

Overview on the QCD phase diagram at large chemical potential and the CBM experiment

A. Andronic - University of Münster

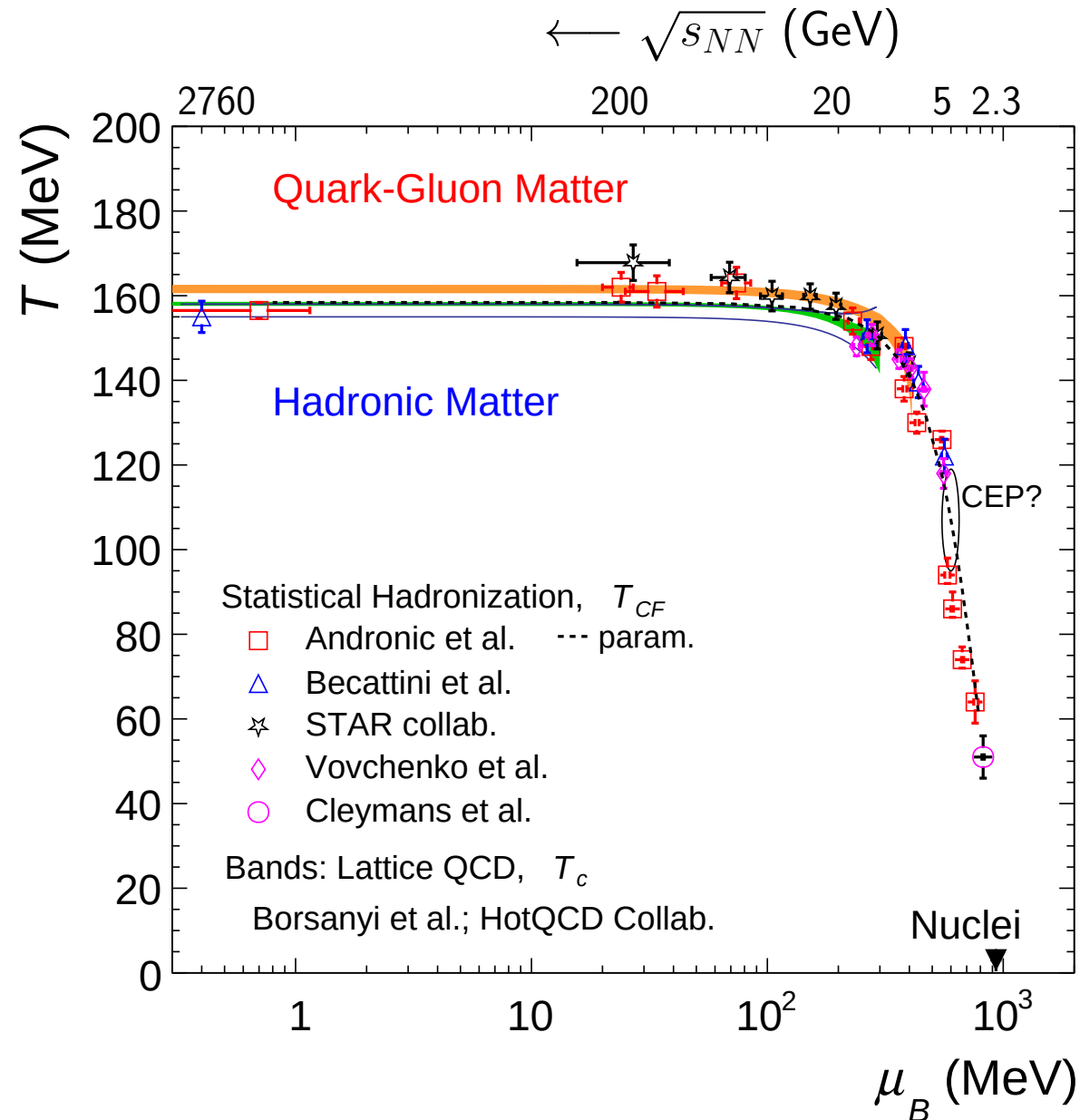


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- Introduction: the phase diagram of QCD
 - The statistical hadronization model and the thermal fits
 - CBM: Detector; Physics goals, performance; Current status
 - Summary / Outlook

The QCD phase diagram

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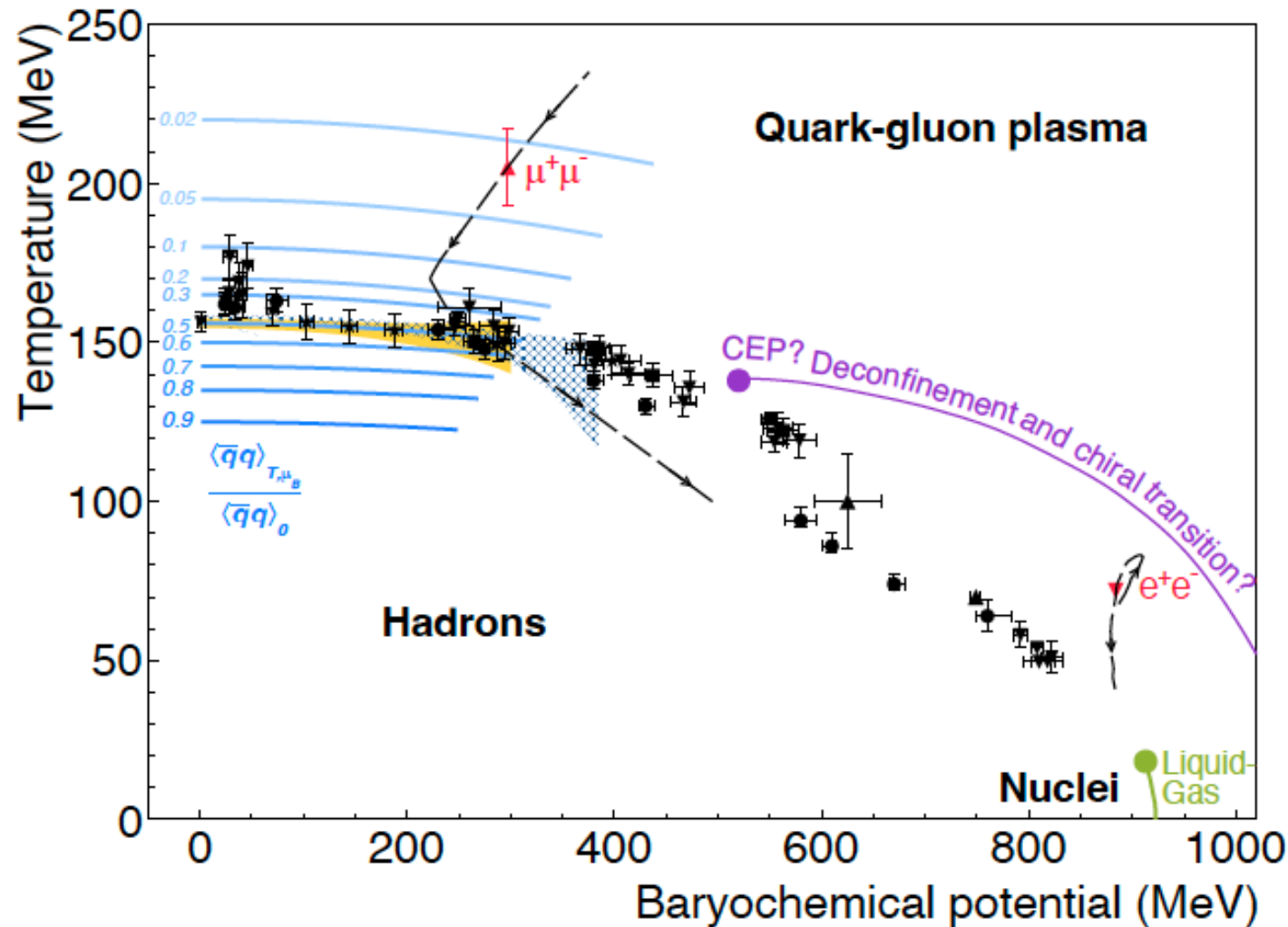
SHM: Andronic, Braun-Munzinger, Redlich, Stachel, [Nature 561 \(2018\) 321](#) (and refs.)

LQCD: Bazavov et al., [PLB 795 \(2019\) 15](#); Borsanyi et al., [PRL 125 \(2020\) 052001](#), [2410.06216](#)

The QCD phase diagram - linear μ_B

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HADES, [Nature Phys. 15 \(2019\) 1040](#)

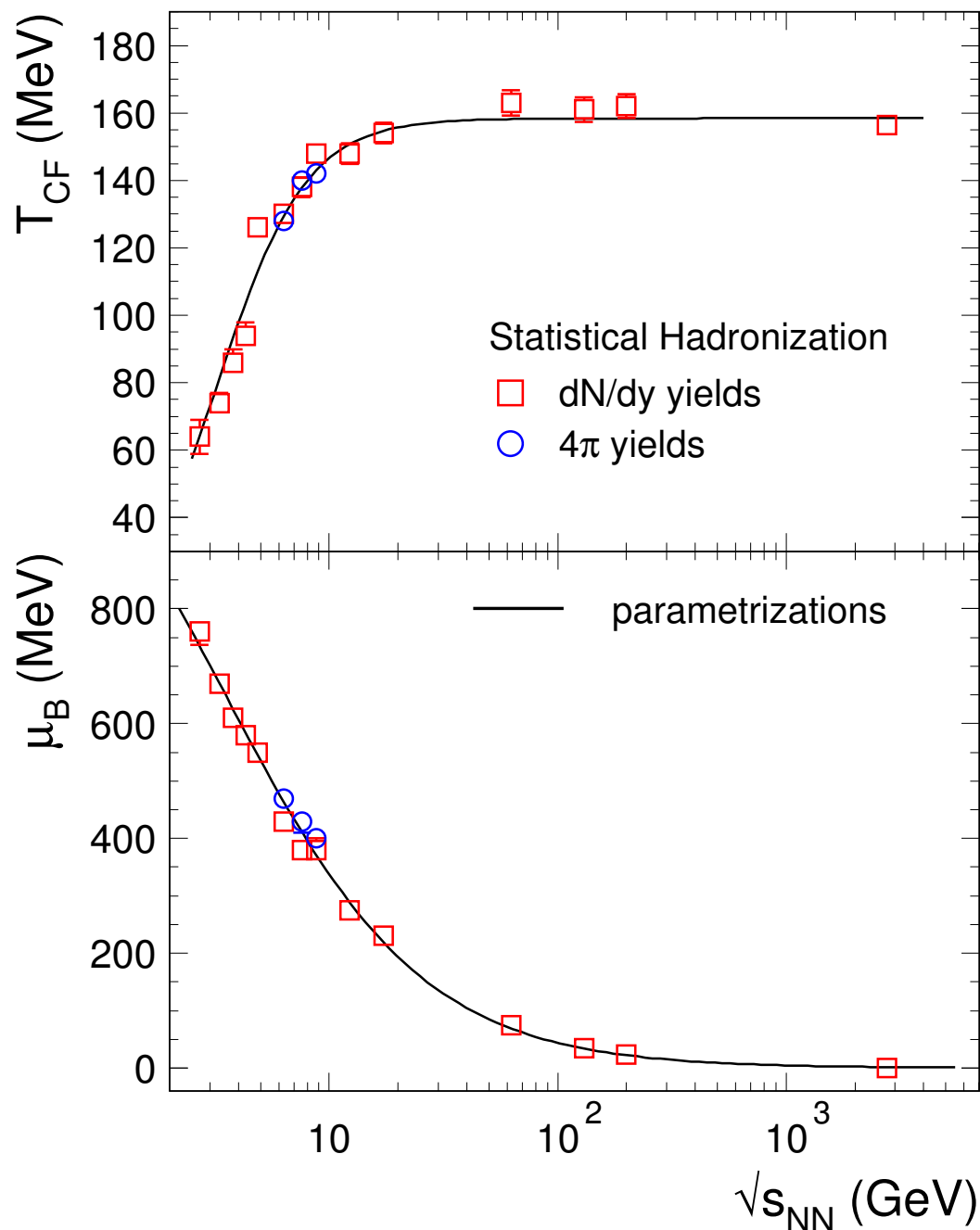
Remarkable “coincidence” of SHM results with Lattice QCD crossover for $\mu_B \lesssim 400$ MeV

Large μ_B : Biswas, Petreczky, Sharma, [PRC 109 \(2024\) 055206](#); Blaschke et al., [PLB 860 \(2025\) 139206](#)

Energy dependence of T , μ_B (central collisions)

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remarkably, thermal fits exhibit a limiting temperature:

$$T_{lim} = 158.4 \pm 1.4 \text{ MeV}$$

$$T_{CF} = T_{lim} \frac{1}{1 + \exp(2.60 - \ln(\sqrt{s_{NN}}(\text{GeV}))/0.45)}$$

$$\mu_B[\text{MeV}] = \frac{1307.5}{1 + 0.288\sqrt{s_{NN}}(\text{GeV})}$$

NPA 772 (2006) 167, PLB 673 (2009) 142

μ_B is a measure of the net-baryon density, or matter-antimatter asymmetry

determined by the "stopping" of the colliding nuclei

grand canonical partition function for specie (hadron) i :

$$\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 dp \ln[1 \pm \exp(-(E_i - \mu_i)/T)]$$

$g_i = (2J_i + 1)$ spin degeneracy factor; T temperature;

$E_i = \sqrt{p^2 + m_i^2}$ total energy; (+) for fermions (−) for bosons

$\mu_i = \mu_B B_i + \mu_{I_3} I_{3i} + \mu_S S_i + \mu_C C_i$ chemical potentials

μ ensure conservation (on average) of quantum numbers, fixed by “initial conditions”

i) isospin: $\sum_i n_i I_{3i} / \sum_i n_i B_i = I_3^{tot} / N_B^{tot}$, $N_B^{tot} \sim \mu_B$

I_3^{tot} , N_B^{tot} isospin and baryon number of the system ($\simeq 0$ at high energies)

ii) strangeness: $\sum_i n_i S_i = 0$

iii) charm: $\sum_i n_i C_i = 0$.

also known as: thermal / hadron resonance gas model

...is in a way the simplest model

the analysis of hadron yields within the thermal model provides a “snapshot” of a nucleus-nucleus collision at *chemical freeze-out*

(the earliest in the collision timeline we can look with hadronic observables)
test hypothesis of hadron abundancies in equilibrium (chemical)

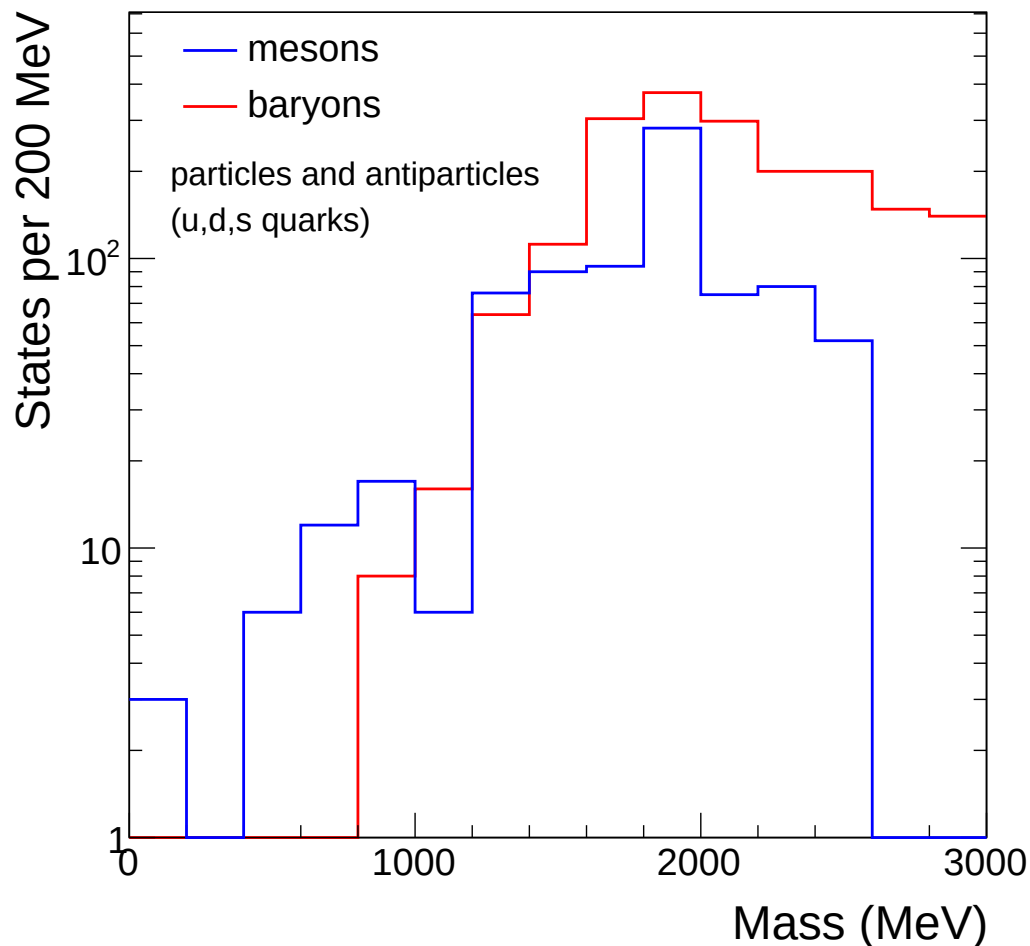
...but the devil is in the details (sources of syst. uncert.) ...one needs :

- a complete hadron spectrum (all species of hadrons, see [PDG](#), extra states?)
- canonical approach at low energies (and smaller systems)
- treatment of interactions
- to understand the data well (Ex.: control fractions from weak decays)

Model input: hadron spectrum

...embodies low-energy QCD ...*vacuum masses*

well-known for $m < 2$ GeV; many confirmed states above 2 GeV, still incomplete



for high m , BR not well known, but can be reasonably guessed

T found to be robust in fits with spectrum truncated above 1.8 GeV

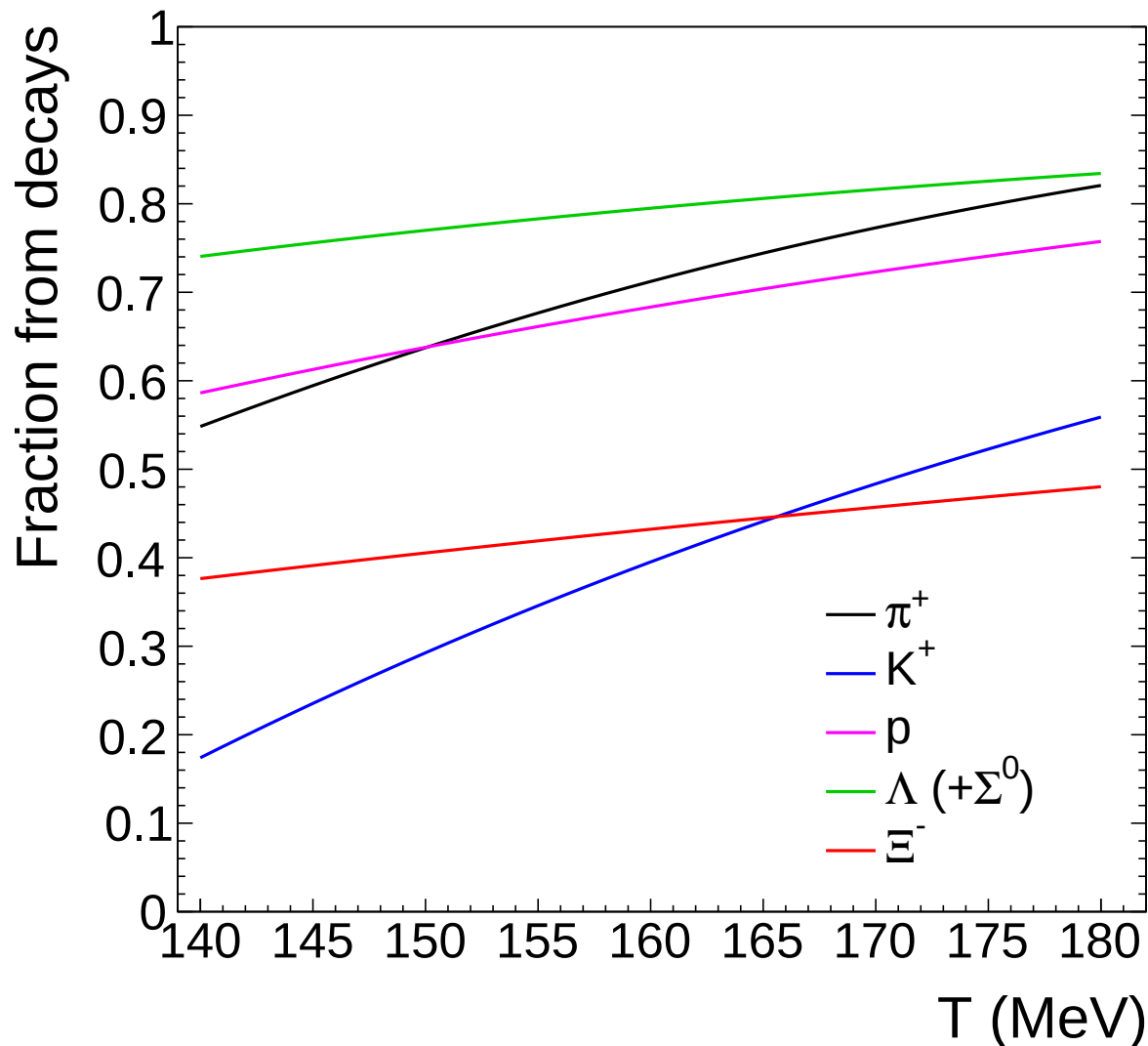
$$\rho(m) = c \cdot m^{-a} \exp(m/T_H)$$

$$T_H \simeq 180 \text{ MeV (max } T \text{ for hadrons)}$$

$(2J + 1)$ counted in

Decays (feed-down)

(almost all) hadrons are subject to strong and electromagnetic decays



$$\Delta \rightarrow p(n) + \pi, \rho \rightarrow \pi + \pi$$

$$\Sigma^0 \rightarrow \Lambda + \gamma$$

weak decays can be treated as well ...to account for the exact experimental situation

contribution of resonances is significant (and particle-dependent)

(plot for $\mu_B=0$)

$$n_i = N_i/V = -\frac{T}{V} \frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp[(E_i - \mu_i)/T] \pm 1}$$

$$n_i = \frac{g_i}{2\pi^2} \frac{1}{N_{BW}} \int_{M_{thr}}^\infty dm \int_0^\infty \frac{\Gamma_i^2}{(m - m_i)^2 + \Gamma_i^2/4} \cdot \frac{p^2 dp}{\exp[(E_i^m - \mu_i)/T] \pm 1}$$

M_{thr} threshold mass for the decay channel.

