The QCD Medium Properties at Finite Baryon Density

- Search for the QCD Critical Point in HIC

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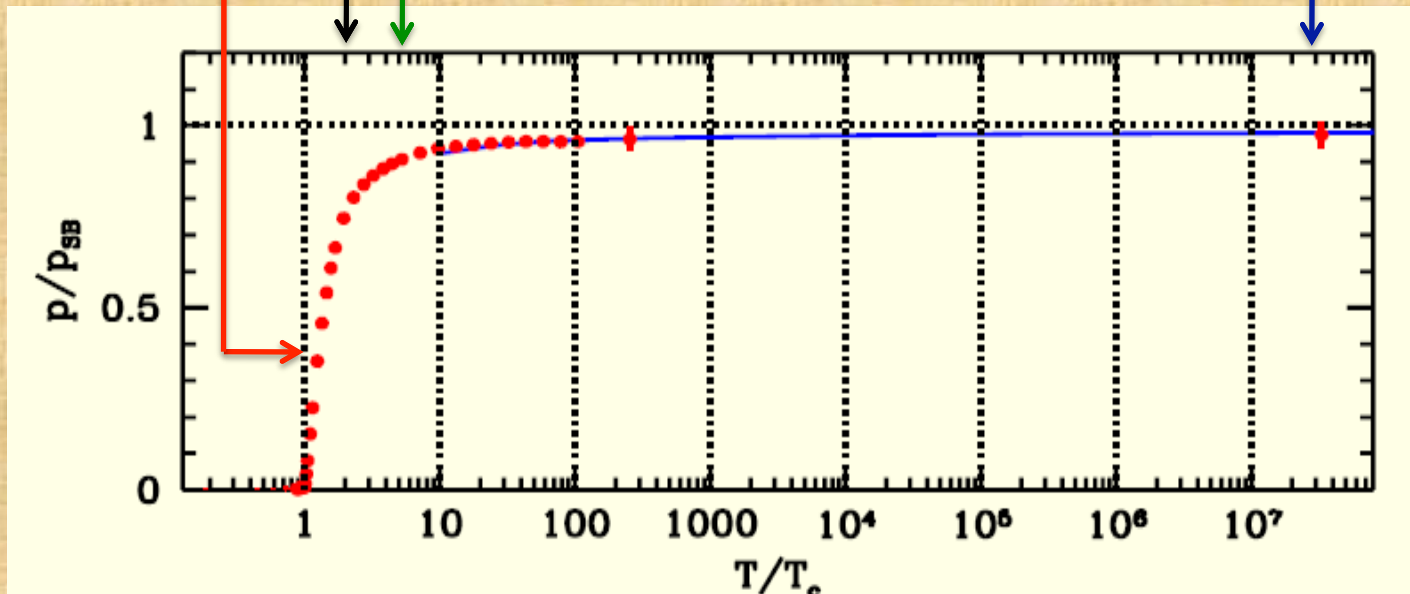
QCD Thermodynamics

CBM&RHIC-BES RHIC LHC SB Ideal Gas



Zoltan Fodor, Lattice 2007

1) At μ_B = *0: smooth* crossover transition, *150 < T_c <170 MeV*
2) The SB ideal gas limit: $T/T_c \sim 10^7$
3) T_{ini}(LHC) ~ 2-3*T_{ini}(RHIC) , RHIC and LHC are similar
4) Dynamic changes at finite μ_B: BES@RHIC and CBM + …

Outline

(1) Introduction

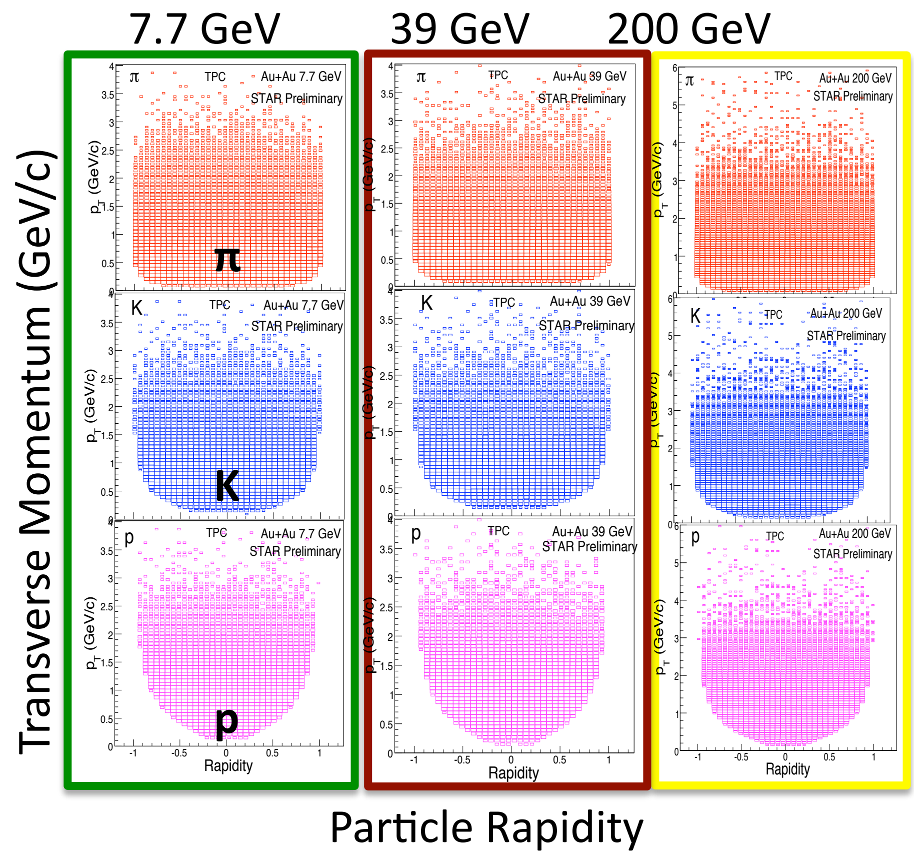
(2) Recent Results from BES-I at RHIC

(i) Collectivity; (ii) Chirality; **(iii) Criticality**

(3) Summary and Outlook

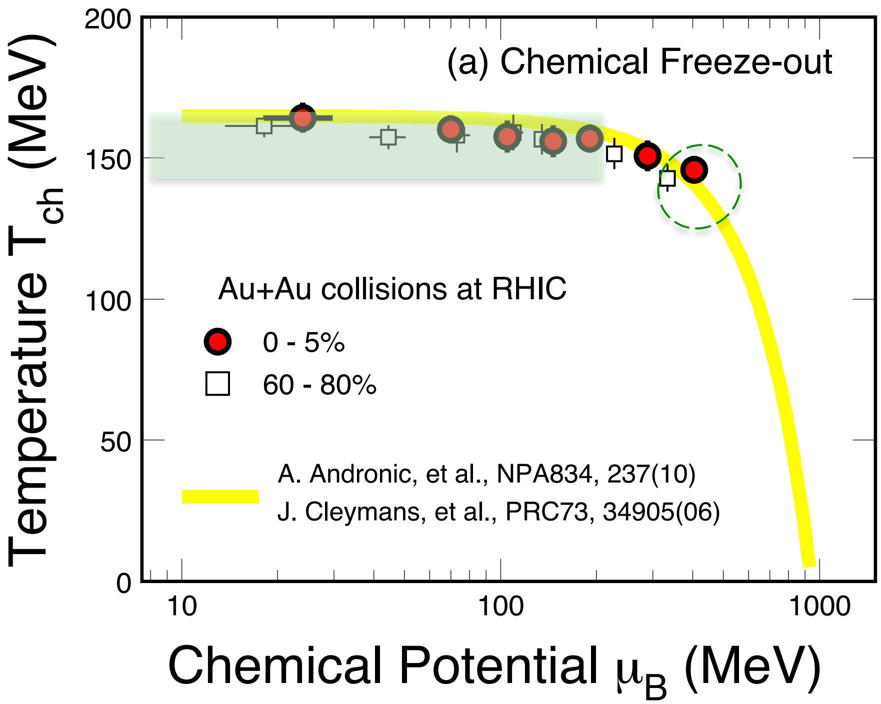
Data Sets for BES-I Program

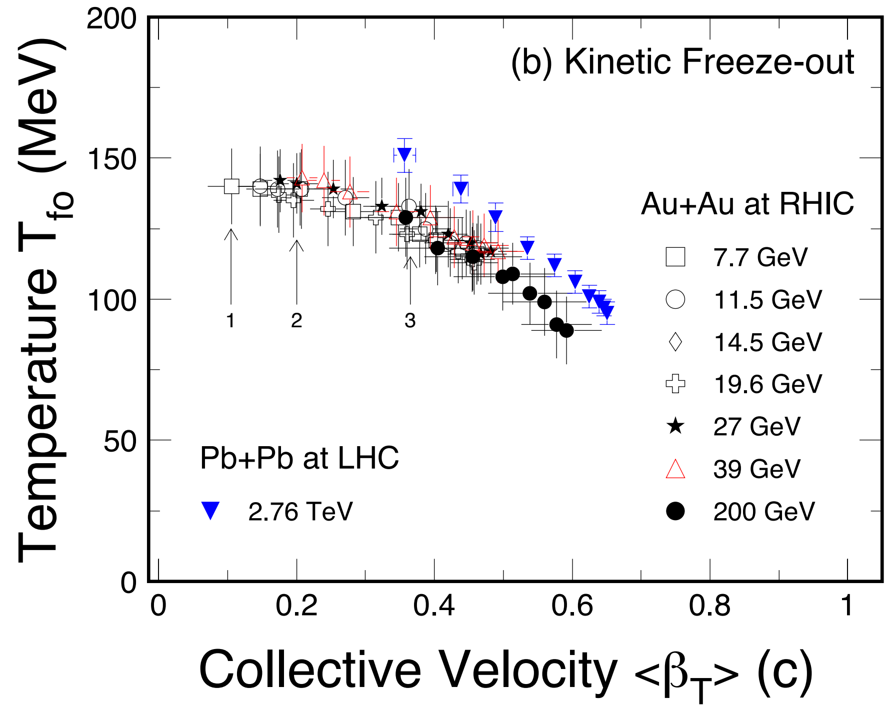
$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	Year
200	350	2010
62.4	67	2010
39	39	2010
27	70	2011
19.6	36	2011
14.5	20	2014
11.5	12	2010
7.7	4	2010



