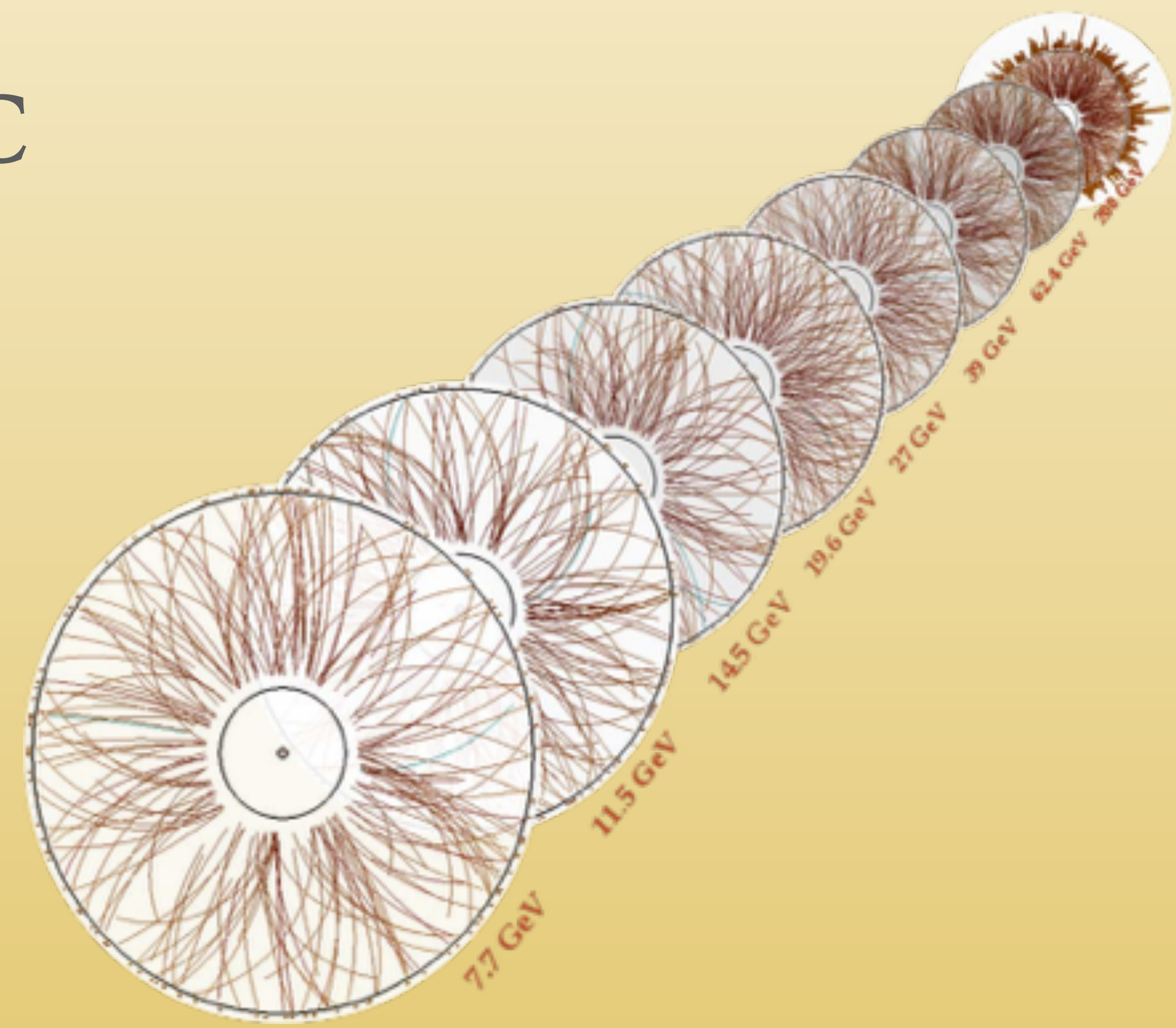
THE RHIC BEAM ENERGY SCAN: PHYSICS AND UPGRADES

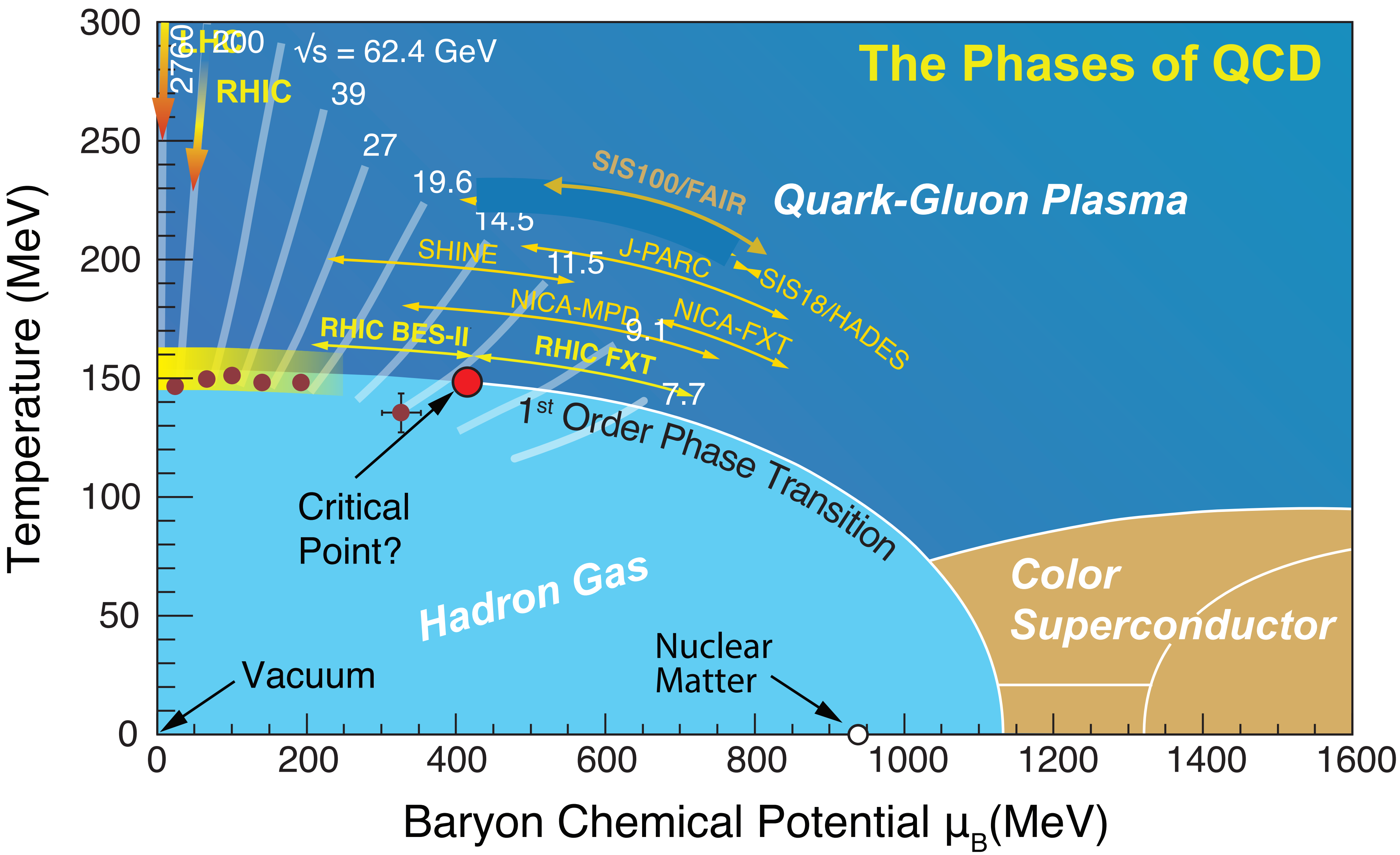
David Tlusty (Rice University)

Outline

- QCD phase diagram and RHIC Beam Energy Scan
- results from phase I
- projections for phase II



QCD PHASE DIAGRAM



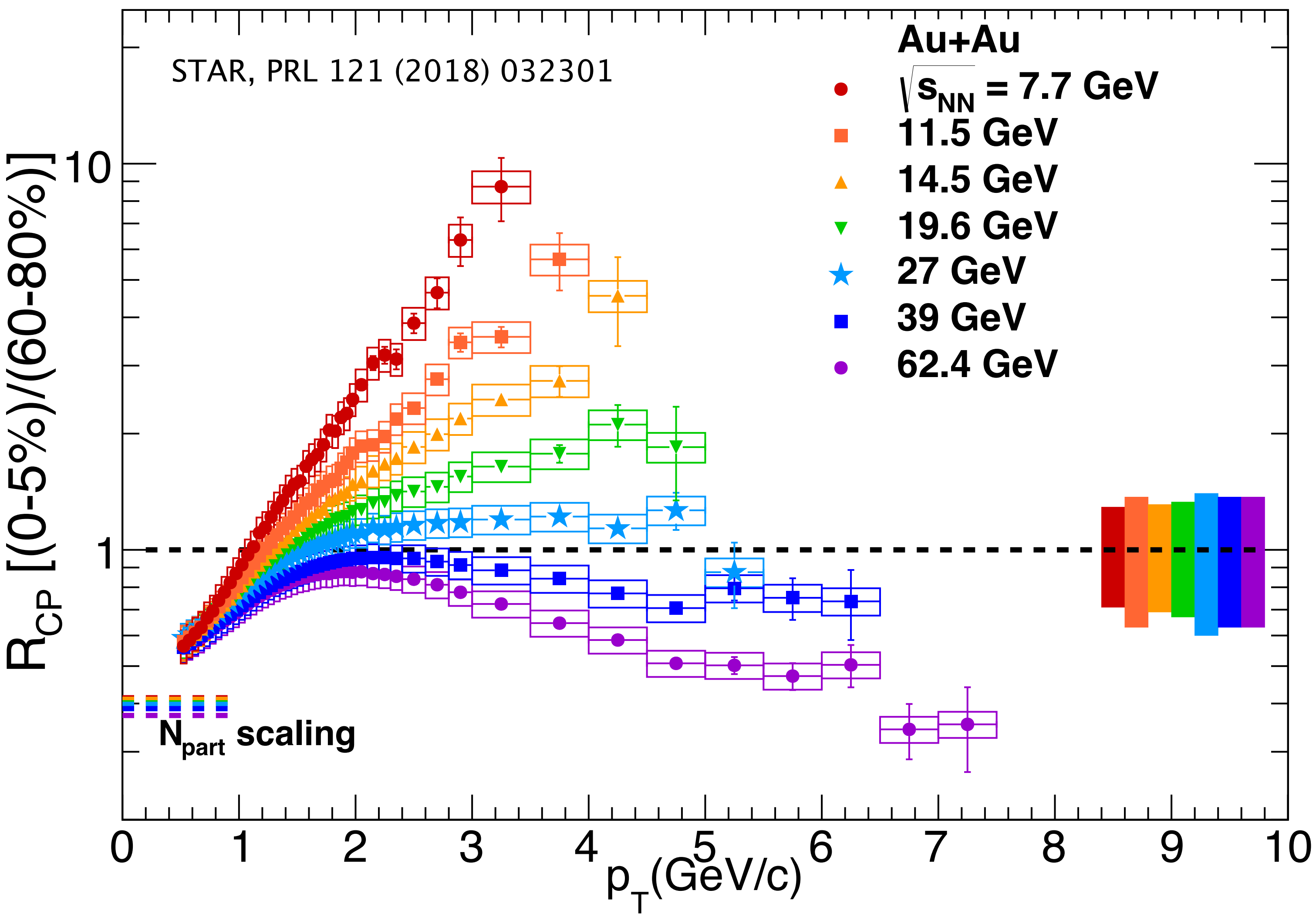
- experimentally, one can access different regions of phase diagram by varying centre-of-mass energy $\sqrt{s_{NN}}$
- RHIC beam energy scan (BES) covers both μ_B regions with crossover and possible 1st order phase transition and critical point

QCD PHASE DIAGRAM – CONTINUATION

- Turn-off of QGP signatures - suppression, elliptic flow
- Critical point - divergence of the correlation length ⇒ non-monotonic behavior of higher moments of conserved quantities
  - experimentally, skewness S, and kurtosis κ of the event-by-event net-particle distributions
- First-order phase transition - changes in the equation of state (EoS) due to attractive force (softest point) ⇒
  - non-monotonic behavior of directed flow slope at mid-rapidity ($\mathrm{d}v_1/\mathrm{d}y|_{y=0}$)
  - non-monotonic behavior of triangular flow scaled by multiplicity density
  - "step" in mean transverse mass of identified particles

PART I – RESULTS FROM BES-I

ONSET OF DECONFINEMENT – SUPPRESSION (1)



- nuclear modification factor R_{CP} STAR, PRL 121 (2018) 032301
  - smooth transition from suppression to enhancement
  - $R_{CP} > 1$ does not mean automatically absence of QGP
  - Cronin-like enhancement competes with the suppression effect

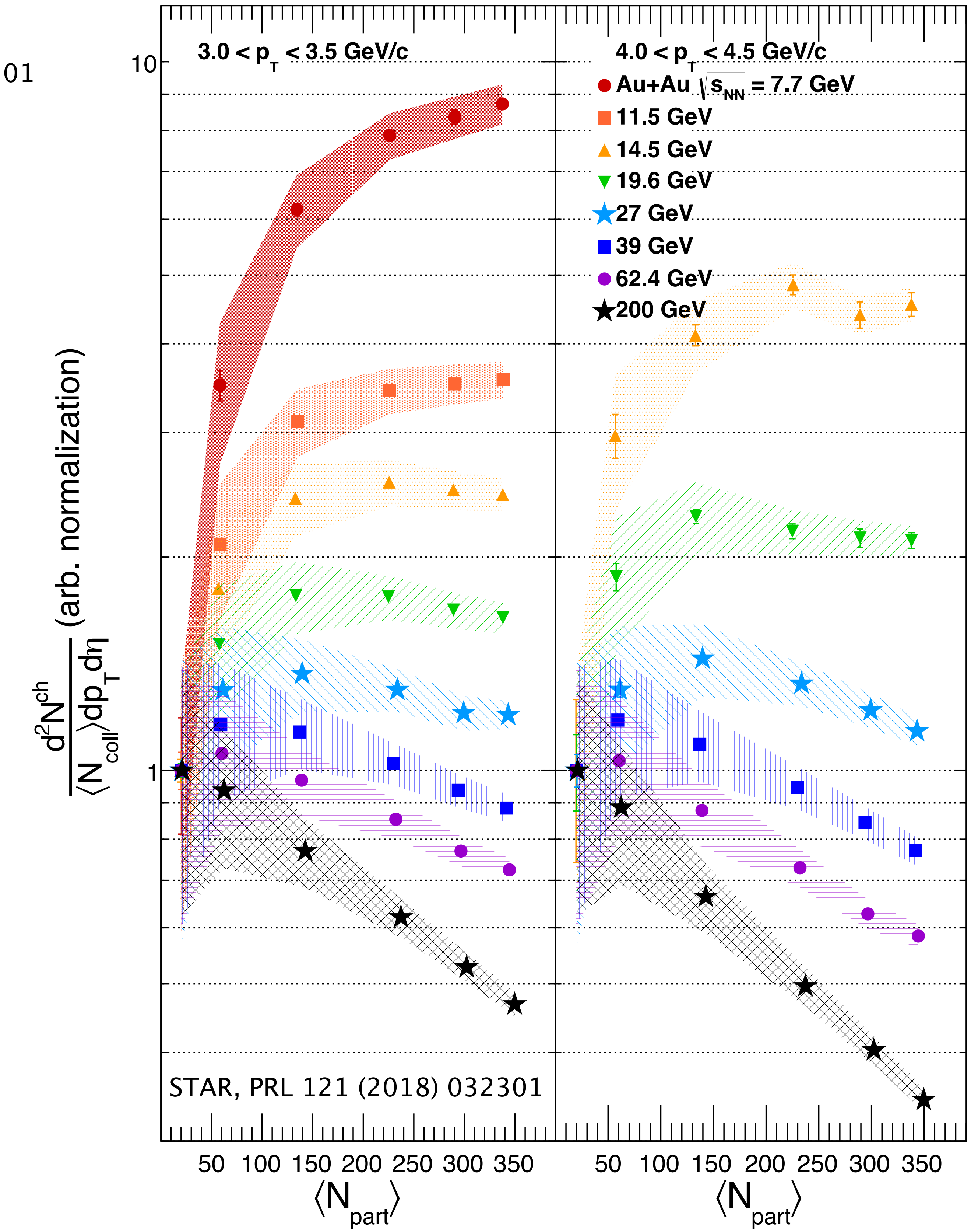
NA49 has reported that the onset of deconfinement occurs at 7.7 GeV [PRC 77,024903]

ONSET OF DECONFINEMENT – SUPPRESSION (2)

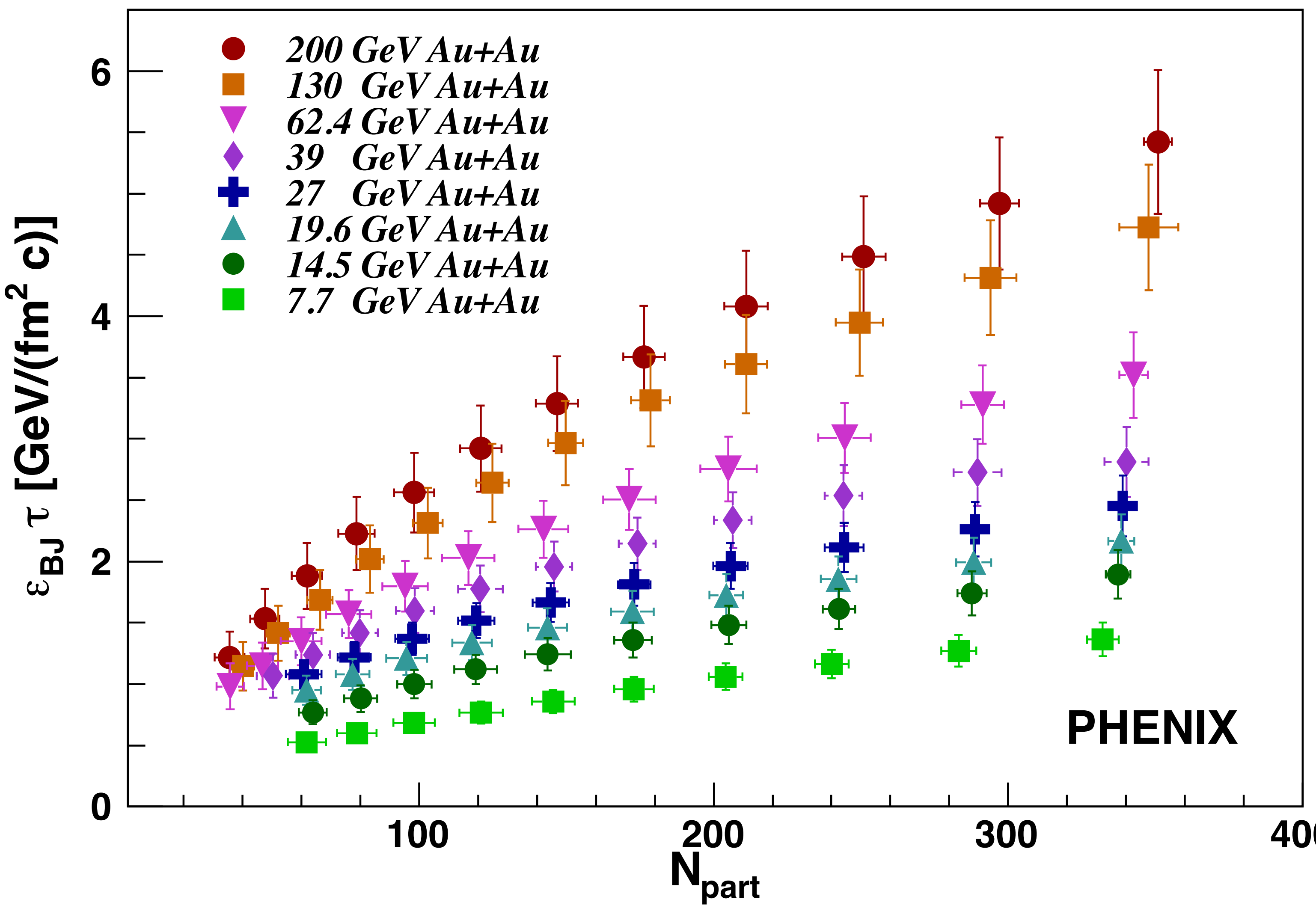
- more differential method to study jet-quenching: STAR, PRL 121 (2018) 032301

$$Y(\langle N_{\text{part}}\rangle) = \frac{1}{\langle N_{\text{coll}}\rangle}\frac{d^2N}{dp_{\text{T}}d\eta}(\langle N_{\text{part}}\rangle)$$

  - normalized by its content in the most peripheral bin
  - sensitive to growth of suppression vs enhancement
  - 27,39 vs 7.7, 11.5 GeV

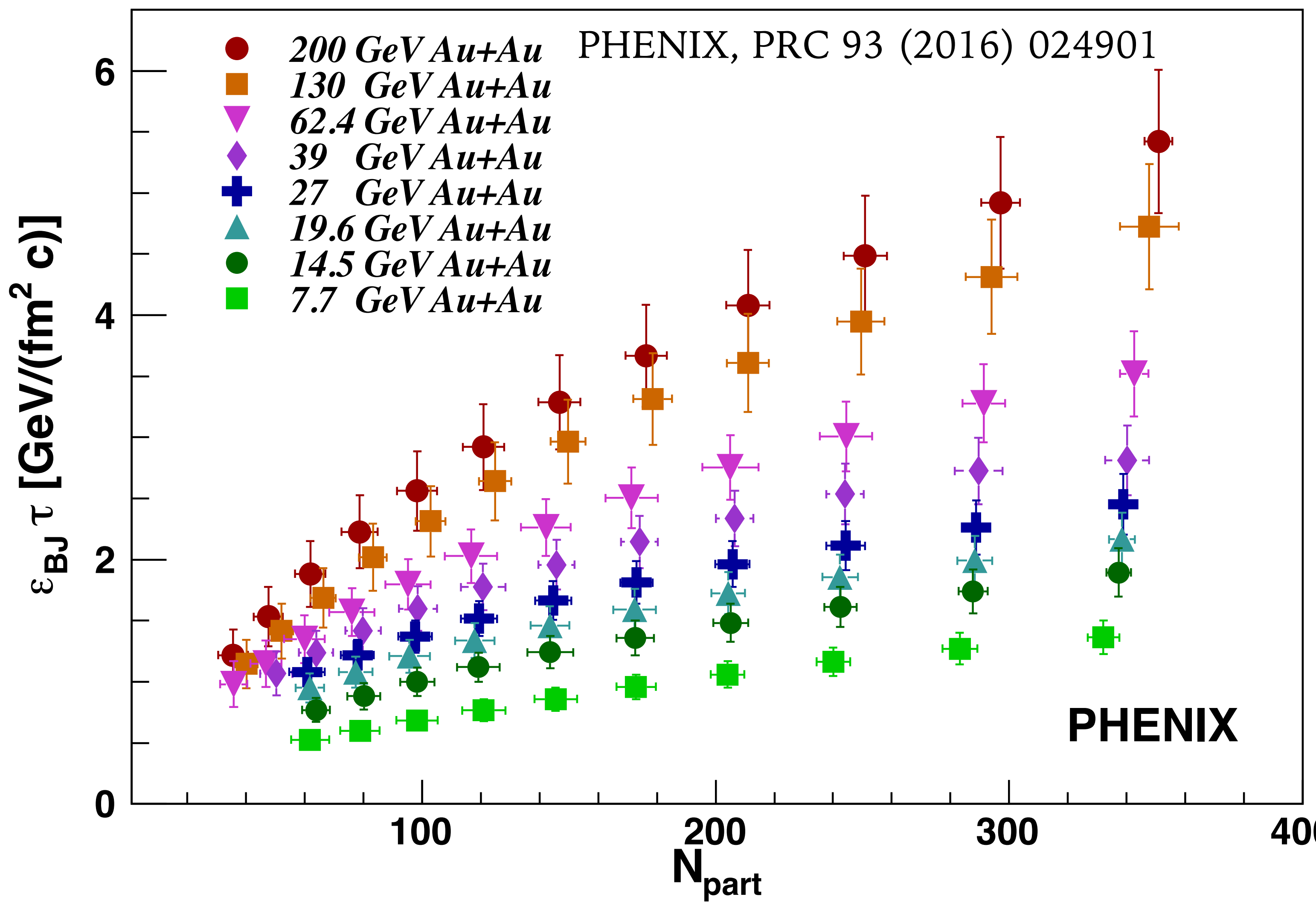


ENERGY DENSITY



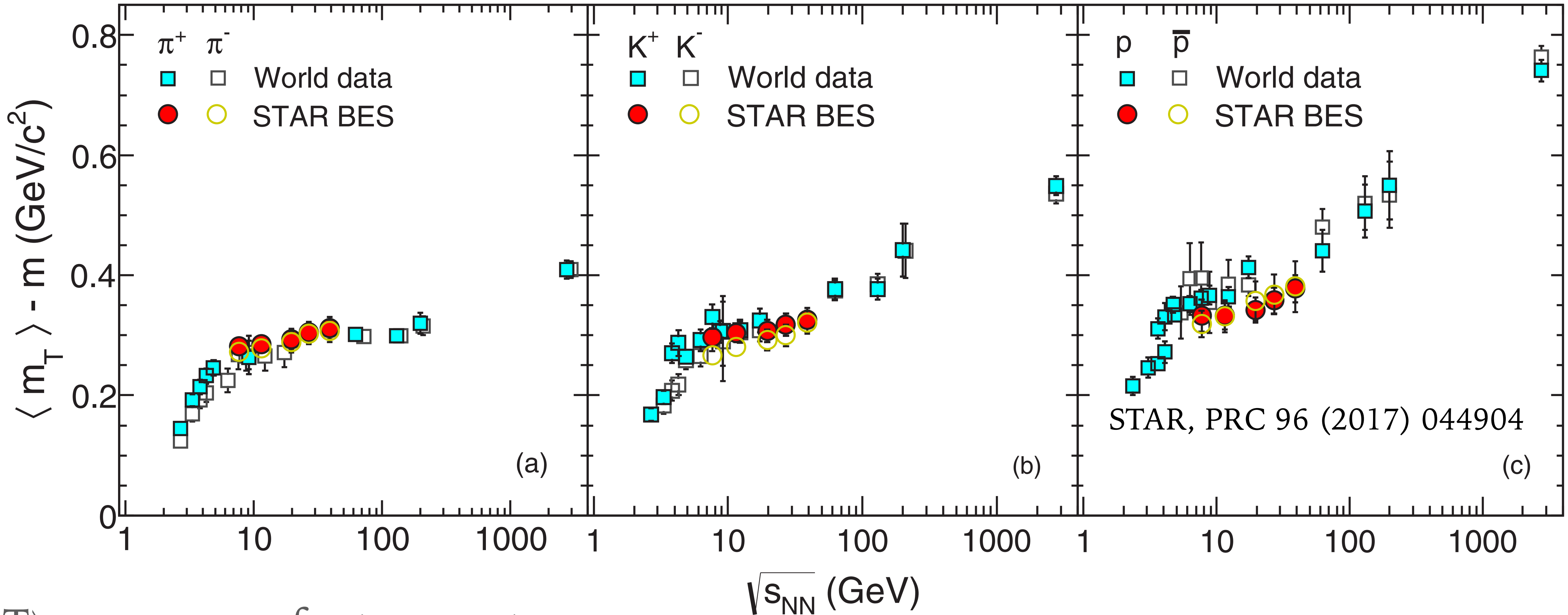
- J. D. Bjorken[PRD 27 (1983) 140]: QGP needs $\varepsilon_{BJ} > 1.0$ GeV/(fm^2c) (for a formation time of 1 fm/c)
- Lattice QCD[F. Karsch, LNP 583 (2002) 209][G. Martinez, arXiv:1304.1452]: critical energy density = 0.7 ± 0.3 GeV/fm^3

ENERGY DENSITY



- J. D. Bjorken[PRD 27 (1983) 140]: QGP needs $\varepsilon_{BJ} > 1.0$ GeV/(fm^2c) (for a formation time of 1 fm/c)
- Lattice QCD[F. Karsch, LNP 583 (2002) 209][G. Martinez, arXiv:1304.1452]: critical energy density = 0.7 ± 0.3 GeV/fm^3

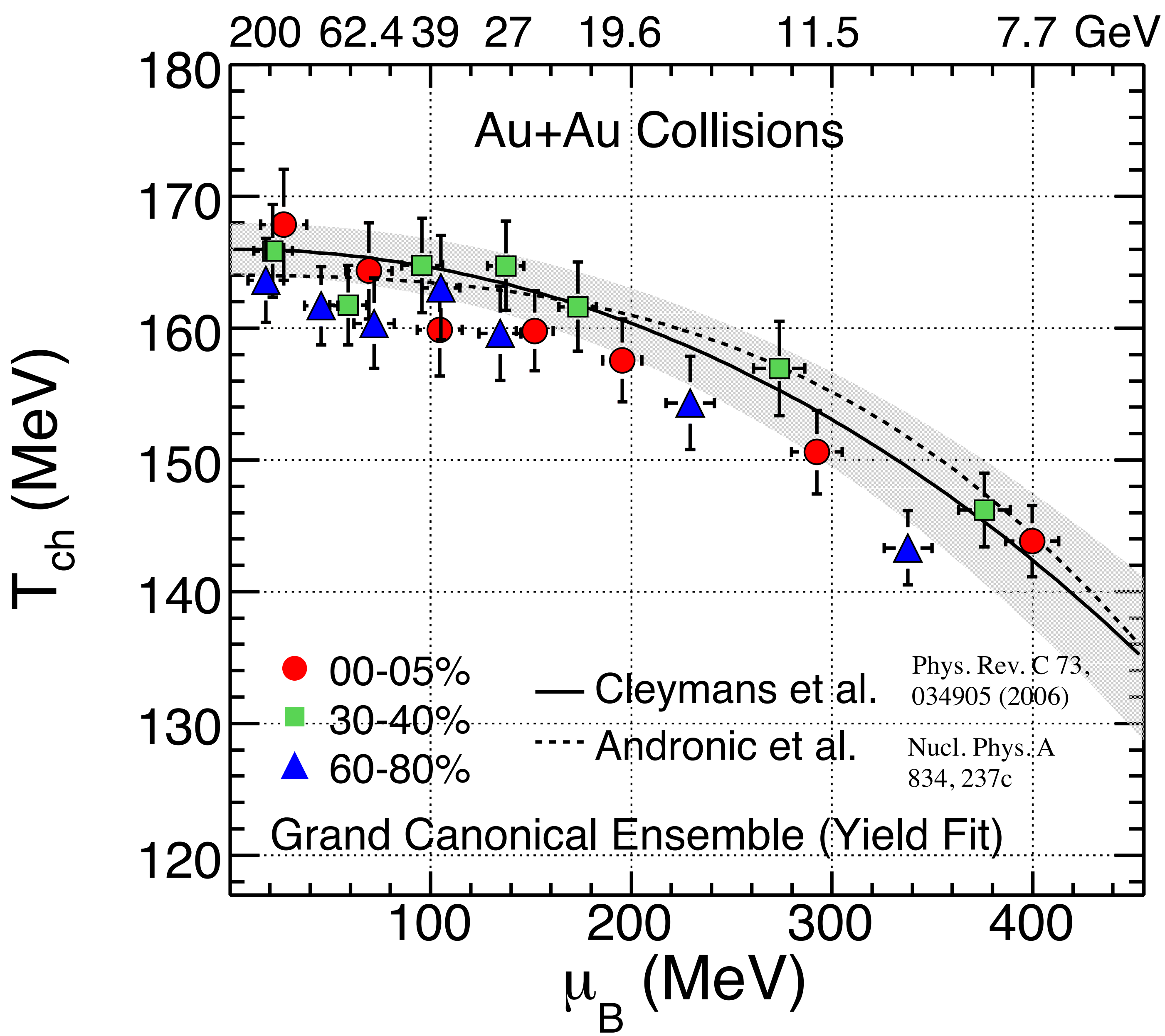
ENERGY DENSITY AND MEAN TRANSVERSE MASS



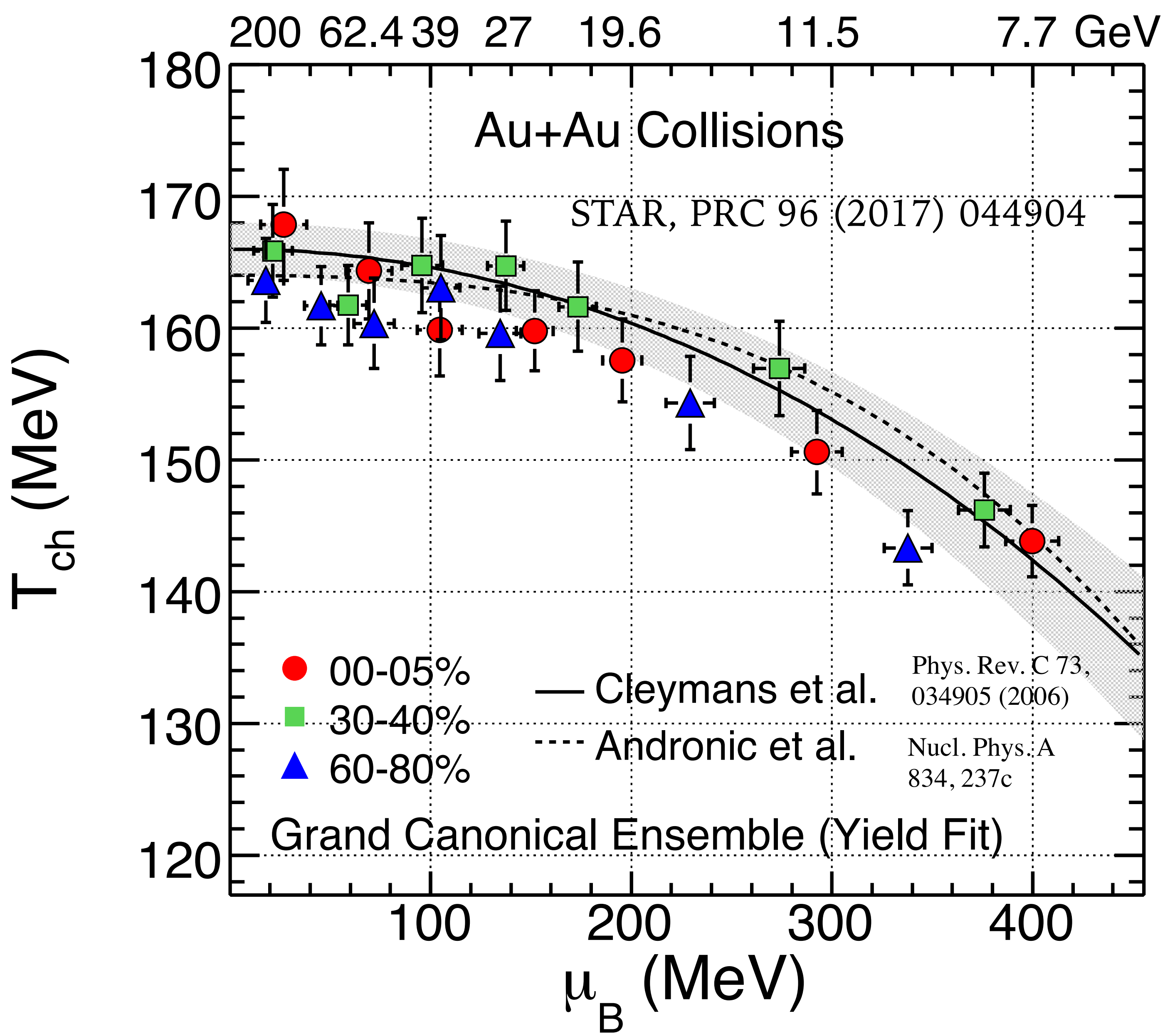
World data: AGS (0-5%), SPS (0-7%), RHIC (0-5%), LHC (0-5%)

