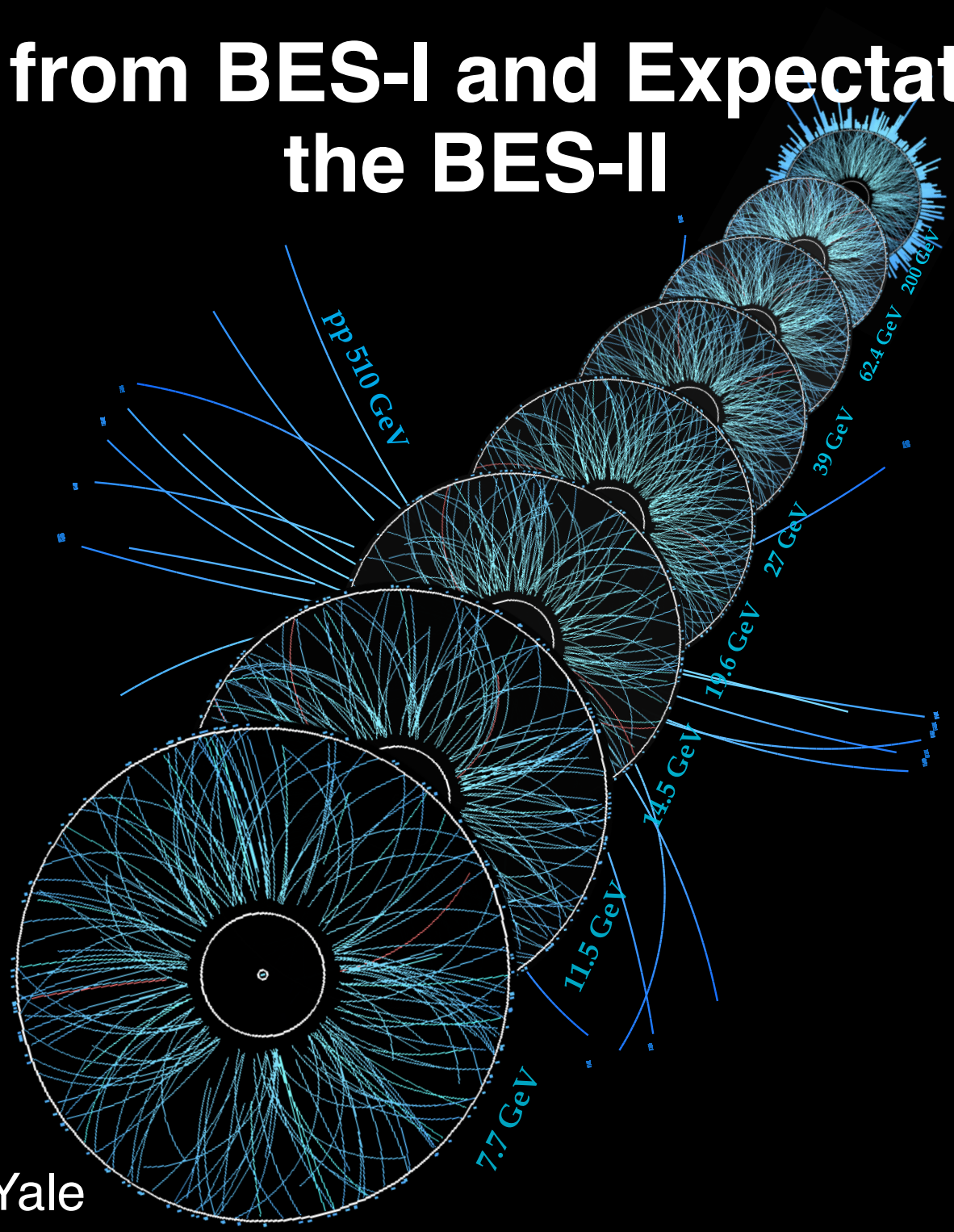
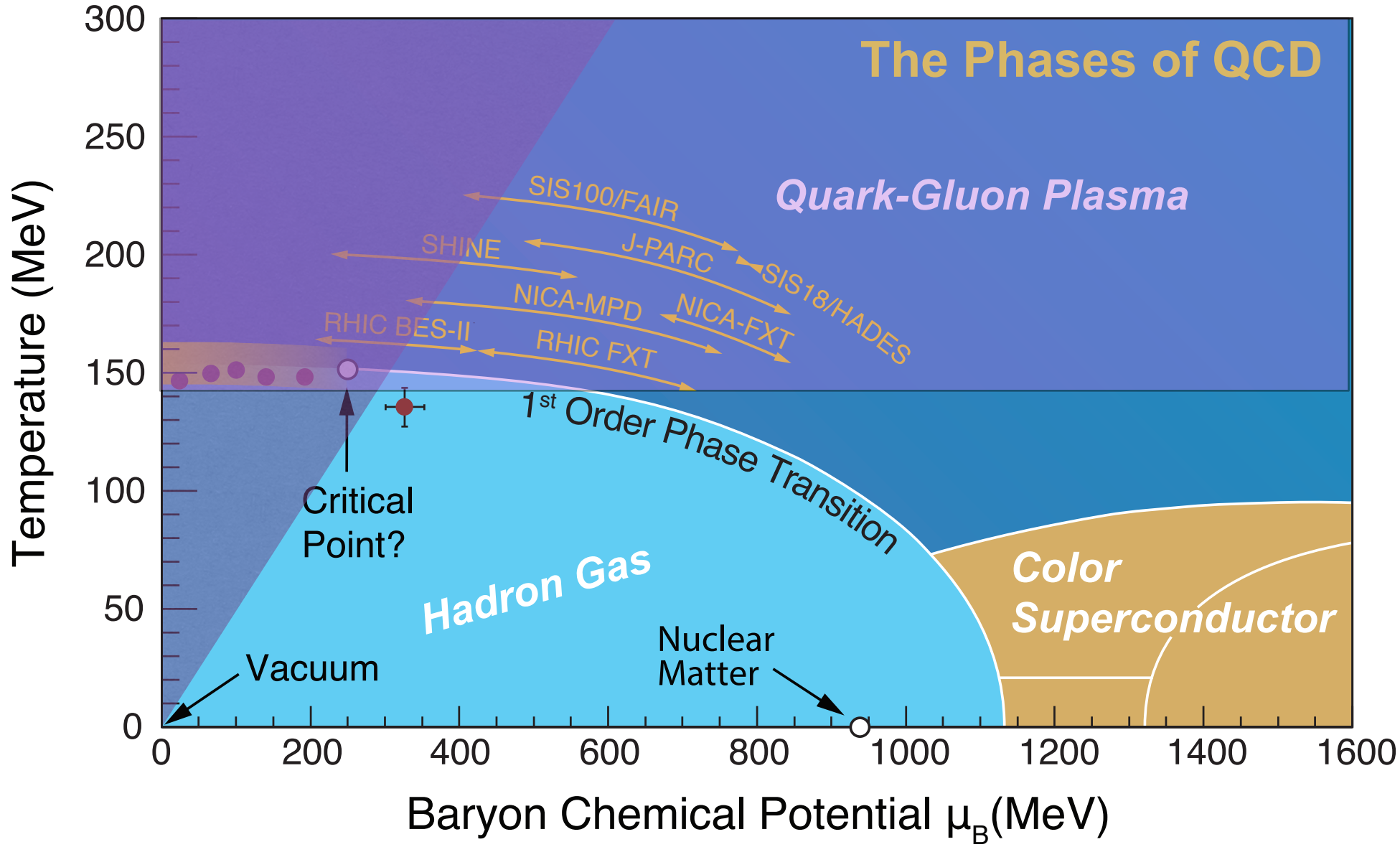
Results from BES-I and Expectations for the BES-II



Helen Caines, Yale

Critical point expectations

Bazavov et al, arXiv:1701.04325
Karsch INT-BES 2017



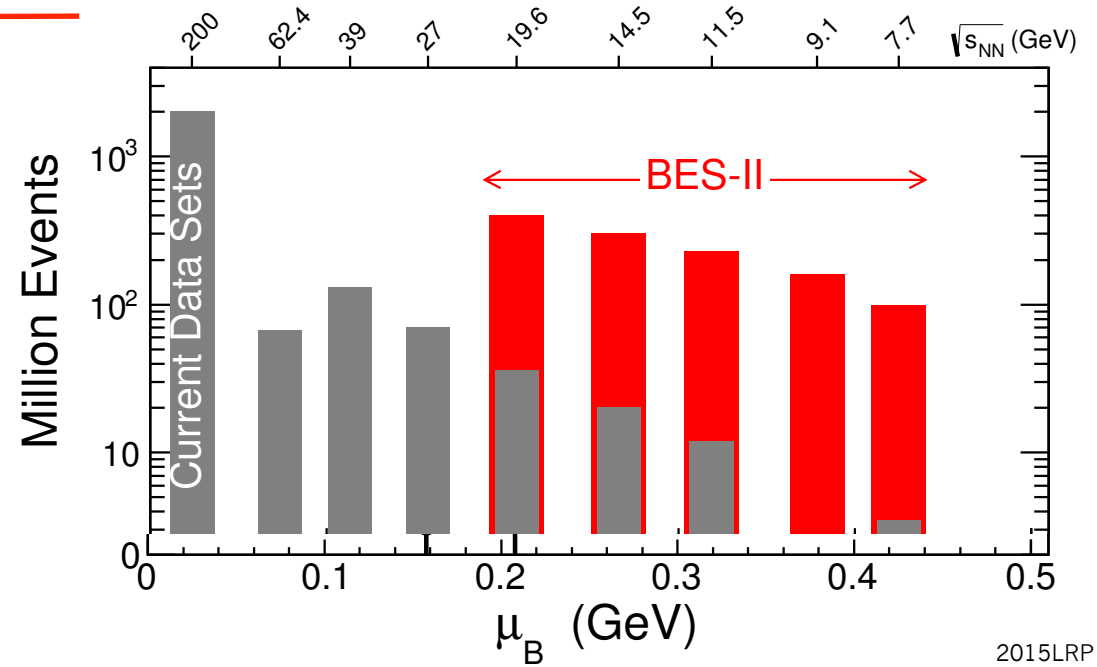
We are focusing in on the right region

Calculations disfavor C.P. where $\mu_B/T < 2$ and $T/T_C(\mu_B = 0) > 0.9$

From BES-I to BES-II

Future data:

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



+ 1 B events at 27 GeV (recent request for Run 18)

+ FXT program with 100M MB events at
7.7, 6.2, 5.2 4.5, 3.9, 3.5, 3.0 GeV (asked for 3.0 from Run 18)

RHIC eCooling - Enables the significant statistics enhancement

Turn trends and features
into definitive conclusions

Establishing the "basics": Density and Freezeout

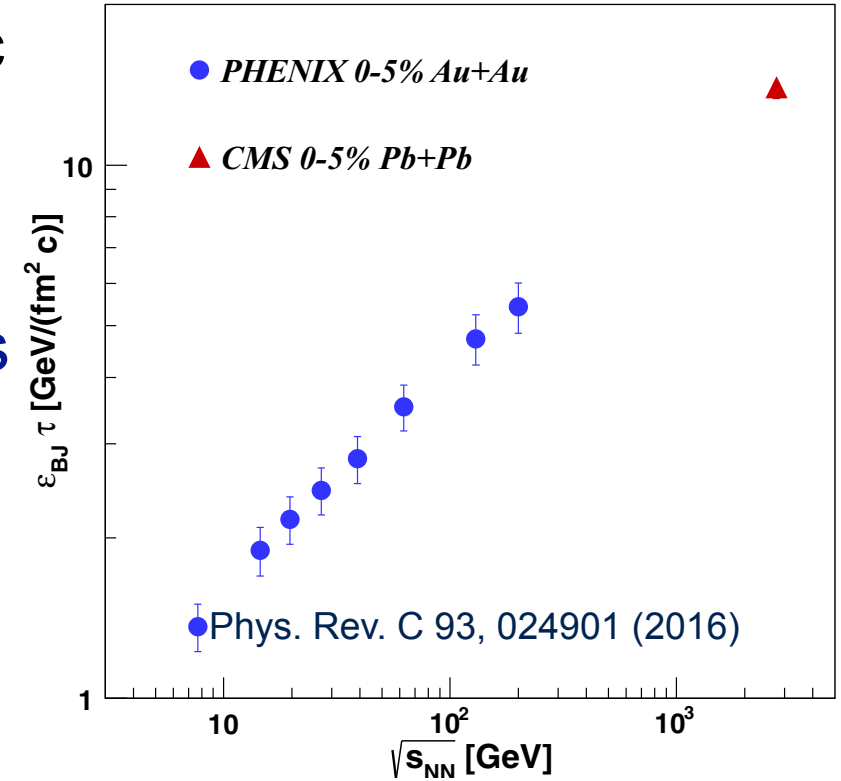
For central events:

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)

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

Can we establish τ?



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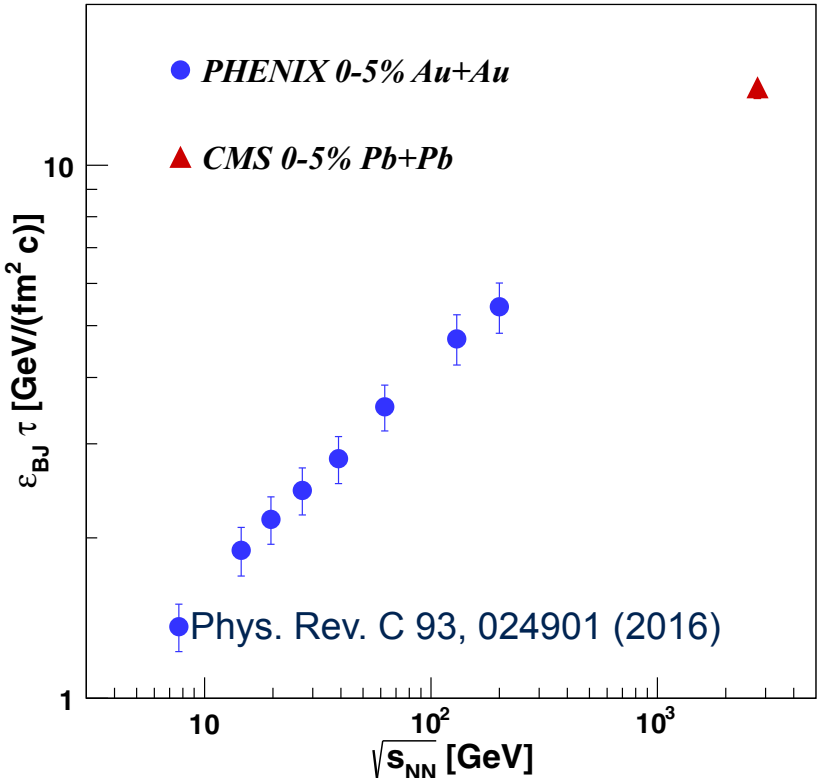
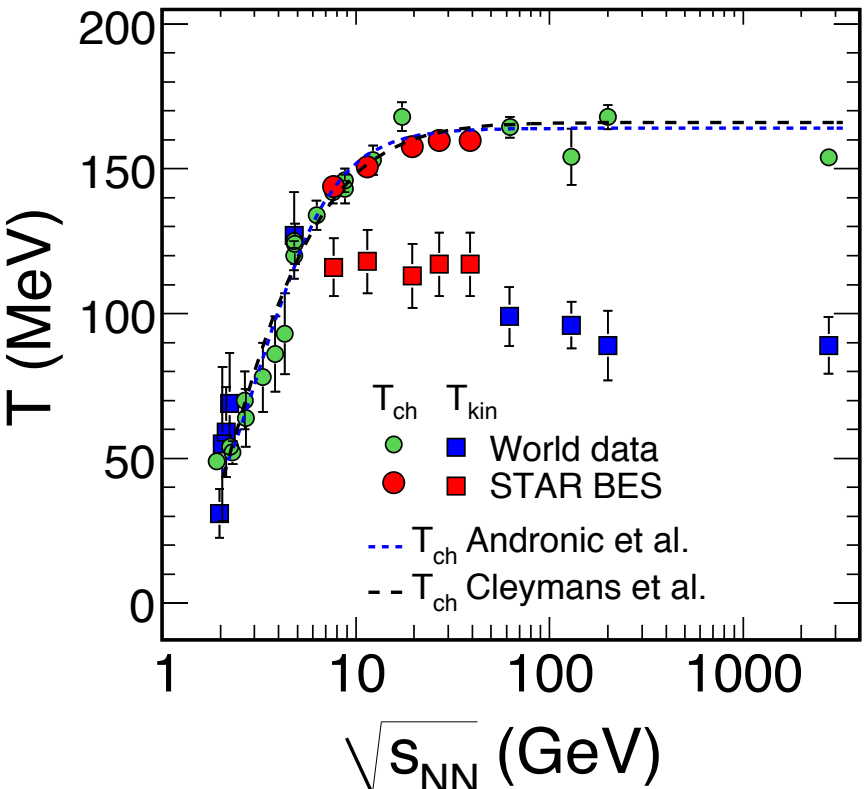


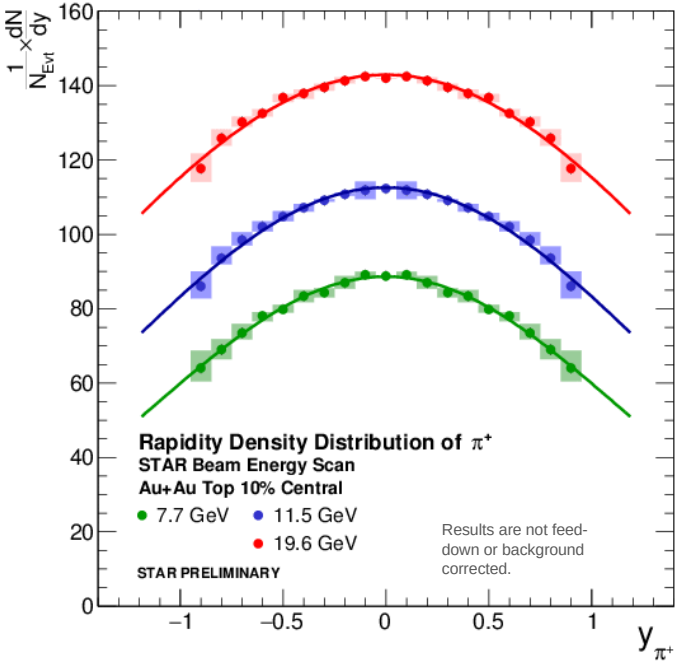


Stronger collectivity at higher $\sqrt{s}$

Lower T→ higher β

T_{kin}~T_{ch} below $\sqrt{s}$ ~ 7 GeV

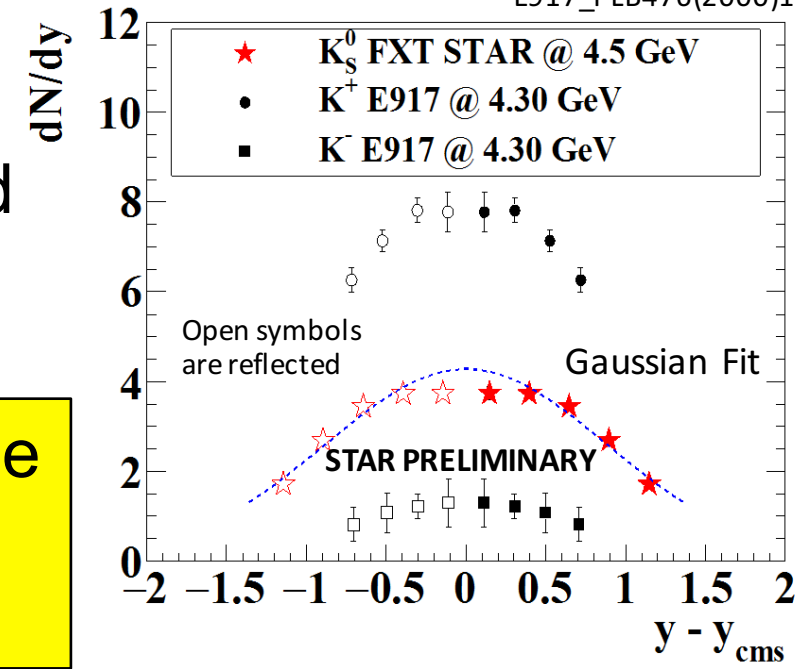
Establishing the "basics": Yields

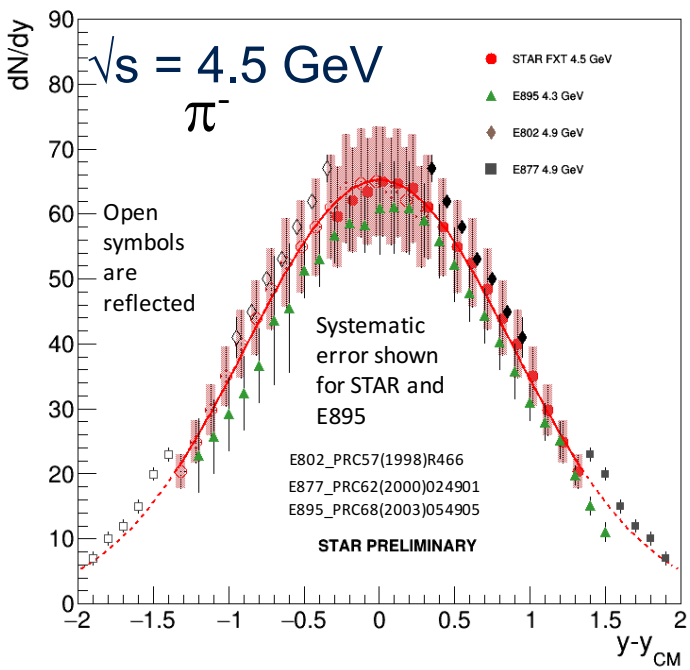


STAR can measure forward and backwards

Close to full phase space measurements

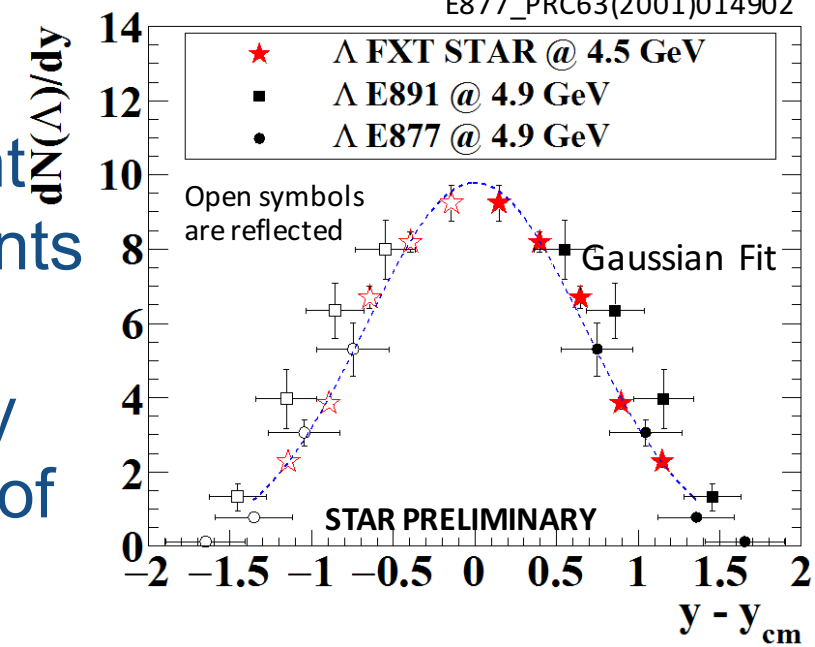
E917_PLB476(2000)1



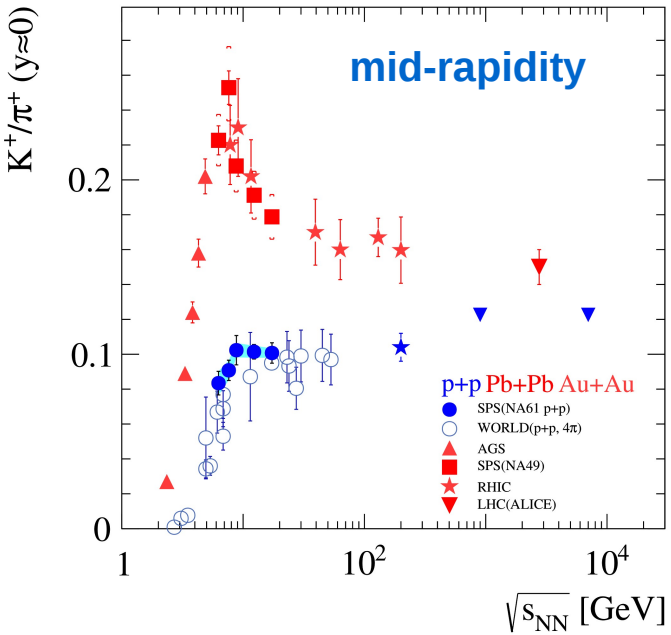


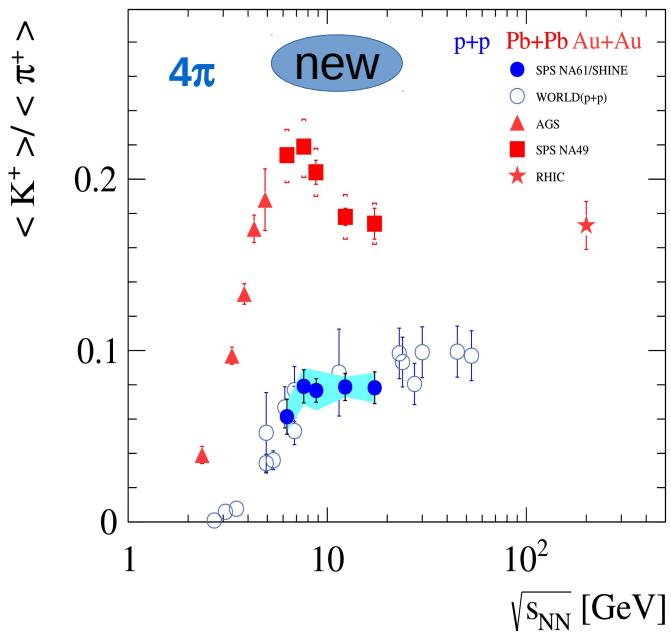
Good agreement between experiments : Fixed target program officially proposed as part of BES-II

