Results and Future of Beam Energy Scan Program at RHIC

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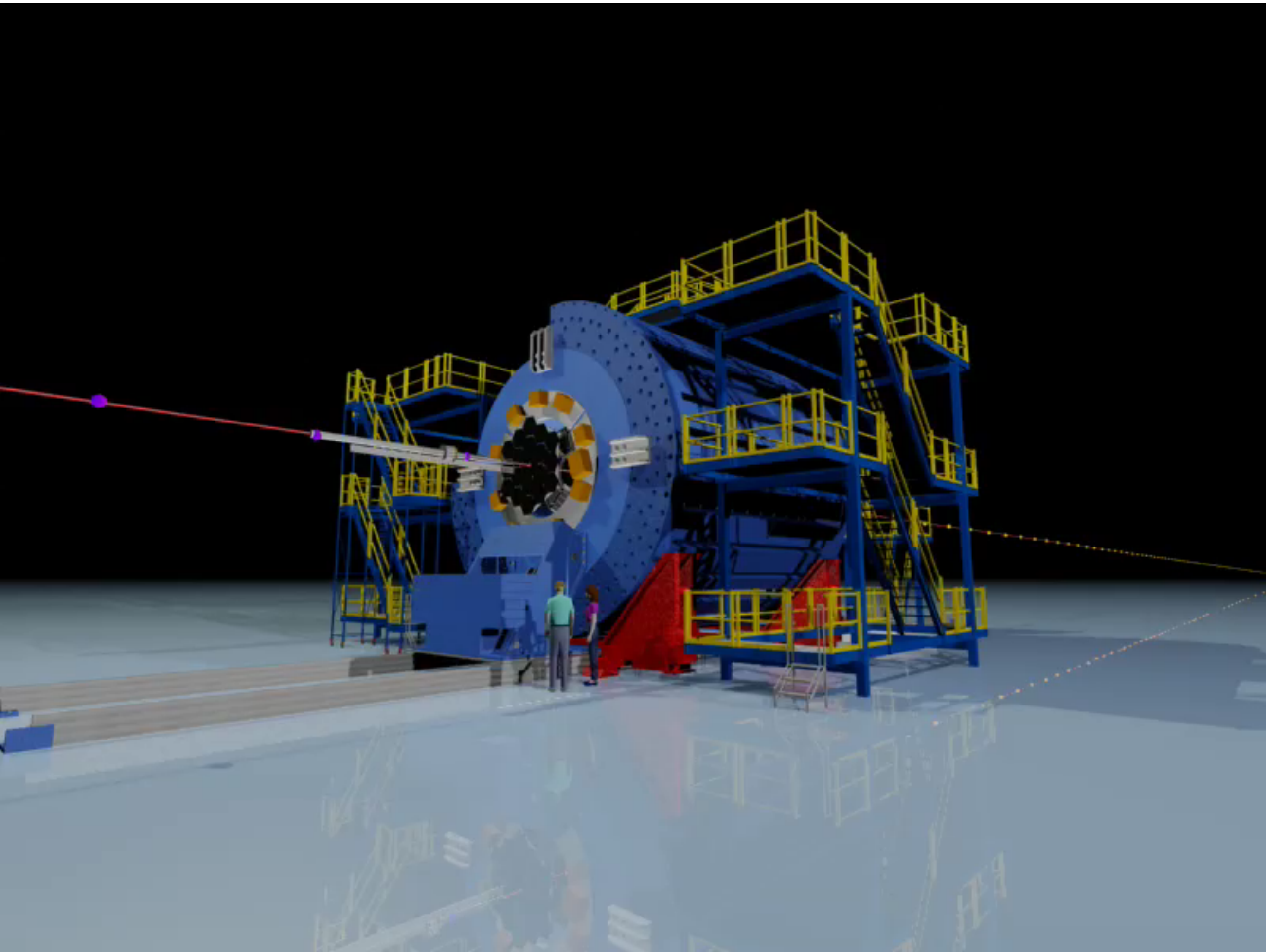

Outline:
1. Intro : Why BES ?
2. Past : BES I selected results
3. Future : BES II (+FT)

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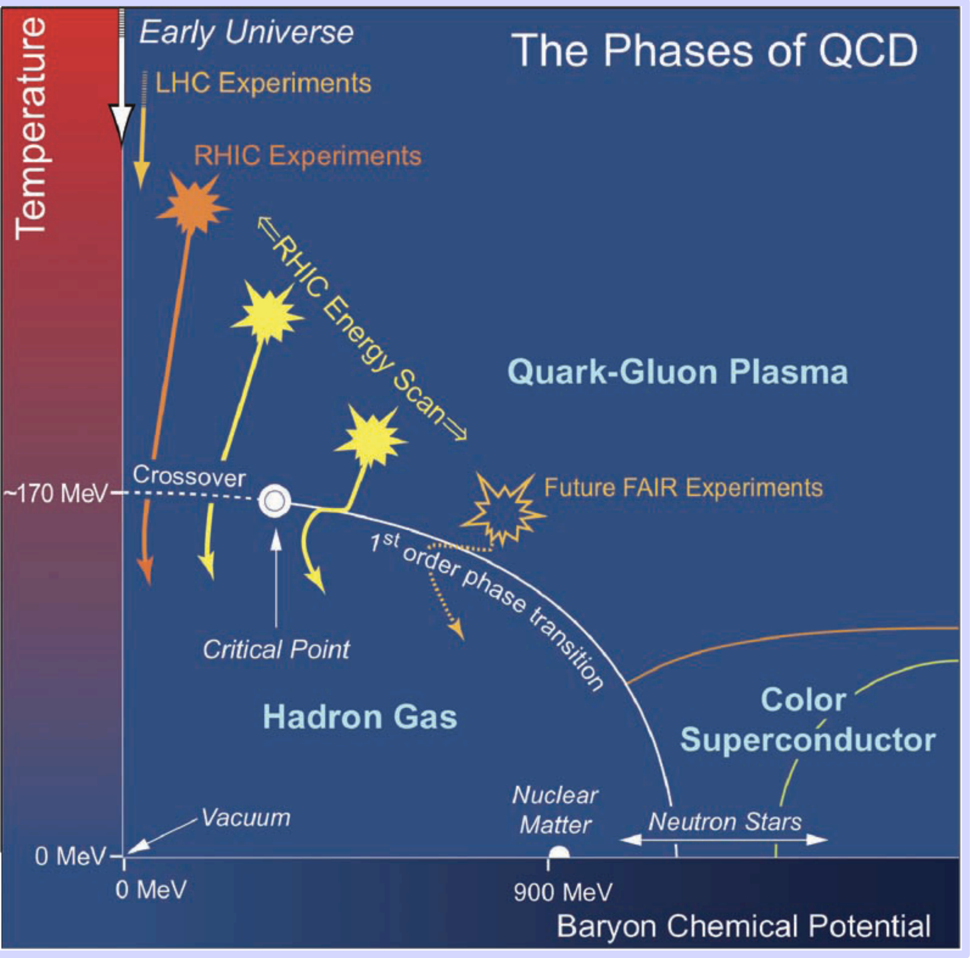
U.S. DEPARTMENT OF ENERGY

QCD Phase Diagram

- single most important graph of our field
- still highly speculative



Results from top RHIC energy suggest the existence of QGP (with unique and unexpected properties)

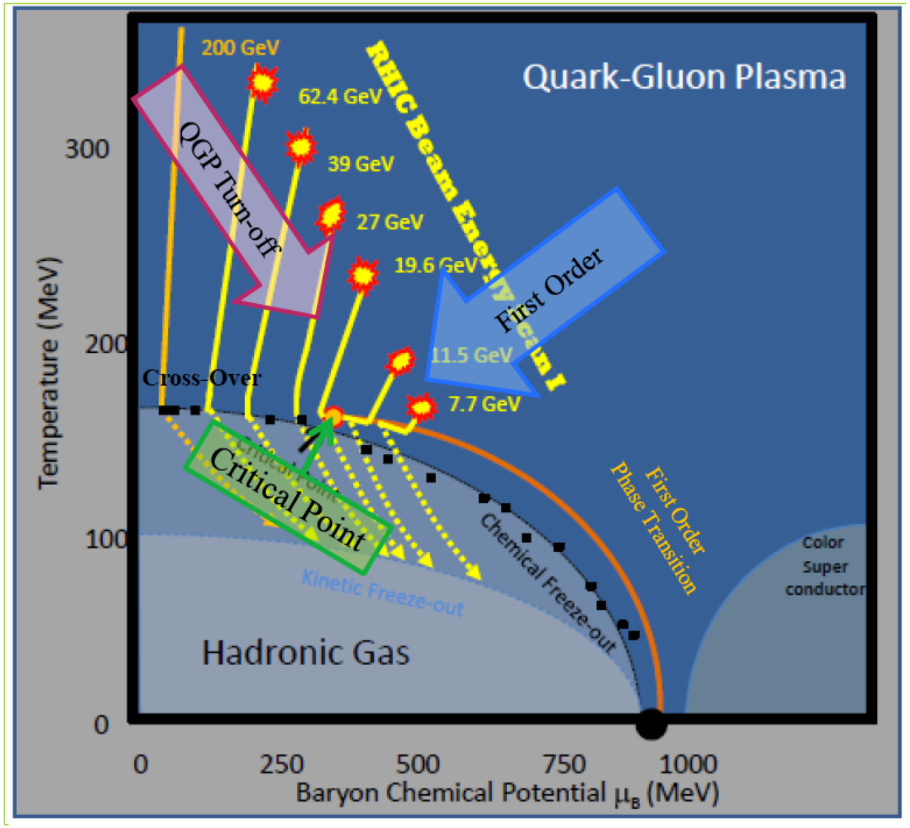
The main task now, besides study of properties of QGP, is to understand the structure of QCD phase diagram

Not much is really known:

- at high energies cross-over transition
  (top RHIC energy, $\mu_B \sim 0$)
- at lower – should be 1st order phase transition
- CP ?

⬇

BES program at RHIC <u>to map out QCD matter phase diagram</u>



BES at RHIC – phase I

Search the QCD phase diagram for evidence of :

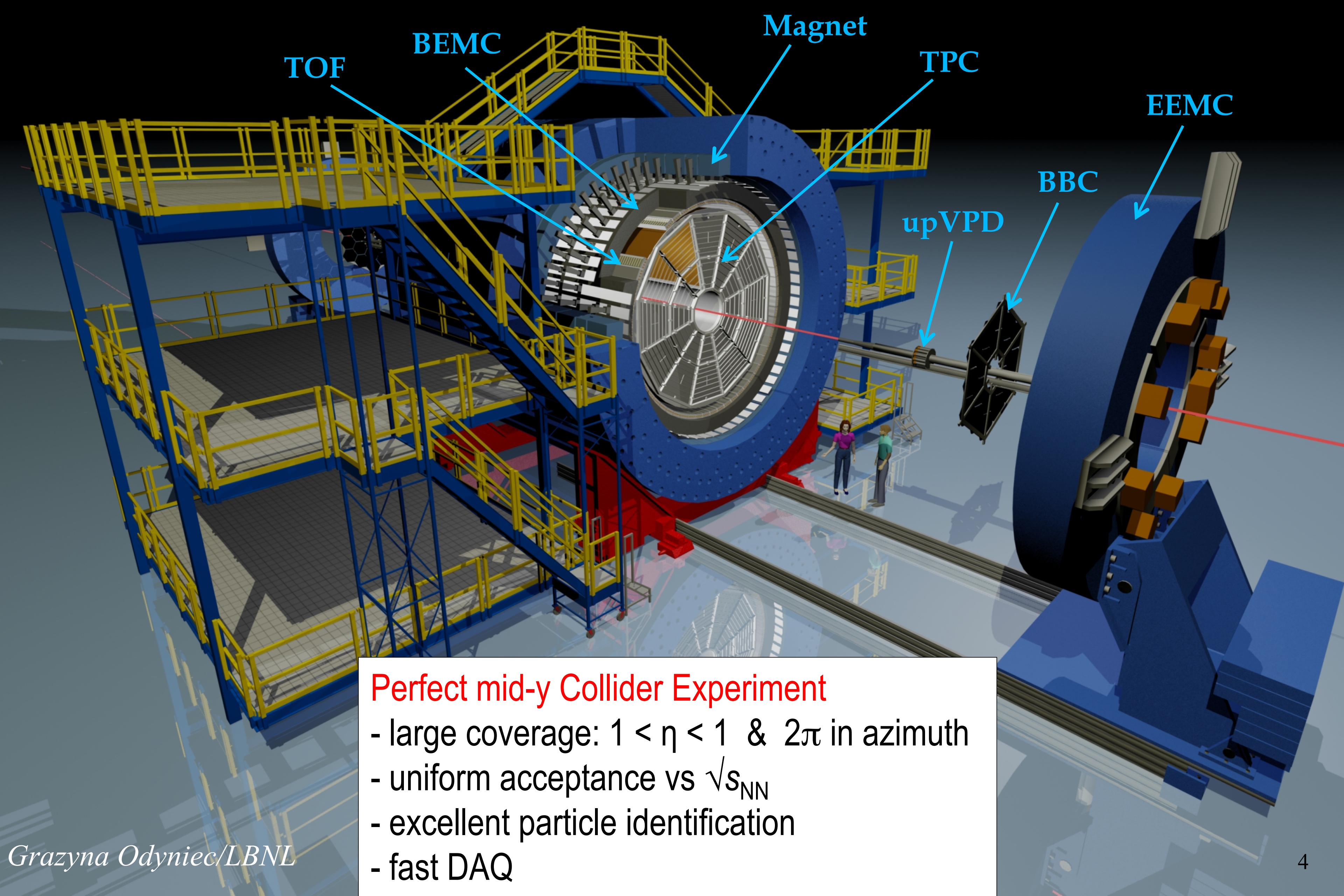
1. critical point fluctuations
2. signals of 1st order phase transition
3. turn-off of sQGP signatures

$\sqrt{s_{NN}}$ (GeV)	Good events recorded (M events)	Year	μ_B (MeV) [0-5%]	T (MeV) [0-5%]
7.7	4	2010	422	140
11.5	12	2010	316	152
14.5	20	2014	264	156
19.6	36	2011	206	160
27	70	2011	156	162
39	130	2010	112	164
62.4	67	2010	73	165
200	350	2010	24	166

BES I Au+Au:

$\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5,19.6, 27, 39, 62.4, (130) and 200 GeV

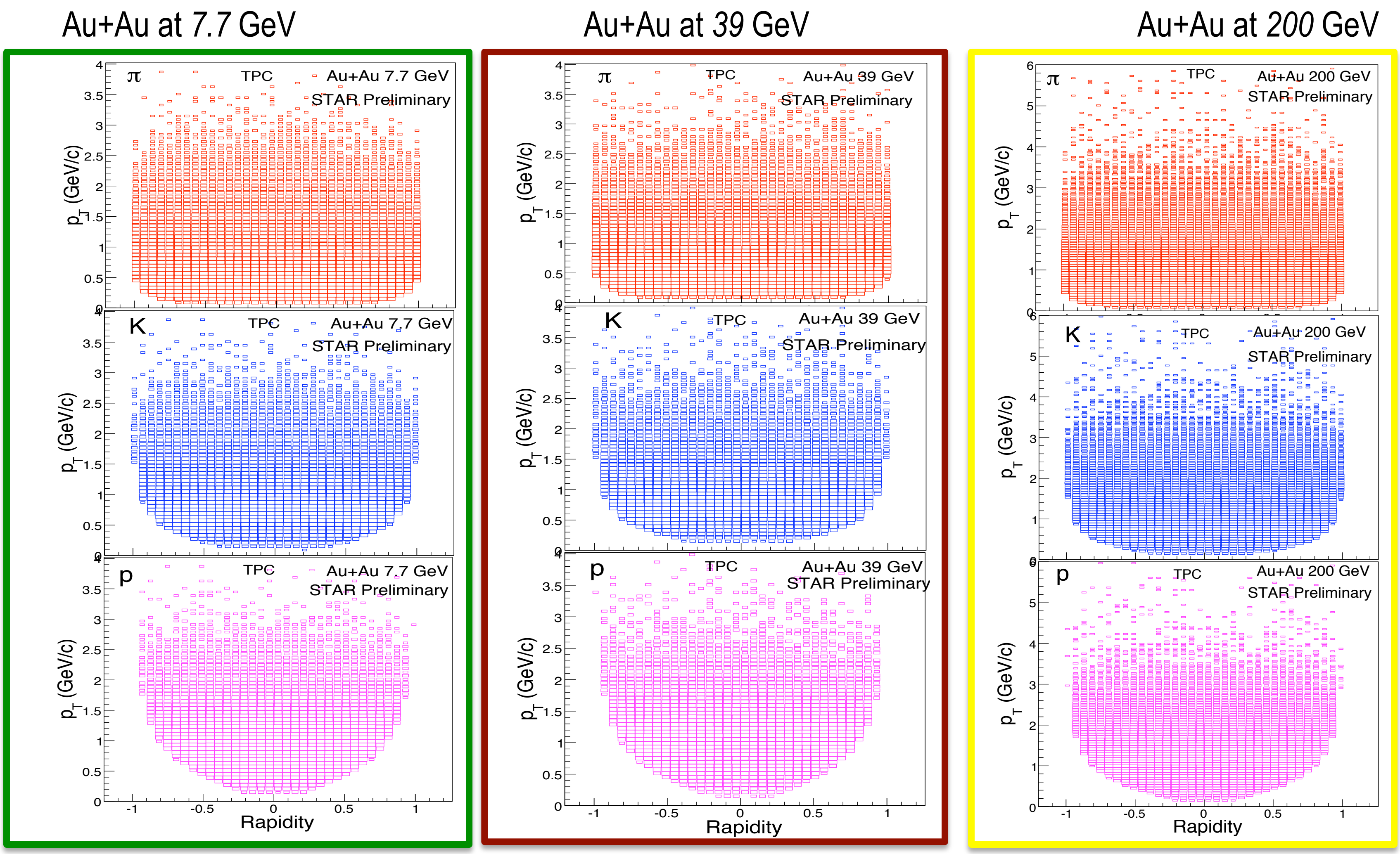
The Solenoid Tracker At RHIC (STAR)



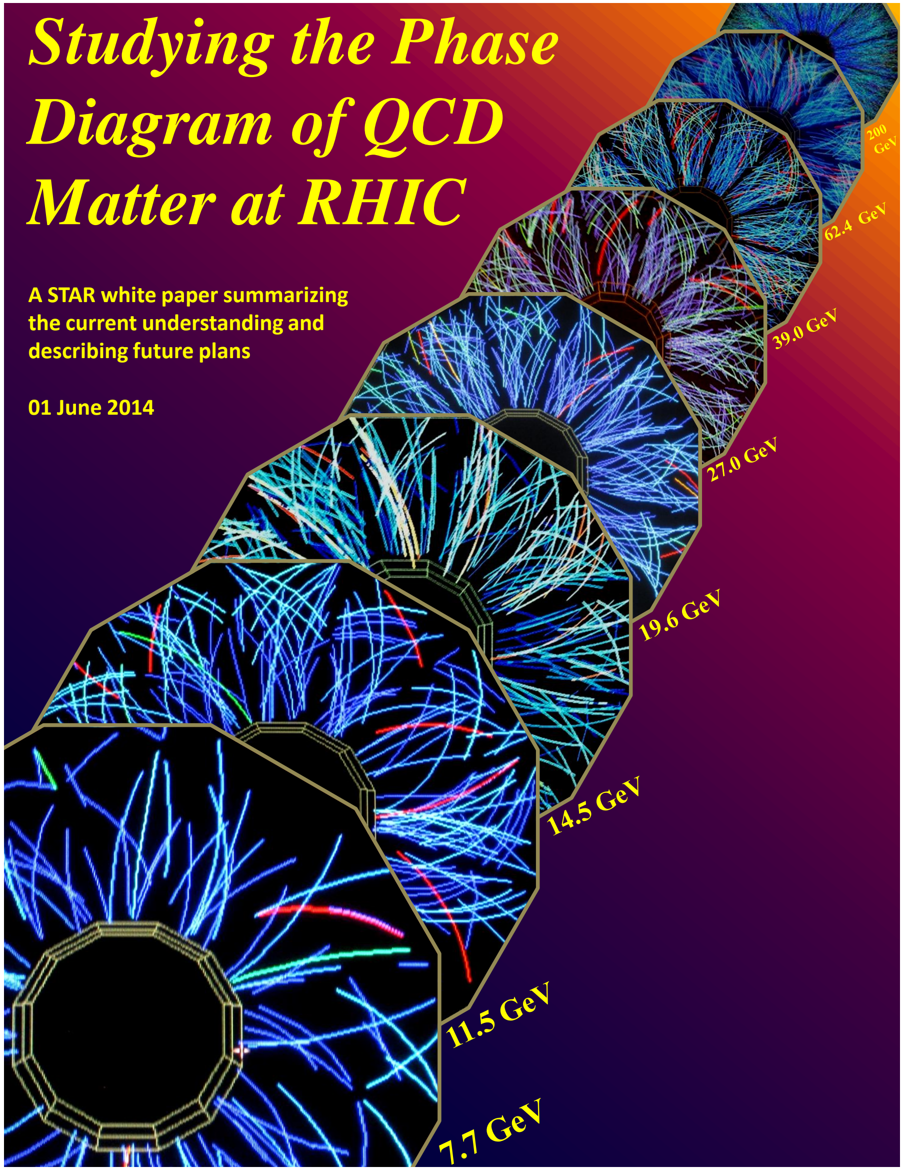
Perfect mid-y Collider Experiment

- large coverage: $1 < \eta < 1$ & 2π in azimuth
- uniform acceptance vs $\sqrt{s_{NN}}$
- excellent particle identification
- fast DAQ

