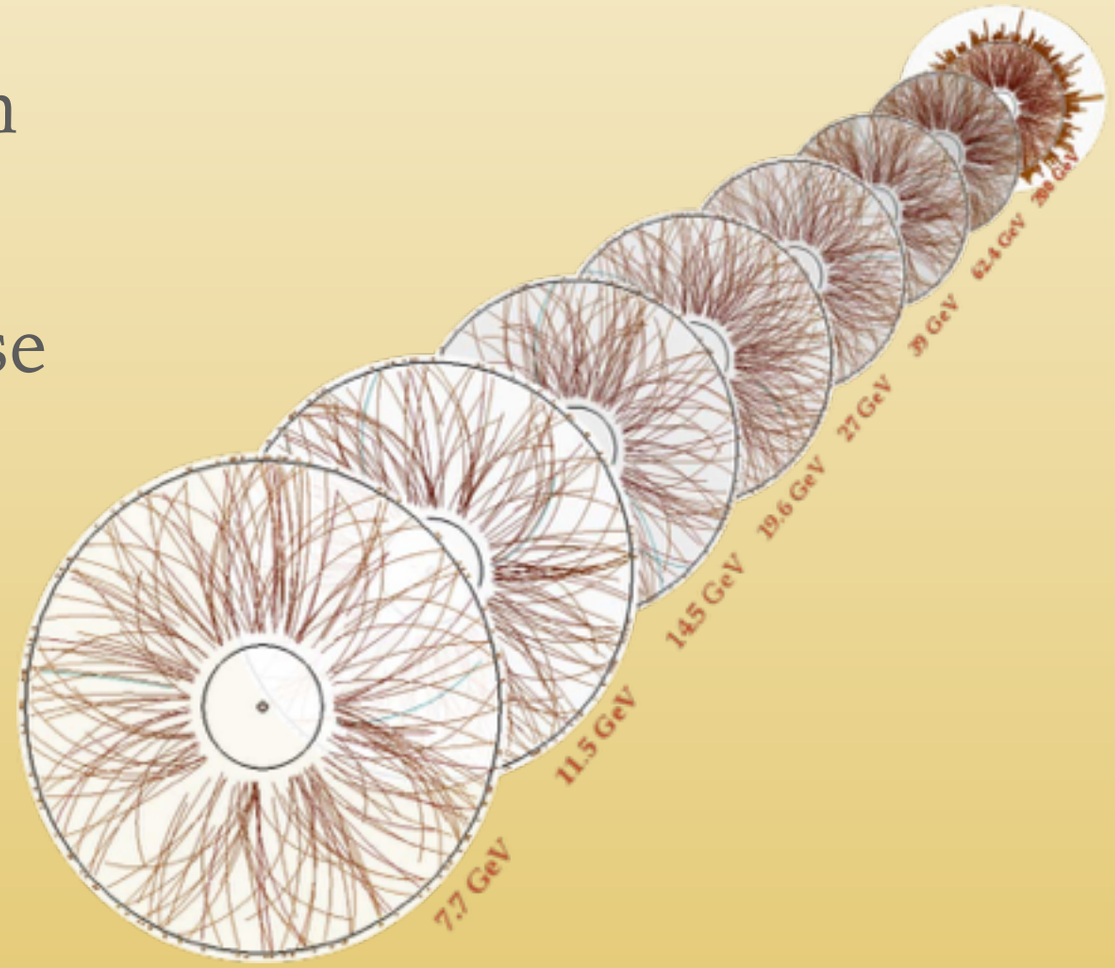
THE RHIC BEAM ENERGY SCAN PHASE II: PHYSICS AND UPGRADES

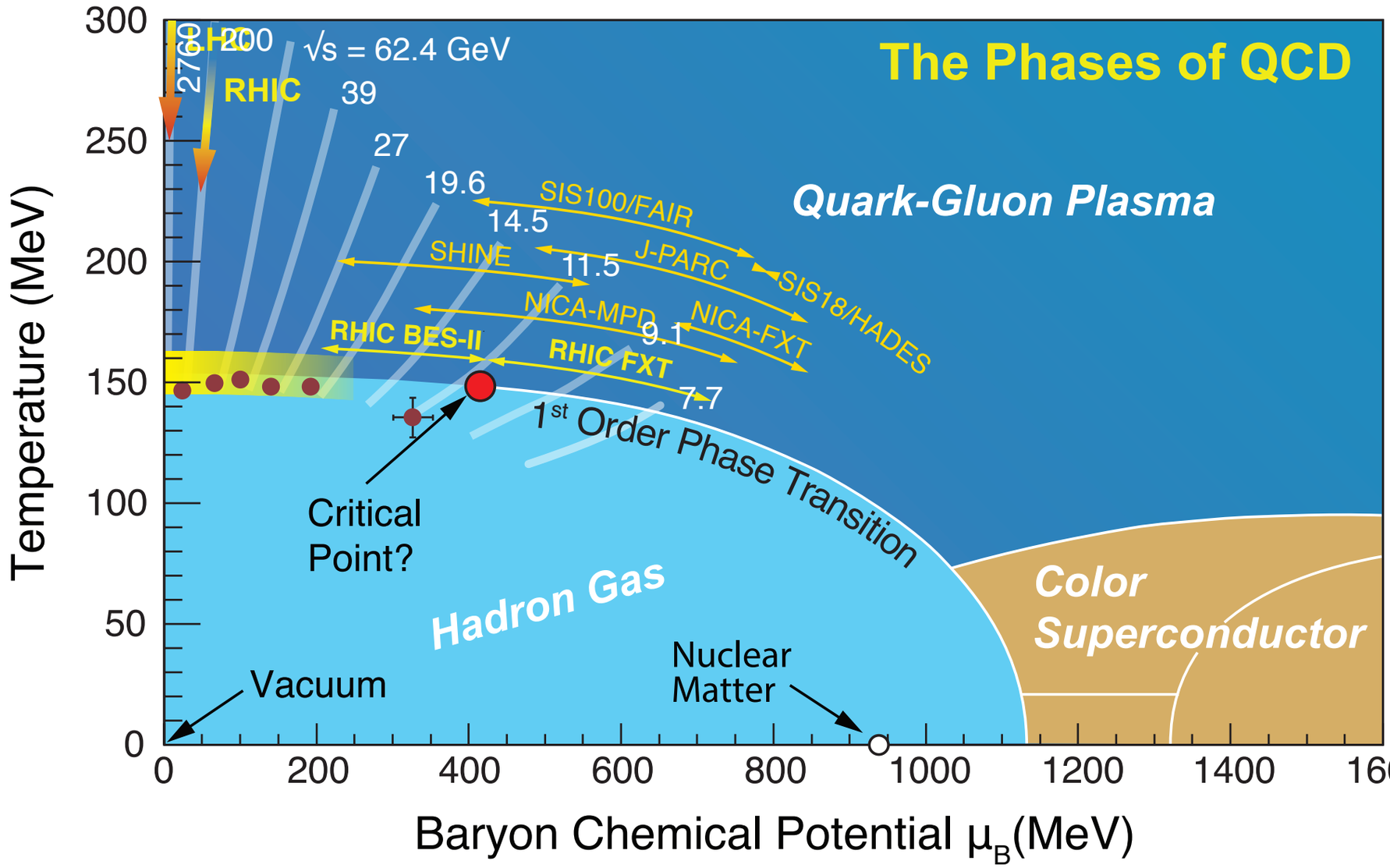
David Tlusty (Rice University)

Outline

- QCD phase diagram and RHIC Beam Energy Scan
- observables used to explore the phase diagram
- facility upgrades
- detector upgrades
- fixed target



QCD PHASE DIAGRAM



$\sqrt{s_{NN}}$	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	
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3.0	1.05	721	

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

- 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 1. order phase transition and critical point
- BES-II is scheduled to start in 2019-2020

QCD PHASE TRANSITION AT BES ENERGIES

- Critical point - divergence of the correlation length ⇒ non-monotonic behavior of higher moments of conserved quantities
  - experimentally, one can measure mean M, variance σ^2, skewness S, and kurtosis κ of the event-by-event net-particle distributions (particle multiplicity minus antiparticle multiplicity, e.g. net-proton, net-kaon, net-charge)
- 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 ($dv_1/dy|_{y=0}$)

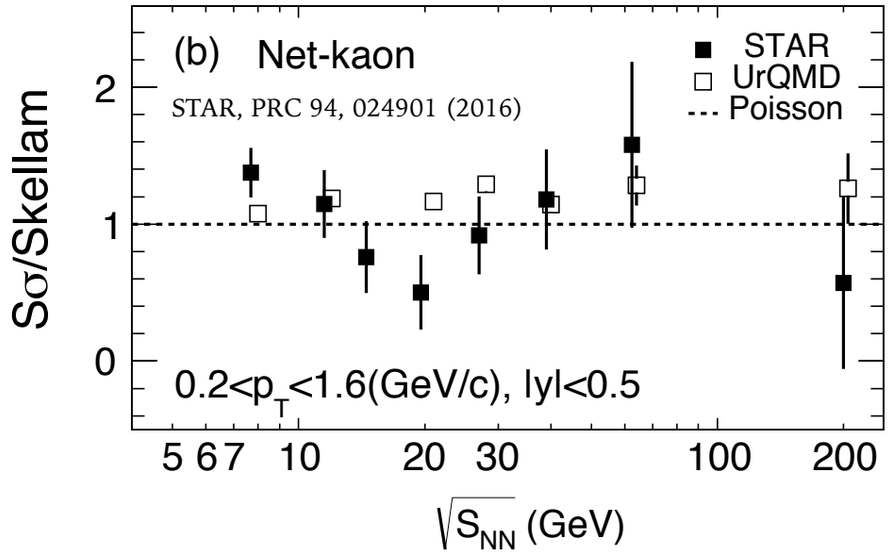
CUMULANT RATIOS OF NET-PROTON(KAON,CHARGE) MULTIPLICITY

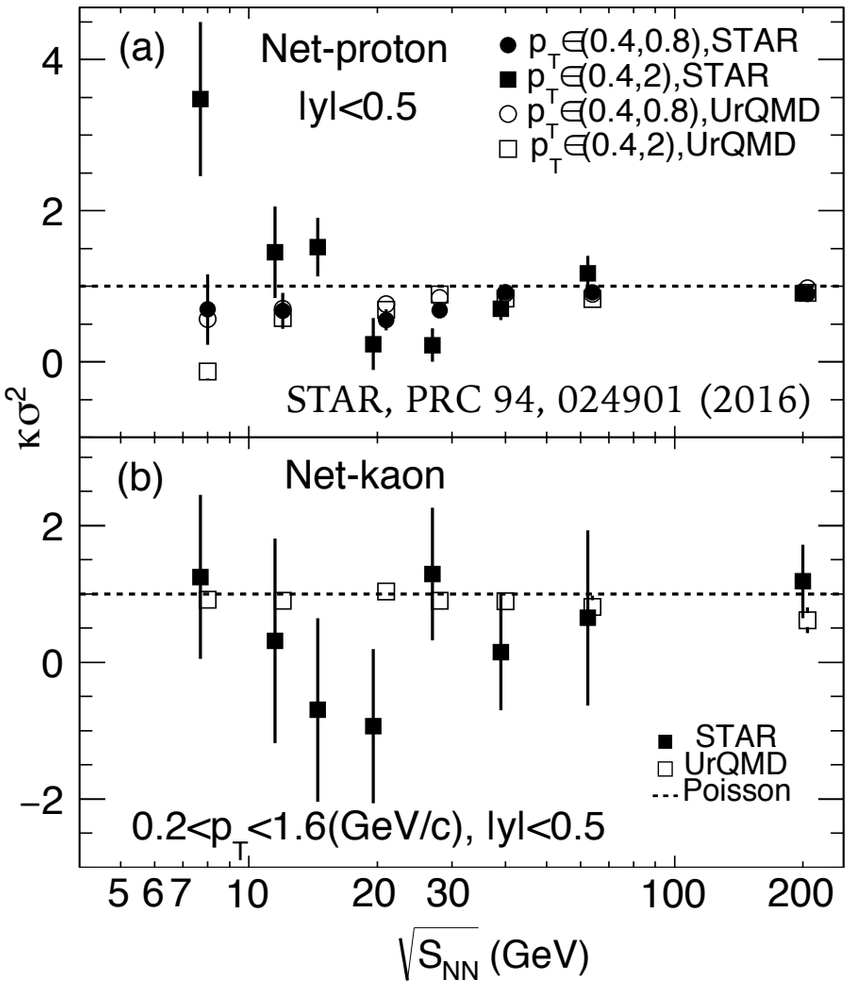
- moments of net-particle multiplicity distributions can be related to susceptibilities of conserved charges calculated on the lattice [P. Alba et al., Phys. Rev. C 92, 064910 (2015)]

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

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

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





- 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

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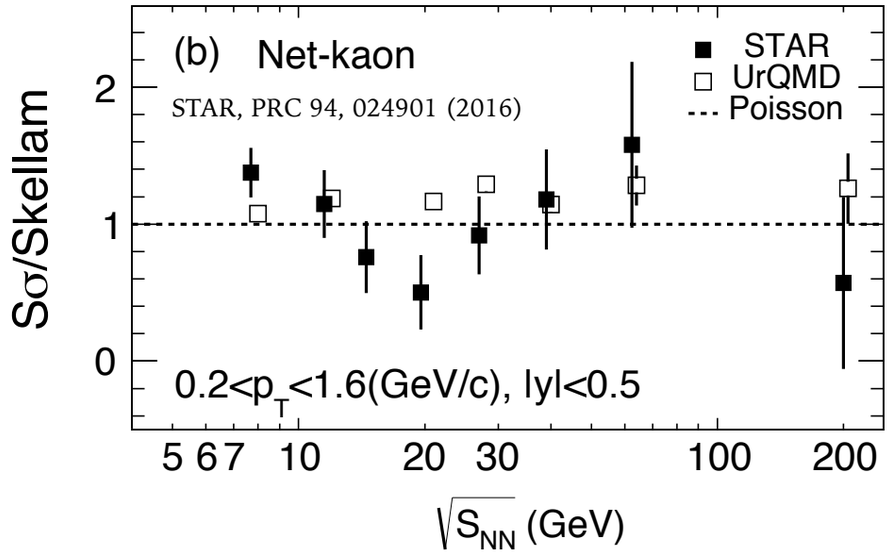