1) Largest data sets versus collision energy
2) STAR: Large and homogeneous acceptance, excellent particle identification capabilities. Especially important for fluctuation analysis

Bulk Properties at Freeze-out



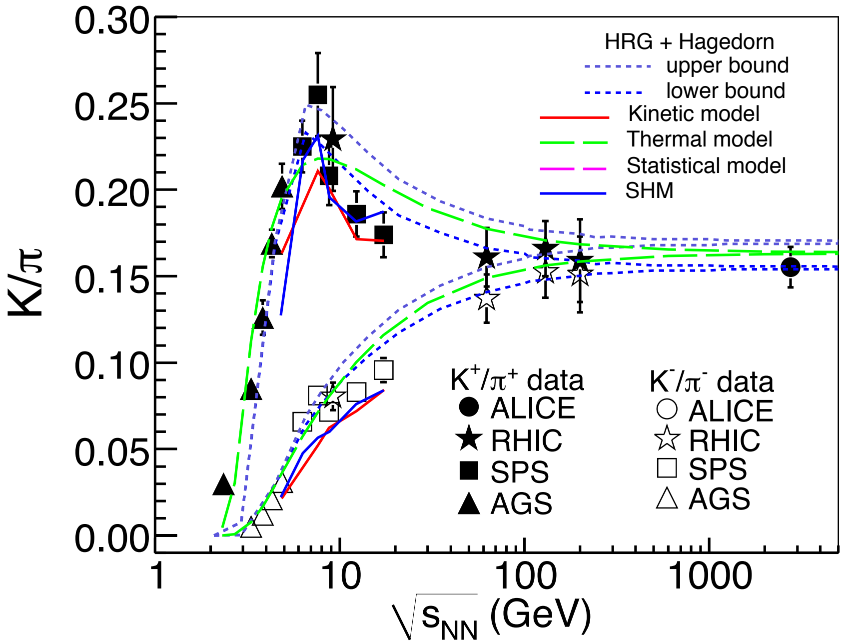


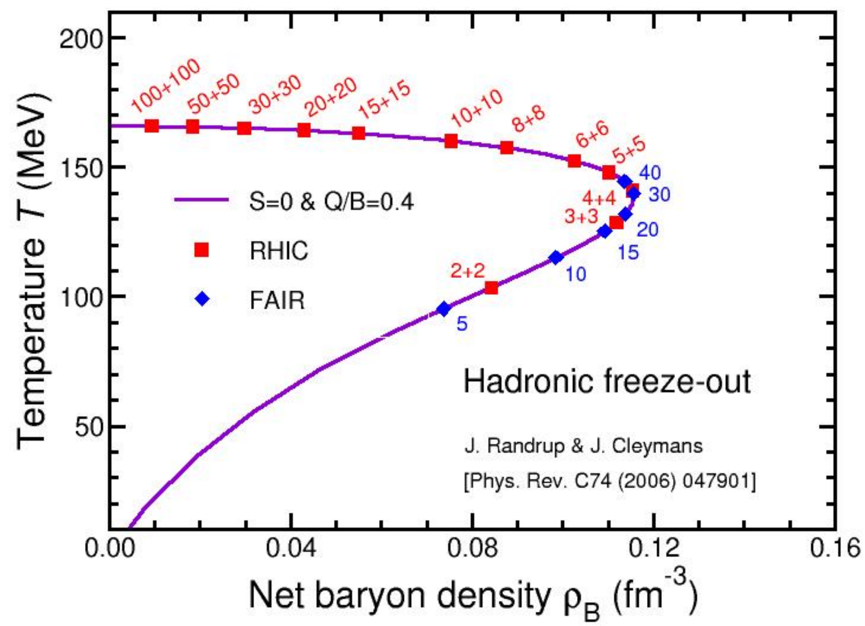
Chemical Freeze-out: (GCE)
- Weak temperature dependence
- Centrality dependence $\boldsymbol{\mu_B}$!
- LGT: **CP about $\mu_B \geq 500$ MeV?**

Kinetic Freeze-out:
- Central collisions => lower value of T_{fo} and larger collectivity β_T
- Stronger collectivity at higher energy, even for peripheral collisions

ALICE: B.Abelev et al., PRL109, 252301(12); PRC88, 044910(2013).
STAR: J. Adams, et al., NPA757, 102(05); X.L. Zhu, NPA931, c1098(14); L. Kumar, NPA931, c1114(14)

K/π Ratios and Baryon Density

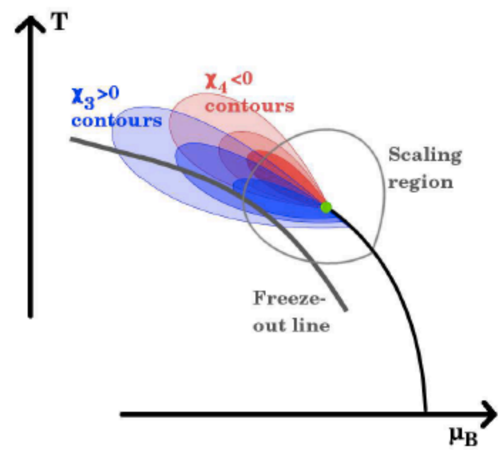




1) In heavy ion collisions **K⁺/π** ratio peaks at √***s***$_{NN}$ ~ 8 GeV, **K⁻/π** ratio merges with **K⁺/π** at higher collision energy
2) Model: Baryon density peaks at √***s***$_{NN}$ ~ 8 GeV
3) **At √*s*$_{NN}$ > 8 GeV, pair production becomes important**

L. Kumar, *et al.*1304.2969; J. Randrup and J. Cleymans, Phys. Rev. **C74**, 047901(2006)

Criticality



Susceptibilities and Moments

Thermodynamic function:

$$\frac{p}{T^4} = \frac{1}{\pi^2}\sum_i d_i (m_i / T)^2 K_2(m_i / T)\cosh[(B_i\mu_B + S_i\mu_S + Q_i\mu_Q)/T]$$

The susceptibility: $T^{n-4}\chi_q^{(n)} = \frac{1}{T^4}\frac{\partial^n}{\partial\left(\mu_q/T\right)^n} P\left(\frac{T}{T_C},\frac{\mu_q}{T}\right)\Big|_{T/T_C}, \qquad q = B,Q,S$

$$\chi_q^{(1)} = \frac{1}{VT^3}\left\langle \delta N_q \right\rangle$$

$$\chi_q^{(2)} = \frac{1}{VT^3}\left\langle \left(\delta N_q\right)^2 \right\rangle$$

$$\chi_q^{(3)} = \frac{1}{VT^3}\left\langle \left(\delta N_q\right)^3 \right\rangle$$

$$\chi_q^{(4)} = \frac{1}{VT^3}\left(\left\langle \left(\delta N_q\right)^4 \right\rangle - 3\left\langle \left(\delta N_q\right)^2 \right\rangle^2\right)$$

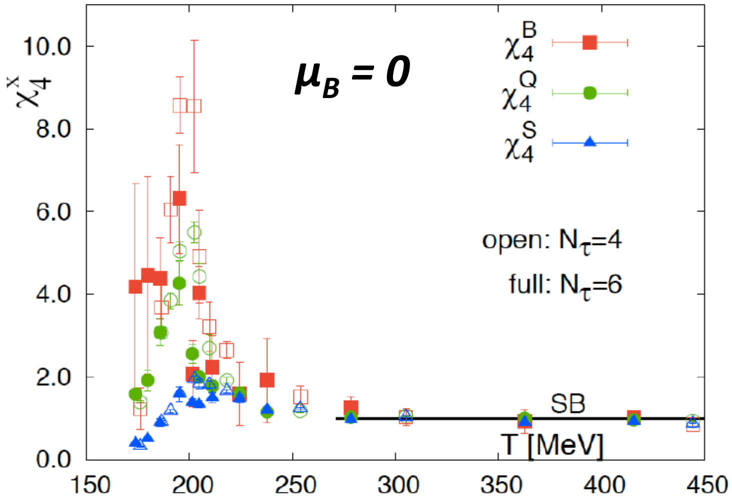
$$\frac{T^2\chi_q^{(4)}}{\chi_q^{(2)}} = \kappa\sigma^2$$

