Study the QCD Phase Structure in High-Energy Nuclear Collisions

Recent Results from RHIC BES-II

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Outline

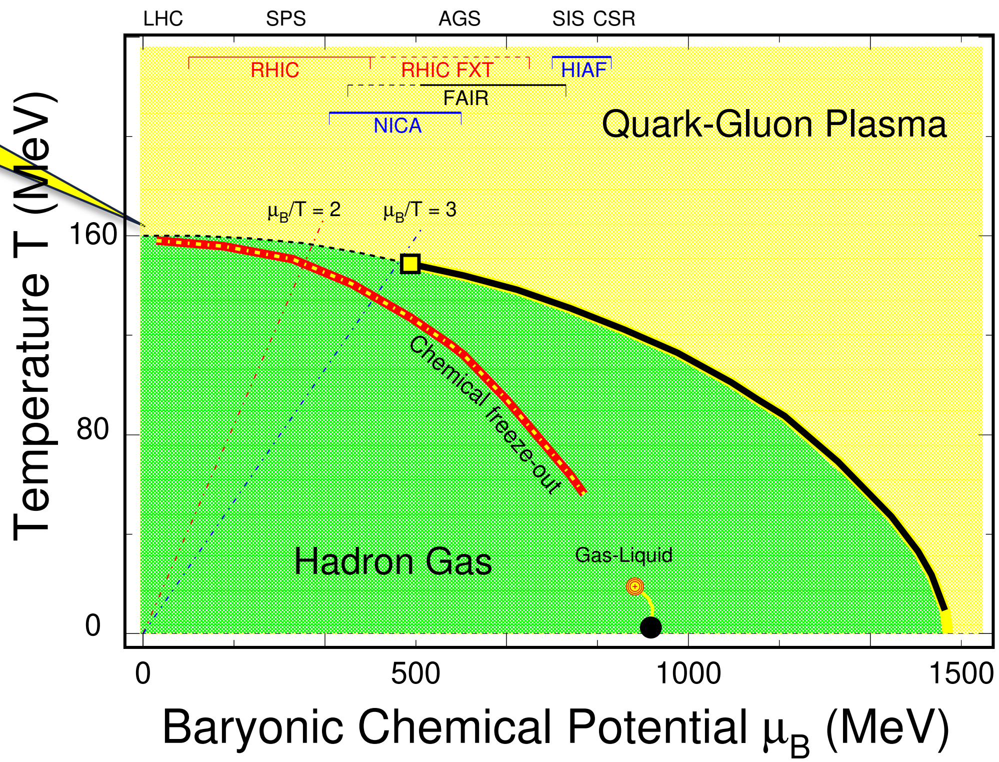
1) **Introduction**

2) Selected Recent Results from RHIC BES-II
   - ➢ Collectivity;
   - ➢ Criticality;
   - ➢ Baryon Correlations

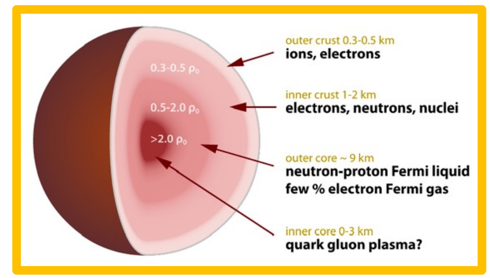
3) Summary and Outlook

Nuclear Collisions and QCD Phase Diagram

Early Universe



High baryon density:
Inner structure of
compact stars

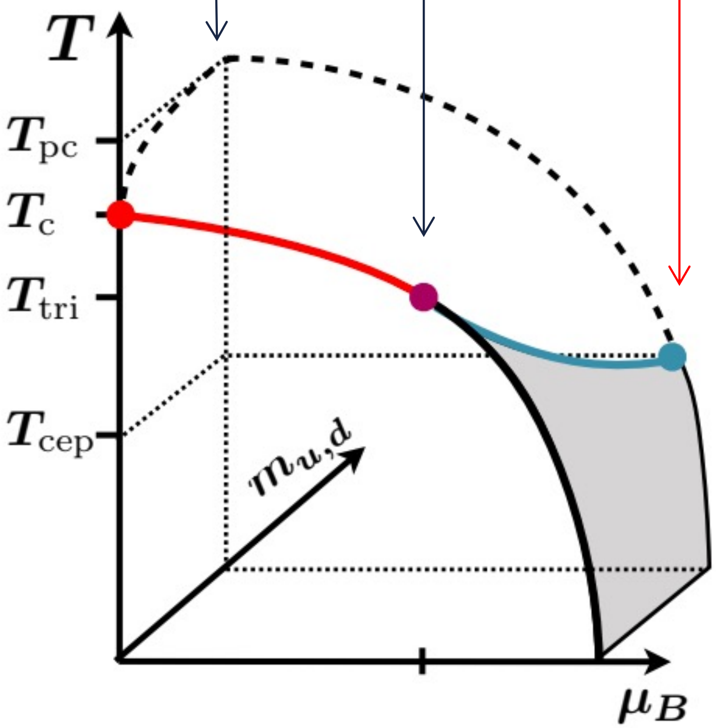


1) RHIC BES: → search for the 1st phase transition and QCD CEP;
2) Hyper-nuclei productions
3) Baryon correlations

} inner structure of compact stars

QCD Phase Structure (LQCD)

T_C^0 T_{PC} T^{TriC} T^{CEP}



F. Karsch *et al.*, 2020

1) QCD transition temperature:

$$\mathbf{T_{PC} = 156.5 \pm 1.5\ MeV}$$

2) Chiral crossover line

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

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

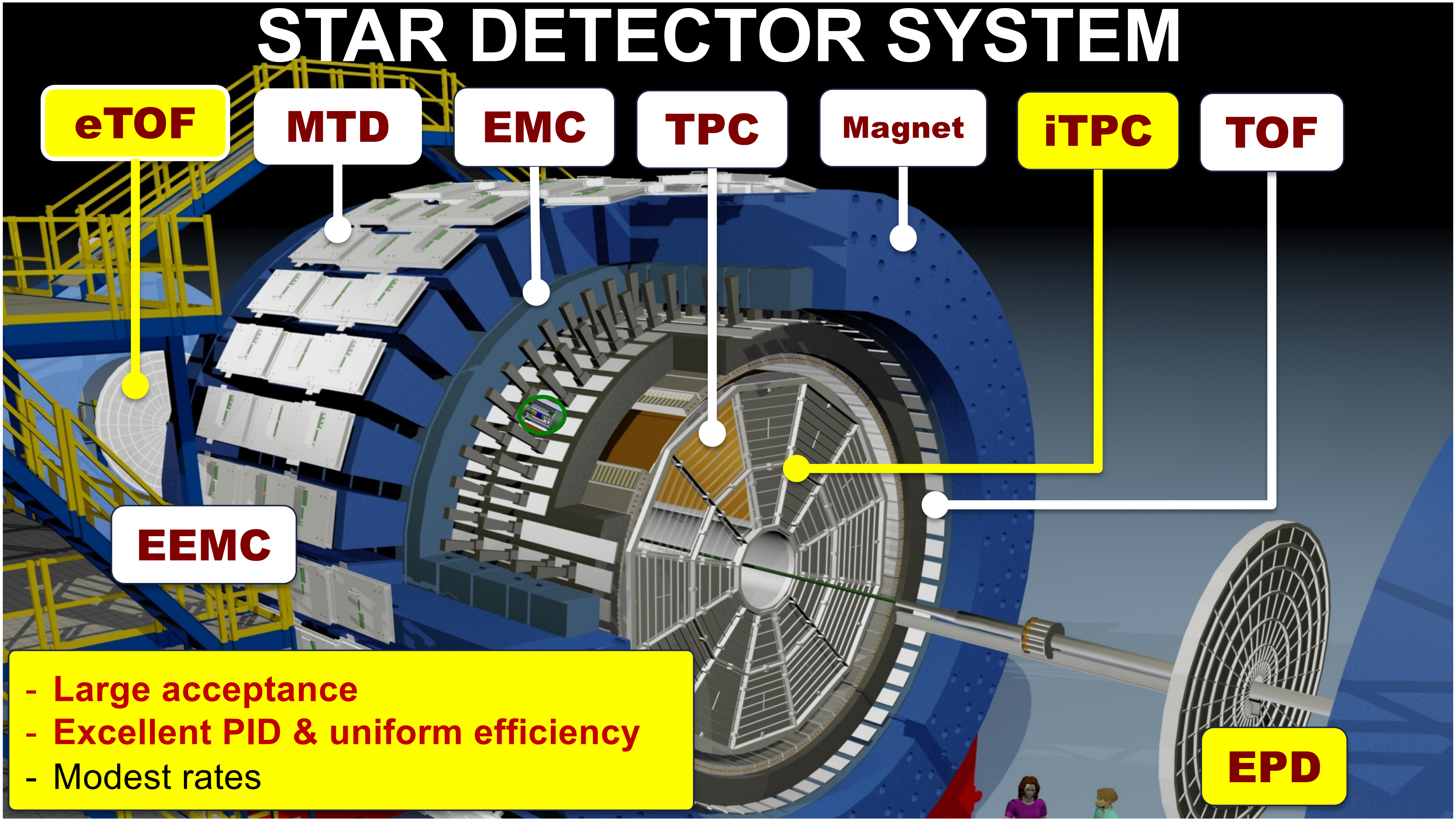
3) Chiral transition temperature:

$$\mathbf{T_C = 132^{+3}_{-6}\ MeV}$$

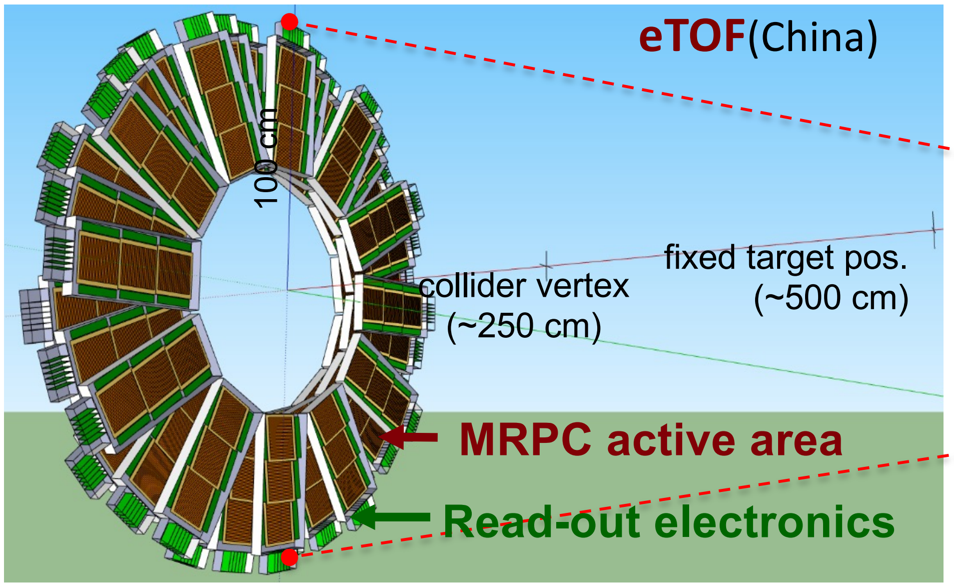
4) QCD critical end point, if exits:

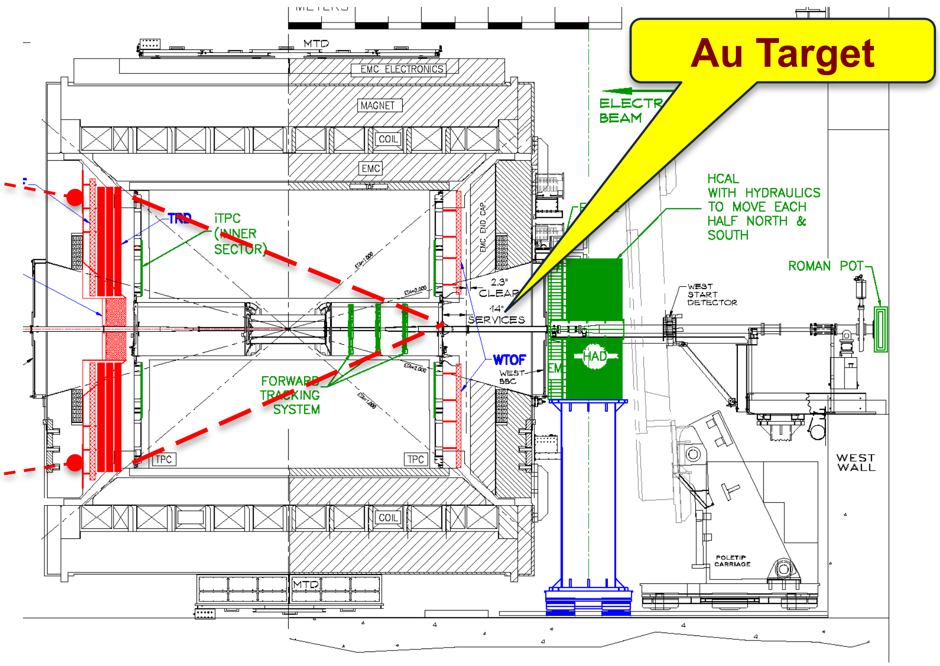
$$\mathbf{T^{CEP} < T_C, \quad \mu_B^{CEP} \gtrsim 3T_C}$$

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


STAR DETECTOR SYSTEM
eTOF
MTD
EMC
TPC
Magnet
iTPC
TOF
EEMC
EPD
- Large acceptance
- Excellent PID & uniform efficiency
- Modest rates

STAR Fixed Target Setup





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

- Complementary to CBM program: $\sqrt{s_{NN}}$ = 3 - 7.2 GeV (**760 ≥ 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						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	57 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)	**260** + 2000 M	**760** MeV	-1.05	Run-18, 21

Most precise data to map the QCD phase diagram

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

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Collectivity

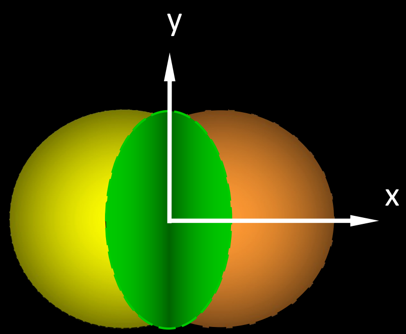
$$\partial_\mu[(\varepsilon + p)u^\mu u^\nu - pg^{\mu\nu}] = 0$$
$$\partial_\mu[s\, u^\mu] = 0$$

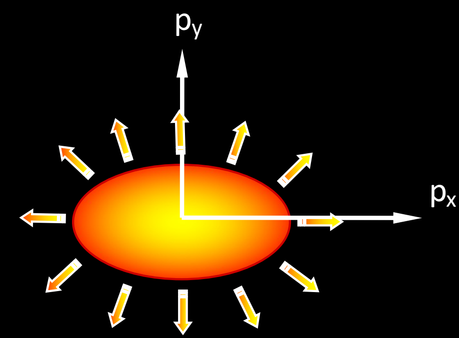
$$\frac{d^2N}{p_T dp_T d\varphi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T}\left\{1 + \sum_{n=1}^{\infty} 2v_n(p_T)cos[n(\varphi - \Psi_R)]\right\}$$

