Exploring the Phase Diagram of QCD Matter: What have we learned and where are we going?

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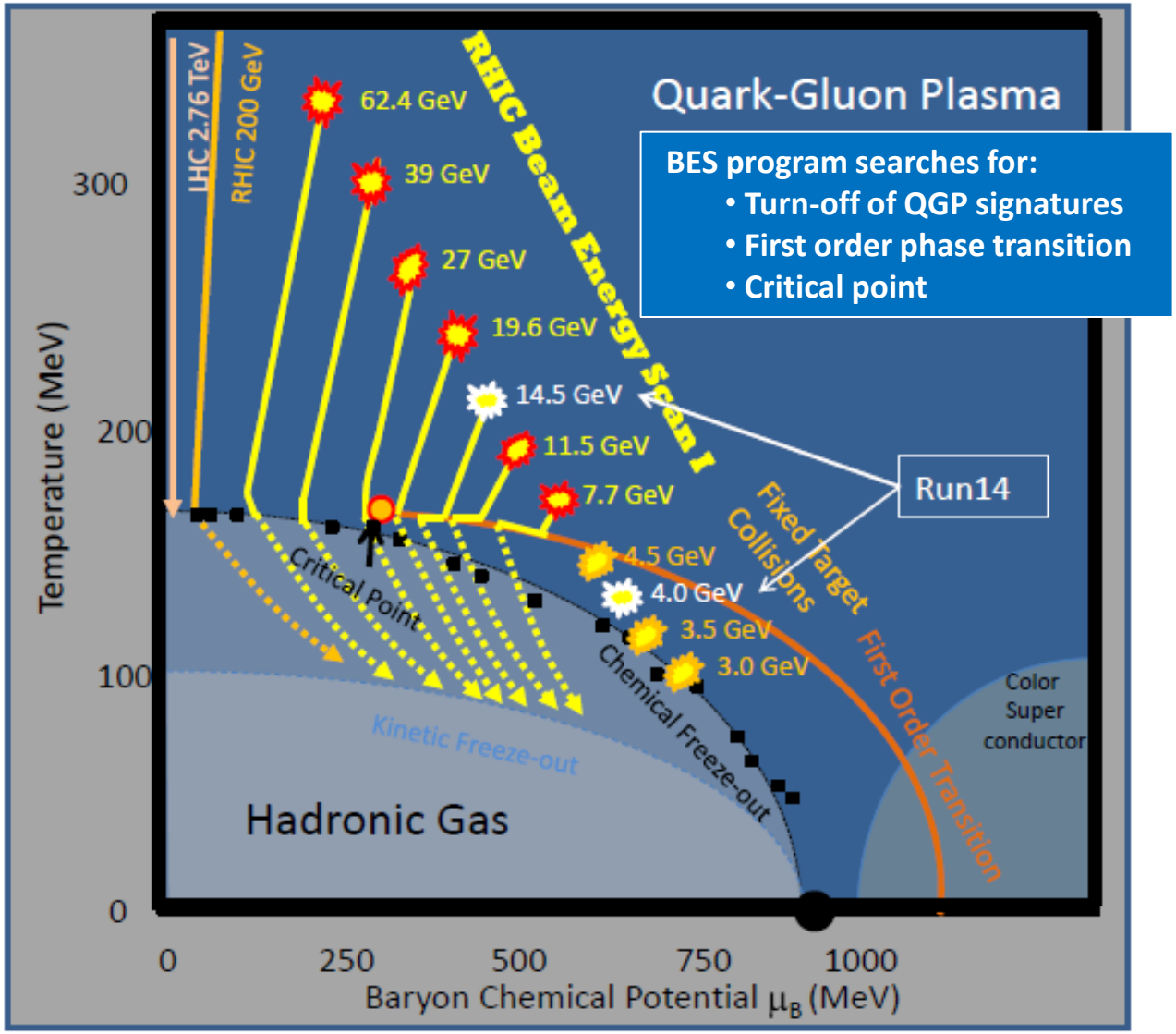
For the STAR Collaboration

Phase Diagram of QCD Matter



	Energy (GeV)	Baryon Chemical Potential* μ_B	Pred. Temp.* (MeV)
LHC	2760.0	2	166.0
RHIC	200.0	24	165.9
RHIC	130.0	36	165.8
RHIC	62.4	73	165.3
RHIC	39.0	112	164.2
RHIC	27.0	156	162.6
RHIC	19.6	206	160.0
SPS	17.3	229	158.6
RHIC	14.5	262	156.2
SPS	12.4	299	153.1
RHIC	11.5	316	151.6
SPS	8.8	383	144.4
RHIC	7.7	422	139.6
SPS	7.7	422	139.6
SPS	6.4	476	131.7
AGS	4.7	573	114.6
RHIC	4.5	589	111
AGS	4.3	602	108.8
RHIC	3.9	633	101
AGS	3.8	638	100.6
RHIC	3.5	666	93
AGS	3.3	686	88.9
RHIC	3.0	721	76
AGS	2.7	752	70.4
SIS	2.3	799	55.8

* PRC73 (2006) 34905

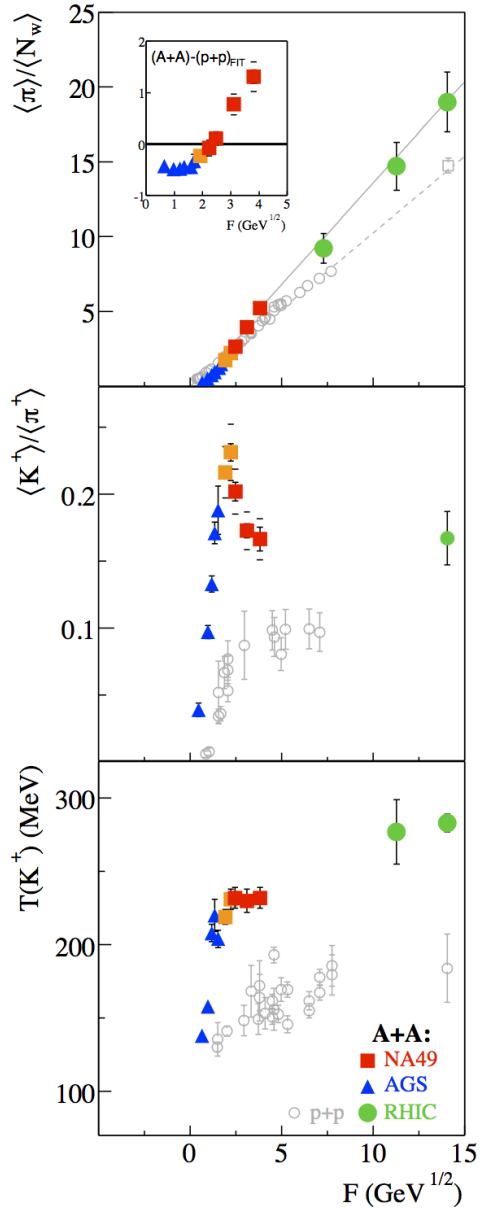
Beam Energy Scan I (2010-2011)

Final Physics Results from BES I	Exp	Journ.	Reference
v_2 of inclusive hadrons	ST	PRC	86 (2012) 054908
J/Psi suppression	PH	PRC	86 (2012) 064901
π^0 suppression	PH	PRL	109 (2012) 152301
v_2 of identified hadrons	ST	PRC	88 (2013) 14902
v_2 of particles and anti-particles	ST	PRL	110 (2013) 14301
Net proton higher moments	ST	PRL	112 (2014) 32302
Directed flow of pions and protons	ST	PRL	112 (2014) 162301
Net-charge higher moments	ST	PRL	113 (2014) 92301
Chiral Magnetic Effect	ST	PRL	113 (2014) 52302
Particle ratio fluctuations	ST	arXiv	1401.5375
HBT freeze-out eccentricities	ST	arXiv	1403.4972
v_2 of non-photonic electrons	ST	arXiv	1405.6348
HBT pion emission source	ST	arXiv	1410.2559
Dielectron excess at 19.6 and 200 GeV	PH	arXiv	1501.05341
Chiral Magnetic wave	ST	arXiv	1504.02175

Preliminary Physics Results from BES I	EXP	Year Exp.	Conference Ref
Net-charge higher moments	PH	2015	CPOD2014
Global Variables	PH	2015	CPOD2014
π,K,p mid-rapidty spectra	ST	2015	QM2014
R_{CP} inclusive and identified hadrons	ST	2015	QM2012
Strange particle production	ST	2015	
Fixed target results from Au+Al	ST	2015	
Dielectron production in BES	ST	2015	
Net-Kaon higher moments	ST	2015	QM2014
v_n higher flow harmonics	ST	2016	
2 and 3 particle correlations	ST	2016	
Kaon directed flow	ST	2016	
Rapidity dependence of π,K,p	ST	2016	
Kaon femtoscopy	ST	2016	
Proton and anti-proton femtoscopy	ST	2016	

What Was Learned in the Earlier Scans?

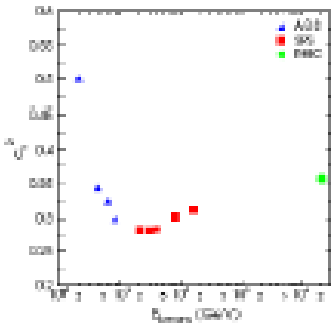
- Summary of AGS, SPS, and early RHIC Results
- Inclusive observables ➔ *onset of deconfinement* at 7-8 GeV.
- The observables suggest a change in the nature of the system.
- More discriminating studies were needed to understand the nature of the phase transition and to search for critical behavior.
- It is best to study regions above and below the possible onset energy.



Onset of Deconfinement:
early stage hits transition line,
observed signals: kink, horn, step
Predictions SMES: APP B30 2705 (99), *Results: PR C77 024903 (08)*

Kink

the dale
sound velocity from
width of pion rapidity spectra
nucl-th/0611001

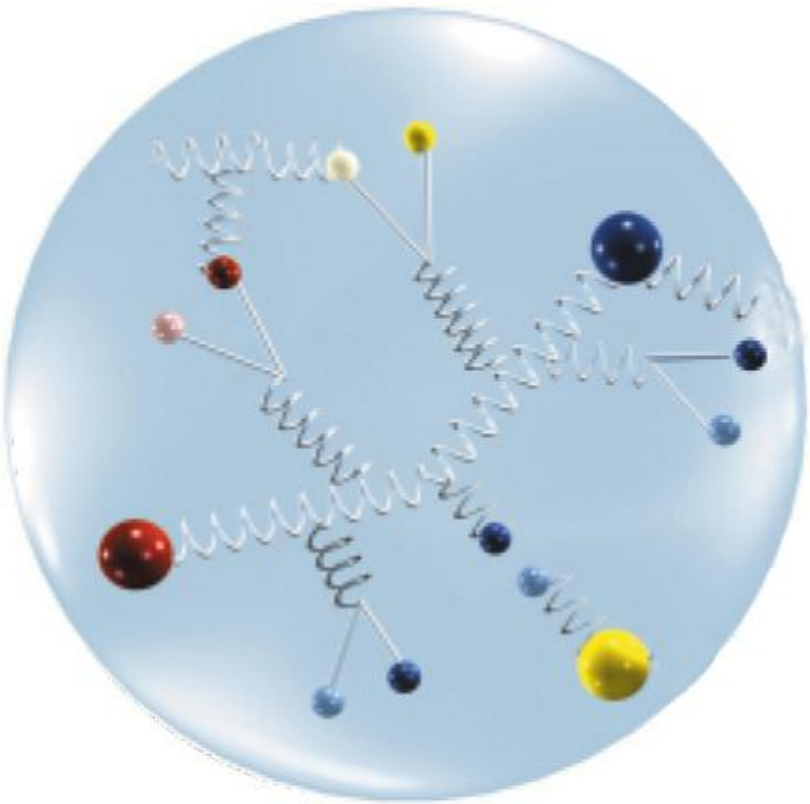


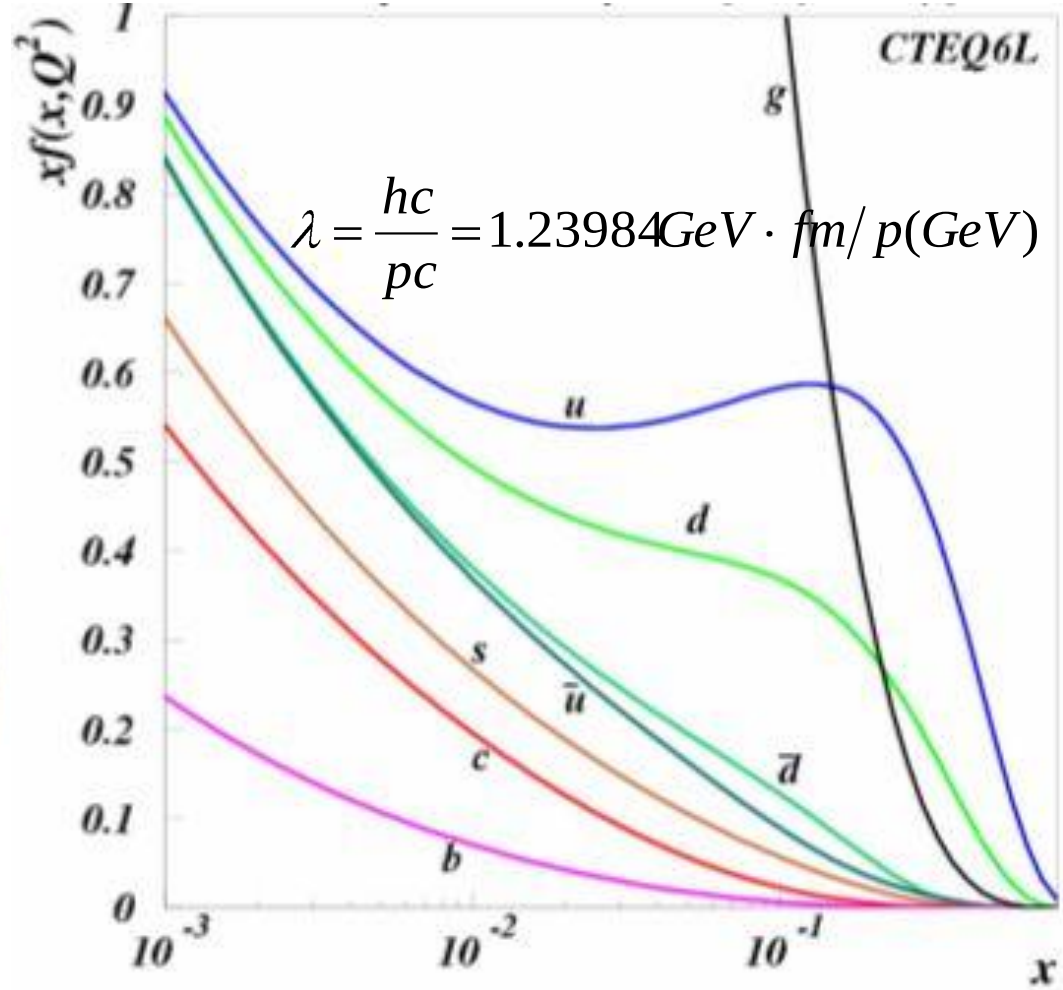
Horn

Step

Parton Distribution Functions

Pdf's tell us the partonic make-up of the nucleon



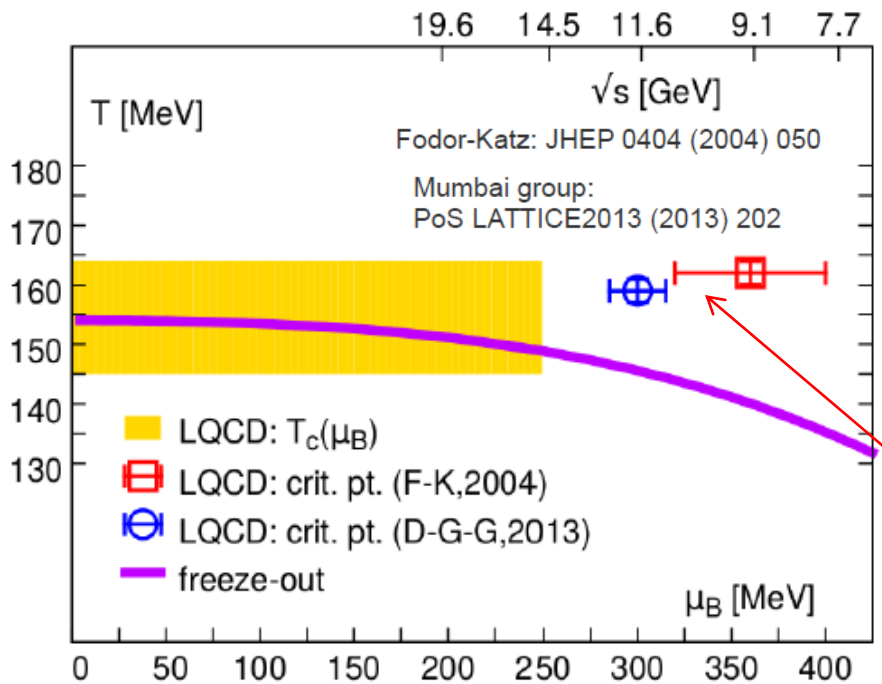


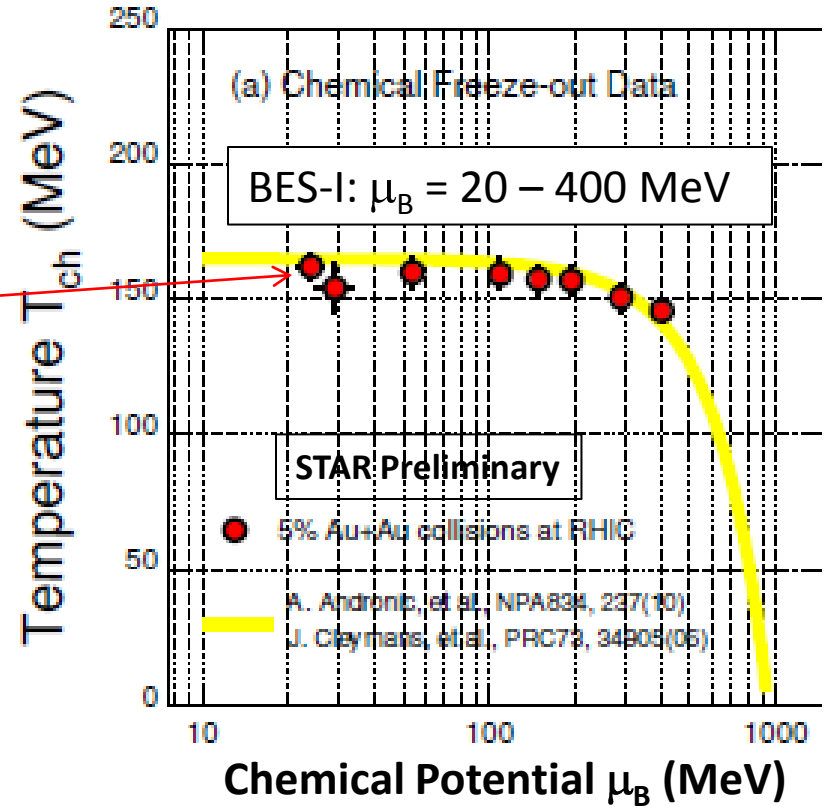
$$\lambda = \frac{hc}{pc} = 1.23984 GeV \cdot fm / p(GeV)$$

Setting the Scene

Using a statistical equilibrium model and the measured particle yields (π, K, p, Λ, Ξ, ϕ, Ω), one can estimate the location in the phase diagram.

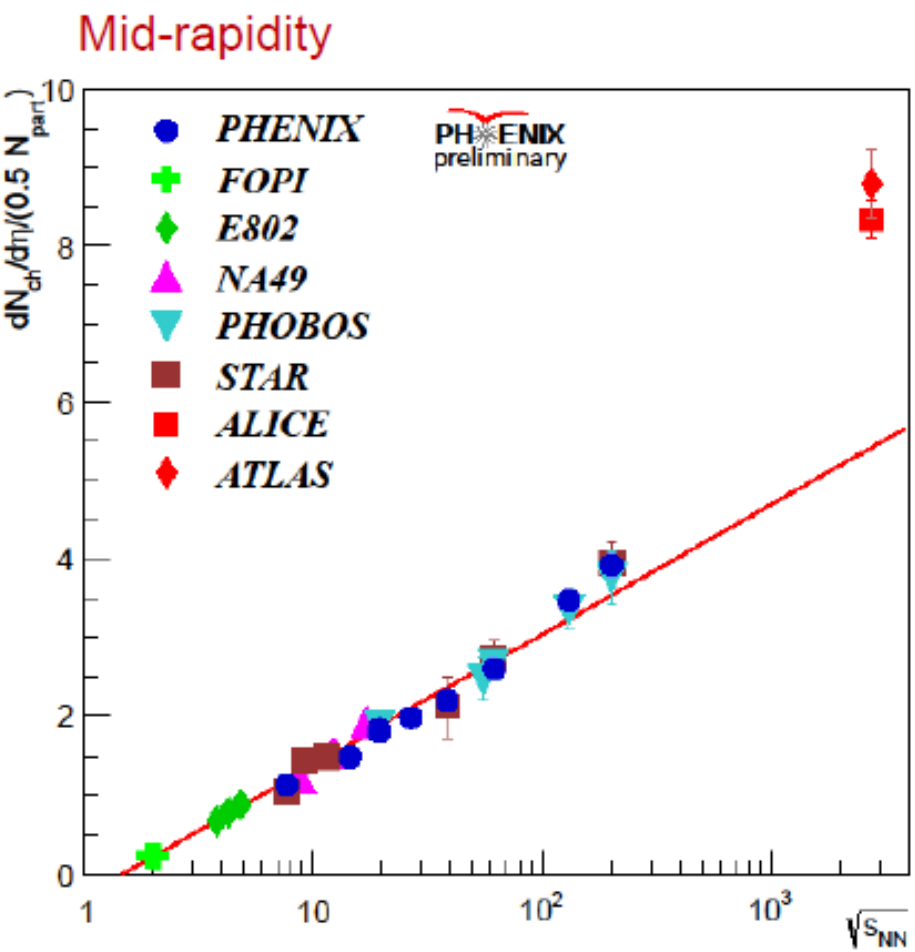
$$N_i/V = \frac{g_i}{(2\pi)^3}\gamma_S^{S_i}\int \frac{1}{\exp\left(\frac{E_i-\mu_B B_i-\mu_S S_i}{T_{ch}}\right)\pm 1}d^3p$$



