Hadron Results from the RHIC Beam Energy Scan

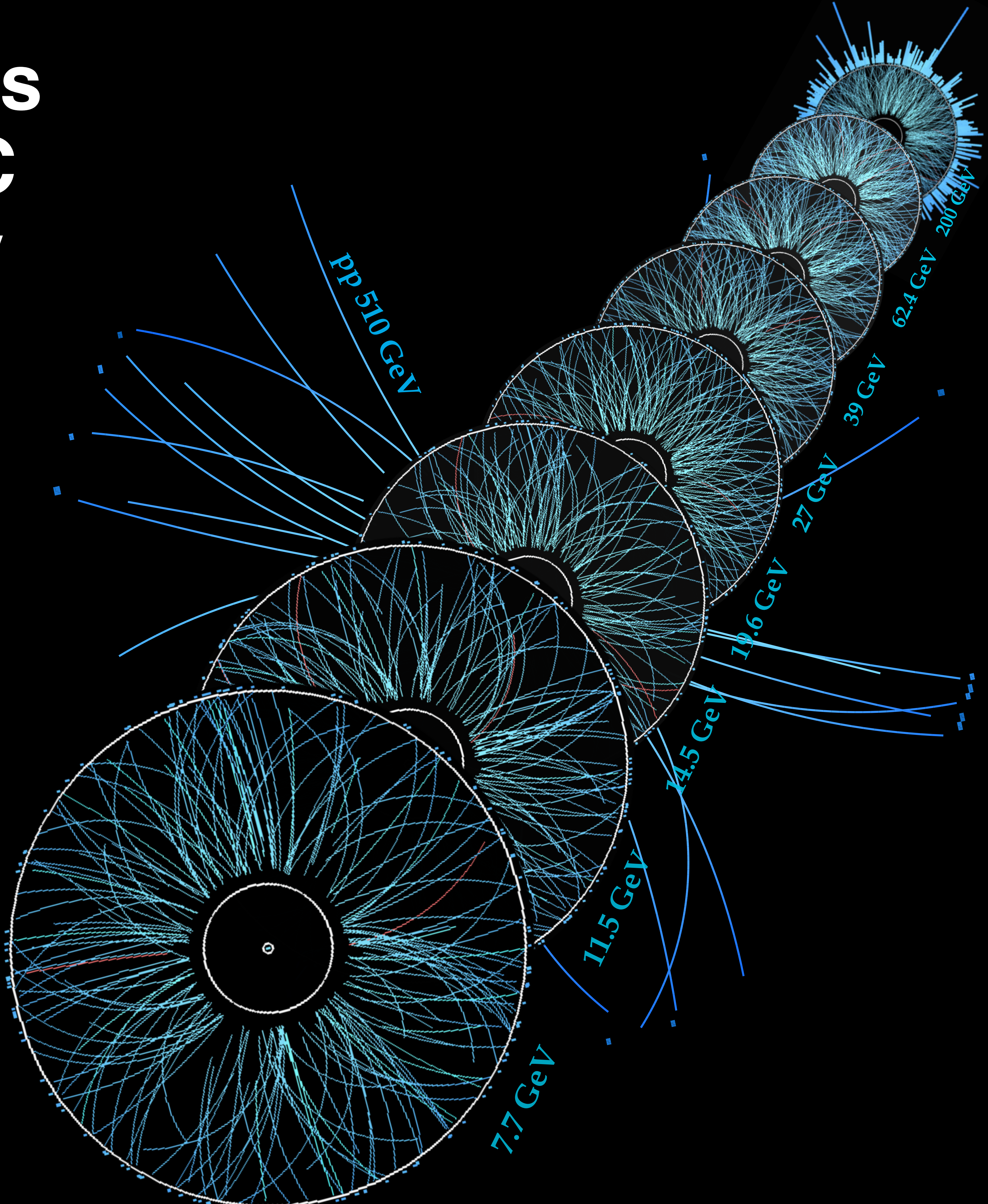
Helen Caines

Yale University

EMMI Workshop

GSI

February 2019



Yale

RHIC BES-I and BES-II

$\sqrt{s_{NN}}$(GeV)	μ_B(MeV)	T_{ch}(MeV)	Events(10^6)	BES-II / BES-I
200	20	166	350	2010
62.4	70	165	67	2010
54.4			1200	2017
39	115	164	130	2010
27	155	162	500/70	2018/2011
19.6	205	160	400/36	2019/2011
14.5	266	156	300/20	2019/2014
11.5	315	152	230/12	2020/2011
9.1	370	140	160	2020
7.7	420	140	100/4	2021/2010

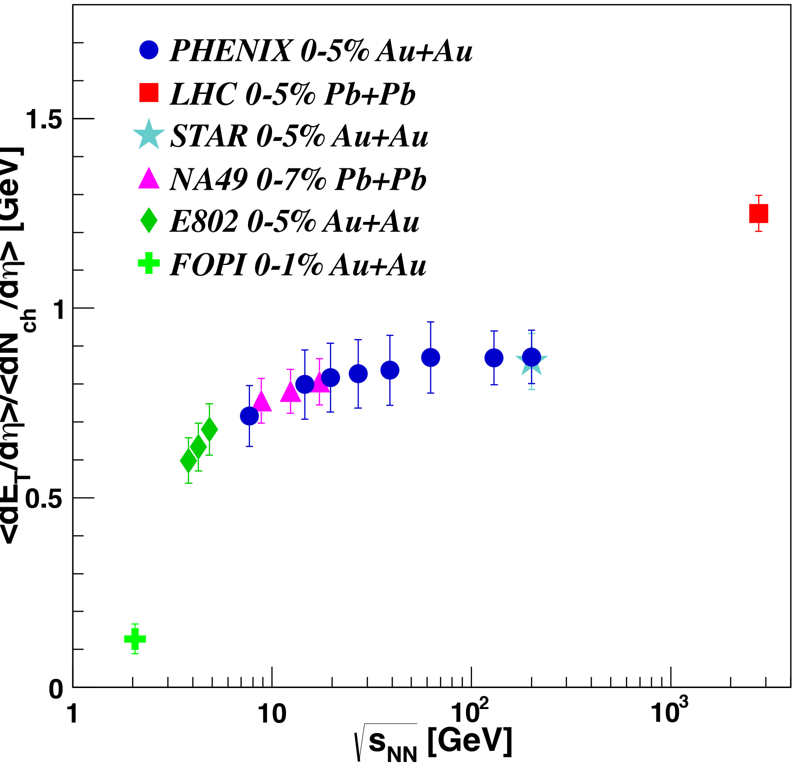
+FXT running already discussed by Daniel Cebra:

$\sqrt{s}$ =7.7-3 GeV

μ_B =720-420 MeV

~100 M events each

The established "basics": Energy density



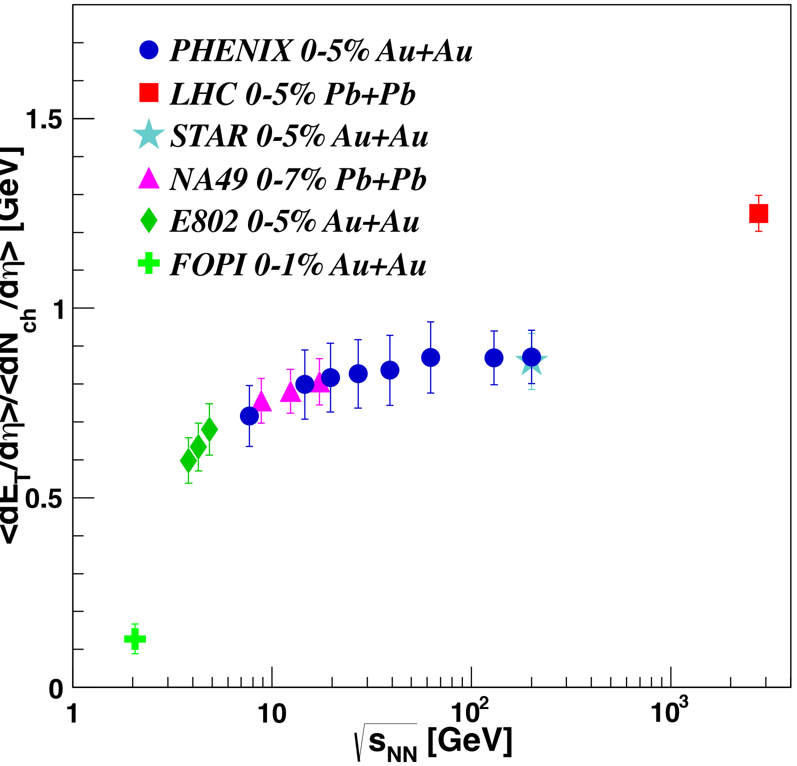
E_T/N_{ch} relates to average transverse mass of produced particles

- rises, plateaus, rises again
- constant as function of N_{part}

Leveling off starts around √s ~ 7 GeV

PHENIX: PRC 93, 024901 (2016)

The established "basics": Energy density



E_T/N_{ch} relates to average transverse mass of produced particles

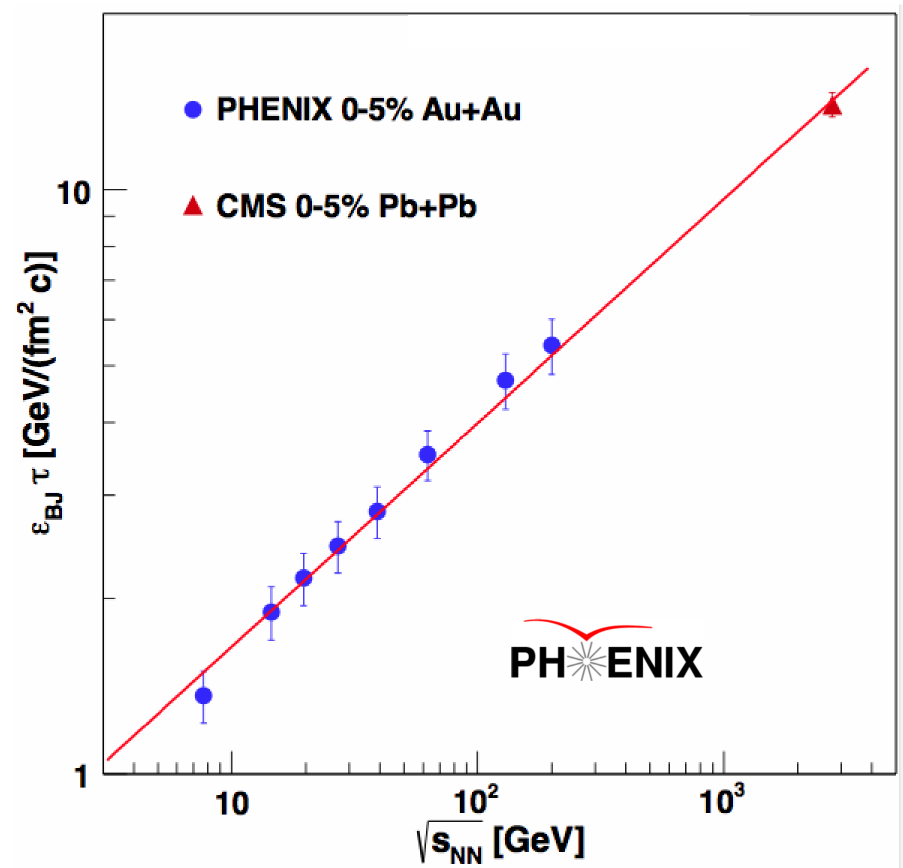
- rises, plateaus, rises again
- constant as function of N_{part}

Leveling off starts around $\sqrt{s}$ ~ 7 GeV

For central events:

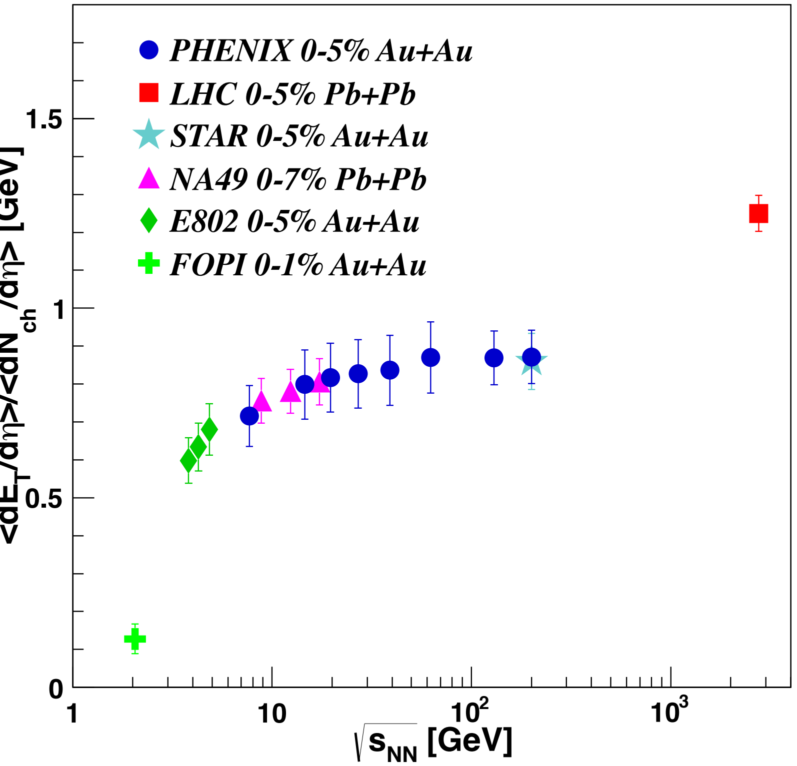
Bjorken energy density× τ > 1 GeV/fm^{2}c

$\varepsilon_{BJ}\tau \propto e[b\times\log(\sqrt{s_{NN}})]$; (b = 0.422 ± 0.035)



PHENIX: PRC 93, 024901 (2016)

The established "basics": Energy density

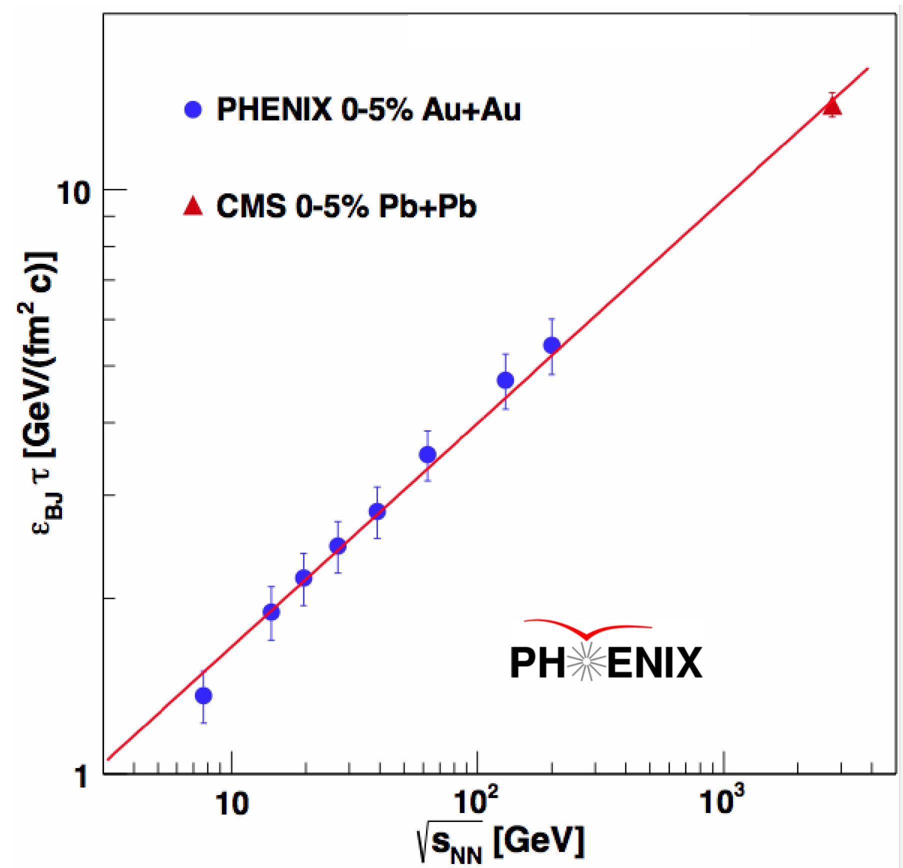


E_T/N_{ch} relates to average transverse mass of produced particles

rises, plateaus, rises again

constant as function of N_{part}

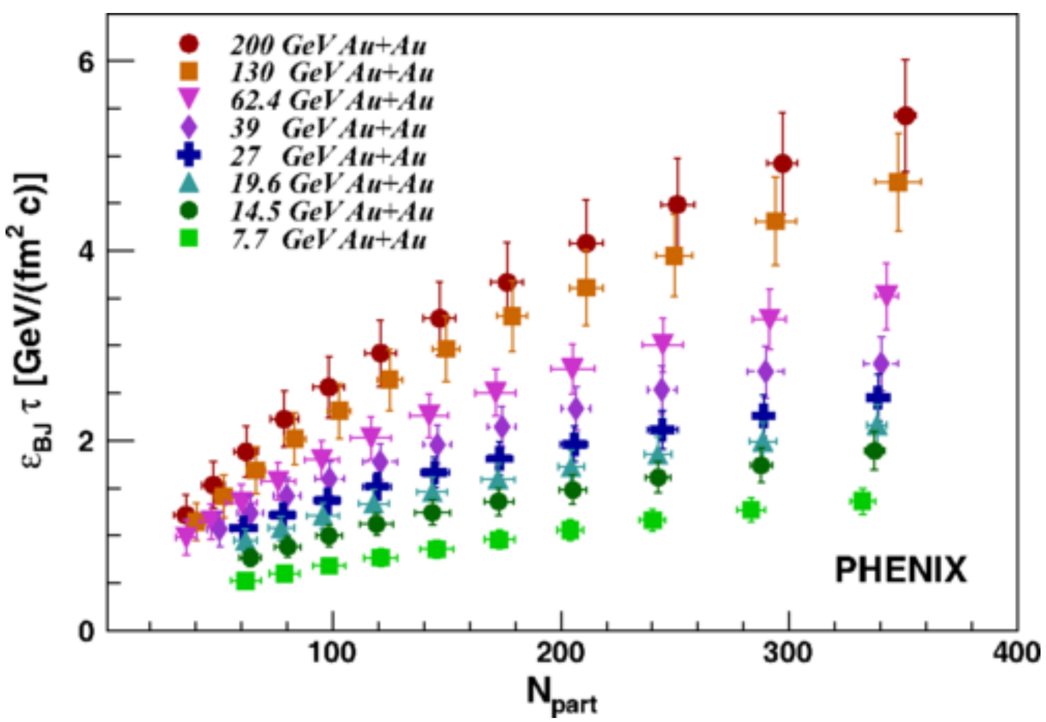
Leveling off starts around √s ~ 7 GeV



For central events:

Bjorken energy density× τ > 1 GeV/fm²c

$\varepsilon_{BJ}\tau \propto e[b\times\log(\sqrt{s_{NN}})]$; (b = 0.422 ± 0.035)

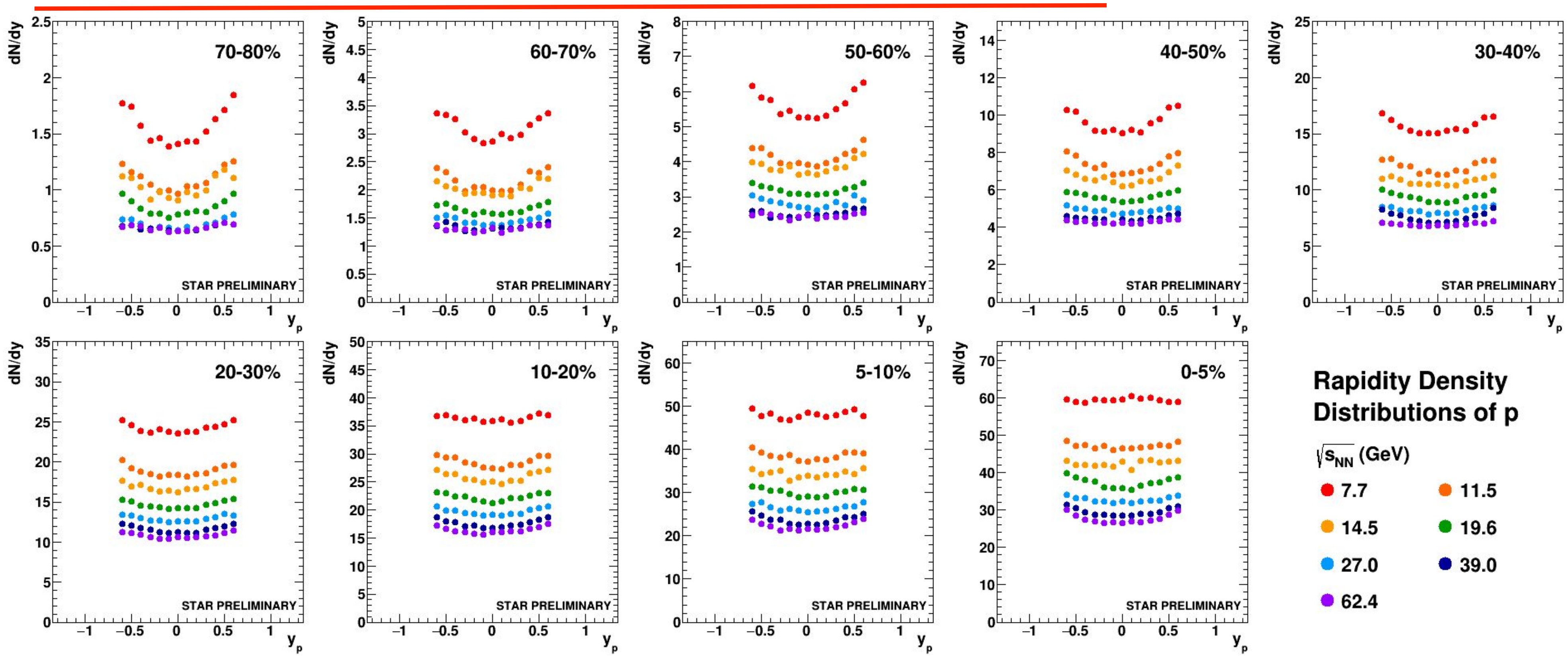


$\varepsilon_{BJ}\tau$ < 1 for low energy peripheral events

Can we establish τ?

PHENIX: PRC 93, 024901 (2016)

Establishing the “basics”: Yields and spectra



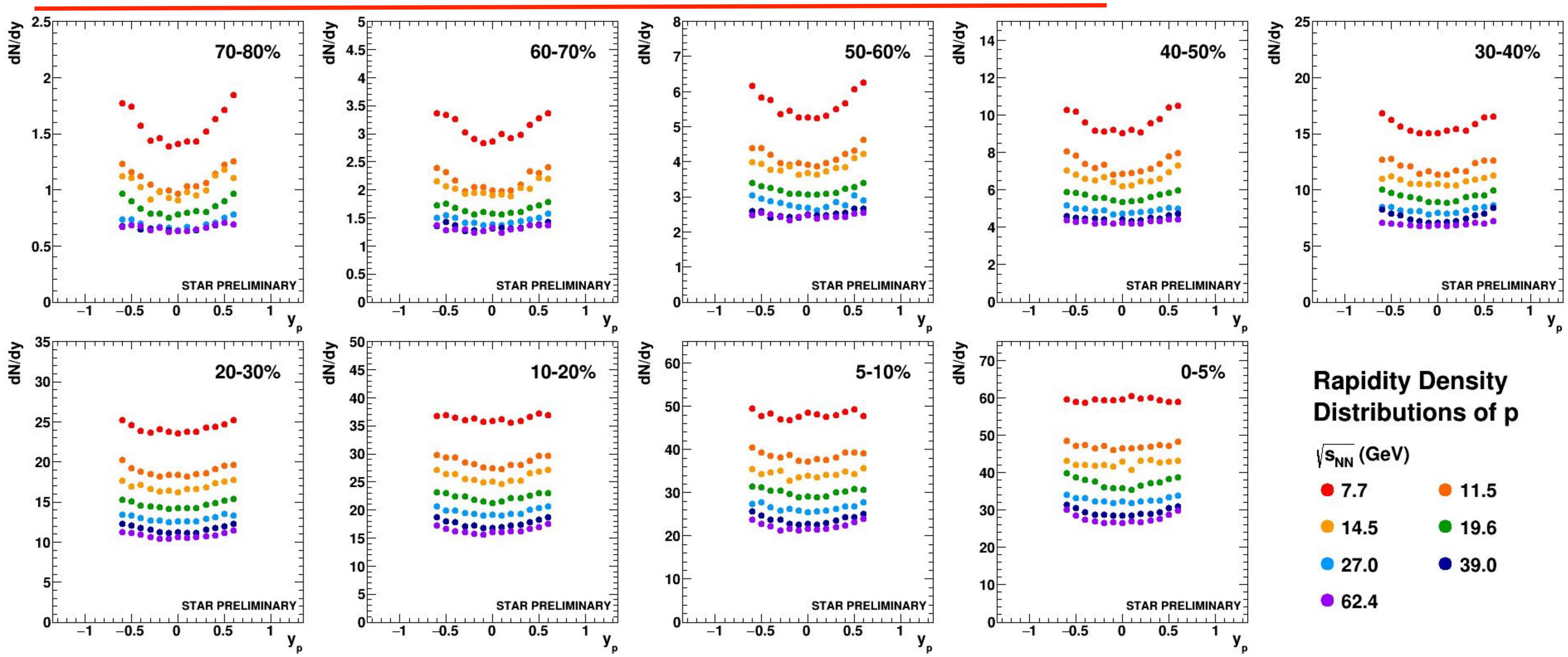
Inching towards full phase space measurements

In collider mode STAR can measure forwards and backwards

Strong centrality evolution for 7.7 GeV

STAR Preliminary results for pions, anti-p available with same binning

Establishing the "basics": Yields and spectra

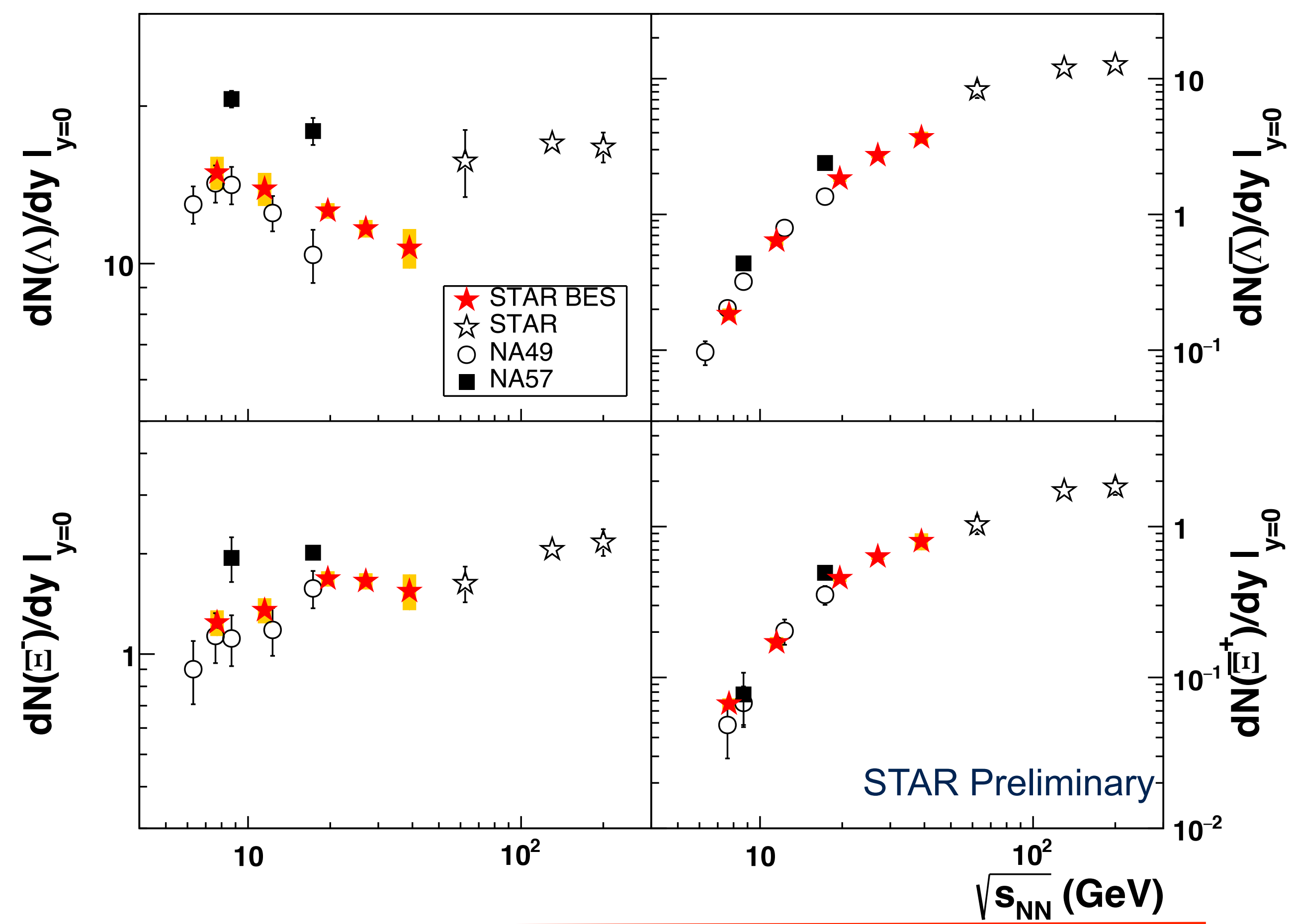


Inching towards full phase space measurements

In collider mode STAR can measure forwards and backwards

Strong centrality evolution for 7.7 GeV

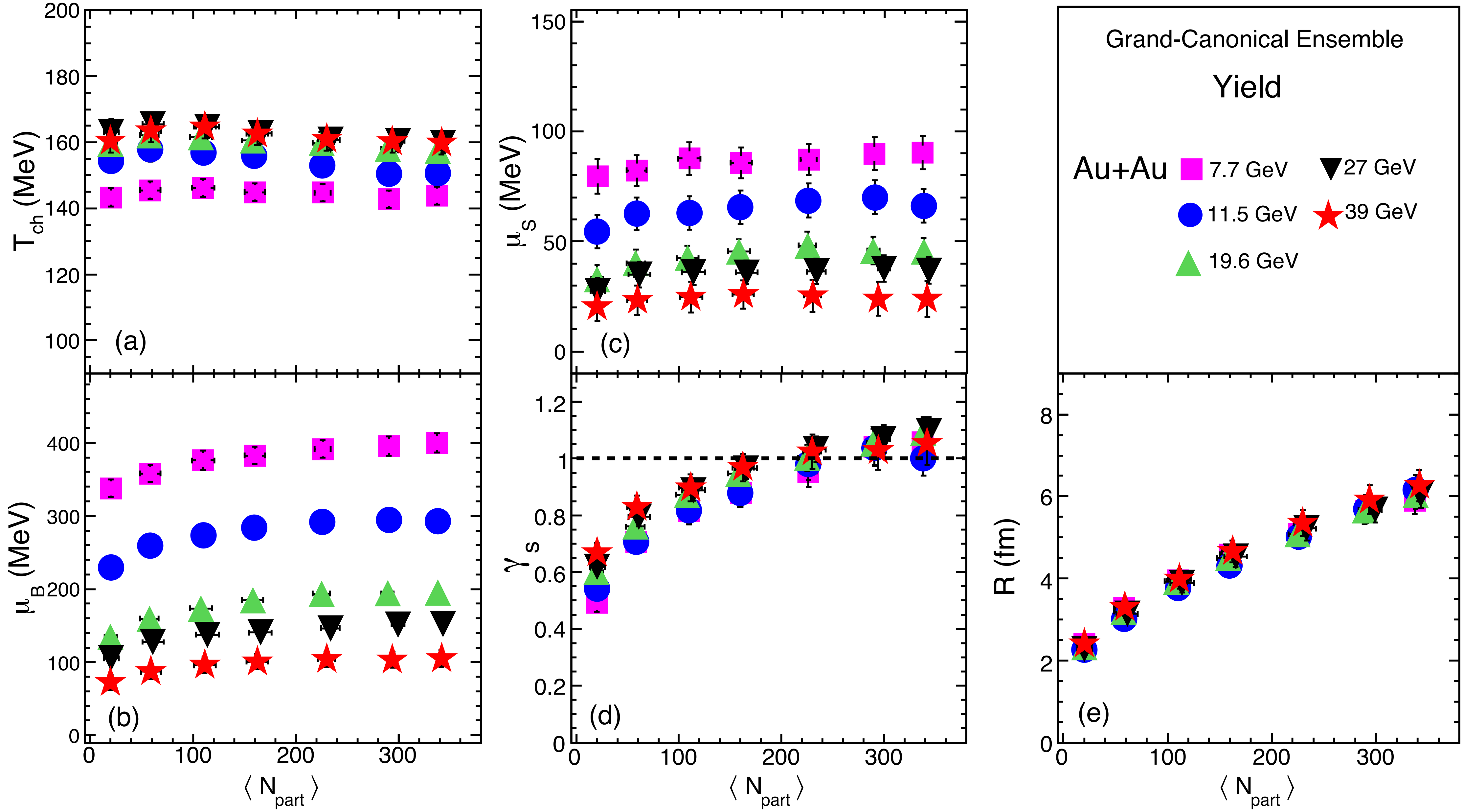
Non-trivial √s dependence of strange baryons



Strangeness results submitted for publication soon

STAR Preliminary results for pions, anti-p available with same binning

The established "basics": Hadro chemistry



Results need "ALL" strange hadrons included

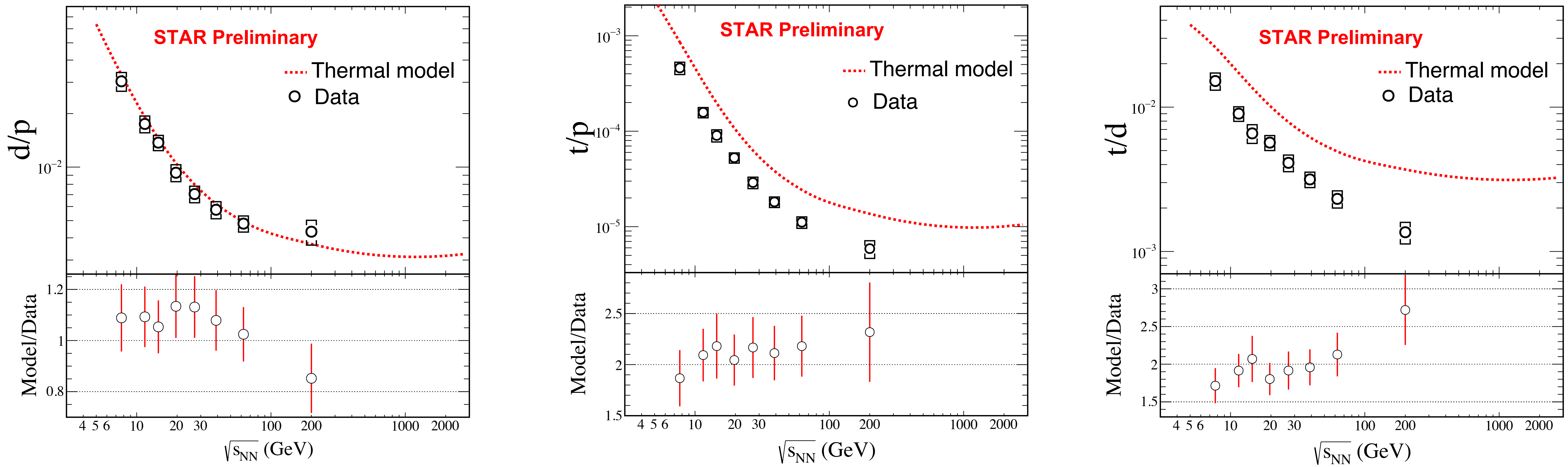
No significant difference seen in BES energies using GCE or SCE

Lattice based calc. using fluctuations: ~agreement with Thermal model

All data fit smoothly into model expectations

STAR: PRC **96** (2017) 44904
PHENIX: PRC 93, (2016) 011901

Deuteron and triton in statistical model



$$T_{CF} = T_{CF}^{lim}/(1 + \exp(2.60 - \ln(\sqrt{s_{NN}})/0.45)) \qquad \mu_B = a/(1 + 0.288\sqrt{s_{NN}})$$

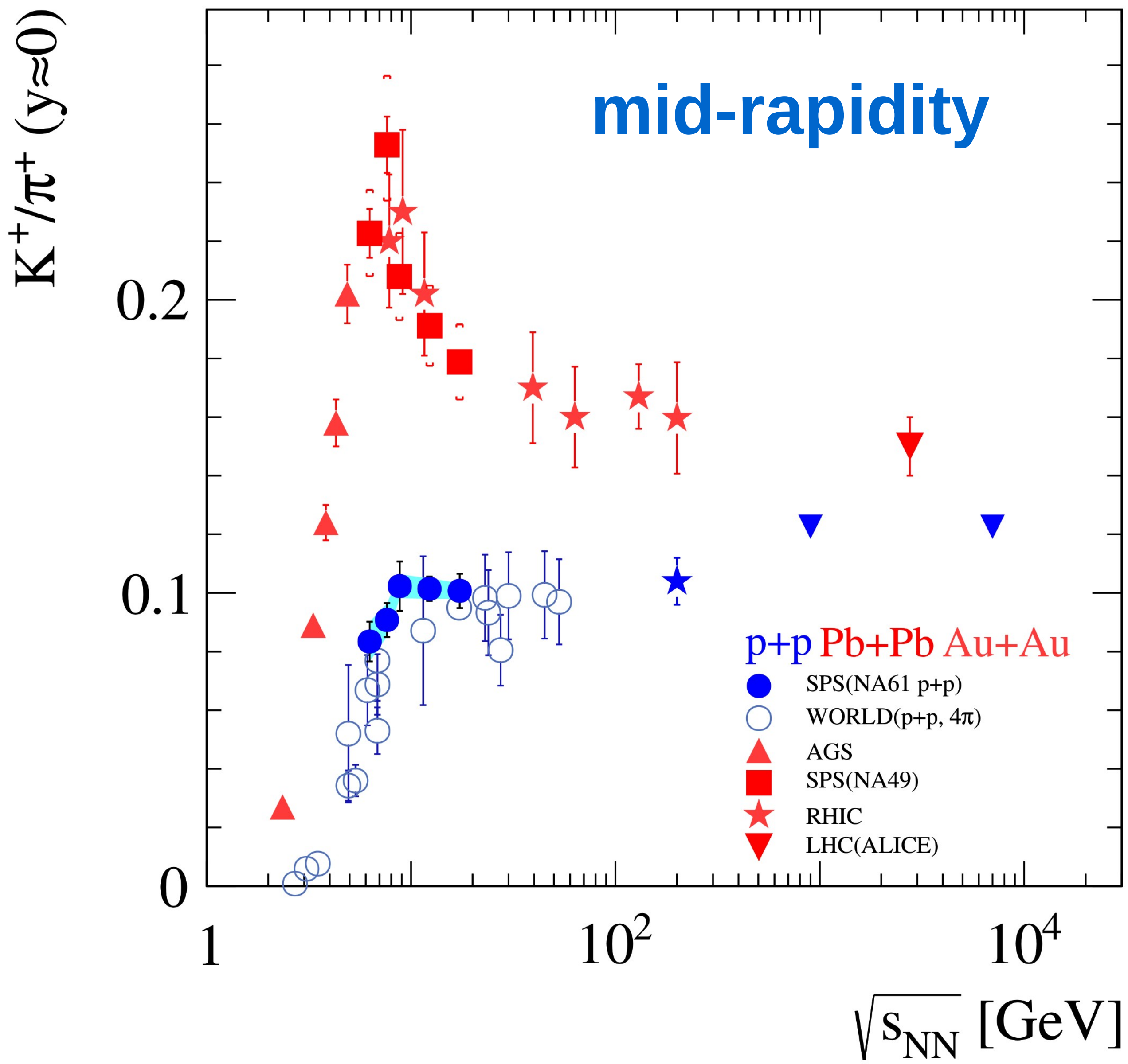
With $\sqrt{s_{NN}}$ in GeV and $T_{CF}^{lim} = 158.4$ MeV and a = 1307.5 MeV.

