Exploring the QCD matter at the crossroads with CBM

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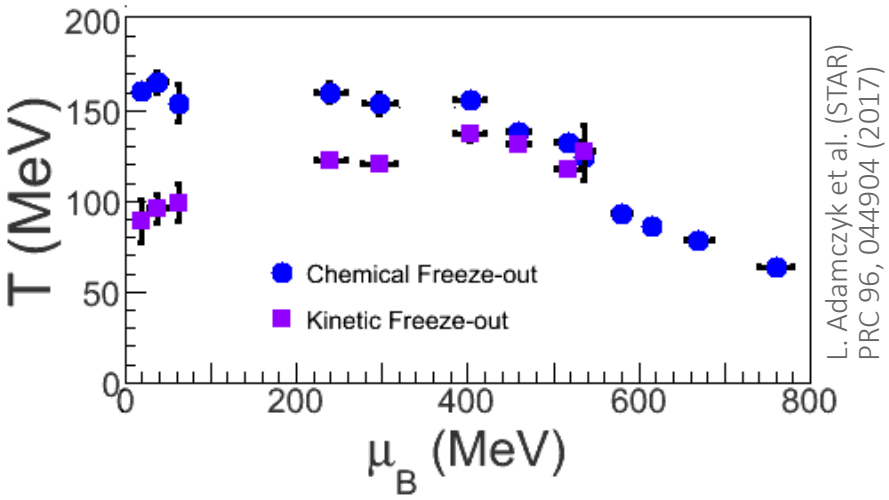
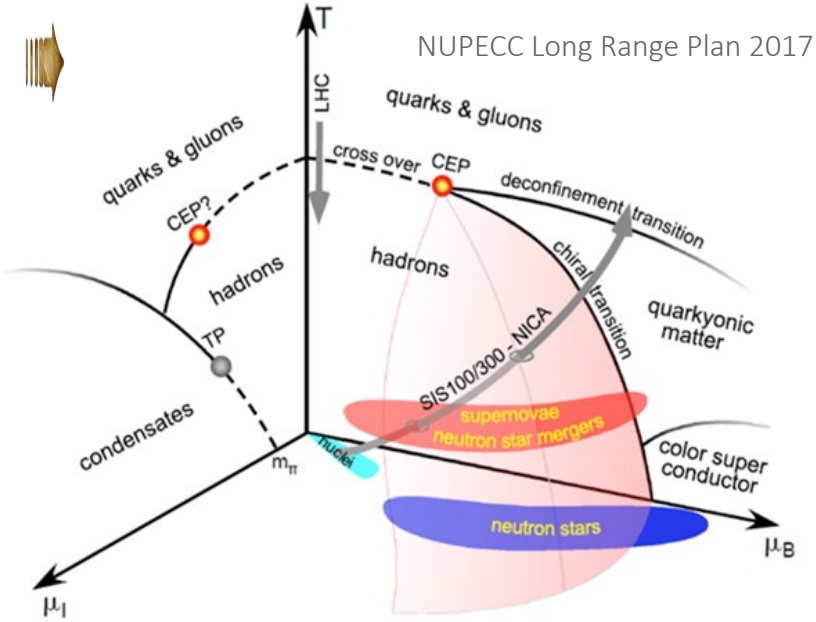
Rotunda of Felix and Adauctus
Carbon-dated to 970 CE !

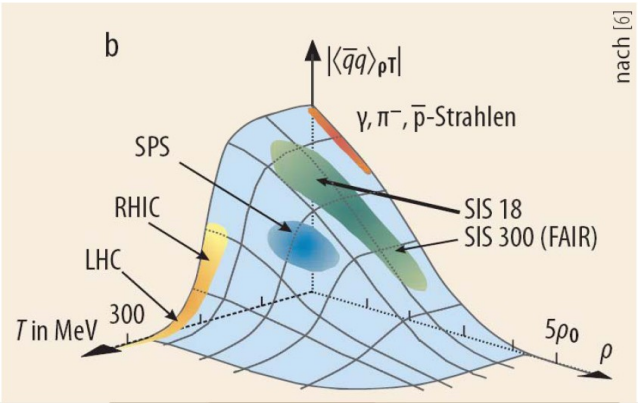
Wikimedia commons

Gross features of physical landscape

- **QCD phase diagram**: what we know … what we think







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

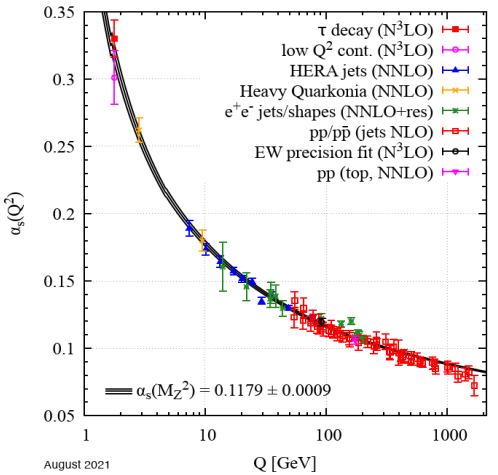
Gell-Mann Oakes Renner – relation

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

Partial restoration of chiral symmetry

Running strong coupling constant

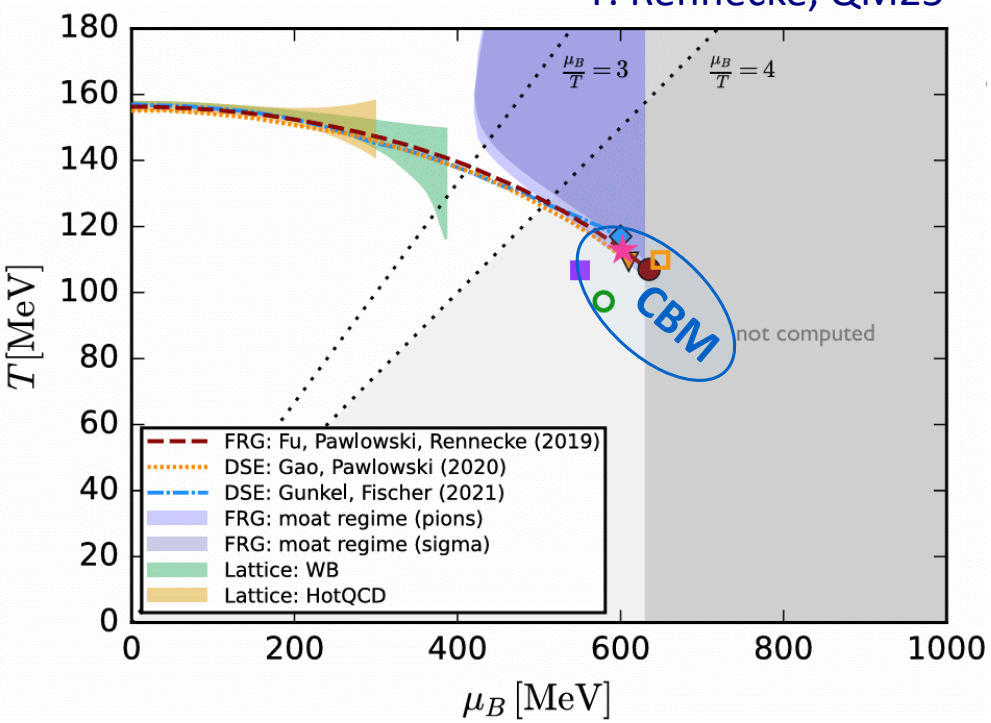
high $T \Rightarrow$ high p transfer $\Rightarrow$ perturbative QCD



Gross features of physical landscape

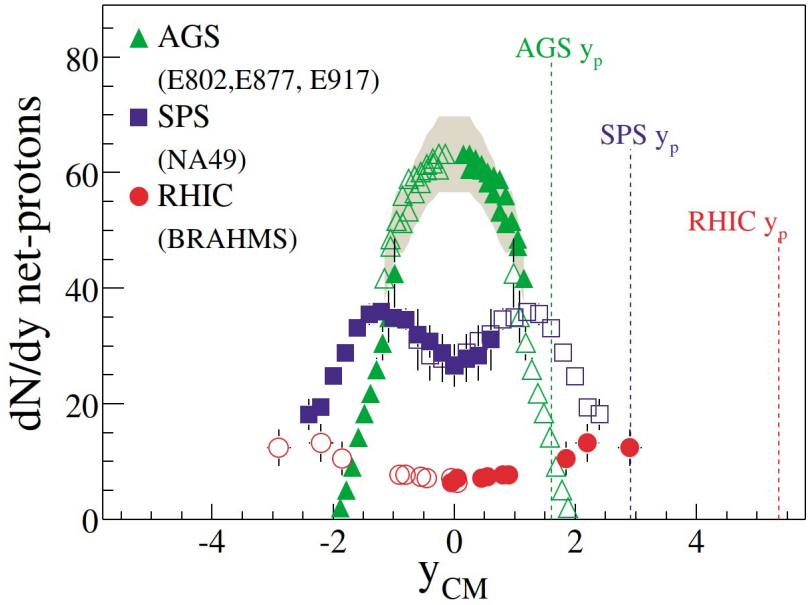
- **Critical End-Point**: possible current location – good chance to coincide with CBM energies ($\sqrt{s_{NN}} \approx$ 2.7 - 4.9 GeV)

F. Rennecke, QM25



- CBM: creation of high-density QCD medium

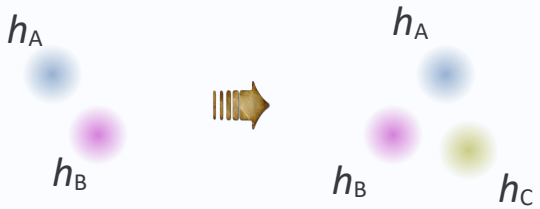
I.G. Bearden et al. (Brahms) PRL 93, 102301



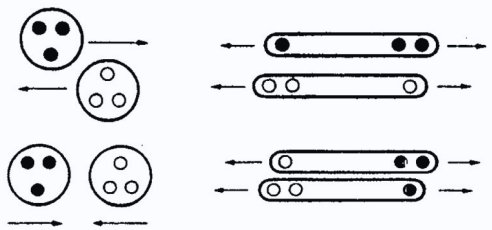
- CBM Goal: Isolate unambiguous signals of new phases of QCD matter, order of phase transitions, chiral symmetry restoration (CSR)

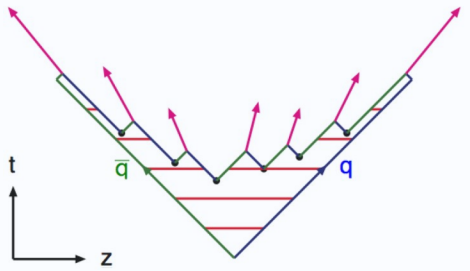
Transport models: h → q transition region

