

# STUDYING THE NUCLEAR (AND NEUTRON) MATTER EQUATION OF STATE WITH THE CBM EXPERIMENT AT FAIR

Kshitij Agarwal

Eberhard Karls Universität Tübingen (DE)

*Hirschegg 2020 – Nuclear Equation Of State and Neutron Stars*

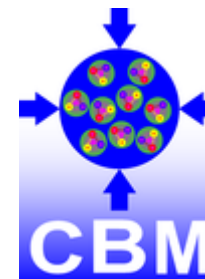
*International Workshop XLVIII on Gross Properties of Nuclei and Nuclear Excitations*

*Hirschegg, Kleinwalsertal, Austria, January 12 - 18, 2020*

EBERHARD KARLS  
UNIVERSITÄT  
TÜBINGEN



MATHEMATISCH-  
NATURWISSENSCHAFTLICHE FAKULTÄT  
Physikalisches Institut



- **Heavy Ion Collisions  $\leftrightarrow$  Astrophysical Events & Objects**
- **High Density EoS Observables for CBM@FAIR**
  - **Nuclear Symmetric Matter EOS**
  - **Neutron Matter EOS**
    - **Symmetry Energy**
    - **Hyperons in Dense Matter:  $\Lambda N$ ,  $\Lambda NN$ , and  $\Lambda\Lambda N$  interactions**
- **Experimental Challenges**
- **Summary and Outlook**

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## Other relevant 'experiment' talks in this workshop:

- **Mo. 17:00**                      **William Lynch (MSU) – Experimental Constraints on the EoS of Dense Matter**
- **Mo. 17:40**                      **Peter Senger (GSI) – Nuclear Equation of State from Reactions**
- **Wed. 17:00**                      **Arnaud Le Fevre (GSI) – Asymmetry energy and nuclear matter EoS: What have we learnt from experiments at SIS18?**

HEAVY ION COLLISIONS



ASTROPHYSICAL EVENTS AND OBJECTS

# HEAVY ION COLLISIONS $\leftrightarrow$ ASTROPHYSICAL EVENTS & OBJECTS

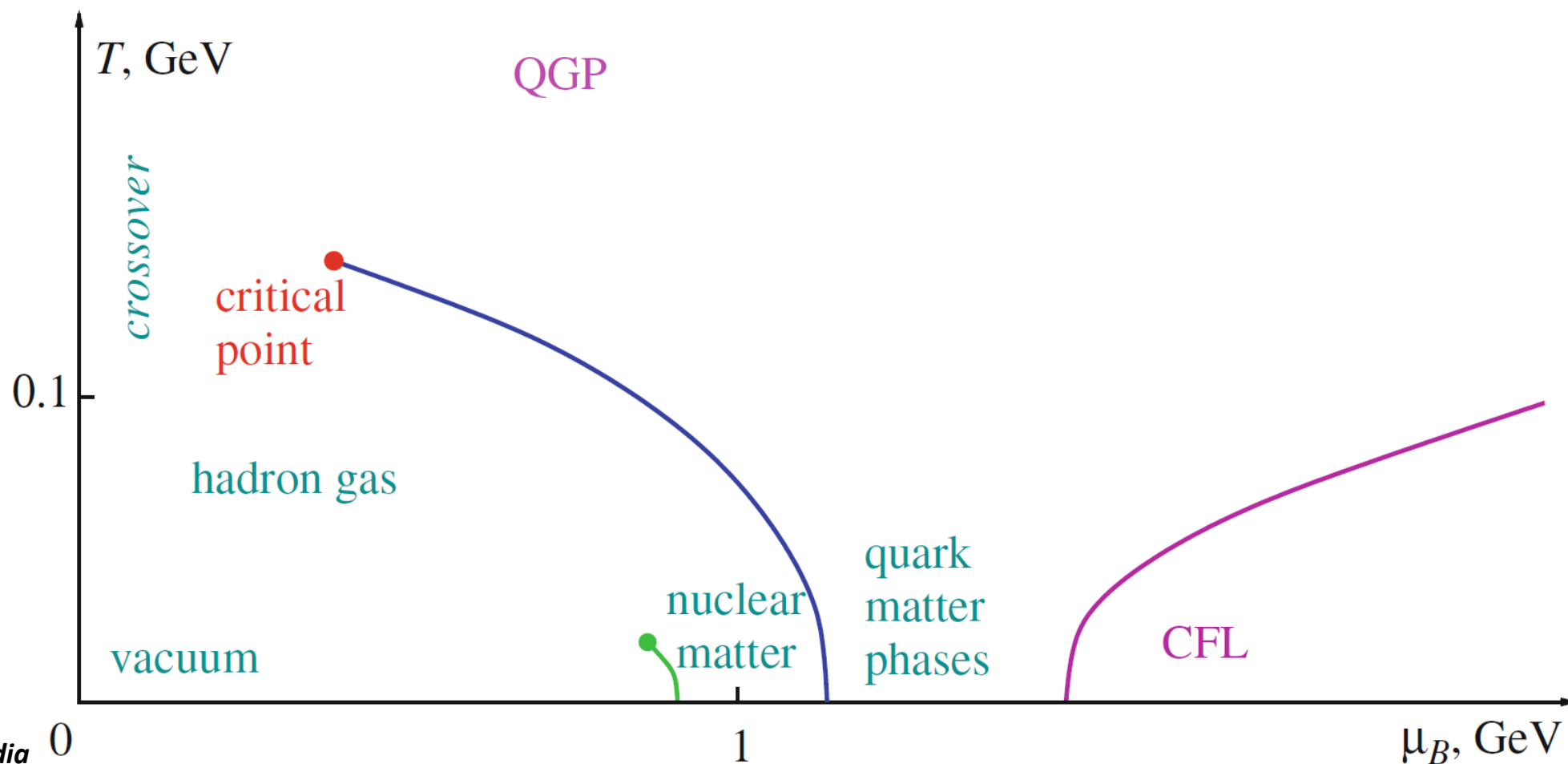
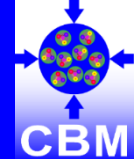


Image credits: Wikimedia

Robin Dienel, Carnegie Institution for Science  
Friman et al., *The CBM Physics Book*, Springer (2010)  
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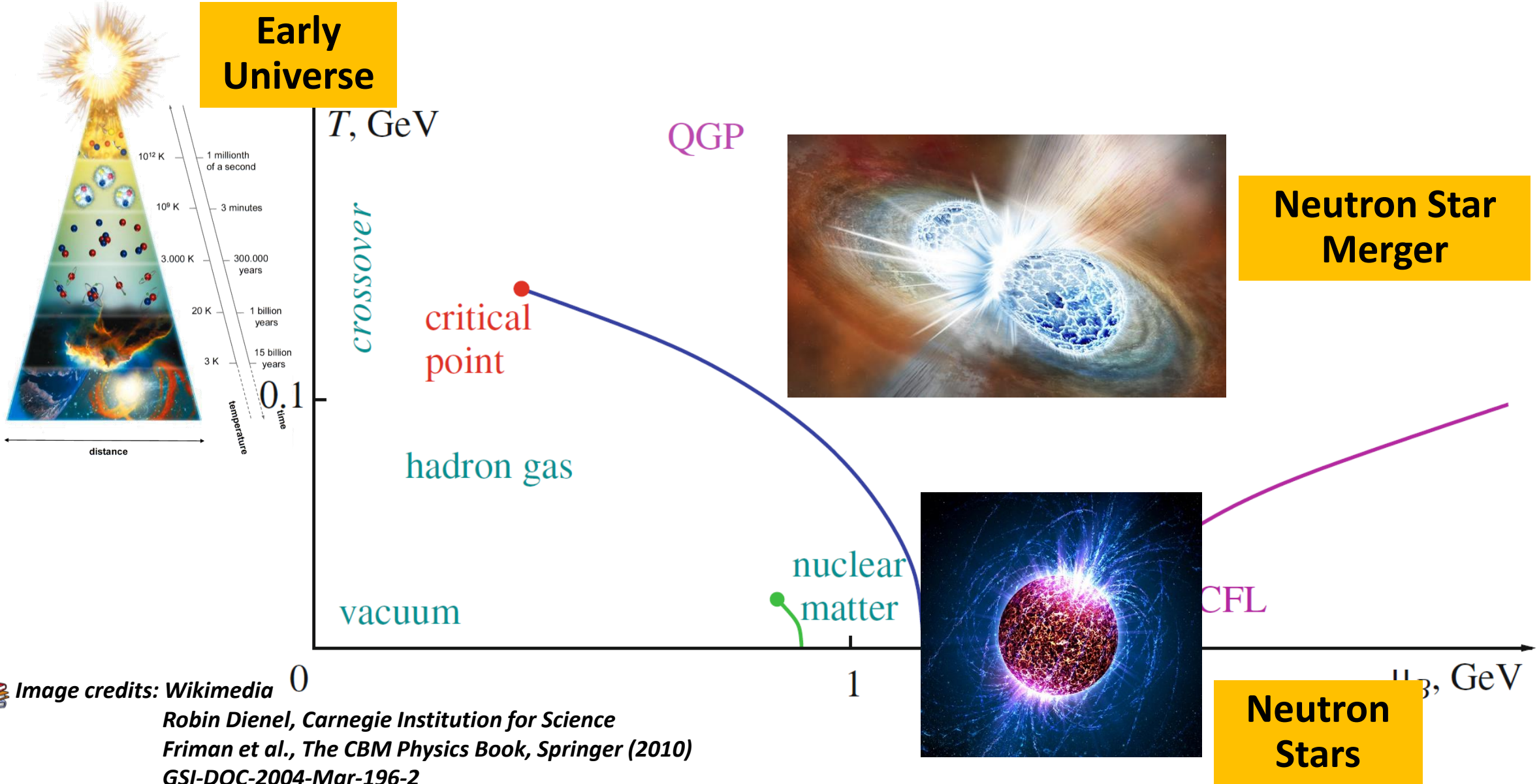
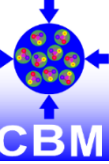


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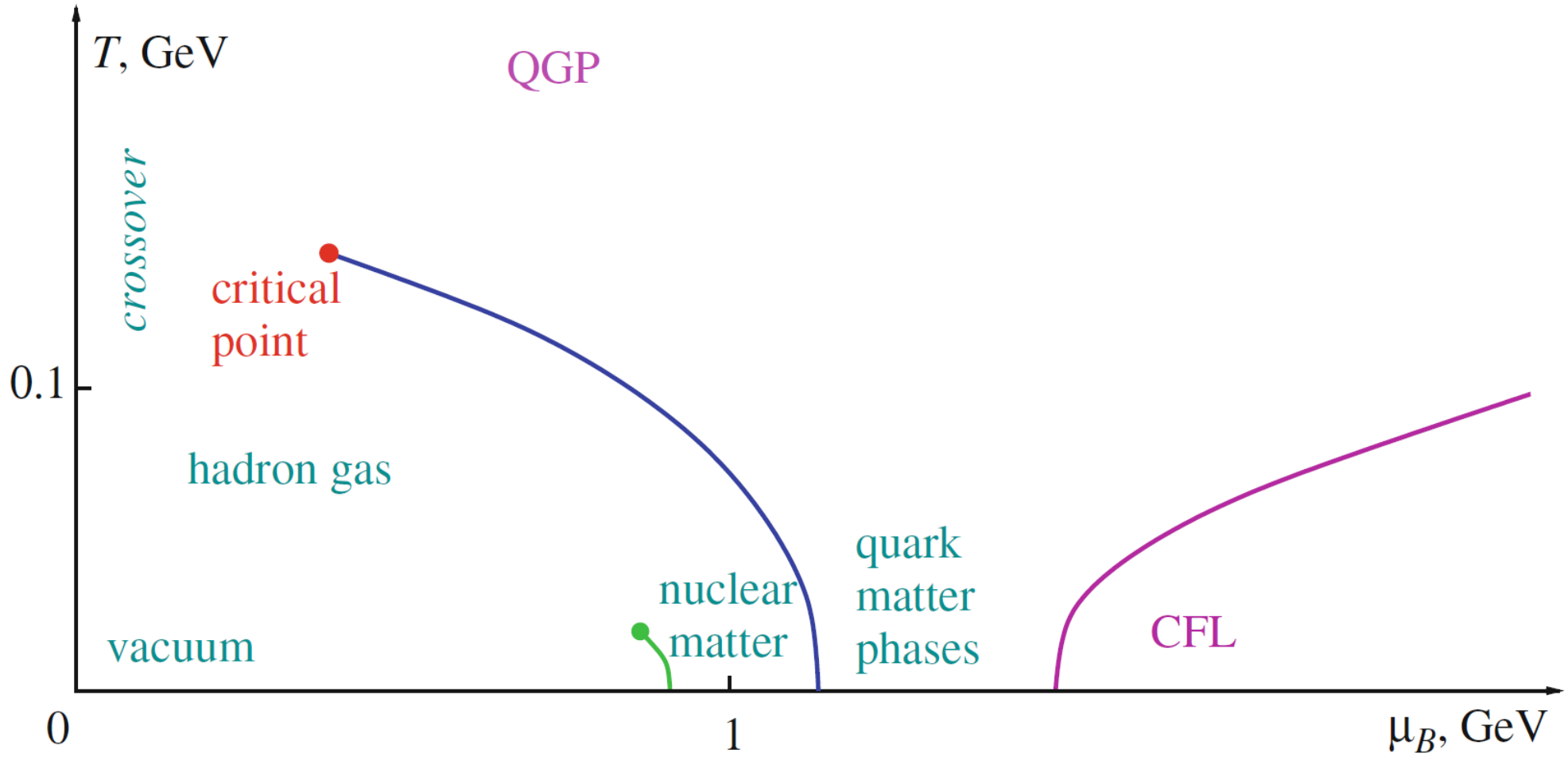
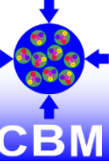


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T. Galatyuk, WE-Heraeus Physics School – 2017

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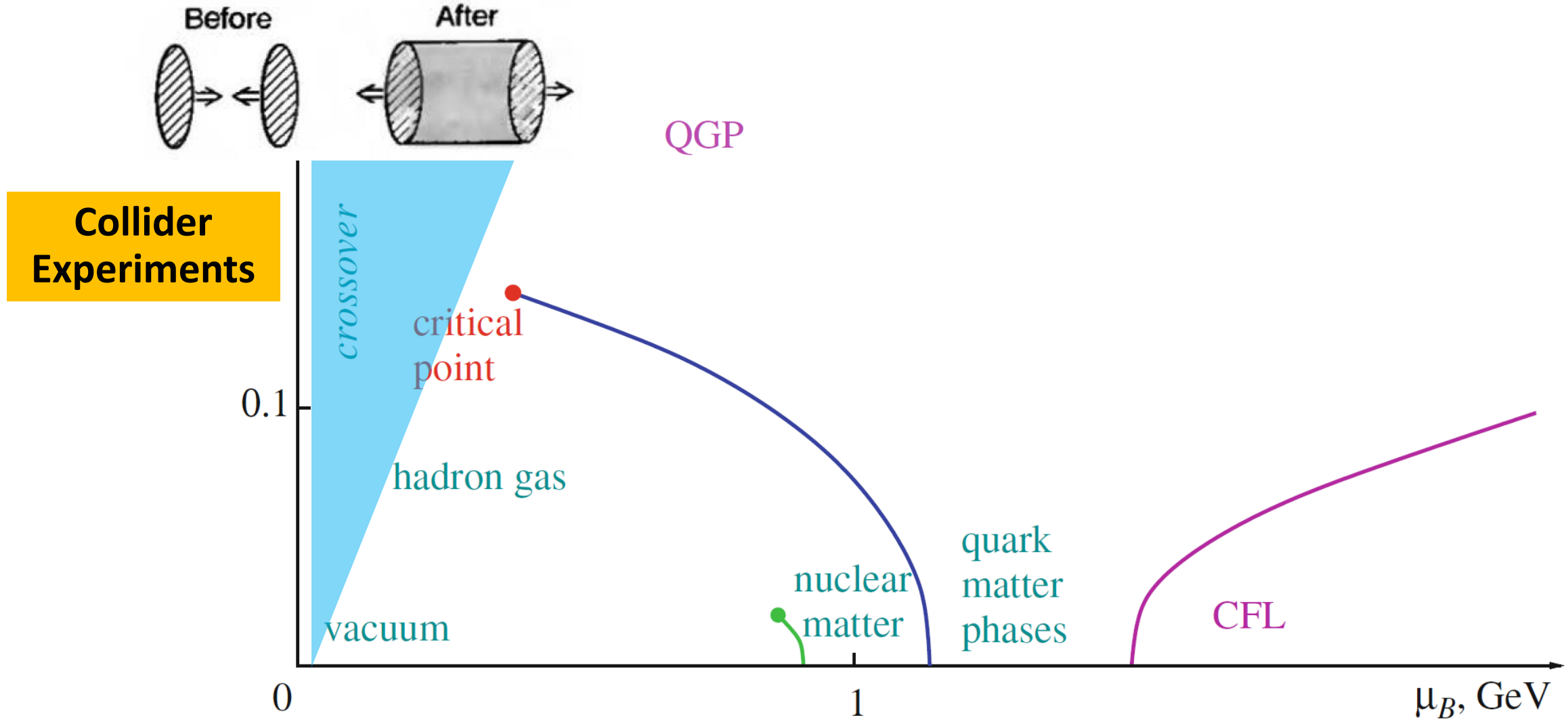
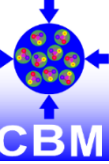


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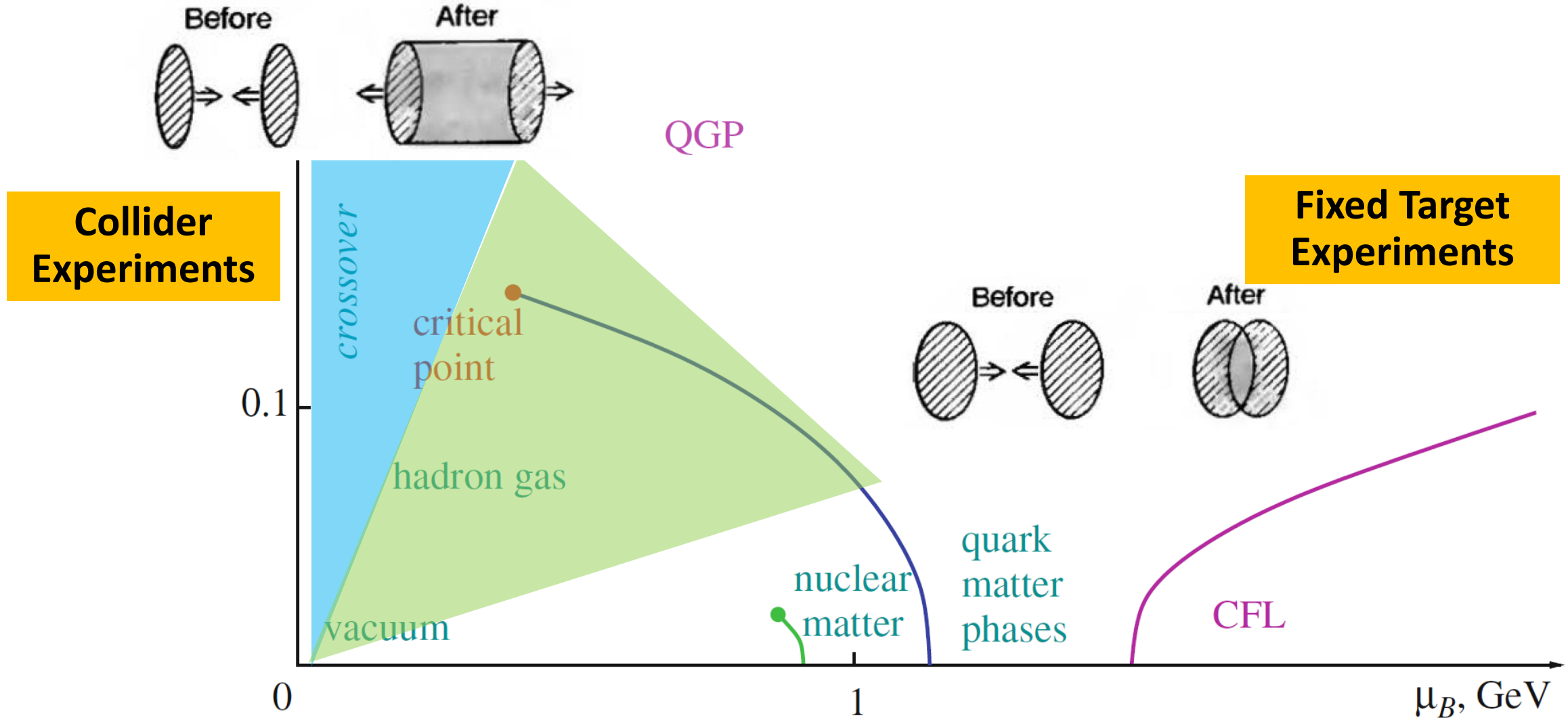
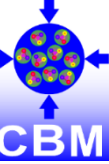


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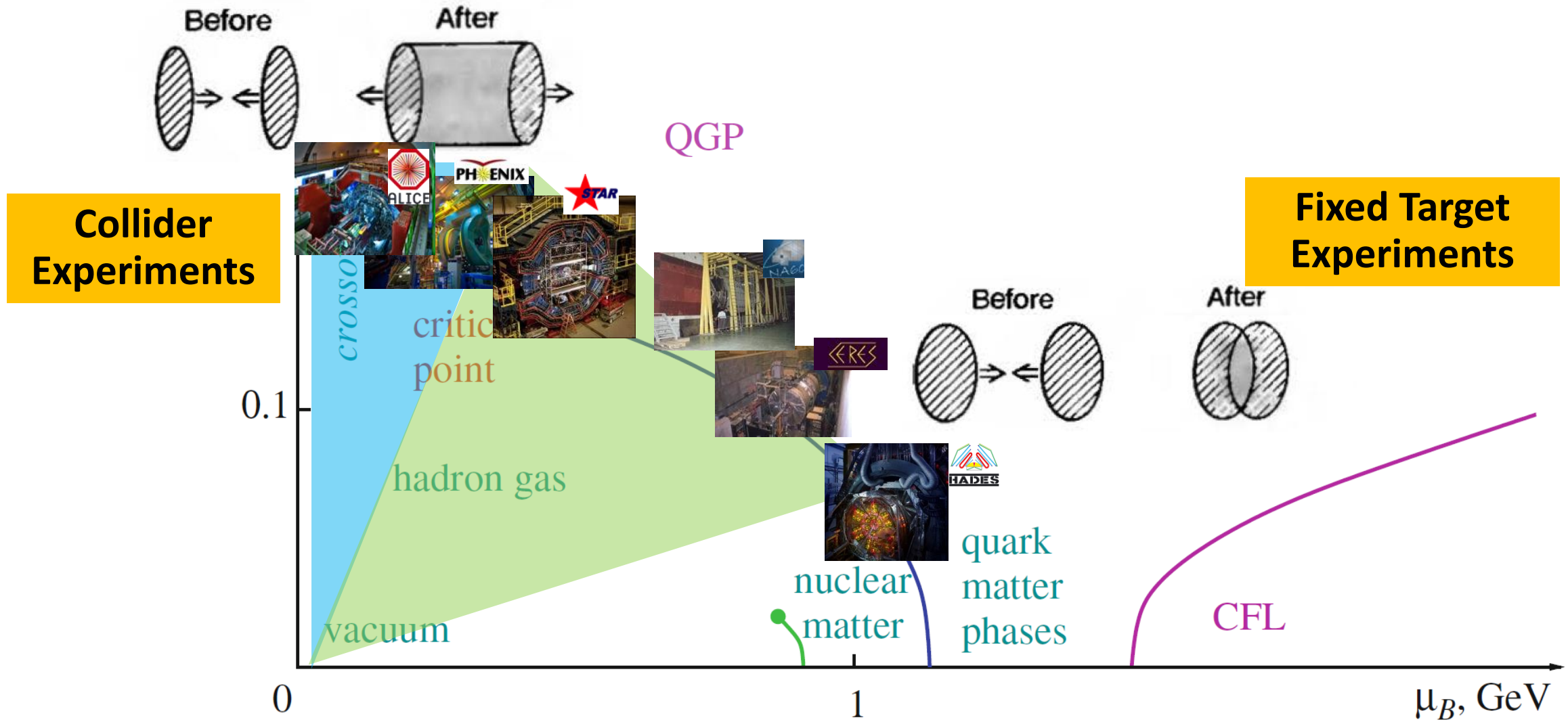
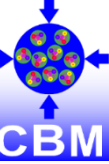
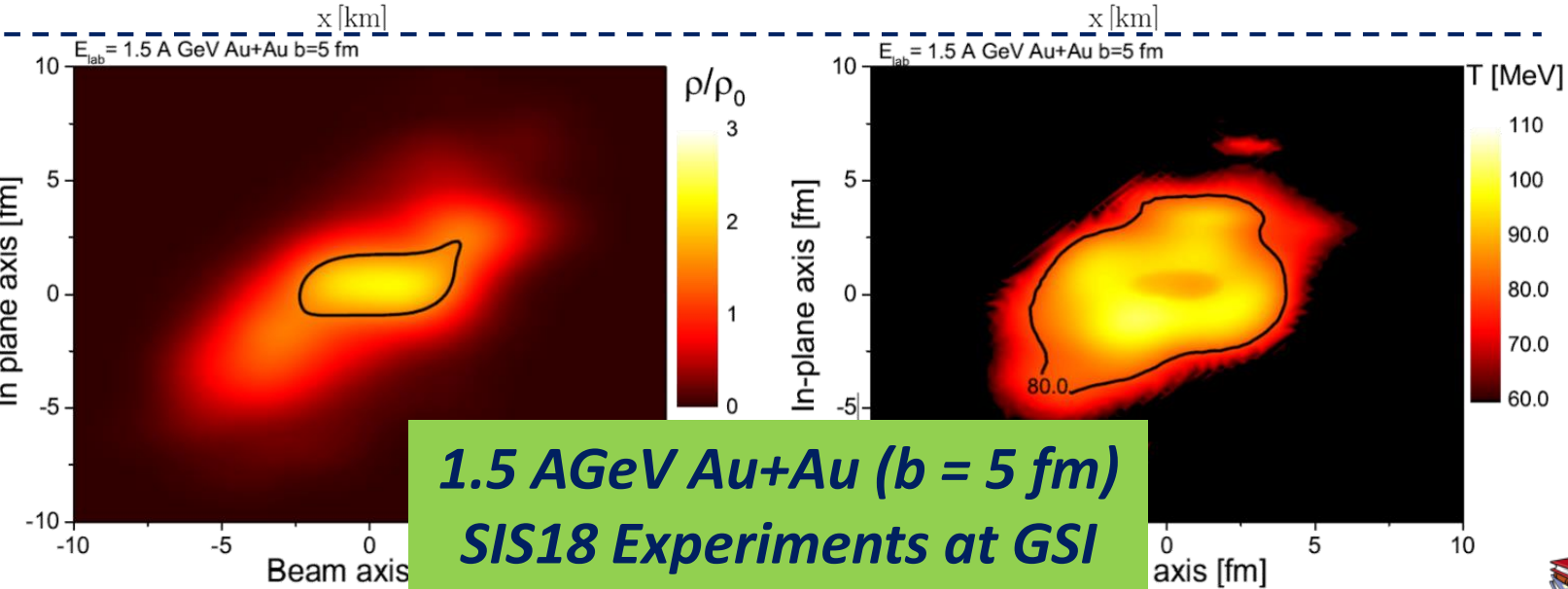
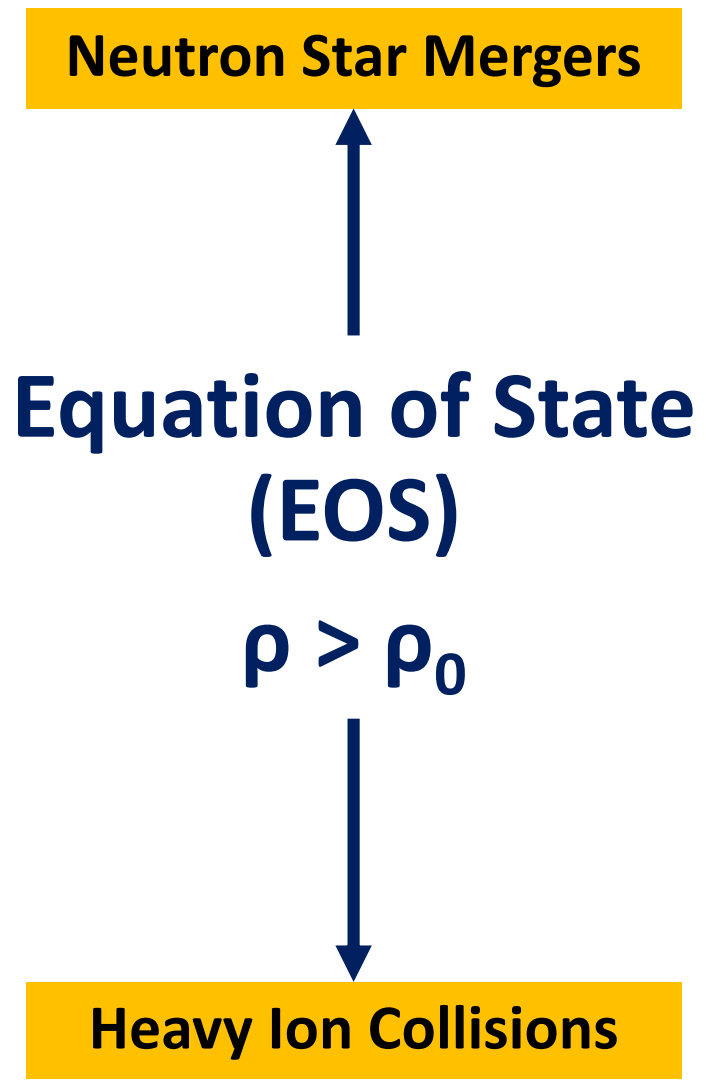
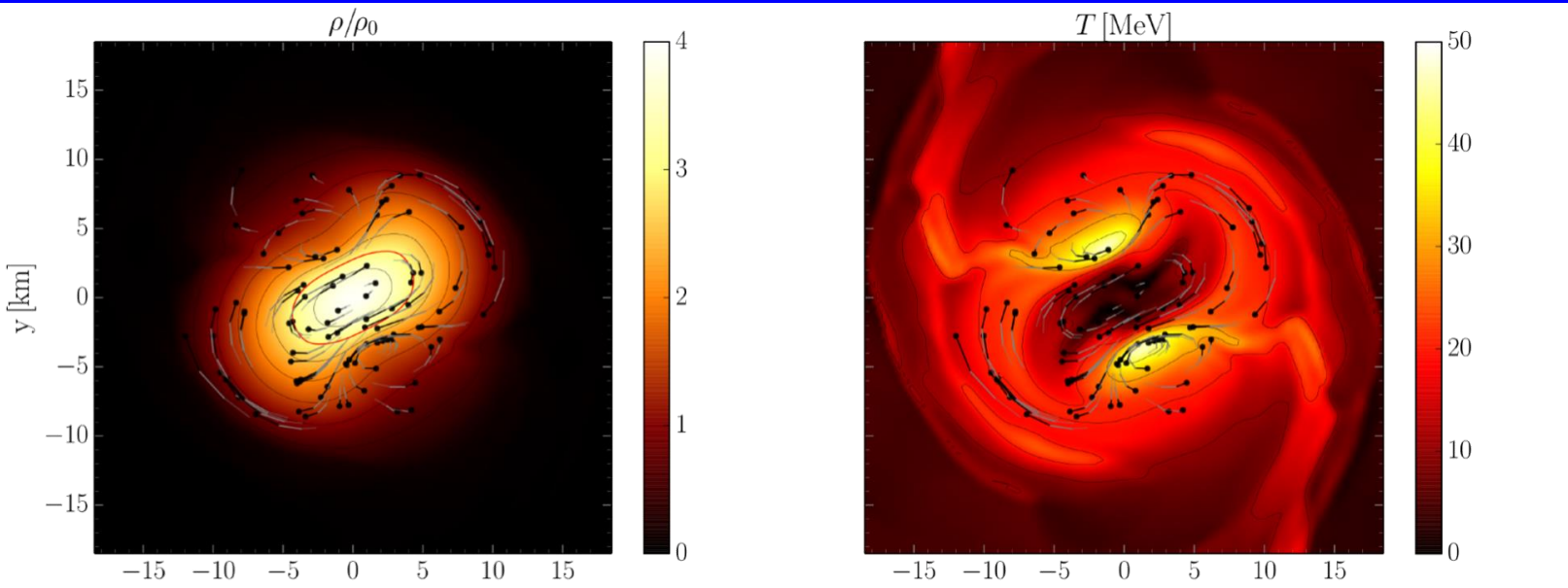
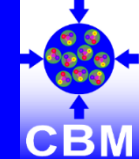


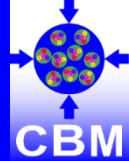
Image credits: Friman et al., *The CBM Physics Book*, Springer (2010)  
 T. Galatyuk, *WE-Heraeus Physics School* – 2017

# CREATING HIGH-DENSITY (AND HIGH-TEMPERATURE) MEDIUM

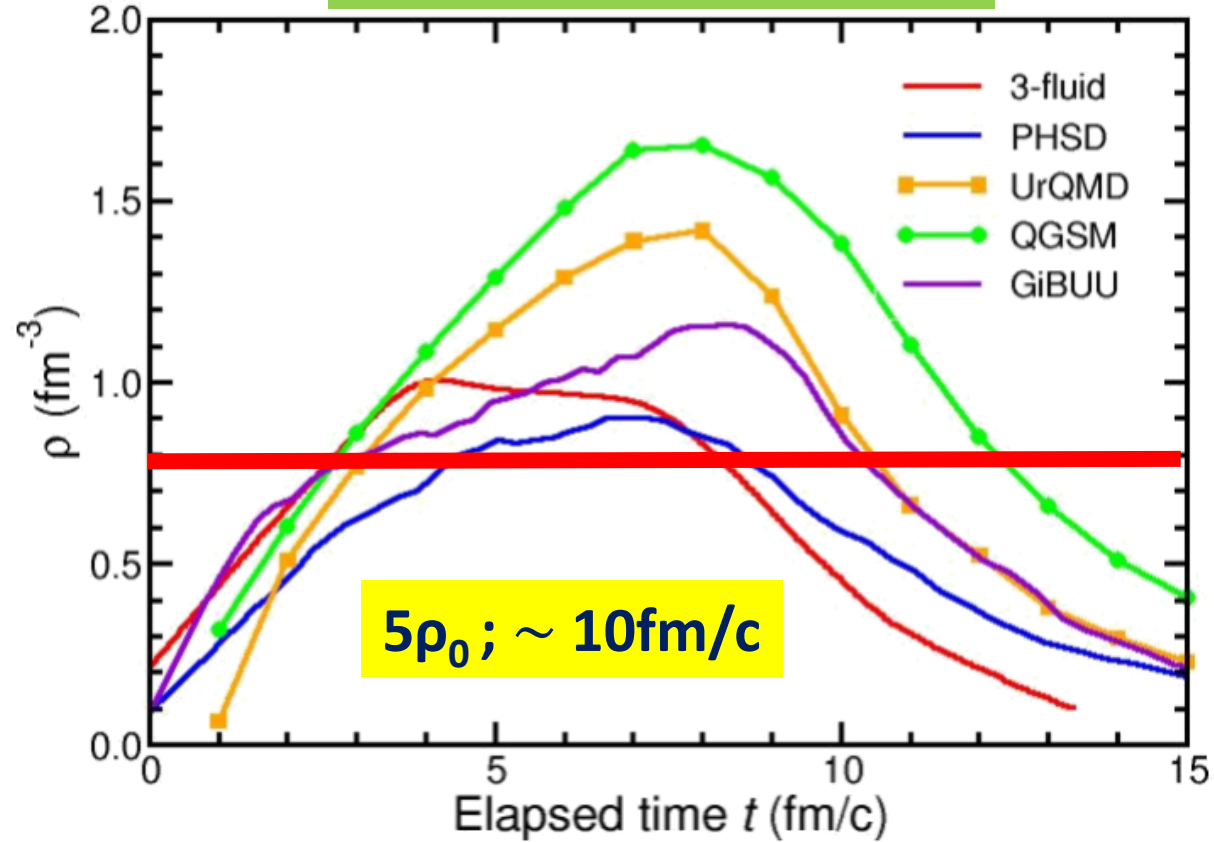


M. Hanauske et al., 2017 J. Phys.: Conf. Ser. 878 012031

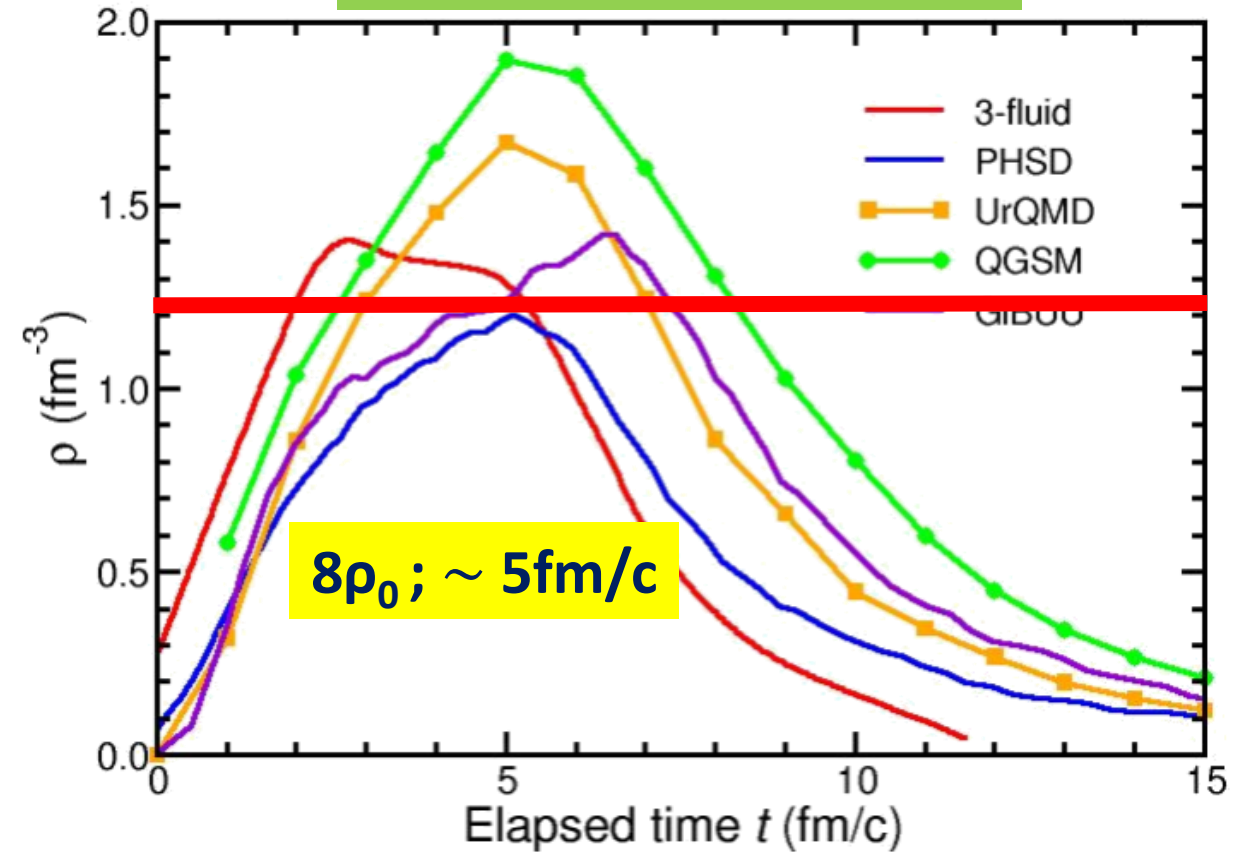
# EVEN HIGHER ACHIEVABLE DENSITIES IN Au-AU COLLISIONS



5 A GeV Au+Au ( $b = 0$ )



10 A GeV Au+Au ( $b = 0$ )



**Compressed Baryonic Matter (CBM) Experiment**  
**GSI-FAIR SIS100 accelerator – 11 AGeV (Au),  $8\rho_0$**

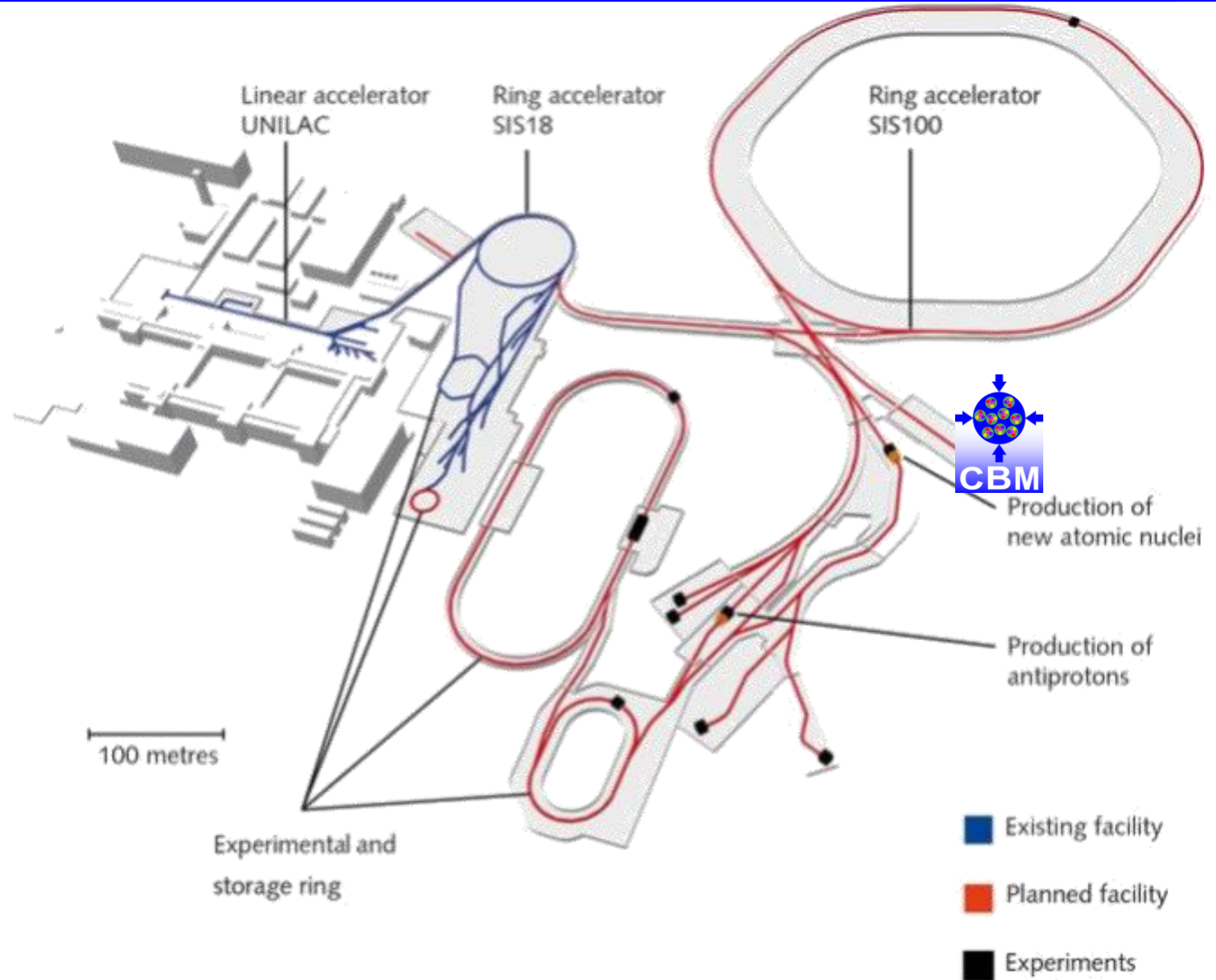
J. Randrup & J. Cleymans, *PRC* 74 (2006) 047901  
 I.C. Arsene et al., *PRC* 75 (2007) 034902  
 Friman et al., *The CBM Physics Book*, Springer (2010)

## Collision Energies and Systems available at SIS100

Beam	Z	A	E (AGeV)
p	1	1	29
d	1	2	14
Ca	20	40	14
Ni	28	58	13.6
In	49	115	11.9
Au	79	197	11
U	92	238	10.7

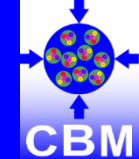
## CBM Collision Energies:

$$\sqrt{s_{NN}} = 2.5 \dots 4.9 \text{ GeV}$$



# HIGH DENSITY EOS OBSERVABLES FOR CBM@FAIR

# NUCLEAR MATTER EQUATION OF STATE (EOS)



**EOS** – Equation relating the state variables, such as pressure, temperature, density, energy and isospin asymmetry, under a given set of physical conditions

**Binding Energy per nucleon:**  
(semi-empirical mass formula)

$$\frac{E}{A}(\delta) = \underbrace{\left[ -a_{vol} + \frac{a_{surf}}{A^{1/3}} + a_c \frac{Z^2}{A^{4/3}} + \frac{E_{pair}}{A} \right]}_{\text{Symmetry Term}} + \underbrace{\left[ a_{sym} \left( \frac{N-Z}{A} \right)^2 \right]}_{\text{Asymmetry Term}}$$

**Symmetry Term**  
# protons = # neutrons

**Asymmetry Term**  
# protons ≠ # neutrons

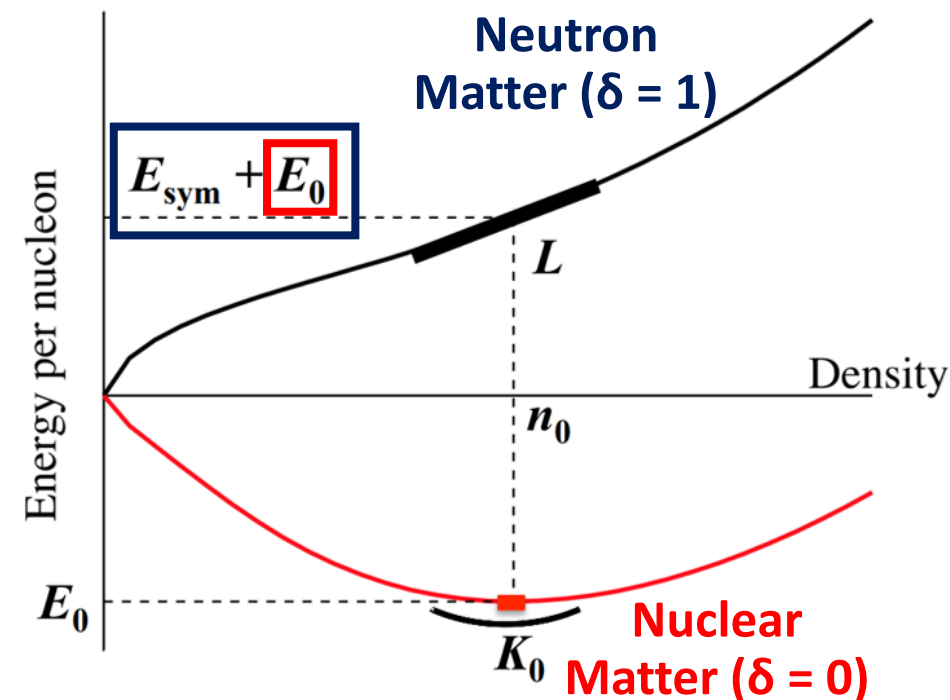
$$\frac{E}{A}(\rho, \delta) = \left[ \frac{E}{A}(\rho, 0) \right] + [E_{sym}(\rho) \times \delta^2]$$

**Neutron  
Matter EOS**

**Nuclear/Symmetric  
Matter EOS**

**Symmetry  
Energy**

where,  $\delta = \frac{\rho_N - \rho_P}{\rho_N + \rho_P}$



# EoS W/ CBM CASE #1

SYMMETRIC MATTER EQUATION OF STATE

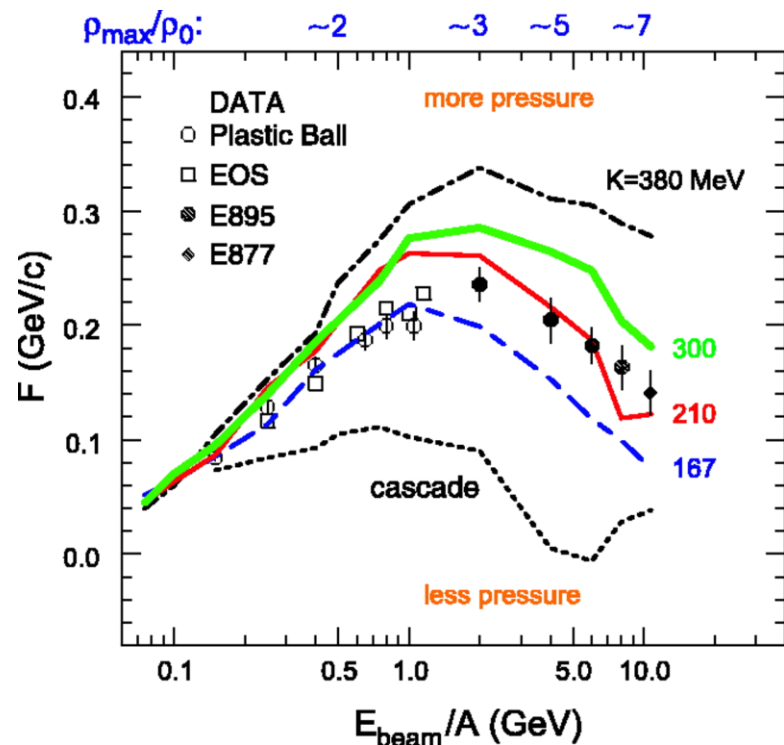
$$E_A(\rho, \delta) = E_A(\rho, 0) + E_{\text{SYM}}(\rho) \cdot \delta^2$$



**Collective flow of nucleons driven by the pressure gradient –  
Sensitive to nuclear incompressibility,  $\kappa \rightarrow$  Equation of State**

**Two observables of the high pressures results in matter to be ejected in specific directions:**

Collective flow of nucleons driven by the pressure gradient –  
Sensitive to nuclear incompressibility,  $\kappa \rightarrow$  Equation of State

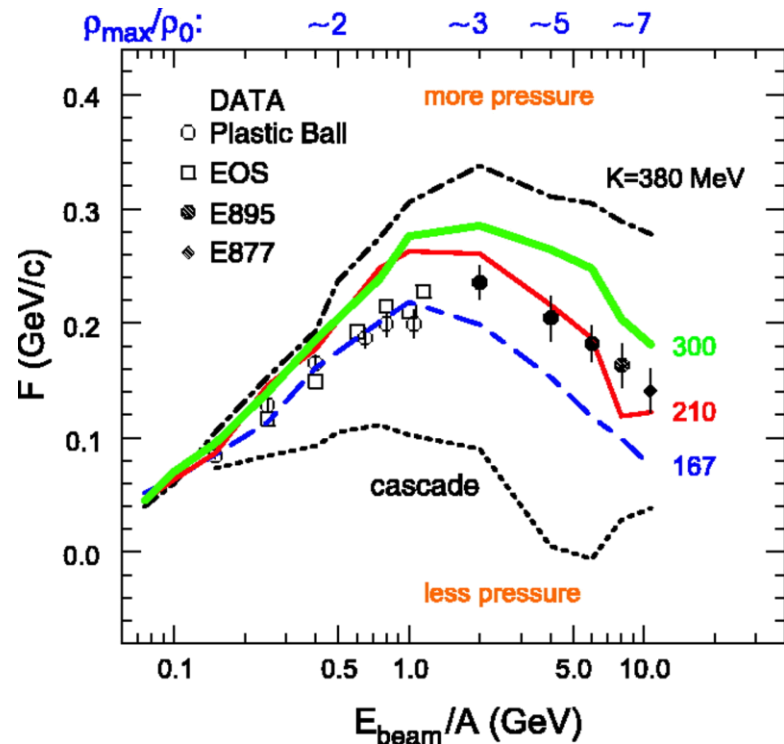


$F \equiv$  Magnitude of  
sideward deflection  
 $\downarrow$   
 $\kappa = 170 - 210 \text{ MeV}$

Two observables of the high pressures results in matter to be ejected in specific directions:

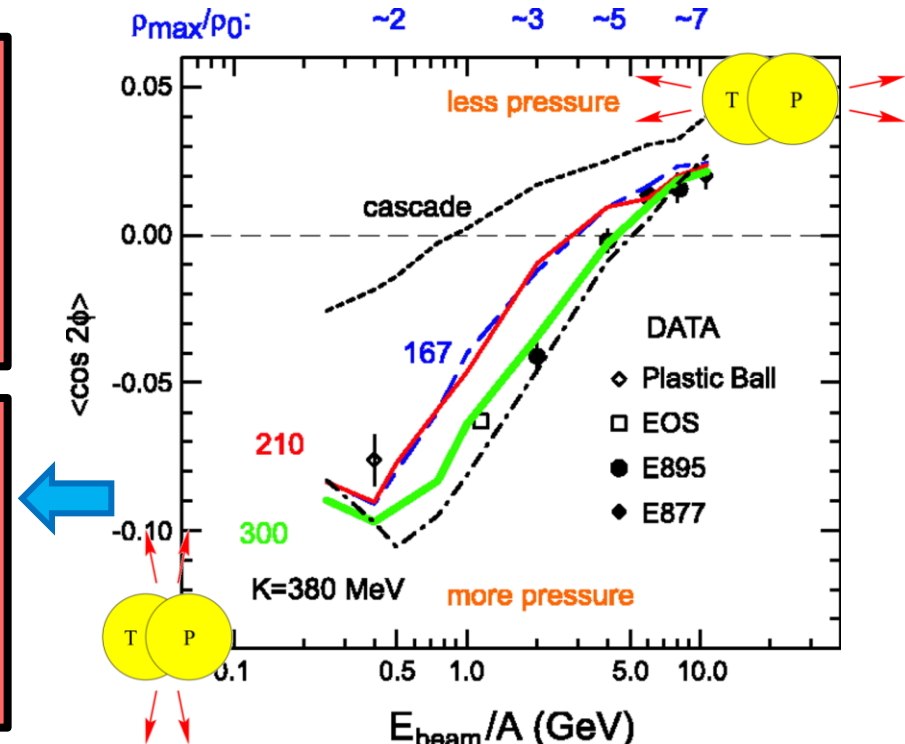
- Directed Flow  $v_1$  Nucleons deflected sideways in the reaction plane

Collective flow of nucleons driven by the pressure gradient –  
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$F \equiv$  Magnitude of  
sideward deflection  
 $\downarrow$   
 $\kappa = 170 - 210 \text{ MeV}$

$\langle \cos(2\phi) \rangle \equiv$  Direction of  
particle ejection  
 $\downarrow$   
 $\kappa = 170 - 370 \text{ MeV}$



Two observables of the high pressures results in matter to be ejected in specific directions:

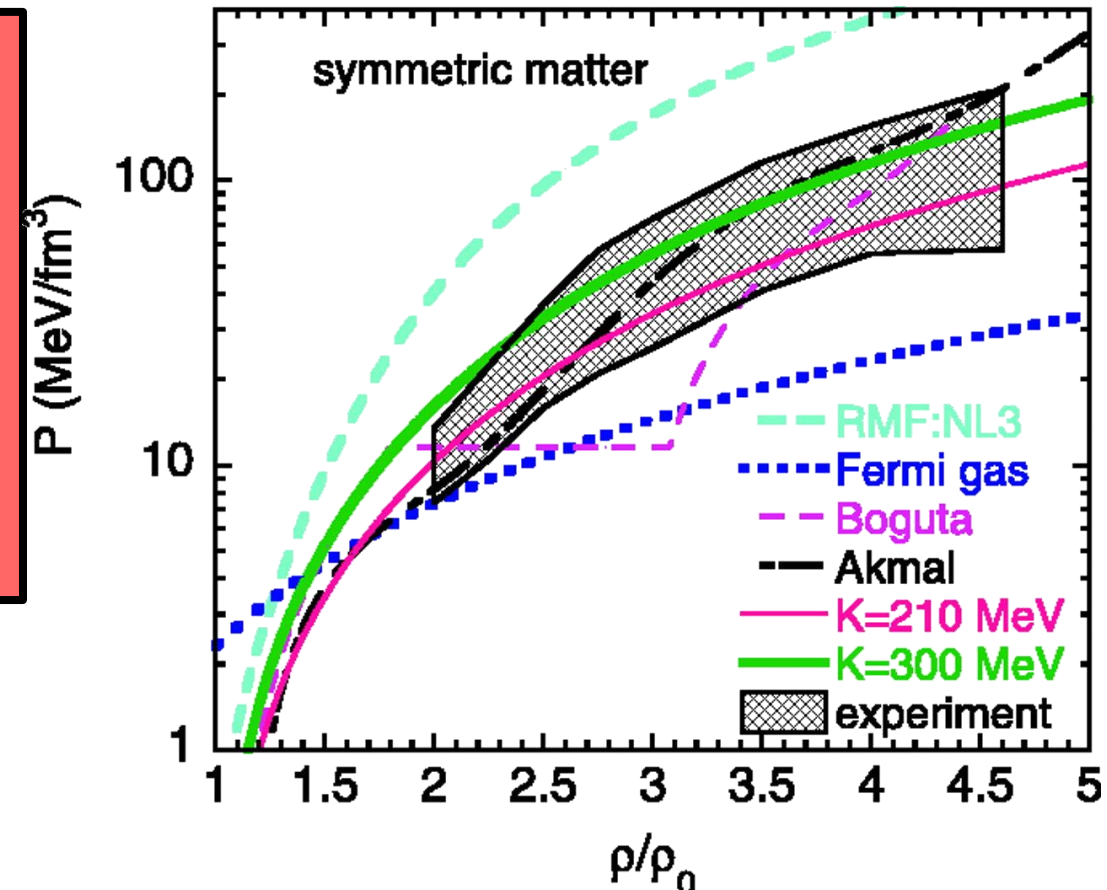
- Directed Flow  $v_1$  Nucleons deflected sideways in the reaction plane
- Elliptic Flow  $v_2$  Nucleons are “squeezed out” above and below or “expanded in” the reaction plane

## Collective flow of nucleons driven by the pressure gradient – Sensitive to nuclear incompressibility, $\kappa \rightarrow$ Equation of State

**Nuclear Incompressibility,  $\kappa \sim 200 - 300$  MeV**

Reflects that the interpretation of proton flow data using transport models is not straight forward as it depends on:

- Equation of state
- In-medium nucleon-nucleon cross section
- In-medium momentum-dependent interactions
- Nucleonic clusters



 P. Danielewicz et al., *Science* 298 (2002) 1592

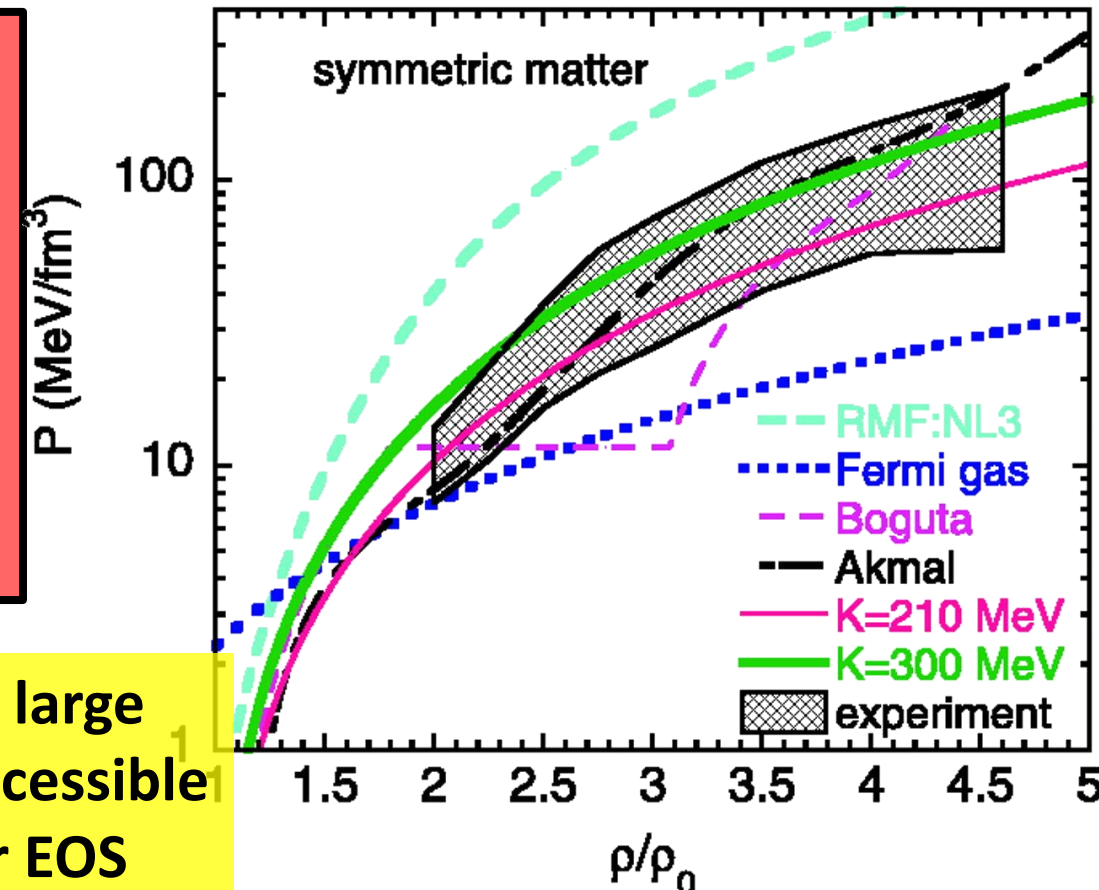
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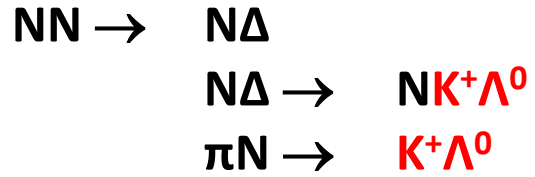
- Equation of state
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**Precise multi-differential flow measurements for a large variety of hadron species over a range of densities accessible with CBM can narrow down the symmetric matter EOS**



 P. Danielewicz et al., *Science* 298 (2002) 1592

**Idea: Strangeness Yield  $\propto$  Baryonic Density  $\propto$  Compressibility  $\propto$  EOS**



$E_{\text{threshold}} = 1.58 \text{ GeV}$

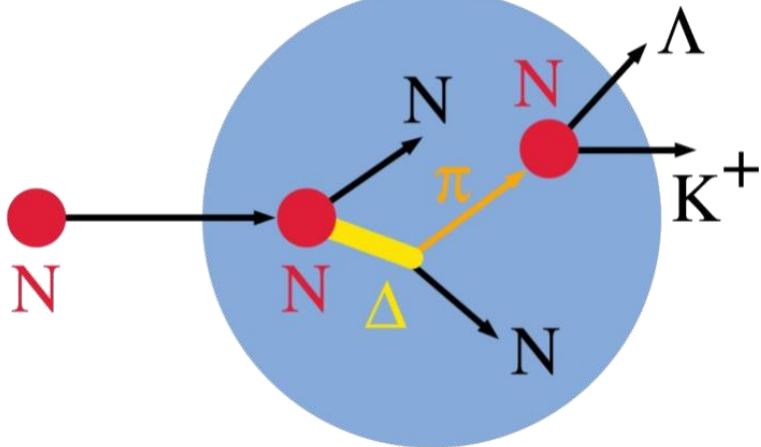
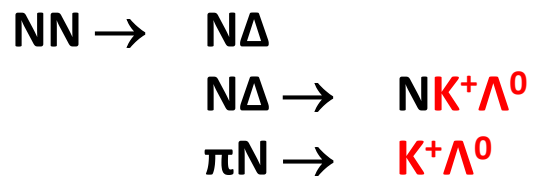


 Image credit: P. Senger, GSI-Darmstadt

**Idea: Strangeness Yield  $\propto$  Baryonic Density  $\propto$  Compressibility  $\propto$  EOS**

**Experimentally at SIS18: Measuring  $K^+$  yields in a system where compression is expected (Au-Au) w.r.t. system where no compression is expected (C-C)**



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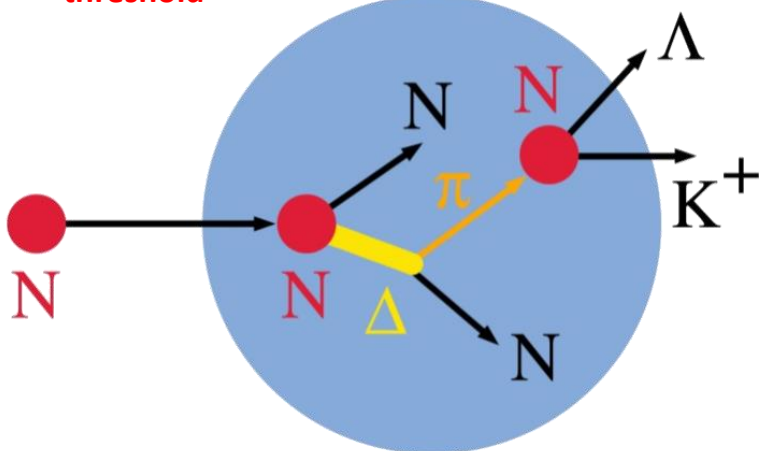
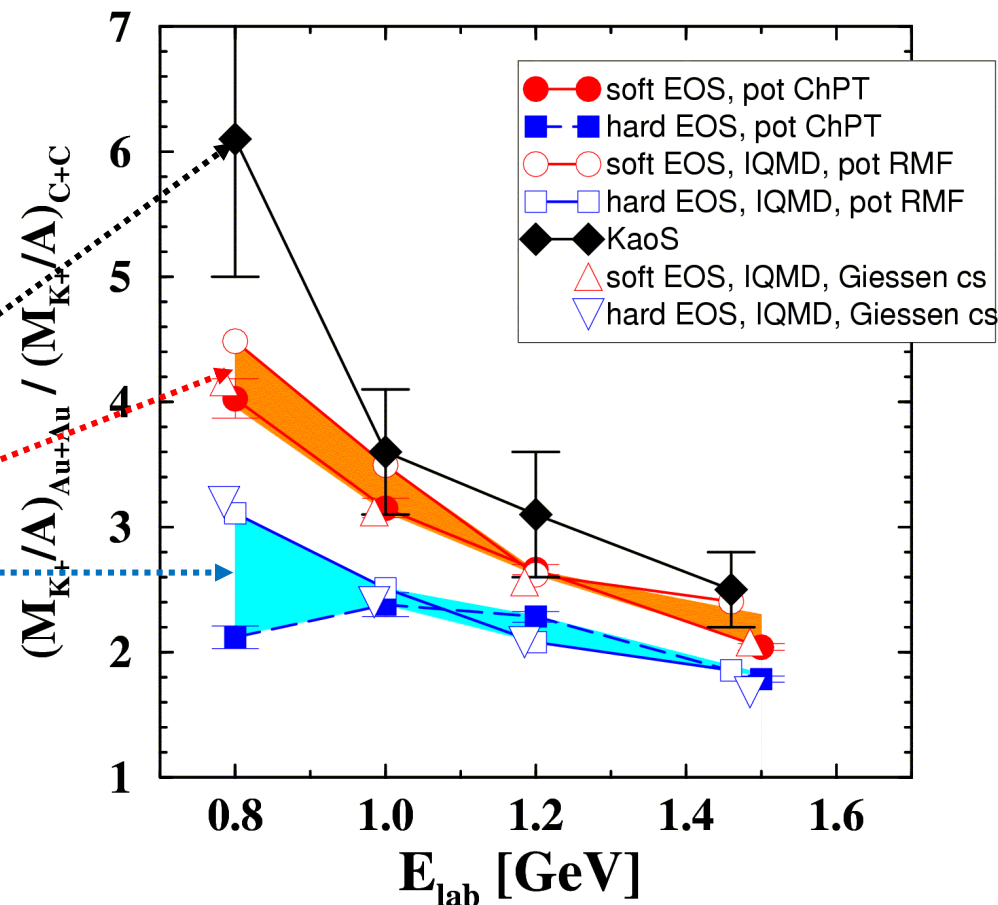


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KaoS (Exp.)

