



Precise multidimensional exploration of QCD matter with CBM spectrometer

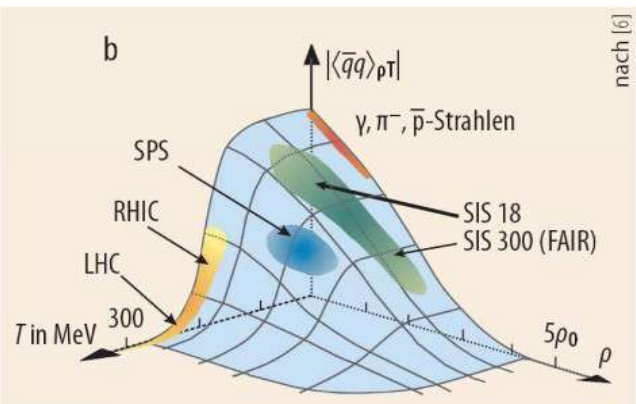
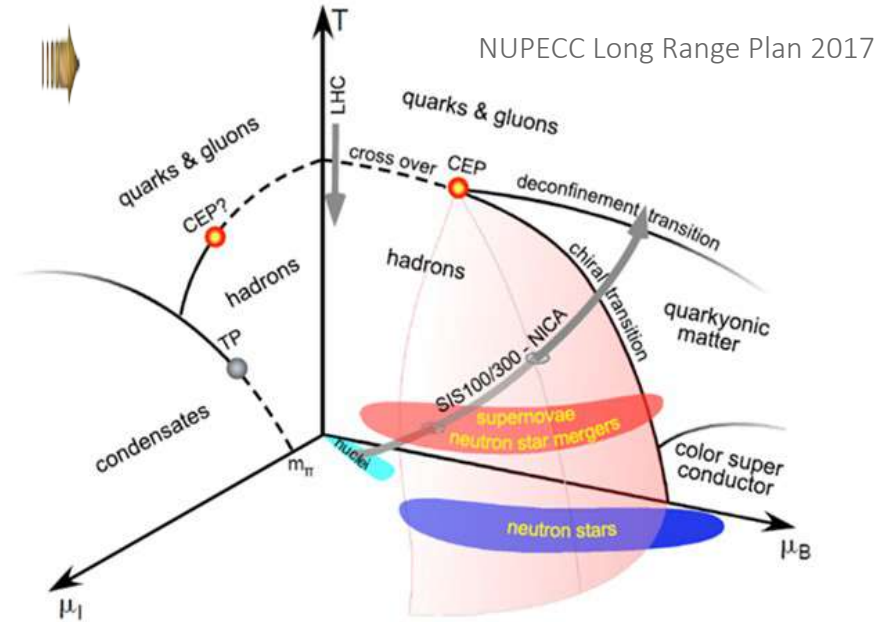
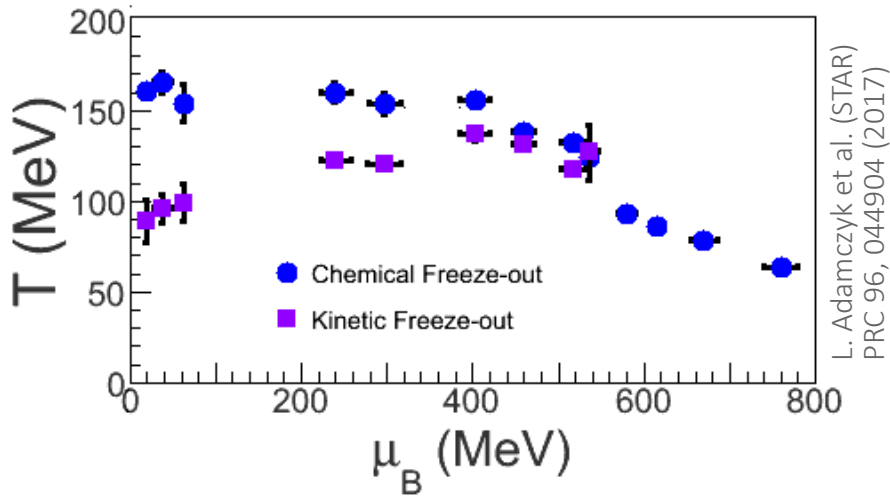
Krzysztof Piasecki

University of Warsaw, Faculty of Physics



Gross features of physical landscape

QCD phase diagram: what we know ... what we think



M. Kotulla et al., Physik Journal 8, 3 (2009)

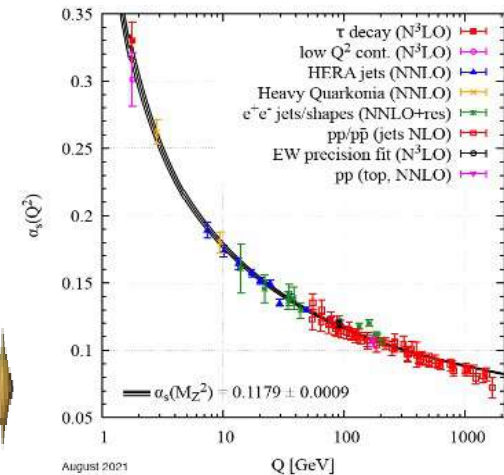
Gell-Mann Oakes Renner – relation

$$m_K^{*2} f_K^{*2} = -\frac{m_u + m_s}{2} \langle 0 | u\bar{u} + s\bar{s} | 0 \rangle + \Theta(m_s^2)$$

Partial restoration of chiral symmetry

Running strong coupling constant

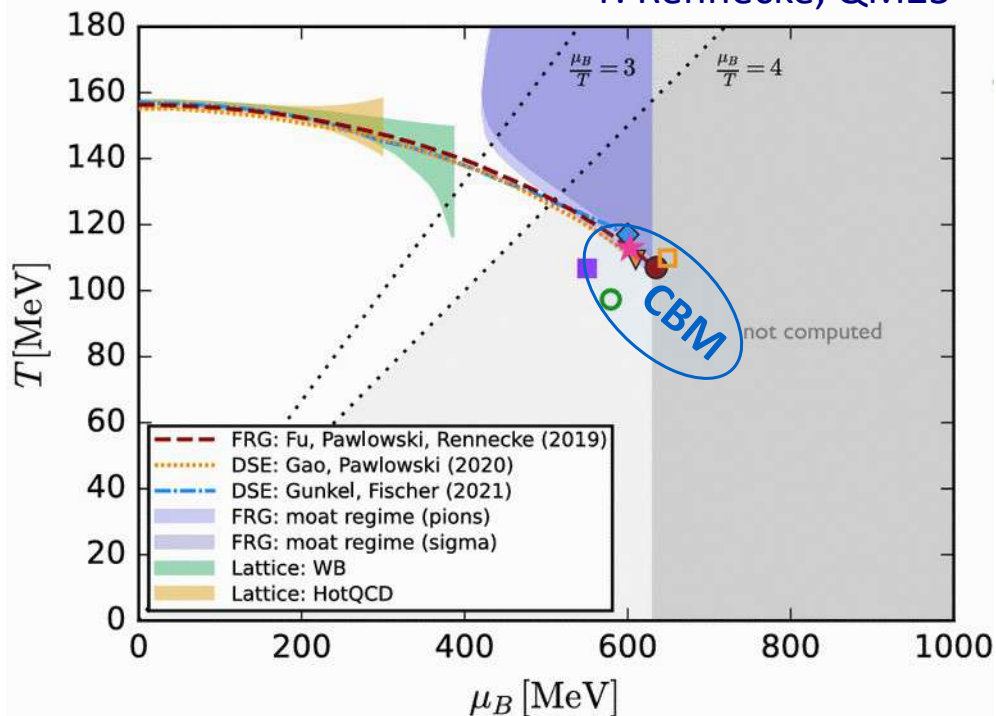
high $T \Rightarrow$ high p transfer \Rightarrow perturbative QCD



Gross features of physical landscape

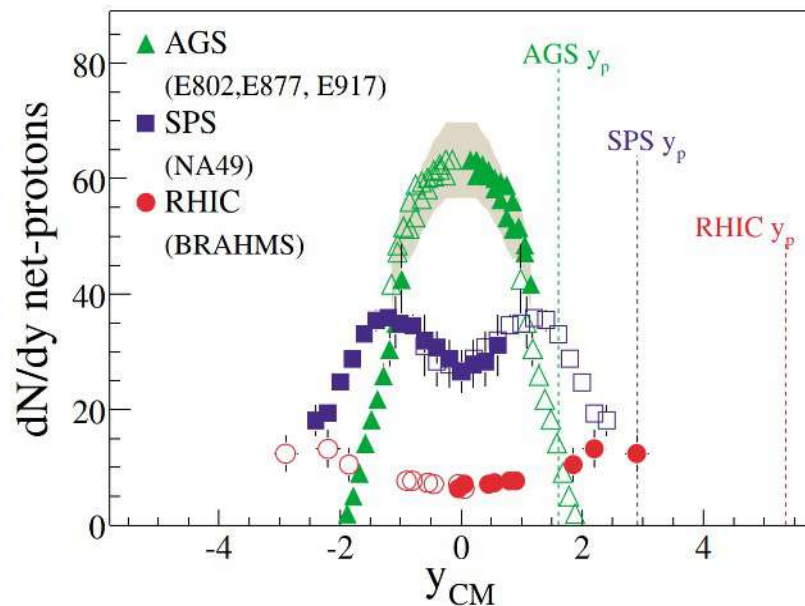
- **Critical End-Point:** possible current location – good chance to coincide with CBM energies
 ($T_{\text{Beam}} \approx 2 - 11 \text{ A GeV}$ or $\sqrt{s_{\text{NN}}} \approx 2.7 - 4.9 \text{ GeV}$)

F. Rennecke, QM25



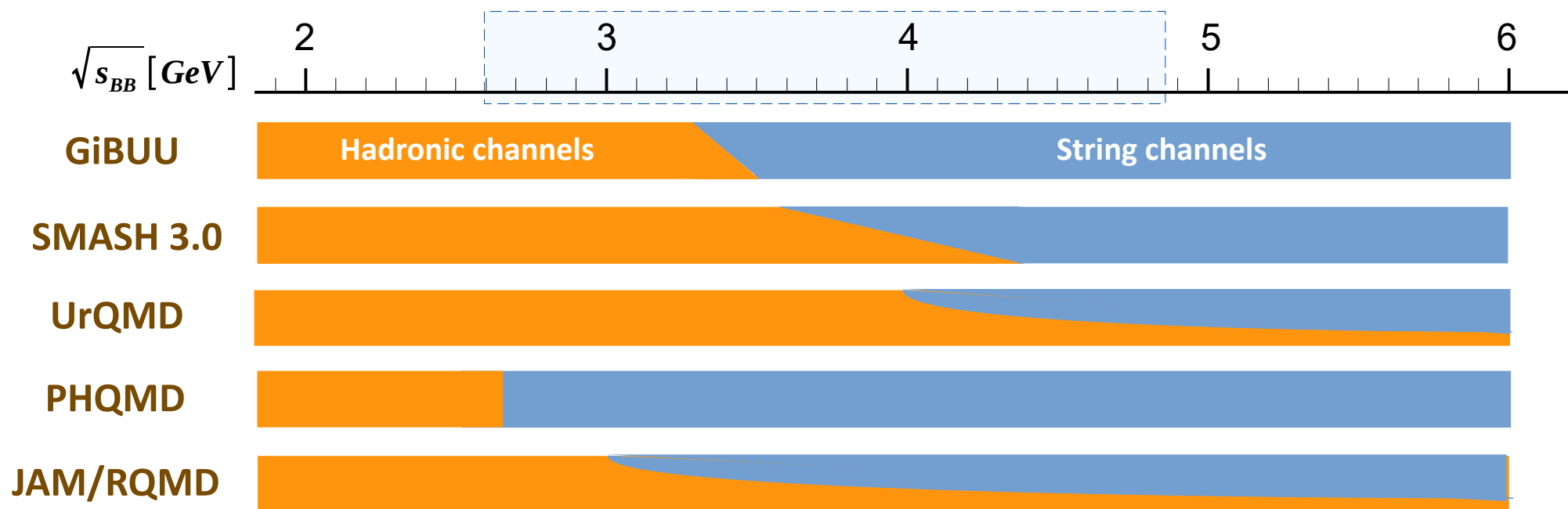
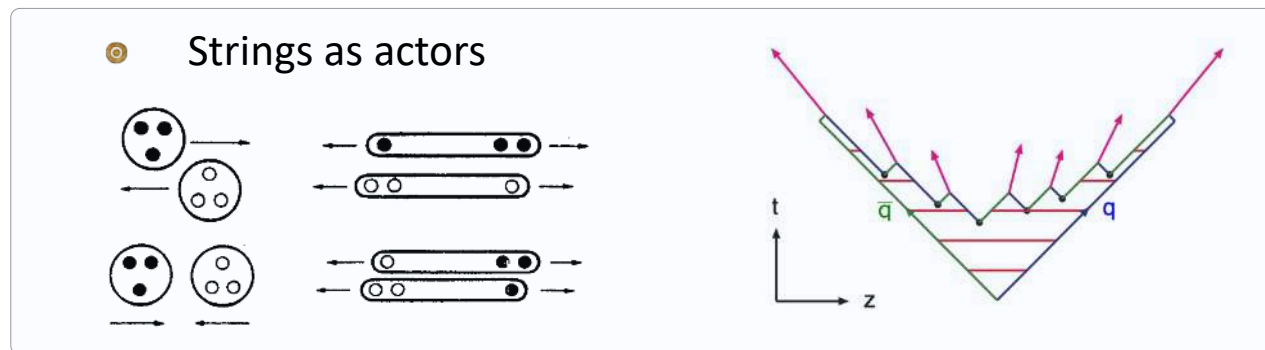
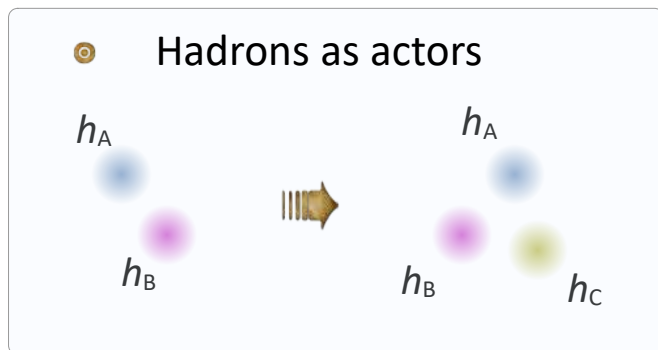
- ▷ CBM: creation of high-density QCD medium

I.G. Bearden et al. (Brahms) PRL 93, 102301



- CBM Goal: Isolate unambiguous signals of new phases of QCD matter, order of phase transitions, chiral symmetry restoration (CSR)

