SQM2022
The 20th International Conference on Strangeness in Quark Matter
13-17 June 2022 Busan, Republic of Korea

Experimental Summary I

- Study QCD Phase Structure in High-Energy Nuclear Collisions

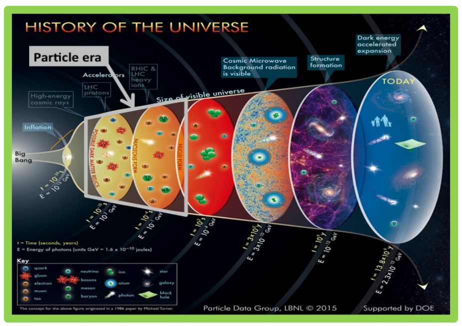
Nu Xu

1) **Collectivity**
2) **Criticality**
3) **Hyper-nuclei**

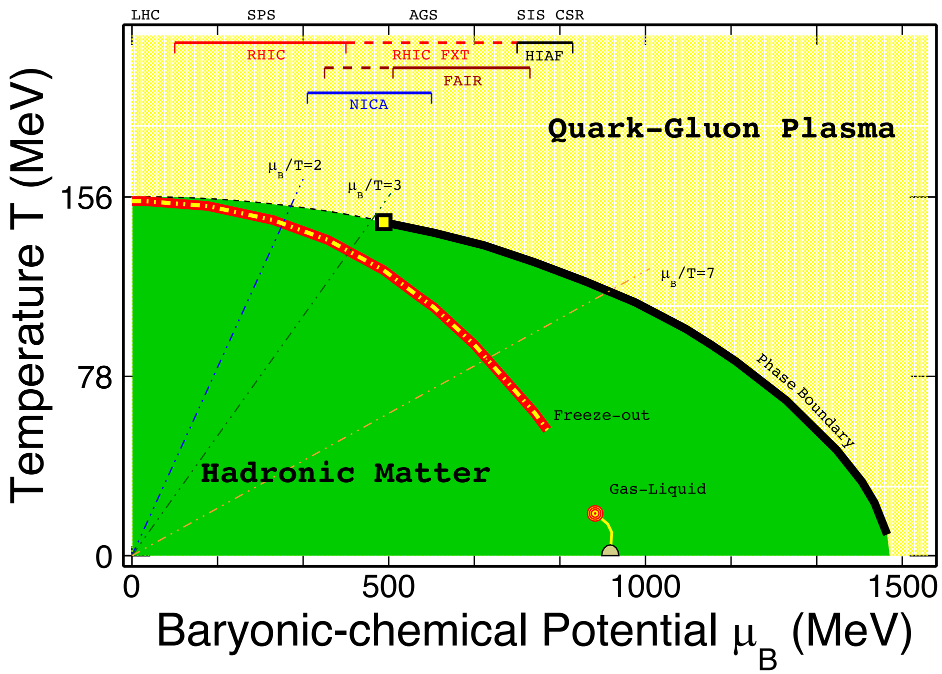
QCD Phase Structure

High-Energy Nuclear Collisions and QCD Phase Diagram

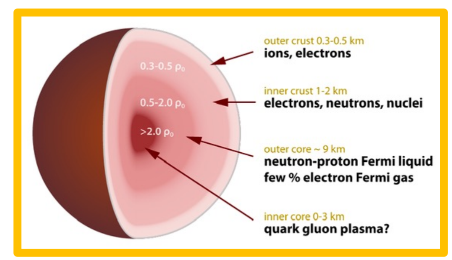
LHC | RHIC BES | FAIR, NICA, …



High temperature:
Early Universe evolution



High baryon density:
Inner structure of
compact stars



1) At $\mu_B = 0$, smooth crossover (LGT + data) ;

2) Large μ_B, 1st order phase transition → **QCD critical point**

Collectivity

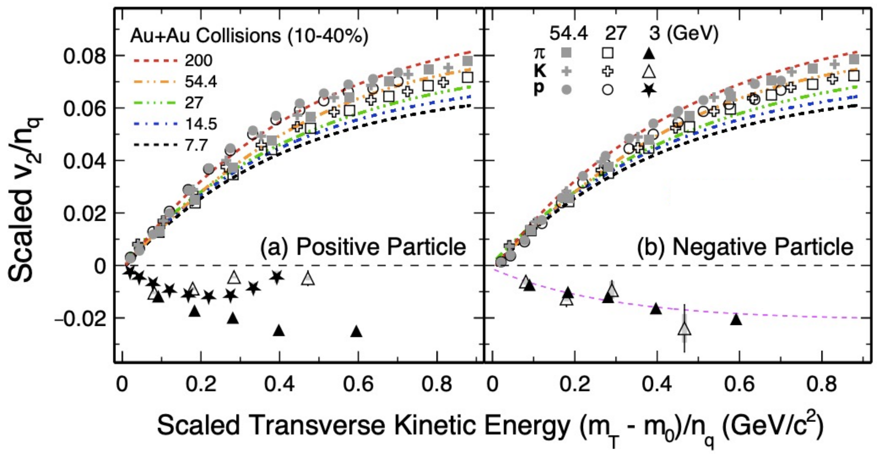
$$\partial_\mu[(\varepsilon + p)u^\mu u^\nu - pg^{\mu\nu}] = 0$$
$$\partial_\mu[s\, u^\mu] = 0$$

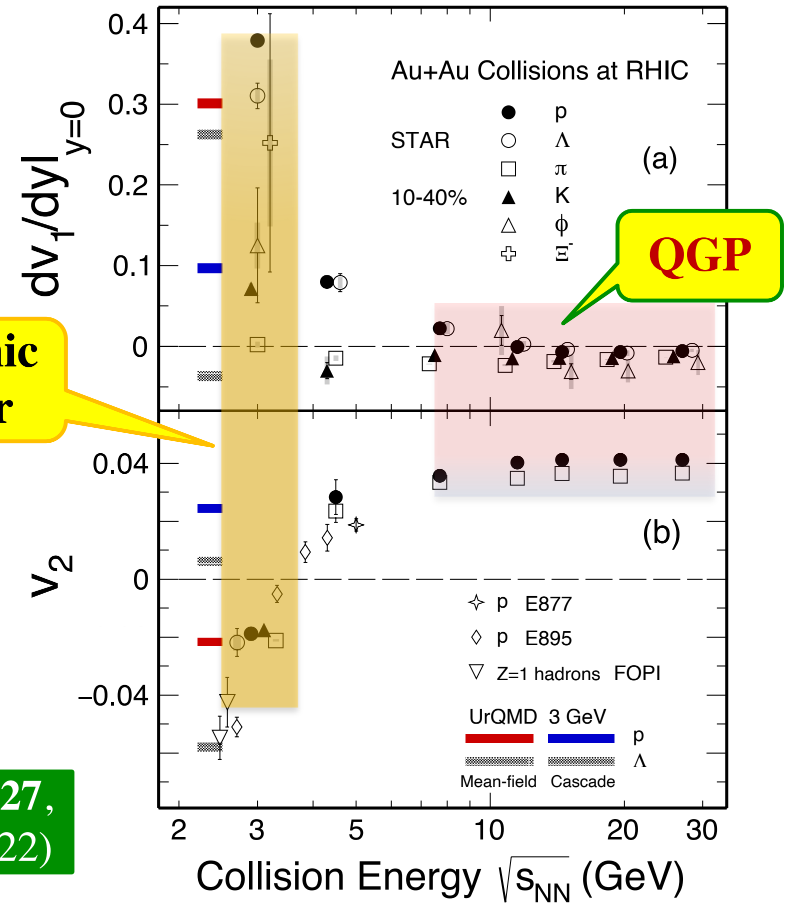
$$\frac{d^2N}{p_T dp_T d\varphi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T}\left\{1 + \sum_{n=1}^{\infty} 2v_n(p_T)cos[n(\varphi - \Psi_R)]\right\}$$

$- v_1$ Directed flow;

$- v_2$ Elliptic flow; $- v_3$ Triangle flow

SQM2022 Disappearance of Partonic Collectivity at 3 GeV

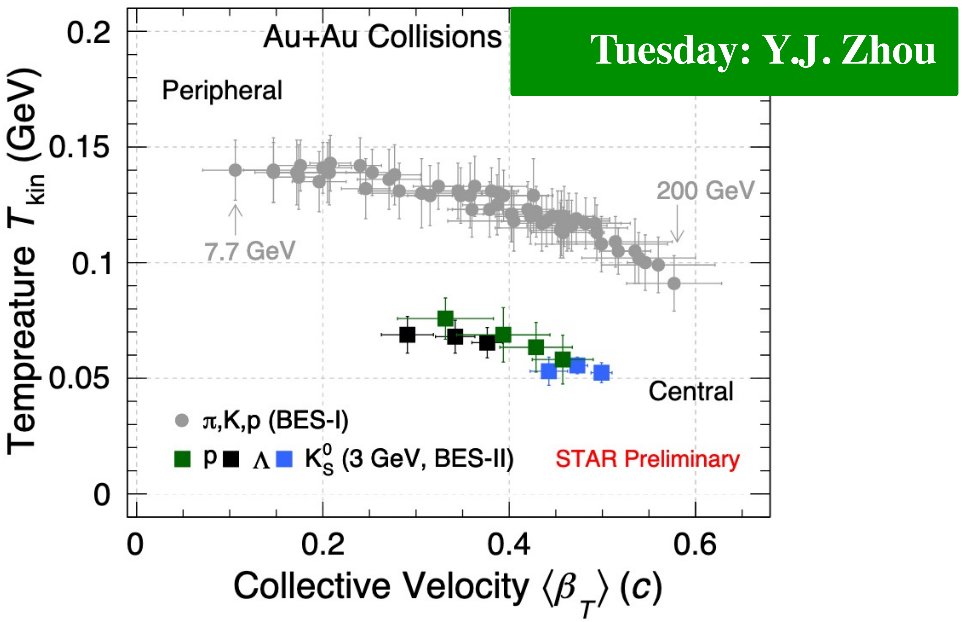


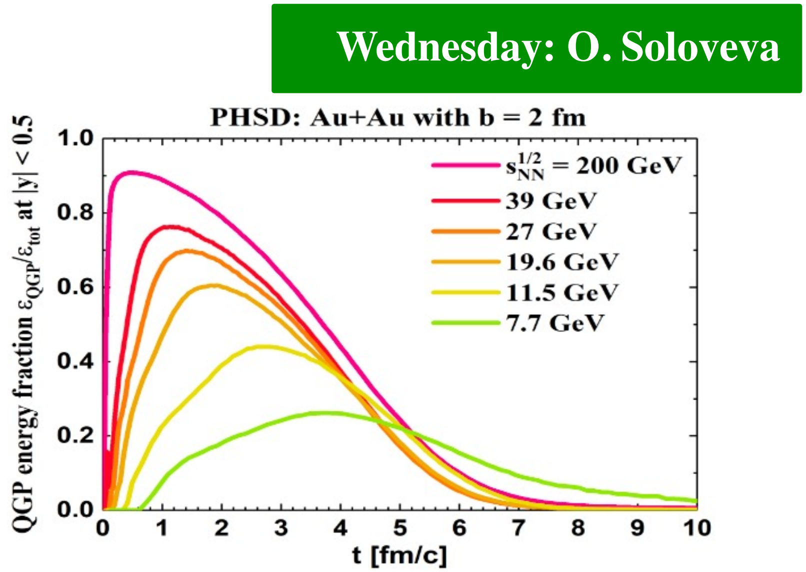


- At 3 GeV, NCQ scaling is absent, hadronic interactions dominant!
- Transport model calculations, with baryonic mean field, reproduced both v_1 and v_2 results

