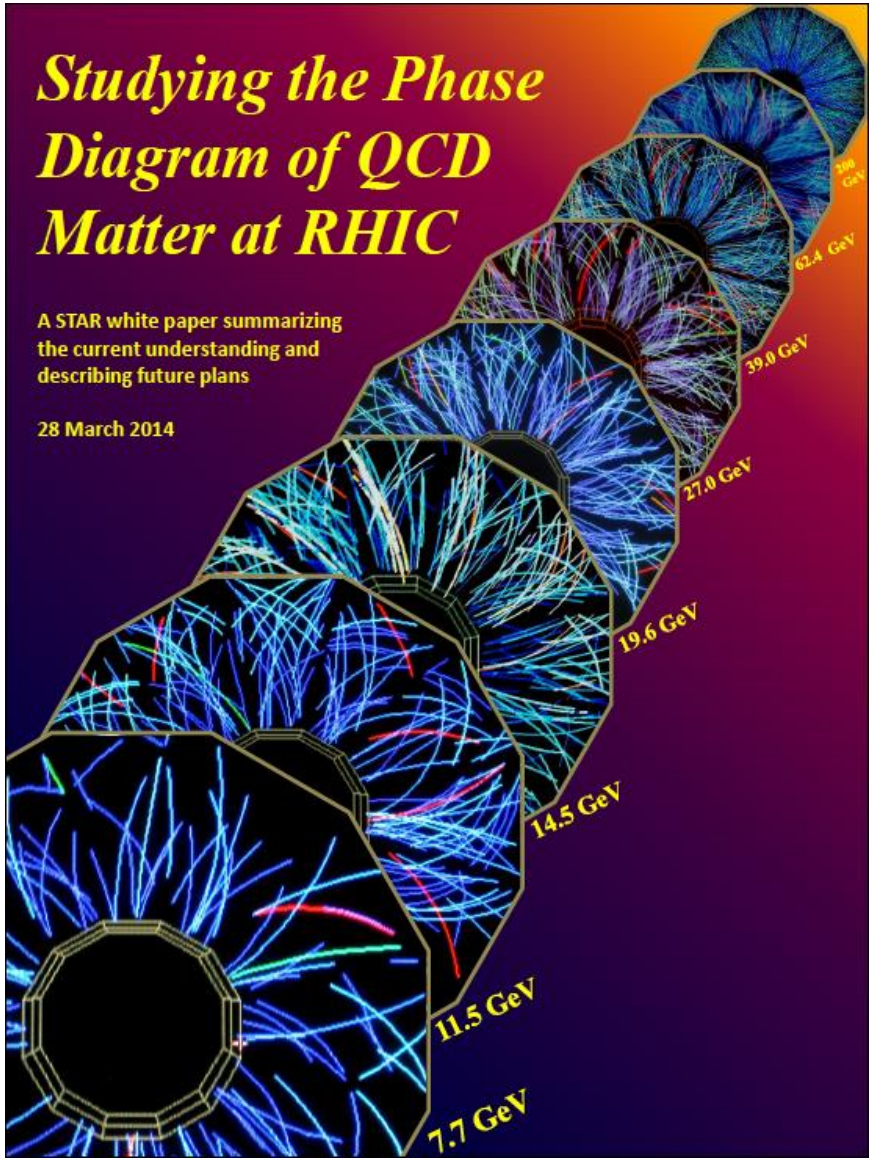
Future of the Beam Energy Scan Program

STAR/RHIC preparation for the BES II era



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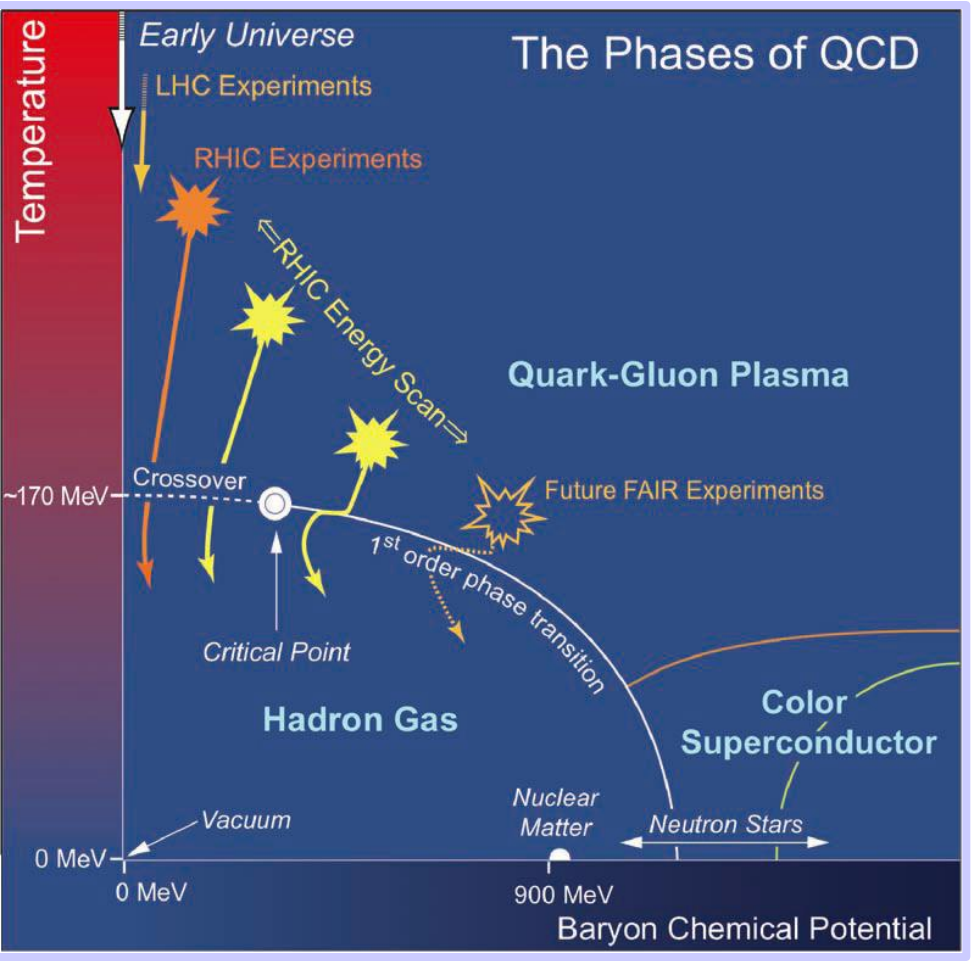
Outline:

1. Intro : Why BES ?
2. Past : BES I selected results
3. Future : BES II + STAR fixed-target program

3rd International
Conference on New Frontiers in Physics
Crete, Greece, July 28-August 6, 2014

QCD Phase Diagram

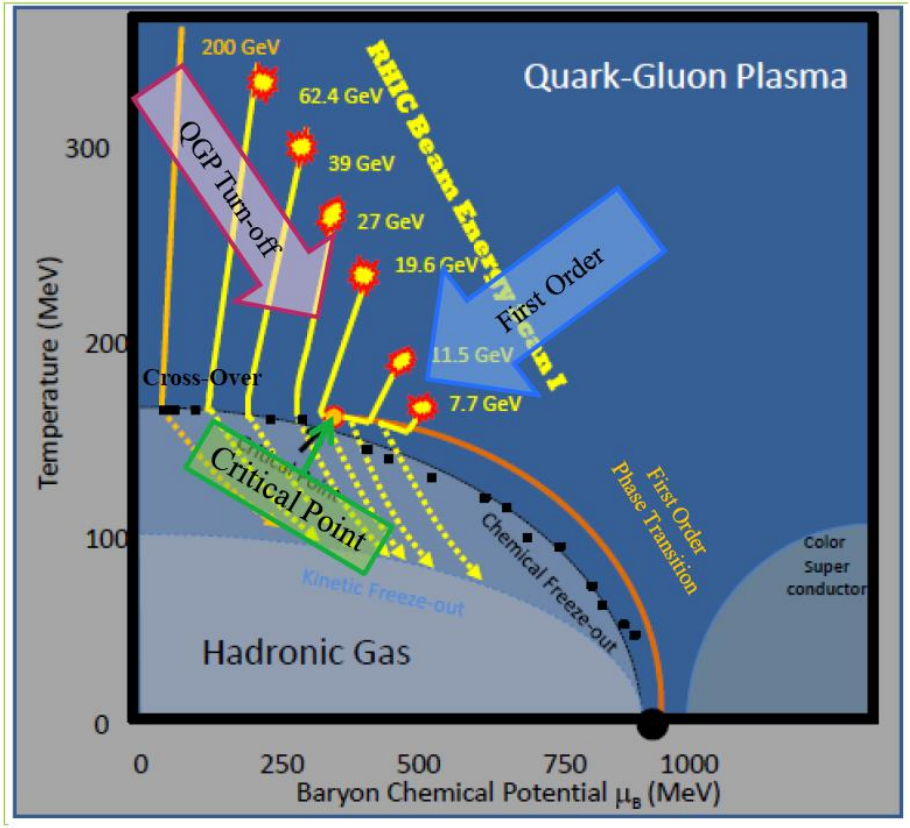
- single most important graph of our field
- still highly speculative



We built RHIC to find QGP – and we did it (with unique and unexpected properties)

Huge progress:
- 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 to map out QCD matter phase diagram



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

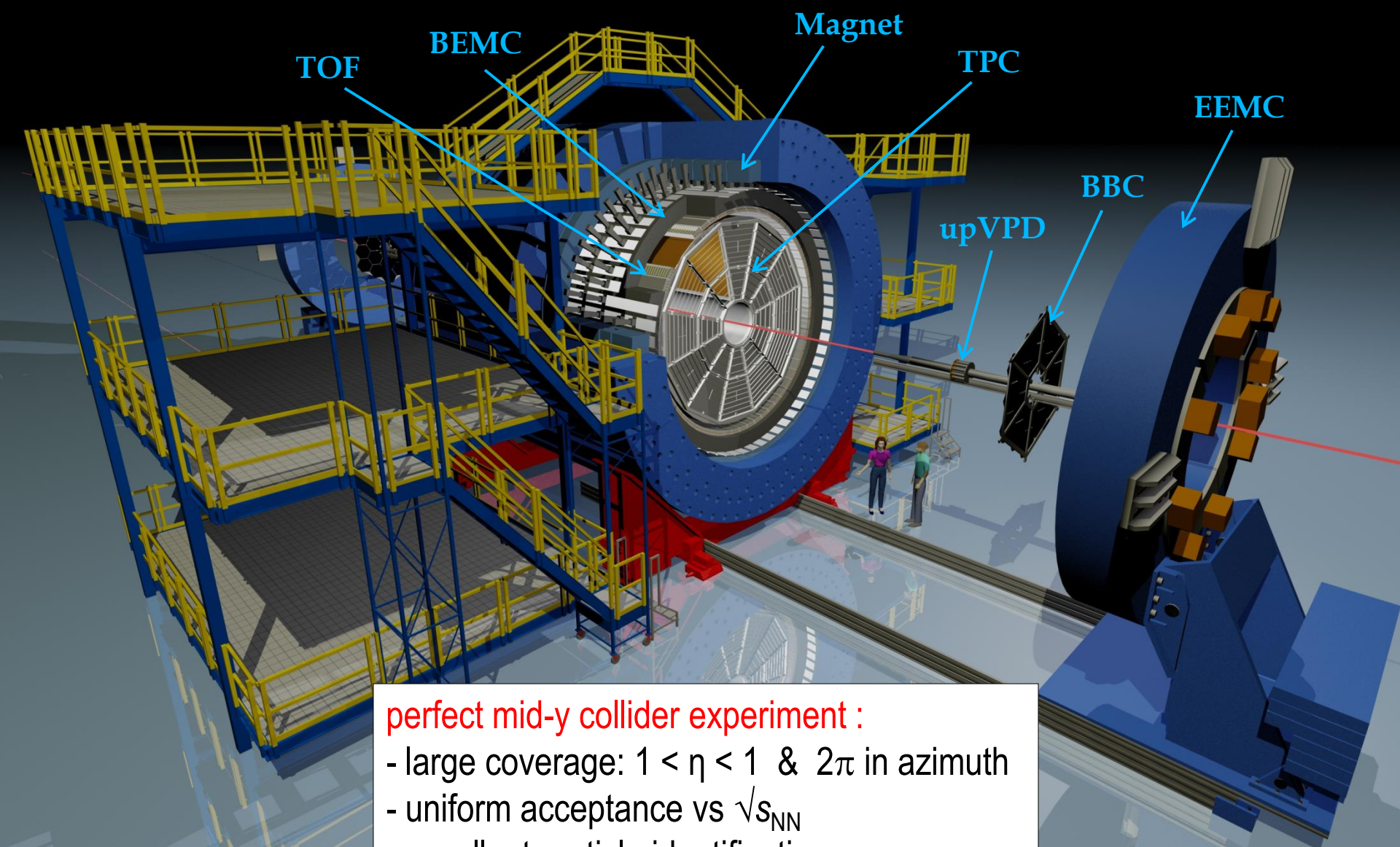
$\sqrt{s_{NN}}$	M_{events} in $-1<\eta<1$
7.7	4.3
11.5	11.7
14.5	24**
19.6	35.8
27	70.4
39	130.4
62.4	67.3