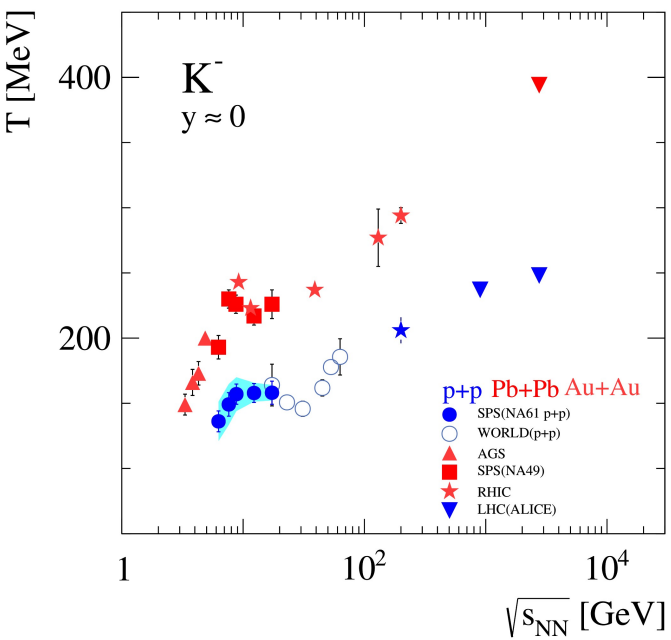
E877_PRC63(2001)014902

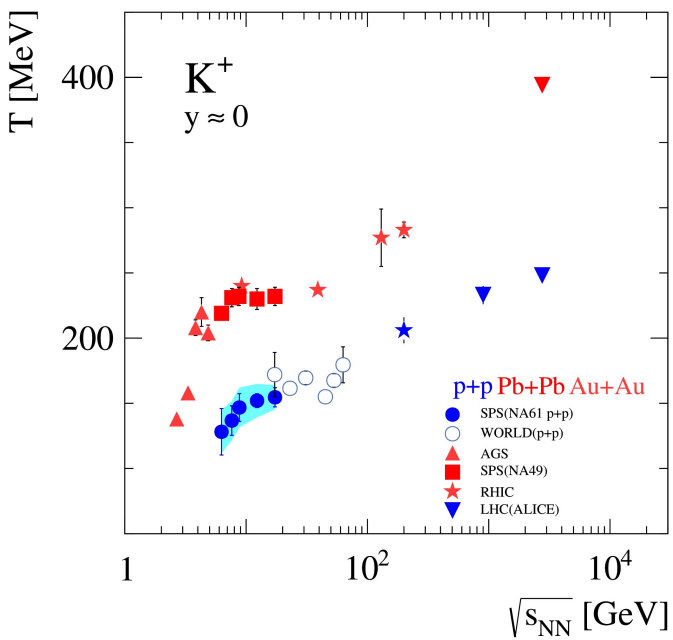


Horns and plateaus









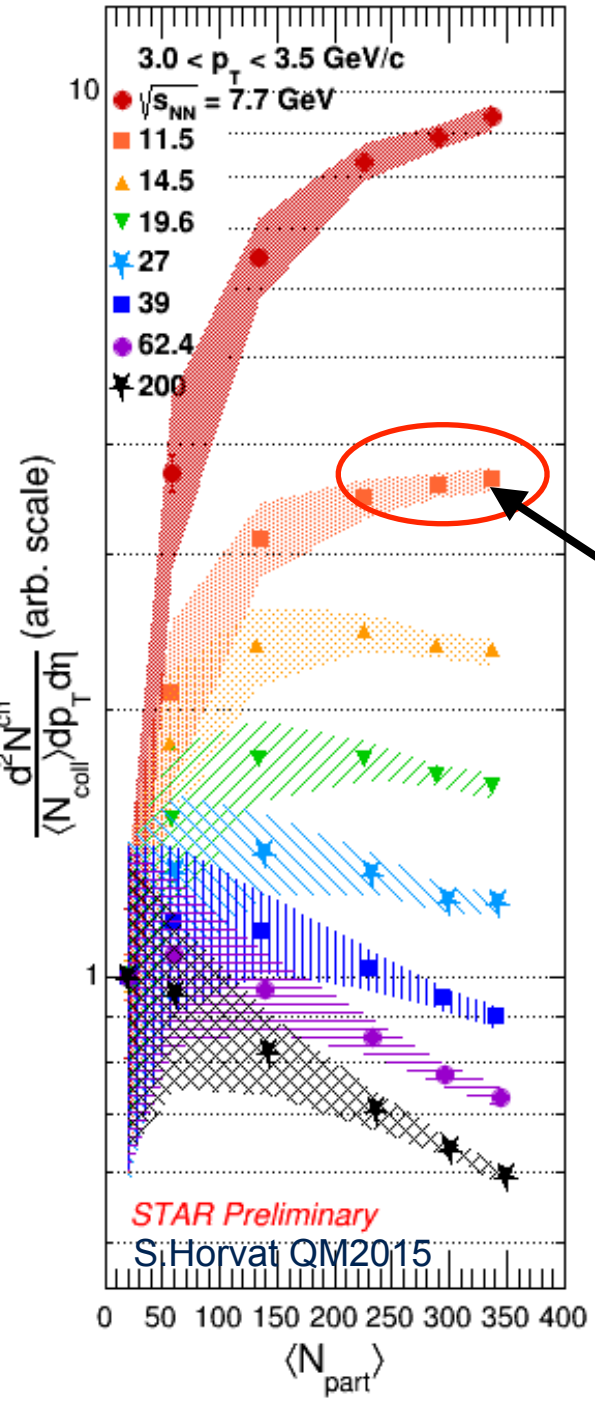
RHIC data suggests horn less pronounced

Same result for mid-rapidity as total yield

Models show baryon density also peaks √s ~7 GeV

Similar plateau in T_{kin} for pp

Disappearance of QGP?

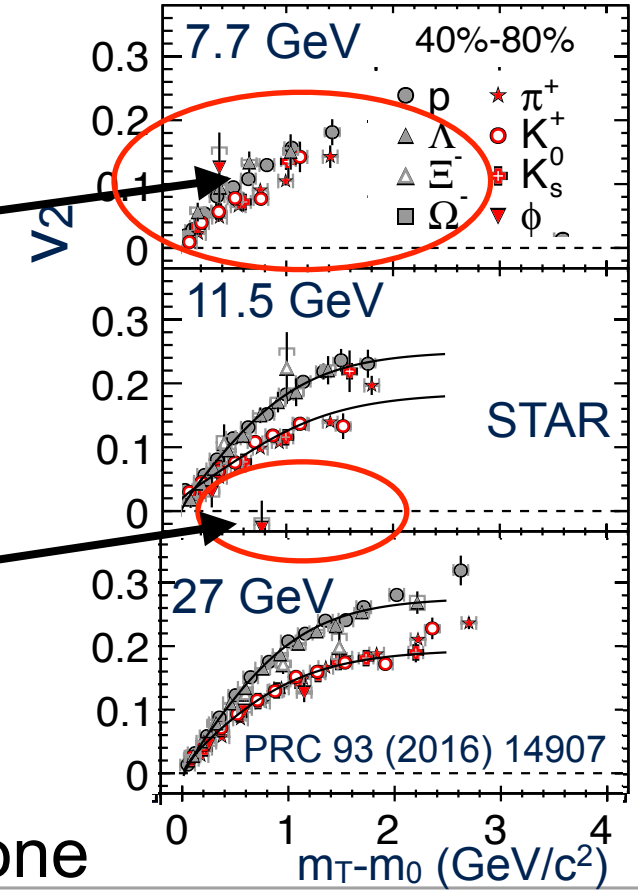


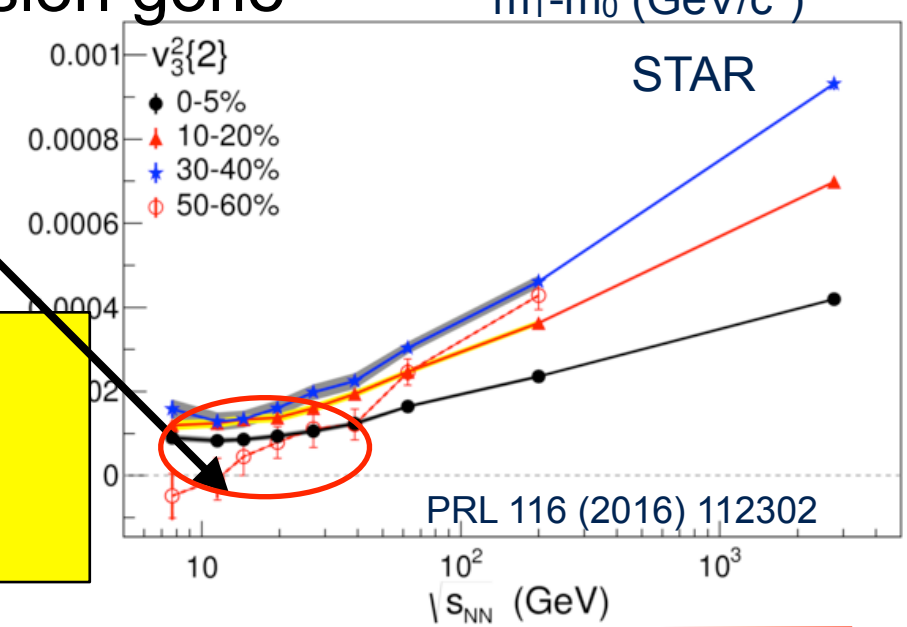
B-M v_2 separation gone

ϕ v_2 ~ 0

High p_T suppression gone

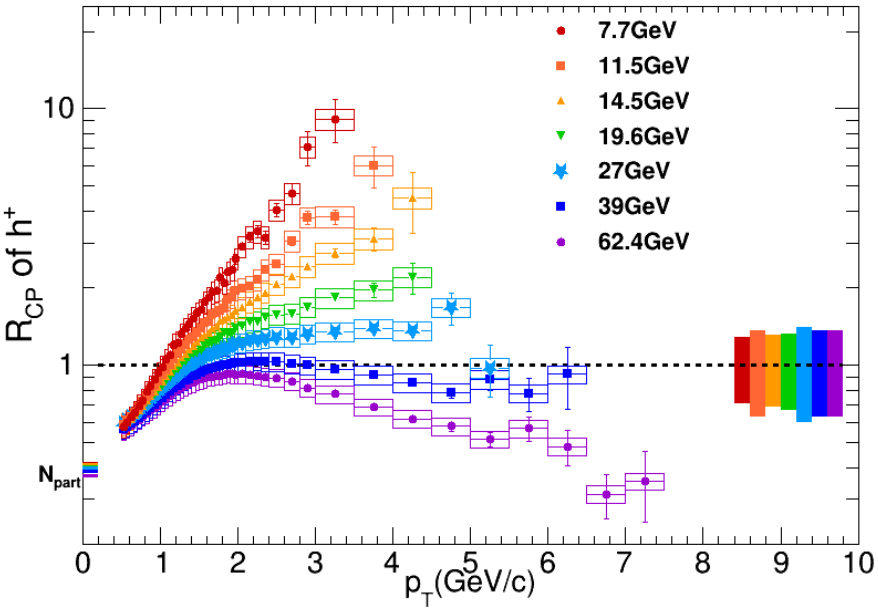
v_3 ~ 0

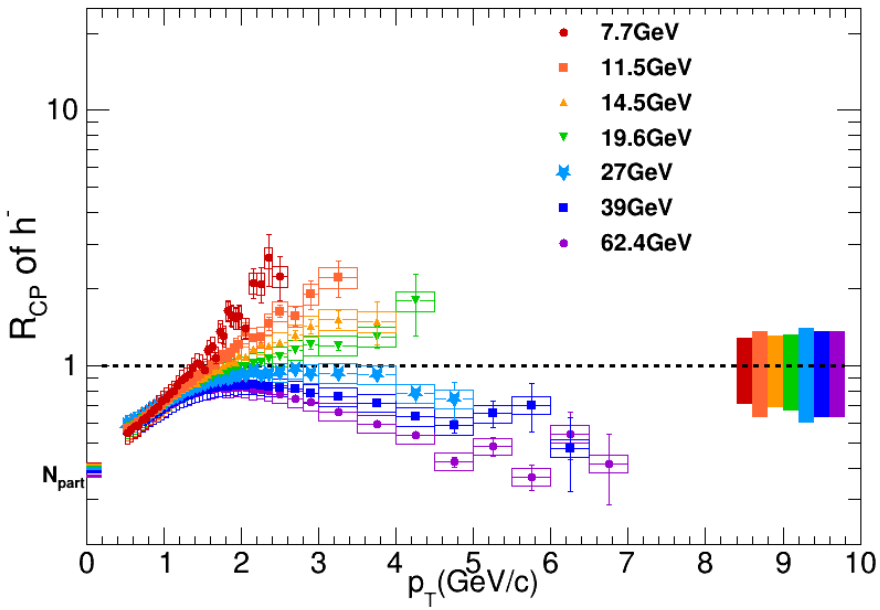




Several standard signals disappear at $\sqrt{s}$ <~ 20 GeV

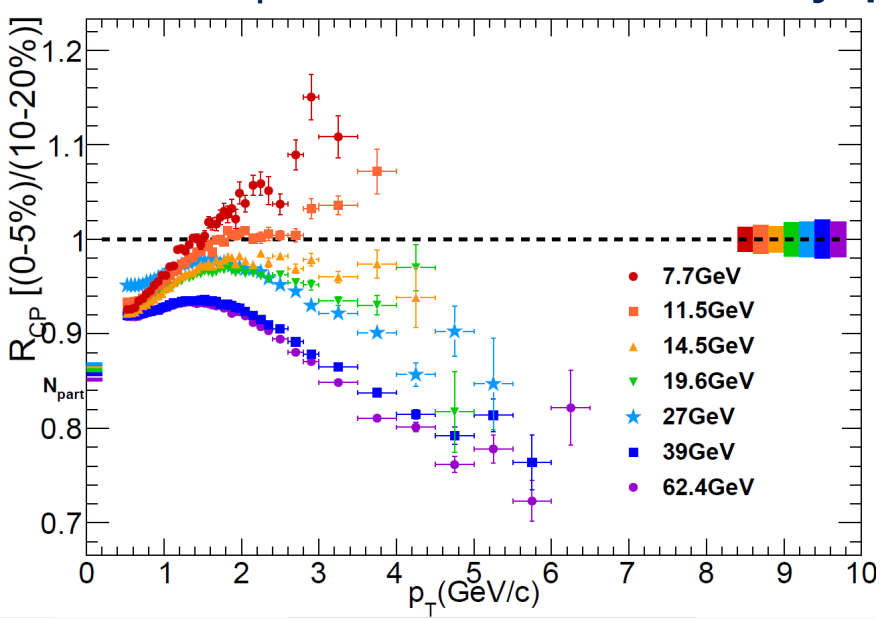
Another look at jet quenching





R_{cp} h^+ - Contribution from protons changing with $\sqrt{s}$

R_{cp} h^- - Dominated by pions for all $\sqrt{s}$



High-p_T suppression for ≥ 14.5 GeV

New limit for lowest collision energy that evidence of partonic energy-loss has been presented at

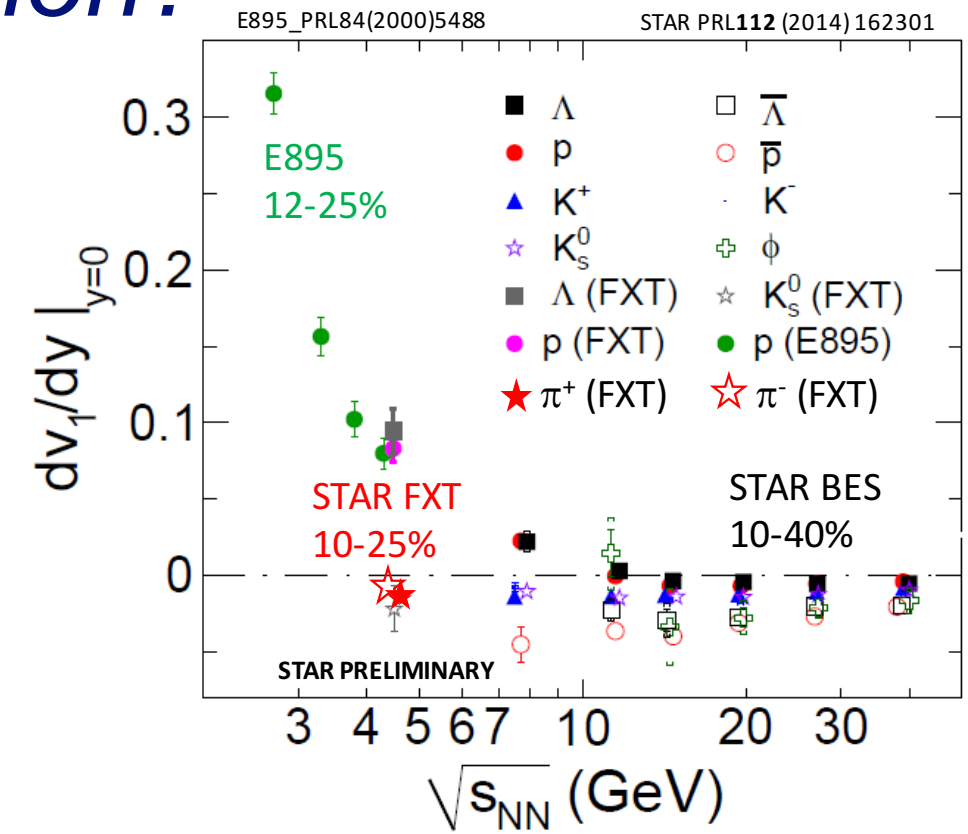
First order phase transition?

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



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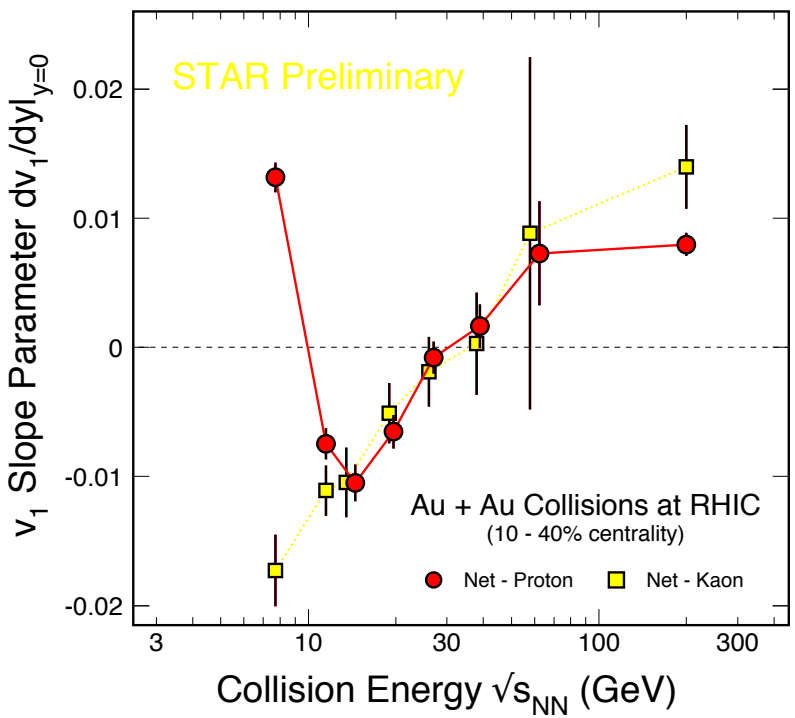
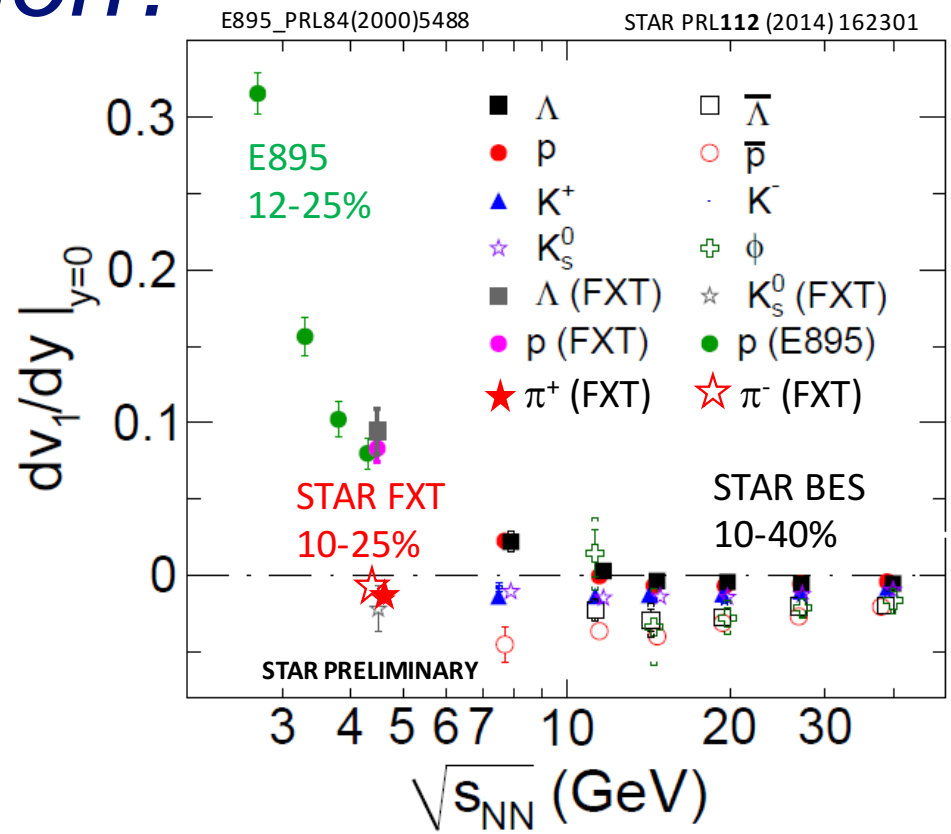




Net-proton isolates directed flow of transported baryons:

Double sign change in dv_1/dy

Not seen in net-kaons

Results not yet reproduced by theory

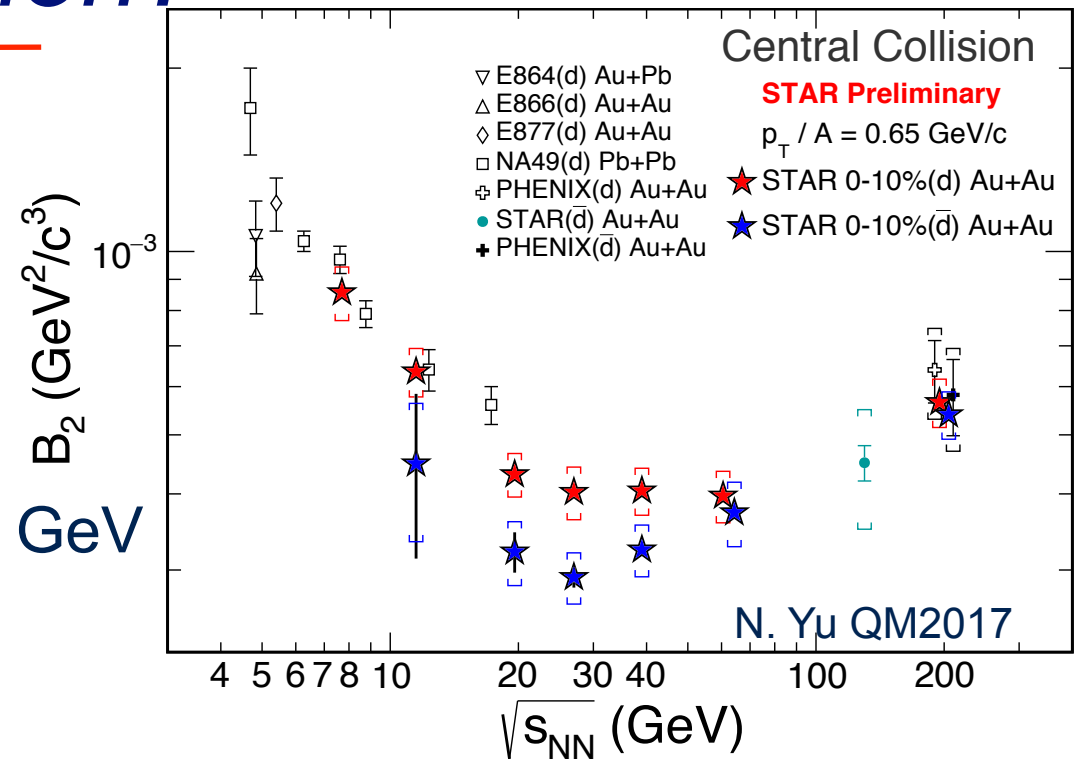
Softening of EoS ?