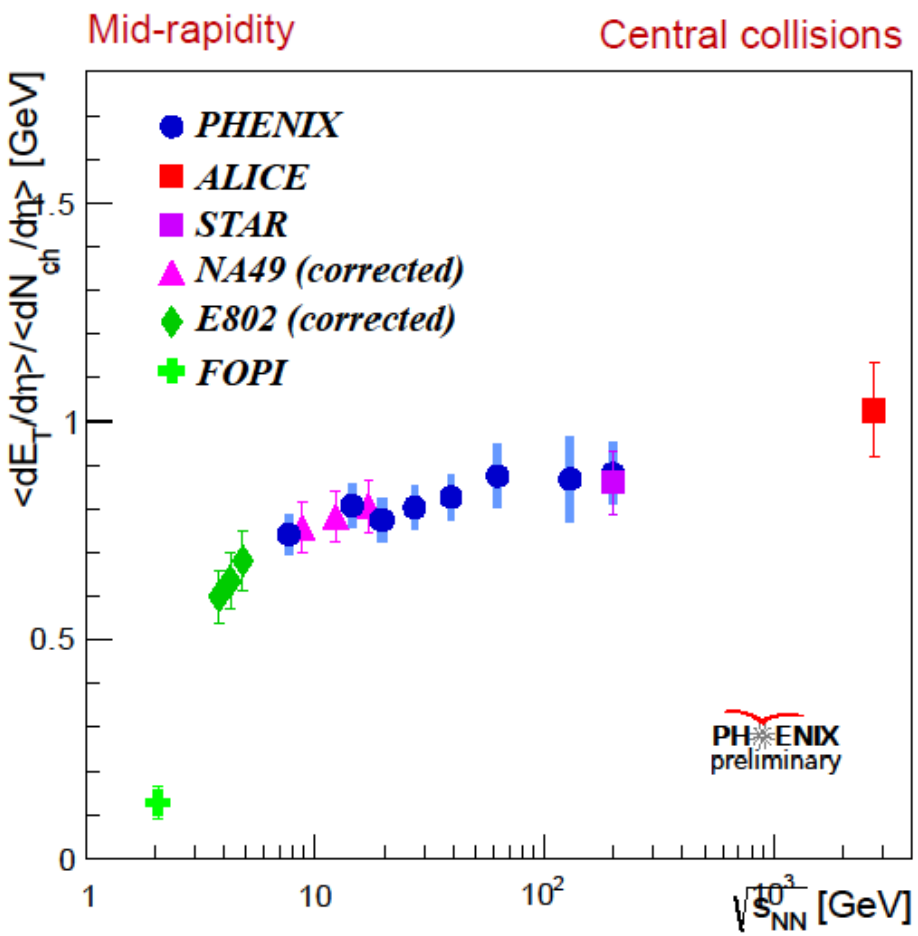


Some Lattice Gauge Theory predictions suggest that the low end of the BES-I may find the critical point

Global Observables



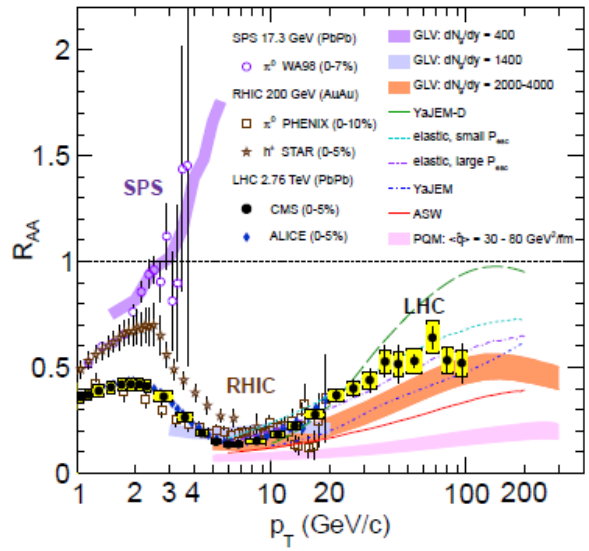
LHC rises above the near linear trend

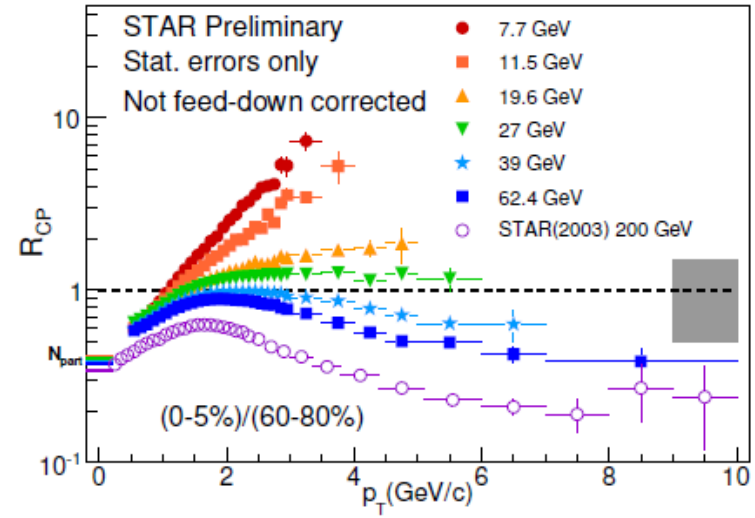


Energy per charged particle flat in RHIC BES

Disappearance of QGP Signatures - R_{CP}

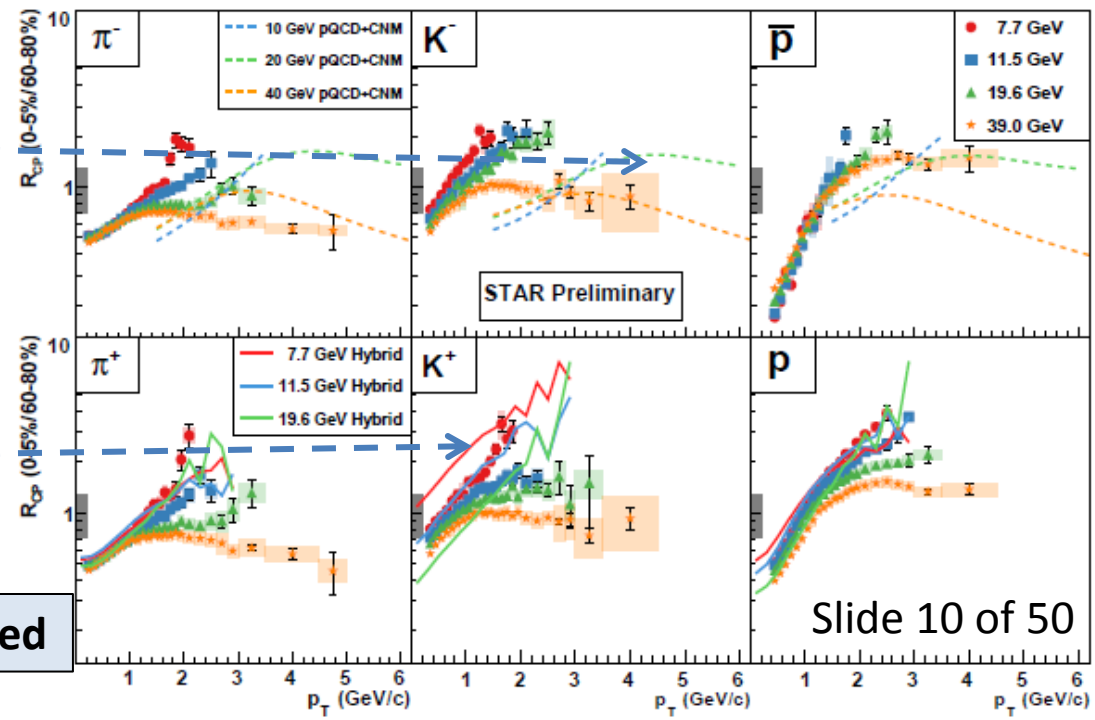
- R_{CP} for hadrons and for identified particles can provide a measure of partonic energy loss in the medium.
- Not sufficient reach to search for evidence of high p_T suppression below 19.6 GeV
- Stopped Baryons complicate inclusive R_{CP} measurements
- pQCD calculations show high p_T suppression
- Hybrid calculations describe the low p_T behavior





pQCD calculations

Hybrid calculations

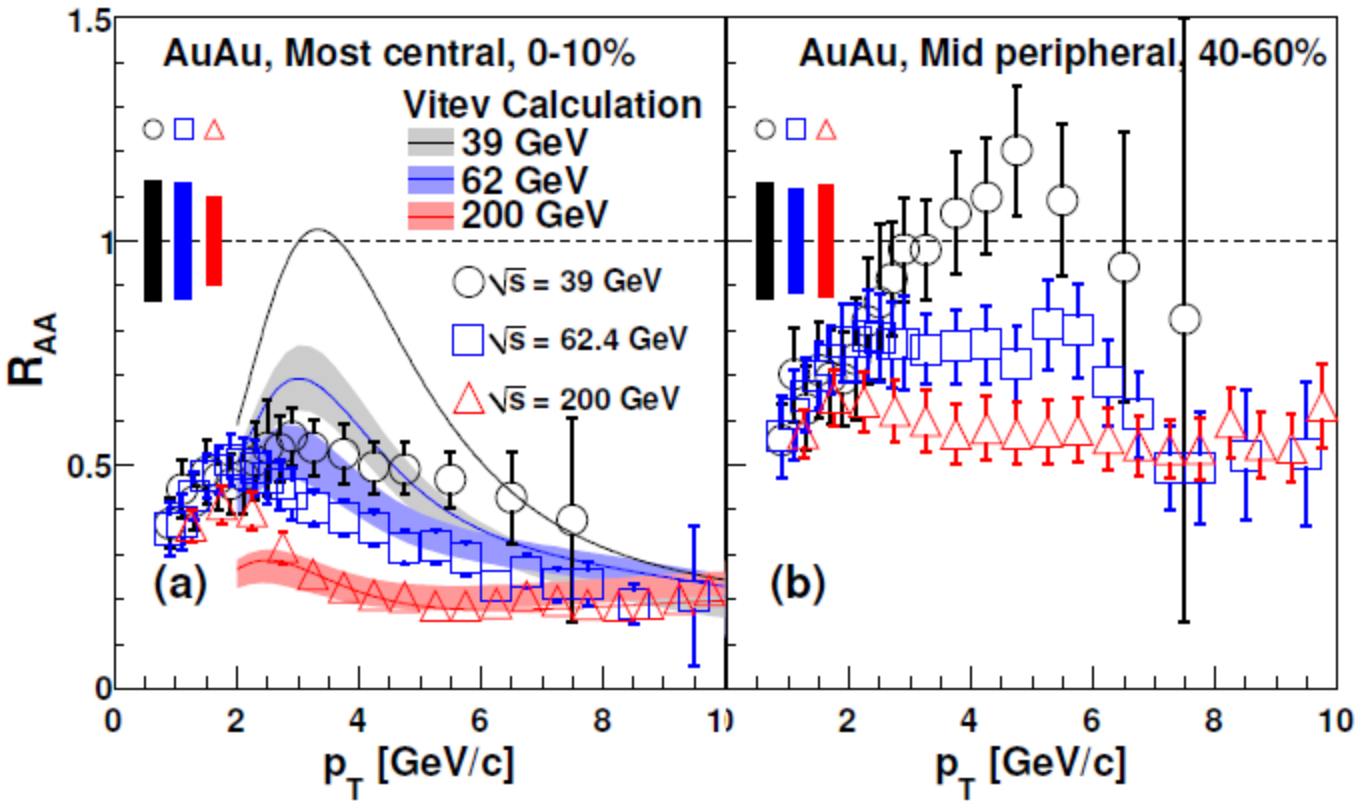


More p_T reach is needed

Disappearance of QGP Signatures - R_{AA}

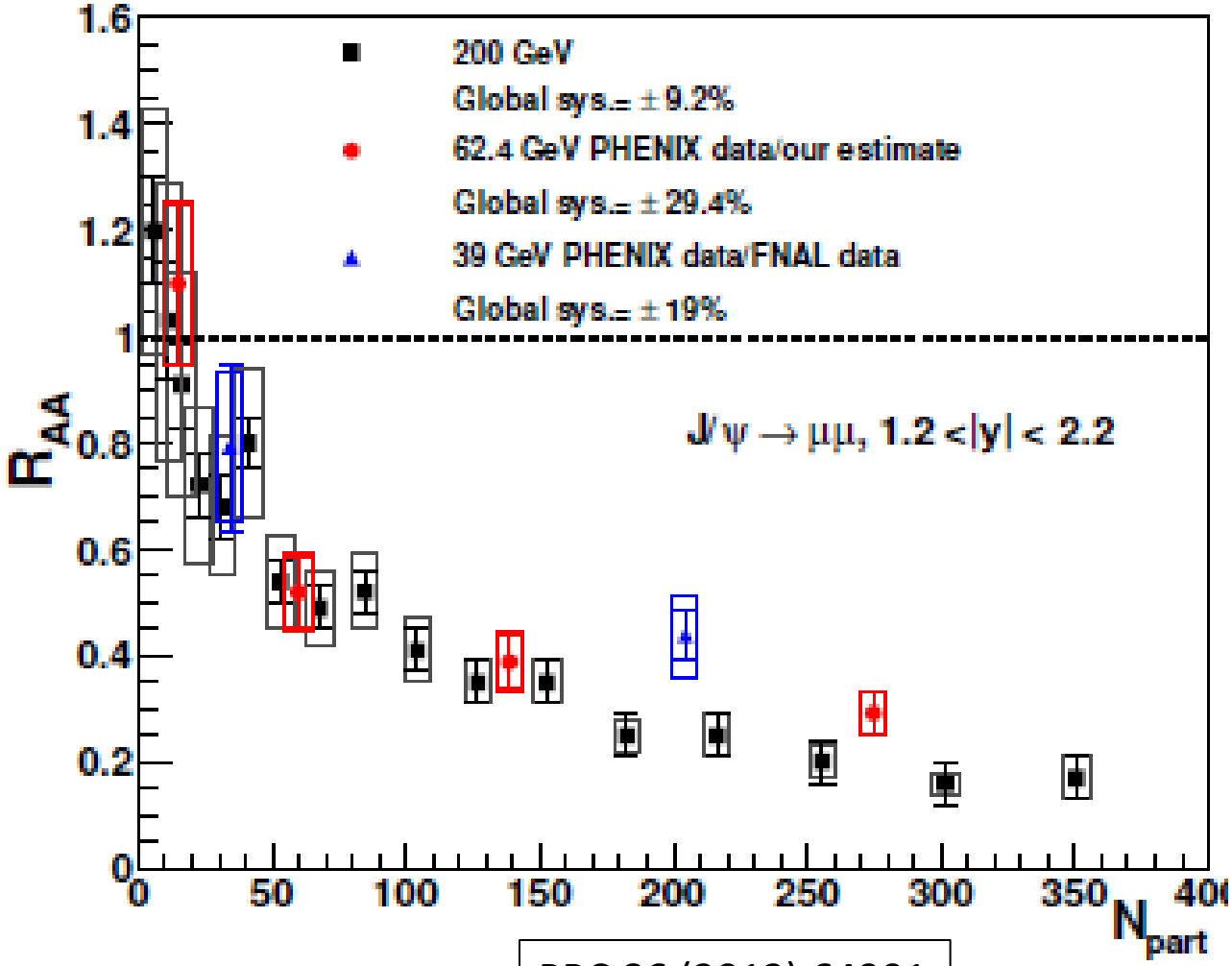
π^0 Nuclear modication factor in Au+Au collisions for the most central 0-10% and mid-peripheral 40-60% bin.

Also shown for central collisions are two pQCD calculations with Cronin-effect (solid lines) and with the Cronin-effect reduced (bands) for all three energies.



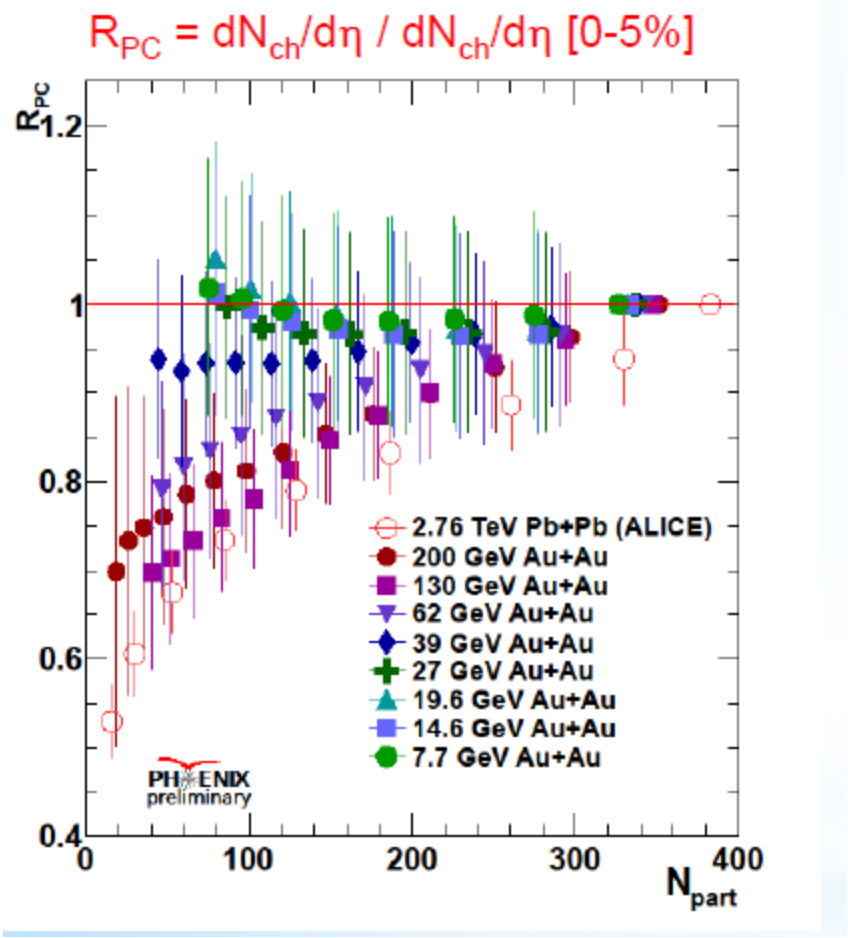
PRL 109 (2012) 152301

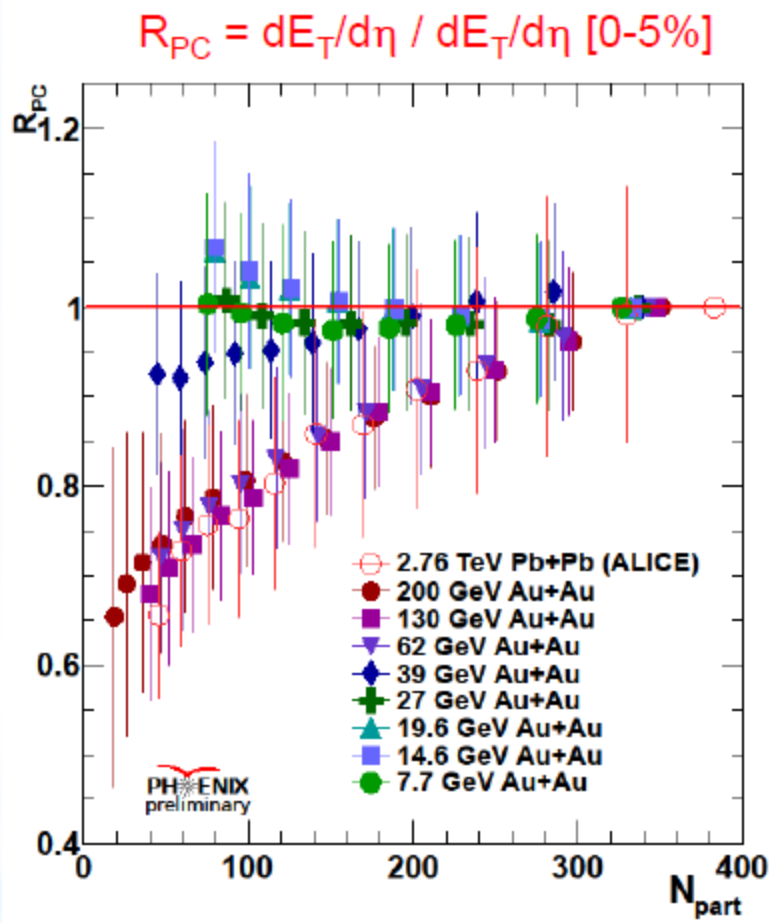
Disappearance of QGP Signatures - R_{AA}



PRC 86 (2012) 64901

Disappearance of QGP Signatures - R_{AA}

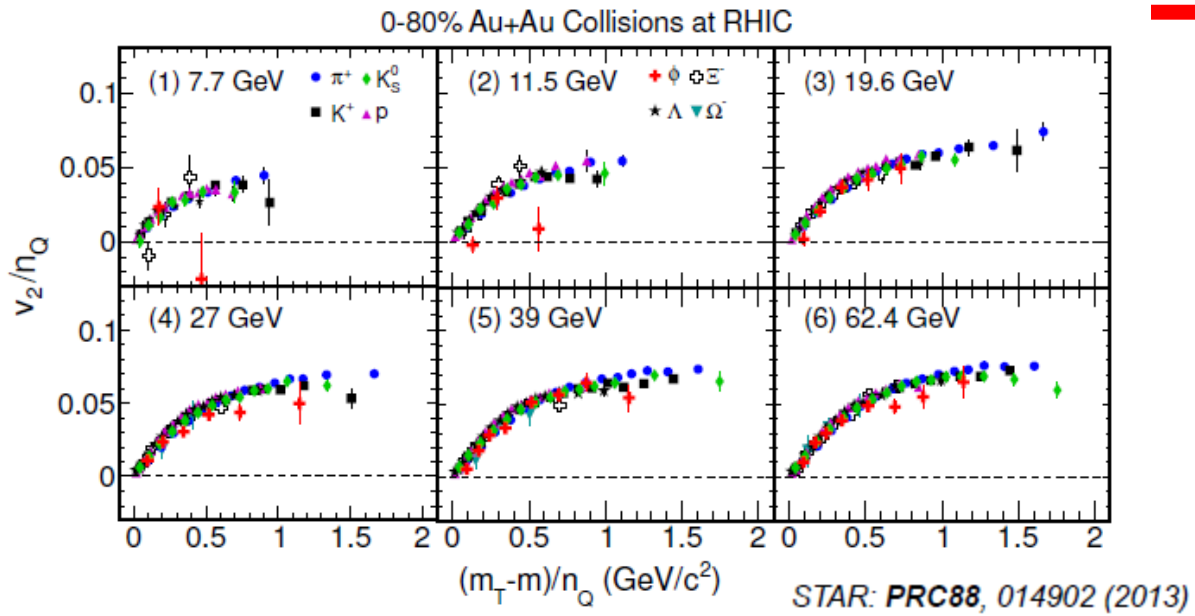


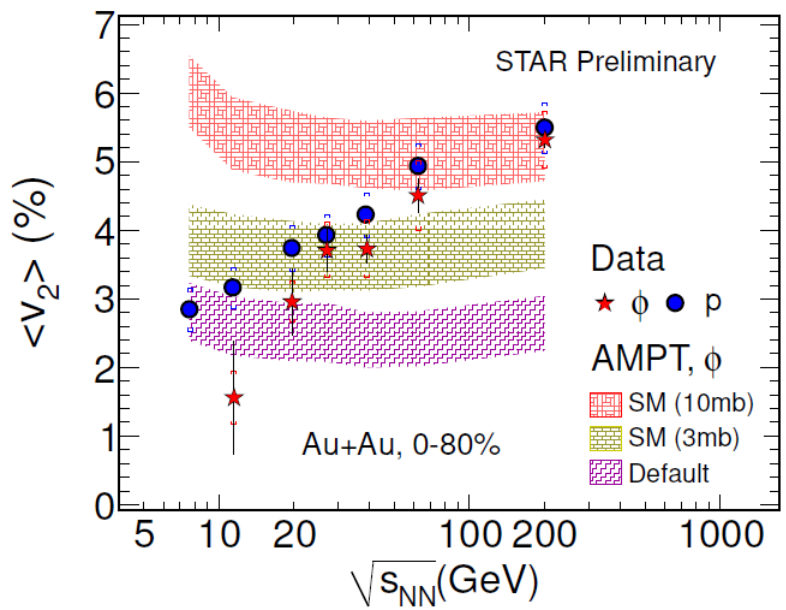


10.1103/PhysRevC.89.044905

Disappearance of QGP Signatures – v_2

- Constituent quark scaling is seen as an indication of partonic behavior
- Particles and anti-particles are seen to follow separate scalings
- The ϕ meson no longer follows the trends at 11.5 or 7.7 GeV
- This is further illustrated when the $<v_2>$ for the ϕ is compared to protons and to models.

