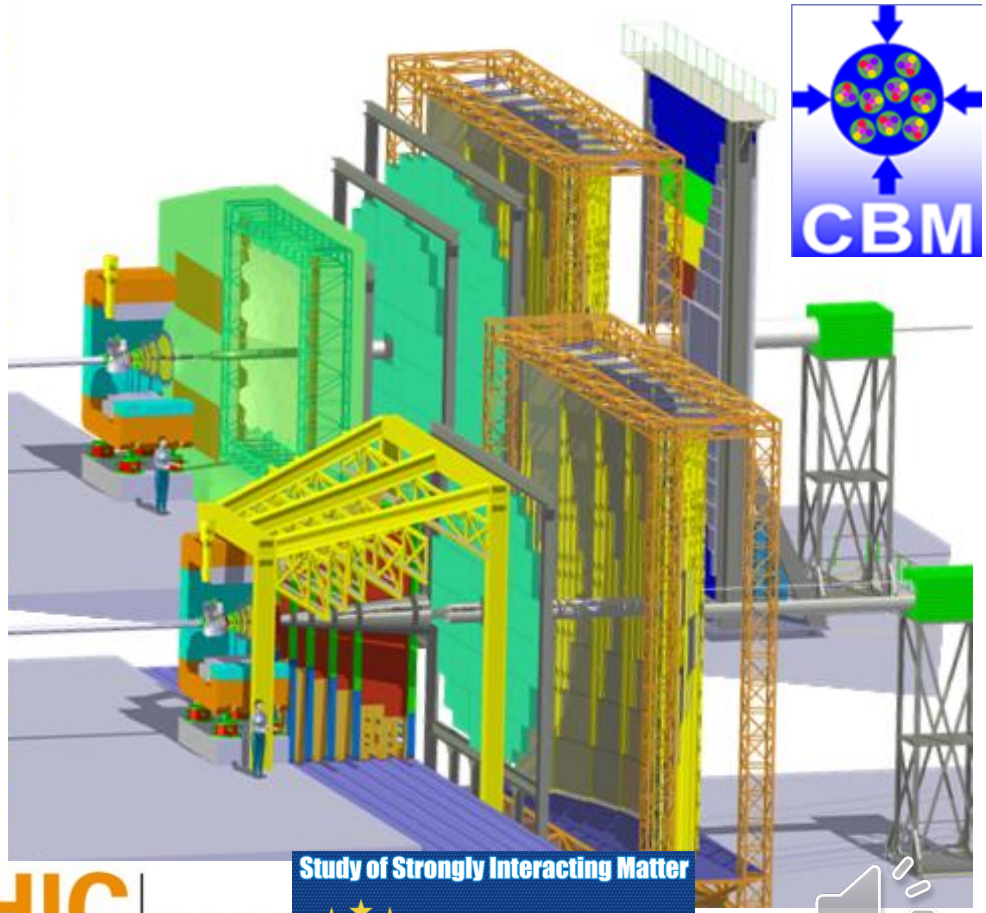
The Compressed Baryonic Matter (CBM) experiment

Selim SEDDIKI – on behalf of the CBM collaboration

Outline:

- Physics goals of CBM at FAIR
- Experimental challenge
- Detector concept and status of preparation



GSI

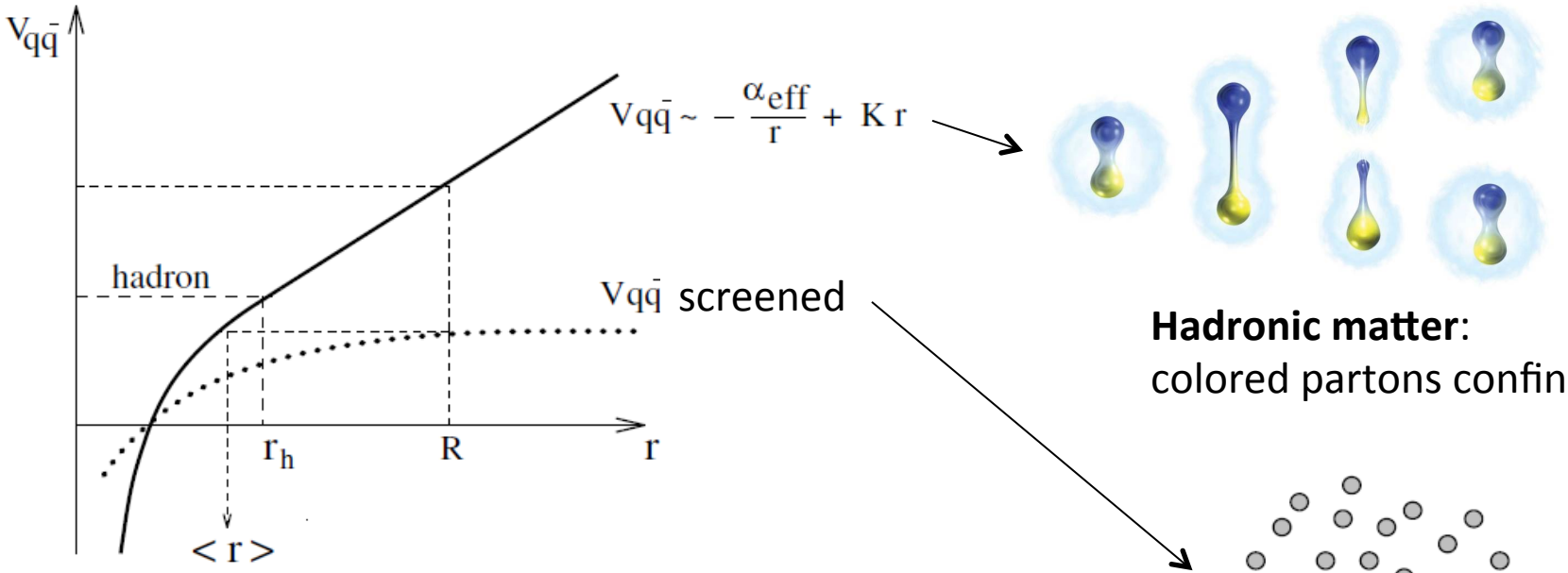
Bundesministerium für Bildung und Forschung

HIC for FAIR
Helmholtz International Center

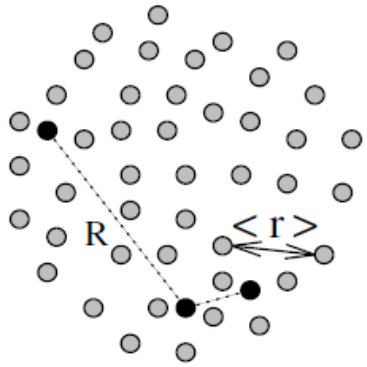
Study of Strongly Interacting Matter
HadronPhysics

Fundamental questions of QCD

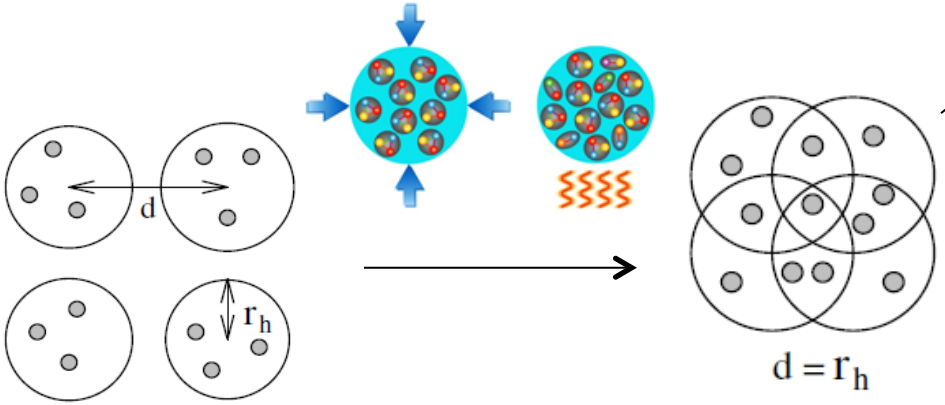
- Mechanism of confinement/deconfinement of colored partons ? -



Hadronic matter:
colored partons confined



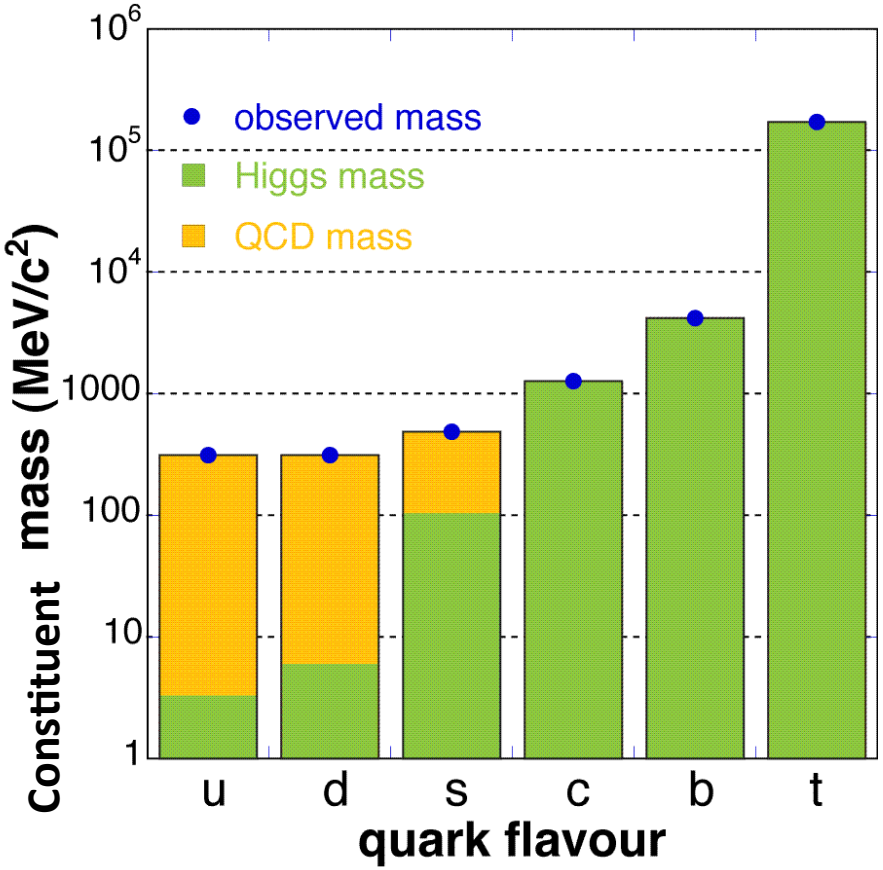
Idea:



Quark Gluon Plasma (QGP):
colored partons = effective d.o.f. at large distances

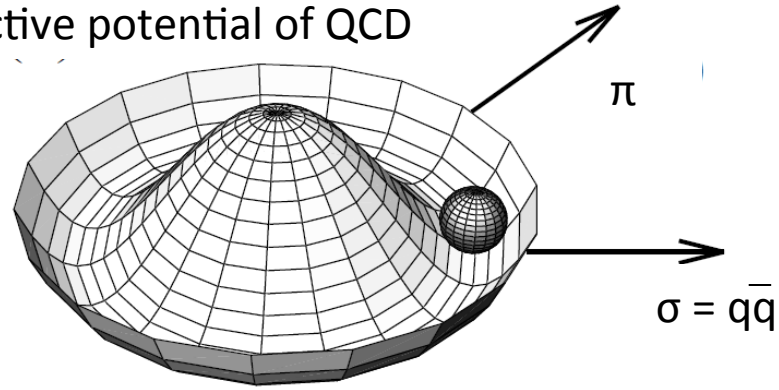
Fundamental questions of QCD

- Generation of the mass of most of the visible universe ? -



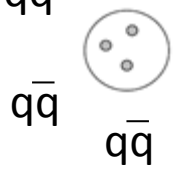
Idea: **spontaneous breaking of chiral symmetry**

Effective potential of QCD



QCD lagrangian symmetric but not ground state!
→ condensation of $q\bar{q}$ pairs in QCD vacuum

In simple σ -model: $M_{nucleon} \sim \langle\sigma\rangle$
V. Koch, Int. J. Mod. Phys. E6, 203-250 (1997)

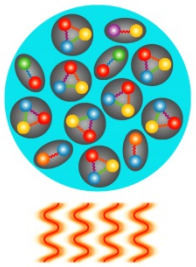


Constituent mass of quarks dynamically generated through iteractions with σ field

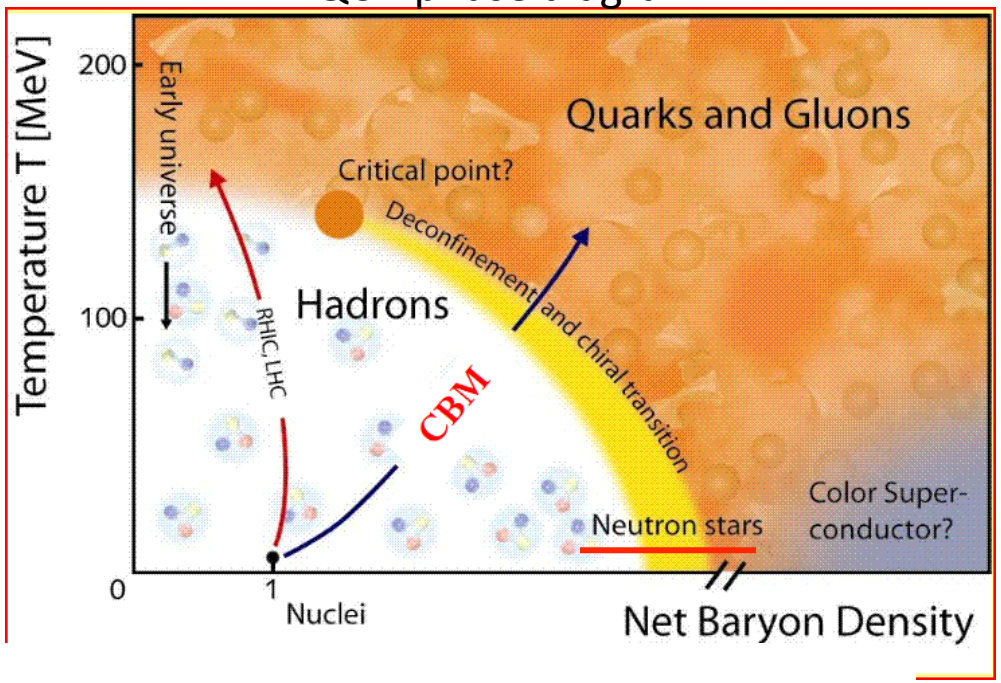
Fundamental questions of QCD

- Properties and degrees-of-freedom of nuclear matter under extreme conditions ? -

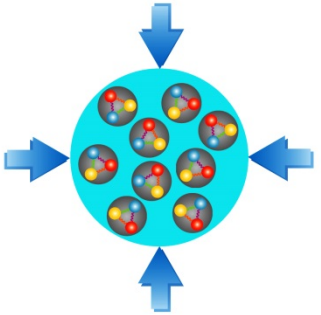
very high T



QCD phase diagram



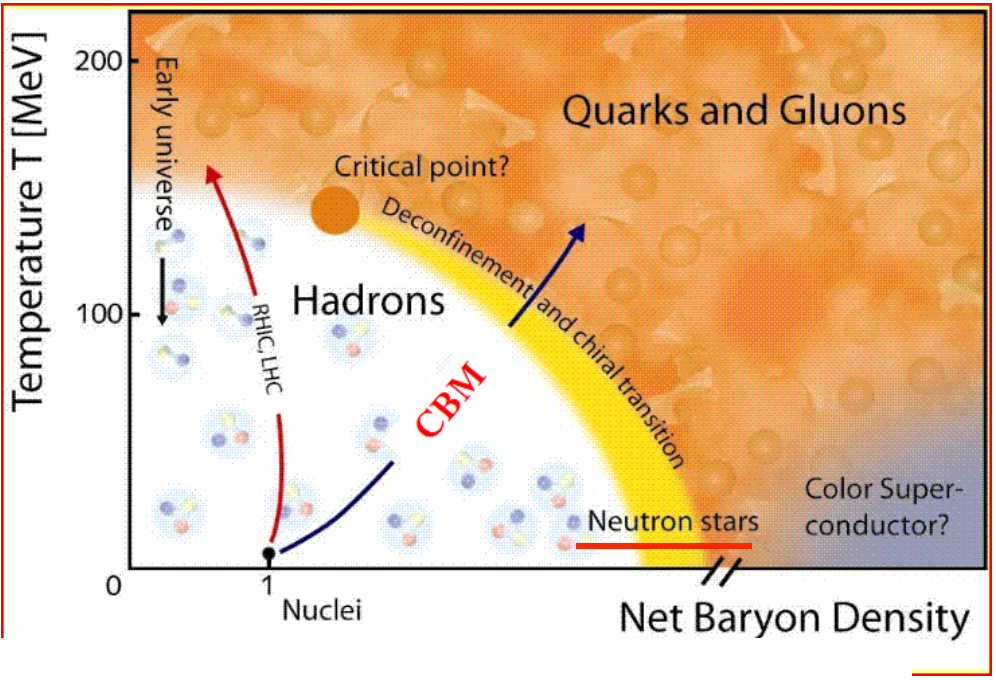
very high density



LHC & top RHIC energies → probe matter existing a few µs after Big Bang

Beam energy scan @ RHIC, NA61 @ CERN-SPS, **CBM @ FAIR**, MPD @ NICA
→ probe matter at **neutron star core densities**

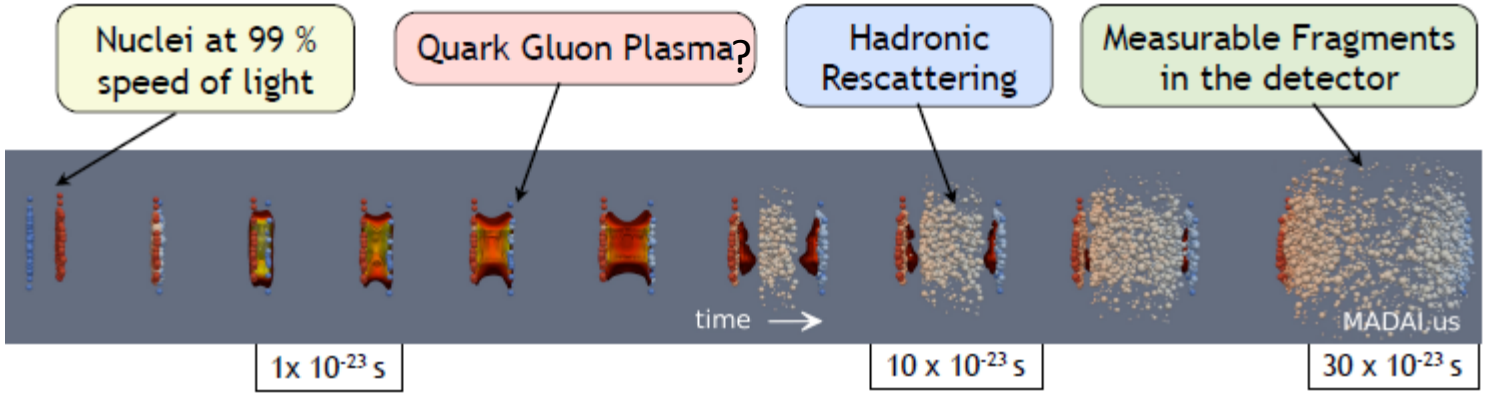
CBM goal: explore the QCD phase diagram at high net baryon density (ρ_B)



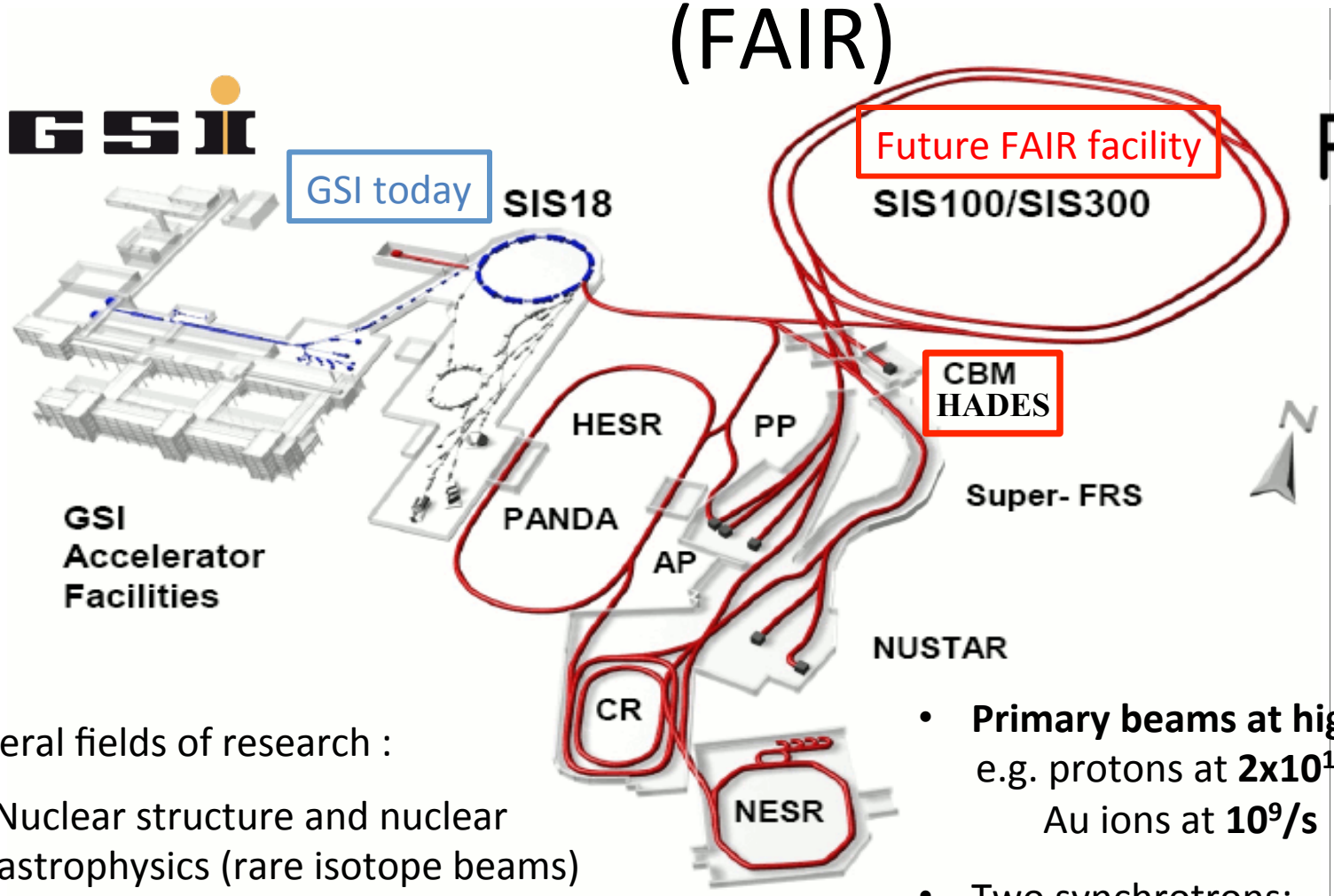
Key questions:

- **Phase Transition** (PT) **to a QGP at high ρ_B** & its nature? (predicted **1st order PT**)
- Existence & location of **QCD critical point?**
- Modification of hadron properties in dense matter? Connection to a **chiral PT**?
- **Properties of nuclear matter at high ρ_B ?** (EoS, transport properties, etc)
- **Exotic states of nuclear matter?**

By means of **heavy ion collisions**



The Facility for Anti-proton & Ion Research (FAIR)



Several fields of research :

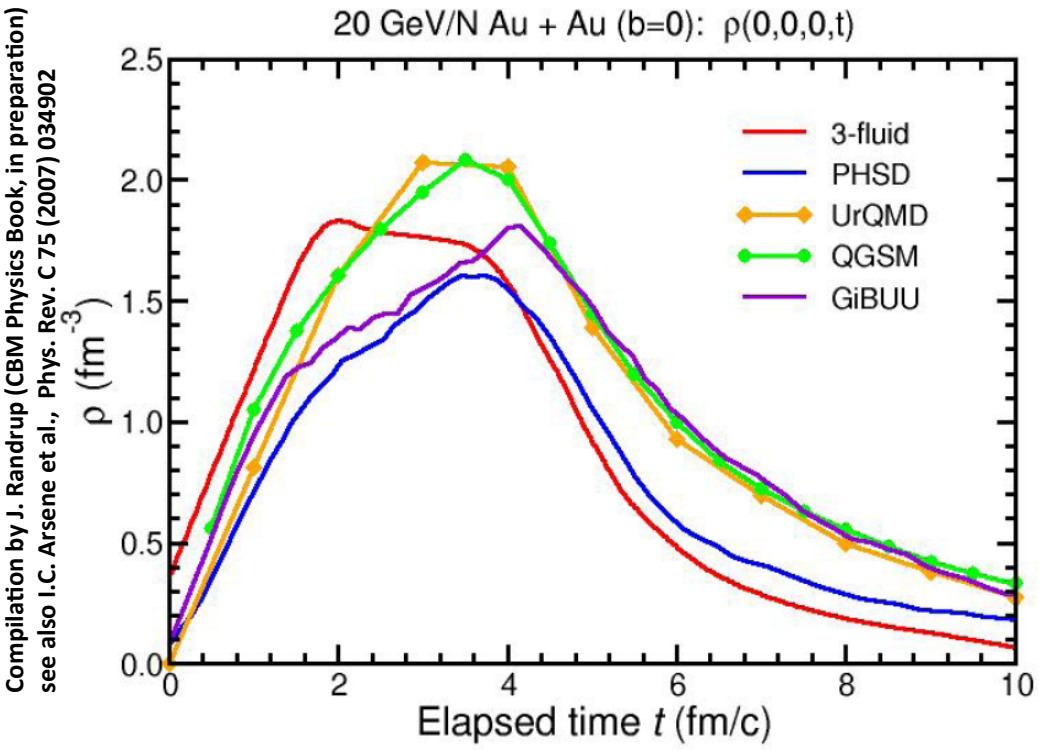
- Nuclear structure and nuclear astrophysics (rare isotope beams)
- Hadron physics (antiproton beams)
- **High energy heavy-ion collisions (CBM)**
- Physics of dense plasmas
- Atomic physics
- Accelerator physics

- **Primary beams at high intensities**
  e.g. protons at **2×10^{13}/s**
  Au ions at **10^{9}/s**
- Two synchrotrons:

Beam energy [AGeV]	Heavy ions	Protons
SIS100 (1st meas.: 2019)	**up to 11**	**up to 30**
SIS300 (>2019)	**up to 45**	**up to 90**

Fireball conditions in A+A at FAIR energies

Broad energy range for heavy-ions at FAIR
(e.g. for Au ions: 2 → 35 AGeV)
→ **Maximum net baryon densities (ρ_{max}) achievable in heavy ion collisions**



Compilation by J. Randrup (CBM Physics Book, in preparation)
see also I.C. Arsene et al., Phys. Rev. C 75 (2007) 034902

Net baryon density (ρ) = f(t)
in the core of central Au+Au:
Remarkable agreement between various transport (& hydro.) models

At the early stage & in the core of central Au+Au from 5 - 35 AGeV:
→ **ρ_{max} ~ (6–12) ρ_0**

CBM at FAIR: a high rate experiment

Experiment	A+A reaction rate [Hz]
STAR@RHIC (BNL)	1 (low $\sqrt{s_{NN}}$) – 800 (limited by **luminosity**)
NA61@SPS (CERN)	80 (limited by **detector**)
MPD@NICA (INR)	~ 1000 (limited by **luminosity**)
CBM@FAIR (GSI)	10^5 – 10^7 (limited by **detector**)

- **Designed operation in CBM: collision rate up to 10 MHz**

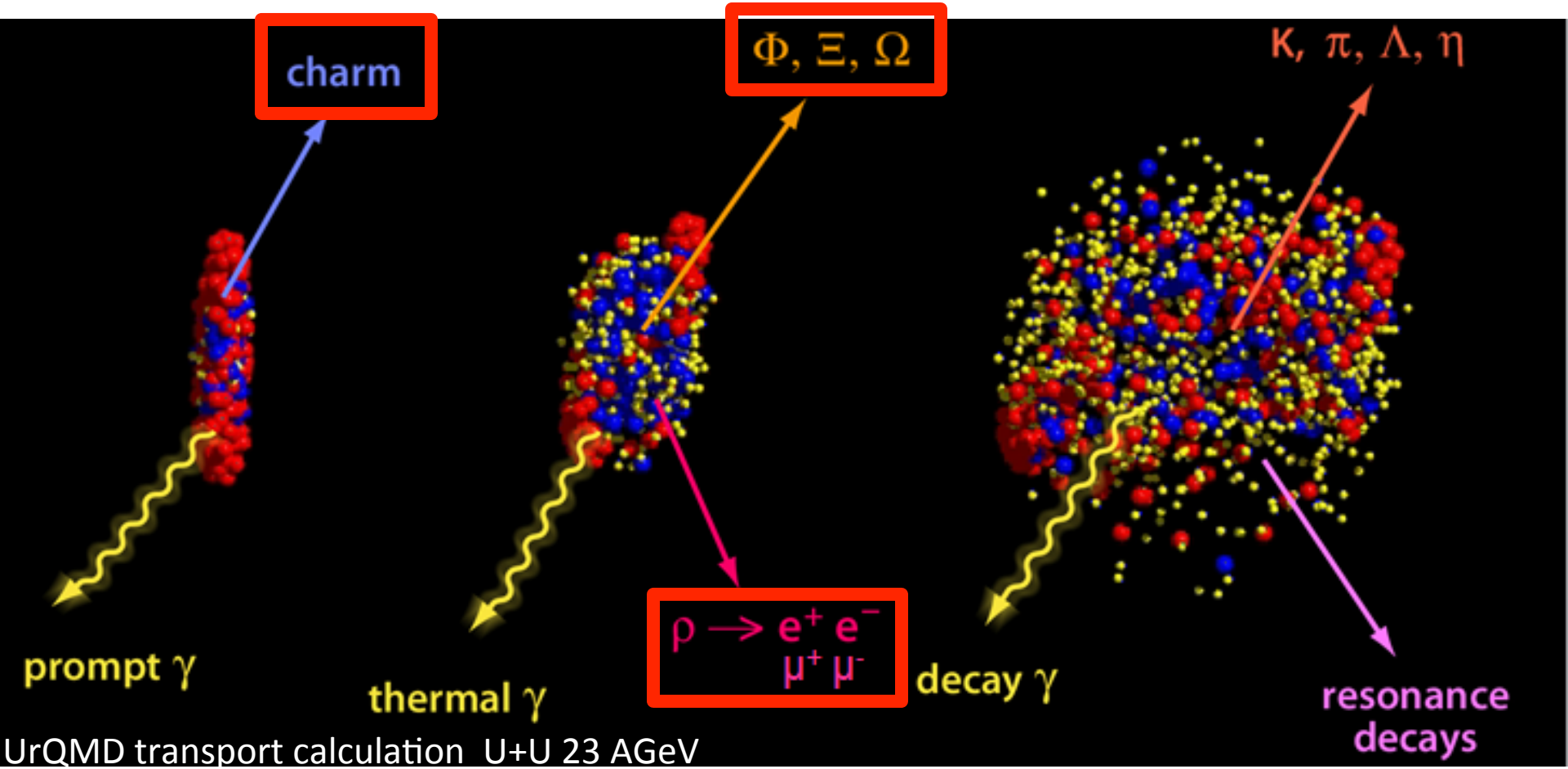
  → **Strong constraints on read-out speed & radiation tolerance of the detector**

- **Parallel operation of several (up to 5) experiments at FAIR**
  (~ 4 months/year H.I. beams)

High collision rates and high beam availability
→ Detailed measurements, **including rare probes**
(e.g. charmonium, open charm, light vector mesons decaying into lepton pairs)

No measurement in heavy ion collisions at FAIR energies

Rare and penetrating probes



Initial stage High density phase freeze-out

More sensitive to the early & dense phase of A+A reactions

(e.g. formation time of $c\bar{c}$ quarks $\sim 1 / 2m_c \leq 0.1$ fm/c)

CBM physics topics and observables

Onset of deconfinement phase transition at high net baryon density (ρ_B)

- Excitation function and flow of strangeness (K, Λ, Σ, Ξ, Ω, ϕ)
- Excitation function and flow of charm (J/ψ, ψ', $D^{+/-}$, D^0, Λ_c)