Soft EOS (Th.)

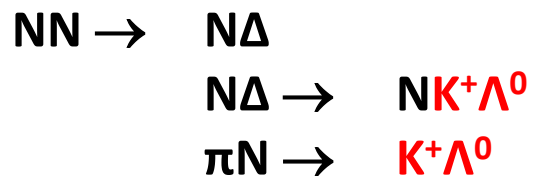
Hard EOS (Th.)



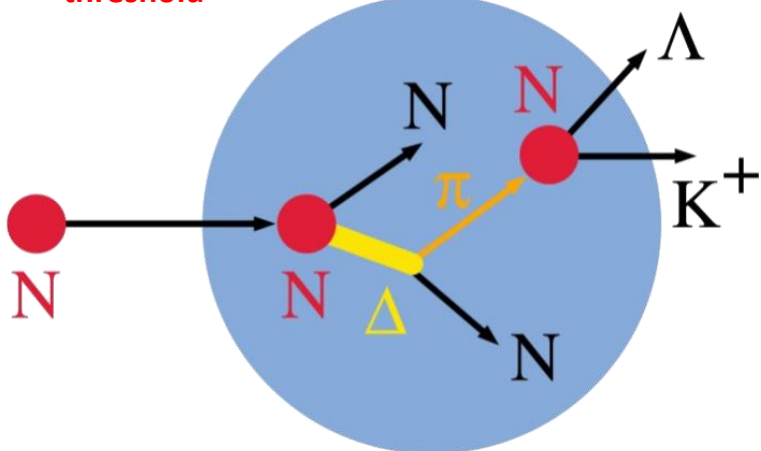
**Experiment:** C. Sturm et al., (KaoS Collaboration) *Phys. Rev. Lett.* **86** (2001) 39  
**Theory:** QMD Ch. Fuchs et al., *Phys. Rev. Lett.* **86** (2001) 1974  
 IQMD Ch. Hartnack, J. Aichelin, *J. Phys. G* **28** (2002) 1649

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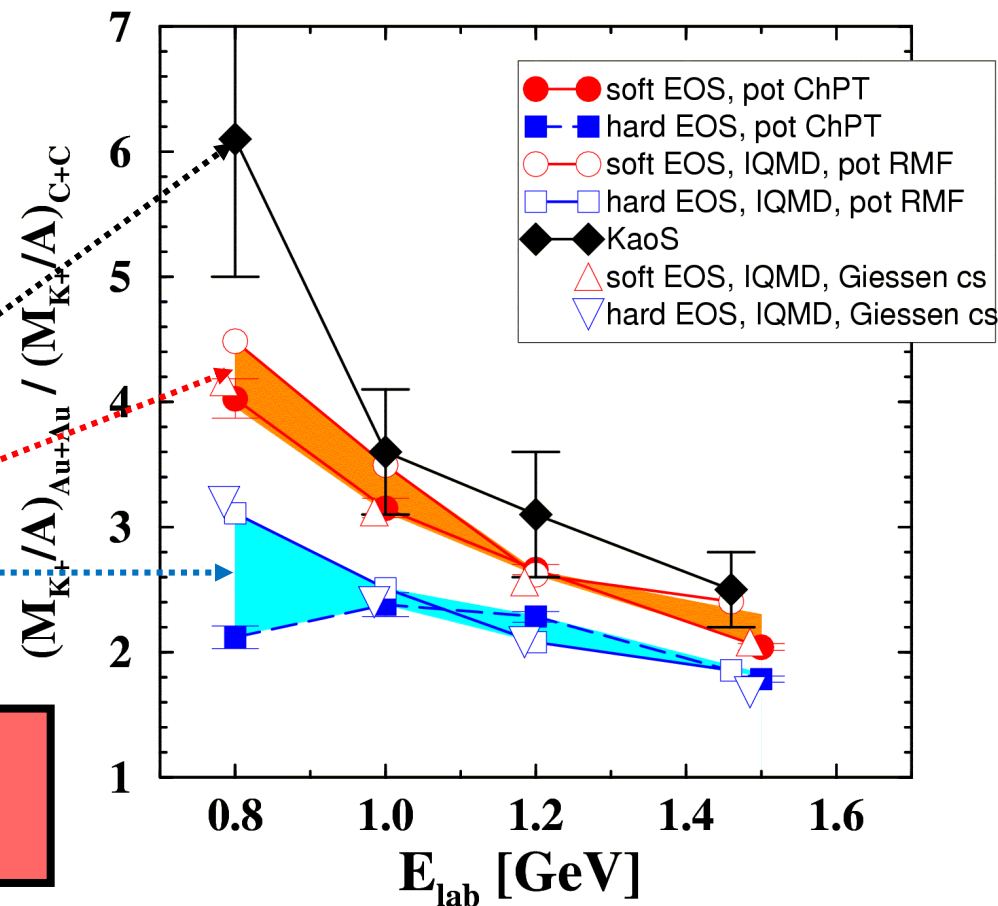


KaoS (Exp.)

Soft EOS (Th.)

Hard EOS (Th.)

**Soft Nuclear EOS**  
 $\kappa \approx 200 (2-3 \rho_0)$




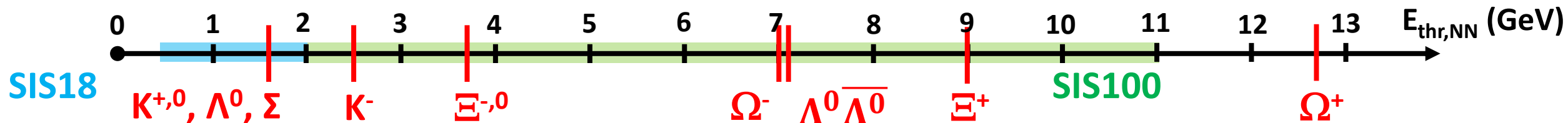
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 Image credit: P. Senger, GSI-Darmstadt



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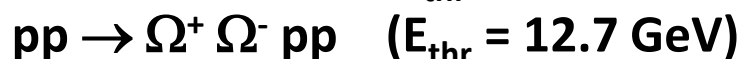
## Direct Kaon & Hyperon

### Production:

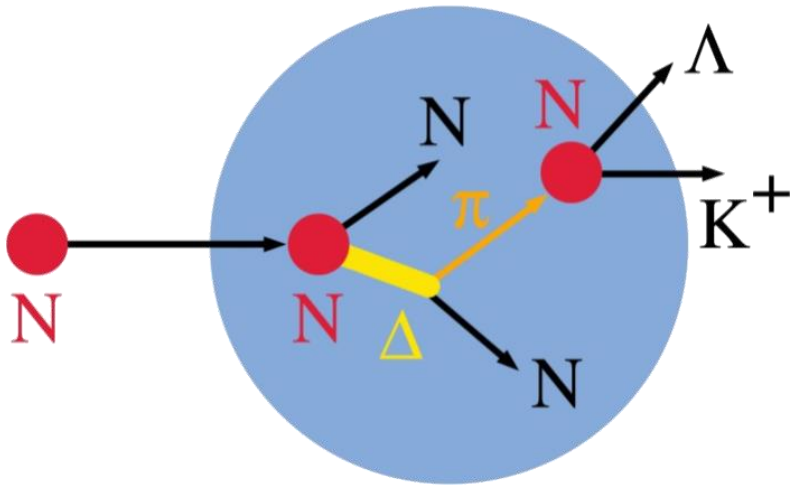
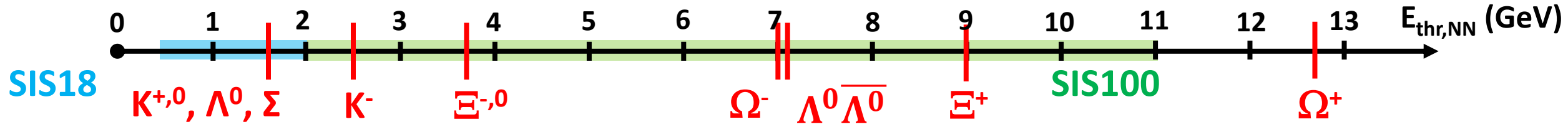


## Direct Multi-Strange Hyperon

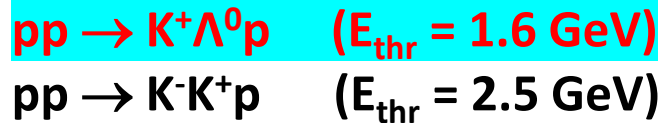
### Production:



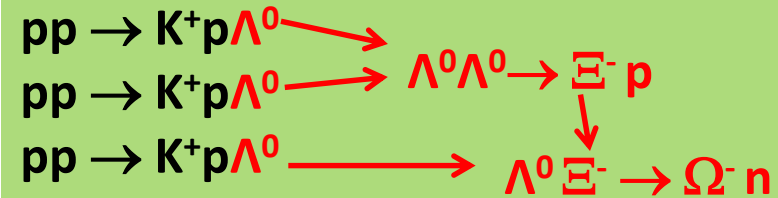
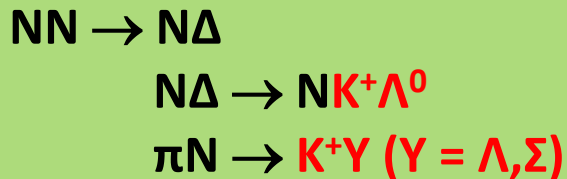
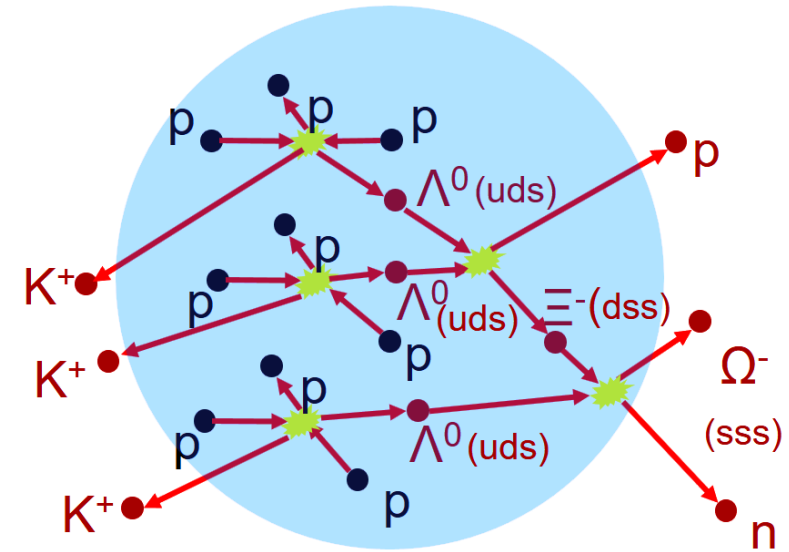
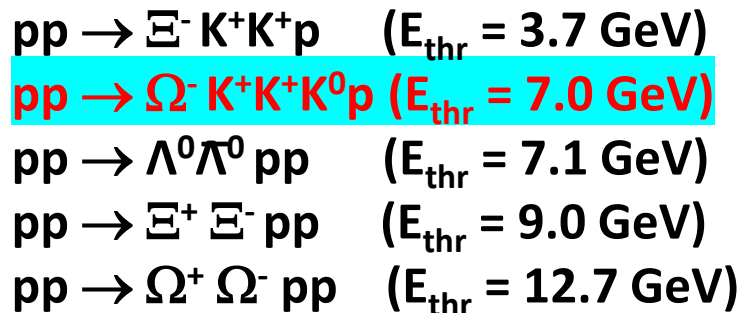
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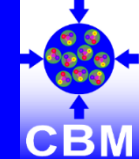
### Direct Kaon & Hyperon Production:



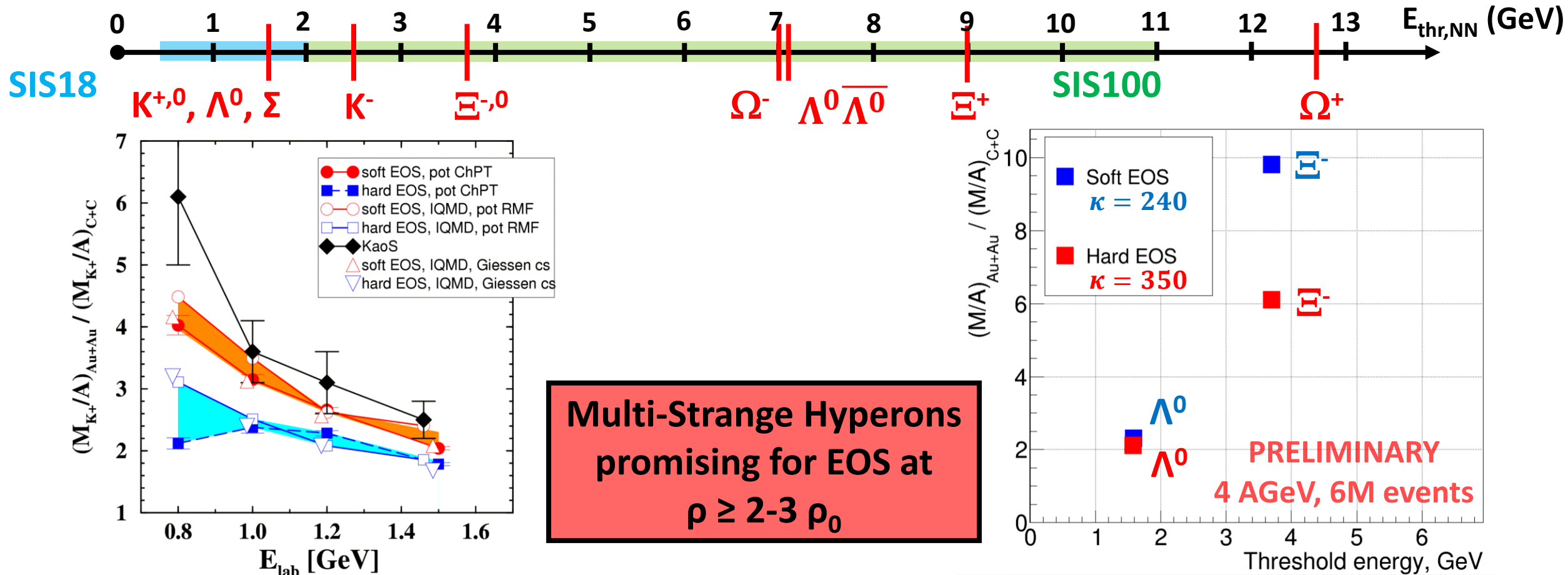
### Direct Multi-Strange Hyperon Production:



# EXPERIMENTAL OBSERVABLES [II] – (SUB)THRESHOLD PRODUCTION



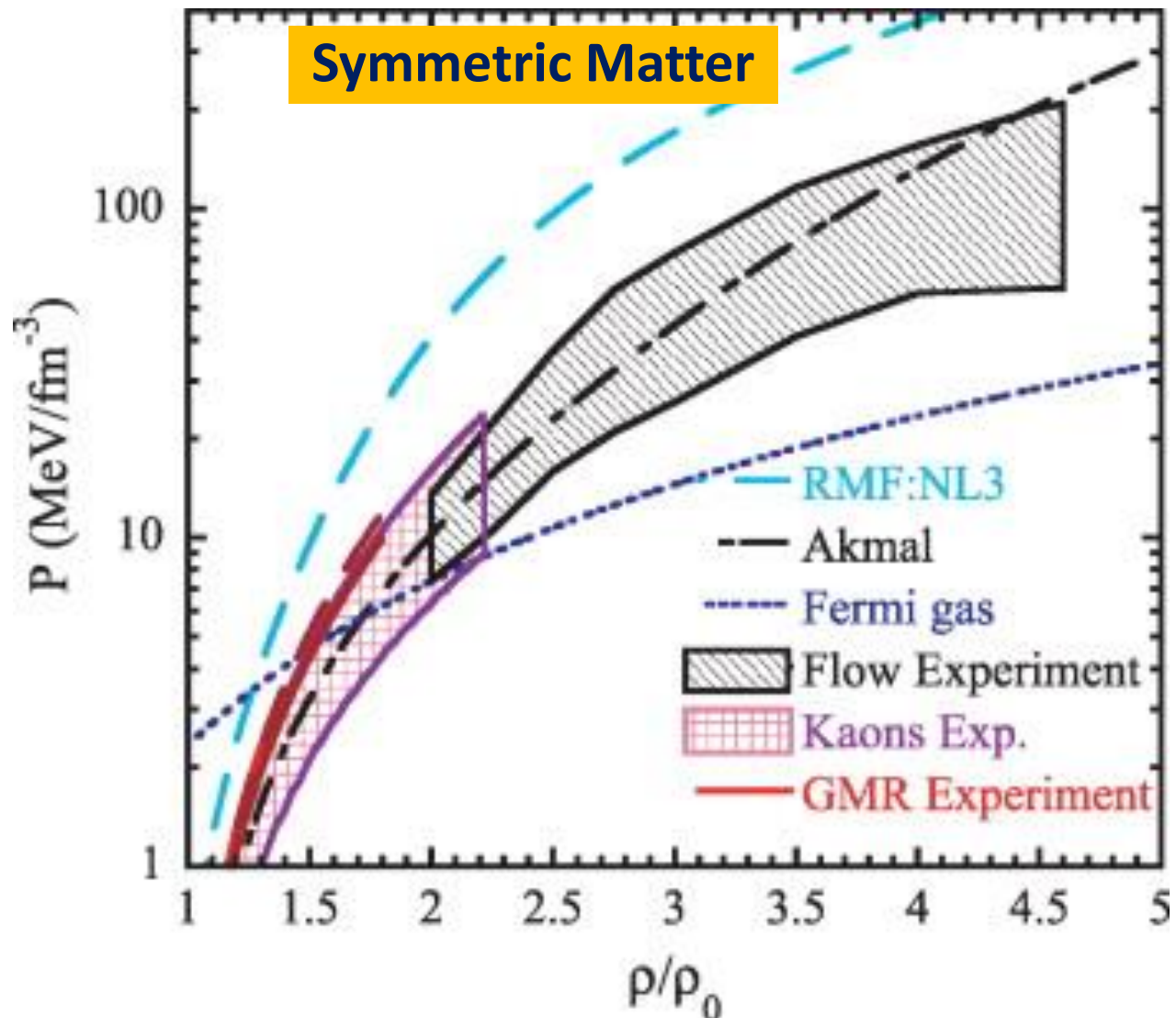
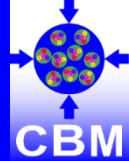
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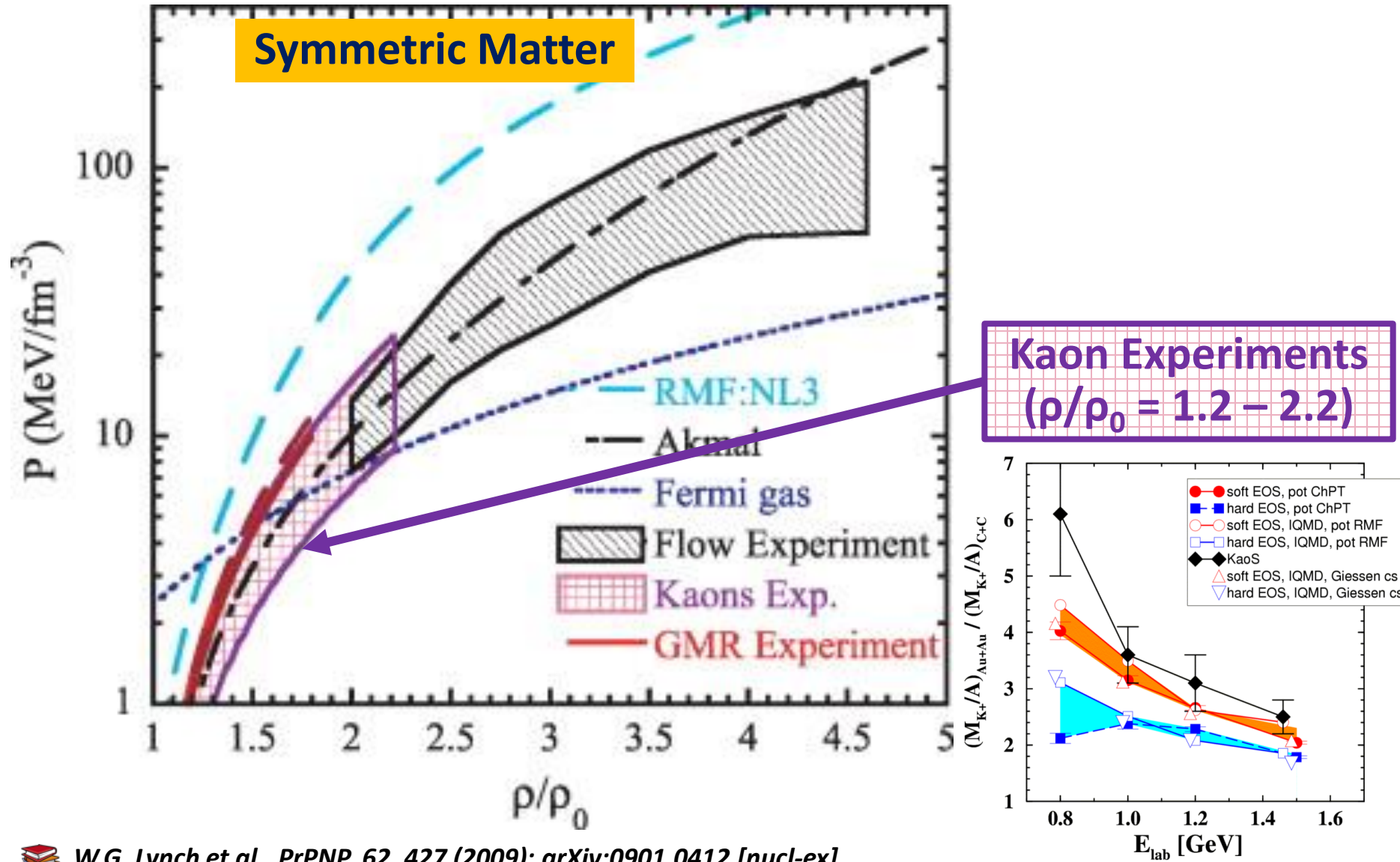
**PHQMD:** J. Aichelin, E. Bratkovskaya, V. Kireyeu et al.  
 P. Senger, 4<sup>th</sup> CBM China Workshop (2019)

# SYMMETRIC MATTER EQUATION OF STATE (EOS) – CURRENT STATUS

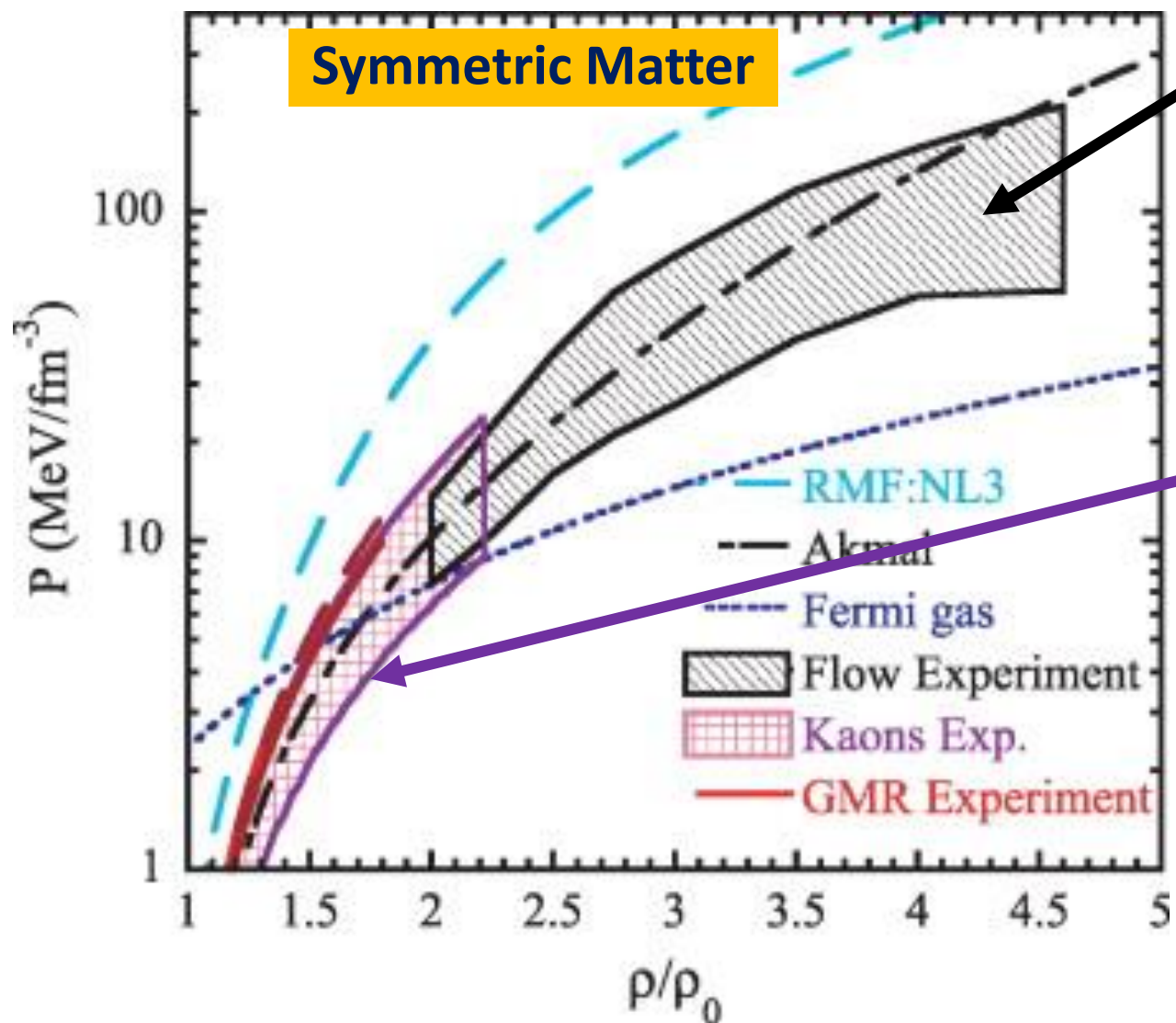
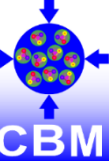


W.G. Lynch et al., *PrPNP*, 62, 427 (2009); [arXiv:0901.0412 \[nucl-ex\]](https://arxiv.org/abs/0901.0412)

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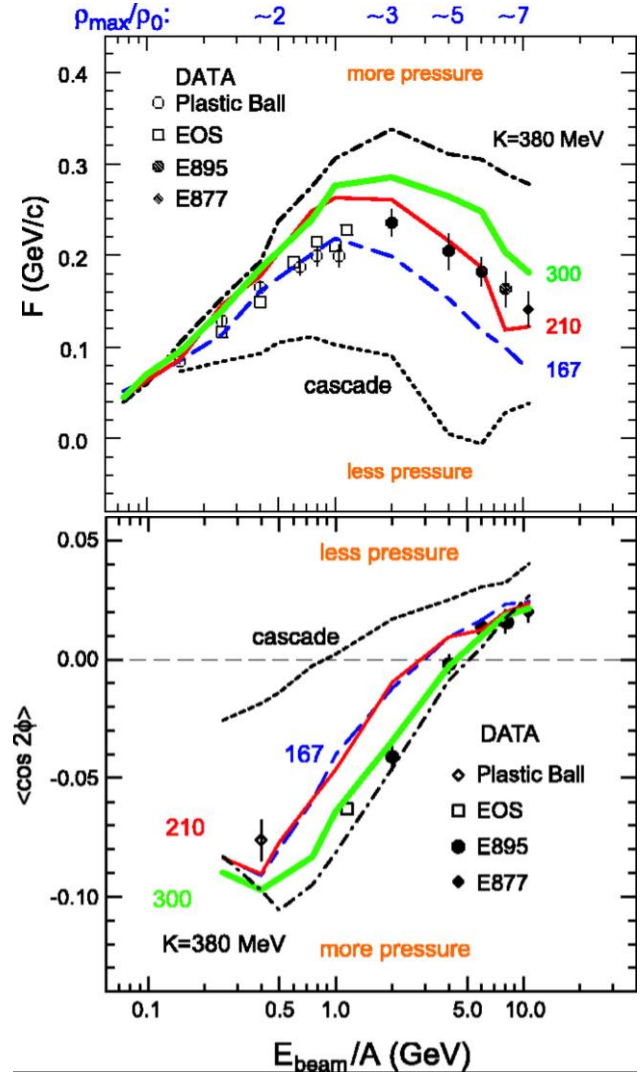
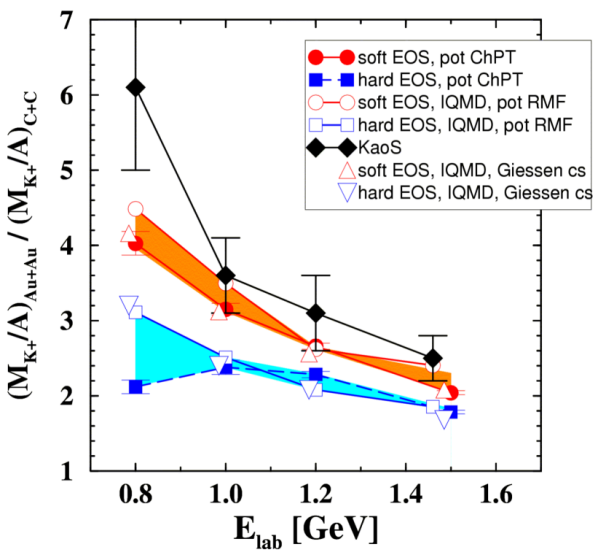


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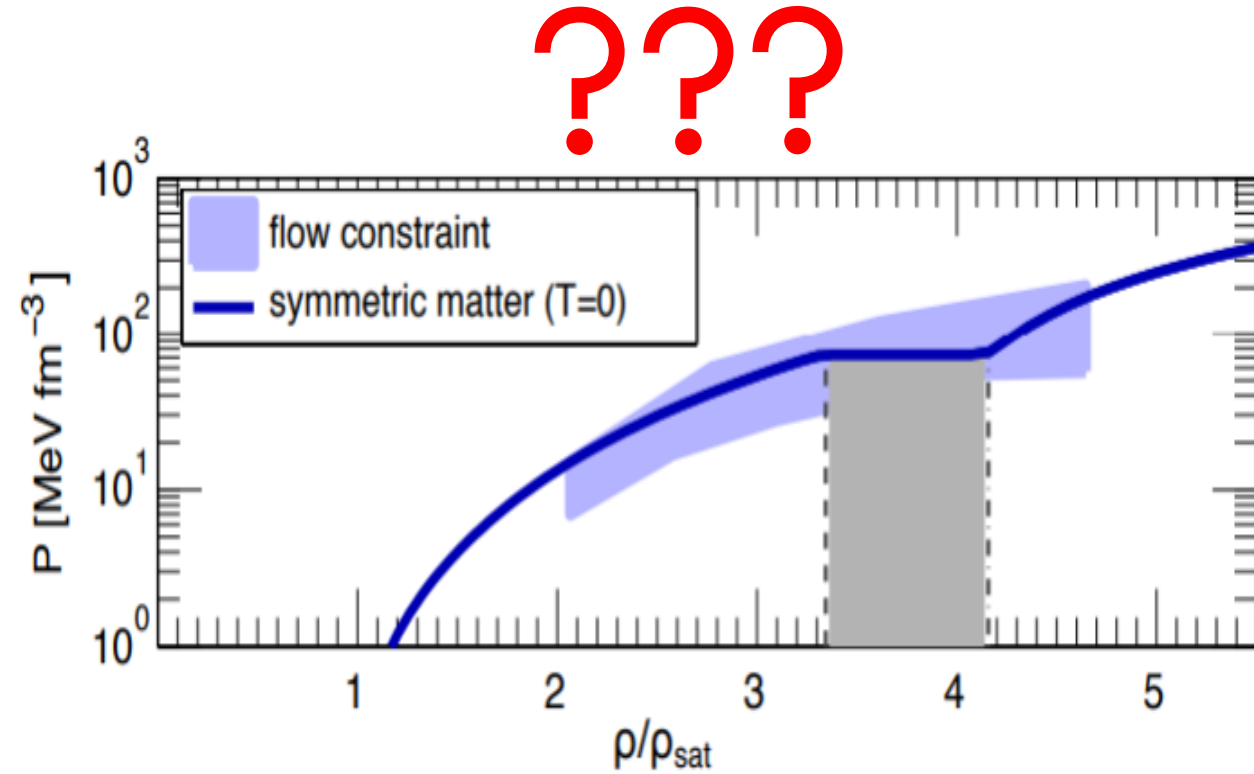
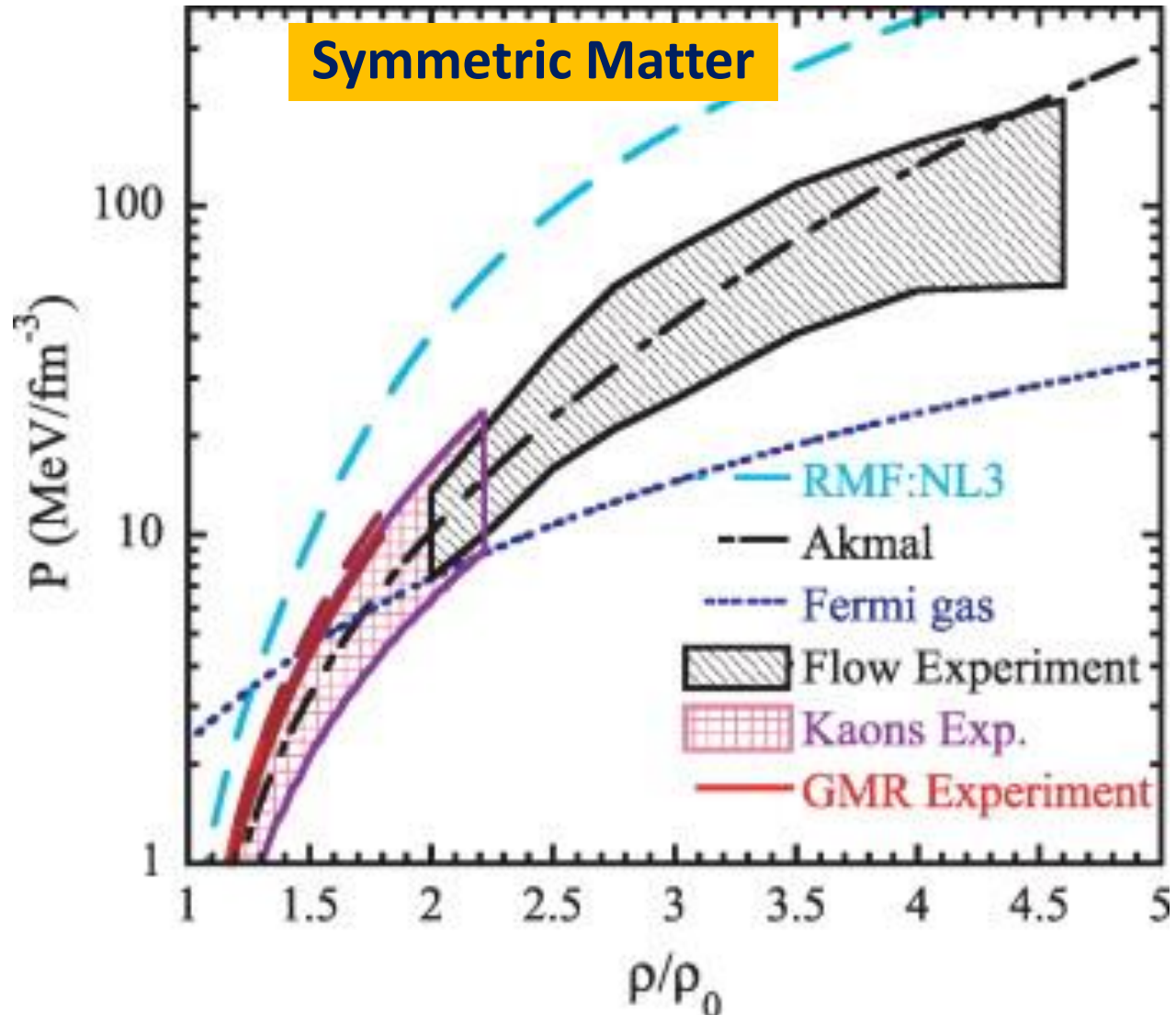


**Flow Experiments**  
( $\rho/\rho_0 = 2 - 4.5$ )

**Kaon Experiments**  
( $\rho/\rho_0 = 1.2 - 2.2$ )



# SYMMETRIC MATTER EQUATION OF STATE (EOS) – FUTURE ?



**Precision measurement of EOS can enable CBM to detect phase transition in symmetric nuclear matter at high  $\rho$**

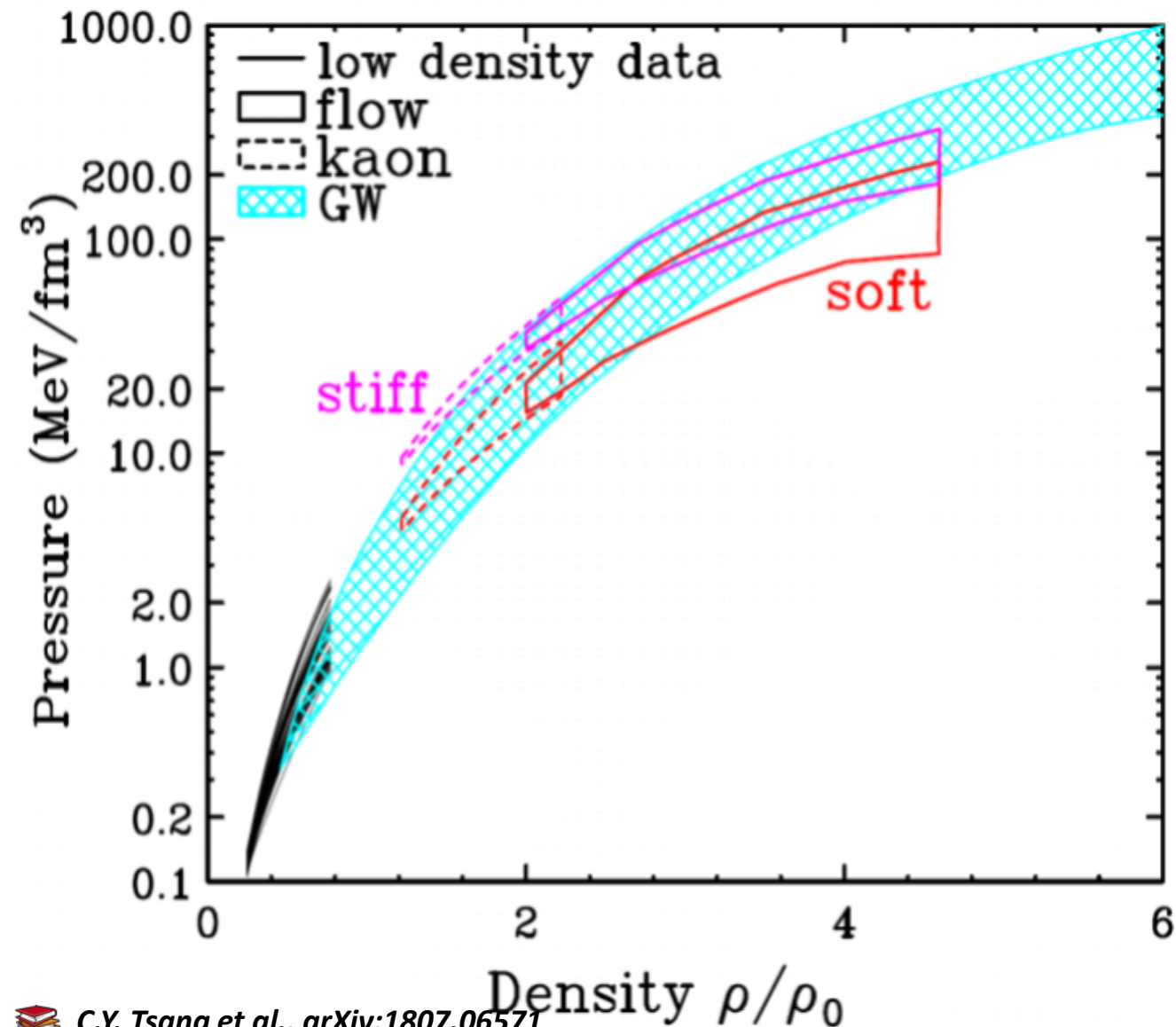
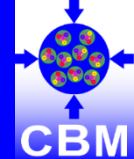
# EoS W/ CBM CASE #2

## NUCLEAR SYMMETRY ENERGY

$$E_A(\rho, \delta) = E_A(\rho, 0) + E_{\text{SYM}}(\rho) \cdot \delta^2$$



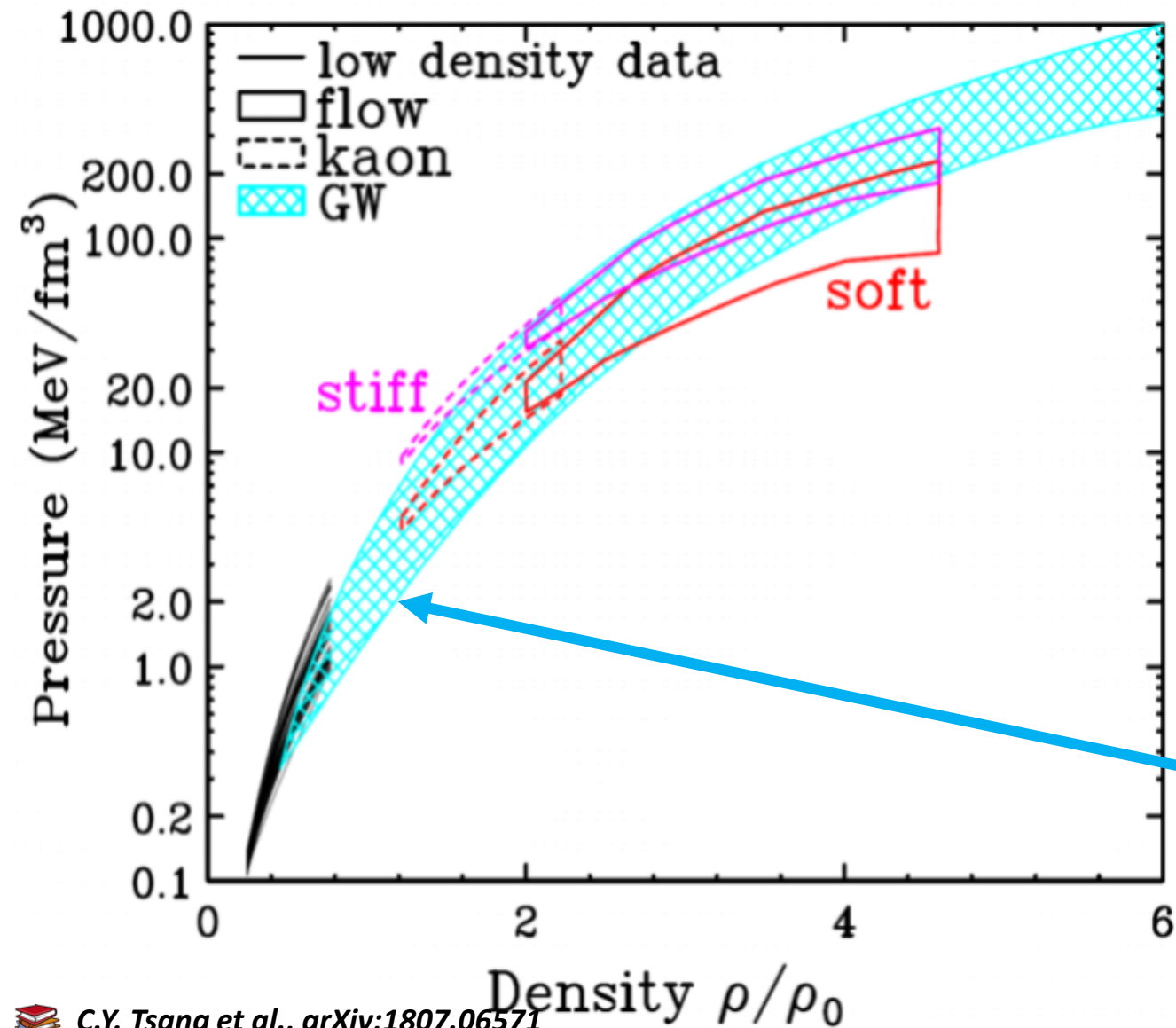
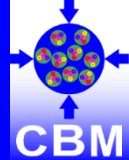
# NEUTRON MATTER EQUATION OF STATE (EOS) – CURRENT STATUS



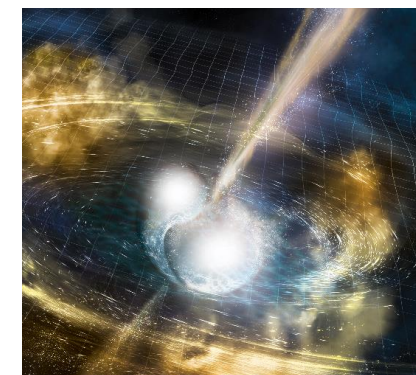
 C.Y. Tsang et al., arXiv:1807.06571

LIGO-VIRGO: B. P. Abbott, et al., arXiv:1805.11581 (2018)

# NEUTRON MATTER EQUATION OF STATE (EOS) – CURRENT STATUS



Graviational Waves  
GW170817



C.Y. Tsang et al., arXiv:1807.06571

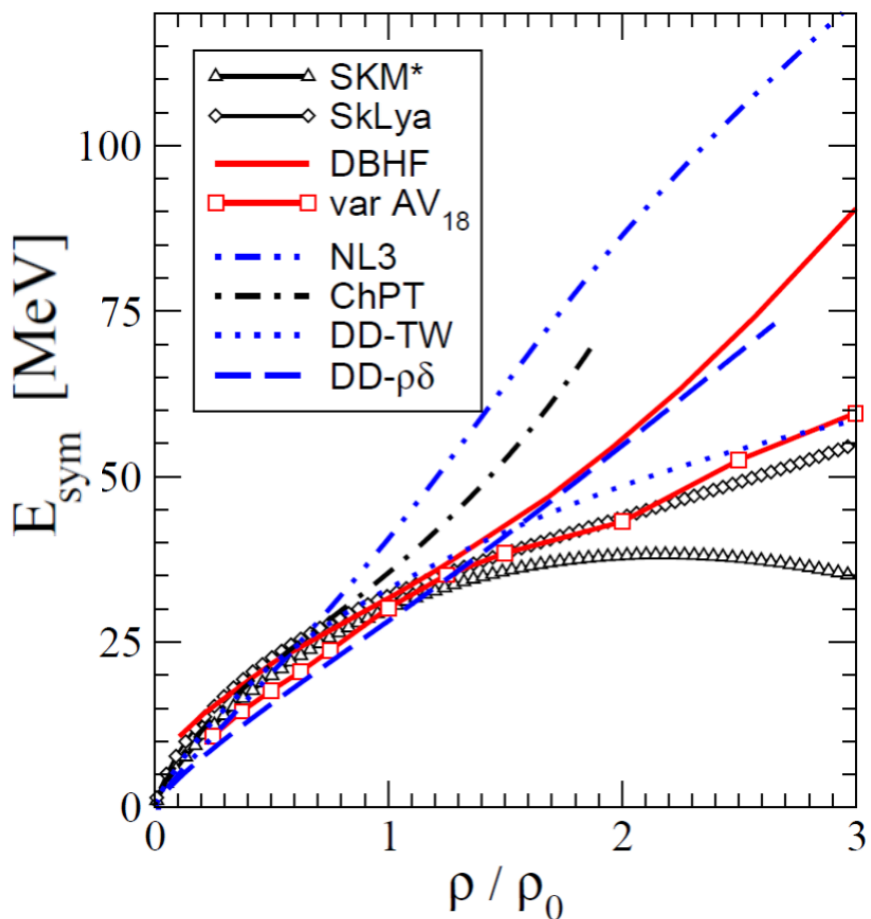
LIGO-VIRGO: B. P. Abbott, et al., arXiv:1805.11581 (2018)





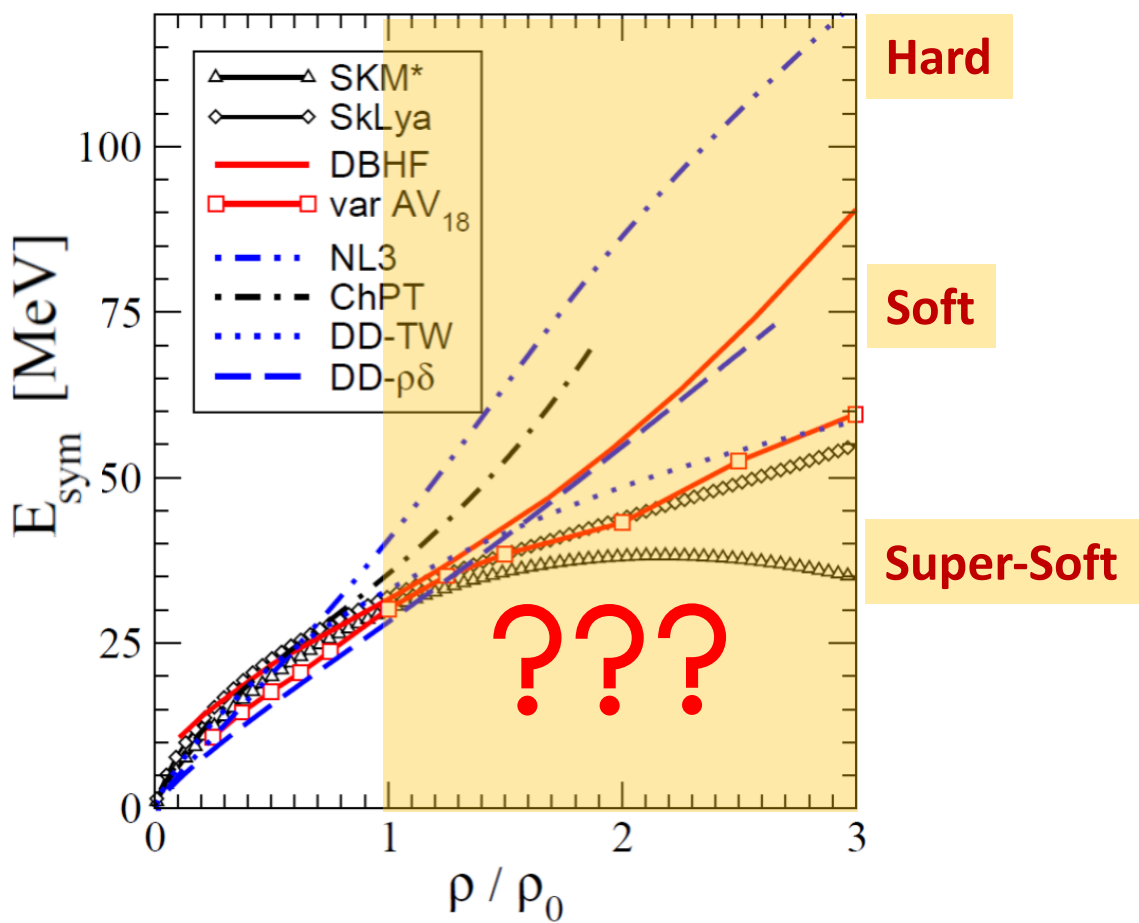
# NUCLEAR SYMMETRY ENERGY: $E_A(\rho, \delta) = E_A(\rho, 0) + E_{\text{SYM}}(\rho) \cdot \delta^2$

$$E_{\text{sym}}(\rho) = E_{\text{sym}}(\rho_0) + \underbrace{\frac{L}{3} \left( \frac{\rho - \rho_0}{\rho_0} \right)}_{\text{Slope}} + \underbrace{\frac{K_{\text{sym}}}{18} \left( \frac{\rho - \rho_0}{\rho_0} \right)^2}_{\text{Curvature}} + \dots$$




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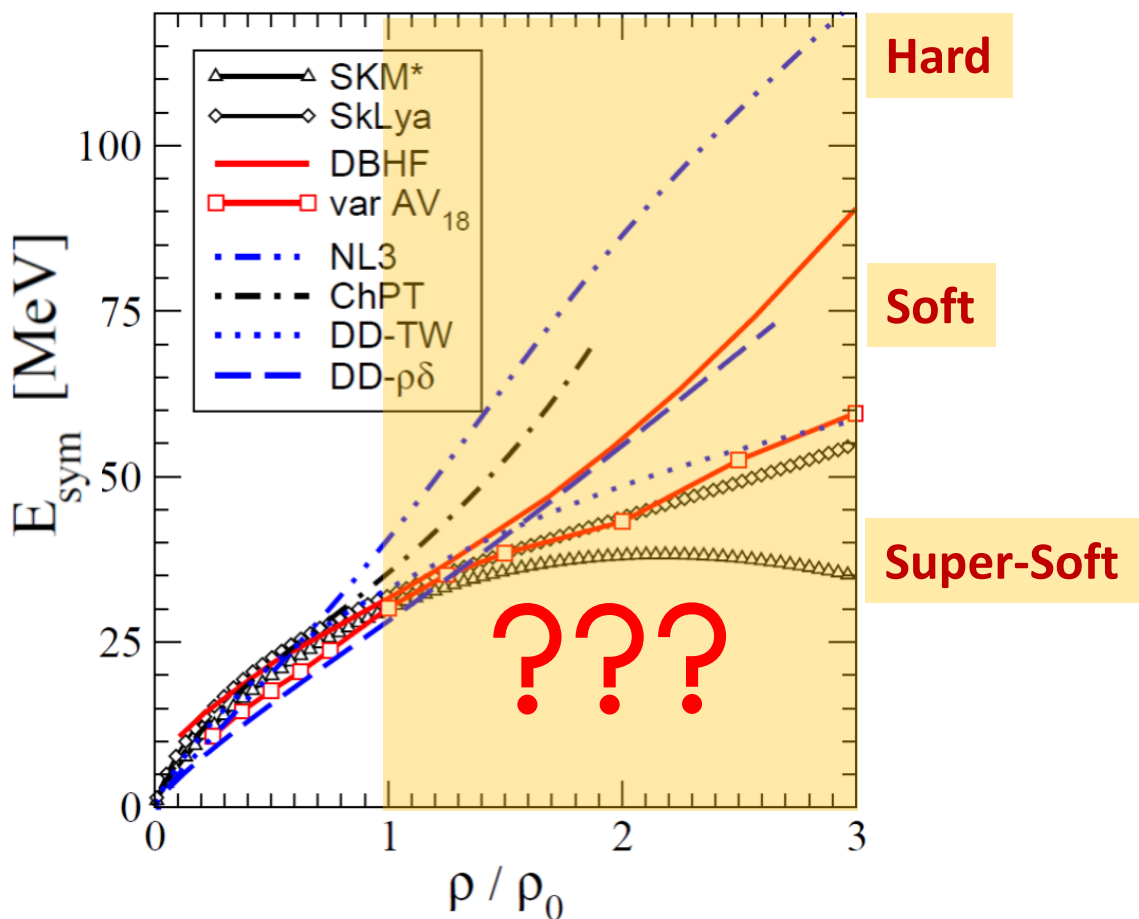
Slope                      Curvature

**Largely unconstrained at densities  $\rho > \rho_0$**   
**Related to uncertainty of three-body and tensor forces at high density**

 C. Fuchs, H.H. Wolter, EPJA 30 (2006) 5  
 B-A Li, À. Ramos, G. Verde et al., Eur. Phys. J. A (2014) 50: 9

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Slope

Curvature

**Largely unconstrained at densities  $\rho > \rho_0$**   
**Related to uncertainty of three-body and tensor forces at high density**

**Identification of differential observables (e.g. differences or ratios of observables) to enhance the response to asymmetry as the iso-scalar dynamics largely cancels**

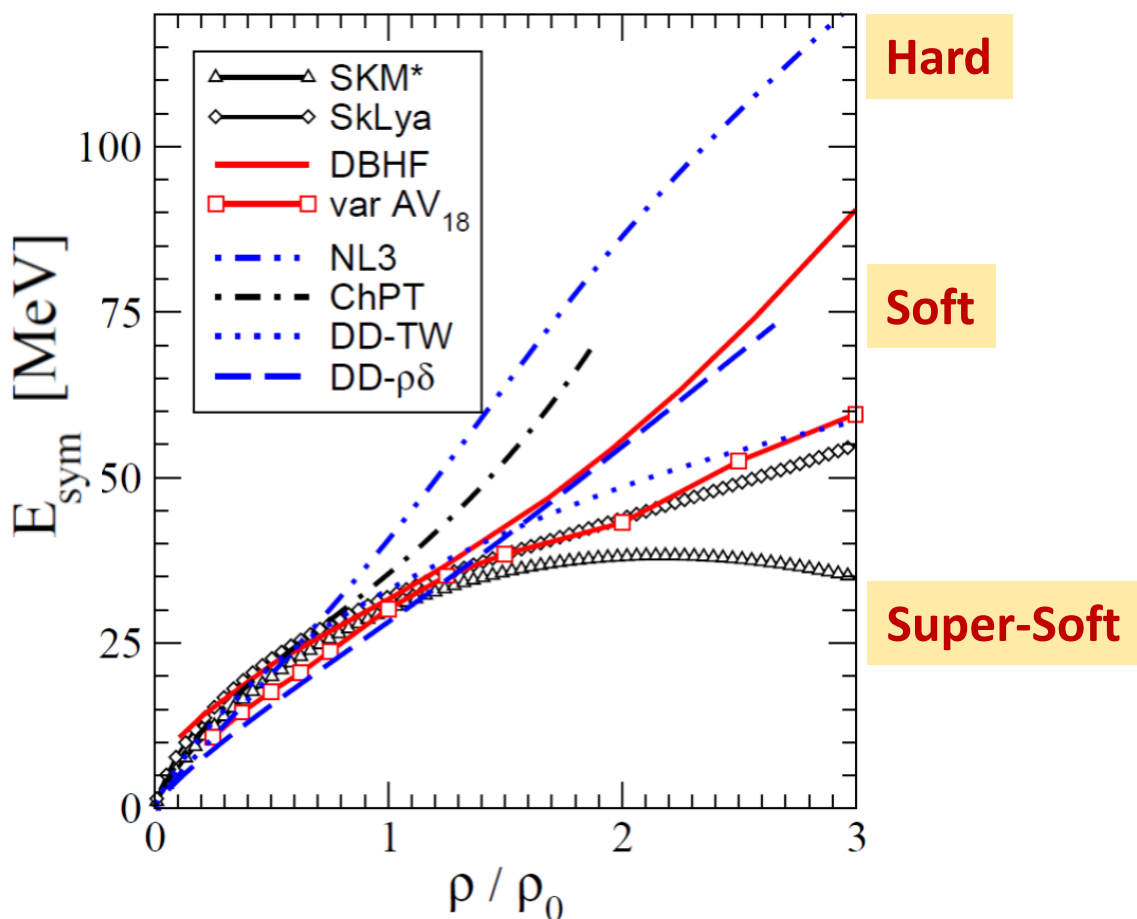
 C. Fuchs, H.H. Wolter, EPJA 30 (2006) 5  
 B-A Li, À. Ramos, G. Verde et al., Eur. Phys. J. A (2014) 50: 9

# NUCLEAR SYMMETRY ENERGY: $E_A(\rho, \delta) = E_A(\rho, 0) + E_{\text{SYM}}(\rho) \cdot \delta^2$

Parameterization in transport (UrQMD, IQMD)

$$E_{\text{sym}}(\rho) = 22 \text{ MeV} \left( \frac{\rho}{\rho_0} \right)^\gamma + 12 \text{ MeV} \left( \frac{\rho}{\rho_0} \right)^{2/3}$$