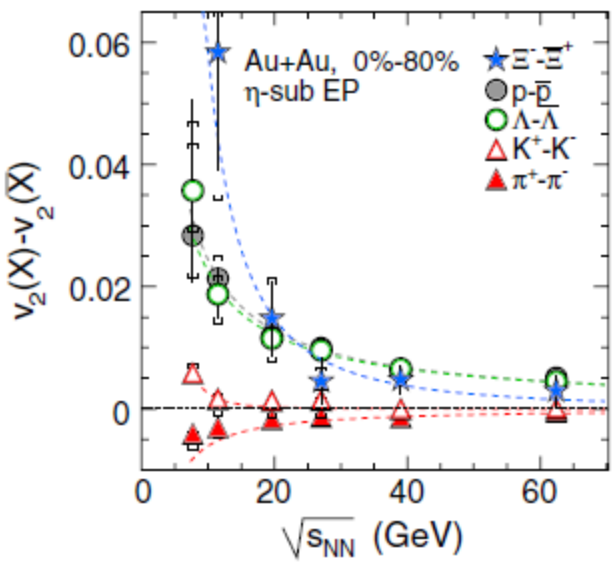




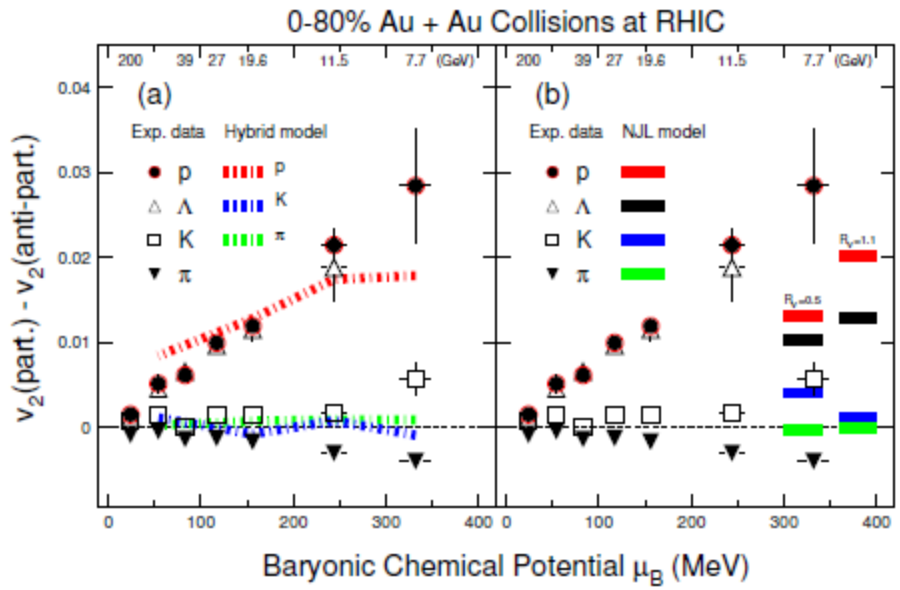
Disappearance of QGP Signatures – Δv_2

• There is a remarkable difference between particles and their anti-particles, especially for the lowest energies in the range.

*STAR: **PRL110**, 142301 (2013), **PRC88**, 014902 (2013)*



*Hybrid model: **PRC86**, 044903 (2012)*
*NJL model: **PRL112**, 012301 (2014)*



· Hybrid model: Hybrid model (UrQMD + hydro) with baryon stopping
· Nambu-Jona-Lasinio (NJL): Using vector mean-field potential, repulsive or quarks, attractive for anti-quarks

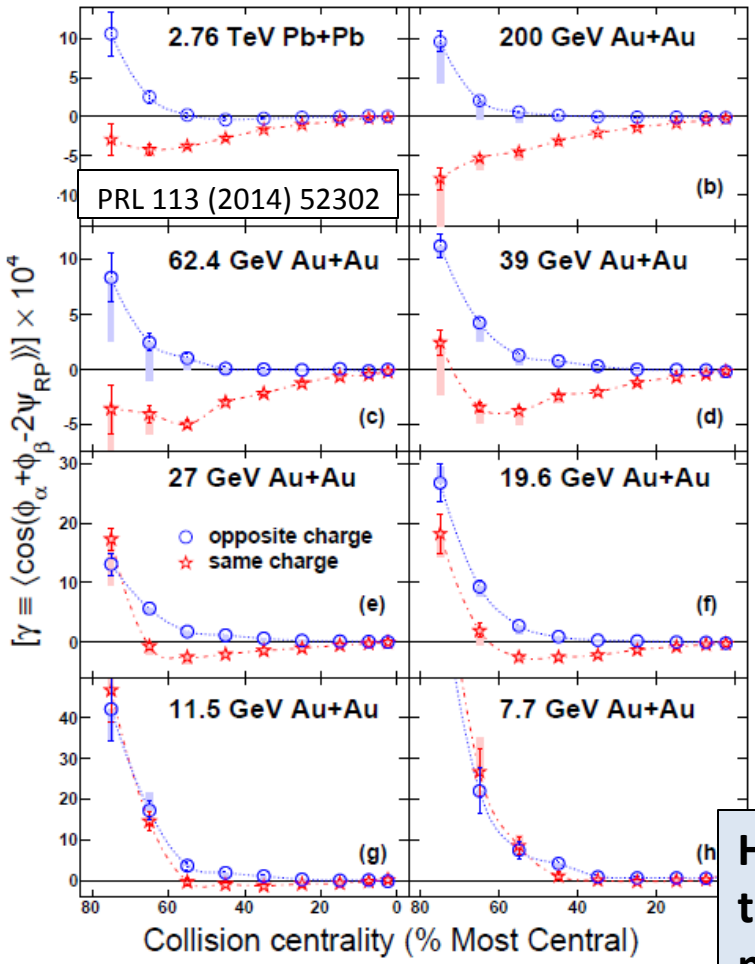
•Difference between particles and their anti-particle decreases with increasing beam energy

• The difference seems to track with chemical potential

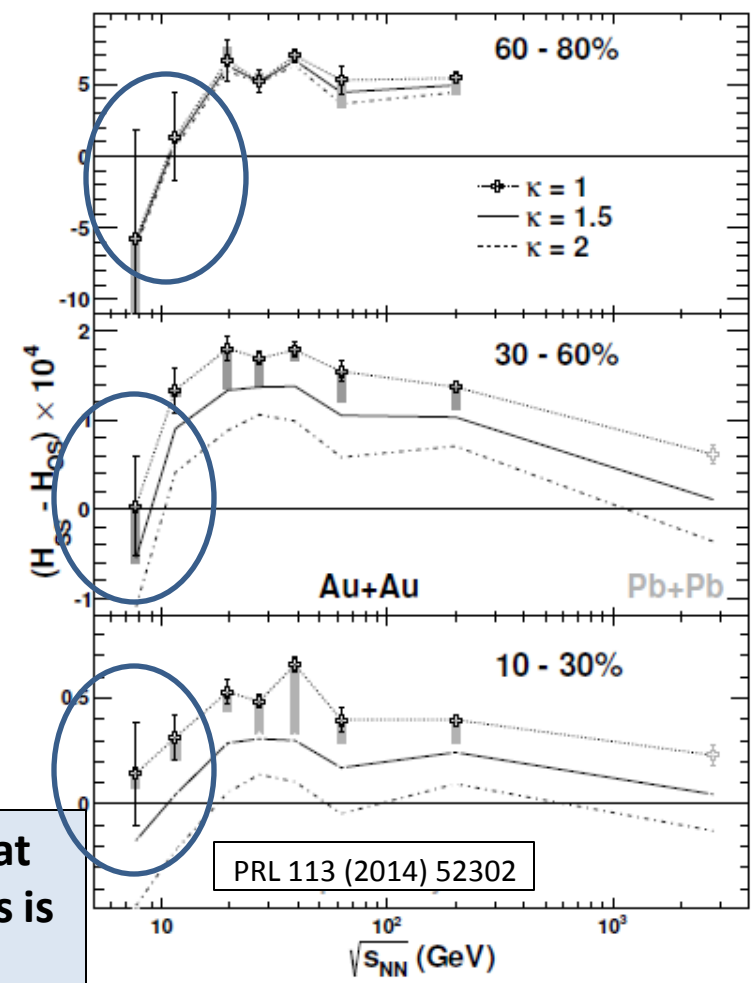
Disappearance of QGP Signatures -- CME

Same-charge and opposite-charge are shown separately, while the signal is opposite - same

Here signal minus background is shown. Background is other physics coupled to v_2



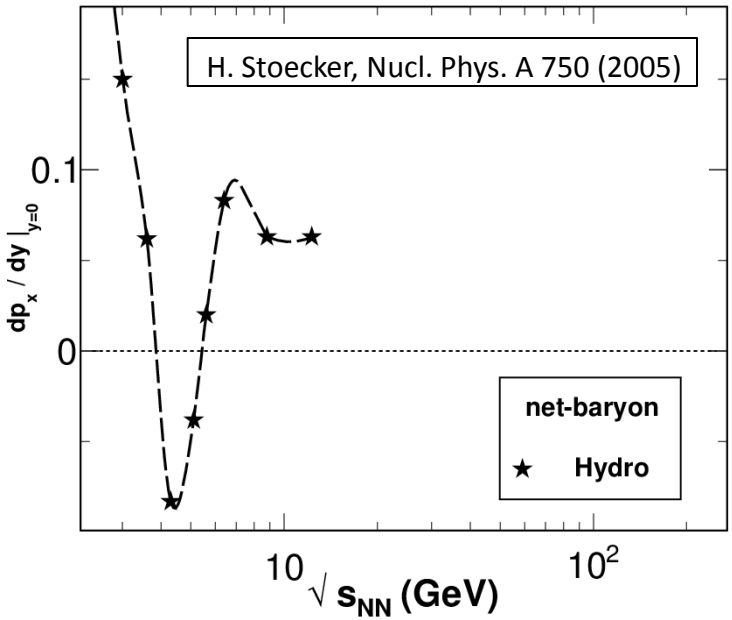
- Three particle correlators show an effect which may be CME
- This effect disappears at the lowest beam energies.

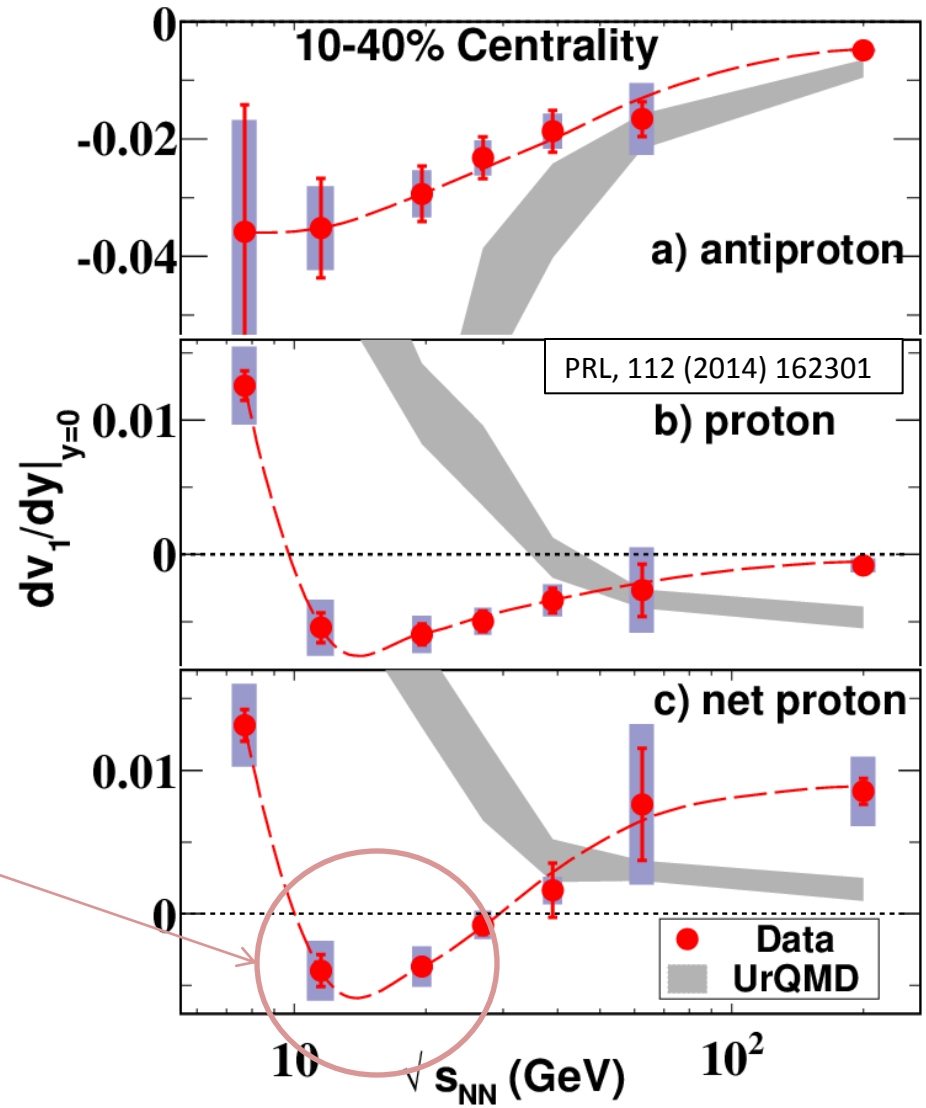


Higher Resolution at the lowest energies is needed

CME = Chiral Magnetic Effect

Search for 1st Order Phase Transition – v_1





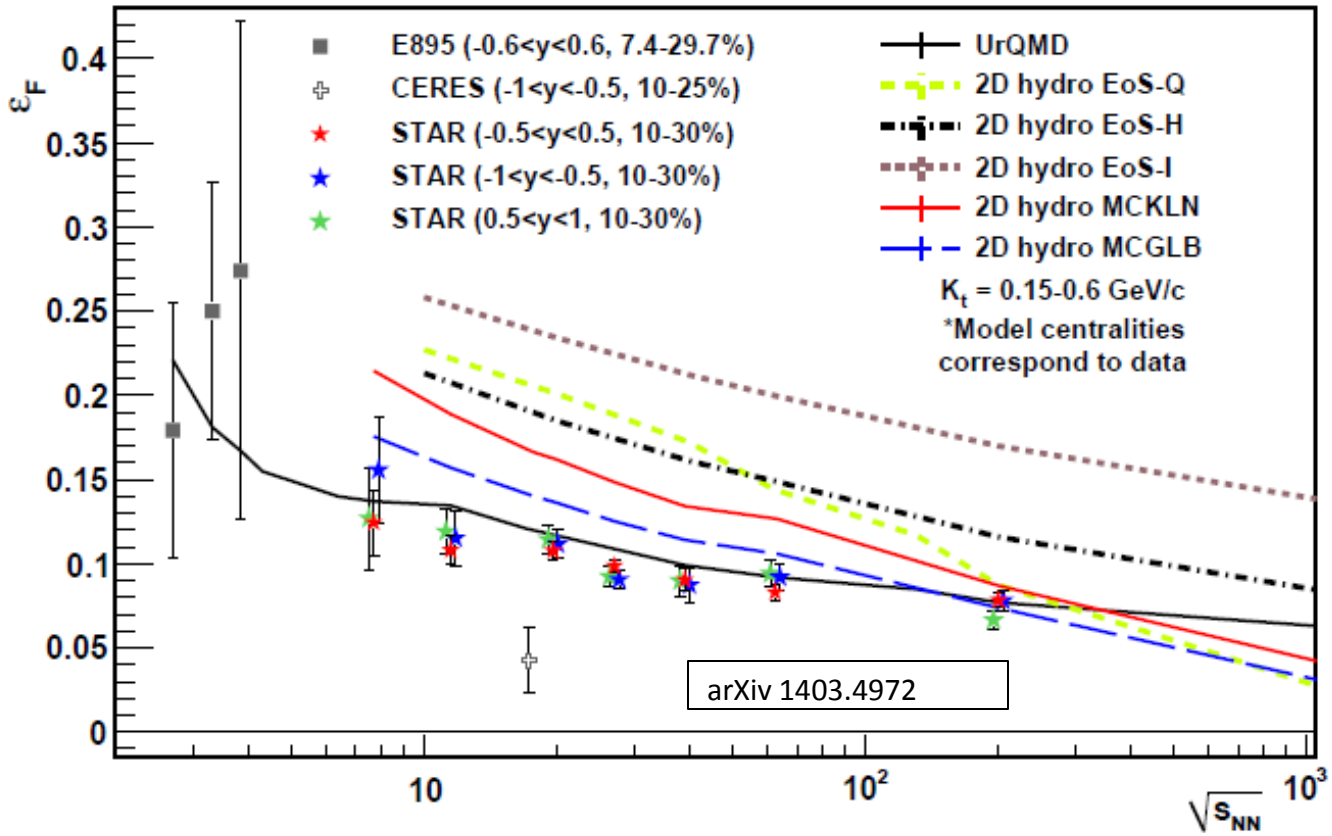
- First order phase transition is characterized by unstable coexistence region. This spinodal region will have the softest Equation of State
- v_1 is a manifestation of early pressure in the system

Search for 1st Order Phase Transition - asHBT

- Pion asHBT allows a study of the coordinate space "almond shape" (ε_F) after expansion

- The expansion in coordinate space slows above 7.7 GeV. But no strong minimum is observed.

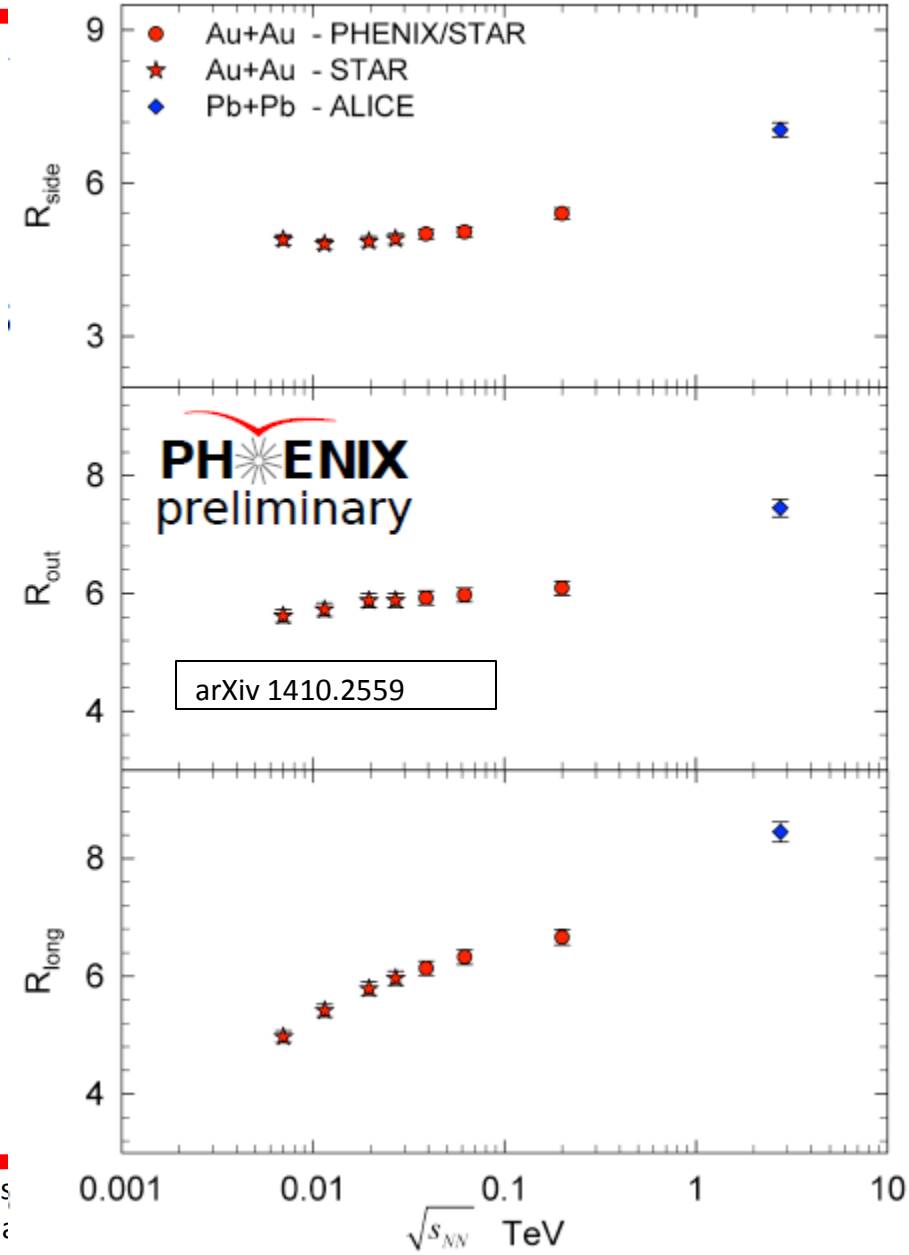
- Late signature, therefore may not have sufficient sensitivity



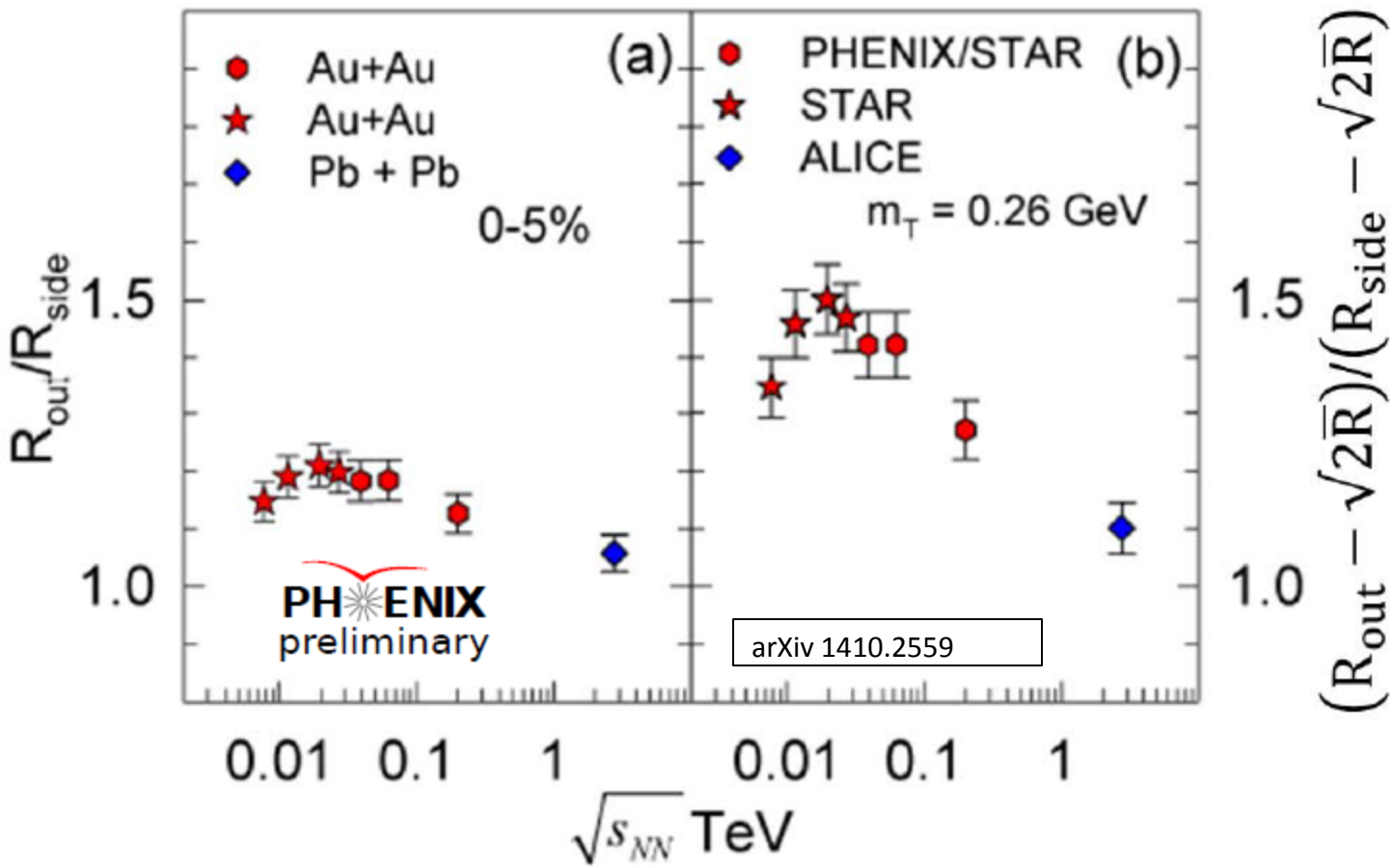
Search for 1st Order Phase Transition -HBT

PHENIX,STAR,ALICE data

- m_T=0.26 GeV Interpolations
- R_{long} decreasing with $\sqrt{s_{NN}}$
- Rout,Rlong curvature Differ from R_{side}
- construct ratios and differences



Search for 1st Order Phase Transition



Search for the Critical Point – $\kappa\sigma^2$

- Fluctuations of conserved quantities in a region of limited acceptance are the best observables to use to search for the critical point
- Some differences are seen between the $\kappa\sigma^2$ signals and baselines.
- These may be significant, however the uncertainties are quite large.