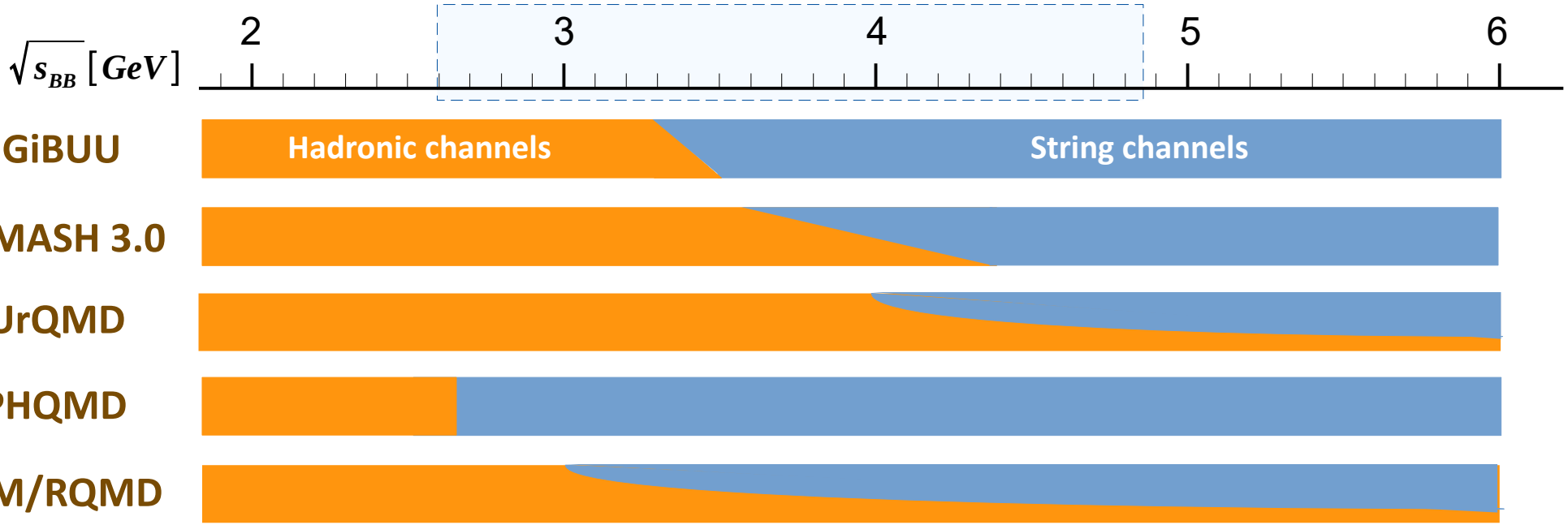
- Hadrons as actors



- Strings as actors

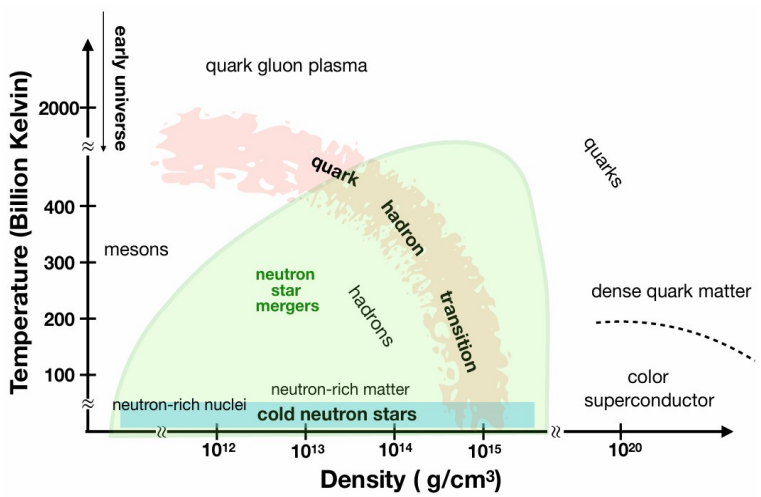


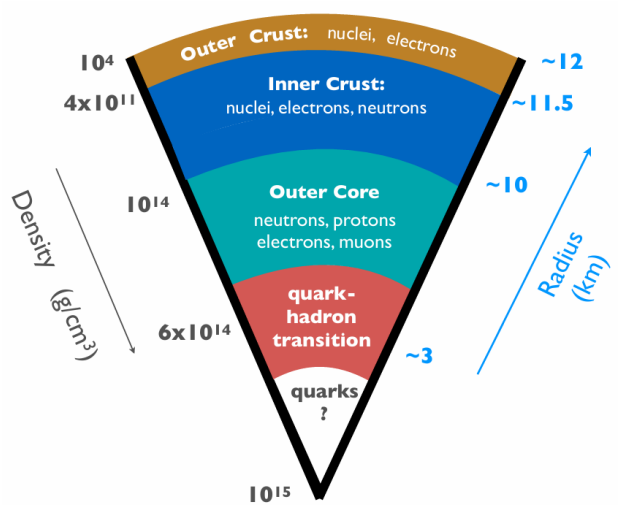




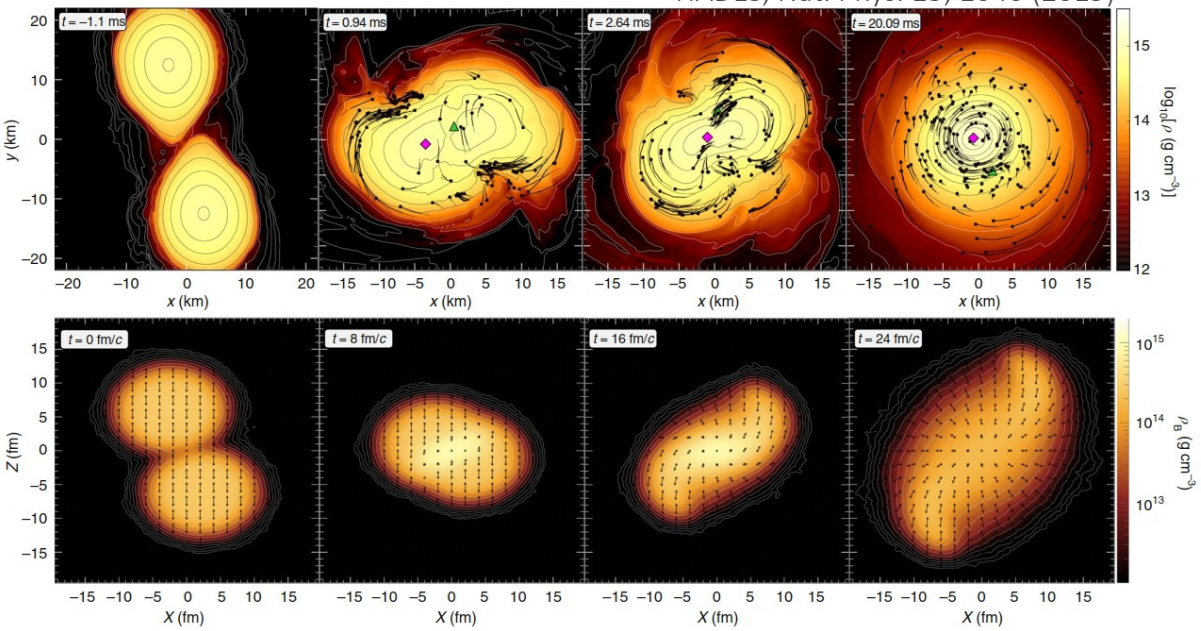
Phase space distributions of hadrons from AA (hA, hh) : possible testing ground of hadron ↔ string transition

HIC as input to Astrophysics





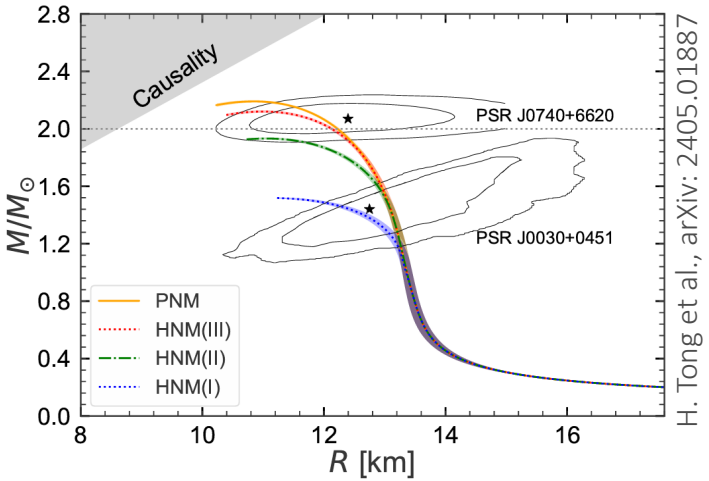
HADES, Nat. Phys. 15, 1040 (2019)



Hyperon puzzle:
can it be solved?

HNM : hyper neut. matter
HNM I : NΛ
HNM II : NNΛ
HNM III: NΛΛ

PNM : pure neut. matter



V. Kalogera et al., arXiv: 2111.06990

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_{preeq}, T_{Chem}, T_{Kin}, μ's)

- **Equation of State**, accounting for $N \neq Z$ terms

- **YN (hh) interactions**

- Exploring **hadron gas ⇒ 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 $f(p_T, y)$
- K multiplicity as $f(\langle A_{part} \rangle)$

- femtoscopy (3D)
- hypernuclei, multi-strange hadrons

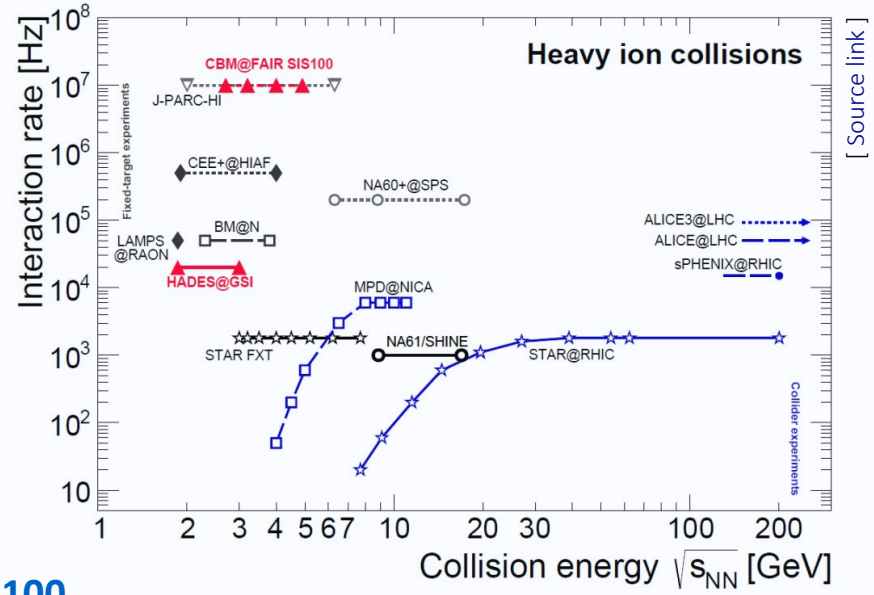
- fluctuations of conserved charges
- multi-strange production as $f(\sqrt{s})$

- Ξ (Λπ channel), Σ (Nπ + kink), Ω (ΛK channel)
- J/Ψ (dilepton channel), D mesons (Kπ channel)

- LCP distributions of $d^2N/dp_T dy$

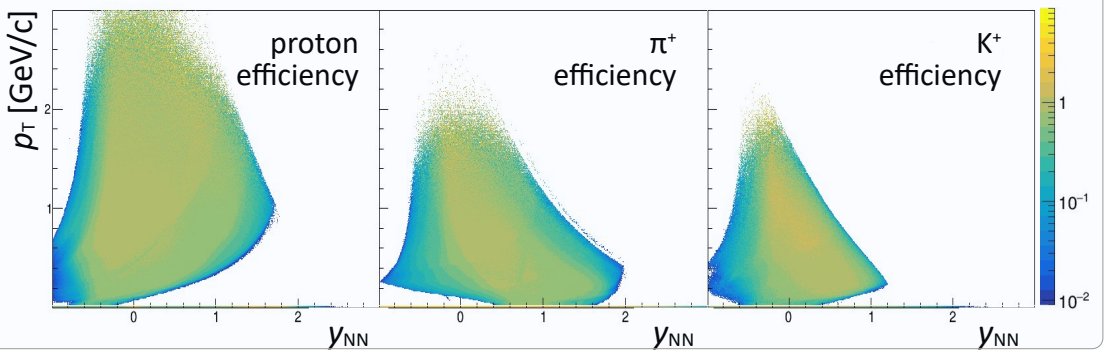
Rare probes ↔ **very high intensities** SIS100 + CBM