Equation of state of nuclear matter at high ρ_B

- Particle production at threshold energies (strangeness @ SIS100, charm @ SIS300)
- Collective flow of hadrons (including strangeness & charm)

Existence & location of QCD critical point

- Excitation function of event-by-event particle yield & yield ratio fluctuations

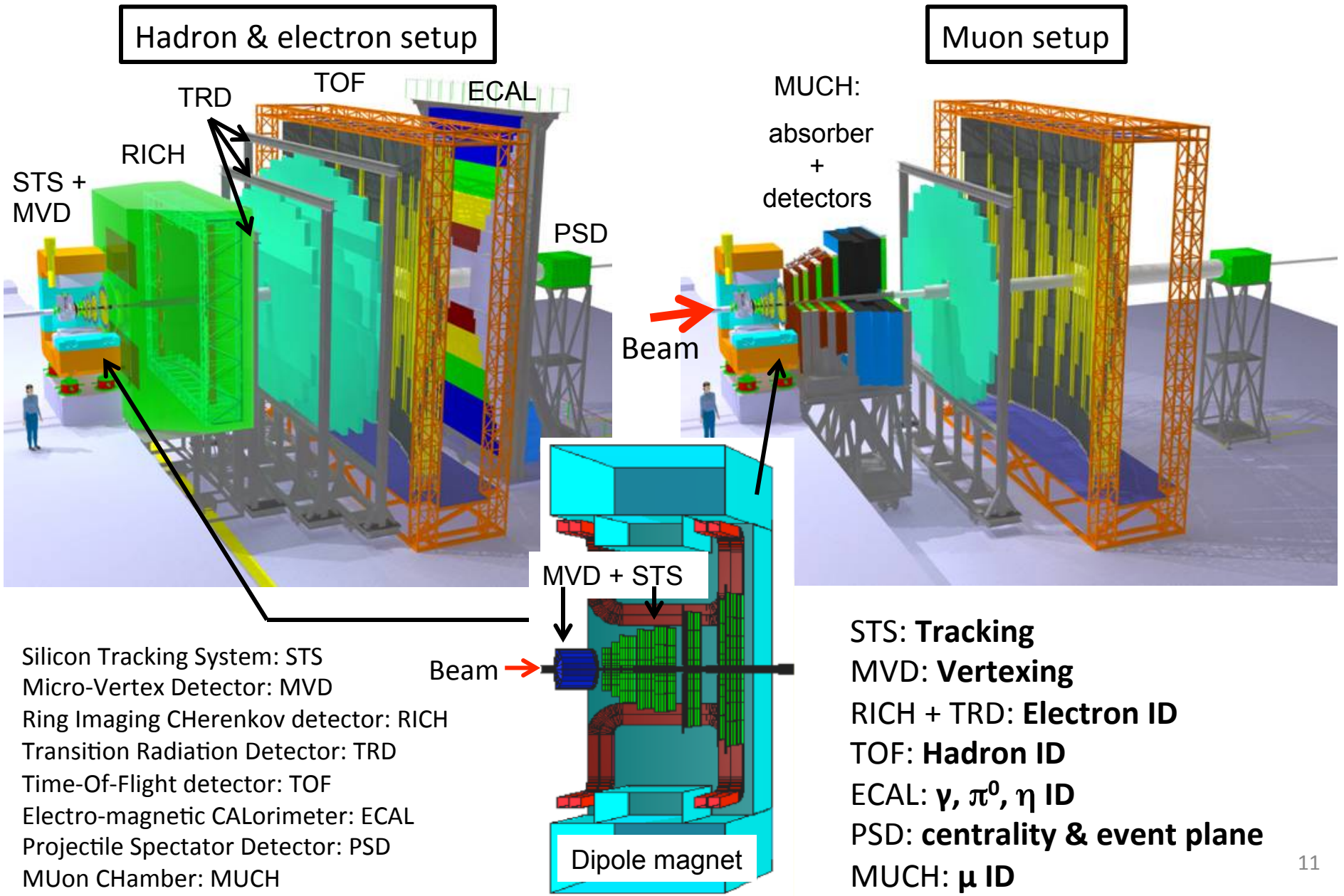
In-medium modifications of hadron properties (chiral symmetry restoration)

- Open charm (D-mesons) yields & m_T-spectra
- Spectral function of light vector mesons (ρ, ω, ϕ)

Experimental task:
High statistics and **accurate** measurements of all these observables:
A+A collisions from 2 to 45 GeV (small steps), p+p & p+A collisions up to 90 GeV
→ Search for **discontinuities** in energy or system size dependences

Channels: open charm & strangeness weak decay into **charged hadrons**
charmonium & light vector meson decay into **lepton pairs (both e^+e^- & $\mu^+\mu^-$)**

CBM experimental setup

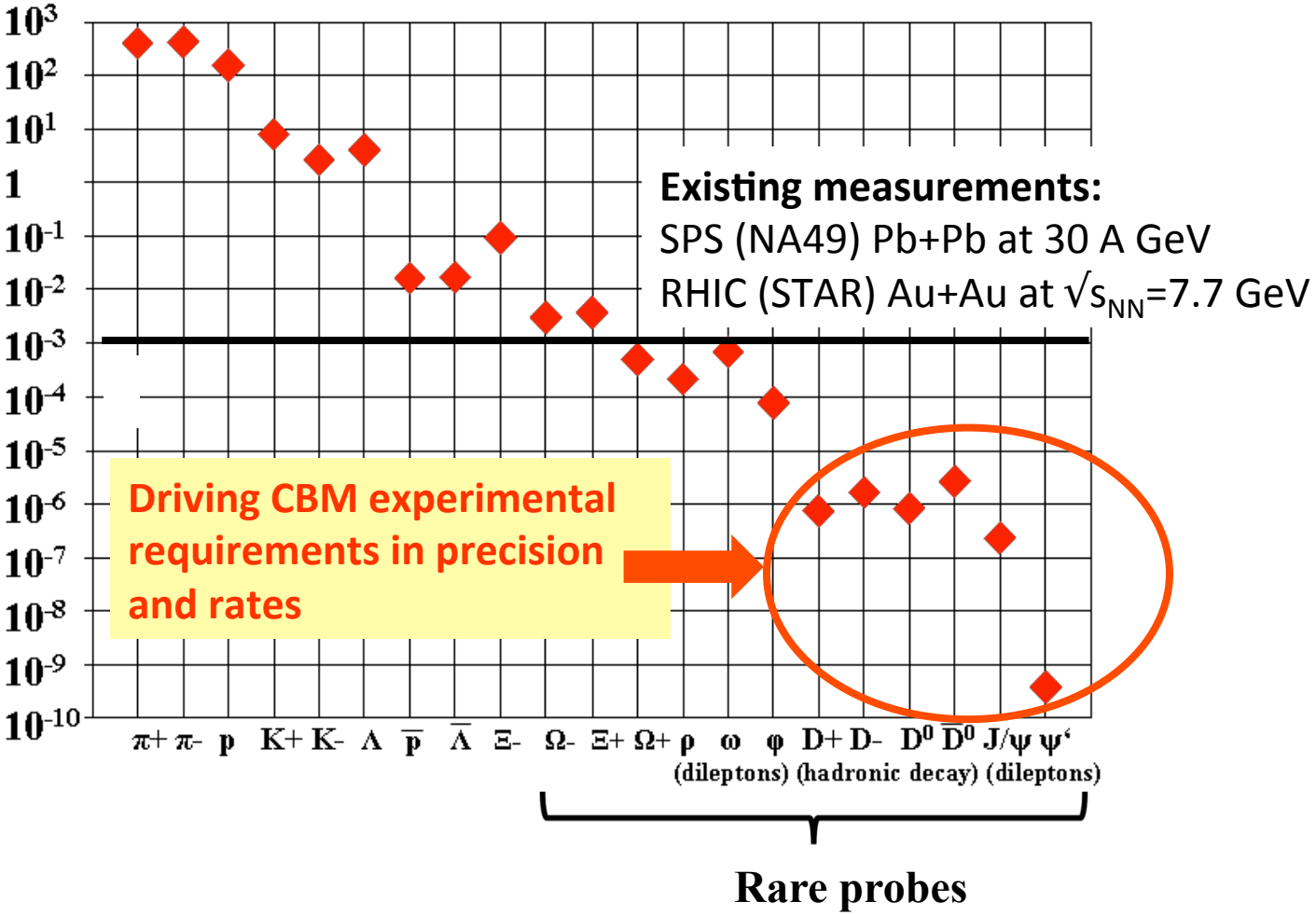


Silicon Tracking System: STS
Micro-Vertex Detector: MVD
Ring Imaging CHerenkov detector: RICH
Transition Radiation Detector: TRD
Time-Of-Flight detector: TOF
Electro-magnetic CALorimeter: ECAL
Projectile Spectator Detector: PSD
MUon CHamber: MUCH

STS: **Tracking**
MVD: **Vertexing**
RICH + TRD: **Electron ID**
TOF: **Hadron ID**
ECAL: **γ, π^0, η ID**
PSD: **centrality & event plane**
MUCH: **μ ID**

CBM experimental challenge

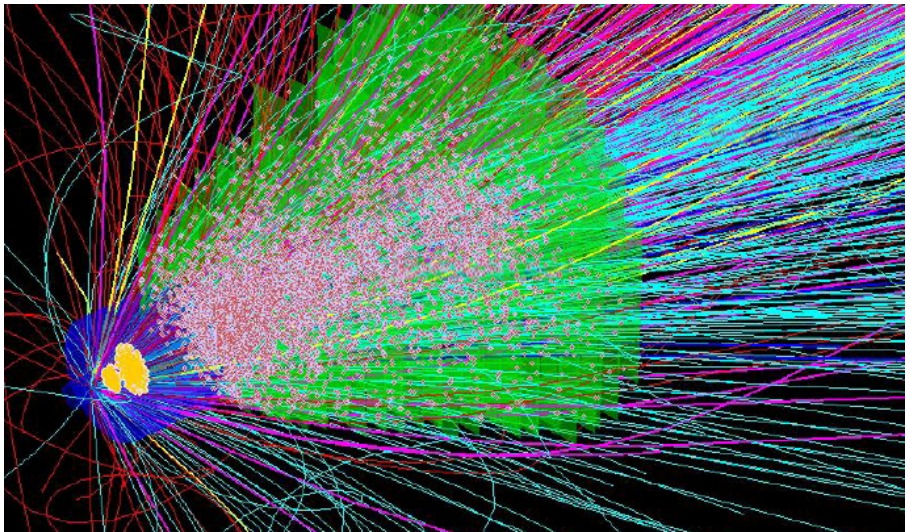
Particle multiplicity x branching ratio for minimum bias Au+Au collisions at 25 A GeV
(from HSD and SHM models)



CBM experimental challenge

- **High rates** for rare probes (charm, light vector mesons, multi-strange hyperons): up to 10^7 (10^5 - 10^6) A+A reactions/s for charmonium (for open charm)
- **Large acceptance** (including mid- & forward rapidity, low and high p_T coverage)
- **High performance & fast tracking** in high background environment
- Determination of **(displaced) decay vertices with high resolution** (< 100 μm)
- High performance **hadron & lepton ID**
- **Fast** and **radiation hard** detectors, **self-triggered (& free-streaming) readout electronics**
- **High speed data acquisition and online event reconstruction (→ trigger on rare probes!)**

central Au(25 AGeV)+Au coll. (UrQMD + GEANT)



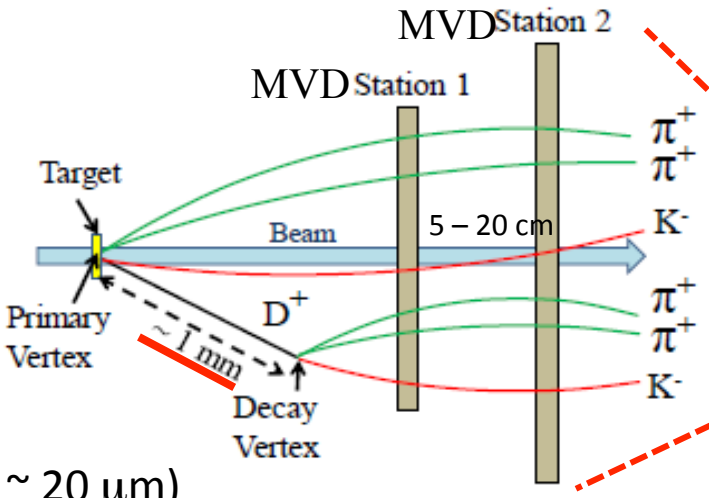
Heavy ion collisions @ FAIR energy

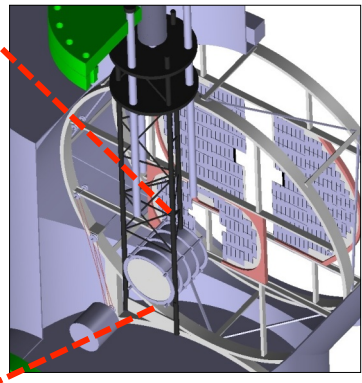
- several hundred tracks / reaction
- up to several 10^9 tracks /s ($\theta \leq 25^o$)
- **M(rare probes) << M(charged hadrons)**

MVD – precise vertexing for open charm

Task

- **Primary & secondary decay vertex reconstruction**
- Primary vertex resolution ~ 1 µm
  & decay vertex resolution < 100 µm
  (crucial for background rejection)





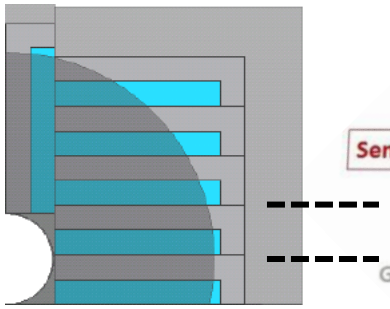
Detector geometry

- **Thin** (~ 50 µm) & **highly granular** (pitch ~ 20 µm) commercial CMOS silicon pixel sensors
- 2 – 3 stations **close to the target** @ 5 – 20 cm (> 10^8 channels)
- **Low-mass** (diamond) cooling support & cables
- **Operation in vacuum**

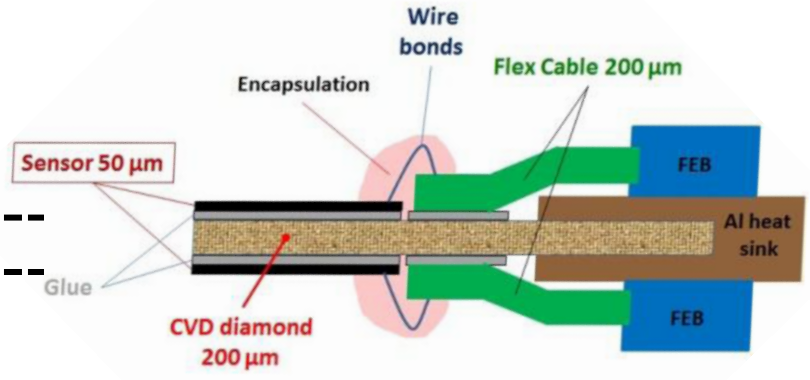
$D^+ \rightarrow \pi^+\pi^+K^-$ (cτ = 312 µm, BR 9%)
$D^0 \rightarrow K^-\pi^+$ (cτ = 123 µm, BR 3.85%)
$\Lambda_c \rightarrow pK^-\pi^+$ (cτ = 60 µm, BR 5%)

γβ ~ 3.8 in Au(25 AGeV)+Au

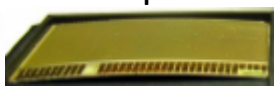
1 station quadrant



Sensor intergration (IKF-Frankfurt):



CMOS pixel sensor:



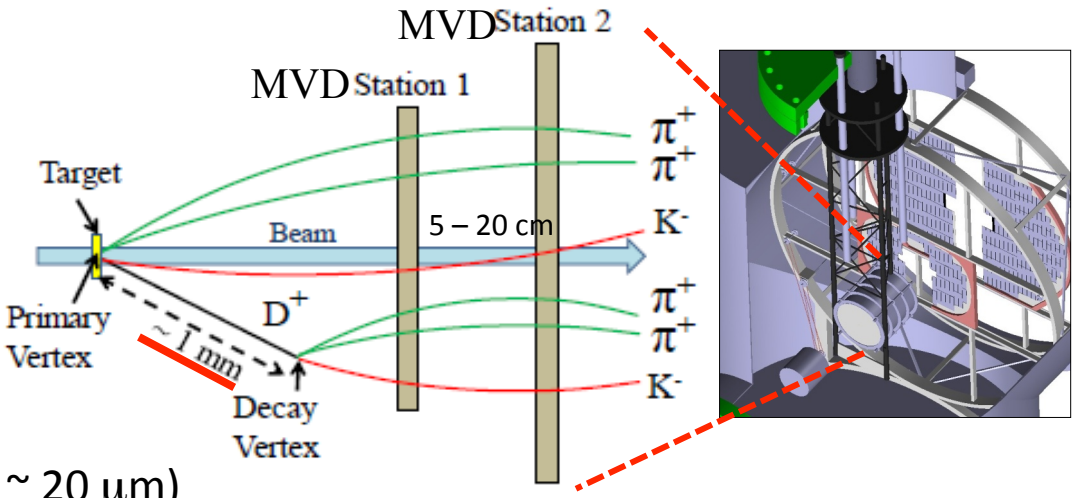
Mimosa-26
(IPHC-Strasbourg)

MimoSIS:
CBM, > 2017

MVD – precise vertexing for open charm

Task

- **Primary & secondary decay vertex reconstruction**
- Primary vertex resolution ~ 1 µm
  & decay vertex resolution < 100 µm
  (crucial for background rejection)



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- **Operation in vacuum**

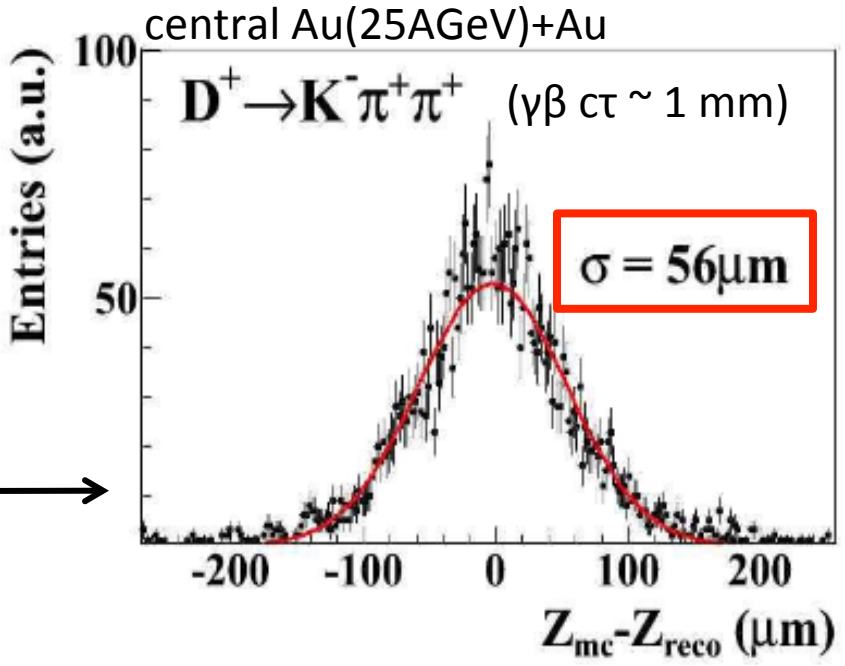
Vertexing in simulation

- realistic material budget (cooling support + cables)
- realistic CMOS performance

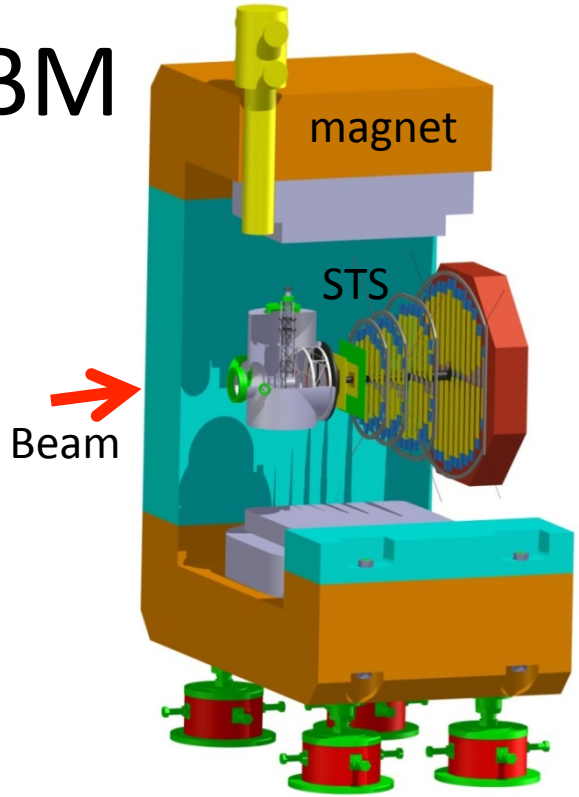
Typical CMOS performance

Spatial resolution [µm]	**< 5**
Material budget [%X_0]	≤ 0.05[1]

[1]Sensor only



STS tracking – core of CBM



Task

- **Track reconstruction** inside magnetic dipole field
- Momentum determination: 0.1 GeV/c < p ≤ 10-12 GeV/c & $\Delta p/p \approx 1\%$ (p=1 GeV/c , Bρ=1Tm)

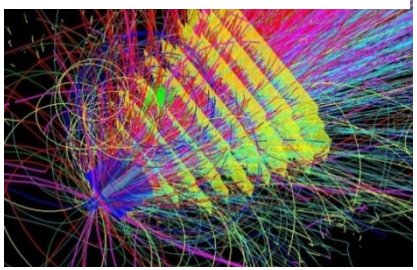
Detector geometry

- **Thin & high resolution** double-sided silicon strip sensors (58 µm pitch, 300 µm thickness)
- 8 stations @ 0.3 to 1m (0.2 – 0.8 m^2) , > 2 10^6 channels
- **Low-mass** carbon support structures

Tracking in simulations

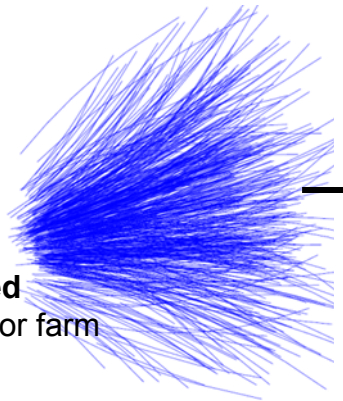
- **Realistic material budget** (with support + cables)
- Track finding - Cellular Automaton
- Track and vertex fitting - Kalman filter
- Running on many-core CPUs → **fast**

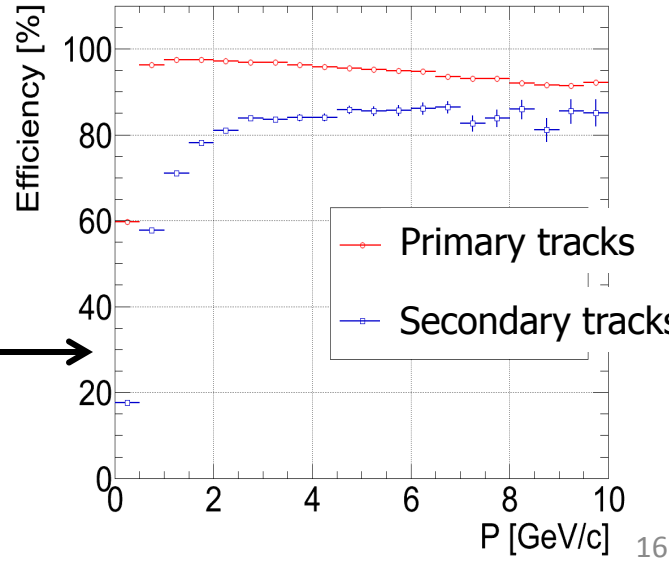
MC simulation central Au+Au collision 25 A GeV



Fast track reconstruction

- **~ 50 ms / event / core**
- scalability to multi-cores architecture **demonstrated**
- online analysis in processor farm with **~ 60.000 cores**





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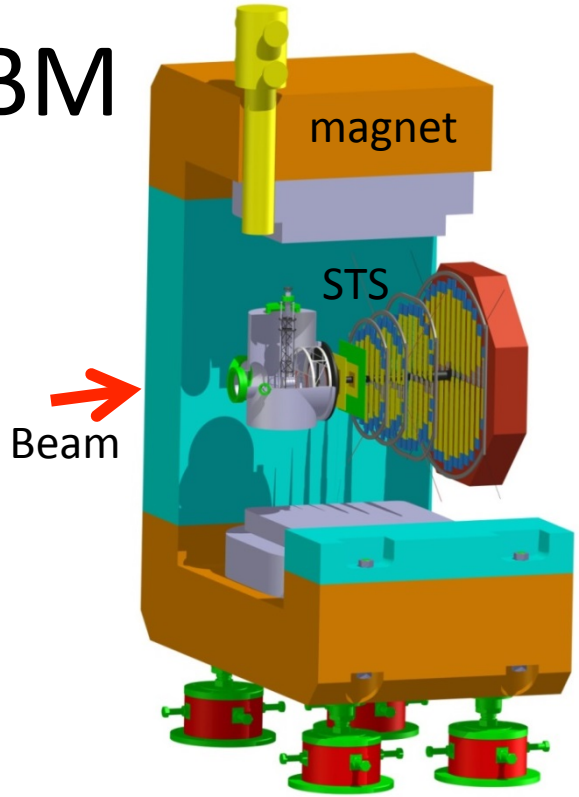

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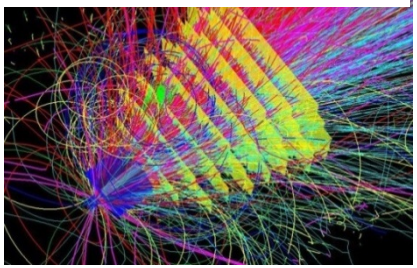

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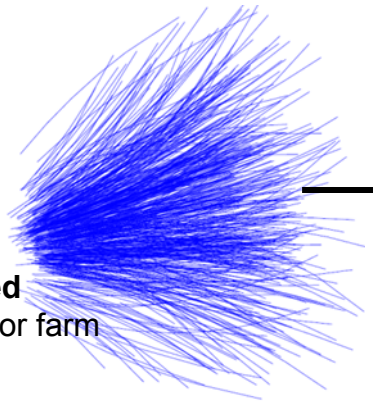
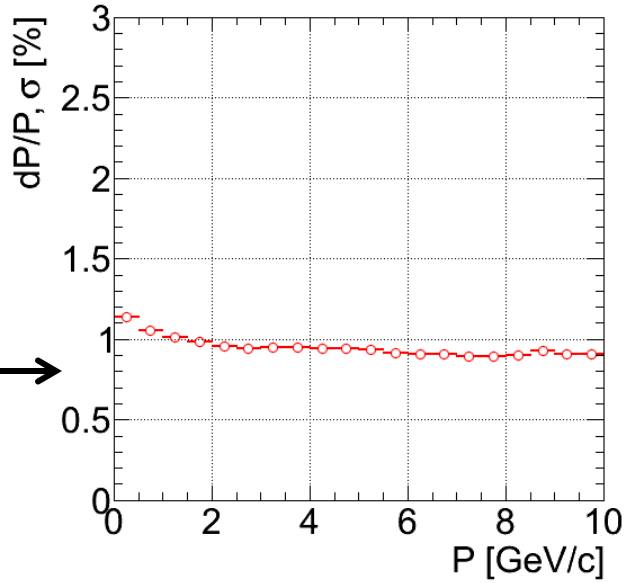
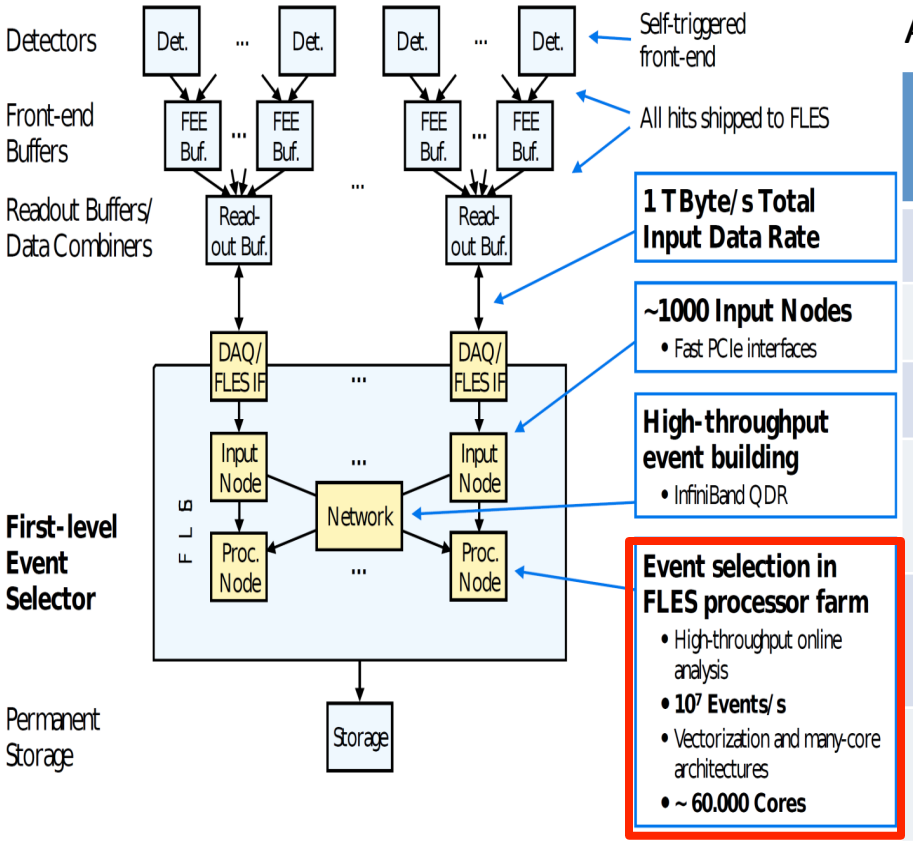




Free streaming data read-out & ultra fast online event selection



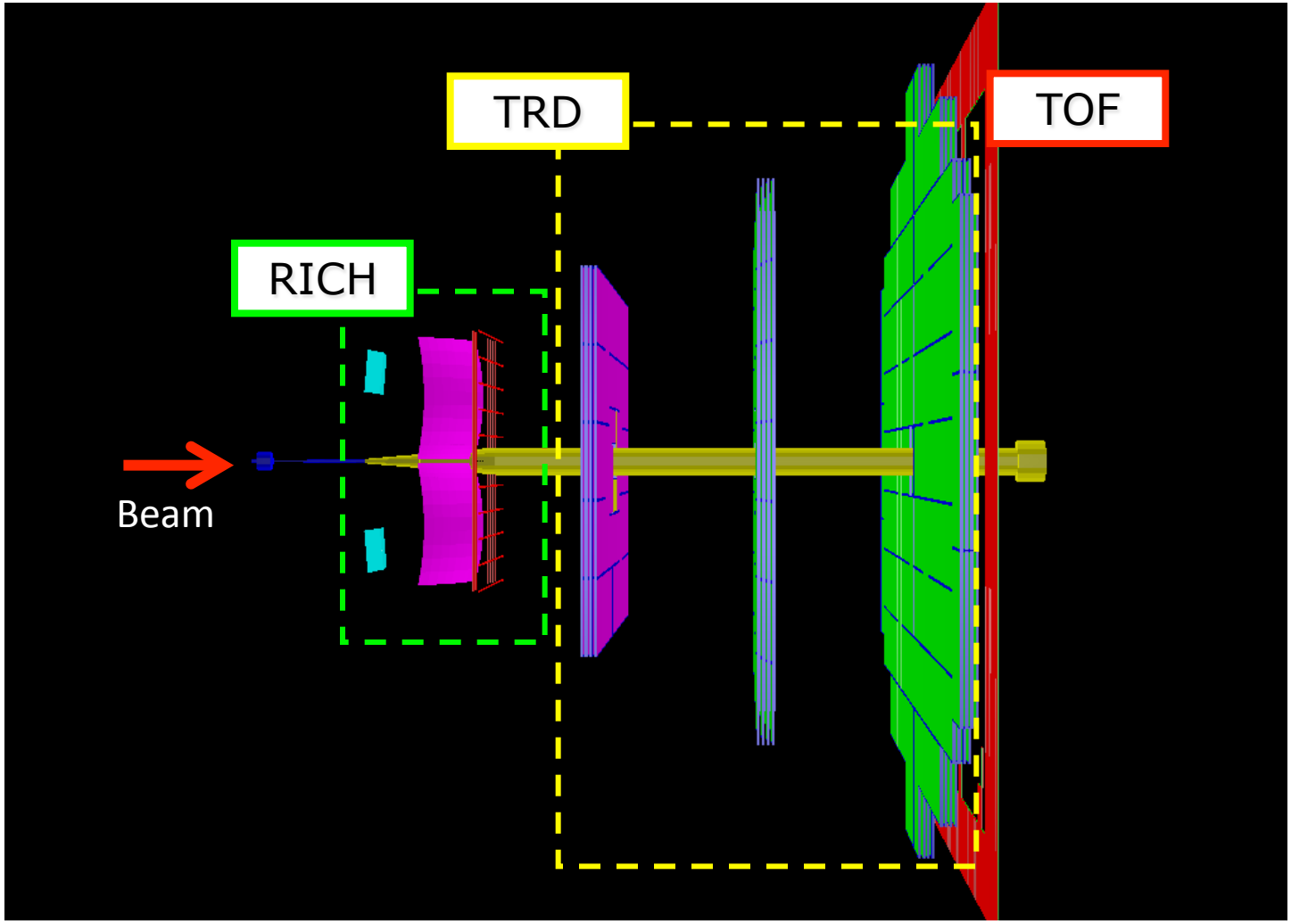
Au(25 AGeV)+Au event stats expected with **CBM**

