BES program in STAR

and what's next …

Grazyna Odyniec

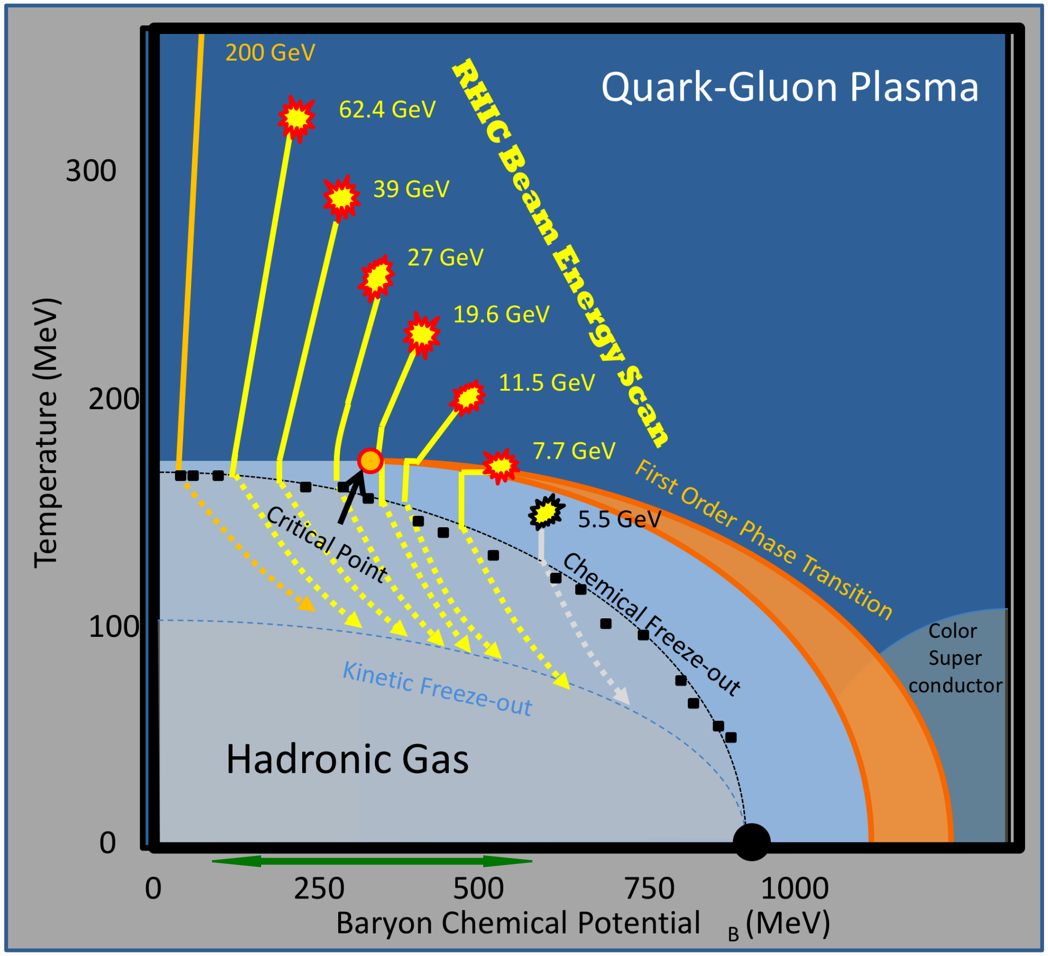
Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

1. Introduction and motivations
2. Phase I - some results
   - what questions are we able to answer ? **
3. Phase II* (completion of BES program)

*work in progress

**some light at the end of the tunnel … ?

Beam Energy Scan at RHIC: $\sqrt{s_{NN}}$ ~ 5-50 GeV



160 MeV<μ_B<500 MeV

We built RHIC to find QGP.

And we did it !

but,

QGP- new and complicated phase of matter with unique and unexpected properties

Huge progress in understanding its nature:

@high energy – cross over transition

@lower – should be 1st order transition

→ **critical point** could exist (?)

→ **BES program was born**

With RHIC beams:

(1) Study properties of sQGP

(2) Map out QCD matter phase structure

Structure of QCD matter phase diagram is

fundamental

(will be in text books in future decades)

