Hyperons @ CBM @ FAIR

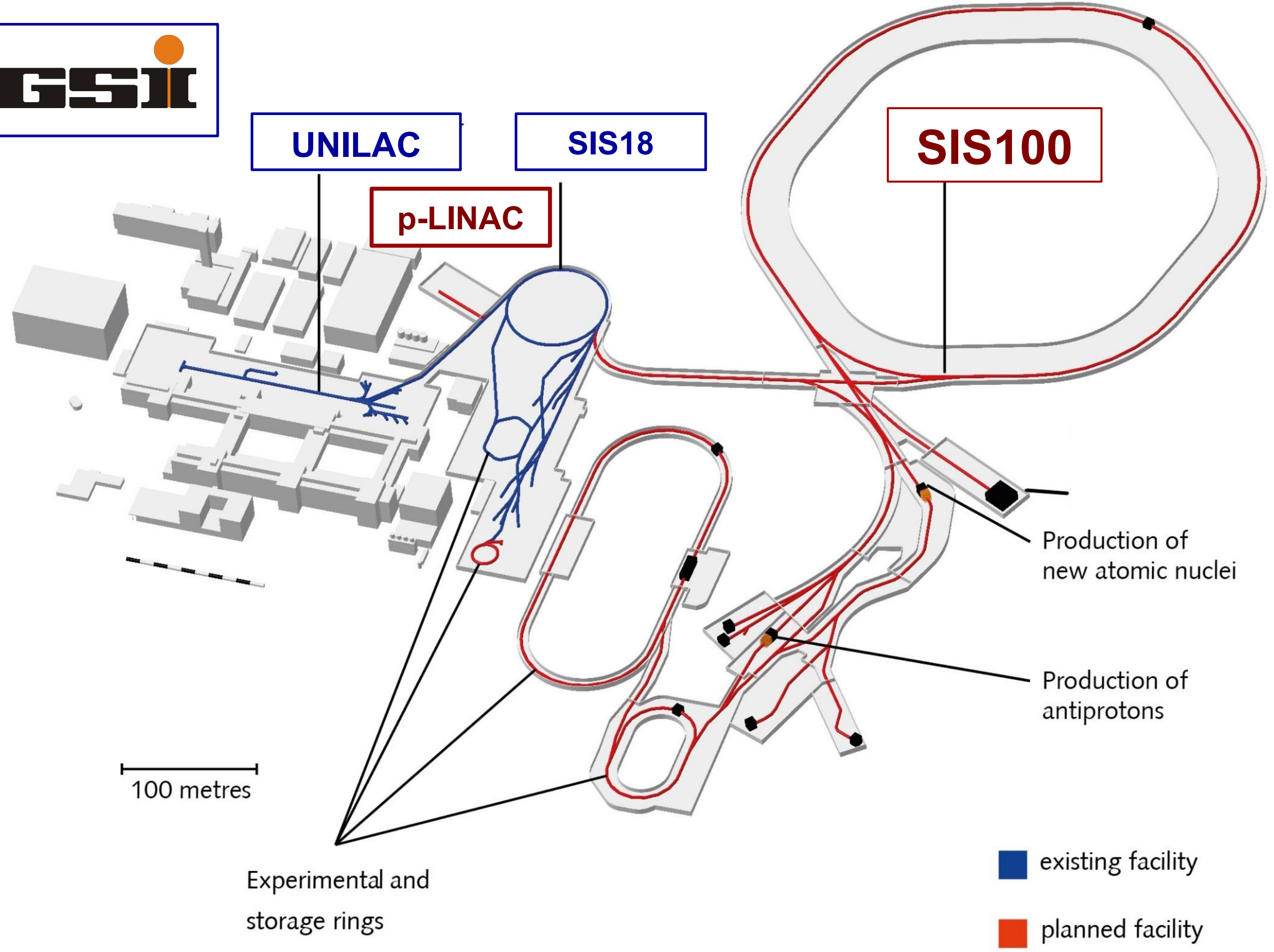
Ilya Selyuzhenkov (GSI / MEPhI)

for the CBM Collaboration

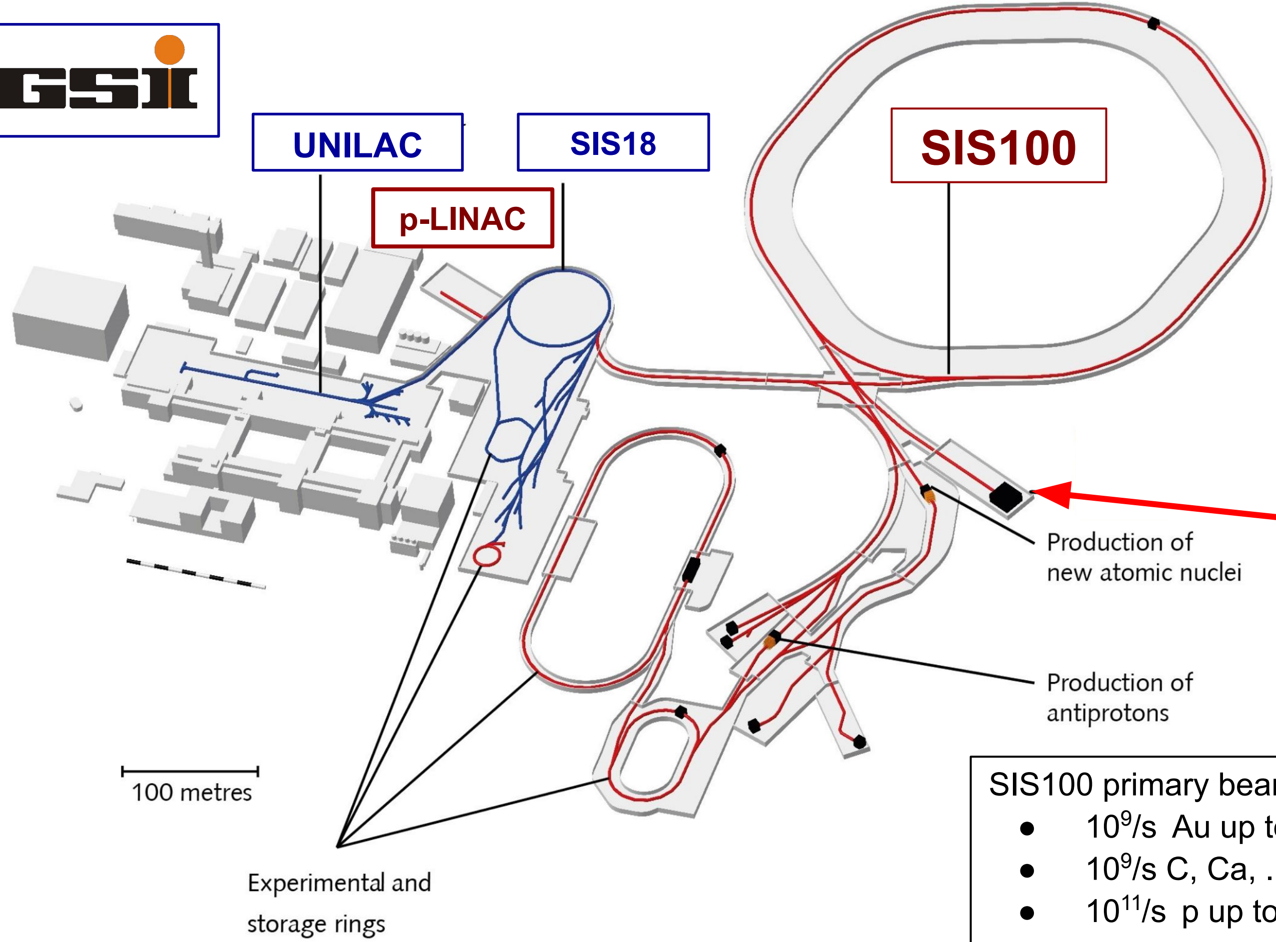
CBM

Mini-symposium “Hyperons@FAIR”, 25 October, 2021

Facility for Antiproton and Ion Research



Facility for Antiproton and Ion Research



Compressed
Baryonic
Matter
Experiment

SIS100 primary beams:

- 10^9/s Au up to 11 GeV/u
- 10^9/s C, Ca, ... up to 14 GeV/u
- 10^{11}/s p up to 29 GeV

CBM building at FAIR

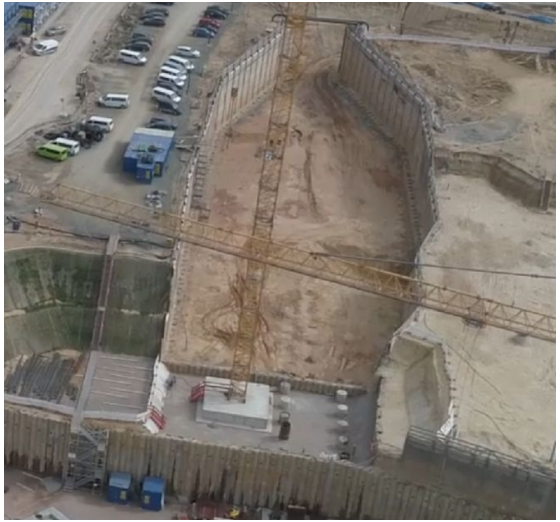
HADES: p+p, p+A, A+A
limited to low multiplicity A+A, optimized for dileptons

CBM: p+p, p+A, A+A
designed for high multiplicity, general purpose detector

Complementary operation of HADES and CBM at FAIR

CBM construction status

2019 → **September 2021**



Shell construction is progressing well

- Beam dump installed in April-May 2021
- Roofing ongoing
- CBM building ready for detector installation in 2022

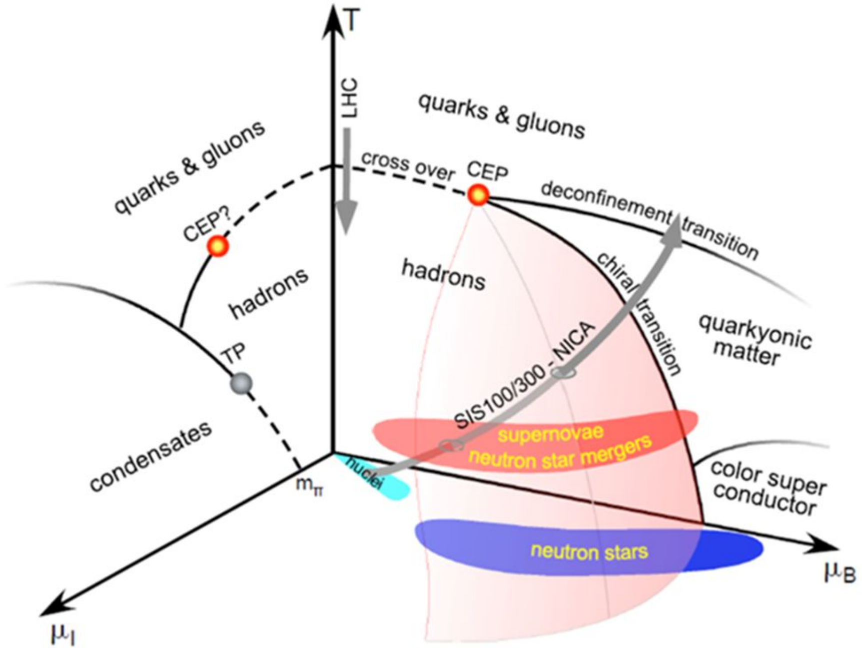
drone video (September 30, 2021): https://youtu.be/Y82ZeLH1vZs

