The CBM experiment at FAIR

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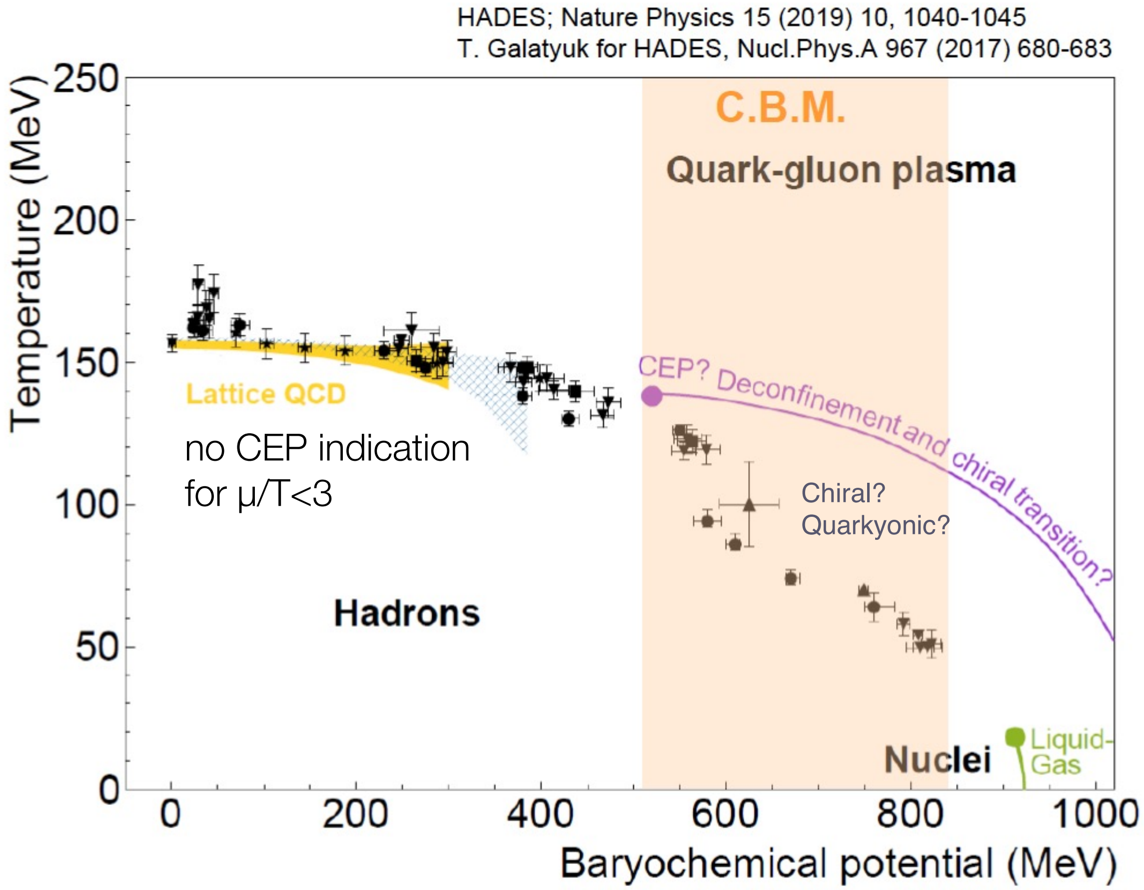
Sept 26th 2024, FAIRNess, Croatia

CBM: QCD phase diagram at high μ_B

Experimental investigation of the region with approx. 500 MeV < μ_B < 850 MeV



Characterization of high μ_B matter

Phase transition: deconfinement + chiral symmetry restoration
- 1st order phase transition (PT)
- QCD Critical end point (CEP)
- new phases of QCD (e.g. quarkyonic matter)

Critical point predictions from theory

T ~ 90-120 MeV, μ_B ~500-650 MeV
If true, reachable in heavy-ion collisions at 3 < $\sqrt{s}$ <5 GeV.

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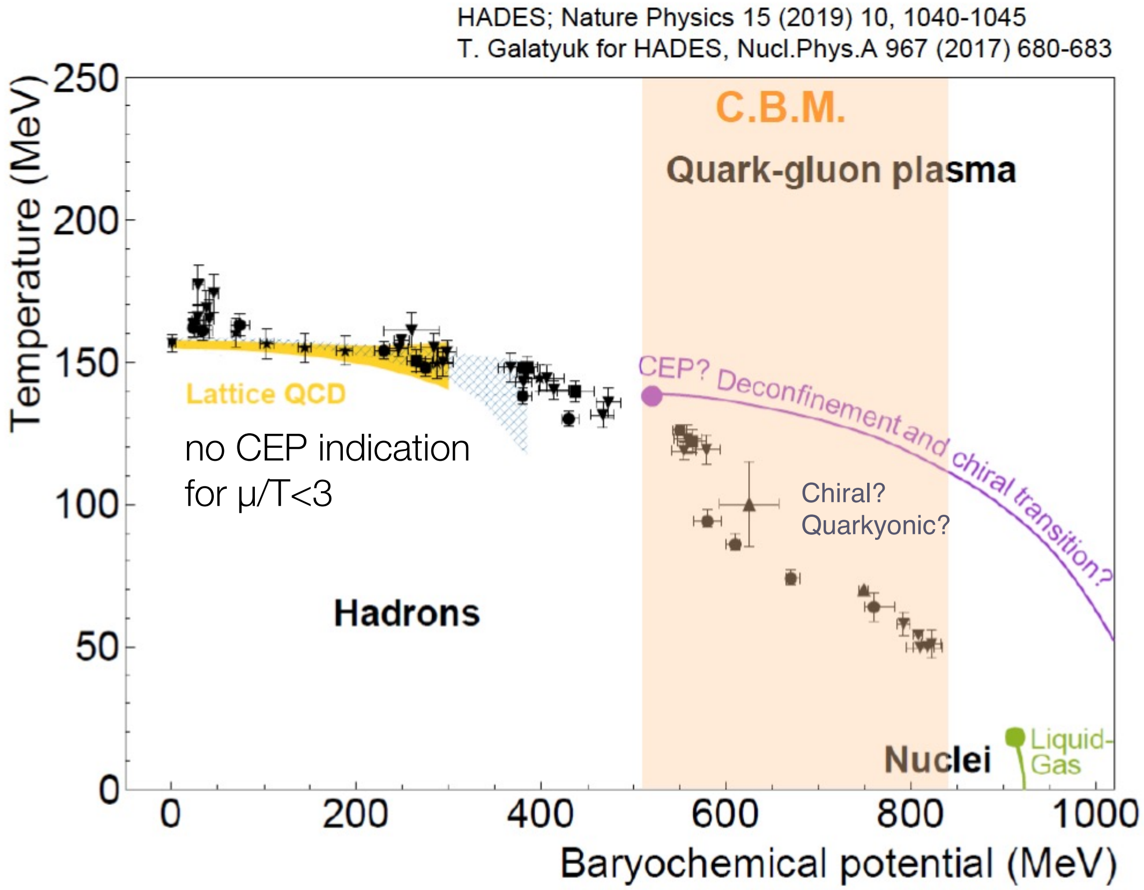