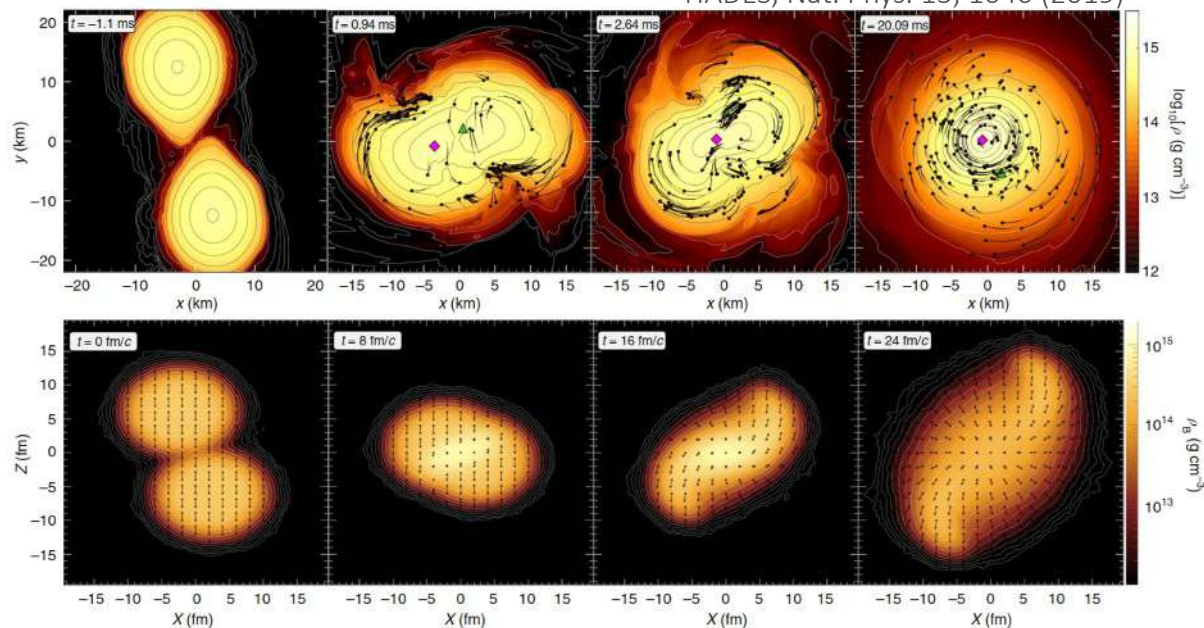
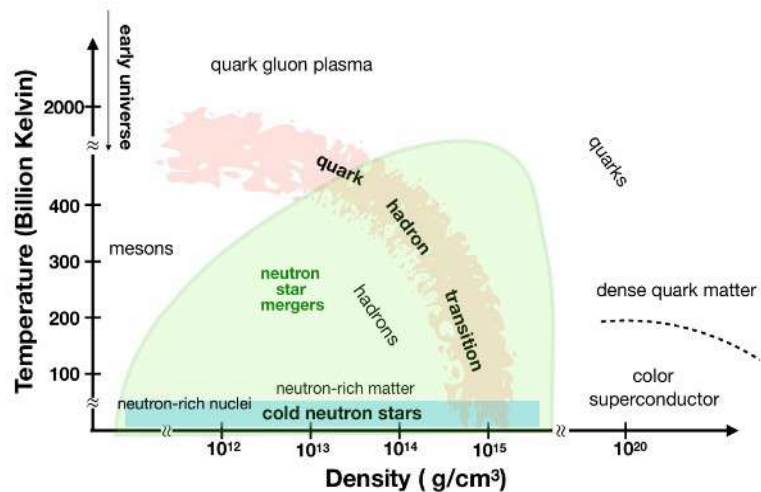
Transport models: $h \rightarrow q$ transition region



Phase space distributions of hadrons from AA (h_A, h_h) : possible testing ground of hadron \leftrightarrow string transition

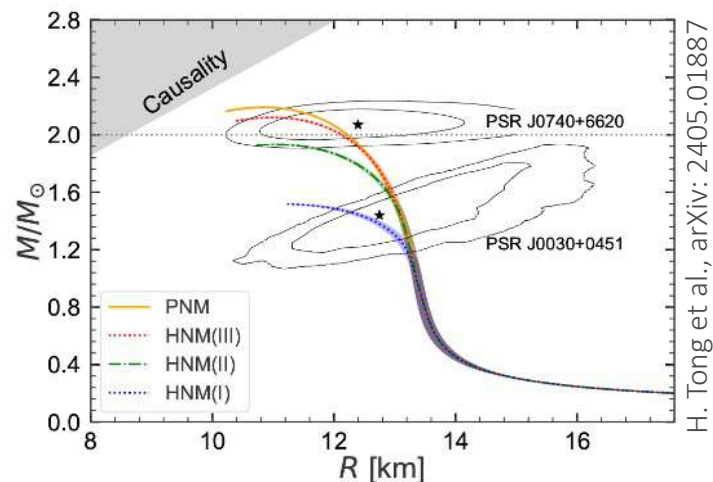
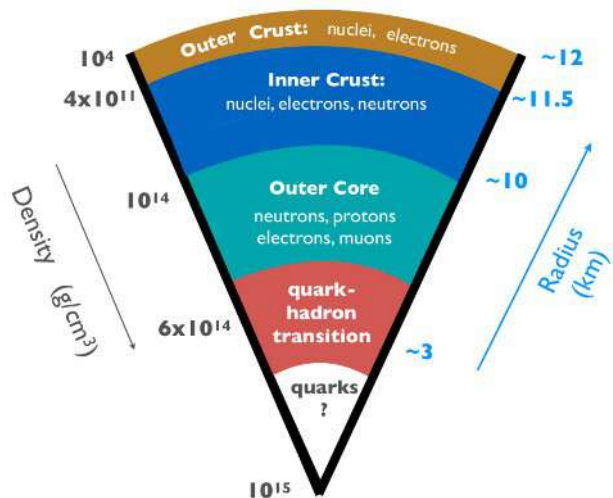
HIC as input to Astrophysics

HADES, Nat. Phys. 15, 1040 (2019)



Hyperon puzzle:
can it be solved?

- HNM : hyper neut. matter
- HNM I : $N\Lambda$
- HNM II : $NN\Lambda$
- HNM III: $N\Lambda\Lambda$
- PNM : pure neut. matter



H. Tong et al., arXiv: 2405.01887

CBM physics topics vs observables

- **Partial Chiral Symmetry Restoration**
(changes of masses, decay widths of hadrons in medium)
- **Thermal approach to collision** ($T_{\text{preeq}}, T_{\text{Chem}}, T_{\text{Kin}}, \mu$'s)
- **Equation of State**, accounting for $N \neq Z$ terms
- **YN (hh), 3-body interactions**
- Exploring **hadron gas** \Rightarrow **QGP** transition, **Quarkyonic matter** + **Critical point** searches
- **Transport**: σ /channels upgrade via subthreshold data
 - $|S| = 2, 3$ hadrons
 - Charm
- Transport: (dynamic) **treatment of clusters**
 - LCP spectra and yields

- Rare probes of bulk matter, e.g.
- ρ meson profile in dilepton M_{Inv} spectrum
 - K, Y distributions of $d^2N/dp_T dy$, v_n as $f(p_T, y)$
 - K^*, Σ^* widening of widths (?)
 - hadron multiplicities
 - hadron spectra
 - dilepton M_{Inv} spectrum: thermal component
 - bulk matter flow v_n as $f(p_T, y)$
 - $P(K) = f(A_{\text{part}})$, Σ^-/Σ^+ and $\Xi^-/\Xi^+ = f(E_{\text{Kin}})$
 - femtoscopy (3D)
 - hypernuclei, multi-strange hadrons
 - fluctuations of conserved charges
 - multi-strange production as $f(\sqrt{s})$
 - Ξ ($\Lambda\pi$ channel), Σ ($N\pi$ + kink), Ω (ΛK channel)
 - J/Ψ (dilepton channel), D mesons ($K\pi$ channel)
 - LCP distributions of $d^2N/dp_T dy$

Rare probes



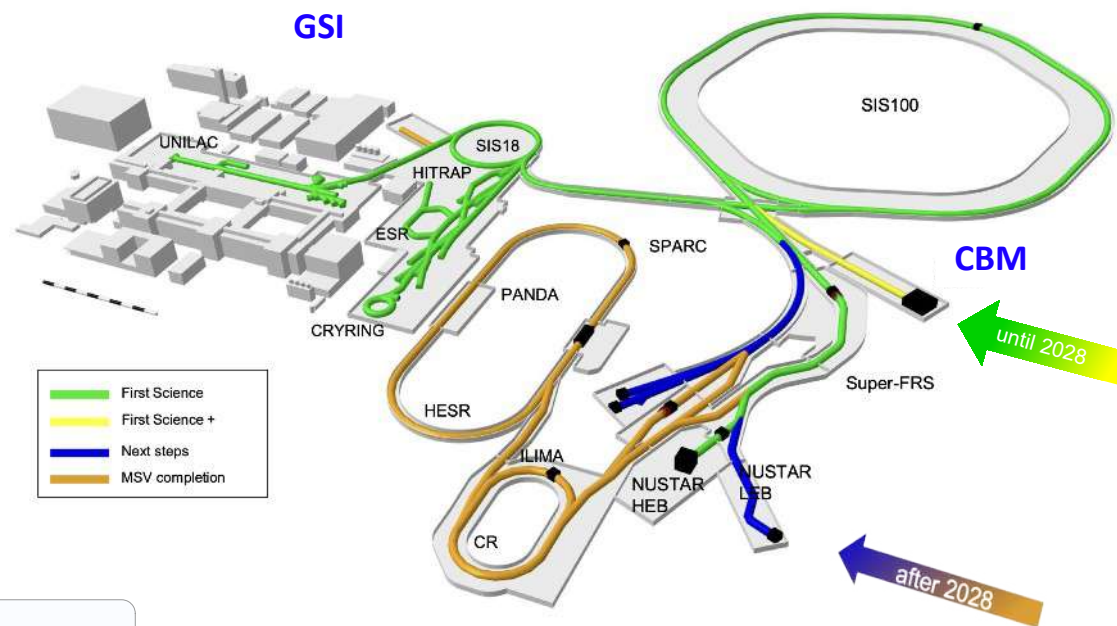
very high intensities SIS100 + CBM

SIS100

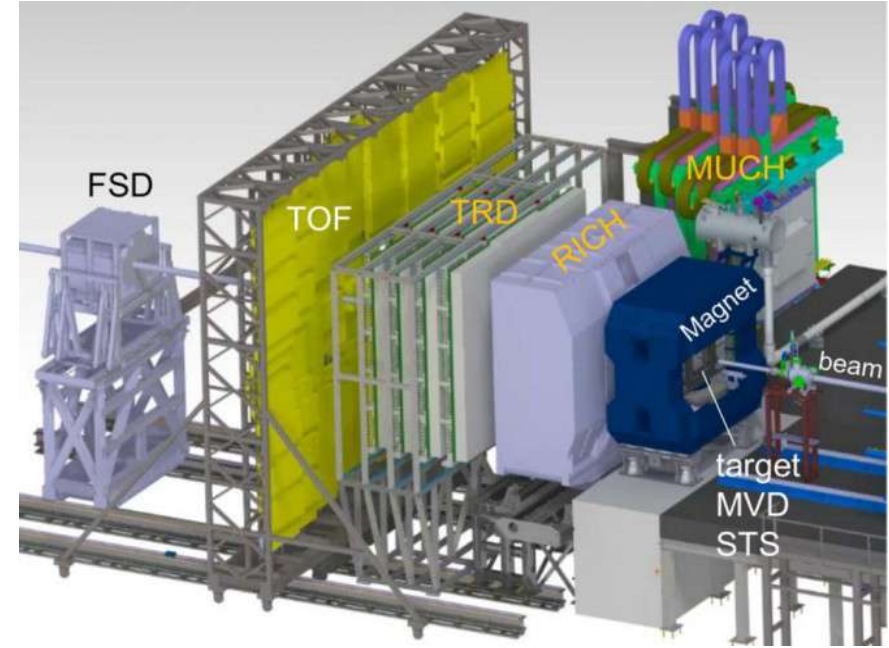
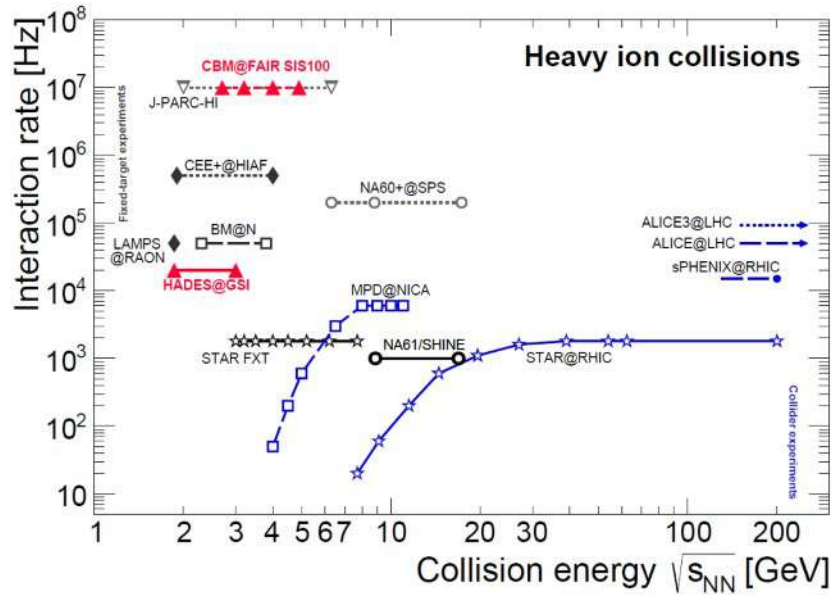
Beam intensity: $\leq 10^{11}$ Hz for U, $\leq 10^{13}$ Hz for p

SIS-100 beams		
Beam	$p_{lab, max}$ [GeV/c]	$\sqrt{s_{NN, max}}$ [GeV]
Heavy ions (Au)	$12 \cdot A$	4.9
Light ions ($Z/A = 0.5$)	$14 \cdot A$	5.5
Protons	29	7.6

- 2017: Start of excavation and trench sheeting
- 2018: Start of shell construction
- 2022: Staging review
- 2023: Buildings completed (First Science+ and Next steps)
- 2024: Start of installation
- 2025: Start of commissioning
- **2028: FAIR 2028 Operation**

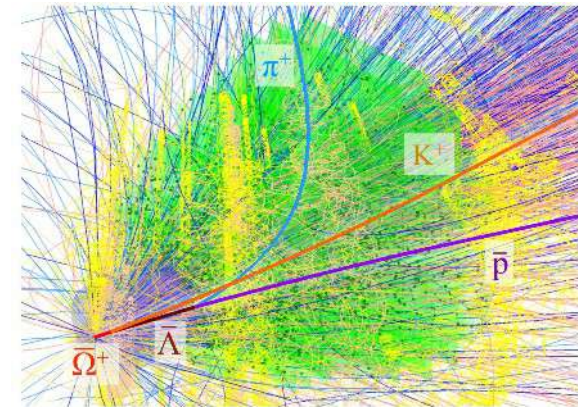


- **APPA** - Atomic, Plasma Physics and Applications
- **CBM** - Compressed Baryonic Matter
- **NUSTAR** - Nuclear Structure, Astrophysics and Reactions
- **PANDA** - Physics with High Energy Antiprotons



