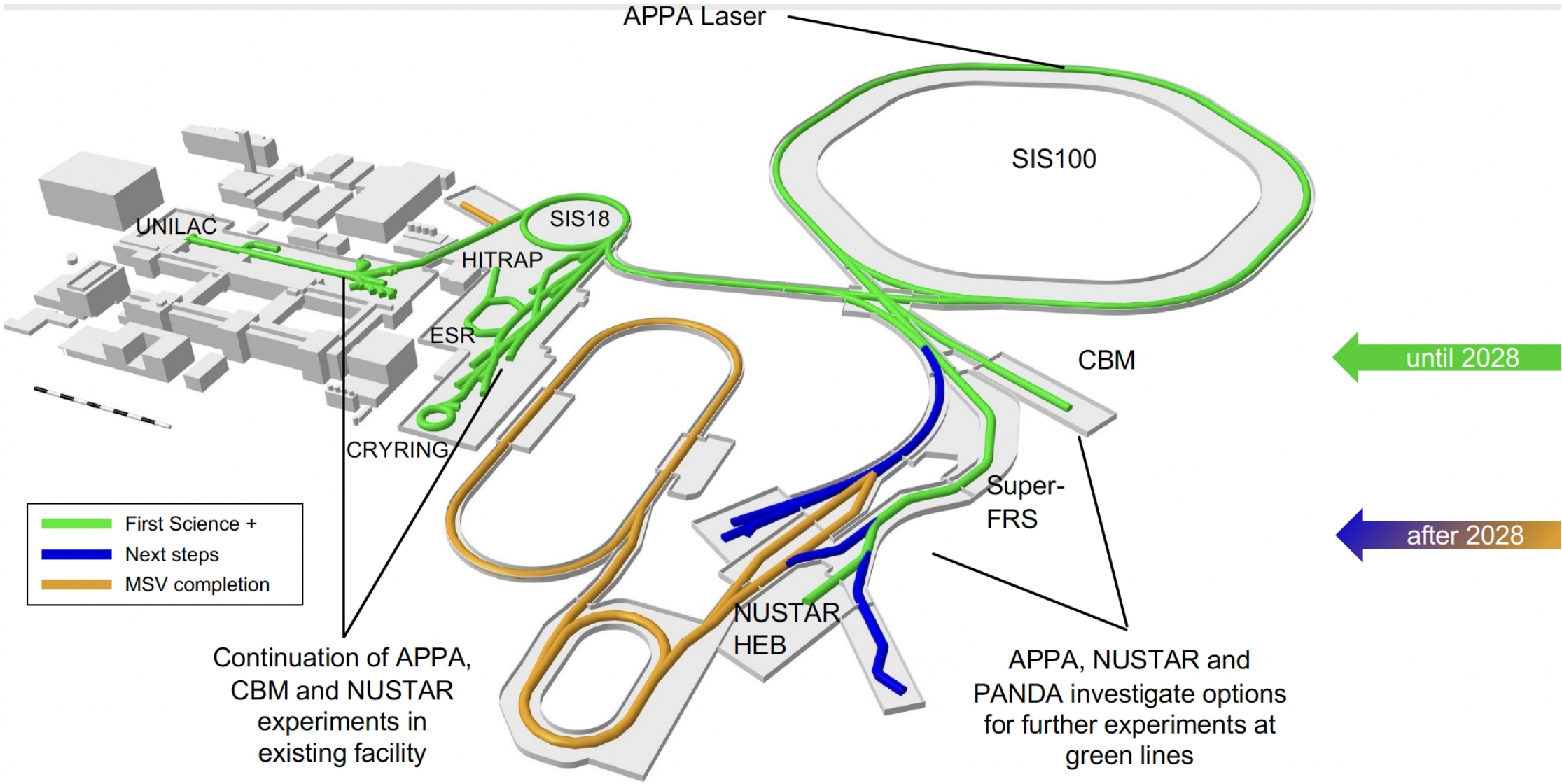
The CBM experiment at FAIR: overview and physics performance

A. Andronic - University of Münster

for the CBM Collaboration

- FAIR
- CBM
  - Detector
  - Physics: motivation, goals, performance
  - Current status
- Summary / Outlook (Extra slides: SHM, charm at high-μ_B)

FAIR Complex at GSI Darmstadt




Facility for Antiproton and Ion Research
multi-purpose (strong interaction) facility
FAIR
• Civil construction work completed
• Installation of accelerator components begun
Sep. 2024

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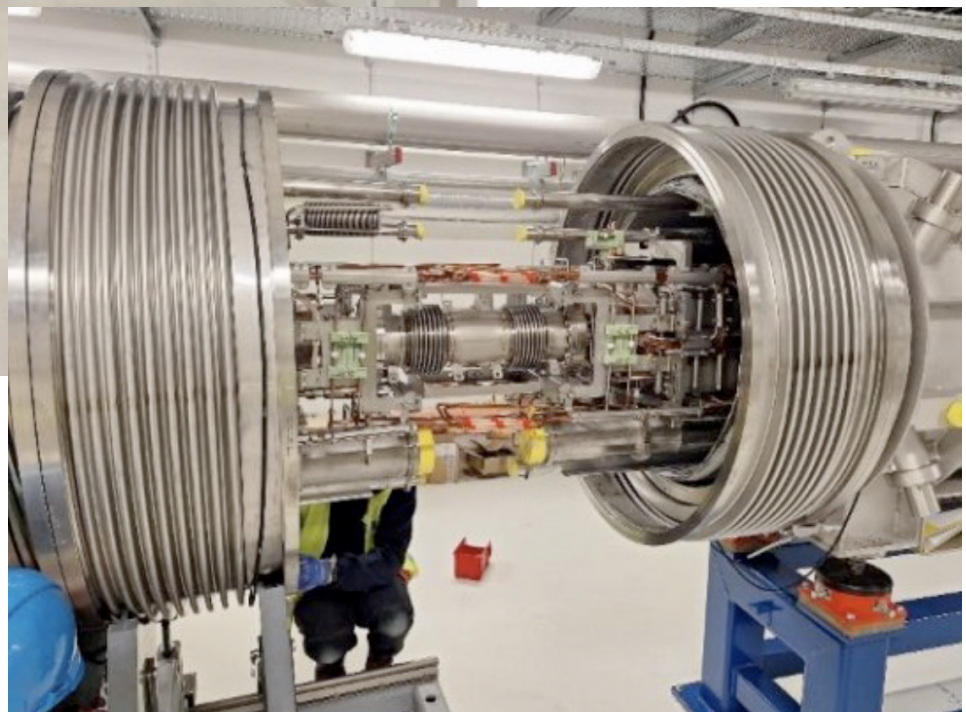
Sep. 2024

Inside FAIR

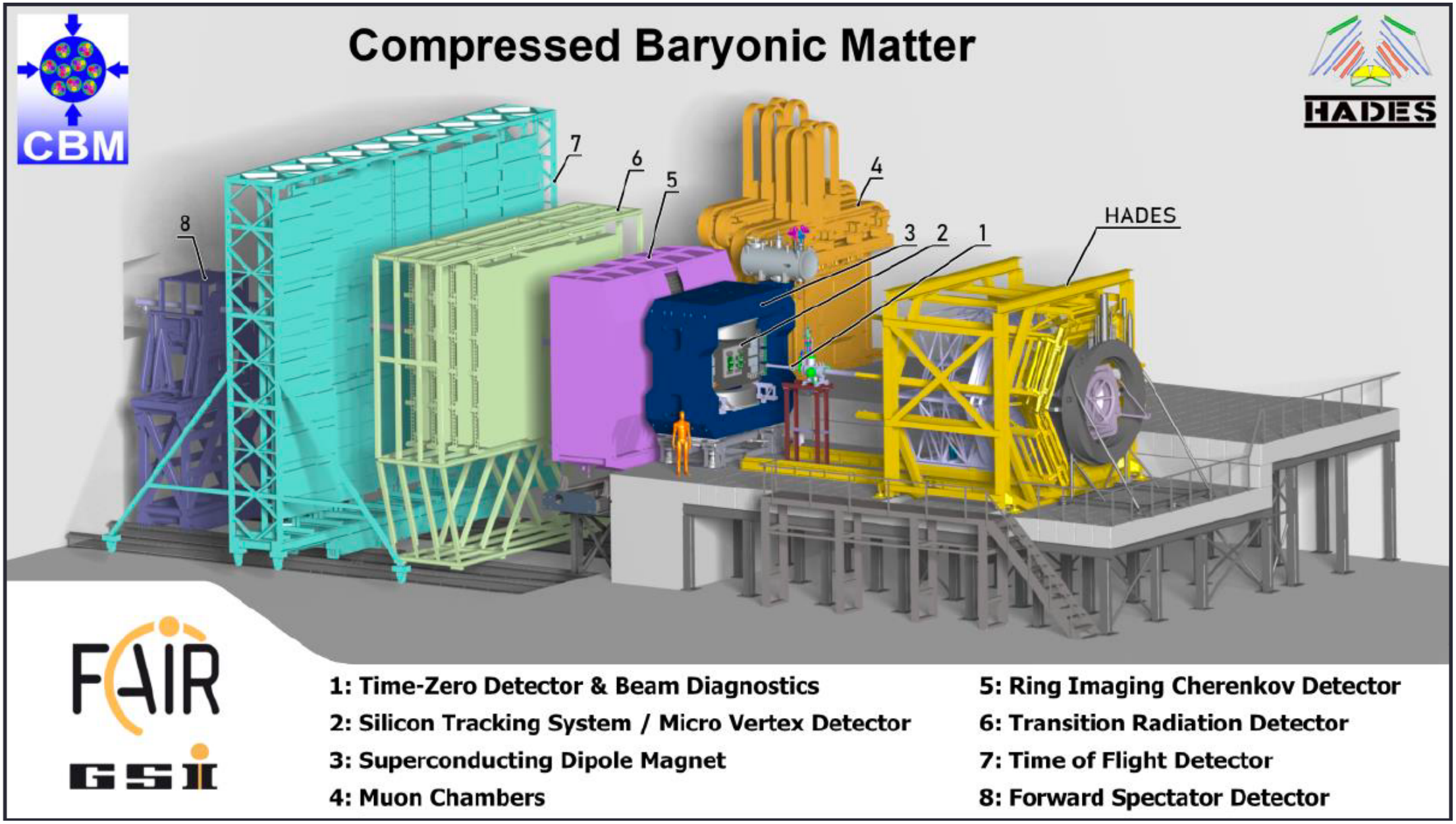


see More photos, videos

Inside FAIR


Compressed Baryonic
HADES
CBM
FAIR
GSI
Diagnostics
Vertex Detector

CBM Detector



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

CBM: heavy-ion collisions at FAIR energies

Au-Au collisions, E_{beam} =2-11 GeV/nucleon on fixed target

$$\sqrt{s_{NN}} = 2.7 - 4.9 \text{ GeV}$$

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

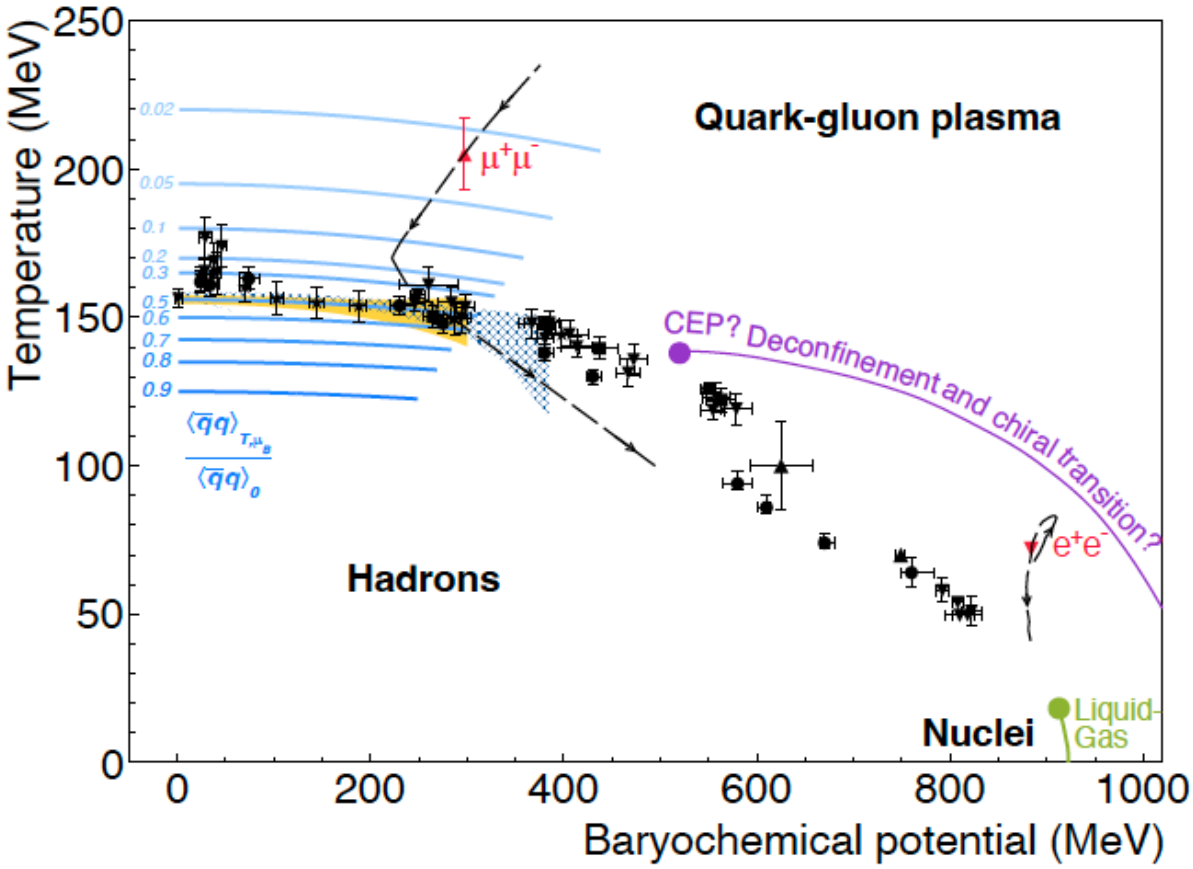
...a report on this topic will be published later this year

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)

CBM mission

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



HADES, Nature Phys. 15 (2019) 1040

Andronic et al, Nature 561 (2018) 321

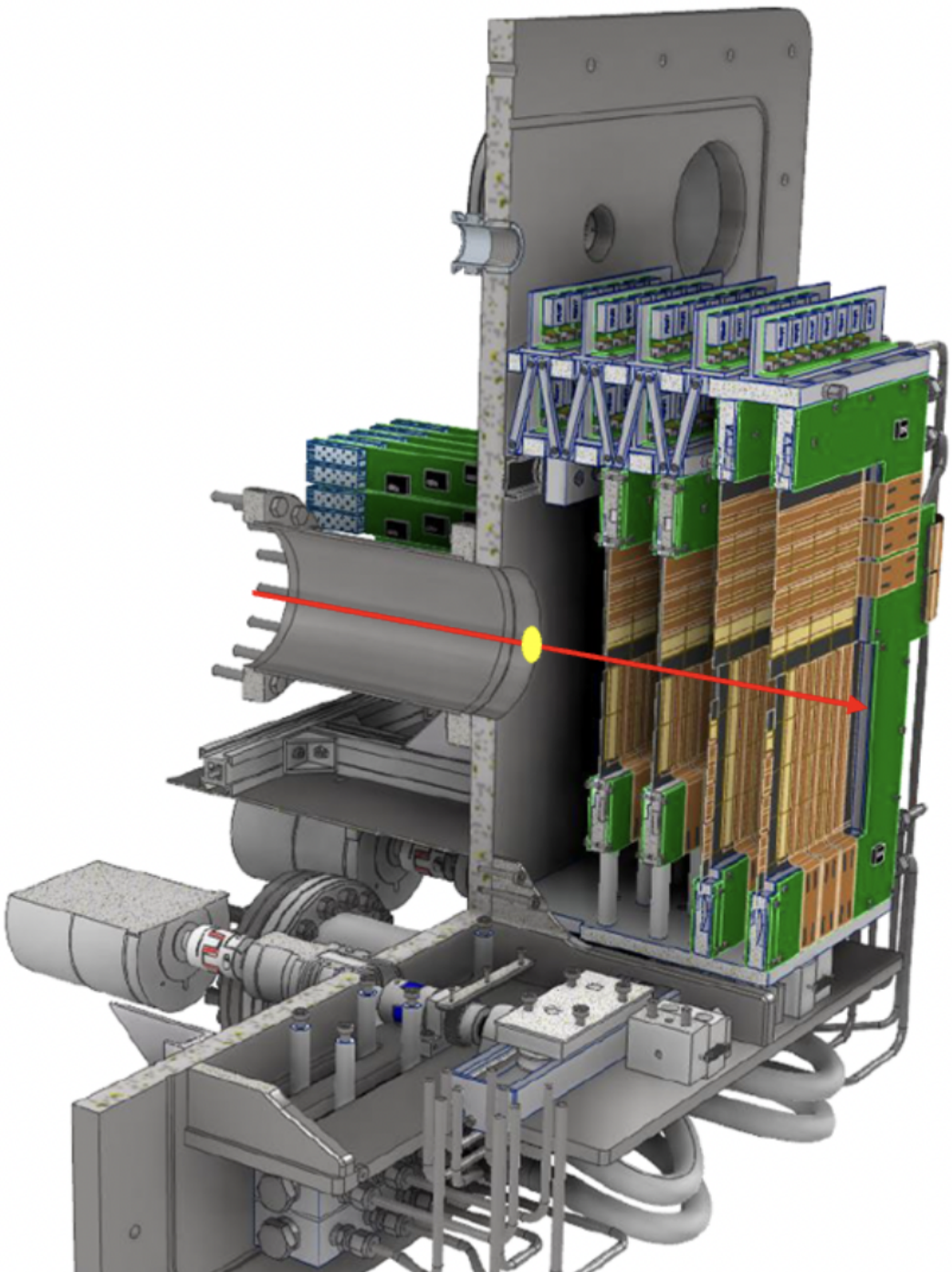
Observables (abundant/rare):