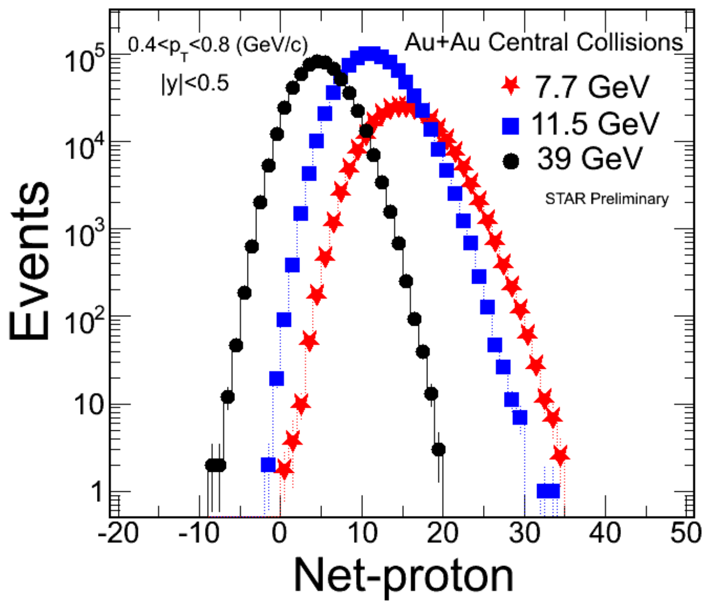
$$\frac{T\,\chi_q^{(3)}}{\chi_q^{(2)}} = S\sigma$$

Thermodynamic function ⇔ Susceptibility ⇔ Moments

Model calculations, *e.g.* LGT, HRG ⇔ Measurements

Higher Moments and Criticality





1) Higher moments of conserved quantum numbers: ***Q, S, B***, in high-energy nuclear collisions

2) Sensitive to critical point (ξ correlation length):

$$\left\langle (\delta N)^2 \right\rangle \approx \xi^2, \ \left\langle (\delta N)^3 \right\rangle \approx \xi^{4.5}, \ \left\langle (\delta N)^4 \right\rangle \approx \xi^7$$

3) Direct comparison with calculations at any order:

$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

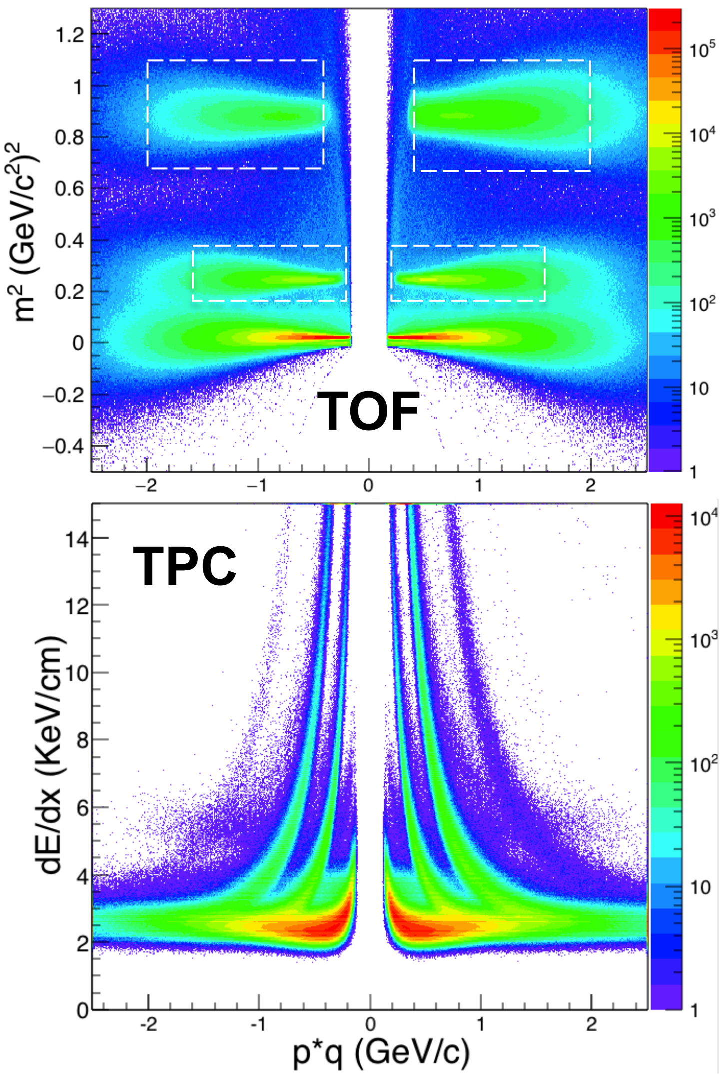
4) **Extract susceptibilities and freeze-out temperature**. An independent/important test of thermal equilibrium in heavy ion collisions.

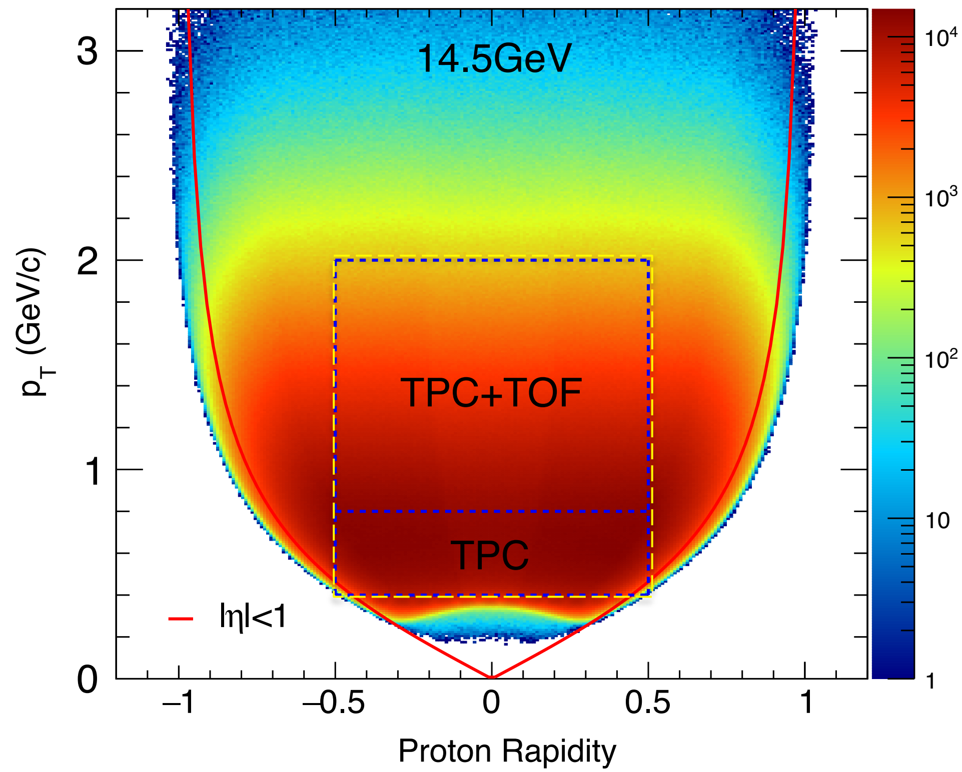
References:

- STAR: *PRL* **105**, 22303(10); *ibid*, **112**, 032302(14)
- S. Ejiri, F. Karsch, K. Redlich, *PLB633*, 275(06) // M. Stephanov: *PRL*102, 032301(09) // R.V. Gavai and S. Gupta, *PLB696*, 459(11) // F. Karsch et al, *PLB695*, 136(11),
- A. Bazavov et al., PRL109, 192302(12) // S. Borsanyi et al., PRL111, 062005(13) // V. Skokov et al., PRC88, 034901(13)
- PBM, A. Rustamov, J. Stachel, arXiv:1612.00702

Proton Identification with TOF

Published net-proton results: Only TPC used for proton/anti-proton PID. TOF PID extends the phase space coverage.





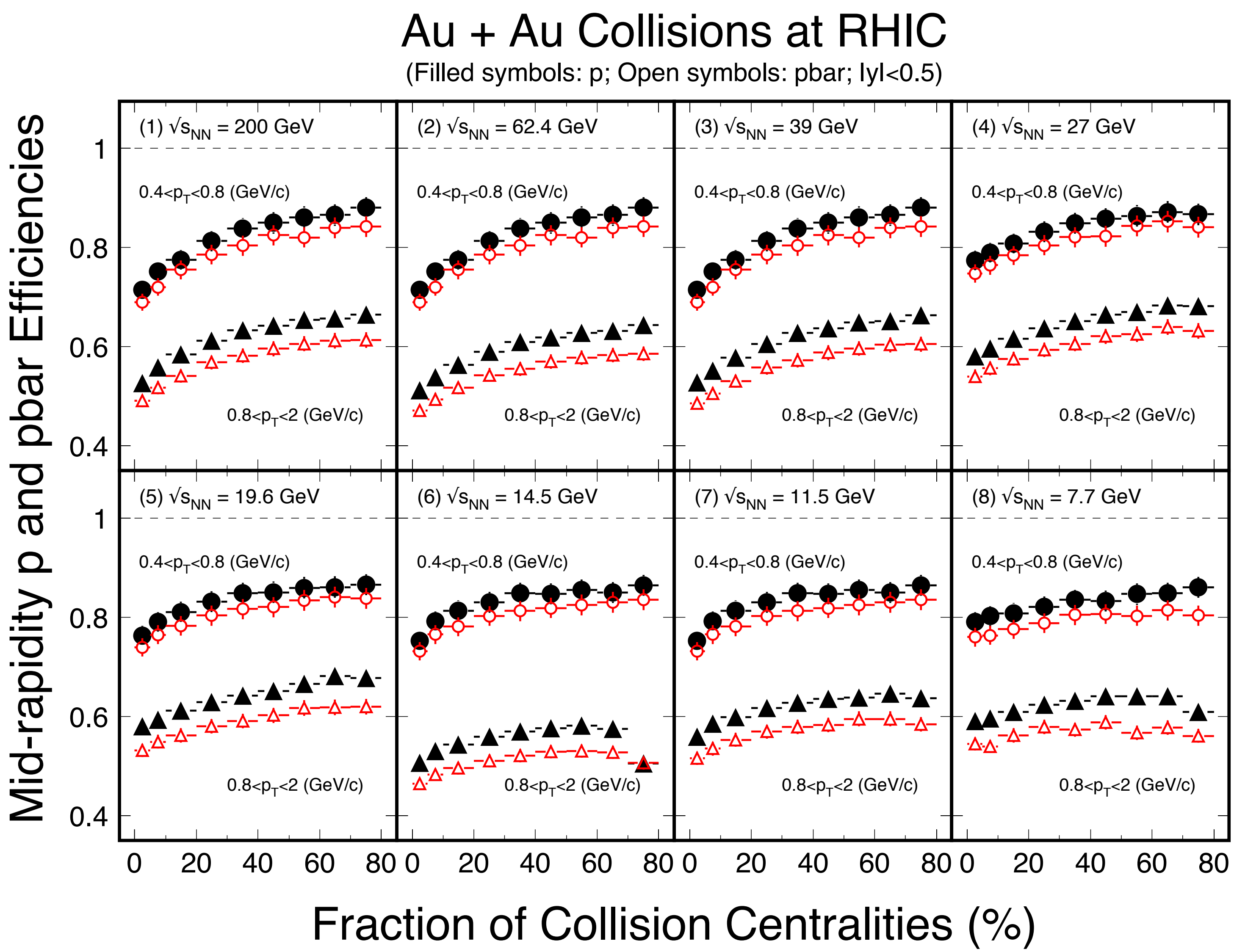
Acceptance: $|y| \leq 0.5$, $0.4 \leq p_T \leq 2$ GeV/c