Can describe preliminary d/p as function of √s but not t/p or t/d

Same model works well at LHC energies

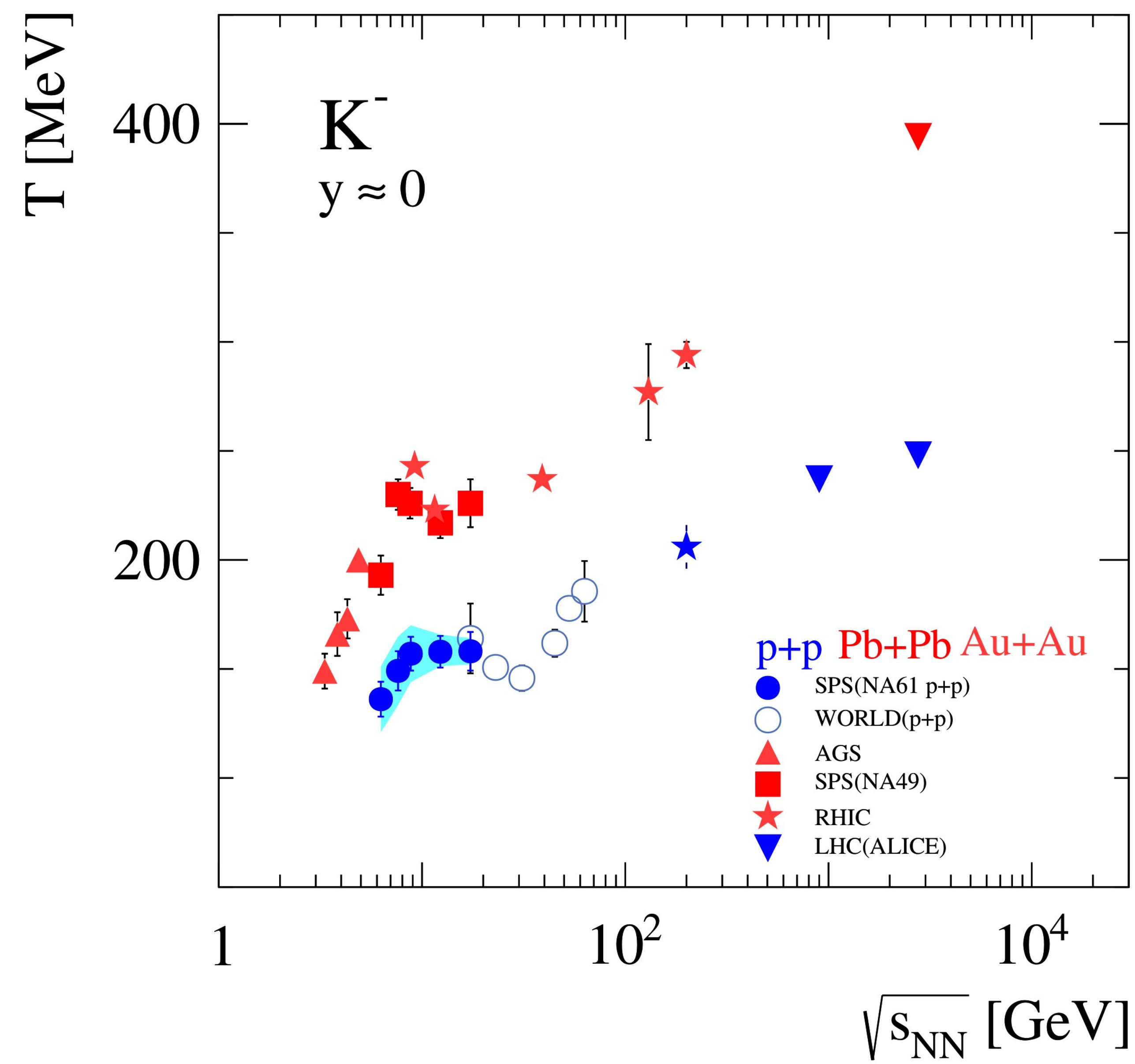
A.Andronic et al. PLB 697 (2011) 203

Horns and plateaus



RHIC data suggests horn less pronounced

Baryon density peaks at √s ~7 GeV

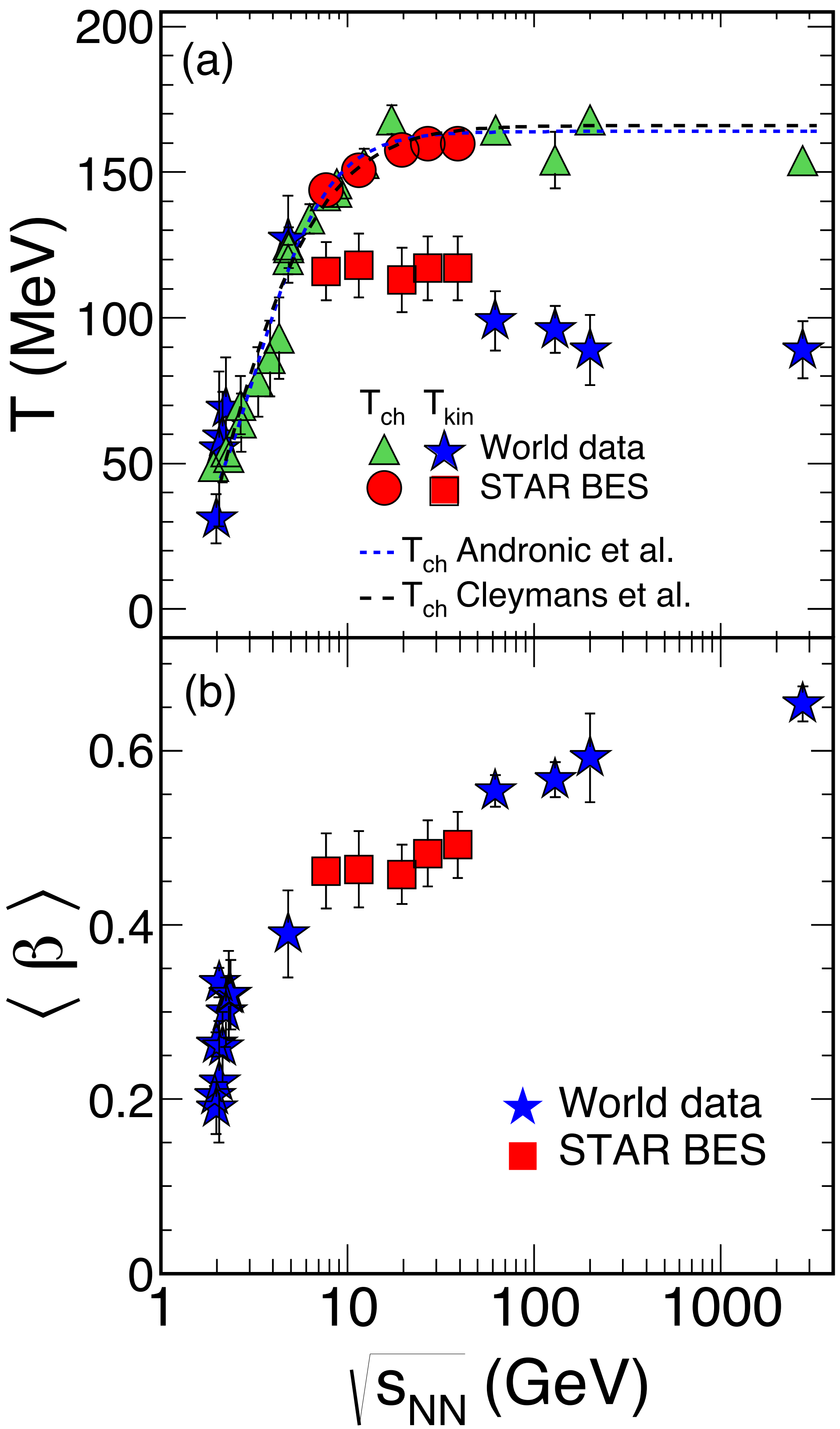


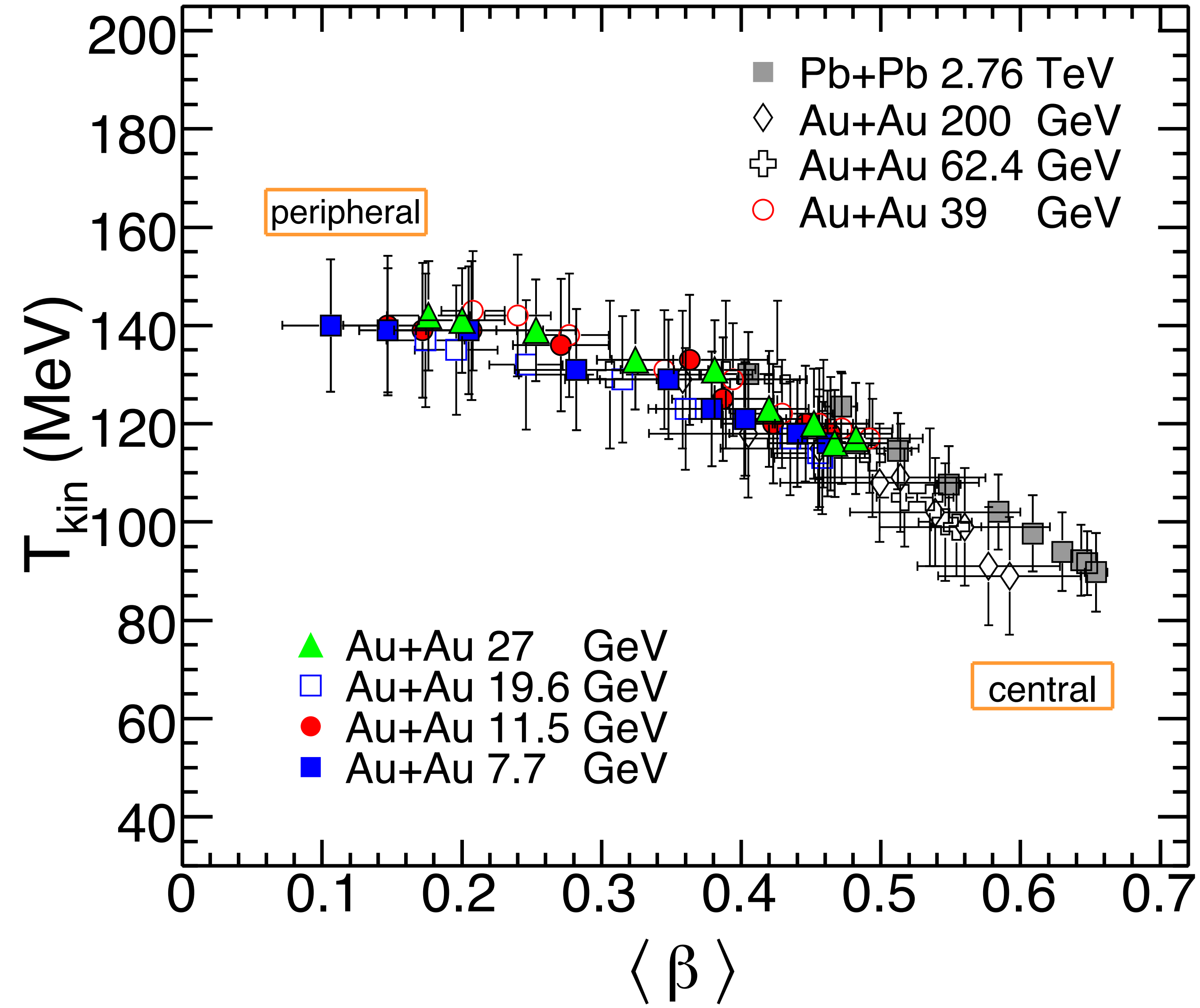
T:

pp values lower but trend similar to A+A

K. Grebieszkow CPOD16
STAR: PRC 96 (2017) 44904

Established “basics”: Kinetic freeze-out





Central collisions:

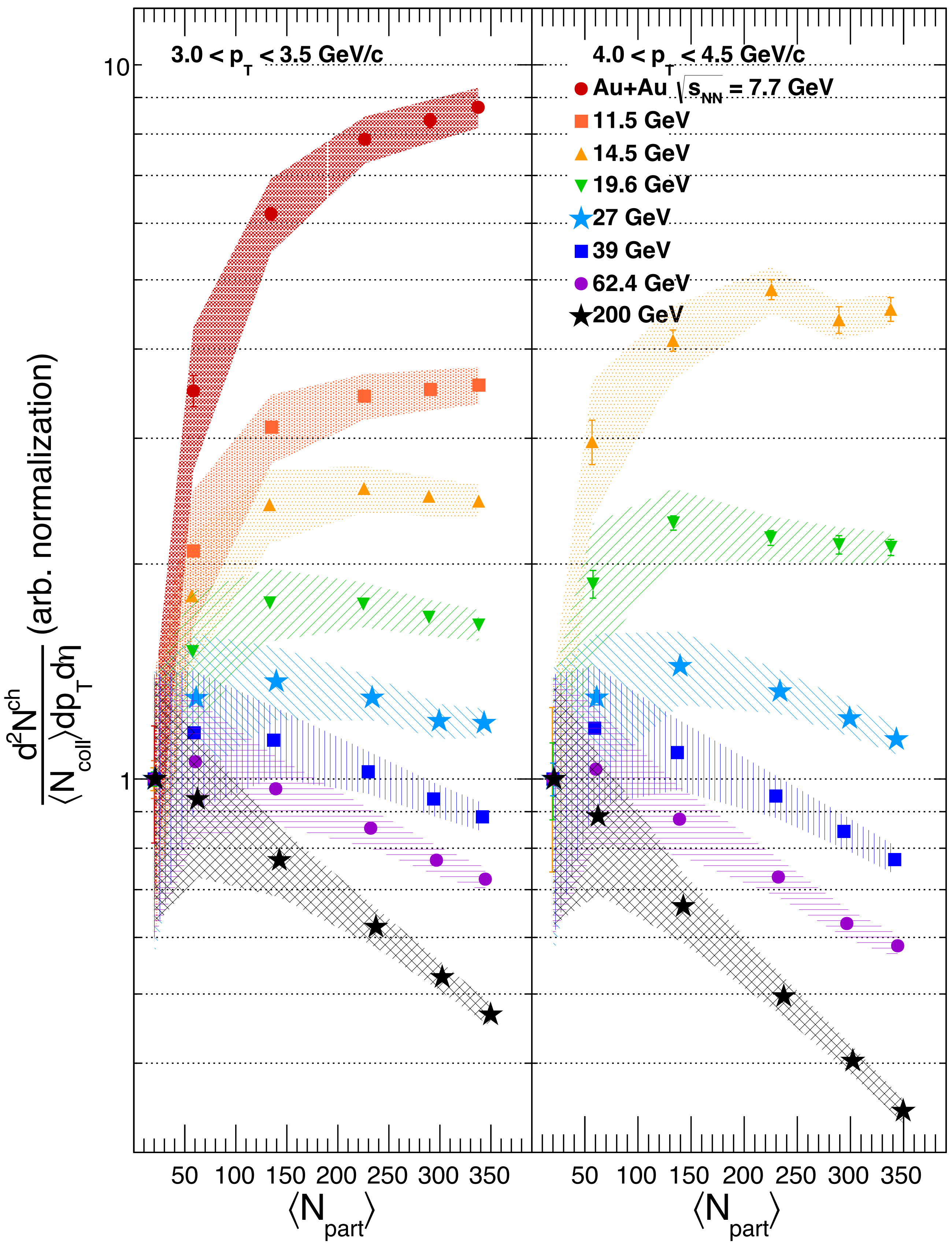
- Lower T→ higher β
- Do values depend only on N_{ch}?

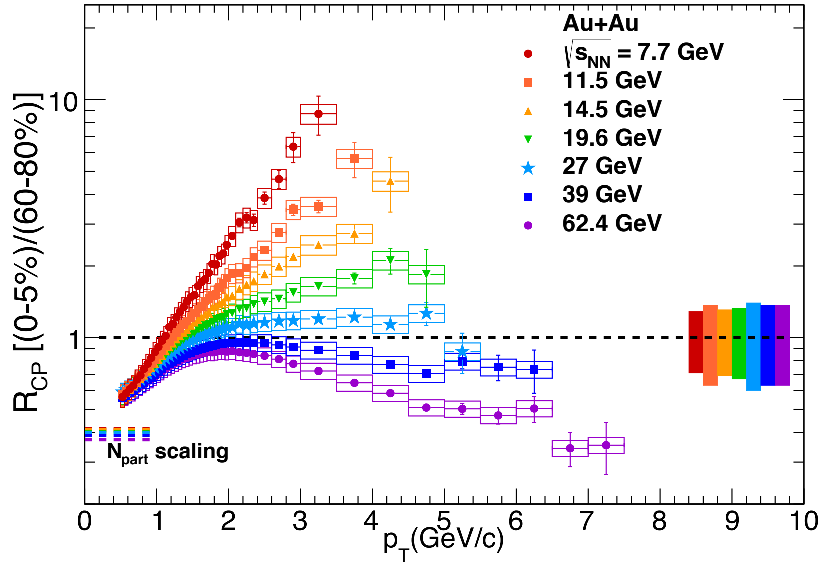
Second rise in K slope - β increase

T_{kin}~T_{ch} below √s ~ 7 GeV

STAR: PRC **96** (2017) 44904

QGP creation: Jet quenching





Cronin may be hiding E_{loss}

For $\sqrt{s_{NN}}$ ≥ 14.5 GeV central events show suppression compared to next peripheral bin

7.7 and 11.5 GeV - increase monotonically

200 GeV - decrease monotonically

Where does d+Au data sit?

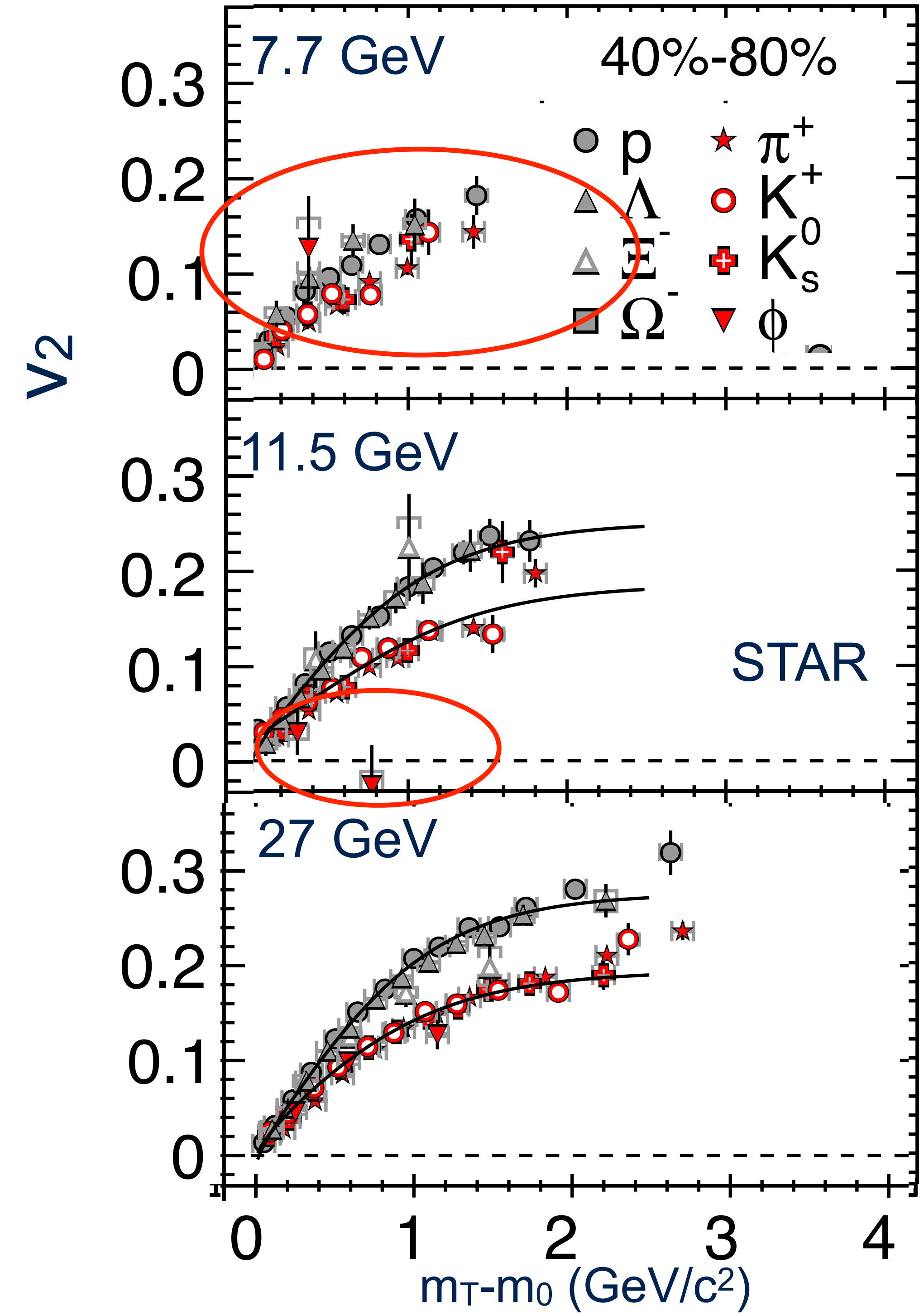
STAR: PRL **121** (2018) 32301

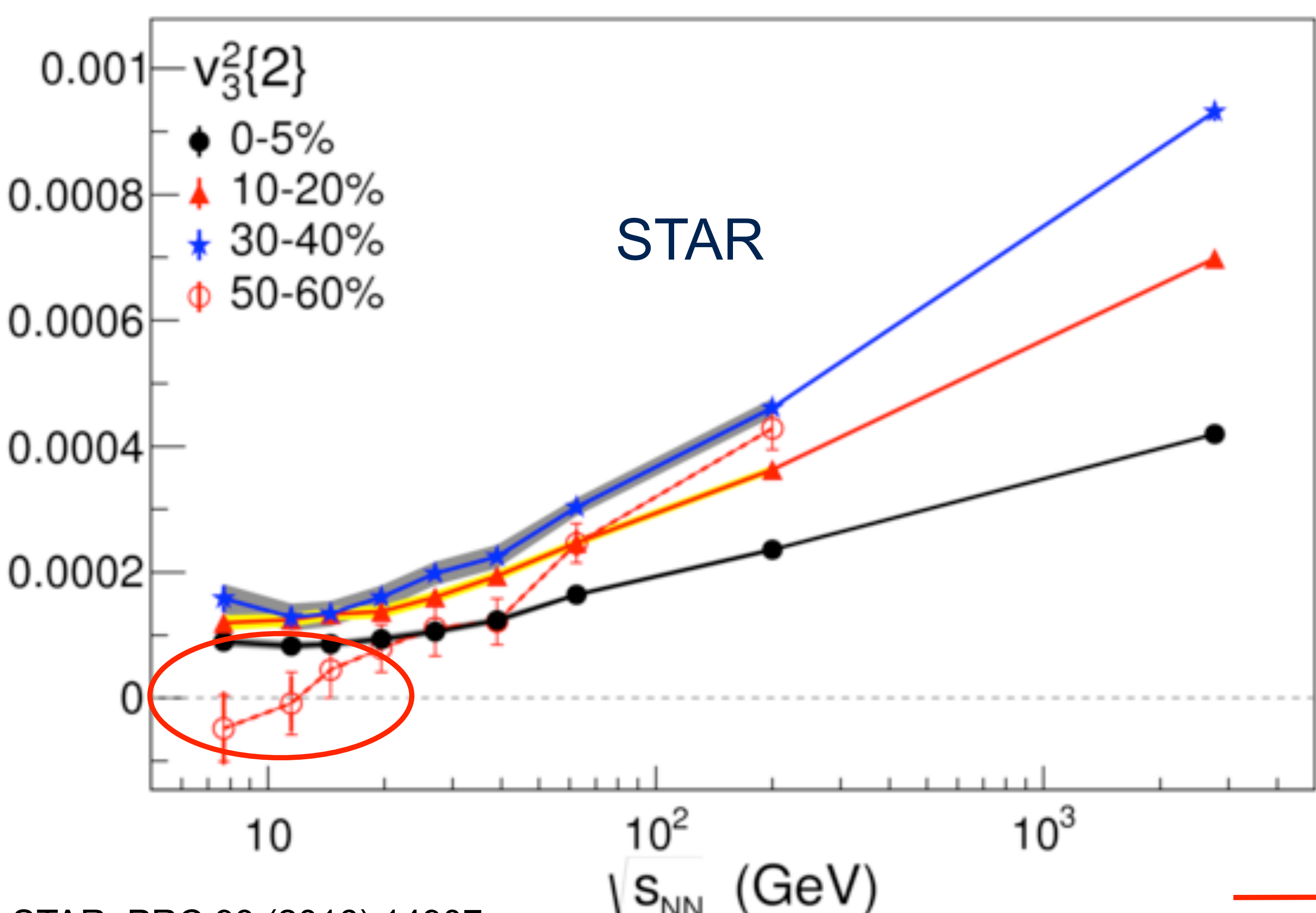
QGP creation: v_2 and v_3

Baryon-Meson v_2 separation disappears

No evidence of ϕ v_2 (large error bars)

- absence of quark degrees of freedom?





v_3 compatible with zero for peripheral events - absence of low viscosity QGP phase?

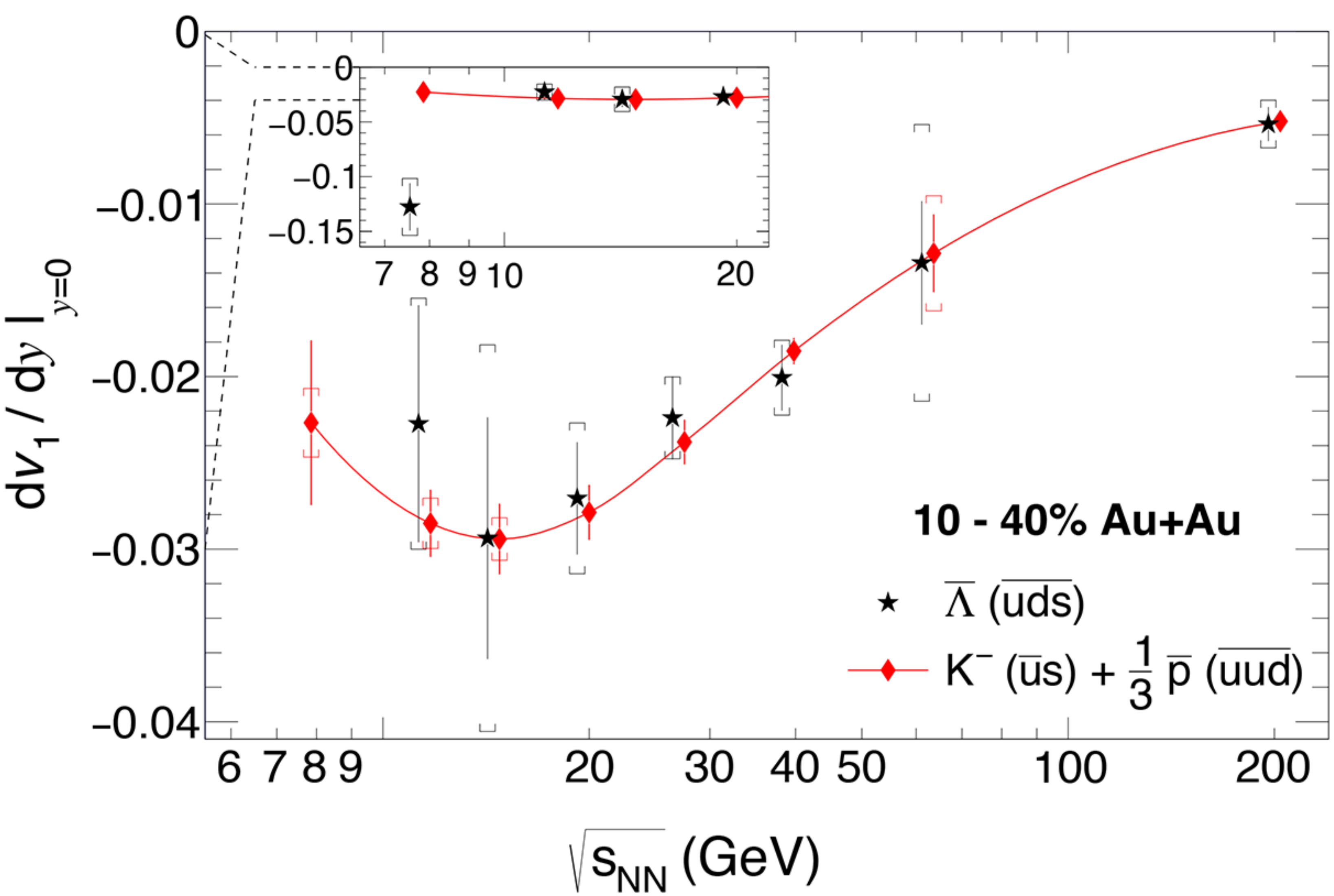
All occurs around √s < 15 GeV

STAR: PRC 93 (2016) 14907
STAR: PRL 116 (2016) 112302

Coalescence of "produced" particles

Assumptions:

- v_1 is developed in prehadronic stage
- Hadrons are formed via coalescence: $(v_n)_{hadron} = \Sigma(v_n)_{constituent\ quarks}$
- $(v_1)_{\bar{u}} = (v_1)_{\bar{d}}$ and $(v_1)_s = (v_1)_{\bar{s}}$



anti-Λ predicted from quark values deduced from K and p

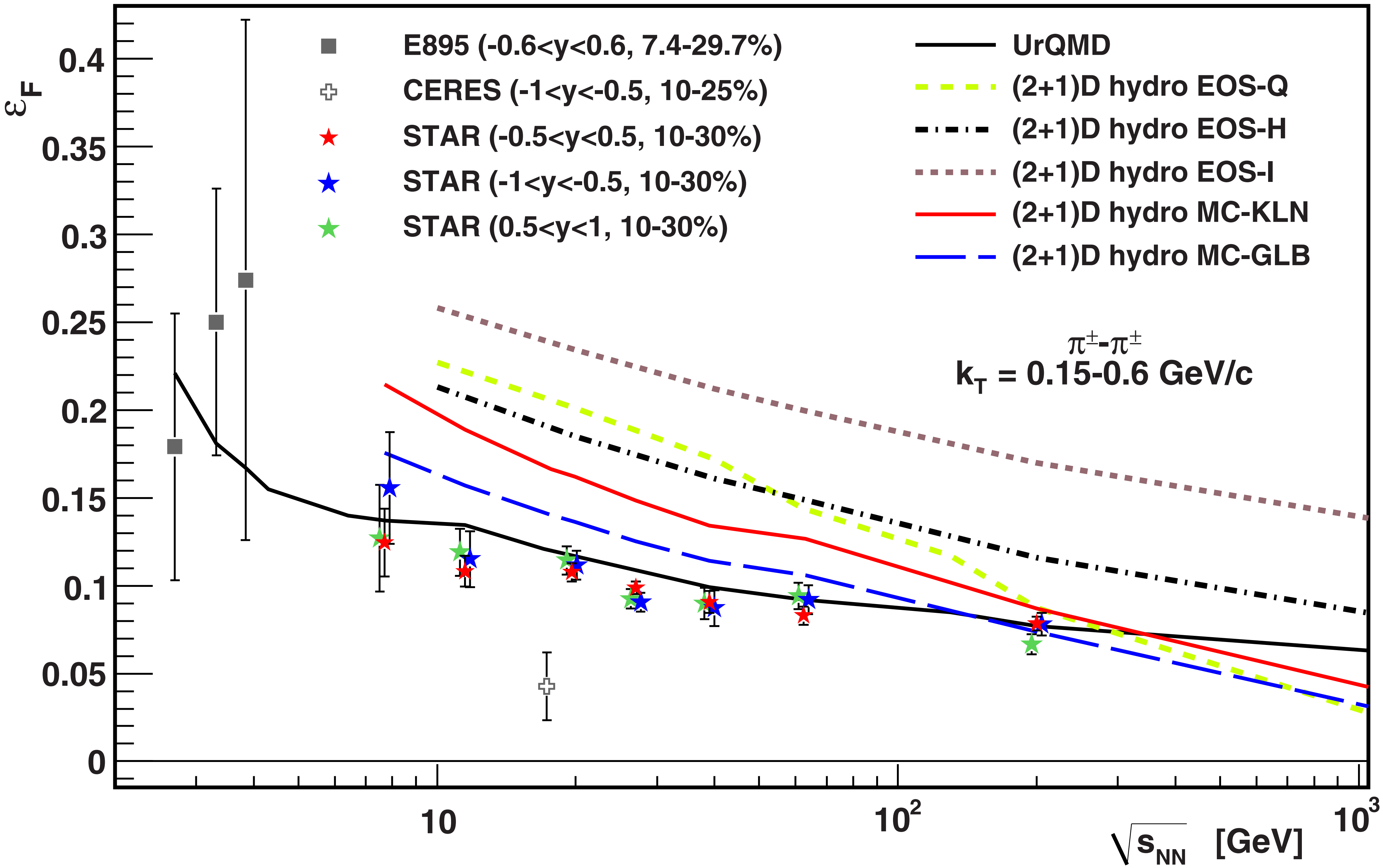
Fails for 7.7 GeV -
At least one assumption incorrect

What happens at lower √s?
Finer centrality bins?

STAR: PRL 120 (2018) 62301

Eccentricity at freeze-out

Accessed via azimuthal HBT



Sensitivity to the EoS

STAR data show trend smooth over all √s

No evidence of change in EoS

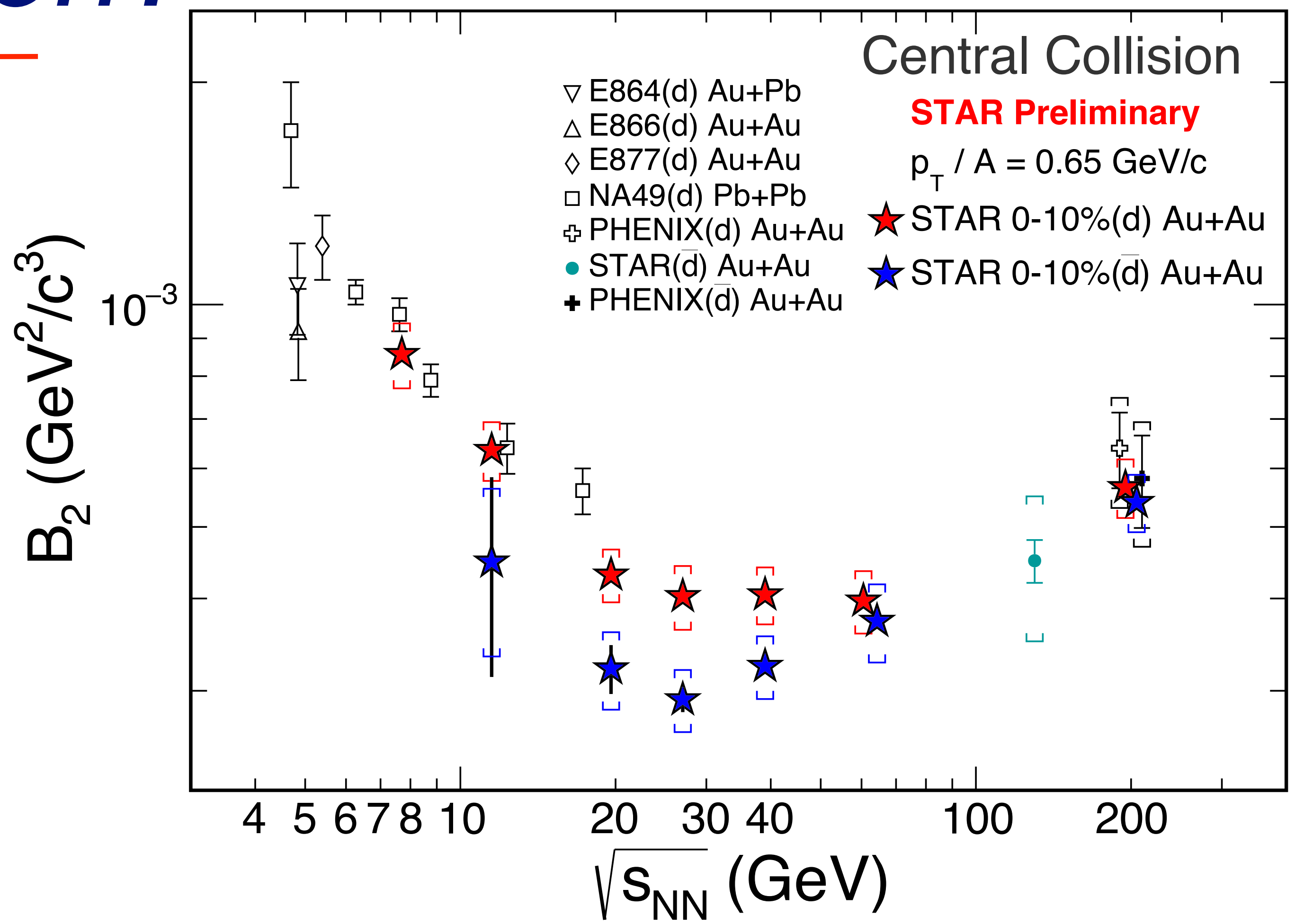
STAR: PRC 92 014904 (2015)

Stalling of the expansion?

d final state coalescence access to nucleon freeze-out volume

$$E_A \frac{d^3N_A}{d^3p_A} \approx B_A \left(E_p \frac{d^3N_p}{d^3p_p}\right)^A \quad B_2 = \frac{6\pi^3 R_{np} m_d}{m_p^2 V_f}$$

B_2 minimum (V max) $\sqrt{s_{NN}}$ ~ 20 GeV
Anti-d freeze out from larger source?