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

CBM Detector

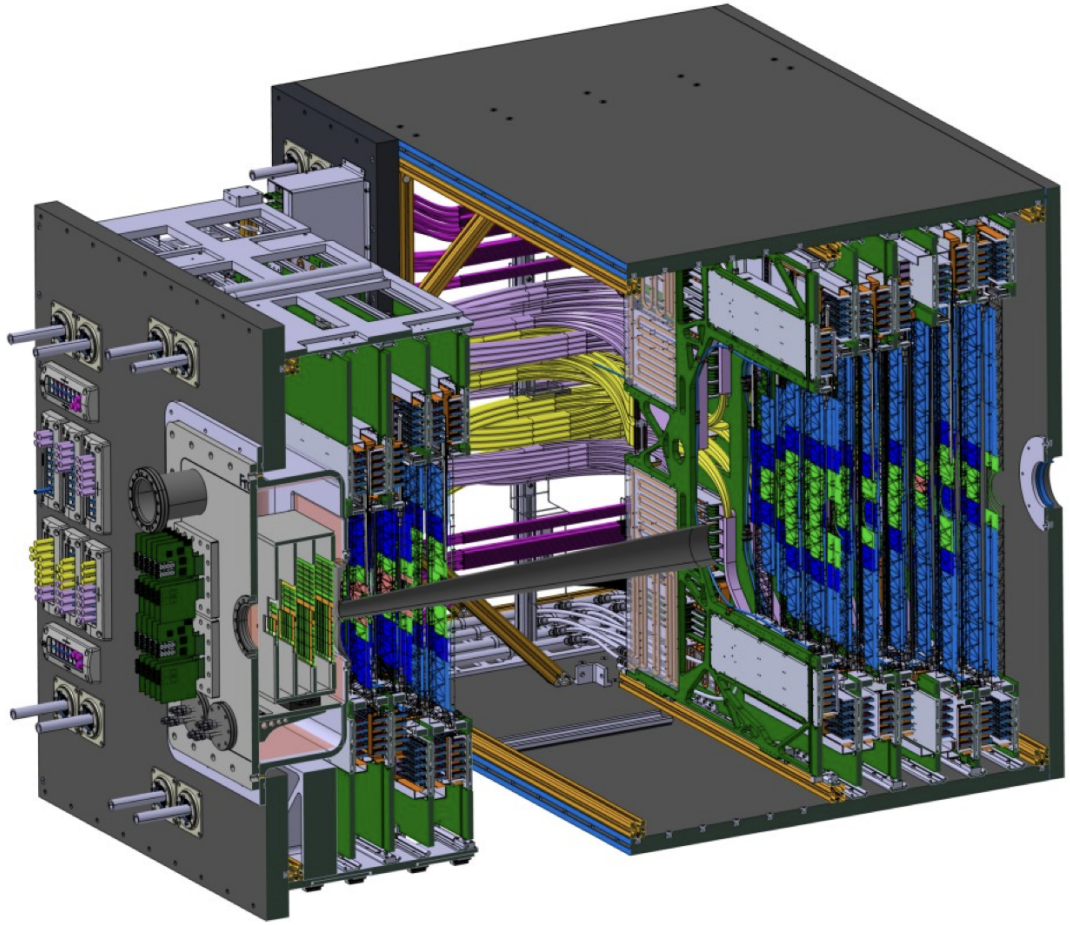
Goal: CBM Start Version installed and operational in 2028 (for beams in 2029)

CBM: MVD



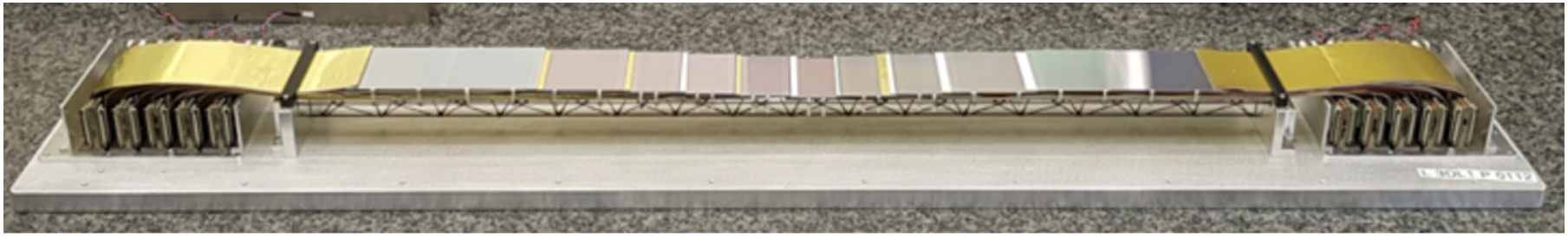
- Charmed-hadron reconstruction
- MAPS (180 nm CMOS, Tower; MIMOSIS-3)
- $\sigma_{x,y} = 5\,\mu$m; Power: 100 mW/cm^2
- Radiation:
  5 Mrad & $5{\times}10^{14}\,\mathrm{n_{eq}/cm^2}$
- 4 planes, operated in vacuum

CBM: STS

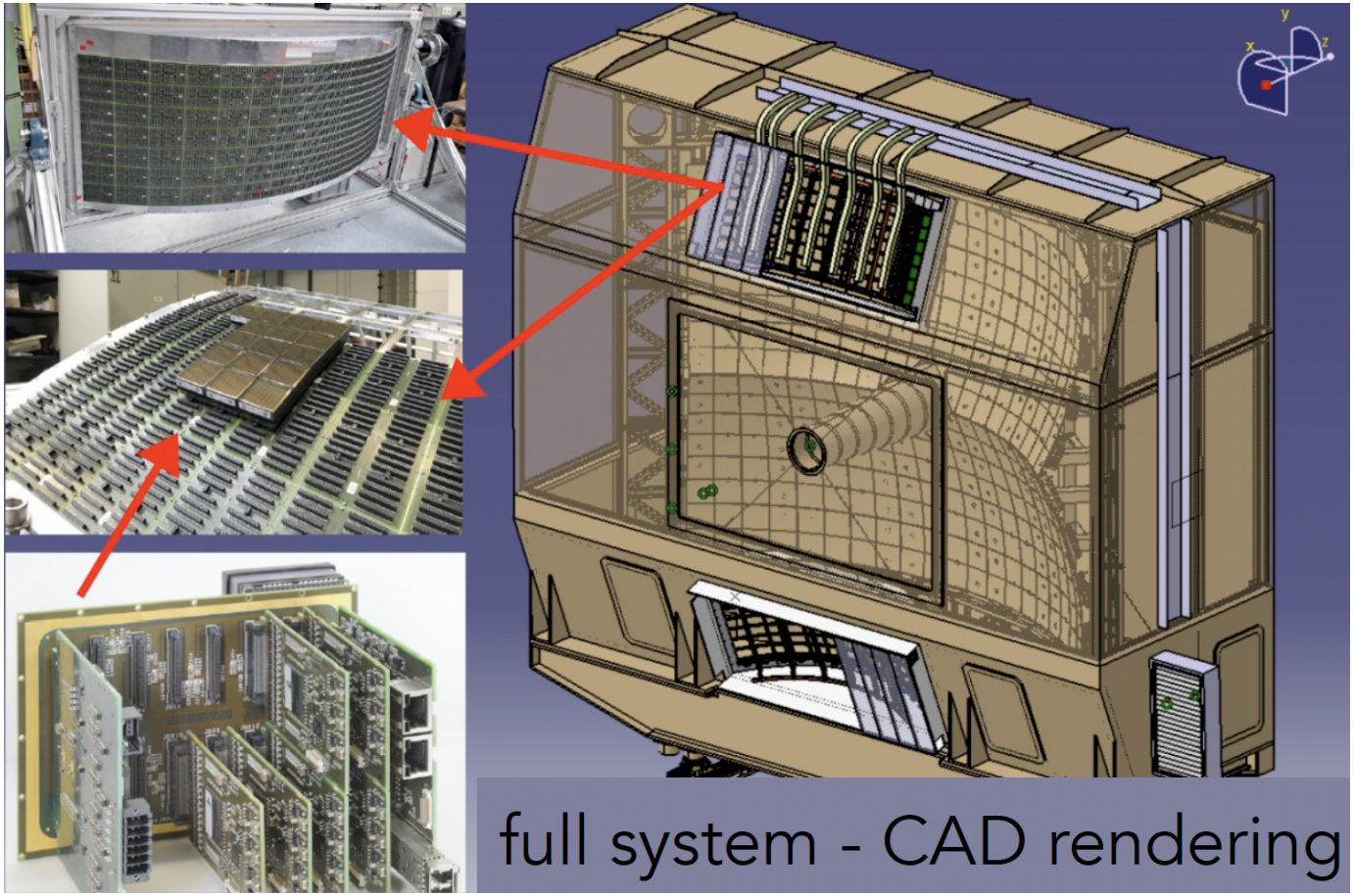


- Tracking and momentum measurement, $\Delta p/p$ =1-2% (B=1 T)
- $\sigma_{x,y} = 30\,\mu$m; $\sigma_t = 5$ ns
- Low material budget (2-8%X_0)
- Double-sided silicon strip det.
- 8 planes
- 876 modules, 2x1024 ch. each
  (62x22, 42, 62, 124 mm^2)
  106 ladders (up to 10 modules)

see JINST 9 (2024)

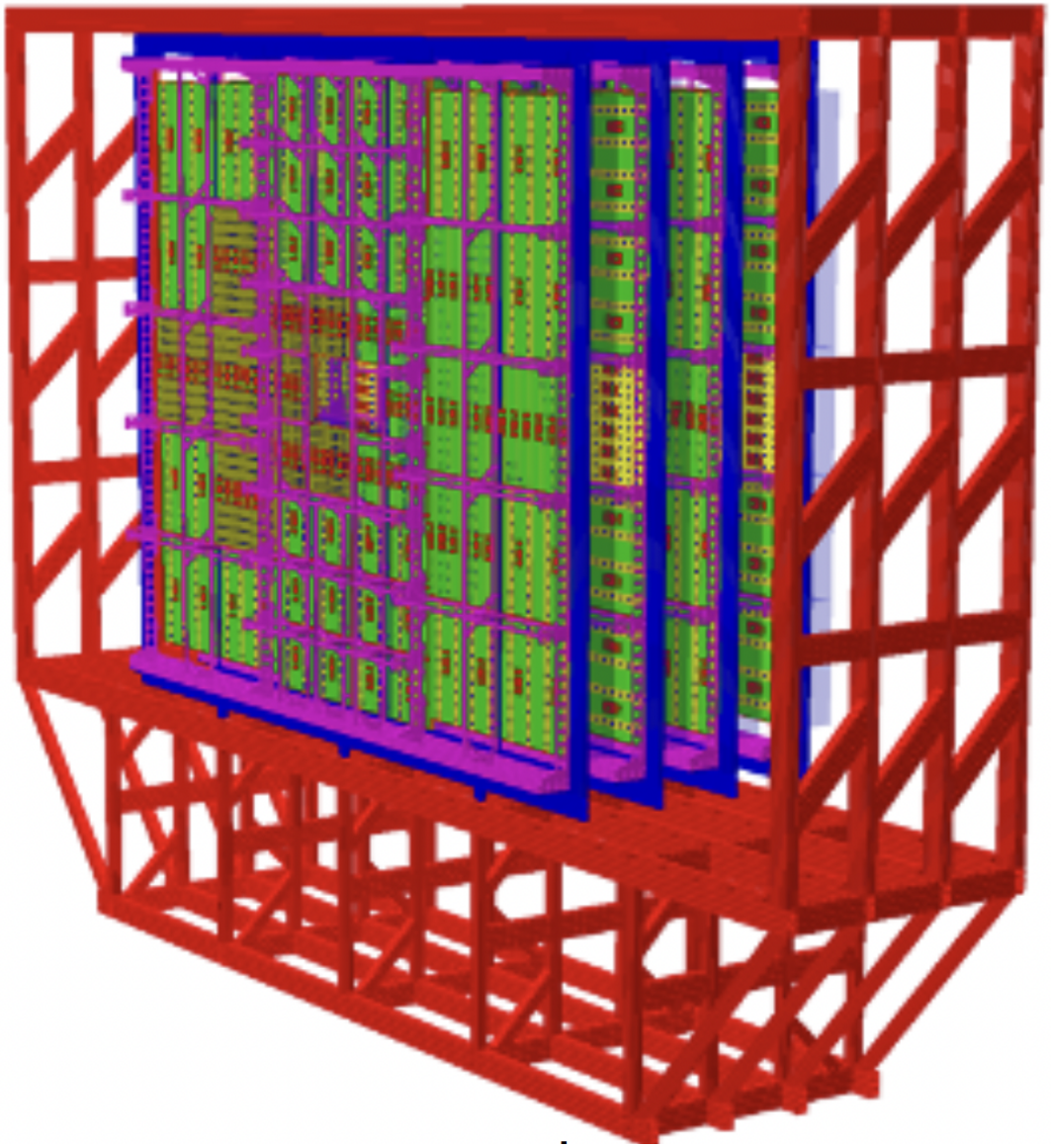


CBM: RICH

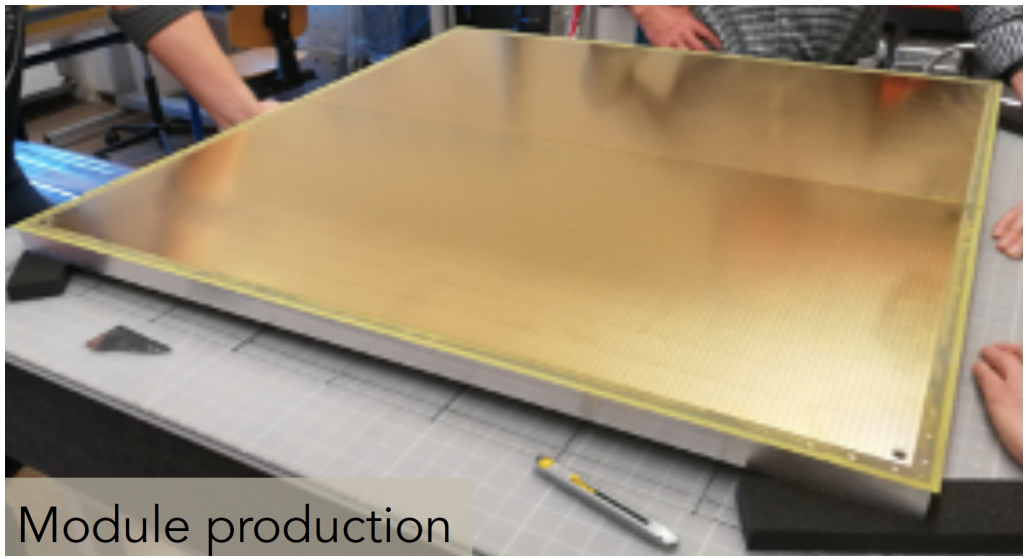


- Electron identification
- CO_2 at normal pressure n=1.00043, $\gamma_{thr} = 33$ $p^{\pi}_{thr} \simeq 4.8$ GeV/c
- R^e=4.8 cm
- 2 mirrors, focal length 1.5 m
- Multi-anode PMTs (1100) 70k pixels

CBM: TRD

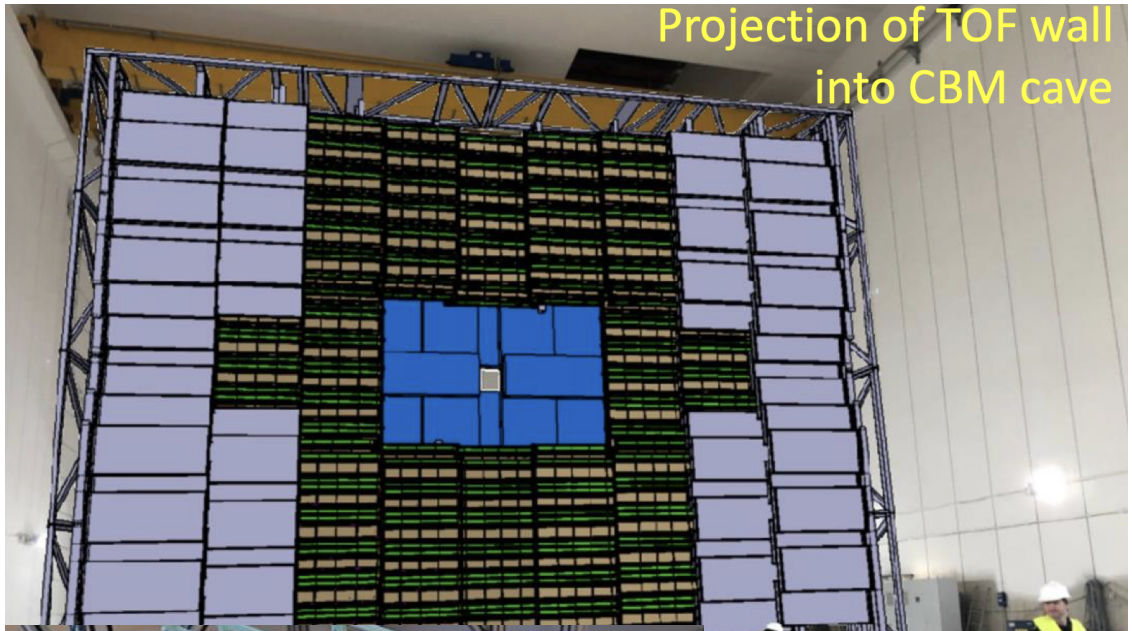


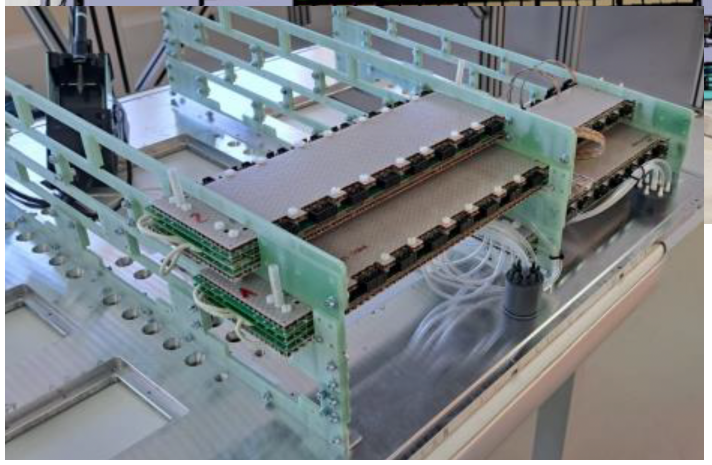
- Electron, light nuclei identification
  Track matching STS-TOF
- $\sigma_{x,y} = 100 - 300\,\mu$m
  (outer, long pads: $\sim$cm)
- Radiator (PE foam), TR: 5-30 keV
  MWPC (1.2 cm, Xe-CO_2)
- Pad readout, FADC; 250k channels