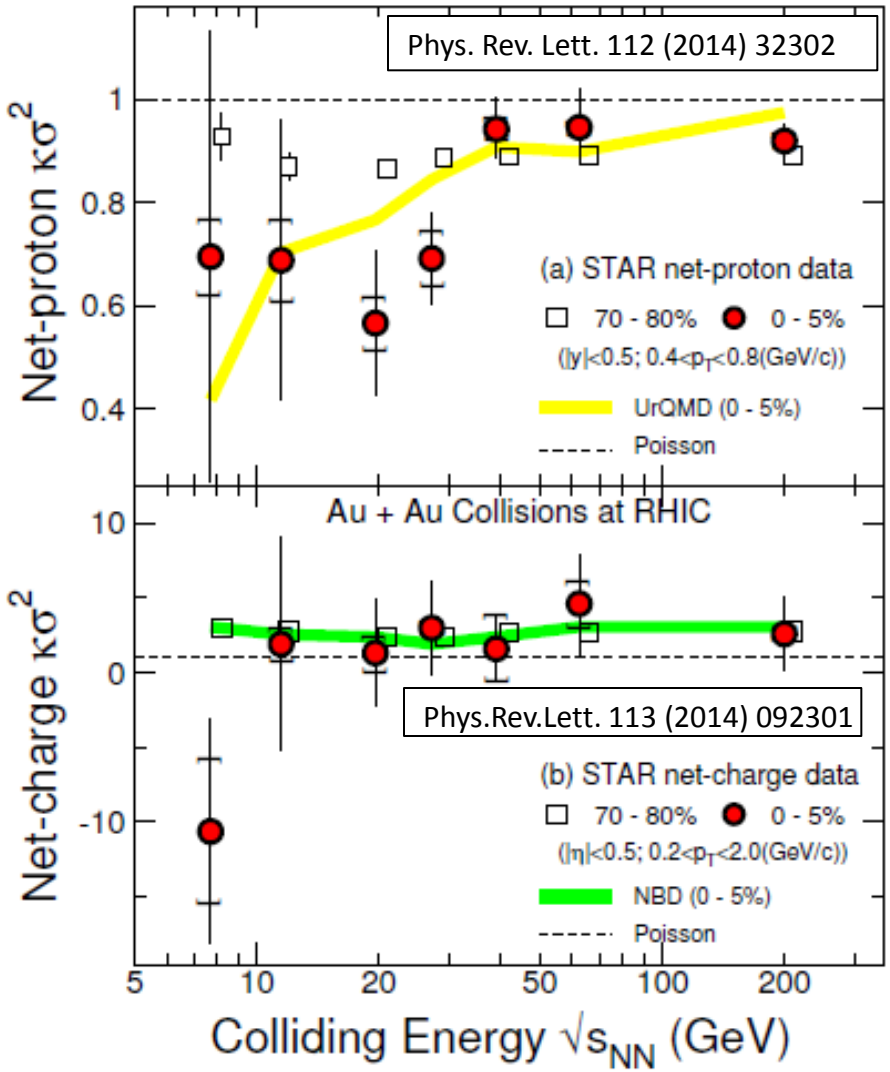
$$\chi_B^{(n)} = \left.\frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n}\right|_T$$

Volumes cancel

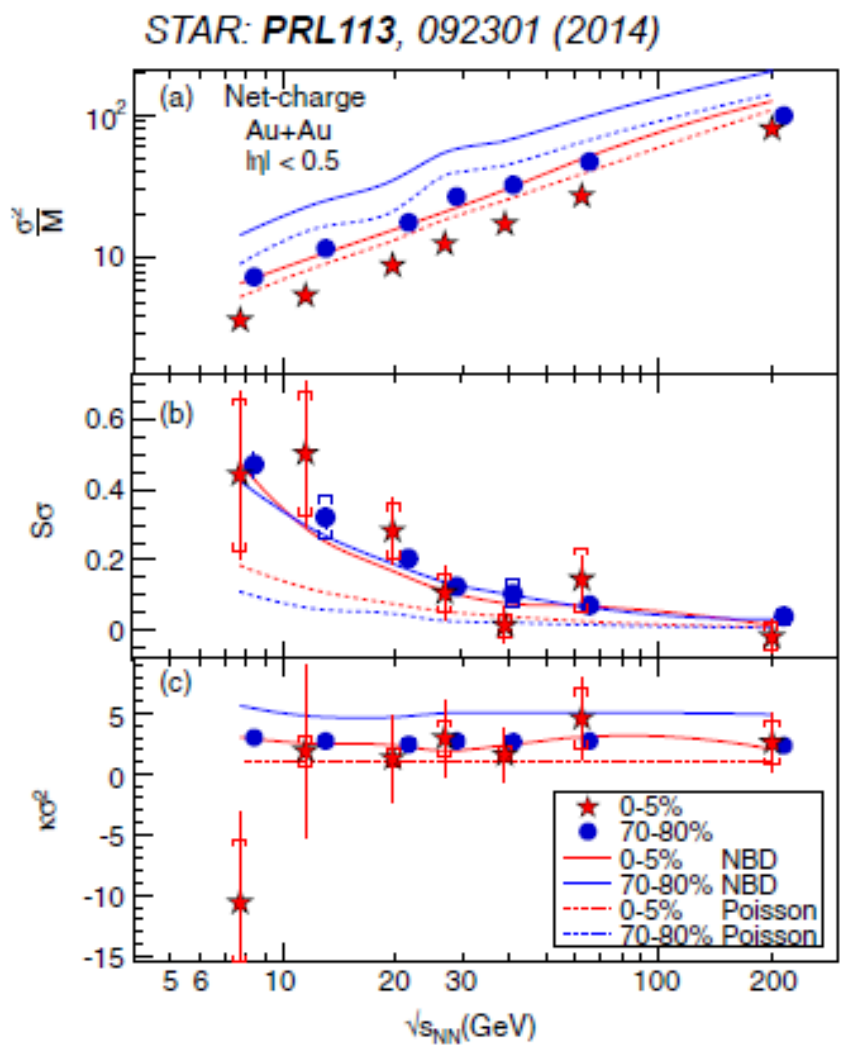
$$\chi_B^4 / \chi_B^2 = (\kappa\sigma^2)_B$$
$$\chi_B^3 / \chi_B^2 = (S\sigma)_B$$

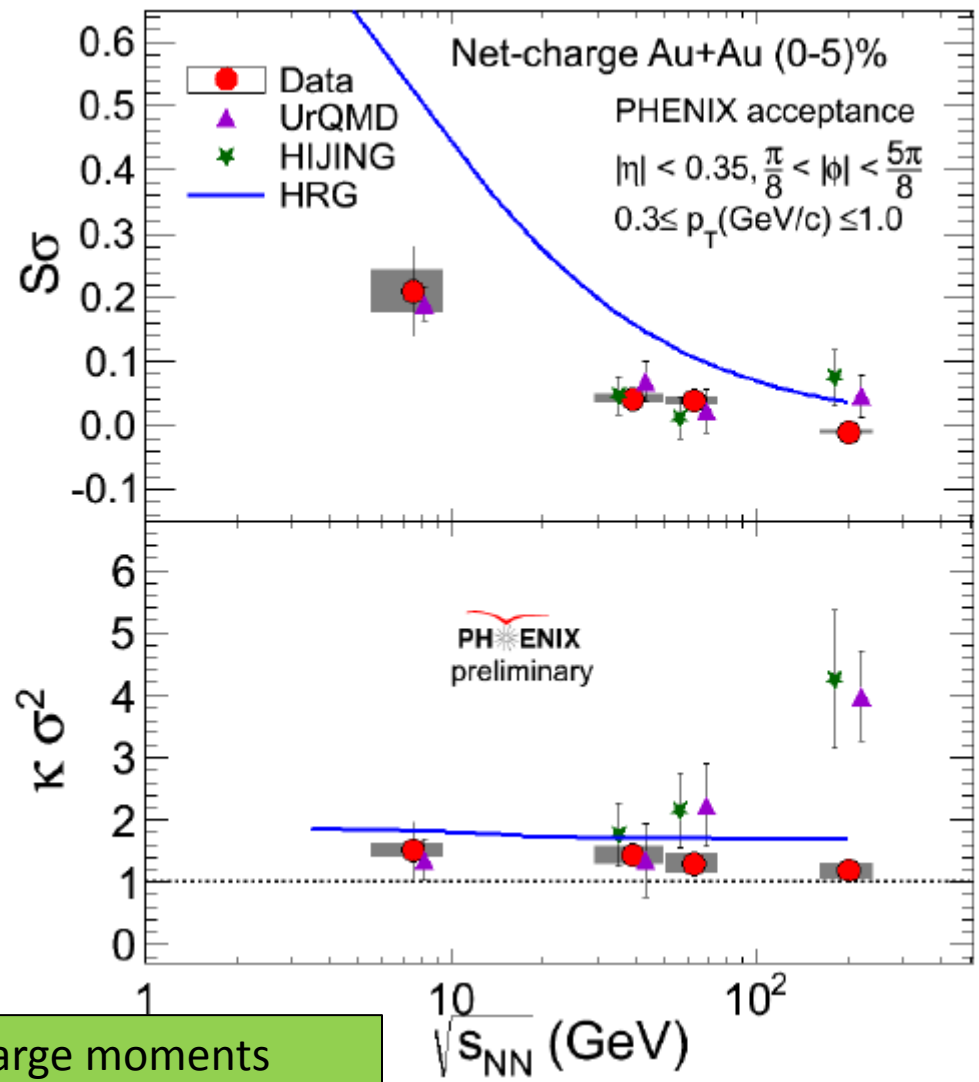
F. Karsch, PoS (CPOD07) 026, PoS (Lattice 2007) 015

More data are needed



Search for the Critical Point – $\kappa\sigma^2$

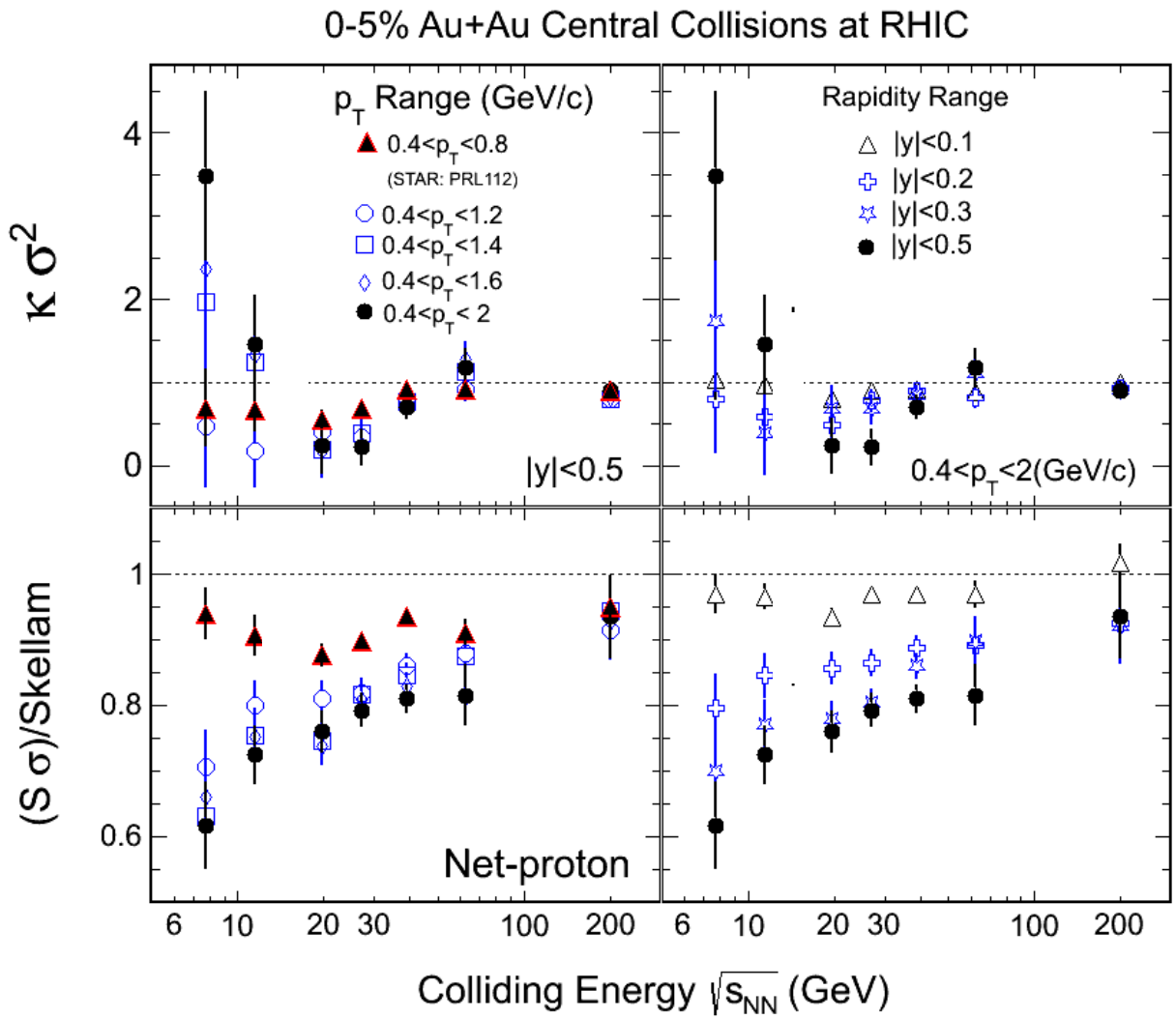




The products of the net charge moments show no significant increase above URQMD, HIJING, or HadronResonance Gas predictions.

Search for the Critical Point – $\kappa\sigma^2$

Acceptance studies shows that the sensitivity of the measurements increases with increasing p_T and rapidity coverage



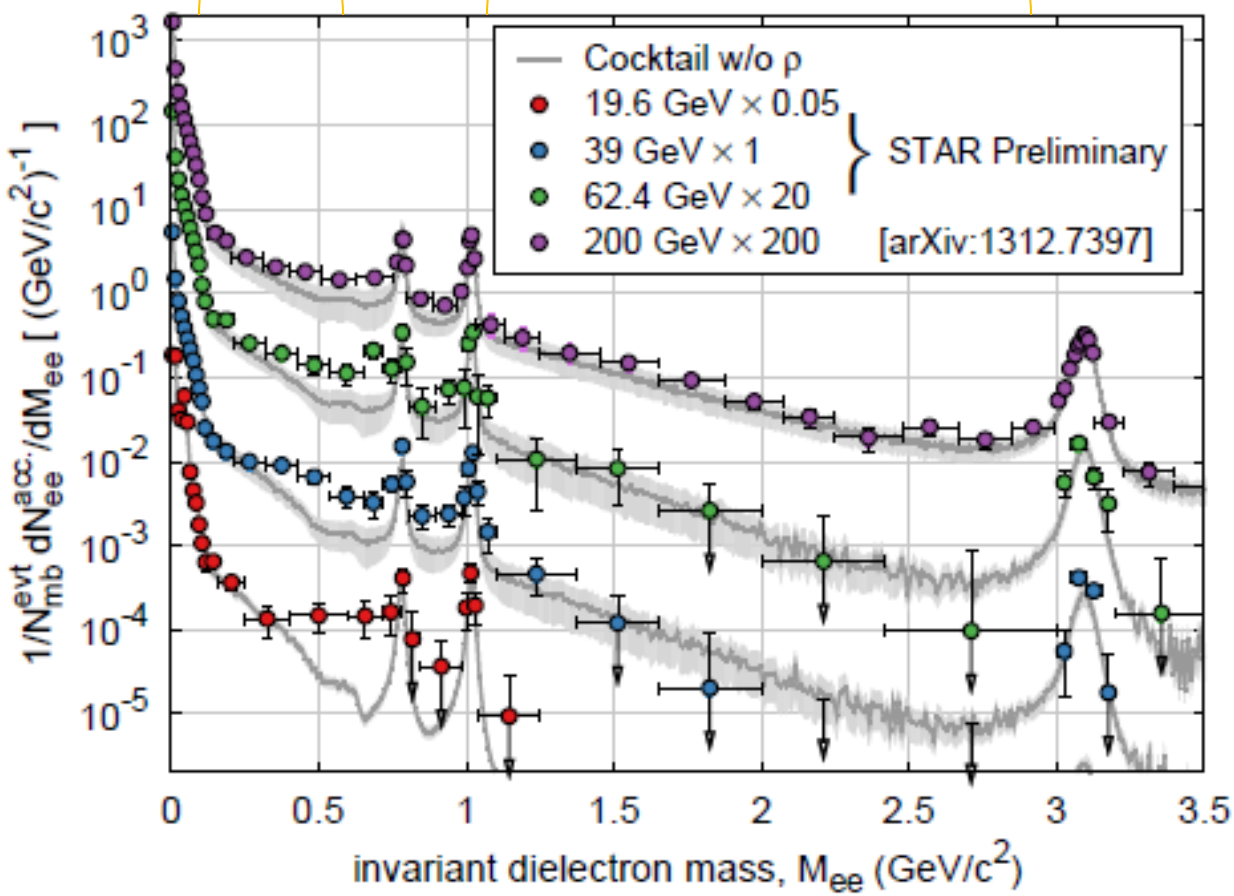
Xiaofeng Luo, CPOD 2014 arXiv:1503.02558

Bulk Penetrating EM Probes

Low Mass Region:
ρ in medium modification tied to chiral symmetry restoration

Intermediate Mass Region:
QGP Thermal Radiation

- No strong √s dependence of LMR excess yield
- Constant Baryon density (ρ) from 200 GeV down to 19.6 GeV
- Not enough statistics in IMR
- No handle on charm continuum (in IMR)