	Decay mode	<R/s> (MHz)	Evt stats (MEvts) - per 2 months -
K	----	0.025	$1.25\ 10^5$
ϕ	$e^+ e^-$	0.025	$1.25\ 10^5$
ϕ	$\mu^+ \mu^-$	0.5 (T)	$2.5\ 10^6$
Λ, Ξ, Ω	Charged hadrons	0.025	$1.25\ 10^5$
Open Charm	Charged hadrons	> 0.1 (T)	$5\ 10^5$
Hidden cham	di-leptons	10 (T)	$5\ 10^7$

Fast & "**on-the-fly**" event reconstruction (tracking, vertexing, decay reco., etc) in **large & high performance processor farm**

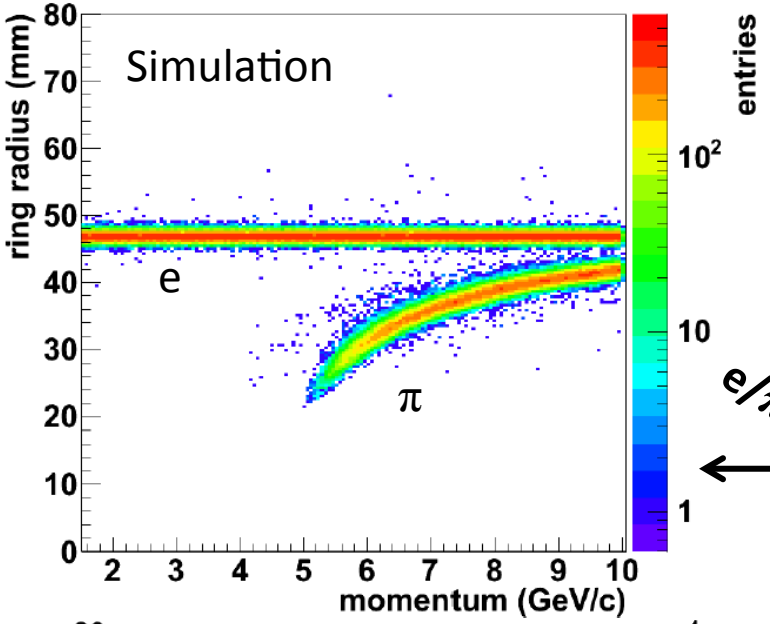
Event archiving rate of 1 Gbytes/s (evt rate ~25kHz)
→ need **event reduction factor of up to 10 - 400**
→ Trigger (T): open charm displaced decay vertex,

Particle ID detectors

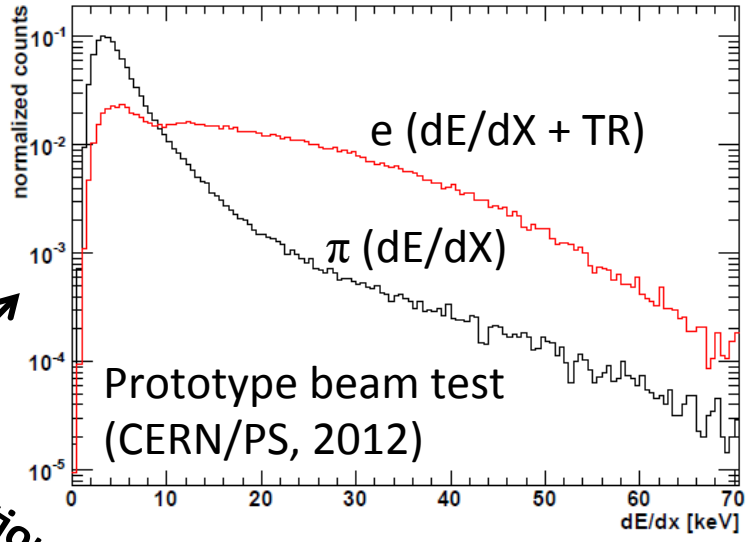


Particle ID detectors

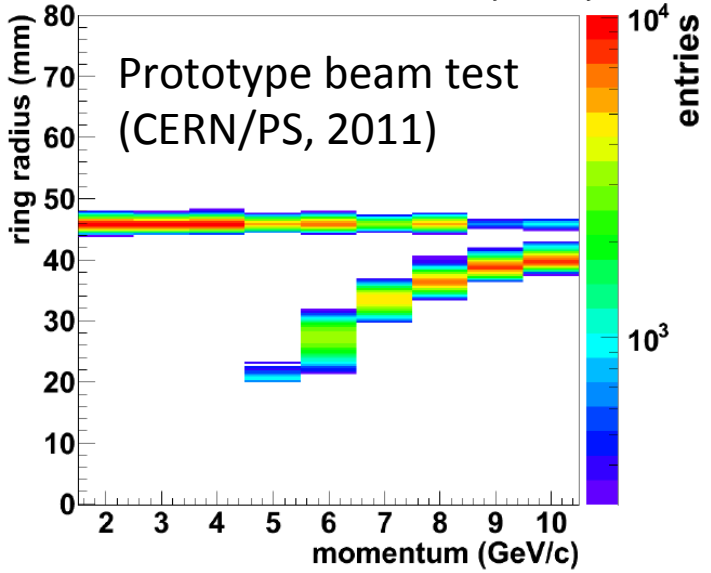
RICH



TRD

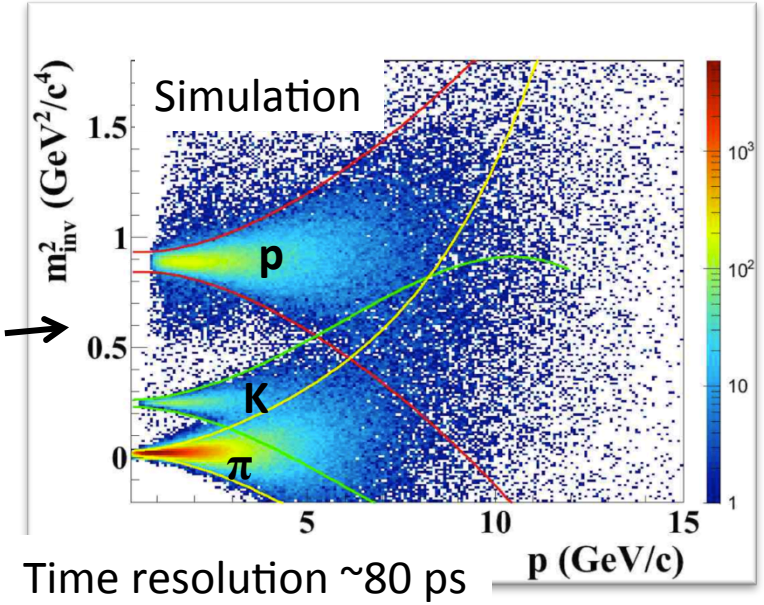


e/π discrimination



TOF

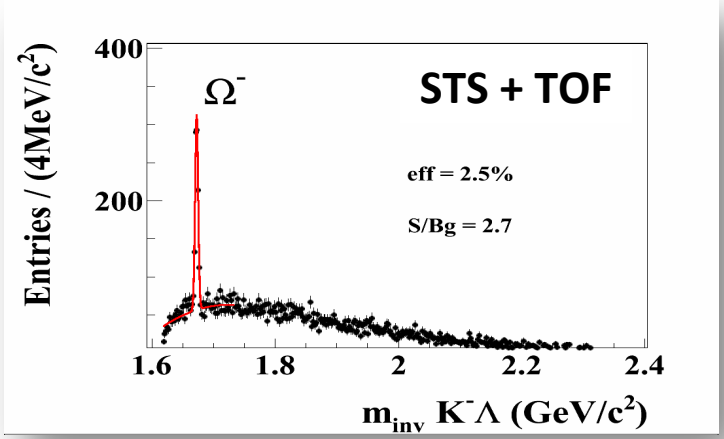
Hadron ID →

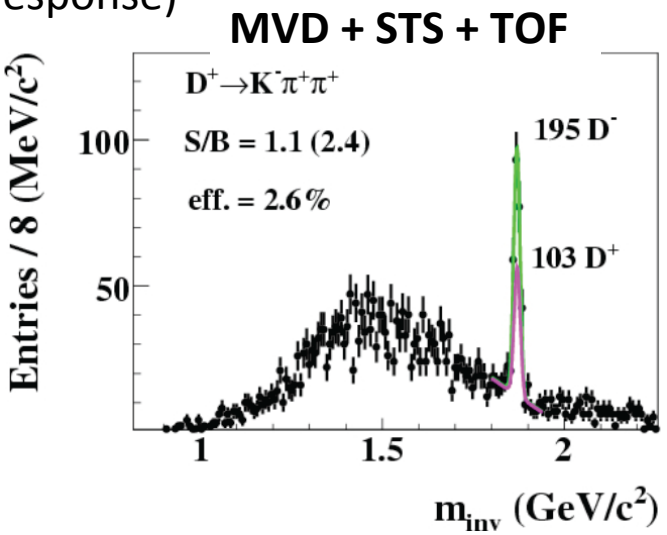


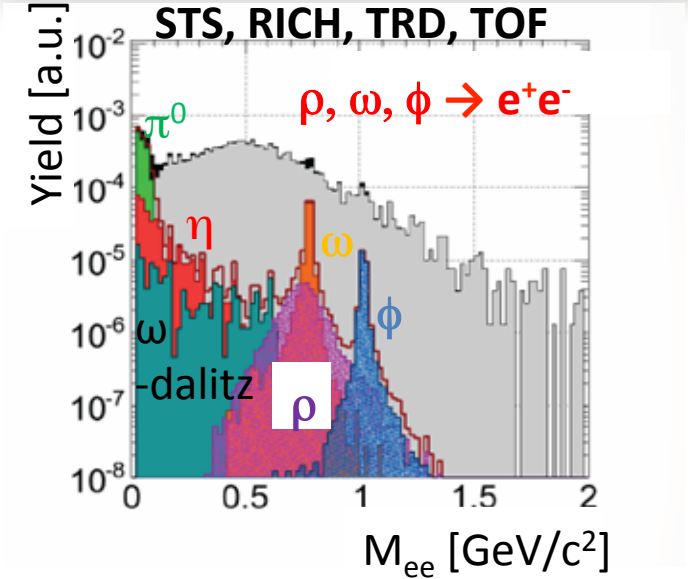
Time resolution ~80 ps

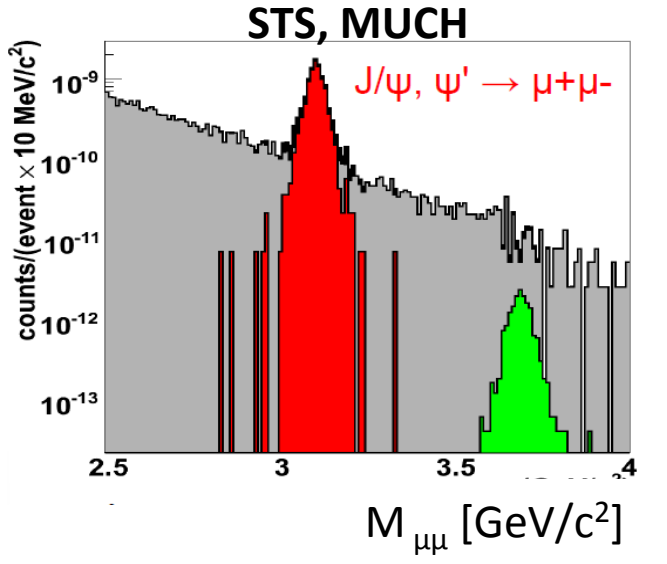
Feasibility studies (selection)

- Full simulations: realistic background (UrQMD), transport (GEANT) + track reconstruction + vertex finder + etc
- Realistic detector geometry (material budget & response)
- Ex. in central Au(25 AGeV)+Au





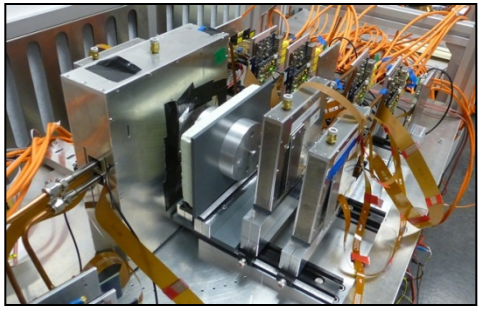




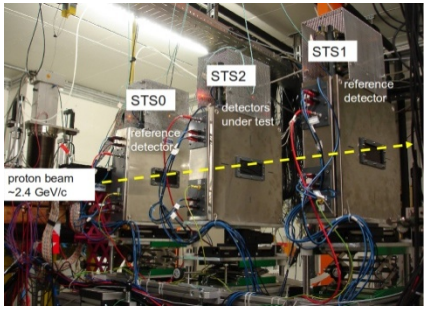
CBM technical developments

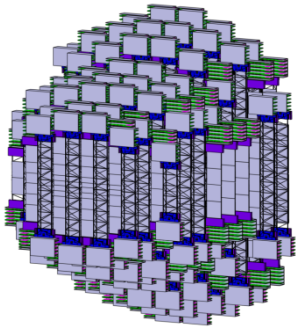
SC Magnet: JINR Dubna

Micro-Vertex Detector:
Frankfurt, Strasbourg



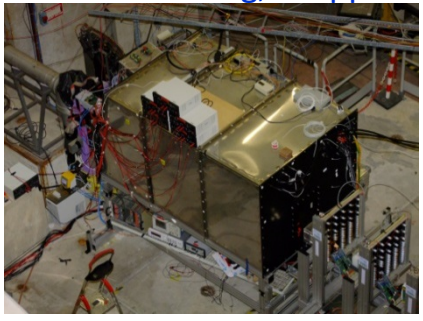
Silicon Tracking System: Darmstadt, Dubna, Krakow, Kiev, Kharkov, Moscow, St. Petersburg, Tübingen



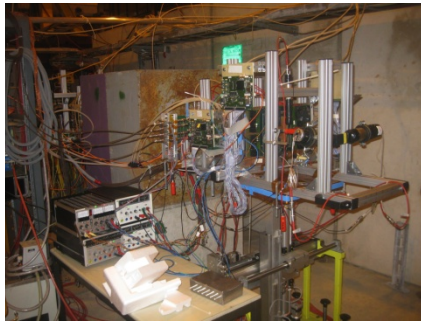


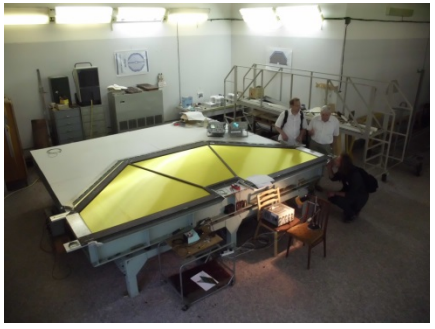
MRPC ToF Wall: Beijing, Bucharest, Darmstadt, Frankfurt, Hefei, Heidelberg, Moscow, Rossendorf, Wuhan, Zagreb

RICH Detector:
Darmstadt, Giessen, Pusan, St. Petersburg, Wuppertal

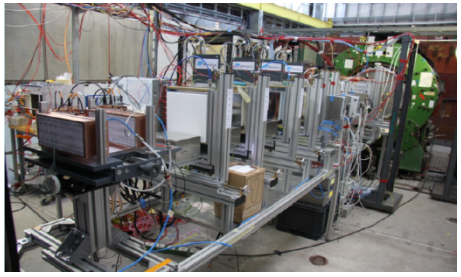


Muon detector:
Kolkata + 13 Indian Inst., Gatchina, Dubna

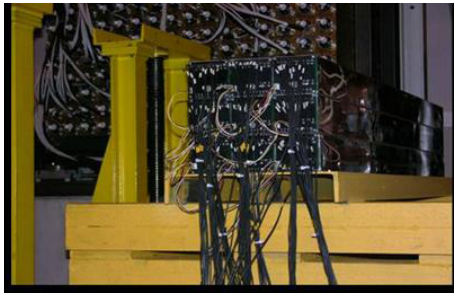




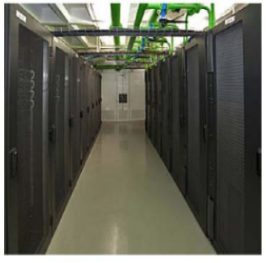
Transition Radiation Detector:
Bucharest, Dubna, Frankfurt, Heidelberg, Münster



Forward calorimeter:
Moscow, Prague, Rez

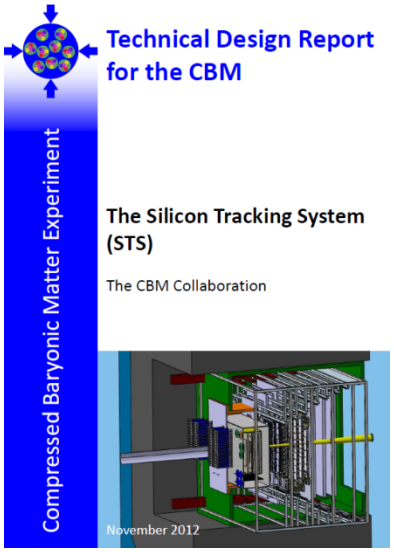


DAQ and online event selection:
Darmstadt, Frankfurt, Heidelberg, Kharagpur, Warsaw

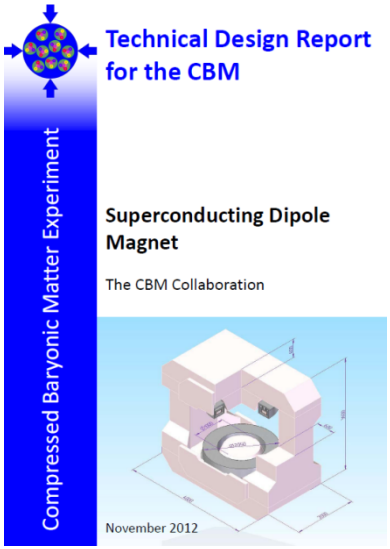


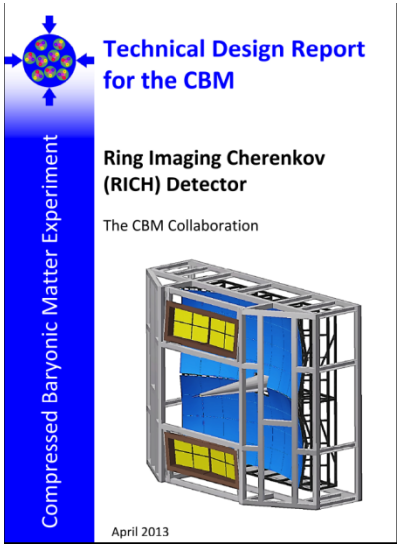
CBM Technical Design Reports

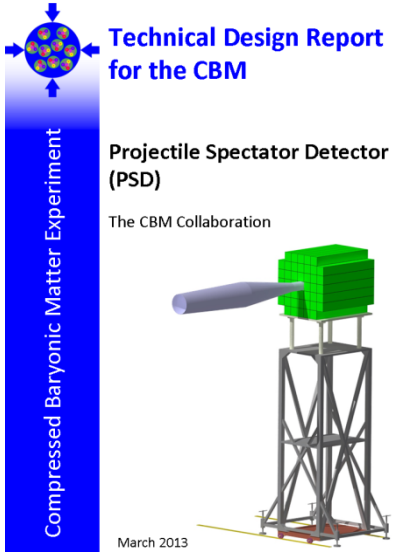
Recommended for approval by ECE:



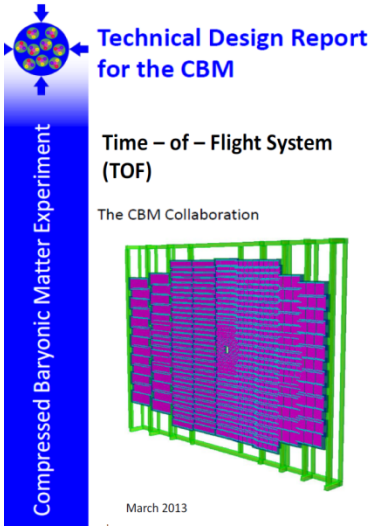
In evaluation:

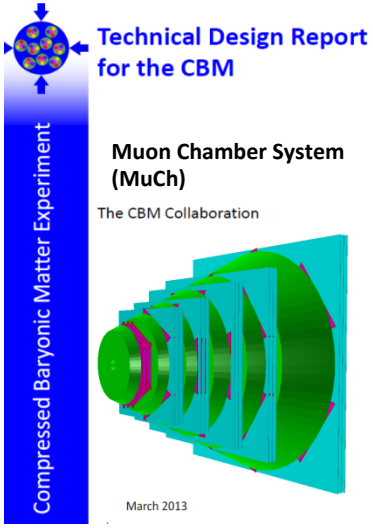






To be submitted in 2013:





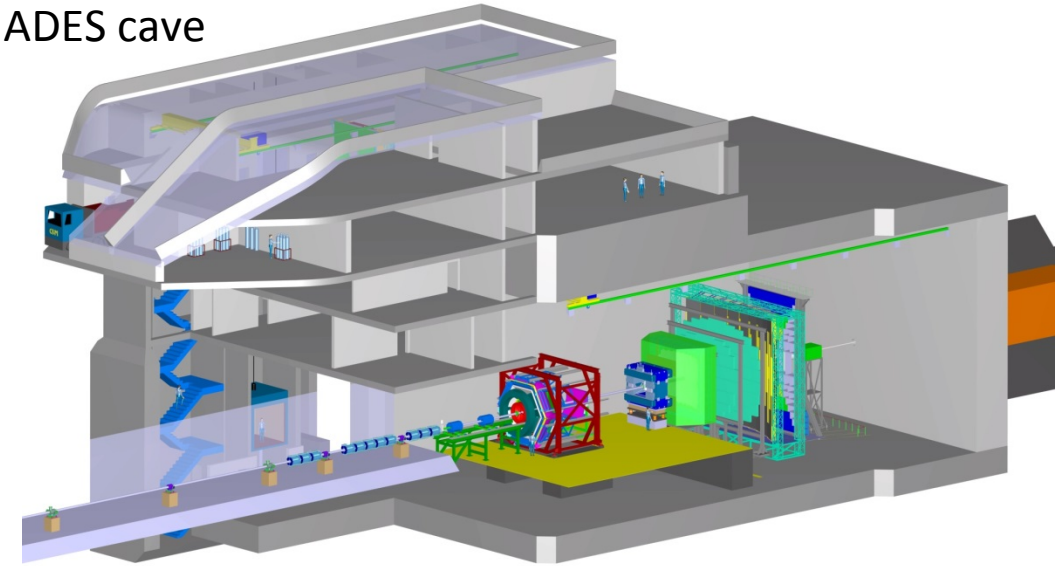
FAIR/CBM time line

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Construction												
Installation												
Commissioning												
Expts. at SIS100											?	
Expts. at SIS300												

Cave ready

SIS100 ready

CBM + HADES cave



Summary

CBM scientific program:

Exploration of the QCD phase diagram in the region of high net baryon densities, poorly known both theoretically & experimentally
→ large discovery potential at SIS100/300.

Experimental approach:

High-precision measurements of multi-differential observables including particles with small cross sections
for a variety of beam energies and collision systems.

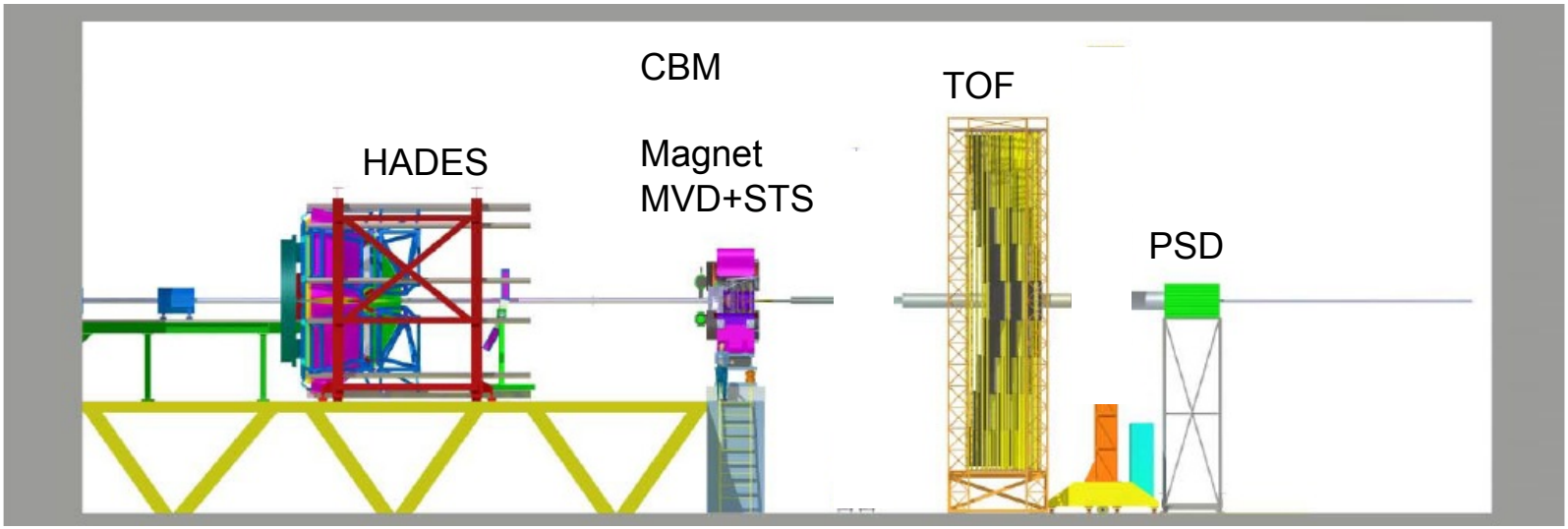
Status of experiment preparation:

Prototype detector performances fulfill CBM requirements.
TDRs: 1 recommended for approval, 3 in evaluation,
2 to be submitted soon.

Funding:

Substantial part of the CBM start version for SIS100 is financed

CBM physics program at SIS-100



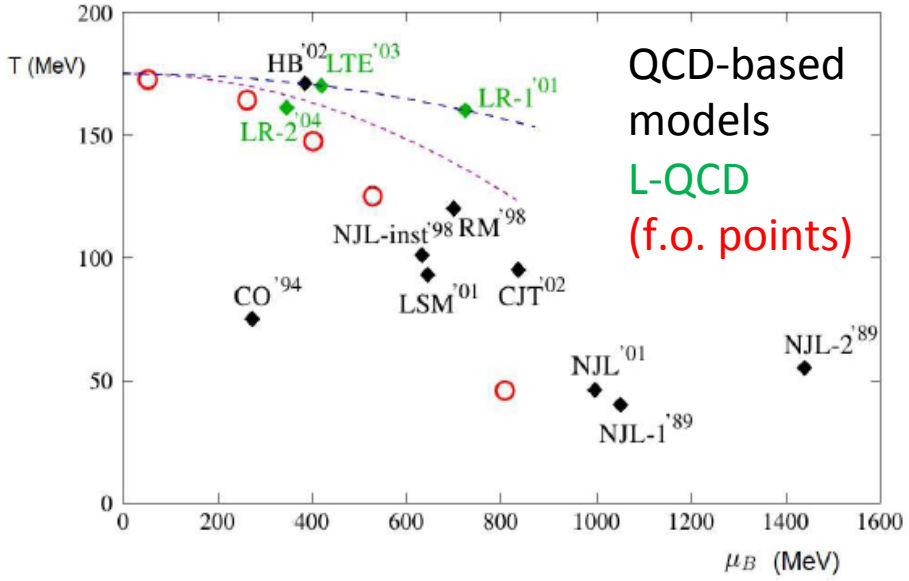
- First measurement @ SIS-100 expected in 2019
- CBM core setup: MVD + STS + TOF + PSD
- A+A up to 10 AGeV: **strangeness yields & flow excitation functions** (already neutron star core densities reached in A+A @SIS100)
- p+p, p+A up to 30 GeV: **charm production at threshold** (no data & crucial ref. for A+A)

- Di-electron spectra with HADES upgrade

Back-up slides

QCD phase diagram - speculations

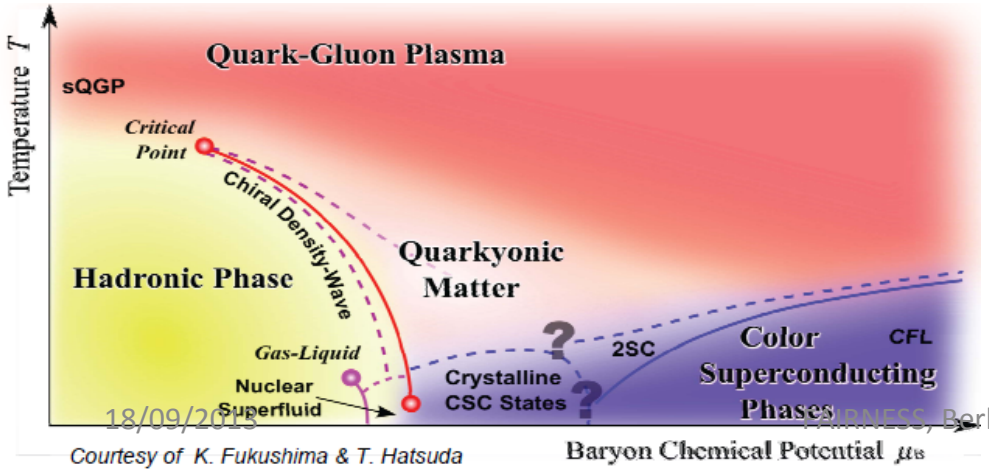
QCD critical point predictions
M. Stephanov, Journal of Physics:
Conference Series 27, 144-153 (2005)



- **Existence of QCD Critical** Point (CP) still under debate:

  Z. Fodor and S. D. Katz, JHEP, 03:014 (2002)
  P. de Forcrand et al., PoSLAT2007:178 (2007)

- If existing, CP location (L-QCD):
  150 MeV < T < 200 MeV
  200 MeV < μ_B < 800 MeV
  → **large systematic errors!**
  → motivates **experimental** search



Exotic states of nuclear matter at high μ_B:

- Color super-conductor?

M.G.Alford et al,Rev. Mod. Phys. 80,1455-1515(2008)

- Quarkyonic matter?