Key observables – systematic measurements:

Dileptons
→ Emissivity of dense baryonic matter: lifetime, temperature, density, in-medium properties

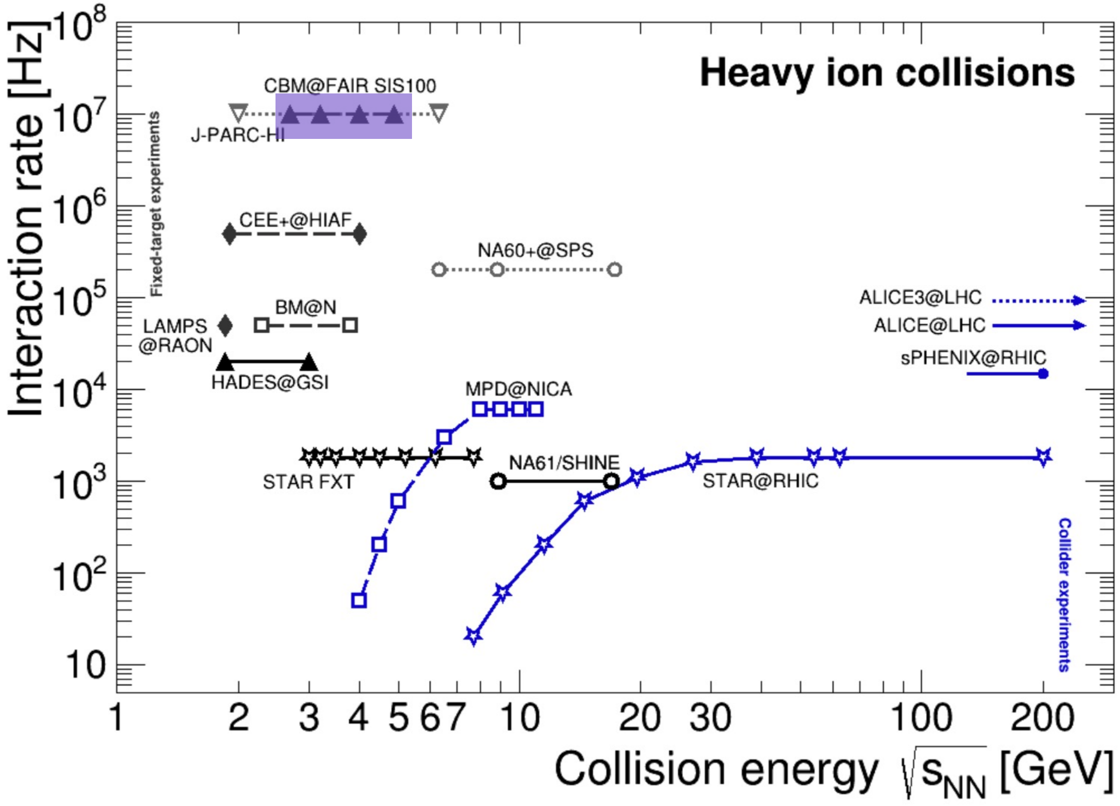
Fluctuations
→ System transition via 1st order PT line, CEP

Hadrons/ Strangeness/ Charm
→ System in equilibrium, Equation of Stage (EoS), Flow, Vorticity, Hypernuclei

Correlations
→ Flow, Vorticity, YN & YNN interactions

Almost unexplored (so far not accessible) in the high μ_B region

High μ_B facilities



T. Galatyuk, NPA 982 (2019), update 2023
https://github.com/tgalatyuk/interaction_rate_facilities,
CBM, EPJA 53 3 (2017) 60

Worldwide effort to investigate high-μ_B region of the QCD phase diagram

Key observables are rare:
Program needs precise data (statistics!) and sensitivity for rarest signals!

Systematic investigation in dependence on energy, system size/centrality

CBM: very high rate capability, energy range $3 < \sqrt{s_{NN}} < 5$ GeV

CBM detector for high interaction rates

CBM @ FAIR
2.5° - 25° polar angle coverage,
tracking in large gap dipole magnet, particle ID downstream

315 full members from 10 countries
47 full member institutions
10 associated member institutions

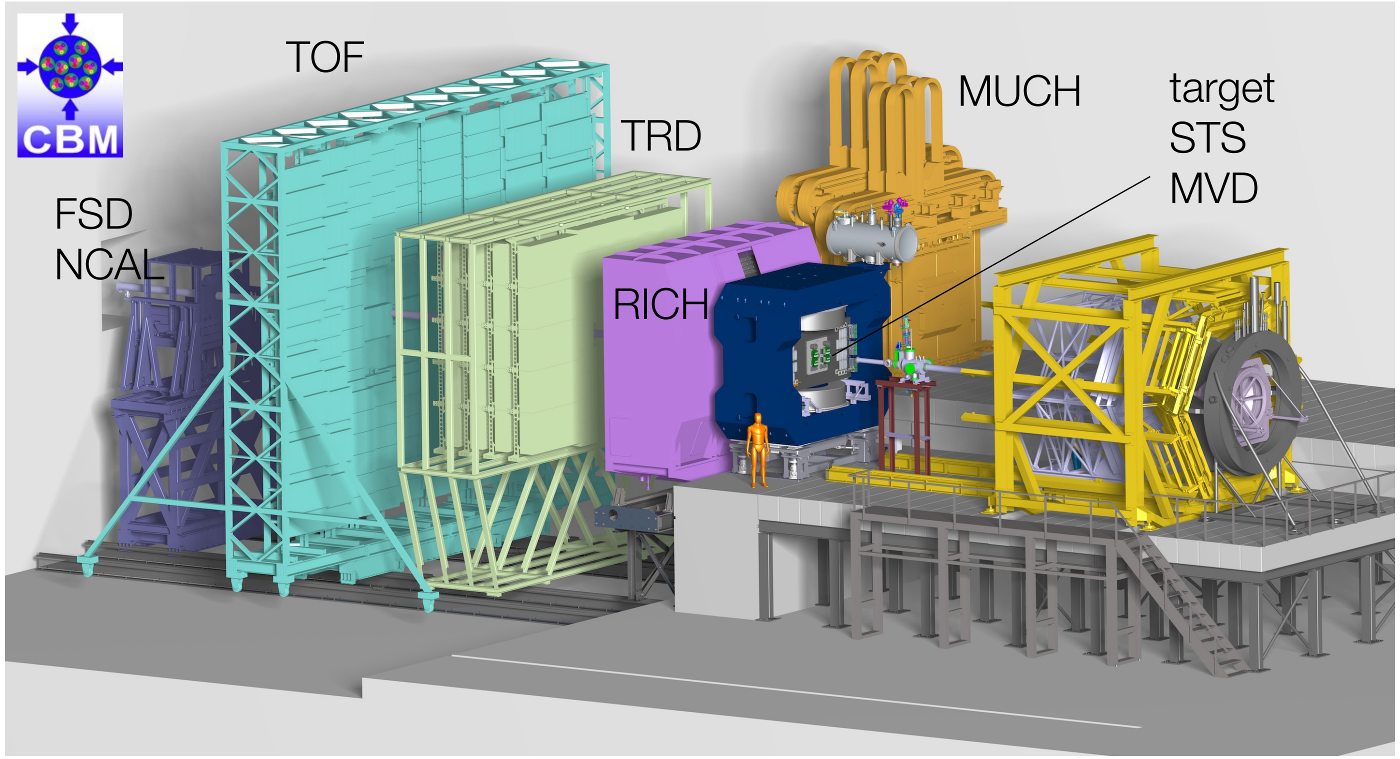
Fixed target experiment
→ obtain highest luminosities