STAR: PRC 92 014904 (2015)

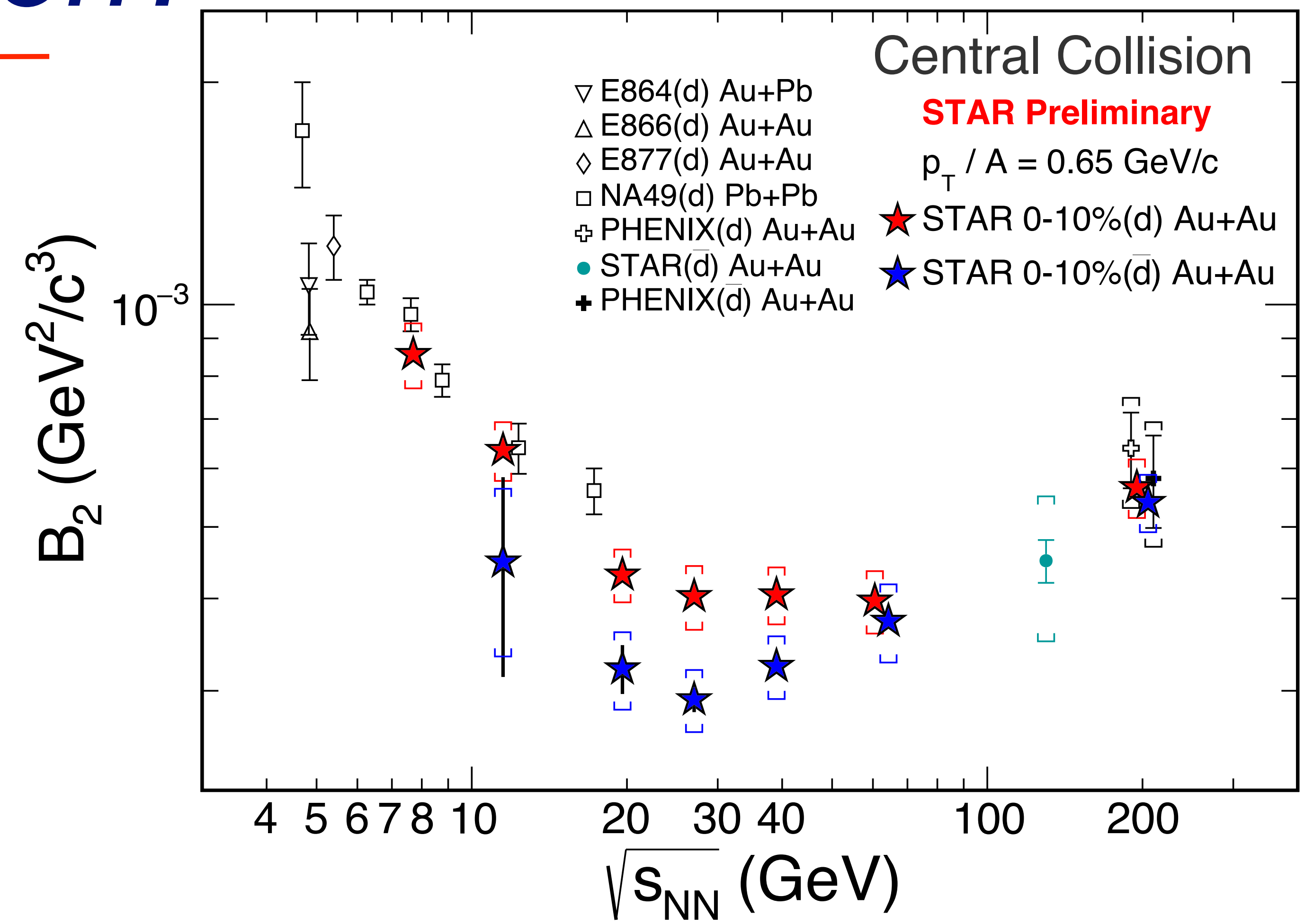
Stalling of the expansion?

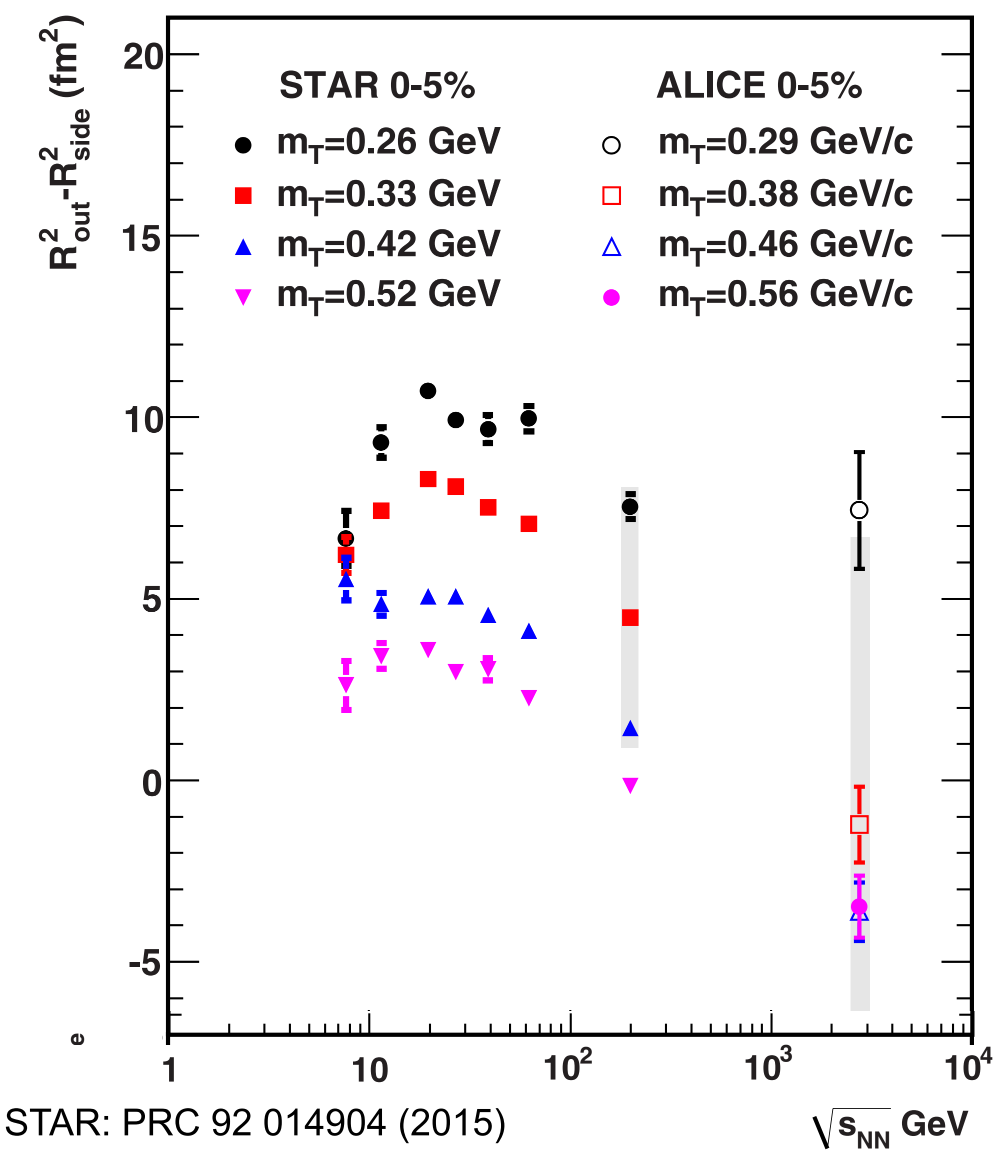
d final state coalescence access to nucleon freeze-out volume

$$E_A \frac{d^3N_A}{d^3p_A} \approx B_A \left(E_p \frac{d^3N_p}{d^3p_p}\right)^A \quad B_2 = \frac{6\pi^3 R_{np} m_d}{m_p^2 V_f}$$

B_2 minimum (V max) $\sqrt{s_{NN}}$ ~ 20 GeV

Anti-d freeze out from larger source?





STAR: PRC 92 014904 (2015)

(R^2_{out} - R^2_{side}) sensitive to emission duration

Maximum at $\sqrt{s_{NN}}$ ~ 20 GeV

Softening of EoS?

Sign of entering compressed baryonic matter regime?

"Dale" in longitudinal expansion

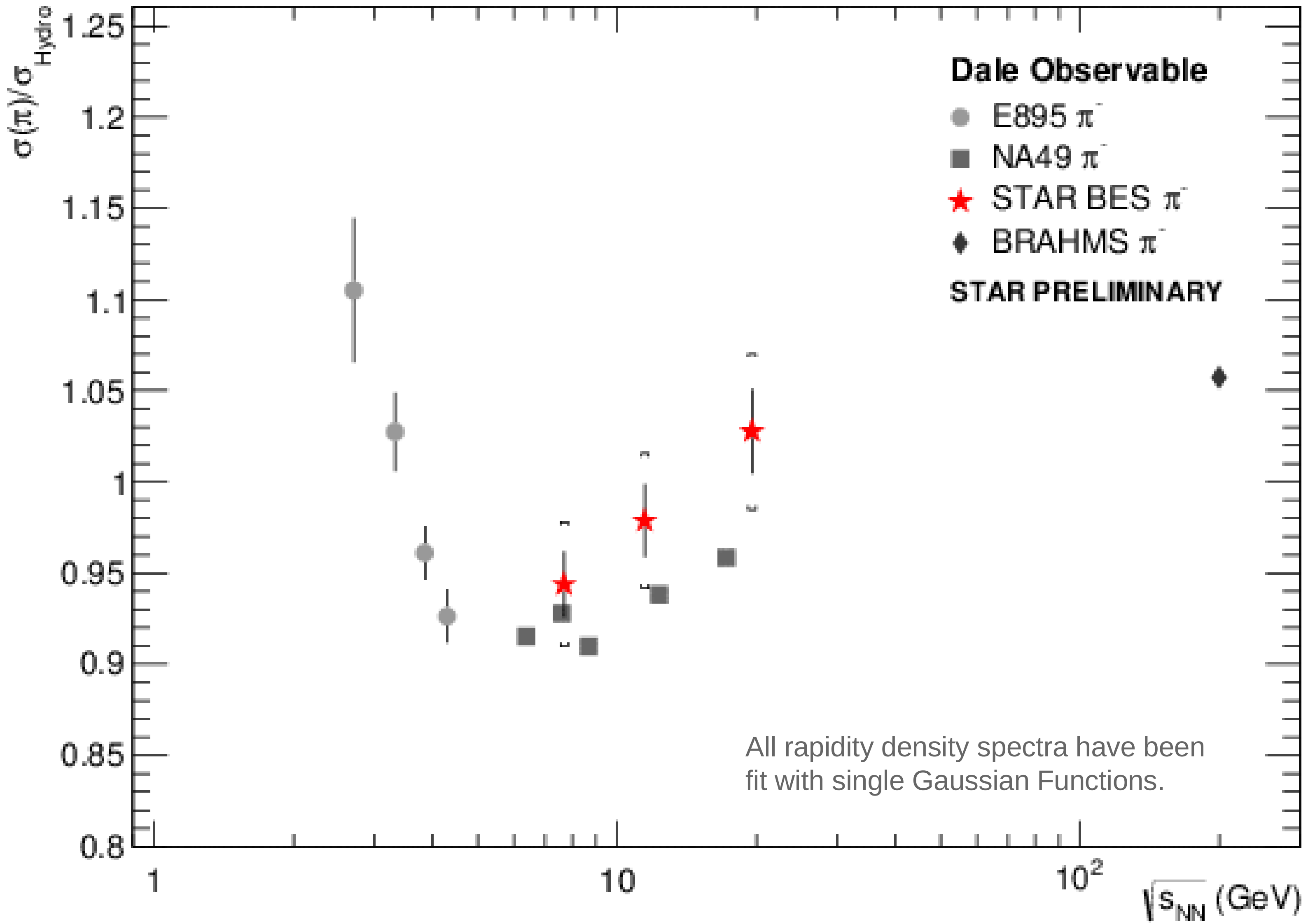
Probe expansion dynamics:

Width of rapidity distribution compared to Landau hydro. expansion predictions

Minimum observed at $\sqrt{s}$ = ~7 GeV

Minimum in the speed of sound?

$c_s^2 \sim 0.26$



E895: J. L. Klay et al, PRC 68, 05495 (2003)
NA49: S. V. Afanasiev et al. PRC 66, 054902 (2002)
BRAHMS: I.G. Bearden et al., PRL 94, 162301

Another indication of softening of EoS?

NA61/SHINE see minima in similar place for pp data

BES results for π^+ and π^-

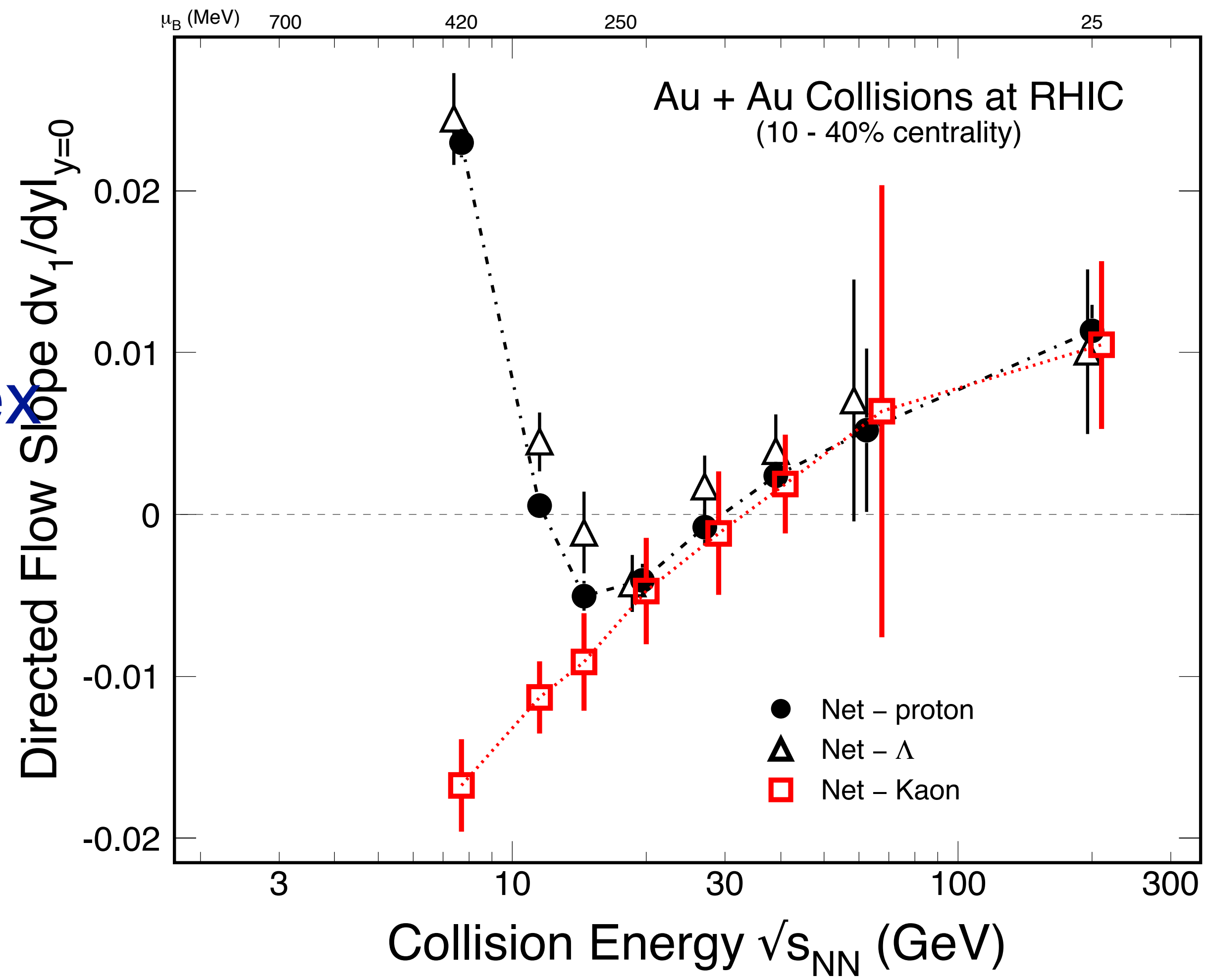
First order phase transition?

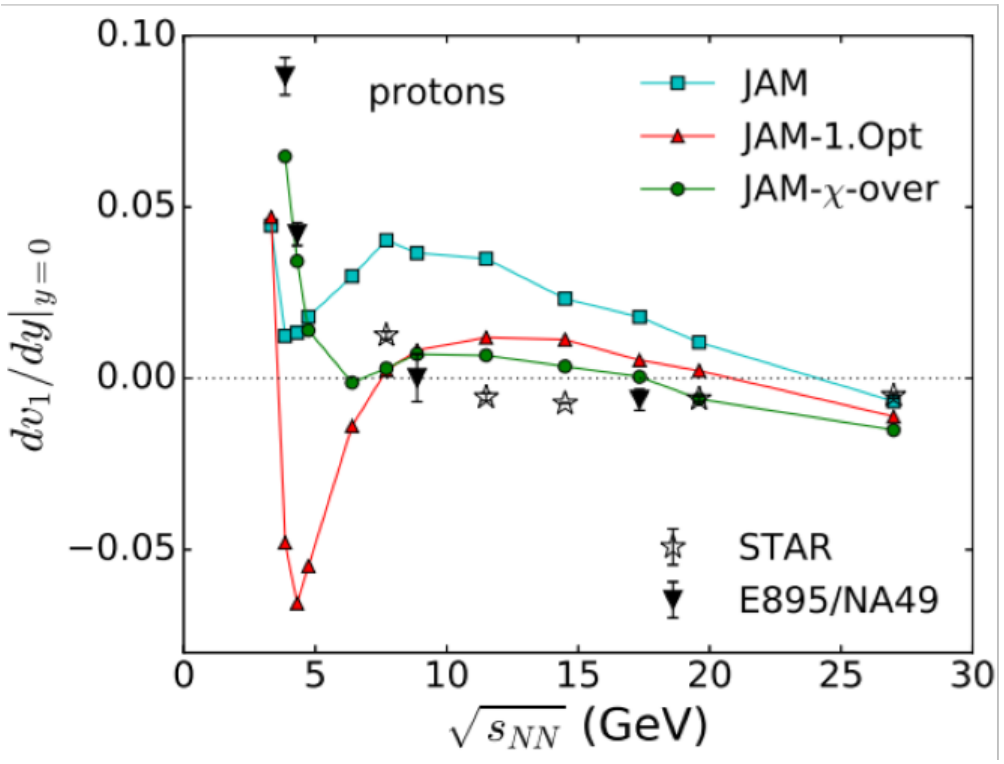
Low √s : slope v_1(baryons) positive
slope v_1 (mesons) negative

Beam energy baryon dv_1/dy trend complex interplay of:

v_1 baryons transported from beam

v_1 from pair production





STAR: PRL 112 162301 (2014), PRL 120 (2018) 62301
Y.Nara et al. PLB769 (2017) 543

First order phase transition?

Low √s : slope v_1(baryons) positive
slope v_1 (mesons) negative

Beam energy baryon dv_1/dy trend complex interplay of:

v_1 baryons transported from beam

v_1 from pair production

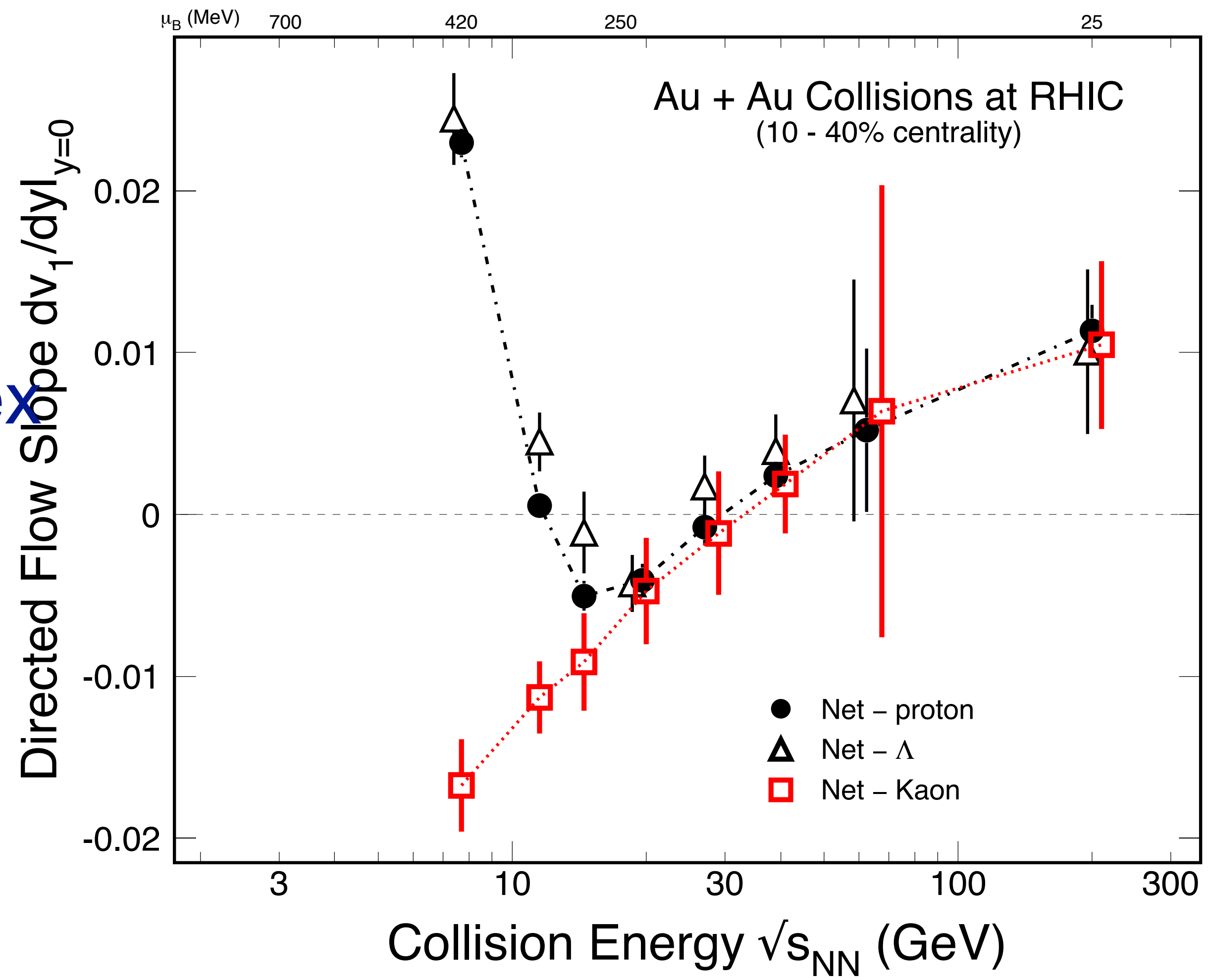
Net-proton isolates directed flow of transported baryons:

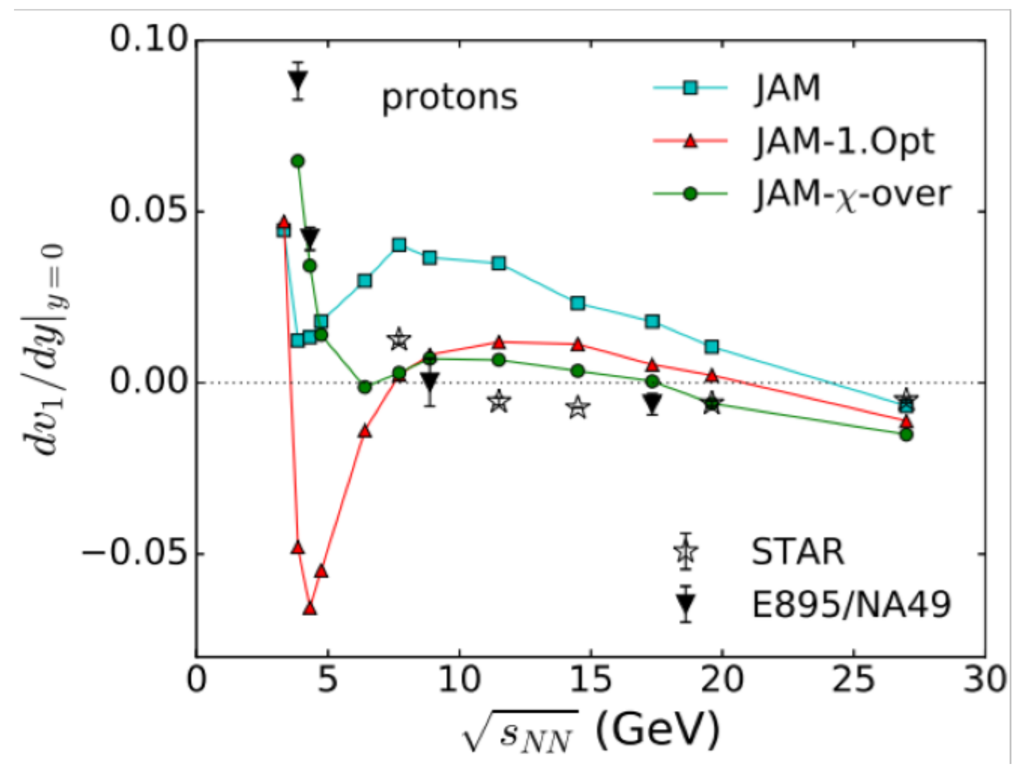
Double sign change in dv_1/dy

Not seen in net-kaons

Results not yet reproduced by theory
Recent calculations consistent with original 2005 prediction

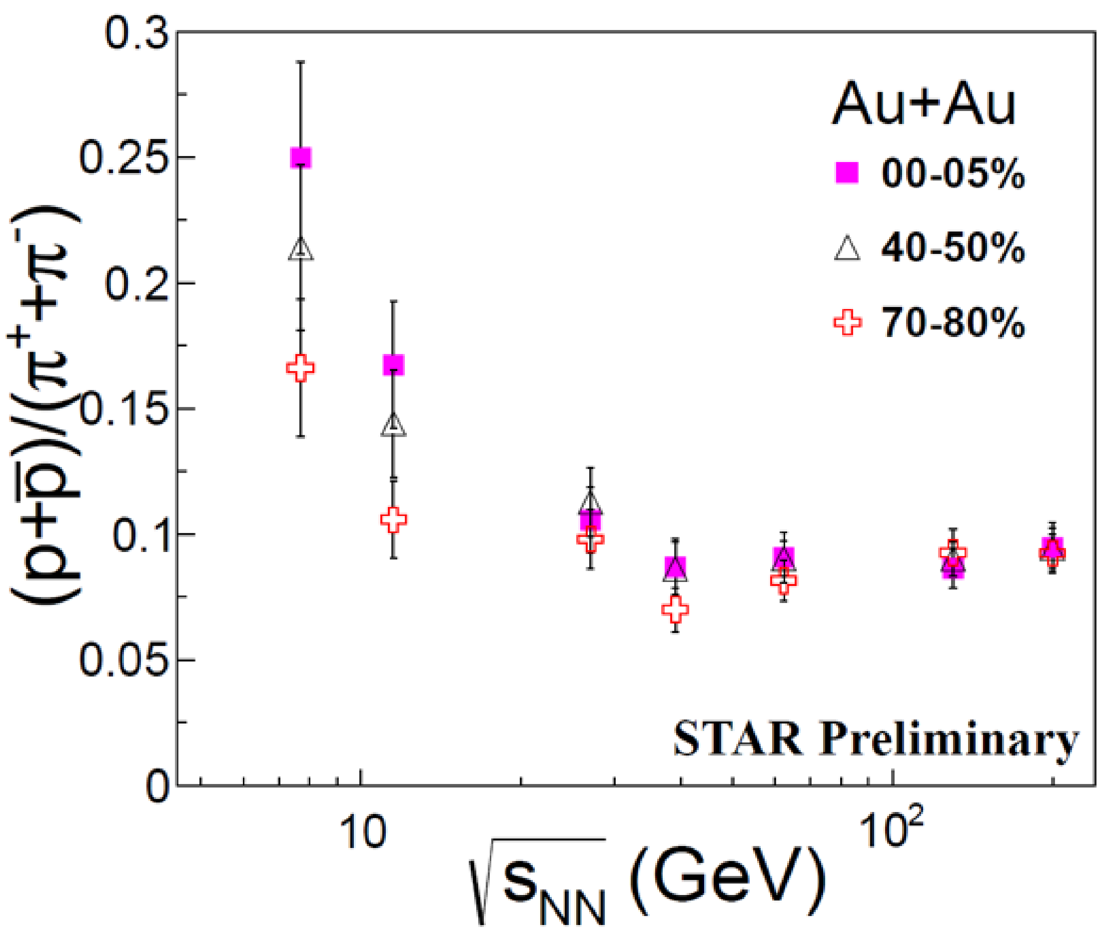
Softening of EoS ?

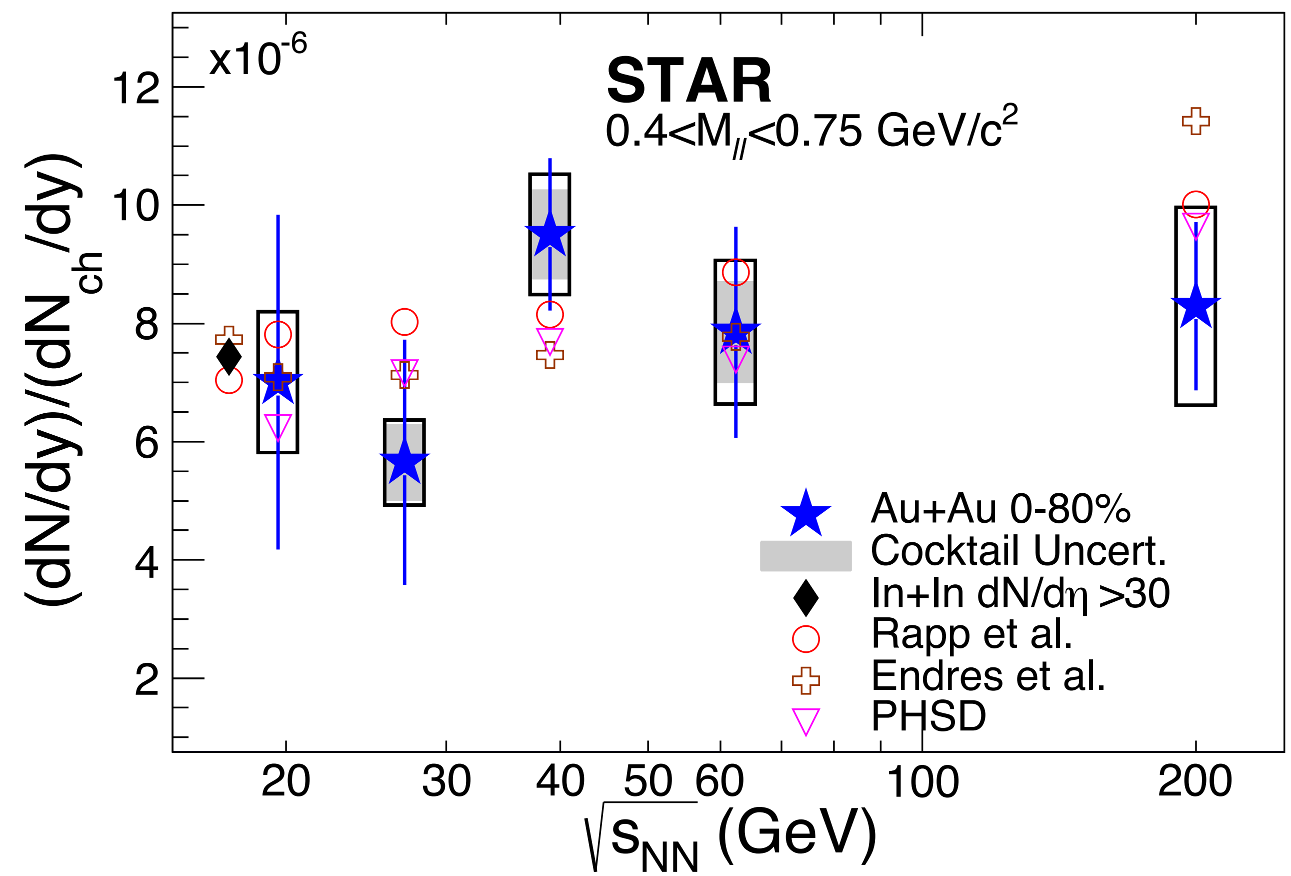




STAR: PRL 112 162301 (2014), PRL 120 (2018) 62301
Y.Nara et al. PLB769 (2017) 543

Low mass di-lepton excess





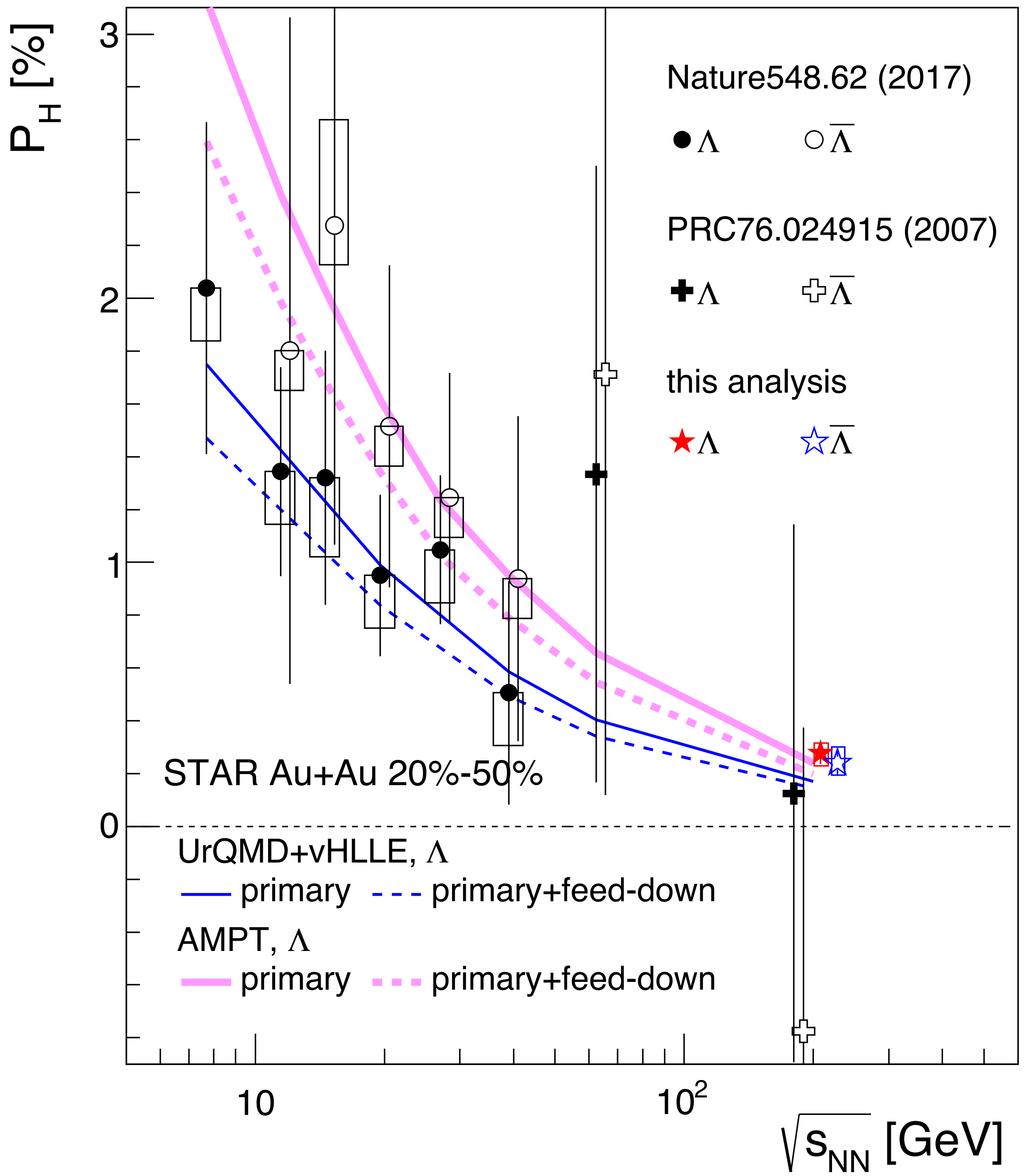
Above 20 GeV
Total baryon density ~constant
T_{fo} also ~constant

Low mass excess independent of beam energies and centralities

Consistent with models incorporating ρ broadening

Excess driven by convolution of **total baryon** density, **hot dense** medium effects and the medium's **lifetime**