Example: for $\Delta^{++} \rightarrow p + \pi^+$, $M_{thr}=1.068$ GeV ($m_{\Delta^{++}}=1.232$ GeV)

Important mainly at “low” temperatures ($T \lesssim 150$ MeV)

Canonical treatment (“canonical suppression”)

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needed whenever the abundance of hadrons with a given quantum number is very small ...so that one needs to enforce exact quantum-number conservation in AA collisions: strangeness at low energies; (mid)peripheral collisions full treatment is laborious, see Braun-Munzinger, Redlich, Stachel, [nucl-th/0304013](https://arxiv.org/abs/nuc-th/0304013)

approximation often used:

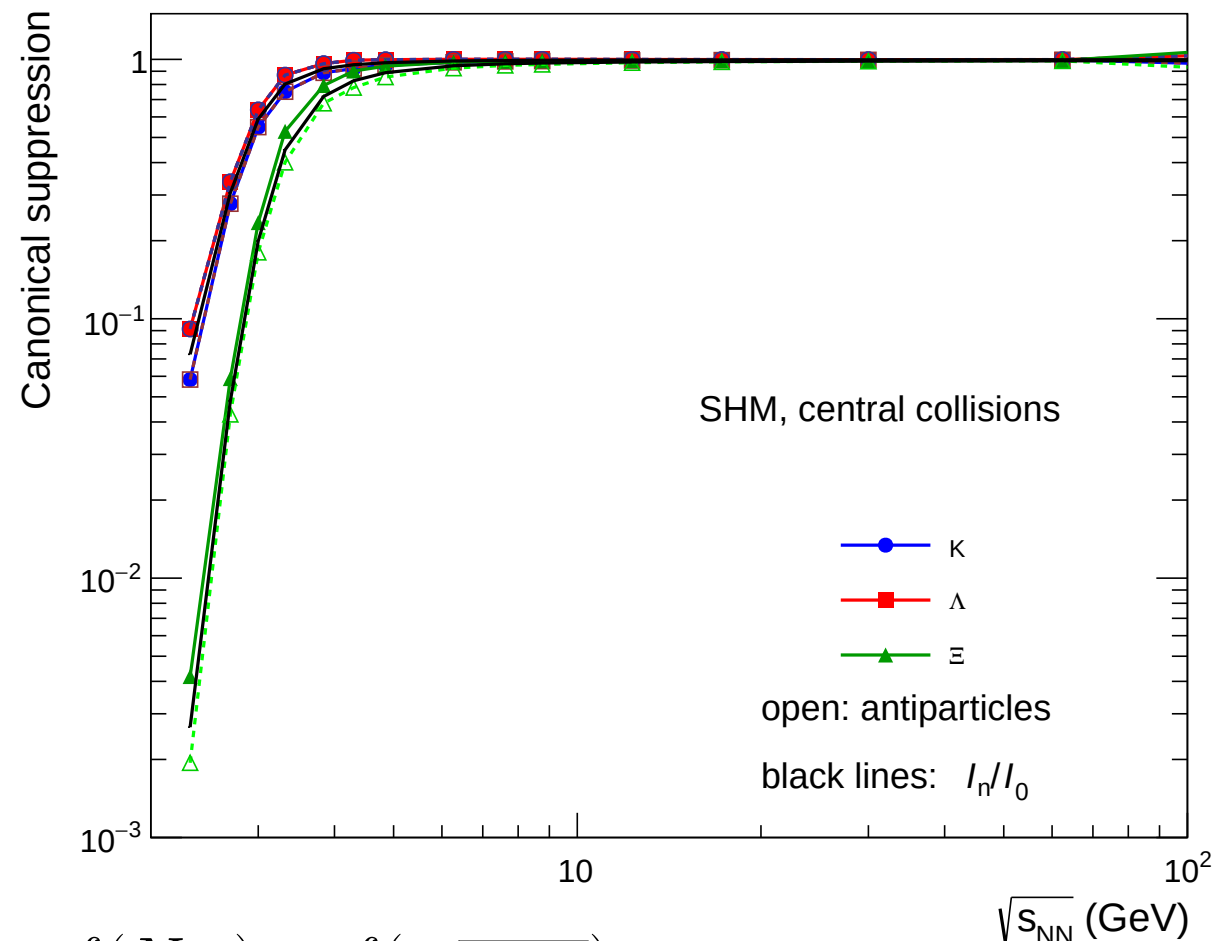
$$n_{i,S}^C = n_{i,S}^{GC} \cdot \frac{I_S(x)}{I_0(x)}$$

$$x = 2\sqrt{N_S N_{\bar{S}}}$$

$N_S = V_c \cdot \sum S \cdot n_{i,S}$, total amount of strangeness-carrying hadrons (part., antipart.)

$$n_{K,\Lambda}^C = n_{K,\Lambda}^{GC} \cdot \frac{I_1(x)}{I_0(x)},$$

$$n_{\Xi}^C = n_{\Xi}^{GC} \cdot \frac{I_2(x)}{I_0(x)}, \quad n_{\phi}^C = n_{\phi}^{GC}$$

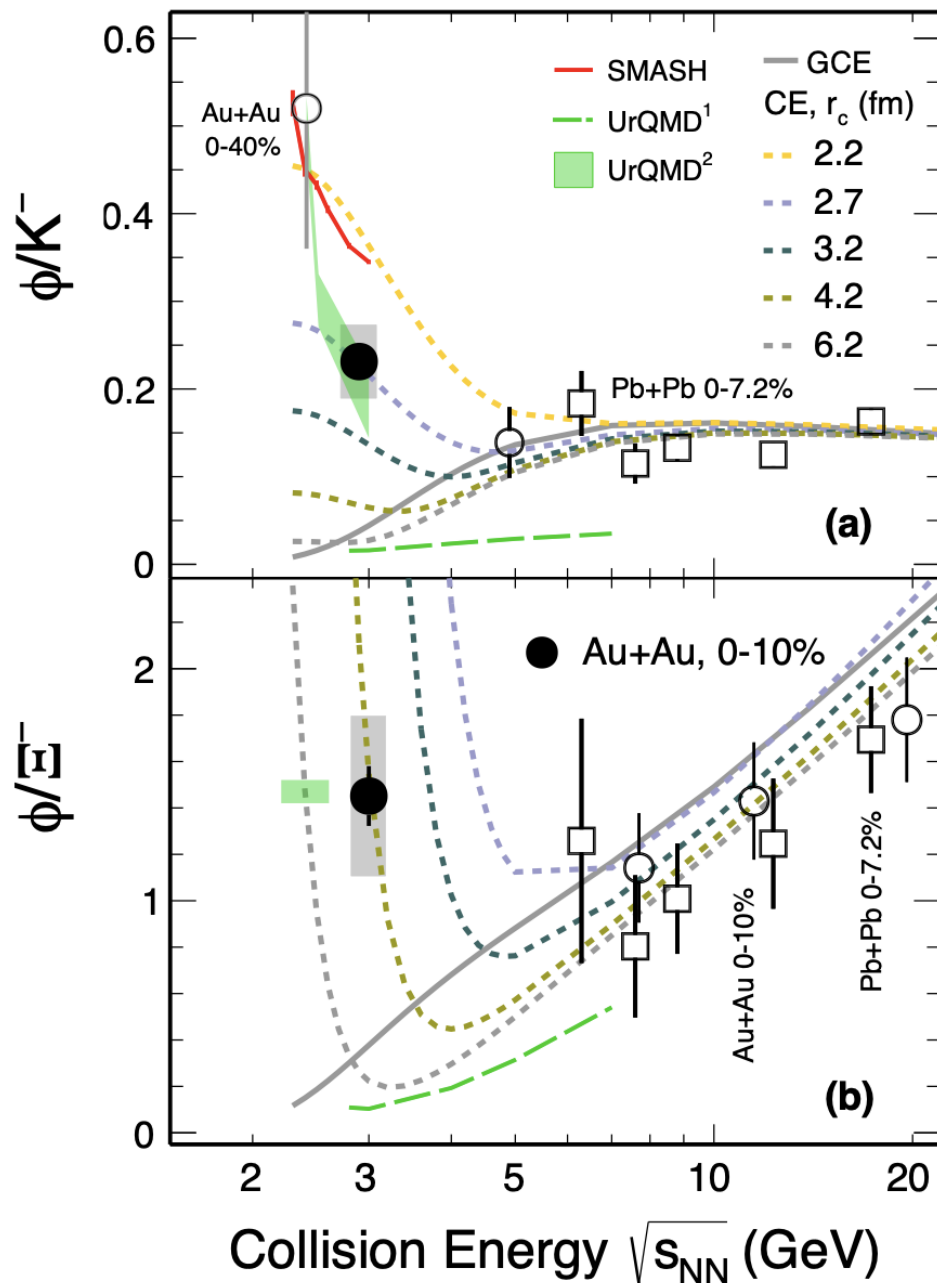


V_c canonical (correl.) volume, $V_c = f(N_{ch}) = f(\sqrt{s_{NN}})$

Canonical treatment (“canonical suppression”)

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STAR, [PLB 831 92022](#)) 137152

r_c radius of canonical (correl.) volume

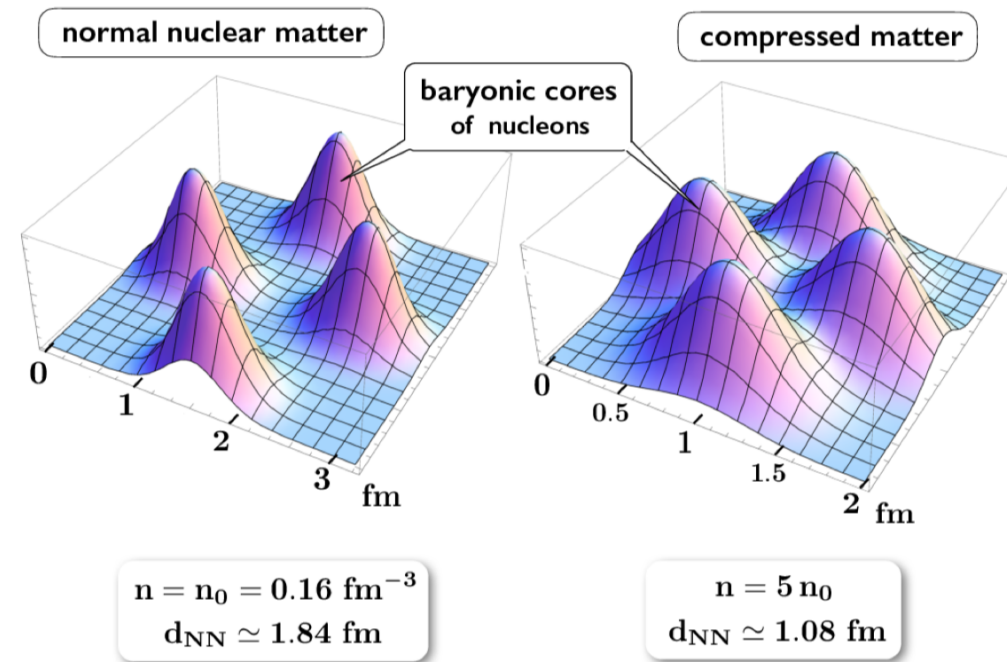
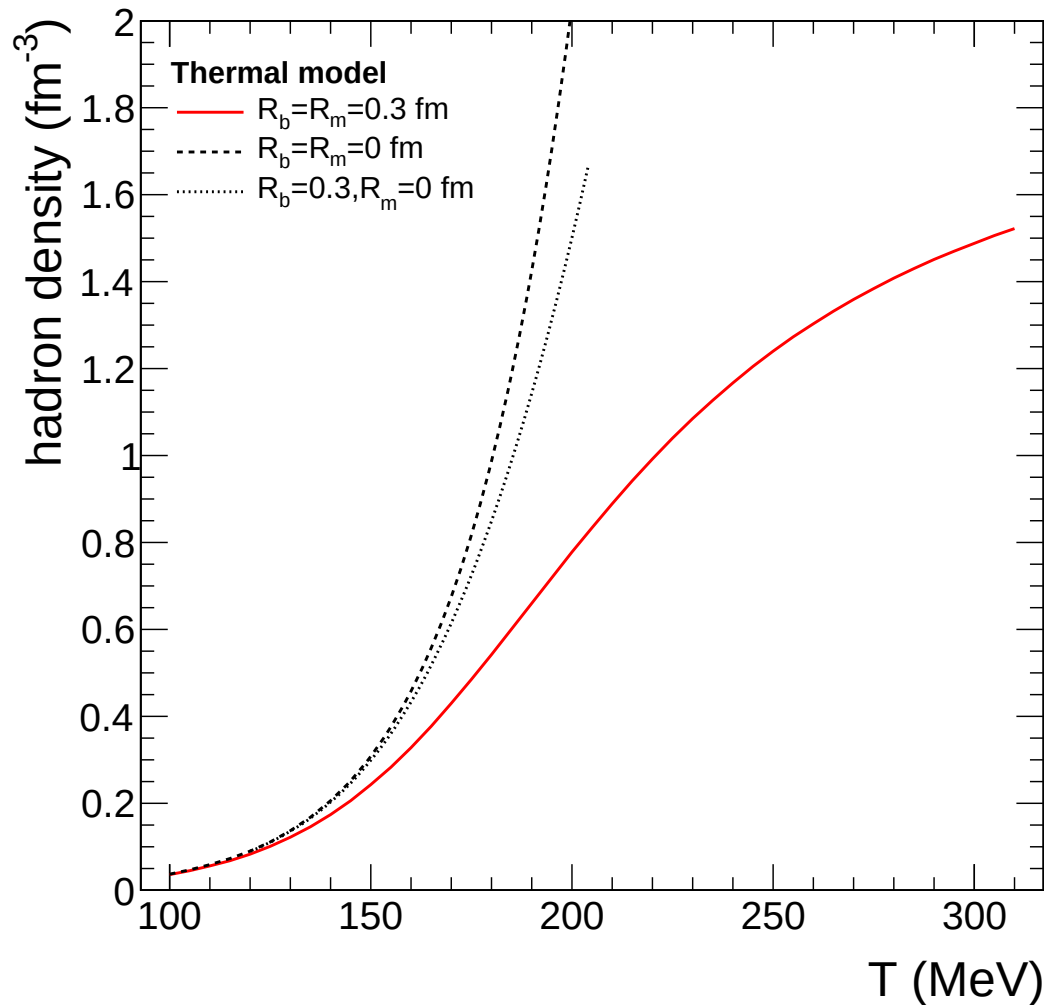
to constrain V_c a large set of hadron yields is needed (STAR, CBM)

V_c : strangeness correlation volume

Hadron densities

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Weise, [arXiv:1811.09682](https://arxiv.org/abs/1811.09682)

(baryons: gaussians, $r=0.5 \text{ fm}$)

"hadron gas": a dense system (also nuclear matter is rather a liquid than a gas)
(the usual case is $R_{baryon} = R_{meson} = 0.3 \text{ fm}$...hard-sphere repulsion)

Air at NTP: inter-molecule distance $\simeq 50 \times$ molecule size

hadron eigenvolumes ...to mimick interactions (beyond low-density, Dashen-Ma)

we consider that $R_{meson} = 0.3, R_{baryon} = 0.3$ fm is a reasonable case
point-like hadrons lead to same T , but volume larger by 20-25%

an extreme case, $R_{meson} = 0, R_{baryon} = 0.3$ fm leads to
 $T = 161.0 \pm 2.0$ MeV, $\mu_B = 0$ fixed, $V = 3470 \pm 280$ fm³

NB: in this case, the result is rather sensitive on the set of hadrons in the fit
for instance, using hadrons up to Ω , cannot constrain T (unphysically large)

Vovchenko, Stöcker (et al.), [JPG 44 \(2017\) 055103](#), [arXiv:1606.06350](#)

...and anything else can be imagined, see (R dependent on mass & strangeness)

Alba, Vovchenko, Gorenstein, Stöcker, [NPA 974 \(2018\) 22](#), etc.

Energy-dependent Breit-Wigner resonance widths:

Vovchenko, Gorenstein, Stöcker, [PRC 98 \(2018\) 034906](#)

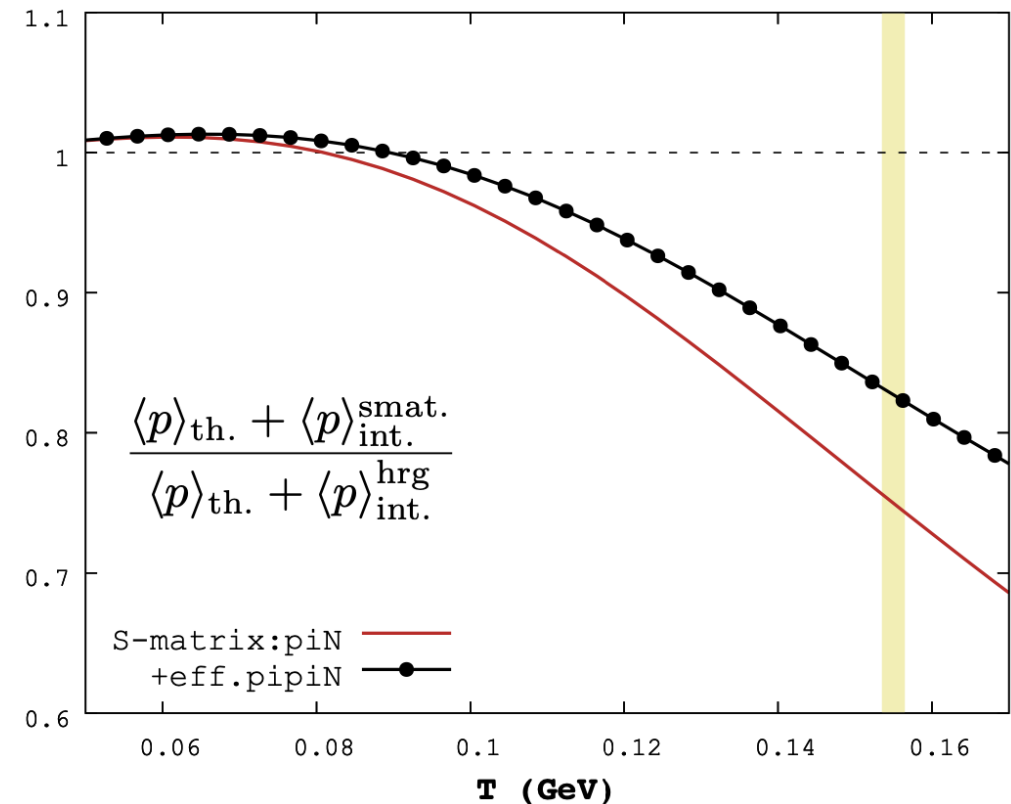
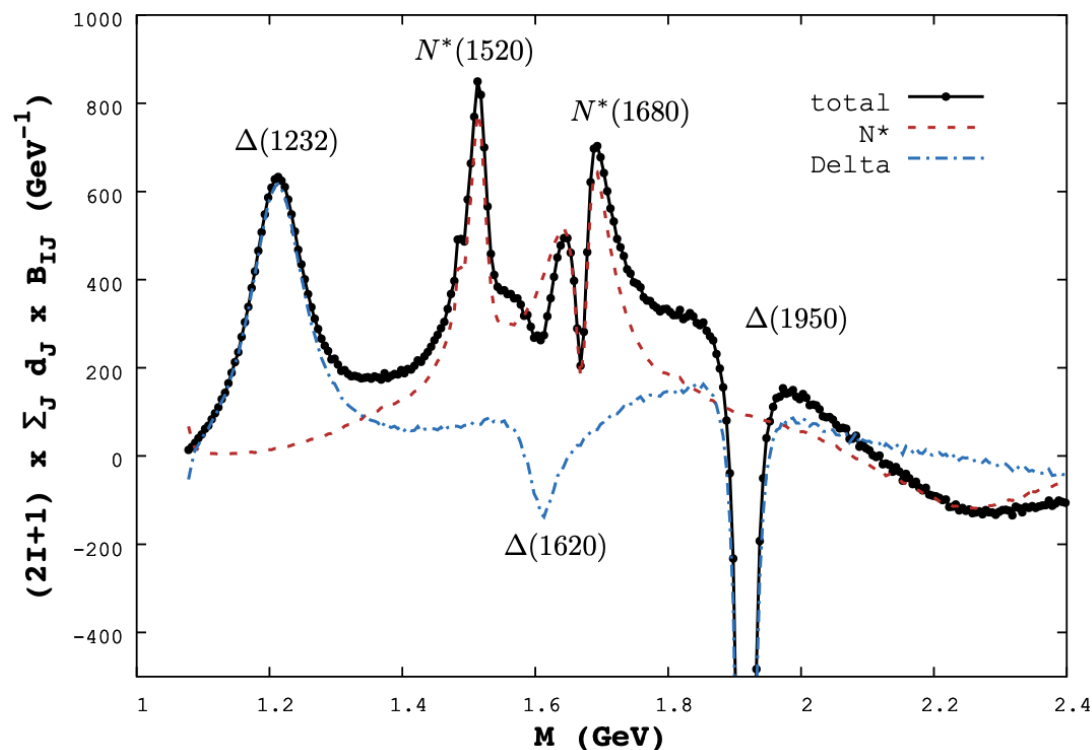
non-strange baryon sector treated in S-matrix formalism (P.M.Lo):
 πN scattering phase shifts, *including non-resonant contributions*

PLB 792 (2019) 304

...for now only at the LHC ($\mu_B \simeq 0$)

GWU/SAID PWA $\rightarrow$ effective spectral f.

correction of proton dens.



$\pi\pi N$: effective, from matching to χ_{BQ} in LQCD

solved the so-called "proton puzzle" (too many protons in the statistical model)
for $T=156.5$ MeV, proton yield decreased by 17% compared to point-like
still missing: strange baryon sector ($\sim 7\%$ of protons from Λ^* , Σ^* , T -dep.)

[PRC 98 \(2018\) 044910](#)

NB: presence of resonances implies interaction
(this is why moderate $R = 0.3$ fm is a reasonable choice)

$$n_i = N_i/V = -\frac{T}{V} \frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp[(E_i - \mu_i)/T] \pm 1}$$

Latest PDG hadron mass spectrum ...quasi-complete up to $m=2$ GeV;
our code: ~ 600 species (including fragments, charm and bottom hadrons)

for resonances, the width is considered in calculations

canonical treatment whenever needed (small abundances)

$$\text{Minimize: } \chi^2 = \sum_i \frac{(N_i^{\text{exp}} - N_i^{\text{therm}})^2}{\sigma_i^2}$$

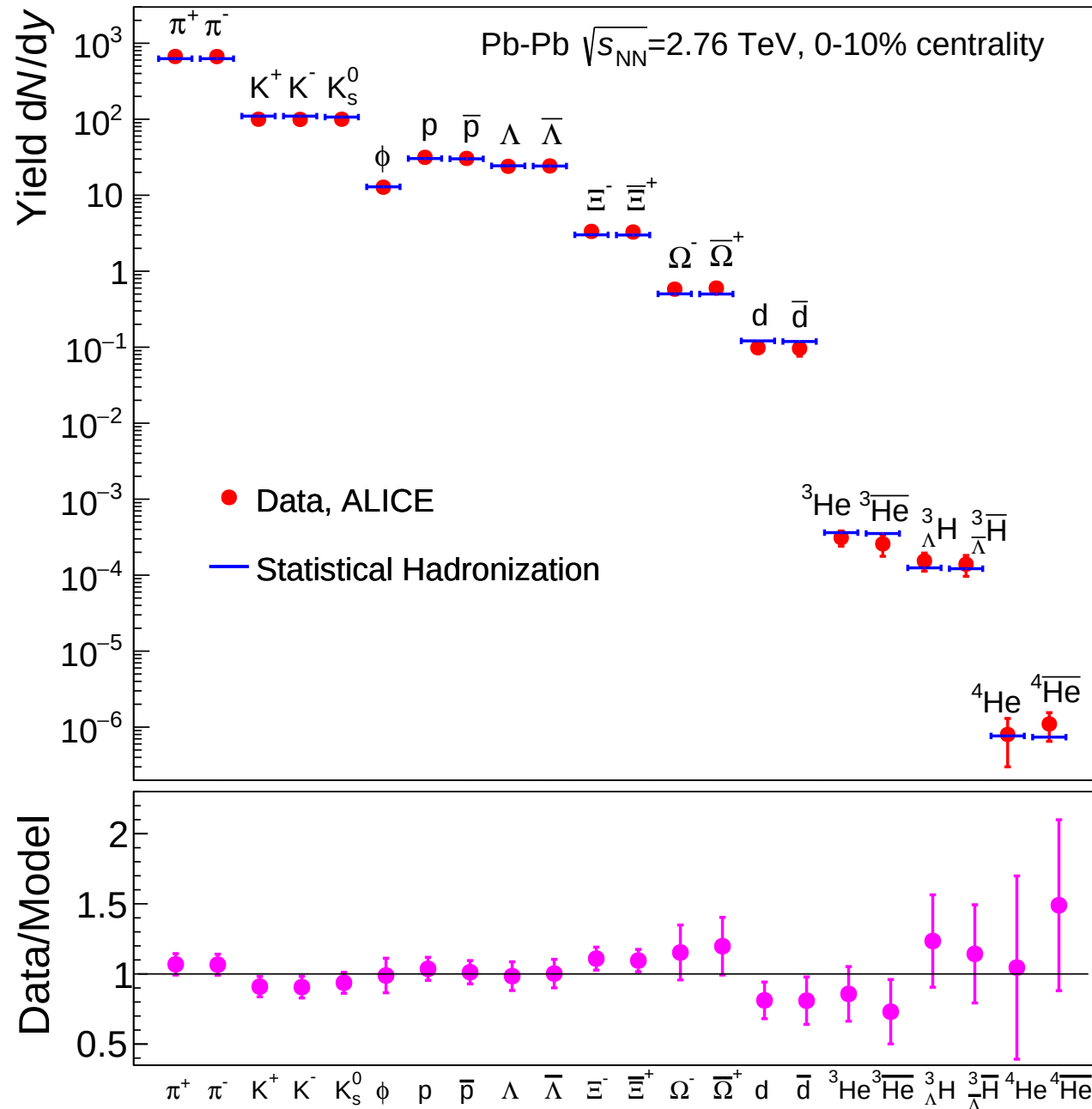
N_i hadron yield, σ_i experimental uncertainty (stat.+syst.)