$\gamma$	0.5	1.0	1.5
L [MeV]	57	90	123



 C. Fuchs, H.H. Wolter, EPJA 30 (2006) 5  
B-A Li, À. Ramos, G. Verde et al., Eur. Phys. J. A (2014) 50: 9

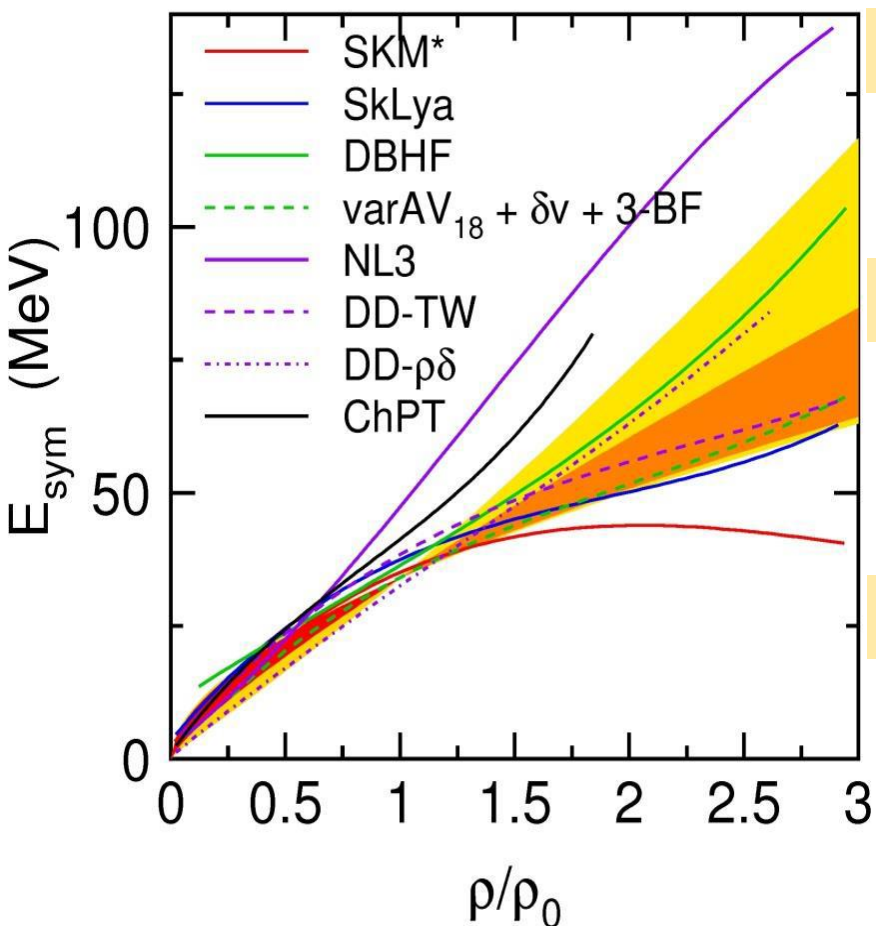


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Hard

**Idea:** Measurement of differential collective flow of neutrons w.r.t. protons or overall charged particles

Soft

FOPI-LAND:  $\gamma = 0.90 \pm 0.40$

ASY-EOS:  $\gamma = 0.72 \pm 0.19$

Super-Soft

**Au-Au 0.4 AGeV**  
**FOPI-LAND and ASY-EOS @ SIS18**

**L = 72 ± 13 MeV**

**K<sub>sym</sub> = -70 ... -40 MeV**



P. Russotto et al., Phys.Lett. B697 (2011) 471-476

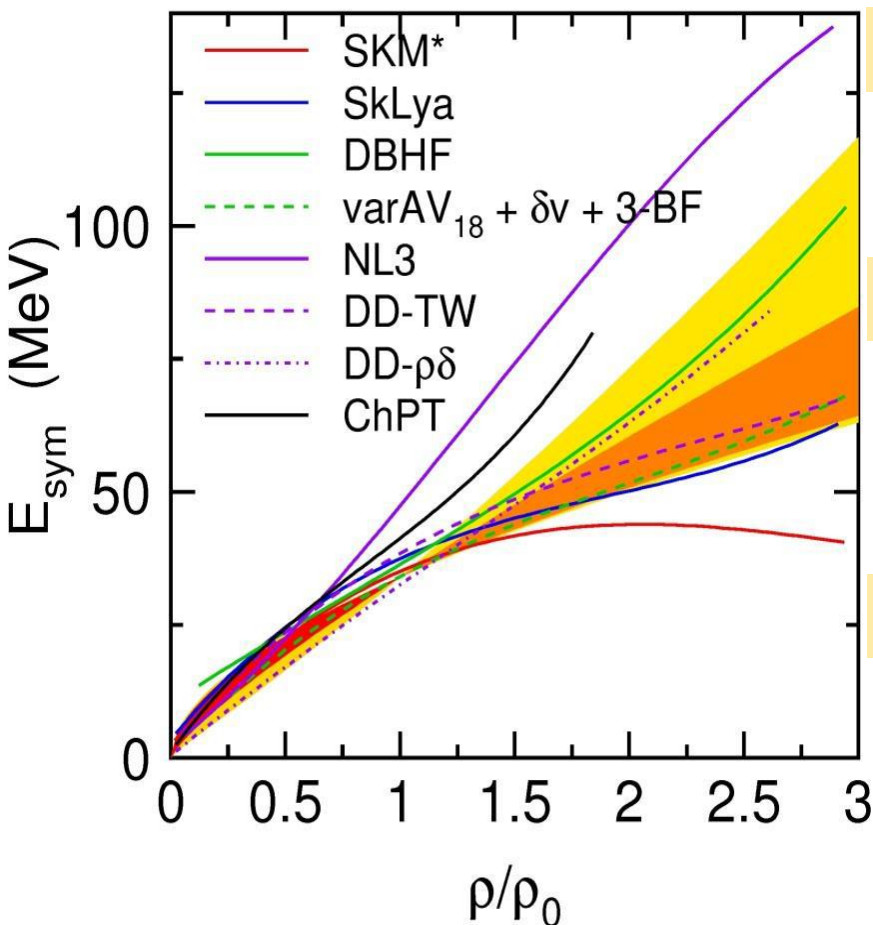
P. Russotto et al., Phys.Rev. C94 (2016) no.3, 034608

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$L = 72 \pm 13 \text{ MeV}$

$K_{\text{sym}} = -70 \dots -40 \text{ MeV}$

**Moderately soft asy-EOS  $\leq 2\rho_0$**   
**Possible at higher densities ( $\geq 2\rho_0$ ) with CBM**



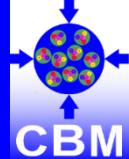
P. Russotto et al., Phys.Lett. B697 (2011) 471-476

P. Russotto et al., Phys.Rev. C94 (2016) no.3, 034608

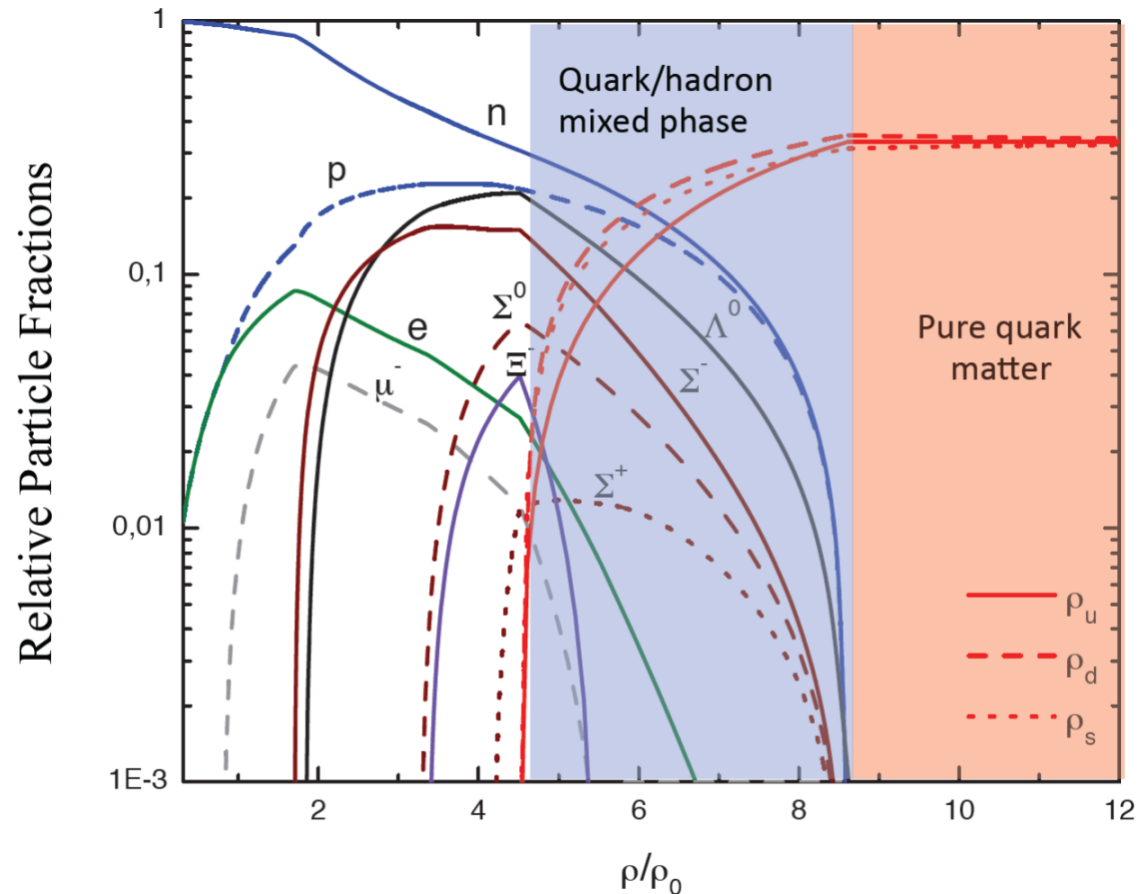
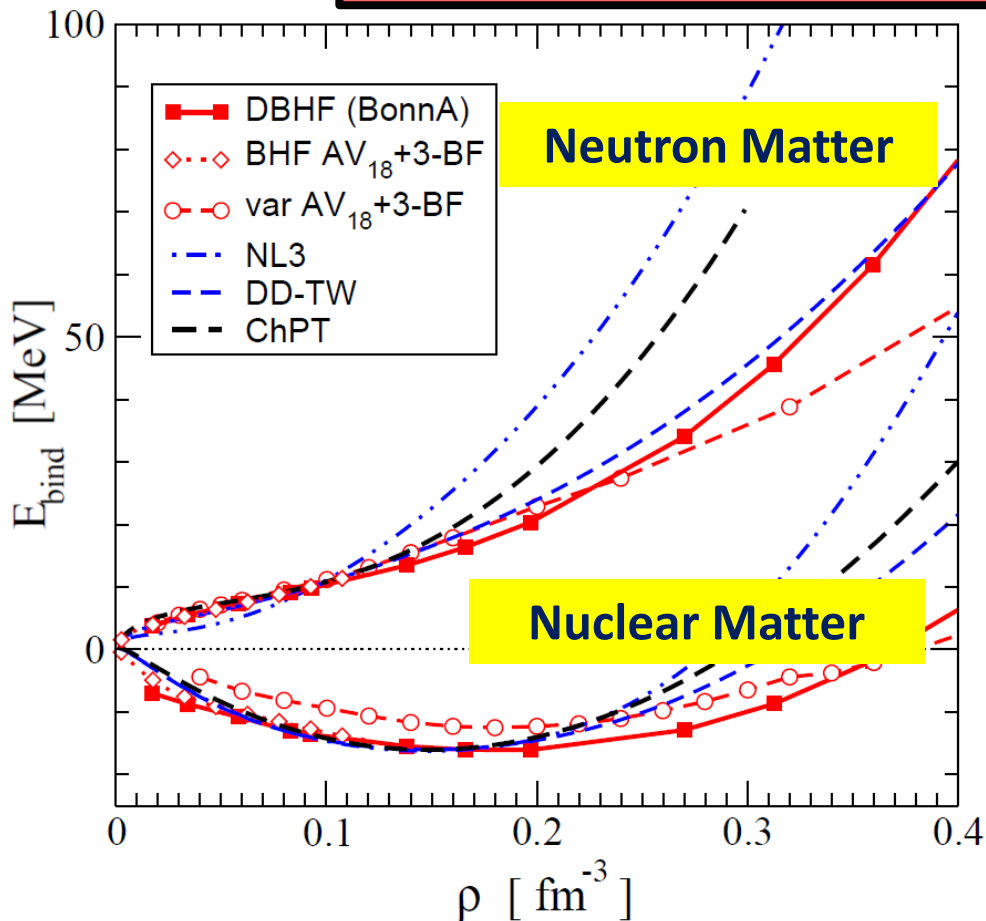
# EoS W/ CBM CASE #3

## 2,3-BODY HYPERON-NUCLEON ( $\Lambda$ -N) AND HYPERON-HYPERON ( $\Lambda$ - $\Lambda$ ) INTERACTIONS

# 'STRANGE MATTER' – HYPERONS IN MASSIVE NEUTRON STARS



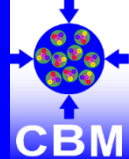
At higher densities ( $> 4\rho_0$ ), inclusion and interactions of hyperons become an important ingredient to microscopically connect nuclear and neutron matter



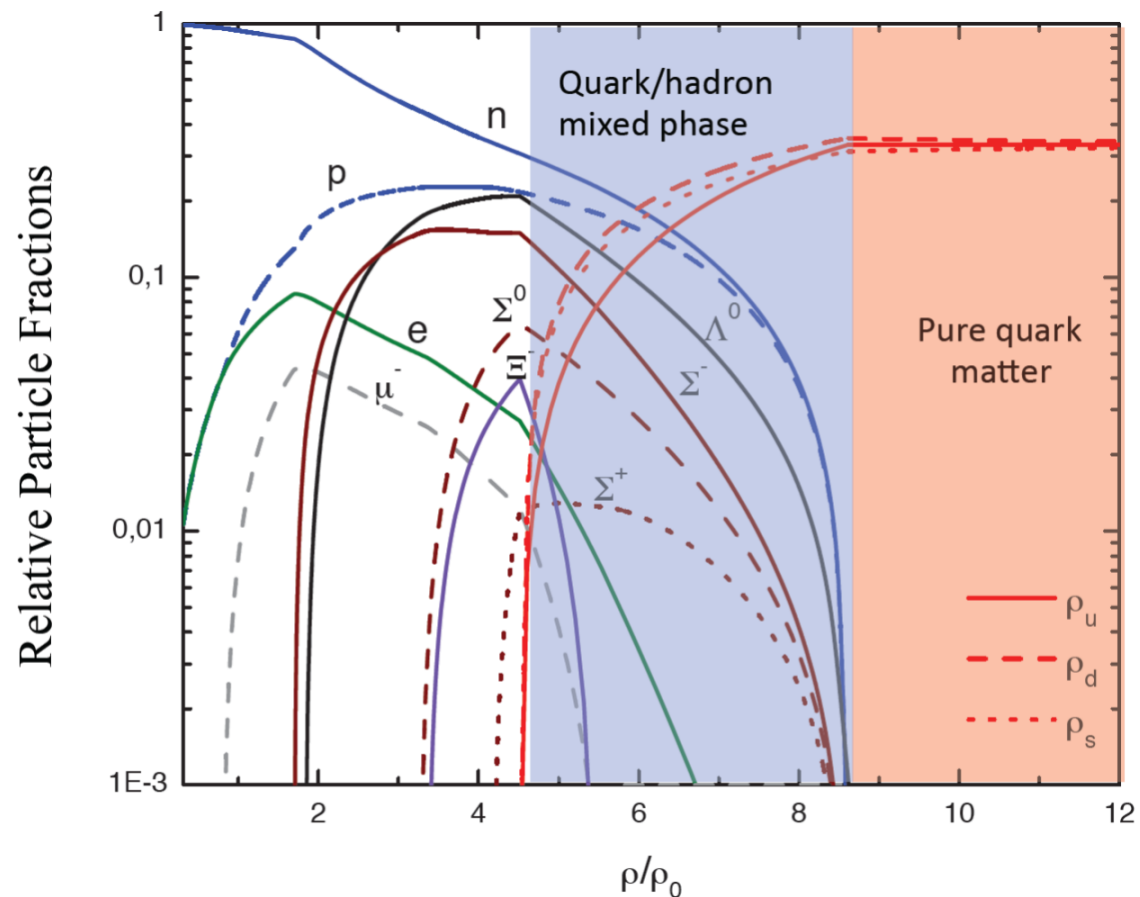
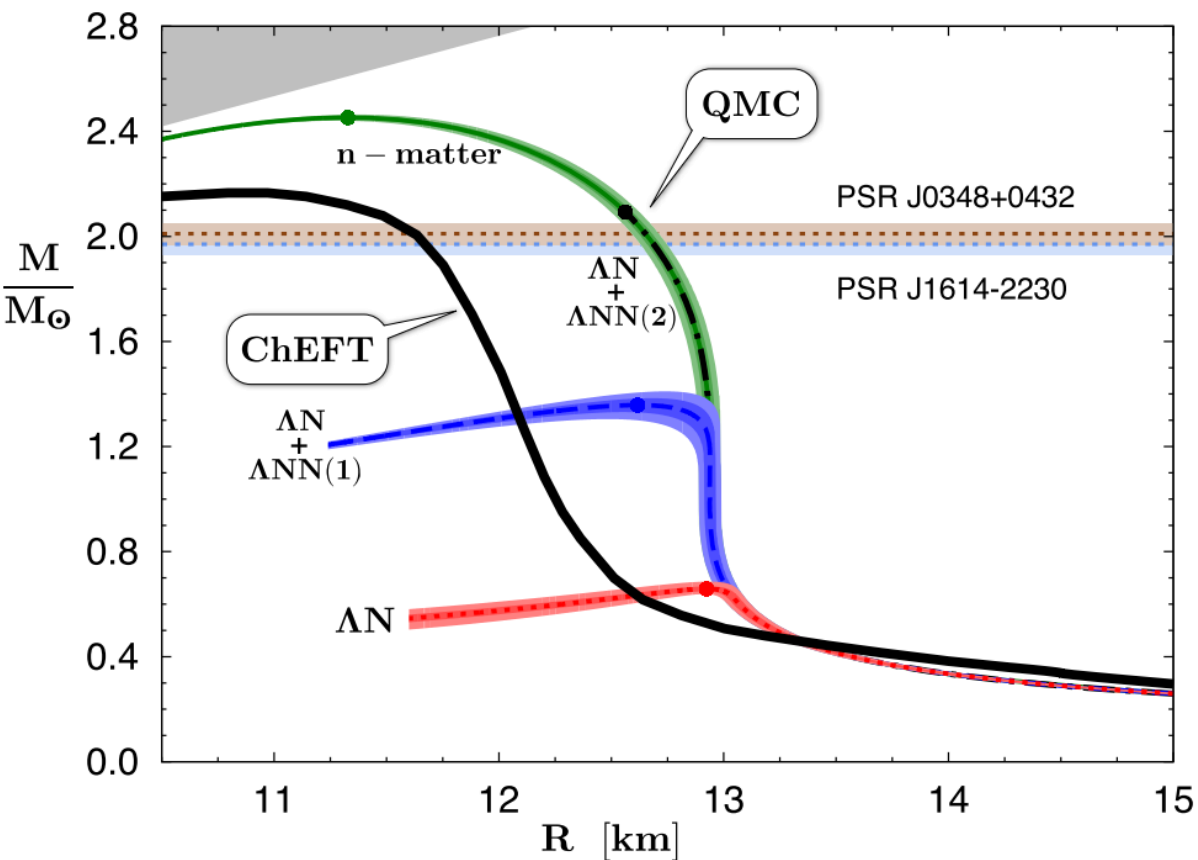
C. Fuchs, H.H. Wolter, EPJA 30 (2006) 5  
 B-A Li, À. Ramos, G. Verde et al., Eur. Phys. J. A (2014) 50: 9

M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, arXiv:1308.1657  
 Phys. Rev. C 89, 015806, 2014

# 'STRANGE MATTER' – HYPERONS IN MASSIVE NEUTRON STARS



**But: Inclusion of hyperons results in EoS too soft to support 2-solar-mass n-stars**  
**Unless: Strong repulsion in YN and YNN ... interactions**

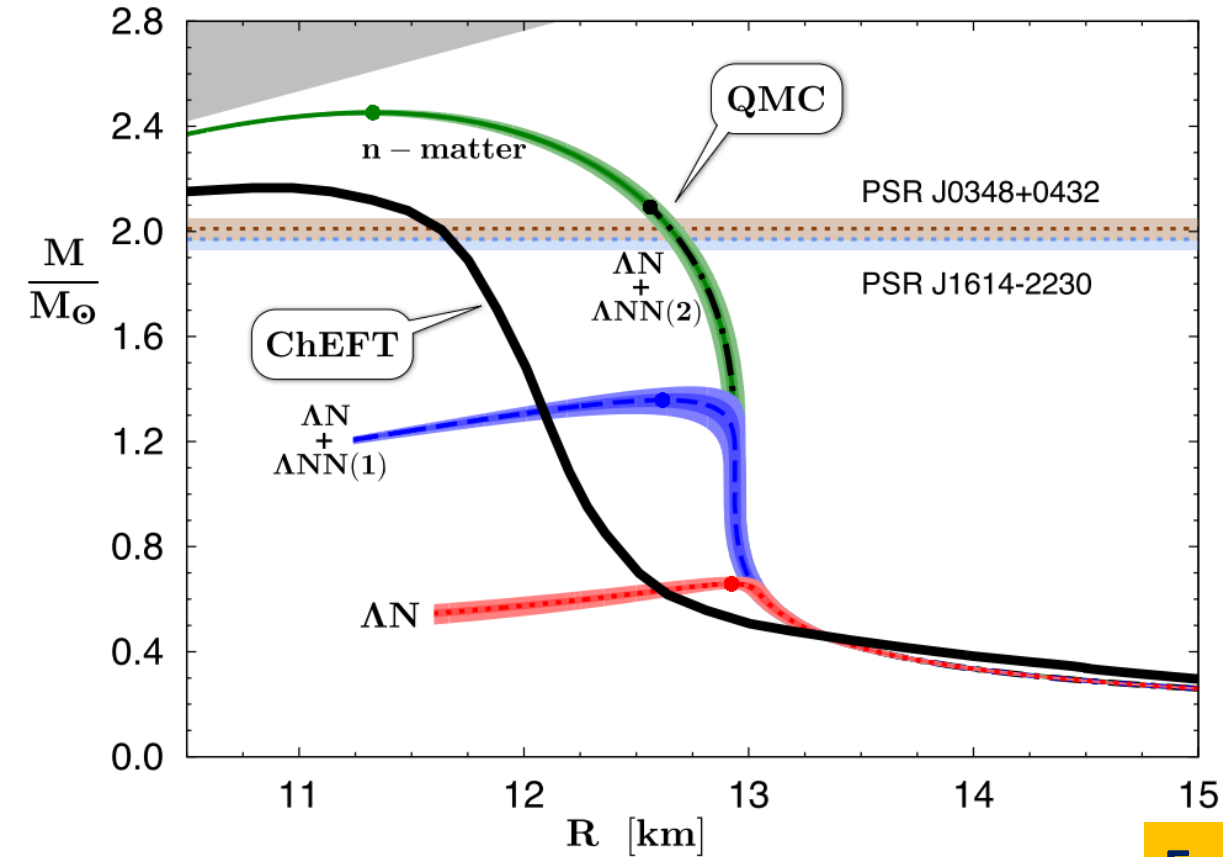


W. Weise, EMMI Workshop - Probing Dense Baryonic Matter with Hadrons (2019)

M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, arXiv:1308.1657 Phys. Rev. C 89, 015806, 2014

# 'STRANGE MATTER' – HYPERONS IN MASSIVE NEUTRON STARS

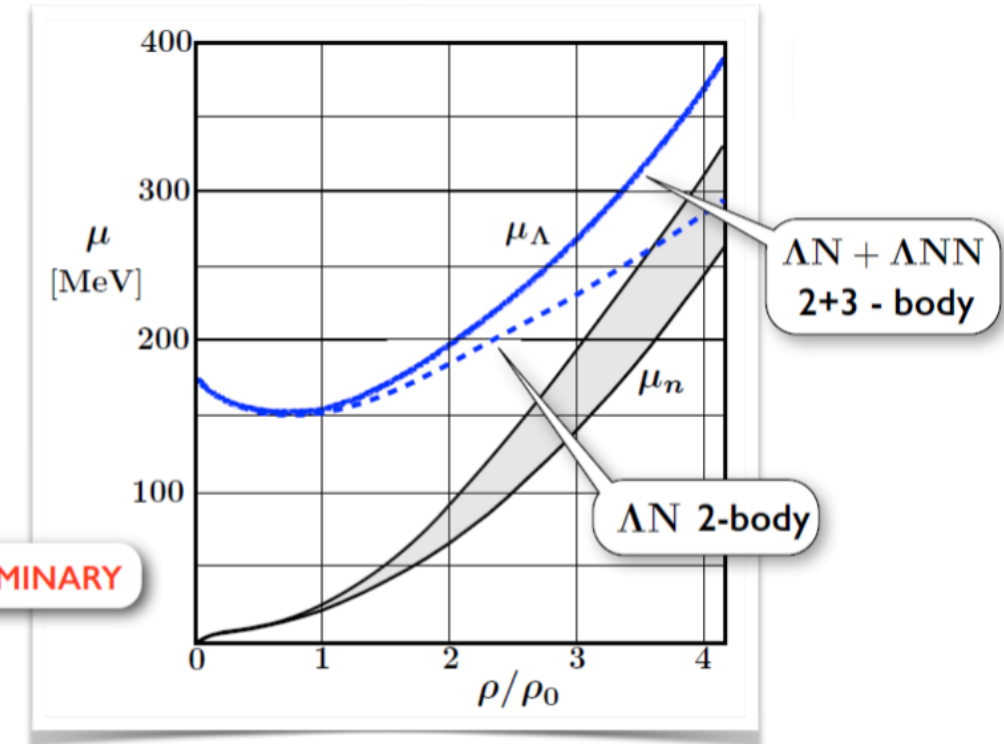
**But:** Inclusion of hyperons results in EoS too soft to support 2-solar-mass n-stars  
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chemical potentials

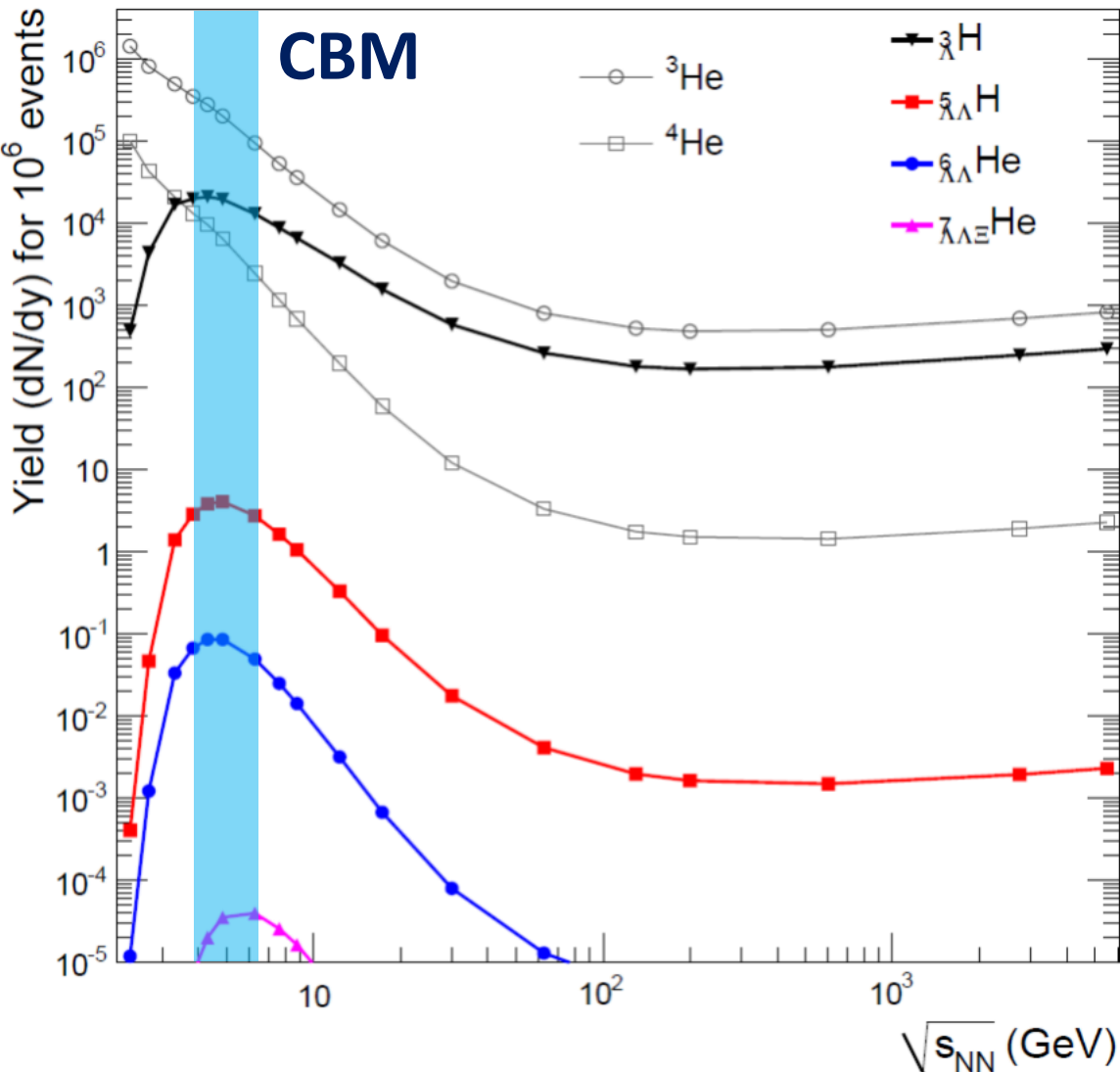
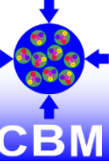
$$\mu_i = \frac{\partial \mathcal{E}}{\partial \rho_i}$$

PRELIMINARY

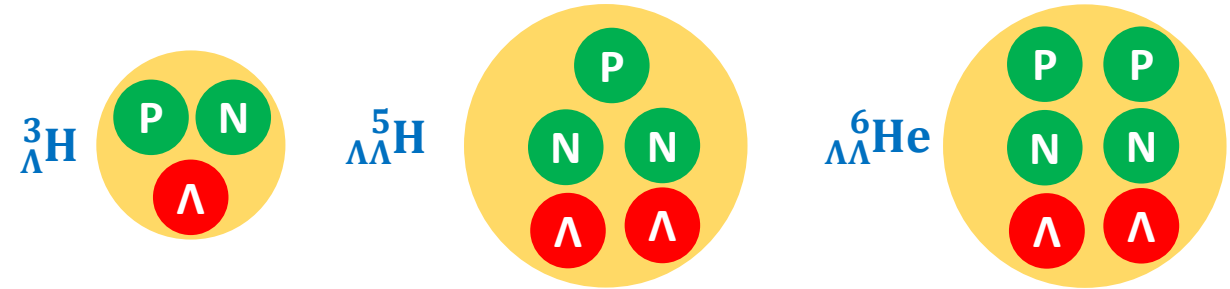


**Extrapolations using  $\Lambda$  single particle potential in neutron (star) matter from Chiral SU(3) EFT interactions**

# UNDERSTANDING $\Lambda$ -N, $\Lambda$ - $\Lambda$ INTERACTIONS WITH CBM



**Hypernuclei produced in dense matter are excellent particles to study  $\Lambda$ -N,  $\Lambda$ - $\Lambda$  interactions!**

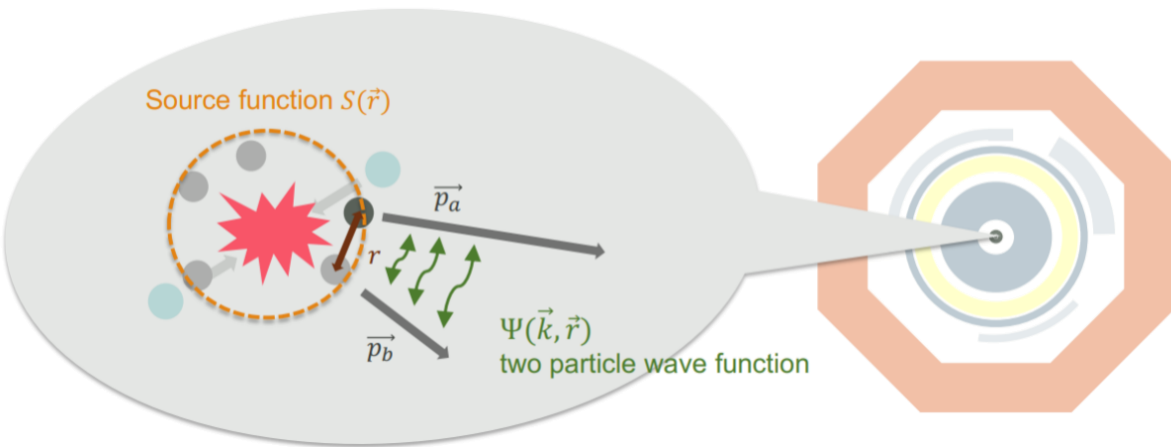


- Experimental Observables**
- Particle Yields (also shown in the image)
  - Lifetimes
  - Collective Flow

**No experimental data in CBM energy range  
Huge discovery potential !!!**

Thermal Model: A. Andronic et al., Phys. Lett. B697 (2011) 203

**Idea:** Femtoscopy to study the correlation functions (cross-sections) w.r.t. momentum



Statistical definition

Experimental definition

Theoretical definition

$$C(k) = \frac{\mathcal{P}(\vec{p}_a, \vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} = \mathcal{N} \frac{N_{\text{Same}}(k)}{N_{\text{Mixed}}(k)} = \int S(\vec{r}) |\Psi(\vec{k}, \vec{r})|^2 d^3\vec{r} \xrightarrow{k \rightarrow \infty} 1$$

Single-particle momenta

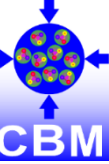
Relative distance / reduced momentum in the rest frame of the pair

Lisa, Pratt, Wiedemann, Solz,  
Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402

$$k^* = |\vec{p}_a^* - \vec{p}_b^*| \text{ and } \vec{p}_a^* + \vec{p}_b^* = 0$$



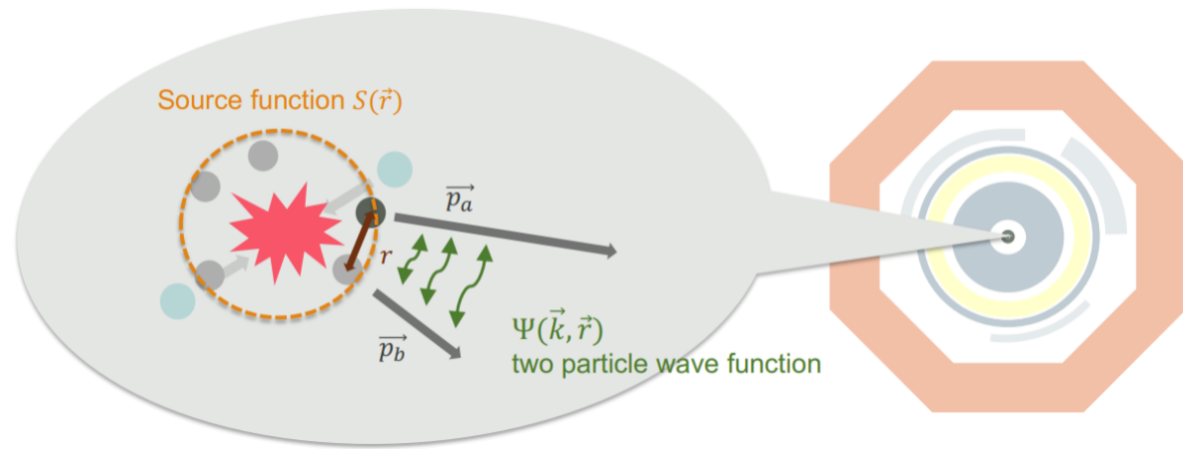
# UNDERSTANDING $\Lambda$ -N, $\Lambda$ - $\Lambda$ INTERACTIONS WITH CBM



**Idea:** Femtoscopy to study the correlation functions (cross-sections) w.r.t. momentum

CATS – Correlation Analysis Tool Using the Schrödinger Equation (TUM - Fabbietti et al.)

Numerical sol. of the Schrödinger Solution to obtain ‘exact’ solutions to obtain the correlation functions



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Lisa, Pratt, Wiedemann, Solz,  
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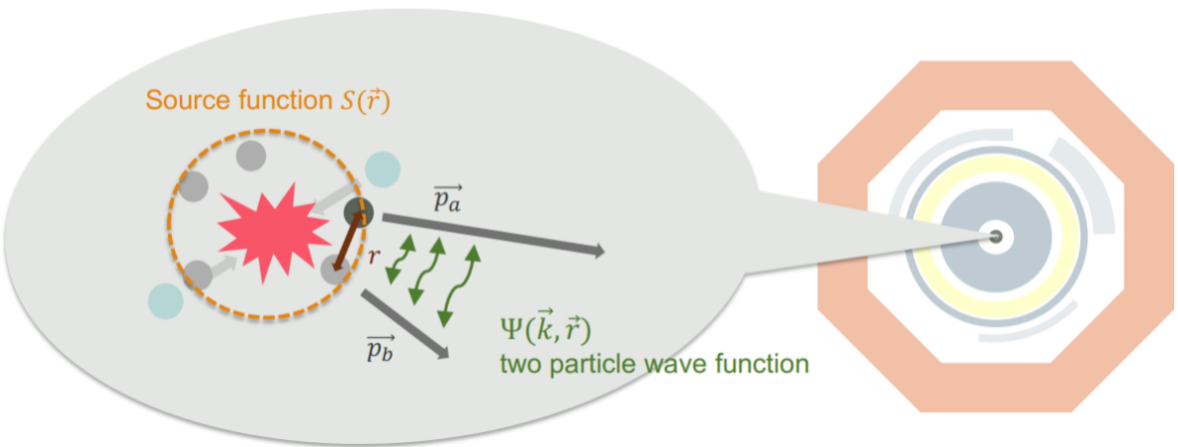
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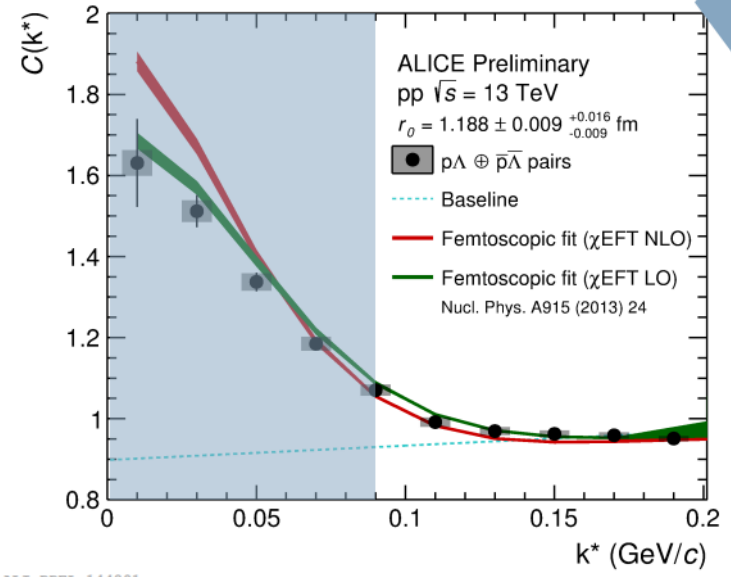


**Statistical definition**      **Experimental definition**      **Theoretical definition**

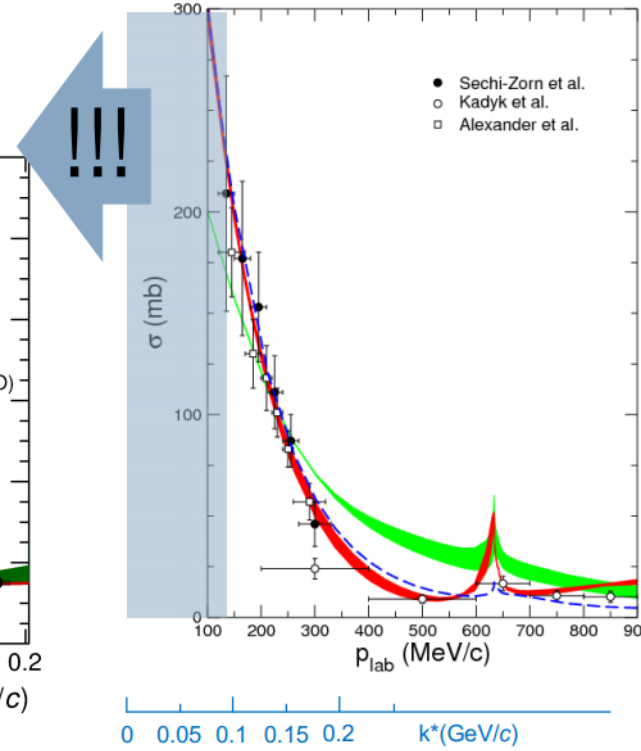
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Single-particle momenta      Relative distance / reduced momentum in the rest frame of the pair

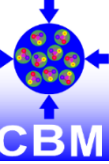
$$k^* = |\vec{p}_a^* - \vec{p}_b^*| \text{ and } \vec{p}_a^* + \vec{p}_b^* = 0$$



Lisa, Pratt, Wiedemann, Solz,  
Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402



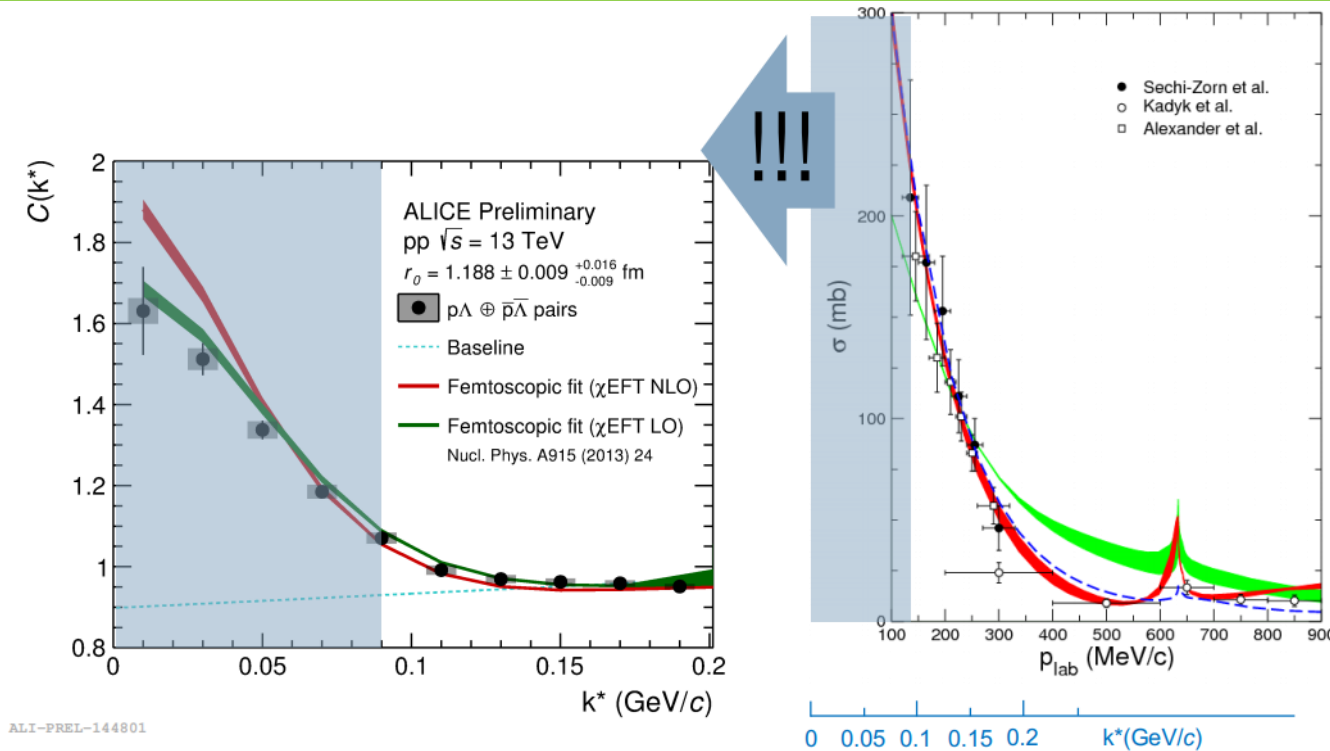
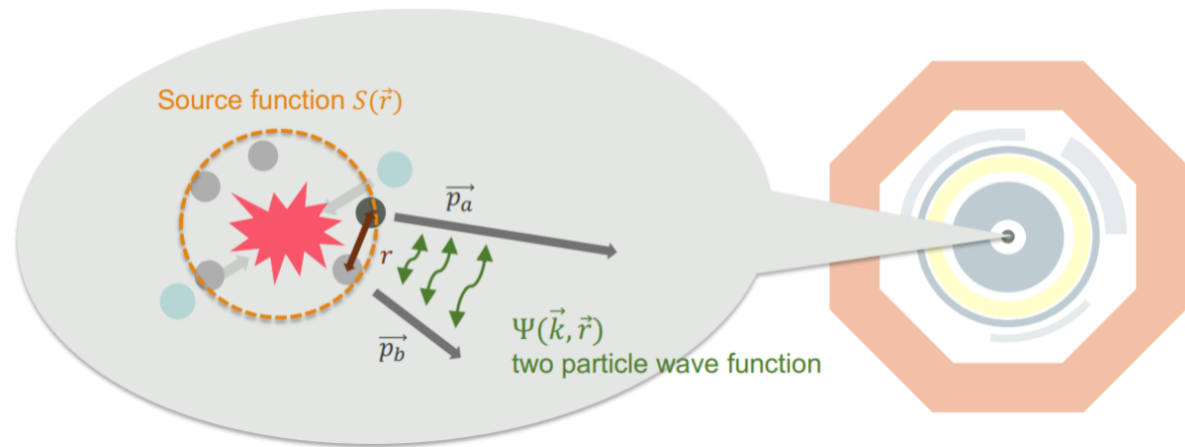
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Statistical definition      Experimental definition      Theoretical definition

Single-particle momenta      Relative distance / reduced momentum in the rest frame of the pair

Lisa, Pratt, Wiedemann, Solz, Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402

**Experimentally shown for ALICE@LHC ( $\mu_B = 0$ )**  
**Possible at CBM@FAIR ( $\mu_B > 0$ )?**

## **Nuclear Symmetric Matter EOS:**

- Collective flow of Baryons ( $\pi$ ,  $K$ ,  $p$ ,  $\Lambda$ ,  $\Xi$ ,  $\Omega$ ,...) driven by the fireball's pressure gradient
- Sub-Threshold Particle Production of Multi-Strange Hyperons via multi-step processes

## **Neutron Matter EOS:**

### **Symmetry Energy:**

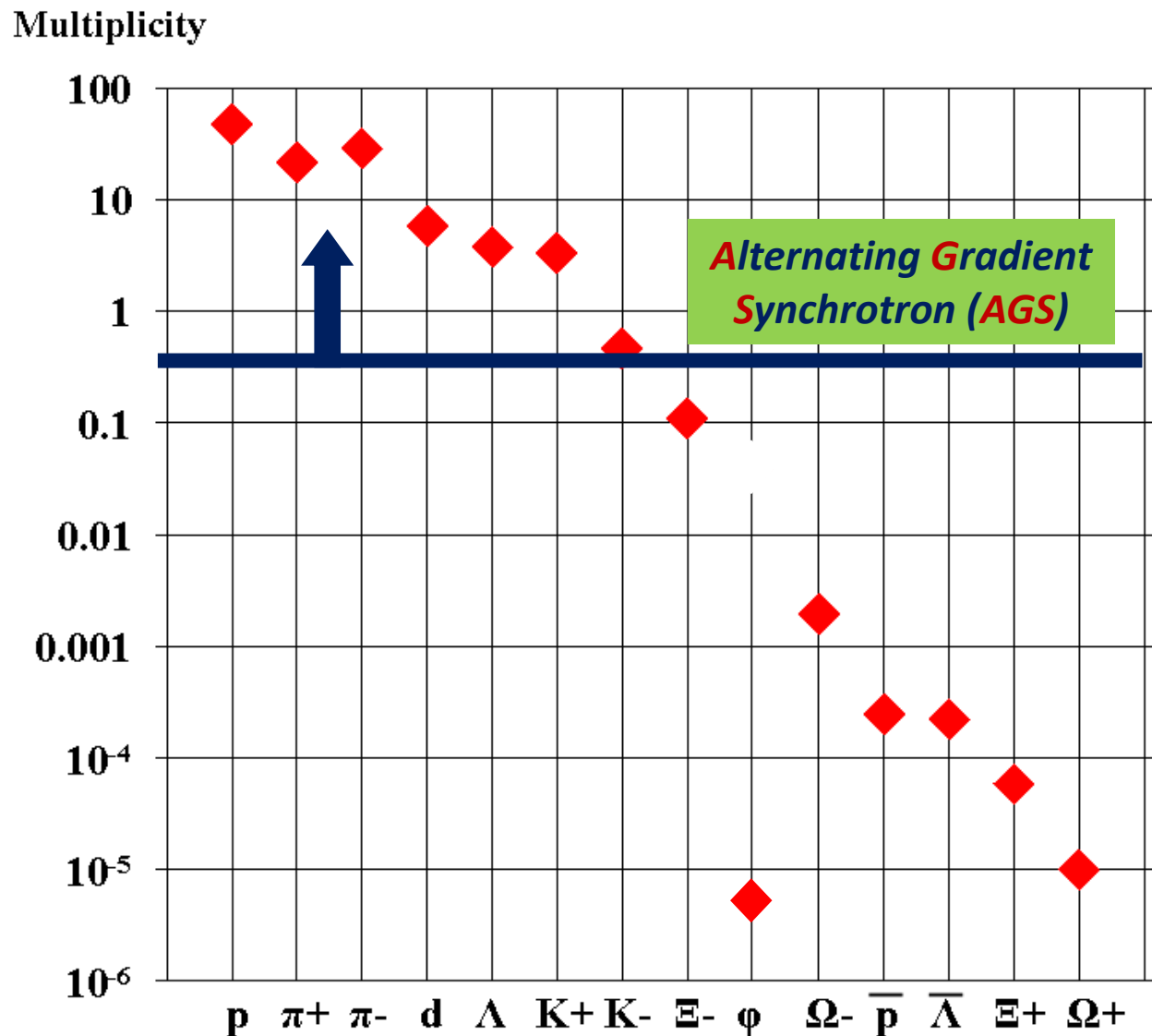
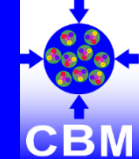
- Neutron/Proton Elliptic Flow
- Sub-Threshold Particle Production of isospin-opposite particles ( $I_3 = \pm 1$ ) ?

### **Hyperon Puzzle ( $\Lambda N$ , $\Lambda NN$ , and $\Lambda\Lambda N$ interactions)**

- Hypernuclei production and yields
- Hypernuclei lifetime
- Hypernuclei Collective Flow
- Correlation functions to study interaction cross-sections by using CATS

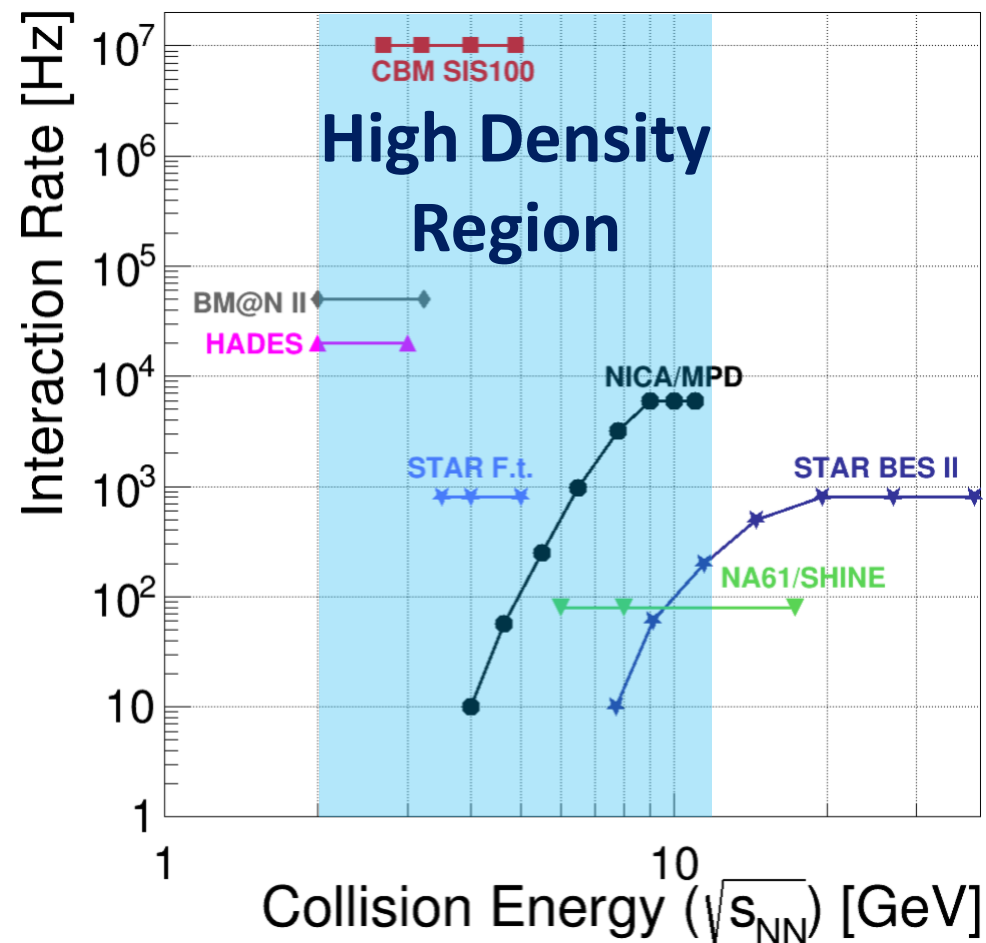
# EXPERIMENTAL CHALLENGES

# (TOO) RARE PROBES



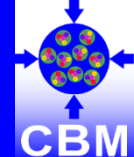
Statistical model, A. Andronic, priv. comm. to P. Senger

## CBM Interaction Rates – 10MHz



T. Ablyazimov et al. [CBM Collaboration] Eur. Phys. J. A (2017)

# DAY-1: EXPECTED PARTICLE YIELDS Au+Au @ 6, 10 AGeV



Particle (mass MeV/c <sup>2</sup> )	Multiplicity central ev. 6 AGeV	Multiplicity central ev. 10 AGeV	decay mode	BR	ε (%)	yield in 90 days 6AGeV	yield in 90 days 10 AGeV	IR MHz
$\bar{\Lambda}$ (1115)	$5.1 \cdot 10^{-3}$	0.041	$\bar{p}\pi^+$	0.64	19.7	$1.2 \cdot 10^8$	$1.0 \cdot 10^9$	<b>0.1</b>
$\Xi^-$ (1321)	0.11	0.36	$\Lambda\pi^-$	1	9.9	$2.0 \cdot 10^9$	$7.0 \cdot 10^9$	<b>0.1</b>
$\Xi^+$ (1321)	$1.8 \cdot 10^{-3}$	$1.5 \cdot 10^{-2}$	$\bar{\Lambda}\pi^+$	1	8.7	$3.0 \cdot 10^7$	$2.5 \cdot 10^8$	<b>0.1</b>
$\Omega^-$ (1672)	$6.8 \cdot 10^{-4}$	$4.4 \cdot 10^{-3}$	$\Lambda K^-$	0.68	4.4	$4.0 \cdot 10^6$	$2.6 \cdot 10^7$	<b>0.1</b>
$\Omega^+$ (1672)	$1.4 \cdot 10^{-5}$	$2.6 \cdot 10^{-3}$	$\bar{\Lambda} K^+$	0.68	3.9	$7.0 \cdot 10^4$	$1.4 \cdot 10^7$	<b>0.1</b>
${}^3_{\Lambda}H$ (2993)	$4.2 \cdot 10^{-2}$	$3.8 \cdot 10^{-2}$	${}^3He\pi^-$	0.25	12.7	$2.7 \cdot 10^8$	$2.5 \cdot 10^8$	<b>0.1</b>
${}^4_{\Lambda}He$ (3930)	$2.4 \cdot 10^{-3}$	$1.9 \cdot 10^{-3}$	${}^3He p\pi^-$	0.32	11.4	$1.7 \cdot 10^7$	$1.4 \cdot 10^7$	<b>0.1</b>
${}^5_{\Lambda\Lambda}He$ (5047)		$5.0 \cdot 10^{-6}$	${}^3He 2p 2\pi$	0.01	3	15	250	<b>0.1</b>
${}^6_{\Lambda\Lambda}He$ (5986)		$1.0 \cdot 10^{-7}$	${}^4He 2p 2\pi$	0.01	1.2			<b>0.1</b>

# EXPERIMENTAL CHALLENGES

PHYSICISTS &  
ENGINEERS

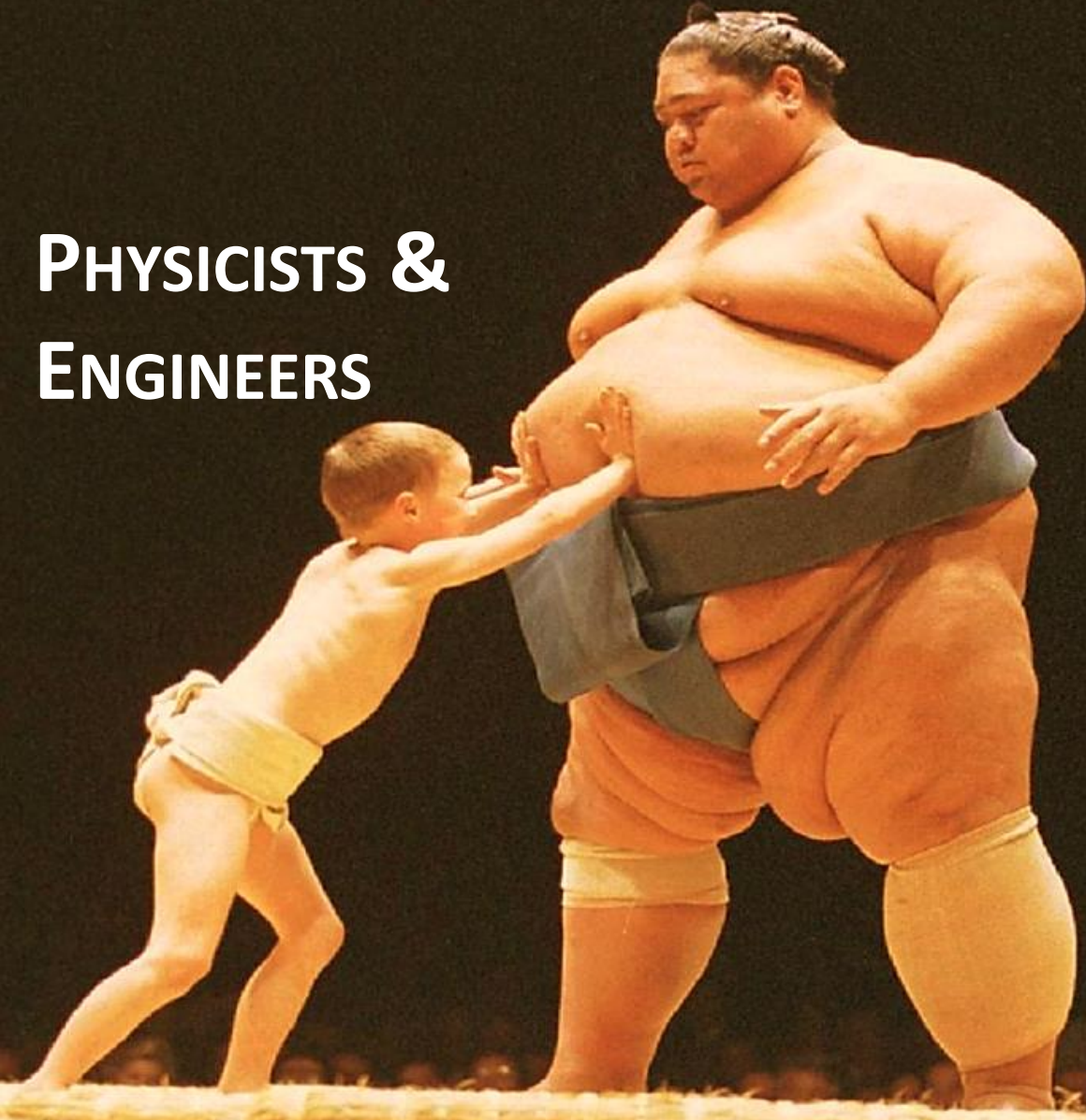
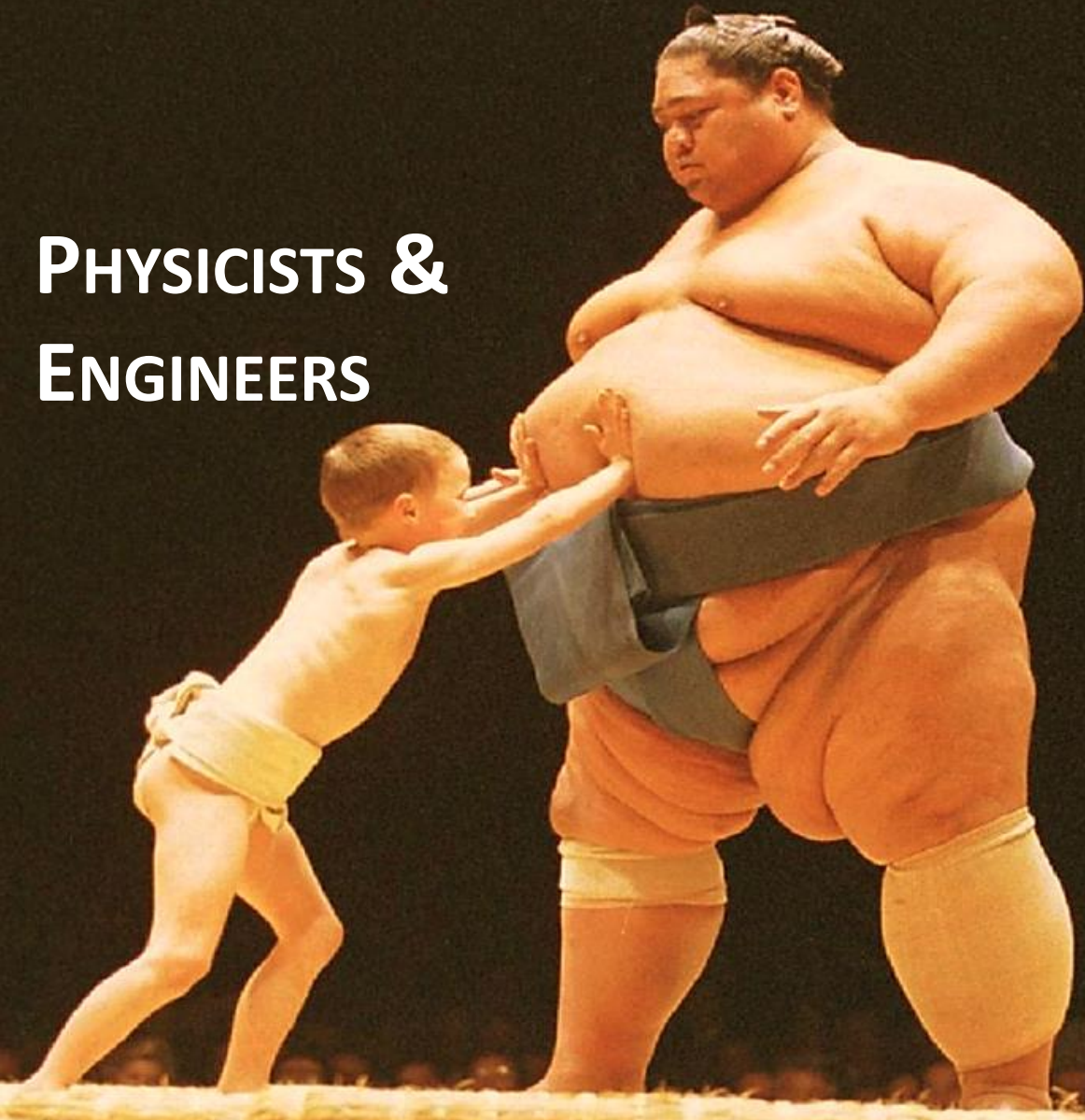


