Study of the QCD Phase Structure

- Recent Results from RHIC BES Program

Nu Xu

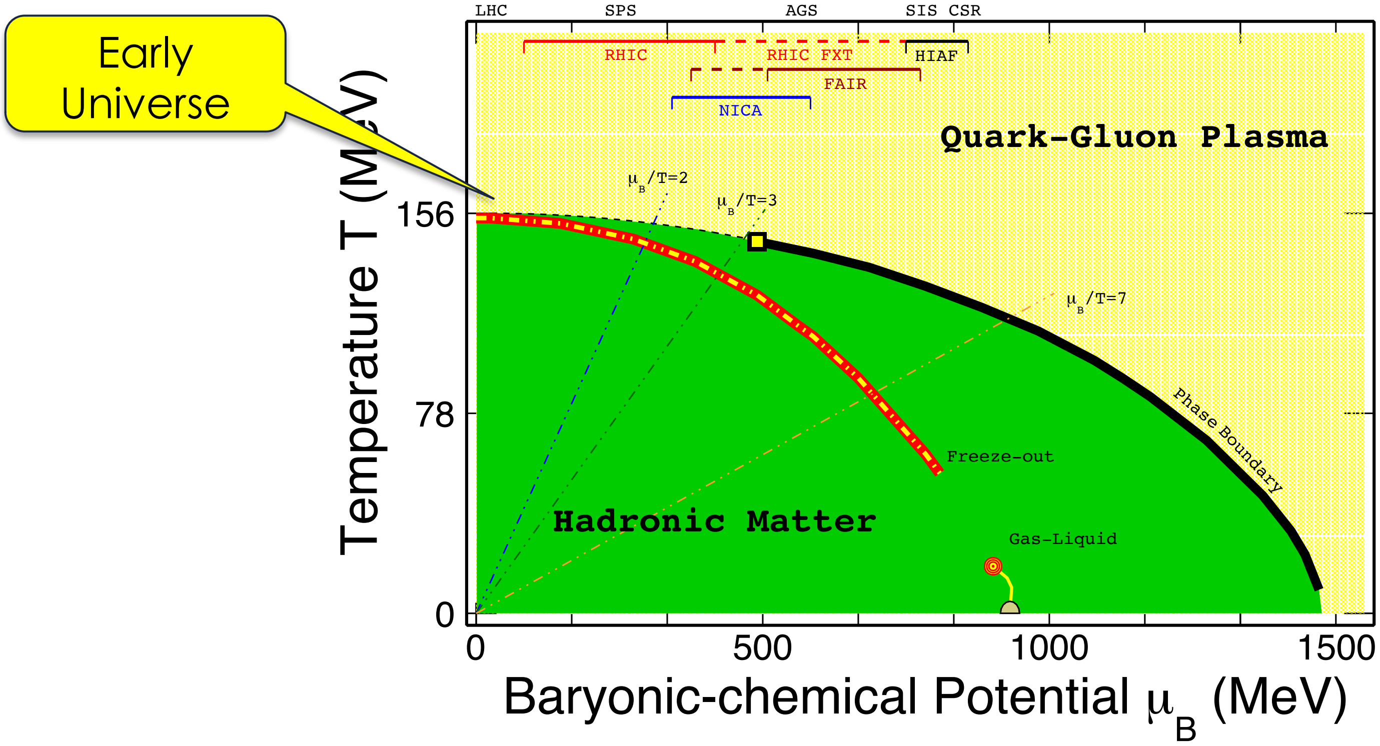
Outline

1) **Introduction**

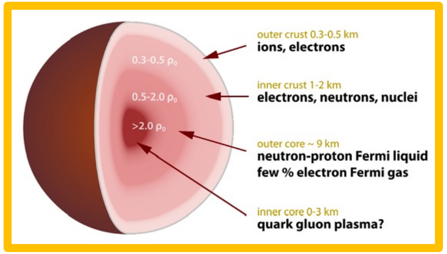
2) Selected Results
   - Collectivity
   - Baryon Correlations and Hyper-Nuclei Productions
   - Criticality from BES-II (collider energy $7.7 \leq \sqrt{s_{NN}} \leq 27$ GeV)

3) Summary and Outlook

Nuclear Collisions and QCD Phase Diagram



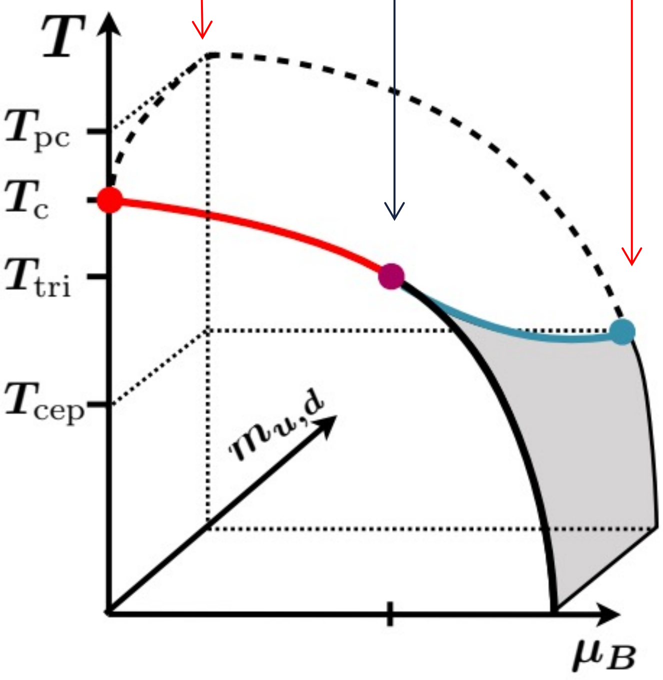
High baryon density: Inner structure of compact stars



1) RHIC BES: → search for 1st-order phase transition and **QCD critical point**;
2) Baryon interactions (*e.g.* $N-N, Y-N$) → inner structure of compact stars

LGT: QCD Phase Structure

T_C^0 | T_{PC} | T^{TC} | T^{CEP}



F. Karsch *et al.*, 2020

1) QCD transition temperature:
   $\mathbf{T_{PC} = 156.5 \pm 1.5\ MeV}$

2) Chiral crossover line

$$T_{PC}(\mu_B) = T_{PC}^0\left[1 - \kappa_2\left(\frac{\mu_B}{T_{PC}^0}\right)^2 - \kappa_4\left(\frac{\mu_B}{T_{PC}^0}\right)^4\right]$$

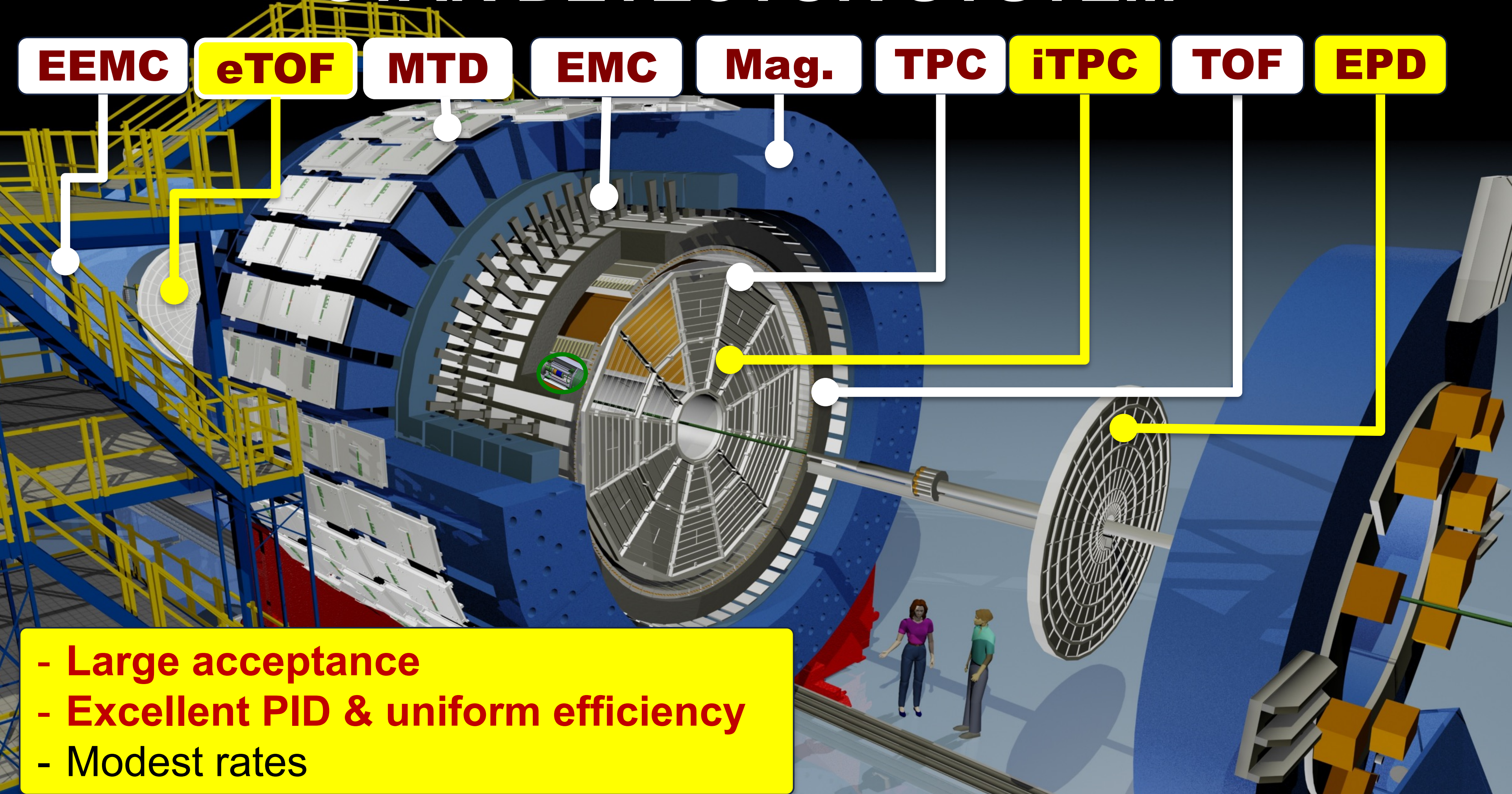
$\kappa_2 = 0.012(4),\ \kappa_4 = 0.00(4)$