Identified Particle Acceptance at STAR



At collider geometry - similar acceptance for all particles and energies a year ago:



http://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Contents

(some of) observables

- disappearance of QGP signatures (partonic vs. hadronic dof) :
  - R_{cp} (R_{AA}) – nuclear modification factor
  - NCQ scaling, v_2
  - charge separation

- 1st order phase transition:
  - directed flow v_1
  - azimuthally sensitive HBT

- critical point:
  - fluctuations

- chiral symmetry restoration (?) -> spectral function change
  - di-lepton production

http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493, *arXiv:1007.2613*
http://drupal.star.bnl.gov/STAR/starnotes/public/sn0598, *BES II White Paper, 2014*

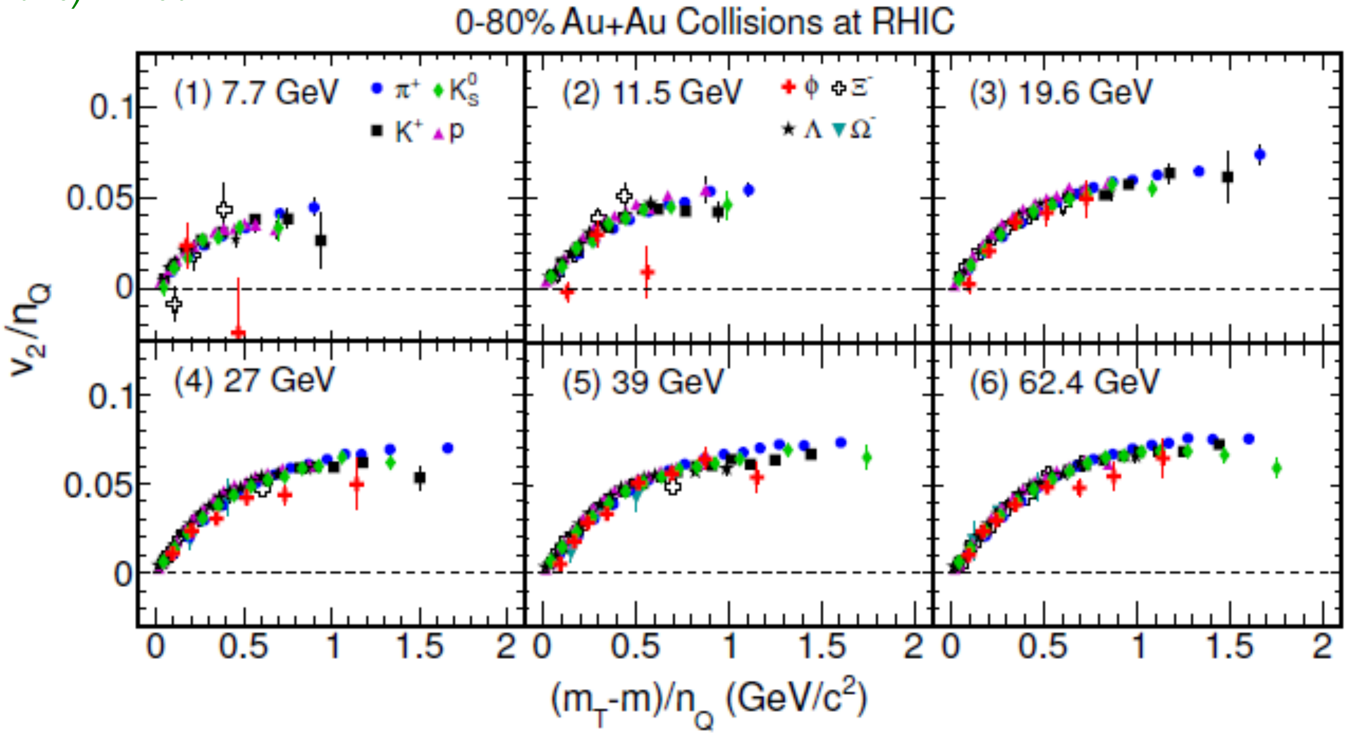
the easiest one …

disappearance of signals of partonic degrees of freedom seen at 200 GeV

do QGP signatures (v_2, R_{cp}, …) turn-off ?

Number of Constituent Quark scaling of v_2

PRL 110 (2013) 142301

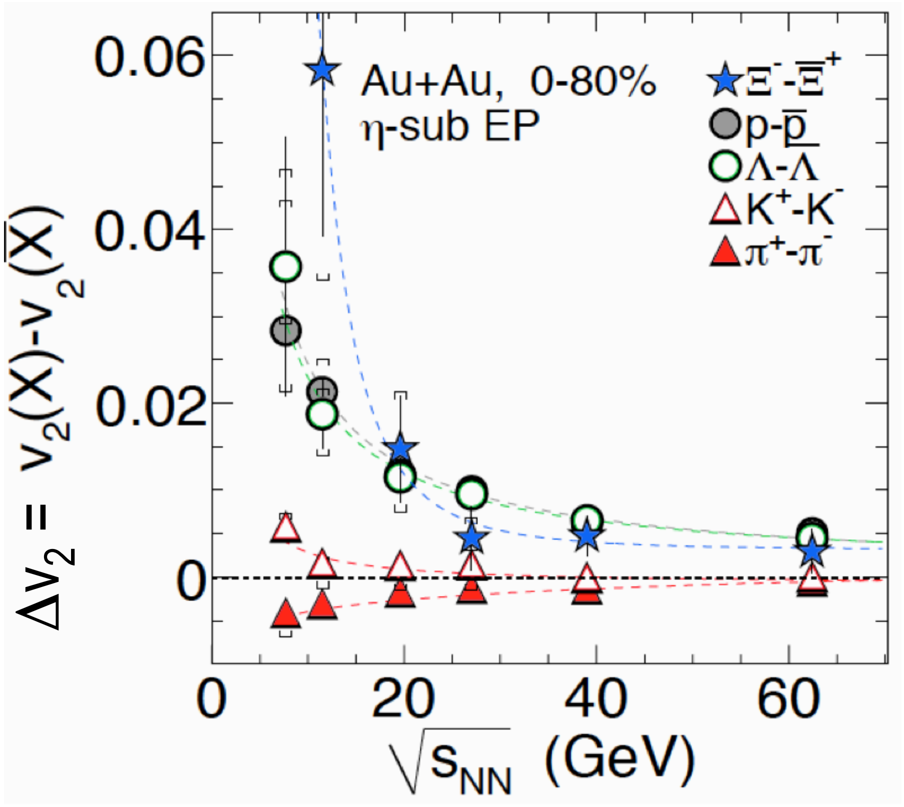


- NCQ scaling holds for particles and anti-particles separately at all energies -> possibly an indicator of partonic dof -> deconfinement in high energy
- ϕ meson may not follow the trends (11.5 and 7.7 GeV) ?

ϕ is key for differentiating hadronic and partonic flow but has large errors ⟶

need for more statistics at 7.7 and 11.5 GeV (more p_t reach)

$\Delta v_2 = v_2$(particle)-v_2(***anti***particle)



remarkable difference between particle and antiparticle is observed

-> break down of NCQ scaling between particles and *anti*particles at lower energies

-> consistent with hadronic interactions becoming dominant

-> indication for a phase transition ?

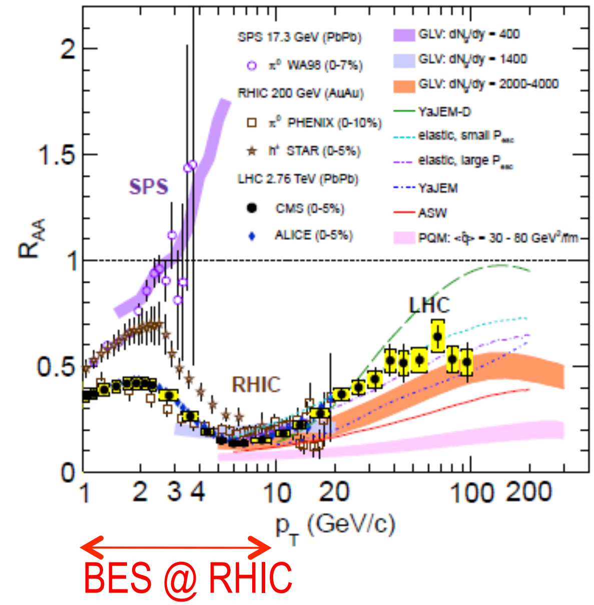
$\Delta v_{2:}$

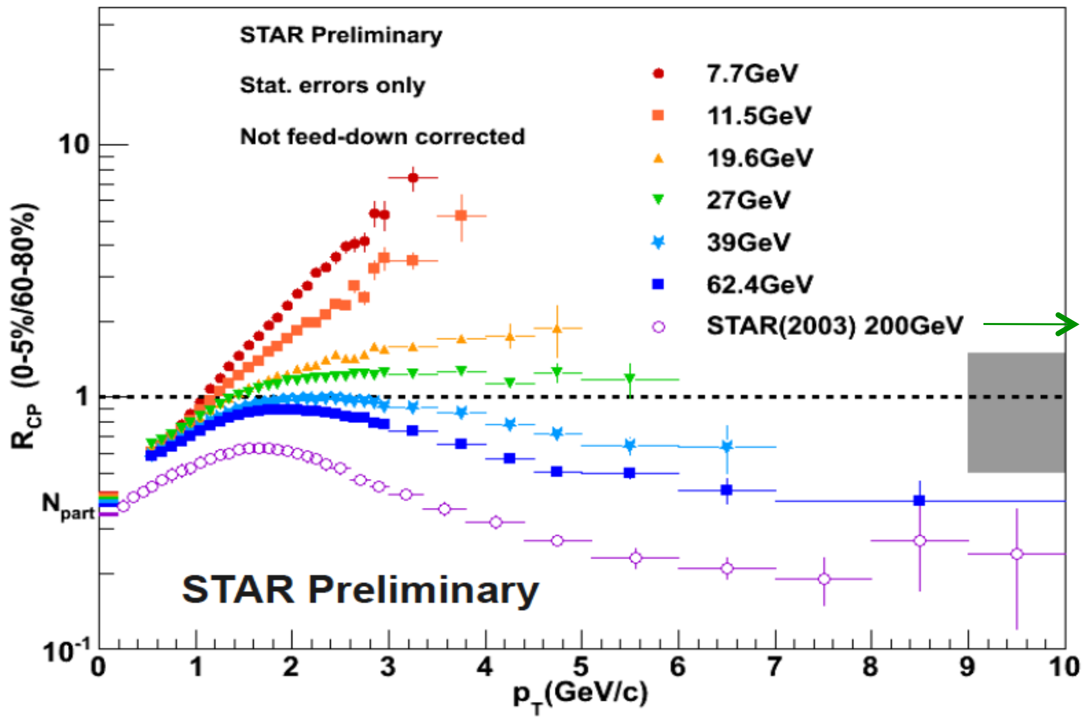
- is larger for baryons than for mesons
- nonlinear increase with decrease of $\sqrt{s_{NN}}$

Charged hadrons R_{cp}

measure of partonic energy loss in medium :

$$\mathbf{R_{CP}} = \frac{d^2Ndp_T d\eta / \langle N_{bin} \rangle (central)}{d^2Ndp_T d\eta / \langle N_{bin} \rangle (peripheral)}$$



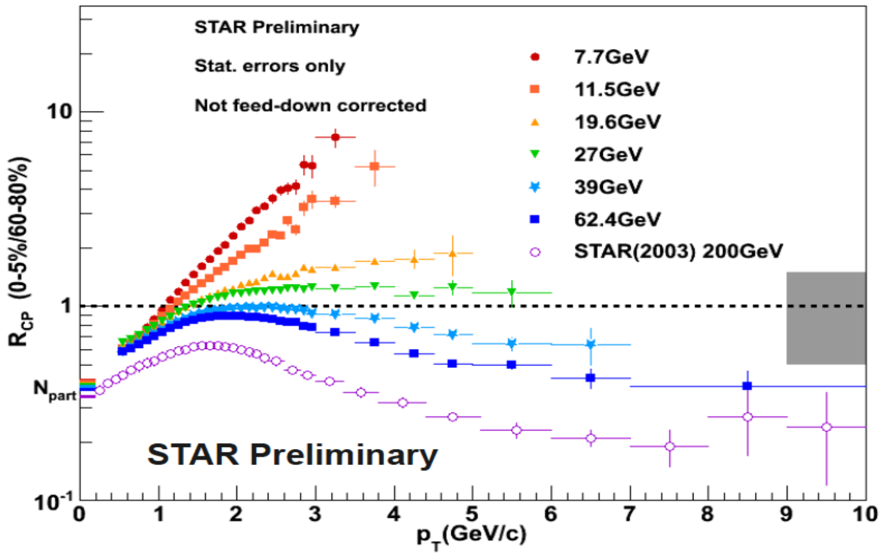


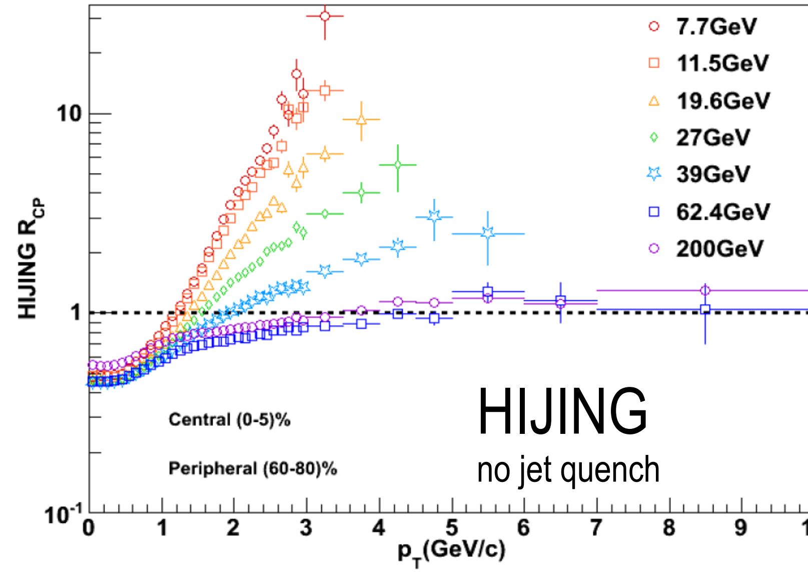
J.Adams et al., (STAR coll.) PRL 91, 172302 (2003)

- High p_t suppression seen at 39, 62.5 and 200 GeV
- Signature "turn-off" between 27 and 39 GeV

But insufficient reach to search for evidence of high p_t suppression below 19.5 GeV

BES: R_{cp} for charged and identified particles



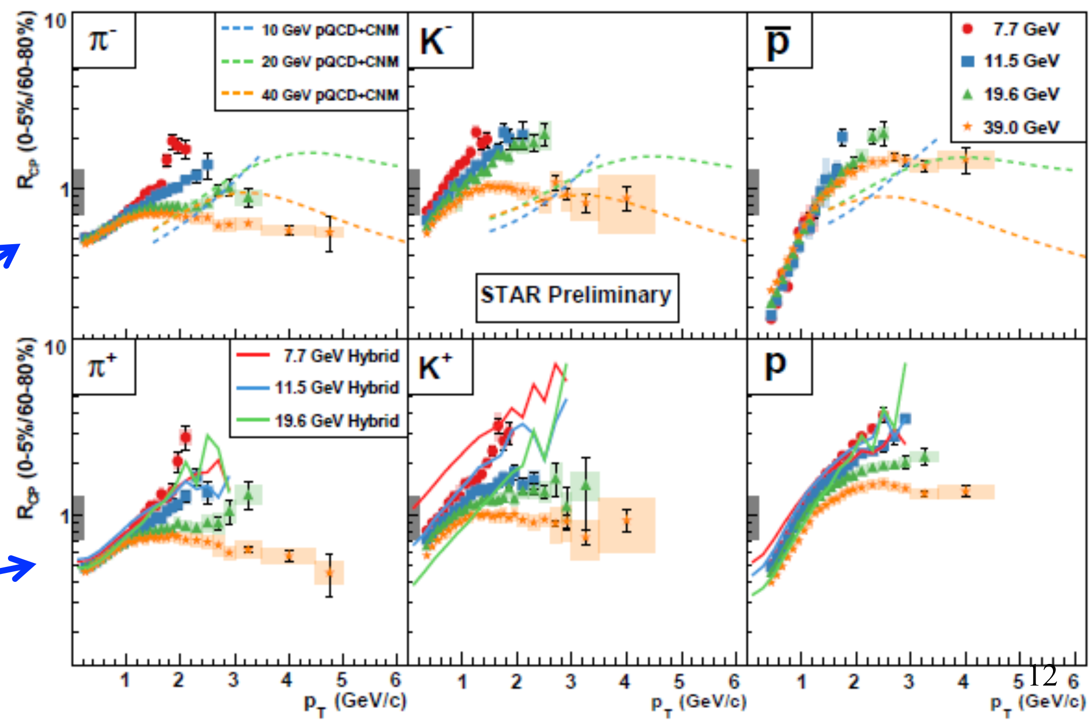


HIJING without jet quenching but with Cronin effect (though k_T broadening) resembles $\sqrt{s_{NN}}$ dependence at low energies

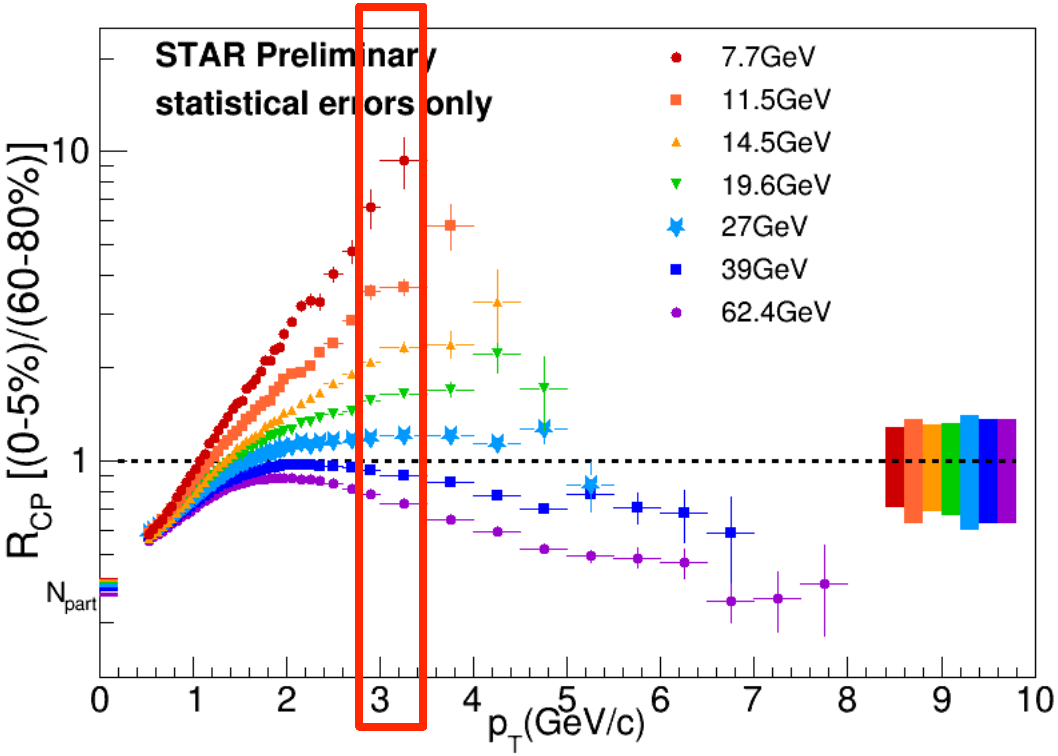
pQCD calculations show high p_t suppression

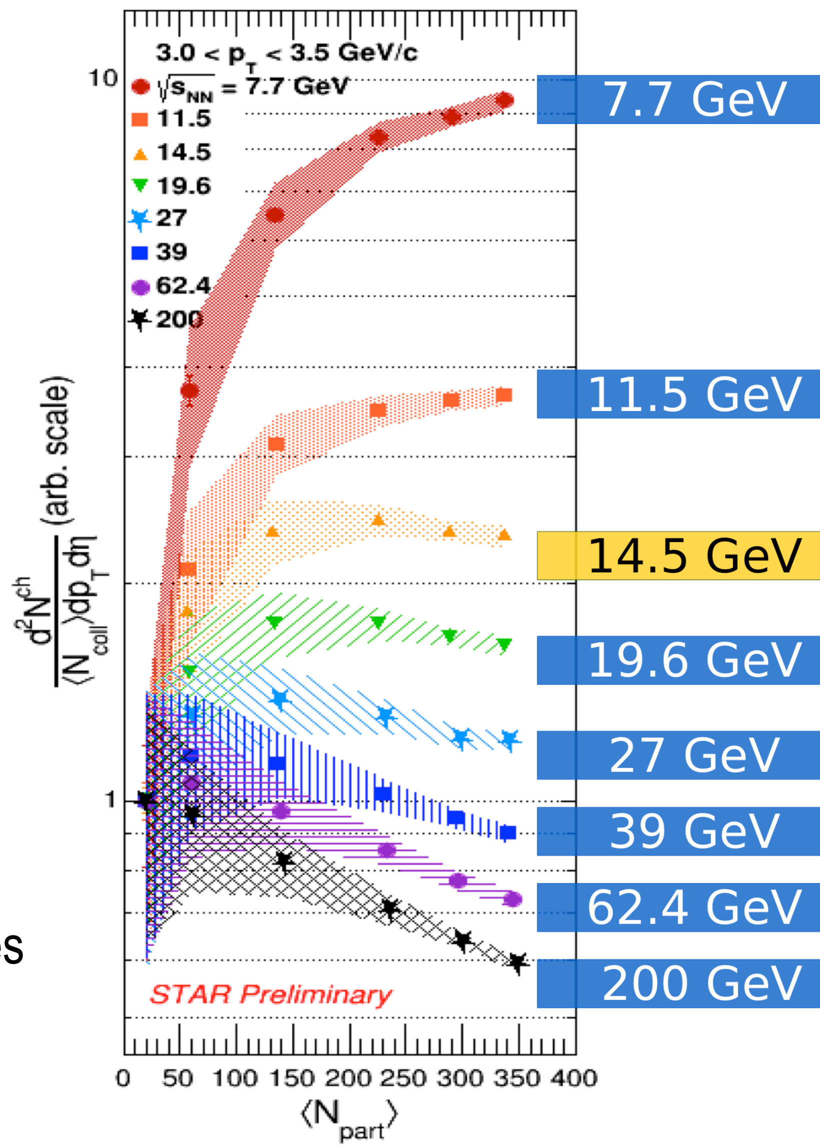
Hybrid model calculations describe low p_t behavior

high statistics, more p_t reach needed



Since QM 2015, Kobe - Update:





- Smooth transition from strong suppression at high energies to enhancement at lower beam energies
- Cronin effect may play a bigger role at lower energies
- Yields per binary collision show a balance of enhancement and suppression at $\sqrt{s_{NN}}$ = 14.5 GeV

Lesson learned …

These observations:

- baryon/meson grouping for *anti*particles starts to collapse at 11.5 GeV
- break down of N_q scaling between particles and *anti*particles
- disappearance of high p_t suppression
- R_{cp} shows smooth transition from suppression at high energies to enhancement at lower beam energies
- local parity violation decreases with decrease of $\sqrt{s_{NN}}$
- disappearance of charge separation
- …

indicate that hadronic interactions become dominant at lower beam energies

the most anticipated …

Critical Point

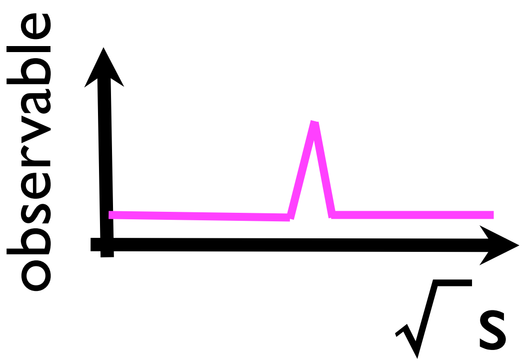
CP: Why fluctuations and correlations ?