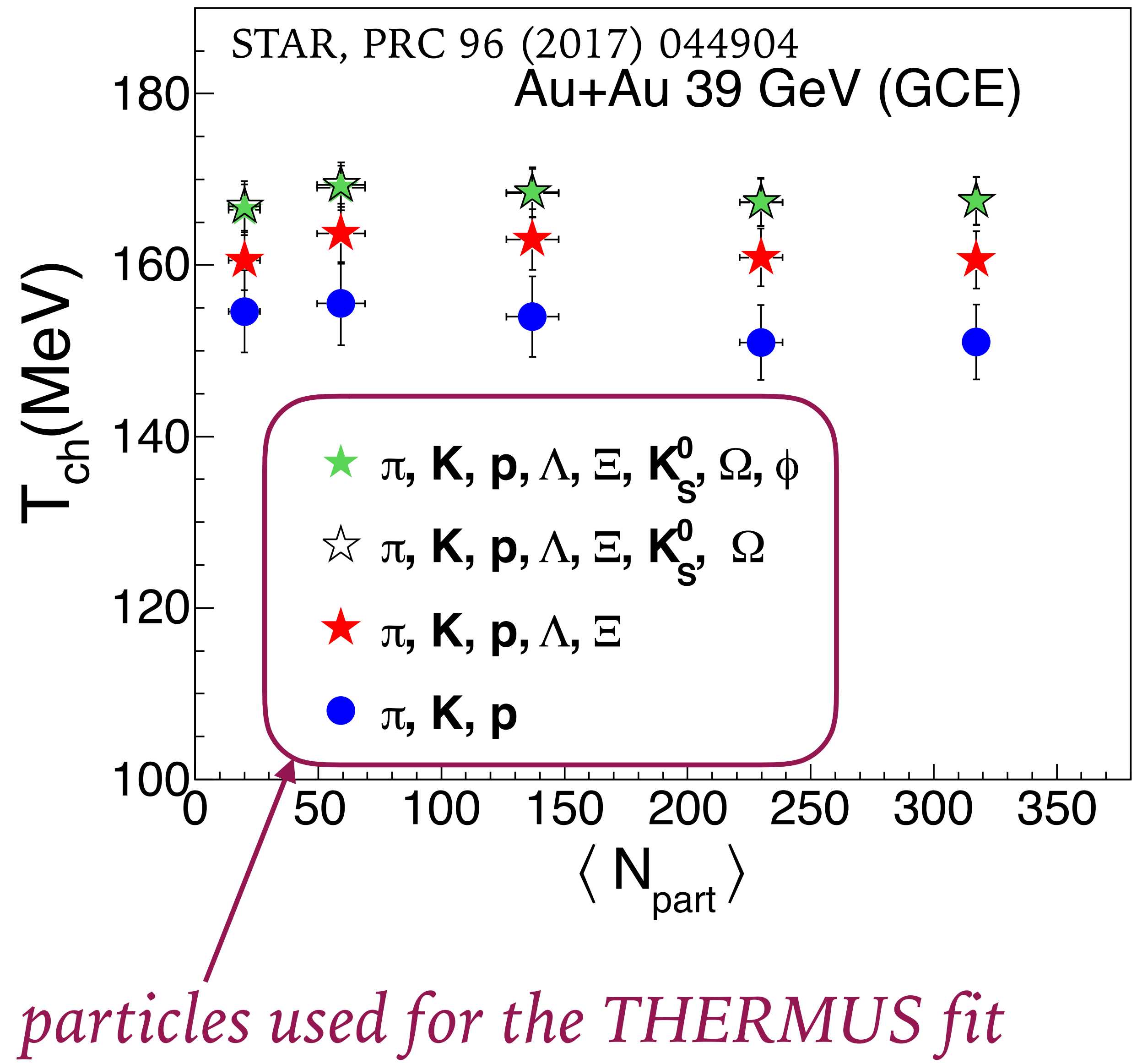
- $\langle mT \rangle - m$: proxy for temperature
- $\ln(s_{NN}) \sim dN/dy$: proxy for entropy
  - except of K^+ (associated production + pair production), p (baryon stopping)
- "step" reproduced by 3+1 Hydro model [Gaździcki et al., BJP 34 322 (2003)]
  - assumes 1st order phase transition (modification of EoS [Van Hove, PLB 118 138 (1982)])
- but also with UrQMD based [Petersen, et al., J. Phys. G 36 055104 (2009)]
  - either 1st order phase transition or EoS effectively softened due to non-equilibrium effects in the hadronic transport calculation

TEMPERATURE OF CHEMICAL FREEZE-OUT AND BARYON DENSITY



TEMPERATURE OF CHEMICAL FREEZE-OUT AND BARYON DENSITY



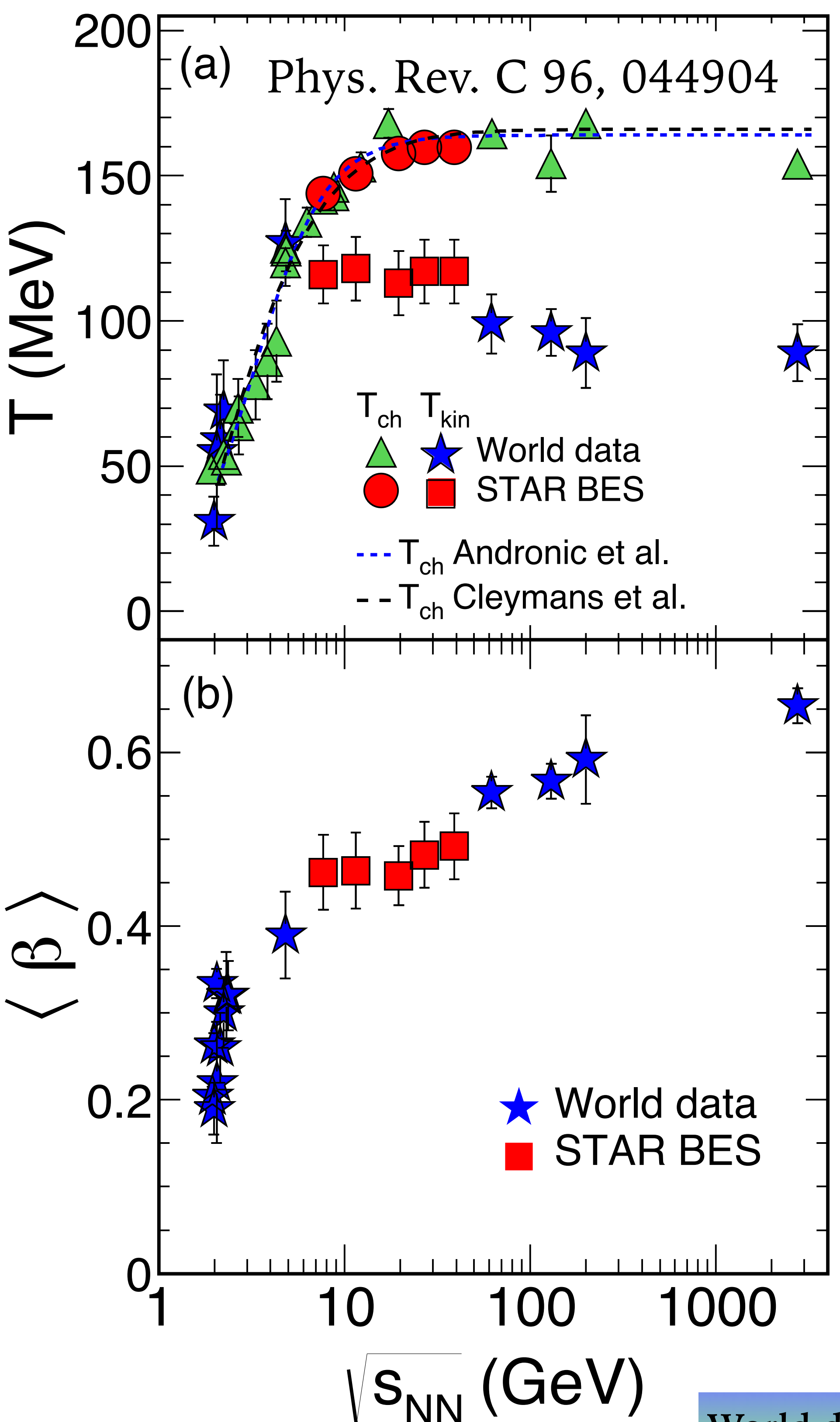


- particles included in the THERMUS model fit were π, K, p, p̄, Λ, and Ξ

  [Wheaton et al., CPC180 (2009) 84]

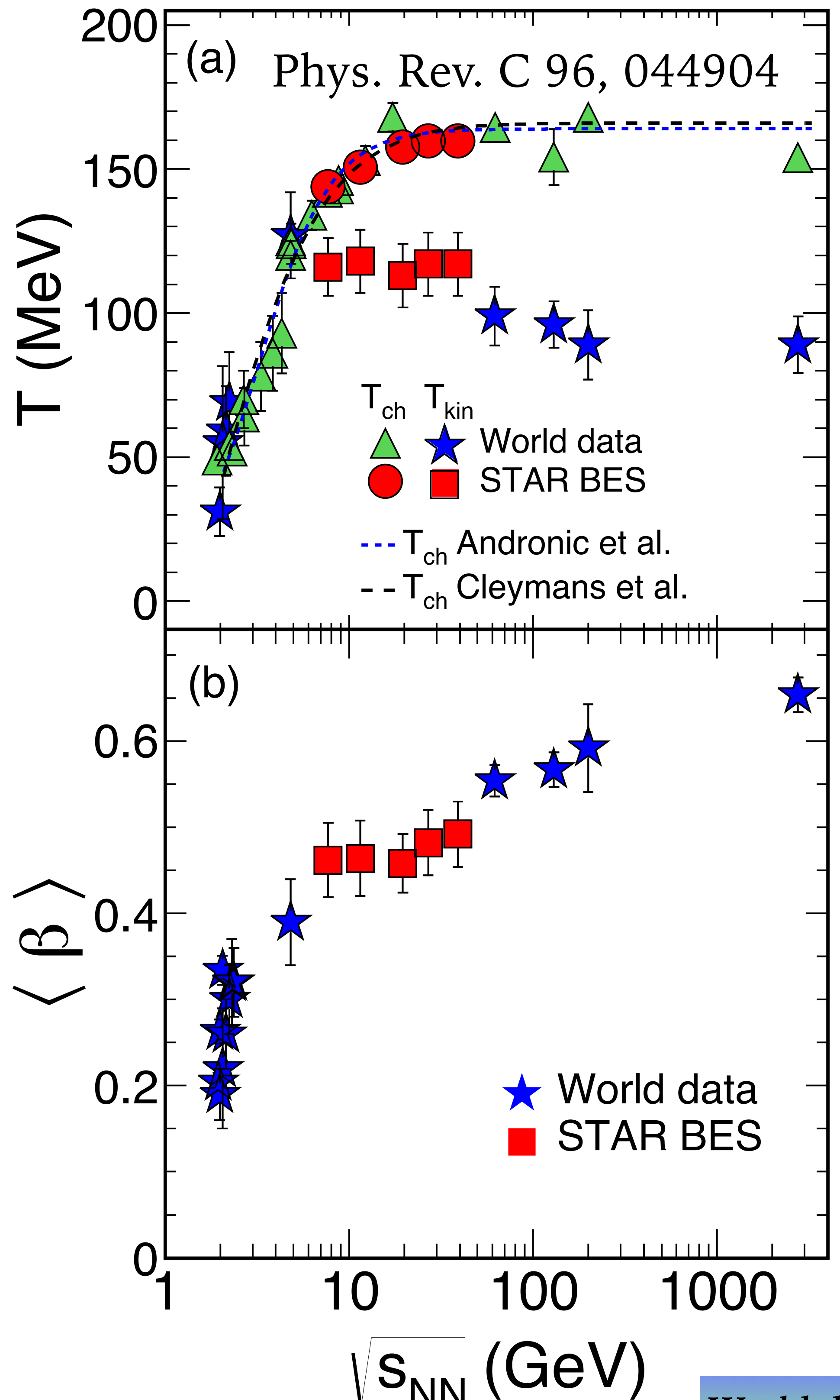
- T_{ch} appears to be lower when strange particles were excluded from the fit

TEMPERATURE OF KINETIC FREEZE-OUT



World data: AGS (0-5%), SPS (0-7%), RHIC (0-5%), LHC (0-5%)

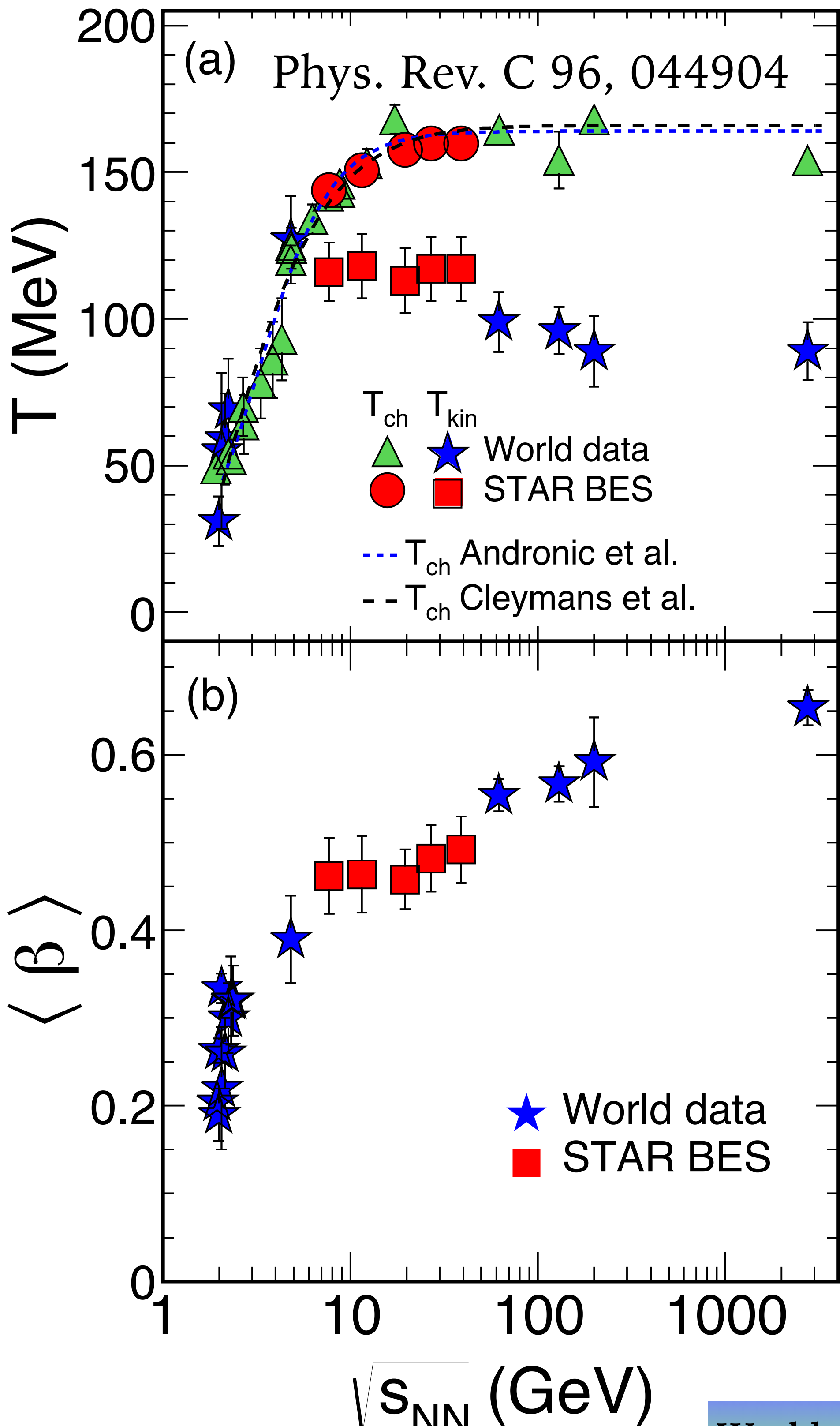
TEMPERATURE OF KINETIC FREEZE-OUT



- ➤ the separation between between temperatures of kinetic and chemical freeze-out grows with increasing energy
  - ➤ might suggest the effect of increasing hadronic interactions between chemical and kinetic freeze-out at higher energies

World data: AGS (0-5%), SPS (0-7%), RHIC (0-5%), LHC (0-5%)

TEMPERATURE OF KINETIC FREEZE-OUT

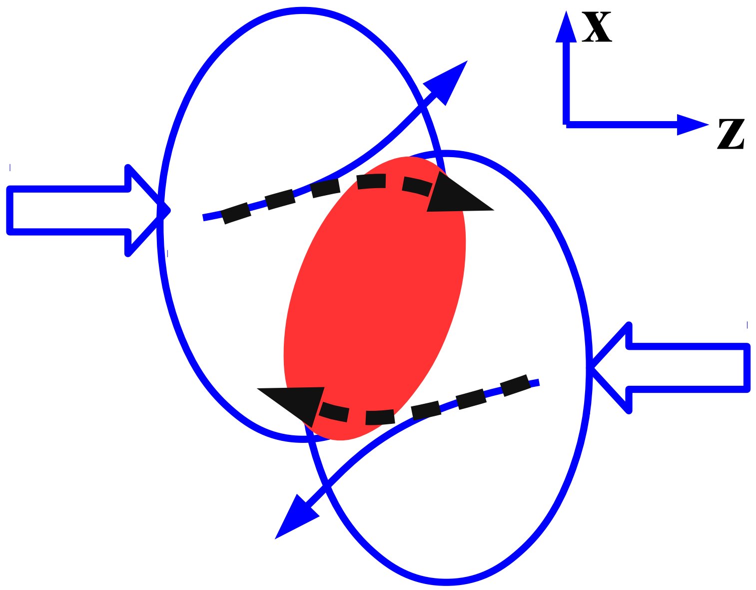


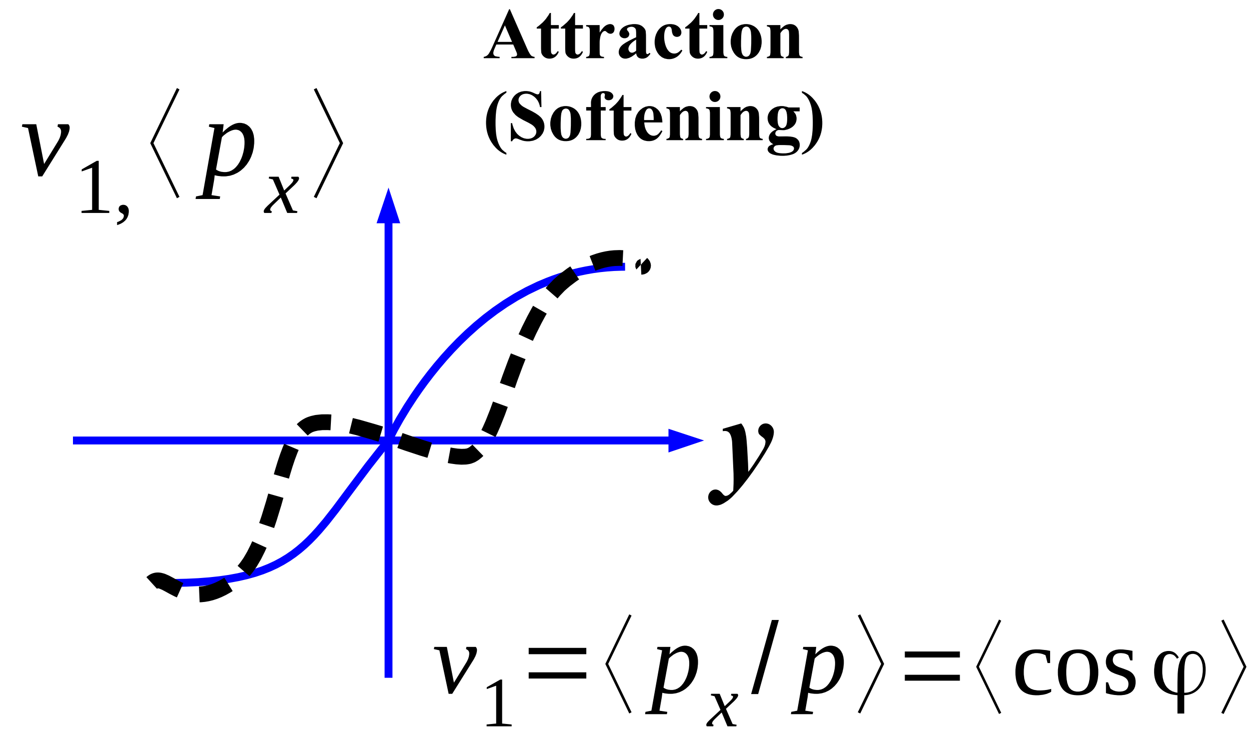
- the separation between between temperatures of kinetic and chemical freeze-out grows with increasing energy
  - might suggest the effect of increasing hadronic interactions between chemical and kinetic freeze-out at higher energies
- radial flow velocity shows rapid increase at very low energies and slower increase at higher energies

World data: AGS (0-5%), SPS (0-7%), RHIC (0-5%), LHC (0-5%)

DIRECTED FLOW

[A. Ohnishi, CPOD 2016]

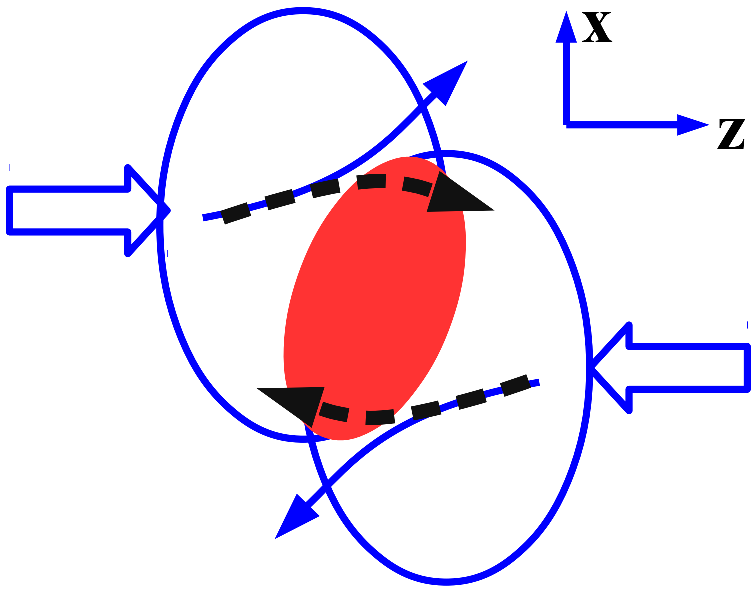


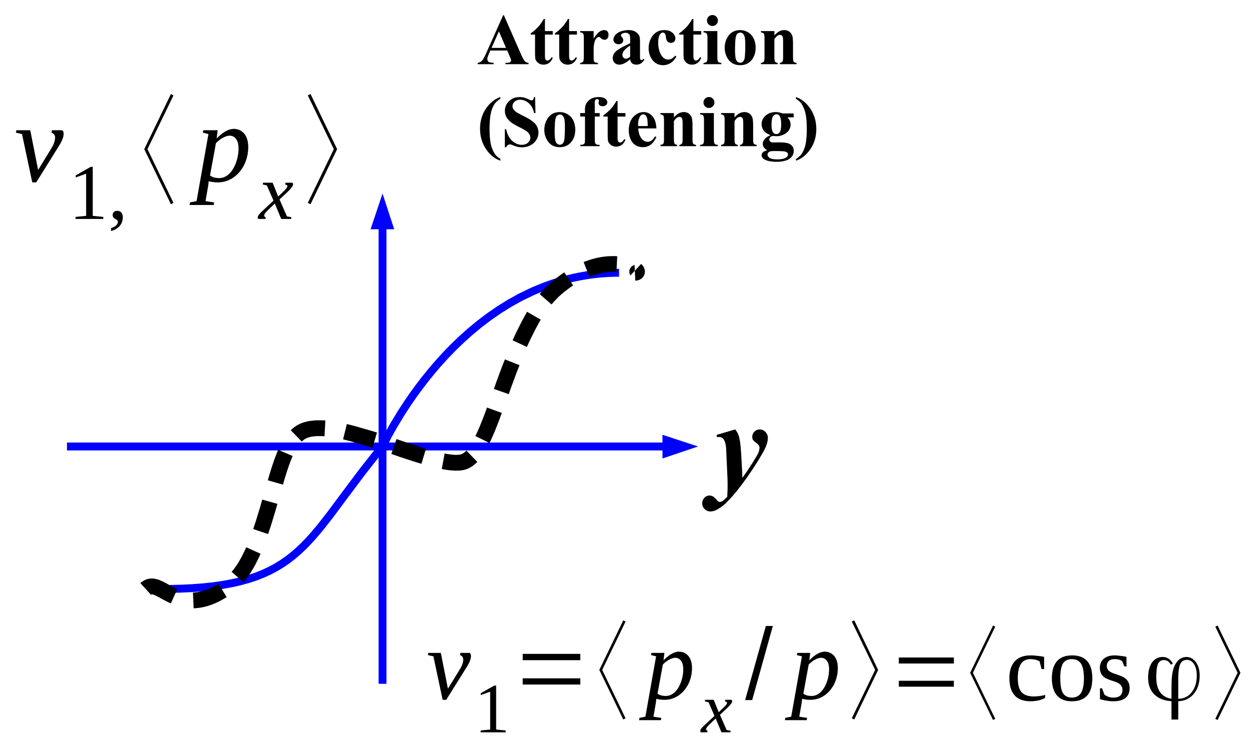


[Y. Nara et al., PRC 94 (2016) 034906]

DIRECTED FLOW

[A. Ohnishi, CPOD 2016]



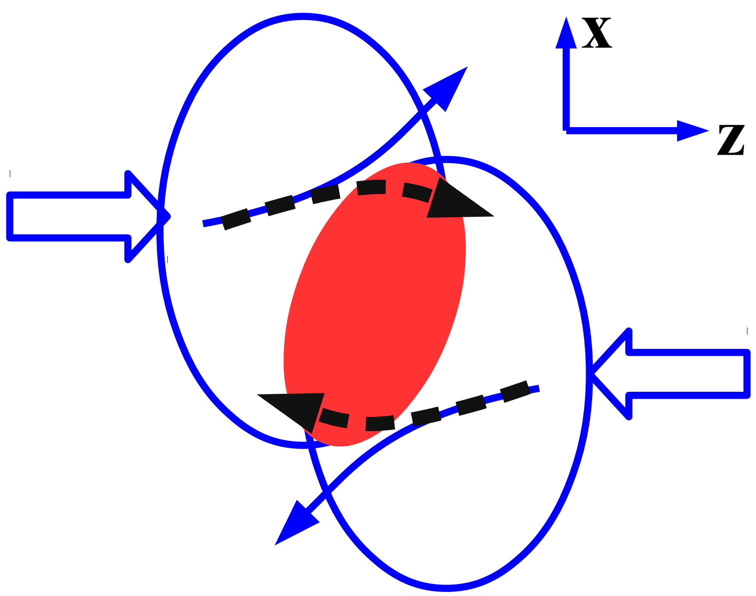


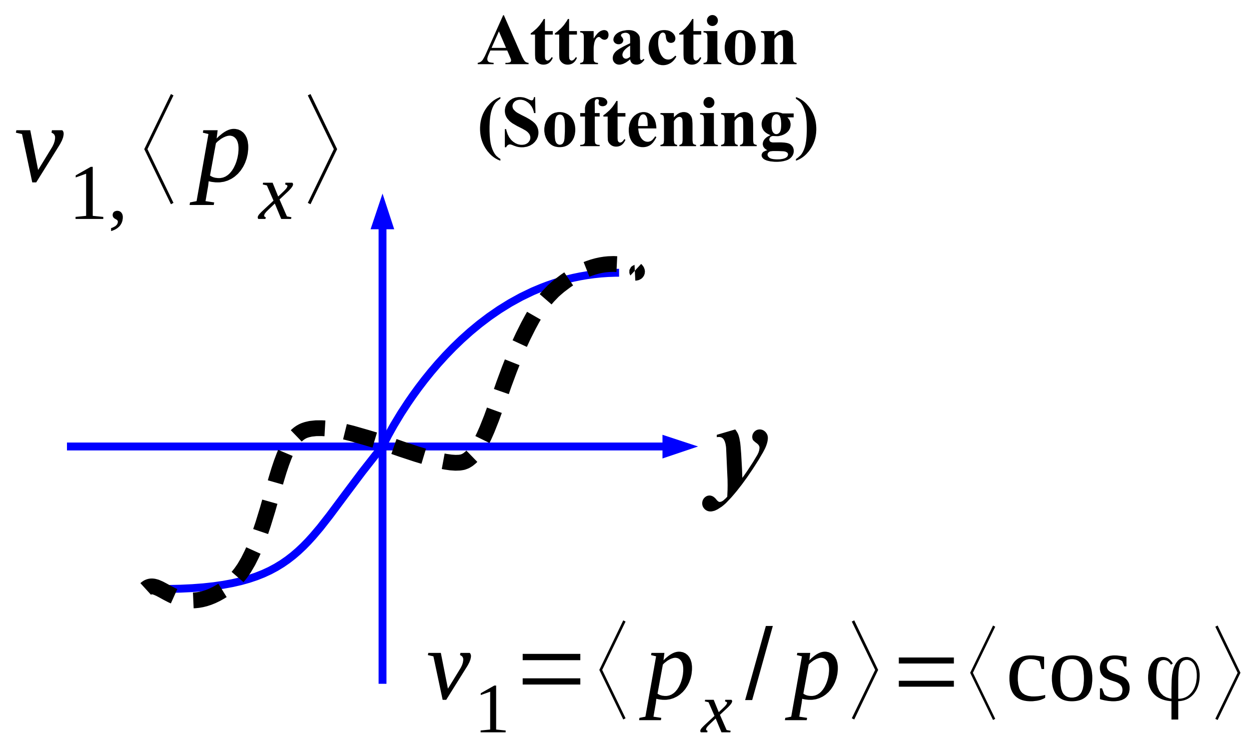
➤ directed flow v_1 is sensitive to the EoS in the early stage

[Y. Nara et al., PRC 94 (2016) 034906]

DIRECTED FLOW

[A. Ohnishi, CPOD 2016]



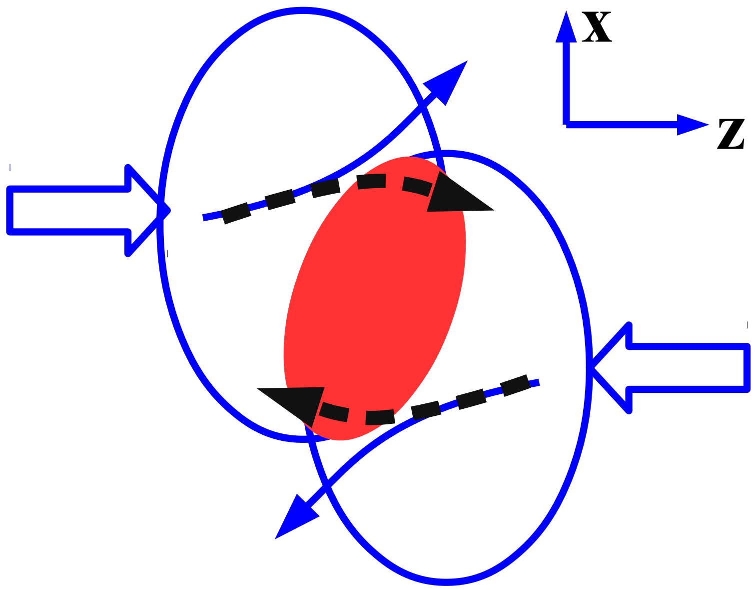


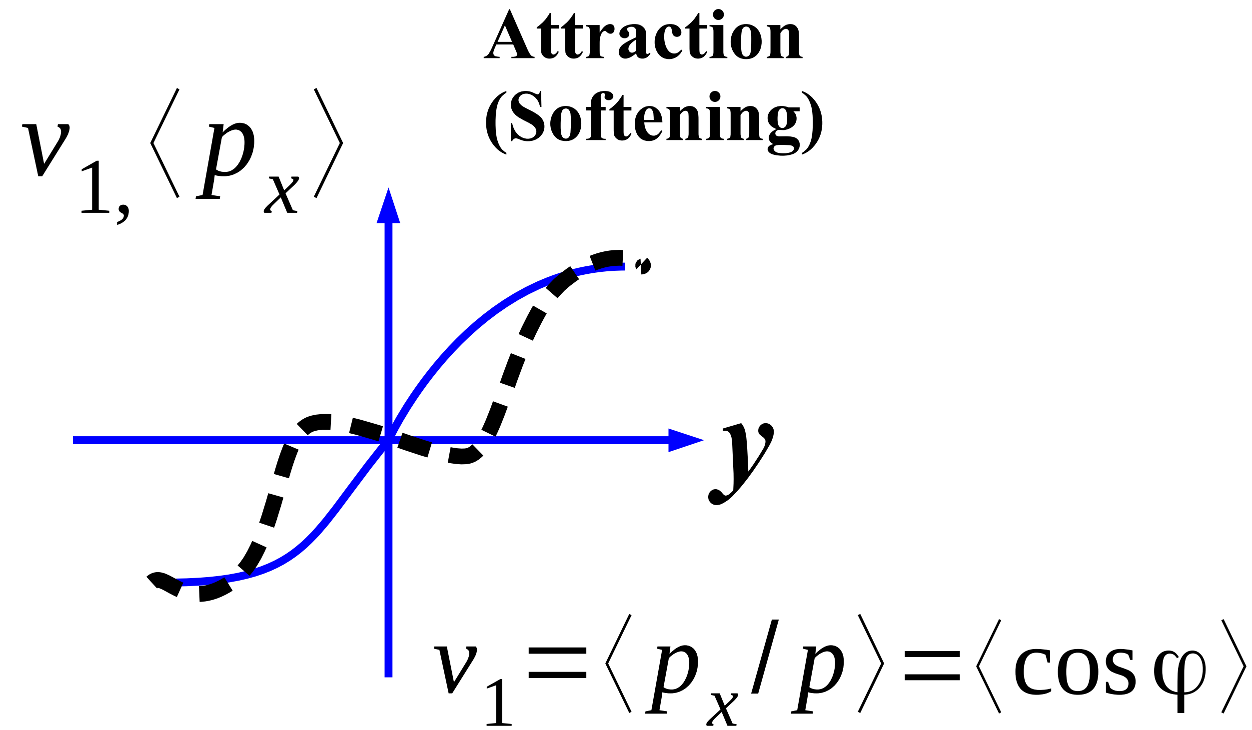
- directed flow v_1 is sensitive to the EoS in the early stage
- EoS with a 1st order phase transition exhibits a very pronounced softest point at large chemical potentials