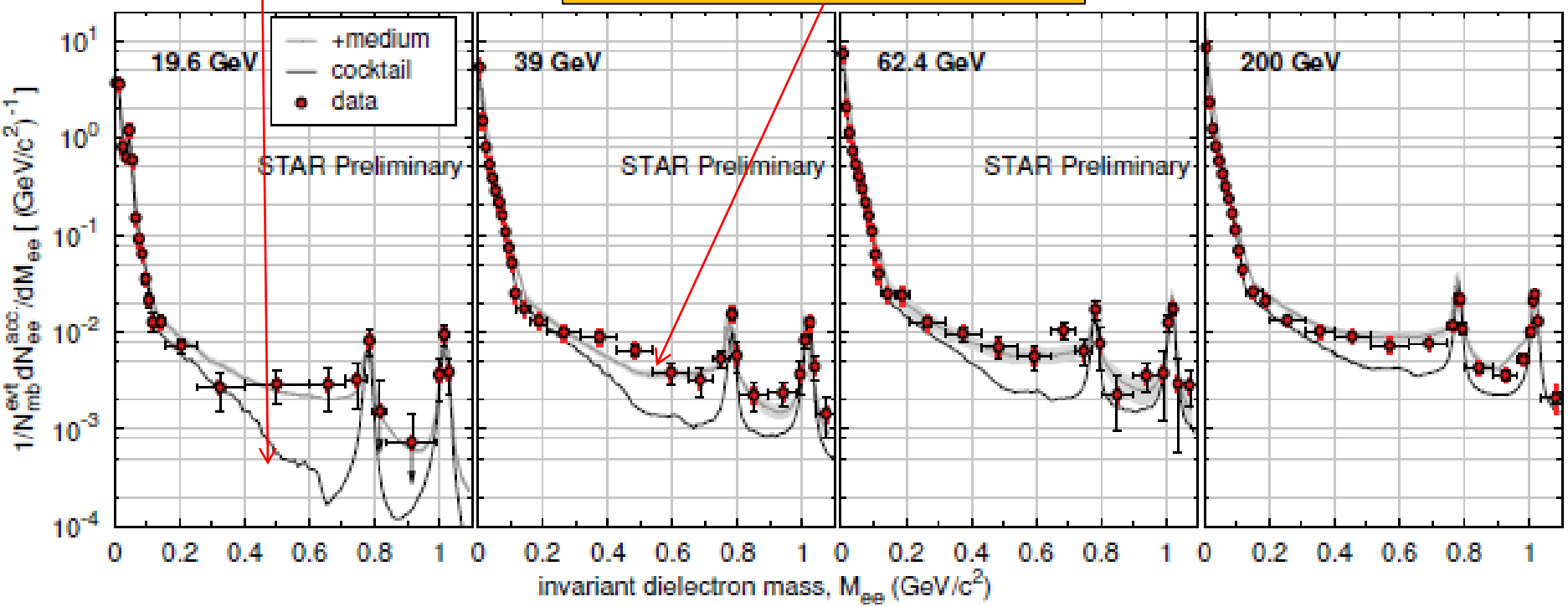
Bulk Penetrating EM Probes

R. Rapp, private communication,
R. Rapp Adv. Nucl. Phys. 25,1 (2000)

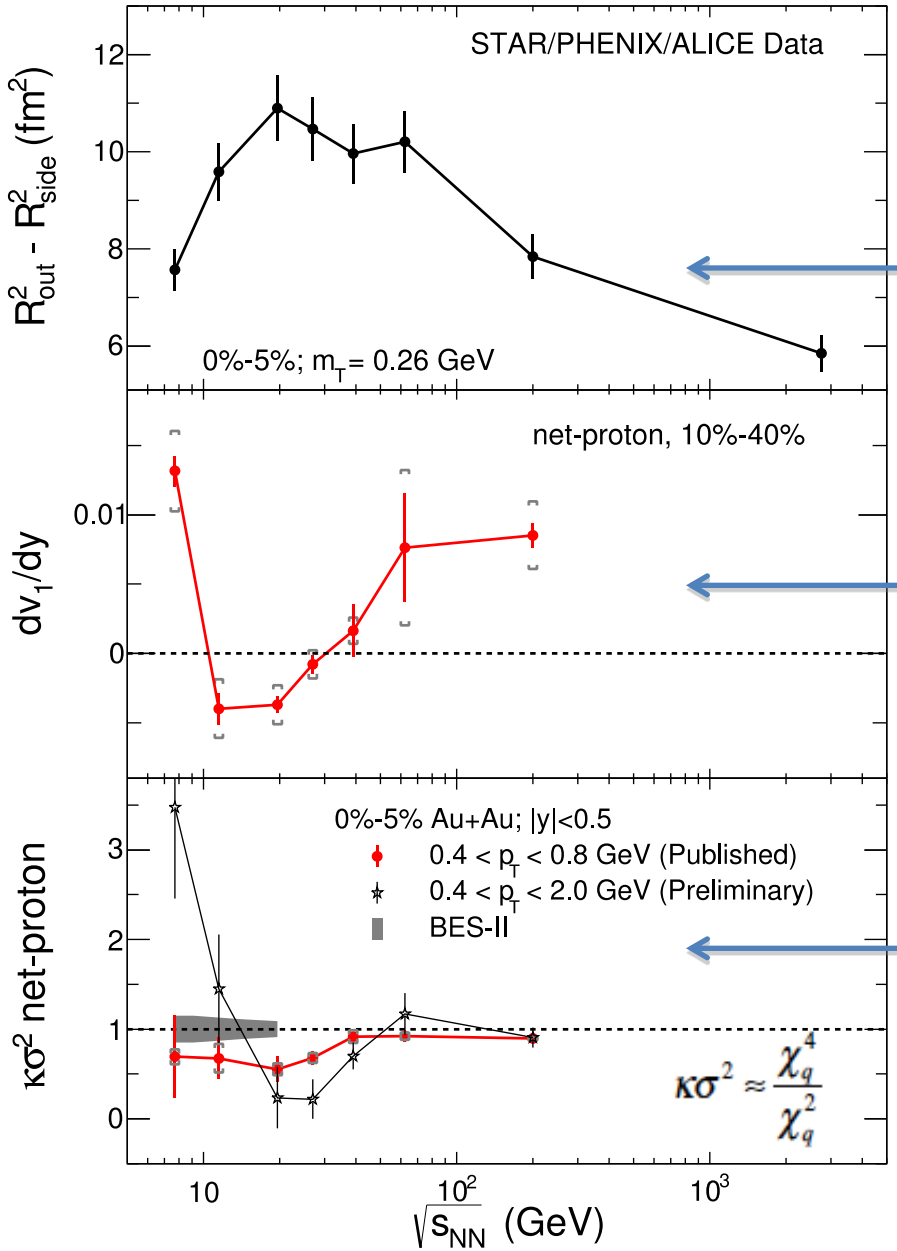
Low Mass Region:
Black lines are the Cocktail (excluding the ρ meson)

Grey lines are in medium calculations from R. Rapp which include both HG and QGP components (including medium broadened ρ meson). Model is able to match the data

Low Mass Region:
Emission depends on T, total baryon density, and lifetime



First Beam Energy Scan: Exploratory Study



Many measurements suggest anomalies in the pressure

Related to the lifetime

Related to the early pressure

Related to the susceptibilities: derivatives of the pressure

Region of interest: $\sqrt{s_{NN}} \lesssim 20$ GeV

BES Phase I – What have We Learned

- The BES at RHIC spans a range of μ_B that could contain features of the QCD phase diagram.

- Signatures consistent with a parton dominated regime either disappear, lose significance, or lose sufficient reach at the low energy region of the scan.

- There are indicators pointing towards a softening of the equation of state which can be interpreted as evidence for a first order phase transition.

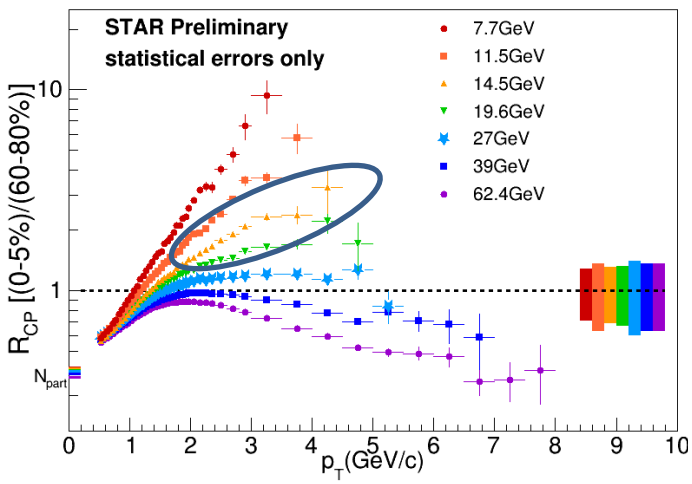
- The higher moment fluctuation is sensitive to critical phenomena, but these analyses place stringent demands on the statistics.

- Dilepton mass spectra show a broadening consistent with models including hadron gas and quark-gluon plasma components.

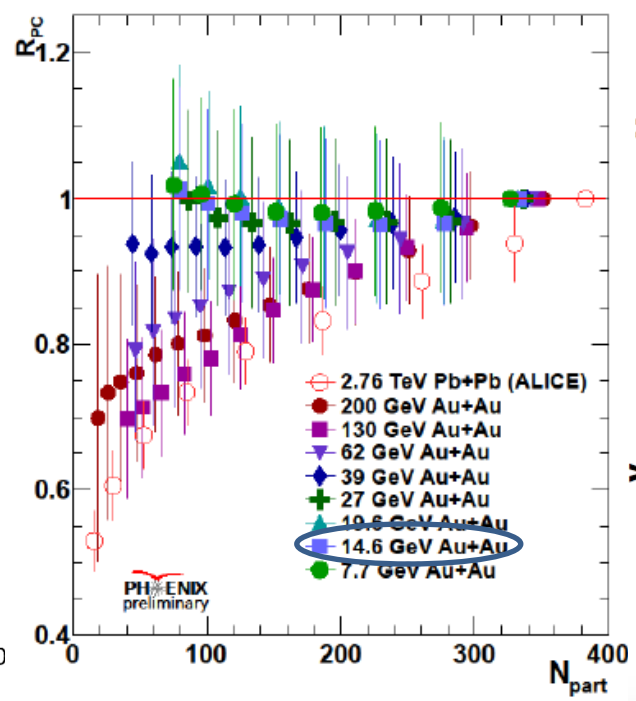
14.5 GeV Results

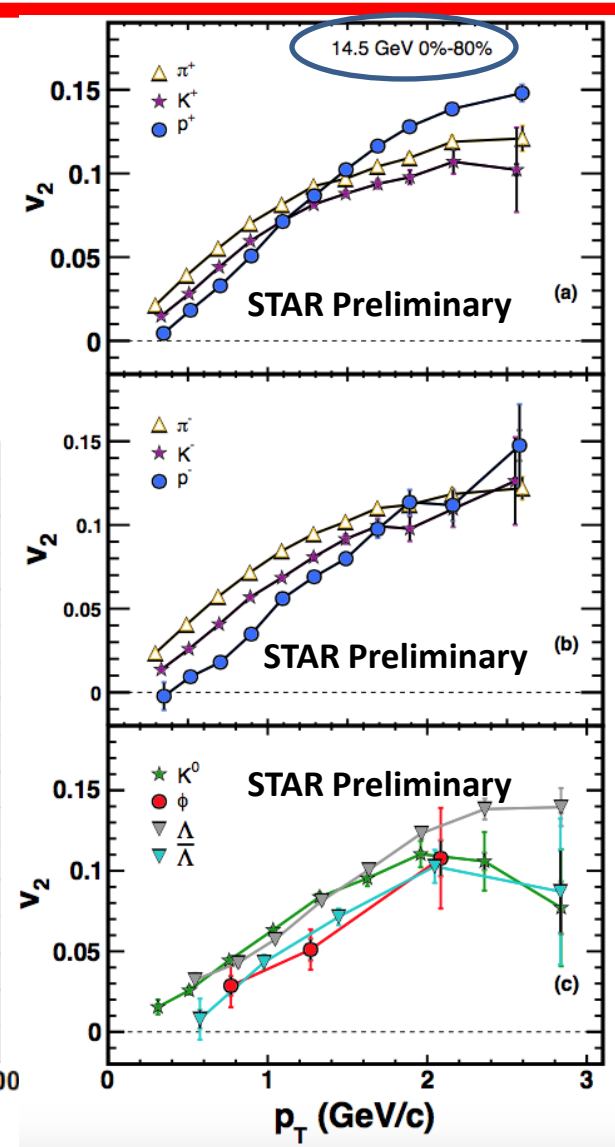
- Preliminary results are available for all key BES analyses
- Most key results will be presented at QM2015
- Publication strategy has been developed for all analyses

- Here we preview a few results:



$R_{PC} = dN_{ch}/d\eta \,/\, dN_{ch}/d\eta$ [0-5%]



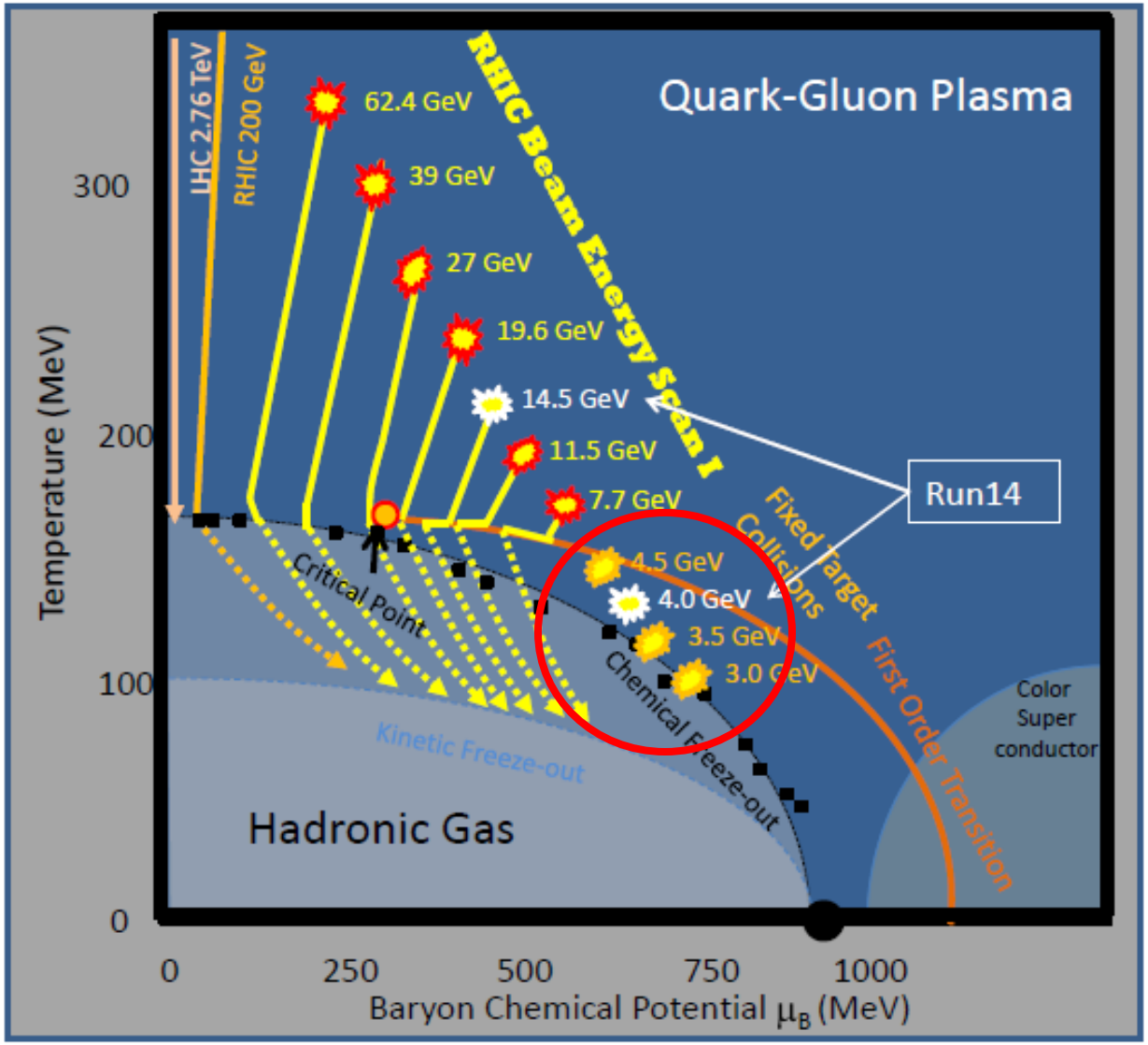


Fixed-Target Program 3.0 to 4.5 GeV

The Fixed-Target Program will extend the reach of the RHIC BES to higher μ_B.

Goals:

1) Search for evidence of the first entrance into the mixed phase
2) Control measurements for BES collider program searches for Onset of Deconfinement
3) Control measurements for Critical Point searches

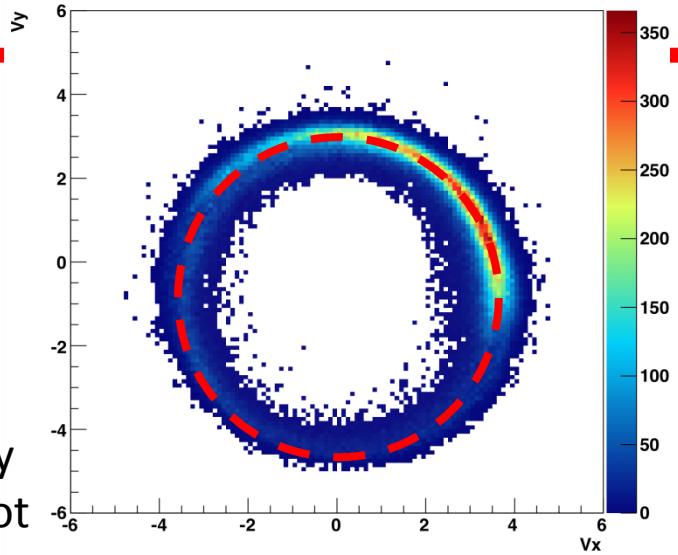


Fixed Target Timeline

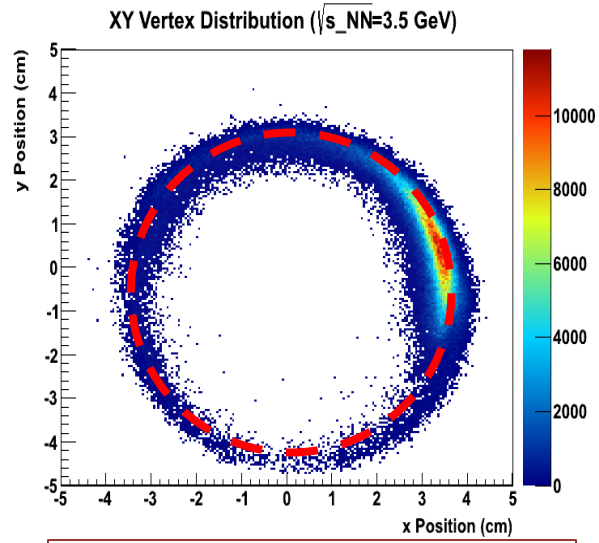
- 2008: Triggering problem for low energy collisions- start studying why trigger misfires on background
- 2009: Started analyzing Au + Al beampipe collisions
- 2010-2011: Au+Al background during BES program
- 2013: Au +Au fixed target program proposed
- 2014: First Preliminary Physics Results: Coulomb Analysis (Au + Al) (3.0, 3.5, and 4.5 GeV)
- 2014: Gold target inserted in 14.5 GeV Au + Au run (3.9 GeV)
- 2015: Test run with beam lowered for direct collisions with target (4.5 GeV)

Note: there is consistently a bright spot to the positive *x* value in the plane of the beam

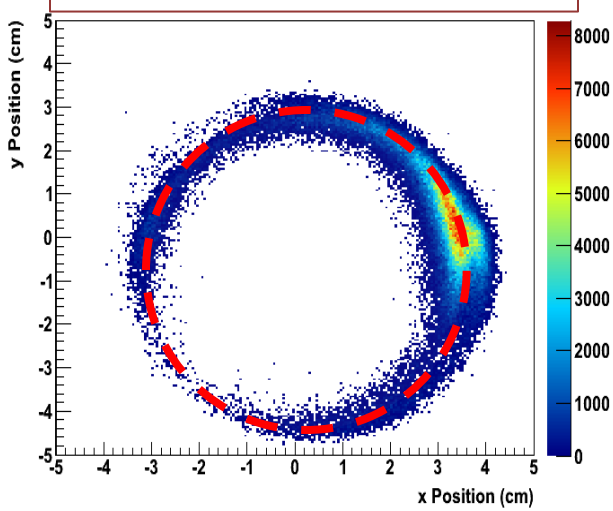
7.7 GeV Au+Au (2010)



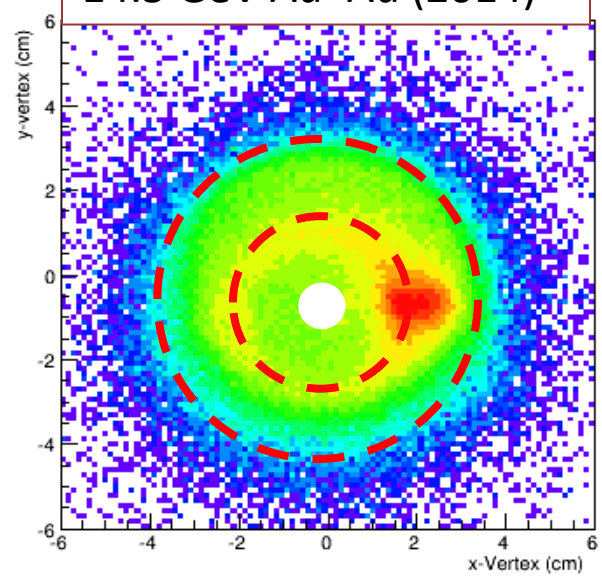
11.5 GeV Au+Au (2010)

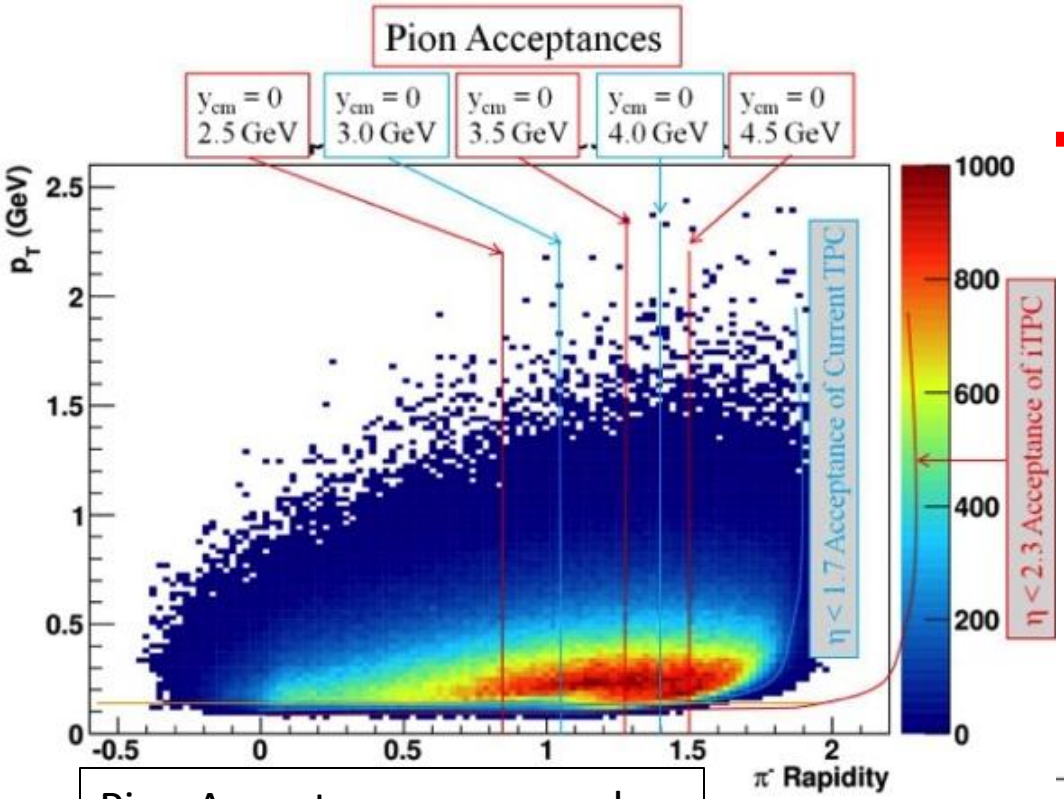


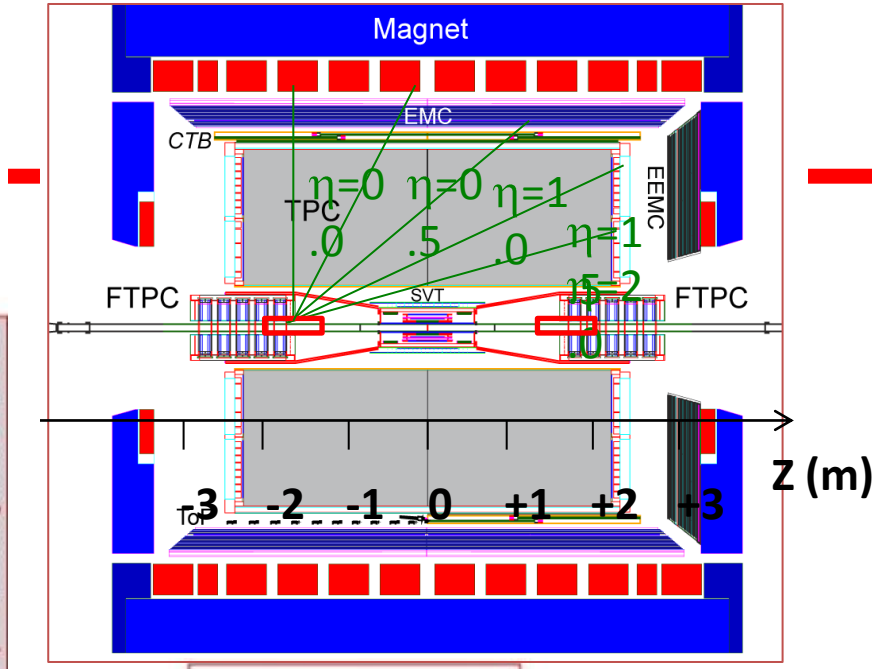
19.6 GeV Au+Au (2011)