Versatile detector systems
→ optimal setup for given observable

Tracking based entirely on silicon
→ fast and precise track reconstruction

Free-streaming FEE
→ nearly dead-time free data taking

On-line event selection
→ highly selective data reduction



Talks by :

RICH: Jesus Pena Rodriguez
FSD: Radim Dvorak
NCAL: Dachi Okropiridze

STS: Dario Ramirez
Lady Maryann Collazo Sánchez
TRD: Nikolai Podgornov

Strangeness

Strange hyperons:
- subthreshold production
- multi-strange hyperons: produced in sequencial collisions w/ K & Λ

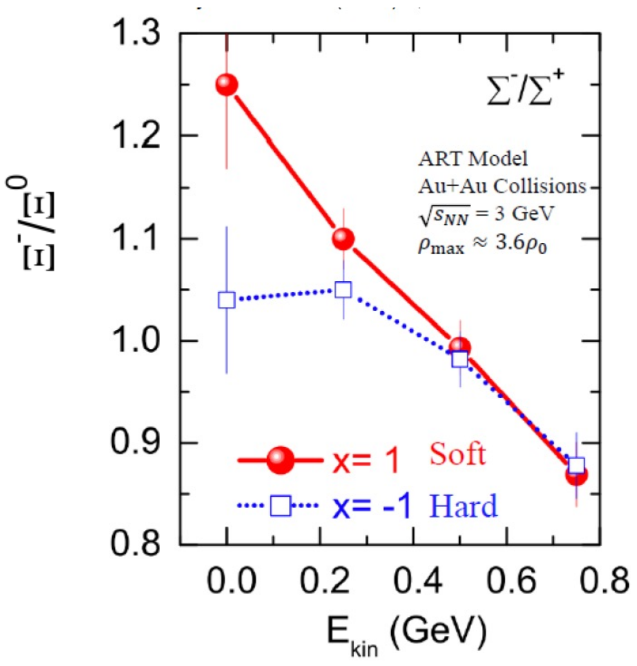
$$\pi^{-,+}N(n,p) \rightarrow \Sigma^{-,+} \quad \rightarrow \quad \Lambda\Sigma^{-,+} \rightarrow \Xi^{-,0}$$

=> sensitive to the density in the fireball: shed light on the compressibility of nuclear matter

=> flow measurements from hyperons to get insights into the EoS at high baryon densities

=> comparison of Ω/Ξ with chemical equilibrium multiplicities: potential sign for QGP

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



→ S-/S+ ratio is expected to carry $E_{sym}(\rho)$ (nuclear symmetry energy) information (stiff/soft)
→ access to isospin dependence?

Strangeness: Flow and EoS

Nuclear equation of state (EOS):
relation between energy/nucleon and density

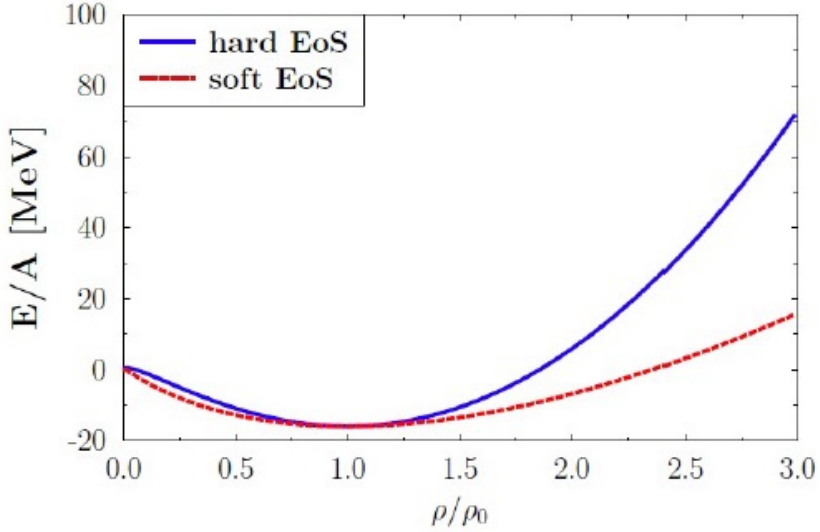
$$\varepsilon(\rho,T) = \varepsilon_T(\rho,T) + \varepsilon_C(\rho,T=0) + \varepsilon_0 \qquad (\varepsilon = E/A)$$

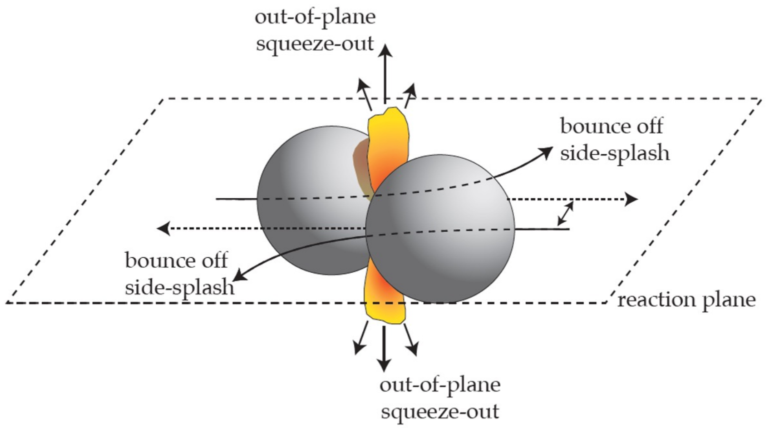
thermal **compressional** **ground state energy**

compression modulus

--- κ=380 MeV
— κ=200 MeV

Flow:
particle emission pattern transverse to the reaction plane
driven by pressure from overlap region