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 maximum) $\sqrt{s_{NN}}$ ~ 20 GeV



PRC 92 014904 (2015)

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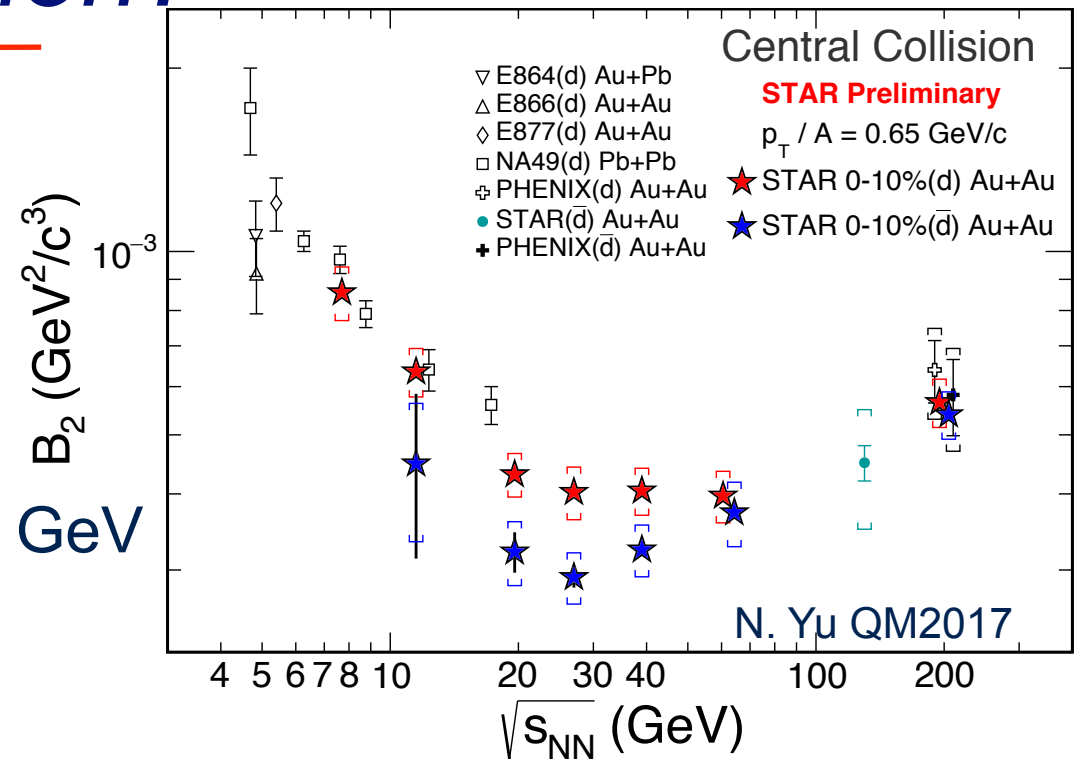
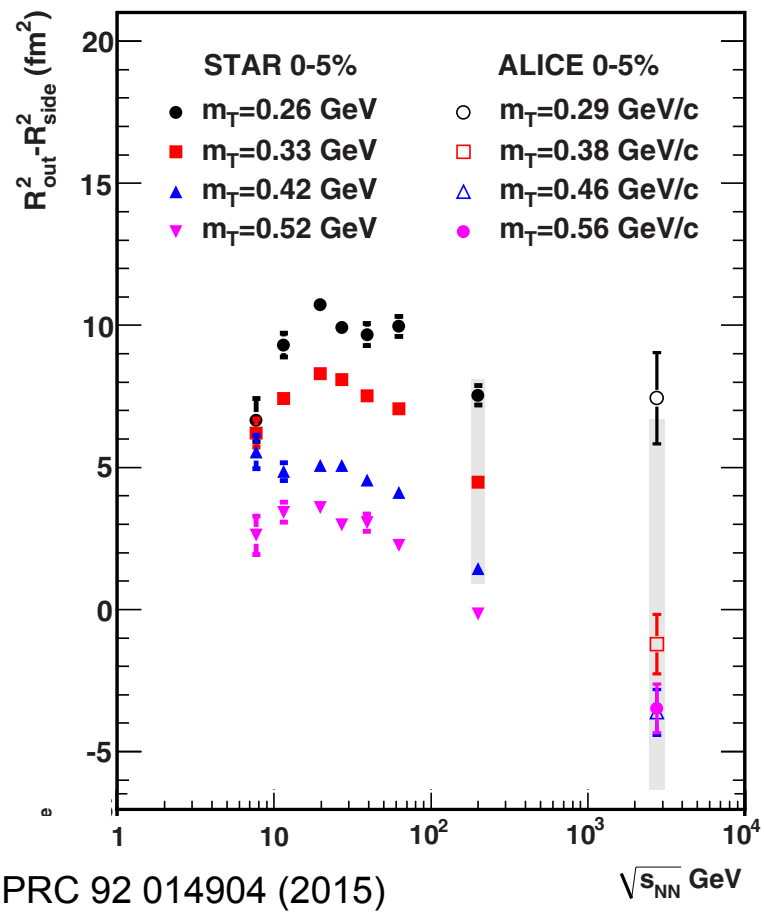




PRC 92 014904 (2015)

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

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

Softening of EoS?

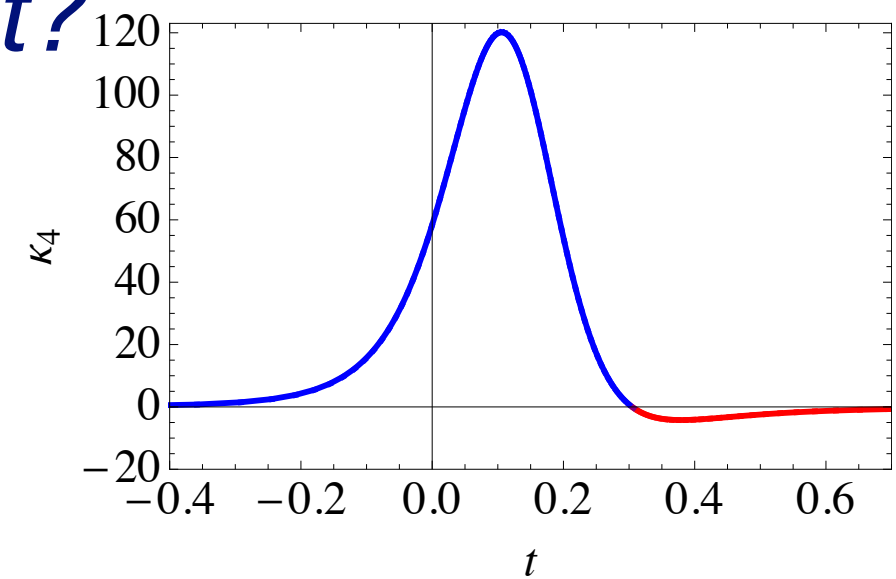
Sign of entering compressed baryonic matter regime?

Presence of Critical Point?

M. Stephanov. PRL 107:052301(2011)

Critical Points:

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



Correlation lengths diverge

→ Net-p $\kappa\sigma^2$ diverge

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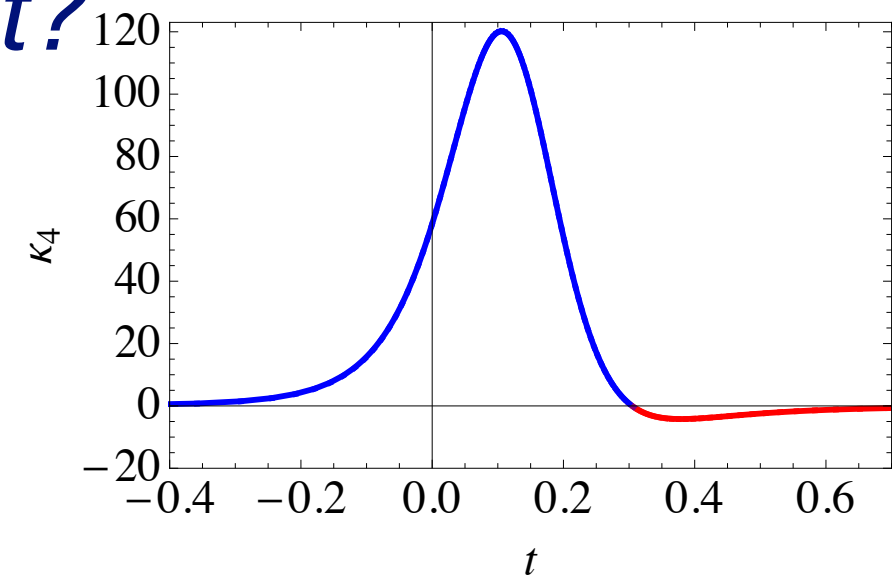
M. Stephanov. PRL 107:052301(2011)



Critical Points:

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

Correlation lengths diverge

→ Net-p $\kappa\sigma^2$ diverge

Top 5% central collisions:

- Non-monotonic behavior
- Enhanced p_T range → enhanced signal

Peripheral collisions:

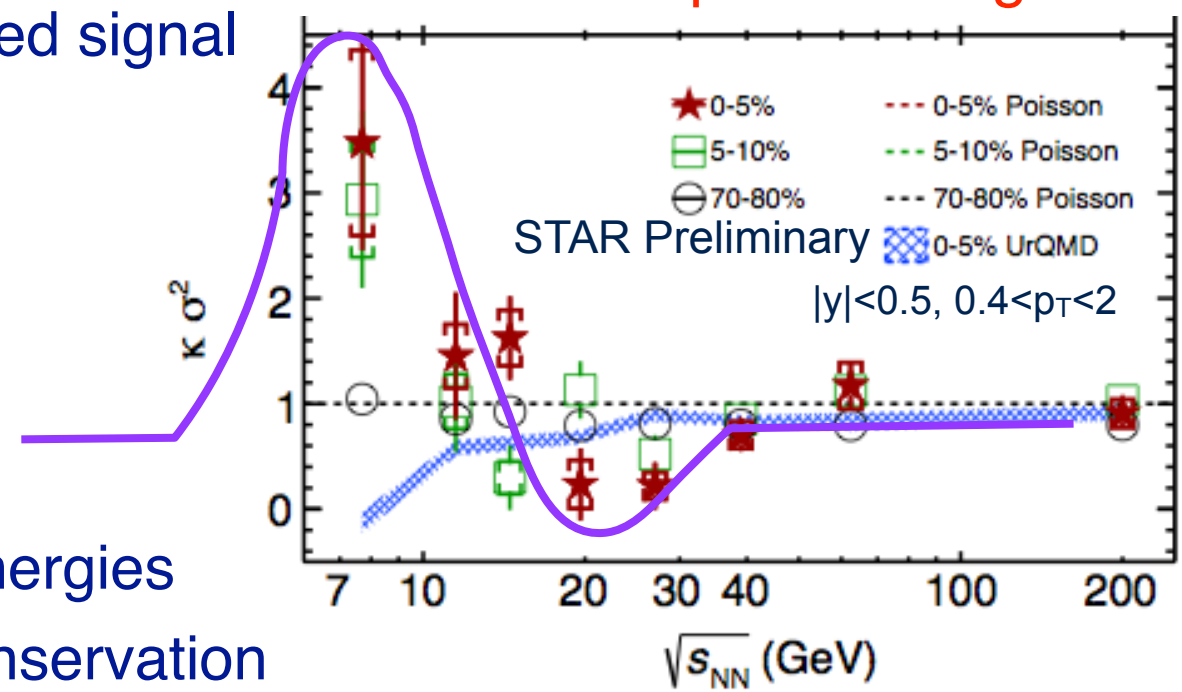
- smooth trend

5-10% central collisions:

- in between

UrQMD (no Critical Point):

- shows suppression at lower energies
  - due to baryon number conservation



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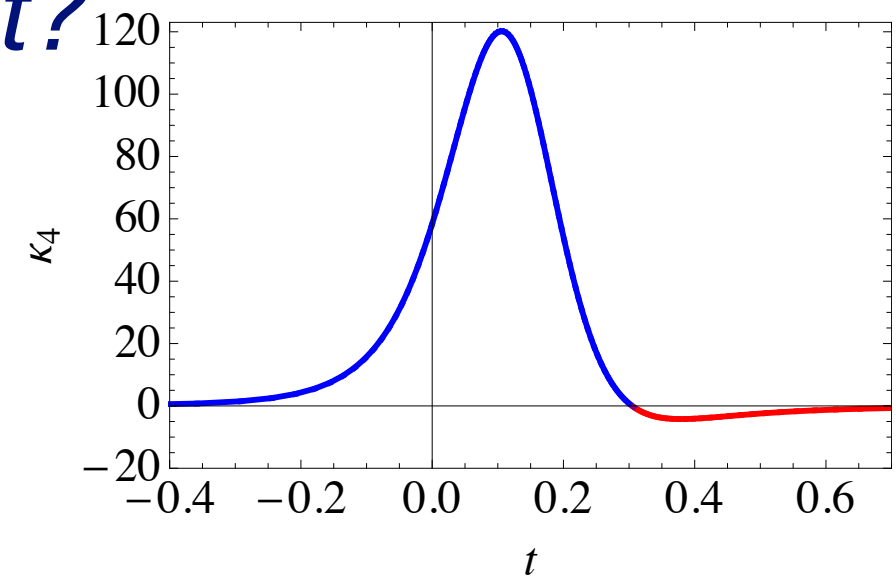
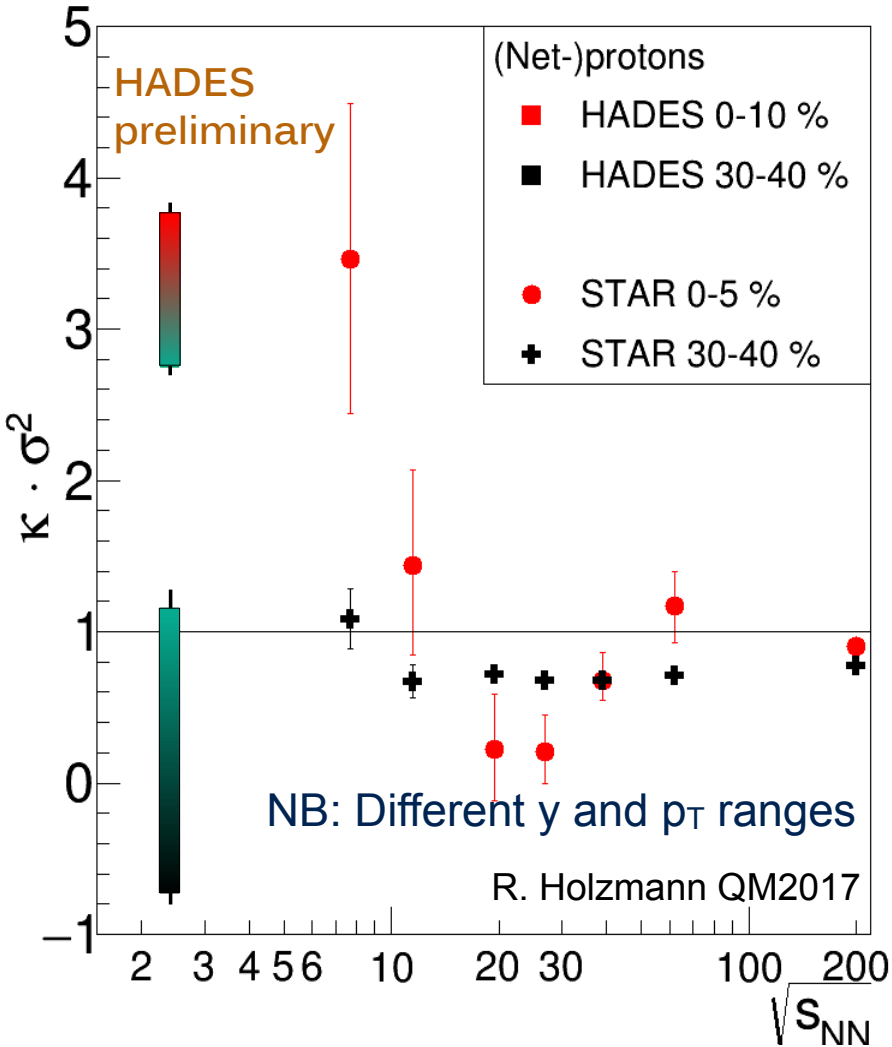


HADES data + upcoming FXT testing if mapping correct

New HADES data causing some tension



Correlation lengths diverge

→ Net-p $\kappa\sigma^2$ diverge

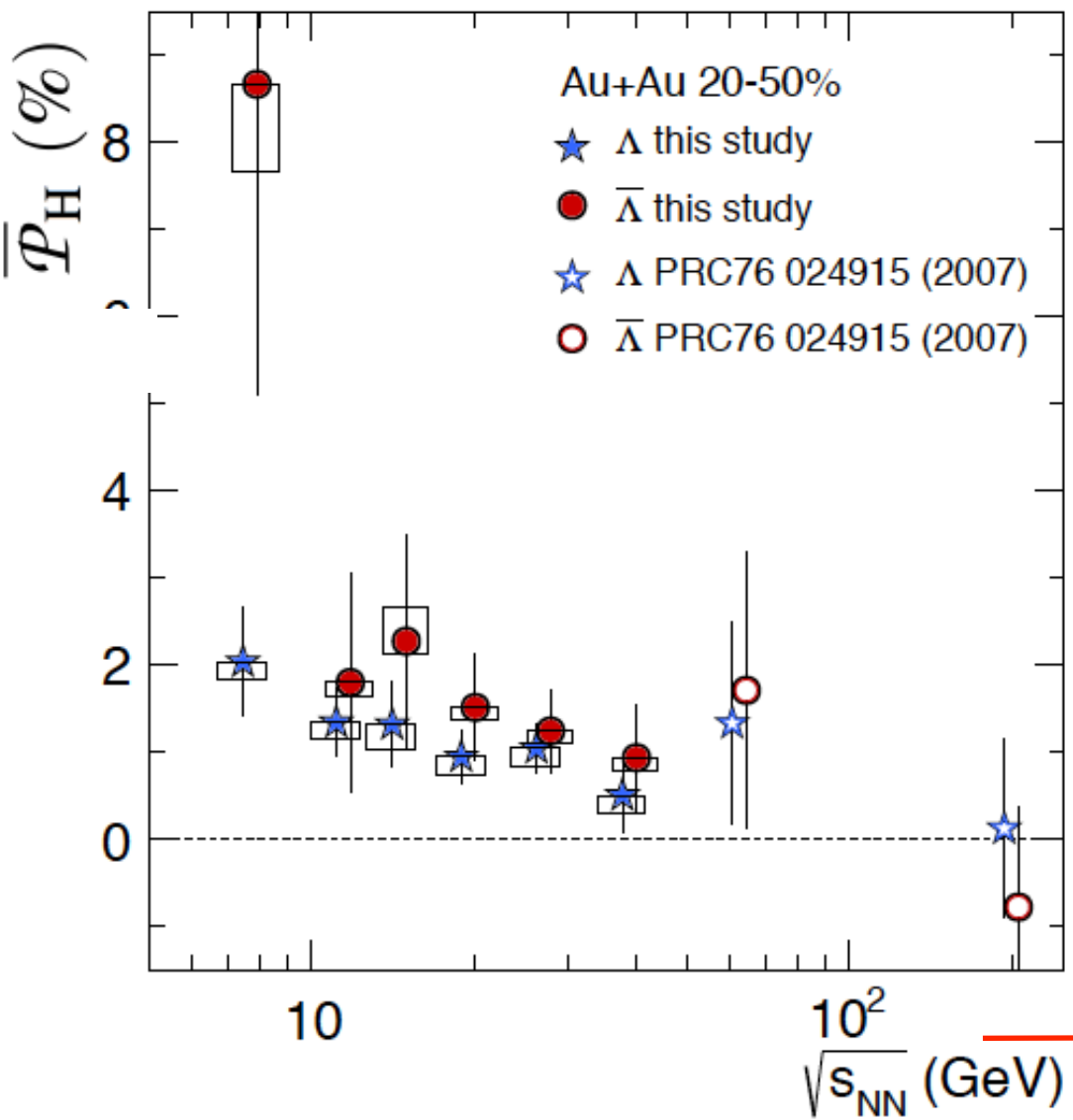
Hints of Critical fluctuations

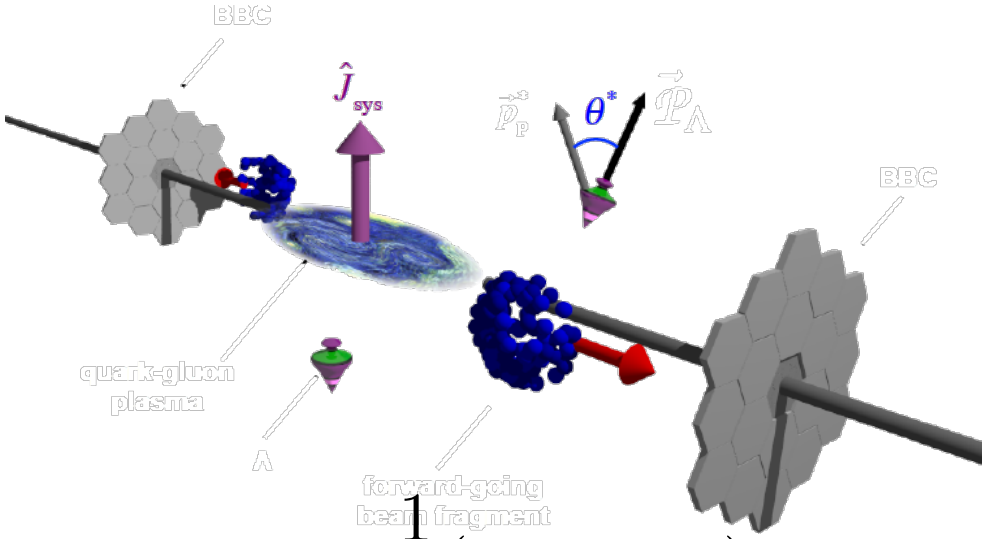
N.B. non-monotonic behavior not observed by PHENIX - due to different acceptances?
(PRC 93, 011901 (2016))

Nor in pp or light nuclei by NA61 (PRC 93, 011901 (2016))