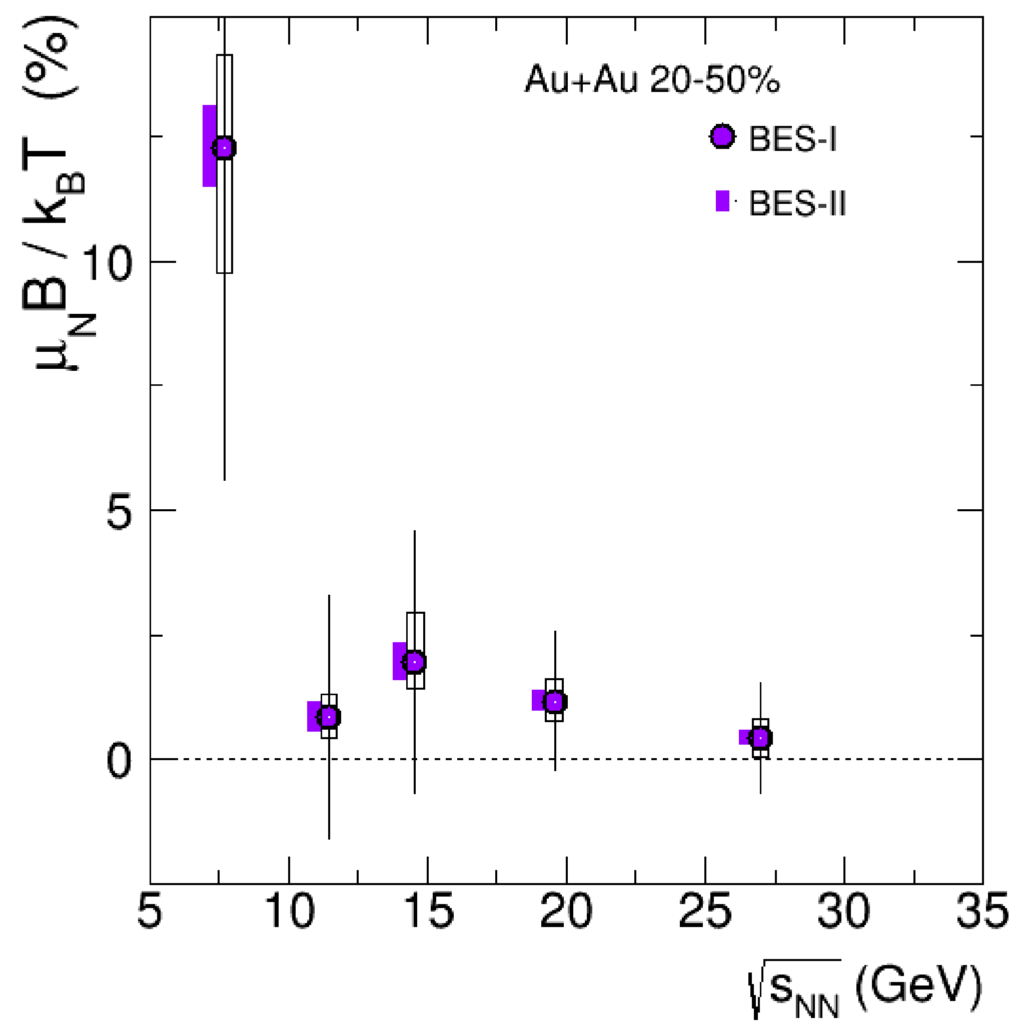
Sensing the magnetic field



Non-zero measurement now demonstrated 200 GeV

Also as function of centrality and p_T

Consistent polarization for particle and anti-particle (within statistical precision)



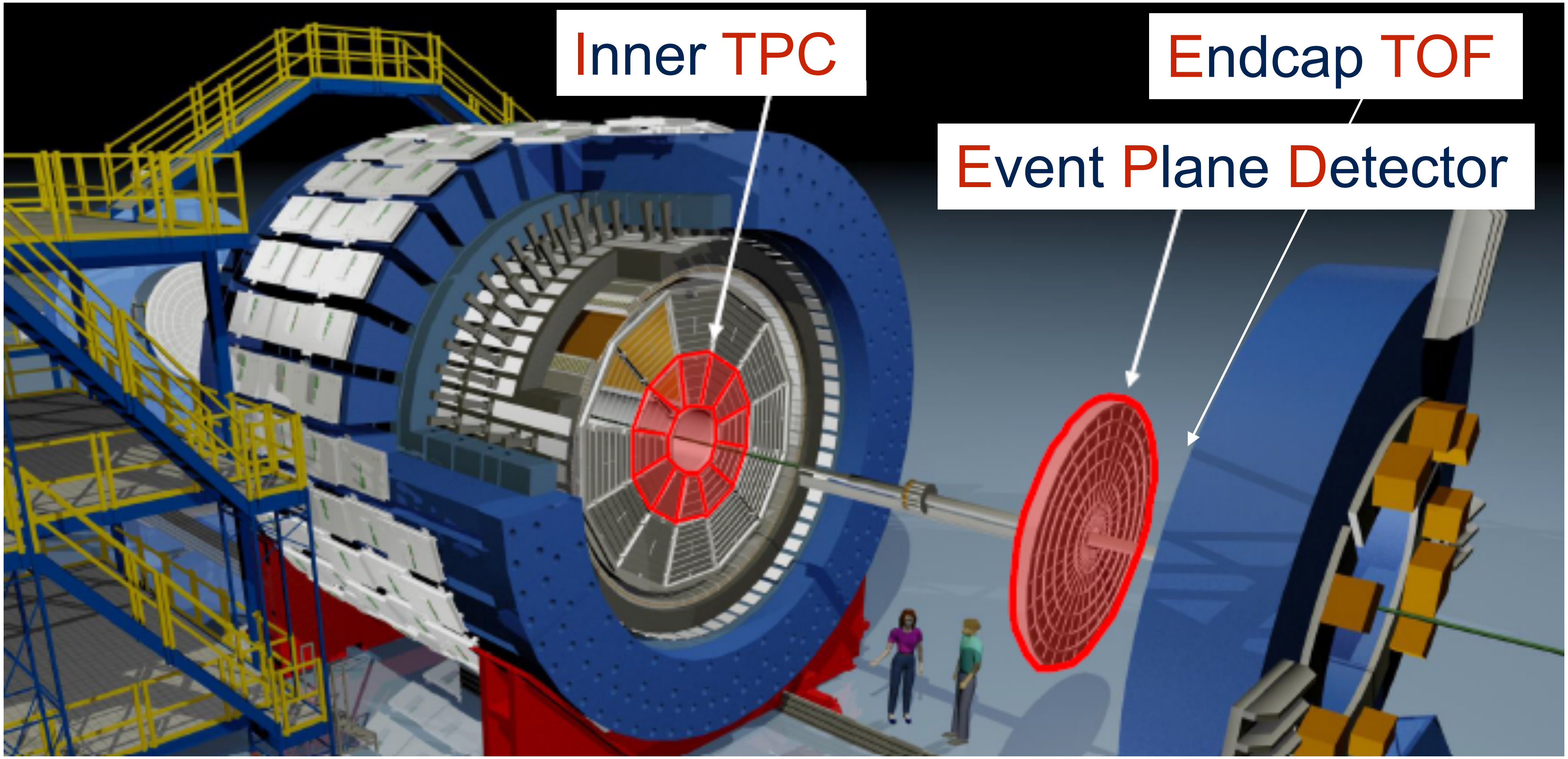
Difference ∝ B-field/T

10% on y axis corresponds to 8×10^{14} T

BES-II resolve >5σ difference

STAR: PRC **98** (2018) 14910

STAR upgrades for BES-II

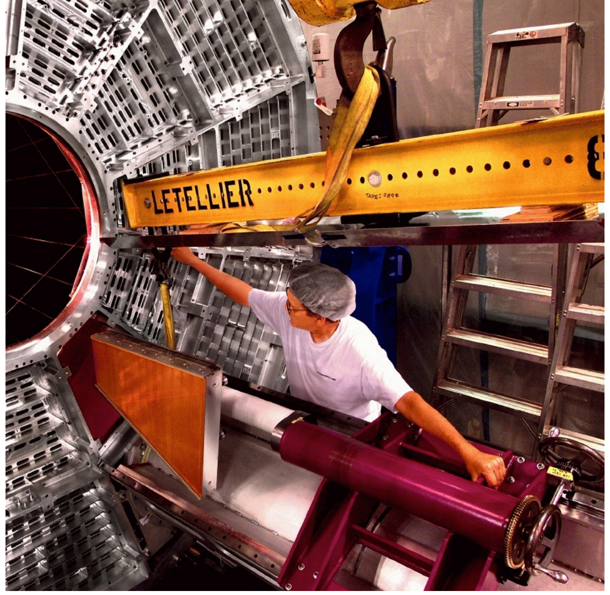


Enhanced Acceptance
Enhanced PID mid and forward
Enhanced Event Plane Resolution
Enhanced Centrality Definition
Enhanced √s range

⟺

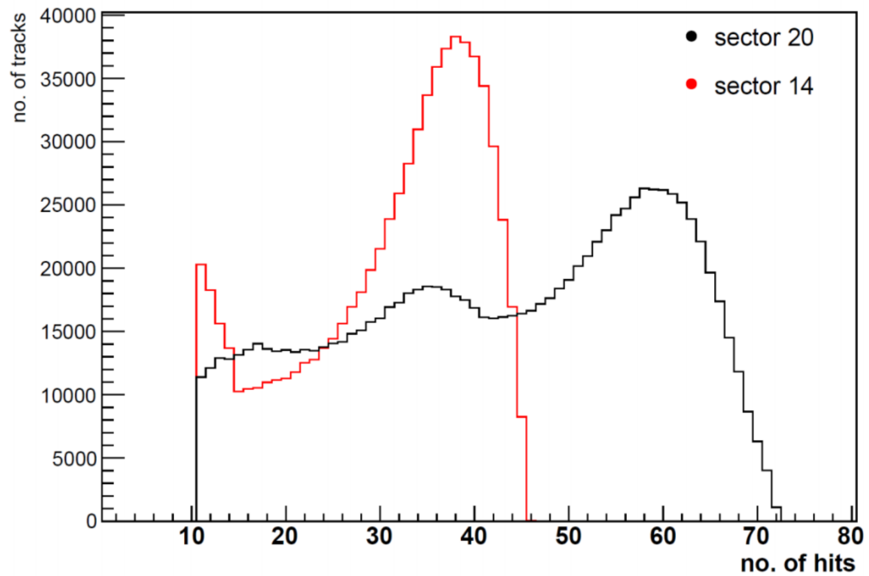
iTPC, EPD, eTOF (joint with CBM/Fair Phase0), Fixed target

iTPC: first commissioning results

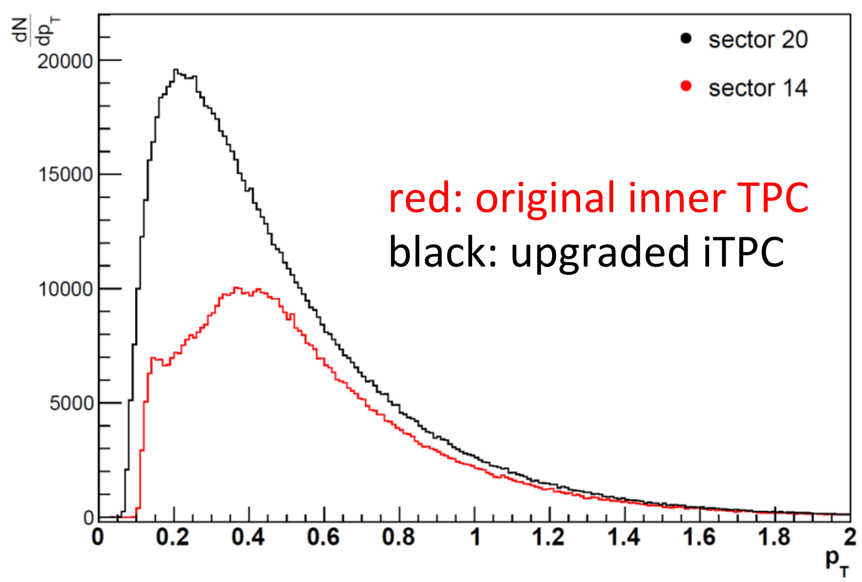


One sector installed and operated in Run 18

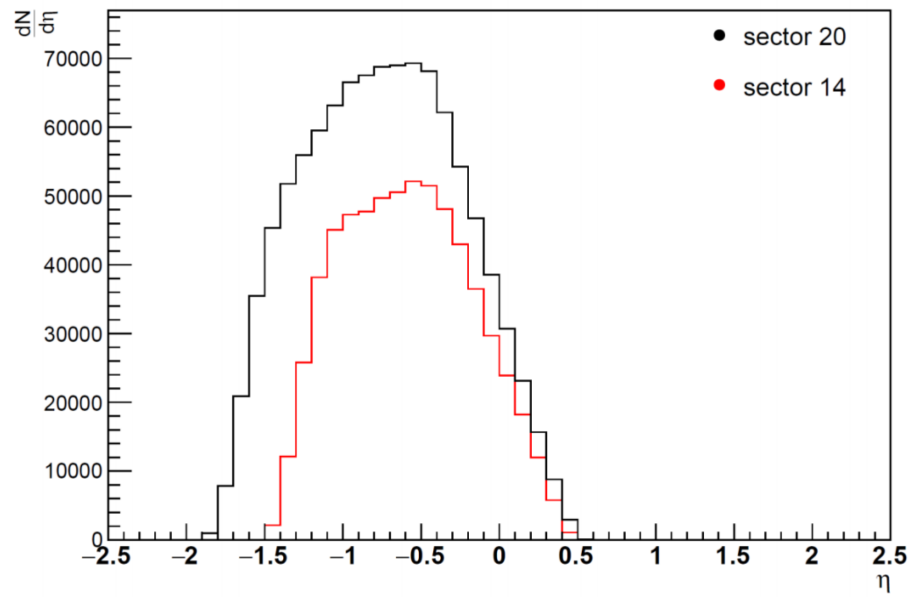
Analysis software for iTPC fully functional



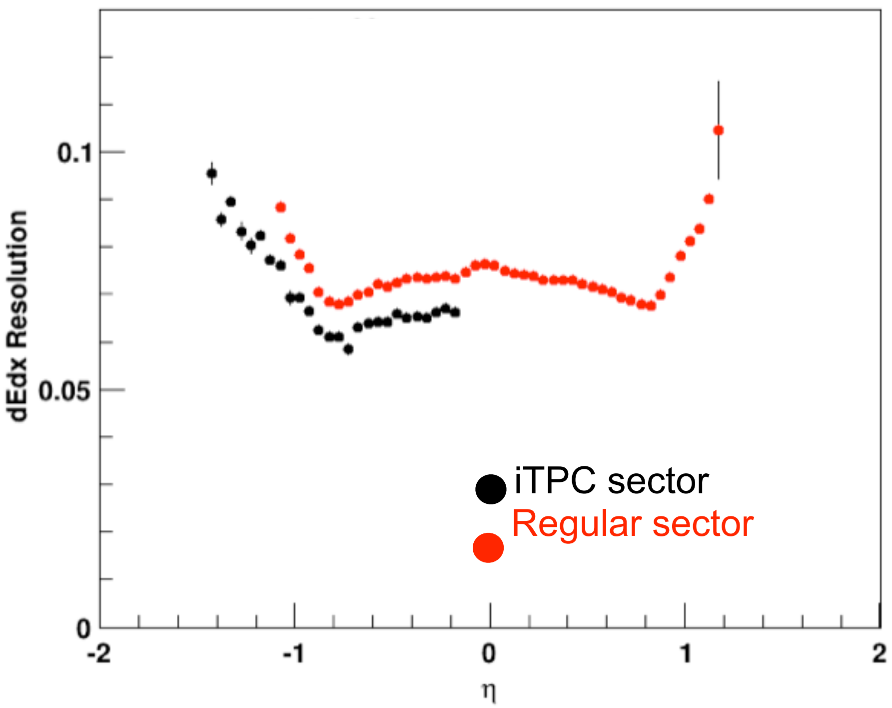
Hits/track 45—> 72



p_T threshold 60 MeV/c



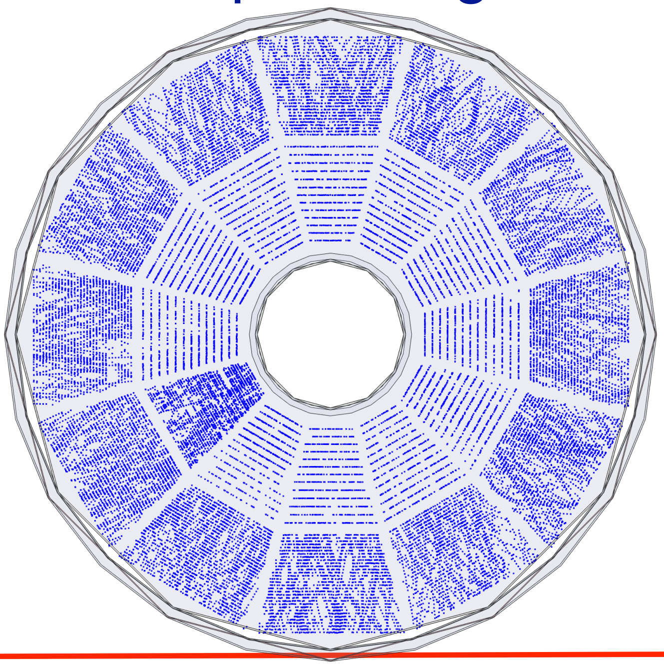
η coverage to 1.7



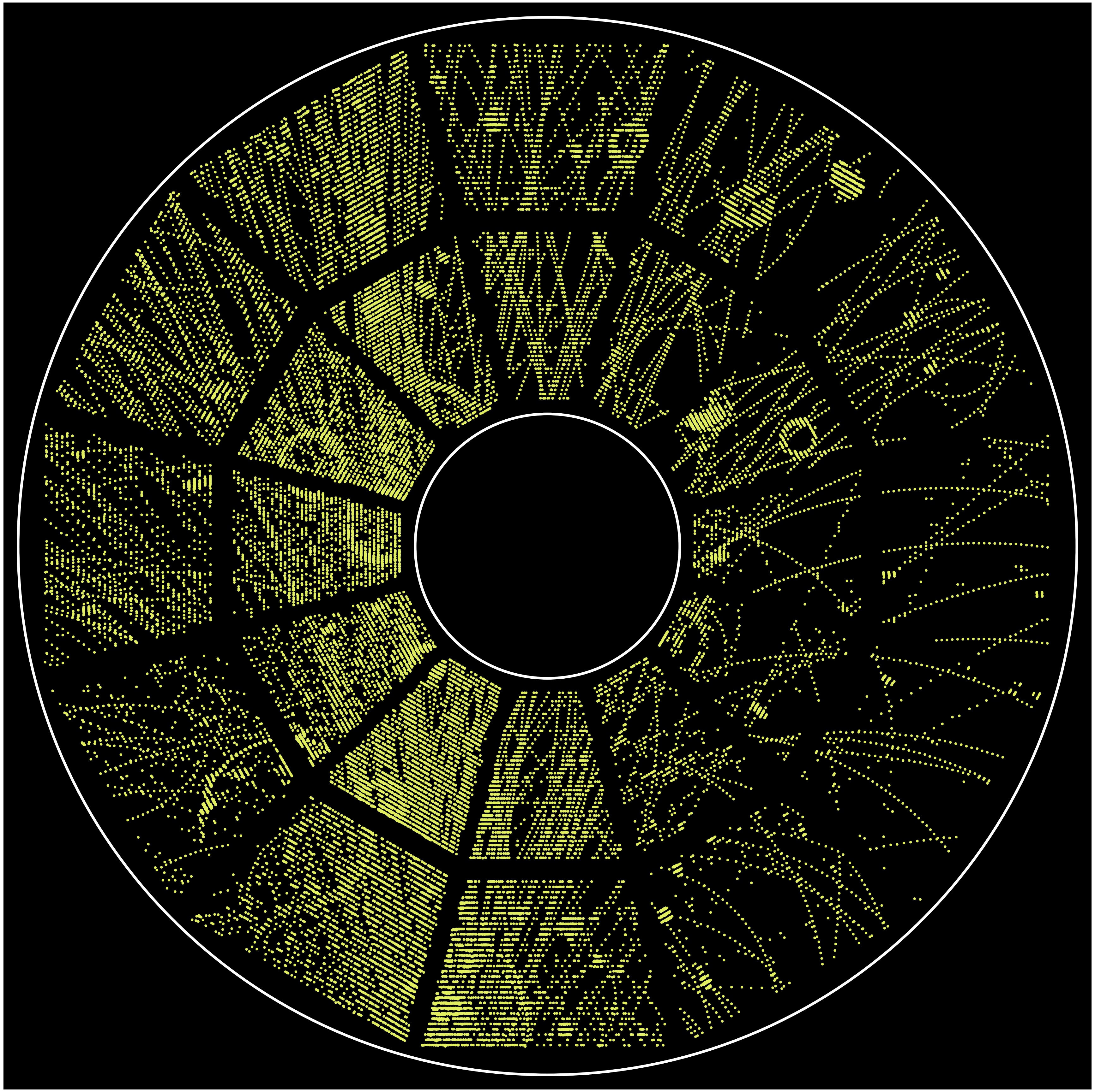
dE/dx performance improvement

Performance so far reaching expectations

Cosmic ray commissioning underway

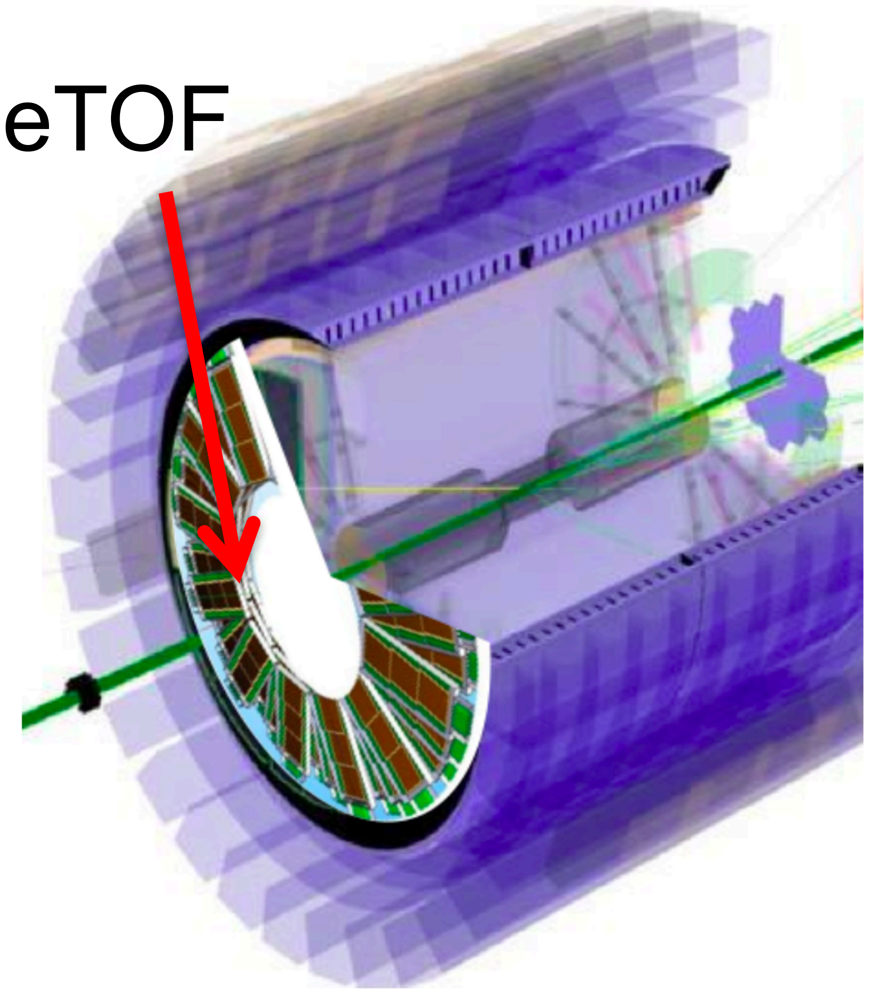


The whole TPC is back in action!



Cosmic ray
Feb 2019

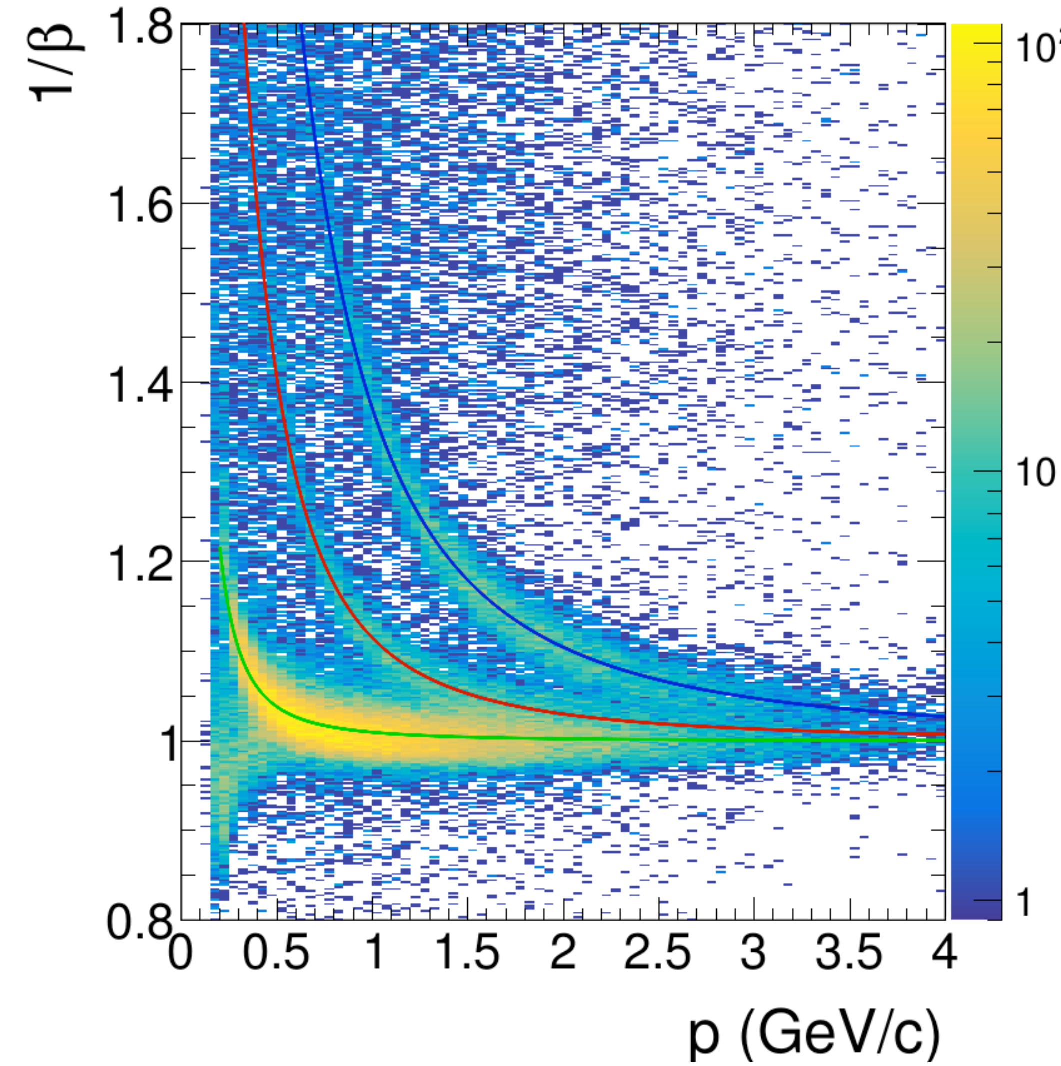
Endcap Time-Of-Flight: eTOF



Forward PID over iTPC η range

$-1.6 < \eta < -1.1$

TPC dE/dx effic. drops rapidly in this range due to p_Z boost



Clear 1/ β bands visible

Joint STAR-CBM agreement

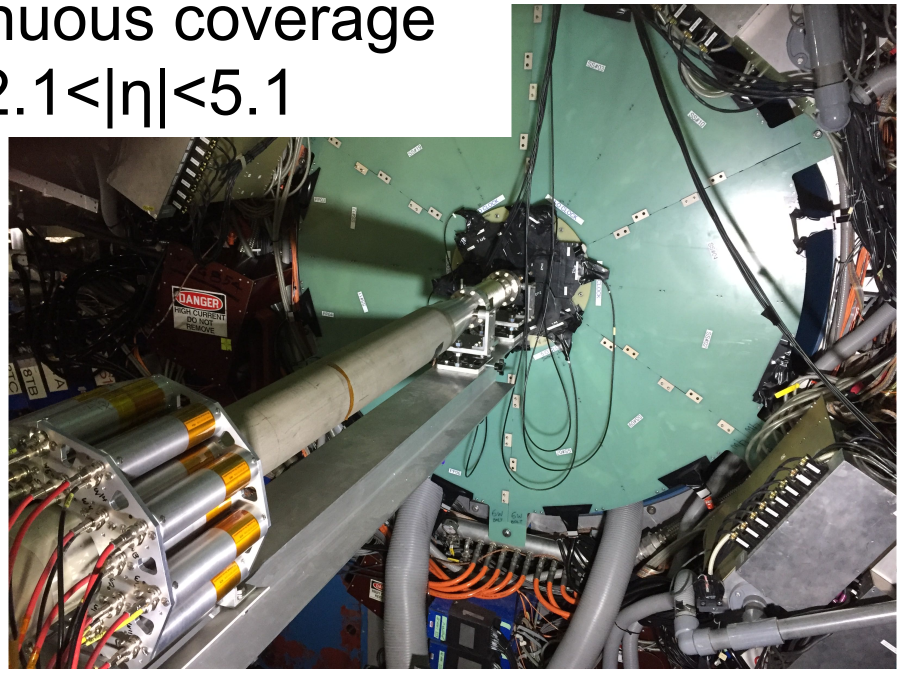
- 36 (1/10th) MRPC based TOF modules installed inside East pole-tip
- Large-scale integration test of system for CBM

3 modules in data taking in Run 18

Full detector currently being commissioned

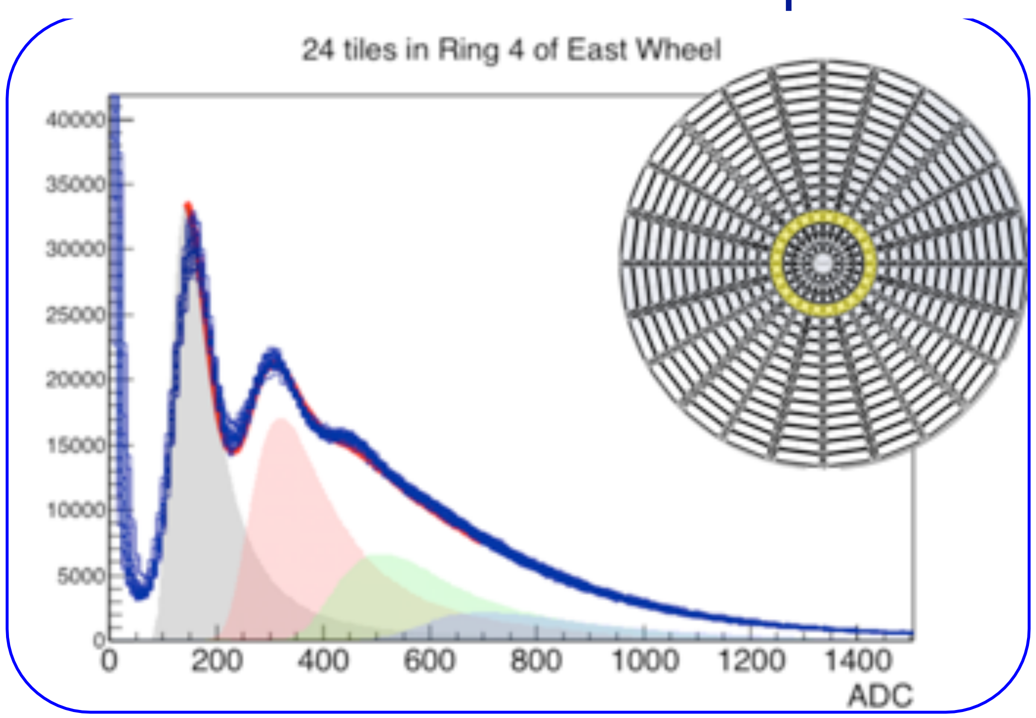
Event Plane Detector: EPD

Replacing BBC
Continuous coverage
2.1<|η|<5.1



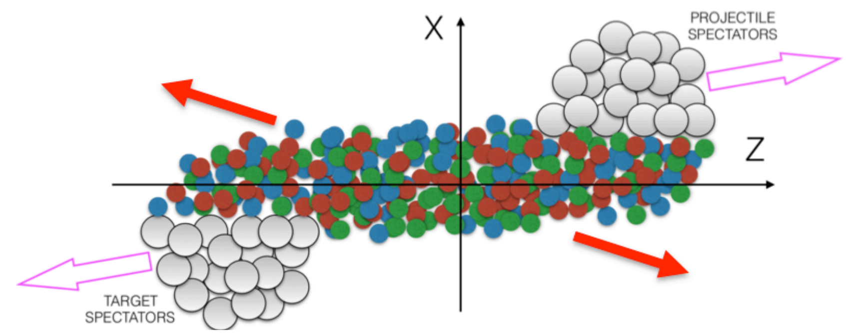
744/744 channels timed in and fully operational within first day of operations

Extremely uniform and stable tile operation
Well-understood response



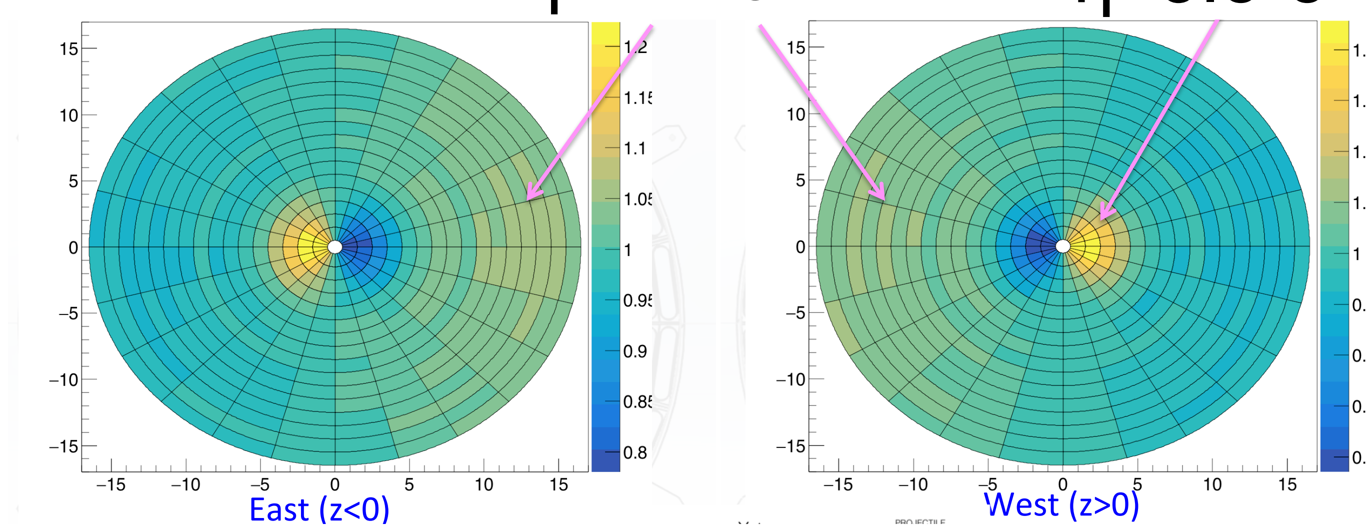
Determine Centrality away from mid-rapidity
Better trigger & background reduction

Greatly improved EP Resolution especially 1st-order EP



forward participants hotspots η~2-2.5

spectators hotspot η~3.5-5



At 27 GeV - Directed flow over 10 units

Summary

Wealth of data published for $\sqrt{s}$ = 7-200 GeV by STAR and PHENIX

Strong theoretical interest

Significantly extended detection capabilities installed and operational

iTPC → enhanced y- p_T acceptance

EPD → crucially improved EP resolution

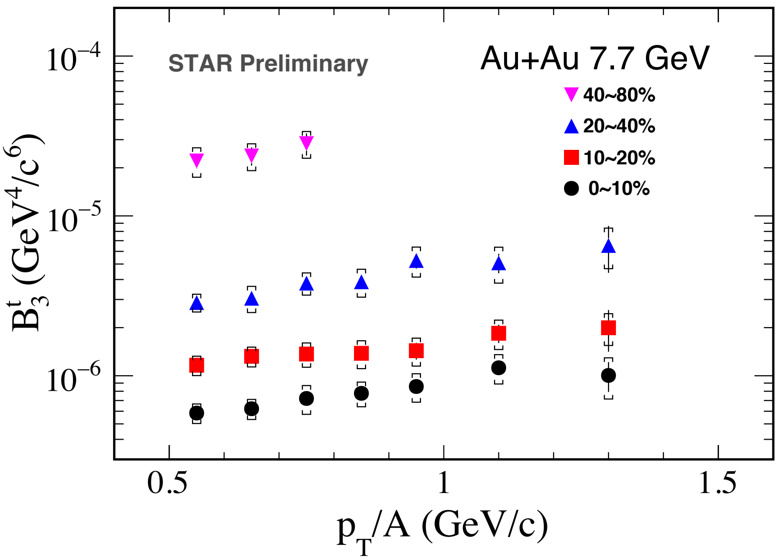
eTOF → significant improvement to PID eCooling → higher beam luminosities, better statistics

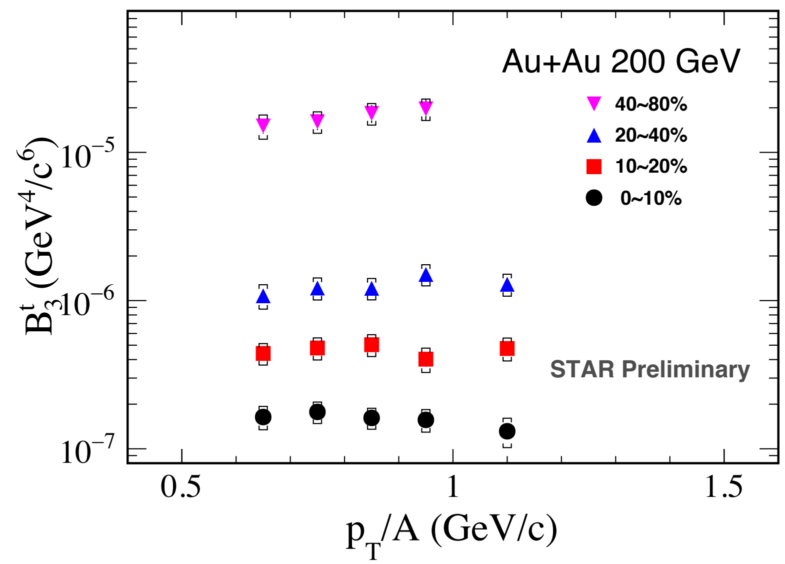
In conjunction: Turn trends and features into definitive conclusions

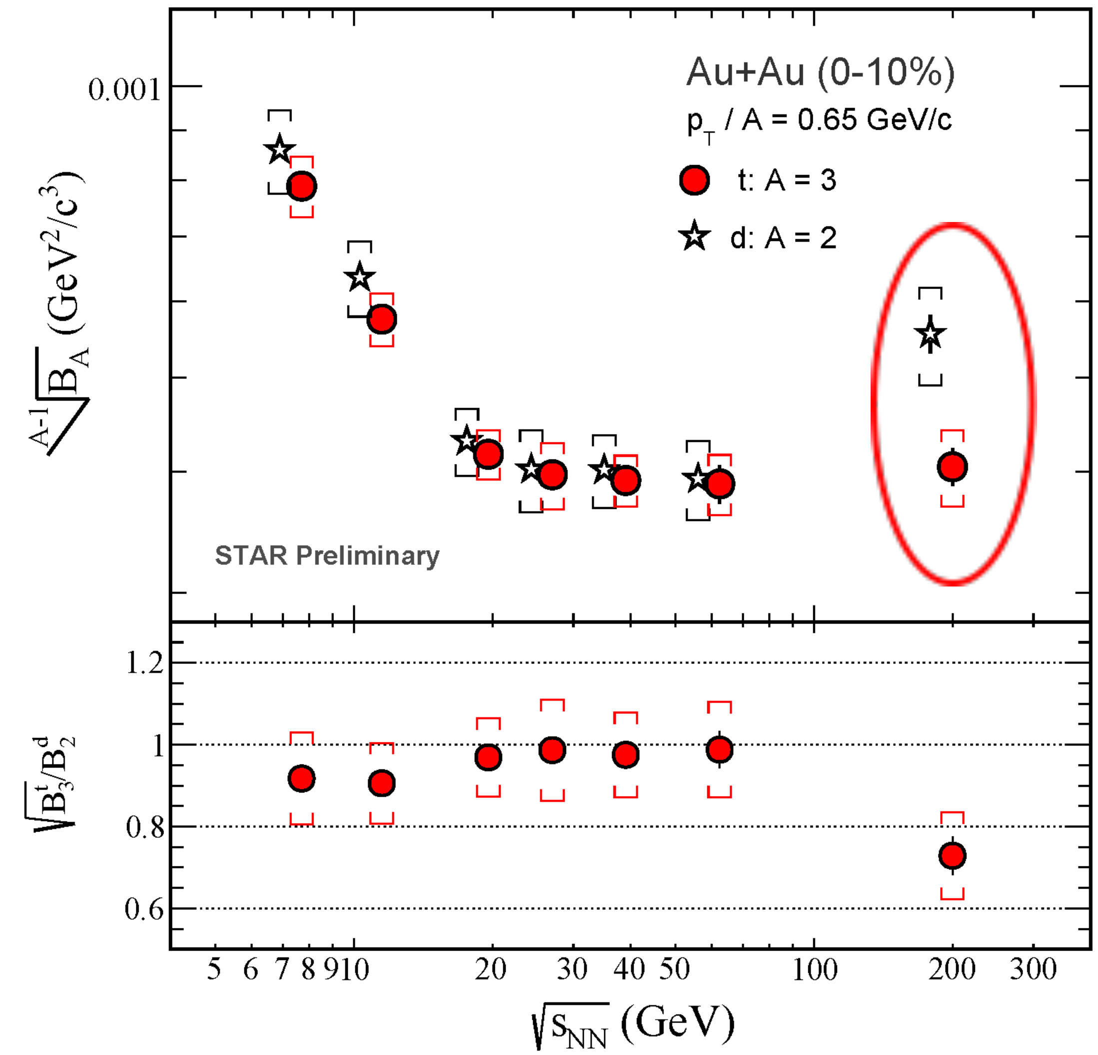
The BES-II high statistics exploration of QCD phase diagram and its key features starts next week!