$\Rightarrow (T, \mu_B, V)$...tests chemical freeze-out (chemical equilibrium)

Thermal fit – LHC, Pb–Pb, 0-10%

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matter and antimatter produced in equal amounts

$$T_{CF} = 156.6 \pm 1.7 \text{ MeV}$$

$$\mu_B = 0.7 \pm 3.8 \text{ MeV}$$

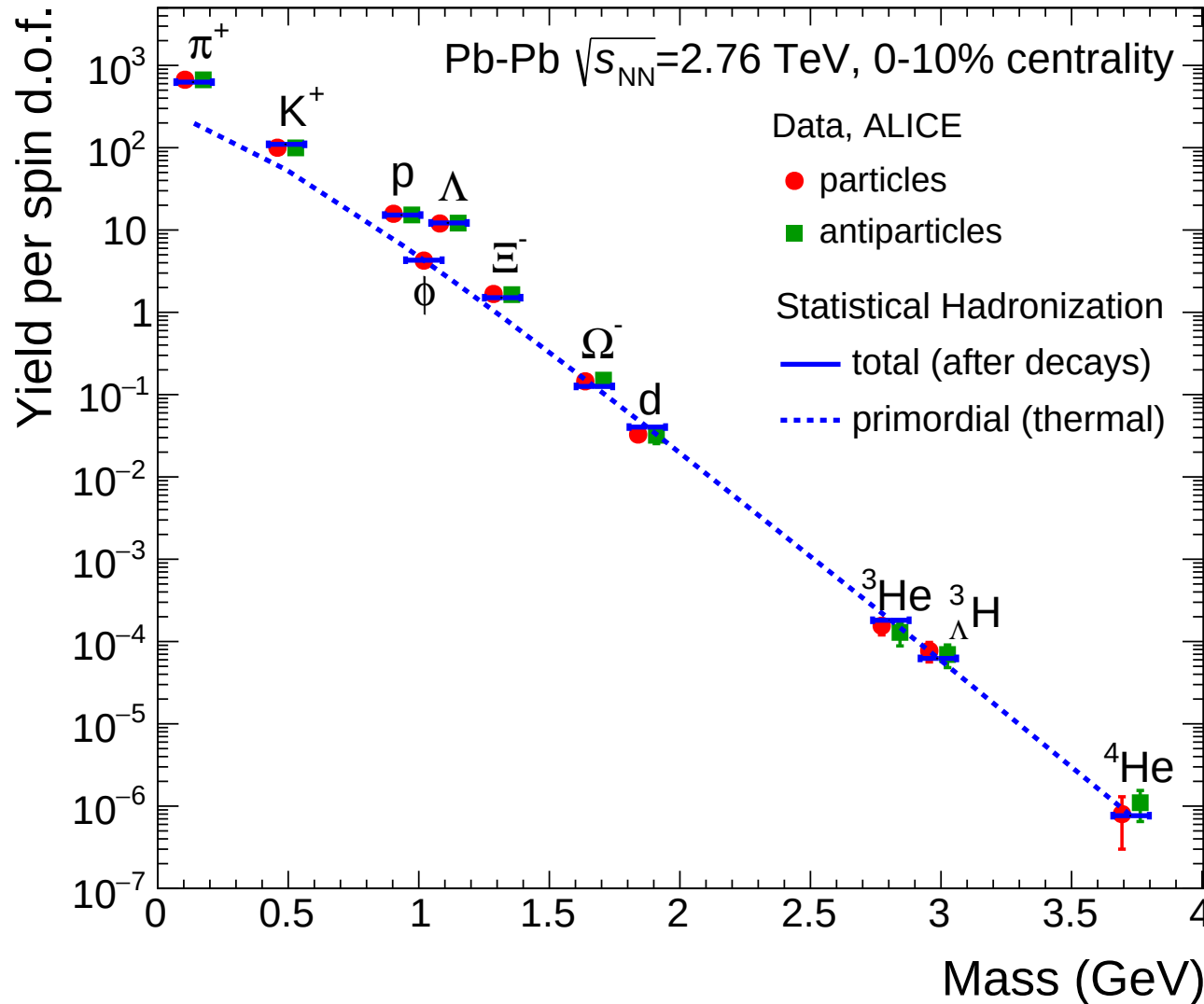
$$V_{\Delta y=1} = 4175 \pm 380 \text{ fm}^3$$

$$\chi^2/N_{df} = 16.7/19$$

S-matrix treatment

remarkably, loosely-bound objects are also well described (${}^3_\Lambda\text{H}$ with 25% B.R.)

hadronization as bags of quarks and gluons?



contribution of resonances
is significant
(and particle-dependent)

Fit of ϕ , Ω , d , ${}^3\text{He}$, ${}^3_\Lambda\text{H}$, ${}^4\text{He}$:

$$T_{CF} = 156 \pm 2.5 \text{ MeV}$$

$$(\chi^2/N_{df} = 7.4/8)$$

Fit of nuclei (d , ${}^3\text{He}$, ${}^4\text{He}$):

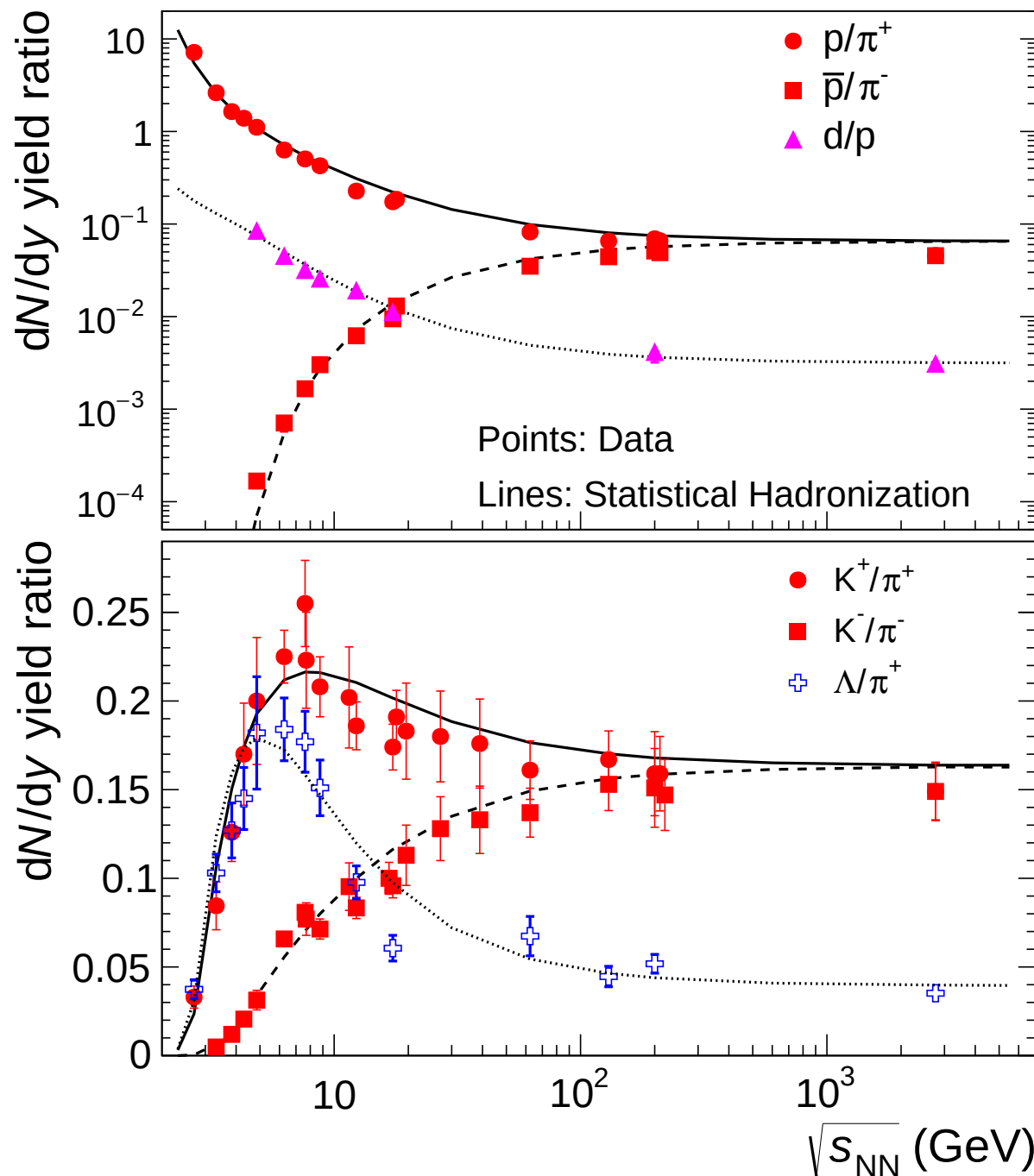
$$T_{CF} = 159 \pm 5 \text{ MeV}$$

3-4 MeV upper bound of systematic uncertainty due to hadron spectrum

The grand (albeit partial) view

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Data:

AGS: E895, E864, E866, E917, E877

SPS: NA49, NA44

RHIC: STAR, BRAHMS

LHC: ALICE

NB: no contribution from weak decays

no S-matrix correction ($p, \bar{p}$)

d/p ratio is well described for all energies

“structures” described by SHM
...determined by strangeness conservation

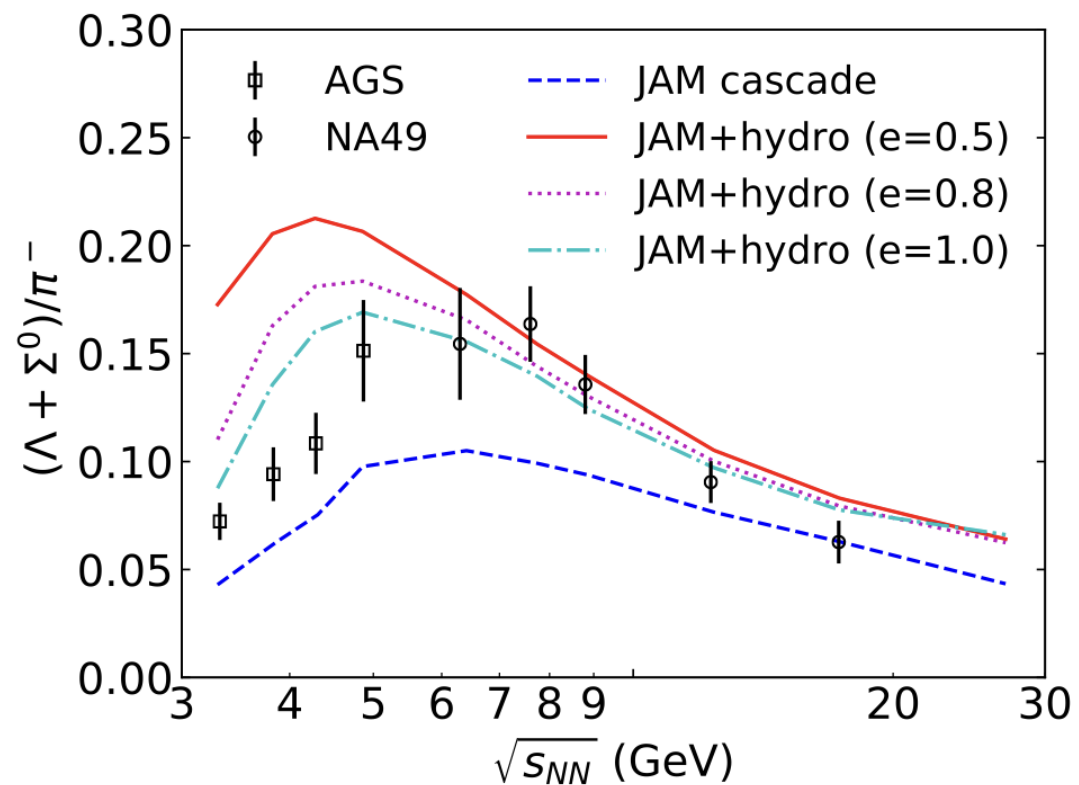
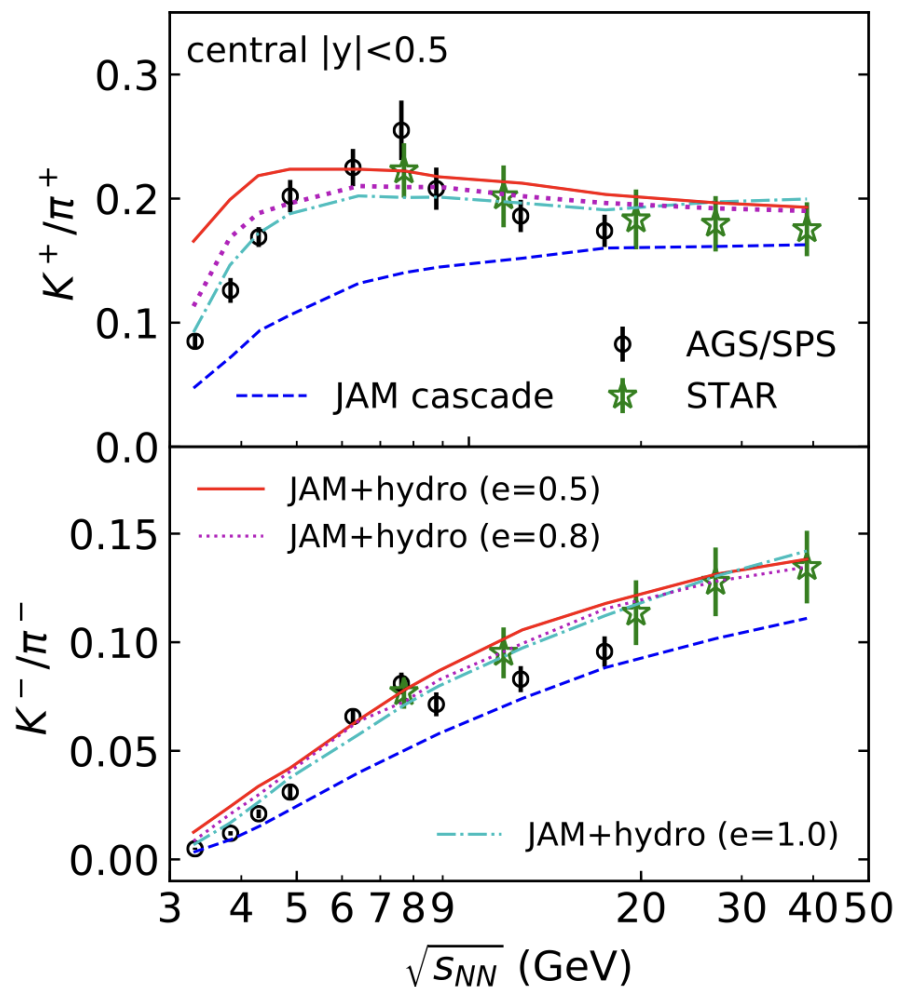
Λ/π peak reflects increasing T
and decreasing μ_B

For comparison: the JAM model (hydro+transport)

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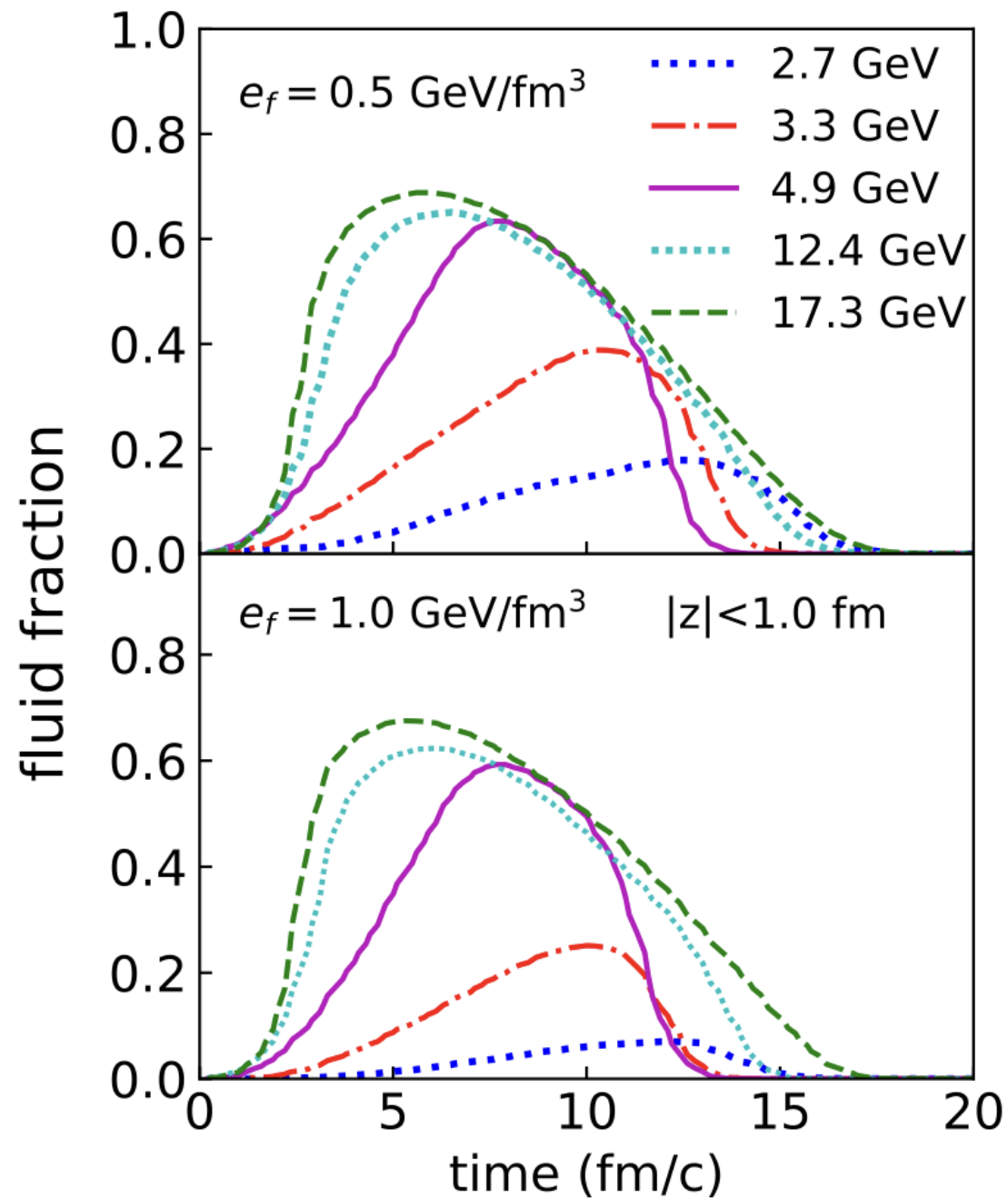
20

Akamatsu et al., [PRC 98 \(2018\) 024909](#)



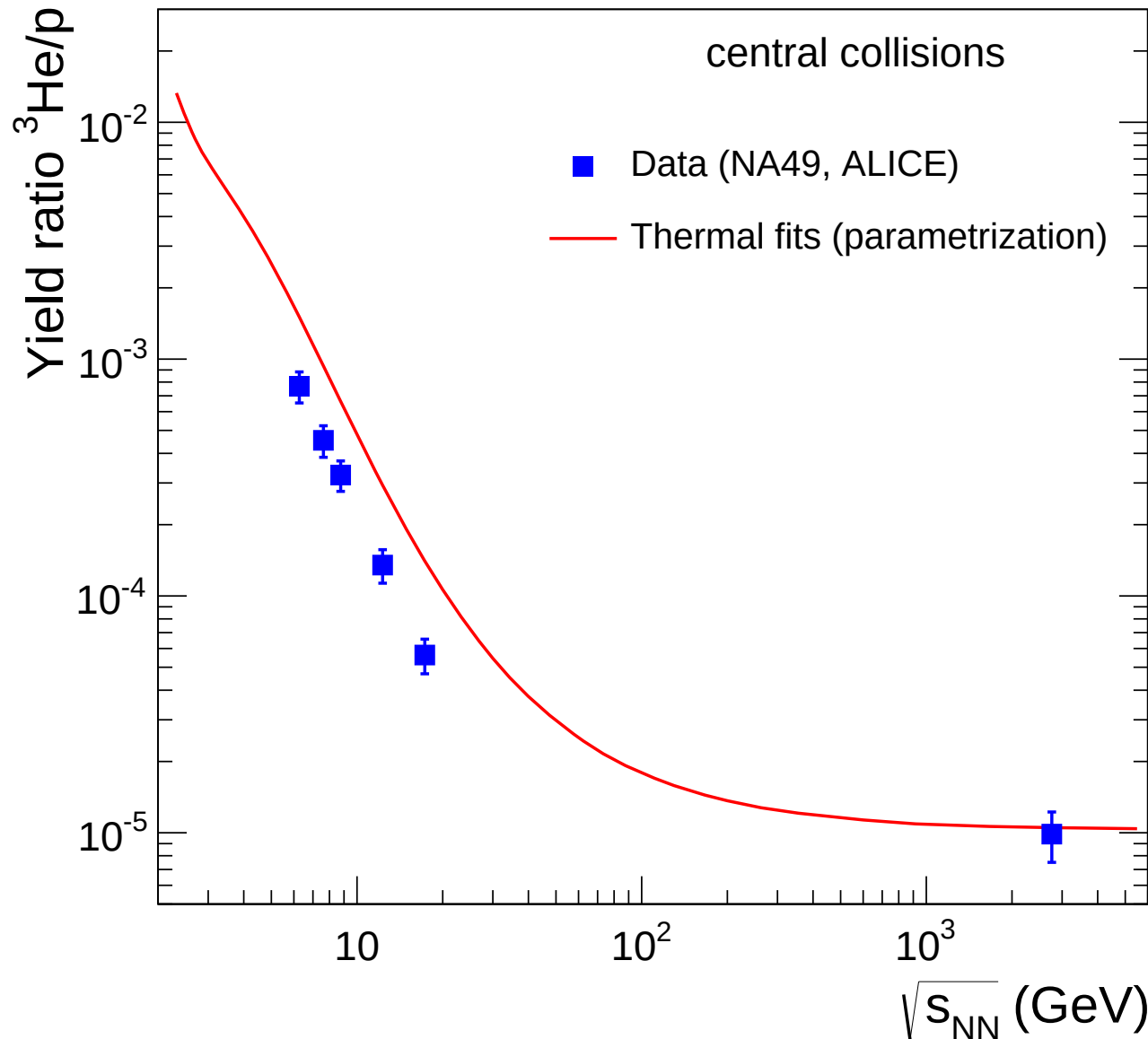
e (in GeV/fm^3): fluid (QGP) density

The JAM model (hydro+transport)



Something that doesn't work so well in SHM?

$^3\text{He}/p$ ratio well described at the LHC, but not at lower energies



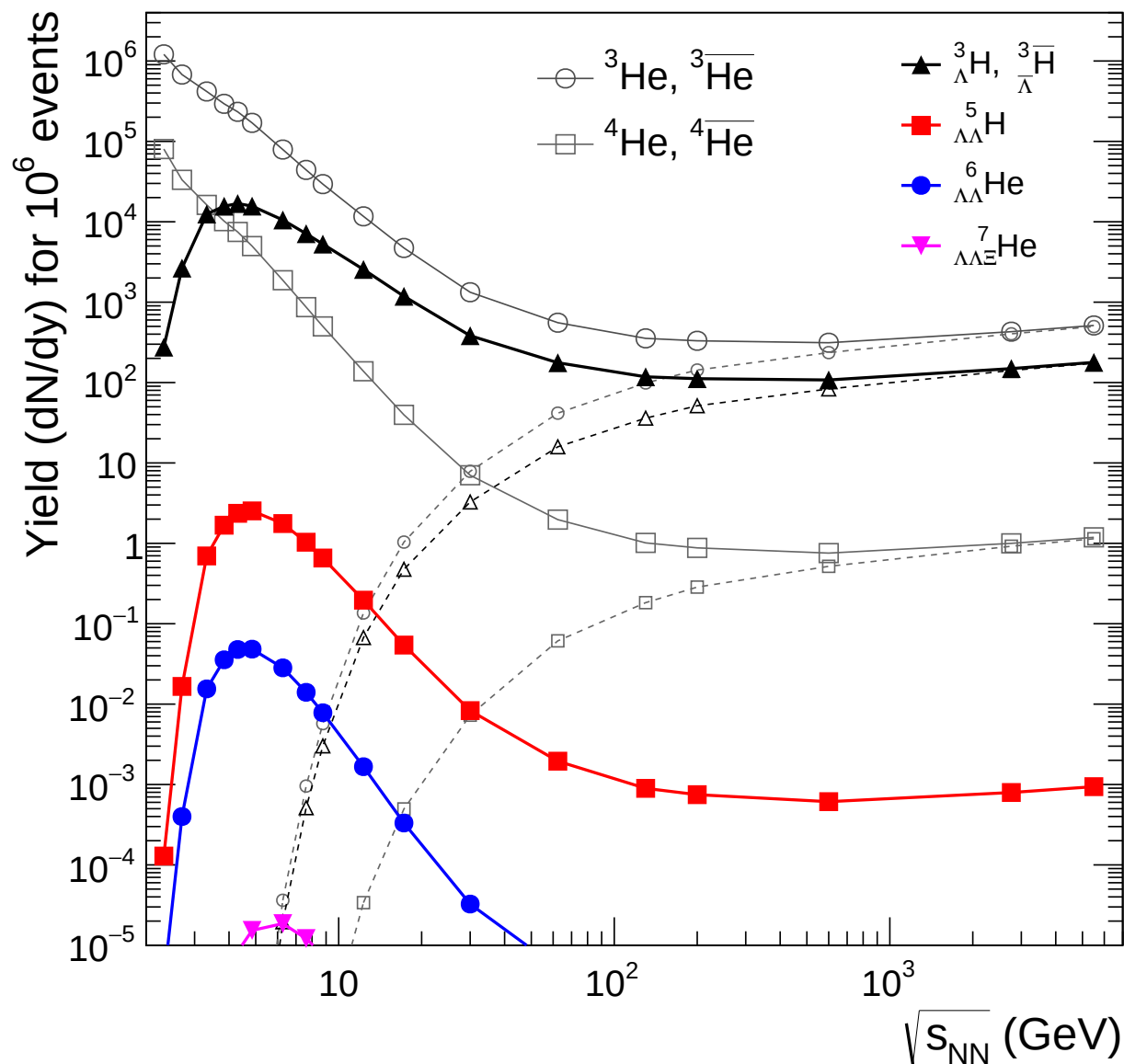
ALICE 5.02 TeV:
 $(0.7 \pm 0.1) \cdot 10^{-5}$

Complex objects

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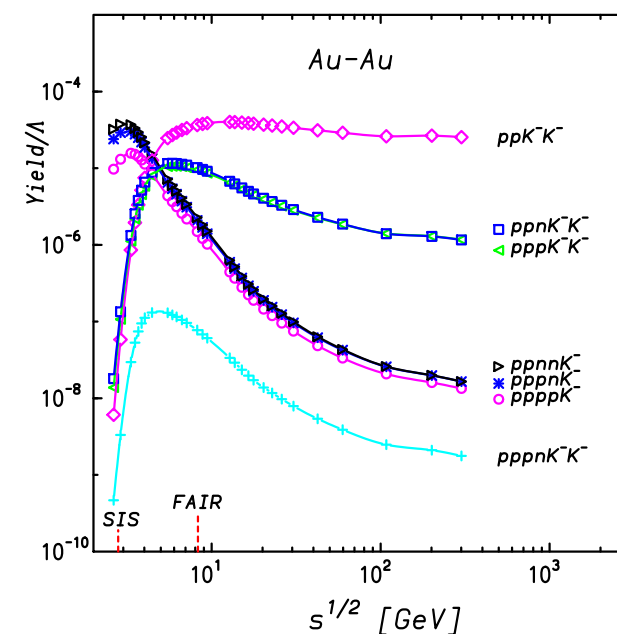
...are copiously produced at low (RHIC-BES/FAIR) energies



...some to be discovered

maybe also nucleon- K^- clusters?