The spinning QGP

First observation of non-zero global angular momentum transfer to hyperon polarization





$$P_{vortical} = \frac{1}{2}(P_\Lambda + P_{\bar{\Lambda}})$$

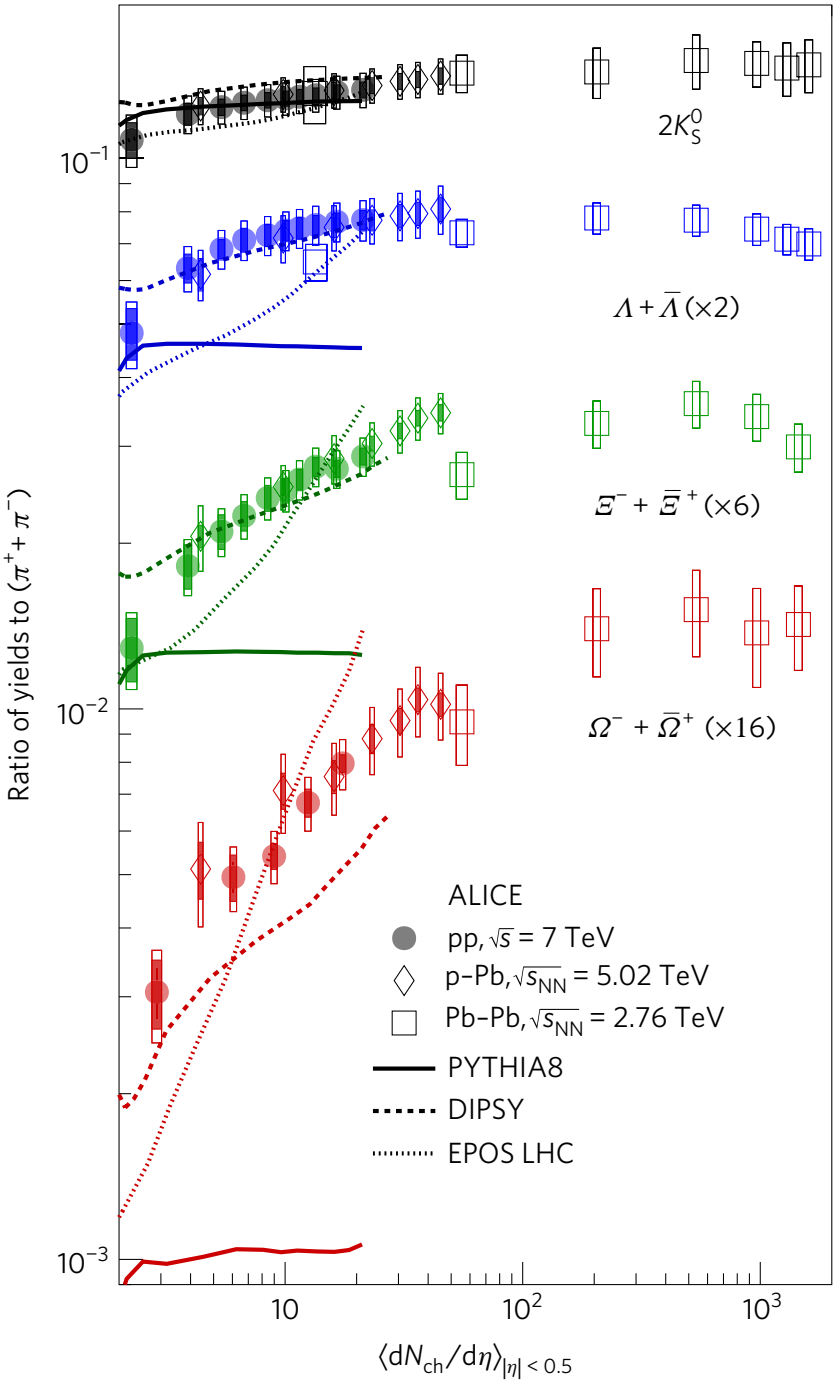
Highly vortical fluid:
$\omega = (9 \pm 1)\times 10^{21}\ s^{-1}$

$$P_{EM} = \frac{1}{2}(P_\Lambda - P_{\bar{\Lambda}})$$

anti-Λ > Λ

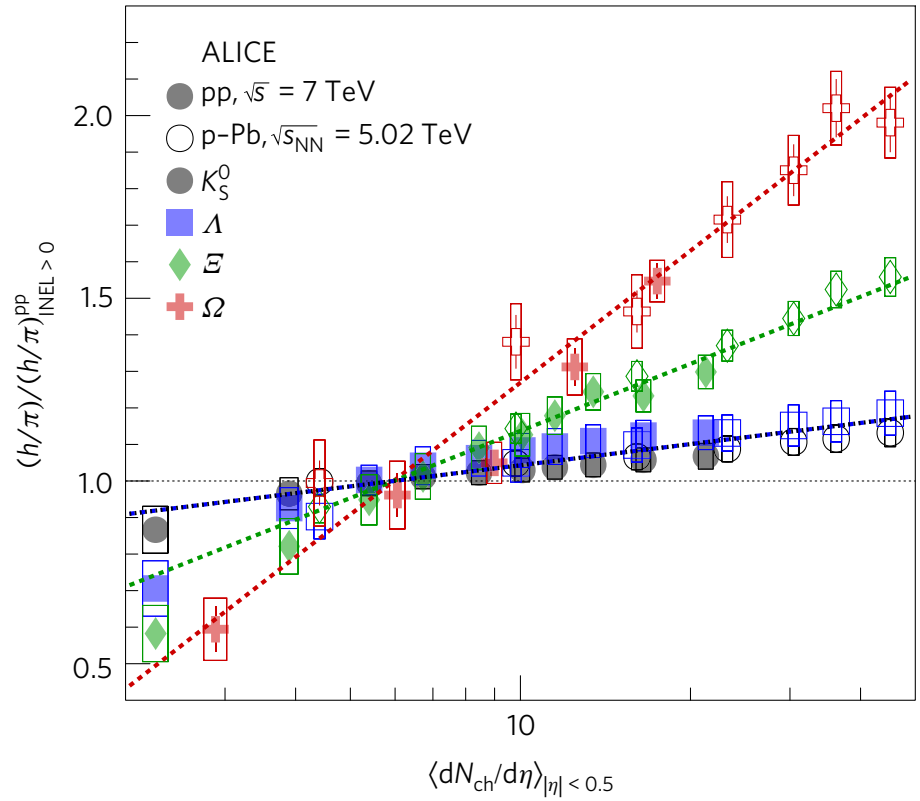
Effects of initial B field

New spin on strangeness enhancement



Nature Physics 13, 535–539 (2017)

Strangeness Yield/π vs dN_{ch}/dy: trends independent of √s and species



$$\frac{(h/\pi)}{(h/\pi)^{pp}_{INEL>0}} = 1 + a\, S^b \log\left[\frac{\langle dN_{ch}/d\eta\rangle}{\langle dN_{ch}/d\eta\rangle^{pp}_{INEL>0}}\right]$$

a = 0.083 ± 0.006, b = 1.67± 0.09

What happens at lower √s?

Coming back to entropy

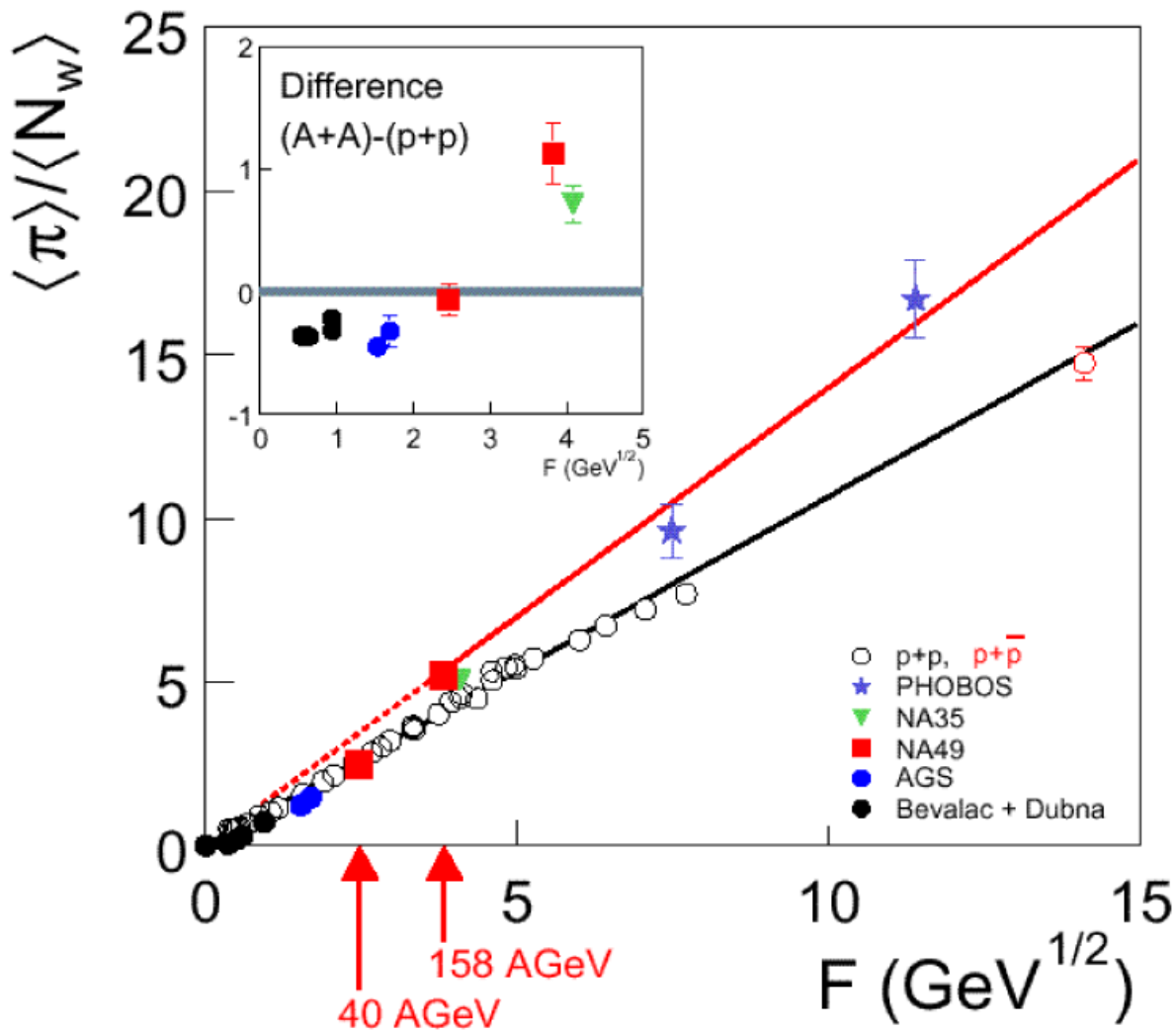
Landau and Fermi (50s)

(assume thermalized source expanding adiabatically)

$$\frac{S}{V} \sim \varepsilon^{3/4}$$

$$F = \frac{(\sqrt{s_{NN}} - 2m_N)^{3/4}}{\sqrt{s_{NN}}^{1/4}}$$

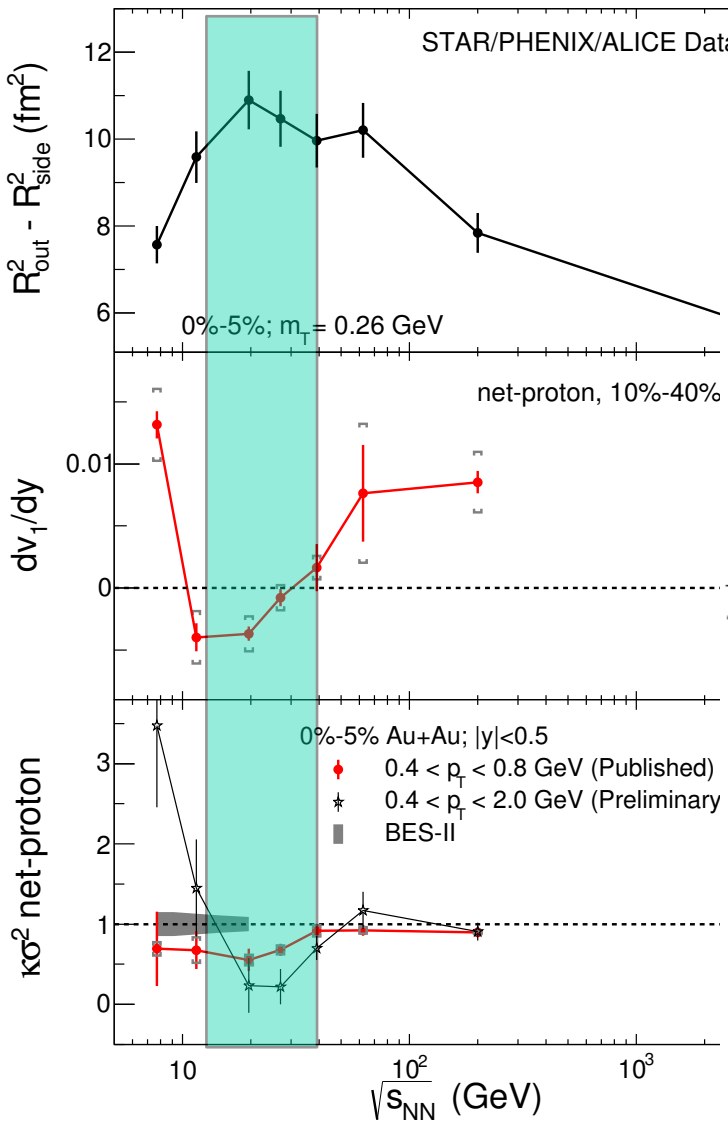
$$\frac{S}{V} \sim \frac{\langle \pi \rangle}{\langle N_p \rangle} \sim F$$

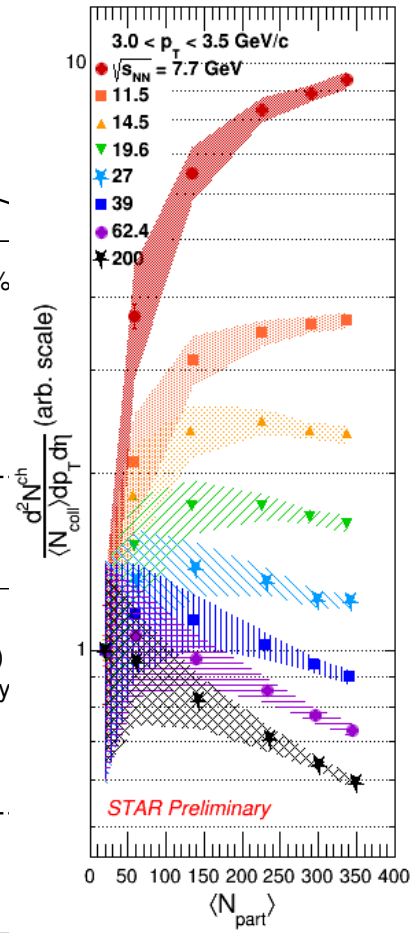


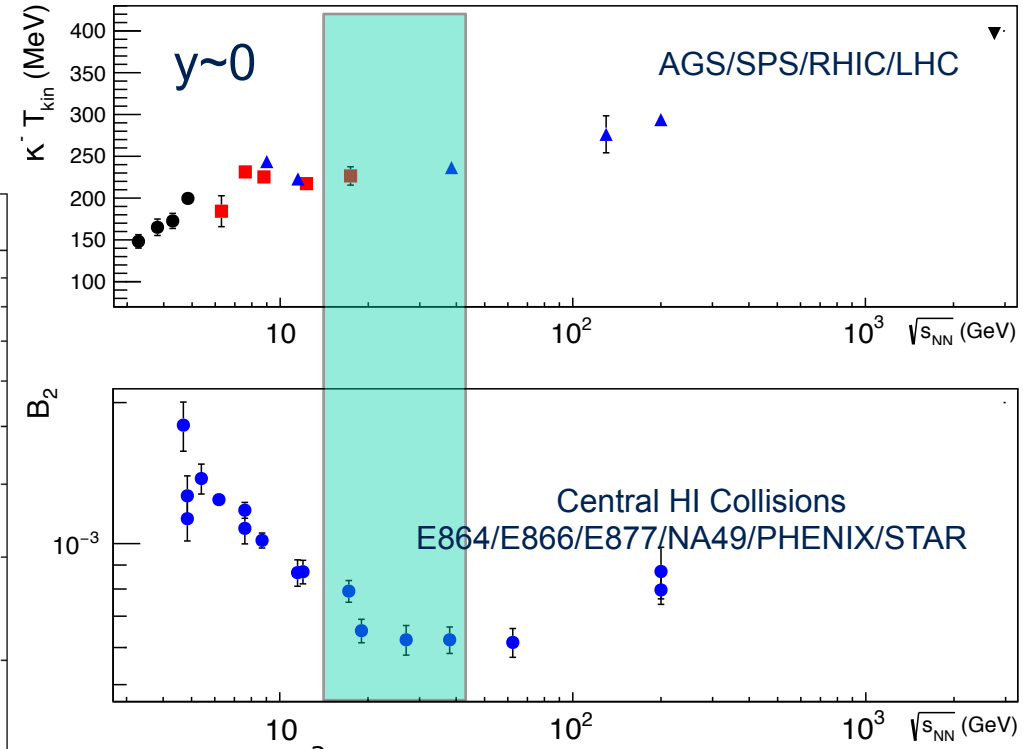
Entropy in Heavy Ion
> Entropy in p-p?

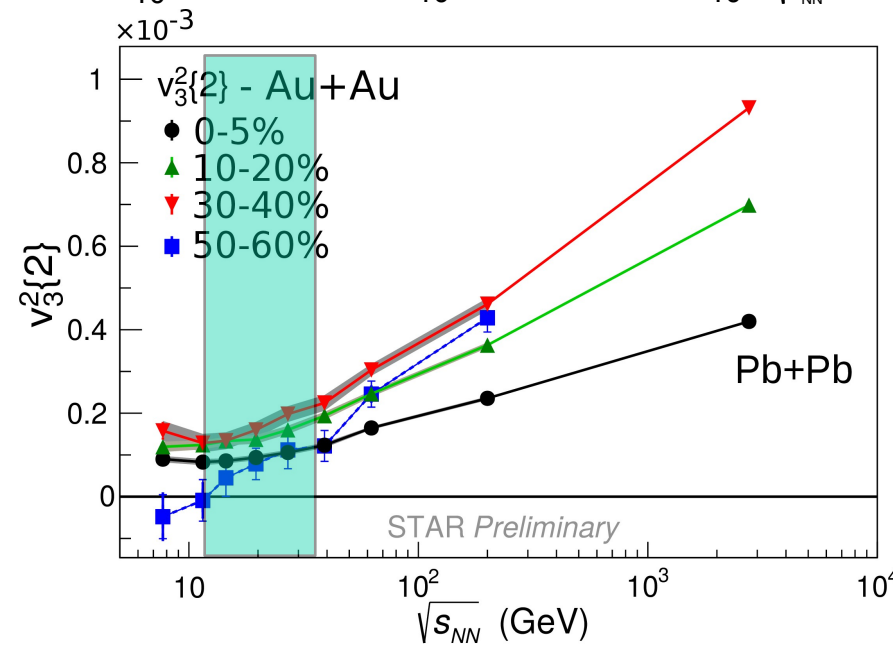
How do BES, asymmetric, and high mult. pp data fit into the picture?

A lot is happening around 20 GeV



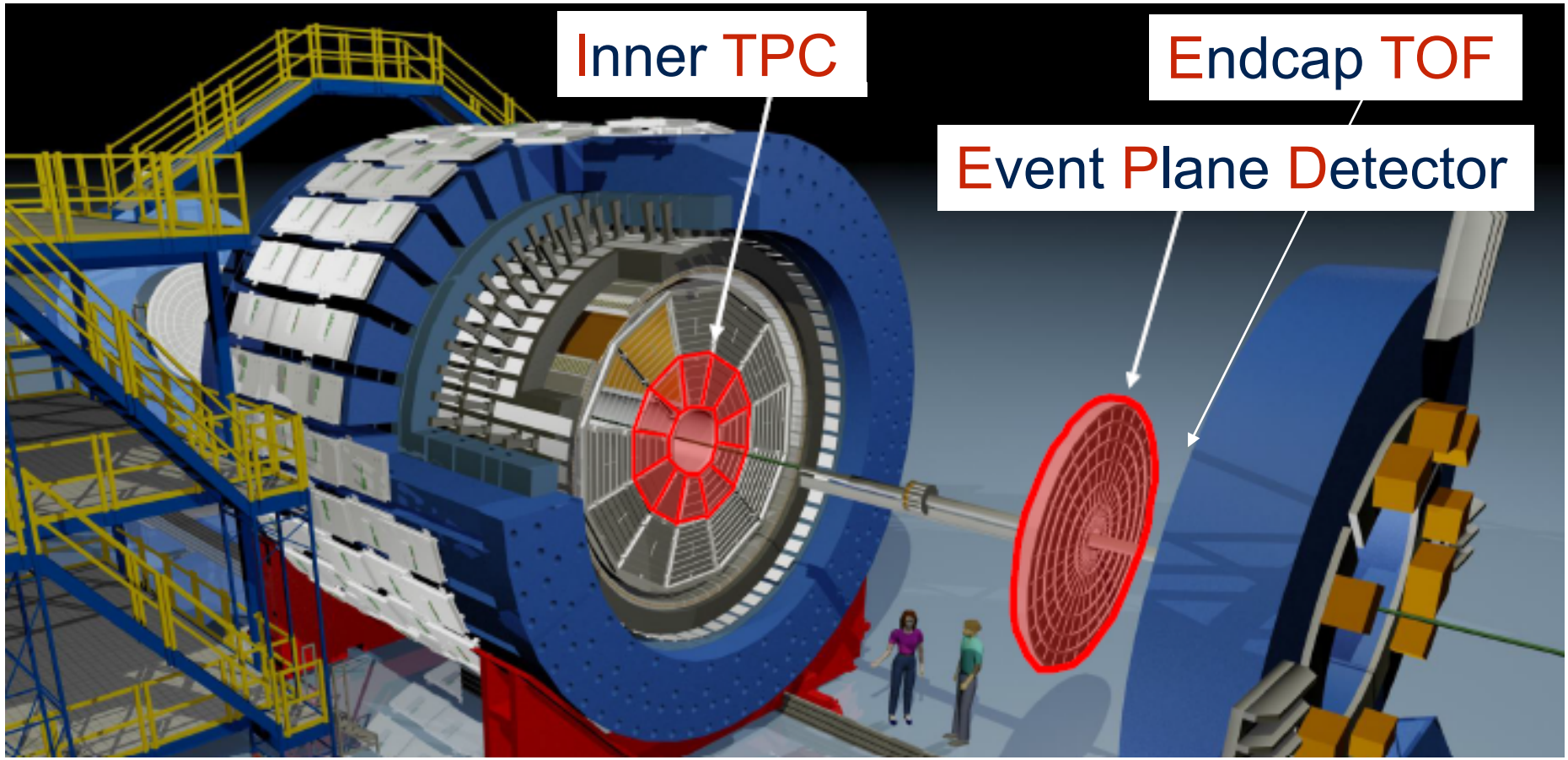






Hard to believe this is a conspiracy of different underlying causes

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 (from CBM),
Fixed target

C. Yang QM2017

iTPC

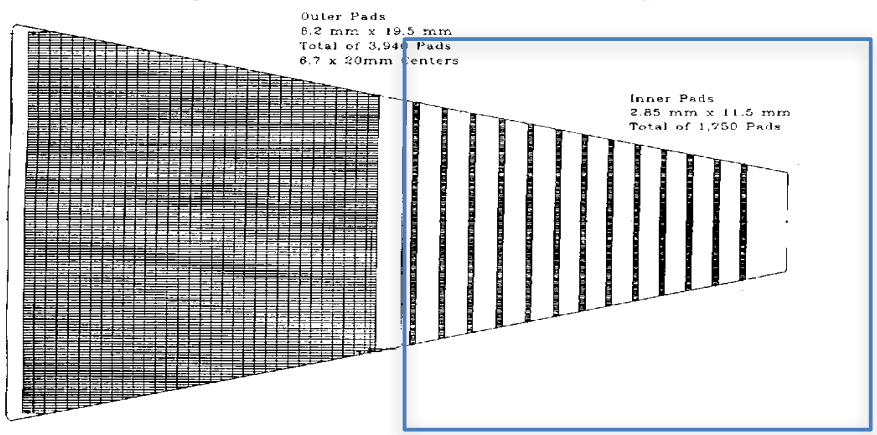
Increase in #channels in 24 inner sectors by ~factor 2