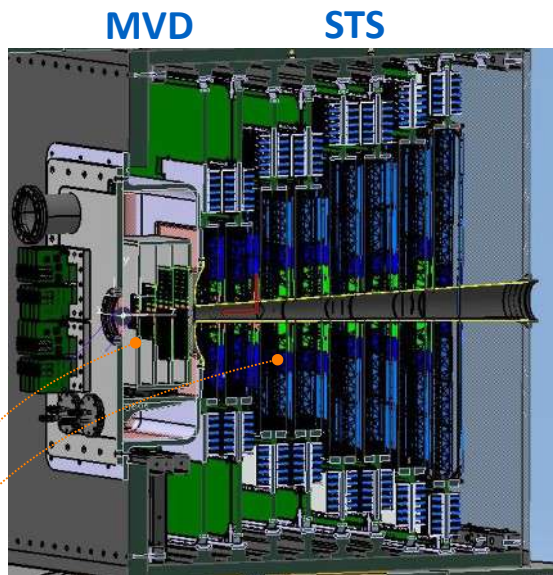
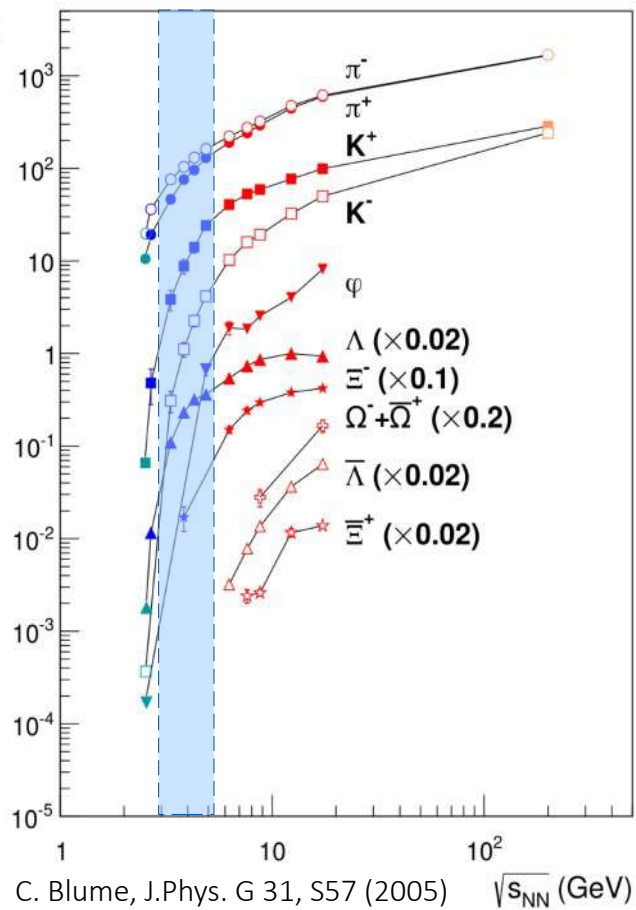
CBM

- ▷ Event rates: up to 10^7 Hz
- ▷ Radiation rate: up to 7×10^{13} 1-MeV $n_{eq} / \text{cm}^2 / \text{yr}$ (MVD)
- ▷ Detectors: fast and radiation-hard
- ▷ FEE: free-streaming
- ▷ DAQ: high-speed (up to 100 kHz, 1 TB/s)
- ▷ Event Selection: on-line @ high performance farm
- ▷ Data volume: 10-20 PB / yr
- ▷ Polar coverage $2^\circ < \vartheta_{\text{Lab}} < 25^\circ$, full φ coverage
- ▷ Y_{NN} coverage for all beam energies



CBM simulation, central Au+Au @ 10 AGeV/c

- CBM energies:
sharp rise of strangeness

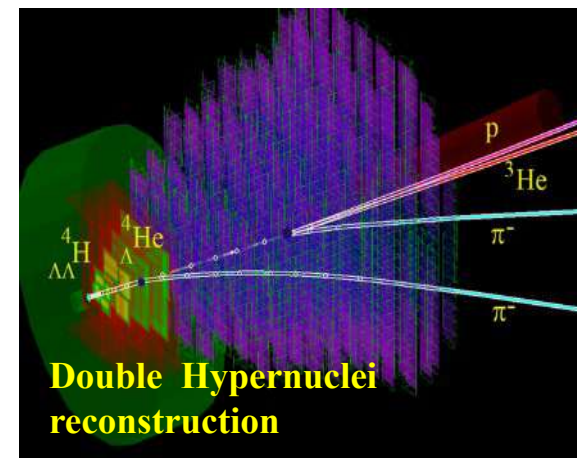


MVD

- 4 tracking stations, MAPS technology, dedicated CBM pixel sensors MIMOSIS
- Operability at 100 kHz Au+Au @ 11 AGeV and 10 GHz p+Au @ 30 AGeV
- Non-uniform hit density in time and space
- High radiation environment, operating in a vacuum

STS

- 8 tracking stations, silicon μ -strip sensors
- $\Delta p/p < 2\%$ for $p < 10$ GeV/c
- Radiation tolerance: $\sim 10^{14}$ 1-MeV n_{eq}/cm^2 over lifetime

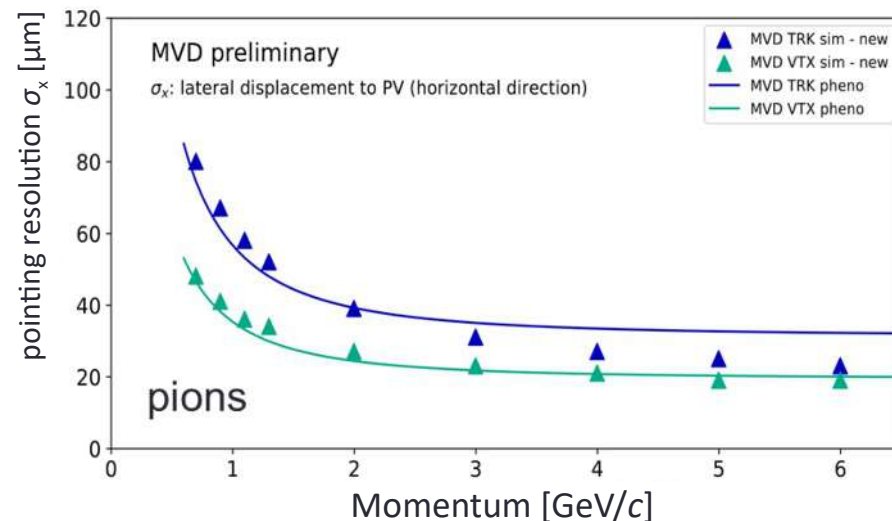


MVD + STS : heart of measurement

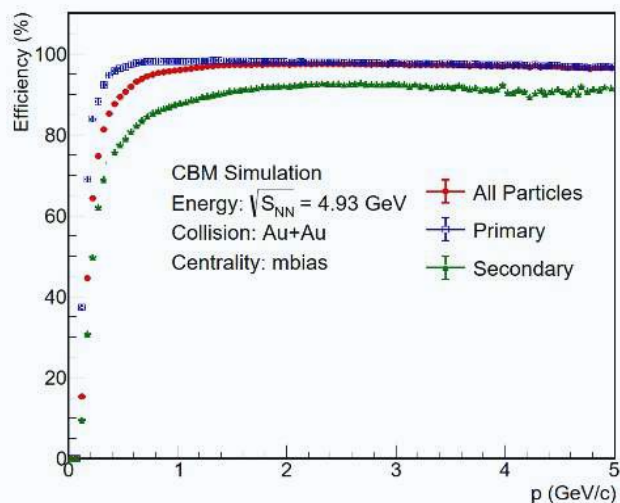
- Physics motivation: open charm measurement

$$\begin{aligned} c\tau (\Lambda_c) &= 60 \mu\text{m} & \gamma (T_B = 2A \text{ GeV}) &= 1.4 \\ c\tau (D^0) &= 120 \mu\text{m} & \gamma (T_B = 11A \text{ GeV}) &= 2.6 \end{aligned}$$

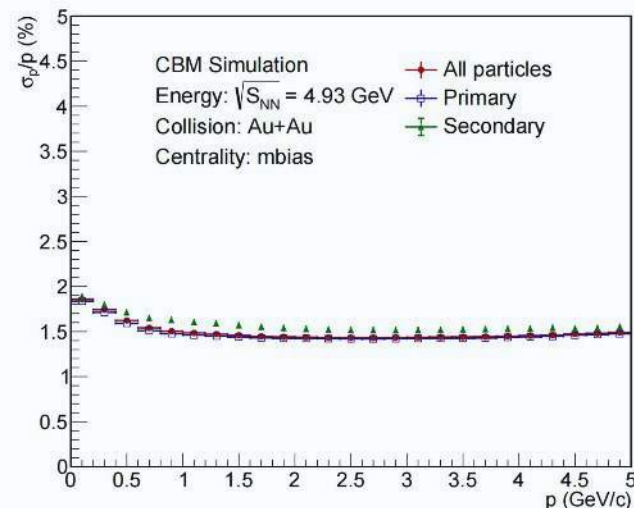
- MVD: resolution of π tracks pointing to primary vertex



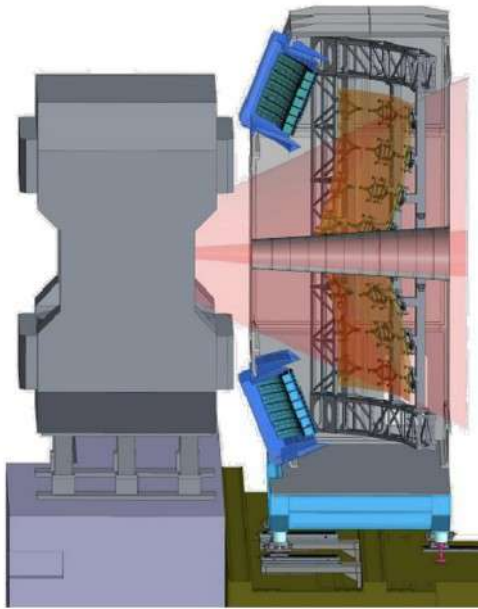
- STS: reconstruction efficiency = $f(p)$



- STS: momentum resolution (σ_p/p)



RICH & MUCH : dielectrons vs dimuons



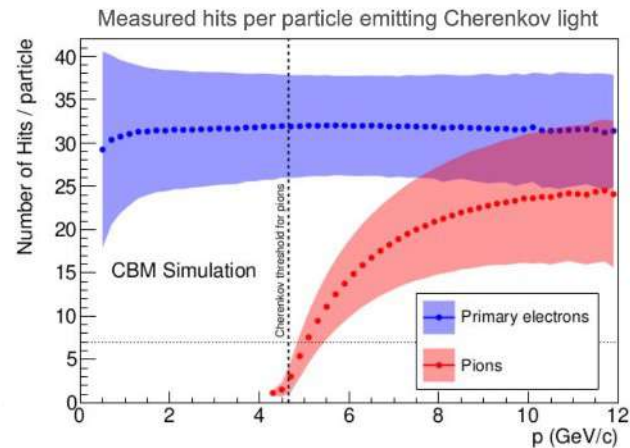
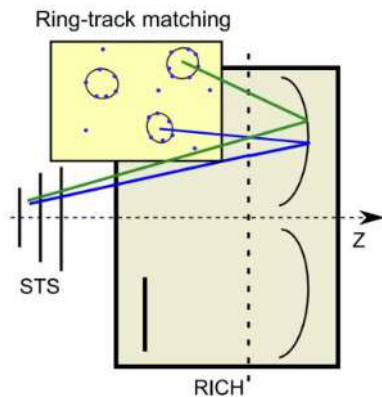
RICH

Aim: identify electrons via Čerenkov rings.

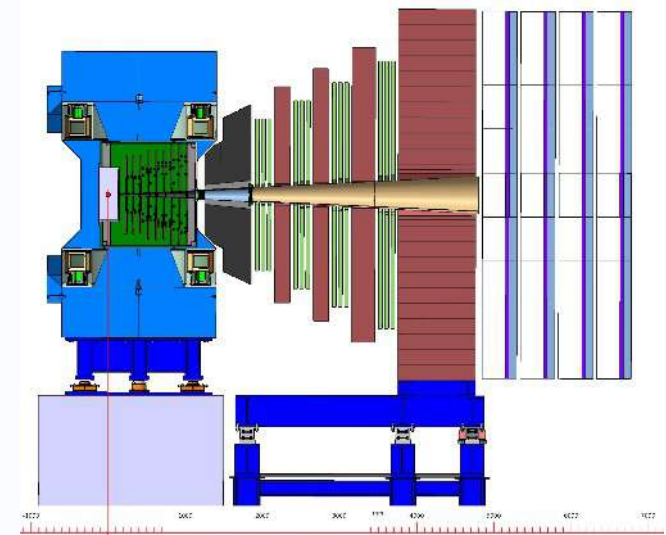
Gaseous (CO₂) detector.

$\sigma_{\text{Timing}} \sim 300$ ps.

Separation of e from p: ok for $p < 8$ GeV/c.



MuCH

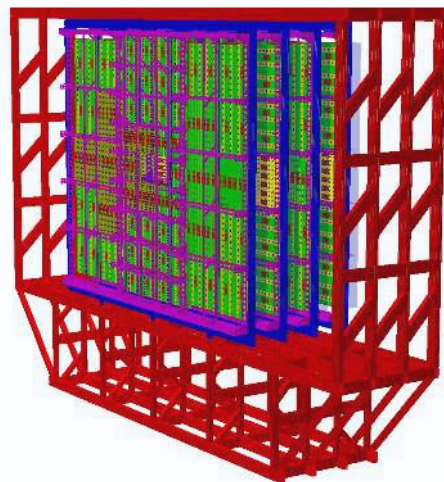


Aim: suppress hadrons, track muons

Basis: traversing hadrons generate cascades, whereas leptons - not.

