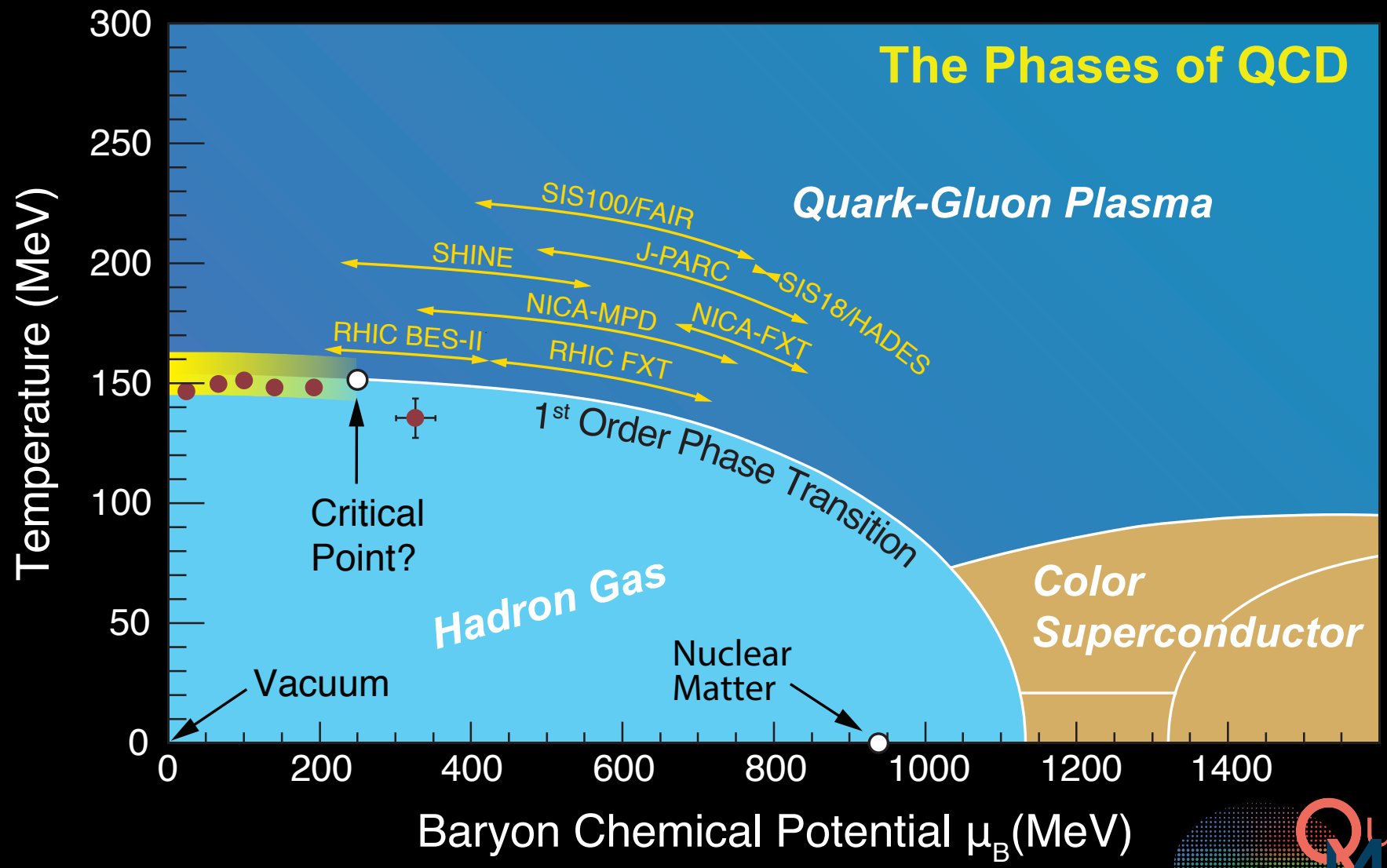
The Search for Critical Behavior (and Other Features of the QCD Phase Diagram)
Status and Future



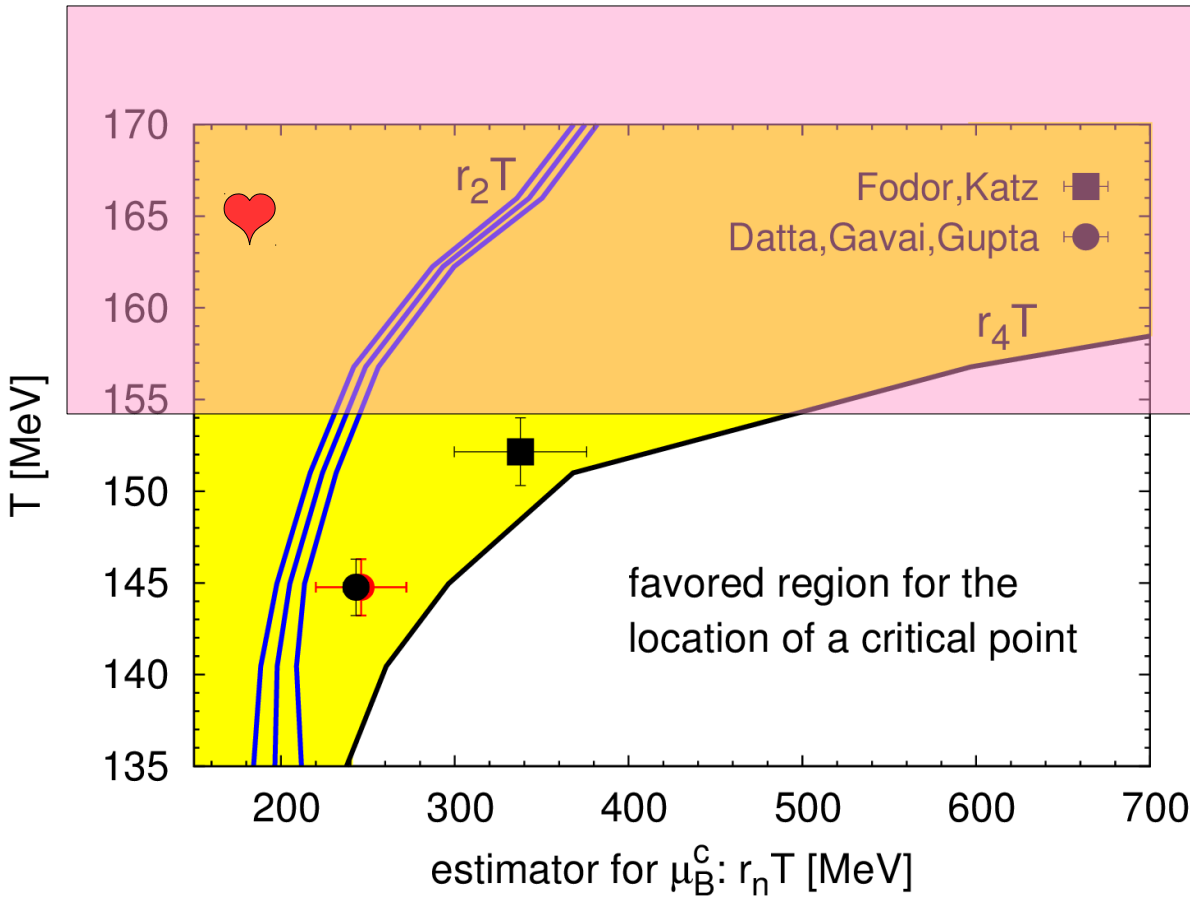
Helen Caines, Yale

Quark Matter 2017

Critical point expectations

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

Ruled out by thermodynamics at $\mu_B=0$



Still theoretical debate as to Critical Points existence

Lattice Gauge Theory calculations are becoming increasingly accurate

T_c = 154(9) MeV

and sophisticated away from $\mu_B=0$

Calculations suggest C.P. above $\mu_B/T > 2$ and $T/T_C(\mu_B = 0) > 0.9$

Critical point expectations

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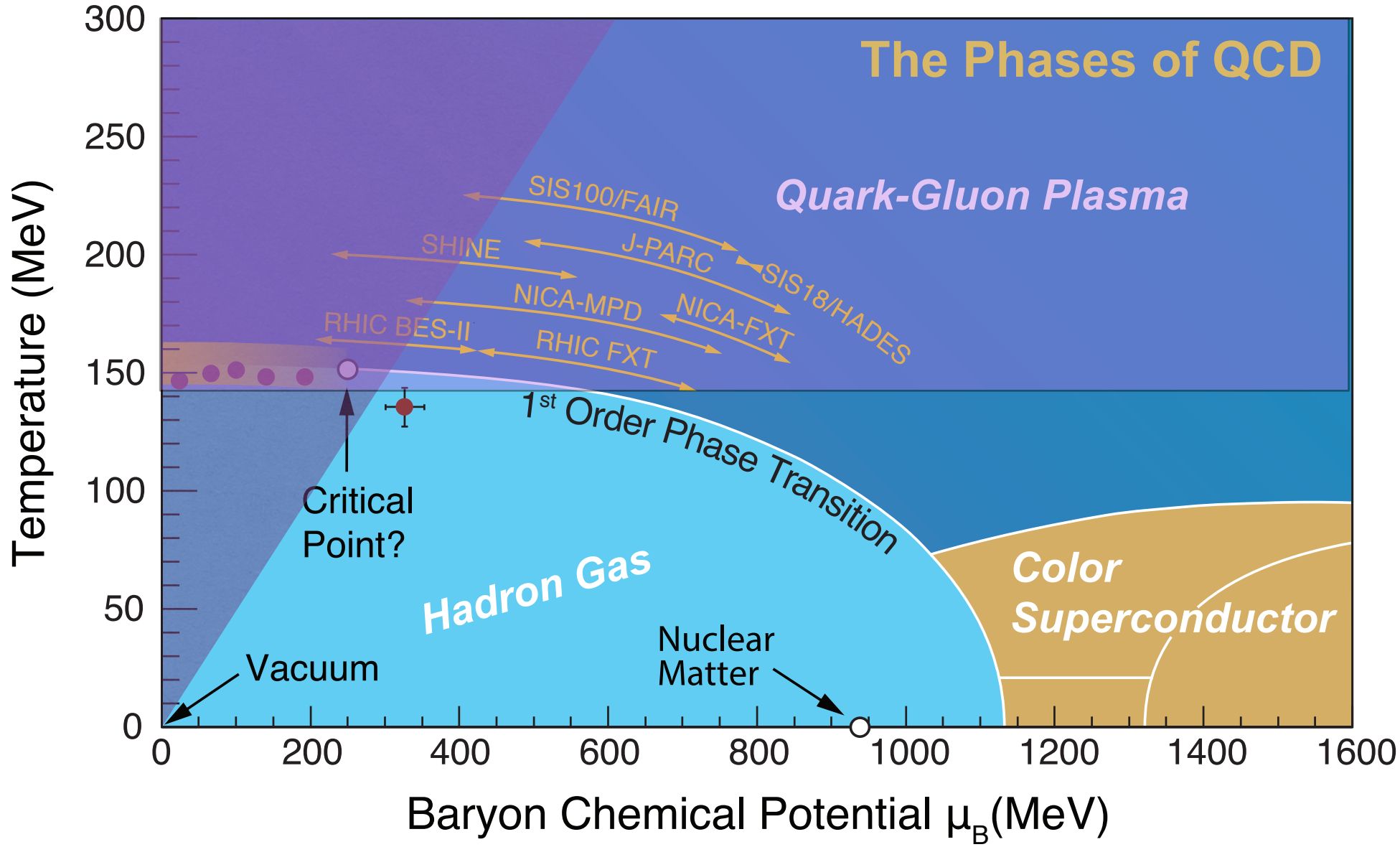
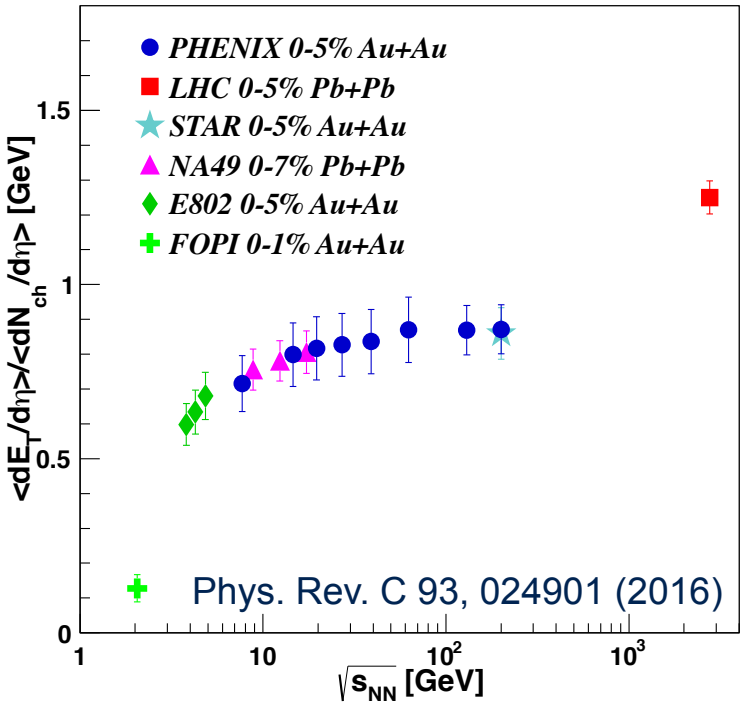


We are focusing in on the right region

Calculations suggest C.P. above $\mu_B/T > 2$ and $T/T_C(\mu_B = 0) > 0.9$

Establishing the "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

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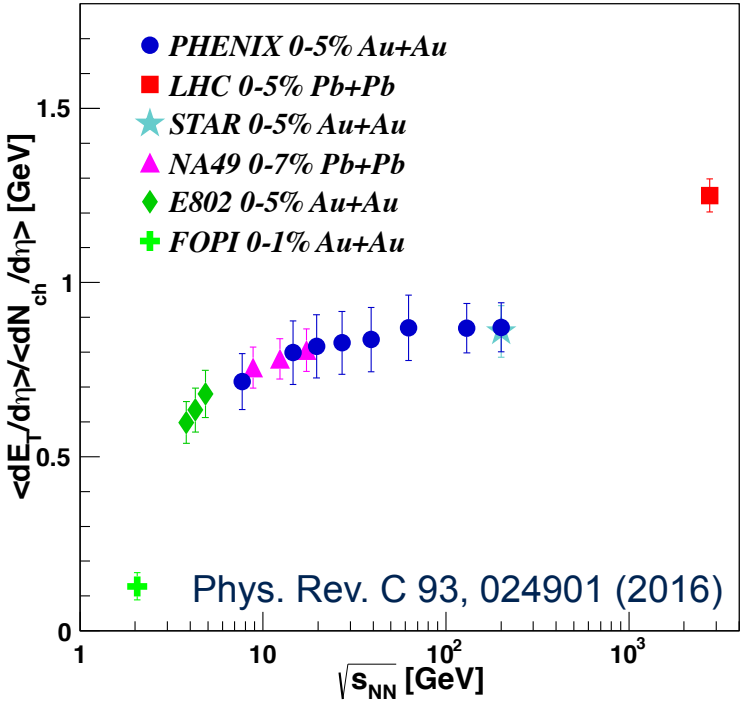

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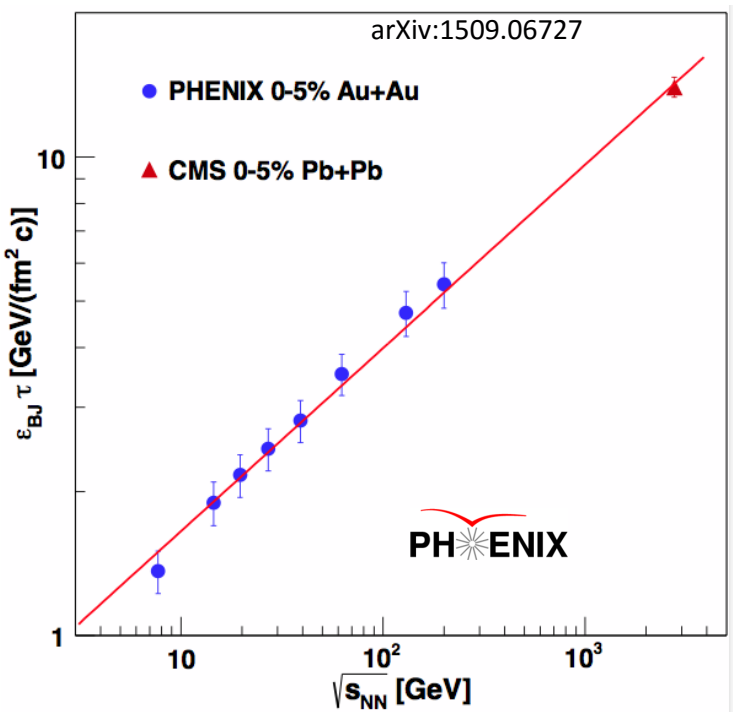


For central events:

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

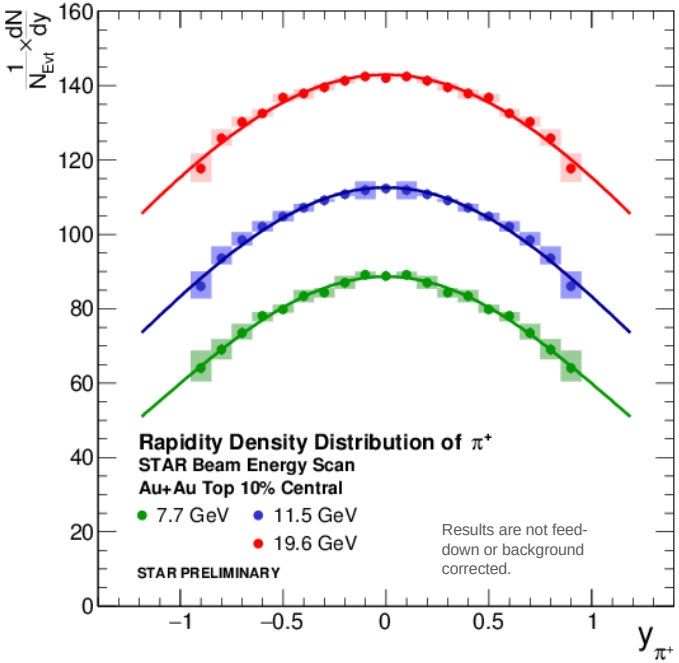
$\varepsilon_{BJ}\tau$ follows power law behavior

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

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

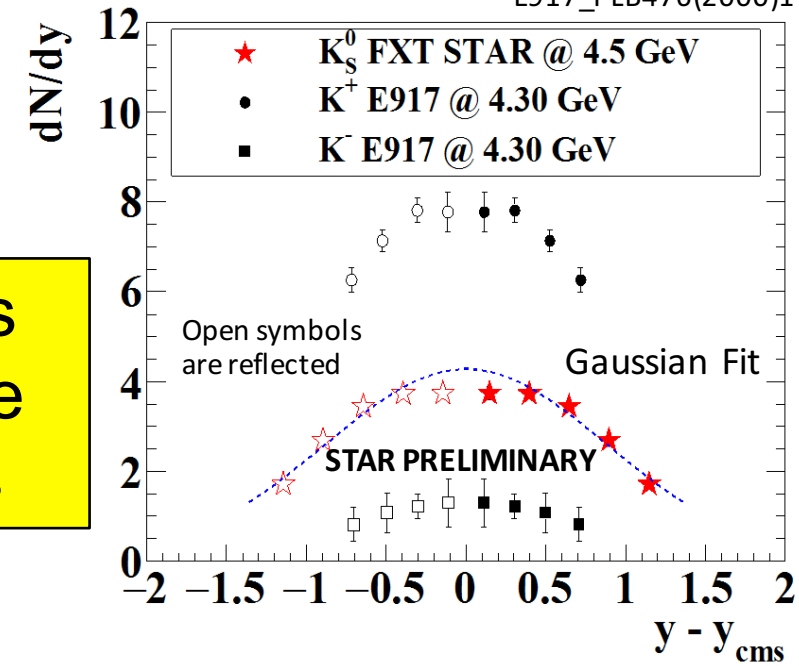
Can we establish τ?

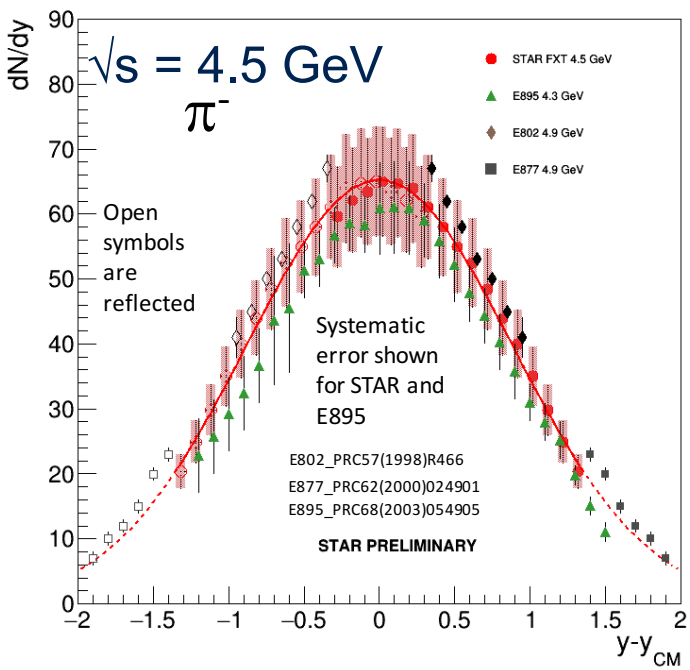
Establishing the "basics": Yields



Moving towards full phase space measurements

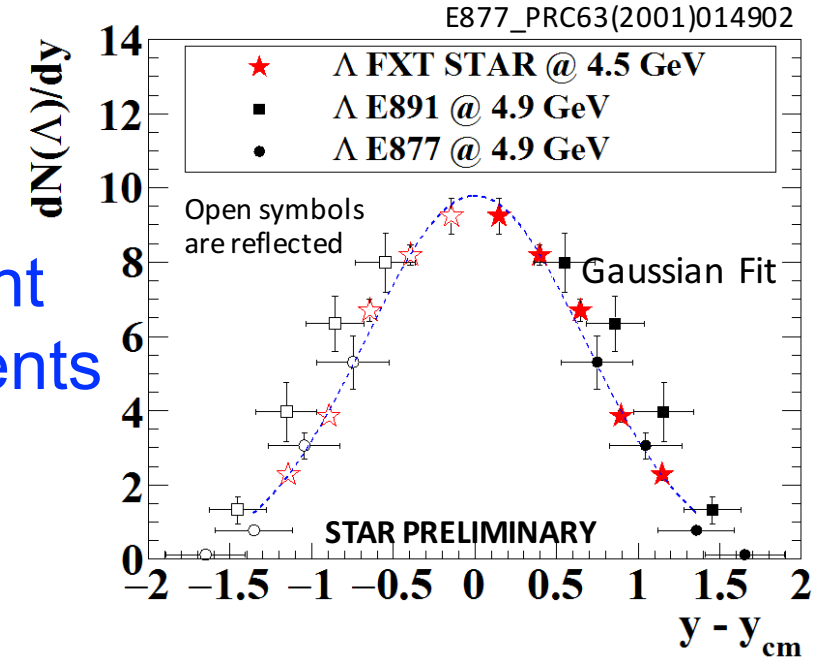
E917_PLB476(2000)1



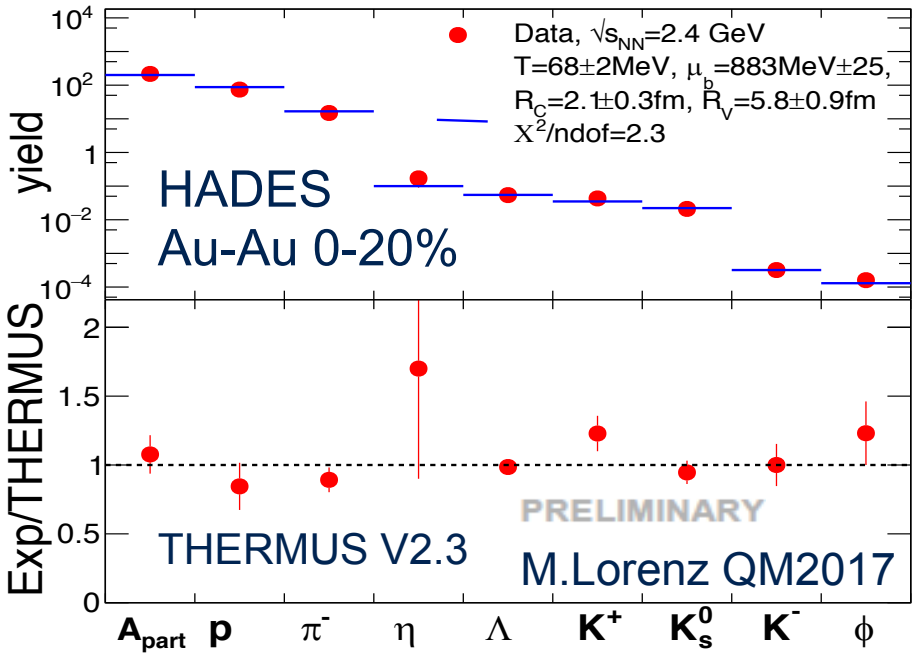


Good agreement between experiments

E877_PRC63(2001)014902



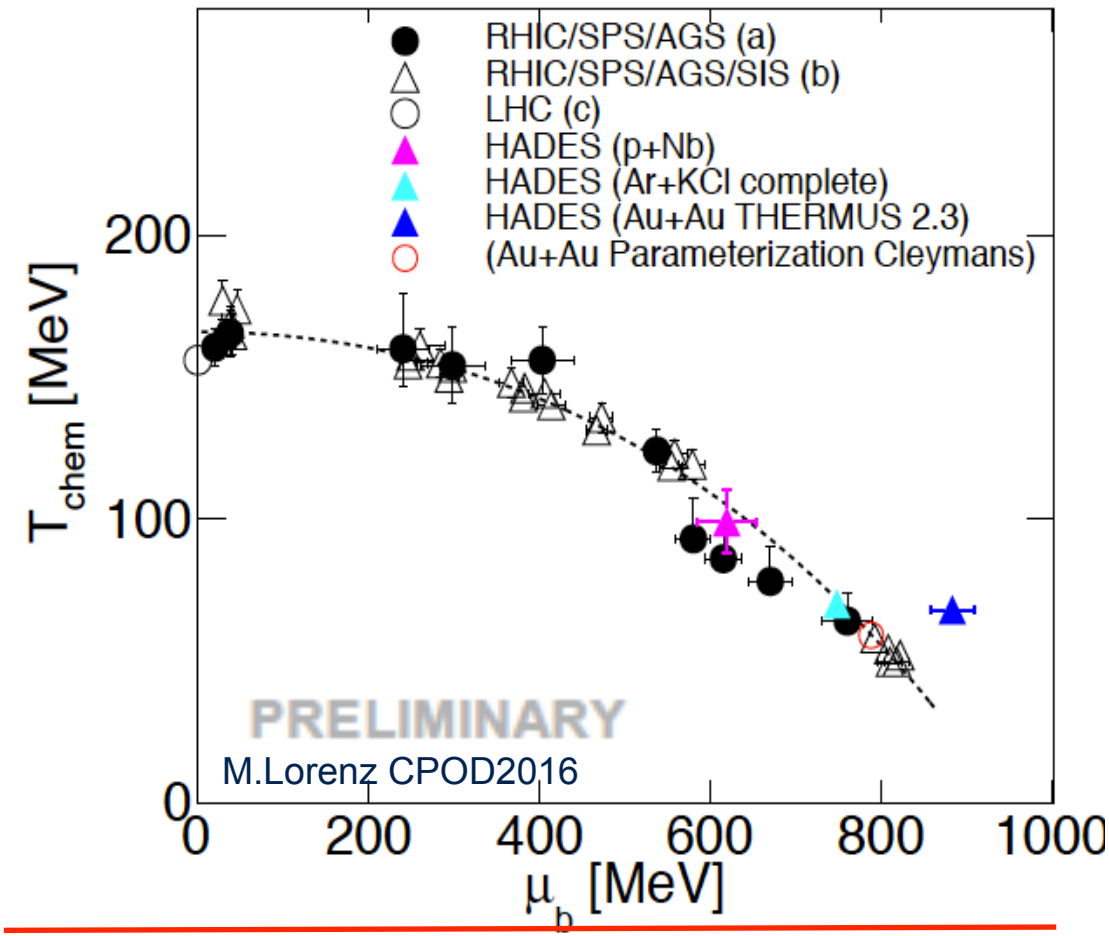
Establishing the "basics": Hadro chemistry



Thermal fits "work" at √s = 2.4 GeV

HADES data above "universal curve expectations"

No longer in equilibrium?