STAR: Phys. Lett. B**827**, 137003 (2022)

Disappearance of Partonic Collectivity at 3 GeV

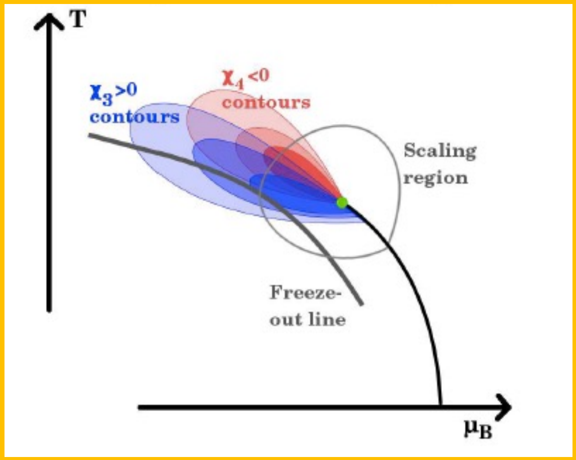




- At 3 GeV, freeze-out parameters are different from that from high energies!
- Among (π, K, p, Λ), *no common* overlap region at 3 GeV, unlike the case at higher collisions energies!

→ Different EOS at 3 GeV, **hadronic interaction dominant!**

Criticality



Conserved Quantities (B, Q, S)

1) In strong interactions, baryons (B), charges (Q) and strangeness (S) are conserved;
2) Higher order moments/cumulants describe the shape of distributions and quantify fluctuations. They are sensitive to the correlation length ξ, phase structure;
3) Direct connection to theoretical calculations of susceptibilities

Measured multiplicity N, $\langle \delta N \rangle = \mathrm{N} - \langle N \rangle$

mean: $M = \langle N \rangle = C_1$

variance: $\sigma^2 = \langle (\delta N)^2 \rangle = C_2$

skewness: $S = \langle (\delta N)^3 \rangle / \sigma^3 = C_3/C_2^{3/2}$

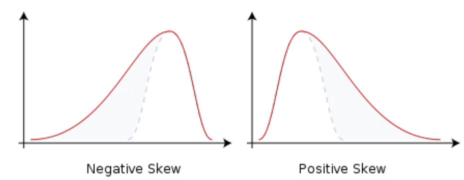
kurtosis: $\kappa = \langle (\delta N)^4 \rangle / \sigma^3 - 3 = C_4/C_2^2$

Moments, cumulants and susceptibilities:

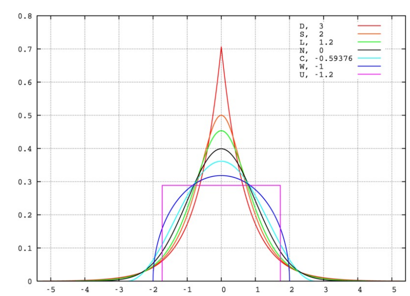
2nd order: $\sigma^2/M \equiv C_2/C_1 = \chi_2/\chi_1$

3rd order: $S\sigma \equiv C_3/C_2 = \chi_3/\chi_2$

4th order: $\kappa\sigma^2 \equiv C_4/C_2 = \chi_4/\chi_2$



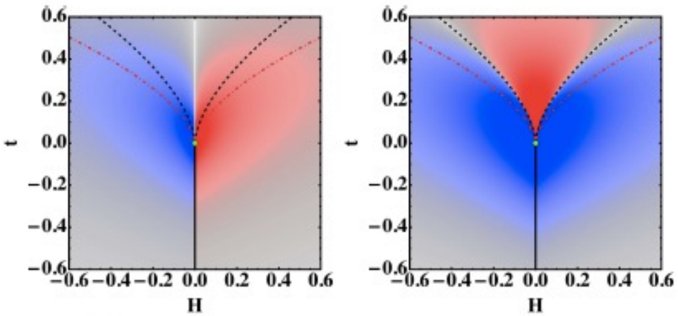
skewness (S)
→ asymmetry

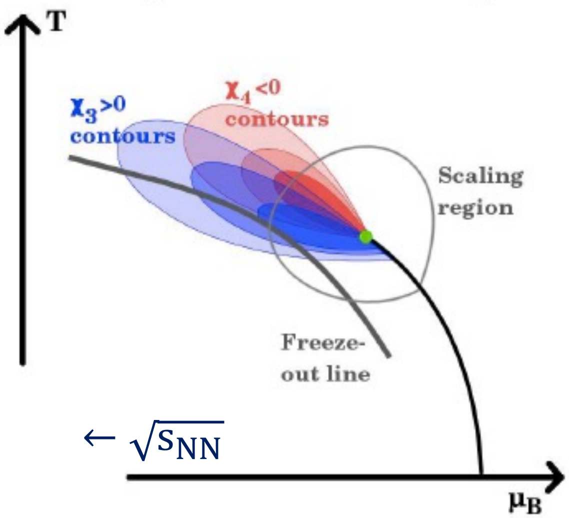


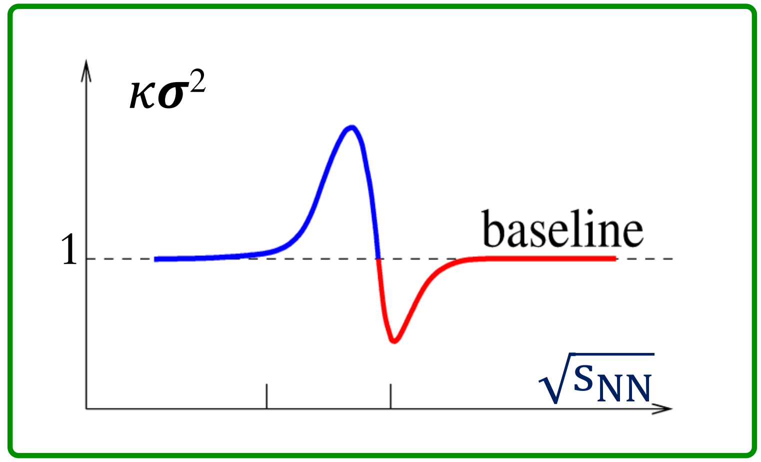
kurtosis (κ)
→ sharpness

INT 2008-2b : The QCD Critical Point

Model Expectations



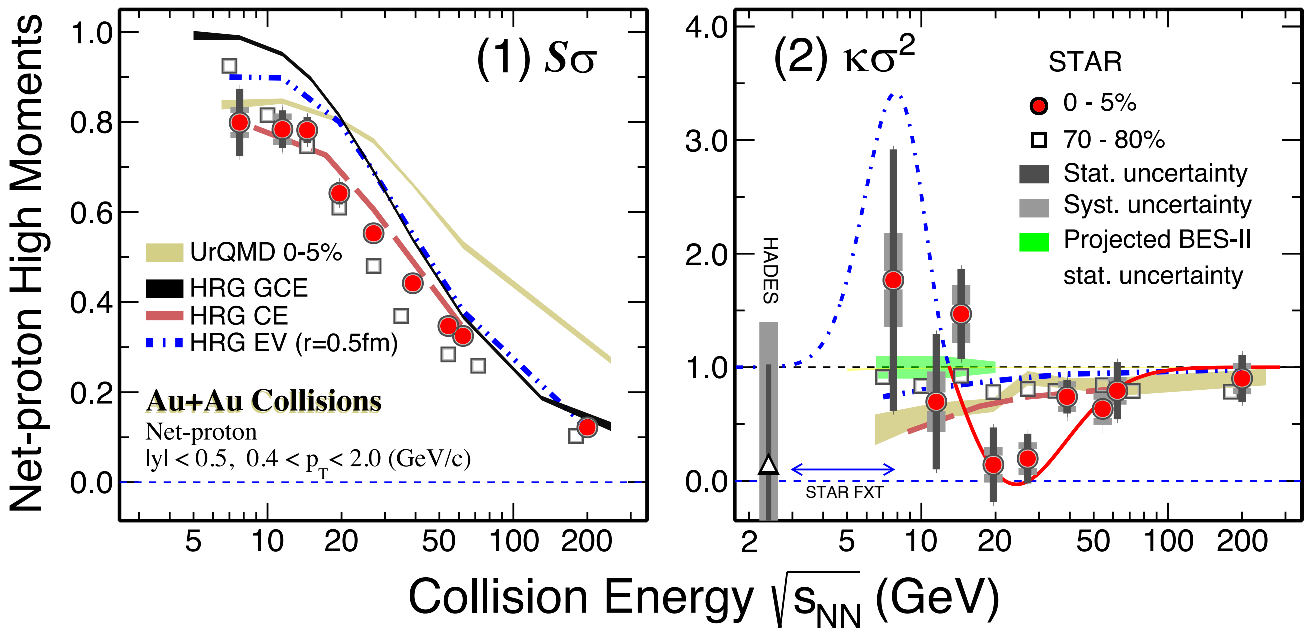




- Characteristic "Oscillating pattern" is expected for the QCD critical point but the exact shape depends on the location of freeze-out with respect to the location of CP
- Critical Region (CR)