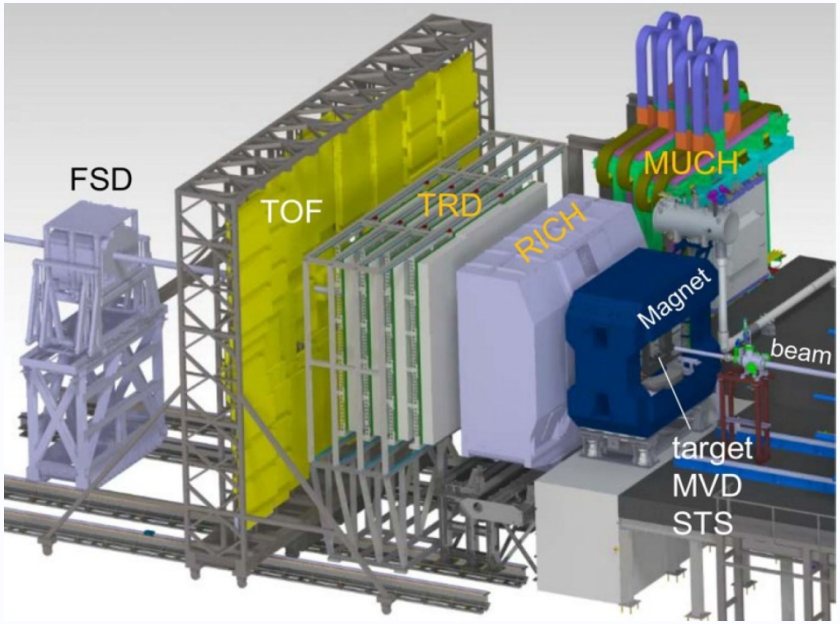
Main features of CBM Experiment



- **SIS100**
  - AA collisions: $\sqrt{s_{NN}} \in [2.7 .. 4.9]$ GeV (for Au+Au)
  - Beam intensity: up to 10^9 Hz

- Efficiency × acceptance of p, π, K from Au+Au @ 12A GeV

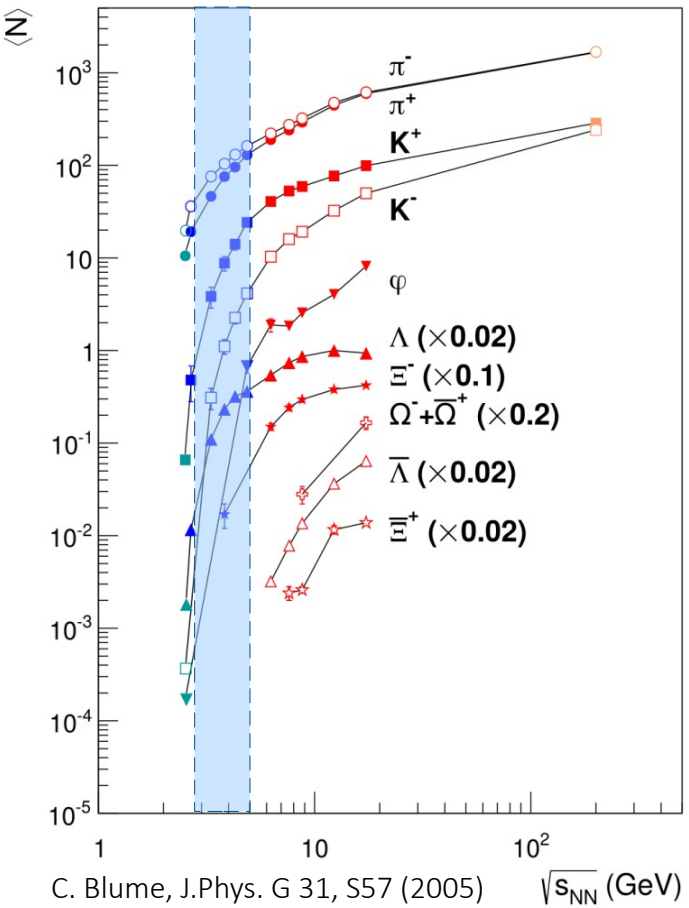




- **CBM**
  - Polar coverage $2° < \vartheta_{Lab} < 25°$, full φ coverage
  - Y_{NN} coverage for all energies
  - RICH and MUCH systems interchangeable
  - Highest interaction rates of all present setups
  - Free-streaming FEE
  - On-line event selection
  - DAQ capability up to 100 kHz (1 TB/s)

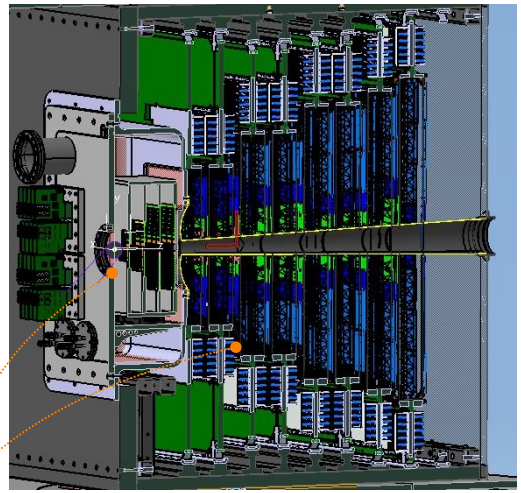
MVD + STS - heart of measurement

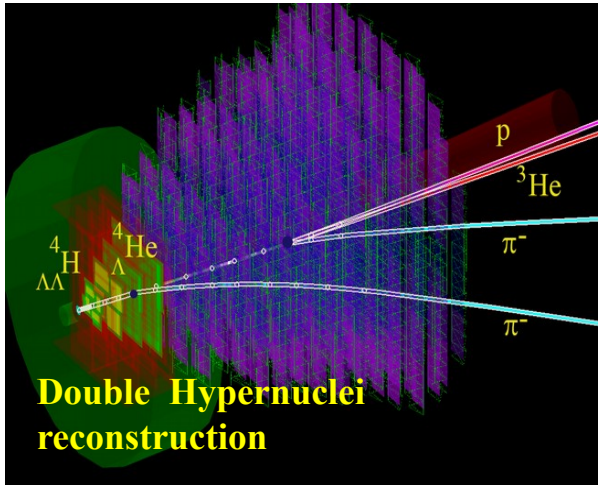
- CBM energies:
  sharp rise of strangeness



C. Blume, J.Phys. G 31, S57 (2005)

MVD STS





MVD

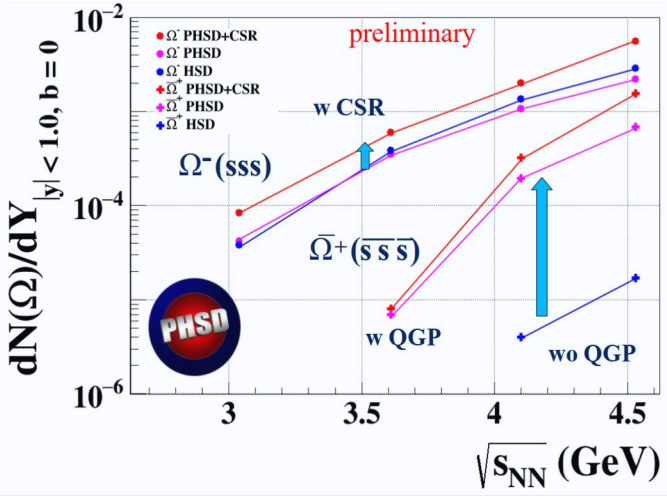
- 4 tracking stations, MAPS technology, dedicated CBM pixel sensors MIMOSIS
- 100 kHz Au+Au @ 11 AGeV and 10 GHz p+Au @ 30 AGeV
- Non-uniform hit density in time and space
- High radiation environment, operating in a vacuum

STS

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

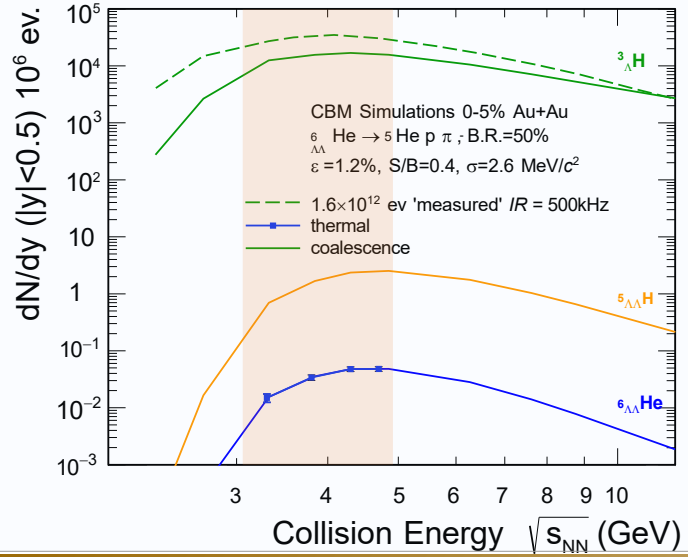
Strange hadrons and hypernuclei

- (P)HSD predictions of P(Ω, Ω) w/wo CSR



W. Cassing et al. PRC 93, 014902 (2016)

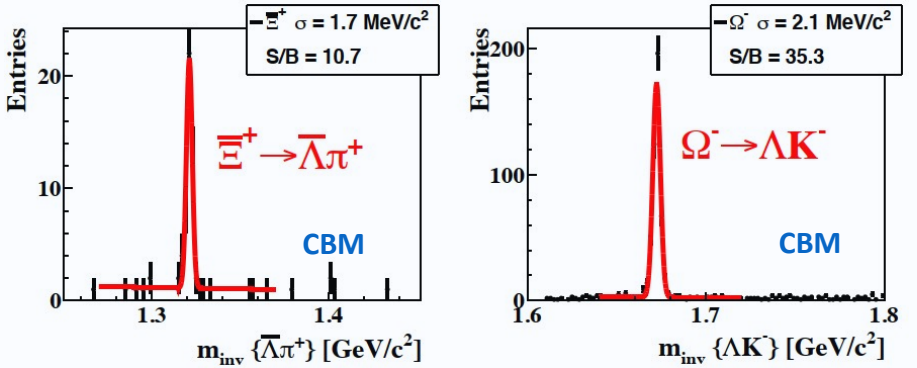
- CBM: max. of hypernuclei production



KF Particle Finder:

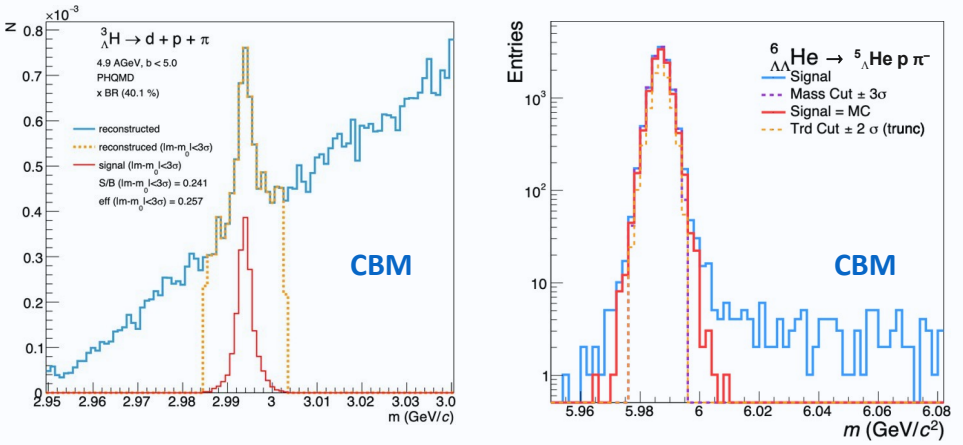
- high-perf. reconstruction of (multi)strange Y's, Y-nuclei etc.
- kink-based finder of neutral particles

UrQMD Au+Au @ 10A GeV, central, 5M events → CBM simulations

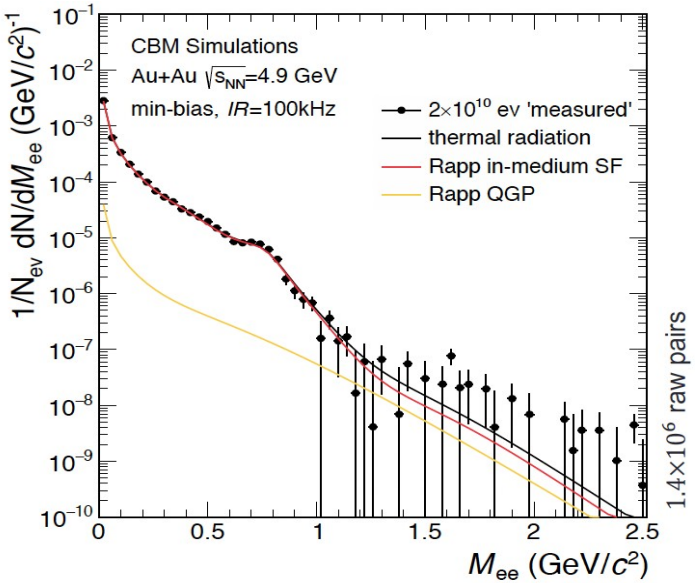


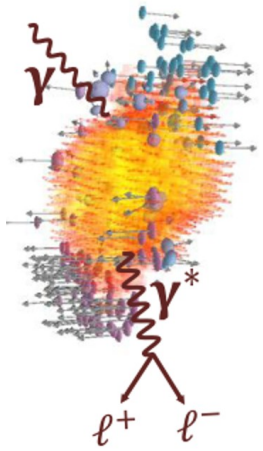
I. Kisel, J. Phys: Conf. Ser. 1602, 012006 (2020)

PHQMD Au+Au @ 11A GeV, central, 5M events → CBM simulations



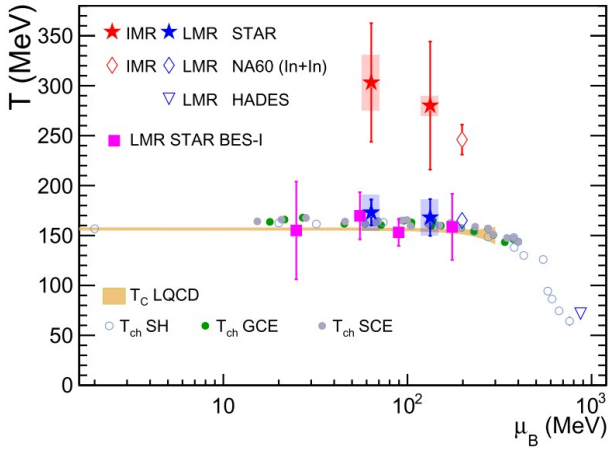
Dileptons: thermometer + chronometer

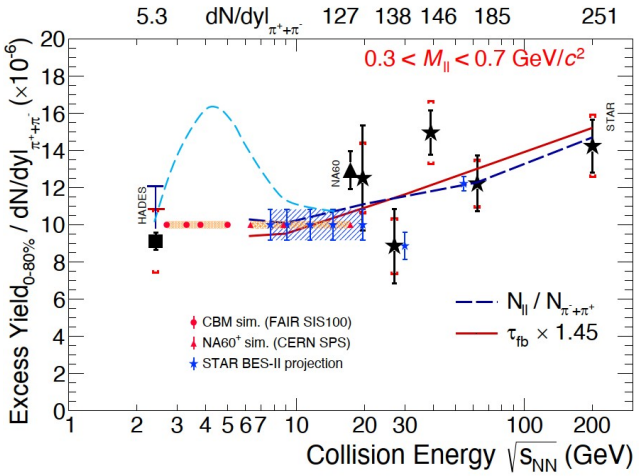




- **Dilepton radiation**
  - Strong interaction - free ⇒ probe of earlier stages
  - IMR (1 < $M_{\ell\ell}$ [GeV] < 3) : preequilibrium / QGP
    LMR (0.3 < $M_{\ell\ell}$ [GeV] < 1) : hadronic phase
  - Thermal components:
    - temperatures of earlier and hadronic phase
  - IMR: "*Excess*" radiation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

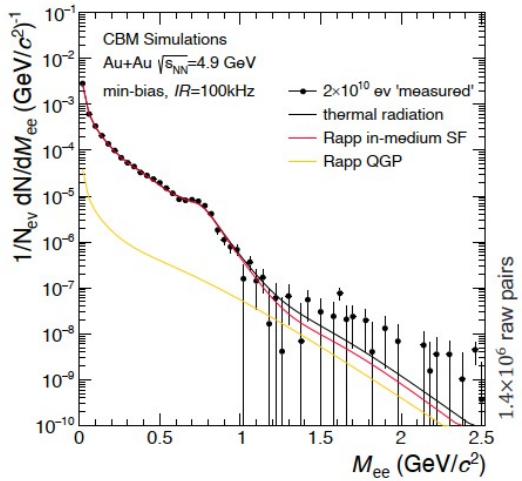
STAR, arXiv: 2402.01998

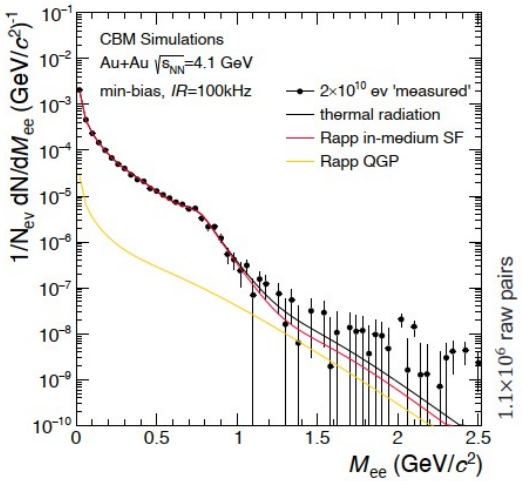


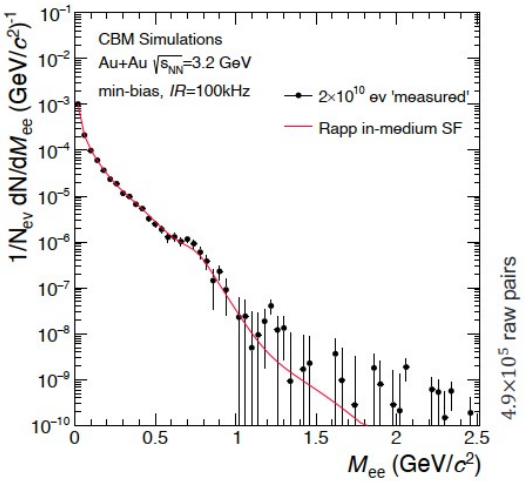


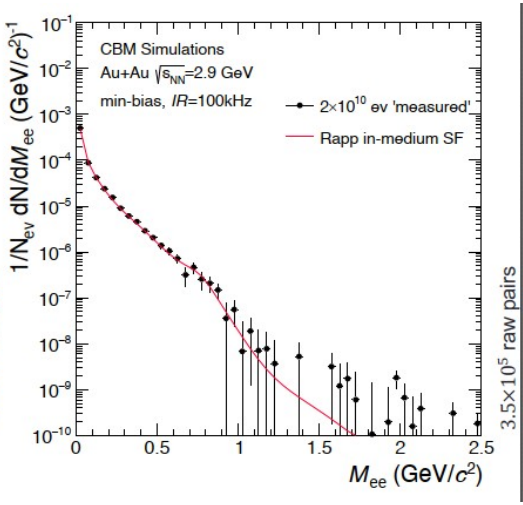
- Rare probes ⇒ high stats (CBM ✓)
- Inspectable via ee, μμ (CBM ✓)
- Suppression of π bkgnd (CBM ✓)
- Suppression of γ conversion (CBM ✓)

Dileptons: thermometer + chronometer



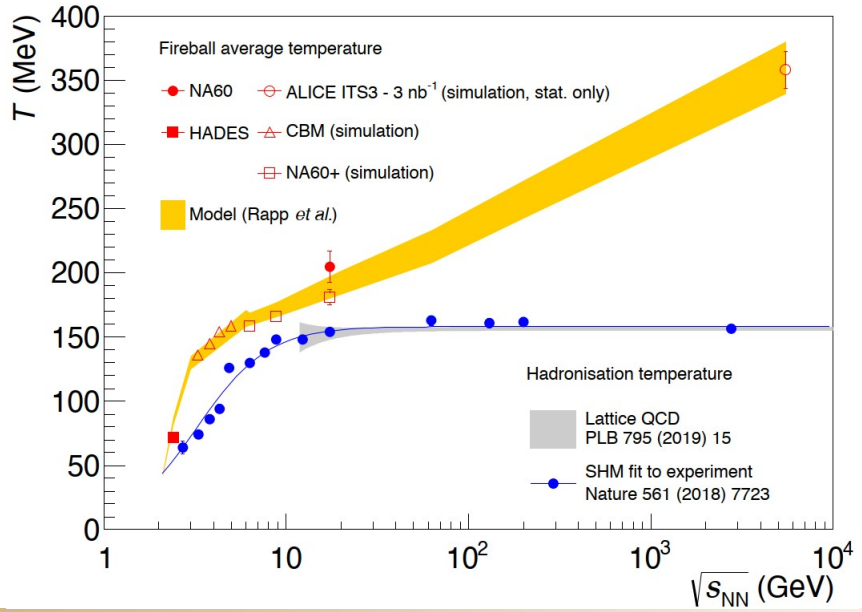






CBM dielectron performance

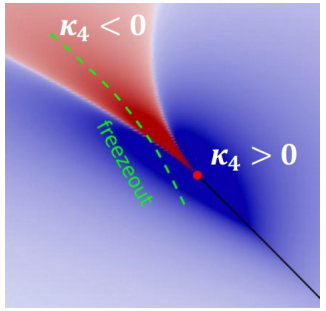
- 5 days of beam / energy
- LMR: excess radiation reconstructed w/ precision 1.5 - 4.5%
- IMR accessible but more statistics is appreciable