L. McLerran, arXiv:0808.1057v1 [hep-ph] (2008)

- etc …

→ **rich discovery potential** in "terra incognita"

CBM at FAIR – a high rate experiment

Au(25 AGeV)+Au event stats with **CBM** T = Trigger

	Decay mode	<R/s> (MHz)	Evt stats (MEvts) - per 2 months -
K	----	0.025	$1.25\ 10^5$
ϕ	$e^+ e^-$	0.025	$1.25\ 10^5$
ϕ	$\mu^+ \mu^-$	0.5 (T)	$2.5\ 10^6$
Λ, Ξ, Ω	Charged hadrons	0.025	$1.25\ 10^5$
Open Charm	Charged hadrons	> 0.1 (T)	$5\ 10^5$
Hidden cham	di-leptons	10 (T)	$5\ 10^7$

At low energy, factor 10^4 – 10^6 more event statistics with CBM w.r.t. BES II

Au+Au event stats with **STAR BES**

$\sqrt{S_{NN}}$ (GeV)	19.6	15	11.5	7.7
μ_B (GeV)	205	250	315	420
BES I (MEvts)	36	---	12	5
BES II (MEvts)	**400**	**100**	**120**	**80**

→ **Depends on luminosity & relies on e-cooling capability**

CBM Physics Book
Nuclear matter physics at SIS-100,
CBM Report 2012-01 (2012)

→ **Collision rates rather independent on beam energy** (depends on event archiving rate of 1 Gbytes/s & multiplicity/event)

CBM: Estimated particle yields for minimum bias Au+Au collisions at 25 AGeV

particle, mass (MeV)	N	decay mode	BR	R/s (MHz)	T	ε (%)	Y/s	Y/10 w
η (547)	6.6	$\mu^+\mu^-$	$5.8 \cdot 10^{-6}$	0.25	y	3	0.28	$1.7 \cdot 10^6$
K^+ (494)	8	-	-	0.025	n	20	$4 \cdot 10^4$	$2.4 \cdot 10^{11}$
K^- (494)	2.6	-	-	0.025	n	20	$1.3 \cdot 10^4$	$7.8 \cdot 10^{10}$
K_s^0 (497)	5.4	$\pi^+\pi^-$	0.69	0.025	n	10	$9.3 \cdot 10^3$	$5.6 \cdot 10^{10}$
ρ (770)	4.6	e^+e^-	$4.7 \cdot 10^{-5}$	0.025	n	5.4	0.29	$1.8 \cdot 10^6$
ρ (770)	4.6	$\mu^+\mu^-$	$4.6 \cdot 10^{-5}$	0.25	y	2.7	1.4	$8.6 \cdot 10^6$
ω (782)	7.6	e^+e^-	$7.1 \cdot 10^{-5}$	0.025	n	7.2	1	$6 \cdot 10^6$
ω (782)	7.6	$\mu^+\mu^-$	$9 \cdot 10^{-5}$	0.25	y	3.7	6.3	$38 \cdot 10^6$
ϕ (1020)	0.256	e^+e^-	$3 \cdot 10^{-4}$	0.025	n	9.6	0.18	$1 \cdot 10^6$
ϕ (1020)	0.256	$\mu^+\mu^-$	$2.9 \cdot 10^{-4}$	0.25	y	6	1.	$6.7 \cdot 10^6$
Λ (1115)	6.4	p π^-	0.64	0.025	n	10.6	$1.1 \cdot 10^4$	$6.5 \cdot 10^{10}$
Ξ^- (1321)	0.096	Λ π^-	0.999	0.025	n	2.1	50.4	$3 \cdot 10^8$
Ω^- (1672)	0.0044	Λ K^-	0.68	0.025	n	1	0.75	$4.5 \cdot 10^6$
D^0 (1864)	$7.5 \cdot 10^{-6}$	$K^-\pi^+$	0.038	0.1	y	3.25	$8.5 \cdot 10^{-4}$	$5.1 \cdot 10^3$
$\bar{D}^0$ (1864)	$7.5 \cdot 10^{-6}$	$K^-\pi^+\pi^+\pi^-$	0.075	0.1	y	0.37	$2.1 \cdot 10^{-4}$	$1.3 \cdot 10^3$
D^0 (1864)	$2.3 \cdot 10^{-5}$	$K^+\pi^-$	0.038	0.1	y	3.25	$2.6 \cdot 10^{-3}$	$1.6 \cdot 10^4$
D^+ (1869)	$8 \cdot 10^{-6}$	$K^-\pi^+\pi^+$	0.092	0.1	y	4.2	$3.1 \cdot 10^{-3}$	$1.9 \cdot 10^4$
D^- (1869)	$1.8 \cdot 10^{-5}$	$K^+\pi^-\pi^-$	0.092	0.1	y	4.2	$7 \cdot 10^{-3}$	$4.2 \cdot 10^4$
$\Lambda_c(2285)$	$4.9 \cdot 10^{-4}$	$pK^-\pi^+$	0.05	0.1	y	0.5	$1.2 \cdot 10^{-2}$	$7.4 \cdot 10^4$
J/ψ (3097)	$3.8 \cdot 10^{-6}$	e^+e^-	0.06	1-10	y	14	0.032 - 0.32	$1.9 \cdot 10^{5-6}$
ψ' (3686)	$5.1 \cdot 10^{-8}$	e^+e^-	$7.3 \cdot 10^{-3}$	1-10	y	15	$5.6 \cdot 10^{-(5-4)}$	$3.4 \cdot 10^{2-3}$
J/ψ (3097)	$3.8 \cdot 10^{-6}$	$\mu^+\mu^-$	0.06	10	y	16	0.36	$2.2 \cdot 10^6$
ψ' (3686)	$5.1 \cdot 10^{-8}$	$\mu^+\mu^-$	$7.3 \cdot 10^{-3}$	10	y	19	$7.1 \cdot 10^{-4}$	$4.3 \cdot 10^3$

Deconfinement in A+A at FAIR?

PHSD: heavy-ion collisions

Initial A+A collisions: HSD, string formation and decay to pre-hadrons

Fragmentation of pre-hadrons into quarks using the quark spectral functions from the Dynamical Quasi-Particle Model (DQPM) – approximation to QCD

Partonic phase: quarks and gluons with constituent mass and broad spectral functions. **Widths, masses** defined by DQPM. **Elastic and inelastic parton-parton interactions** (effective cross sections adjusted to the DQPM in equilibrium):

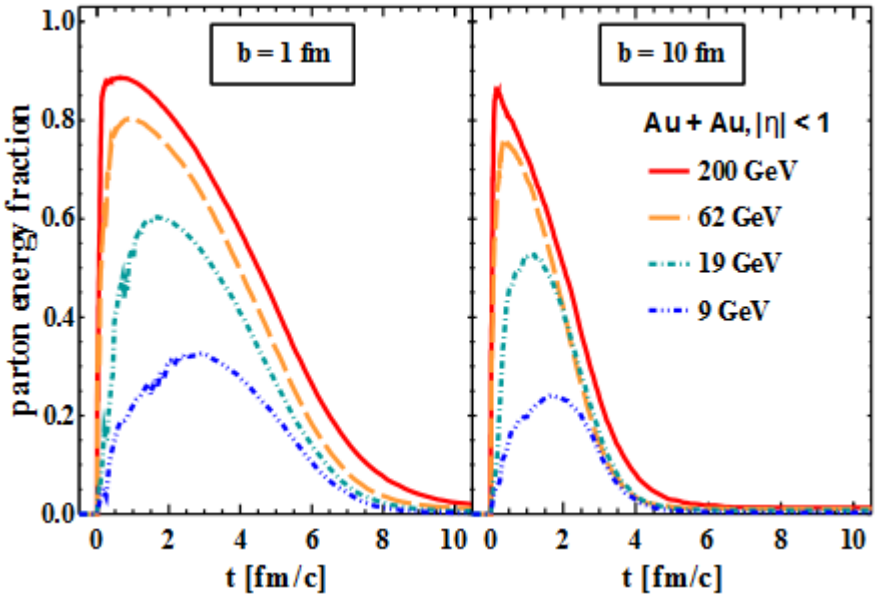
- ✓ q + qbar (flavor neutral) <=> gluon (colored)
- ✓ gluon + gluon <=> gluon (possible due to large spectral width)
- ✓ q + qbar (color neutral) <=> hadron resonances

Hadronization: dynamical and off-shell transitions. Massive, off-shell quarks and gluons with broad spectral functions hadronize **to off-shell hadrons:**

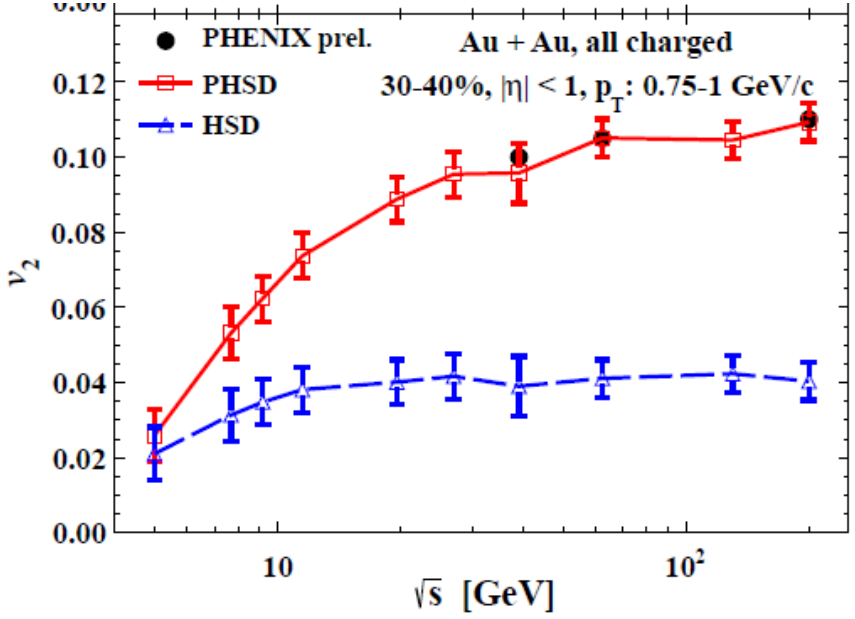
- ✓ gluons → q + qbar; q + qbar → off-shell meson or ‚string‘;
- ✓ q + q +q → baryon or ‚string‘; (‚strings‘ act as doorway states)

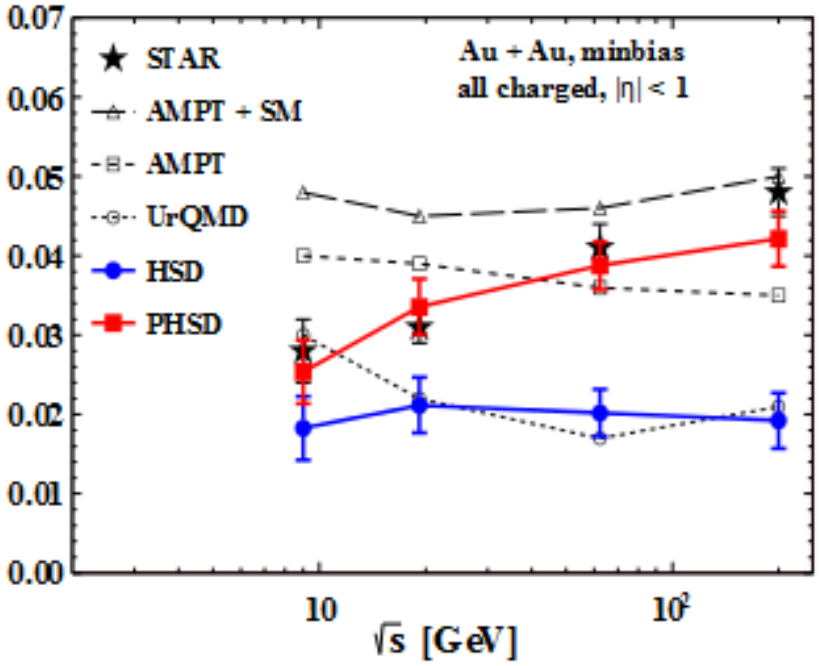
Hadronic phase: hadron-string interactions and propagation by off-shell HSD

PHSD: relative partonic contribution to total energy density (at mid-Y) [%]

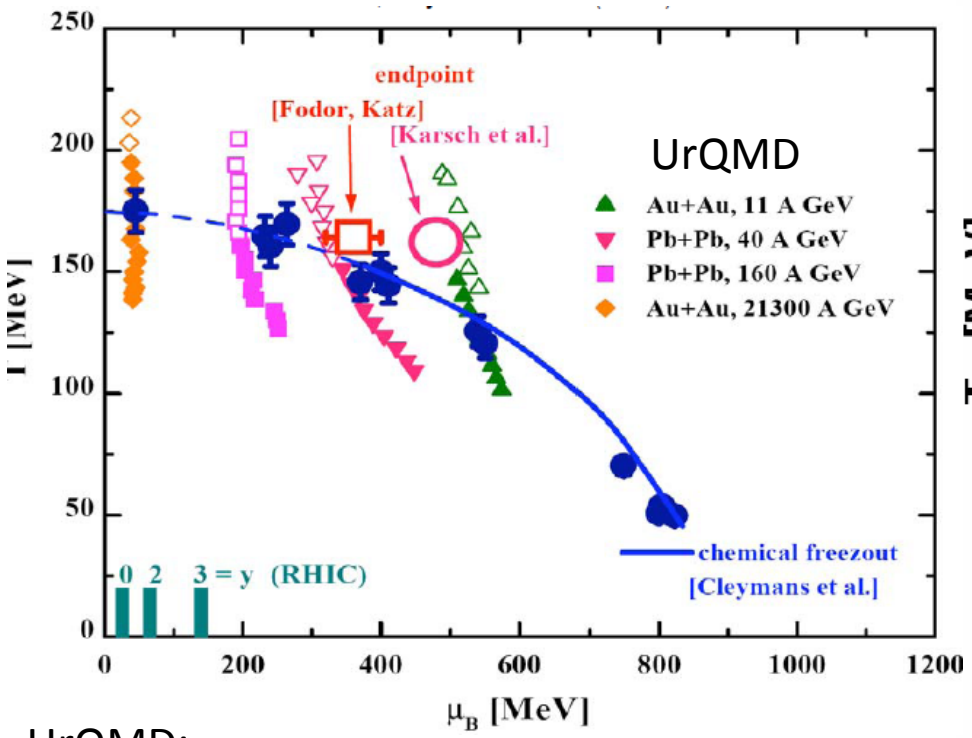


E.L.Bratkovskaya et al, arXiv:1304.4115 [nucl-th]

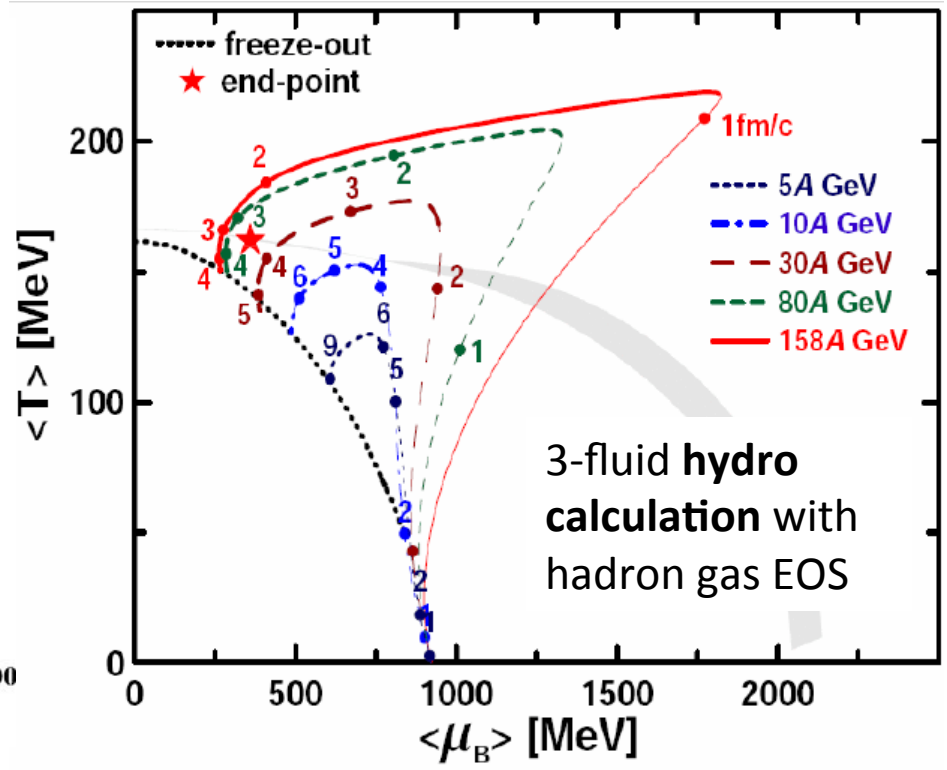




L.V. Bravina et al., Phys. Rev. C60 (1999) 044905



Yu. B. Ivanov et al., Phys. Rev. C 73, 044904 (2006)
central Pb + Pb collisions



UrQMD:

- **Deconfinement phase transition** may be reached already at $\mathbf{E_{beam}}$ **= 11 GeV/nucleon**
- QCD critical point may be in reach at FAIR energies

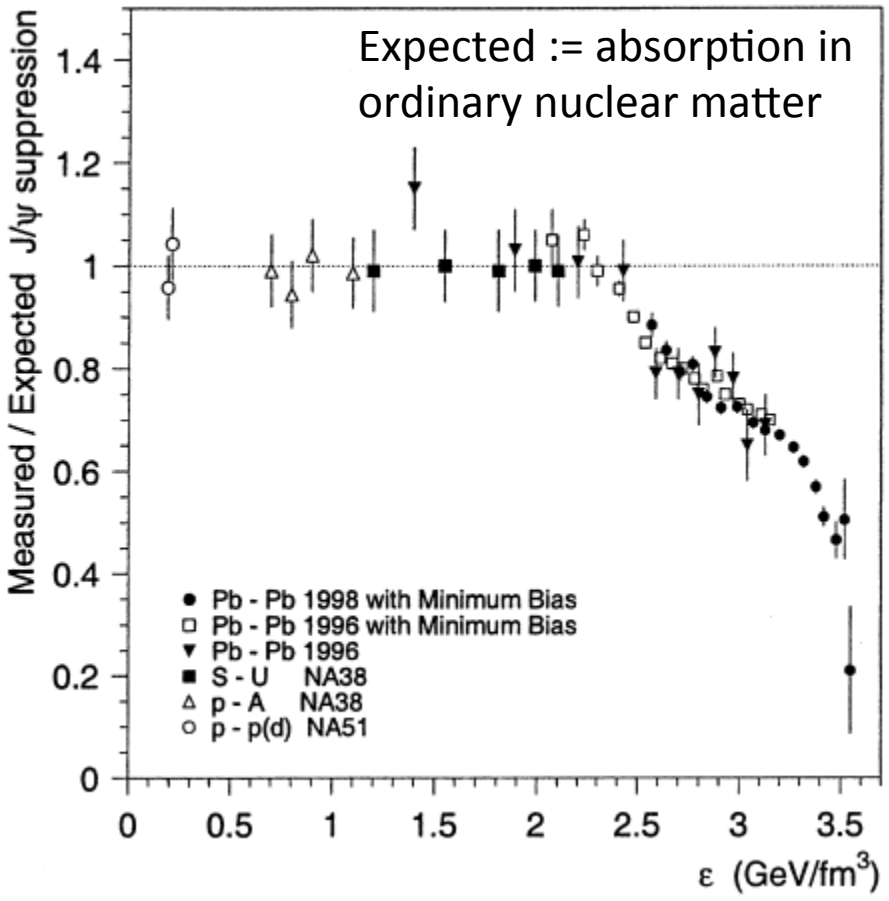
Phase boundary reached already at 10 AGeV

predicts to hit critical point at ~ 30 AGeV

CBM observables

Observable: J/Ψ suppression

M.C. Abreu et al., NA38 Collaboration, Phys. Lett. B 466, 408 (1999)



Anomalous suppression of J/Ψ mesons observed in Pb+Pb **at top SPS energies**

First predicted by Matsui: **debye screening** of $c\bar{c}$ binding potential as an effect of the **high color charge density in QGP**
T. Matsui and H. Satz, Phys. Lett. B 178, 416 (1986)

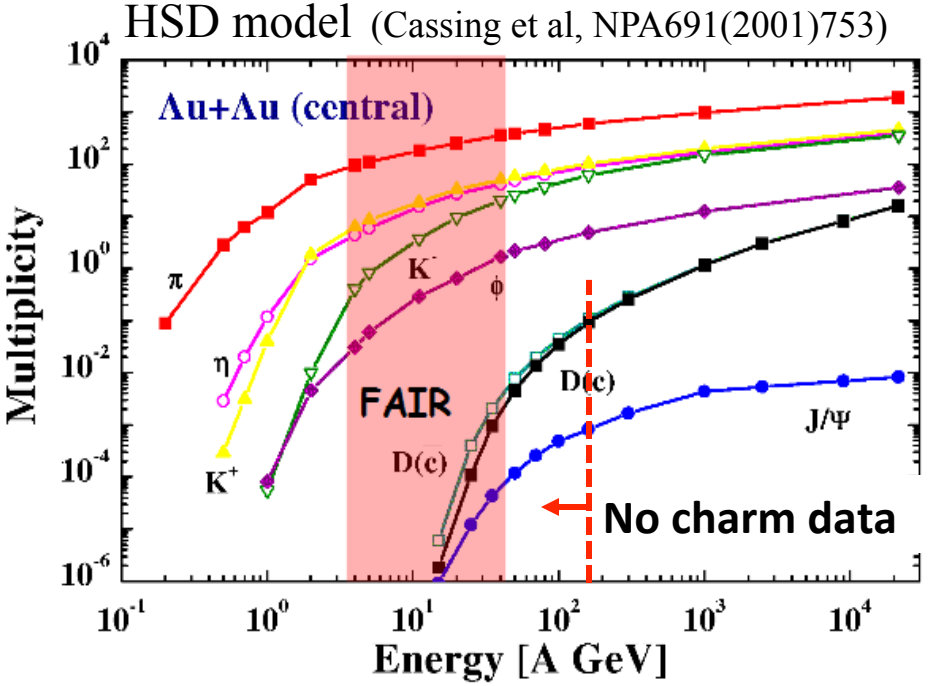
→ **Search for the onset of suppression at lower, FAIR energies where onset of deconfinement expected to set in** (presumably 1st order phase transition)

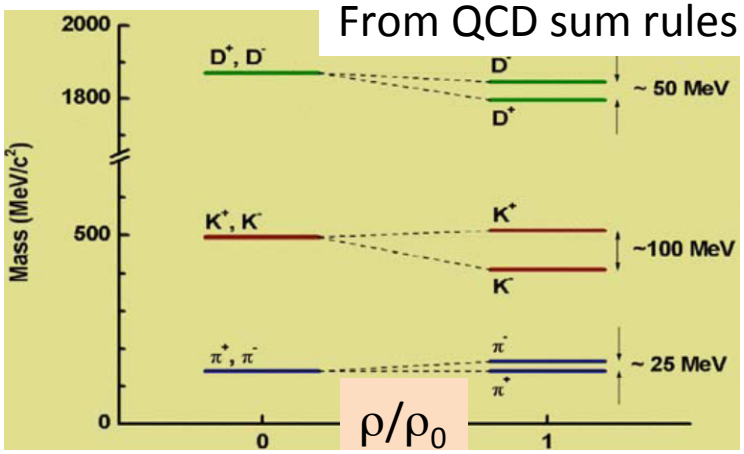
→ **Measure: p+p, p+A & A+A → J/Ψ + X** (small energie steps)

Note: other conventional absorption mechanisms by co-moving hadrons can contribute to the observed absorption
O. Linnyk et al., Nucl. Phys. A 786, 183-200 (2007)

→ measurements at FAIR should settle this issue

Observable: open charm yields





In-medium mass modification of open charm supported by chiral SU(4) model
Mishra et al, PRC 69, 015202 (2004)

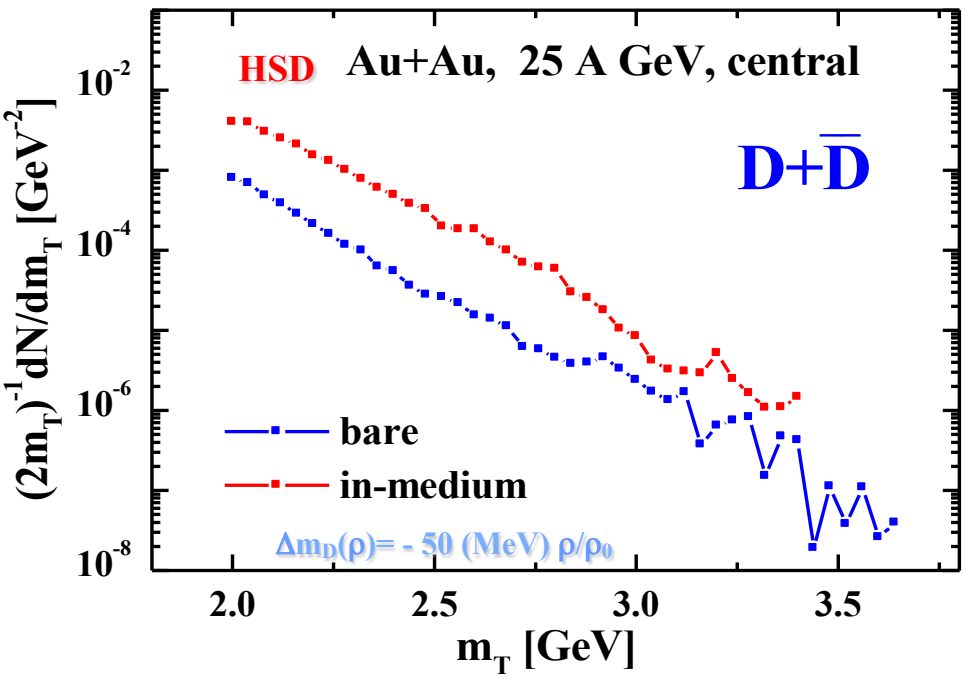
FAIR energies @ **charm production threshold**
→ **open charm yields very sensitive to in-medium effects**
(possibly related to a chiral phase transition)

Detailed measurements: D^+, D^-, D^0, $\bar{D}^0$, Λ_c (in p+p, p+A & A+A)

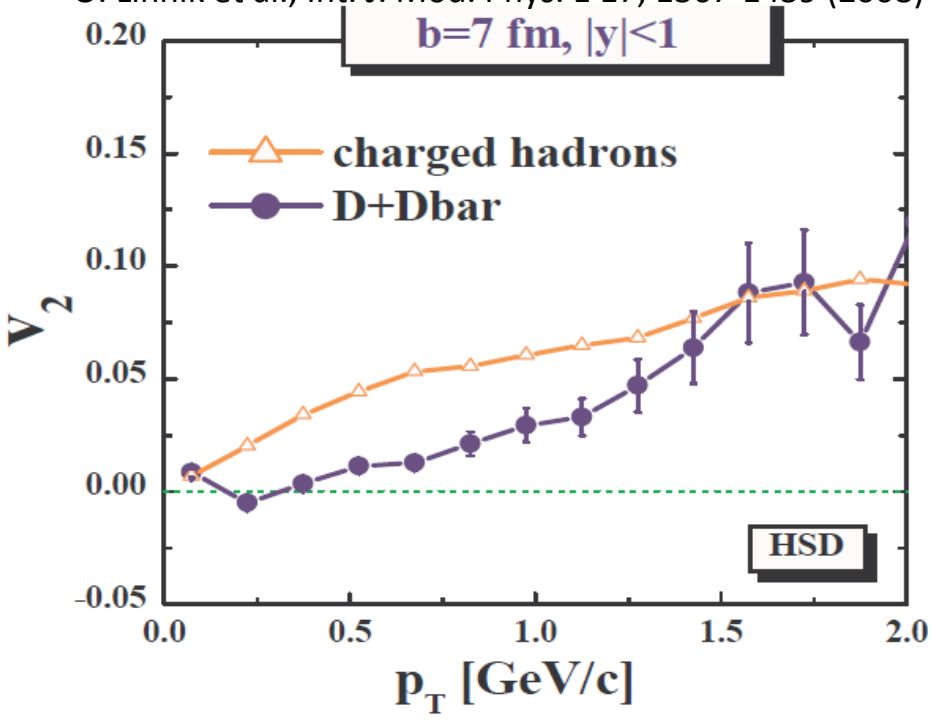
Open charm measurement is crucial (in particular: **Λ_c at high ρ_B**):
1) **No charm data below $\sqrt{s_{NN}}$ ~ 20 GeV** → cc production cross-section?
2) **Complementary with J/psi suppression**

Observables: m_T-spectrum & elliptic flow of open charmed mesons

W. Cassing et al., Nucl. Phys. A 691 (2001) 753



O. Linnik et al., Int. J. Mod. Phys. E 17, 1367-1439 (2008)

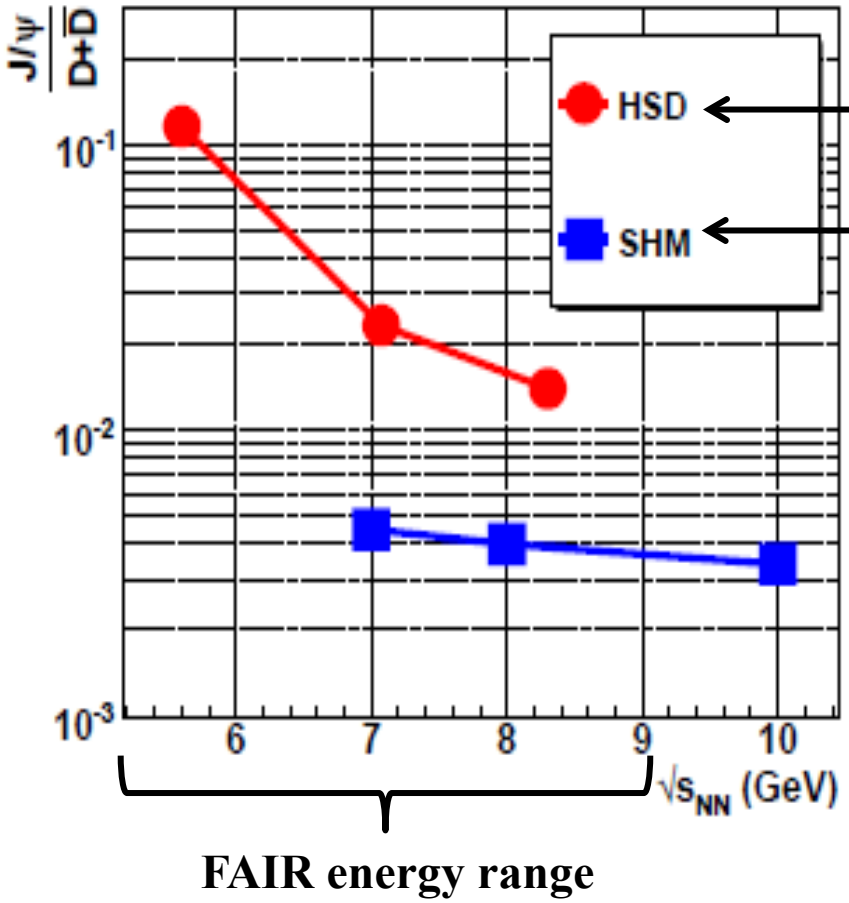


In-medium effect in dense matter: attractive D-N potential, i.e. a mass shift of -50 x ρ/ρ_0 [MeV] → **Increase of about 1 order of magnitude of D-meson production rate**

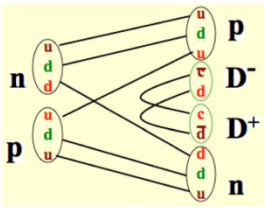
weak D-meson v2 w.r.t. hadron v2 in hadronic scenario
-> **D-meson v2 expected to be particularly sensitive to early partonic collectivity**

Observable: charm quark distribution among charmed hadrons

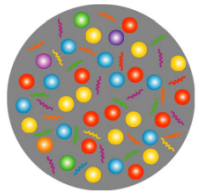
HSD: O. Linnyket al., Nucl. Phys. A786 (2007) 183
SHM: A. Andronic, et al., arXiv:0708.1488