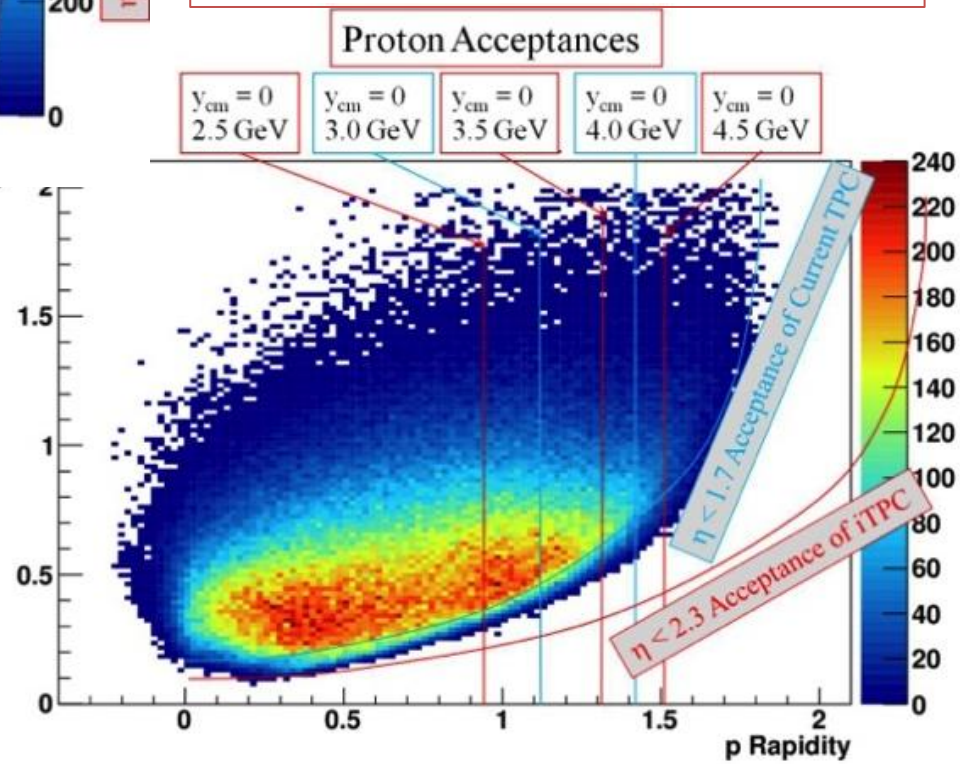


14.5 GeV Au+Au (2014)





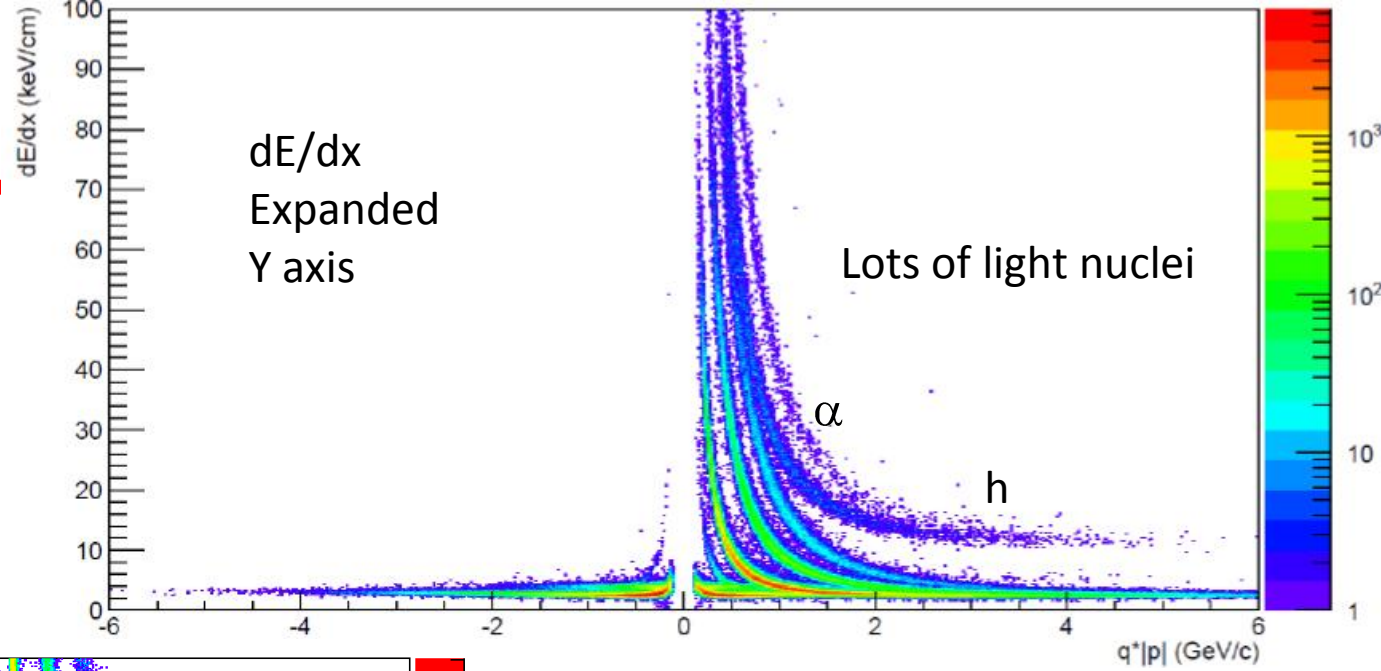


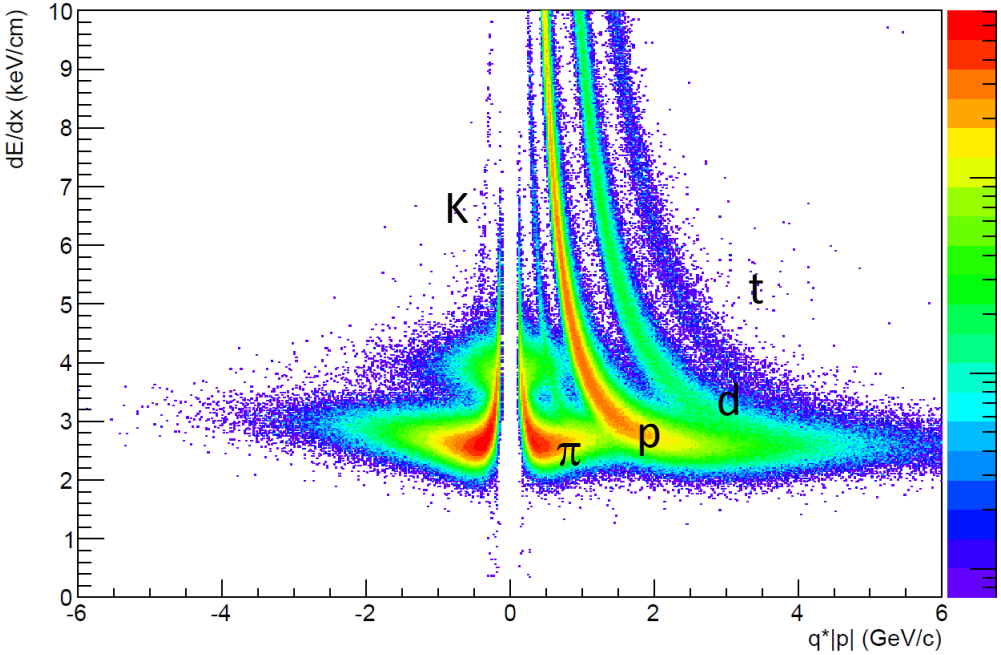


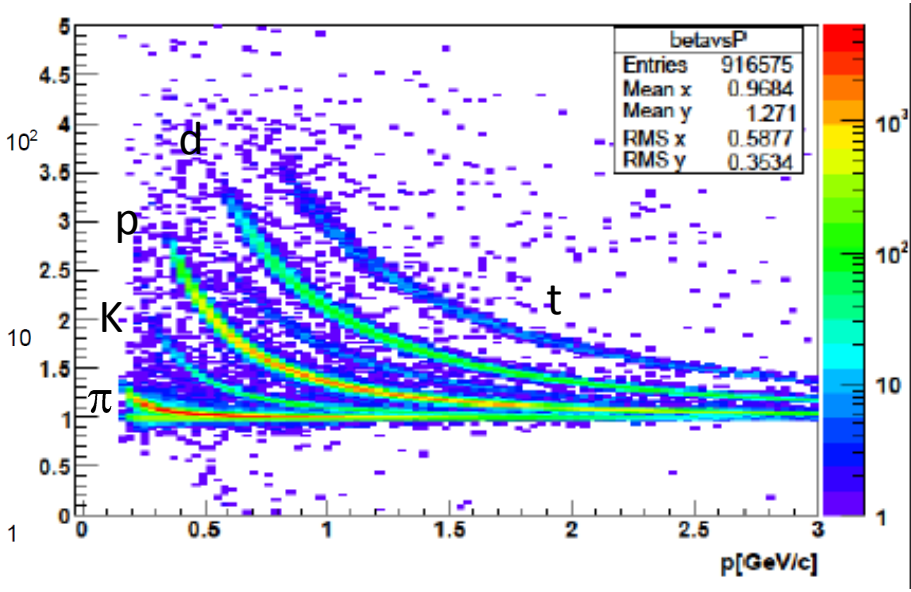
Pion Acceptances are good from target to mid-rapidity for all BES II energies

Proton Acceptances have low p_T acceptance threshold. An iTPC would greatly improve the acceptance reach here.

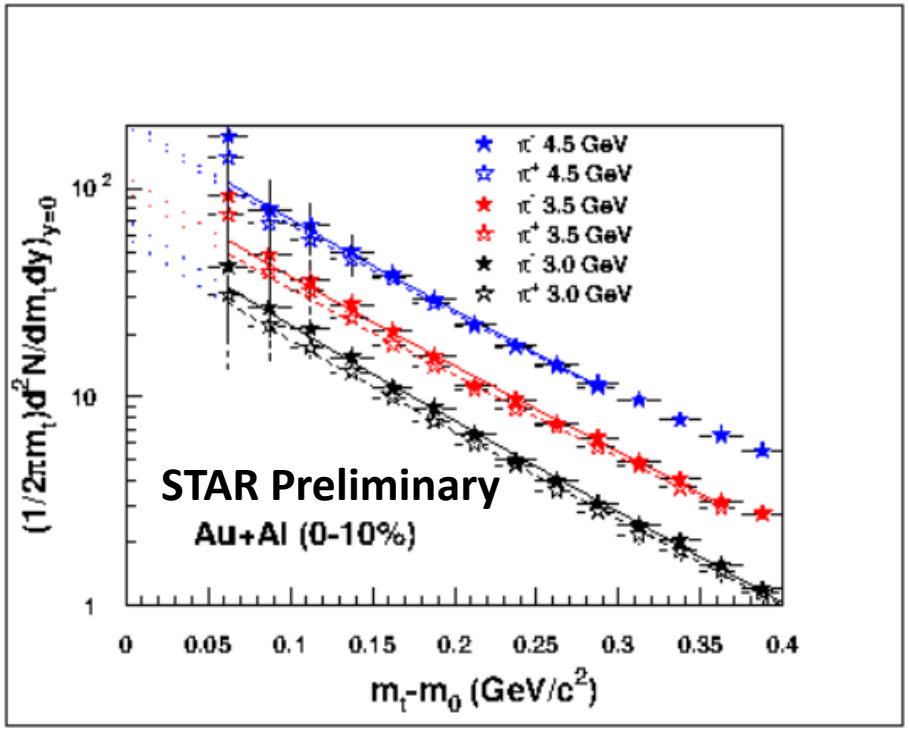
Particle Identification using dE/dx and TOF



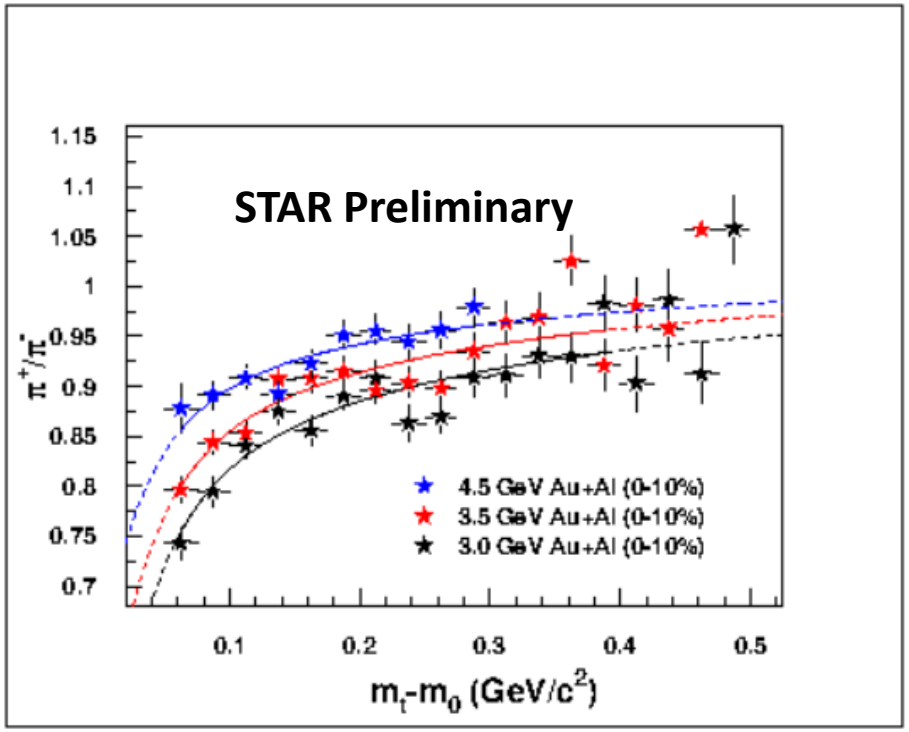




Au + Al Results: Spectra and ratios

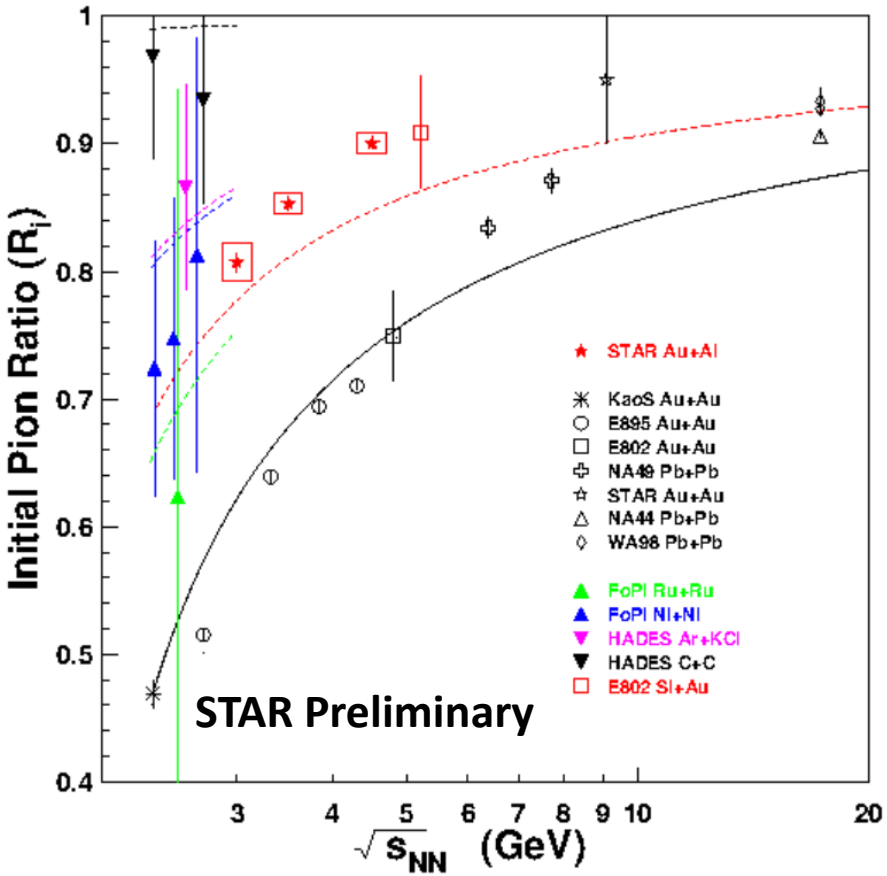


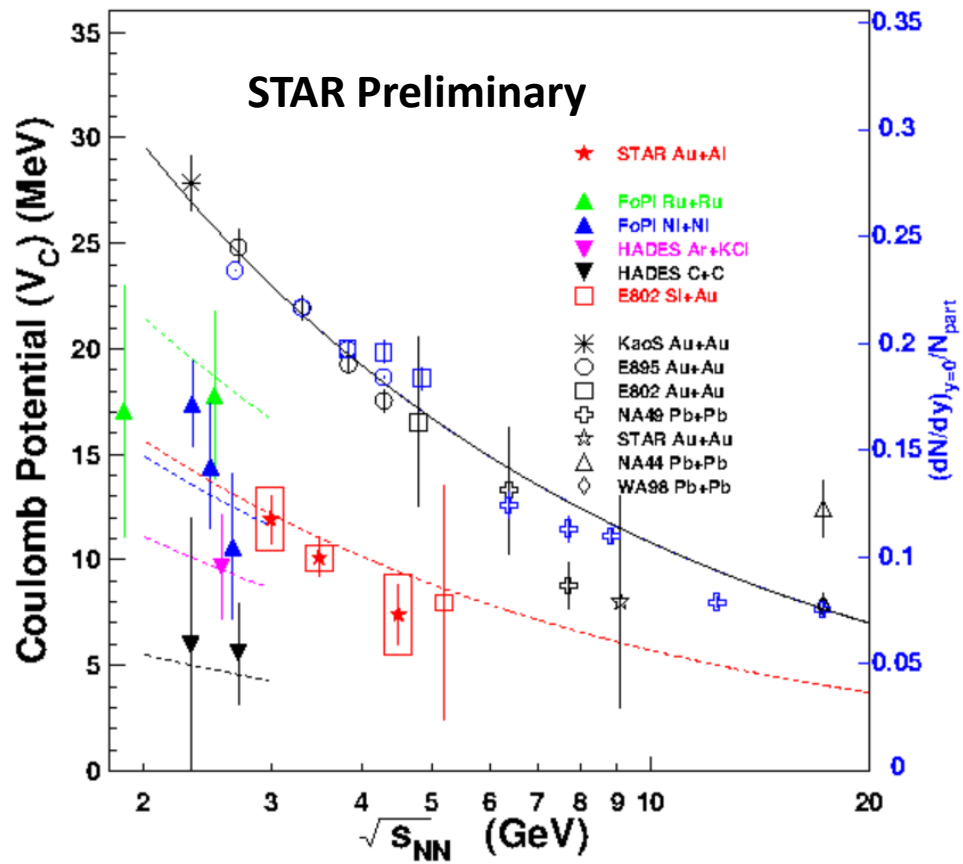
Spectra fit with Bose-Einstein Functions