Theory:

System at the QCD critical point region is expected to show a sharp increase in the correlation length, thus <u>large non-statistical fluctuations</u>

⟶ search for increase (/discontinuities) in fluctuations and correlations as function of $\sqrt{s_{NN}}$

Fluctuations <u>maximized</u> at Critical Point



Higher moments: net-protons

$$\sigma^2 = \langle (N - \langle N \rangle)^2 \rangle$$
$$S = \langle (N - \langle N \rangle)^3 \rangle / \sigma^3$$
$$\kappa = \langle (N - \langle N \rangle)^4 \rangle / \sigma^4 - 3$$

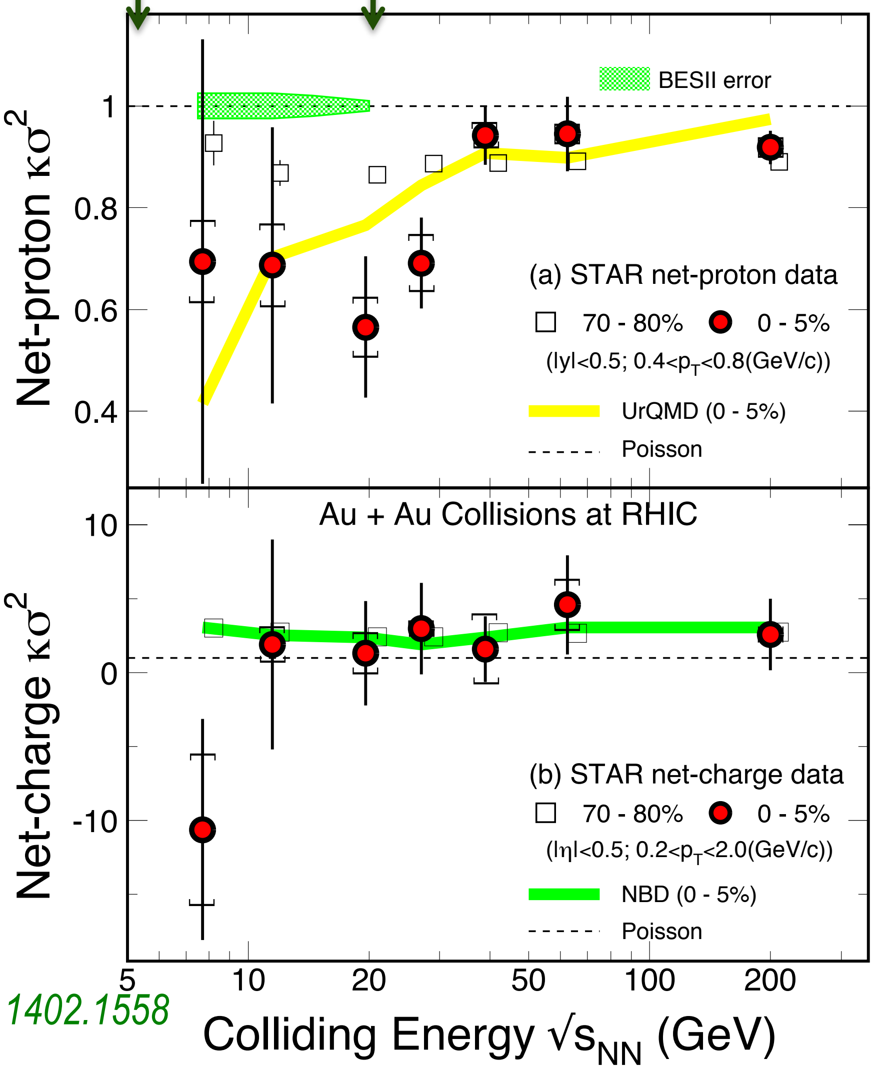
- higher moments of conserved quantities (B,Q,S) measure non-Gaussian nature of fluctuations and are more sensitive (than variance σ^2) to CP induced fluctuations (to correlation length)
- allows for direct comparison to theory – cumulants of conserved quantities proportional to susceptibilities
- products of the moments ($S\sigma$ & $\kappa\sigma^2$) are constructed to cancel volume effects

$$\left\langle (\delta N)^2 \right\rangle \approx \xi^2, \; \left\langle (\delta N)^3 \right\rangle \approx \xi^{4.5}, \; \left\langle (\delta N)^4 \right\rangle \approx \xi^7$$

$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

Higher moments of net-proton and net-charge distributions

*STAR: **PRL112**, 32302(14), arXiv: 1309.5681*



arXiv: 1402.1558

net-proton (proxy for net-baryon)

- no significant evidence of critical fluctuations, but possible structure around 19.6 GeV
- UrQMD model shows monotonic behavior in the moment products

net-charge

- no non-monotonic behavior
- affected by the resonance decays

BES-II

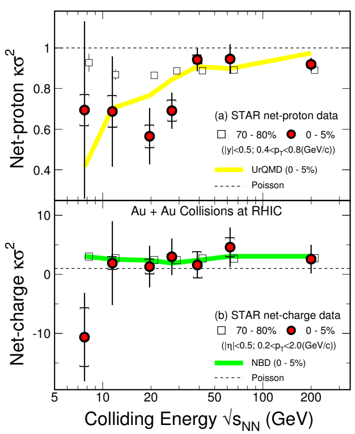
- higher statistics and better control of systematic needed for collisions at $\sqrt{s_{NN}}$ < 20 GeV

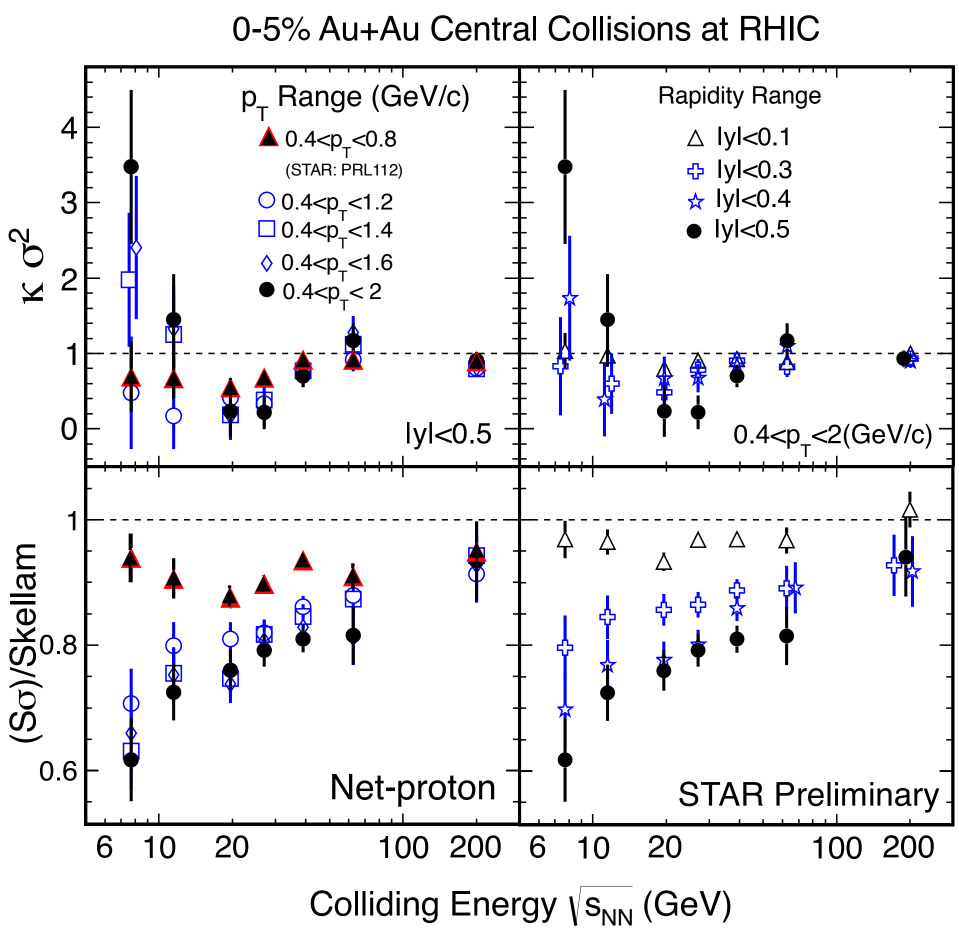
but acceptance is small …

Extended phase space coverage to due to TOF

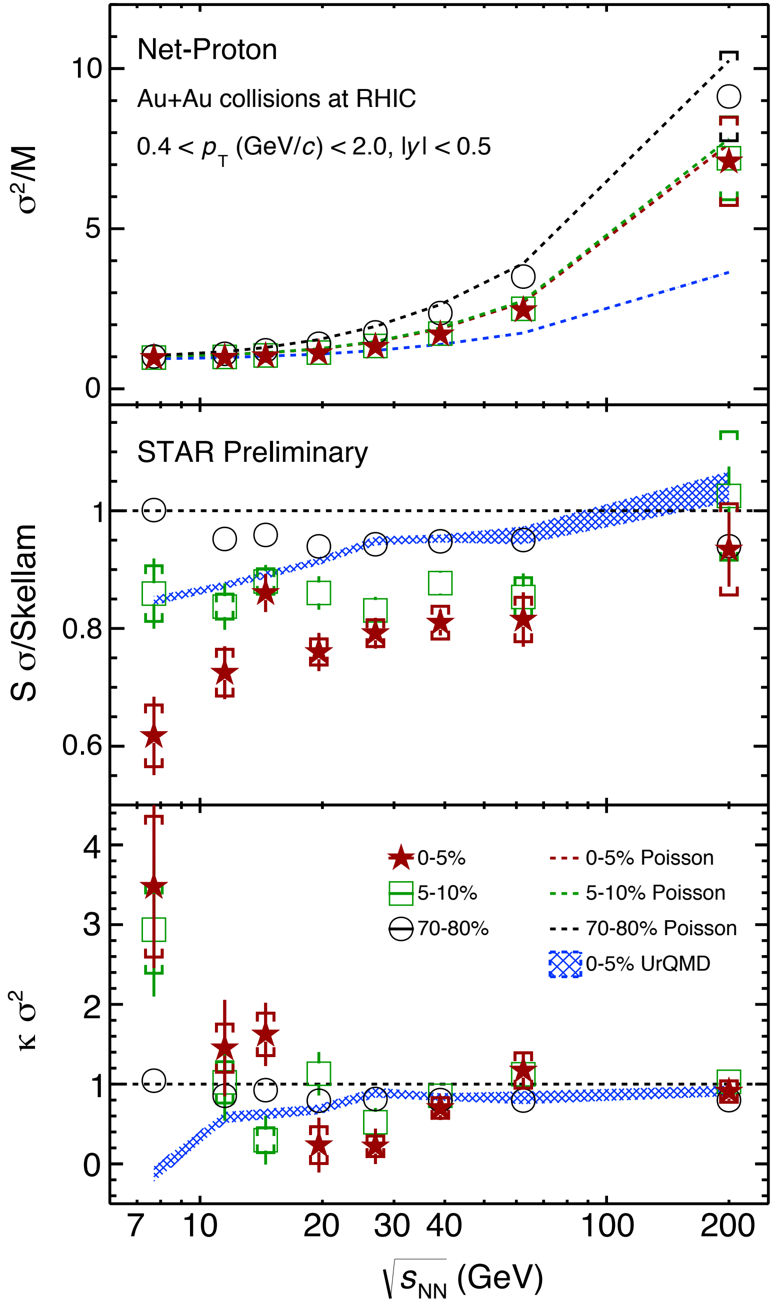
from p_t (0.4-0.8) to (0.4 – 2 GeV)

X.Luo arXiv:1503.02558





Phase space coverage is <u>crucial</u> for fluctuation analysis



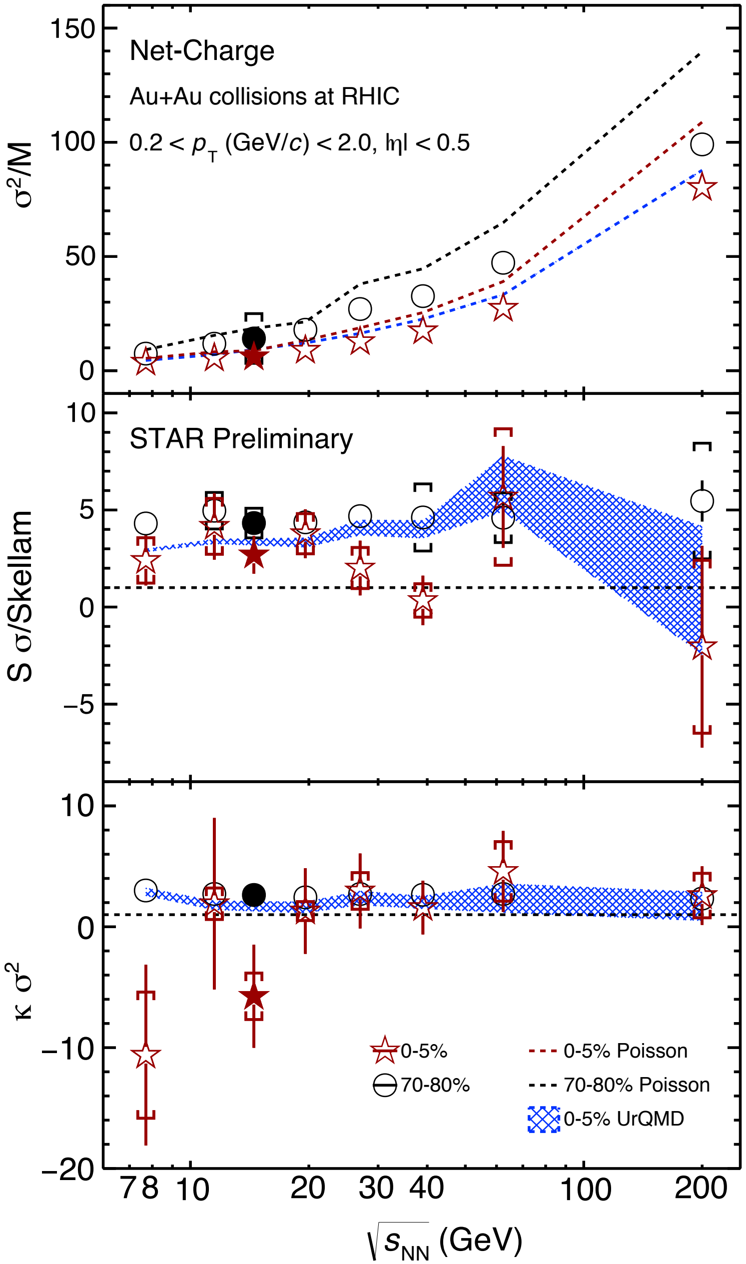
Net-proton cumulant ratio collision energy dependence

σ^2/M and Sσ/Skellam increase with energy

Non-monotonic behavior of net-proton $K\sigma^2$ seen for most central collisions (0-5%)

- 5-10% central coll. in between however, smooth trend in centrality
- peripheral coll. show smooth trend
- extensive studies still in progress

UrQMD (no CP) shows suppression at lower energies - due to baryon number conservation



Net-charge cumulant ratio collision energy dependence

14.5 GeV data-point added to published Phys.Rev.Lett. 113, 092301 (2014)
- fits well into trends

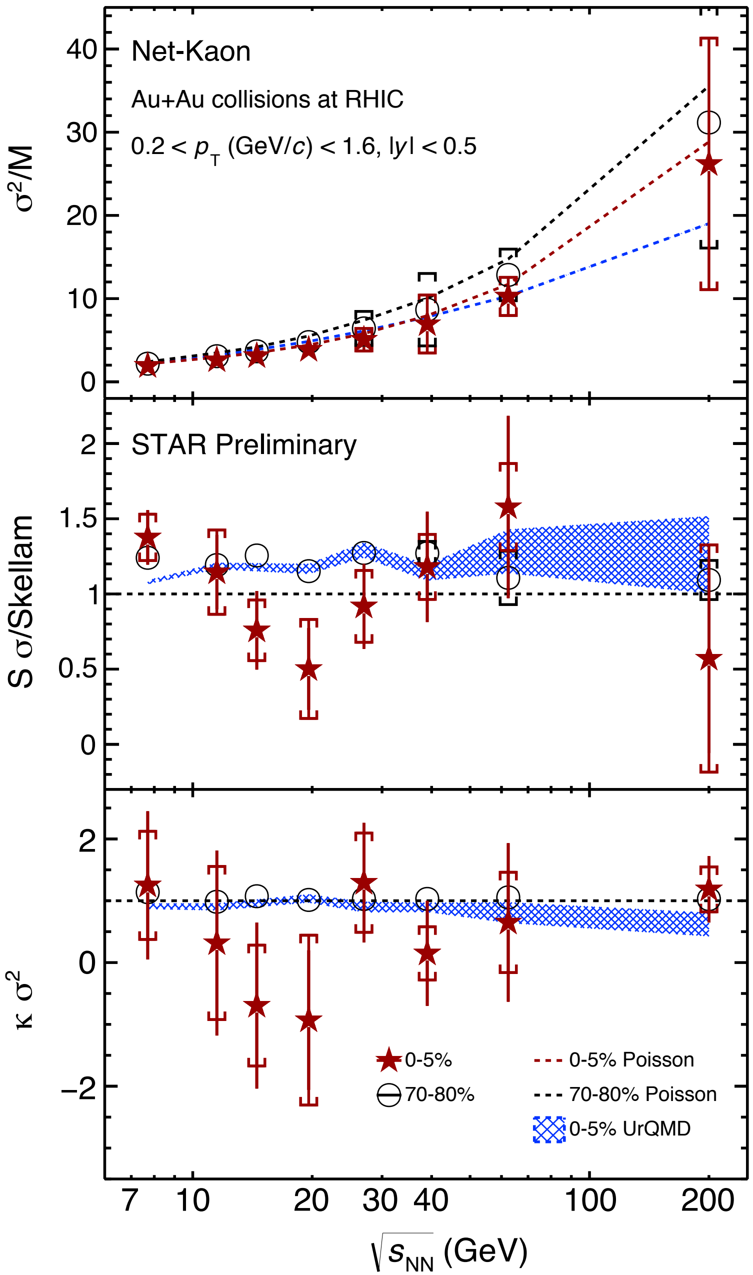
σ^2/M increases with increasing coll. energy

for most centrals (0-5%), $\kappa\sigma^2$ and Sσ/Skellam are consistent with unity

UrQMD (no CP) shows no energy dependence

QM 2015, Kobe: PHENIX showed net-charge cumulant ratios, smaller errors because much smaller acceptance <-> smaller number of particles, different method for corrections…

arXiv: 1506.07834



Net-kaon cumulant ratio collision energy dependence

σ^2/M increases with increasing coll. energy

σ^2/M and Sσ/Skellam are consistent with Poisson expectation for most central collisions

Kσ^2 is consistent with unity (= Poisson expectation) for most central collisions (0-5%)

UrQMD (no CP) shows no energy dependence

Lesson learned …

These observations:

- non-motonic behavior seen in net-proton $K\sigma^2$

- new results at 14.5 GeV for net-protons, net-charge and net- kaon

- studies of pseudo-rapidity and p_t depebndance shows that acceptance is crucial for the critical point search

RHIC BES II will bring larger event sample and larger phase space to boost critical point search

search for

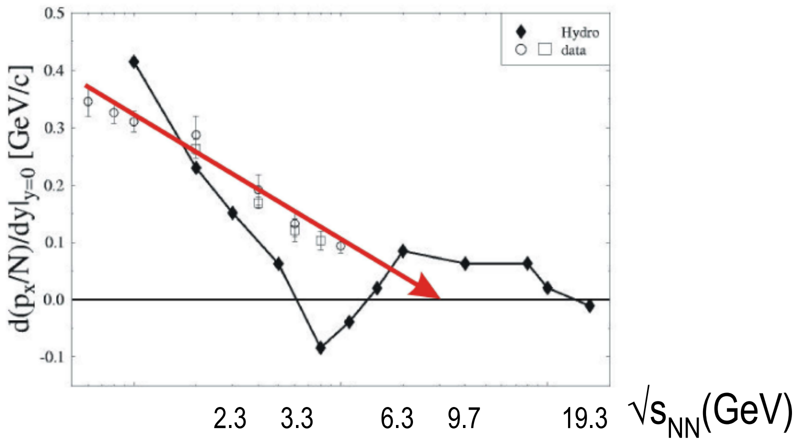
1^{st} order phase transition

can we demonstrate the softening of EOS ?