[Y. Nara et al., PRC 94 (2016) 034906]

DIRECTED FLOW

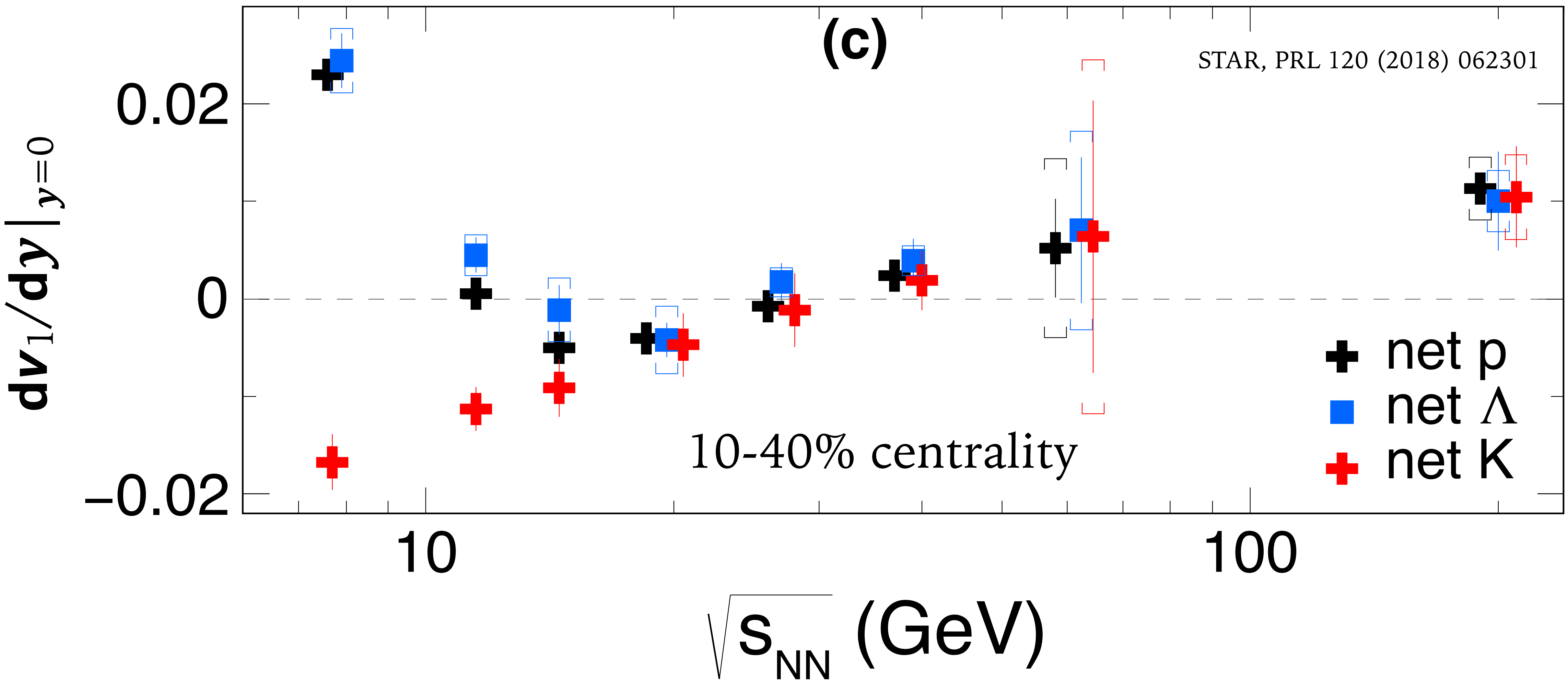
[A. Ohnishi, CPOD 2016]





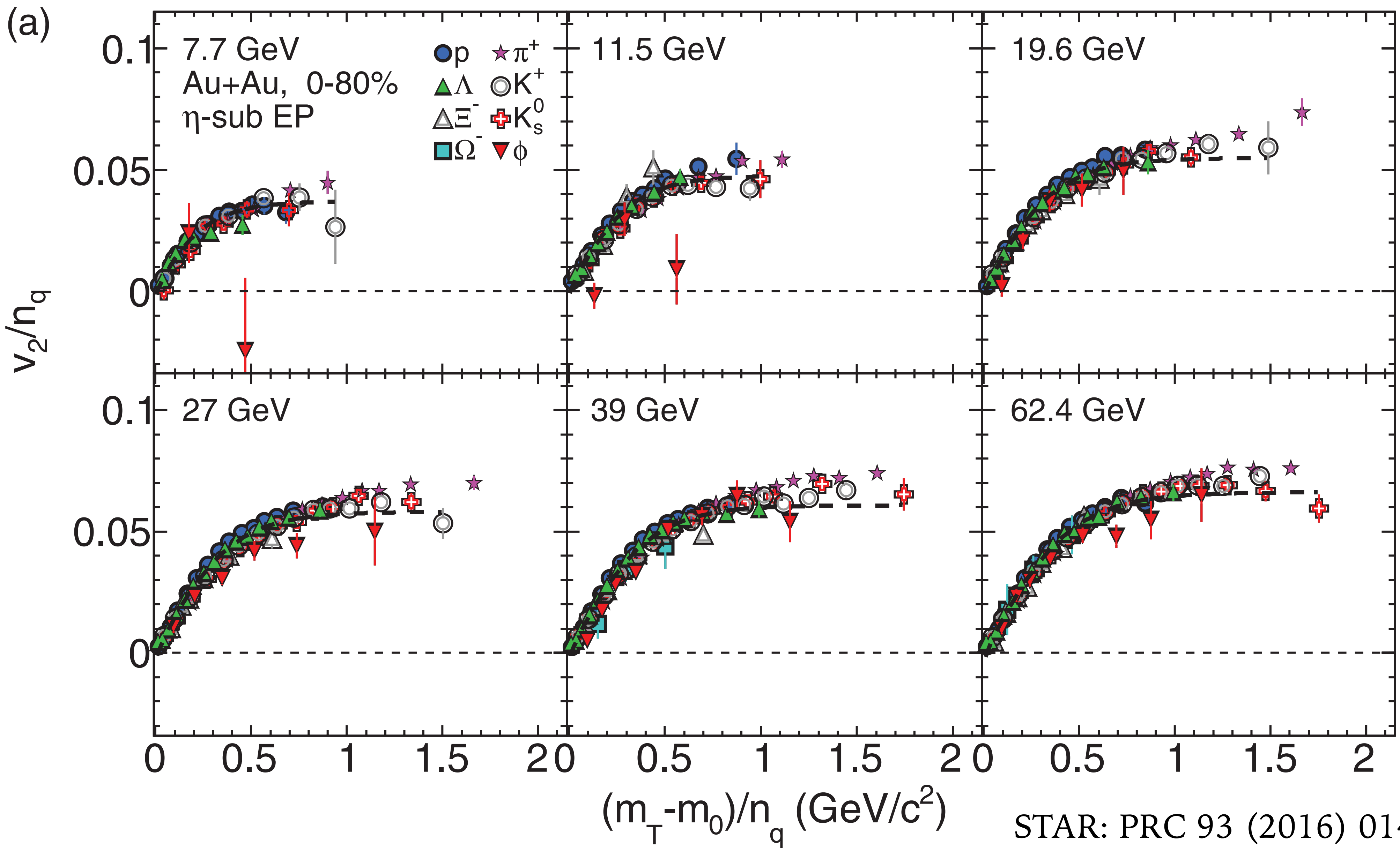
- directed flow v_1 is sensitive to the EoS in the early stage
- EoS with a 1st order phase transition exhibits a very pronounced softest point at large chemical potentials
- non-monotonic dependence [Y. Nara et al., PRC 94 (2016) 034906]
  - softening (crossover or 1st order phase transition)
  - geometry (tilted ellipsoid expansion, relevant at $\sqrt{s_{NN}} \gtrsim 27$ GeV)
  - transport

DIRECTED FLOW FROM BES-I



- net baryons show hints of a minimum and double-sign change ⇒ indicative of a softening equation of state
- fine centrality binning (by 5%) possible in BES-II
  - STAR detector upgrade (reduction of systematic errors) and RHIC luminosity increase (reduction of statistical uncertainties)

ELLIPTICAL FLOW OF IDENTIFIED HADRONS



STAR: PRC 93 (2016) 014907

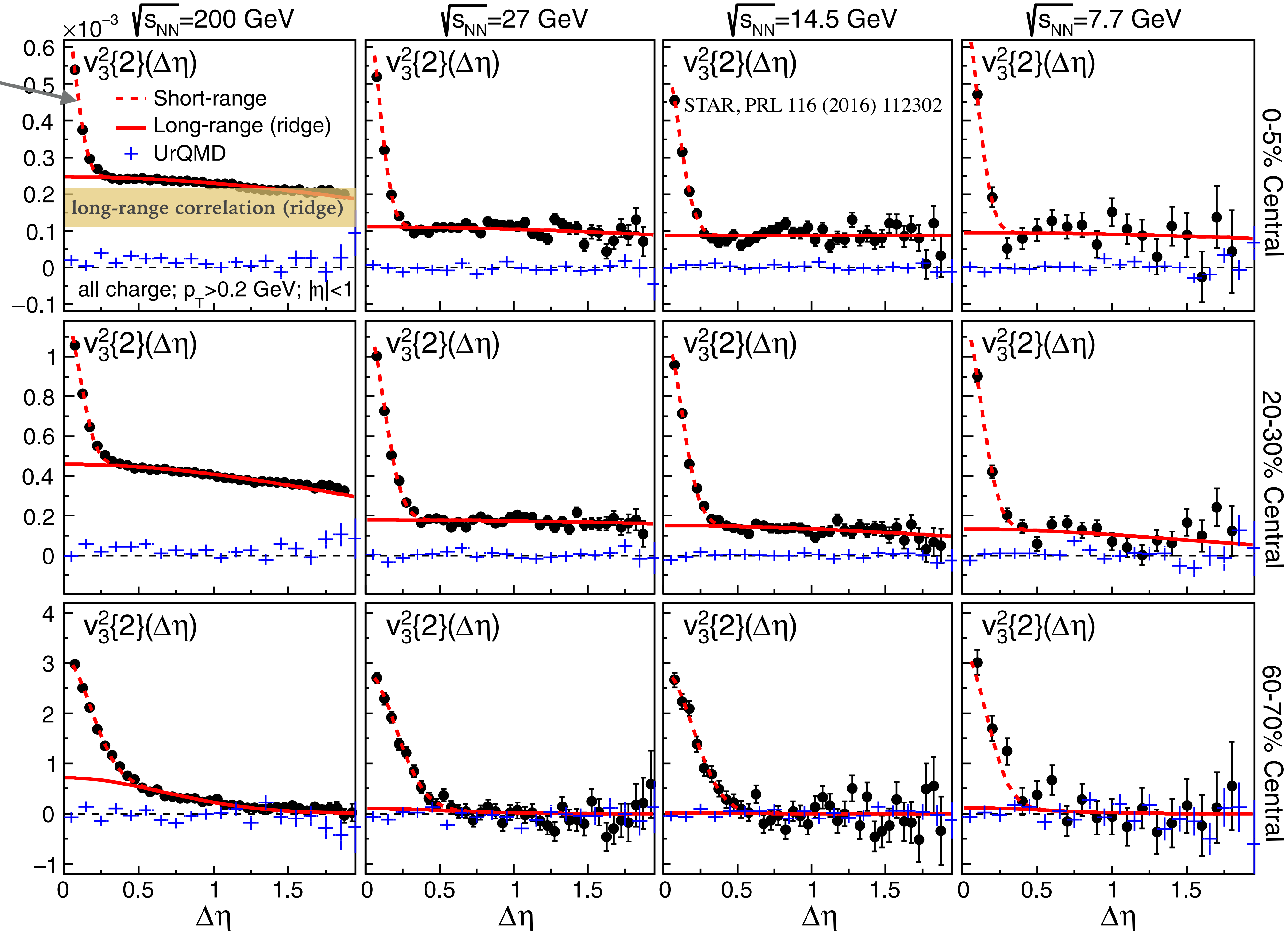
- ϕ meson's NCQ scaling seems to break down at 11.5 and 7.7 GeV
- ϕ meson has significantly lower collision cross section in hadron gas

TRIANGULAR FLOW (1)

quantum interference effects

STAR, PRL 116 (2016) 112302

- very sensitive to the presence of QGP at early stages of collision (viscosity)
- ridge persists to the lowest energies in central collisions
- UrQMD matches data only in peripheral collisions at lower energies

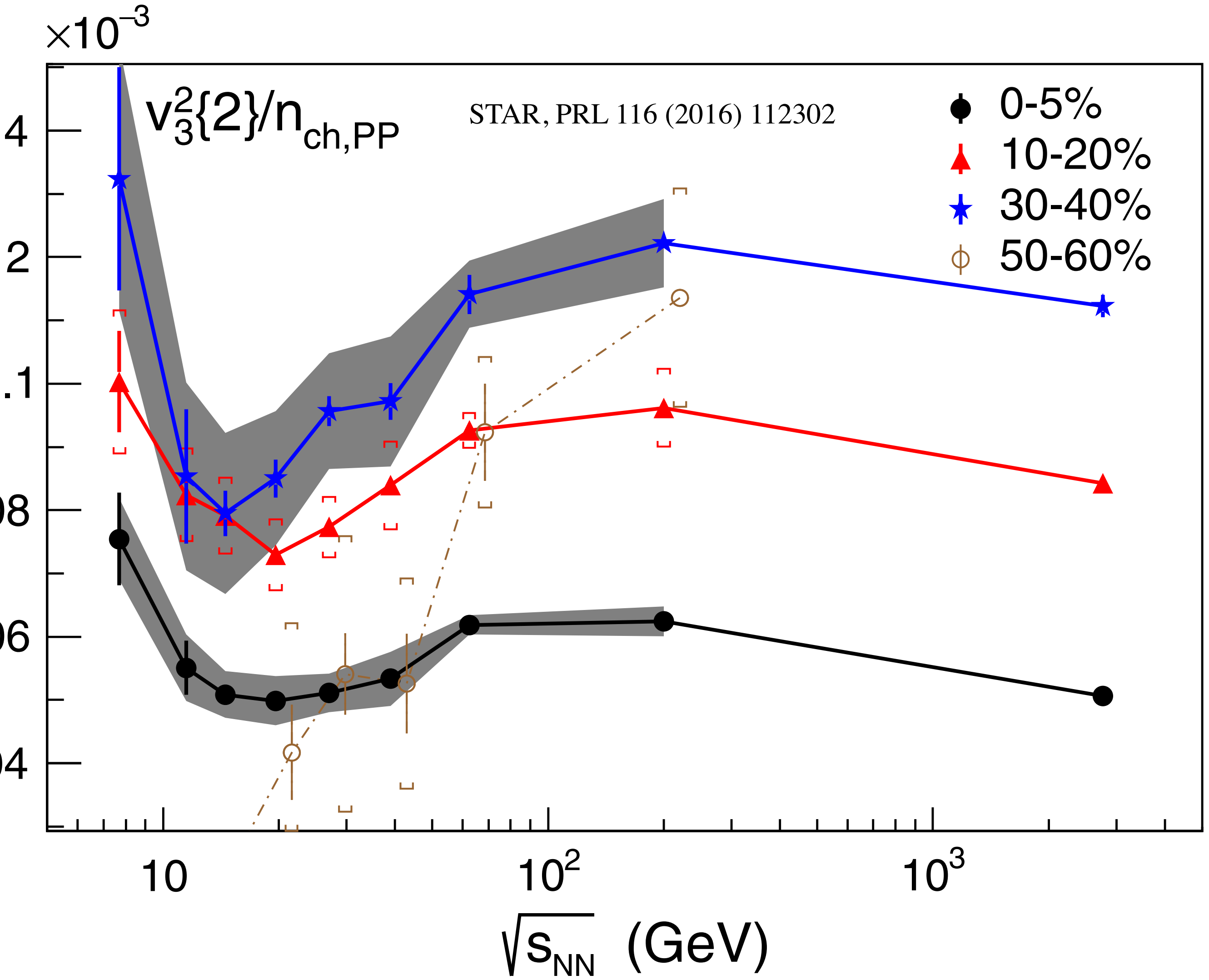


TRIANGULAR FLOW (2)

$$n_{\text{ch,PP}} = (2/N_{\text{part}})dN_{\text{ch}}/d\eta$$

mid-rapidity, charged-particle multiplicity density per participant pair

systematic errors as either shaded bands or capped bars



- the local minimum could be an indication of an anomalously low pressure, but
    - the minima could depend on specific scaling scheme
    - the changes in baryon-to-meson ration, baryon stopping, and longer crossing times for nuclei at lower energies need to be taken into account
- motivation for further investigation and more rigorous theoretical modelling

LOCALIZATION OF CRITICAL POINT

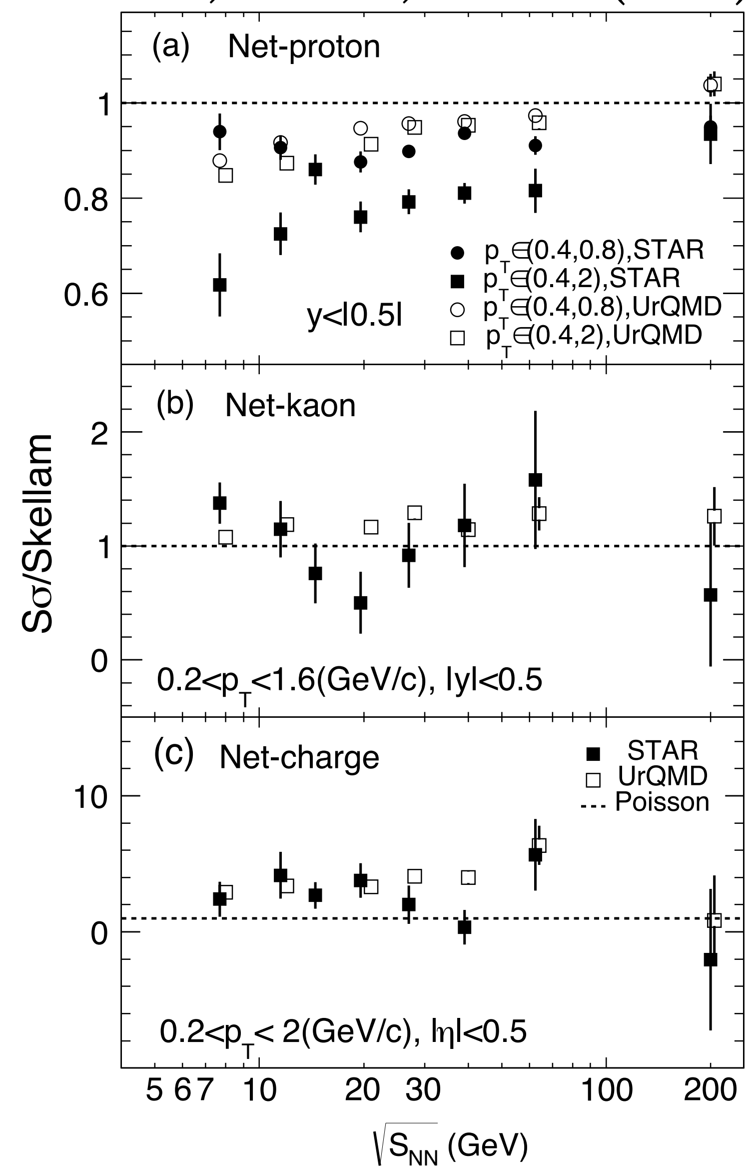
- moments of net-particle multiplicity distributions can be related to susceptibilities of conserved charges calculated on the lattice [P. Alba et al., Phys. Rev. C 92, 064910 (2015)]

$$S\sigma = \frac{\chi^{(3)}}{\chi^{(2)}}$$

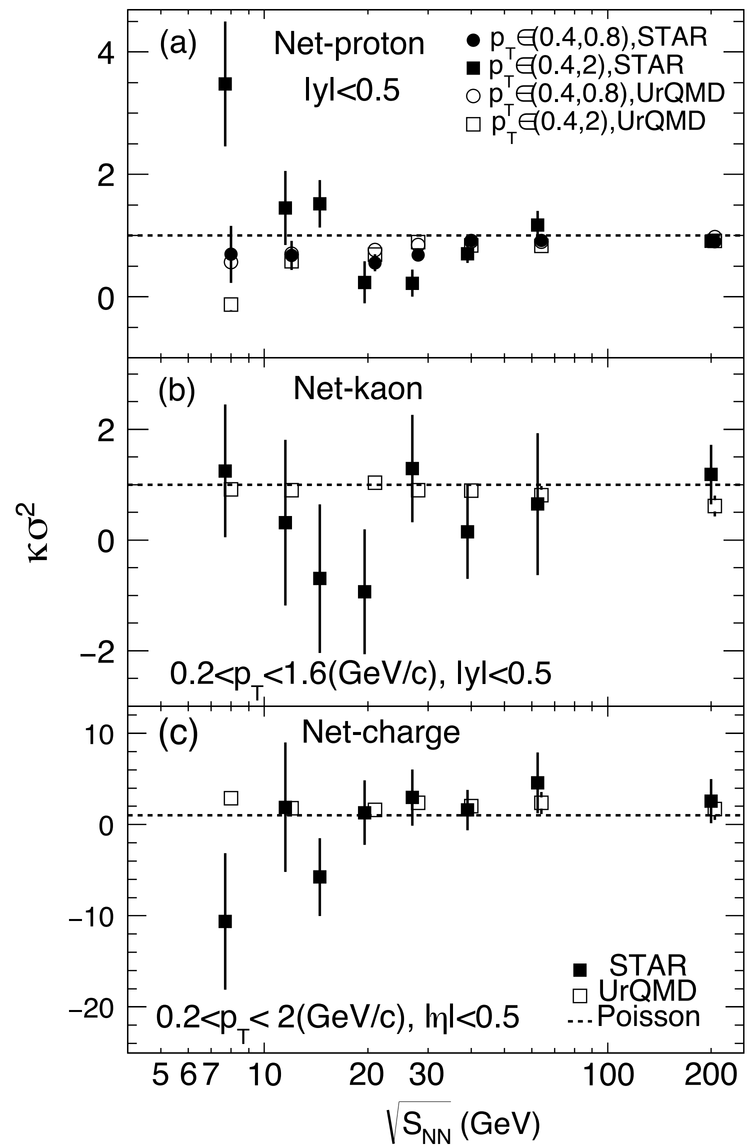
$$\kappa\sigma^2 = \frac{\chi^{(4)}}{\chi^{(2)}}$$

The higher moments of conserved quantum numbers (B, Q, S) are sensitive to the correlation length

STAR, PRC 94, 024901 (2016)



STAR, PRC 94, 024901 (2016)



LOCALIZATION OF CRITICAL POINT

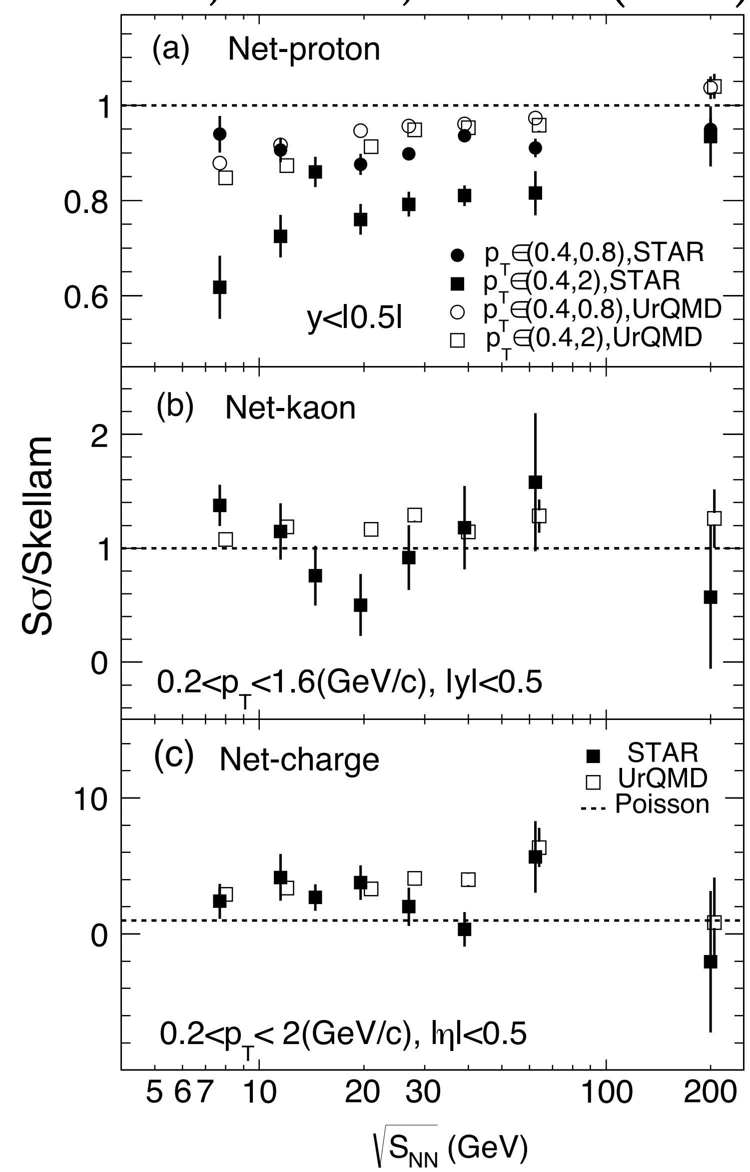
- moments of net-particle multiplicity distributions can be related to susceptibilities of conserved charges calculated on the lattice [P. Alba et al., Phys. Rev. C 92, 064910 (2015)]

$$S\sigma = \frac{\chi^{(3)}}{\chi^{(2)}}$$

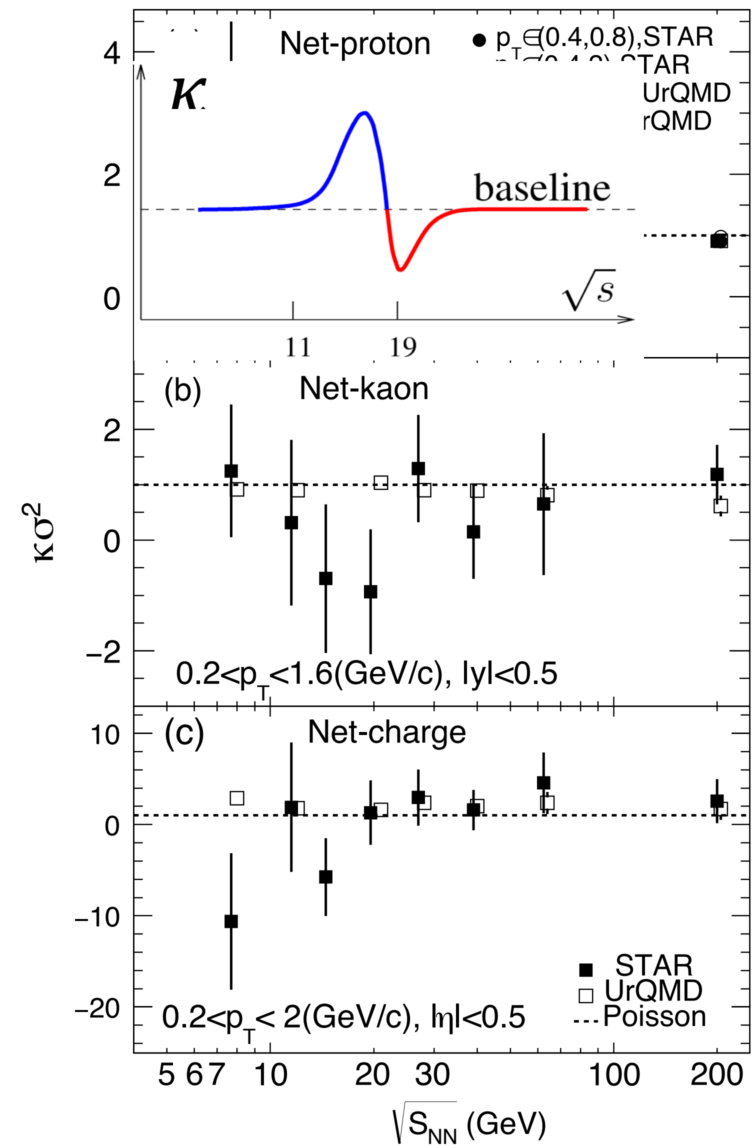
$$\kappa\sigma^2 = \frac{\chi^{(4)}}{\chi^{(2)}}$$

The higher moments of conserved quantum numbers (B, Q, S) are sensitive to the correlation length

STAR, PRC 94, 024901 (2016)



STAR, PRC 94, 024901 (2016)



LOCALIZATION OF CRITICAL POINT

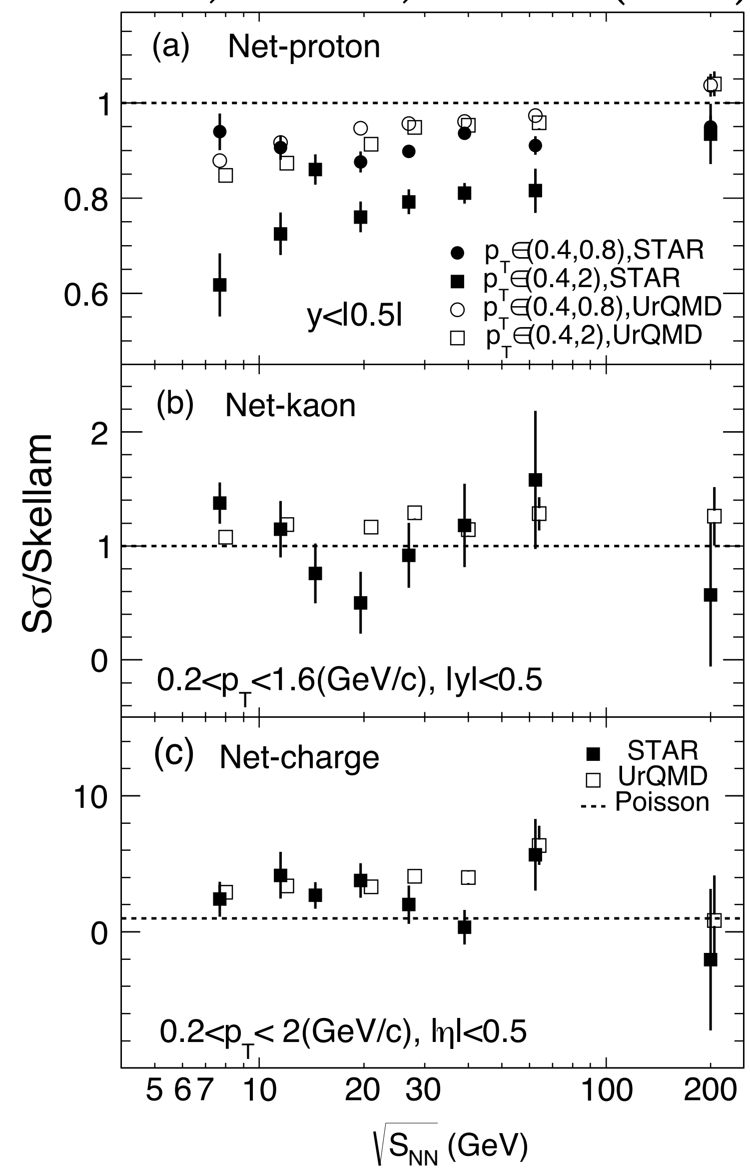
- moments of net-particle multiplicity distributions can be related to susceptibilities of conserved charges calculated on the lattice [P. Alba et al., Phys. Rev. C 92, 064910 (2015)]

$$S\sigma = \frac{\chi^{(3)}}{\chi^{(2)}}$$

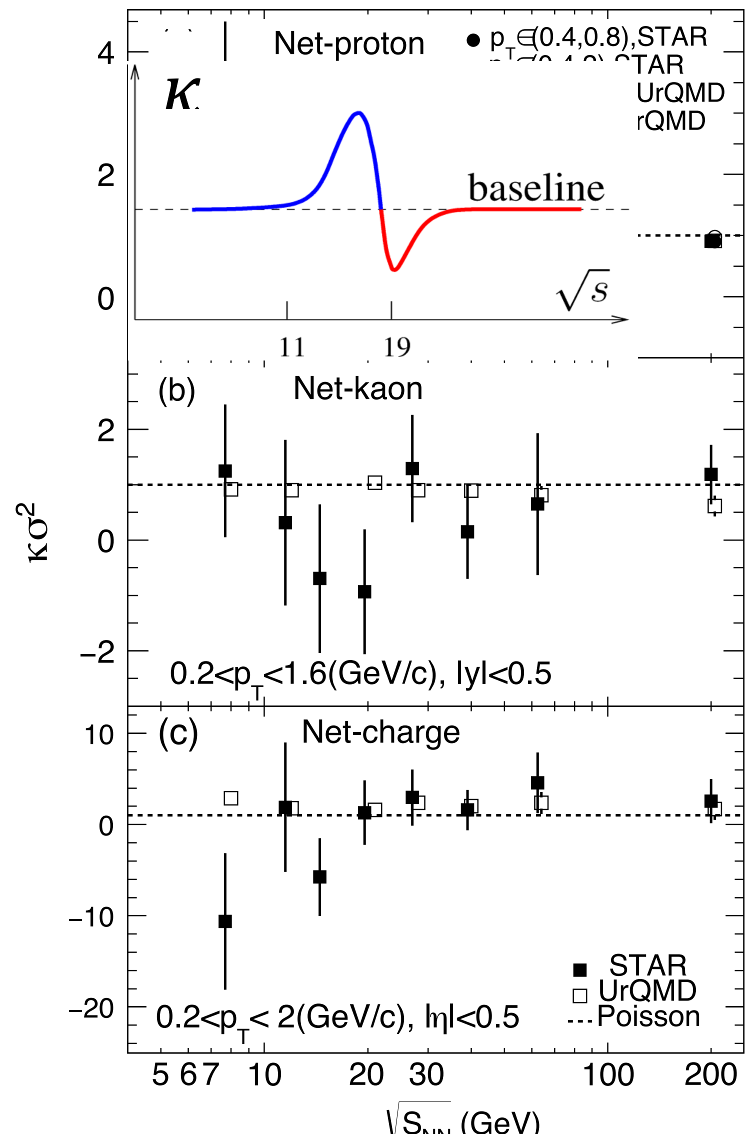
$$\kappa\sigma^2 = \frac{\chi^{(4)}}{\chi^{(2)}}$$