CBM physics and observables

CBM Collaboration, Eur.Phys.J. A53 (2017) no.3, 60

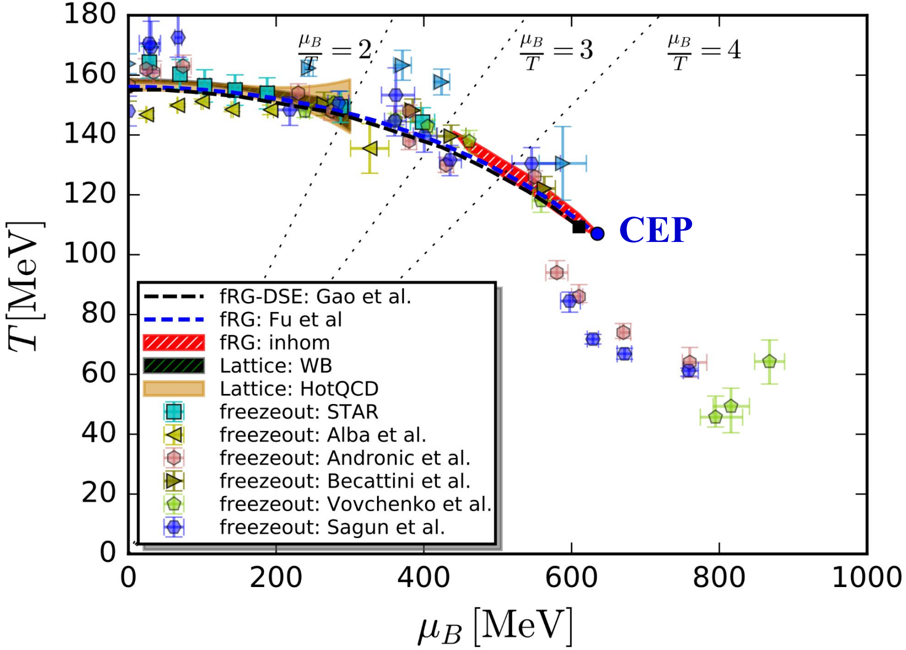
https://inspirehep.net/record/1474181

Rich structure of the QCD matter phase diagram



NUPECC Long Range Plan 2017

Fu, Pawlowski, Rennecke, PRD 101 (2020) 5, 054032



$(T, \mu_B)_{CEP} = (107, 635)$ MeV: $\sqrt{s_{NN}} = 3.7$ GeV

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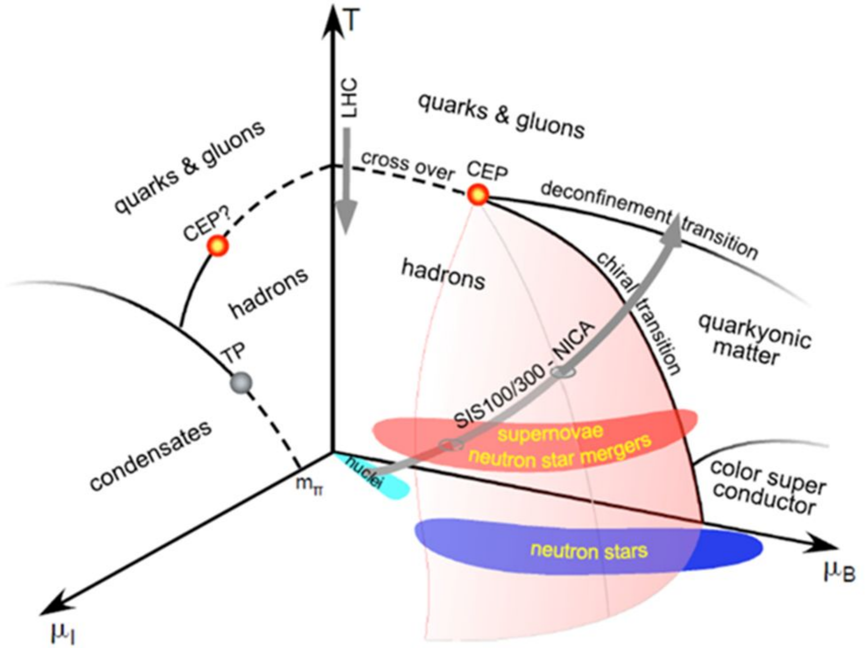

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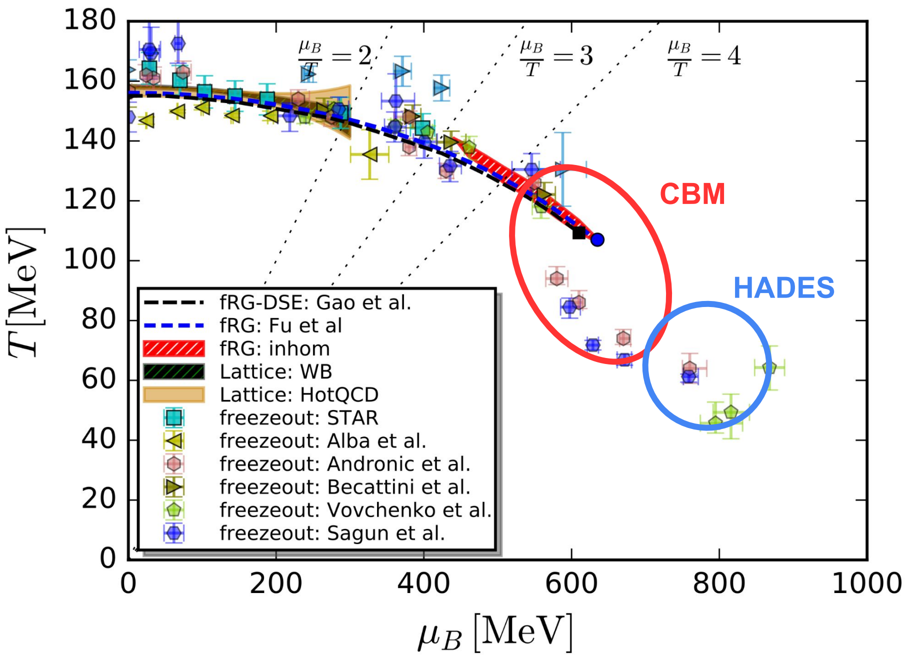
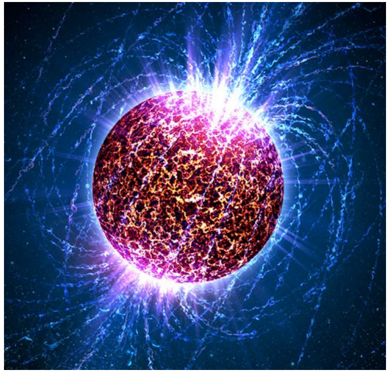
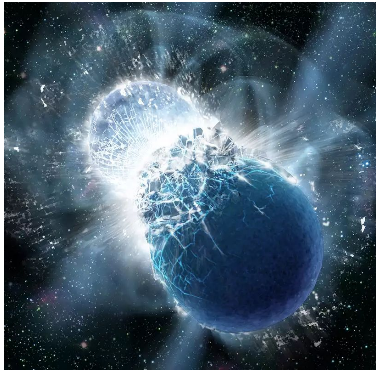
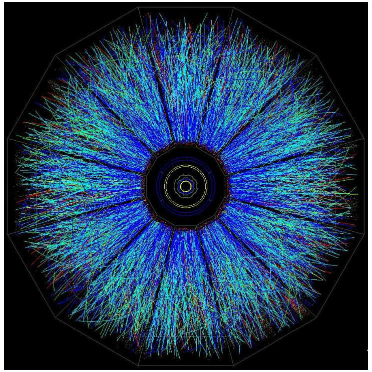


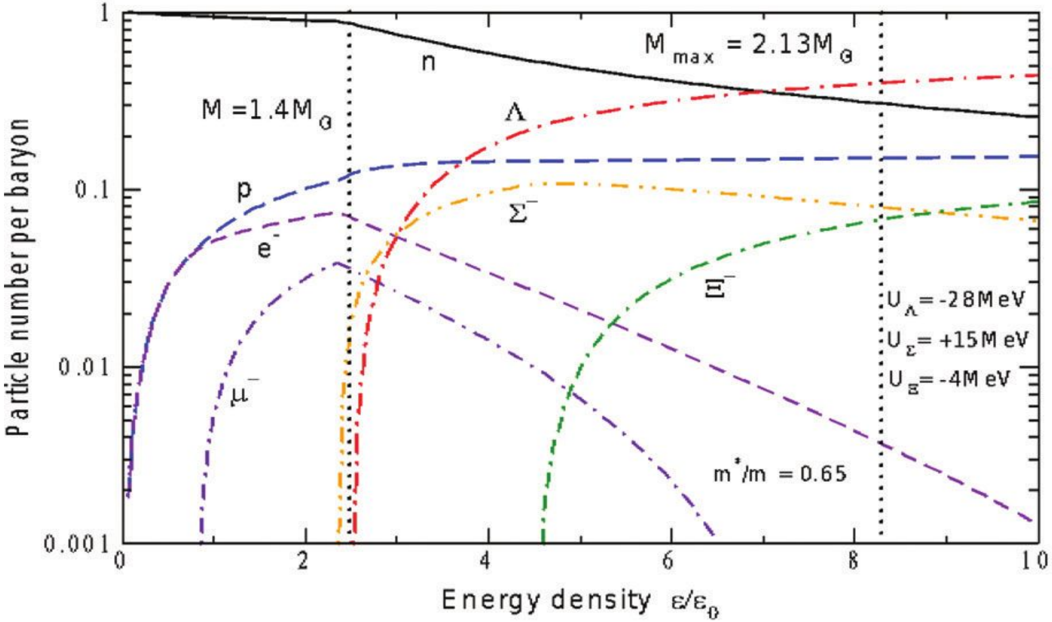
$(T, \mu_B)_{CEP} = (107, 635)$ MeV: $\sqrt{s_{NN}} = 3.7$ GeV

Dense Baryonic Matter

	Neutron stars	Neutron star merger	Heavy ion collisions
		 GW170817	 SIS100 energies
Temperature	$T < 10$ MeV	$T \sim 10\text{-}100$ MeV	$T < 120$ MeV
Nuclear density	$\rho < 10\ \rho_0$	$\rho < 2 - 6\ \rho_0$	$\rho < 5 - 15\ \rho_0$
Lifetime / Reaction time	$t \sim$ infinity	$t \sim 10$ ms	$t \sim 10^{-23}$ s

CBM physics and observables:
QCD matter Equation of State (EoS) at large baryon densities

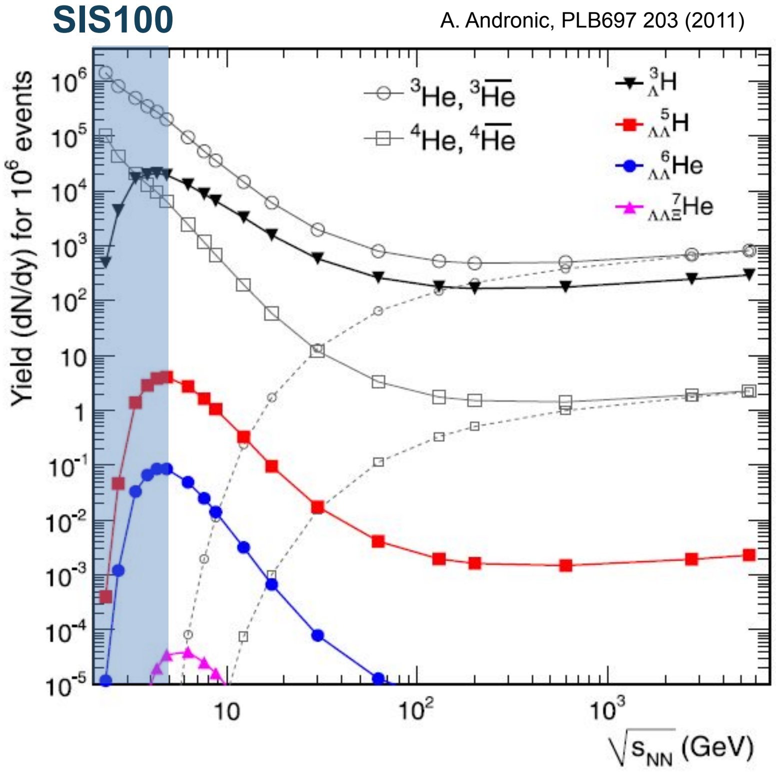
J. Schaffner-Bielich, DOI:10.1017/9781316848357.008



QCD matter EoS at large baryon densities; coexistence (quarkyonic) & partonic phases:

- Hadron yields, collective flow, correlations, fluctuations
- (Multi-)strange hyperons (K, Λ, Σ, Ξ, Ω)
- production at (sub)threshold energies

CBM physics and observables: Strange nuclear matter and baryon-baryon interactions