3) Chiral transition temperature:
   $\mathbf{T_C = 132^{+3}_{-6}\ MeV}$

4) QCD critical end point:
   $T^{CEP} < T_C,\quad \mu_B^{CEP} \gtrsim 3T_C$

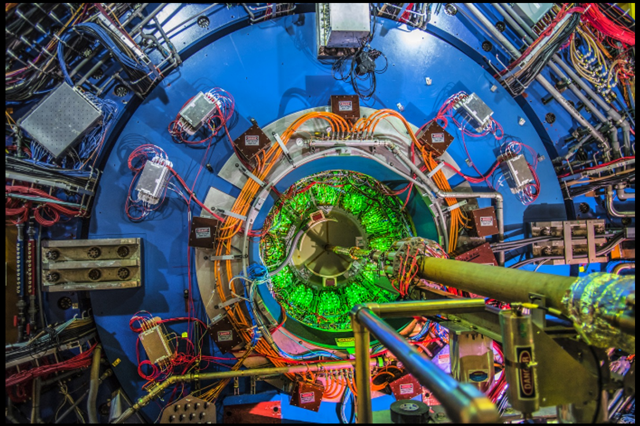
HotQCD: Phys.Lett.**B795**, 15(2019);
Phys. Rev. Lett. **123**, 062002(2019)

STAR DETECTOR SYSTEM



- Large acceptance
- Excellent PID & uniform efficiency
- Modest rates

Major Upgrades for BES-II



iTPC:
- Improves dE/dx
- Extends η coverage from 1.0 to 1.6
- Lowers p_T cut-in from 125 to 60 MeV/c
- Ready in 2019

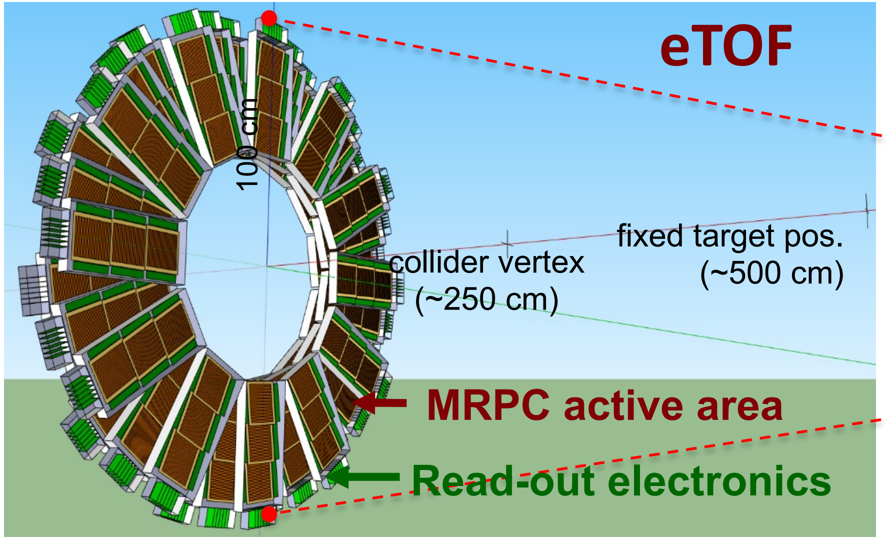
eTOF:
- Forward rapidity coverage
- PID at η = 0.9 to 1.6
- **Borrowed from CBM-FAIR**
- Ready in 2019

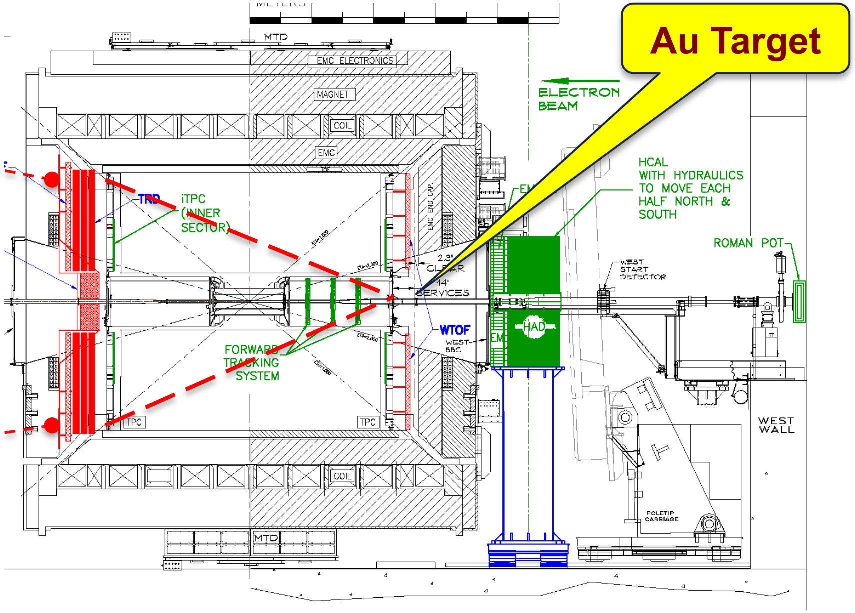
EPD:
- Improves trigger
- Better centrality & event plane measurements
- Ready in 2018

1) Enlarge rapidity acceptance
2) Improve particle identification
3) Enhance centrality/event plane resolution

iTPC: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
eTOF: STAR and CBM eTOF group, arXiv: 1609.05102
EPD: J. Adams, et al. NIM **A968,** 163970 (2020)

STAR Fixed Target Setup





CBM participates in RHIC BES-II in 2019 – 2021:

- Complementary to CBM program: $\sqrt{s_{NN}}$ = 3 - 7.2 GeV (**750 ≥ μ_B ≥ 420 MeV**)
- Strange-hadron, hyper-nuclei and fluctuation at the high baryon density region

STAR BES Data Sets

Au+Au Collisions at RHIC

Collider Runs

	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	**200**	380 M	**25** MeV	5.3	Run-10, 19
2	62.4	46 M	75 MeV		Run-10
3	54.4	1200 M	85 MeV		Run-17
4	39	86 M	112 MeV		Run-10
5	27	585 M / **220**	156 MeV	3.36	Run-11, 18
6	19.6	595 M/ **270 M**	206 MeV	3.1	Run-11, 19
7	17.3	256 M / **116 M**	230 MeV		Run-21
8	14.6	340 M/ **145 M**	262 MeV		Run-14, 19
9	11.5	257 M/ **110 M**	316 MeV		Run-10, 20
10	9.2	160 M/ **78 M**	372 MeV		Run-10, 20
11	7.7	104 M / **45 M**	420 MeV		Run-21

Fixed-Target Runs

	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	11.5 (70)	50 M	320 MeV	-2.51	Run-21
3	9.2 (44.5)	50 M	370 MeV	-2.28	Run-21
4	7.7 (31.2)	260 M	420 MeV	-2.1	Run-18, 19, 20
5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
11	3.2 (4.59)	200 M	699 MeV	-1.13	Run-19
12	**3.0** (3.85)	**260** + 2000 M	**760** MeV	-1.05	Run-18, 21

Most precise data to map the QCD phase diagram

$3 < \sqrt{s_{NN}} < 200$ GeV; $760 > \mu_B > 25$ MeV

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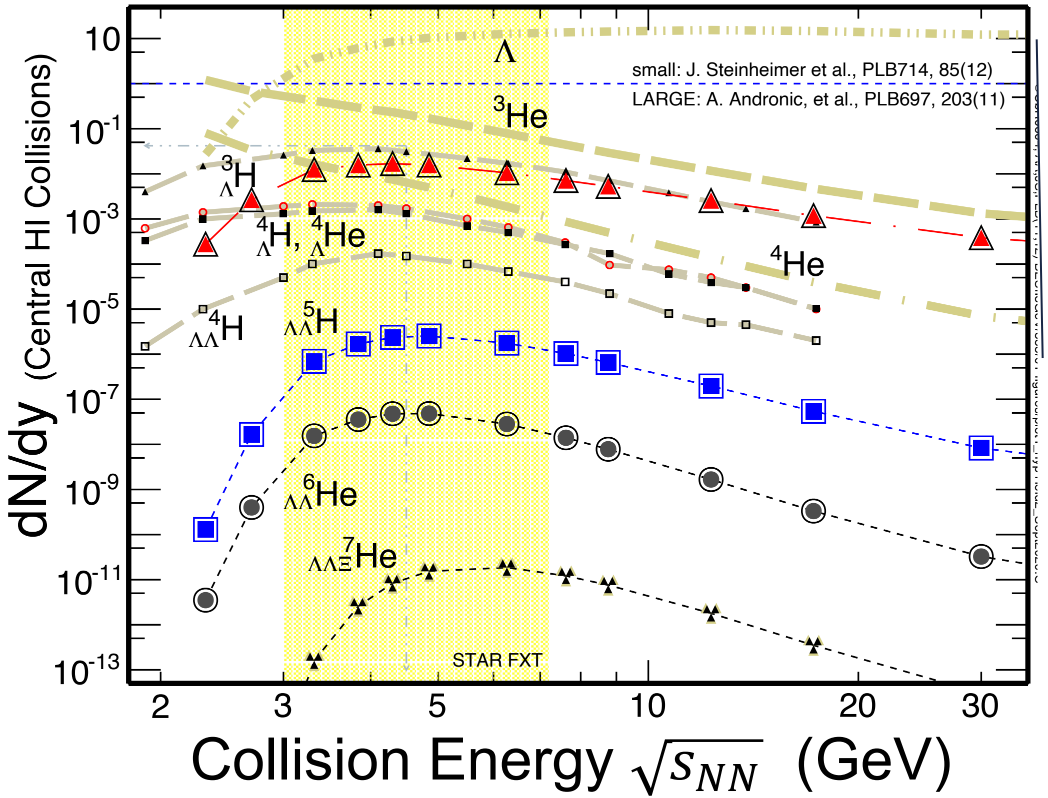
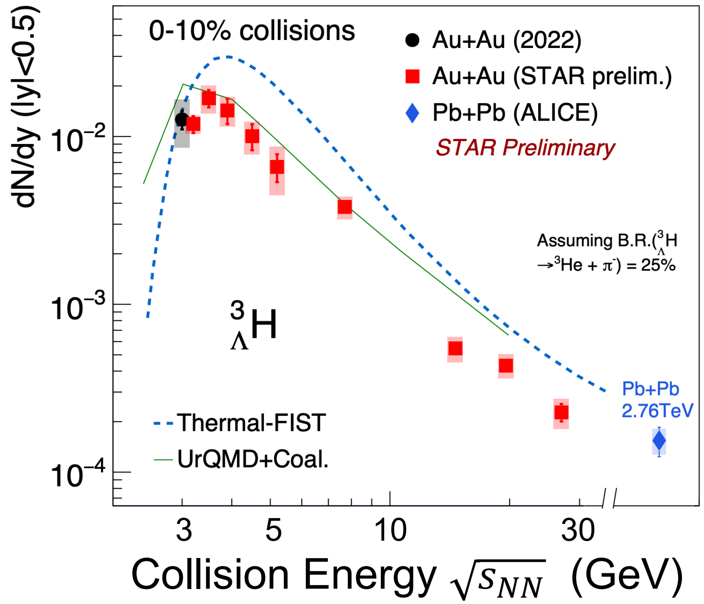
3) Summary and Outlook