The higher moments of conserved quantum numbers (B, Q, S) are sensitive to the correlation length

STAR, PRC 94, 024901 (2016)

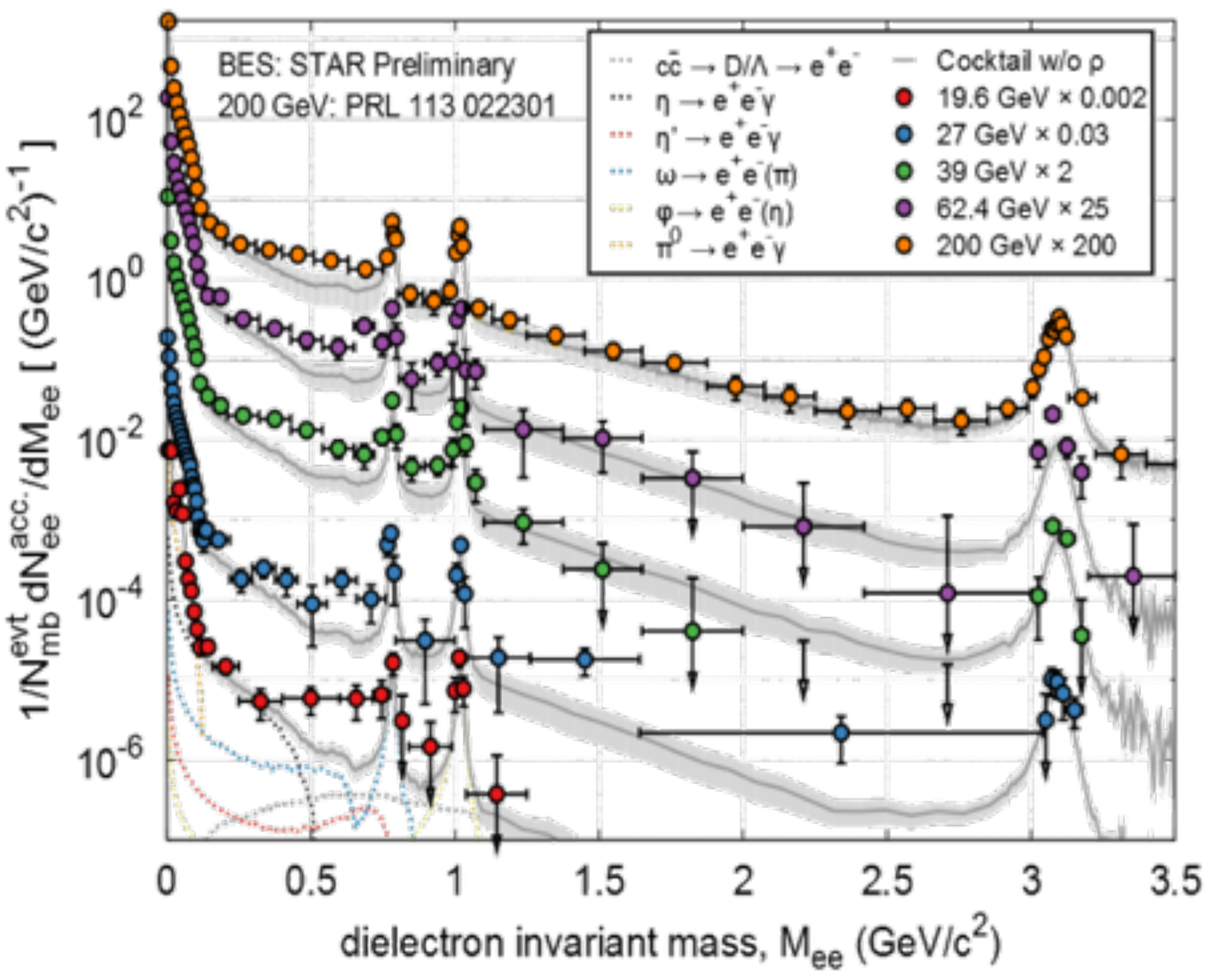


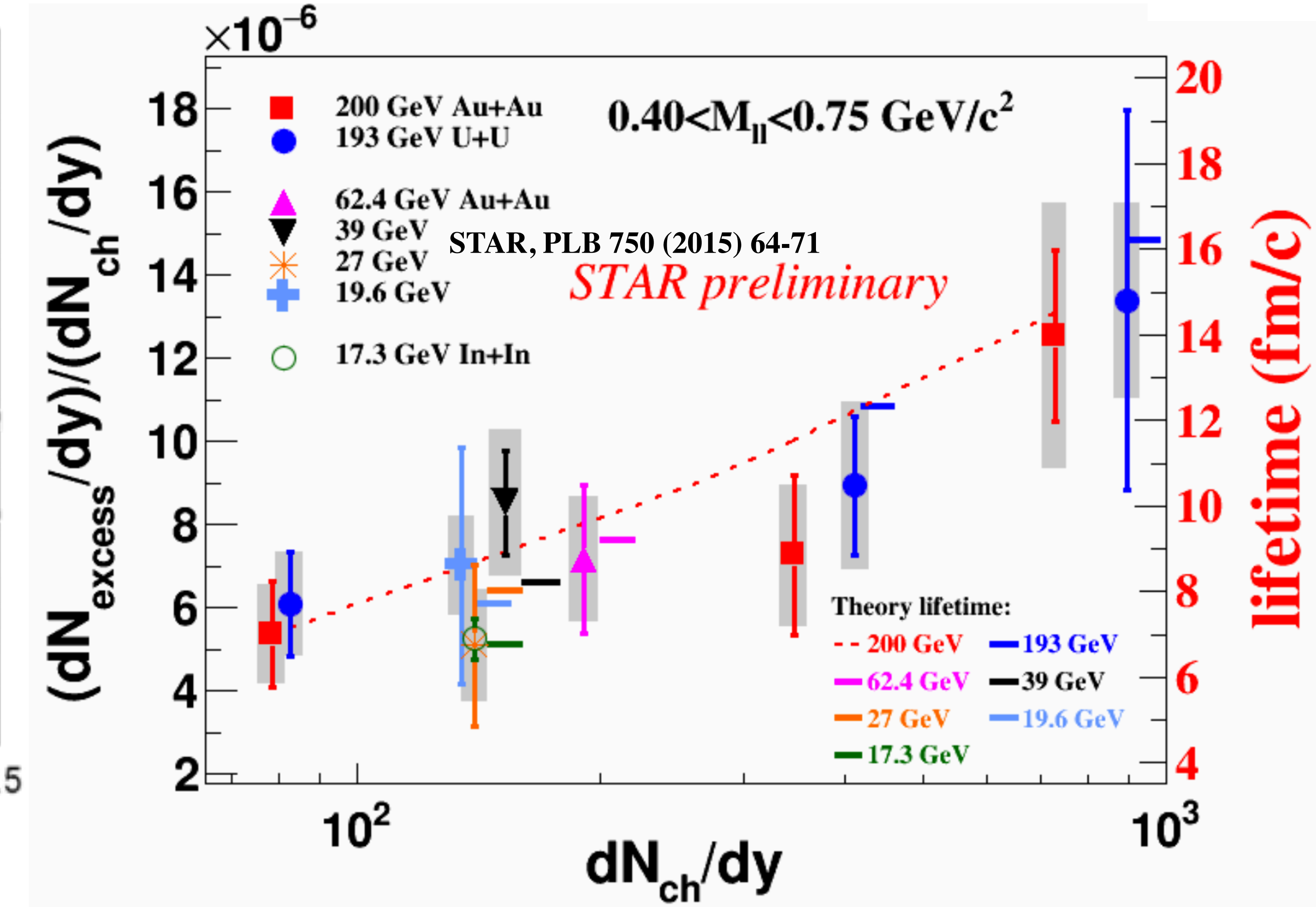
STAR, PRC 94, 024901 (2016)



- non-monotonic energy dependence of net-proton $\kappa\sigma^2$ and net-kaon $S\sigma$
  - missing data in the region below 7.7 GeV ⇒ fixed-target

CRITICAL POINT: LIFETIME INCREASE

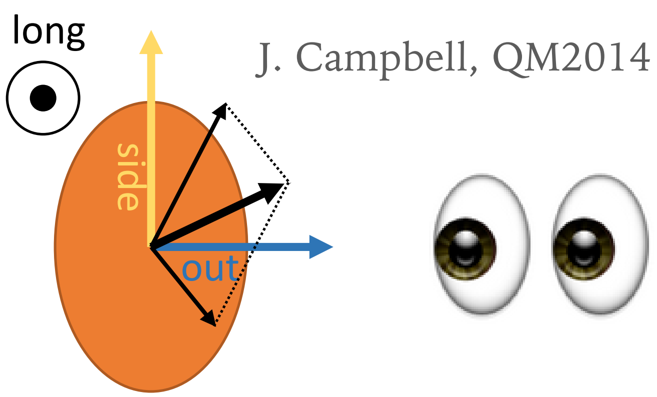




- dilepton yields sensitive to life time of the QGP?
  - increase in correlation lengths expected close to Critical Point ⇒ anomalous increase in the lifetime of the fireball
  - not enough statistics for any meaningful measurement < 19.6 GeV in BES-I
  - can we observe this in an increase of e^+e^- rates?

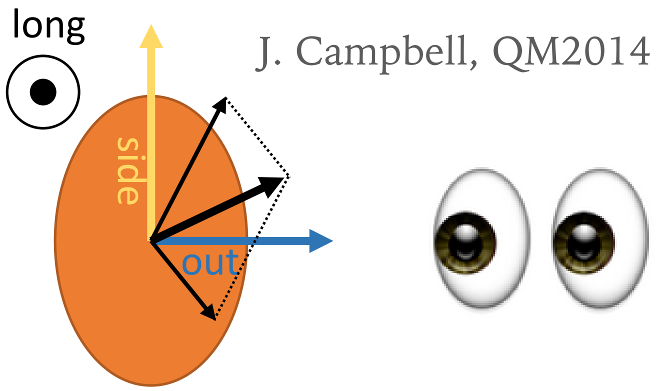
H. van Hees, R. Rapp
PRL 97 (2006)102301

CRITICAL POINT: PION INTERFEROMETRY



R - radius of a homogenous source of particle emission

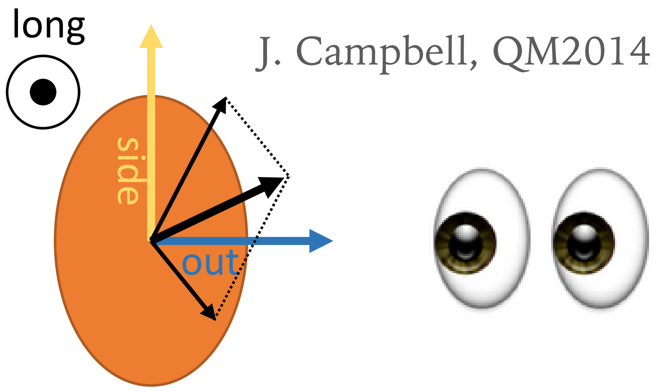
CRITICAL POINT: PION INTERFEROMETRY



R - radius of a homogenous source of particle emission

- R_{out}, R_{side}, and R_{long} used to orthogonally decompose the Gaussian radii

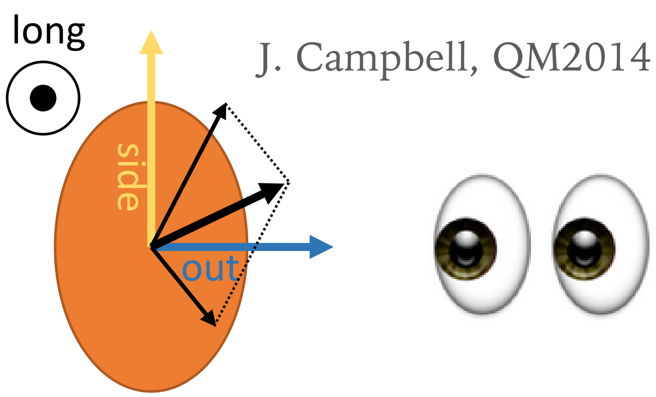
CRITICAL POINT: PION INTERFEROMETRY



R - radius of a homogenous source of particle emission

- R_{out}, R_{side}, and R_{long} used to orthogonally decompose the Gaussian radii
- difference $R^2_{out} - R^2_{side}$ related to the time duration of emission

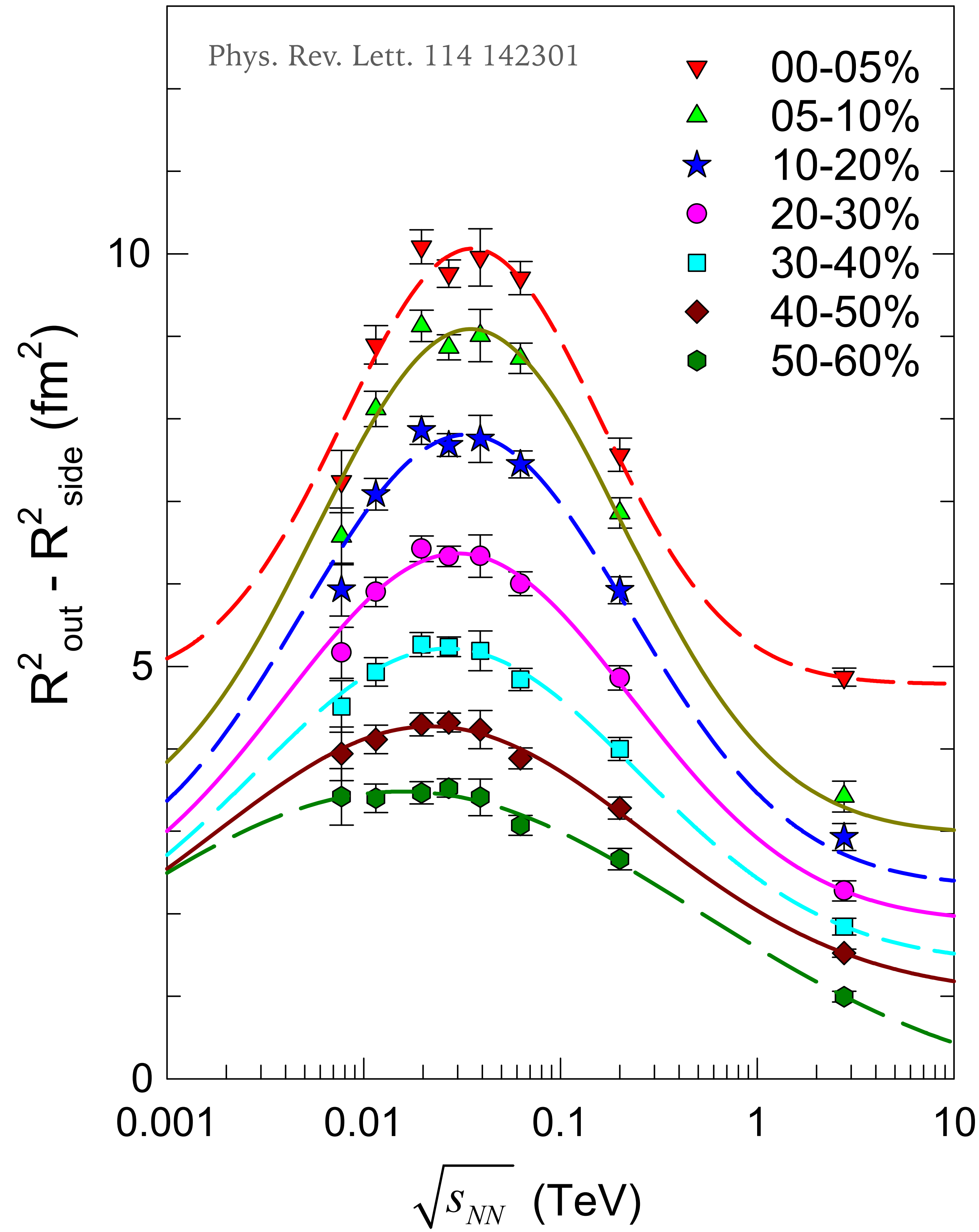
CRITICAL POINT: PION INTERFEROMETRY



R - radius of a homogenous source of particle emission

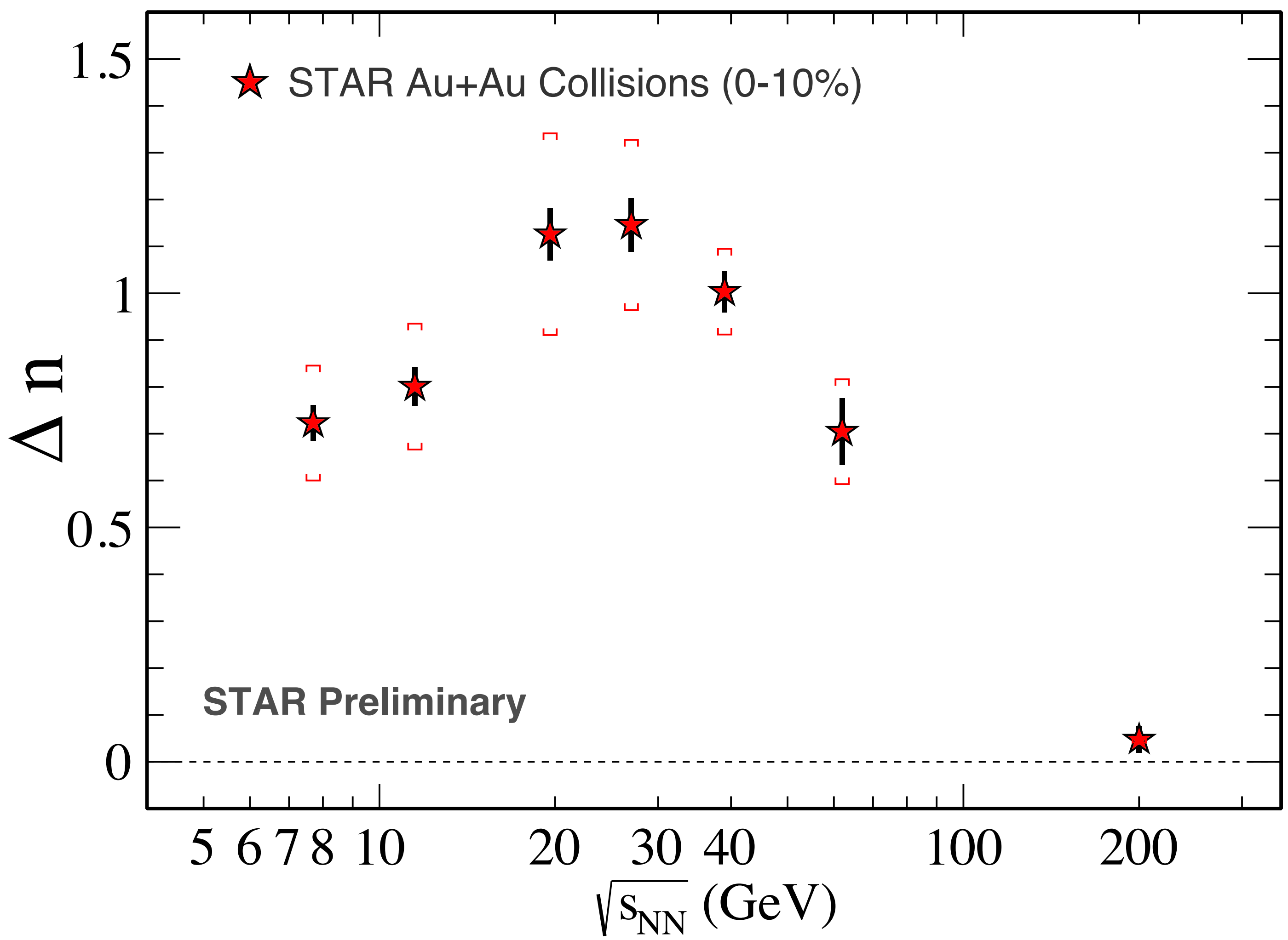
- R_{out}, R_{side}, and R_{long} used to orthogonally decompose the Gaussian radii
- difference $R^2_{out} - R^2_{side}$ related to the time duration of emission
- data at all centralities vary according to the Finite Size Scaling (FSS) behavior

[Phys. Rev. Lett. 114 142301]



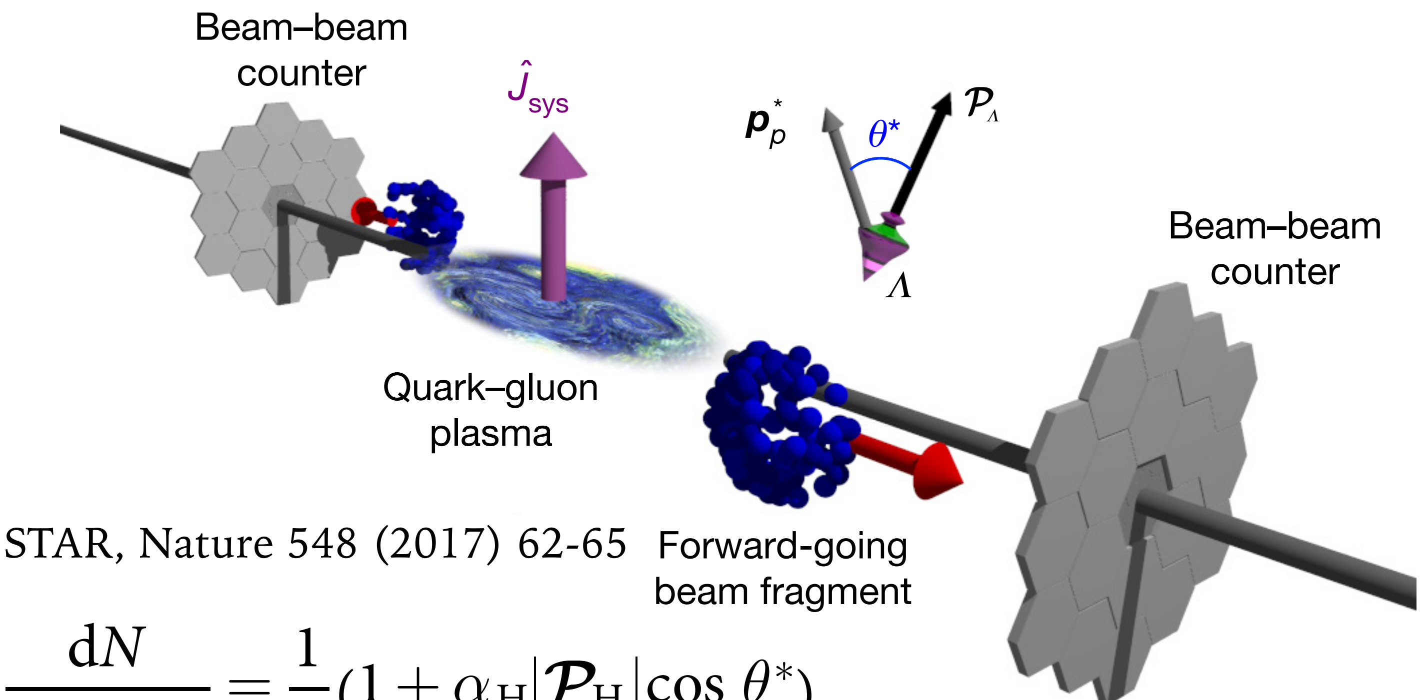
CRITICAL POINT: NEUTRON DENSITY FLUCTUATION

- can be derived from the yield ratio of light nuclei $N_t N_p / N_d^2 \approx g(1+\Delta n)$, $g=0.29$ [PLB 774 (2017) 103]
- non-monotonic energy dependence with a peak around 20 - 27 GeV



GLOBAL HYPERON POLARIZATION

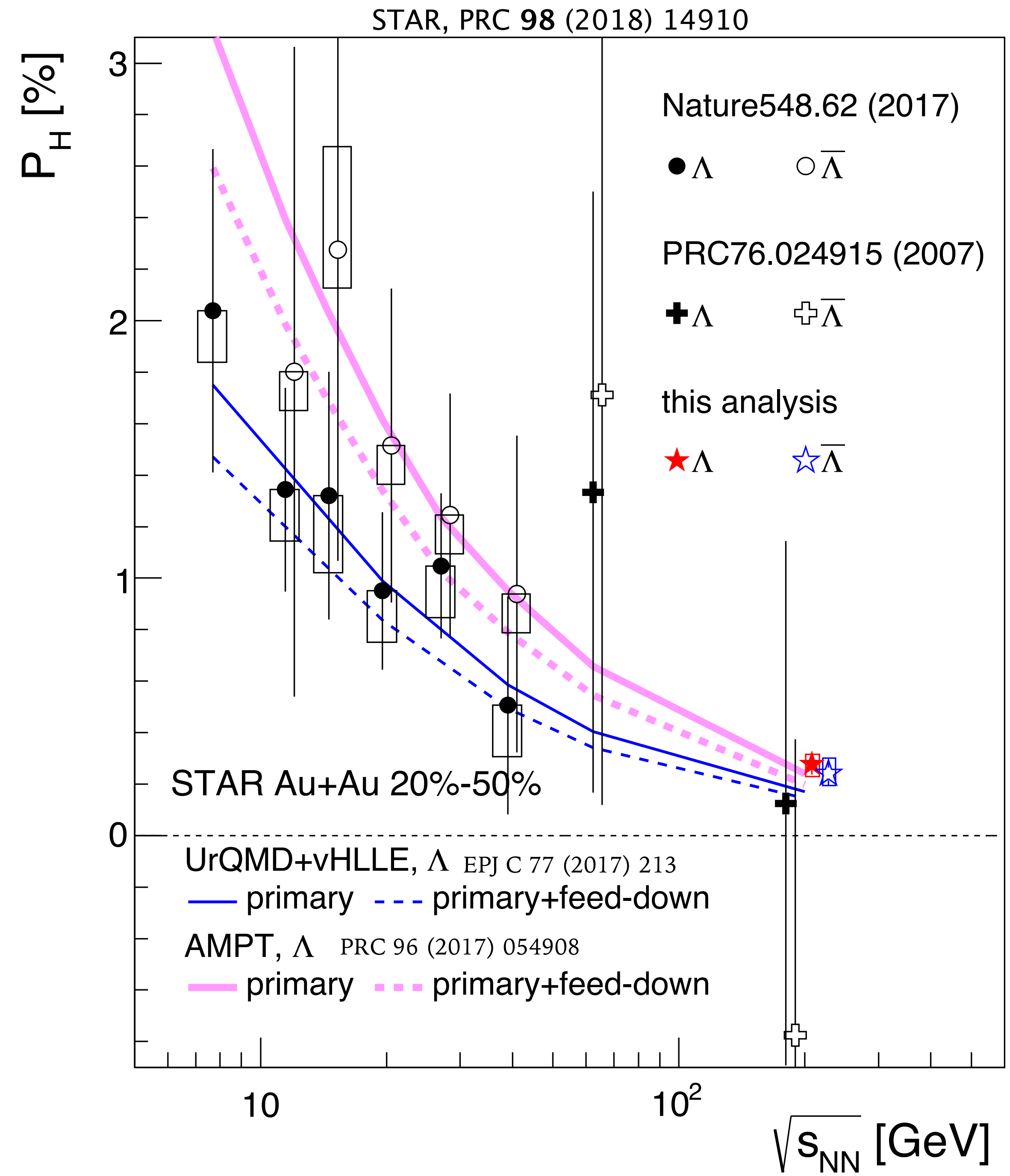
- measurement of vorticity ω of the QGP (perfect liquid)



STAR, Nature 548 (2017) 62-65

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}(1+\alpha_H|\mathcal{P}_H|\cos\theta^*)$$

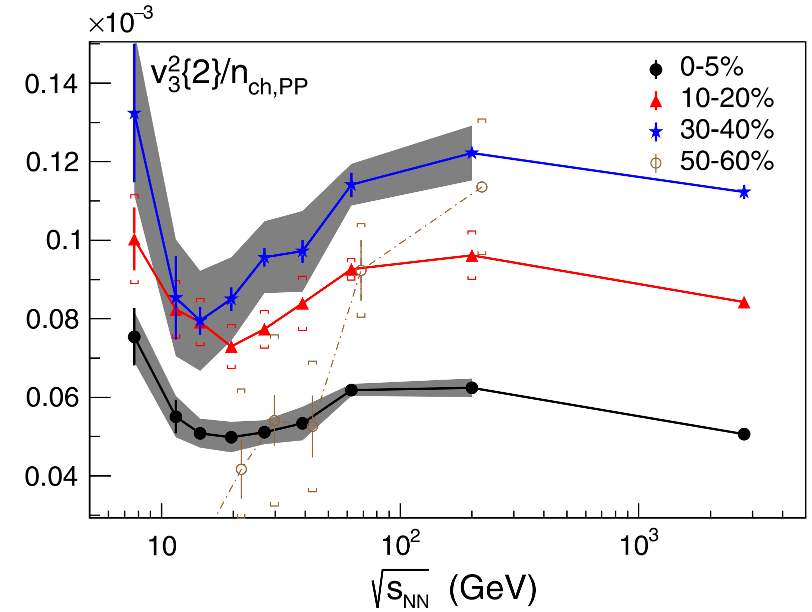
$$\omega = k_B T\left(\overline{\mathcal{P}}_{\Lambda'} + \overline{\mathcal{P}}_{\overline{\Lambda}'}\right)/\hbar$$

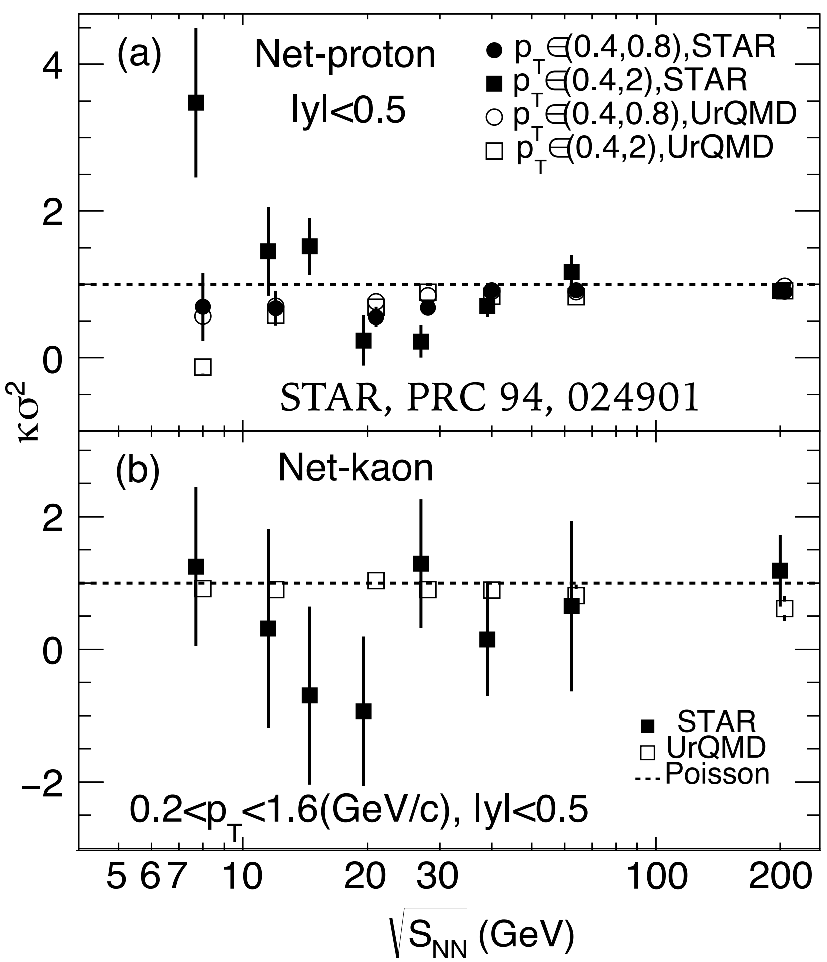


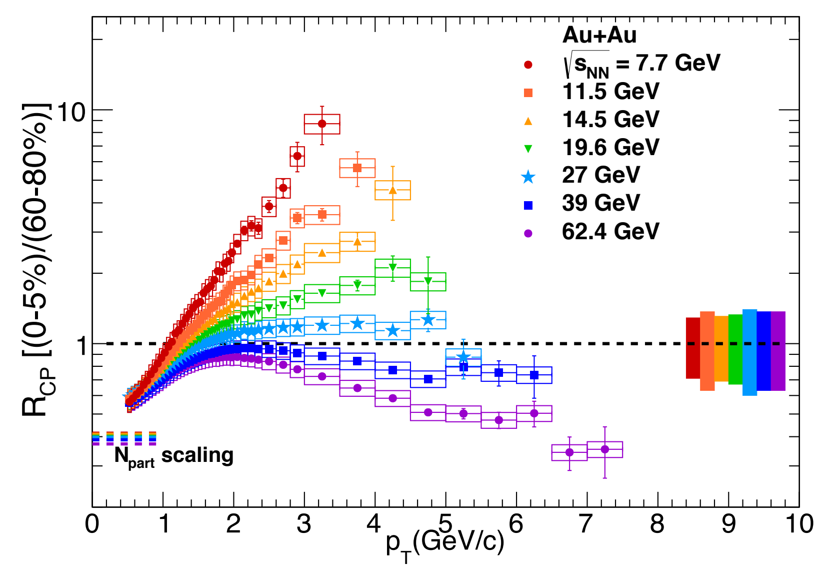
- with the new 200 GeV results, the polarization is found to decrease at higher collision energy
- might provide important information on the the system
  - axial charge separation due to the Chiral Vortical Effect [PRC 97 (2018) 041902]
- difference between P_H and $P_{\overline{H}}$ provide constraints on the magnitude and the lifetime of the magnetic field in heavy-ion collisions [PRC 95 (2017) 054902]