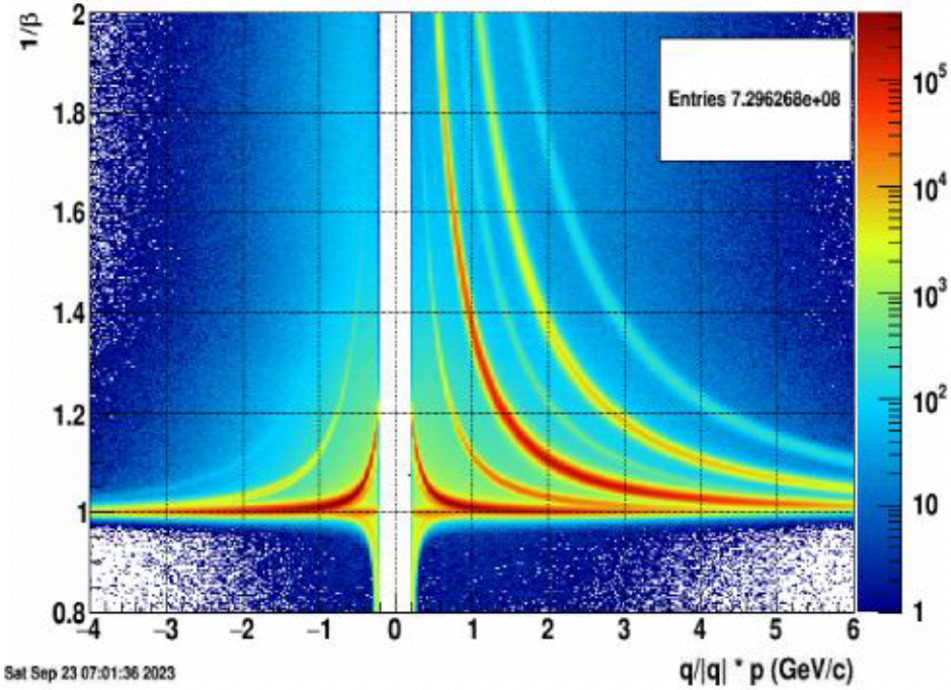
Module production

CBM: TOF





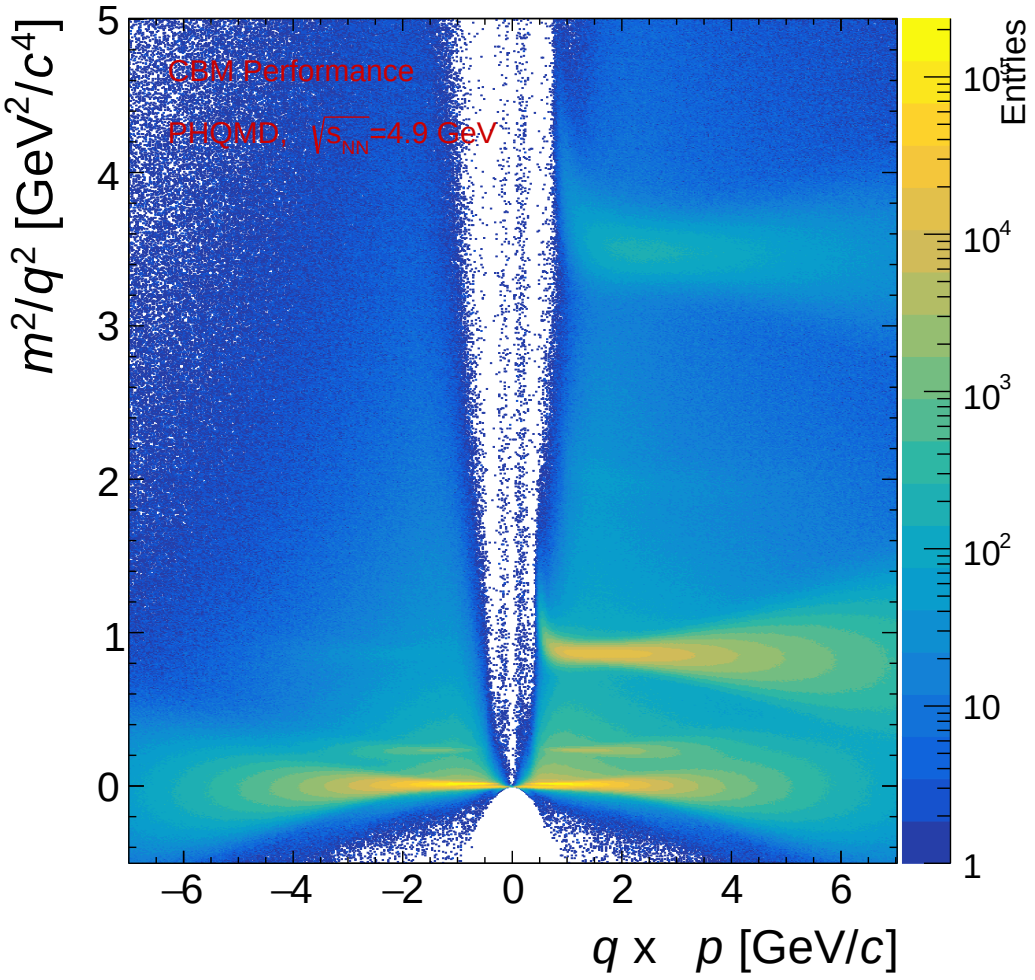
- Hadron identification
- Multi-gap RPCs (glass, strips)
- System resolution: 80 ps

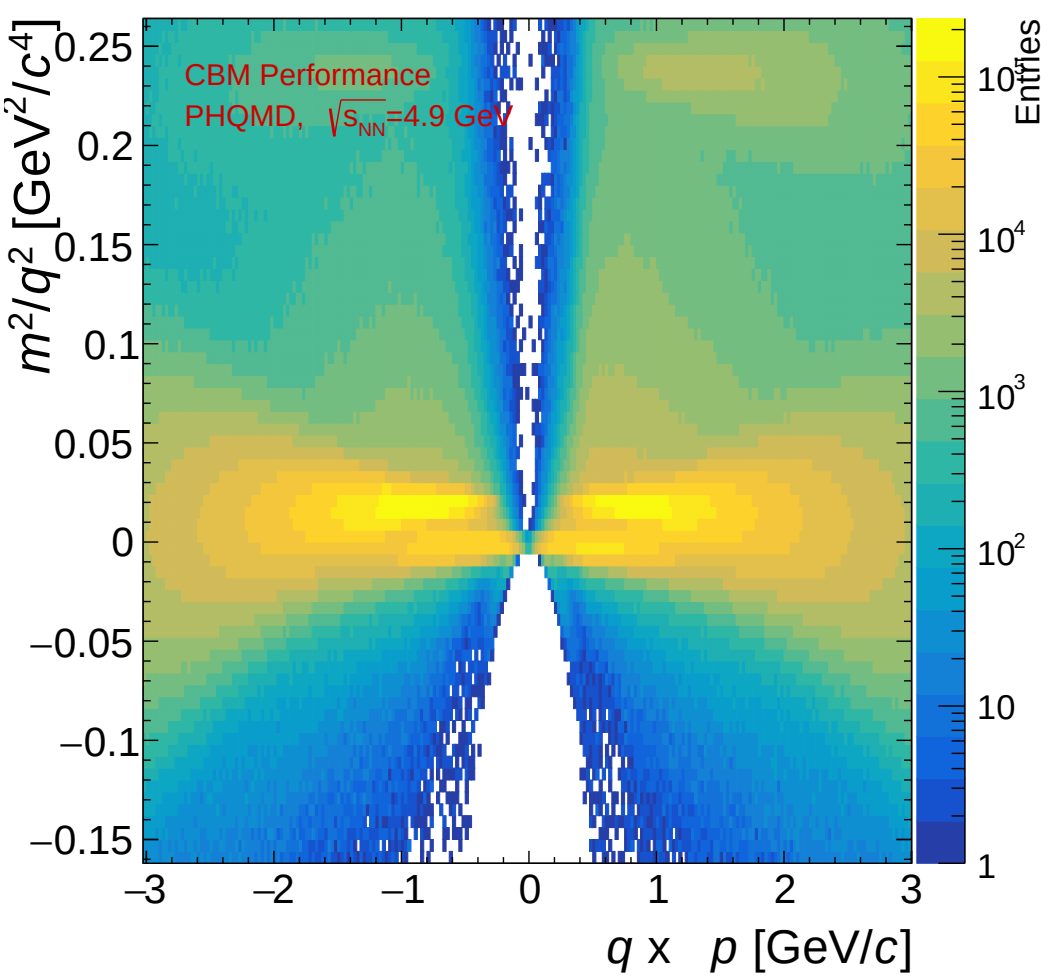


Modules installed in STAR, FXT program

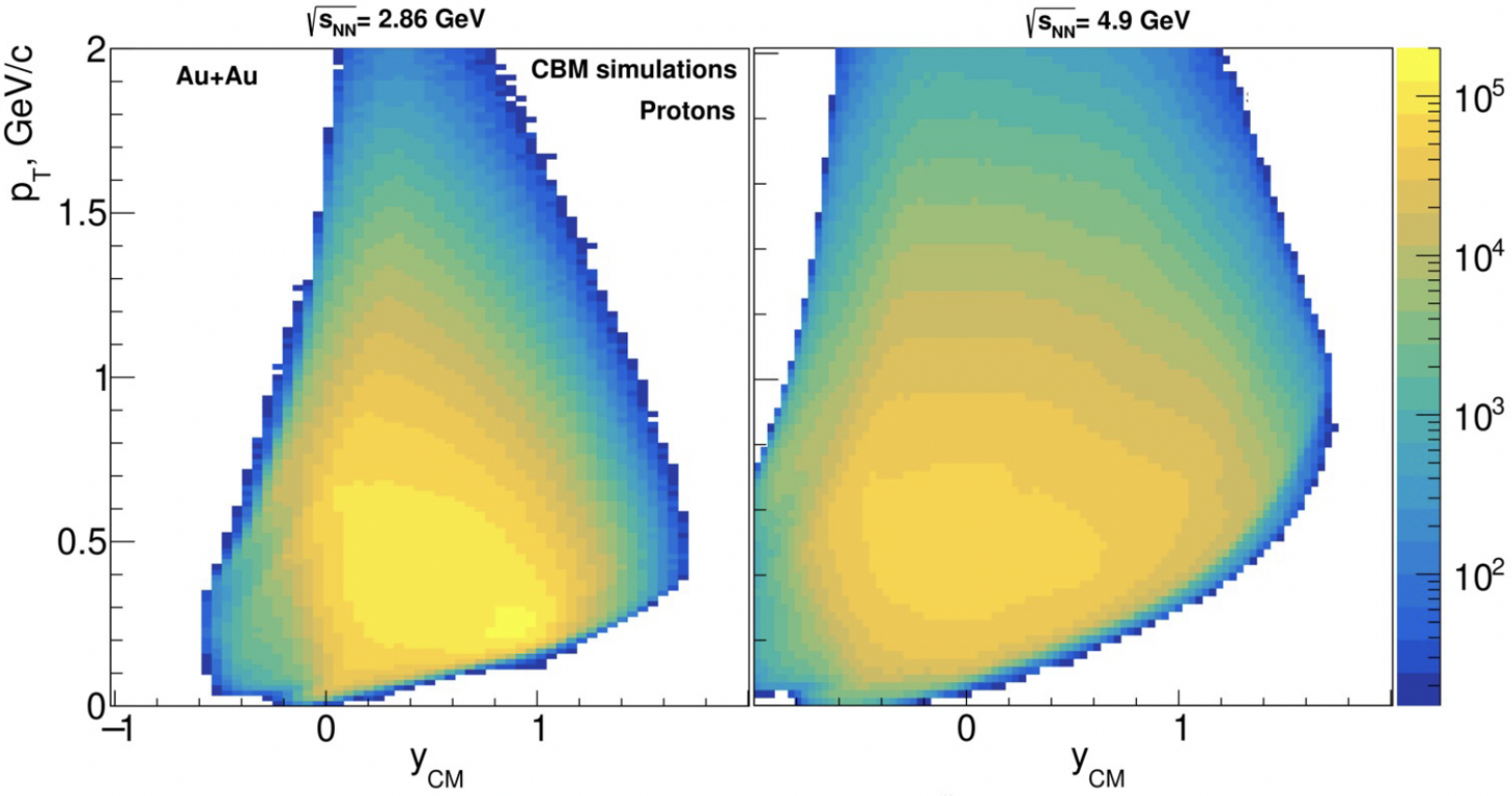
CBM: TOF PID

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





CBM: acceptance, protons

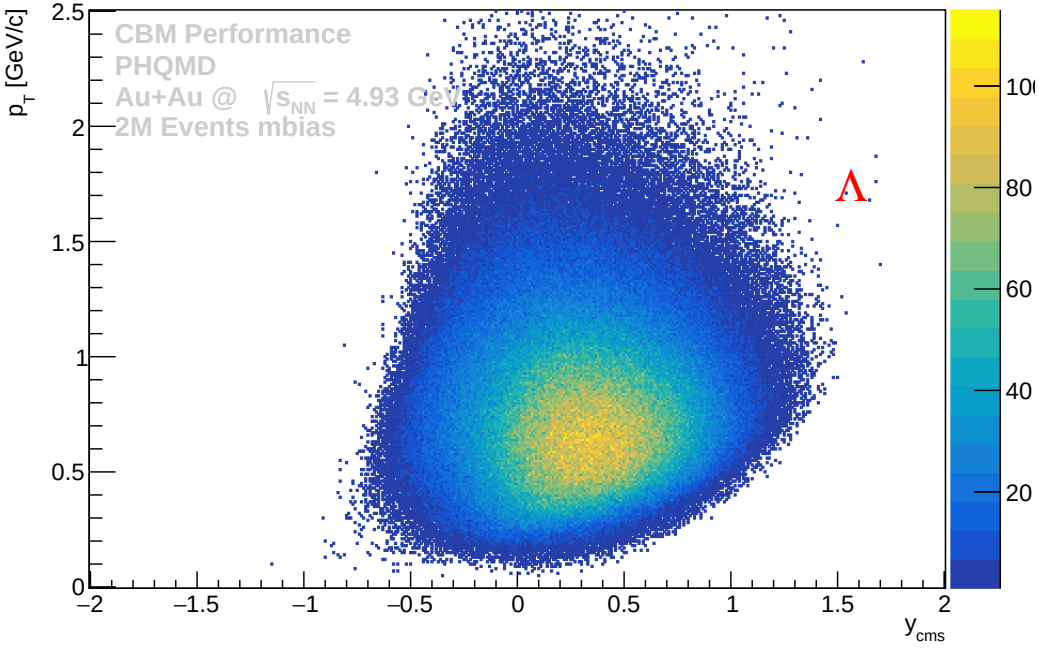


broad phase space coverage, down to low p_T (but of course $\sqrt{s_{NN}}$-dependent)

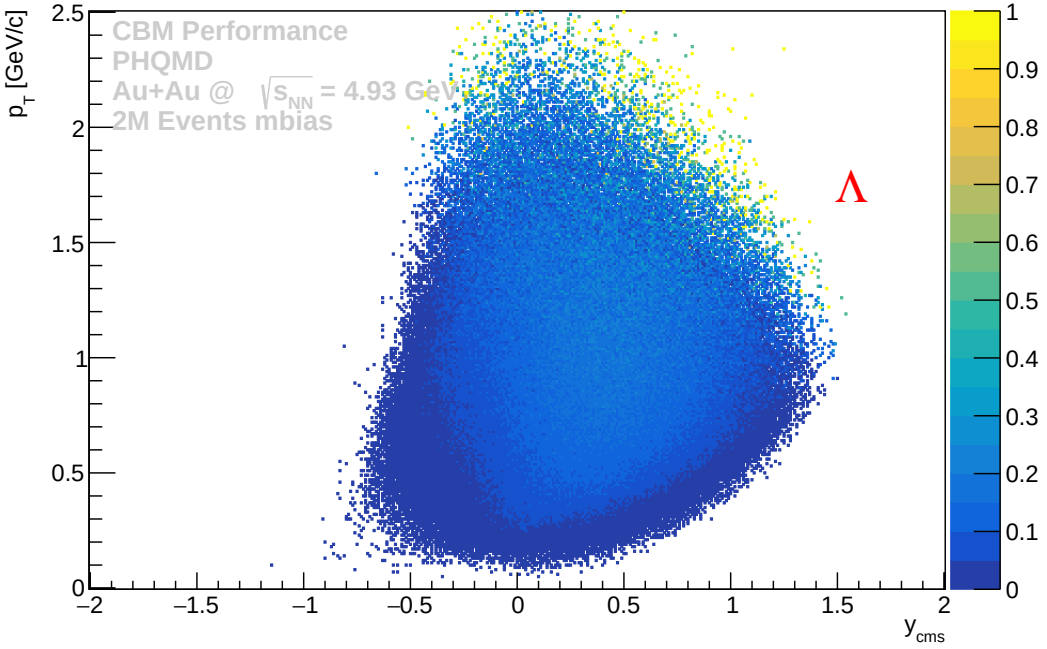
CBM: acceptance, Λ hyperons

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

raw yield



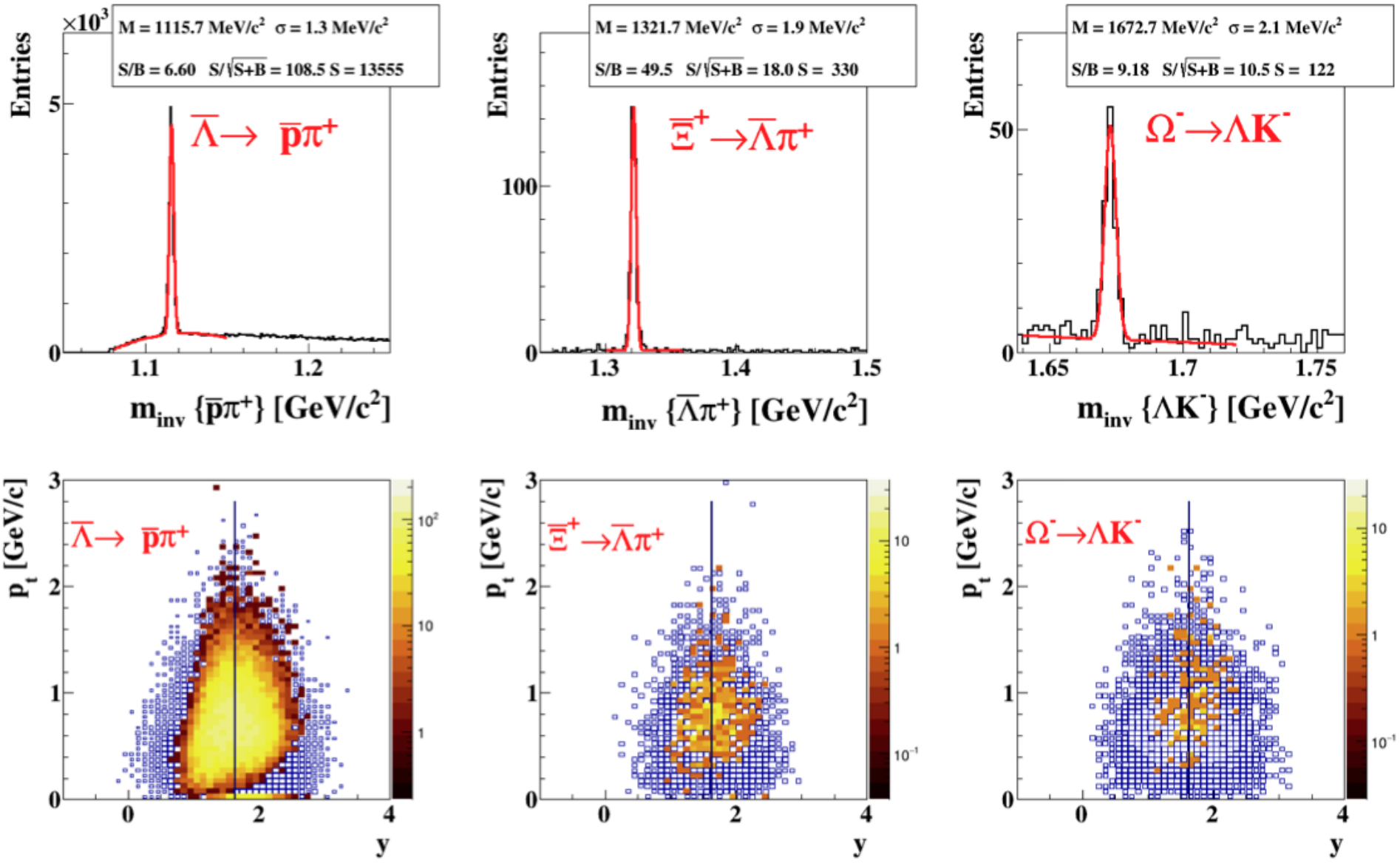
efficiency



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

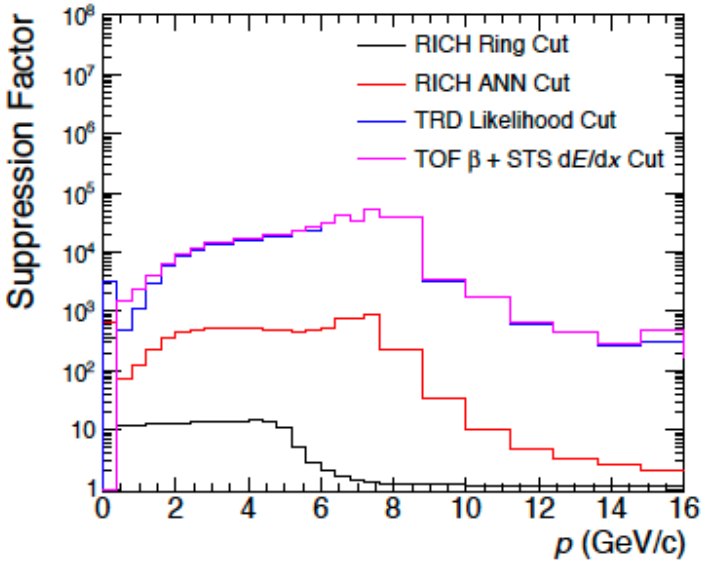
A. Puntke (PhD, U. Münster)

