Challenges in QCD matter physics

The scientific programme of the Compressed Baryonic Matter experiments at FAIR

Claudia Höhne, University Giessen & GSI

HADES & CBM collaboration

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Helmholtz Forschungsakademie Hessen für FAIR

Bundesministerium für Bildung und Forschung

Open QCD questions

…. See e.g. workshop program, white paper(s), …..

- Phase structure of QCD at finite density
  - EOS at high densities
  - Connection to neutron stars
- Formation of hadrons, hadron spectra
  - Chiral symmetry
  - Hadron masses in vacuum/ dense matter
  - Confinement
- Formation of nuclei
  - Light nuclei in HIC
  - Hypernuclei

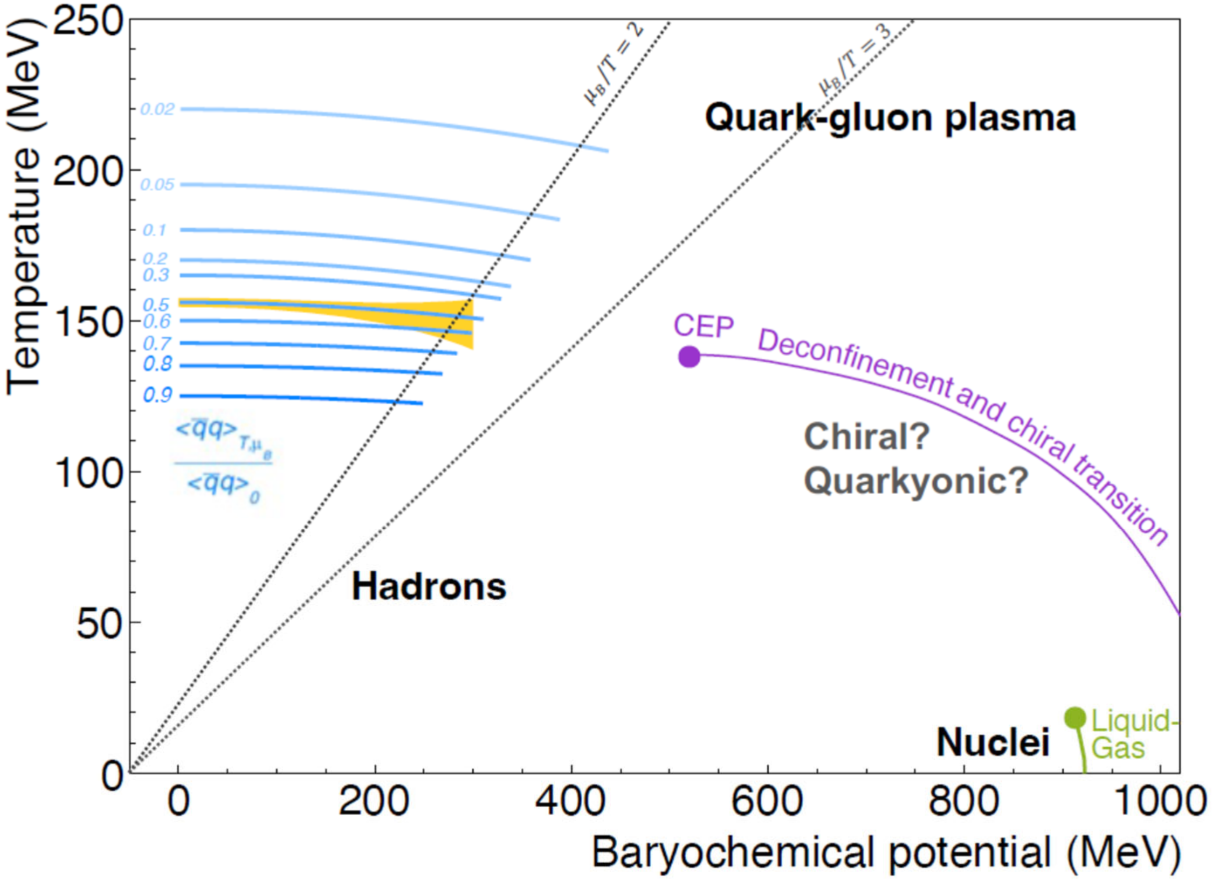
QCD phase diagram

High T, low μ_B
- Crossover

→ Consistent in theory & Experiment!

Lower T, high μ_B
- CEP?
- 1st order phase transition?
- EOS?
- Properties of hadrons/ limits of existence?

HADES; Nature Physics 15 (2019) 10, 1040-1045



Borsanyi *et al.* [Wuppertal-Budapest Collab.], JHEP 1009 (2010) 073
Isserstedt, Buballa, Fischer, Gunkel, PRD 100 (2019) 074011
Gao, Pawlowski, PLB 820 (2021) 136584
Cuteri, Philipsen, Sciarra, JHEP 11 (2021) 141

QCD phase diagram

C.B.M. = HADES & CBM

- Experimental investigation of region with 500 MeV < μ_B < 850 MeV

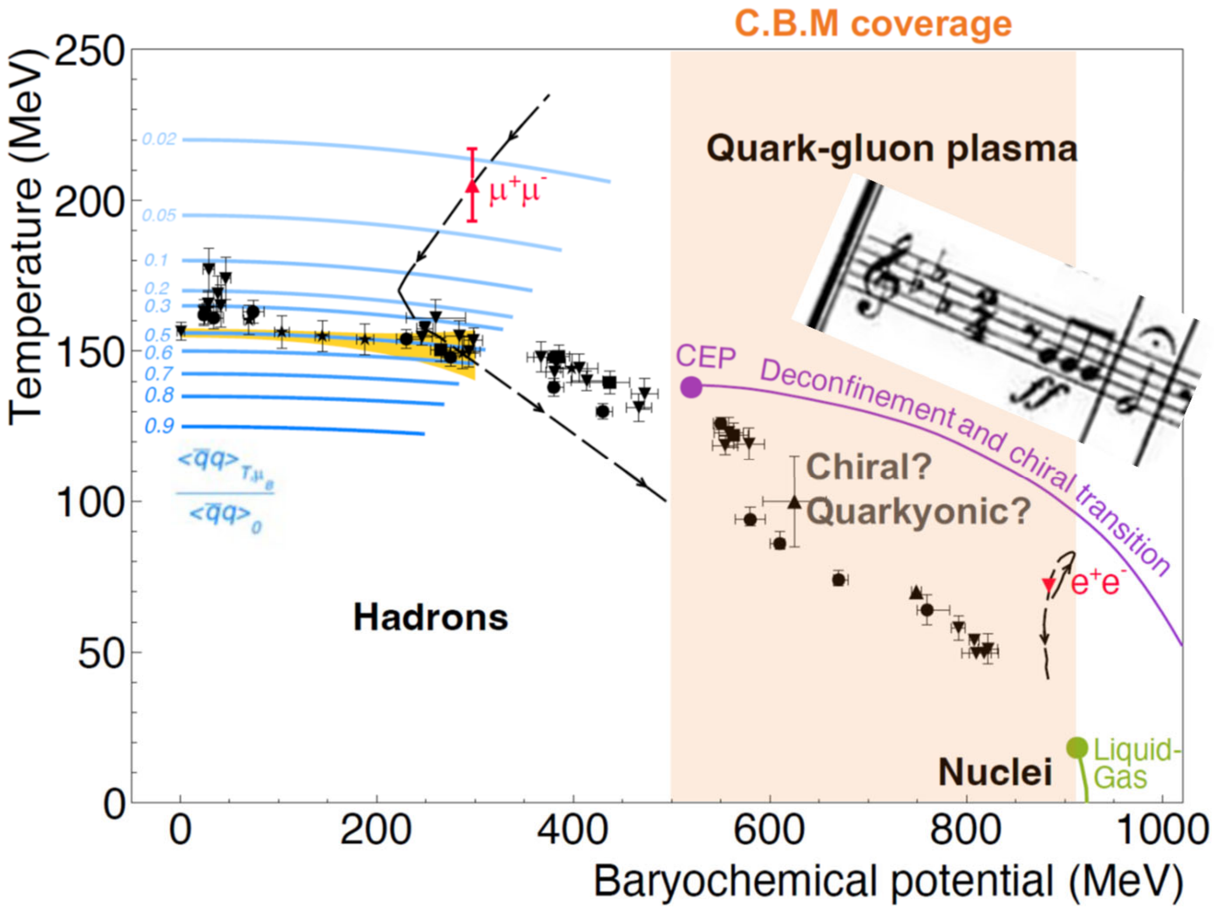
Observables?

- Fluctuations
- Dileptons
- Strangeness
- Hypernuclei
- ….?

	$\sqrt{s_{NN}}$ [GeV]	μ_B [MeV]
SIS 18	2 – 2.5	830 – 760
SIS 100	2.3 – 5.3	785 – 520
STAR Collider	7.7 – 200	400 – 22
STAR FXT	3 – 13.7	700 – 265

$\mu_B(\sqrt{s_{NN}})$ from A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Nature 561, no. 7723, 321 (2018)

HADES; Nature Physics 15 (2019) 10, 1040-1045
T. Galatyuk for HADES, Nucl.Phys.A 967 (2017) 680-683



Borsanyi *et al.* [Wuppertal-Budapest Collab.], JHEP 1009 (2010) 073
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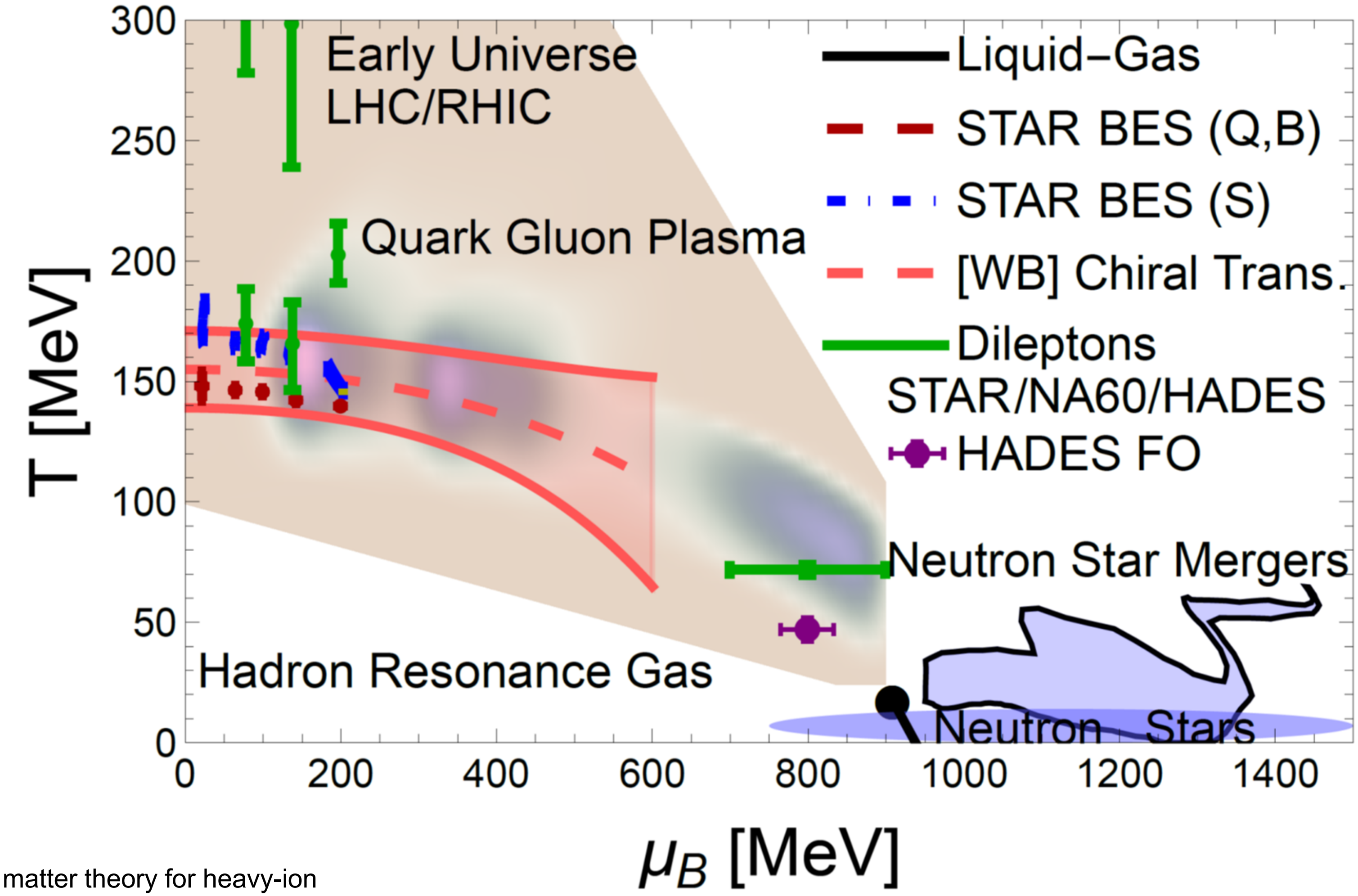
Beethoven, 5. Sinfonie

Neutron stars/ Neutron star mergers

With (not any more so new ;-)) observation of neutron star mergers revival of combined analysis and cross-disciplinary discussions



[Long Range Plan: Dense matter theory for heavy-ion collisions and neutron stars, nucl−th 2211.02224]

Neutron stars/ Neutron star mergers

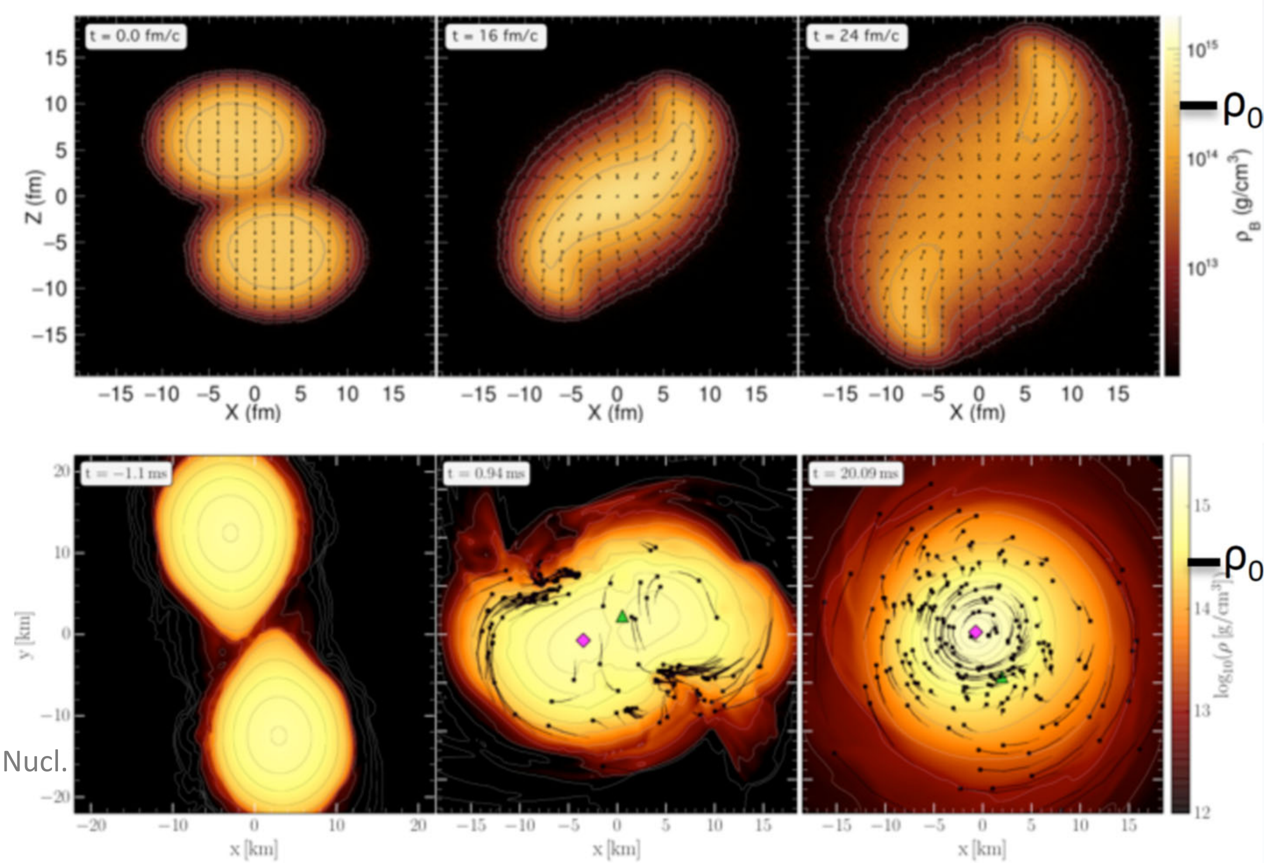
With (not any more so new ;-)) observation of neutron star mergers revival of combined analysis and cross-disciplinary discussions

T < 70 MeV, $\rho \approx 3\rho_0$ in both cases

Central Au+Au collisions,

$\sqrt{S_{NN}} = 2.4\ GeV$

Neutron Star Merger

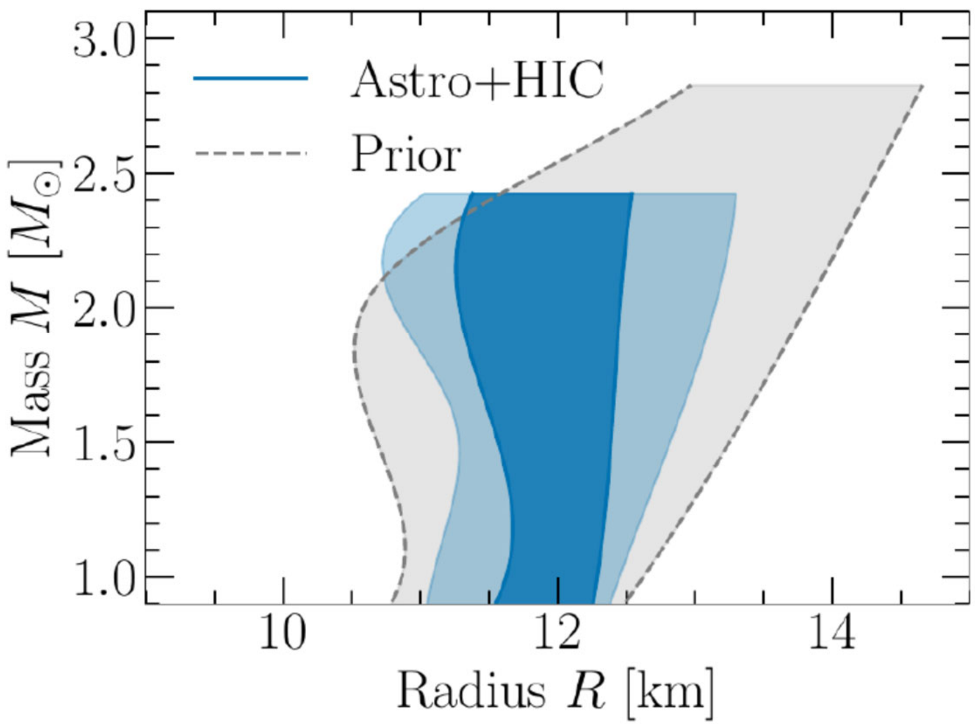


M. Hanauske, J.Phys.: Conf. Series878 012031 (2017)
L. Rezzolla et. al. PRL 122, n0.6, 061101 (2019)h
Au+Au simulation UrQMD: S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 255 (1998).
Fig. credit T. Galatyuk & Florian Seck

Example:

Inclusion of HIC shifts NS radii to larger values, consistent with recent results from NICER

(D) HIC and Astro combined:



Constraining Neutron-Star Matter with Microscopic and Macroscopic collisions
S. Huth, P.T.H. Pang et al., Nature 606 (2022) 276-280

Observables

What to measure?
Challenges/ difficulties/ opportunities for high-μ_B facilities?