- M. Stephanov, PRL **107**, 052301(2011) - V. Skokov, Quark Matter 2012
- J.W. Chen, J. Deng, H. Kohyama, Phys. Rev. **D93** (2016) 034037

Energy Dependence: $s\sigma$ and $\kappa\sigma^2$

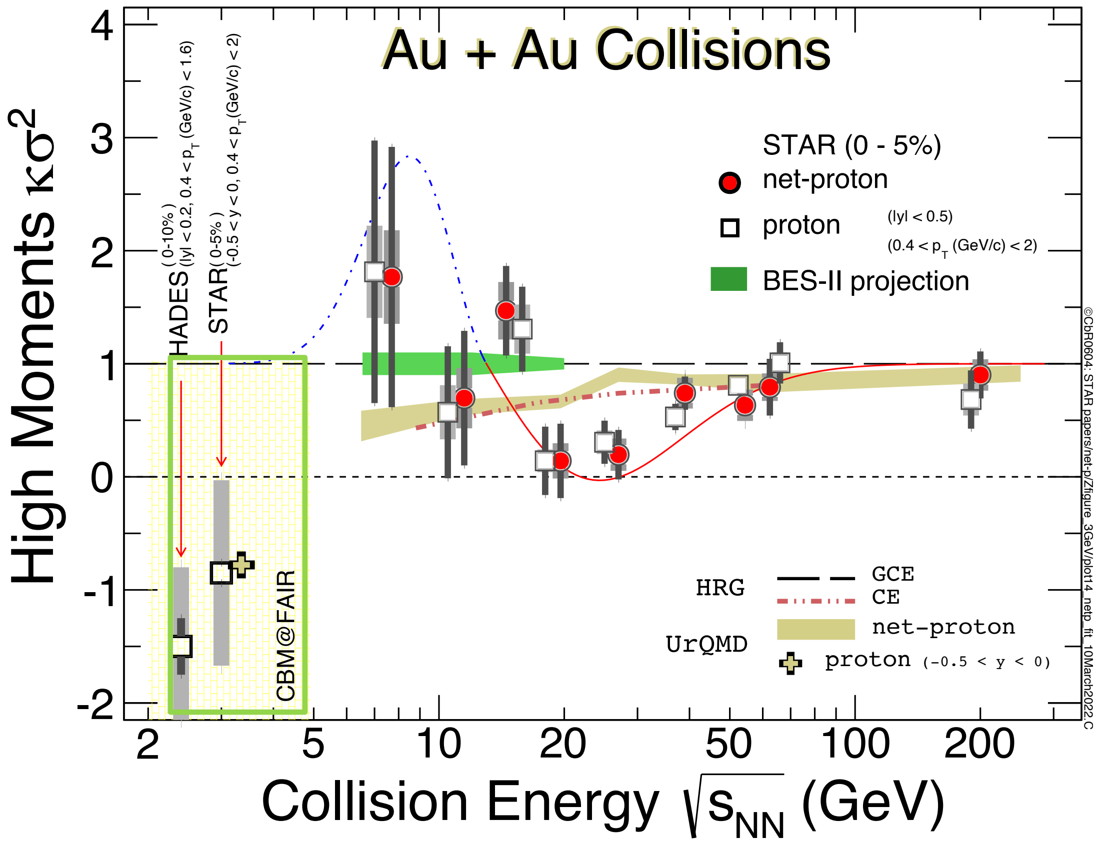


STAR: PRL**126**, 92301(2021)
HADES: PRC**102**, 024914(2020)

P. Braun-Munzinger *et al*.
NPA**1008** (2021)122141

1) Non-monotonic dependence in top 5% central Au+Au collisions;
2) In case of C_4/C_2: transport model UrQMD traces CE calculation. But over predict C_3/C_2;
3) Gap between 3 and 7.7 GeV, important for critical point search

Energy Dependence



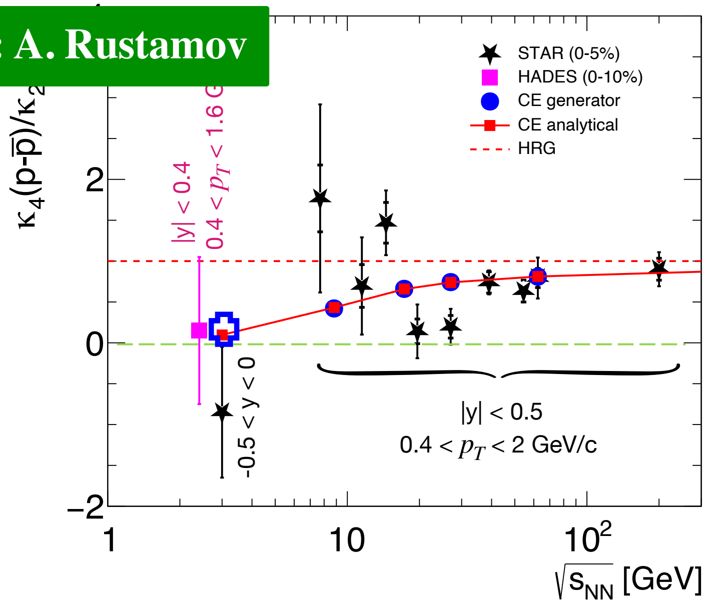
1) UrQMD fully reproduced the 3 GeV data;
2) Energy gap between 3 and 7.7 GeV, important for Critical Point search;
3) CBM experiment: covers proton mid-rapidity over 2 – 4.9 GeV

STAR: PRL**126**, 92301(2021)
HADES: PRC**102**, 024914(2020)

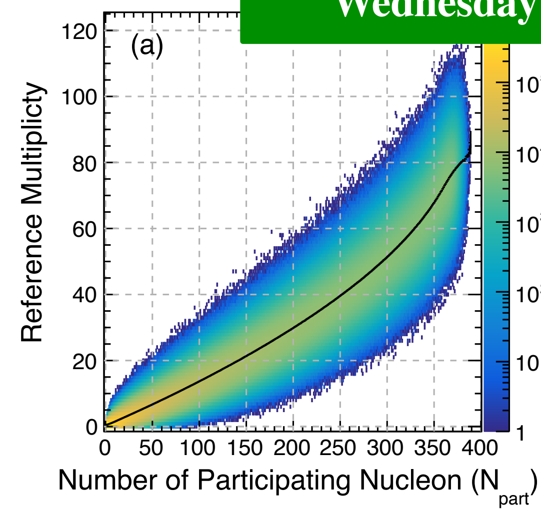
Phys. Rev. Lett. **128**, 202303 (2022)

Centrality Measurement at Low Collision Energy

Monday : A. Rustamov



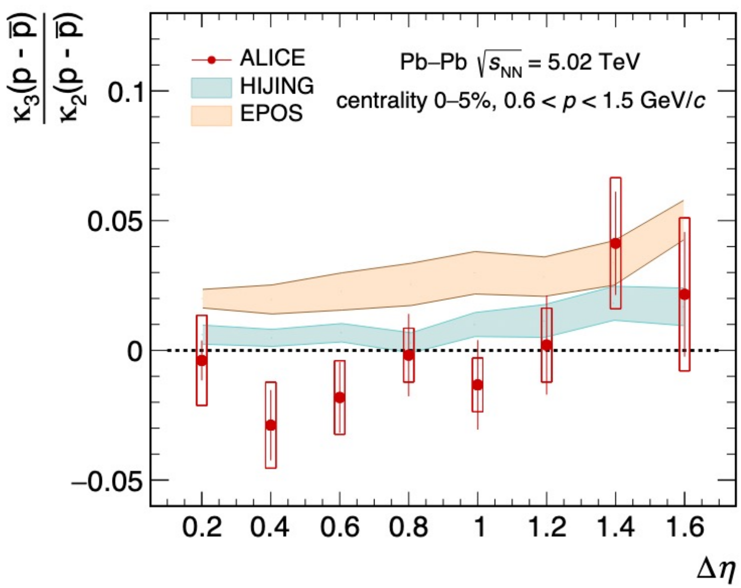
Wednesday : H.S. Ko

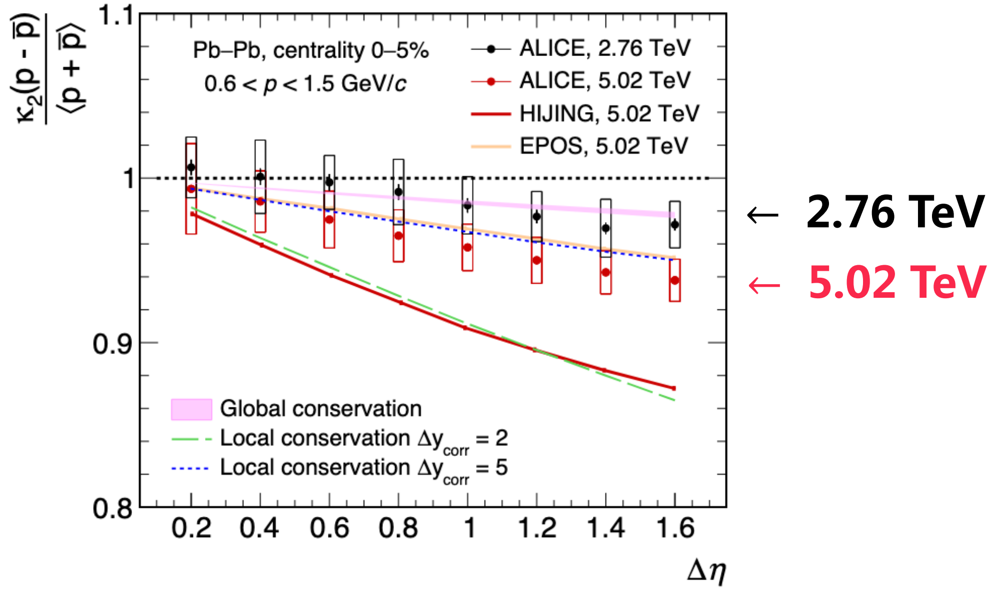


1) $C_4/C_2 \geq 0$, according to CE and UrQMD* calculations ( );
2) Initial volume fluctuation leads to more suppression and correction can be model dependent;

→ Direct measurement of N_{part} is necessary!