(Anti)Hyperon reconstruction

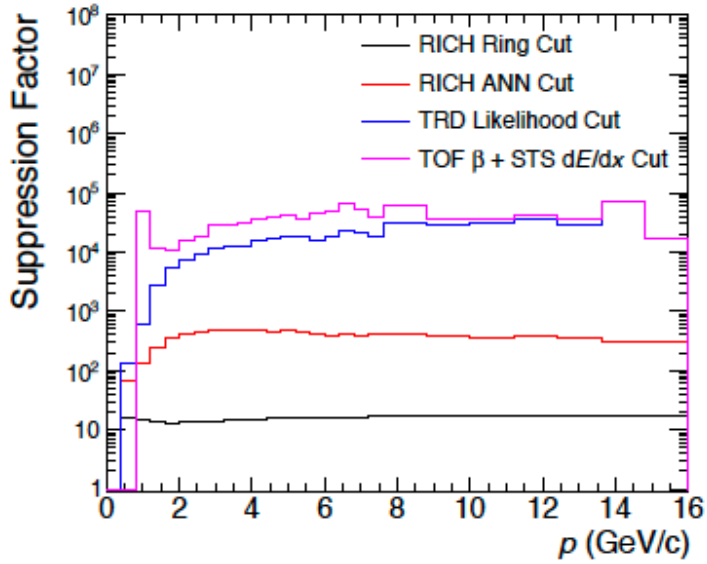


Au-Au, $\sqrt{s_{NN}} = 4.9$ GeV - PHQMD; KFParticleFinder

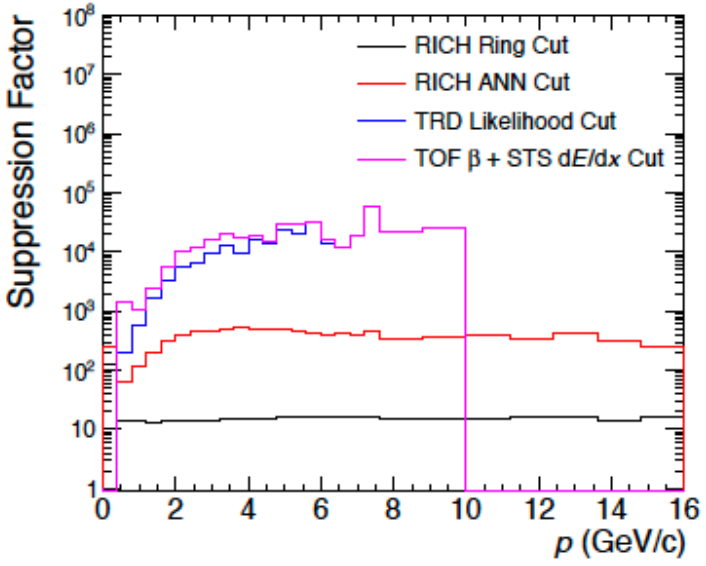
Electron identification performance: cut-based



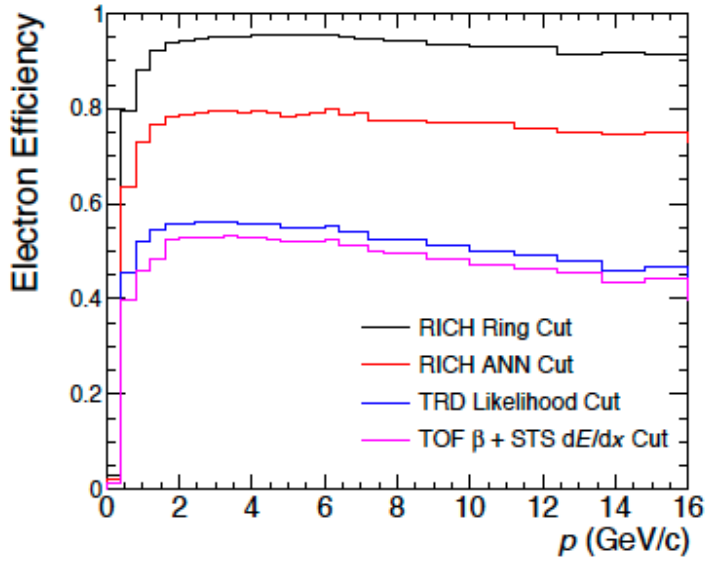
(a) Pions



(b) Protons

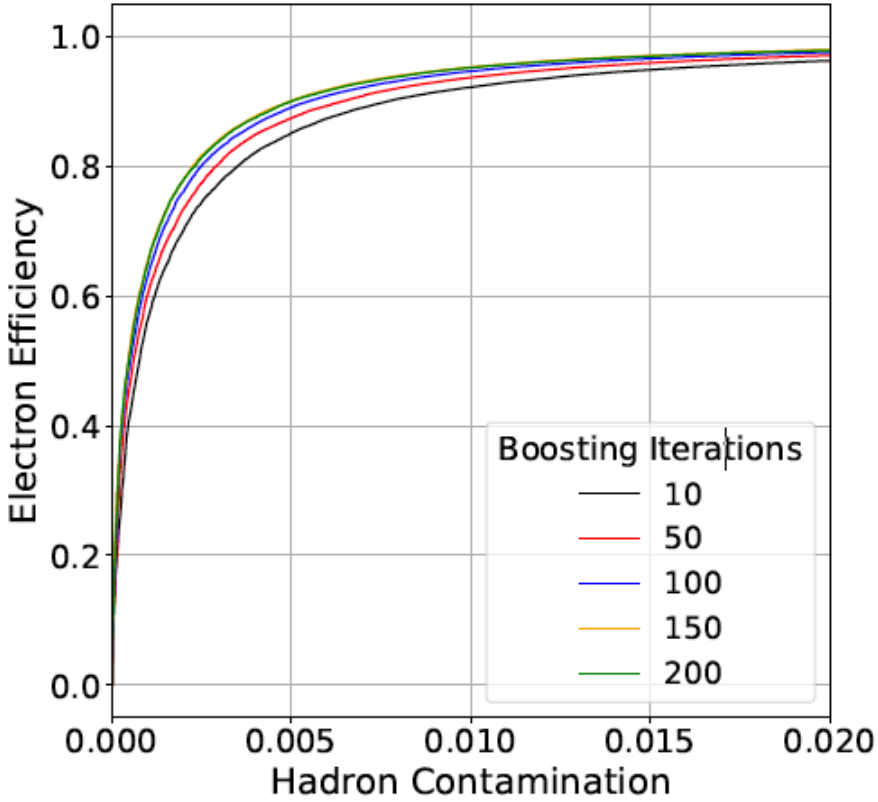


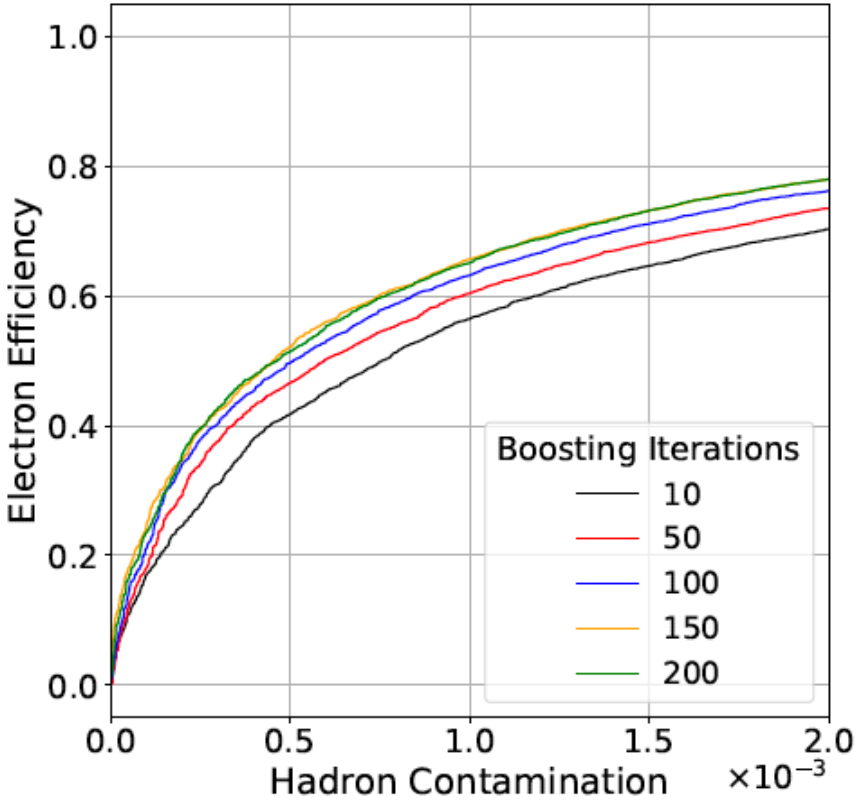
(c) Kaons



(d) Electrons

Electron identification performance: ML-based



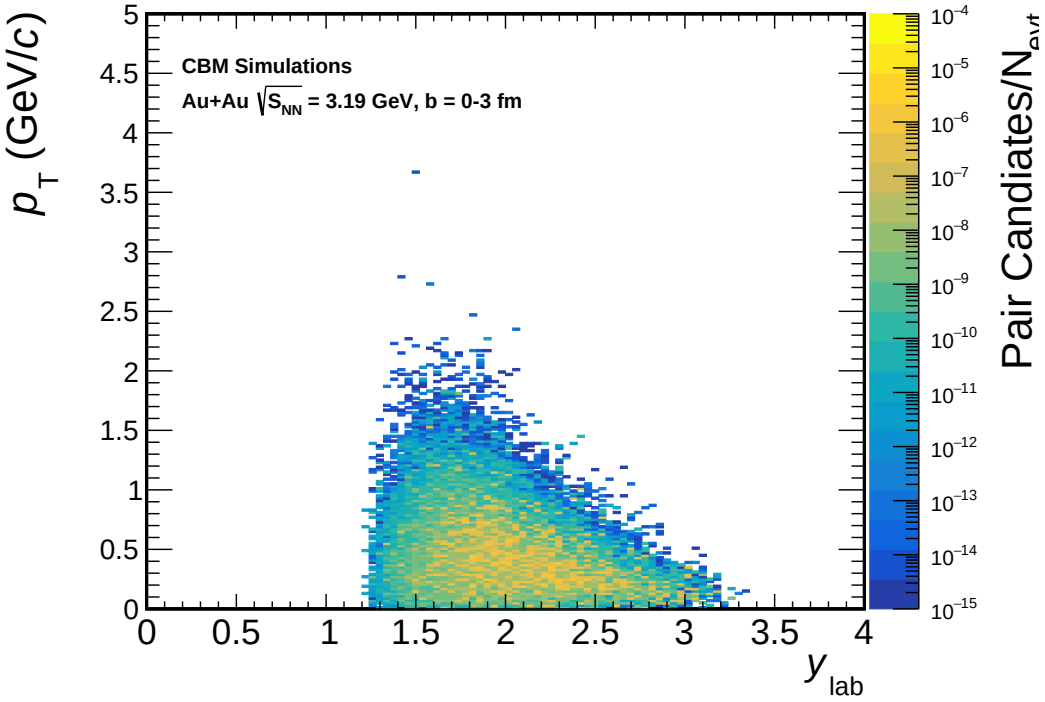


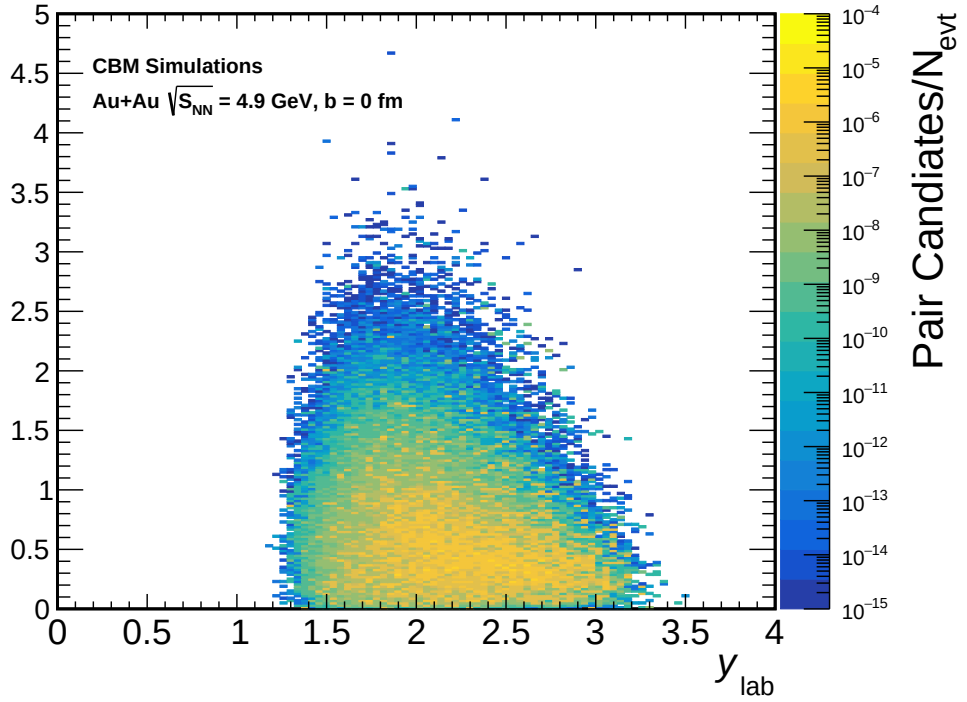
Combined RICH-TRD-TOF, BDT method (Au-Au, $\sqrt{s_{NN}} = 4.9$ GeV)

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

CBM: acceptance, dielectrons

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





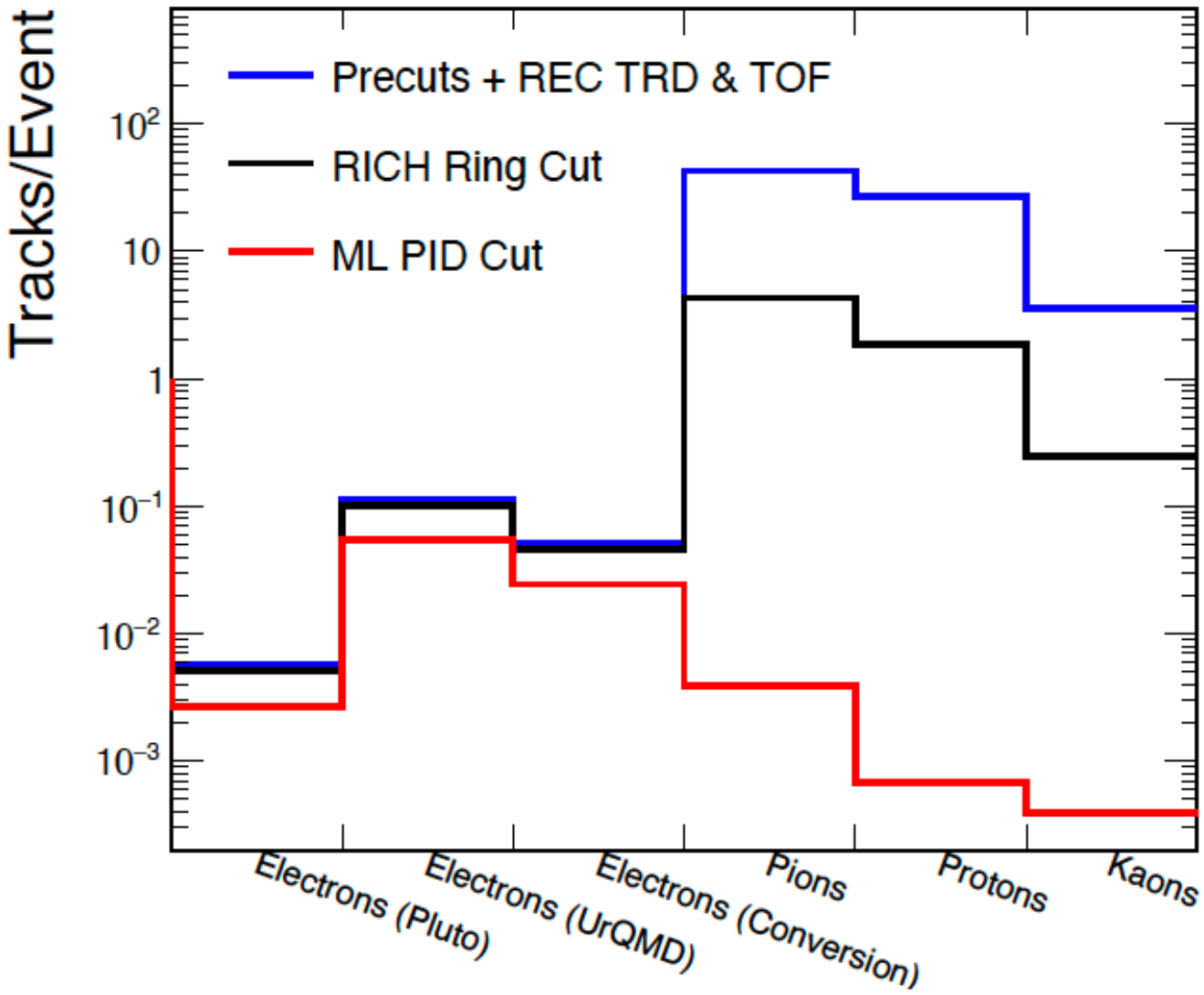
$y^{cm}_{lab} = 1.13$ $y^{cm}_{lab} = 1.62$

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]