AA, PBM, K.Redlich, NPA 765 (2006) 211



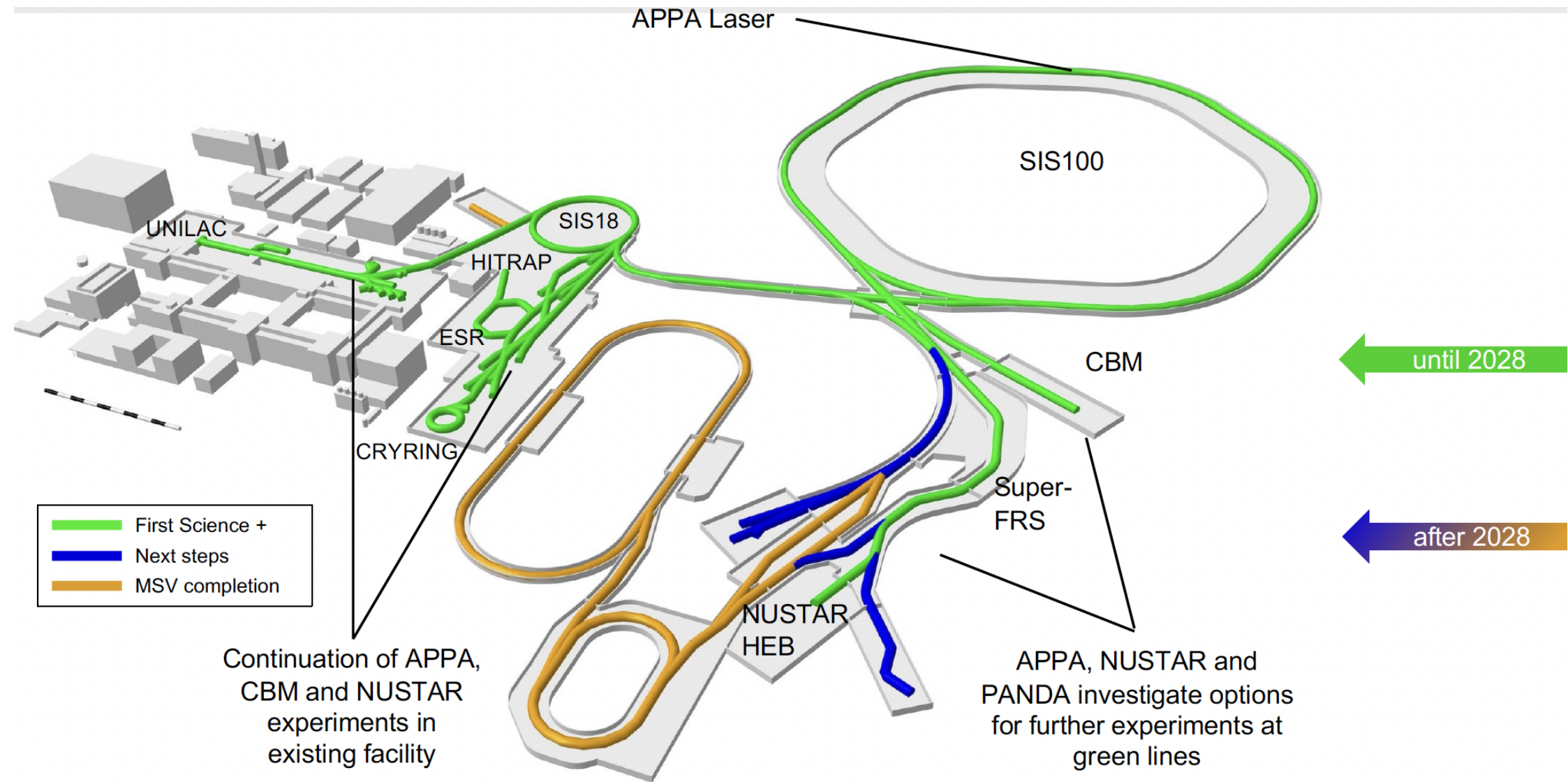
AA, PBM, JS, HS, PLB 697 (2011) 203

FAIR Complex at GSI Darmstadt

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Facility for Antiproton and Ion Research multi-purpose (strong interaction) facility



FAIR

- Civil construction work completed
- Installation of accelerator components begun

Facility for Antiproton and Ion Research multi-purpose (strong interaction) facility



CBM cave

FAIR

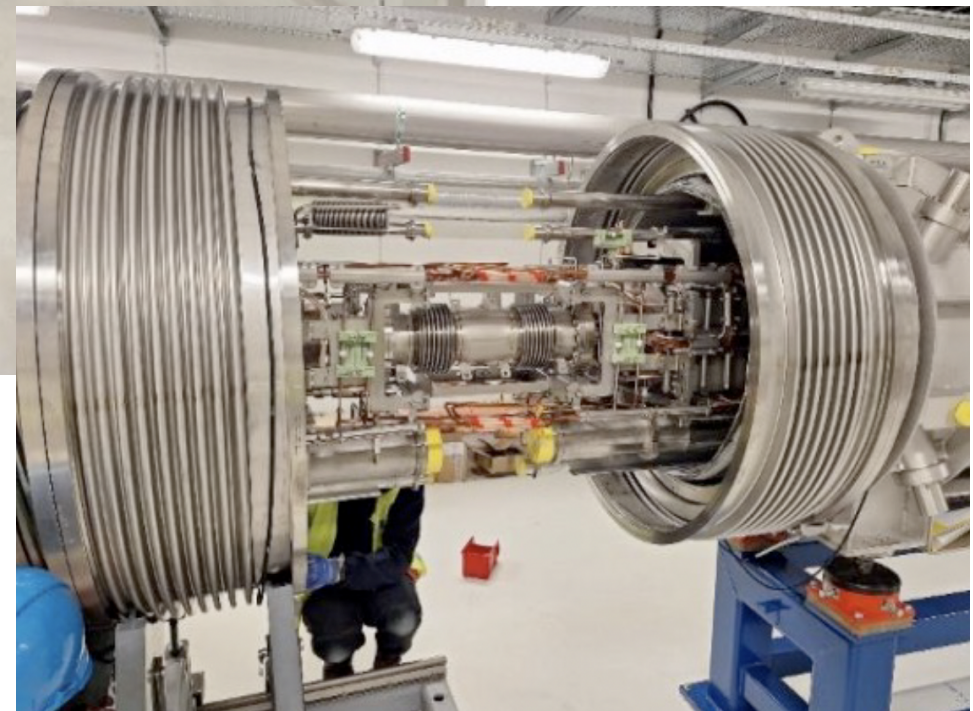
- Civil construction work completed
- Installation of accelerator components begun

Inside FAIR



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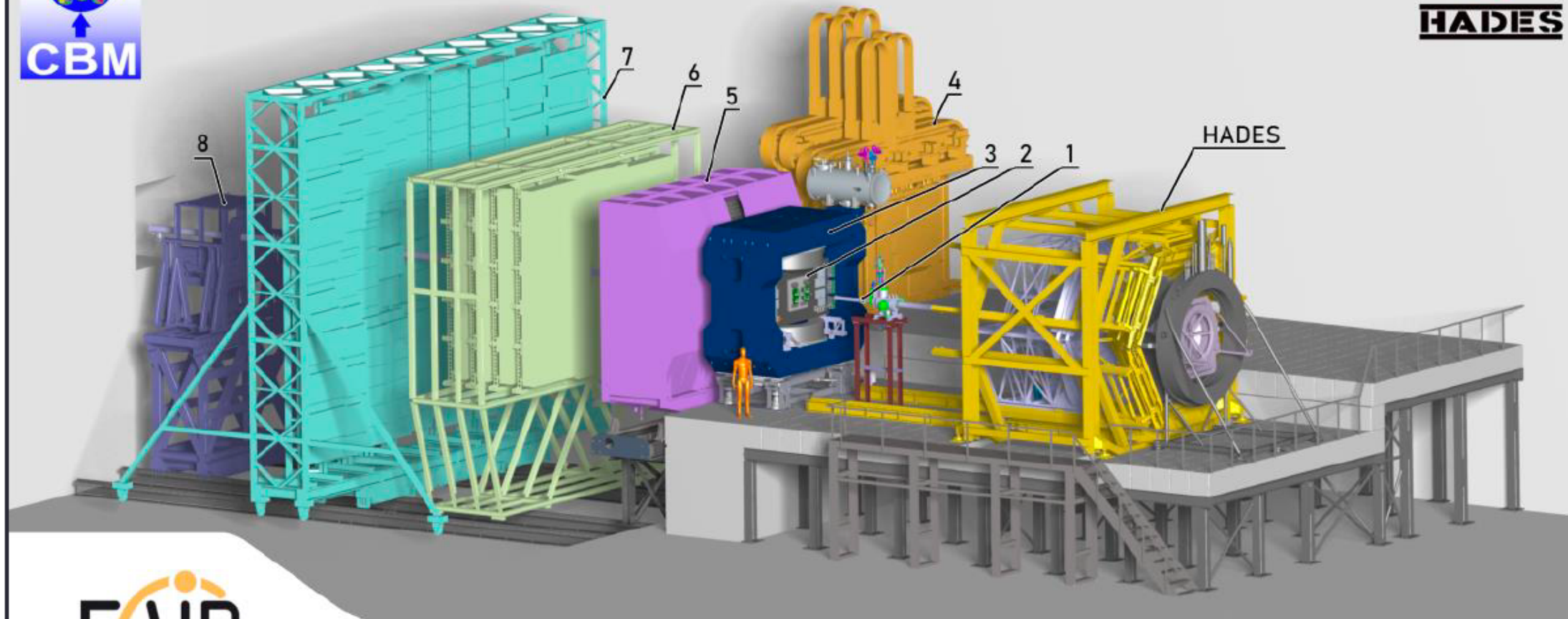


see [More photos, videos](#)





Compressed Baryonic Matter



1: Time-Zero Detector & Beam Diagnostics

2: Silicon Tracking System / Micro Vertex Detector

3: Superconducting Dipole Magnet

4: Muon Chambers

5: Ring Imaging Cherenkov Detector

6: Transition Radiation Detector

7: Time of Flight Detector

8: Forward Spectator Detector

Challenges: huge variation in occupancy (fixed-target); event rates up to 10 MHz

Au-Au collisions, $E_{beam} = 2-11$ GeV/nucleon on fixed target
 $\sqrt{s_{NN}} = 2.7 - 4.9$ GeV

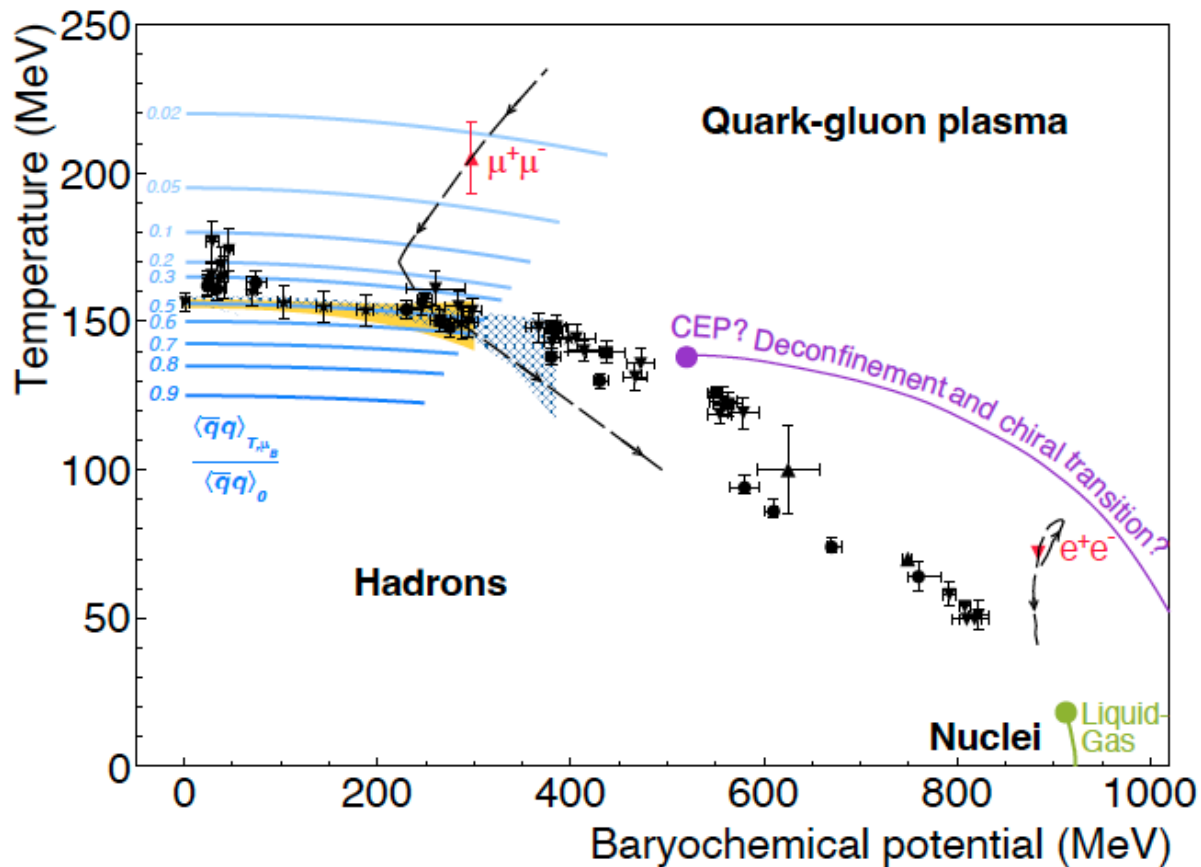
CBM will measure pA collisions too, rich hadron physics program
(proton momentum up to 30 GeV/c)

...a report on this topic will be published later this year

Two CBM configurations (running sequentially):

- “electron setup”: the full suite of CBM physics (focus of my talk)
- “muon setup”: RICH detector replaced by Muon Chambers (instrumented absorber)

- characterize hot and dense QCD matter at high μ_B (500-800 MeV), EoS
- establish order of phase transition(s), conjectured QCD critical point



Observables (abundant/rare):

- light flavour hadrons, incl. multi-strange hyperons
→ chemical freeze-out T, μ_B
flow, vorticity → EoS
- event-by-event fluctuations (criticality)
- dileptons (emissivity)
- charm (transport properties)
- hypernuclei (interaction, prod. mechanism)

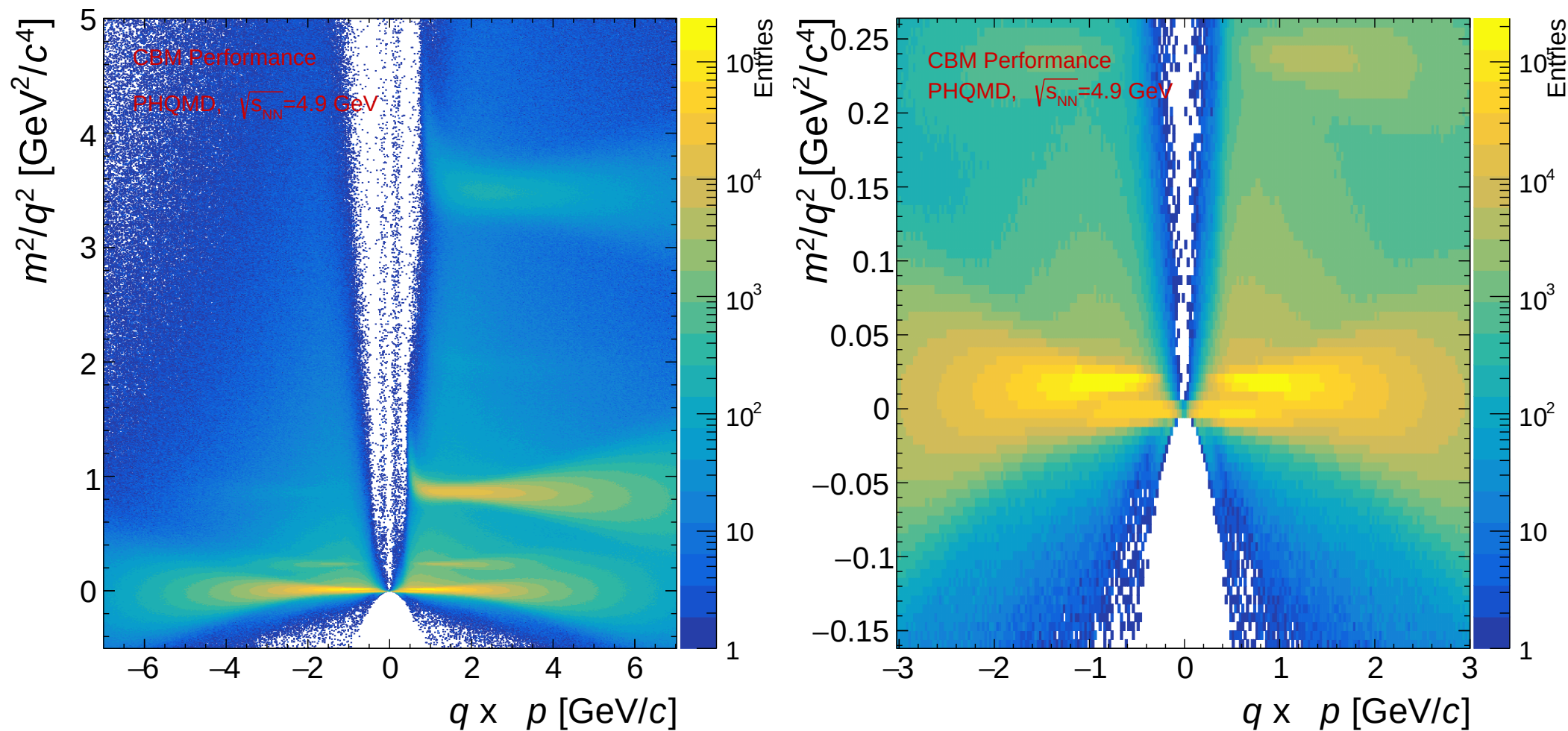
HADES, [Nature Phys. 15 \(2019\) 1040](#)

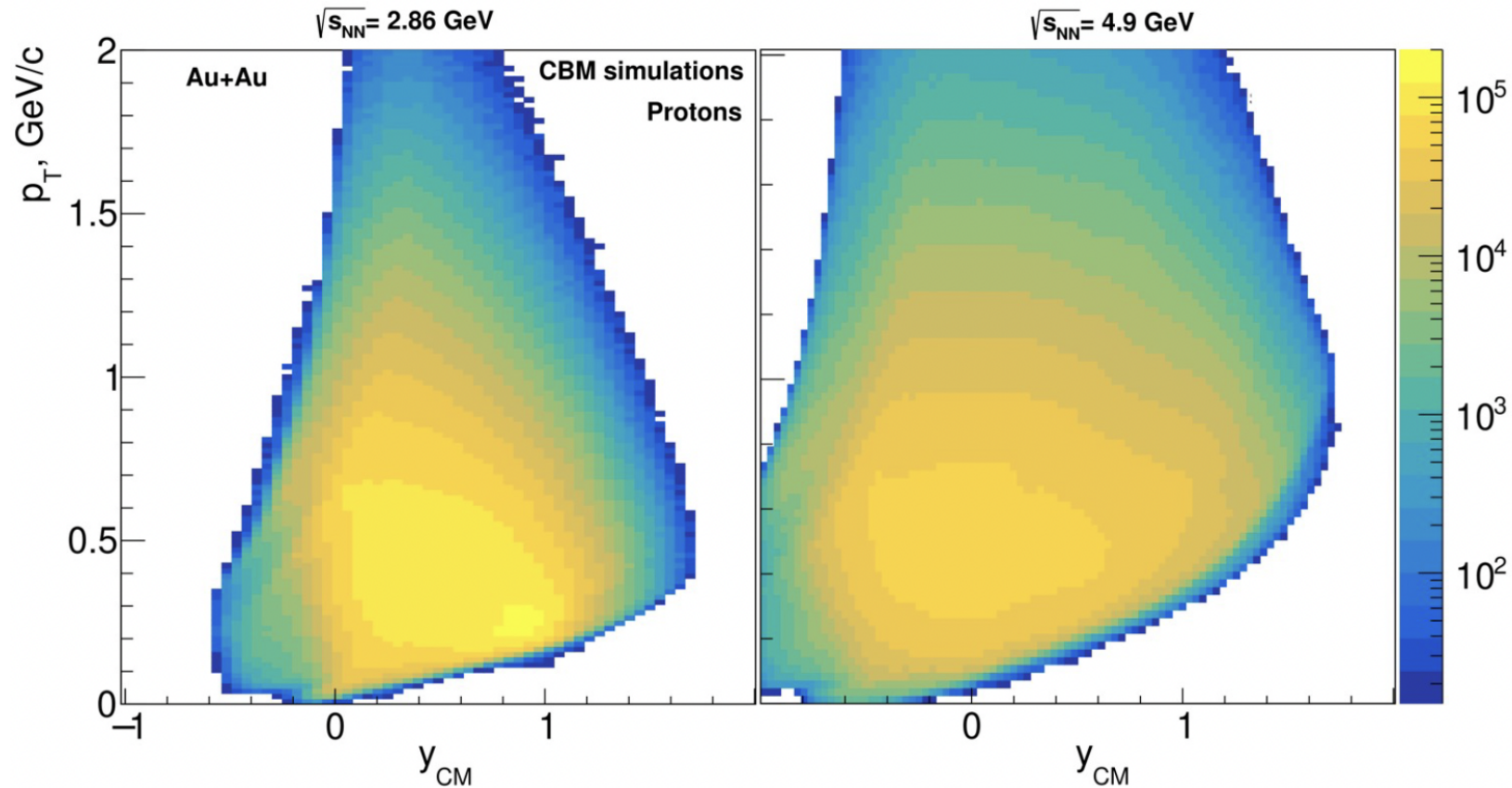
Andronic et al, [Nature 561 \(2018\) 321](#)



Goal: CBM Start Version installed and operational in 2028 (for beams in 2029)

Simulations, PHQMD, $\sqrt{s_{NN}} = 4.9$ GeV

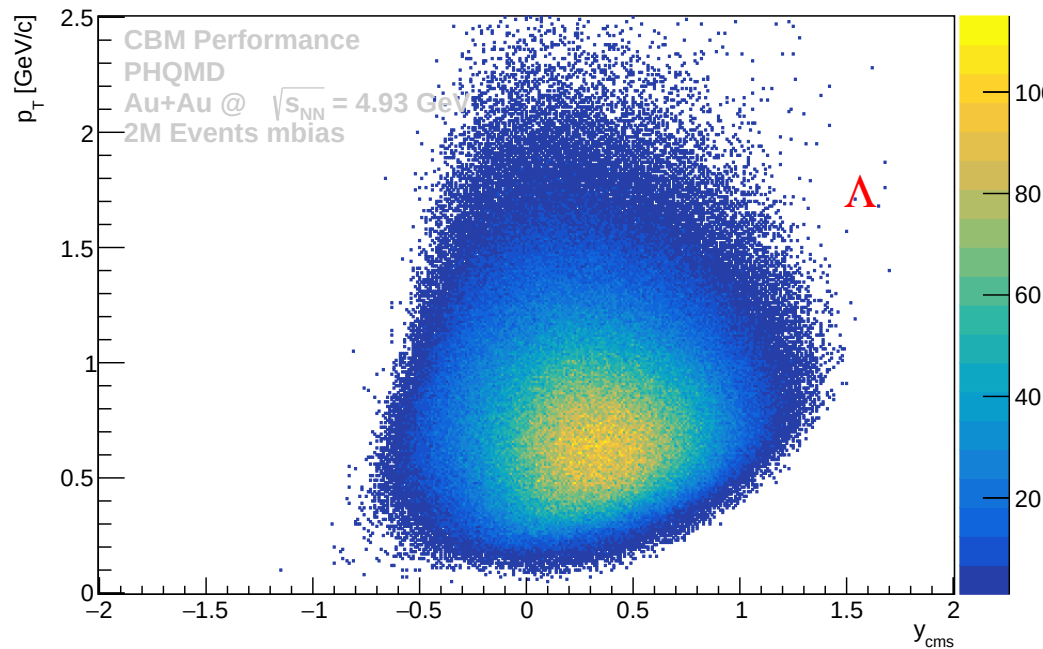




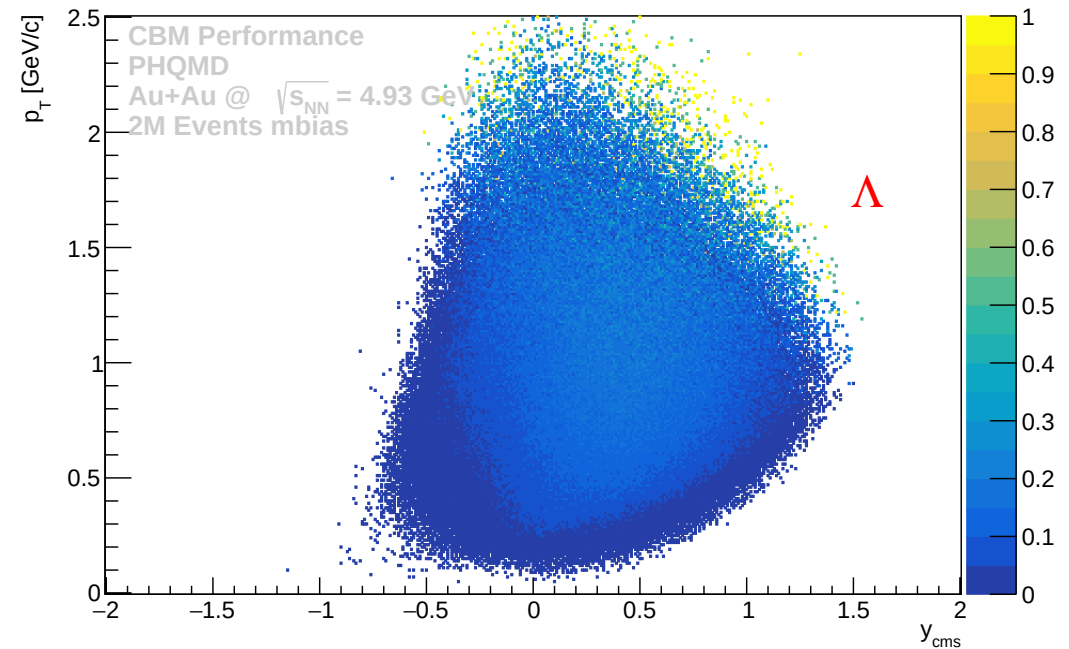
broad phase space coverage, down to low p_T (but of course $\sqrt{s_{NN}}$ -dependent)