Net-p: 2nd & 3rd Order Cumulant Ratios from LHC

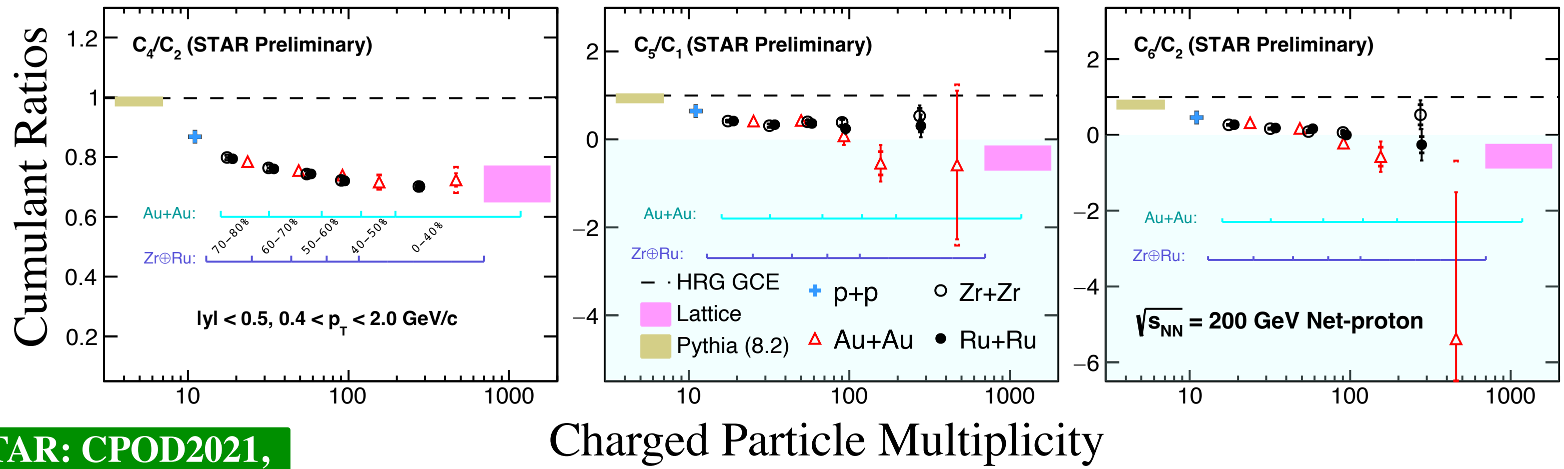




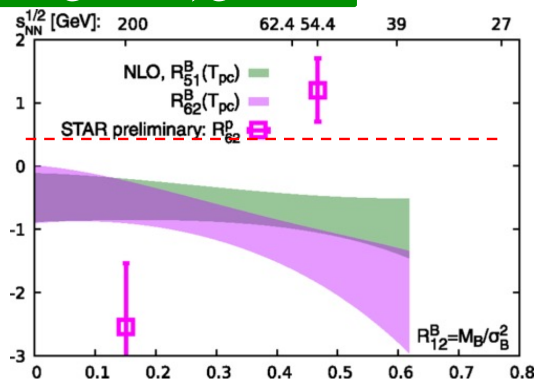
Wednesday : M. Arslandok
ALICE: 2206.03343

- Very nice and long waited results!
- Why the suppression is stronger in 5.02 TeV?

200 GeV p+p and Au+Au Collisions



STAR: CPOD2021, SQM2021,QM2022



1) In 200GeV p+p collisions, high order cumulants ratios of net-protons are found to be positive for , C_4/C_2, C_5/C_2 and C_6/C_2;

2) For QGP matter, LGT predicted negative net-baryon C_5/C_2 and C_6/C_2;

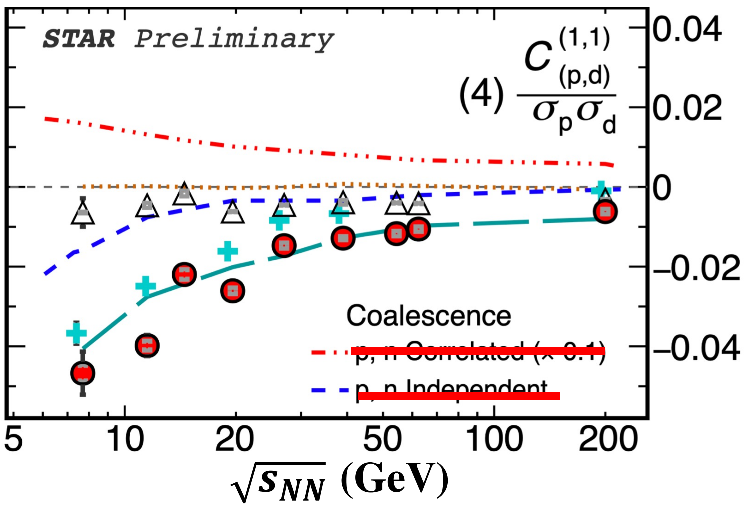
3) Direct **evidence for the QGP formation in 200GeV Au+Au central collisions!**

HotQCD Collaboration, PR**D101**, 074502 (2020)

Proton – deuteron Correlations

STAR: Energy & centrality dependence of proton – deuteron correlations

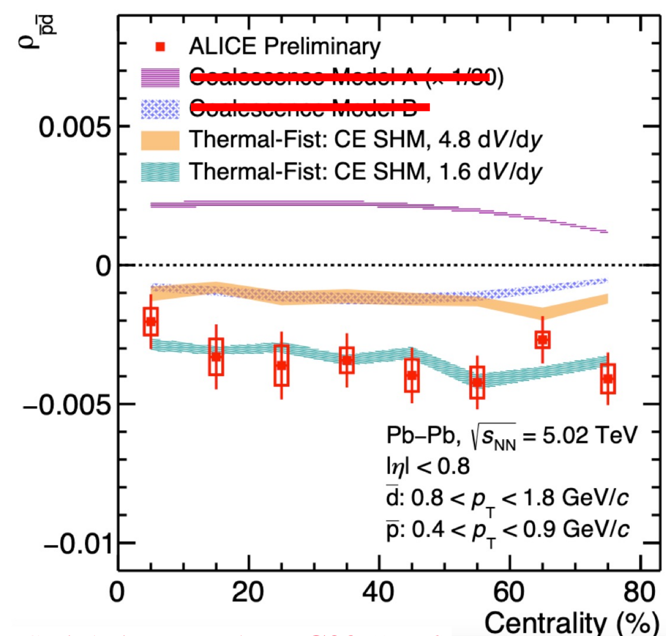
Tuesday (*poster*) : D. Mallick



1) Clear energy dependence;
2) Both CE and *transport model + coalescence* work well!

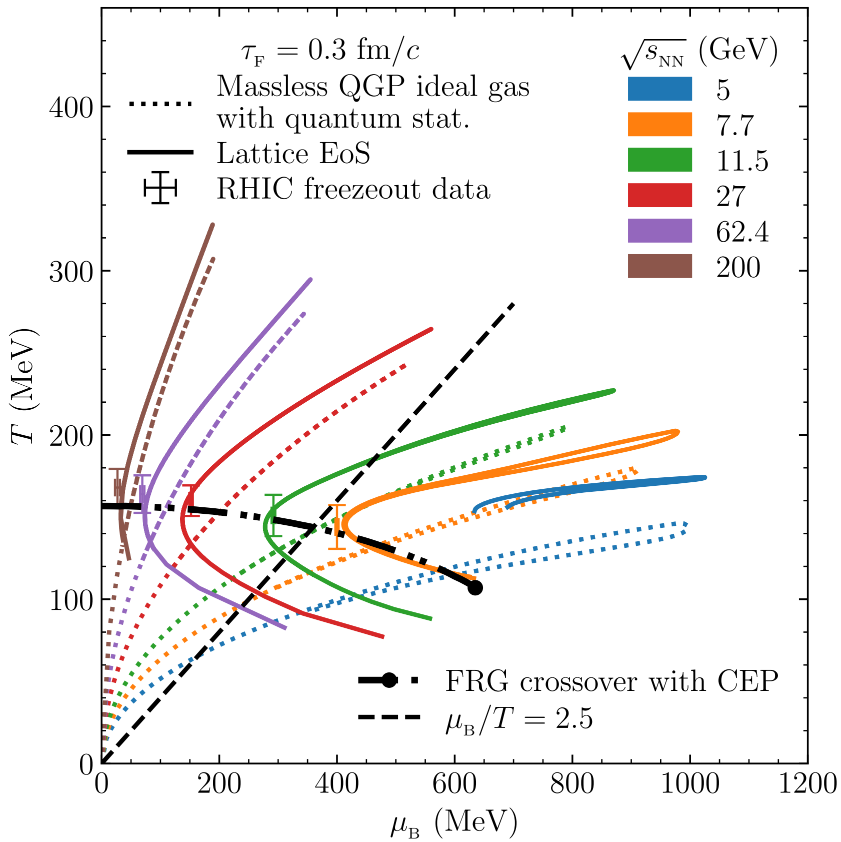
ALICE (5.02 TeV): Centrality dependence anti-proton – anti-deuteron correlations

Tuesday : M. Ciacco
ALICE: 2204.10166



J. Steinheimer *et al.*, PRC**93** (2016)

Semi-analytical Model and QCD Phase Diagram



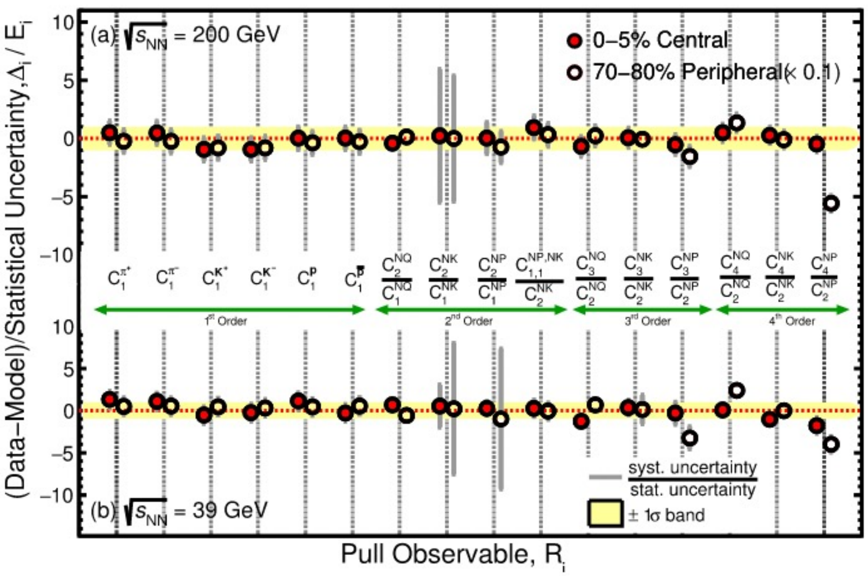
Wednesday: T. Mendenhall
T. Mendenhall and Z.W. Lin: 2111.13932

1) Initial energy density + EOS → $\epsilon_B(t)$ and $n_B(t)$;
2) Lattice EOS, with smooth crossover, leads to the bending near phase boundary where meet with freeze-out parameters determined from data.