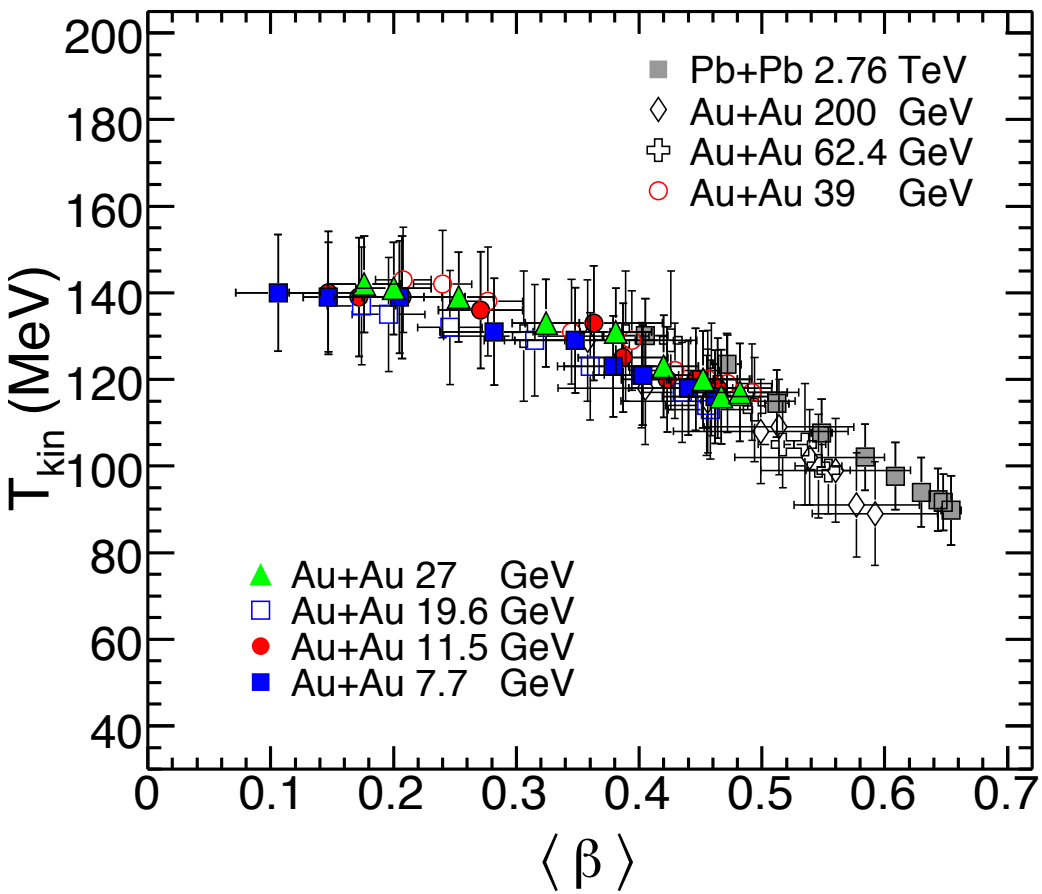


"ALL" strange hadrons needed in fits (STAR)

Lattice based calc. using fluctuations: ~agreement with Thermal model (PHENIX)
(PRC 93, 011901 (2016))

At low √s baryonic resonances required in models (HADES)

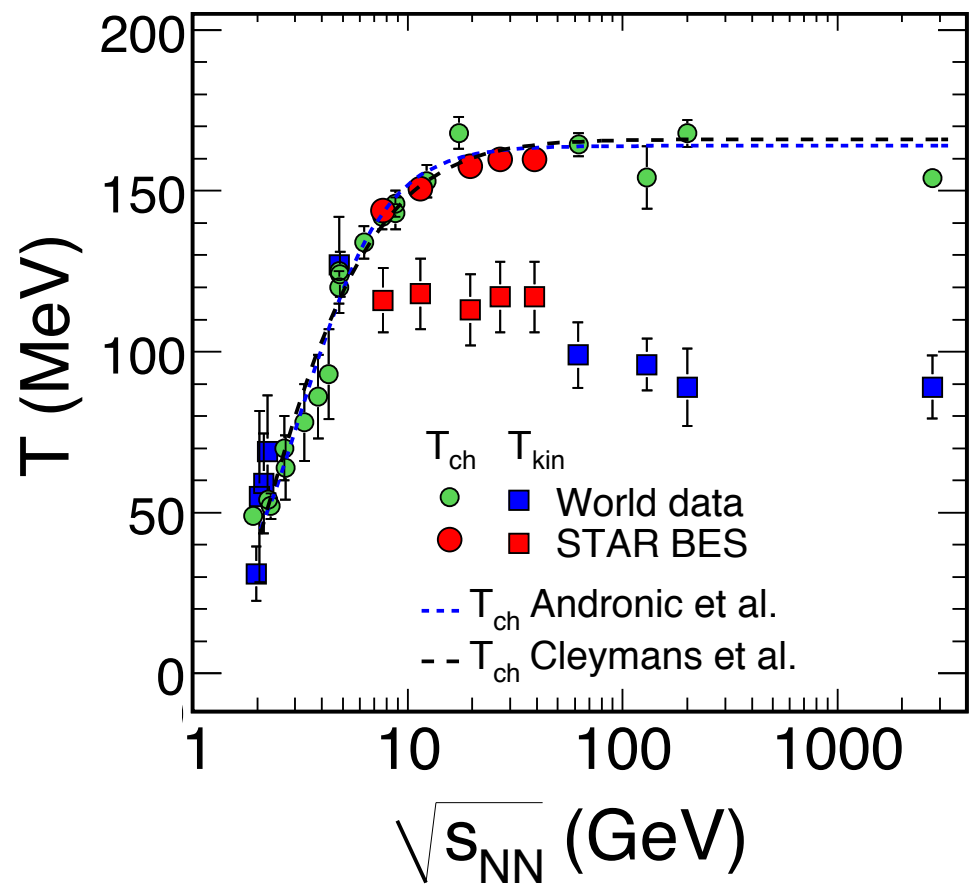
Establishing the "basics": Kinetic freeze-out



Stronger collectivity at higher √s

Central collisions:

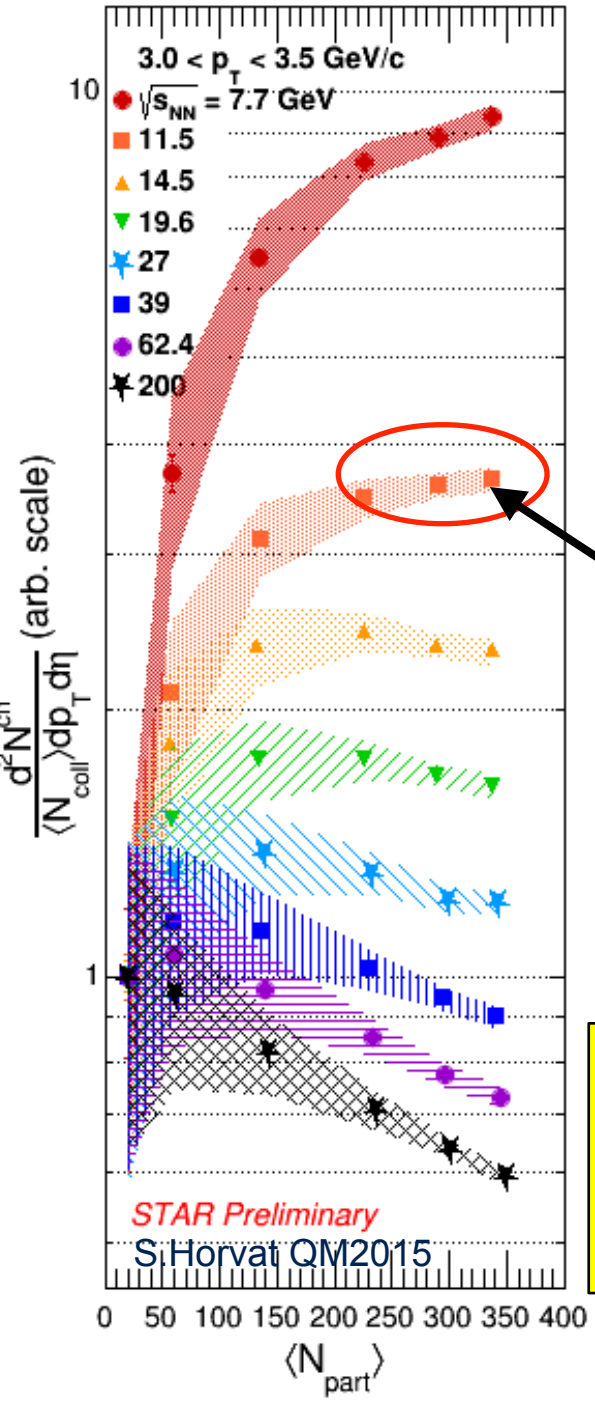
Lower T→ higher β



T_{kin}~T_{ch} below √s ~ 7 GeV

STAR: arXiv:1701.07065

Disappearance of QGP?

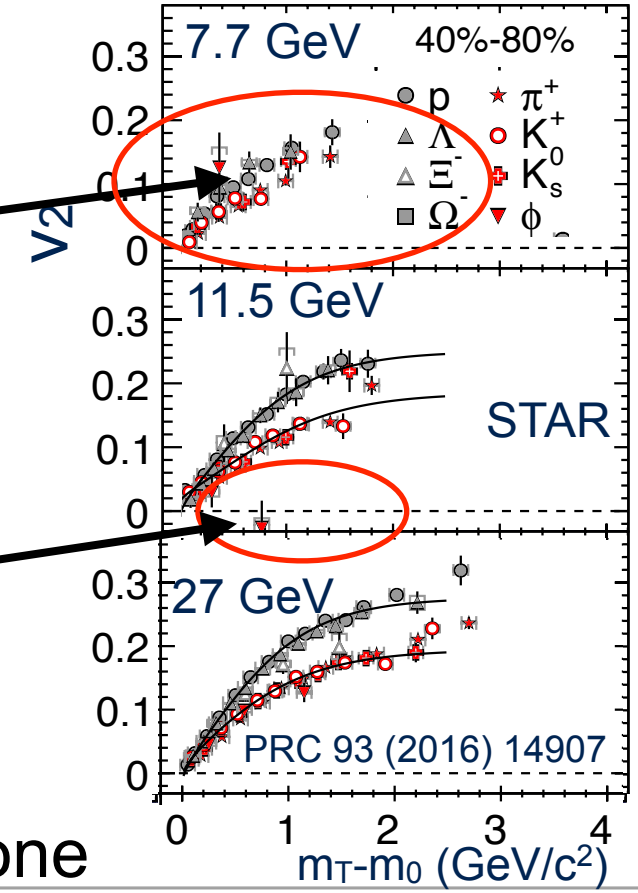


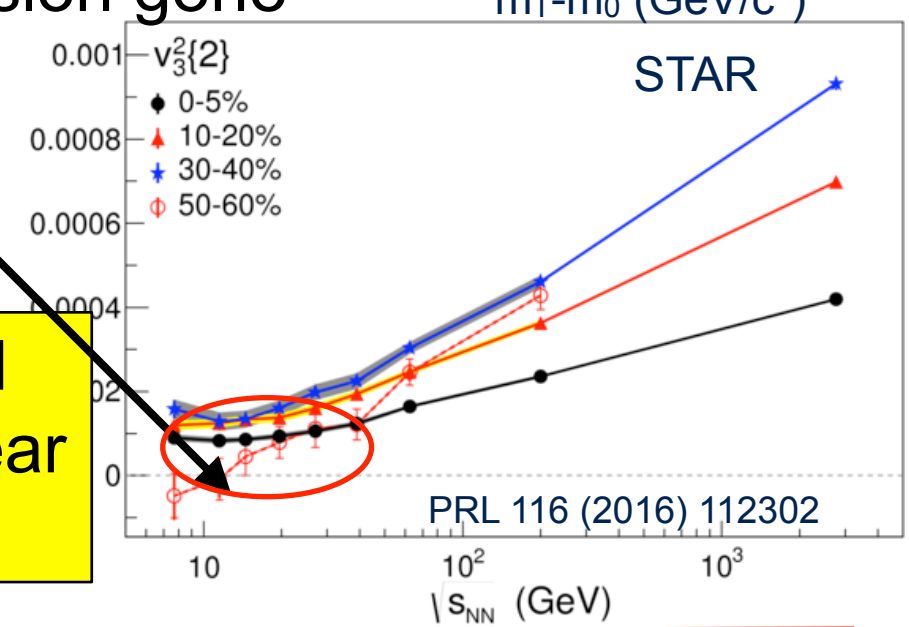
B-M v_2 separation gone

ϕ $v_2 \sim 0$

High p_T suppression gone

$v_3 \sim 0$





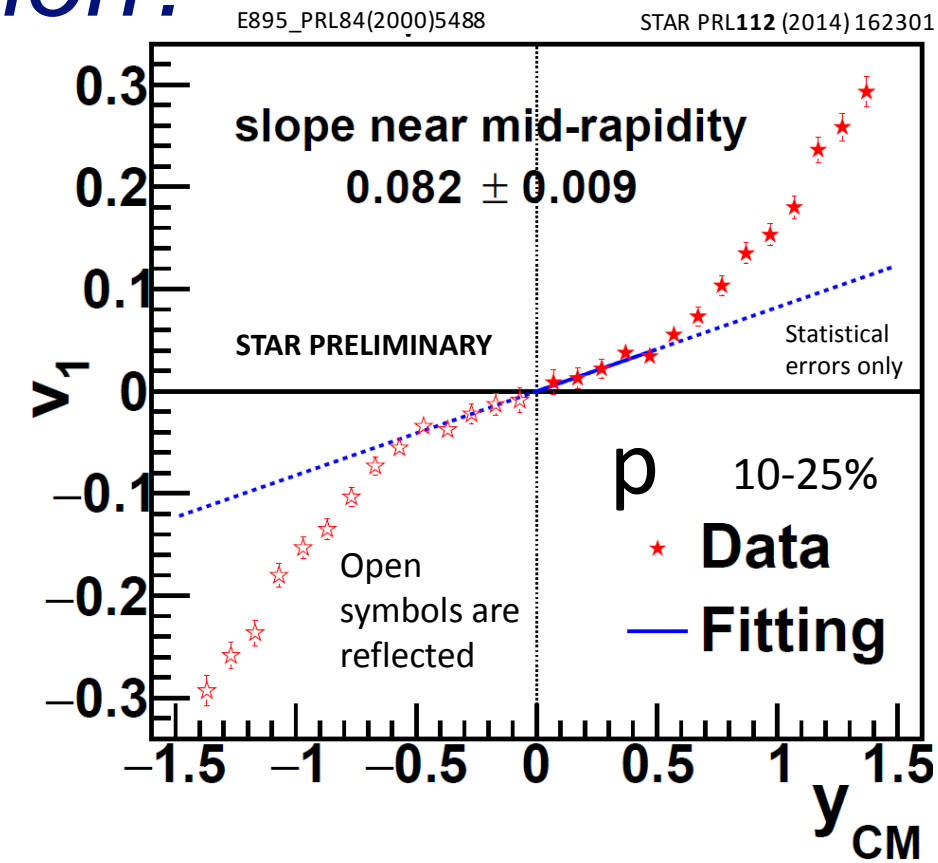
Several standard signatures disappear at $\sqrt{s}$ < 15 GeV

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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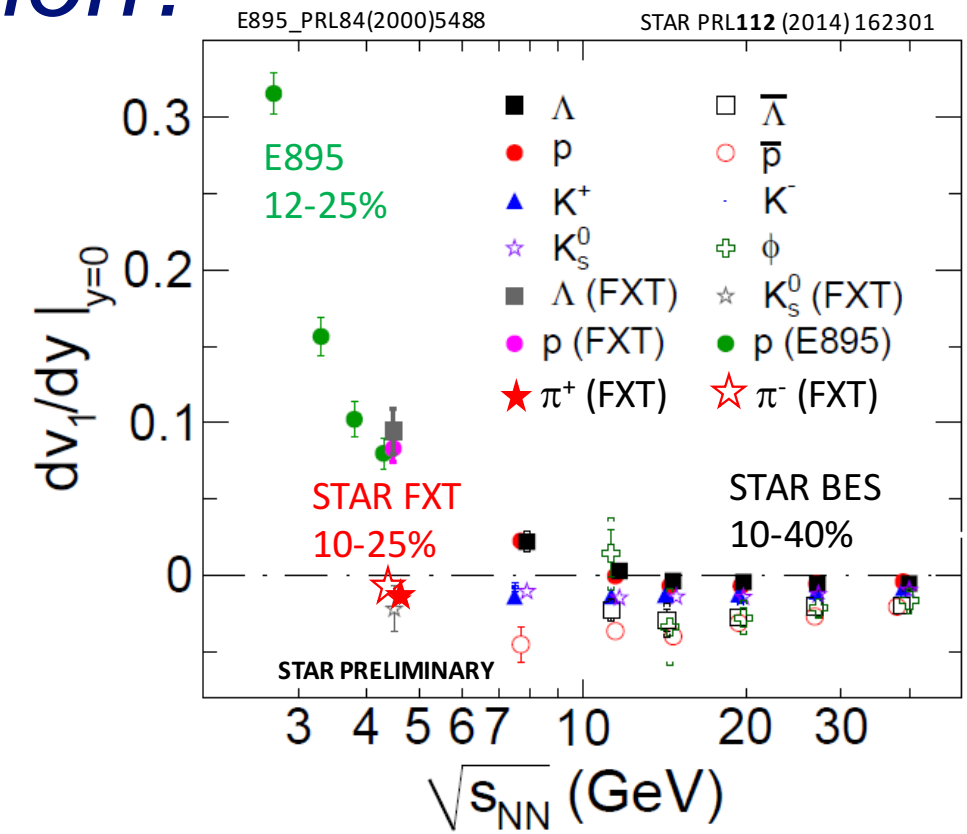

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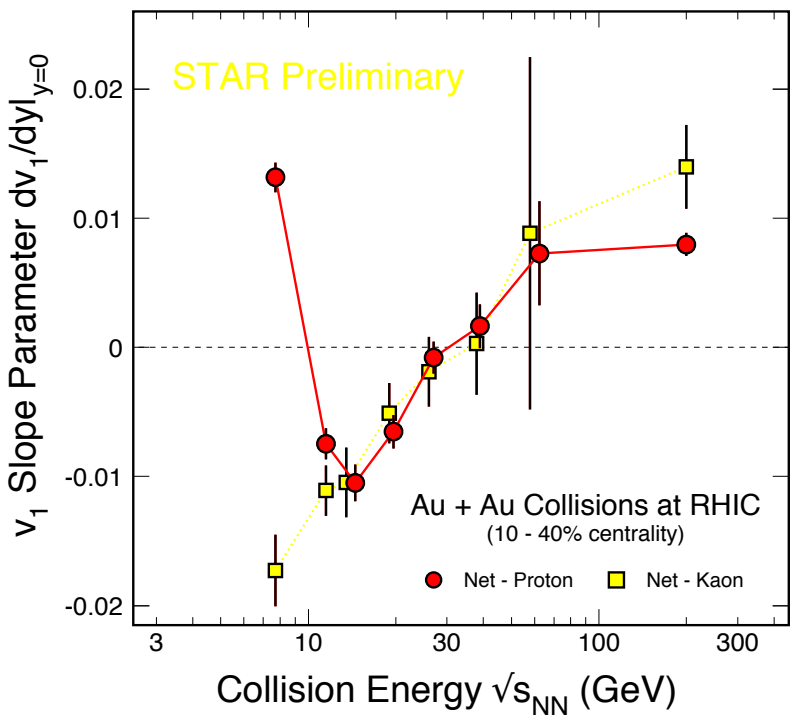
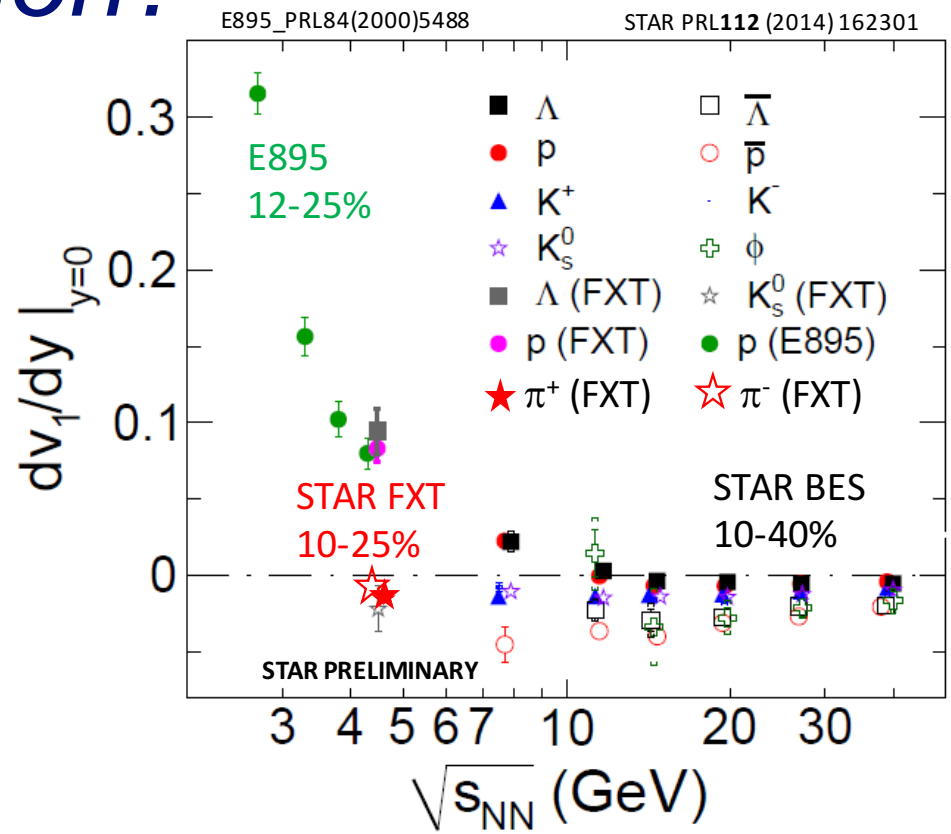




Net-proton isolates directed flow of transported baryons:

Double sign change in dv_1/dy

Not seen in net-kaons

Results not yet reproduced by theory

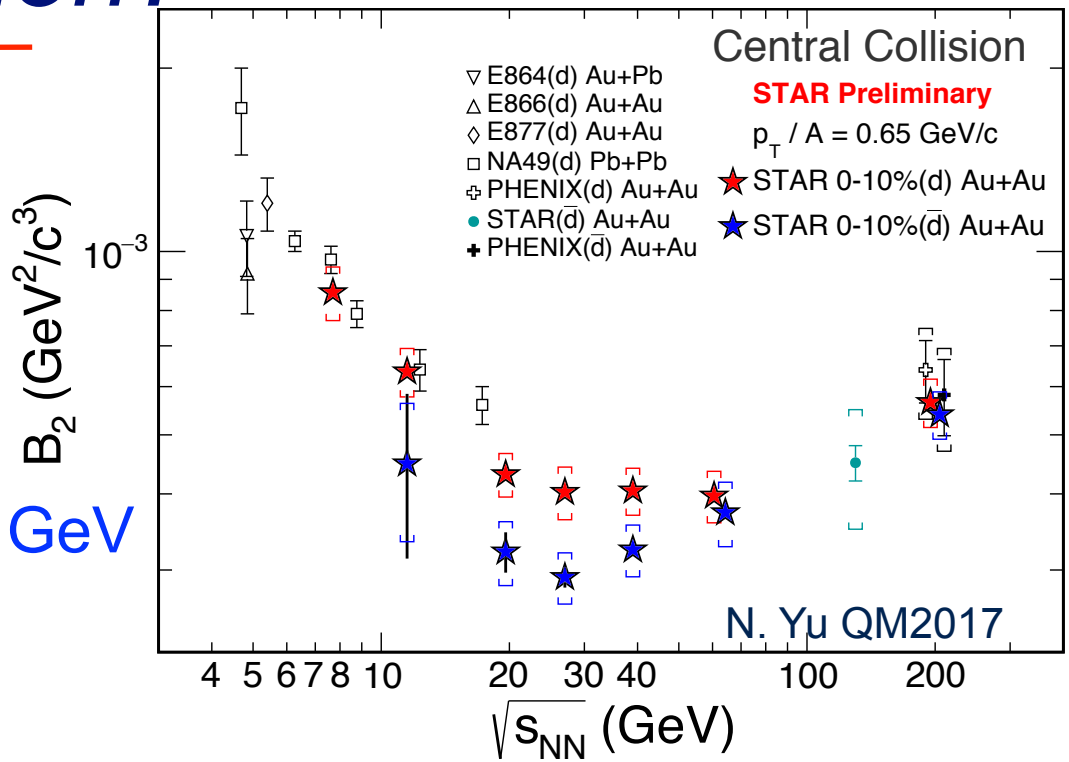
Softening of EoS ?

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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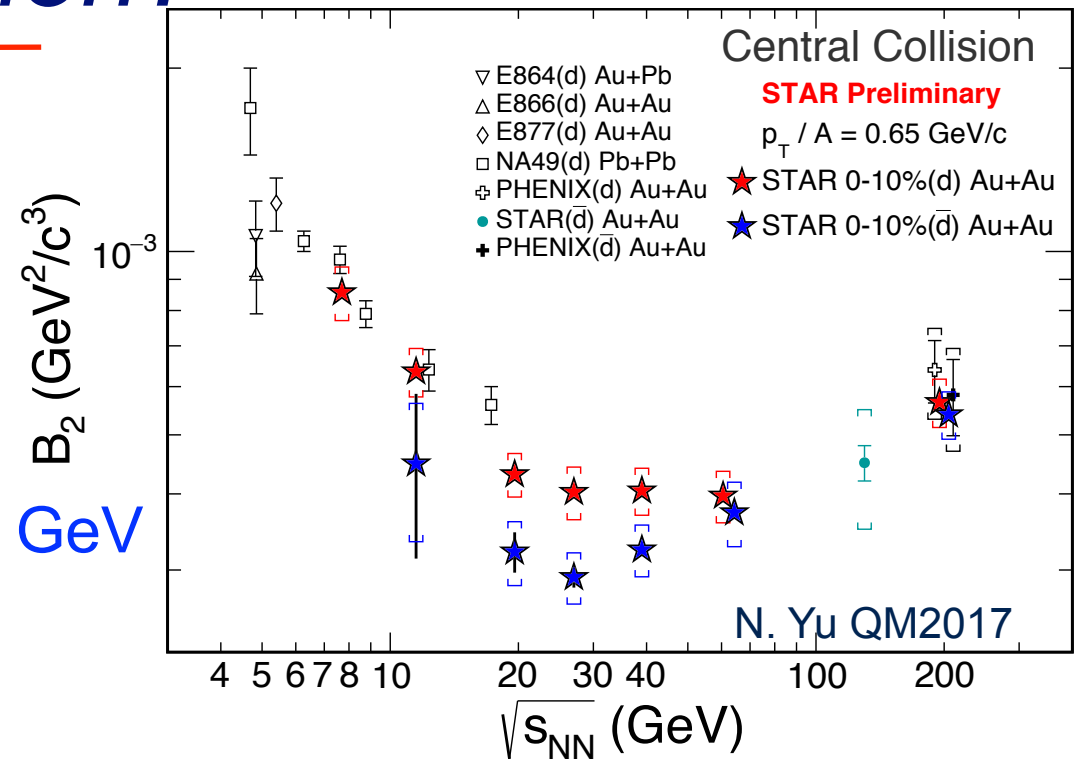
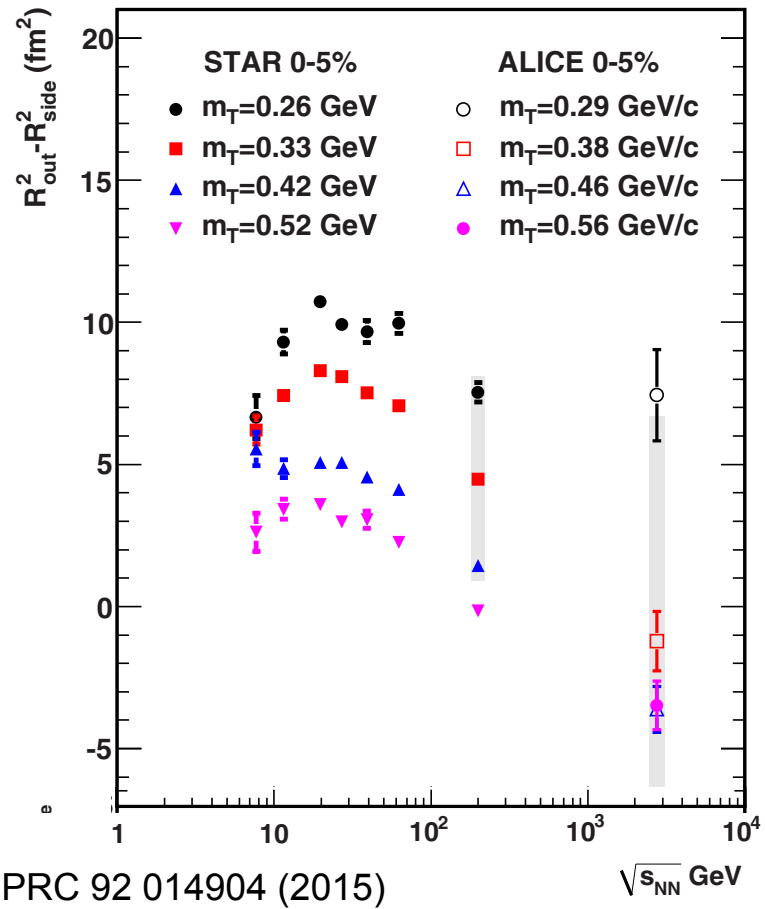




PRC 92 014904 (2015)

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

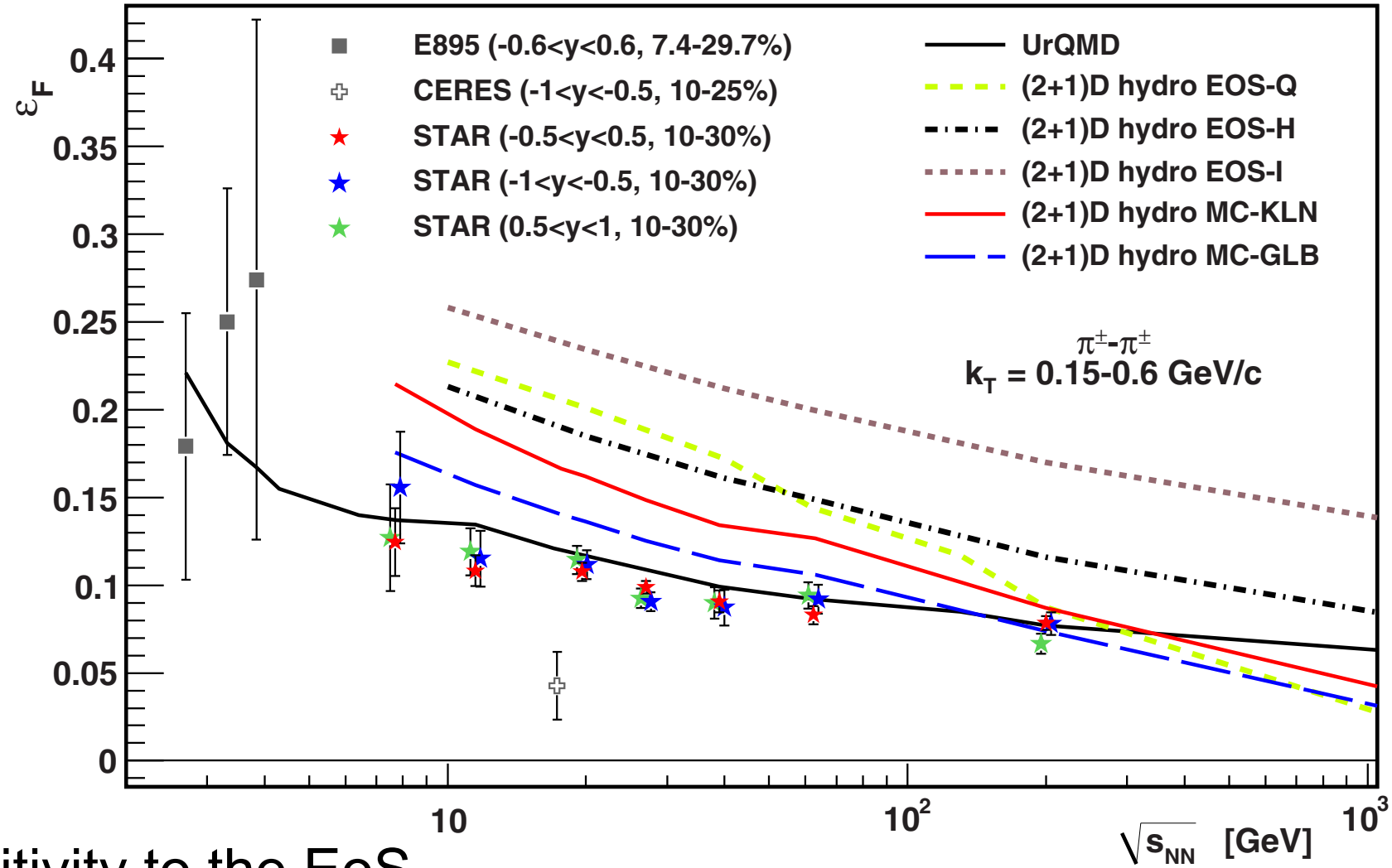
Maximum at $\sqrt{s_{NN}}$ ~ 20 GeV

Softening of EoS?