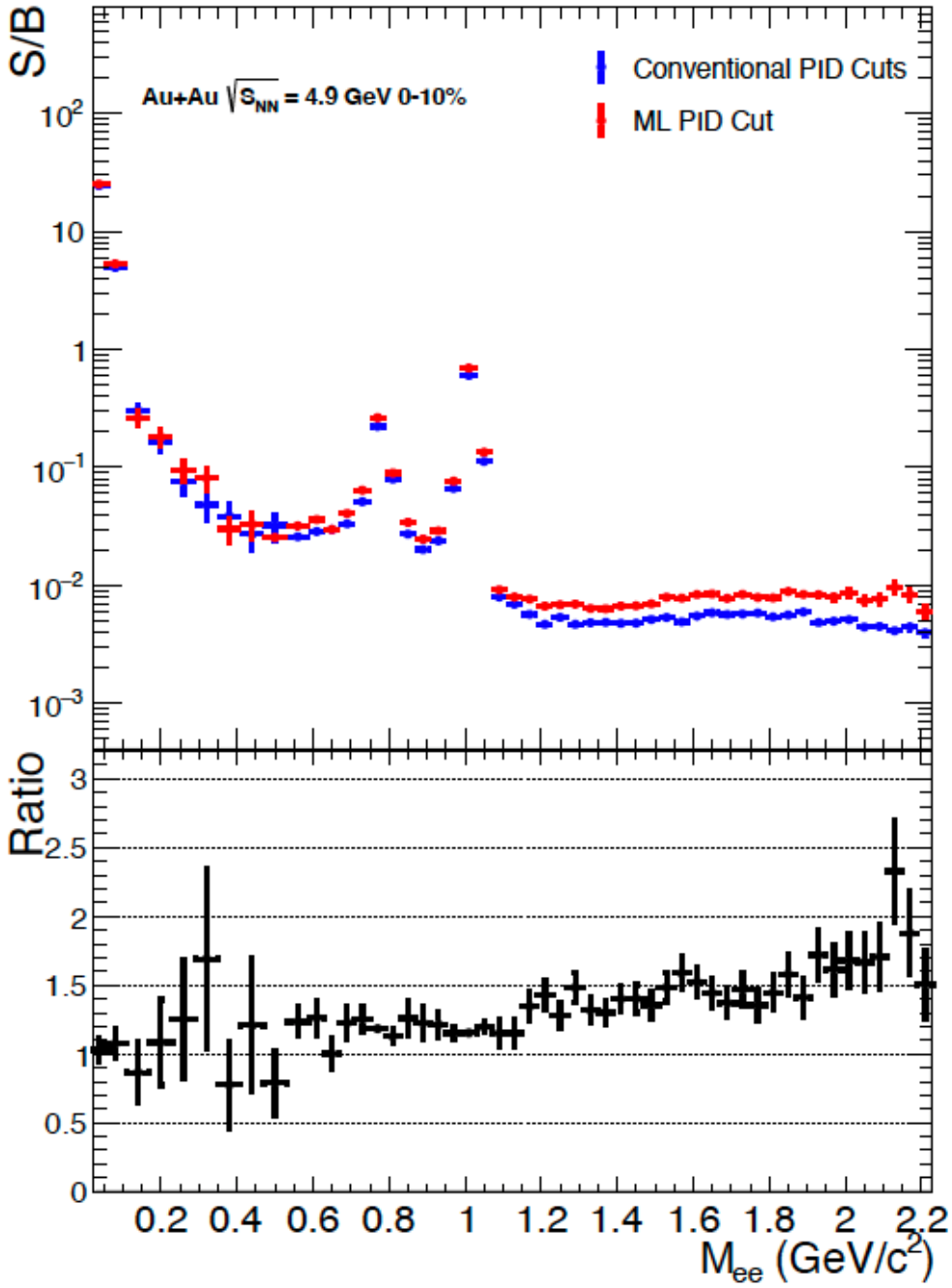
Electron identification performance: ML-based



Pluto generator: $\eta\prime$, Δ, ω, $\phi \rightarrow e^+e^-$ (not in UrQMD)

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

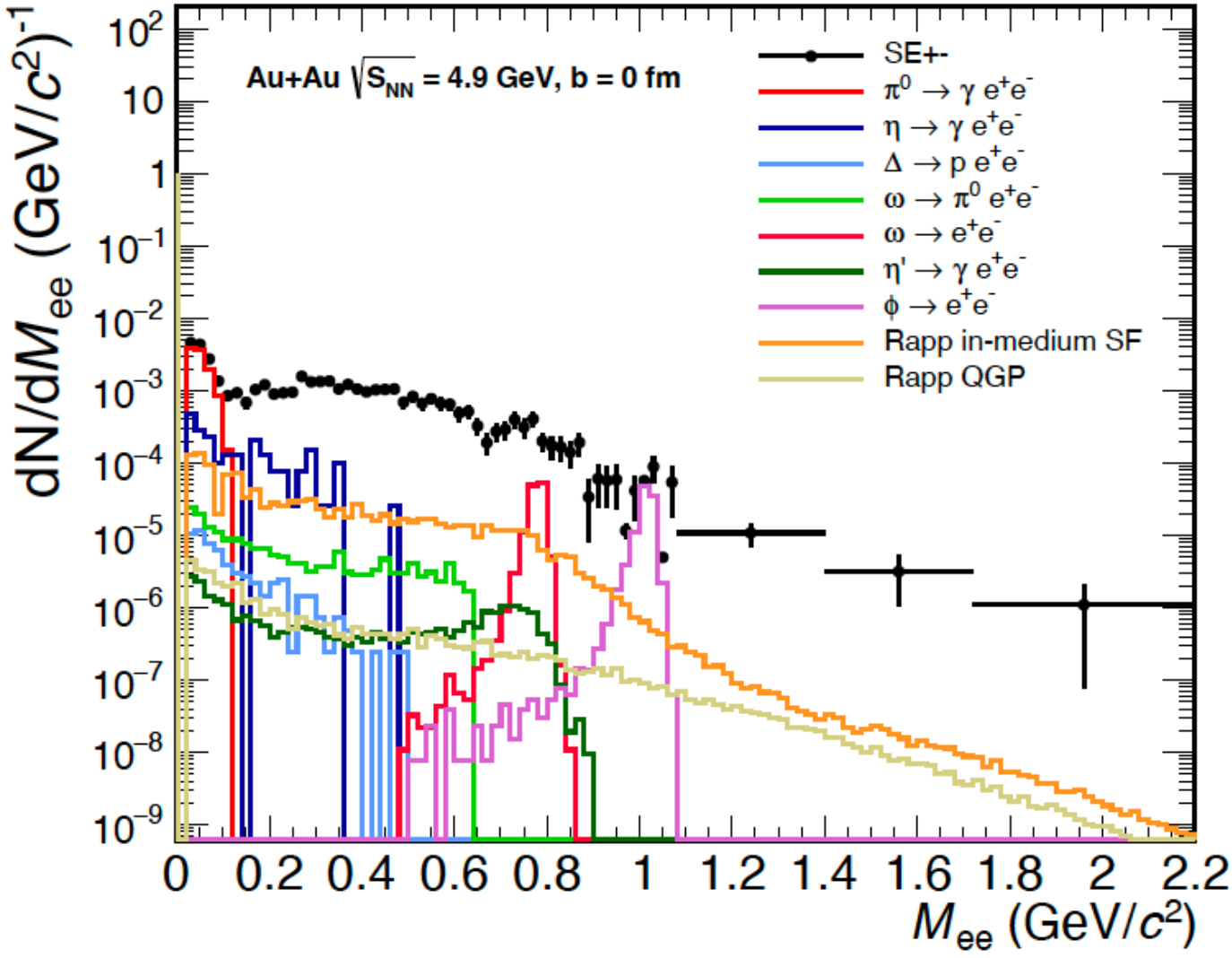
CBM: dielectron performance



CBM: dielectron performance, selection cuts

Cut Class	Cut Name	Range
PreCuts	p_T	$p_T > 0.05$ GeV/c^2
	recSTSMVD	Nr. of STS+MVD-hits > 3
	rec1TRD	Nr. of TRD-hits > 0
	PairPreFilter	m_{inv} of pair candidate > 0.025 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	

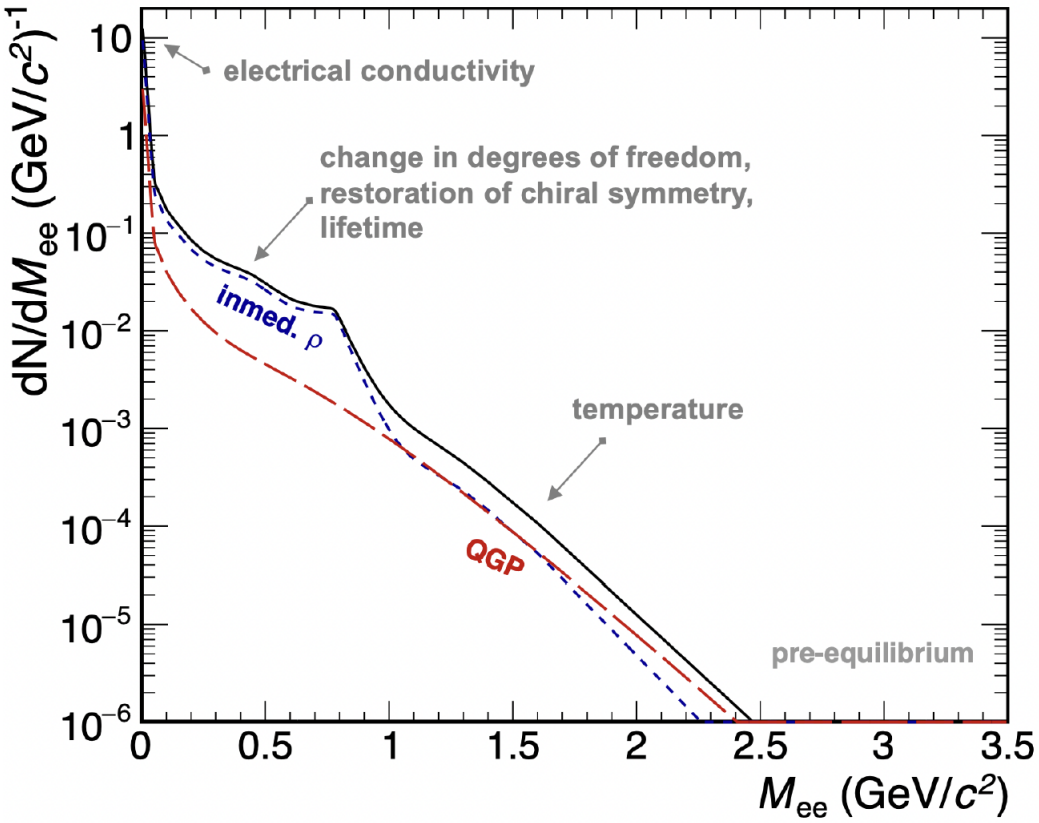
CBM: dielectron performance



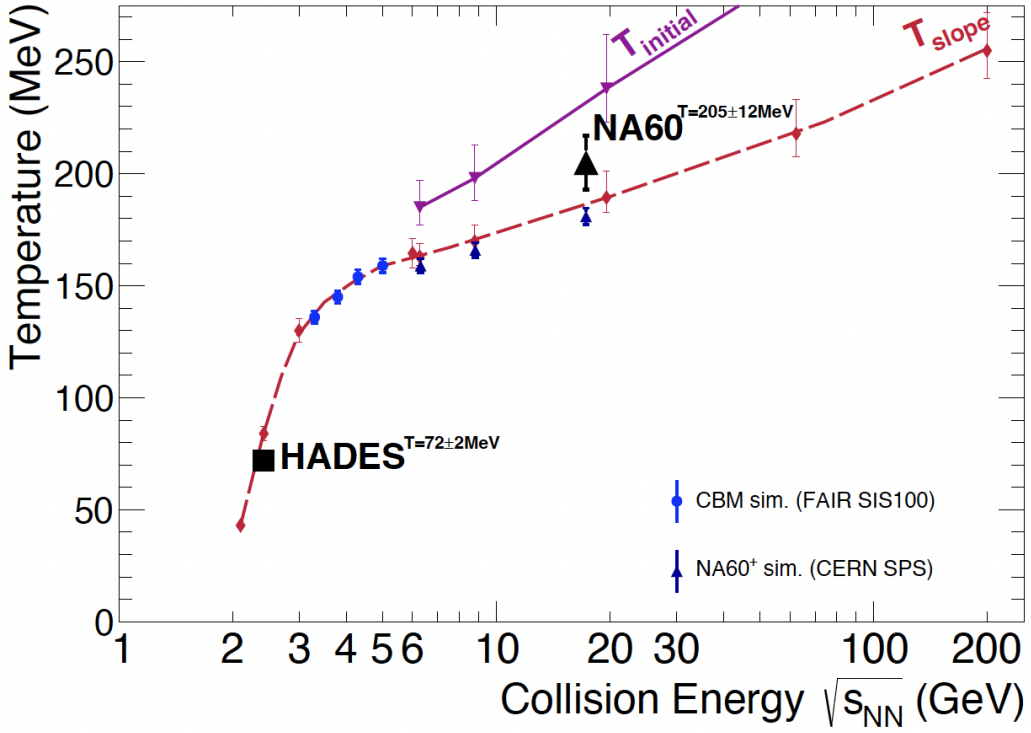
Nr. of 0-10% events needed to reach this performance: $\sim 10^{10}$ (1 day of running at 1 MHz)

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

CBM: dileptons on broader perspective



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



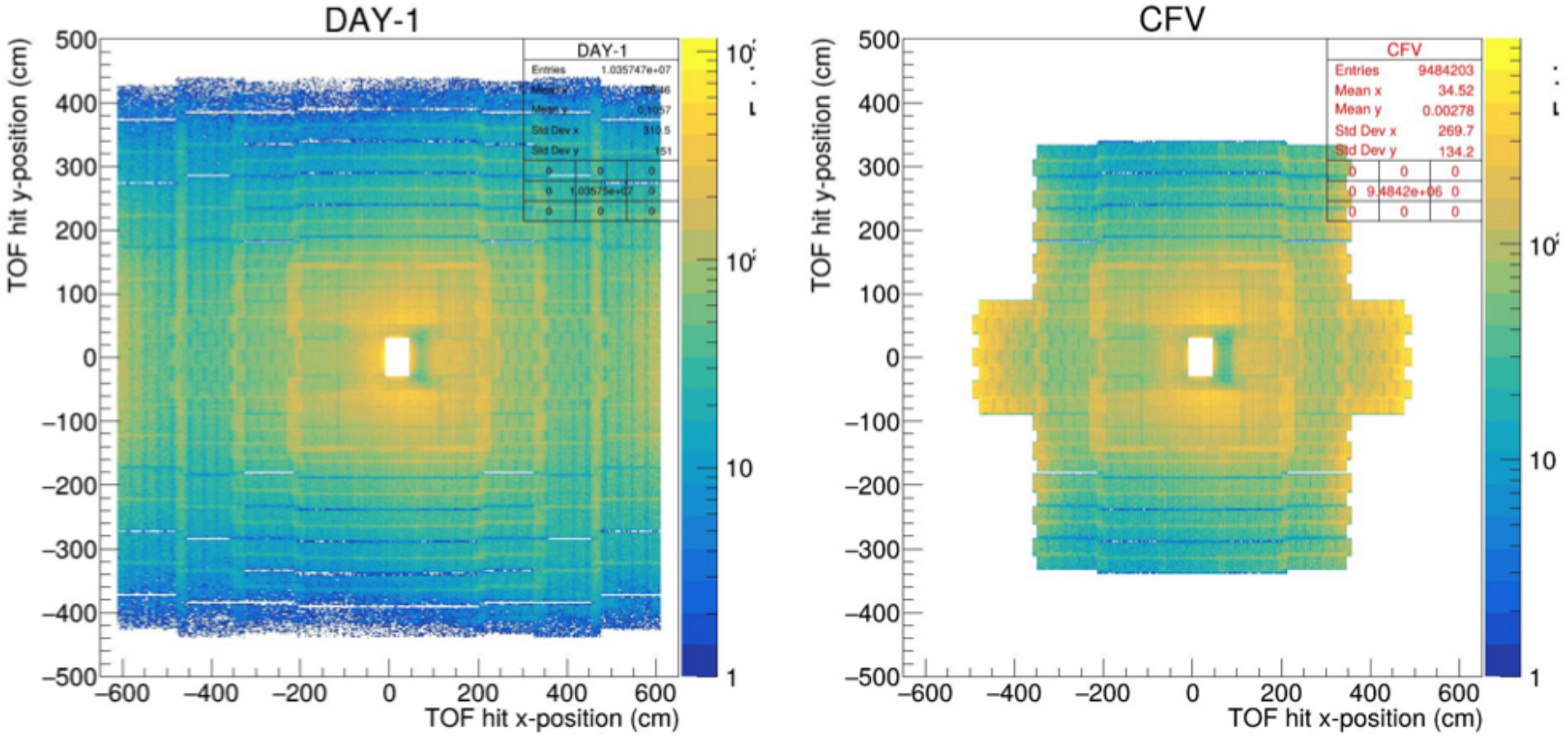
https://github.com/tgalatyuk/QCD_caloric_curve