Λ reconstructed with ML (BDT), realistic p, π PID

raw yield

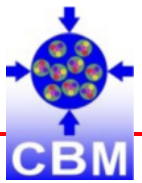


efficiency



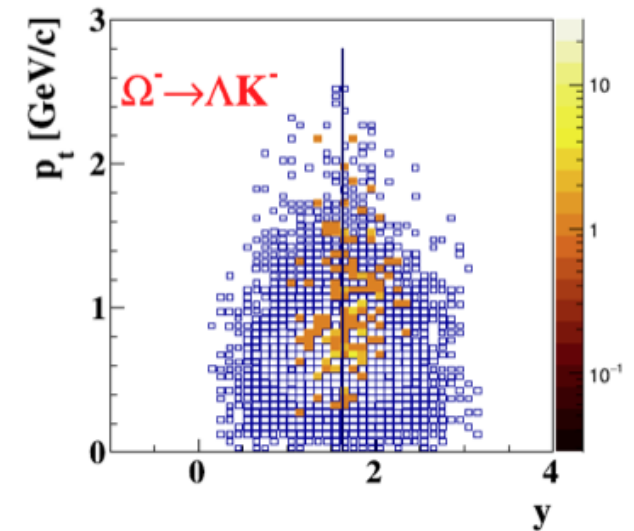
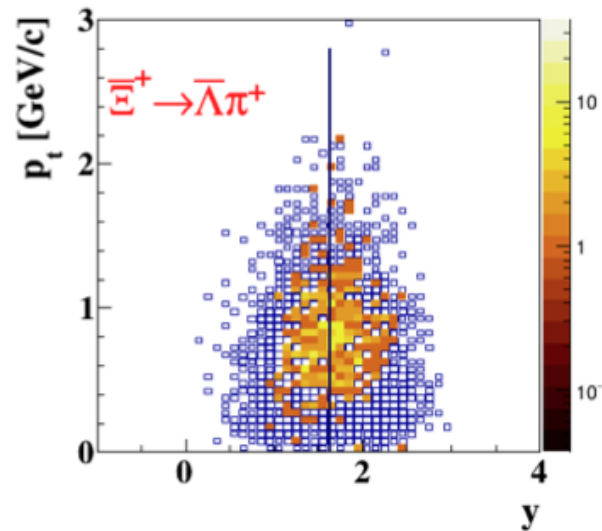
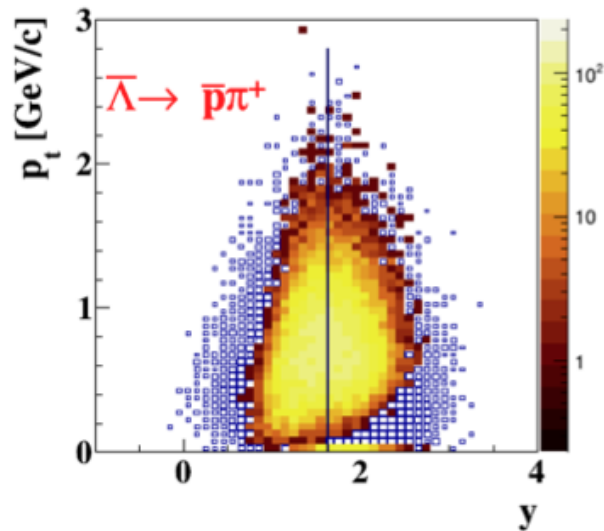
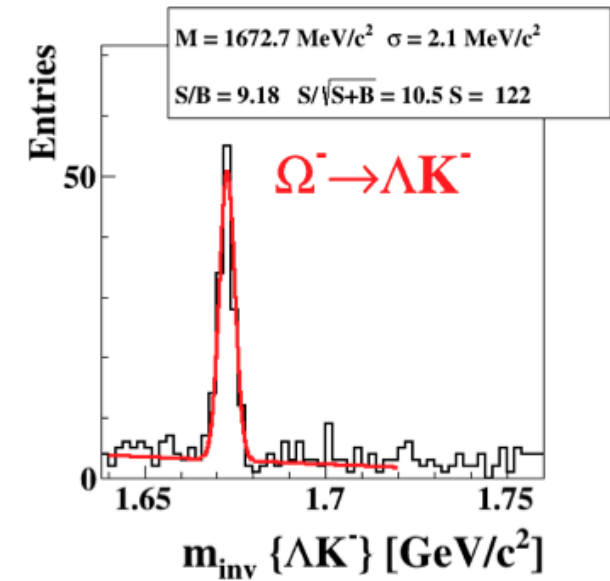
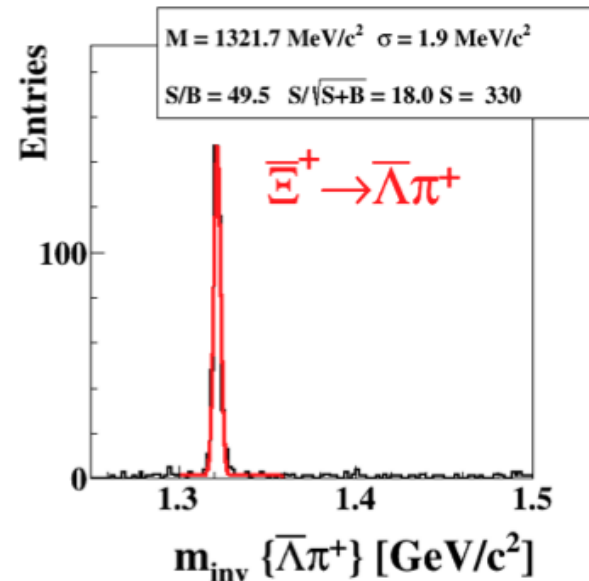
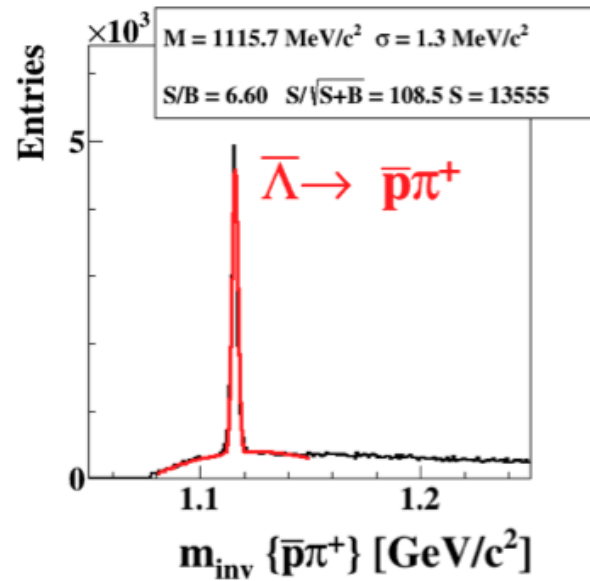
broad phase space coverage, down to low p_T ; 0.325 rec. Λ /event

(Anti)Hyperon reconstruction

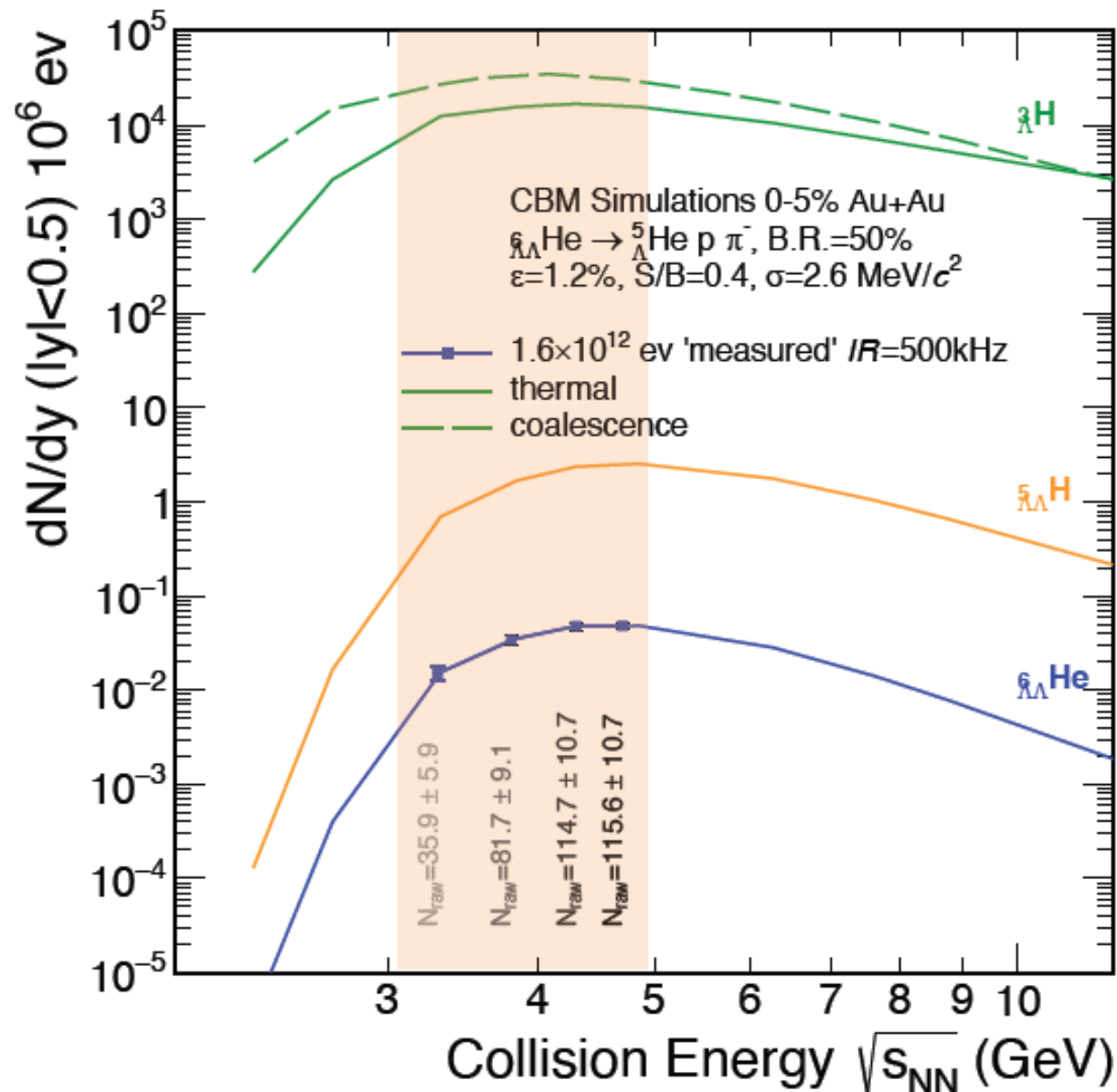


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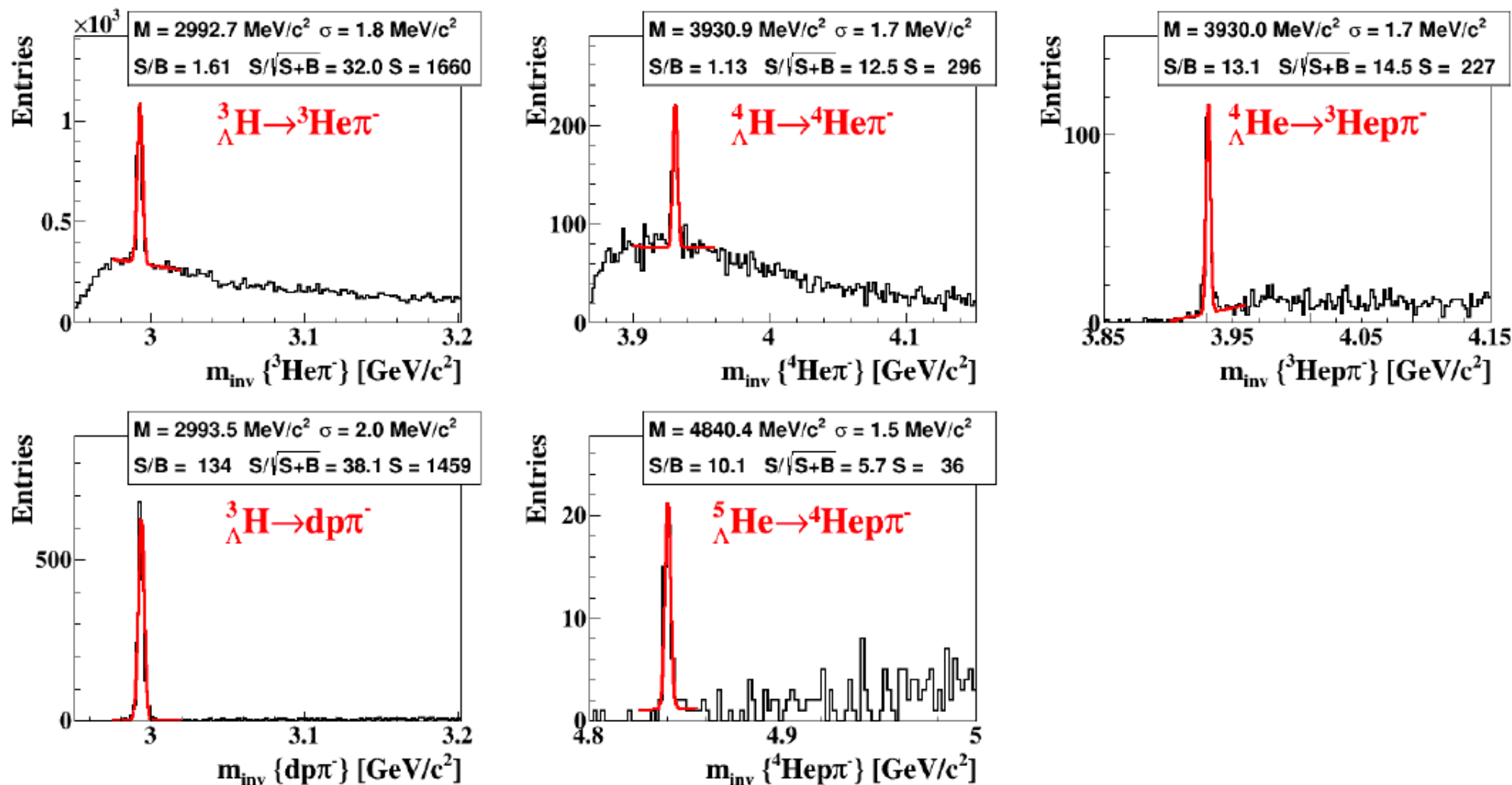


Au-Au, $\sqrt{s_{NN}} = 4.9 \text{ GeV}$ - PHQMD; KFParticleFinder



CBM will study ${}^3_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{H}$ in detail

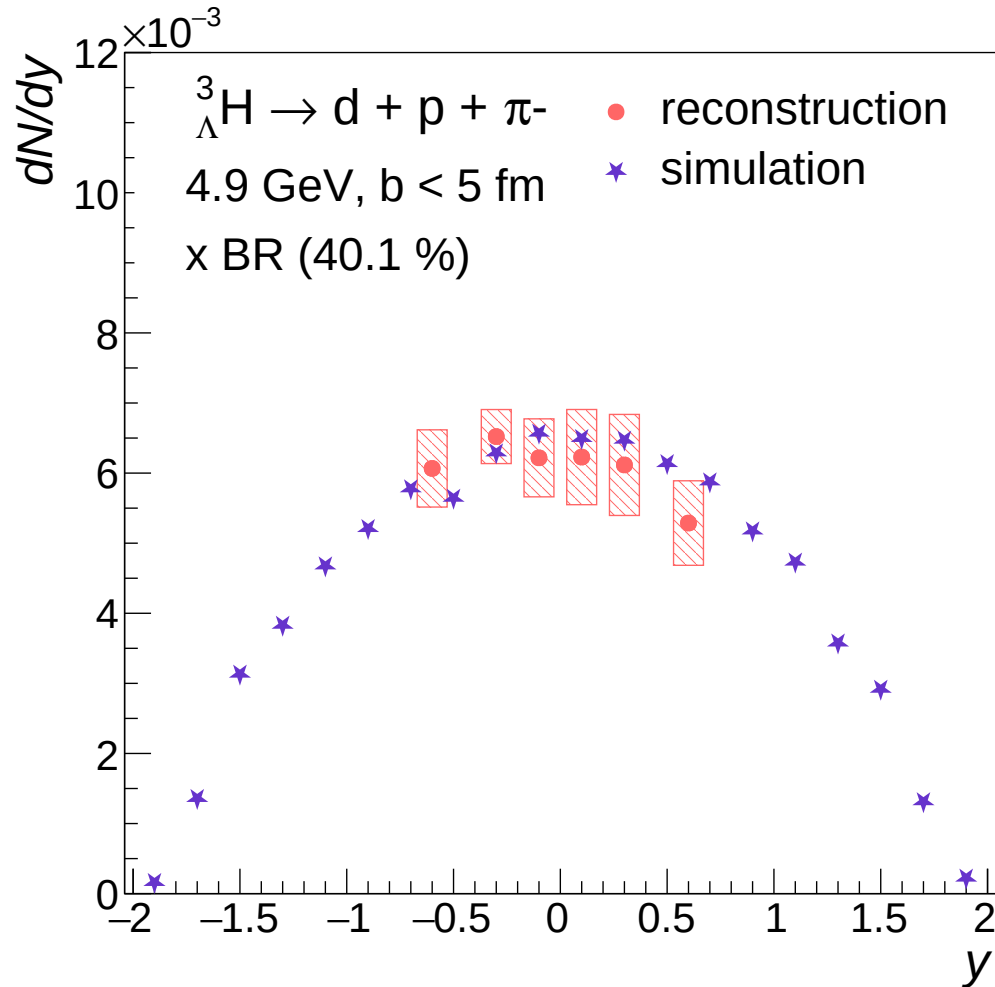
and can discover the double-strange hyperons



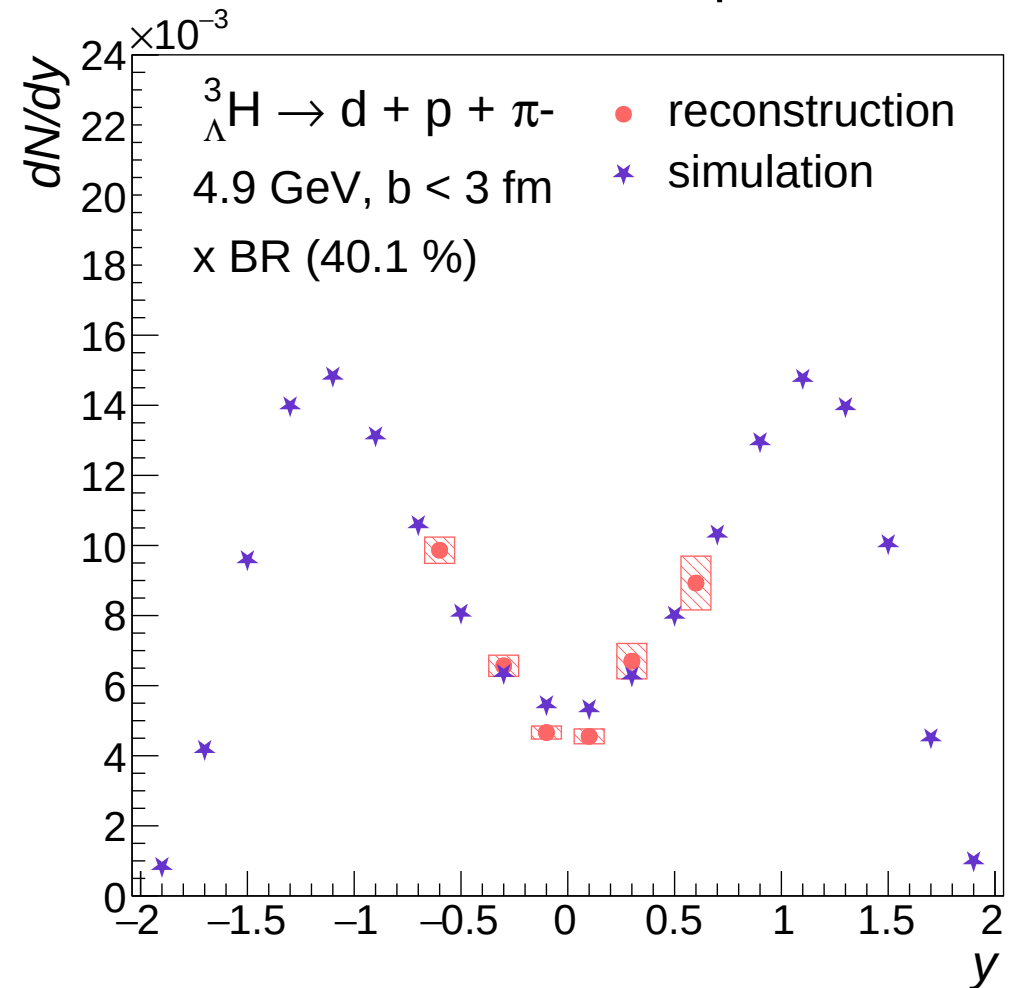
Au-Au, $\sqrt{s_{NN}} = 4.9$ GeV - PHQMD; KFPparticleFinder; Day-1 detector

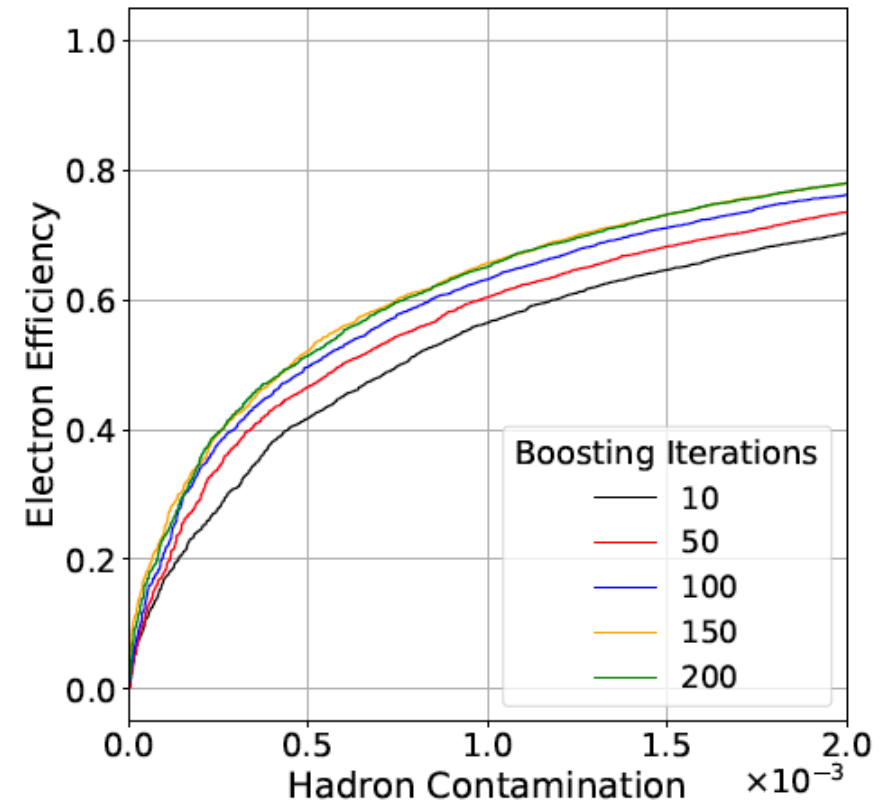
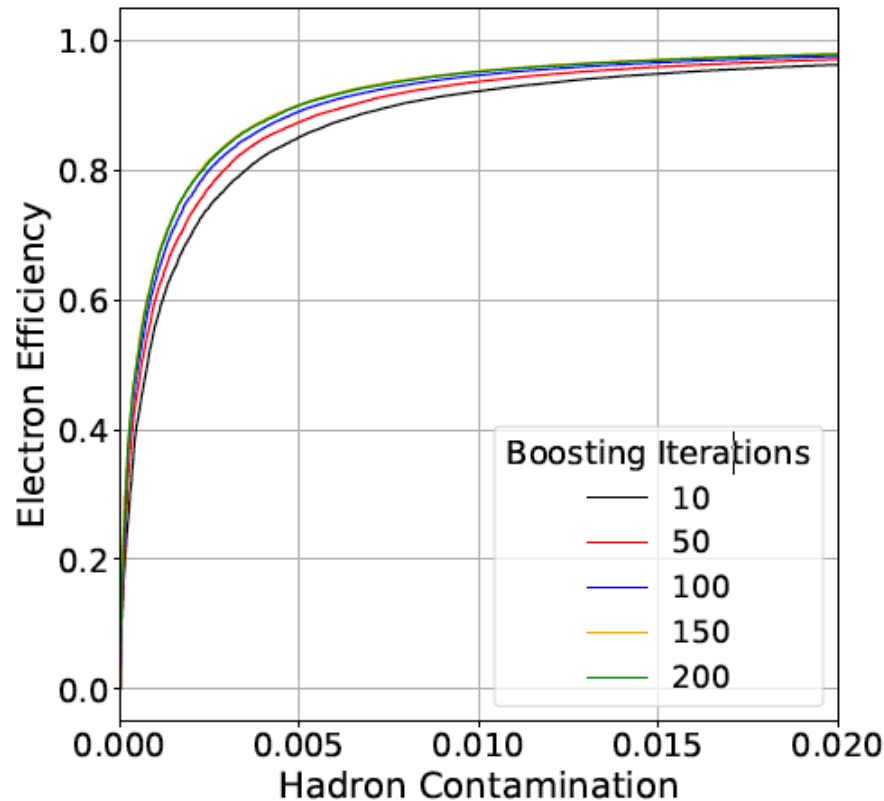
I. Vassiliev (GSI)

PHQMD-native



STAR-data inspired

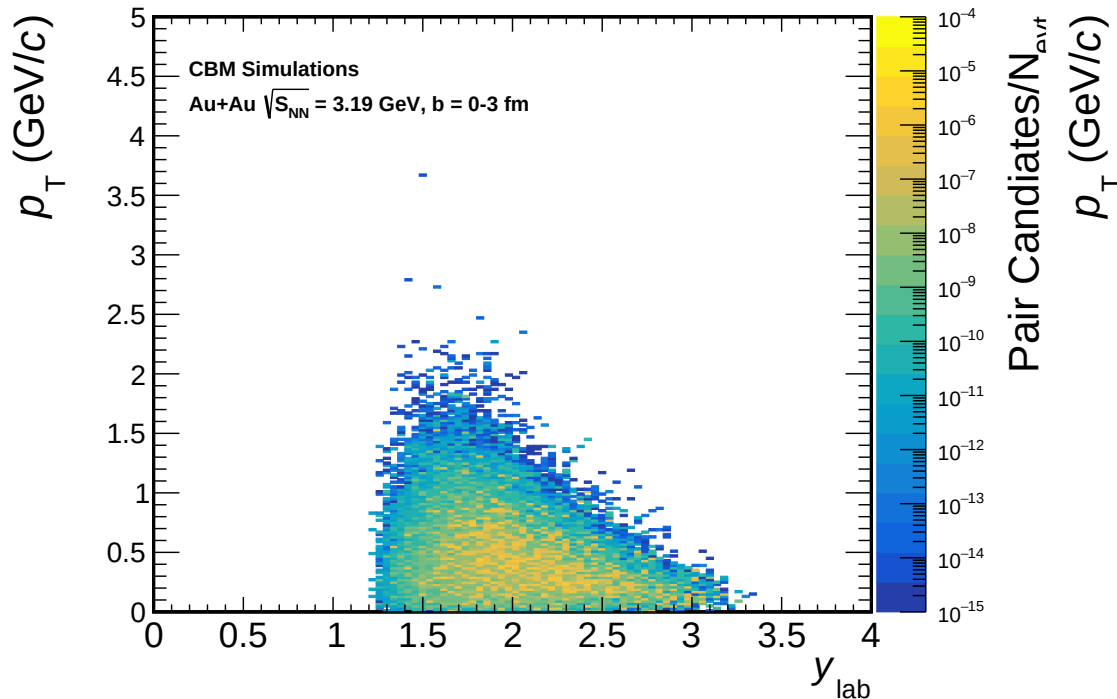




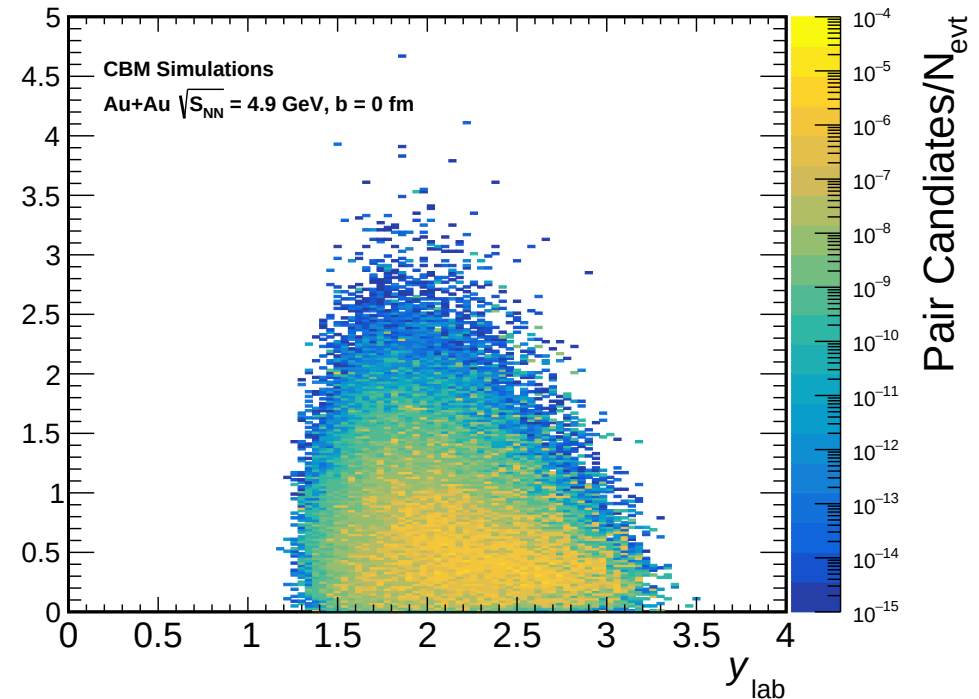
Combined RICH-TRD-TOF, BDT method (Au-Au, $\sqrt{s_{NN}} = 4.9$ GeV)