Sign of entering compressed baryonic matter regime?

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

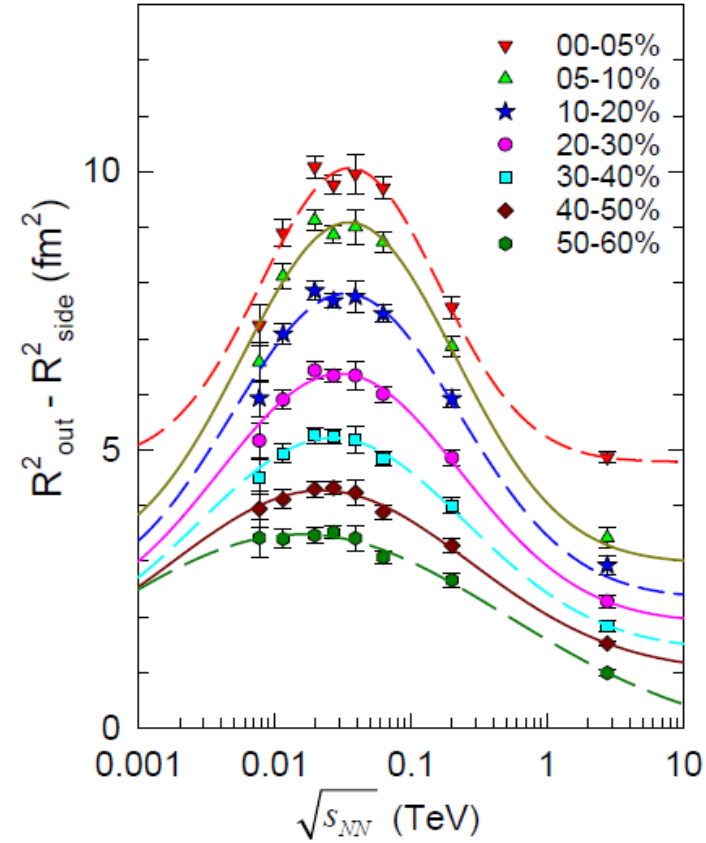
Plot of max (R^2_{out} - R^2_{side}) as function of $R_{glauber}$ - Lifetime to initial transverse size of system mapping?

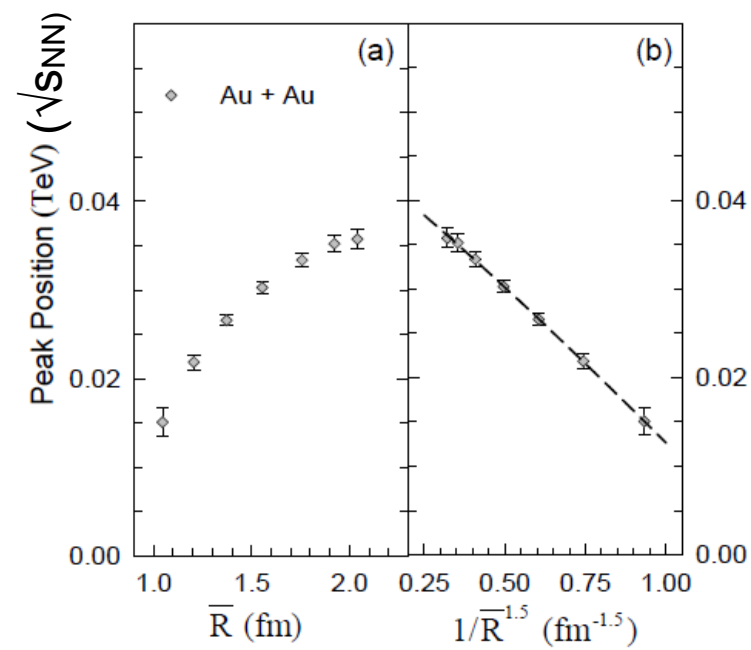
Slope and intercept give information on location of CP at infinite volume and the critical exponents

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





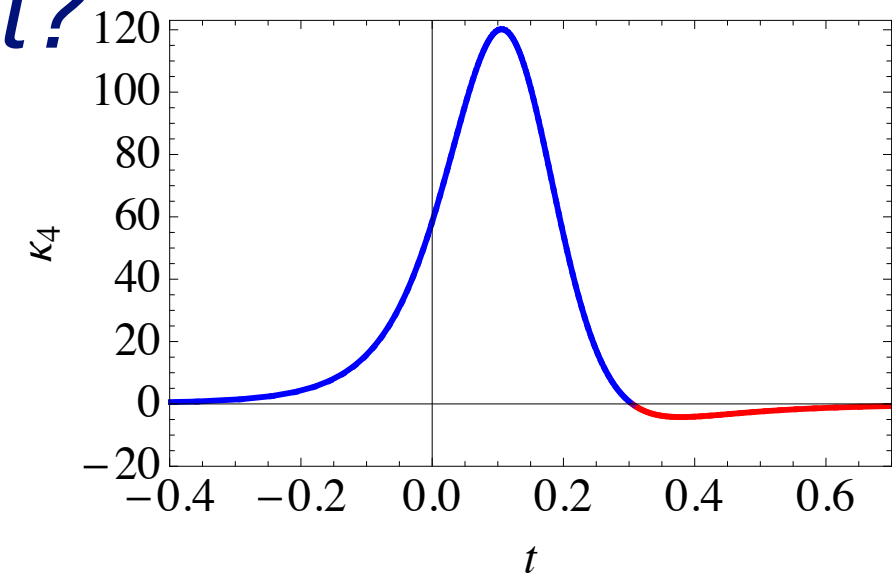
R. Lacey, PRL **114**, 142301

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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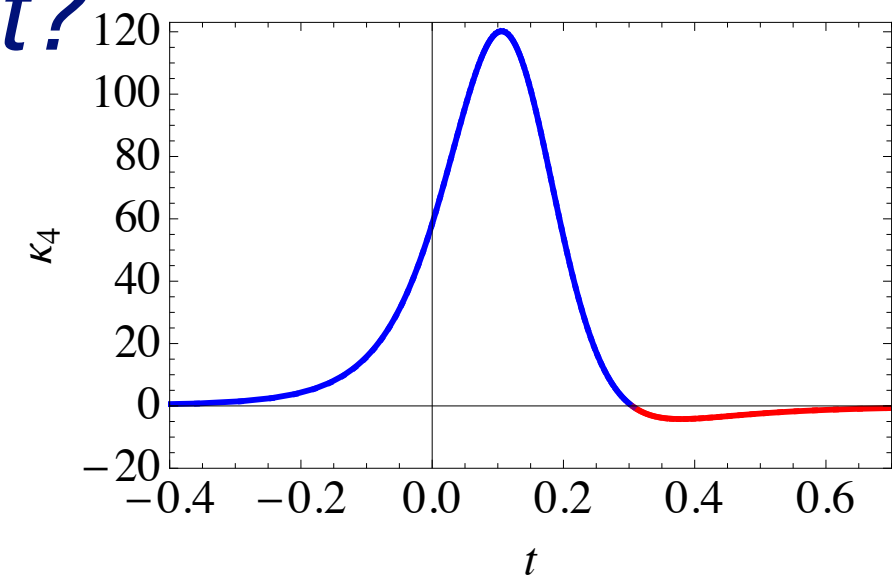

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Top 5% central collisions:

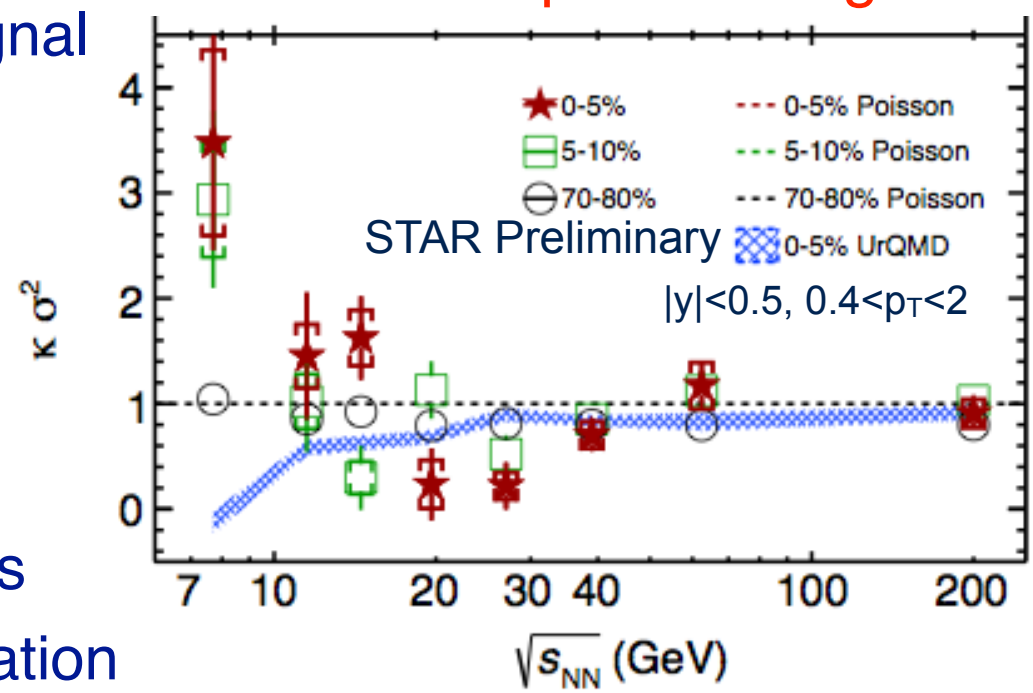
- Non-monotonic behavior
- Enhanced p_T range → enhanced signal

Peripheral collisions:

- smooth trend

UrQMD (no Critical Point):

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



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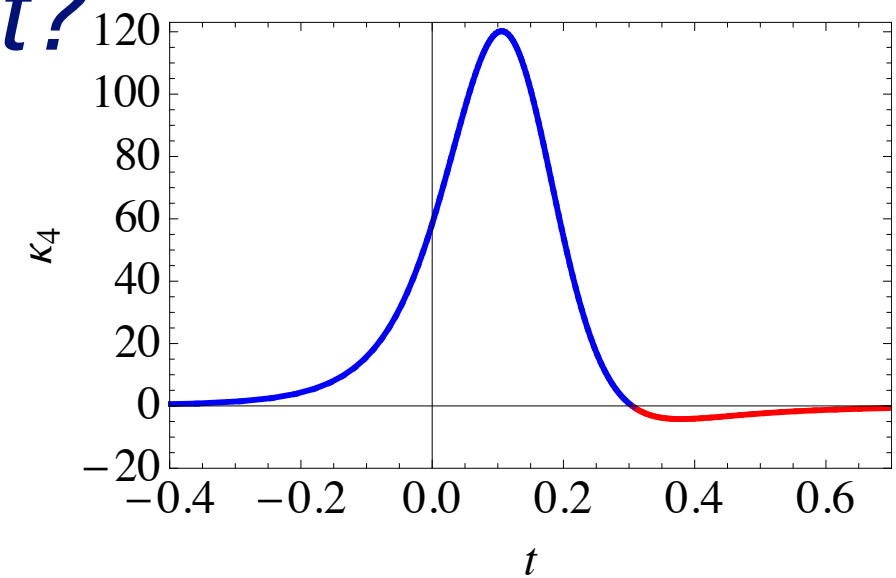

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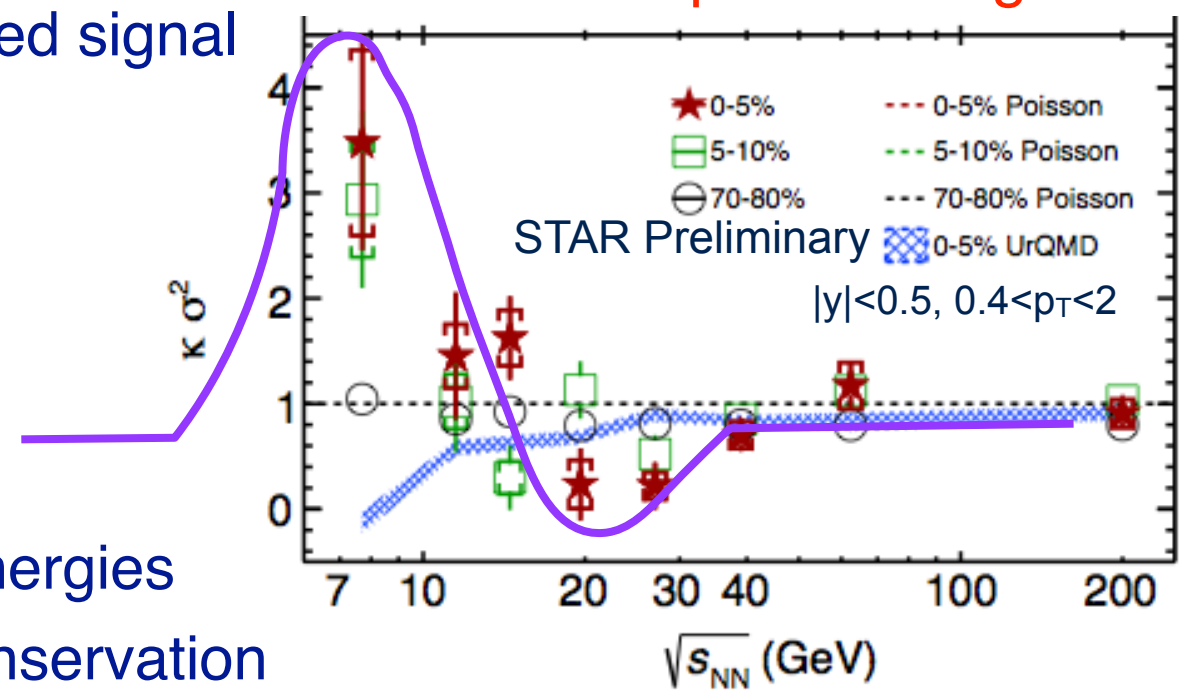

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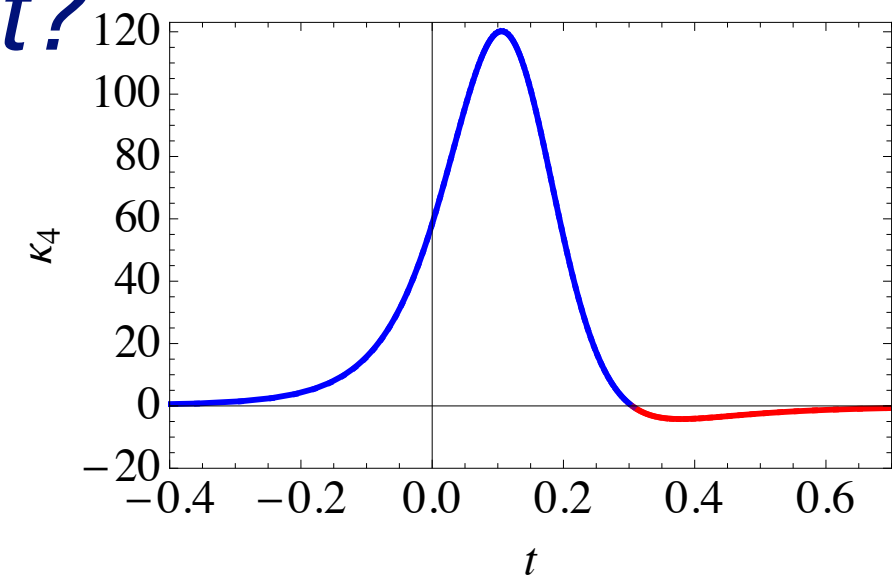
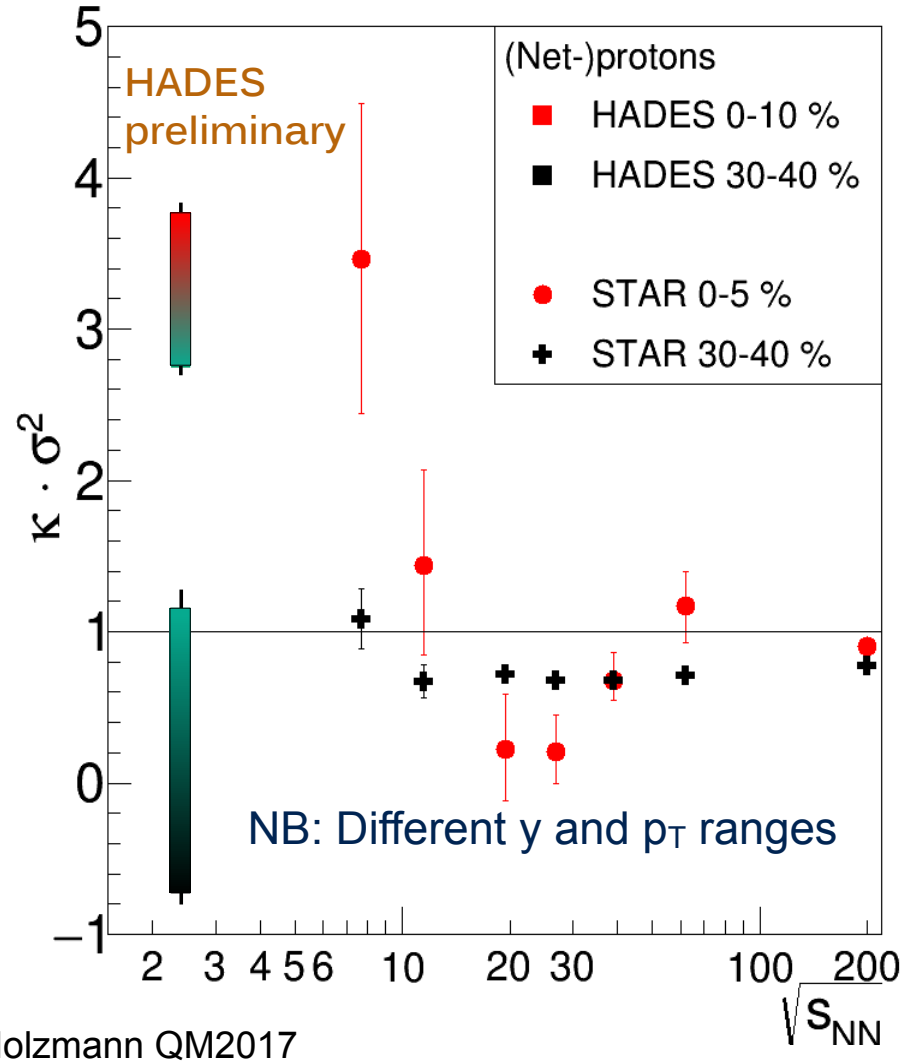


HADES data + upcoming FXT testing if mapping correct

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))

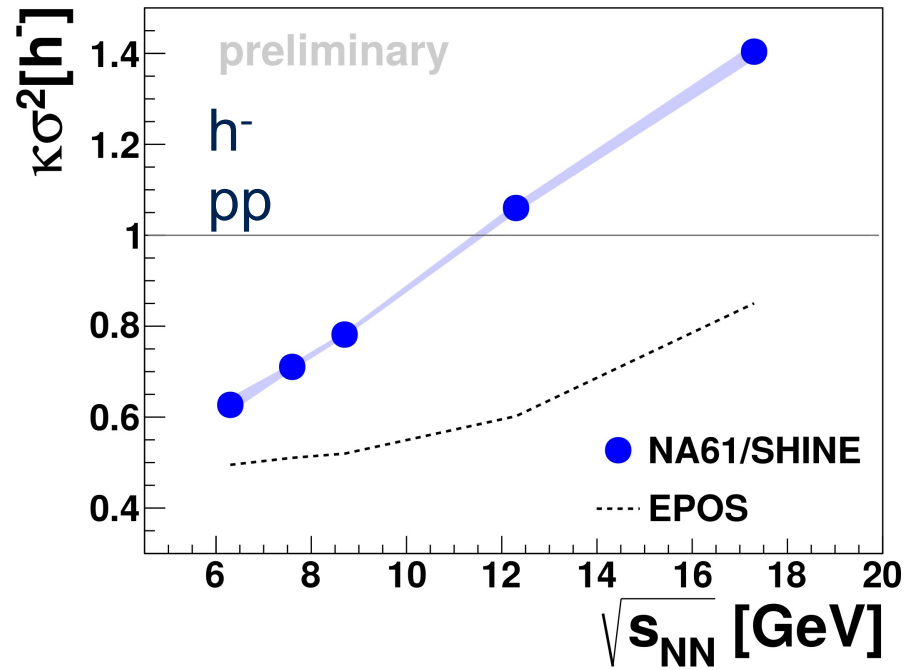
R. Holzmann QM2017

Fluctuations in pp and light-nuclei collisions

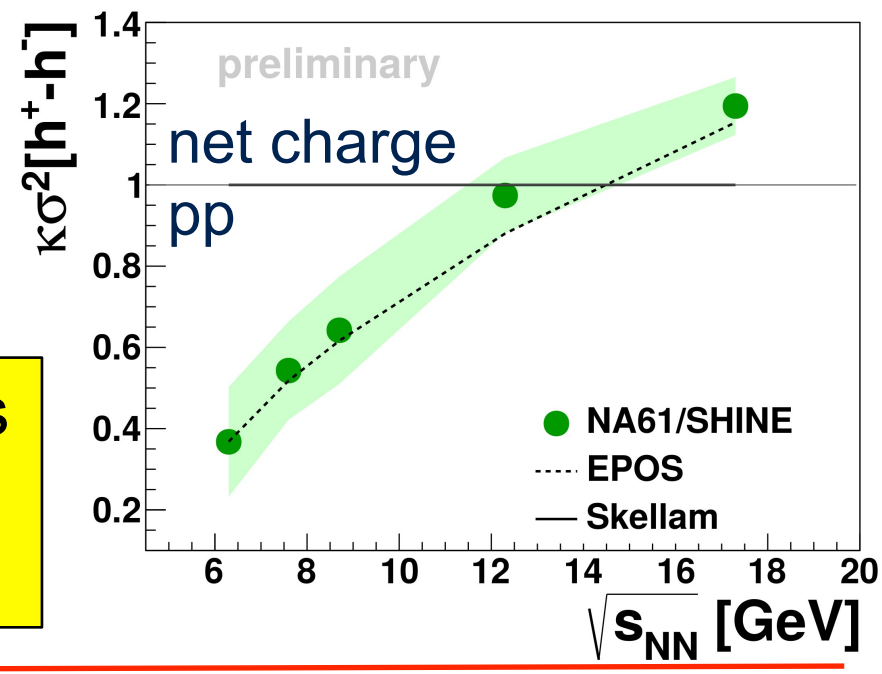
Inelastic pp:

EPOS has variable success

Net charge fluctuations not due to independent emission (Skellam)

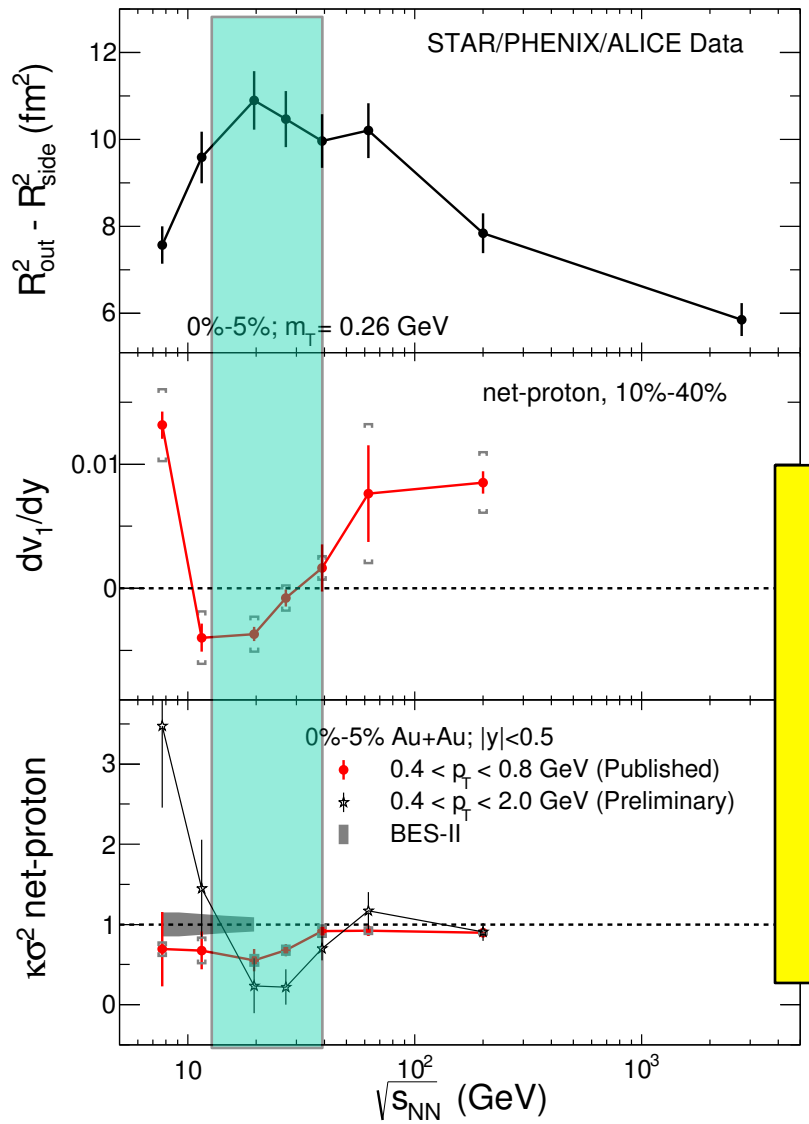


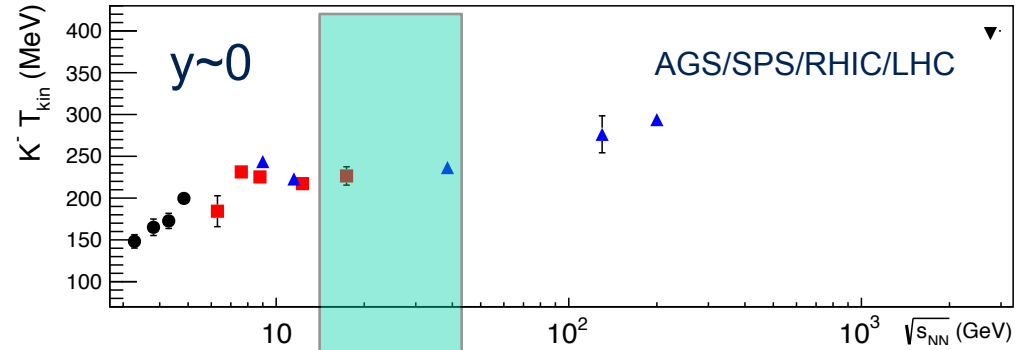
p_T, multiplicity, and forward energy fluctuations also studied in Ar+Sc

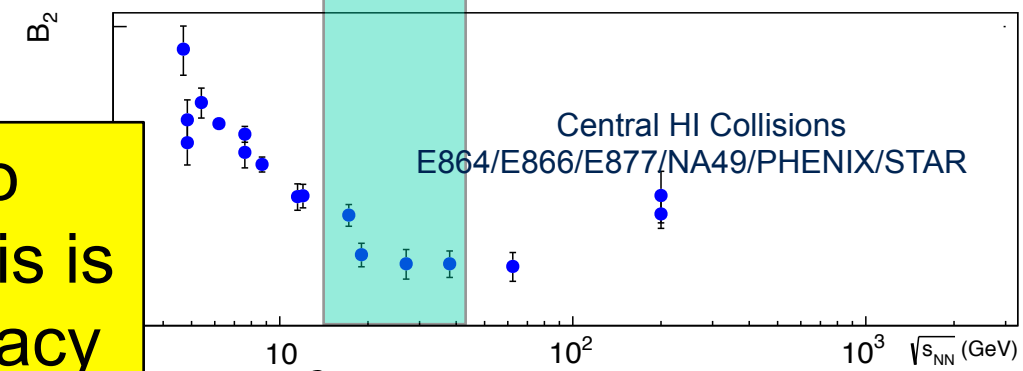


Monotonic behavior of all fluctuations studied for both collision species
- No evidence of CP