fit data with: $\mathrm{d}N/\mathrm{d}M \sim M^{3/2}\exp(-M/T)$

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

CBM: getting practical ...start version

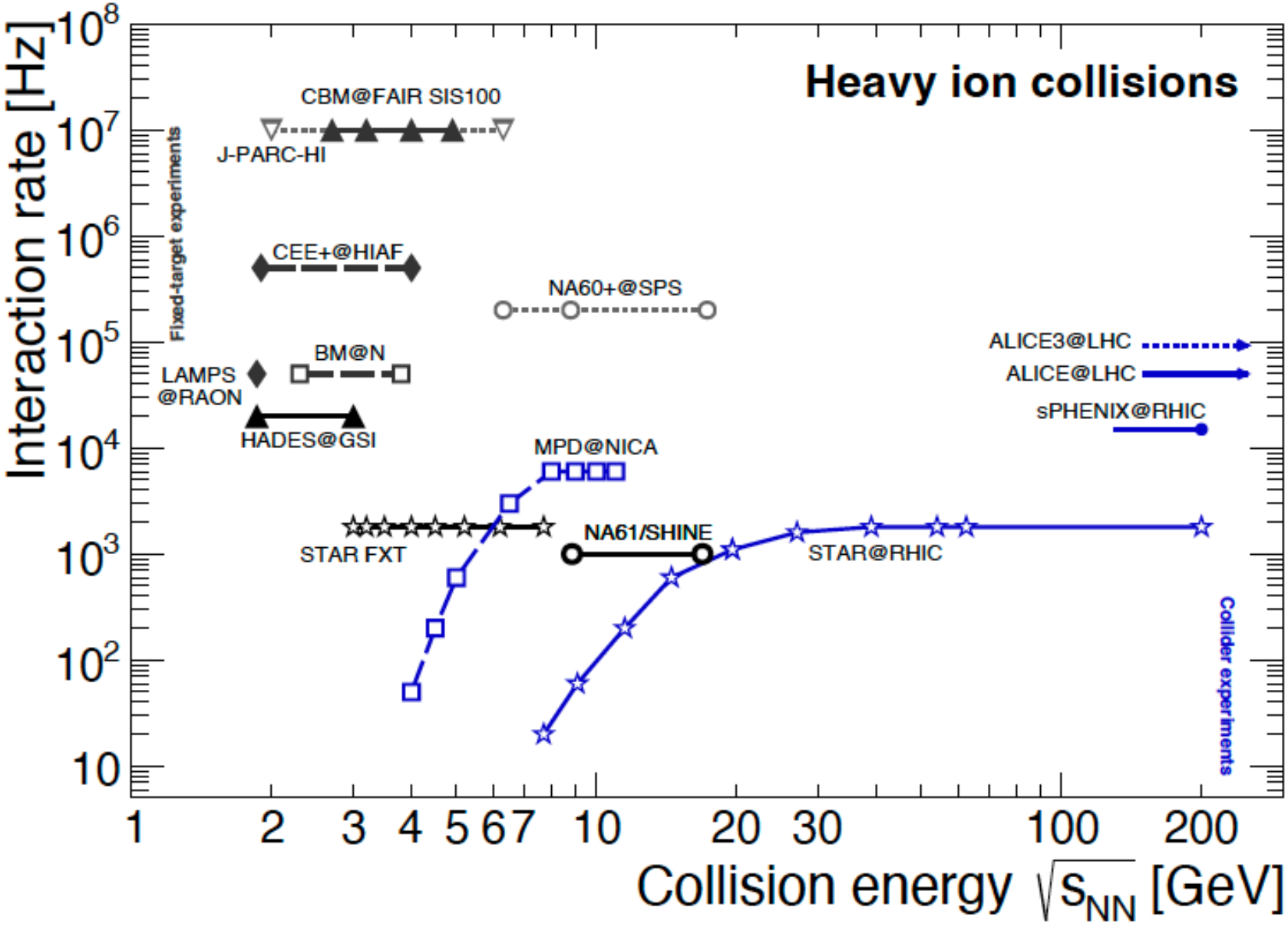
TOF hit-map



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

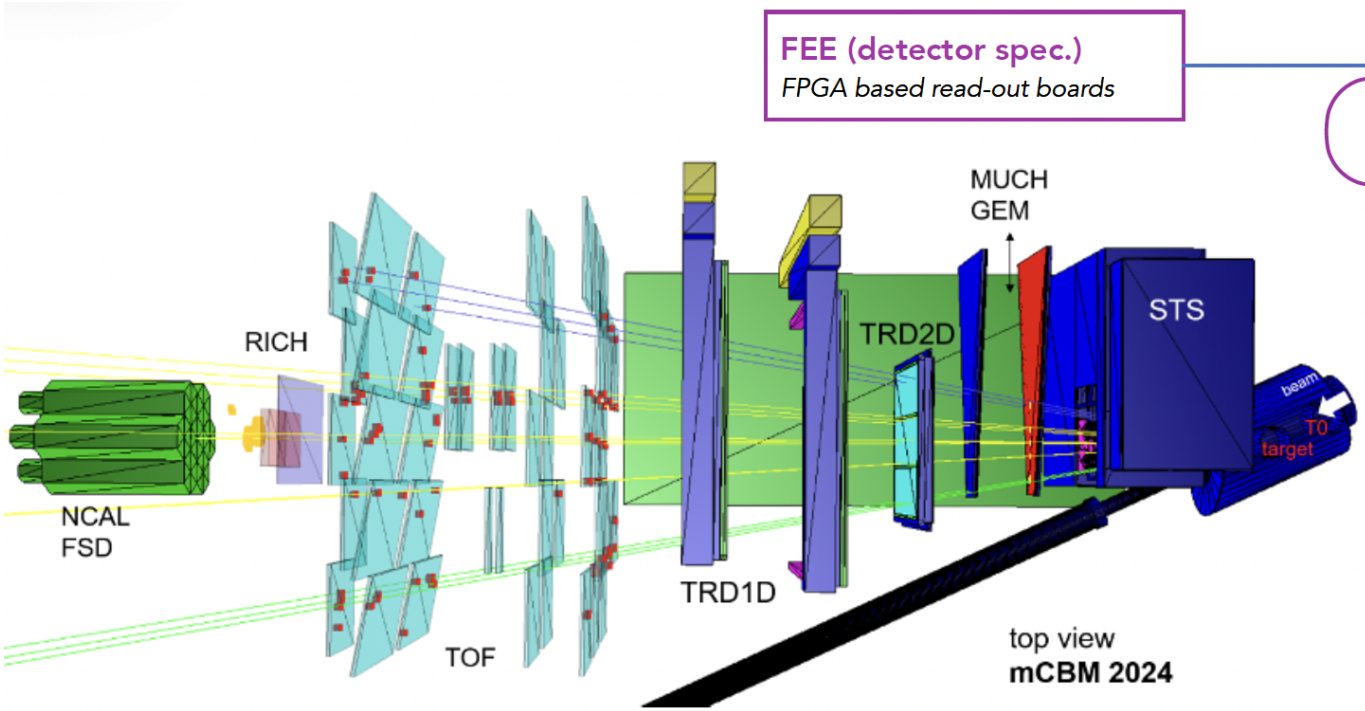


T.Galatyuk, NPA 982 (2019), https://github.com/tgalatyuk/interaction_rate_facilities

CBM: readout and event selection

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

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



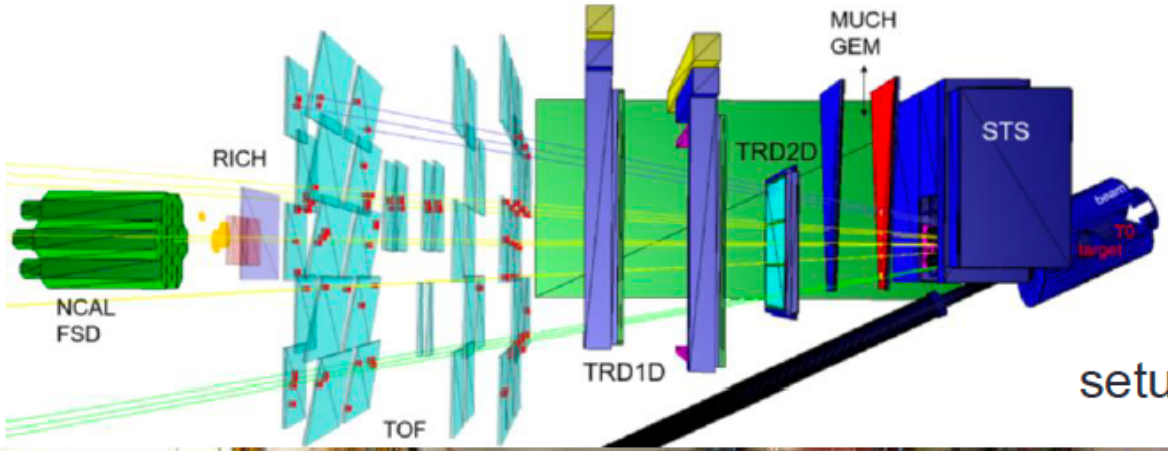
FEE (detector spec.)
FPGA based read-out boards

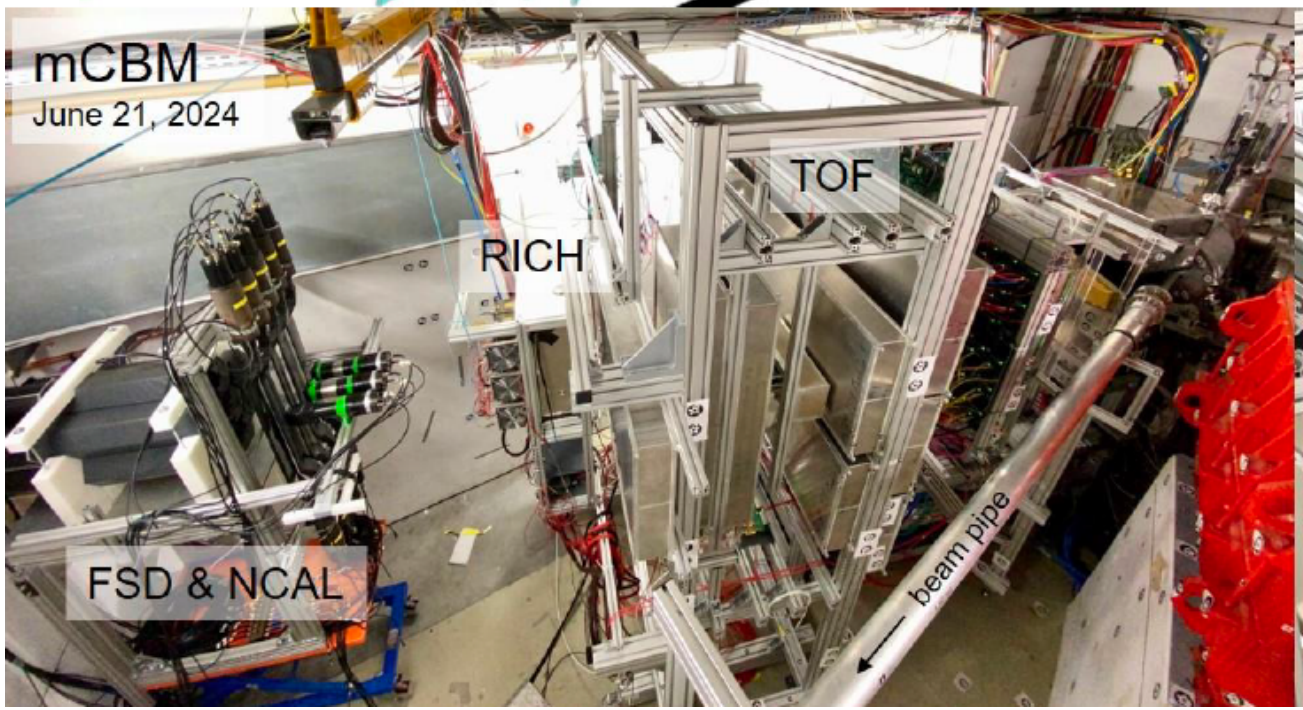
GBTx – Optical
50 m

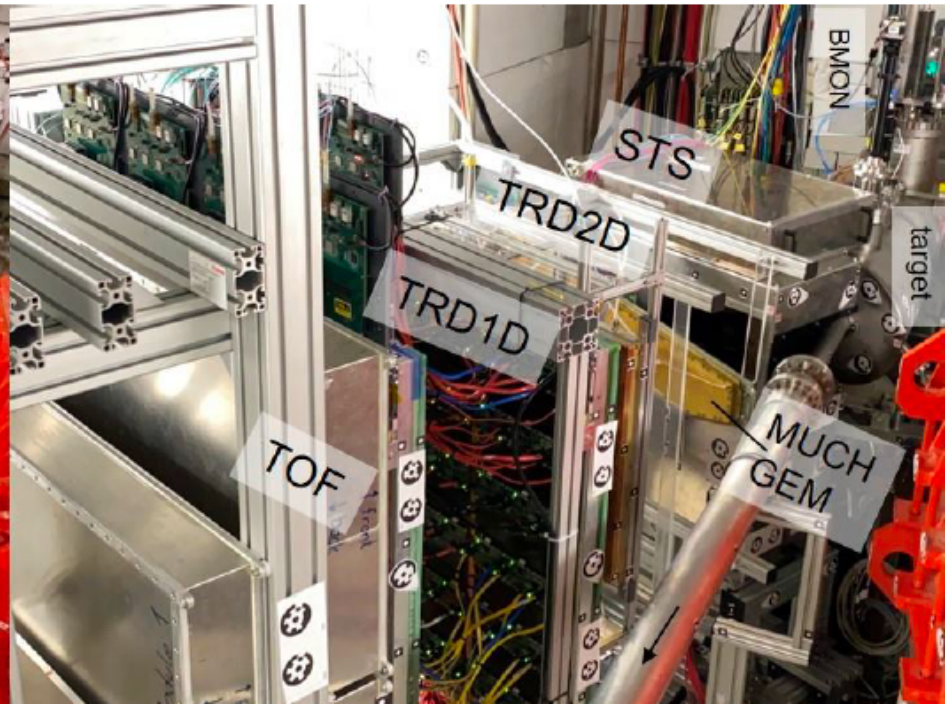
FLES entry nodes
FPGA based read-out boards

InfiniBand – Optical
300 m

FLES on Green IT Cube
Compute nodes
Time correlation→Event reconstruction→Event selection→Storage



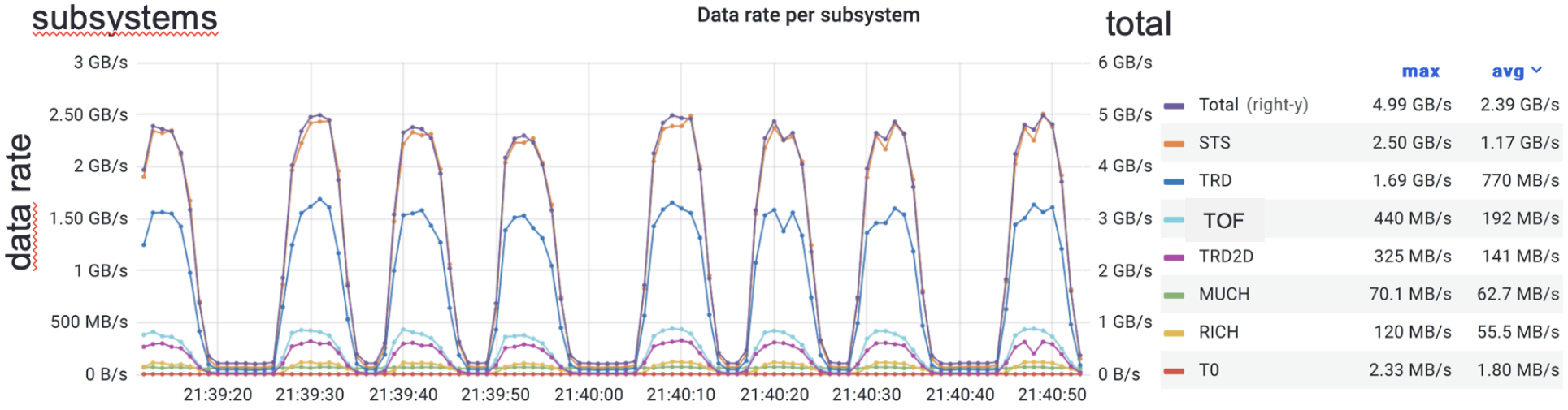




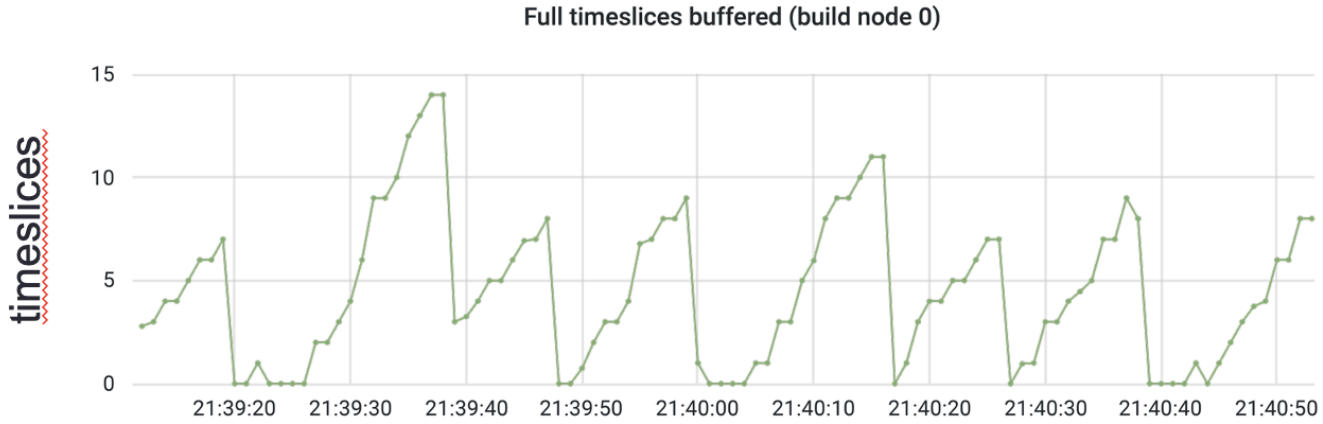
Final prototypes or first-of-series detectors