5 absorbers (Graphite, Fe, Fe, Fe, Fe)

4 detector stations, 3 detector layers each



TRD

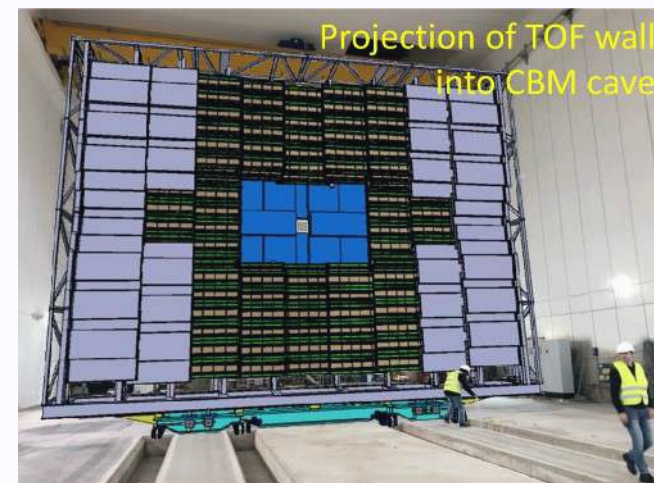
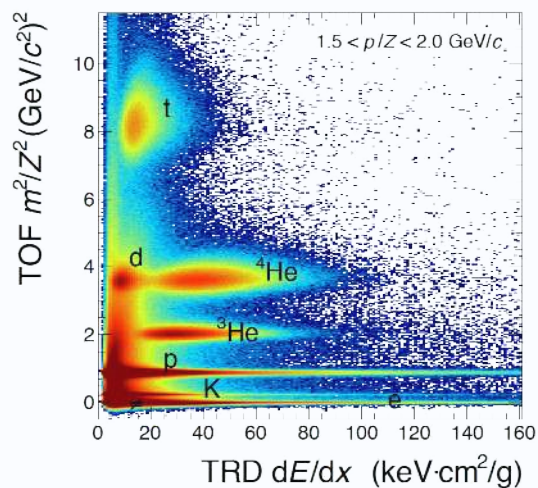
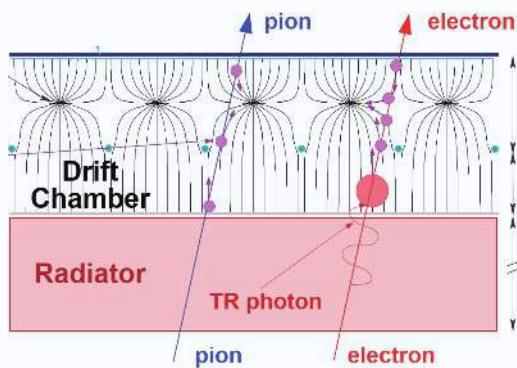
Aims:

- identify e^\pm at high momenta
- separation of $d - {}^4\text{He}$, etc.
- extension of tracking

Basis: a particle transitioning between two media - emits photons.

Intensity rises with γ factor.

\Rightarrow at fixed p , signal stronger for e than π



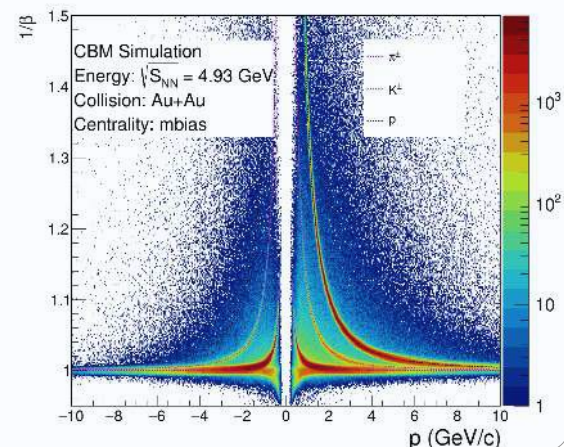
TOF Wall

Aim: precise mass separation via p - v plot

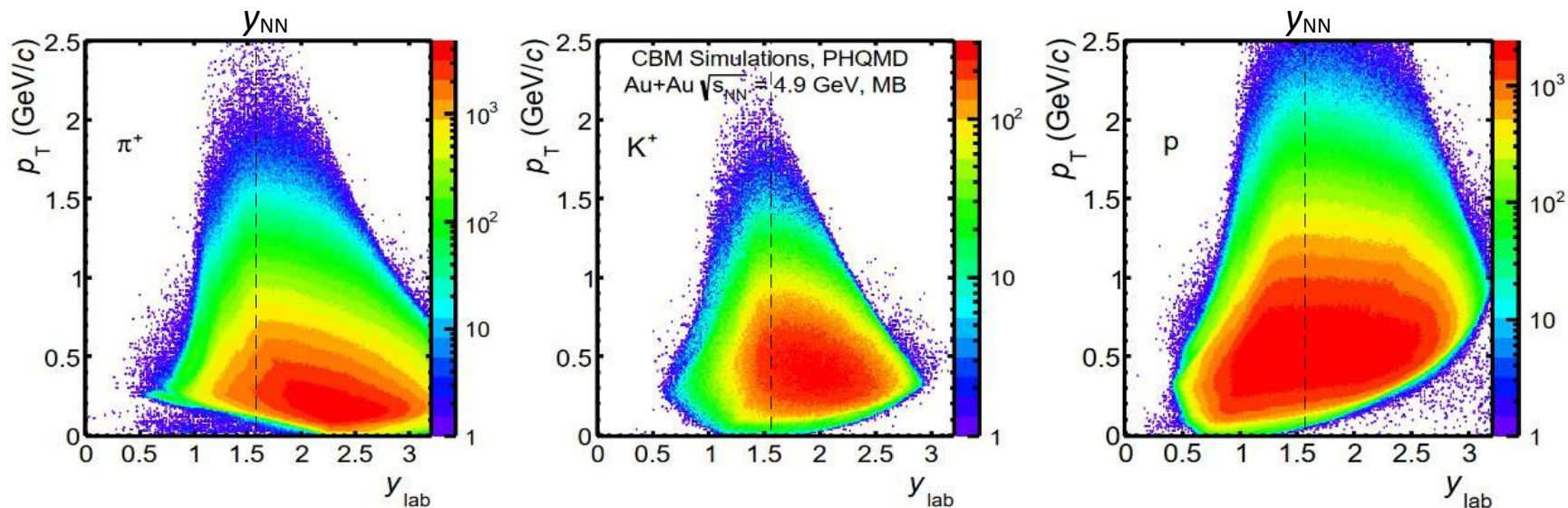
$\sigma_{\text{System}} \approx 80 \text{ ps}$

$\epsilon \gtrsim 95 \%$

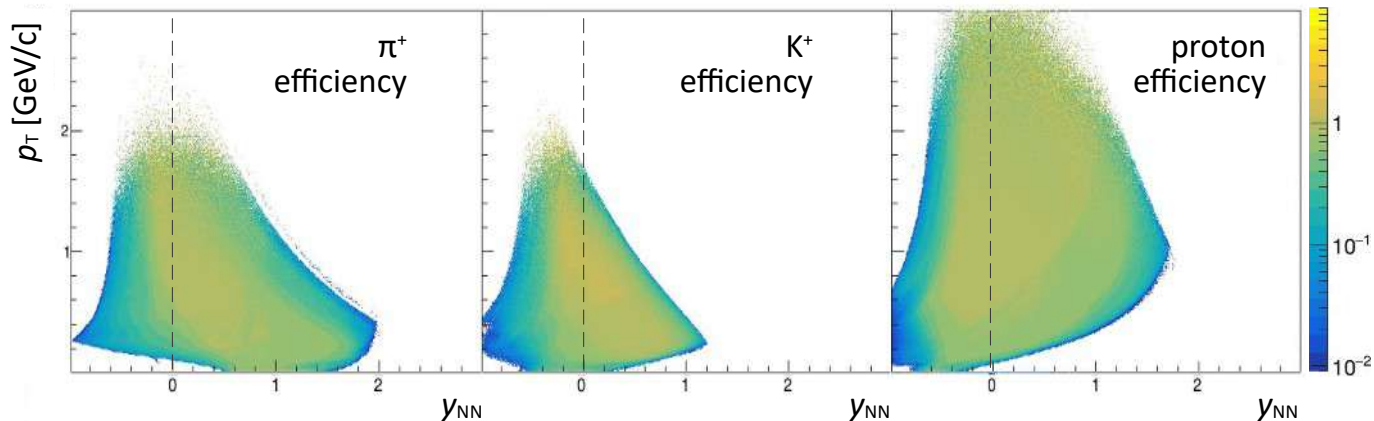
Area: 120 m^2



- Reconstructed distributions of p , π , K from Au+Au @ $T_{\text{Beam}} = 11A$ GeV, studied with PHQMD v5.2

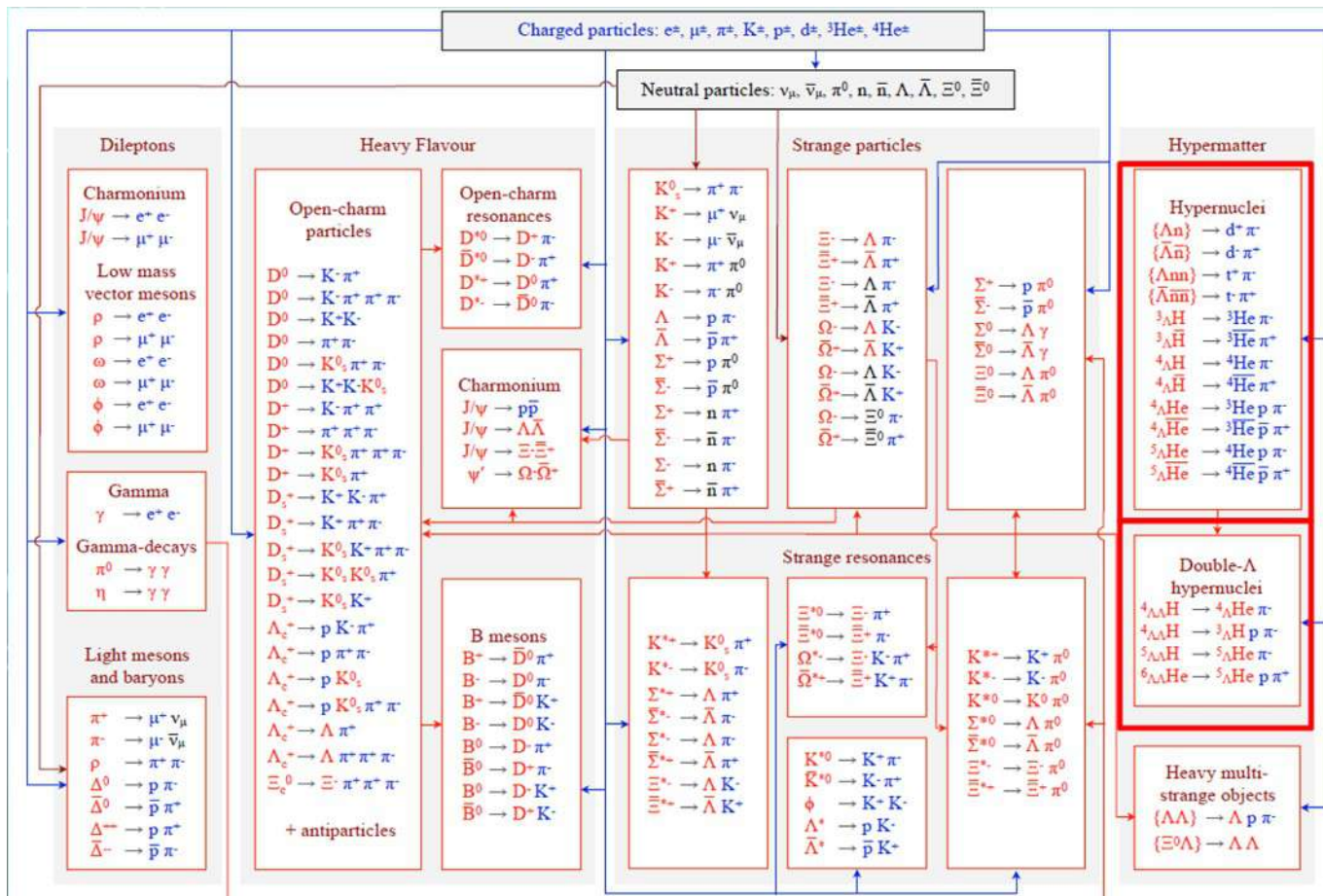
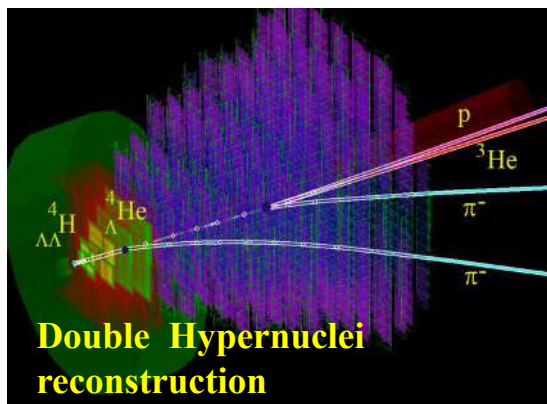
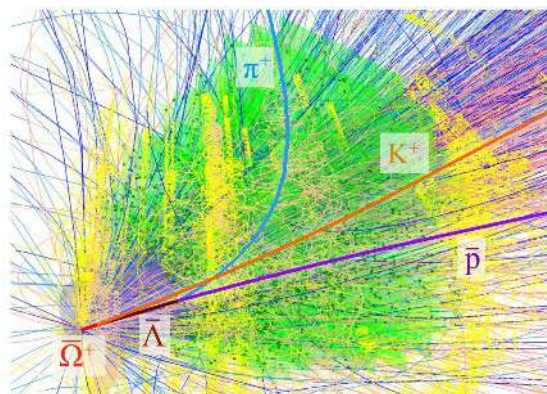


- Efficiency \times acceptance of p , π , K from Au+Au @ $T_{\text{Beam}} = 11A$ GeV, studied with DCM + QGSM + SMM



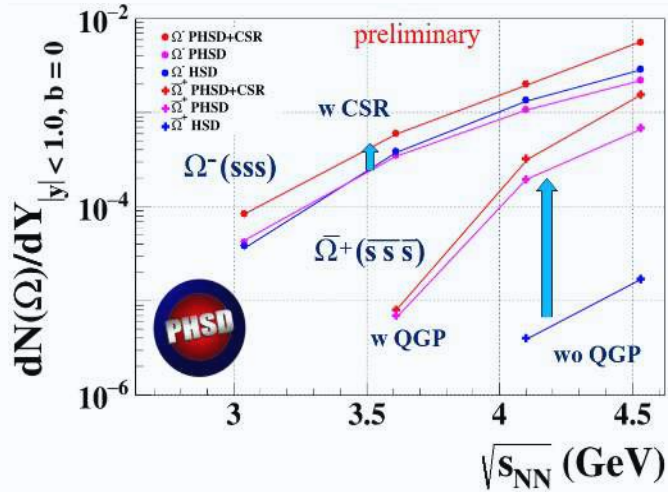
CbmKFPARTICLEFINDER decay reconstruction package

- Package reconstructing decay mother candidates from tracks (260 channels in one go).
 - Reconstructs: (multi-)strange hadrons, charmed hadrons, hypernuclei, hadronic resonances.
 - Fast, integrated with on-line reconstruction chain "FLES" (~ 1 ms / core / 1 Au+Au event of $T_B = 11A$ GeV)
 - CBM-invented, passed tests on real data (STAR, mCBM)
 - Recent: channels with neutral products (e.g. $\Sigma^\pm \rightarrow n\pi^\pm, \rho\pi^0$) using missing mass.