− v_1 Directed flow;
− v_2 Elliptic flow;
− v_3 Triangle flow

Anisotropy Parameter v_2

coordinate-space-anisotropy ⇨ momentum-space-anisotropy

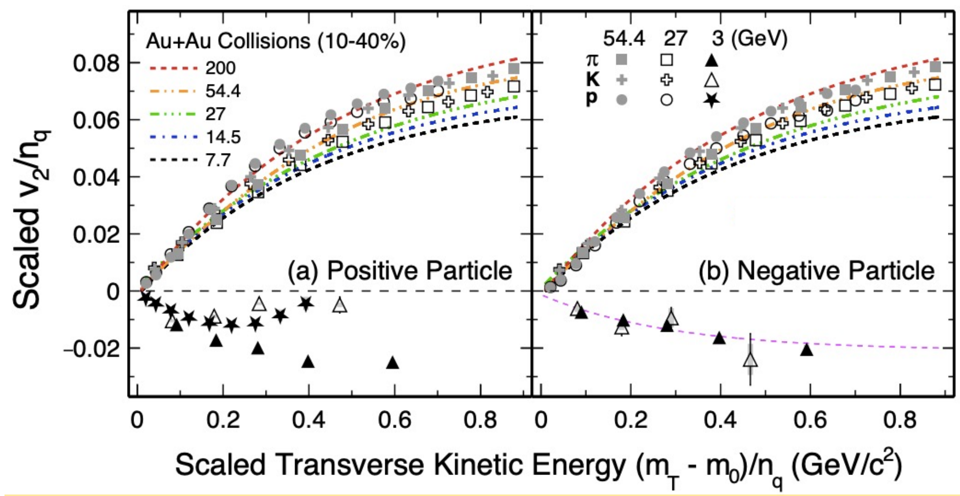


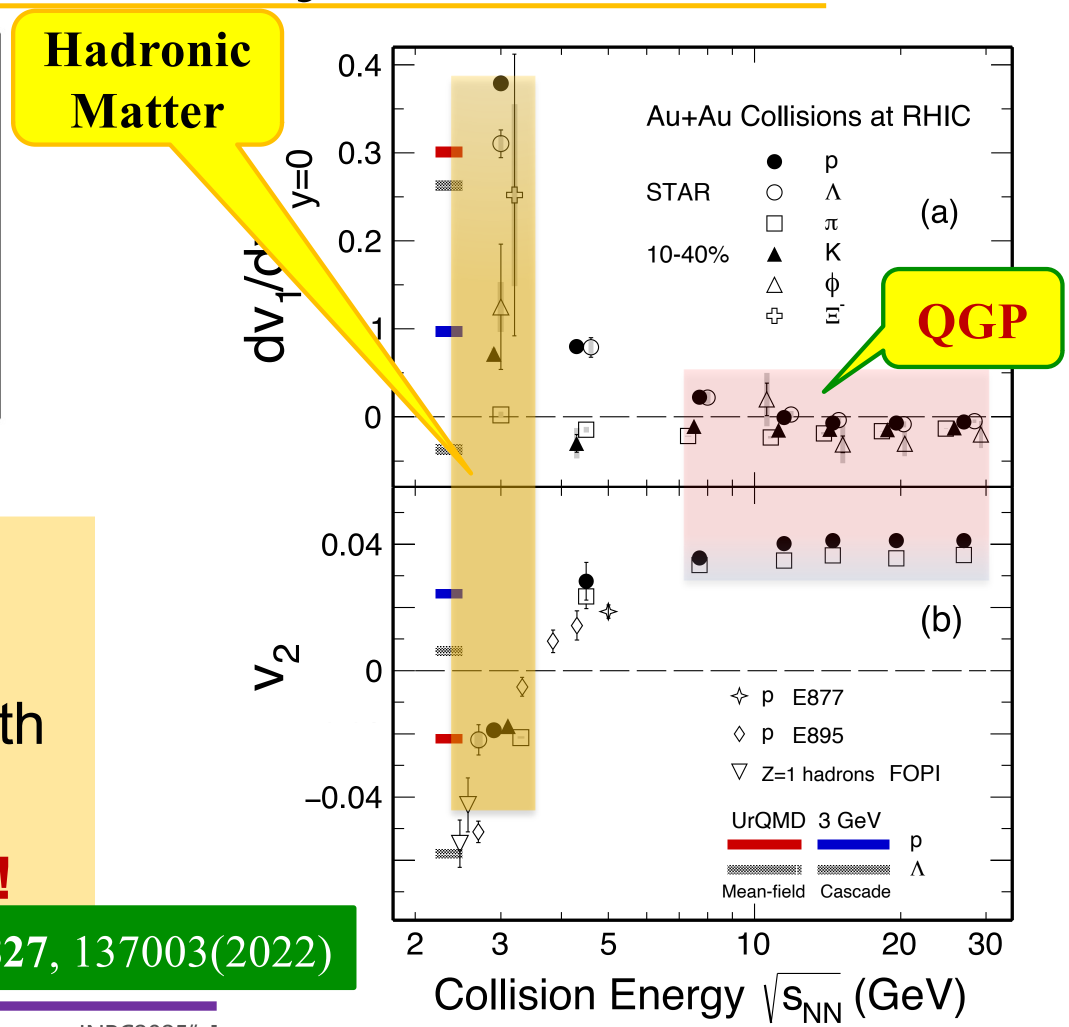


$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle cos2\varphi \rangle, \qquad \varphi = tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Sensitive to initial/final conditions, EoS and degrees of freedom

Partonic Collectivity or Not

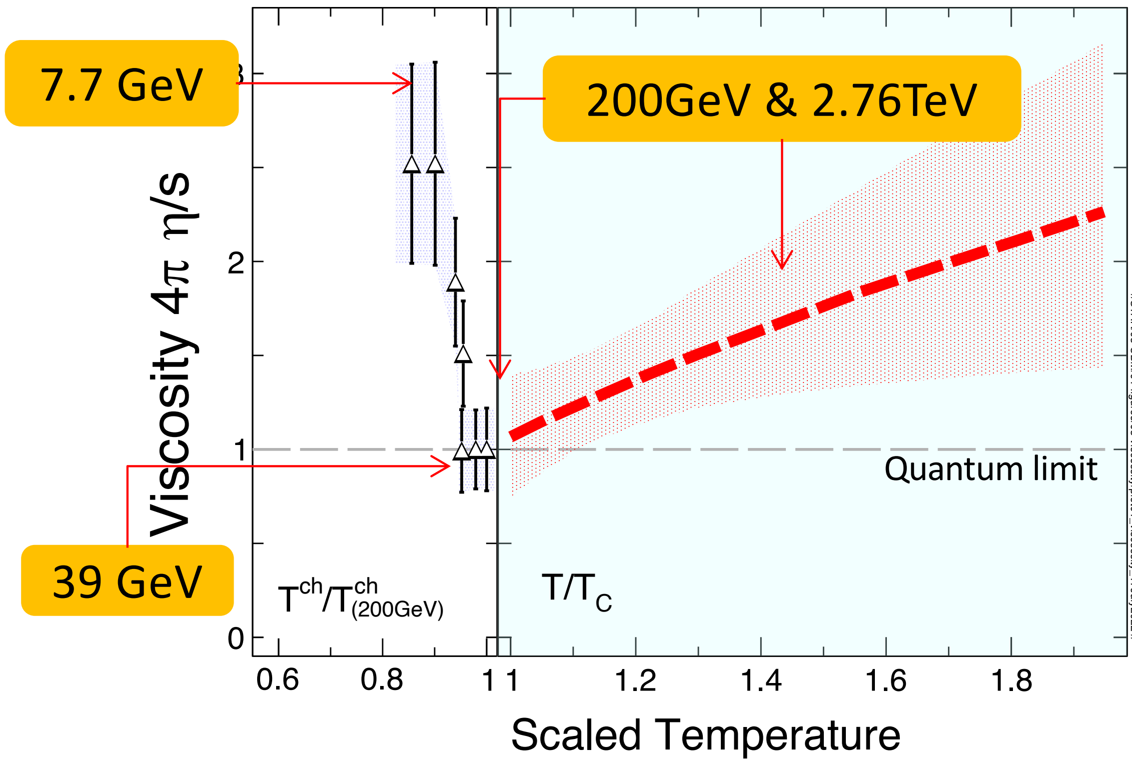




- At **3 GeV**, NCQ scaling is absent;
- Transport model calculations, with baryonic mean field, reproduce both v_1 and v_2 results;
- **Hadronic interactions dominant!**

STAR: PLB**827**, 137003(2022)

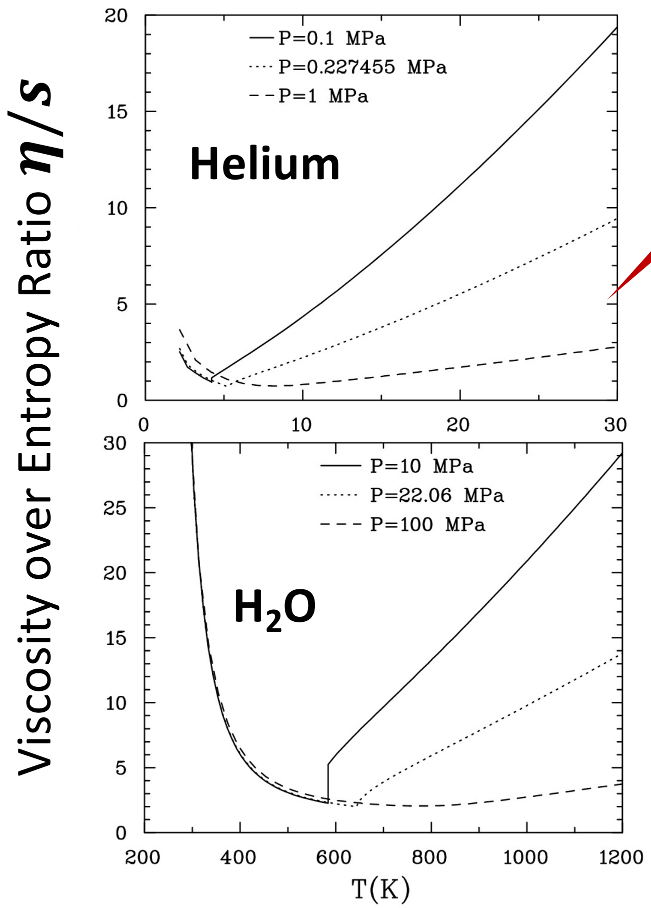
EOS of Strong Interacting Matter



1) Left-plot: Energy dependence of η/s extracted from light-flavor hadron v_2 and v_3. Right-plot: extracted from Bayesian fits to R_{AA} and v_2 at 200GeV collisions;
2) Both sides meet at the unity of the scaled temperature;
3) The values of η/s increase quickly below $\sqrt{s_{NN}}$ = 39 GeV → QGP dominants in higher energies;
4) **Evidence of the QCD transition!**

1) L.P. Csernai, J.I. Kapusta, L.D. McLerran, PRL **97** (2006) 152303
2) X.Dong, Y.J. Lee & R.Rapp, ARNPS, **69** (2019) 417
3) J.E.Bernhard, J.S.Moreland & S. Bass, Nat. Phys. **15** (2015) 1113
4) I. Karpenko, P. Huovinen, H. Petersen, and M. Bleicher, Phys.Rev.**C91**, 064901 (2015).
5) G.Nijs, W.van der Schee, U. Gürsoy and R. Snellings, PRL**126**, (2021) 202301