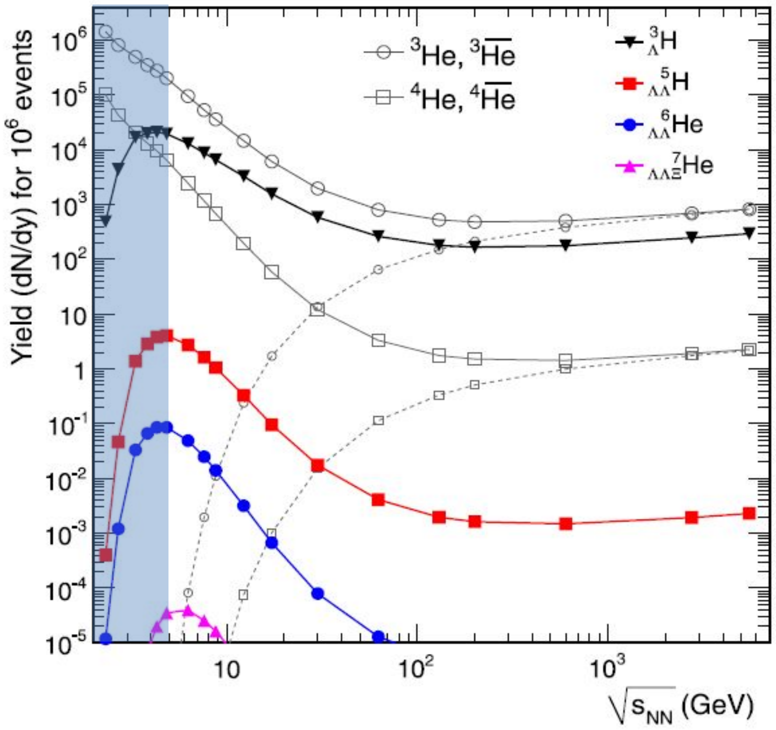
- Production of spatially extended objects (hypernuclei) in high baryon density environment
- Measurements of mass, binding energy, lifetime, branching ratios, etc.
- Sensitive to many-body hyperon interaction
  - (Double-)Λ hypernuclei production

Collision energy range $\sqrt{s_{NN}}$ for CBM can be tuned by changing the size of colliding nuclei

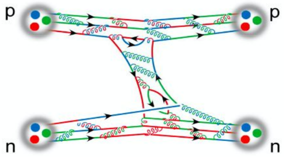
CBM physics and observables:
Strange nuclear matter and baryon-baryon interactions

SIS100

A. Andronic, PLB697 203 (2011)

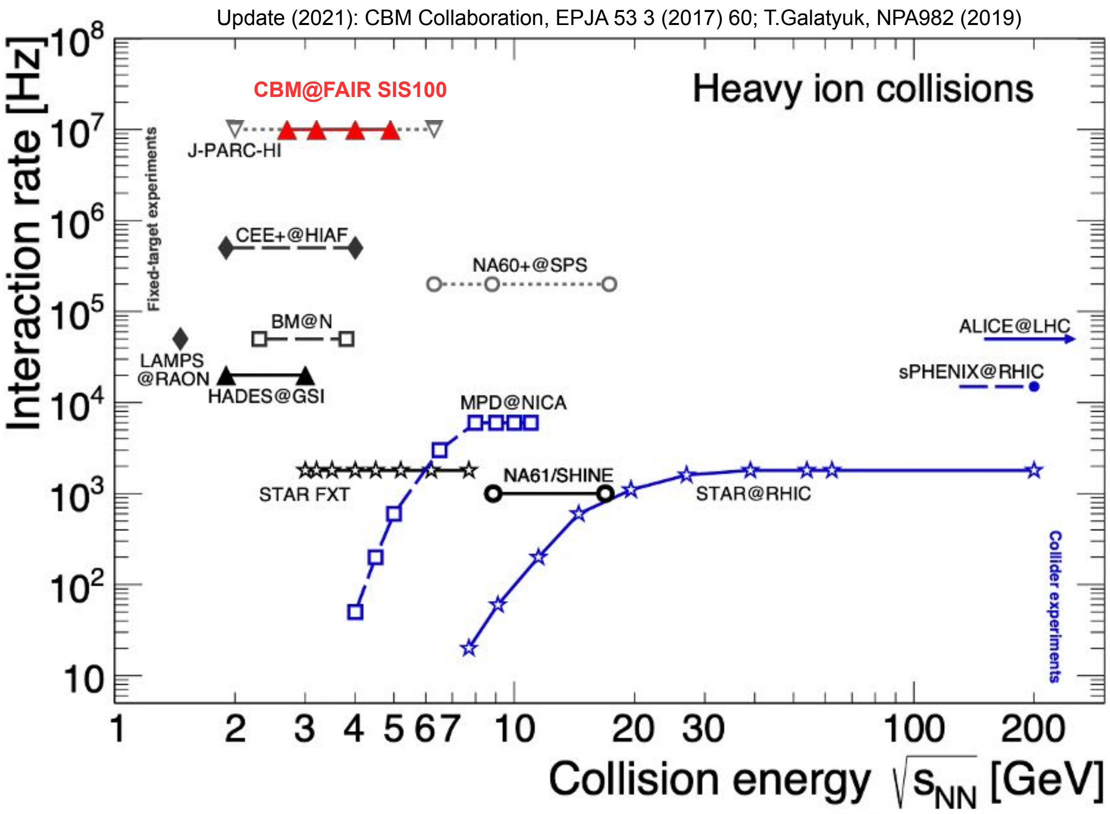


- Production of spatially extended objects (hypernuclei) in high baryon density environment
- Measurements of mass, binding energy, lifetime, branching ratios, etc.
- Sensitive to many-body hyperon interaction
  - (Double-)Λ hypernuclei production
  - baryon-baryon correlations (Λ–N, Λ–Λ, p–Ξ^-, etc)
- Exotics, meta-stable strange states



Collision energy range $\sqrt{s_{NN}}$ for CBM can be tuned by changing the size of colliding nuclei

Heavy-ion experiments worldwide



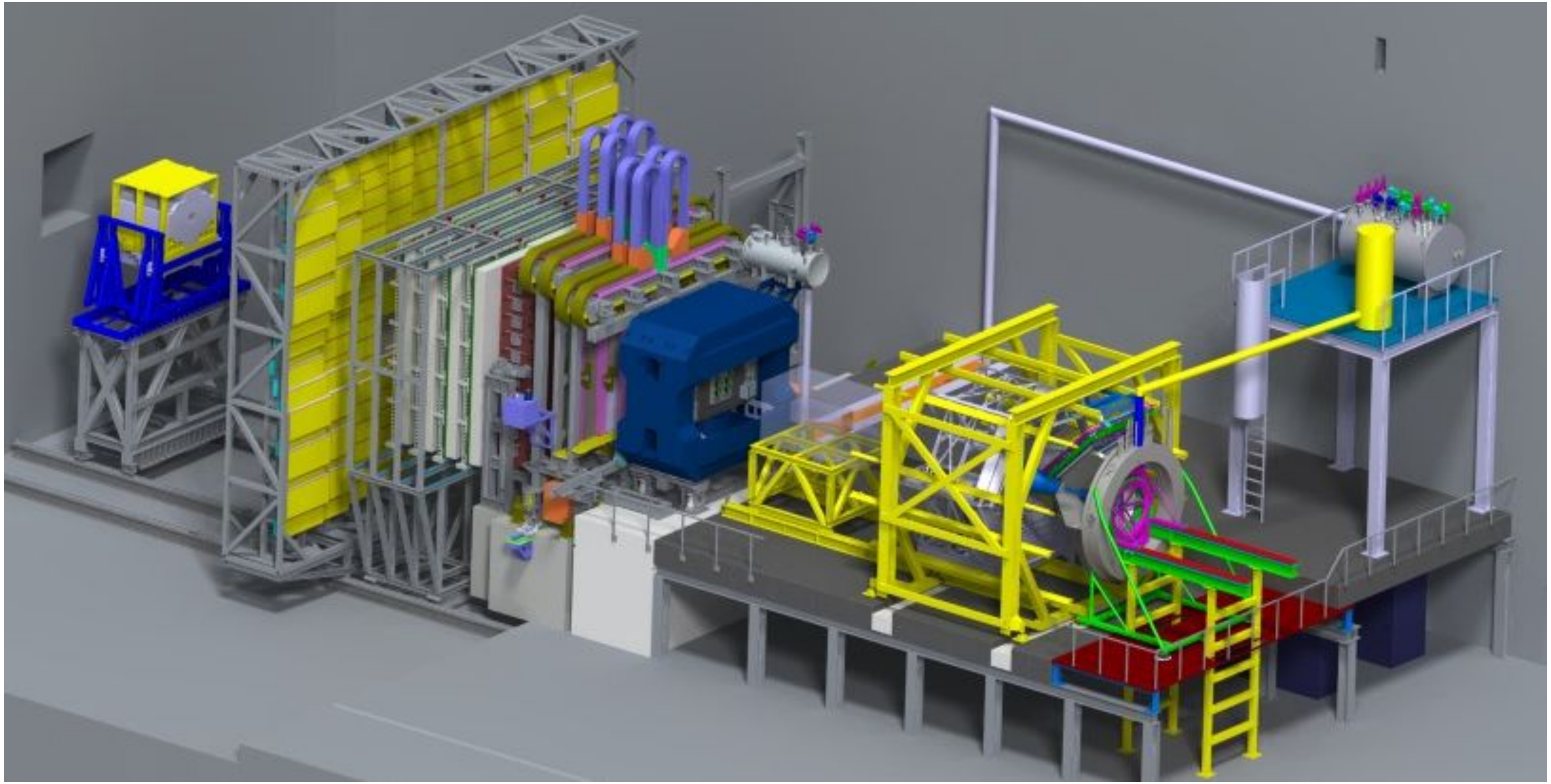
CBM will operate at high reaction rates: 10^5 - 10^7 Au+Au reactions/sec

Main experimental requirements and challenges

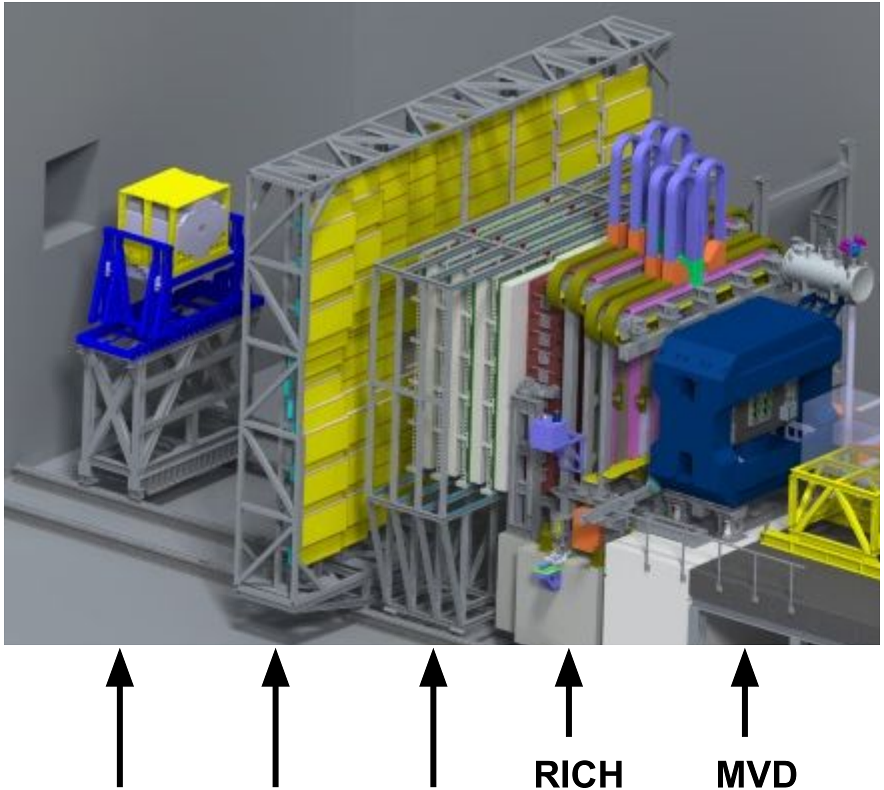
- High statistics needs high event rates: 10^5 - 10^7 Au+Au reactions/sec
- Particle identification:
  hadrons and leptons, displaced ($\sigma \approx 50\ \mu m$) vertex reconstruction for charm measurements
- Fast, radiation hard detectors & front-end electronics
- Free-streaming readout & 4 dimensional (space+time) event reconstruction
- High speed data acquisition & performance computing farm for online event selection