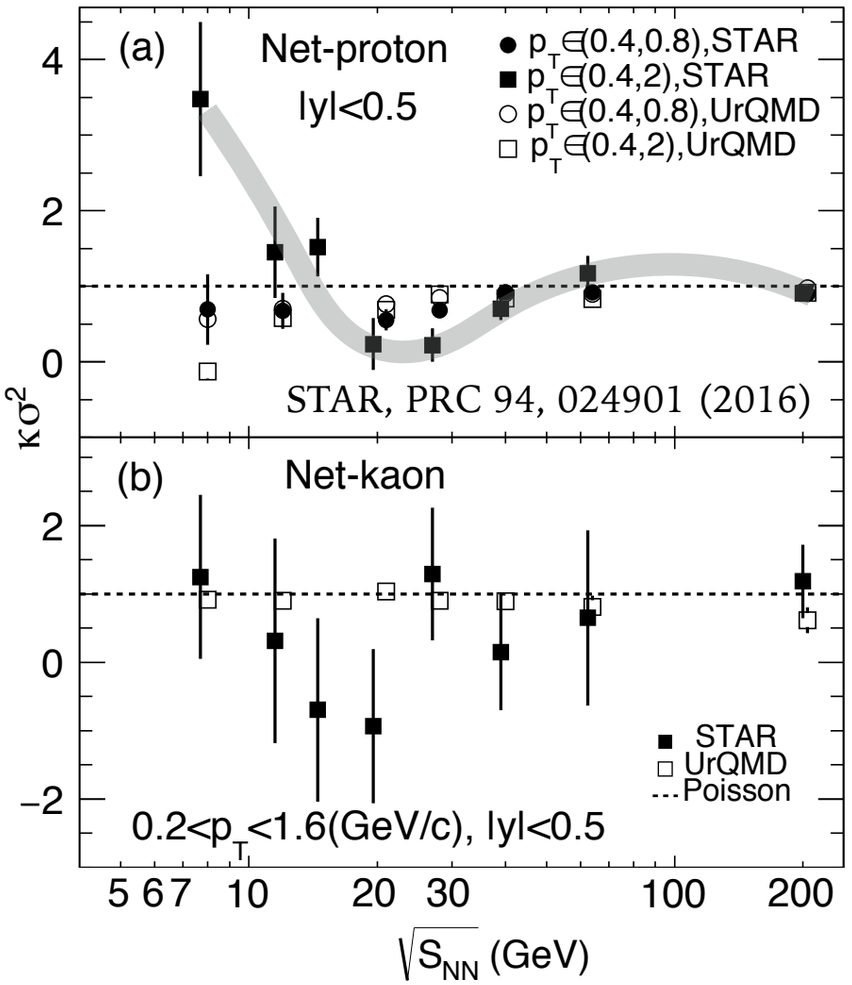

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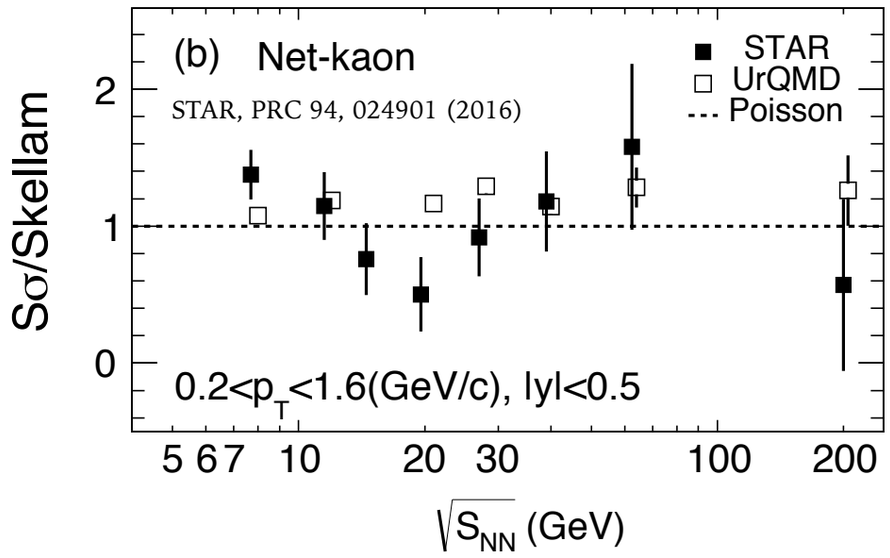

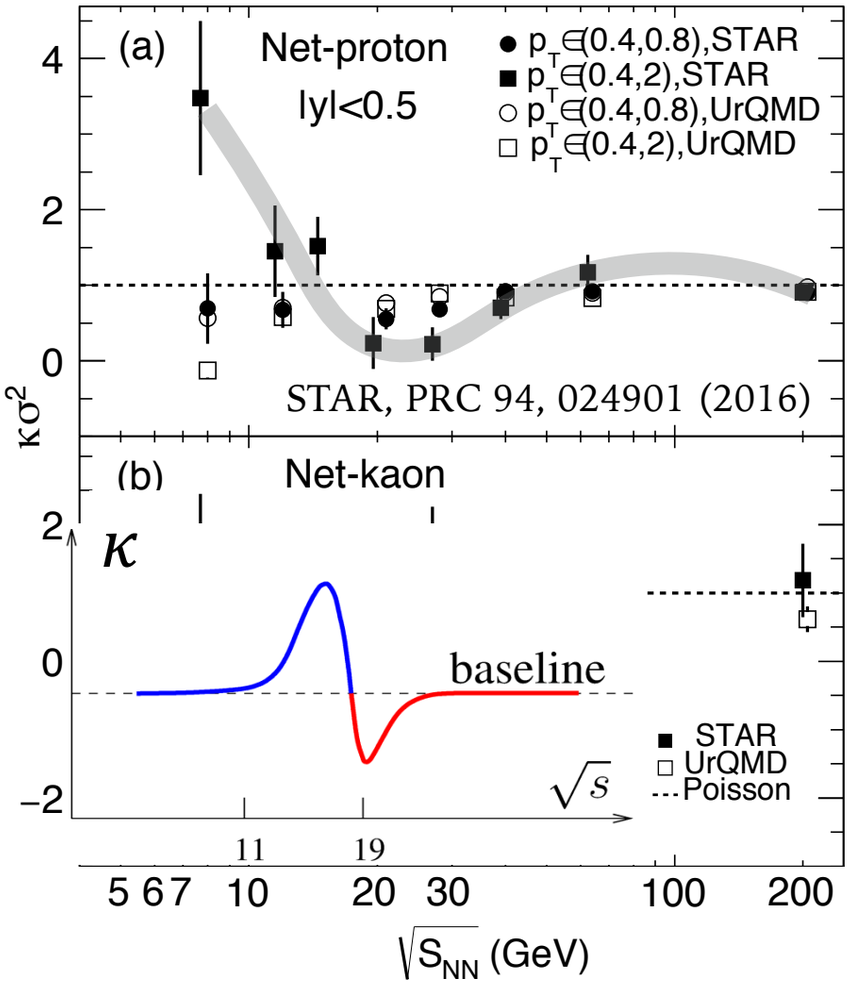

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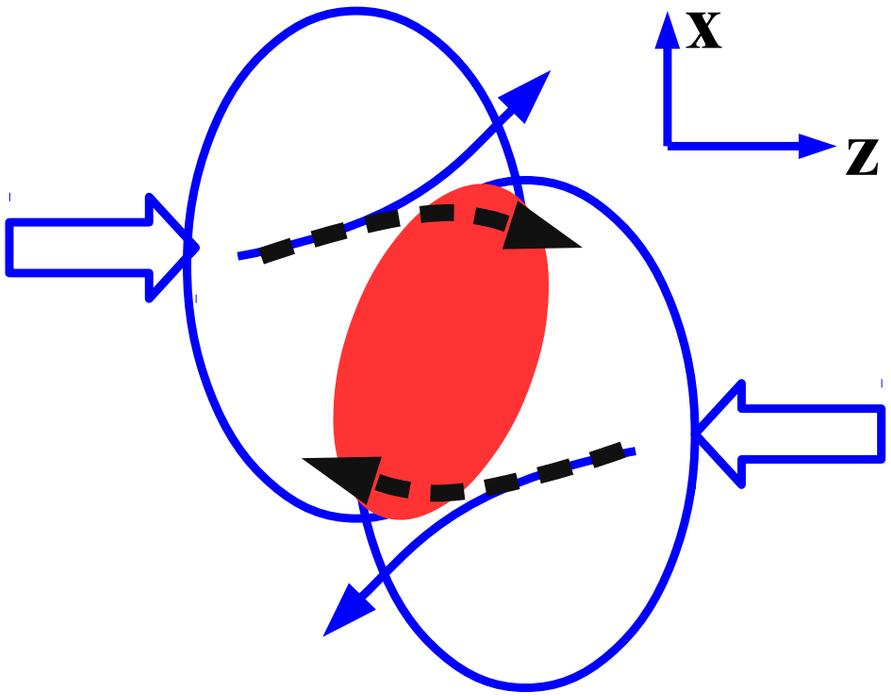
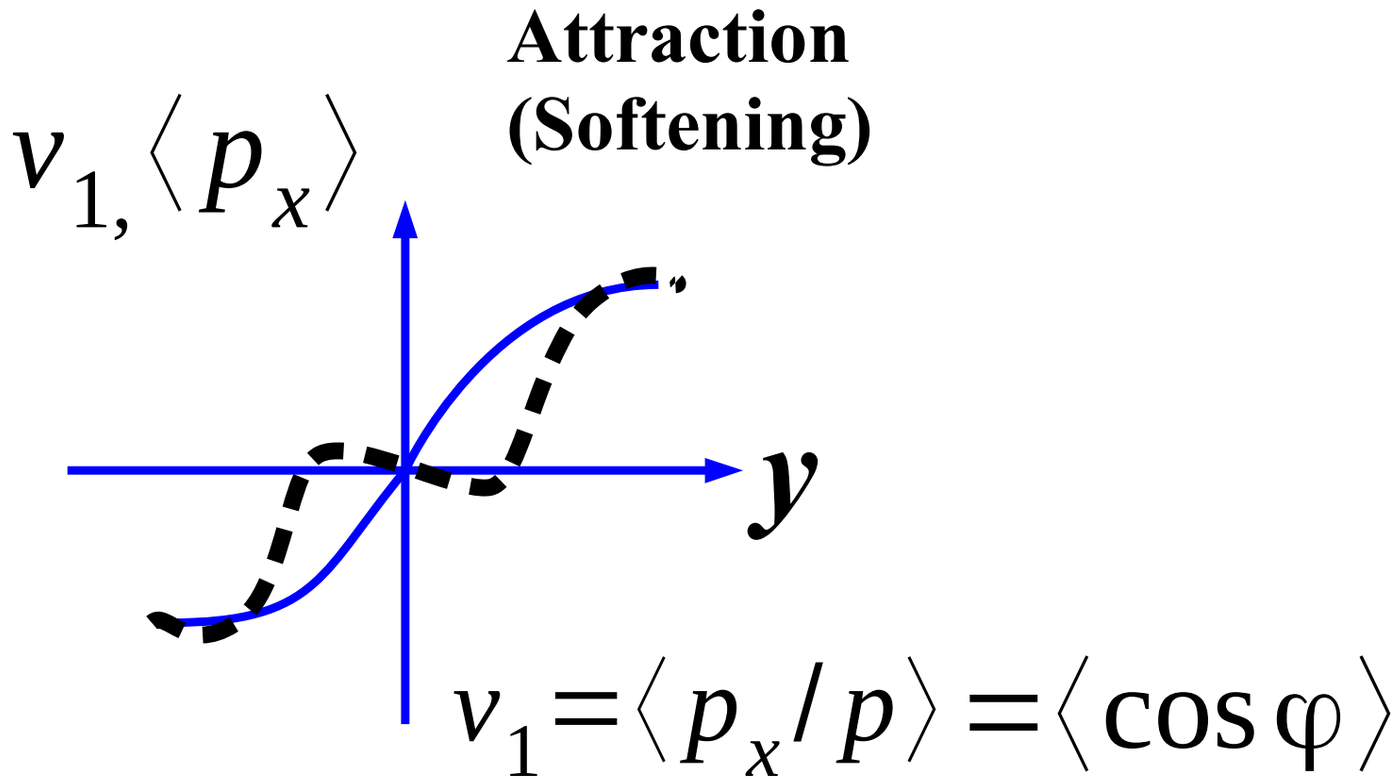
DIRECTED FLOW

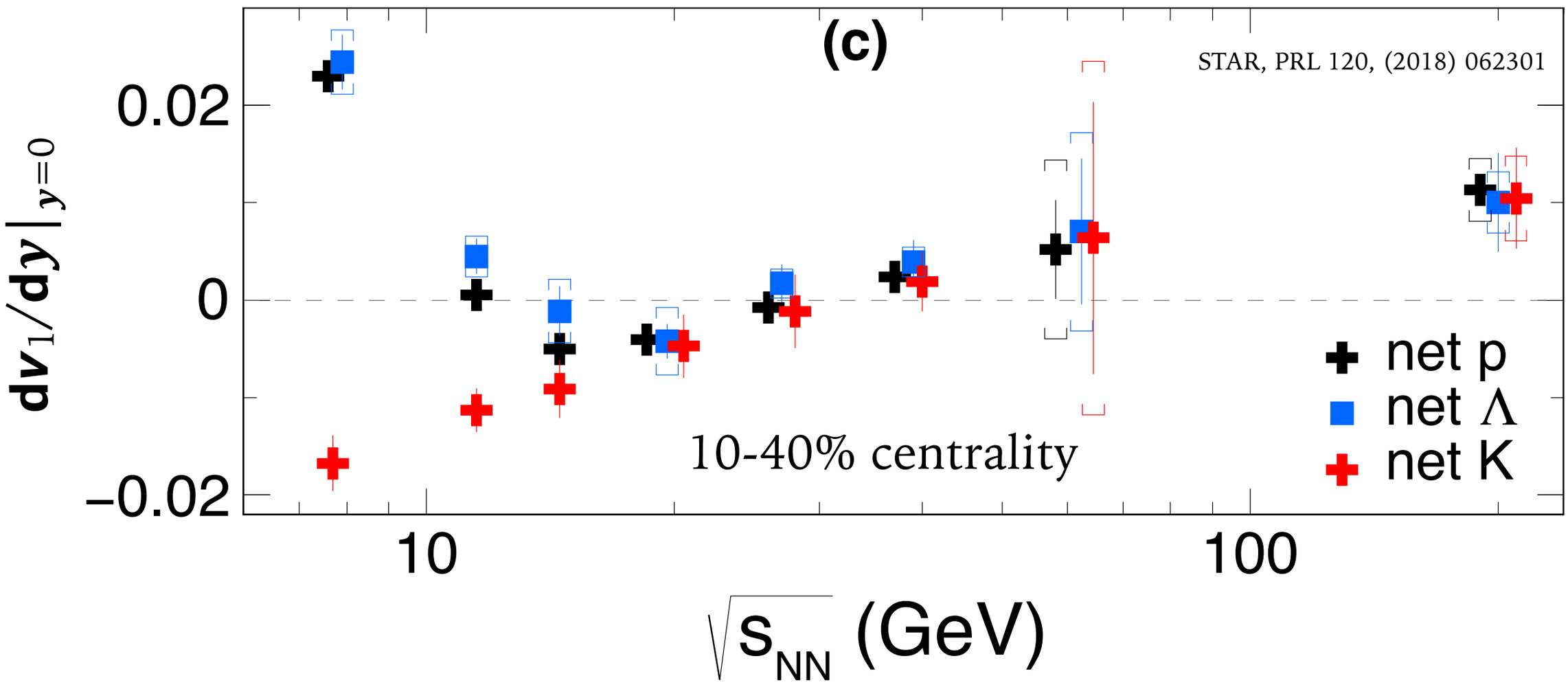
[A. Ohnishi, CPOD 2016]