Image Credits: <https://imgflip.com/memetemplate/166876537/kid-vs-sumo-wrestler>



## PHYSICISTS & ENGINEERS



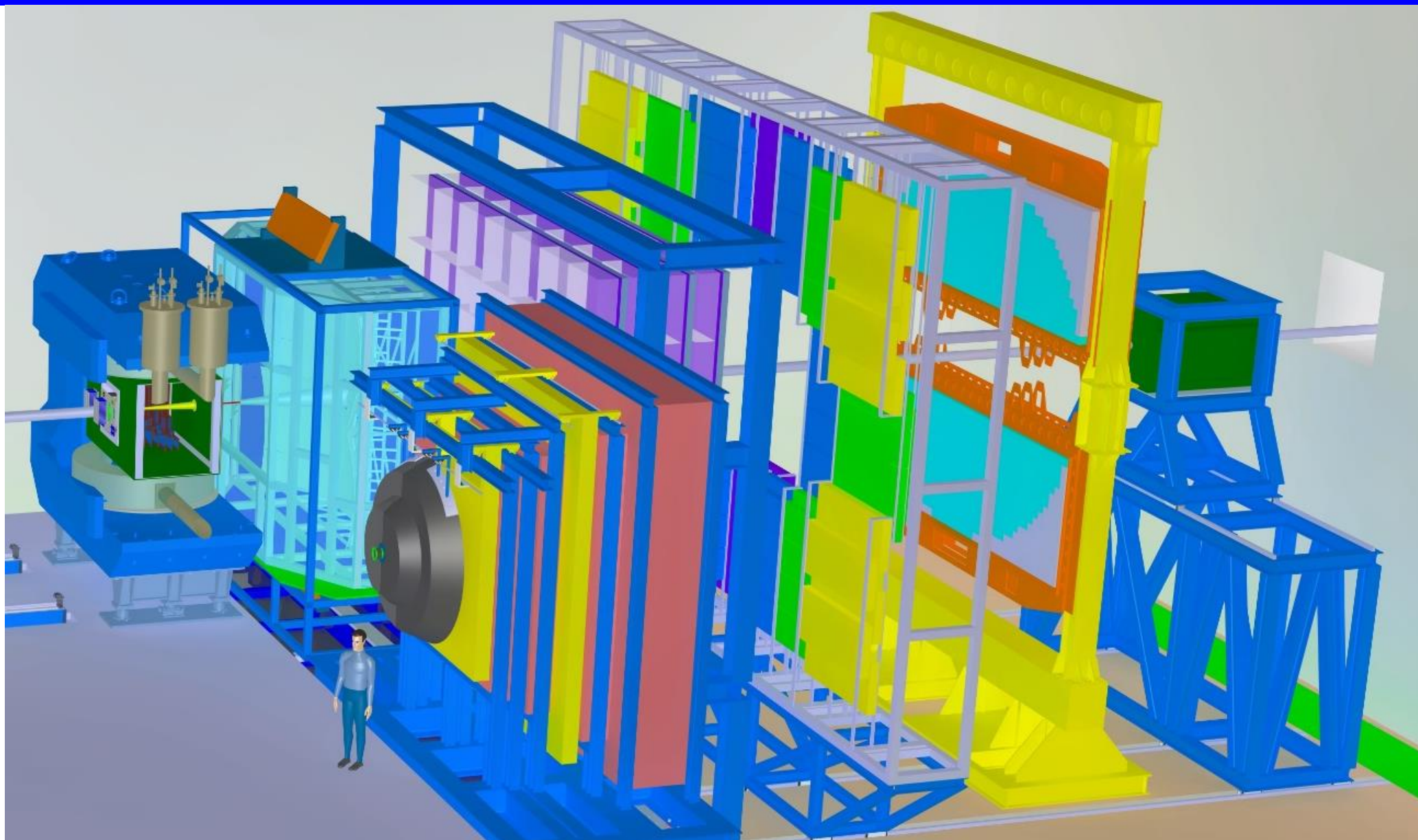
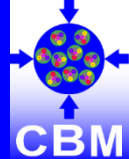
## EXPERIMENTAL CHALLENGES

- $10^5 - 10^7$  Au + Au reactions/sec
- Determination of (displaced) vertices ( $\sigma \approx 50 \mu\text{m}$ )
- Identification of leptons and hadrons
- Fast and radiation hard detectors
- Trigger-less Free-streaming readout electronics
- High speed data acquisition and high performance computer farm for online event selection
- 4-D event reconstruction

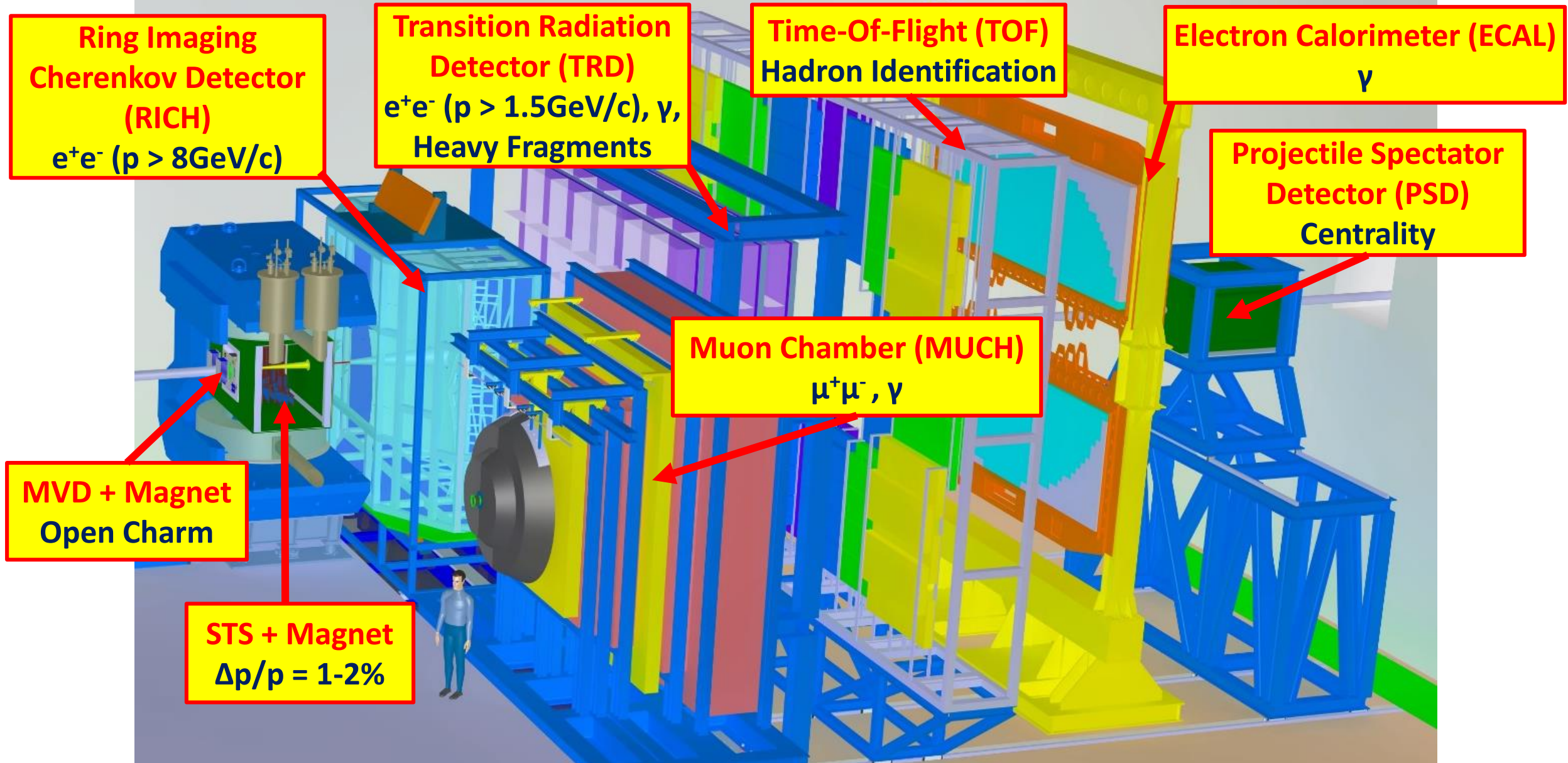
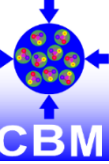


Image Credits: <https://imgflip.com/memetemplate/166876537/kid-vs-sumo-wrestler>

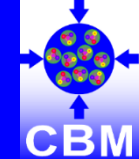
# CBM EXPERIMENTAL SETUP



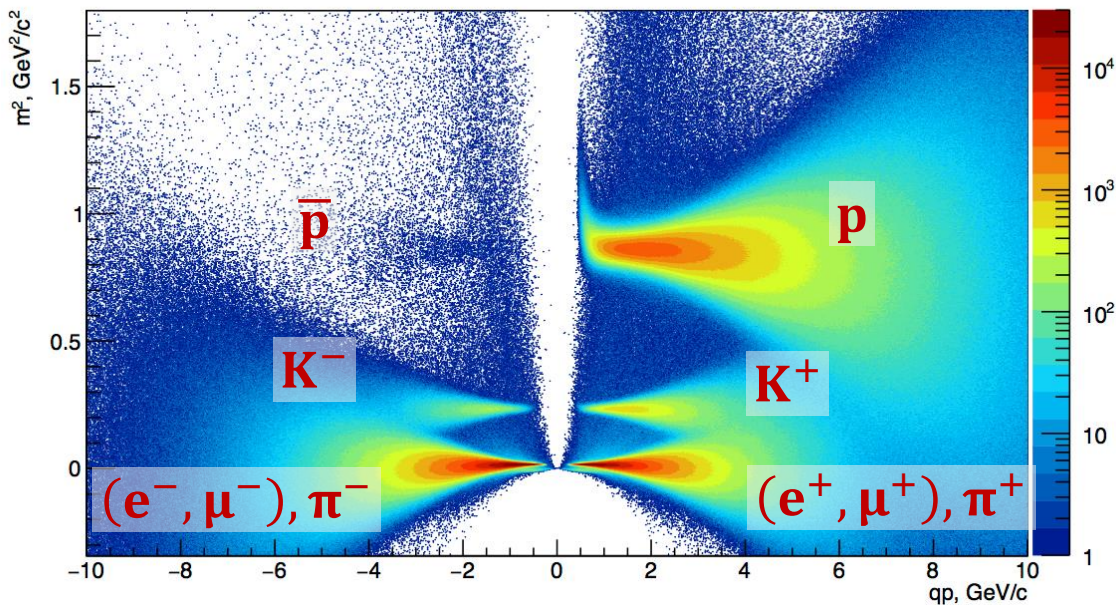
# CBM EXPERIMENTAL SETUP



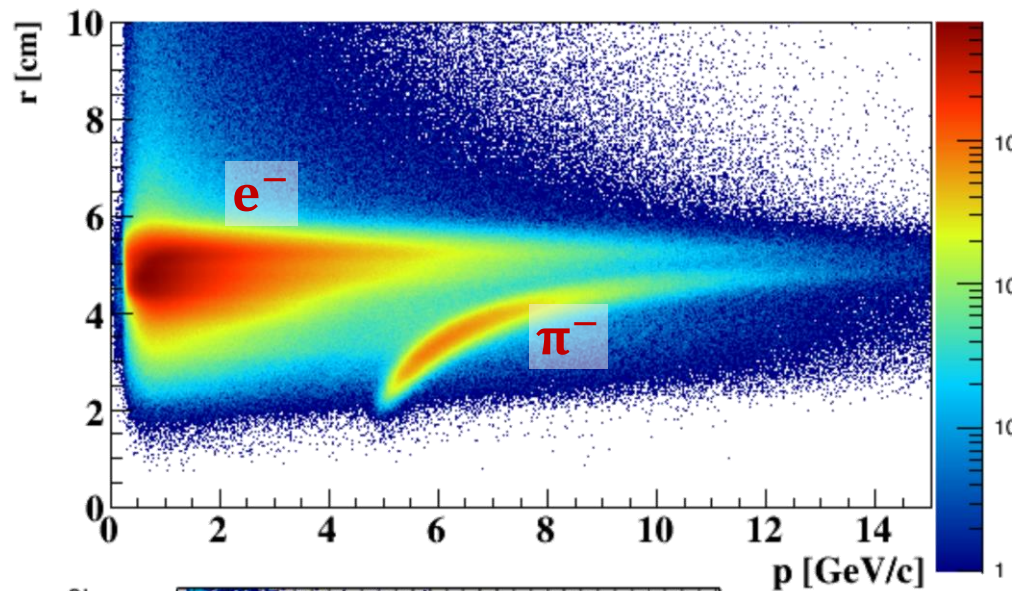
# PARTICLE IDENTIFICATION (PID) WITH CBM



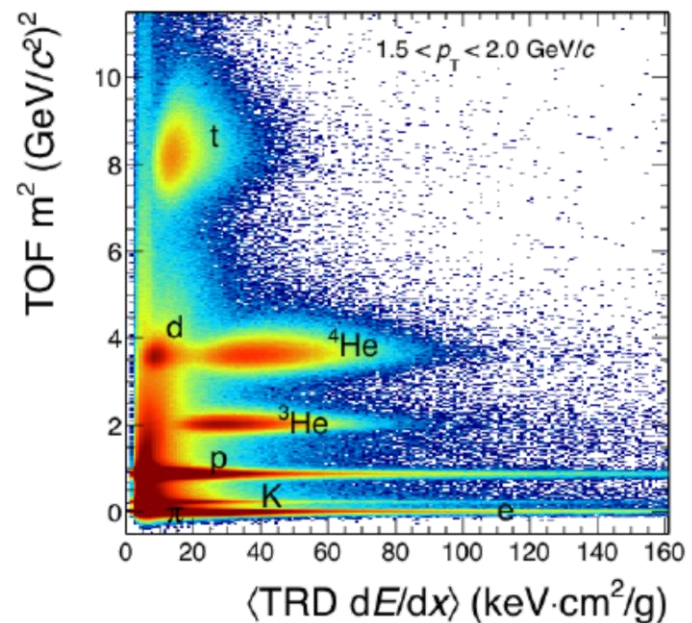
**ToF  
Hadron Identification**



**High purity identification of charged protons, pions, electrons and light nuclei**

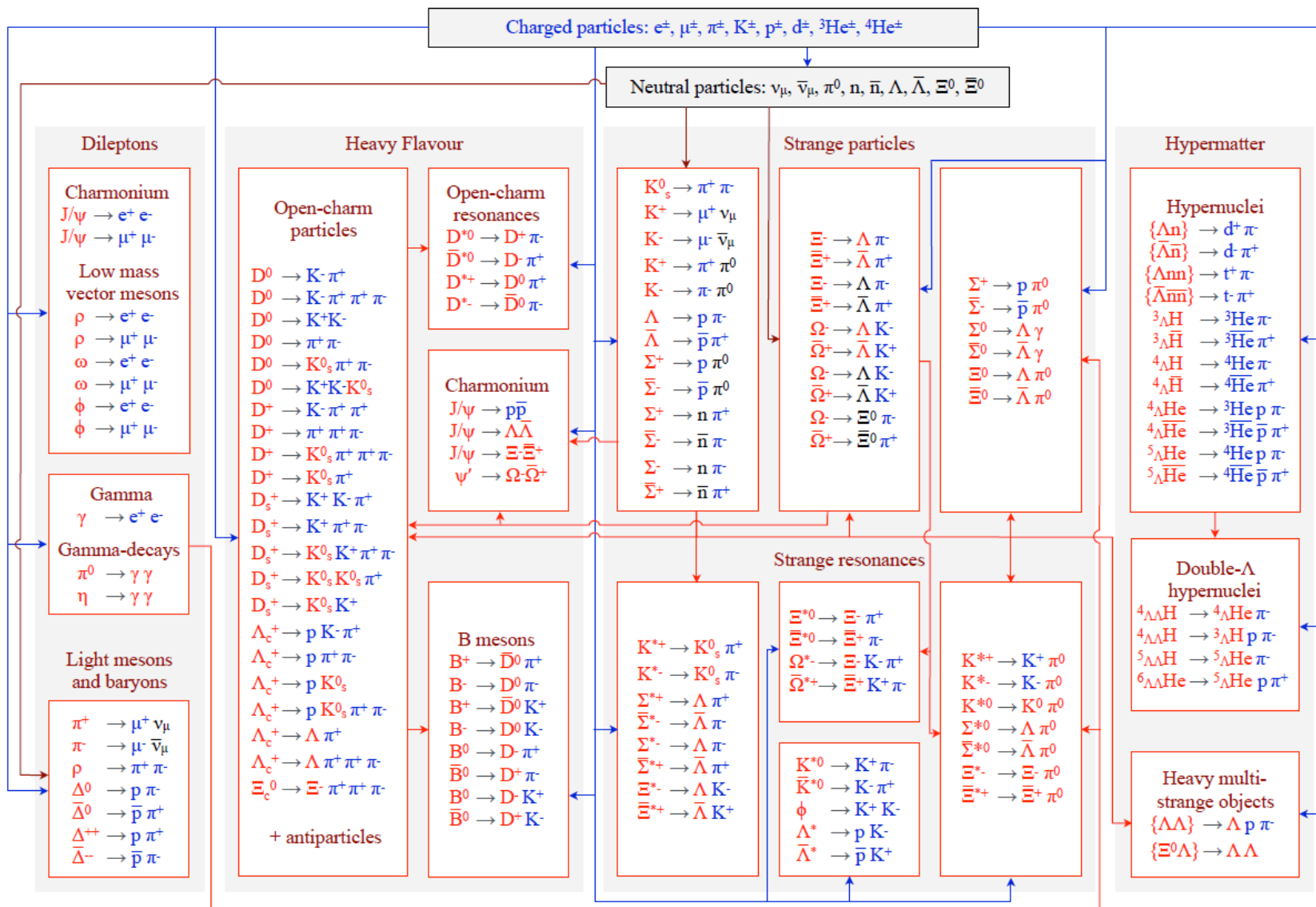
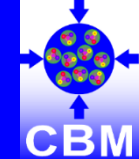


**RICH  
Electron  
Identification**



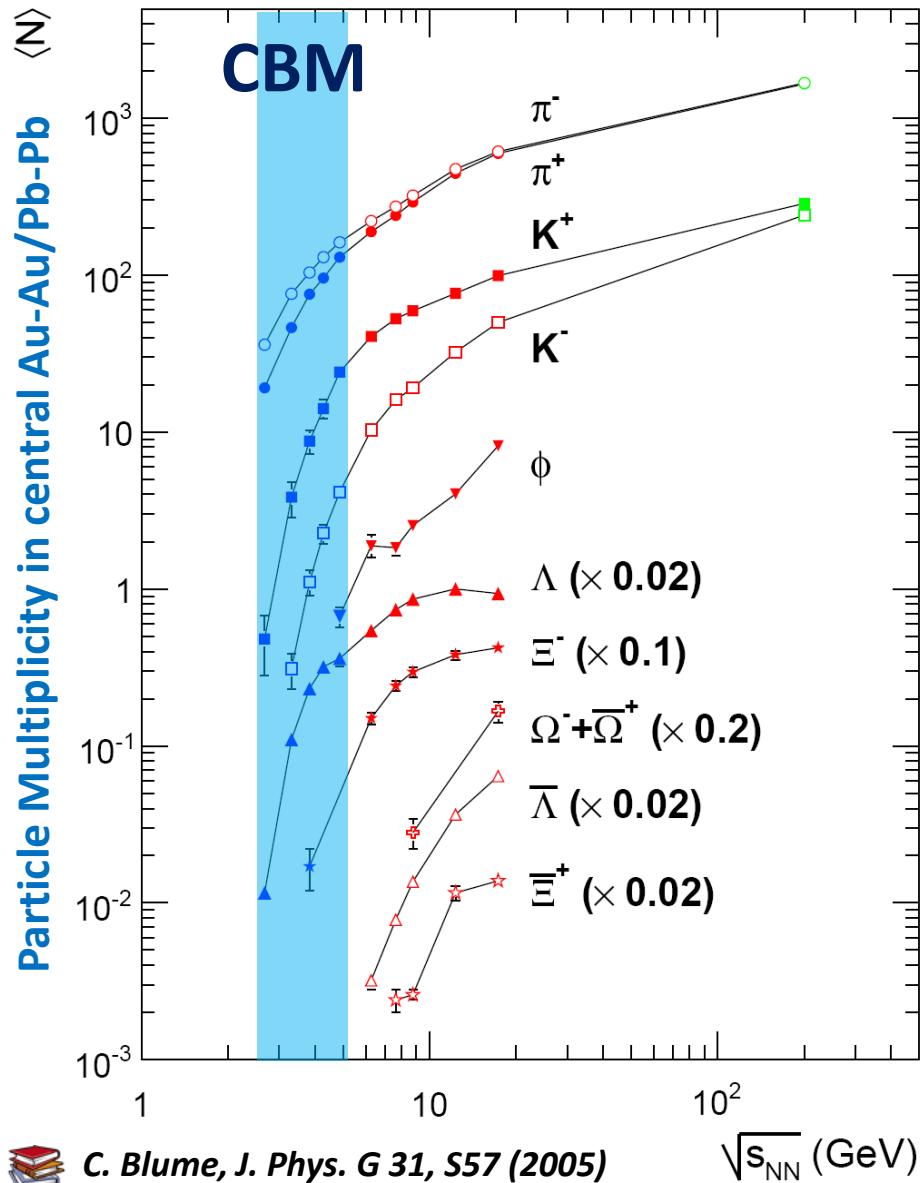
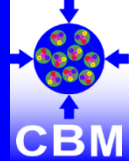
**TRD + ToF  
Electron, Light Nuclei,  
Heavy Fragments**

# KALMAN FILTER PARTICLE FINDER (KFPF)

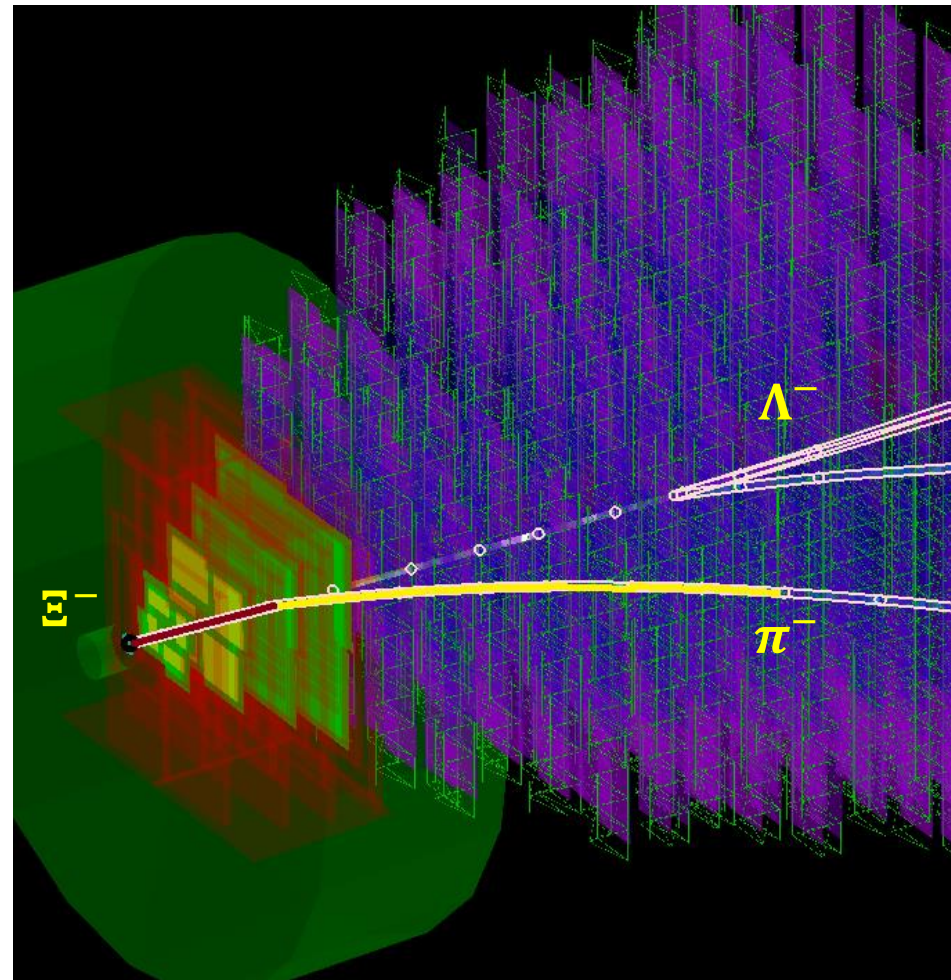


- Almost 150 decays
- All decays are reconstructed in one go – online!
- Based on the Kalman filter method – mathematically correct parameters and their errors
- Available in and approved within STAR, ALICE, PANDA

# CBM'S CAPABILITIES IN HYPERON DETECTION & RECONSTRUCTION

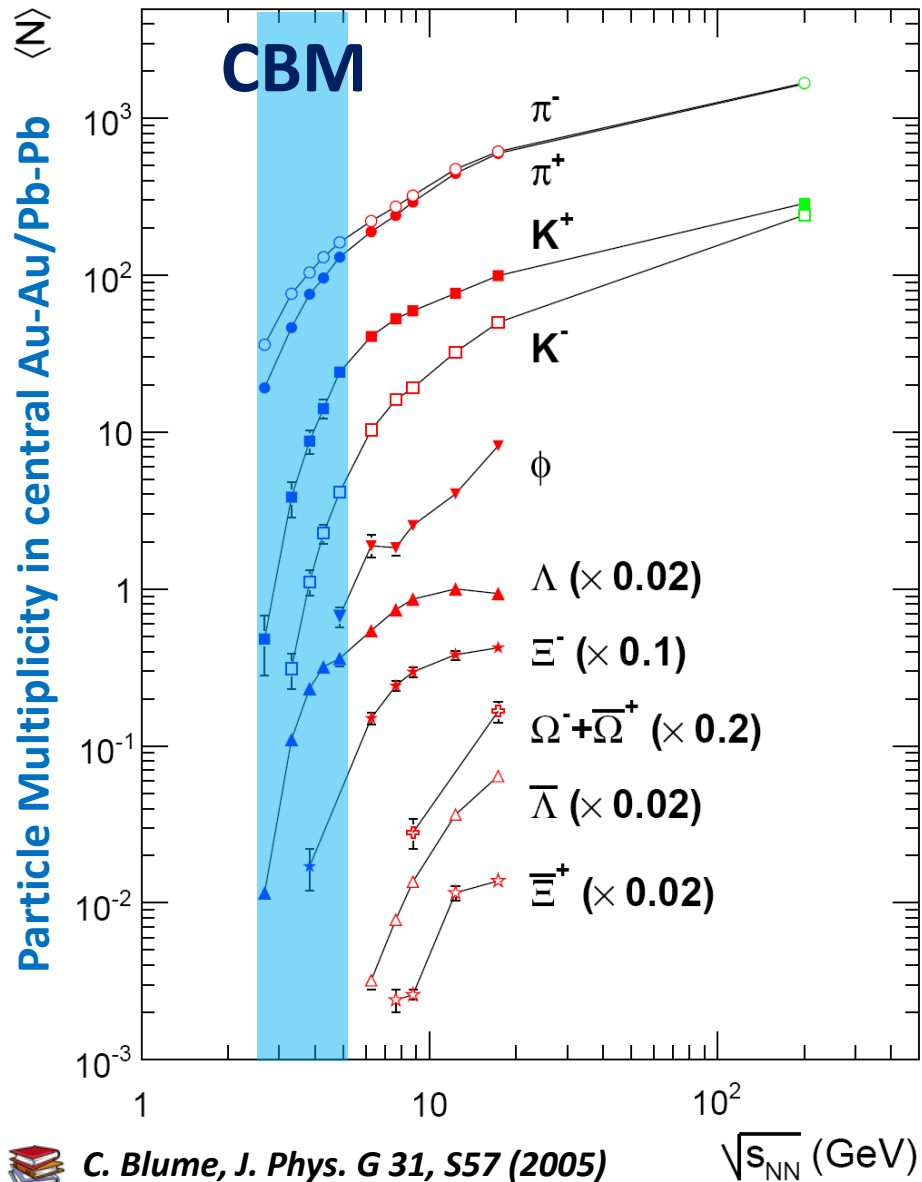
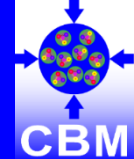


## $\Xi^-$ Decay Topology reconstructed in CBM

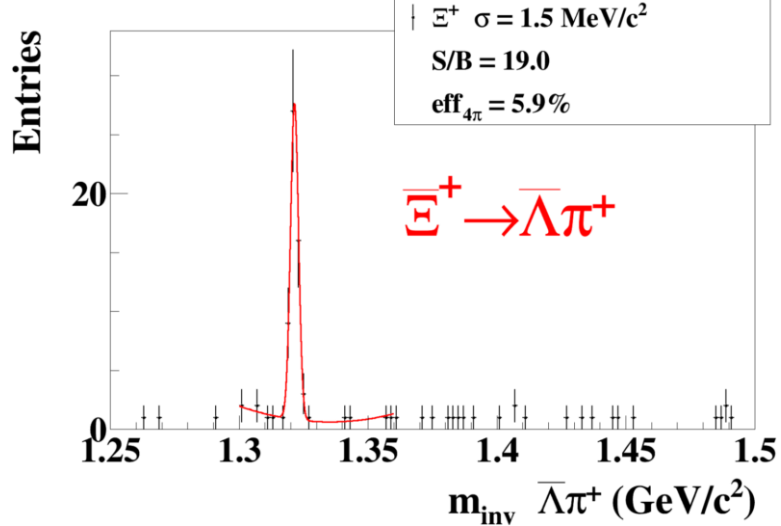
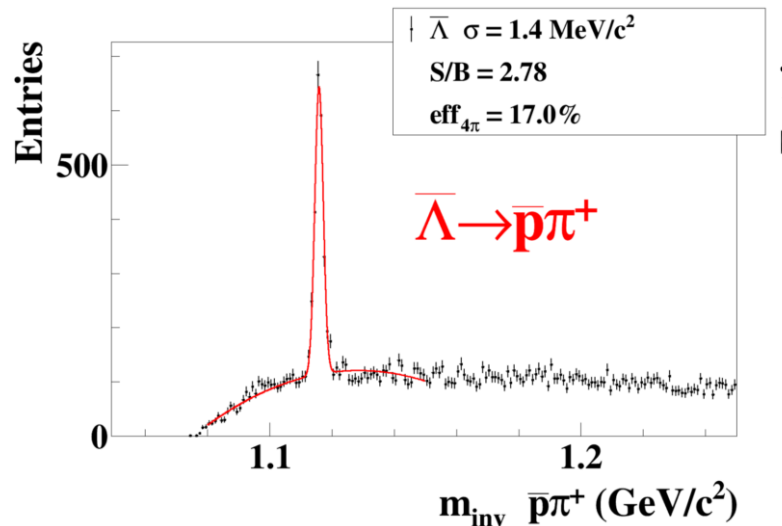
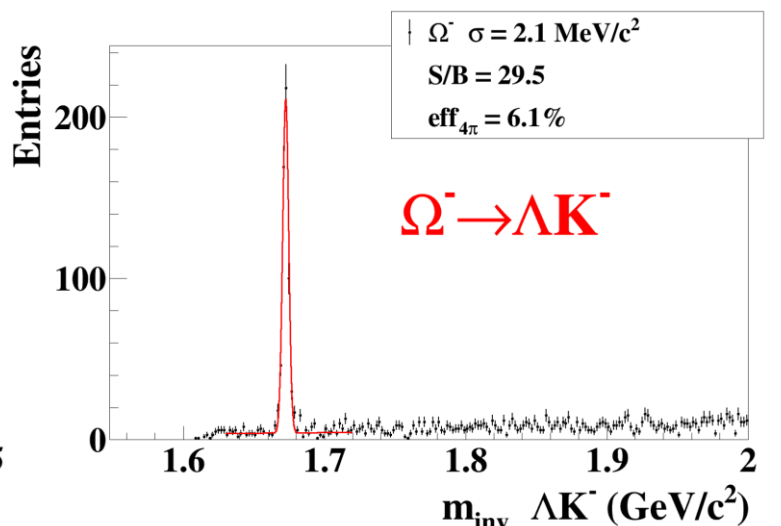
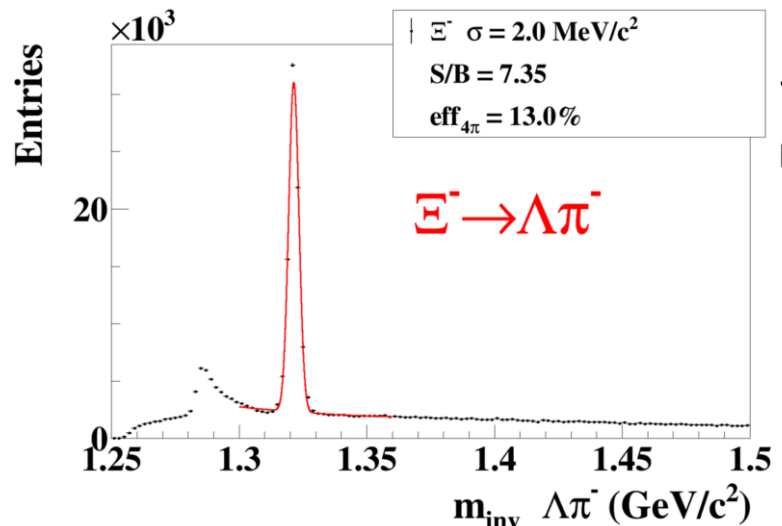


I. Vassiliev, *Quark Matter* (2018)

# CBM'S CAPABILITIES IN HYPERON DETECTION & RECONSTRUCTION

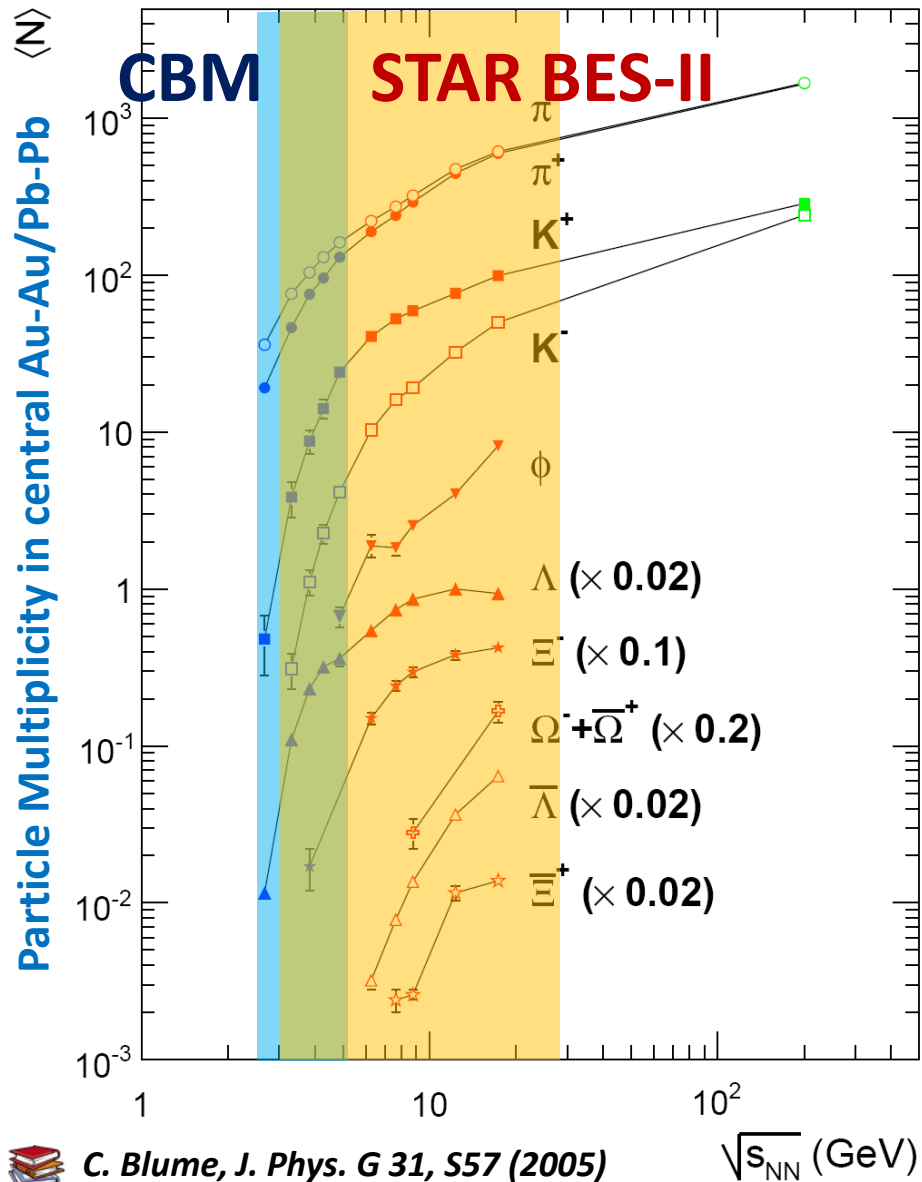
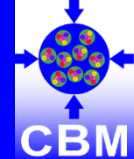


## CBM Performance using UrQMD Au+Au collisions 10 AGeV (b=0)

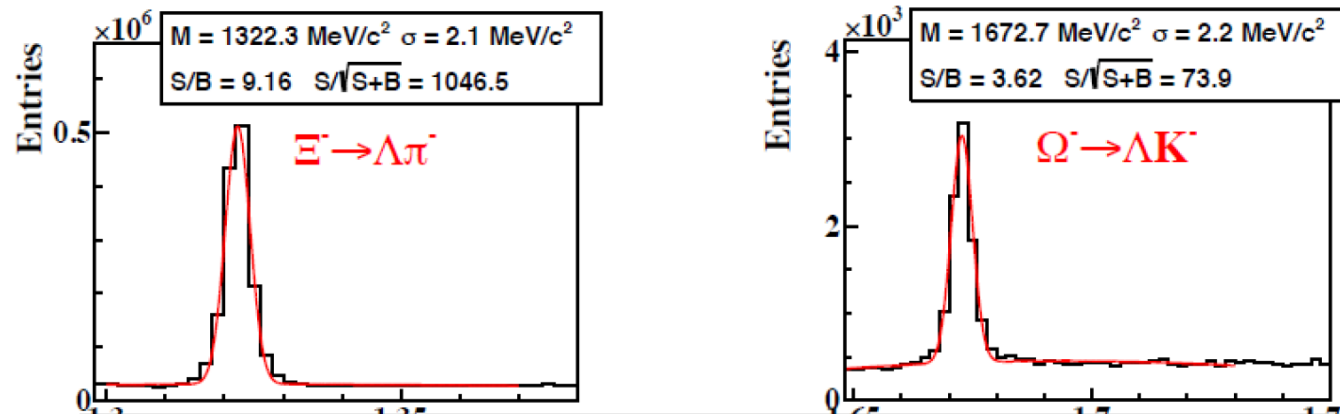


I. Vassiliev, 34<sup>th</sup> CBM Collaboration Meeting (2019)

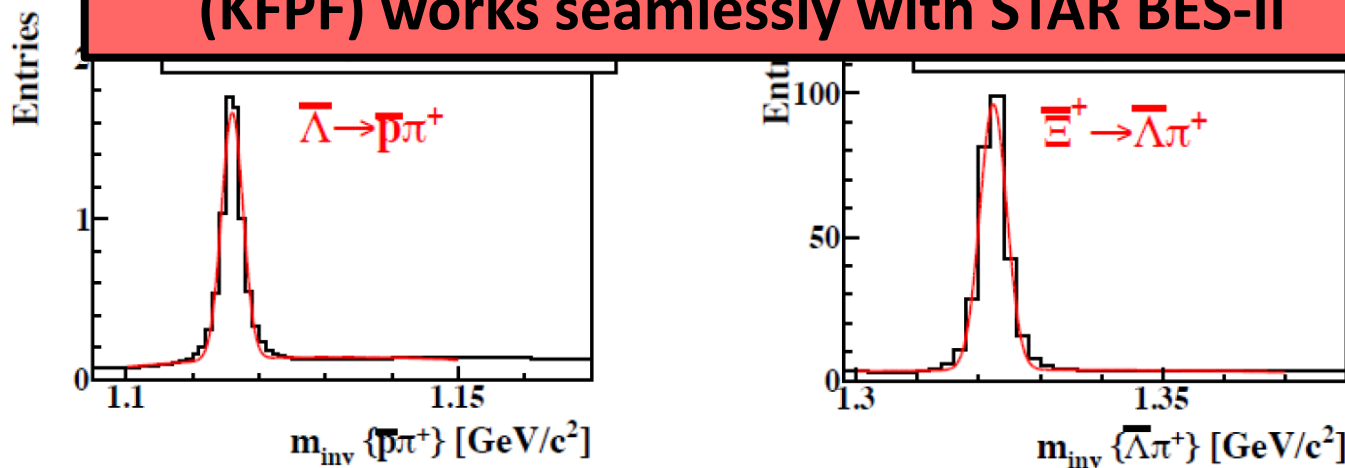
# CBM'S CAPABILITIES IN HYPERON DETECTION & RECONSTRUCTION



## STAR BES-II Performance at Au+Au collisions 14.5 GeV (200M events)



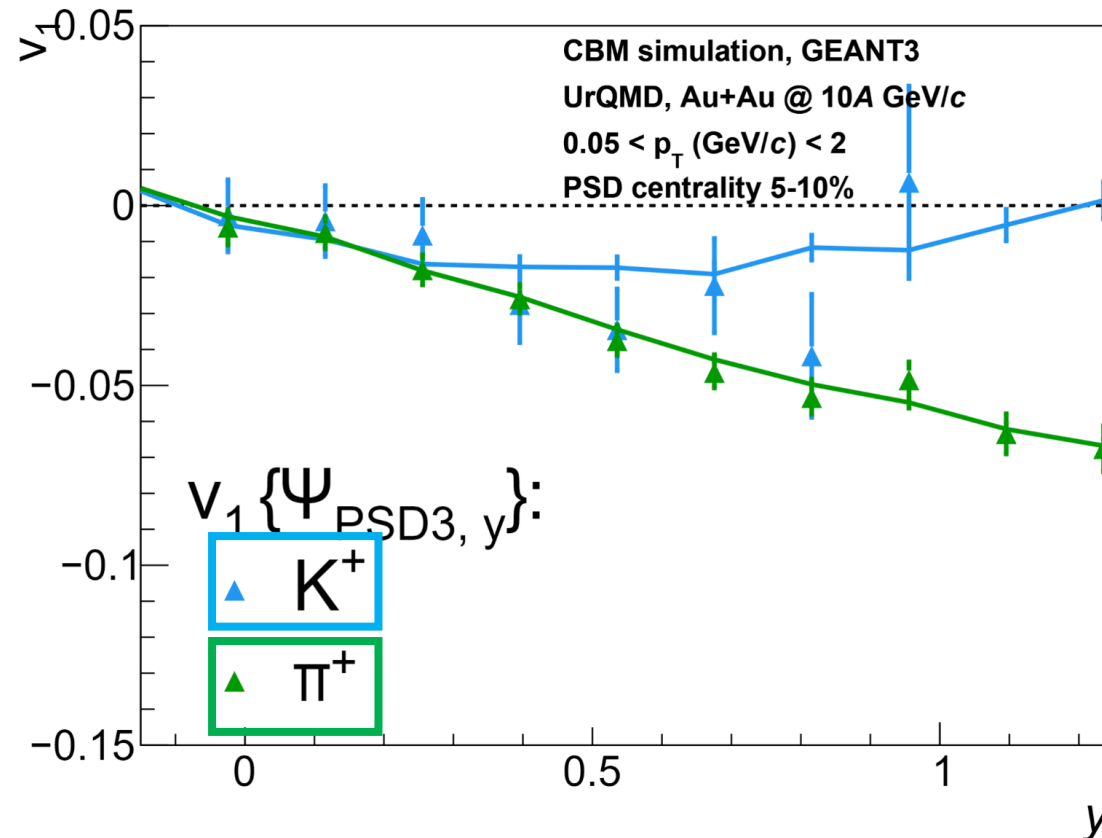
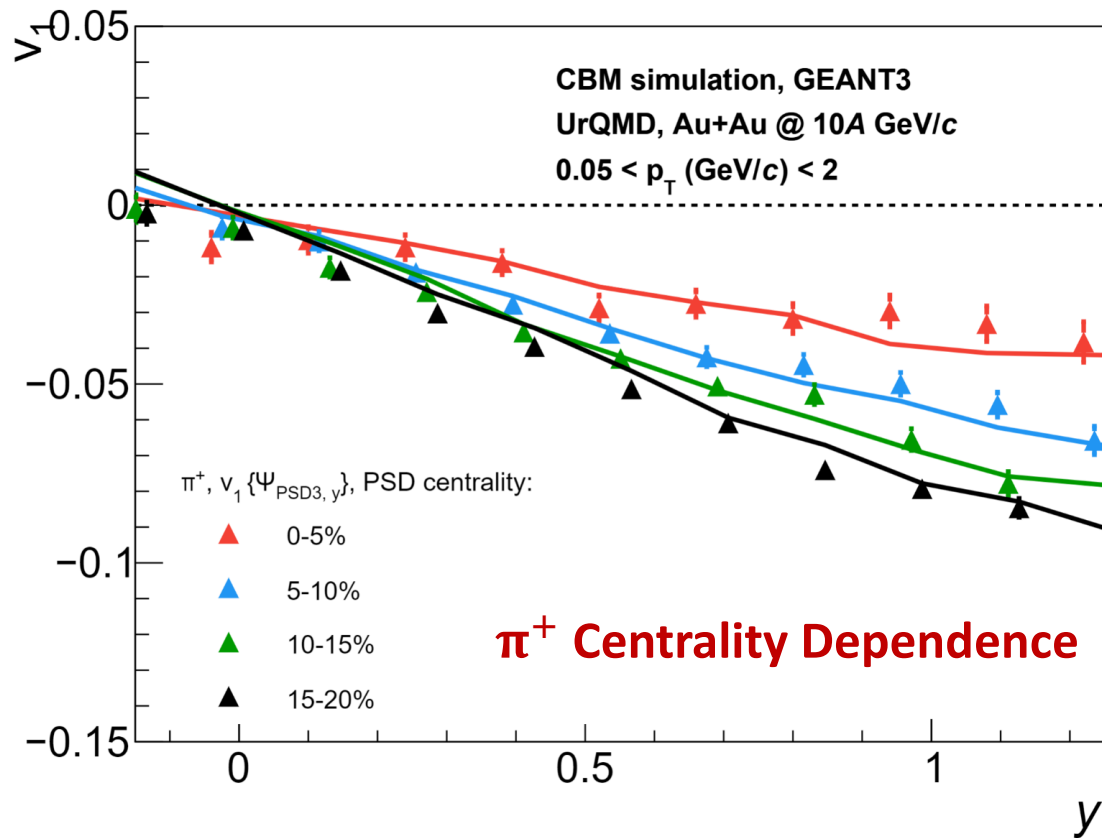
**CBM's online particle reconstruction package (KFPF) works seamlessly with STAR BES-II**



I. Vassiliev, 3rd EMMI Workshop on Anti-Matter, Hyper-Matter and Exotica Production at the LHC (2019)



## CBM Performance using UrQMD Au+Au collisions 10 AGeV



**“Input” model  $v_1$  is recovered using “data-driven” methods with projectile spectators**

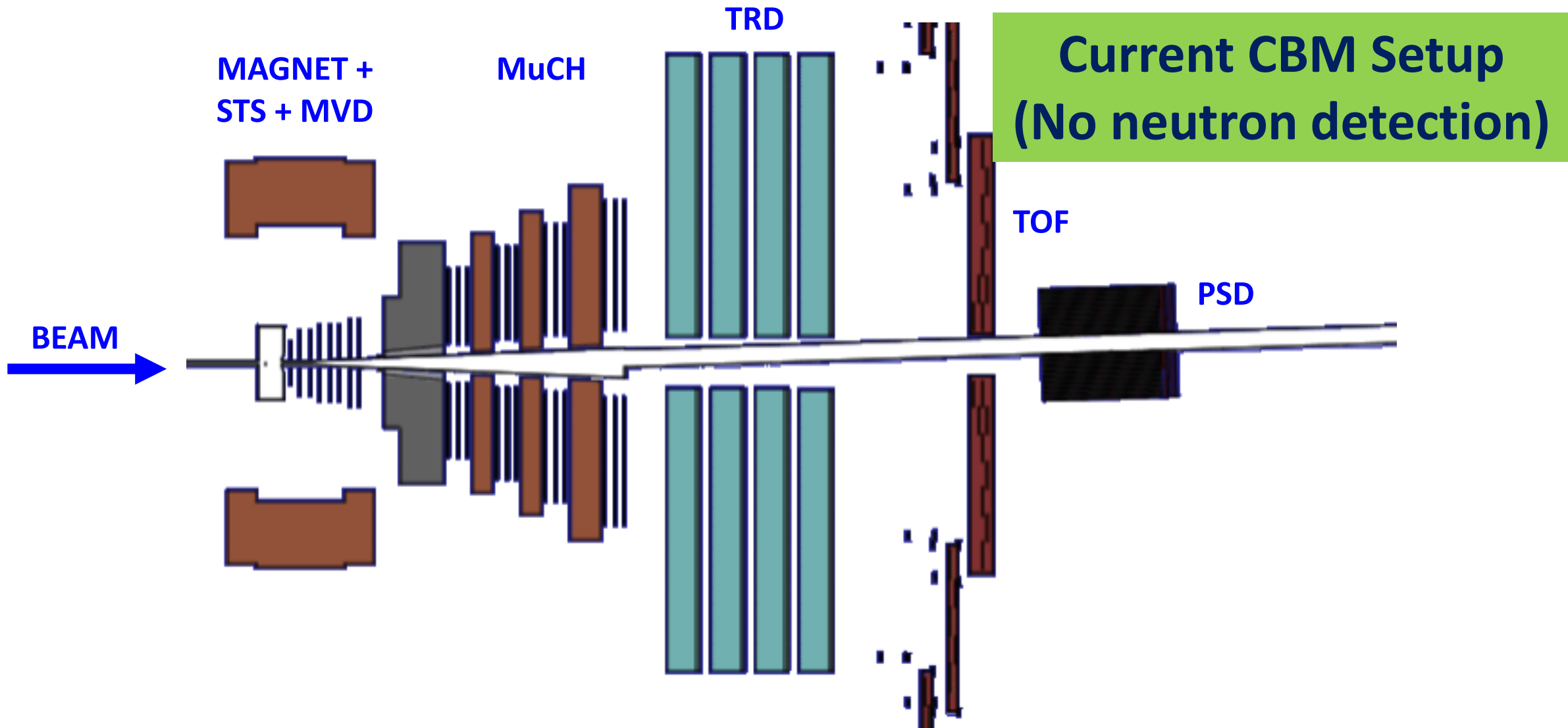
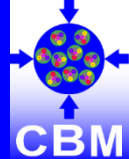


V. Klochov, PhD Thesis – Uni. Frankfurt (2019)

O. Golosov et al., Quark Matter (2019)

O. Golosov et al., 34<sup>th</sup> CBM Collaboration Meeting (2019)

# NUCLEAR SYMMETRY ENERGY AT HIGHER DENSITIES ( $\rho \geq 2\rho_0$ )



# NUCLEAR SYMMETRY ENERGY AT HIGHER DENSITIES ( $\rho \geq 2\rho_0$ )

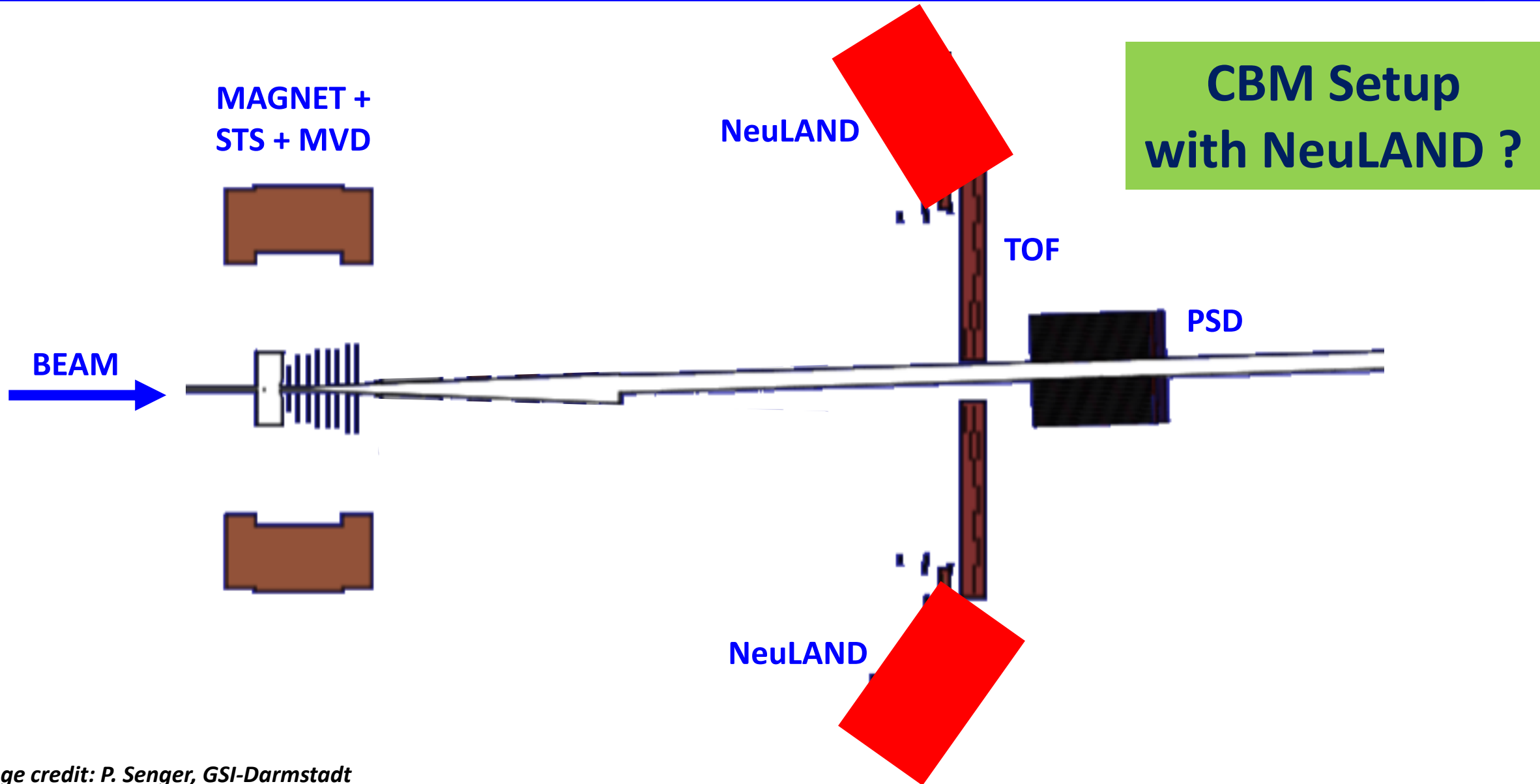
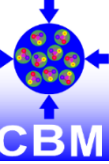
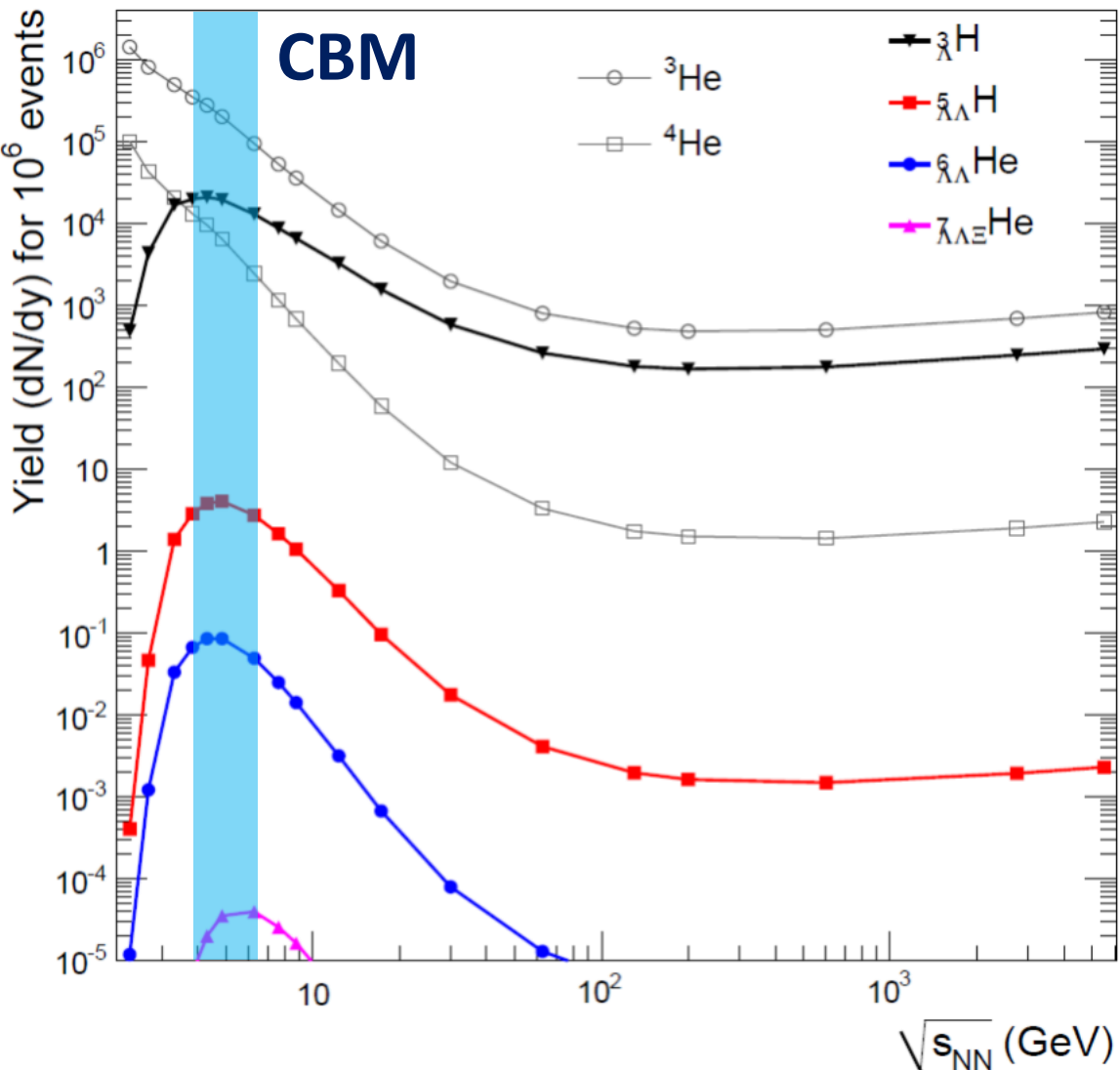
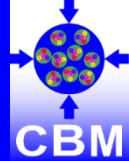
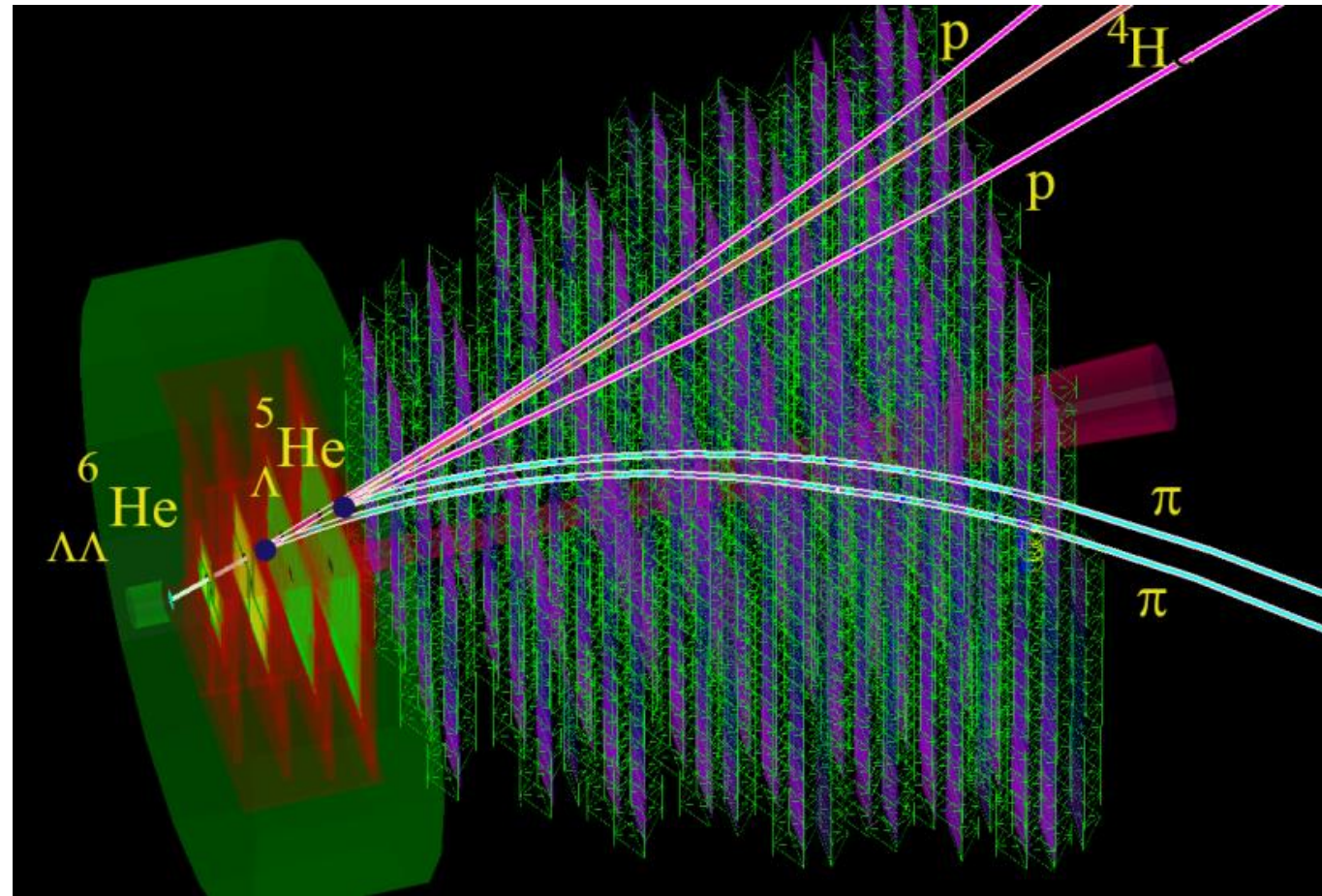


 Image credit: P. Senger, GSI-Darmstadt

# UNDERSTANDING $\Lambda$ -N, $\Lambda$ - $\Lambda$ INTERACTIONS WITH CBM



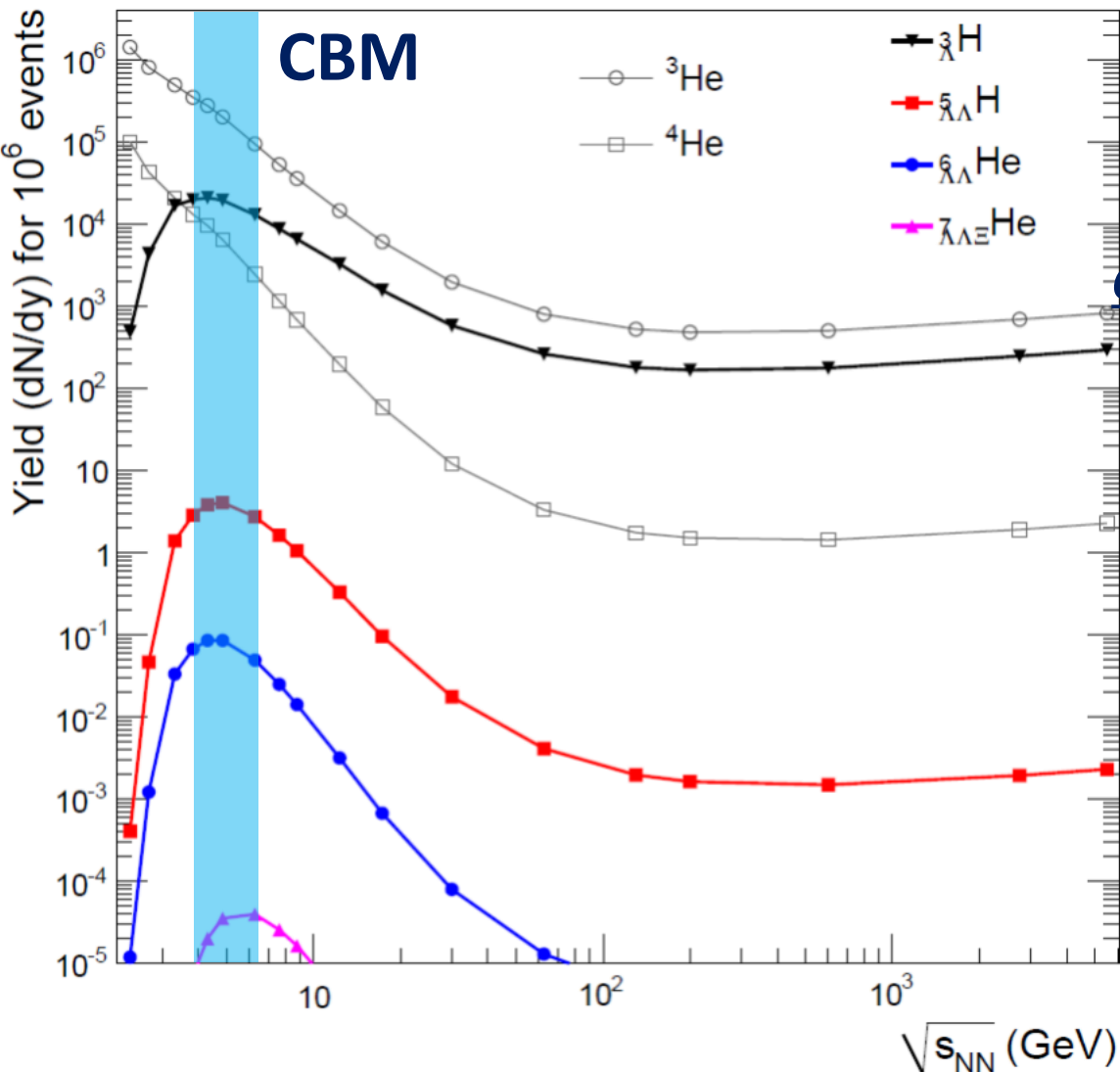
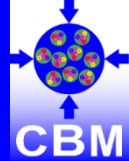
## ${}^6_{\Lambda\Lambda}\text{He}$ Decay Topology reconstructed in CBM