** taken in 2014

BES-I (2010, 2011 and 2014):

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

The Solenoid Tracker At RHIC (STAR)

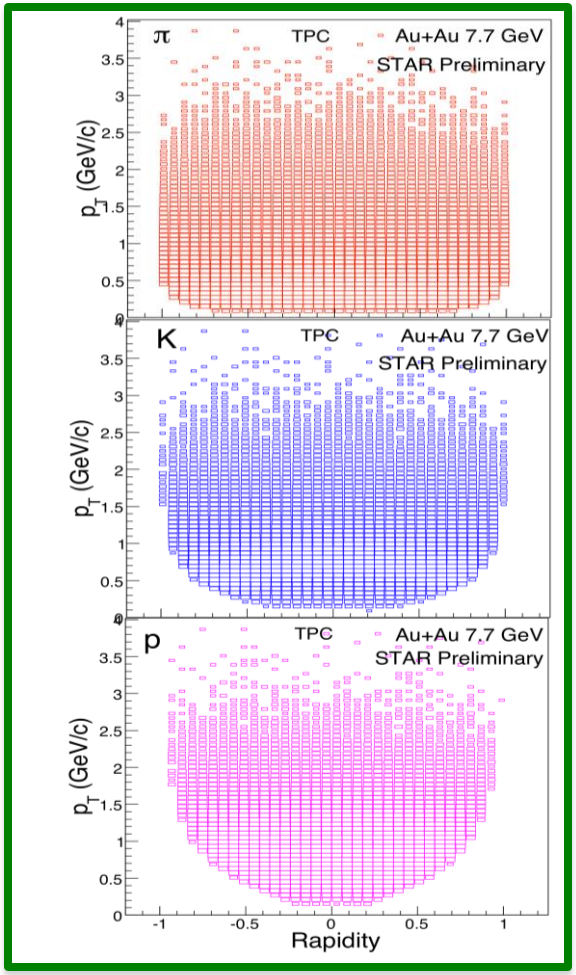


perfect mid-y collider experiment :

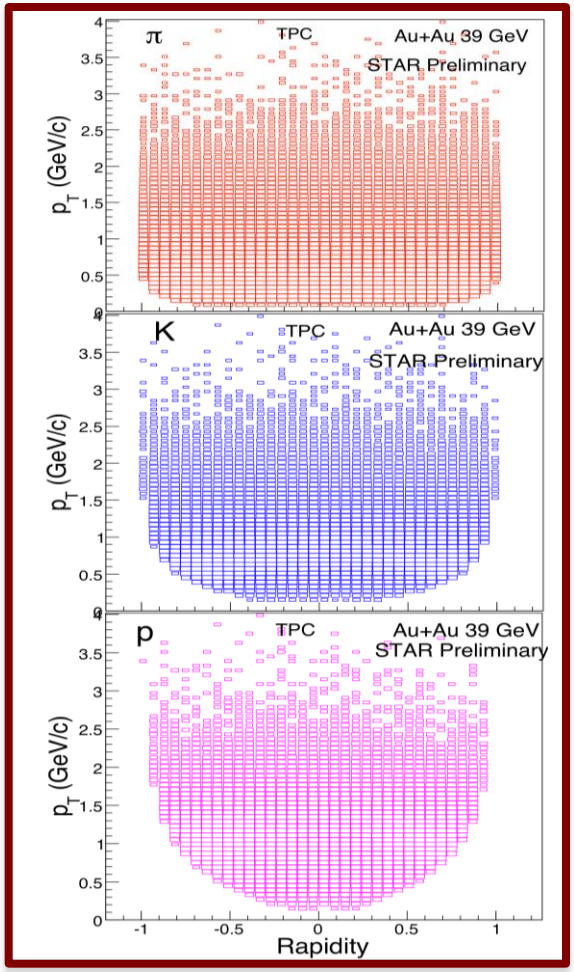
- large coverage: $1 < \eta < 1$ & 2π in azimuth
- uniform acceptance vs $\sqrt{s_{NN}}$
- excellent particle identification
- fast DAQ

Identified Particle Acceptance at STAR

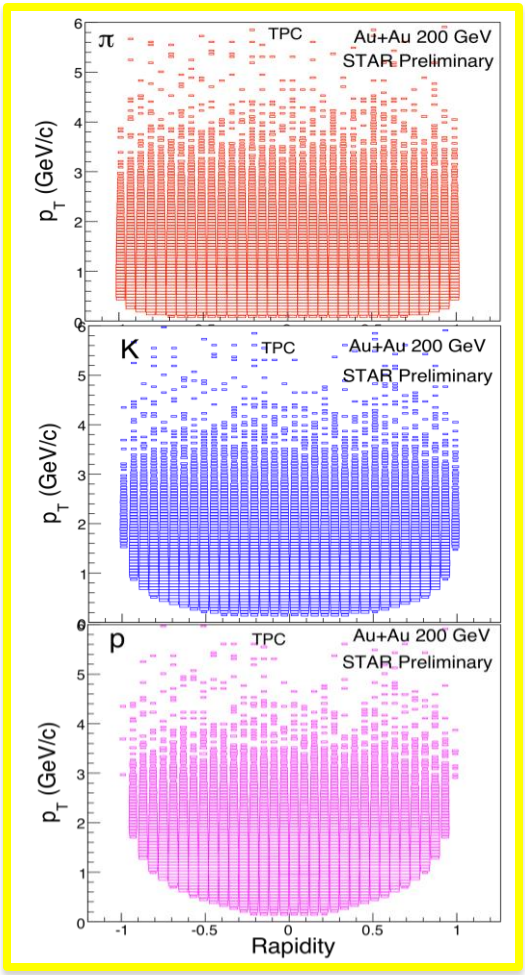
Au+Au at *7.7* GeV



Au+Au at *39* GeV



Au+Au at *200* GeV



At collider geometry - similar acceptance for all particles and energies

(some of) observables

talks by Daniel McDonald and Shusu Si

- 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*

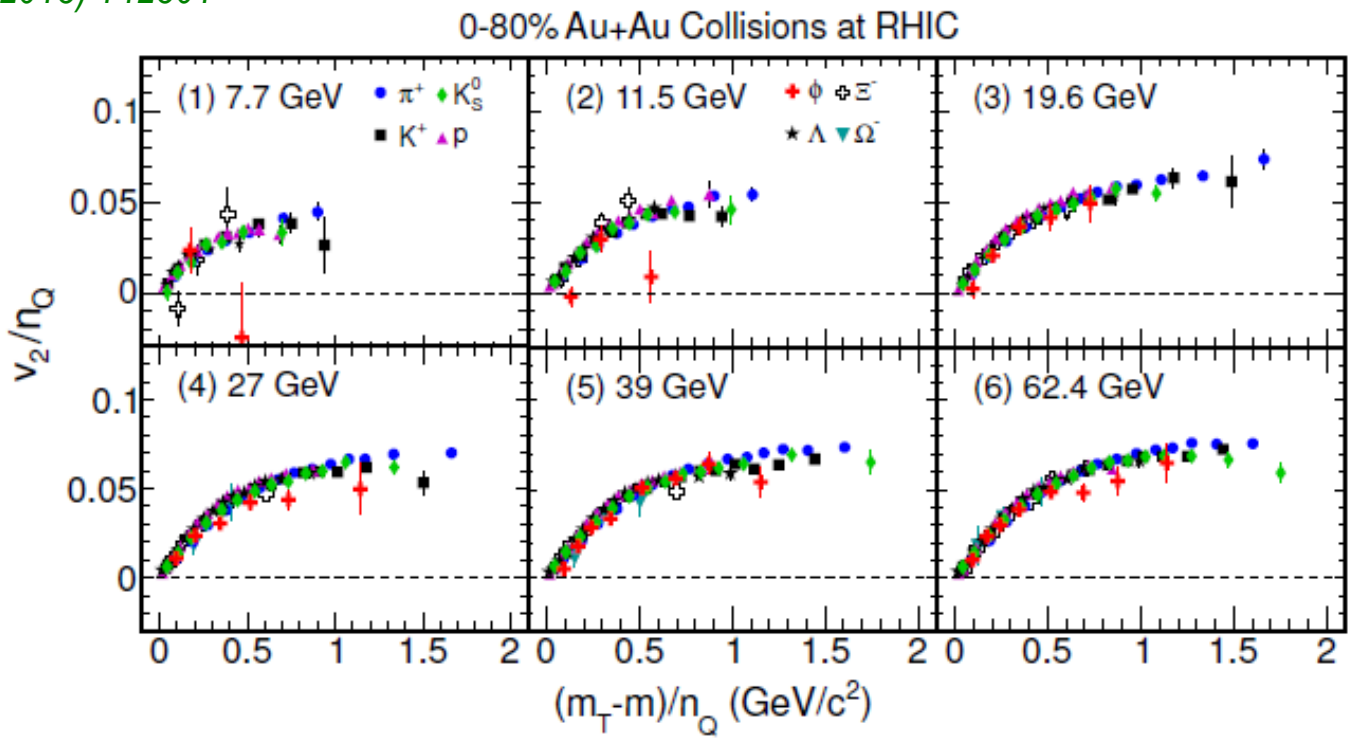
the easiest one …

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

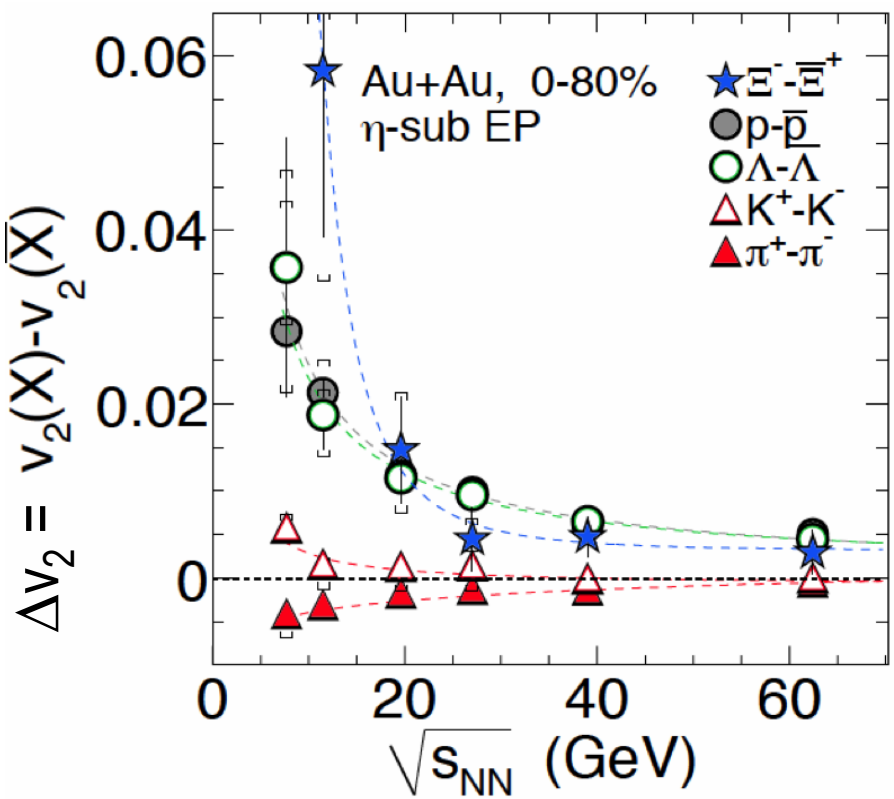


- NCQ scaling holds for particles and anti-particles separately at all energies -> possibly an indicator of partonic dof -> deconfinement in high energy
- ϕ meson may not follow the trends (11.5 and 7.7 GeV) ?