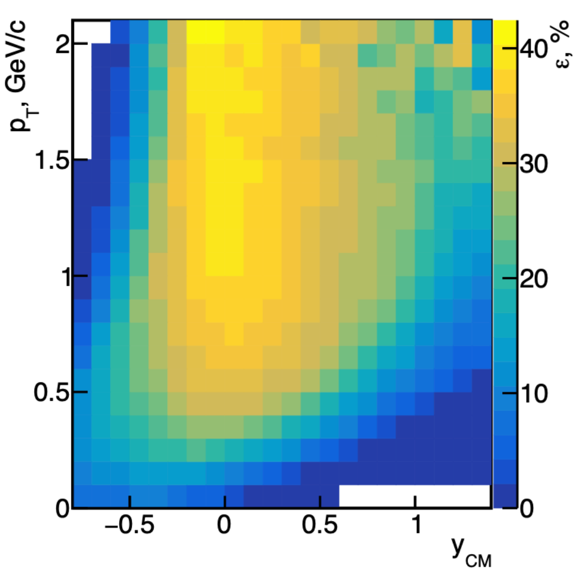


Cbm Strangeness performance

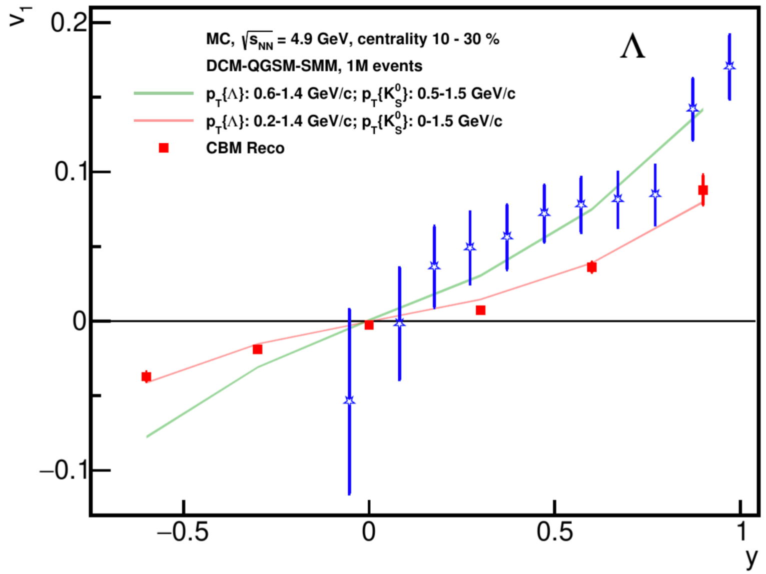
Tracking system allows for precise track and secondary vertex reconstruction, Δp=1%
TOF for hadron ID

Excellent phase space coverage (y_{CM} coverage for all $\sqrt{s_{NN}}$)
- Reconstruction efficiency ~30%
- Event plane resolution $\Re1 \cong 0.8$, $\Re2 \cong 0.5$

Precision measurement of spectra and flow pattern (no data for Ξ, Ω available below AGS energies)
Superior CBM performance to the STAR-FXT flow measurements

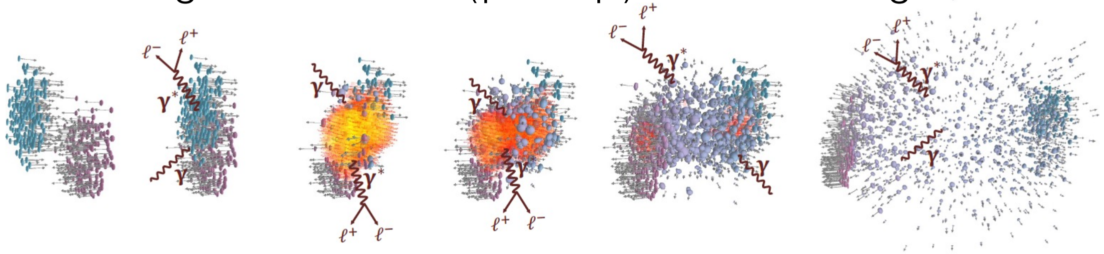


Simulations: UrQMD, 5M central collisions Au+Au, 10 AGeV beam energy



Dileptons

Electromagnetic radiation (γ and γ*) emitted during full fireball evolution from all stages

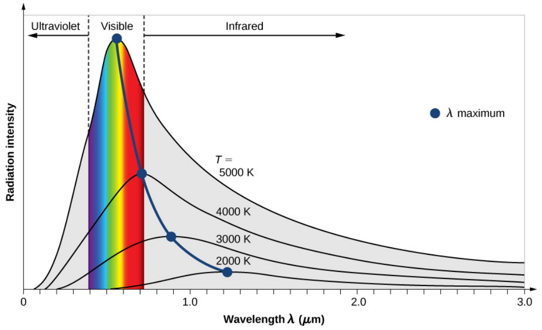


⟶ sensitive to the full duration/evolution of the collision.

⟶ no strong interaction with medium ⟹ escape the reaction volume unmodified

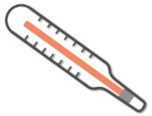
$\rho \longrightarrow e^+ e^-$ (short lifetime)

$\pi^0 / \eta \longrightarrow e^+ e^- \gamma$, $\omega / \phi \longrightarrow e^+ e^-$, $\omega \longrightarrow \pi^0 e^+ e^-$