Thermal Model: A. Andronic et al., Phys. Lett. B697 (2011) 203

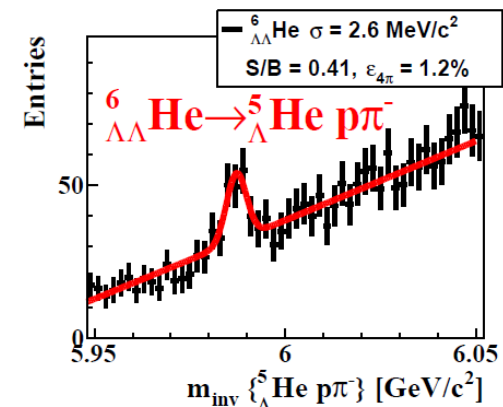
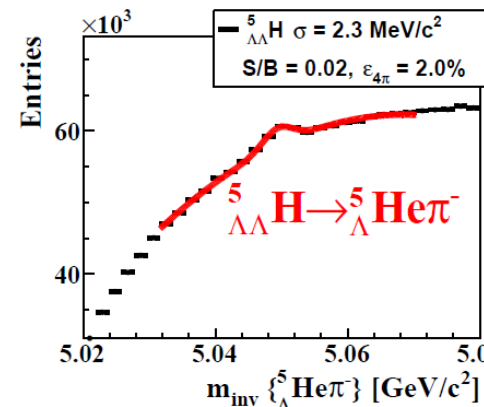
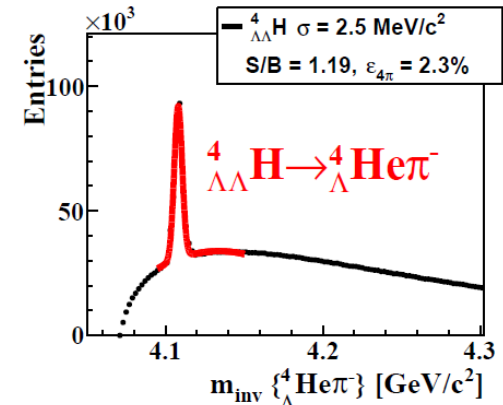
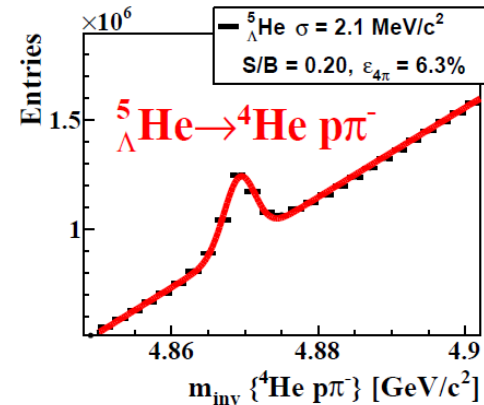
I. Vassiliev, Quark Matter (2018)

# UNDERSTANDING $\Lambda$ -N, $\Lambda$ - $\Lambda$ INTERACTIONS WITH CBM

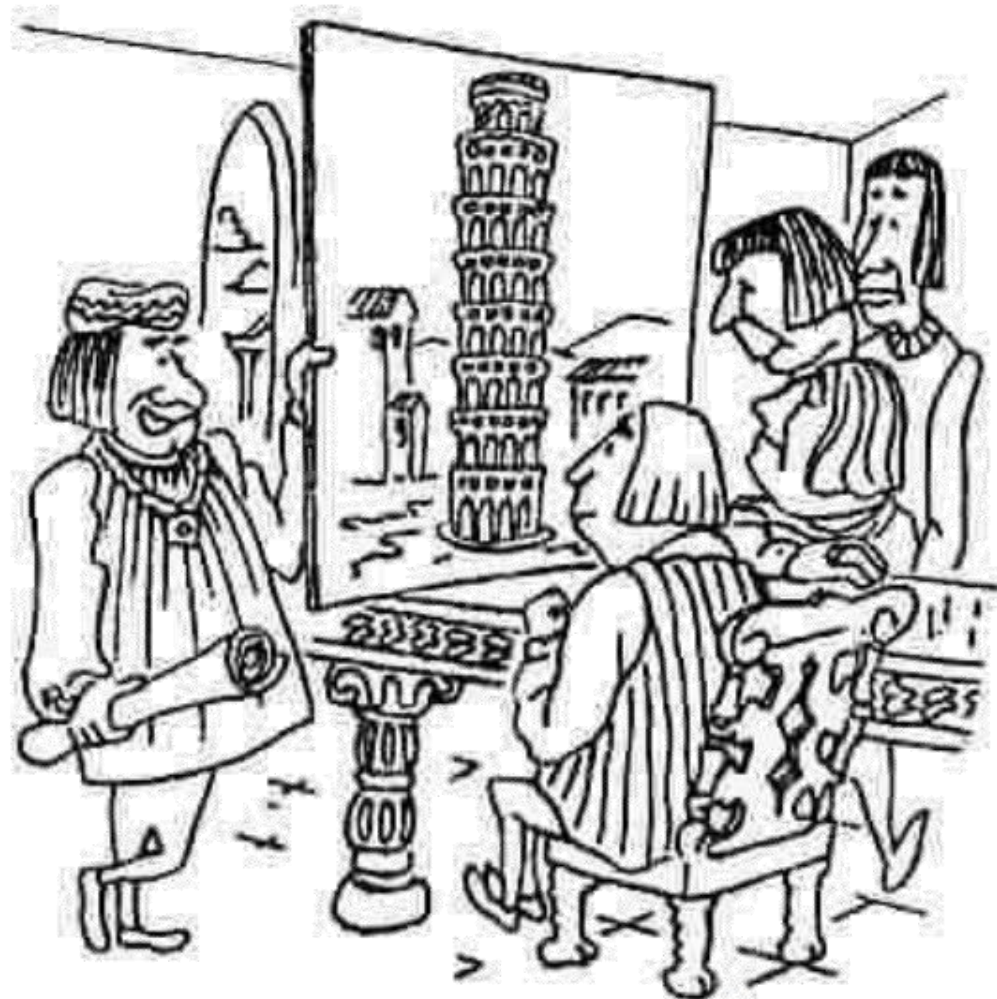


	Multiplicity	Yield 1 week	Int. Rate	Branching Ratio, Efficiency
${}^5_{\Lambda\Lambda}\text{H}$	$5 \cdot 10^{-6}$	3000	1 MHz	10%, 1%
${}^6_{\Lambda\Lambda}\text{He}$	$1 \cdot 10^{-7}$	60	1 MHz	10%, 1%

## CBM Performance using UrQMD Au+Au collisions 10 AGeV ( $b=0$ )



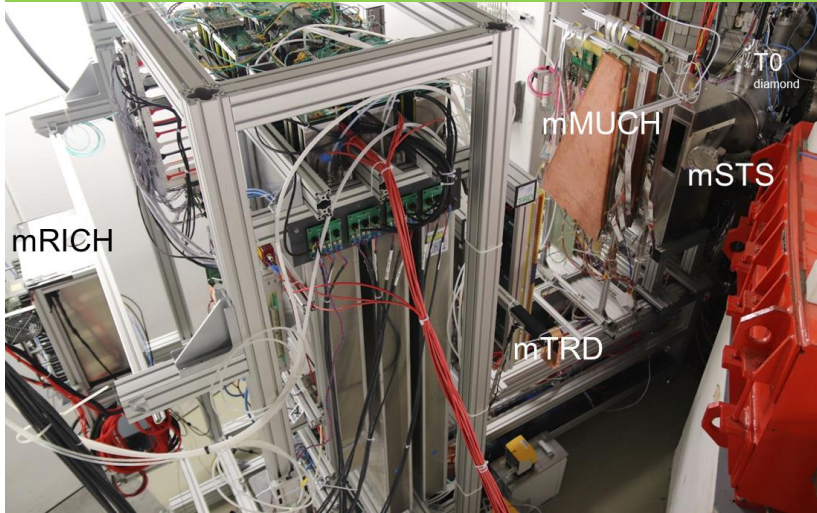
Thermal Model: A. Andronic et al., Phys. Lett. B697 (2011) 203



*“However, we can save 3% and 3 months of work by skipping soil tests!”*

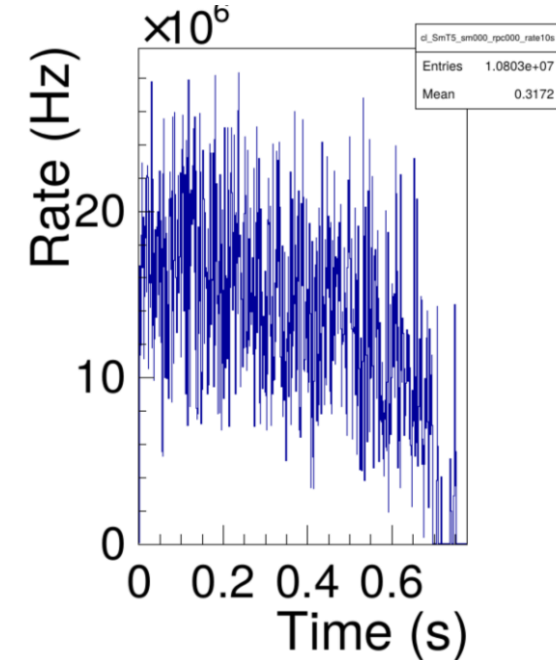


## mCBM @ SIS18

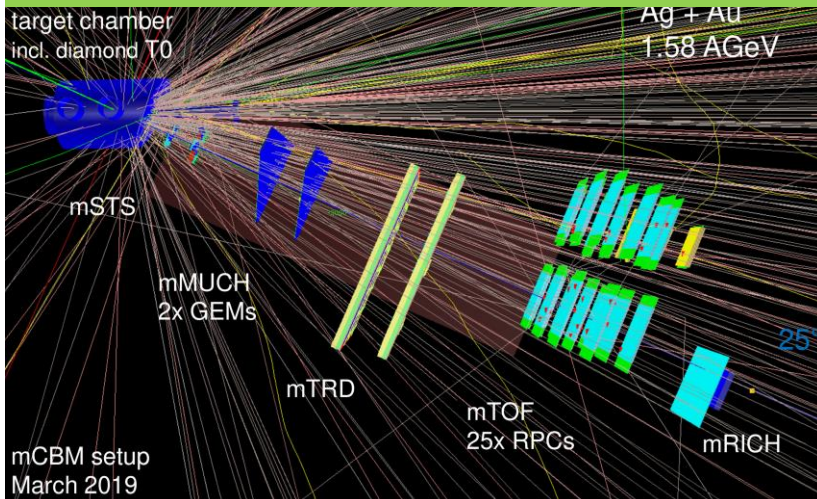


## mCBM – Test-setup at SIS18 at 10 MHz

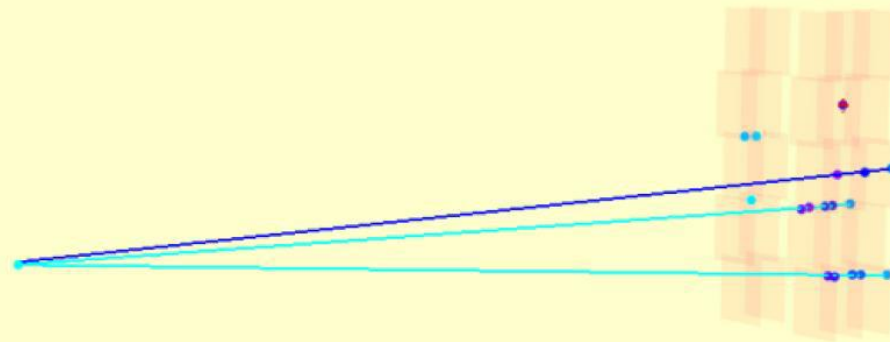
- Free streaming read-out and data transport to the mFLES
- Online reconstruction
- Offline data analysis
- Controls
- Detector tests of final detector prototypes



## UrQMD sim. – Ag+Au 1.58 AGeV



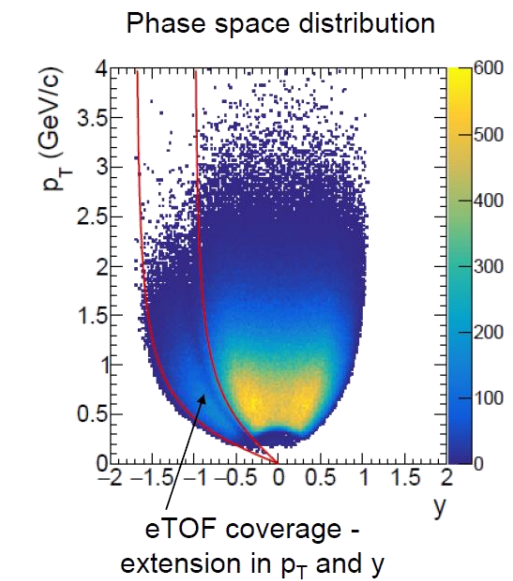
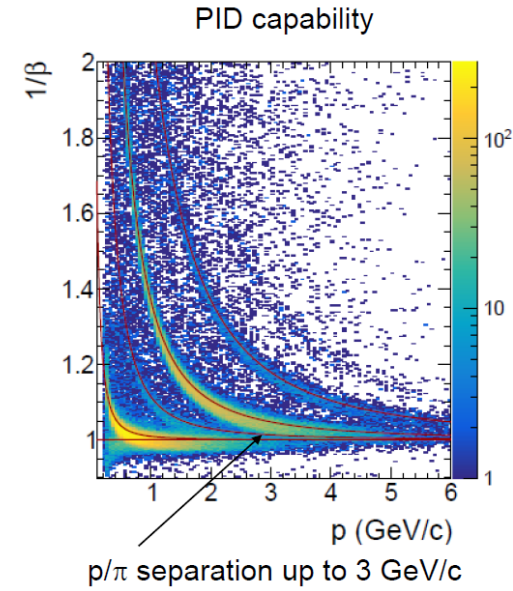
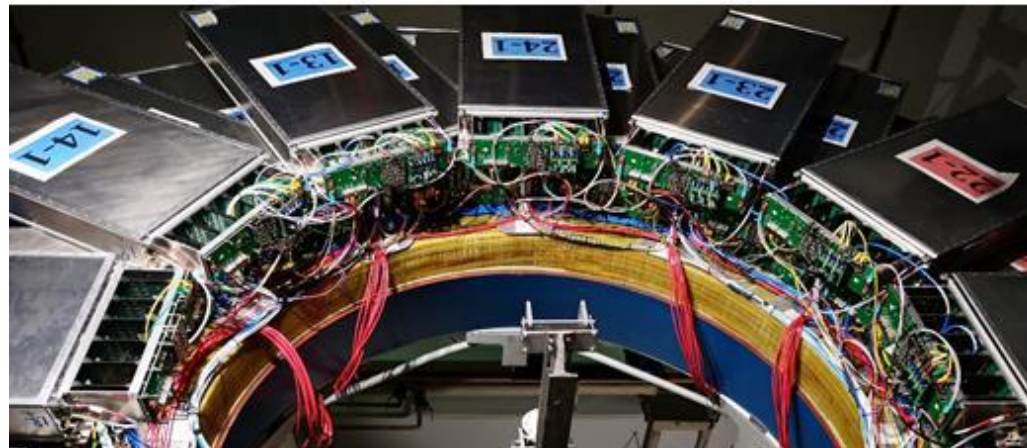
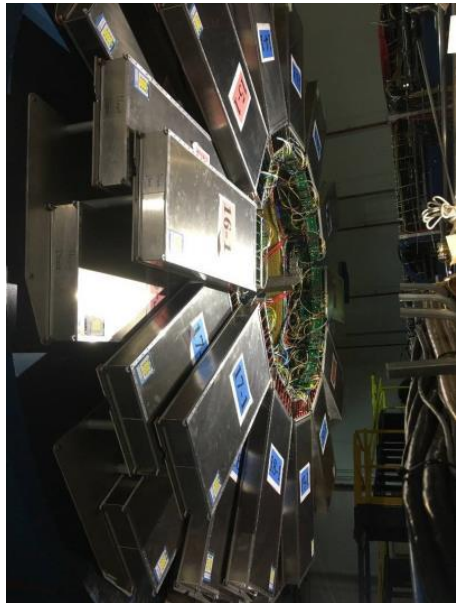
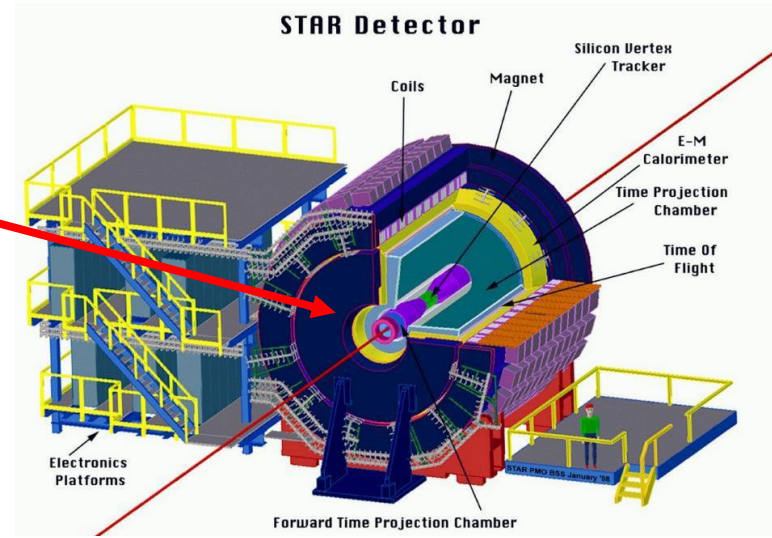
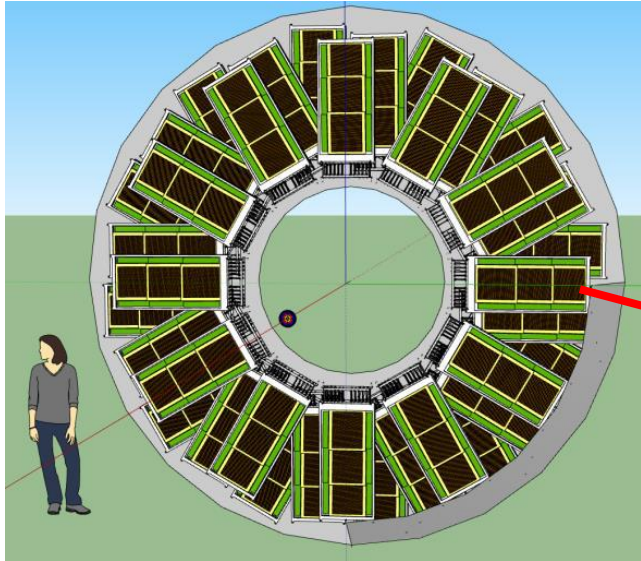
## mToF Event Display



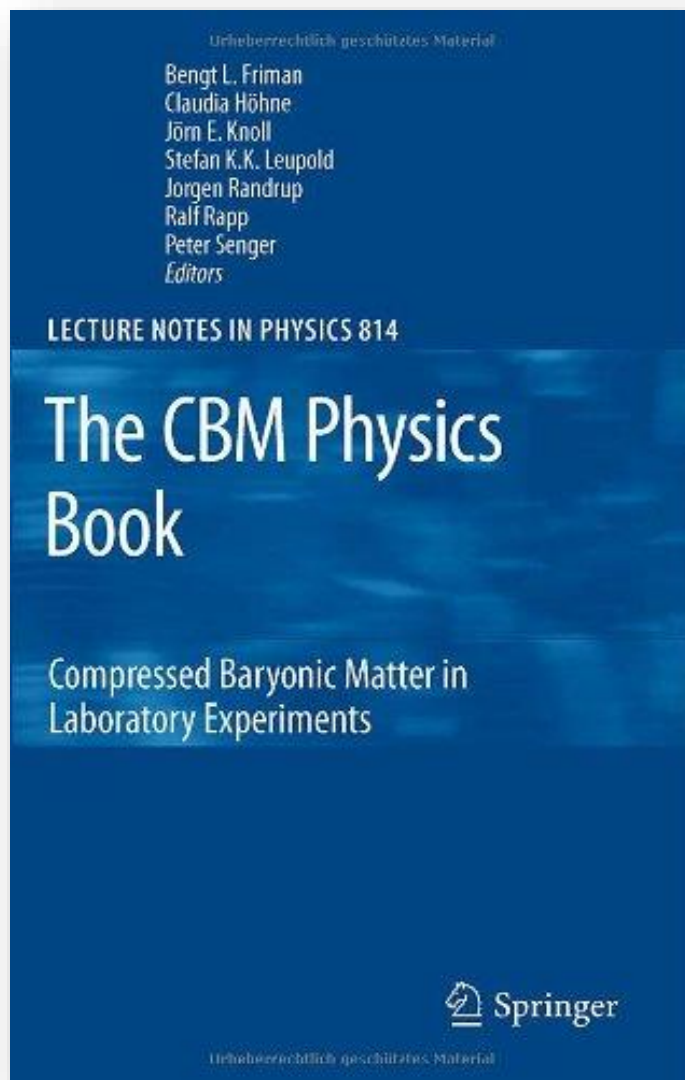
Beam Rate -  $R(T_0)$   $2 \times 10^7$  Hz  
With Target Thickness  $P_{int} = 10\%$   
So, Interaction Rate  $R_{int} = 2 \times 10^6$  Hz

**High rate capability of mCBM demonstrated at 2 MHz!**

**Successfully Installed and Operational  
36 modules, 108 MRPCs, ~7000 channels**





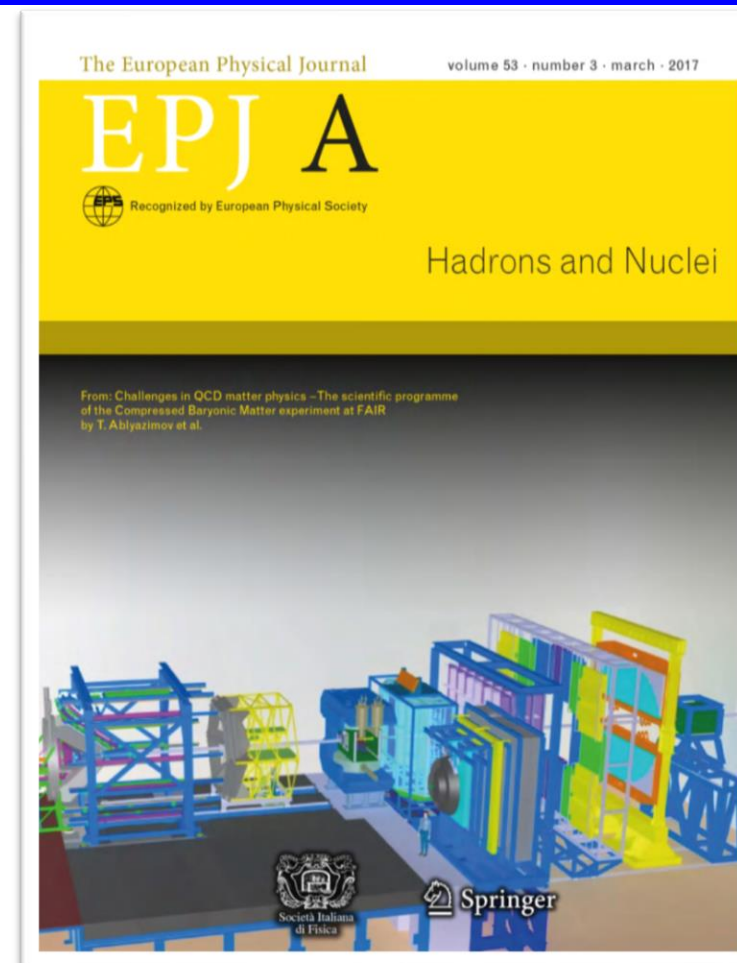


## The CBM Physics Book

Foreword by Frank Wilczek

Springer Series:  
Lecture Notes in Physics, Vol. 814  
1<sup>st</sup> Edition., 2011, 960 p., Hardcover  
ISBN: 978-3-642-13292-6

Electronic Authors version:  
<http://www.gsi.de/documents/DOC-2009-Sep-120-1.pdf>



“Challenges in QCD Matter Physics – the scientific programme of the Compressed Baryonic Matter Experiment at FAIR”

T. Abyazimov et al. [CBM Collaboration] Eur. Phys. J. A (2017)

**CBM@FAIR (2 – 11 AGeV Au-Au) provides unique conditions in lab to probe QCD matter properties at neutron star core densities, including the high density EOS, and the search for new phases expected for densities above  $5\rho_0$**

### **Nuclear Symmetric Matter EOS:**

- **Collective flow of Baryons ( $\pi$ ,  $K$ ,  $p$ ,  $\Lambda$ ,  $\Xi$ ,  $\Omega$ ,...)** driven by the fireball's pressure gradient
- **Sub-Threshold Particle Production of Multi-Strange Hyperons via multi-step processes**

### **Neutron Matter EOS:**

#### **Symmetry Energy:**

- **Neutron/Proton Elliptic Flow  $\rightarrow$  Possible to upgrade with NewLAND**
- **Sub-Threshold Particle Production of isospin-opposite particles ( $I_3 = \pm 1$ ) ?**

#### **Hyperon Puzzle ( $\Lambda N$ , $\Lambda NN$ , and $\Lambda\Lambda N$ interactions)**

- **Hypernuclei production, yields, lifetime, collective flow**
- **Correlation functions to study interaction cross-sections by using CATS**

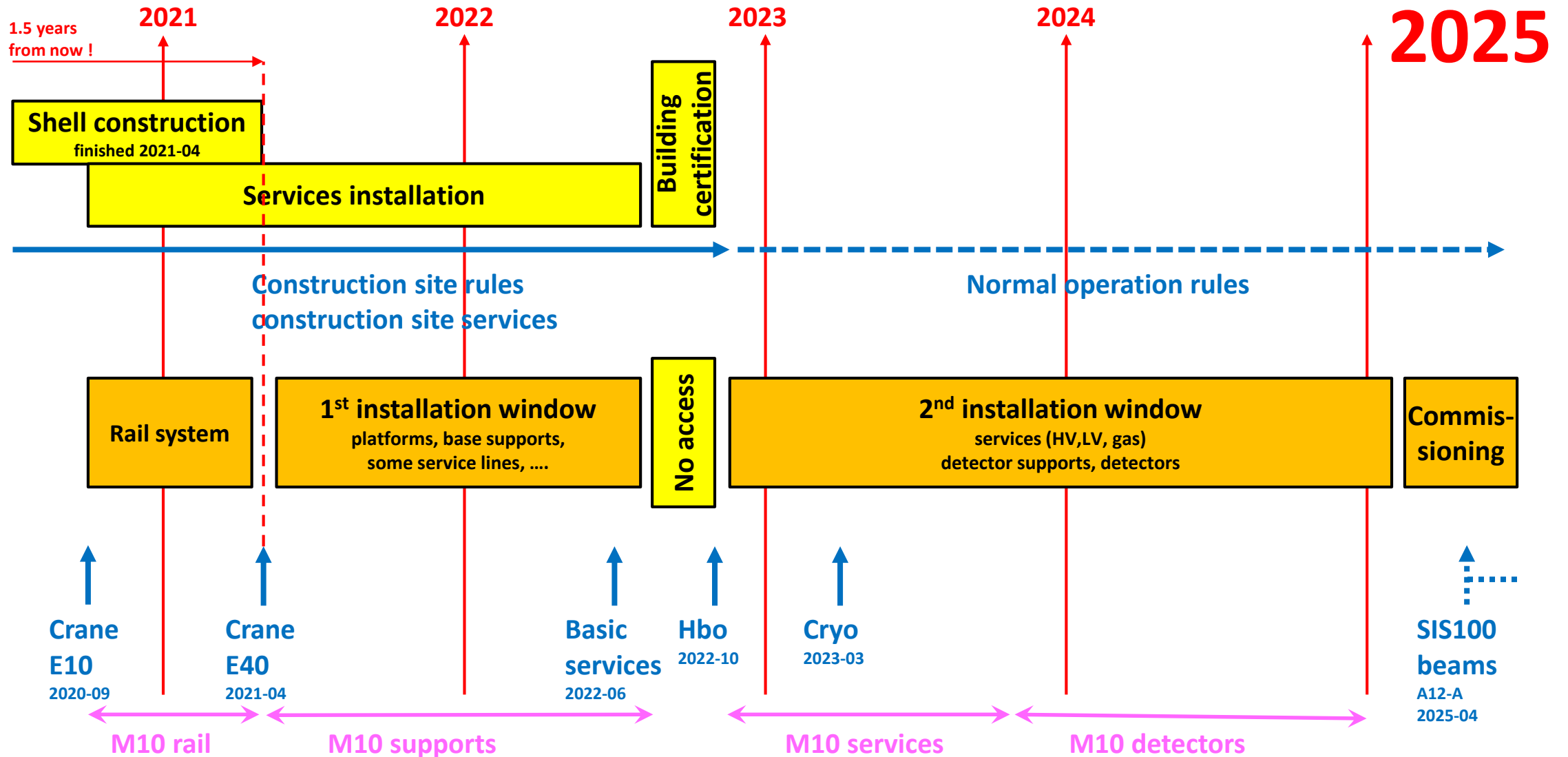
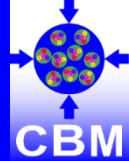
## Experimental Requirements

- Unique measurements of bulk & rare probes with CBM
- High-rate capability of detectors and triggerless DAQ
- Online event reconstruction and selection

## Testing CBM components and analysis methods within FAIR Phase-0

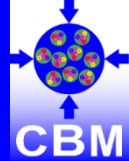
- mCBM campaign ongoing → great learning experience and proof-of-principle for DAQ
- eTOF @ BES-II successfully installed
- KF Particle Finder successfully used in BES-II particle reconstruction

# OUTLOOK – HOPEFULLY THE TIMELINES REMAIN ‘STIFF’

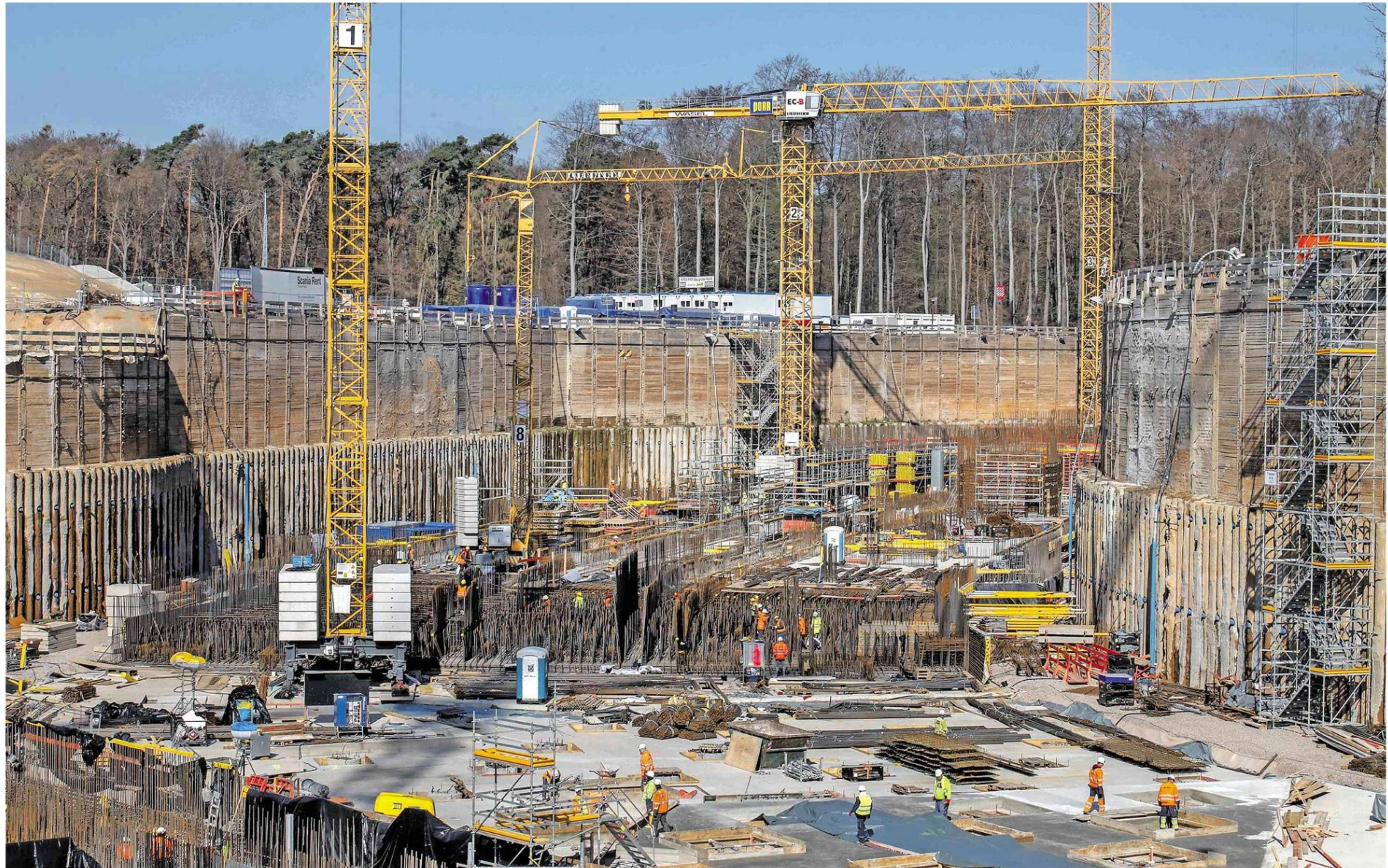


W.F.J. Müller, Joint FAIR ECE 11 and ECSG 02 meeting (2019)

# ALMOST THERE...



# ALMOST THERE...



# ALMOST THERE...



# ALMOST THERE...

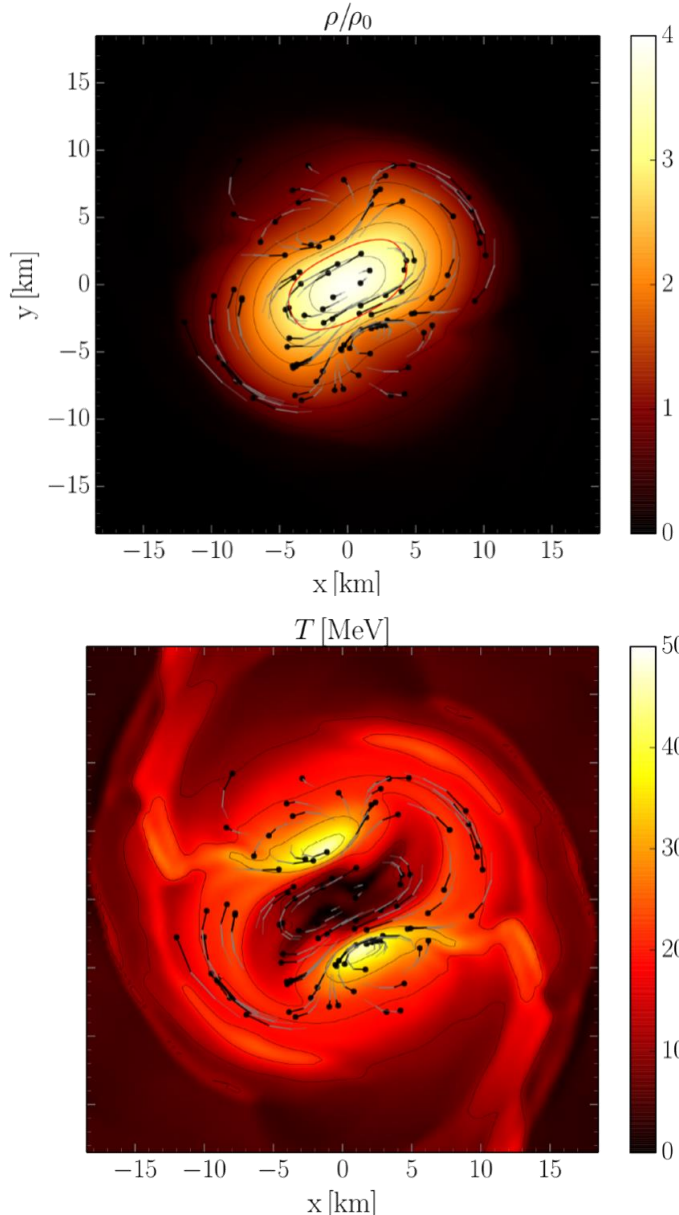




# THANKS A LOT FOR YOUR ATTENTION 😊



# BACK-UP ADDITIONAL SLIDES



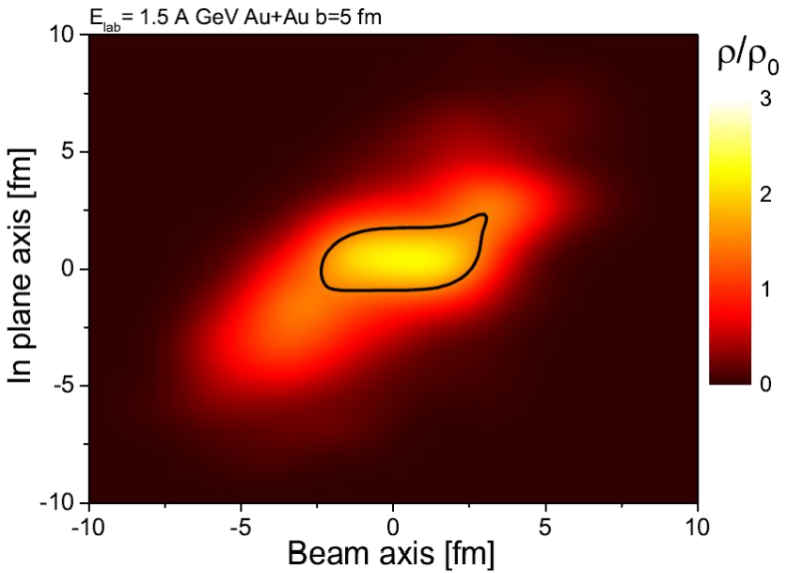
Based on numerical-relativity simulations of merging neutron star binaries, the emitted GW and the interior structure of the generated hyper-massive neutron stars (HMNS) have been analyzed in detail.

Distributions of the rest-mass density  $\rho$  in units of  $\rho_0$  (top panel) and the temperature (bottom panel) on the equatorial plane at a post-merger time of  $t = 6.34$  ms for the LS220-M132 binary.

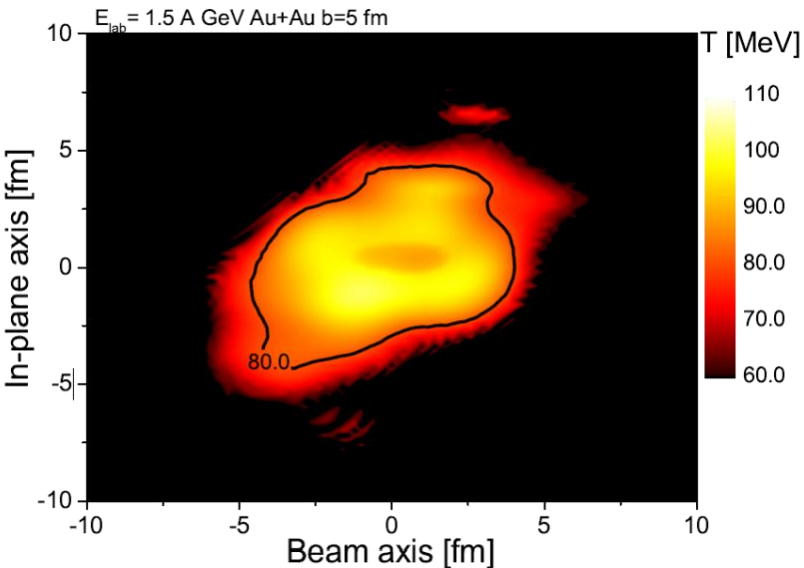
Also shown are portions of the flowlines of several tracer particles that remain close to the  $(x, y)$ -plane and for which we show only the final part of the flowlines.

In the top picture, the black iso-contours have been drawn at  $\rho/\rho_0 = 0.5n$  ( $n \in \mathbb{N}$ ), while the red iso-contour indicates  $\rho = 3\rho_0$ . The temperature iso-contours (right picture) have been drawn at  $T = 10n$  MeV

**1.5 AGeV Au+Au ( $b = 5$  fm, non-central), SIS18 Experiments at GSI  
(Snap-shot of the densities at  $t = 15$  fm/c  $\rightarrow$  partially in local equilibrium)**



- The contour where the density exceeds two times nuclear ground state density is highlighted (black dashed line).
- The densities were calculated using the UrQMD transport model.



- The contour where the temperature exceeds 80 MeV is highlighted (black dashed line).
- The temperature has been calculated from the density and energy density using the Q $\chi$ P model (Quark-Hadron Chiral Parity Doublet Model) for the equation of state.

## 1.5 AGeV Au+Au ( $b = 5$ fm, non-central), SIS18 Experiments at GSI (Snap-shot of the densities at $t = 15$ fm/c → partially in local equilibrium)

**Q $\chi$ P model:** In this approach, an explicit mass term for baryons in the Lagrangian is possible, which preserves chiral symmetry. In this model, the signature for chiral symmetry restoration is the degeneracy of the usual baryons and their respective negative-parity partner states

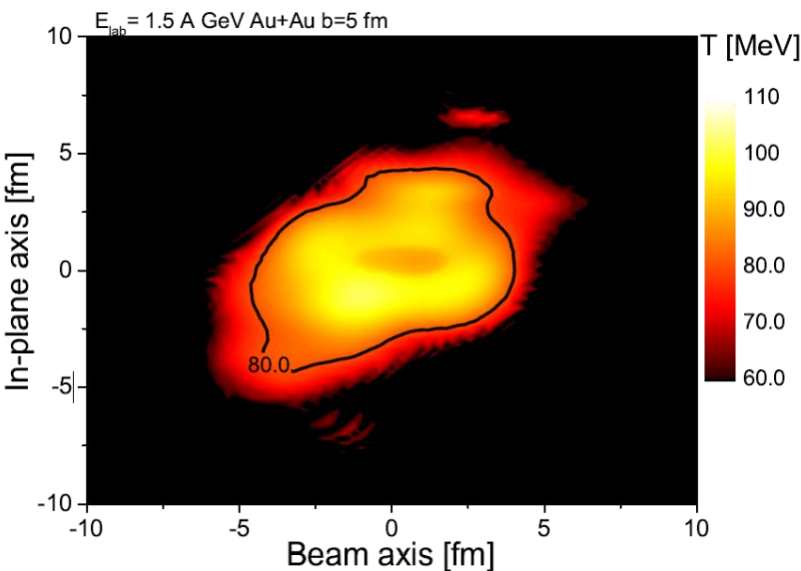
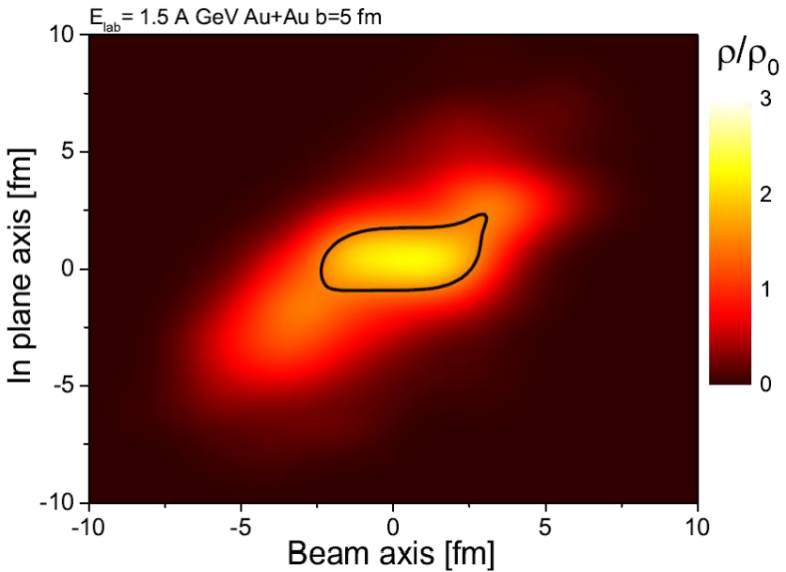
Taking into account the scalar and vector condensates in mean-field approximation, the resulting Lagrangian  $\mathcal{L}_B$  includes [27]

$$\begin{aligned} \mathcal{L}_B = & \sum_i (\bar{B}_i i \not{\partial} B_i) + \sum_i (\bar{B}_i m_i^* B_i) \\ & + \sum_i (\bar{B}_i \gamma_\mu (g_{\omega i} \omega^\mu + g_{\rho i} \rho^\mu + g_{\phi i} \phi^\mu) B_i) , \end{aligned} \quad (6)$$

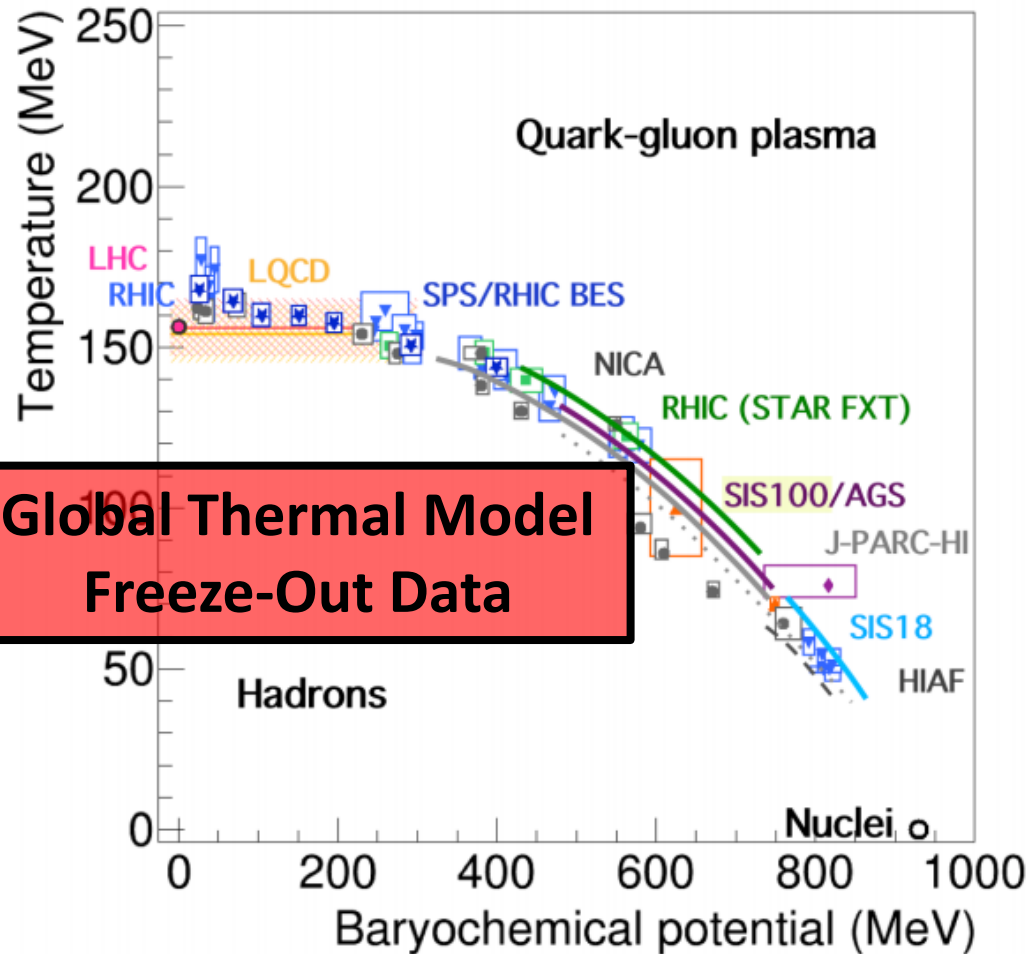
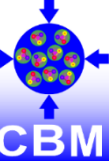
summing over the states of the baryon octet. Furthermore the scalar meson interaction, driving the spontaneous breaking of the chiral symmetry, is expressed in terms of SU(3) invariants  $I_2 = (\sigma^2 + \zeta^2)$ ,  $I_4 = -(\sigma^4/2 + \zeta^4)$  and  $I_6 = (\sigma^6 + 4\zeta^6)$  as:

$$V = V_0 + \frac{1}{2} k_0 I_2 - k_1 I_2^2 - k_2 I_4 + k_6 I_6 , \quad (7)$$

where  $V_0$  is fixed by demanding a vanishing potential in the vacuum. The quark and gluonic degrees of freedom are introduced as done in the PNJL approach [30, 31]. This model uses the Polyakov loop



# HEAVY ION COLLISIONS ↔ ASTROPHYSICAL EVENTS & OBJECTS

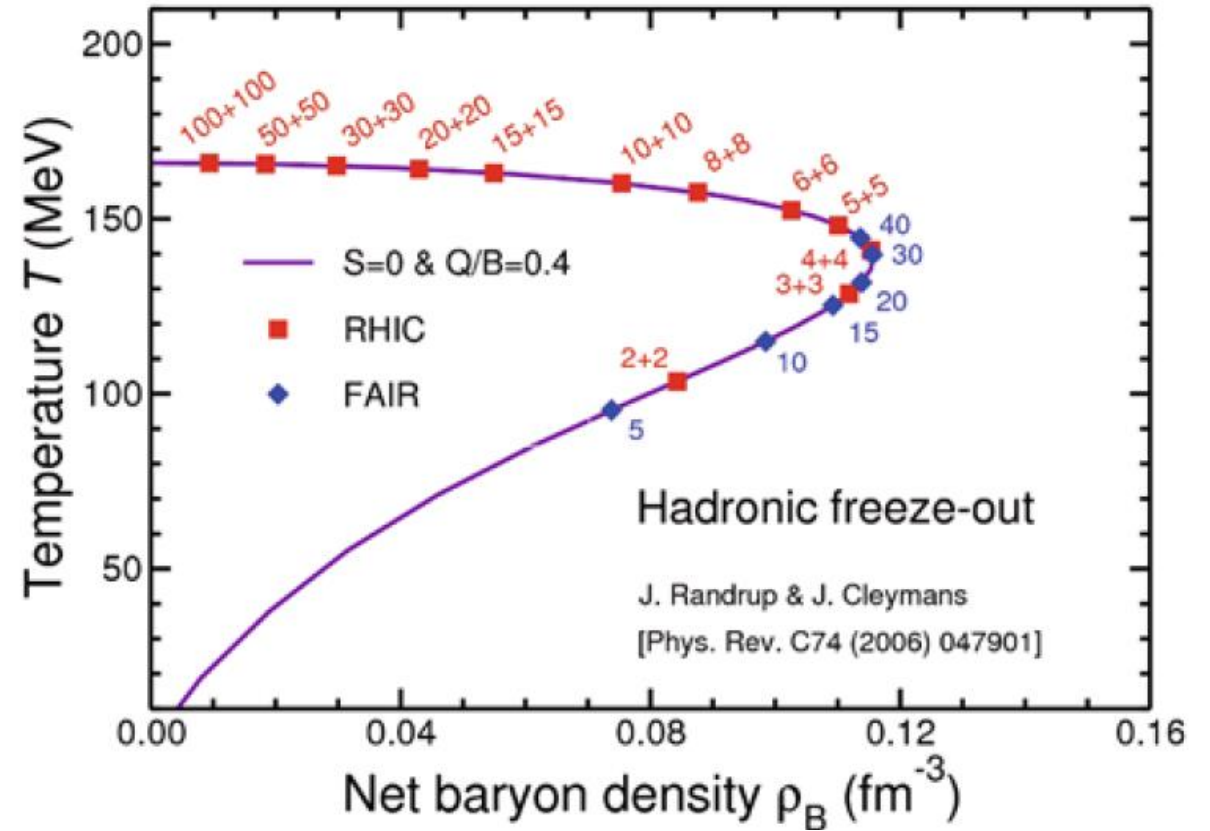


Plot: T. Galatyuk

*Becattini et al., Phys. Lett. B 764 (2017) 241*

*STAR, Phys. Review C 96 (2017) 044904*

*Andronic et al., arXiv:1710.09425 and refs. therein*



**Hadronic Freeze-Out Line comparison  
RHIC v/s FAIR (Au-Au in AGeV)**

## Collision Energies and Systems available at SIS100

Beam	Z	A	E (AGeV)
p	1	1	29
d	1	2	14
Ca	20	40	14
Ni	28	58	13.6
In	49	115	11.9
Au	79	197	11
U	92	238	10.7

$$\frac{E}{A} = \sqrt{\left(0.3 \cdot B \cdot r \cdot \frac{Z}{A}\right)^2 + m^2} - m$$

$B \cdot r$  = Beam Rigidity [T.m]  
= 100 T.m for SIS100

$m$  = Mass of nucleon

**Essentially the energy available is determined by the bending power of the magnets, quantified as Beam Rigidity (B.r)**

$$E_{\text{CM}} = \sqrt{s} = \sqrt{m_1^2 + m_2^2 + 2 \cdot m_2 \cdot E_{\text{proj}}}$$

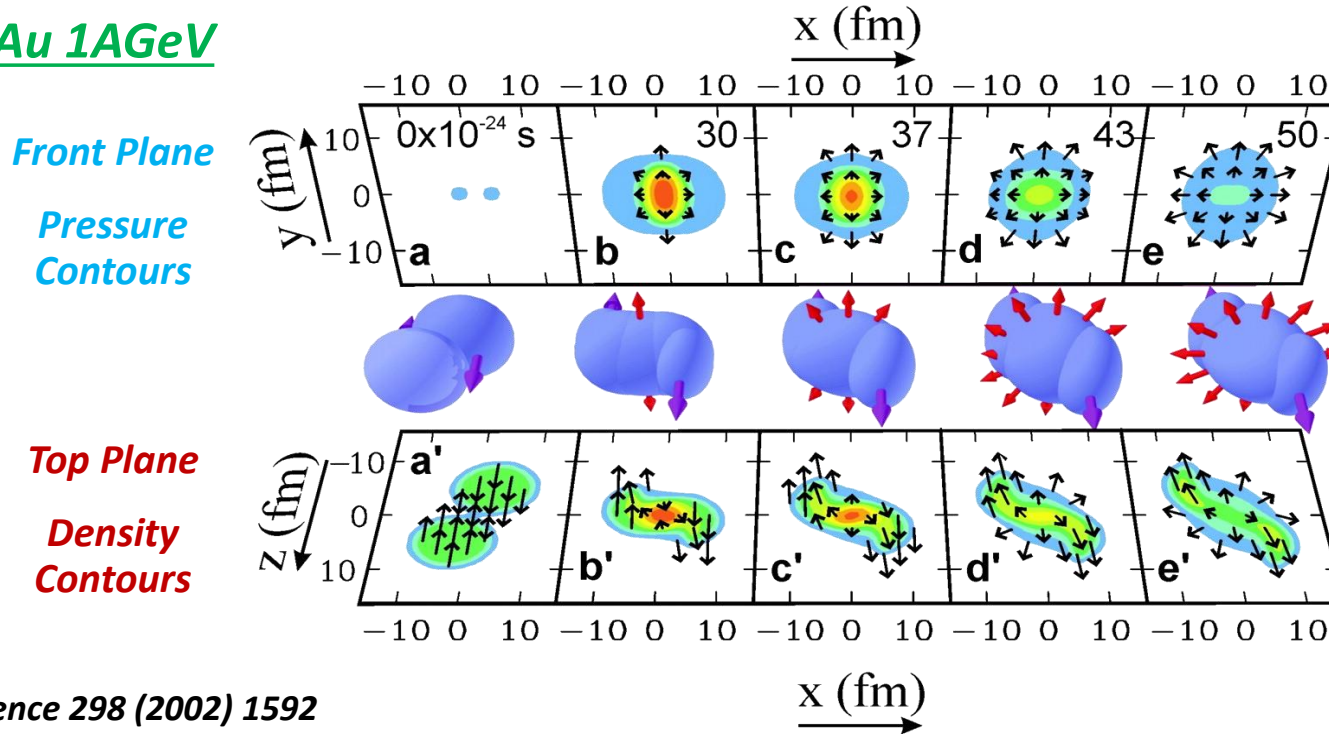
For fixed target experiments,

$$E_{\text{CM}} = \sqrt{s} \cong \sqrt{2 \cdot m_2 \cdot E_{\text{proj}}}$$

$$\sqrt{s_{\text{NN}}} = \frac{\sqrt{s}}{A}$$

## Collective flow of nucleons driven by the pressure gradient – Sensitive to nuclear compressibility: EOS

Au-Au 1A GeV



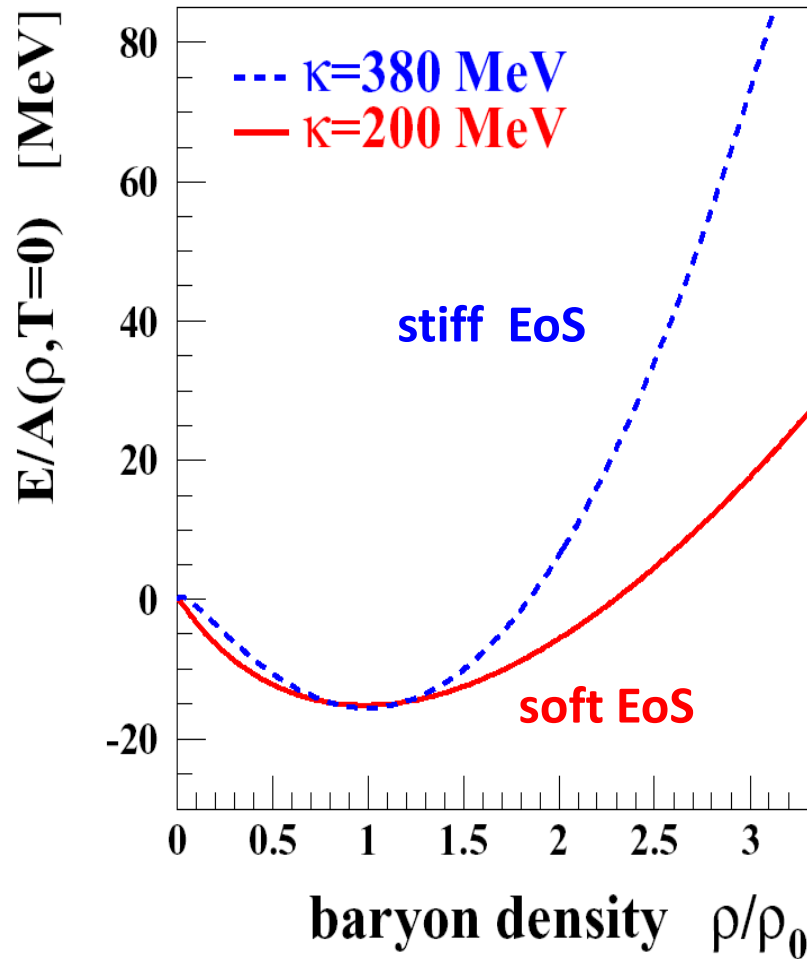
 P. Danielewicz et al., *Science* 298 (2002) 1592

Two observables of the high pressures results in matter to be ejected in specific directions:

- Directed Flow  $v_1$  Nucleons deflected sideways in the reaction plane
- Elliptic Flow  $v_2$  Nucleons are “squeezed out” above and below or “expanded in” the reaction plane



Nuclear equation-of-state at  $T = 0$  :  
 "compressional" energy  $E/A(\rho, T = 0) = \frac{1}{\rho} \int U(\rho) d\rho$



Effective NN-Potential (Skyrme)  $U(\rho) = \alpha \left(\frac{\rho}{\rho_0}\right) + \beta \left(\frac{\rho}{\rho_0}\right)^\gamma$

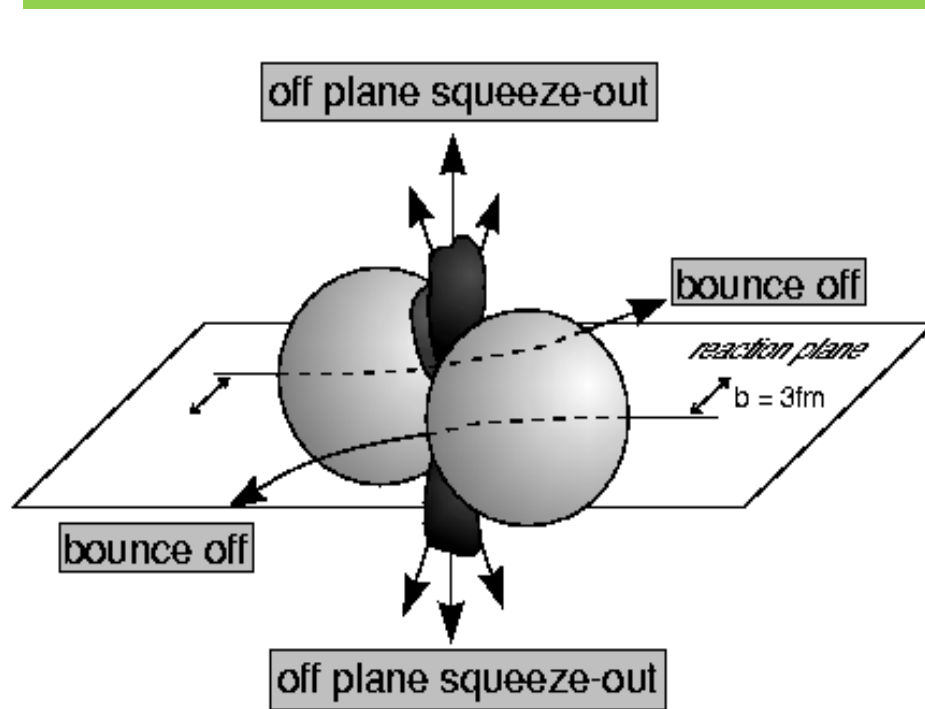
	$\alpha$ [MeV]	$\beta$ [MeV]	$\gamma$
$\kappa = 380$ MeV	-124	70.5	2
$\kappa = 200$ MeV	-356	303	7/6

Compression Modulus :

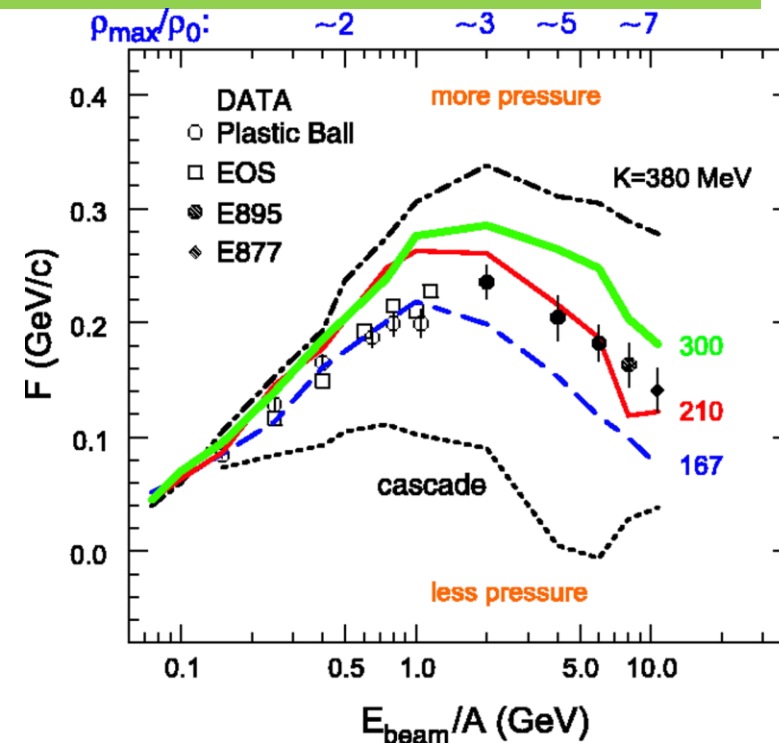
$$\kappa = \left( 9\rho^2 \frac{\partial^2 E/A(\rho, T = 0)}{\partial \rho^2} \right)_{\rho=\rho_0}$$