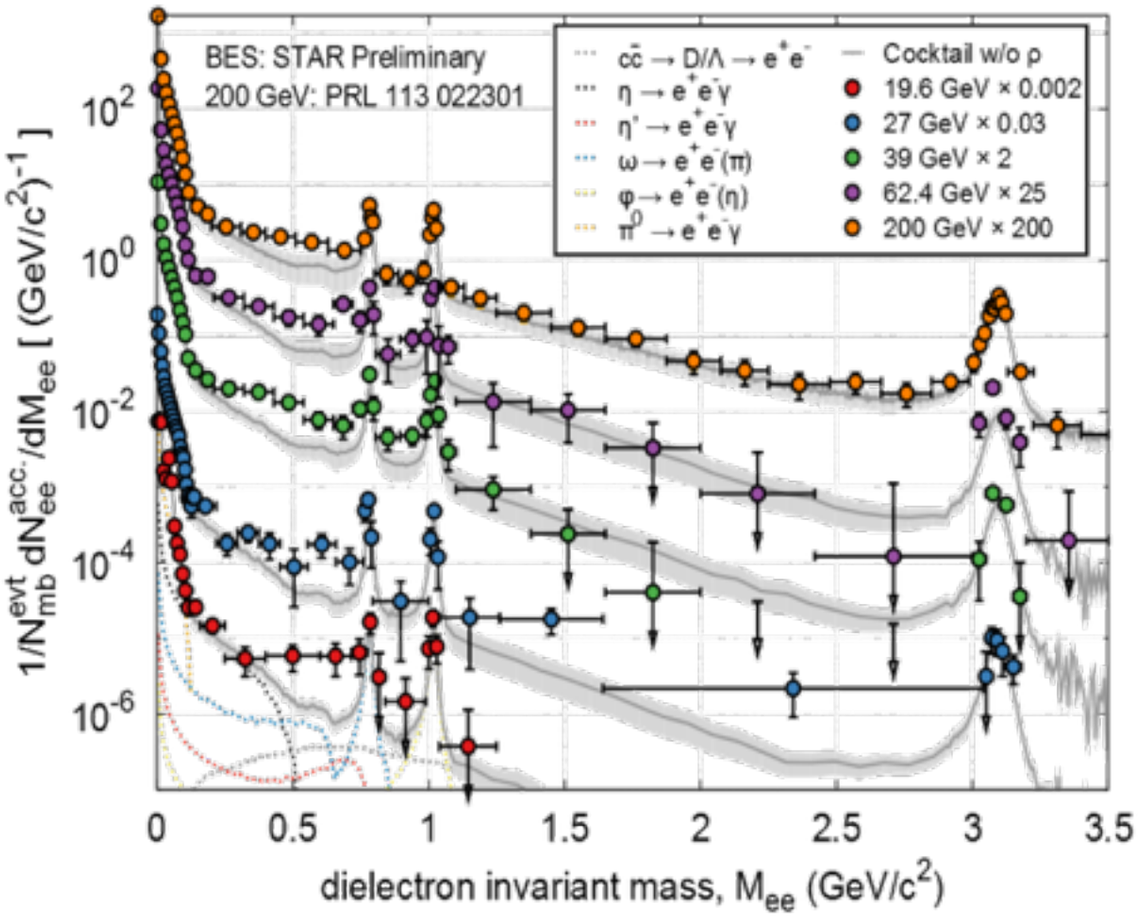
- EoS with a 1st order phase transition exhibits a very pronounced softest point at large chemical potentials [Y. Nara et al., PRC 94 034906 (2016)]
- directed flow v_1 is sensitive to the EoS in the early stage
- non-monotonic dependence
  - softening (crossover or 1st order phase transition)
  - geometry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

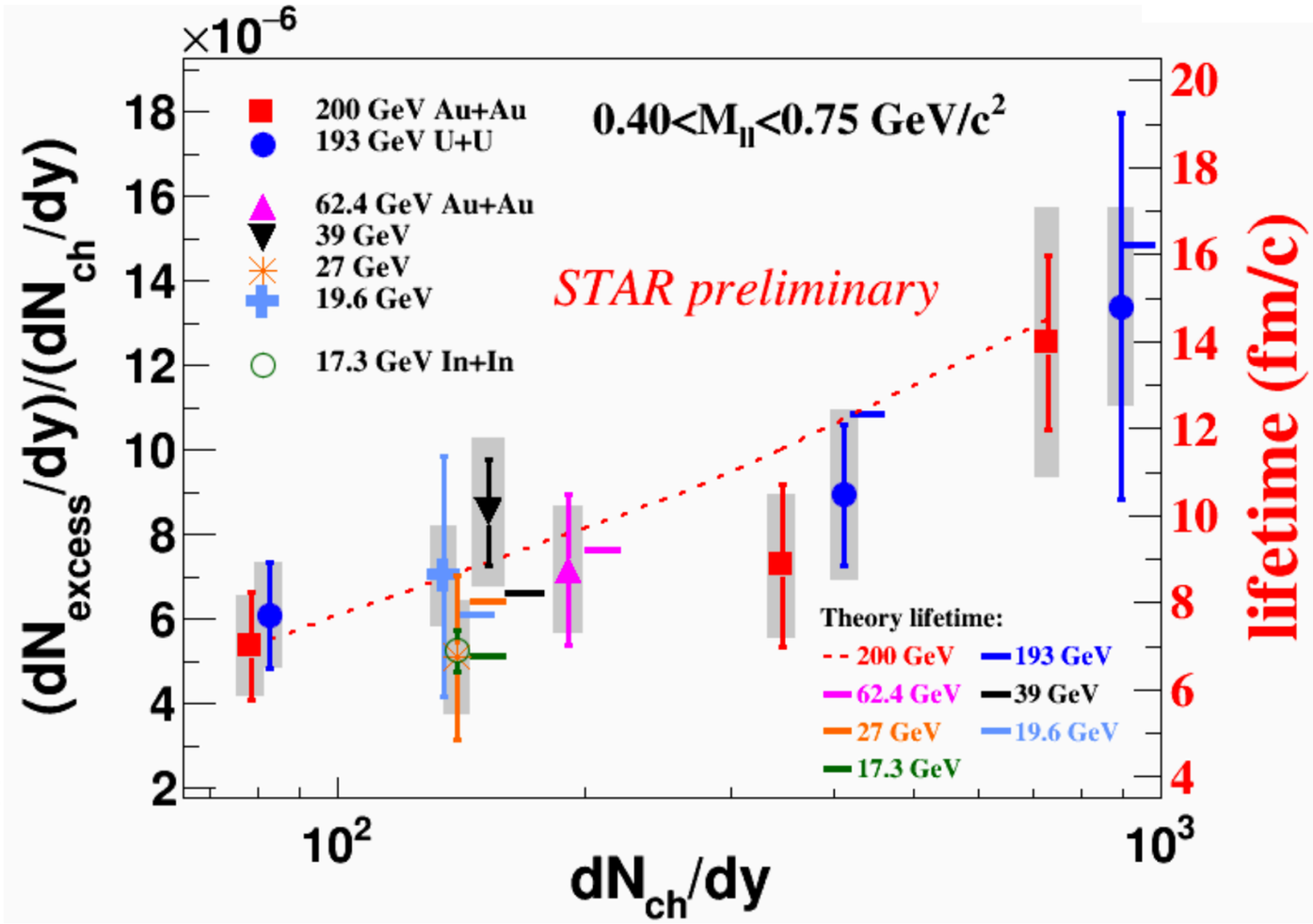
DIRECTED FLOW FROM BES-I



- 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)

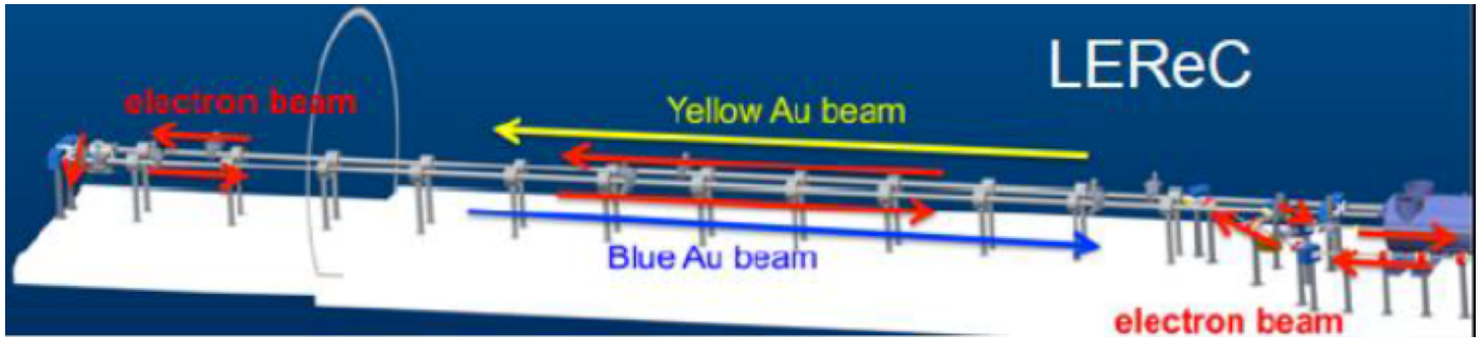
CRITICAL POINT: LIFETIME INCREASE



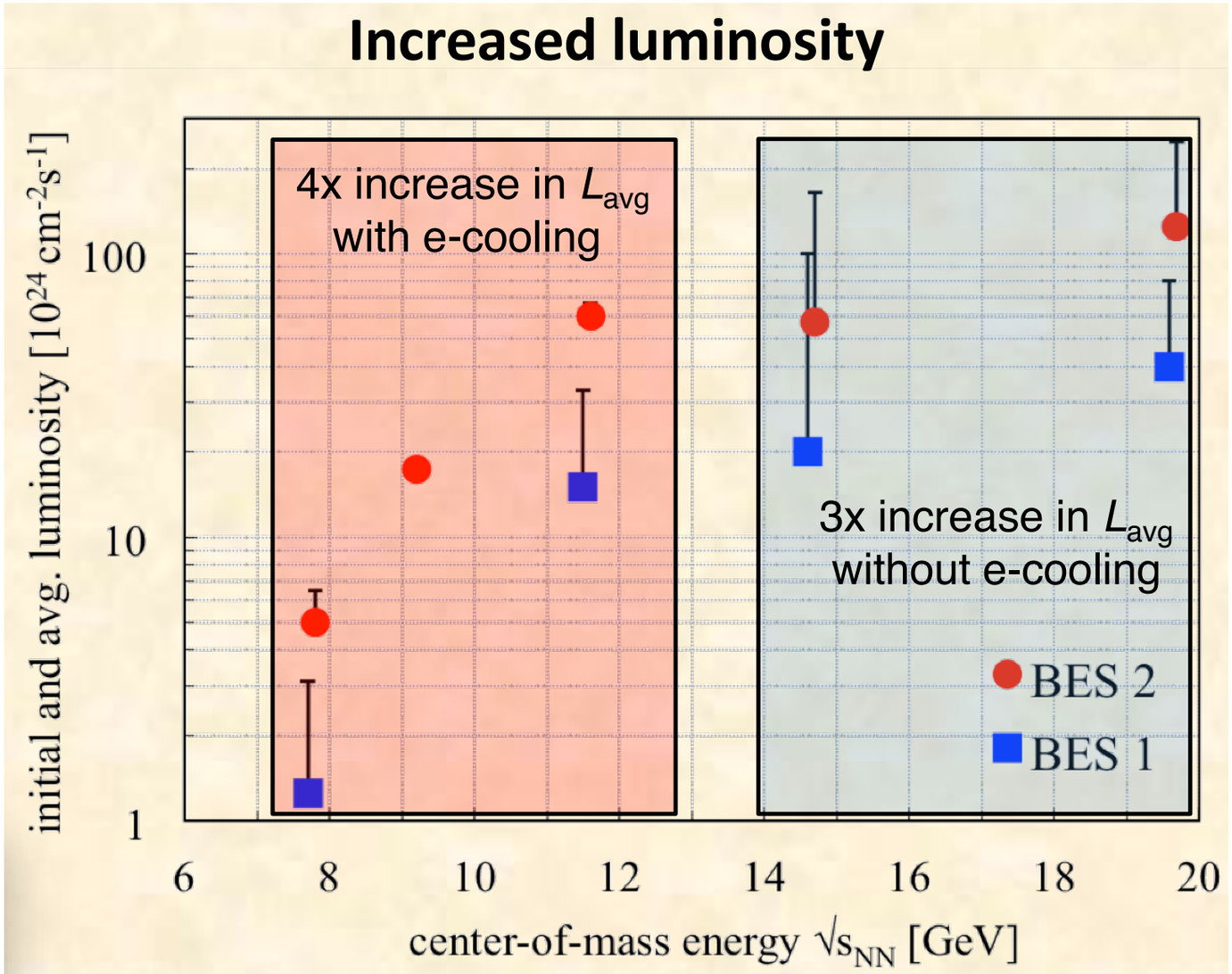


- dilepton yields sensitive to life time of the QGP
  - increase in correlation lengths expected close to Critical Point ⇒ anomalous increase in the lifetime of the fireball - not yet observed, but the lowest energy measured has been 17.3 GeV
- need to extend this measurement to low energies

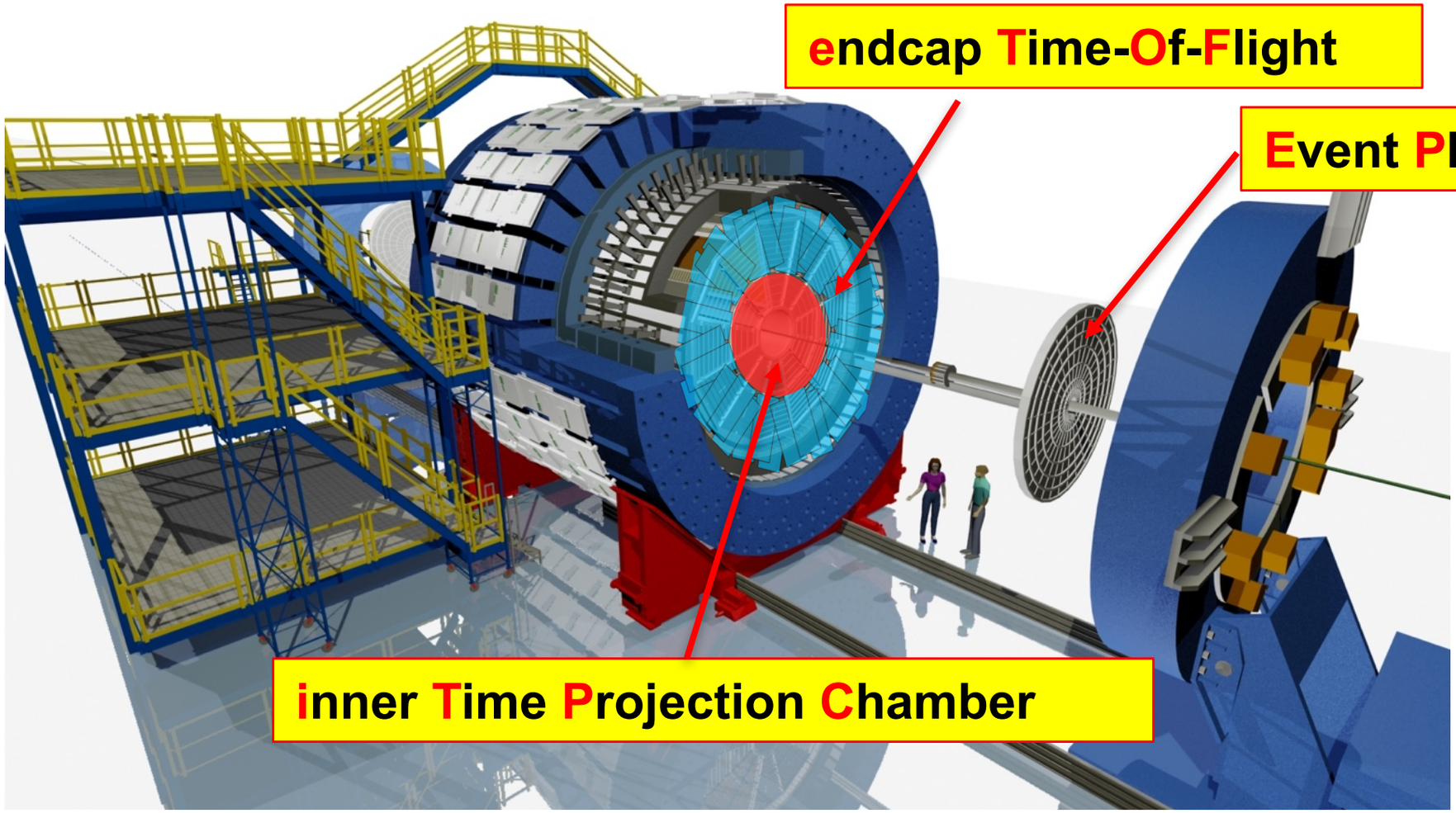
LOW-ENERGY RHIC ELECTRON COOLER (LEREC)