BACK UP

Comparing B_2 and B_3

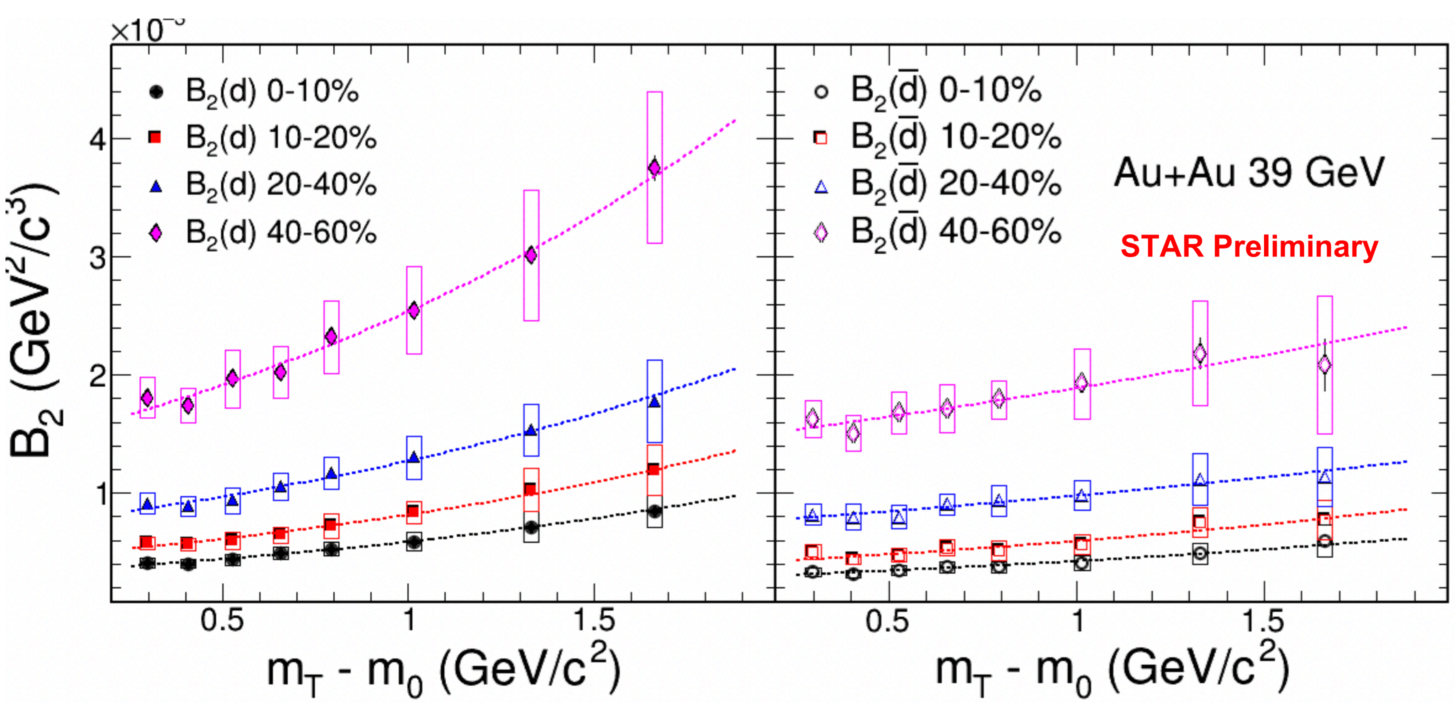






★B_3 decreases from peripheral to central collisions and with increasing collision energy.

★B_2 and $\sqrt{B_3}$ are consistent within uncertainties except 200 GeV.



$$B_2 = a \cdot \exp[b(m_T - m)]$$

★The values of B_2 increase as a function of m_T and decrease with collision centrality: collective expansion.

Presence of Critical Point?

Critical Points:

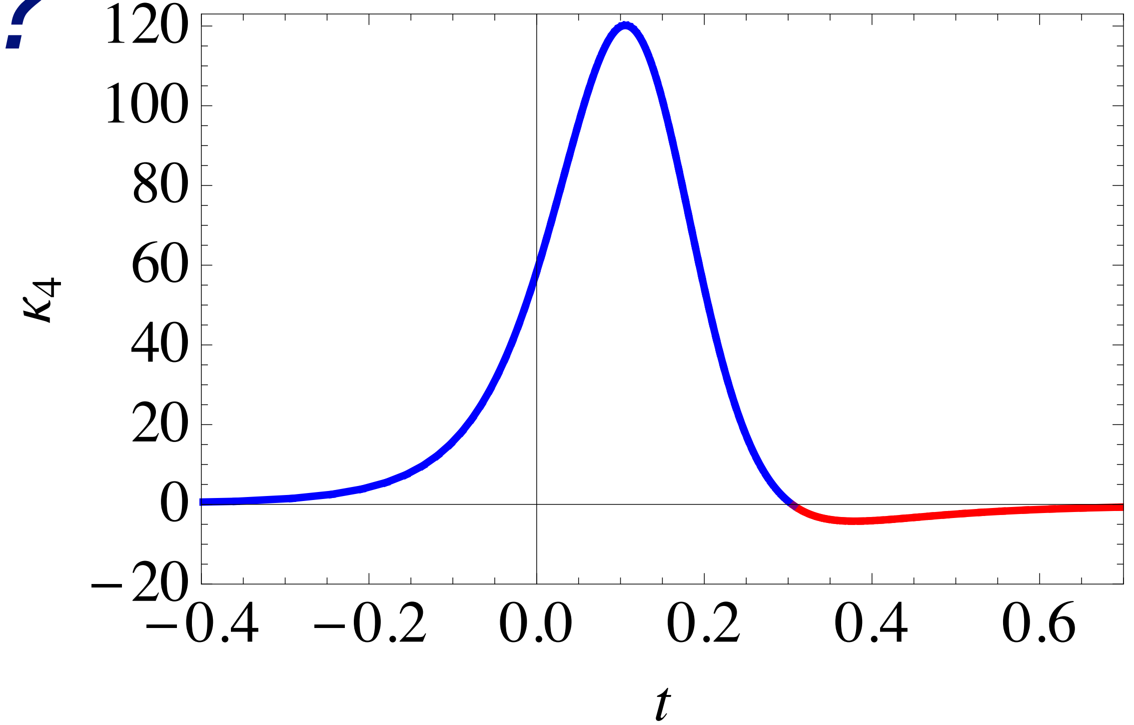
divergence of susceptibilities

e.g. magnetism transitions

divergence of correlation lengths

e.g. critical opalescence

M. Stephanov. PRL 107:052301(2011)



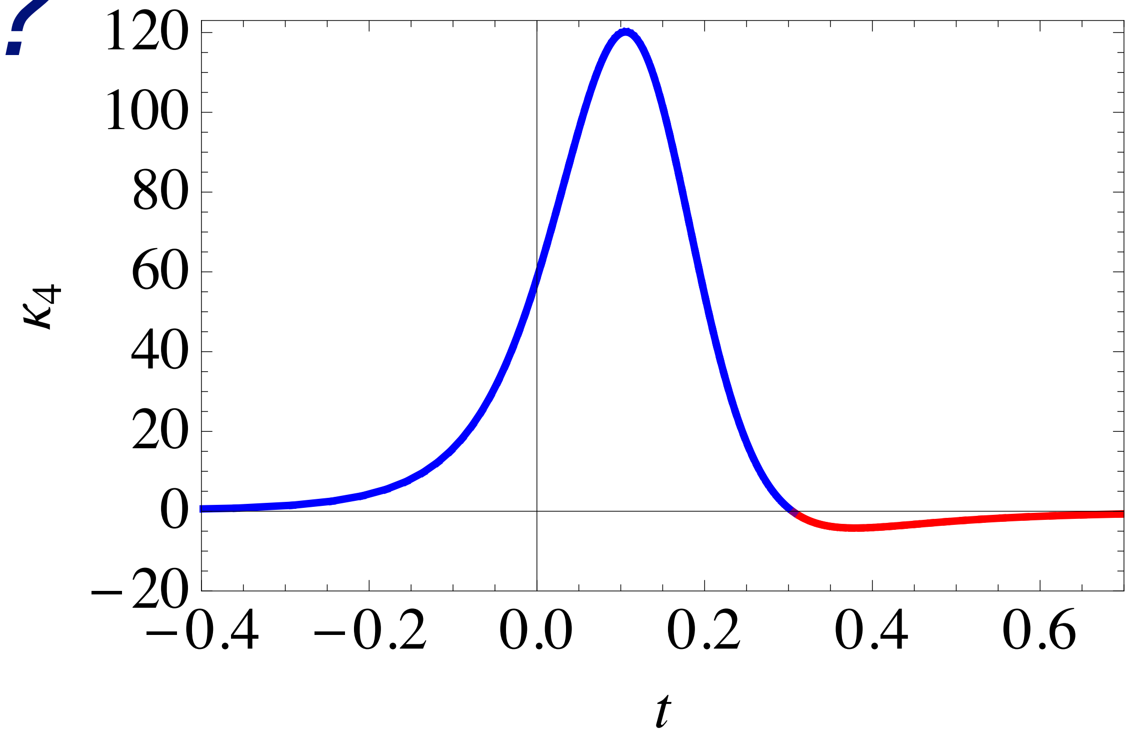
Correlation lengths diverge →

Net-p $\kappa\sigma^2$ diverge

Presence of Critical Point?

Critical Points:
- divergence of susceptibilities
  - e.g. magnetism transitions
- divergence of correlation lengths
  - e.g. critical opalescence

M. Stephanov. PRL 107:052301(2011)



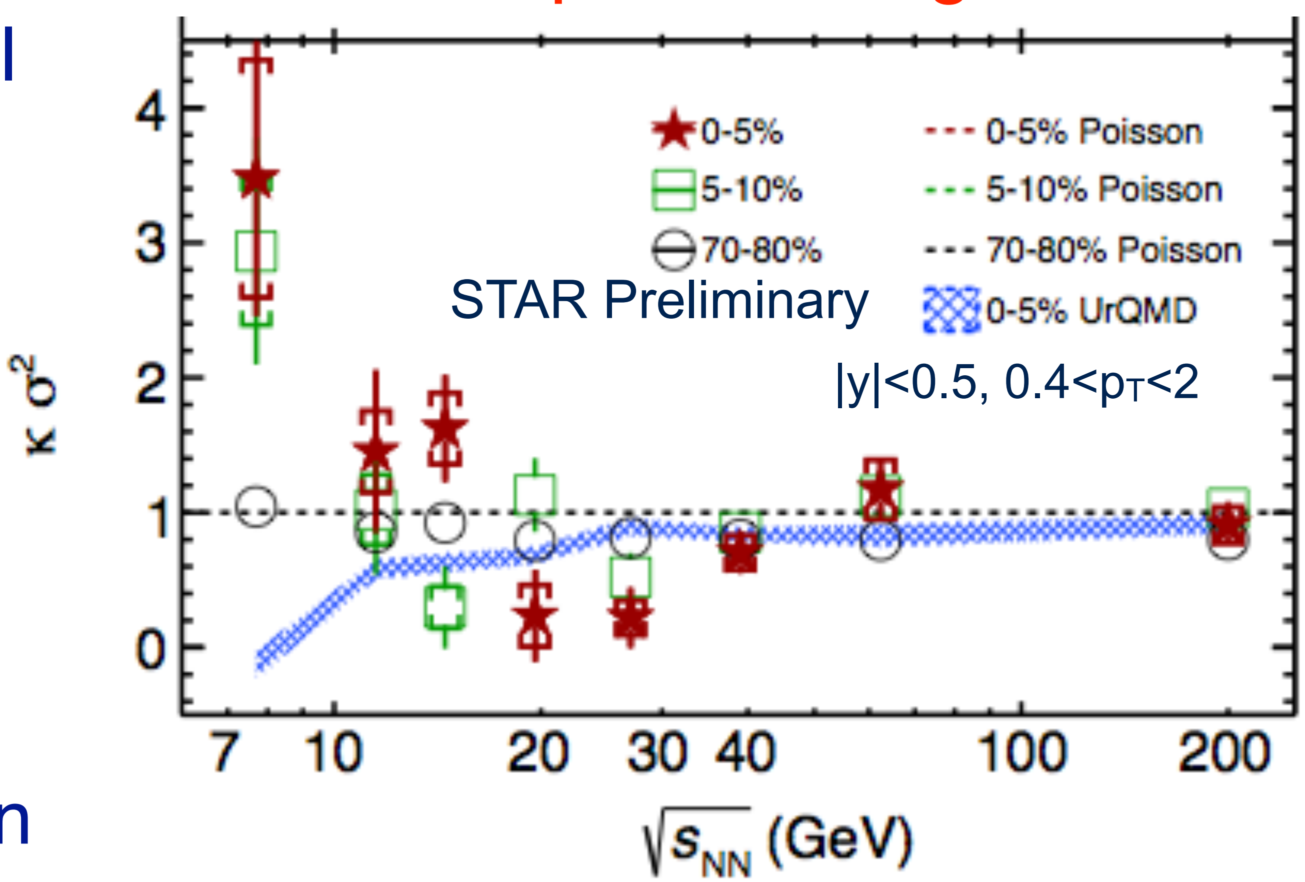
Correlation lengths diverge → Net-p $\kappa\sigma^2$ diverge

Top 5% central collisions:
- Non-monotonic behavior
- Enhanced p_T range → enhanced signal

Peripheral collisions:
- smooth trend

5-10% central collisions:
- in between

UrQMD (no Critical Point):
- shows suppression at lower energies
  - due to baryon number conservation



Presence of Critical Point?

Critical Points:

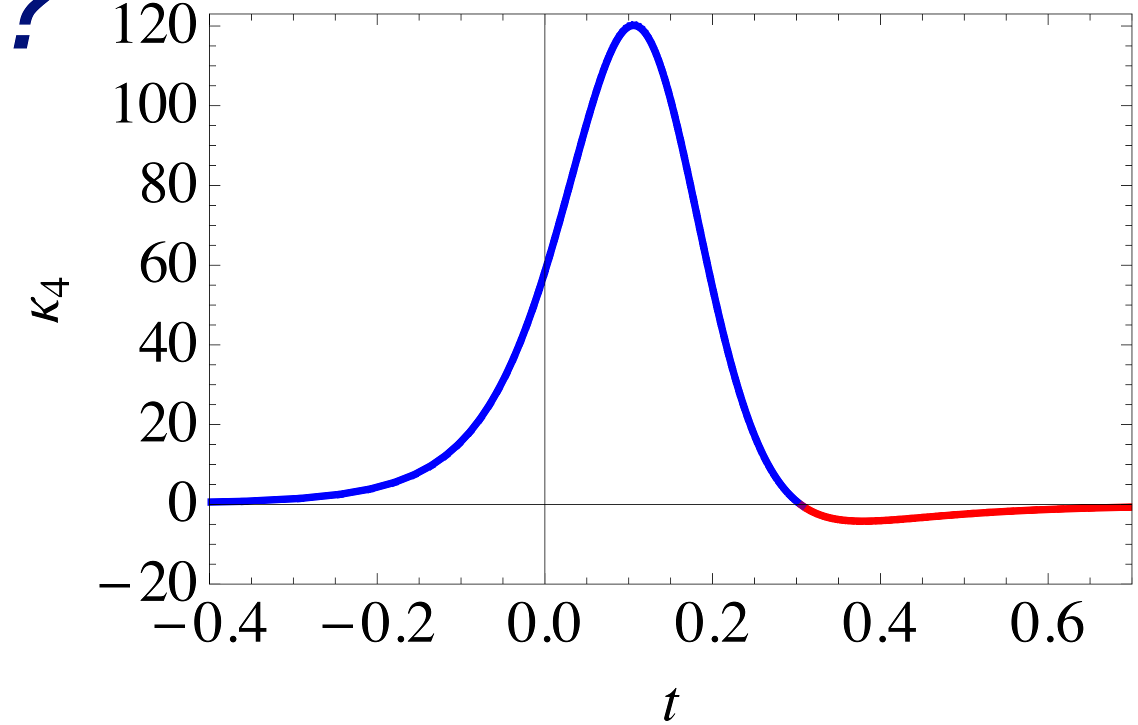
divergence of susceptibilities

e.g. magnetism transitions

divergence of correlation lengths

e.g. critical opalescence

M. Stephanov. PRL 107:052301(2011)



Correlation lengths diverge →

Net-p $\kappa\sigma^2$ diverge

Top 5% central collisions:

Non-monotonic behavior

Enhanced p_T range → enhanced signal

Peripheral collisions:

smooth trend

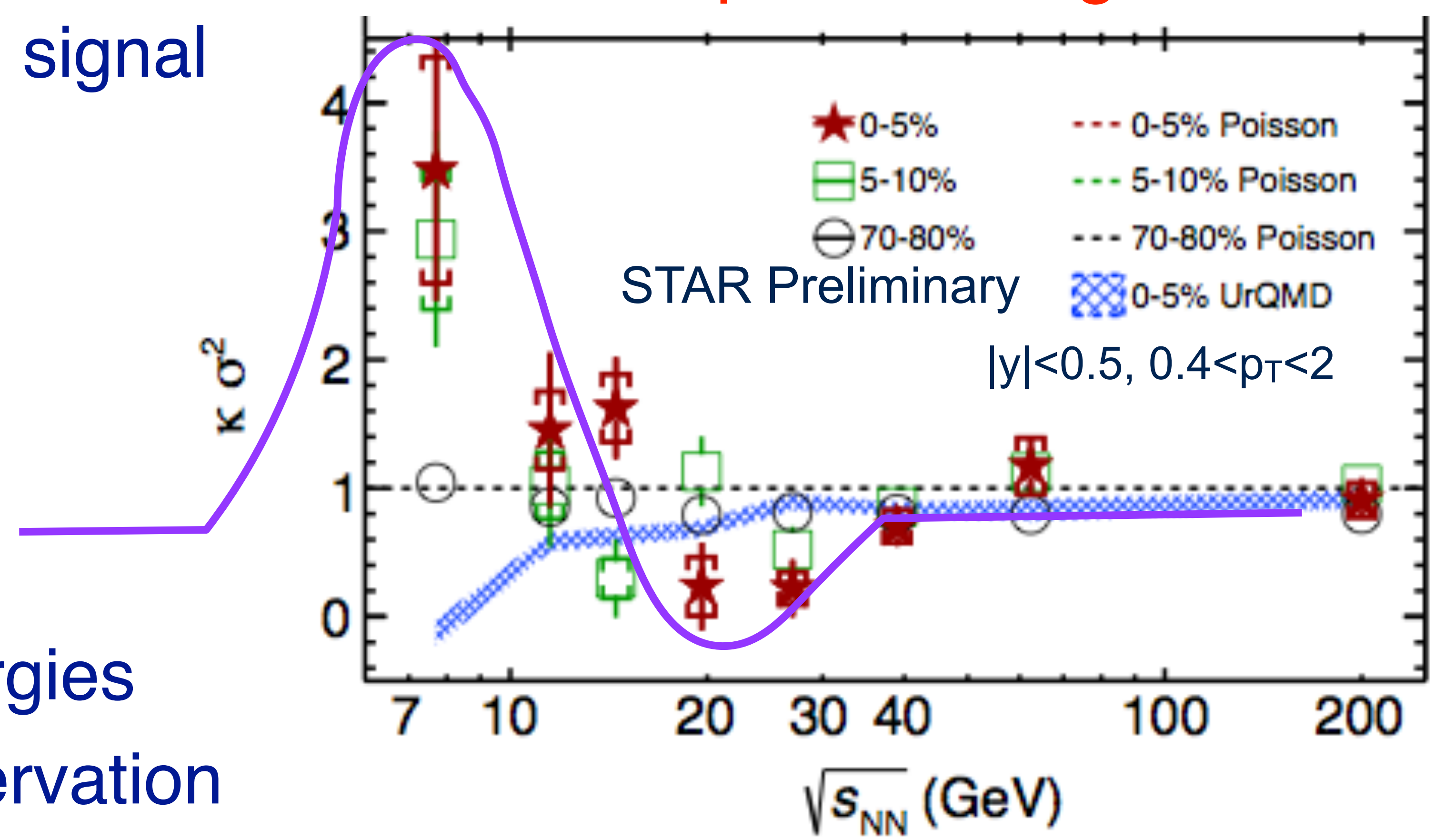
5-10% central collisions:

in between

UrQMD (no Critical Point):

shows suppression at lower energies

- due to baryon number conservation

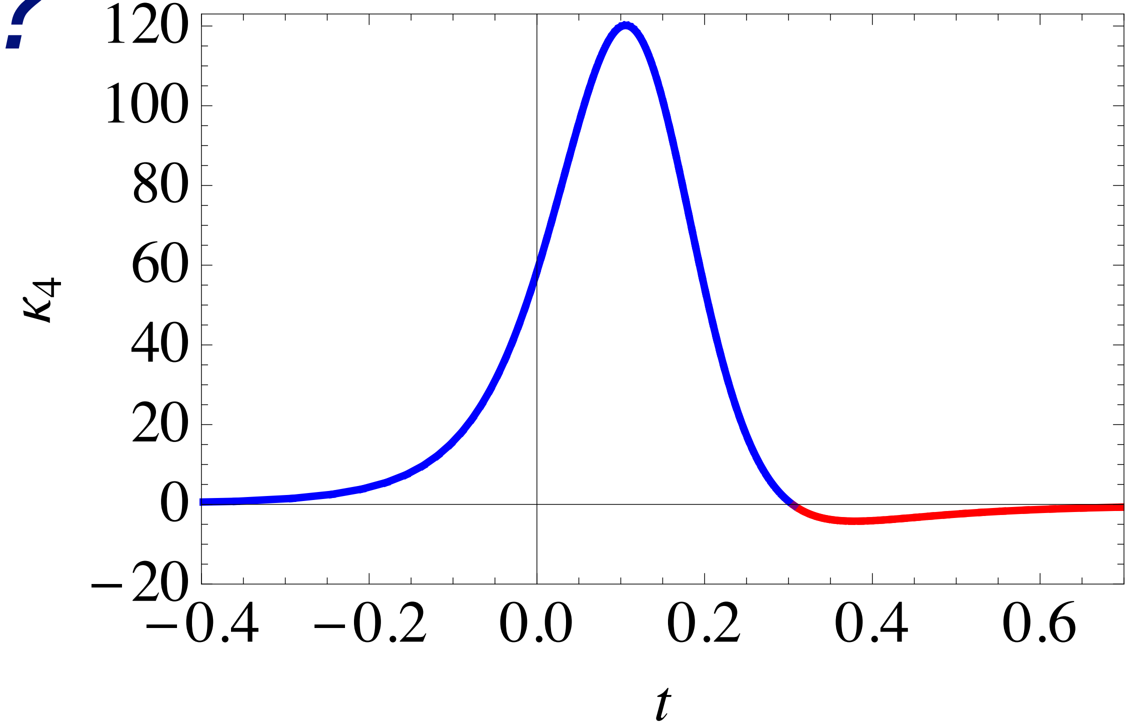


Presence of Critical Point?

HADES data + upcoming FXT
testing if mapping correct

New HADES data causing some tension

M. Stephanov. PRL 107:052301(2011)

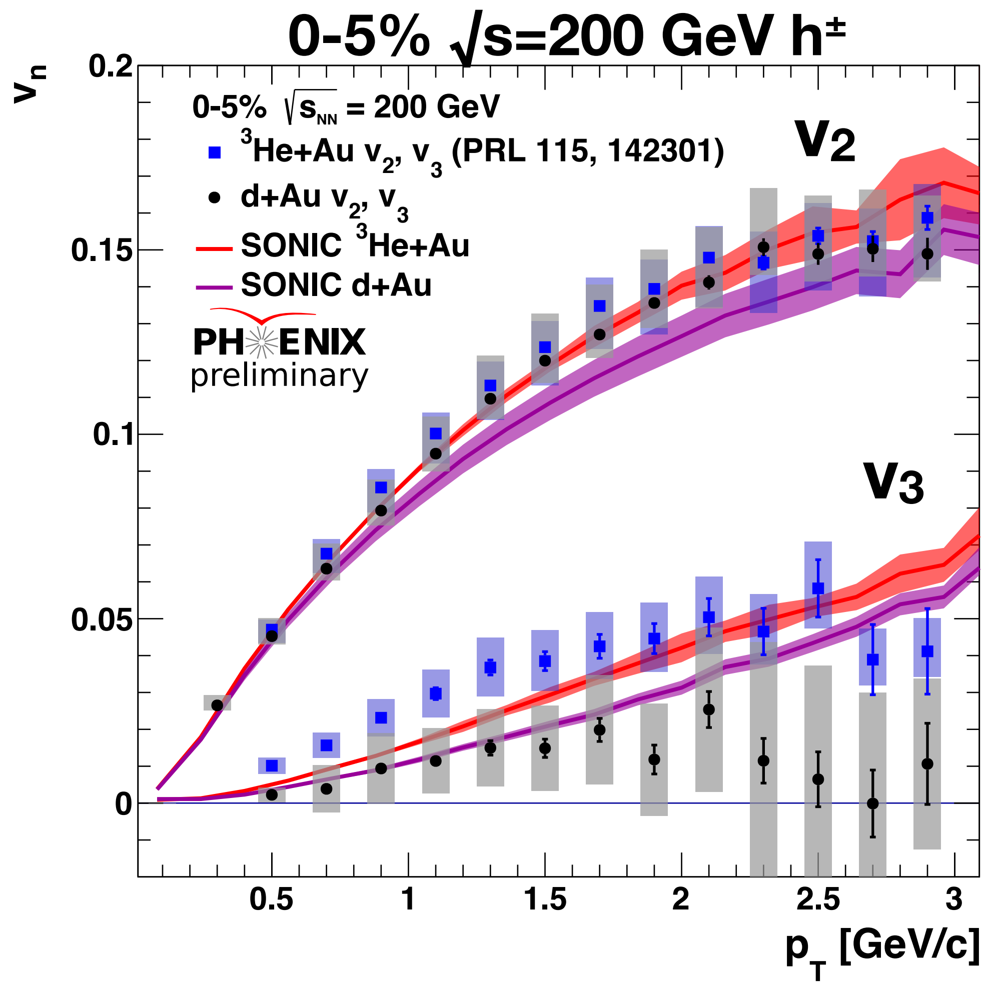


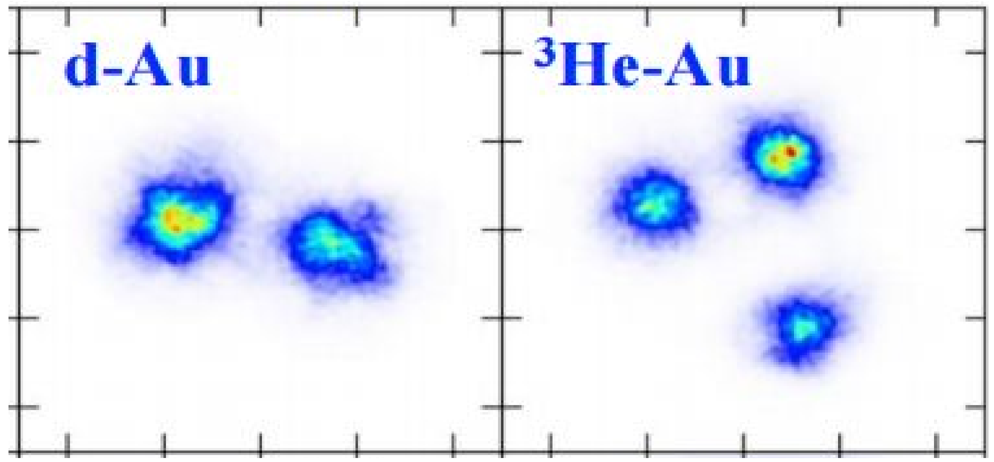
Correlation lengths diverge →

Net-p $\kappa\sigma^2$ diverge

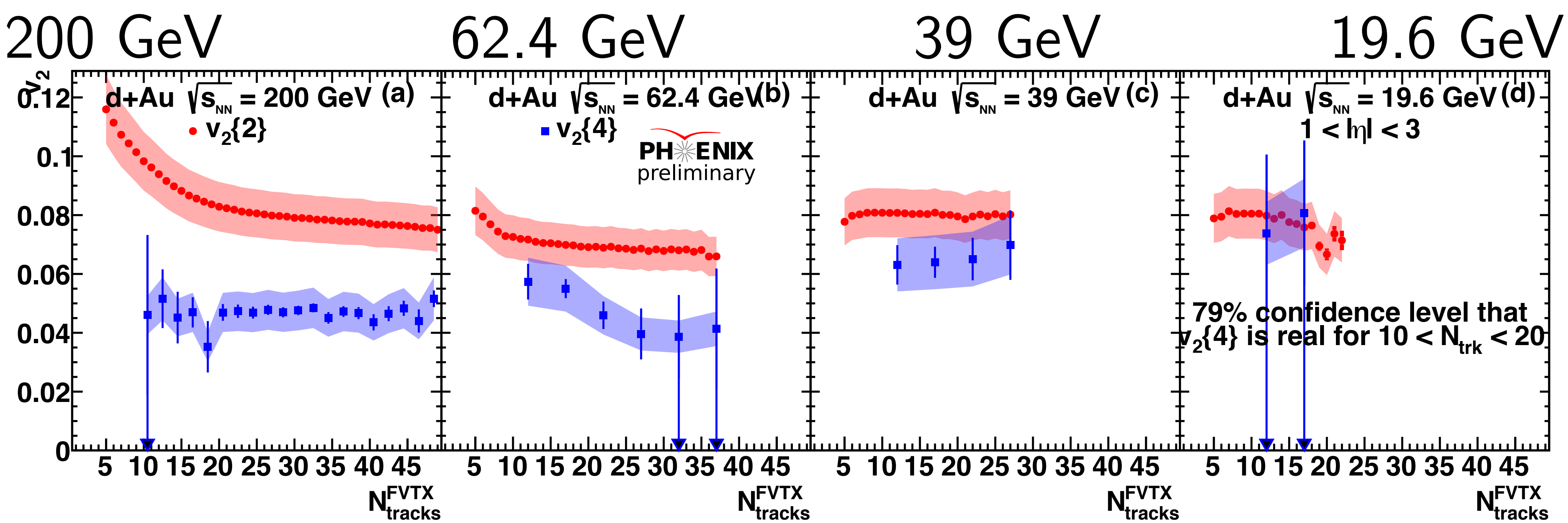
Hints of Critical fluctuations

Varying the small systems





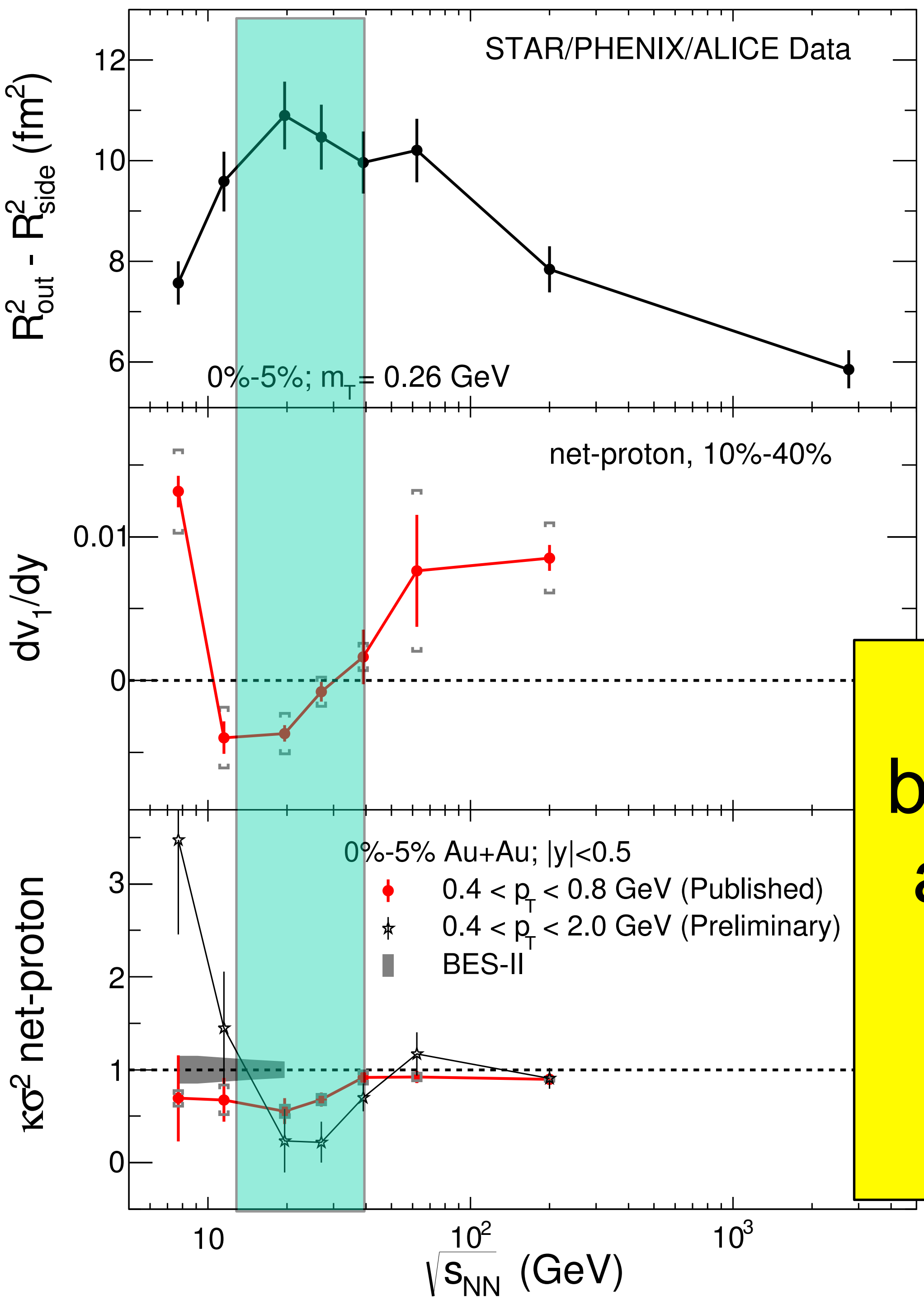
Changing initial collision geometry changes v_n as expected from models



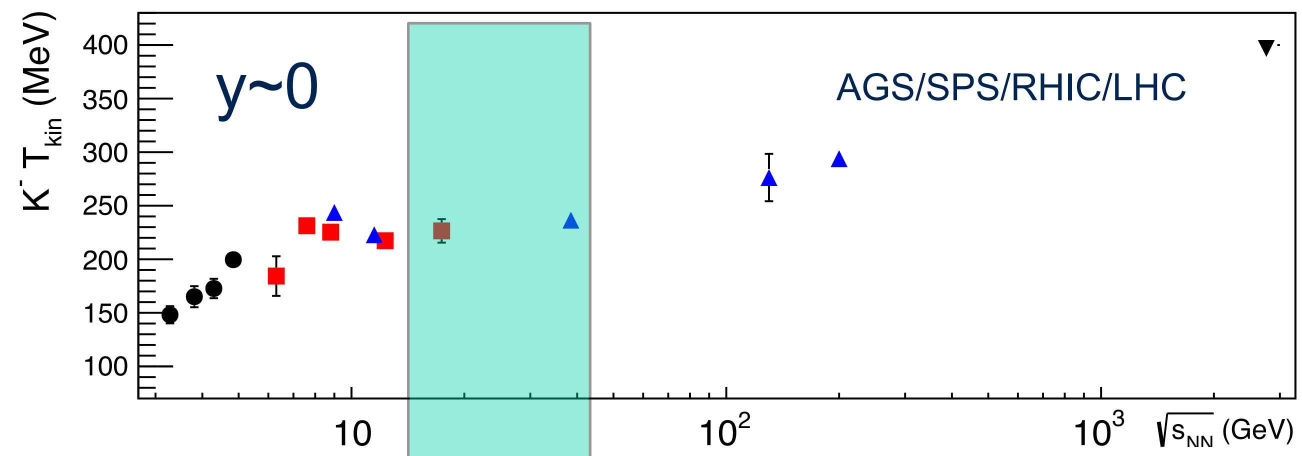
v_2 real down to 20 GeV

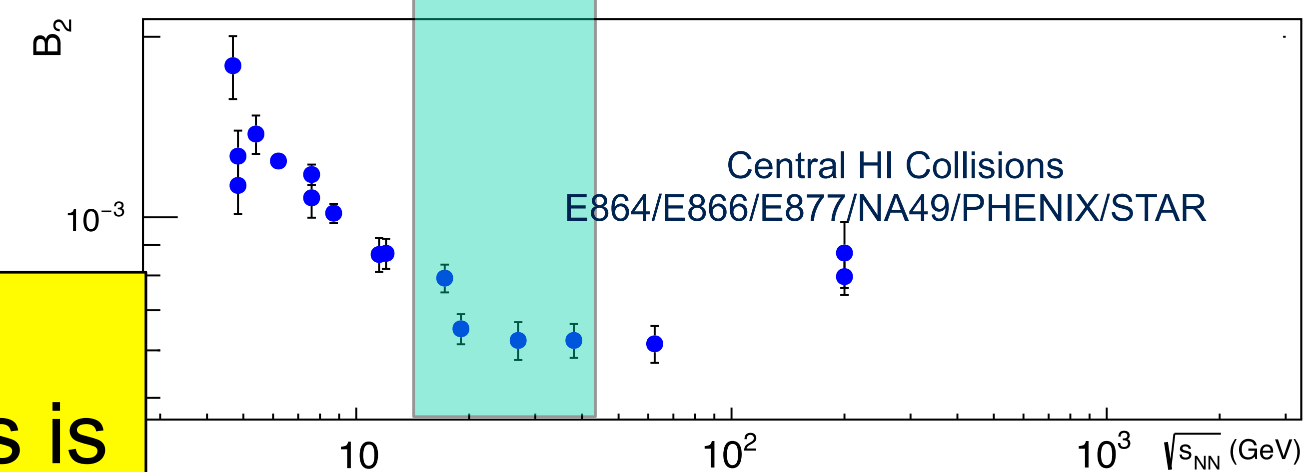
No signs of "rapid" onset in √s or mult.