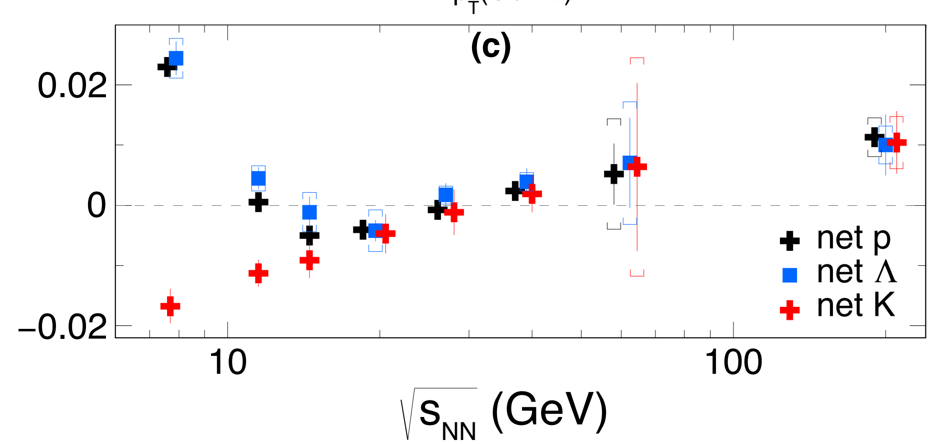
SUMMARY OF BES-I

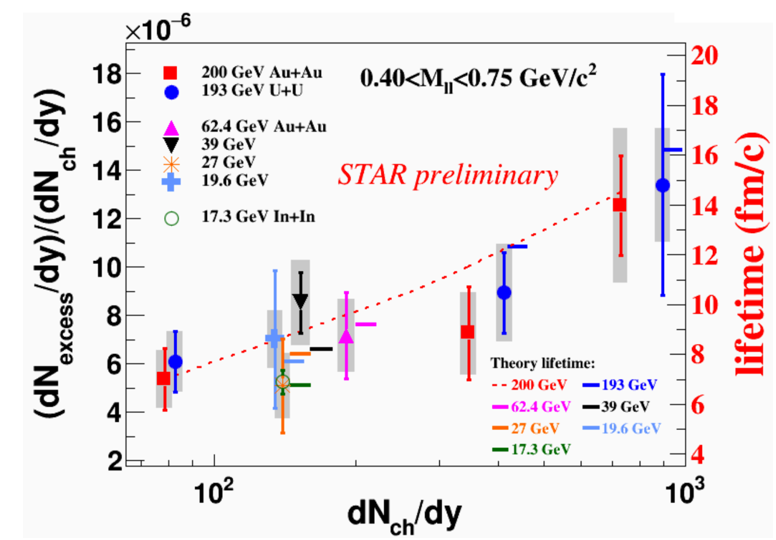
- BES-I results hint at critical behavior
- most measurement were limited by statistics and with large systematic uncertainties
- RHIC BES-II with more statistics and detector upgrades

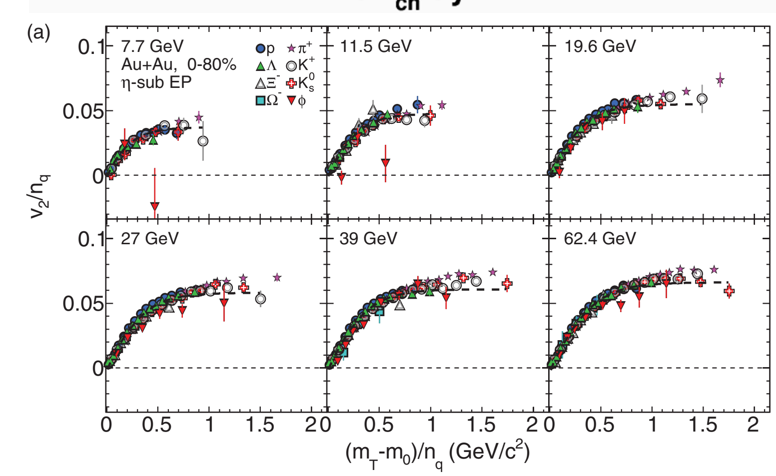






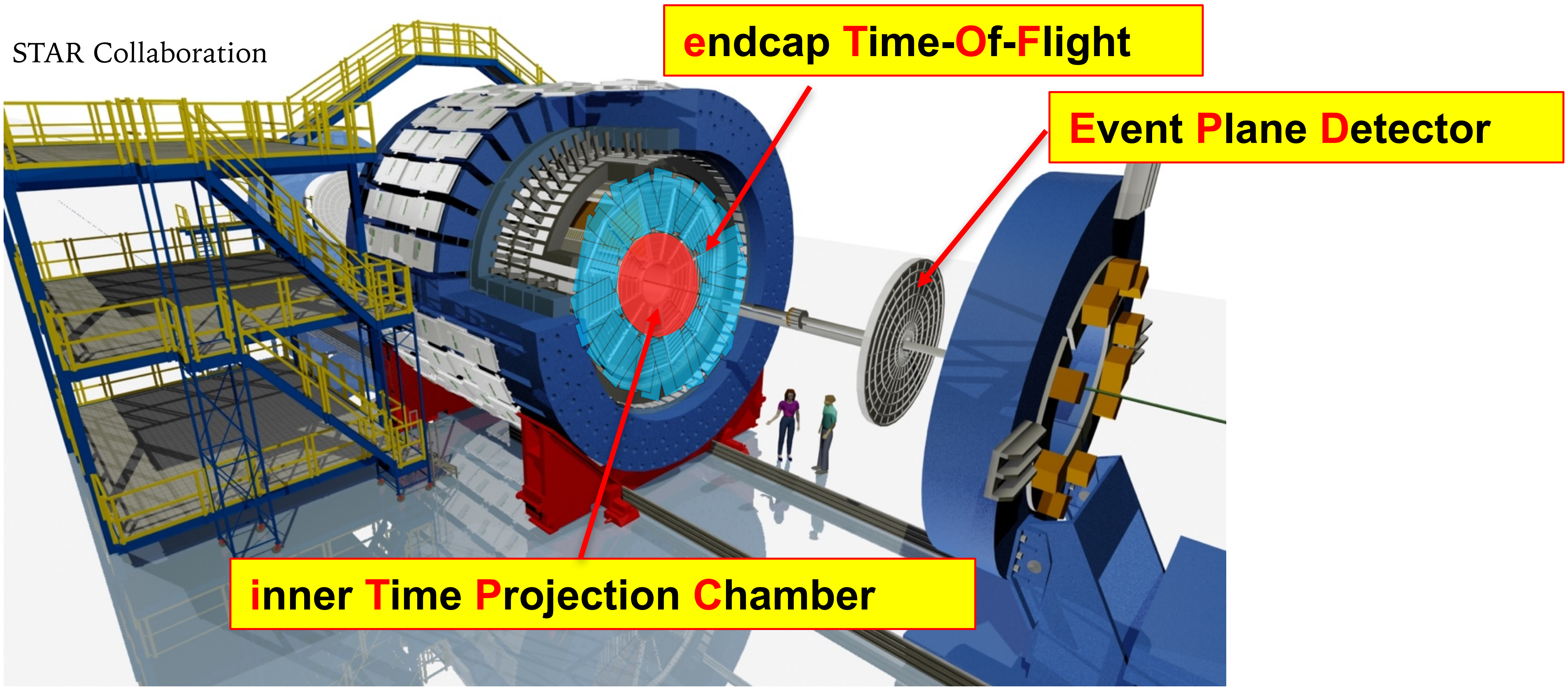






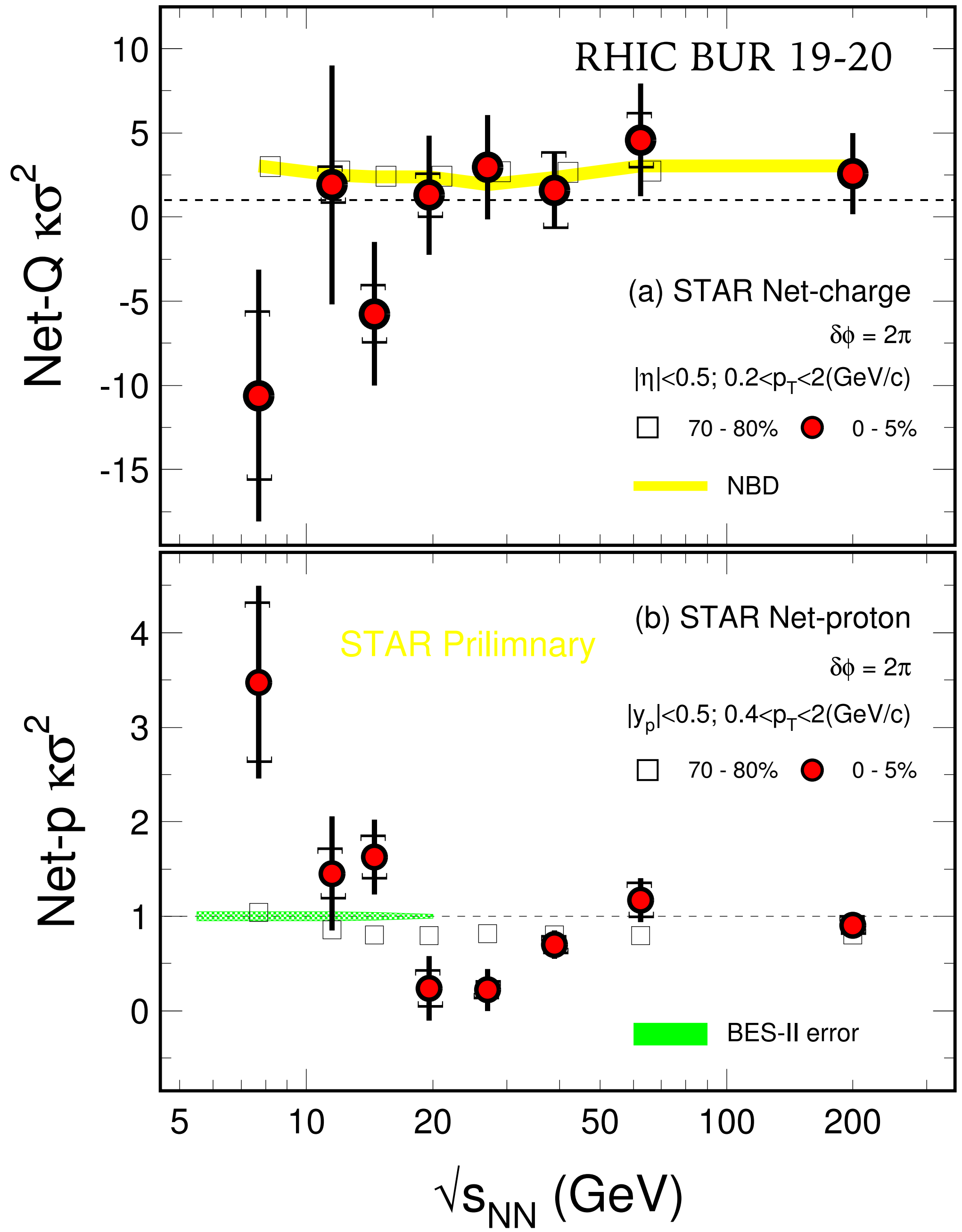
PART II – UPGRADES AND PROJECTIONS FOR BES-II

STAR DETECTOR UPGRADES FOR BES-II



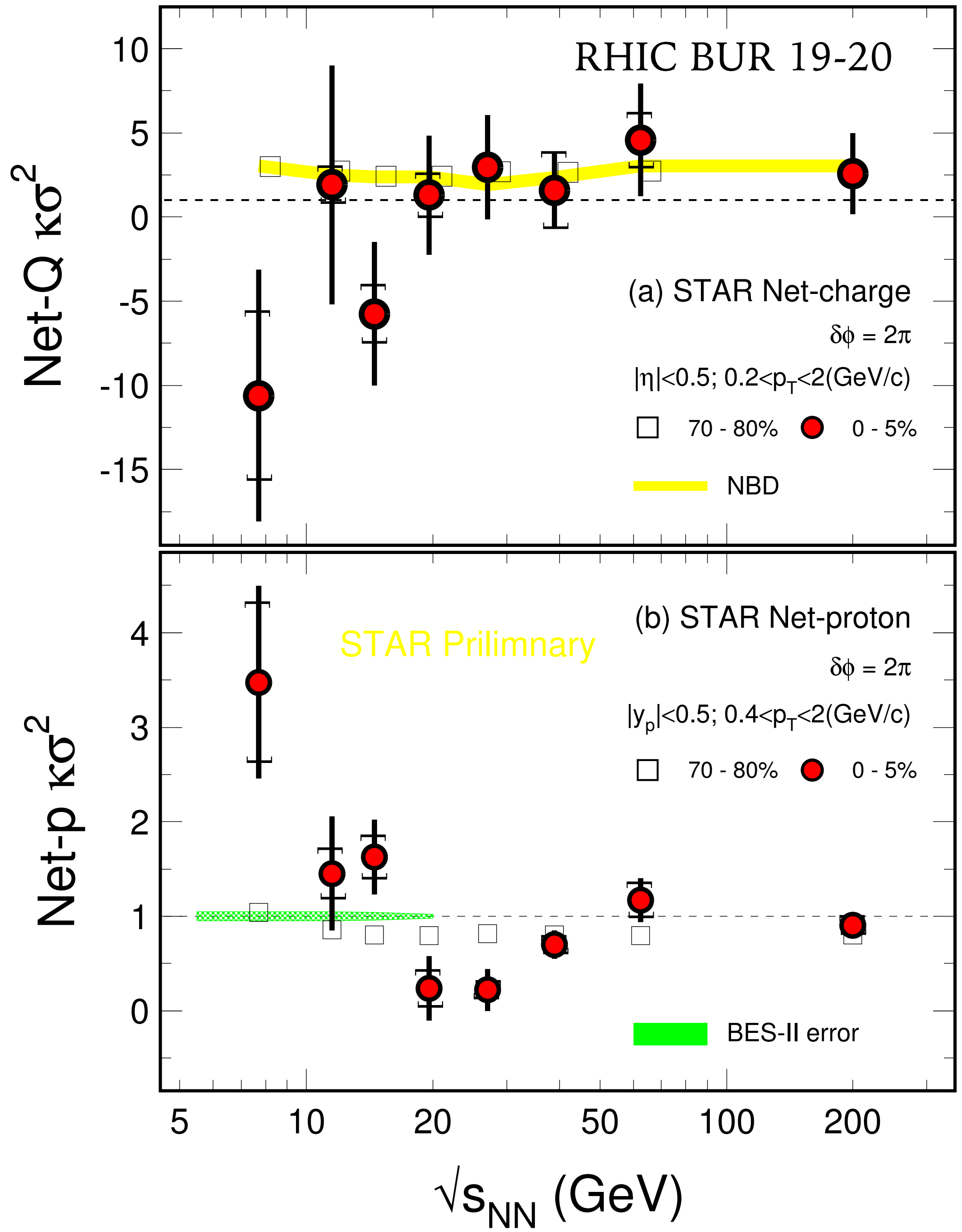
iTPC upgrade	EPD upgrade	eTOF upgrade
Continuous pad rows Replace all inner TPC sectors	**Replace Beam Beam Counter**	**Add CBM TOF modules and electronics (FAIR Phase 0)**
$\|\eta\|<1.5$ (was 1.0)	**$2.1<\|\eta\|<5.1$**	**$-1.6<\eta<-1.1$**
p_T >60 MeV/c (was 150MeV/c)	Better trigger & b/g reduction	Extend forward PID capability
Better dE/dx resolution Better momentum resolution	Greatly improved Event Plane info (esp. 1st-order EP)	Allows higher energy range of Fixed Target program
Fully operational in 2019	**Fully operational in 2018**	**Fully operational in 2019**

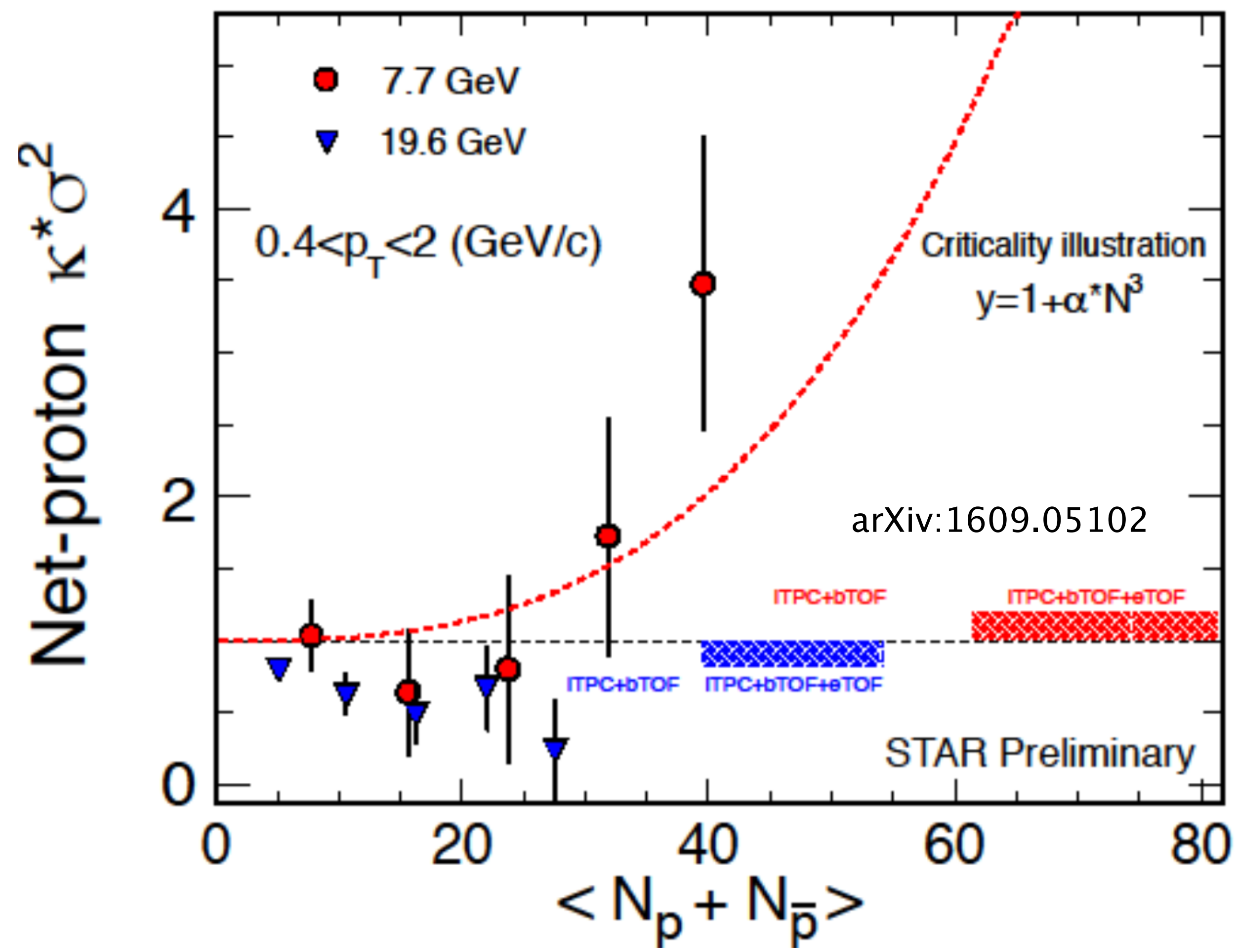
LOCALIZATION OF CRITICAL POINT



- significant contribution of iTPC and eTOF

LOCALIZATION OF CRITICAL POINT



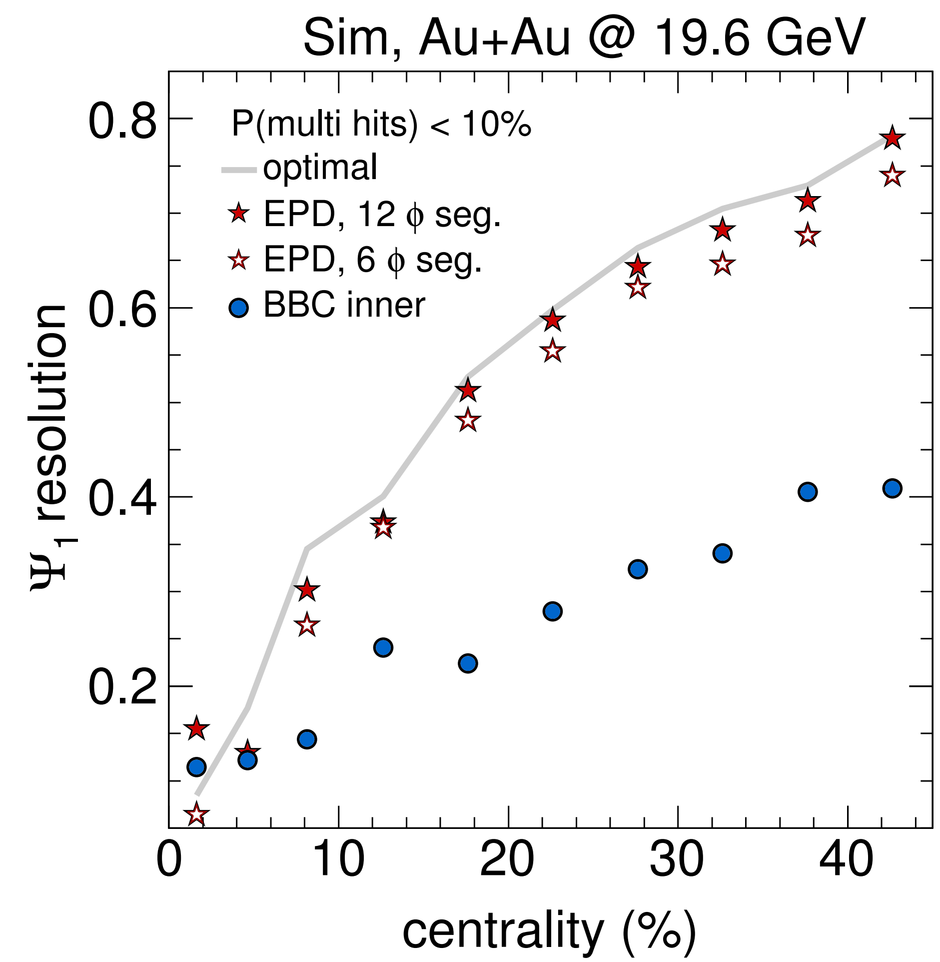


- antiprotons produced more at mid-rapidity
- added coverage by eTOF will enhance the fluctuation signal ⇒ clearer and more significant indication of critical behavior

- significant contribution of iTPC and eTOF

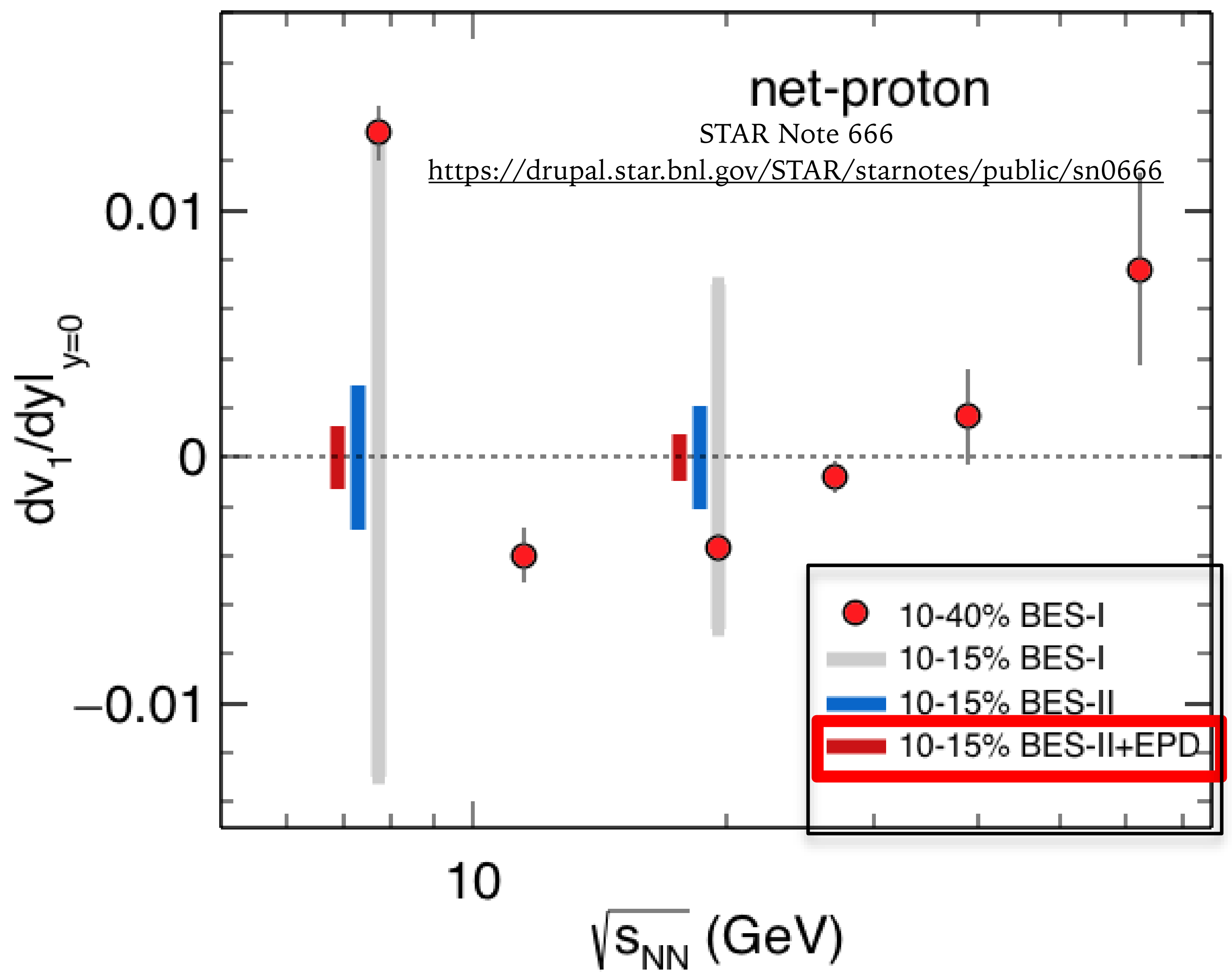
DIRECTED FLOW

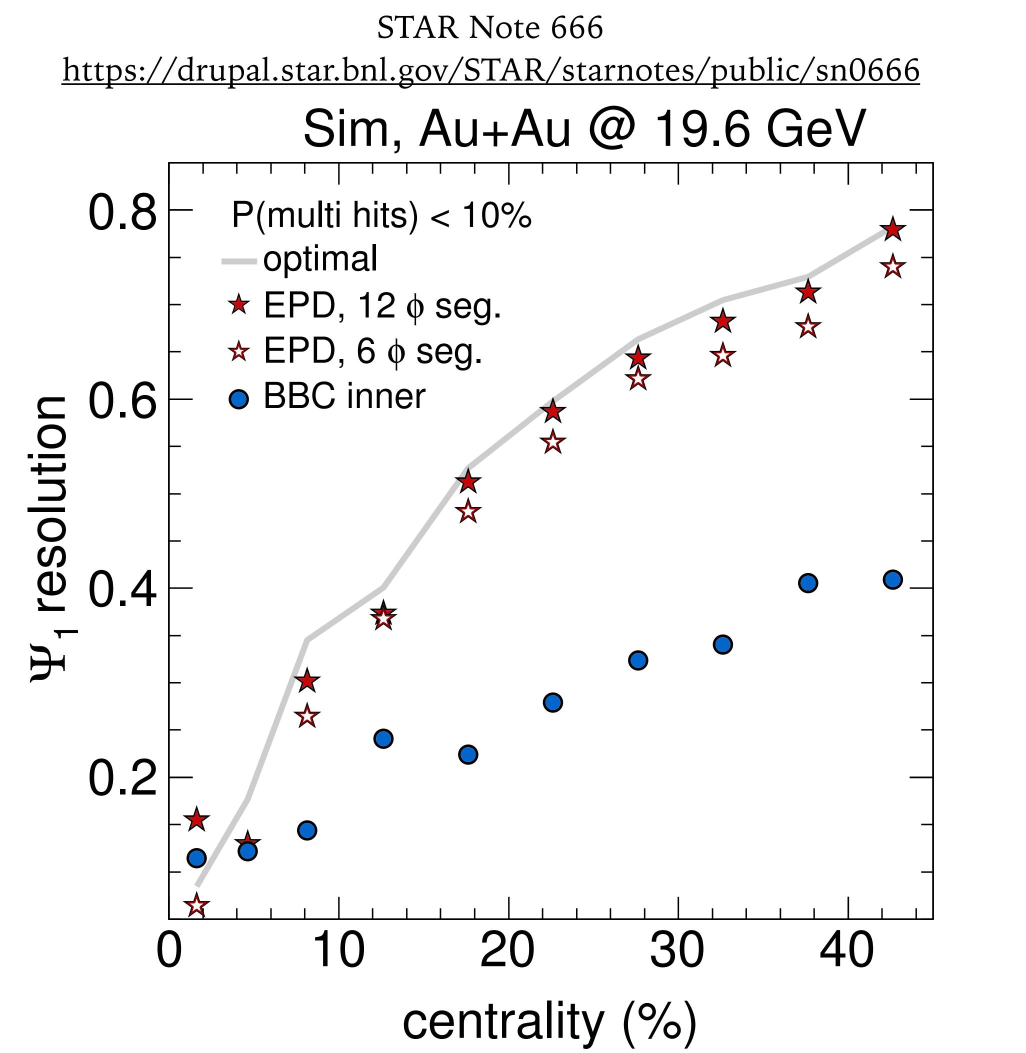
STAR Note 666
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0666



- EPD
  - significantly better event plane resolution than BBC
  - fine centrality binning in BES-II