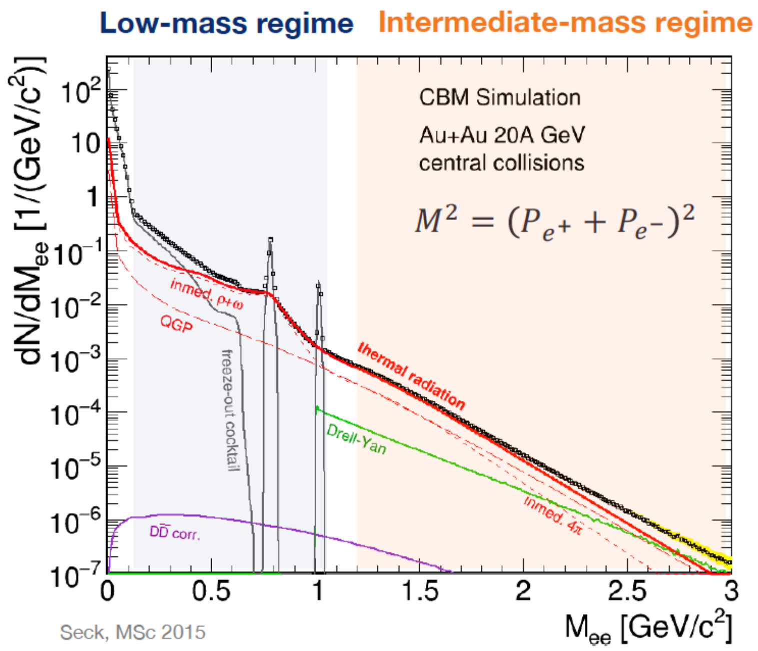


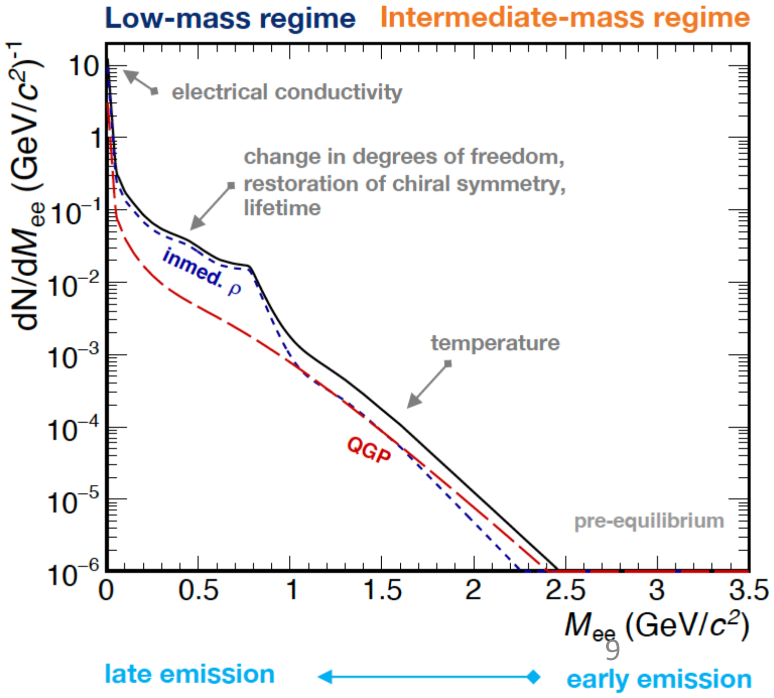
Thermal radiation of medium ⟶ black body rad.

Emission rate of thermal dileptons:
unique direct access to early stage temperature of fireball



Dileptons are a unique probe of
fireball lifetime, temperature, density, restoration of chiral symmetry, ….



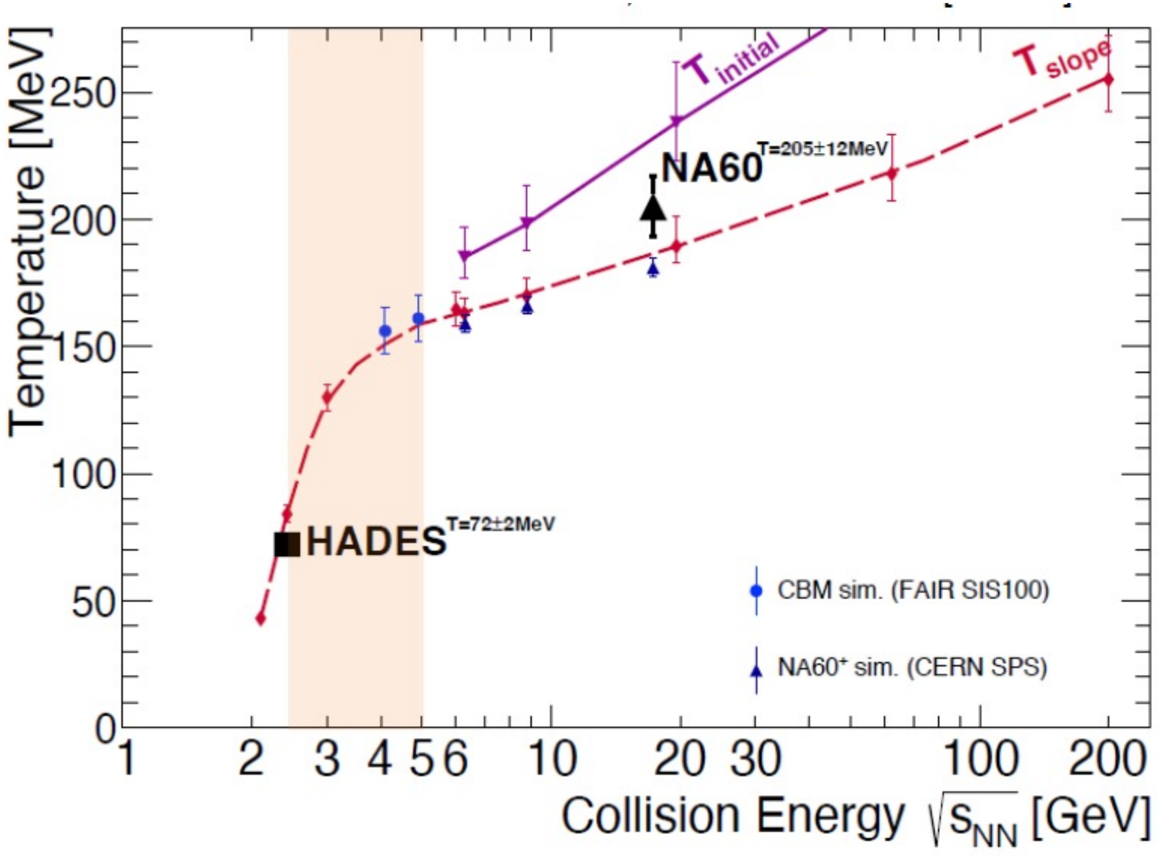


Dileptons

Invariant mass slope measures radiating source T:

Flattening of caloric curve (T vs ε)