- 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

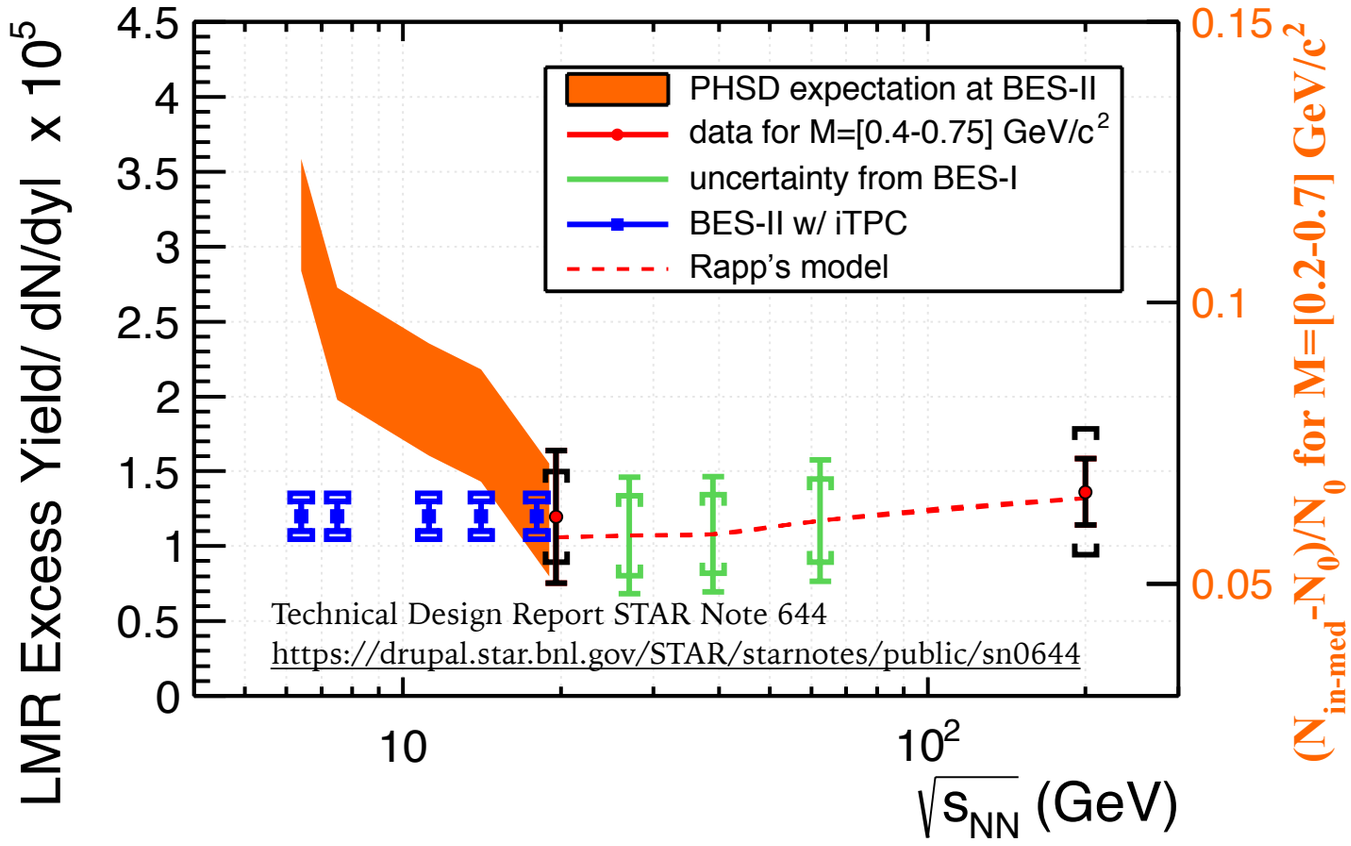


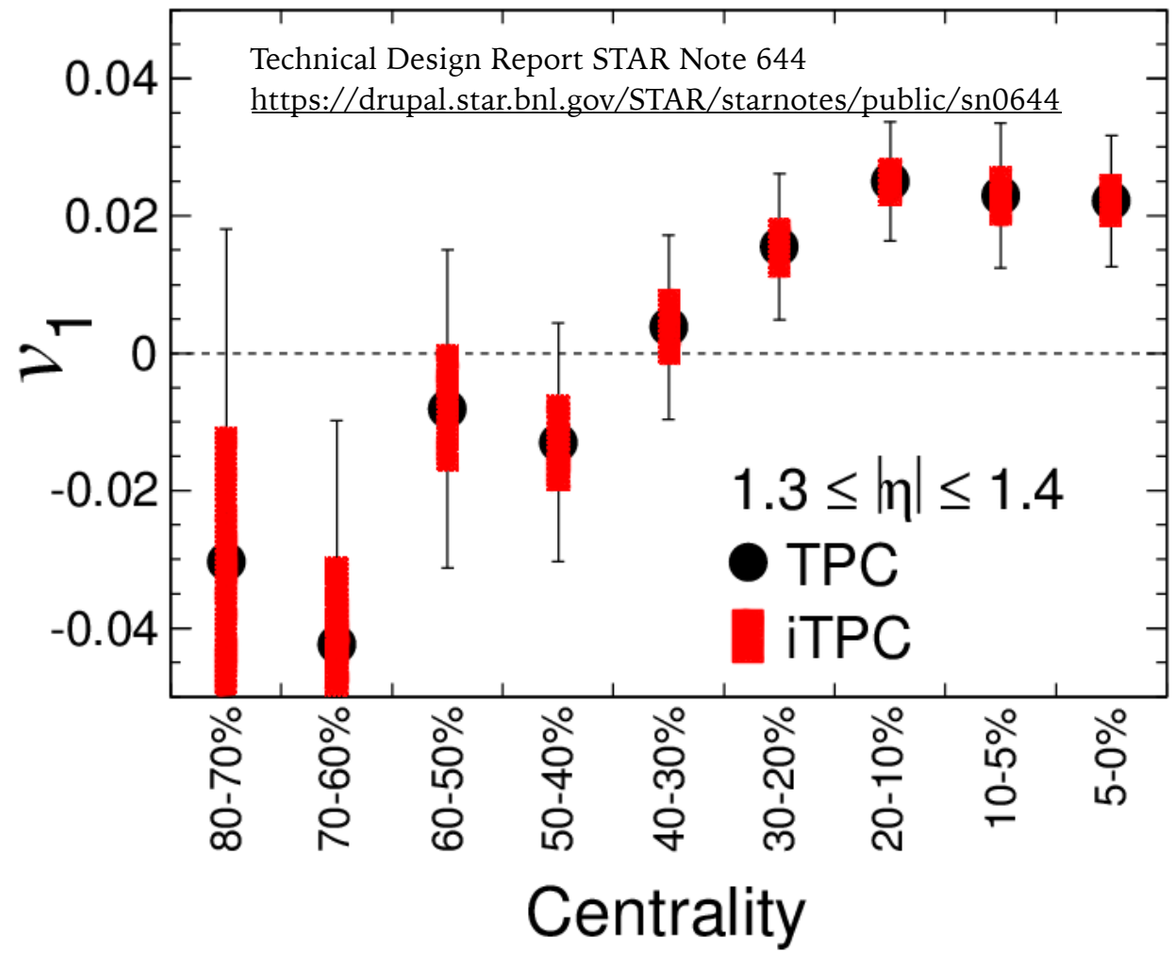
STAR DETECTOR UPGRADES FOR BES-II



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**

INNER TIME PROJECTION CHAMBER (ITPC)





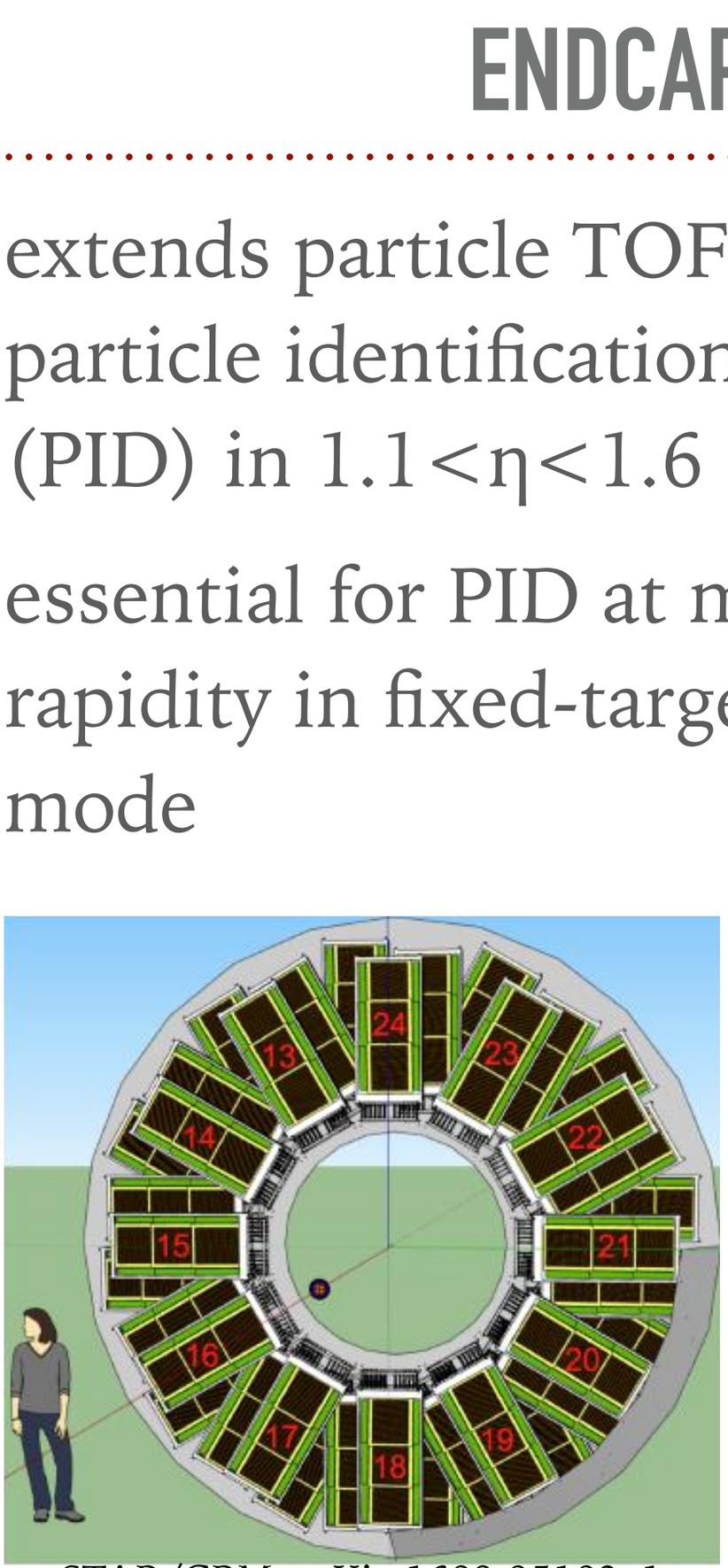
- make possible a systematic study of the dielectron continuum bellow 19.6 GeV

one sector has been installed and operated this year

- make possible to measure directed flow in forward rapidity

ENDCAP TIME OF FLIGHT (ETOF)