ϕ is key for differentiating hadronic and partonic flow but has large errors $\longrightarrow$

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

$\Delta v_2 = v_2(\text{particle}) - v_2(\textit{anti}\text{particle})$



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 ?

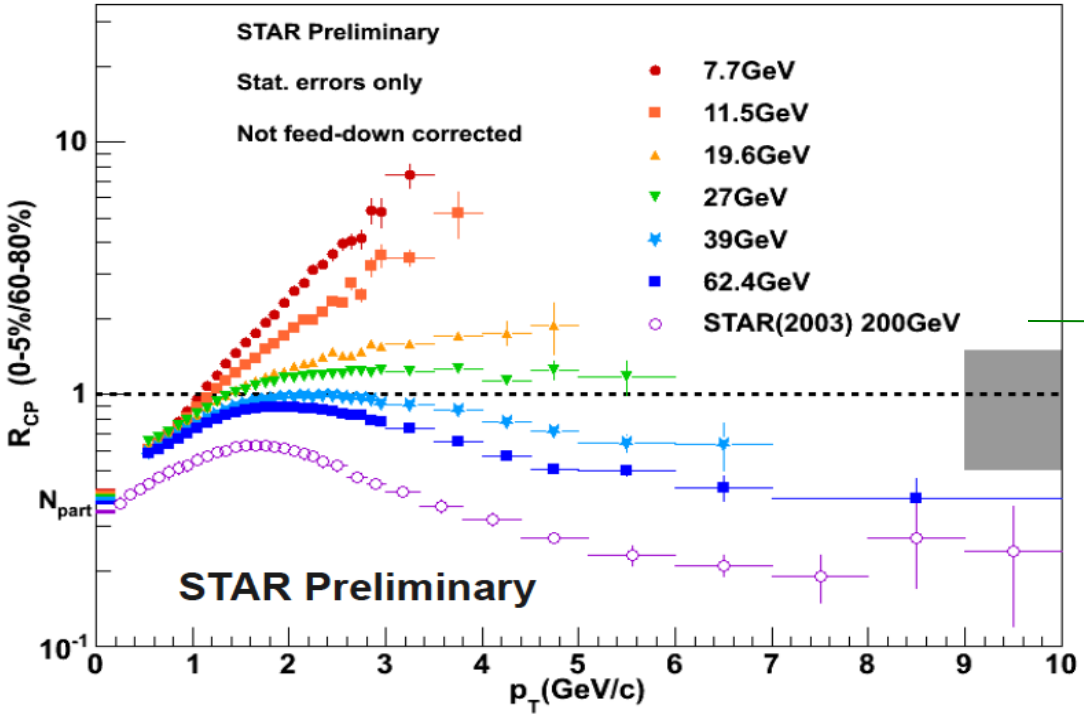
Δv_2:

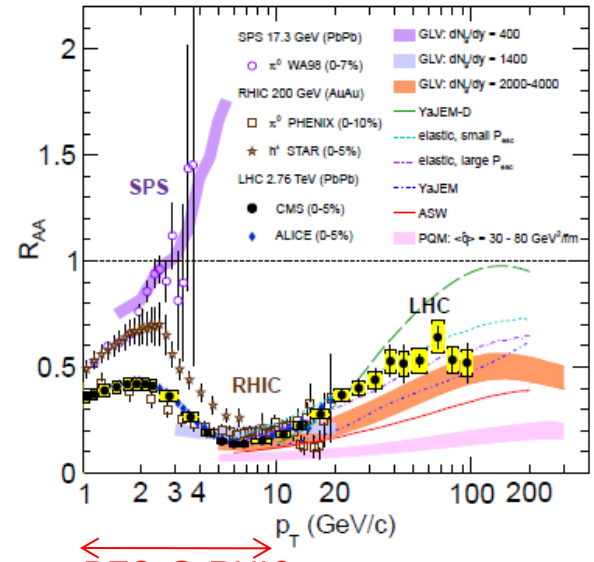
- is larger for baryons than for mesons
- nonlinear increase with decrease of $\sqrt{s_{NN}}$

Charged hadrons R_{cp}

measure of partonic energy loss in medium :

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



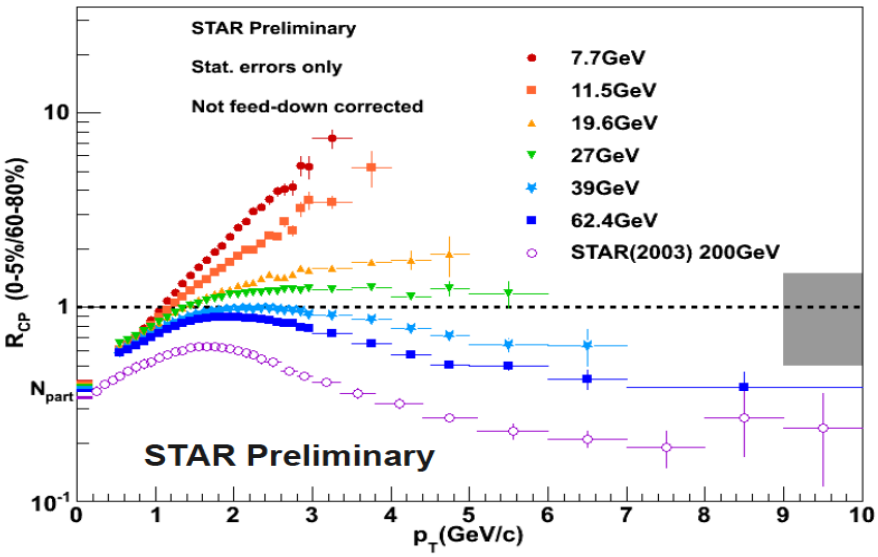


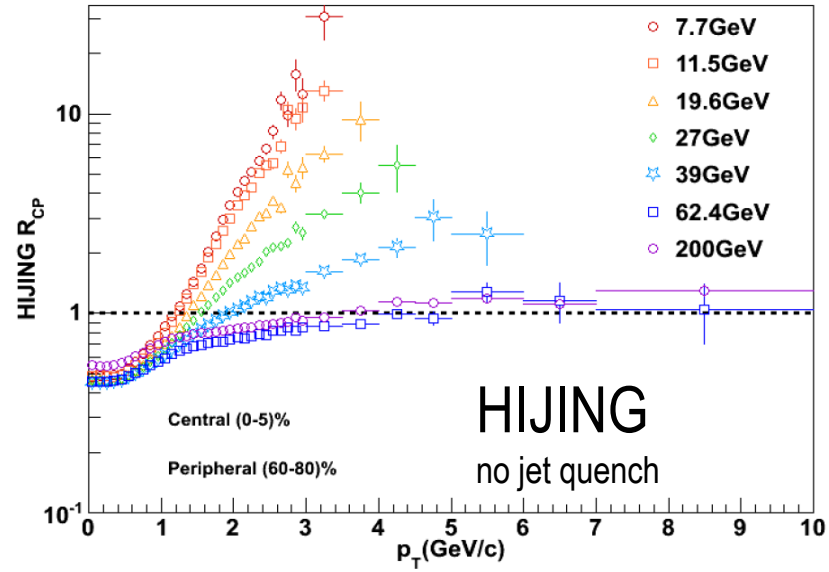
J.Adams et al., (STAR coll.) PRL 91, 172302 (2003)

- 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

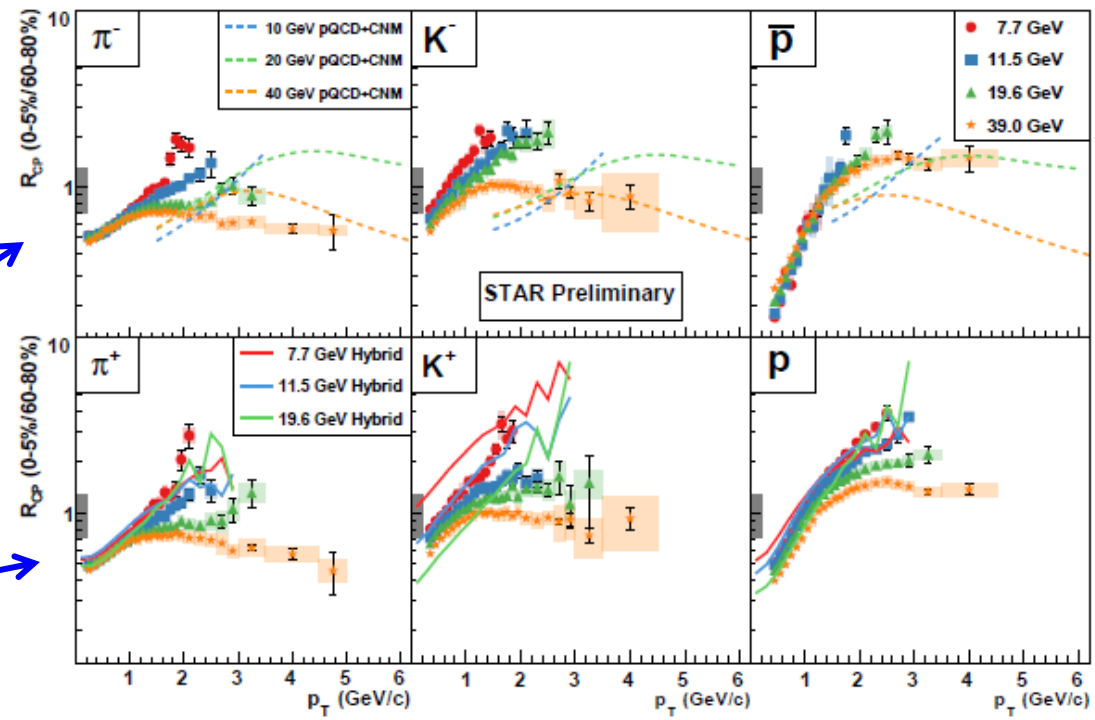




HIJING without jet quenching but with Cronin effect (though k_T broadening) resembles $\sqrt{s_{NN}}$ dependence at low energies

pQCD calculations show high p_t suppression *[I.Vitev – private comm.]*

Hybrid model calculations describe low p_t behavior *[Frankfurt Hybrid]*



high statistics, more p_t reach needed

Lesson learned …

These observations:

- baryon/meson grouping for *anti*particles starts to collapse at 11.5 GeV
- disappearance of high p_t suppression
- disappearance of charge separation
- break down of N_q scaling between particles and *anti*particles
- local parity violation decreases with decrease of $\sqrt{s_{NN}}$
- ...

indicate that hadronic interactions become dominant at lower beam energies

the most anticipated …

Critical Point

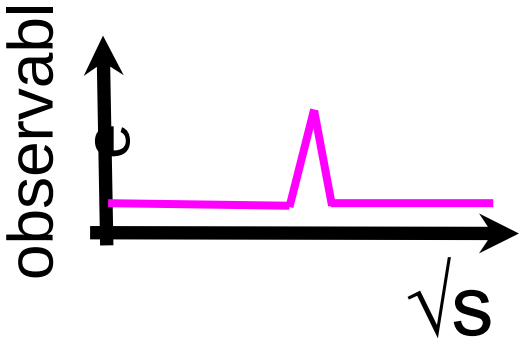
CP: Why fluctuations and correlations ?