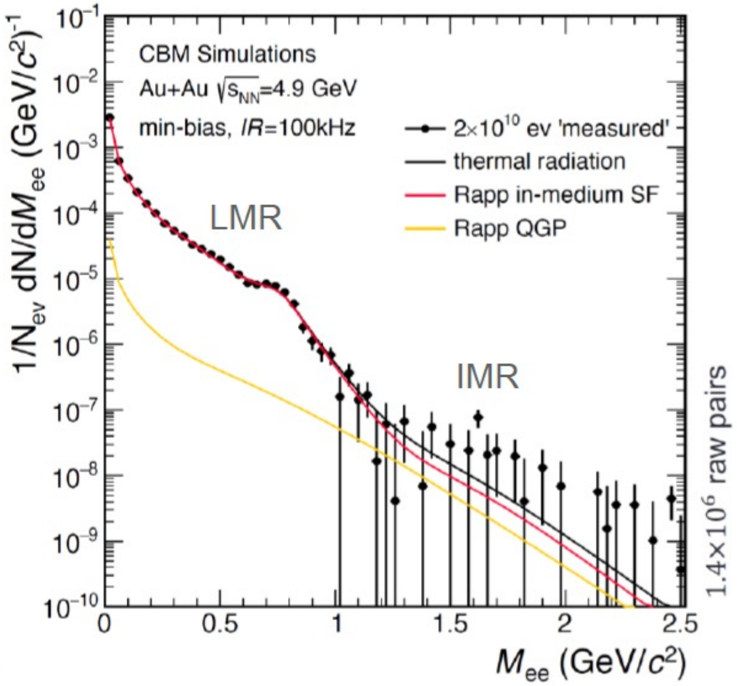
→ positive evidence for a phase transition

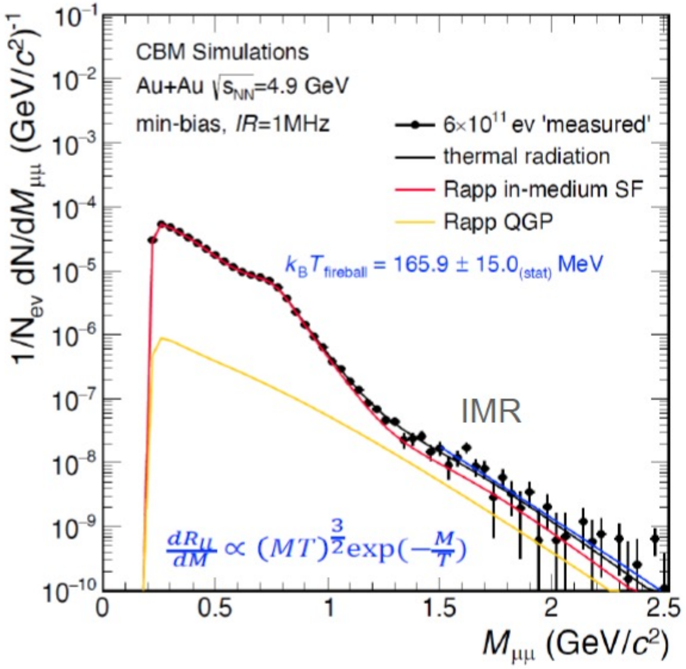


Tripolt et al., NPA 982 (2019) 775
Li and Ko, PRC 95 (2017) no.5, 055203
Seck et al., PRC (2022), arXiv:2010.04614 [nucl-th]
O. Savchuk et al., arXiv:2209.05267 [nucl-th]

CBM dilepton performance

Isolation of thermal radiation by subtraction of measured decay cocktail (π/, η,ω, φ), Drell-Yan, $\bar{c}\ c$ ($\bar{b}\ b$)
Dileptons are rare probes!
Decisive parameters for data quality: interaction rates (IR) and signal-to-combinatorial background ratio (S/CB)





Talks by:
Cornelius Feier-Riesen
Pavish Subramani

Expected dielectron performance
first year, 5 days/ energy (6), 2x10^{10} events each, 100kHz

=> LMR: reconstructed with precision of 1.5 – 4.5%
allows fireball lifetime measurement

Expected dimuon performance
High statistics runs after first 3 years

=> Access IMR range with <10% errrors on $T_{fireball}$

Critical Fluctuations

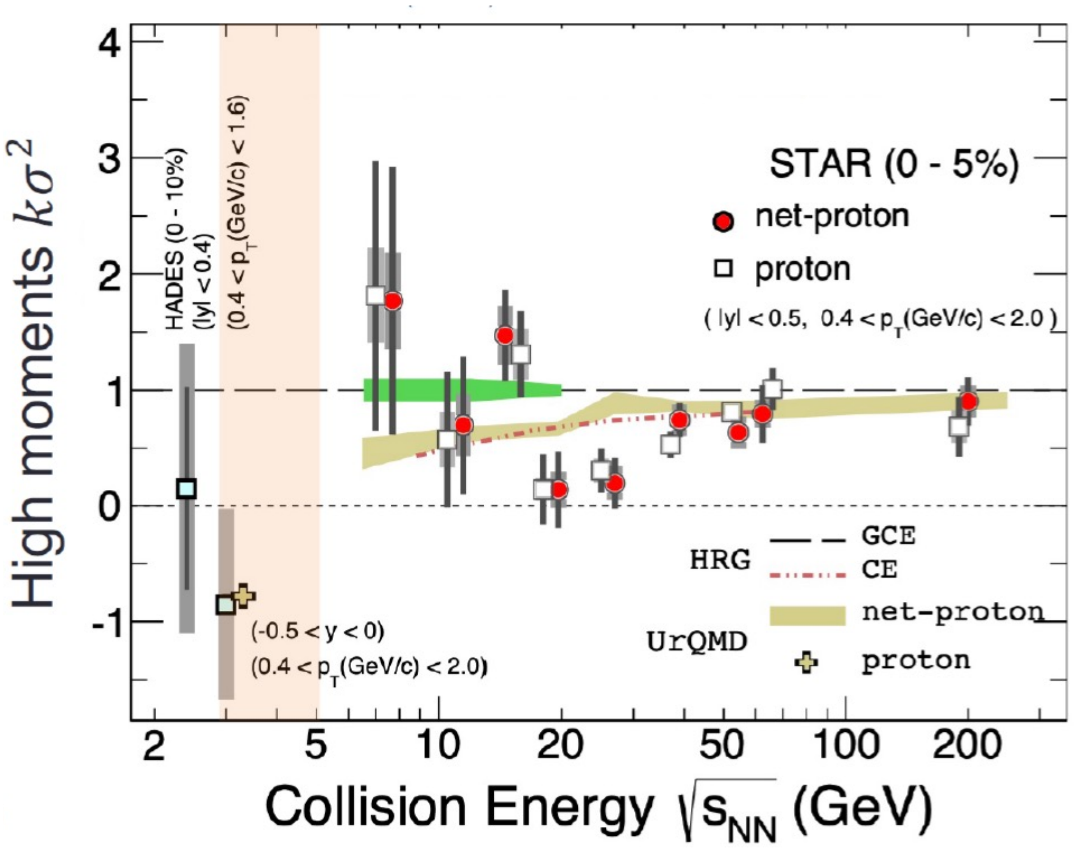
At CEP or when crossing a 1st order phase transition:
density fluctuations/ jump in density
→ both yielding discontinuities/ fluctuations
→ cumulants of baryon number measure derivatives of μ_B