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



STAR/CBM, arXiv:1609.05102v1

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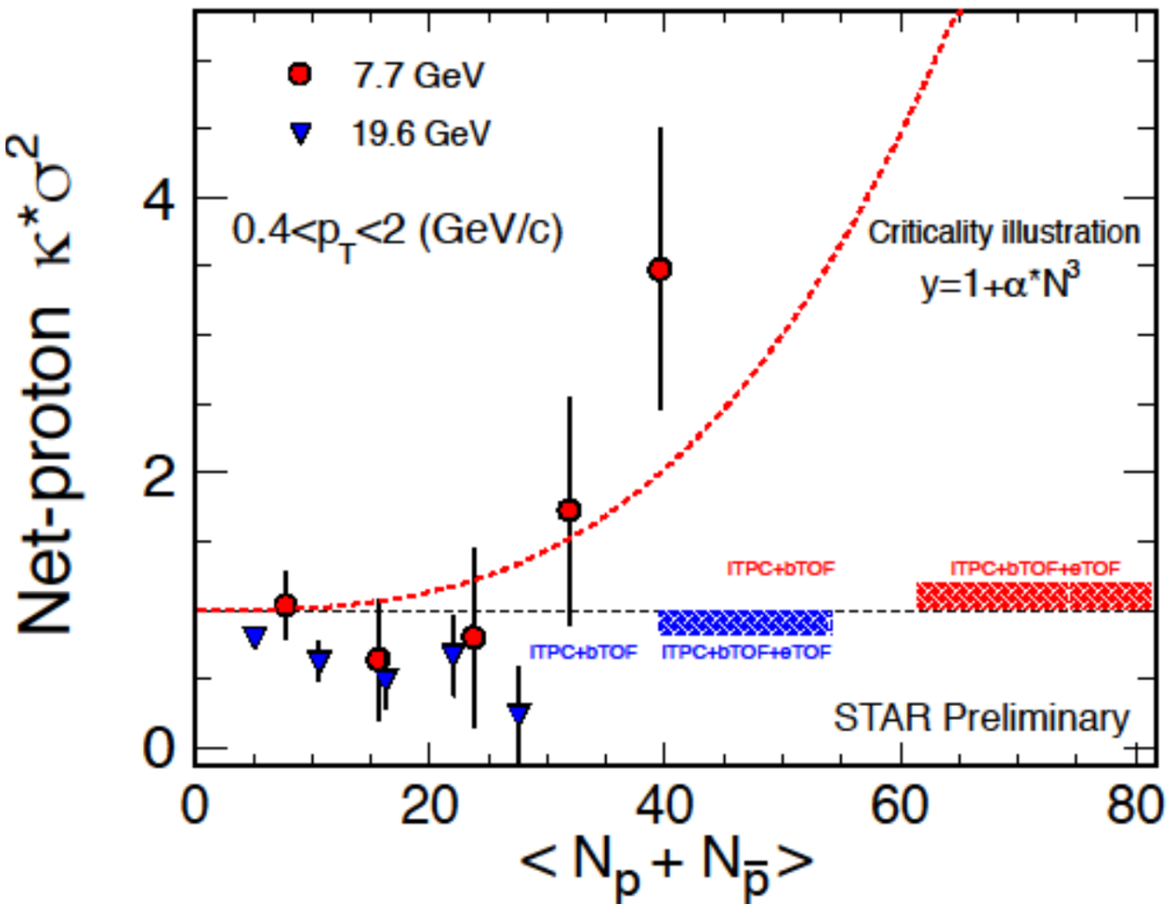
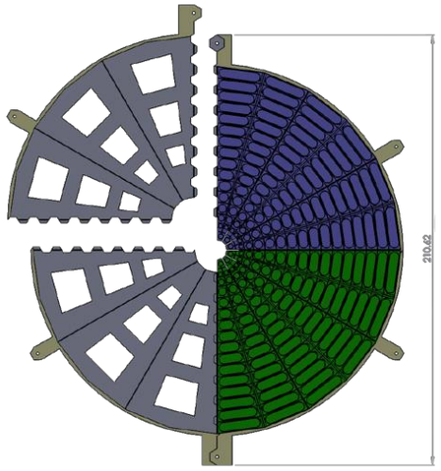
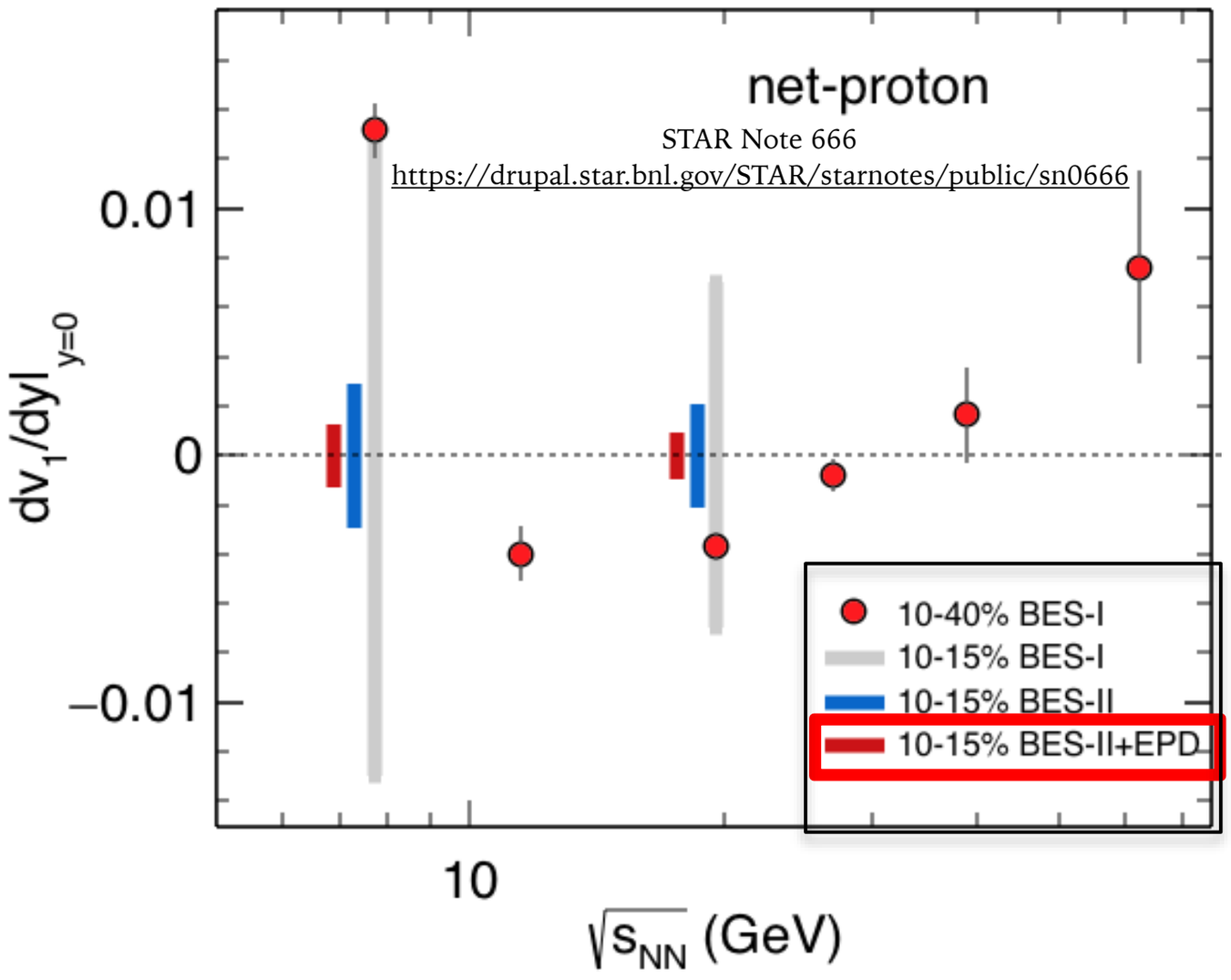


- antiprotons produced more at mid-rapidity
- added coverage by eTOF will enhance the fluctuation signal ⇒ clearer and more significant indication of critical behavior

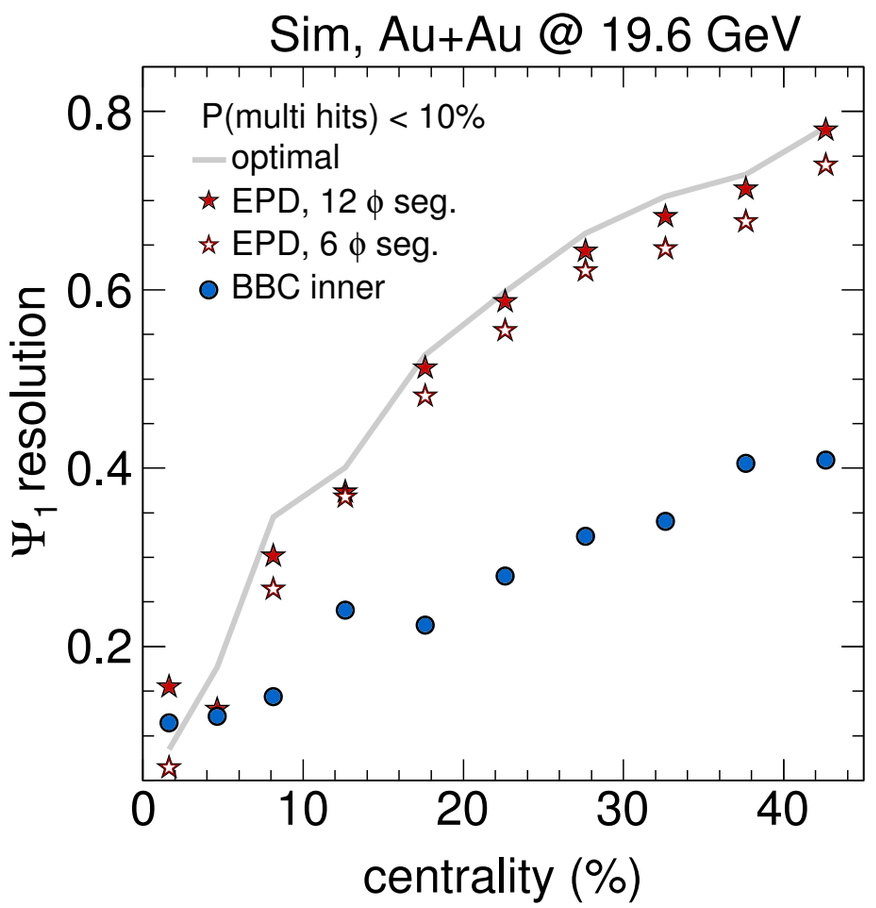
EVENT PLANE DETECTOR (EPD)

- cover $2.1 < |\eta| < 5$
- event Plane determination
- centrality definition
- trigger capabilities



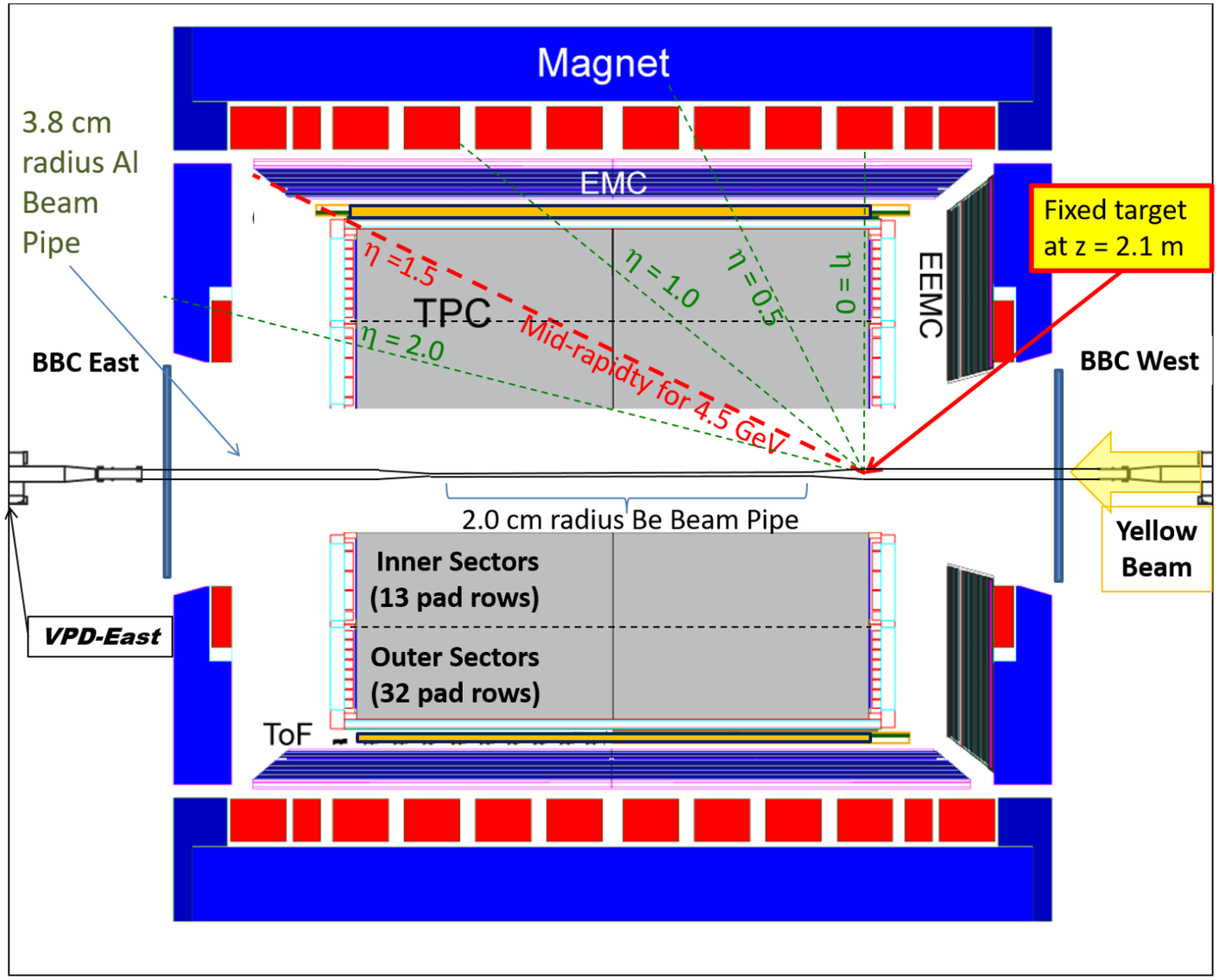


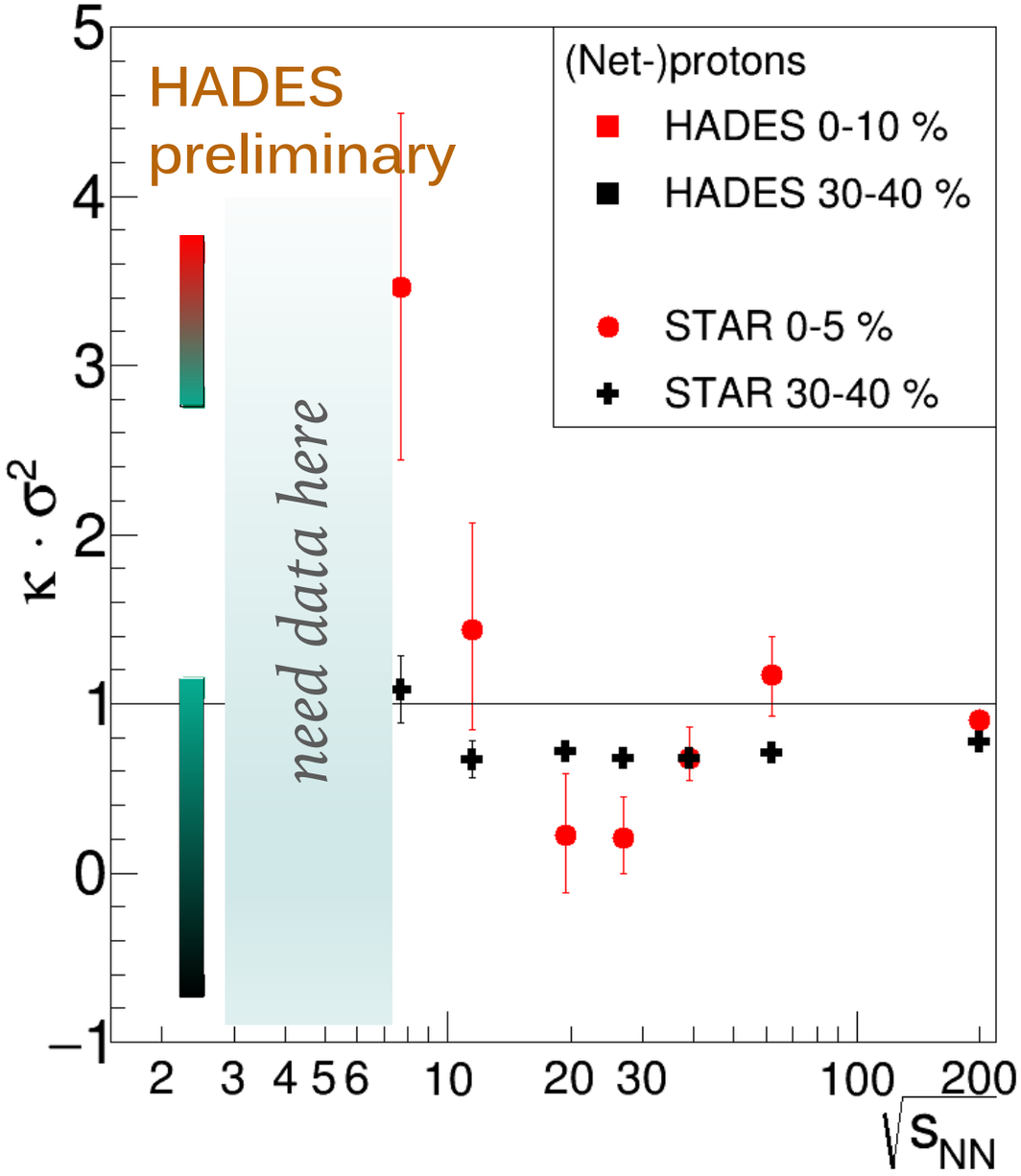
STAR Note 666
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0666