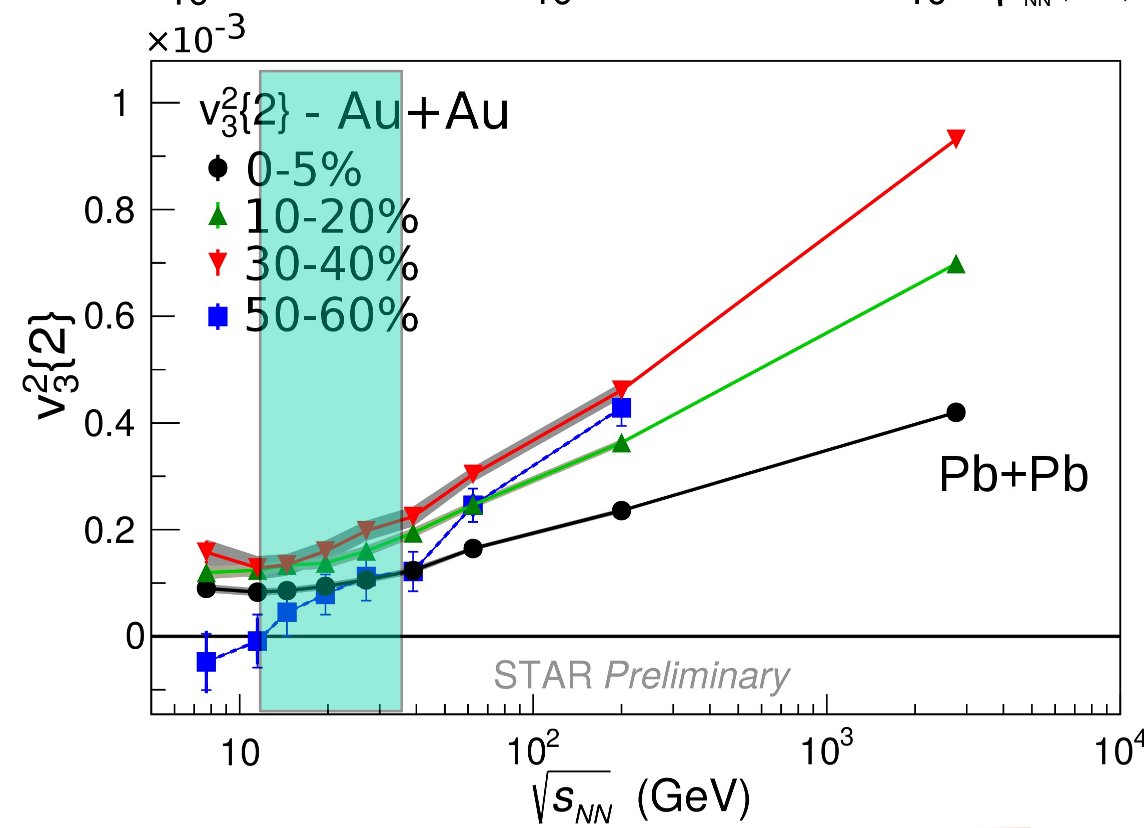
A lot is happening around 20 GeV



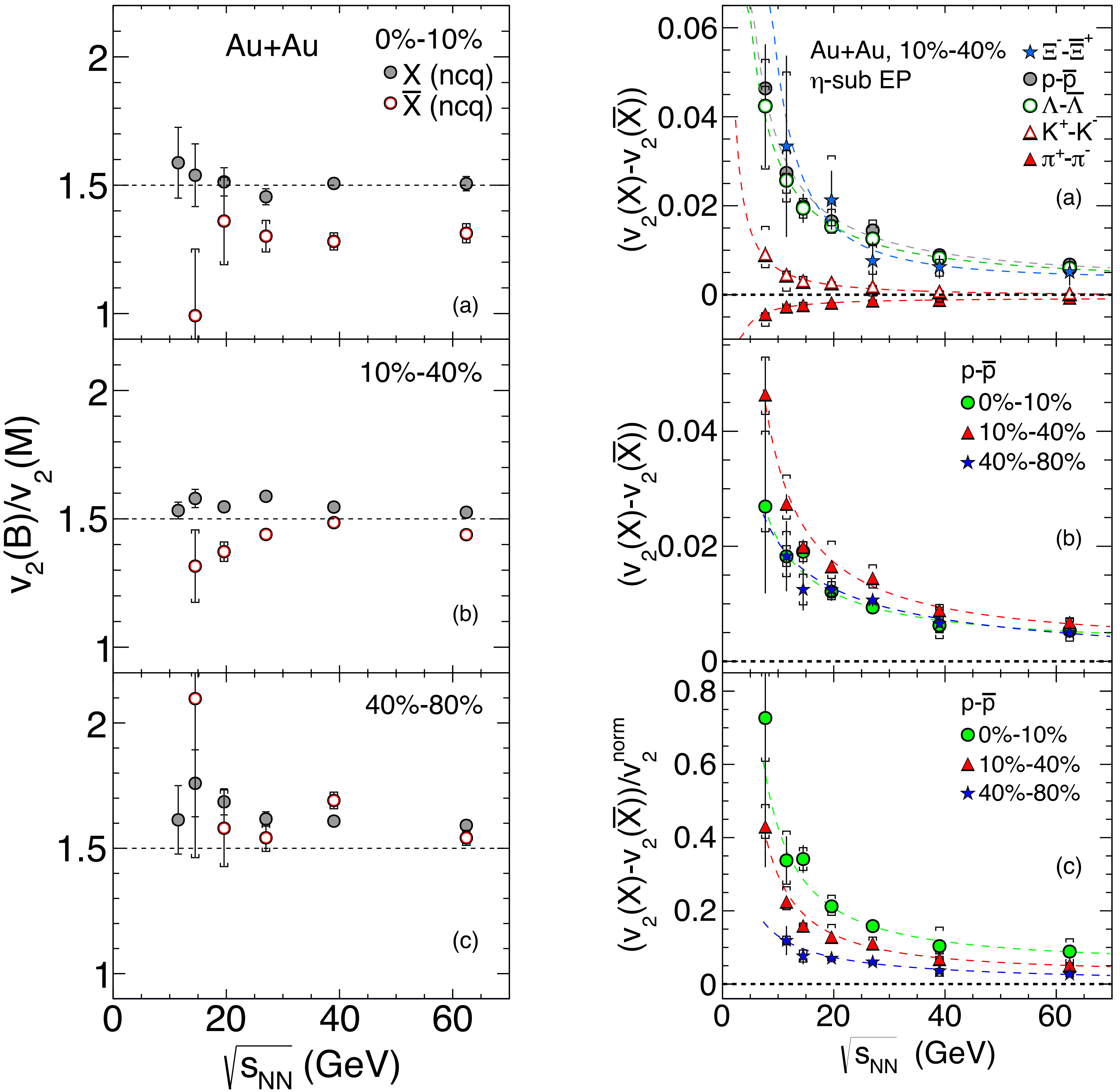
Hard to believe this is a conspiracy of different underlying causes



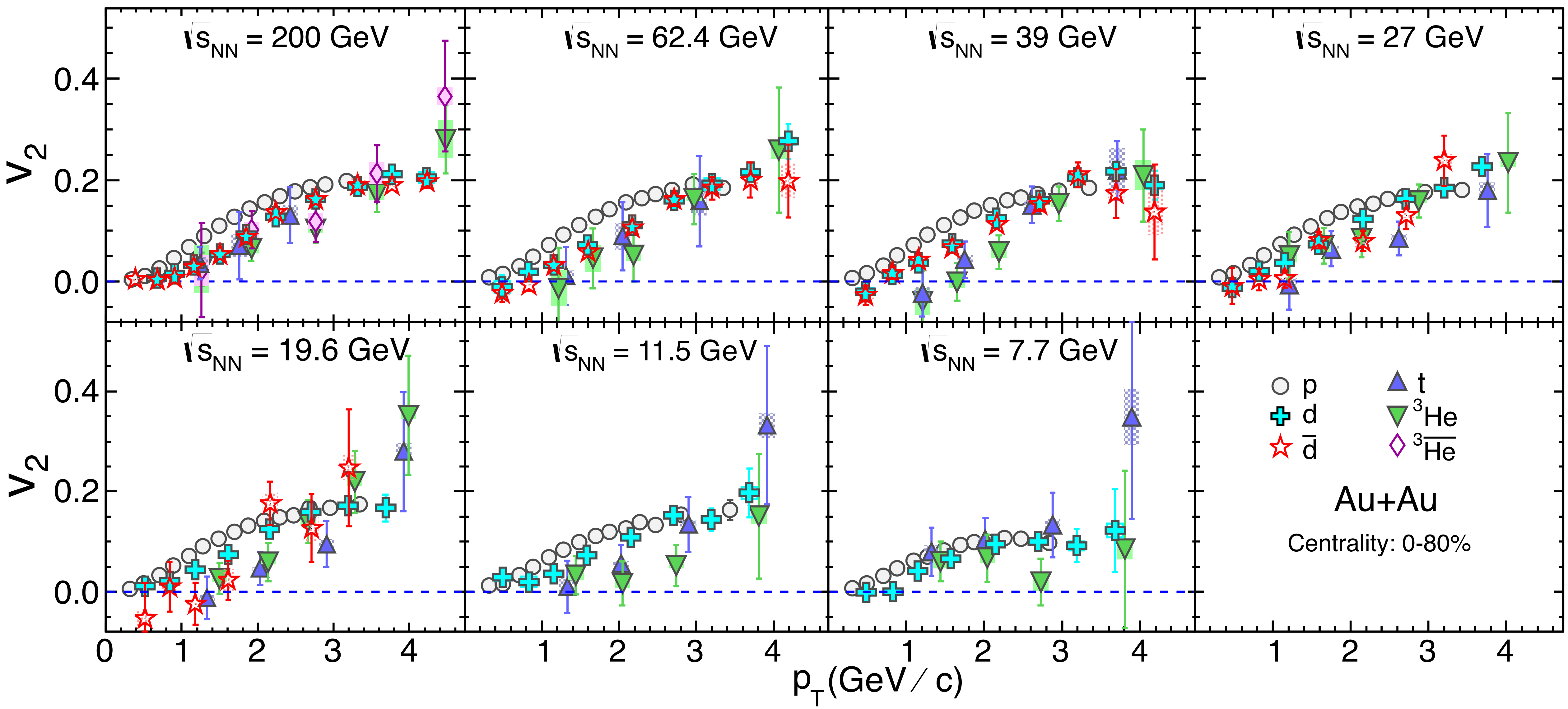




Elliptic flow in the BES



Flow of light nuclei

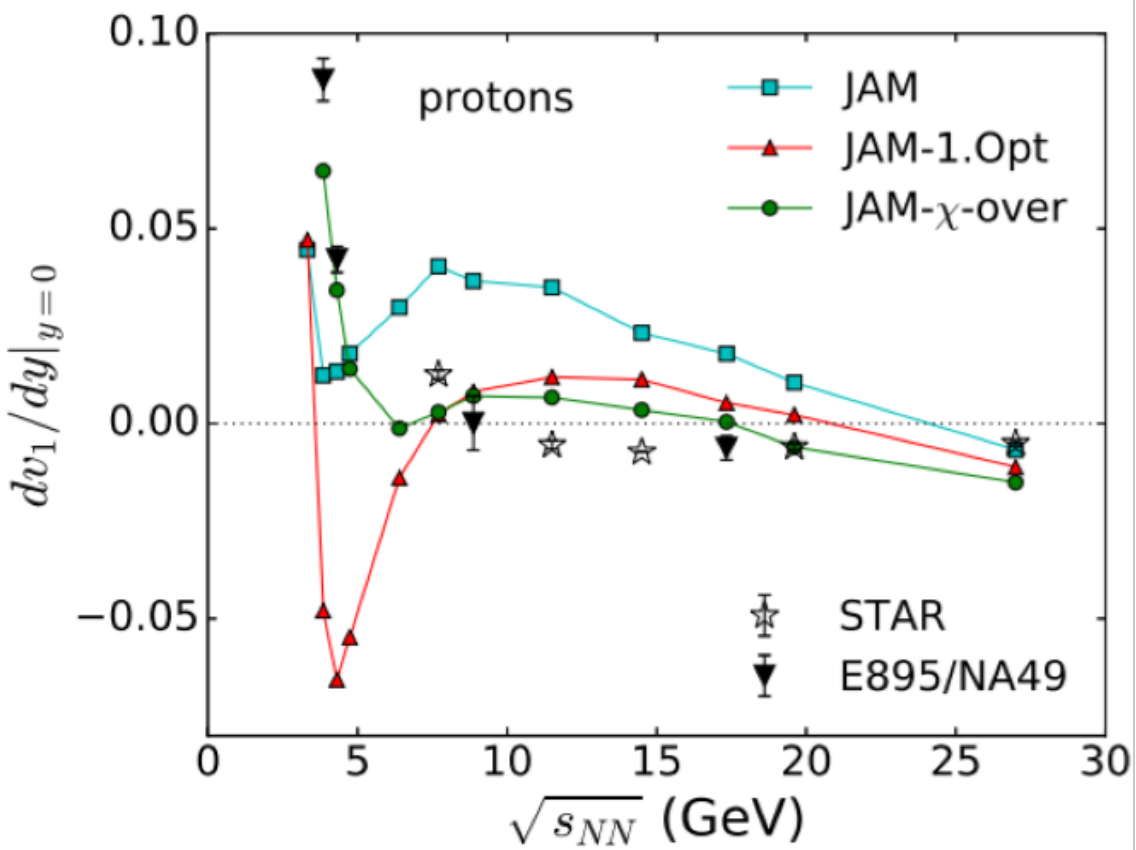


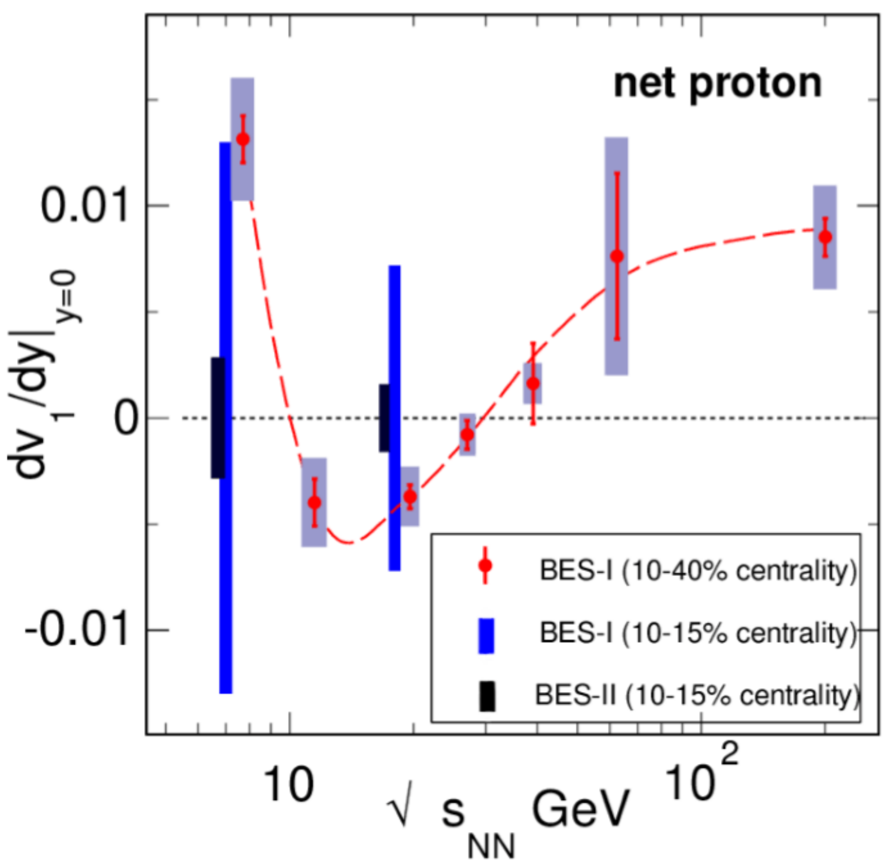
Similar to hadrons over the measured p_T range, light (anti-)nuclei $v_2(p_T)$ show a monotonic rise with increasing p_T, mass ordering at low p_T, and a reduction for more central collisions. It is observed that v_2 of nuclei and anti-nuclei are of similar magnitude for $\sqrt{s_{NN}}$= 39 GeV and above. The difference Δv_2between d and d is found to follow the difference between p and p as a function of collision energy. The blast wave model is found to under-predict the light-nuclei v_2 measured in data.

all the light-nuclei v_2 generally follow an atomic mass number scaling, which indicates that the coalescence of nucleons might be the underlying mechanism of light-nuclei formation in high energy heavy-ion collisions.

Phys. Rev. C **94** (2016) 34908

Softest point in EOS





net-proton directed flow

Recent calculations consistent with original 2005 prediction

JAM 1.0pt: First order phase transition
strong "wiggle"

JAM X-over - Cross over
weaker "wiggle"

JAM - No transition
no "wiggle"

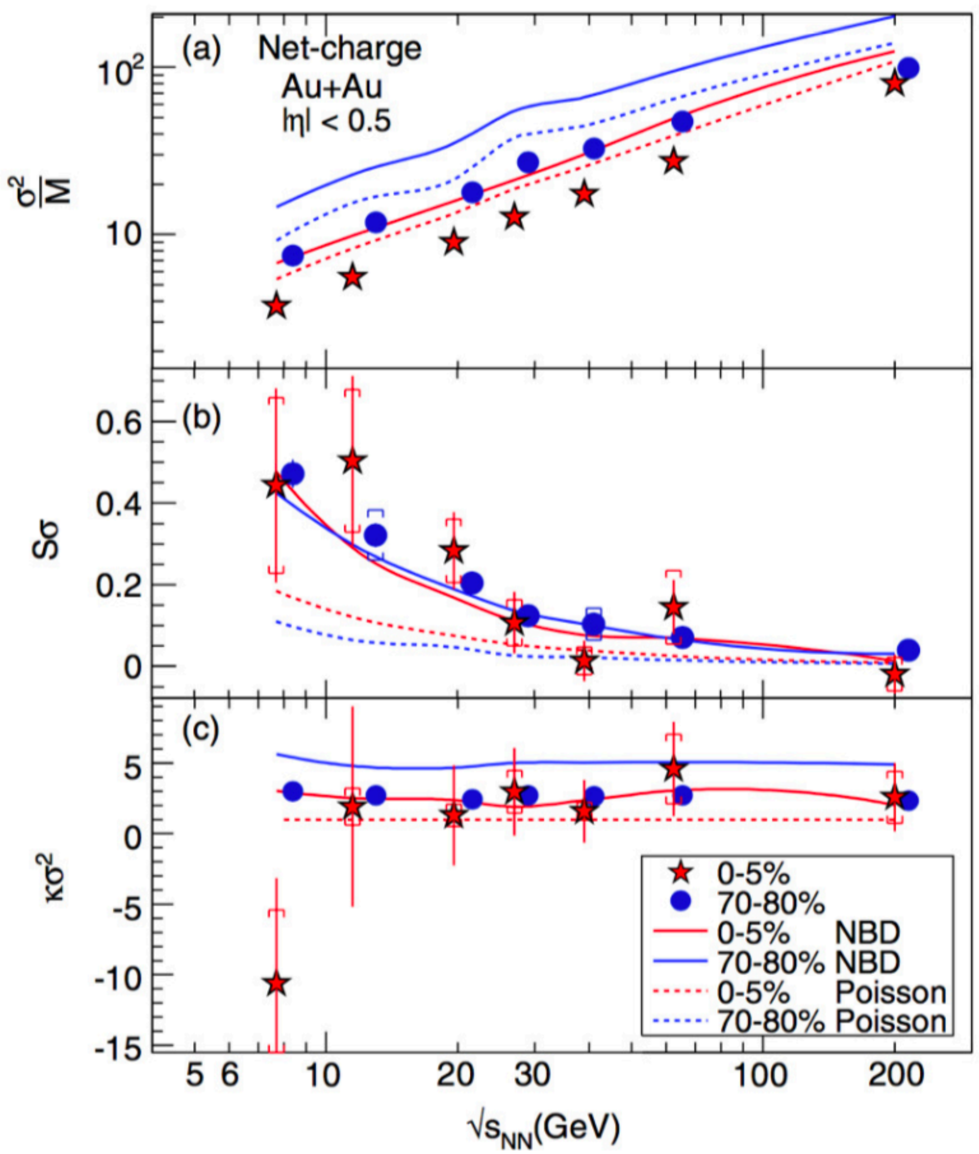
Theoretical calculations do not yet match data

Fine centrality binning possible with BES-II data

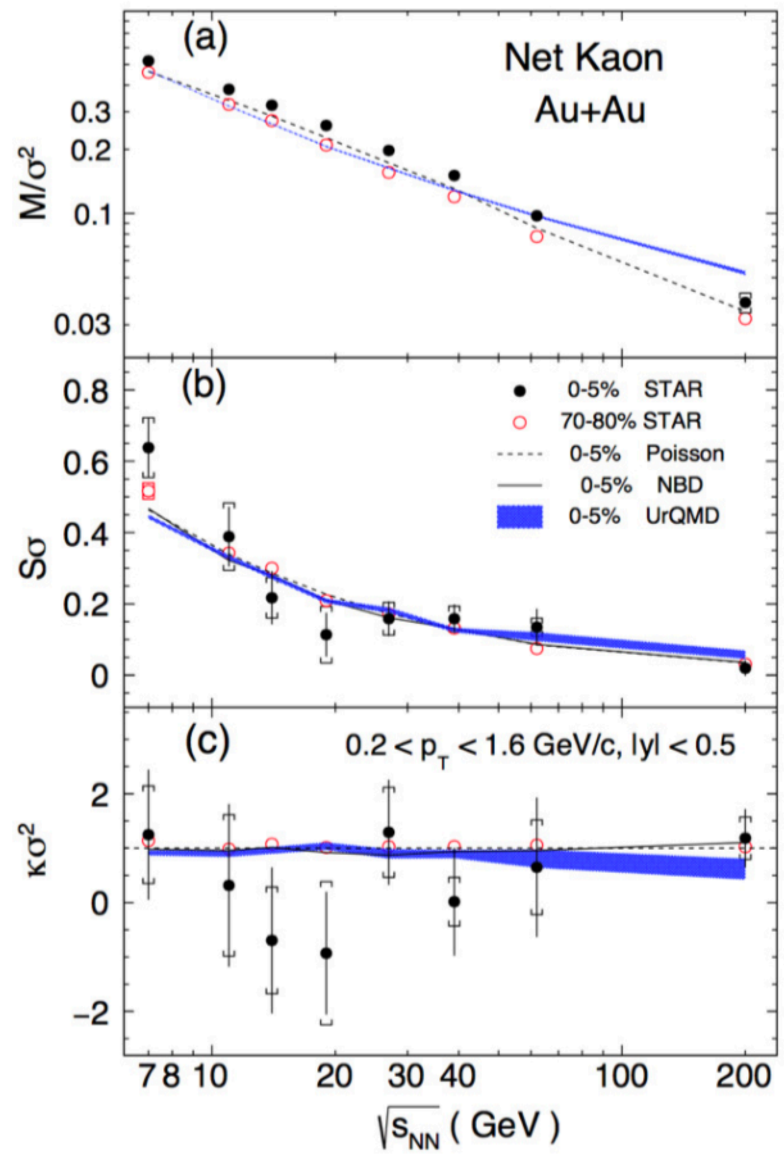
Y.Nara et al. Phys. Lett. B769 (2017) 543

Net-charge and net-kaon fluctuations

PRL113, 092301(2014): STAR



PLB, 785, 551(2018): STAR



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

✓ **Large statistical uncertainties, need more data.**

HBT and the CP

(R^2_{out} - R^2_{side}) sensitive to emission duration

If softening of EoS: Non-monotonic pattern as function of $\sqrt{s_{NN}}$

Finite size scaling effects can be used to extract location of deconfinement transition

Plot of max (R^2_{out} - R^2_{side}) as function of $R_{glauber}$ - Lifetime to initial transverse size of system mapping?

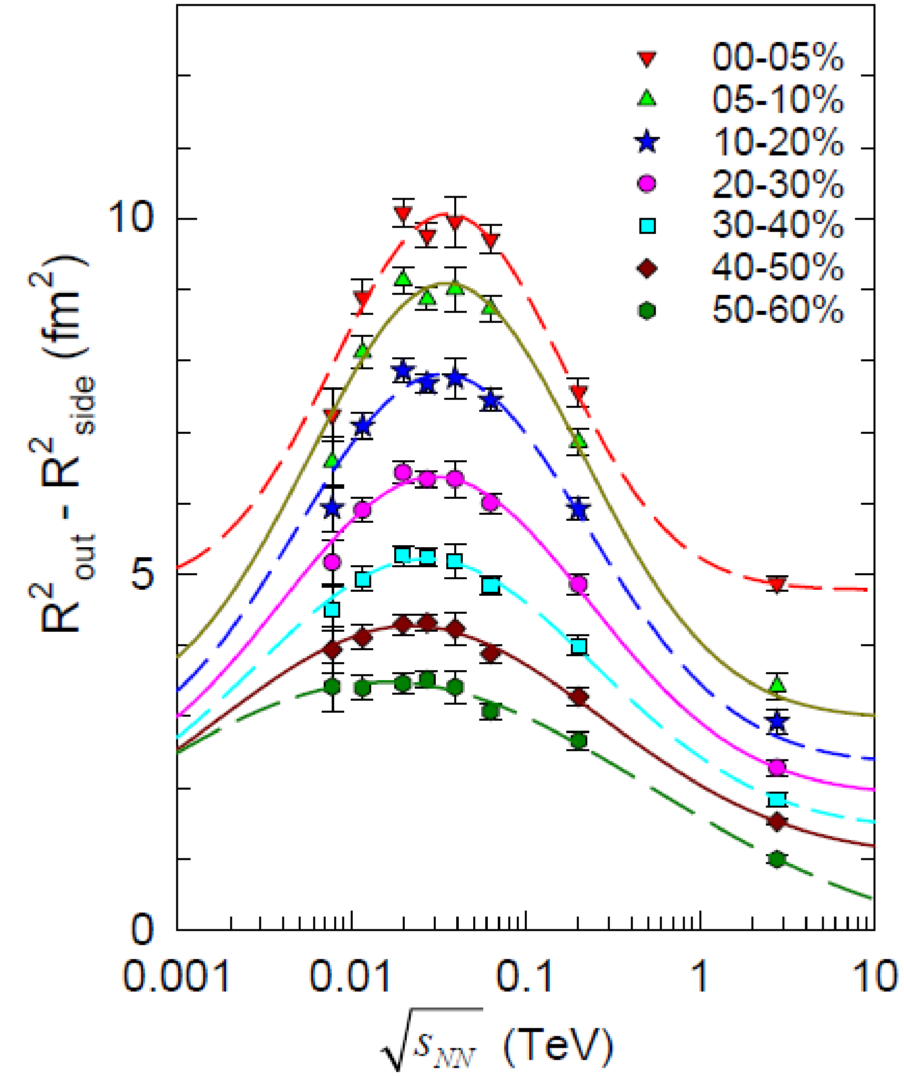
Slope and intercept give information on location of CP at infinite volume and the critical exponents

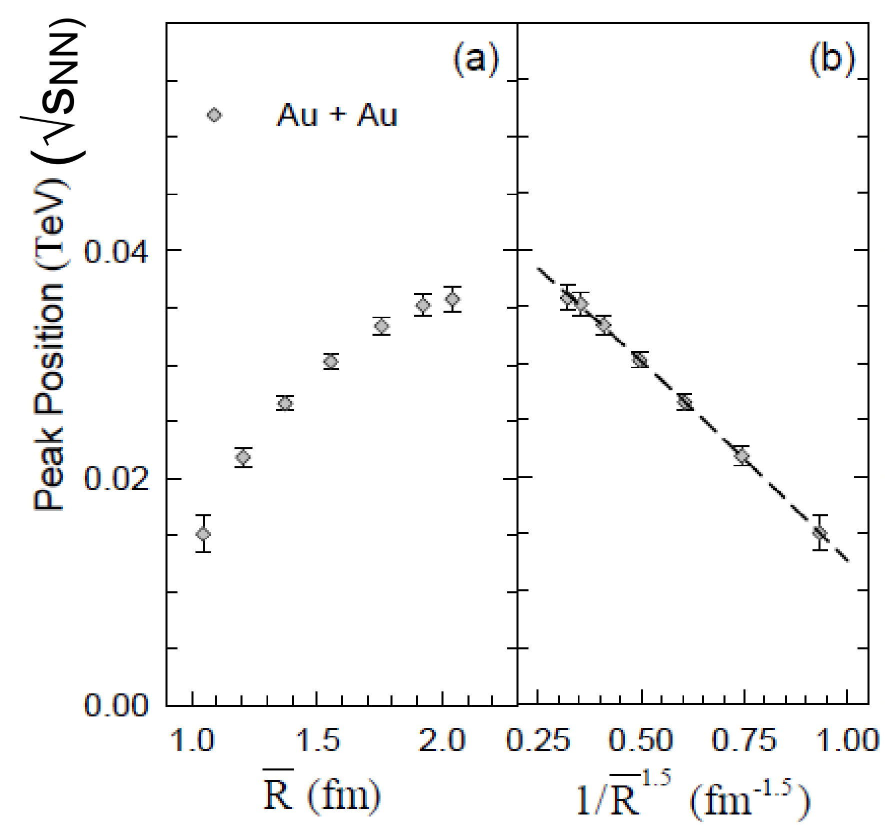
Infinite volume $\sqrt{s_{NN}}$ =47 GeV

$$T^{cep} : 165 \text{ MeV}, \mu_B^{cep} : 95 \text{ MeV}$$

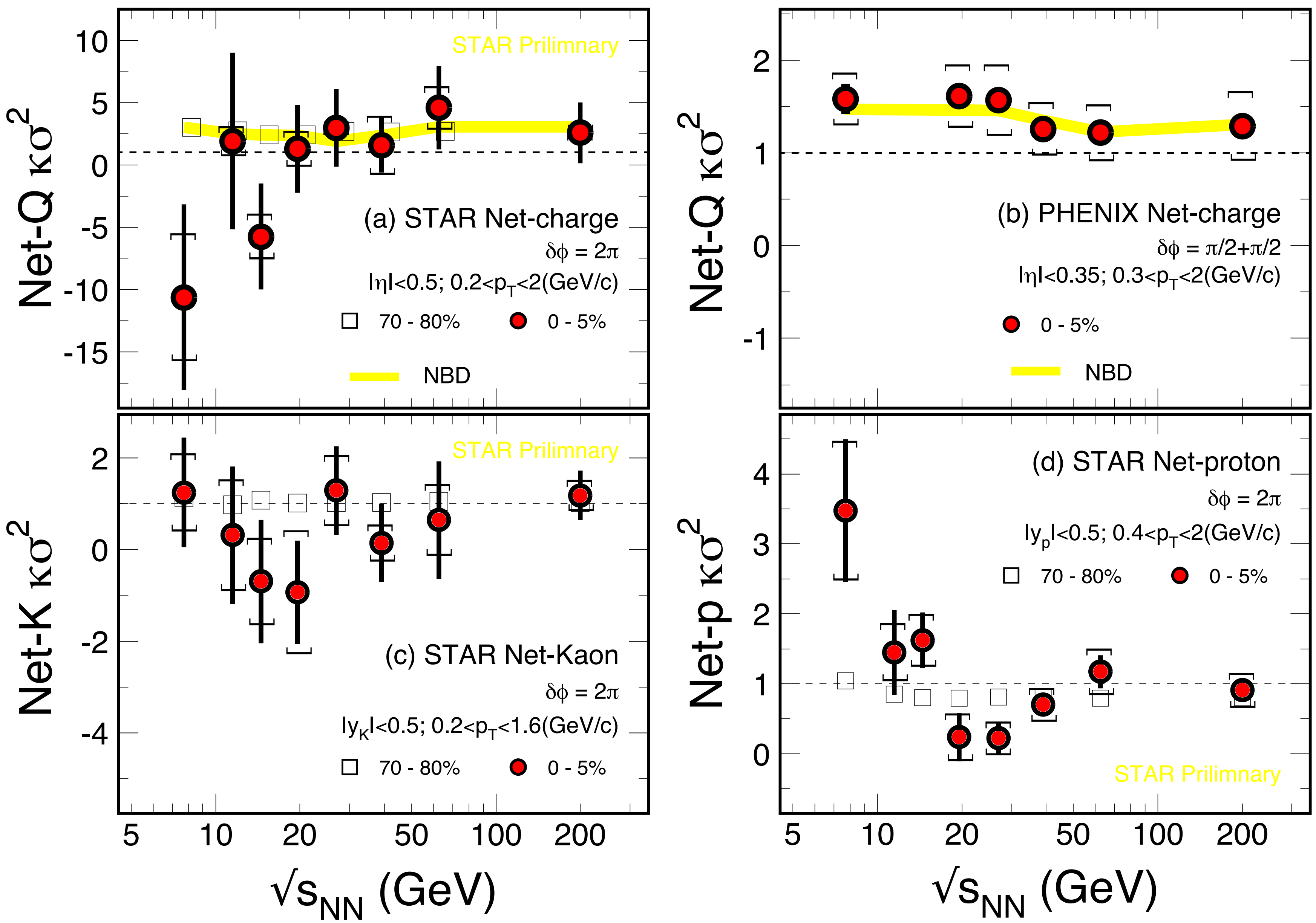
2nd order phase transition, location ruled out by Lattice

R. Lacey, PRL **114**, 142301





Fluctuations at RHIC



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

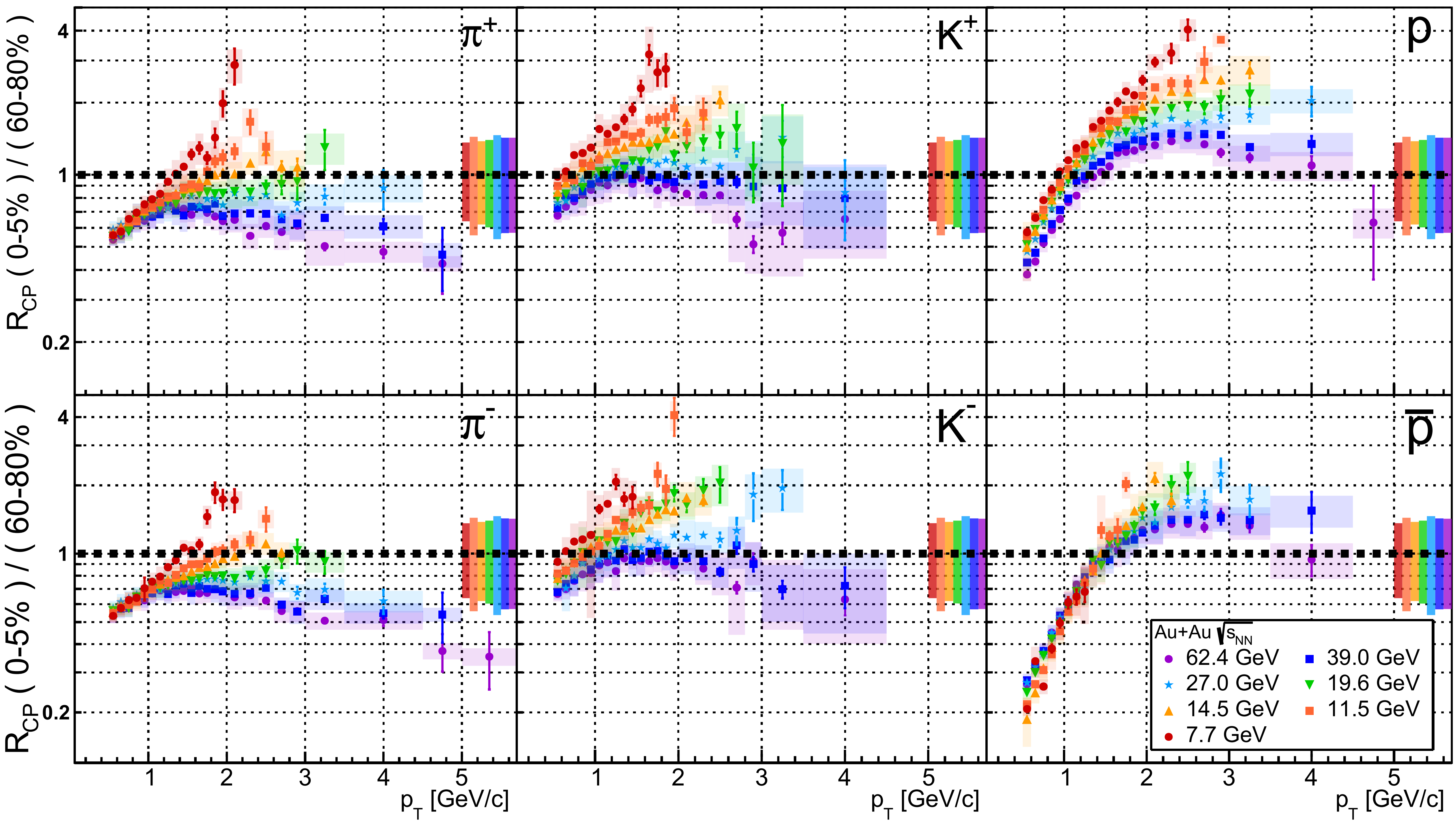
In STAR:

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!