Ratios fit with Coulomb Functions

Pion Ratio and Coulomb Potential Comparison

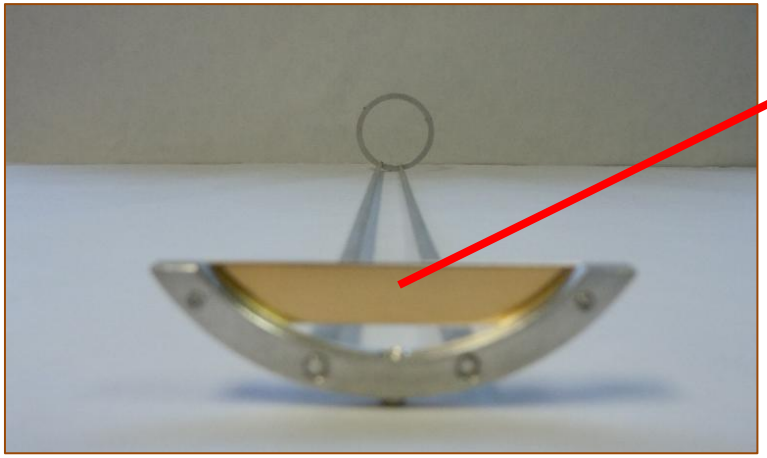


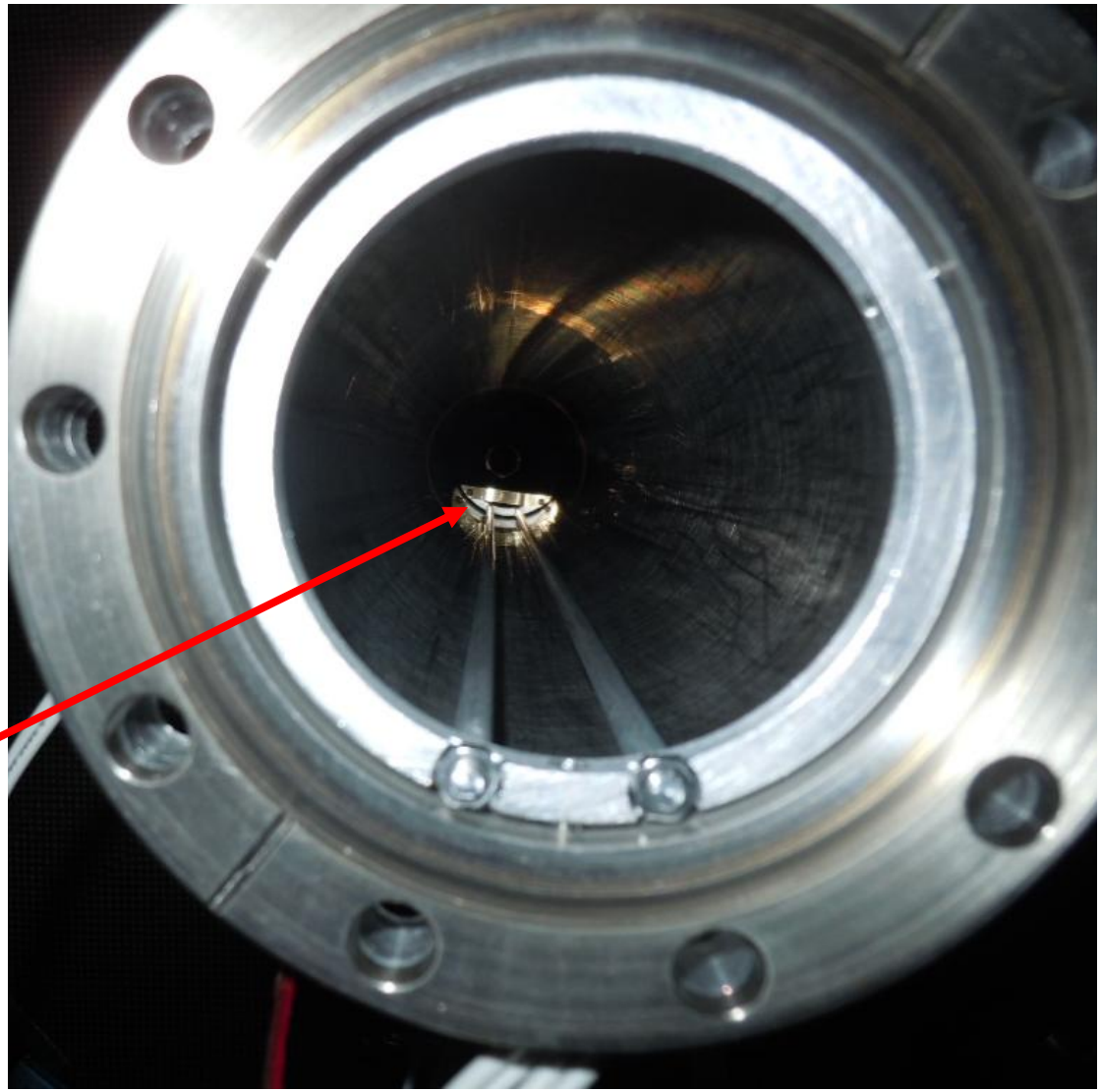


Target Design 2014 and 2015

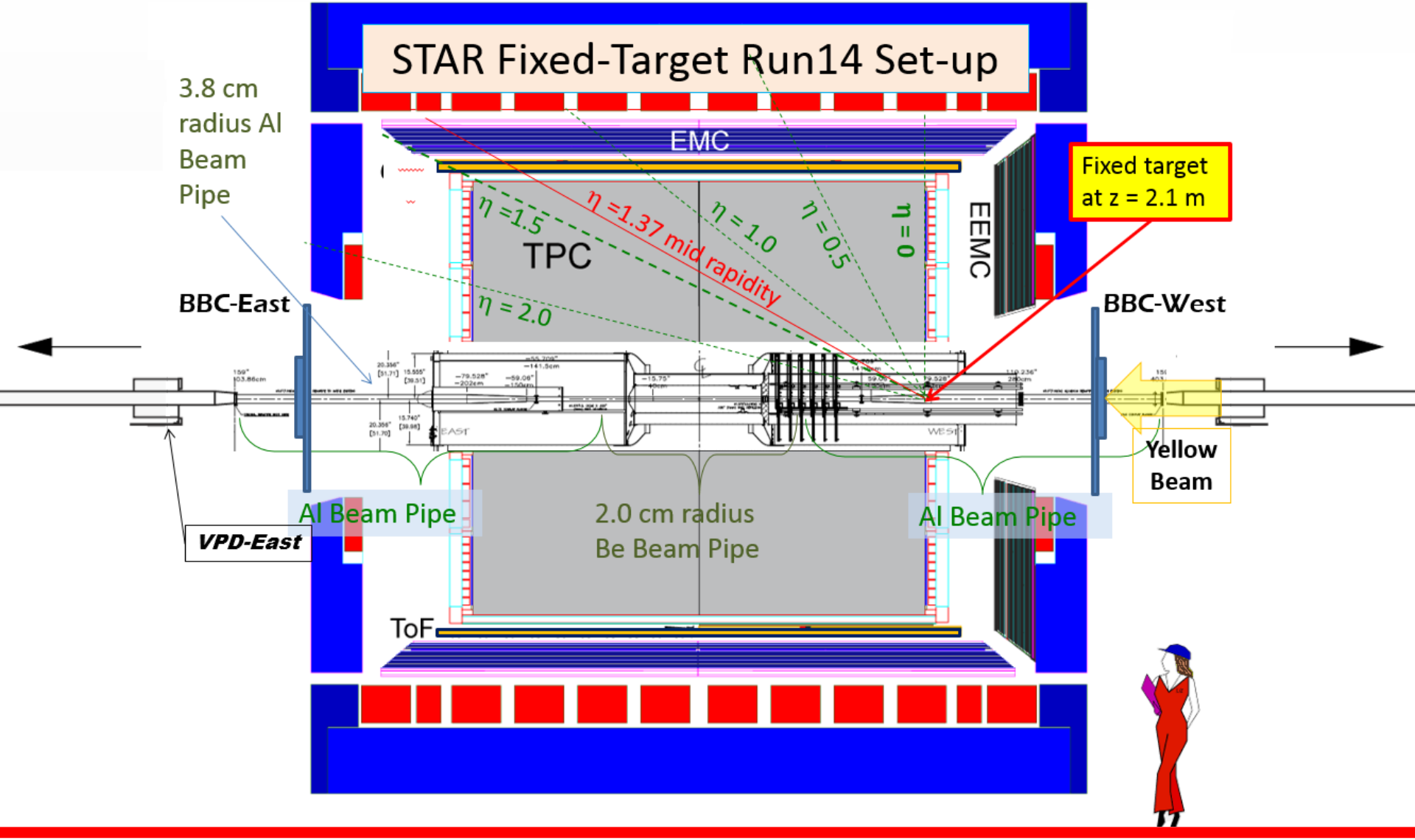
Target design:

- **Gold foil**
- **1 mm Thick**
- **~1 cm High**
- **~4 cm Wide**
- **210 cm from IR**





Run 14 and 15 Setup



Identifying Target Events

Lots of background, but the target events are evident

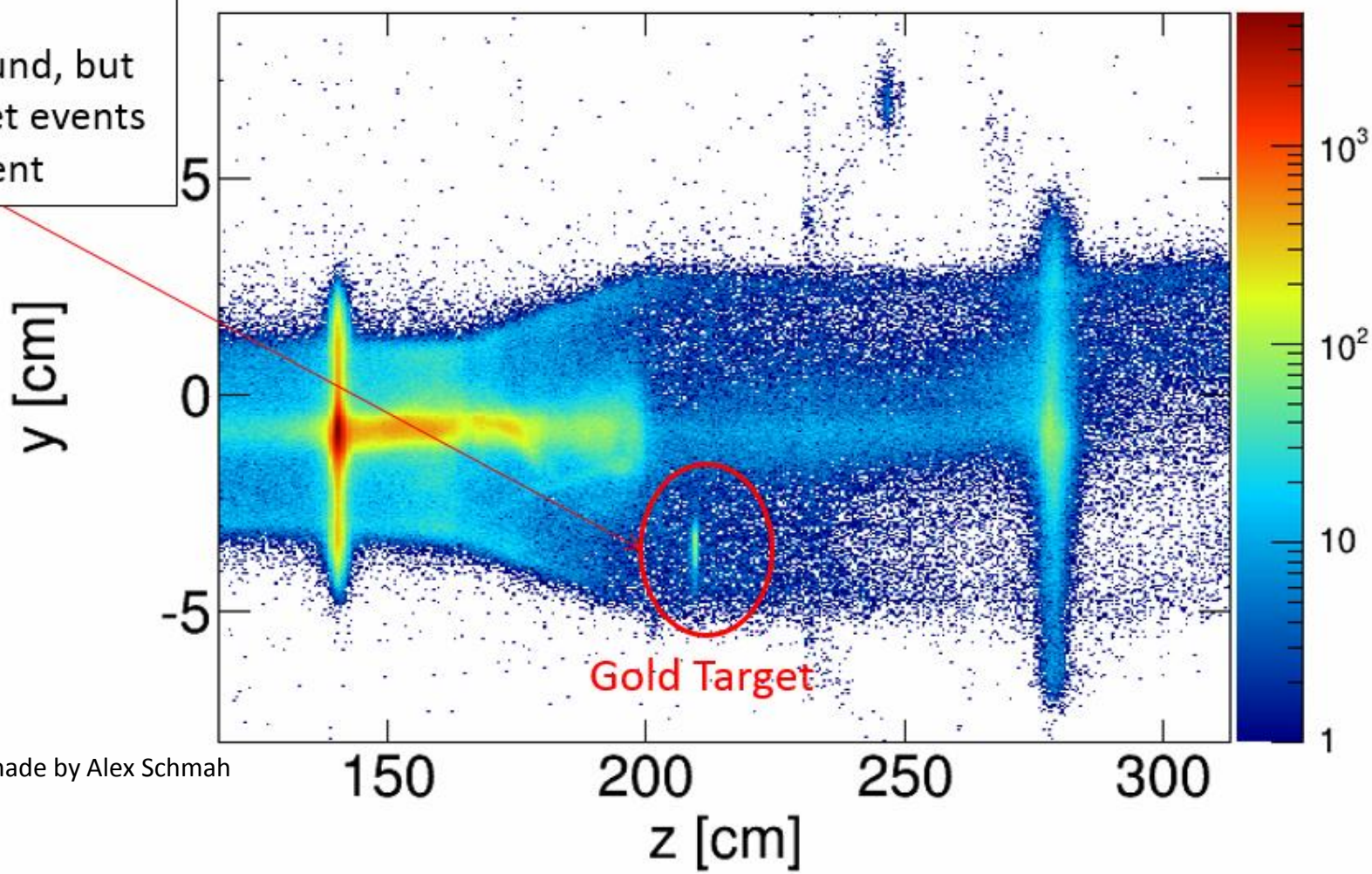
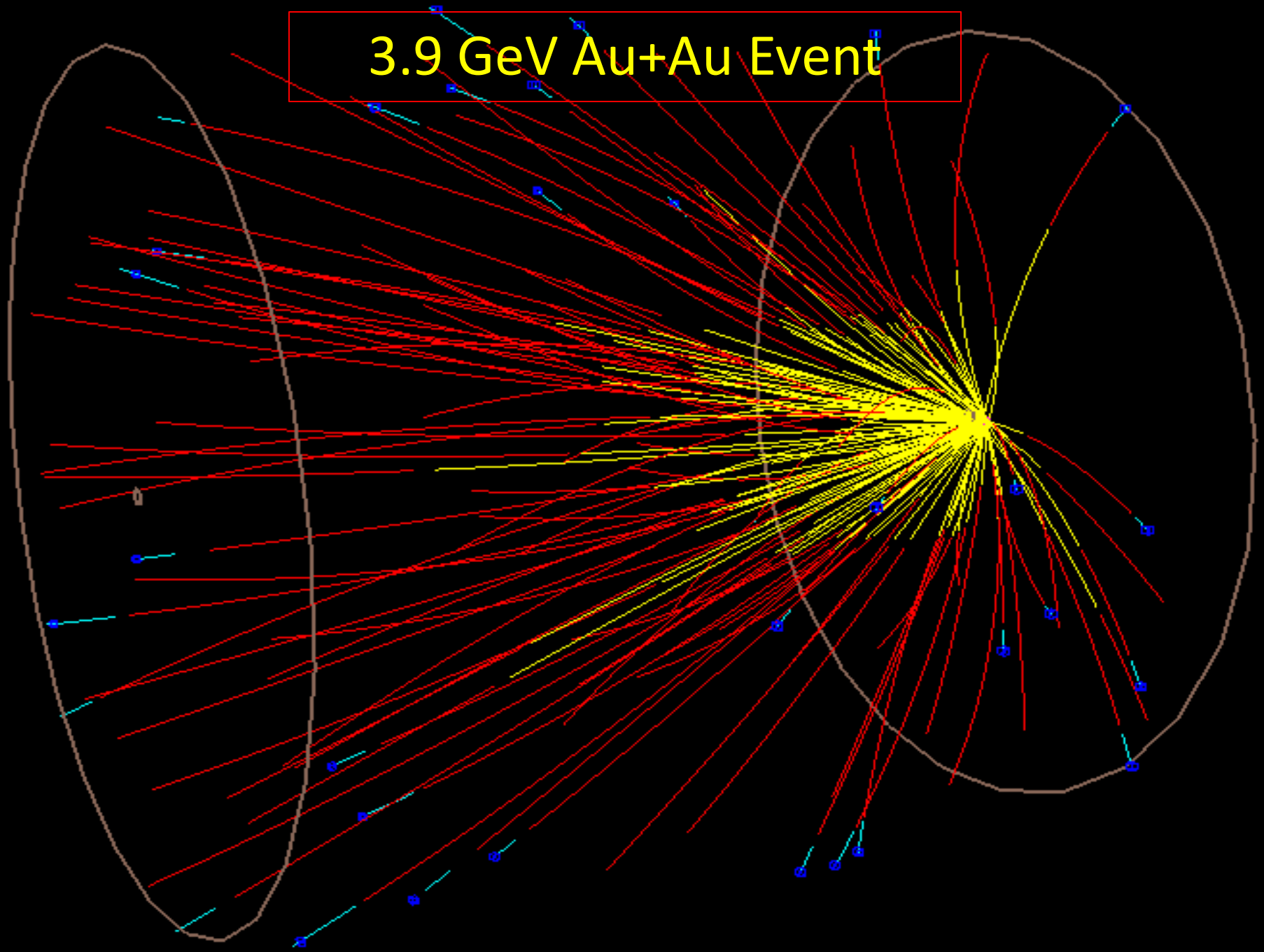


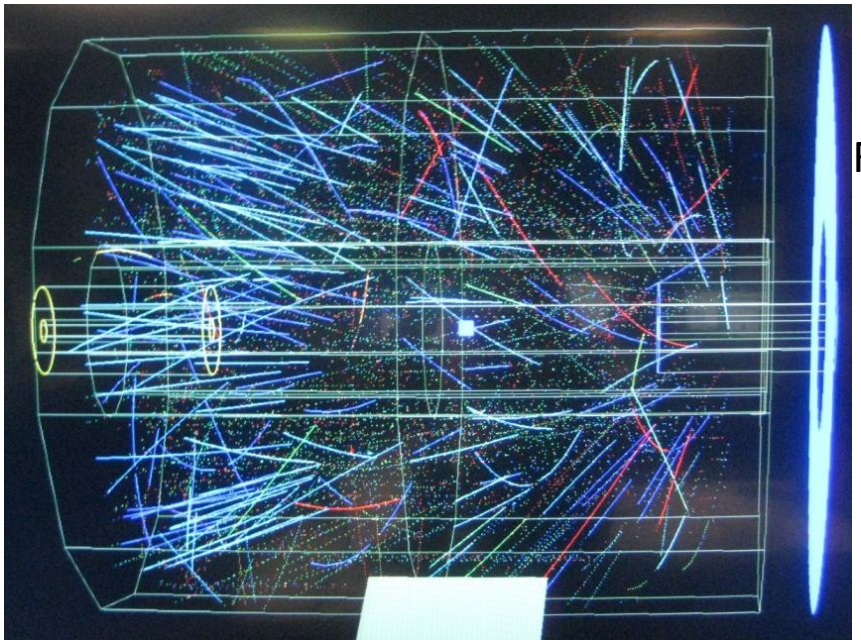
Figure made by Alex Schmah

3.9 GeV Au+Au Event



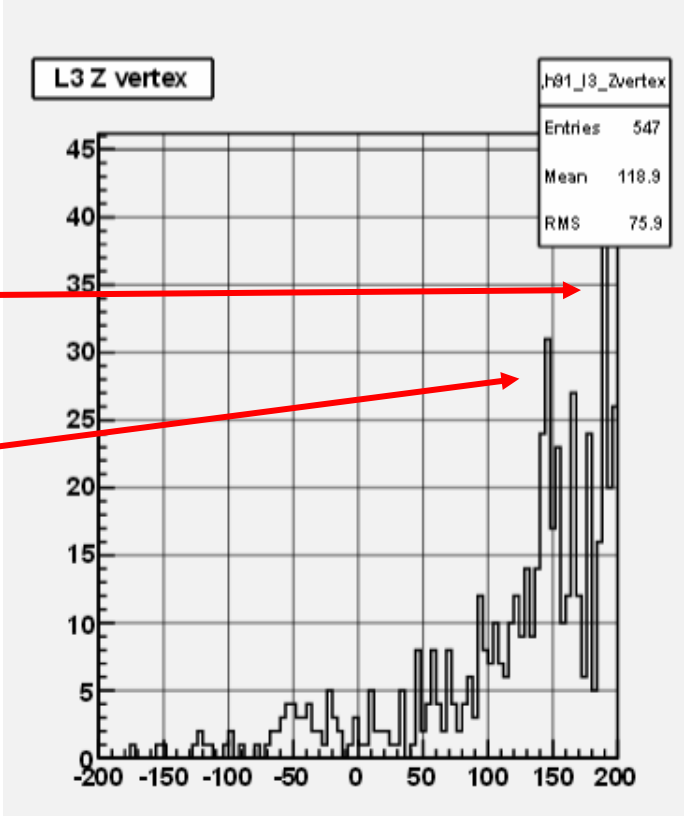
Au + Au Fixed Target 4.5 GeV

- May 2015 – Test run with lowered beam
- 1 millions triggers, ~100k central events



Fixed Target

Beam Pipe Flange

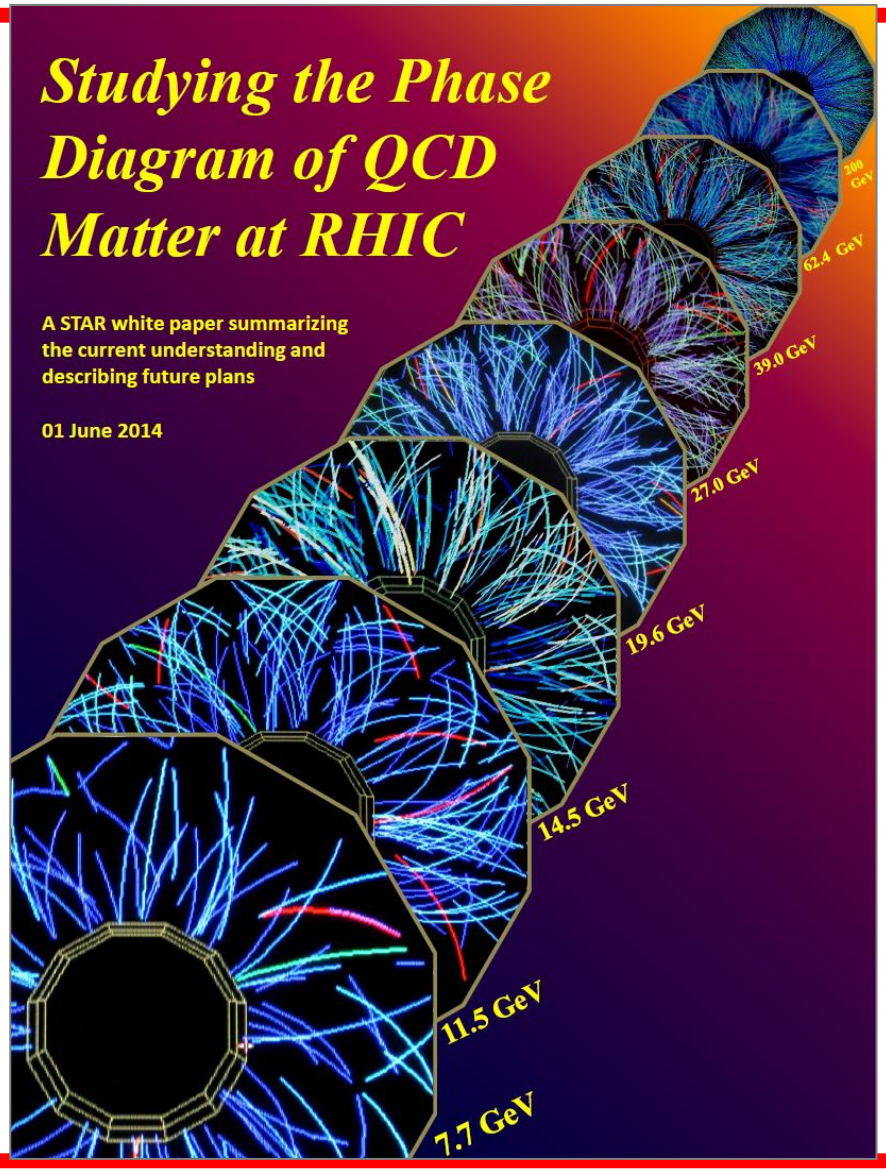


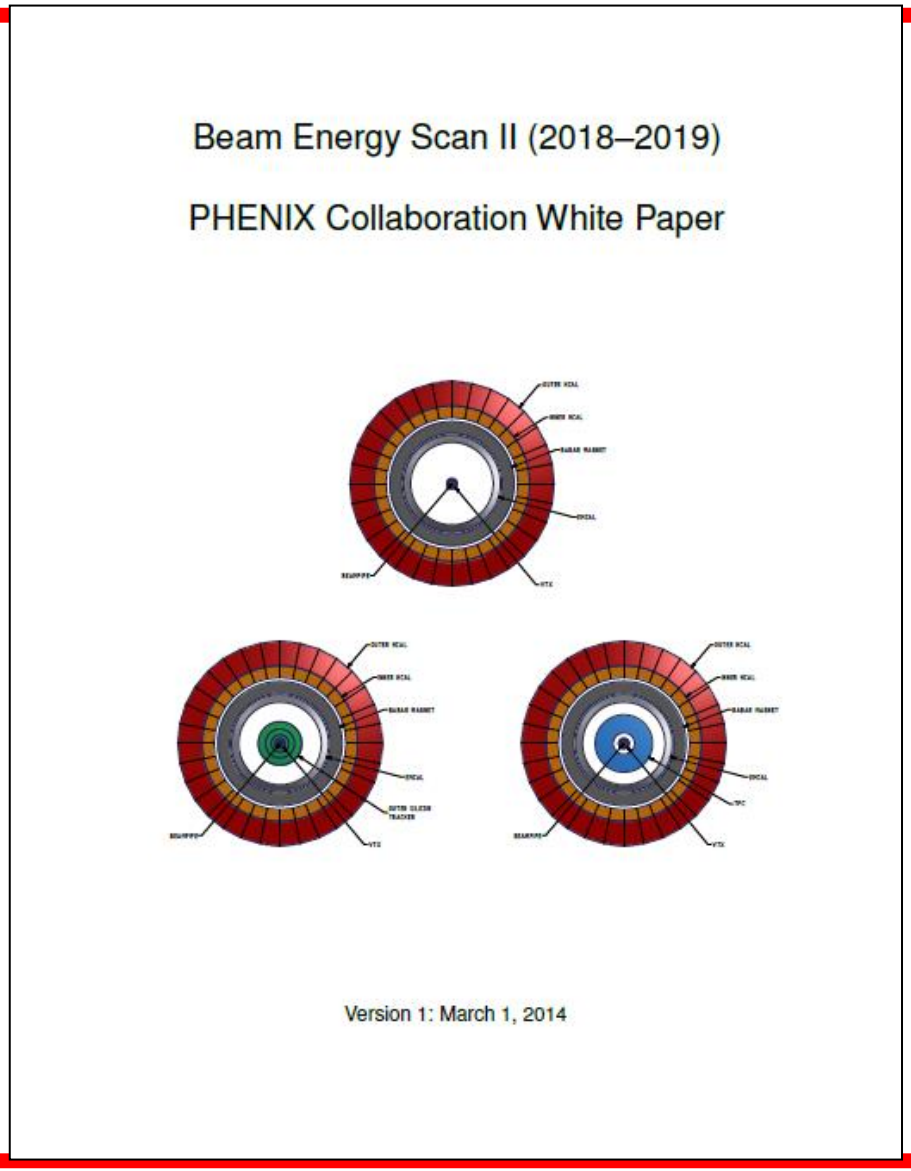
Conclusions for Fixed Target Program

1. STAR detector and software works well for the fixed target configuration for beams at injection energy or lower
2. Event selection criteria can distinguish events on the gold target from background events on the beam pipe and out of time pileup
3. Consistency with published data