 Image and slide credits: C. Sturm, GSI-Darmstadt

## Collective flow of nucleons driven by the pressure gradient – Sensitive to nuclear compressibility: EOS



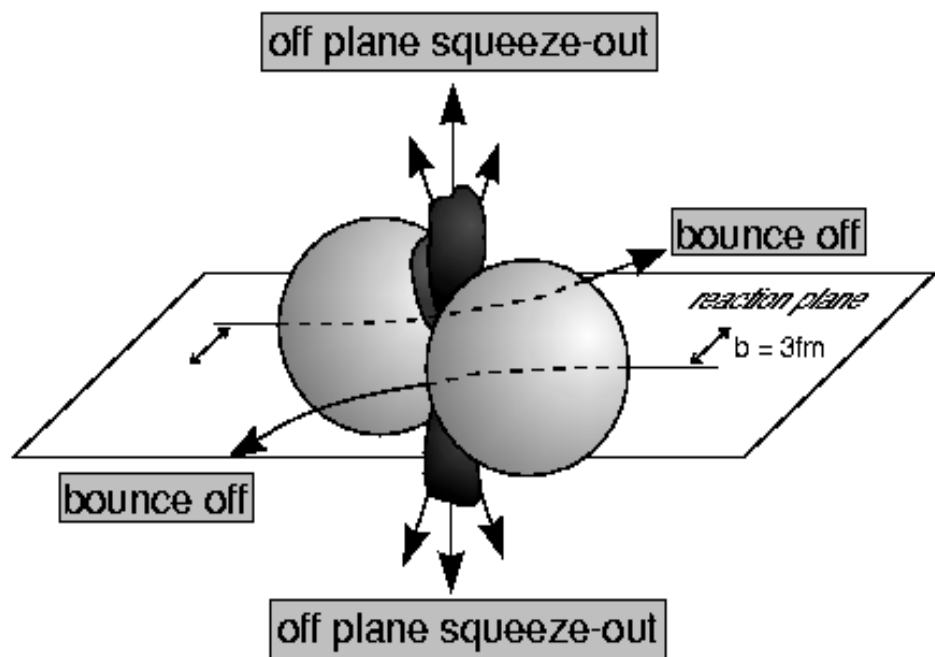
$F \equiv$  Magnitude of  
sideward deflection  
↓  
 $F \propto$  Fireball Pressure  
  
Nuclear Incompressibility,  
 $\kappa = 170 - 210 \text{ MeV}$



Two observables of the high pressures results in matter to be ejected in specific directions:

- Directed Flow  $v_1$  Nucleons deflected sideways in the reaction plane
- Elliptic Flow  $v_2$  Nucleons are "squeezed out" above and below or "expanded in" the reaction plane

## Collective flow of nucleons driven by the pressure gradient – Sensitive to nuclear compressibility: EOS

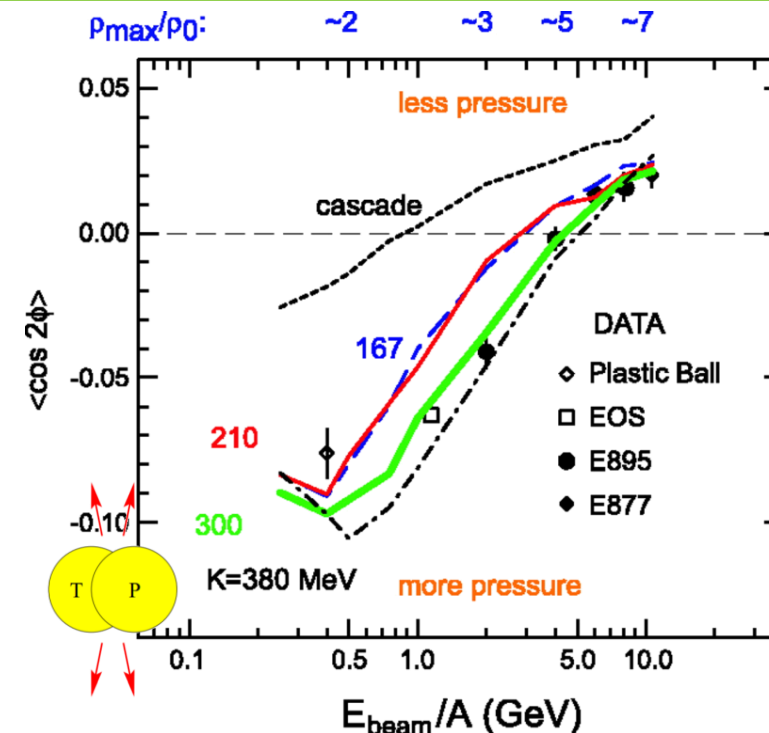


Reflects higher  
pressure of the fireball

$$\downarrow$$

$$[\varphi = 90^\circ, 270^\circ]$$

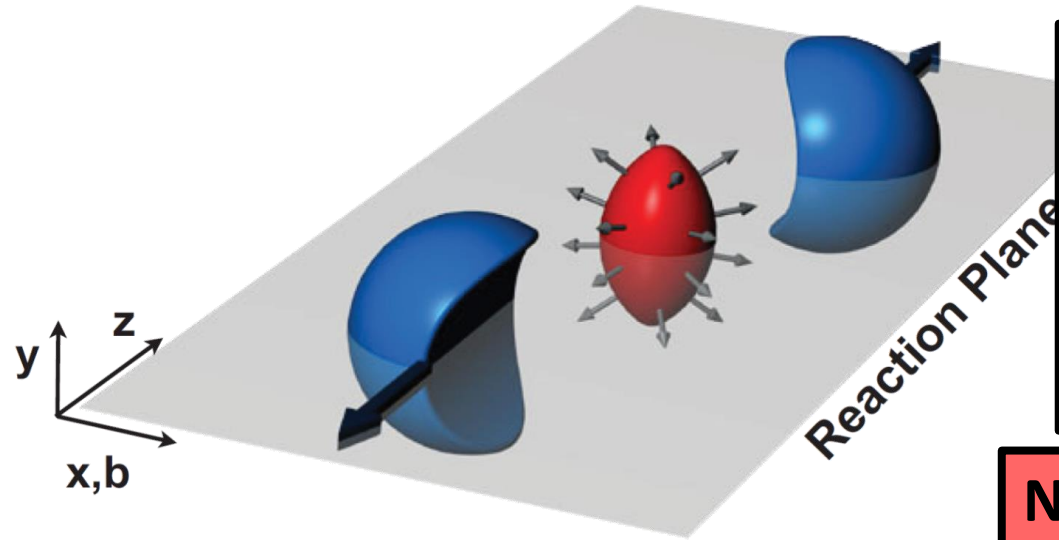
$$[\cos(2\varphi) = -1]$$



Two observables of the high pressures results in matter to be ejected in specific directions:

- Directed Flow  $v_1$  Nucleons deflected sideways in the reaction plane
- Elliptic Flow  $v_2$  Nucleons are "squeezed out" above and below or "expanded in" the reaction plane

## Collective flow of nucleons driven by the pressure gradient – Sensitive to nuclear compressibility: EOS



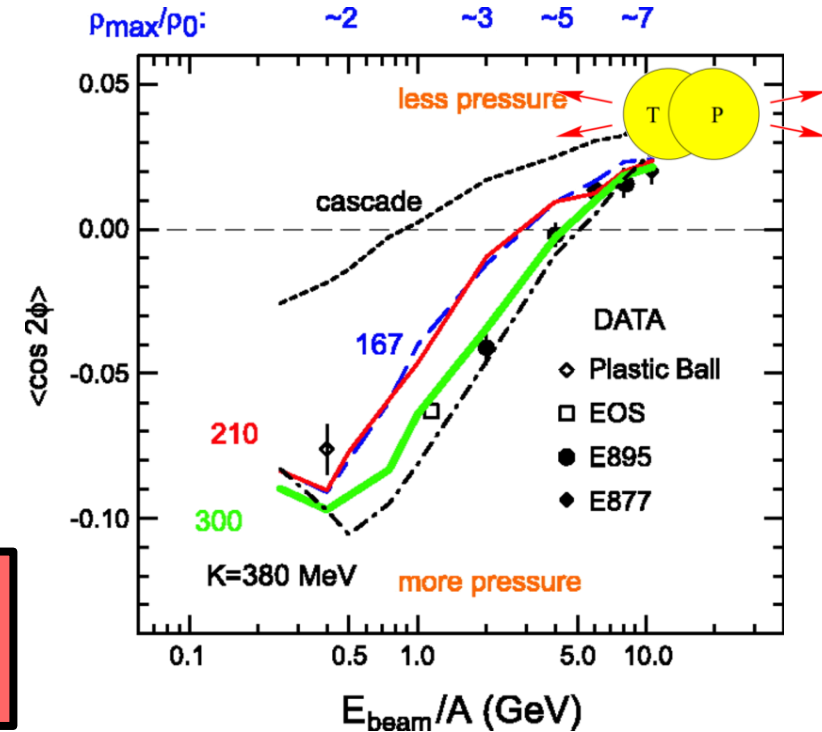
Reflects lower  
pressure of the fireball

$$\downarrow$$

$$[\varphi = 0^\circ, 180^\circ]$$

$$[\cos(2\varphi) = +1]$$

Nuclear Incompressibility,  
 $\kappa = 170 - 370 \text{ MeV}$



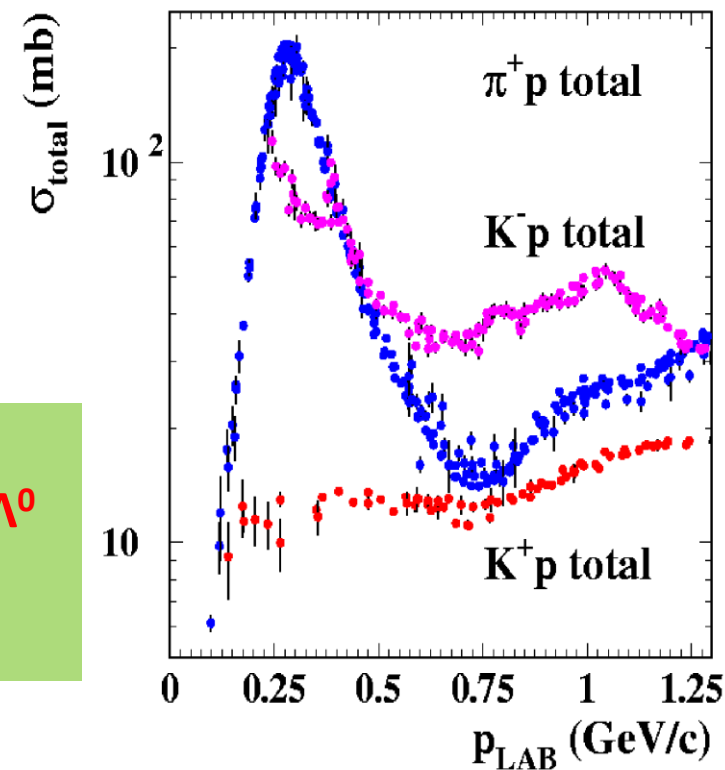
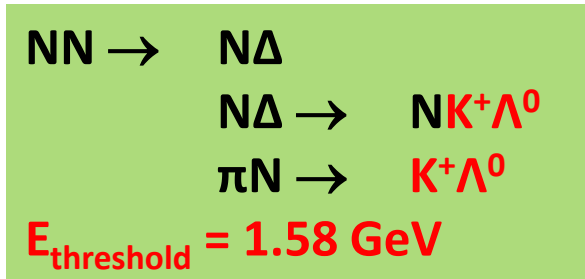
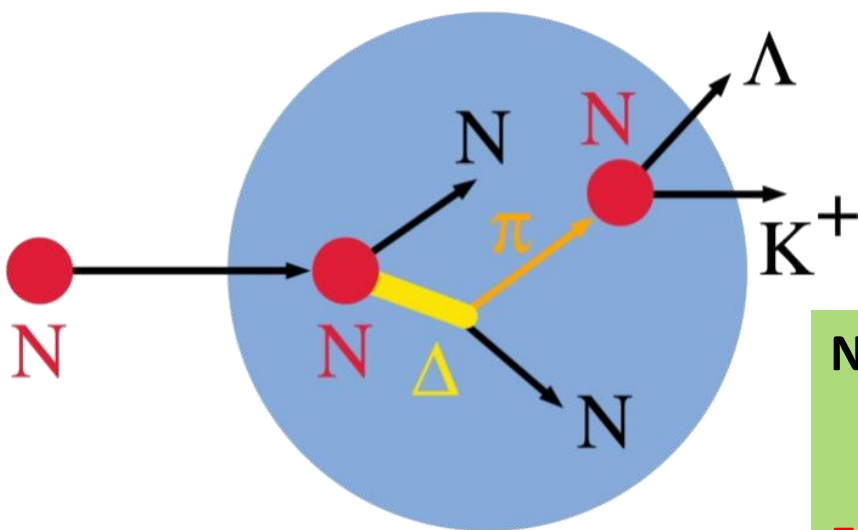
Two observables of the high pressures results in matter to be ejected in specific directions:

- Directed Flow  $v_1$  Nucleons deflected sideways in the reaction plane
- Elliptic Flow  $v_2$  Nucleons are “squeezed out” above and below or “expanded in” the reaction plane

**(Sub)Threshold Particle Production** – Particles NOT produced in initial head-on collisions, but in multiple low energy collisions → Collisions are enhanced in high-density medium

**Strangeness** – Kaon yields ( $K^+(u\bar{s})$ ) are particularly sensitive to the medium density [proven at KAOS-GSI]  
 Long mean-free path length of  $K^+$  (only elastic scattering) & no absorption → Penetrating probe

**Idea: Strangeness Yield ( $K^+$ )  $\propto$  Baryonic Density  $\propto$  Compressibility  $\propto$  EOS**

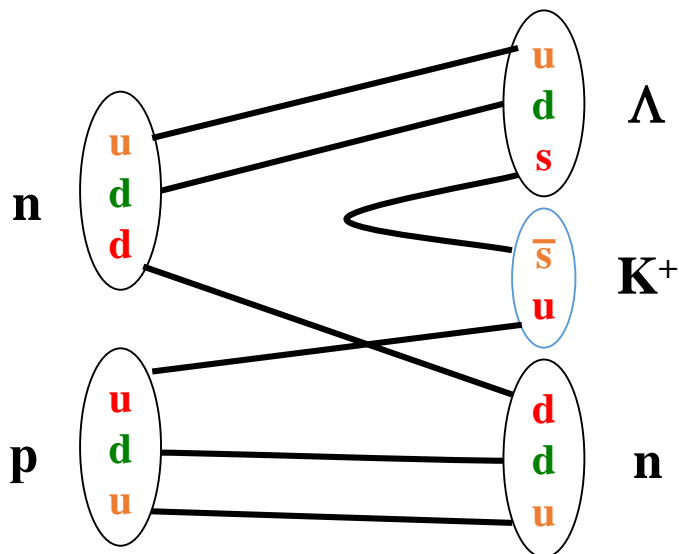


**Mean Free Path at  $\rho_0$**

- $\lambda_{\pi^+} \cong 0.3 \text{ fm}$
- $\lambda_{K^+} \cong 5 \text{ fm}$
- $\lambda_{K^-} \cong 0.8 \text{ fm}$

Image credit: (Left) P. Senger, GSI-Darmstadt  
 (Right) PDG, Phys.Rev D 54, 1 (1996)

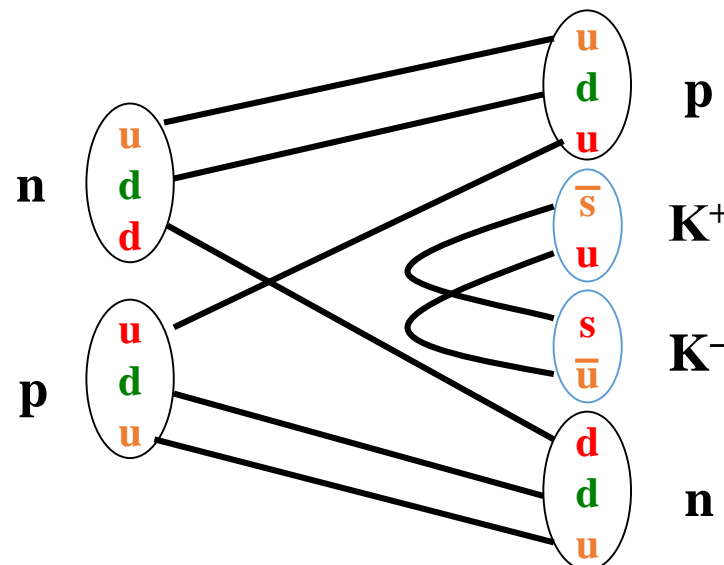
## Kaons



production threshold  
in NN collisions :

$$E_{lab} = 1.58 \text{ GeV}$$

## Antikaons

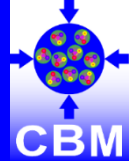


production threshold  
in NN collisions :

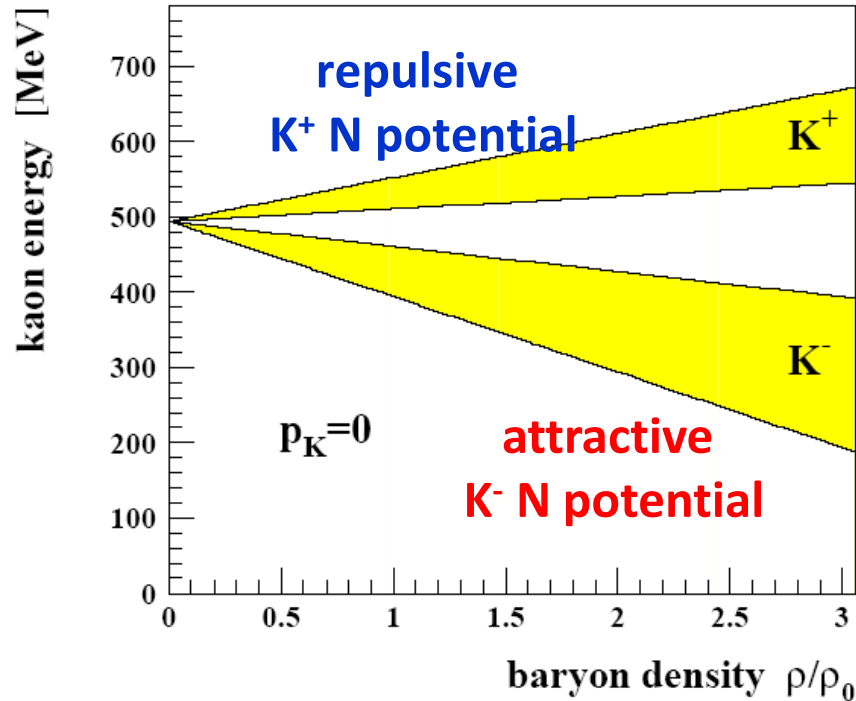
$$E_{lab} = 2.5 \text{ GeV}$$

Associate  $K^+$   
production with  $K^-$

$$V_{K+N} = + 25 \pm 5 \rho/\rho_0 \text{ MeV}$$



**Envelope of several microscopic calculations: all predict the same trend!**



**1. Effect on Production  $\rightarrow$  Yield**  
 Reduced  $K^+$  yield due to increased in-medium  $K^+$  mass

**2. Effect on Propagation  $\rightarrow$  Angular Dist.**  
 Preferential out-of-plane flow (squeeze out) for  $K^+$  suggests repulsive potentials

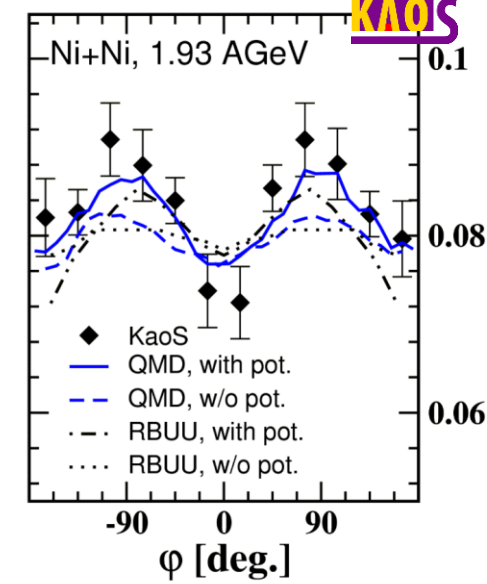
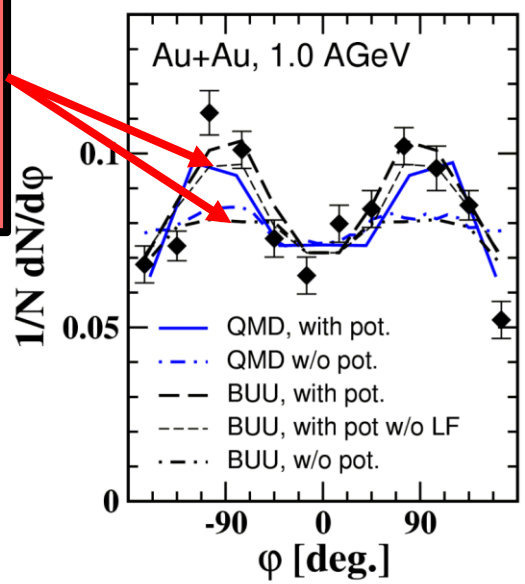
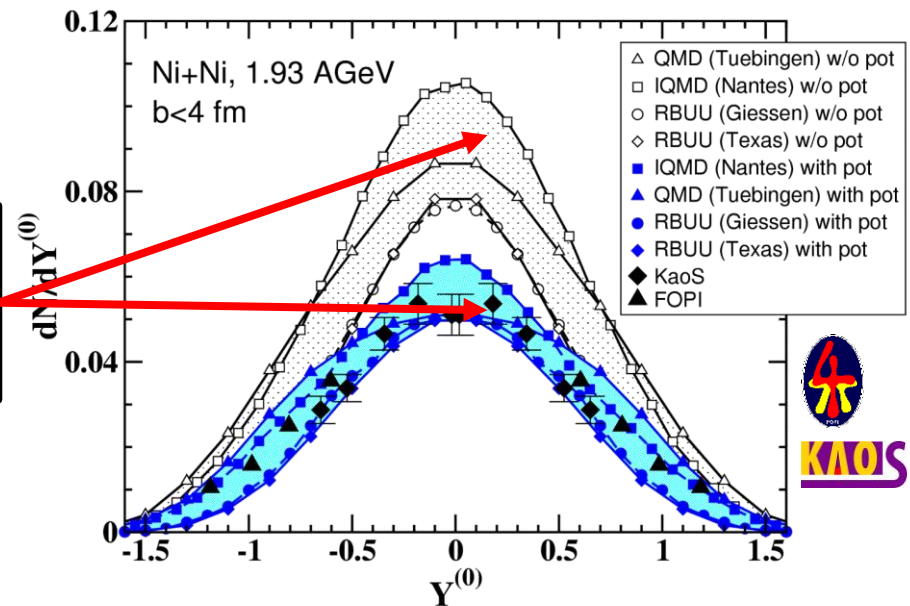
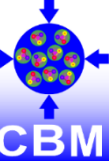
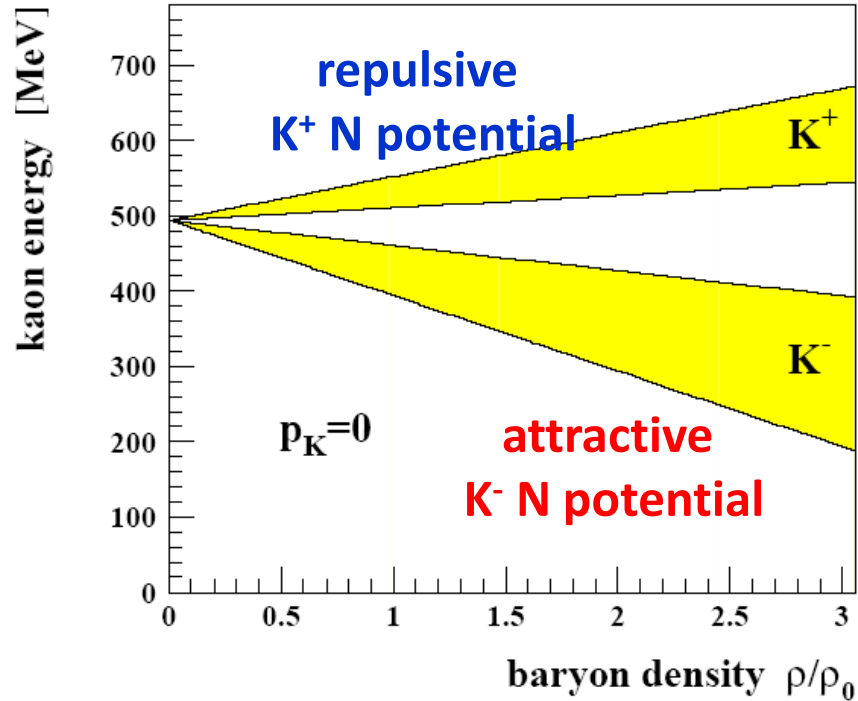


Image and slide credits: C. Sturm, GSI-Darmstadt  
 Image credit (Right-Top):  
 Data: M. Menzel et al., (KaoS Collab.), Phys. Lett. B 495 (2000) 26  
 K. Wisniewski et al., (FOPI Collab.), Eur. Phys. J A 9 (2000) 515  
 Image credit (Right-Bottom):  
 Data: Y. Shin et al., (KaoS Collaboration), Phys. Rev. Lett. 81 (1998) 1576  
 F. Uhlig et al., (KaoS Collaboration), Phys. Rev. Lett. 95 (2005) 012301  
 Calculations: A. Larionov, U. Mosel, nucl-th/0504023

$$V_{K-N} = -80 \pm 20 \rho/\rho_0 \text{ MeV}$$

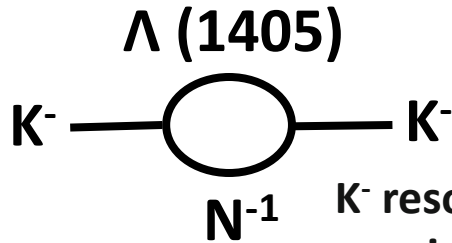
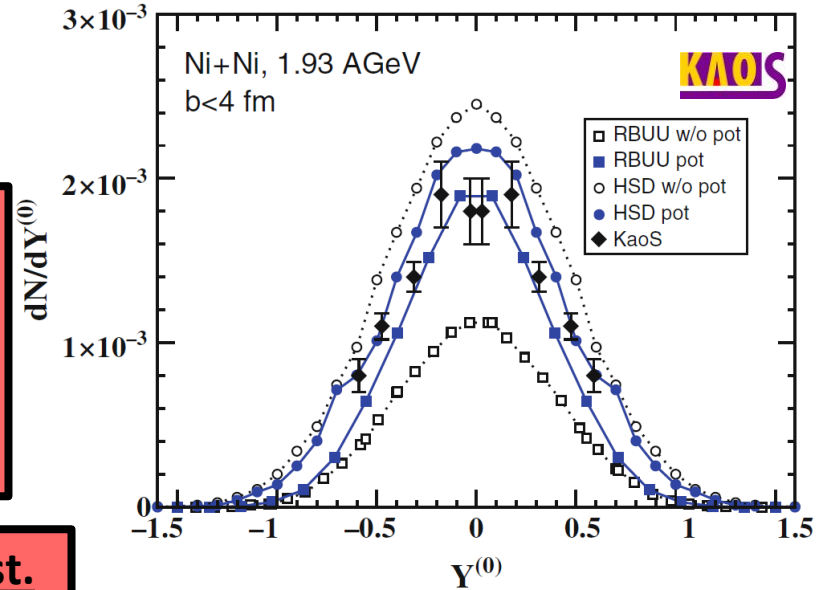


**Envelope of several microscopic calculations: all predict the same trend!**



**1. Effect on Production → Yield**  
The results of the calculations depend on the density dependence of the cross section for strangeness exchange which is still a matter of investigations

**2. Effect on Propagation → Angular Dist.**  
Preferential in-plane flow for K<sup>-</sup> suggests attractive potentials



K<sup>-</sup> resonant around threshold and requires non-perturbative approaches

Density dependency and off-shell behavior of the hyperon resonances?

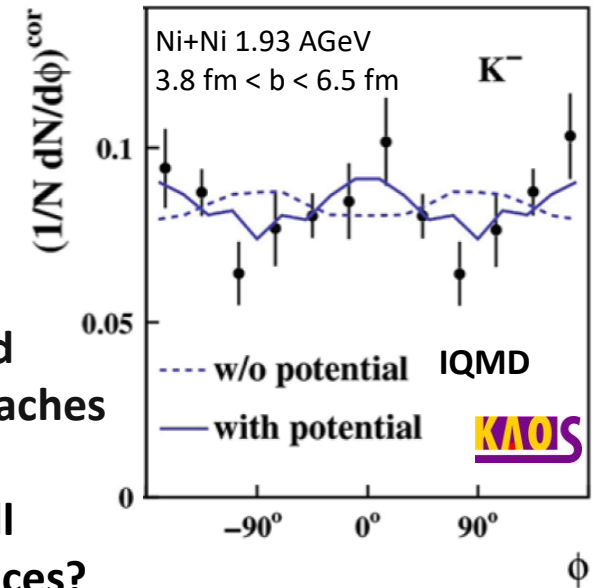


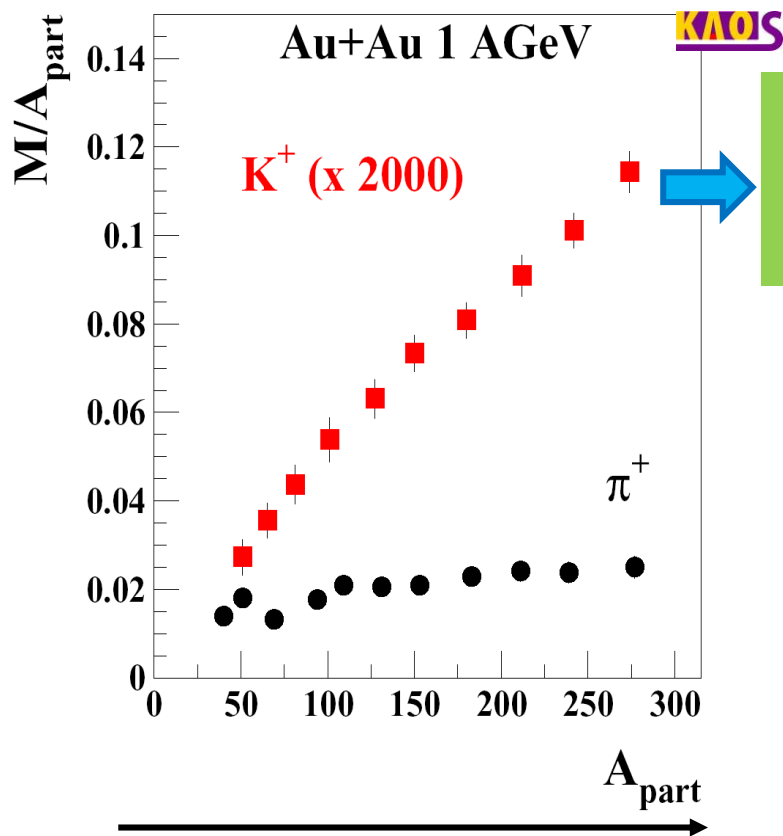
Image and slide credits: C. Sturm, GSI-Darmstadt

Image credit (Right-Top):  
Data: M. Menzel et al., (KaoS Collab.), Phys. Lett. B 495 (2000) 26

Image credit (Right-Bottom):  
Data: F. Uhlig et al., (KaoS Collaboration), Phys. Rev. Lett. 95 (2005) 012301  
Calculations: C. Hartnack, J. Aichelin, J. Phys. G 28, 1649 (2002)

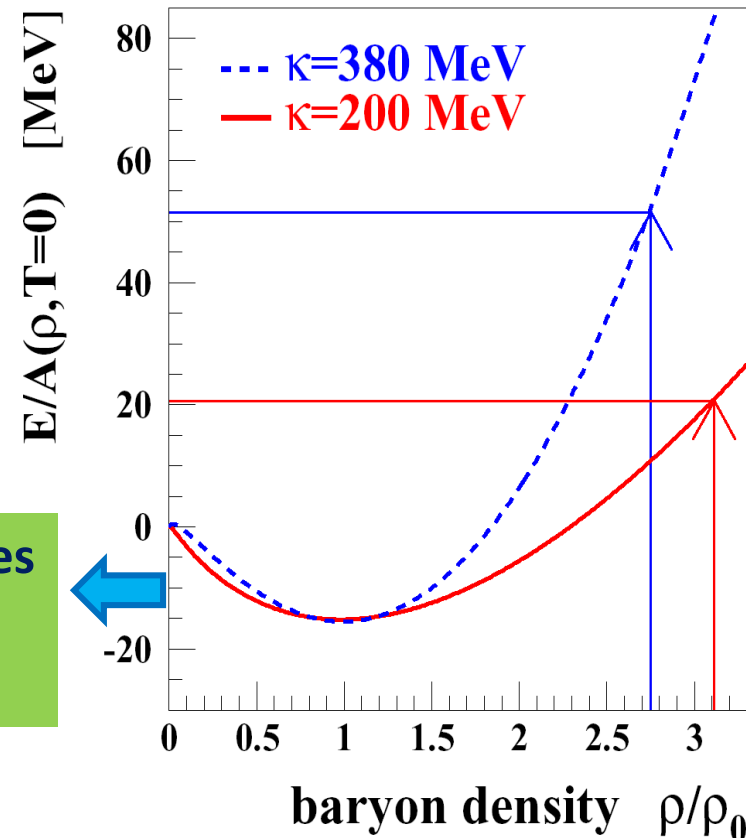


## “Subthreshold” $K^+$ production



“Subthreshold”  $K^+$  mesons predominantly produced by collective effects  $\rightarrow$  multi step processes

Probability of multi step processes increases nonlinearly with the baryon density



**IQMD: Au+Au 1AGeV**

**stiff EoS**  $\rho_{\max} / \rho_0 \cong 2.7$

**soft EoS**  $\rho_{\max} / \rho_0 \cong 3.1$

**M:** multiplicity = number / per collision

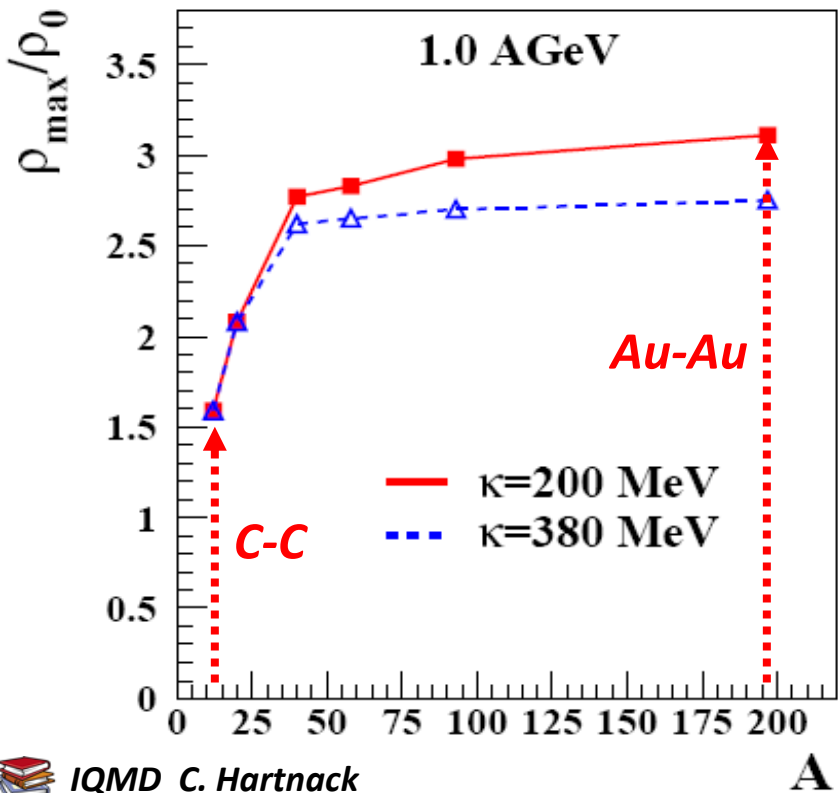
**$A_{\text{part}}$ :** number of participating nucleons

Peripheral  
Collisions

Central  
Collisions

**Idea:** Strangeness Yield ( $K^+$ )  $\propto$  Baryonic Density  $\propto$  Compressibility  $\propto$  EOS

**Experimentally:** Measuring  $K^+$  yields in a system where compression is expected (Au-Au) w.r.t. system where no compression is expected (C-C)

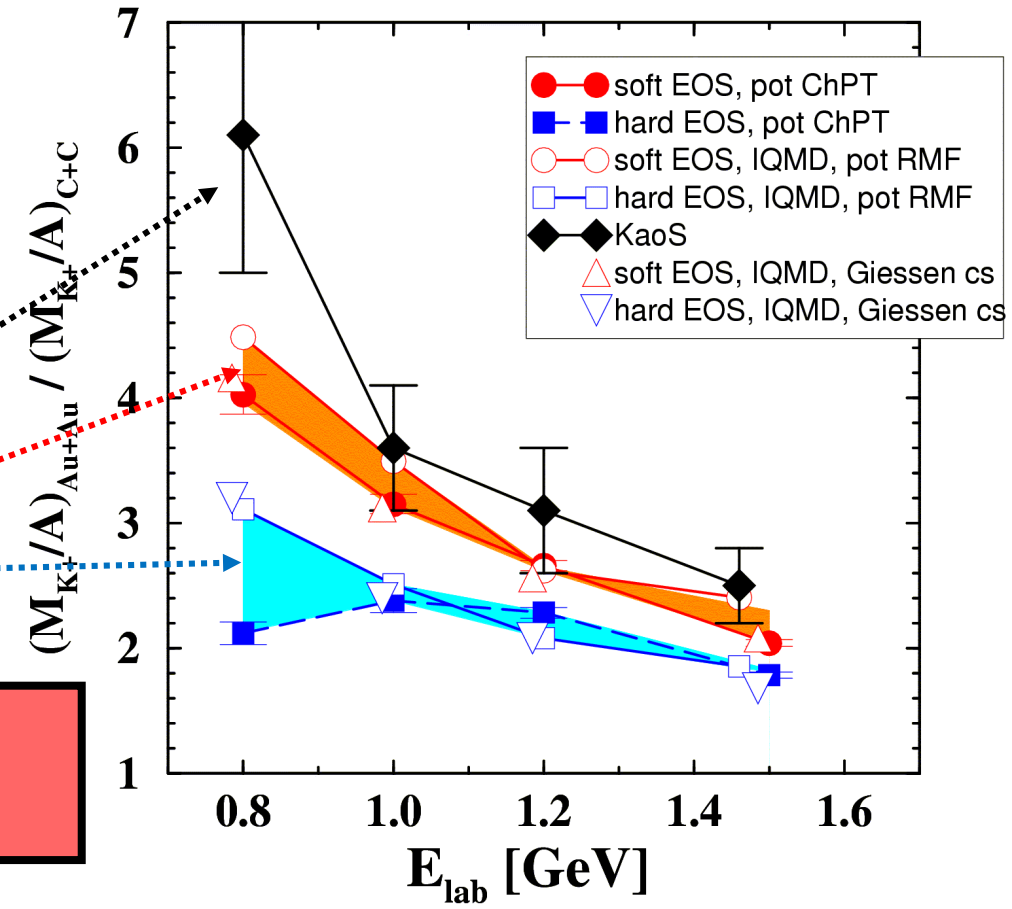


**Soft Nuclear EOS**  
 $\kappa \approx 200$  ( $2-3 \rho_0$ )

KaoS (Exp.)

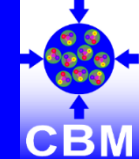
Soft EOS (Th.)

Hard EOS (Th.)

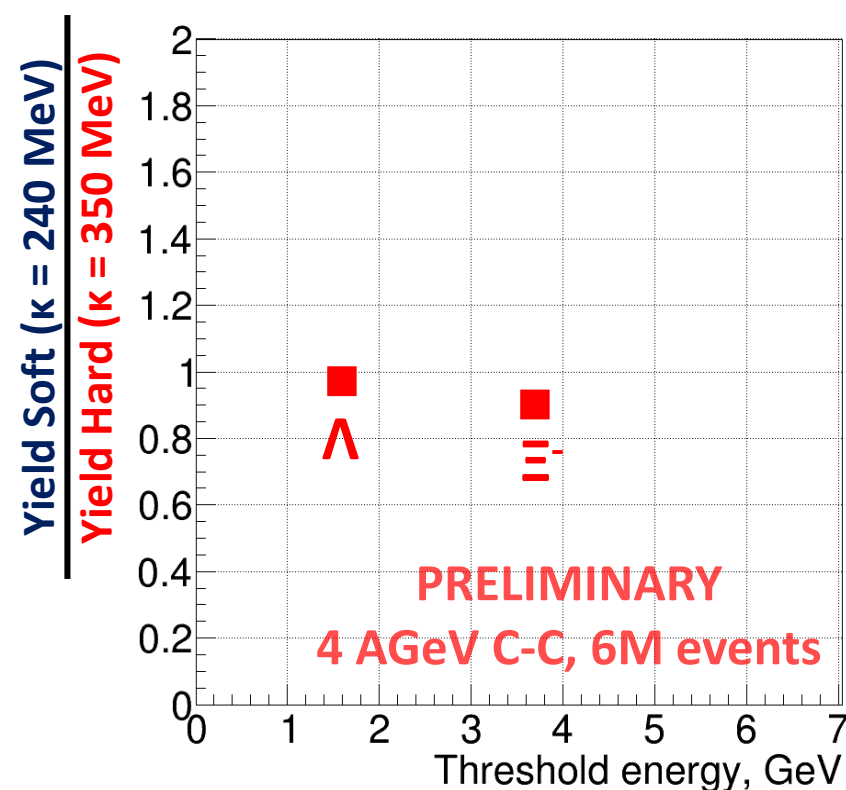
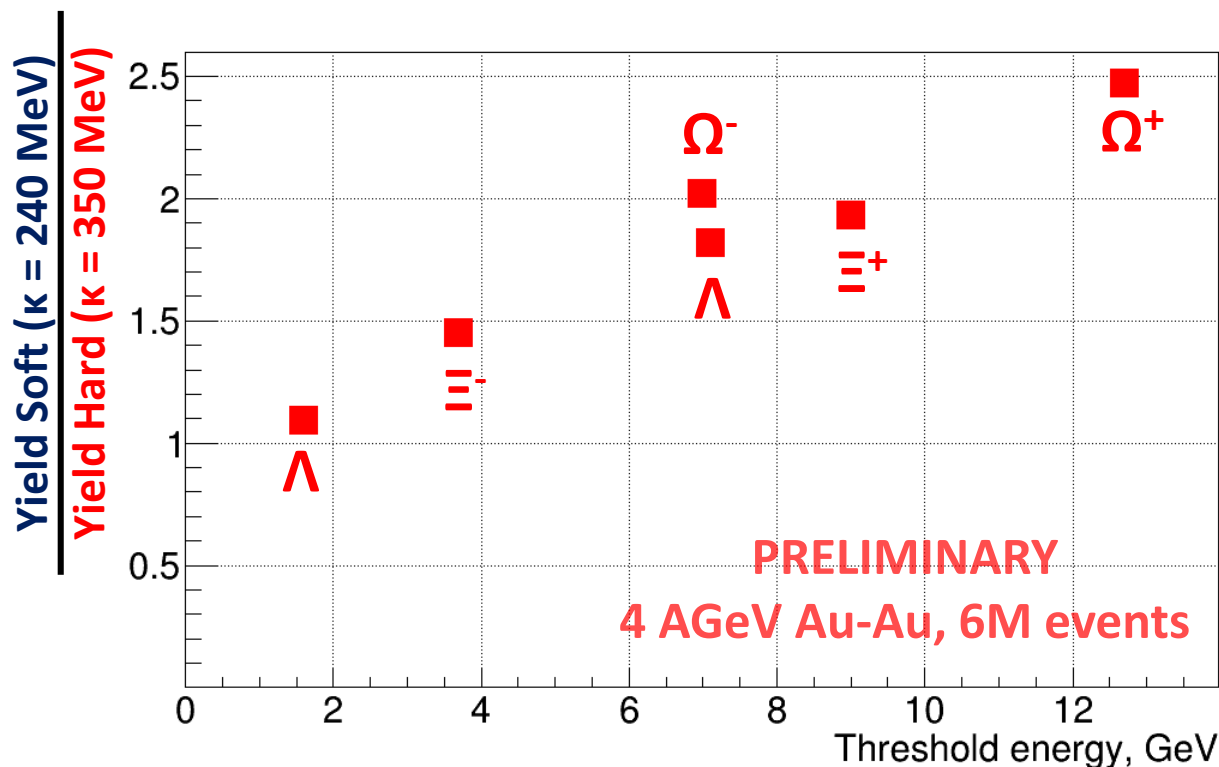
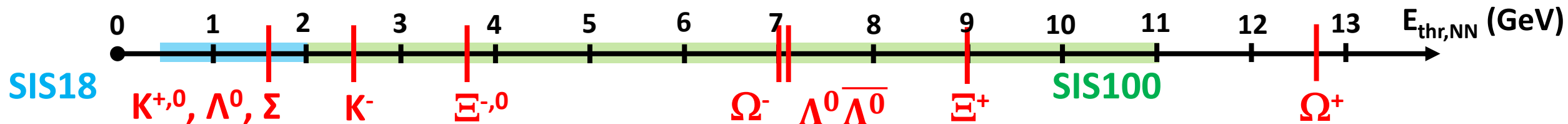


Experiment: C. Sturm et al., (KaoS Collaboration) *Phys. Rev. Lett.* **86** (2001) 39  
 Theory: QMD Ch. Fuchs et al., *Phys. Rev. Lett.* **86** (2001) 1974  
 IQMD Ch. Hartnack, J. Aichelin, *J. Phys. G* **28** (2002) 1649

# EXPERIMENTAL OBSERVABLES [II] – (SUB)THRESHOLD PRODUCTION



**Idea: Strangeness Yield  $\propto$  Baryonic Density  $\propto$  Compressibility  $\propto$  EOS**



PHQMD: J. Aichelin, E. Bratkovskaya, V. Kireyeu et al.  
P. Senger, 4<sup>th</sup> CBM China Workshop (2019)

**The goal:** to develop a unified n-body microscopic transport approach for the description of heavy-ion dynamics and dynamical cluster formation from low to ultra-relativistic energies

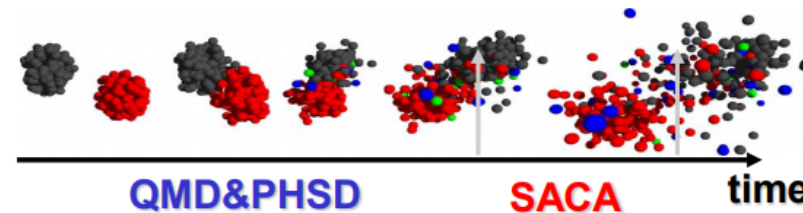
**Realization:** combined model **PHQMD** = (PHSD & QMD) & SACA

## Parton-Hadron-Quantum-Molecular Dynamics

Initialization → propagation of baryons:  
**QMD** (Quantum-Molecular Dynamics)

Propagation of partons (quarks, gluons) and mesons  
+ **collision integral** = interactions of hadrons and partons (QGP)  
from **PHSD** (Parton-Hadron-String Dynamics)

Clusters recognition:  
**SACA** (Simulated Annealing Clusterization Algorithm)  
vs. **MST** (Minimum Spanning Tree)



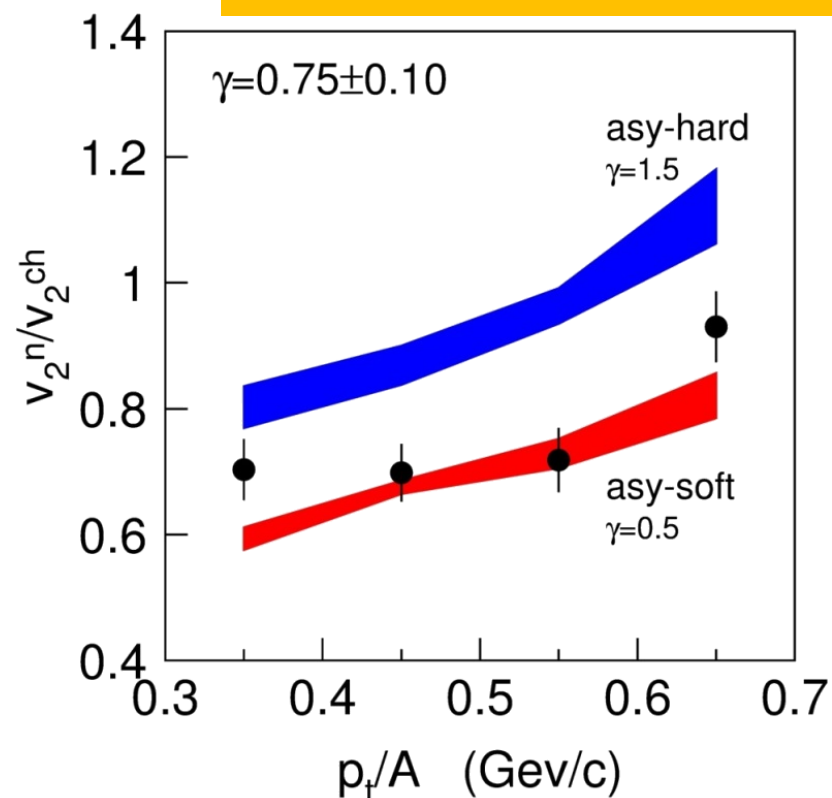
# NUCLEAR SYMMETRY ENERGY: $E_A(\rho, \delta) = E_A(\rho, 0) + E_{\text{SYM}}(\rho) \cdot \delta^2$

Parameterization  
in transport

$$E_{\text{sym}}(\rho) = 22 \text{ MeV} \left( \frac{\rho}{\rho_0} \right)^\gamma + 12 \text{ MeV} \left( \frac{\rho}{\rho_0} \right)^{2/3}$$

$\gamma$	0.5	1.0	1.5
L [MeV]	57	90	123

**Idea:** Measurement of differential collective flow of isospin opposite particles (neutrons w.r.t. protons or overall charged particles)

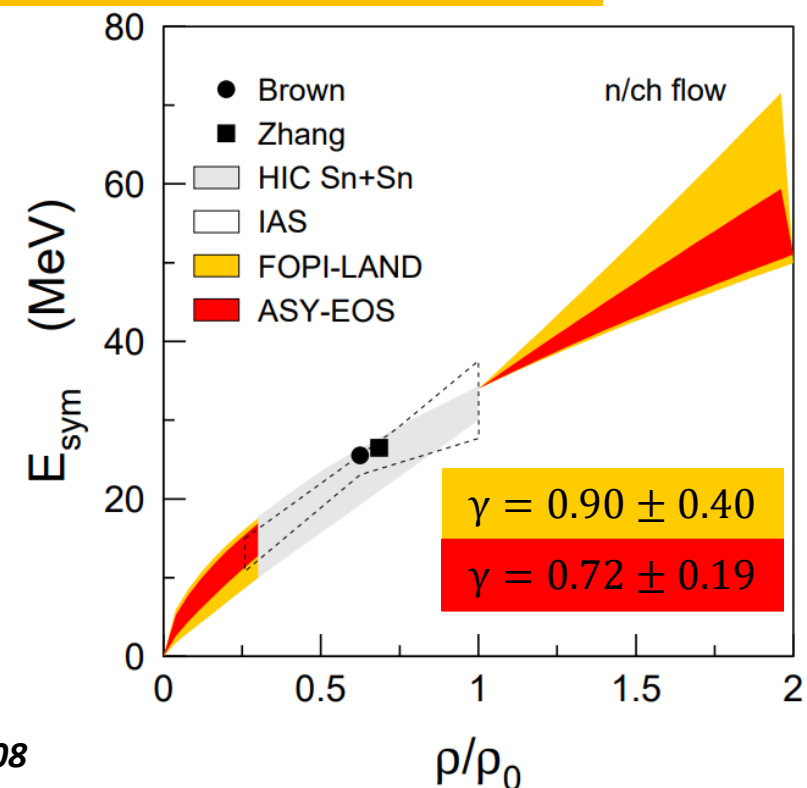


**Au-Au 0.4 AGeV**  
**FOPI-LAND and ASY-EOS**

$L = 72 \pm 13 \text{ MeV}$   
 $K_{\text{sym}} = -70 \dots -40 \text{ MeV}$

**Moderately soft asy-EOS  $\leq 2\rho_0$**   
**Higher densities???**

 P. Russotto et al., Phys.Lett. B697 (2011) 471-476  
P. Russotto et al., Phys.Rev. C94 (2016) no.3, 034608

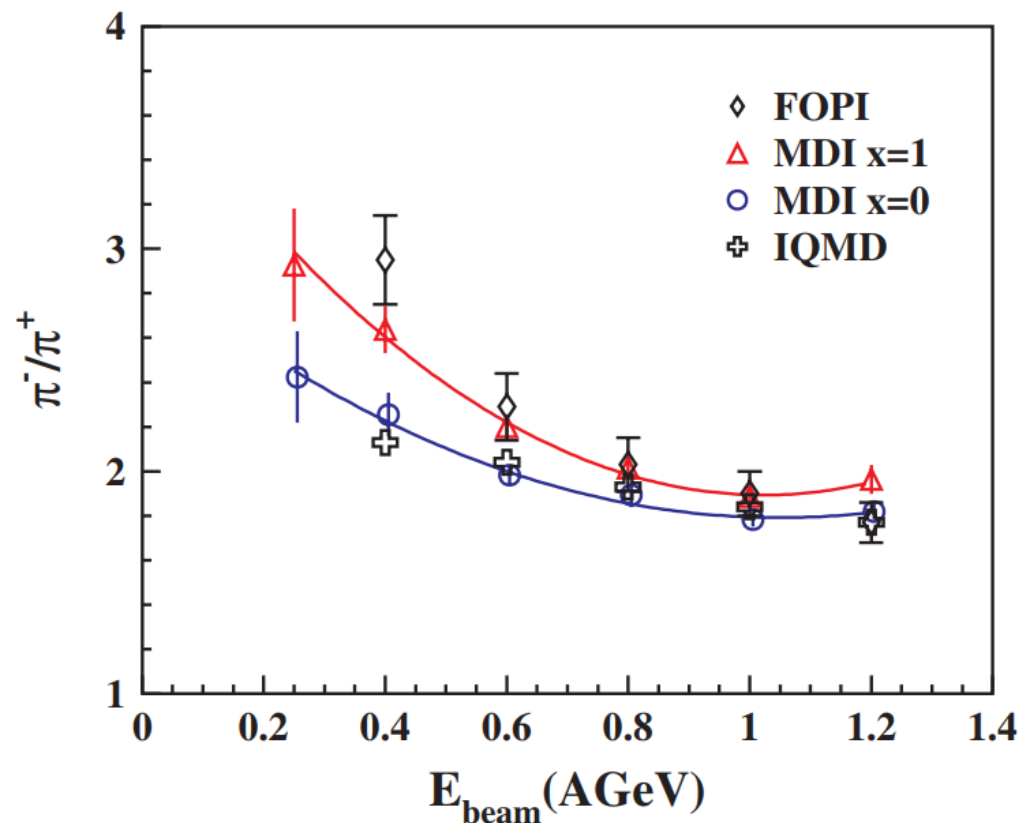


# NUCLEAR SYMMETRY ENERGY: $E_A(\rho, \delta) = E_A(\rho, 0) + E_{\text{SYM}}(\rho) \cdot \delta^2$

**The isospin and momentum-dependent mean-field potential**

$$\begin{aligned}
 U(\rho, \beta, p, \tau, x) = & A_u(x) \frac{\rho_{\tau'}}{\rho_0} + A_l(x) \frac{\rho_{\tau}}{\rho_0} + B \left( \frac{\rho}{\rho_0} \right)^{\sigma} (1 - x\beta^2) \\
 & - 8\tau x \frac{B}{\sigma + 1} \frac{\rho^{\sigma-1}}{\rho_0^{\sigma}} \beta \rho_{\tau'} \\
 & + \frac{2C_{\tau\tau}}{\rho_0} \int d^3 \vec{p}' \frac{f_{\tau}(\vec{r}, \vec{p}')}{1 + (\vec{p} - \vec{p}')^2 / \Lambda^2} \\
 & + \frac{2C_{\tau\tau'}}{\rho_0} \int d^3 \vec{p}' \frac{f_{\tau'}(\vec{r}, \vec{p}')}{1 + (\vec{p} - \vec{p}')^2 / \Lambda^2}, \quad (2)
 \end{aligned}$$

$x$	$L$ (MeV)	$K_{\text{sym}}$ (MeV)
-2	152	418
-1	106	127
0	61	-163
1	15	-454
2	-31	-745



**Idea:** Measurement of particle yields of isospin opposite particles (pions) for lower energies

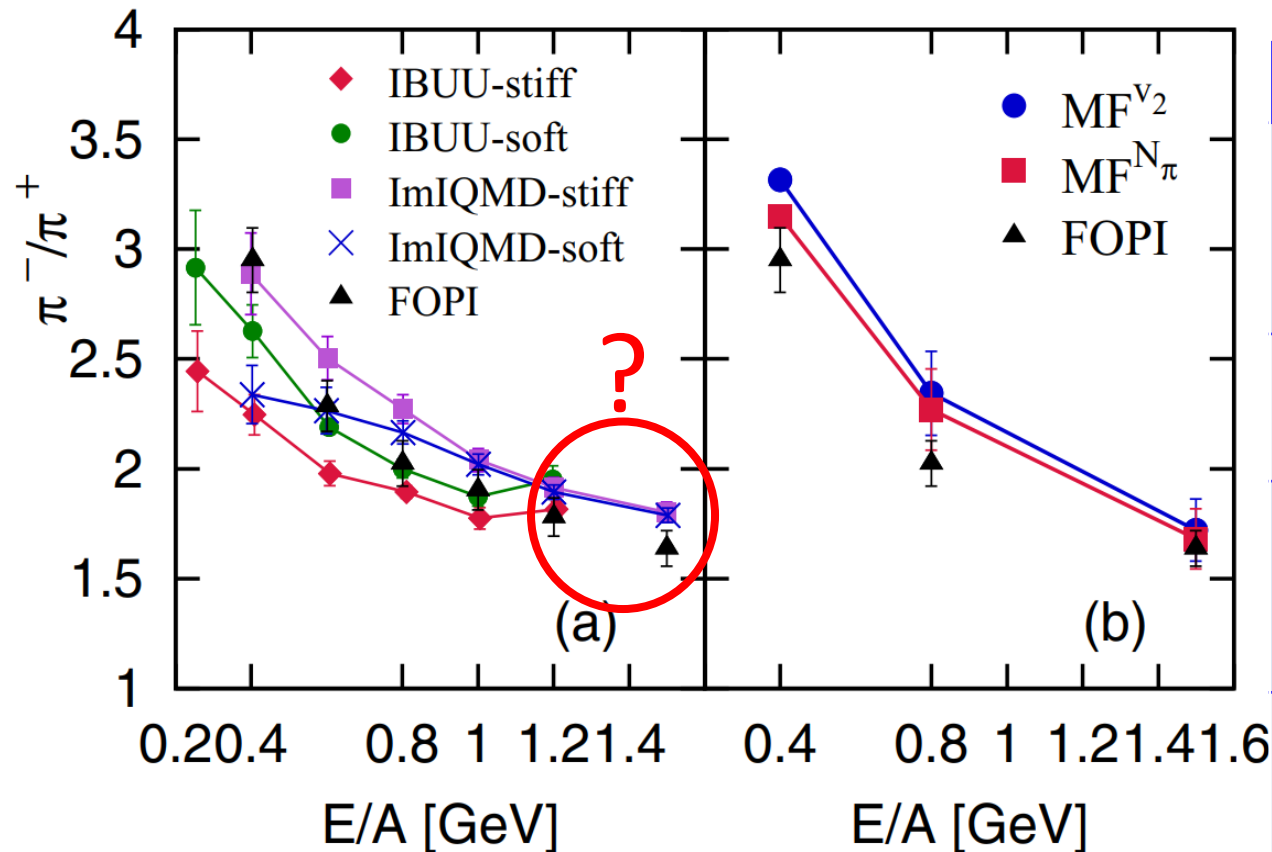
Described by very soft asy-EOS  $\leq 2\rho_0$   
 Inconsistent with the n/p flow data  
 Still true for higher densities???

- pion optical potential
- self energies different for  $\pi^-$  and  $\pi^+$
- potentials and characteristics of  $\Delta$

**WORK IN  
PROGRESS**

 Xiao et al., Phys. Rev. Lett. 102, 062502 (2009)  
 M. D. Cozma, Phys. Rev. C 95, 014601 (2017)

**Idea:** Measurement of yield ratios of isospin opposite particles at sub-threshold energies is suitable for higher energies where pion ratio could lose sensitivity



$I_3$	Particle	Production	$E_{thr}$	Decay
+1	$\Sigma^+(uus)$	$pp \rightarrow \Sigma^+K^+n$ $pp \rightarrow \Sigma^+K^0p$ $pn \rightarrow \Sigma^+K^0n$	1.8 GeV	$\Sigma^+ \rightarrow p\pi^0$ $\Sigma^+ \rightarrow n\pi^+$
-1	$\Sigma^-(dds)$	$pn \rightarrow \Sigma^-K^+p$ $nn \rightarrow \Sigma^-K^+n$	1.8 GeV	$\Sigma^- \rightarrow n\pi^-$
+1/2	$\Xi^0(uss)$	$pp \rightarrow \Xi^0K^+K^0p$ $pn \rightarrow \Xi^0K^0K^0p$ $nn \rightarrow \Xi^0K^0K^0n$	3.7 GeV	$\Xi^0 \rightarrow \Lambda\pi^0$
-1/2	$\Xi^-(dss)$	$pp \rightarrow \Xi^-K^+K^+p$ $pn \rightarrow \Xi^-K^+K^+n$ $nn \rightarrow \Xi^-K^0K^+n$	3.7 GeV	$\Xi^- \rightarrow \Lambda\pi^-$

 Jun Hong and P. Danielewicz, *Phys. Rev. C*90, 024605 (2014)  
 P. Senger, 3<sup>rd</sup> and 4<sup>th</sup> CBM China Meeting (2018-2019)

$$C(k^*) = C_{\text{baseline}}(k^*) \cdot \left( 1 + \lambda_{\text{genuine}} \cdot (C_{\text{genuine}}(k^*) - 1) + \sum \lambda_{ij} \cdot (C_{ij}(k^*) - 1) \right)$$

*Baseline*
*Genuine correlation*
*Residuals*

## CATS

Correlation Analysis Tool Using the Schrödinger Equation

## Lednický

Numerical Solver

Analytical Model

Analytical source distribution  
Distributions from transport models

**Source**

Gaussian source distribution

Solution of the two particle Schrödinger Equation  
➤ Can incorporate any strong interaction potential, Coulomb interaction and effects of quantum statistics

**Wave function**

Based on the effective range expansion  
➤ The interaction is modelled using the scattering length ( $f_0$ ) and the effective range ( $d_0$ )

p-p, p-Ξ and p-Λ (NLO) Correlation function

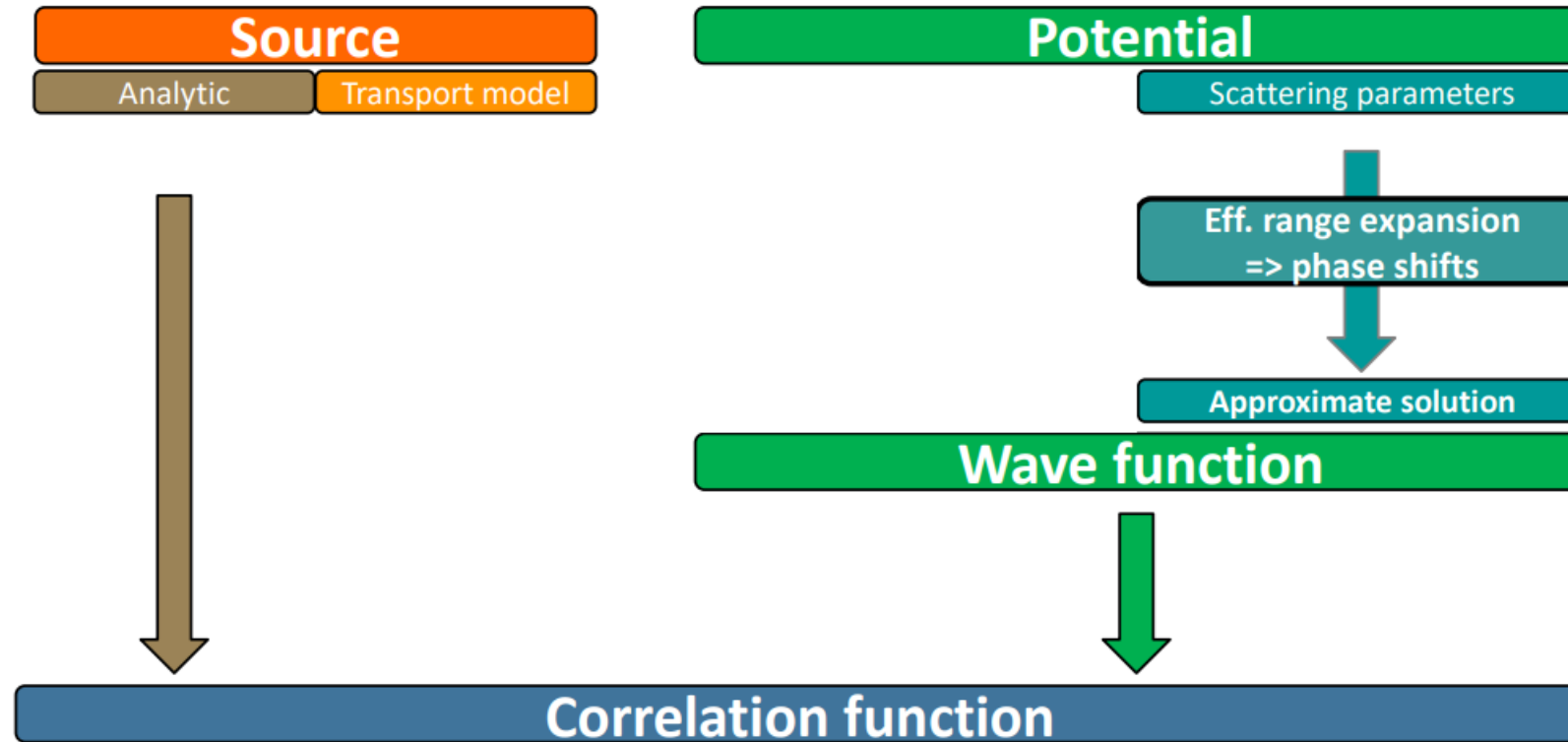
**Used to fit**

p-Λ (LO) and Λ-Λ Correlation function

Eur. Phys. J. C (2018) 78:394.