Fluctuations of conserved charges

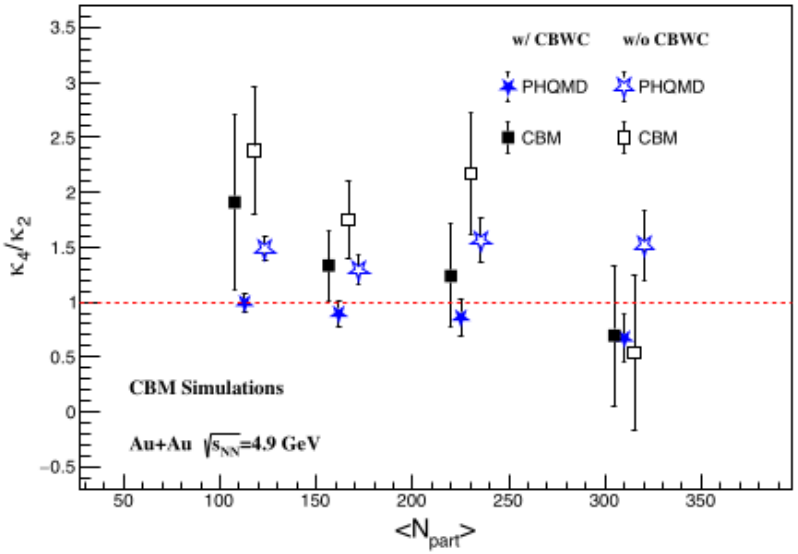
- Strong interactions conserve baryon (B), charge (Q) and strangeness (S) in 4π.
  But in a subspace they fluctuate event-by-event.
  Especially close to **1st order phase transition**, and even more near **Critical End Point**.
- Shape of a distribution is quantified by moments (μ, σ, s, κ, ..) and cumulants (C_n).
  Factorial moments κ_i measure irreducible multi-particle correlations.

M. Stephanov, PRL 107, 052301 (2011)



$$C_1 = M \qquad \kappa_1 = C_1$$
$$C_2 = \sigma^2 \qquad \kappa_2 = -C_1 + C_2$$
$$C_3 = S \cdot \sigma^3 \qquad \kappa_3 = 2C_1 - 3C_2 + C_3$$
$$C_4 = \kappa \cdot \sigma^4 \qquad \kappa_4 = -6C_1 + 11\,C_2 - 6\,C_3 + C_4$$

- Hunting for CEP ⇔ 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.
- First tests: 2M Au+Au @ $\sqrt{s}$ = 4.9A GeV



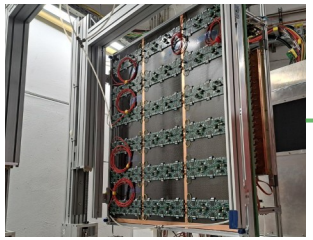
High-statistics CBM measurements give chance for much more sharpened picture

⊕ access to higher moments

CBM & HADES at SIS100 beam: future plan

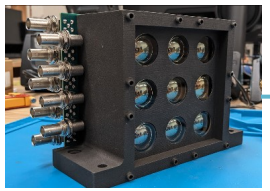
CBM: detector building in advanced stages

Transition Radiation Detector



Pre-production finalisation

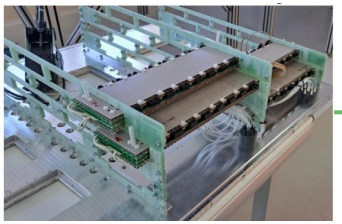
Forward Spectator Detector



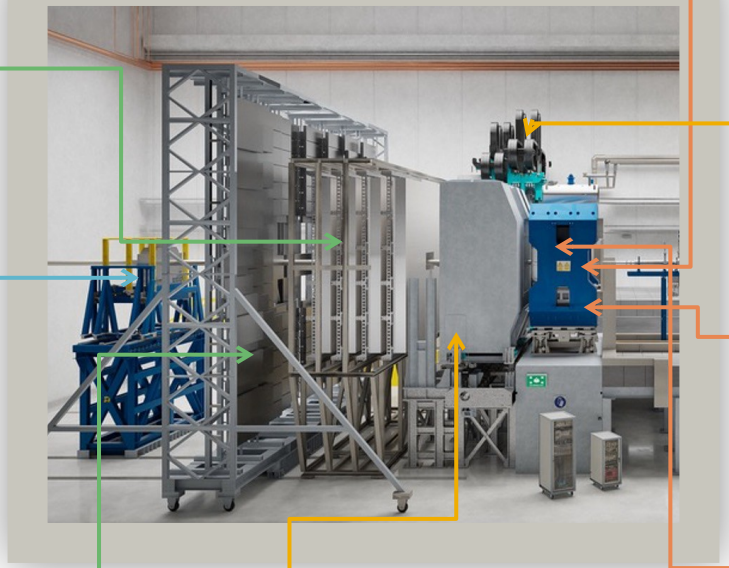
Technical Design Report submisson in January

Time of flight detector

>25% MRPCs produced

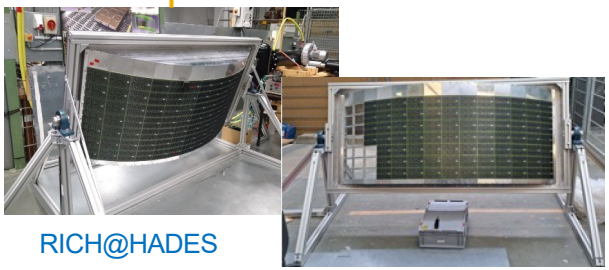


TOF@STAR



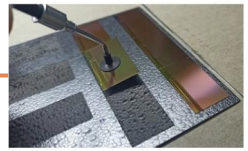
Ring Imaging Cherenkov detector

2 photon cameras ready.
Production readiness for Mirror Wall



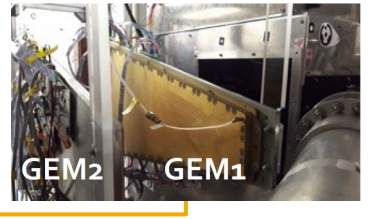
RICH@HADES

Micro Vertex Detector



Production readiness of the final sensor MIMOSIS-3

MUon CHamber system



Production readiness of GEM readout chambers

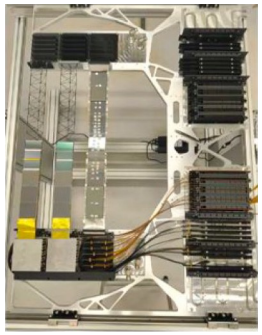
Superconducting dipole magnet

Final Design Ready, production started

BMON

pcCVD sensors ready

Silicon Tracking System



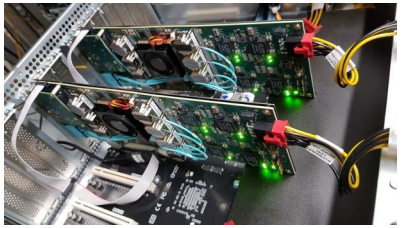
Start of unit assembly

>80% of modules,

>20% of ladders assembled

STS@J-PARC E16

CRI for FLES entry nodes

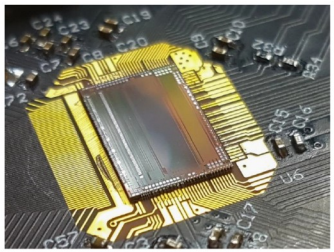


FELIX cards (BNL), tested at mCBM

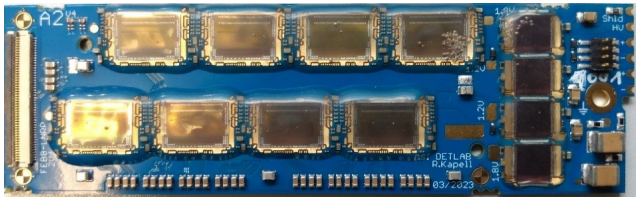
Polish in-kind contribution to CBM

STS sensors + readout

F-E chip: SMX2.2 ASIC

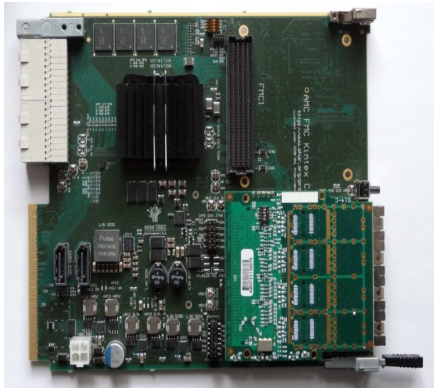


"FEB8_2" board w/ 8 SMX2.2 chips

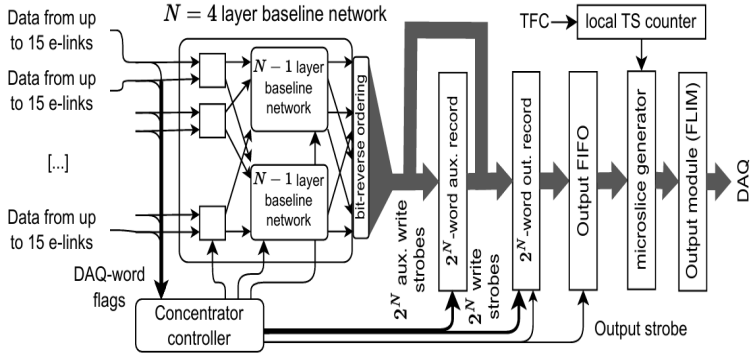


Lt: 2-sided Si det, Rt: readout electronics

Data Readout for STS

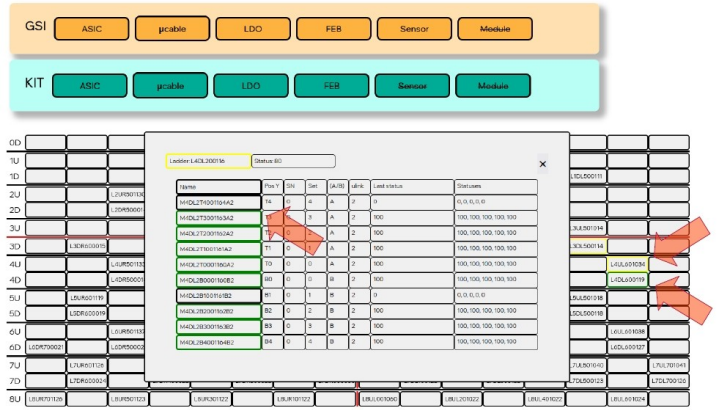


AFCK board (DPB board prototype) for data readout @ CBM



Fast data concentration system for readout using FPGA (EURIZON)

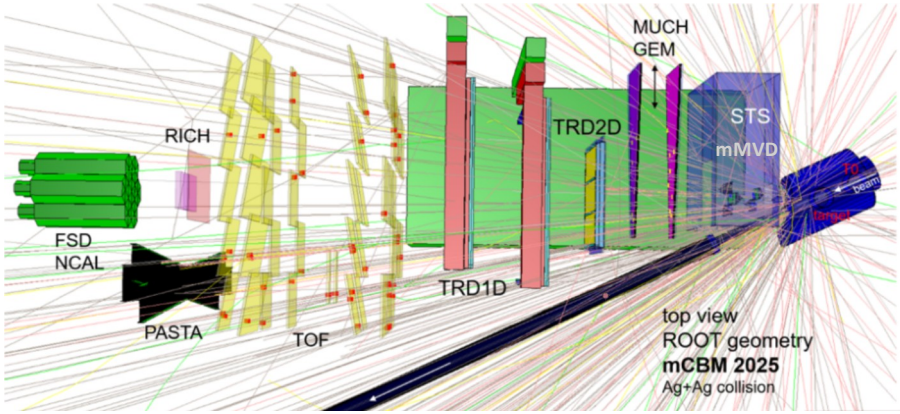
STS database for items and QA integrated w/ testing system