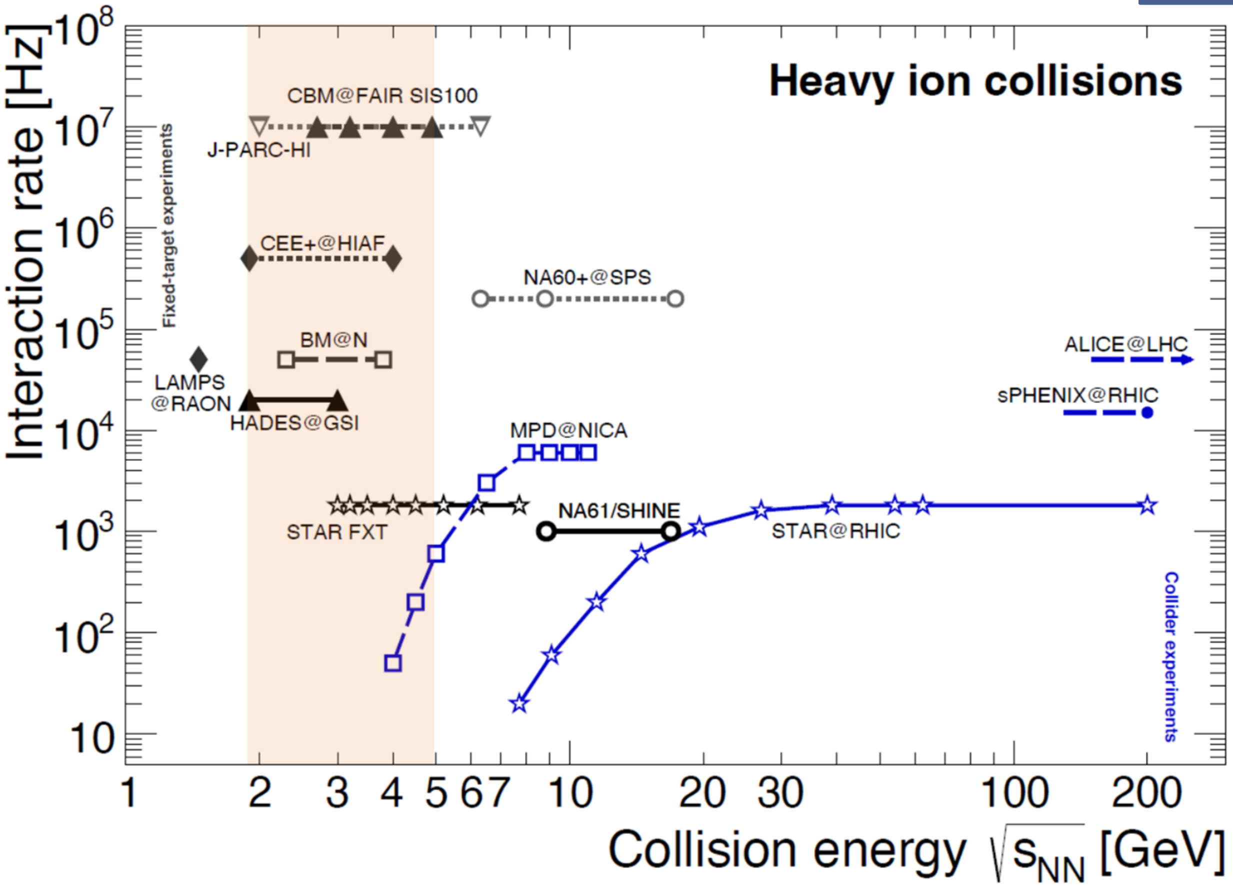
→ Program needs ever more precise data (statistics!) and sensitivity for rarest signals

Critical phenomena
1st oder PT, CEP

EOS
Flow, bulk phenomena

Emissivity
Em probes

Characterization of matter
Hadrons, strangeness,
Hypernuclei, light nuclei
Correlations, vorticity, ….



T. Galatyuk, NPA 982 (2019), update 2021
CBM, EPJA 53 3 (2017) 60

Observables

What to measure?

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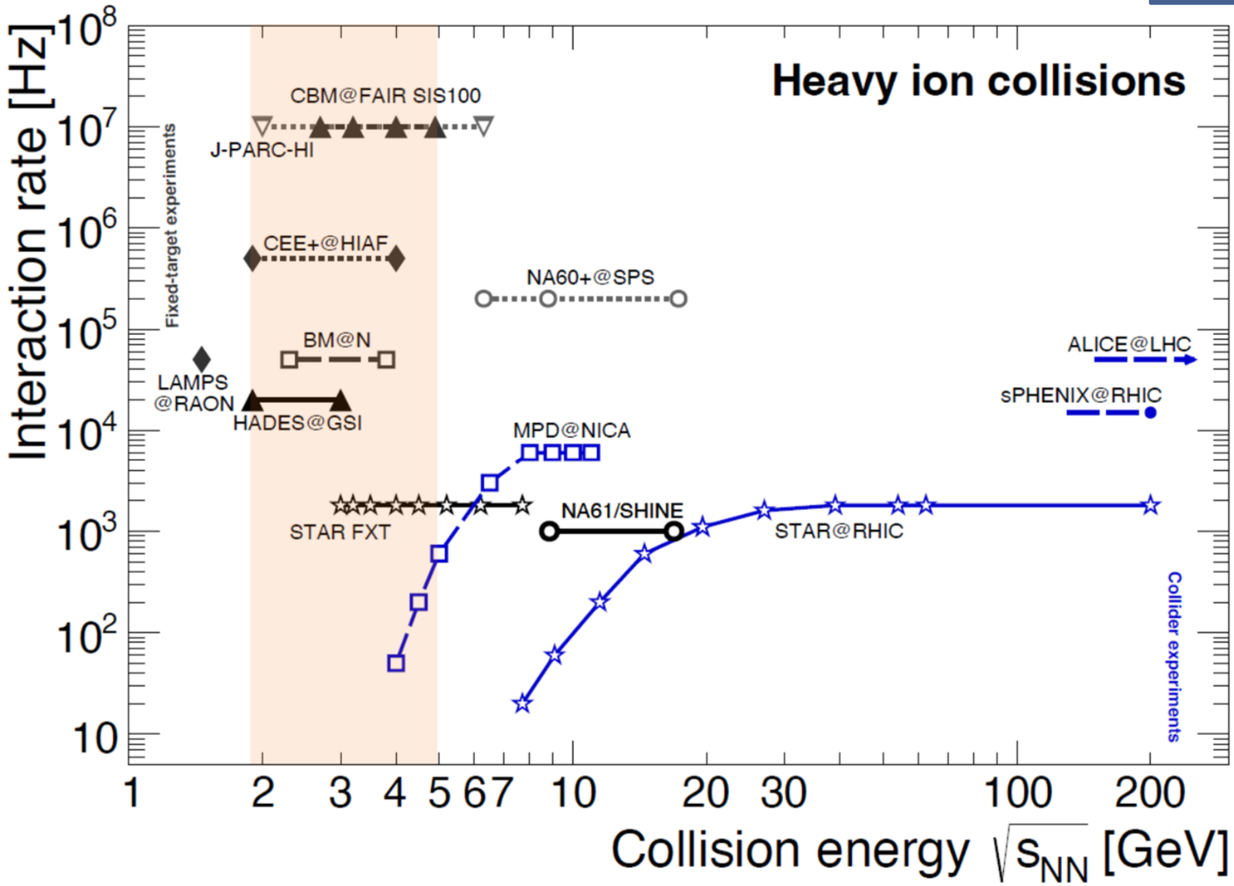
→ Program needs ever more precise data (statistics!) and sensitivity for rarest signals

HADES
well established exp.
Recent upgrades

STAR
Energy scans completed
Lots of data to come

CBM
Dedicated setup to come



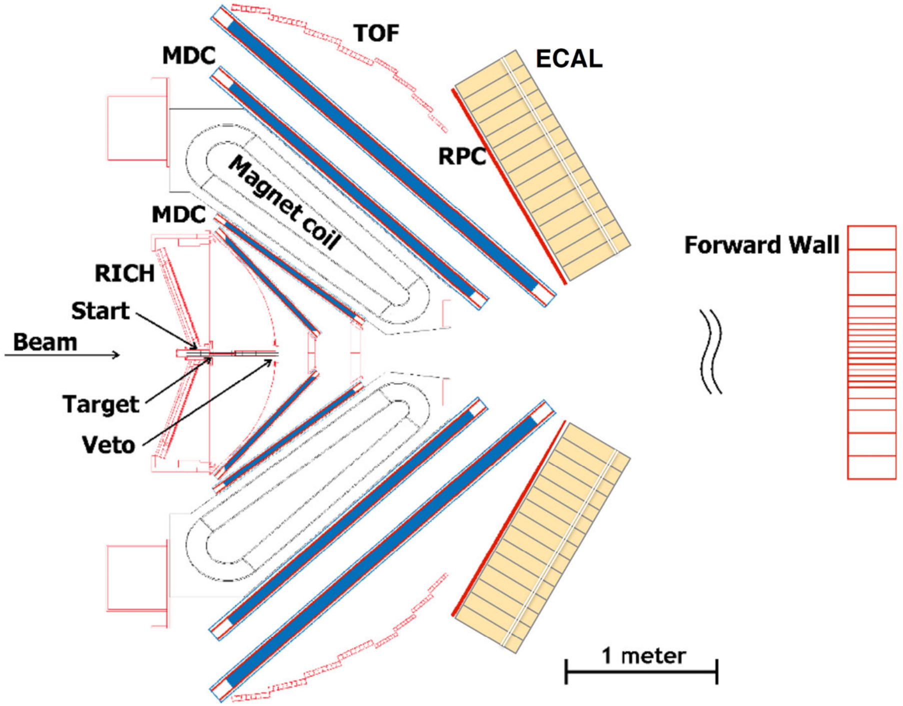
T. Galatyuk, NPA 982 (2019), update 2021
CBM, EPJA 53 3 (2017) 60

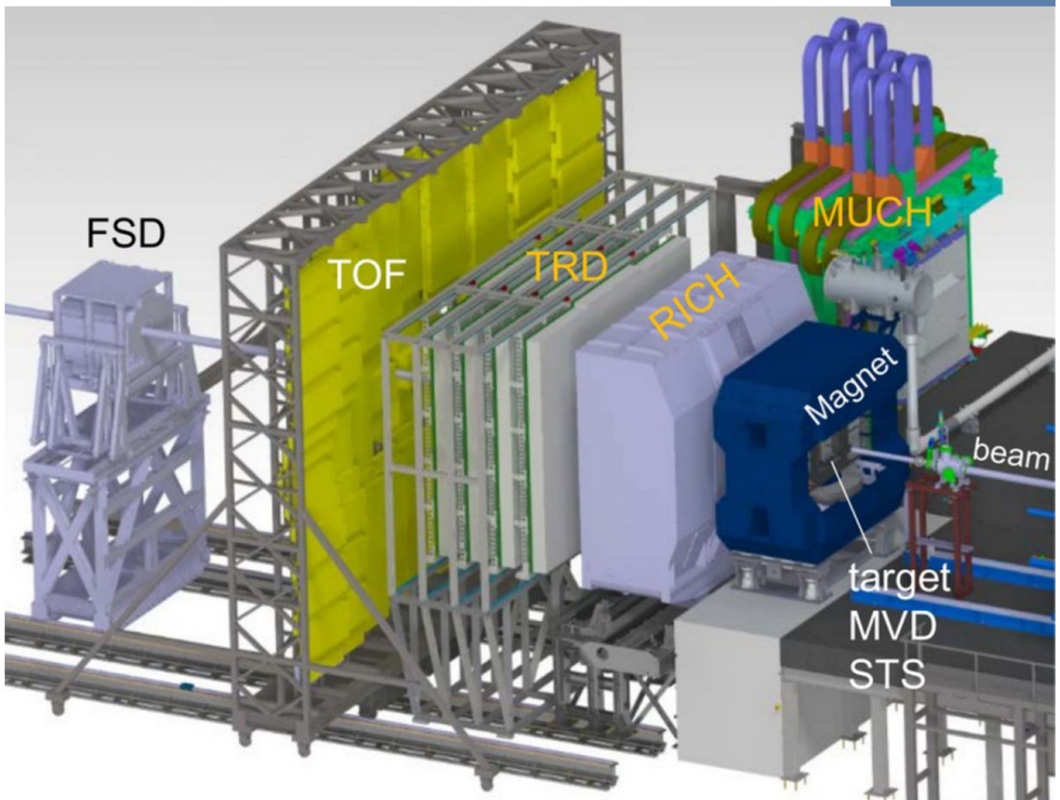
HADES

- 18°- 85° polar angle coverage, symmetric in azimuth
- Electron detection in front of magnetic field and most of the material

CBM

- 2.5° - 25° polar angle coverage, azimuthal symmetry broken by dipole
- Electron detection behind STS and magnetic field





Fluctuations

When crossing a 1st order phase transition: jump in density
→ Measure derivatives!
→ Cumulants of baryon number measure derivatives of μ_B

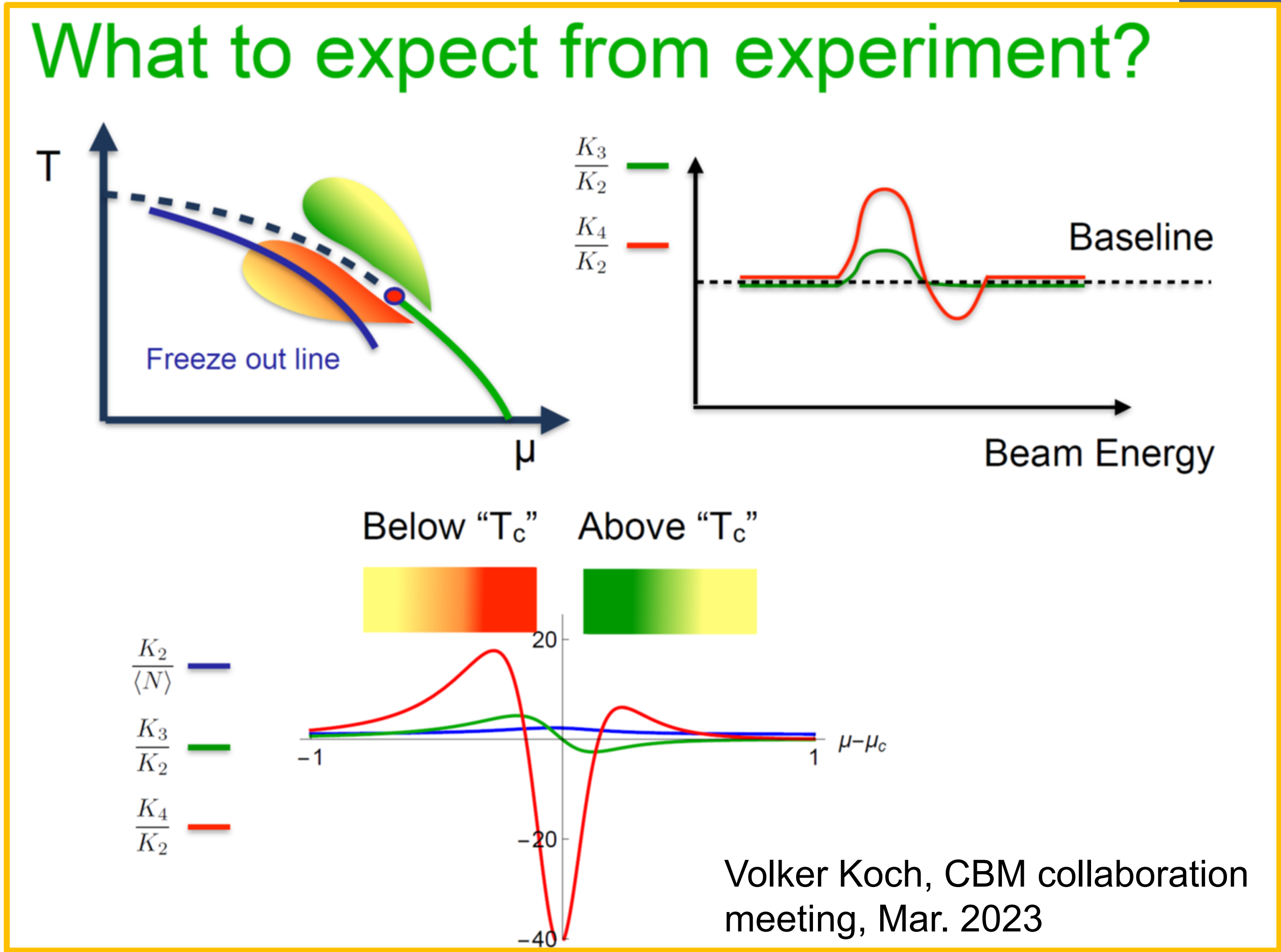
$$\chi_n^B \equiv \frac{\partial^n (p/T^4)}{\partial(\mu_B/T)^n} = \frac{\kappa_n[B]}{V\,T^3}$$

Higher moments
more sensitive!