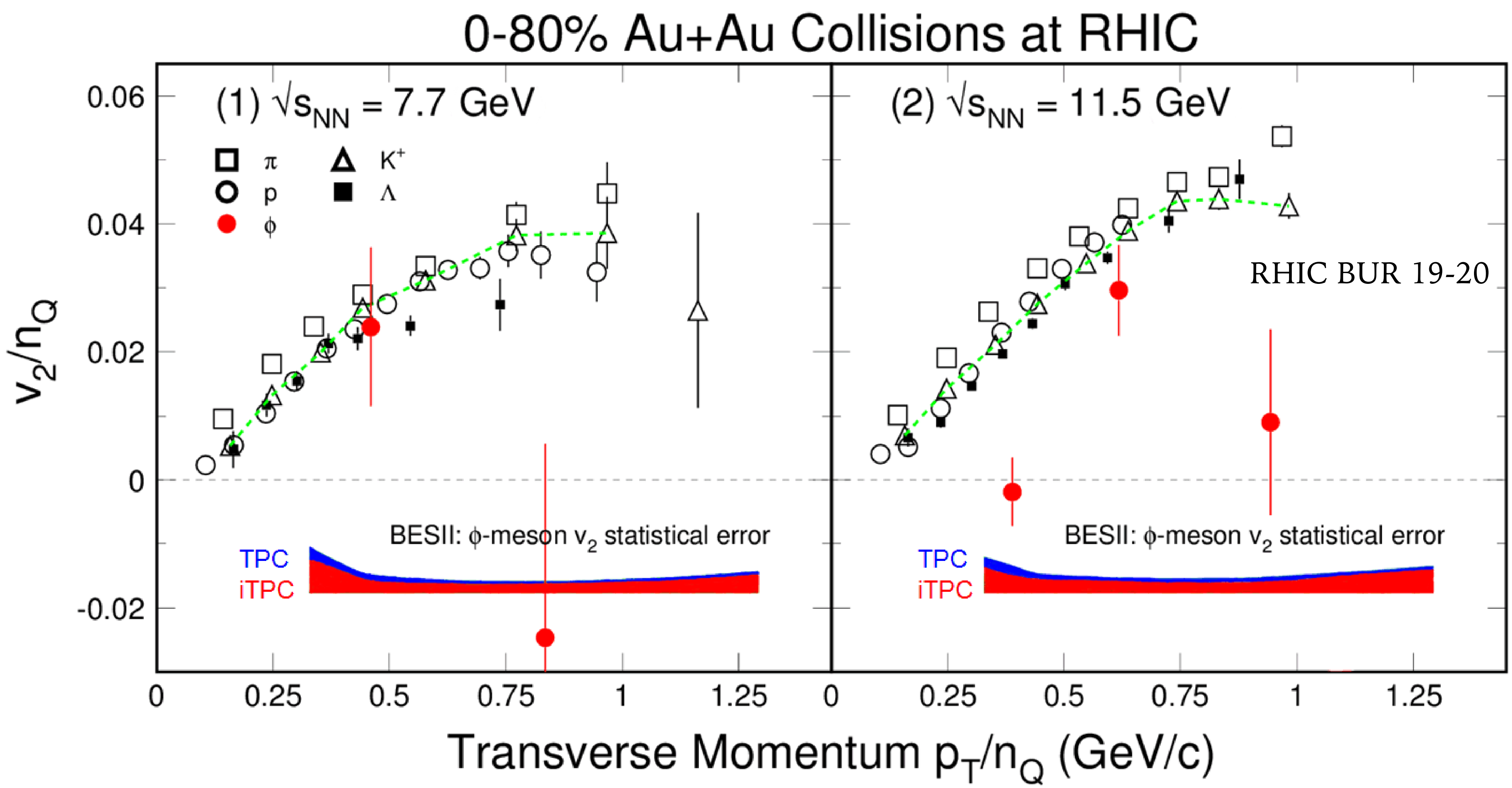
DIRECTED FLOW





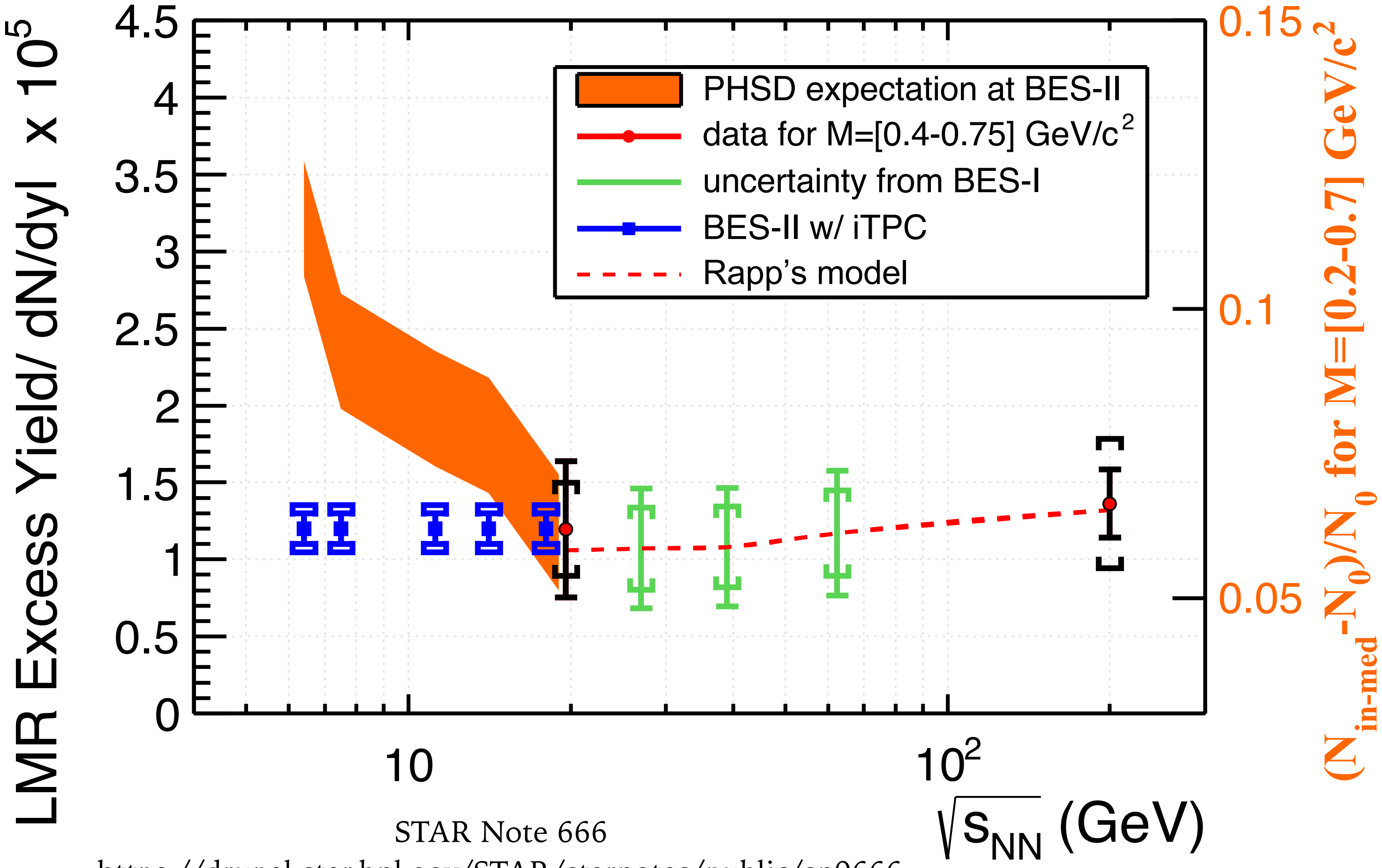
- EPD
  - significantly better event plane resolution than BBC
  - fine centrality binning in BES-II

ELLIPTIC FLOW



- increased statistics in BES-II will allow to reach a meaningful physics conclusion

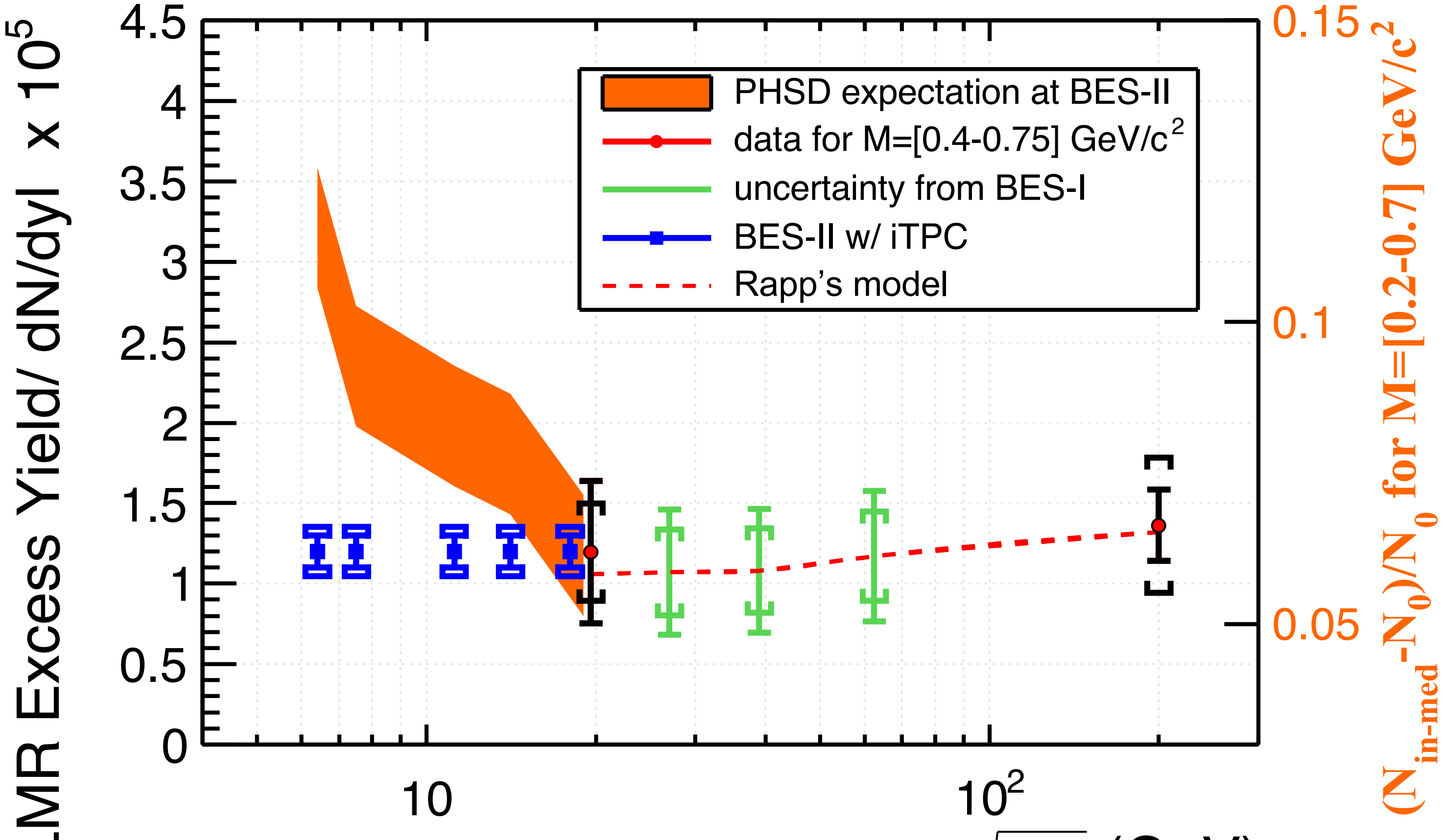
DILEPTON CONTINUUM



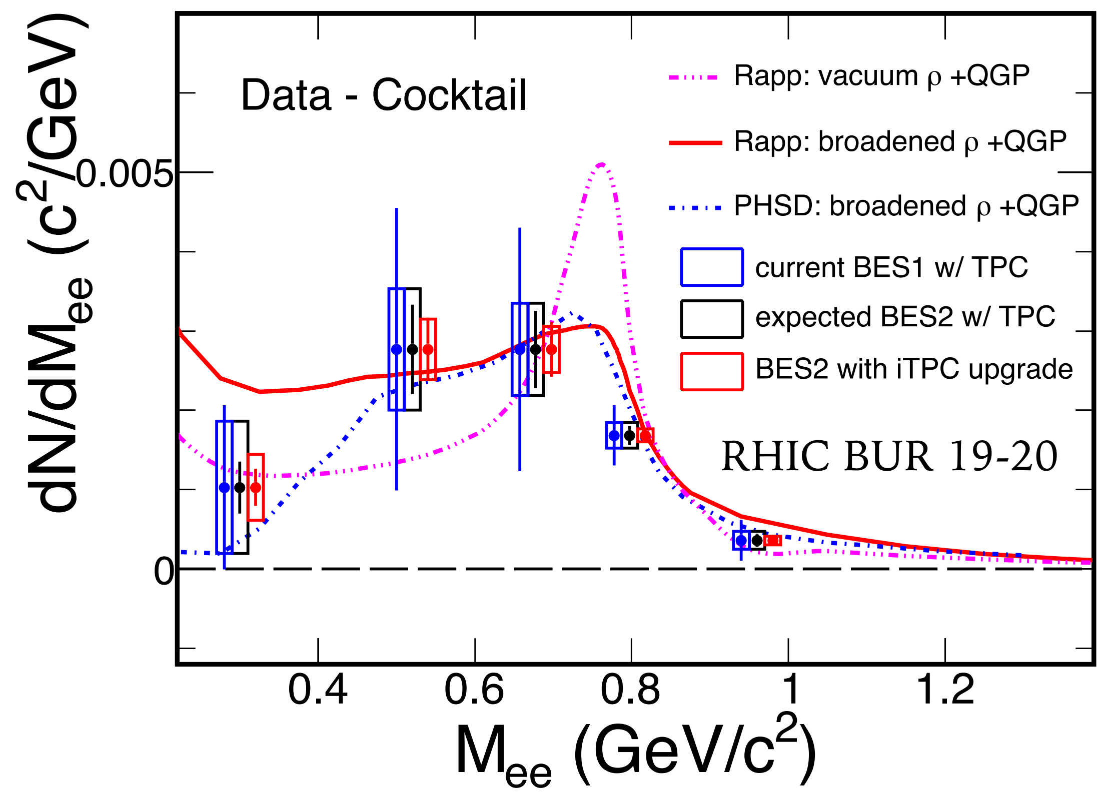
STAR Note 666
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0666

- first measurements for energies < 19.6 GeV possible
- systematic uncertainties reduced by iTPC
- the requested event statistics should allow measurements in the intermediate mass range

DILEPTON CONTINUUM

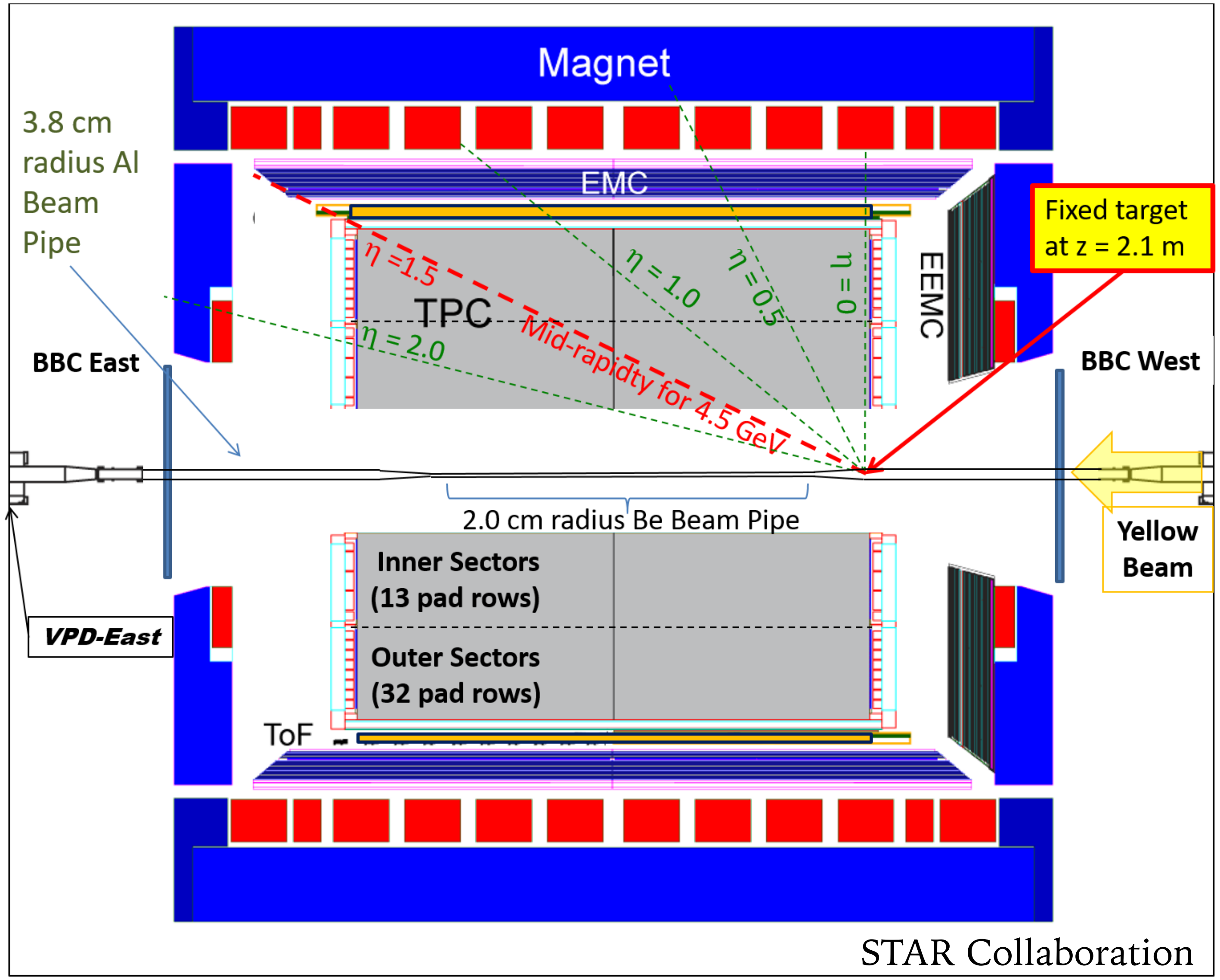


STAR Note 666
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0666



- first measurements for energies < 19.6 GeV possible
- systematic uncertainties reduced by iTPC
- the requested event statistics should allow measurements in the intermediate mass range

FIXED TARGET PROGRAM AT RHIC

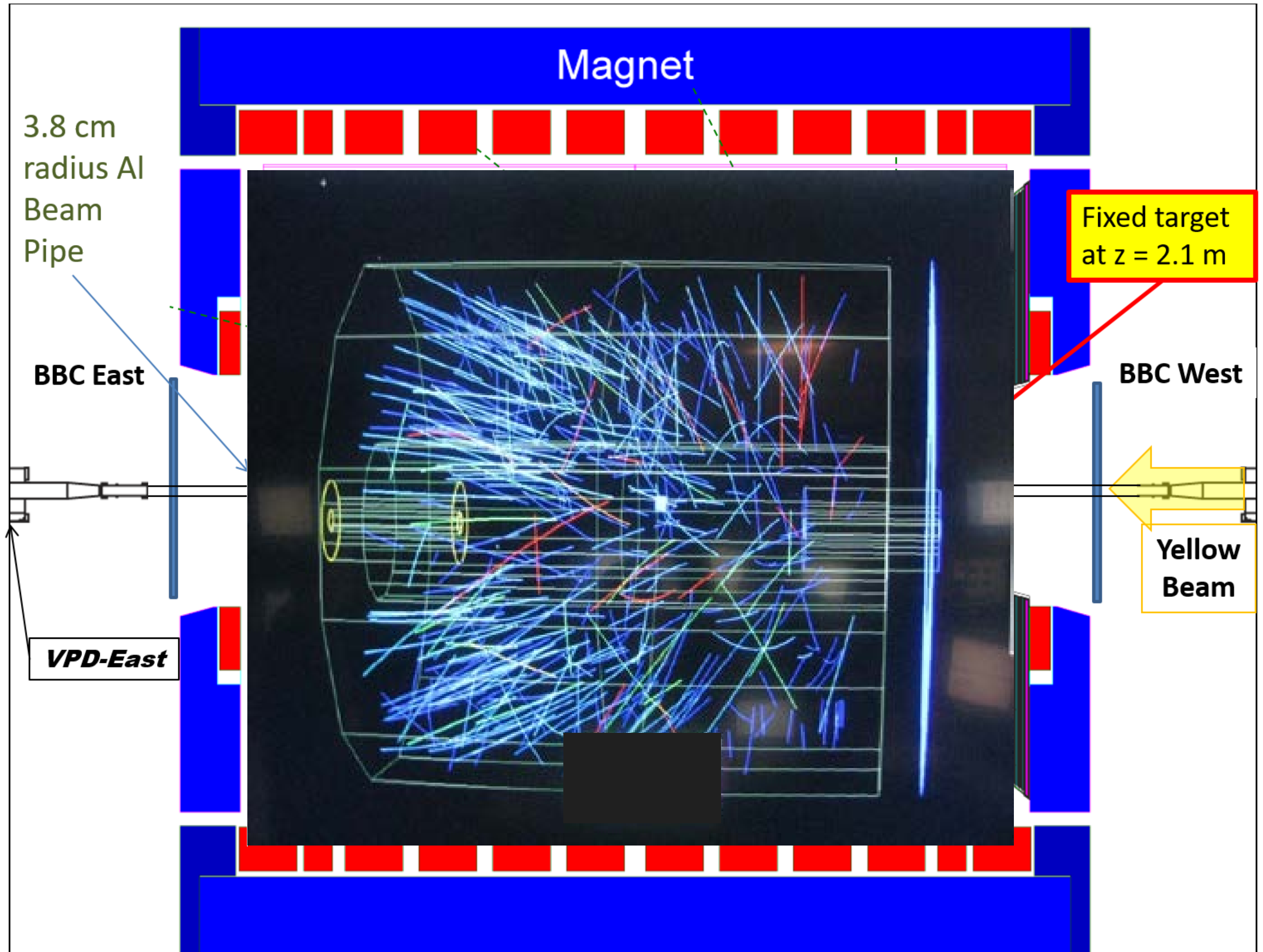


$\sqrt{s_{NN}}$	CMS Rapidity	μ_B [MeV]	
39.0	0	115	*Collider mode*
27.0	0	155	
19.6	0	205	
14.5	0	260	
11.5	0	315	
7.7	0	420	
7.7	2.10	420	*Fixed target mode*
6.2	1.87	487	
5.2	1.68	541	
4.5	1.52	589	
3.9	1.37	633	
3.5	1.25	666	
3.2	1.13	699	
3.0	1.05	721	

J. Cleymans et al., Phys. Rev. C73 (2006) 034905

- luminosity ~ γ^3 (relativistic gamma of an ion beam)
- overlap with collider energies
- STAR took 260M good events at 3.85 GeV this year already

FIXED TARGET PROGRAM AT RHIC



STAR Collaboration

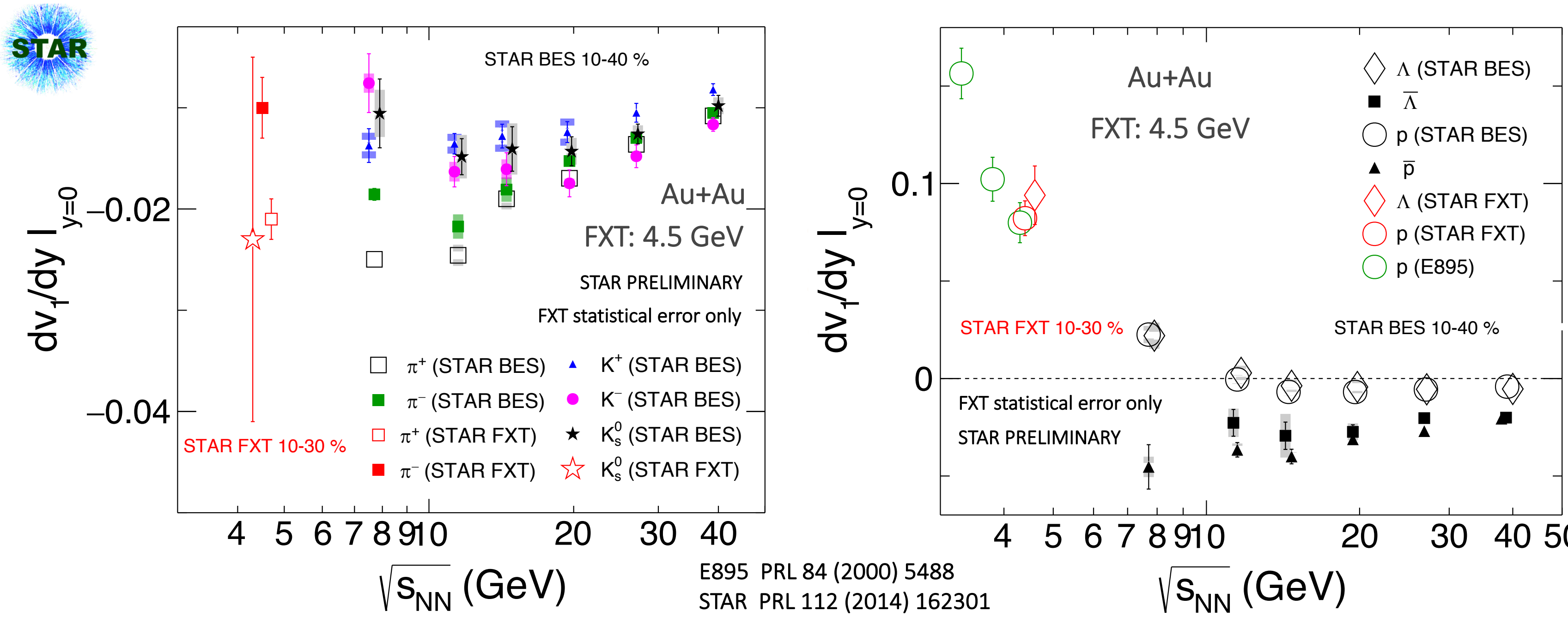
$\sqrt{s_{NN}}$	CMS Rapidity	μ_B [MeV]	Mode
39.0	0	115	*Collider mode*
27.0	0	155	*Collider mode*
19.6	0	205	*Collider mode*
14.5	0	260	*Collider mode*
11.5	0	315	*Collider mode*
7.7	0	420	*Collider mode*
7.7	2.10	420	*Fixed target mode*
6.2	1.87	487	*Fixed target mode*
5.2	1.68	541	*Fixed target mode*
4.5	1.52	589	*Fixed target mode*
3.9	1.37	633	*Fixed target mode*
3.5	1.25	666	*Fixed target mode*
3.2	1.13	699	*Fixed target mode*
3.0	1.05	721	*Fixed target mode*

J. Cleymans et al., Phys. Rev. C73 (2006) 034905

- luminosity ~ γ^3 (relativistic gamma of an ion beam)
- overlap with collider energies
- STAR took 260M good events at 3.85 GeV this year already

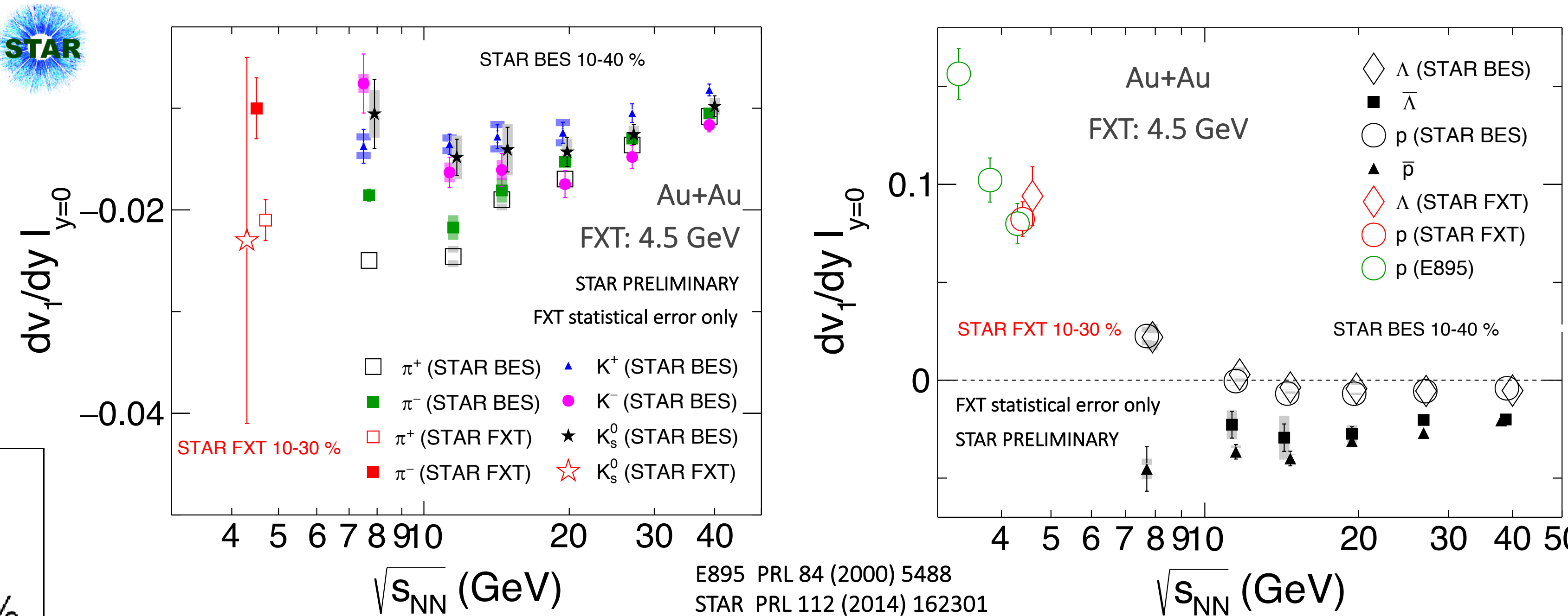
FIXED TARGET PROGRAM AT RHIC

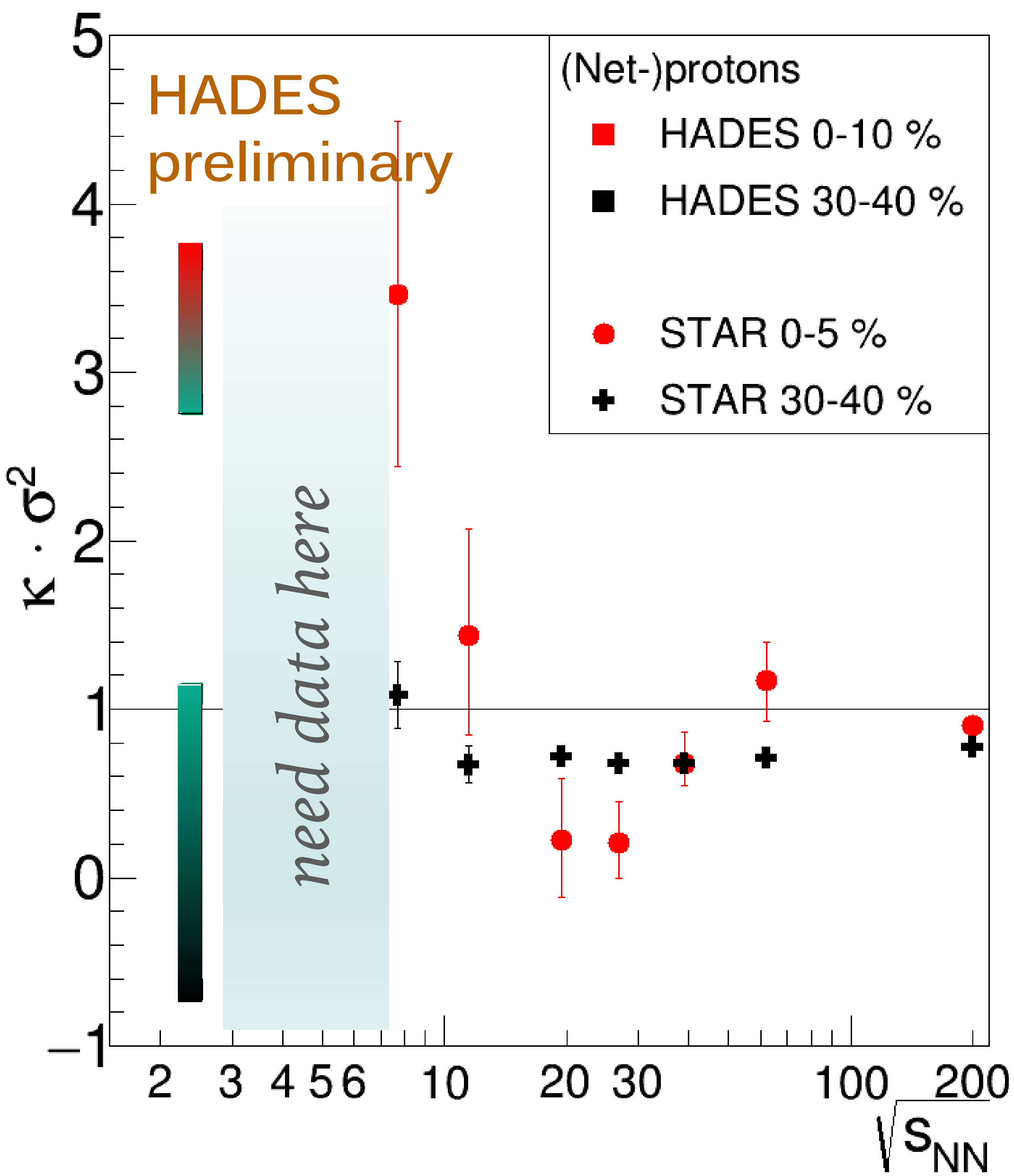
- successful test run in 2015 $\sqrt{s_{NN}} = 4.5$ GeV AuAu



FIXED TARGET PROGRAM AT RHIC

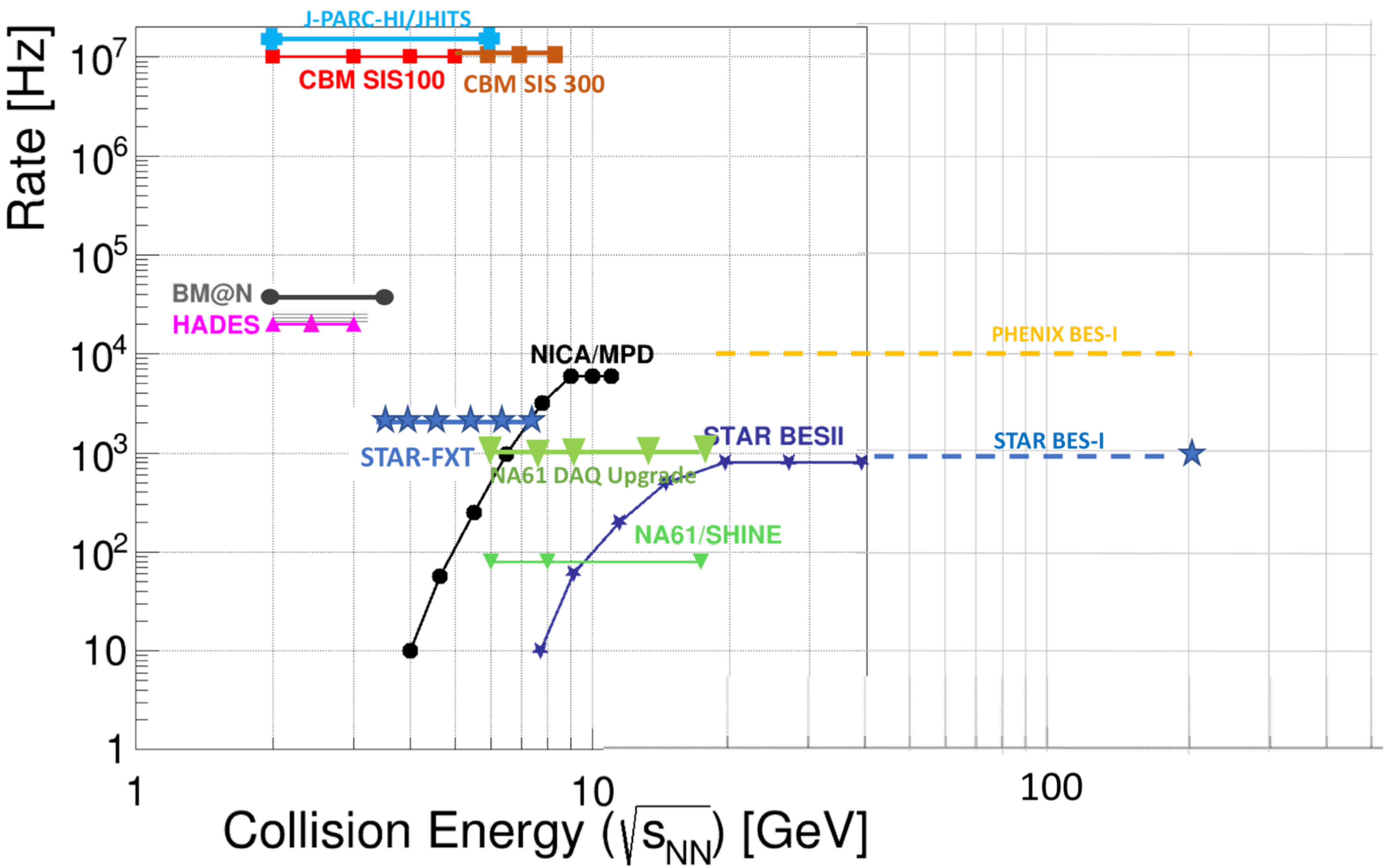
- successful test run in 2015 $\sqrt{s_{NN}}$ = 4.5 GeV AuAu





- expected to confirm turn-off of QGP signatures
- expected to fill the gap between RHIC and SIS energies
  - HADES vs STAR: different acceptances make the comparison non-trivial
- iTPC and eTOF critical

FACILITIES AROUND THE WORLD



SUMMARY AND OUTLOOK:

- BES program allowed for a detailed study of QCD phase diagram
- BES-II follows BES-I, targeting the most interesting region of the phase diagram
  - presented detector upgrades will reduce systematic uncertainties and extend kinematical and PID range
  - RHIC facility upgrades will increase luminosity
  - fixed-target program will extend μ_B range
- significant theoretical interest and effort
- looking forward to other facilities and experiments to soon join the exploration!