Master Thesis, H.Schiller (Münster, 2022); PhD P.Subramani (Wuppertal, 2025), A.Meyer-Ahrens (Münster, 2025)

Simulations, UrQMD, $\sqrt{s_{NN}} = 3.2, 4.9$ GeV; realistic PID (ML)



$$y_{lab}^{cm} = 1.13$$



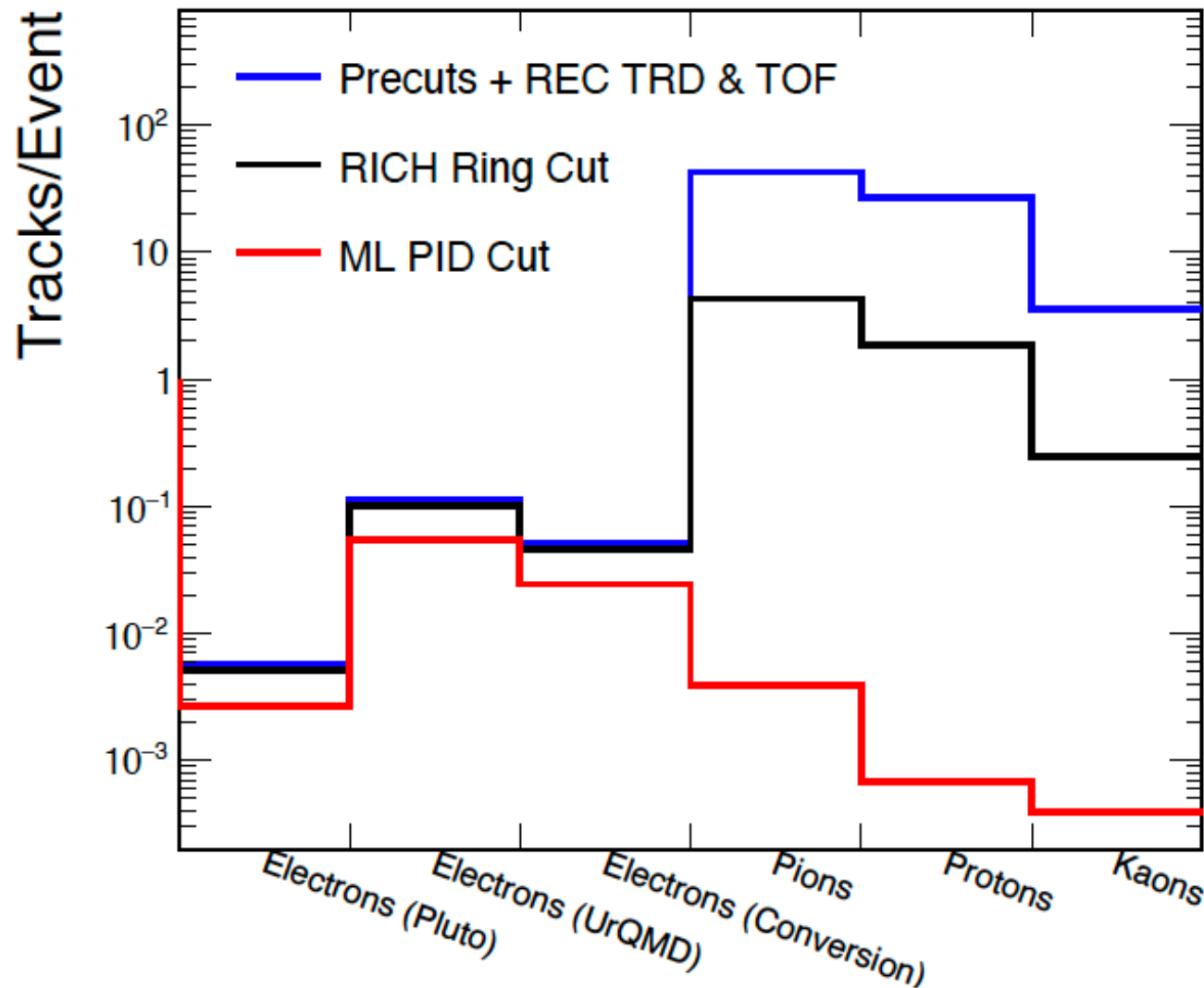
$$y_{lab}^{cm} = 1.62$$

broad phase space coverage, down to $p_T = 0$

following slides: Au-Au, $\sqrt{s_{NN}} = 4.9$ GeV ($b=0$)

PhD Thesis A.Meyer-Ahrens (U.Münster, 2025) [3.2 GeV: L. Faber]

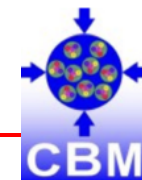
Electron identification performance: ML-based



Pluto generator: $\eta', \Delta, \omega, \phi \rightarrow e^+e^-$ (not in UrQMD)

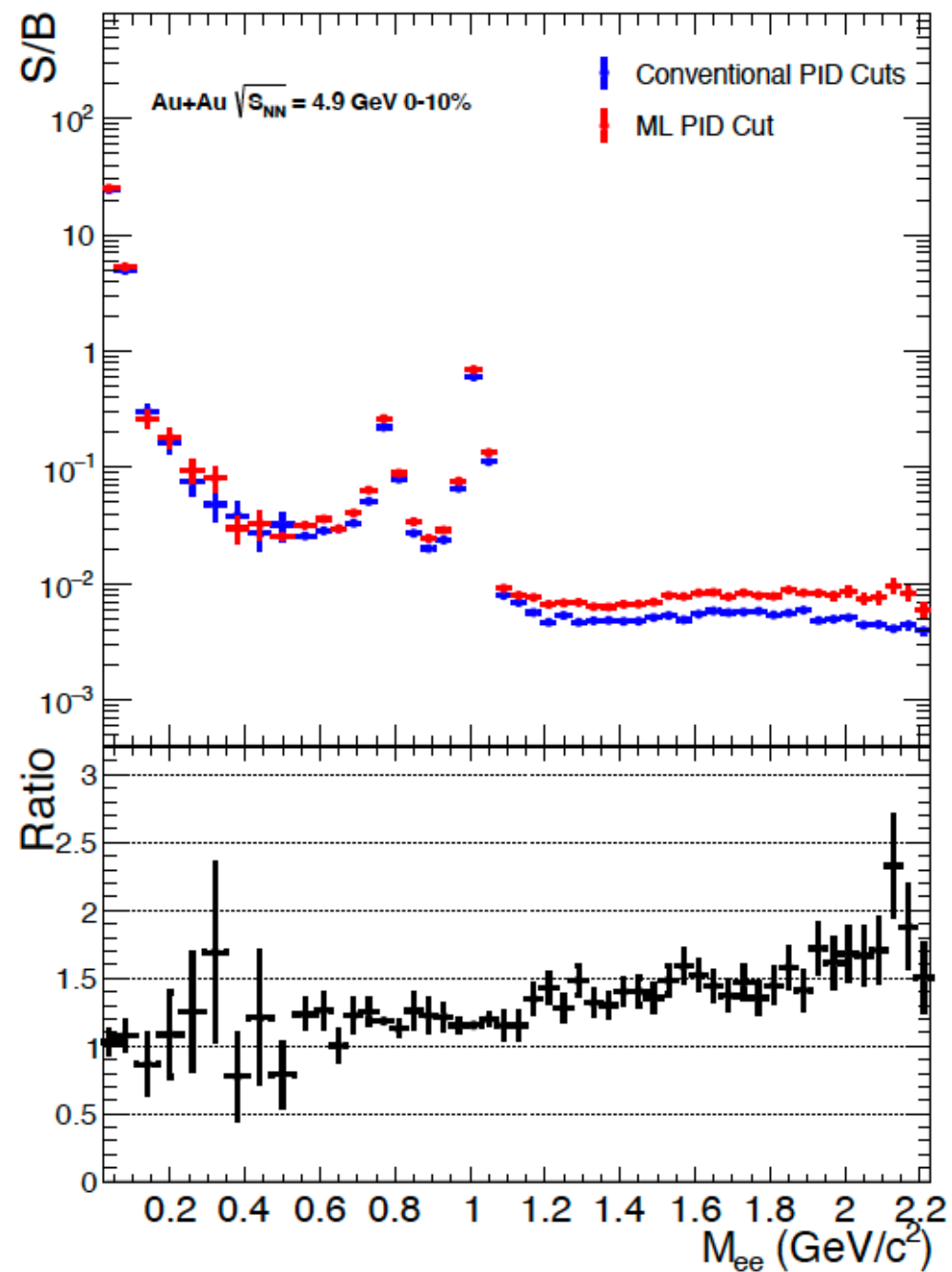
Better rejection of π , K , p by factors of 2.3, 1.4, 1.6 resp., wrt cut-based

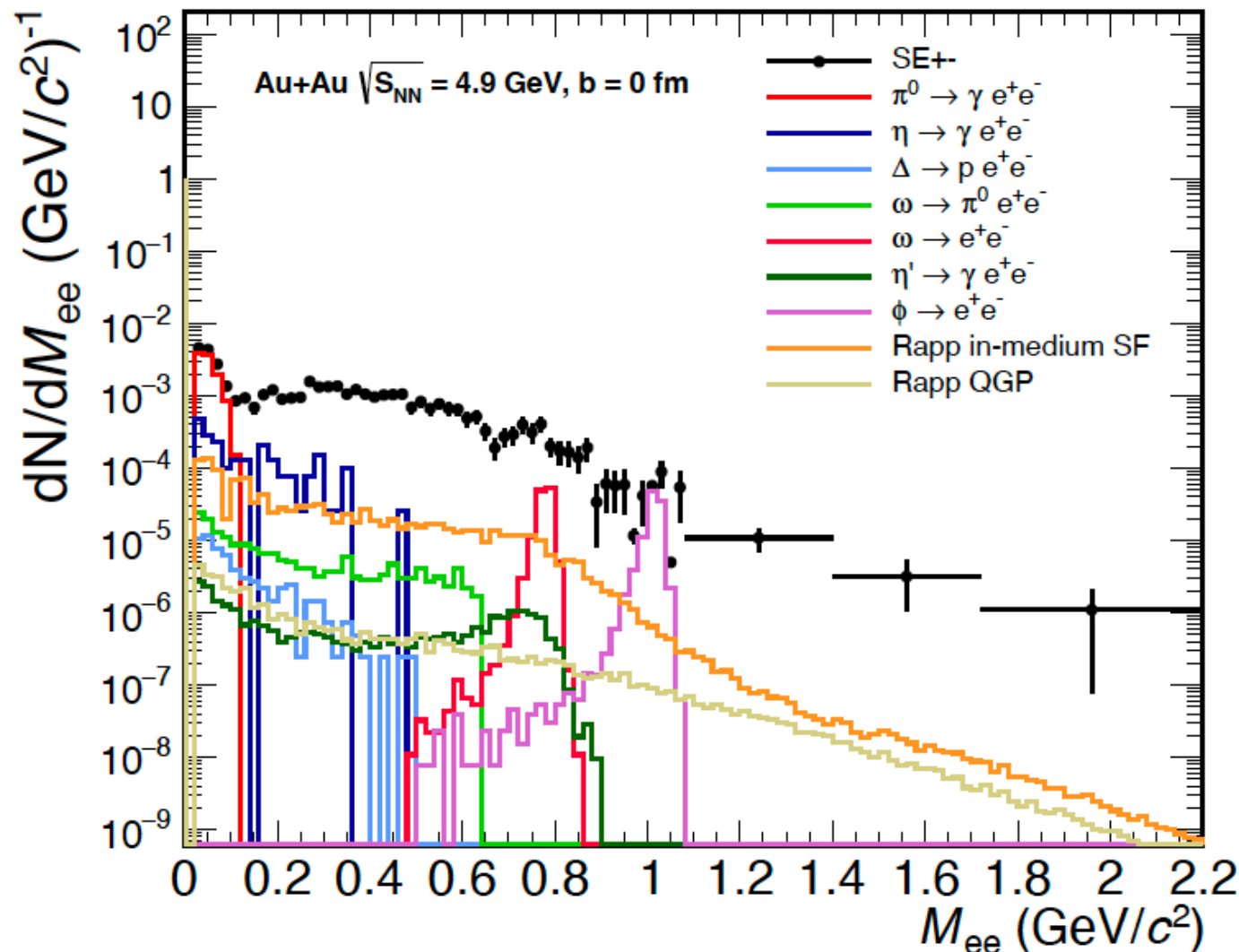
CBM: dielectron performance



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Nr. of 0-10% events needed to reach this performance: $\sim 10^{10}$ (1 day of running at 1 MHz)

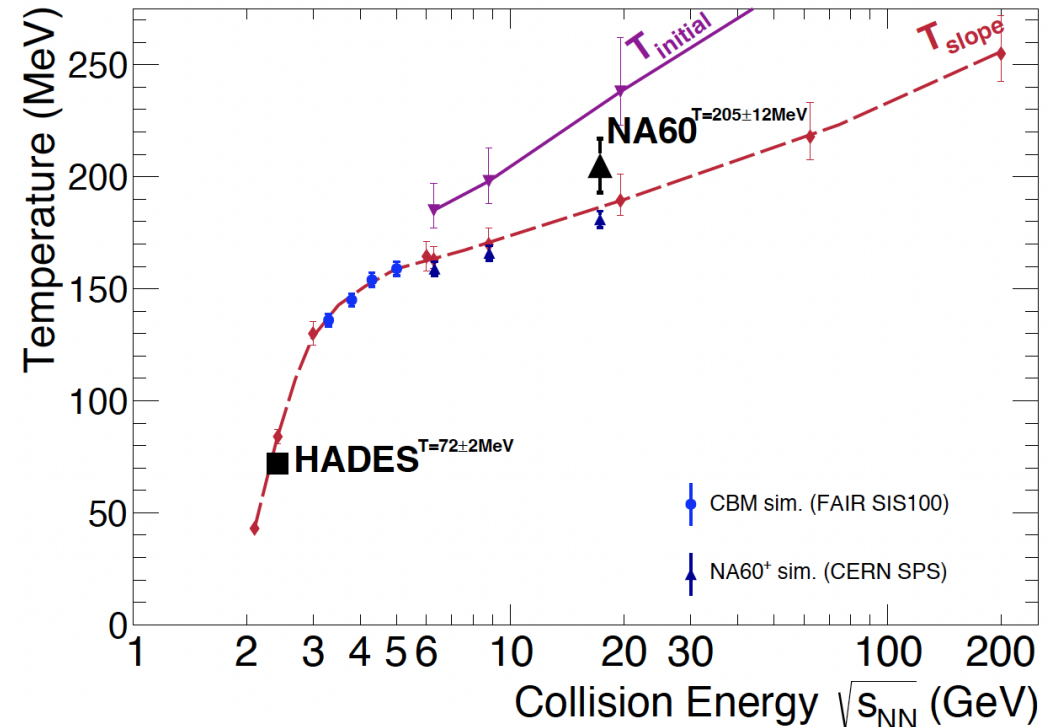
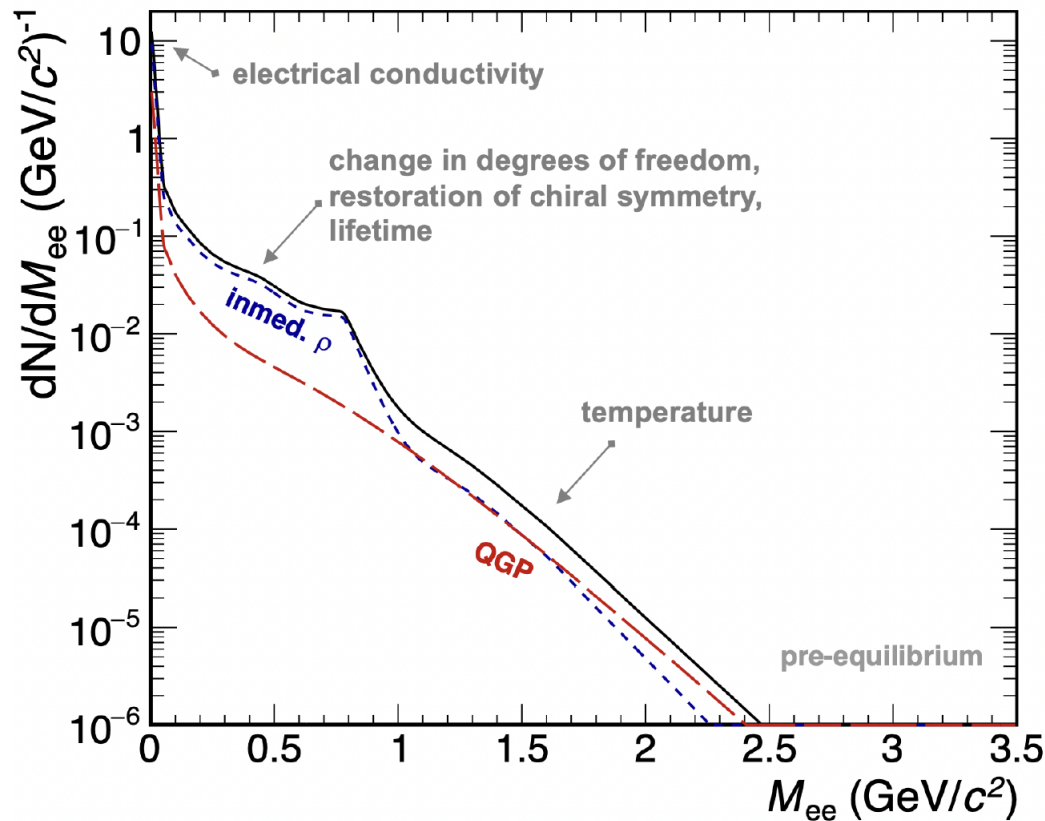
DY-like dileptons (background) for IM need to be quantified (EU Horizon project)

CBM: dileptons on broader perspective



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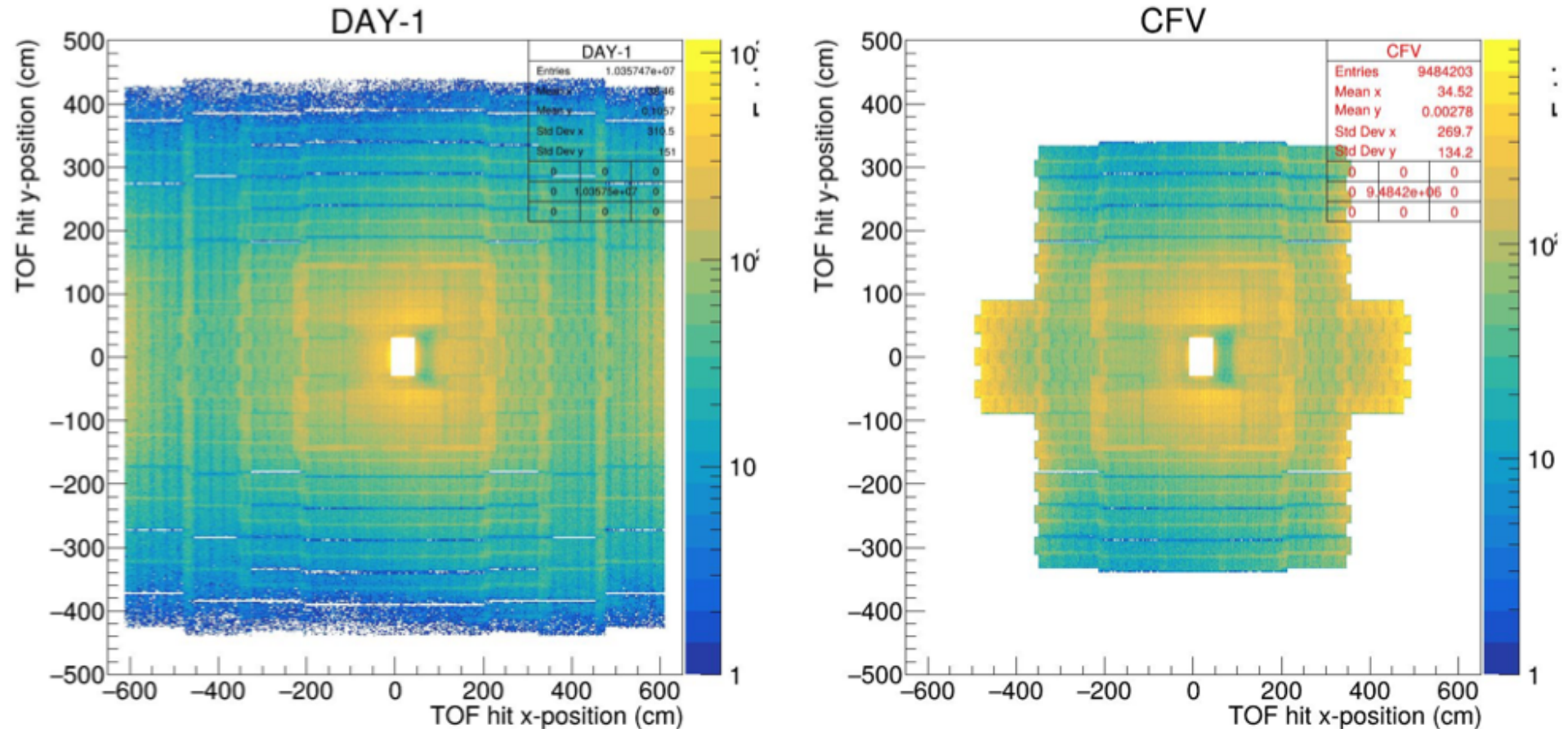
https://github.com/tgalatyuk/QCD_caloric_curve

Rapp, Wambach, *Adv. Nucl. Phys.* (2000) 25

fit data with: $dN/dM \sim M^{3/2} \exp(-M/T)$

Temperature averaged over the lifetime of the fireball (QGP+hadronic phase)

TOF hit-map



Day-1: complete CBM (as designed); CFV: Currently-funded version (2029)

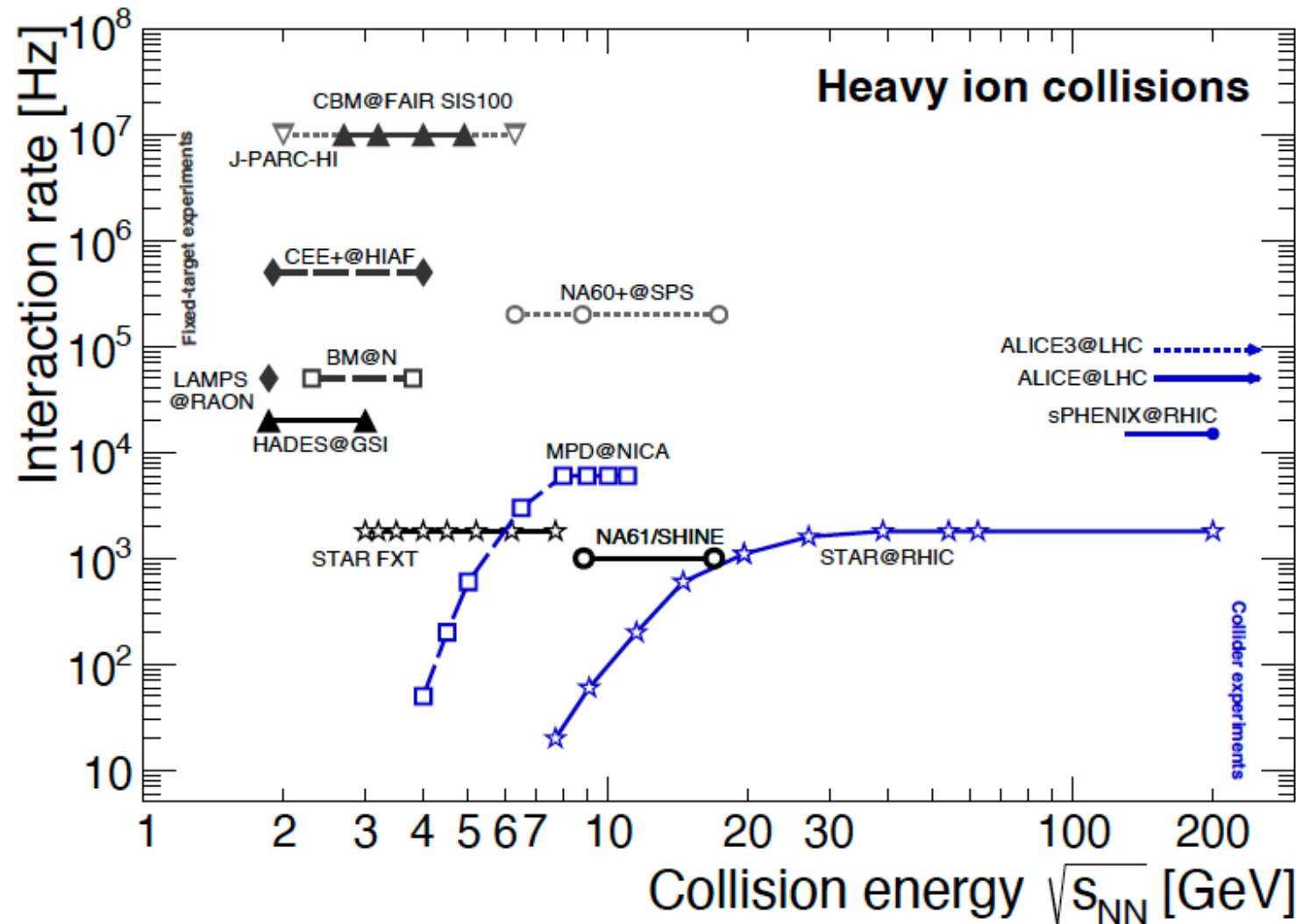
until now: Day-1 geometry; we currently quantify the difference in performance