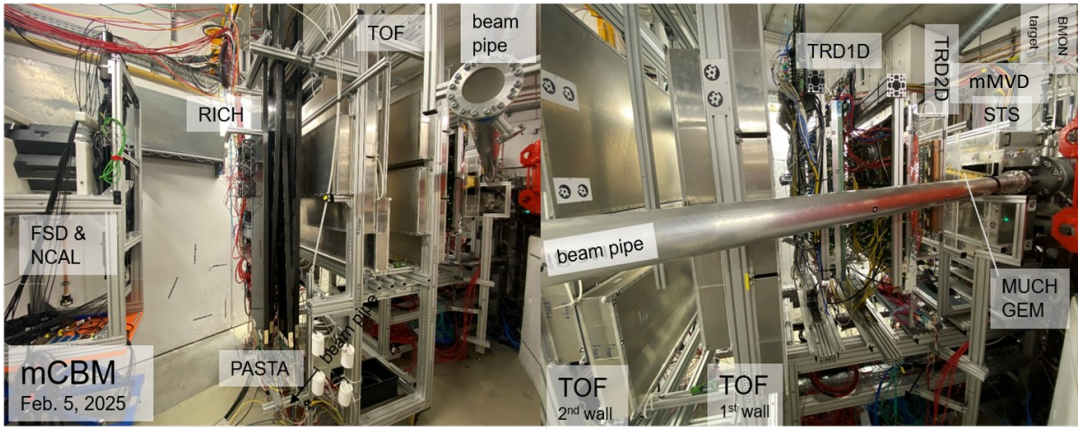


Distributed Data Processing

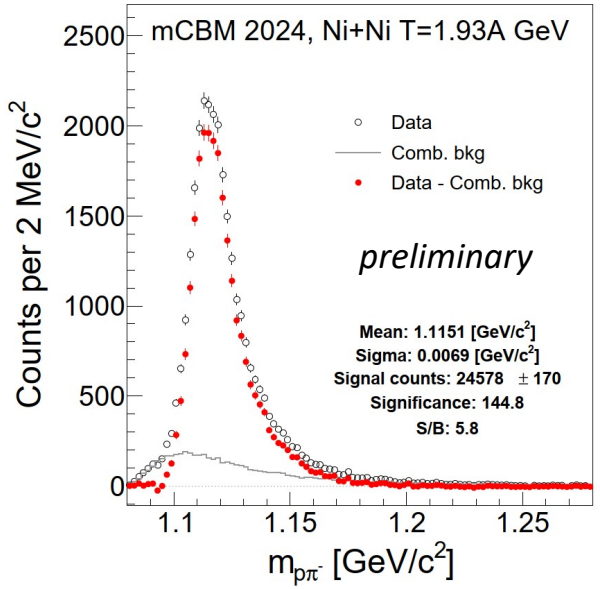
Efficient computing resources utilization towards online event selection (software trigger)

In-beam CBM tests in mCBM cave



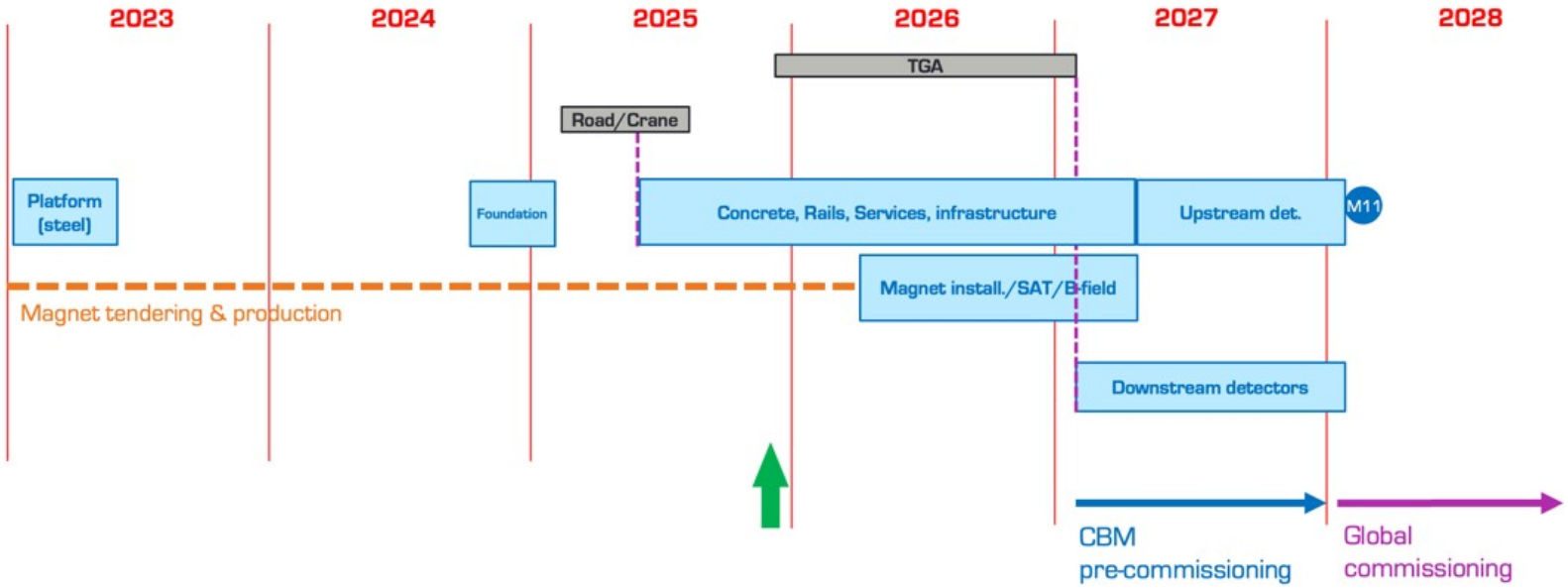


- Pre-series of all the CBM components (except the magnet) are tested in the SIS18 beam.
- Tests of full read-out chain, incl. free-streaming
- Tests for high (up to 10 MHz) collision rates
- Physics program: Λ excitation function @ SIS18 energies
- Continuation of tests in 2026



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 2026/2027

CBM Installation

- Activities (platform) started in 2023
- CBM Ready for beam by 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**

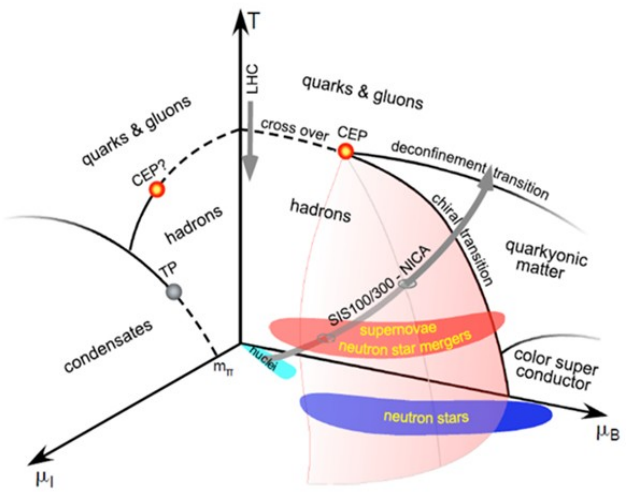
- Demonstrated reconstruction of many particles, also decaying via multi-step topologies
  - multi-strange hadrons
  - hypernuclei
  - subthreshold charm production

- Construction and tests advances (next in-beam tests: 2026). Goal: **CBM beam-ready @ 2028** !

Thank You!

Backup slides

First look at physical landscape



- CBM energies:

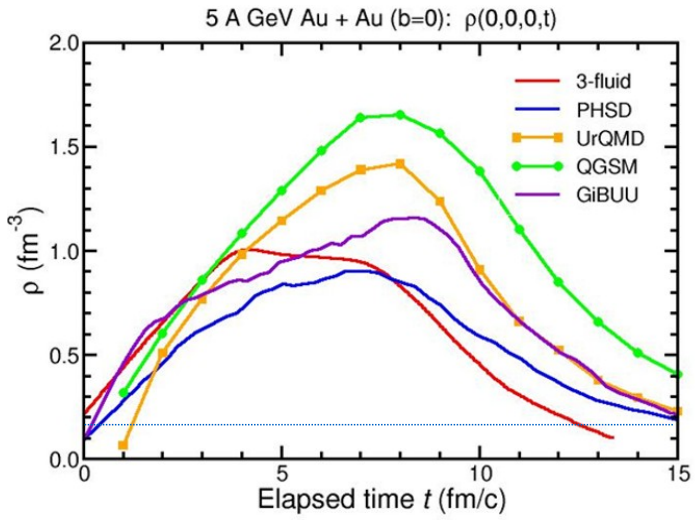
  high densities reached

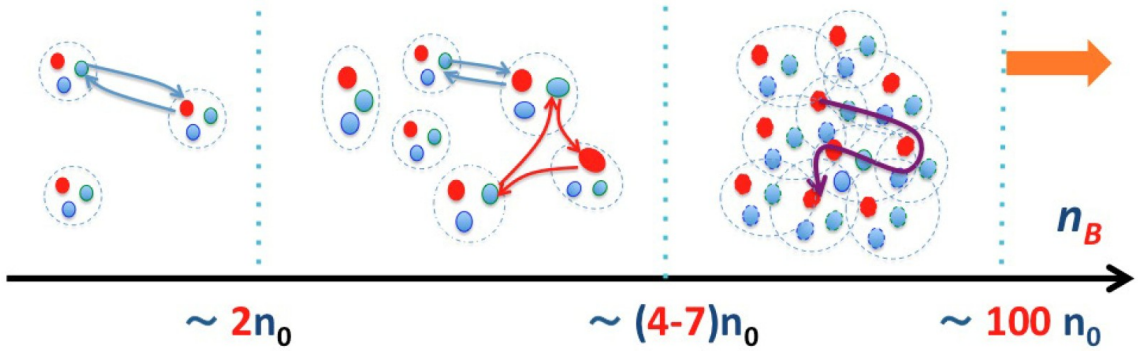
  ⇒ hadrons overlap

  ⇒ quark deconfinement

- **Quarkyonic matter**:
  chirally restored, not deconfined

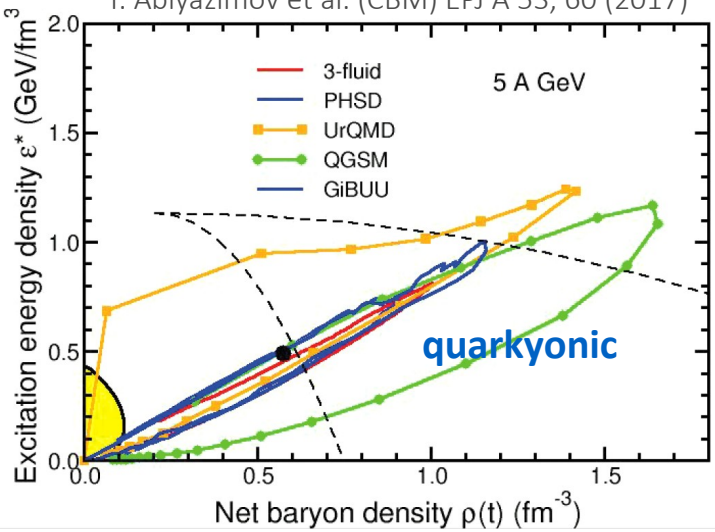
  Predictions: at CBM energies
  large incursions into quarkyonic mat.