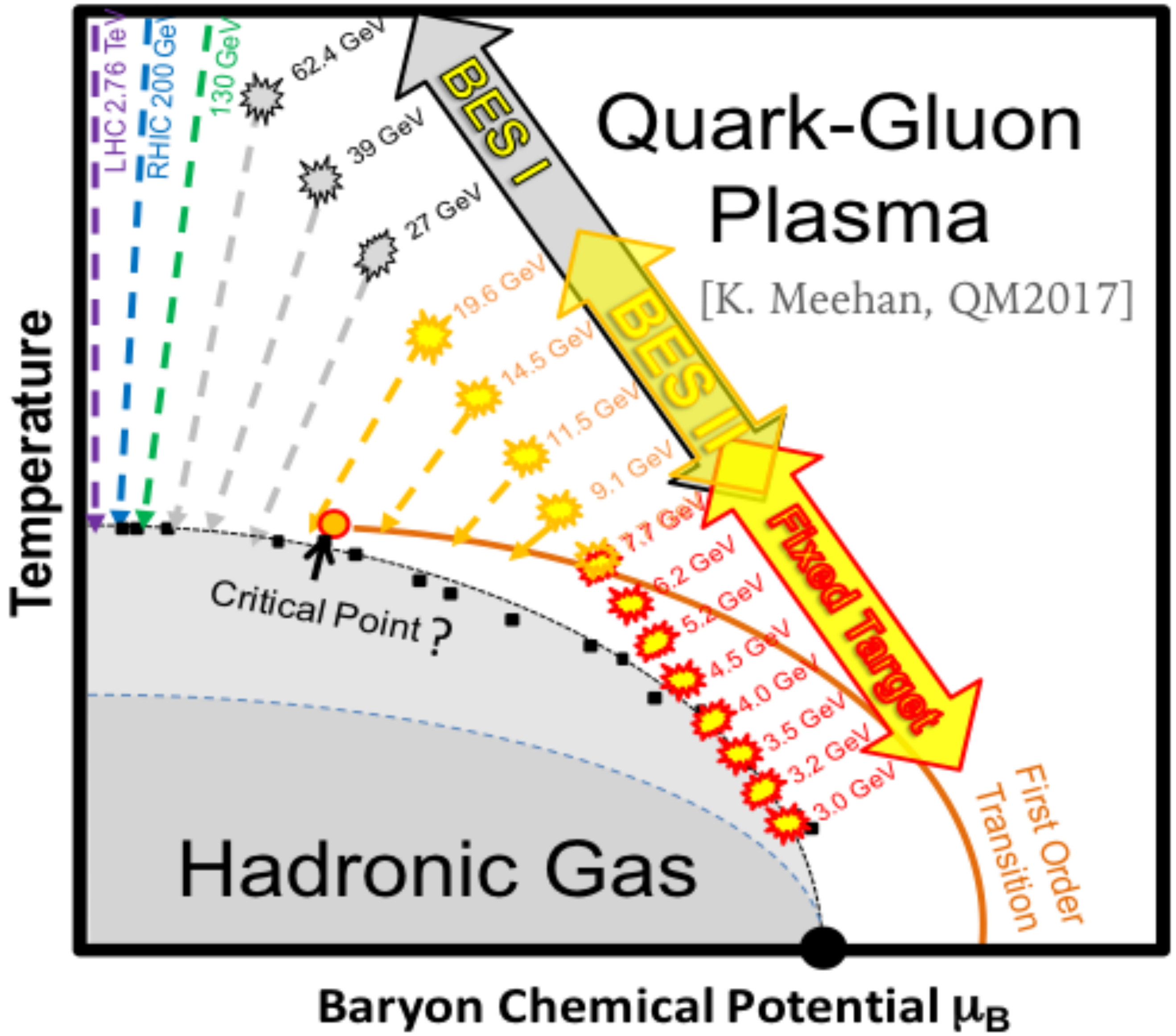
SUMMARY AND OUTLOOK:

- BES program allowed for a detailed study of QCD phase diagram
- BES-II follows BES-I, targeting the most interesting region of the phase diagram
  - presented detector upgrades will reduce systematic uncertainties and extend kinematical and PID range
  - RHIC facility upgrades will increase luminosity
  - fixed-target program will extend μ_B range
- significant theoretical interest and effort
- looking forward to other facilities and experiments to soon join the exploration!

THANK YOU

BACKUP SLIDES

RHIC BEAM ENERGY SCAN

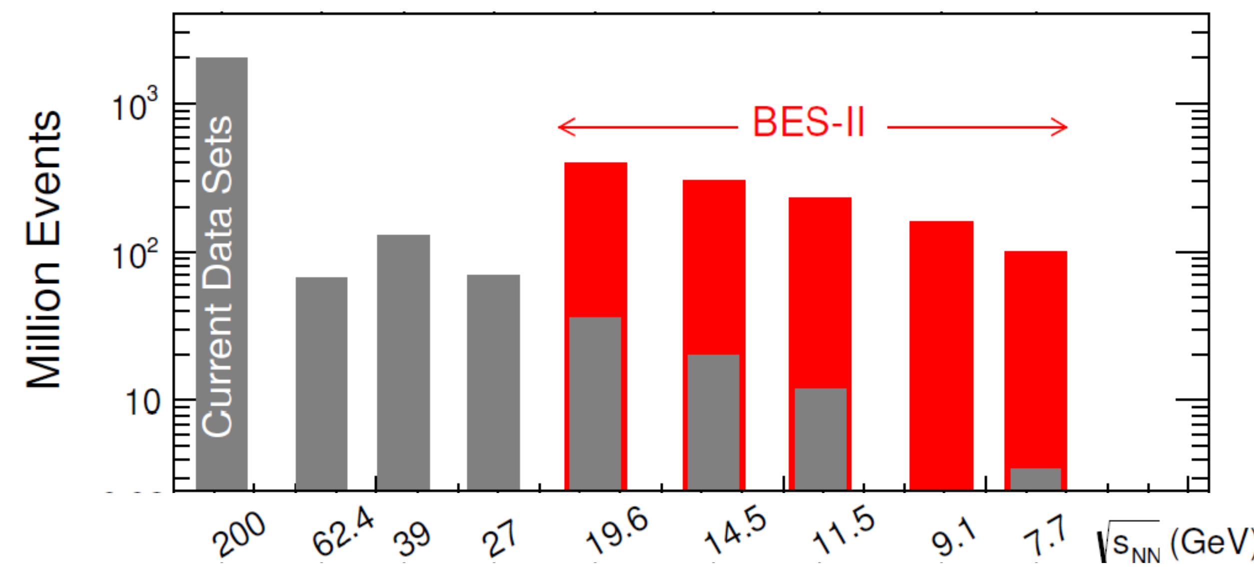


$\sqrt{s_{NN}}$ [GeV]	7.7	11.5	14.5	19.6	27.0	39.0
~μ_B (central) [MeV]	420	315	260	205	155	115

Baryon chemical potential at selected $\sqrt{s_{NN}}$

Star Note 598

https://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf

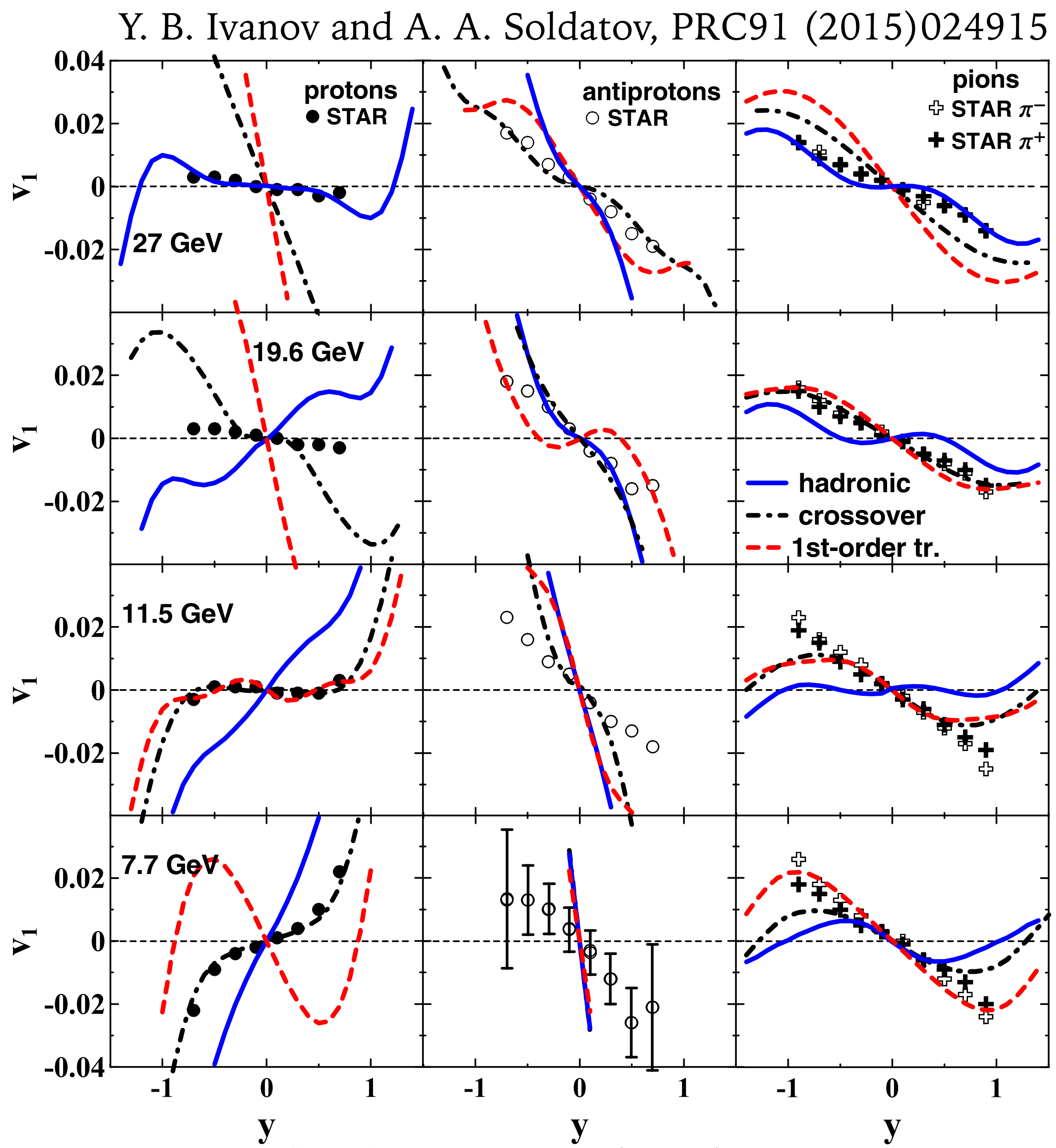


Statistics improvement in BES-II

Collider Energy	Fixed-target Energy	CMS Rapidity	μ_B [MeV]
62.4	7.7	2.10	420
39	6.2	1.87	487
27	5.2	1.68	541
19.6	4.5	1.52	589
14.5	3.9	1.37	633
11.5	3.5	1.25	666
9.1	3.2	1.13	699
7.7	3.0	1.05	721

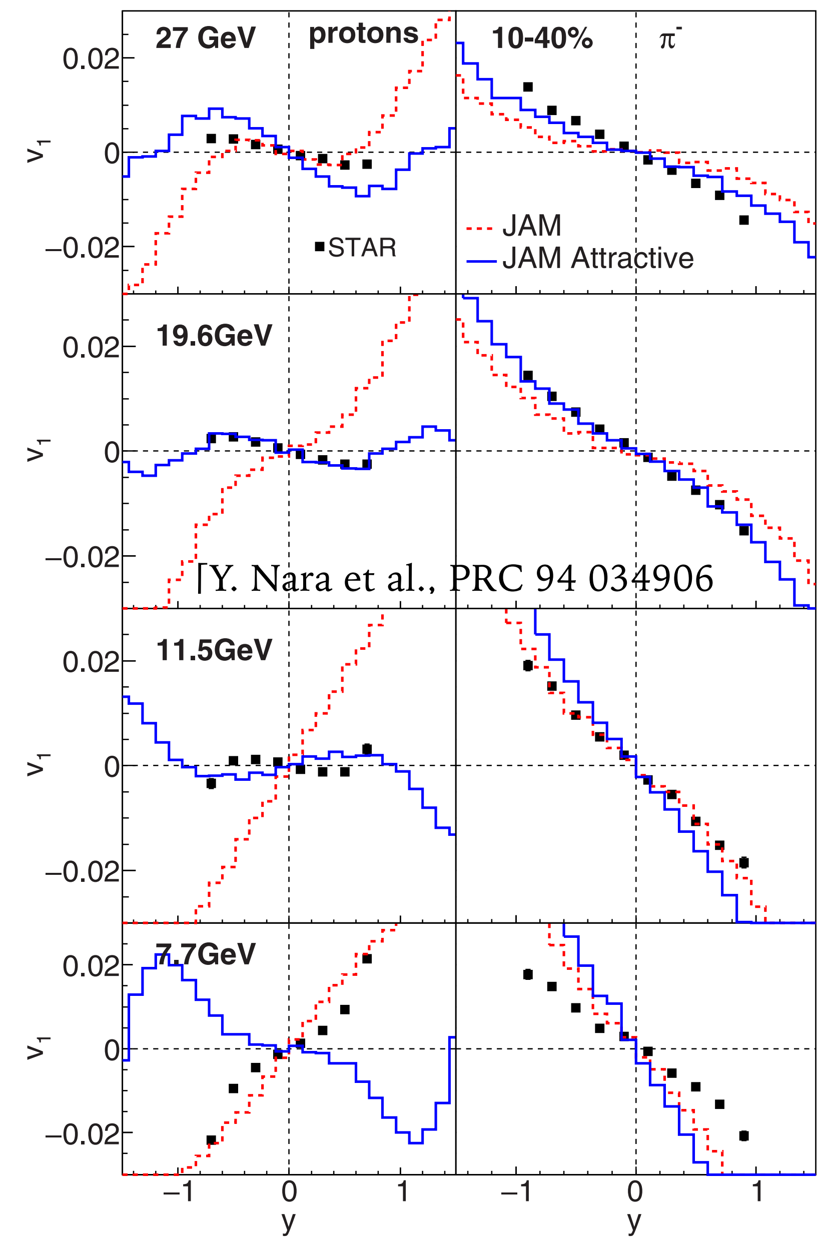
Baryon chemical potential at proposed $\sqrt{s_{NN}}$ in fixed-target mode

EFFECT OF SOFTENING ON DIRECTED FLOW



relativistic 3-fluid Dynamics (3FD) with purely hadronic EoS vs 3FD with crossover transition to QGP vs 3FD with 1st order phase transition

- 3FD with crossover transition best for proton
- with 1st order phase transition best for pions

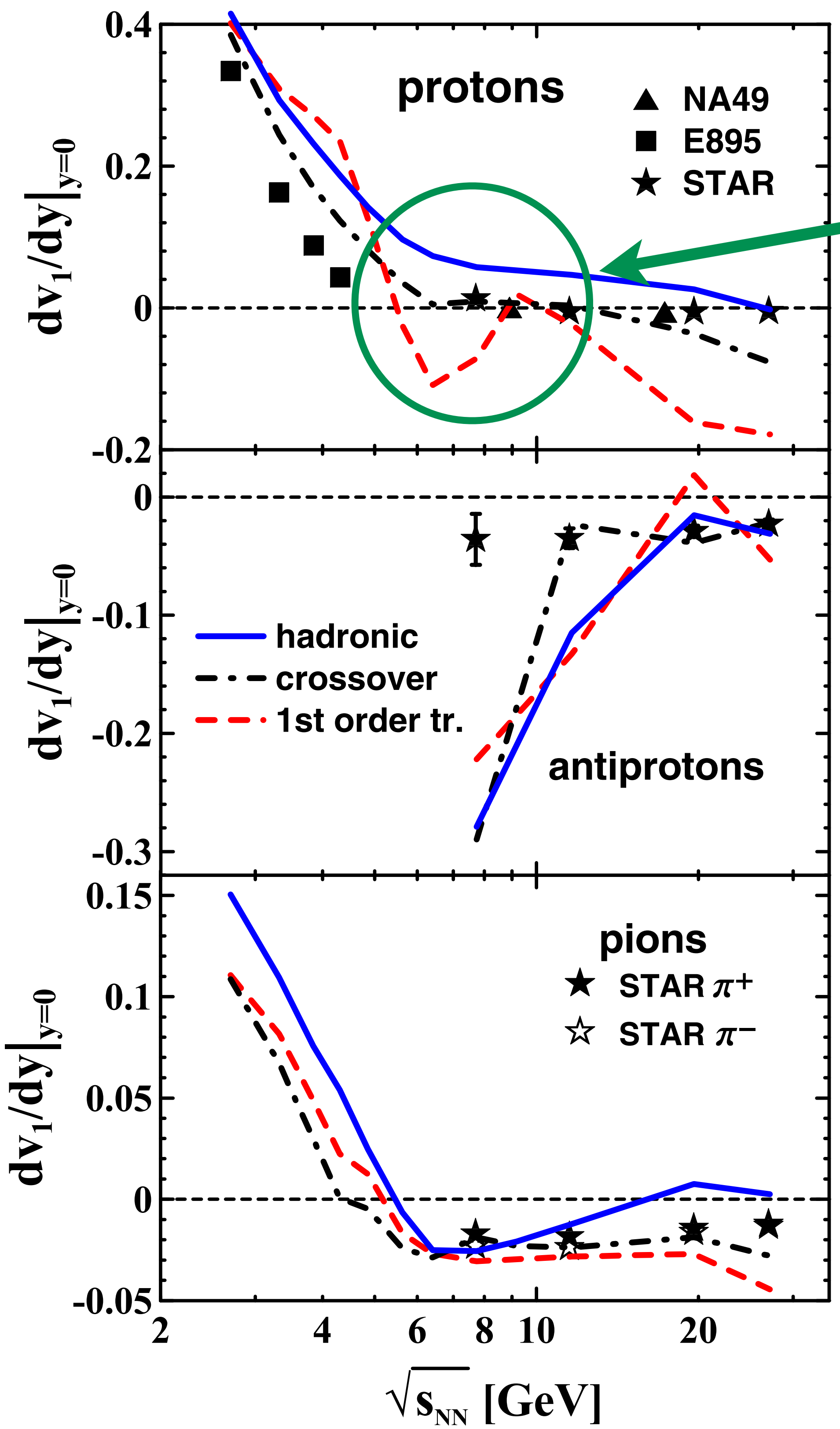


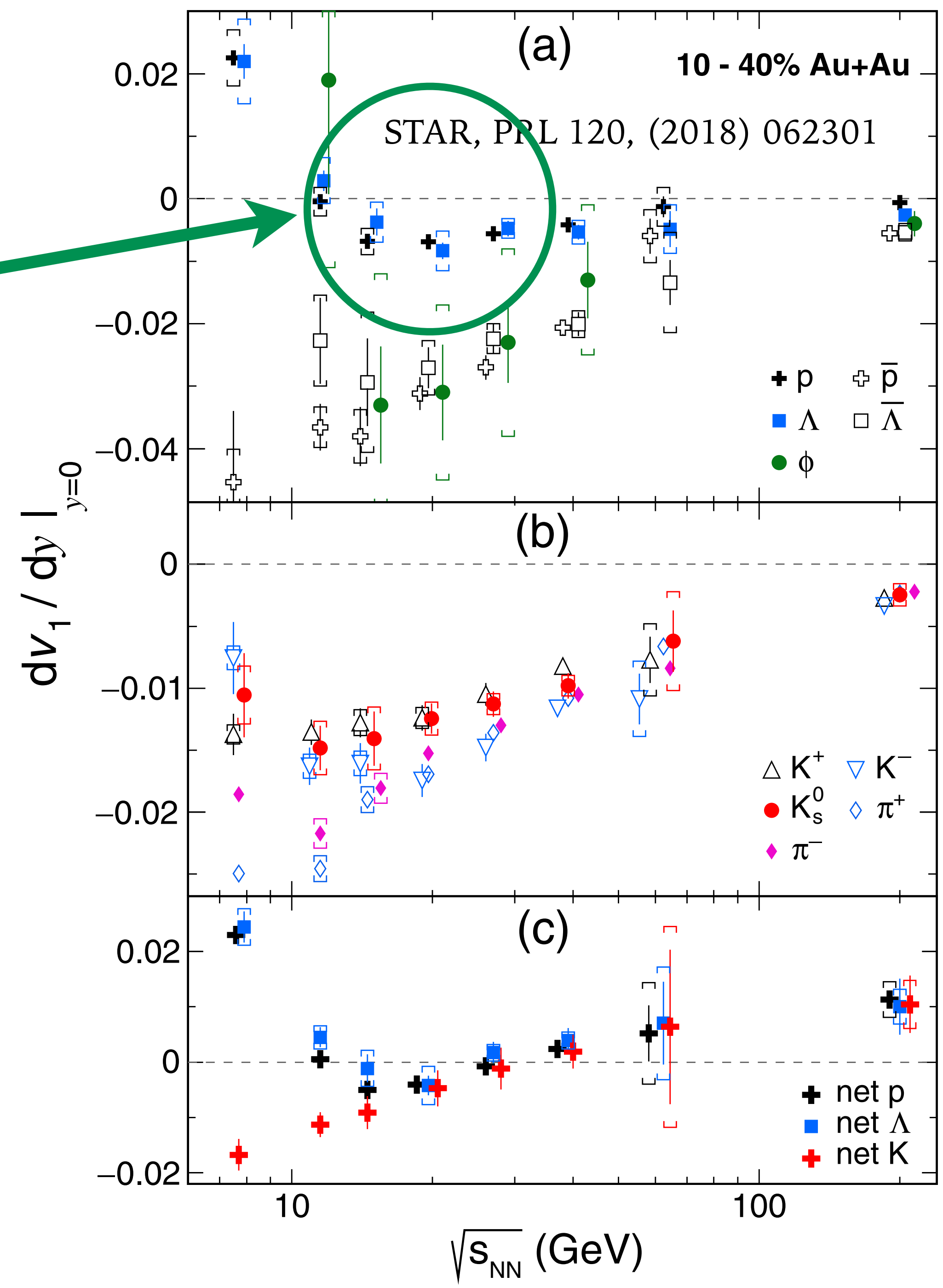
Hadronic transport model JAM with and without attractive orbits for each two-body scattering

- JAM with attractive orbits matches the data well at $\sqrt{s_{NN}}$ = 11.5 and 19.6 GeV

ENERGY DEPENDENCE OF $dv_1/dy|_{y=0}$

Y. B. Ivanov and A. A. Soldatov, PRC91 (2015)024915

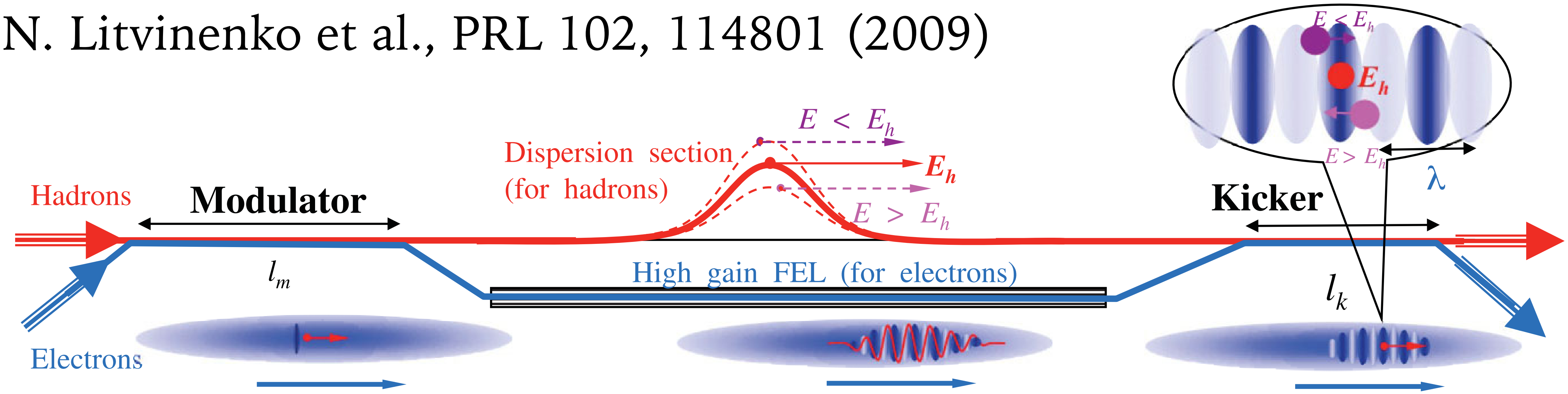




Did we find the energy with the softest EOS?

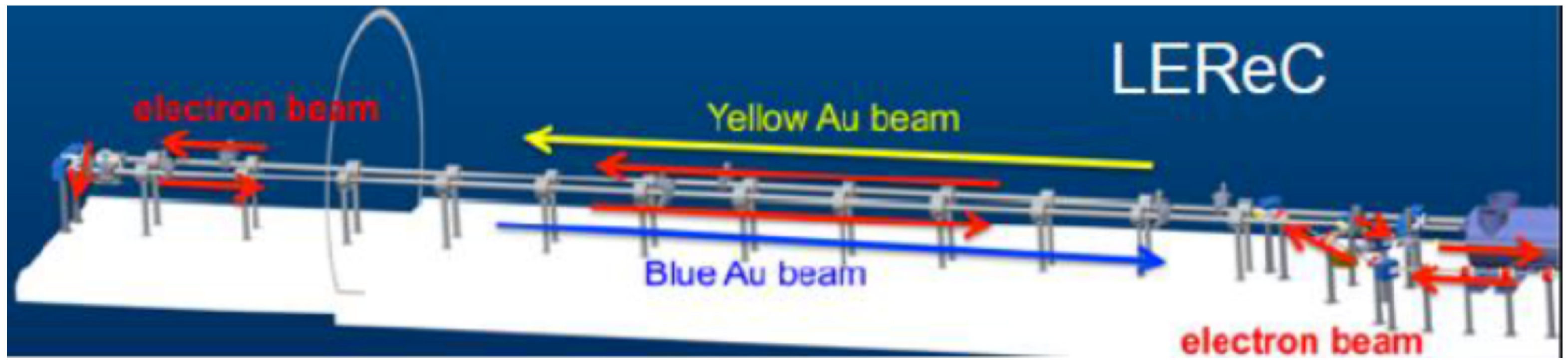
- similar dip like in 3FD model with 1st order phase transition, except at a different energy

V. N. Litvinenko et al., PRL 102, 114801 (2009)

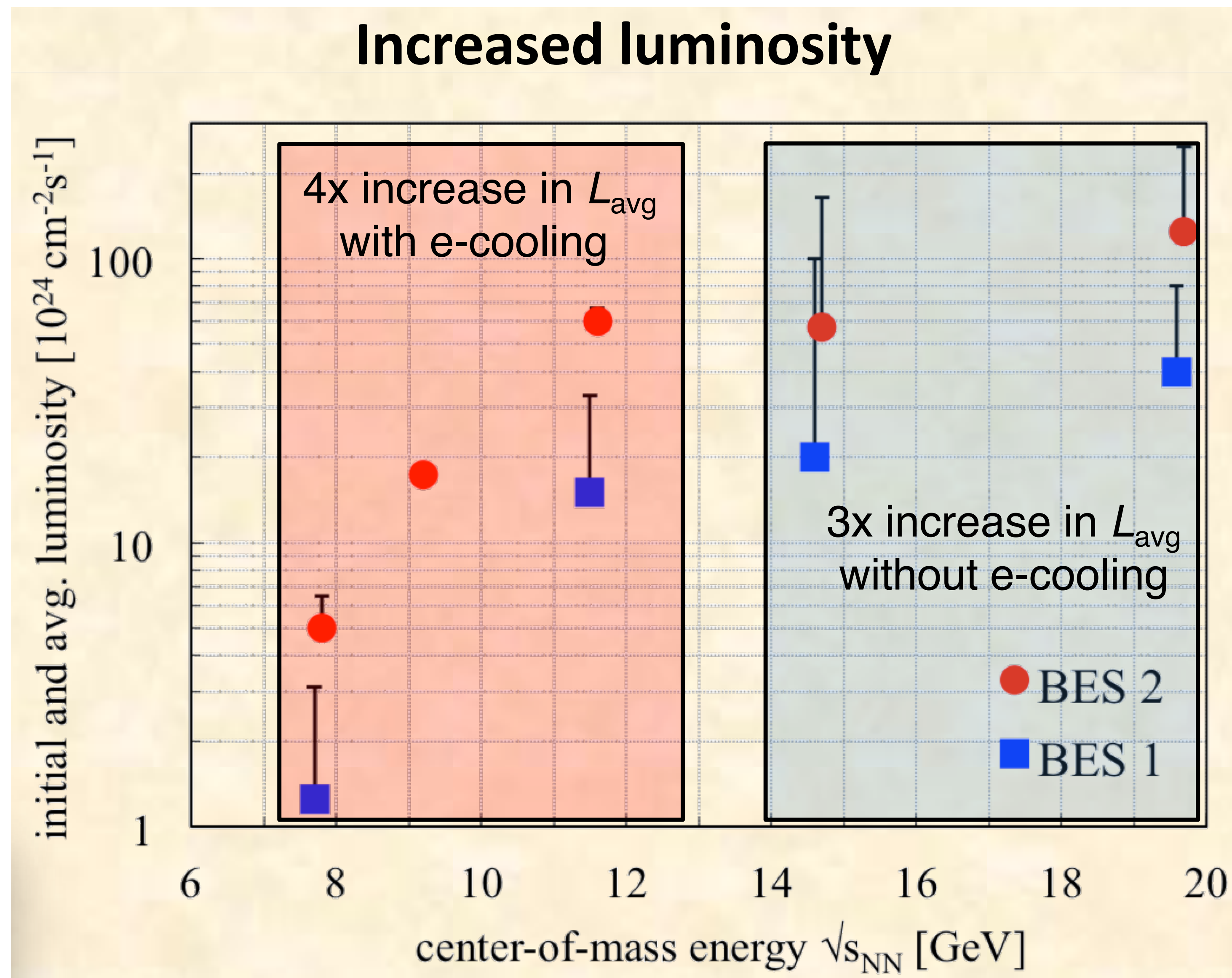


- in Modulator - each ion induces a density modulation in n electron beam ⇒ electron beam carries information about individual hadrons imprinted in density distortions
- in free-electron laser (FEL) - the induced density modulation is amplified
- in Kicker - both beams co-propagate again and the longitudinal electric field inside the electron beam affects the ions' energy ⇒ an ion with higher energy arrives ahead of its respective clump of high density and is pulled back and vice versa
- current status of the equipment [I. Pinayev et al., JACoW COOL2017 WEM22 (2018)]

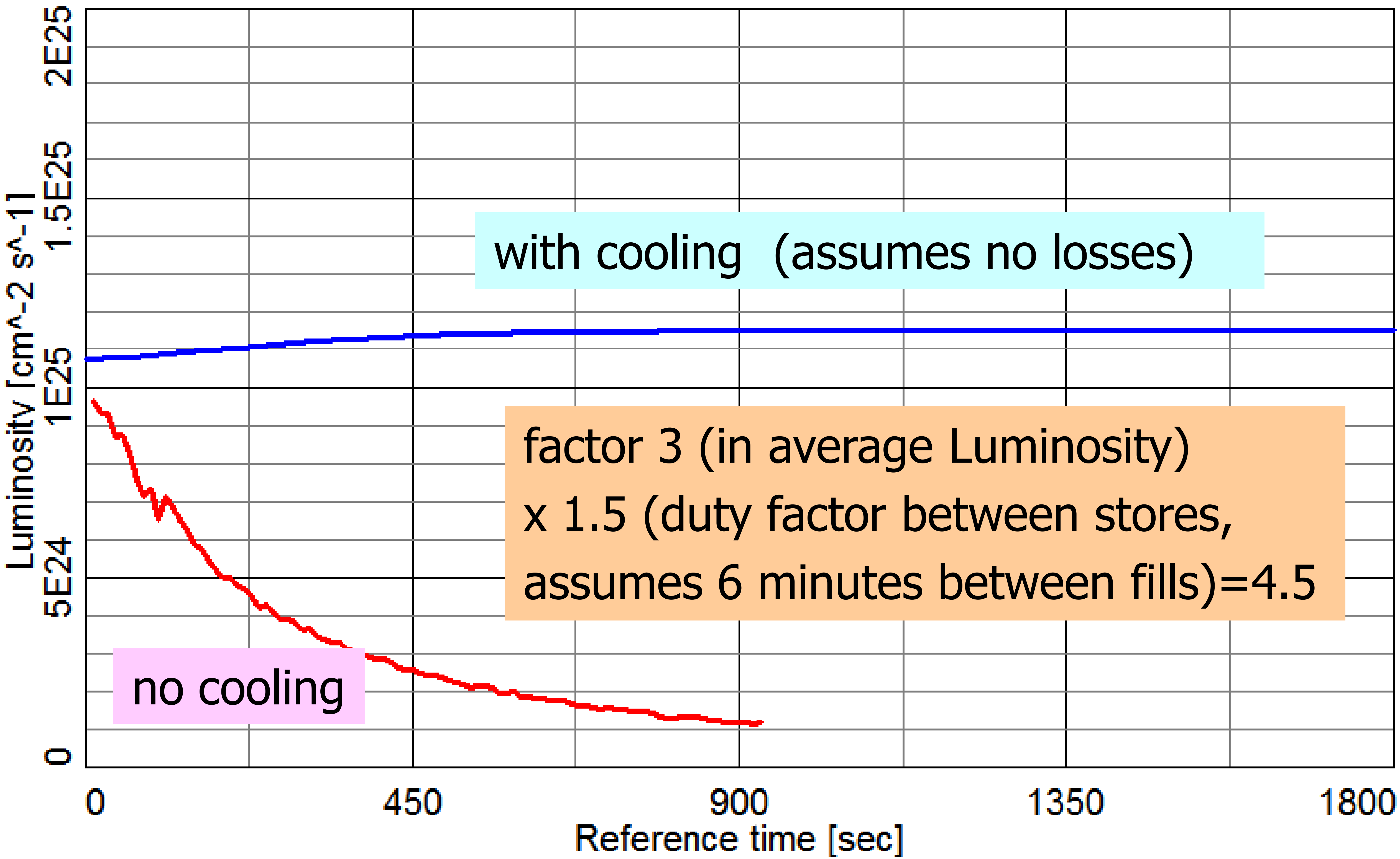
LOW-ENERGY RHIC ELECTRON COOLER (LEREC)