CBM experiment

CBM **HADES**



CBM subsystems: tracking, particle identification, event characterization



PSD | TOF | TRD | RICH or MUCH | MVD & STS

Dipole Magnet
bends charged particles trajectories

STS (Silicon Tracking System)
charged particle tracking

MVD (Micro-Vertex Detector)
secondary vertex reconstruction

RICH (Ring Imaging Cherenkov)
electron identification
or
MUCH (MUon CHambers)
muon tracking & identification

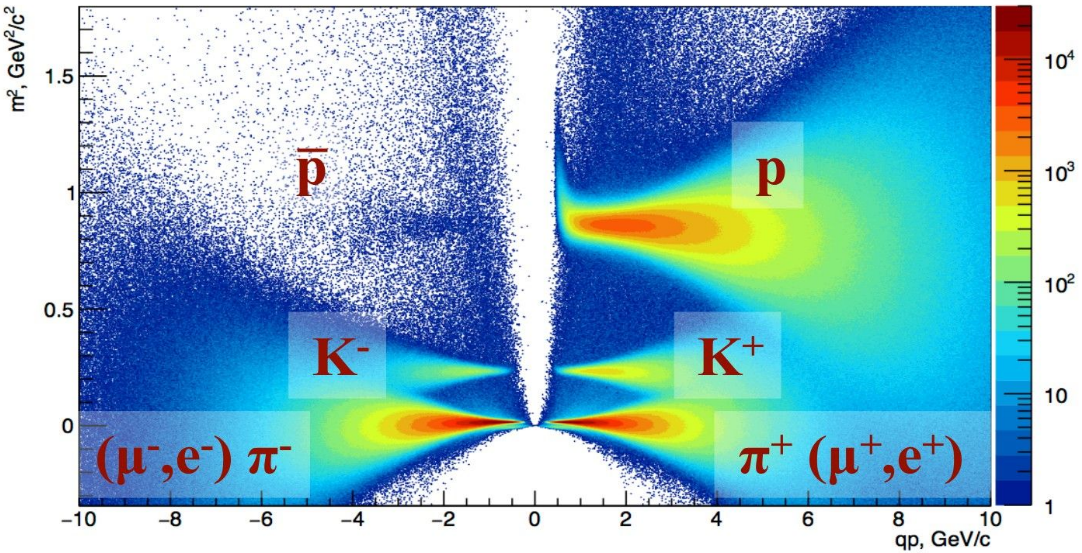
TRD (Transition Radiation Detector)
electron identification

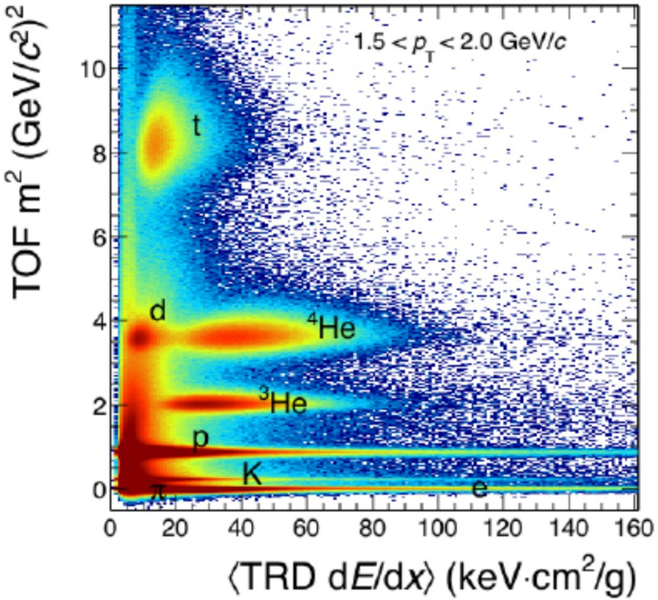
TOF (Time of Flight detector)
hadron identification

PSD (Projectile Spectator Detector)
collision centrality & reaction plane

Identification of light hadrons and nuclei

CBM simulation, central Au+Au @ 10*A* GeV/*c*

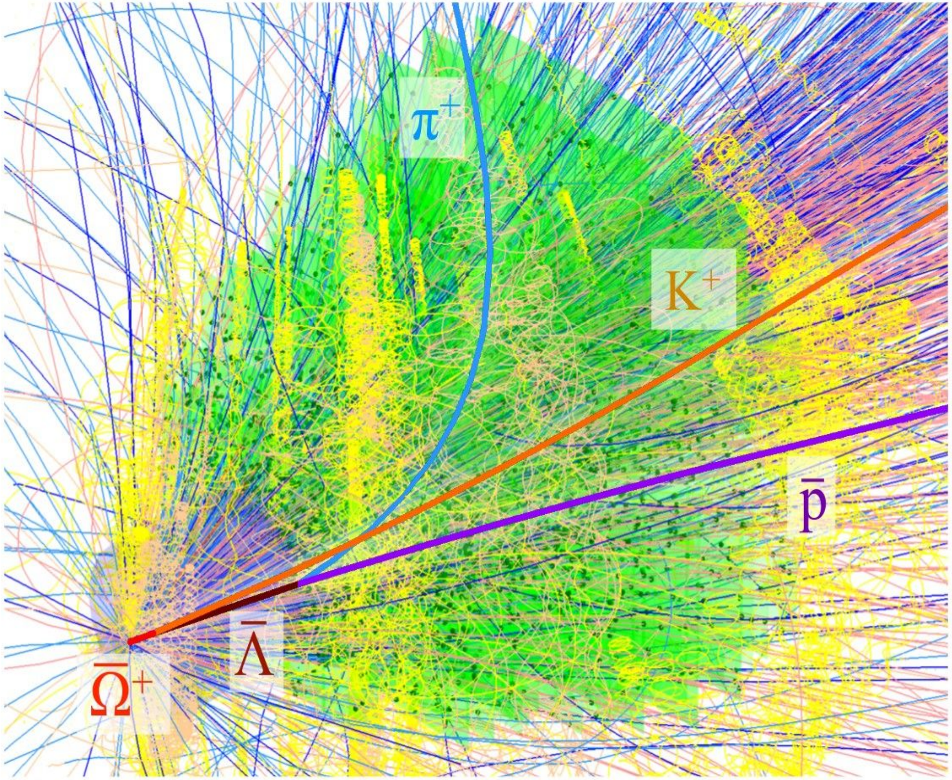




Clear separation between charged protons, pions and kaons

Clear separation of light nuclei

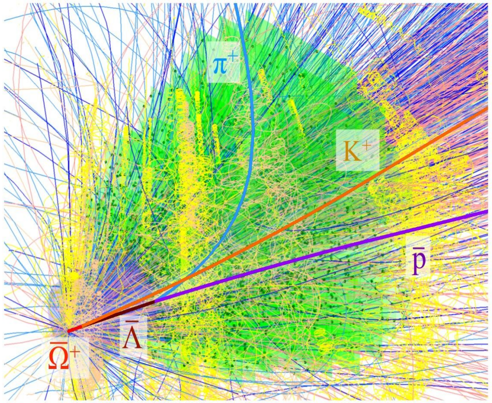
(Multi)-strange hyperons: reconstruction



CBM simulation, Au+Au collisions @ 12*A* GeV/*c*

(Multi)-strange hyperons: reconstruction

Example of Λ reconstruction via $\Lambda \rightarrow p\pi^-$



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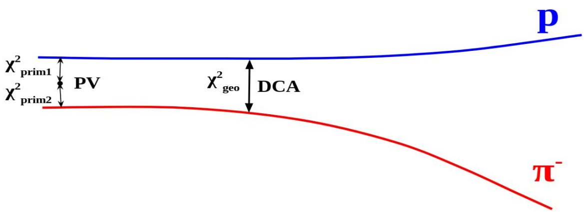
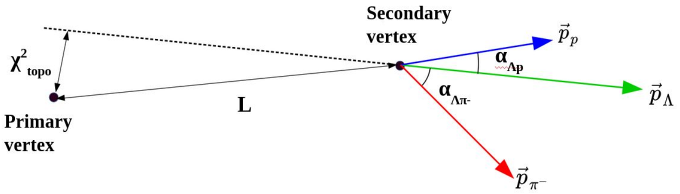
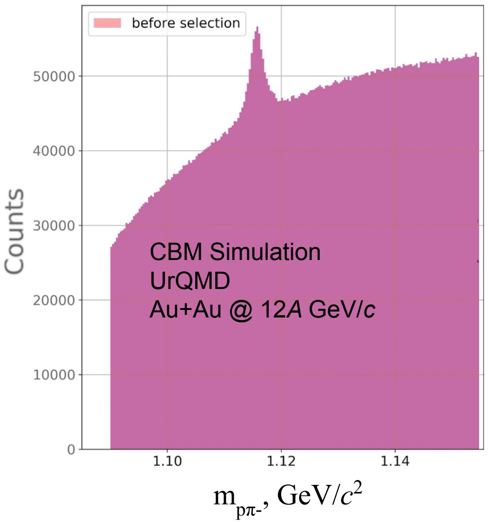
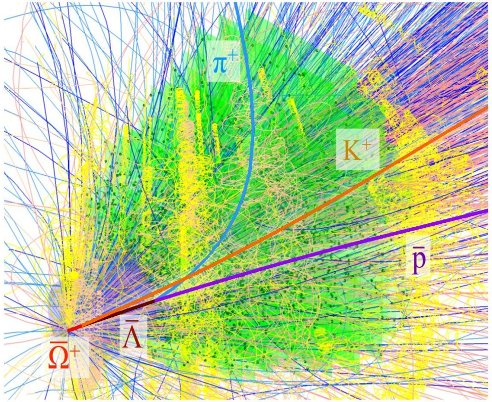


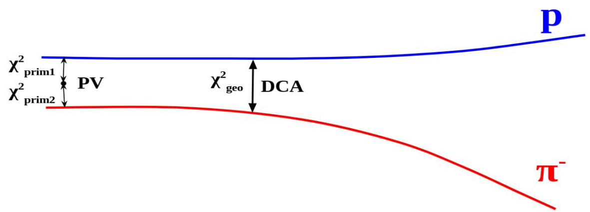


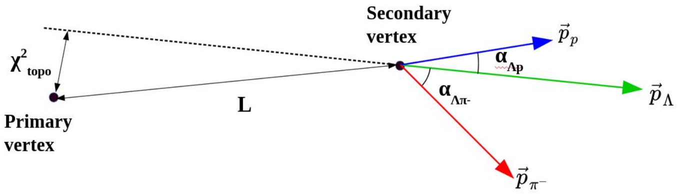


(Multi)-strange hyperons: reconstruction



CBM simulation Au+Au collisions @ 12*A* GeV/*c*





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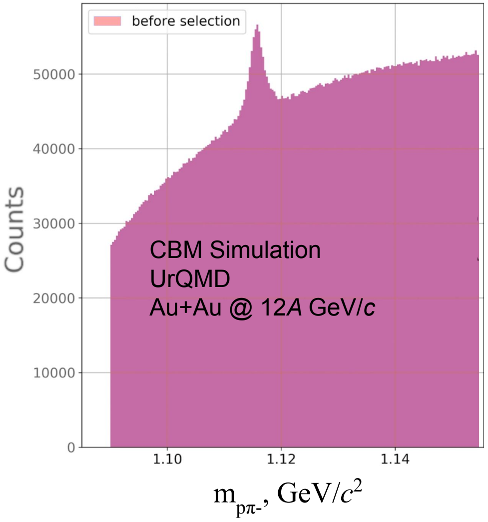
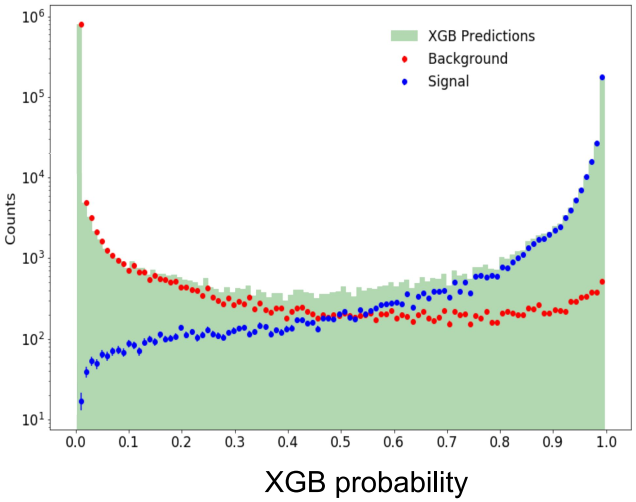
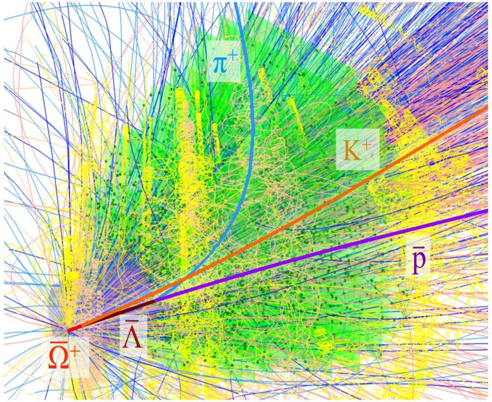