STAR FXT and High Baryon Density Region

A. Andronic *et al*. PL**B697**, 203(2011);
J. Steinheimer *et al*. PL**B714**, 85(2012)



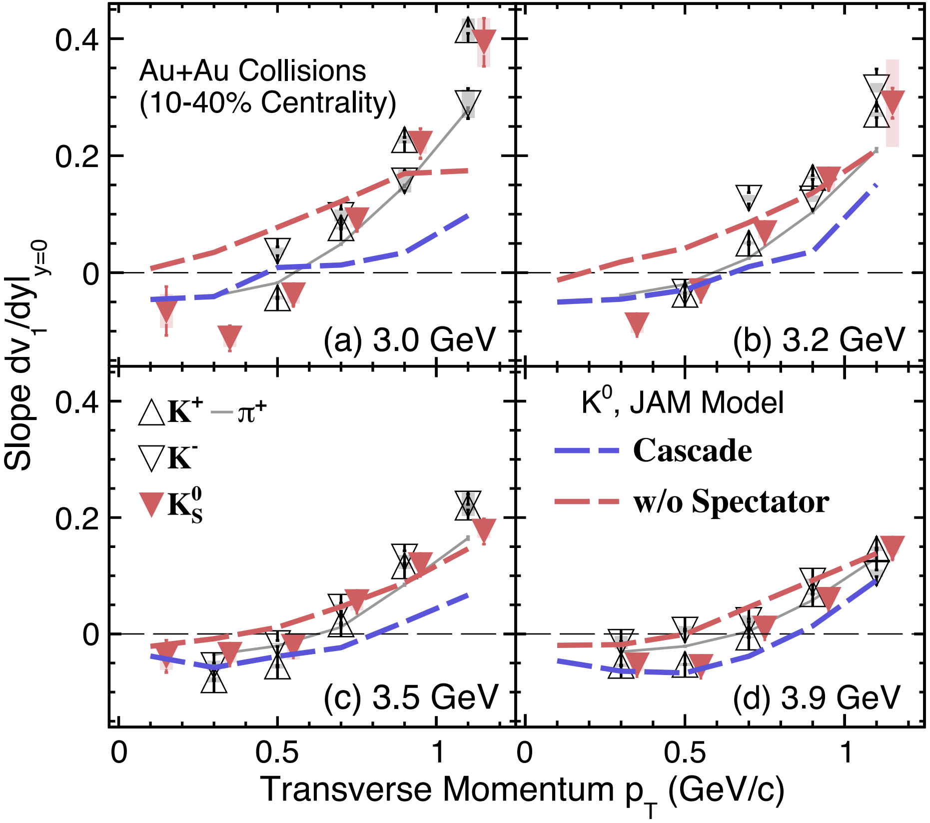
STAR: CPOD2024, SQM2024



1) Hypernucleus: $^3_\Lambda H$ yields versus energy: peaks at 3.2 GeV;
2) For $\sqrt{s_{NN}} < 10$ GeV, calculations from coalescence more consistent with data

Kaon Anti-Flow at High Baryon Density Region

STAR: CPOD2024, SQM2024



1) A systematic analysis of the p_T dependence of the neutral- and charged-Kaon v_1 from Au+Au collisions at $\sqrt{s_{NN}} = 3.0 – 3.9$ GeV;
2) At $p_T < 0.6$ GeV, all mid-rapidity v1 slopes are negative. Kaon potential was proposed to explain the data, ref.[1,2];
3) JAM model calculations suggest that spectator shadowing, similar to the case of elliptical v_2, plays important role for the negative v_1 slope parameter.

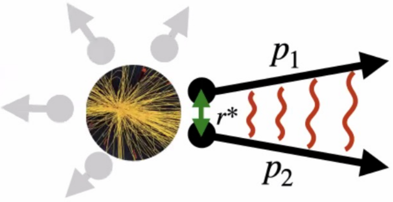
→ Spectator shadowing
→ No Kaon potential is needed

References:

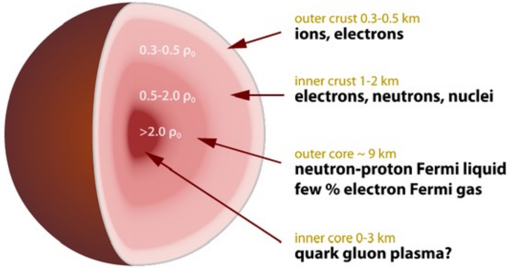
(1) P. Chung *et al.* (E895), PRL **85**, 940(2000);
(2) G.-Q. Li, C. M. Ko, and B.-A. Li, PRL **74**, 235 (1995) and S. Pal, C. M. Ko, Z.-W. Lin, and B. Zhang, PR **C62**, 061903(2000)

The emergent properties of QCD matter

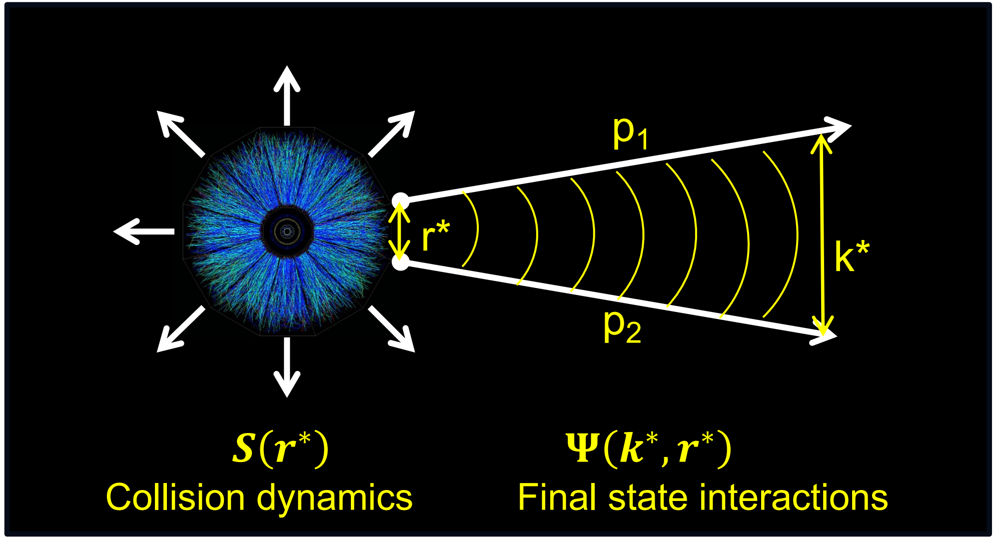
Baryon Correlations



FSI



Baryon Correlation Functions



STAR:

(1) Meson HBT: $\pi-\pi$, $K-K$;

(2) **Baryon Correlations:**

$p-p$	reference	
$p-\Lambda$, $p-\Xi^-$, $p-\Omega$		Y-N
$p-\phi$		
$\Lambda-\Lambda$		Y-Y
$p-d$, $d-d$		N-N-N
$d-\Lambda$		Y-N-N

Source

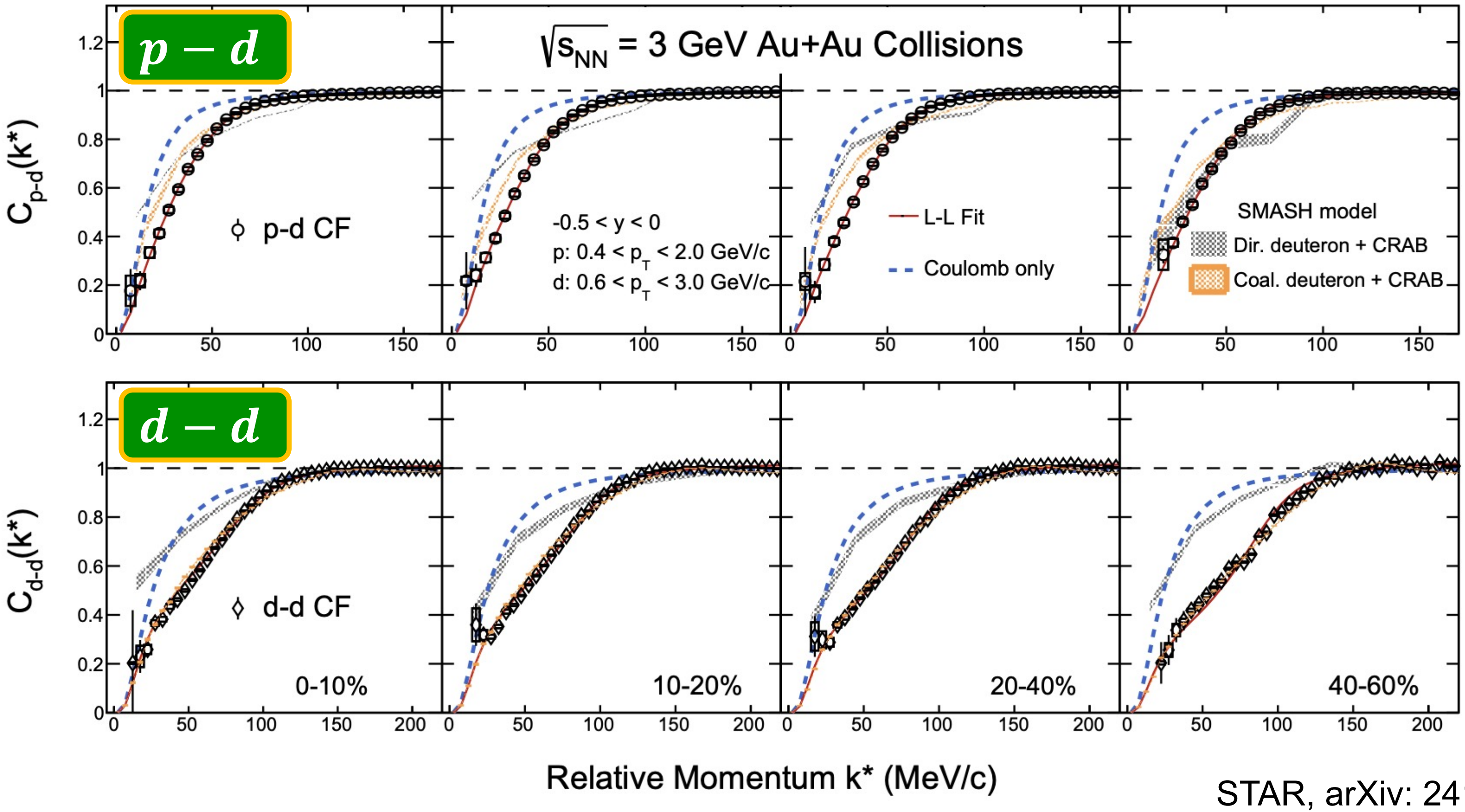
$$C_{the}(k^*) = \frac{1}{4\pi}\int d^3r^* S(r^*)|\Psi(r^*, k^*)|^2$$