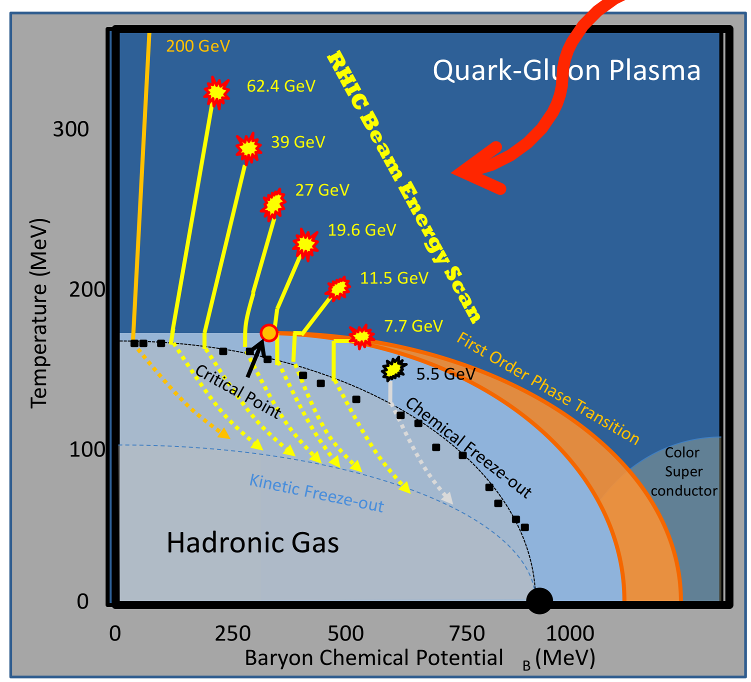
Three BES goals:

1. Search for the QCD critical point
2. Search for the signals of 1st order phase transition (/phase boundary)
3. Search for turn-off of sQGP signatures

Year	$\sqrt{s_{NN}}$ (GeV)	Events (10^6)
2010	39	130
2011	27	70
2011	19.6	36
2010	11.5	12
2010	7.7	5