Provides near complete coverage

New electronics for inner sectors

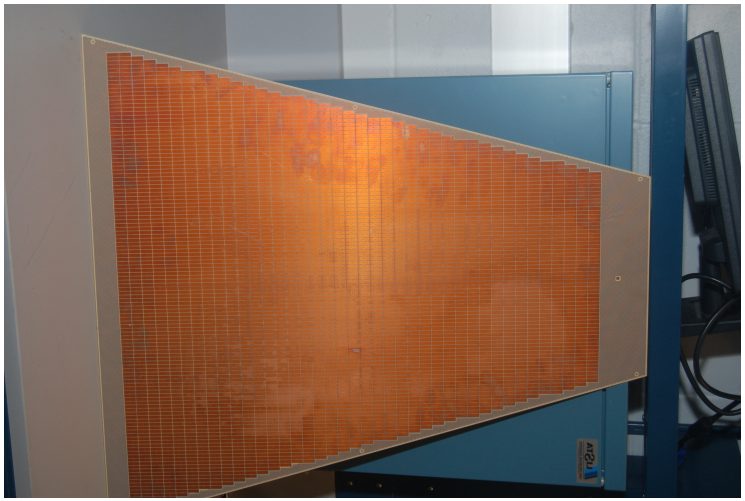
Enhanced rapidity coverage

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



Outer

Inner



Event Plane Detector: EPD

$2.1 < |\eta| < 5.0$

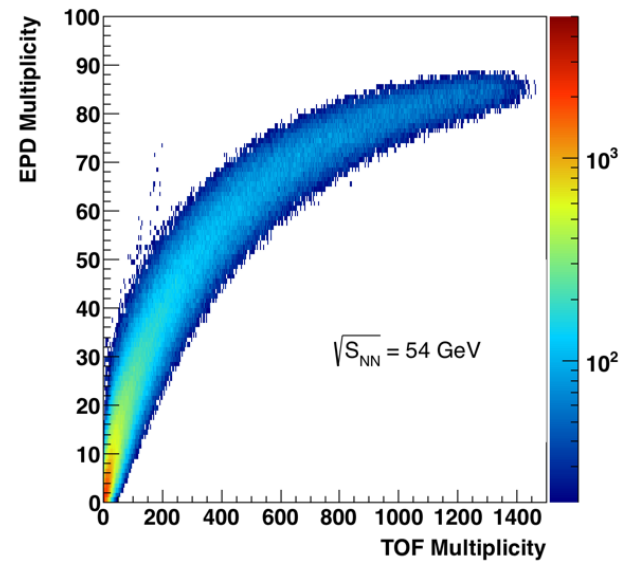
Replacing BBCs

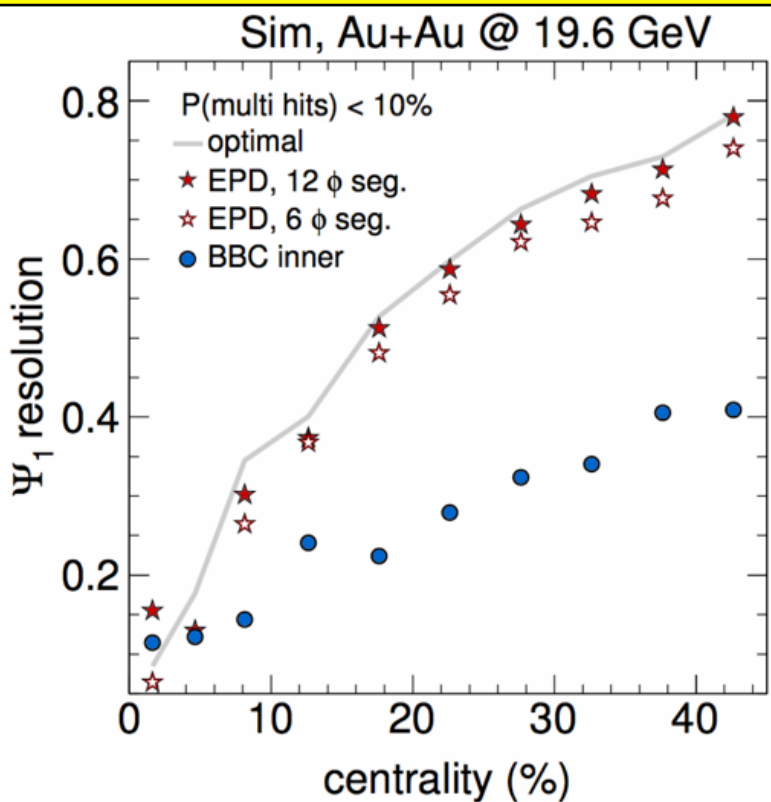
16 radial and 24 azimuthal sections

1/8 Run 17, Full Run 18

Greatly improved Event Plane Resolution

especially 1st-order EP

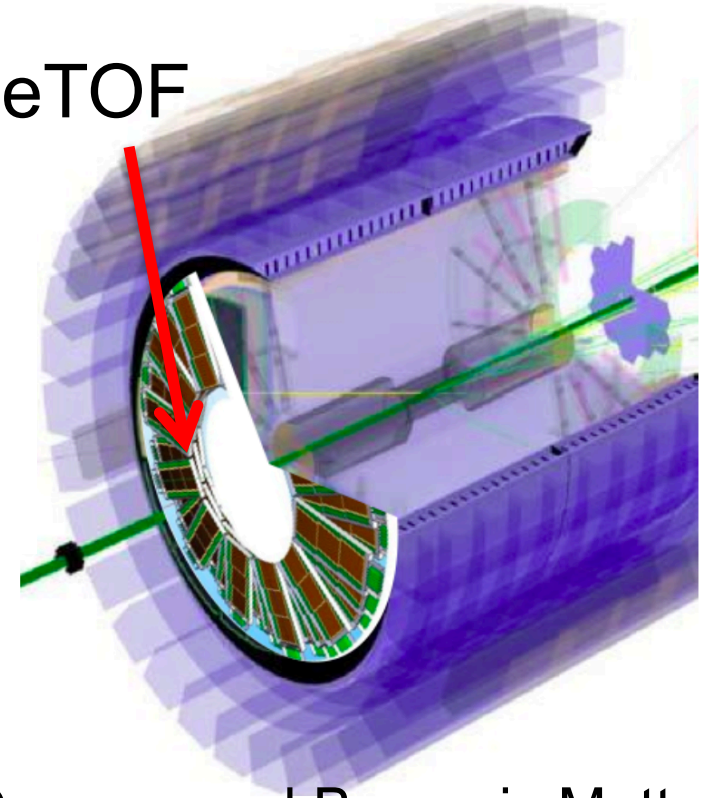




Determine Centrality away from mid-rapidity

Better trigger & background reduction

Endcap Time-Of-Flight: eTOF



Forward PID over iTPC η range

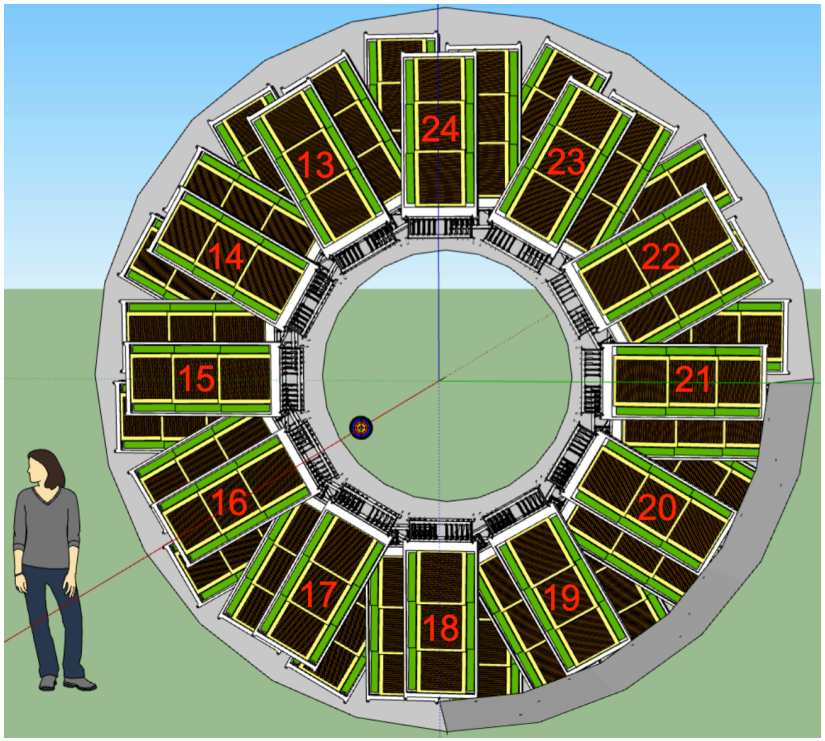
$-1.6 < \eta < -1.1$

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

Compressed Baryonic Matter Experiment (CBM)

- 1/10th TOF modules installed inside East pole-tip

- Large-scale integration test of system for CBM

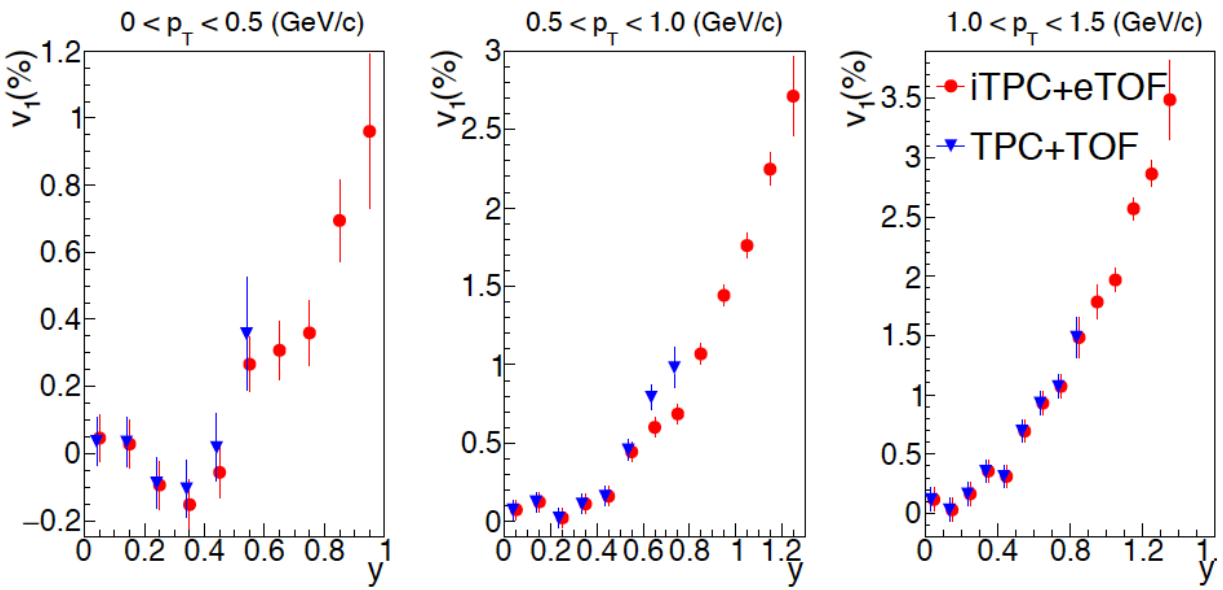


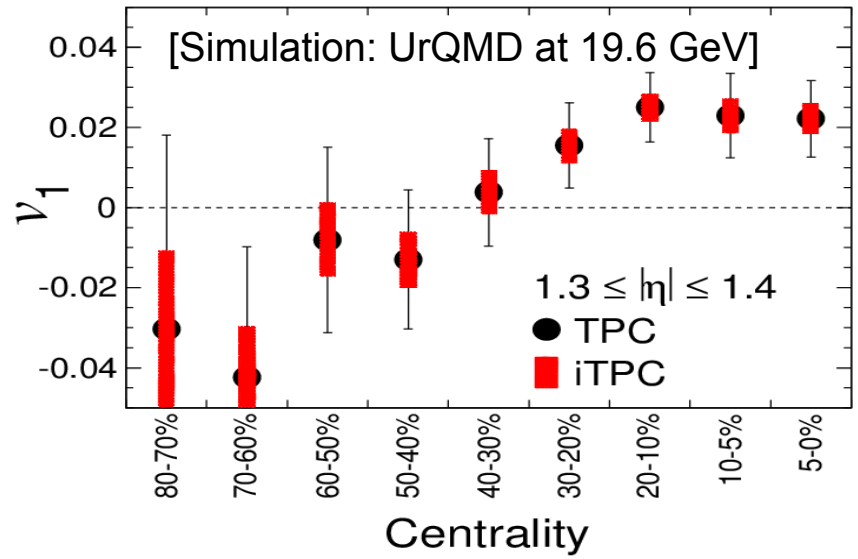
2 prototype modules for Run 17
1 full section Run 18

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

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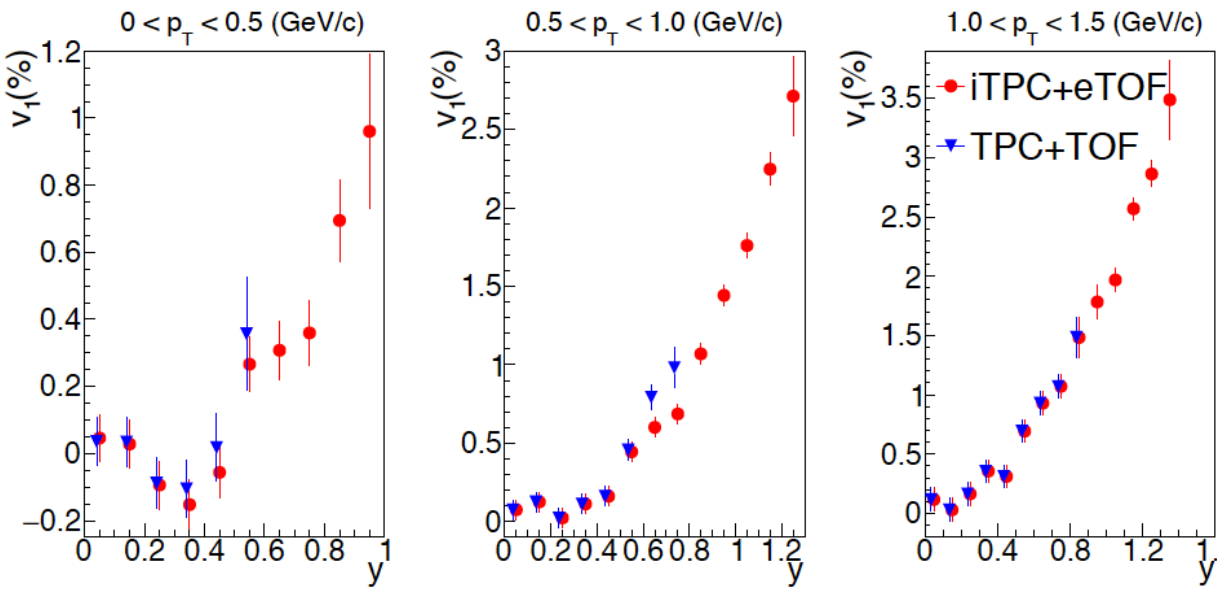
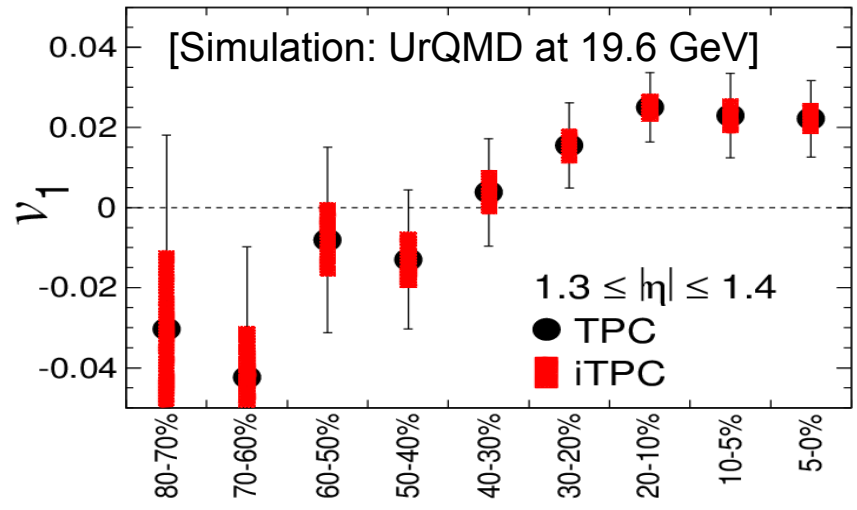
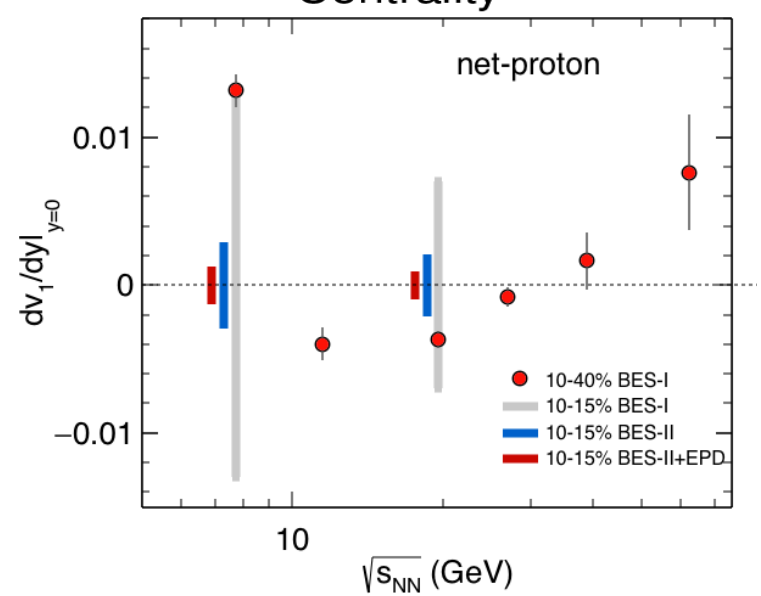






iTPC+ eTOF:

- Enhanced coverage at forward y
  - Signal larger - role of baryon stopping

EPD:

- Enhanced 1st order EP resolution
  - Reduced systematics

BES-II: Critical fluctuations

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

iTPC:

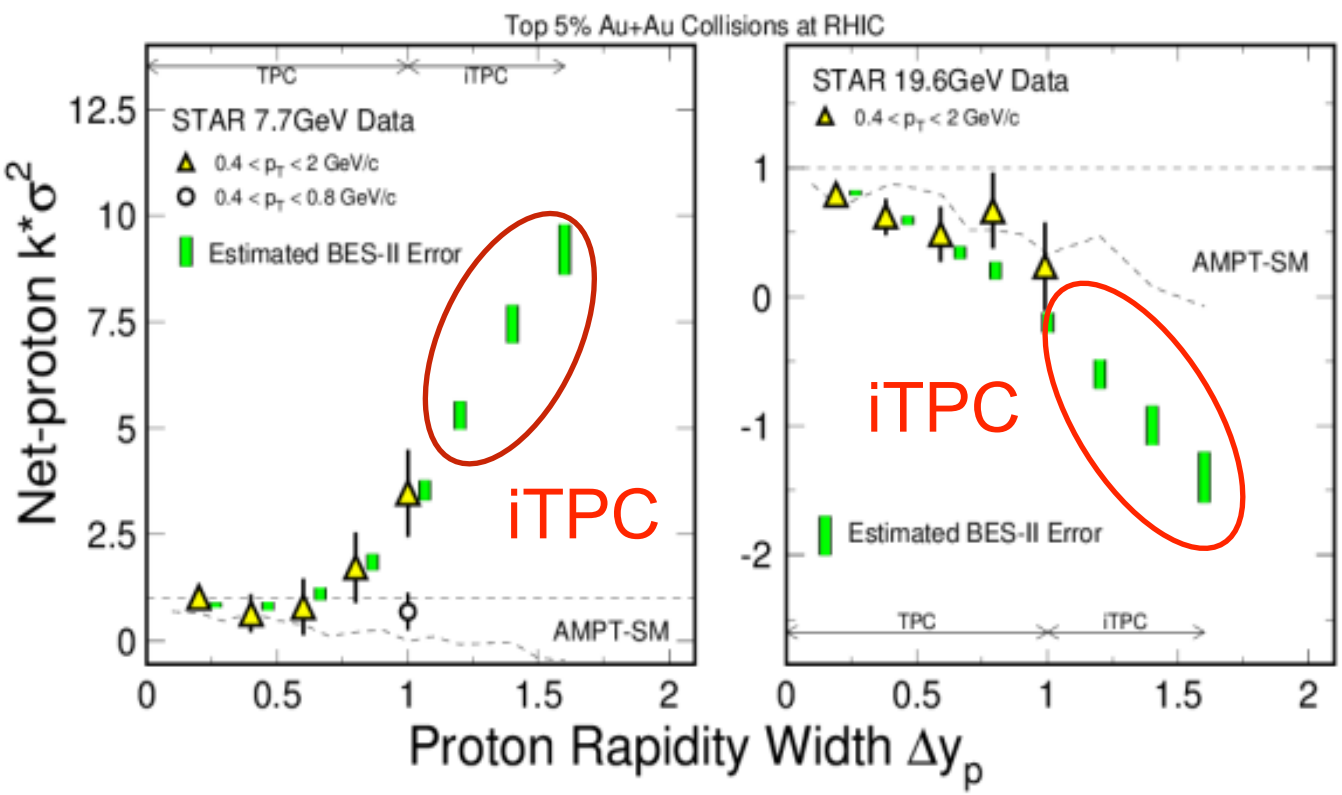
Increase Δy_p acceptance

$\Delta y_p > \Delta y$ correlation

EPD:

Improved centrality selection

Use all TPC for measurement

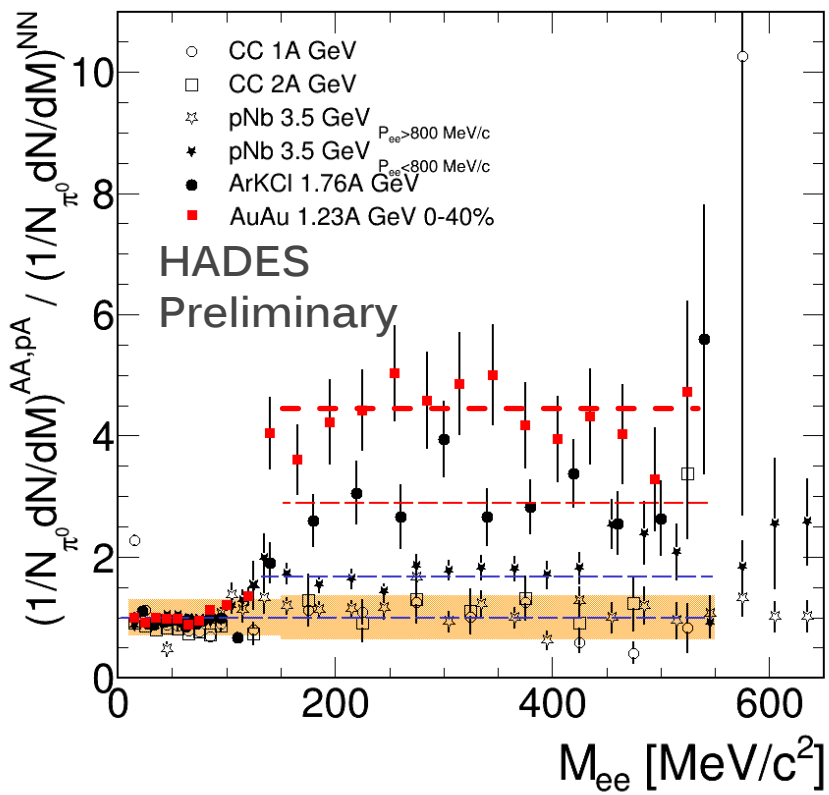


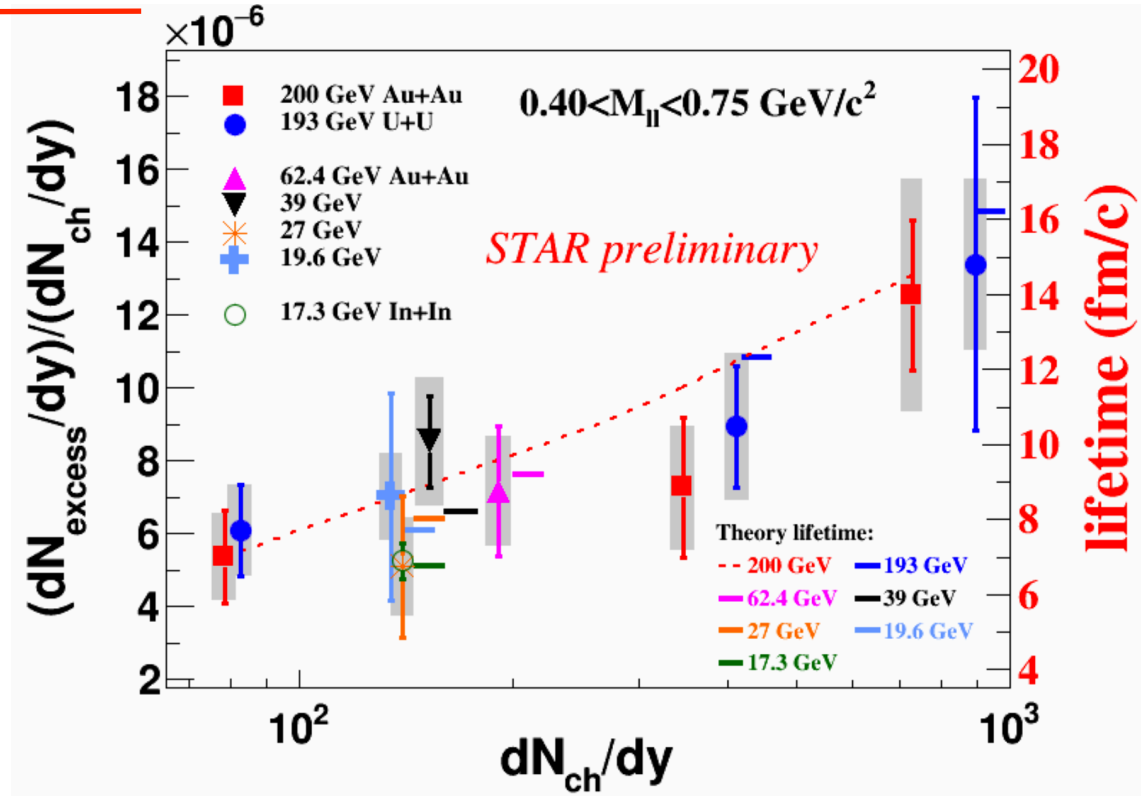
Establish true nature of correlation

Subject actively pursued theoretically

Low mass di-lepton excess

HP2016 J. Butterworth (STAR) P. Sellheim (HADES)