Beam Energy Scan II (2019-2020)

STAR and PHENIX BES-II White Papers




Beam Energy Scan II (2018–2019)

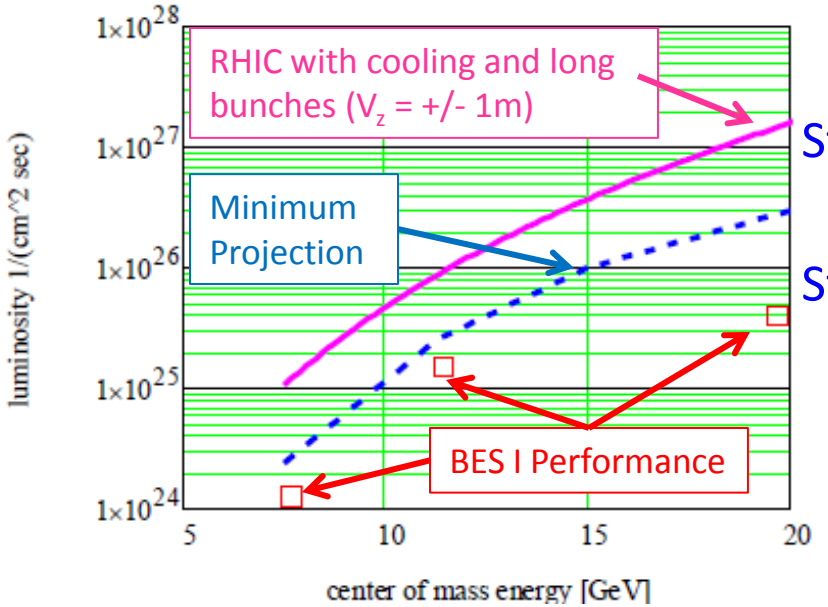
PHENIX Collaboration White Paper

Version 1: March 1, 2014

Low Energy Electron Cooling at RHIC

Electron Cooling can raise the luminosity by a factor of 3-10 in the range from 5 – 20 GeV

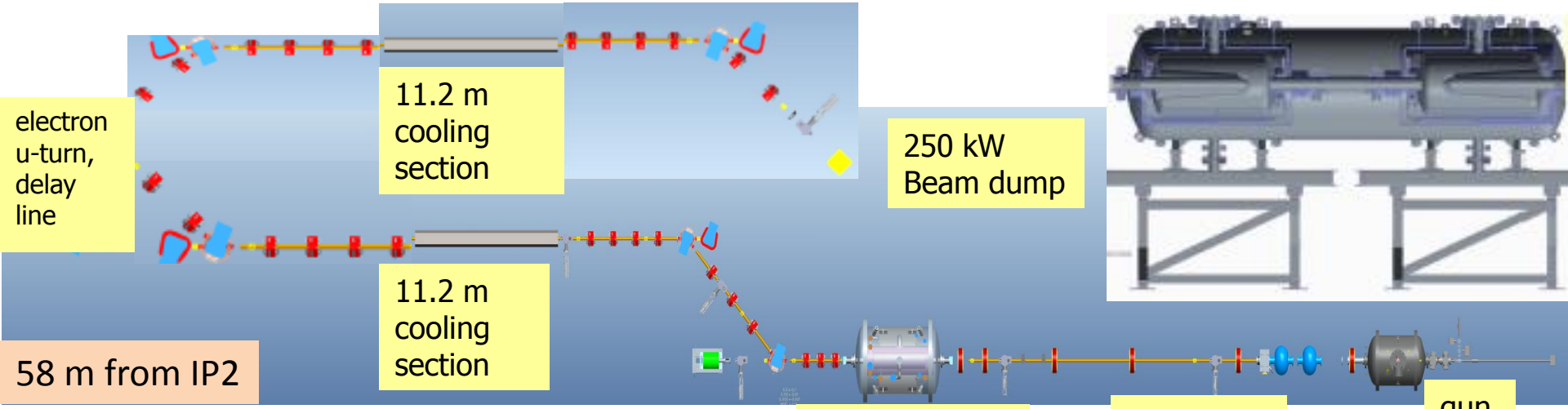
Long Bunches increase luminosity by factor of 2-5



Stage I
$\sqrt{s_{NN}}$ = 5-9 GeV

Stage II -- 3 MeV booster cavity
$\sqrt{s_{NN}}$ = 9-20 GeV

100 MHz SRF Gun



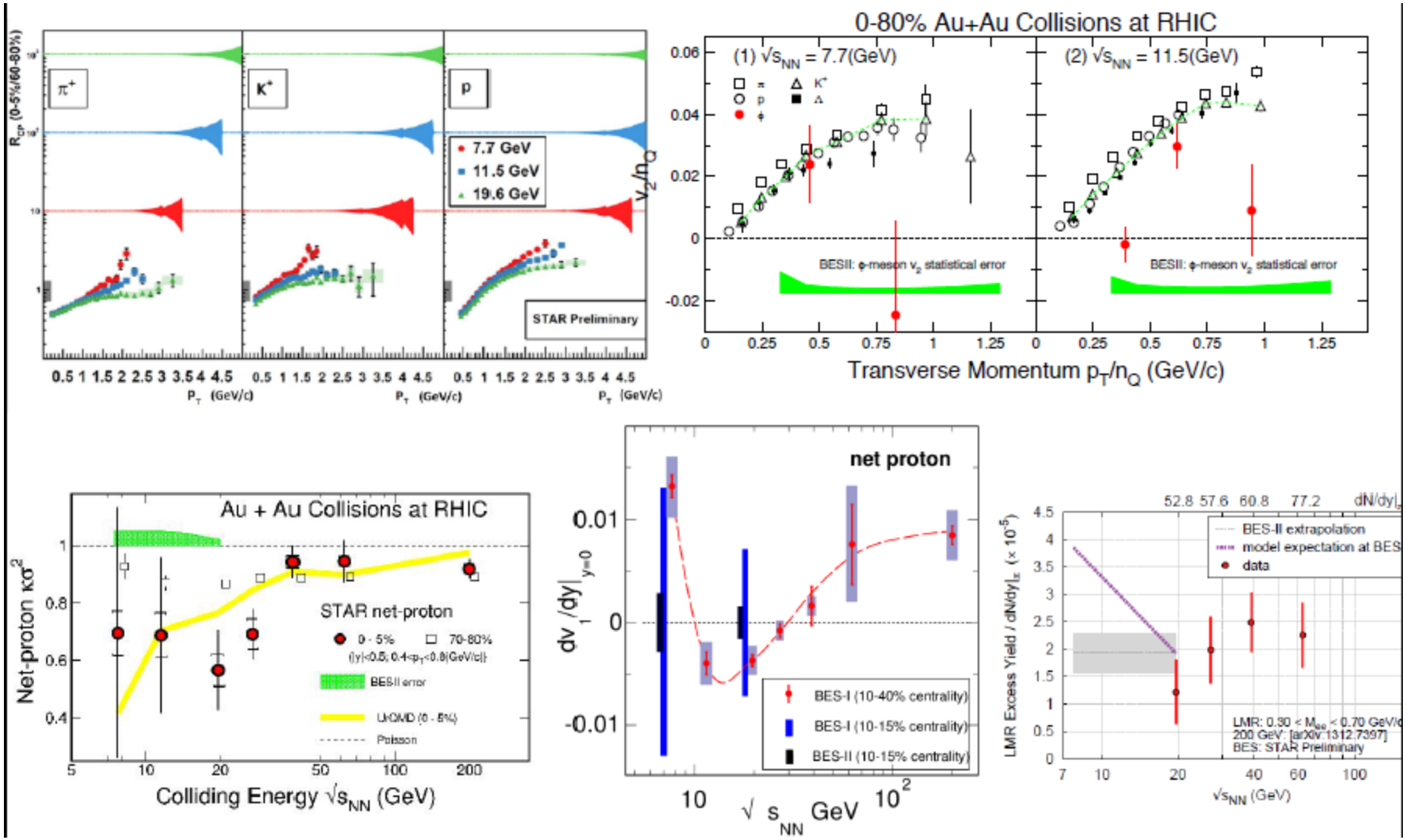
BES Phase II Proposal

BES Phase II is planned for two 22 cryo-week runs in 2019 and 2020

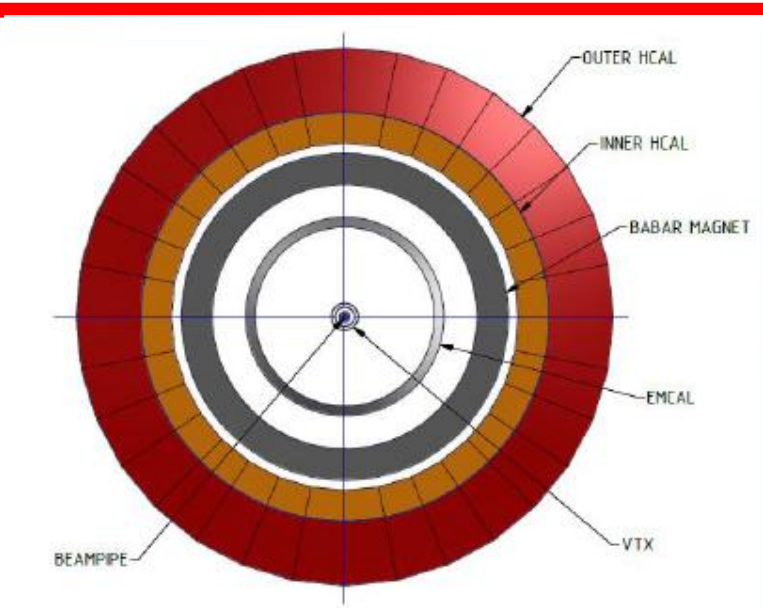
$\sqrt{S_{NN}}$ (GeV)	5.0	7.7	9.1	11.5	13.0	14.5	19.6
μ_B (MeV)	550	420	370	315	290	250	205
BES I (MEvts)	---	4.3	---	11.7	---	24	36
Rate(MEvts/day)		0.25		1.7		2.4	4.5
BES I $\mathcal{L}$ (1×10^{25}/cm^{2}sec)		0.13		1.5		2.1	4.0
BES II (MEvts)		100	160	230	250	300	400
eCooling (Factor)	2	3	4	6	8	11	15
Beam Time (weeks)		**14**	**9.5**	**5.0**	**3.0**	**2.5**	**3.0**

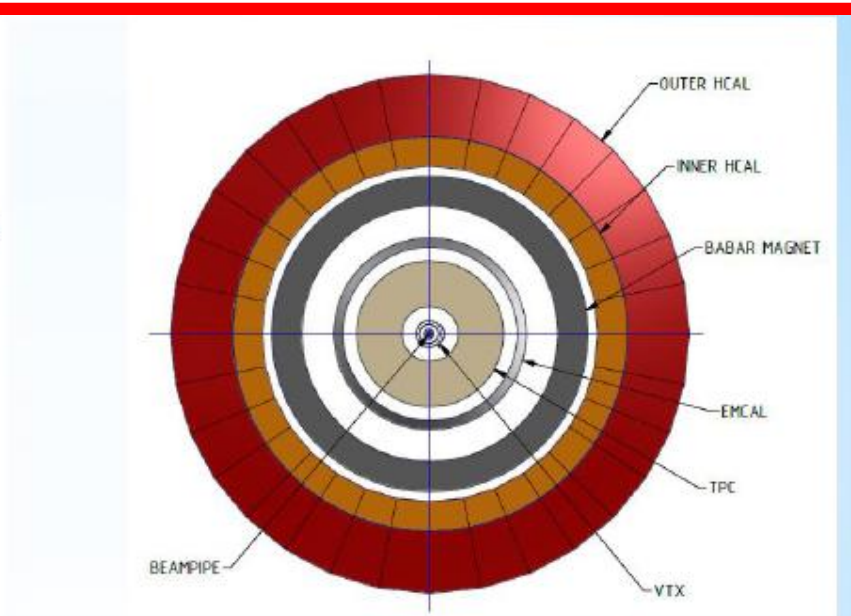
*** Details of the STAR and PHENIX requests still to be reconciled

Reduction in Errors with Improved Statistics



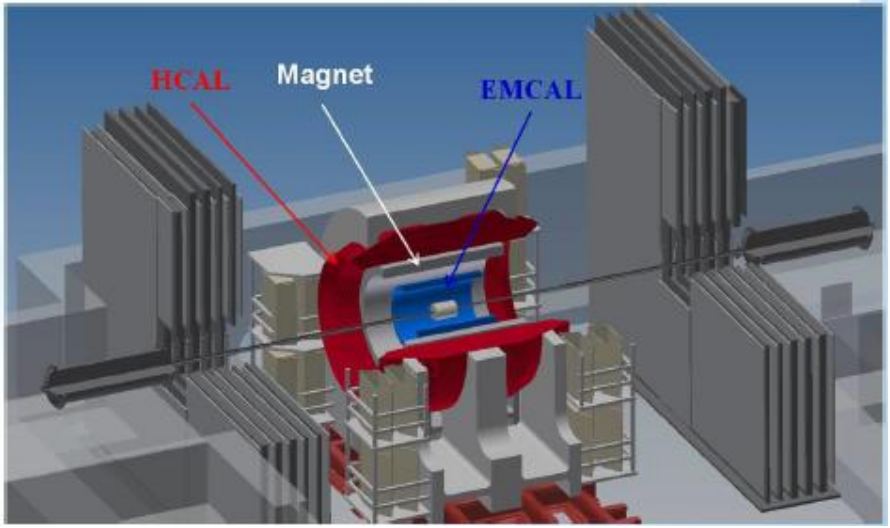
The sPHENIX Upgrades and BES Phase II





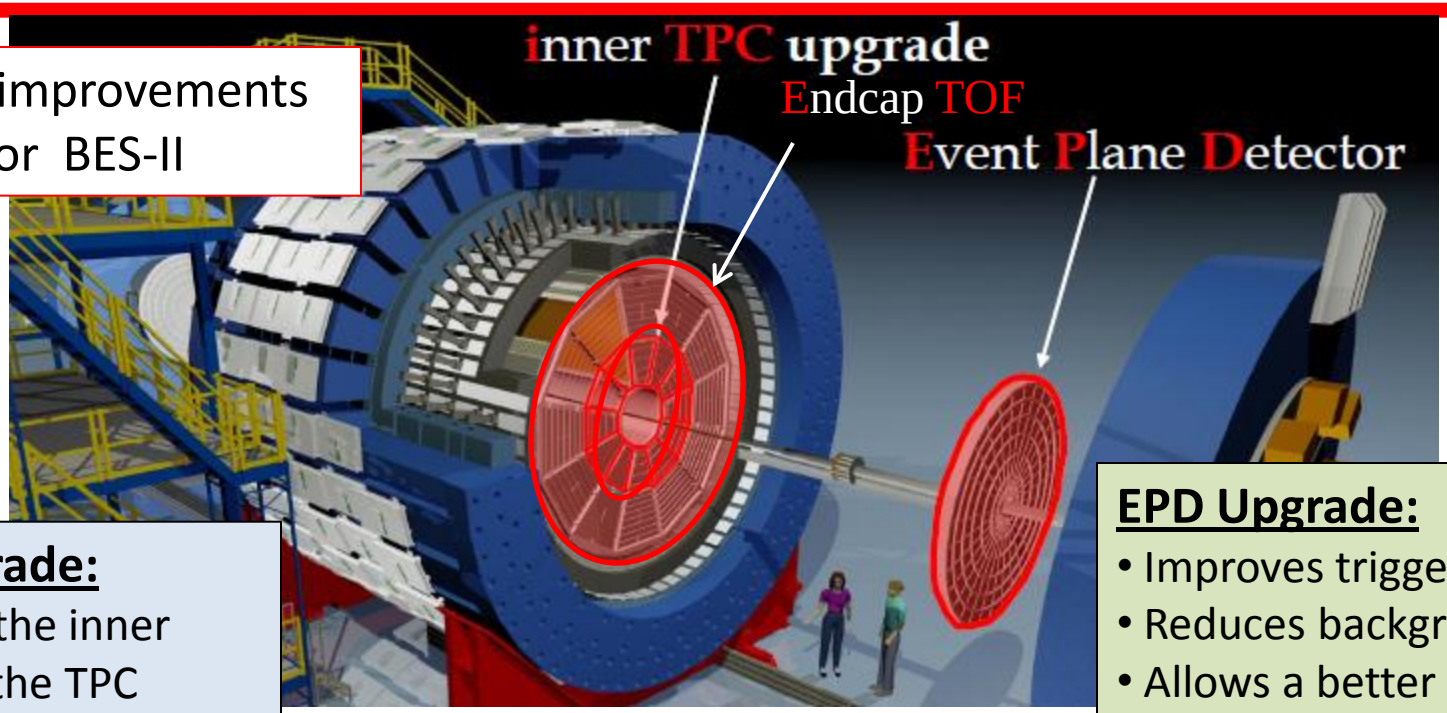
The sPHENIX detector for 2019 will consist of the HCAL, any available portion of the EMCAL, and either a reconfigured VTX detector (above left) or a micro-TPC (above right).

Jeffery T. Mitchell – CPOD 2014 - 11/18/14



The STAR Upgrades and BES Phase II

Major improvements for BES-II



iTPC Upgrade:

- Rebuilds the inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.7
- Lowers p_T cut-in from 125 MeV/c to 60 MeV/c

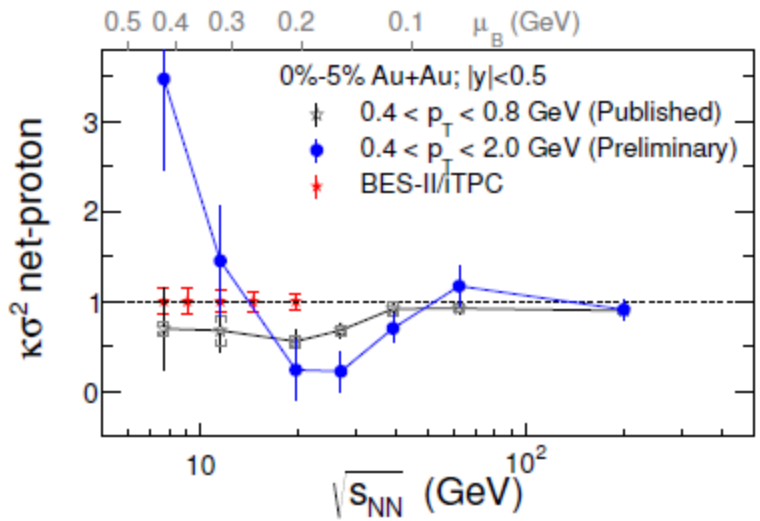
EndCap TOF Upgrade:

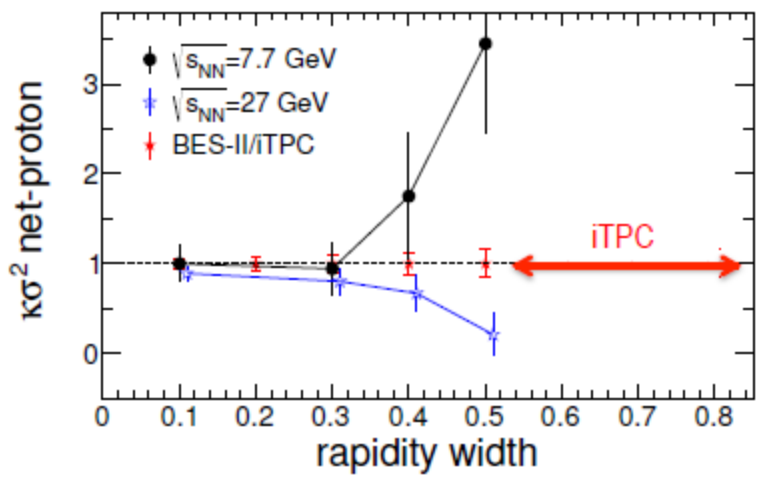
- Rapidity coverage is critical
- PID at forward rapidity
- Improves the fixed target program

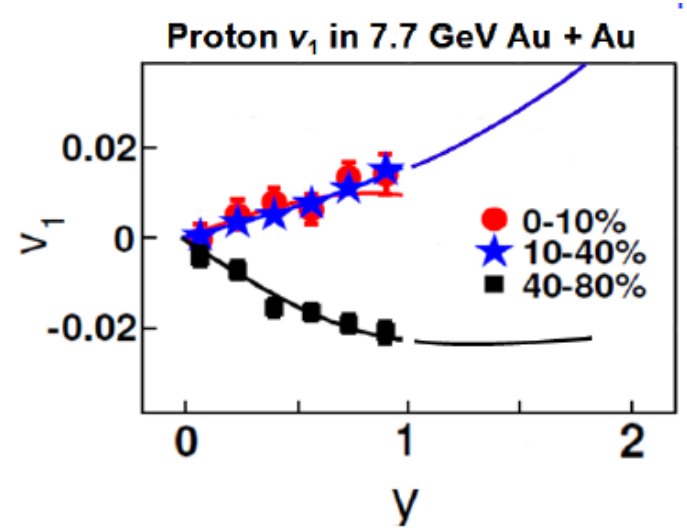
EPD Upgrade:

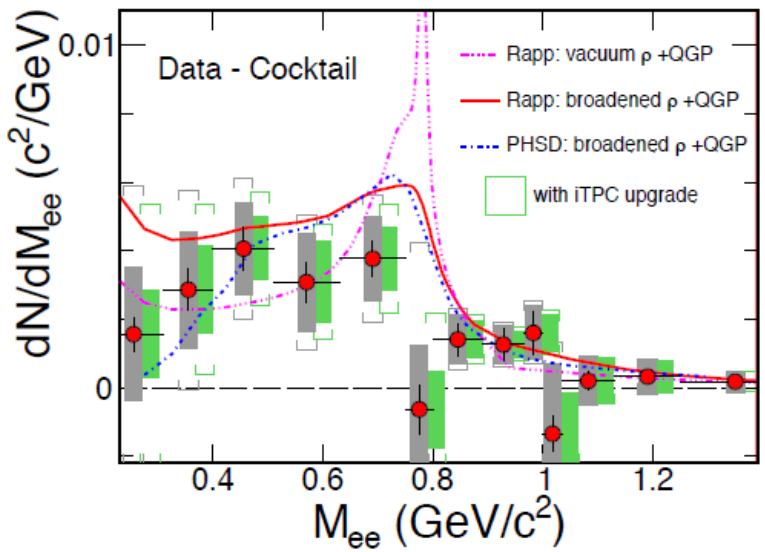
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

Improvements due to Upgrades









Conclusions

- BES Phase I told us the regions of interest
- New 14.5 GeV results will be available soon
- Fixed-target program will extend reach of BES program
- Collider and Detector upgrades ➔ refined searches

The focused and improved studies of BES Phase II will allow us to define the energy of the onset of deconfinement and allow us to characterize the phases and transitions of QCD matter.