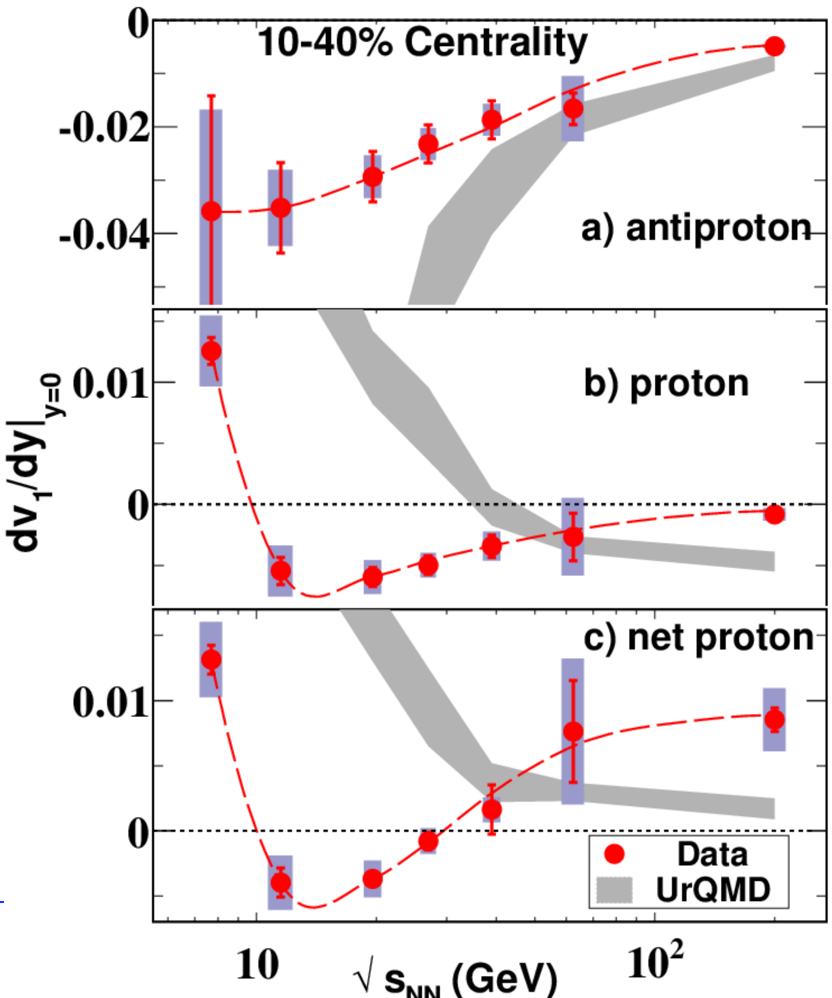
Directed flow (v_1) of identified particles

v_1 probes early stage of collision, sensitive to compression, should be sensitive to 1st order phase transition; change of sign in the slope of dv_1/dy for protons has been proposed to be a probe to the softening of EOS and/or the first-order phase transition …

H.Stocker, NP A750, 121 (2005)



PRL 112, 162301 (2014)



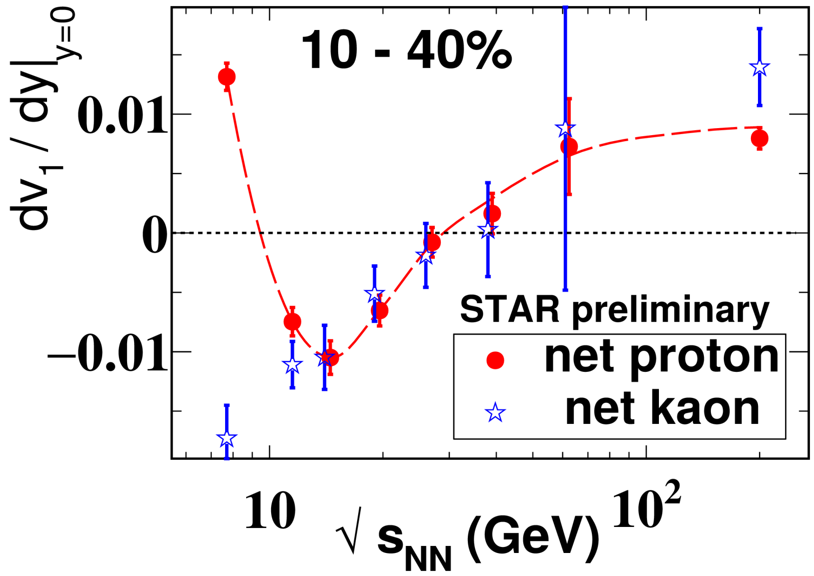
- Net-proton v_1 slope at midrapidity changes sign twice between $\sqrt{s_{NN}}$ = 7.7 - 11.5 GeV
- EOS softest point ? (1st order phase transition ?)

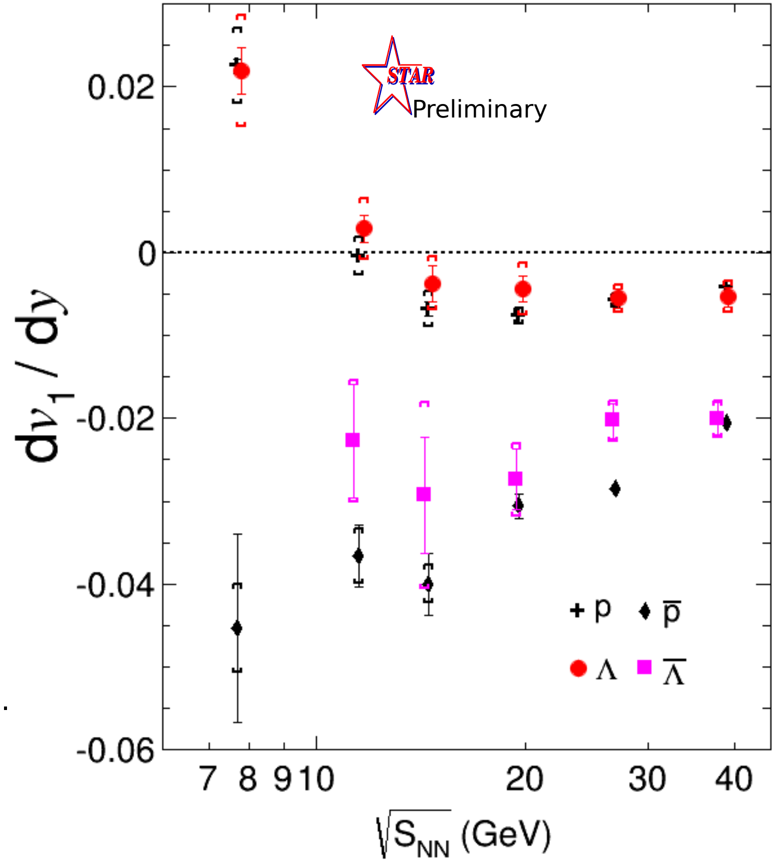
but: - dip at different position than model

- error bars for other particles and different centralities are large – more statistics needed and better RP resolution needed

Model calculations yet to reproduce the observation

Search for phase transition: directed flow





- Dip in $dv_1/dy|_{y=0}$ is argued to indicate an interplay between hydro and transport dynamics (+ baryon/ anti-baryon annihilation)
- Λ/anti-Λ dv_1/dy closely follow those of p/anti-p
- dv_1/dy for net-kaons and net-protons are consistent with each other down to ~ 14.5 GeV, and deviate at lower energies

Observables tied to

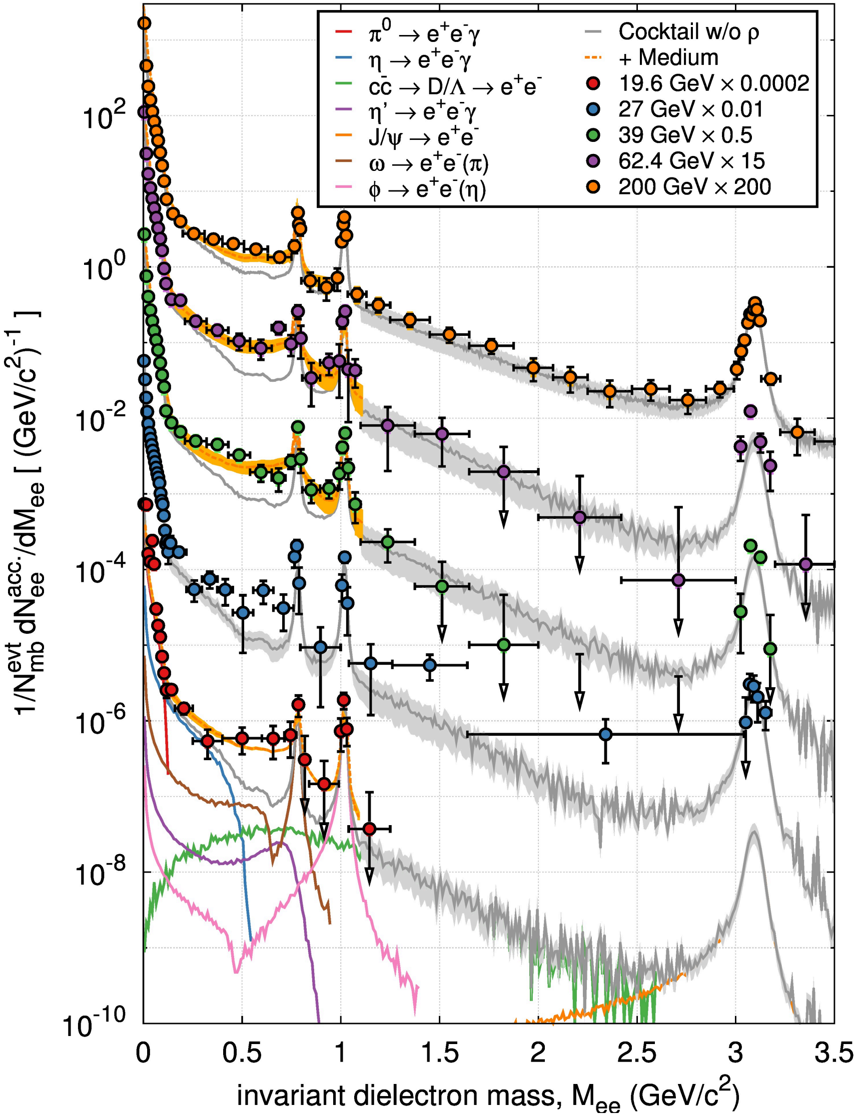
Chiral symmetry restoration

–

chiral phase transition

Di-electron spectra

STAR (200 GeV data): arXiv: 1312.7397, sub. To PRL



- bulk penetrating probes
- agreement with model with in-medium broadened ρ over the whole mass range for all energies

R.Rapp: PoS CPOD13, 008 (2013)
Adv. Nucl. Phys. 25,1 (2000)

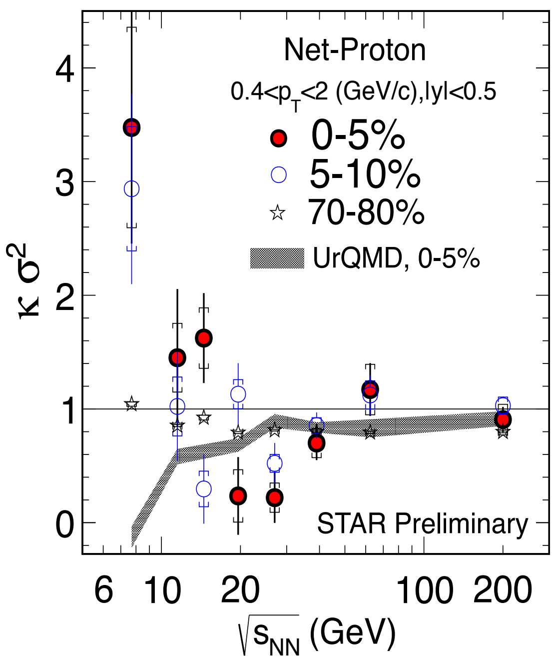
but
charm cross section not known at lower energies
lower energies needed (baryon density larger)

relation to chiral symmetry restoration ?

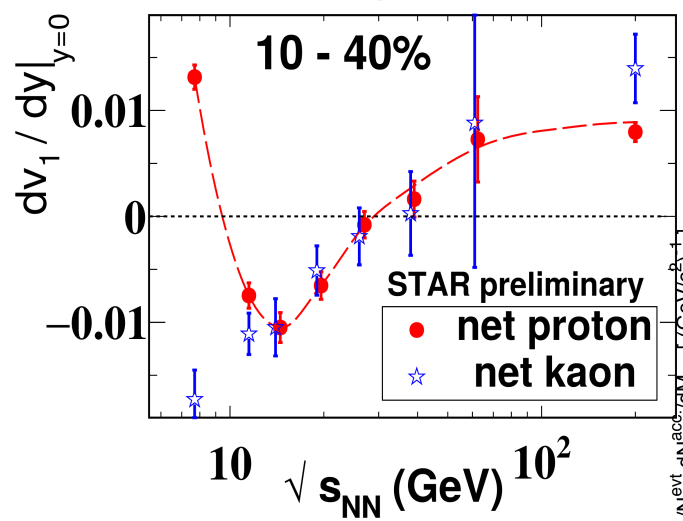
Need BES II with high statistics

among others …

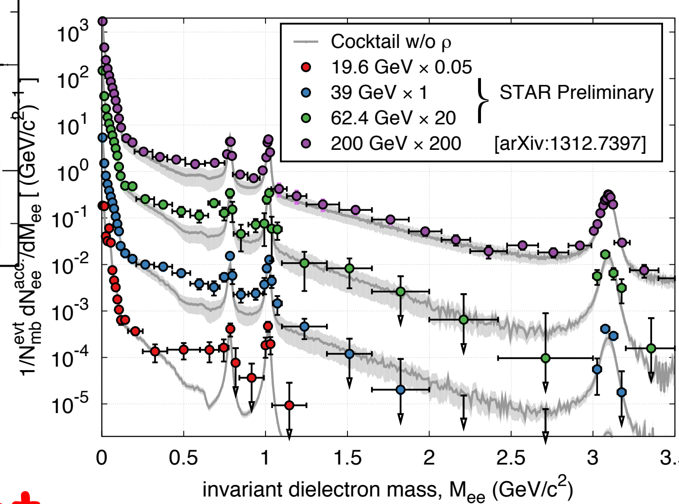
$\kappa\sigma^2$



v_1

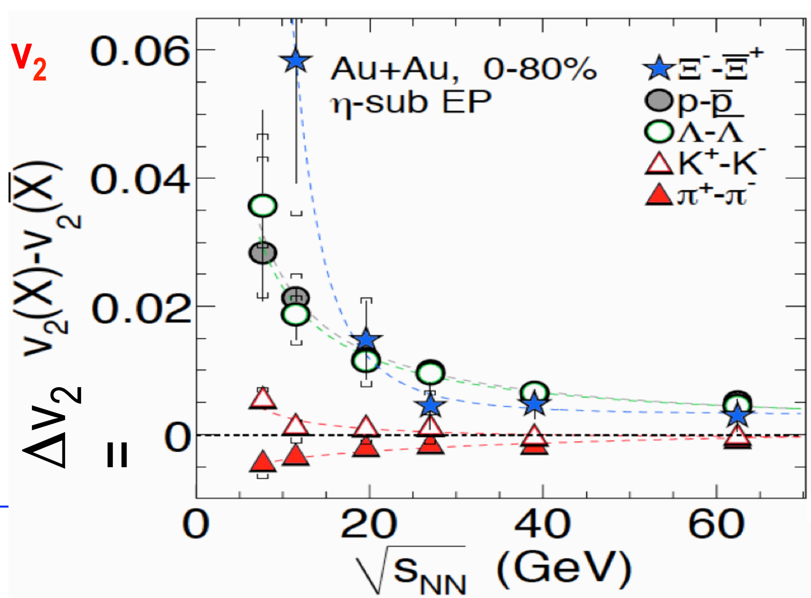


di-e^-

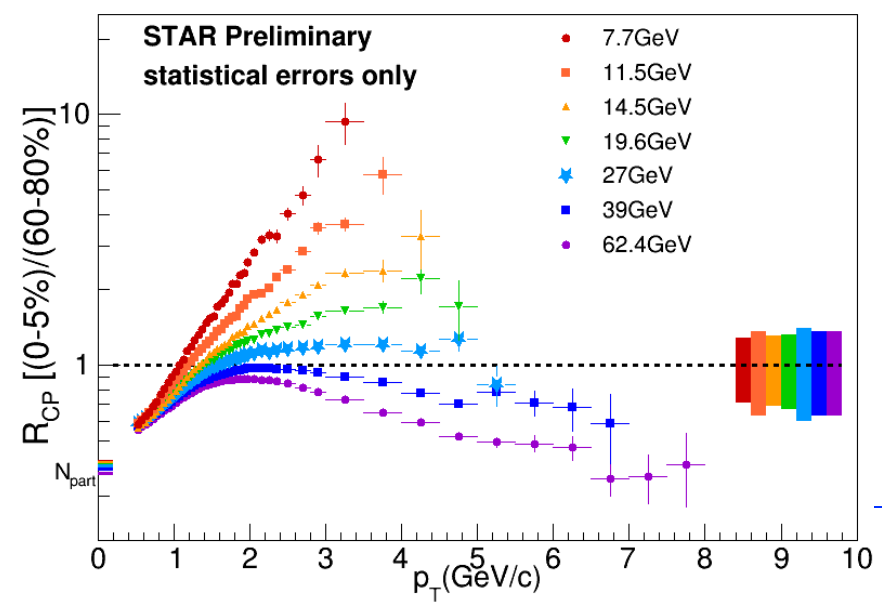


interesting hints
- no conclusions yet

v_2



R_{cp}



What have we learned from BES Phase-I

STAR and RHIC excellent performance down to 7.7 GeV

BES at RHIC fully spans the most promising energy range of the QCD phase diagram

Several signatures demonstrate the dominance of parton regime at the BES high energies, these signatures either disappear, lose significance, or lose sufficient reach in the low energy region of the scan

- *but hard probes become less accessible at lowest collision energies*
- *"turn-off" of hard signature does not imply the absence of deconfinement*

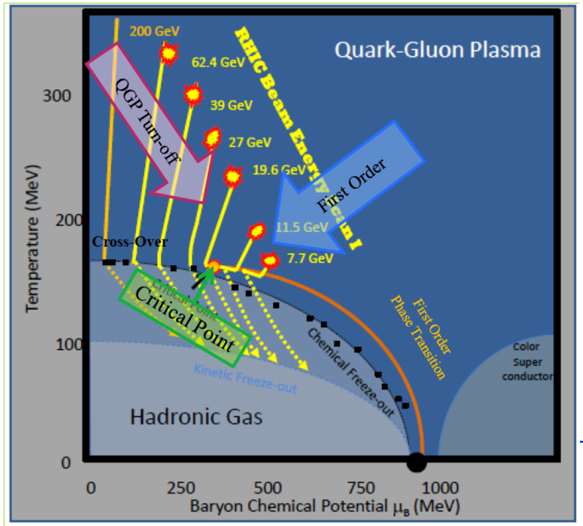
Indication of a softening of EOS around 11.5-19.6 GeV could be indicative of a 1st order phase transition

Suggestive signs of critical fluctuations (?) would present compelling evidence, but these are highly statistics hungry analyses ($\rightarrow$ BES II: larger statistics and smaller steps in μ_B)

Dileptons offer a unique way to study chiral symmetry restoration and QGP thermal radiation, but dileptons are rare and require high statistics data sets ($\rightarrow$ BES II).

from BES II WP Executive Summary:

- The first phase of the Beam Energy Scan program (BES-I) plus the top energy at RHIC has allowed access to a region of the QCD phase diagram covering a range of baryon chemical potential (μ_B) from 20 to 420 MeV corresponding to Au+Au collision energies from $\sqrt{s_{NN}}$ = 200 to 7.7 GeV, respectively. Results from BES-I have further confirmed the evidence for the quark-gluon plasma (QGP) discovery at the top RHIC energy $\sqrt{s_{NN}}$ = 200 GeV. The results of the search for the critical point and the first-order phase boundary have narrowed the region of interest to collision energies below $\sqrt{s_{NN}}$ = 20 GeV. Current lattice QCD calculations suggest that key features of the phase diagram like the critical point and the first-order phase transition lie within the μ_B reach of the RHIC BES Phase-II program.