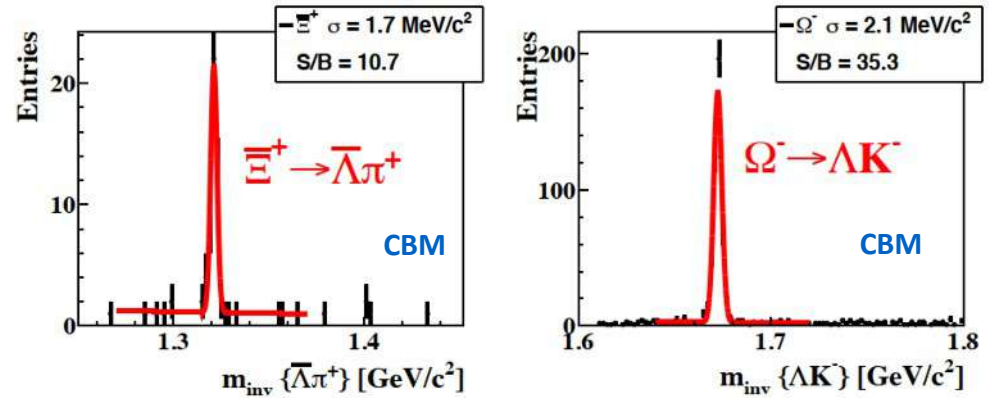
Physics performance. Strangeness

- (P)HSD predictions of $P(\Omega, \bar{\Omega})$ w/wo CSR

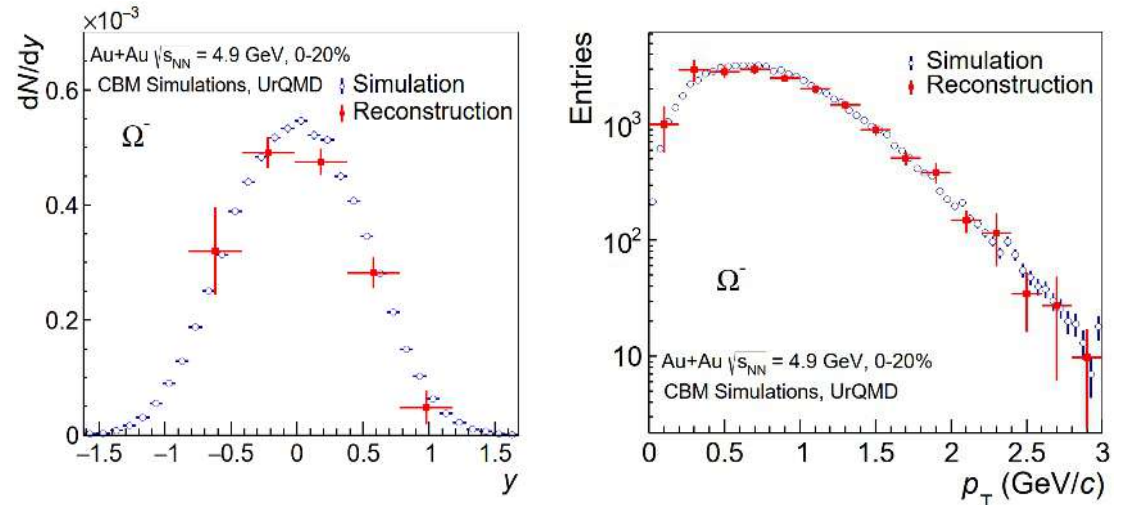


- ▷ Nearly backgroundless reconstruction of doubly- and triply-strange hadrons.
- ▷ Signal clearly seen despite 5..10 MeV only
- ▷ Broad acceptance coverage

- Reconstruction from 5M central UrQMD events of Au+Au @ 10A GeV

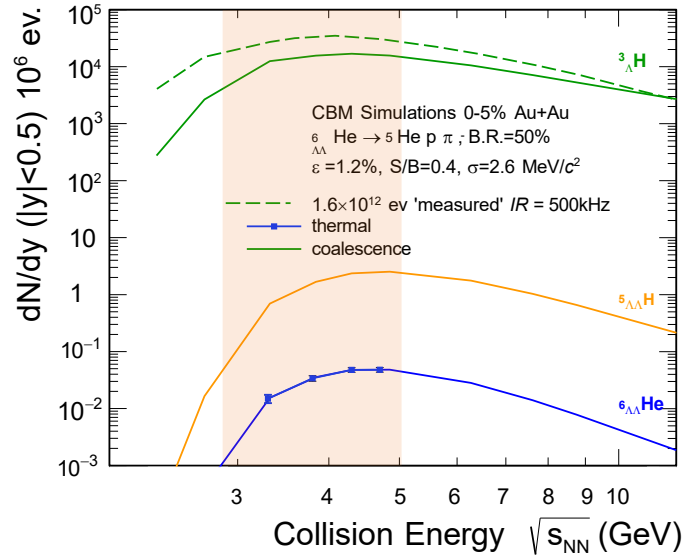


- Reconstruction from 10M central UrQMD events of Au+Au @ 10A GeV

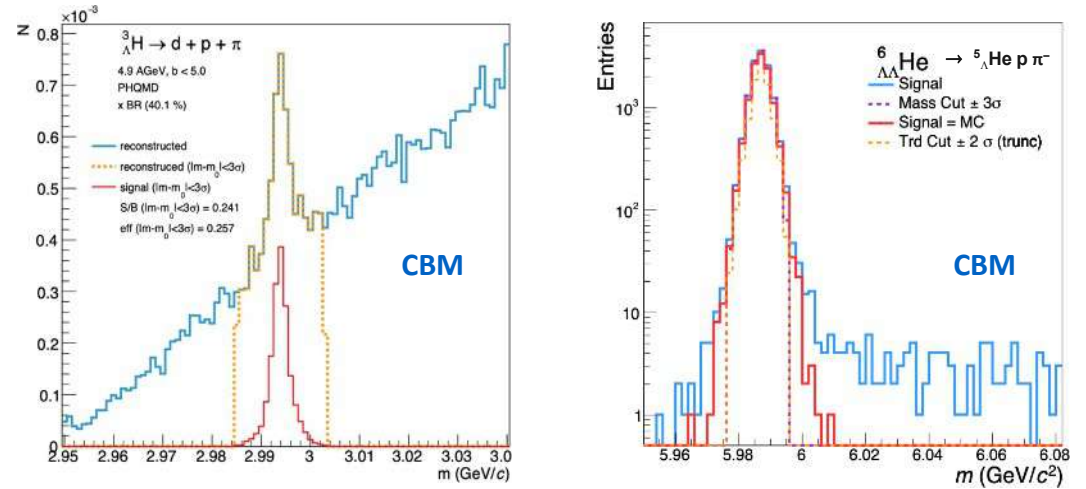


Physics performance. Hypernuclei

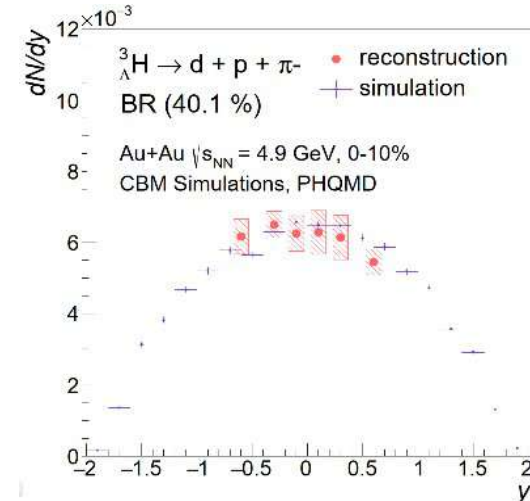
CBM: max. of hypernuclei production



Reconstruction from 5M central PHQMD events of Au+Au @ 11A GeV

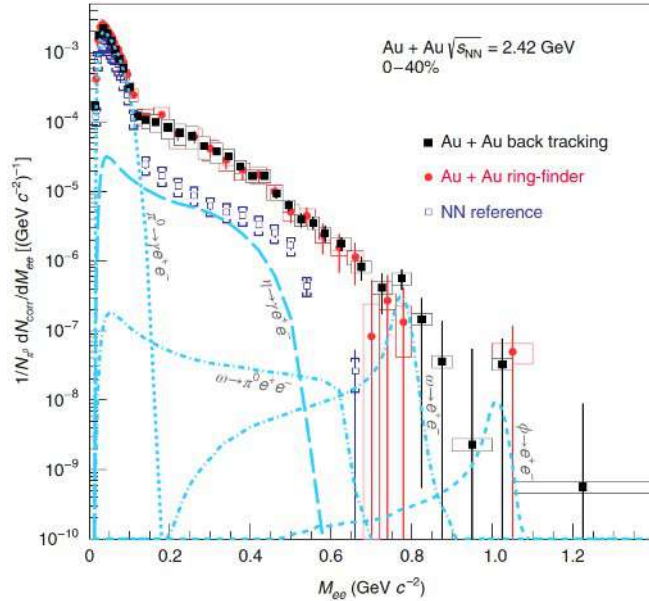


${}^3_{\Lambda}\text{H} \rightarrow d + p + \pi$: Reconstruction of phase space distribution



- ▷ CBM will operate at expected peak of hypernuclear production.
- ▷ Signal clearly observed despite 5..10 Mevt only
- ▷ High discovery potential in double-strange hypernuclei sector
 Potentiality: YN & YY interactions to constrain nuclear EoS
- ▷ ${}^3_{\Lambda}\text{H} \rightarrow d + p + \pi$: acceptance limited.
 This belongs to „problematic“ cases due to 3-body decay.

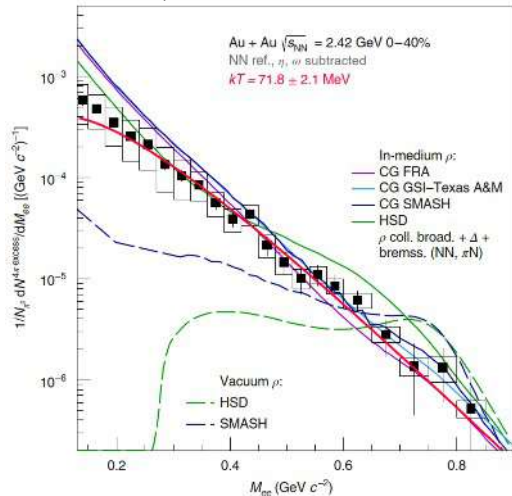
HADES, Nature Phys. 15, 1040 (2019)



Dilepton radiation

- Strong interaction - free \Rightarrow probe of earlier stages
- IMR ($1 < M_{\ell\ell}$ [GeV] < 3) : preequilibrium/QGP
- LMR ($0.3 < M_{\ell\ell}$ [GeV] < 1) : hadronic phase
- Thermal components:
 - temperatures of earlier and hadronic phase
- IMR: "Excess" radiation
 - Yield rises with fireball's lifetime
 - Extra rise - signals phase transition
- ρ - a_1 mixing: convex/straight profile @ 1.1 .. 1.4 GeV

HADES, LMR excess



$\rho \rightarrow \gamma\gamma^* \rightarrow \gamma e^+e^-$: rare but special signal

γ^* couples to EM current of hadrons, and decays into $\ell\bar{\ell}$.

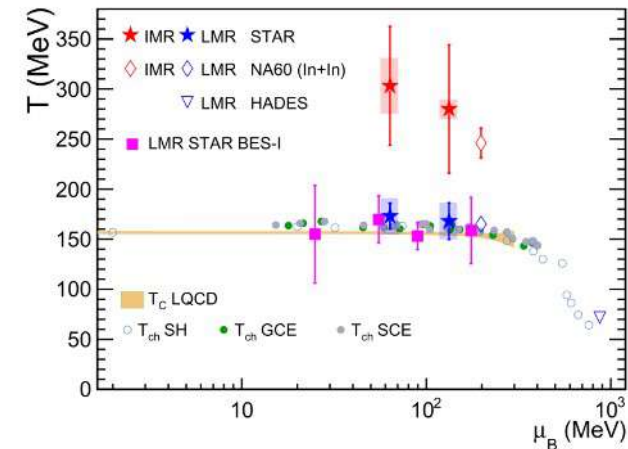
ρ contribution ("mass excess") to M_{ee}

carries the imprint of medium temperature:

$$\frac{dN}{dM_{ee}} \sim (M_{ee})^{3/2} \exp\left(-\frac{M_{ee}}{T}\right)$$

Probe of earlier stages of HI collision.

STAR, arXiv: 2402.01998

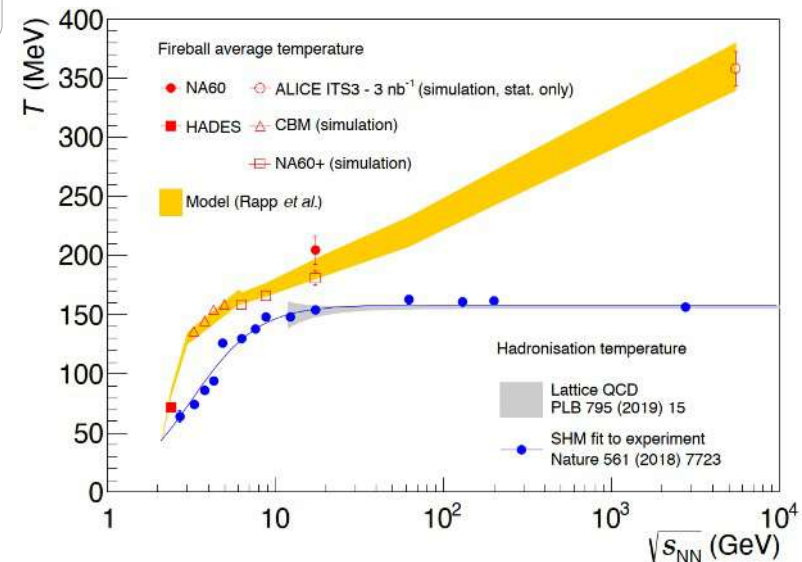
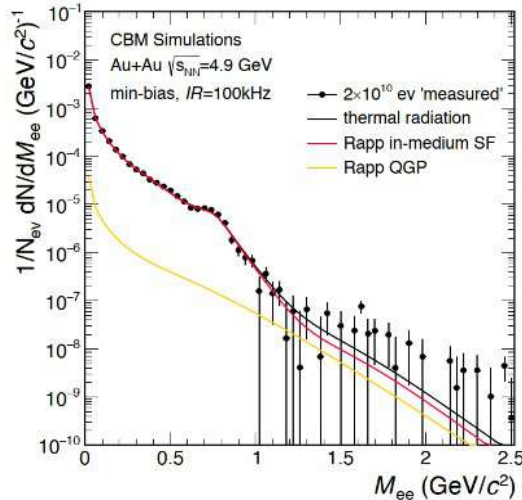
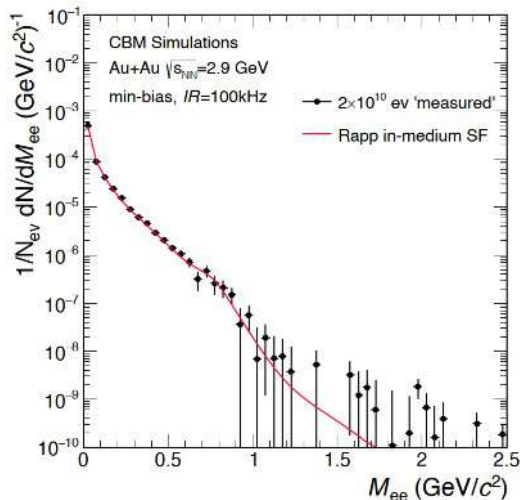
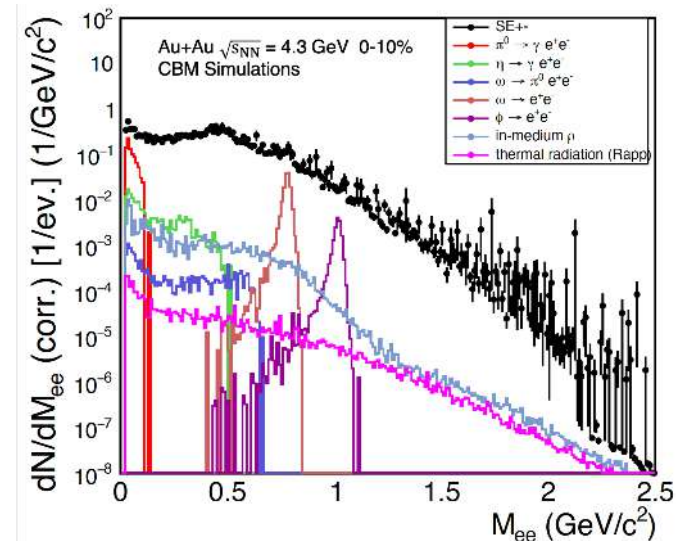