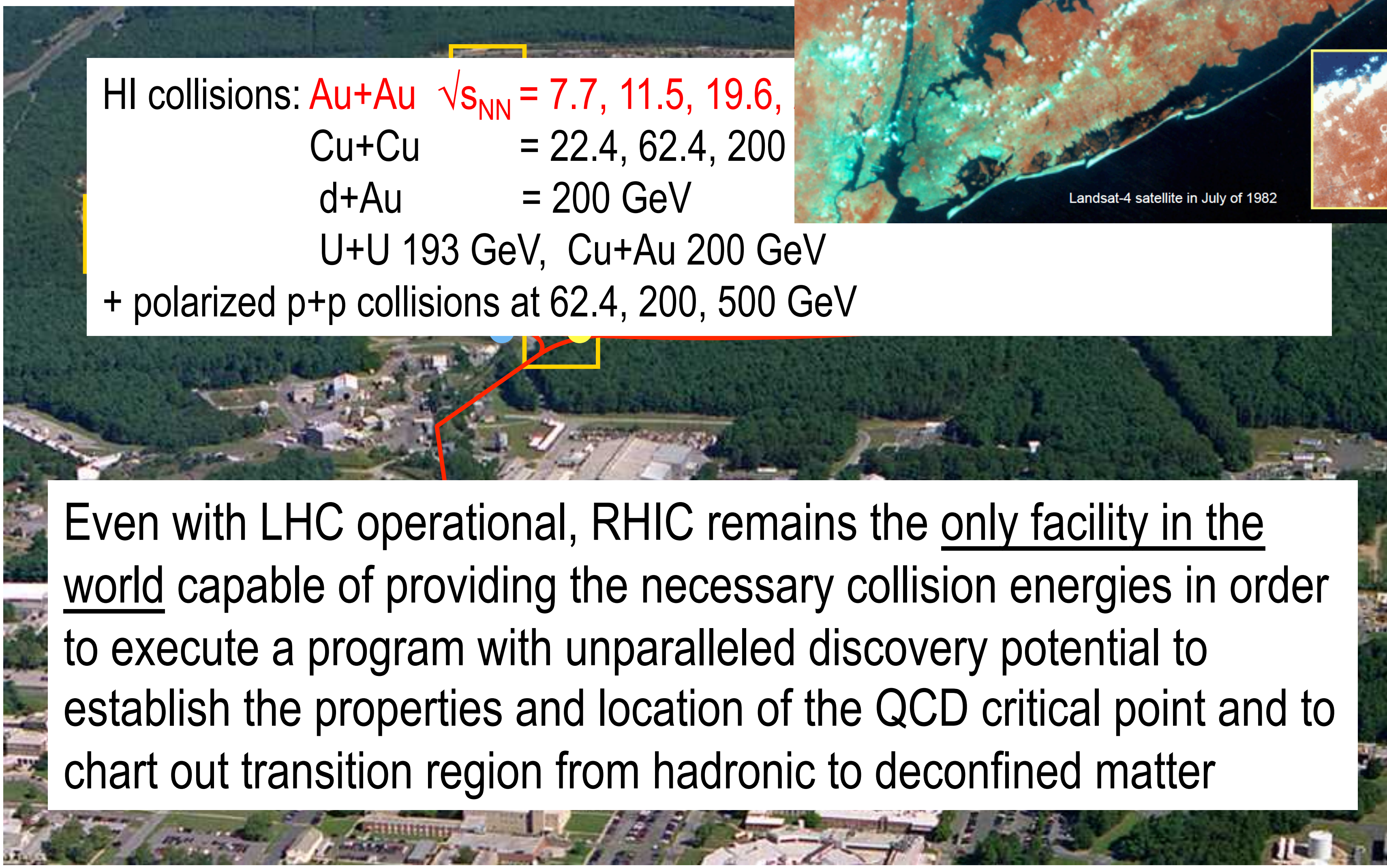
\+ 2012 5 test

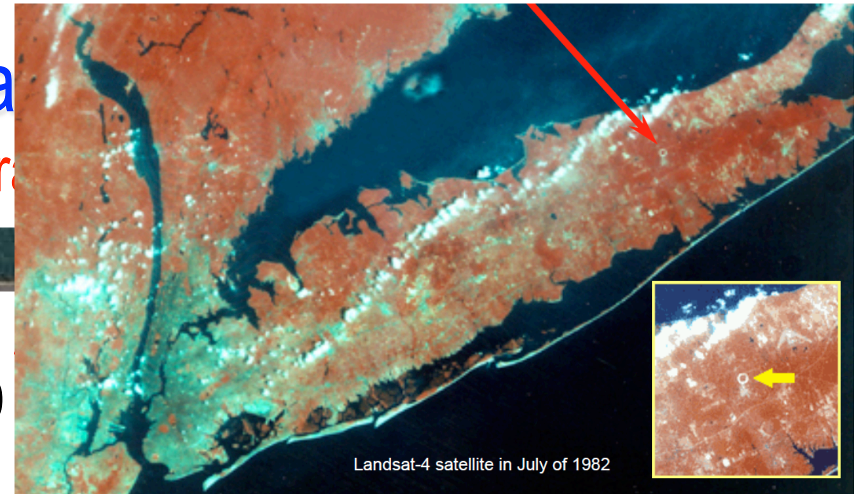
→ Where are we probing on the QCD Phase Diagram ?