R. Lednický and V. L. Lyuboshits, Sov. J. Nucl. Phys. 35, 770 (1982), [Yad. Fiz.35,1316(1981)].

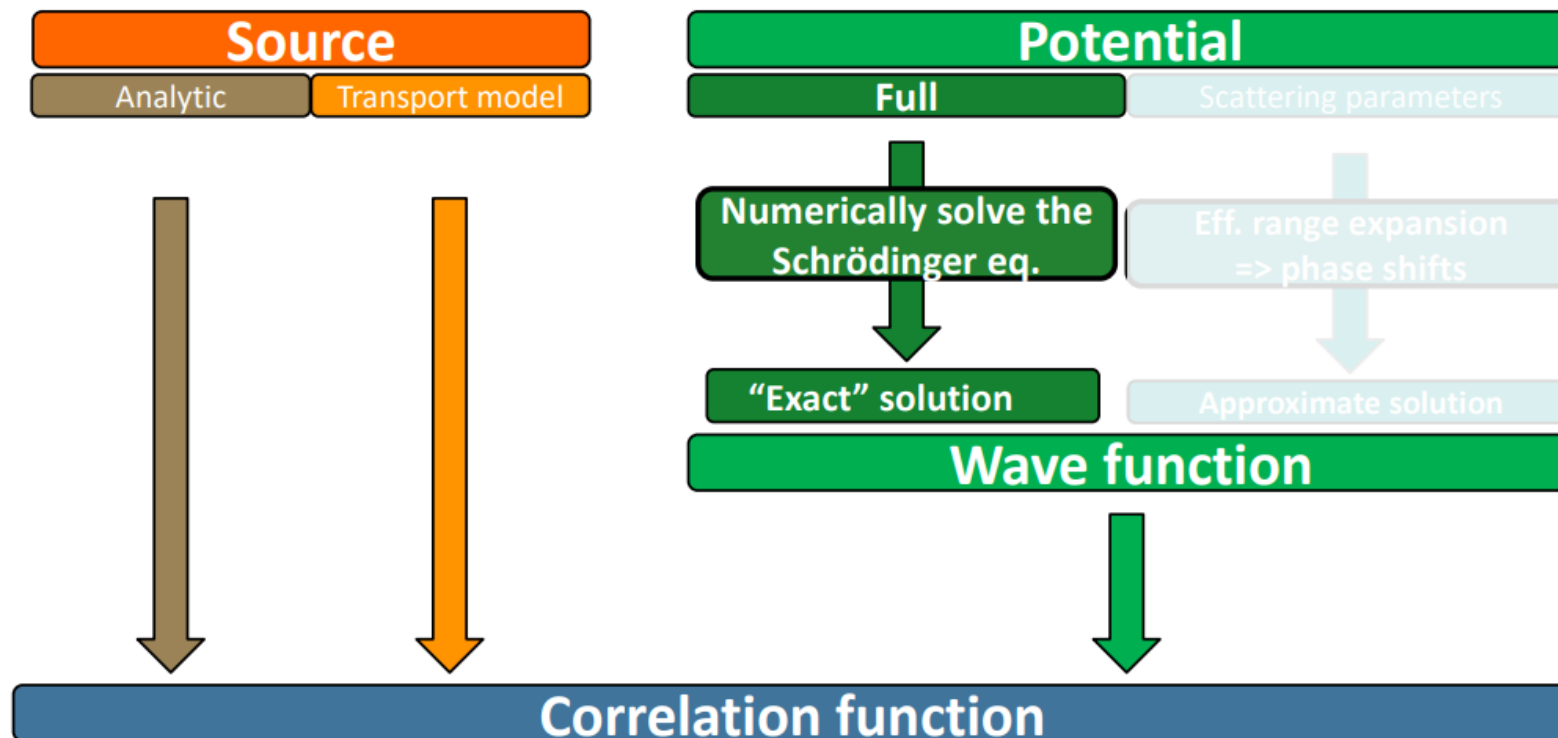




$$C(k) = 1 + \sum_S \rho_S \left[ \frac{1}{2} \left| \frac{f^S(k)}{R_G^{\Lambda p}} \right|^2 \left( 1 - \frac{d_0^S}{2\sqrt{\pi} R_G^{\Lambda p}} \right) + 2 \frac{\Re f^S(k)}{\sqrt{\pi} R_G^{\Lambda p}} F_1(Q R_G^{\Lambda p}) - \frac{\Im f^S(k)}{R_G^{\Lambda p}} F_2(Q R_G^{\Lambda p}) \right]$$

Depends on scattering parameters, might locally break down for small sources

R. Lednický and V. L. Lyuboshits, *Sov. J. Nucl. Phys.* 35, 770 (1982), [*Yad. Fiz.*35,1316(1981)].



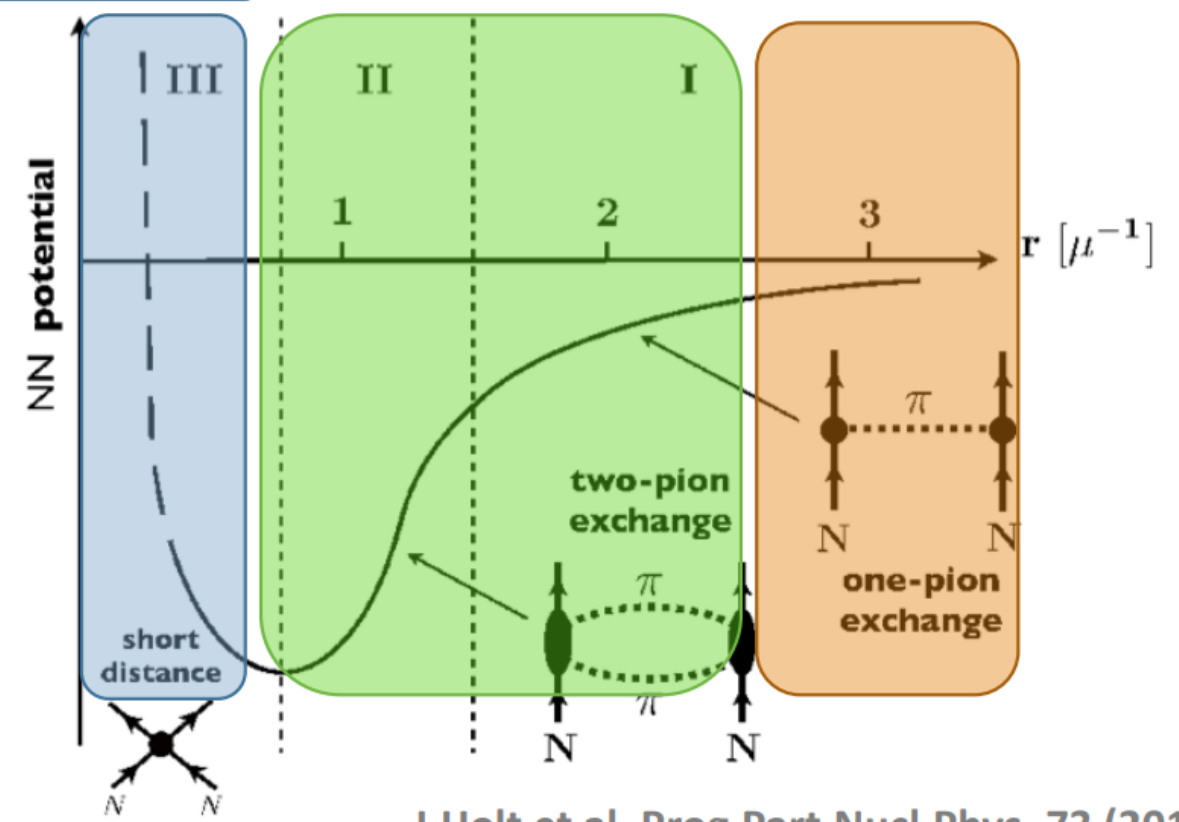
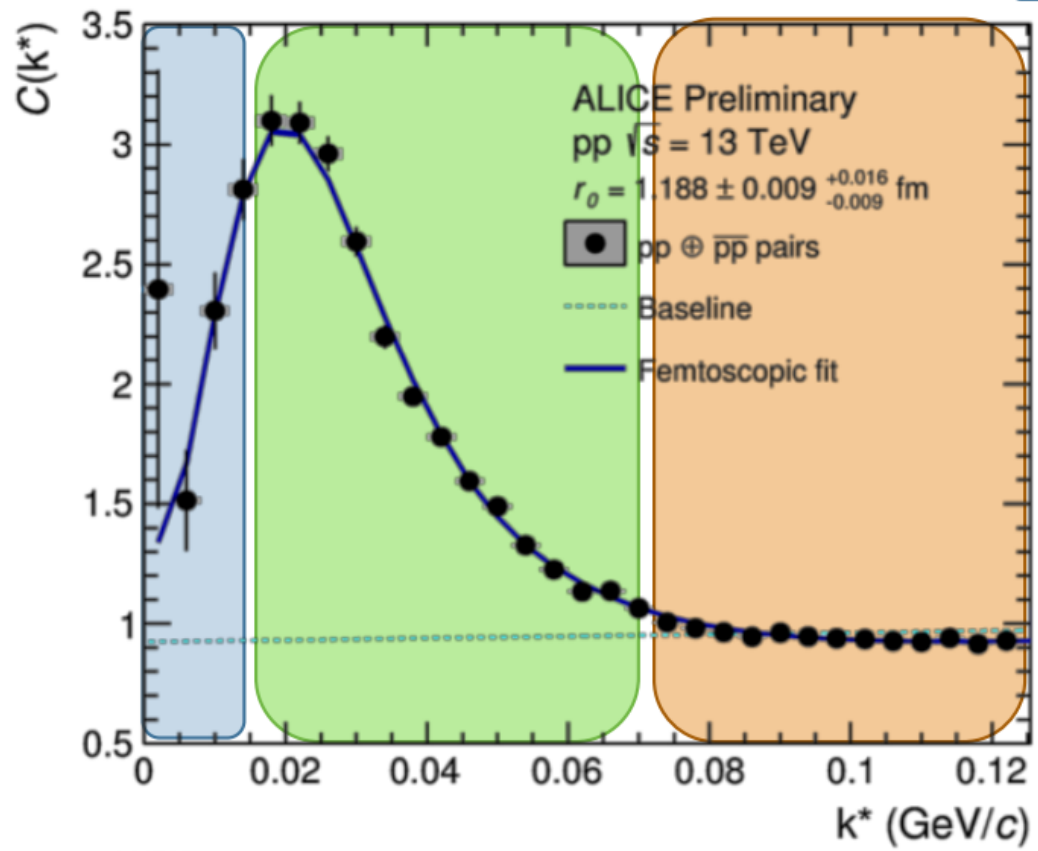
$$C(k) = \int S(\vec{r}, k) |\psi(\vec{r}, k)|^2 d\vec{r} \xrightarrow{k \rightarrow \infty} 1$$

(D.L.Mihaylov et al. Eur.Phys.J. C78 (2018) no.5,394)

# CORRELATION FUNCTIONS AND INTERACTIONS

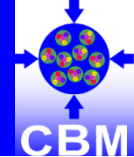
$C(k^*) \rightarrow$

- > 1 attraction
- = 1 no interaction
- < 1 repulsion



J.Holt et al, Prog.Part.Nucl.Phys. 73 (2013)

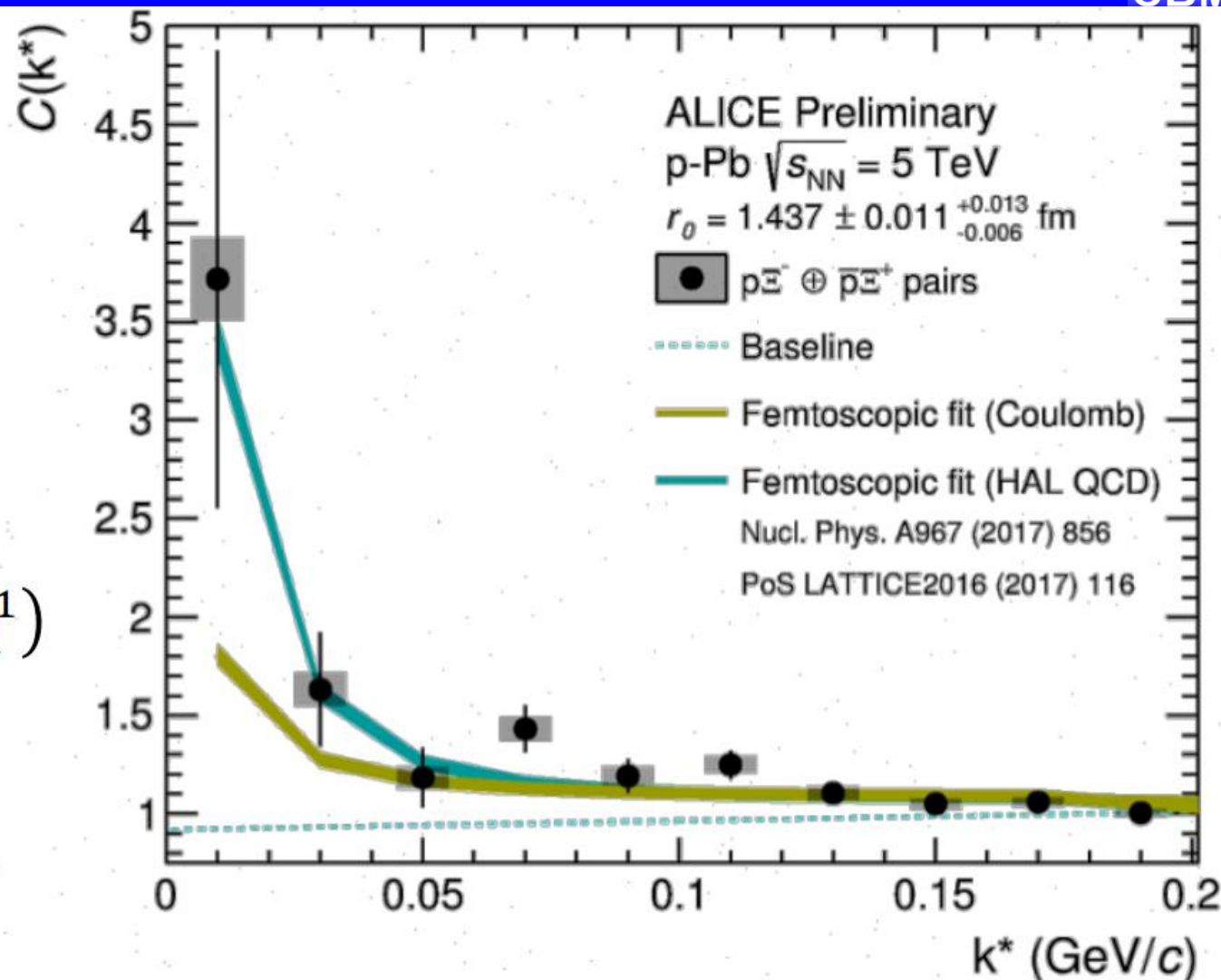
# P-XI- CORRELATION FUNCTION IN P-PB 5.02 TEV



- First observation of strong attractive interaction in p-Ξ<sup>-</sup>
- modeled with preliminary QCD strong potential by the HAL QCD collaboration  
Potential from Hatsuda et al., NPA967 (2017) 856, PoS Lattice2016 (2017) 116)

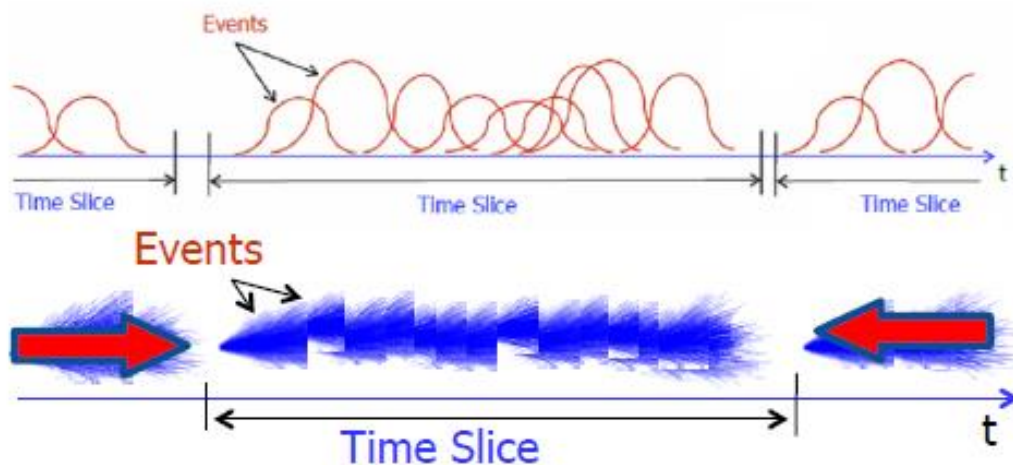
$$C(k^*) = \frac{1}{8} (C_{I=0}^{S=0} + C_{I=1}^{S=0}) + \frac{3}{8} (C_{I=0}^{S=1} + C_{I=1}^{S=1})$$

**COULOMB-ONLY  
HYPHOTESIS EXCLUDED  
AROUND 3σ**



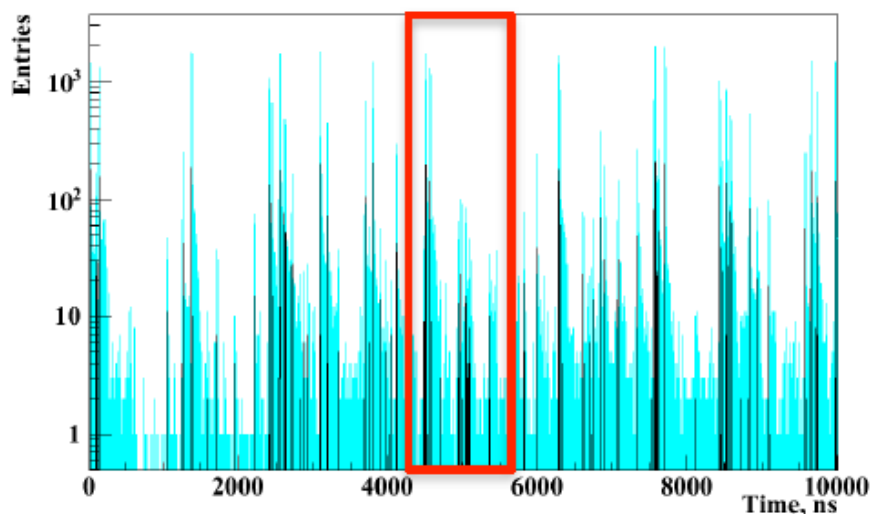
ALI-PREL-144825

# 4D RECONSTRUCTION

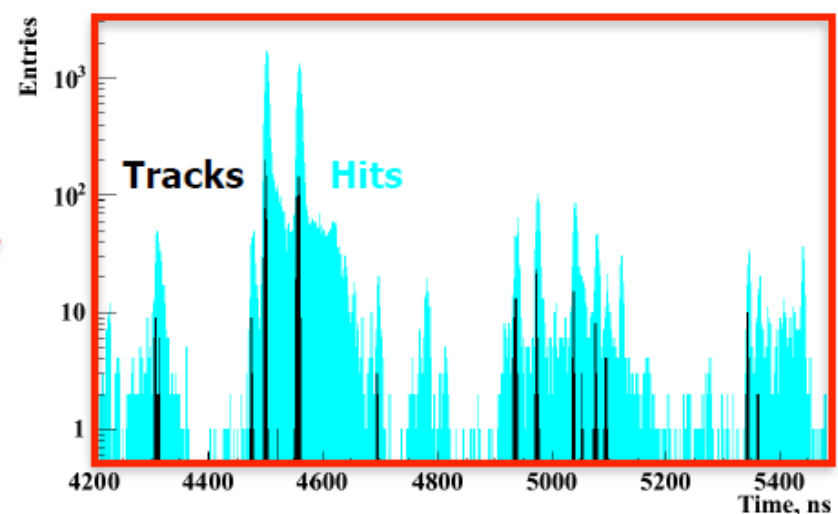


100 AuAu mbias events at 10 AGeV at  $10^7$  Hz

- The beam will be continuous (no bunch structure).
- Detector hits will be marked with a time stamp.
- Events in the selected time window (time slice) will overlap in time.
- Reconstruction will be in 4D  $(x,y,z,t)$ .
- Reconstruction of time slices rather than events will be needed.
- Events will be defined based on the reconstructed tracks.

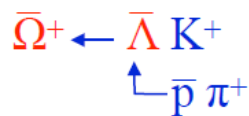
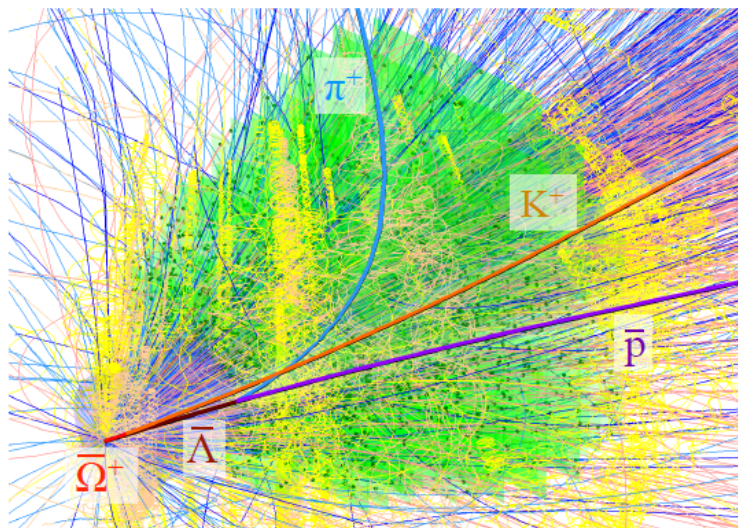


Reconstructed tracks - zoom



Reconstructed tracks clearly represent groups, which correspond to the original events

# Concept of KF Particle



```

KFParticle Lambda(P, Pi);           // construct anti Lambda
Lambda.SetMassConstraint(1.1157);   // improve momentum and mass
KFParticle Omega(K, Lambda);       // construct anti Omega
PV -= (P; Pi; K);                  // clean the primary vertex
PV += Omega;                        // add Omega to the primary vertex
Omega.SetProductionVertex(PV);      // Omega is fully fitted
(K; Lambda).SetProductionVertex(Omega); // K, Lambda are fully fitted
(P; Pi).SetProductionVertex(Lambda); // p, pi are fully fitted
    
```

1. KFParticle class describes particles by:

$$\mathbf{r} = \{ x, y, z, p_x, p_y, p_z, E \}$$

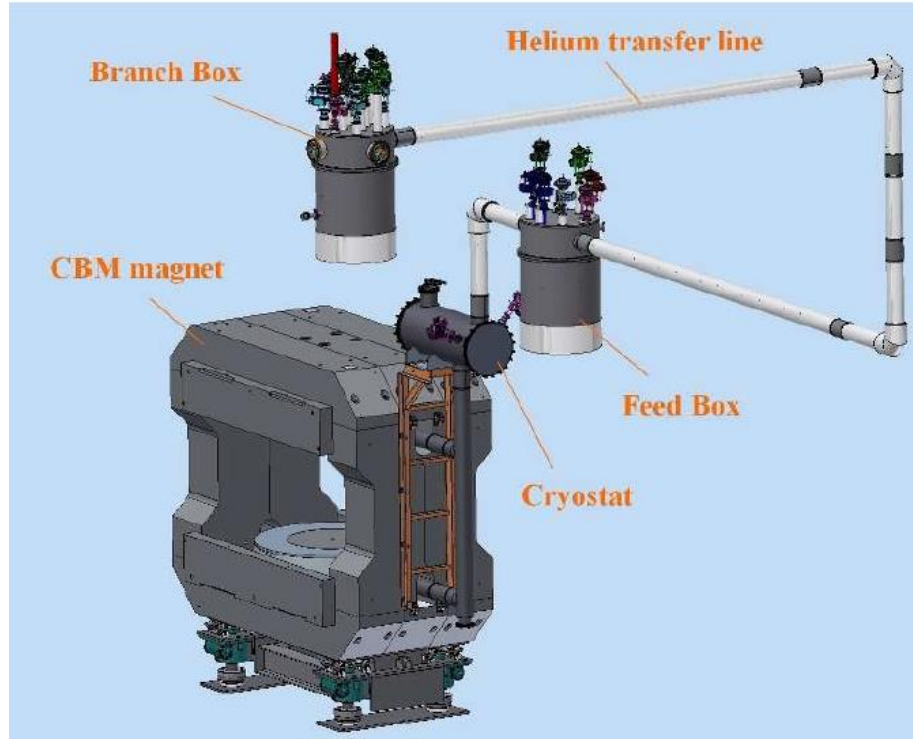
$$\begin{array}{l}
 \text{State vector} \\
 \mathbf{C} = \langle \mathbf{r} \mathbf{r}^T \rangle = \\
 \text{Covariance matrix}
 \end{array}
 \begin{bmatrix}
 \sigma_x^2 & C_{xy} & C_{xz} & C_{xp_x} & C_{xp_y} & C_{xp_z} & C_{xE} \\
 C_{xy} & \sigma_y^2 & C_{yz} & C_{yp_x} & C_{yp_y} & C_{yp_z} & C_{yE} \\
 C_{xz} & C_{yz} & \sigma_z^2 & C_{zp_x} & C_{zp_y} & C_{zp_z} & C_{zE} \\
 C_{xp_x} & C_{yp_x} & C_{zp_x} & \sigma_{p_x}^2 & C_{p_x p_y} & C_{p_x p_z} & C_{p_x E} \\
 C_{xp_y} & C_{yp_y} & C_{zp_y} & C_{p_x p_y} & \sigma_{p_y}^2 & C_{p_y p_z} & C_{p_y E} \\
 C_{xp_z} & C_{yp_z} & C_{zp_z} & C_{p_x p_z} & C_{p_y p_z} & \sigma_{p_z}^2 & C_{p_z E} \\
 C_{xE} & C_{yE} & C_{zE} & C_{p_x E} & C_{p_y E} & C_{p_z E} & \sigma_E^2
 \end{bmatrix}$$

2. Covariance matrix contains essential information about tracking and detector performance.
3. The method for mathematically correct usage of covariance matrices is provided by the KF Particle package based on the Kalman filter (KF) developed by FIAS group<sup>1,2</sup> primarily for CBM and ALICE.
4. Heavy mathematics requires fast and vectorised algorithms.
5. Mother and daughter particles are KFParticle and are treated in the same way.
6. The natural and simple interface allows to reconstruct easily rather complicated decay chains.
7. The package is geometry independent and can be easily adapted to different experiments.

1. KF Particle — S. Gorbunov, "On-line reconstruction algorithms for the CBM and ALICE experiments," Dissertation thesis, Goethe University of Frankfurt, 2012, <http://publikationen.uni-frankfurt.de/frontdoor/index/index/docId/29538>  
 2. KF Particle Finder — M. Zyzak, "Online selection of short-lived particles on many-core computer architectures in the CBM experiment at FAIR," Dissertation thesis, Goethe University of Frankfurt, 2016, <http://publikationen.uni-frankfurt.de/frontdoor/index/index/docId/41428>

# CBM SC magnet

In-kind contribution by Russia, built by BINP Novosibirsk

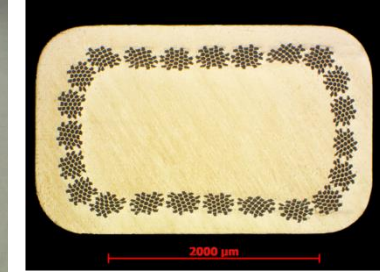


## Production status:

- The bare SC cable is manufactured



Cross section (photo)



- Contract for SC cable insulation signed with VNIKP
- Machining of the magnet yoke will start in October 2019

## Next steps:

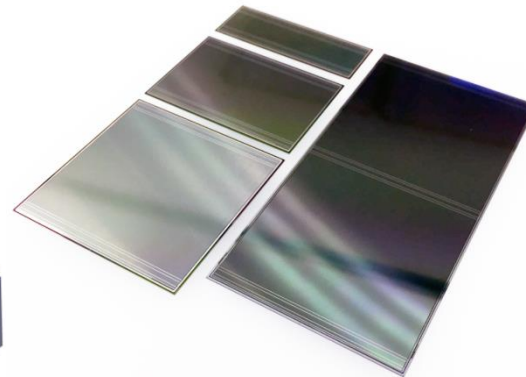
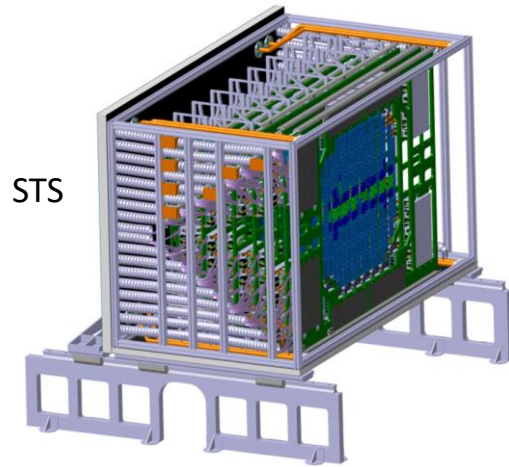
- Preliminary Design Review in Nov. 2019  
Agreement on the cooling circuit, cryostat, coil support struts, control system
- Final Design Review in May 2020  
All technical drawings finished
- Construction in 2020 - 2021

# Silicon Tracking System

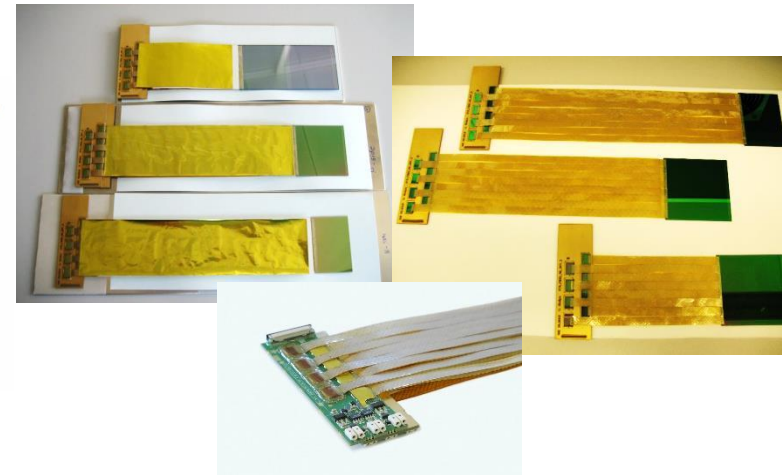
- Charged particle track reconstruction, momentum determination

In-kind contributions by Germany, Russia, Poland:

GSI, JINR, KIT Karlsruhe, JU + AGH Krakow, KINR Kiev, Univ. Tübingen, Warsaw UT



Silicon microstrip sensors



Module assembly at GSI and JINR

## Status:

TDR approved by FAIR in July, 2013

- Radiation tolerance of silicon sensors tested up to  $n_{eq}(1 \text{ MeV}) = 2 \times 10^{14} / \text{cm}^2$ .
- 1100 silicon microstrip sensors ordered from vendor Hamamatsu Photonics, delivery scheduled in batches from 11/2019 to 10/2020.
- Second design iteration of the STS-XYTER ASIC made, applied to prototype modules.
- Carbon fiber ladders ordered in company, delivery until 10/2019.
- Module and ladder assembly procedures established, working towards declaring production readiness. Start of series production in 2020.
- System engineering and system integration progressing.
- Demonstrator detector mSTS operated in mCBM experiment.

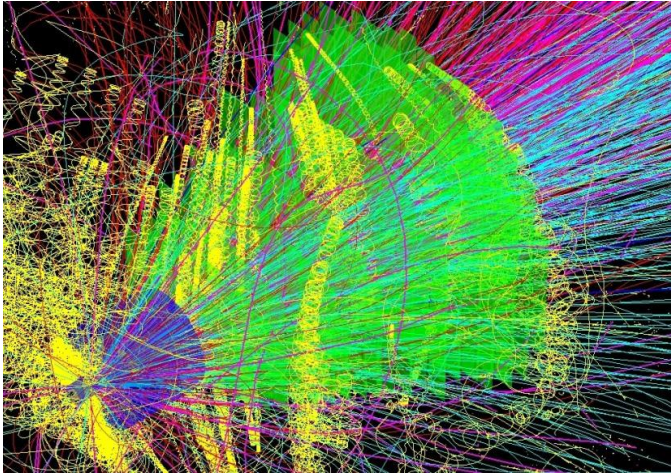


# Charged particle track reconstruction

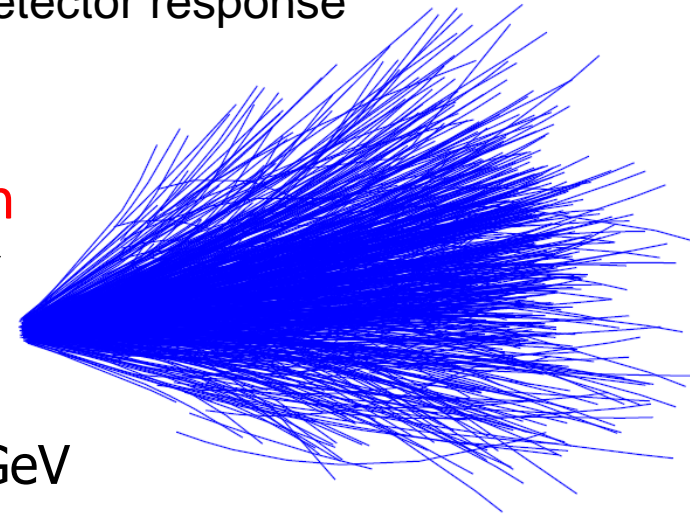
Event generators UrQMD 3.3, PHSD

Transport code GEANT3, FLUKA

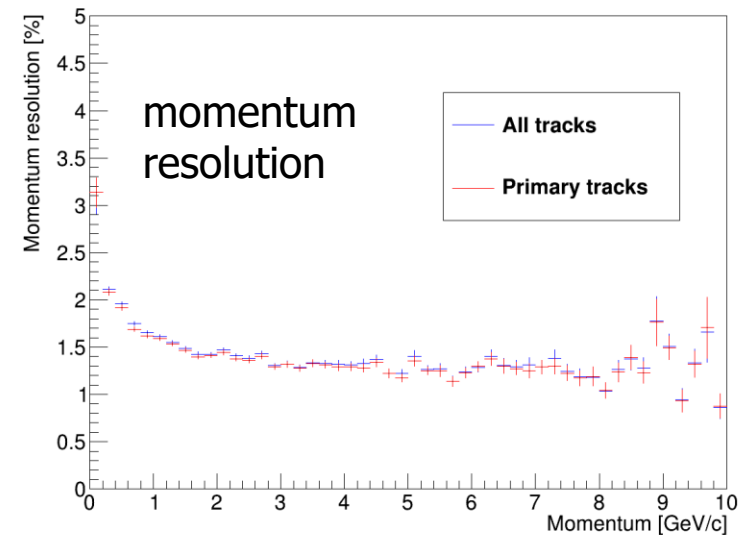
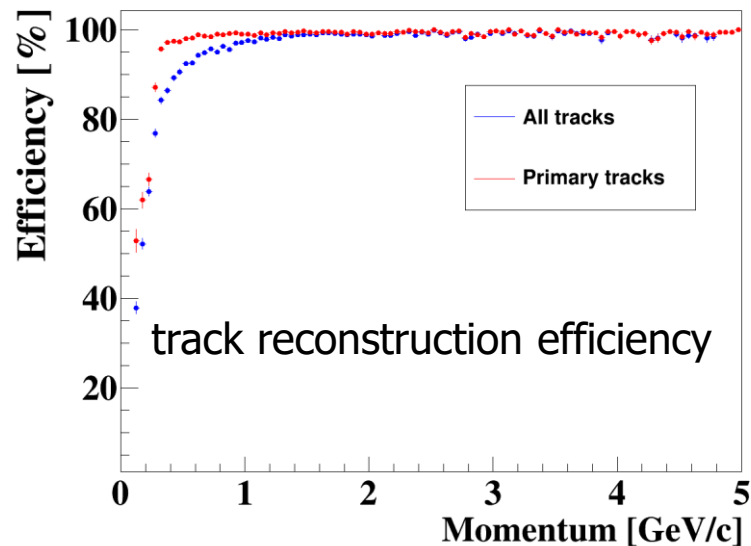
Realistic detector geometries, material budget and detector response



reconstruction



Au+Au 10 A GeV



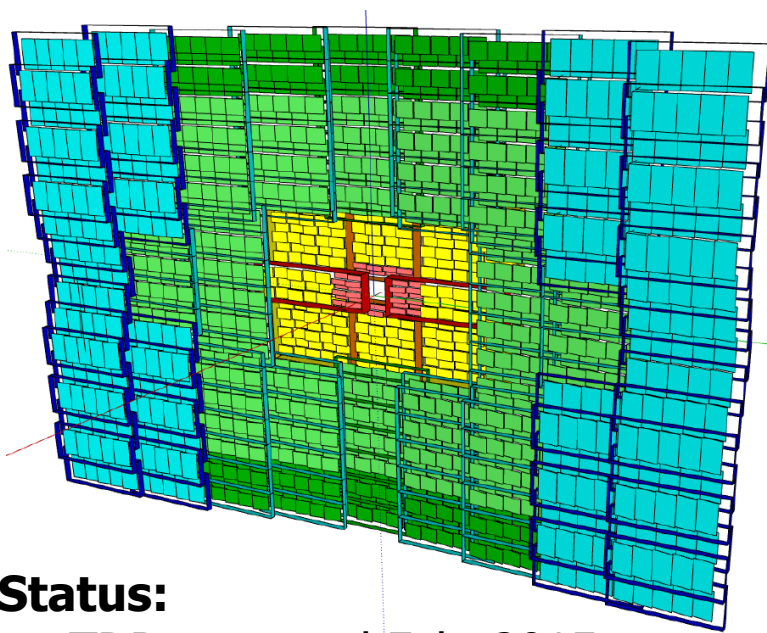
# The high-rate MRPC TOF wall

## ➤ Particle identification

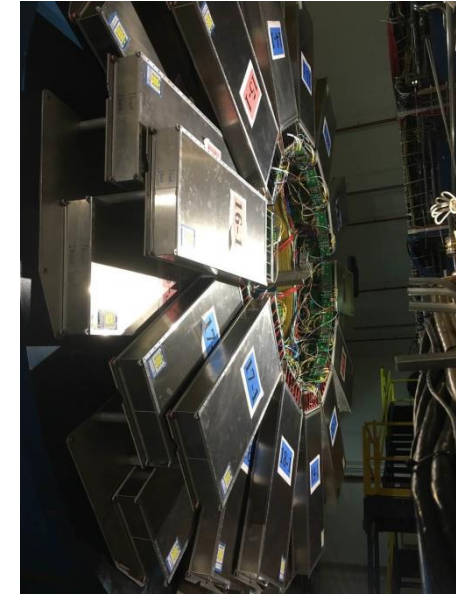
Challenge: Time resolution 50 ps up to 25 kHz/cm<sup>2</sup>. Total area 100 m<sup>2</sup>

In-kind contributions by Germany, China, Romania:

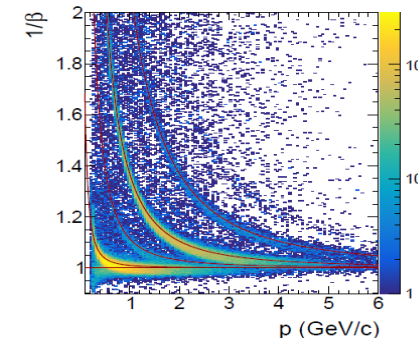
THU Beijing, NIPNE Bucharest, GSI Darmstadt, TU Darmstadt, IfI Frankfurt, USTC Hefei, Univ. Heidelberg, ITEP Moscow, HZDR Rossendorf, CCNU Wuhan.



TOF at mCBM



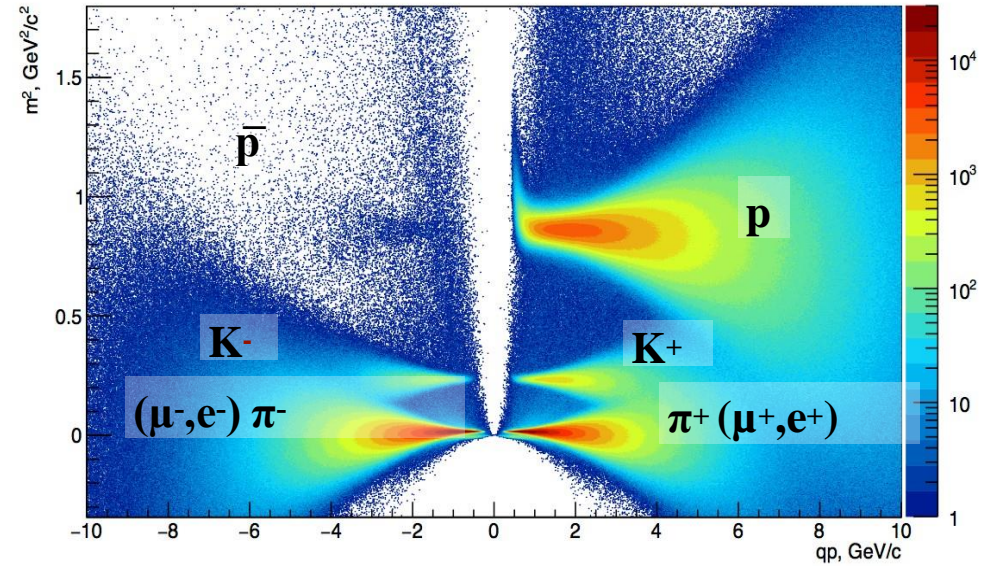
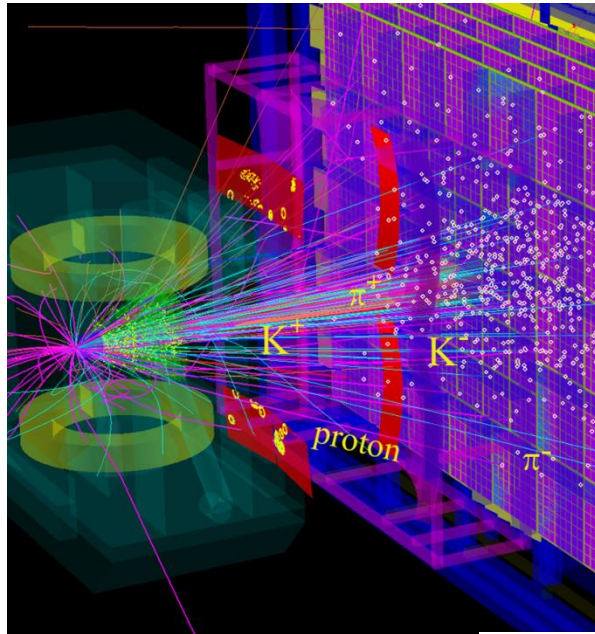
TOF at STAR



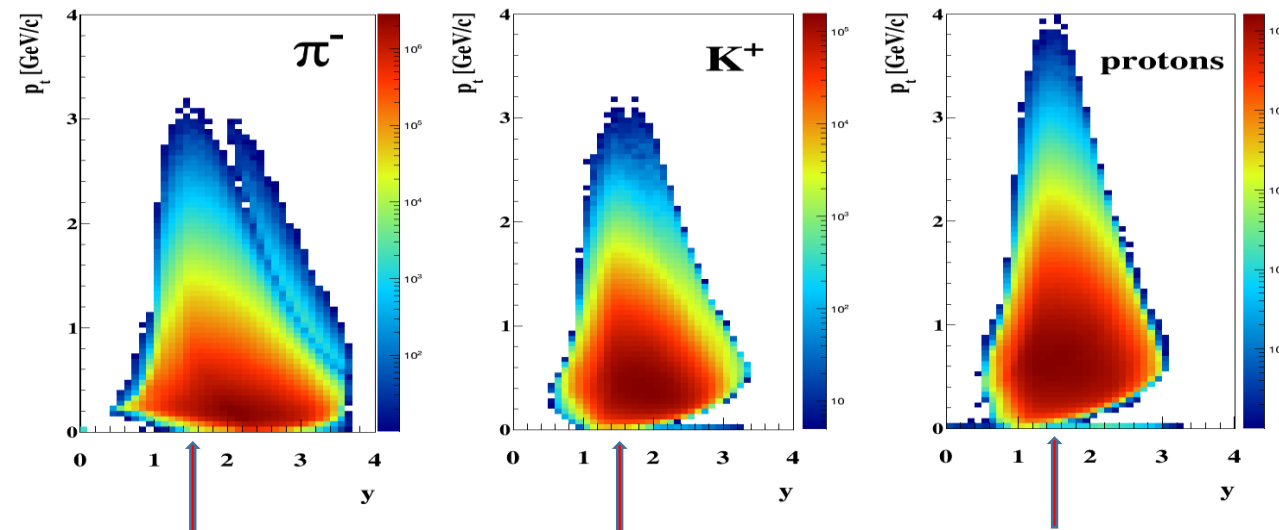
## Status:

- TDR approved Feb. 2015
- Full size prototype TOF MRPC detectors installed and operated at mCBM (GSI) and STAR (RHIC)
- PID capability at STAR demonstrated

# Hadron identification by STS + TOF

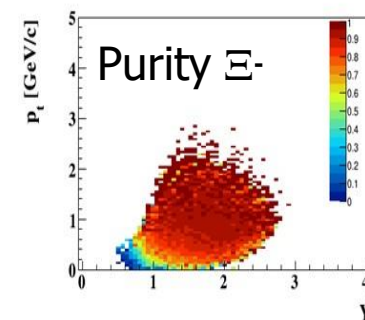
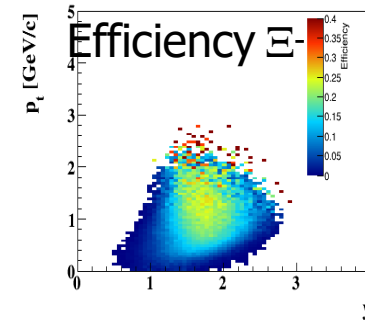
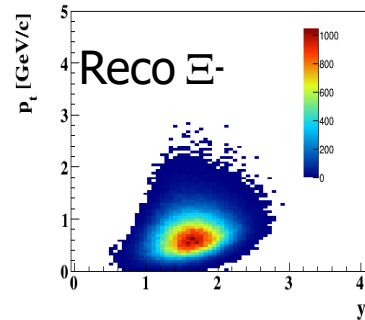
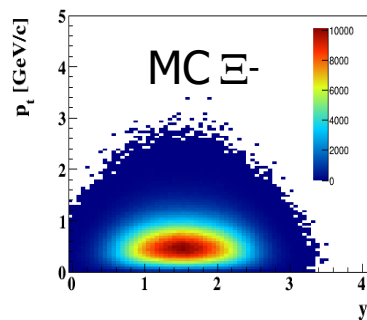
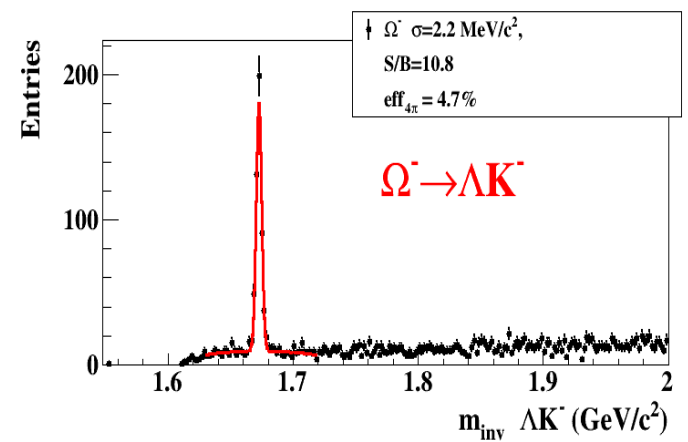
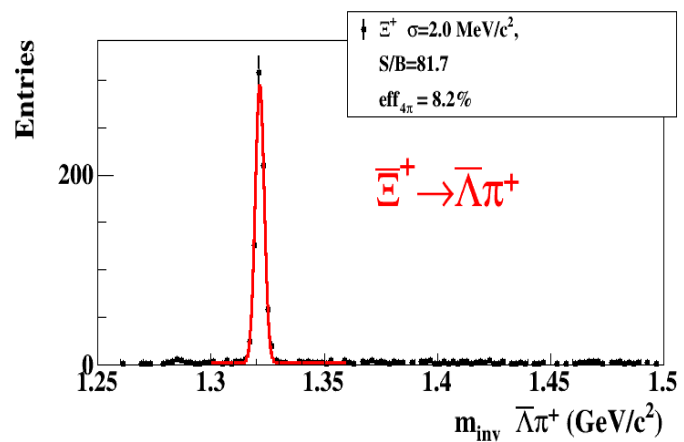
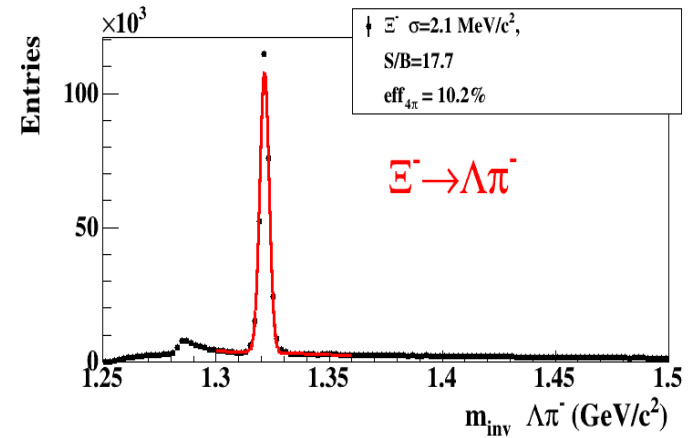
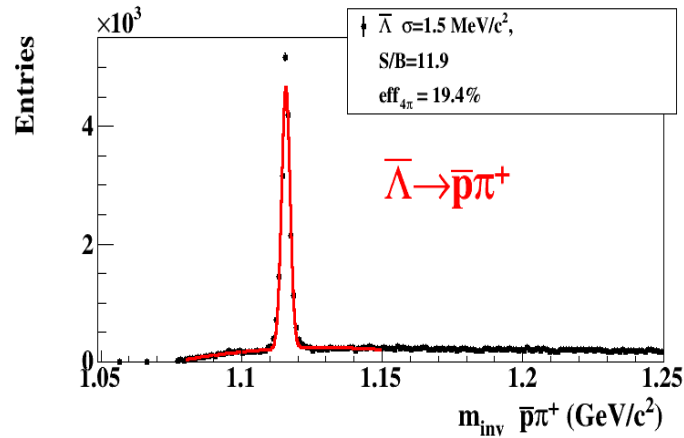


Au+Au collisions  
10 A GeV



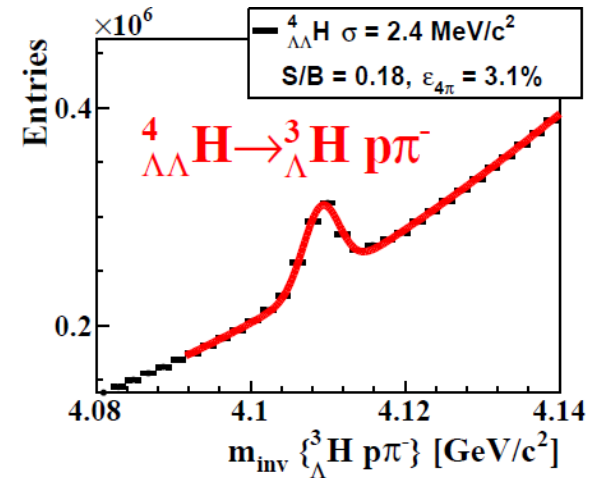
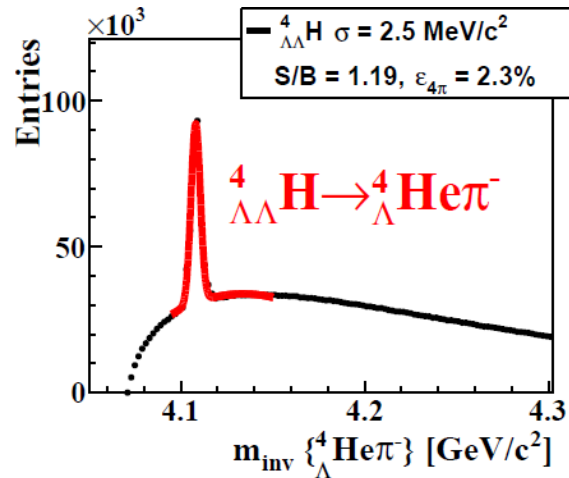
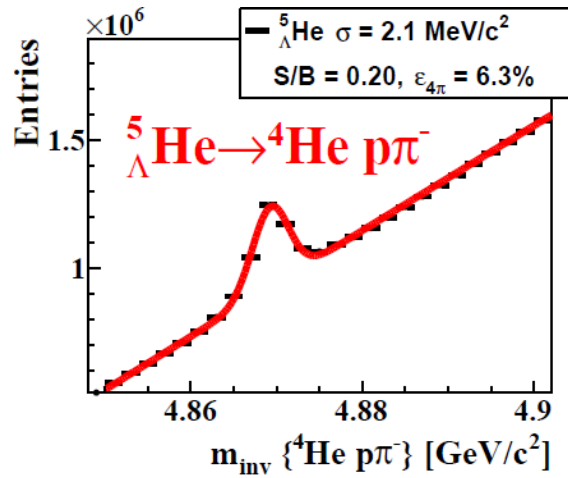
# Hyperon reconstruction (STS+TOF)

5 M central Au+Au collisions 10A GeV/c

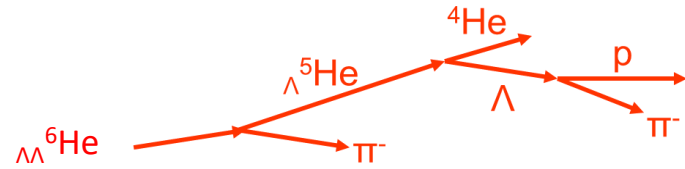


# Hypernuclei reconstruction (STS+TOF)

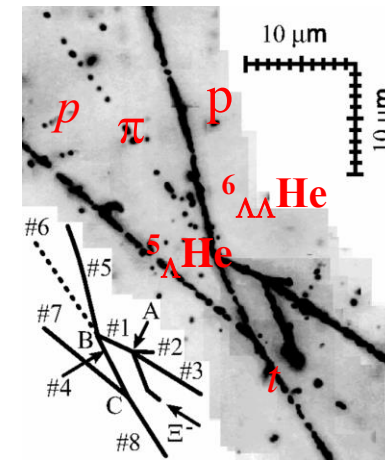
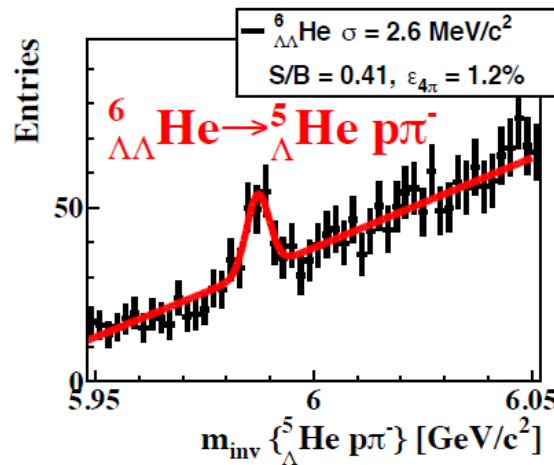
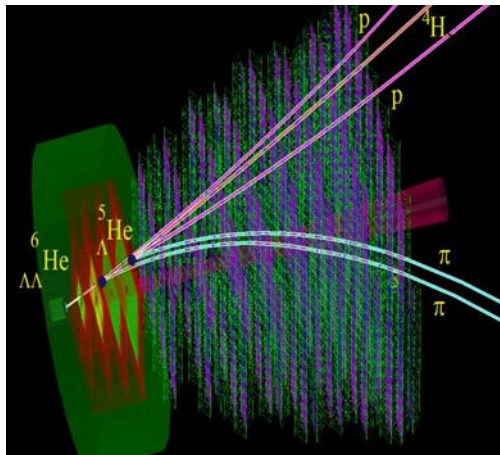
5 M min. bias Au+Au collisions 10A GeV/c



Example:



${}^6_{\Lambda}\text{He}$  yield 60/week  
(reaction rate 1 MHz, BR 10%, efficiency 1%)

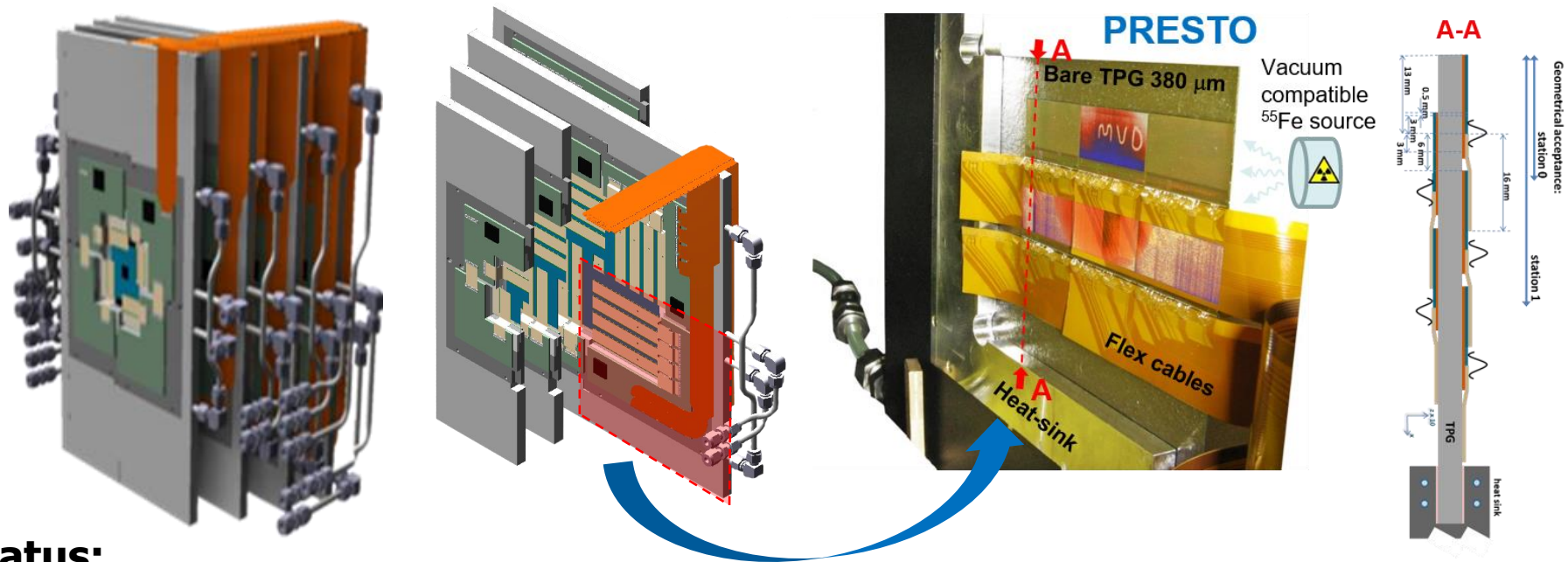


Nagara event

# Micro Vertex Detector (MVD)

In-kind contributions by Germany, France: Univ. Frankfurt, IPHC Strasbourg

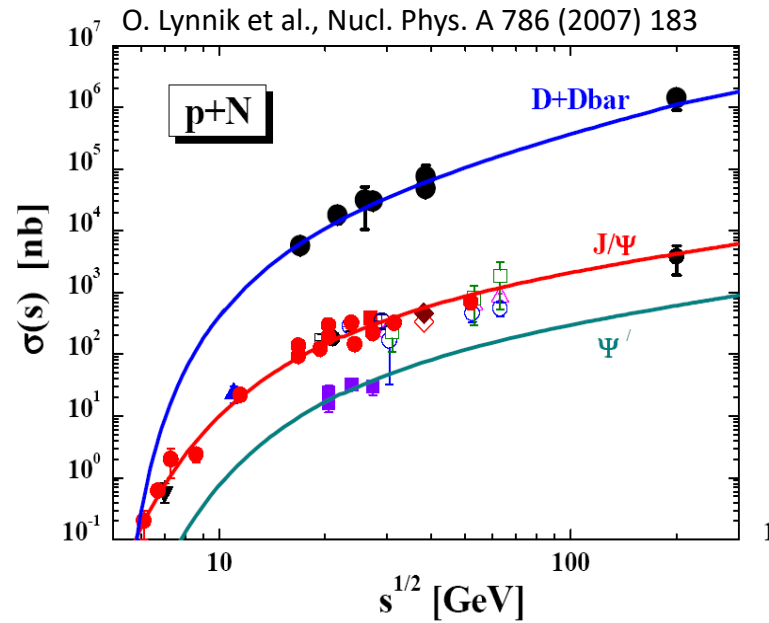
- Background suppression for di-electron measurements
- Determination of secondary vertices of open charm decays ( $\tau = 10^{-12}$ - $10^{-13}$  s)
- Improved tracking for hyperon-ID



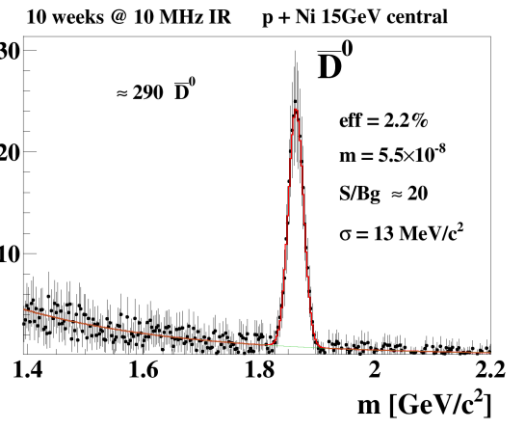
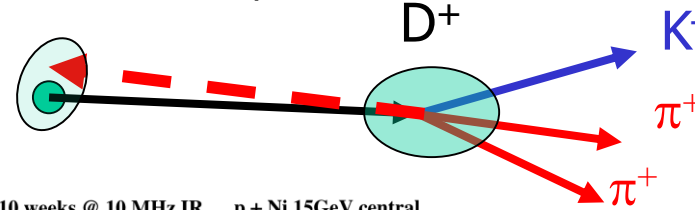
## Status:

- Prototyping well advanced with PRESTO module: integration concept (vacuum operation / material budget) demonstrated
- Dedicated CBM sensor in synergy with ALICE-ITS upgrade: improved in-pixel logic and data throughput, R/O time  $\sim 5 \mu\text{s}$ .
- Dedicated CBM MVD pixels sensor prototype MIMOSIS-0 in house and being characterized.
- First full size sensor MIMOSIS-1 design reviewed, submission in Sept. 19.