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>

$\longrightarrow$ 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

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

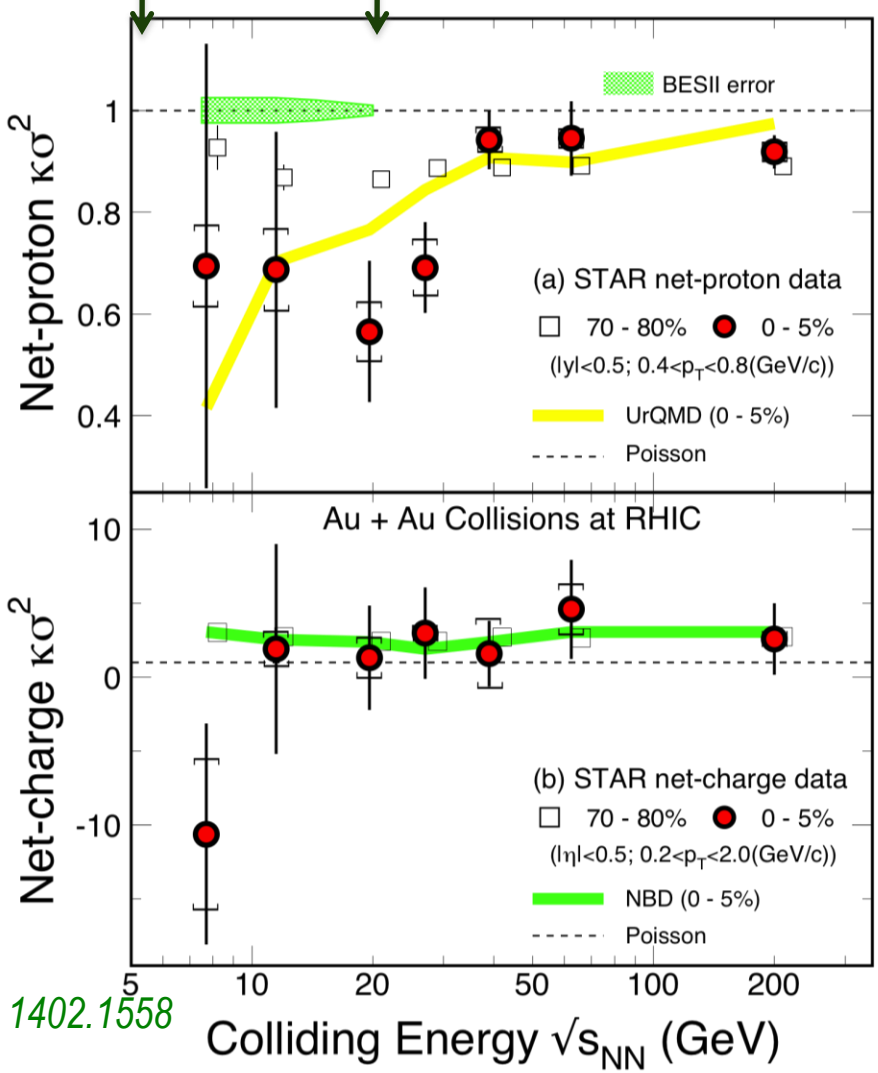
- higher moments of conserved quantities measure non-Gaussian nature of fluctuations and are more sensitive (than variance σ^2) to CP induced fluctuations (to correlation length)
- allows for direct comparison to theory – cumulants of conserved quantities proportional to susceptibilities
- products of 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

Additional energy of 14.5 GeV in 2014

BES-II

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

1st order phase transition

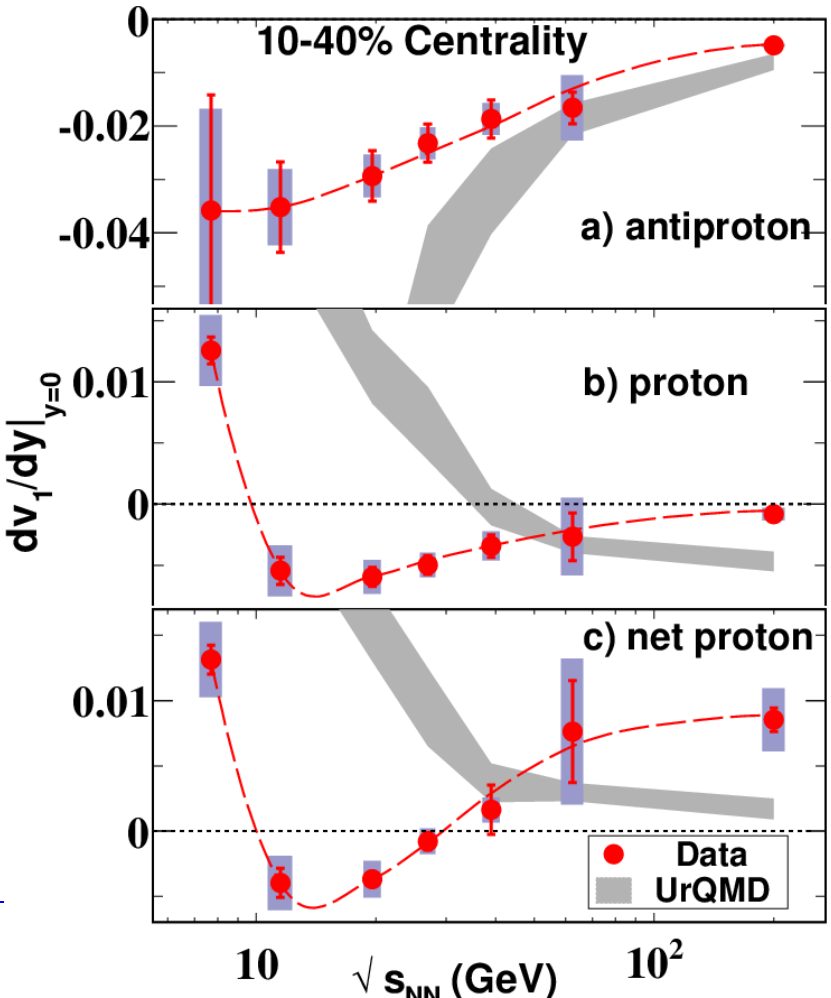
can we demonstrate the softening of EOS ?

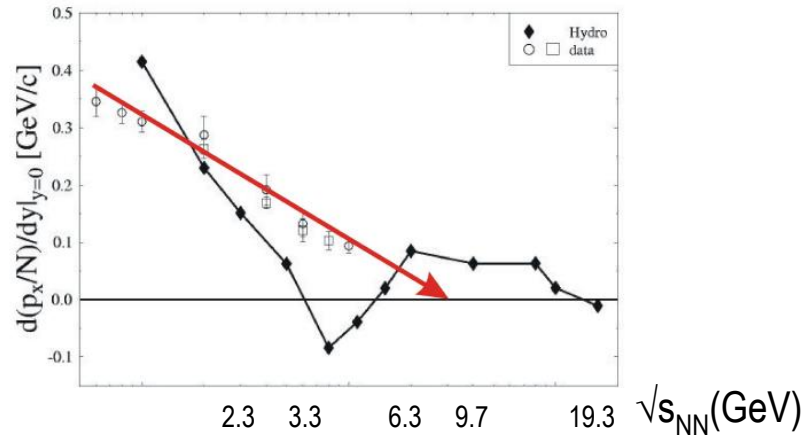
Directed flow (v_1) of identified particles

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

Observables tied to

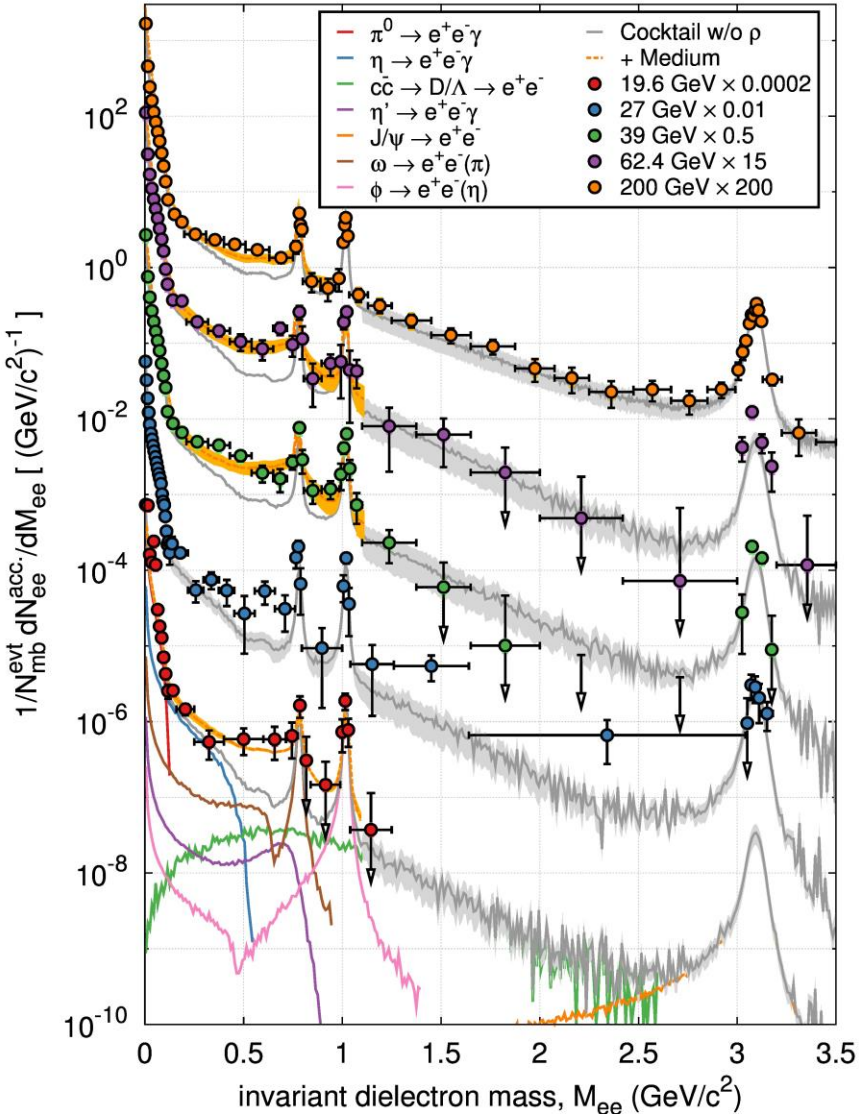
Chiral symmetry restoration

–

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

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*

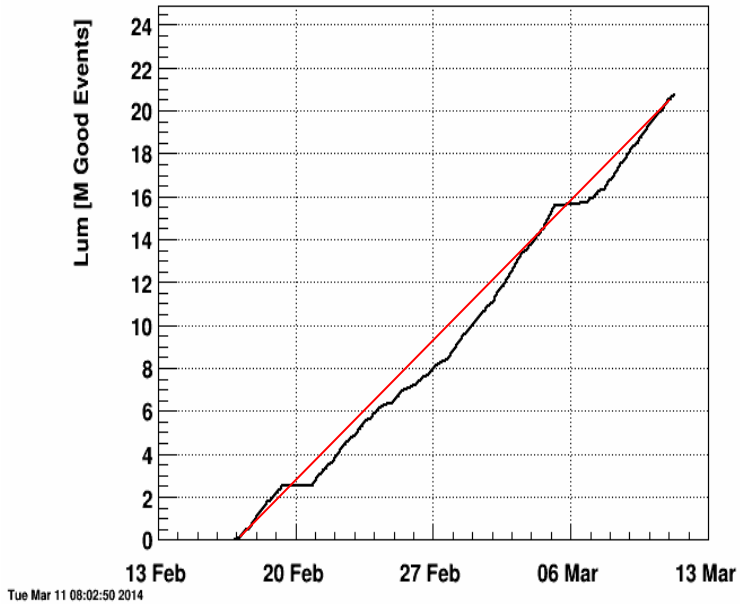
Indication of a softening of EOS around 11.5-19.6 GeV could be indicative of a 1st order phase transition

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)

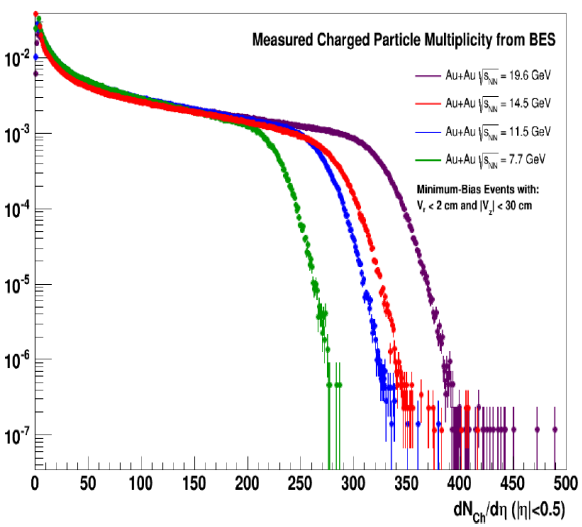
Dileptons offer a unique way to study chiral symmetry restoration and QGP thermal radiation, but dileptons are rare and require high statistics data sets ($\rightarrow$ BES II).