Purely **Hadronic** Model



Purely **Partonic** Model

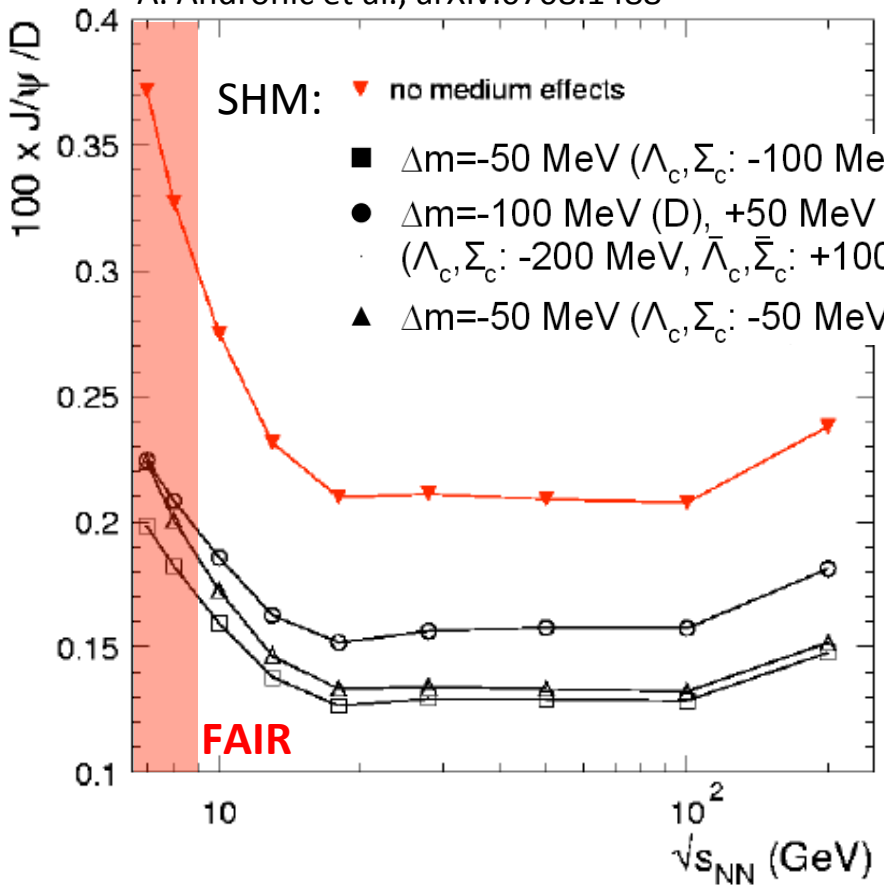


Factor of ~ 5 difference in J/Ψ over D ratio at $\sqrt{s_{NN}}$ ~ 7-9 GeV where **onset of deconfinement** expected to take place

→ Expect **discontinuity in excitation function of J/Ψ over D ratio**

Observable: charm quark distribution among charmed hadrons

A. Andronic et al., arXiv:0708.1488



In-medium mass modification of open charm hadrons

Detailed measurements: J/Ψ, D^+, D^-, D^0, $\bar{D}^0$, Λ_c (in p+p, p+A & A+A)

Observable: strangeness yields

Direct production:

$pn \rightarrow \Xi^- K^+K^+n$ ($\sqrt{s}$ = 3.247 GeV)

$pp \rightarrow \Xi^+ \Xi^- pp$ ($\sqrt{s}$ = 4.518 GeV)

$pp \rightarrow \Omega^- K^+K^+K^+n$ ($\sqrt{s}$ = 4.092 GeV)

$pp \rightarrow \Omega^+ \Omega^- pp$ ($\sqrt{s}$ = 5.220 GeV)

FAIR/SIS100

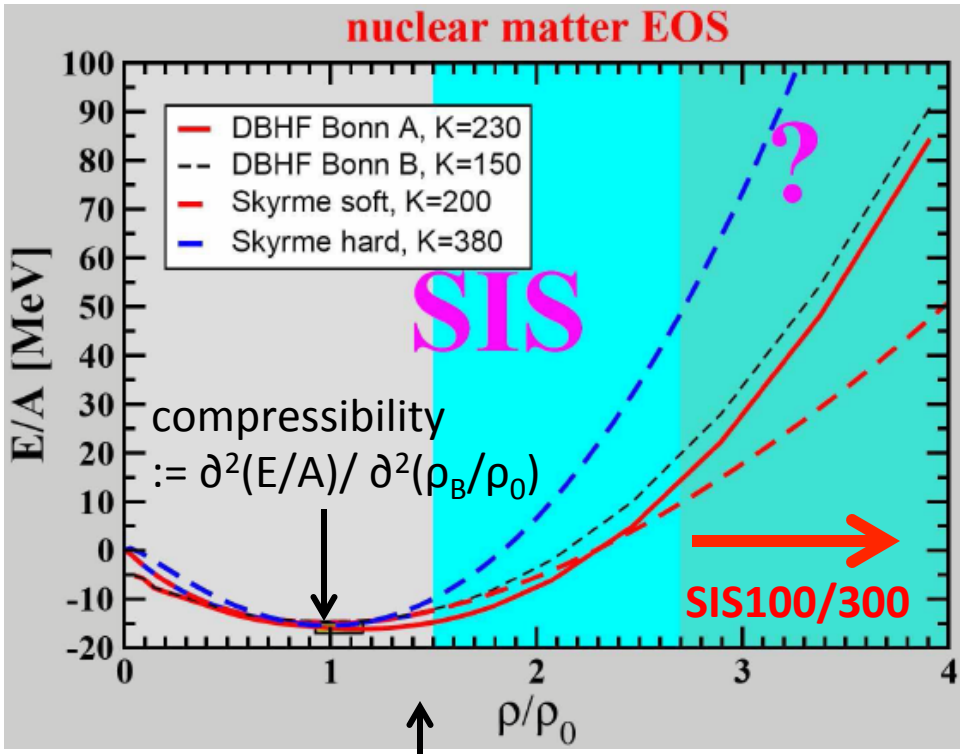
Production via multiple collisions:

Hyperons (s quarks):

1. $pp \rightarrow K^+\Lambda^0 p$, $NN \rightarrow K^+K^-NN$,
2. $\Lambda^0\Lambda^0 \rightarrow \Xi^- p$, $\Lambda^0 K^- \rightarrow \Xi^- \pi^0$
3. $\Lambda^0 \Xi^- \rightarrow \Omega^- n$, $\Xi^- K^- \rightarrow \Omega^- \pi^-$

Antihyperons (anti-s quarks):

1. $pp \rightarrow \Lambda^0\Lambda^0 pp$
2. $\Lambda^0 K^+ \rightarrow \Xi^+\pi^0$,
3. $\Xi^+ K^+ \rightarrow \Omega^+ \pi^+$.



C. Fuchs, Prog. Part. Nucl. Phys. 56, 1 (2006)

study the response of nuclear matter at different densities

favored at high ρ_B

Multi-strange hyperons production at **threshold (FAIR/SIS100)** beam energies proceeds dominantly via strangeness exchange reactions in **multistep processes**

Strong sensitivity of production yields (& flow!) to **the compressibility of baryonic matter**

Observable: strangeness yields

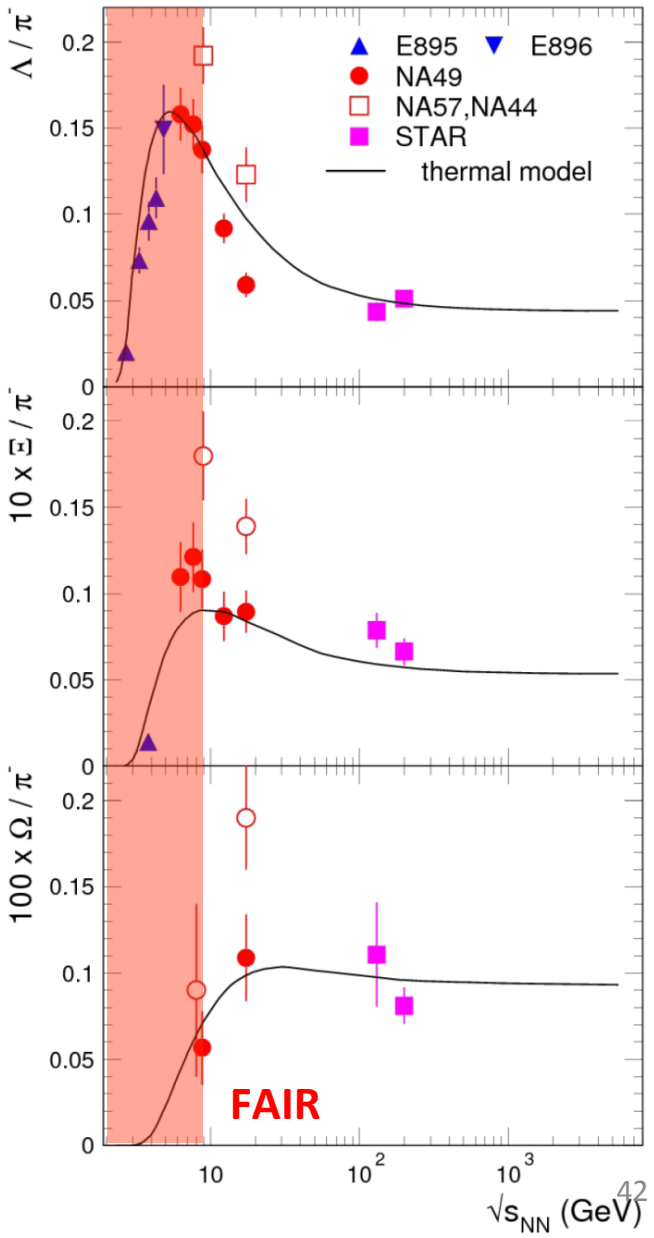
Several anomalies in excitation function of several observables in NA49@SPS at **$\sqrt{s_{NN}}$ ~ 7-9 GeV (FAIR/SIS300)**

Still under debate:

- hadron gas → onset of deconfinement
- baryon dominated → meson dominated matter

See: arXiv:0710.0118v2 [nucl-ex] 15 Oct 2007
Andronic et al. Nucl. Phys. A 772, 167 (2006)

Required: **Precision & high statistics** measurements of excitation function of **strange particle production and propagation (flow), including Λ, Ξ, Ω, ϕ**

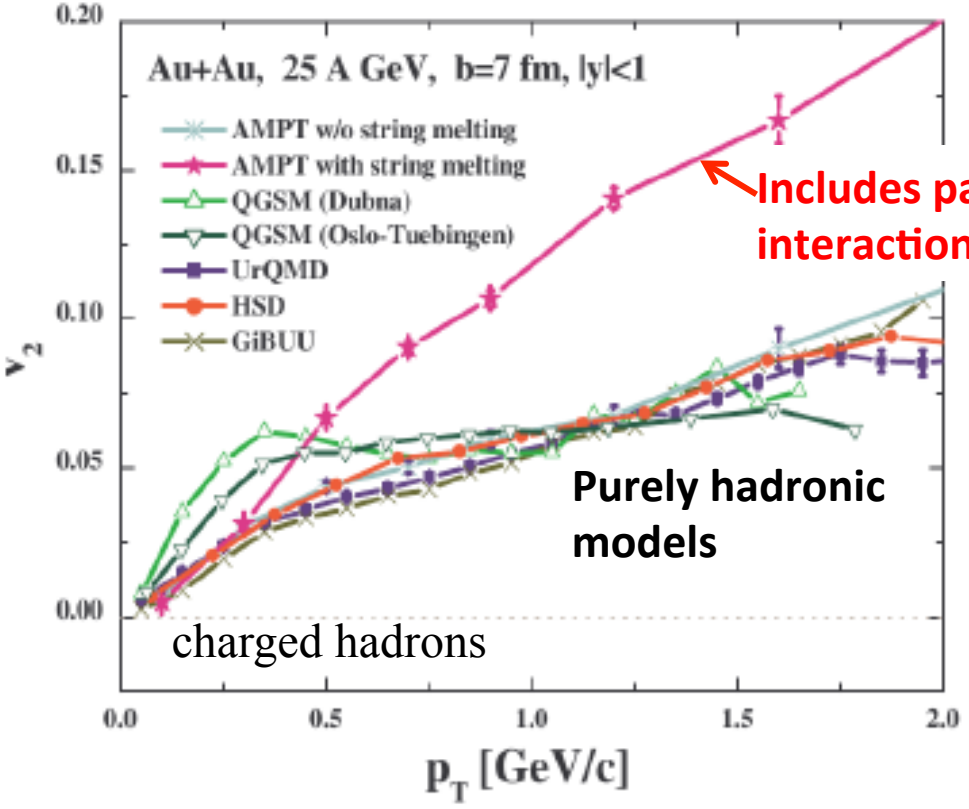


Andronic et al. Nucl. Phys. A 772, 167 (2006)

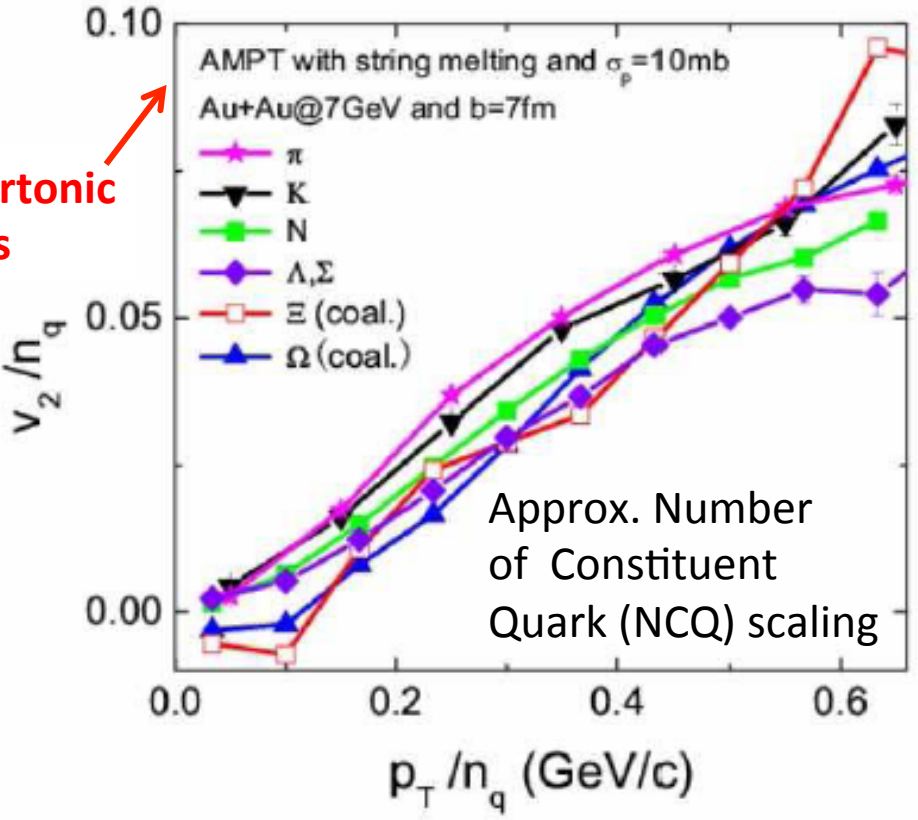
Observable: Elliptic flow

AMPT model: Au+Au, $\sqrt{s_{NN}}$ = 7 GeV

B. Friman et al. CBM Physics Book, Springer Verlag, 2011



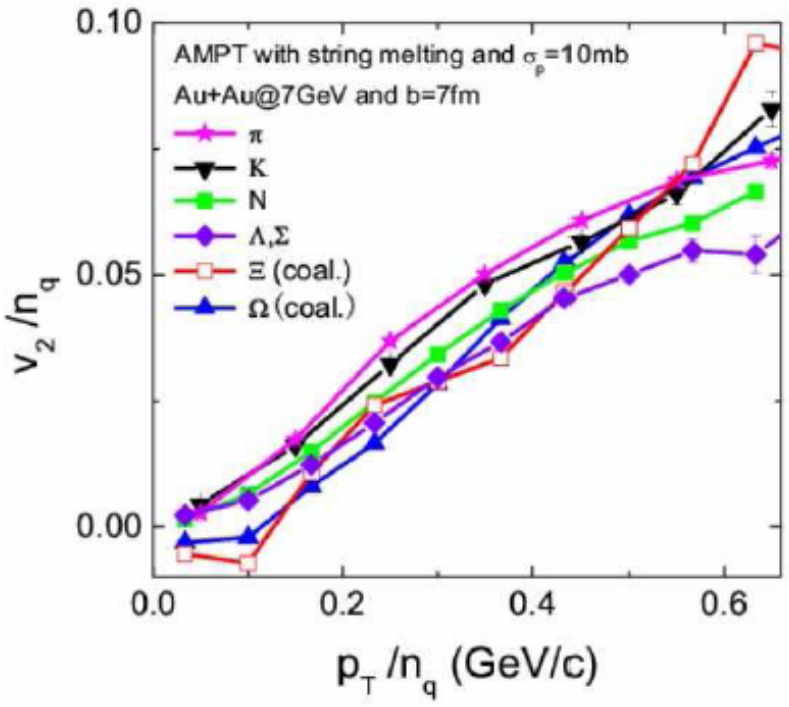
Includes partonic interactions



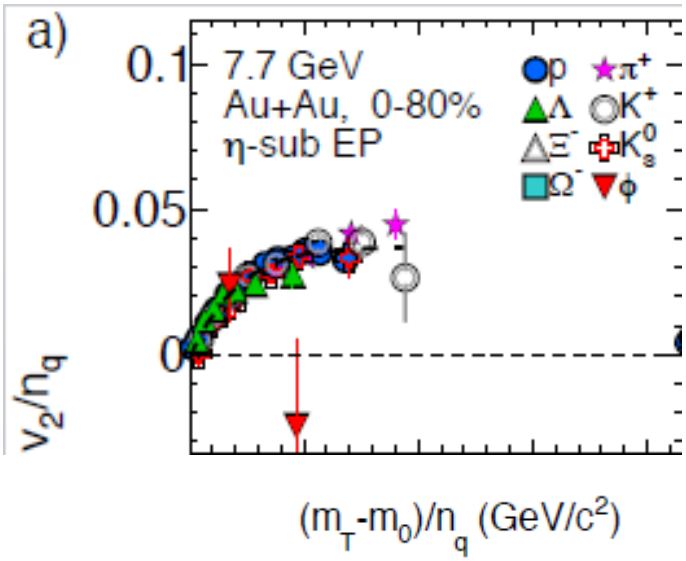
- AMPT: partonic phase expected to show up in **increased flow** and **NCQ scaling**
- NCQ scaling would also hold for multi-strange particles (to take with cautious)

→ Look for onset of these phenomena in flow excitation functions (small steps)

Elliptic flow (v2): physics perspectives at FAIR



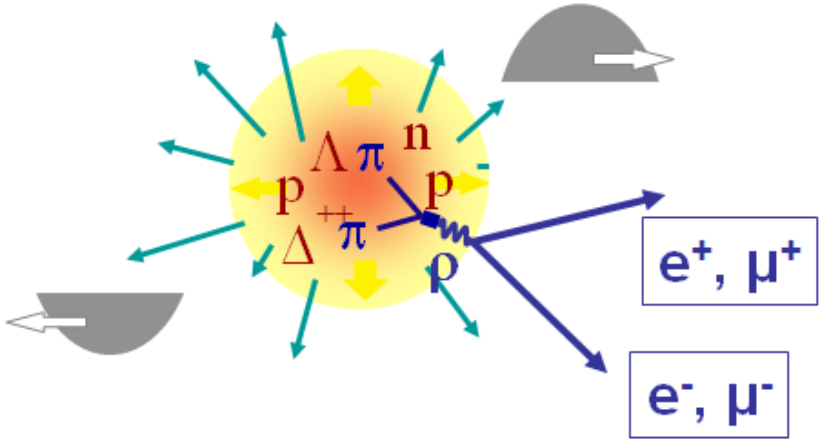
STAR BBES: arXiv:1301.7224v2 [nucl-ex] 31 Jan 2013



At FAIR energies (sqrt(s) ≤ 9.2 GeV), CBM will provide:

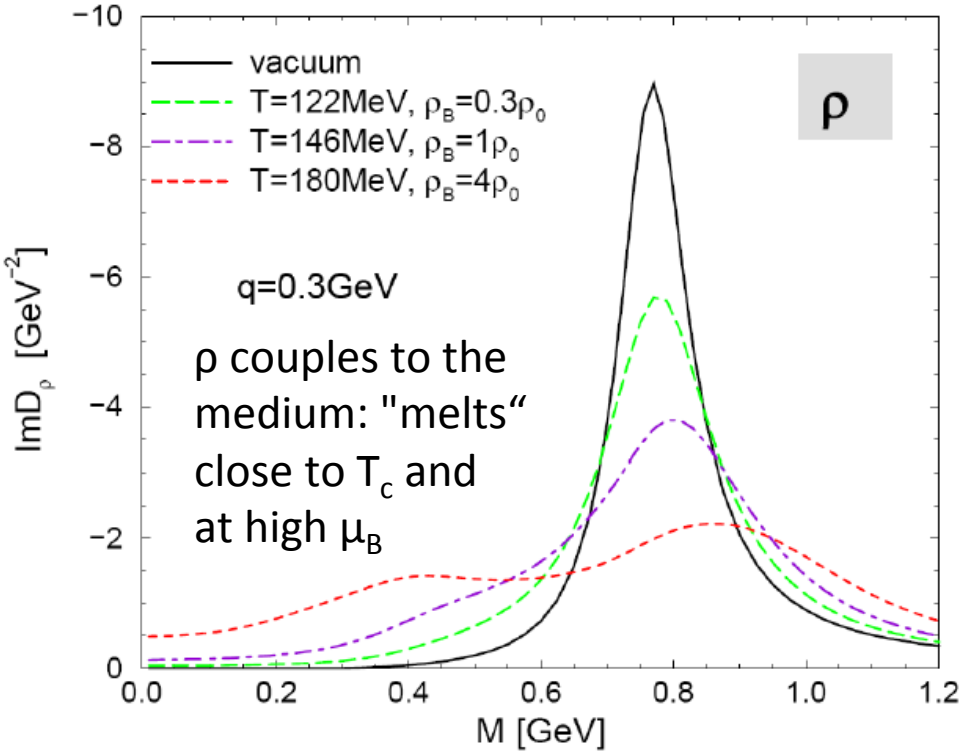
- **More statistics,** in particular for multi-strange particles: only 2 v2 data points available with large errors for ϕ, none for Ξ, Ω
- **More statistics for** anti-strange particles (even more limited statistics) & anti-protons
- 1st measurement of higher hyperon resonances (ex: $\Sigma^{*\pm}$) decay predominantly inside the fireball (very sensitive to early coll. evolution)
- **1st measurement of open (& hidden) charm flow**
- **More precise systematic studies** (v2=f(A, E_{beam}, centrality)) to constrain the models
- **Futher theoretical investigations** to understand hadronic effects more in detail

Observable: spectral function of light vector mesons



ρ, ω, ϕ decaying into leptons pairs
→ Penetrating probes
(e.g. vacuum lifetime of ρ: τ_0 = 1.3 fm/c)

Rapp et al., Adv. Nucl. Phys. 25 (2000) 1,hep-ph/9909229



Model prediction: **modifications of their spectral function in dense baryonic matter**
(connection to chiral symmetry restoration ?)

CBM will investigate these effects **at very high net baryon densities (ρ_B)**
(no measurement between 2-40 AGeV beam energy where max. ρ_B can be achieved)

Observable: event-by-event yield distributions

lQCD: **sharp peak of χ near QCD critical point (CP)**
↔ χ connected to **fluctuations** & **correlations between conserved quantum numbers** (e.g. baryon, strangeness, charge)

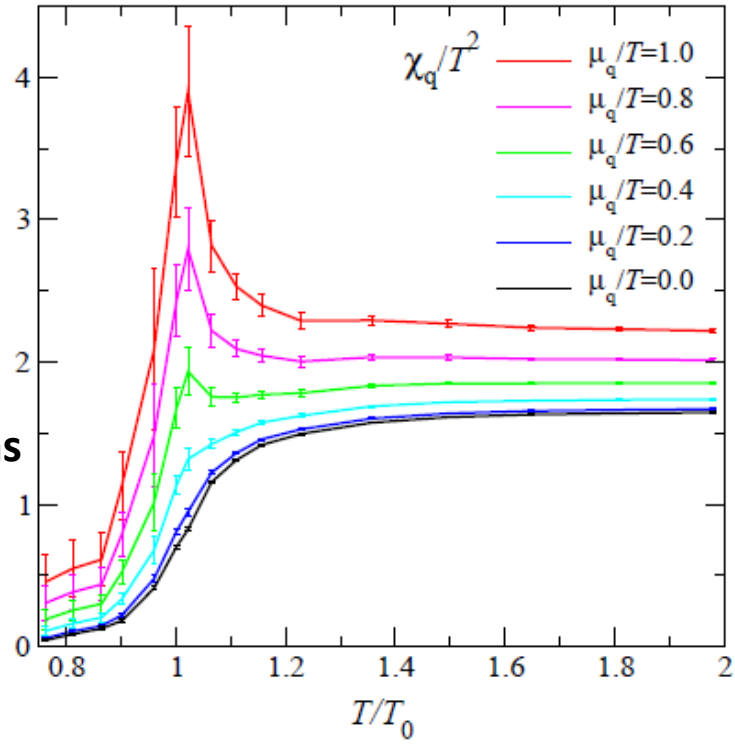
→ **Search for non-monotonous excitation functions of particle yield fluctuations (e.g. net-proton) & yield ratio fluctuations (e.g. p/π, K/π, K/p)**

However, CP effects could be too small:
- correlation length « L » limited by **system size** & **lifetime**
- may be washed out by sub-sequent **hadronic interactions**

2nd moment ~ L^2 (no CP effect seen in STAR BES)

Higher moments: 3rd (skewness) & 4th (kurtosis) ~ L^{4-5-7}
→ more sensitive to CP effects
→ but: more demanding in statistics

lattice QCD (lQCD):
quark number susceptibility χ_q
C.R. Allton et al., Phys. Rev. D 68, 014507(2003)



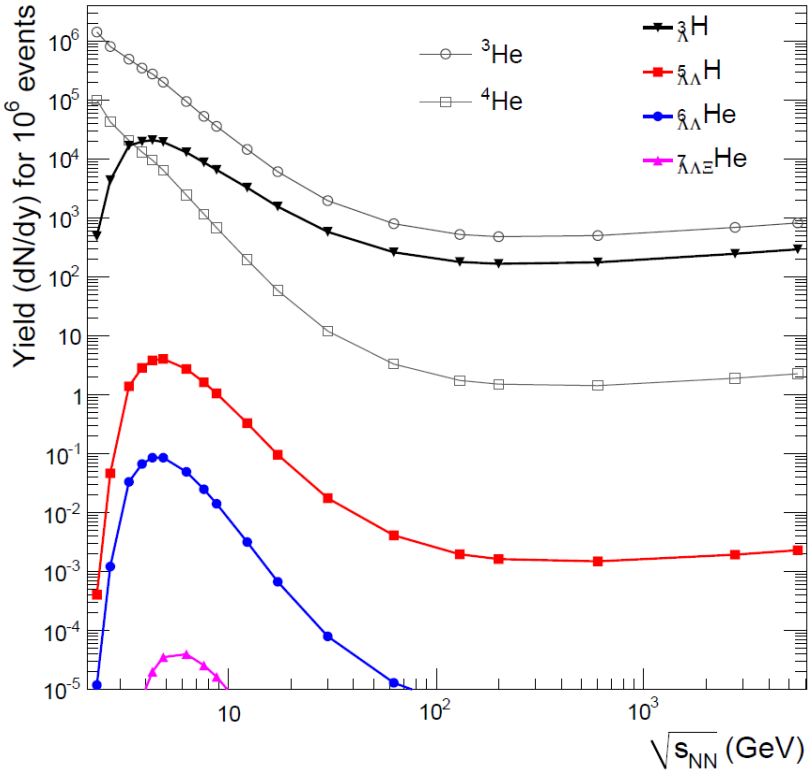
CBM will measure **vey high statistics** of protons & (multi-)strange particles (& anti-particles)

CBM physics cases and observables IV

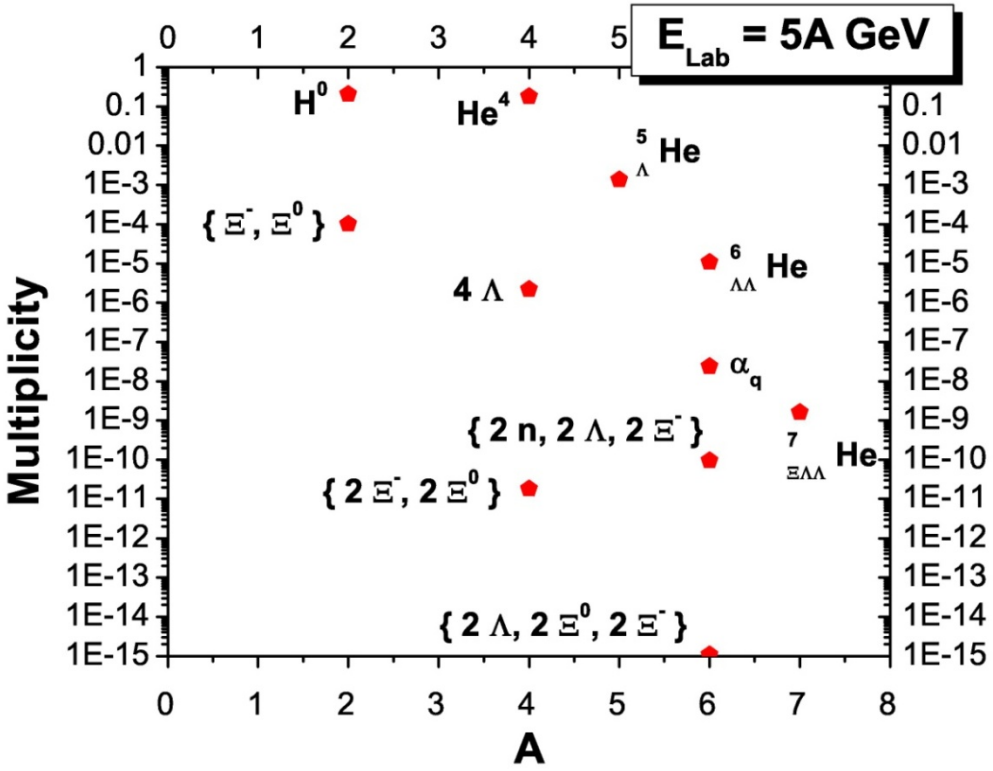
Hypernuclei, strange dibaryons and massive strange objects

Observables:

- Single and double hypernuclei in heavy ion collisions at SIS100
- Search for strange matter in the form of strange dibaryons and heavy multi-strange short-lived objects.