Ratios of cumulants
independent on V

$$\frac{\chi_4}{\chi_2} = \frac{K_4}{K_2} = \kappa\sigma^2$$

V. Vovchenko et al.,
Phys.Lett.B 811 (2020) 135868



Net-proton distributions

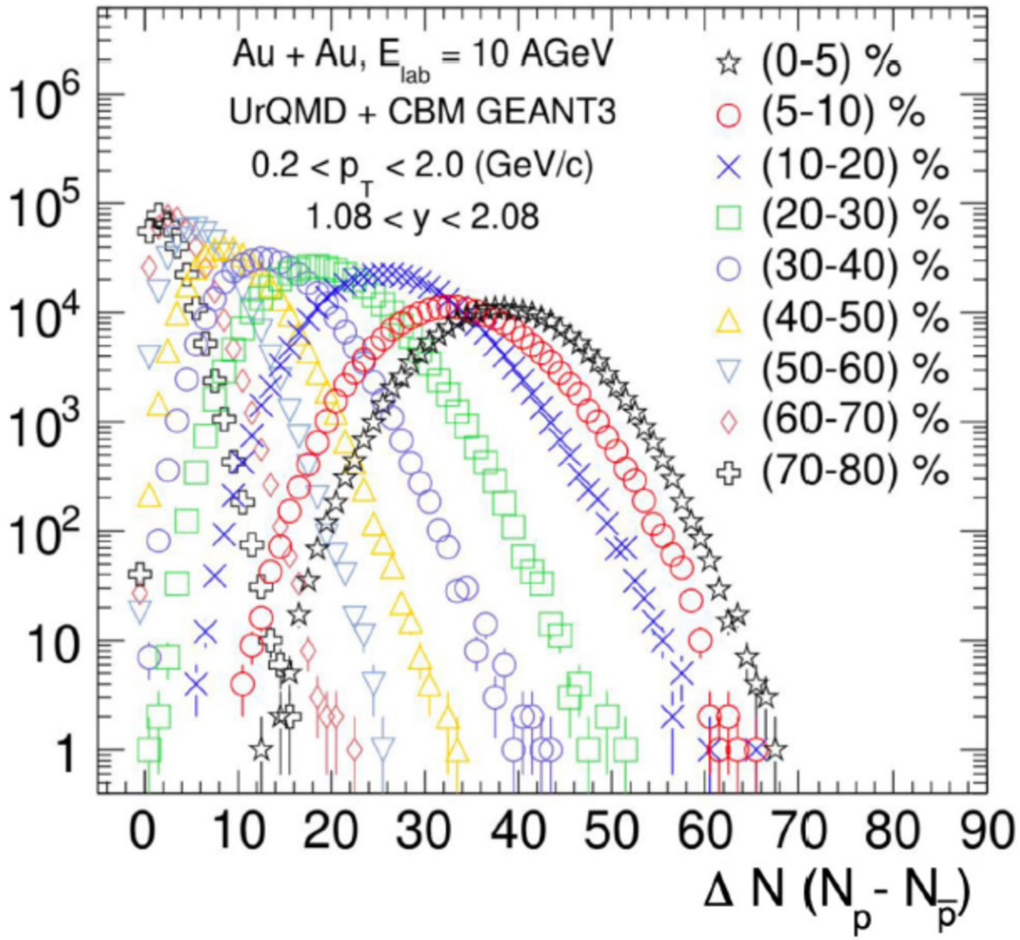
Measure event-by-event net-proton number (protons – antiprotons)
→ Distribution → calculate the moments → higher moments probe the tails!

Challenges:

- Large acceptance in proper (y-pt) bin
- Experimental effects from
  - e-b-e changes of efficiency
  - Baryon contributions in n,d,…
  - Volume fluctuations
  - Conservation laws…
- Higher moments are in the tails!
  → statistics hungry!

$K_2 = \langle N - \langle N \rangle \rangle^2$ etc.

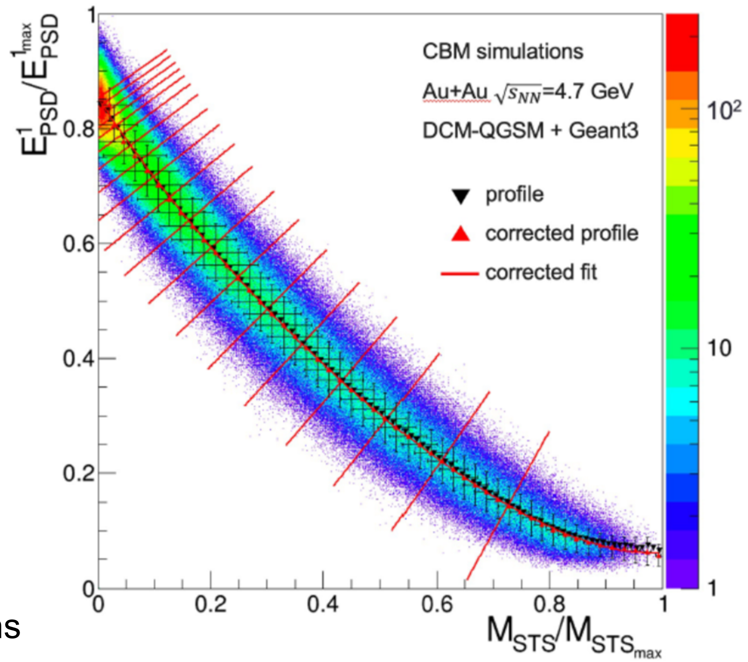
CBM simulations



Possible solution to settle volume fluctuations: A. Rustamov et al., nucl-th 2211.14849

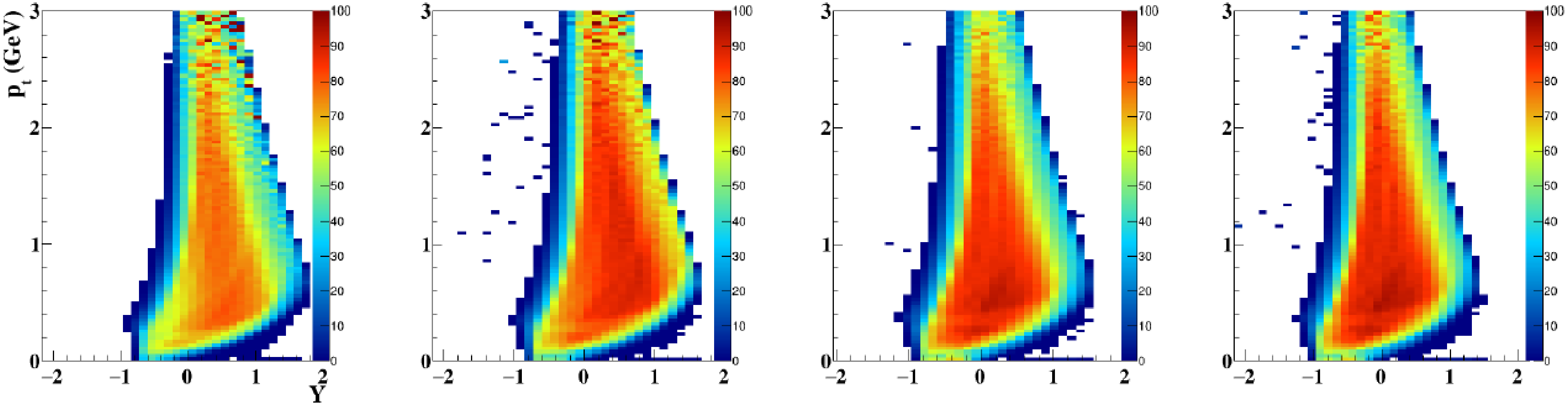
Net-proton distributions

- CBM: Proton acceptance for low p_t and midrapidity for wide range of energies
- Crucial: independent centrality determination with separated detector (PSD → FWD)



CBM simulations

4 AGeV | 6 AGeV | 8 AGeV | 10 AGeV



Critical fluctuations

HADES ✓

… understand volume fluctuations/ acceptance effects of different experiments!

CBM after 3 years – (improve STAR stat. errors by factor of 10):

- measure excitation function (p) for $k\sigma^2 = \frac{\kappa_4}{\kappa_2}$
- First results on κ_6(p)
- Extension to strangeness?

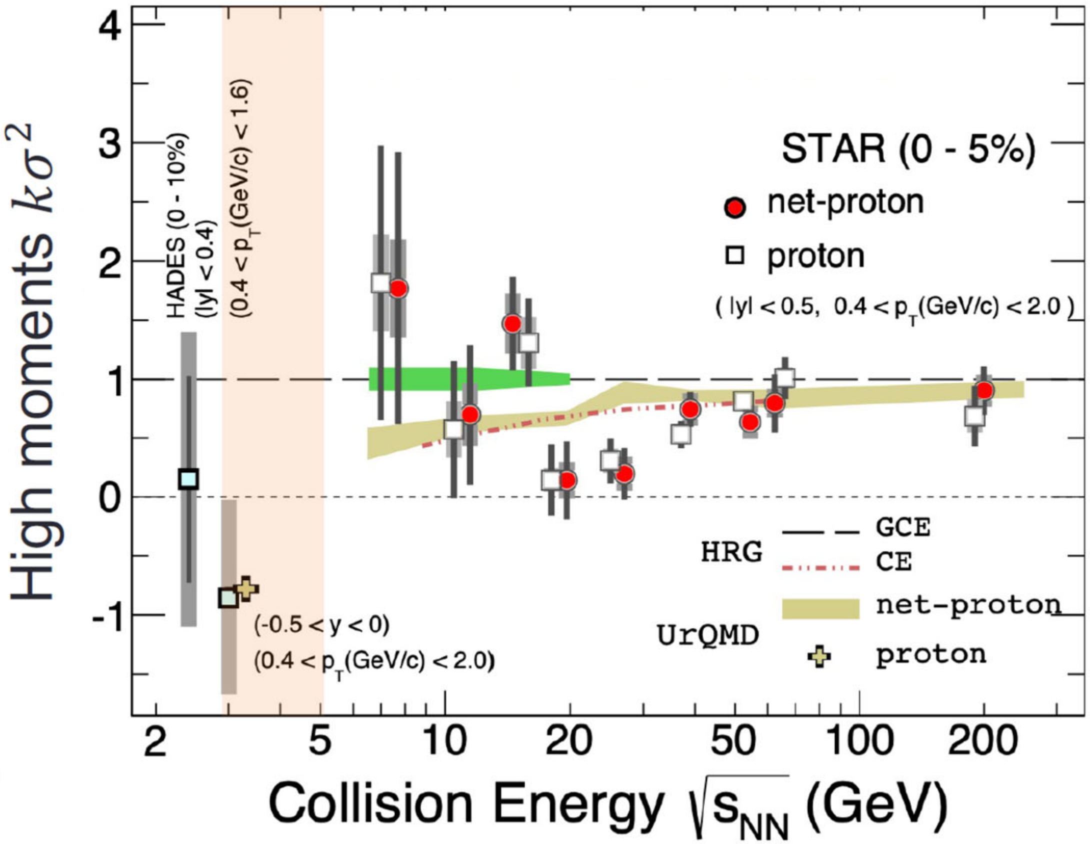
We hope to see:

Discontinuity?!

… that extends to even higher moments?

Understand influence of baryon number conservation at high μ_B

STAR, PRL 128 (2022) 20, 202303
HADES, PRC 102 (2020) 2, 024914

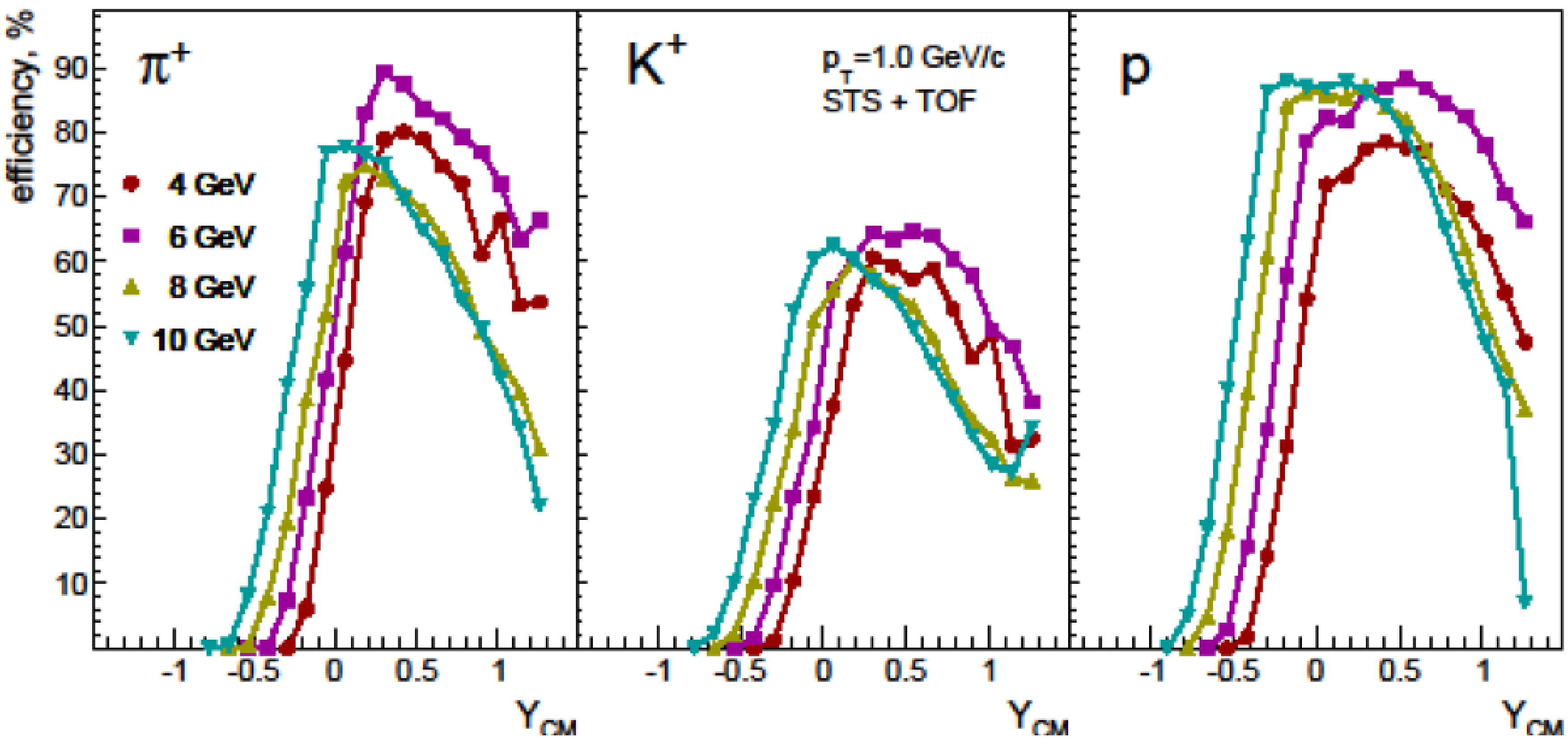


Challenge

What about further conserved number fluctuations?