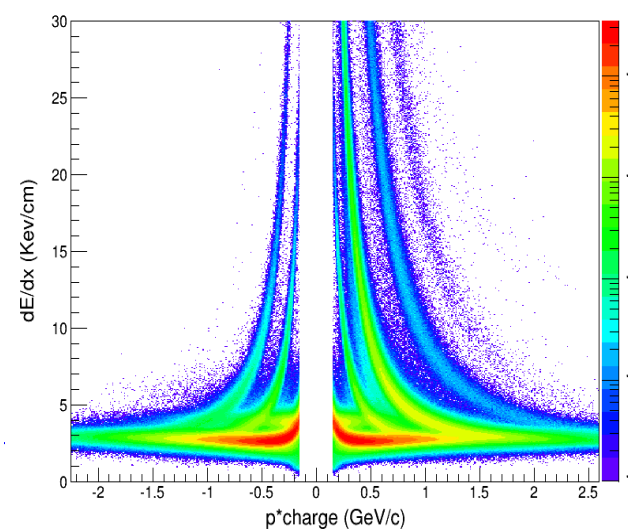
Hot off the presses: 14.5 GeV during run 14

[redacted] Goal of 20 M events met



We've recorded 24 million good TPC centered events, 21 million of which are minimum bias triggers using the Vertex Position Detector





QA:
A fast production of the data (without final calibrations) was run to ensure quality and to get a look at new physics results.

We are not done yet !

BES Phase II

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				
R_{CP} up to p_T 4.5 GeV	NA	NA	160	92	22
Elliptic Flow of ϕ meson (v_2)	100	150	200	300	400
Local Parity Violation (CME)	50	50	50	50	50
Directed Flow studies (v_1)	50	75	100	100	200
asHBT (proton-proton)	35	40	50	65	80
net-proton kurtosis ($\kappa\sigma^2$)	80	100	120	200	400
Dileptons	100	160	230	300	400
Proposed Number of Events:	**100**	**160**	**230**	**300**	**400**

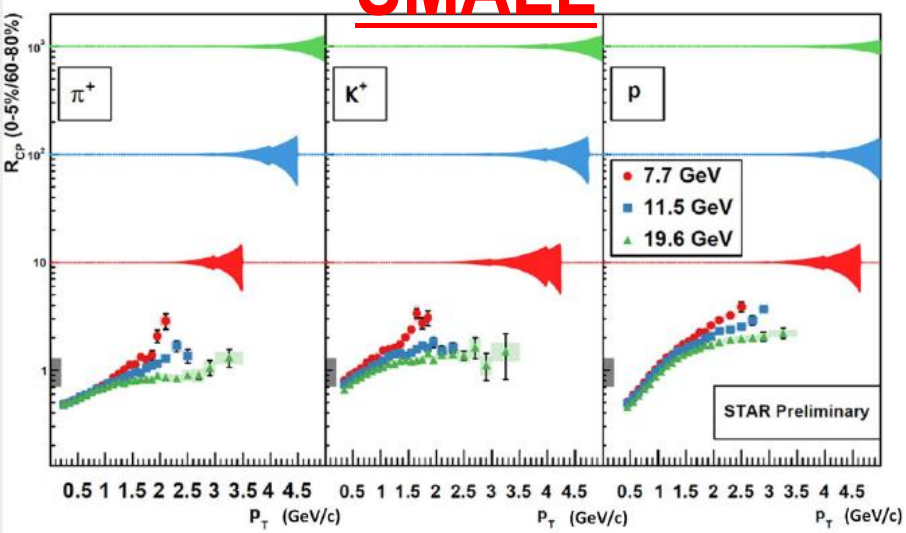
QGP

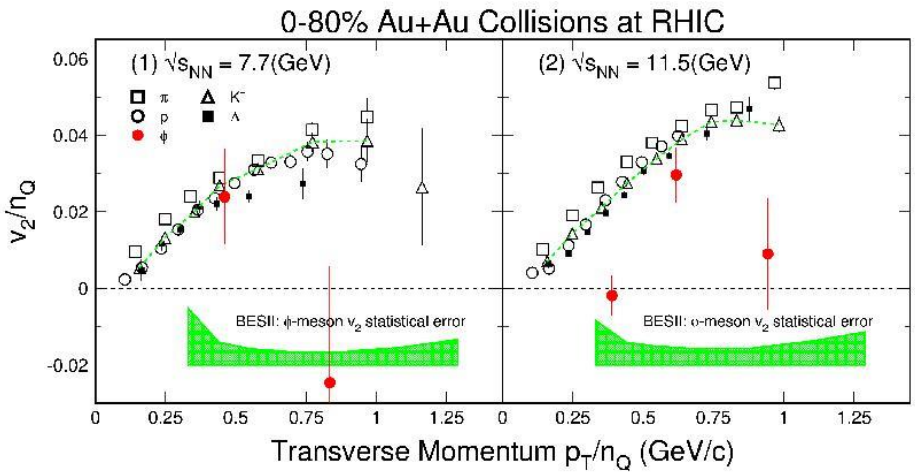
1st P.T.

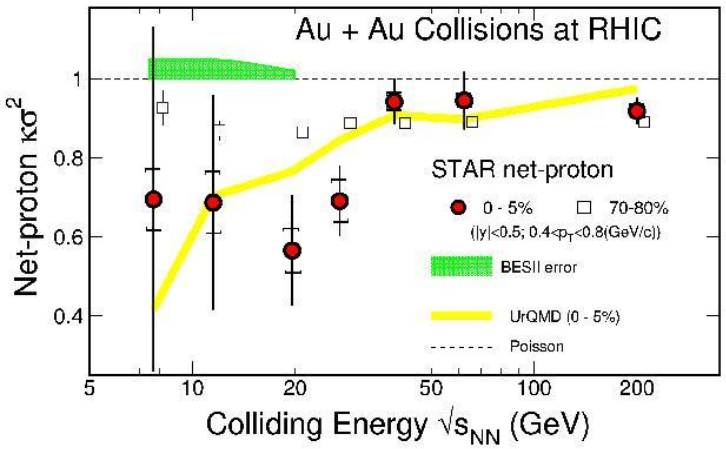
C.P.

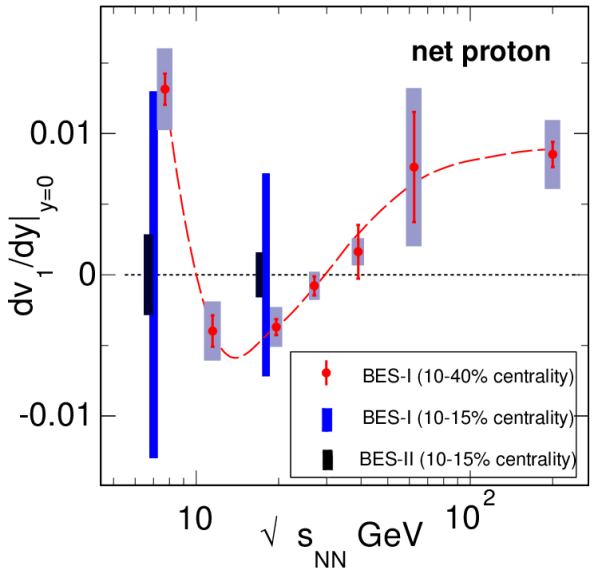
EM Probes

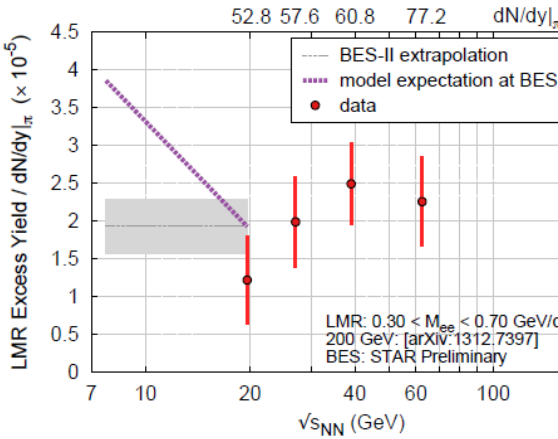
BES II measurement errors will be **SMALL**









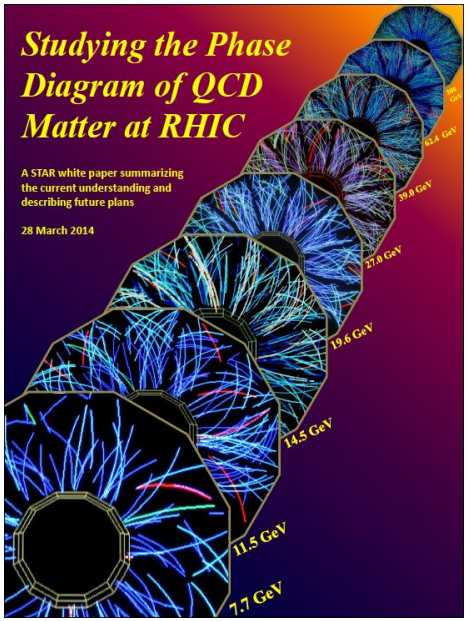


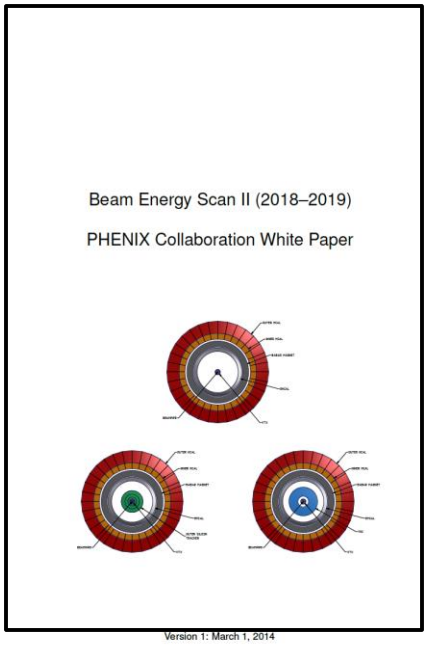
BES II

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

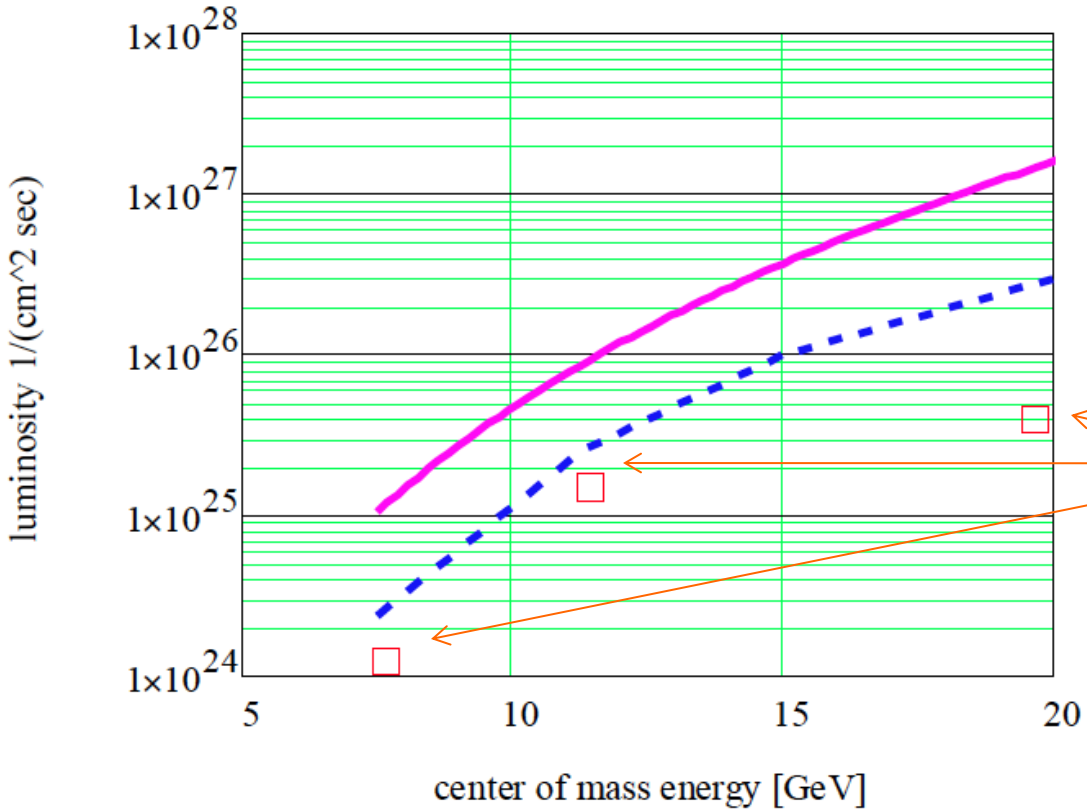
STAR





PHENIX

Luminosity improvements for BES II



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

Minimum projection (e-cooling only)