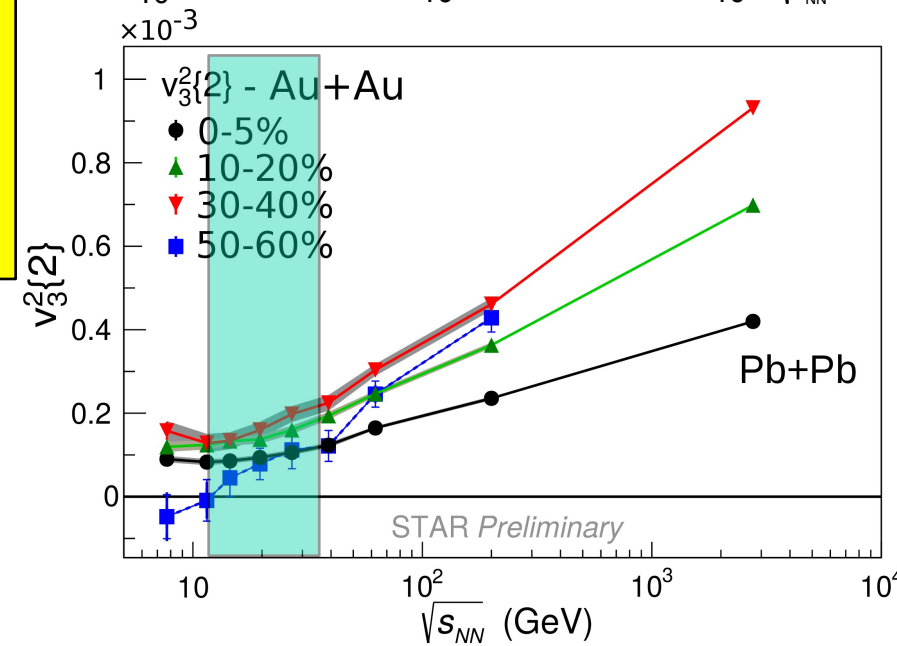
A lot is happening around $\sqrt{s_{NN}}$ =20 GeV

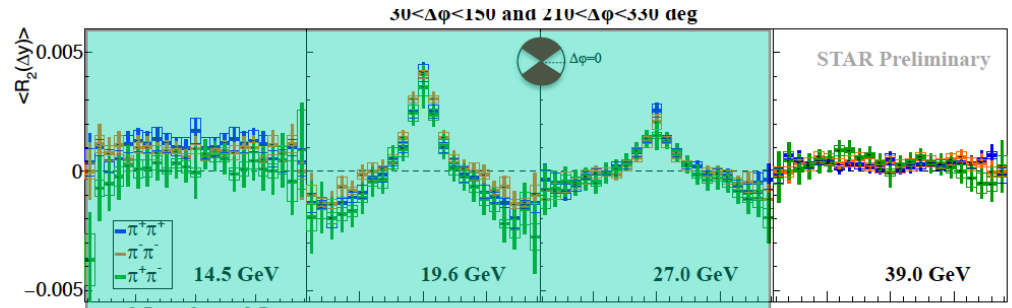






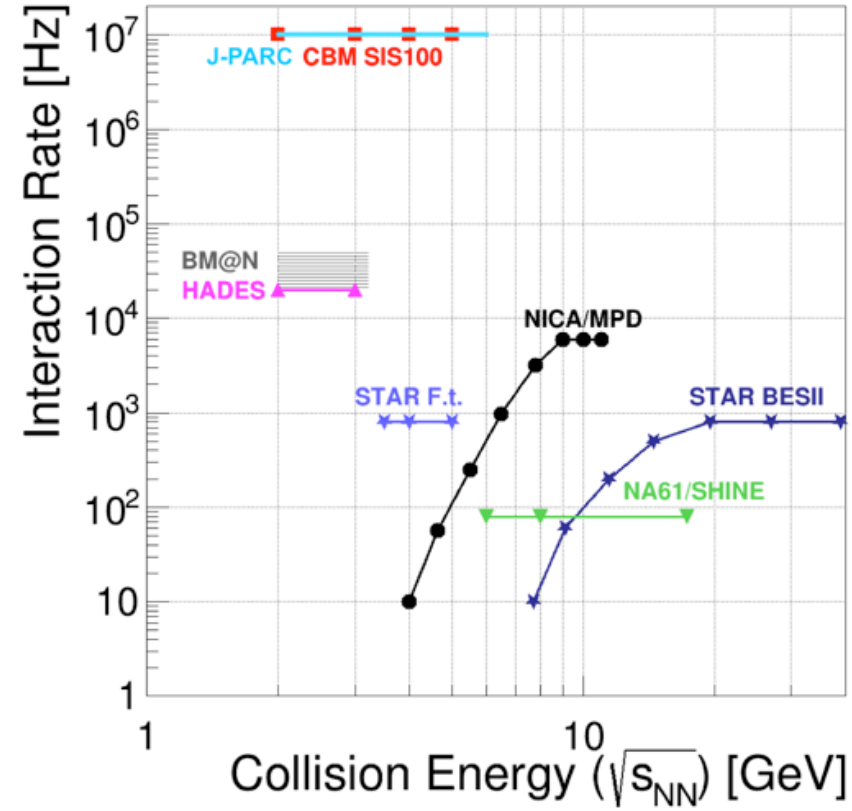
Hard to believe this is a conspiracy of different underlying causes



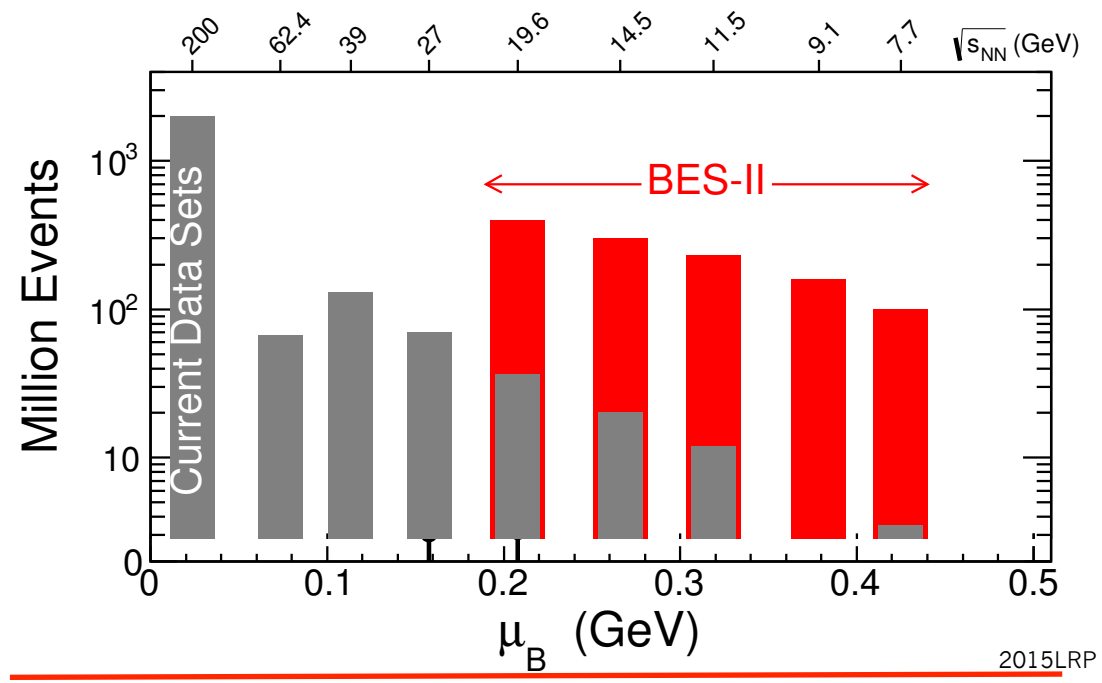


Improving on current data

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

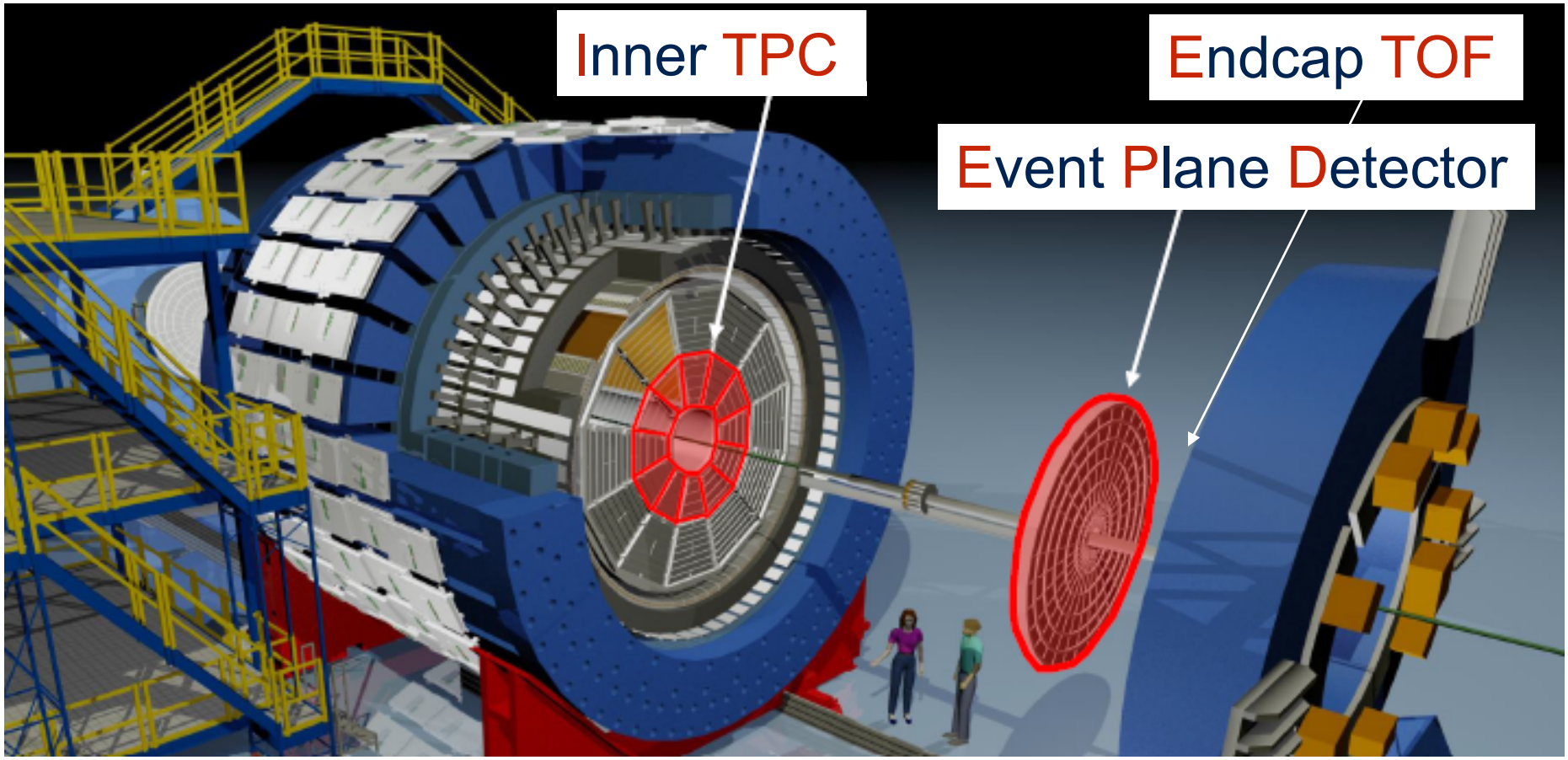
Planned low energy running

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	BM@N	HADES/ miniCBM	STAR	MPD	CBM	
Start Year	2009	2017	2018	2019	2020	2025	2025 (earliest)
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

V.Kekelidze, T.Sakaguchi, P. Senger QM2017

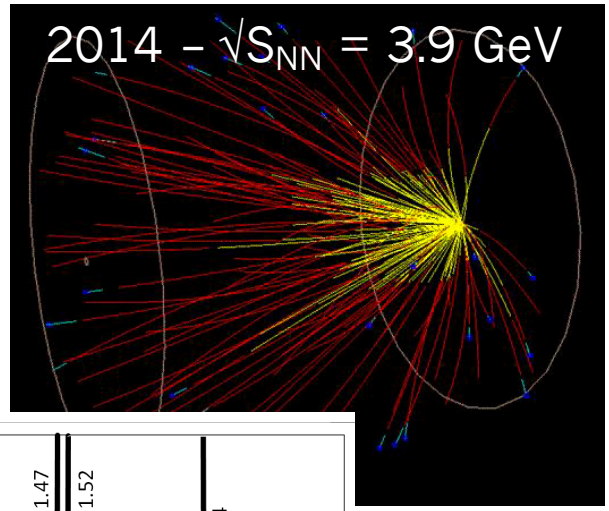
STAR upgrades for BES-II

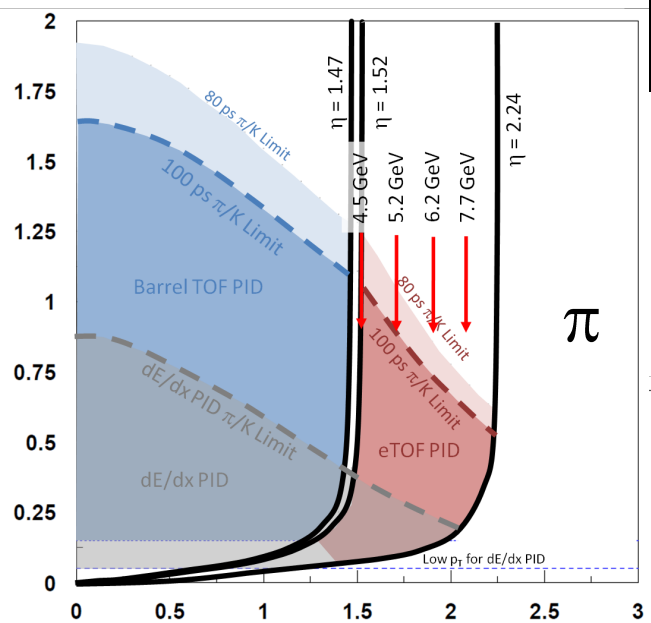


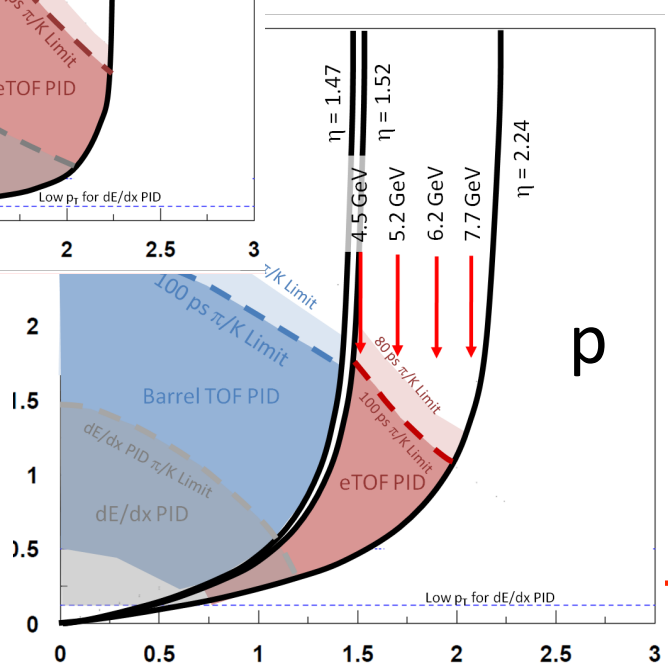
Enhanced Acceptance
Enhanced PID mid and forward
Enhanced Event Plane Resolution
Enhanced Centrality Definition
Enhanced √s range

iTPC, EPD,
eTOF (from CBM),
Fixed target

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:

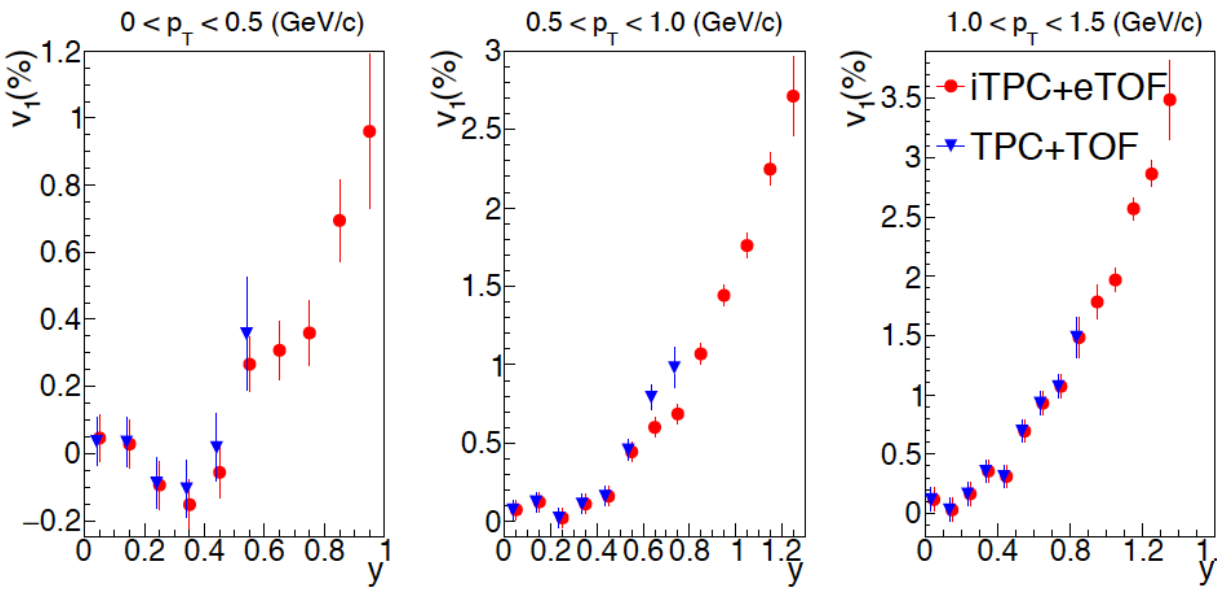
- Forward acceptance in fixed target mid-rapidity range
  - Reach 7.7 GeV for fixed target too

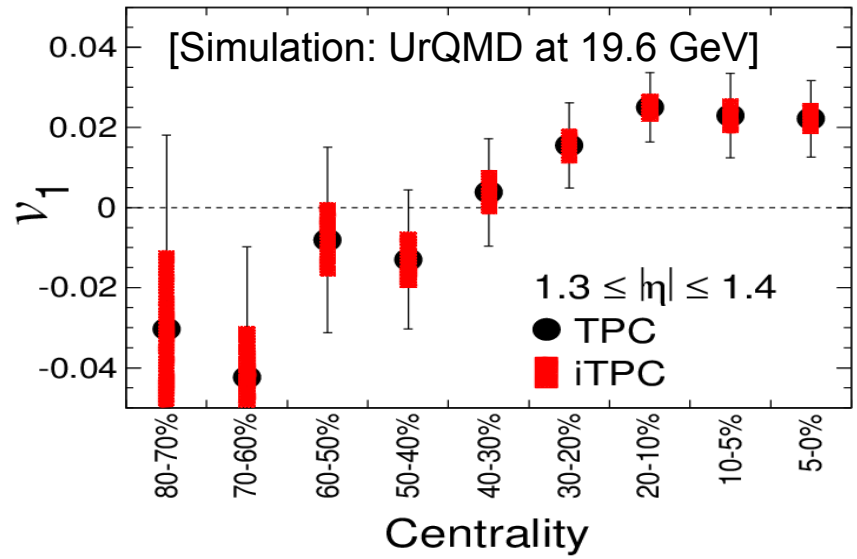
Precision investigation with new techniques and same detector

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

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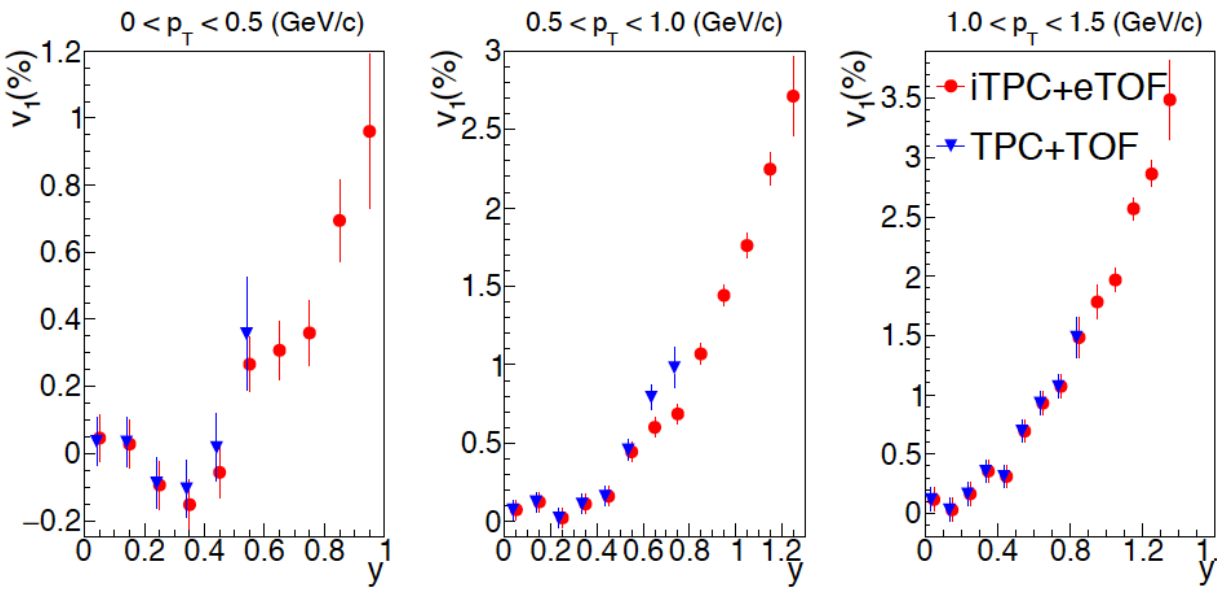
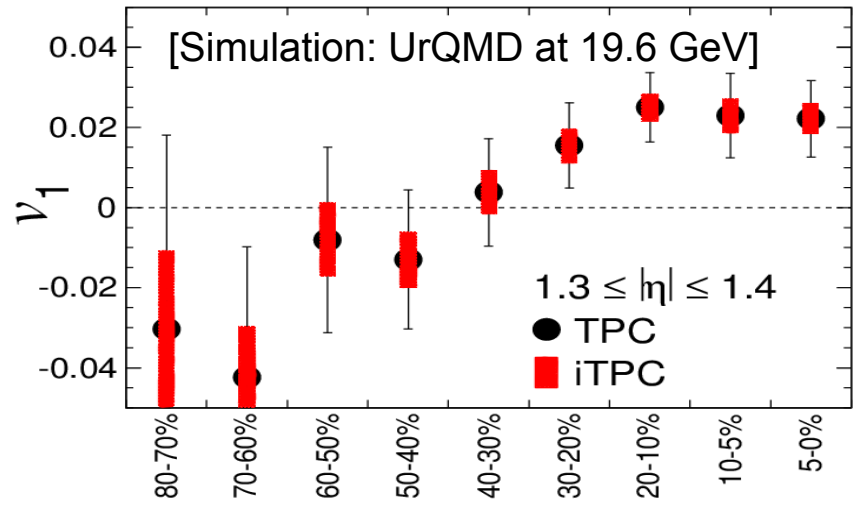
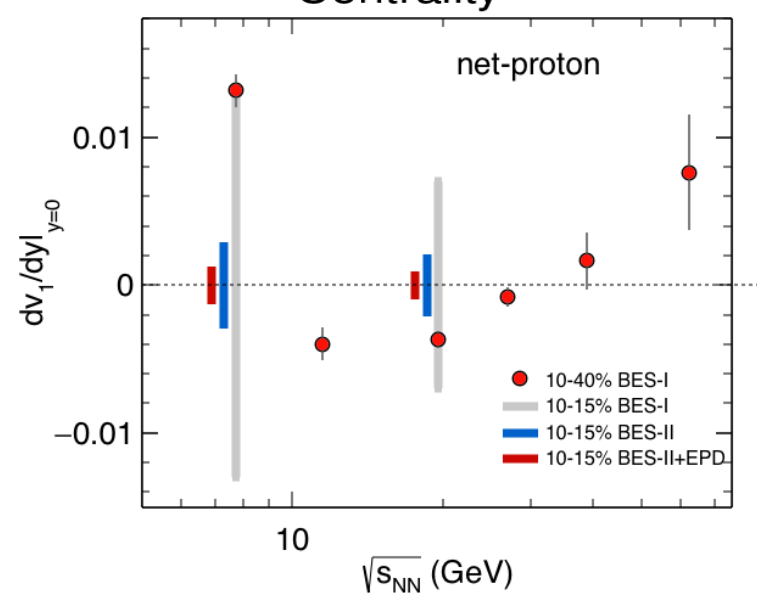






iTPC+ eTOF:

- 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:

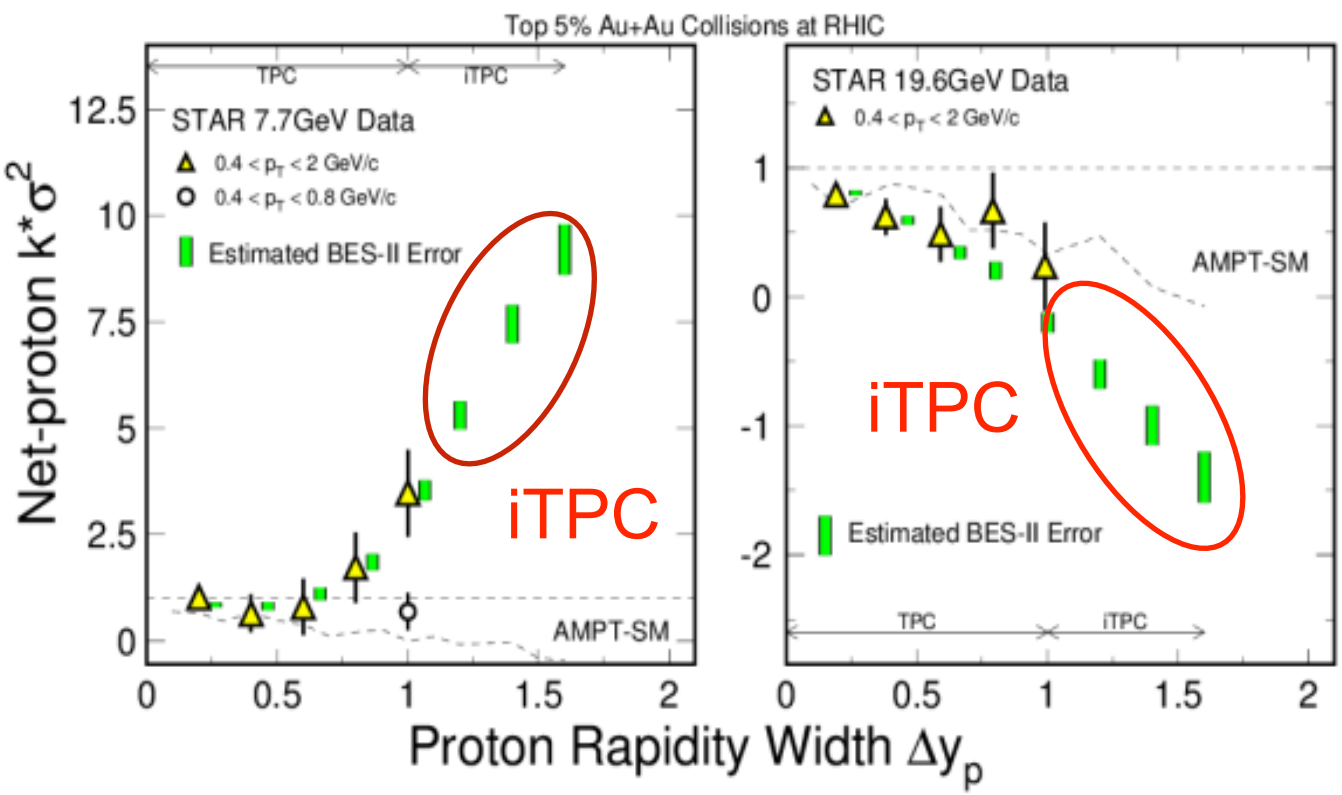
Increase Δy_p acceptance

$\Delta y_p > \Delta y$ correlation

EPD:

Improved centrality selection

Use all TPC for measurement

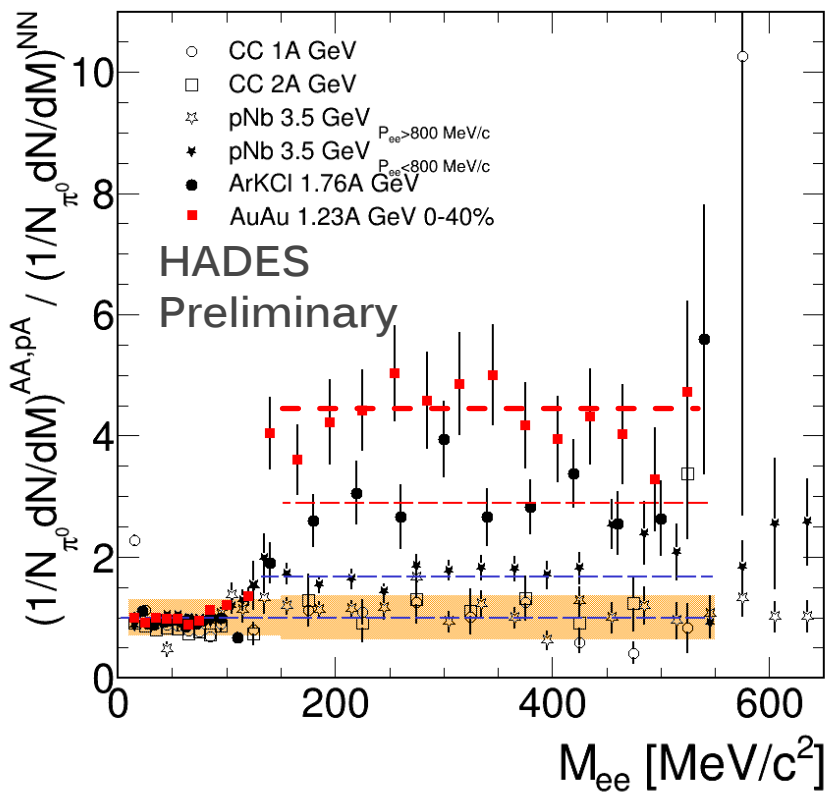


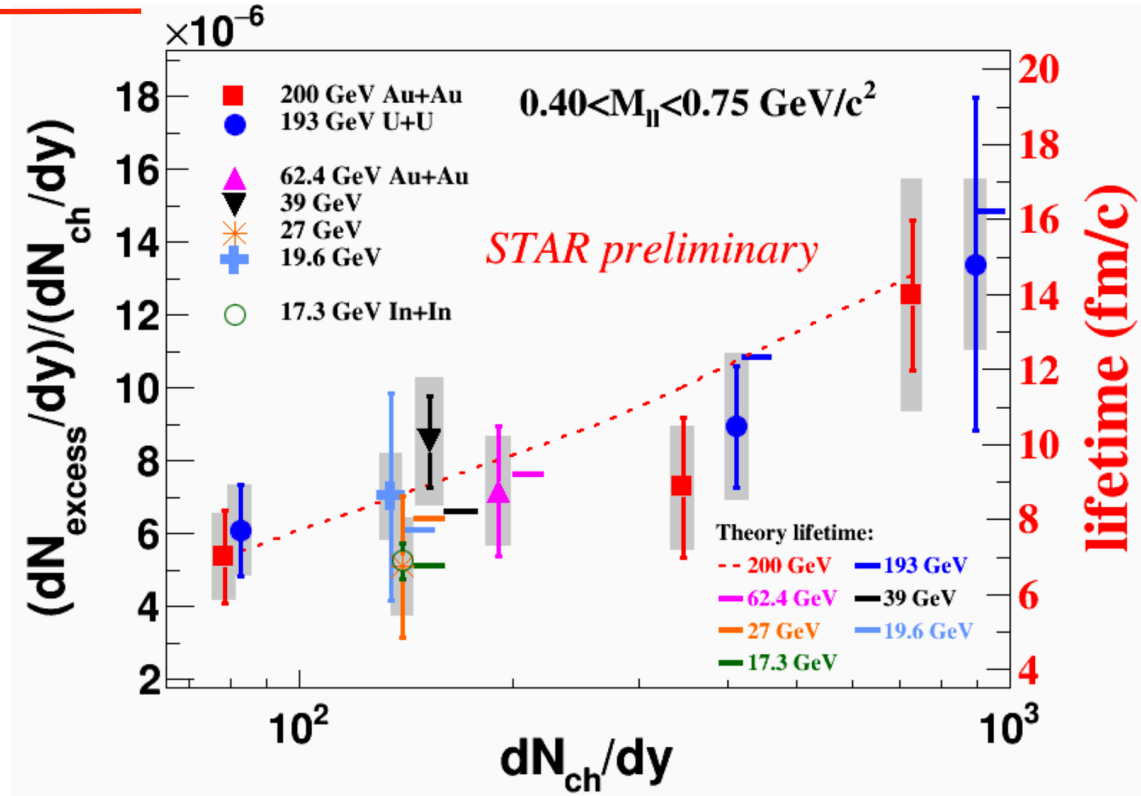
Establish true nature of correlation

Subject actively pursued theoretically

Low mass di-lepton excess

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





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

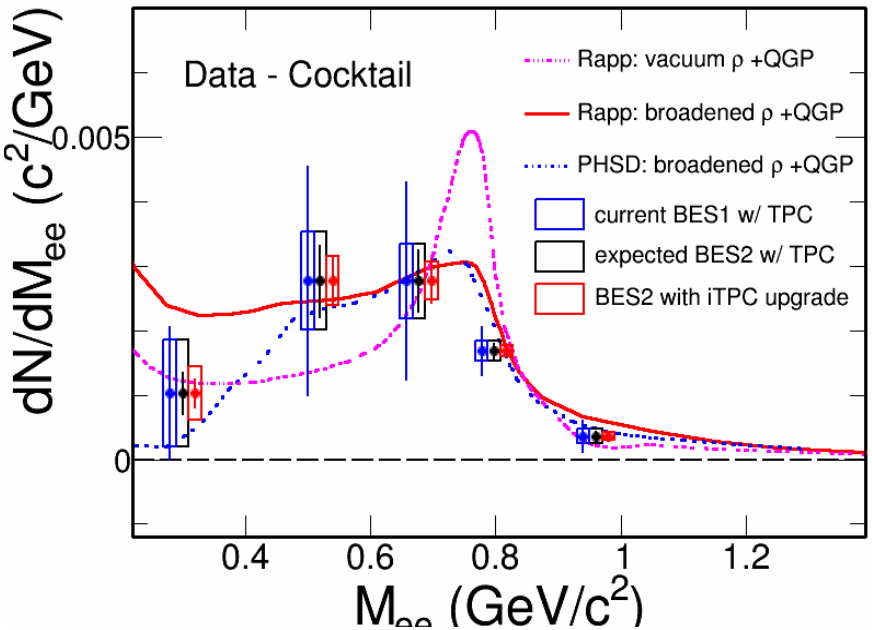
Low mass excess ∝ fireball lifetime

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:

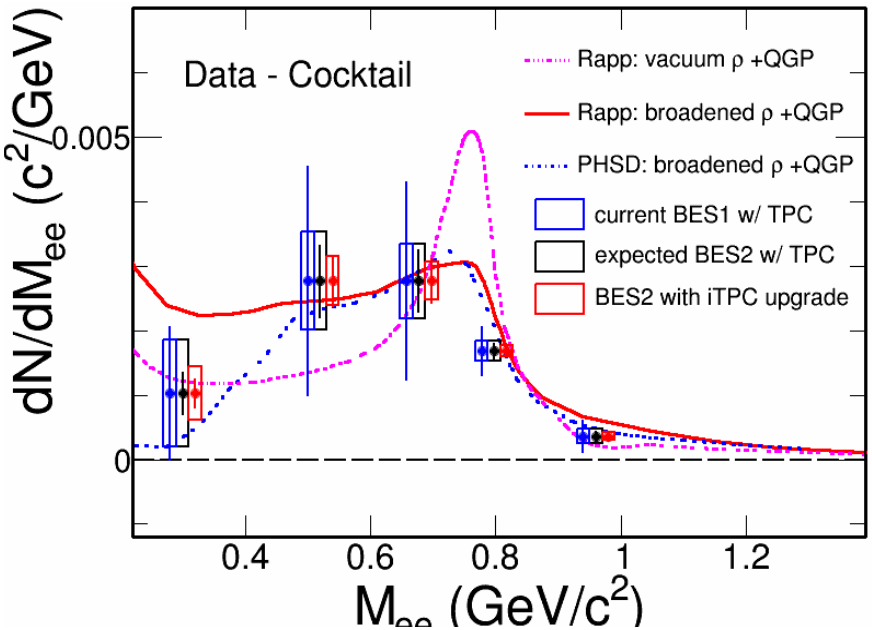
different predictions for di-electron continuum (Rapp vs PHSD)

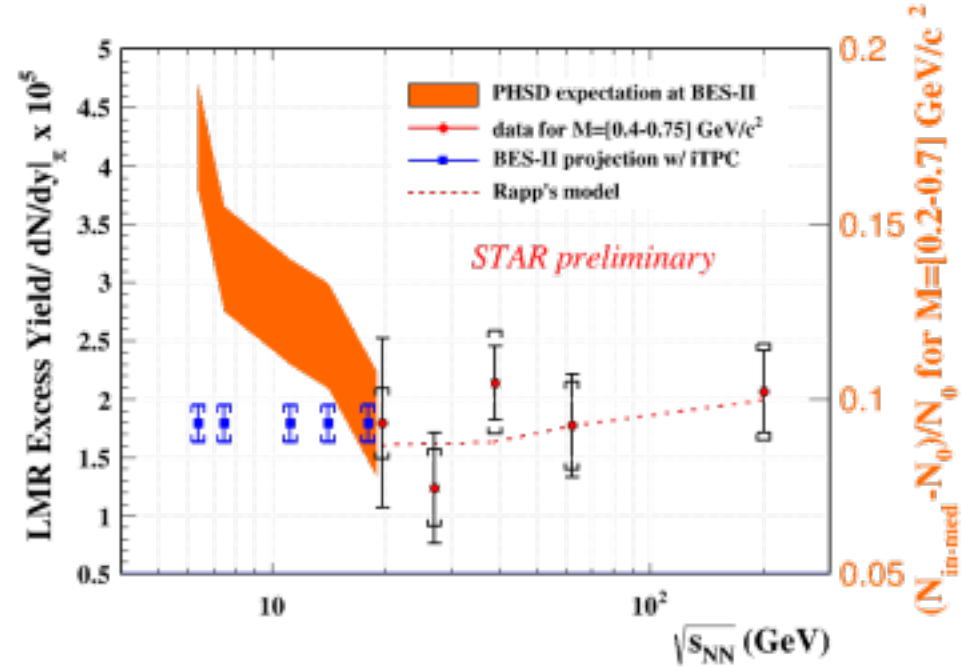
iTPC: Significant reduction in sys. and stat. uncertainties

Enables to distinguish between models for $\sqrt{s}$ =7.7-19.6 GeV

J. Butterworth HP2016, T. Galatyuk, QM2017

Change the total baryon number





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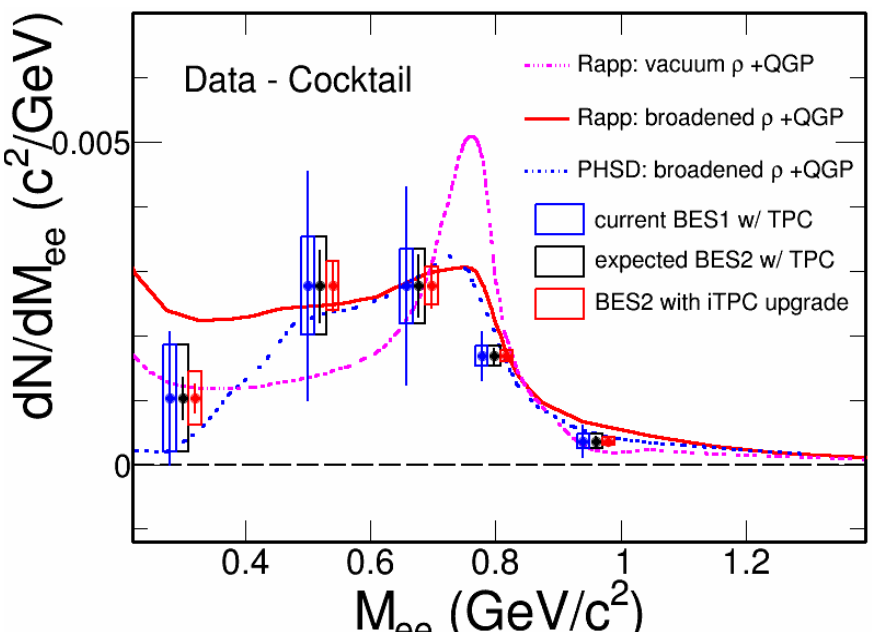
Low Mass Region:

iTPC: Significant reduction in sys. and stat. uncertainties

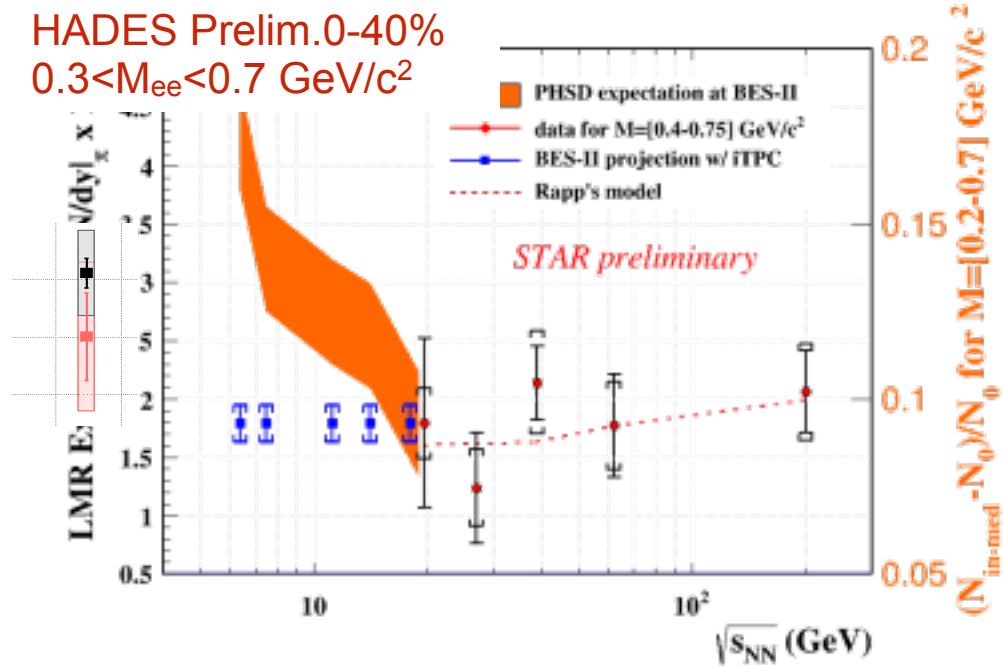
Disentangle total baryon density effects

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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Disentangle total baryon density effects

J. Butterworth HP2016, T. Galatyuk, QM2017

Summary

Data exists over wide range of $\sqrt{s}$ for heavy & light ions, p(d)-A, and pp

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

New data from FAIR, NICA, RHIC and SPS just around the corner

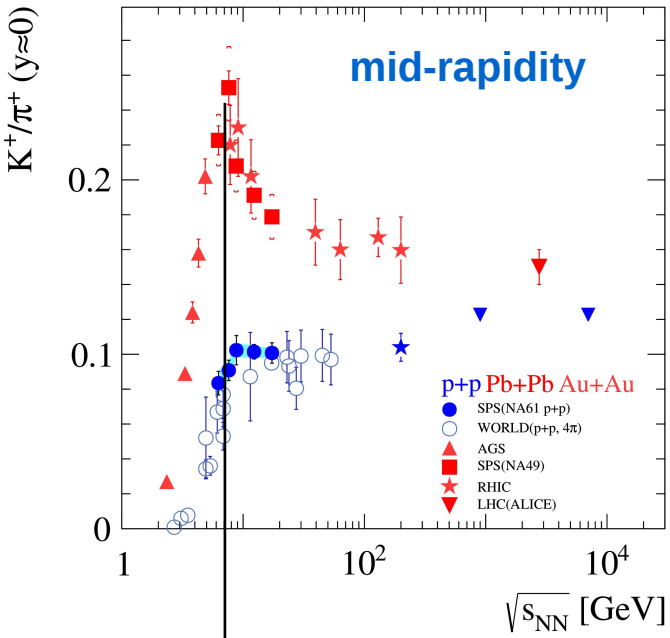
Significantly extended detection capabilities compared to existing data

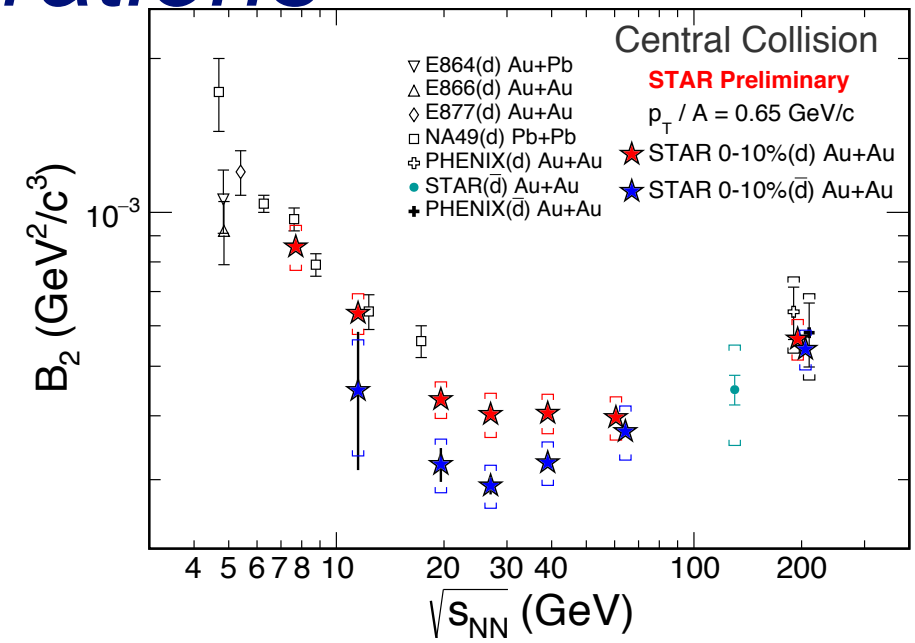
Strong theoretical interest focussed in BEST and HICforFAIR, increased number of focussed workshops

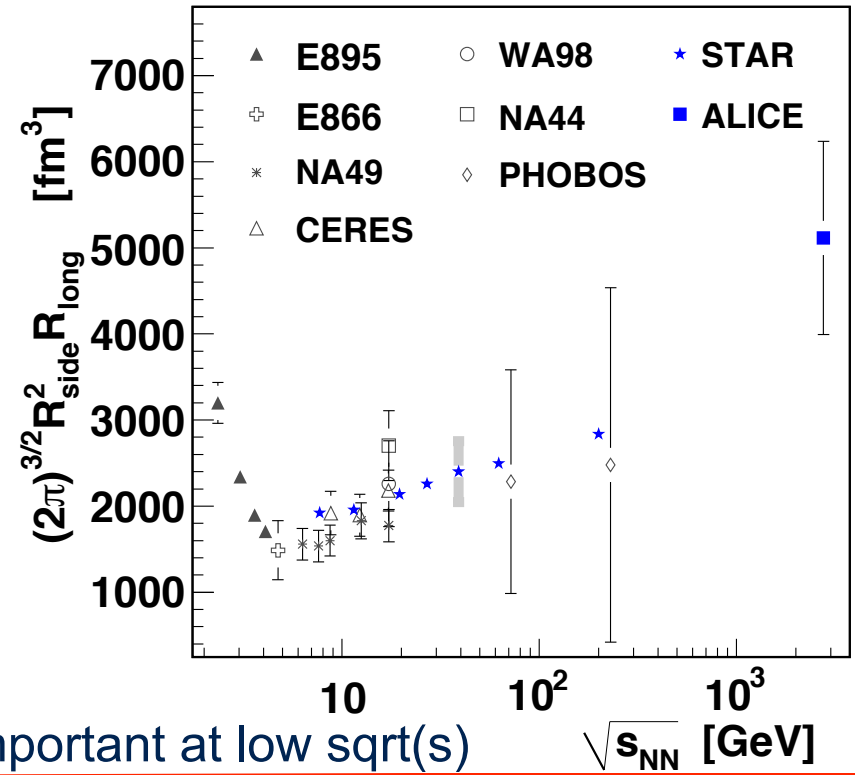
In conjunction: Turn trends and features into definitive conclusions

BACK UP

Baryon density considerations

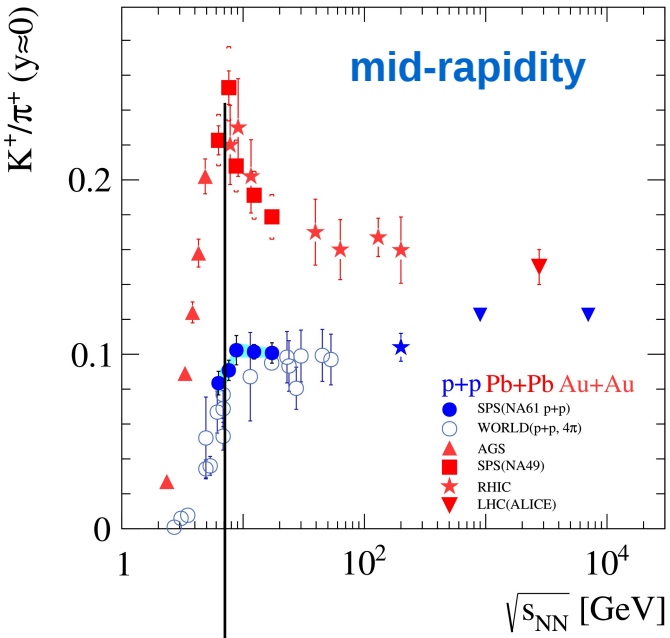


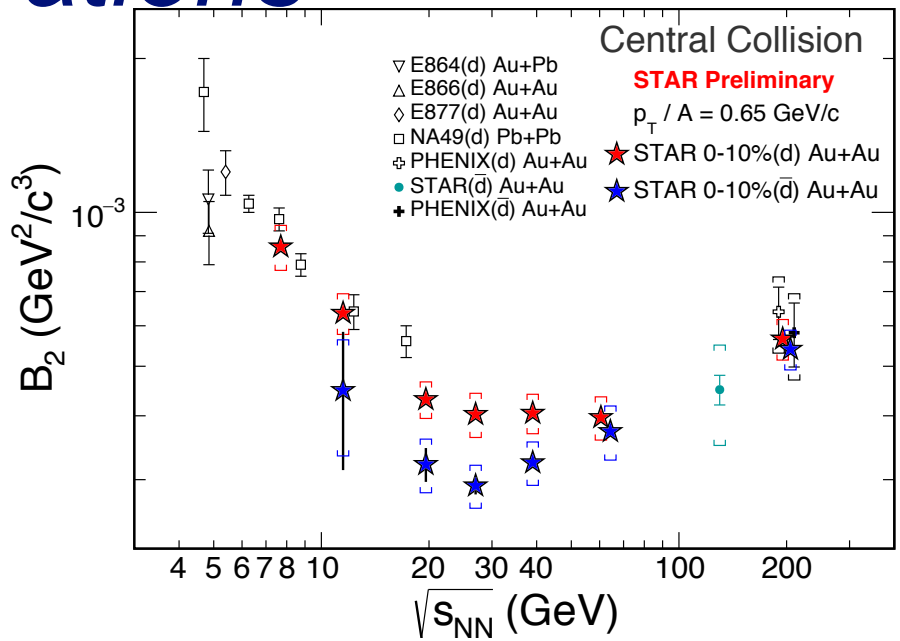


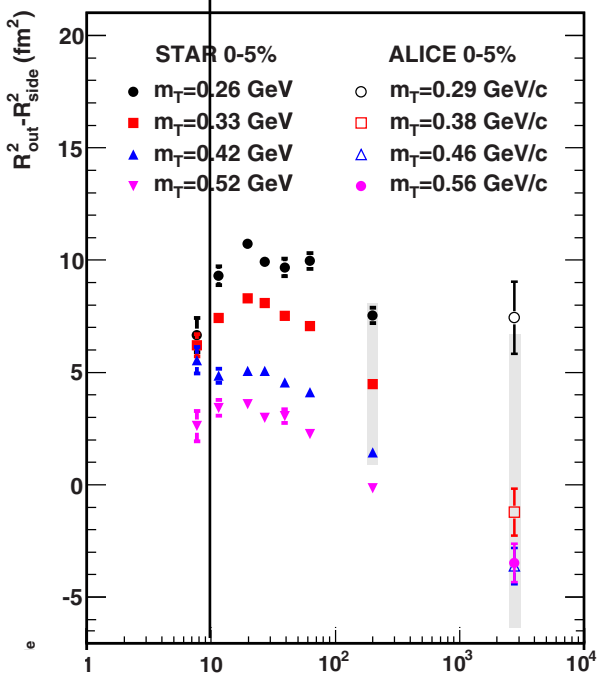


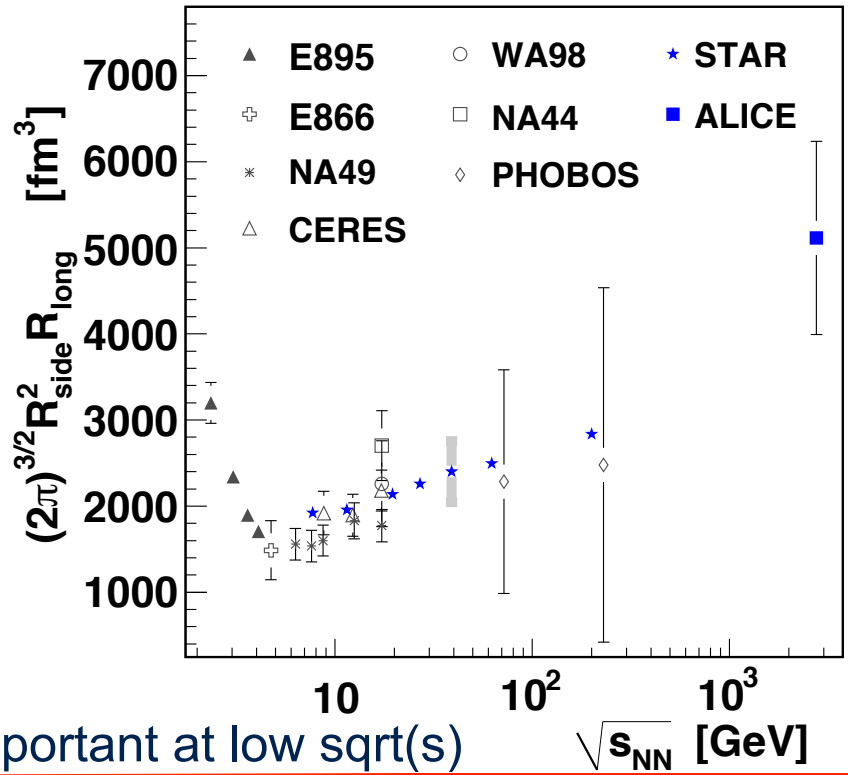
piN cross-section important at low sqrt(s)

Baryon density considerations



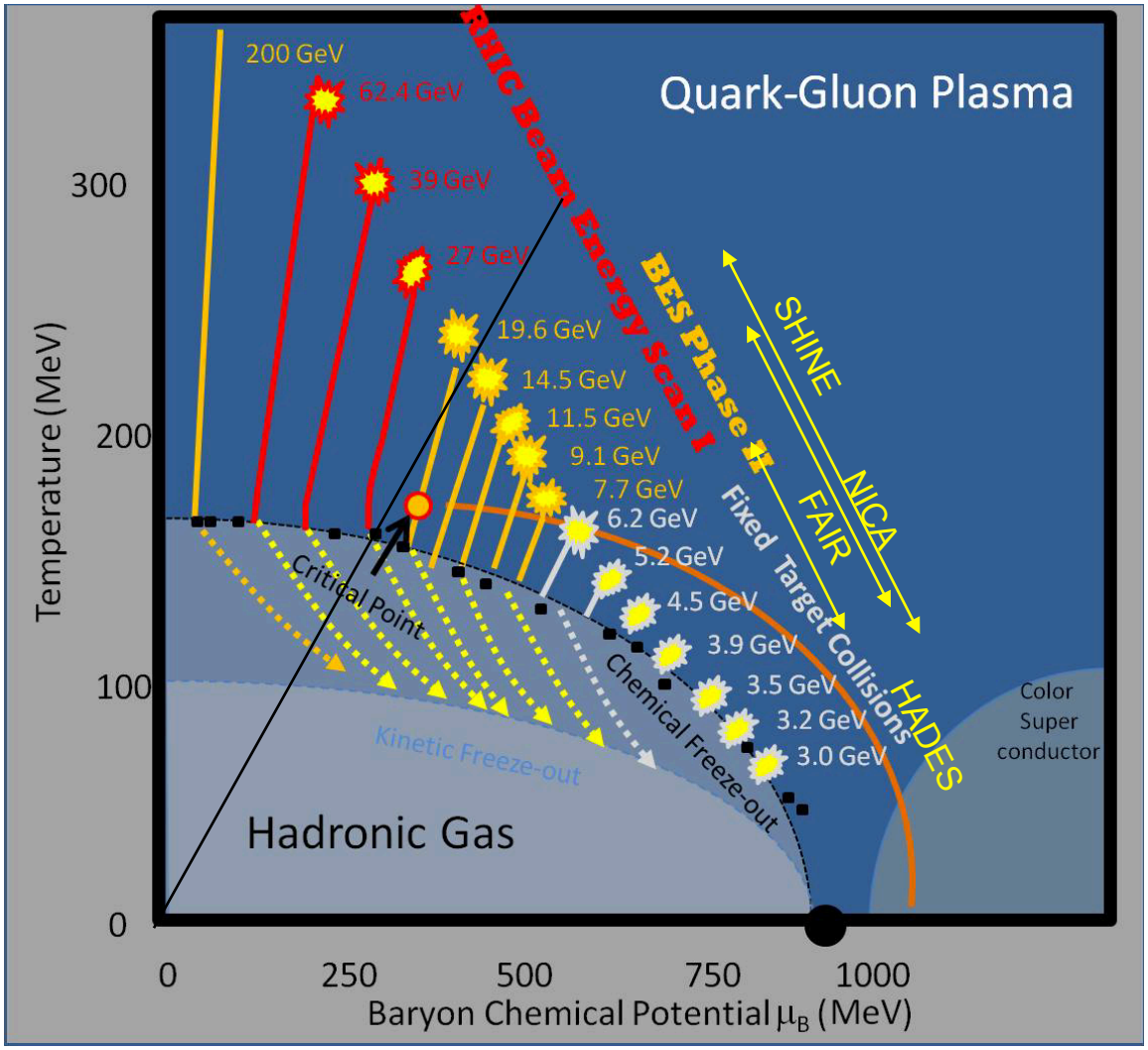






piN cross-section important at low sqrt(s)

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

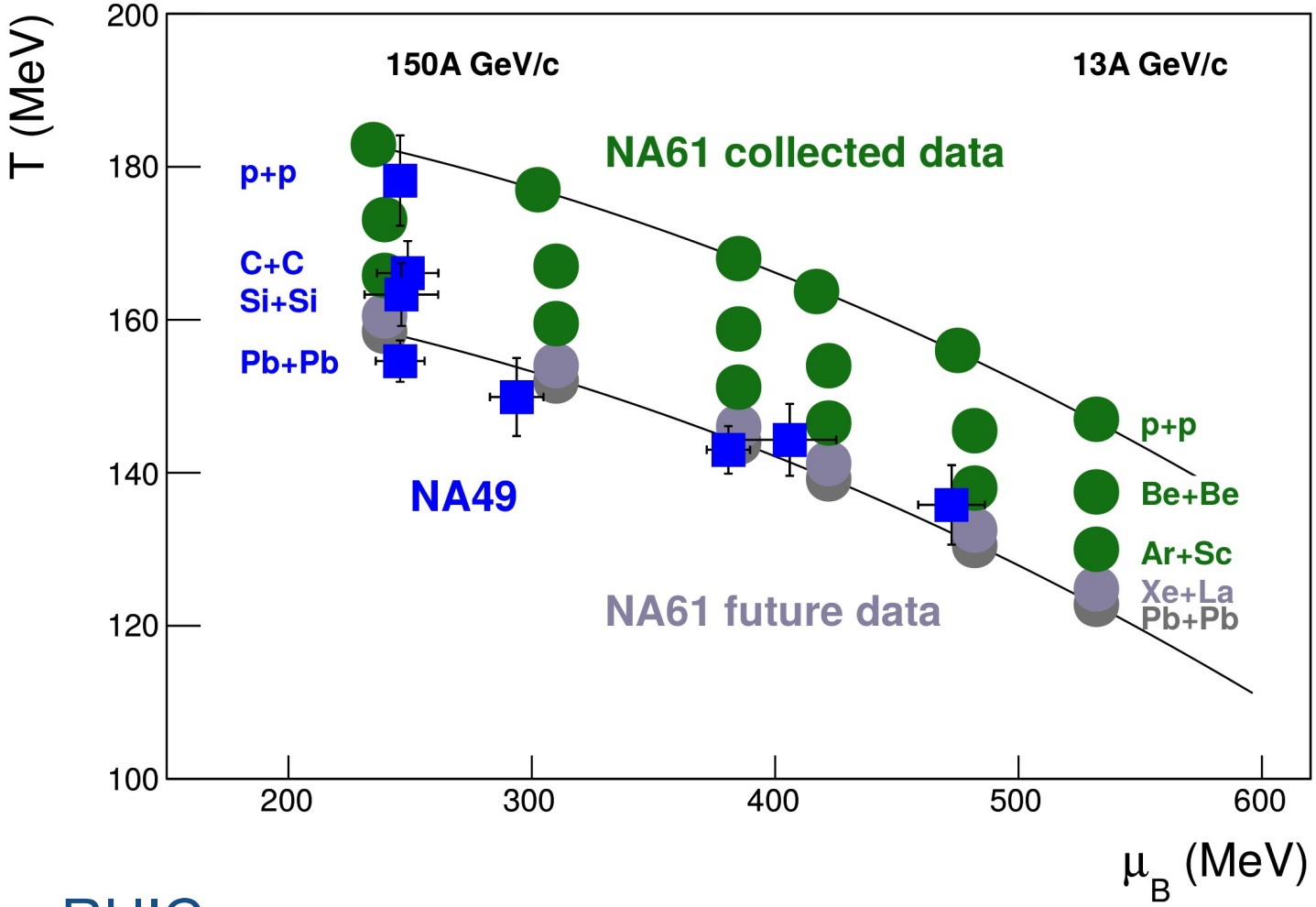
SIS: 2.6, 2.6

FAIR: 2.7-8.2

NICA: 2-11

J-PARC: 2-6.2

Light and intermediate mass collisions



NA61/SHINE:
Comprehensive scan including variety of nuclei

RHIC:
d+Au: 200, 62, 38, 20
Cu+Au: 200, 62
p+Au, p+Al He^3+Au: 200

Can we see evidence of stepping across boundary while keeping μ_B fixed?