Efficiency corrections:

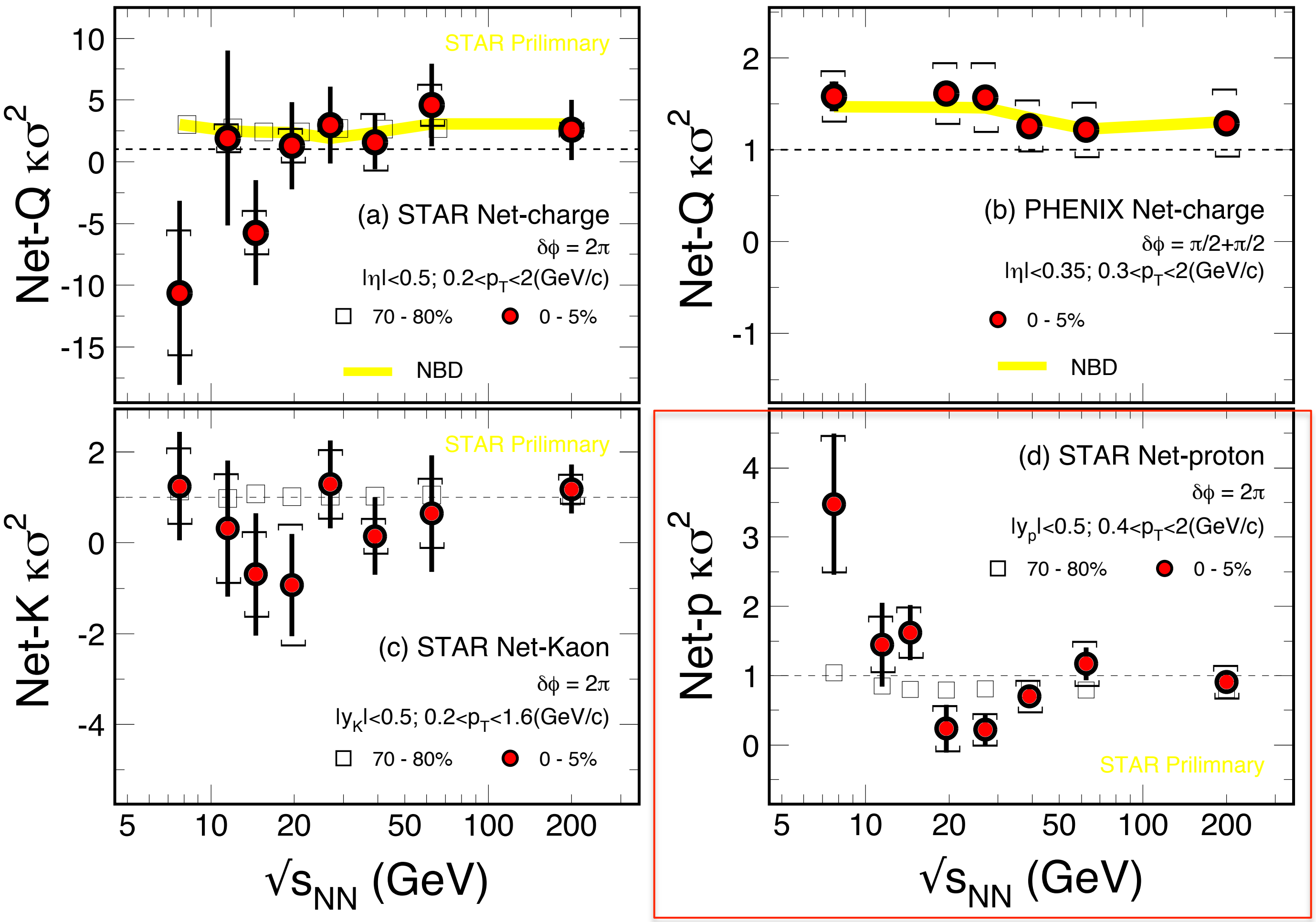
TPC ($0.4 \leq p_T \leq 0.8$ GeV/c): **$\varepsilon_{TPC} \sim 0.8$**

TPC+TOF ($0.8 \leq p_T \leq 2$ GeV/c): **$\varepsilon_{TPC} * \varepsilon_{TOF} \sim 0.5$**

Efficiency Corrections



Higher Moments of Net-Q, -K, -p



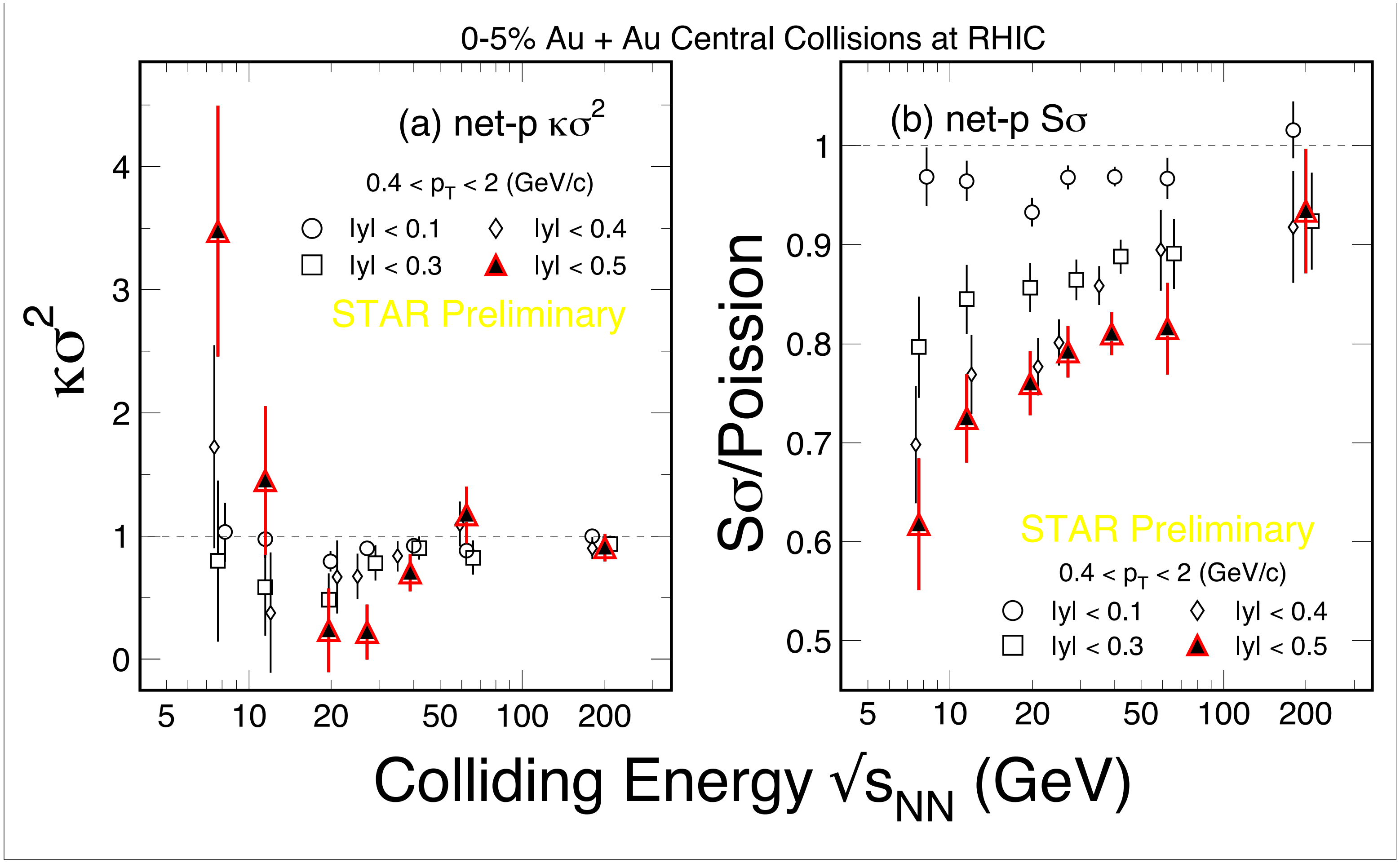
$$error(\kappa * \sigma^2) \propto \frac{1}{\sqrt{N}} \frac{\sigma^2}{\varepsilon^2}$$