$$C_{exp}(k^*) = \lambda \frac{N_{same}(p_1,p_2)}{N(p_1)N(p_2)}$$ → Source and FSI

$$k^* = \frac{1}{2}|p_1^* - p_2^*|$$

Final State Interactions:
(1) Quantum statistics; (2) Coulomb; (3) Strong interaction

$p - d,\ d - d$ Correlation Functions



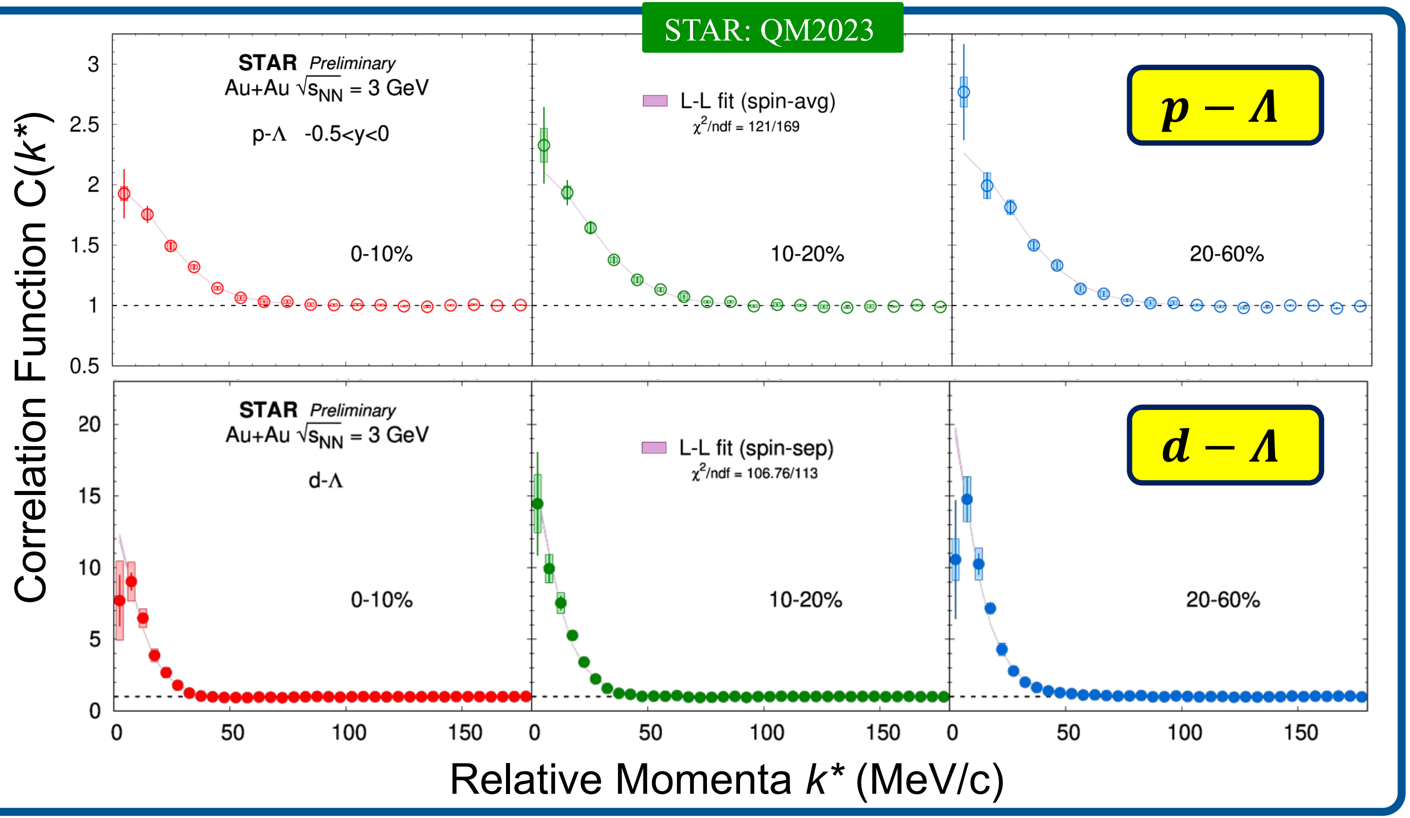
STAR, arXiv: 2410.03436

$p-d,\ d-d$ Correlation Functions

1) Both $p-d$ and $d-d$ CFs can be reproduced by calculations of transport model (SMASH) plus coalescence after-burner. Consistent with the coalescence procedure for deuteron production;

2) LL calculations are used to extract FSI parameters:
   - $f_0 < 0$ is observed
   - *no collision centrality dependence is observed*

$p-\Lambda,\ d-\Lambda$ Correlation Functions



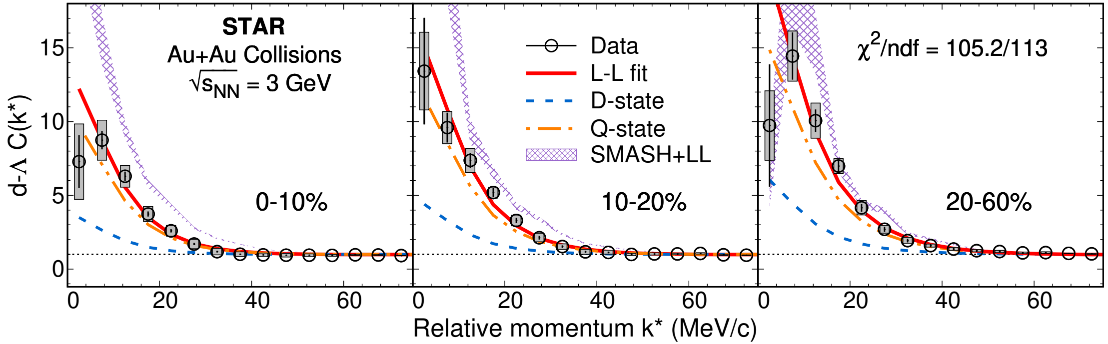
Corrections:

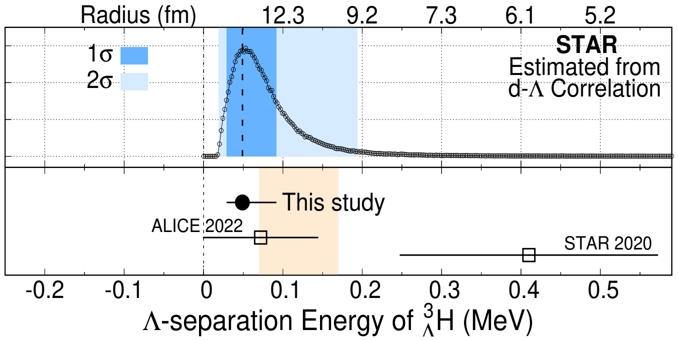
1) Track merging;
2) Track splitting;
3) Resonance decays;
4) Purity;
5) Momentum smearing;
6) Contribution of ${}^{3}_{\Lambda}H$

Acceptance:

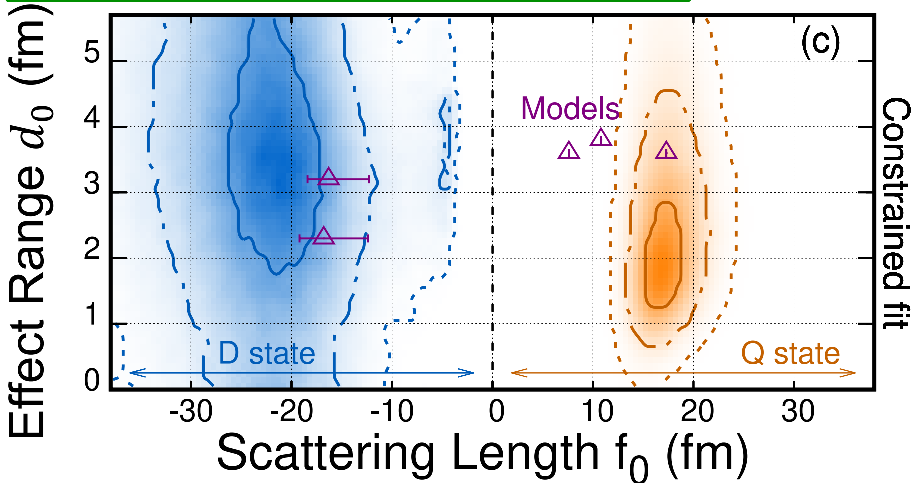
- All: 0.5< y<0;
- **p**: 0.25< p_T < 2 (GeV/c);
- **d**: 0.25< p_T < 3 (GeV/c);
- ***Λ***: 0.25< p_T < 2 (GeV/c)