In Au+Au excess scales as $N^{1.3}_{part}$

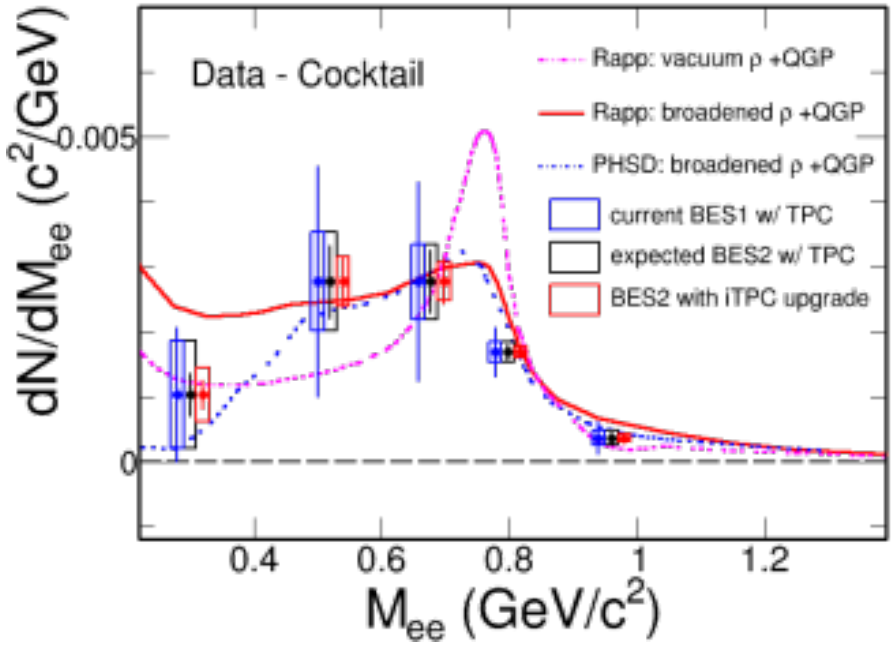
Low mass excess ∝ fireball lifetime

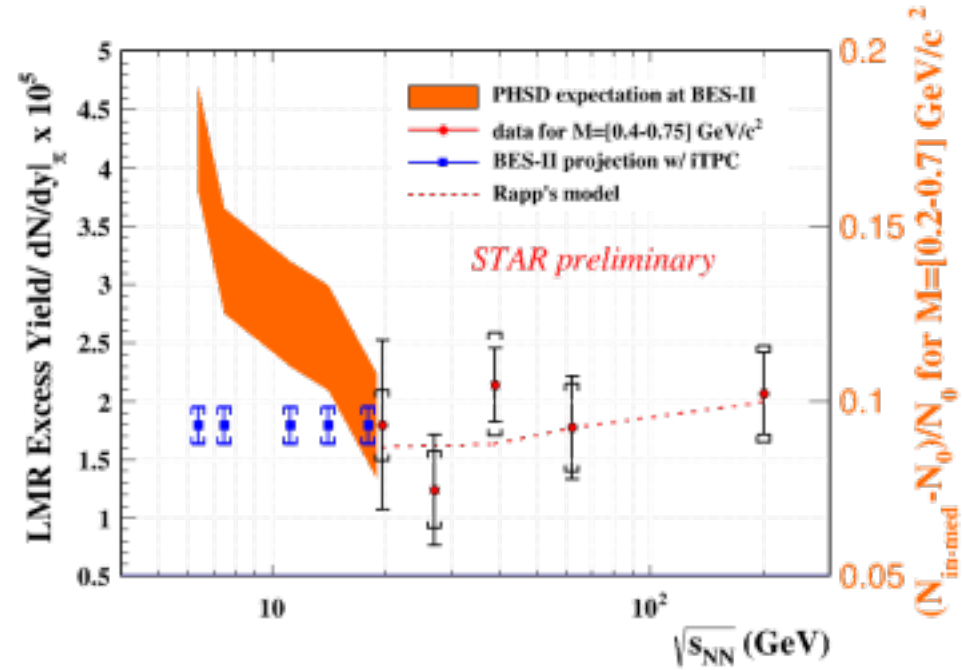
for large range of beam energies and centralities

Results suggest excess from total baryon driven hot dense medium effects and the medium's lifetime

Looking forward to adding more low energy and LHC data into trend plots

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

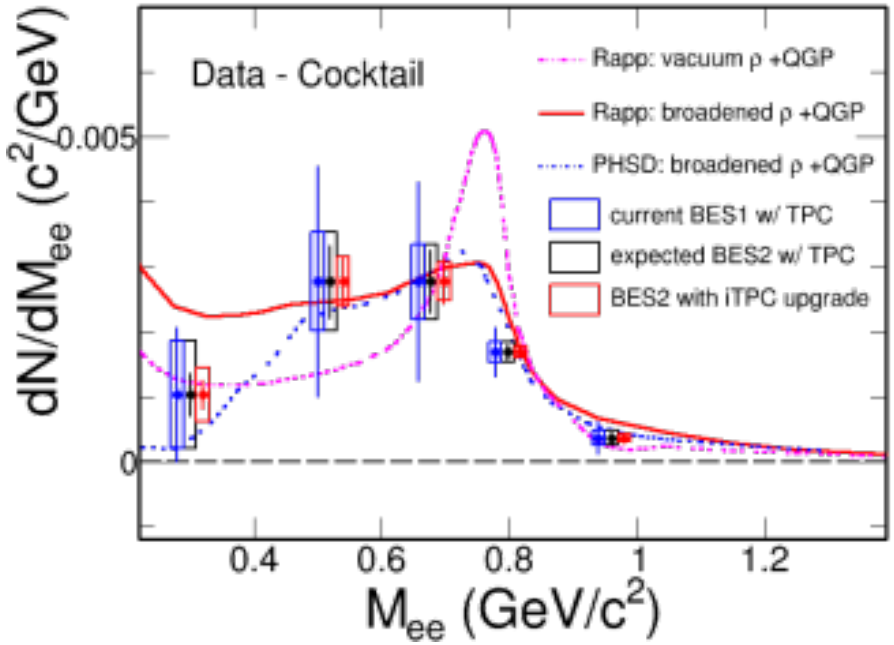
Low Mass Region:

iTPC: Significant reduction in sys. and stat. uncertainties

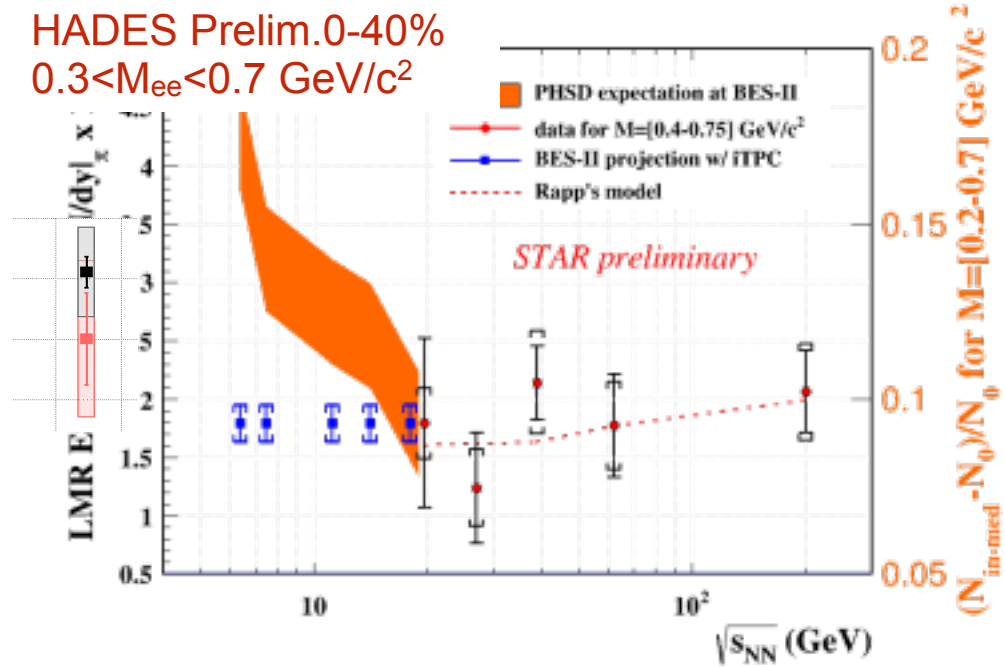
Disentangle total baryon density effects

J. Butterworth HP2016, T. Galatyuk, QM2017

Change the total baryon number



HADES Prelim.0-40%
0.3<M_{ee}<0.7 GeV/c^2



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Summary

High statistics exploration of QCD phase diagram and its key features is about to begin

New data from RHIC BES-II including Fixed Target program hopefully starting next year($\sqrt{s}$ = 27 and 3 GeV)

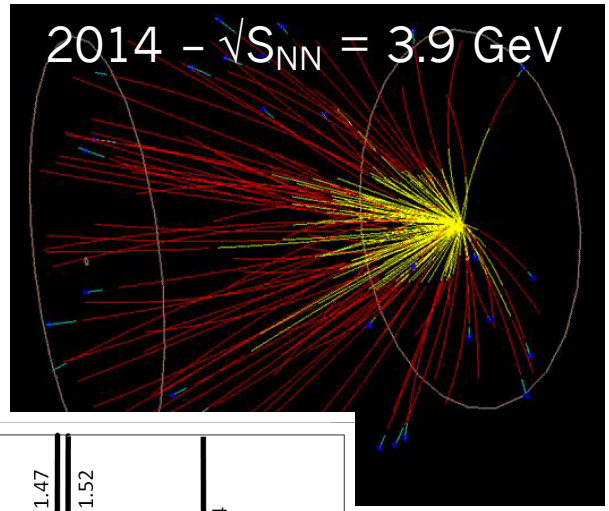
Significantly extended detection capabilities compared to existing data

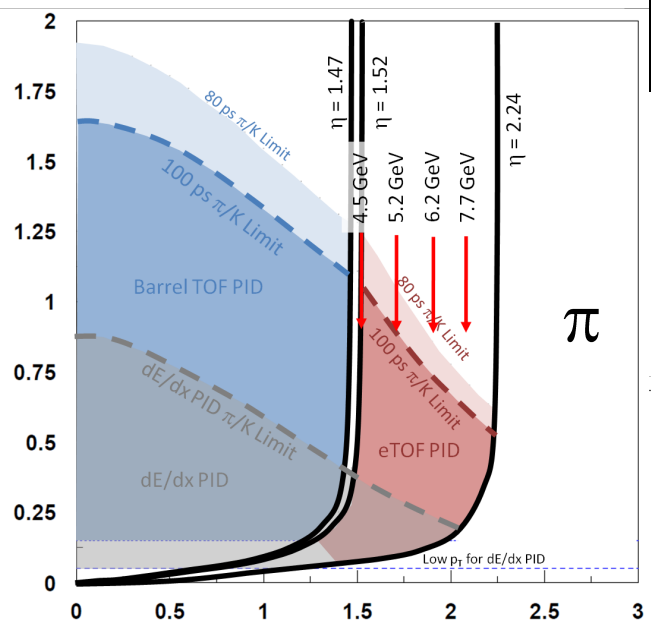
Strong theoretical interest focussed in BEST and HICforFAIR, increased number of focussed workshops

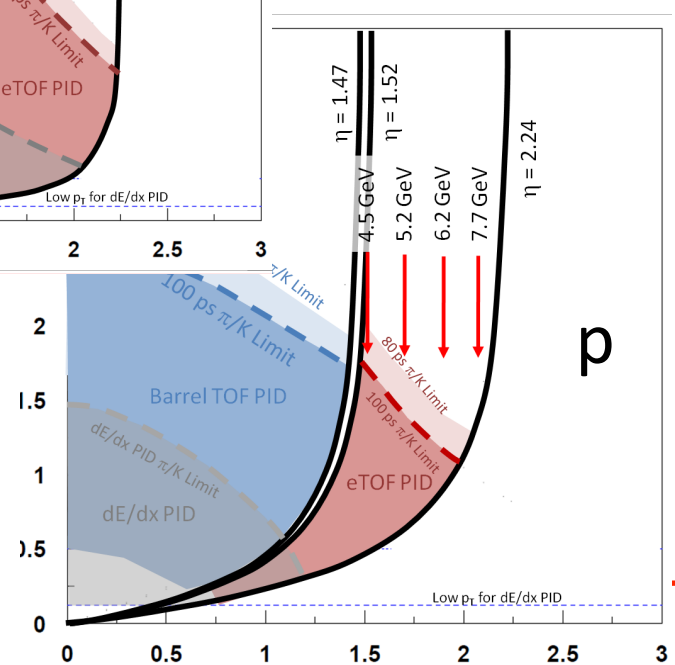
In conjunction: Turn trends and features into definitive conclusions

BACK UP

BES-II: Onset of deconfinement







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

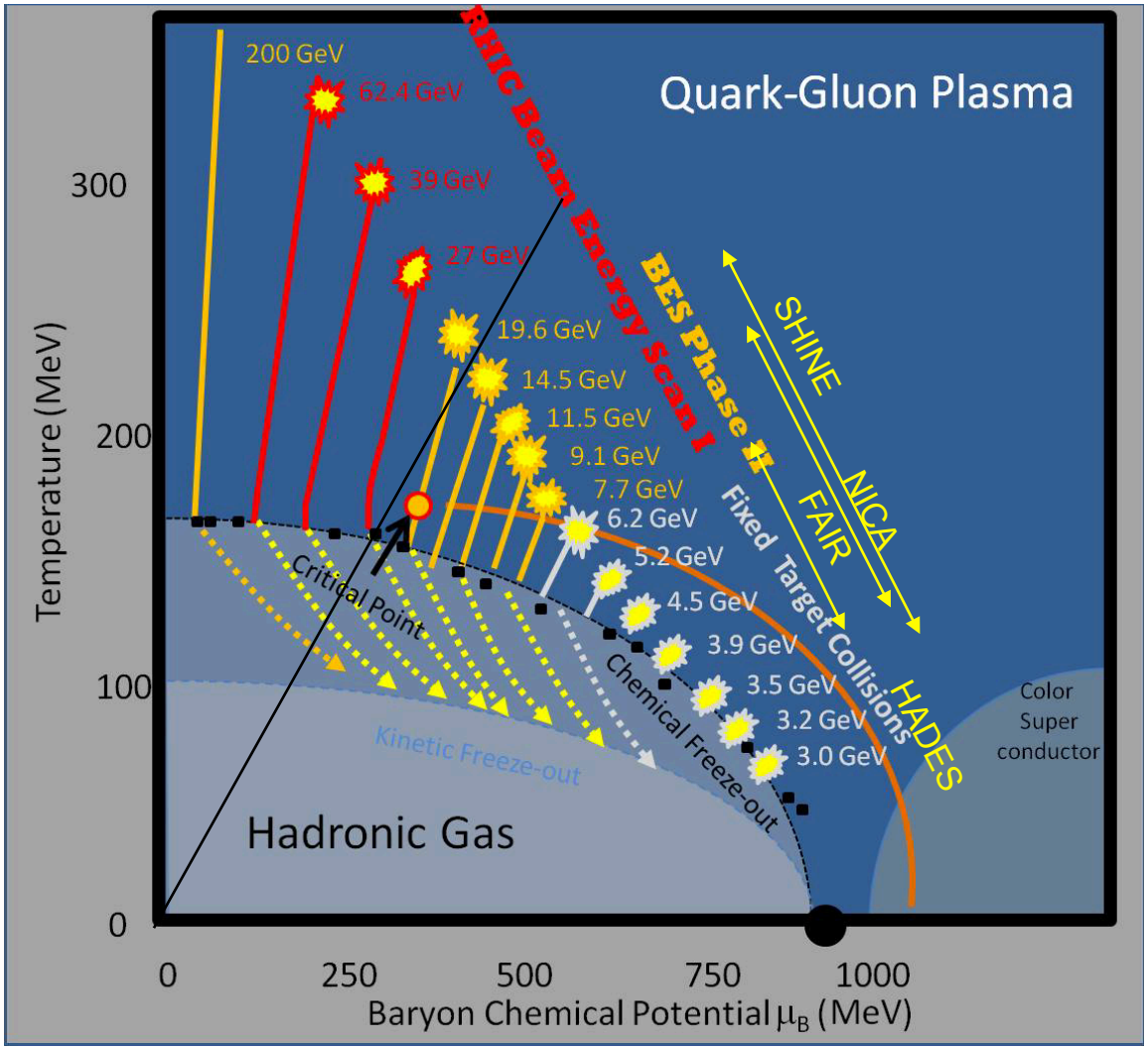
Fixed target program
- Collider can't run below 7.7GeV
- Target in beam pipe at z=210cm

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

Current and expected data



Wealth of data in hand and more coming soon

LHC: 2760, 5000

RHIC: BES-I

BES-II - Fixed target

2.5 - 19.6

d+Au 200, 62, 38, 20

Cu+Au 200, 62

SPS: 5.1-17.3

Lighter ions

SIS: 2.6, 2.6

FAIR: 2.7-8.2

NICA: 2-11

J-PARC: 2-6.2

BES-II: Detailed Run Plan

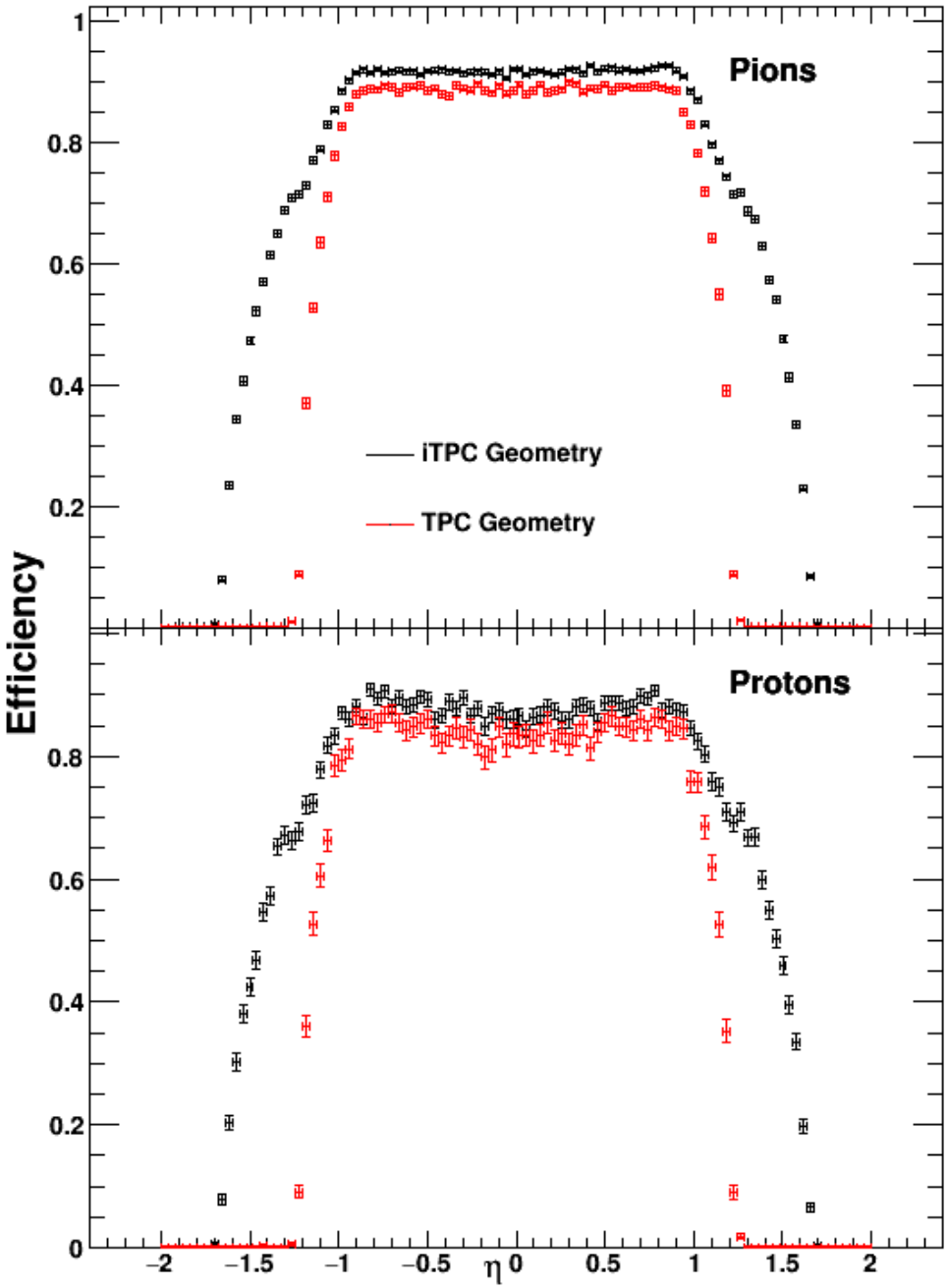
Run in 2019 & 2020 will have significant physics impact

	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				
QGP	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
QGP	Local Parity Violation (CME)	50	50	50	50	50
1st P.T.	Directed Flow studies (v_1)	50	75	100	100	200
1st P.T.	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

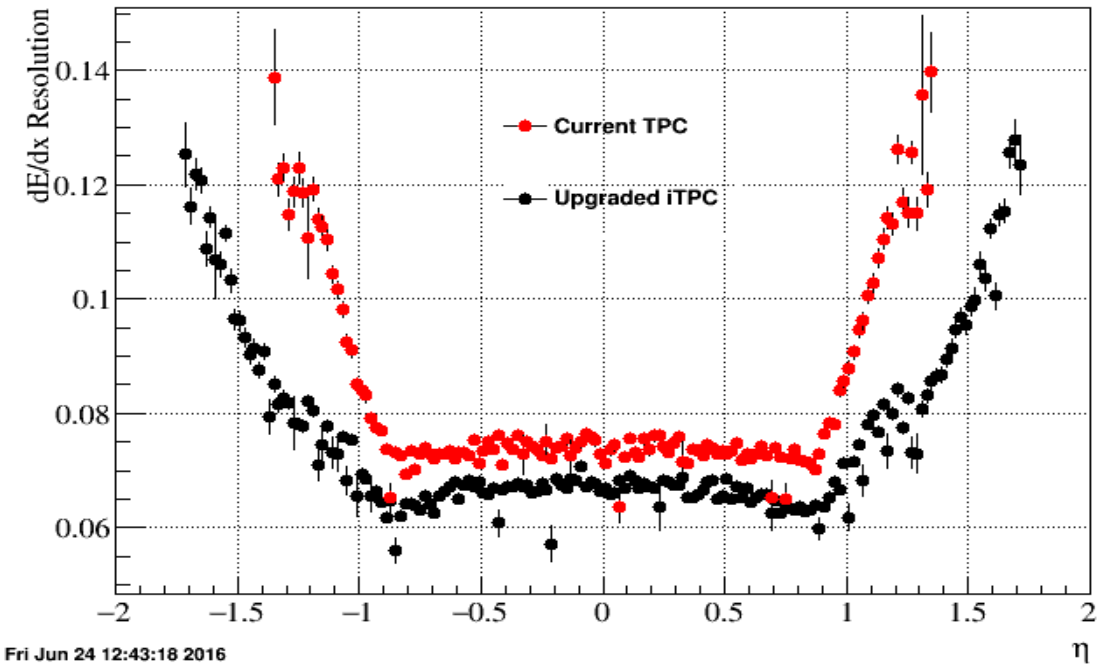
Fixed target running enables data from $\sqrt{s}$ = 3-7.7 GeV

eCooling - Enables the significant statistics enhancement

Enhanced tracking and dE/dx performance

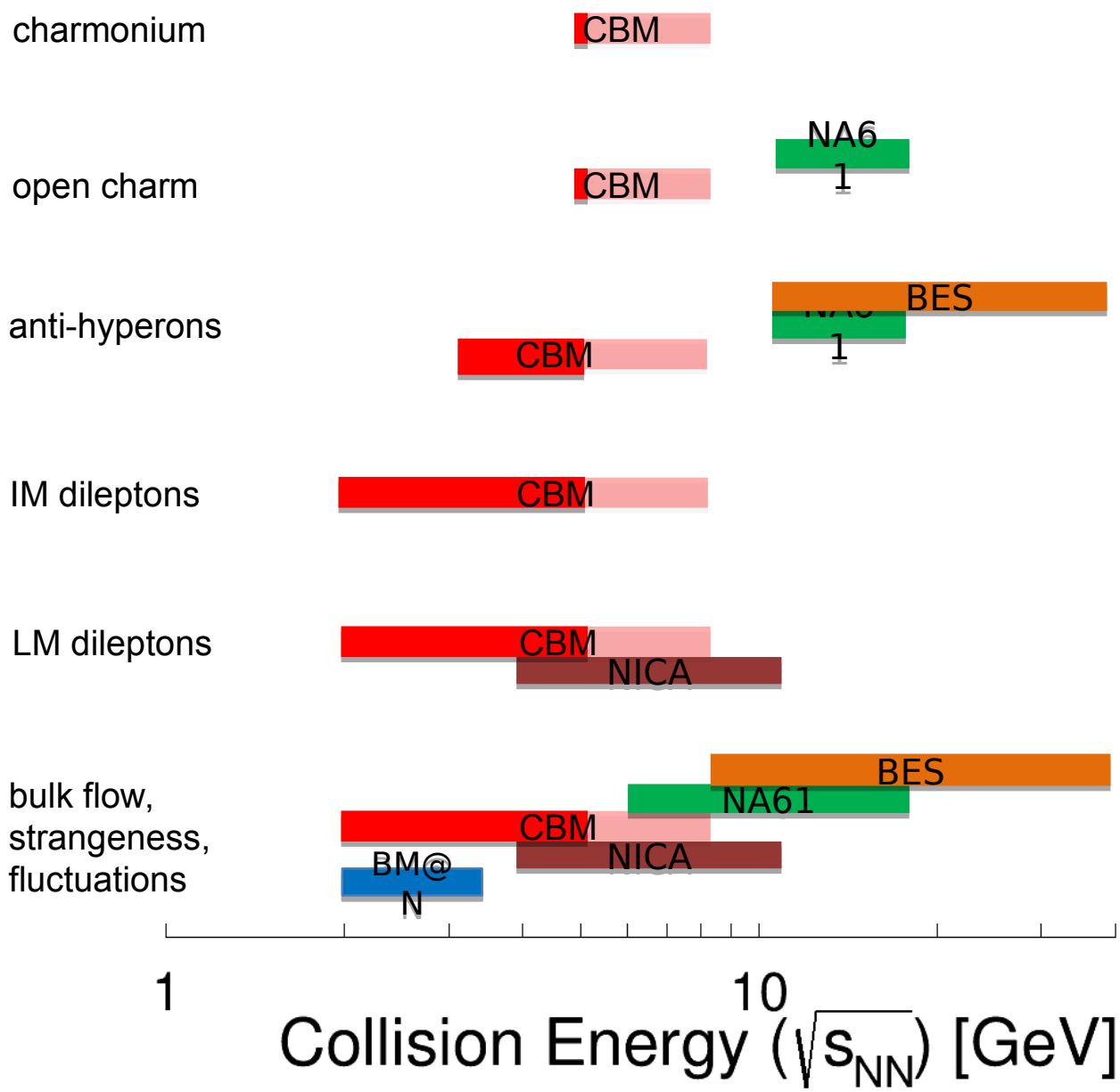


Increased coverage, efficiency and dE/dx resolution out to |η| < 1.5



Who can measure what

restrictions: by rate and/or by instrumentation



"Dale" in longitudinal expansion

Probe expansion dynamics:

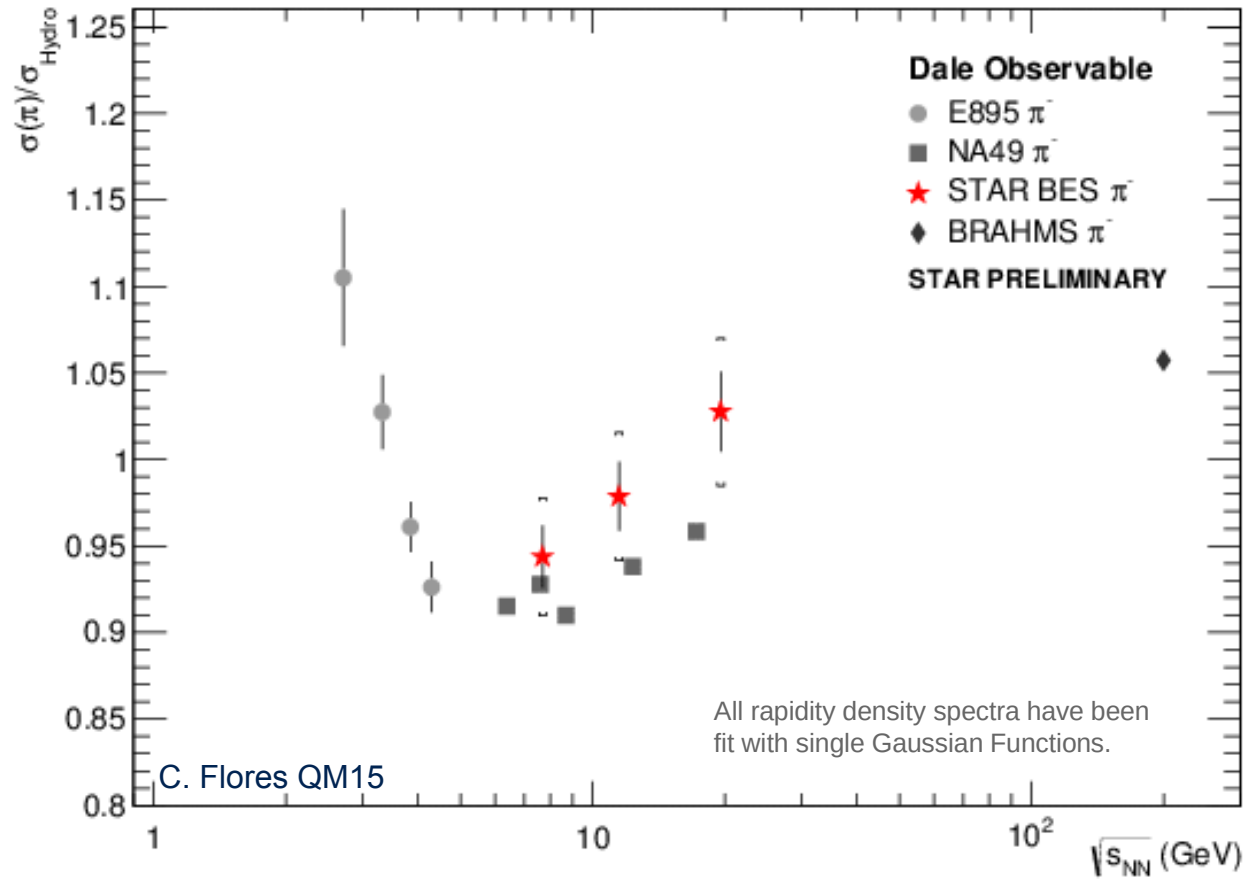
Width of rapidity distribution compared to Landau hydro. expansion predictions

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

Minimum in the speed of sound?

$c_s^2 \sim 0.26$

Another indication of softening of EoS?



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

NA61/SHINE see minima in similar place for pp data

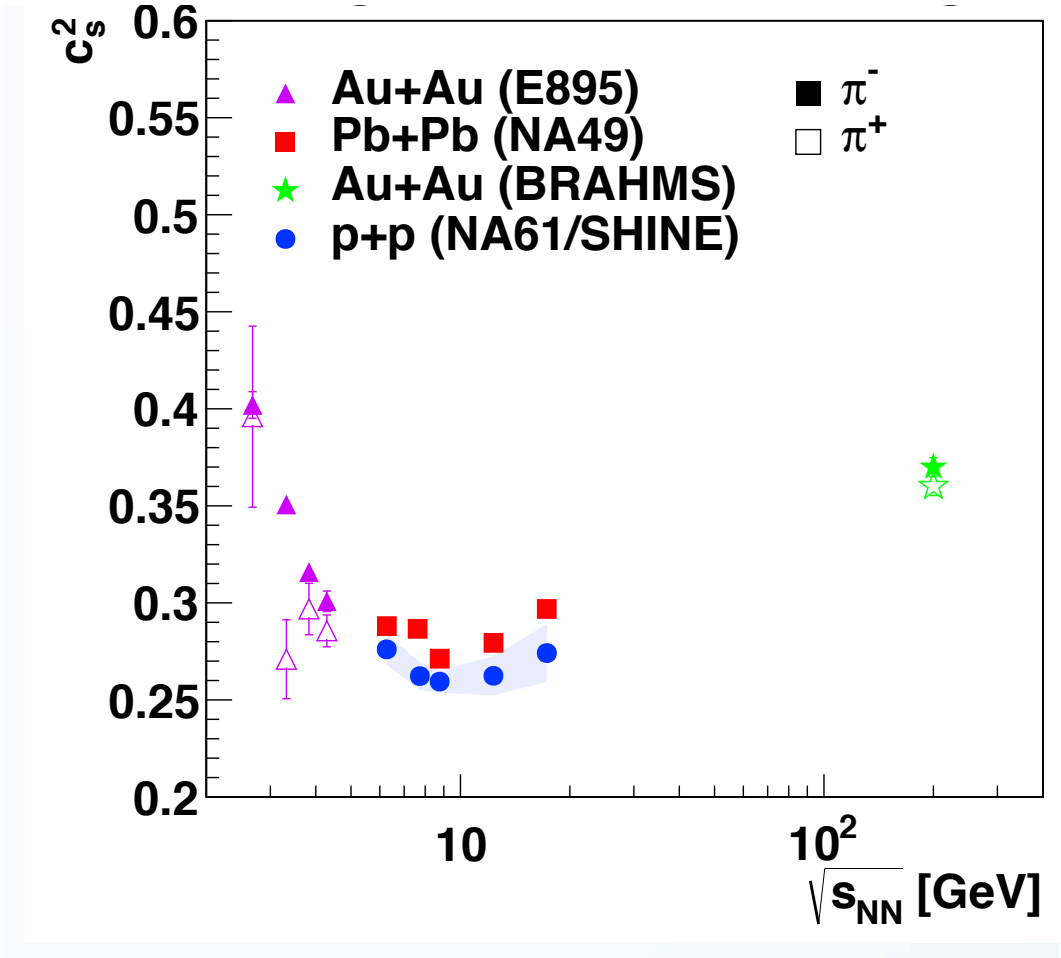
BES results for π^+ and π^-

Longitudinal expansion

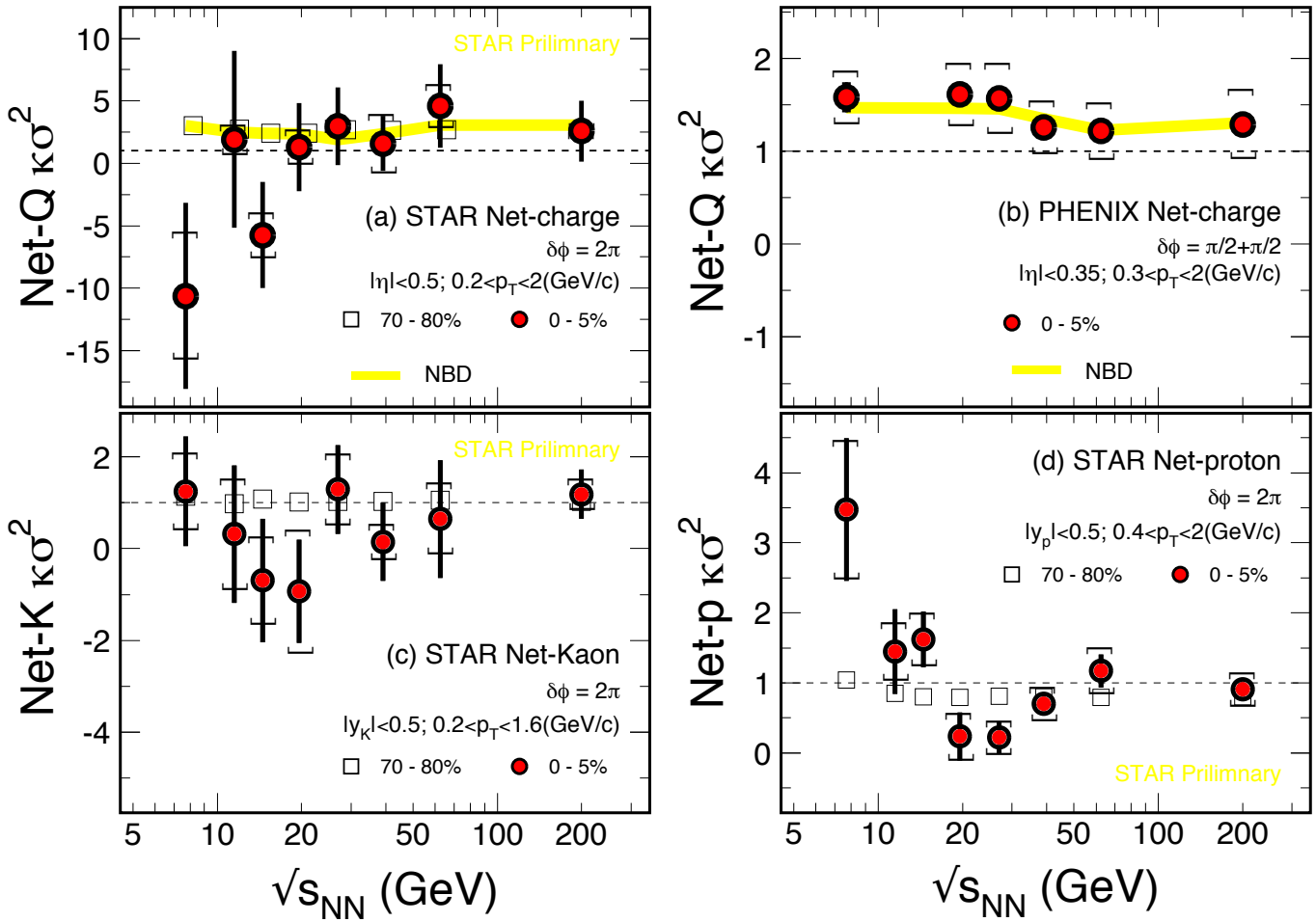
Fermi-Landau initial conditions
Ideal Hydrodynamic expansion

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

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



Fluctuations at RHIC



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

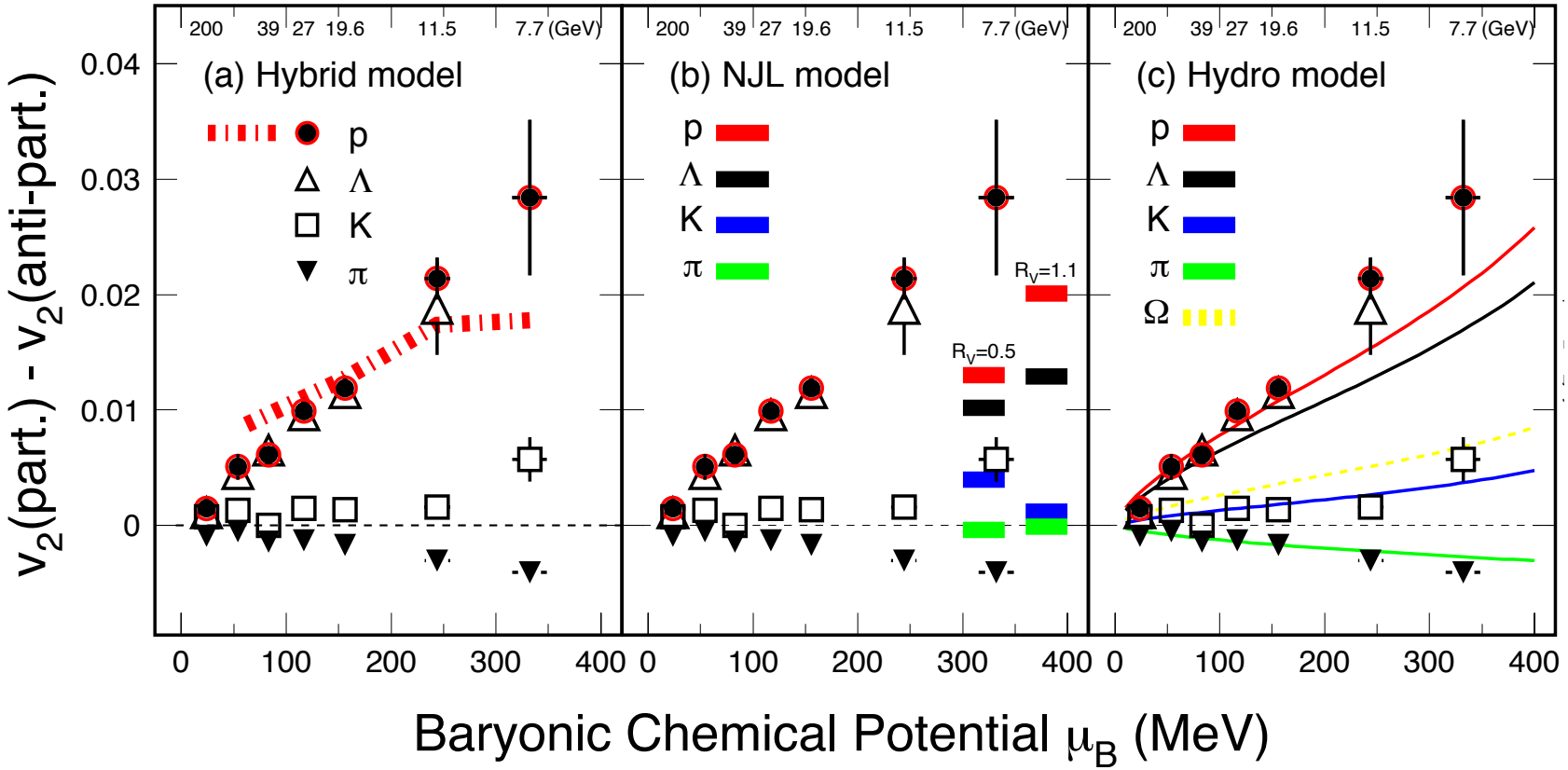
In STAR:

$\sigma(Q) > \sigma(K) > \sigma(p)$

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

Splitting of the v_2

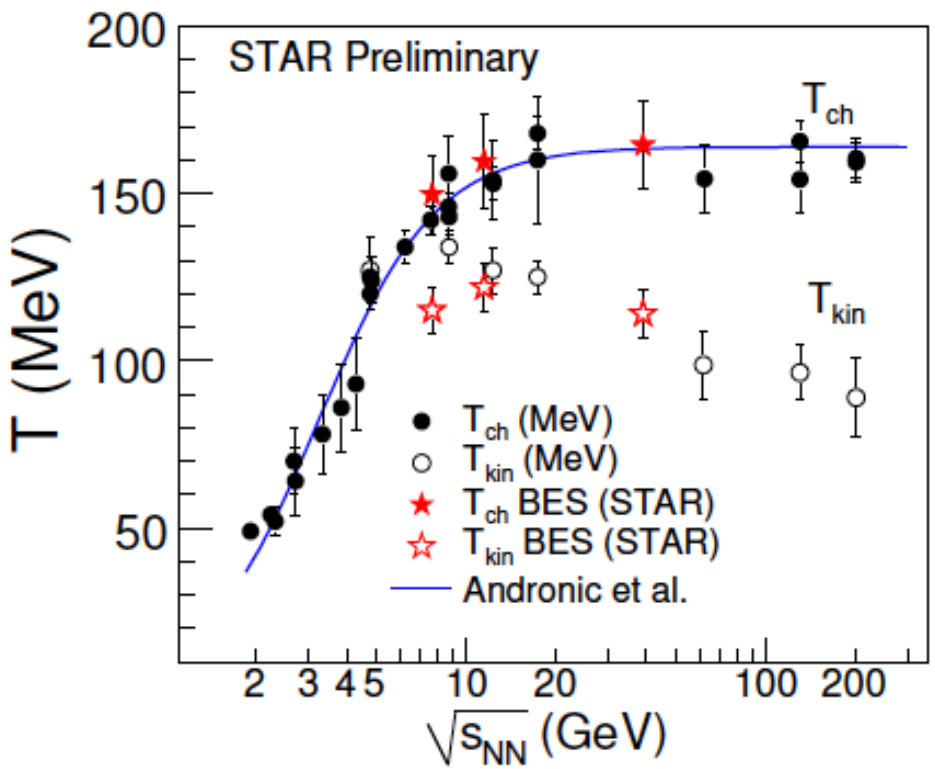


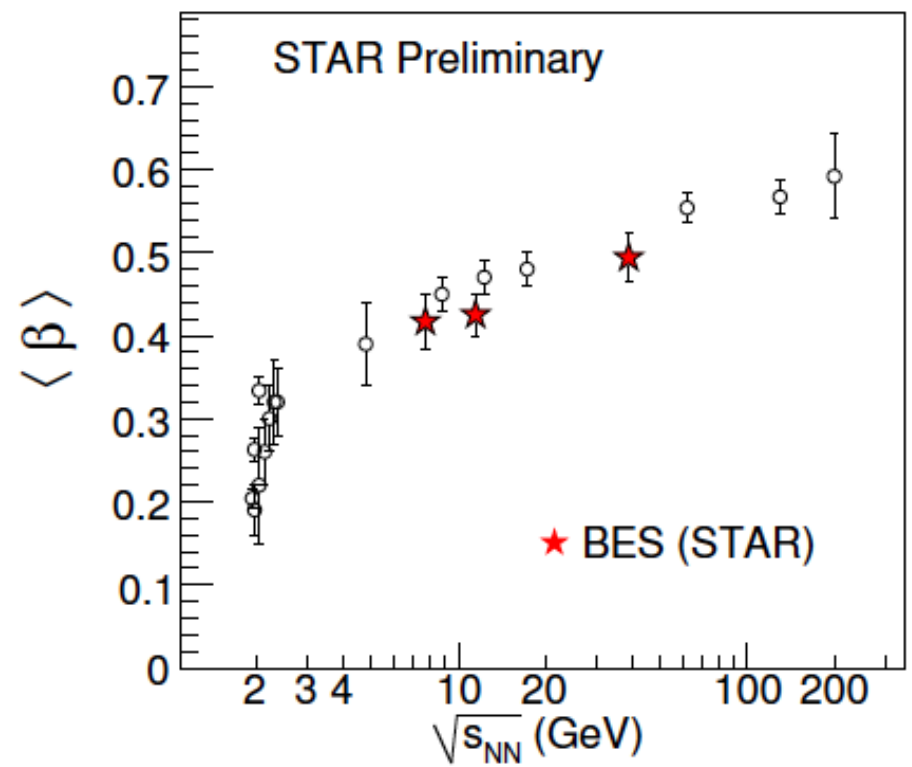
At large μ_B, low collision energies, the number of quark scaling in v_2 is broken

(a) Hydro + Transport: Baryon results fit [J. Steinheimer, et al. PR **C86**, 44902(13)]

(b) NJL model: Sensitive to vector-coupling, **CME, μ_B** driven.
[J. Xu, et al., PRL**112**.012301(14)]

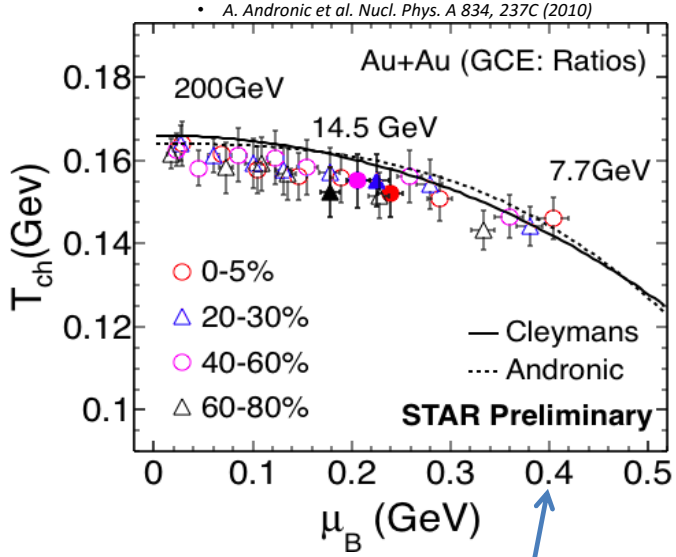
(c) Hydro solution: **Chemical potential μ_B** and **viscosity η/s** driven!
[Hatta et al. PR **D91**, 085024(15); **D92**, 114010(15) //NP **A947**, 155(16)]



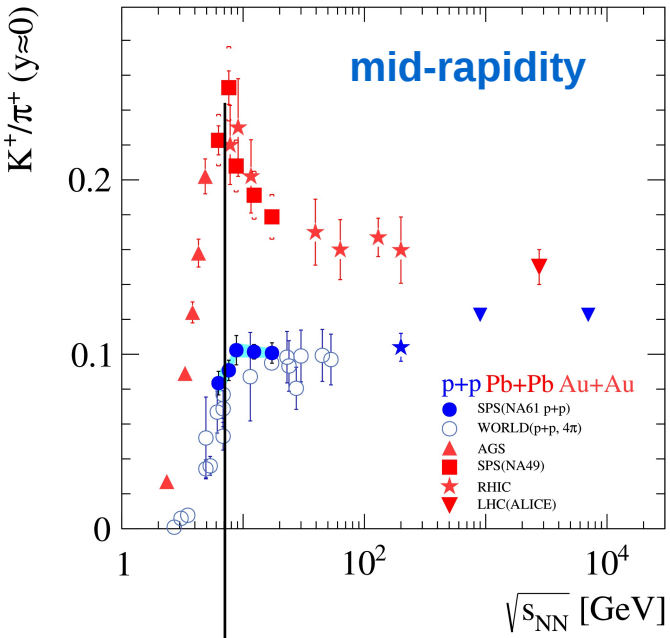


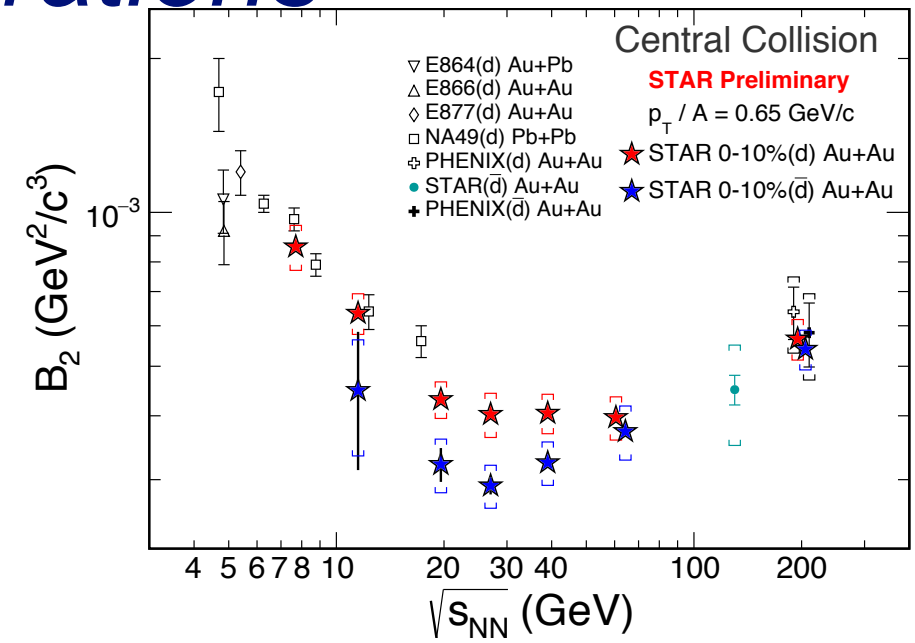
D. Mishra, QM 2015, Kobe, Japan

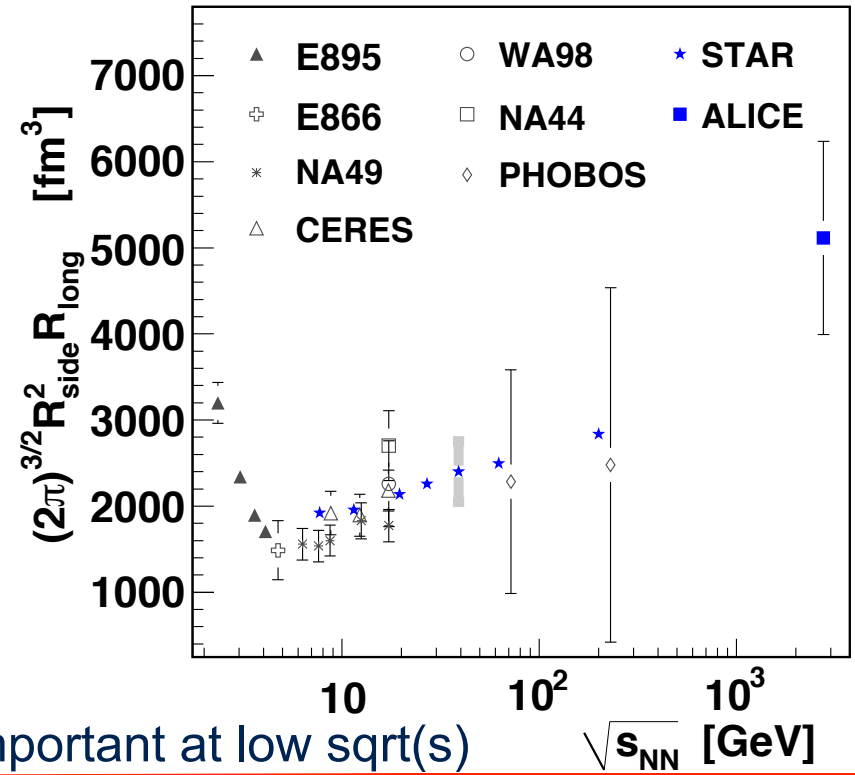
- *J. Cleymans et al. Phys. Rev. C 73, 034905 (2006)*
- *A. Andronic et al. Nucl. Phys. A 834, 237C (2010)*