We are not done yet !

BES Phase II

STAR BES Phase-II program with order of magnitude increase in data samples needs:

- electron cooling in RHIC HI beams to increase luminosity
- detector upgrades to increase reach in p_t and y, and improve PID
- concurrent fixed-target mode to extend μ_B reach to ~720 MeV

Goals of BES Phase II (2018 and 2019)

Quantitatively establish possible non-monotonic variation of net-proton $\kappa\sigma^2$ with beam energy – critical fluctuations via high moment analysis require extremely large event number

Consolidate findings of non-monotonic variation of proton and net-proton $v_1(y)$ slope around midrapidity

Primary QGP signatures (R_{cp}, NCQ scaling, ϕ v_2) require large number of high p_t particles to evaluate
- extend measurement of identified hadrons R_{cp} up to p_t ~ 5 GeV/c
- quantitatively address the absence of partonic collectivity below $\sqrt{s_{NN}}$ = 19.6 GeV, through measurement of v_2 of ϕ mesons
- consolidate the observation of turn-off of CME-like effect at lower energies

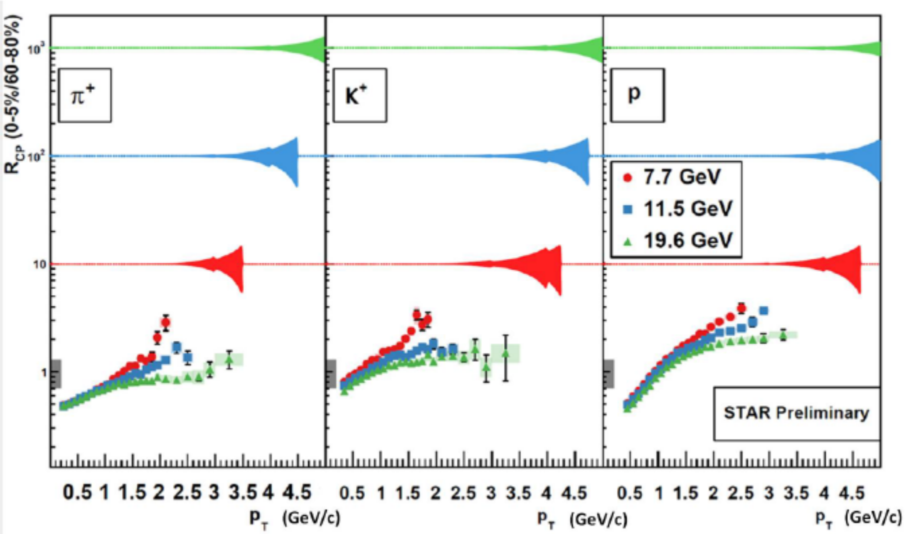
Systematic studies of dilepton production which offer a unique way to explore connections to chiral symmetry and thermal QGP radiation (but dilepton are rare and require high statistics)

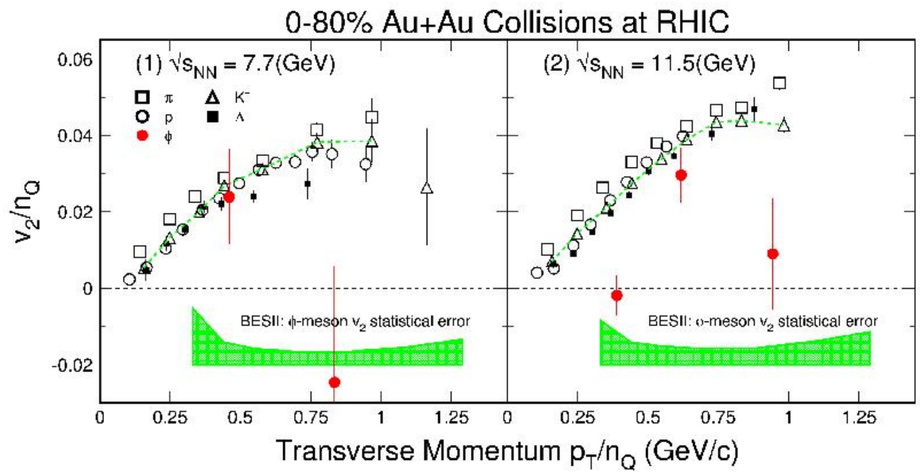
Higher statistics are needed to fully address the goals of BES

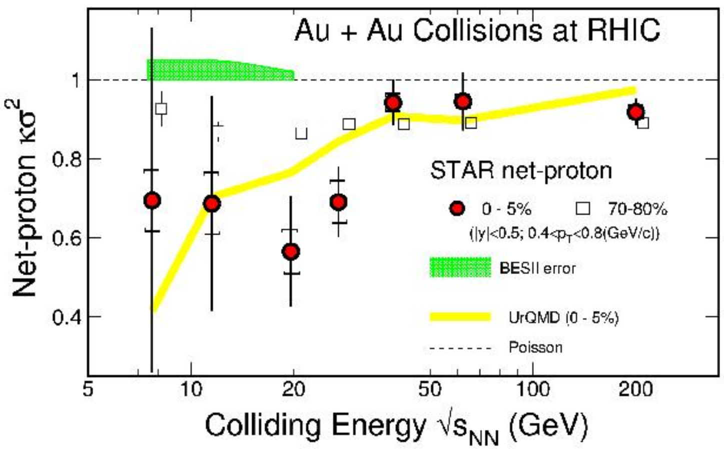
Statistics needed in BES phase II

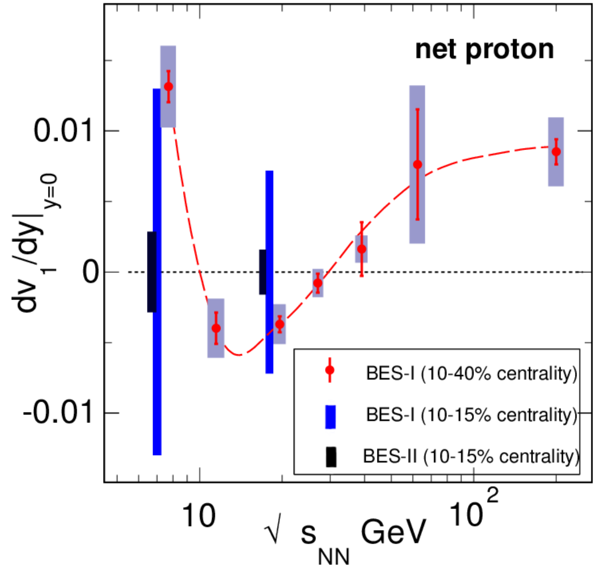
	Collision Energies (GeV):	**7.7**	**9.1**	**11.5**	**14.5**	**19.6**
	Chemical Potenial (MeV):	**420**	**370**	**315**	**260**	**205**
	Observables	Millions of Events Needed				
QGP	R_{CP} up to p_T 4.5 GeV	NA	NA	160	92	22
QGP	Elliptic Flow of ϕ meson (v_2)	100	150	200	300	400
QGP	Local Parity Violation (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**

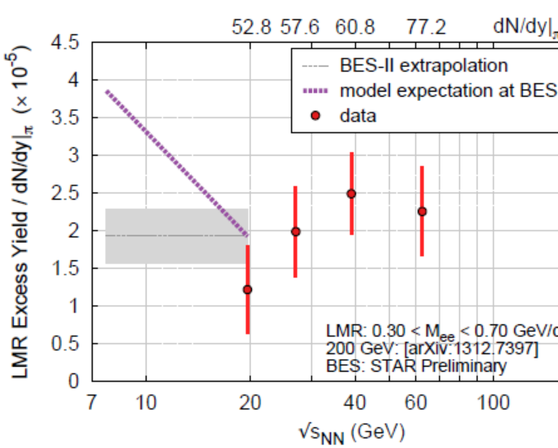
BES II measurement errors will be **SMALL**

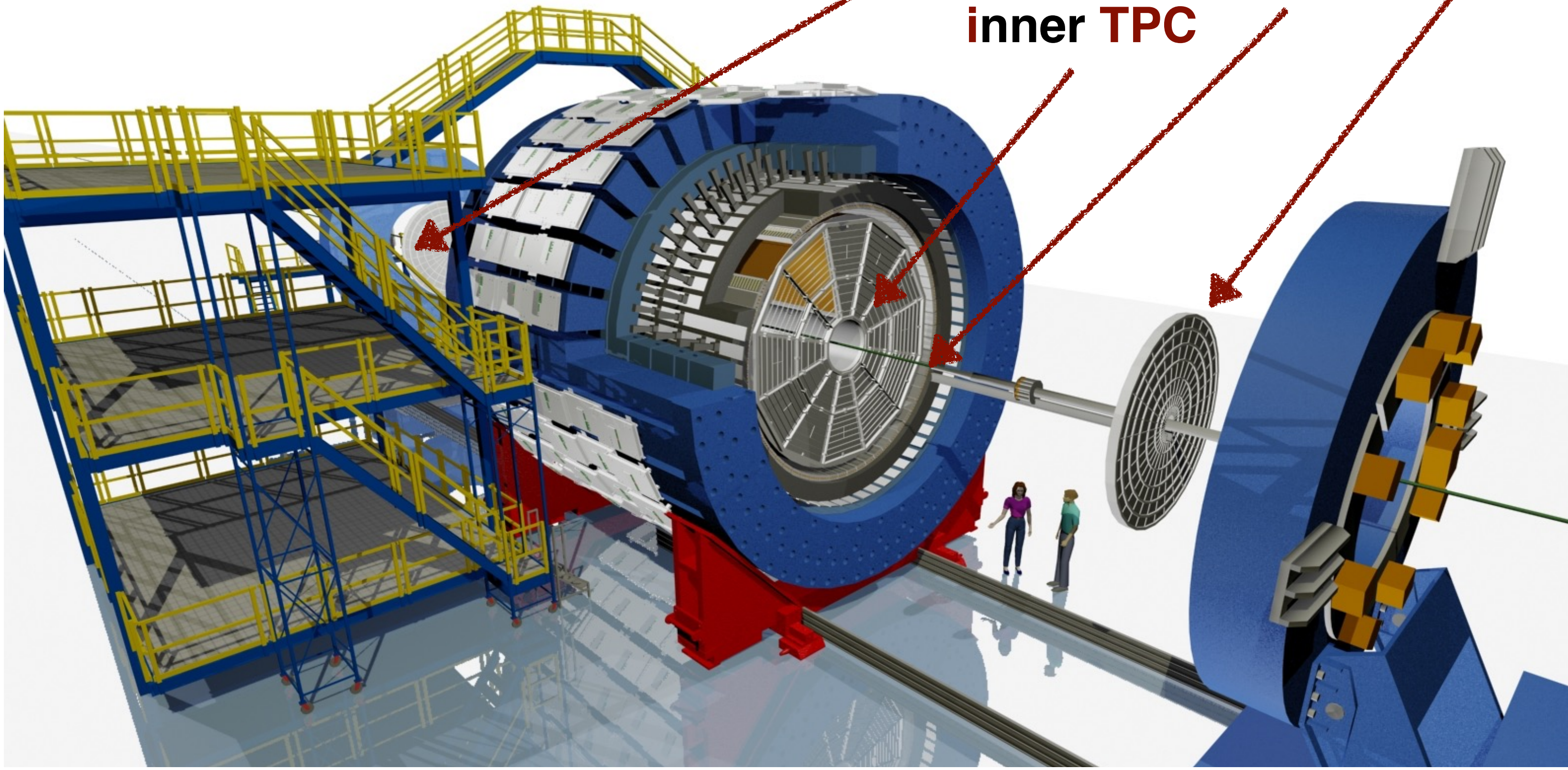










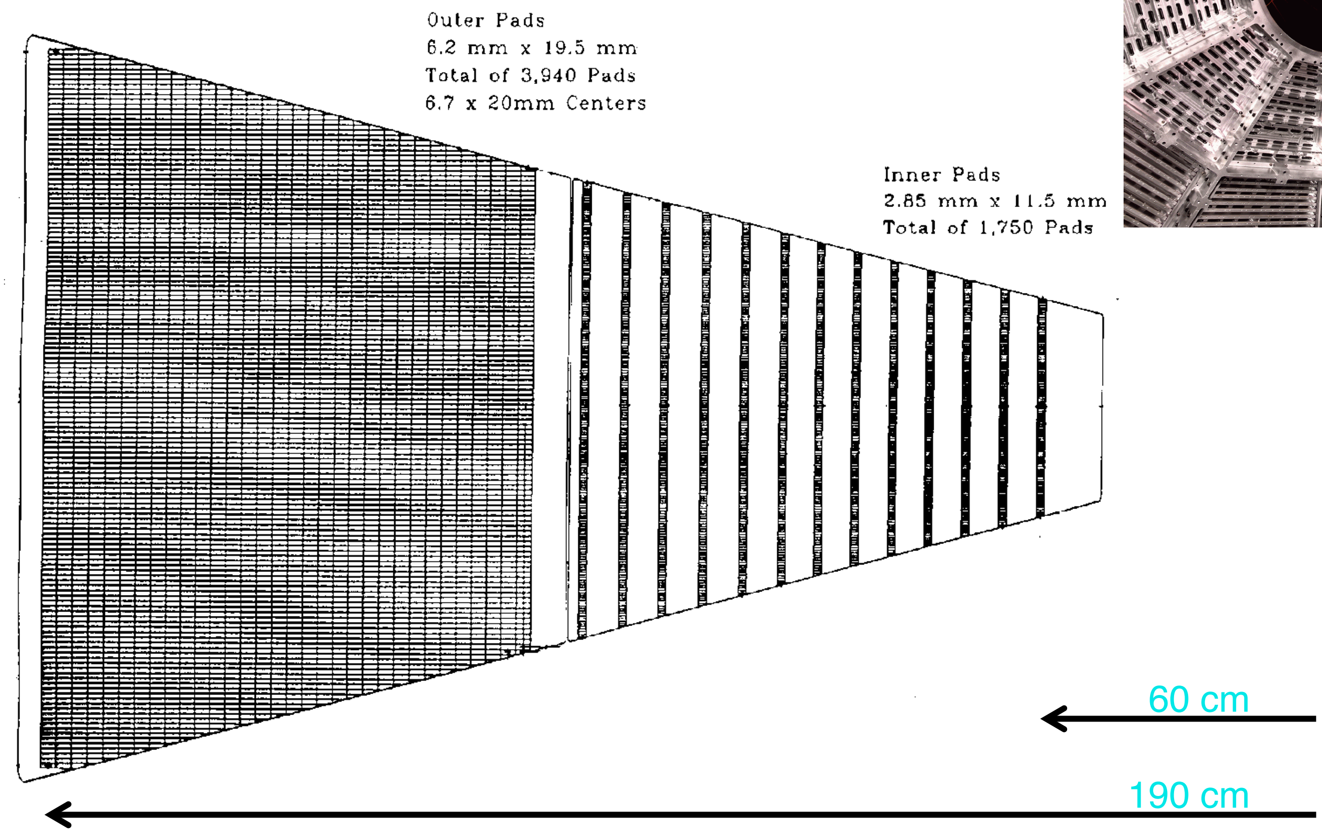


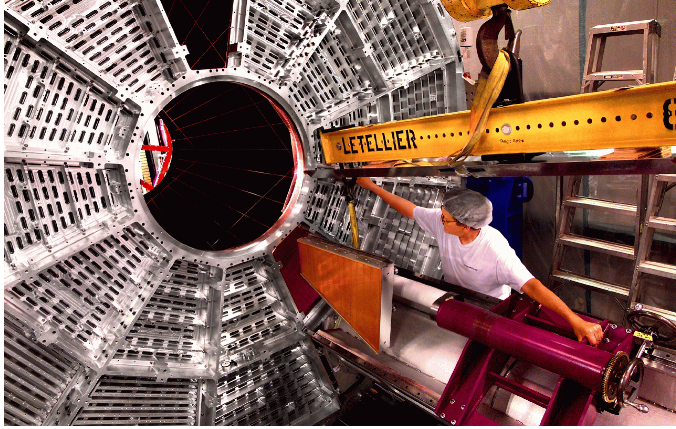
iTPC upgrade :
replace aging wires
full pad coverage
$-1.5<\eta<1.5$, p_t > 60 MeV/c
better dE/dx

EPD upgrade:
replaces aging BBC
event centrality
better trigger, bck reduction
$-4.5<\eta<-1.8$, $1.8<\eta<4.5$

eTOF upgrade:
PID in $1<\eta<1.5$
(together with iTPC)

iTPC Inner sectors upgrade





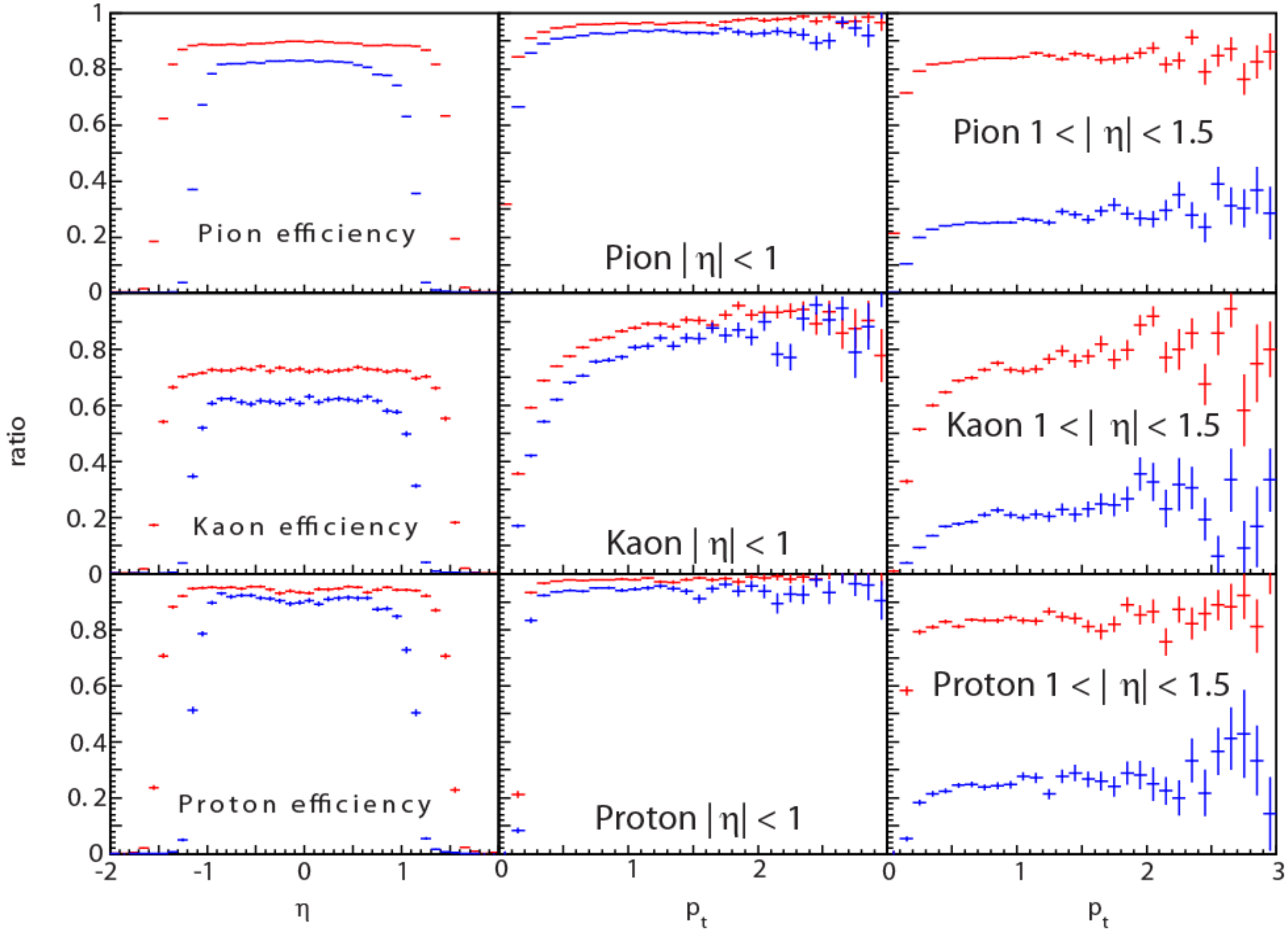
The outer pad plane is hermetic … while the inner pad plane is not

- Increase the segmentation on the inner pad plane!
- Renew the inner sector wires which are showing signs of aging