EOS of Strong Interacting Matter

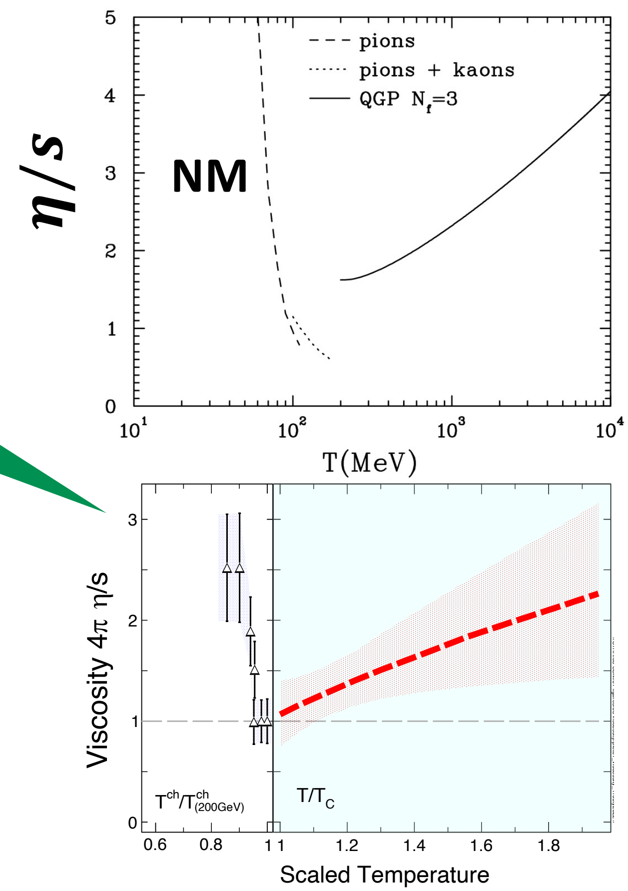


EM interaction
$\eta/s \sim 1$

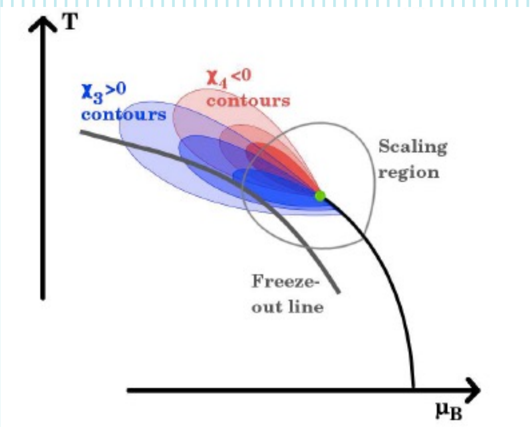
L.P. Csernai, J.I. Kapusta, L.D. McLerran, PRL**97** (2006) 152303

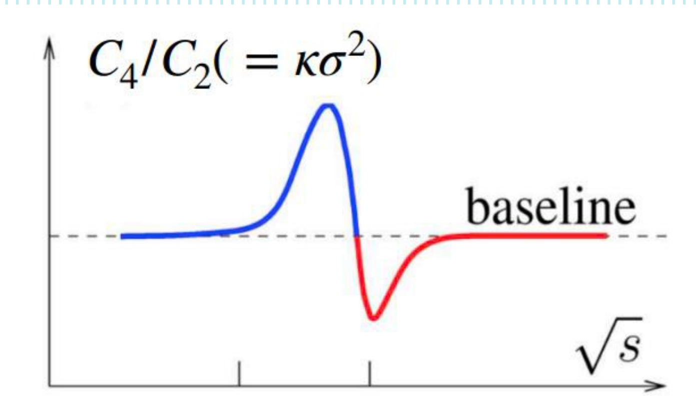
Strong Interaction
$\eta/s \sim 0.1$

- QGP matter in $\sqrt{s_{NN}} \geq 39$ GeV collisions!
- Universal behavior for phase transition!



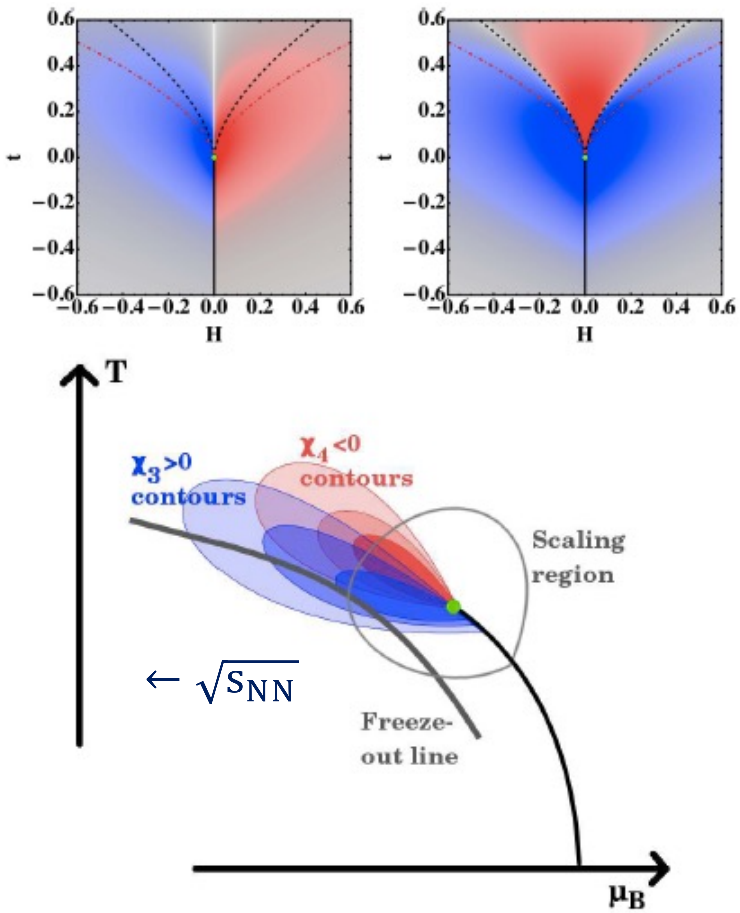
Criticality

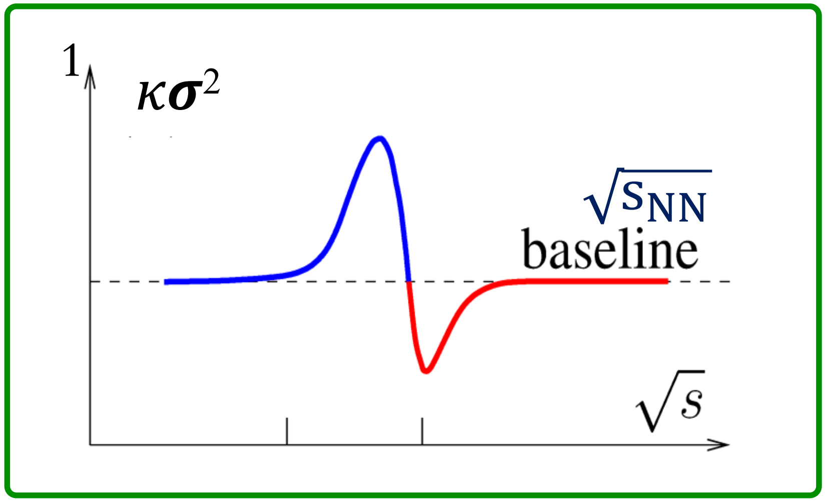




M. A. Stephanov, PRL 107 (2011) 052301

Expectations from Models





- 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. Kohyyama, Phys. Rev. **D93** (2016) 034037

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, are sensitive to the correlation length ξ, and the phase structure;
3) Cumulants are connected directly 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: $\kappa = \langle (\delta N)^4 \rangle / \sigma^3 - 3 = C_4 / C_2^2$

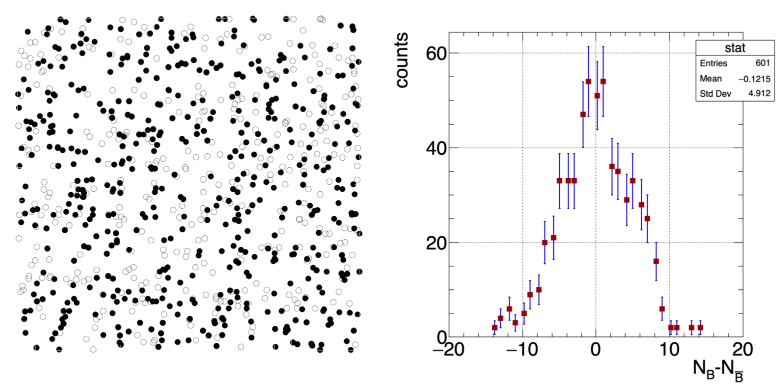
Moments, cumulants and susceptibilities:

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

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

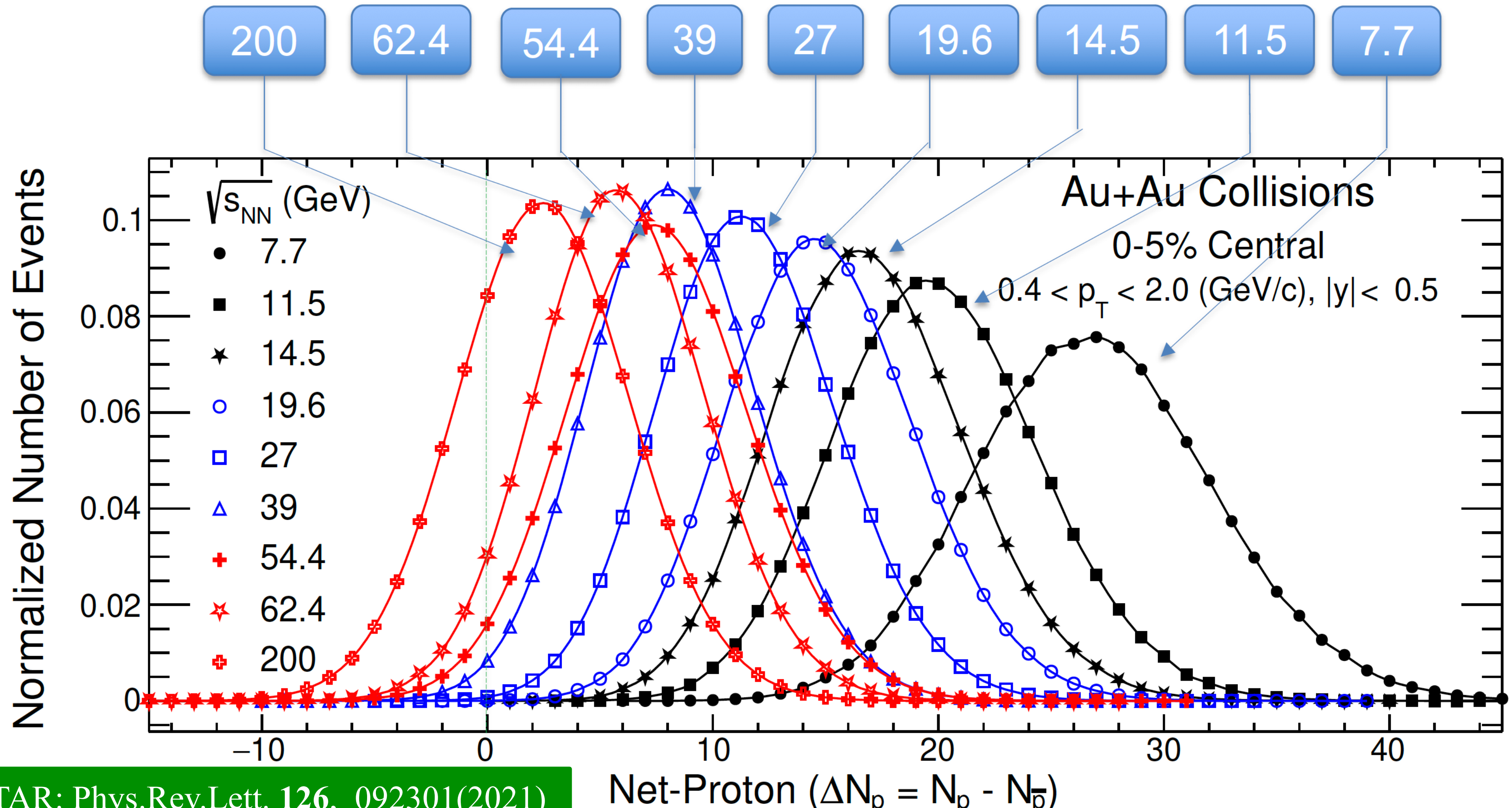
4^{th} order: $\kappa\sigma^2 \equiv C_4/C_2 = \chi_4/\chi_2$

Animation: A.Rustamov



INT 2008-2b : The QCD Critical Point

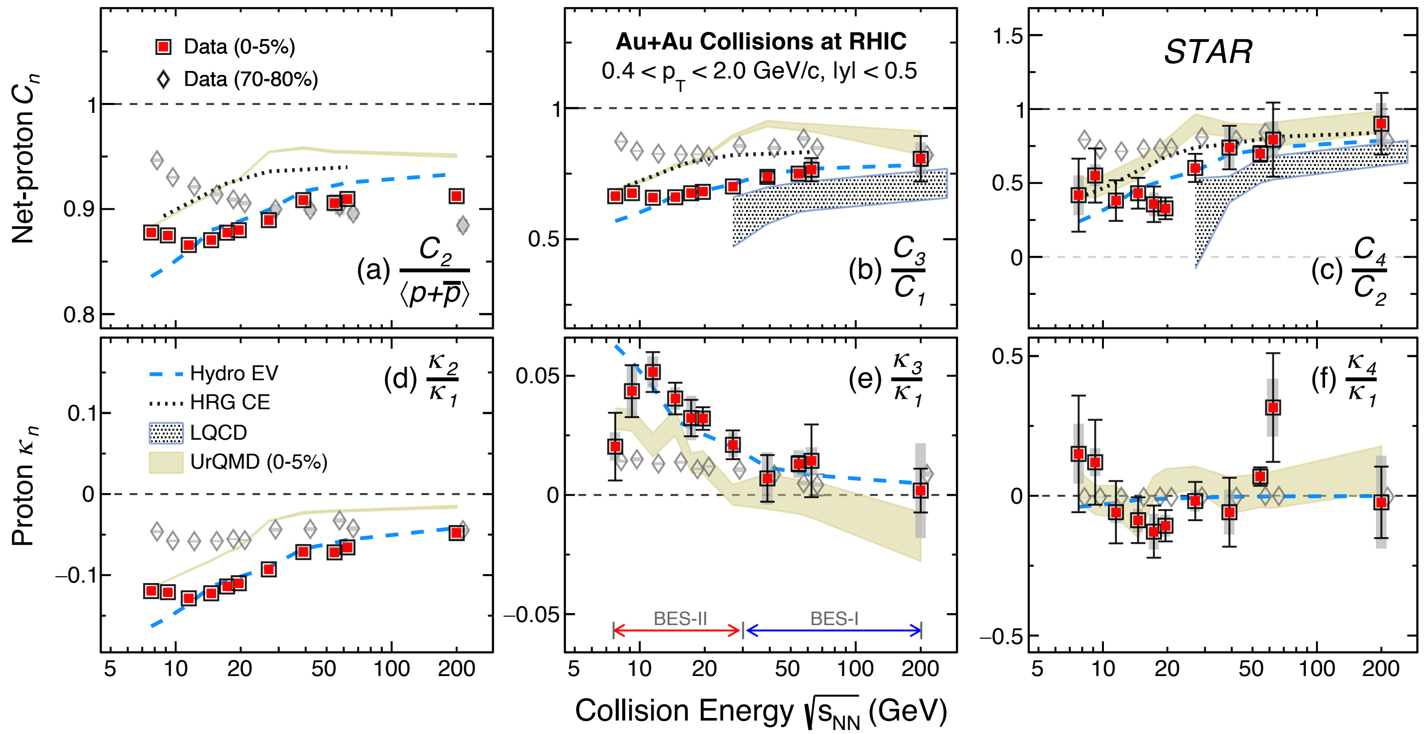
Event-by-Event Net-p Distributions



STAR: Phys.Rev.Lett. **126**, 092301(2021)

Energy Dependence

Au+Au Collisions at RHIC



1) **UrQMD:** (hadronic transport calculations 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, V. Vovchenko *et al.*, Phys. Rev. **C105**, 014904 (2022).

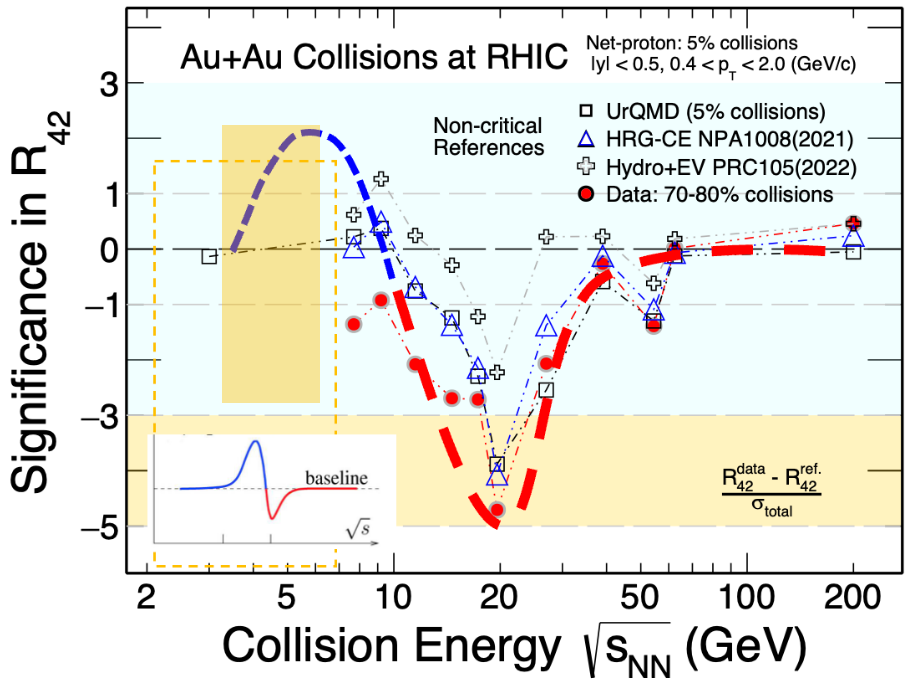
4) **LQCD: (**done for net-baryon) A. Bazavov *et al.*, Phys. Rev. D101, 074502 (2020). arXiv : 2407.09335