$d - \Lambda$ Correlation Functions 3.0 GeV





STAR: CPOD2024, QM2023



1) Centrality dependence of the $d - \Lambda$ correlation functions from 3.0 GeV Au+Au collisions;

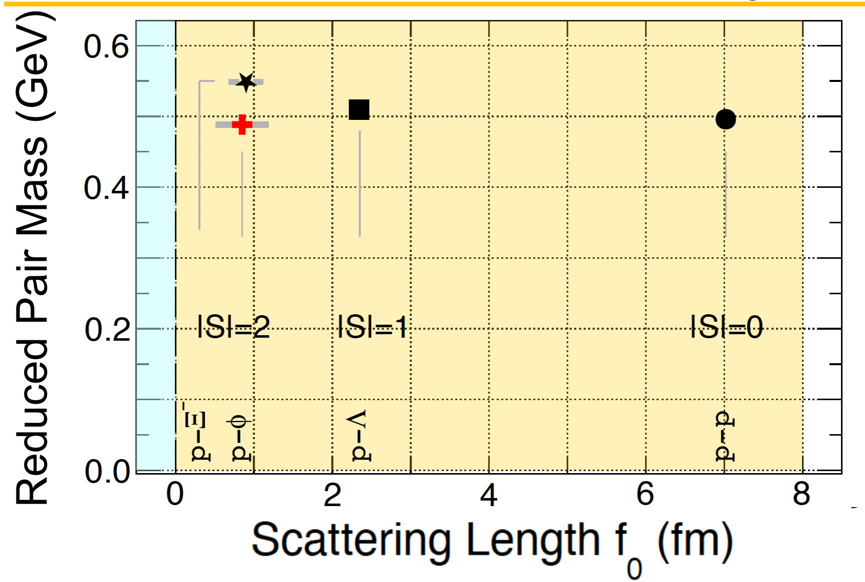
2) For the first time, spin dependent states, *D and Q*, identified experimentally!

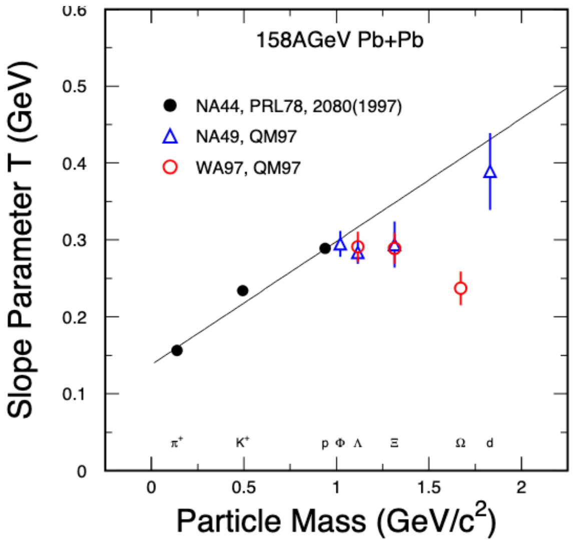
→ New window for studying 3-body interactions in the laboratory

References:

(1) J.M. Lattimer and M. Prakash, Science **304**, 536 (2004);
(2) M. Kohno and H. Kamada, arXiv:2406.13899;
(3) H. W. Hammer, Nucl. Phys. **A705**,173 (2002)

Summary: *NY* Correlations





H. van Hecke, H. Sorge
NX, Phy.Rev.Lett. **81**, 5764(1998). *"Evidence of early multi-strange hadron freeze-out in high energy nuclear collisions"*

→ Rescatterings lead to collectivity

→ Collectivity is reduced as the strangeness content is increased

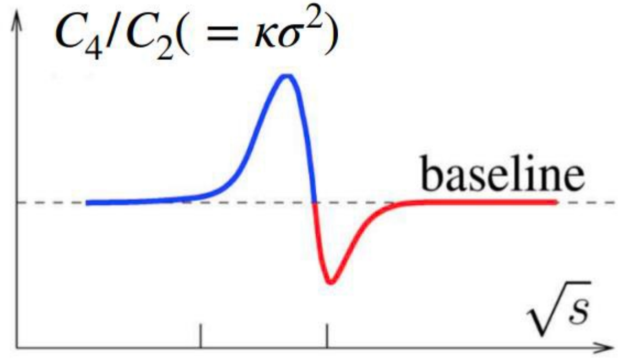
Hierarchy of strangeness content: $f_0(|s|=0) > f_0(|s|=1) > f_0(|s|=2) > 0$

- Interaction section is proportional to f_0^2, the observation implies that the strength of the interaction depends on strangeness;
- Important for understanding EOS of the medium in nuclear collisions and compact stars;

In case of $f_0 < 0$, important for the search for di-baryons, such as $p\Omega$
Understand the strangeness hierarchy in QCD calculations?

Search for QCD Critical Point

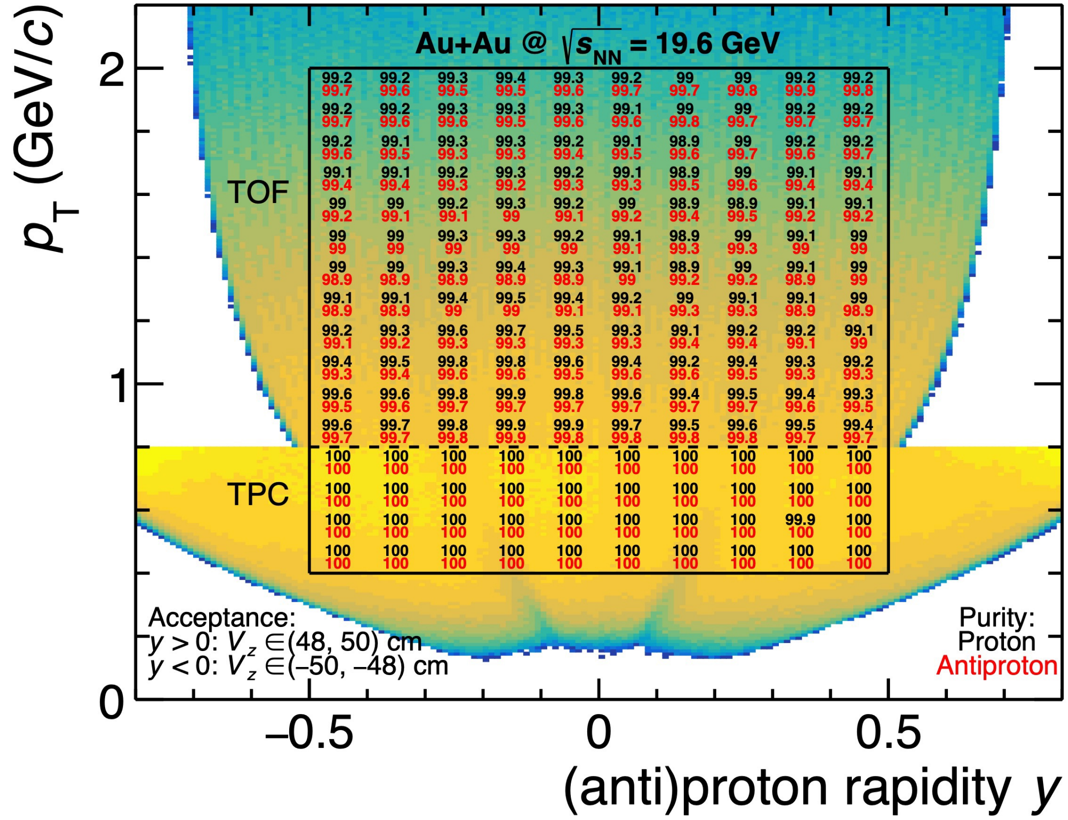
Precision Measurements of (Net-)Proton Number Fluctuations in Au+Au Collisions at RHIC (STAR Collaboration)



M. A. Stephanov, PRL 107 (2011) 052301

Signal for Critical Point:
Non-monotonical energy dependence

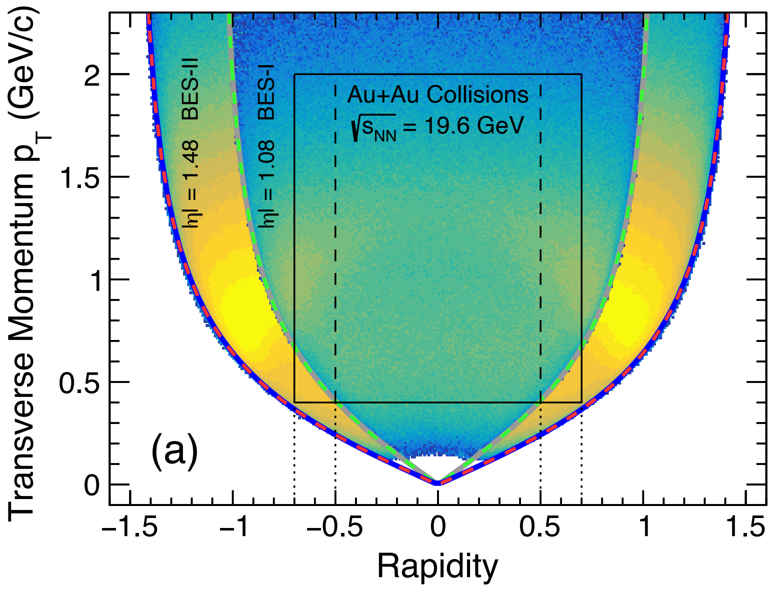
Proton Identification at BES-II

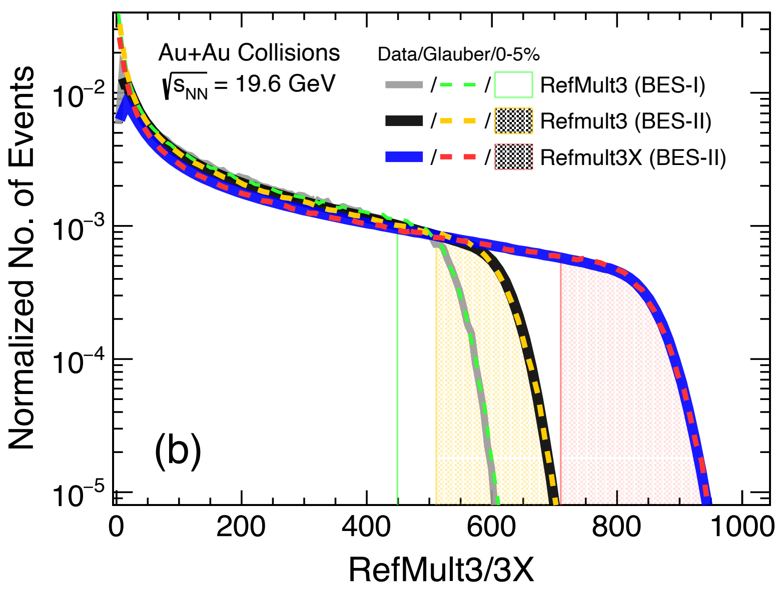


Detector	TPC	TPC+TOF
dE/dx	$\lvert n\sigma \rvert < 2$	
m^2 $(GeV/c^2)^2$	NA	0.6 – 1.2
p_T (GeV/c)	0.4 – 0.8	0.8 – 1.2
rapidity	$\lvert y \rvert < 0.5$	