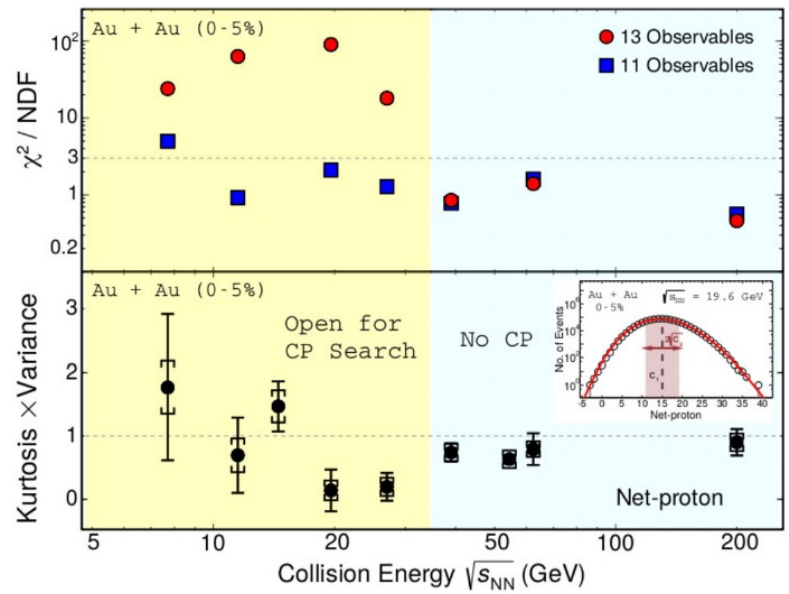
Tests of Thermalization in HIC

S. Gupta *et al*. Phys. Lett. **B829**, (2022) 137021

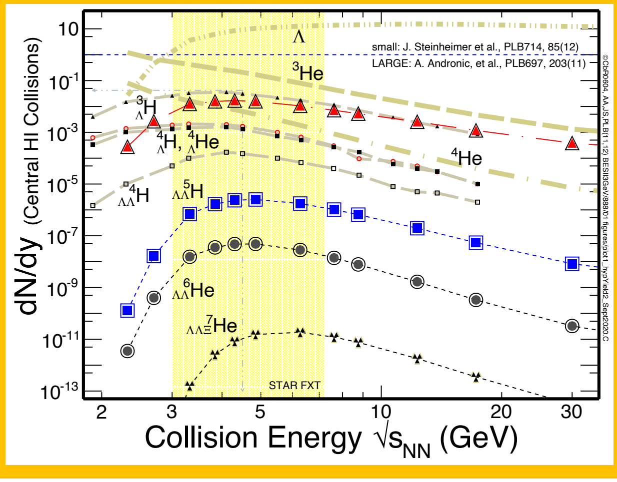
Limits of thermalization in relativistic heavy ion collisions



1) Test of the thermal model with high moments data. 4^{TH} order;
2) Below 39 GeV, **data is not consistent with equilibrium.**



Hyper Nuclei Production



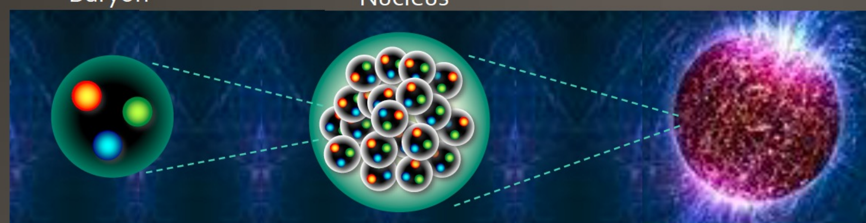
Nuclear Physics :

Study of quantum many-body system governed by the strong interaction

Baryon

(Hyper)
Nucleus

Neutron Star



10^{-15} m

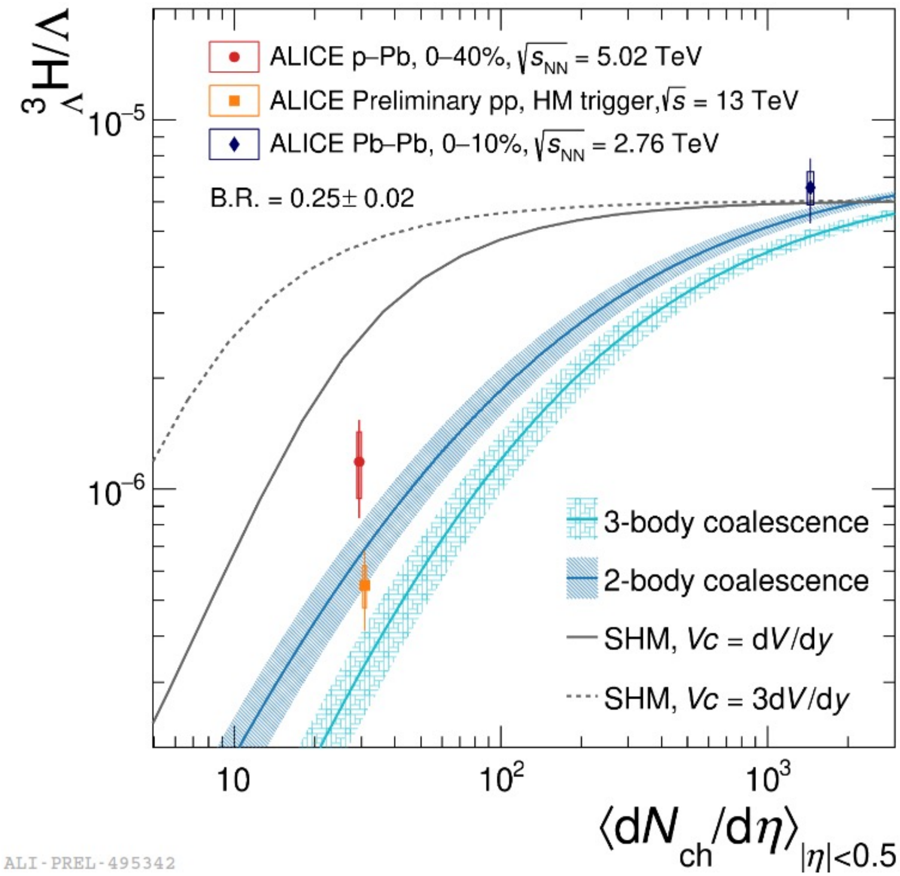
10^{4} m

Terrestrial experiments

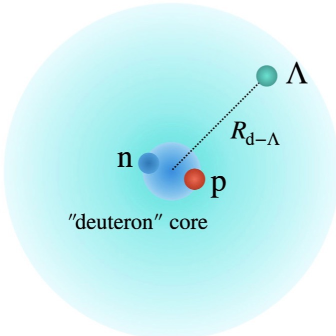
New information from astronomical observation

Understand these systems in the same framework.

${}^{3}_{\Lambda}$H Production at LHC

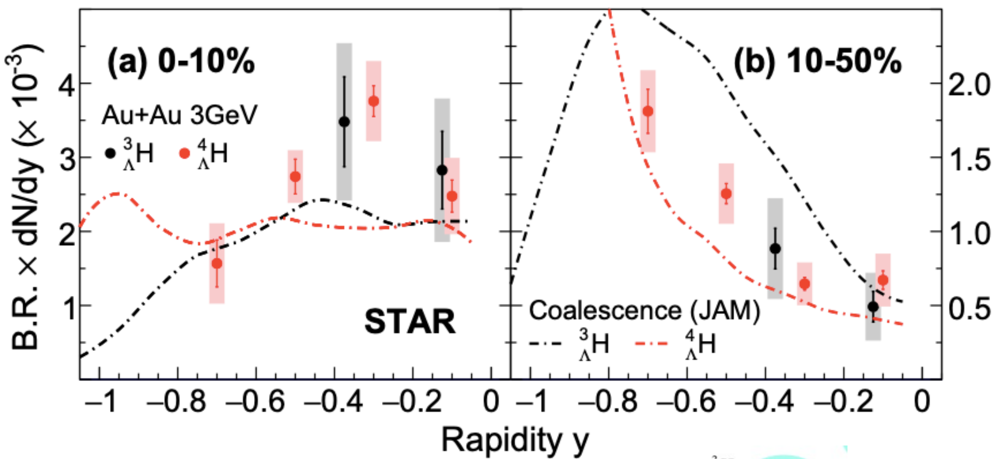


Tuesday: C. Pinto



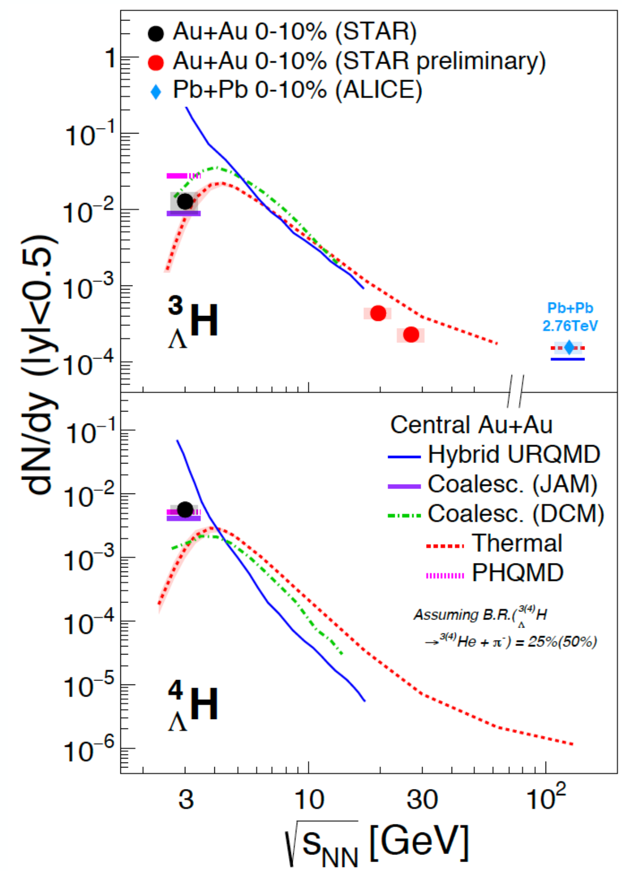
1) In **Pb+Pb collisions**: Both results from thermal model and coalescence are consistent with data;
2) In **p+p and p+Pb collisions**: system size is small, coalescence results fit to data better.