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

Ratios of cumulants independent of volume

$$\frac{\chi_4}{\chi_2} = \frac{\kappa_4}{\kappa_2} = \kappa\sigma^2 \qquad \kappa_4 = \langle N - \langle N \rangle \rangle^2 \text{ etc.}$$

Non-monotonic trend of the higher moments $\kappa 4/\kappa 2$ of net-proton number distributions, visible in a beam energy scan?

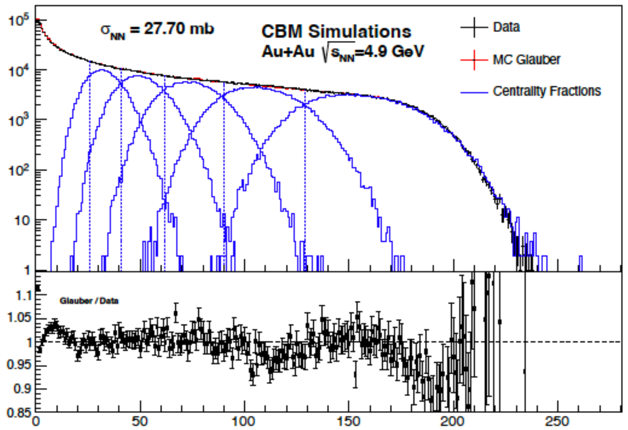


CBM Critical Fluctuations performance

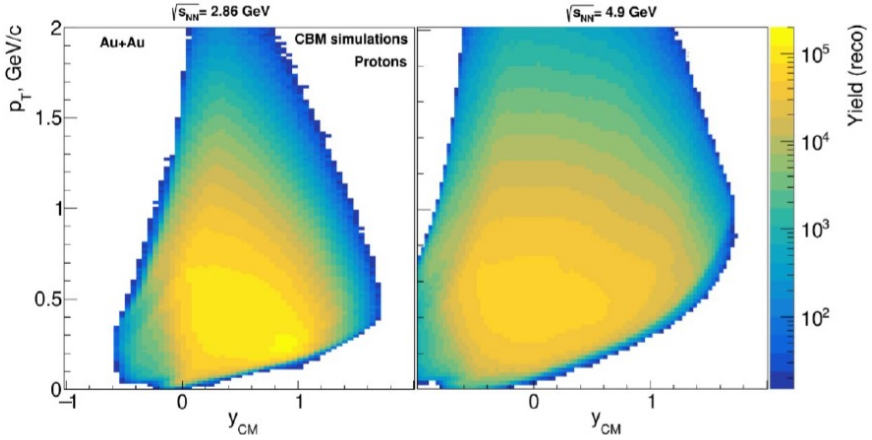
Measure event-by-event net-proton number (p – anti-p)

Sensitivity to features of the QCD phase diagram grows with the order of the moment

Detailed systematic studies of experimental effects is crucial: acceptance, centrality, baryon number conservation at high μ_B

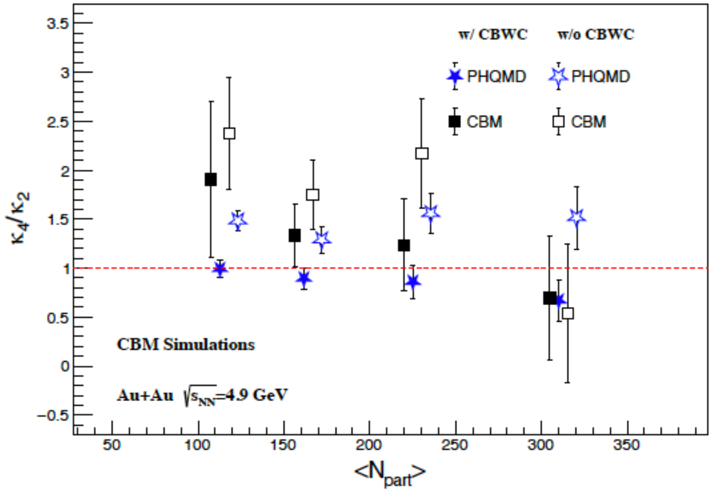


STS charged track multiplicities



Low p_T and midrapidity coverage for all energies

Reconstruction efficiency allows for precision measurement of cumulants



Day-1 statistics sufficient to study cumulants of order > O(4)

Centrality determination with independent detector: avoids bias on e-by-e fluctuation observables

Studies employing FSD centrality detector ongoing

Talk by Beatriz Artur

CBM after 3 years – (improve STAR stat. errors by factor of 10):
– completion of the excitation function for κ_4 (p)
– first results on κ_6 (p)
– extension into strangeness sector κ_4 (Λ)

The future is bright!

FAIR construction progressing SIS 100 tunnel ready
CBM cave ready, Upstream platform is installed
(Pre)-series production of CBM started

First beams in 2028/2029

Years 1-3: (first) energy scan, improved statistical errors of factor 10 vs. STAR
Years 4-8: high statistics measurements → Dilepton IMR, ultra-rare probes

Important milestone: **mCBM @ SIS 18**!
Full system test
Verification of triggerless-free-streaming readout
Up to 10 MHz collision rates