Baryon density considerations

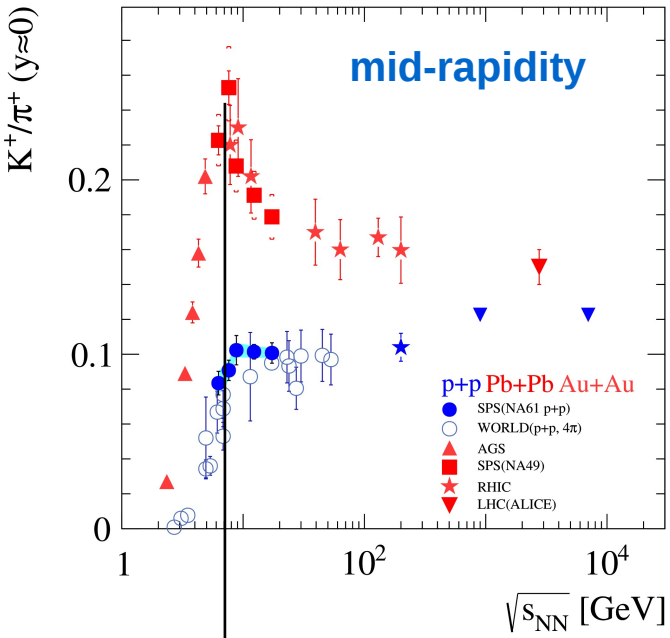


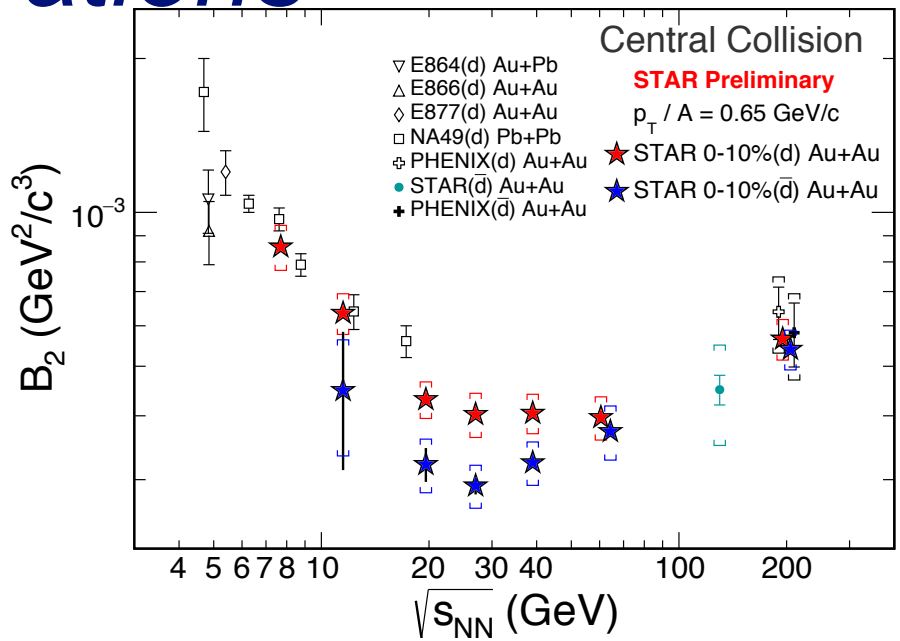


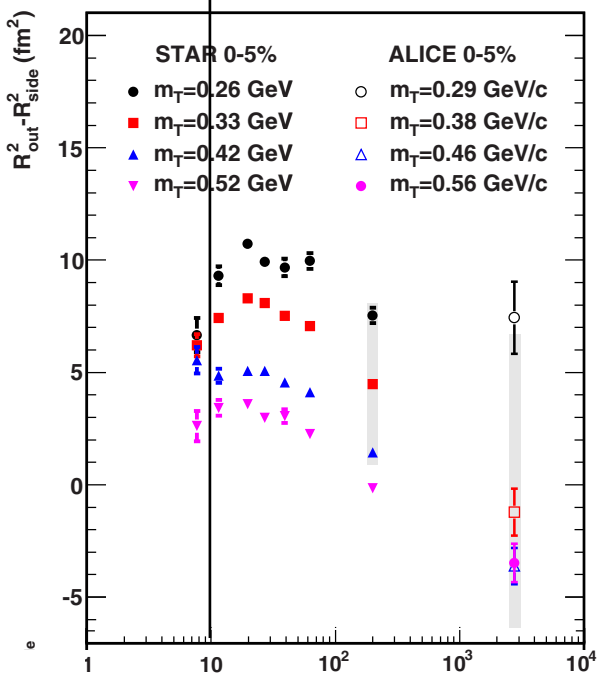


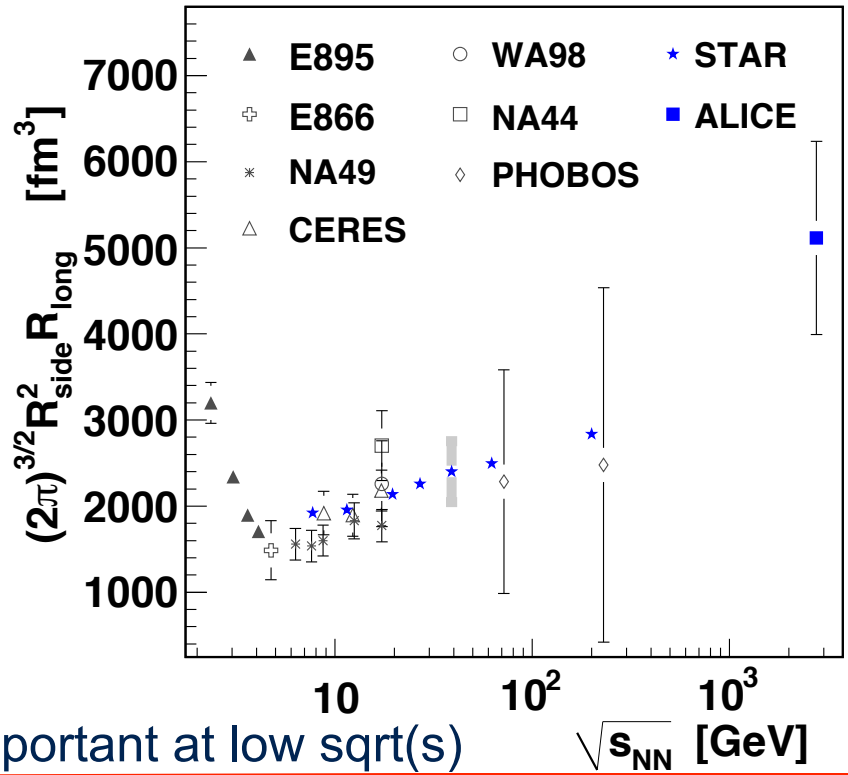
piN cross-section important at low sqrt(s)

Baryon density considerations









piN cross-section important at low sqrt(s)

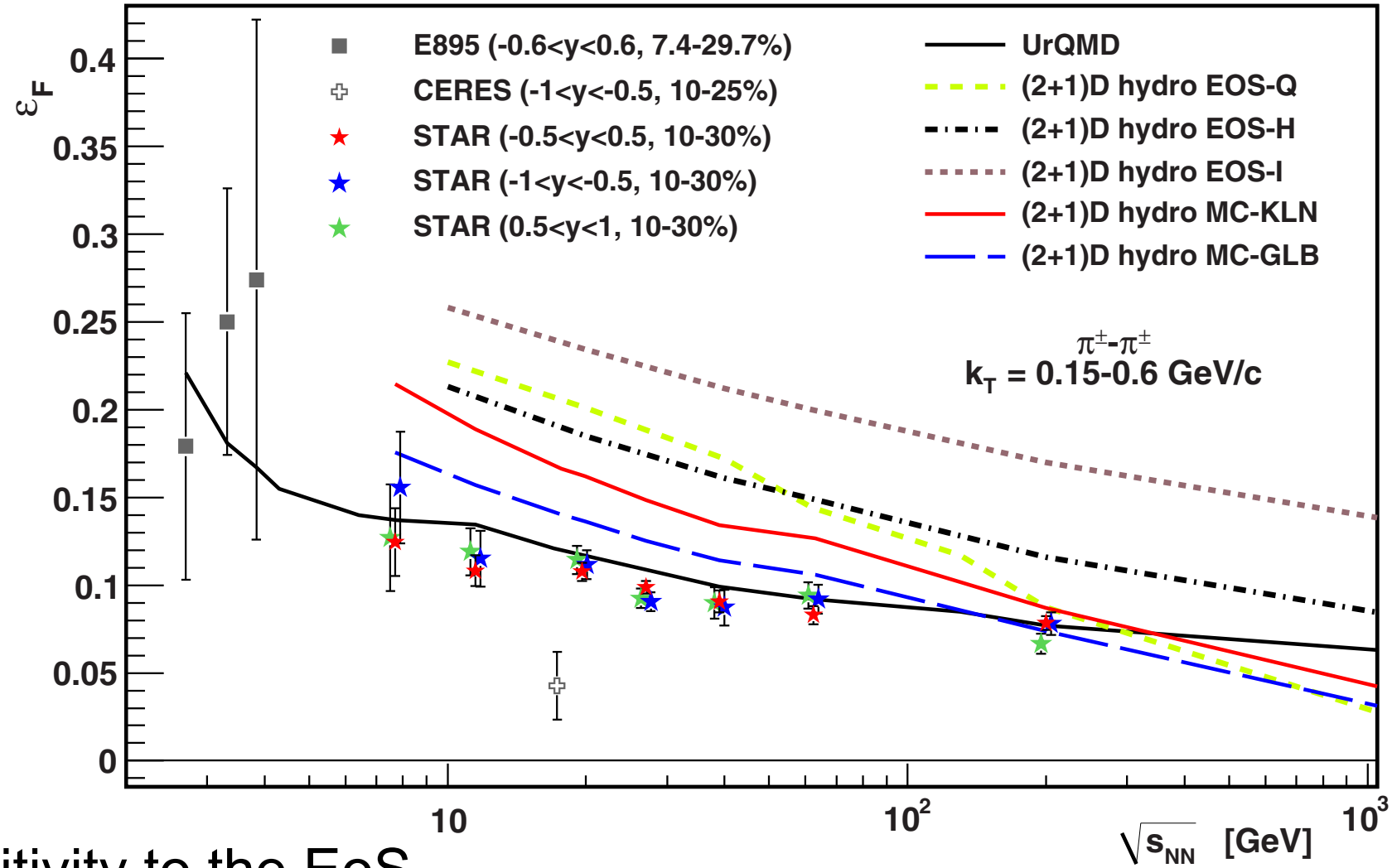
Planned low energy running

μ_B (MeV)	560 - 230	850 - 670	790	720 - 210	750 - 330	780 - 400	850 - 490
$\sqrt{s_{NN}}$ (GeV)	4.9-17.3	2-3.5	2.4	3-19.6	2.7-11	2.7-8.2	2-6.2
Facility	SPS	NICA	SIS-18	RHIC	NICA	SIS-100	J-PARC HI
Experiment	NA61/ SHINE	FXT	HADES	STAR	MPD	CBM	
Start Year	2009	2017	2018	2019	2020	2022	2025
Physics	CP & Onset	Dense Baryon	Dense Baryon	CP and Onset	Onset & Dense Baryon	Onset & Dense Baryon	Onset & Dense Baryon

Expect wealth of new insights over next ~5 years

Eccentricity at freeze-out

Accessed via azimuthal HBT



Sensitivity to the EoS

- trend smooth over all √s
- STAR data does not confirm CERES data

No evidence of change in EoS

STAR PRC 92 014904 (2015)

HBT and the CP

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

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

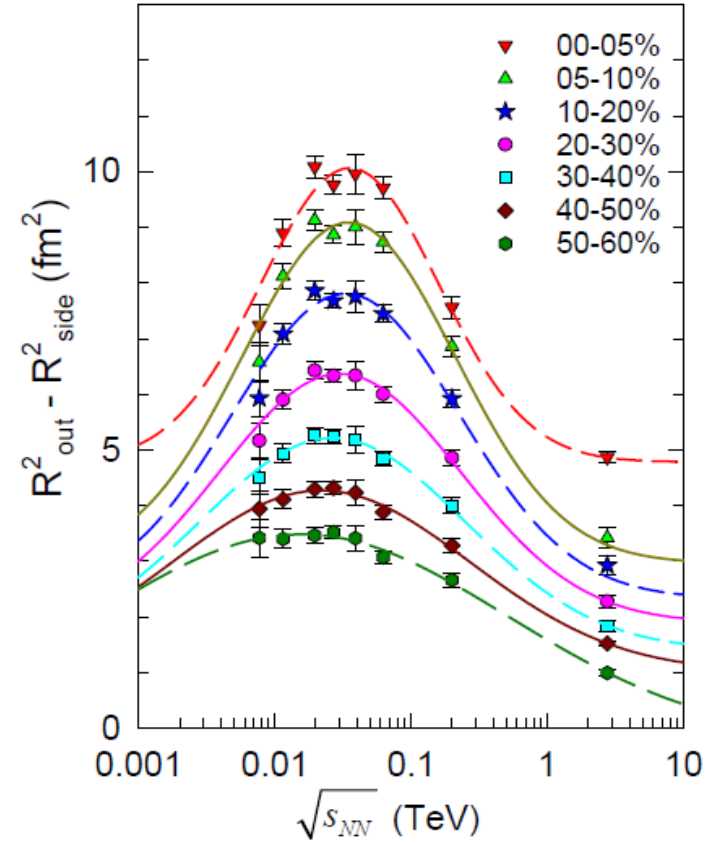
Plot of max (R^2_{out} - R^2_{side}) as function of $R_{glauber}$ - Lifetime to initial transverse size of system mapping?

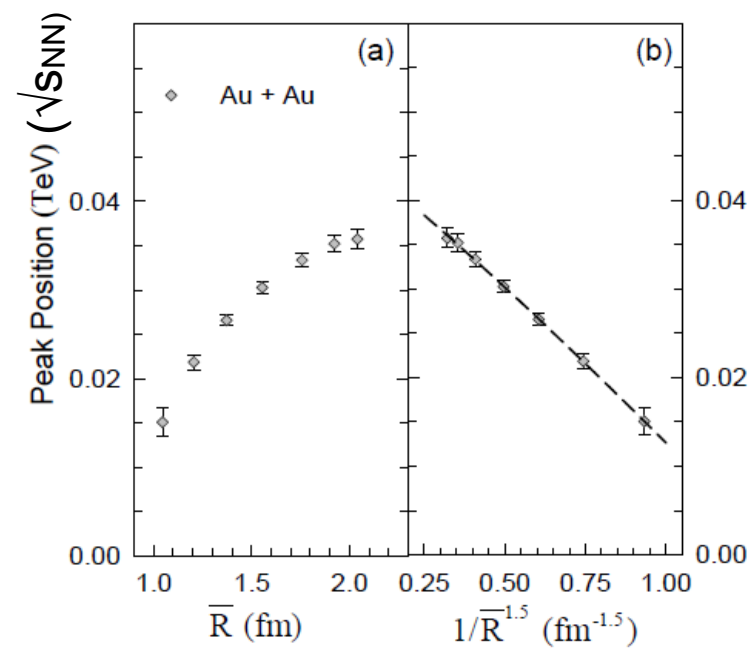
Slope and intercept give information on location of CP at infinite volume and the critical exponents

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

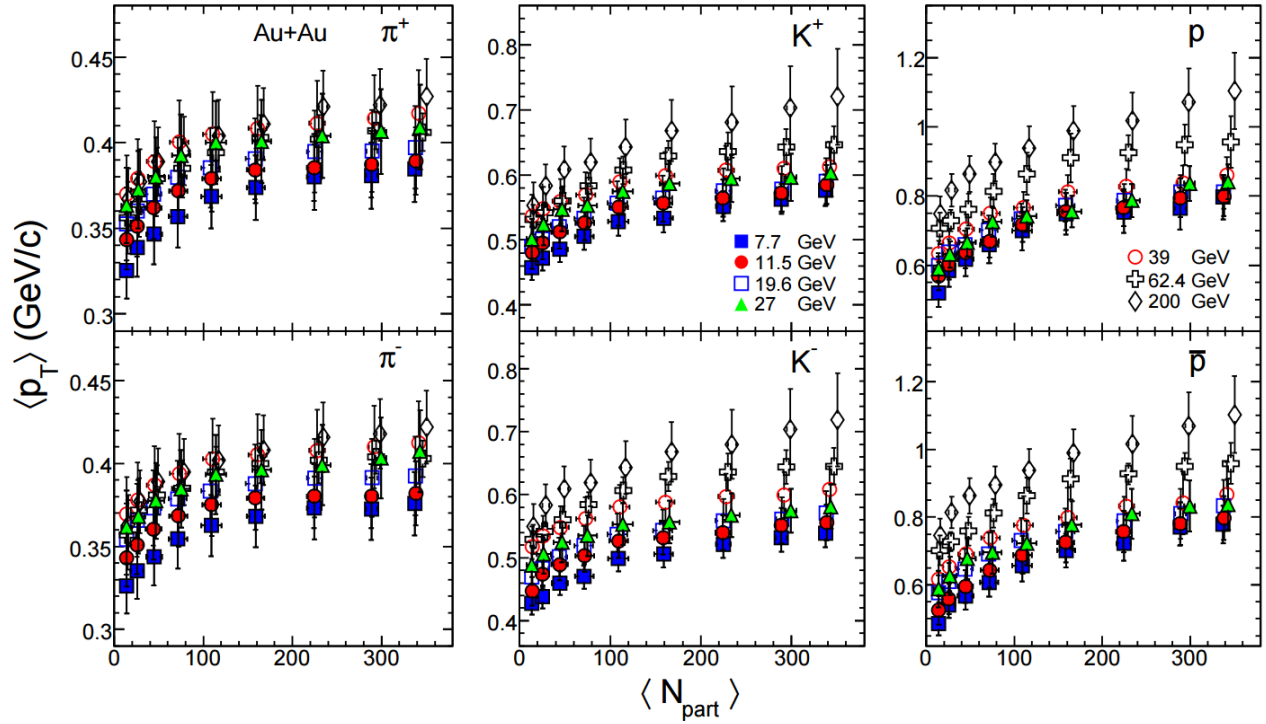
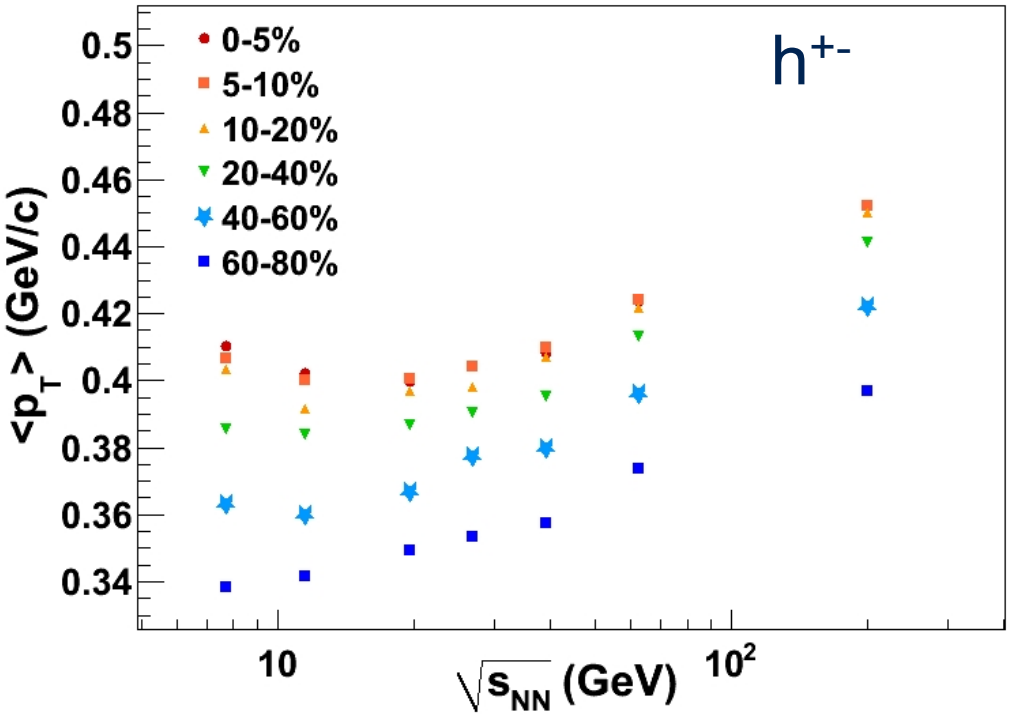
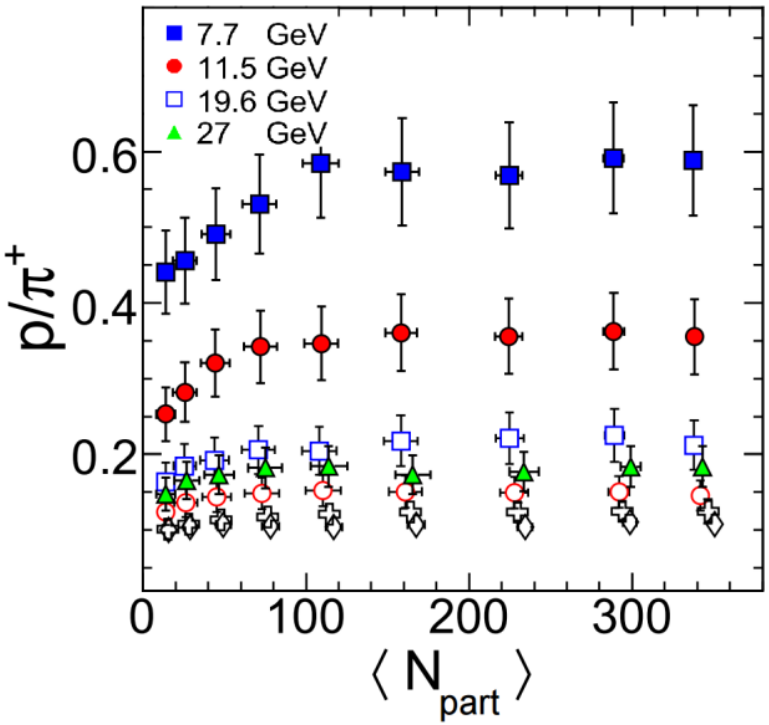
$$T^{cep} : 165 \text{ MeV}, \mu_B^{cep} : 95 \text{ MeV}$$

2nd order phase transition, location ruled out by Lattice





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

Mean p_T

Mean p_T of charged particles as fn sqrt(s) convolution of changing spectral shape and p/pi ratio