Challenge:
CBM acceptance increasingly more forward for lighter particles

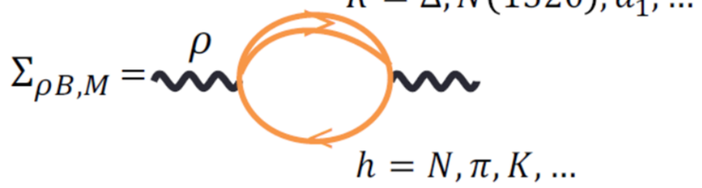
CBM simulations

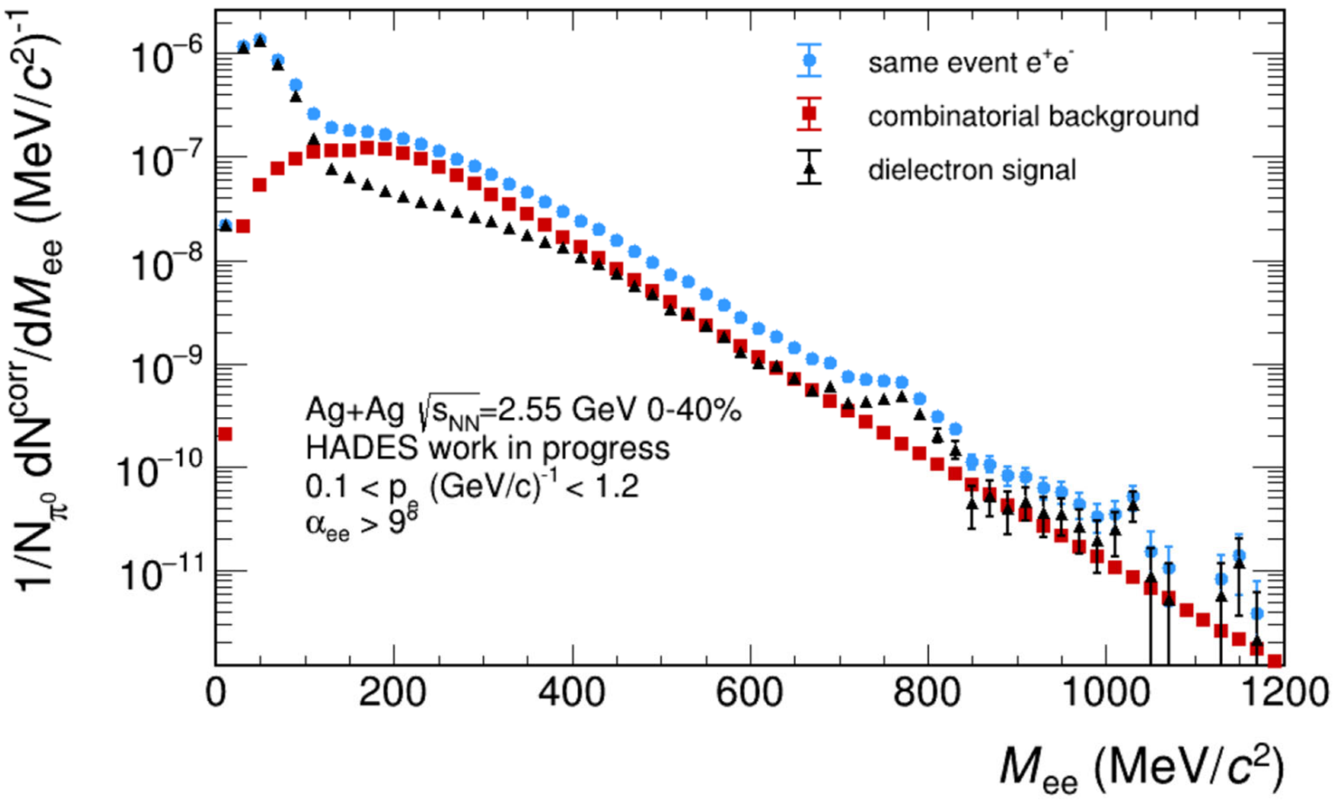


Dileptons

Em probes are sensitive to the full duration/evolution of the collision

- Emission of virtual photons from all stages
- Unique probe of temperature, duration, density, … of the fireball
- Baryon effects are crucial
  → dedicated program in HADES!





[J. Otto for the HADES collaboration, EPJ Web Conf. 274 (2022), 05002]

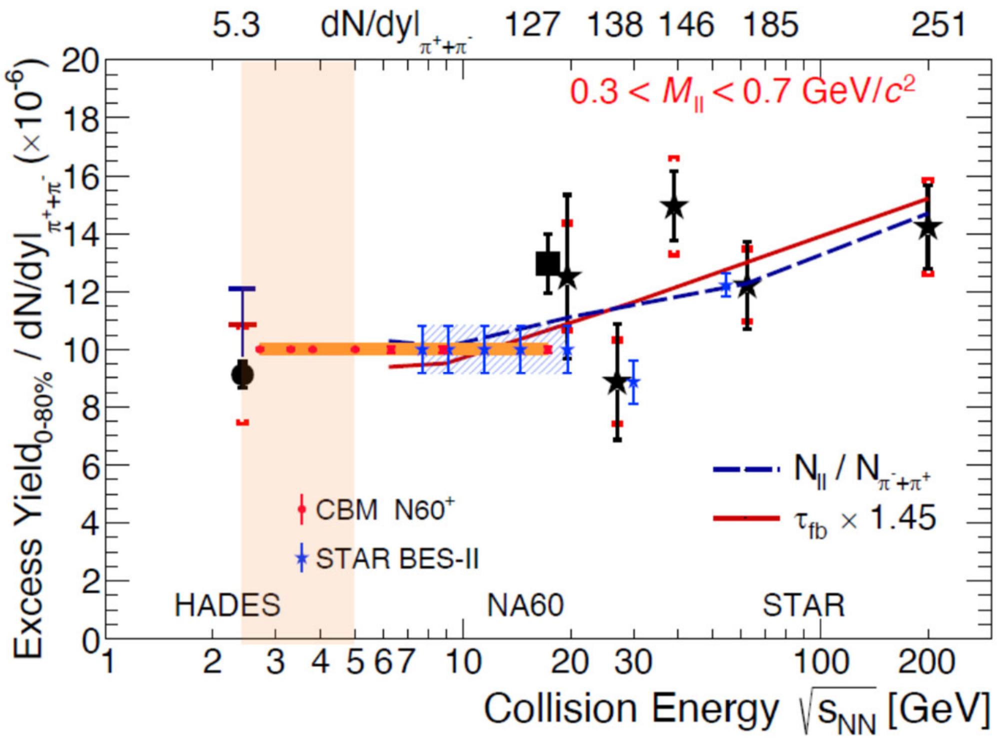
Dileptons

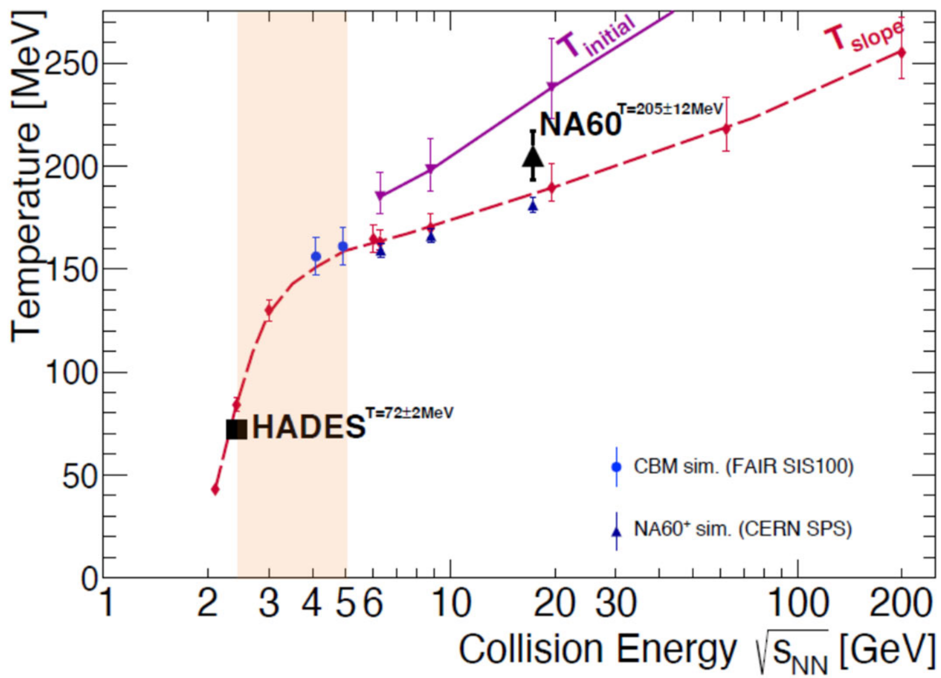
Two key measurements to be made (→ first year of CBM*, HADES ✓)

- Excess yield in LMR → fireball lifetime: extra radiation due to latent heat aroung PT (& CEP?)?
- Invariant mass slope (LMR & IMR) → flattening of caloric curve due to PT ?

* one year 5 days beam on target, 6 energies Au+Au, $2\cdot10^{10}$ ev. each, 100kHz

Tripolt *et al.*, NPA 982 (2019) 775
Li and Ko, PRC 95 (2017) no.5, 055203
Seck *et al.*, PRC (2022), arXiv:2010.04614 [nucl-th]

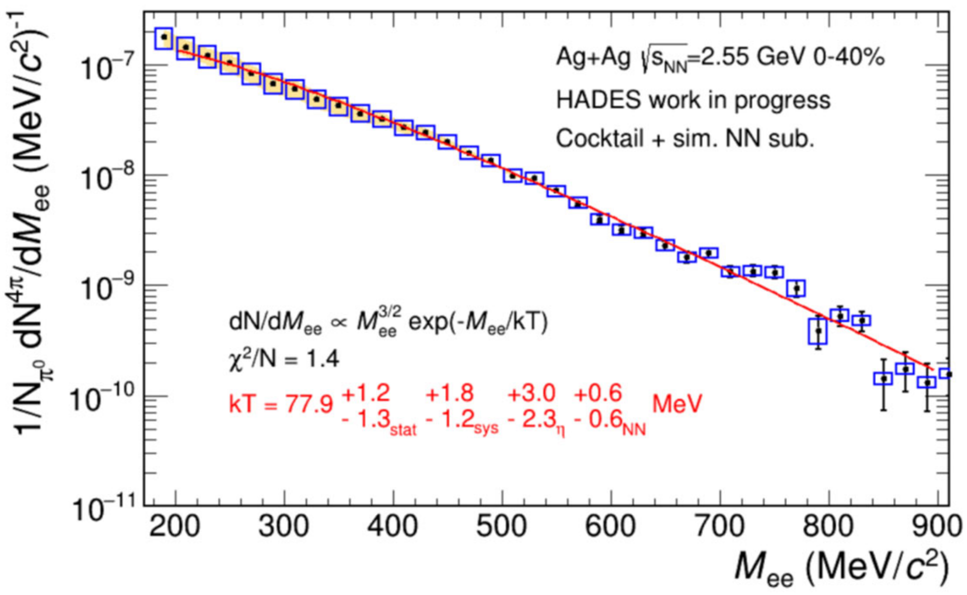


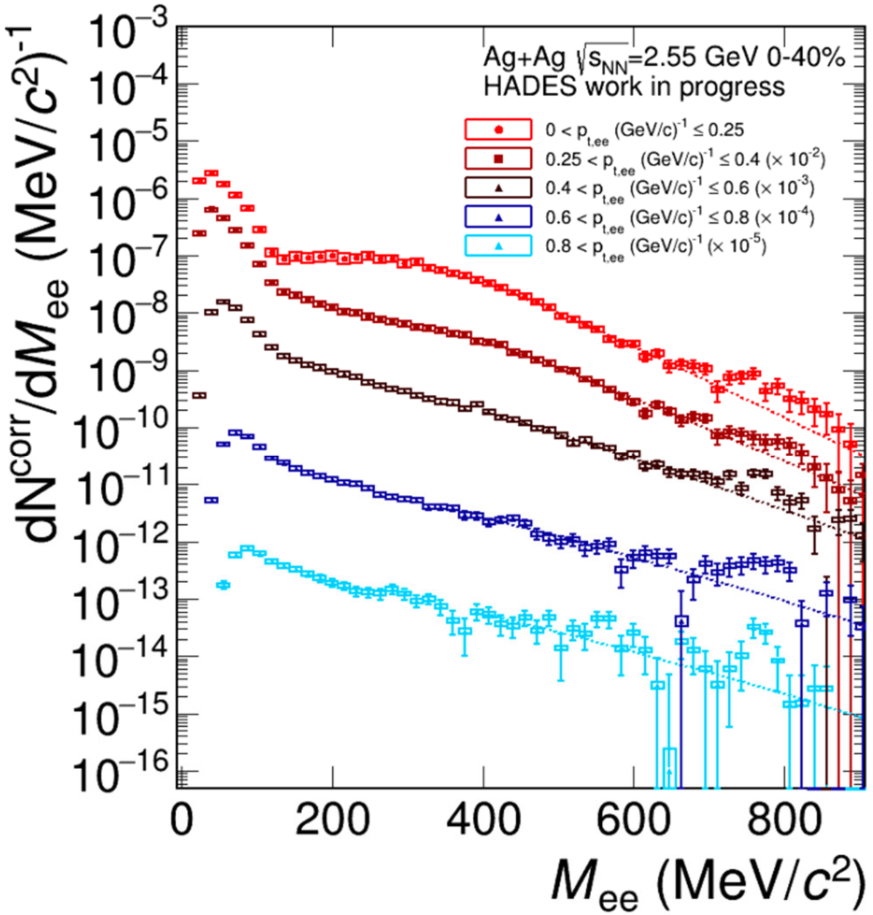


T. Galatyuk, JPS Conf. Proc. 32 (2020) 010079

HADES

- New data from Ag+Ag collisions at slightly higher $\sqrt{s_{NN}}$ → slightly higher T
- p_t dependence accessible with high statistics
  → change in ω/ρ contributions!
- Au+Au energy scan towards lower $\sqrt{s_{NN}}$ to come!

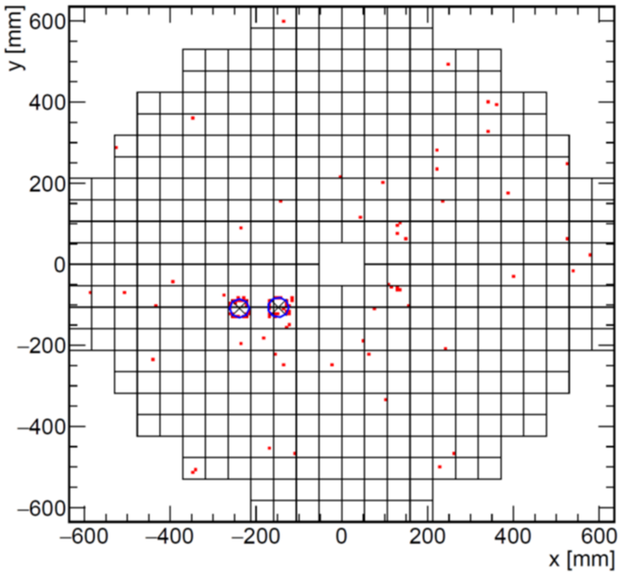


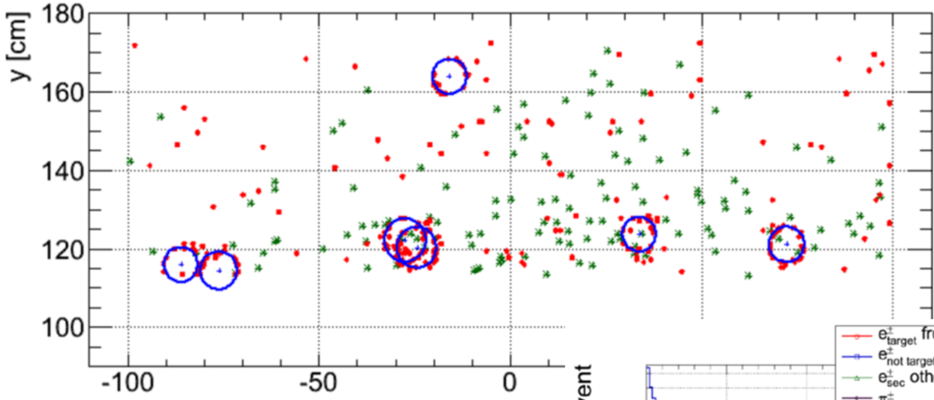


[J. Otto for HADES, EPJ Web Conf. 274 (2022), 05002
J. Otto, PhD thesis, JLU Giessen]

Challenge ?

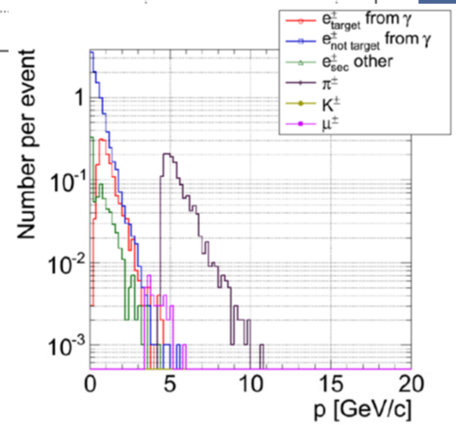
- Background!!!