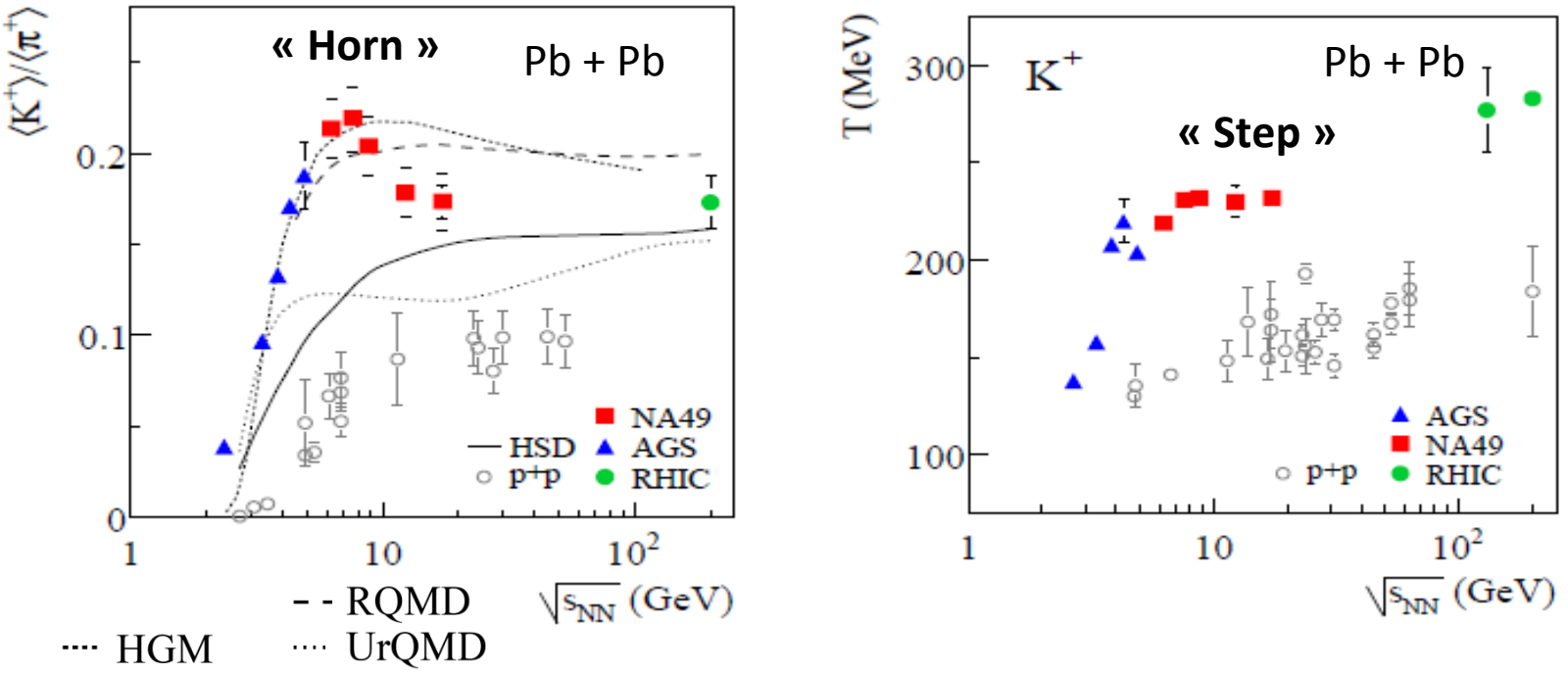
A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stöcker, Phys. Lett. B697 (2011) 203



H. Stöcker et al., Nucl. Phys. A 827 (2009) 624c

SPS & RHIC results

Intriguishing high-ρ_B region



Several anomalies observed by **NA49 (CERN-SPS)** in the excitation functions of various observables measured in A+A collisions

C. Alt et al., NA49 collaboration, Phys. Rev. C 77, 024903 (2008)

- around the same beam energy of 30 GeV/nucleon ($\sqrt{s_{NN}}$ ~ 8 GeV)
- not observed in p+p collisions -> (dense) nuclear matter effect
- not reproduced by hadronic models → **onset of deconfinement ?**

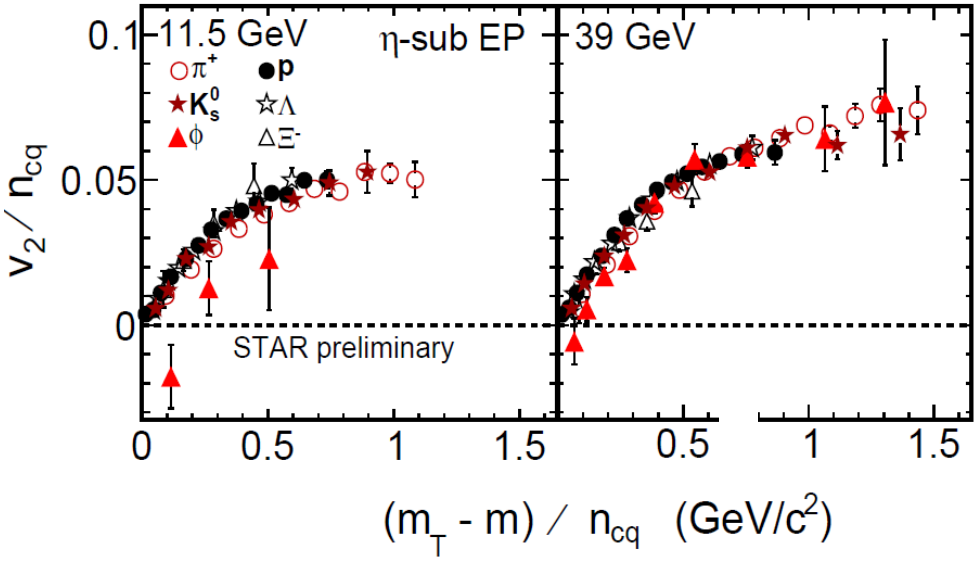
Anomalies confirmed by beam energy scan of STAR

B. I. Abelev et al., STAR Collaboration, Phys. Rev. C 81, 024911 (2010)

Intriguishing high-ρ_B region

S. Shi, STAR collaboration, arXiv:1201.3959v1 [nucl-ex] (2012)

0–80% central Au+Au collisions



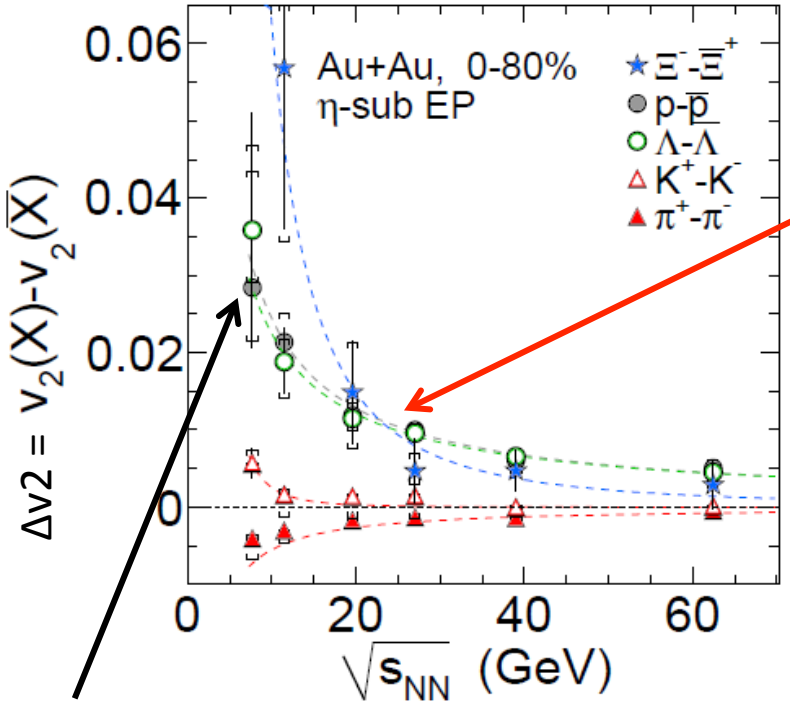
fall-off of ϕ v2 at low $\sqrt{s_{NN}}$ < 11.5 GeV (?)

→ onset of deconfinement ?

CBM will measure excitation functions of **several observables**:
bulk observables but also **rare probes**: J/ψ (& ψ'), open charm, ϕ & multi-strange hyperons **in A-A collisions and also in p-p and p-A**

Elliptic flow (v2): STAR BES

STAR beam energy scan:
0–80% central Au+Au collisions
arXiv : 1301.2348 (STAR) – PRL (in print)



Large errors !
due to limited statistics of strange particles & anti-protons at low energy

Idea: NCQ scaling suggest same v2 for particles and anti-particles (same number of constituent quarks)

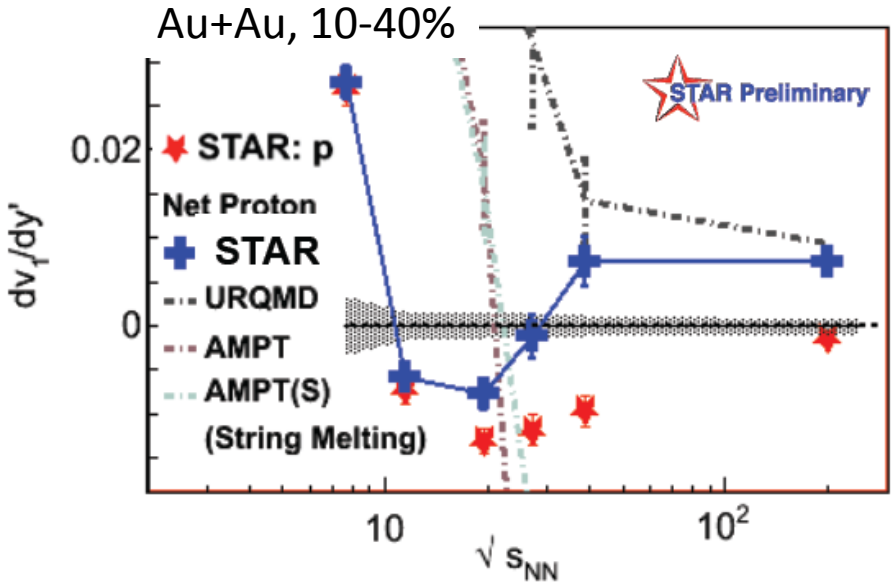
→ however, finite Δv2 observed:
Δv2 increasing going to low energy
Δv2 more important for baryons

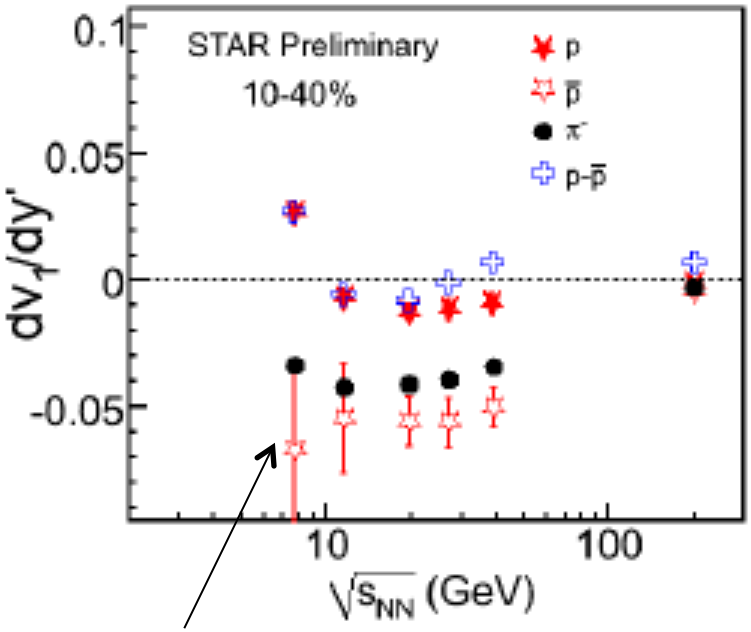
NCQ violation could be an effect of:

- Baryon transport to midrapidity:
  Phys. Rev. C 84, 044914 (2011)
- hadronic mean-field potentials
  Phys. Rev. C 85, 041901 (2012)
- **qualitative** agreement bwt models & data

→ show **particular importance of hadronic effects at low energy**

STAR BES: Directed flow v1 of protons at mid-rapidity





Net-protons signal should correspond to only stopped participants

dv1/dy slope of net-protons at mid-rapidity changes sign twice: minumum between 11.5 – 19.6 GeV → **change in compressibility?**

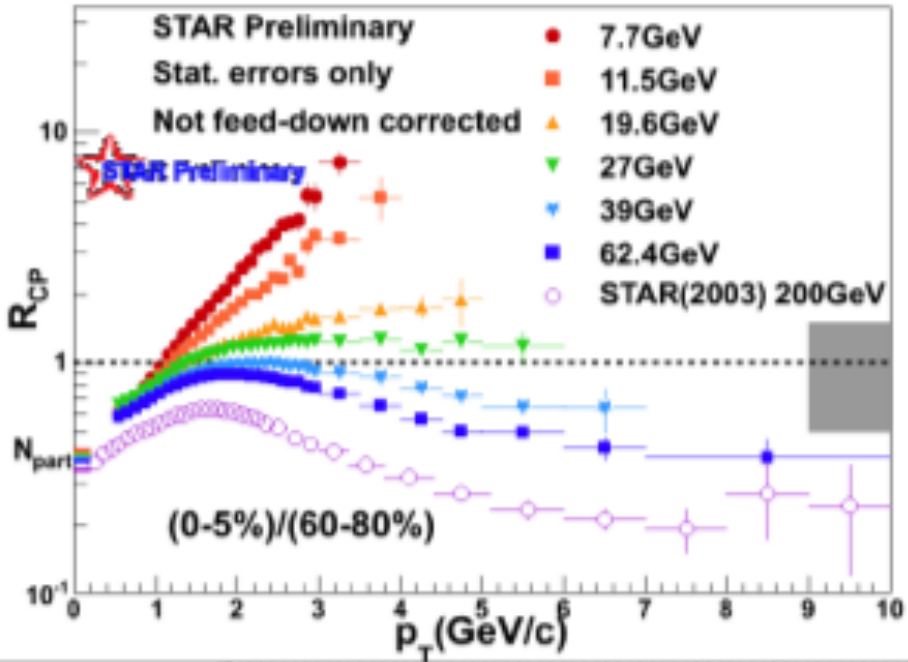
Transport models UrQMD and AMPT can not reproduce observed net-proton v1 slope

However: other physics sources are under investigation → **need more Theory input**

Large errors for anti-proton dv1/dy slope!

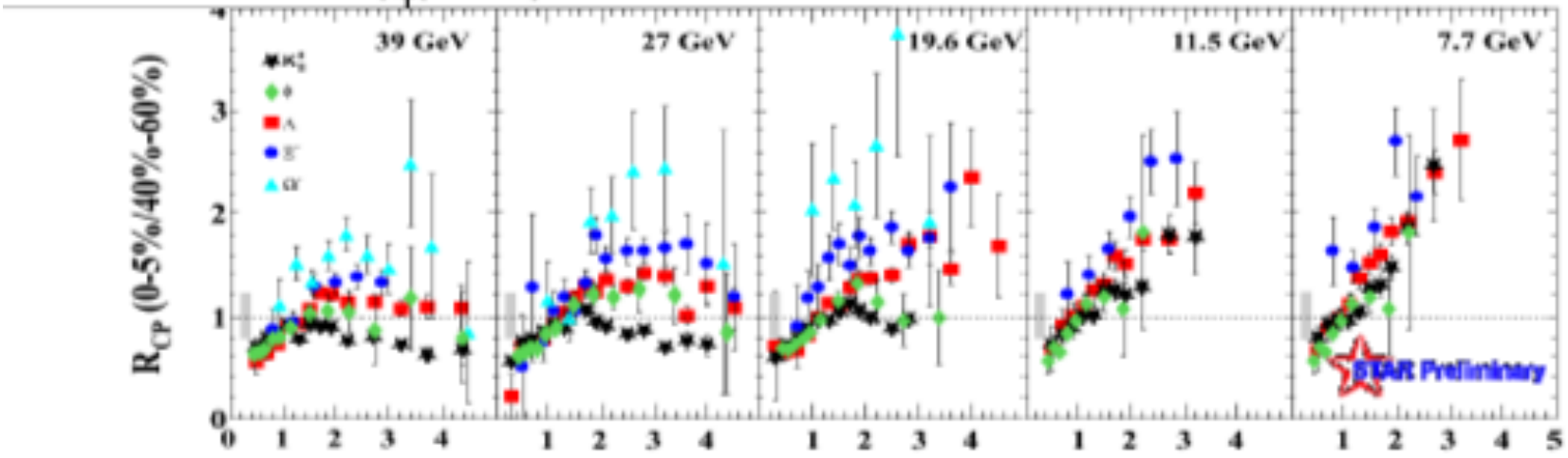
→ Experiment:
need **more statistics, centrality dependence, smaller energy steps at FAIR energies**

STAR BES R_{CP}: high-pT suppression as a clear evidence of energy loss by color objects (quarks) in a color medium (QGP)



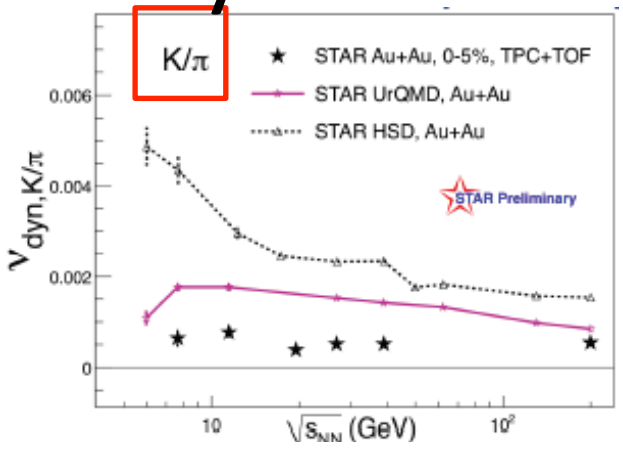
- R_{cp} suppression NOT seen at lower energies
  - Possible disappearance of QGP?
  - Relative contributions of soft physics and hard scattering

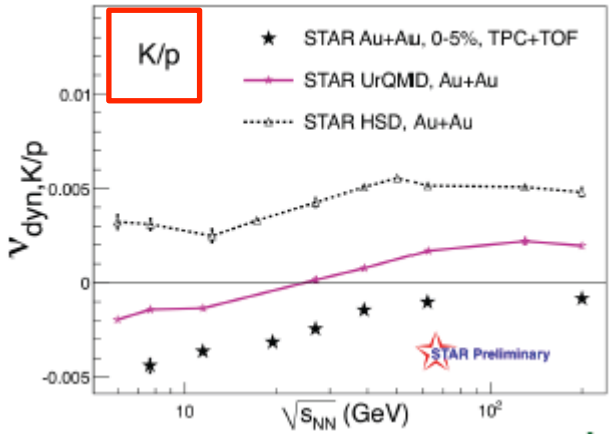
All Charged Particles

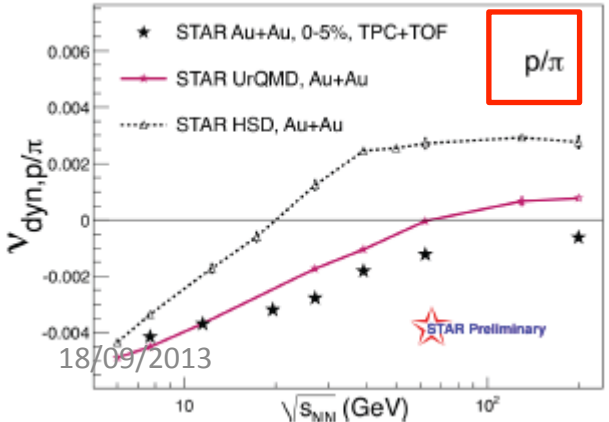


Identified Particles

Dynamical fluctuations in STAR BES







Particle ratio **dynamical** event-by-event fluctuations ν_{dyn}

→ dynamical := substracted from trivial statistical fluctuations (using mixed event ensembles)

Constant …

…. or **monotonic excitation functions** of particle ratio fluctuations observed (trend consistent with UrQMD)

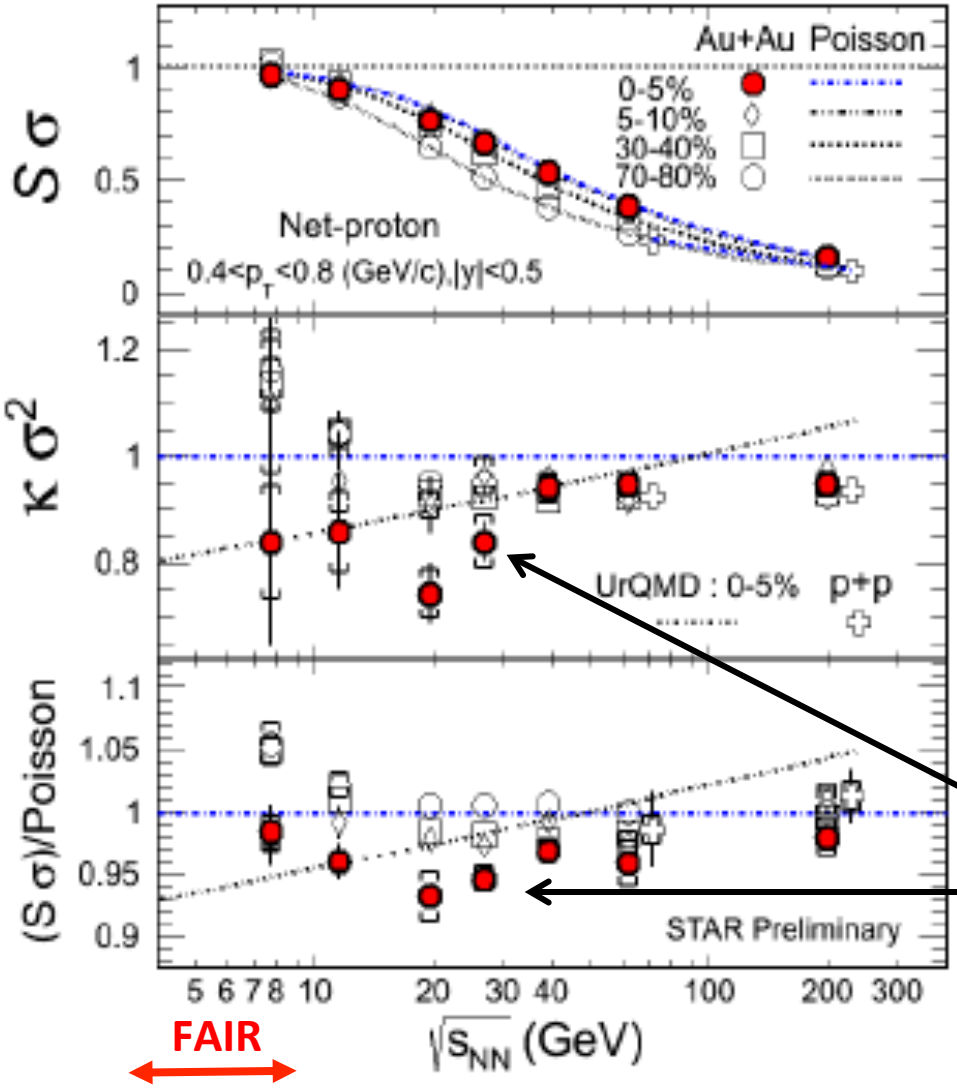
However: CP effects could be too small:

- correlation length « L » limited by **system size** & **lifetime**
- may be washed out by sub-sequent **hadronic interactions**

But: 2nd moment ~ L^2 (only)

Higher moments: 3nd (skewness) & 4th (kurtosis) ~ L^{4-5-7}
→ more sensitive to CP effects

Dynamical fluctuations in STAR BES



Higher moments of net-proton yield distrib.
↔ connected to **baryon quantum number**

$$\sigma^2 = \langle (N - \langle N \rangle)^2 \rangle$$

$$S = \langle (N - \langle N \rangle)^3 \rangle / \sigma^3 \quad \text{Skewness}$$

$$\kappa = \langle (N - \langle N \rangle)^4 \rangle / \sigma^4 - 3 \quad \text{Kurtosis}$$

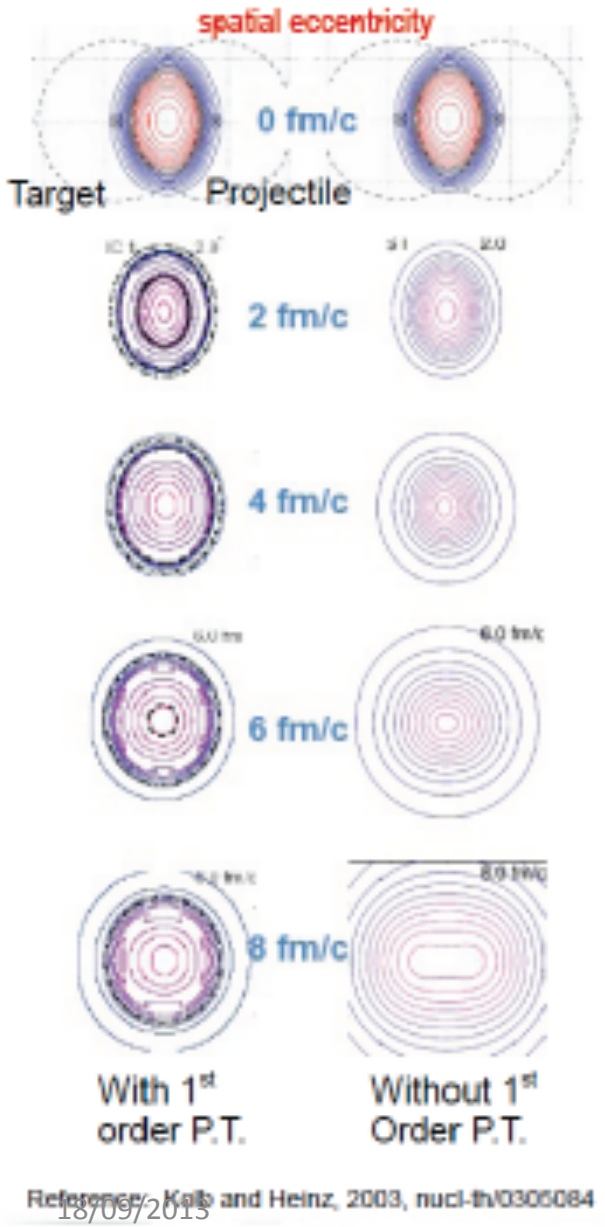
- Idea:
  S & κ measure non-Gaussian fluctuations
  Poisson baseline should reflect pure statistical fluctuations
  (polynomial baseline under way to account for resonance decay effects, etc)

Indications of deviations
w.r.t. Poisson baseline @ sqrt(s) ≤ 27 GeV

But: small effect
& large errors for κ @ sqrt(s) ≤ 11.5 GeV

CBM will measure **vey high statistics** of protons & anti-protons
→ access to **higher moments** of net-proton yield event-by-event distribution with unprecedent precision!

Hanbury-Brown and Twiss correlations



Ideas:

1) Initial out-of-plane excentricity in non-central collisions

2) Stronger in-plane pressure gradients drive in-plane expansion (→ more spherical freeze-out shape)

3) **Measure of freeze-out excentricity** (in coordinate space)**:**

$$\varepsilon_F = \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2}$$

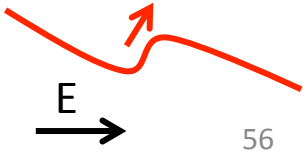
Rx – in-plane HBT radius
Ry – out-of-plane HBT radius

HBT radii w.r.t reaction plane
using 2 particles (ex: pions) correlations

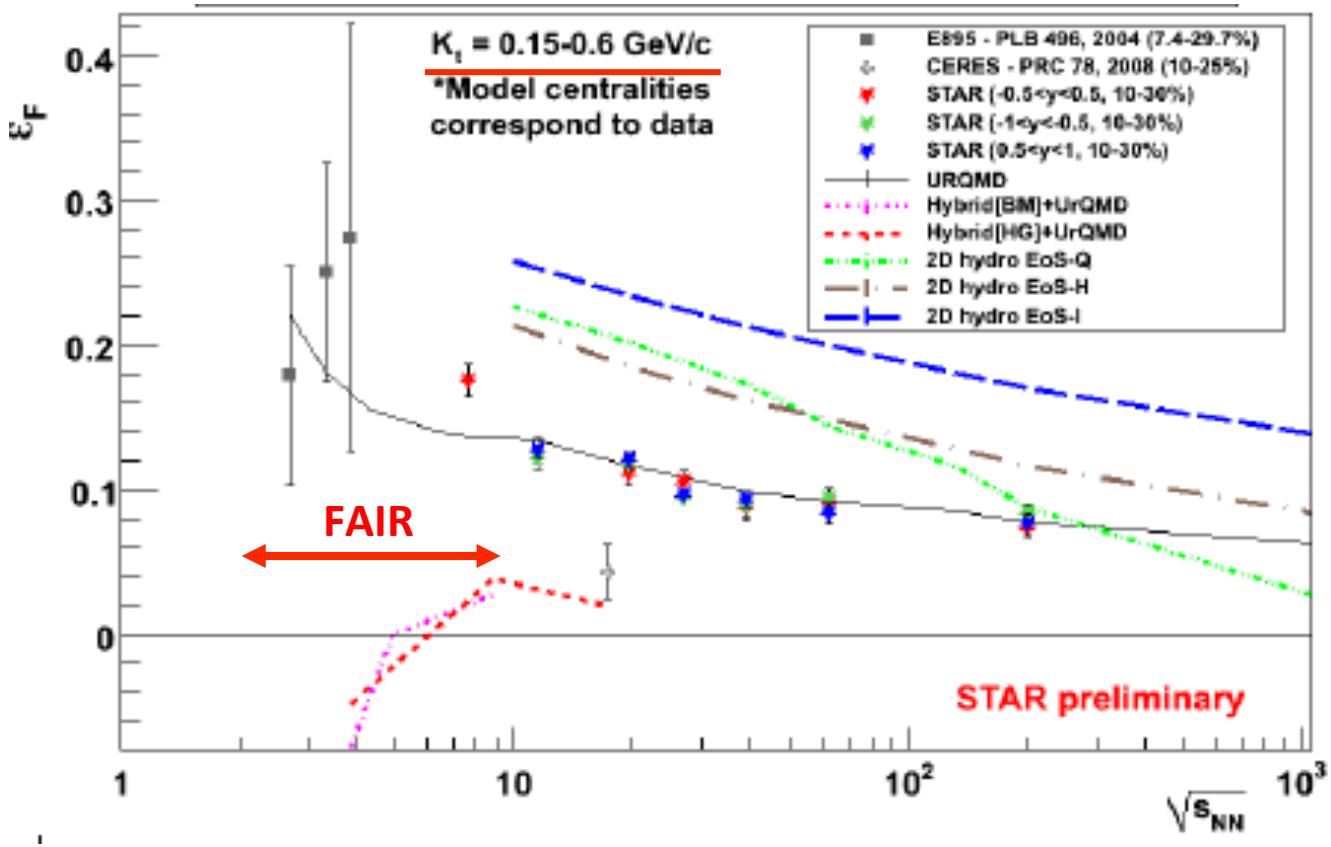
4) Expectation:
ε_F to fall monotonically with increasing energy

5) **Non-monotonic behavior** could indicate a **change in the EoS (softening) related to a 1st order phase transition**

M.Lisa et al., New J.Phys. 13 (2011) 065006
Kolb and Heinz, 2003, nucl-th/0305084



Hanbury-Brown and Twiss correlations



- Smooth decrease from low to high c.m. energies
  No conclusive deviations from UrQMD model observed

- Again: need for **more statistics** (very large errors in AGS data) & **detailed energy scan at FAIR** (small steps)
- Need for **detailed** measurement of ε_F = f(pair momentum or K_t) to probe different part of the source (large K_t bin in STAR data)

Detector development

System	Status	TDR submission
Magnet	design ready	December 2012
Micro-Vertex Detector	successful prototype tests with beams	2014
Silicon Tracking System	design ready, successful prototype tests with beams	December 2012
Ring Imaging Cherenkov detector	design ready, successful prototype tests with beams	spring 2013
Muon Tracking Chambers (MUCH)	prototype MUCH successfully tested with beams	end of 2013
Transition Radiation Detector (TRD)	prototype TRDs successfully tested with beams	2014
Time-of-Flight wall (Multi-gap RPCs)	prototype MRPCs successfully tested with beams	2013
Electromagnetic Calorimeter (ECAL)	design ready, established technology	2013/2014
Projectile Spectator Detector (PSD)	design ready, established technology	spring 2013
DAQ/FLES	prototype tests with beams	2013 – 2016

CBM Technical Design Reports

Project	TDR Submission	TDR Status
Magnet	Dec. 2012	evaluation
STS	Dec. 2012	evaluated (+)
TRD*	2014	preparation
RICH	June 2013	evaluation
TOF	End of 2013	preparation
DAQ*	2014	preparation
FLES*	2014	preparation
MVD	2014	preparation
MuCh*	End of 2013	preparation
PSD	April 2013	evaluation
ECAL*	End of 2013	preparation
ECAL HADES	Mai 2013	evaluation

STS: Silicon Tracking System

TRD: Transition Radiation Detector

RICH: Ring Imaging Cherenkov Detector

TOF: Time-of-Flight wall (MRPCs)

DAQ: Data Acquisition

FLES: First Level Event Selection

MVD: Micro-Vertex Detector

MuCh: Muon Chamber System

PSD: Projectile Spectator Detector

ECAL: Electromagnetic Calorimeter

* to be upgraded for SIS300

Funding CBM@SIS100 (start version)

(according to the CBM pre-construction MoU in prices 2009)

Project	Costs CBM start version @SIS100	secured funding start version @SIS100	additional intended funding start version @SIS100		Costs CBM full version @SIS300
MVD	2.1	0	2.1		2.1
STS	11.5	10.65	1.1		11.5
TRD*	4.0	1.3	2.7		9.6
RICH	5.6	0	5.6		5.6
TOF	6.8	4.6	2.0		6.8
DAQ*	3.0	0.75	2.25		3.9
FLES*	3.0	2.0	1.0		6.0
Magnet	4.3	4.3	0		4.3
MuCh*	4.0	4.0	0		10.6
PSD	1.1	0.9	0.2		1.1
Infrastr.	4.3	4.3	0		4.3
ECAL*	3.0	0	3.0		10.6
Sum in 2009 €	**52.7**	**32.8**	**20.0**		**76.4**
Sum in 2013 € (*1.138)	**60.0**	**37.3**	**22.7**		**86.9**

The funding is considered as secured, as it is covered by German, Russian, Indian, Polish and Romanian FAIR project funds or by commitments of CBM partner institutions