RHIC (Relativistic Hea

has a special and unique role in explor





HI collisions: Au+Au $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6,

Cu+Cu = 22.4, 62.4, 200

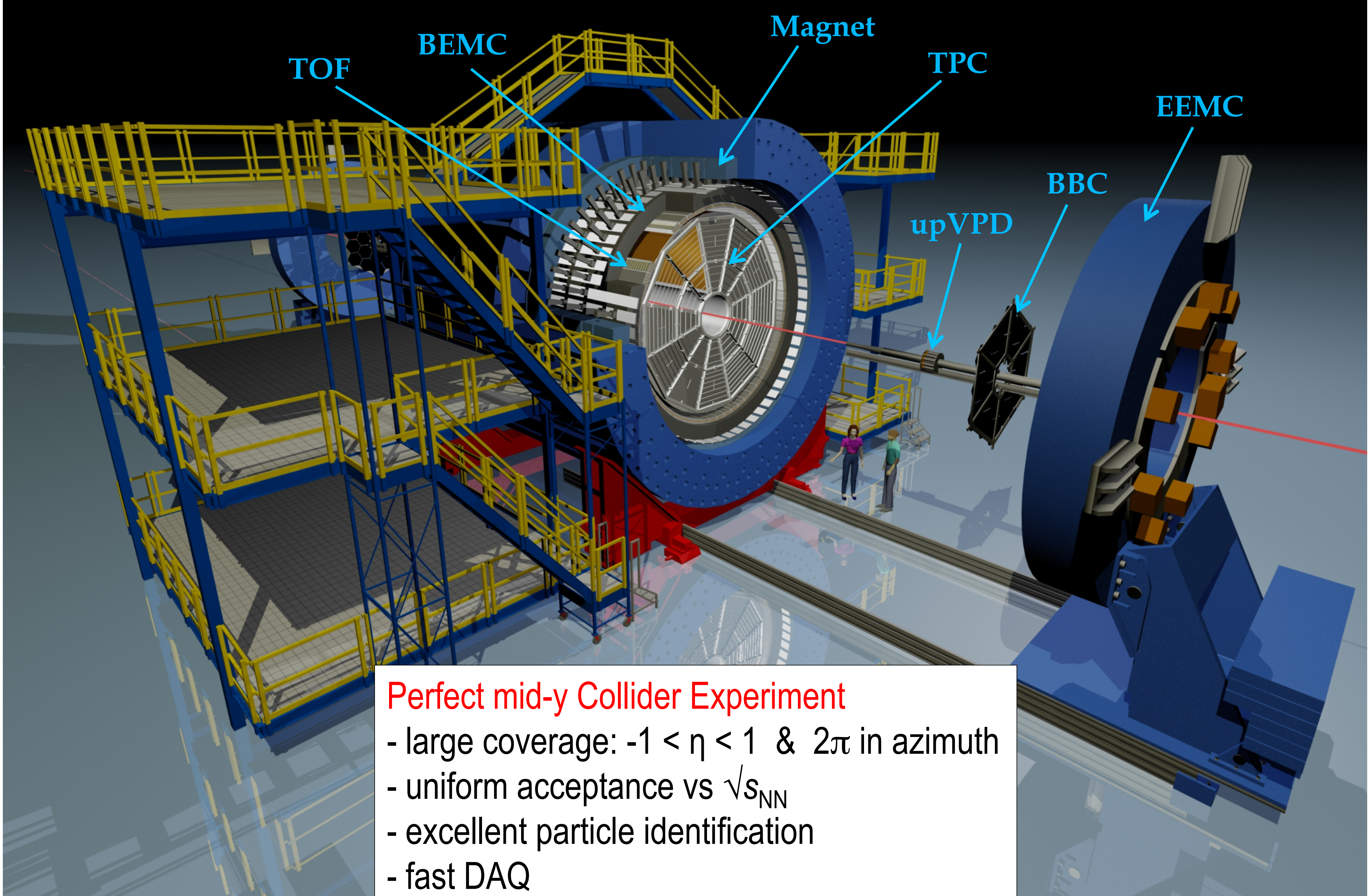
d+Au = 200 GeV

U+U 193 GeV, Cu+Au 200 GeV

+ polarized p+p collisions at 62.4, 200, 500 GeV

Even with LHC operational, RHIC remains the only facility in the world capable of providing the necessary collision energies in order to execute a program with unparalleled discovery potential to establish the properties and location of the QCD critical point and to chart out transition region from hadronic to deconfined matter

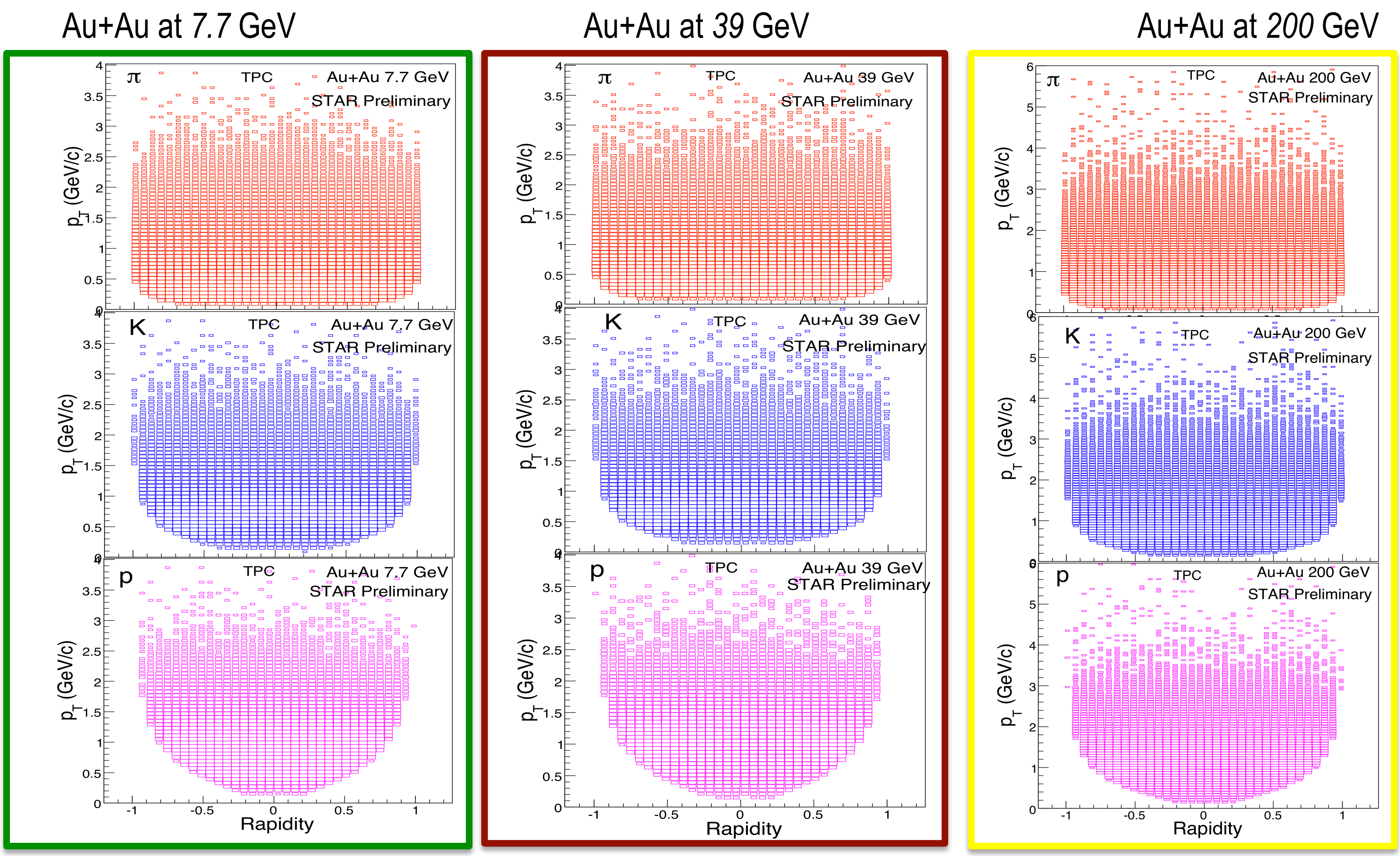
The Solenoid Tracker At RHIC (STAR)