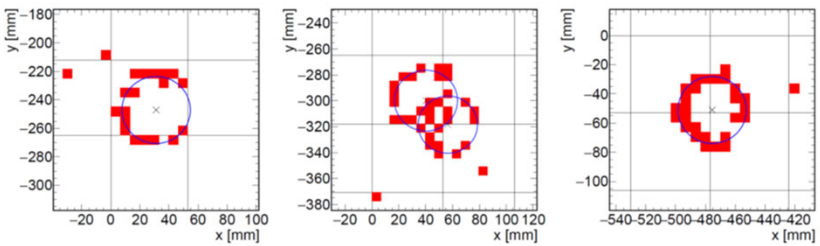
CBM

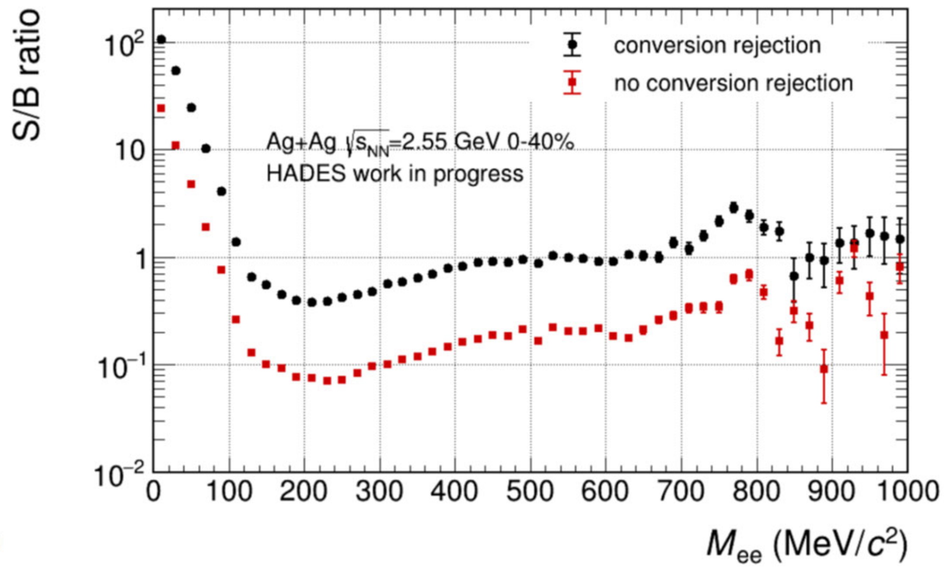
Large conversion probability
more difficult conversion rejection
→ S/B ~ $10^{-1 \ldots -2}$



HADES

Low conversion probability
Conversion rejection
→ S/B ~ 1



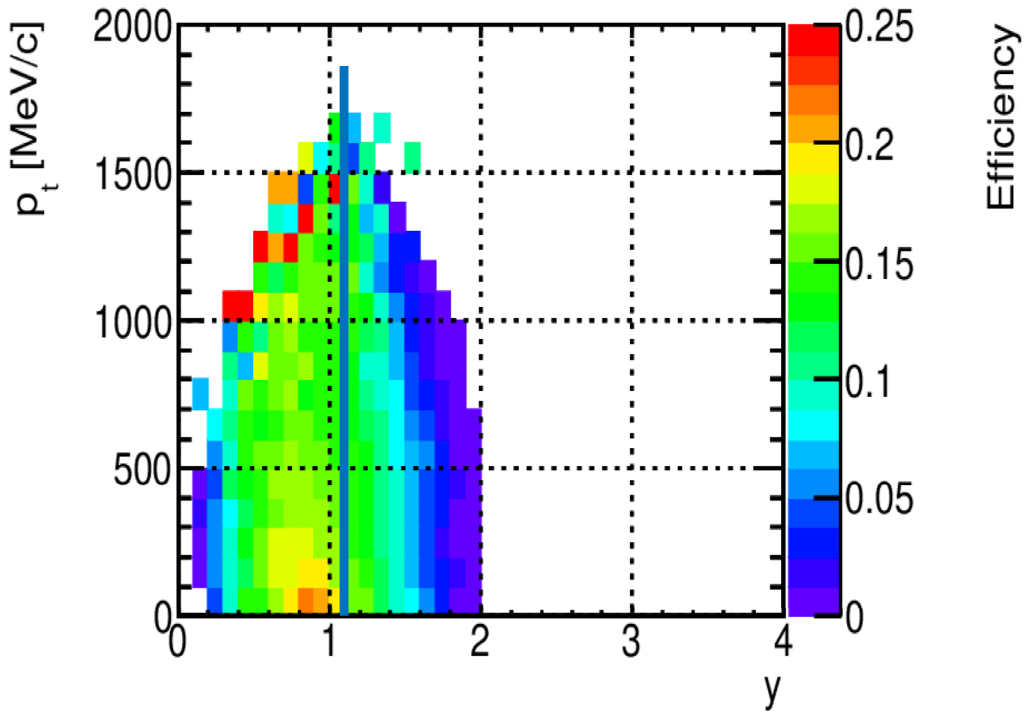


Study dileptons in one common system:
e.g. Ag+Ag collisions at 4.5 GeV beam energy (midrapidity 1.1)

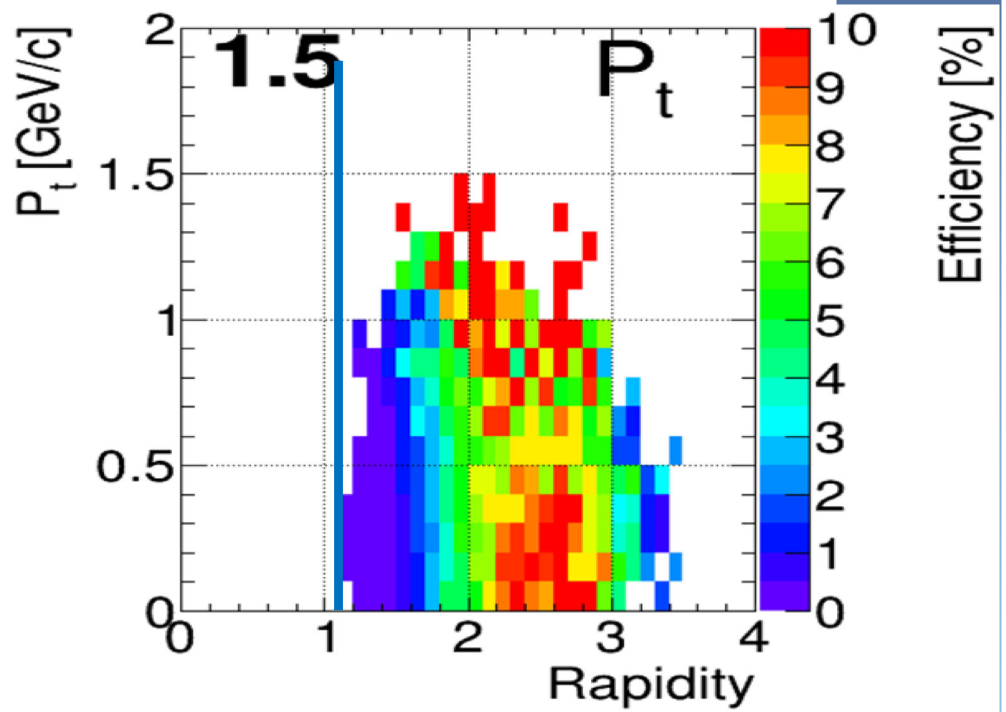
- reconstruction efficiency of ω-meson HADES vs CBM (60% field)

→ Compare spectra in same phase space region!

HADES



CBM

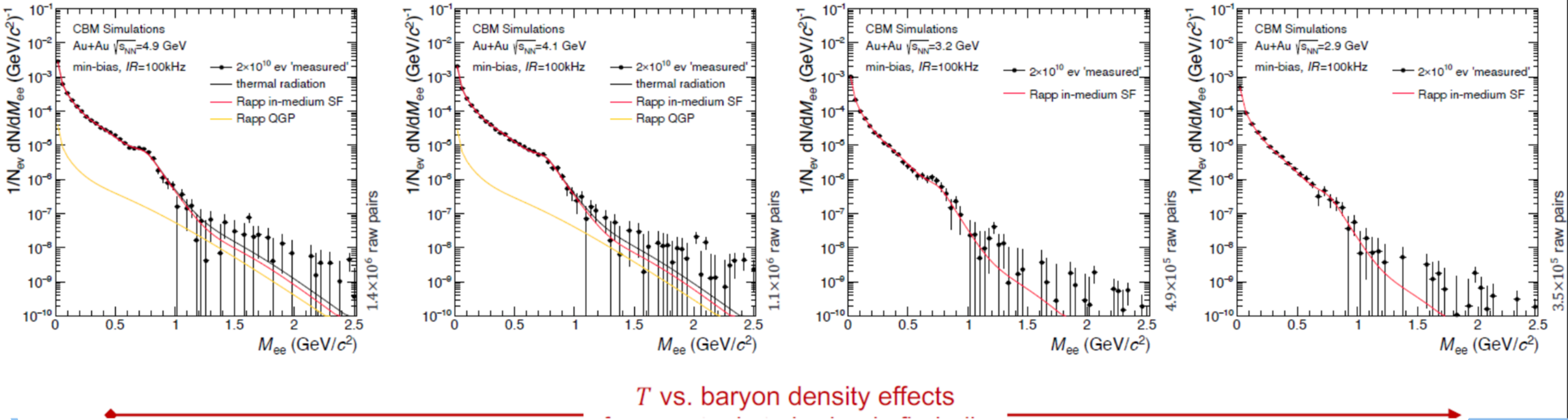


Marten Becker, master thesis, JLU Giessen
Gregor Pitsch, master thesis, JLU Giessen

CBM

Expected **CBM** dielectron performance
(first year, 5 days/ energy, 2×10^{10} events each)

- LMR (M_{ll} < 1 GeV/c^2) well measured, need to determine background with 0.1% precision for 10% signal precision: excess ratio, T_{LMR}
- IMR (M_{ll} > 1 GeV/c^2) acessible, needs dedicated high statistics runs, measure $\mu^+\mu^-$ channel in addition → year „2“



FAIR Review, June 2022, T. Galatyuk for CBM

* one year 5 days beam on target, 6 energies Au+Au, $2 \cdot 10^{10}$ ev. each, 100kHz

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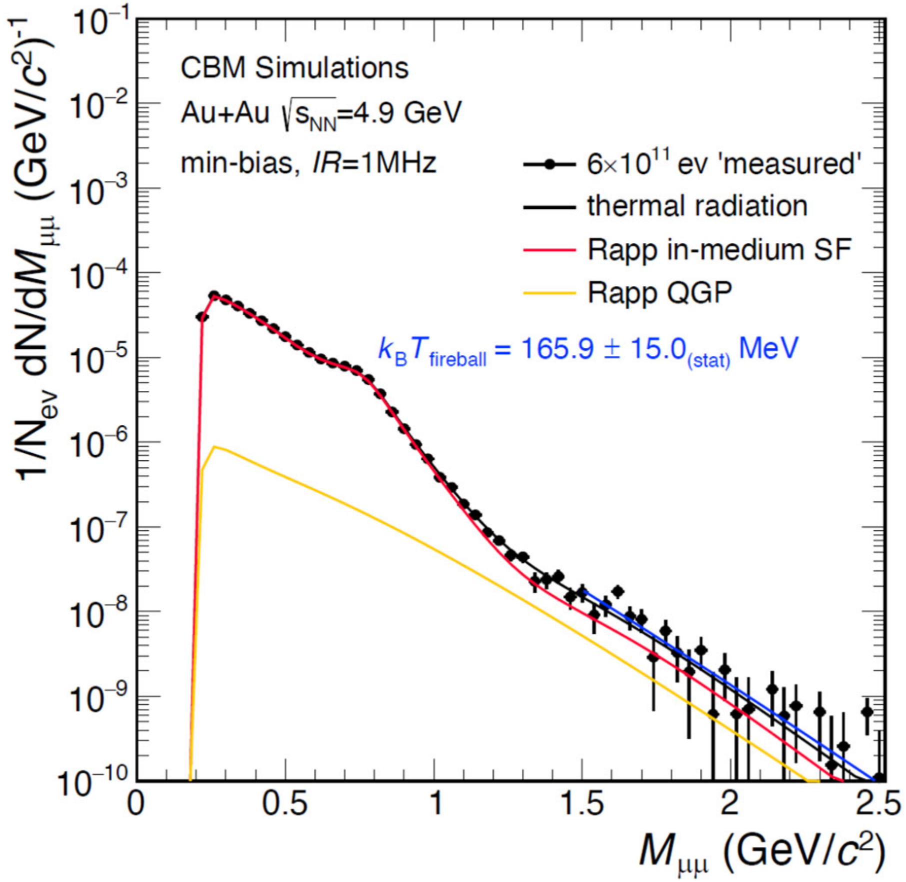
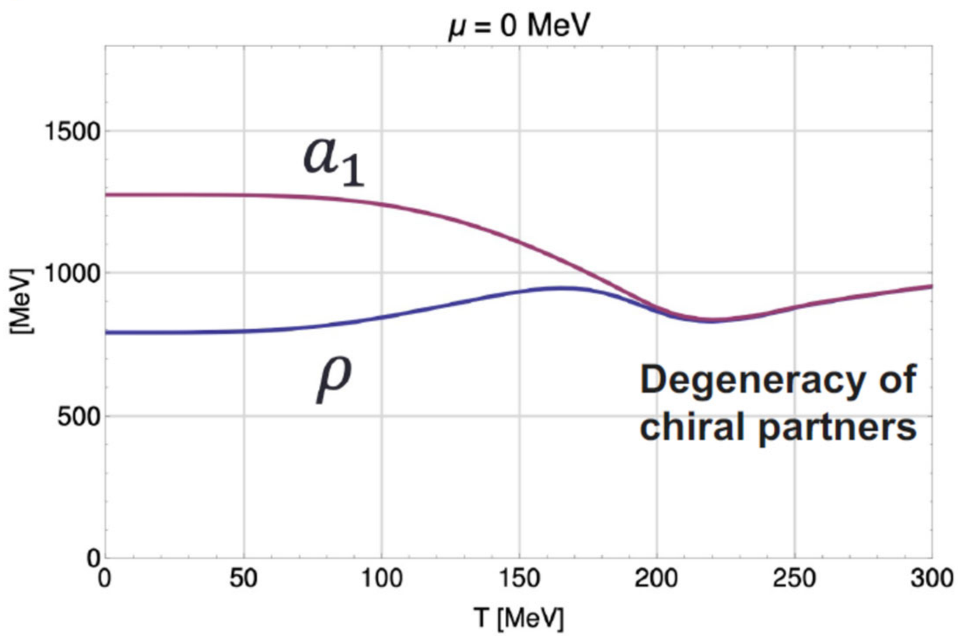


FAIR Review, June 2022, T. Galatyuk for CBM

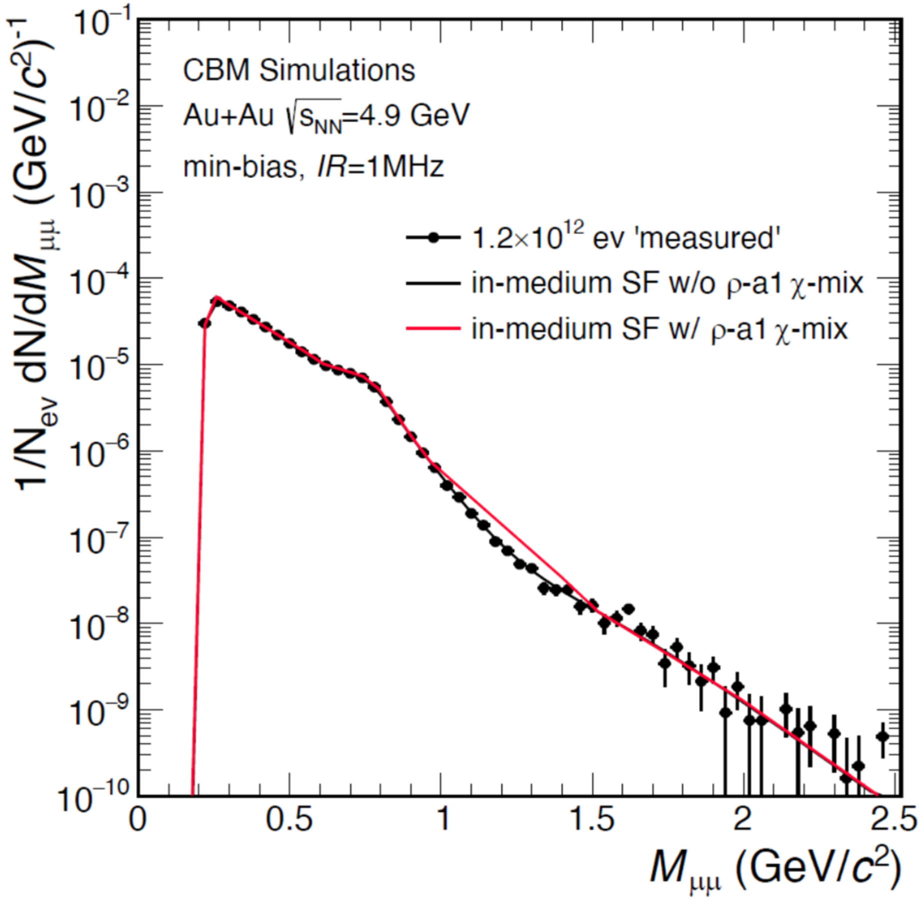
Dileptons

…. more than excess yield and T if you cope with the challenge:

Prediction:
see sign of chiral symmetry restoration in dilepton spectra M > 1 GeV/c^2
→ Mixing of ρ and a_1 due to restoration of chiral symmetry



Jung *et al.*, PRD 95, 036020 (2017)
Hohler and Rapp, PLB 731 (2014)



FAIR Review, June 2022, T. Galatyuk for CBM

Freeze-out conditions

Dileptons offer access to fireball contributions before freeze-out

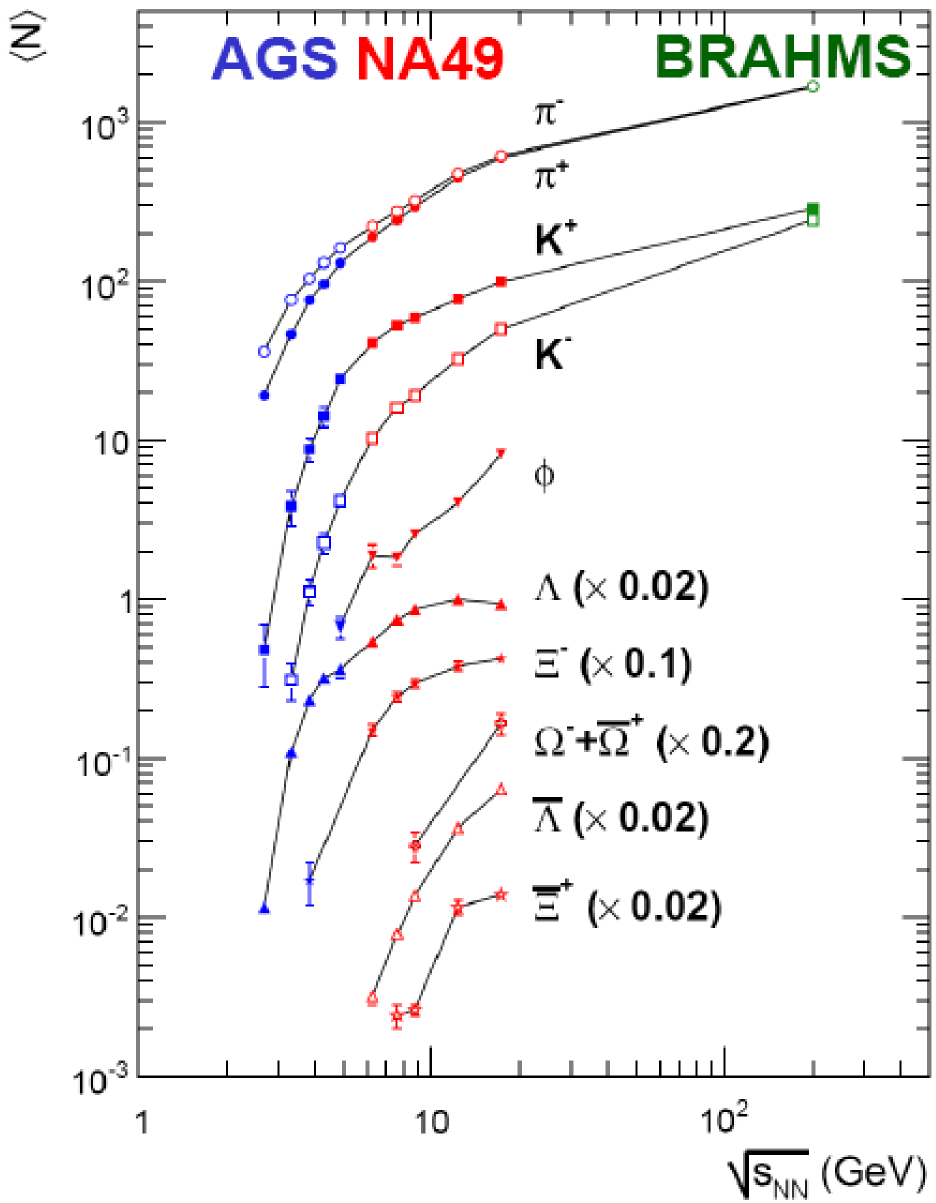
Conditions at freeze-out?
Pressure during evolution?