"Dale" in longitudinal expansion

Probe expansion dynamics:

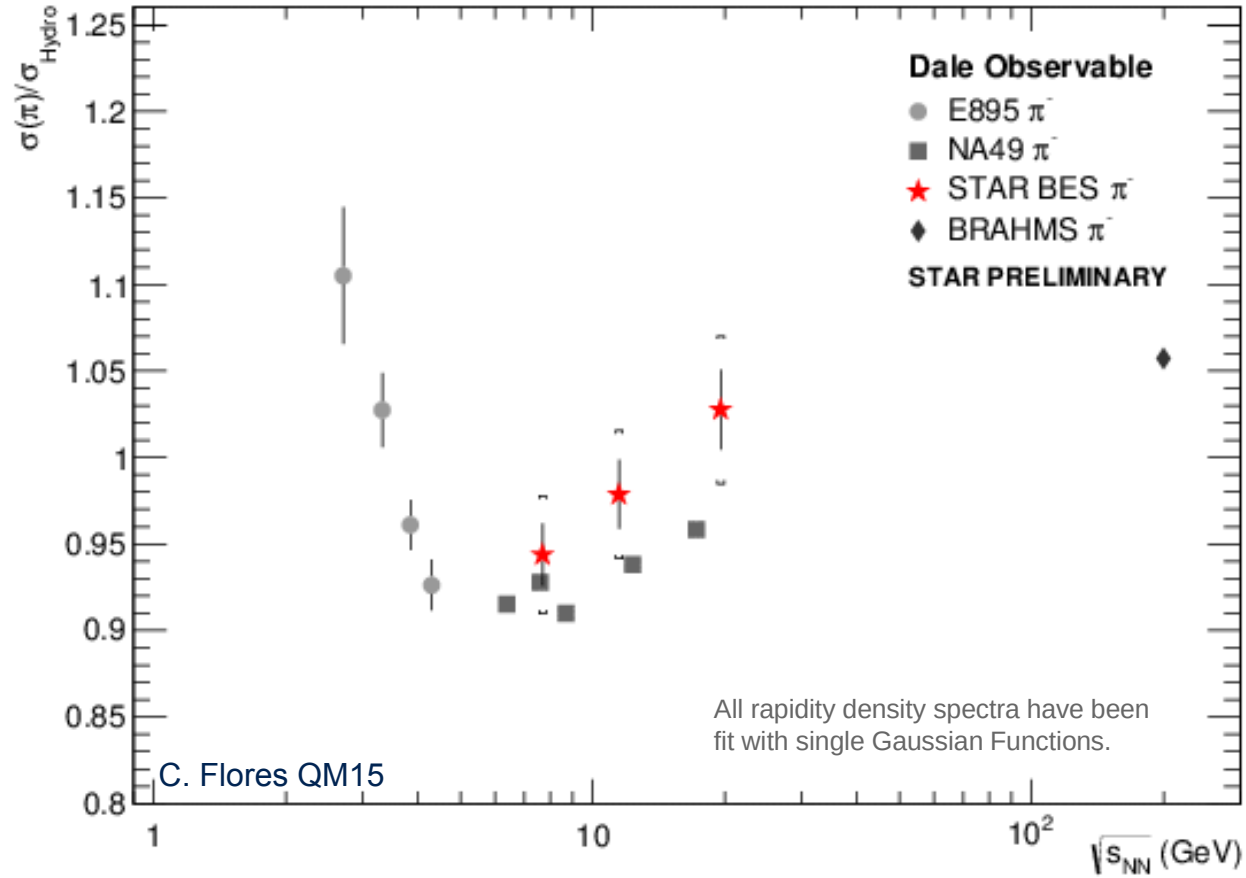
Width of rapidity distribution compared to Landau hydro. expansion predictions

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

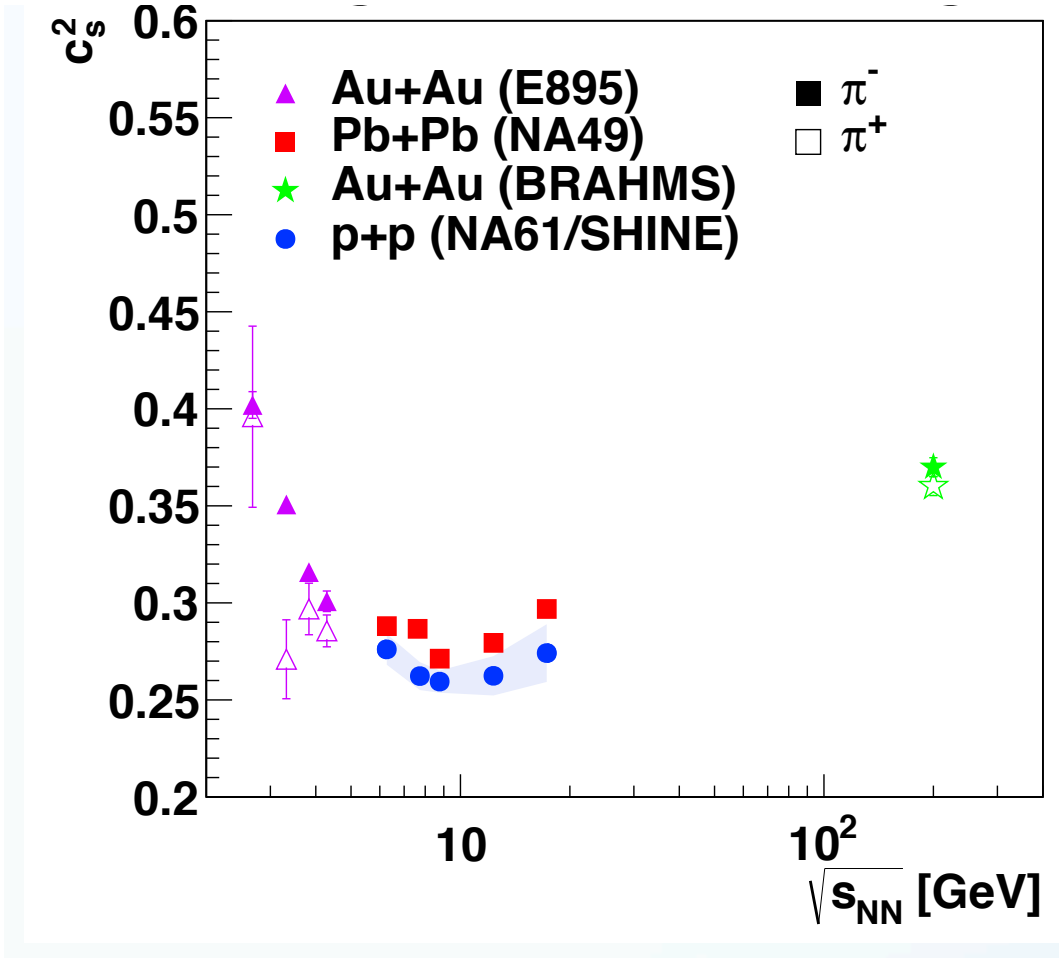
BES results for π^+ and π^-

Longitudinal expansion

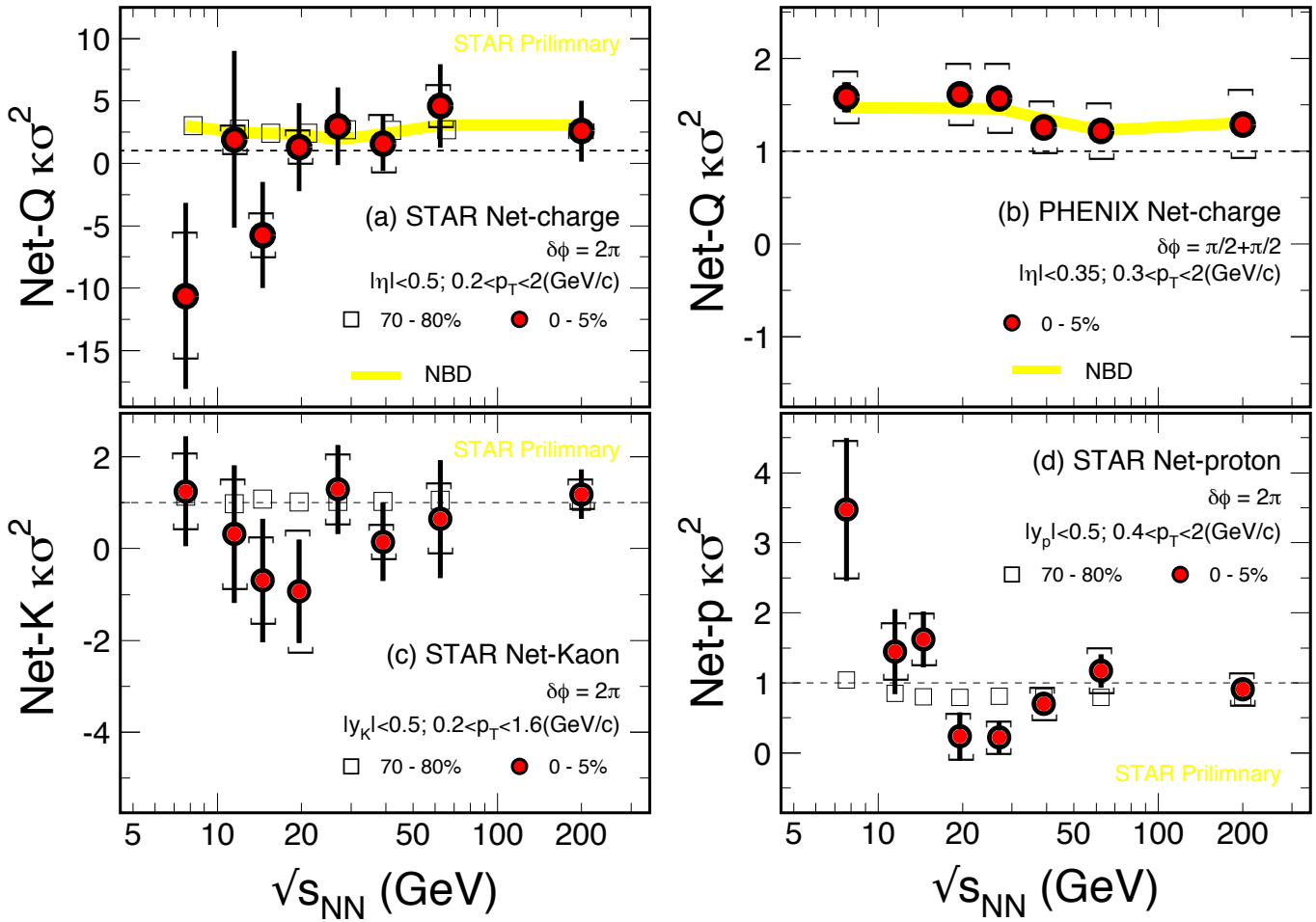
Fermi-Landau initial conditions
Ideal Hydrodynamic expansion

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

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



Fluctuations at RHIC



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

In STAR:

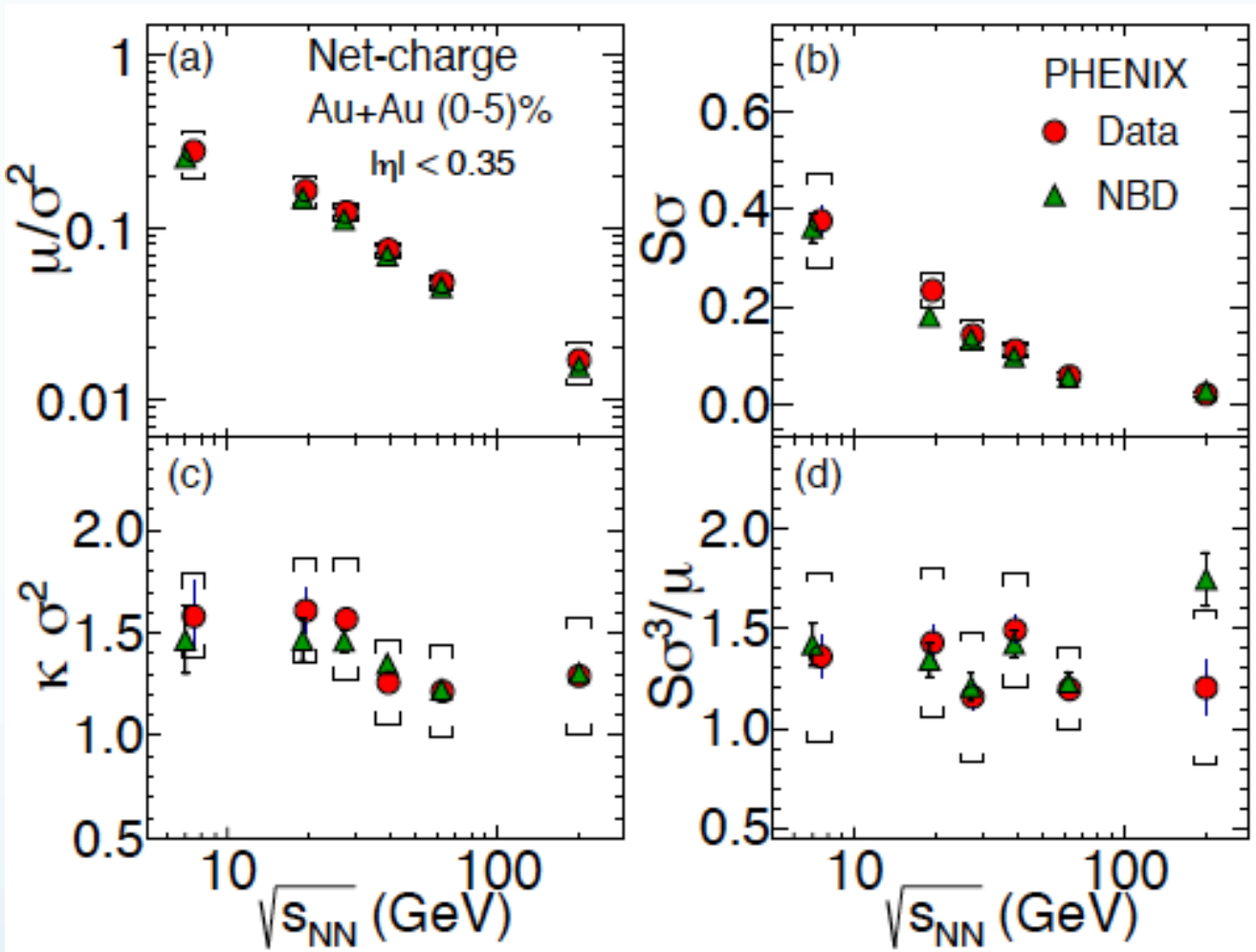
$\sigma(Q) > \sigma(K) > \sigma(p)$

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

Net charge fluctuations at RHIC

PHENIX



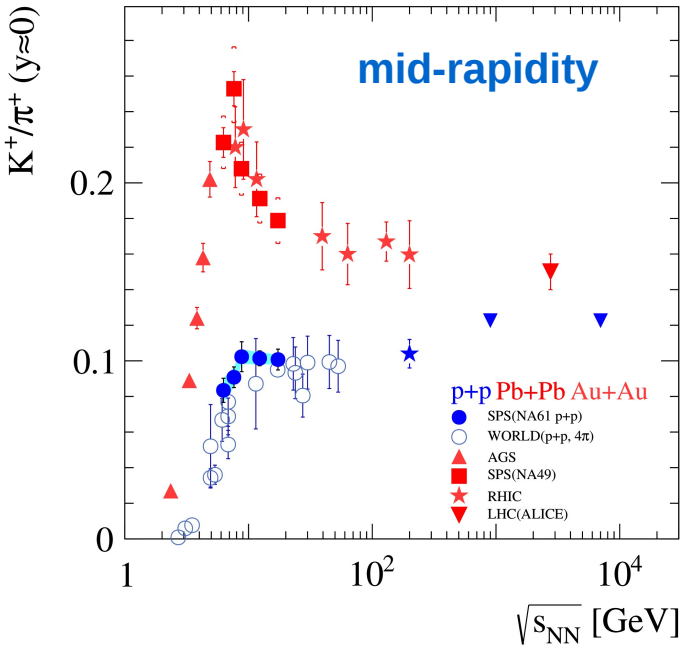
PRC93 (2016) 011901(R)

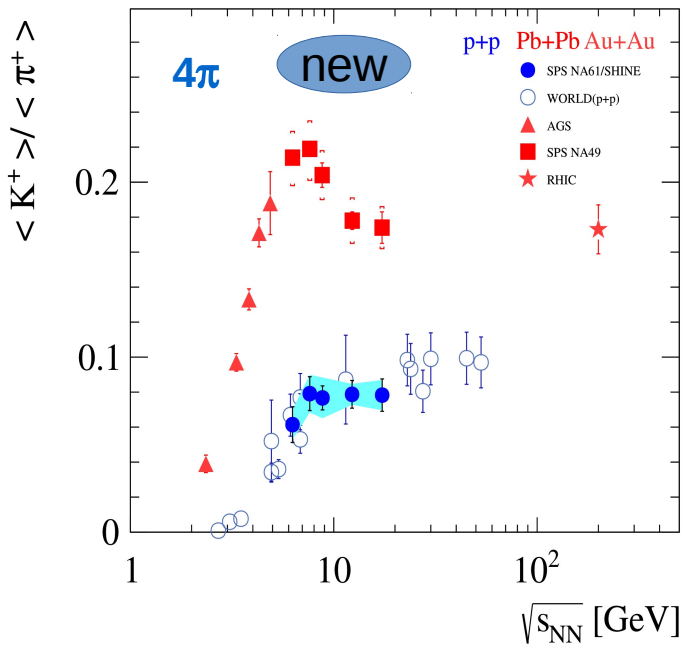
Data in agreement with NBD calculations

Can't make direct comparison because of differing acceptances

Horns and plateaus

K/π ratio:

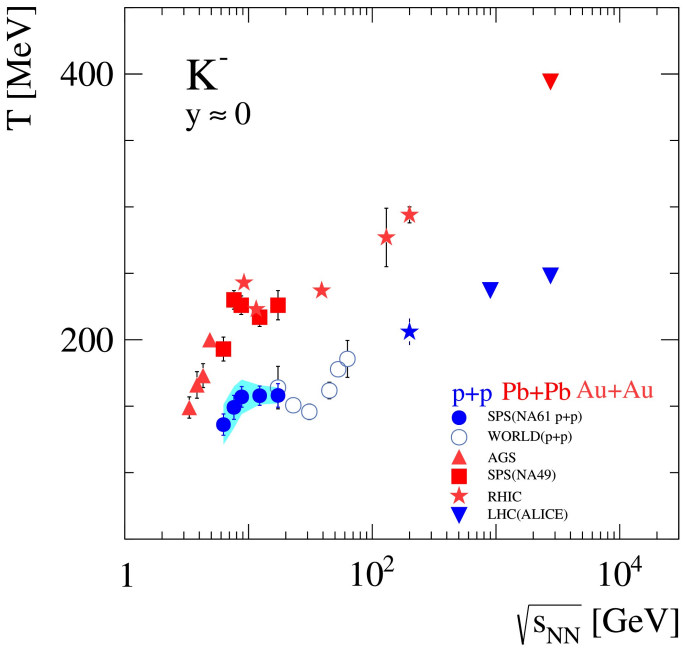


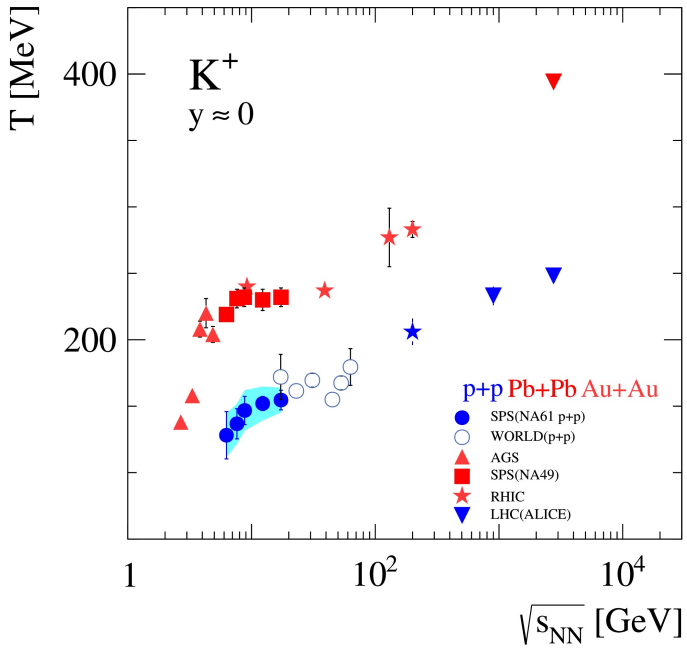


Mid-rapidity same results at total yield

Baryon density peaks at √s ~ 7 GeV as models suggest

RHIC data suggests horn less pronounced





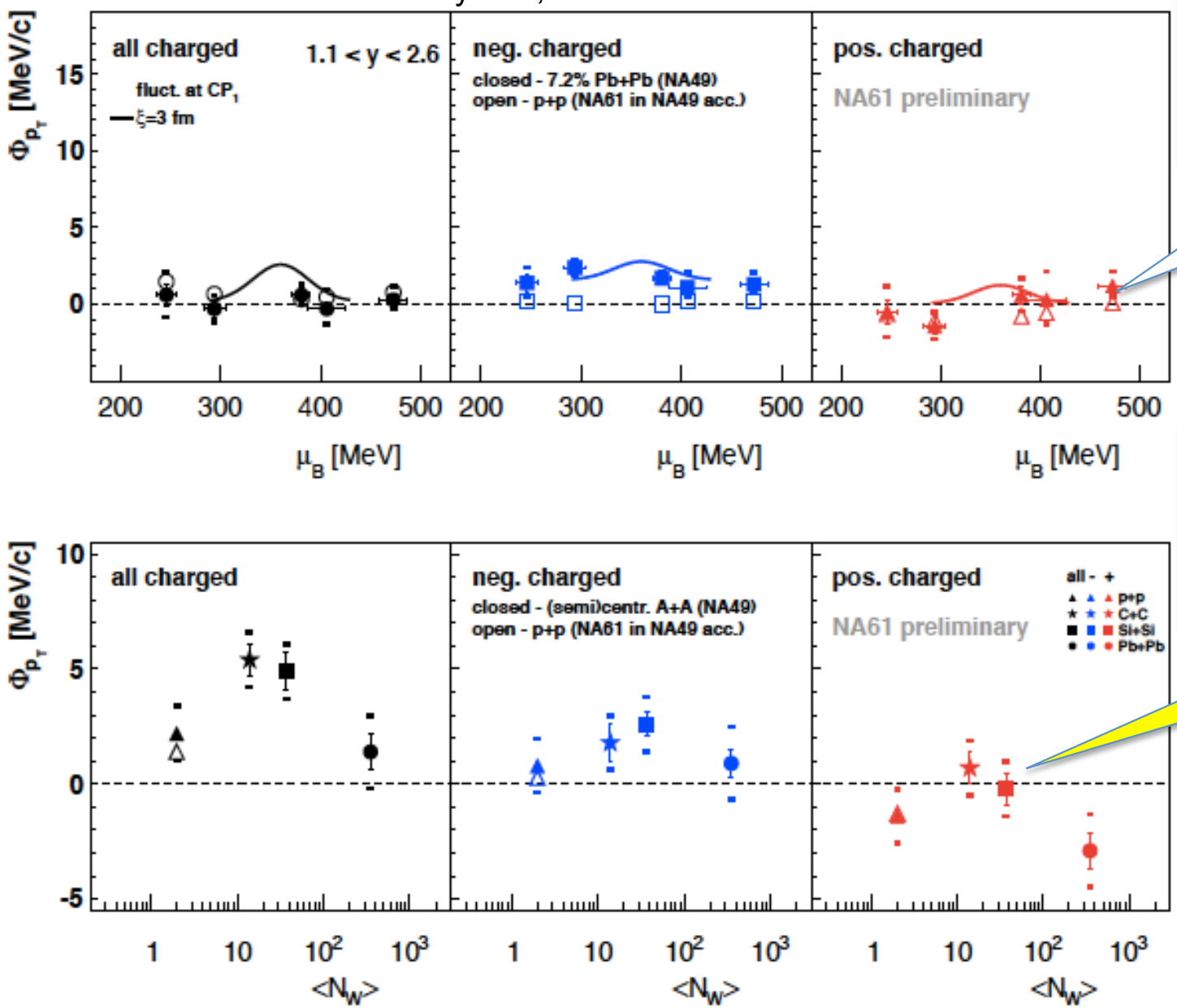
T_{kin}:

pp values lower but trend similar to A-A

A. Aduszkiewicz QM2017, K. Grebieszkow CPOD16

Fluctuation at NA61

M. Gazdzicki and P. Seyboth, arXiv: ***1506.08141***

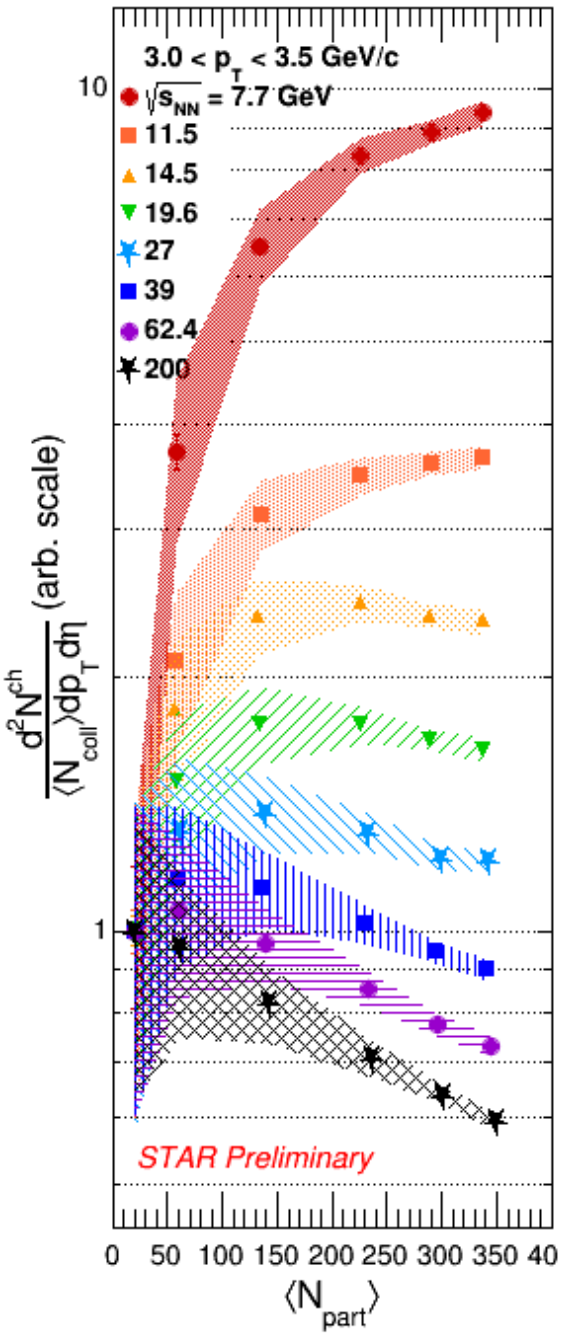


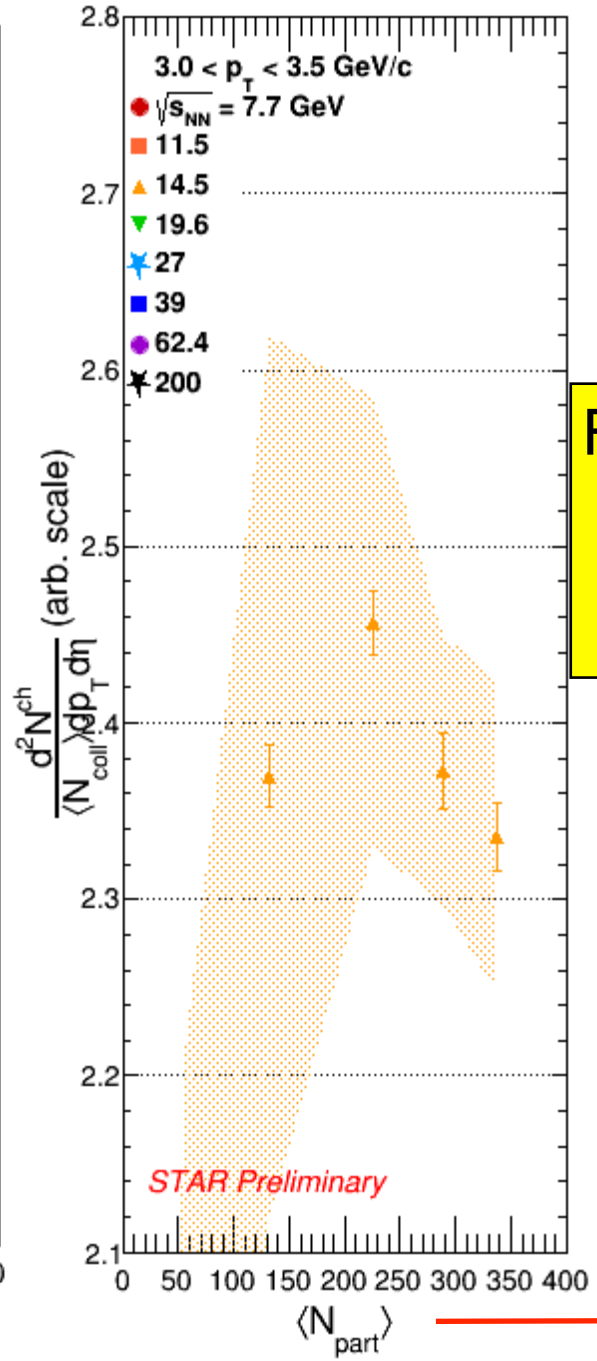
- Central Pb+Pb collisions (7.2%) vs. collision energy
- Flat strcture

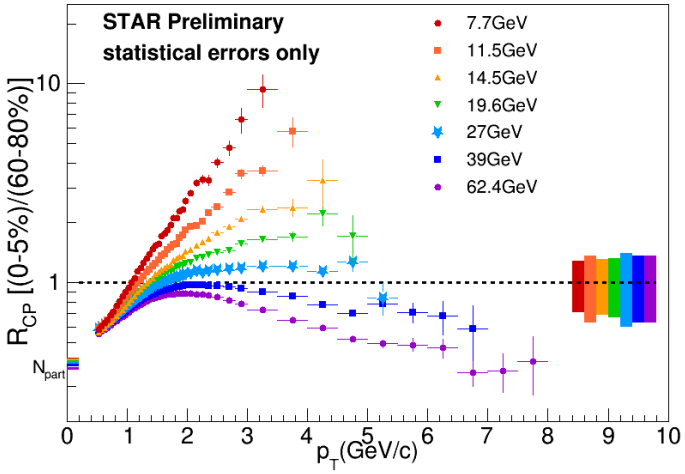
- Collision centrality dependence at 158 GeV/c.
- Peak around C+C, Si+Si collisions

Real critical behavior?