(largely) funded

partly funded

62.2% of the CBM start version is funded

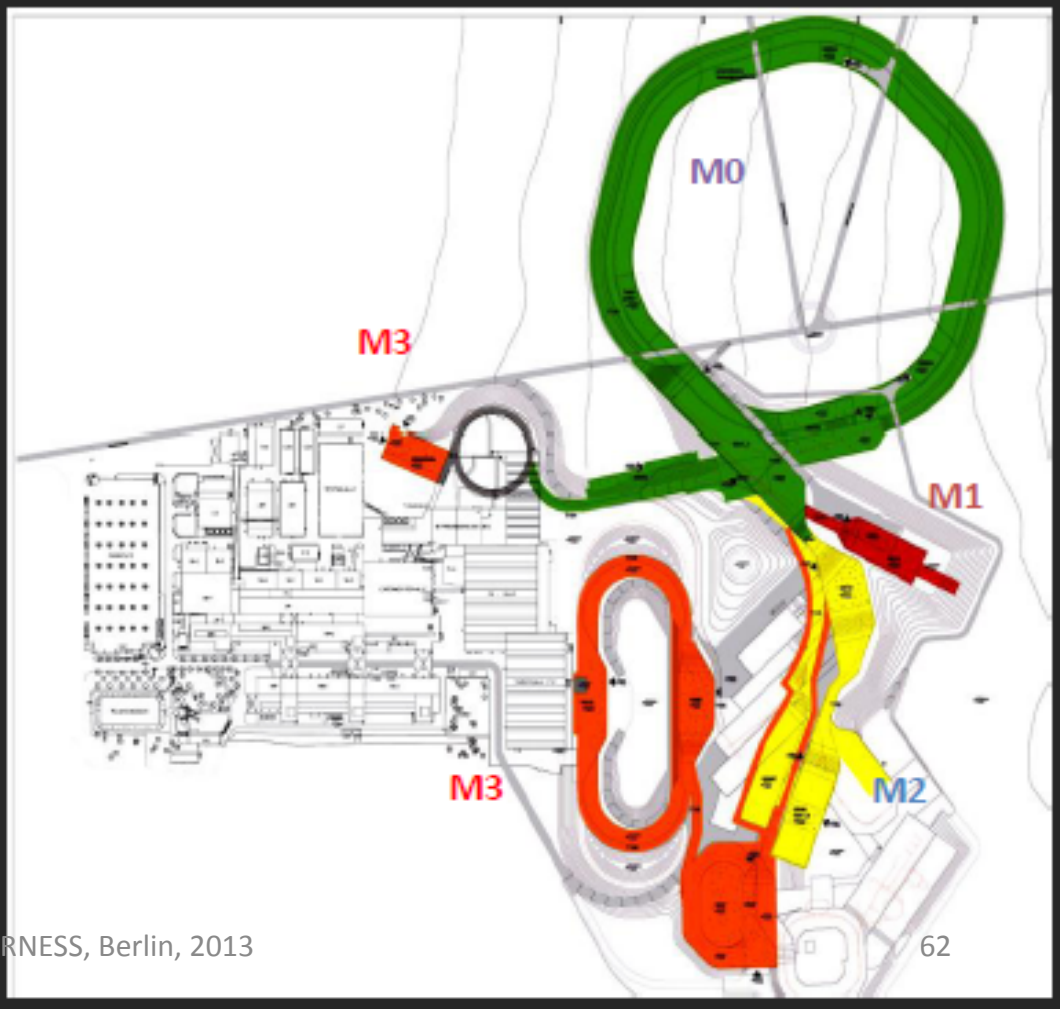
TRD*, DAQ*, FLES*, MuCh*, ECAL*: will be upgraded for SIS300

Staged realization

2012: start of civil construction

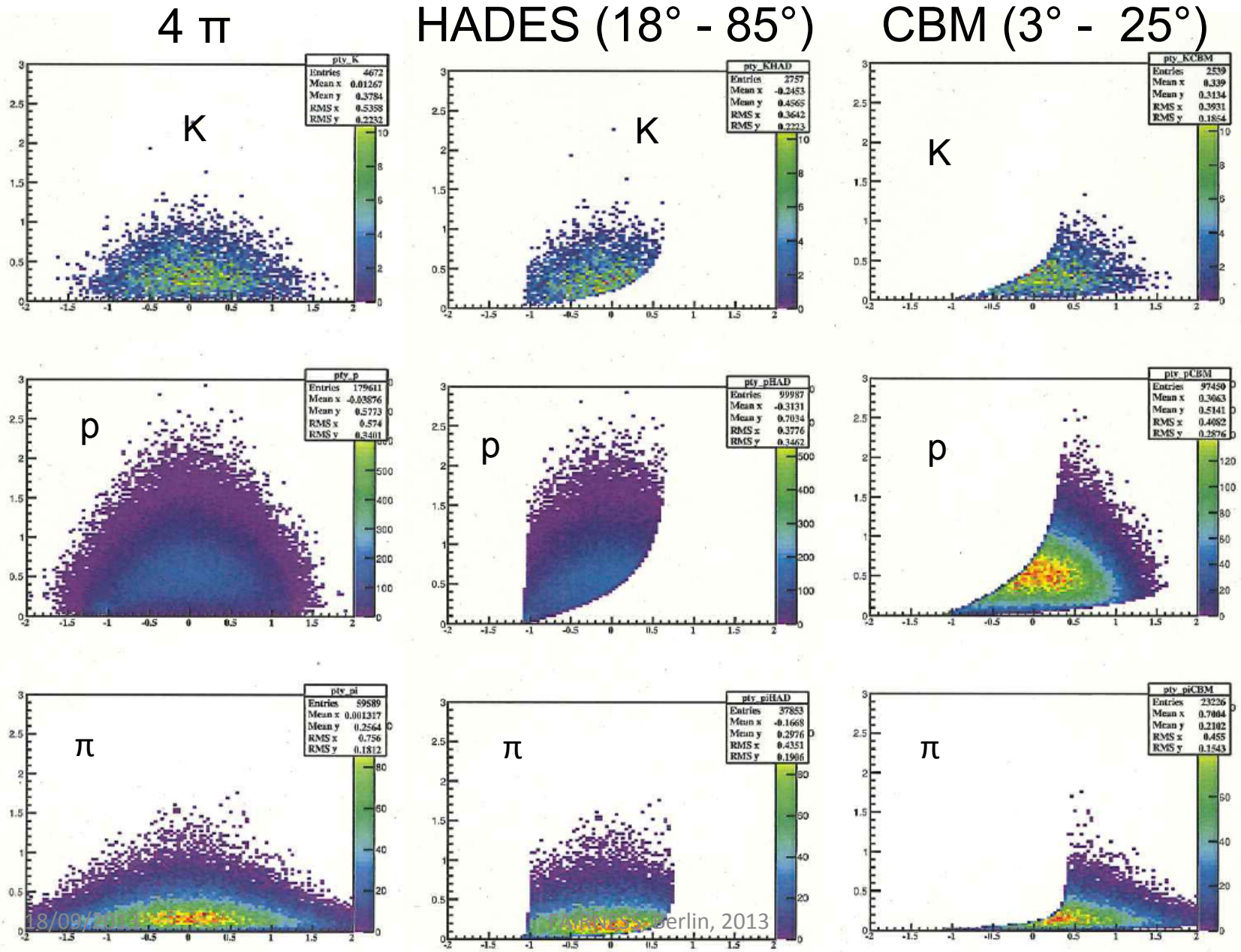
2018: first beam

- Modularized start version:
  - M0: SIS100
  - M1: APPA
  - M1: CBM/HADES
  - M2: NuSTAR
  - M3: PANDA

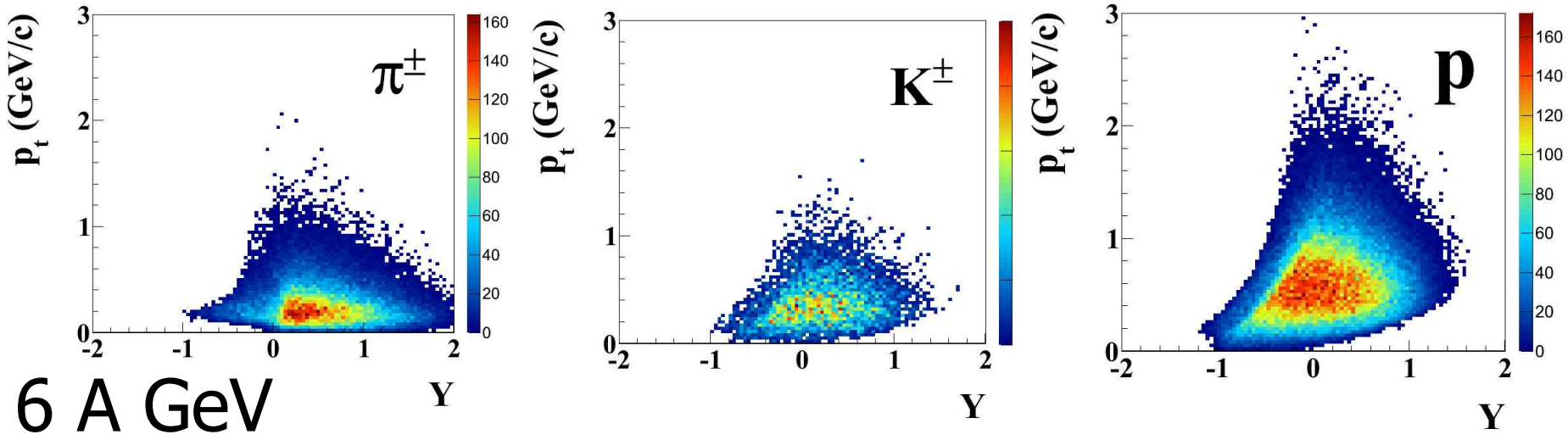


Detector acceptance

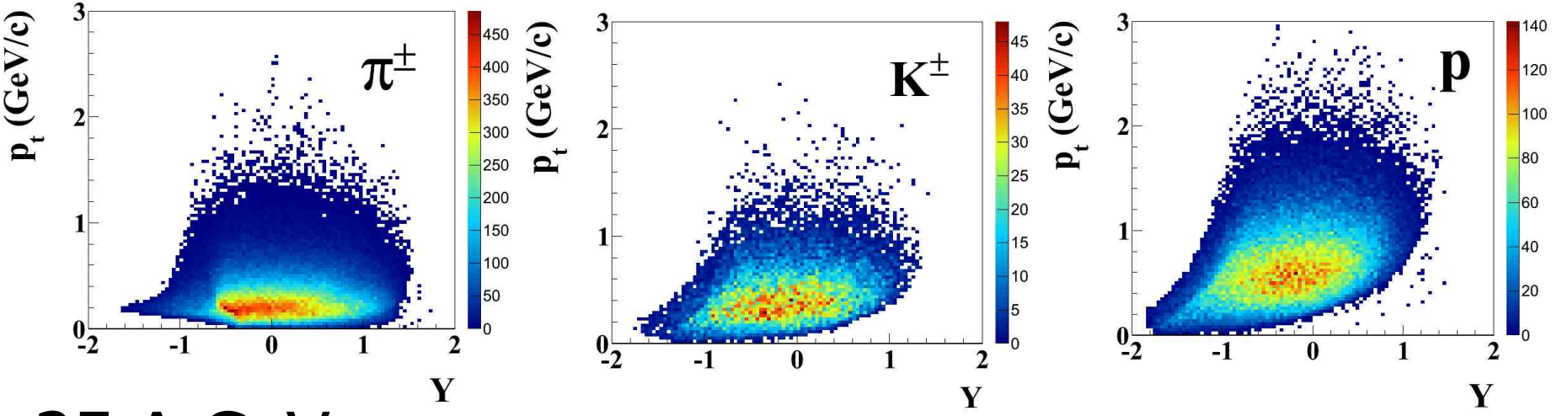
Acceptances for Au+Au collisions at 4 A GeV



CBM acceptance for central Au+Au collisions at SIS100 and SIS300 beam energies



6 A GeV



25 A GeV

ρ → e^+e^-

J/Ψ → e^+e^-

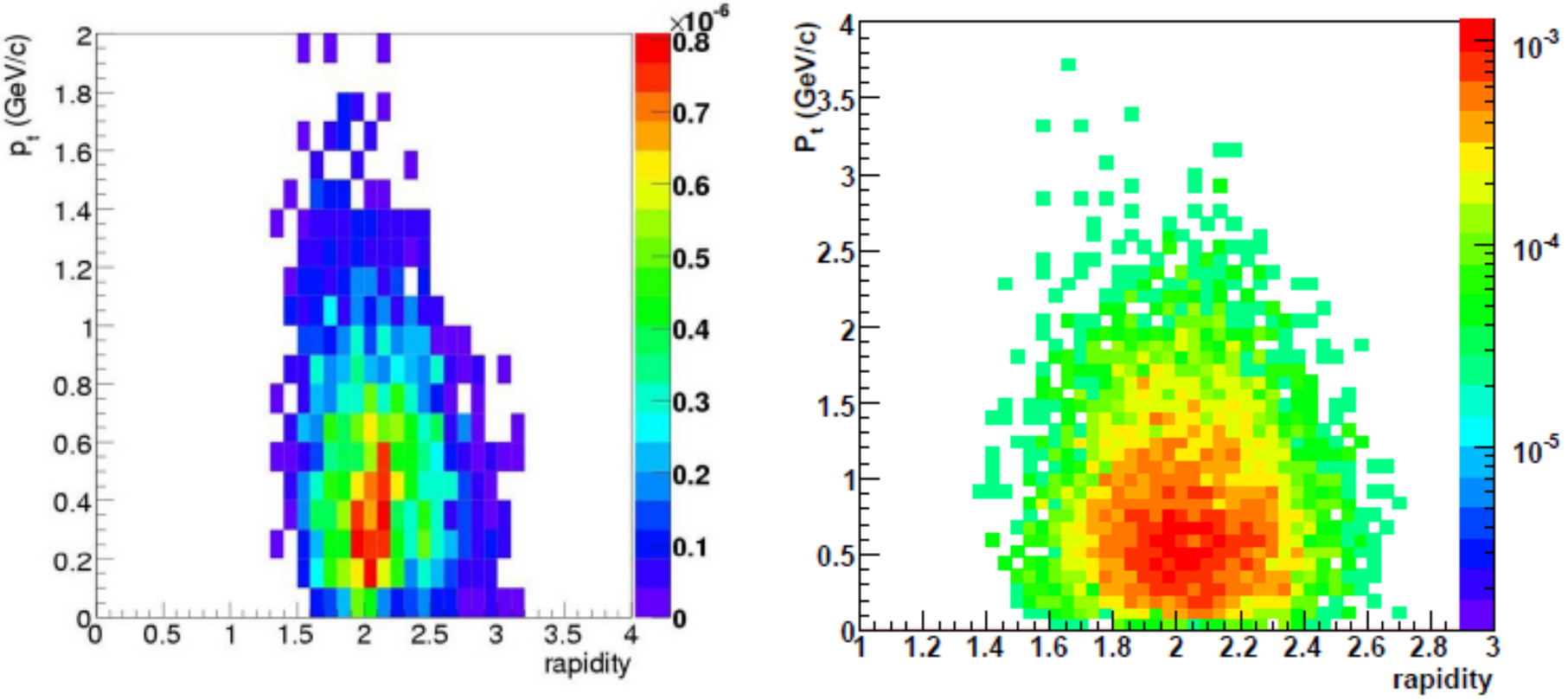


Fig. 3.17 Phase space distribution in transverse momentum versus rapidity for reconstructed and identified ρ mesons (left) and J/ψ mesons (right) in central Au+Au collisions at 25 AGeV beam energy (midrapidity = 2) (color online).

ρ → μ⁺μ⁻

J/Ψ → μ⁺μ⁻

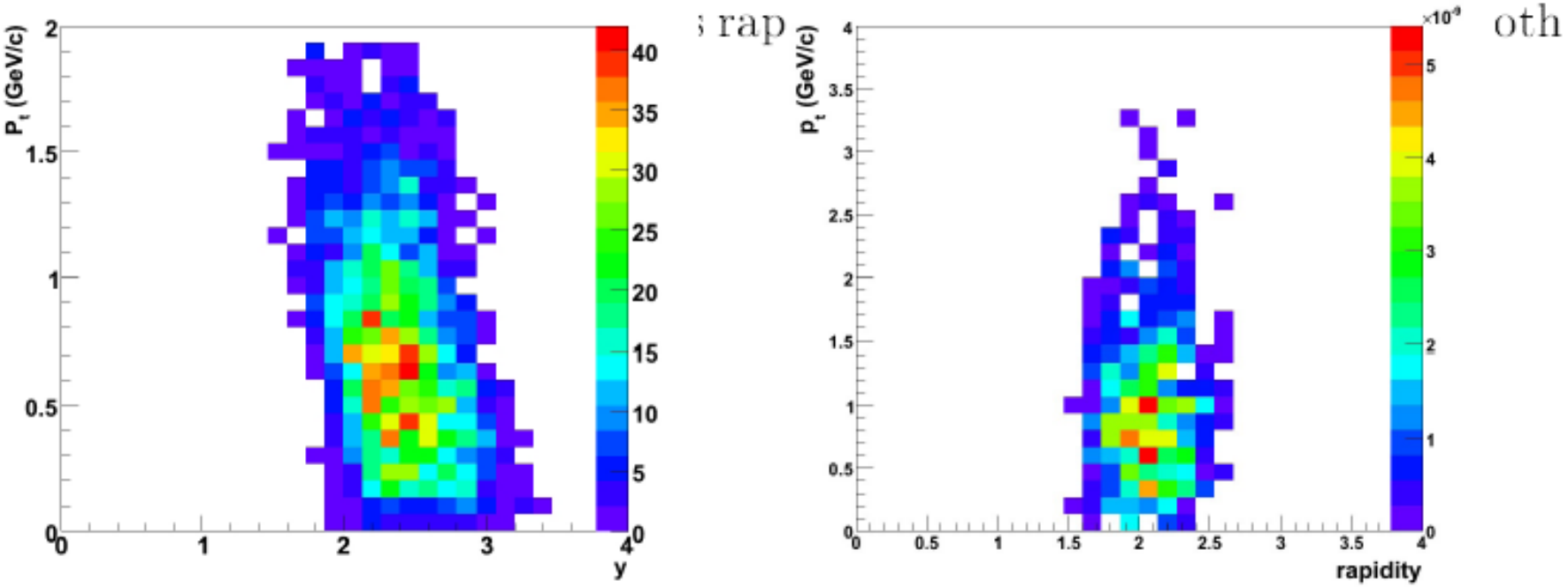


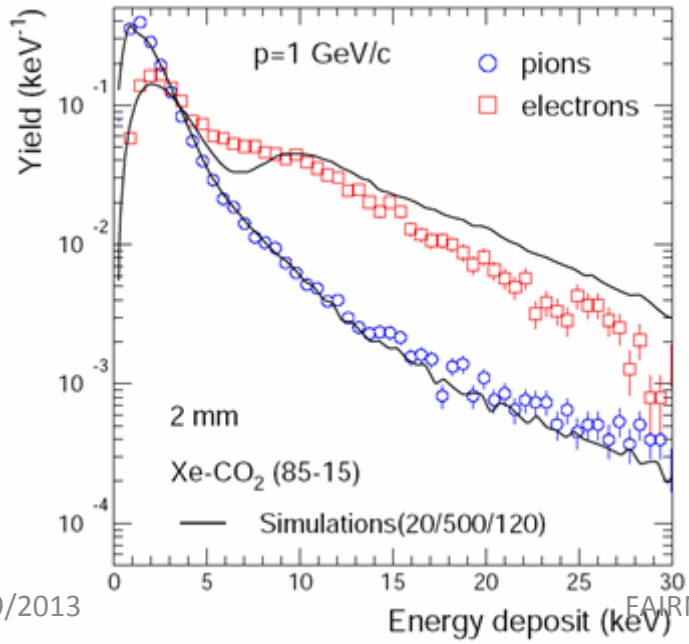
Fig. 3.23 Phase space coverage for dimuon pairs as a function of transverse momentum and rapidity calculated for central Au+Au collisions at 25A GeV beam energy (midrapidity is at y = 2). Left panel: ρ mesons, both "hard-hard" and "hard-soft" muon pairs were included in the analysis . Right panel: J/ψ mesons (color online).

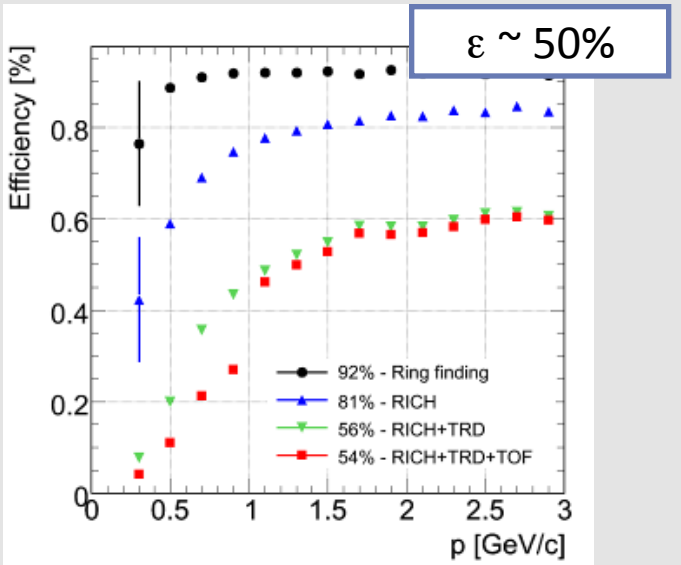
Particle ID

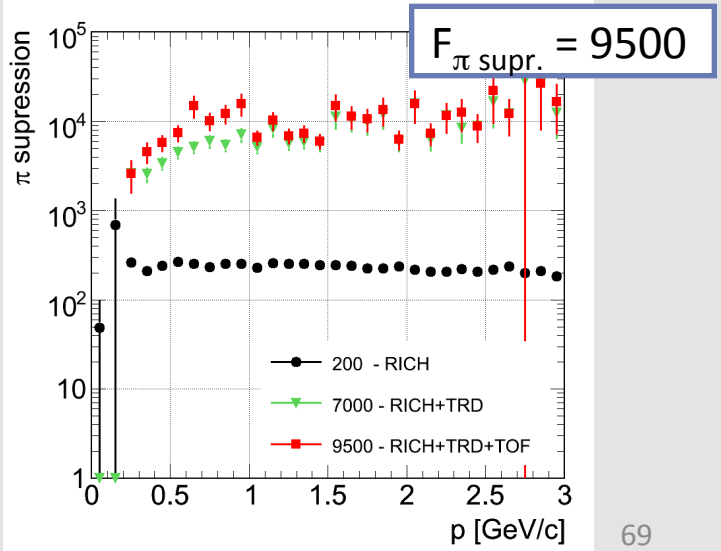
Electron identification using TRD

- TRD: strategy and R&D
  - Thin gap design based on ALICE TRD
- 3 TRD detectors, each consist of 4 layers

Use statistical analysis of the energy loss spectra to further discriminate π





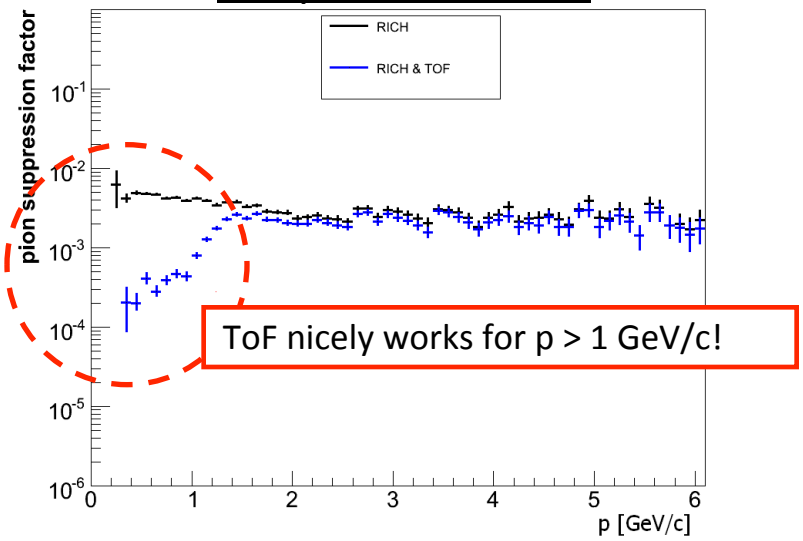


Electron option

Electron identification using Time-Of-Flight information

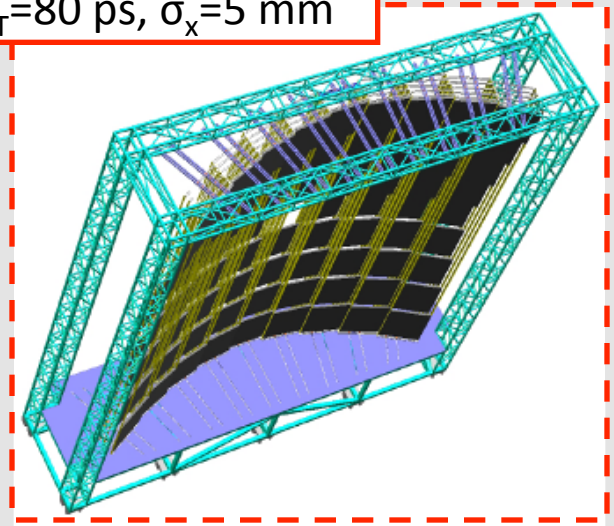
Electron option

π supression factor

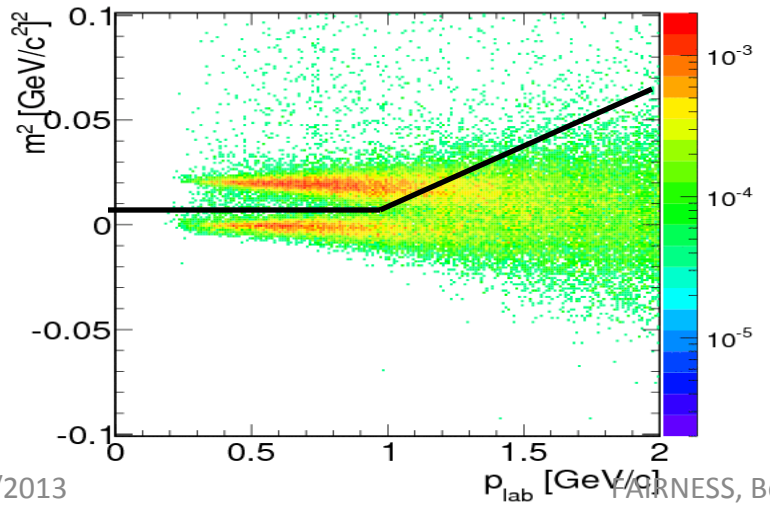


ToF nicely works for p > 1 GeV/c!

σ_T=80 ps, σ_x=5 mm

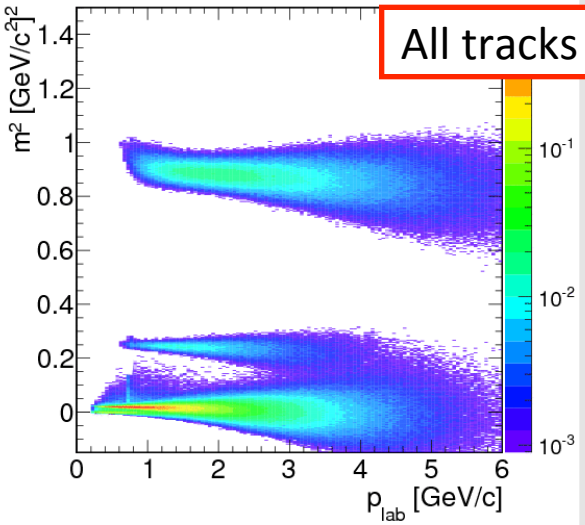


RICH identified electrons in TOF



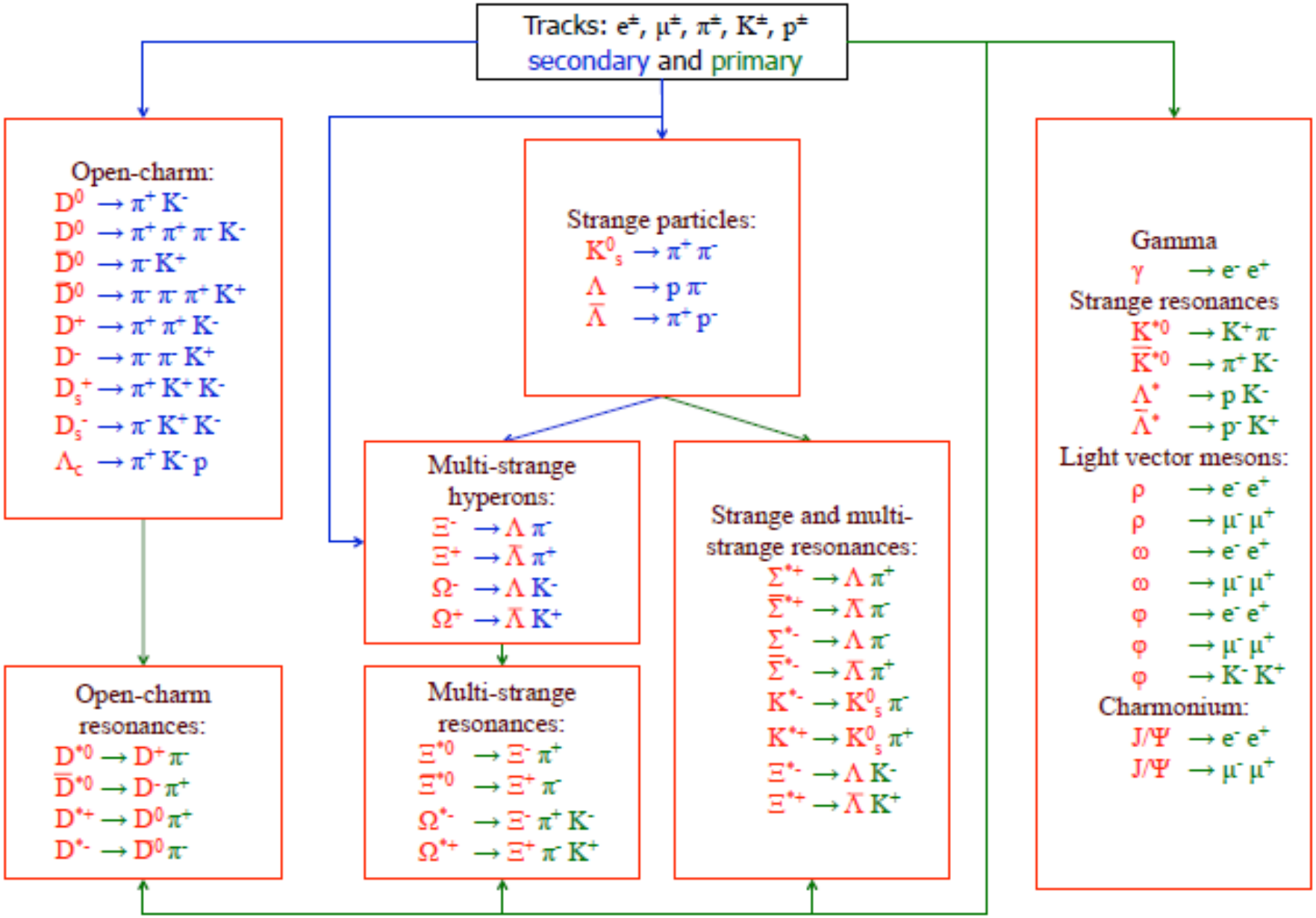
m^2 vs momentum distribution

All tracks



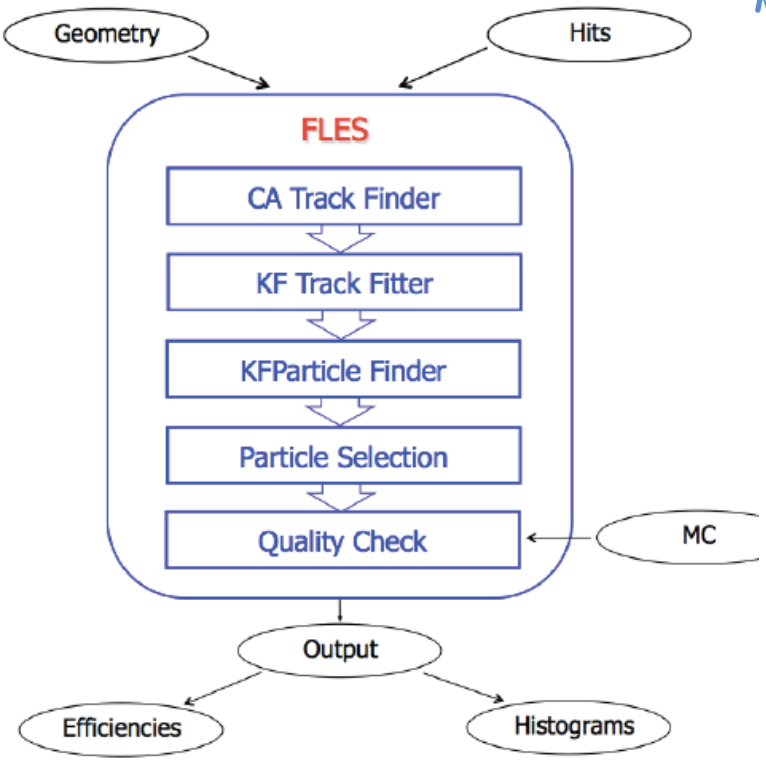
Trigger

KFParticle finder: reconstructed channels (simultaneous reco.)