Measure yields and phase space distributions of „all“ particles
→ Extract T, μ_B with thermal model
→ System in equilibrium?
→ ….. including multi-s?

Measure correlations
→ size at freeze out!
→ Signs of longer lifetime due to PT?

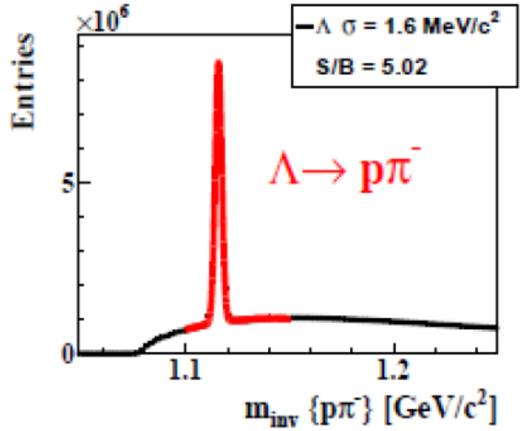
Measure flow
→ EOS

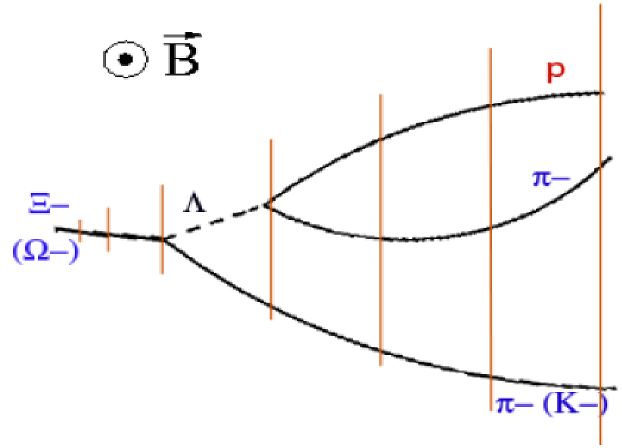
[C. Blume, JP 31 (2005) S57]



Weak decays in CBM

- Tracking system allows for precise reconstruction
- (also measure flow, correlations, Λ polarization, …)

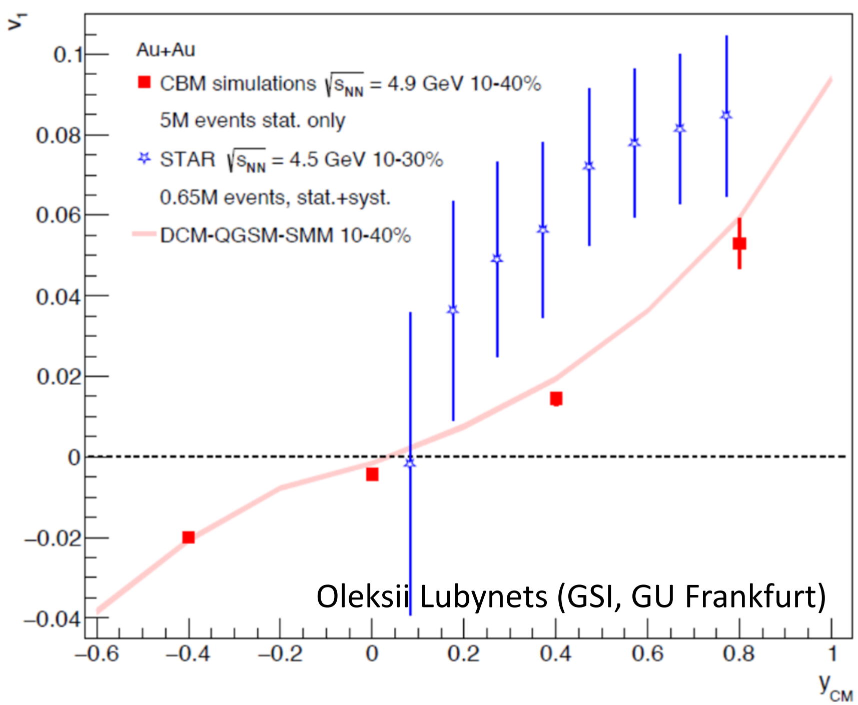




Particle (mass MeV/c²)	Multiplicity at 6AGeV	Multiplicity at 10 AGeV	decay channel	BR	Efficiency
$\bar{\Lambda}(1115)$	$4.6 \cdot 10^{-4}$	0.034	$\bar{p}\pi^+$	0.64	0.11
$\Xi^-(1321)$	0.054	0.222	$\Lambda\pi^-$	1	0.06
$\Xi^-(1321)$	$3.0 \cdot 10^{-5}$	$5.4 \cdot 10^{-4}$	$\Lambda\pi^+$	1	0.03
$\Omega^-(1672)$	$5.8 \cdot 10^{-4}$	$5.6 \cdot 10^{-3}$	ΛK^-	0.68	0.05
$\Omega^+(1672)$	-	$7.0 \cdot 10^{-5}$	ΛK^+	0.68	0.03

event wise reconstruction by KFParticle package

CBM simulation, Λ-baryons



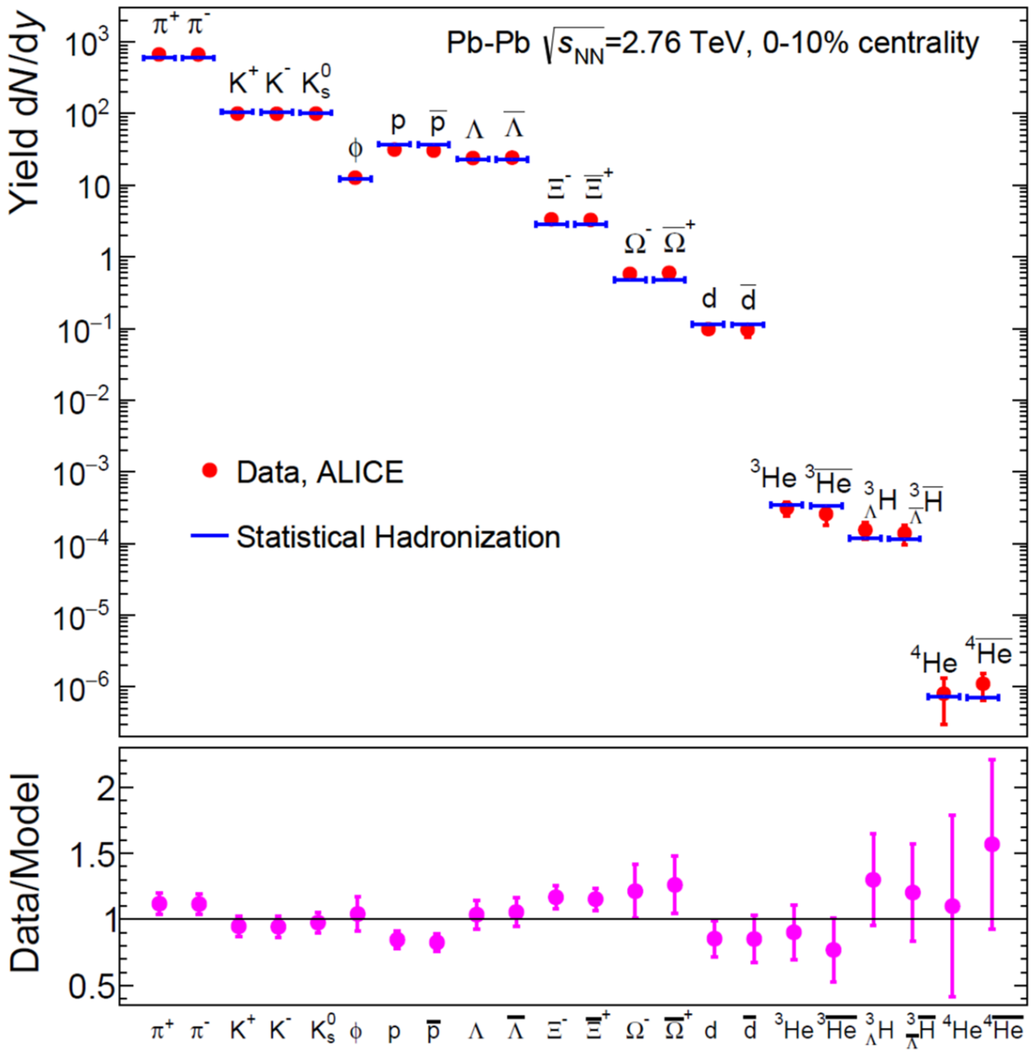
Thermal model – low μ_B

„Any“ model at „any“ low μ_B collision system results in very good description of particle yields in a thermal model

Lower energies/ high μ_B: production cross-sections for strangeness decrease rapidly (below unity)

Implement strangeness conservation!
Strong effect on multi-s hadrons!

„Equilibrium“?



A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Nature 561, no. 7723, 321 (2018)

Thermal model

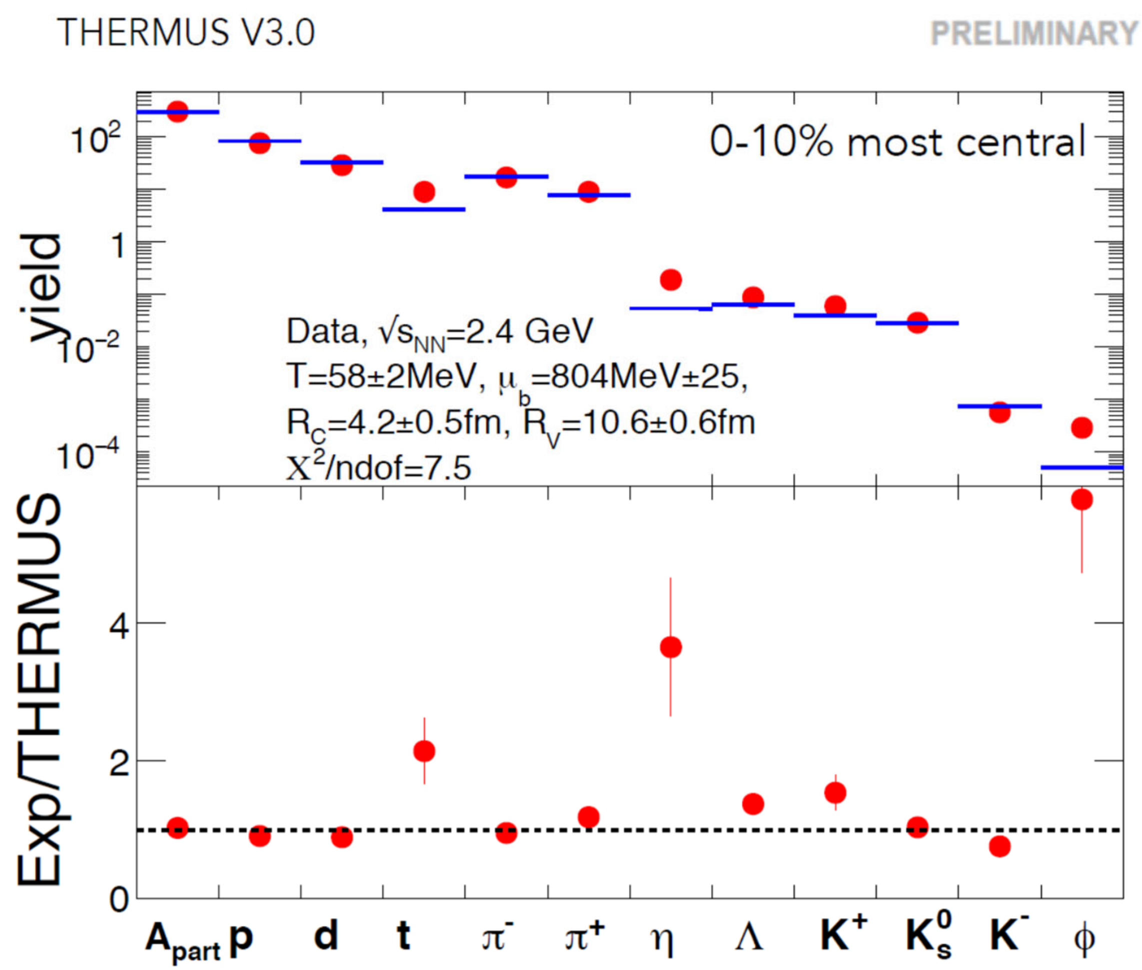
HADES, Au+Au collisions @ $\sqrt{s_{NN}}$=2.4 GeV

- Tensions in description of all hadron yields with thermal model
- All strangeness production below free NN production threshold!

Is there an energy from where on all hadrons can be described as „in thermal equilibrium"?

Or gradual approach?

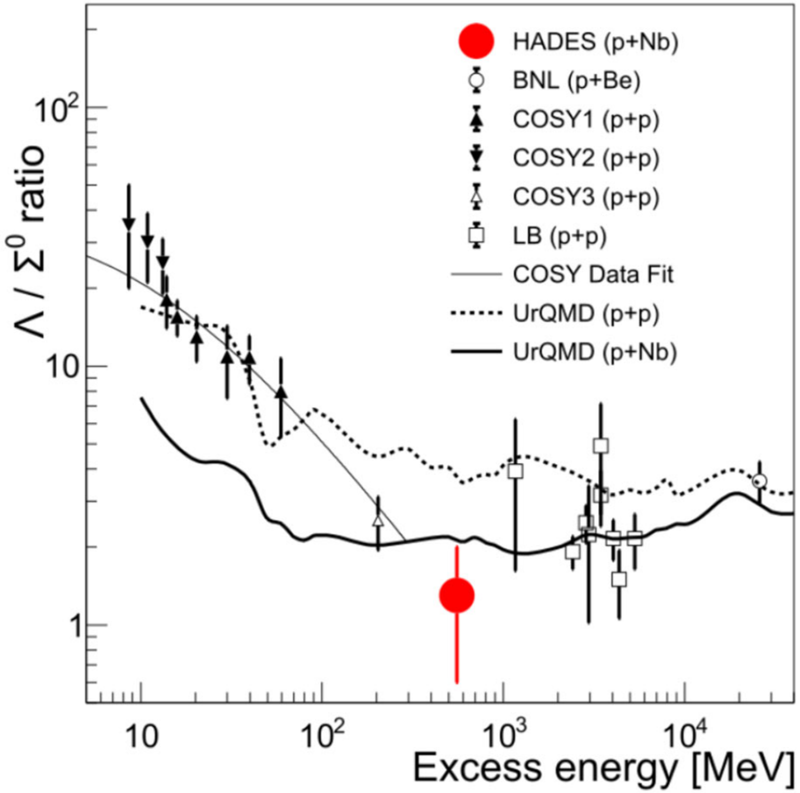
Hadronization at high μ_B?