CBM dielectron opportunity:

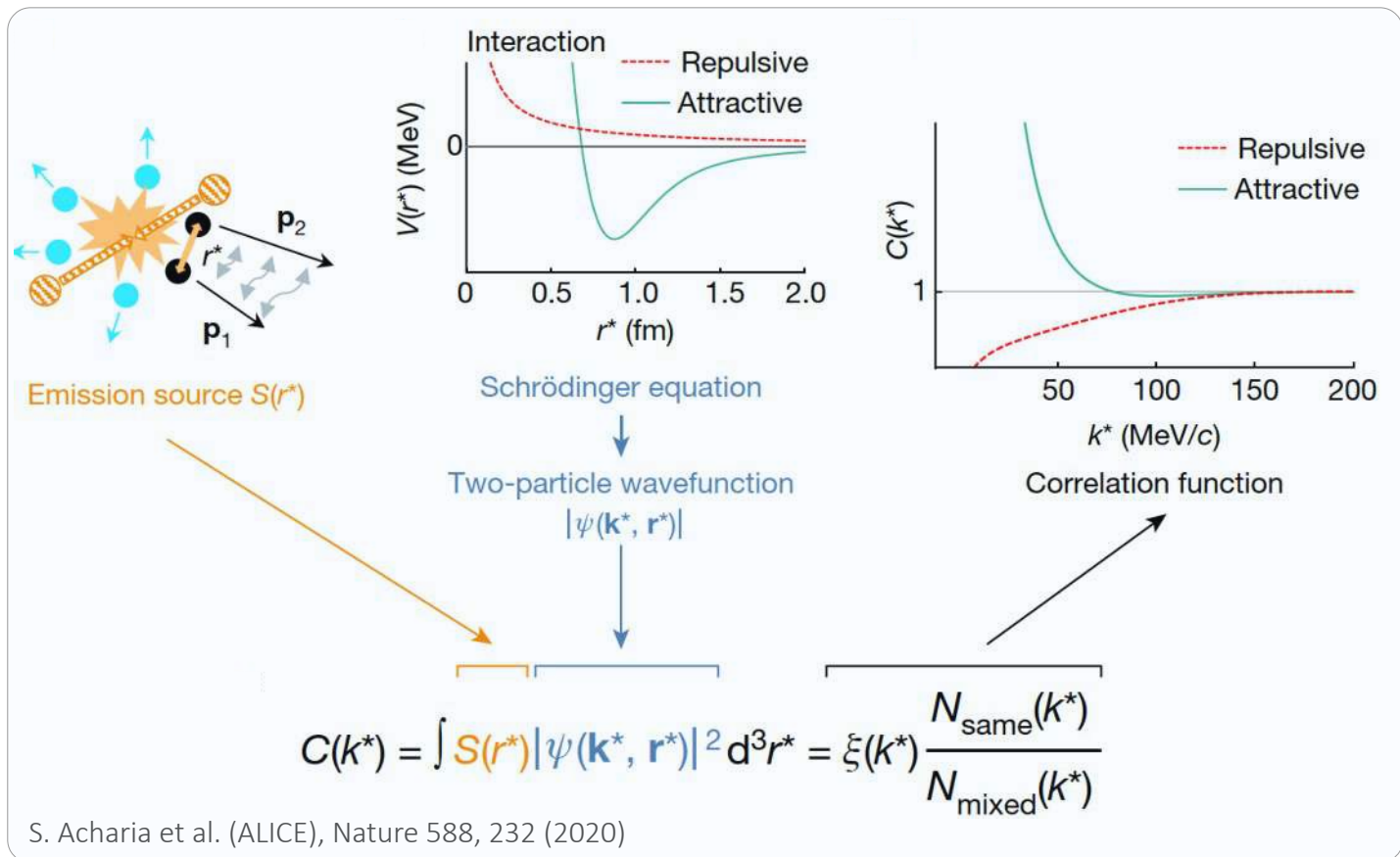
- Rare probes \Rightarrow high stats (✓)
- Inspectable via $ee, \mu\mu$ (✓)
- Suppression of π bkgnd (✓)
- Suppression of γ conversion (✓)

CBM dielectron performance:

- ▷ cocktail w/ in-medium ρ spectral function + QGP ($h\bar{h} \rightarrow \gamma^* \rightarrow \ell\bar{\ell}$) (Rapp-Wambach model). 5 days of beam / energy
- ▷ Isolated excess radiation reconstructed with 1.5 .. 4.5% precision
- ▷ Model temperatures nicely reconstructed.
- ▷ IMR accessible, more stats appreciated



femtoscopy: measurement of interactions



Lednický-Lyuboshitz FSI model

A.P.Hun. New Ser. HI Phys. 3, 93 (1996)

Assumptions:

- static + spherical Gaussian source

$$S(x, p^*) \sim e^{-x^2/R_G^2} \cdot \delta(t-t_0)$$

- wave function approximated by asymptotic form

f_0 : scattering length
 d_0 : effective range ($\sim V$ width)

Message:

we can extract interaction info from correlation functions!

$$C(k^*) \approx 1 + \frac{|f(k^*)|^2}{2R_G^2} \left(1 - \frac{d_0}{2\sqrt{\pi}R_G}\right) + \frac{2\Re f(k^*)}{\sqrt{\pi}R_G} F_1(2k^*R_G) - \frac{\Im f(k^*)}{R_G} F_2(2k^*R_G)$$

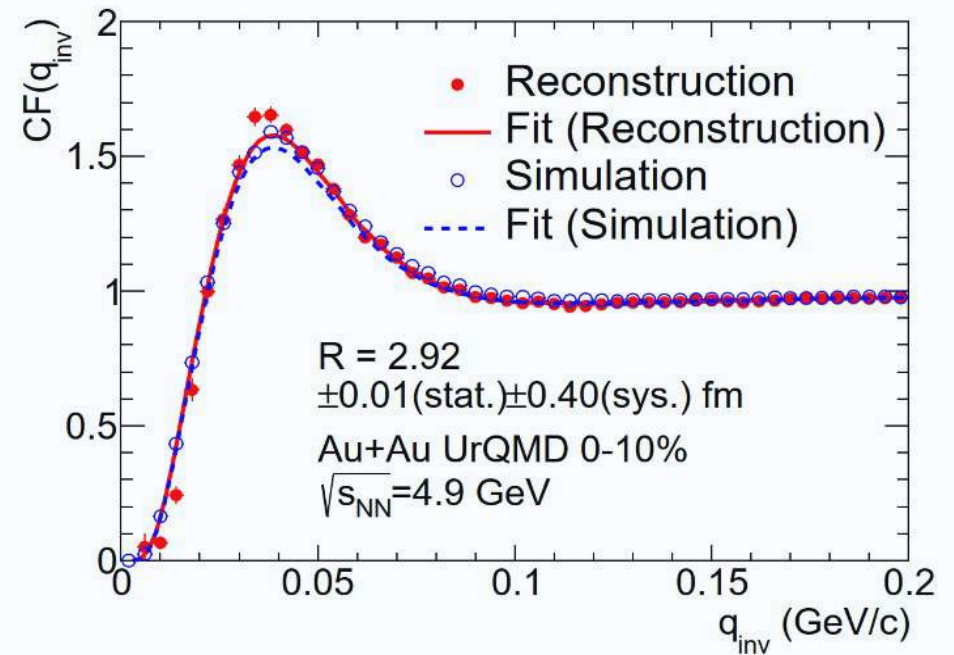
$$\frac{1}{f(k^*)} \approx \frac{1}{f_0} + \frac{d_0 \cdot (k^*)^2}{2} - ik^*$$

$$F_1(z) = \int_0^z dx \frac{\exp(x^2 - z^2)}{z}$$

$$F_2(z) = \frac{1 - \exp(-z^2)}{z}$$

proton-proton Correlation Function

- ▷ central Au+Au collisions at $T_{\text{Beam}} = 11\text{A GeV}$, within UrQMD v4.0 model
- ▷ Reconstructed profile agrees quite well with the simulated one
- ▷ Data fitted with Lednicky-Lyuboshitz ansatz. It's doable!



Fluctuations of conserved charges

- Strong interactions conserve baryon (B), charge (Q) and strangeness (S) in 4π . But in a subspace they fluctuate event-by-event. Especially close to **1st order phase transition**, and even more near **Critical End Point**.
- Shape of a distribution is quantified by its moments κ_n :

$$\begin{aligned} \kappa_1 = \mu &= \langle N \rangle &= VT^3 \chi \\ \kappa_2 = \sigma &= \langle N^2 \rangle - \langle N \rangle^2 &= VT^3 \chi_2 \\ \kappa_3 = S \cdot \sigma^3 &= \langle N^3 \rangle - 3\langle N^2 \rangle \langle N \rangle + 2\langle N \rangle^3 &= VT^3 \chi_3 \\ \kappa_4 = \kappa \cdot \sigma^4 &= \langle N^4 \rangle - 4\langle N^3 \rangle \langle N \rangle - 3\langle N^2 \rangle^2 + 12\langle N^2 \rangle \langle N \rangle^2 - 6\langle N \rangle^4 &= VT^3 \chi_4 \end{aligned}$$

where susceptibility $\chi_n = \frac{\partial^n}{\partial (\mu_B/T)^n} \left(\frac{p}{T^4} \right)$.

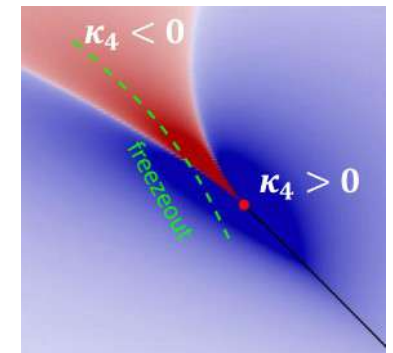
- Near a Critical Point, the RHS are proportional to the **critical length ξ** to some power:

$$\begin{aligned} \kappa_2 &\sim \xi^2 \\ \kappa_3 &\sim \xi^{4.5} \\ \kappa_4 &\sim \xi^7 \end{aligned}$$

- Hunting for CEP \Leftrightarrow looking for anomalies of these observables wrt no-CEP baselines.
- E.g. kurtosis is expected to change sign around CEP.
- Ratios of cumulants eliminate the volume.

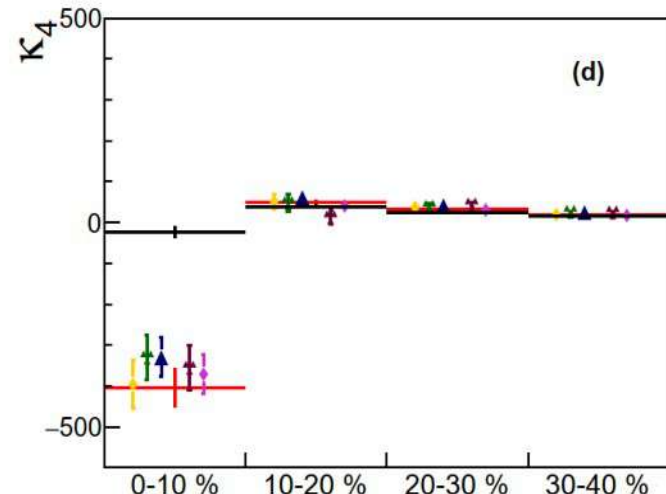
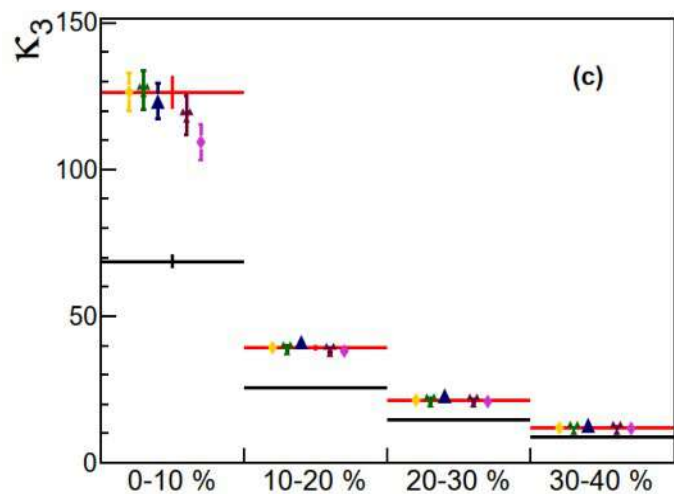
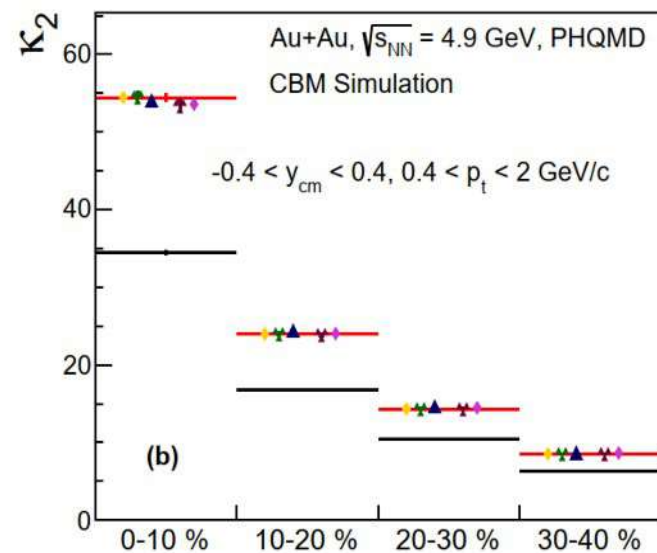
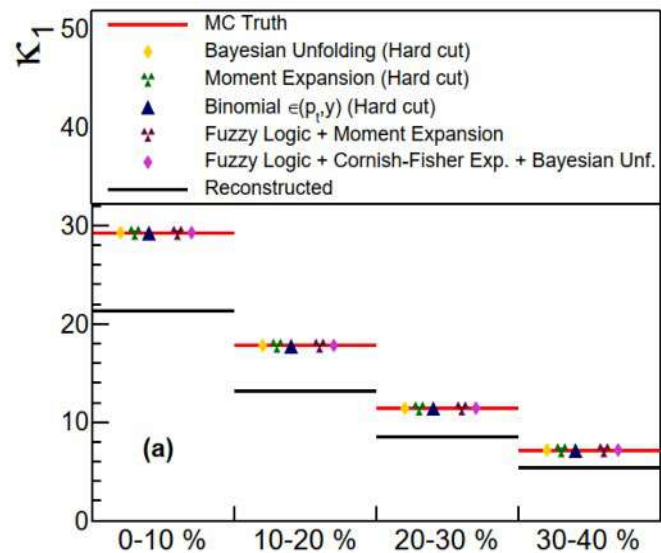


M. Stephanov, PRL 107, 052301 (2011)



Proton number correlations

- central Au+Au collisions at $T_{\text{Beam}} = 11A$ GeV, within PHQMD v5.2 model
- After accounting for losses, reconstructed profile agrees with the simulated one







Transition Radiation Detector



Pre-production finalisation

Forward Spectator Detector



Technical Design Report submission in June

Time of flight detector

>25% MRPCs produced



TOF@STAR

Ring Imaging Cherenkov detector

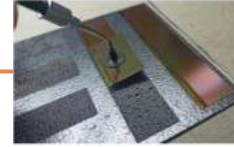
2 photon cameras ready.