Perfect mid-y Collider Experiment

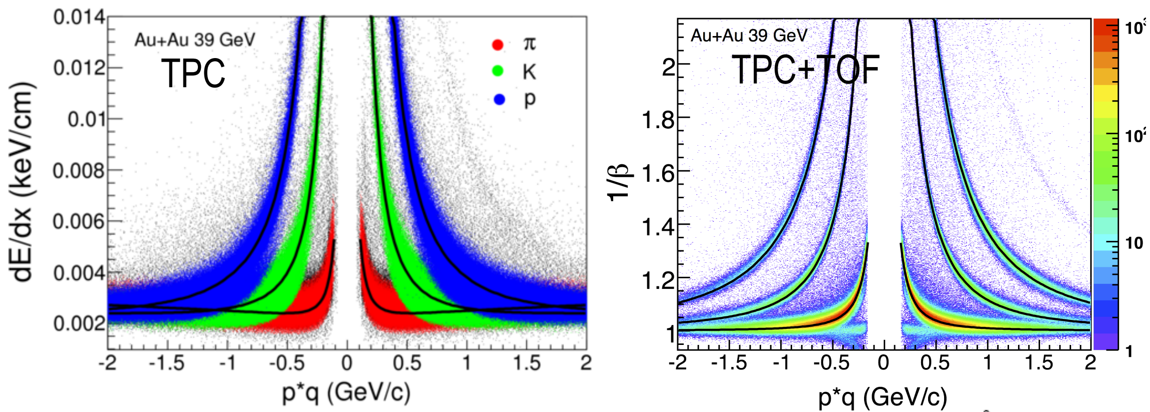
- large coverage: $-1 < \eta < 1$ & 2π in azimuth
- uniform acceptance vs $\sqrt{s_{NN}}$
- excellent particle identification
- fast DAQ

Identified Particle Acceptance at STAR



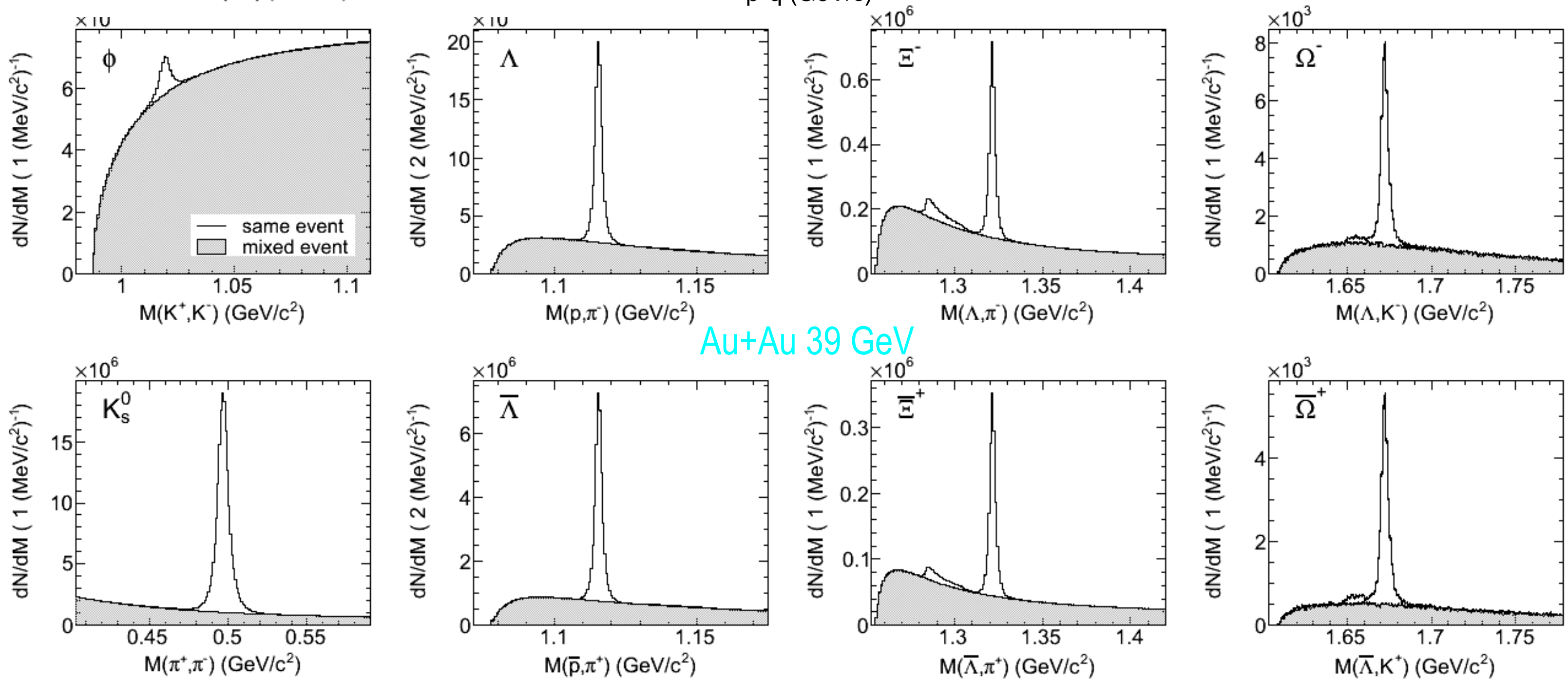
At collider geometry - similar acceptance for all particles and energies