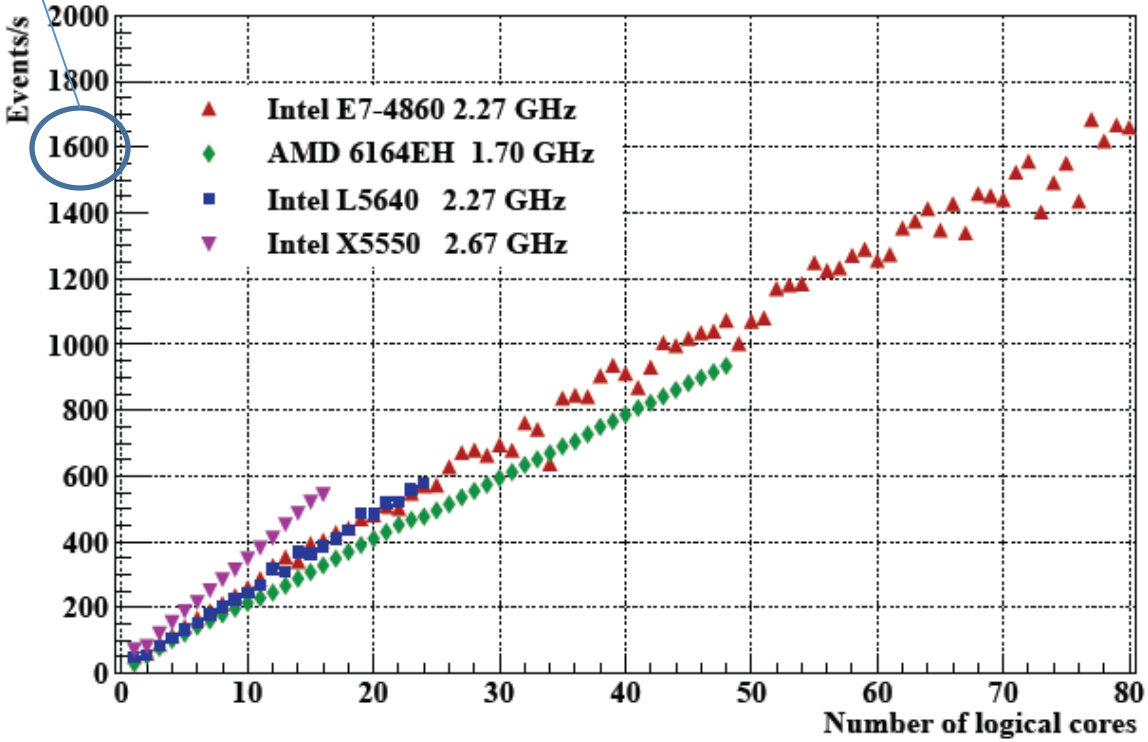


a factor > 10 faster for strangeness & LVM measurements
a factor > 100 faster for open charm
a factor > 1000 faster for charmonium -> scability!!

FLES package



Scalability of the FLES package on many-core servers



GSI „Minicube“ with several 10.000 cores -> up to 60 000 cores in future

Event selection in FLES processor farm

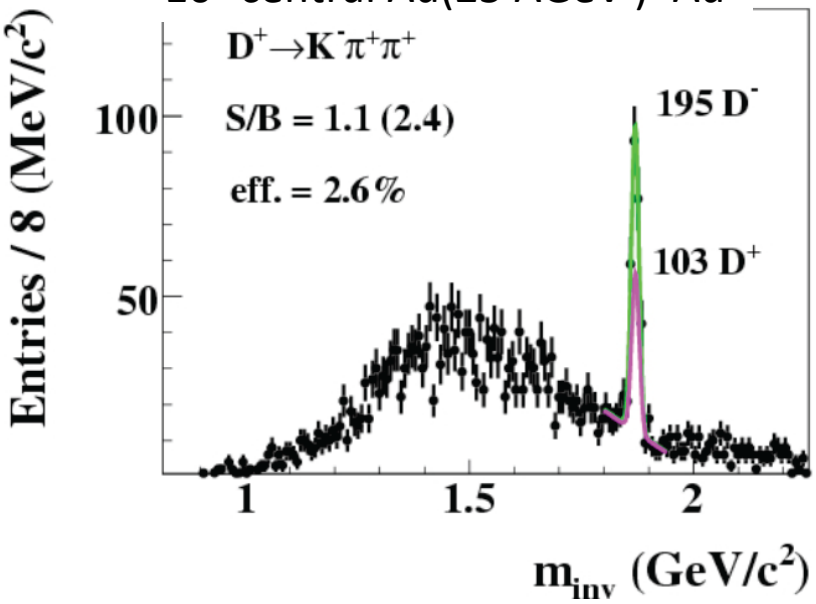
- High-throughput online analysis
- **10^7 Events/ s**
- Vectorization and many-core architectures
- **~ 60.000 Cores**

Feasibility studies

Feasibility studies: open charm

- Full simulations: UrQMD events, transport with GEANT + track reconstruction + vertex finder
- Realistic detector geometry: **MVD + STS** (material budget & response)

10^9 central Au(25 AGeV)+Au



HSD: < D^+ > = 4.2 x 10^{-5}/central evt

1st MVD station		D^+	D^+
thickness	position	efficiency	S/B (2σ)
150 μm	10 cm	4.2%	9
500 μm	10 cm	1.05%	0.93
300 μm	5 cm	2.6%	1.1

→ need for **thin** MVD stations, **close to target**!

Expected **D-meson statistics** for 2 x 10^{11} central Au(25 AGeV)+Au (2 months CBM run @ 400kHz)

Decay channel	Multiplicity HSD	Multiplicity SHM	BR [%]	Reco. eff. [%]	Particles/year HSD	Particles/year SHM
$D^+ \to \pi^+ \pi^+ K^-$	4.2×10^{-5}	8.4×10^{-5}	9.5	2.0	1.5×10^4	3.0×10^4
$D^- \to \pi^- \pi^- K^+$	8.9×10^{-5}	2.9×10^{-4}	9.5	1.4	2.3×10^4	7.5×10^4
$D^0 \to \pi^+ K^-$	3.7×10^{-5}	2.0×10^{-4}	3.9	2.0	5.8×10^3	3.2×10^4
$\bar{D}^0 \to \pi^- K^+$	1.1×10^{-4}	6.1×10^{-4}	3.9	2.0	1.7×10^4	9.6×10^4
$D^0 \to \pi^+ \pi^+ \pi^- K^-$	3.7×10^{-5}	2.0×10^{-4}	7.7	0.4	2.1×10^3	1.2×10^4
$\bar{D}^0 \to \pi^- \pi^- \pi^+ K^+$	1.1×10^{-4}	6.1×10^{-4}	7.7	0.4	6.4×10^3	3.5×10^4
$D_s^+ \to \pi^+ K^+ K^-$	5.4×10^{-6}	1.4×10^{-4}	5.3	1.0	5.8×10^2	1.5×10^4
Sum					6.9×10^4	3.0×10^5

Expected CMOS performance (2018)

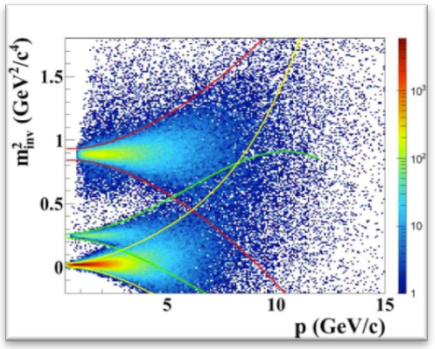
Radiation tolerance [n_{eq}/cm^2]	**~ 3 x 10^{13}**
Read-out time [μs]	~ 10

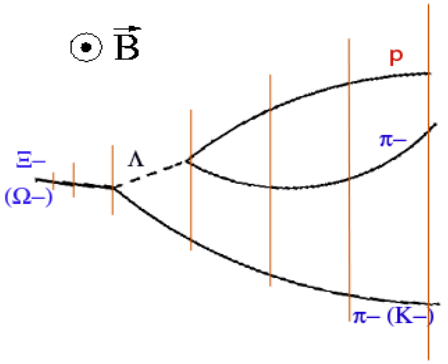
→ limits coll. rates to a few times 100 kHz

Feasibility studies: strange particles

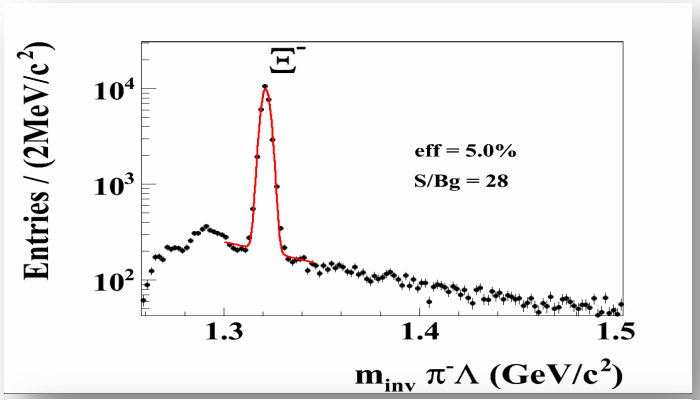
Simulations:

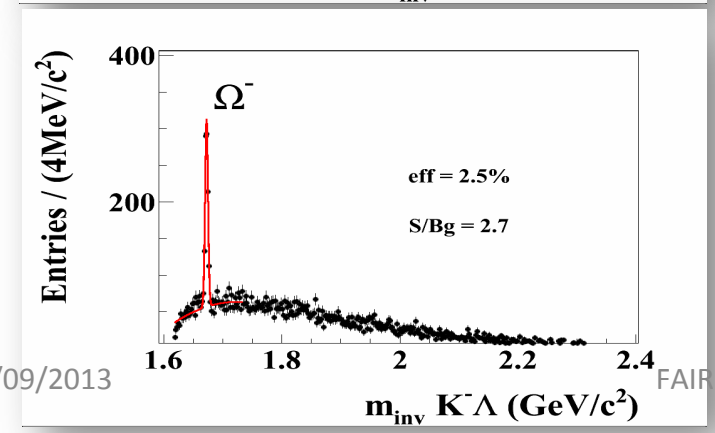
- **STS** with realistic geometry, material budget & detector response
- **TOF** at 10 m, time resolution 80 ps





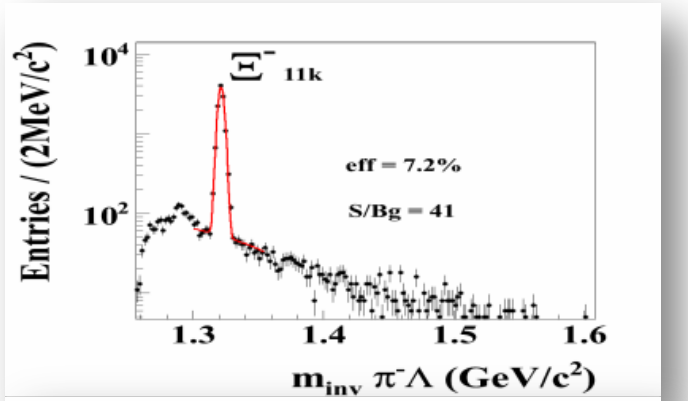
Central Au + Au at 25 A GeV, 1 Mio events

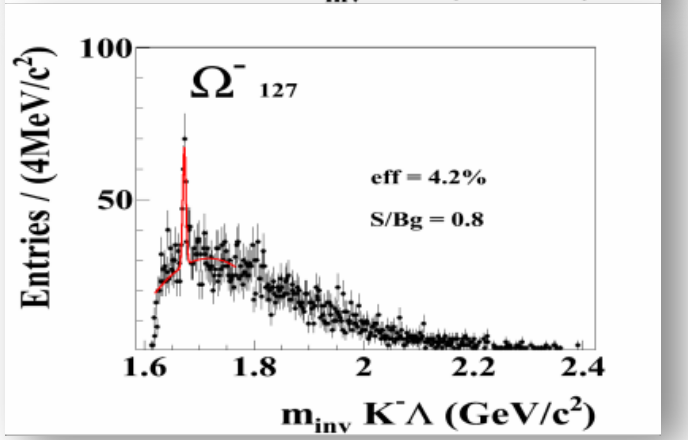




corresponds to ~1 mn CBM run only!

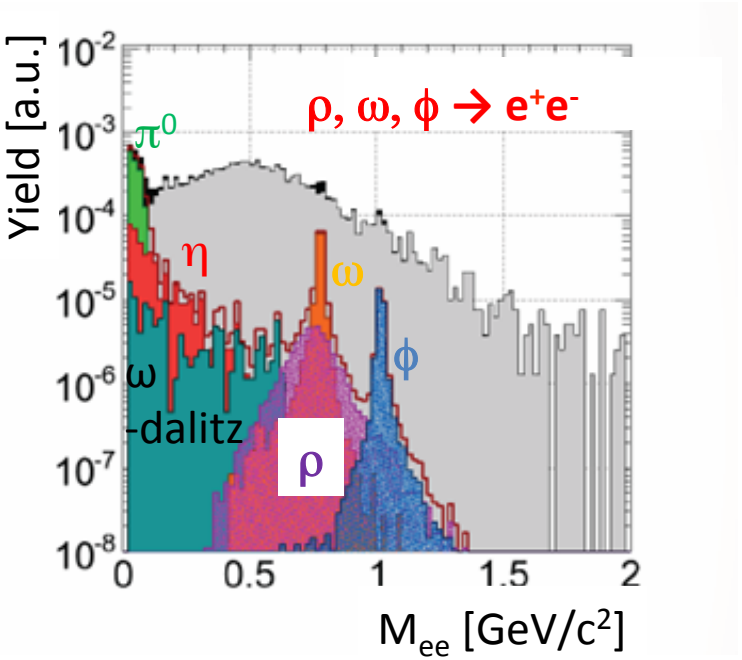
Central Au + Au at 8 A GeV, 1 Mio events

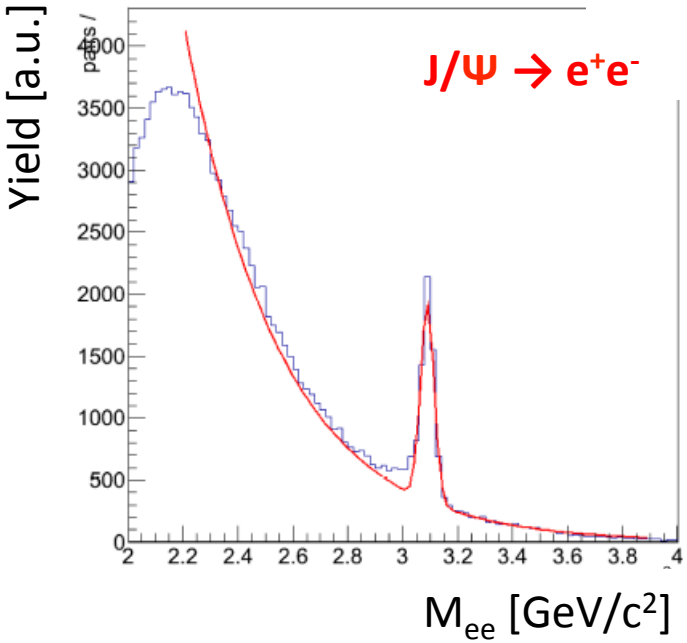




Feasibility studies: e^+e^- pairs

central Au(25 AGeV)+Au: **STS, RICH, TRD, TOF**



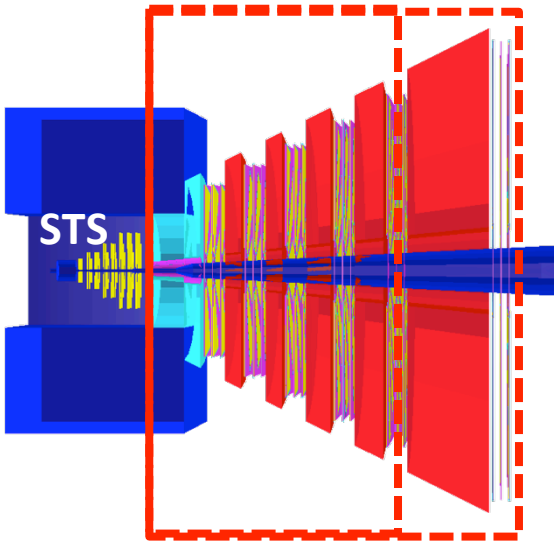


Background dominated by physical sources (75%)

- γ conversion in detector materiel (mostly in target)
- π^0 dalitz decay

Particle	S/B	ε [%]
ρ	---	4.4
ω	0.3	5.5
ϕ	0.1	7.1
J/Ψ	2.0	0.1

Feasibility studies: $\mu^+\mu^-$ pairs



MUCH

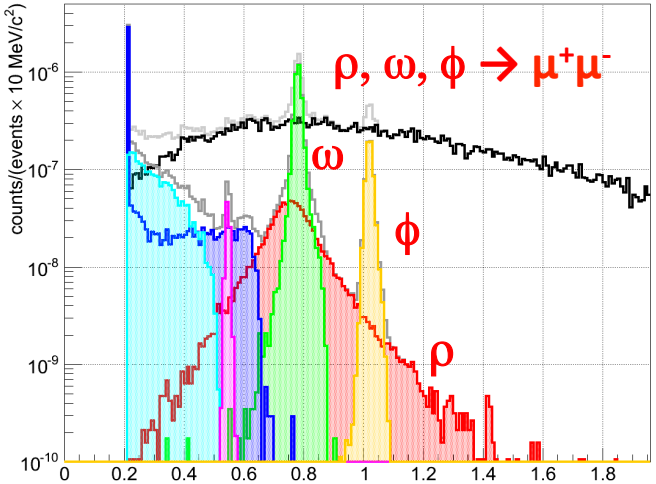
Absorber:
carbon 60cm + iron 20+20+30+35cm (ρ, ω, ϕ)
carbon 60cm+ iron 20+20+30+35 +100cm (J/ψ)

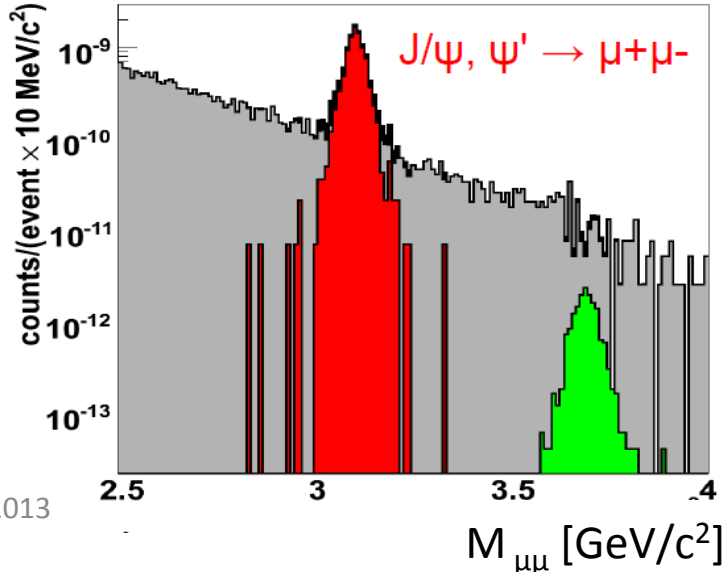
6 detector triplets:
3 GEM+2 straw tubes +TRD

Particle	S/B	ε [%]
ρ	0.002	3
ω	0.11	4
ϕ	0.06	7
J/Ψ	18	13
Ψ'	1	16

Background dominated by misidentified muons (π-decay)

central Au(25 AGeV)+Au: **STS, MUCH**

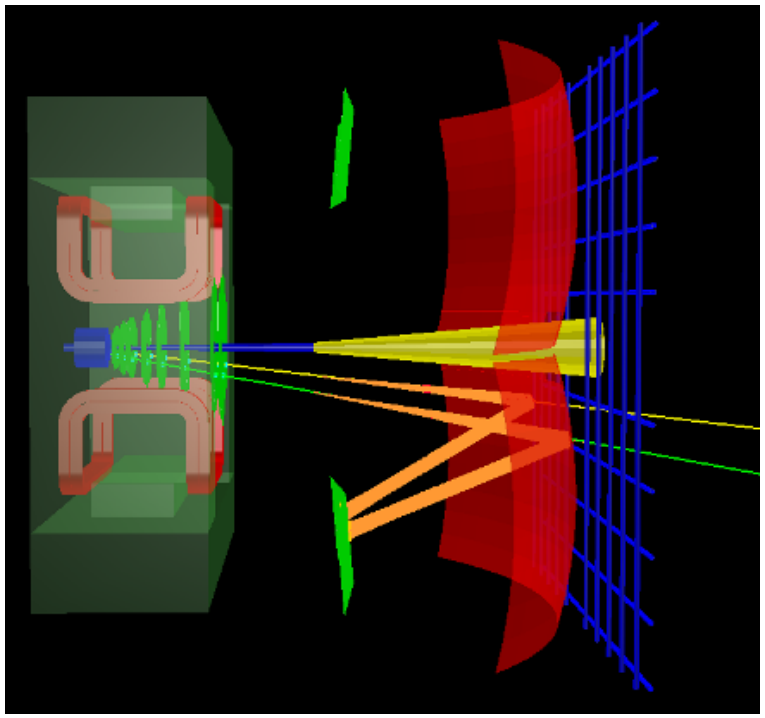




Di-lepton

Di-eletron reconstruction in CBM: the challenge

Electron option



- Without hadron-blind detector before the tracknig
- Background due to material budget of the STS
- Sufficient π discrimination (misidentification $<10^{-4}$)

UrQMD: Au+Au collision at beam energy 25AGeV, zero impact parameter

$e^+ e^- \gamma$

1.2%

↑

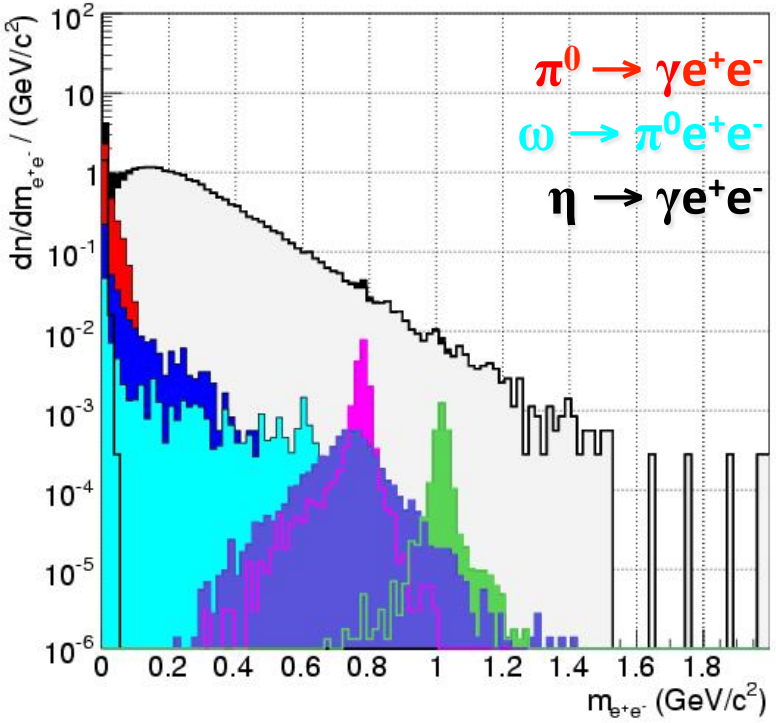
~350 $\pi^0 \rightarrow 98.8\%\ \gamma\gamma$

~3 $\gamma_{target} \rightarrow e^+e^-$

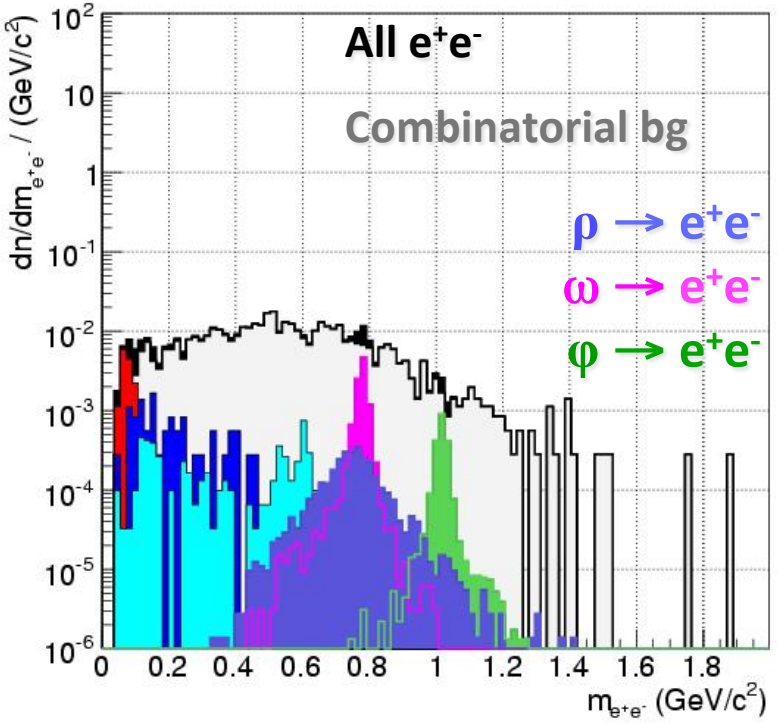
~700 $\pi^{+/-}$ could be identified as an electron

Invariant mass spectra

Identified e^+e^-



After all cuts applied



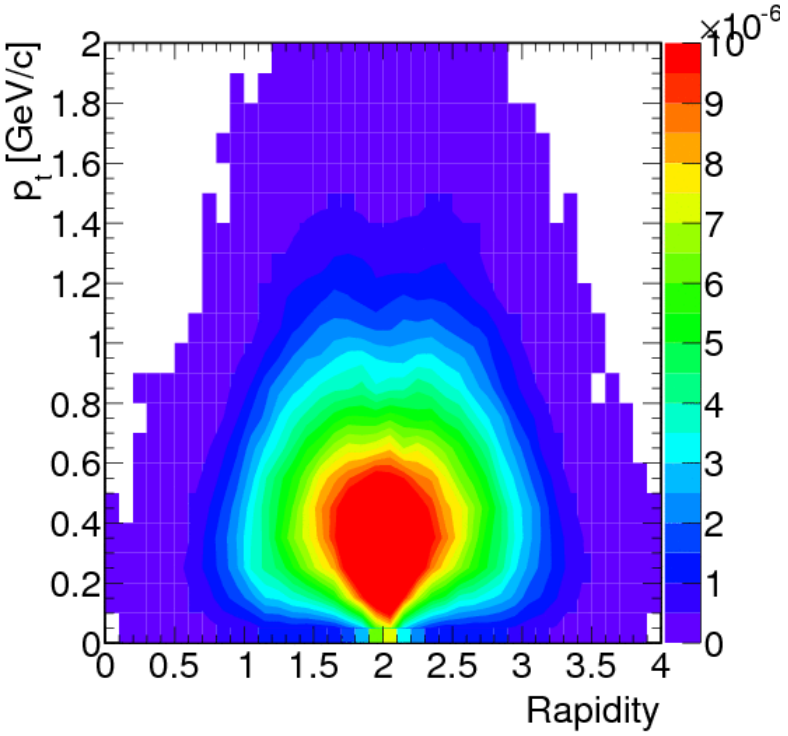
Electron option

Free cocktail only (without medium contribution)
Simulated statistics is 200k events

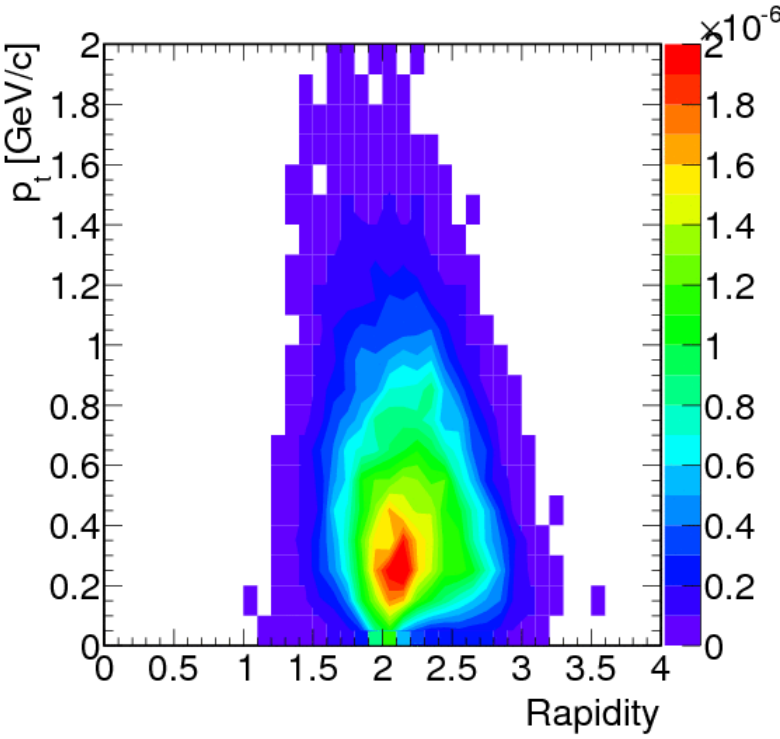
Central Au+Au@25AGeV

Phase space coverage (ρ^0 meson)

Full phase space



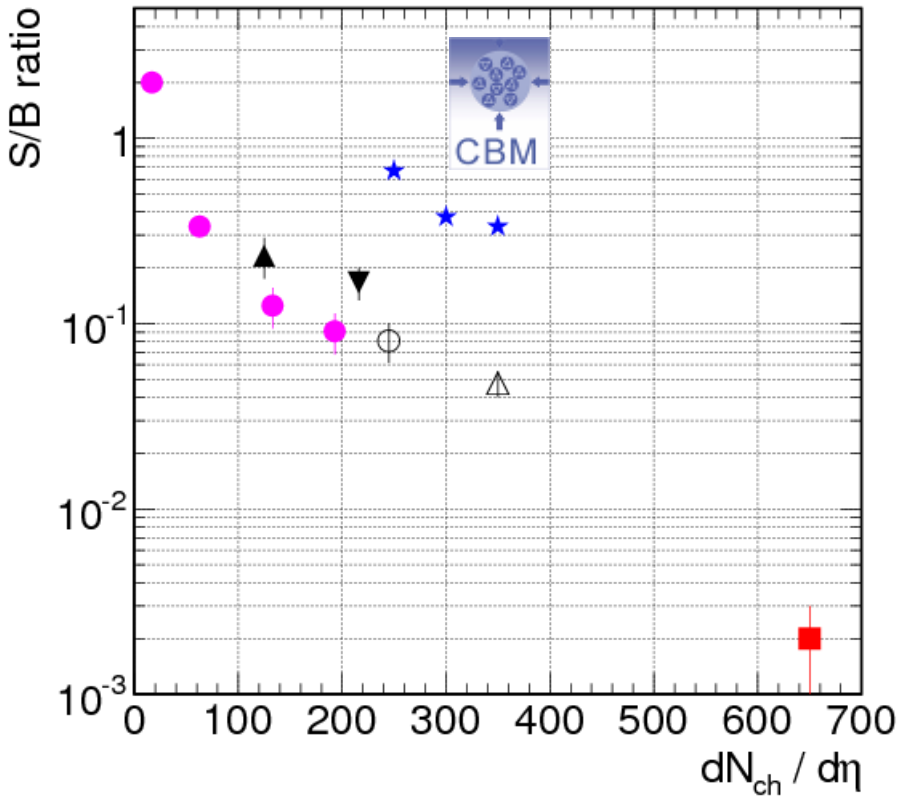
After full event reconstruction, ID and pair analysis



Electron option

No phase space limitation!

Signal-to-Background ratio for CBM



safety factor ☺

- NA60 In+In @ 158 AGeV
- CERES Pb+Au @ 40 AGeV
- CERES Pb+Au @ 158 AGeV (σ/σ_{tot} = 28%)
- CERES Pb+Au @ 158 AGeV (σ/σ_{tot} = 7%)
- CERES Pb+Au @ 158 AGeV
- PHENIX Au+Au @ $\sqrt{s}$ = 200 AGeV

The Low-mass signal