Production readiness for Mirror Wall



RICH@HADES

Micro Vertex Detector



Production readiness of the final sensor MIMOSIS-3



MUon Chamber system

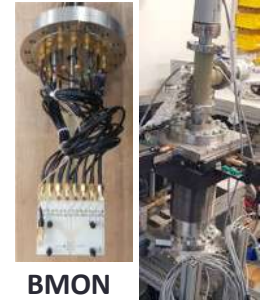


GEM2 GEM1

Production readiness of GEM readout chambers

Superconducting dipole magnet

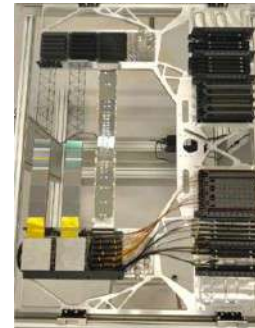
Final Design Ready, production started



BMON

pcCVD sensors ready

Silicon Tracking System



STS@J-PARC E16

Start of unit assembly

>80% of modules,

>20% of ladders assembled

CRI for FLES entry nodes



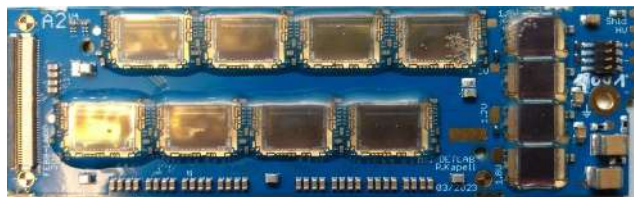
FELIX cards (BNL), tested at mCBM

STS sensors + readout

F-E chip: SMX2.2 ASIC



"FEB8_2" board w/ 8 SMX2.2 chips



Lt: 2-sided Si det, Rt: readout electronics



Data Readout for STS



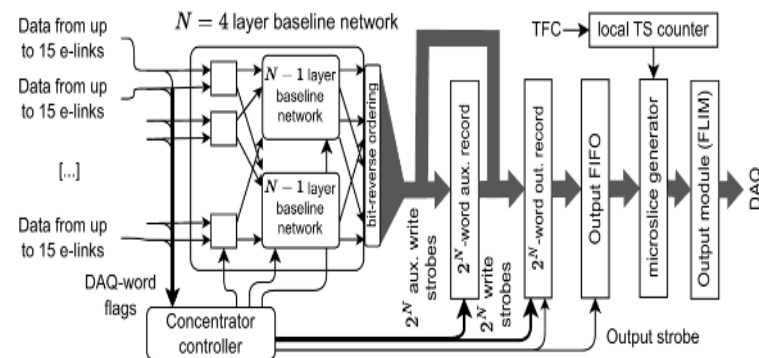
AFCK board (DPB board prototype) for data readout @ CBM

STS database for items and QA integrated w/ testing system

GSI
ASIC
pcAIO
LDO
FEB
Sensor
Module

KIT
ASIC
pcAIO
LDO
FEB
Sensor
Module

Item	Label	Part	Qty	Unit	Unit Price	Unit Cost	Unit Value
10	ASIC	ASIC	1	PCB	100	100	100
20	pcAIO	pcAIO	1	PCB	100	100	100
30	LDO	LDO	1	PCB	100	100	100
40	FEB	FEB	1	PCB	100	100	100
50	Sensor	Sensor	1	PCB	100	100	100
60	Module	Module	1	PCB	100	100	100

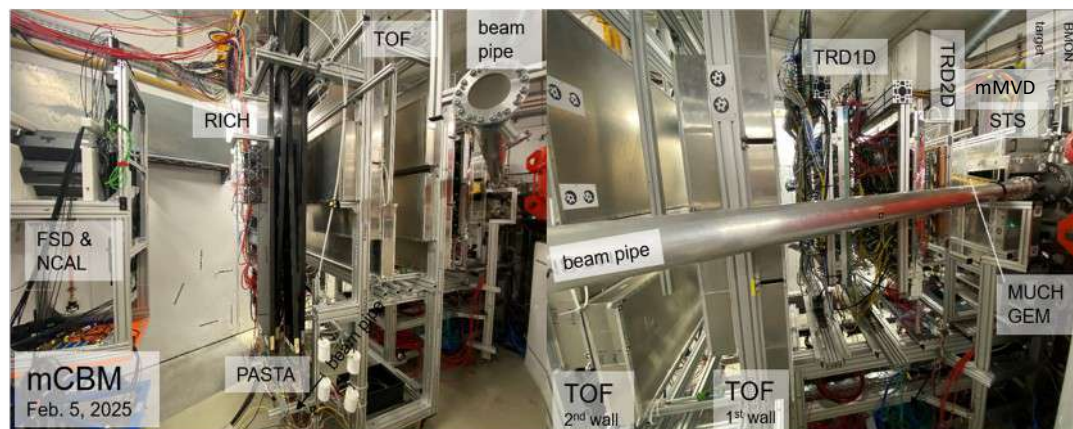
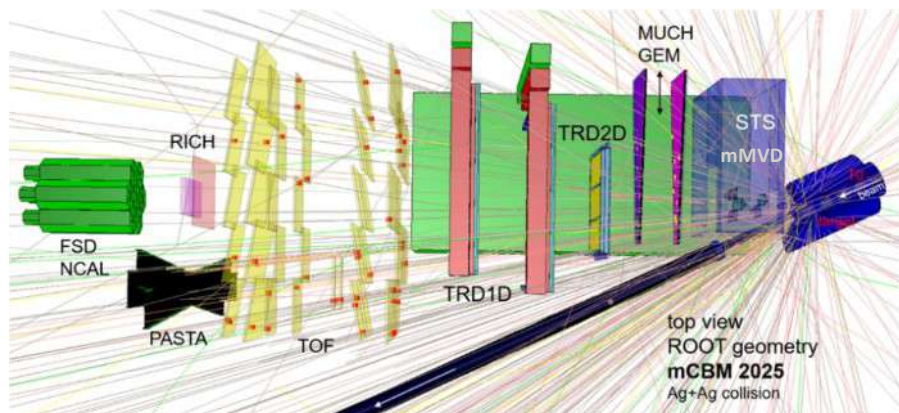


Fast data concentration system for readout using FPGA (EURIZON)

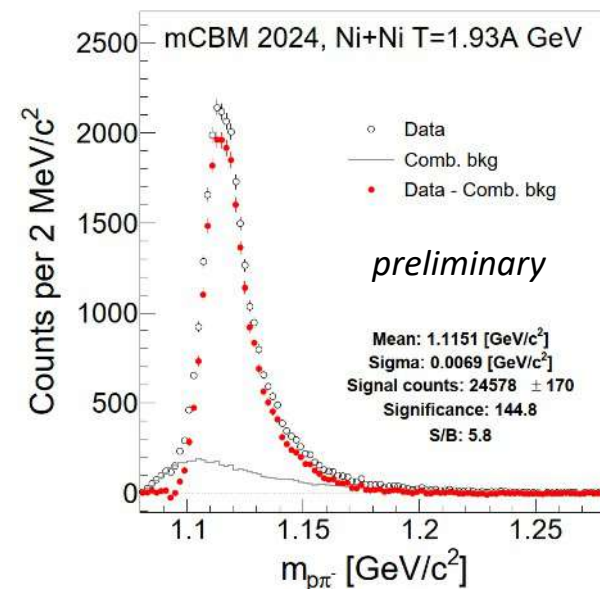
Distributed Data Processing



Efficient computing resources utilization towards online event selection (software trigger)

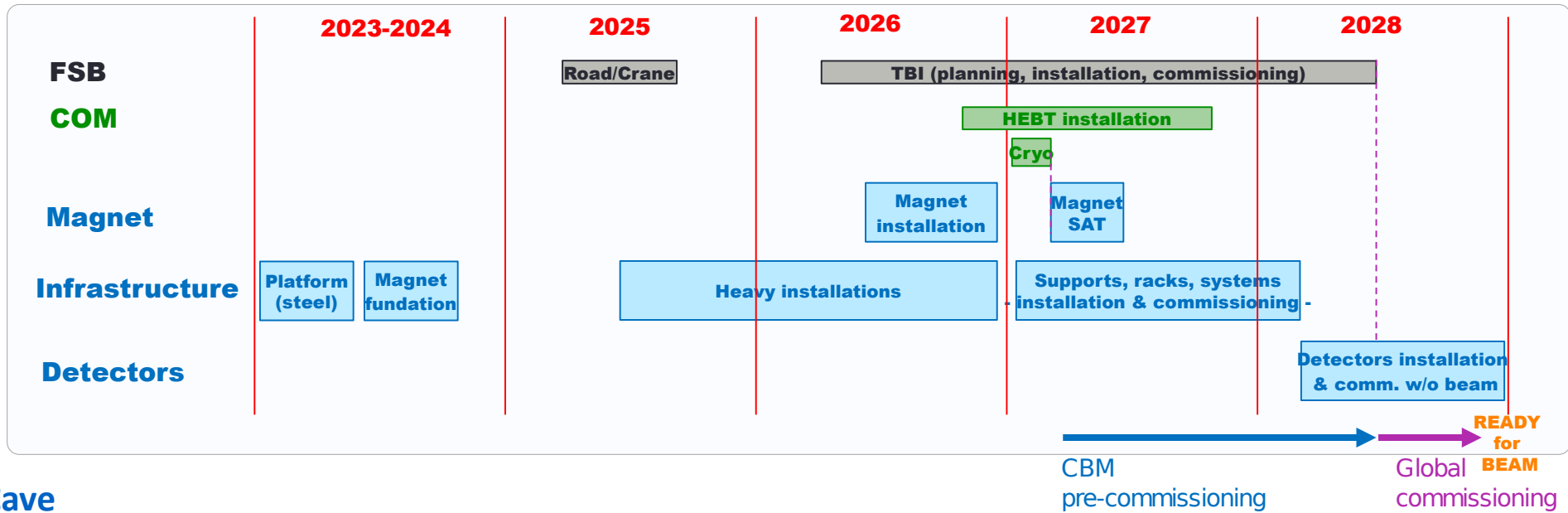


- ▷ Pre-series of all the CBM components (except the magnet) are tested in the SIS18 beam.
- ▷ Tests of full read-out chain, incl. Free-streaming electronics
- ▷ Tests for high (up to 10 MHz) collision rates
- ▷ Physics program: Λ excitation function @ SIS18 energies
- ▷ Continuation of tests in 2027



500 kHz collision rate, $6.6 \cdot 10^9$ events

CBM Installation / Commissioning / Day-1



CBM Cave

- ▷ a dedicated cave with massive beam dump for high-intensity, high-energy beams
- ▷ CBM cave/building shell completed, road, crane
- ▷ Technical Building Infrastructure in 2026 - 28

CBM Installation

- ▷ Activities (platform) started in 2023
- ▷ CBM Ready for beam by end of 2028

First 3 years scenario: focus on beam energy scan

- ▷ 60 days / year beam on target
- ▷ different detector configurations

Setup	Included subsystems	Average day-1 interaction rate
ELEHAD	MVD,STS,RICH,TRD,TOF,FPW	0.1 MHz
MUON	STS,MUCH,TRD,TOF,FPW	1 MHz
HADR	STS,TRD,TOF,FPW	0.5 MHz

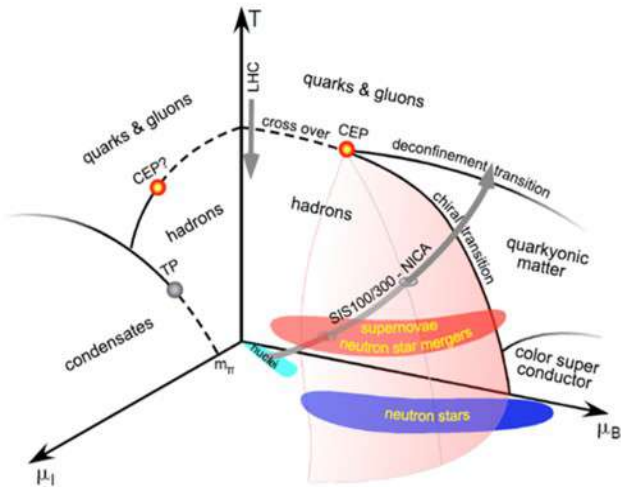
Summary

- 📄 **CBM** : we build a **precise** instrument for a **multimessenger** exploration of baryonic matter
- ⦿ Demonstrated capability of **high-rate** measurement:
 - high radiation tolerance
 - free-streaming data acquisition
 - ➡ ready for exploring **rare signals**
- ⦿ Demonstrated physics performance:
 - reconstruction of (multi-)strange hadrons, hypernuclei
 - dielectron measurement
 - femtoscopy, fluctuations of conserved charges
- ⦿ Construction and tests advances (next in-beam tests: 2027). Goal: **CBM beam-ready @ 2028 !**