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

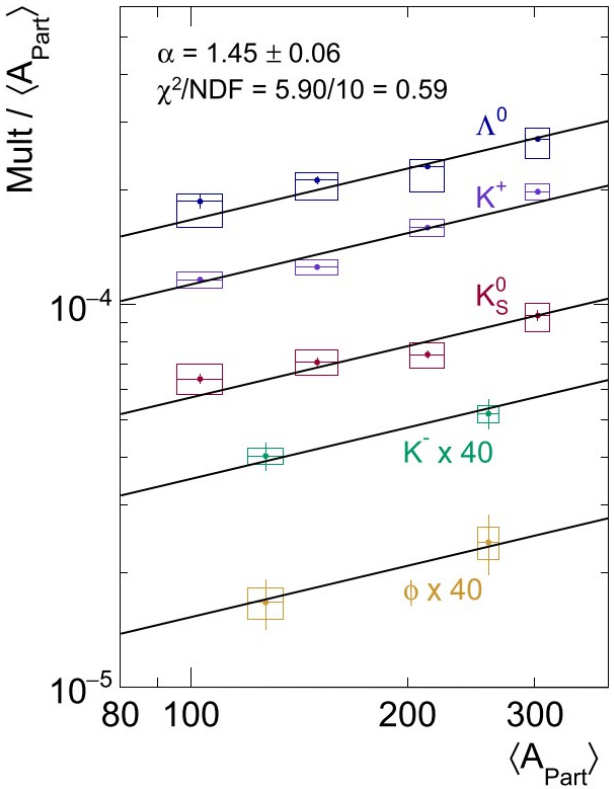
T. Ablyazimov et al. (CBM) EPJ A 53, 60 (2017)



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
⇒ more medium-demanding channels
⇒ in $P \sim A_{part}^{\alpha}$, α should rise with dropping $\sqrt{s}$ below NN threshold
At given beam energy α (ϕ) > α (K, Λ)

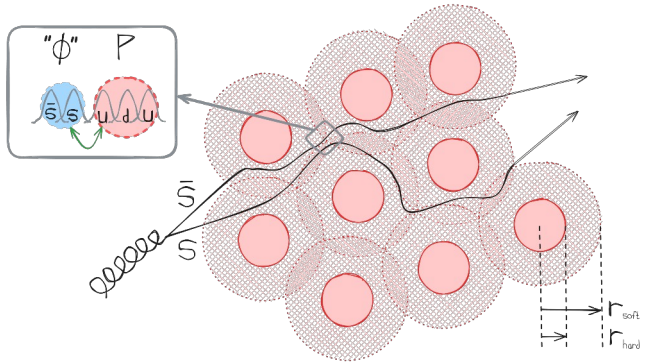
… but fits to hadron species with common α look okay!

Another hypothesis ($s\bar{s}$ ⊕ **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.

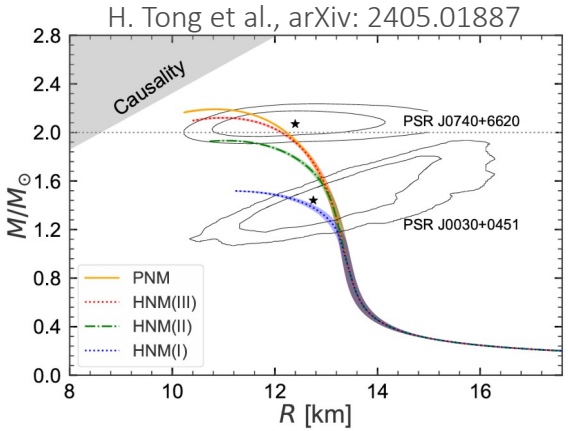
⇒ More statistics needed ⊕ energy scan.

CBM will be perfectly suited!



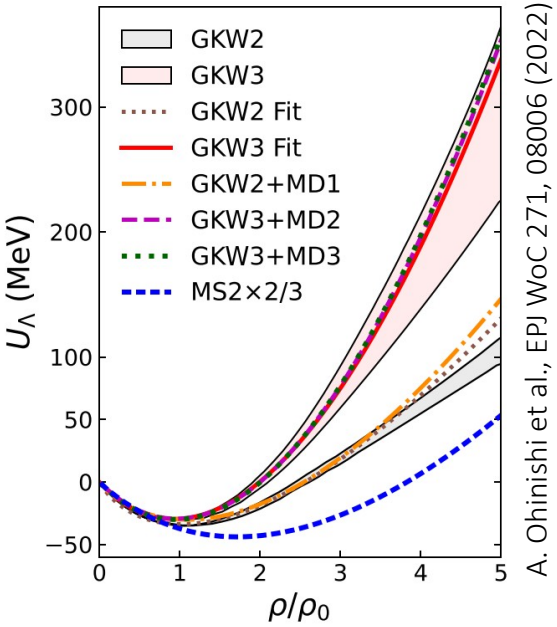
Author: M. Kohls, HADES

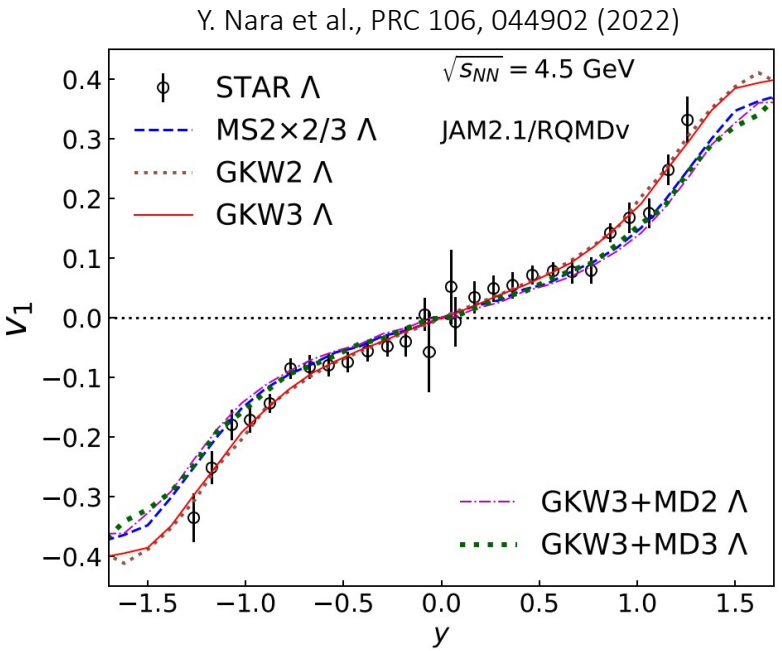
Λ Flow as testing ground for Neutron Stars

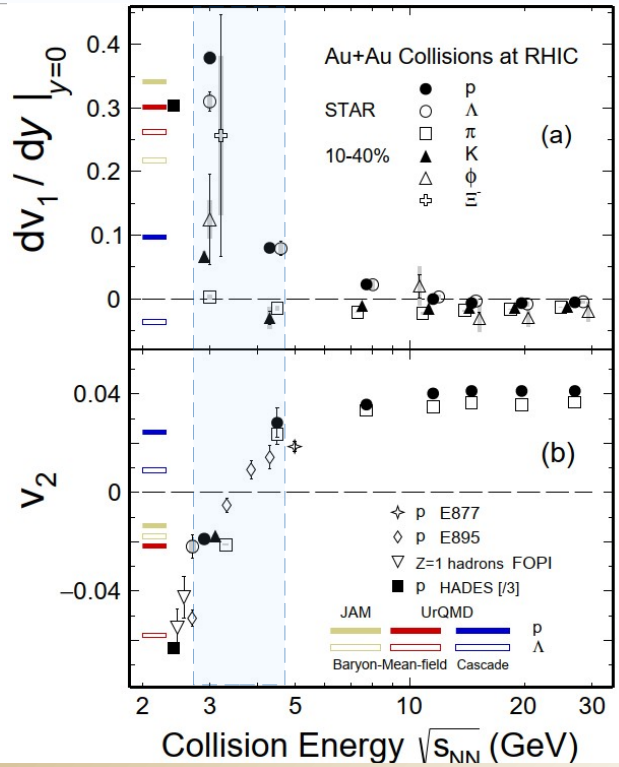


- **Hyperon puzzle**:
  - Inclusion of hyperons into model: observed masses $\sim 2M_\odot$ unjustified.
  - Adding YNN repulsion may restore agreement.

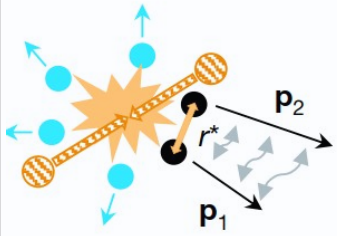
Modelling within RQMDv the YNN interactions = $f(\rho)$
v_1 (y) for Λ from Au+Au @ √s = 4.5 GeV (STAR)
Experiment-transport comparison: rather favors addition of YNN,
but more precise data needed. ⇐ CBM can contribute!