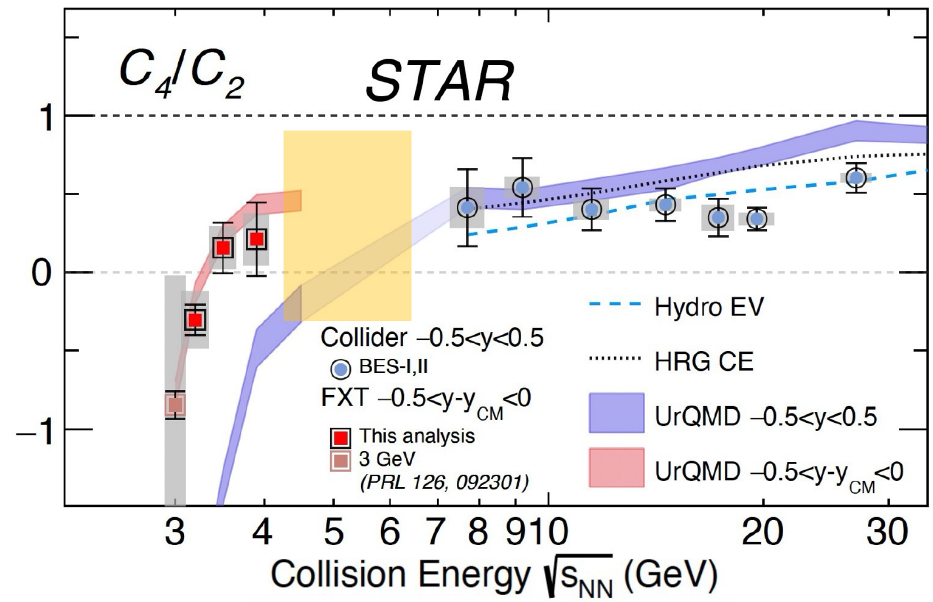
STAR: 2504.00817

1) Results of LQCD and thermal model are consistent with data at high energy;
2) Deviations appear below $\sqrt{s_{NN}} < 35$ GeV

Search for the QCD CEP

0-5% Au+Au Collisions at RHIC

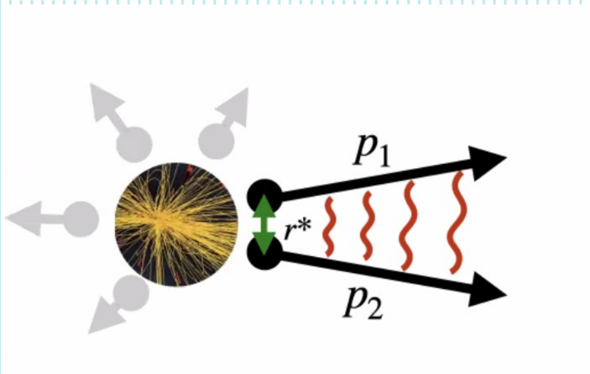




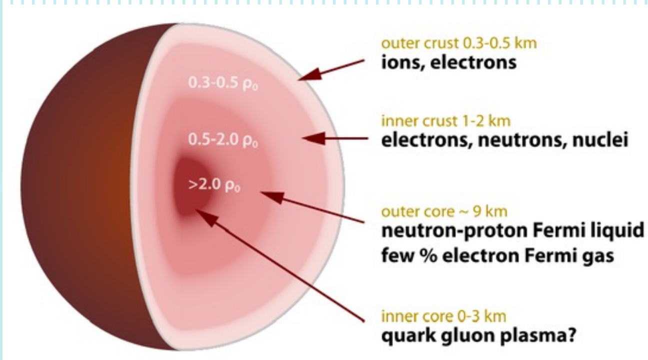
STAR: 2504.00817

1) Experimental results between 3.5 – 8 GeV are crucial;
2) CBM at FAIR will play important role for the search of QCD critical point

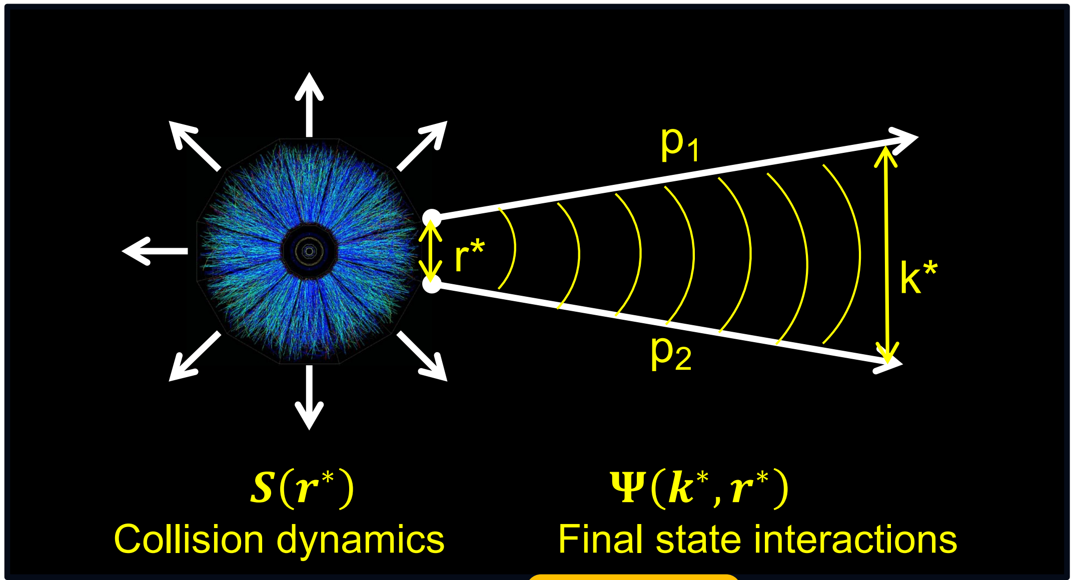
Baryon Correlations



FSI



Baryon Correlation Functions



Source

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

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

STAR:

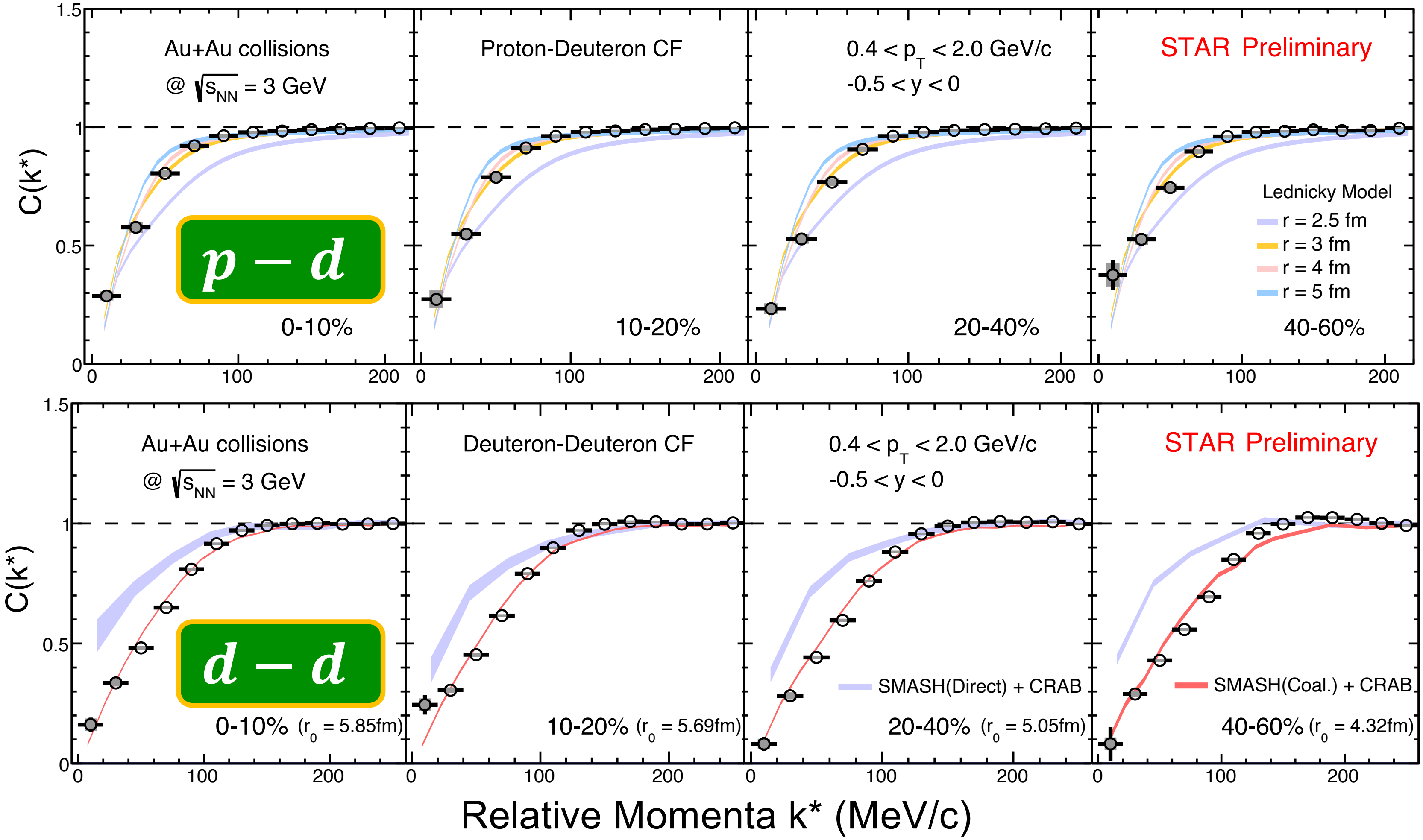
(1) Meson HBT: $\pi - \pi$, $K - K$;