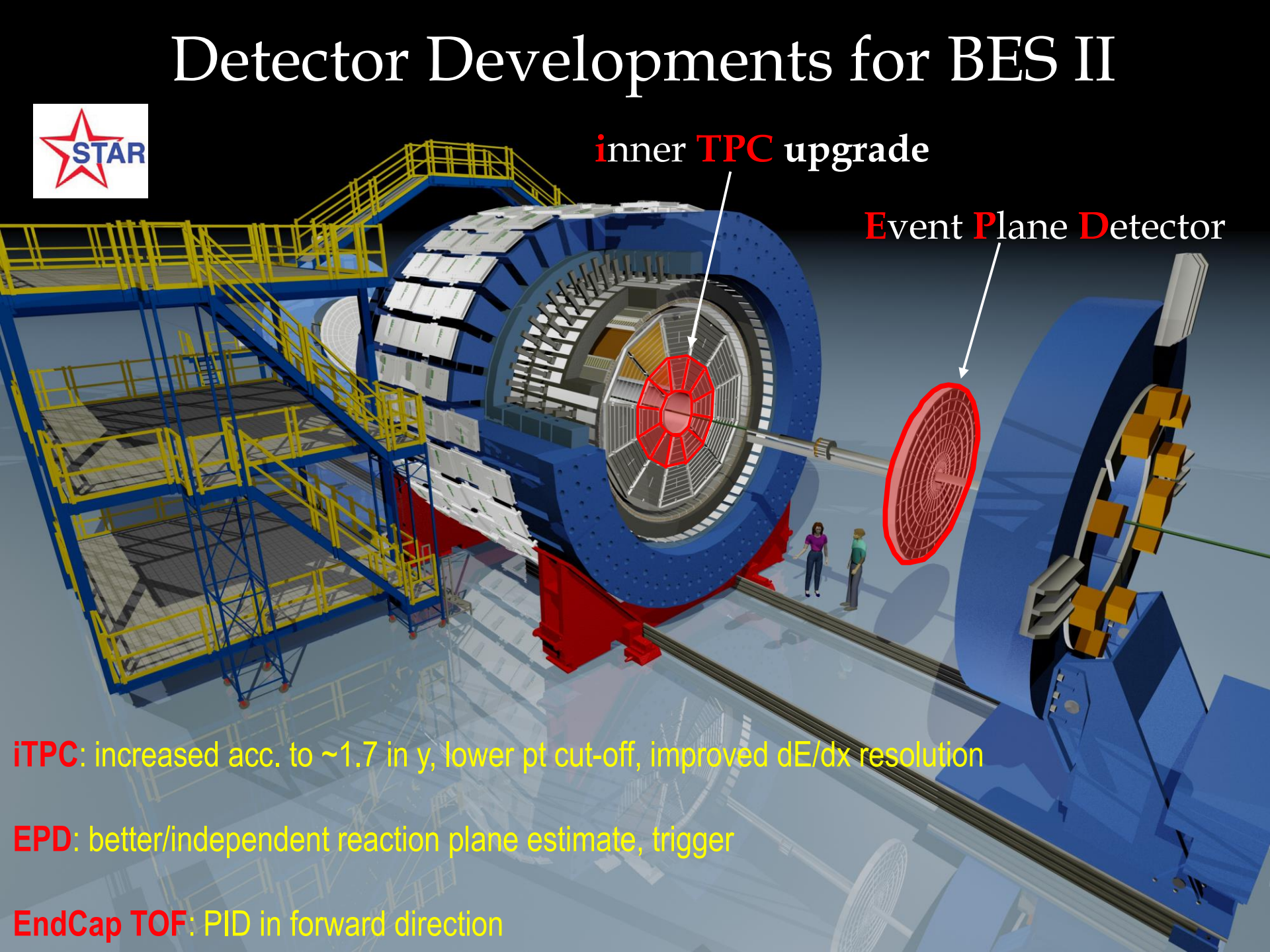
BES I performance

Implementation:
2018 - $\sqrt{s_{NN}}$ 5 - 9 GeV
2019 - $\sqrt{s_{NN}}$ 9 - 20 GeV

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

Every energy available with electron cooling

Detector Developments for BES II



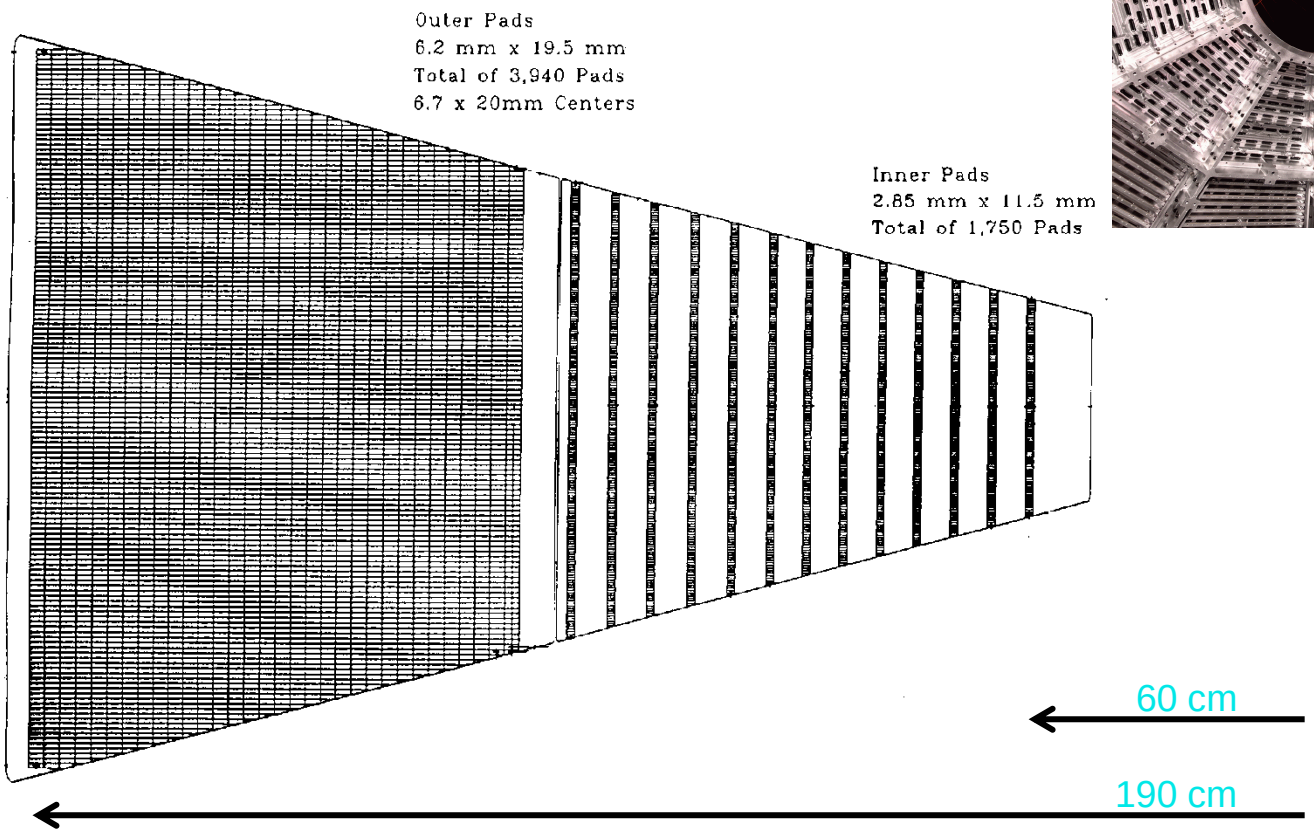
iTPC: increased acc. to ~1.7 in y, lower pt cut-off, improved dE/dx resolution

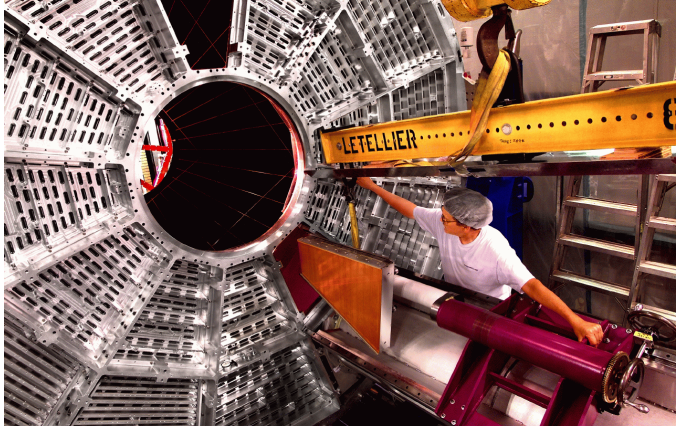
EPD: better/independent reaction plane estimate, trigger

EndCap TOF: PID in forward direction

iTPC

Inner sectors upgrade



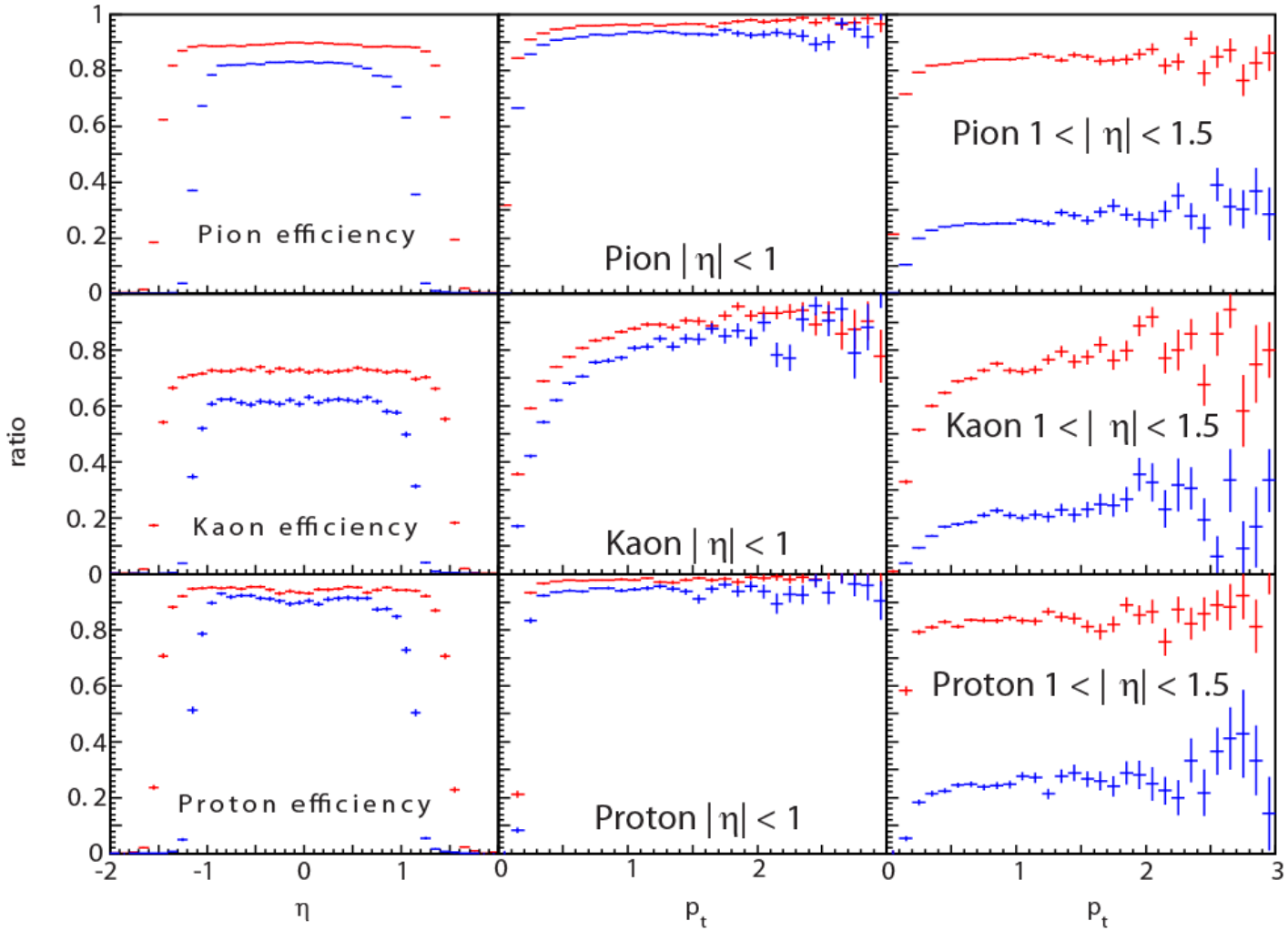


The outer pad plane is hermetic … while the inner pad plane is not

- 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 upgrade - improved acceptance at high η