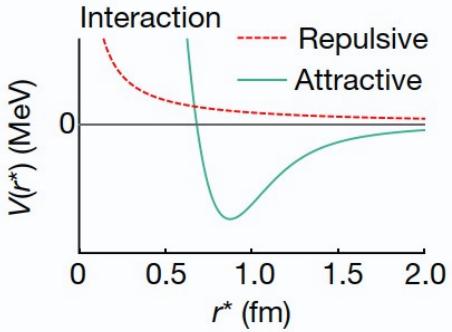




p-Λ femtoscopy: measure of interactions



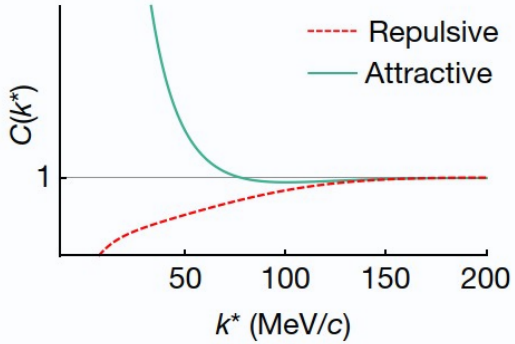
Emission source $S(r^*)$



Schrödinger equation

Two-particle wavefunction

$|\psi(\mathbf{k}^*, \mathbf{r}^*)|$

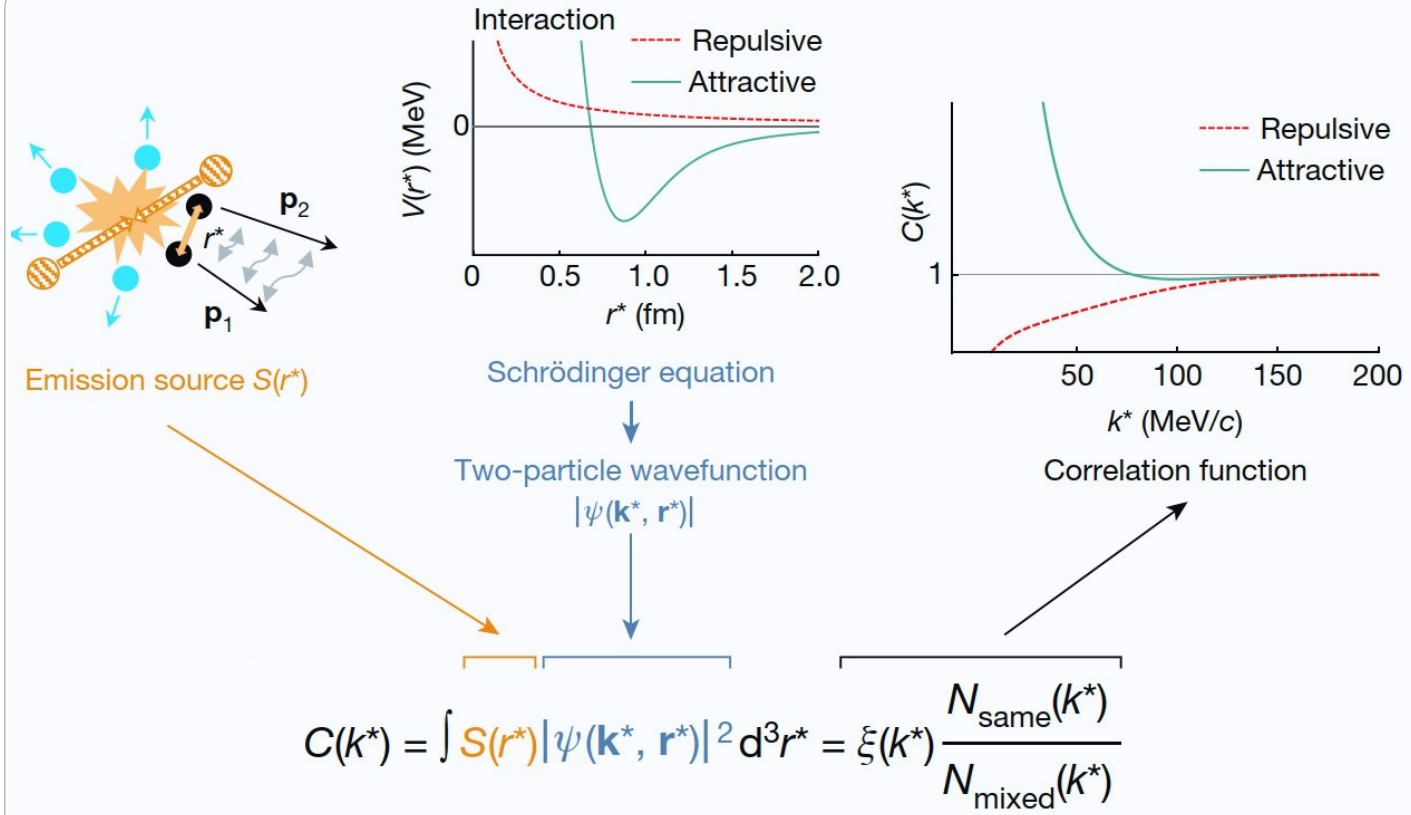


Correlation function

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

S. Acharia et al. (ALICE), Nature 588, 232 (2020)

p-Λ femtoscopy: measure of interactions



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

S. Acharia et al. (ALICE), Nature 588, 232 (2020)

Lednický-Lyuboshitz FSI model

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

Assumptions:

- static + spherical Gaussian source

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

- 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!

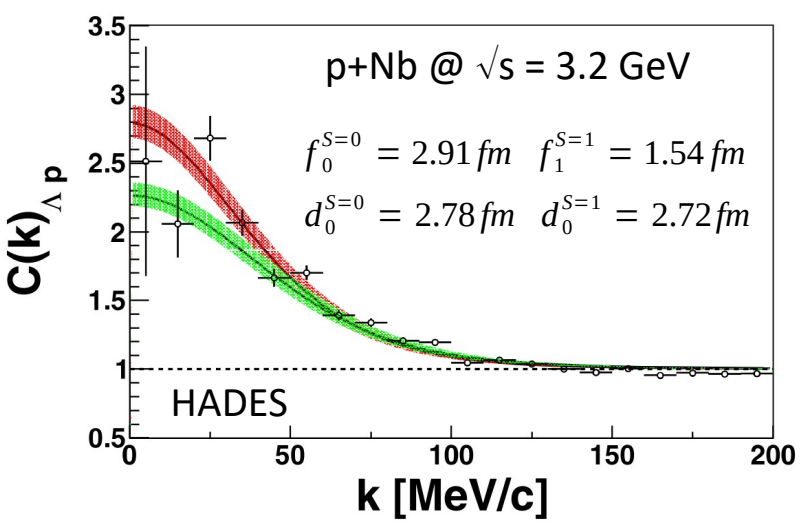
$$C(k^*) \approx 1 + \frac{|f(k^*)^2|}{2R_G^2}\left(1 - \frac{d_0}{2\sqrt{\pi}\,R_G}\right) + \frac{2\Re f(k^*)}{\sqrt{\pi}\,R_G} F_1(2k^* R_G) - \frac{\Im f(k^*)}{R_G} F_2(2k^* R_G)$$

$$\frac{1}{f(k^*)} \approx \frac{1}{f_0} + \frac{d_0 \cdot (k^*)^2}{2} - ik^* \qquad F_1(z) = \int_0^z dx\, \frac{\exp(x^2 - z^2)}{z} \qquad F_2(z) = \frac{1 - \exp(-z^2)}{z}$$

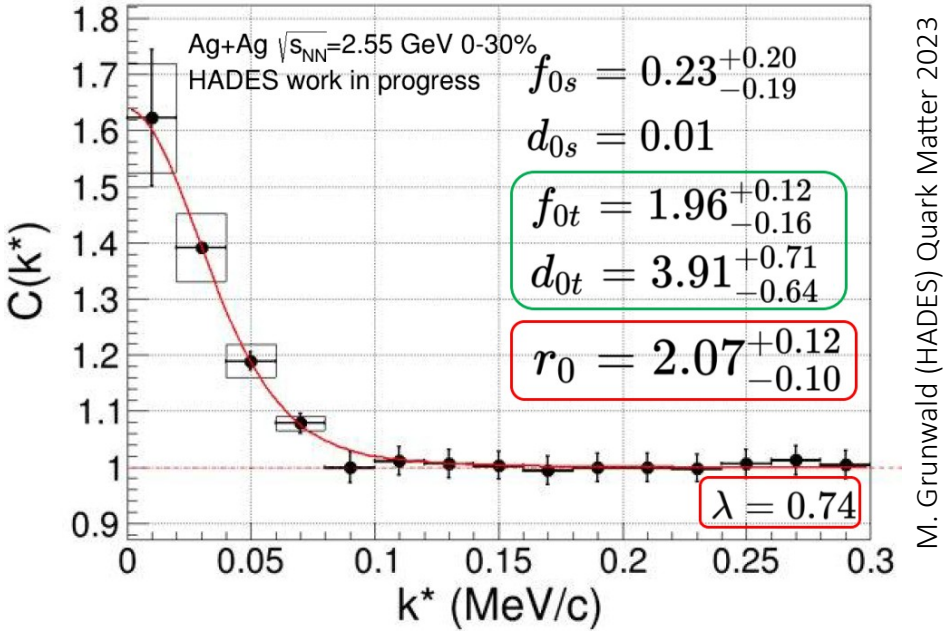
p-Λ femtoscopy: measure of interactions

- **pΛ femtoscopy** results in $\sqrt{s}$ region around CBM:
  - only one result published: p+Nb @ $\sqrt{s}$ = 3.2 GeV
  - two analyses under way: Ag+Ag @ $\sqrt{s}$ = 2.6 GeV, Au+Au @ $\sqrt{s}$ = 3.0 GeV

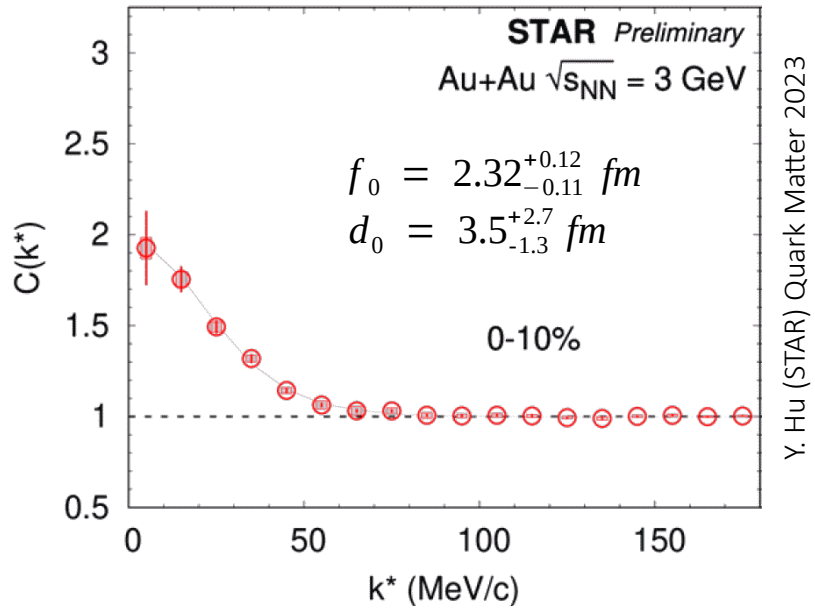
CBM aims to provide high-stat, fine *E* scan up to $\sqrt{s} \approx 5$ GeV (also study pΣ, pΞ, pΩ, ... interactions)



J. Adamczewski-Musch et al (HADES), PRC 94, 025201 (2016)

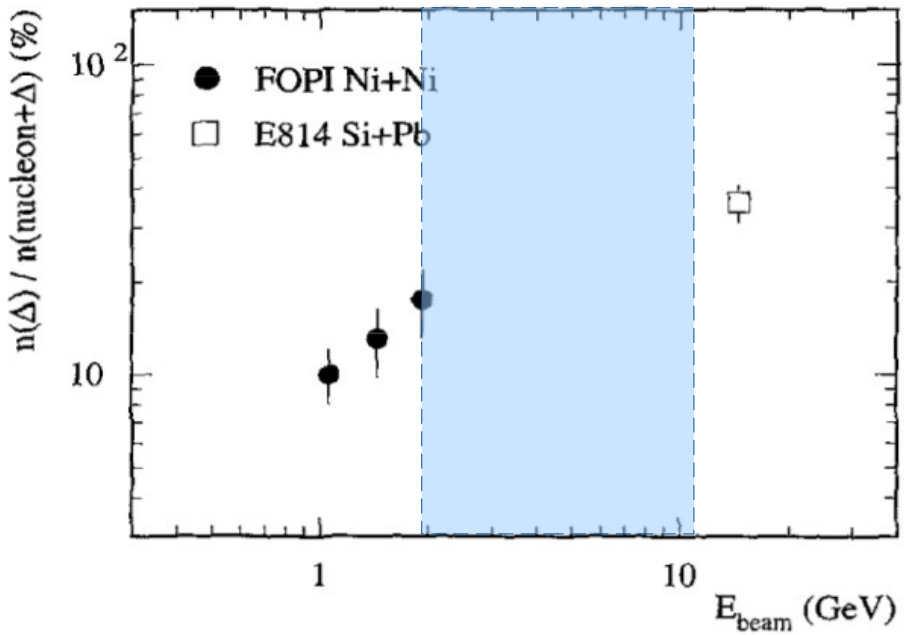


M. Grunwald (HADES) Quark Matter 2023



Y. Hu (STAR) Quark Matter 2023

- CBM: region of **resonant matter**



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