Hyper-nuclei Production in HIC

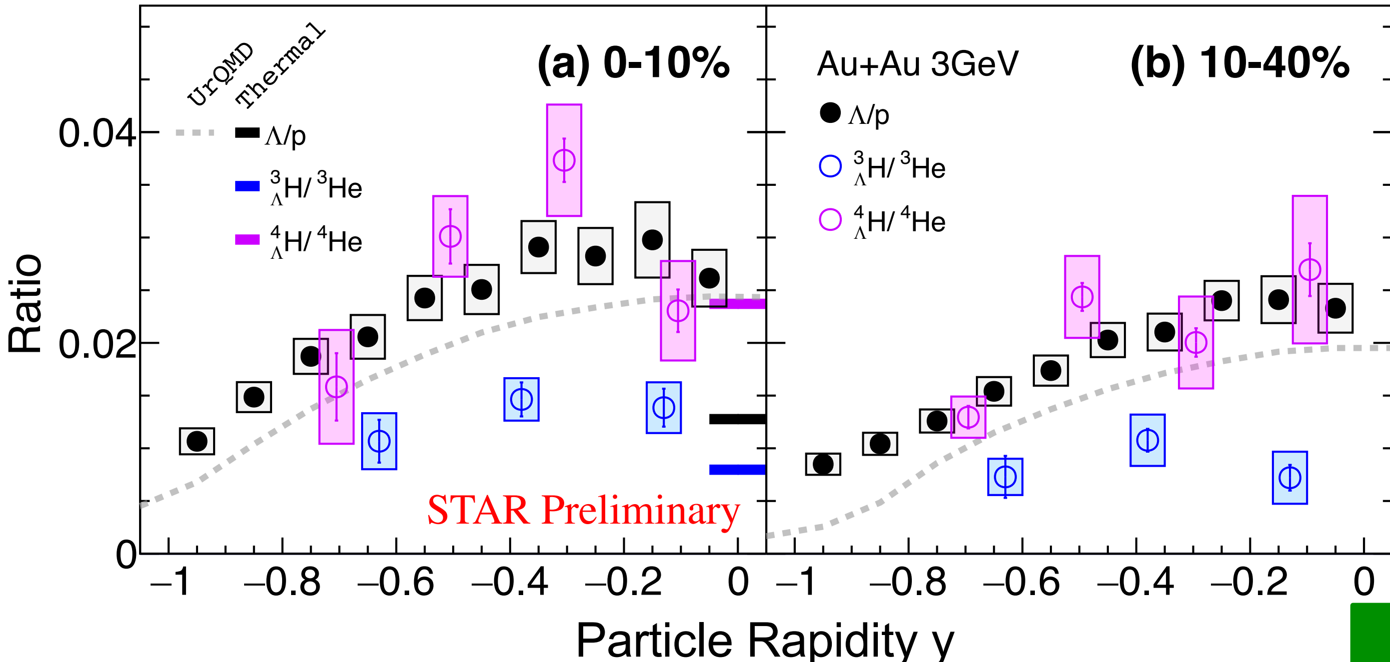


Phys. Rev. Lett. **128**, 202301(2022)

1) Thermal model w/ CE consistent with $^{3}_{\Lambda}H$, but underestimate $^{4}_{\Lambda}H$
2) Transport models (JAM or PHQMD) consistent with data, within uncertainties



Rapidity Dependence

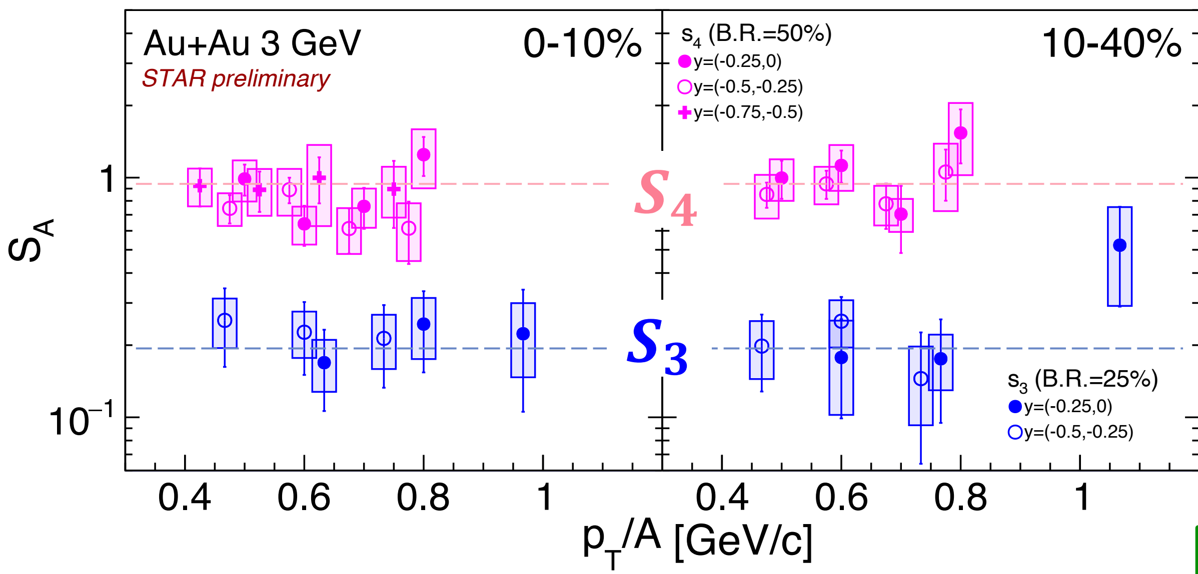


$$R^{A} = \frac{n_{\Lambda}^{A}}{n^{A}}$$

Tuesday : Y.J. Ji

1) First results on the rapidity dependence of the hyper-nuclei production;
2) **$R^1 \sim R^4 \sim 2R^3$**: Enhanced production of Λ and hyper-nuclei at mid-rapidity;
3) UrQMD and thermal model *underpredict* those ratios at mid-rapidity

Rapidity Dependence

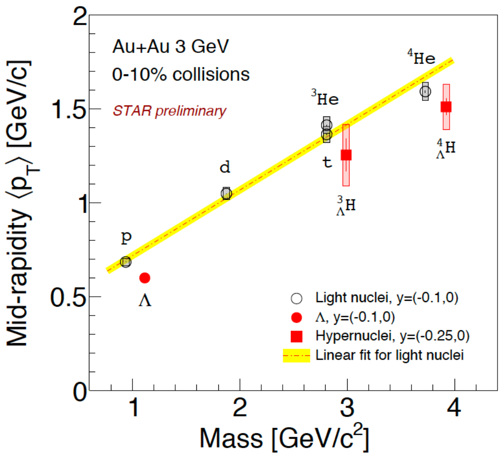


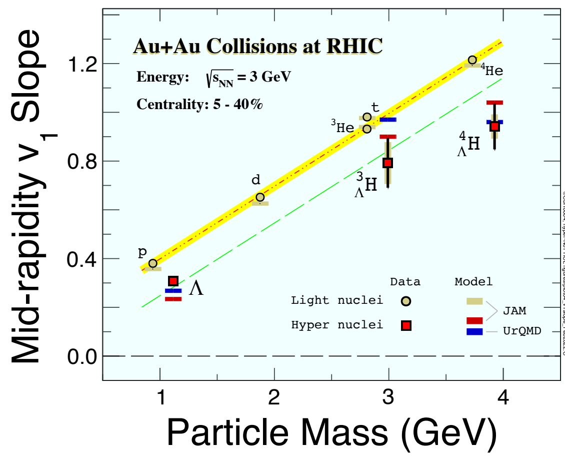
$$S_A = \frac{n_{\Lambda}^{A}}{n_A}\frac{p}{\Lambda} = R^A \frac{p}{\Lambda}$$

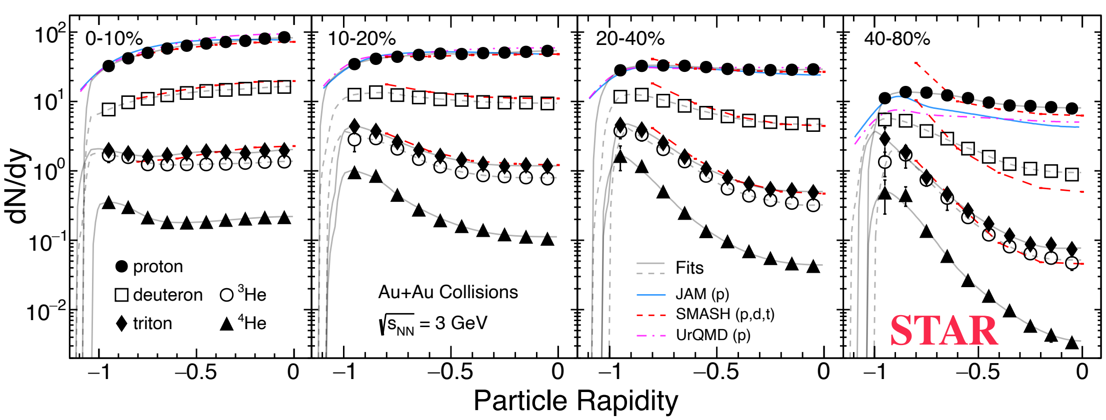
Tuesday : Y.J. Ji

1) S_3 and S_4 are found to be constants versus centrality, rapidity and p_T;
2) $S_4 \sim$ unity $\sim 5\ S_3$?
3) Theory inputs needed to understand the results.