mCBM: readout

FLES input

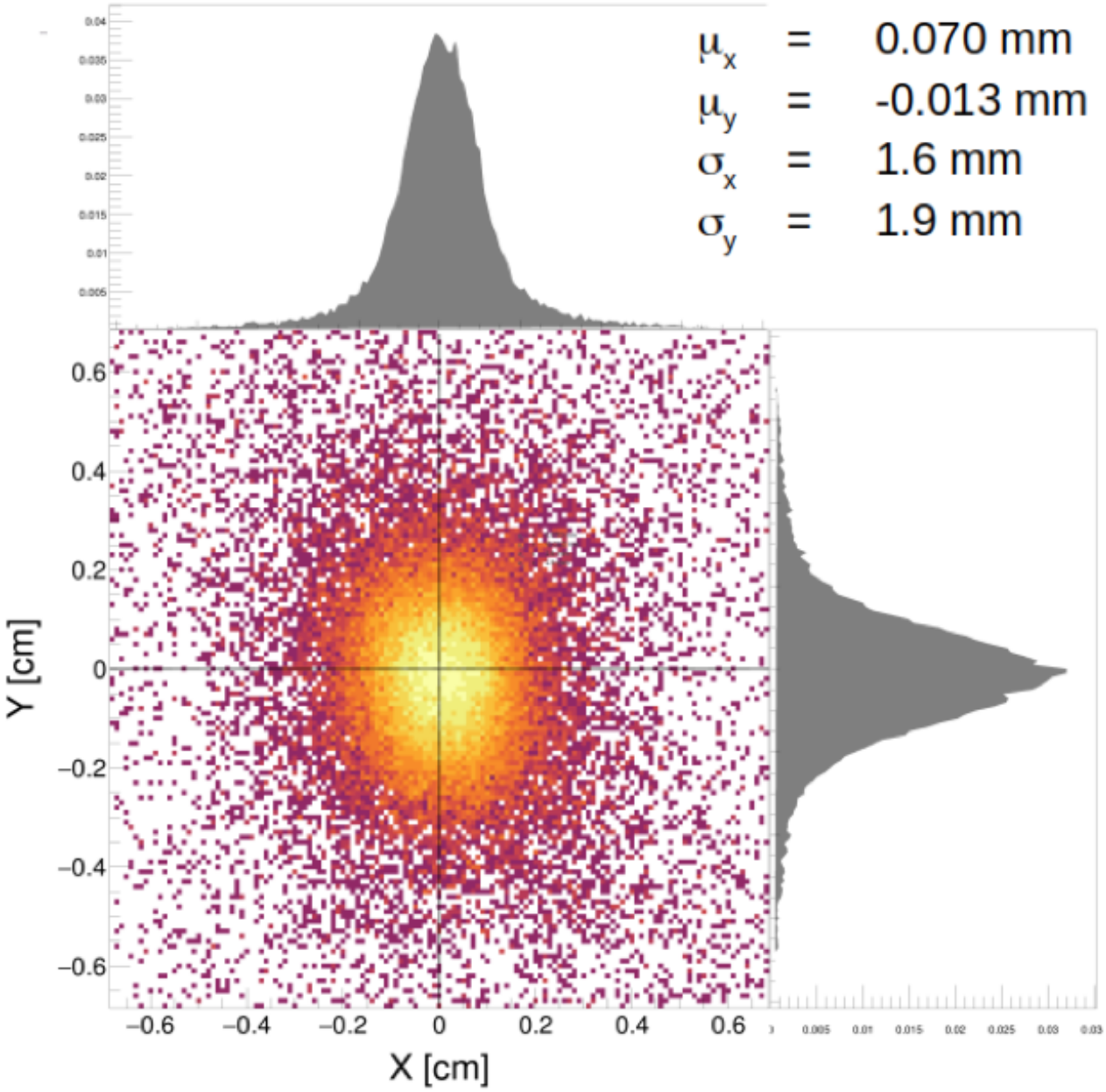


FLES output



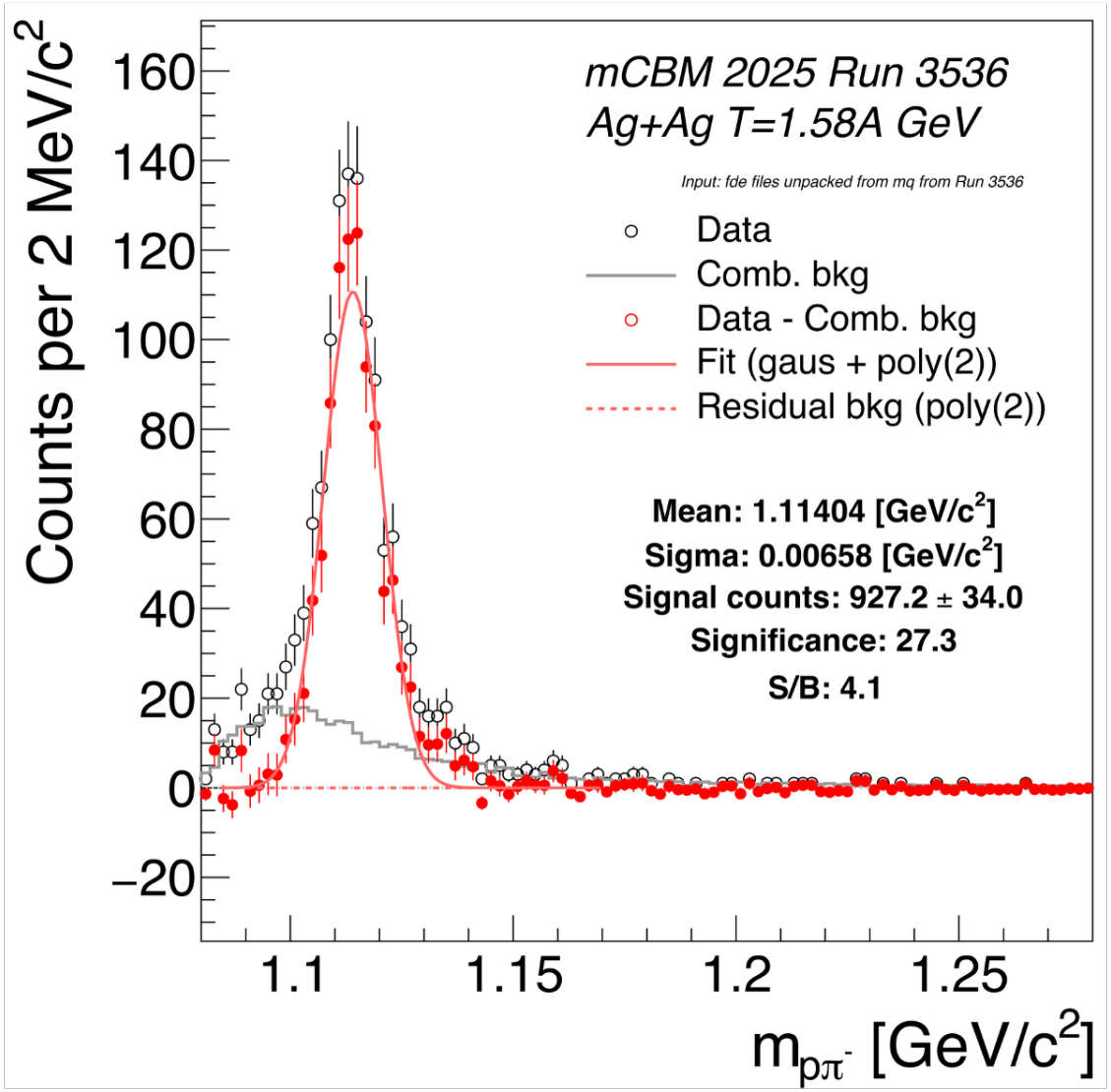
mCBM run 2448
June 16, 2022
Au + Au, T = 1.23 AGeV
av. collision rate: 300 - 400kHz
av. data rate 2.4 GB/s to disc

mCBM: tracking, primary vertex (beam spot)



arXiv:2505.20517

mCBM: Λ reconstruction (benchmark observable)



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

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

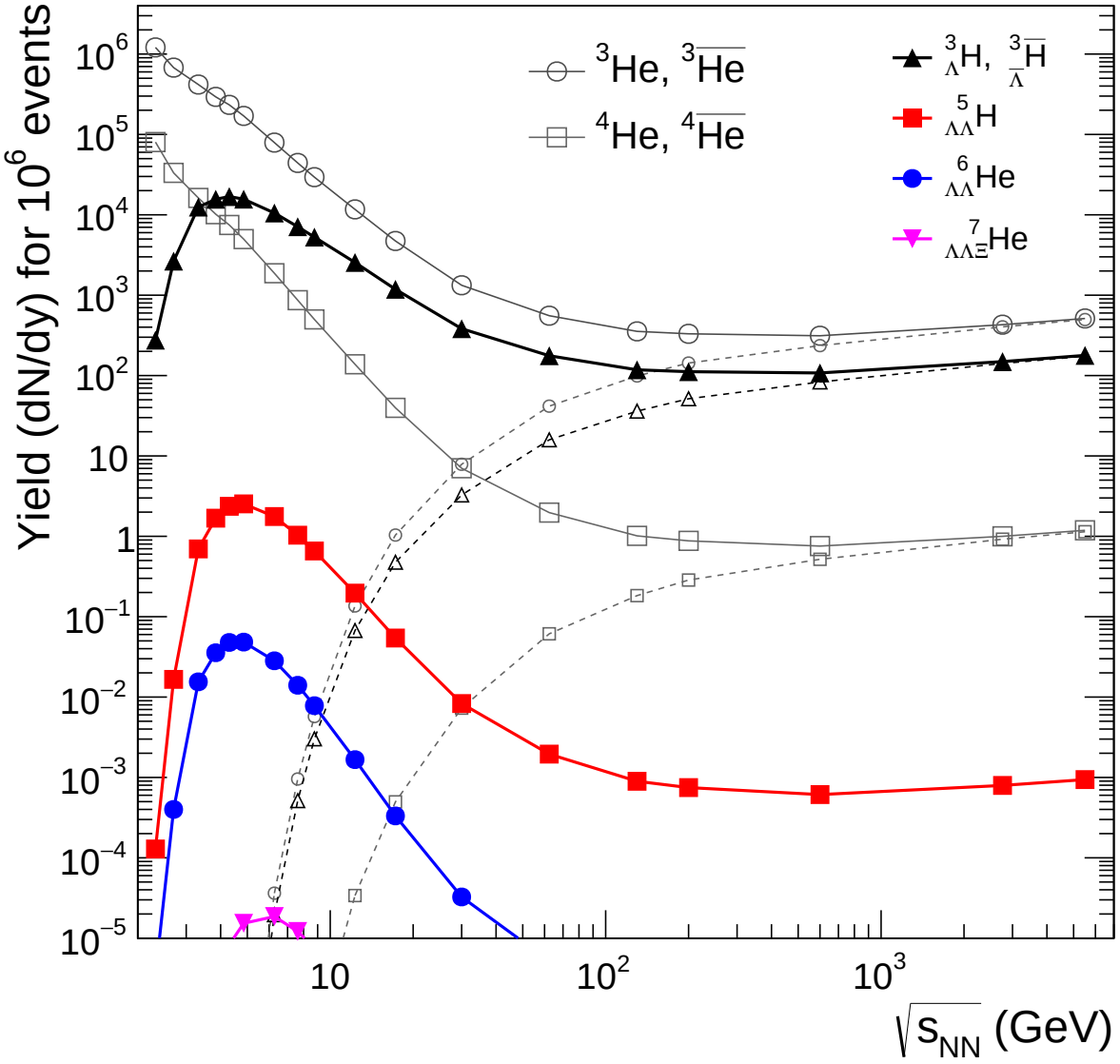
Summary / Outlook

- CBM 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 commisioning/data-taking with cosmics/beam in 2028/29
- Continuous improvements in MC description of det. (Geant4 still to come)
- More and more realistic physics performance with MC (incl. syst. uncert.)

Thank you for your attention!

Additional slides

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



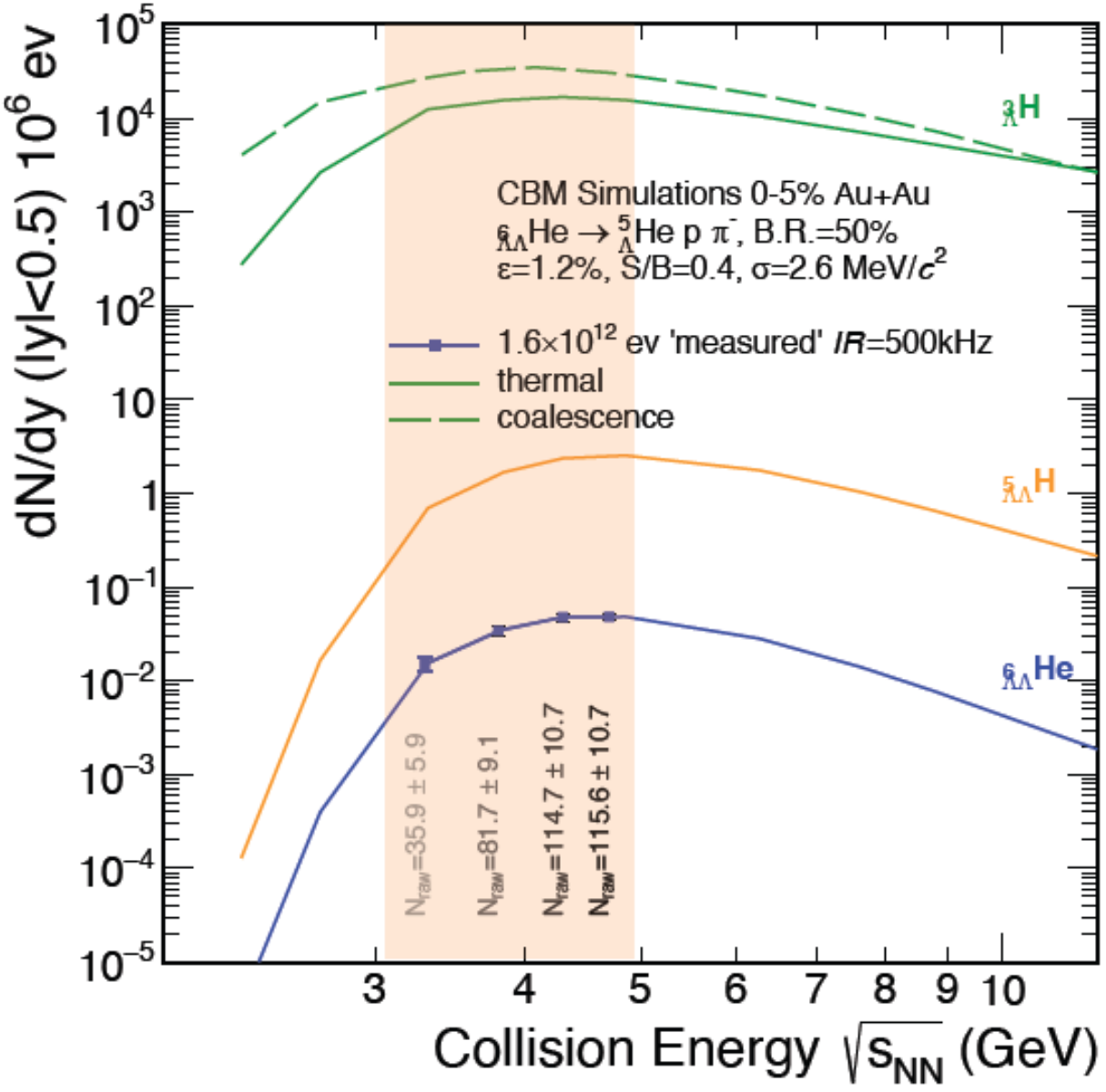
Statistical Hadroniz. Model (thermal)