(2) **Baryon Correlations:**

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

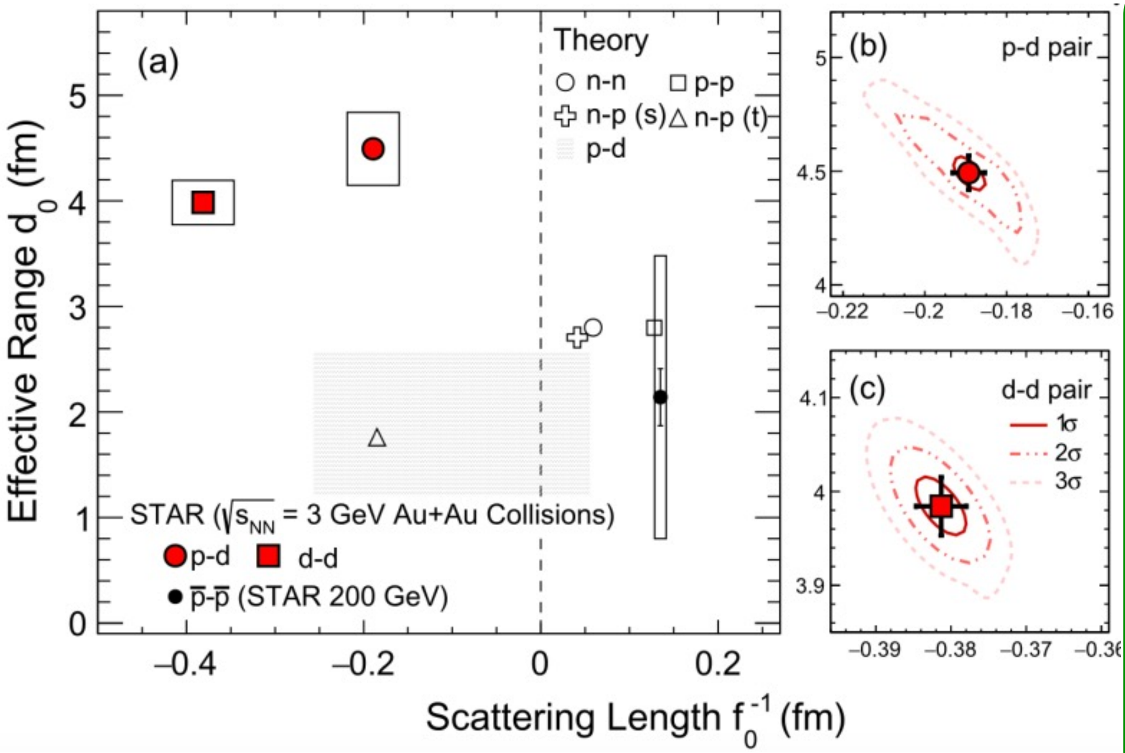
$$C_{exp}(k^*) = \lambda \frac{N_{same}(p_1, p_2)}{N(p_1)N(p_2)}$$

p-d, d-d Correlation Functions



STAR: Phys.Lett. B (2025)

p-d, d-d Correlation Functions

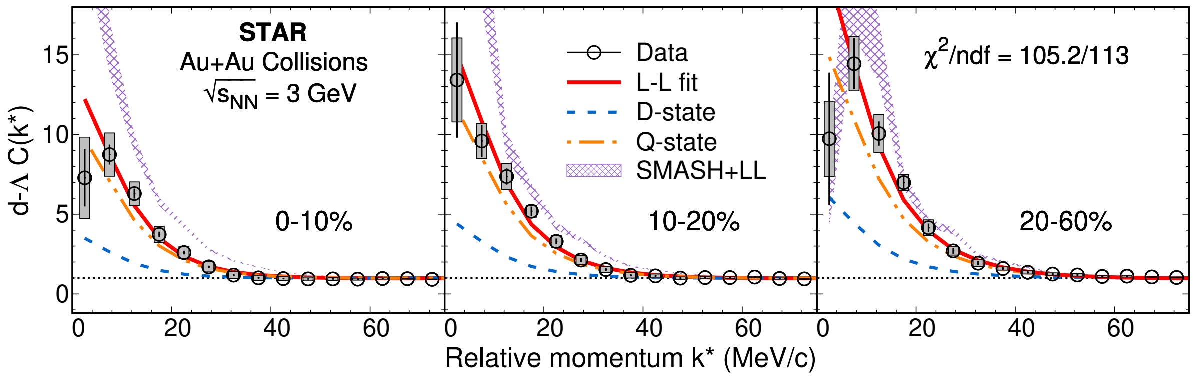


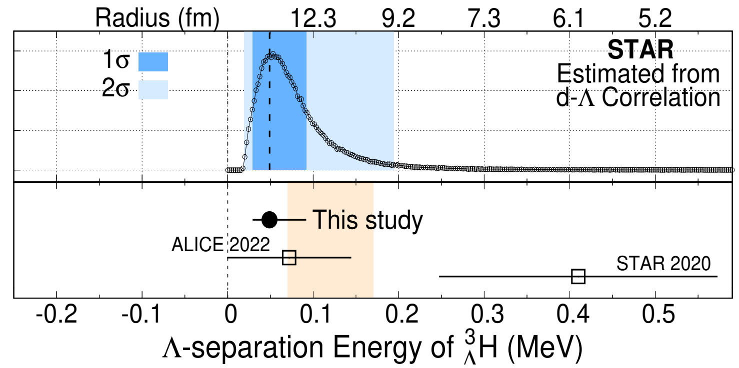
STAR: Phys.Lett.**B864**, 139412 (2025)

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;*

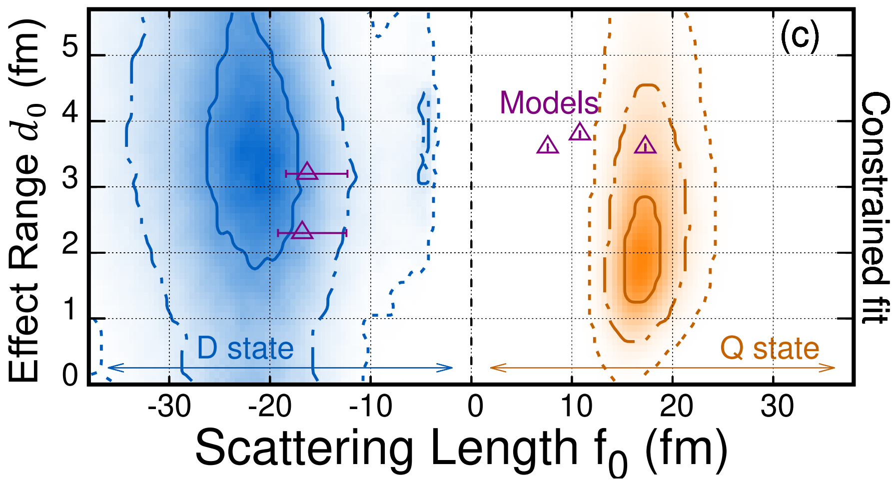
2) LL calculations are used to extract FSI parameters:
   - $f_0 < 0$ is observed
   - *no collision centrality dependence is observed*

$d - \Lambda$ Correlation Functions





STAR: CPOD2024, QM2024



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

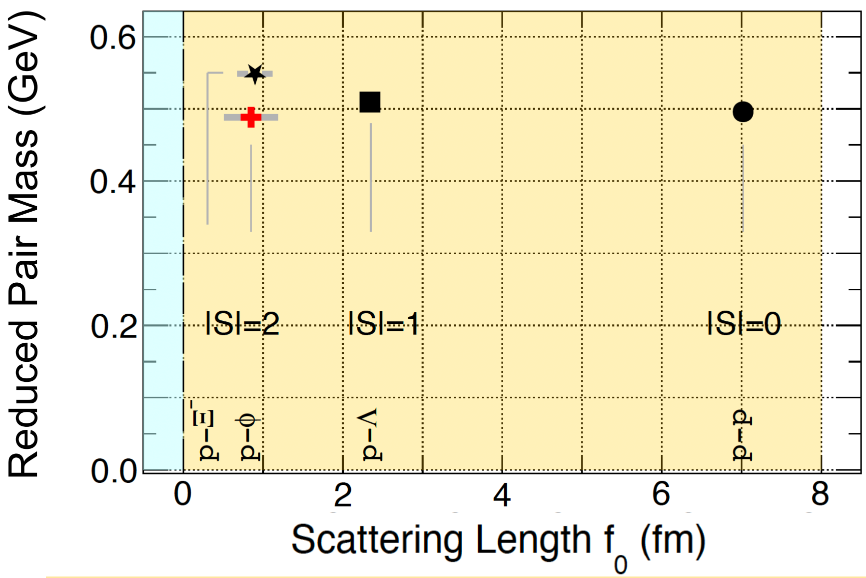
2) For the first time, spin dependent states, *D and Q*, identified experimentally!