PHENIX: talk by P. Garg at QM2015; STAR: talk by J. Thäder and poster by J. Xu at QM2015

QGP Creation: Jet Quenching



STAR: PRL **121** (2018) 32301

Searching for a Critical Point

Critical Points:

divergence of susceptibilities

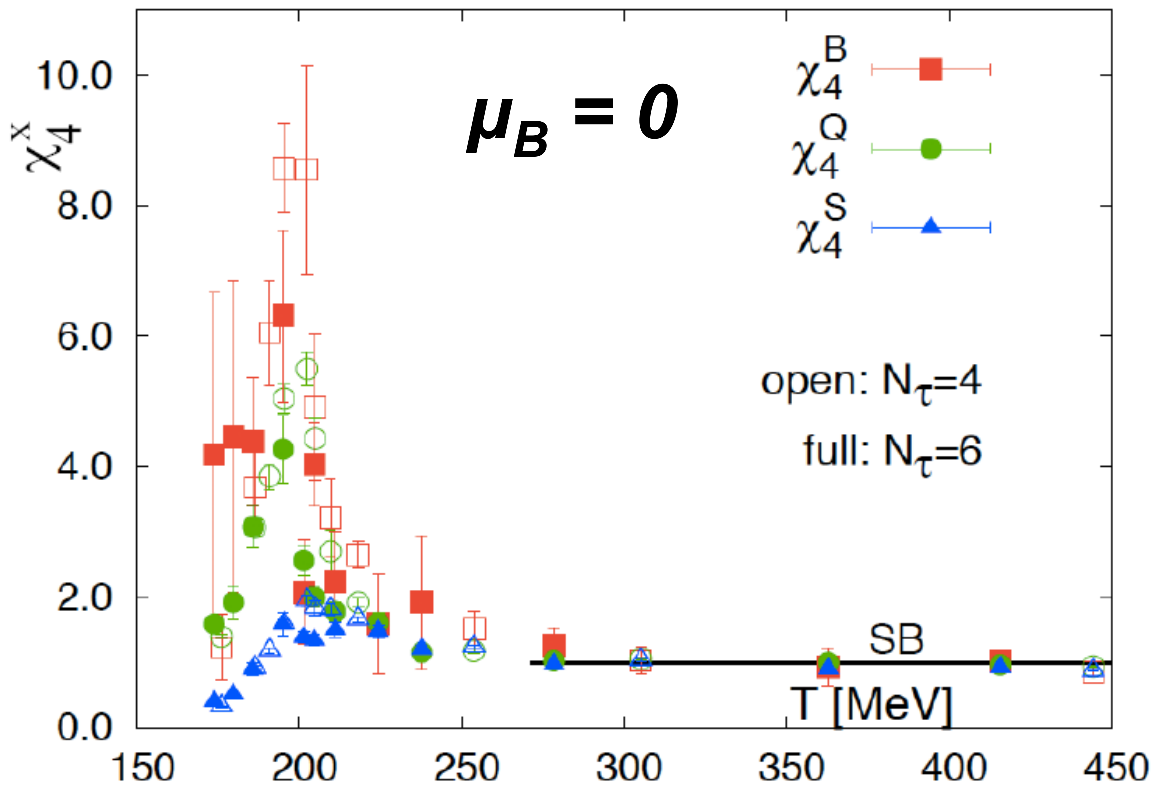
e.g. magnetism transitions

divergence of correlation lengths

e.g. critical opalescence

Lattice QCD:

Divergence of susceptibilities for conserved quantities (B,Q,S) at critical point



Searching for a Critical Point

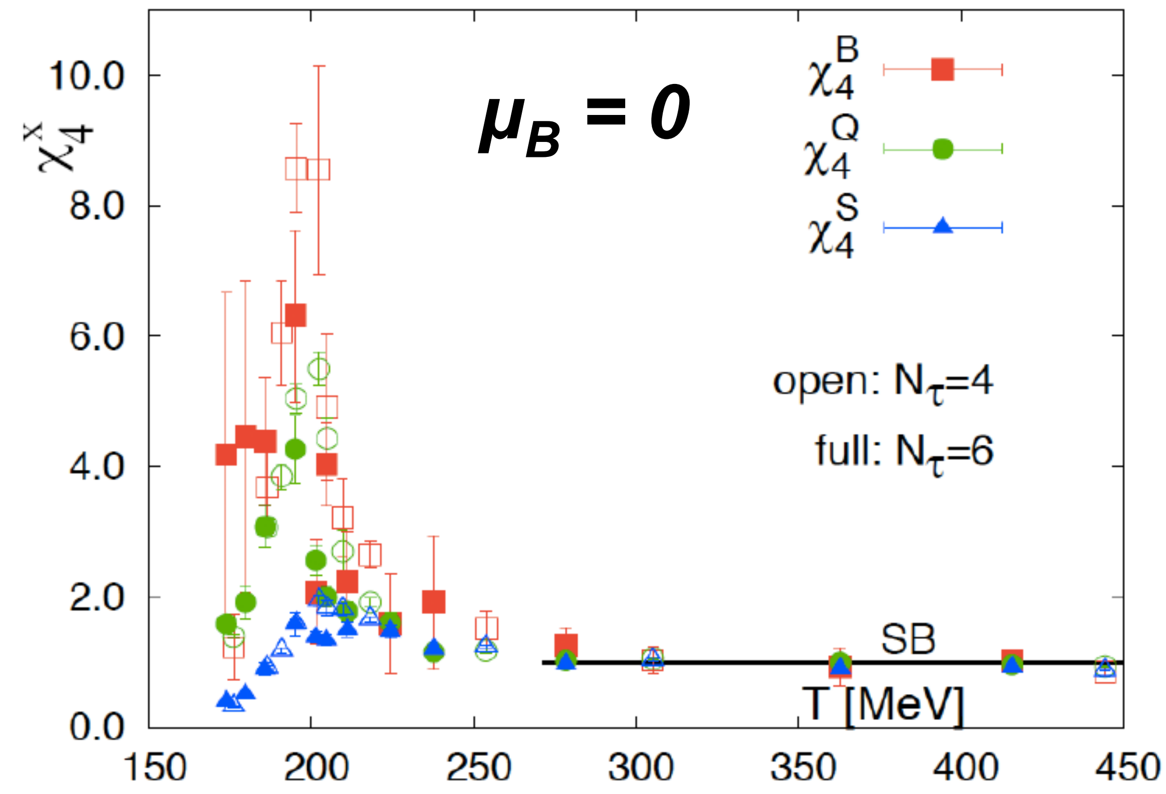
Critical Points:

divergence of susceptibilities

e.g. magnetism transitions

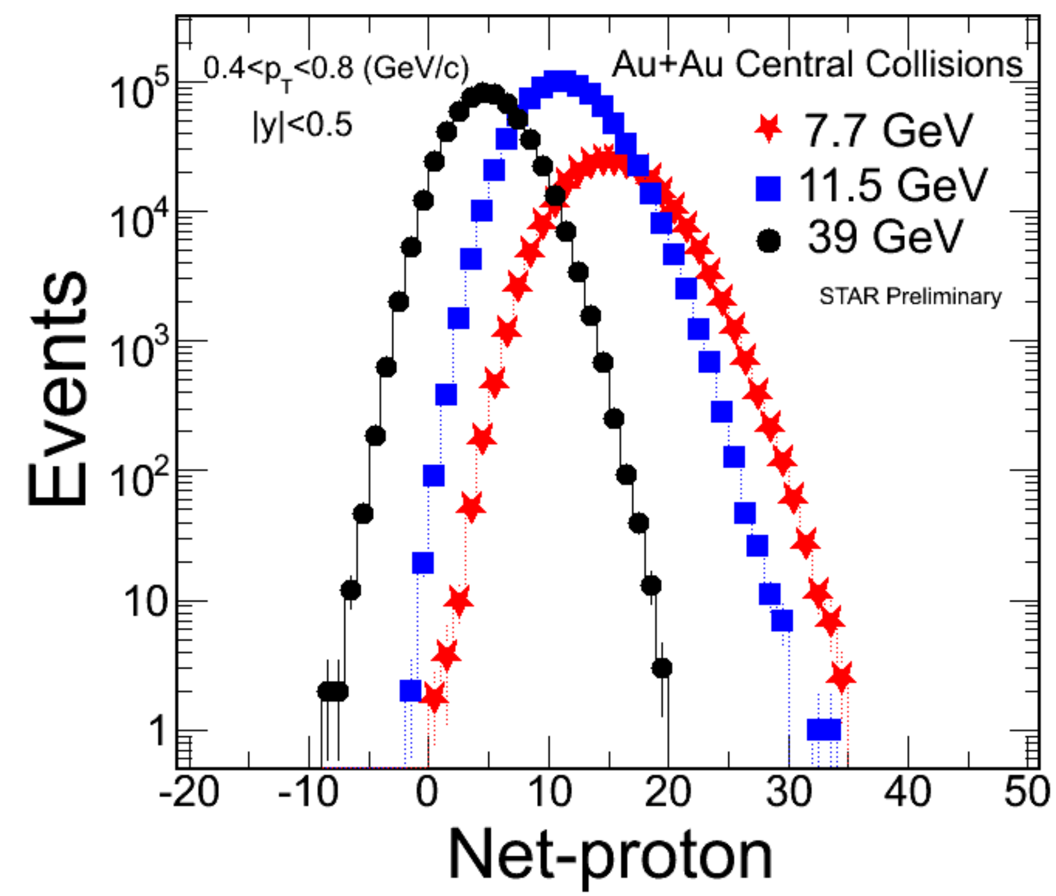
divergence of correlation lengths

e.g. critical opalescence



Lattice QCD:

Divergence of susceptibilities for conserved quantities (B,Q,S) at critical point



Divergences of conserved quantities may survive in the final state

⇒ non-gaussian fluctuations of net-baryon density

Kurtosis x Variance² ~ $\chi^{(4)}/\chi^{(2)}$

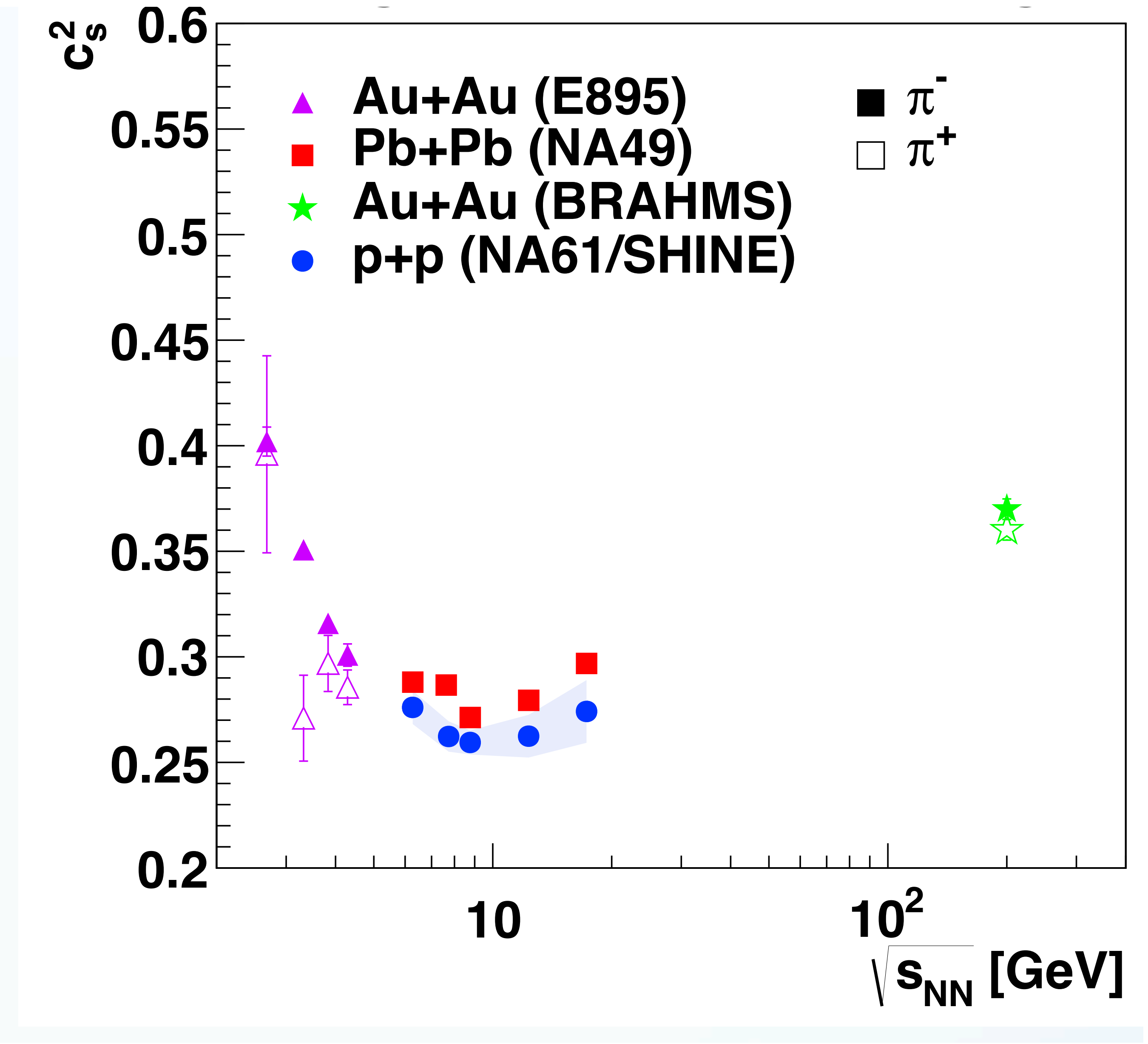
Kurtosis - 4th moment - "tailiness" of distribution

Longitudinal expansion

Fermi-Landau initial conditions
Ideal Hydrodynamic expansion

$$p(\varepsilon) = c_s^2 \varepsilon$$

$$\frac{dn}{dy} = \frac{K s_{NN}^{1/4}}{\sqrt{2\pi\sigma_y^2}} e^{-\frac{y^2}{2\sigma_y^2}} \qquad \sigma_y^2 = \frac{8}{3} \frac{c_s^2}{1 - c_s^4} \ln\left(\frac{\sqrt{s}}{2m_N}\right)$$



BES-II: Detailed Run Plan

Run in 2019 & 2020 will have significant physics impact

	Collision Energies (GeV):	**7.7**	**9.1**	**11.5**	**14.5**	**19.6**
	Chemical Potential (MeV):	**420**	**370**	**315**	**260**	**205**
	Observables	Millions of Events Needed				
	R_{CP} up to p_T 4.5 GeV	NA	NA	160	92	22
QGP	Elliptic Flow of ϕ meson (v_2)	100	150	200	300	400
	Local Parity Violation (CME)	50	50	50	50	50
1st P.T.	Directed Flow studies (v_1)	50	75	100	100	200
	asHBT (proton-proton)	35	40	50	65	80
C.P.	net-proton kurtosis ($\kappa\sigma^2$)	80	100	120	200	400
EM Probes	Dileptons	100	160	230	300	400
	Proposed Number of Events:	**100**	**160**	**230**	**300**	**400**
	BES-I stats.	4	N/A	12	20	36

Fixed target running enables data from $\sqrt{s}$ = 3-7.7 GeV

eCooling - Enables the significant statistics enhancement

Improving on current data

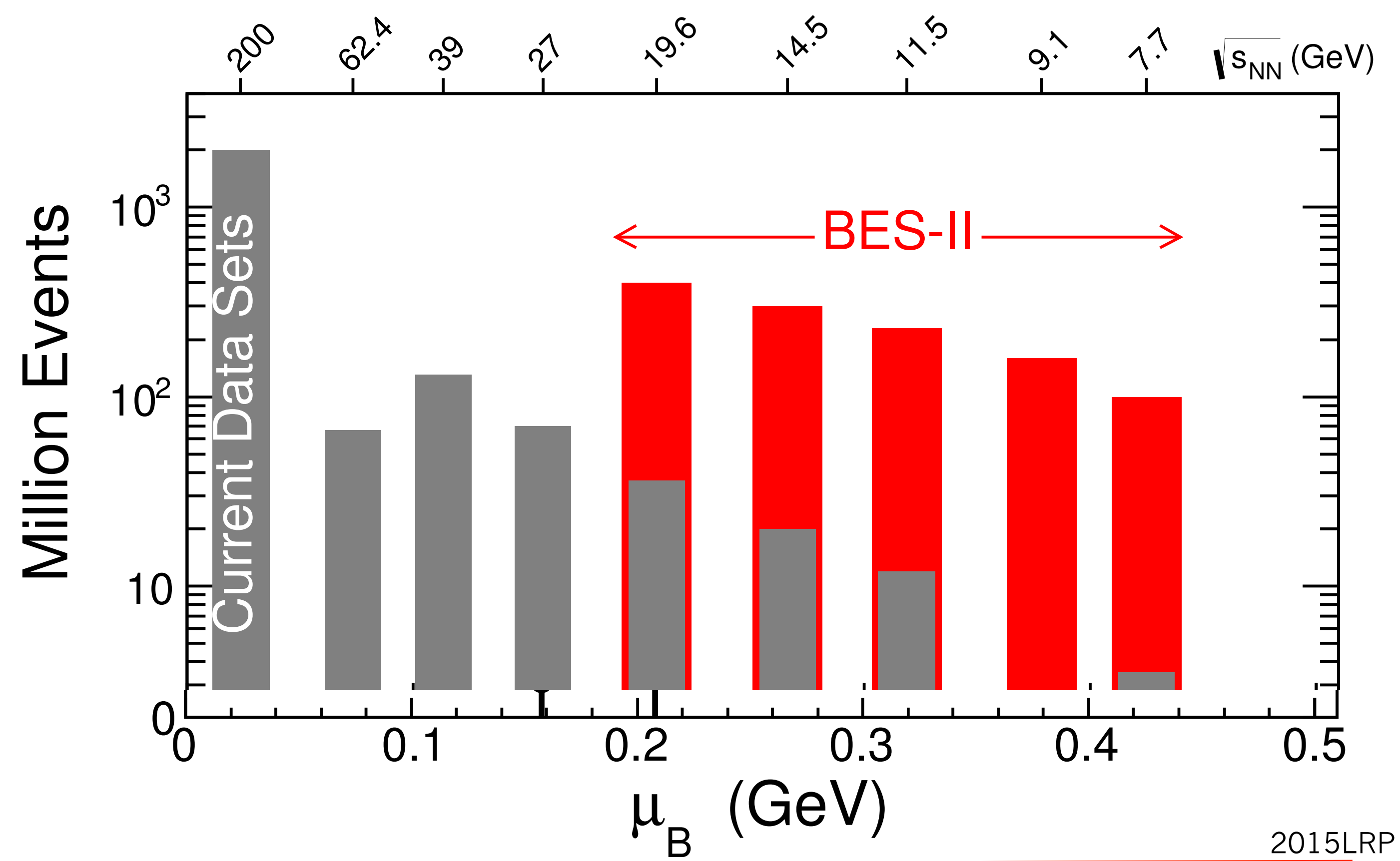
Current low energy data:
Hints that at low √s

- QGP turns off
- Ordered phase transition
- Critical Point

Future data:

- Examine regions of interest
- Maximizing fraction particles measured
- Probe lower √s
- High(er) luminosities
- Change species

Turn trends and features into definitive conclusions



iTPC: design

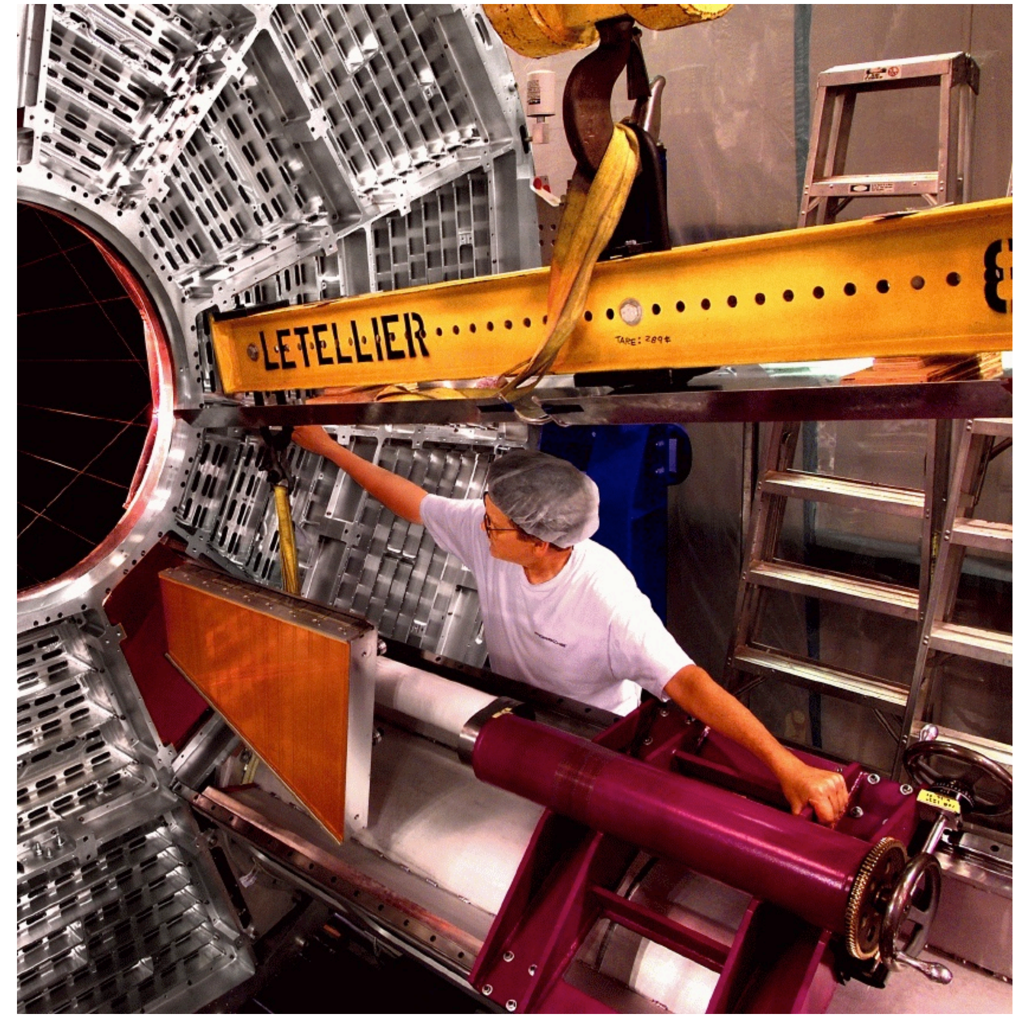
Increase in #channels in 24 inner sectors by ~factor 2

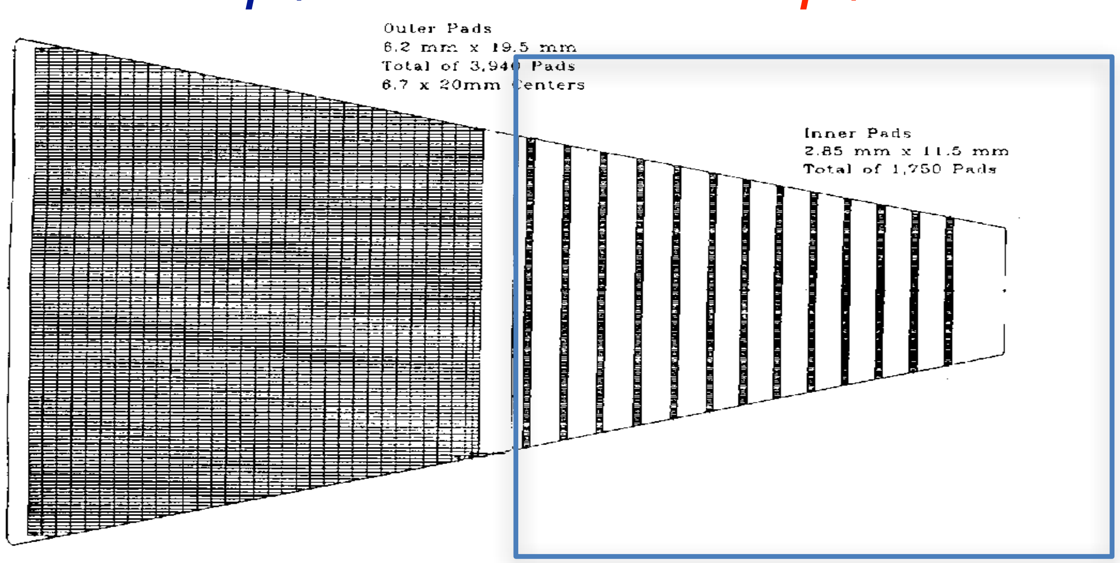
Provides near complete coverage

New electronics for inner sectors

Enhanced rapidity coverage

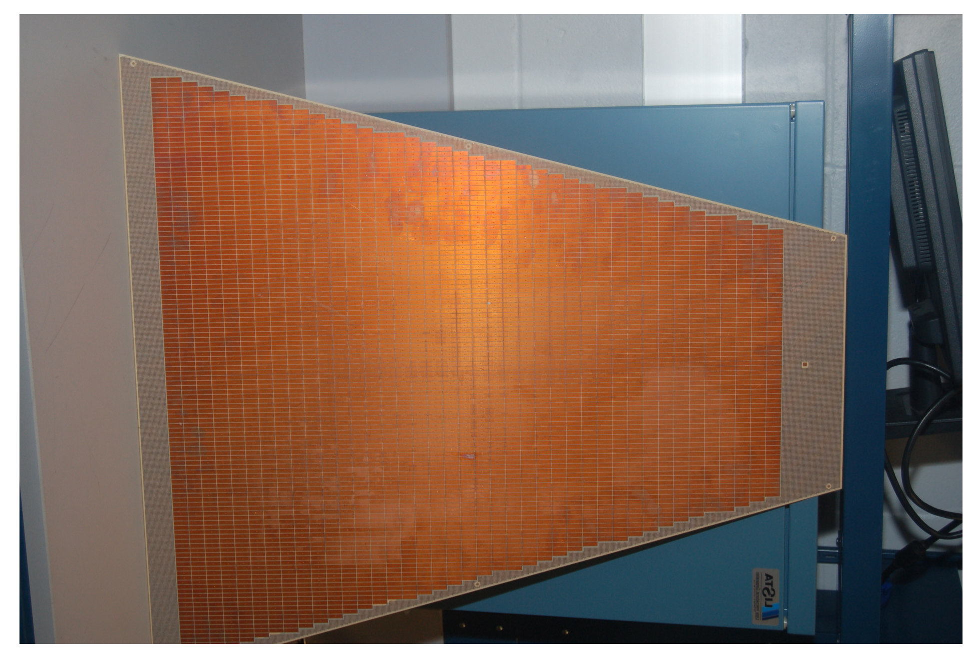
Old	New
	better *dE/dx*;
$-1 < \eta < 1$	$-1.5 < \eta < 1.5$;
p_T >125 MeV/*c*	p_T > 60 MeV/*c*.



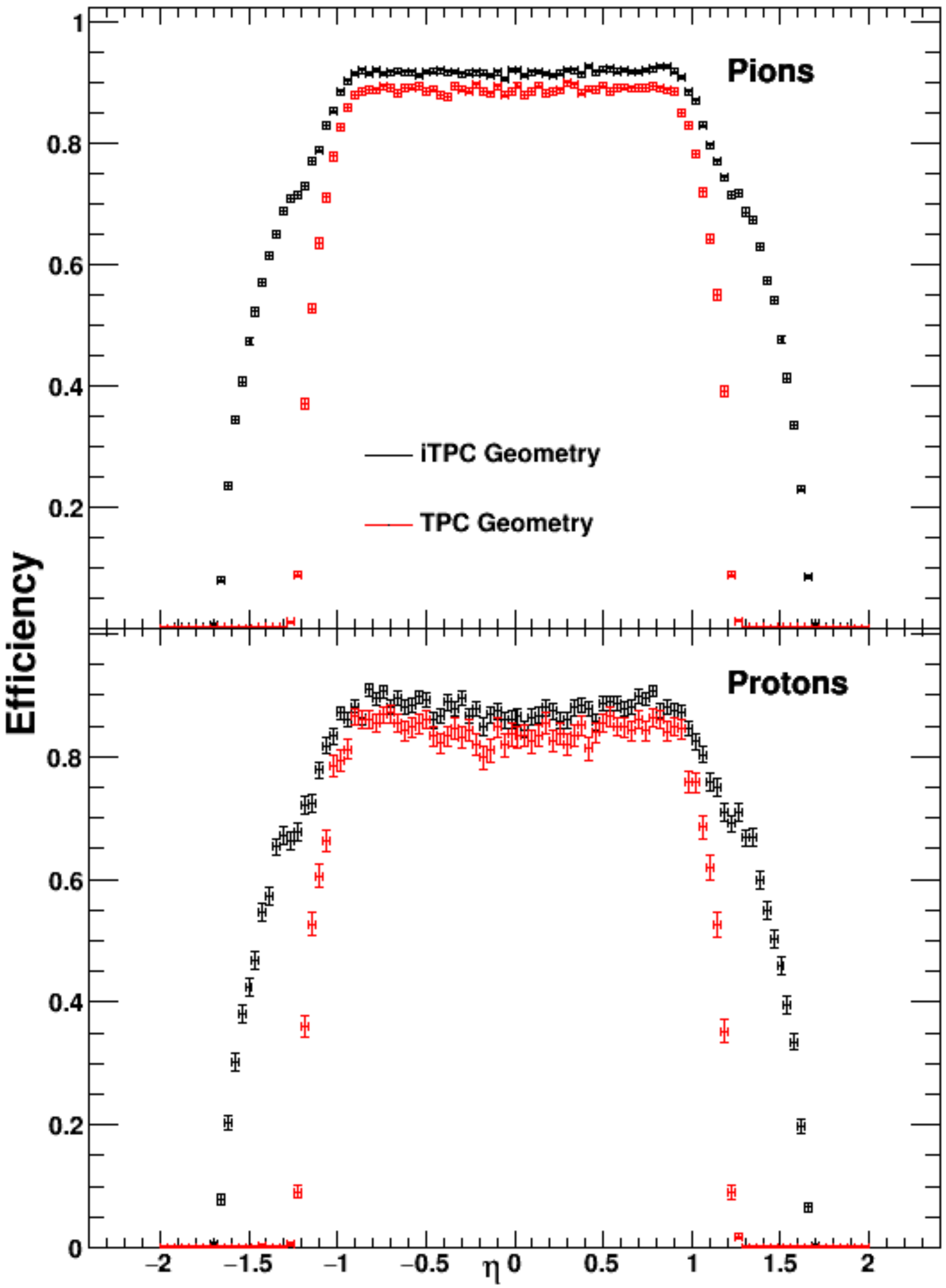


Inner

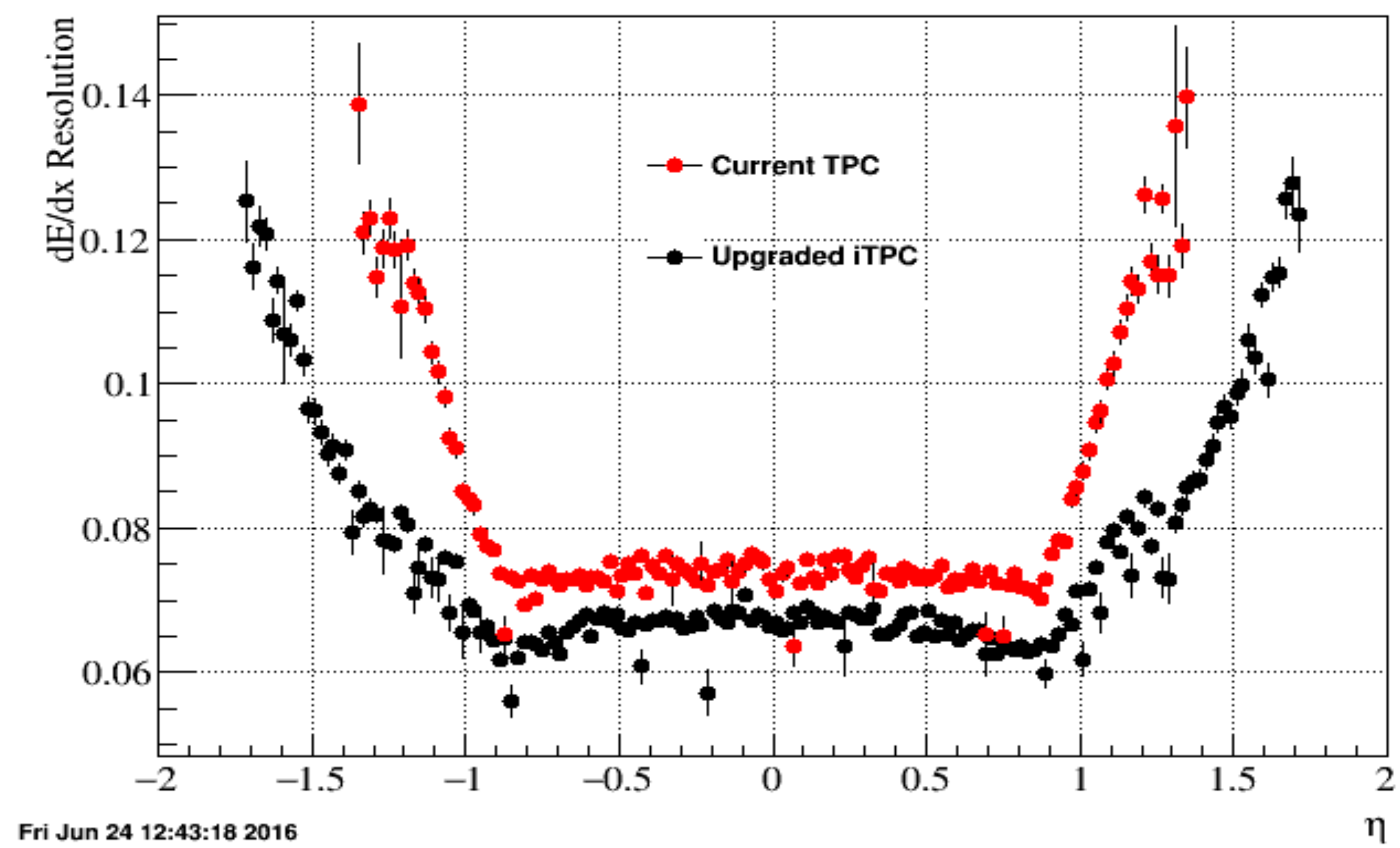
Outer



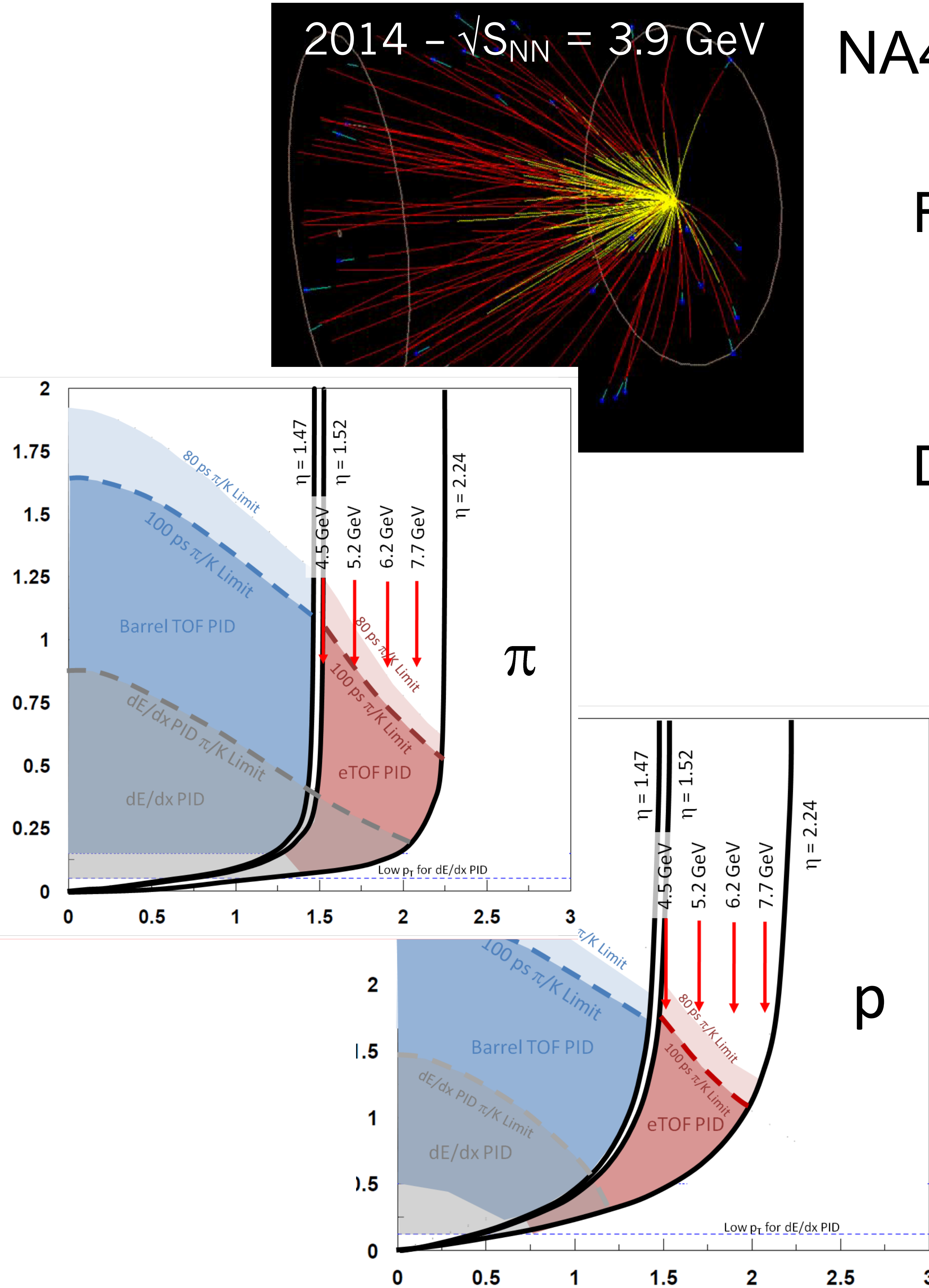
Enhanced tracking and dE/dx performance



Increased coverage, efficiency and dE/dx resolution out to |η| < 1.5



BES-II: Onset of deconfinement



NA49 - claim onset of deconfinement at $\sqrt{s}$ = 7.7 GeV

Fixed target program
- Collider can't run below 7.7GeV
- Target in beam pipe at z=210cm