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

FIXED TARGET PROGRAM AT RHIC





- successful test run in 2015 $\sqrt{s_{NN}}$ = 4.5 GeV AuAu, paper in preparation
- STAR is taking data at 3.85 GeV this week
- fixed-target is expected to fill the gap between RHIC and SIS energies
  - HADES vs STAR: different acceptances make the comparison non-trivial

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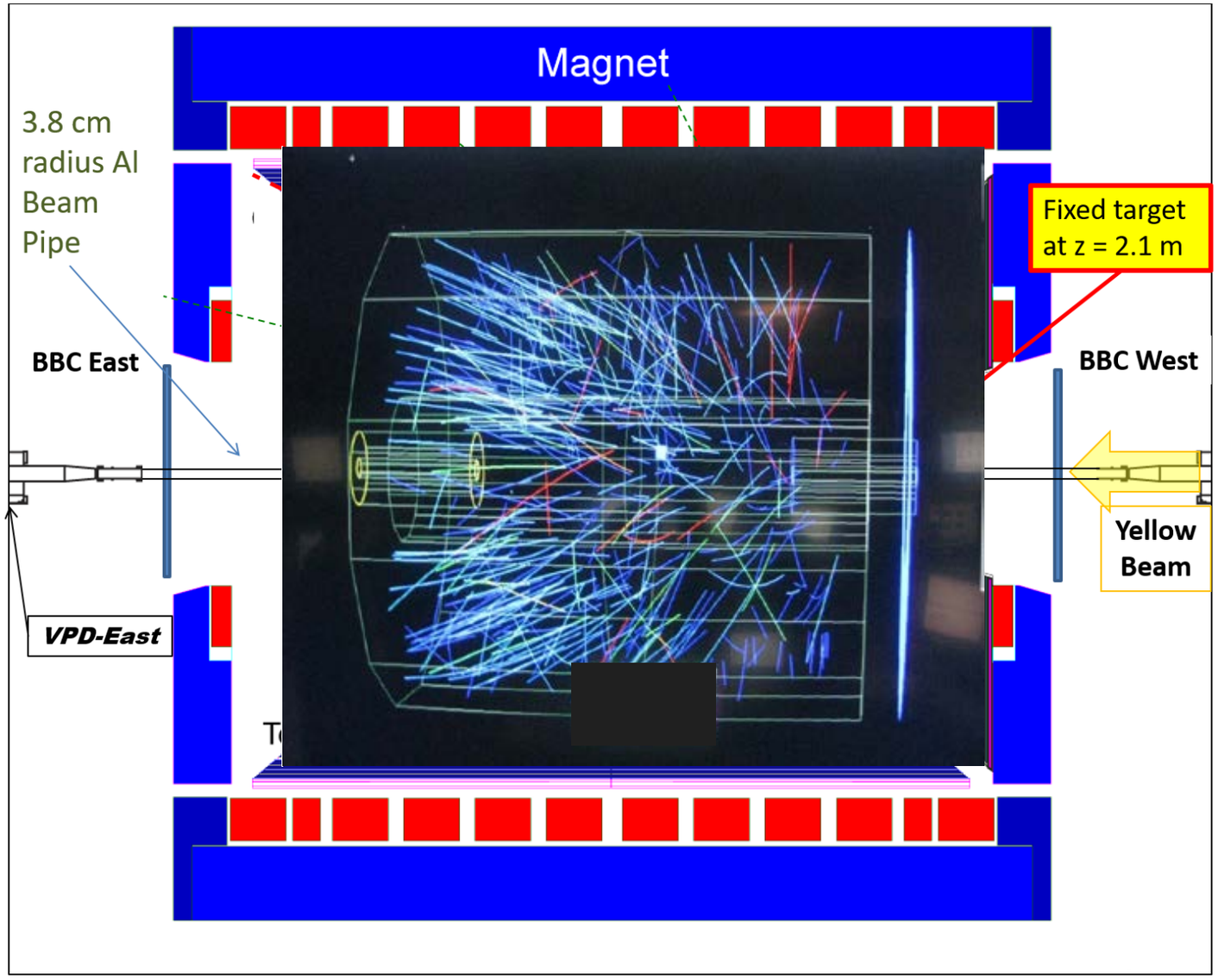

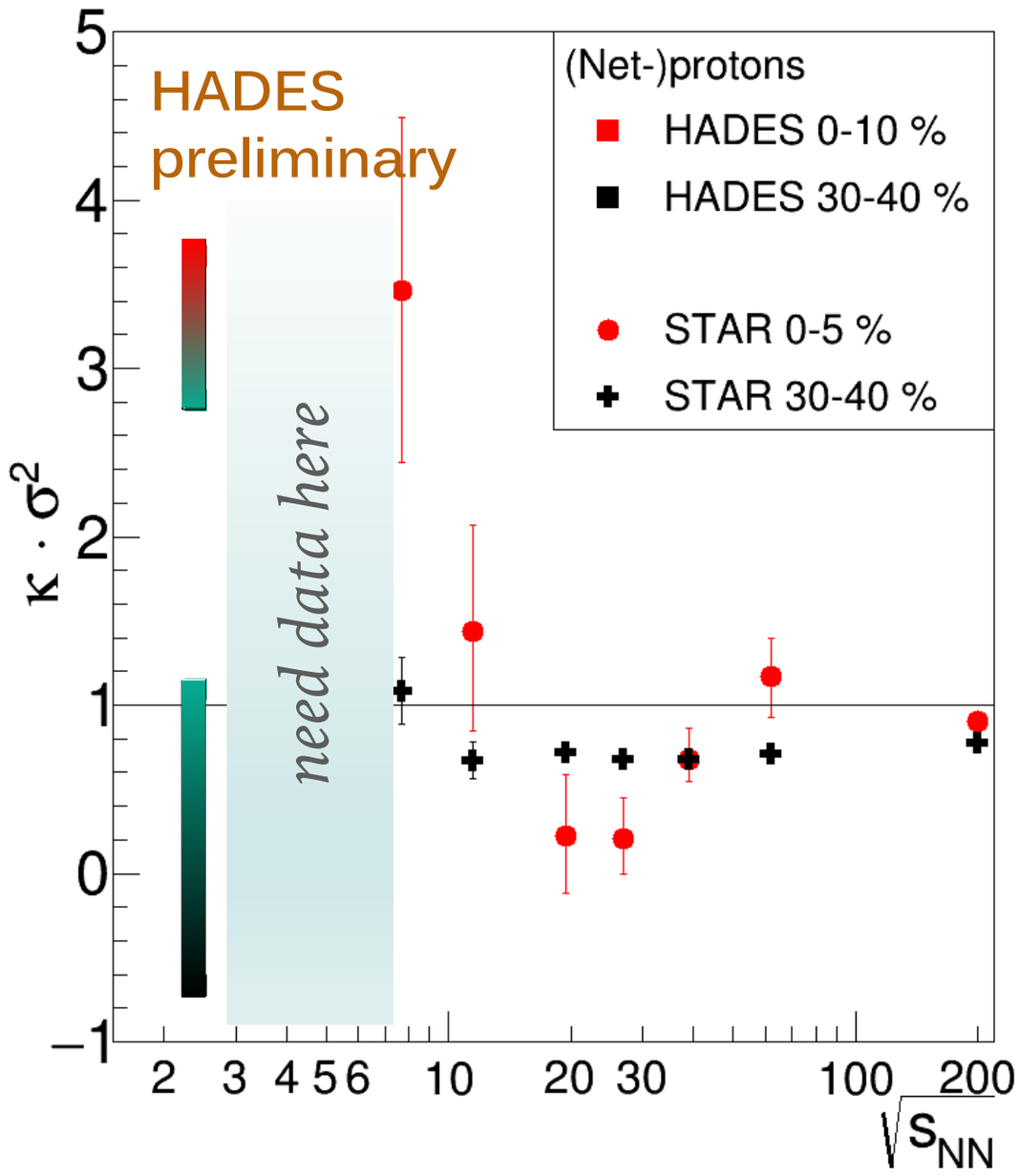

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SUMMARY:

- BES-I results hint critical behavior
- many critical measurements require larger statistics and acceptance
- BES-II provides a well defined plan for a targeted study of a phase transition and localization of the critical point
  - 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
- looking forward to new precision data from RHIC

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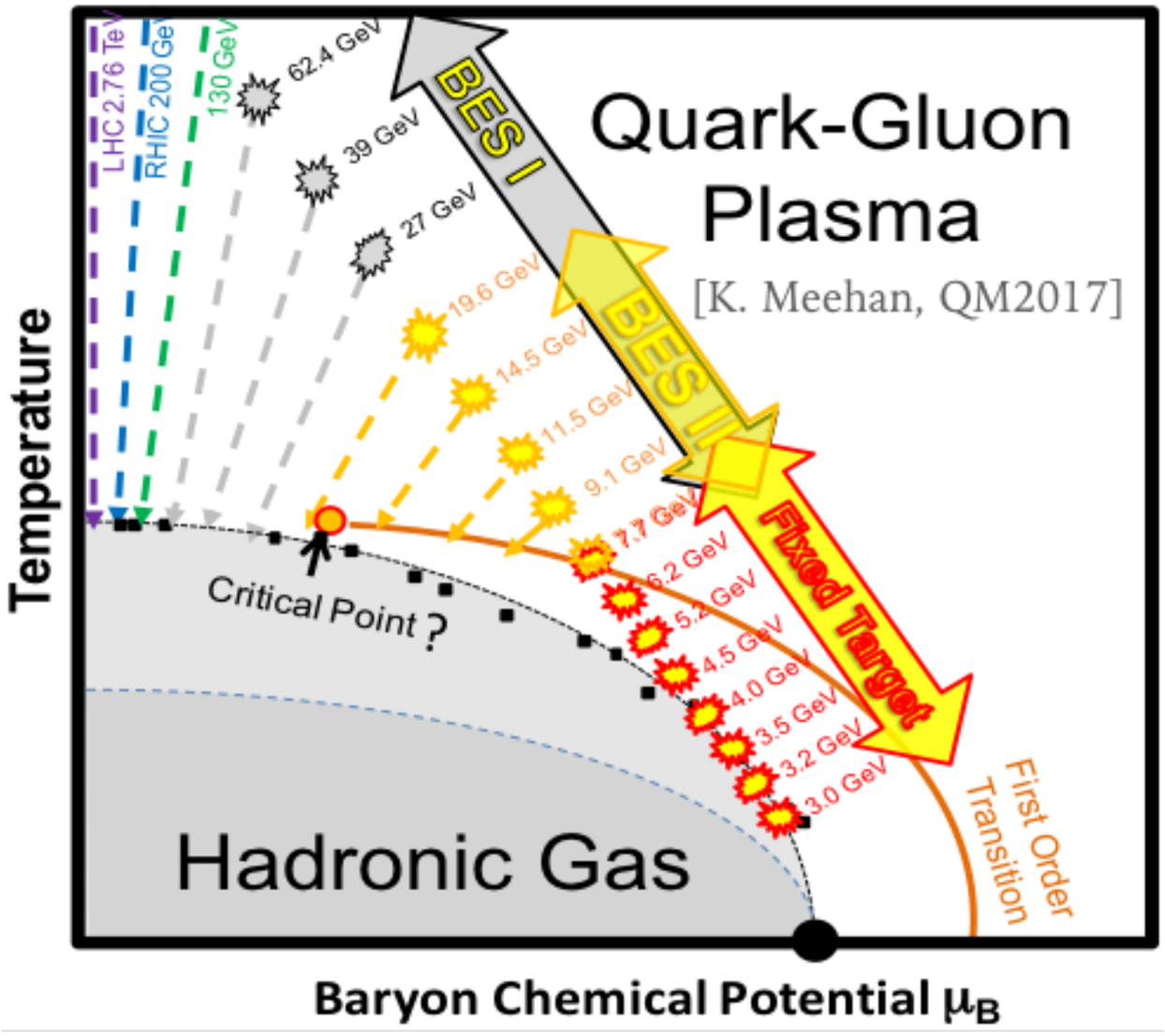
THANK YOU

BACKUP SLIDES

RHIC BEAM ENERGY SCAN

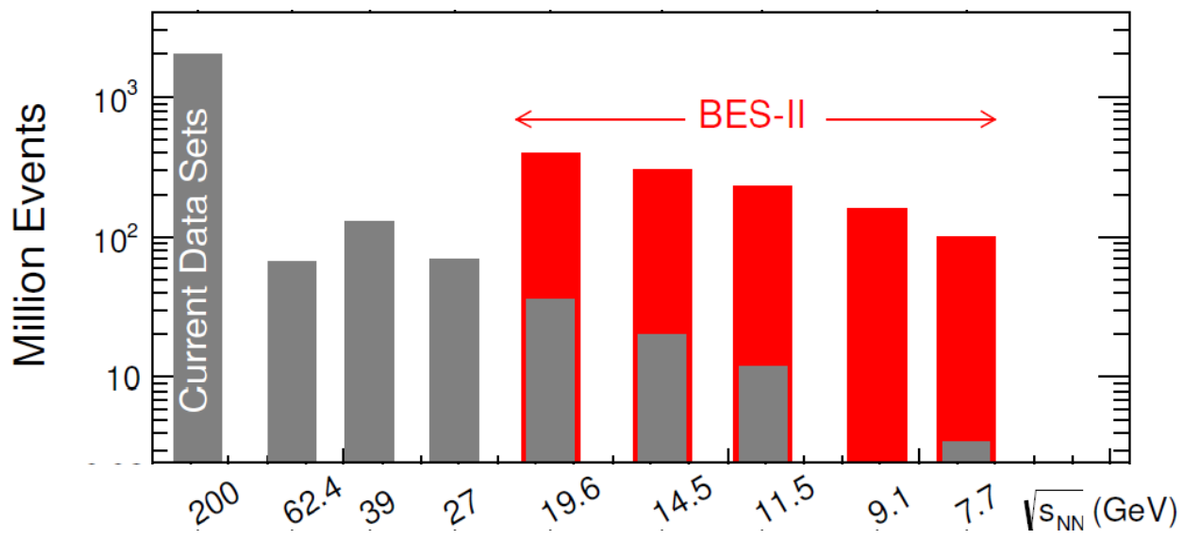


$\sqrt{s_{NN}}$ [GeV]	7.7	11.5	14.5	19.6	27.0	39.0
~μ_B (central) [MeV]	420	315	260	205	155	115