Better momentum resolution, better dE/dx resolution, and improved acceptance at high η

iTPC

iTPC upgrade - improved acceptance at high η

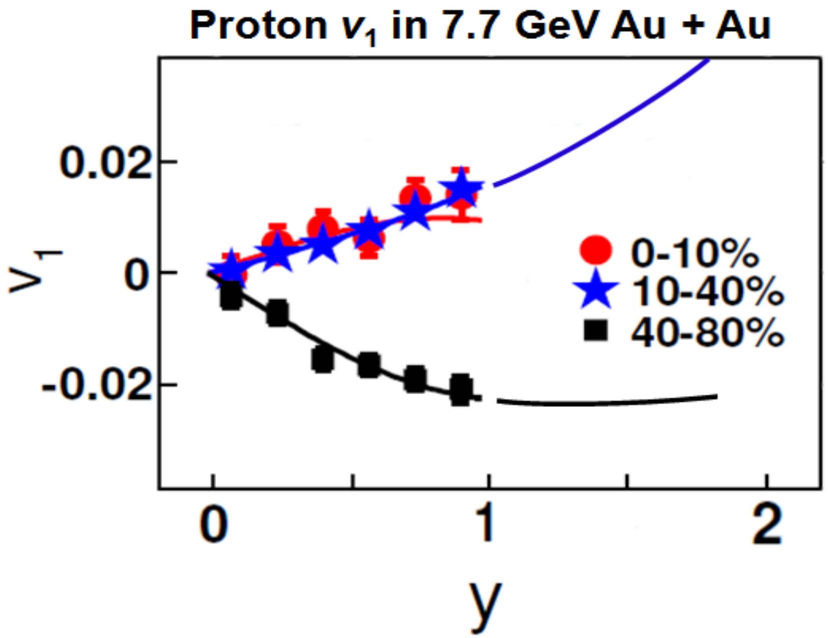


extended the meaningful acceptance from 1.0 to 1.5 units for all particles

iTPC

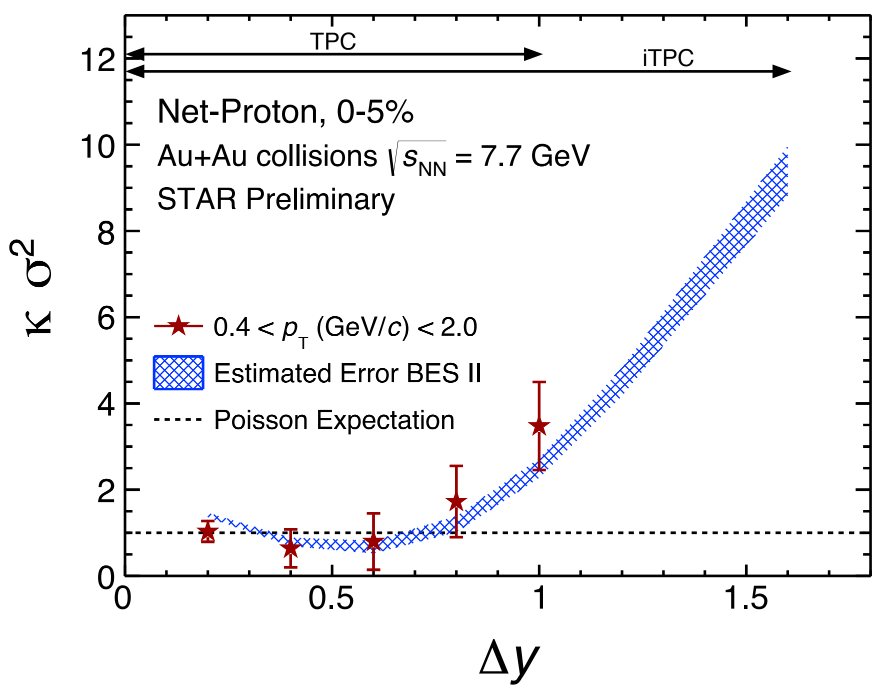
iTPC improvements ⇒ better physics

- Plan: Hermetic coverage; add pads & rows on the inner sectors
  - 2x increase of electronics channels
- Increase the useful rapidity coverage of the TPC
  - Full efficiency (flattop) goes from 1.0 to 1.5
  - limit at 1.6 with 15 hits/track, or 5 hits per track puts limit at 1.8
  - increase tracking efficiency by x10 for strange hadrons $p_T < 1$ GeV
- Improve dE/dx and tracking for high η tracks
  - Currently, only about 20% of a track crossing an inner sector is sampled
  - Obviously, add more points on every track improves dE/dx



Increase in magnitude of signal with larger rapidity range

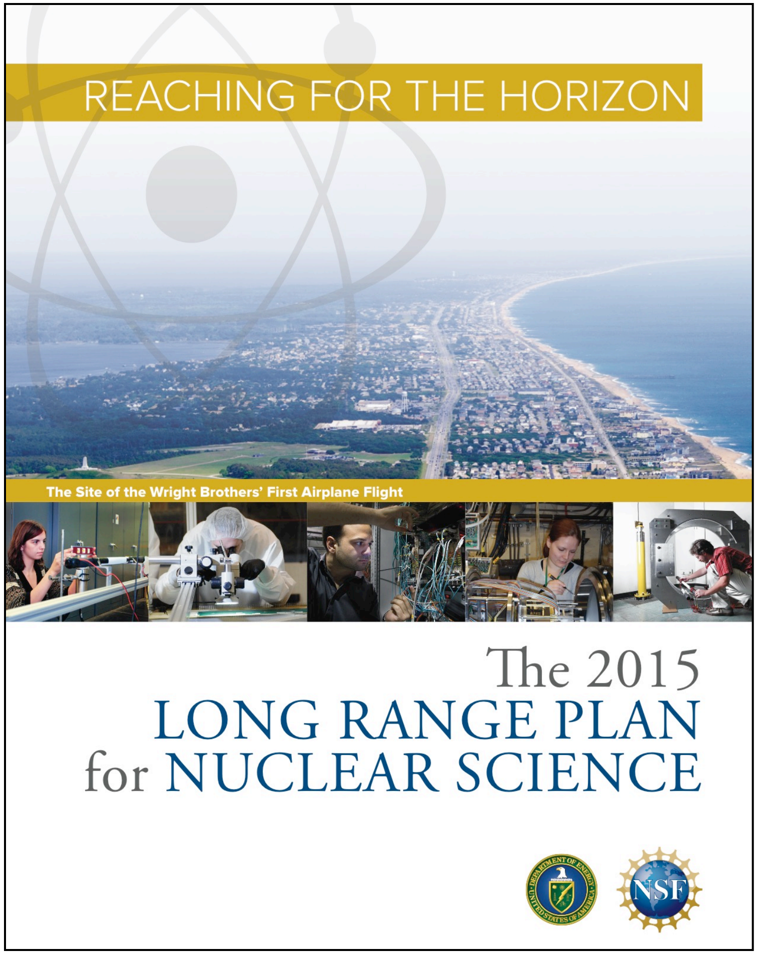
directed flow $v_1(y)$ for protons for Au + Au collisions at $\sqrt{s_{NN}}$ = 7.7 GeV
solid curves - cubic fit to measured data
these curves are extrapolated into iTPC rapidity region



$K\sigma^2$ analysis in increasing rapidity bins
For Au+Au at 7.7 GeV

→ rapid increase of signal

From LRP document 2015:



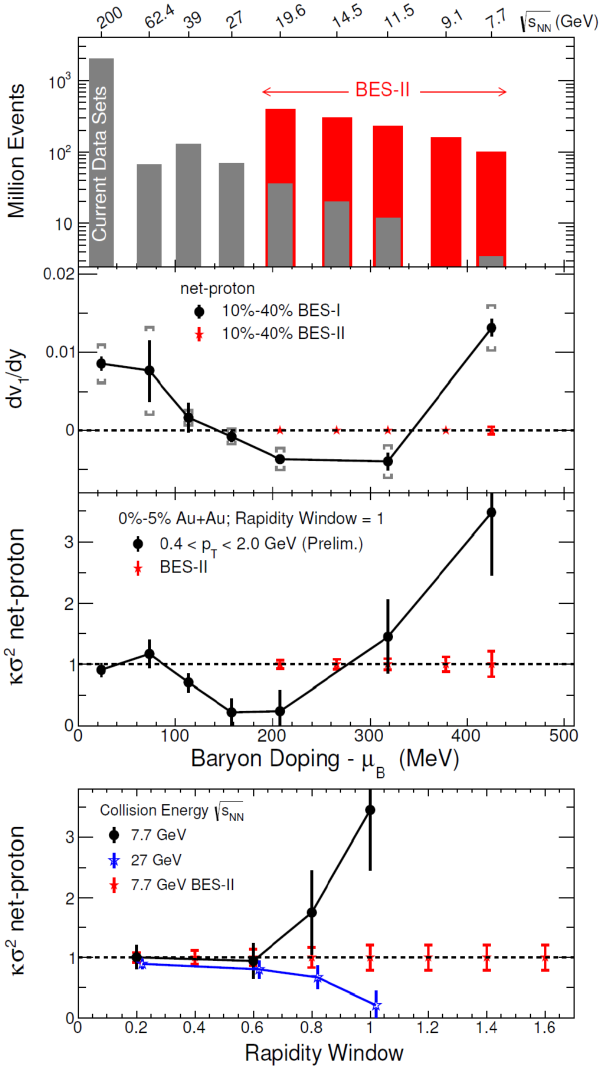


Figure 2.10: *The top panel shows the increased statistics anticipated at BES-II; all three lower panels show the anticipated reduction in the uncertainty of key measurements. RHIC BES-I results indicate nonmonotonic behavior of a number of observables; two are shown in the middle panels. The second panel shows a directed flow observable that can encode information about a reduction in pressure, as occurs near a transition. The third panel shows the fluctuation observable understood to be the most sensitive among those measured to date to the fluctuations near a critical point. The fourth panel shows, as expected, the measured fluctuations growing in magnitude as more particles in each event are added into the analysis.*

Signal is expected to be significantly bigger !

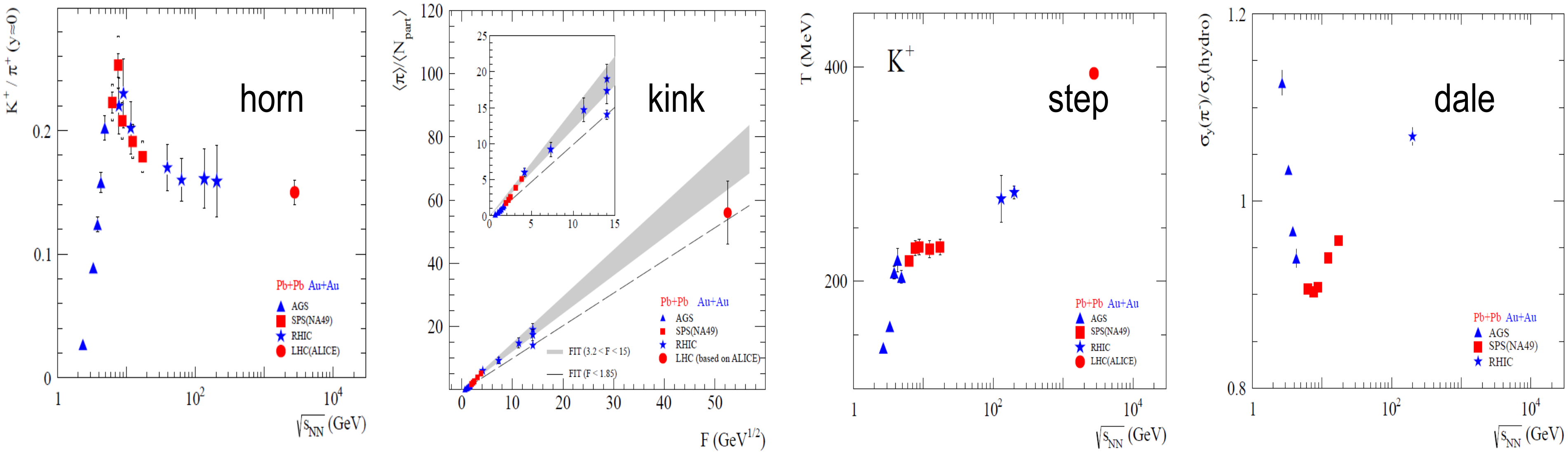
Fixed Target

Extending μ_B reach

Many physics opportunities in revisiting 7.7 – 19.6 GeV

but what if some very interesting physics happens below 7.7 GeV ?

NA 49: *arXiv:1201.4520*



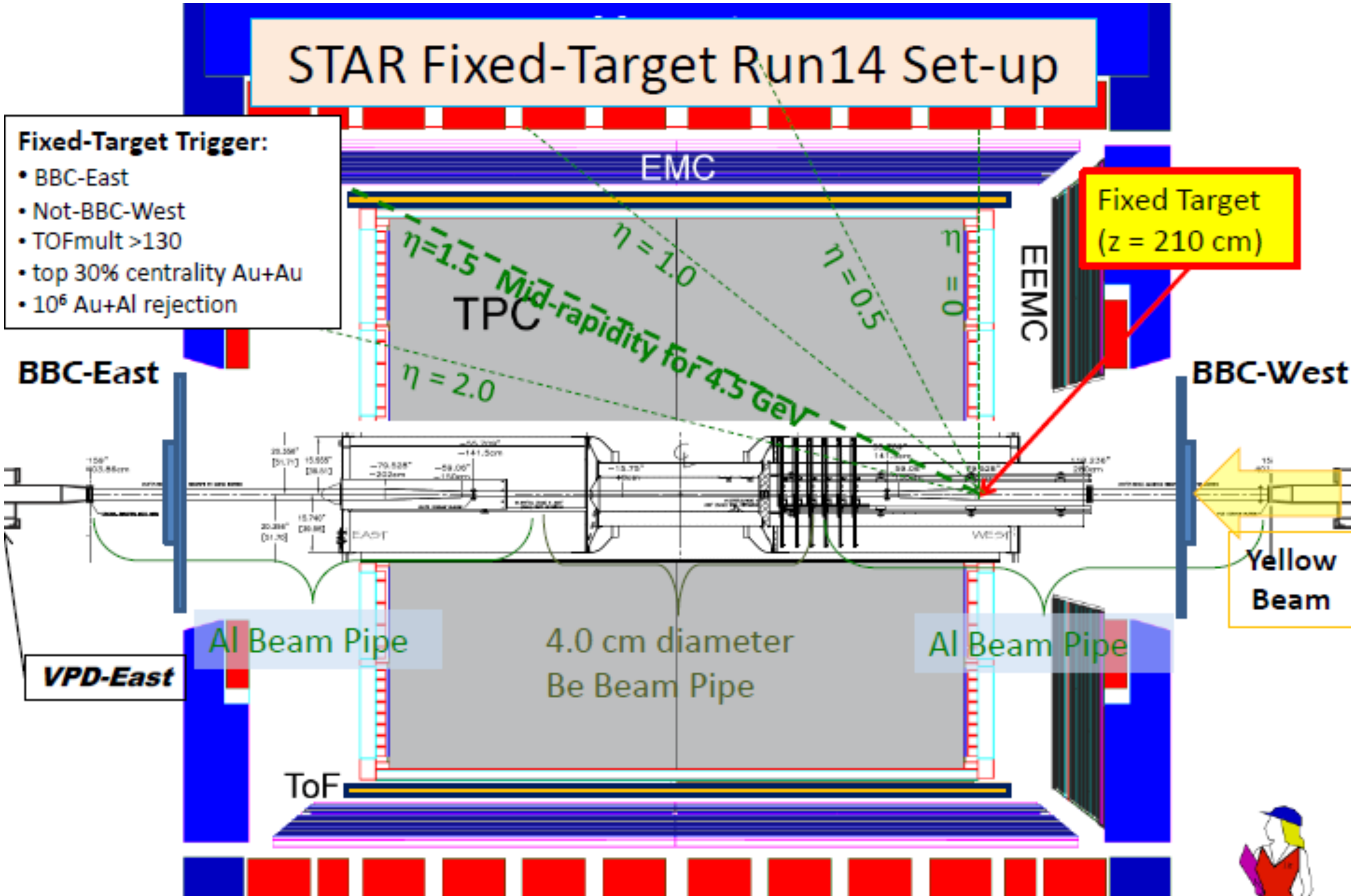
NA49: onset of deconfinement occurs at ~ 7.7 GeV

-> it is crucial to measure collisions below this

-> Au fixed-target inserted into the beam pipe to produce collisions below 7.7 GeV to explore the onset of deconfinement with a single experiment

Fixed target geometry in STAR in 2014

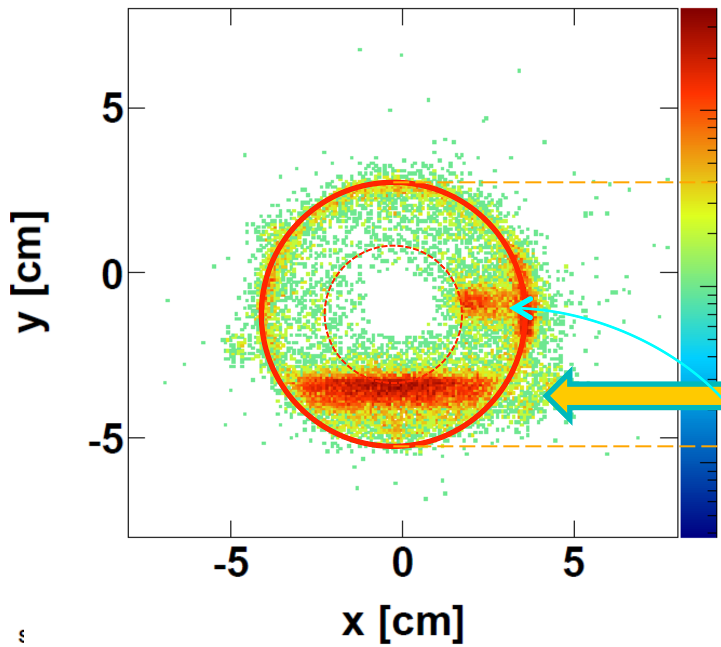
20 MeV< μ_B<720 MeV

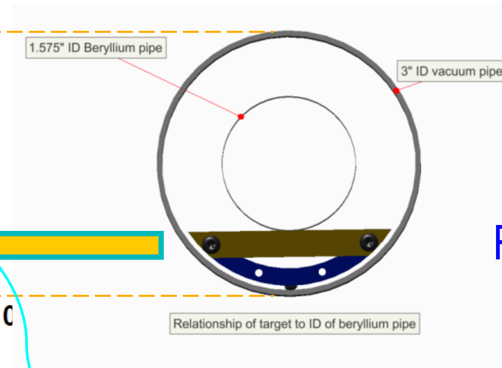


Collider mode Energies (GeV)	7.7	11.5	***14.5***	19.6
Fixed Target $\sqrt{s_{NN}}$ (GeV)	*3.0*	*3.5*	***3.9***	*4.5*
Fixed Target μ_B (MeV)	*720*	*670*	***633***	*585*

- Schematic diagram of STAR showing the fixed-target location
- The target is a gold foil
- The projectiles are ions from the halo of the "yellow beam"

Au target is in place: 3.9 GeV Au+Au event in STAR (2014)

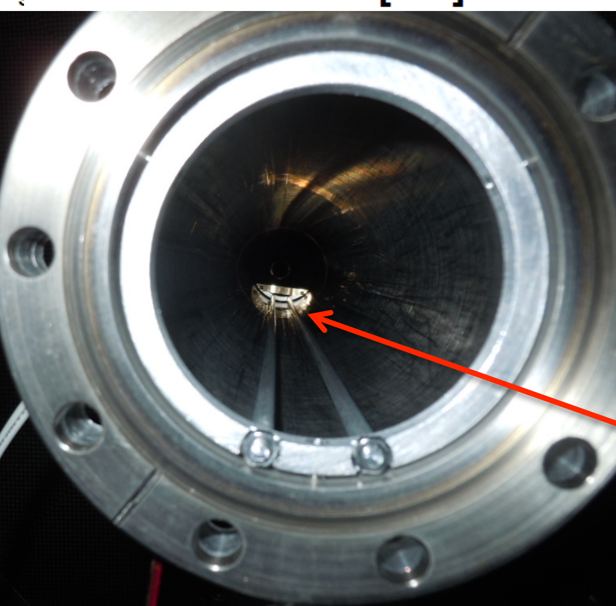


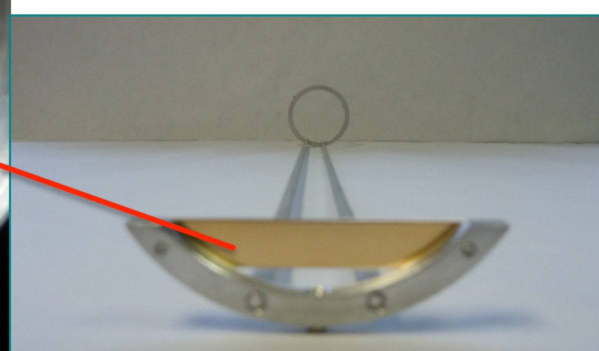


Left: *x-y* vertex location for events with 208.5 < V_z < 210.2 cm

Right: Schematic of the target mount.