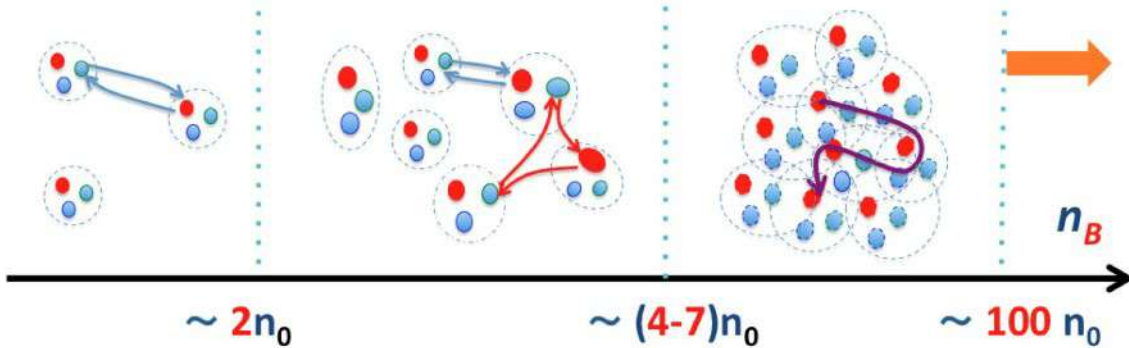
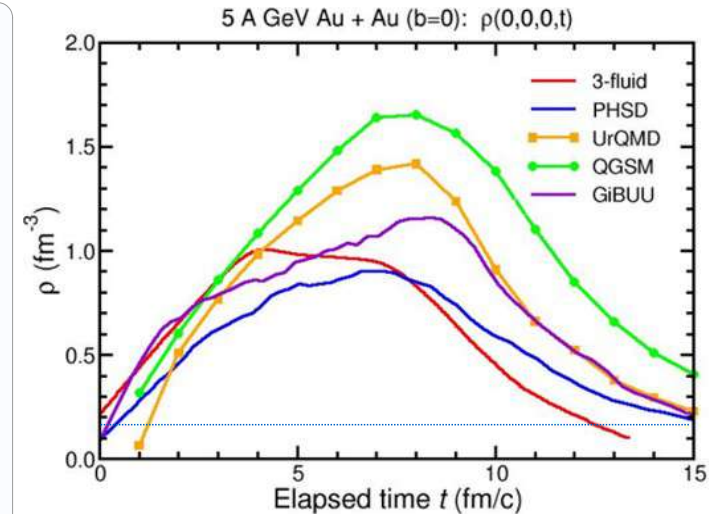
*Thank
You!*

Backup slides

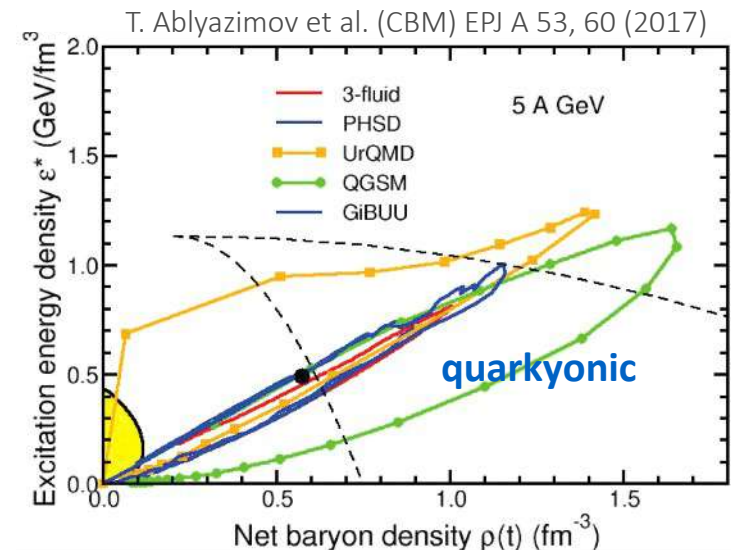
First look at physical landscape



- **CBM energies:**
 high densities reached
 \Rightarrow hadrons overlap
 \Rightarrow quark deconfinement
- **Quarkyonic matter:**
 chirally restored, not deconfined
 Predictions: at CBM energies
 large incursions into quarkyonic mat.



G. Baym et al. Rep. Prog. Phys. 81, 056902 (2018)



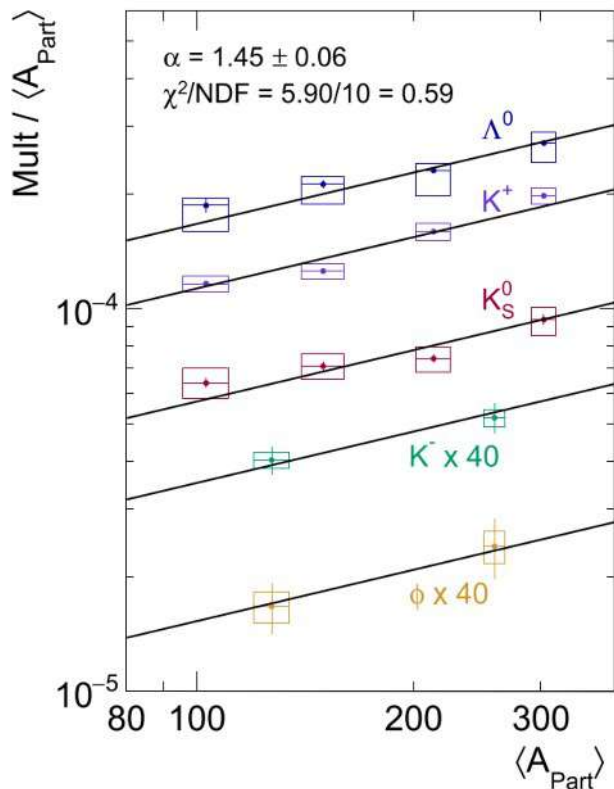
T. Aabyazimov et al. (CBM) EPJ A 53, 60 (2017)

Strangeness production mechanism

Au+Au $\sqrt{s} = 2.4$ GeV [HADES]

Fit to 5 hadrons:

$$\alpha = 1.45 \pm 0.06$$



J. Adamczewski-Musch et al. (HADES)
PLB 793, 457 (2019)

Strangeness production @ SIS18 has been described within **hadronic channels**

[eg. C.Fuchs PPNP 56, 1 (2006)]

More subthreshold production

\Rightarrow more medium-demanding channels

\Rightarrow in $P \sim A_{part}^\alpha$, α should rise with dropping \sqrt{s} below NN threshold

At given beam energy $\alpha(\phi) > \alpha(K, \Lambda)$

... but fits to hadron species with common α look okay!

Another hypothesis (**$s\bar{s}$ \oplus soft deconfinement**) [K.Fukushima, PRD 102, 096017 (2020)]

- ① $s\bar{s}$ pair is created, with some α exponent in $P \sim A_{part}^\alpha$
- ② s and \bar{s} percolate through matter
- ③ they interact with: core quarks or pion cloud - and hadronize

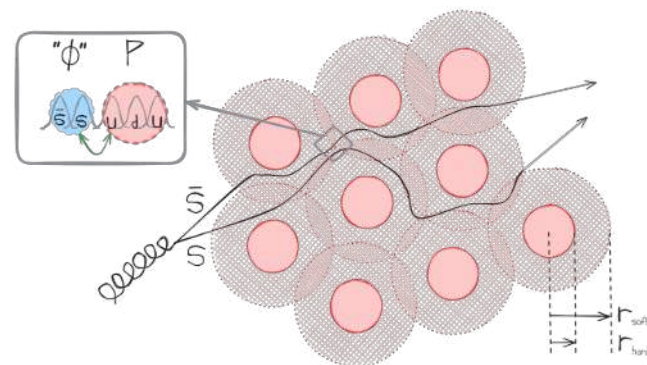
But...

statistics for ϕ at low \sqrt{s} is usually small.

Both hypotheses depend on ϕ .

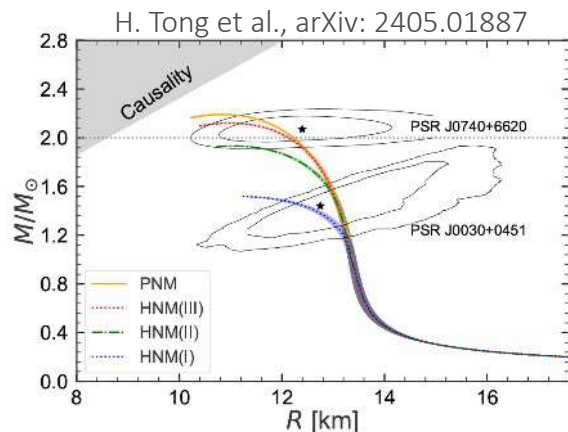
\Rightarrow More statistics needed \oplus energy scan.

\leftarrow CBM will be perfectly suited!



Author: M. Kohls, HADES

Λ Flow as testing ground for Neutron Stars



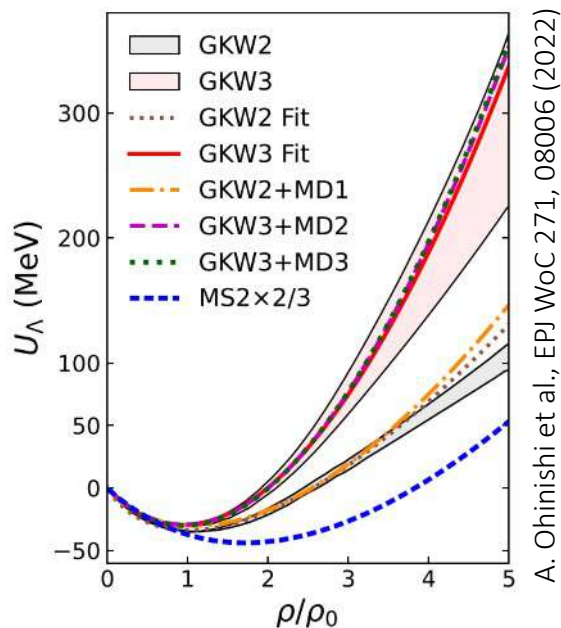
Hyperon puzzle:

- Inclusion of hyperons into model: observed masses $\sim 2M_{\odot}$ unjustified.
- Adding YNN repulsion may restore agreement.

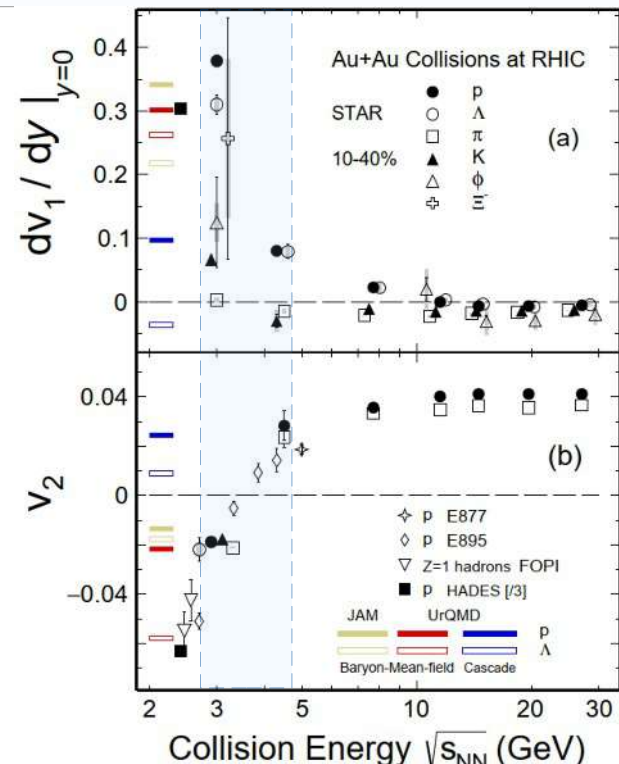
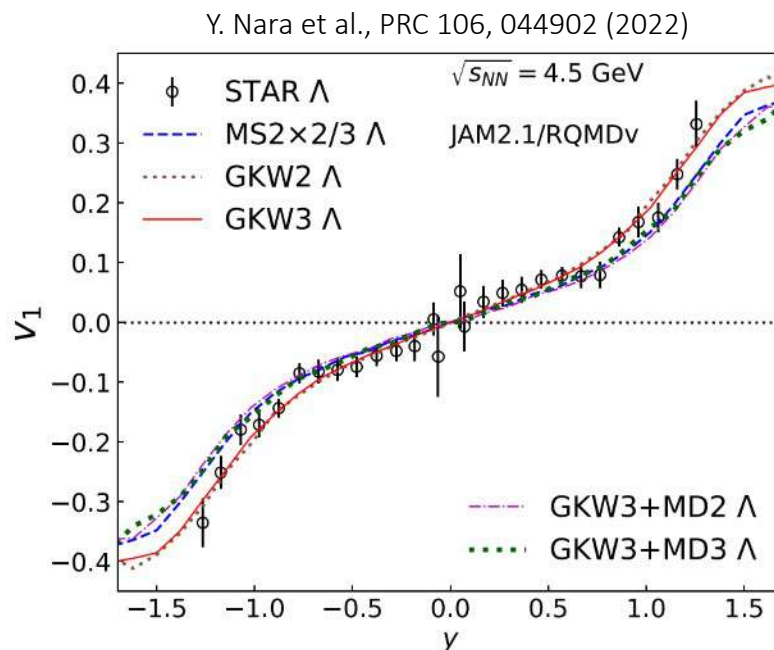
Modelling within RQMDv the YNN interactions = $f(\rho)$

$v_1(y)$ for Λ from Au+Au @ $\sqrt{s} = 4.5$ GeV (STAR)

Experiment-transport comparison: rather favors addition of YNN, but more precise data needed. \Leftarrow CBM can contribute!

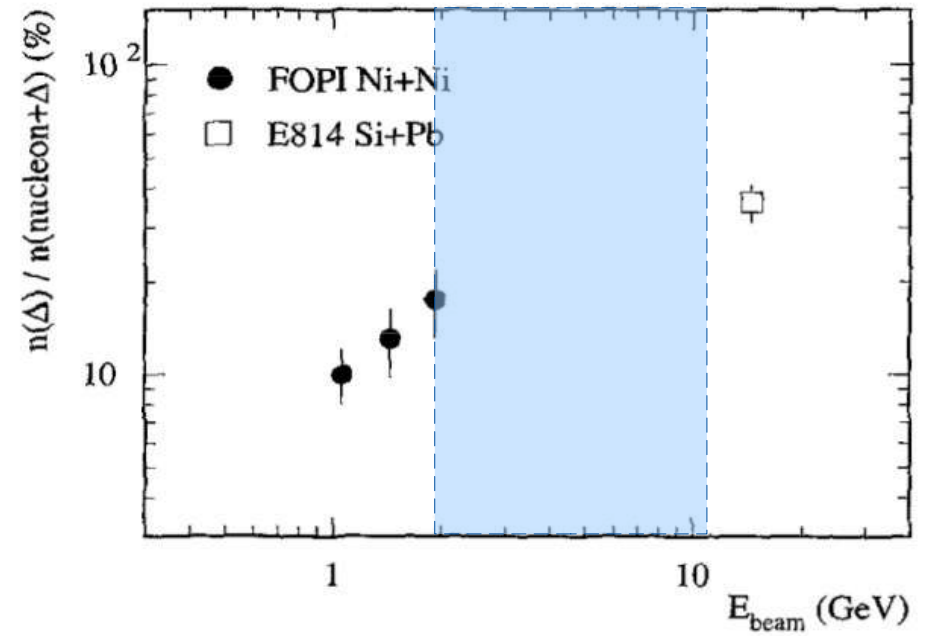


A. Ohinishi et al., EPJ WoC 271, 08006 (2022)



M. Abdallah (STAR) PLB 827, 137003 (2022)

- CBM: region of **resonant matter**



B.Hong et al., Phys. Lett. B 407, 115 (1997)