QGP Creation: Jet Quenching







Cronin may be hiding E_{loss}

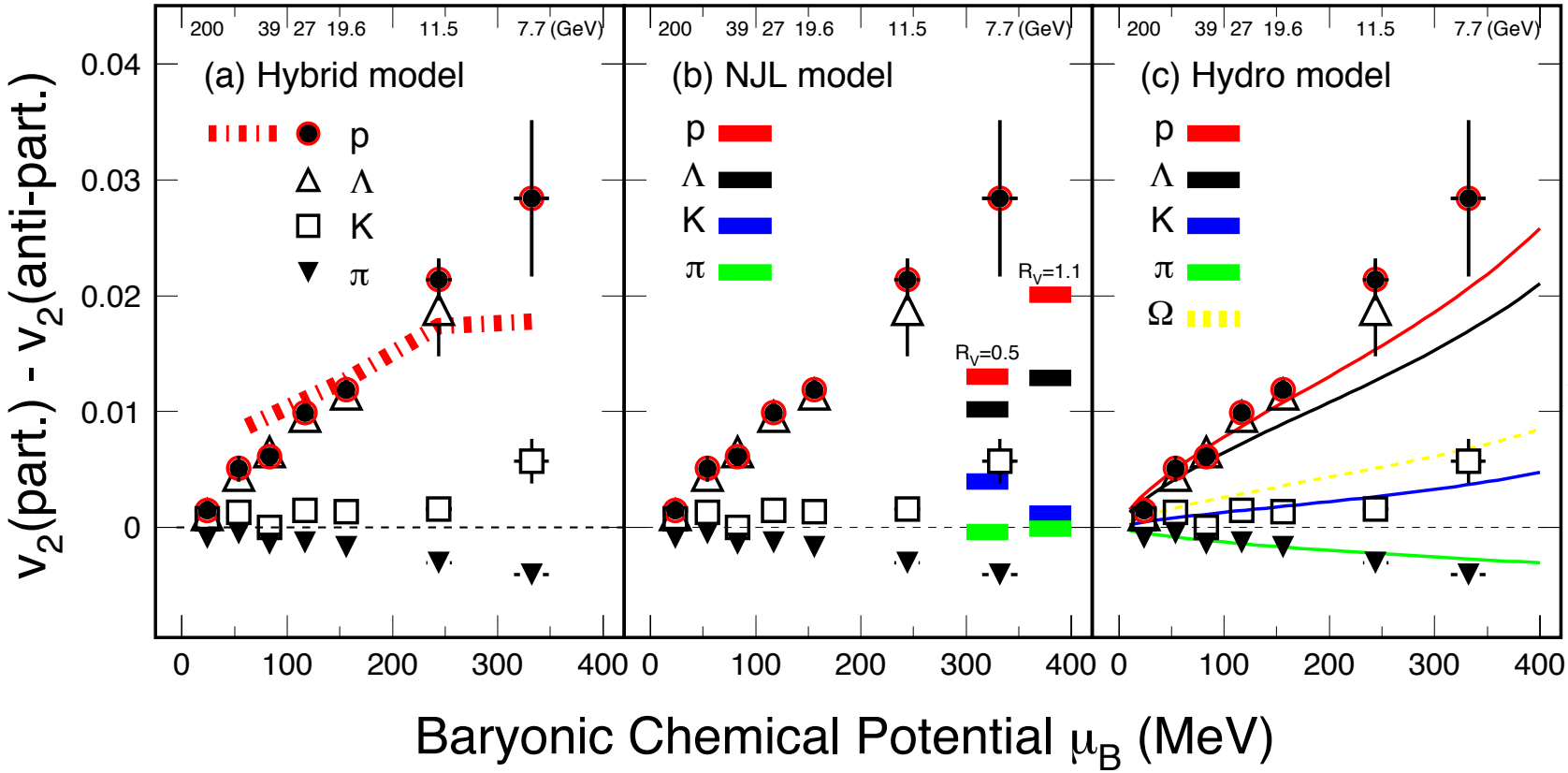
For $\sqrt{s_{NN}}$ ≥ 14.5 GeV central events show suppression compared to next peripheral bin

7.7 and 11.5 GeV results increase monotonically

200 GeV results decrease monotonically

Where does d+Au data sit?

Splitting of the v_2

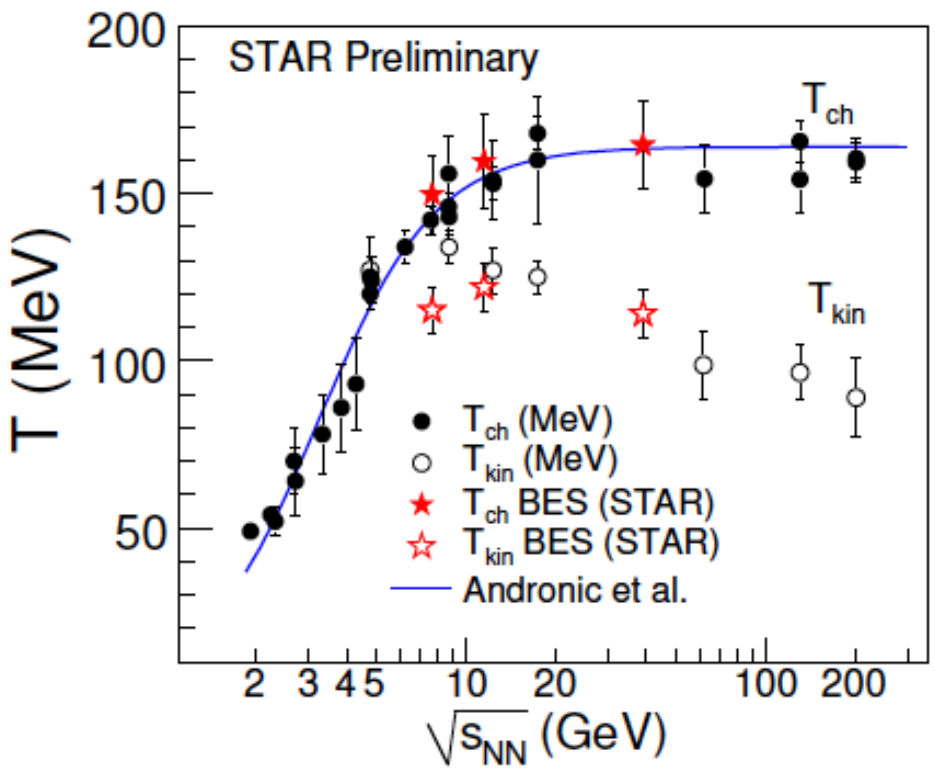


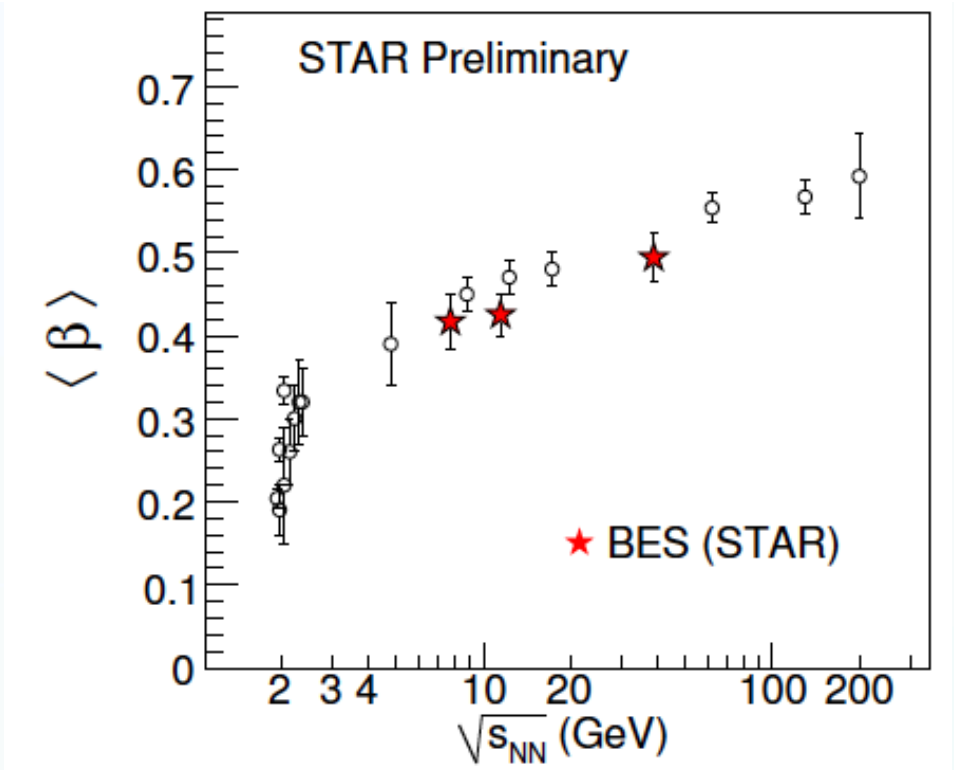
At large μ_B, low collision energies, the number of quark scaling in v_2 is broken

(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)]

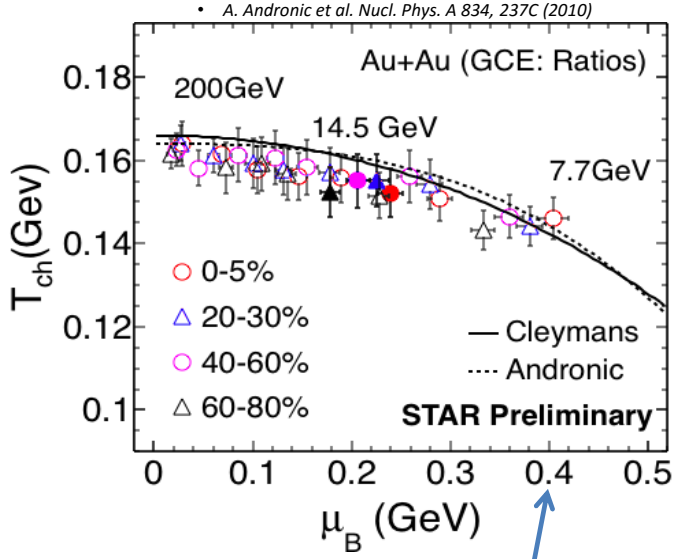
(c) Hydro solution: **Chemical potential μ_B** and **viscosity η/s** driven!
[Hatta et al. PR **D91**, 085024(15); **D92**, 114010(15) //NP **A947**, 155(16)]





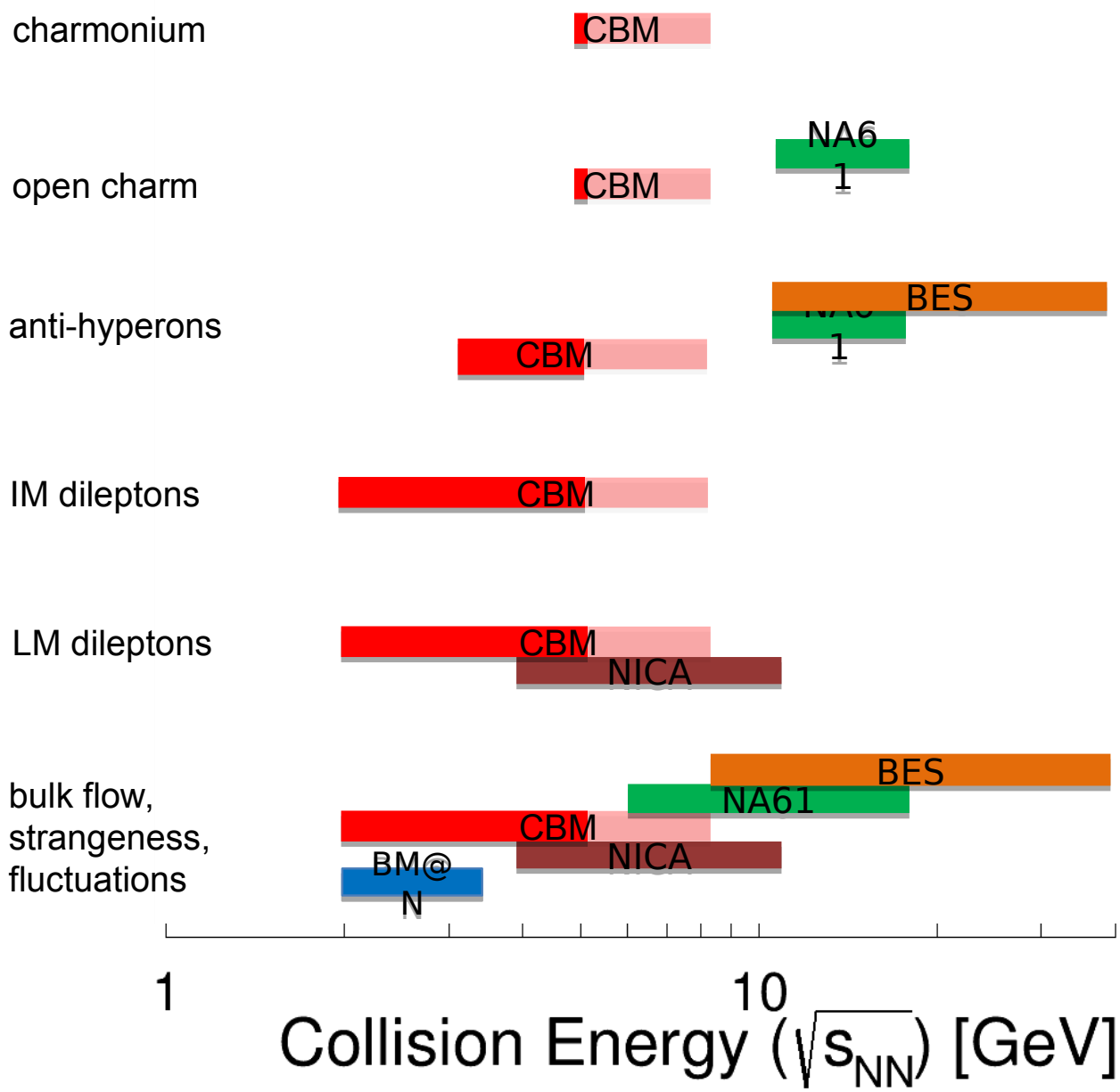
D. Mishra, QM 2015, Kobe, Japan

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

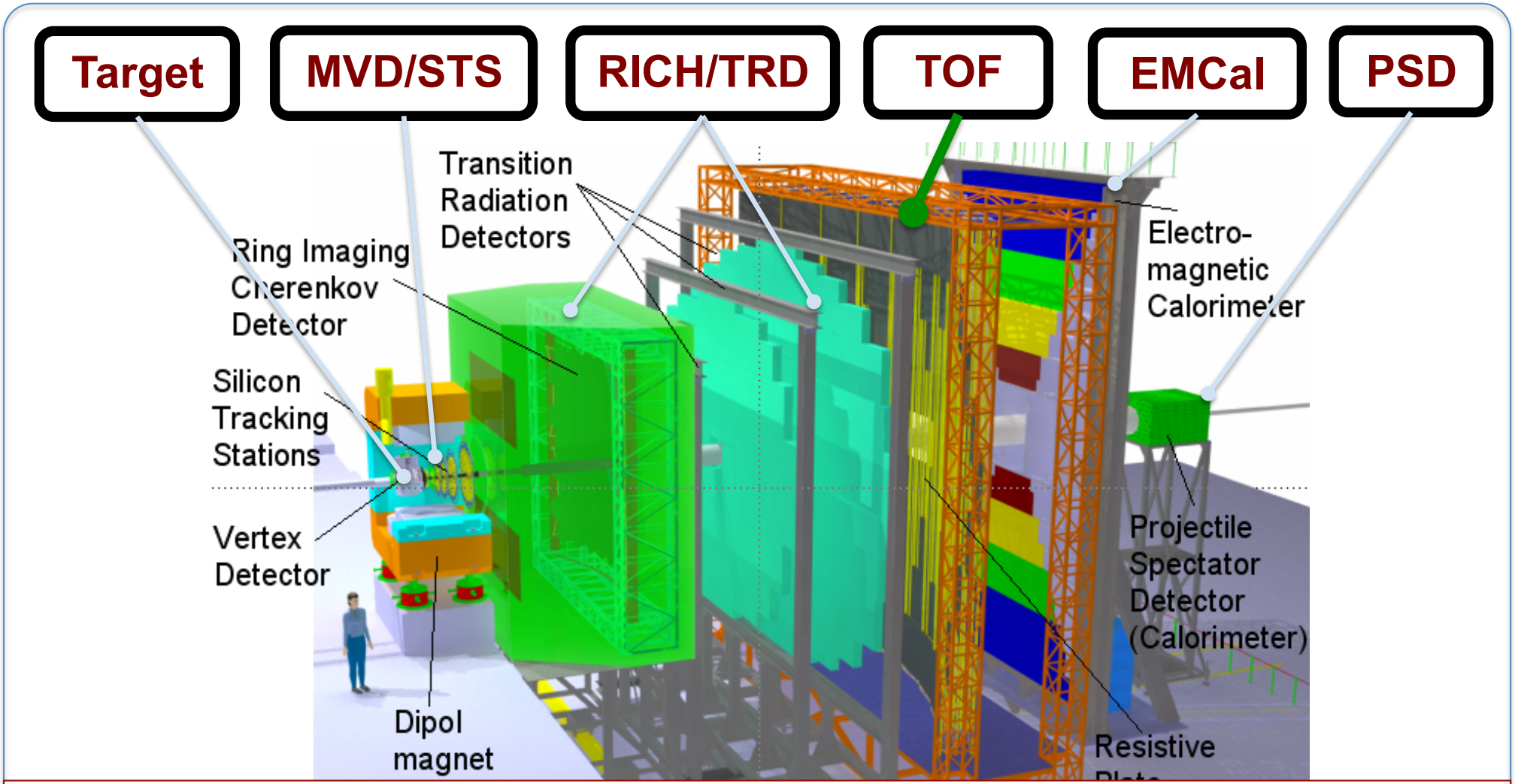


Who can measure what

restrictions: by rate and/or by instrumentation



CBM at FAIR

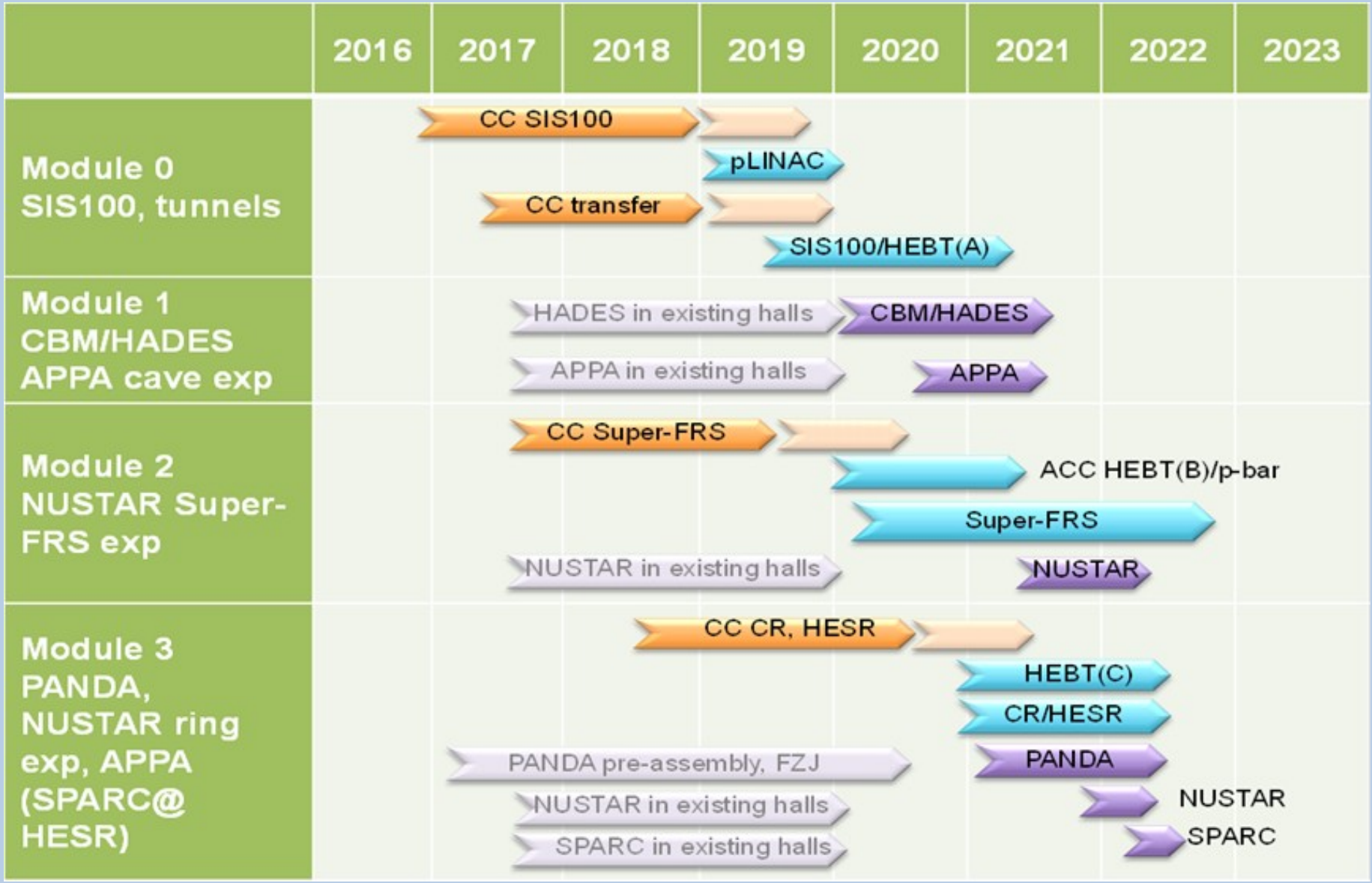


FAIR: One of the highest intensity accelerator complex in the 21st century

Precision measurements at high baryon density region for:

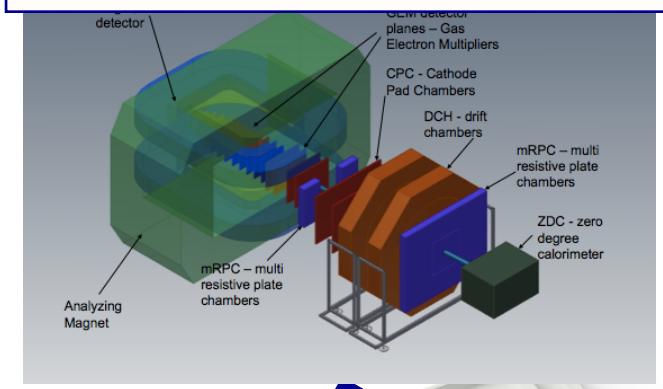
(i) Dileptons (***e, μ***); (ii) High order correlations; (iii) Flavor productions (***s, c***)

FAIR-MSV Schedule



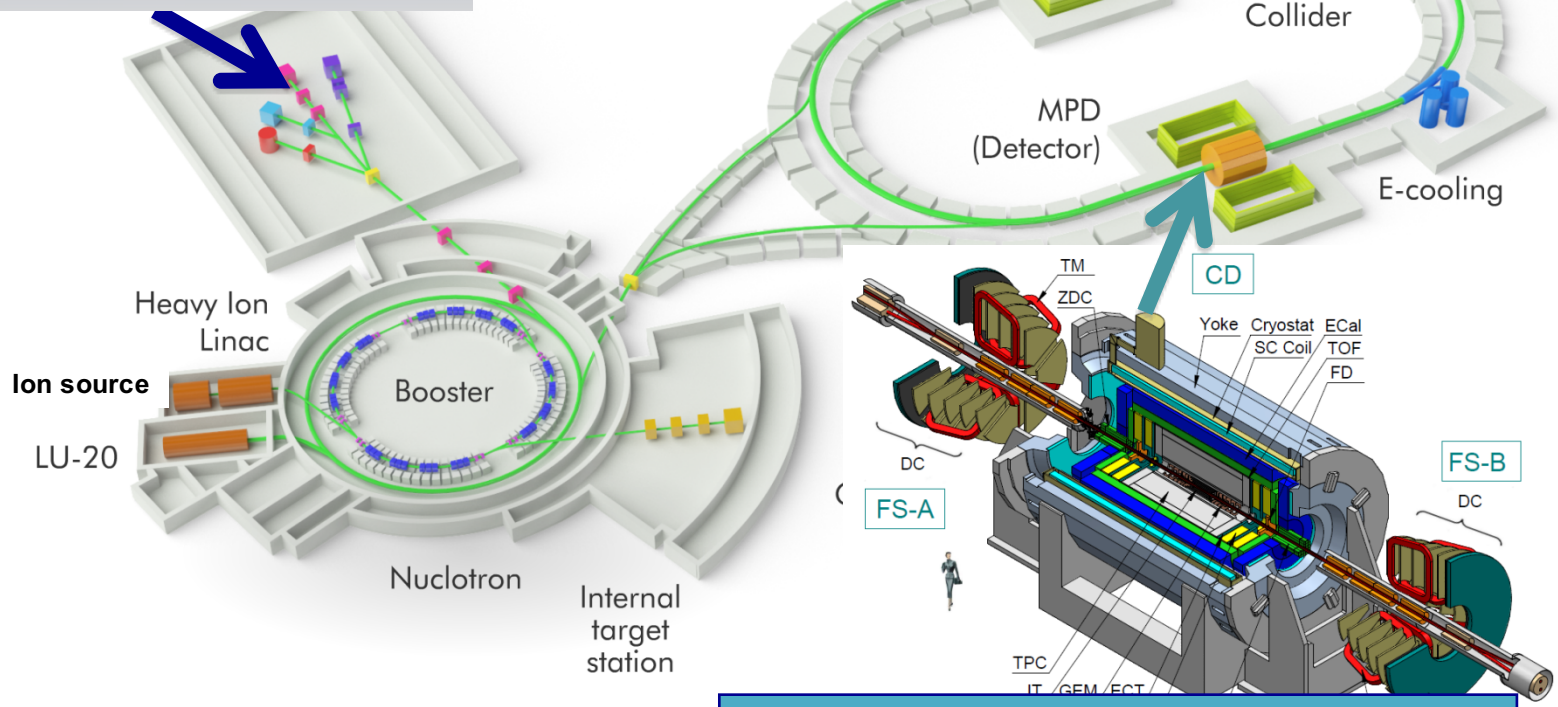
NICA

Baryonic Matter at Nuclotron (BM@N)



SPD (Spin Physics Detector)

Ring circumference
503.04 m.