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

iTPC improvements ⇒ better physics

- Plan: Hermetic coverage; add pads & rows on the inner sectors
  - 2x increase of electronics channels

- Plan: Lower mass in the internal area of the sector
  - Move the readout electronics to the edges of the sector
  - Lighter support structures

- 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

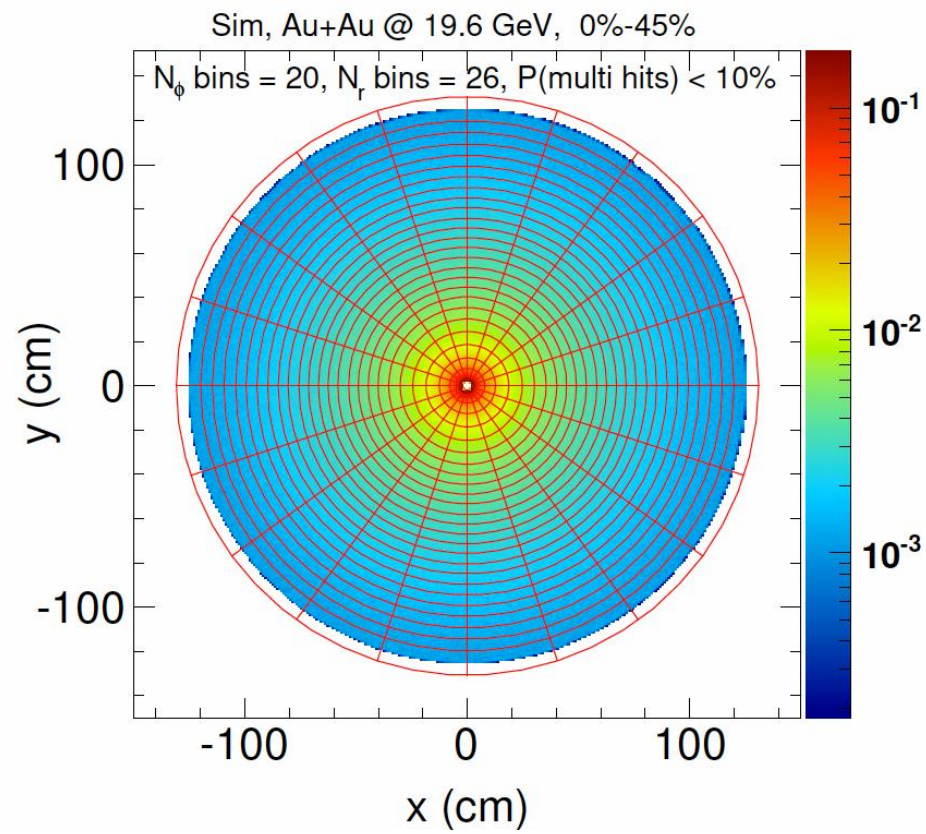
- Simulations suggest reduction in self-correlations and improved reaction plane resolution by factor of 2
  - Especially important in v_2 studies with BES II

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



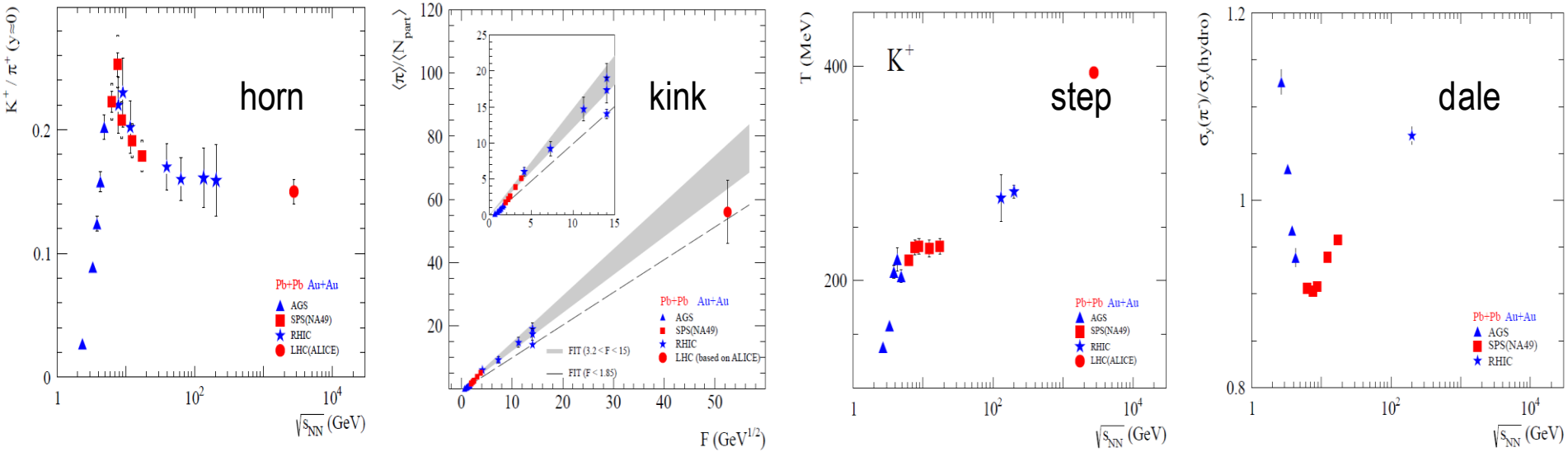
- Pie shape detector is optimal
  - symmetry, η segmentation
- Detector will be optimized for a limited number of different tile shapes for cost effectiveness
- Large area coverage
  - plastic scintillator (fast, efficient, cheap)
- Silicon PhotoMultiplier (SiPM)
  - for readout of tiles
  - cheap, equivalent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

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*



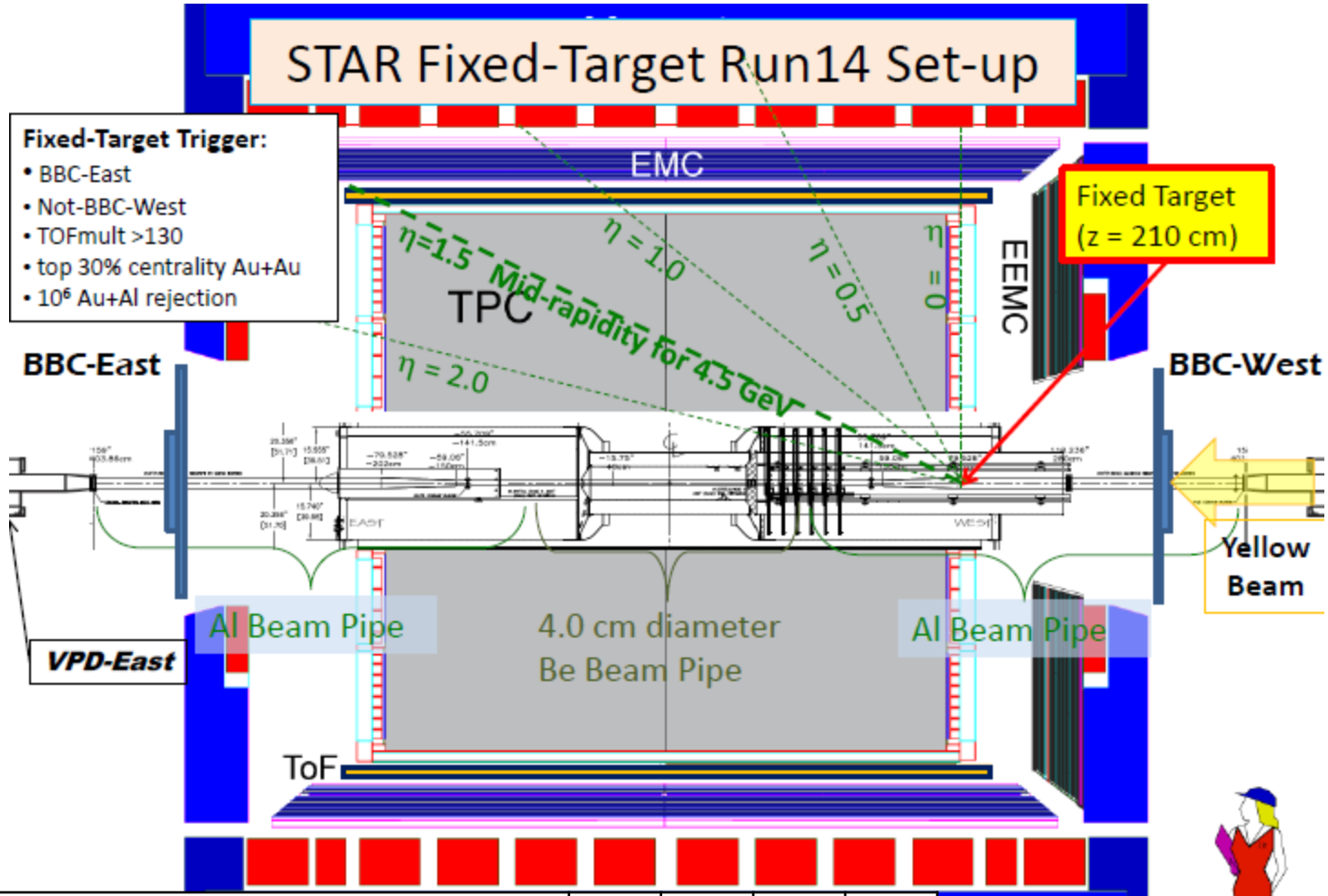
NA49: onset of deconfinement occurs at ~ 7.7 GeV