Dedicated short runs
- More efficient
- Successful tests completed

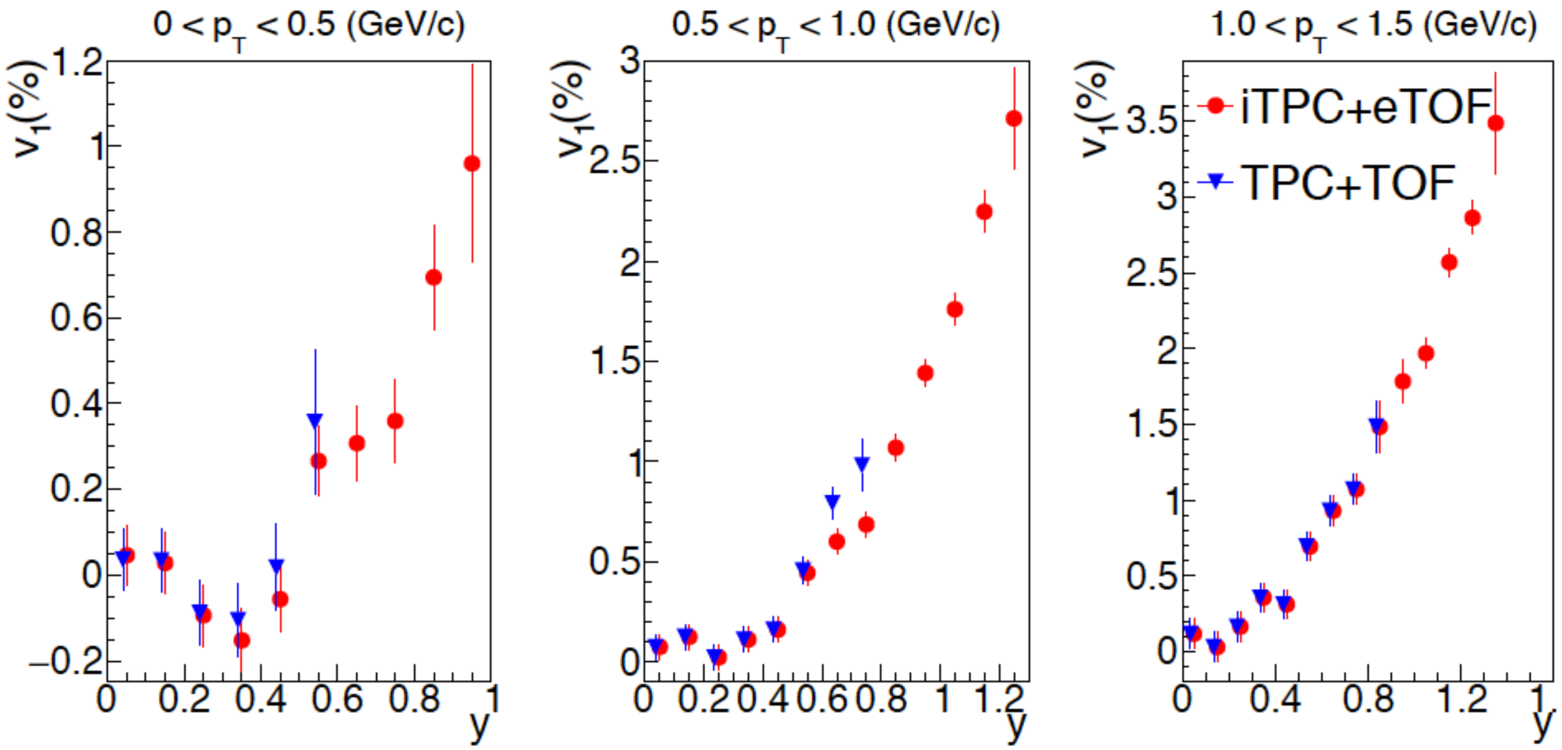
TOF+iTPC:
- Forward acceptance in fixed target mid rapidity range
  - Reach 7.7 GeV for fixed target too

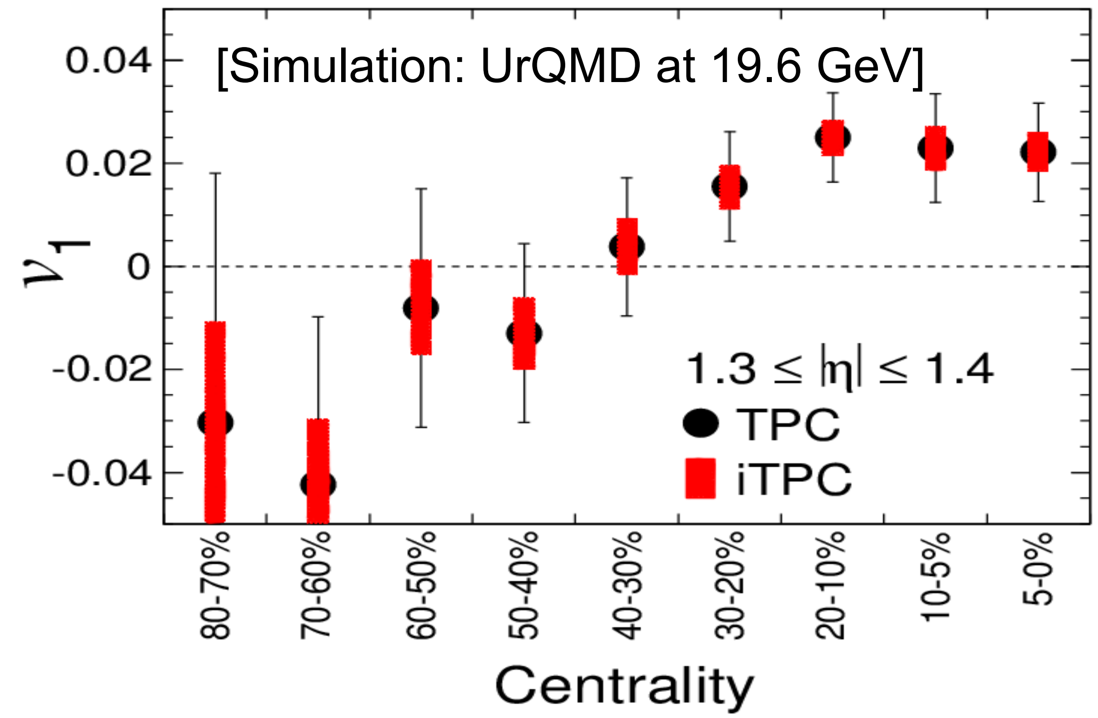
Precision investigation with new techniques and same detector

BES-II: Softening of EoS

Current data: Double sign change of v_1

Precision measurement of dv_1/dy as function of centrality





iTPC+ eTOF:

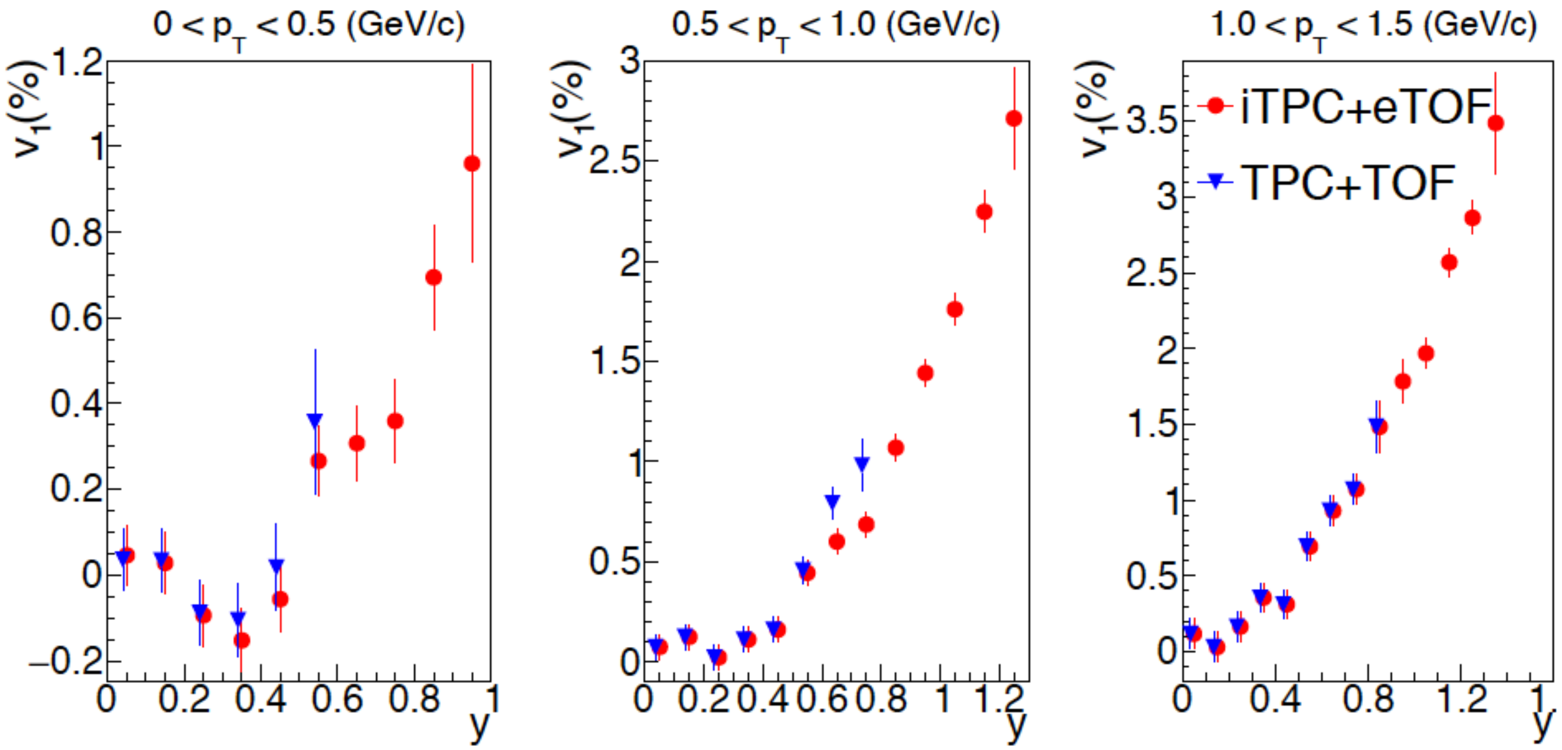
Enhanced coverage at forward y

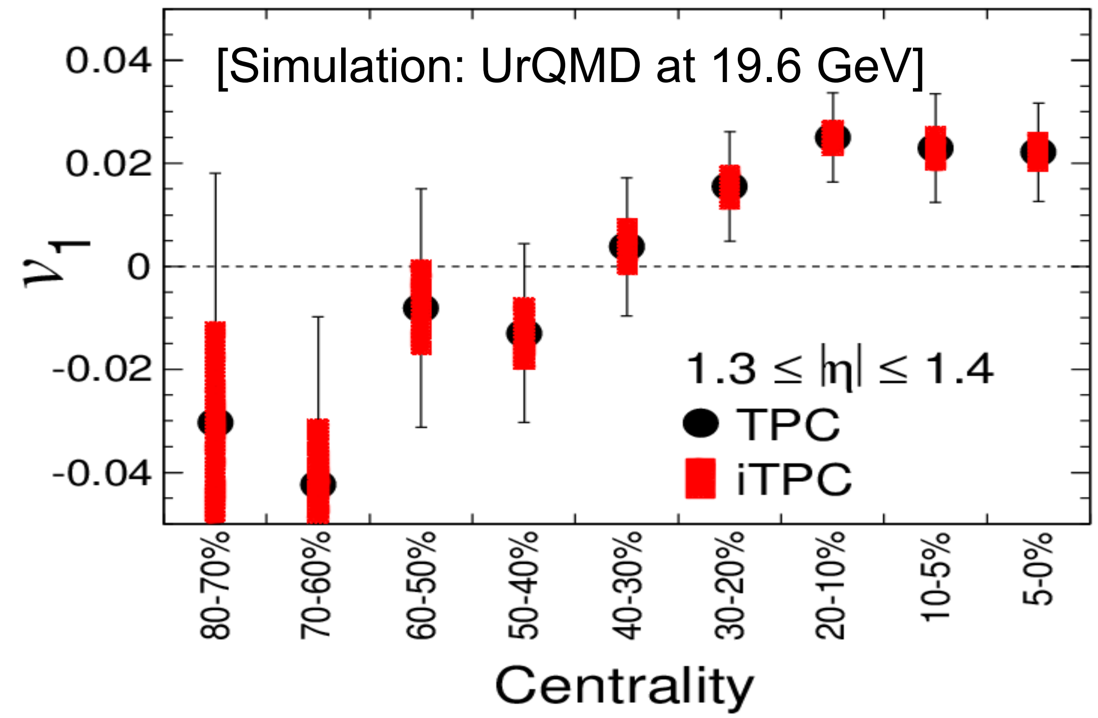
Signal larger - role of baryon stopping

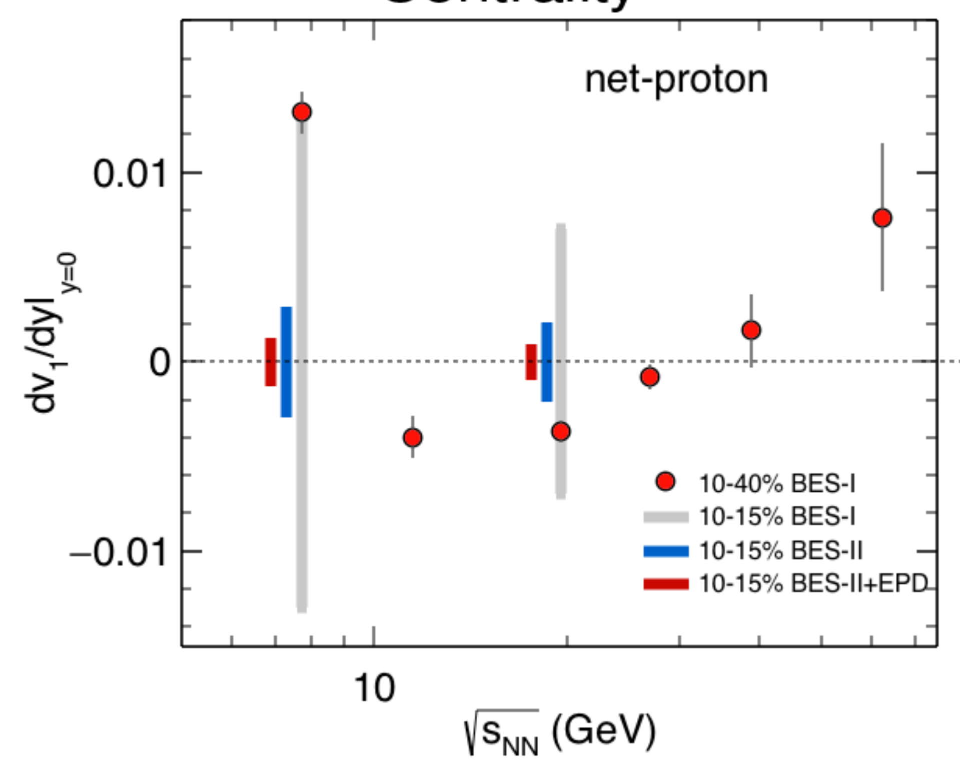
BES-II: Softening of EoS

Current data: Double sign change of v_1

Precision measurement of dv_1/dy as function of centrality







iTPC+ eTOF:

Enhanced coverage at forward y

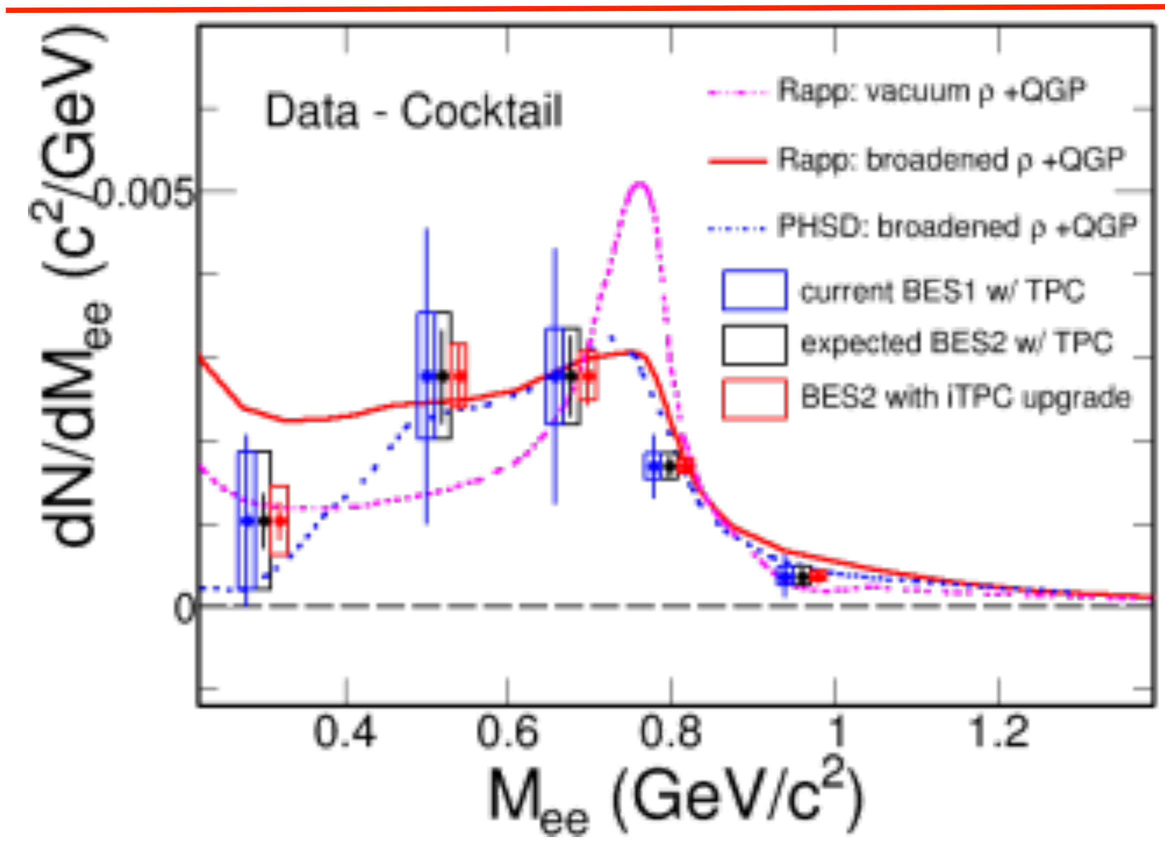
Signal larger - role of baryon stopping

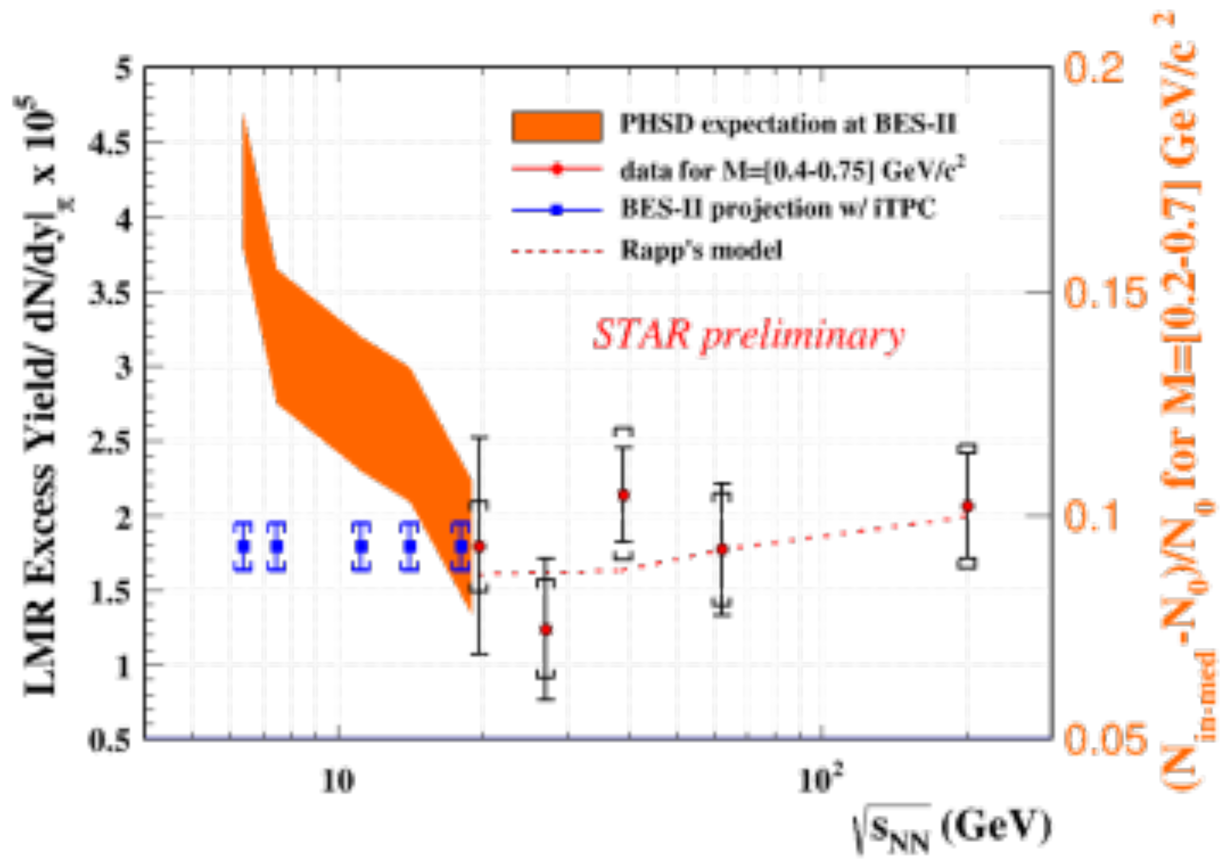
EPD:

Enhanced 1st order EP resolution

Reduced systematics

Change the total baryon number





ρ-meson broadening:

different predictions for di-electron continuum (Rapp vs PHSD)

iTPC: Significant reduction in sys. and stat. uncertainties

Enables to distinguish between models for √s =7.7-19.6 GeV

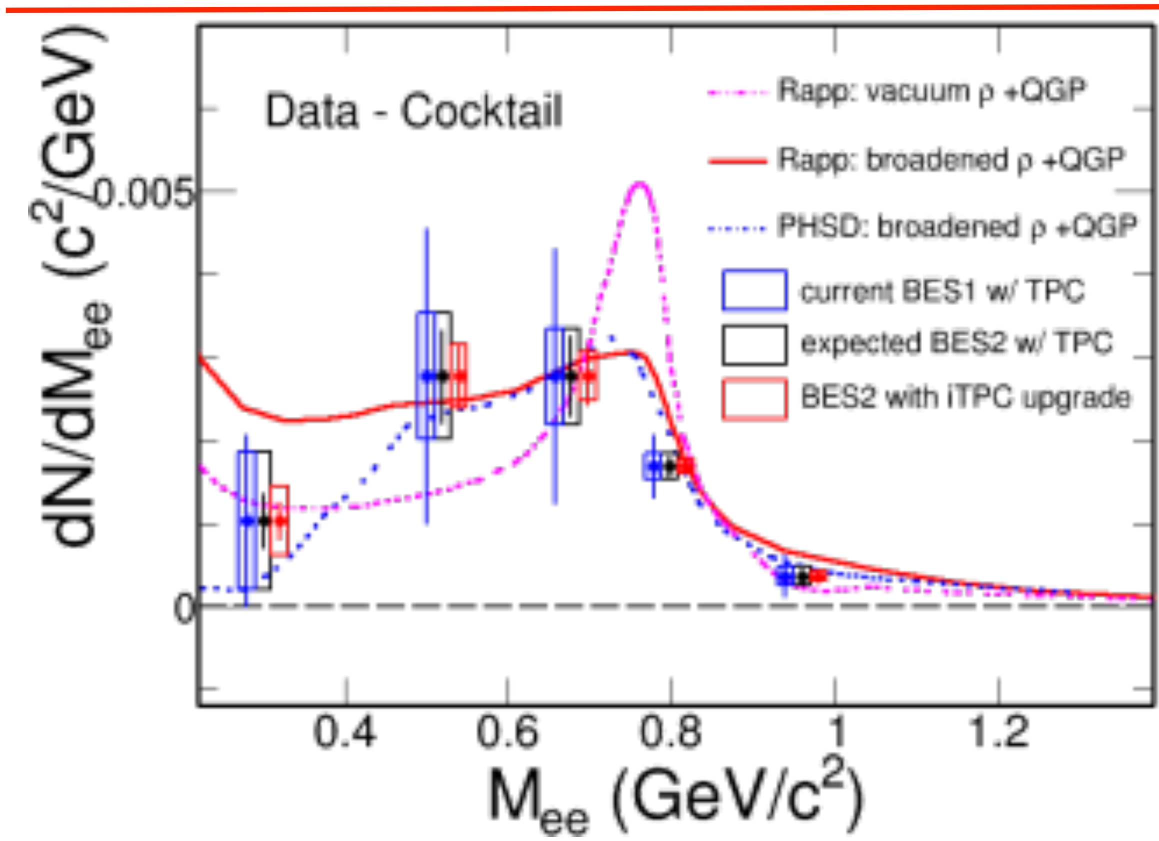
Low Mass Region:

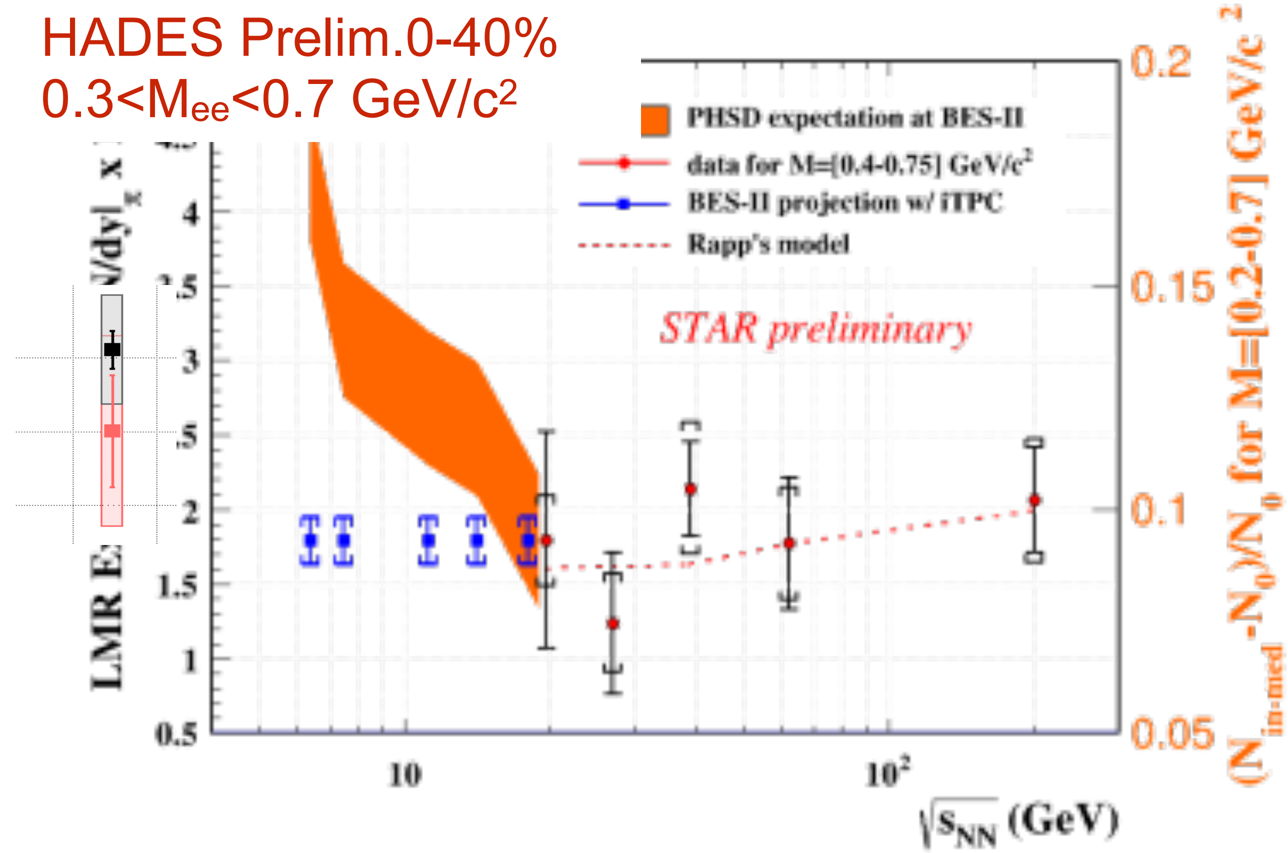
iTPC: Significant reduction in sys. and stat. uncertainties

Disentangle total baryon density effects

J. Butterworth HP2016, T. Galatyuk, QM2017

Change the total baryon number





ρ-meson broadening:

different predictions for di-electron continuum (Rapp vs PHSD)

iTPC: Significant reduction in sys. and stat. uncertainties

Enables to distinguish between models for √s =7.7-19.6 GeV

Low Mass Region:

iTPC: Significant reduction in sys. and stat. uncertainties

Disentangle total baryon density effects

J. Butterworth HP2016, T. Galatyuk, QM2017

BES-II: Critical fluctuations

Current data: Suggestive of non-trivial √s dependence of net proton cumulant ratios

iTPC:

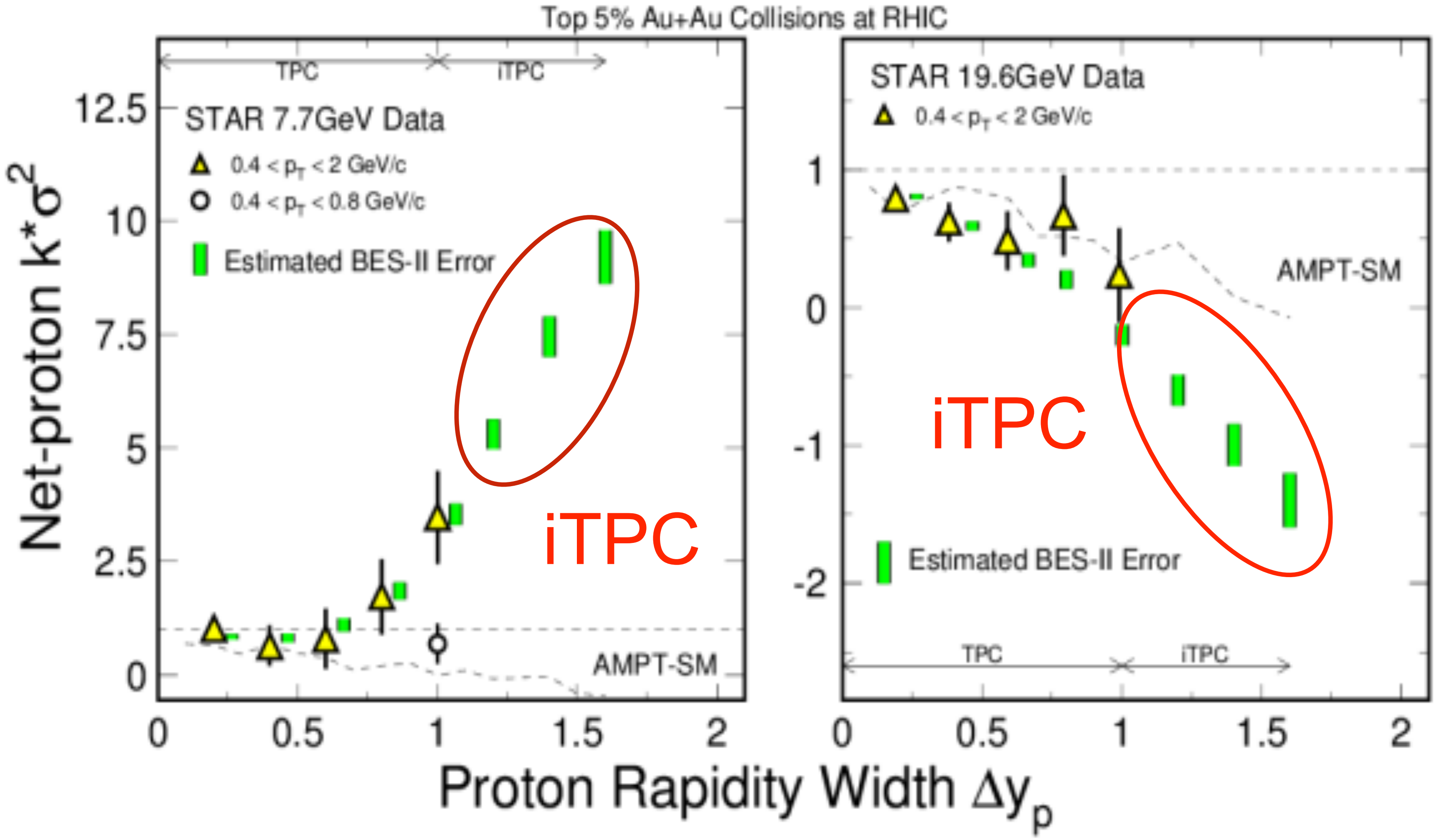
Increase Δy_p acceptance

$\Delta y_p > \Delta y$ correlation

EPD:

Improved centrality selection

Use all TPC for measurement

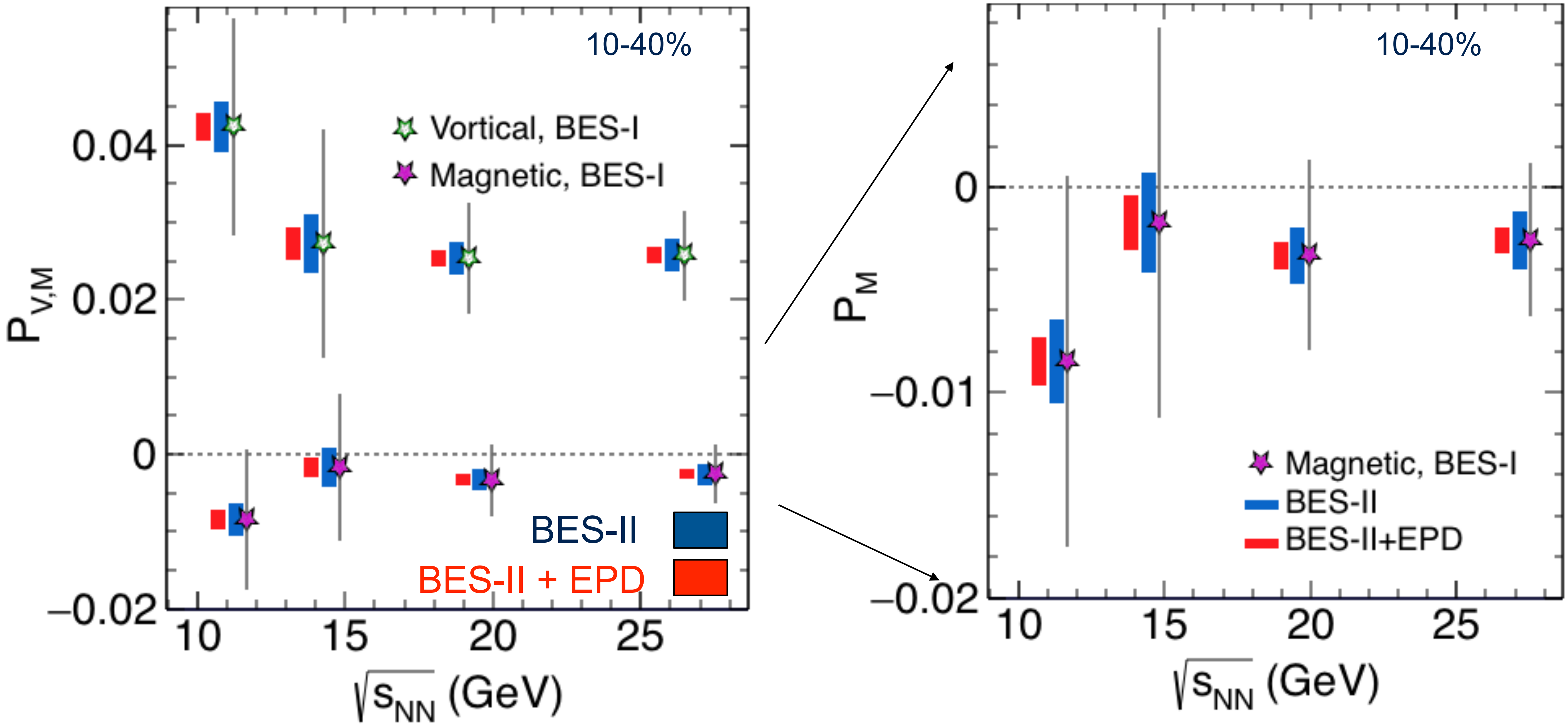


Establish true nature of correlation

Subject actively pursued theoretically

BES-II: Vorticity and Initial B-field

BES-I: First measurement of Λ **Global** Polarization



Vortical + Magnetic Contributions:

Current data barely stat. significant

EPD:

Improved EP resolution

BES-II: 3σ effect

Unique measurement of B
Significant input to CME/CVE interpretations