In STAR:

σ(Q) > σ(K) > σ(p)

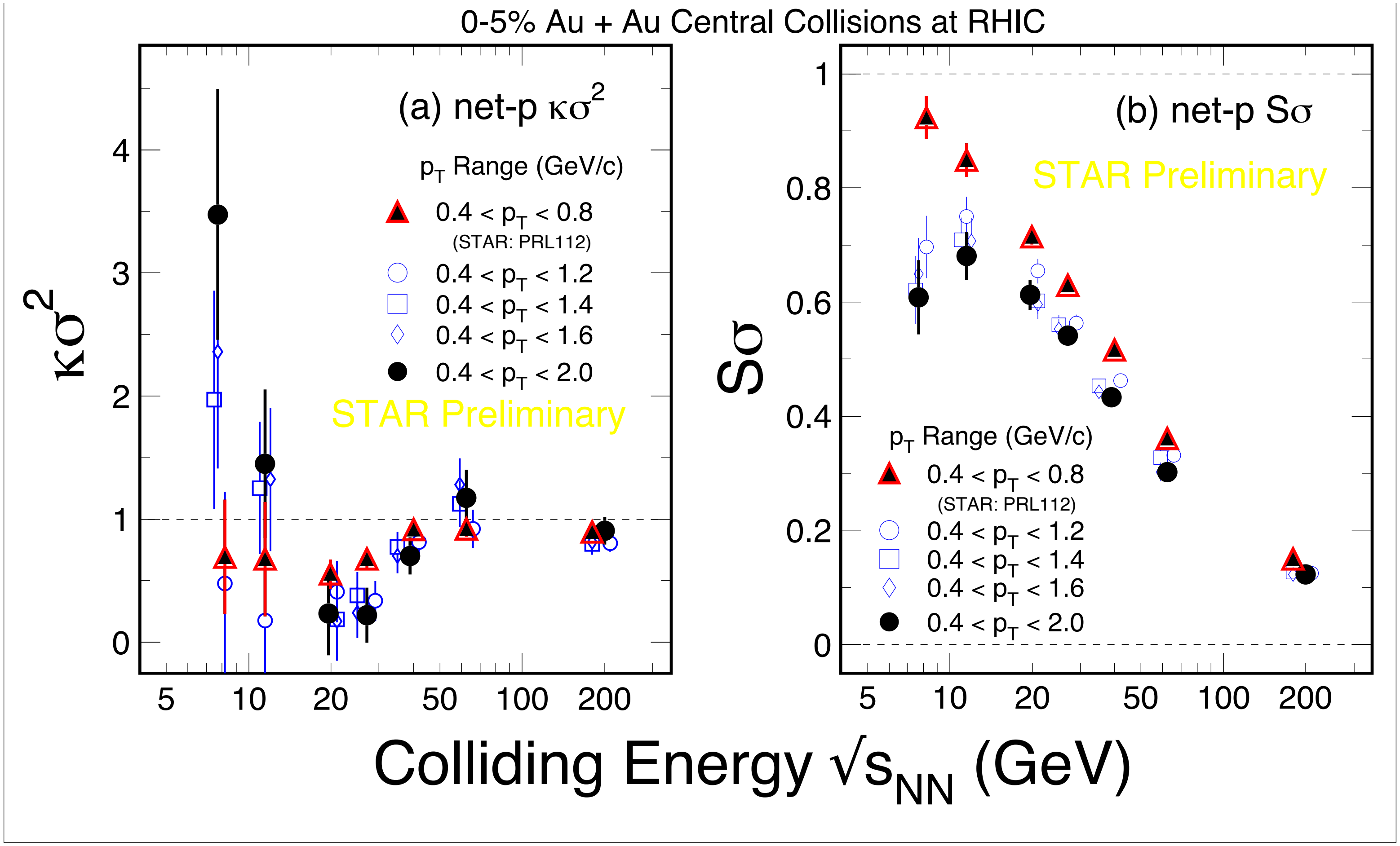
1) The results of net-Q and net-Kaon show flat energy dependence.
2) Net-p shows **non-monotonic energy dependence** in the most central Au+Au collisions starting at $\sqrt{s_{NN}}$ < 27 GeV!

Rapidity Dependence



Sensitive to rapidity coverage!

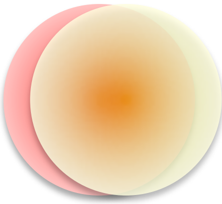
Transverse Momentum Dependence

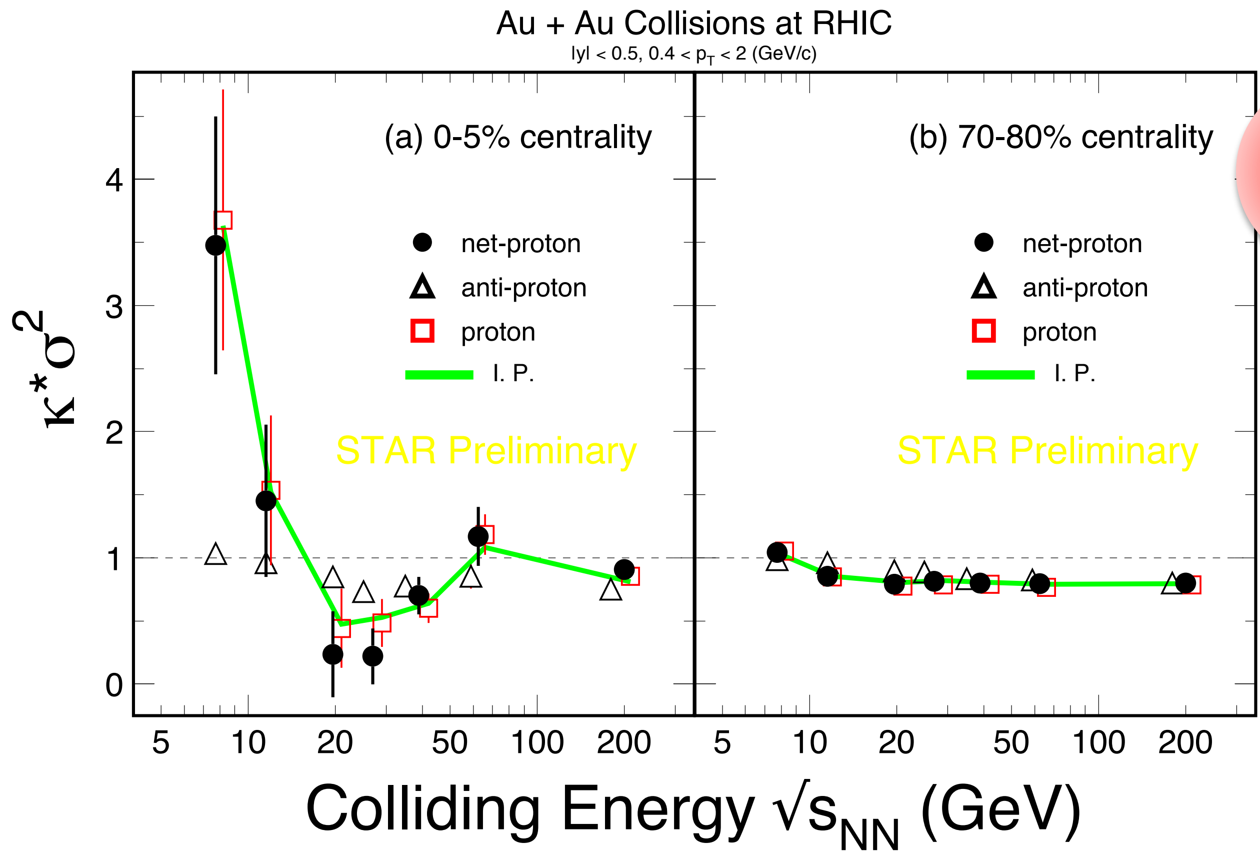


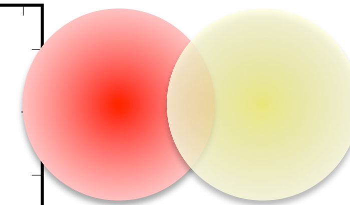
Sensitive to p_T coverage!

Phase space coverage is important!!!