M. Lorenz, SQM 2019

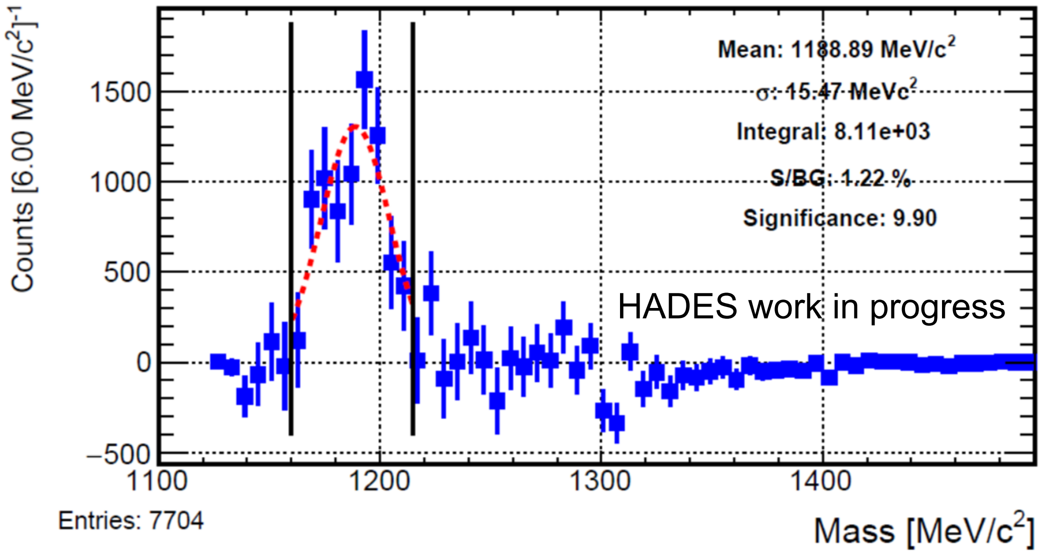
HADES

- Measurement of $\Sigma^0 \rightarrow \Lambda\gamma$ decay in Ag+Ag collisionen at $\sqrt{s_{NN}}$ = 2.55 GeV (corresponds to Λ threshold)
- Result of analysis: $(\Lambda+\Sigma^0)/\Sigma^0 = 4.2 \pm 0.9$
- In agreement with expectation from isospin considerations (4)
- No influence of NN threshold



HADES, Phy. Lett. B 781 (2018) 735-740

Marten Becker, DPG 2023



Σ prospects with CBM

- Identification of Σ^+ and Σ^- via their decay topology

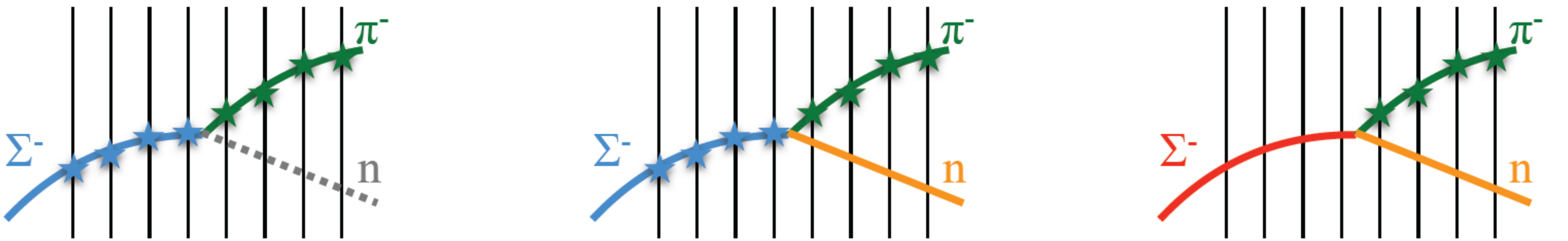
$$\Sigma^+ \rightarrow p\pi^0 \qquad \bar{\Sigma}^+ \rightarrow \bar{p}\pi^0 \qquad BR = 51.6\%$$
$$\Sigma^+ \rightarrow n\pi^+ \qquad \bar{\Sigma}^+ \rightarrow \bar{n}\pi^- \qquad BR = 48.3\%$$
$$\Sigma^- \rightarrow n\pi^- \qquad \bar{\Sigma}^- \rightarrow \bar{n}\pi^- \qquad BR = 99.8\%$$

- Method:
  - Find all primary and secondary tracks, use TOF PID for sec. track
  - Search whether two would fit together with a kink
  - From momentum conservation get momentum of neutral particle
  - Assume e.g. Σ^- decay, calculate (missing) mass of neutral particle
  - Select neutron candidates, recalculate Σ mass

Find tracks of Σ and its charged daughter in STS and MVD

Reconstruct a neutral daughter from the mother and the charged daughter

Reconstruct Σ mass spectrum from the charged and obtained neutral daughters

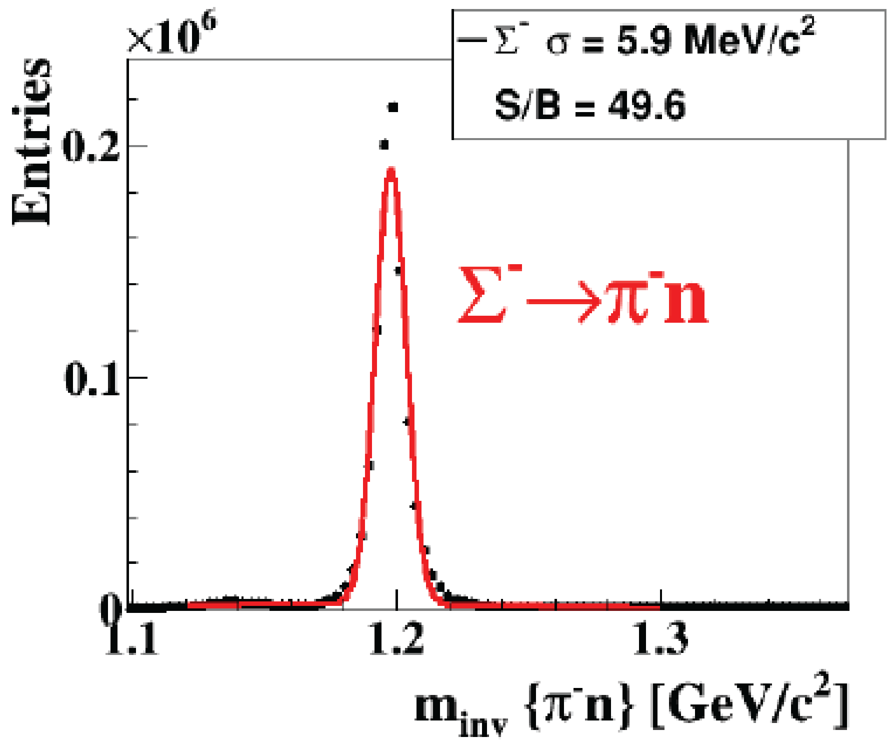


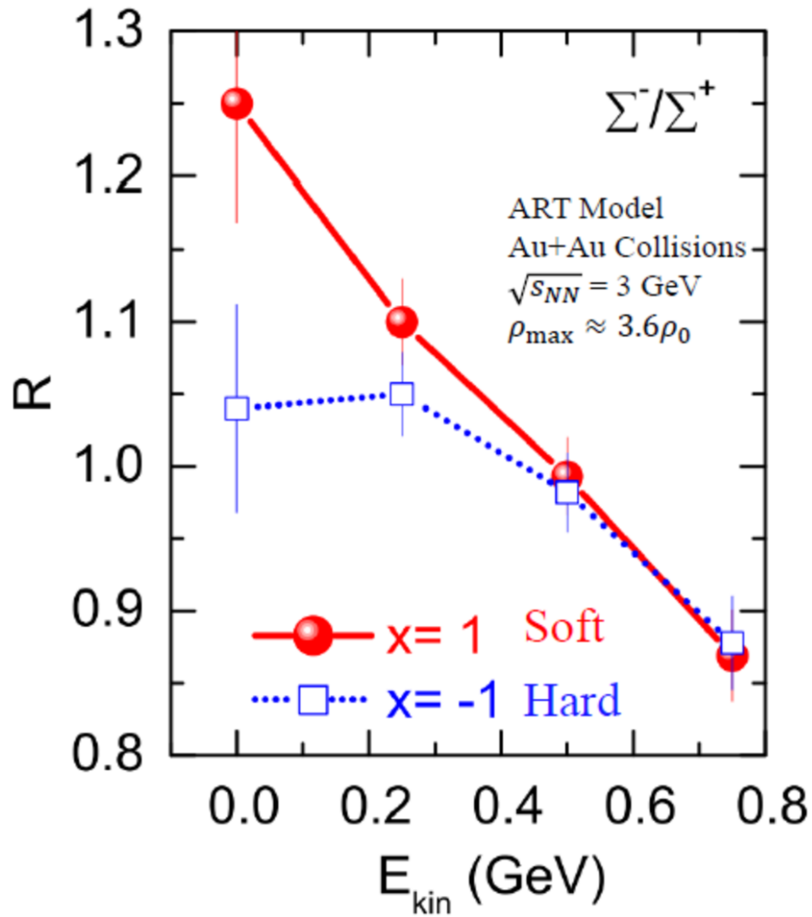
Σ prospects with CBM

- Simulations: UrQMD, 5M central collisions Au+Au, 10 AGeV beam energy

→ (p/n) like ratios! → access to isospin dependence?

→ Σ^-/Σ^+ ratio is expected to carry $E_{sym}(\rho)$ information (stiff/soft)

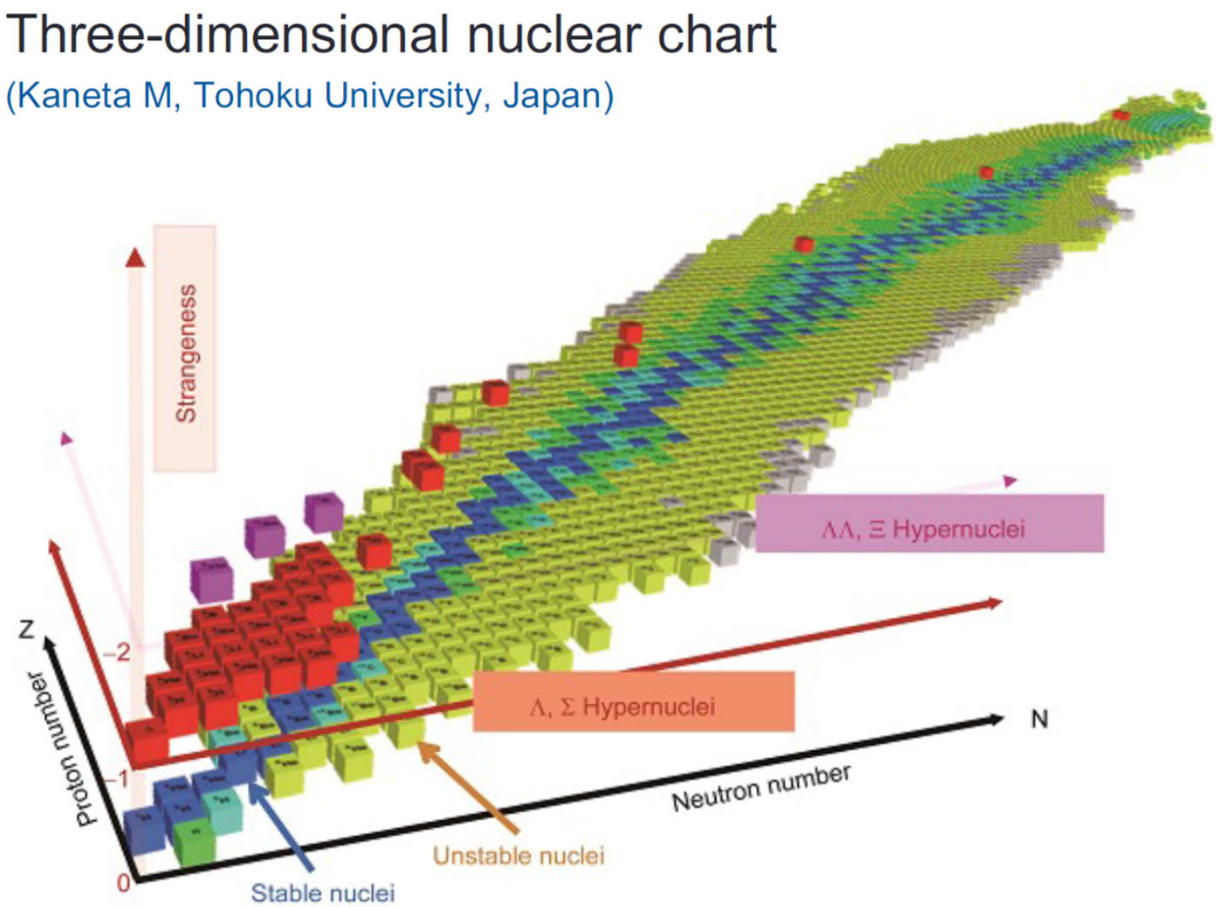




G.C. Yong et al,
Phys.Rev.C 106 (2022) 2, 024902

Hypernuclei

- Hypernuclei interesting/ important objects for neutron star descriptions
- Formation? YN and YY interactions? Influence on EOS for high densities?
- CBM energies optimum for production
- Reconstruction routines tested with STAR FXT data



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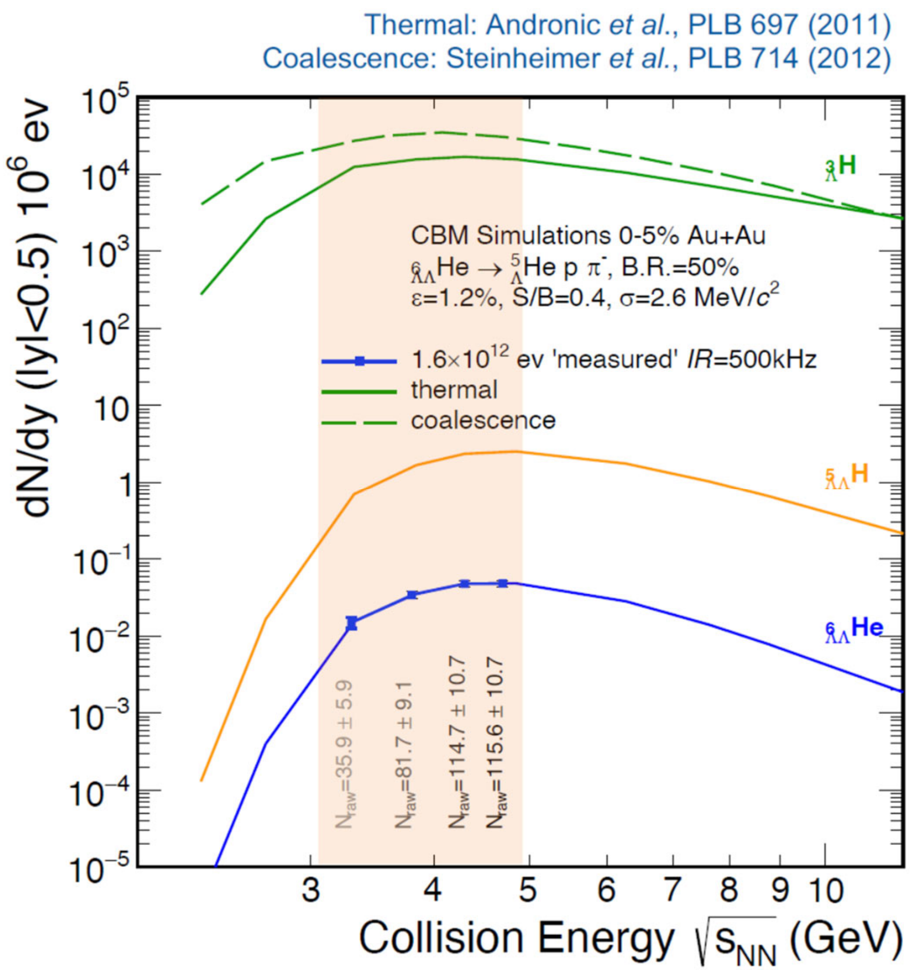
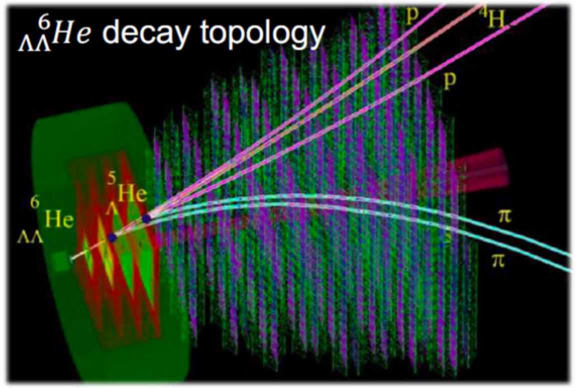
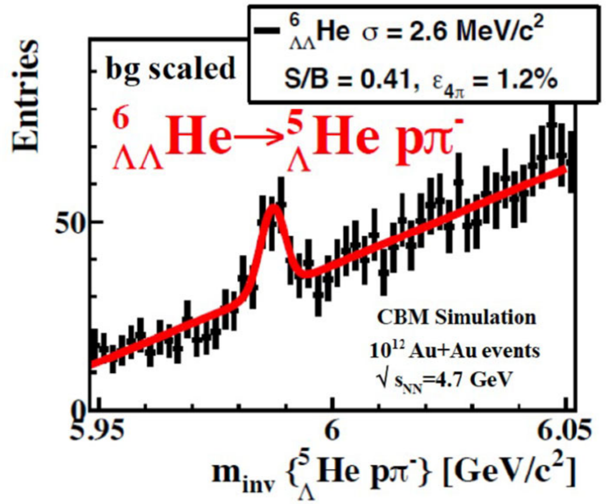
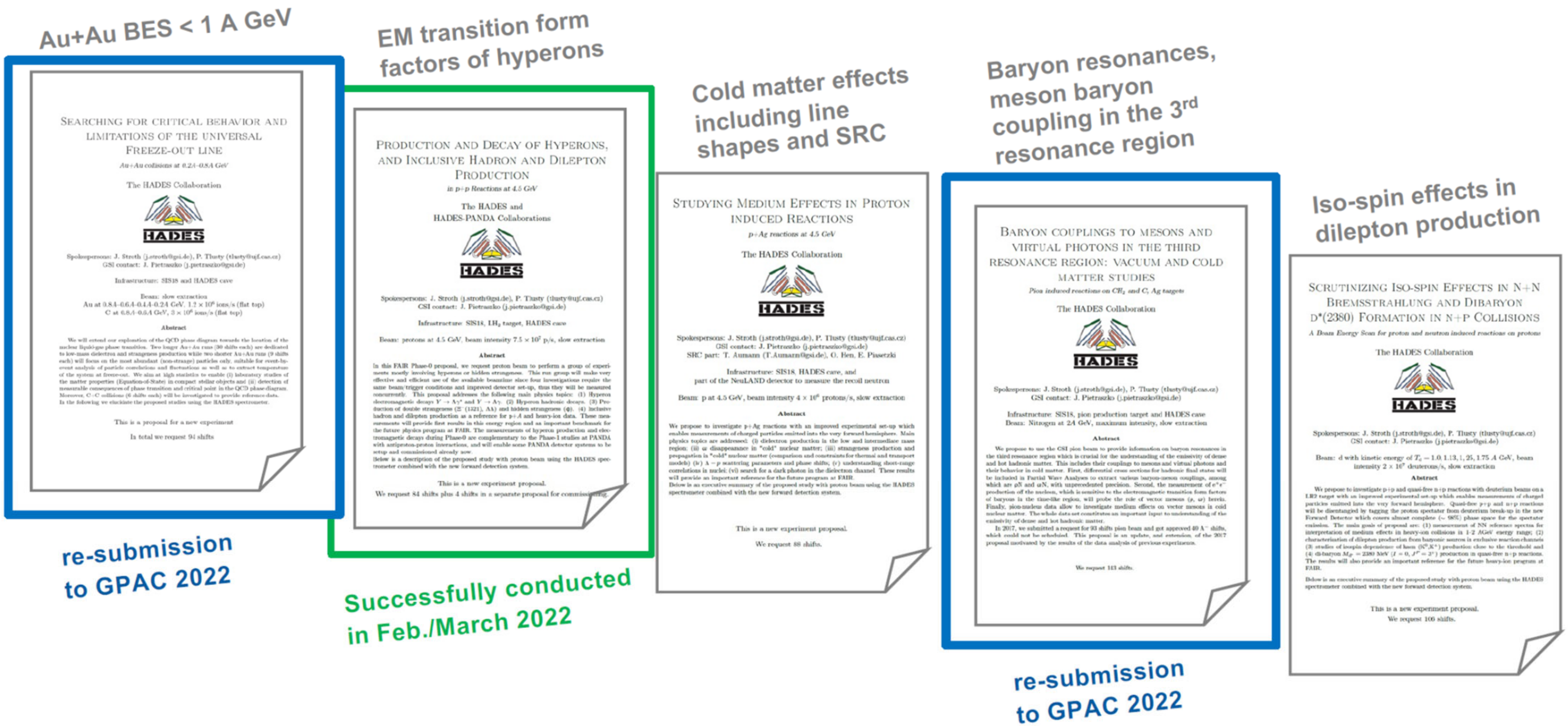