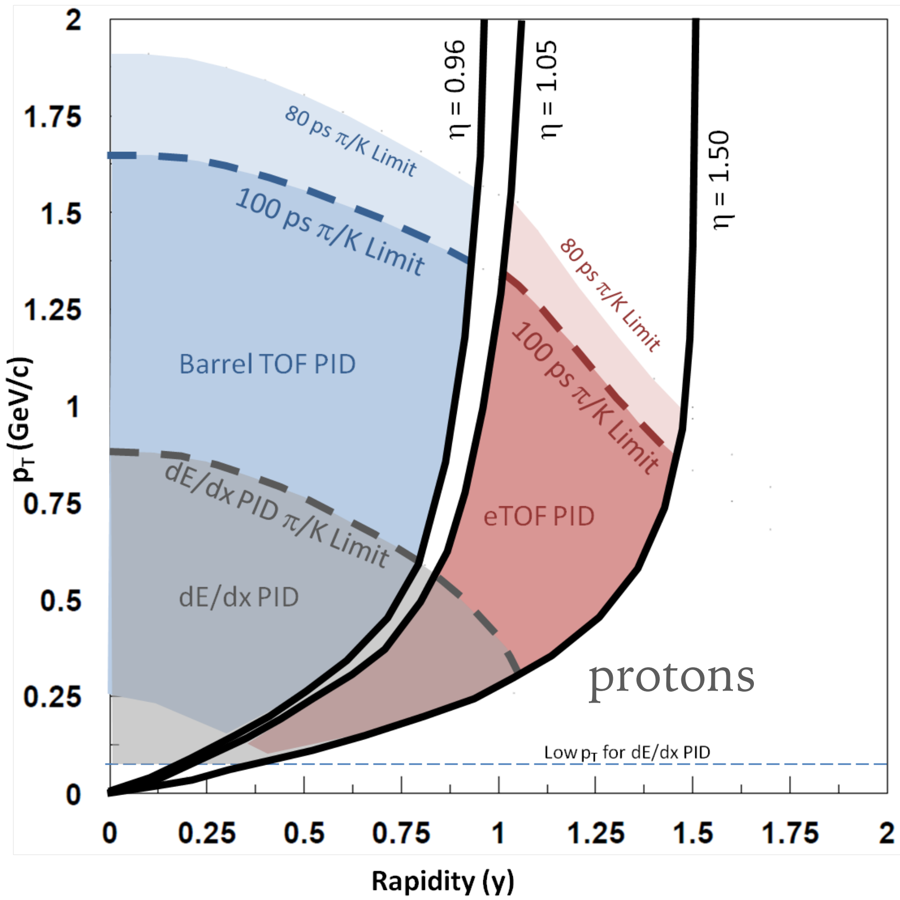
- improve luminosity for low energy beams:
  - 2019 (without LEReC)
    - 3x for $\sqrt{s_{NN}}$ = 14.5 and 19.6 GeV
  - 2020 (with LEReC)
    - 4x for $\sqrt{s_{NN}}$ = 7.7, 9.1, and 11.5 GeV

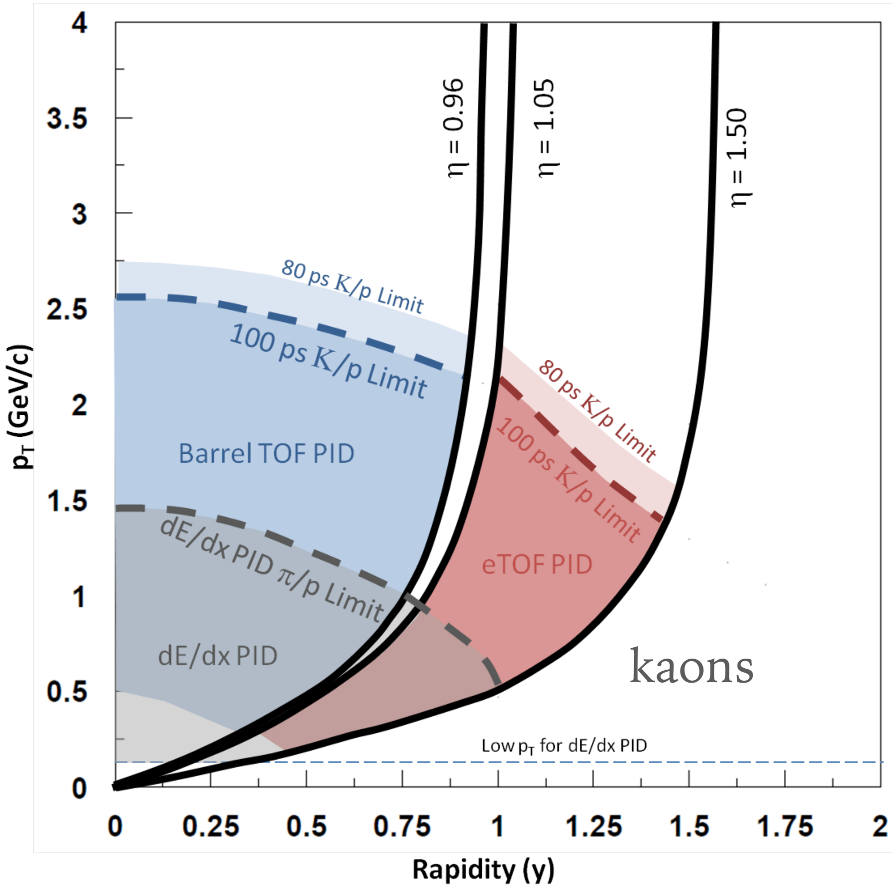


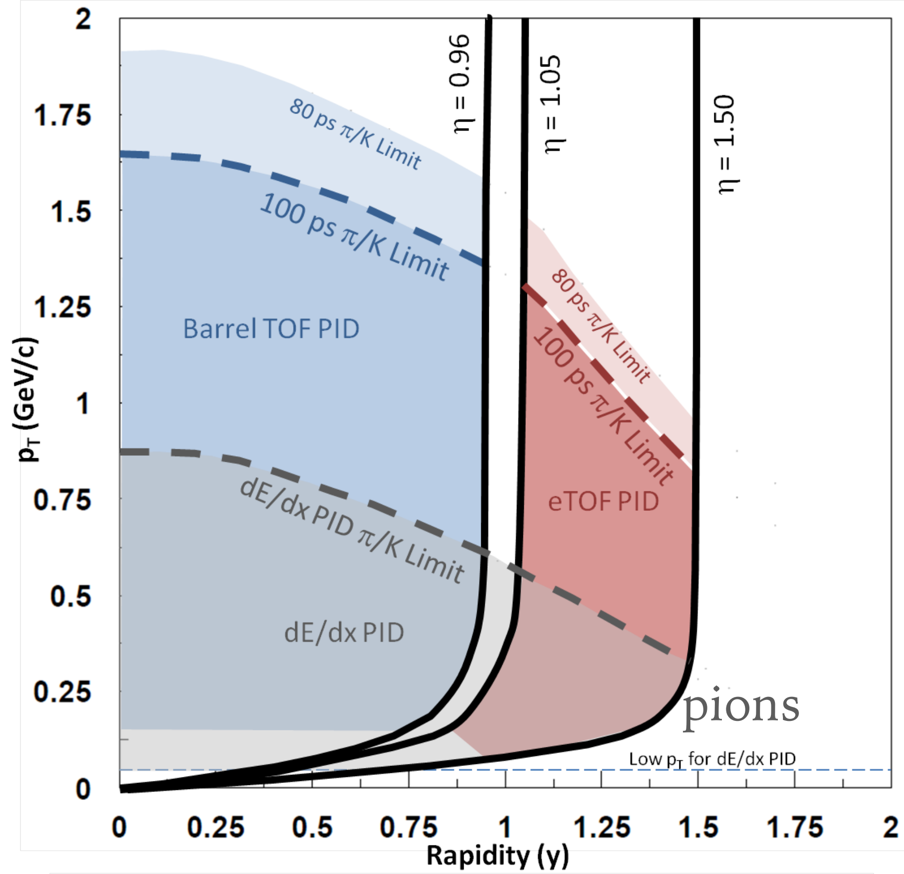
A. Fedotov, RHIC/AGS Users Meeting (2012)

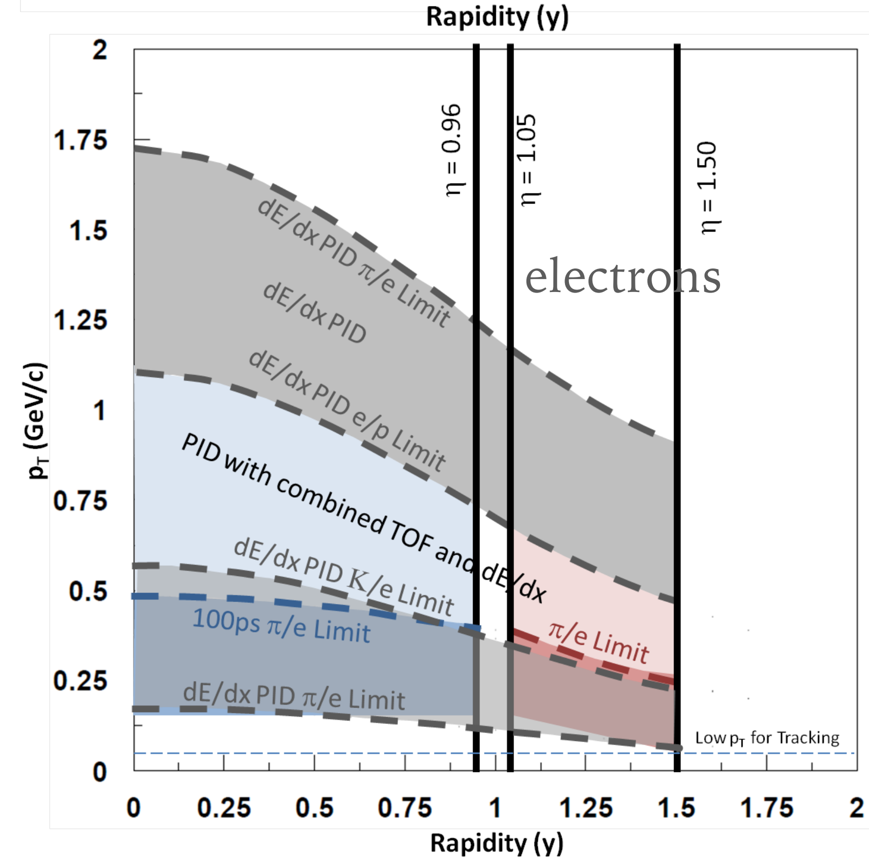


STAR ACCEPTANCE AND PID IMPROVEMENT







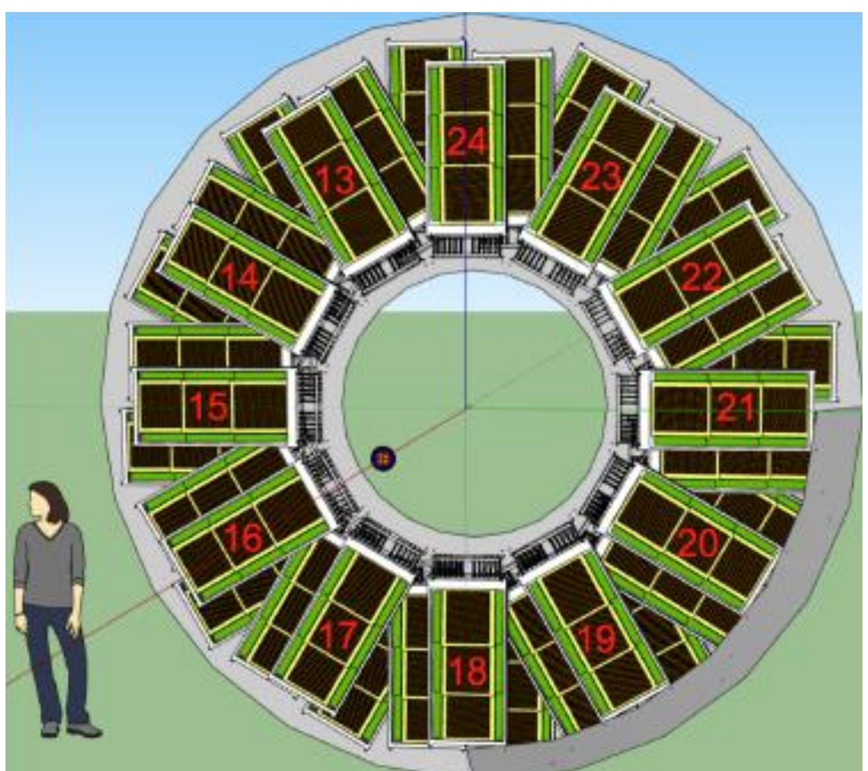


- significant extension of PID beyond rapidity = 1
- very important for fixed-target regime

STAR/CBM, arXiv:1609.05102v1

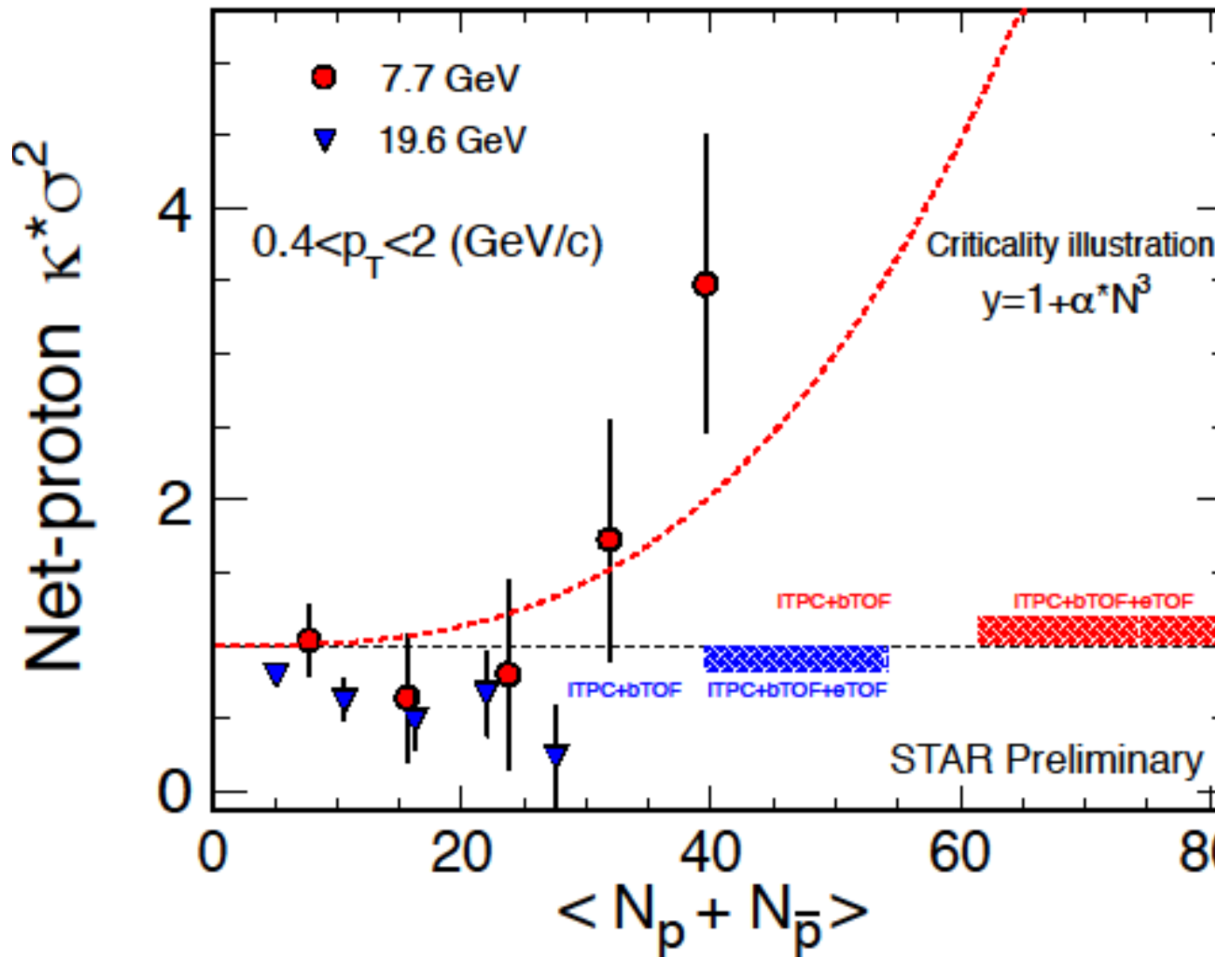
ENDCAP TIME OF FLIGHT (ETOF)

- extends particle TOF particle identification (PID) in 1.1<η<1.6
- essential for PID at mid-rapidity in fixed-target mode



STAR/CBM, arXiv:1609.05102v1

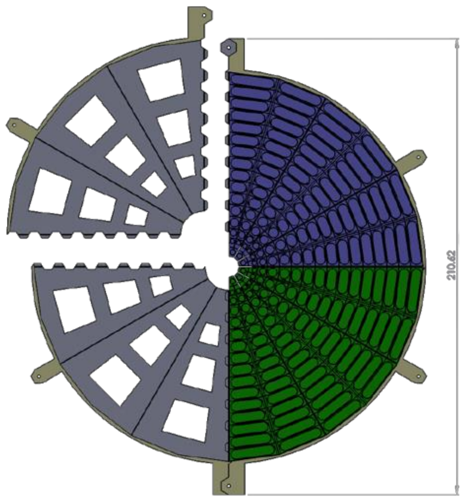
STAR/CBM, arXiv:1609.05102v1

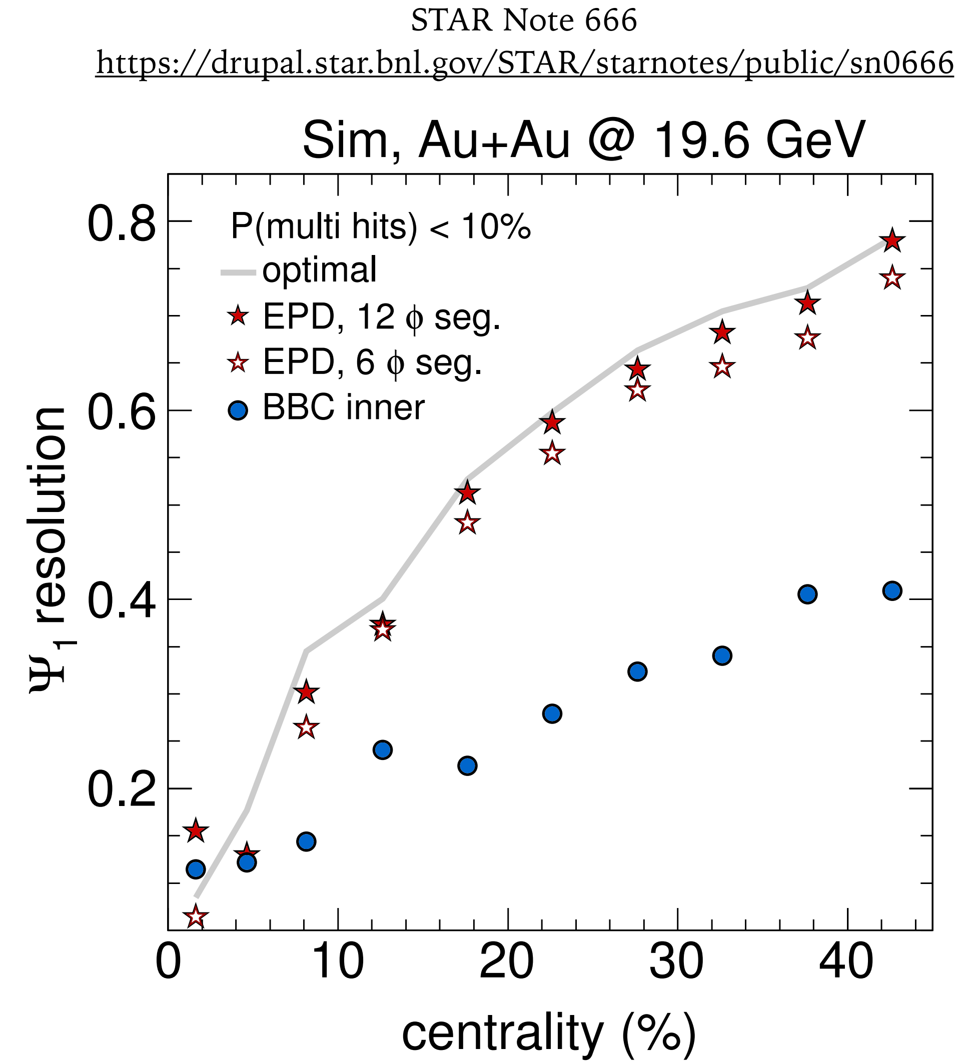


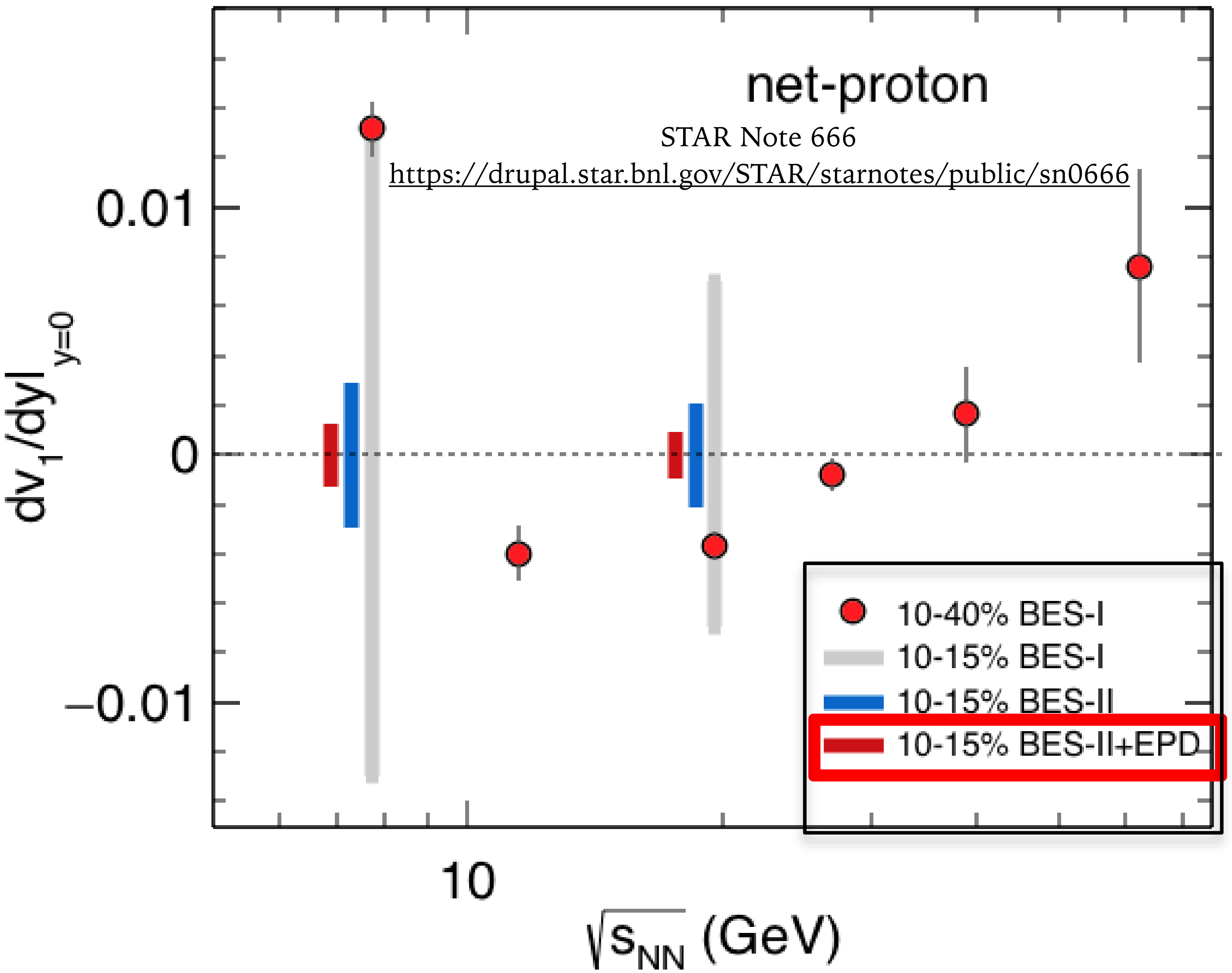
- antiprotons produced more at mid-rapidity
- added coverage by eTOF will enhance the fluctuation signal ⇒ clearer and more significant indication of critical behavior

EVENT PLANE DETECTOR (EPD)

- cover 2.1 < |η| < 5
- event Plane determination
- centrality definition
- trigger capabilities

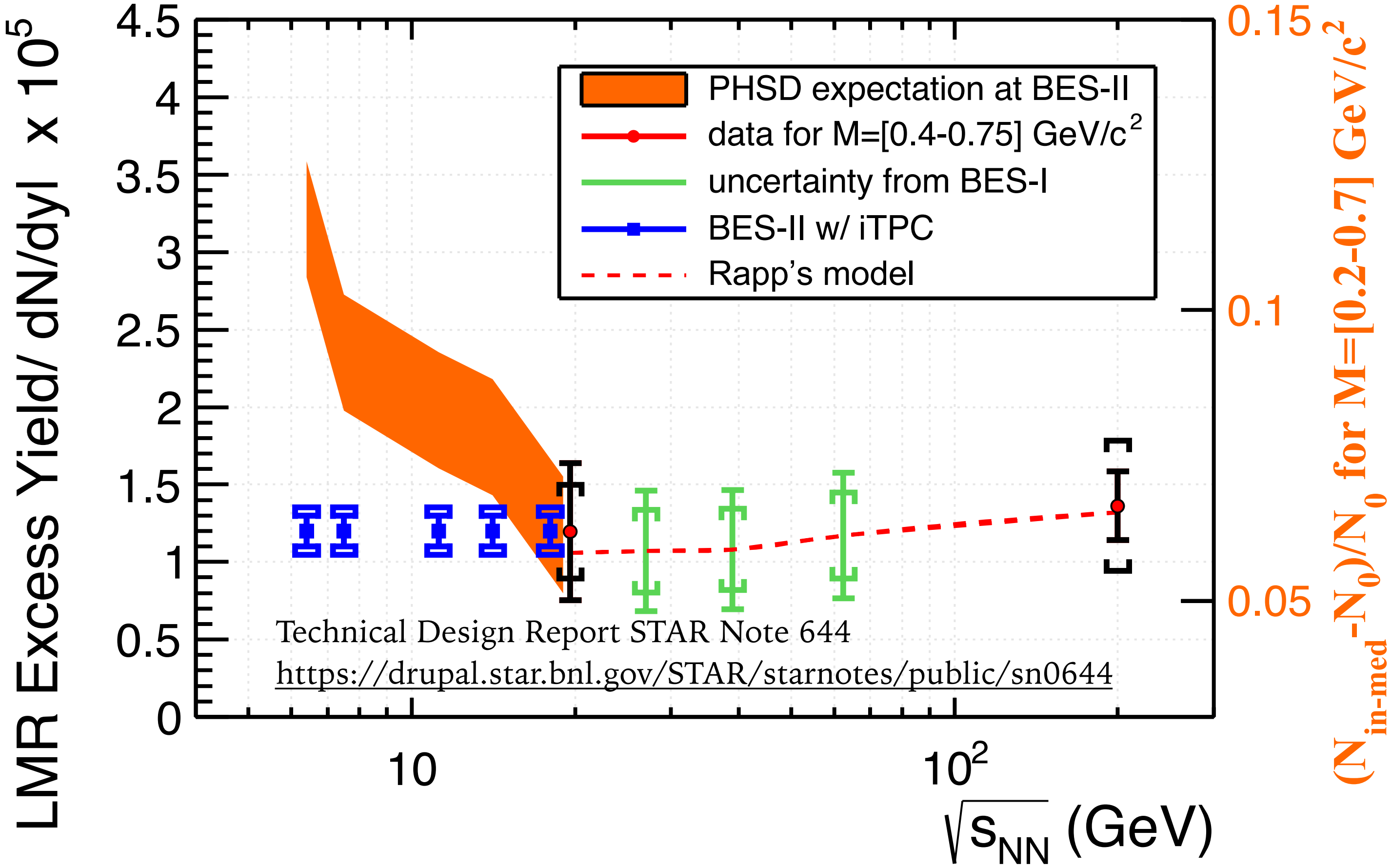


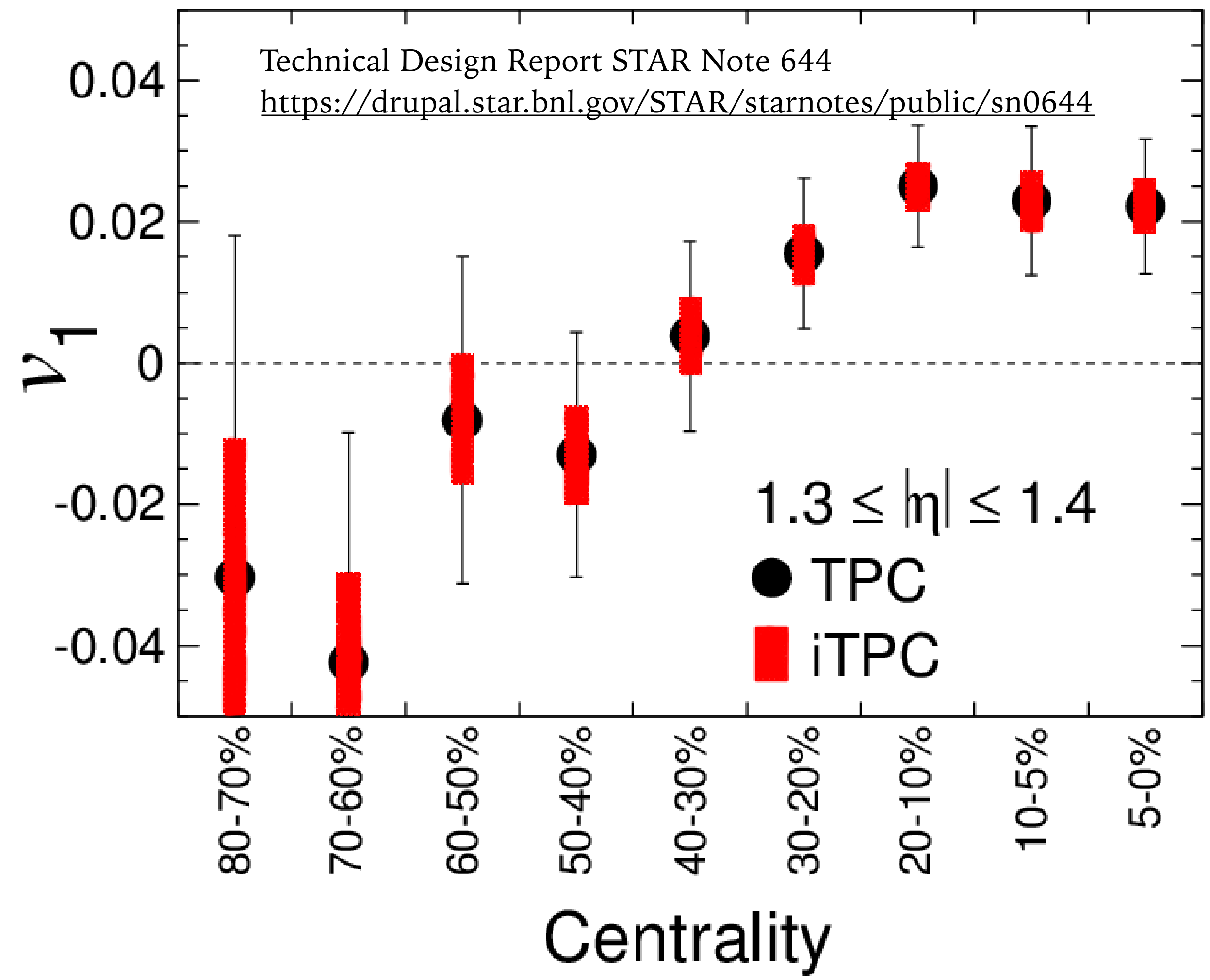




- significantly better event plane resolution than BBC
- fine centrality binning in BES-II

INNER TIME PROJECTION CHAMBER (ITPC)





- make possible a systematic study of the dielectron continuum below 19.6 GeV

one sector has been installed and operated this year

- make possible to measure directed flow in forward rapidity