-> 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

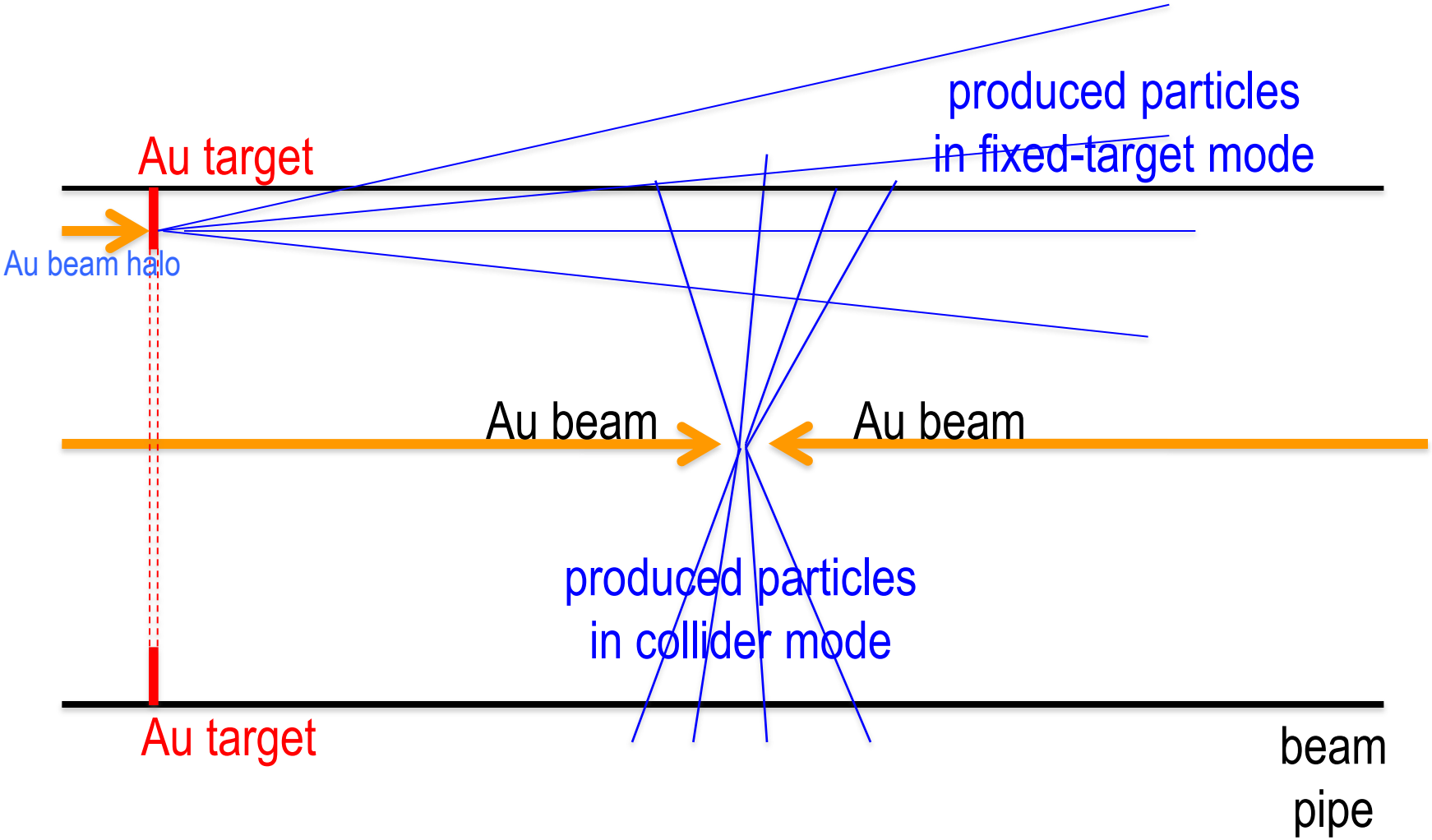
20 MeV< μ_B<720 MeV



- 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"

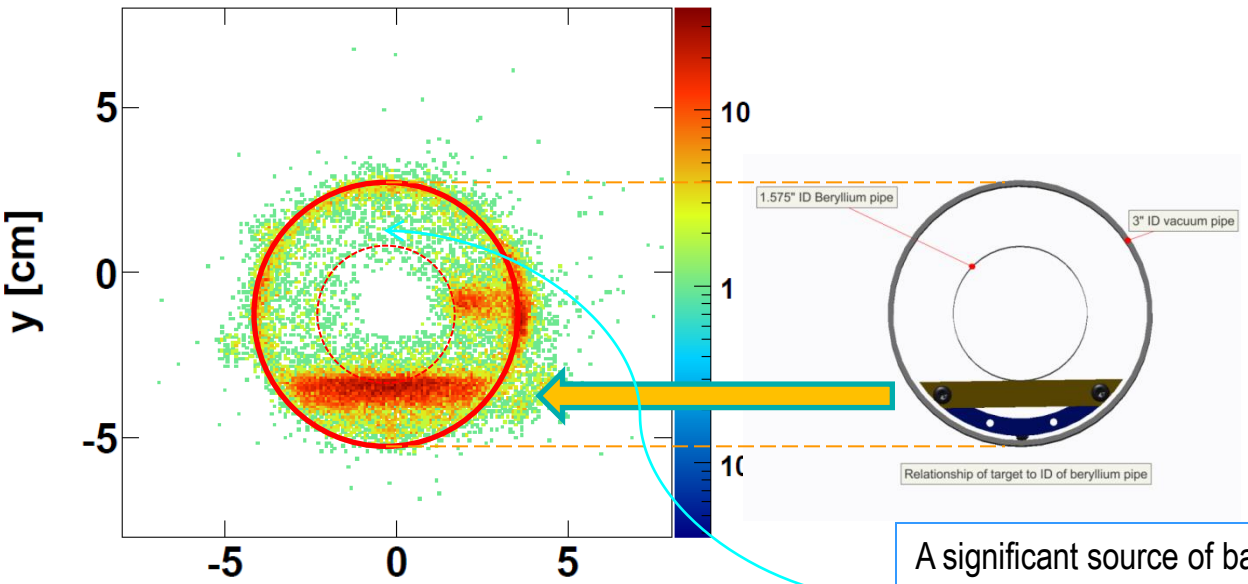
Collider mode Energies (GeV)	7.7	11.5	***14.5***	19.6
Fixed Target $\sqrt{s_{NN}}$ (GeV)	*3.0*	*3.5*	***3.9***	*4.5*
Fixed Target μ_B (MeV)	*720*	*670*	***633***	*585*

Fixed-target: schematics of concurrent running in STAR



fixed-target events taken while waiting for collider mode collisions

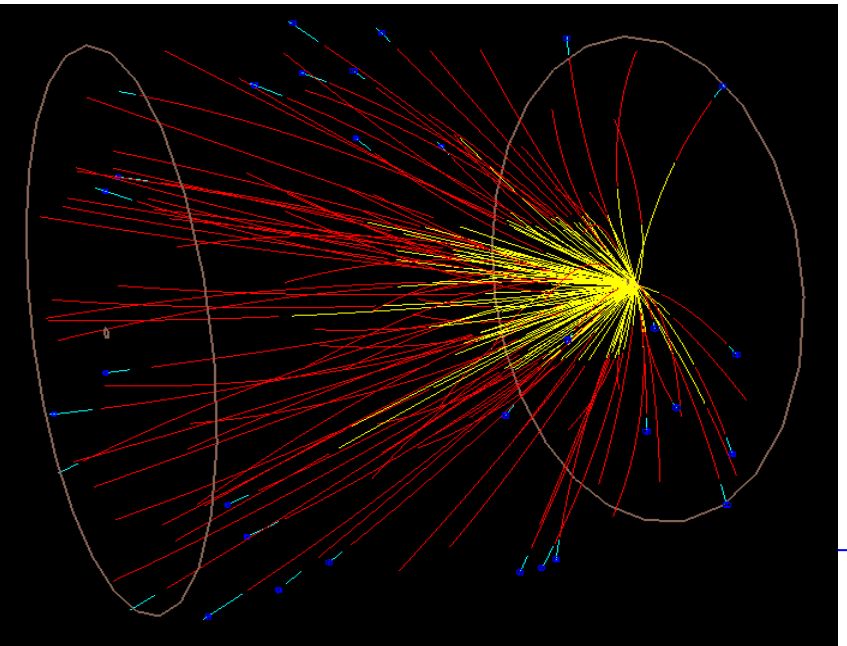
Au target is in place: 3.9 GeV Au+Au event in STAR (2014)



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.



Reconstructed tracks for an event coming from the fixed gold target

-tracking and PID looks good

-50 k events

-spectra analysis possible

Summary / Outlook

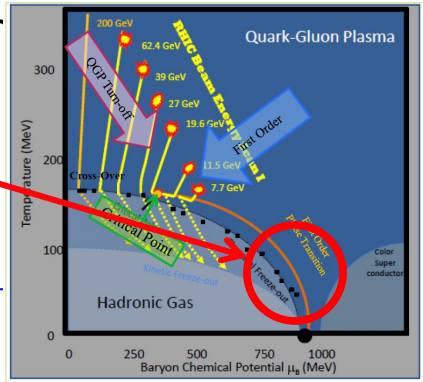
Many interesting STAR results have come out of the BES-I

- 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

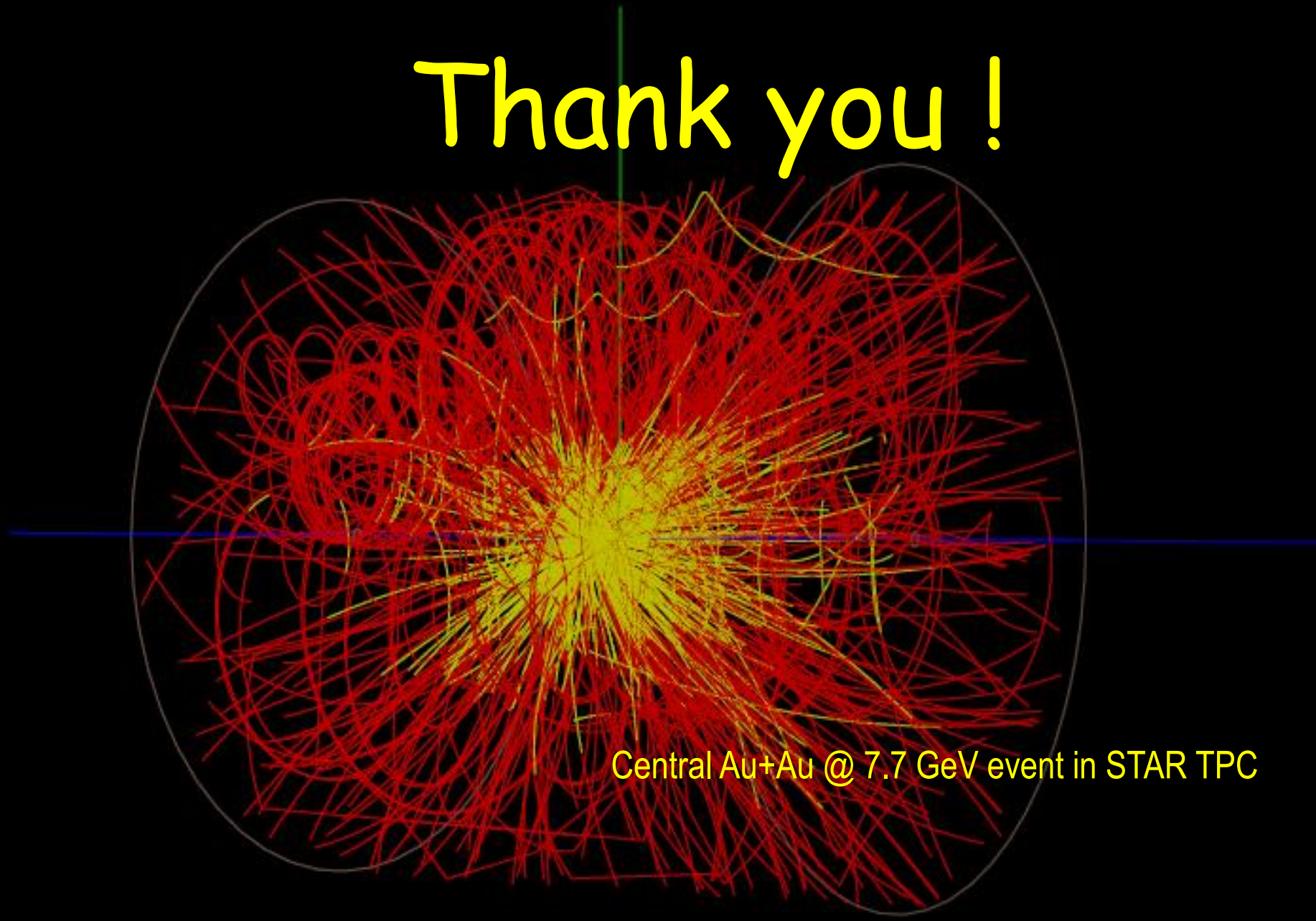
BES Phase II will make new physics accessible, particularly at the lowest collision energies

- high p_T probes, higher moment fluctuations, dileptons, ϕ v_2, etc
- will include fixed-target program which may 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
  - allows us to evaluate the possibility of the onset of deconfinemer

STAR is actively planning for the Beam Energy Scan Phase II program: iTPC, EPD, perhaps even an endcap TOF upgrade …



Thank you !



Central Au+Au @ 7.7 GeV event in STAR TPC