Machine learning (XGBoost)

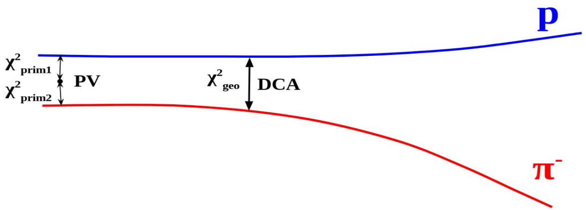


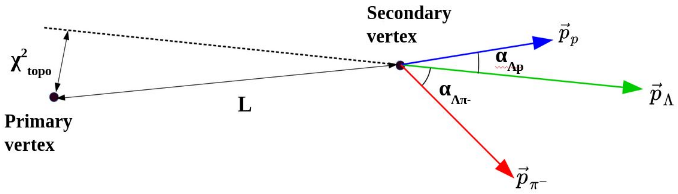
Selection criteria are optimized multi-dimensionally and non-linearly using Machine Learning algorithms

(Multi)-strange hyperons: reconstruction



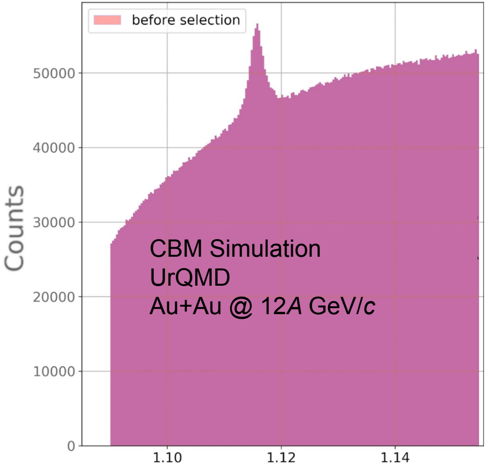
CBM simulation Au+Au collisions @ 12*A* GeV/*c*





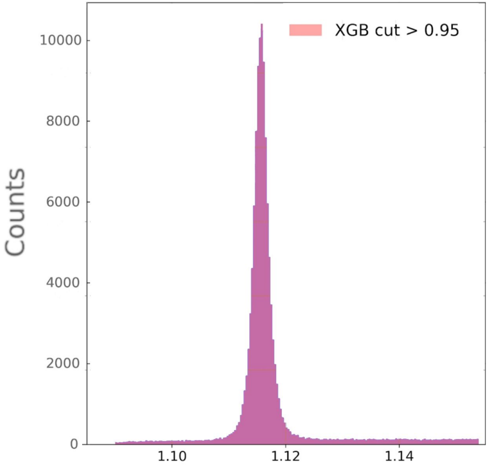
Example of Λ reconstruction via $\Lambda \rightarrow p\pi^-$

before selection

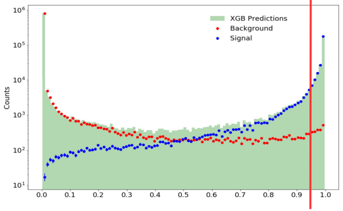


$m_{p\pi^-}$, GeV/c^2

after XGB selection

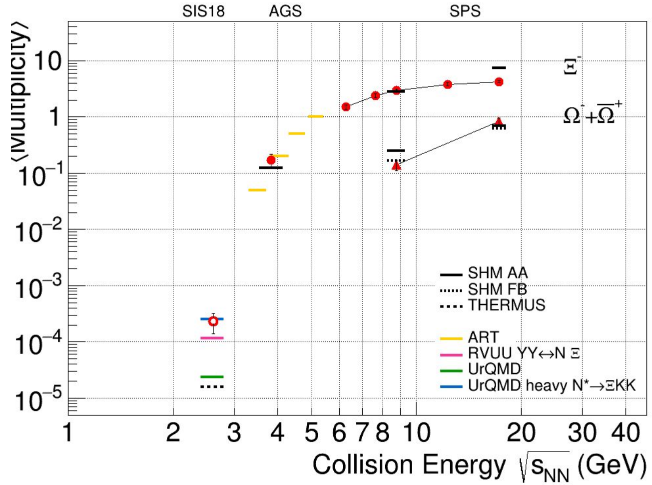


$m_{p\pi^-}$, GeV/c^2



XGB probability > 0.95

(Multi)-strange hyperons: yield projections

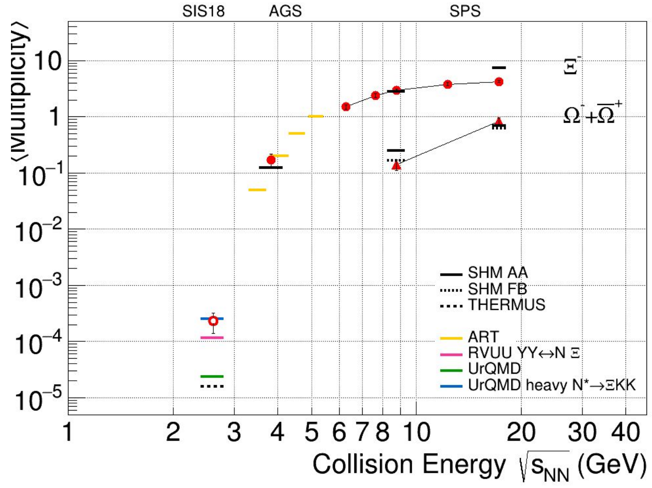


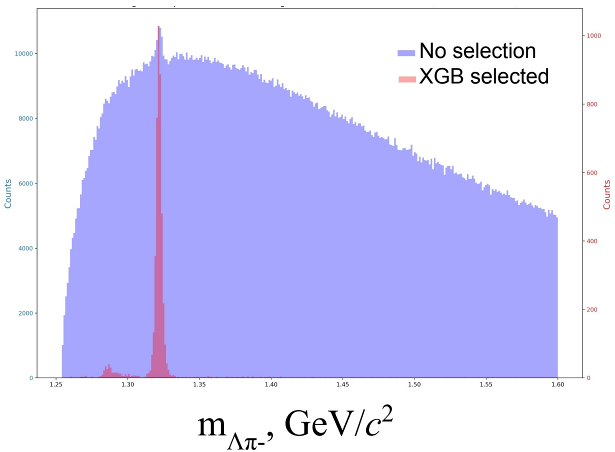
C. Blume, C. Markert, PPNP 66 (2011)
HADES Collaboration, PLB 778 (2018), PRL 103 (2009) 132301
RVUU: F. Li et al., PRC 85 (2012) 064902
UrQMD: J. Steinheimer et al., JPG43 (2016) 015104
ART: C.M. Ko et al., PLB595 (2004) 158-164
A. Andronic et al., NPA 772 (2006)
F. Becattini et al., PRC69 (2004) 024905
E. Seifert et al., PRC97 (2018)

Compilation TG, QM2018

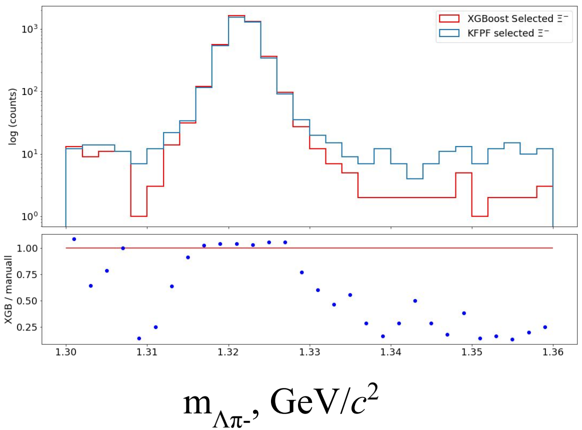
(Multi)-strange hyperons: yield projections

$\Xi^- \rightarrow \Lambda + \pi^-$





Machine learning (XGBoost) performance



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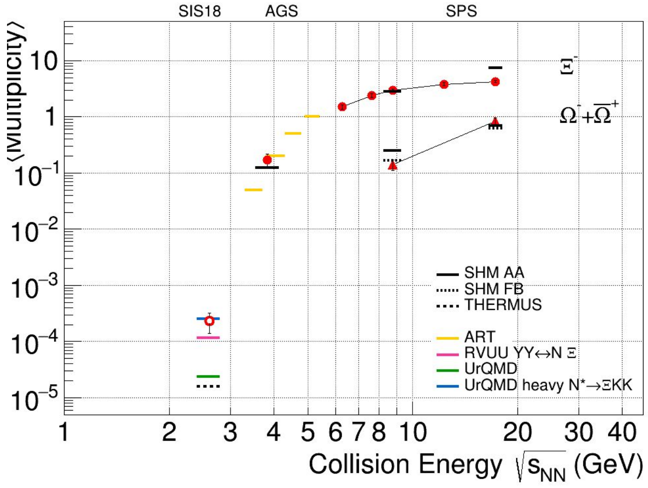

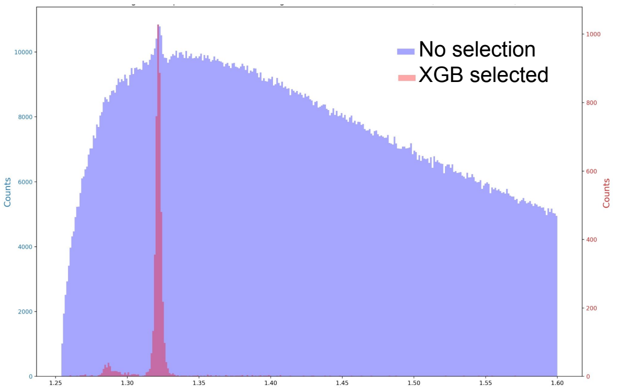

$m_{\Lambda\pi^-}$, GeV/c^2

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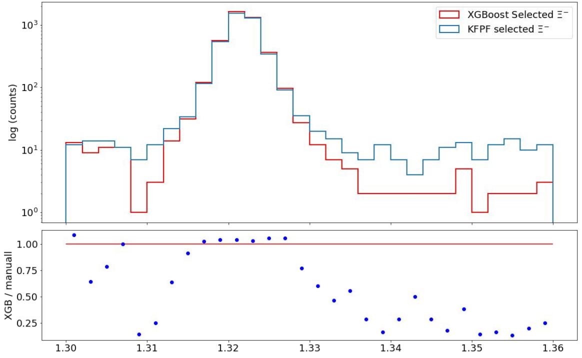