Talk by
Abhishek Anil Deshmukh

44th CBM collaboration meeting in Prague, September 2024

BACKUP

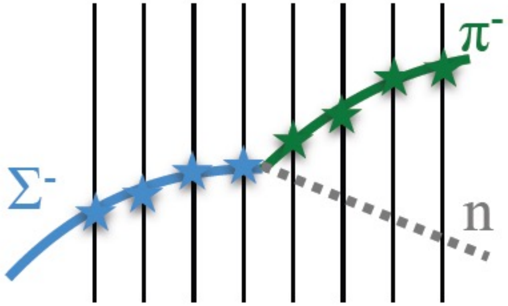
Cbm Strangeness performance

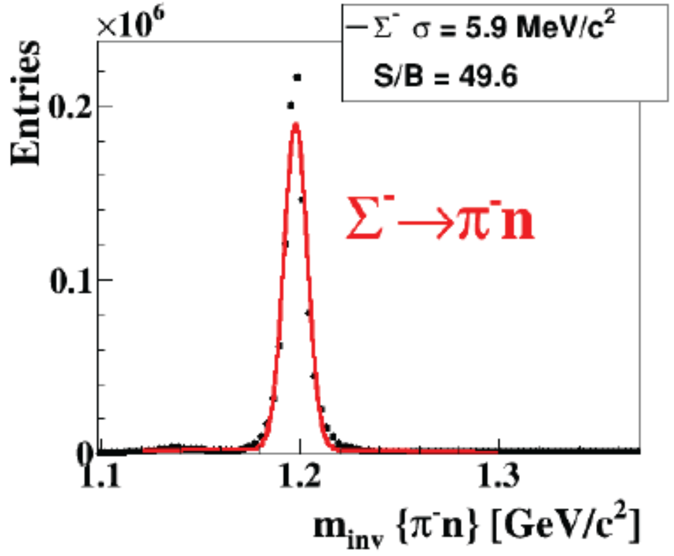
Identification of (multi-)strange particles via their decay topology:

employ decay-vertex topology in the vertex spectrometer

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

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





large statistical significance for K^0_S, Λ, Ξ, Ω as well as $\phi \to K{+}K{-}$
allows multi-differential analysis of yield (flow, correlations polarization)

Strangeness

Strange hyperons:
- subthreshold production
- multi-strange hyperons: produced in sequencial collisions w/ K & Λ

=> sensitive to the density in the fireball: shed light on the compressibility of nuclear matter
=> flow measurements from hyperons to get insights into the EoS at high baryon densities
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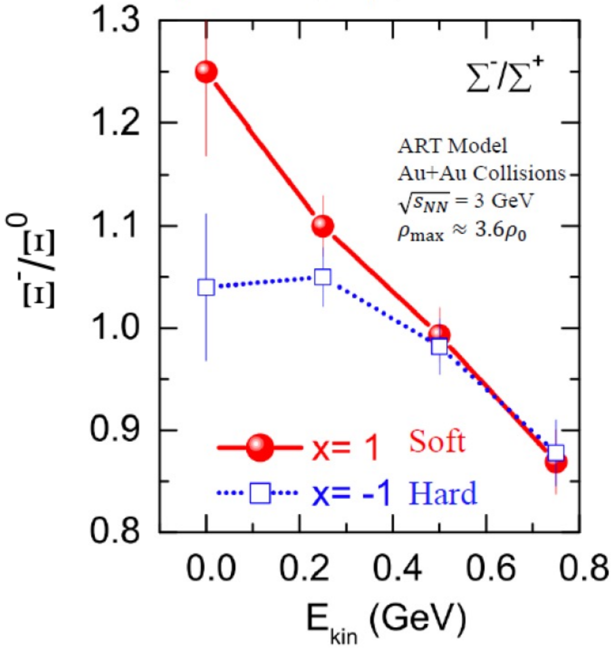

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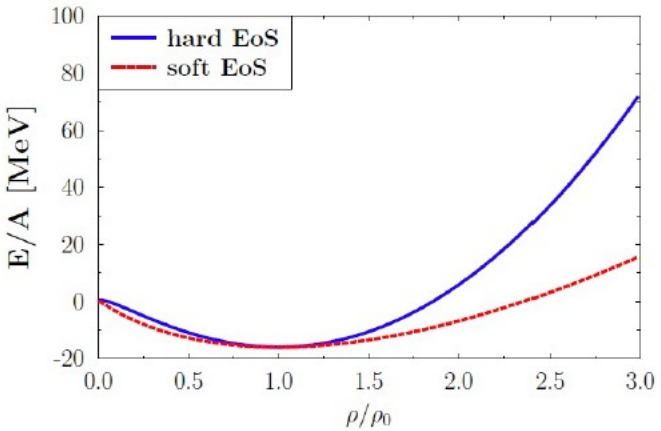
thermal **compressional** **ground state energy**



compression modulus

- - - κ=380 MeV
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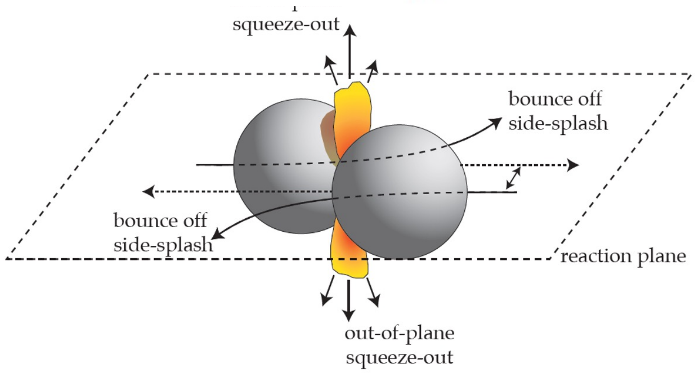

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First 3 years scenario (as of May 2022)

Year	Setup	Reaction	Beam Energies T_{lab} [AGeV]	Days on Target	Number of events	Remarks
0	ELEHAD	C+C, Ag+Ag, Au+Au	2,4,6,8,10,max	60		Commissioning
1	ELEHAD	Au+Au	2,4,6,8,10,max	30 (5 each)	$2\cdot10^{10}$ each	EB minBias
1	ELEHAD	C+C	2,4,6,8,10,max	18 (3 each)	$4\cdot10^{10}$ each	minBias
1	ELEHAD	p+Be	3,4,8,29	12 (3 each)	$2\cdot10^{11}$ each	minBias
2	MUON	Au+Au	2,4,6,8,10,max	30 (5 each)	$2\cdot10^{11}$ each	minBias
2	MUON	C+C	2,4,6,8,10,max	18 (3 each)	$4\cdot10^{11}$ each	minBias
2	MUON	p+Be	3,4,8,29	12 (3 each)	$2\cdot10^{12}$ each	minBias
3	HADR	Au+Au	2,4,6,8,10,max	12 (2 each)	$4\cdot10^{11}$ each	EB + Selector(s)
3	HADR	C+C	2,4,6,8,10,max	6 (1 each)	$8\cdot10^{11}$ each	
3	HADES	Ag+Ag	2,4	28 (14 each)	10^{10} each	
3	ELEHAD	Ag+Ag	2,4	8 (4 each)	$2\cdot10^{10}$ each	minBias

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

- **Focus on beam energy scan**
- 60 days / year beam on target → factor 100 more statistics w.r.t. STAR FXT

- Different detector configurations (Piotr's talk)
- Subject to a reshaping depending on findings (*e.g.* long run at maximum $\sqrt{s_{NN}}$ with MUON setup)