central AA collisions

maxima: interplay between T and μ_B vs. $\sqrt{s_{NN}}$

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

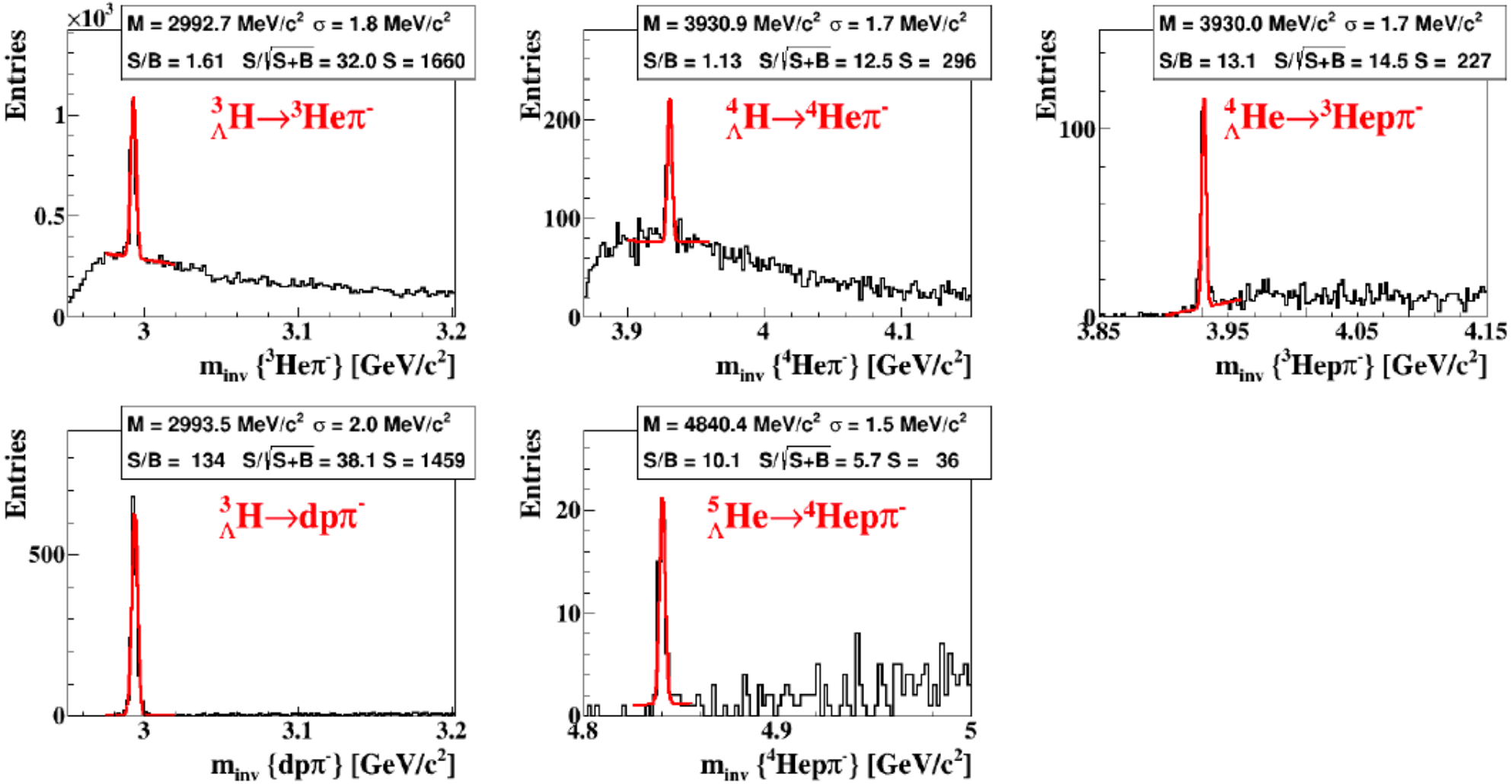
CBM: hypernuclei



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

and can discover the double-strange hyperons

CBM: Hypernuclei reconstruction

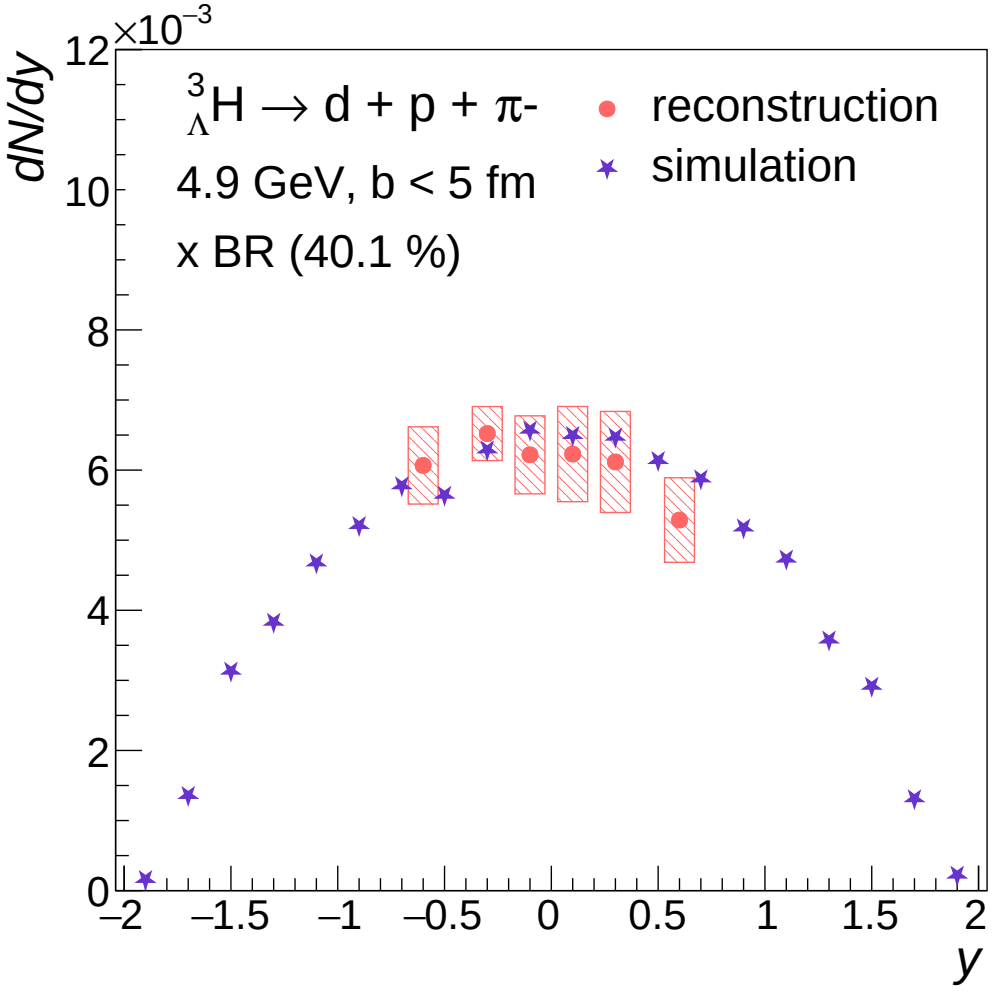


Au-Au, $\sqrt{s_{NN}} = 4.9$ GeV - PHQMD; KFParticleFinder; Day-1 detector

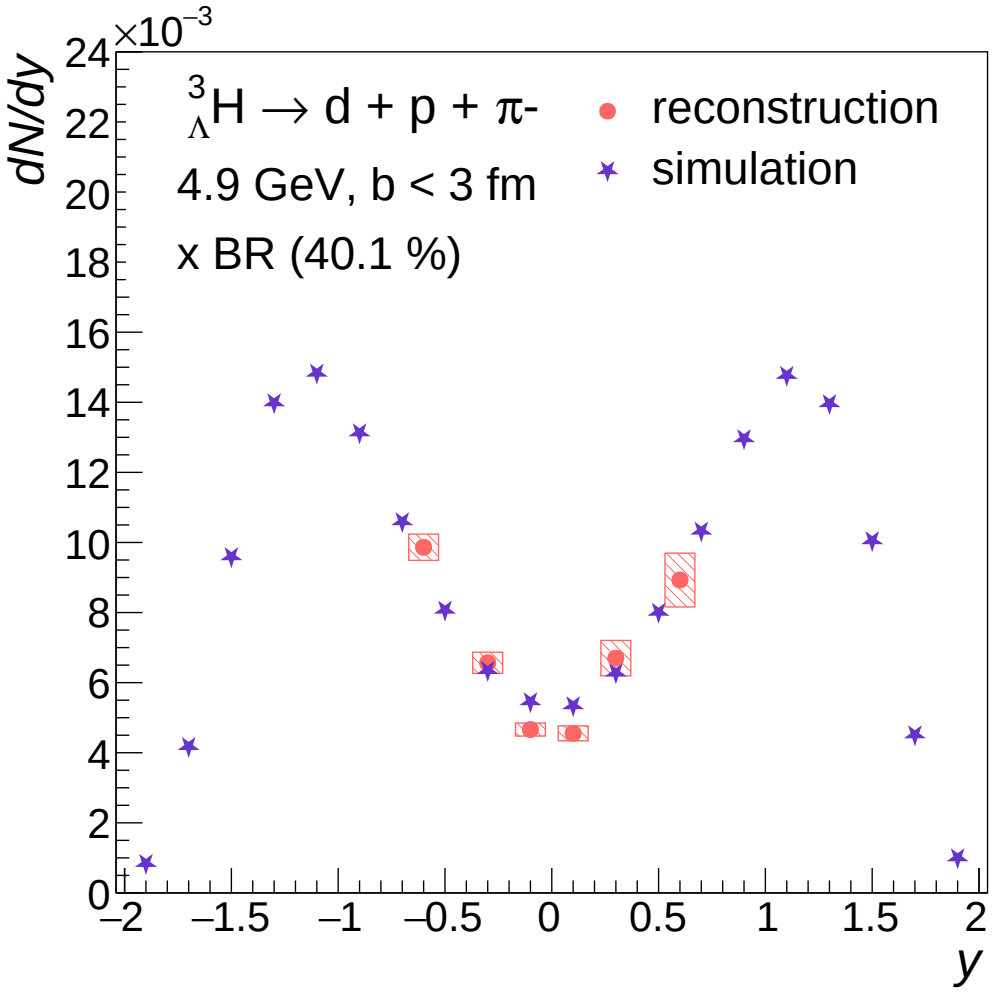
I. Vassiliev (GSI)

CBM: Hypertriton reconstruction

PHQMD-native

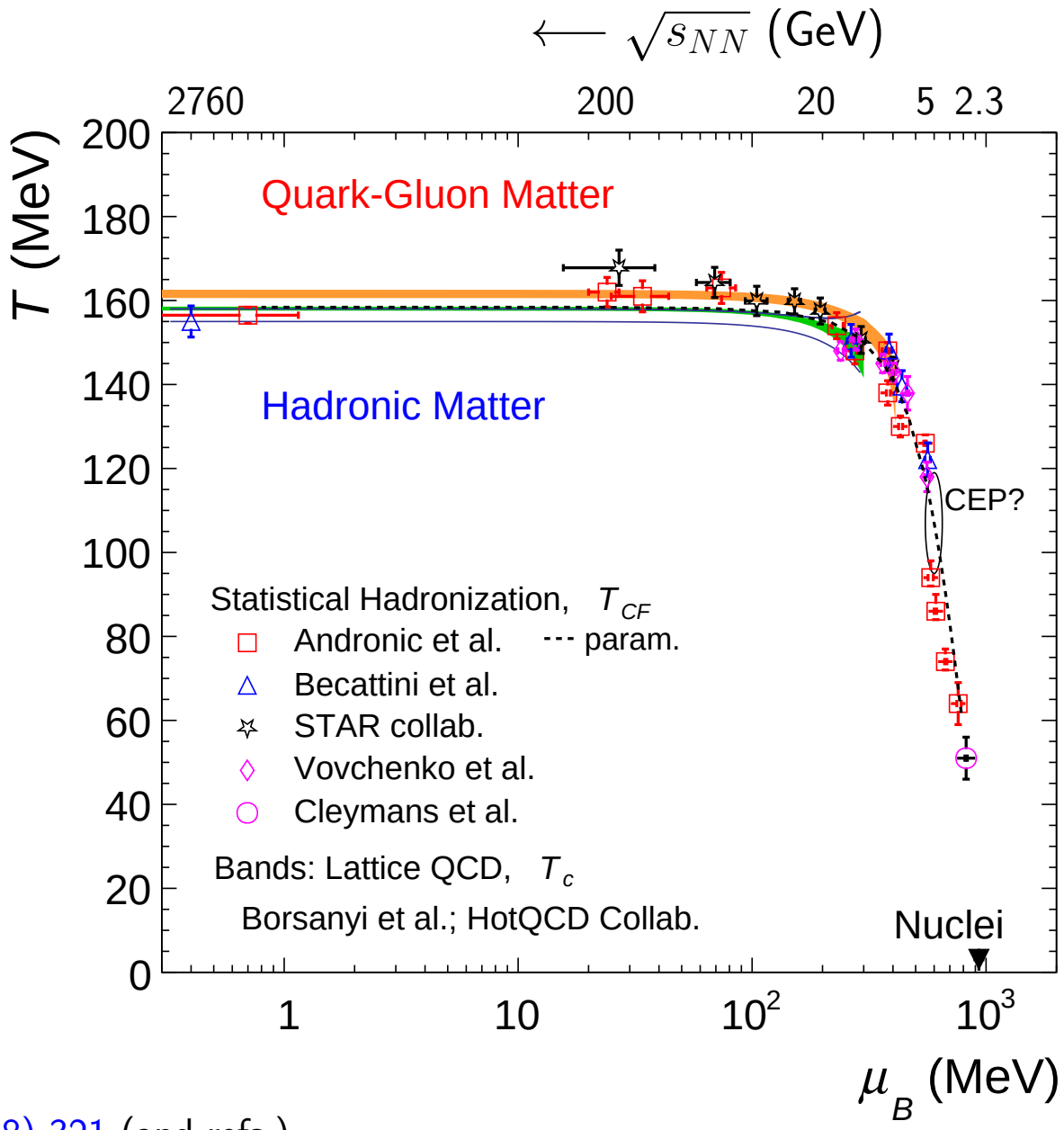


STAR-data inspired



S.Glässel (PhD, U. Frankfurt)

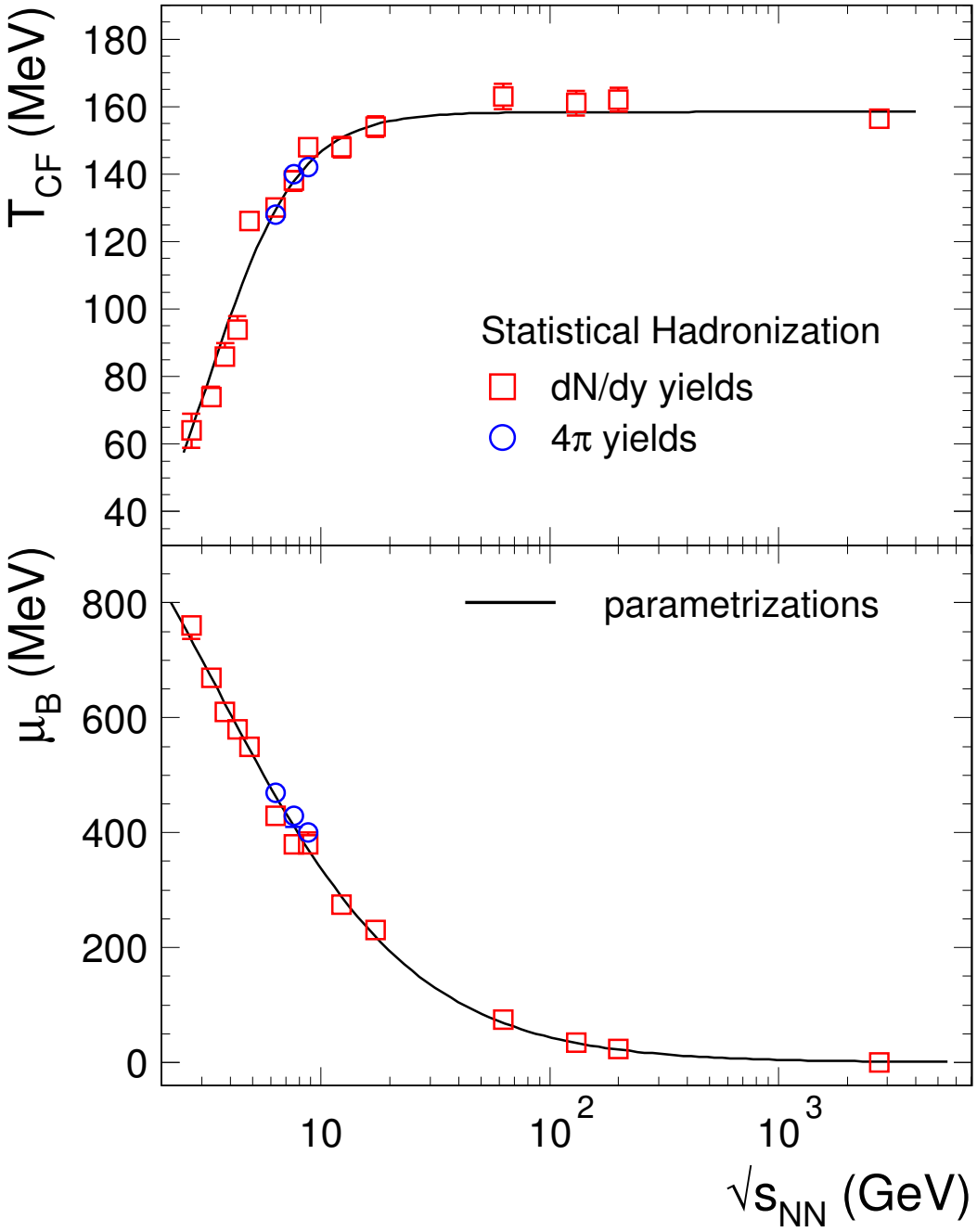
SHM and the QCD phase diagram



SHM: Nature 561 (2018) 321 (and refs.)

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

Energy dependence of T, μ_B (central collisions)



thermal fits exhibit a limiting temperature:

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

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

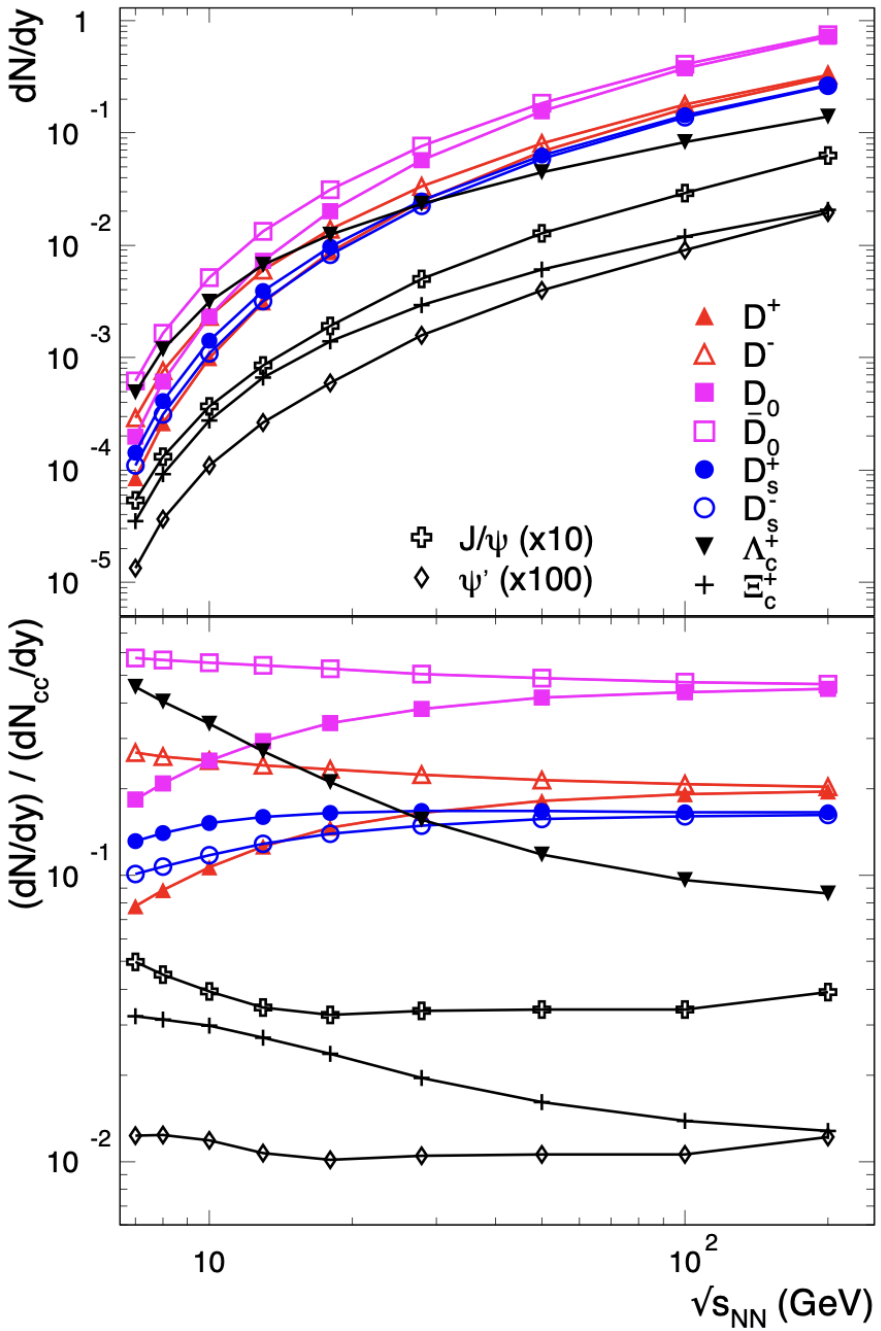
$$\mu_B[\text{MeV}] = \frac{1307.5}{1+0.288\sqrt{s_{NN}}(\text{GeV})}$$

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

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

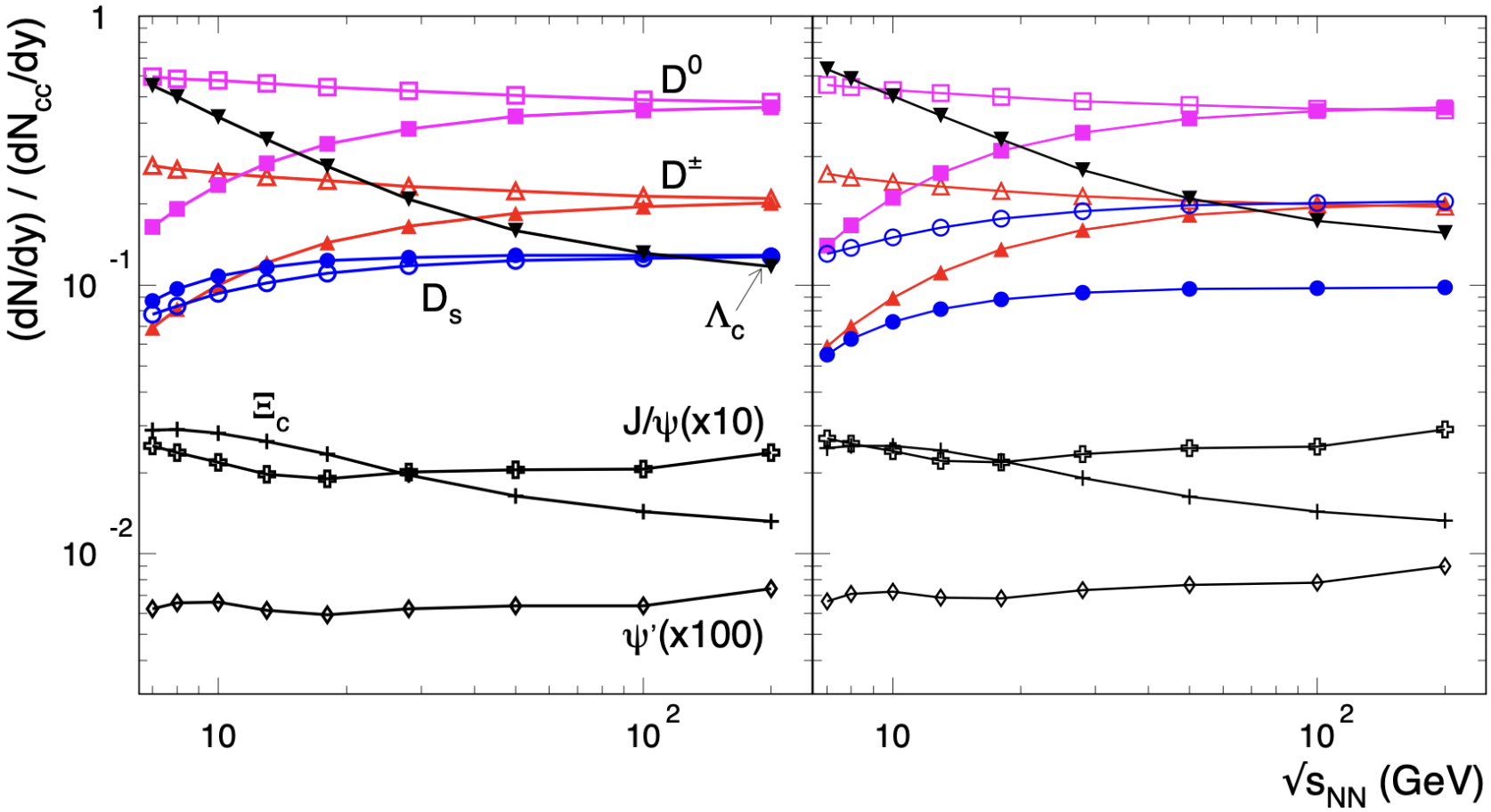
determined by the "stopping" of the colliding nuclei

SHM: charm at high-μ_B



AA et al, PLB 659 (2008) 149

SHM: charm at high-μ_B, in-medium masses?



AA et al, PLB 659 (2008) 149

2 scenarios for in-medium masses:

i) left: Δm=-50 MeV for all charmed mesons (incl. antiparticles); -100 MeV for Λ_c, Σ_c

ii) right: Δm=-100 MeV for charmed mesons, Δm=+50 MeV for antiparticles; as i) for baryons