HADES

HADES prepared a list of proposals for FAIR phase-0
- Proposed program will take at least until 2026 (one 4-weeks run per year), but likely longer
- Transferring HADES to the new cave is expected to take two years



Status of FAIR & CBM

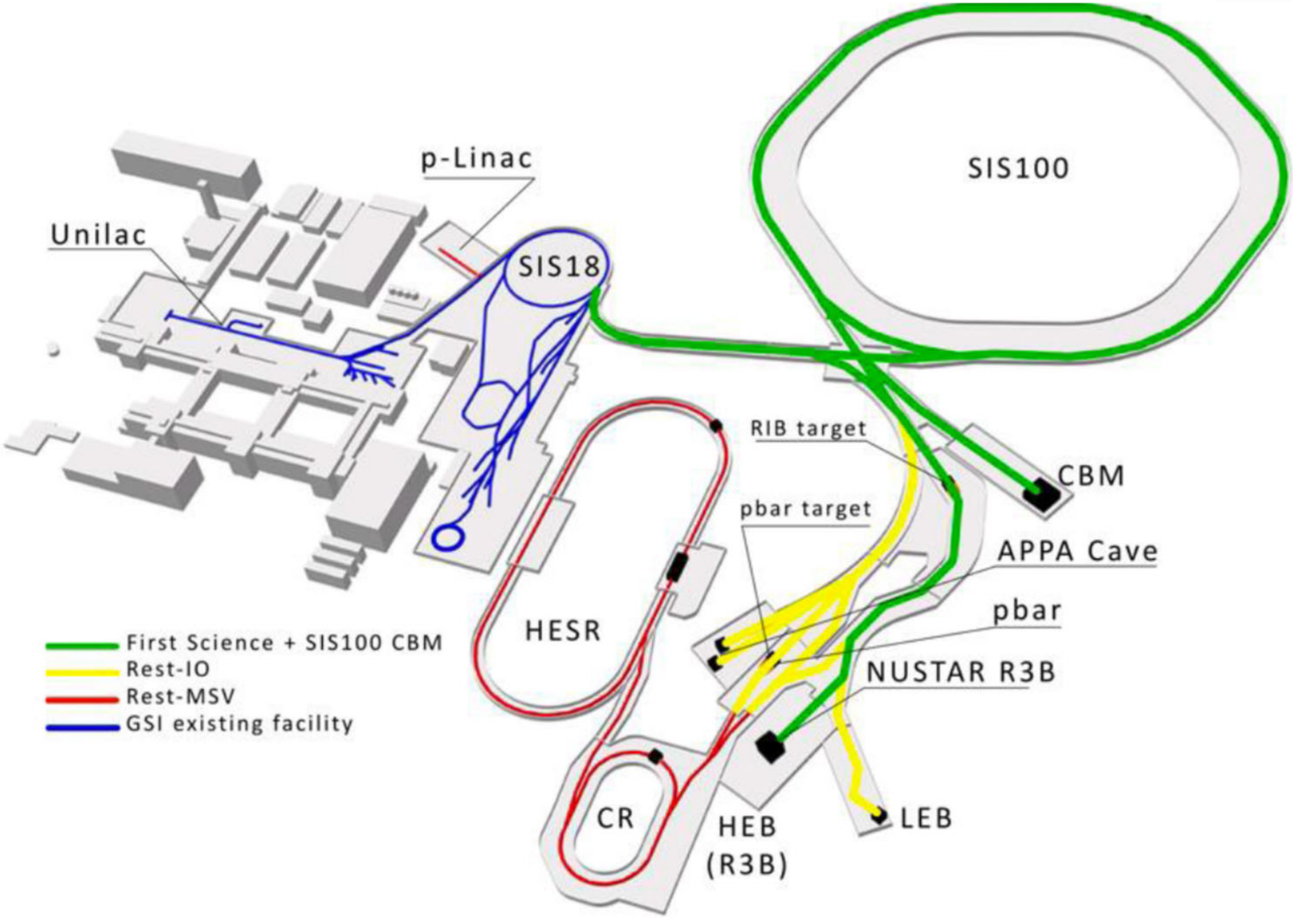
FAIR (still) under construction ….
CBM (still) plans for first beams in 2028/2029

After 3 years of running:

- (First) energy scan completed, improved statistical errors of factor 10 with respect to STAR

Years 4-8:

- High statistics measurements →dilepton IMR, ultra-rare probes



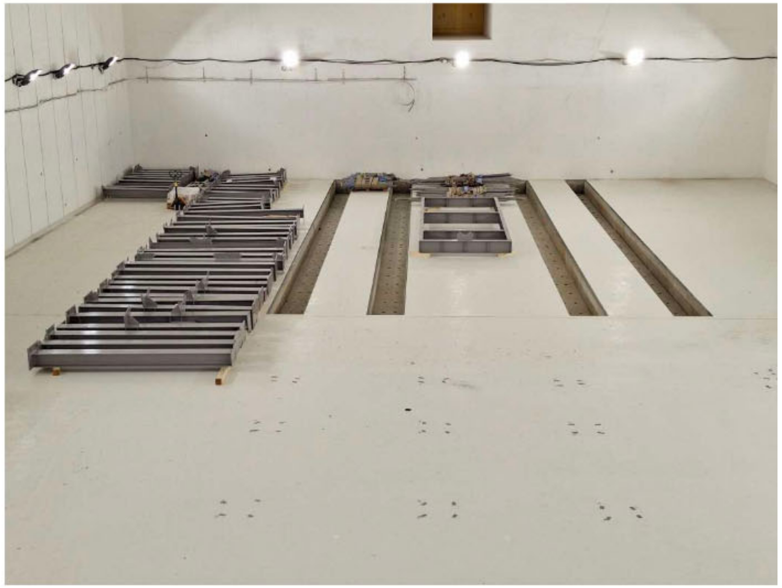
Status of FAIR & CBM

- FAIR construction progressing
  - ✓ SIS 100 tunnel ready
  - ✓ CBM cave ready
  - ✓ In CBM cave first user installations of FAIR ongoing (upstream platform

Status of FAIR & CBM

CBM cave

Start of installation of upstream platform!



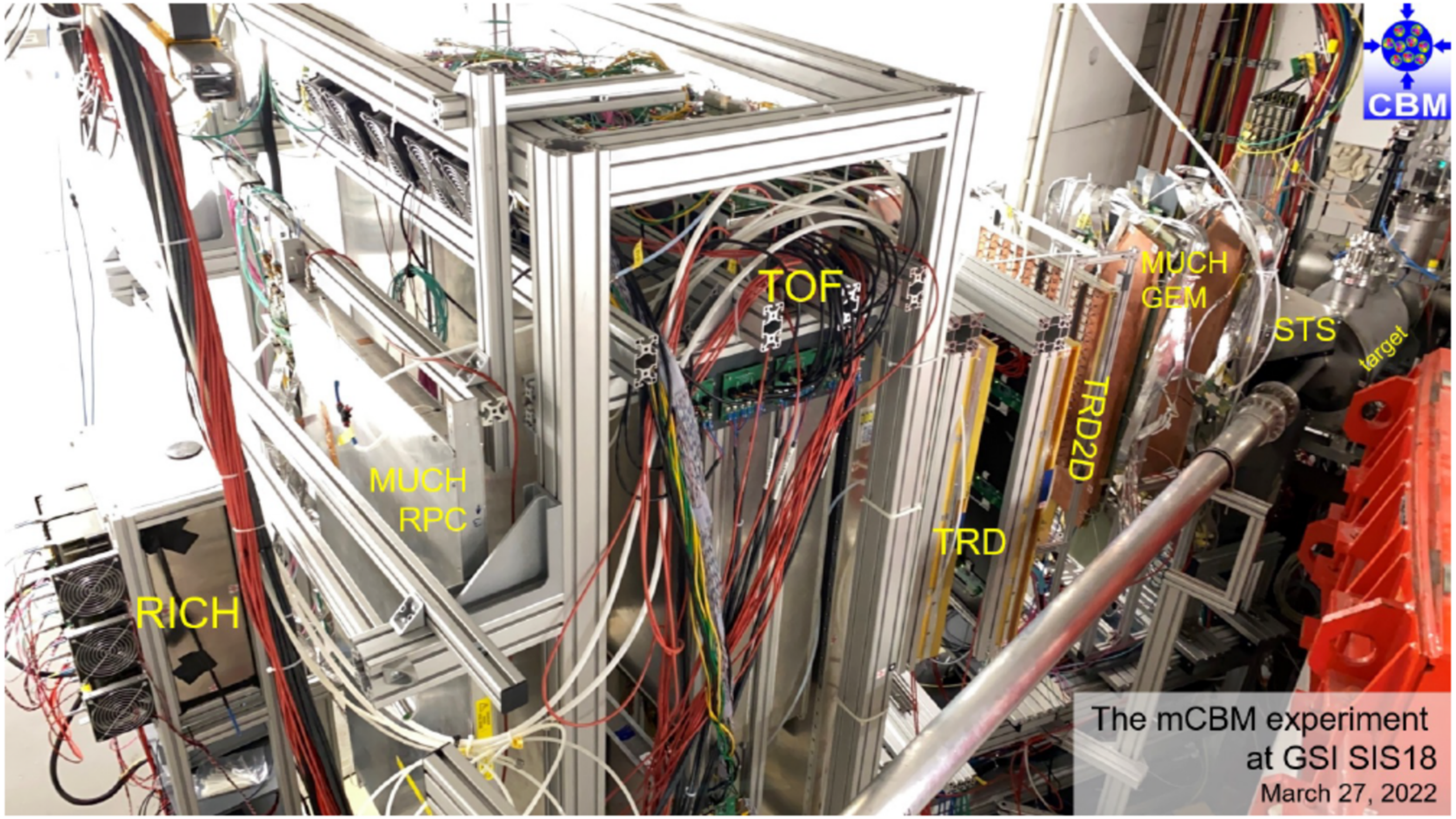
mCBM @ SIS18 (FAIR phase 0)

One of the CBM challenges are the high rates:

- Free streaming readout
- Online reconstruction & trigger

Important milestone: mCBM @ SIS 18!

- Full system test, verification of triggerless-free-streaming readout, data transport to CBM, online reconstruction
- High rate detector tests up to 10 MHz collision rates

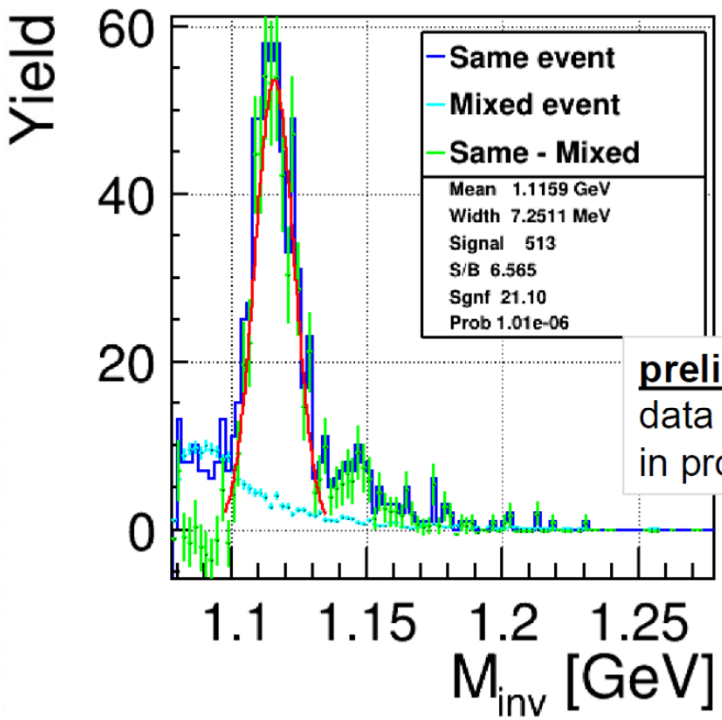


mCBM @ SIS18 (FAIR phase 0)

Benchmark run: Ni+Ni collisions at 1.93 AGeV

Full timeslices buffered (build node 0)

Λ reconstruction
400-500kHz average collision rate
Offline analysis
Next step: online reconstruction



preliminary
data analysis
in progress

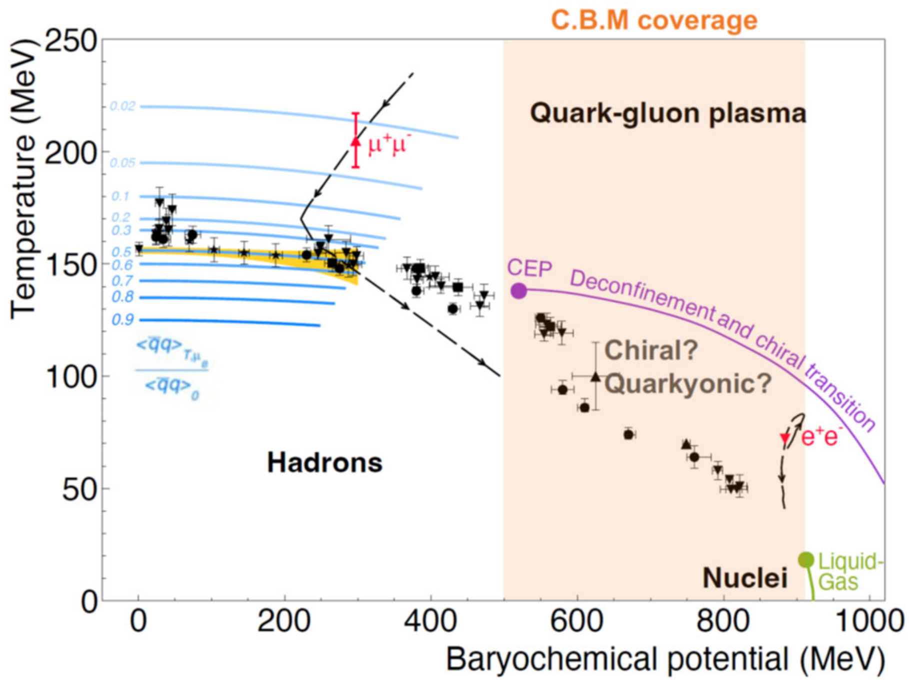
Summary & Outlook

Future is bright!

- Lots of interesting results from HADES – more to come
- Work for timely construction of CBM

→ Experimental data to contribute to open QCD questions:

- Phase structure of QCD at finite density
- Formation of hadrons, hadron spectra
- Formation of nuclei



HADES; Nature Physics 15 (2019) 10, 1040-1045

That‘s us ....


XLIV HADES collaboration meeting, Mar. 2023 GSI Darmstadt


41st CBM collaboration meeting, Mar. 2023, TUD, Darmstadt