Particle Identification



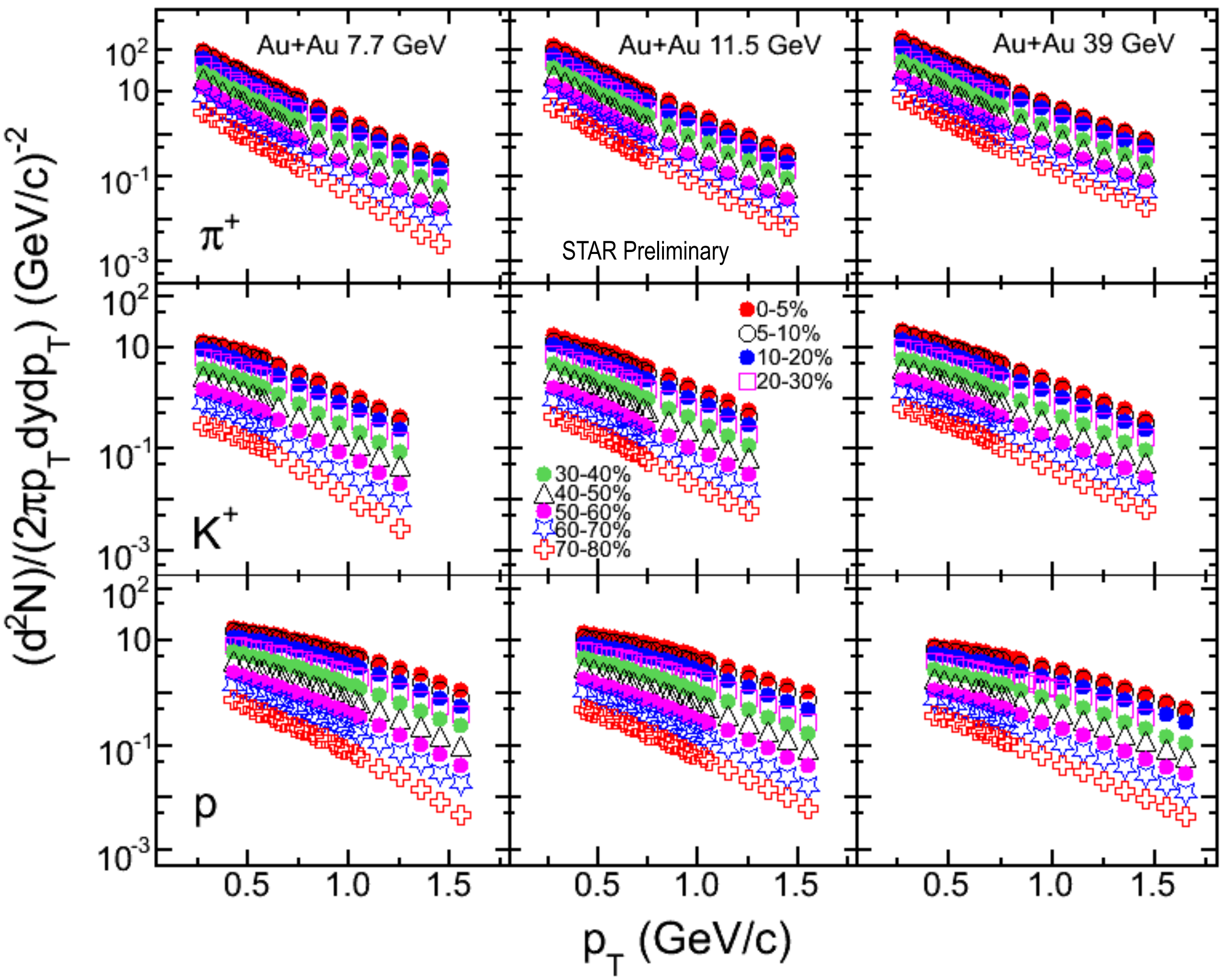
PID (TPC+TOF):
pion/kaon: p_T~1.6 GeV/c
proton p_T~3.0 GeV/c