Hyper-nuclei Collectivity

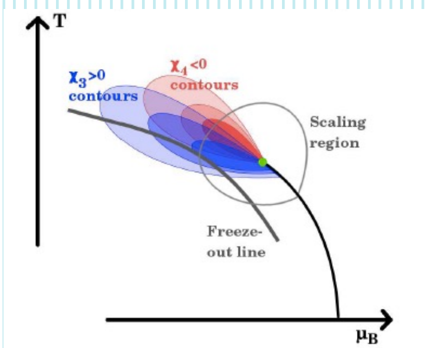


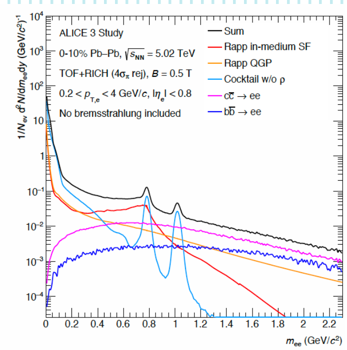


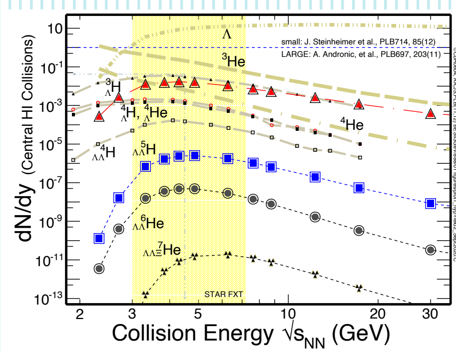


1) First observation of hyper nuclei collective flow, as strong as that of light nuclei;
2) Coalescence procedure for production;
3) **Why does coalescence work for $^{3}_{\Lambda}H$?**

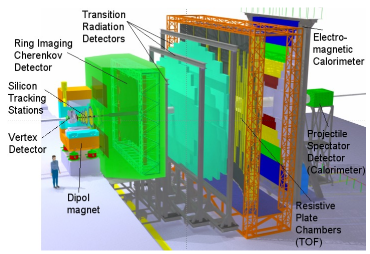
Future Programs





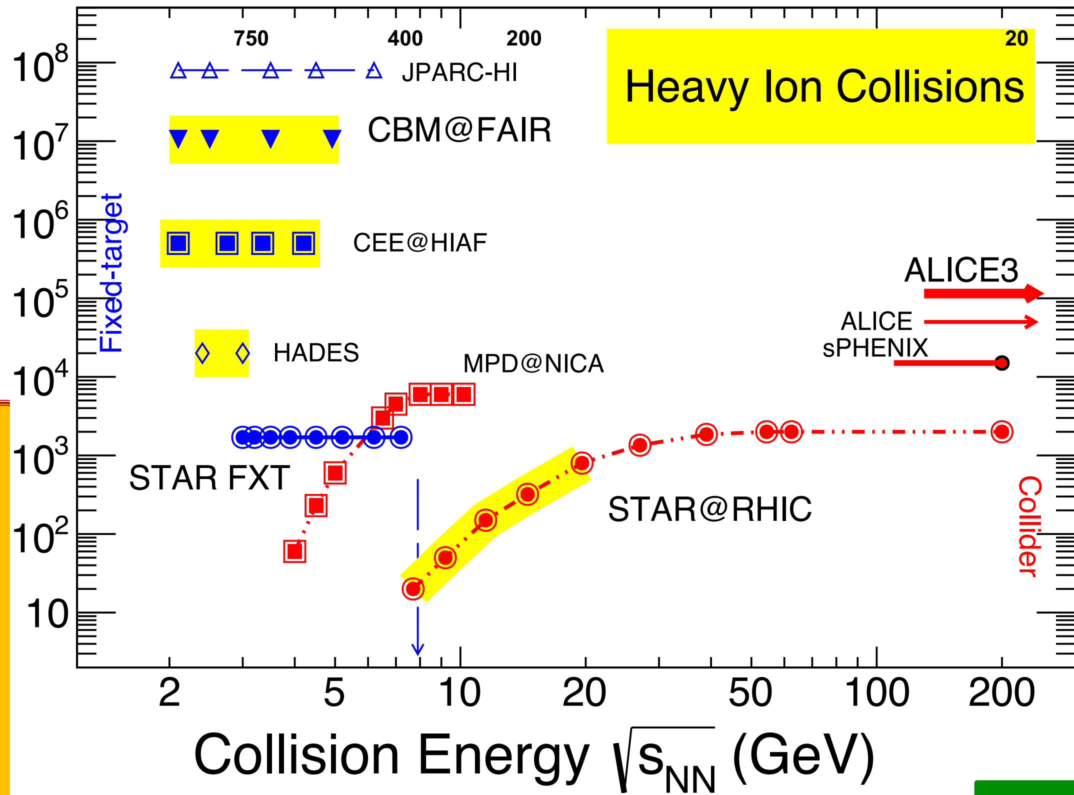


Future Facilities for Heavy-Ion Collisions



CBM at FAIR
(μ_B = 780MeV)

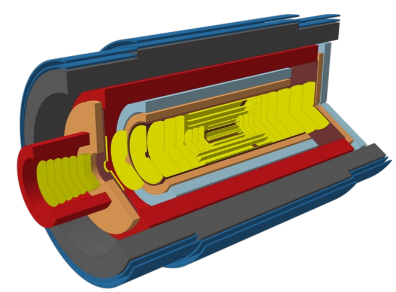
1) Phase boundary and QCD CP;
2) Hyper-Nuclei and Y-N interactions
3) Compact stars



ALICE3 at LHC
(μ_B = 0)

1) Crossover
2) Dileptons and high moments

Dream detector !



Wednesday: A. Yuncu
Thursday: R. Bailhache

BES-I and BES-II Data Sets

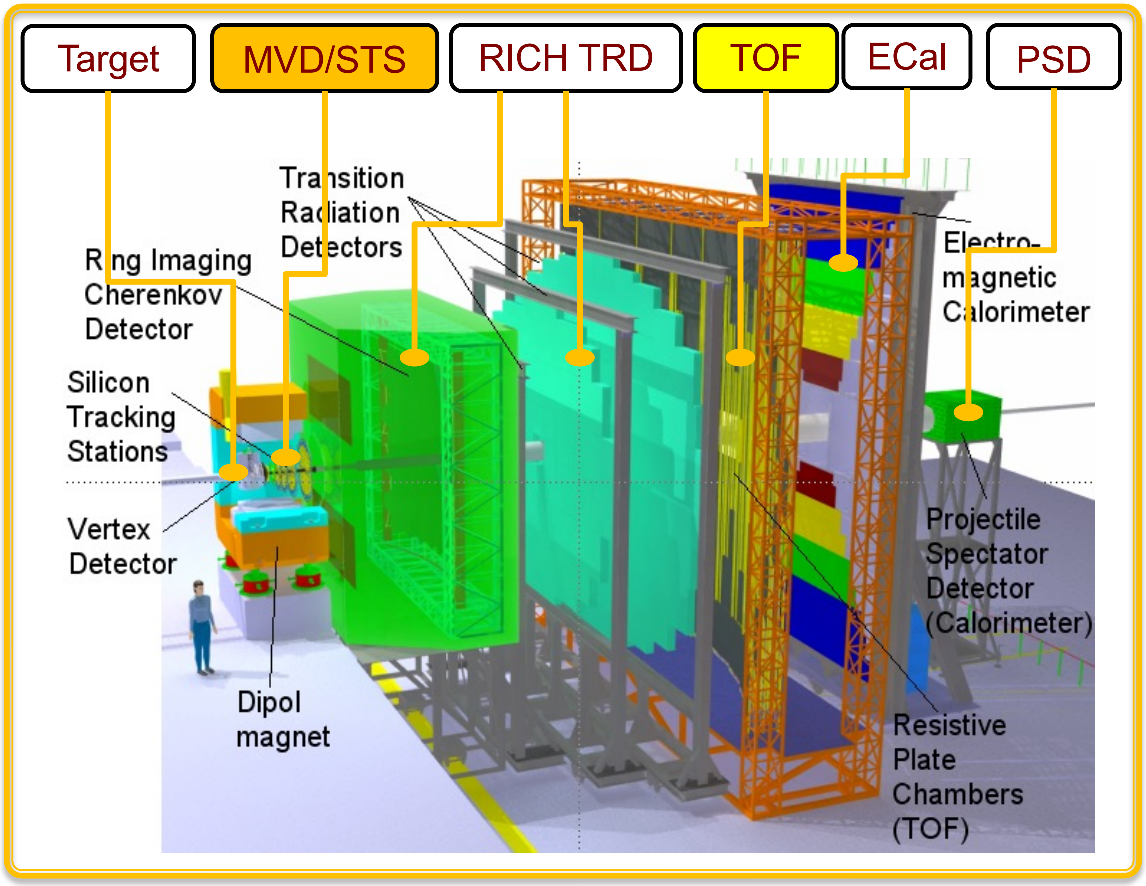
Au+Au Collisions at RHIC

Collider Runs						Fixed-Target Runs					
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	**200**	380 M	**25** MeV	5.3	Run-10, 19	1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	62.4	46 M	75 MeV		Run-10	2	**11.5 (70)**	50 M	320 MeV	-2.51	Run-21
3	54.4	1200 M	85 MeV		Run-17	3	**9.2 (44.5)**	50 M	370 MeV	-2.28	Run-21
4	39	86 M	112 MeV		Run-10	4	**7.7 (31.2)**	260 M	420 MeV	-2.1	Run-18, 19, 20
5	27	585 M	156 MeV	3.36	Run-11, 18	5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	19.6	595 M	206 MeV	3.1	Run-11, 19	6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	17.3	256 M	230 MeV		Run-21	7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	14.6	340 M	262 MeV		Run-14, 19	8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	**11.5**	157 M	316 MeV		Run-10, 20	9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	**9.2**	160 M	372 MeV		Run-10, 20	10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
11	**7.7**	104 M	420 MeV		Run-21	11	3.2 (4.59)	200 M	699 MeV	-1.13	Run-19
						12	**3.0** (3.85)	2000 M	**750** MeV	-1.05	Run-18, 21