CBM: the highest-rate experiment



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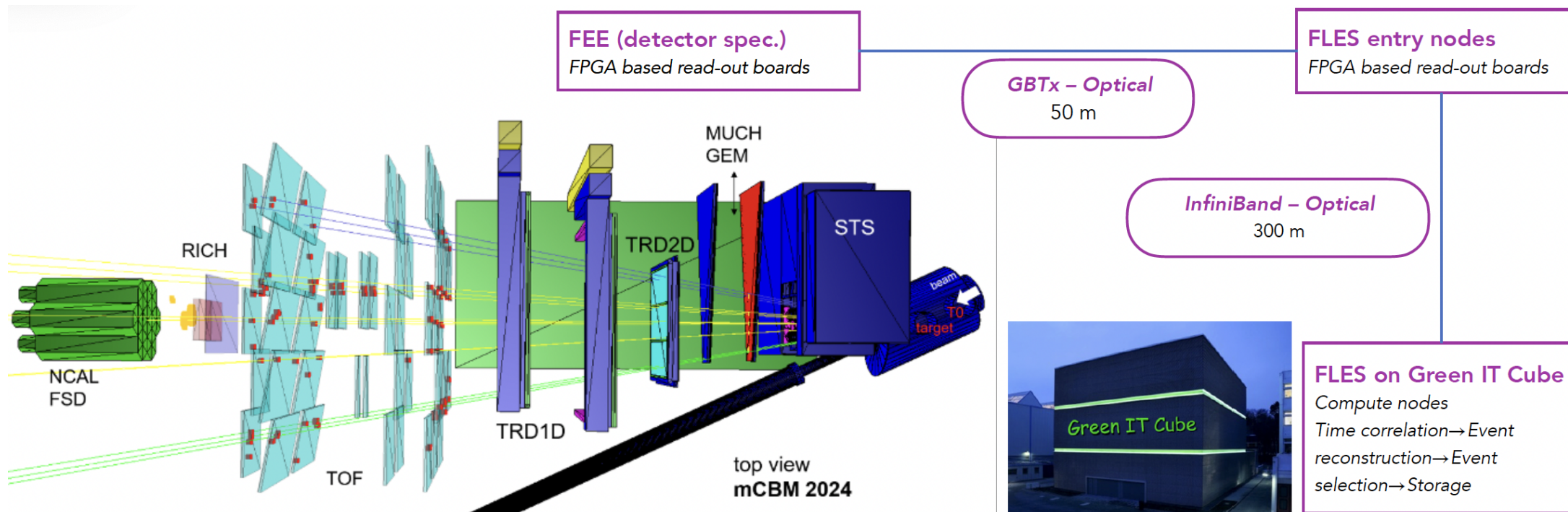


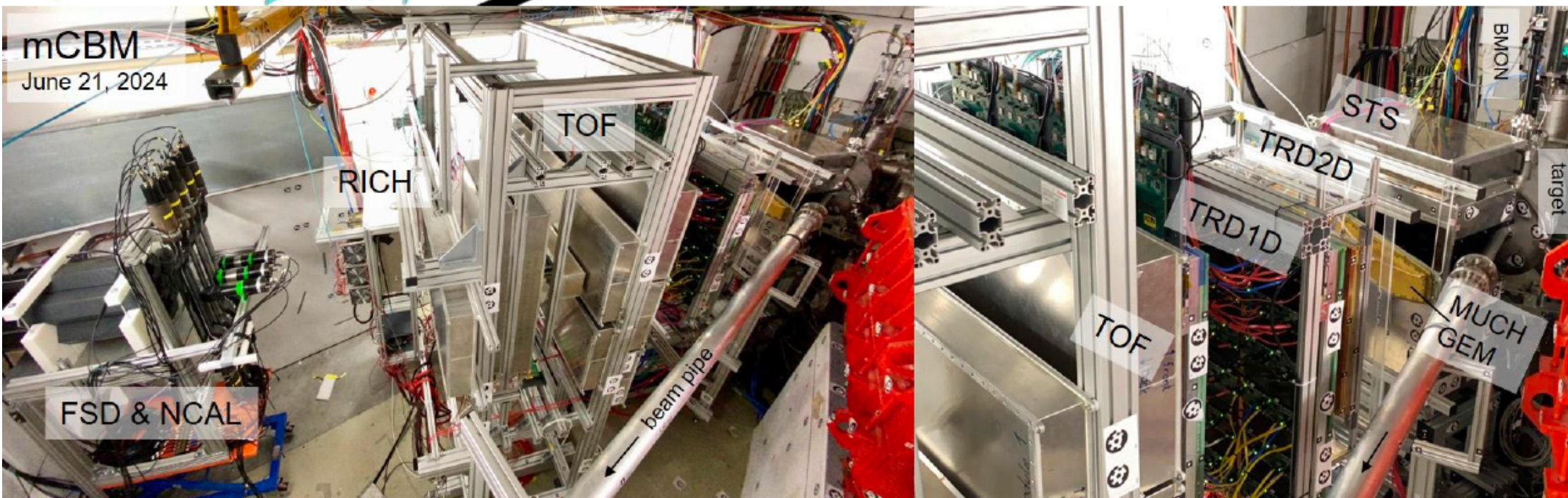
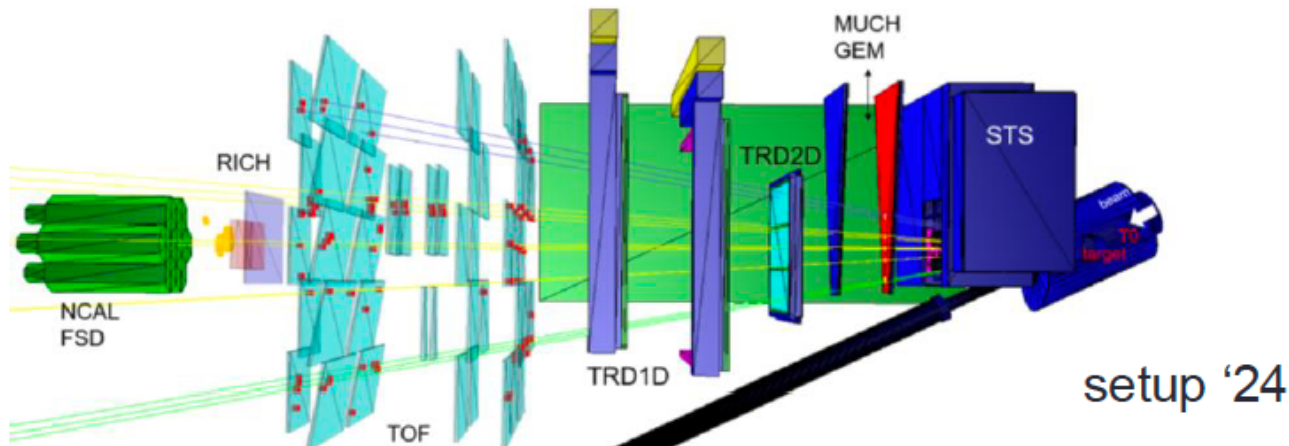
T.Galatyuk, NPA 982 (2019), https://github.com/tgalatyuk/interaction_rate_facilities

...but we will start “modestly”, with 100 kHz data taking (upgrades needed for 1-10 MHz)

Free-streaming readout and First Level Event Selection (FLES)

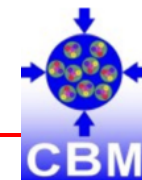
Full readout in mCBM@SIS18, currently commissioning FLES (Λ production)





Final prototypes or first-of-series detectors

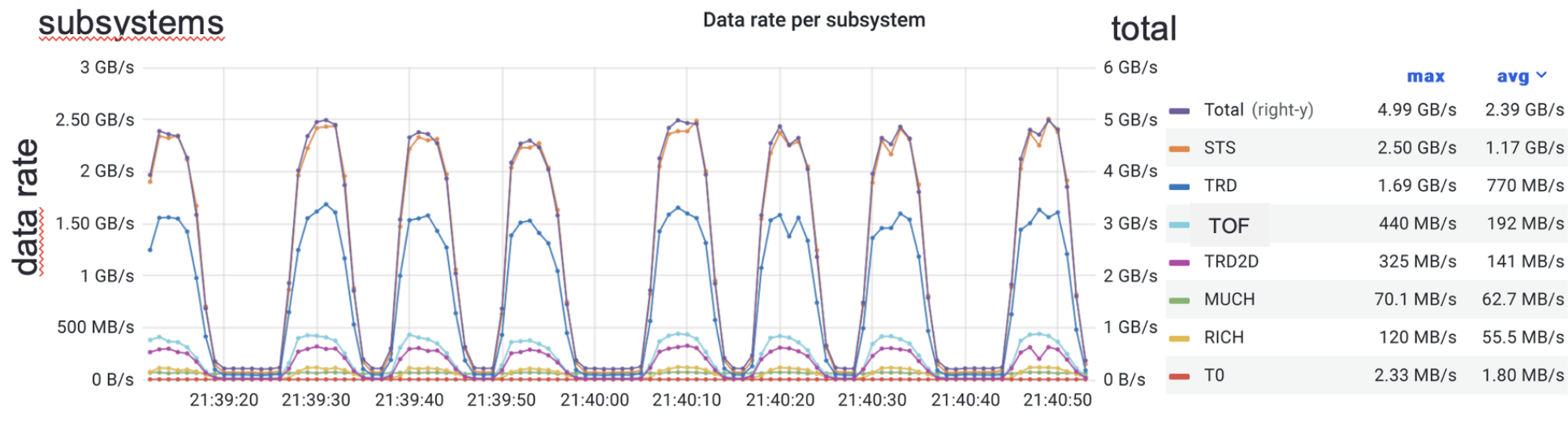
mCBM: readout



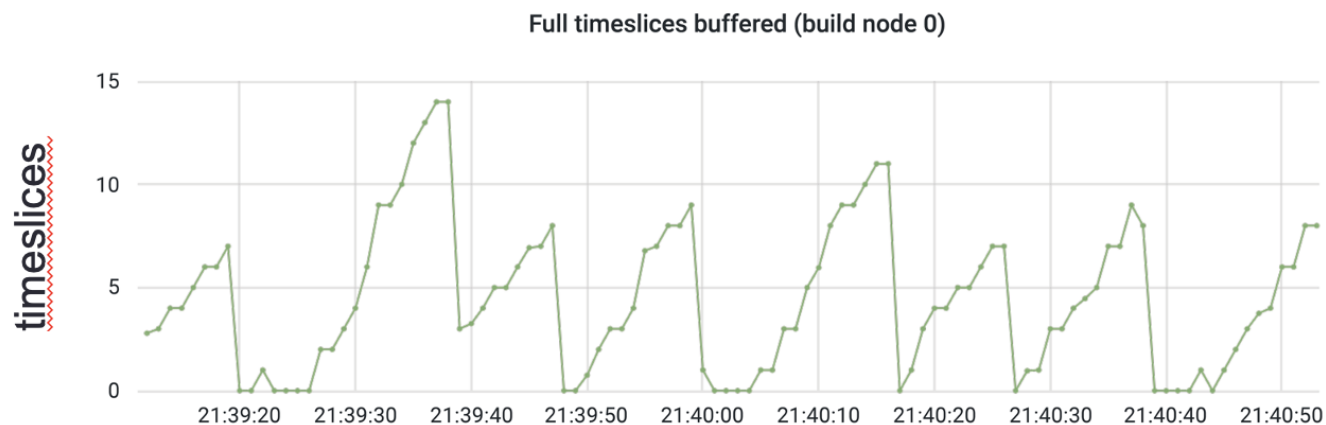
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FLES
input



FLES
output



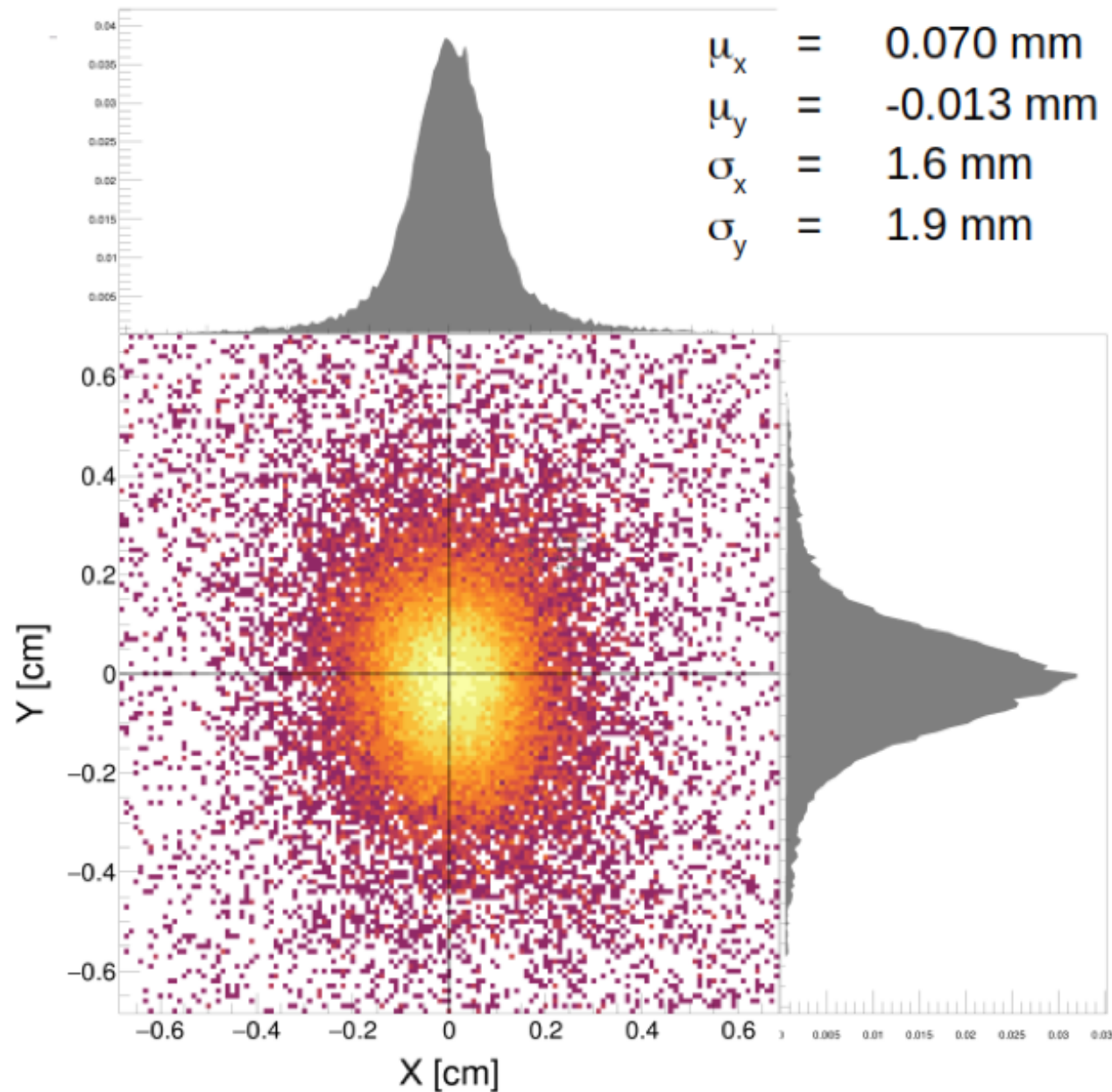
mCBM run 2448
June 16, 2022
Au + Au, $T = 1.23$ AGeV
av. collision rate: 300 - 400kHz
av. data rate 2.4 GB/s to disc

mCBM: tracking, primary vertex (beam spot)

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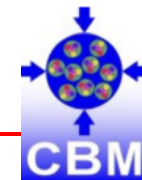


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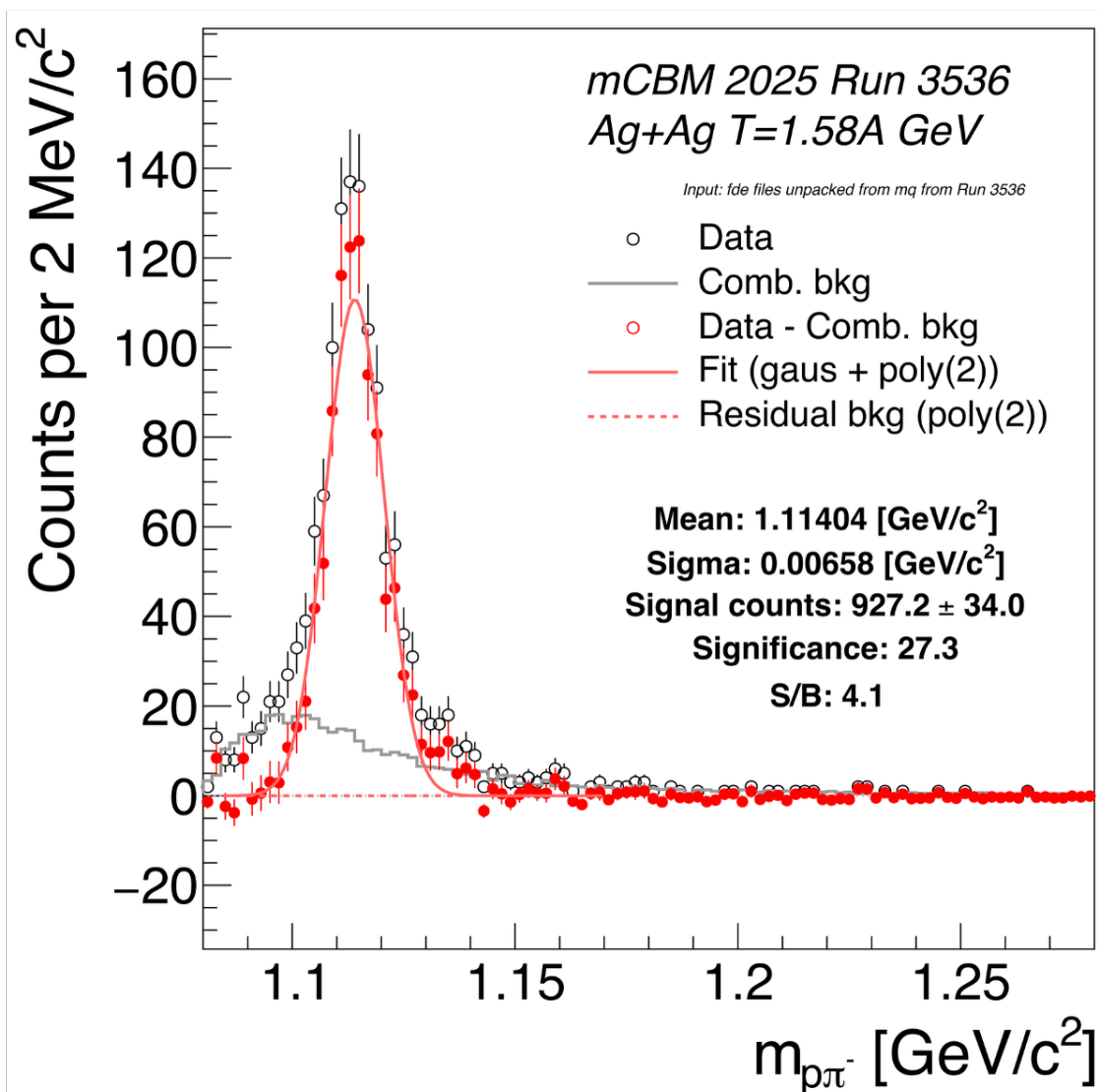


mCBM: Λ reconstruction (benchmark observable)

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- CA track reconstruction
- KFParticle package
- Goal: online reconstruction, event selection

Y.Hang, N. Herrmann (U. Heidelberg)

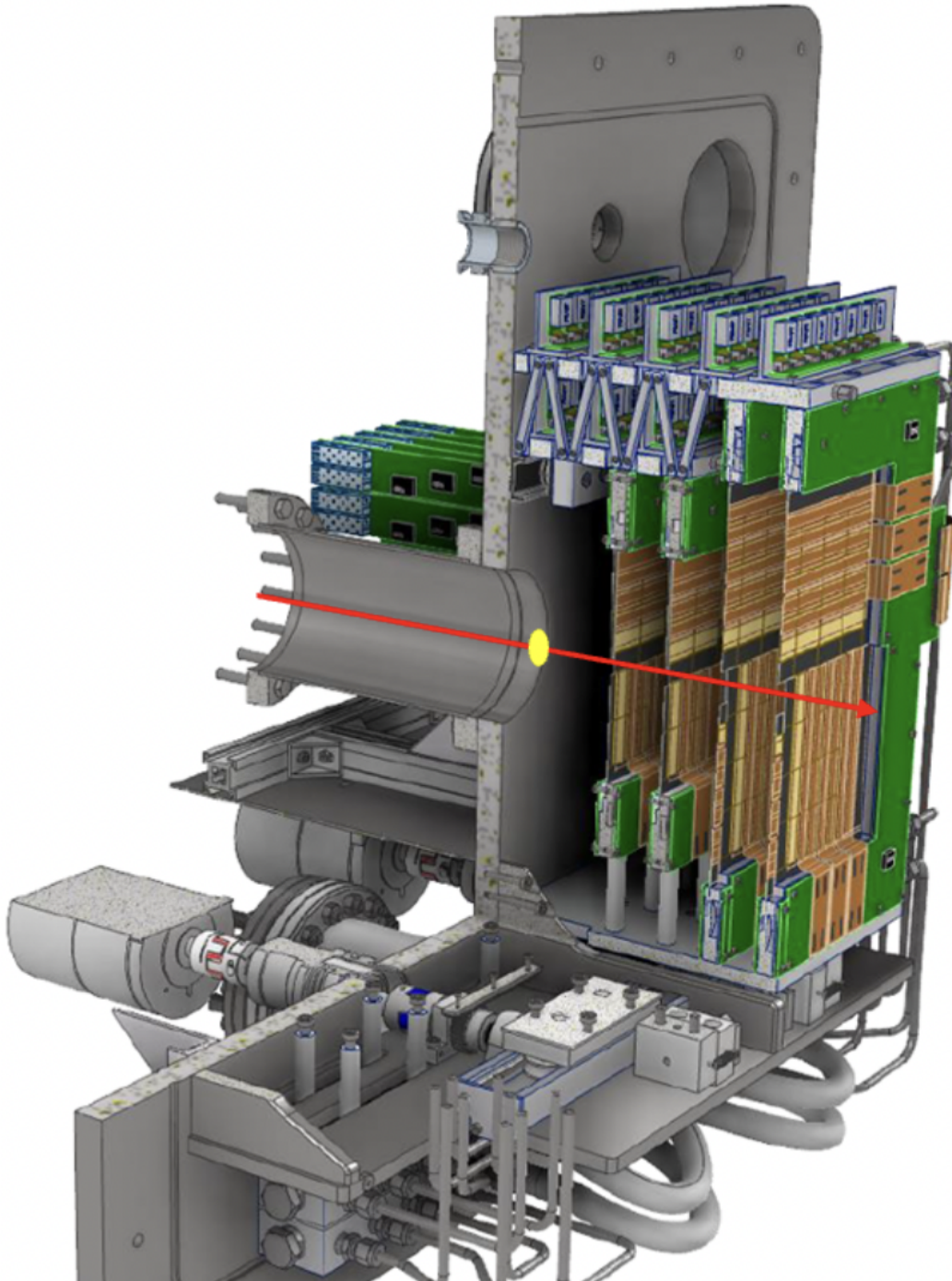
- the stat. hadr. model provides a simple way to access the QCD phase boundary
...*at high energies* (at low energies canonical suppression needs more care)
...but is it more than a 1st order description (of loosely-bound objects)?
...and what fundamental point does it make about hadronization?
(statistical features dominate, but understanding still missing as a dynamical process)
- CBM will study the QCD phase diagram in the high- μ_B ($\gtrsim 500$ MeV) region
is progressing well towards the science program with SIS100 beams
High-rate capabilities (detector, readout) achieved in extensive R&D phase
Almost all systems in (pre-)series production
Start of commissioning/data-taking with cosmics/beam in 2028/29
More and more realistic physics performance with MC (incl. syst. uncert.)