Strange hadrons: decay topology & invariant mass



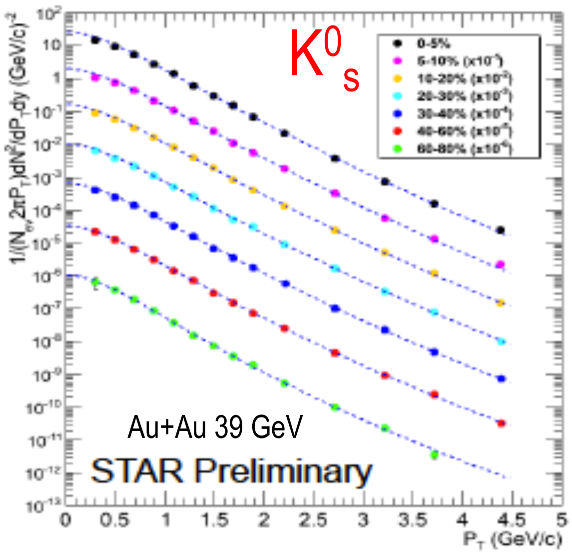
Environment

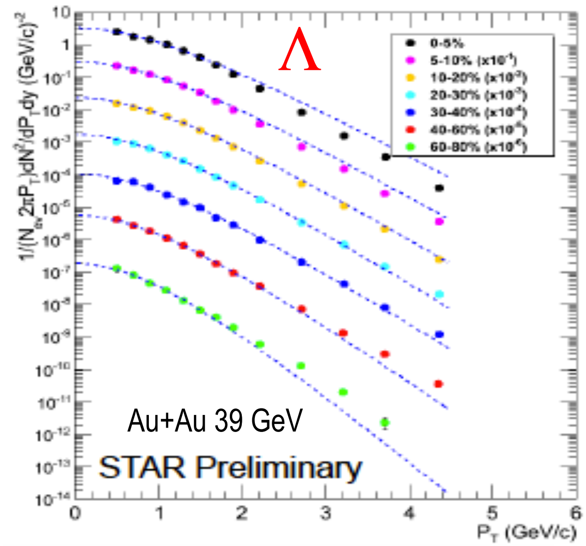
Spectra: π, K, p

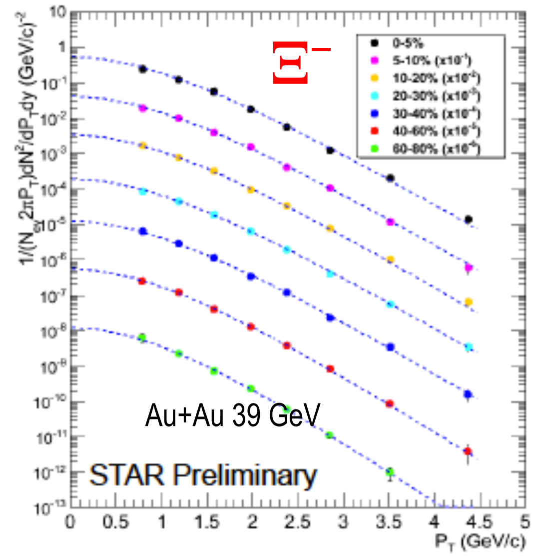


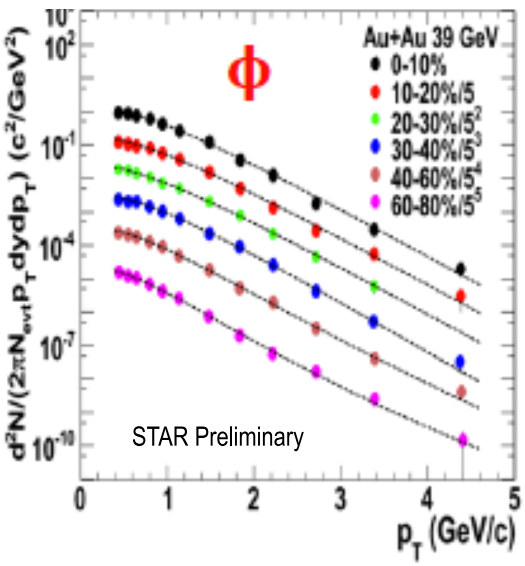
π, K, p yields within measured p_T ranges: 70-80% of total yields