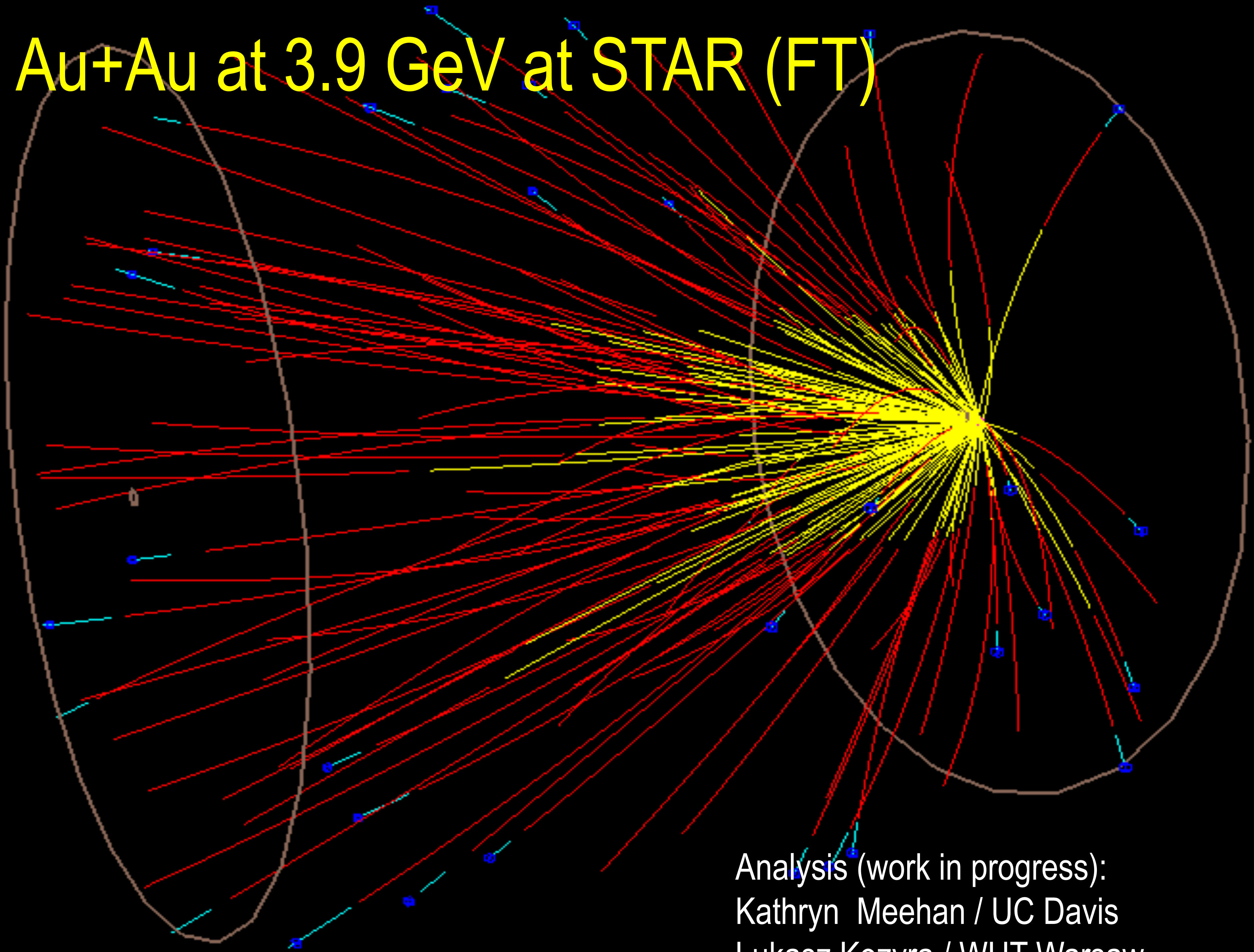
A significant source of background comes from beamlike projectiles deflected by the dipole magnets in the positive *x* direction. These are most likely secondaries from beam gas collisions.





Target:- gold foil:
1 mm thick
~ 1 cm high
~ 4 cm wide
210 cm from IR

Au+Au at 3.9 GeV at STAR (FT)

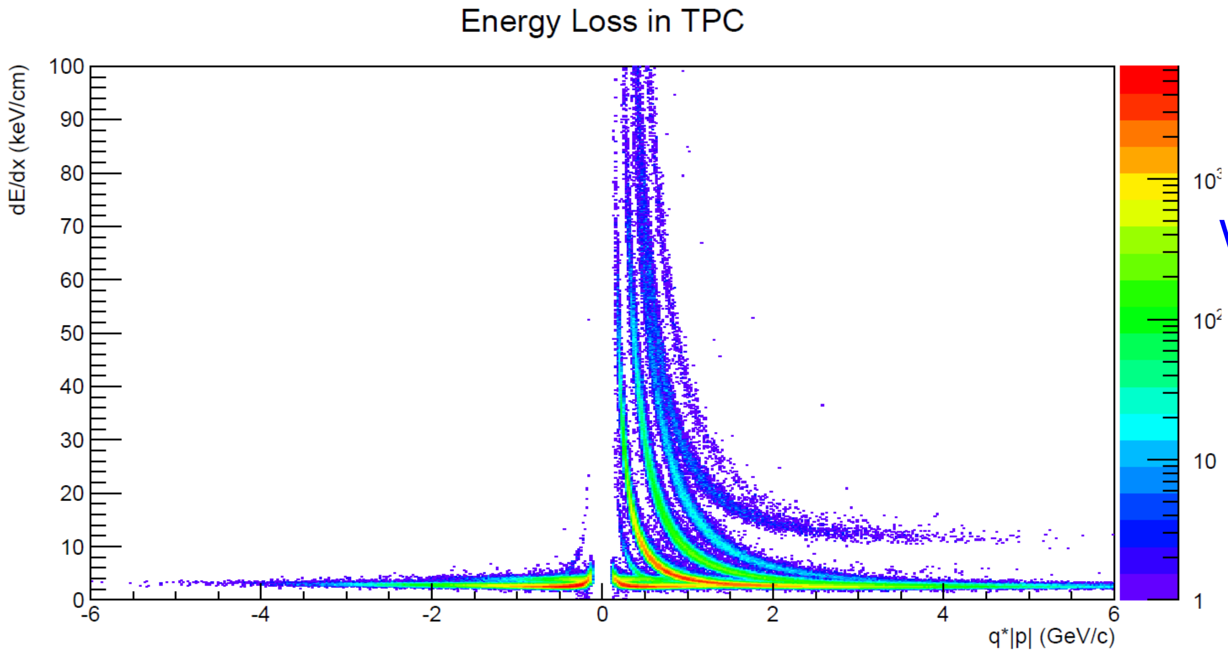


Analysis (work in progress):
Kathryn Meehan / UC Davis
Lukasz Kozyra / WUT Warsaw

Kathryn Meehan/UCD

y[cm]

Serious concern: PID in FT data



very good PID

Second successful test in May 2015:

4.5 GeV Au,

1M events with ~10% centrals

Au target lowered by 1 cm

⟶ allowed for making estimates for a future FT runs: up to 50M/day

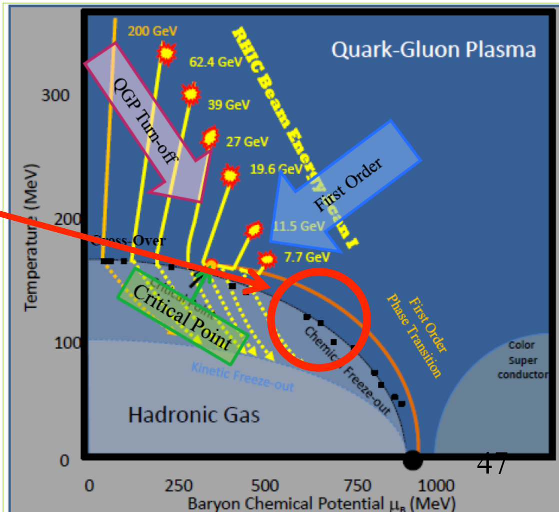
Summary / Outlook

Many interesting STAR results have come out of the BES I

- possibly softest point in the equation of state around 11.5-19.6 GeV
- signs of deconfinement down to at least 27 GeV
- no significant evidence of critical fluctuations, but possible structure around 19.6 GeV

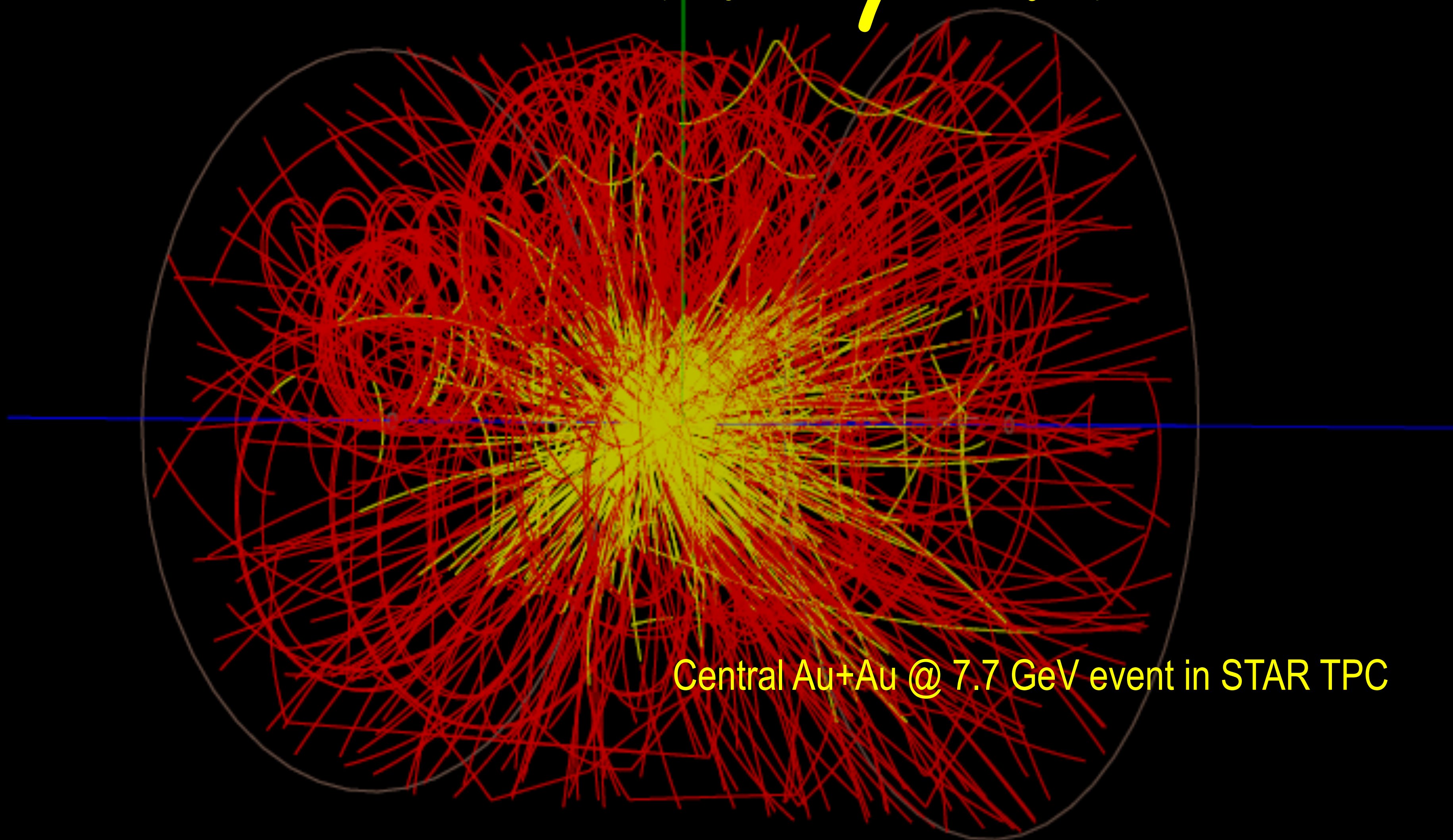
BES II will make new physics accessible, particularly at the lowest collision energies

- higher moment fluctuations, dileptons, ϕ v_2, high p_T probes, etc
- will include fixed-target program which will add additional collision energies: 3.0, 3.5, 3.9, and 4.5 GeV
  - extends the chemical potential reach of the scan to 720 MeV



STAR is actively planning for Beam Energy Scan Phase II (2019 – 2020+) program with iTPC, EPD, eTOF upgrades

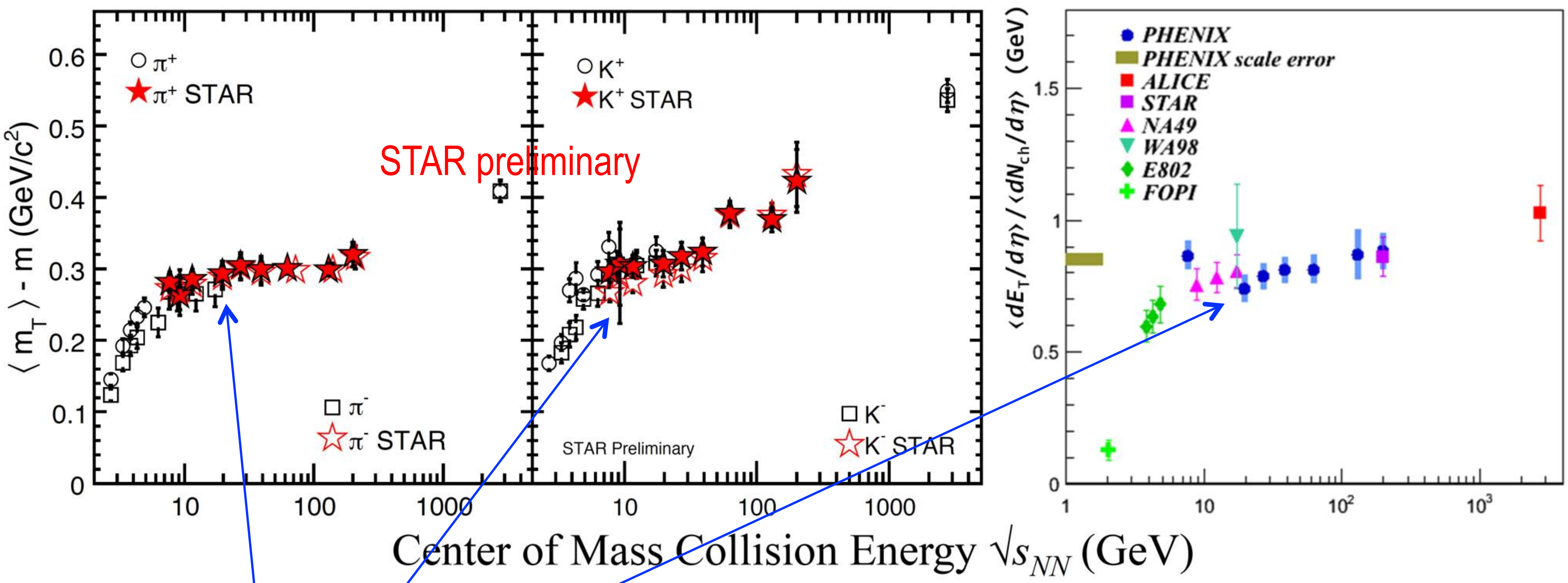
Thank you !



Central Au+Au @ 7.7 GeV event in STAR TPC

back-up slides

plateau in <m_T>

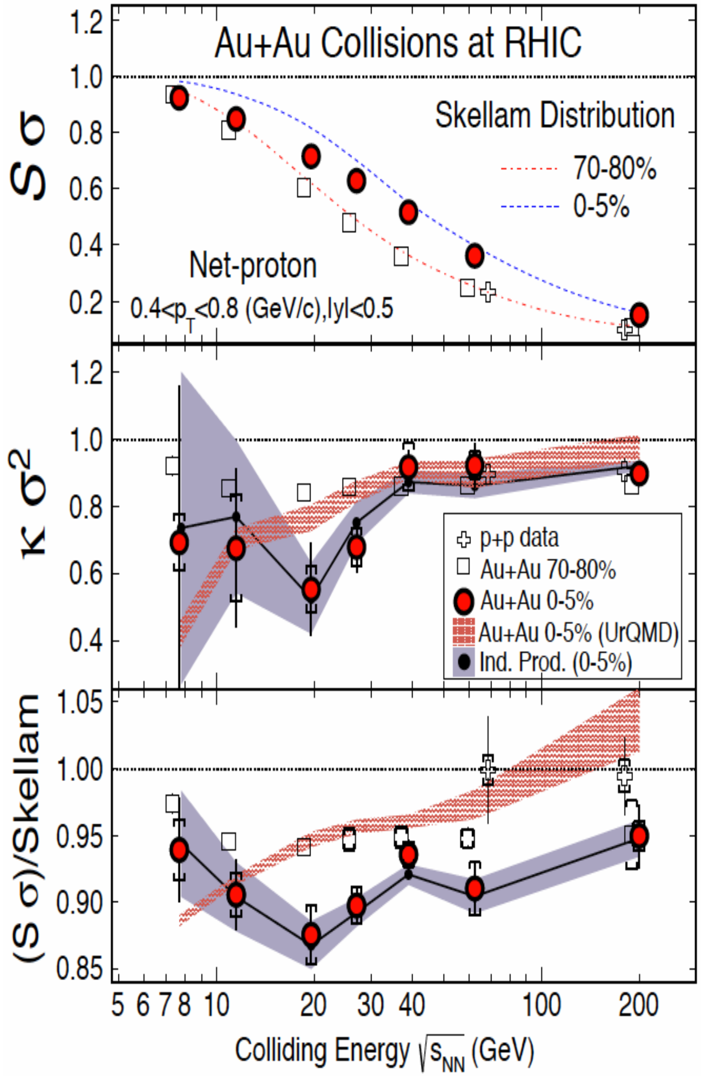


• <m_T> - m is a measure of the thermal excitation, i.e. temperature
• observed plateau in <m_T> is characteristic of a 1st order phase transition
• dN/dy ~ ln($\sqrt{s_{NN}}$) may represent the entropy
• E_T includes mass and is assocaited with the energy density

Higher moments of

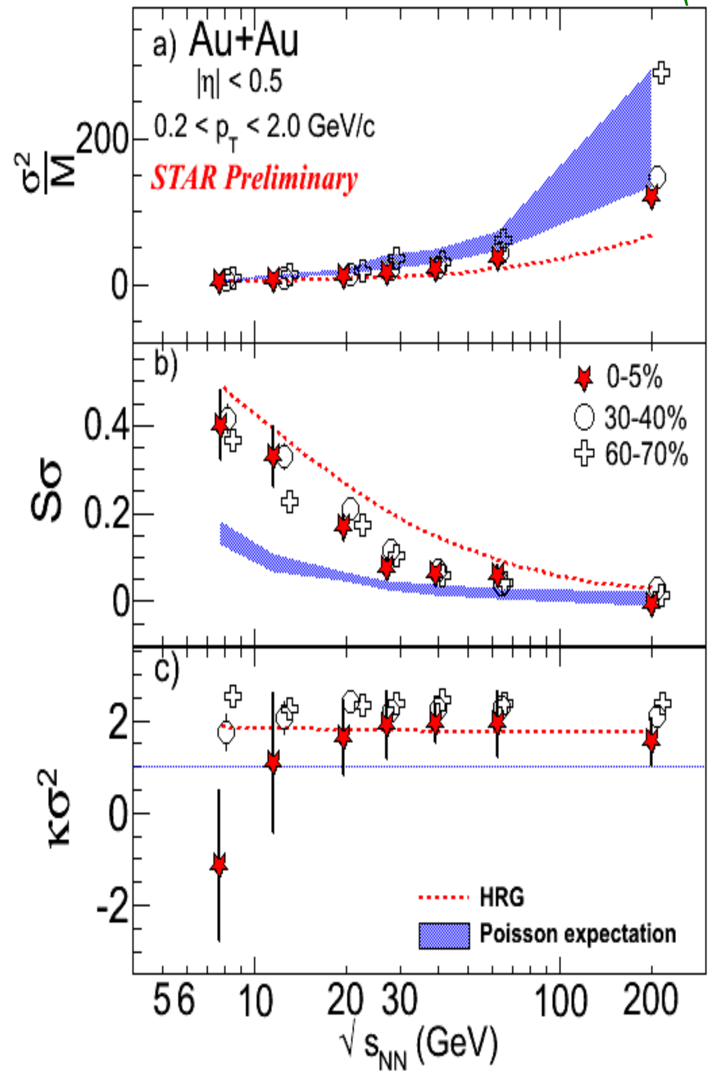
net-protons

PRL 112 (2015) 32302



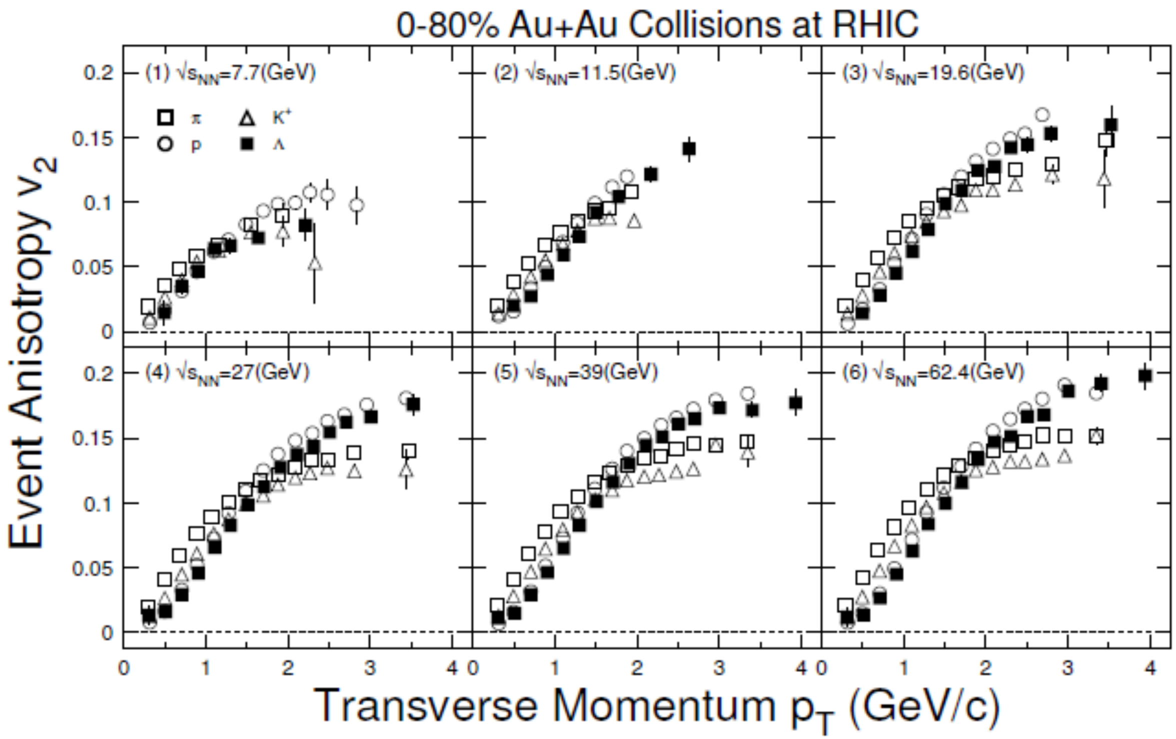
charged

PRL 112 (2014) 162301



Elliptic flow - v_2

Phys. Rev. C 88, 014902 (2013)

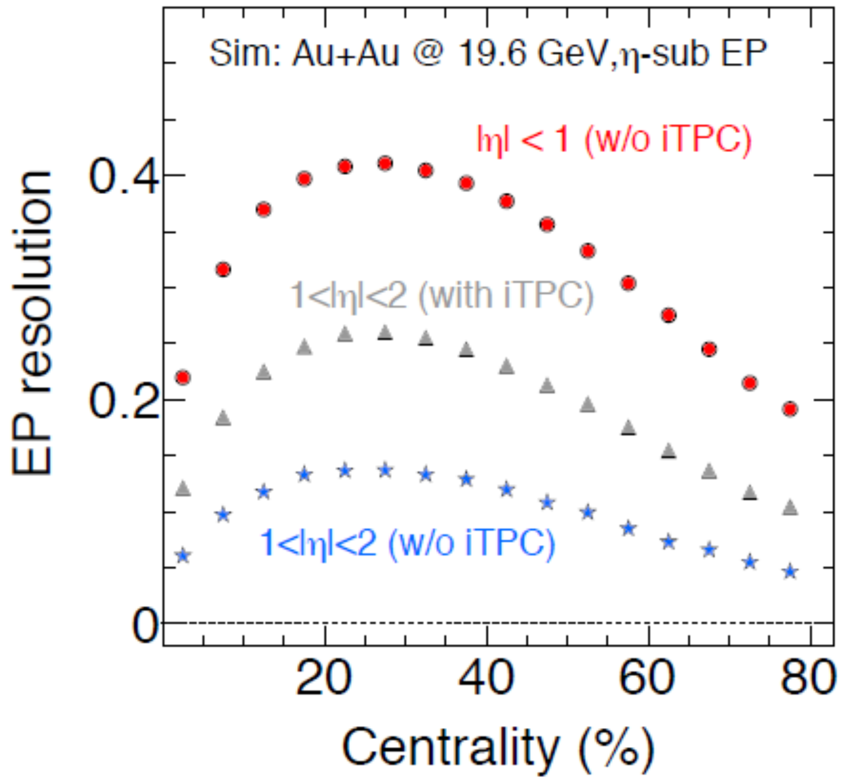


Large (similar) collectivity at all energies ?

but particle composition changes with energy !