Precision data to map the QCD phase diagram

$3 < \sqrt{s_{NN}} < 200$ **GeV;** $750 < \mu_B < 25$ **MeV**

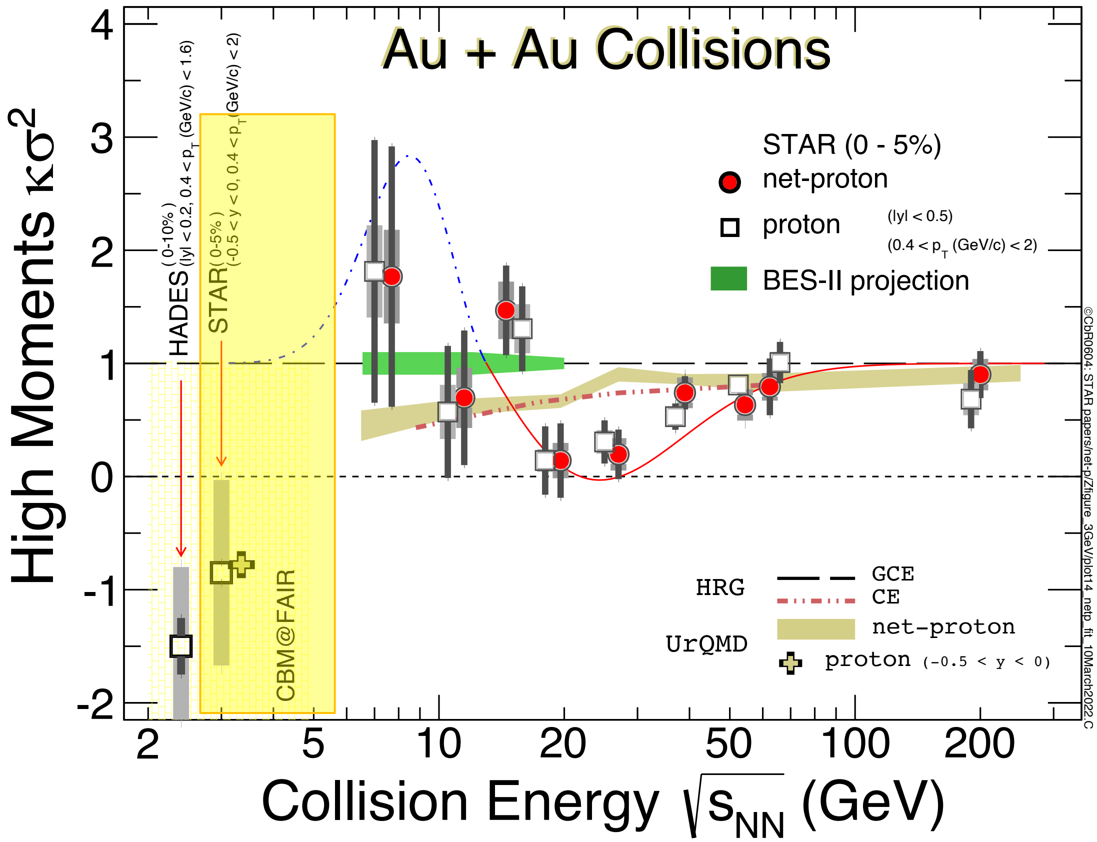
CBM Experiment at FAIR



- FAIR: One of the brightest accelerator complexes
- Precision measurements at high baryon density region:
  (i) Dileptons (*e, μ*);
  (ii) High order correlations;
  (iii) Flavor productions (*s, c*) and hyper-nuclei

CBM: BES-III experiment

Fluctuations: Energy Dependence



FAIR SIS100

1) **CBM Experiment: covers proton mid-rapidity between 2 – 4.9 GeV**

Important for QCD critical point search!

2) **Hyper-nuclei production at the high baryon region**

SQM2022

ALICE III

https://cds.cern.ch/record/2803563/files/LHCC-I-038.pdf

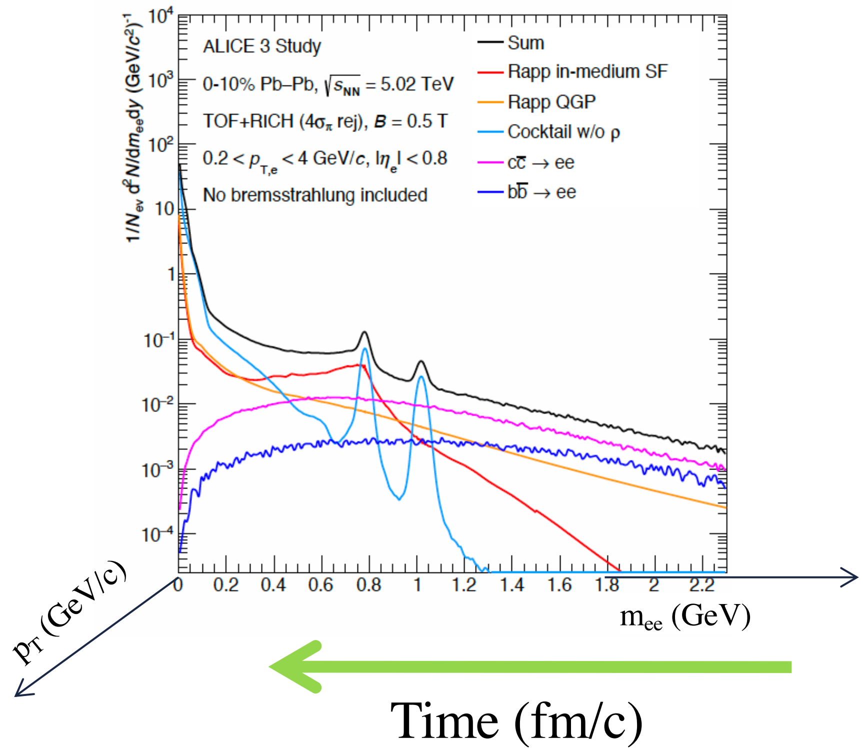
Time Traveling with $1/m_{ee}$

- $m_{ee} > 5$: initial condition;
- $5 > m_{ee} > 1$: QGP thermal property ;
- $0.5 > m_{ee}$: hadronic decays

Measurements:

1) **v_n and p_T spectra** of di-leptons at each mass bin → $\langle p_T \rangle$ or (T_{fo}, $\langle \beta_T \rangle$) vs. m_{ee};

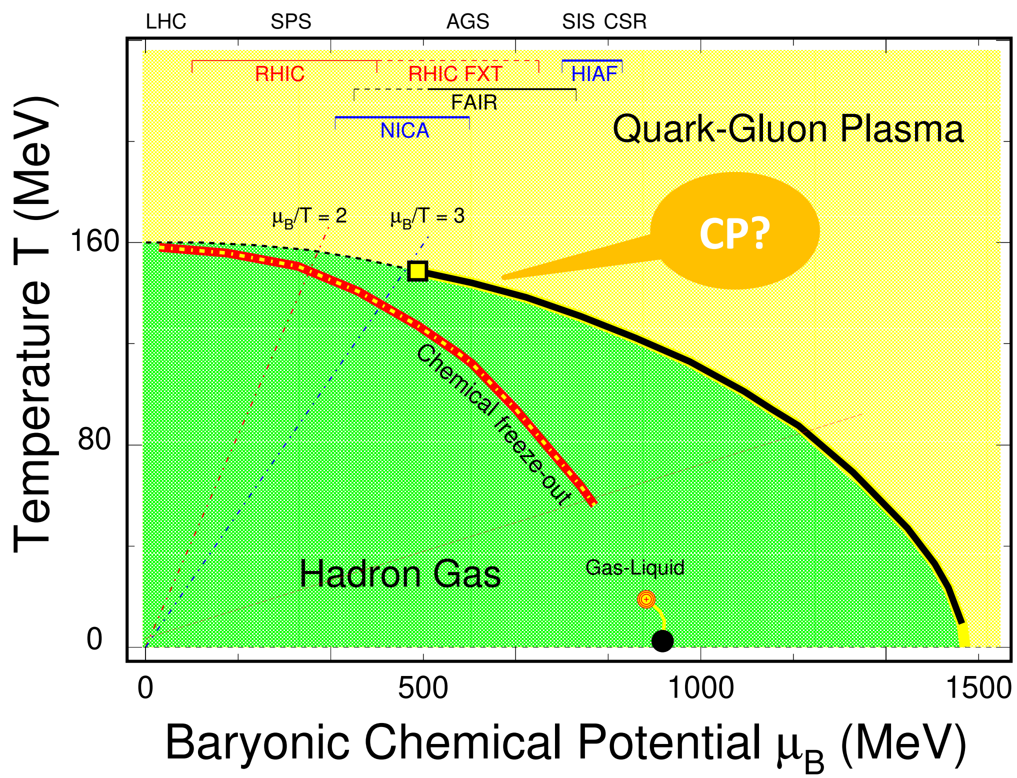
2) **Polarization versus m_{ee}**;
$\Longrightarrow$
Properties of smooth crossover at $\mu_B \sim 0$!



E. Shuryak: 1203.1012 "*Dilepton invariant mass can be used as a clock*"

Wednesday: A. Yuncu
Thursday: R. Bailhache

Summary



1) BES-I data: QCD critical point lies between 3 – 50 GeV Au+Au collisions;
2) At $\mu_B \sim 0$ MeV: Properties of QGP and smooth crossover. RHIC top energy and LHC
3) At high baryon density region, $\mu_B \sim 750$ MeV: QCD critical point and 1st-order phase boundary. RHIC BES-II and FAIR CBM

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// BLUE: Theory // **RED**: Exp., high moment //

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