1) Uniform acceptance for (anti-) protons |y|<0.5 with |Vz| < 50cm;
2) (anti-)protons identified using TPC dE/dx and TOF
3) Bin-by-bin purity > 99% in the full acceptance range and for all energies

BES-II: Centrality Determination



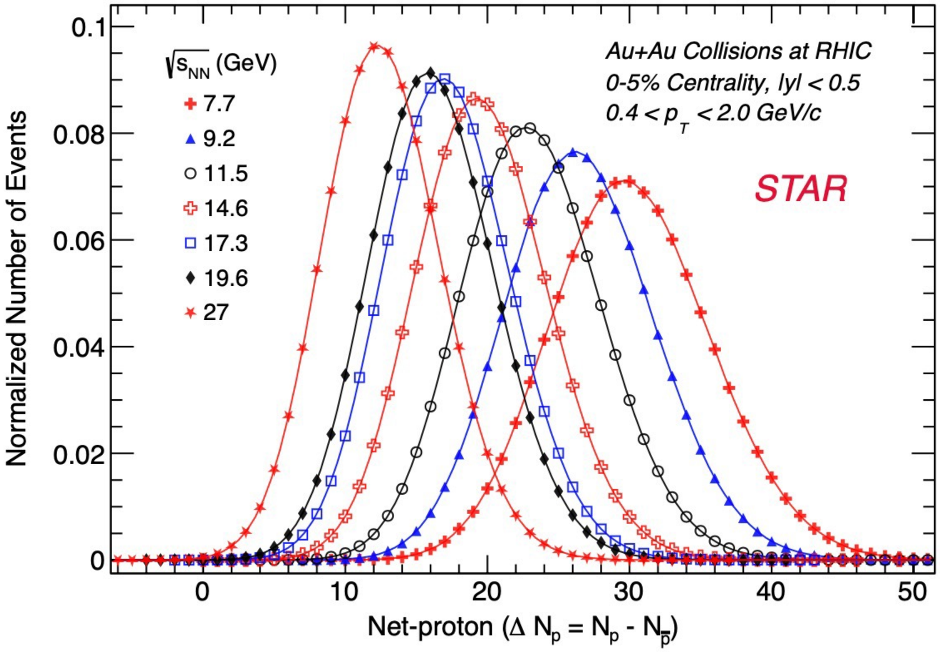


Reference multiplicity measurements **RefMult3**: *TPC measured charge particles except (anti-)protons*

1) RefMult3: **($|\eta|<1.0$)** for both BES-I and BES-II **2) RefMult3X:** **($|\eta|<1.6$)** for BES-II

→ Larger acceptance → larger multiplicity → better centrality resolution

Net-p from BES-II



1) Raw number distributions from BES-II: Uncorrected for detector efficiency;
2) Mean increases with decreasing collision energy: Effect of baryon stopping;
3) The increase in the width is due to the increase of proton numbers at lower energy

0-5%: C_4/C_2 improvement factor BES-II / BES-I			
7.7 GeV		19.6 GeV	
Stat.	Syst.	Stat.	Syst.
4.7	3.2	4.5	4
*Embedding statistics increased by a factor of 5!			

STAR: CPOD2024, SQM2024

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, $\langle \delta N \rangle = \mathbf{N} - \langle N \rangle$

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

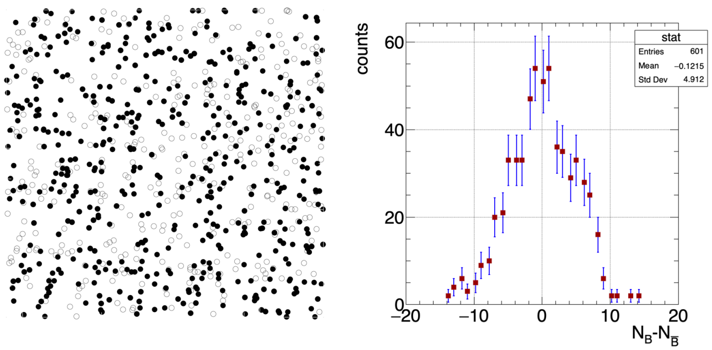
Moments, cumulants and susceptibilities:

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

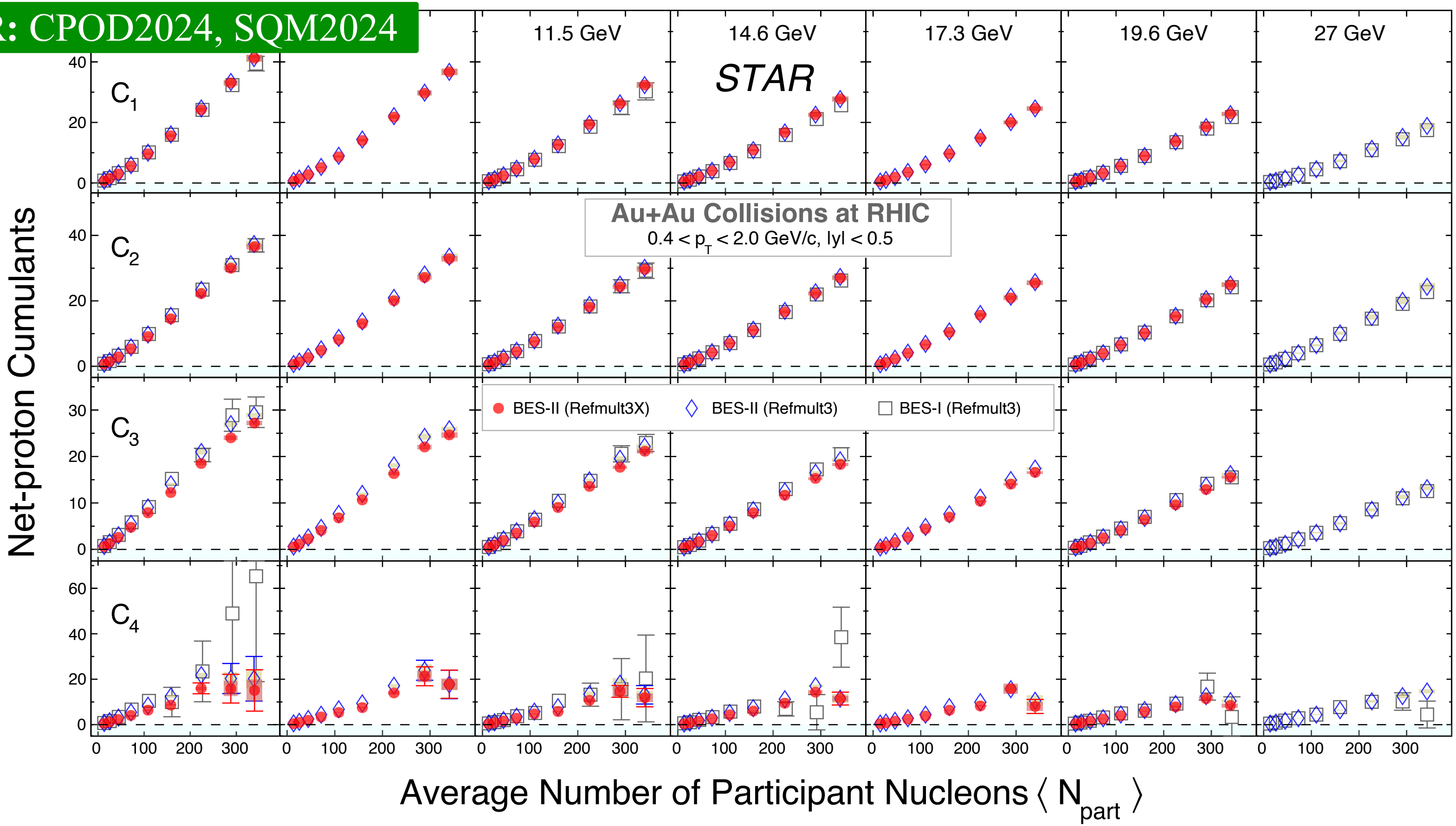
Animation: A.Rustamov



INT 2008-2b : The QCD Critical Point

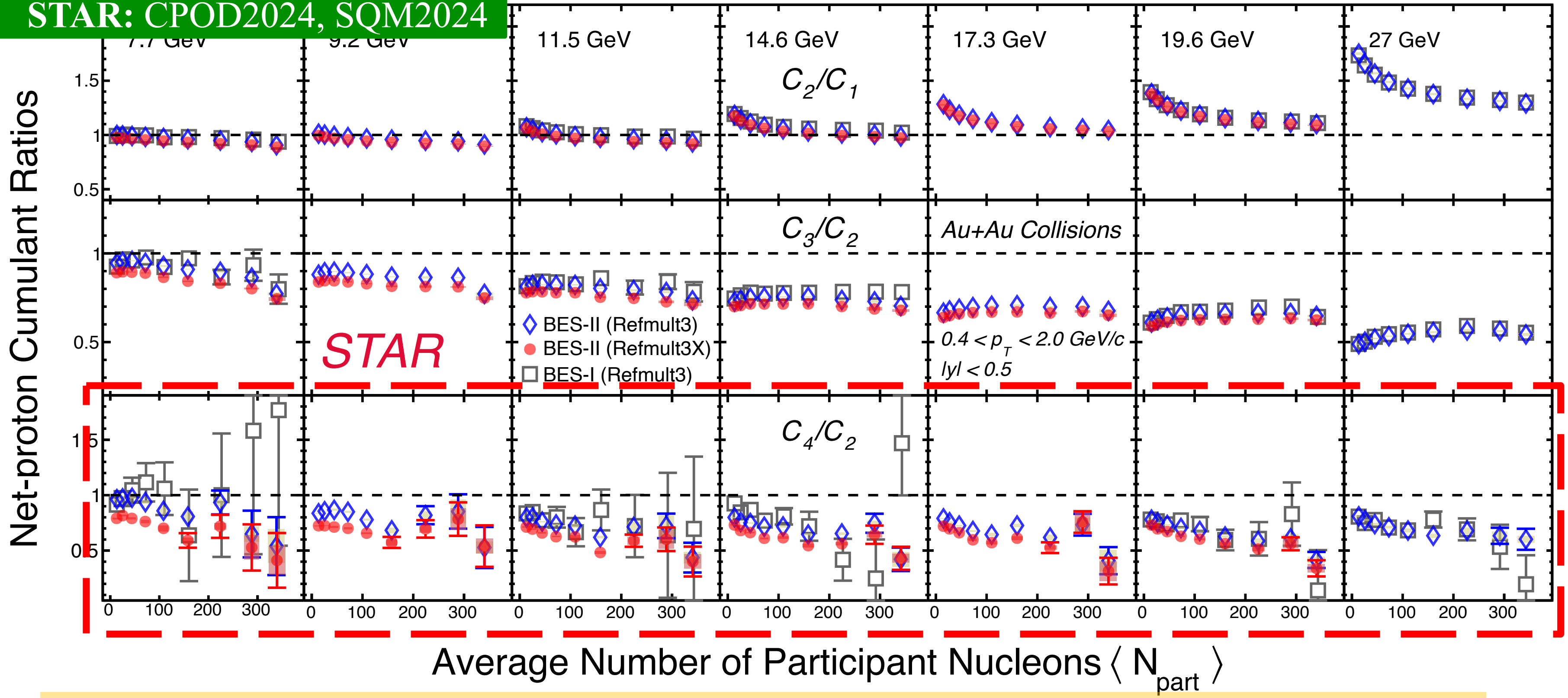
Cumulants of Net-p from BES-II

STAR: CPOD2024, SQM2024



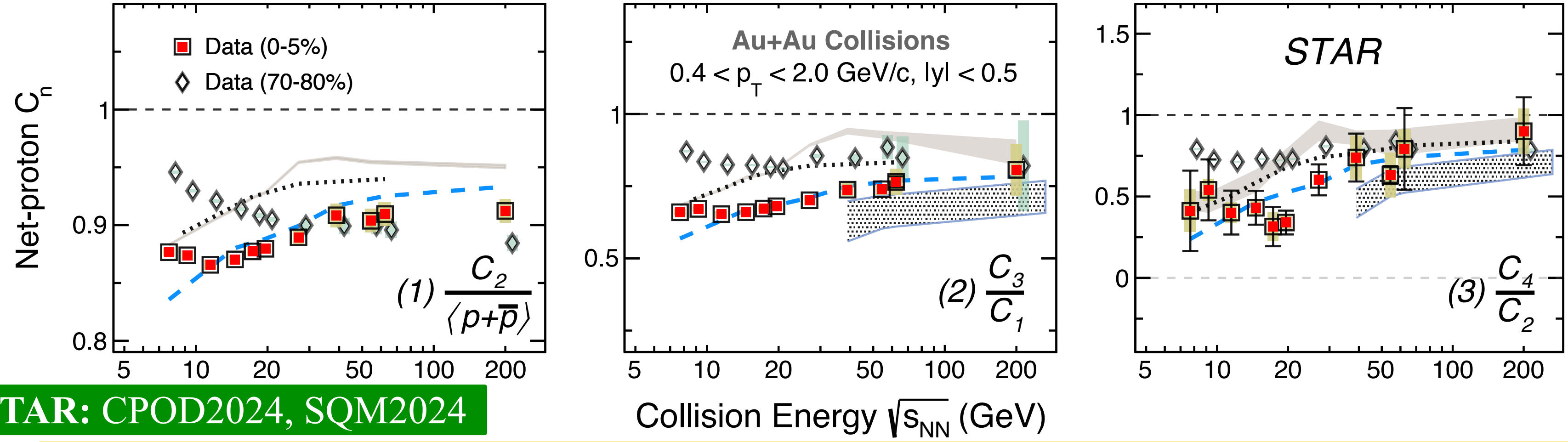
Net-p Cumulant Ratios

STAR: CPOD2024, SQM2024



In 0-5% central collisions, values of C_4/C_2 are consistent among BES-I and BES-II

Energy Dependence of Cumulant Ratios

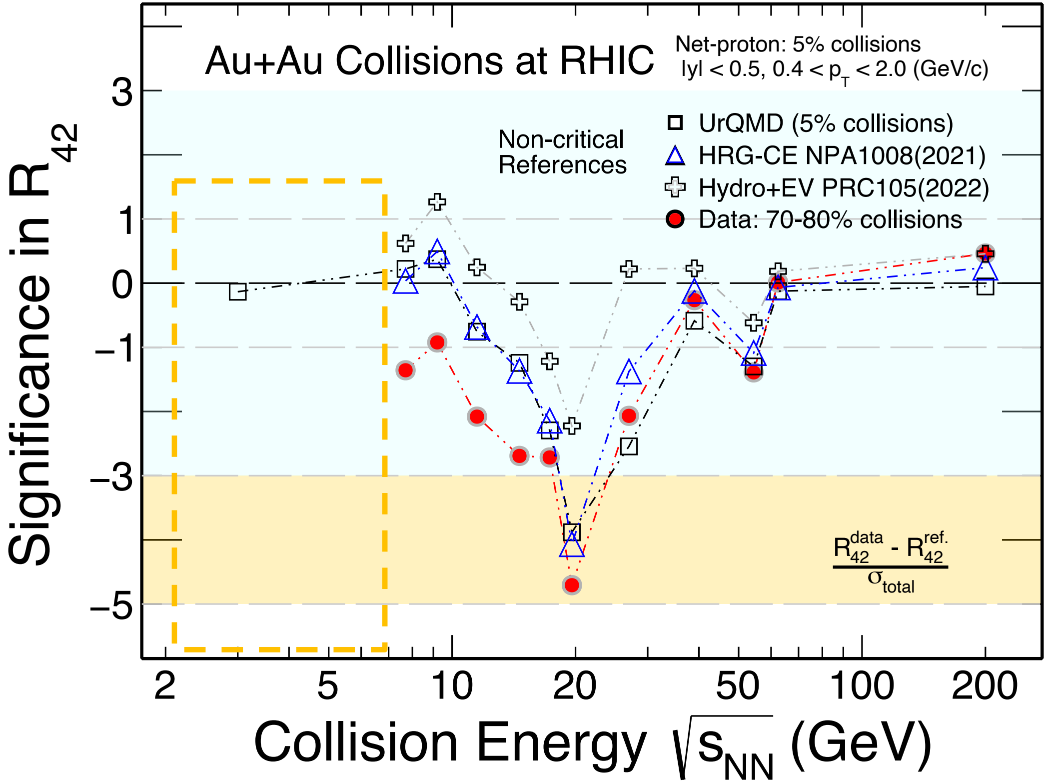


STAR: CPOD2024, SQM2024

1) **UrQMD:** hadronic transport and the results are analyzed in the same way as data.
   S. Bass *et al*., Prog. Part. Nucl. Phys., **41**, 255 (1998);
2) **HRG CE:** P.B. Munzinger *et al.* Nucl. Phys. **A1008**, 122141(2021);
3) **Hydro - HRG CE + EV + Collectivity:** V. Vovchenko *et al.*, Phys. Rev. **C105**, 014904 (2022).
4) **LQCD GCE:** done for net-baryon A. Bazavov *et al.,* Phys. Rev. D101, 074502 (2020).

Baryon conservations applied in all model calculations except LQCD!

Deviations from Non-CP Models



0-5% central collisions:

1) C_4/C_2 ratios: show minima at 19.6 GeV, **2-5σ effects**, depends on reference;

2) **Future data from**
   (i) STAR FXT;
   (ii) HADES at GSI and
   (iii) CBM experiment at FAIR (2028) will cover the energy region $\sqrt{s_{NN}}$ = 2.4 – 4.9 GeV

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3) **Summary and Outlook**

Summary

(1) Baryon correlations: Hierarchy of strangeness content in f_0!