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

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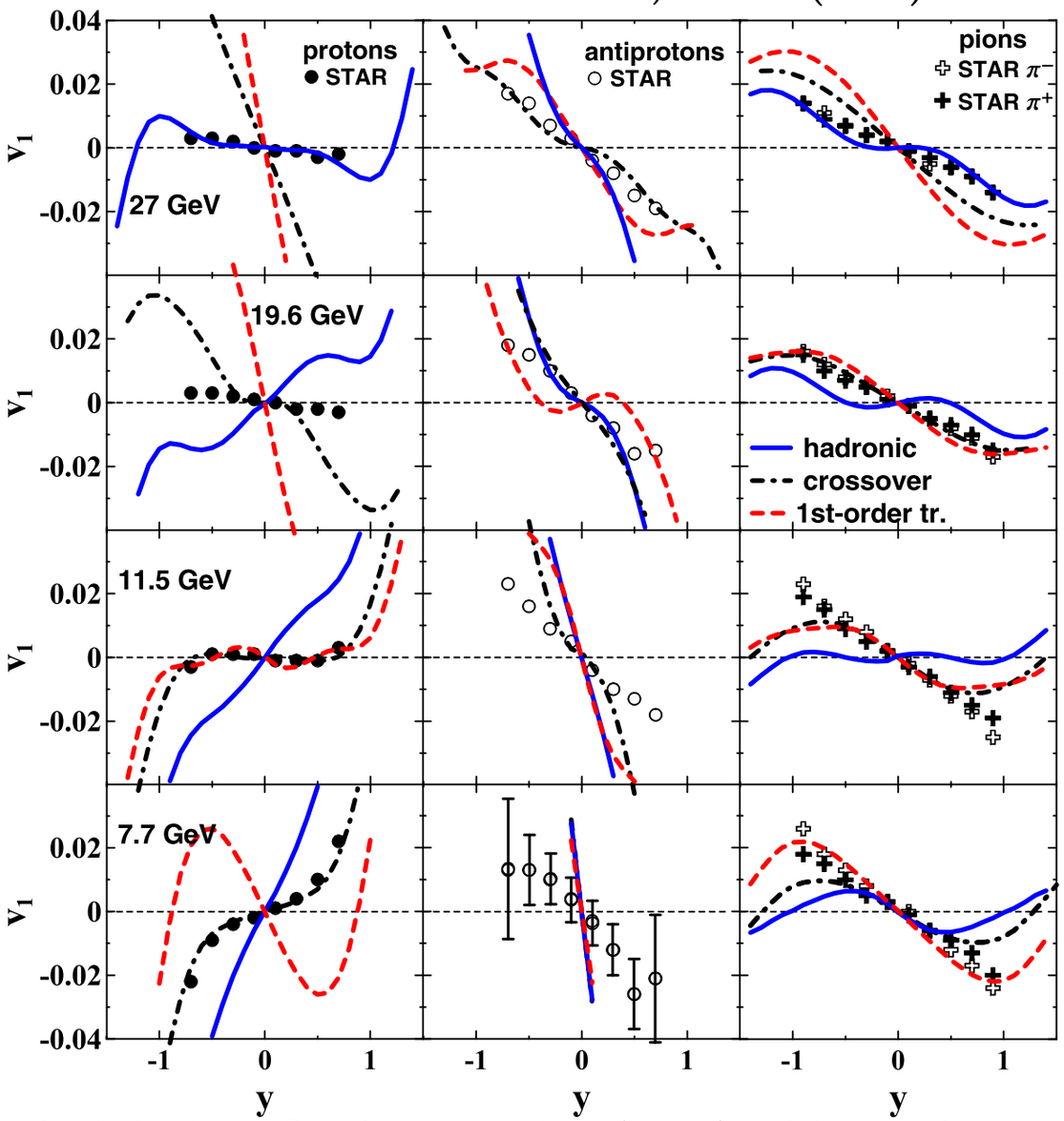
Baryon chemical potential at proposed $\sqrt{s_{NN}}$ in fixed-target mode

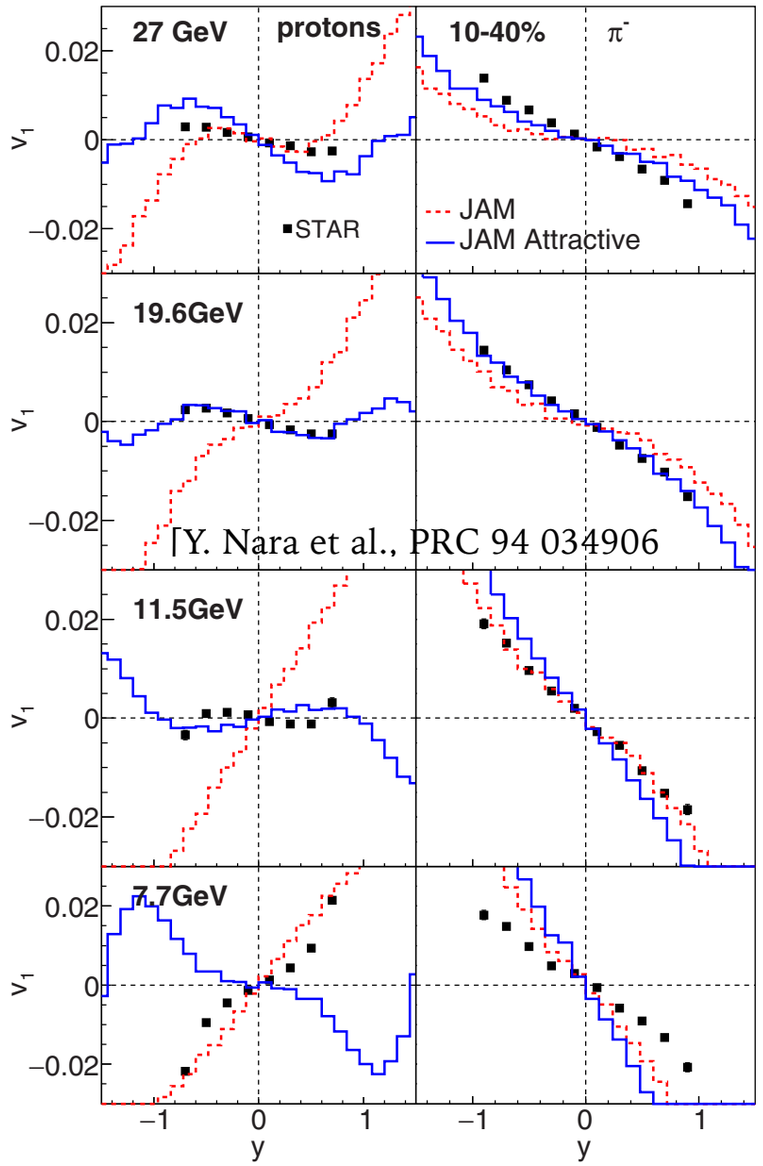
EFFECT OF SOFTENING ON DIRECTED FLOW

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



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



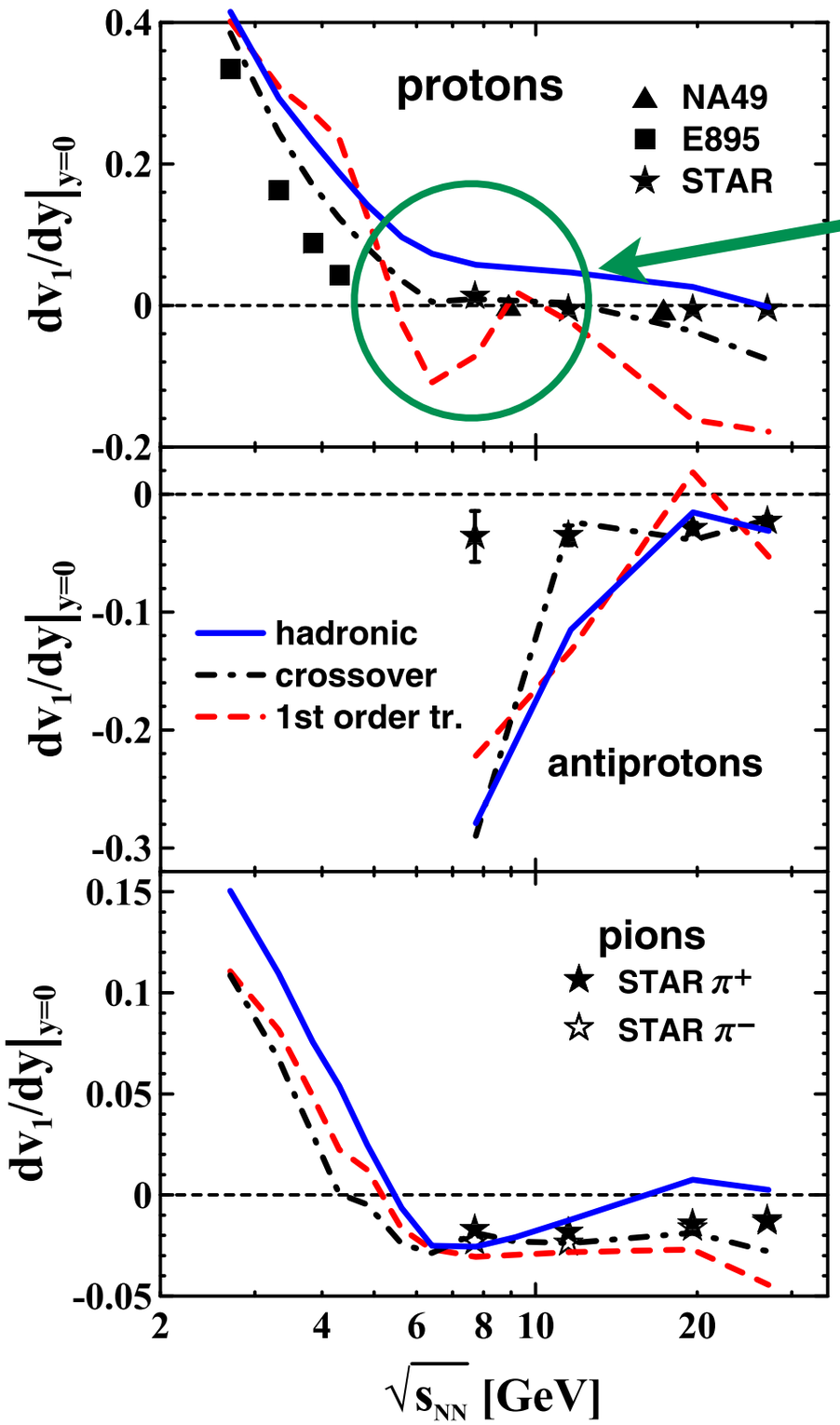
[Y. Nara et al., PRC 94 034906

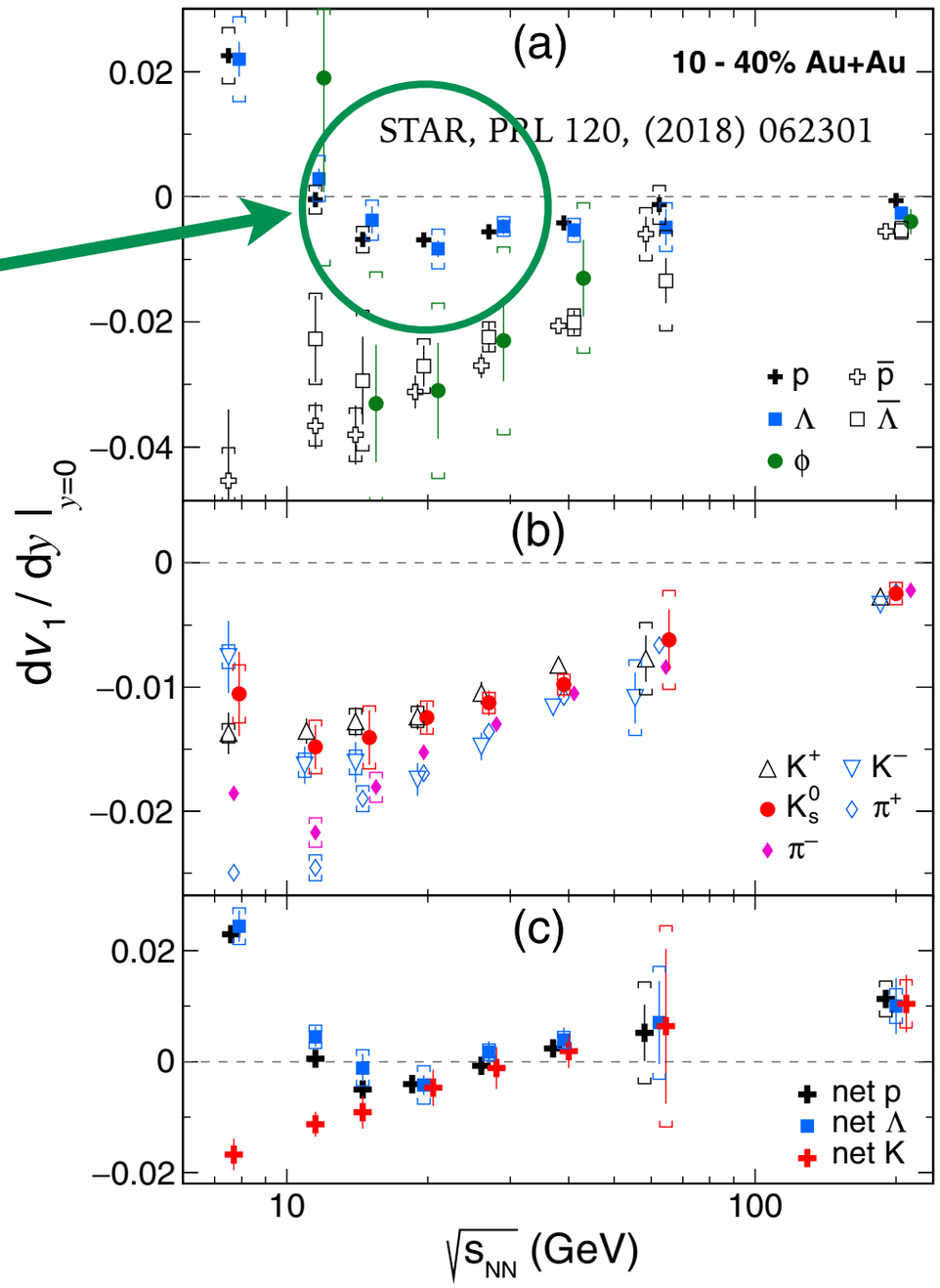
Hadronic transport model JAM with and without attractive orbits for each two-body scattering

- ➤ 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



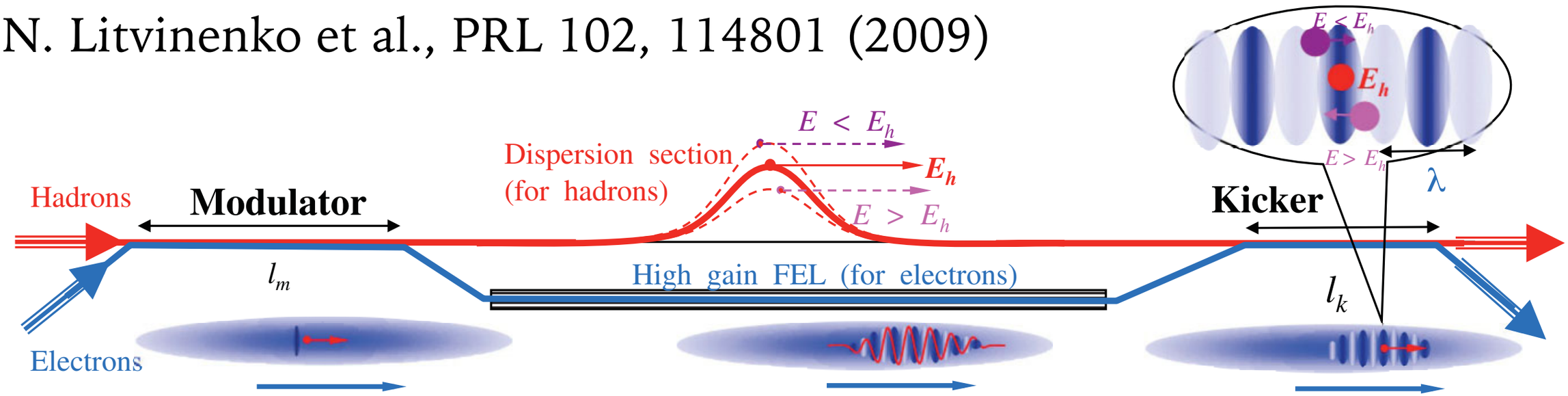


Did we find the energy with the softest EOS?