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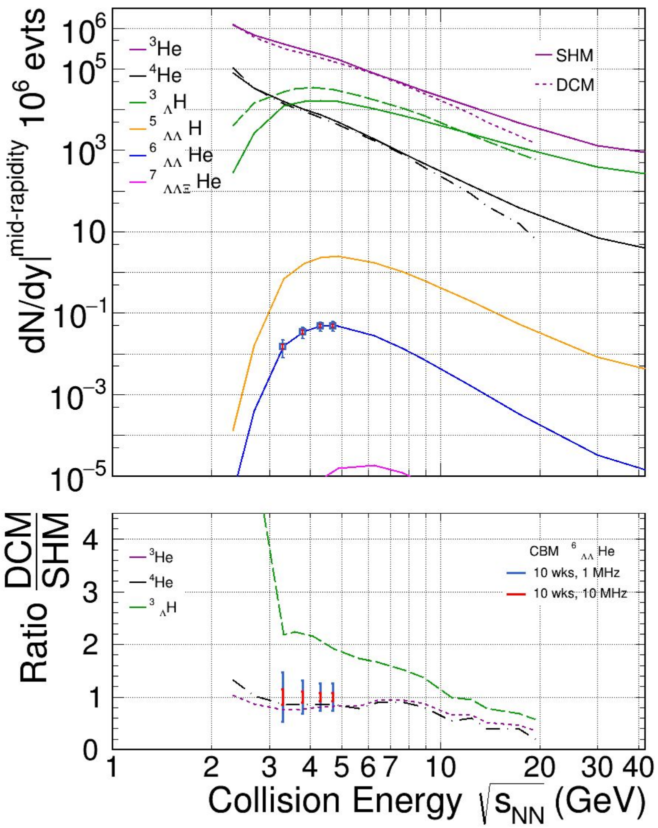
Compilation TG, QM2018

experiment	$\sqrt{s_{NN}}$, GeV	Run time (weeks)	R_{int}, kHz	Ξ^-	$\overline{\Xi}^+$	$\overline{\Omega}^+$
HADES (Ag)	2.6	4	10	2.5×10^3		
MPD S1	11	10	5	1.5×10^6	8×10^4	1.5×10^4
CBM	3.8	1	1000	4×10^9	5×10^6	3.3×10^5

Hypernuclei: reconstruction & yield projections



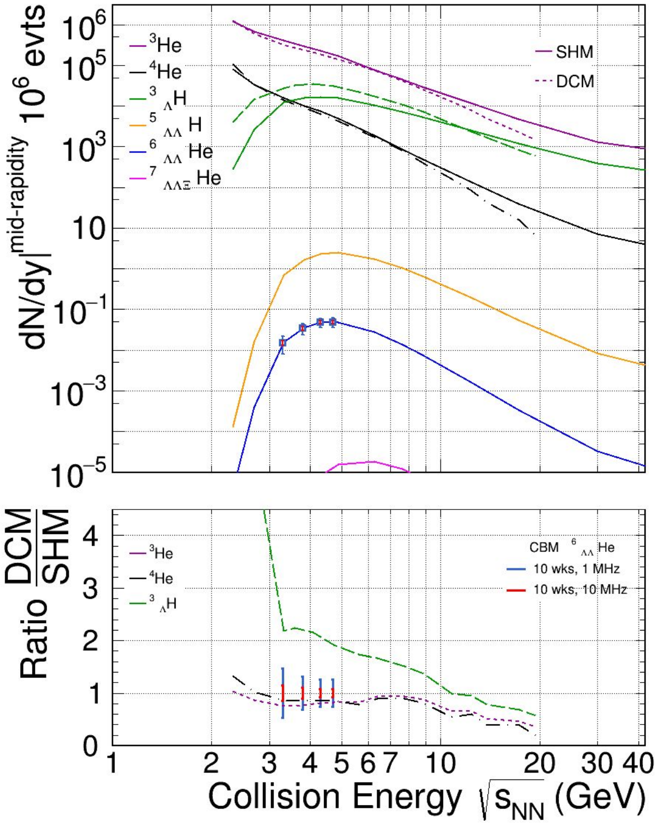
Recent developments in coupling dynamical & statistical mechanisms of cluster production
Botvina, Buyukcizmeci, Bleicher, [PRC103 (2021) 6, 064602]

Blue & red lines: precision of measurable yields assuming various scenario

A. Andronic et.al. PLB 697 (2011) 203-207
J. Steinheimer et.al., PLB 714 (2012) 85-91

Compilation TG, QM2018

Hypernuclei: reconstruction & yield projections



A. Andronic et.al. PLB 697 (2011) 203-207
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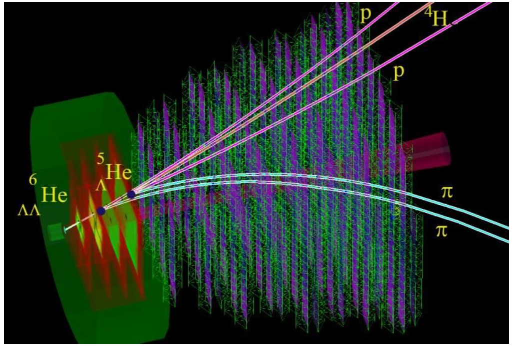
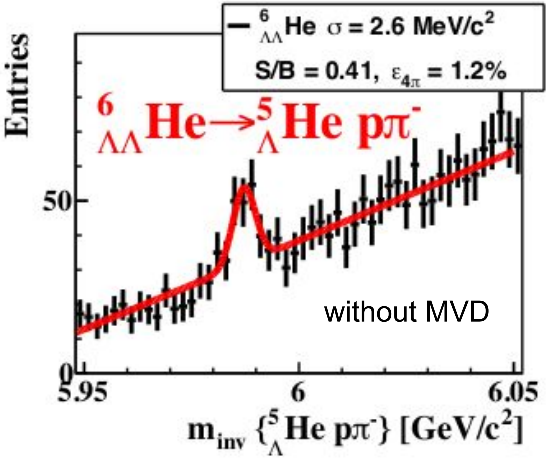
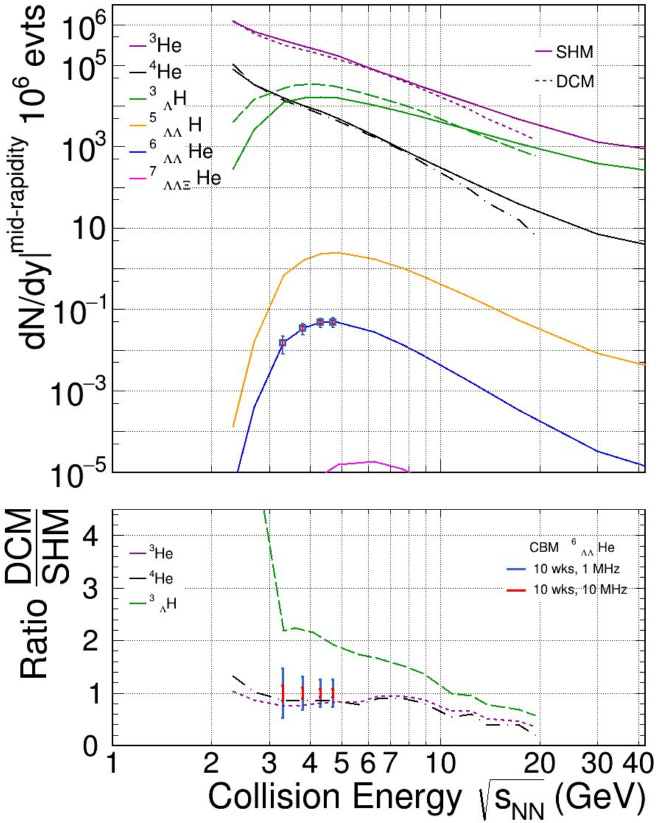
Compilation TG, QM2018

Double-Λ hypernuclei reconstruction in CBM





Hypernuclei: reconstruction & yield projections



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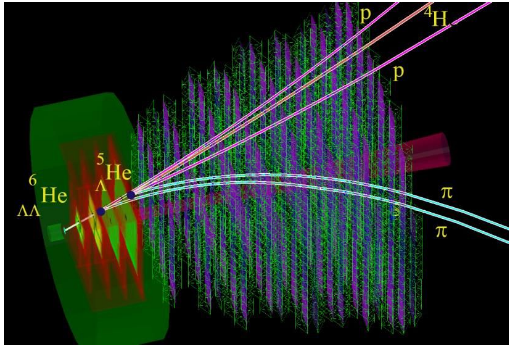
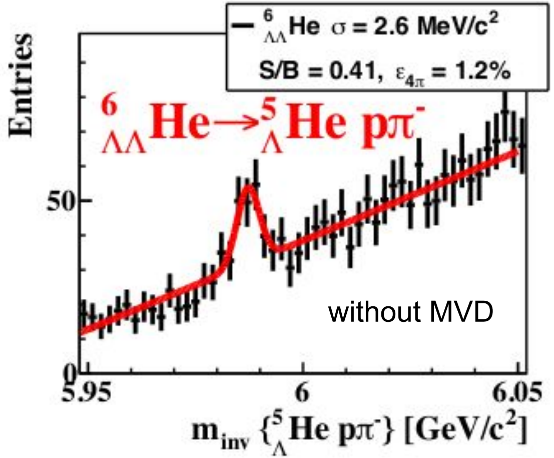
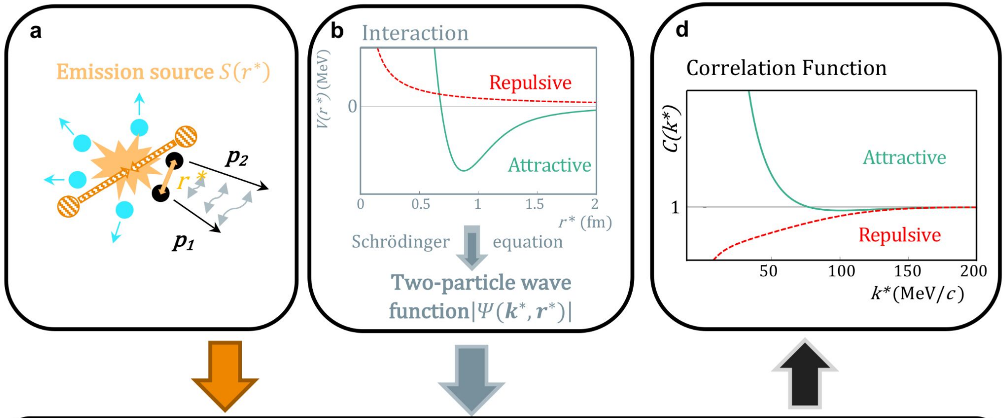




CBM	$\sqrt{s_{NN}}$, GeV	Run time, weeks	eff, %	R_{int}, MHz	Duty F %	Yield
${}^{3}_{\Lambda}H$	4.7	1	19	10	50	5.5x10^{9}
${}^{4}_{\Lambda}He$	4.7	1	15	10	50	2.7x10^{8}
${}^{6}_{\Lambda\Lambda}He$	4.7	10	1	10	50	146

Rate estimates for 10Mhz are without MVD

Using femtoscopy to study hyperon-hyperon interaction



c

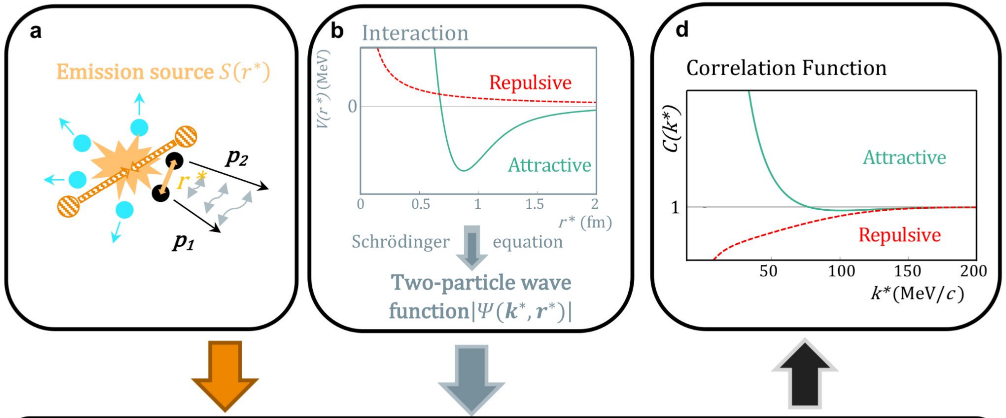
$$C(k^*) = \int S(r^*) \, |\Psi(\mathbf{k}^*, \mathbf{r}^*)|^2 \, d^3r^* = \xi(k^*) \cdot \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

Precision measurements of baryon-baryon interaction:

- study strong interactions between (multi)-strange baryons

  In baryon reach (A+A) environment
- Possibility to study many-body interaction
- Compare with predictions from lattice calculations

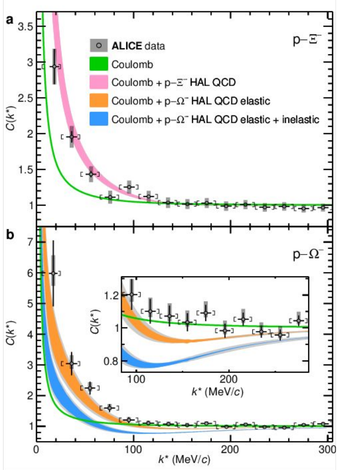
Using femtoscopy to study hyperon-hyperon interaction



c

$$C(k^*) = \int S(r^*) \; |\Psi(k^*, r^*)|^2 \, d^3r^* = \xi(k^*) \cdot \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

ALICE Collaboration, Nature 588 (2020) 232

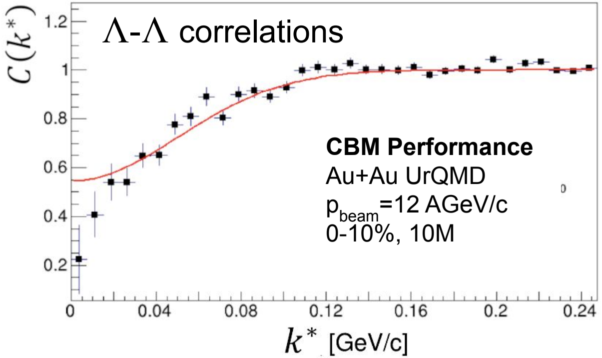


$p - \Xi^-$

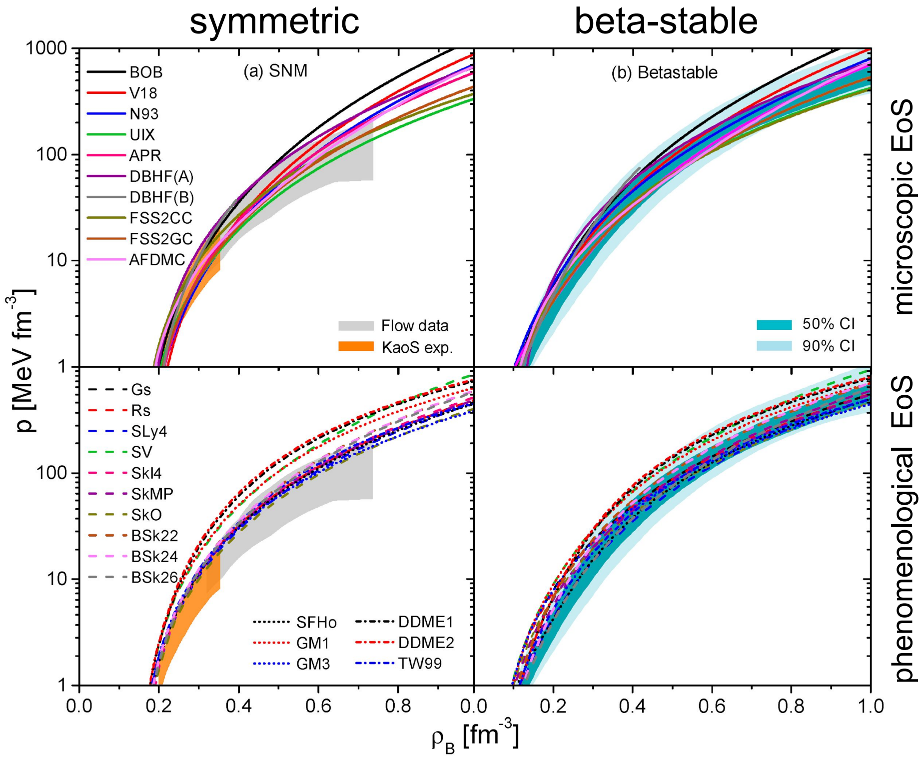
$p - \Omega^-$

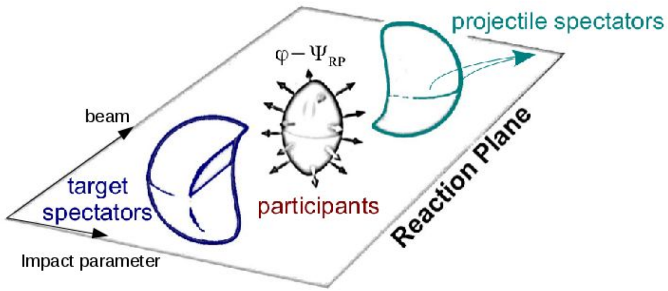
Precision measurements of baryon-baryon interaction:

- study strong interactions between (multi)-strange baryons
  In baryon reach (A+A) environment
- Possibility to study many-body interaction
- Compare with predictions from lattice calculations



Probing QCD Equation of State: collective flow of hyperons



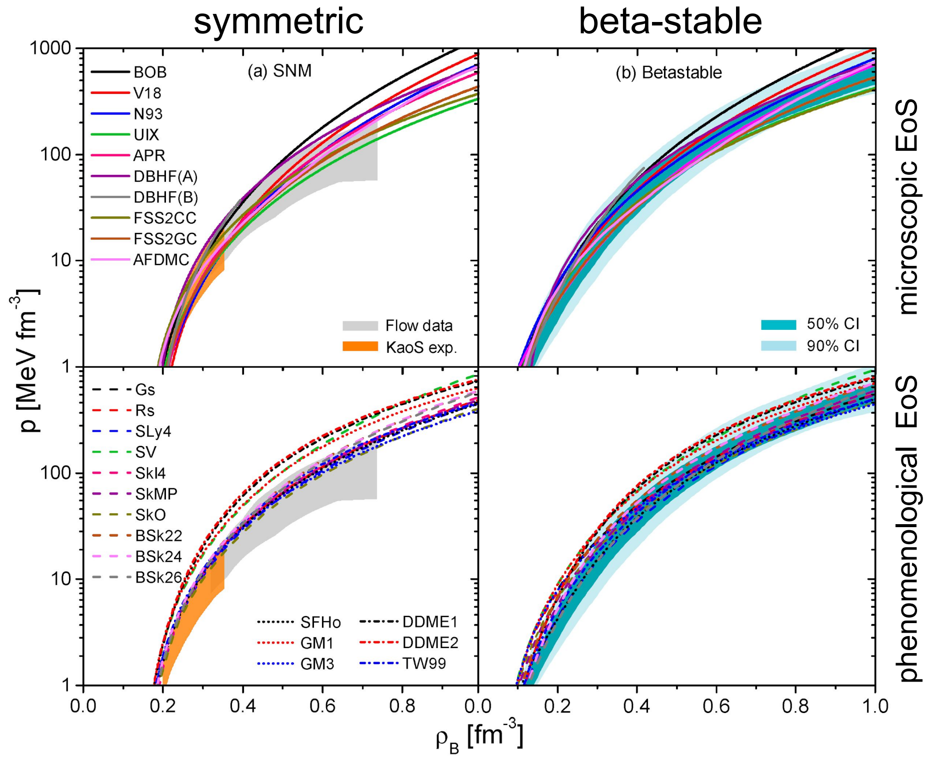


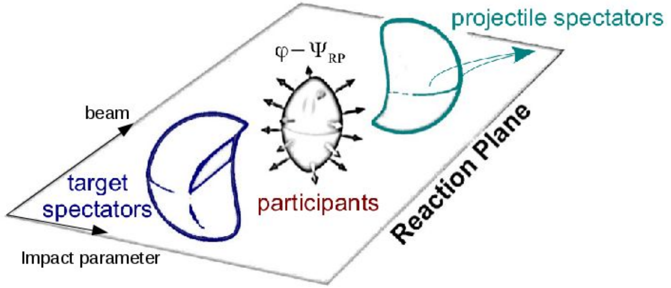
$$v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$

orange KaoS experiment
grey Flow data
blue GW170817 limits

G. Burgio et al., Symmetry 13(3), 400 (2021)

Probing QCD Equation of State: collective flow of hyperons





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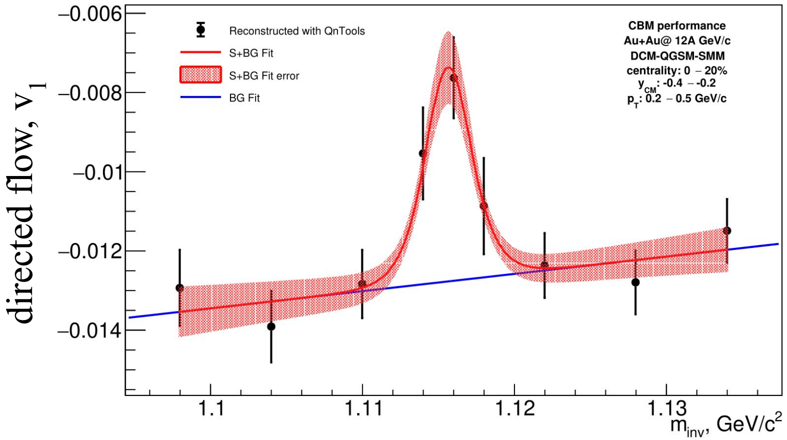

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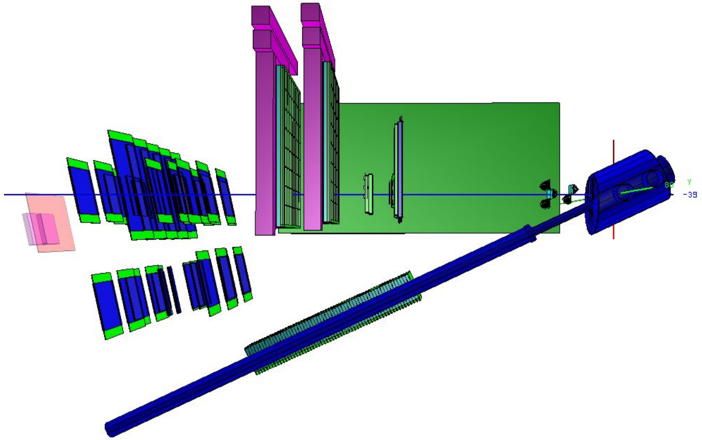
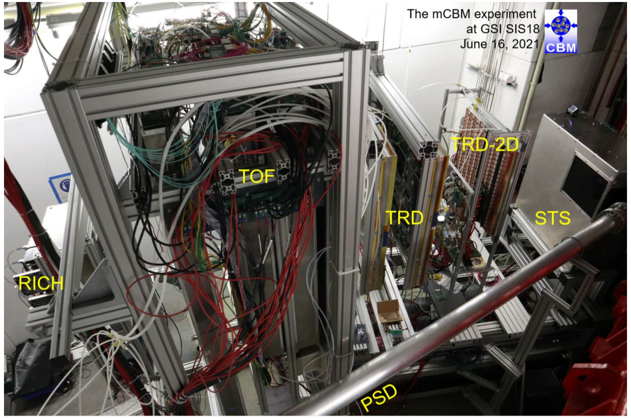
G. Burgio et al., Symmetry 13(3), 400 (2021)

FAIR Phase-0: CBM performance at high-rates with mCBM

mCBM subsystems in 2021



mCBM setup in 2021



Month in 2021	beam ion	Energy, AGeV	target	rate per spill	duration, sec
March	^{208}Pb (67+)	1.06	Ni	2 x 10^9	10
May	^{124}Xe (46+)	1.3	Ni	3 x 10^9	10
June	^{16}O (8+)	2	Ni	10^{11}	10