# Open charm (MVD + STS + TOF)

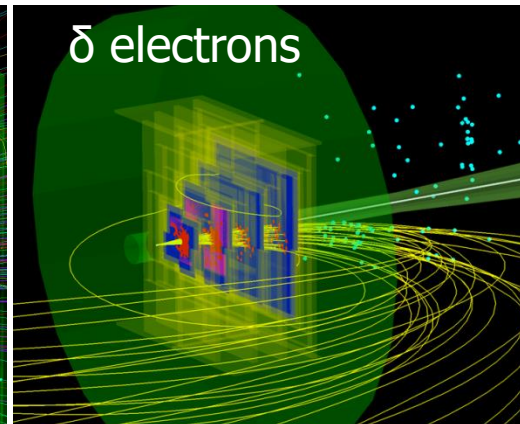
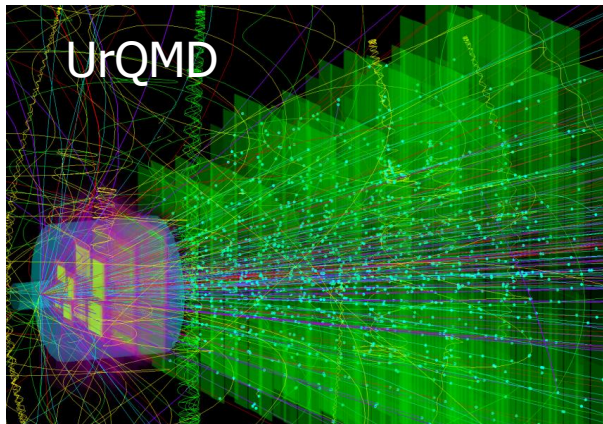


CT = 60...312  $\mu\text{m}$

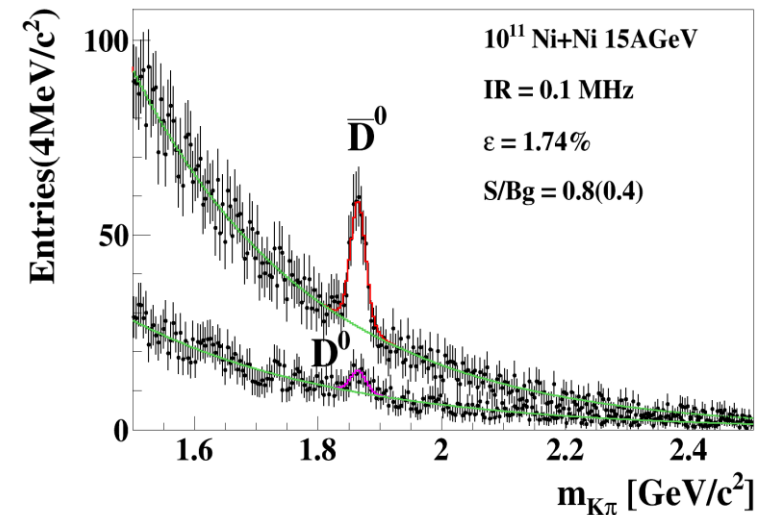


Simulation p + N 15 GeV

Ni + Ni central collisions at 15 A GeV



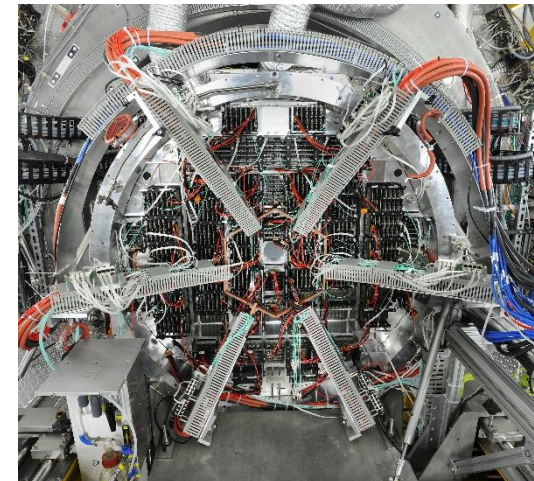
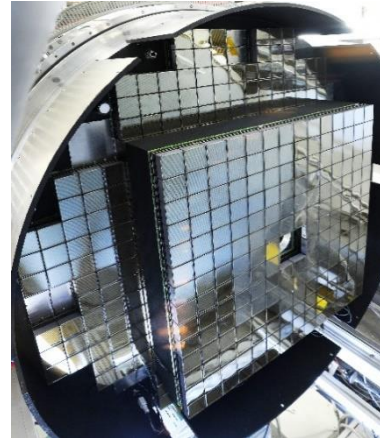
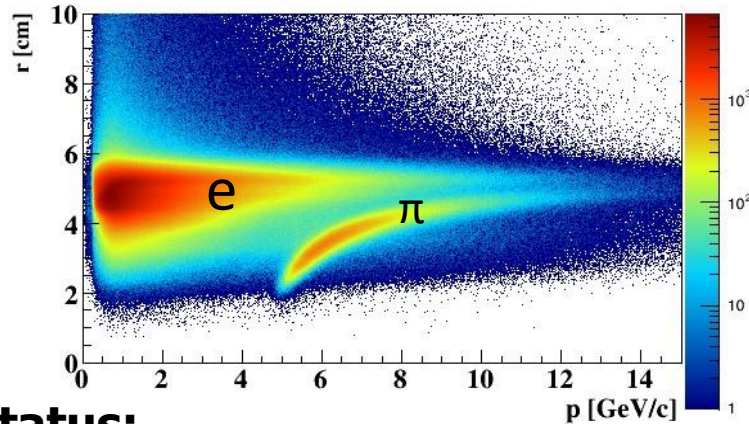
260  $\bar{D}^0$  and 45  $D^0$  in 2 weeks at IR = 0.1 MHz



# Ring-Imaging Cherenkov (RICH) Detector

## ➤ Electron identification

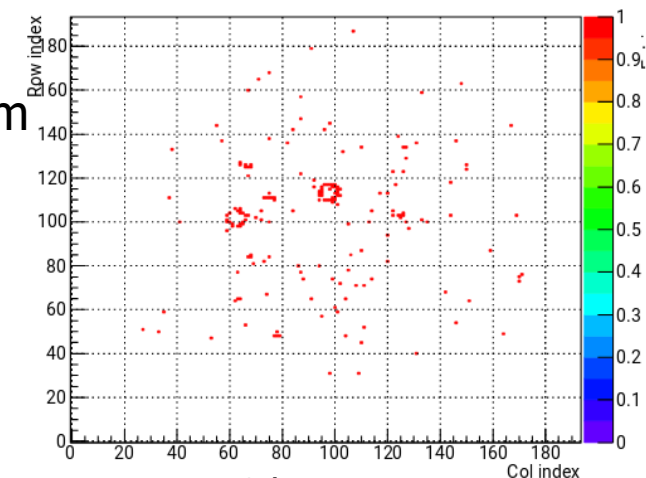
In-kind contributions by Germany, Russia:  
Univ. Gießen, Univ. Wuppertal, PNPI Gatchina, GSI



## Status:

- All 1100 H12700 MAPMTs delivered and tested, 428 MAPMTs including readout chain integrated in HADES RICH detector; successful participation in HADES beam time 2019
- Concept for new structure of mirror wall with substantially reduced material budget, first prototype under stress test
- First hardware/ software implementation for the measurement of mirror misalignments and software correction cycle ready

hRichCalsColRowEvent 4.3.2019 1:59:45



HADES beam time: 120  
 $\omega$ -meson candidate



# Transition Radiation Detector (TRD)

- Electron identification, energy-loss measurements

In-kind contributions by Germany, Romania:

NIPNE Bucharest, Univ. Frankfurt, Univ. Heidelberg, Univ. Münster

Challenge:  
 $\epsilon(e^\pm) = 90\%$   
 $\epsilon(\pi) = 5\%$   
at 100 kHz/cm<sup>2</sup>

Status:

Beam and laboratory tests

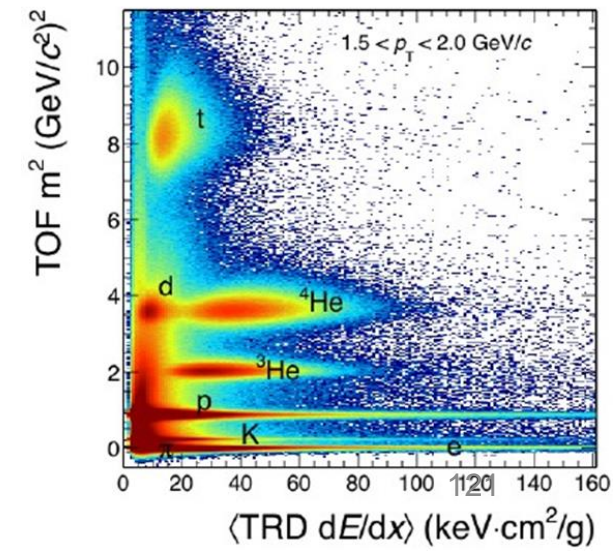
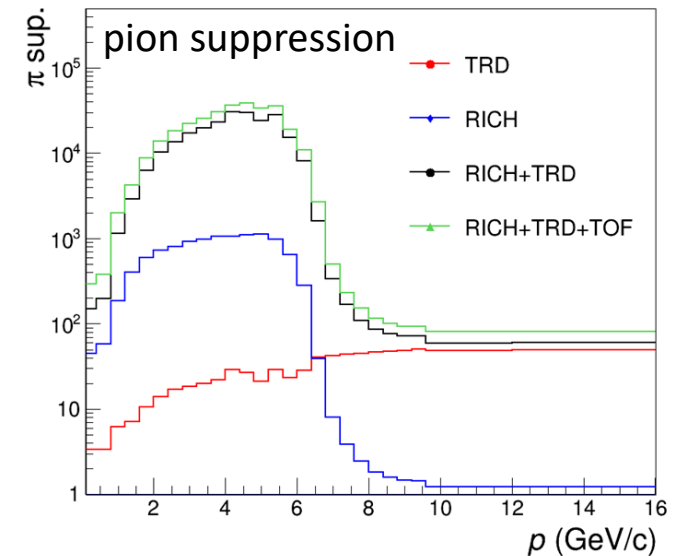
- First results from GIF++: Stable chamber and readout operation at high  $\gamma$ -irradiation
- X-ray test setup in Bucharest: 2-D position reconstruction of irradiated area

Infrastructure

- First design suggestions for support structure (Münster)
- Integration of type-1 modules in progress (Bucharest)

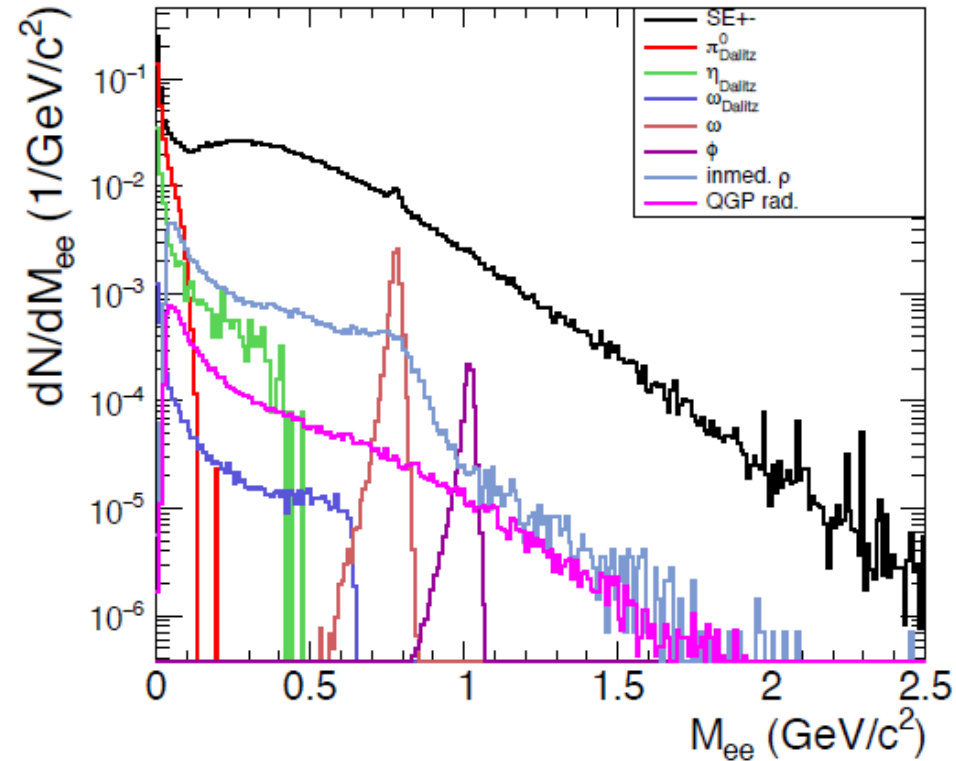
Front-end electronics

- 15000 SPADIC2.2 chips (final version) produced in engineering run
- Chips are packaged (BGA) and being mounted on FEBs



# Dilepton invariant mass spectra for central Au+Au collisions at 8A GeV

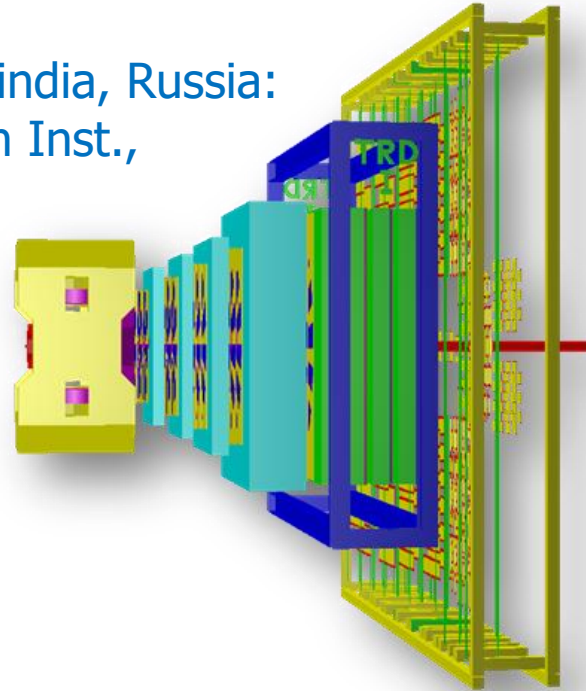
Di-electrons: MVD+STS+RICH+TRD+TOF



# Muon Chamber (MuCh) System

## ➤ Muon identification

In-kind contributions by india, Russia:  
VECC Kolkata +12 Indian Inst.,  
PNPI Gatchina,

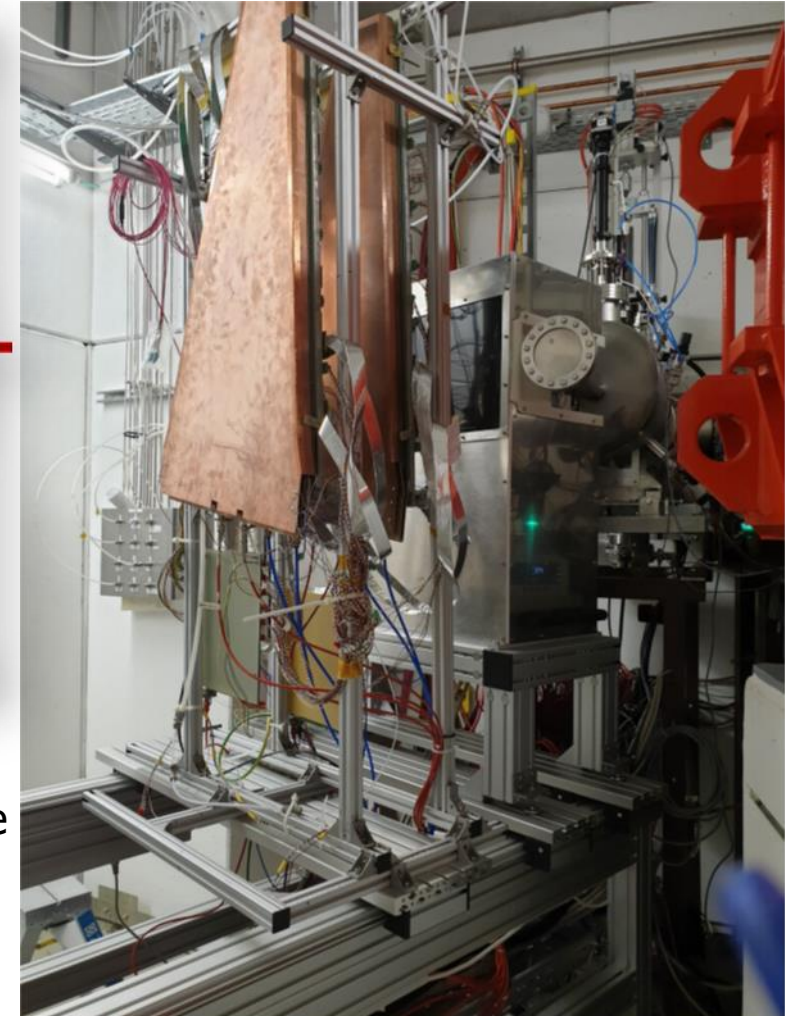


## MuCh at SIS100:

- 2 GEM triplets, 2 tracking detector triplets, TRD
- Bakelite RPCs under investigation for stations 3 and 4.
- High rate (kHz) operation requires low resistivity Bakelite

## **Status:**

- TDR approved in Feb. 2015
- Full size prototype GEM detectors build at VECC and under test in mCBM
- The GBTx emulator was implemented and tested.
- mainframe and absorbers and under construction at PNPI

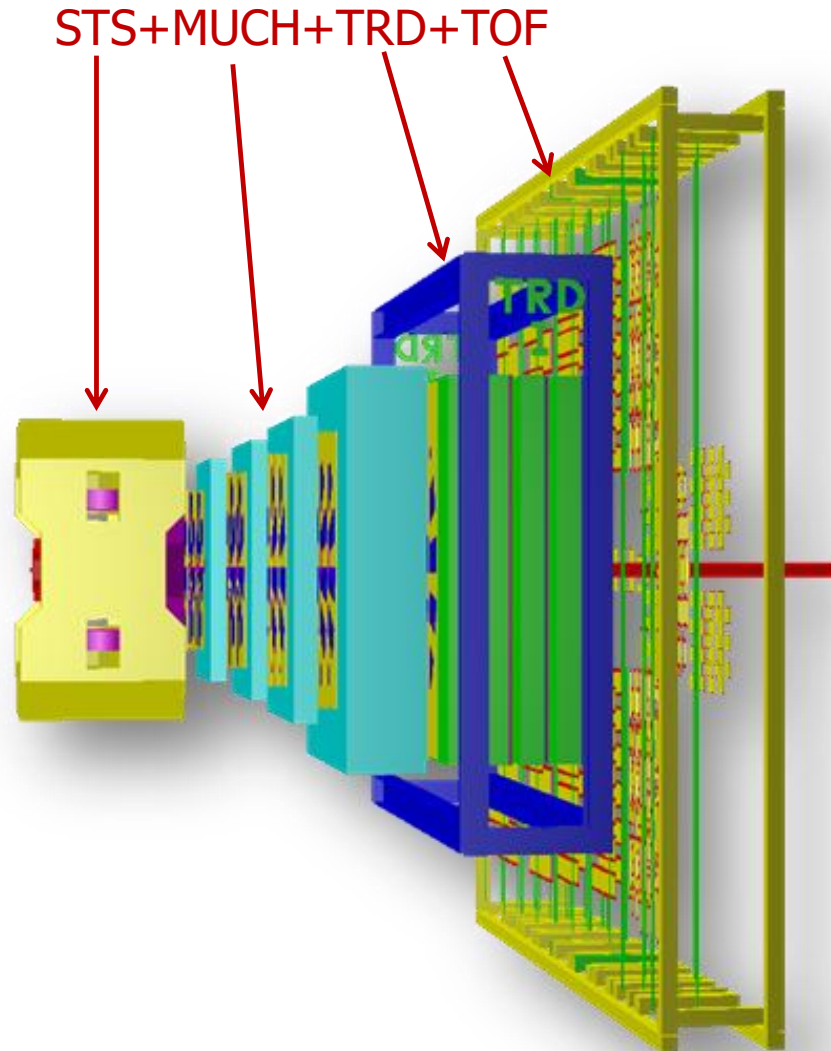


Full size GEM detectors tested with free-streaming read-out electronics in the mCBM setup at GSI 2019



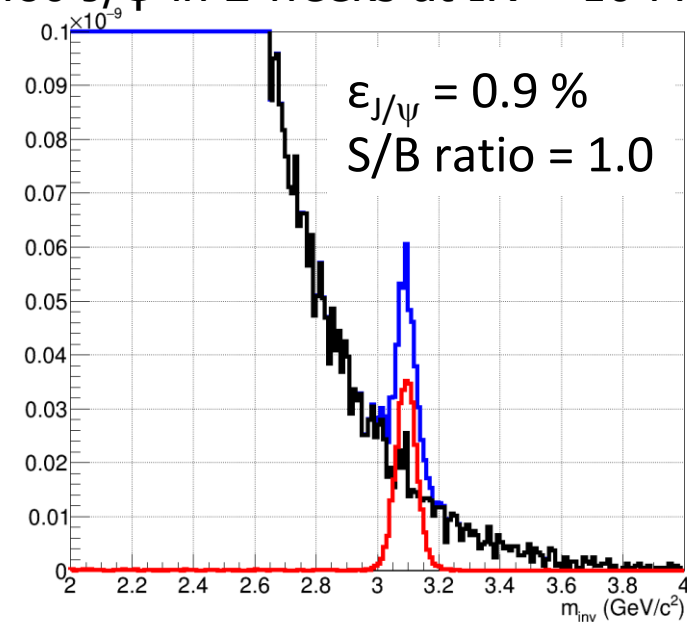
# Charmonium

## for central Au+Au collisions at 10A GeV



*Sub-threshold charm production in nuclear collisions J.*  
Steinheimer, A. Botvina, M. Bleicher arXiv:1605.03439

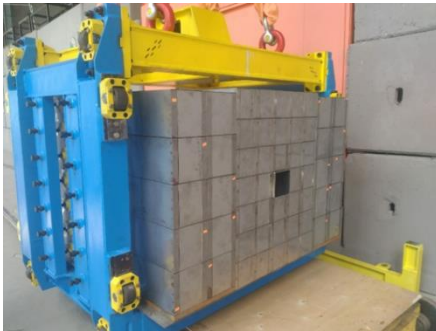
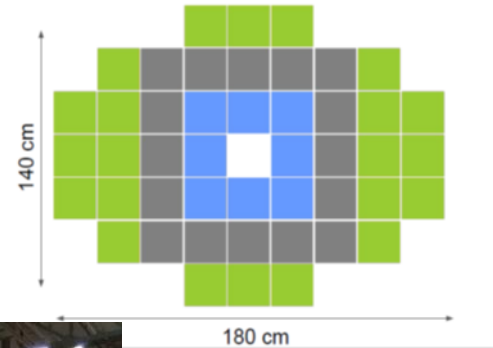
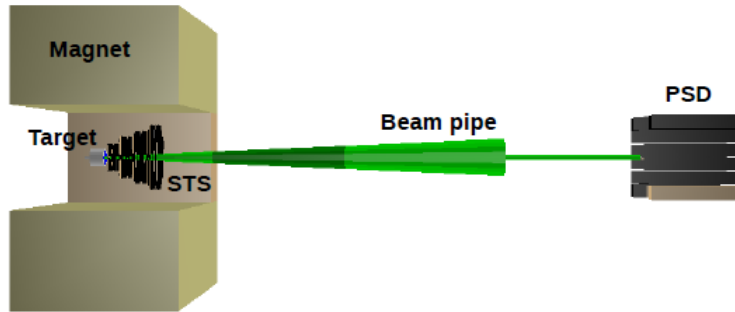
6480 J/ $\psi$  in 2 weeks at IR = 10 MHz



# Projectile Spectator Detector

- determination of collision centrality and orientation of the reaction plane

In-kind contributions by Russia, Czech Rep.: INR Moscow, TU Darmstadt, Rez Prague



PSD at  
BM@N JINR  
20 modules.  
June 2019



PSD at  
NA61 CERN SPS.  
13 modules.  
April 2019



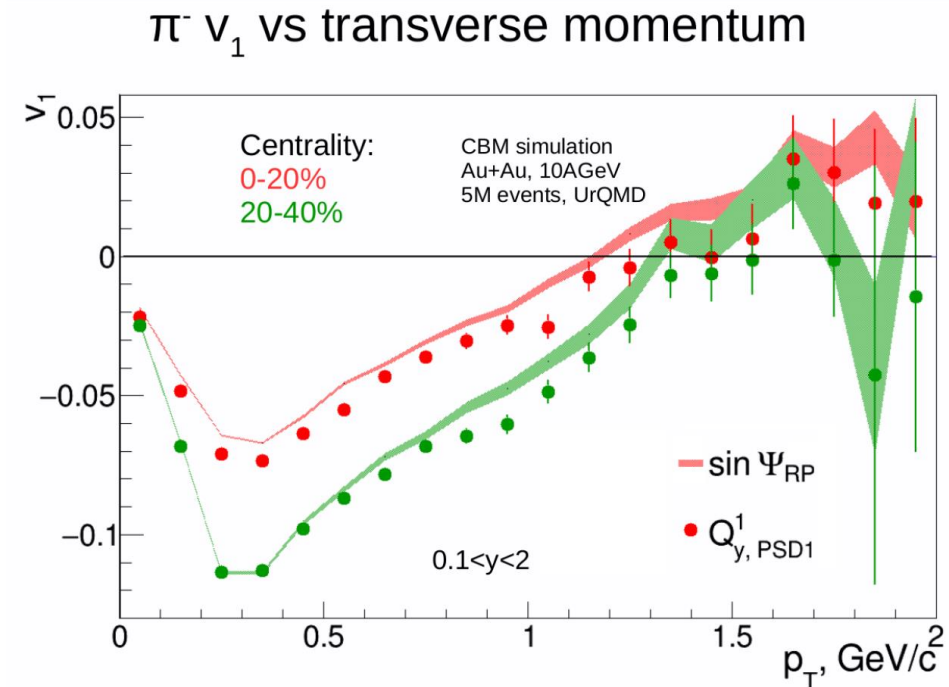
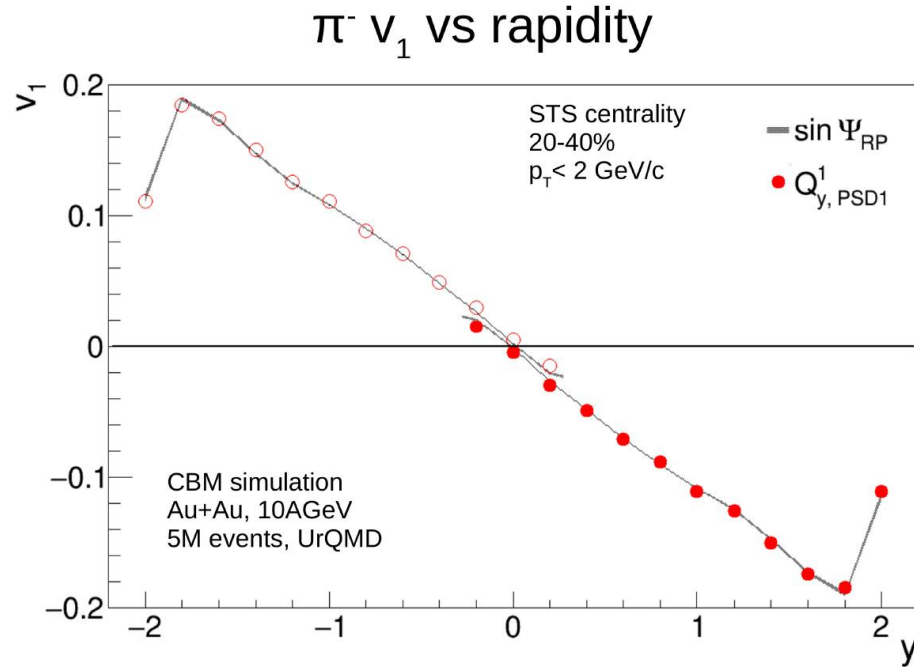
PSD at  
mCBM GSI.  
1 module.  
April 2019

## Status:

- TDR approved Feb. 2015;
- At present, all 44 PSD CBM modules have been fully assembled at INR, Moscow;
- Prototype of the PSD readout electronics based on PANDA ECAL sampling ADC is tested and integrated for mPSD readout at mCBM;
- PSD modules tested with cosmic rays at INR Moscow and with hadron beams at CERN
- Most of the PSD CBM modules have been already integrated in the BM@N, NA61 and mCBM experiments and will be used during FAIR-Phase-0;
- Reconstruction algorithms for the reaction plane and centrality determination were developed

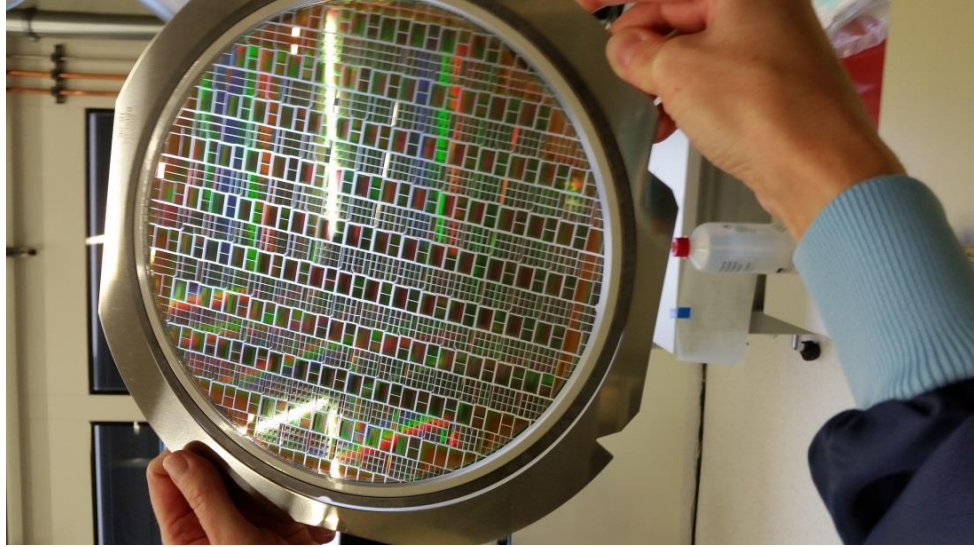
# Projectile Spectator Detector

Reconstructed directed flow of  $\pi^-$  in Au+Au collisions at 10 A GeV



# Successful Multi Project Chip Prototyping for CBM

In-kind contributions by Germany, Poland: GSI Darmstadt, Univ. Heidelberg, AGH Krakow

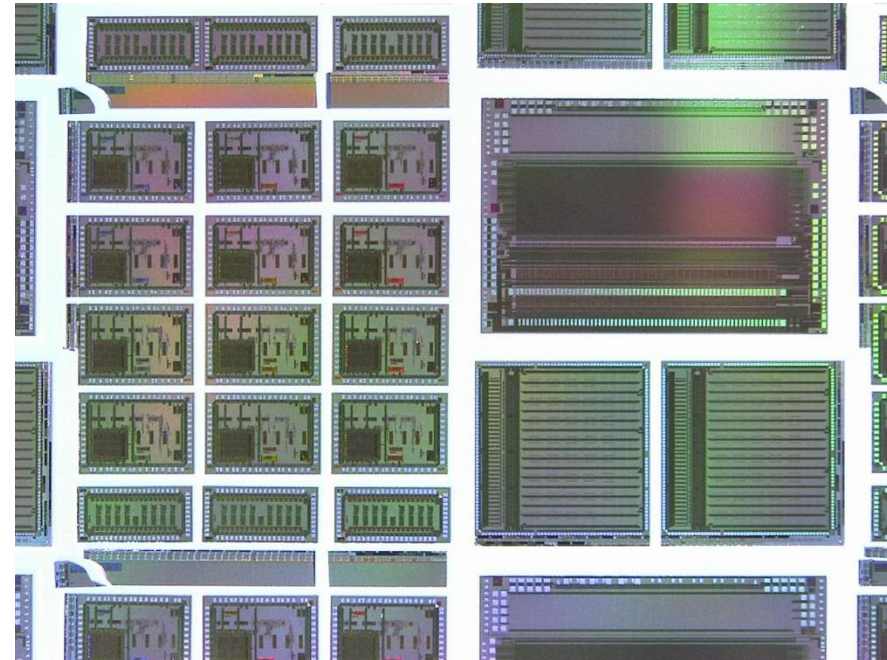


## 5 final prototype chips for CBM:

- STS-XYTER and Much-XYTER
- Get4 in two versions for TOF
- PADI production for CBM@STAR
- SPADIC for CBM-TRD

## Produced Chips:

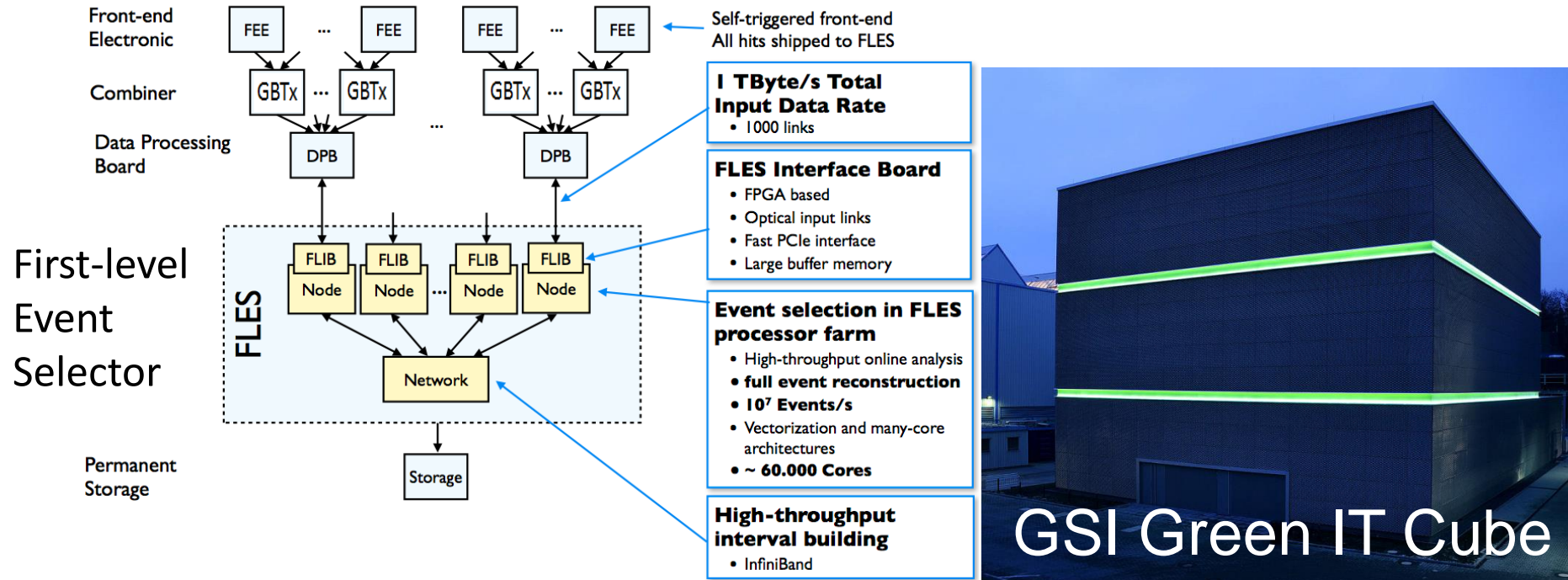
- Several thousand STS-XYTER and MUCH-XYTER Chips for detector prototyping
- Full number of PADI Chips needed for CBM-Tof at STAR
- Full number of Get4 TDC chips needed for CBM-Tof at STAR
- Full number of SPADIC Chips for CBM-TRD





# CBM online systems

In-kind contributions by Germany, Poland, India:  
Univ. Frankfurt, FIAS, GSI Darmstadt, KIT Karlsruhe, IIT Kharagpur, Warsaw UT



Novel readout system: no hardware trigger on events, detector hits with time stamps, full online 4-D track and event reconstruction.

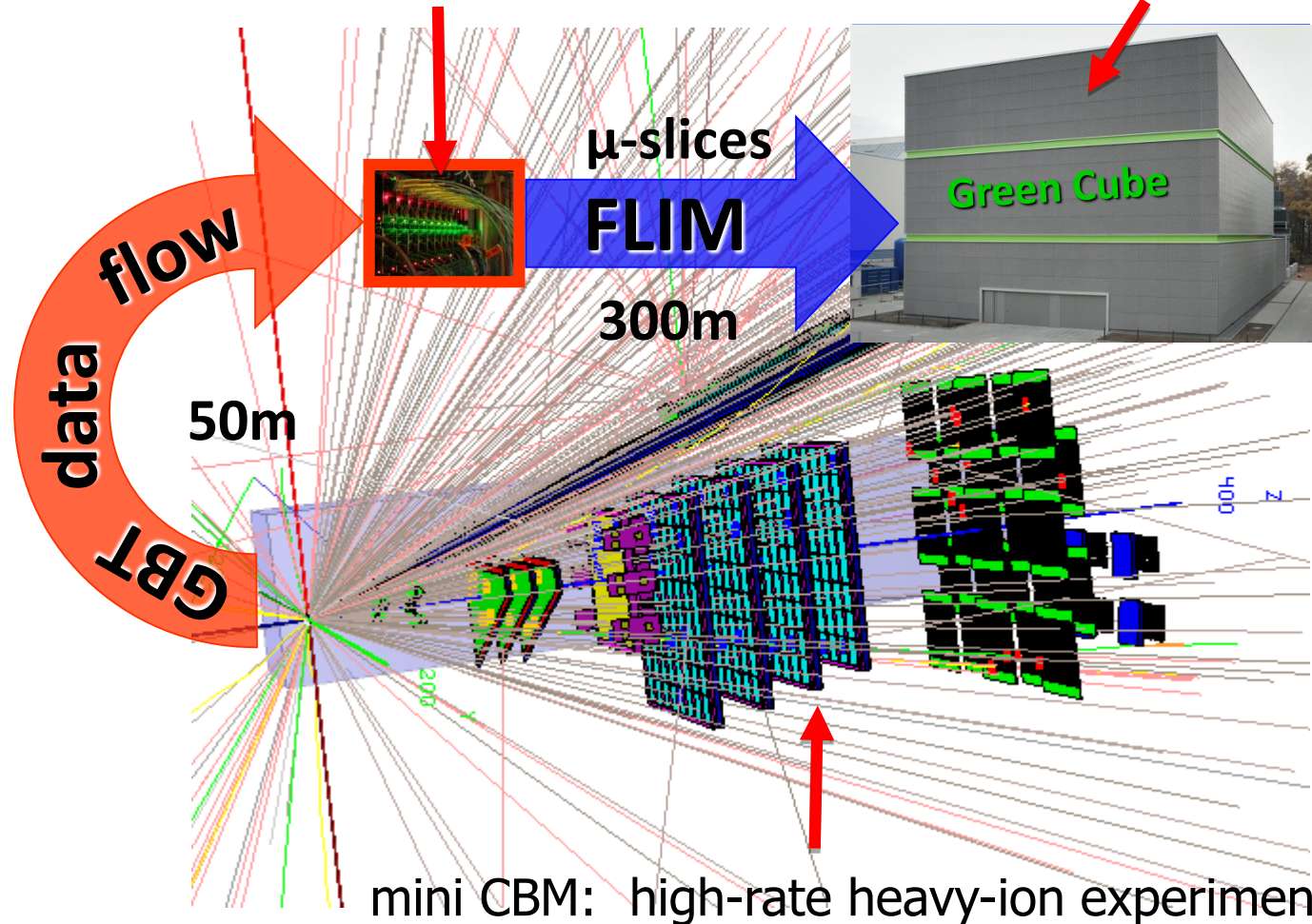
## Status:

- FLES input interface designed
- FLESnet software successfully applied in beam tests with detectors
- TDRs on DAQ, FLES

# mCBM DAQ

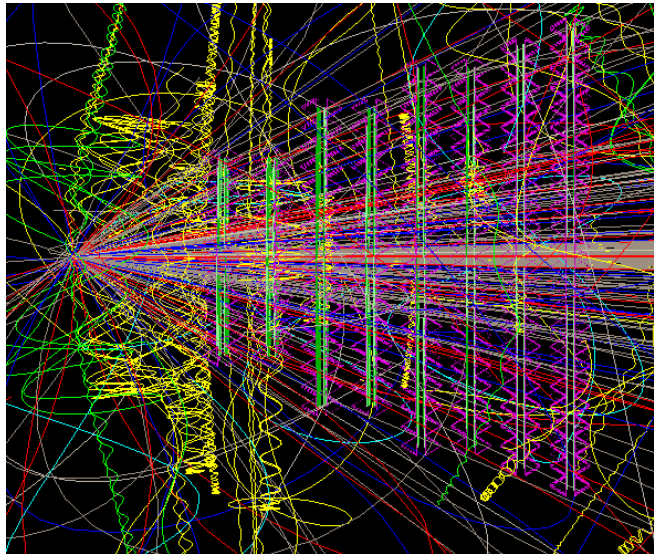
mCBM DAQ container:  
data pre-processing

Green Cube: online  
timeslice building  
and event selection

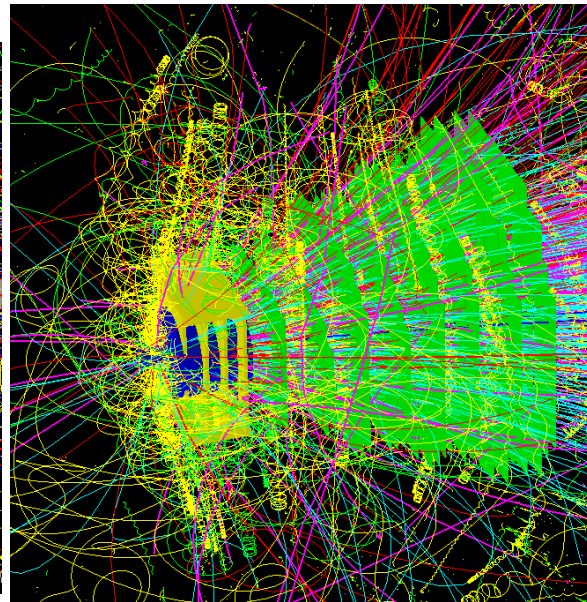


# 4D track and event reconstruction

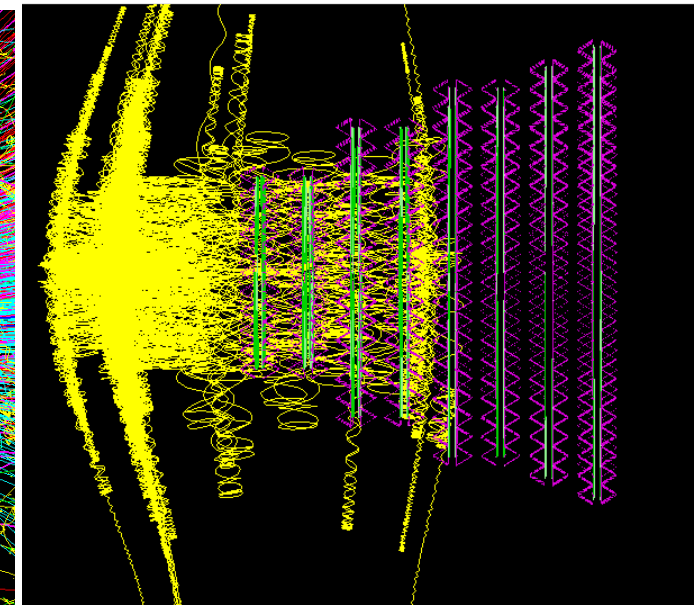
Au+Au 8 A GeV  
peripheral collision  
UrQMD + GEANT3



Au+Au 8 A GeV  
central collision  
UrQMD + GEANT3

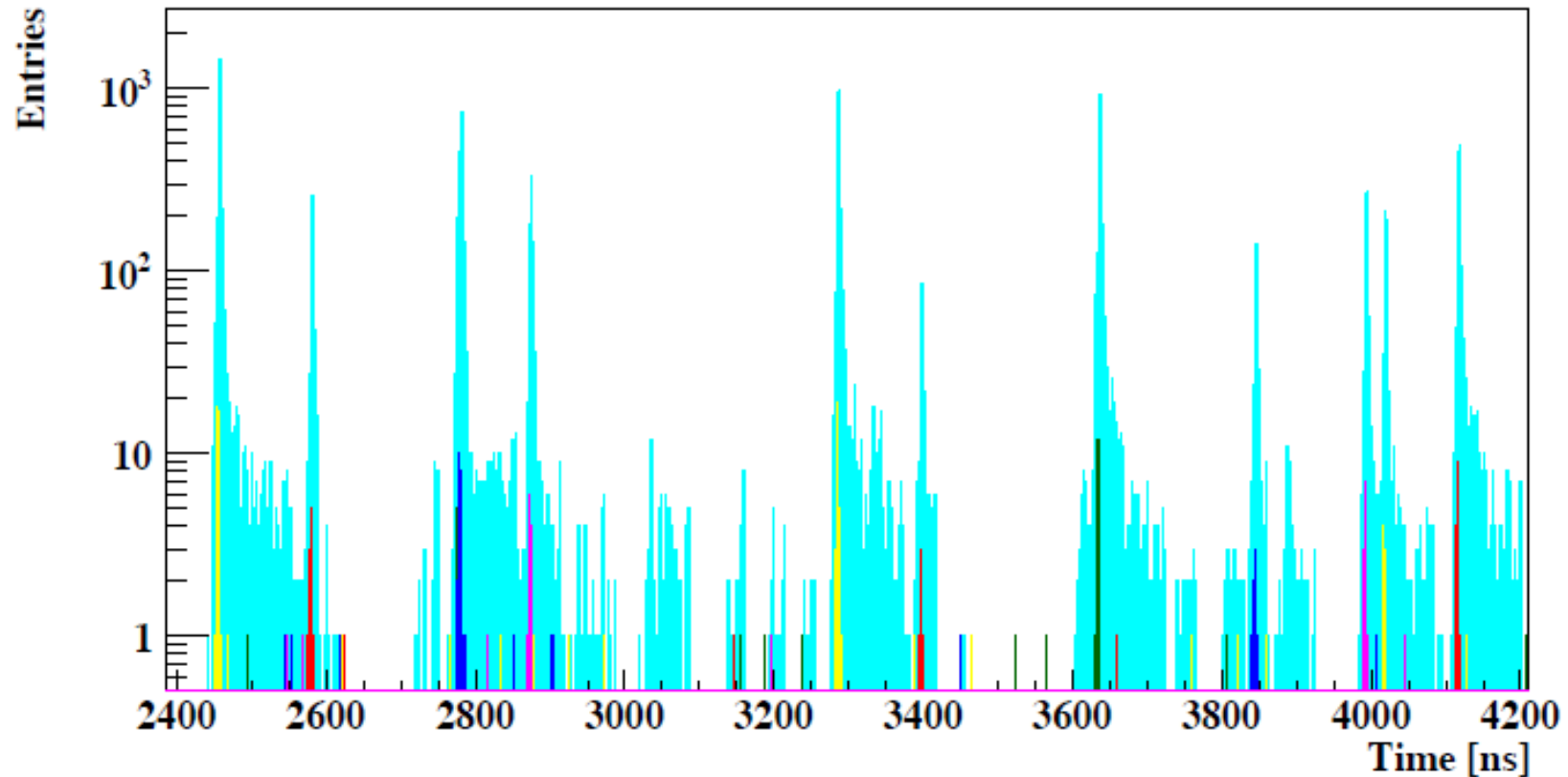


Au beam 8 A GeV  
one single ion  
passing the target  
FairIon + GEANT3



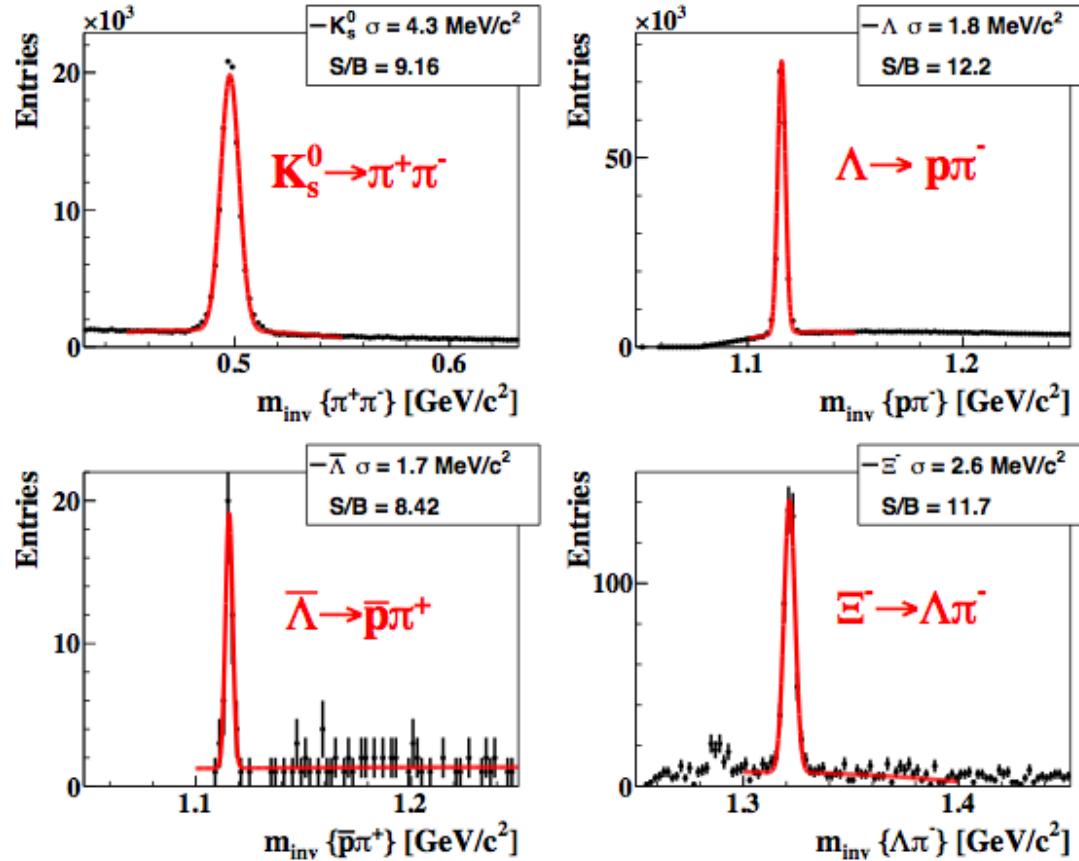
# 4D track and event reconstruction

Hit and track time distribution for  
Au+Au 10 AGeV mbias events at 10 MHz (UrQMD)



# 4D reconstruction

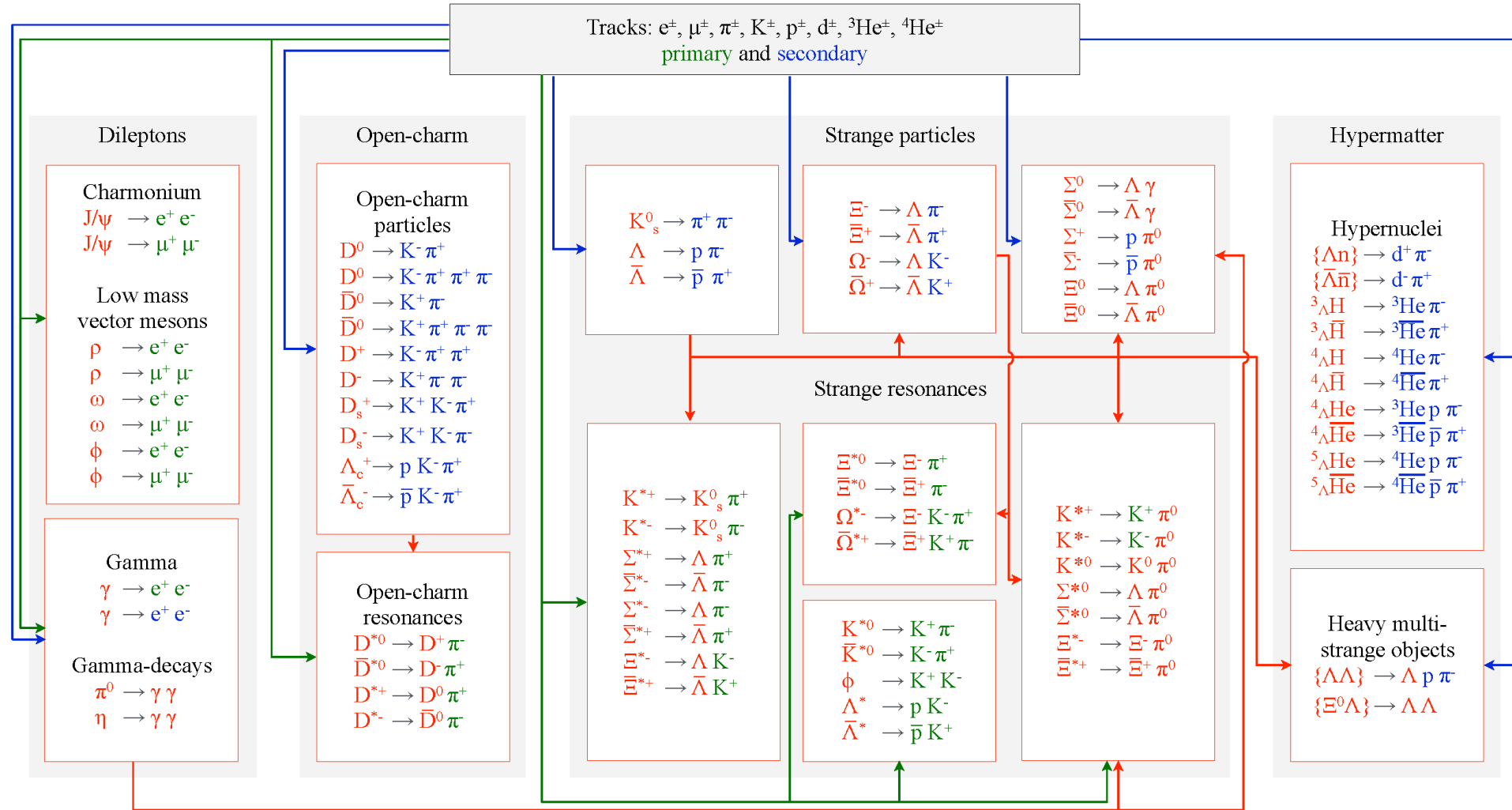
10 MHz Au+Au, 10 AGeV,  
300k mbias UrQMD events, ideal PID



		$K^0_s$	$\Lambda$	$\bar{\Lambda}$	$\Xi^-$
3 D	$\epsilon_{\text{method},r} \%$	68.6	61.2	67	46.7
	$\epsilon_{4\pi,r} \%$	20.7	19.4	28	10.5
	S/B	10.6	23.7	12.7	21.8
0.1 MHz	$\epsilon_{\text{method},r} \%$	68.5	62.0	62	45.2
	$\epsilon_{4\pi,r} \%$	21.1	20.6	32	11.7
	S/B	9.8	12.9	10	14.2
1 MHz	$\epsilon_{\text{method},r} \%$	67.5	60.9	59	46.0
	$\epsilon_{4\pi,r} \%$	19.4	18.7	26	10.6
	S/B	9.3	12.5	10	12.3
10 MHz	$\epsilon_{\text{method},r} \%$	66.8	60.0	64	41.8
	$\epsilon_{4\pi,r} \%$	17.6	16.7	28	8.2
	S/B	9.2	12.2	8	11.7

all mother particles emitted from one primary vertex

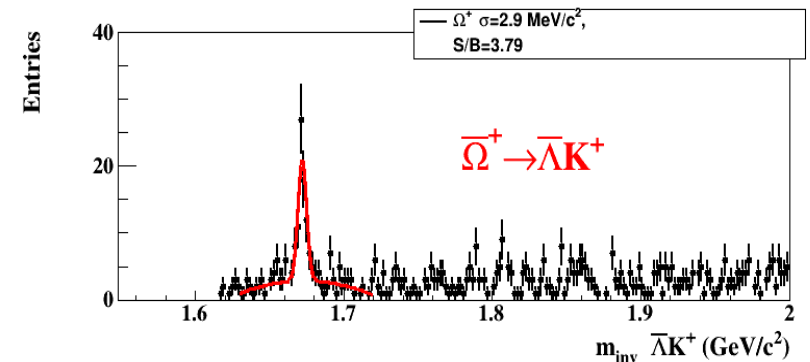
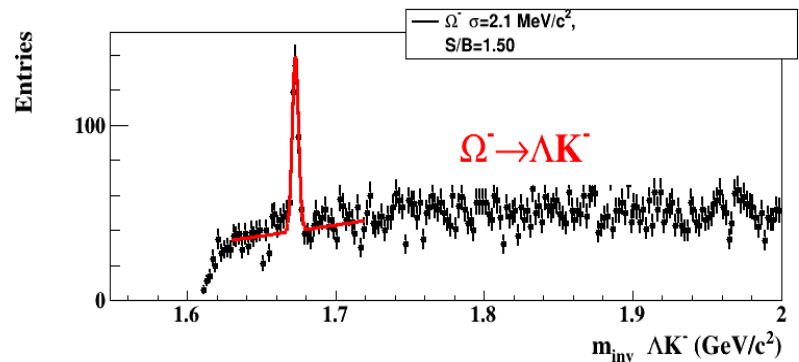
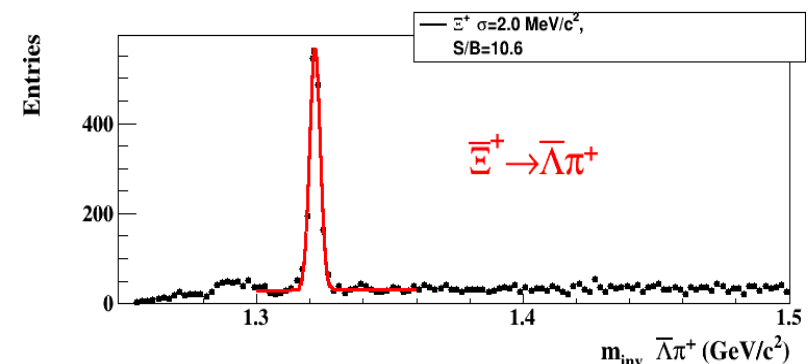
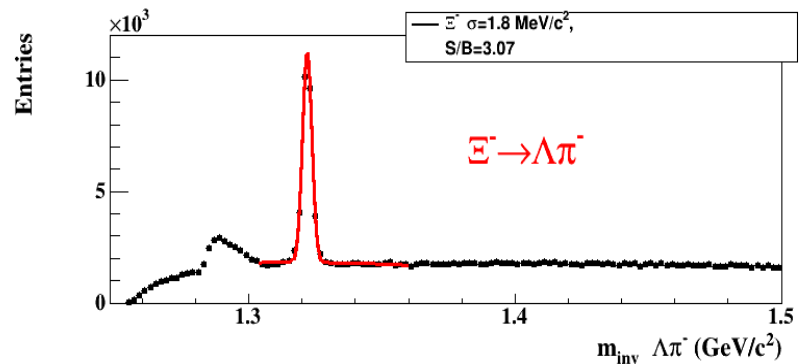
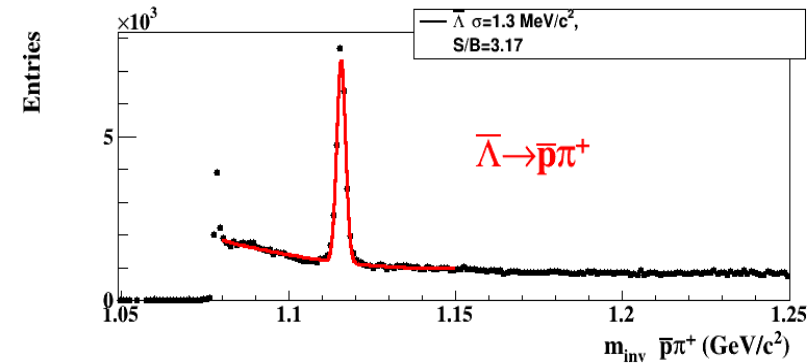
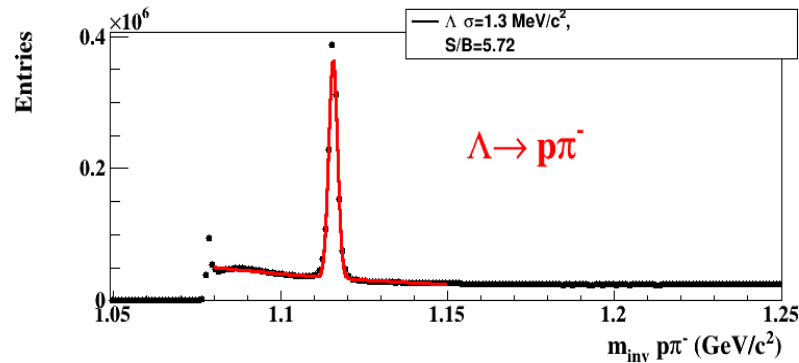
# Titelmasterformat durch Klicken bearbeiten

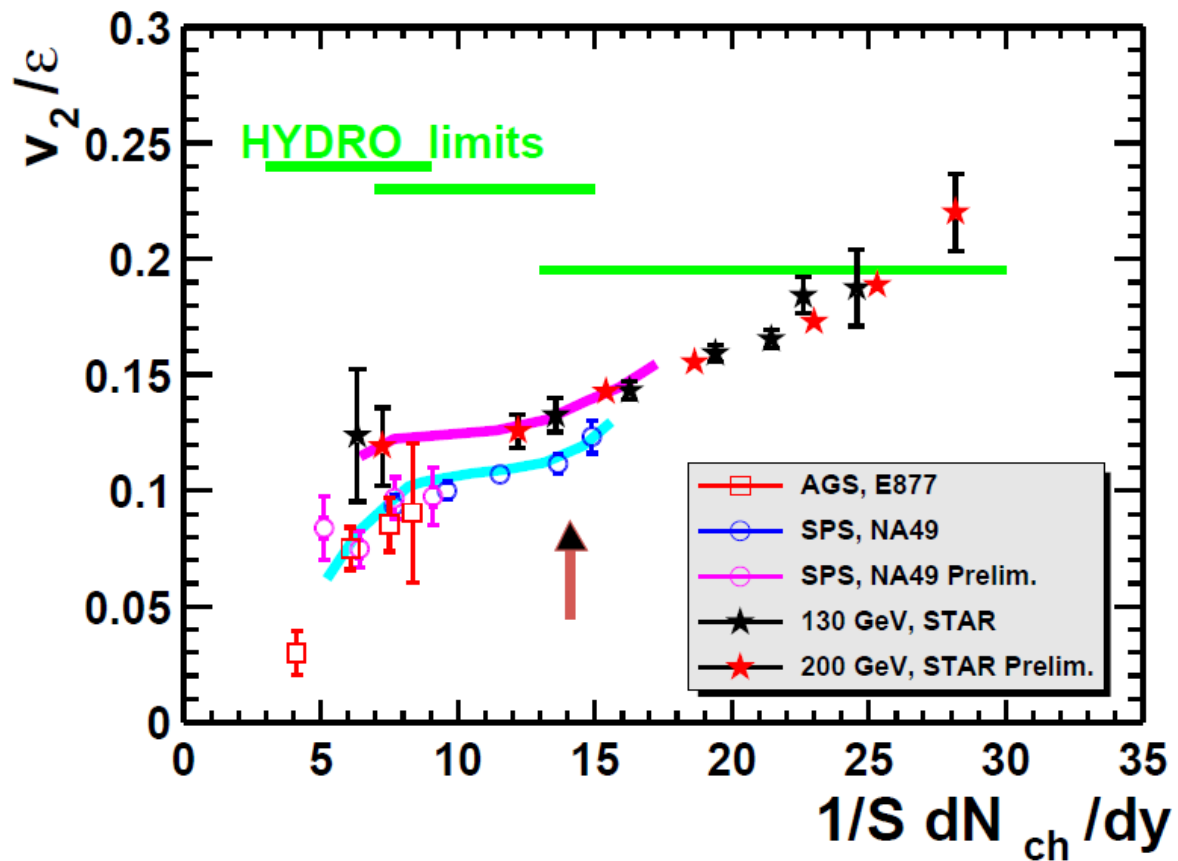


successfully used online in the STAR experiment

# Real data analyzed with CBM KF Particle Finder

## STAR 4.4 M mbias AuAu collisions, $\sqrt{s_{NN}}=7.7$ GeV





What makes 3FD-Hydro so special to be used even at SIS energies, despite being below the HYDRO limits (perfect fluid)?

This indicates the transition from density-driven dynamics with non-vanishing viscosity to the geometry-driven dynamics of almost perfect hydrodynamics. It suggests that at RHIC energies particle densities are already large enough, respectively interaction lengths short enough, for the systems to reach the hydrodynamical limit.