Net-proton Higher Moment



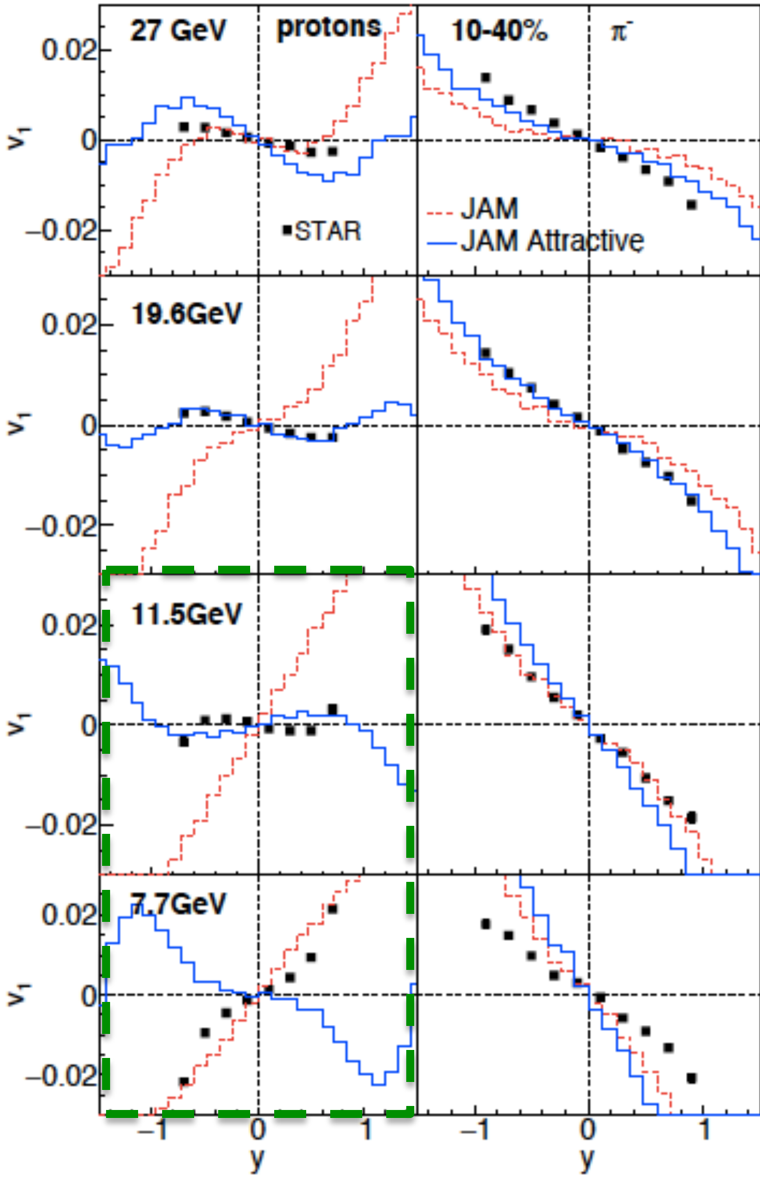


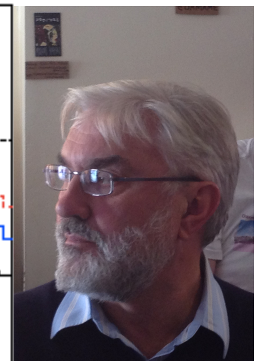


1) Flat energy dependence for 70-80% peripheral collisions
2) Non-monotonic behavior in the most central 0-5%, and 5-10% collisions. Net-p follow protons, especially at lower collision energies

X.F. Luo, CPOD2014, QM2015

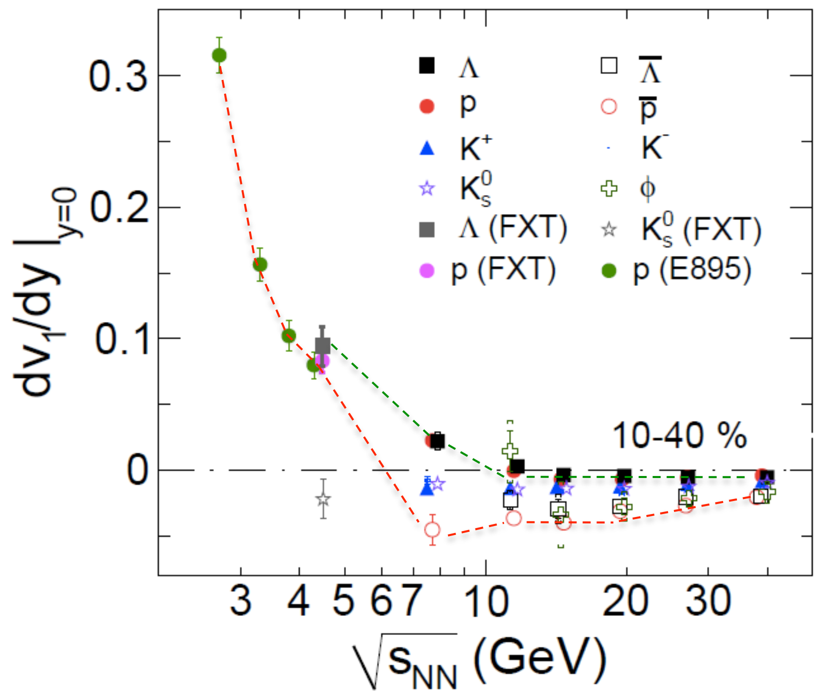
v_1 vs. Energy: Softest Point?





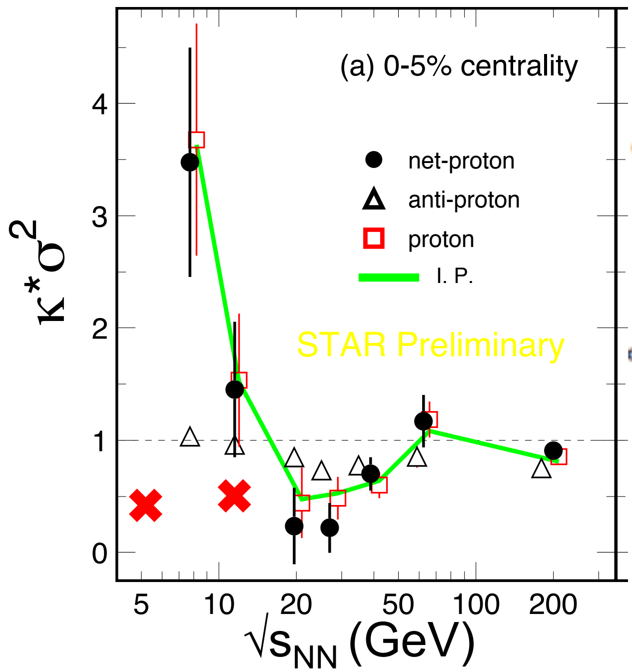
"Attractive force" ➔
Change of the EOS
~ "softest point"

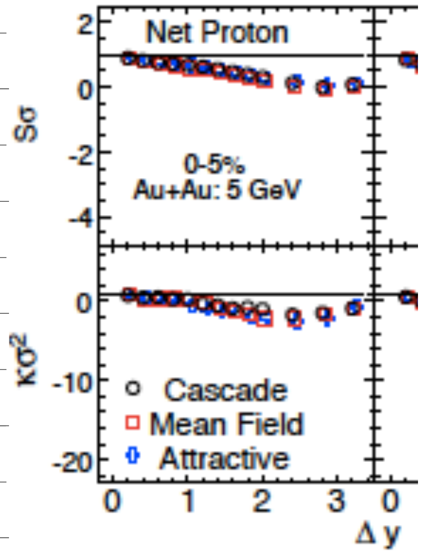
- Y. Nara, A. Ohnishi, H. Stoecker,
  arXiv: **1601.07692** ; PRC94, 034906(2016)

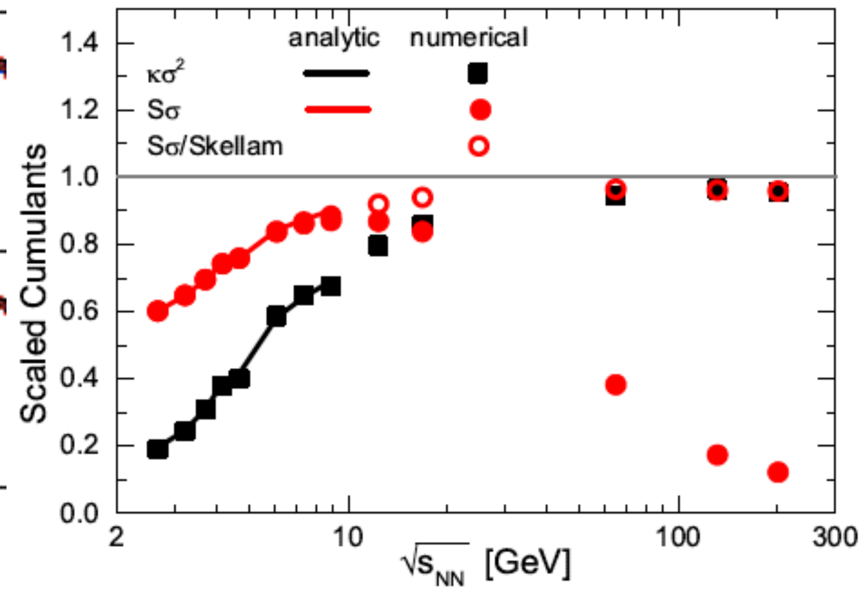


Kathryn Meehan, QM2017

All Model Are Wrong!