→ **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)

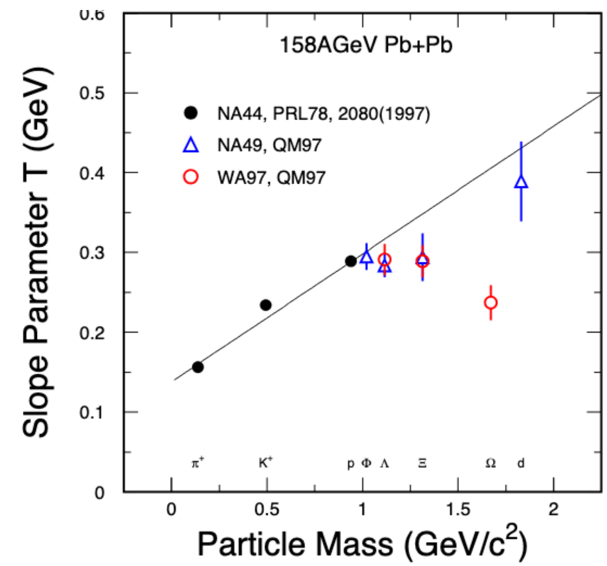
NN, NY, YY Interactions



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

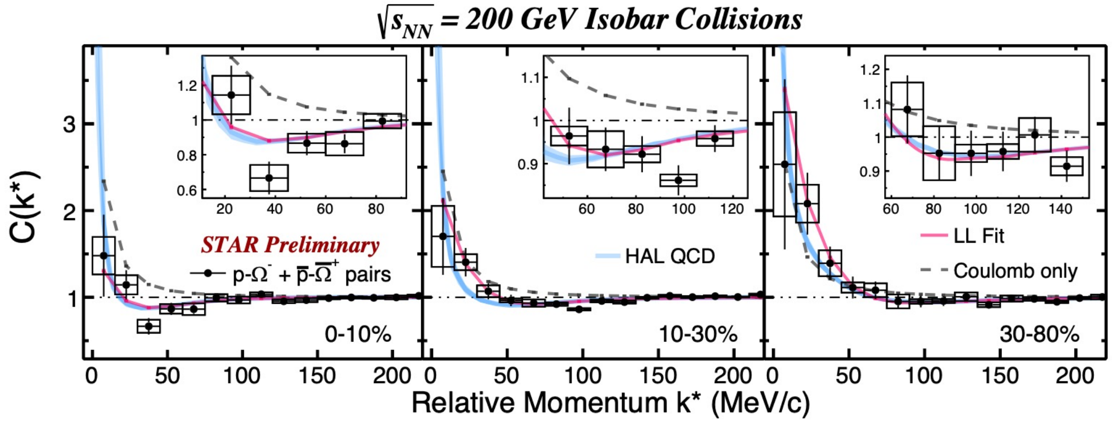


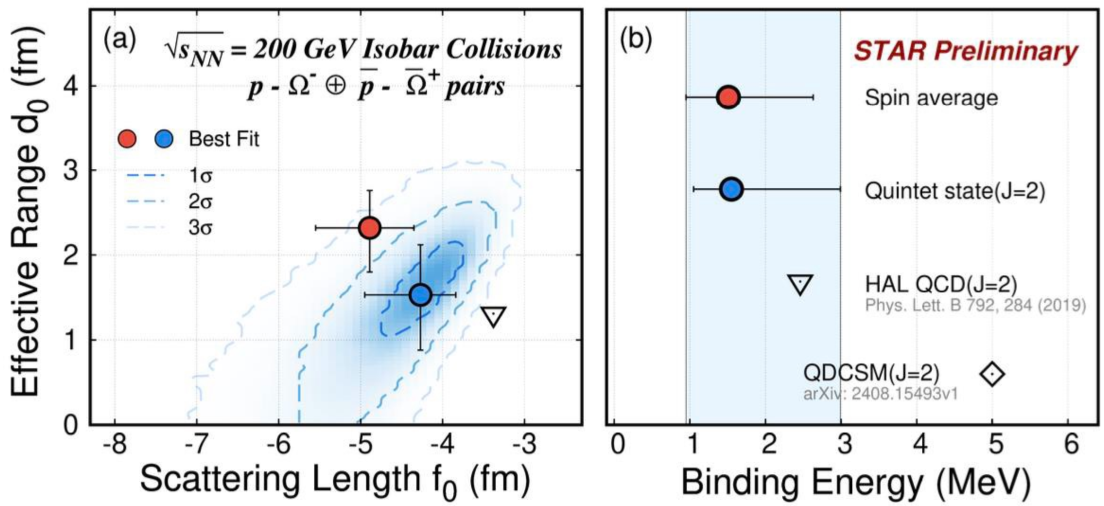
Hierarchy of strangeness content:

$$\boldsymbol{f_0(|s|=0) > f_0(|s|=1) > f_0(|s|=2) > 0}, \quad f_0^2 \propto \sigma_{interaction}$$

- Interaction cross section is proportional to f_0^2. This observation implies that the *strength of the interaction depends on strangeness contents*;
- Understand the strangeness hierarchy in QCD?

Evidence of Strange Dibaryon





1) STAR presents precision results of the $p-\Omega$ correlation functions from 200GeV isobar collisions;
2) Extracted negative f_0 ($|f_0| > 2d_0$) by spin average method and Quintet (J=2) methods. $\mathbf{BE = 1.5^{+1.1}_{-0.6}}$ **MeV**, consistent with that of HAL-QCD prediction;
3) First experimental evidence of the **Strange Dibaryon!**

	Spin ave.	Quintet	HAL QCD
f_0 (fm)	$-4.89^{+0.54}_{-0.66}$	$-4.27^{+0.43}_{-0.68}$	-3.38
d_0 (fm)	$2.32^{+0.44}_{-0.52}$	$1.53^{+0.54}_{-0.66}$	1.31
BE (MeV)	$1.51^{+1.12}_{-0.56}$	$1.55^{+1.44}_{-0.50}$	2.27

STAR: QM2025

et al., Phys. Rev. C 101, 015201 (2020)

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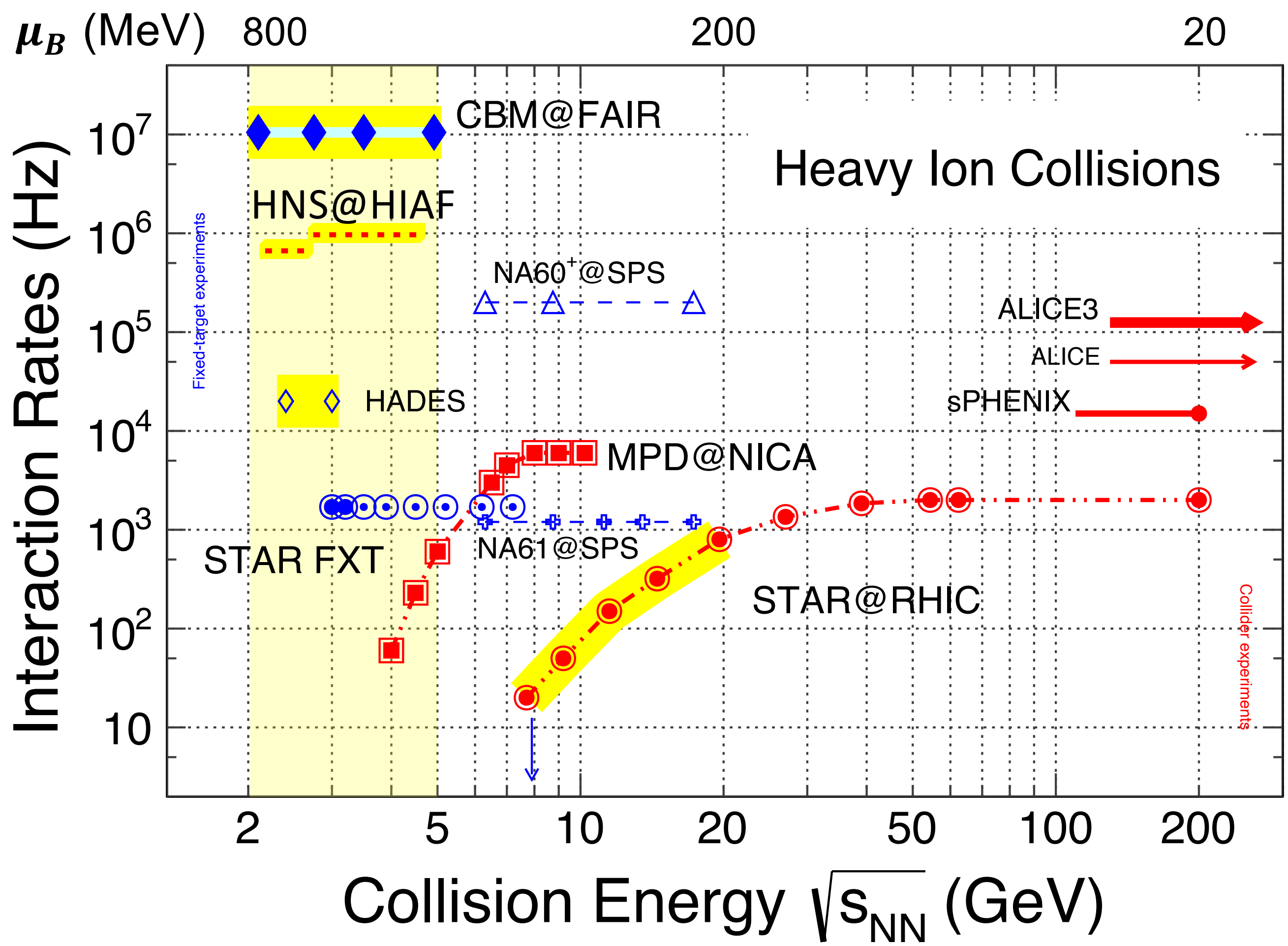
Future High Rates Experiments



HIAF: 2025

FAIR: 2028

ALICE3: 2034

Acknowledgements:

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

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

Thank you for your attention!
Many Thanks to Organizers!