Baryon/Meson Splitting is seen at the higher energies (19.6 GeV and higher)

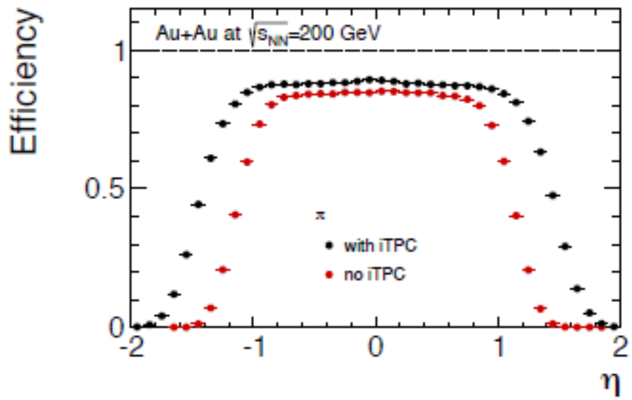
Elliptic flow Improvements with iTPC upgrade



Input v_2 and multiplicity to reproduce the event plane resolution at 19.6 GeV

Apply the efficiency from Hui Wang from 200 GeV (thanks to Hui)
http://www.star.bnl.gov/protected/bulkcorr/wanghui6/my_talks/iTPC/9_20_iTPC.pdf

assume efficiency is the same at 19.6 GeV



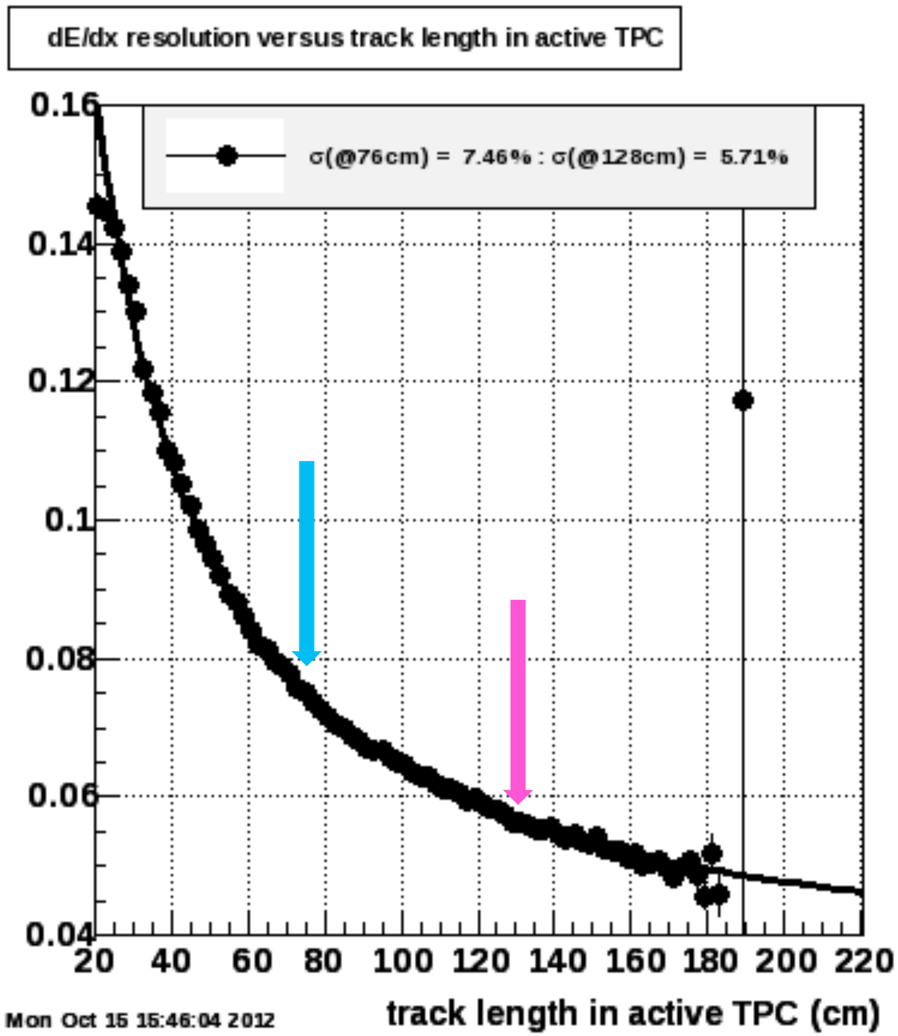
- A factor of ~2 improvement in $1<|\eta|<2$

H. Masui, A. Schmah / LBNL

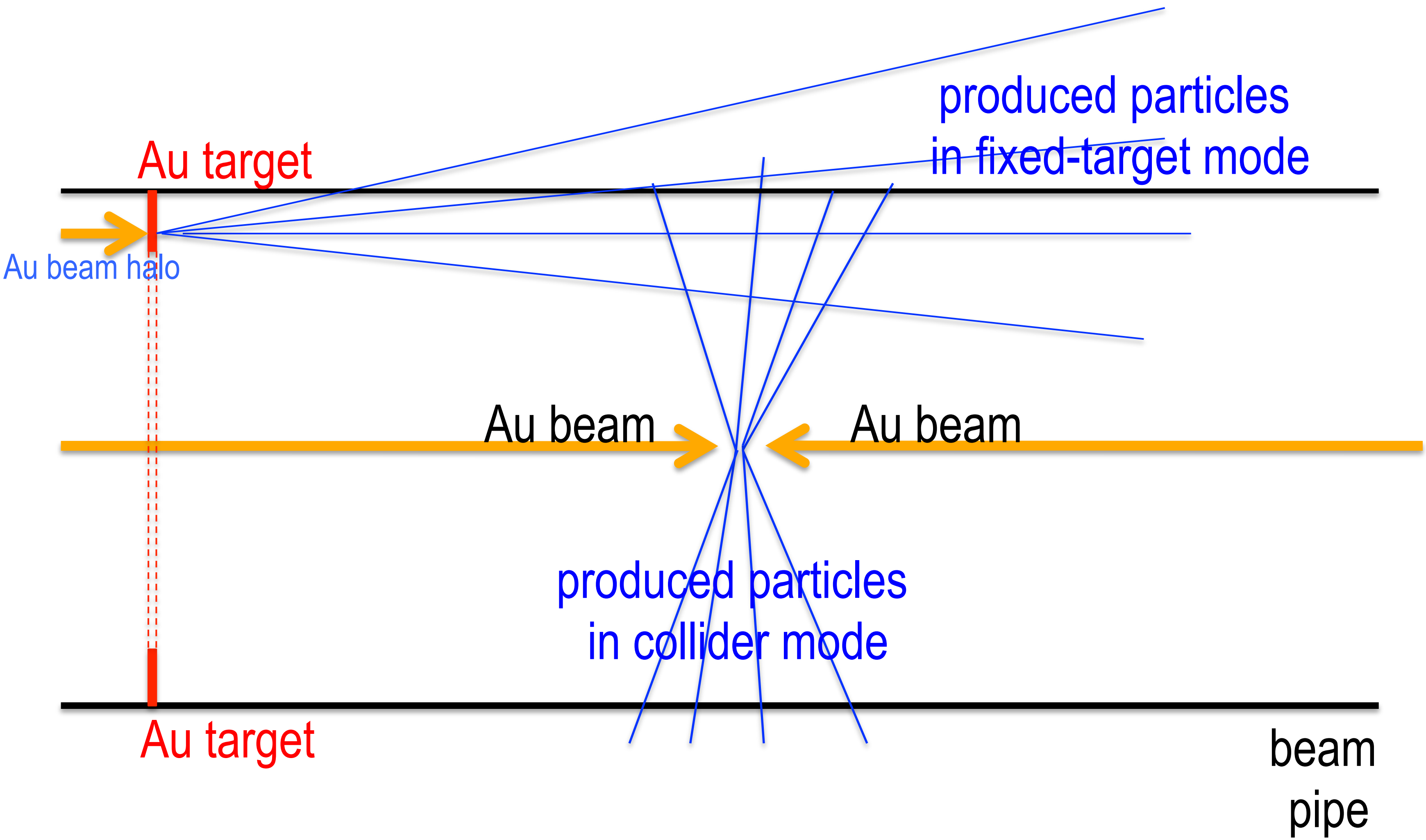
Simulation of improved dE/dx Resolution

Sampled Track Length vs dE/dx

Simulation from HiJing Au+Au 200 GeV

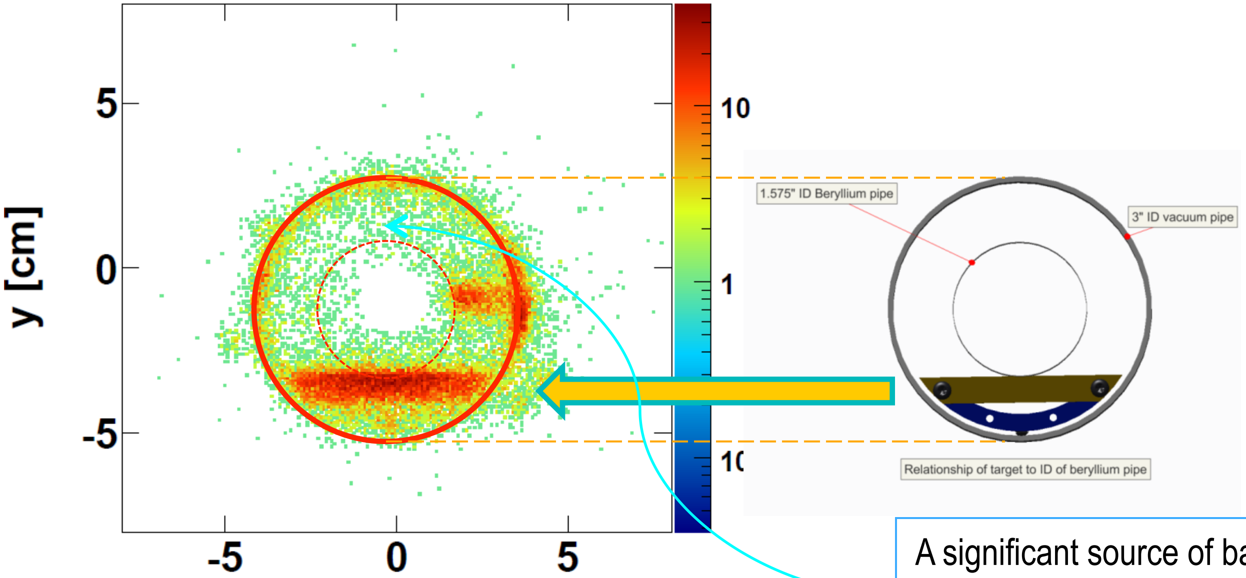


Fixed-target: schematics of concurrent running in STAR



fixed-target events taken while waiting for collider mode collisions

Au target is in place: 3.9 GeV Au+Au event in STAR (2014)



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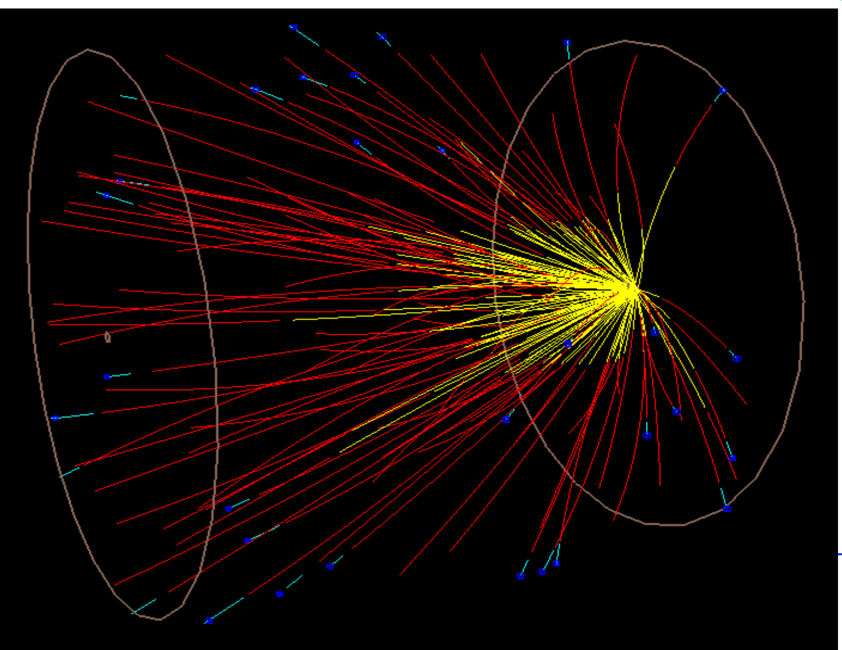


Reconstructed tracks for an event coming from the fixed gold target

-tracking and PID looks good

-50 k events

-spectra analysis possible

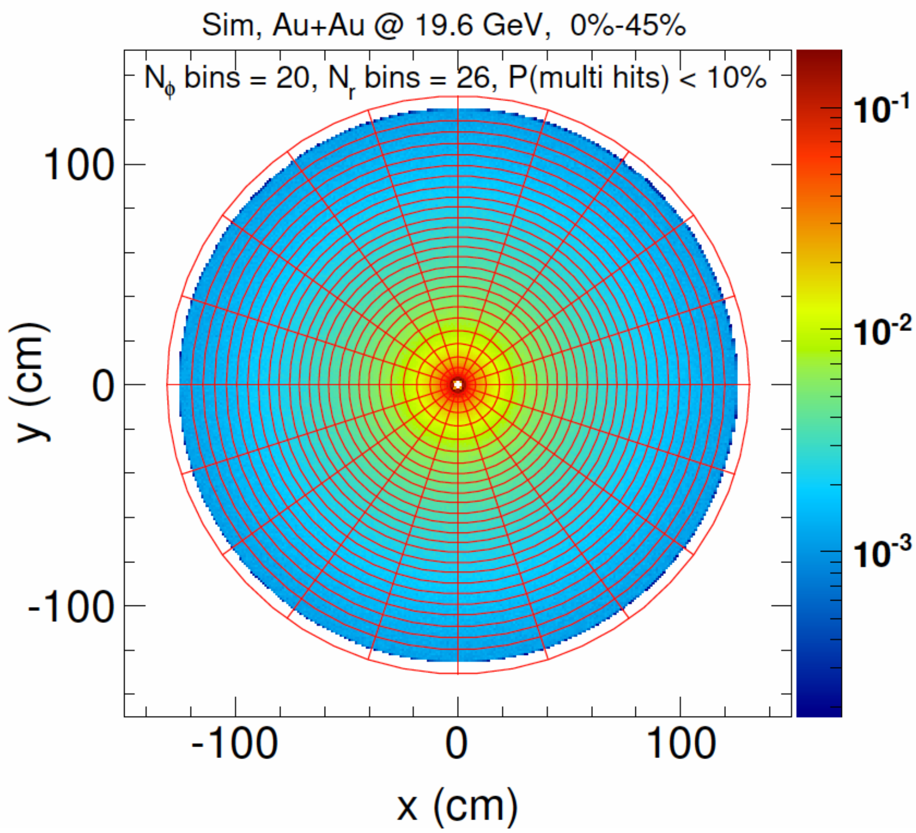
EPD

Essential requirements for an EPD

TPC independent reaction plane detector is essential for BES II success

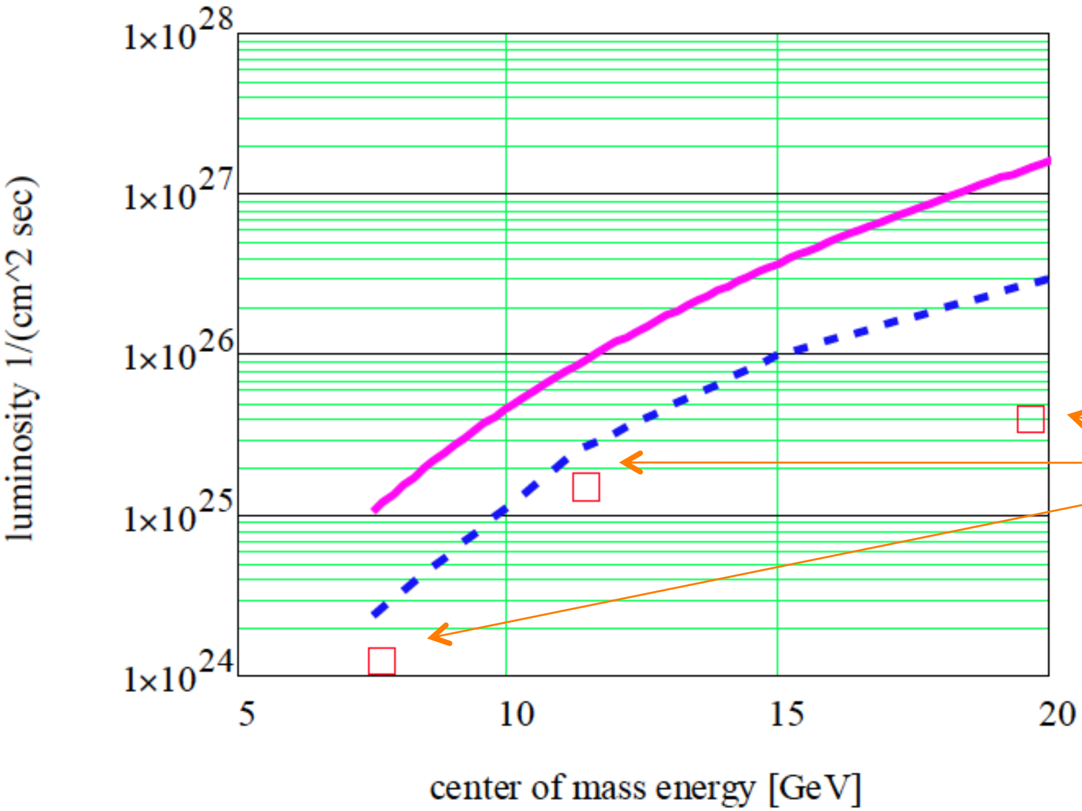
- Large acceptance to maximize event plan resolution
- Fine granularity & single hit resolution for good event plane determination and centrality resolution
- Large rapidity gap with respect to the TPC to minimize non-flow effects and self-correlations (and other correlations)
- Good radial segmentation (η segmentation) to reduce event plane biases
- Symmetric in pseudo-rapidity (East vs West) to achieve an unbiased event plane and to capture as many particles as possible

EPD conceptual design



- Pie shape detector is optimal
  - symmetry, η segmentation
- Detector will be optimized for a limited number of different tile shapes for cost effectiveness
- Large area coverage
  - plastic scintillator (fast, efficient, cheap)
- Silicon PhotoMultiplier (SiPM)
  - for readout of tiles
  - cheap, equivalent to standard photomultiplier

Luminosity improvements for BES II



RHIC with e-cooling and long bunches ($v_z = \pm$ 1m)

Minimum projection (e-cooling only)

BES I performance

Implementation:
2020 - $\sqrt{s_{NN}}$ 5 - 9 GeV
No e-cooling $\sqrt{s_{NN}}$ >10 GeV

Electron cooling + longer beam bunches for BES II provide factor <u>4-15 improvement</u> in luminosity compared to BES I

<u>Every energy</u> available with electron cooling