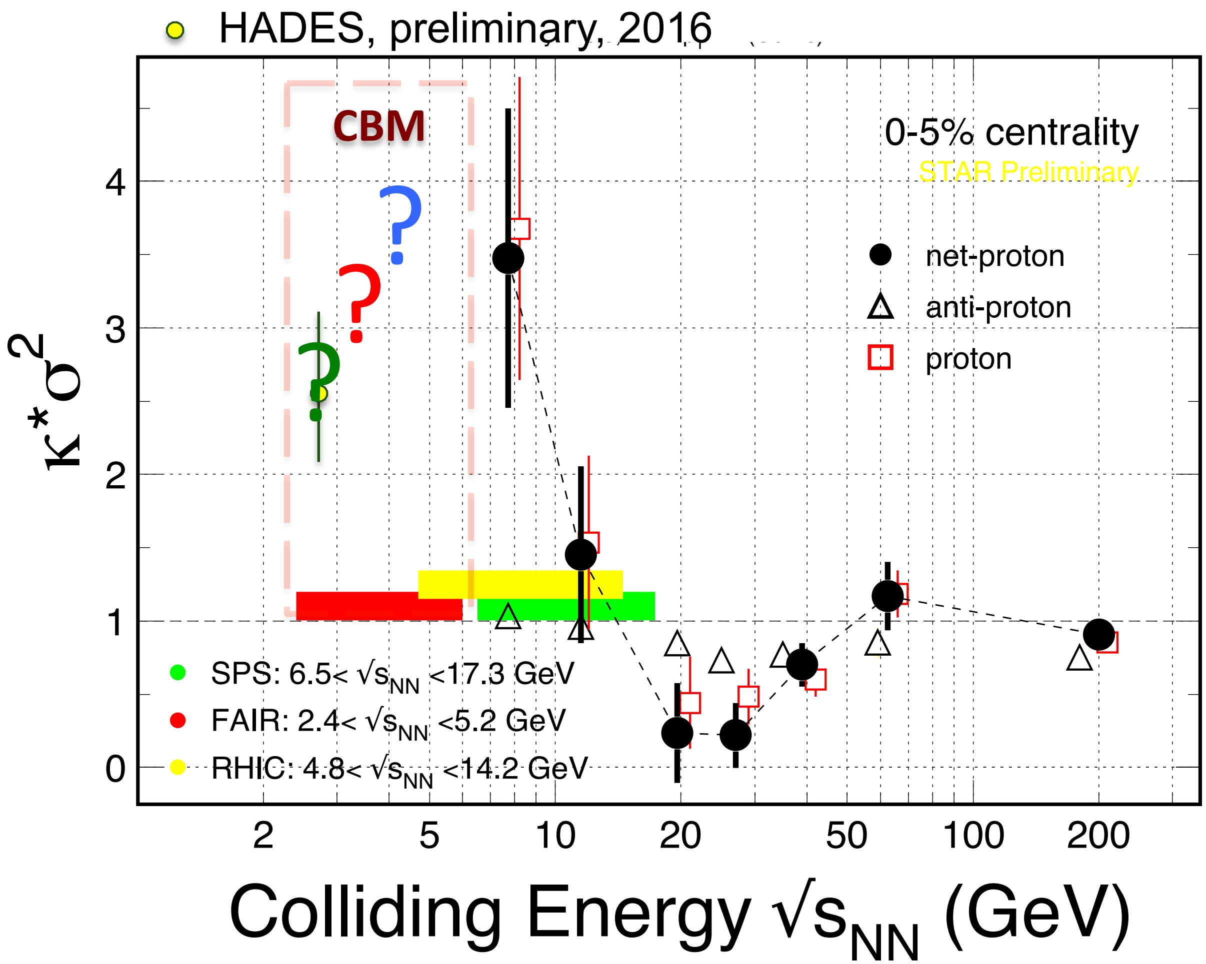
At $\sqrt{s_{NN}} \leq 10$ GeV: Data: **$\kappa\sigma^2 > 1$!** Model: **$\kappa\sigma^2 < 1$!**

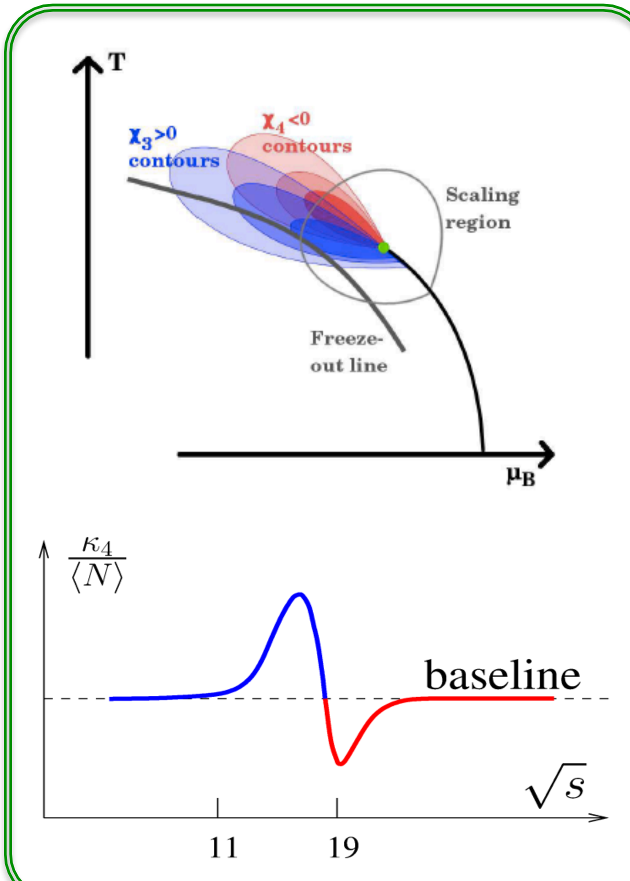
*All models: **suppress higher order net-proton fluctuations***

(UrQMD, AMPT, HRG and JAM do not reproduce data)

1) Z. Feckova, J. Steonheimer, B. Tomasik, M. Bleicher, 1510.05519, PR**C92**, 064908(15)
2) X.F. Luo *et al*, NP **A931**, 808(14)
3) P.K. Netrakanti *et al.* 1405.4617, NP **A947**, 248(16)
4) P. Garg *et al.* Phys. Lett. **B726**, 691(13)
5) Baryon mean-field (**attractive**): Shu He et al., 1607.07276

Search at Large μ_B is Critical





CBM/HADES Experiment (2.5 < $\sqrt{s_{NN}}$ < 8 GeV) :

Key region for CP search

STAR Data: X.F. Luo et al, PRL**112** (2014) 32302; X.F. Luo, PoS(CPOD14)019; QM plenary (15)

Summary (CP)

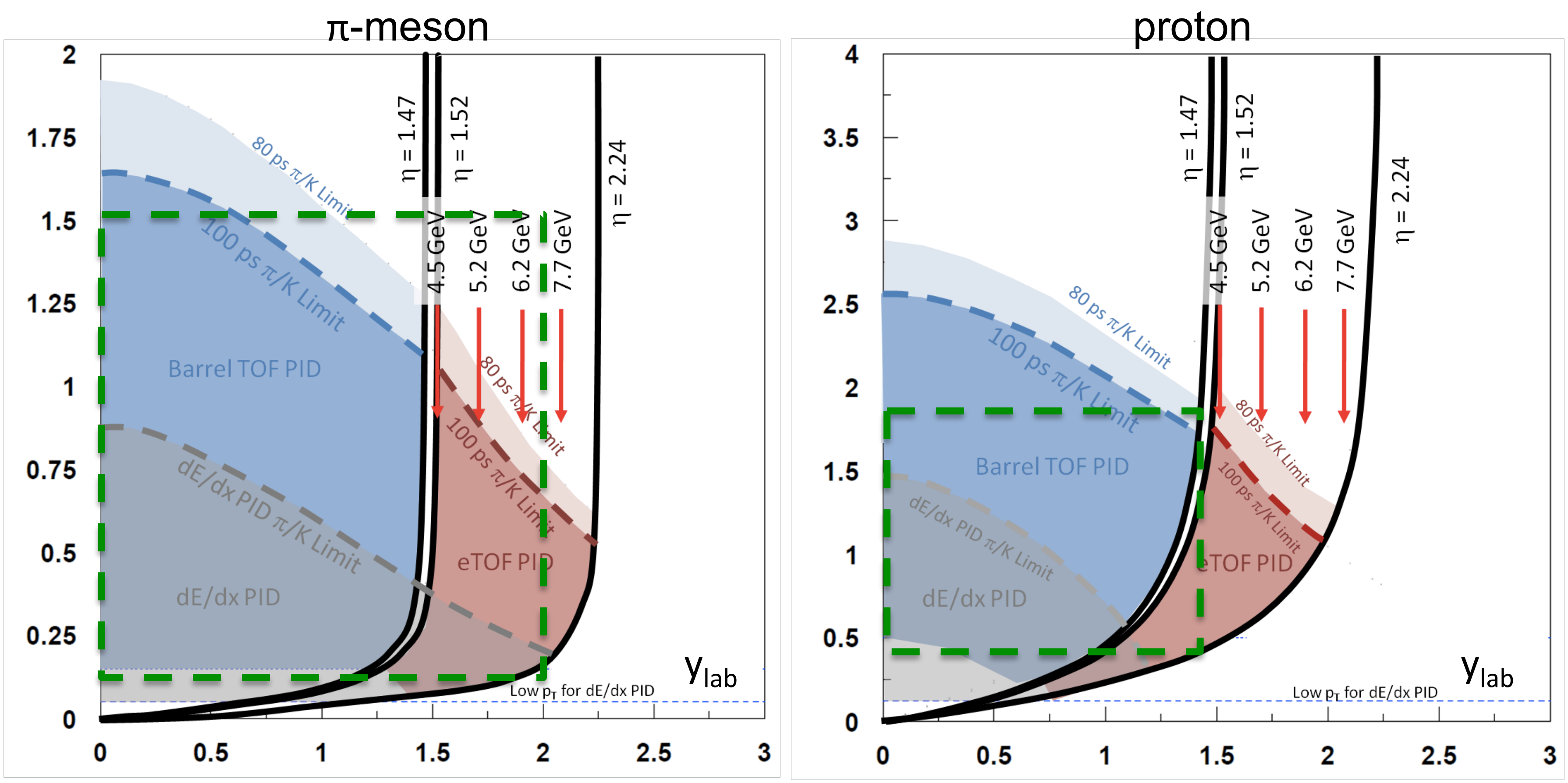
1) Below $\sqrt{s_{NN}}$ ~ 15 GeV the slope of net-p $v_1 > 0$ implies repulsive interactions. But, net-p Kurtosis > 1, indicating attractive force.