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

RHIC COHERENT ELECTRON COOLING UPGRADE

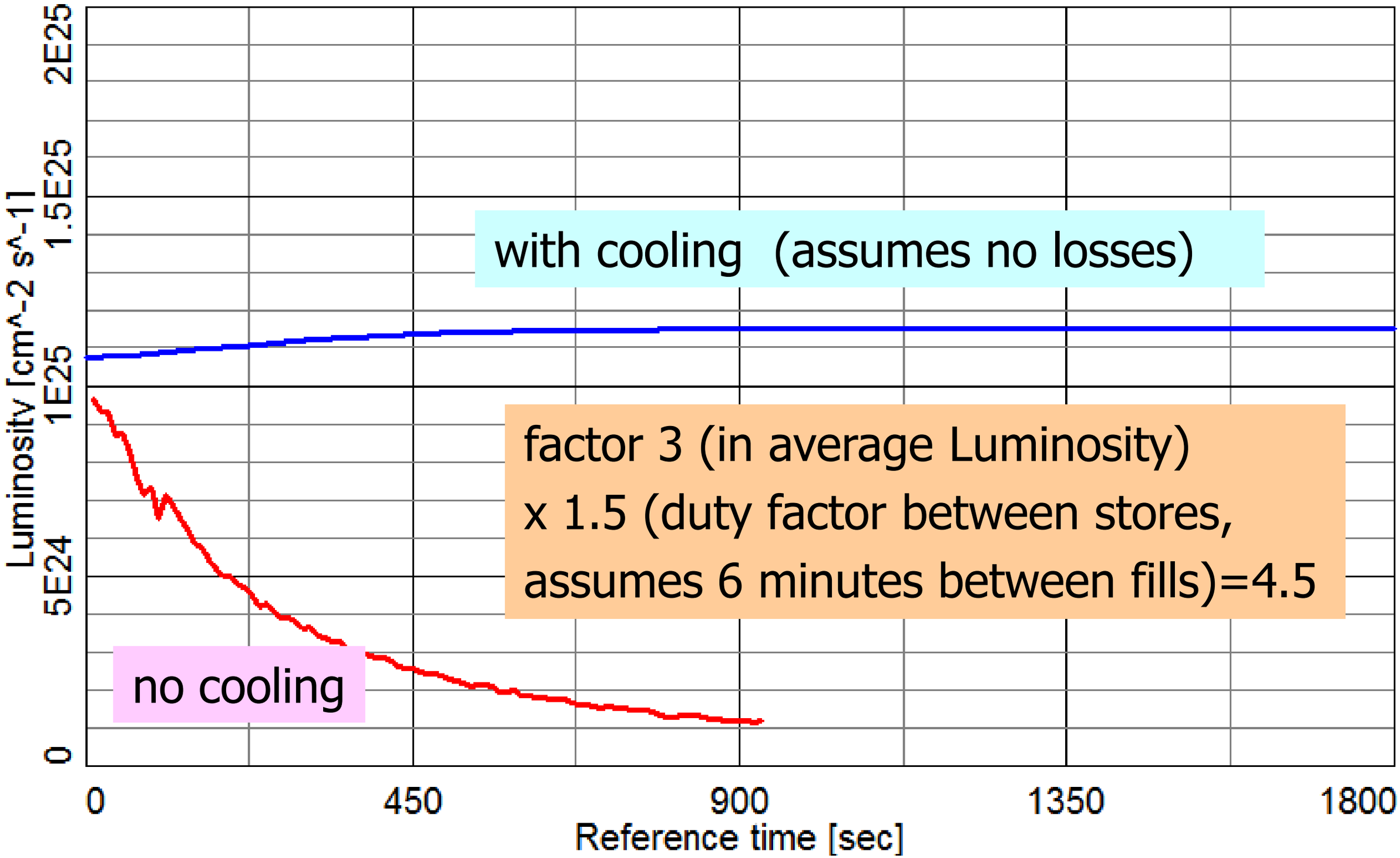
V. N. Litvinenko et al., PRL 102, 114801 (2009)



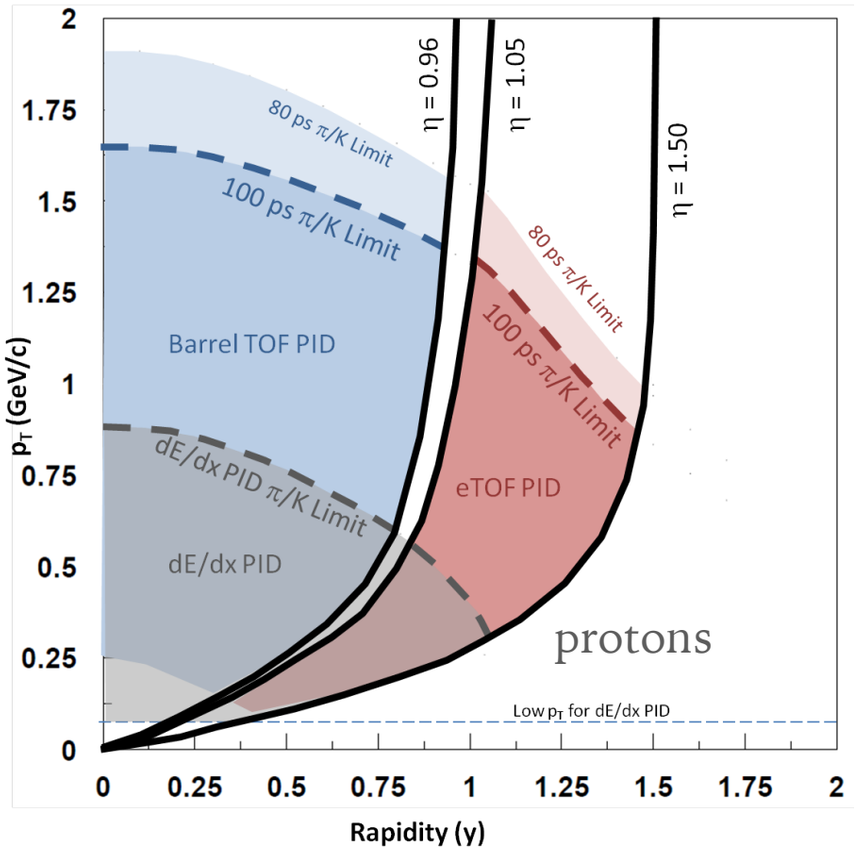
- in Modulator - each ion induces a density modulation in n electron beam ⇒ electron beam carries information about individual hadrons imprinted in density distortions
- in free-electron laser (FEL) - the induced density modulation is amplified
- in Kicker - both beams co-propagate again and the longitudinal 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)]

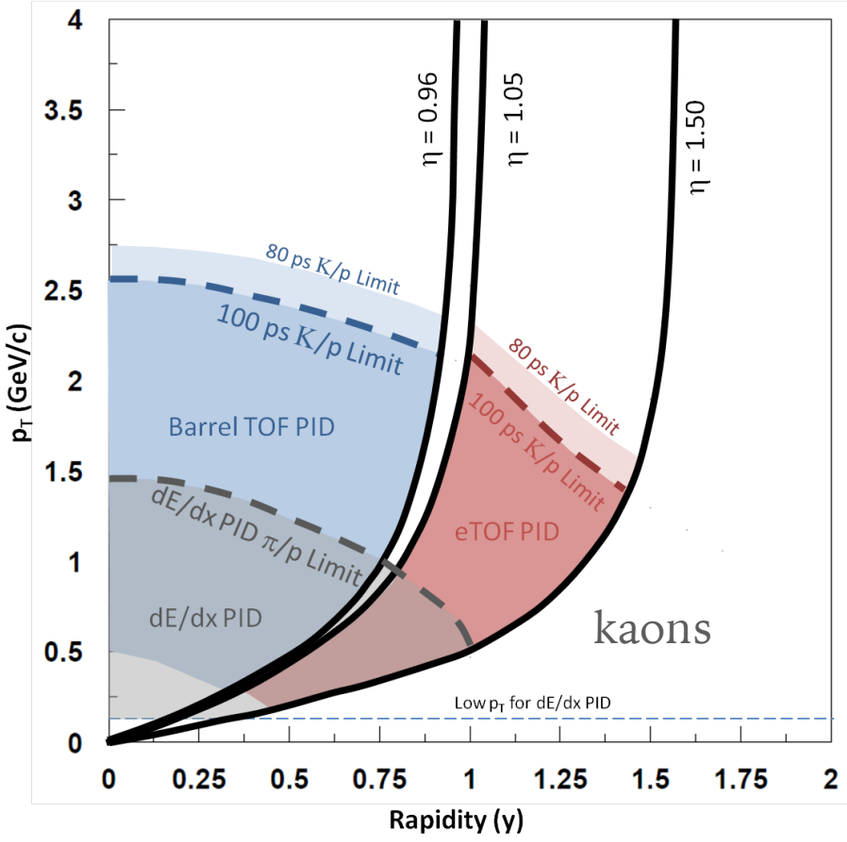
SIMULATION OF LUMINOSITY WITH ELECTRON COOLING FOR COLLISIONS AT $\sqrt{S_{NN}}$=7.7 GeV

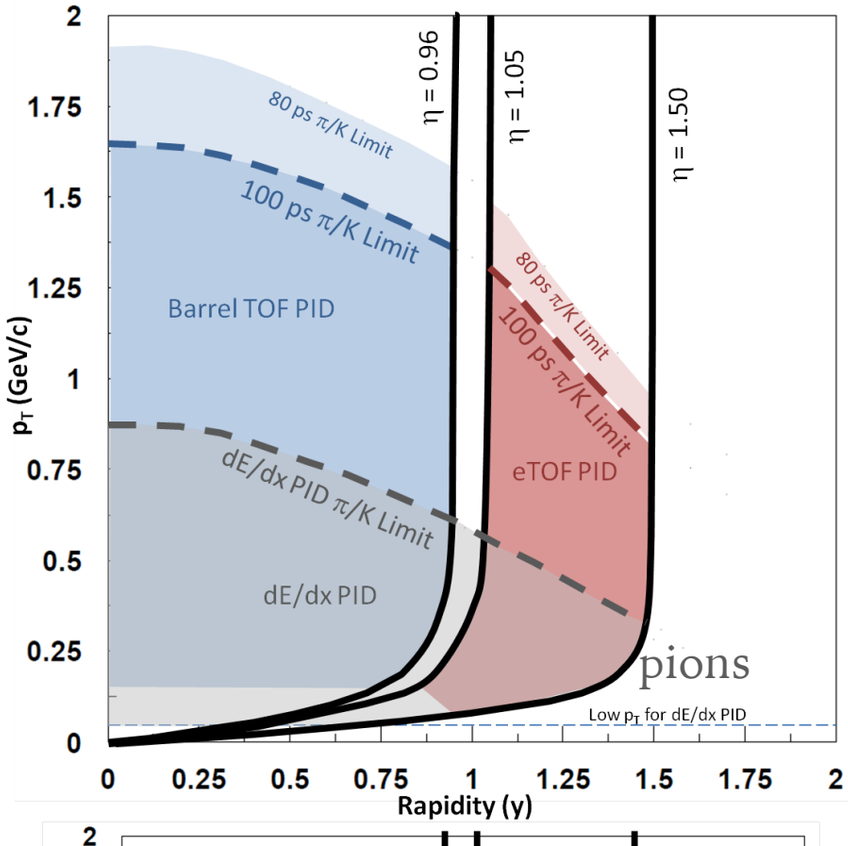
A. Fedotov, RHIC/AGS Users Meeting (2012)



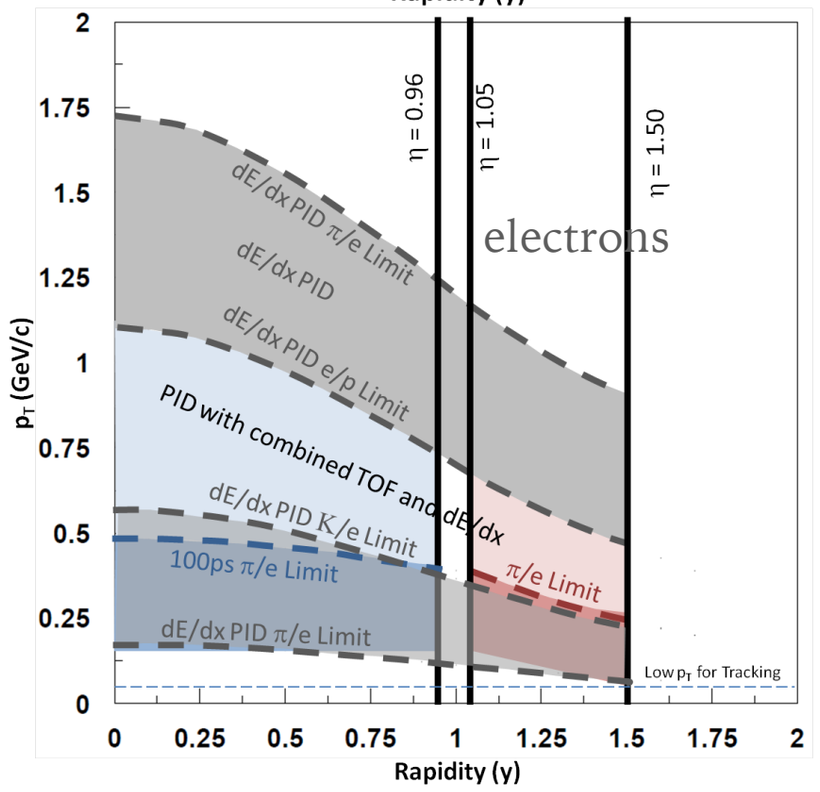
STAR ACCEPTANCE AND PID IMPROVEMENT







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



STAR/CBM, arXiv:1609.05102v1