MultiPurpose Detector (MPD)

5

NICA

Heavy ion colliding beams up to $^{197}Au^{79+}$ + $^{197}Au^{79+}$

at s_{NN} = 4 ÷ 11 GeV , $L_{average}$= 1x10^{27} cm^{-2}s^{-1}

Light-Heavy ion colliding beams of the same s_{NN} and the same or higher $L_{average}$

Polarized beams of protons and deuterons in collider mode:

pp ? s_{pp} = 12 ÷ 26 GeV L_{max} ≈ 1x10^{32} cm^{-2}s^{-1}

dd s_{NN} = 4 ÷ 13.8 GeV

Extracted beams of light ions and polarized protons and deuterons for fixed target experiments:

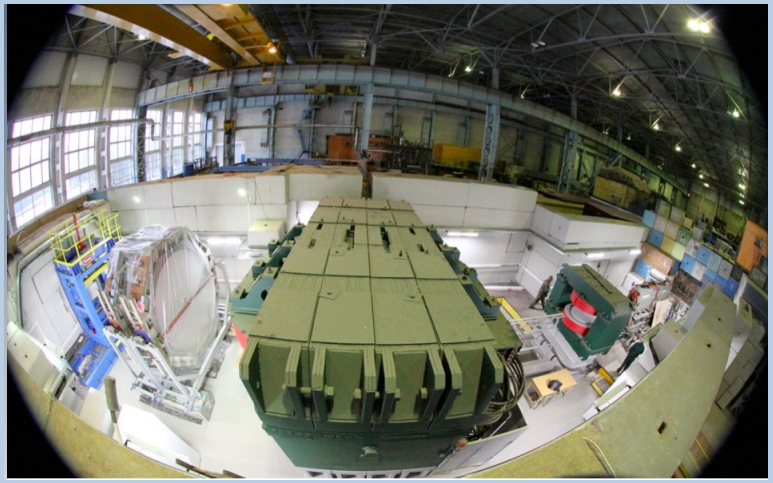
Li Au = 1 4.5 GeV /u ion kinetic energy

p, p = 5 ÷ 12.6 GeV kinetic energy

d, d = 2 ÷ 5.9 GeV/u ion kinetic energy

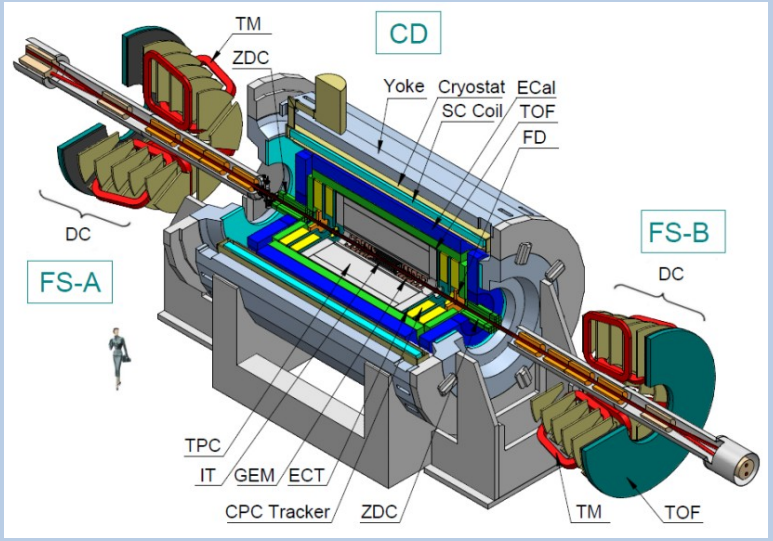
Applied research on ion beams at kinetic energy above 3 MeV/u

QCD Matter Physics at NICA



BM@N:

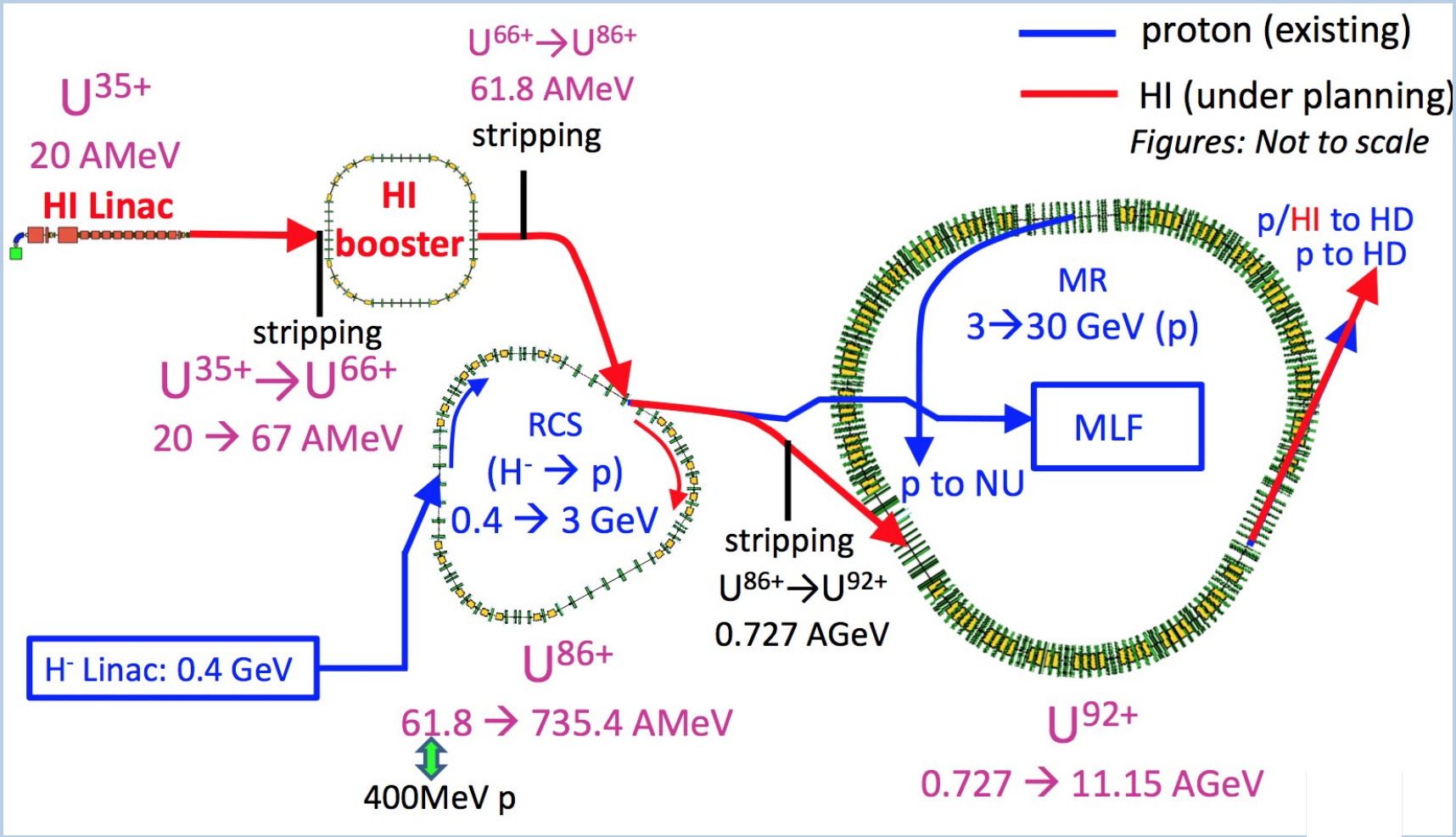
- Fixed-target, E_{beam} = 1A – 4.5A GeV from Nuclotron
- Interaction rates up to 50 kHz
- Measurement of hadrons
- Time line: light ion beams 2017, heavy ion beams 2019



MPD:

- Collider experiment, sqrt(s_{NN}) = 4 – 11 GeV
- Interaction rate up to 10 MHz (depending on energy)
- Hadron and lepton measurements
- Time line (staged): 2019 - 2013

Plans at J-PARC



Additional ion acceleration scheme
Extracted beams for fixed-target experiments
Energy: 1A – 19A GeV
Extreme rates (4 x 10^{11} / cycle)

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

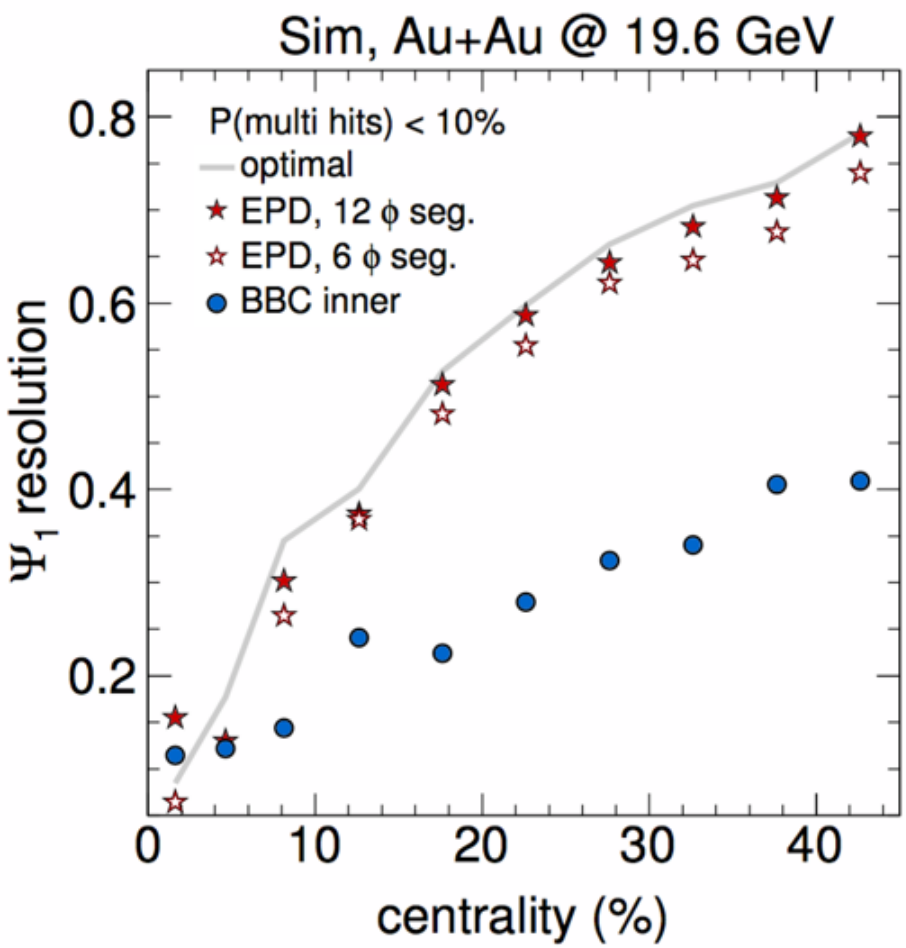
eCooling - Enables the significant statistics enhancement

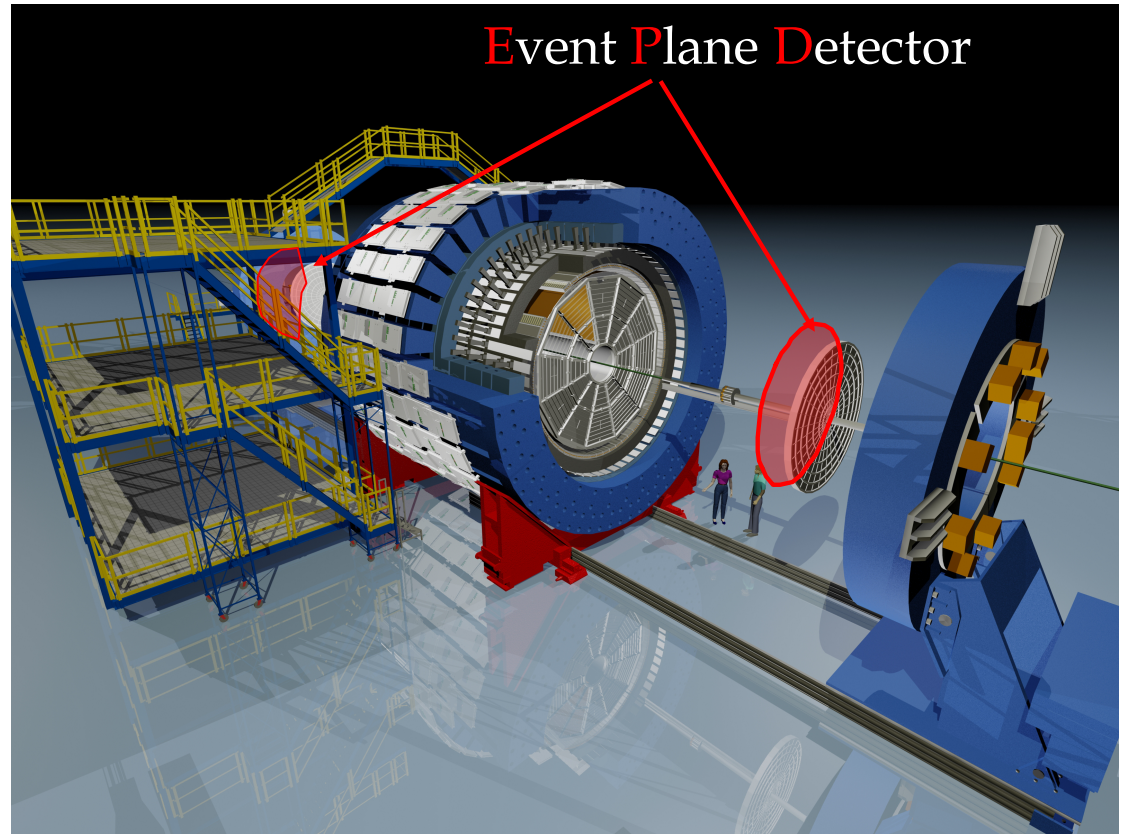
Event Plane Detector: EPD

$2.1 < |\eta| < 5.0$

Replacing BBCs

16 radial and 24 azimuthal sections





Greatly improved Event Plane Resolution

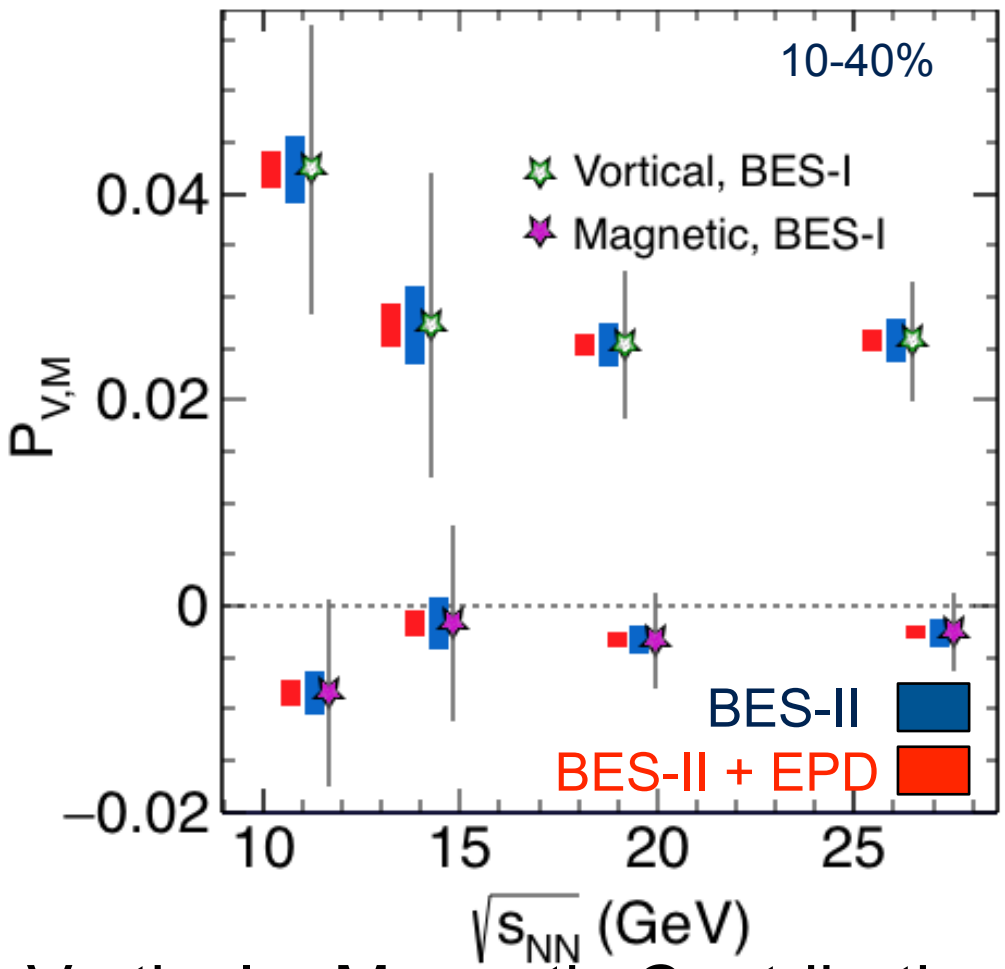
especially 1st-order EP

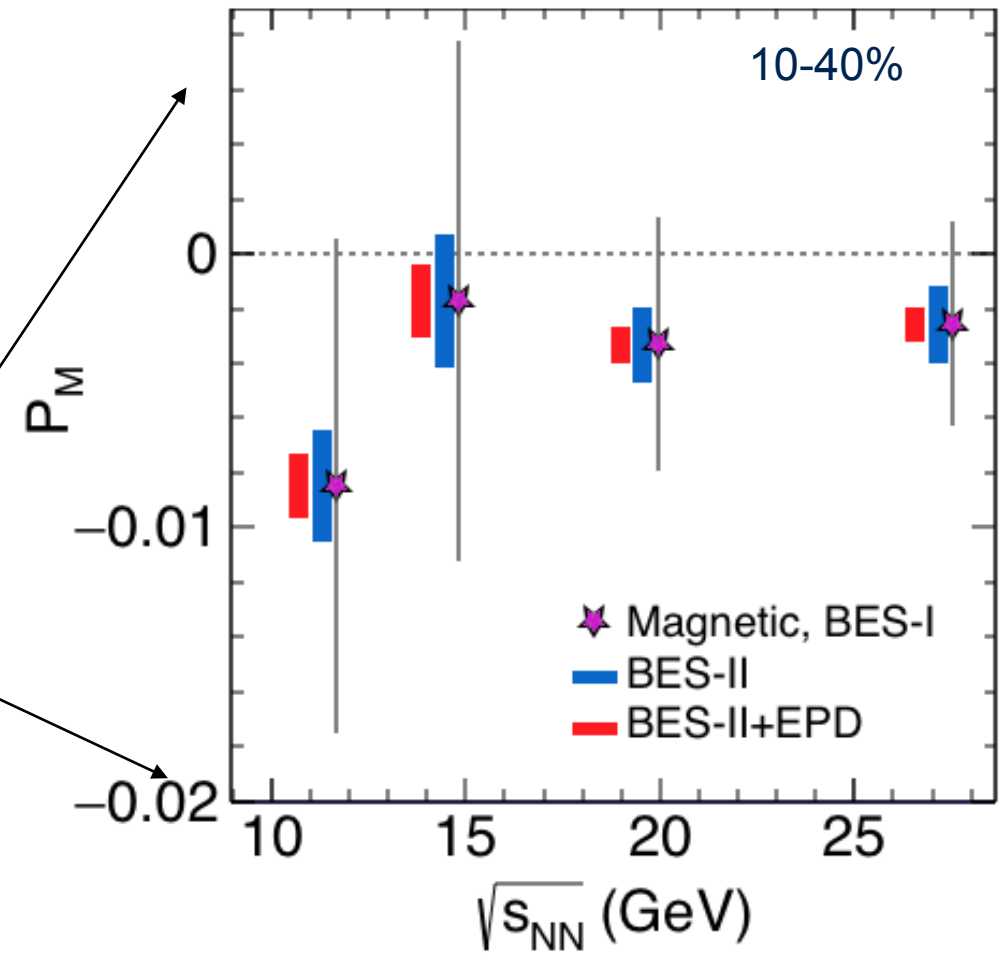
Determine Centrality away from mid-rapidity

Better trigger & background reduction

BES-II: Vorticity and Initial B-field

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





Vortical + Magnetic Contributions:

Current data barely stat. significant

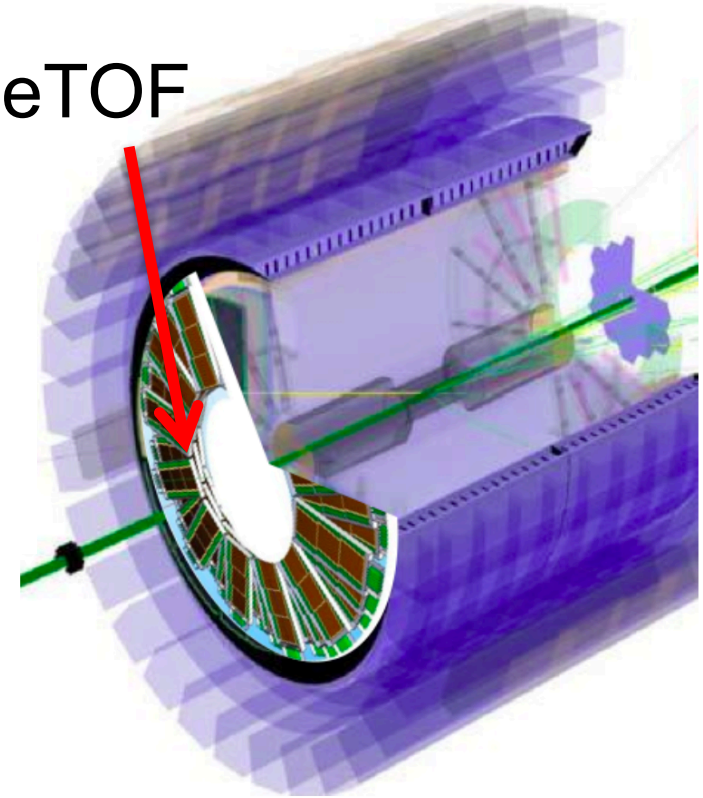
EPD:

Improved EP resolution

BES-II: 3σ effect

Unique measurement of B
Significant input to CME/CVE interpretations

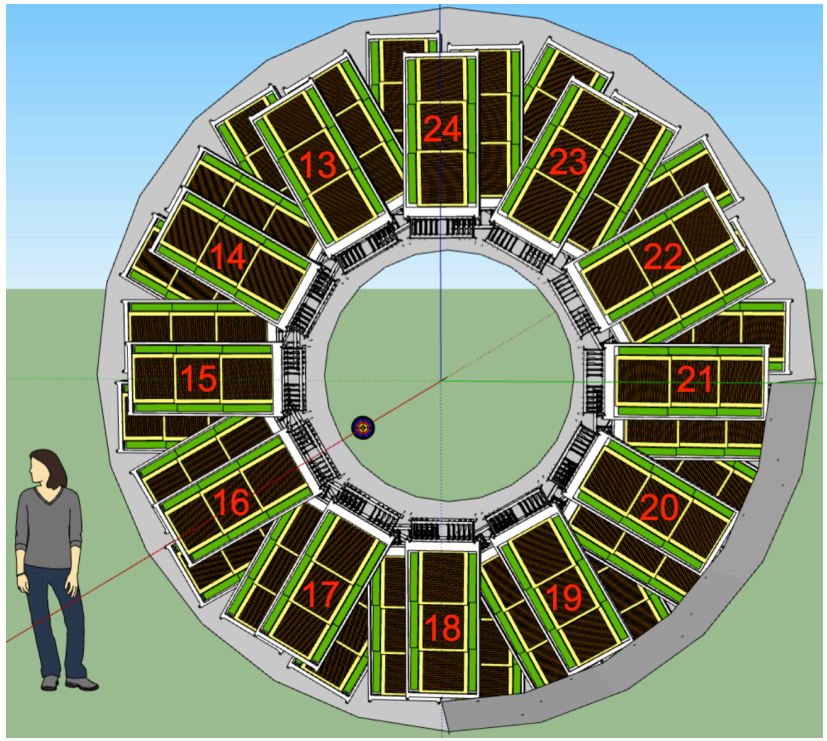
Endcap Time-Of-Flight: eTOF



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

Single TOF module for Run-17
- integration test

iTPC

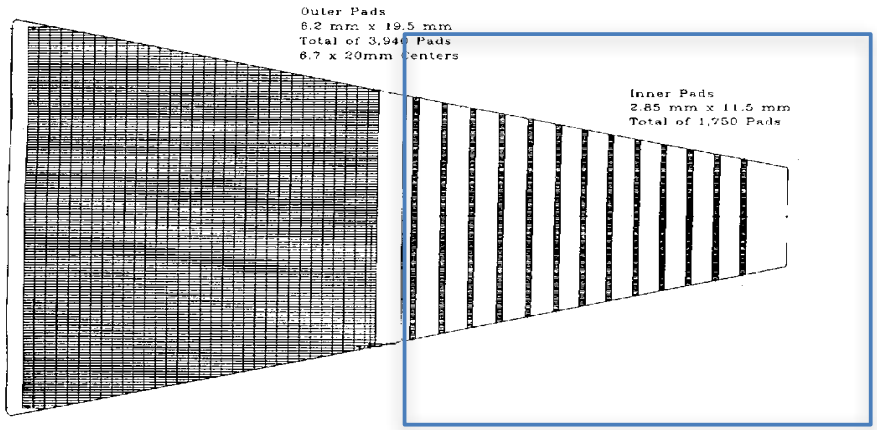
Increase in #channels in 24 inner sectors by ~factor 2

Provides near complete coverage

New electronics for inner sectors

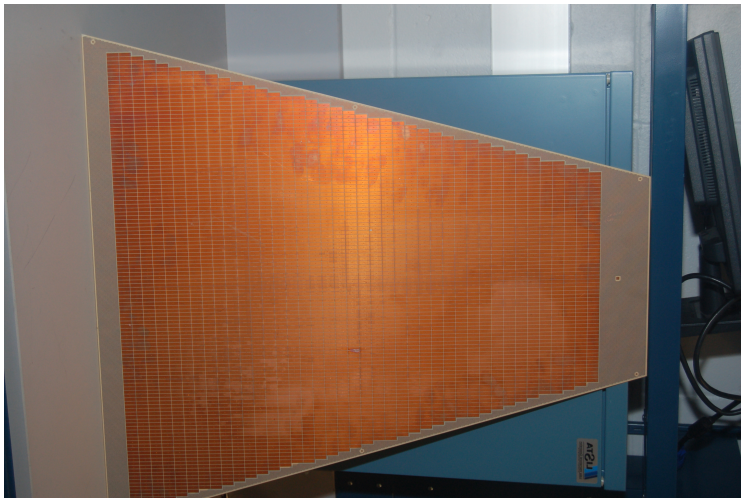
Enhanced rapidity coverage

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

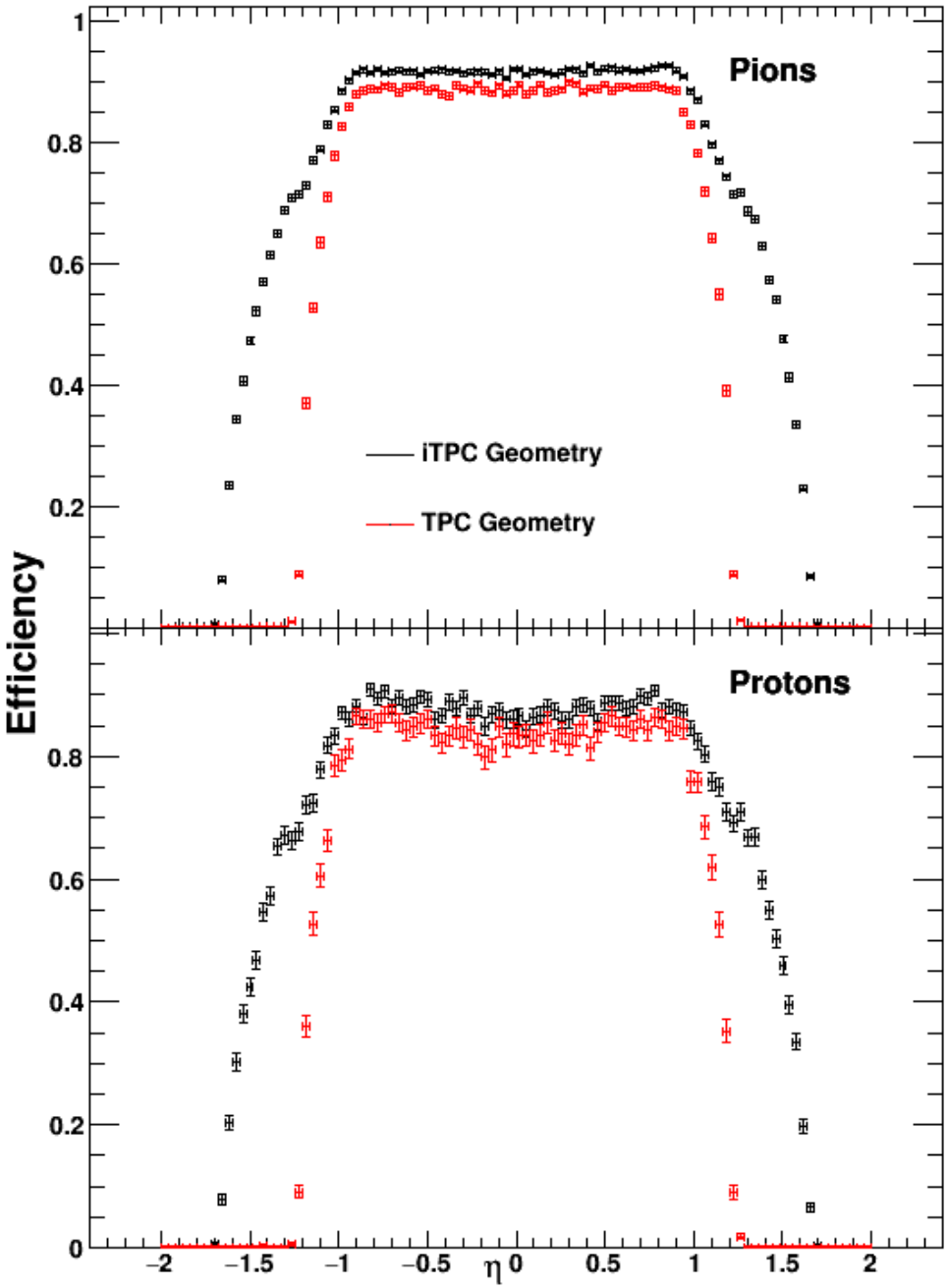


Outer

Inner



Enhanced tracking and dE/dx performance



STAR TPC in the BES-II

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