2) No model can reproduce both results. Especially, all predictions show suppression for net-p κ.

3) BES-II at RHIC: reduce error bars.

4) FTX experiments needed to 'contain' the possible critical region below $\sqrt{s_{NN}}$ ~ 8 GeV.

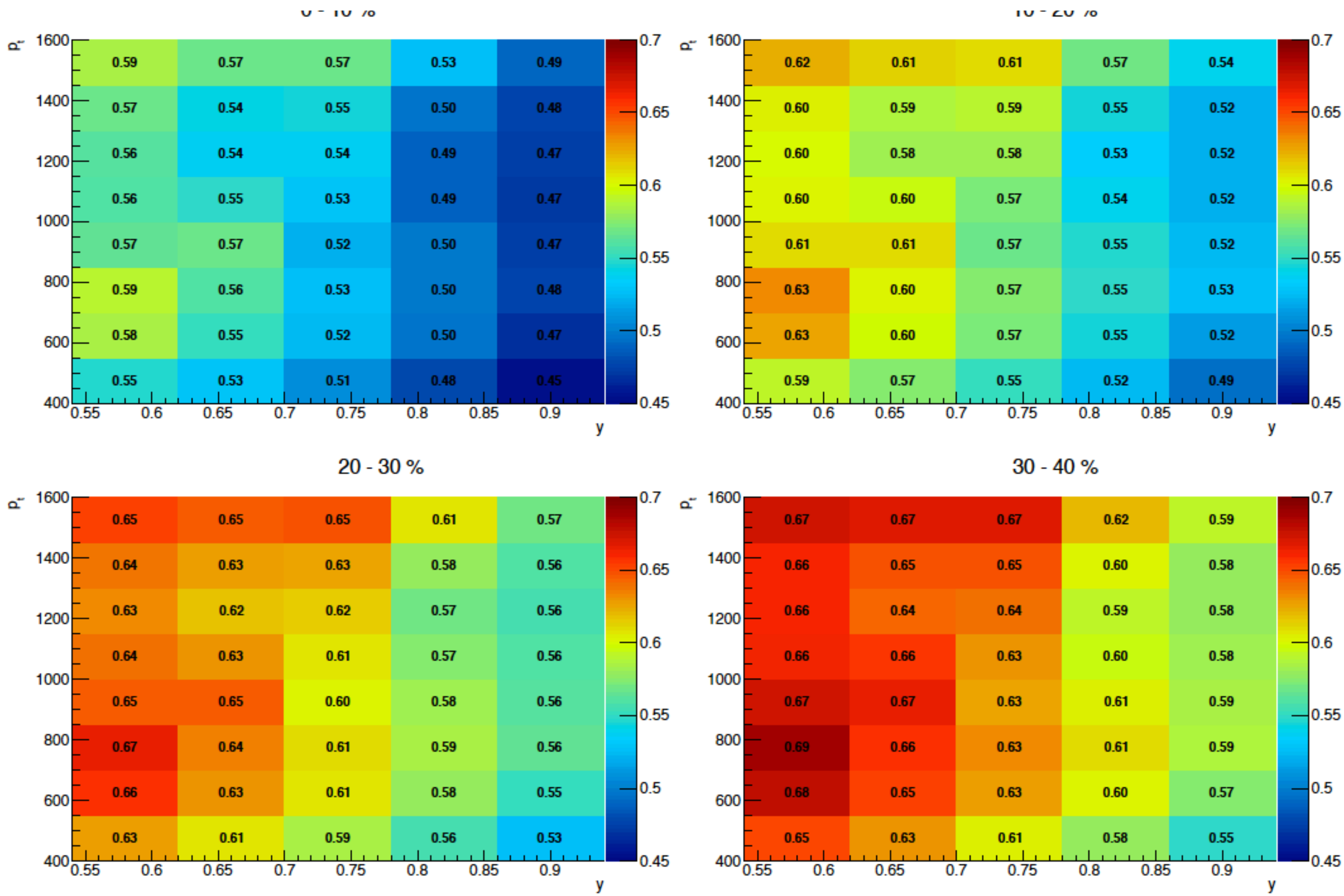
FXT-STAR Acceptances (Kathryn Meehan, Mar. 2017)



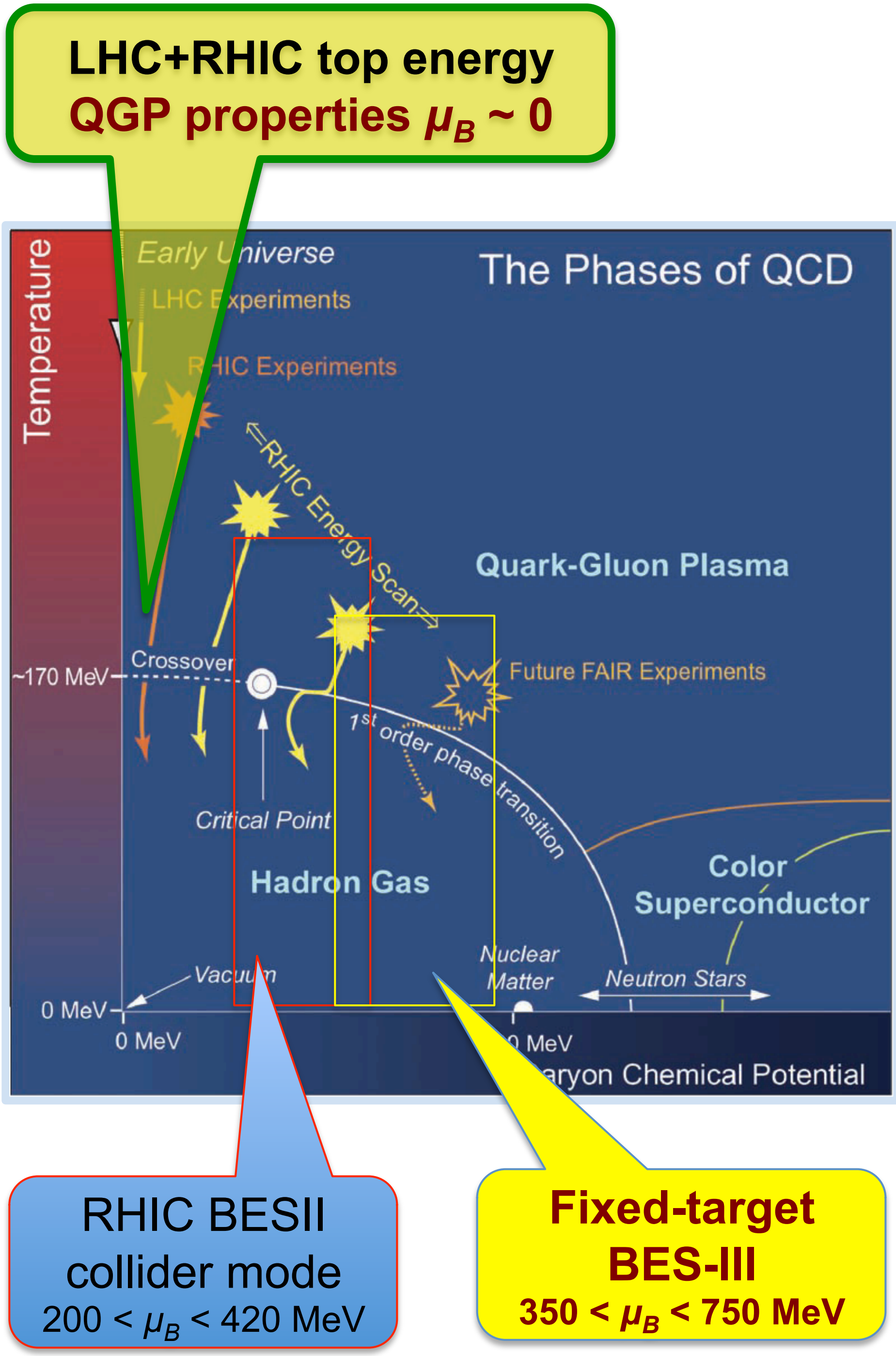
1) FXT coverage is diferent from that of collider mode
2) Need careful studies: acceptance & efficiency in the FXT program for the fluctuation analysis

HADES: Au+Au Collisions at $\sqrt{s_{NN}}$ = 2.4 GeV

Manuel Lorenz



Z-Axis: Efficiency and Acceptance for Protons



Outlook

BES-III ($350 < \mu_B < 750$ MeV, $2 < \sqrt{s_{NN}} < 8$ GeV)

FXT experiments at large net-baryon density

- **Correlation of baryons**:
  - nucleon v_1
  - high moments, light nuclei
- **Strangeness production**:
  - ϕ/K ratios
  - spectra and v_2 of ϕ-meson

➔ **Phase boundary**

➔ **QCD Critical Region**

Thank you!

GO BES-III !!!