Additional slides

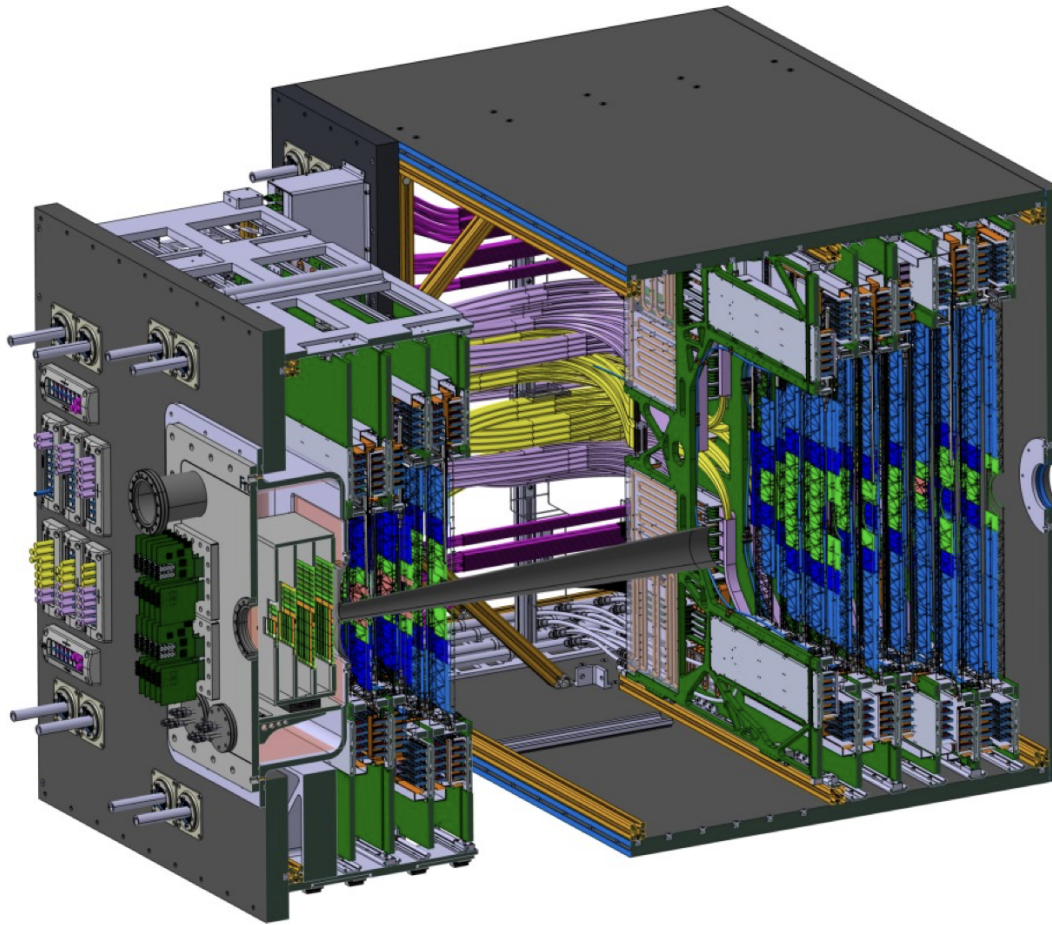
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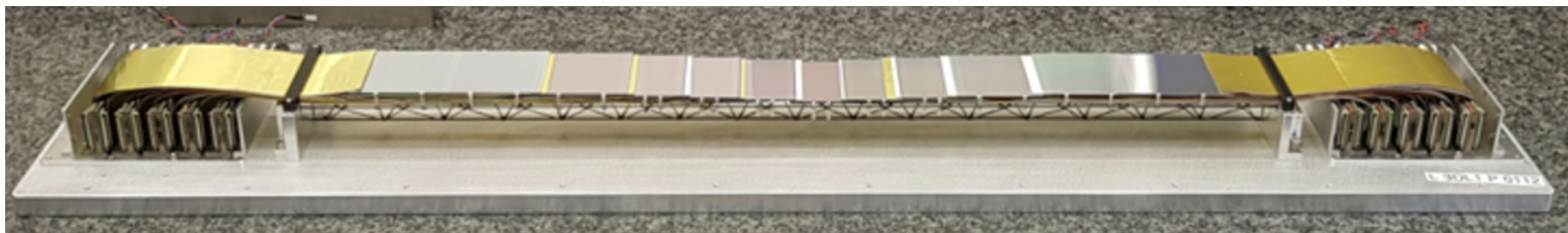


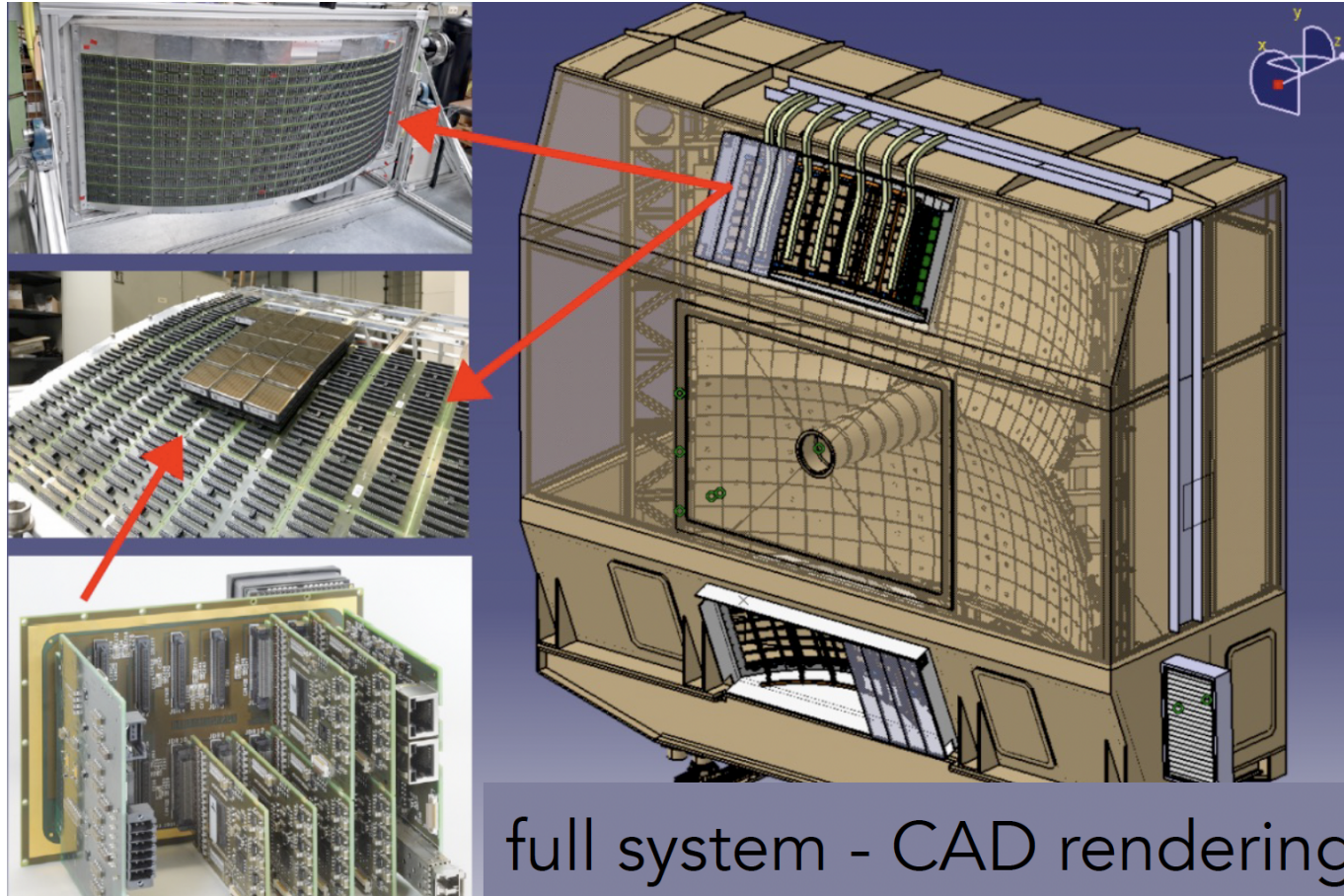
- Charmed-hadron reconstruction
- MAPS (180 nm CMOS, Tower; MIMOSIS-3)
- $\sigma_{x,y} = 5 \mu\text{m}$; Power: $100 \text{ mW}/\text{cm}^2$
- Radiation:
 5 Mrad & $5 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$
- 4 planes, operated in vacuum



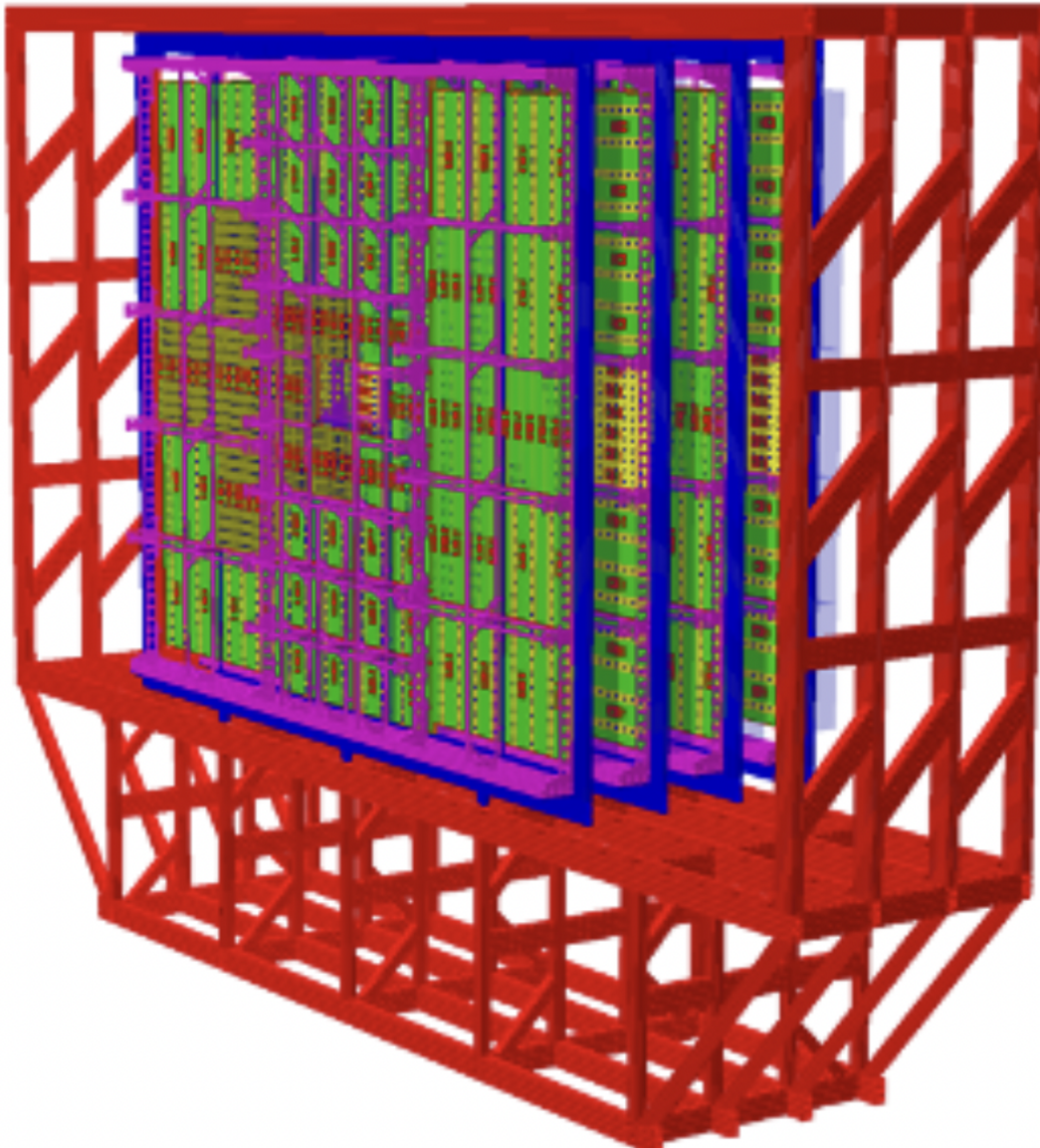
- Tracking and momentum measurement, $\Delta p/p = 1-2\%$ ($B=1$ T)
- $\sigma_{x,y} = 30 \mu\text{m}$; $\sigma_t = 5$ ns
- Low material budget ($2-8\% X_0$)
- Double-sided silicon strip det.
- 8 planes
- 876 modules, 2×1024 ch. each
(62×22 , 42 , 62 , 124 mm^2)
106 ladders (up to 10 modules)

see [JINST 9 \(2024\)](#)

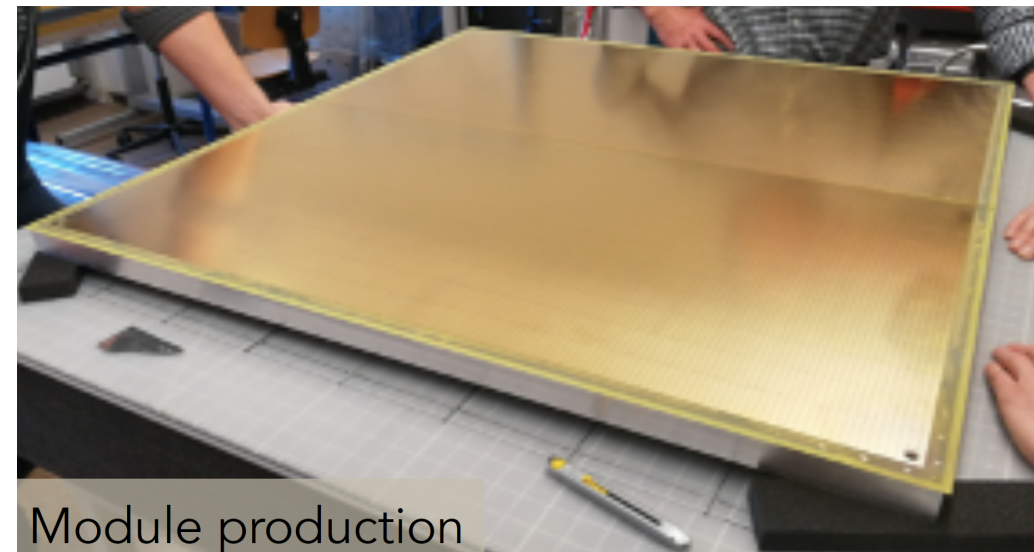




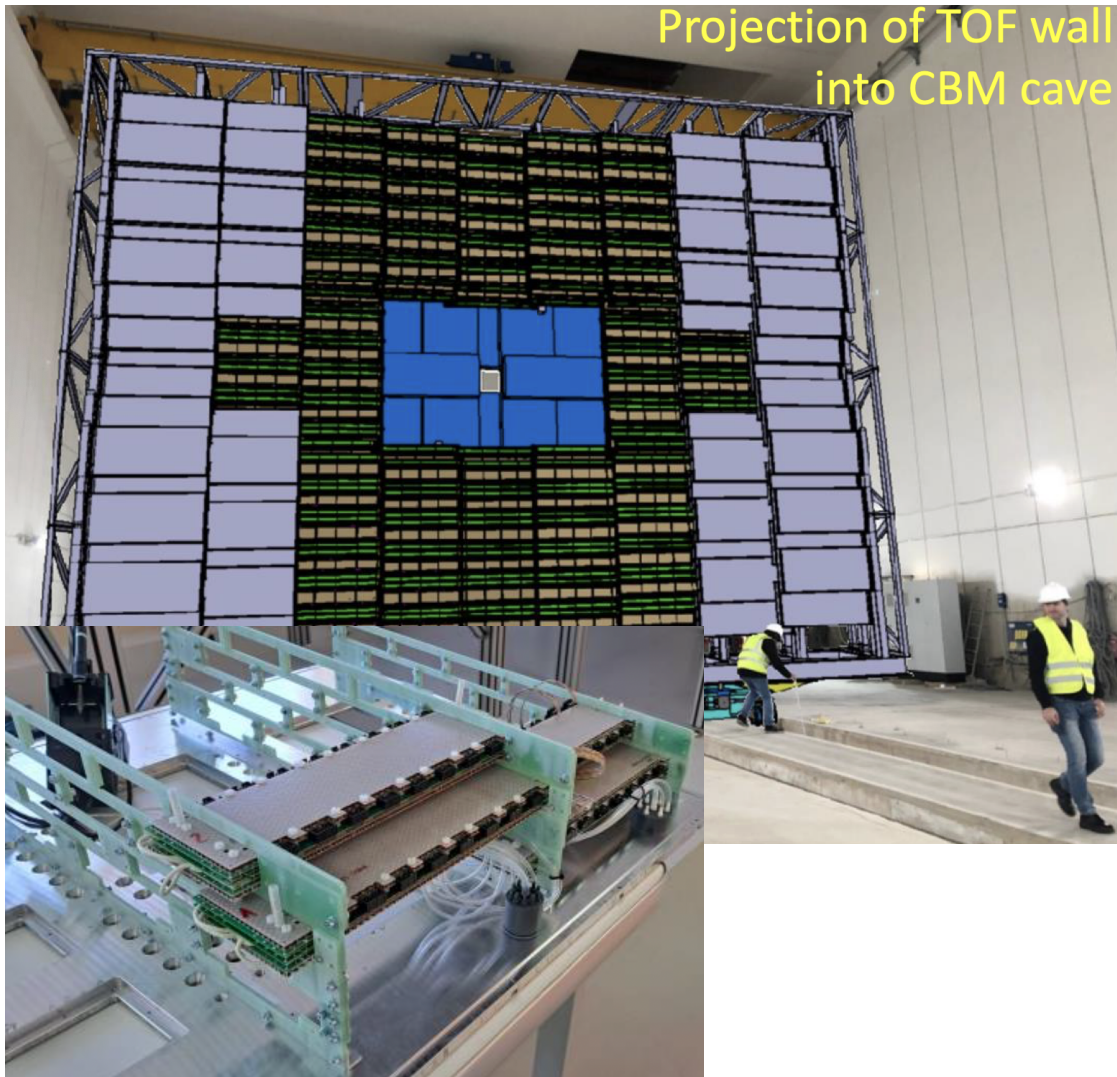
- Electron identification
- CO_2 at normal pressure
 $n=1.00043$, $\gamma_{thr} = 33$
 $p_{thr}^\pi \simeq 4.8 \text{ GeV}/c$
- $R^e=4.8 \text{ cm}$
- 2 mirrors, focal length 1.5 m
- Multi-anode PMTs (1100)
70k pixels



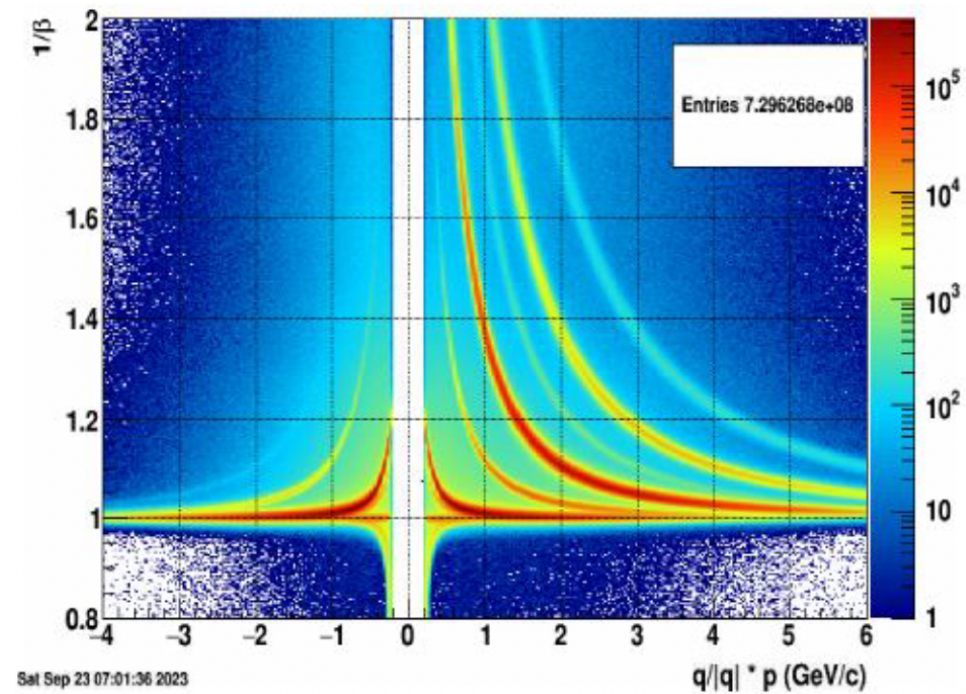
- Electron, light nuclei identification
Track matching STS-TOF
- $\sigma_{x,y} = 100 - 300 \mu\text{m}$
(outer, long pads: $\sim\text{cm}$)
- Radiator (PE foam), TR: 5-30 keV
MWPC (1.2 cm, Xe-CO₂)
- Pad readout, FADC; 250k channels



Projection of TOF wall
into CBM cave

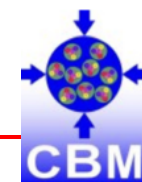


- Hadron identification
- Multi-gap RPCs (glass, strips)
- System resolution: 80 ps



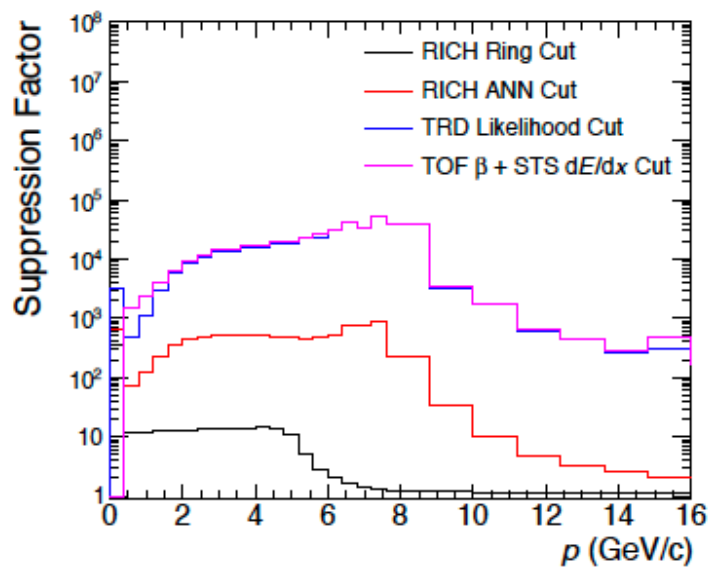
Modules installed in STAR, FXT program

Electron identification performance: cut-based

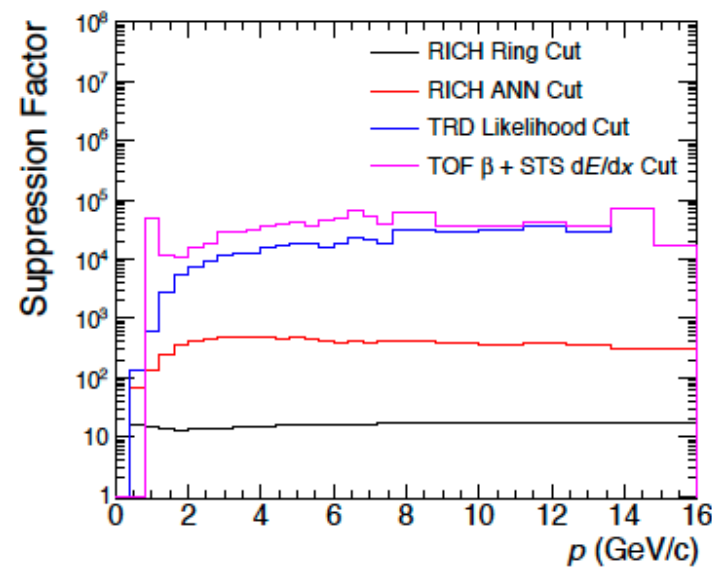


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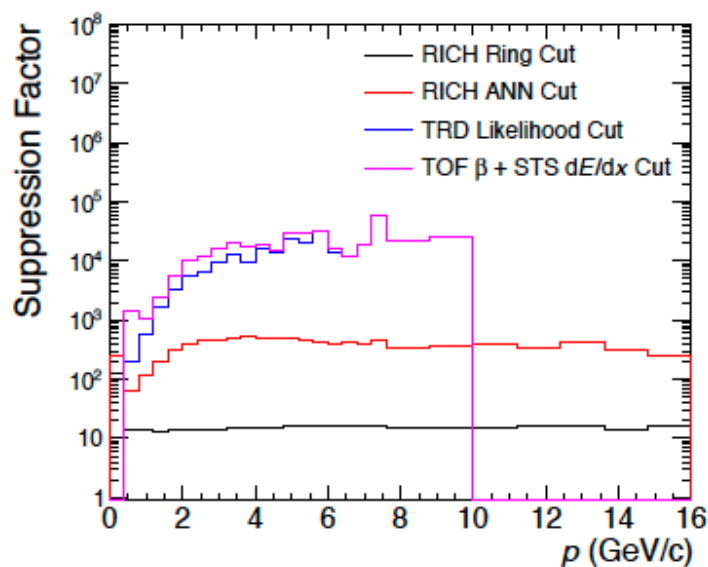
60



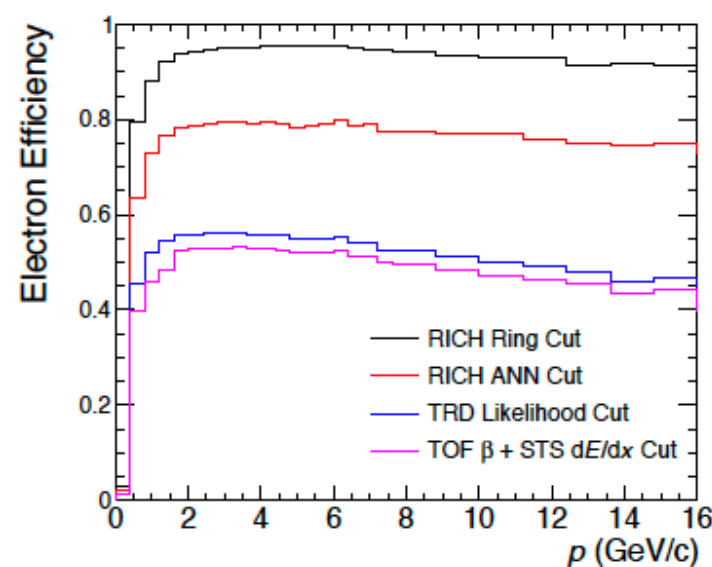
(a) Pions



(b) Protons



(c) Kaons



(d) Electrons

Cut Class	Cut Name	Range
PreCuts	p_T	$p_T > 0.05 \text{ GeV}/c^2$
	recSTSMVD	Nr. of STS+MVD-hits > 3
	rec1TRD	Nr. of TRD-hits > 0
	PairPreFilter	m_{inv} of pair candidate $> 0.025 \text{ GeV}/c^2$
	Chi2/NDF to VTX	χ^2/NDF to vertex ≤ 3
	recSTS	Nr. of STS-hits > 2
	recMVD	Nr. of MVD-hits > 2
RECCutsPID	recTRD	Nr. of TRD-hits > 2
	recTOF	Nr. of TOF-hits > 0
PIDCuts	recRICH	Nr. of RICH-hits > 5
	Global BDT Classifier (XGBoost)	50% Ele. Efficiency
Segment Cut	Opening Angle	