(2) Search for QCD critical point:

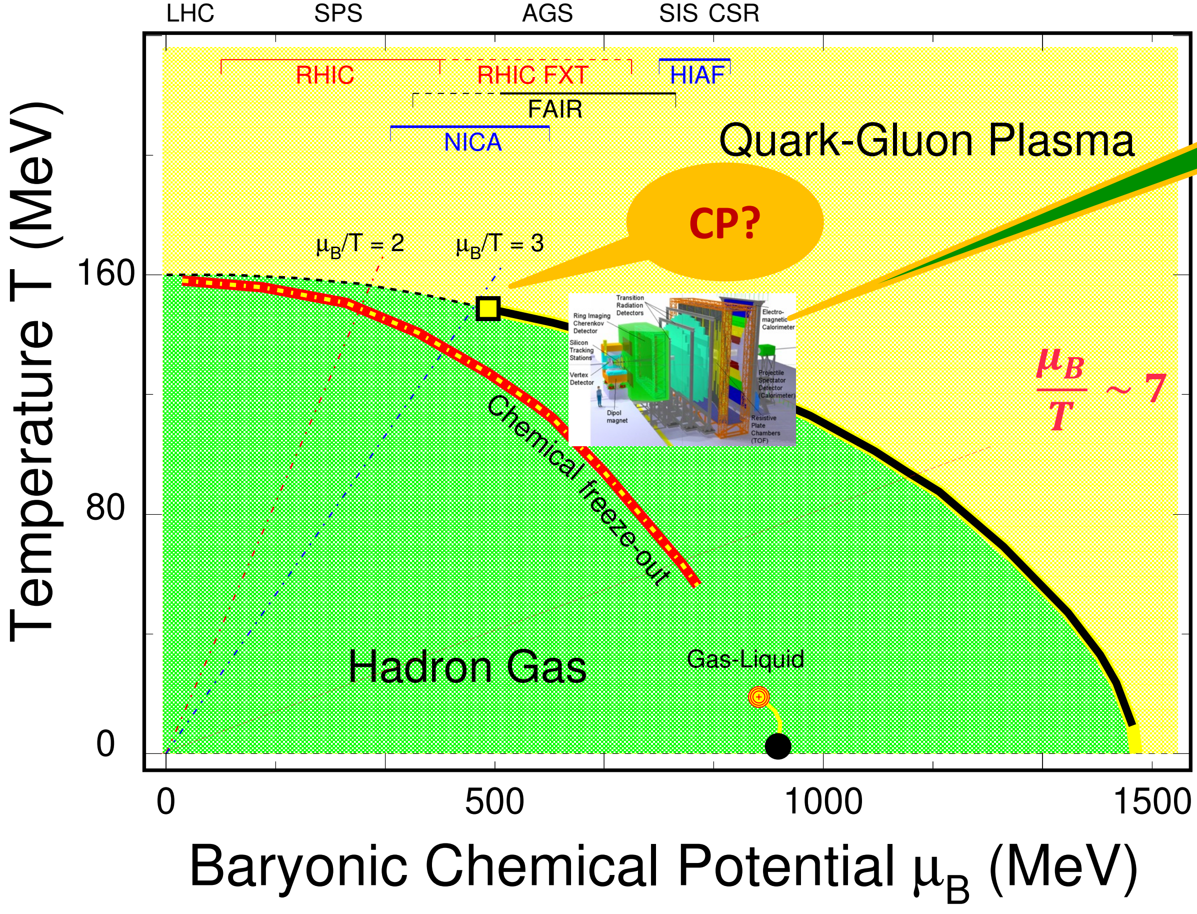
- BES-II data offered high statistics, better acceptance, centrality resolution and systematic;
- Known model calculations **Do Not** reproduce the energy dependence ($\sqrt{s_{\mathrm{NN}}}$ = 7.7 – 200 GeV)

(3) Outlook:

(i) Transverse momentum p_T and rapidity scan;
(ii) Higher orders: C_5, and C_6 analysis;
(iii) Complete FXT data analysis at $\sqrt{s_{\mathrm{NN}}}$ = 3 – 3.9 GeV

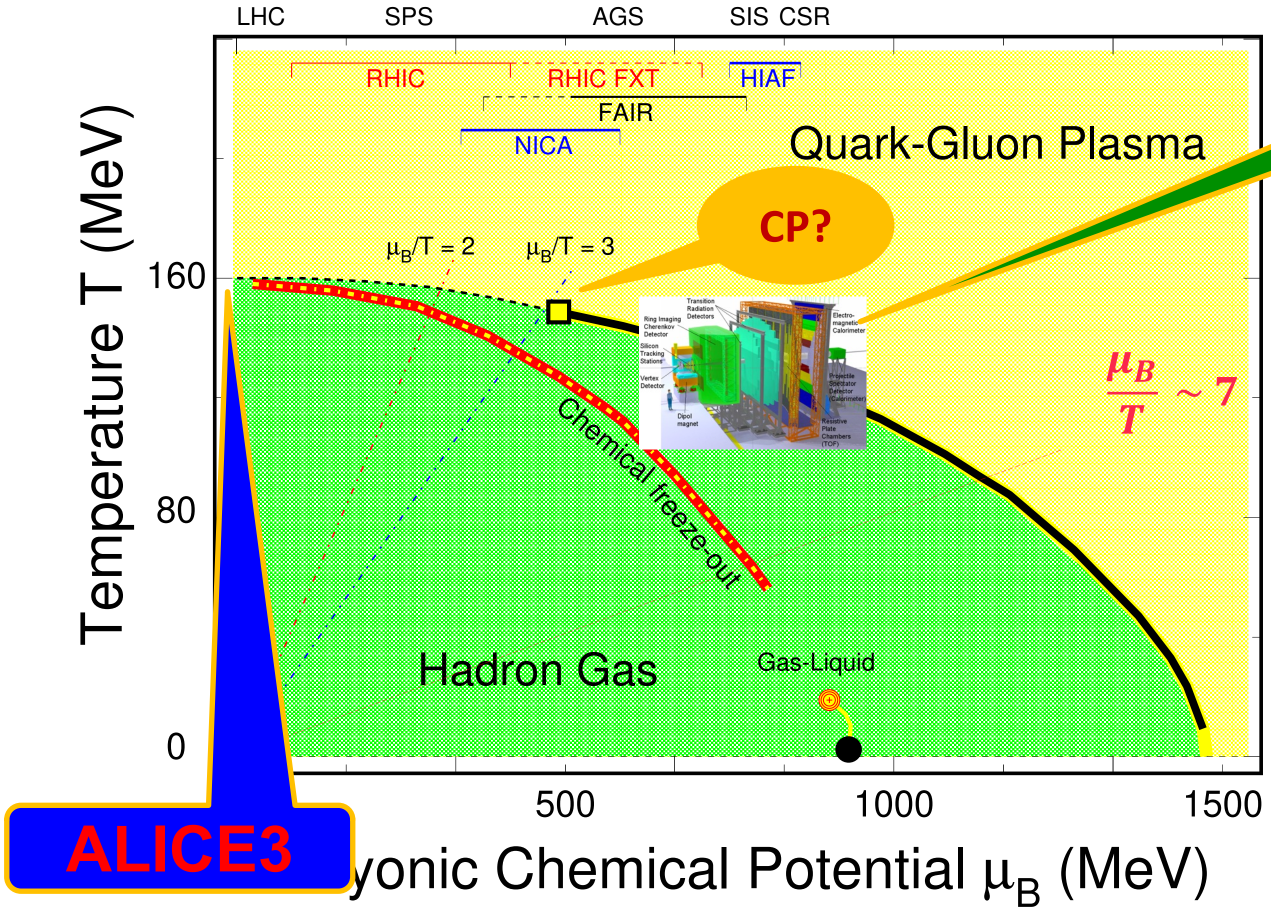
Future Physics Programs at High μ_B

CBM 2028



- ➢ Critical point and phase boundary;
- ➢ Nuclear matter EOS at high baryon density;
- ➢ Y-N interactions, inner structure of compact stars

Future Physics Programs at High μ_B



- Critical point and phase boundary;
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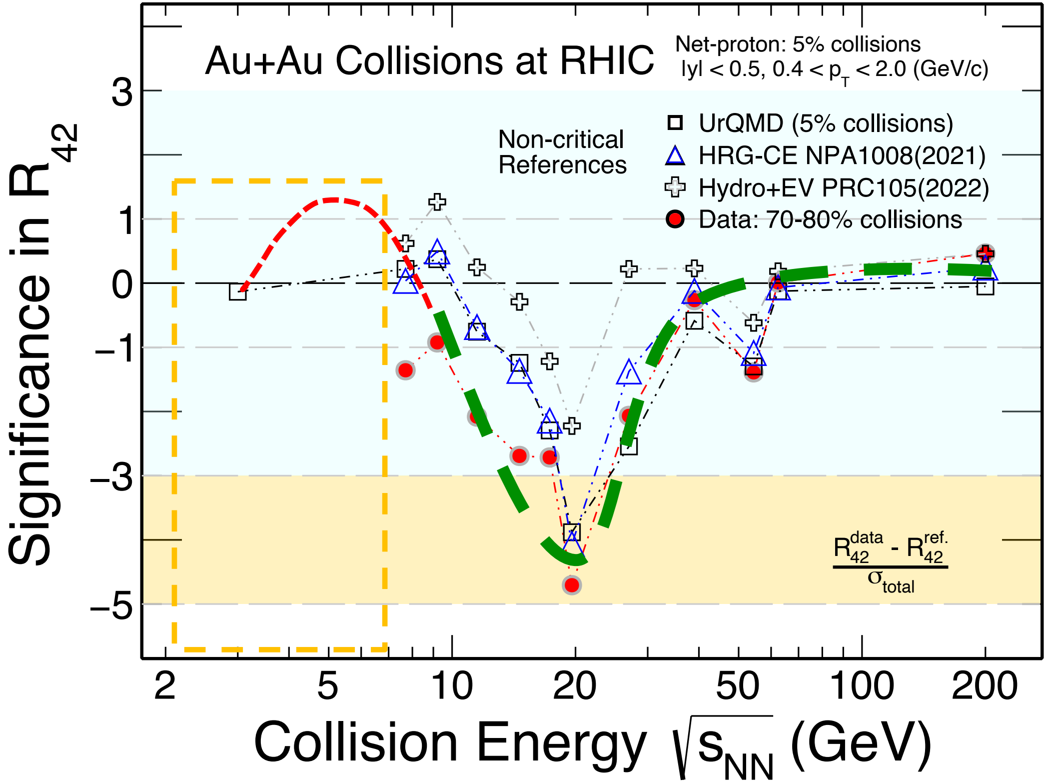
Key Measurements at CBM Experiment



1) **CBM covers the key energy region for CP search**
$\sqrt{s_{NN}}$ = 2.4 – 4.9 GeV

2) **Key measurements at CBM:**
- Leptons
- Collective flow
- High moments of proton
- NN and YN correlation
- (m)Hyper-nuclei production

→ **The detector must be ready by 2028**

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RHIC and STAR Experiment

P. Braun-Munzinger, X. Dong, S. Esumi, ***Y. Hu***, F. Karsch, ***K. Mi***, V. Koch, XF. Luo, B. Mohanty, ***A. Pandav***, A. Rustamov, K. Redlich, M. Stephanov, J. Stachel, J. Stroth, V. Vovchenko, ***Y. Zhang***

// BLUE: Theory // **RED**: Exp. //

EMMI/GSI

Thank you for your attention!