FAIR Phase-0: CBM performance at high-rates with mCBM

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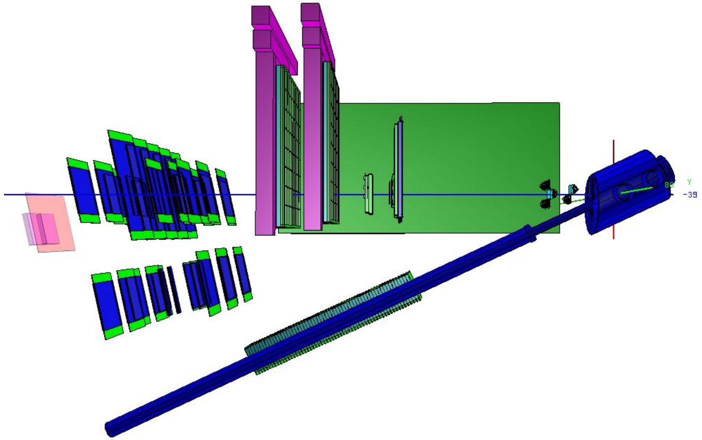
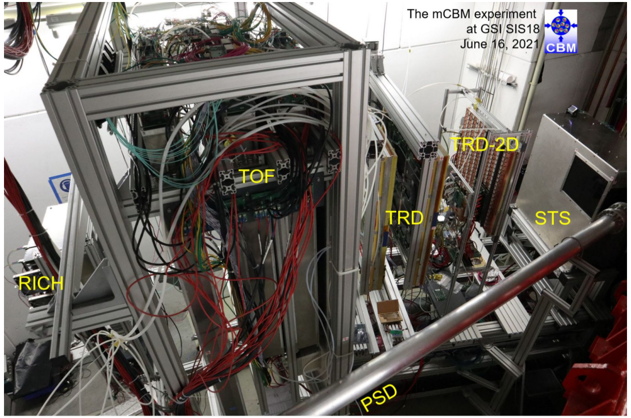
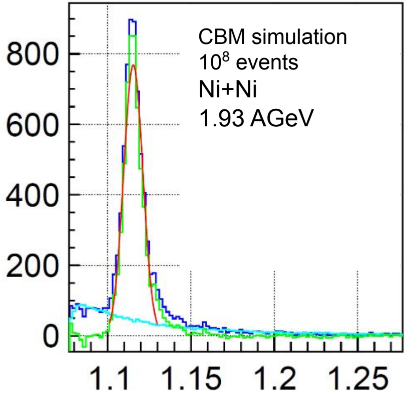


mCBM setup in 2021



$\Lambda \rightarrow p\pi^-$



$m_{p\pi^-}$, GeV/c^2

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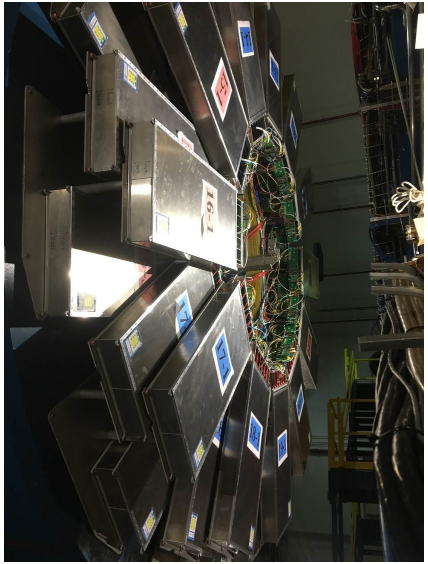
Λ hyperon yield is a benchmark CBM measurements: compare with published data (FOPI, HADES)

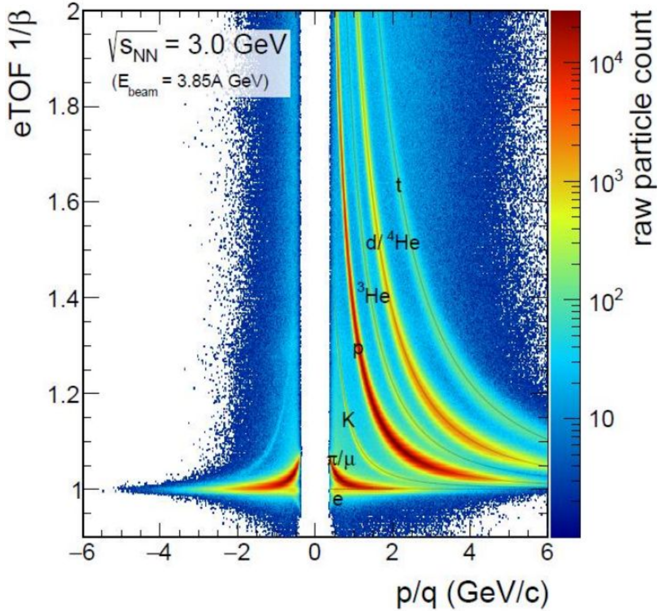
Measure excitation function and system size dependence of sub-threshold Λ production

FAIR Phase-0: eTOF @ STAR

TOF @ STAR

E_{beam}= 3.85 GeV, STAR Fixed target mode

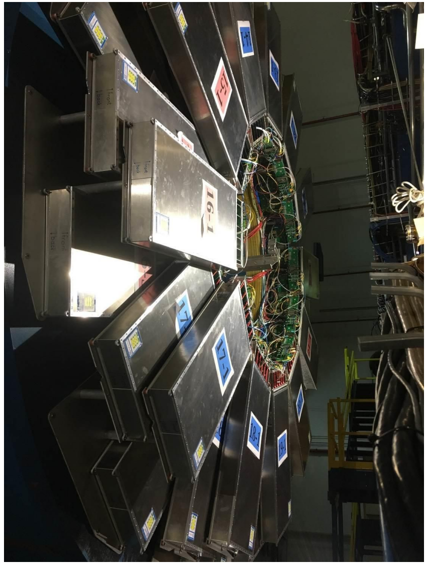




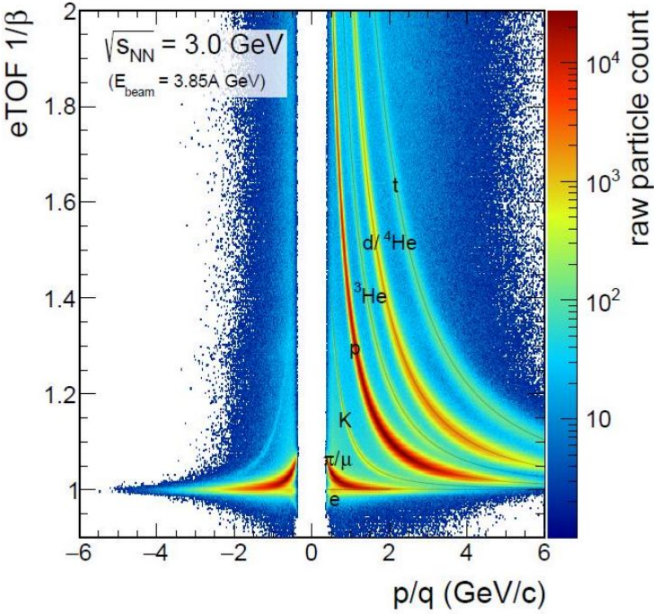
eTOF @ STAR is installed, commissioned and used during STAR-FXT data tacking

FAIR Phase-0: eTOF @ STAR

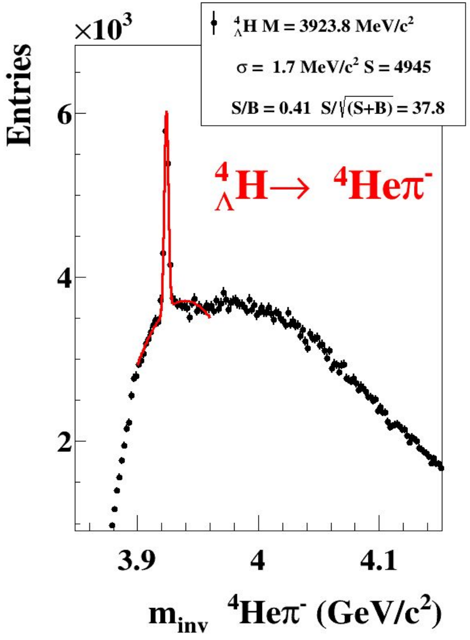
TOF @ STAR



E_{beam}= 3.85 GeV, STAR Fixed target mode



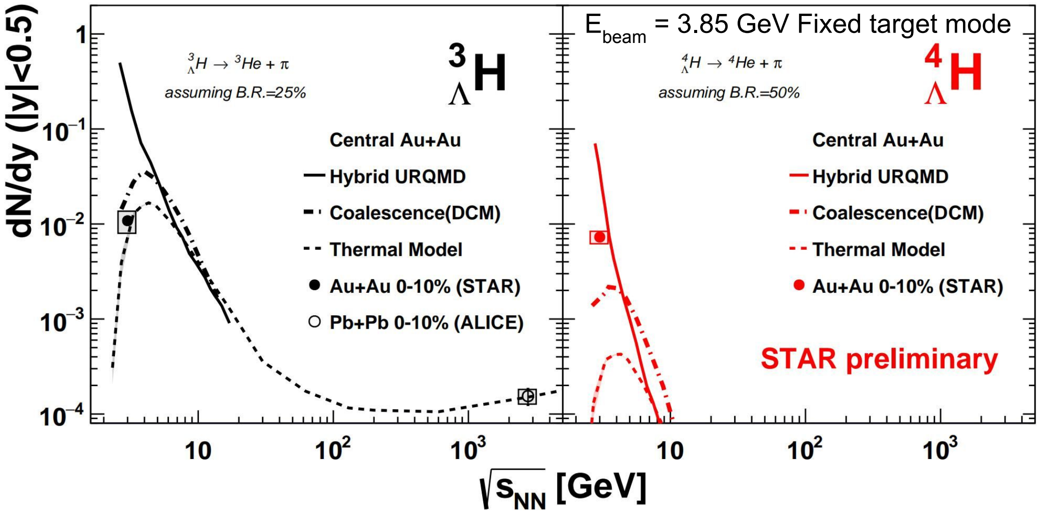
Validating CBM online tools at STAR: KFParticleFinder



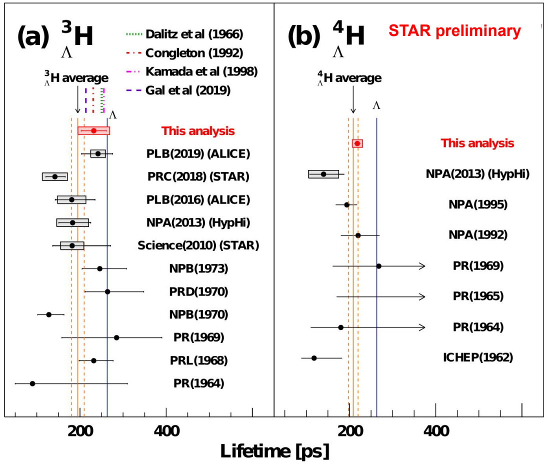
eTOF @ STAR is installed, commissioned and used during STAR-FXT data tacking

FAIR Phase-0: Single-Λ hypernuclei @ STAR fixed target

Hypernuclei yield vs. $\sqrt{s_{NN}}$



Single-lambda hypernuclei yield vs $\sqrt{s_{NN}}$



- Yields vs $\sqrt{s_{NN}}$, differentially in p_T (m_T), rapidity, etc.: probing different production mechanisms
- Mass, binding energy, lifetime, branching ratios, etc.: lifetime of the $^{4}_{\Lambda}He$ differs from that of free Λ
- STAR can access 3-body decays, only single-Λ hypernuclei p to $^{5}_{\Lambda}He$

STAR (Hu Chenlu) at SQM2021 https://indico.cern.ch/event/985652/contributions/4305131/attachments/2244913/3813304/SQM2021_Chenlu_v7.pdf

Summary

CBM physics program at SIS100 is unique:

- Precision study of the QCD phase diagram in the region of extreme high net-baryon densities

Unique measurements of rare diagnostic probes with CBM:

- High-precision multi-differential measurements of hadron yield and correlations including (multi-)strange hyperons for different beam energies and collision systems
- Studies of light (multi-lambda)hypernuclei
- Extensive physics performance studies for many physics observables

CBM FAIR-Phase 0 program (HADES, STAR, BM@N, NA61/SHINE, mCBM)

- Activities are targeted towards usage and understanding of major components and their integration
- Produce physics results with CBM devices:
    - hypernuclei production at STAR FXT
    - measurement of subthreshold Λ excitation function at mCBM

The CBM Collaboration: 55 institutions, 413 members

China
Czech Republic
France
Hungary
Germany
India
Korea
Romania
Poland
Russia
Ukraine