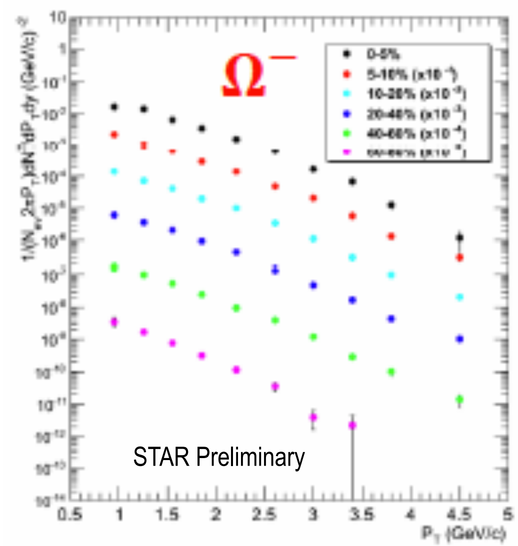
Spectra : strange hadrons











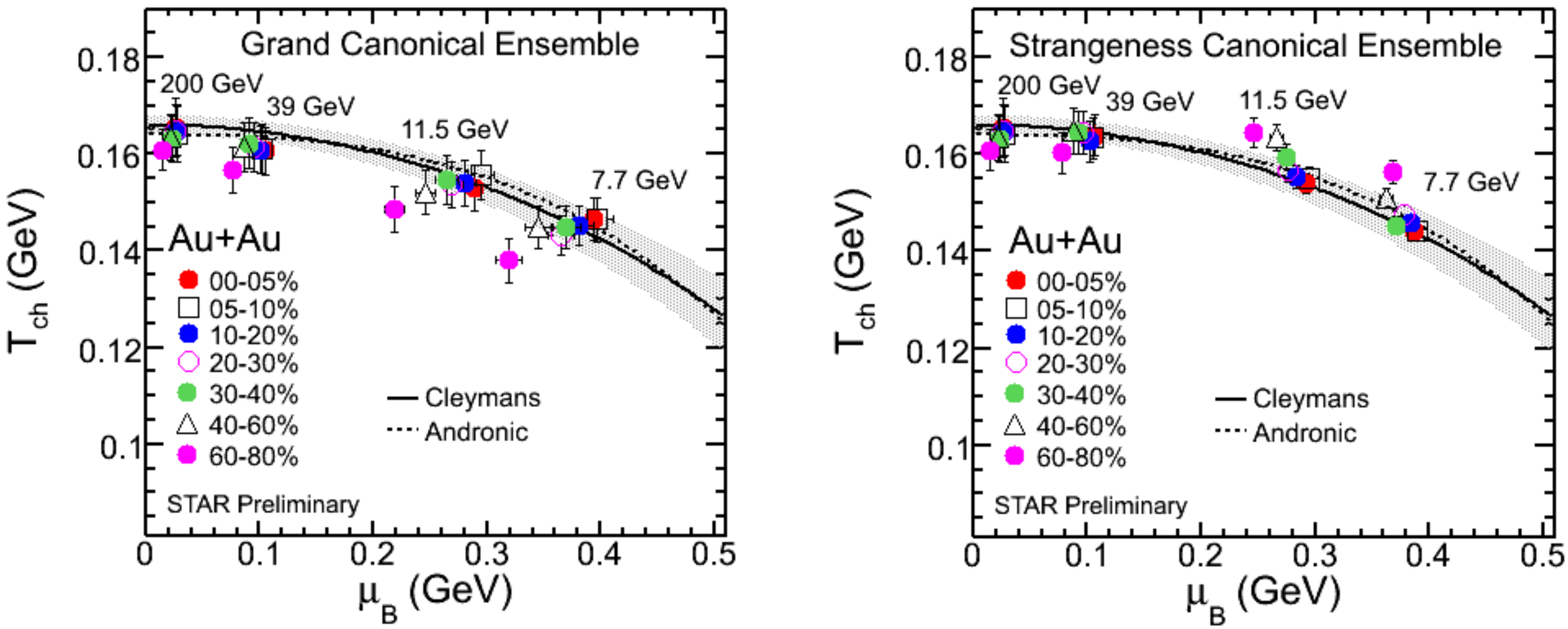
ϕ, K^0_s: Levy function fit

Λ, Ξ : Boltzmann fit

Λ: feed-down corrected

Chemical freeze-out parameters extracted from spectra and ratios of measured particles with THERMUS fits

(Wheaton and Cleymans, Comput. Phys. Commun. 180, 84 (2009))



BES data (Phase I) extends relevant region of QCD Phase Diagram from μ_B= 20 MeV to ~ 400 MeV ($\sqrt{s_{NN}}$ =7.7 GeV)

centrality dependence of μ_B still under study

BES: Experimental Program

STAR: *http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493,* *arXiv:1007.2613*

Obsevables:

(1) indications of the existence of Critical Point

- fluctuation measures
  - higher moments of conserved quantities (net proton distribution -> kurtosis)
  - particle ratio fluctuations

(2) signatures of phase transition (softening of EOS)

- azimuthally-sensitive femtoscopy
- direct flow v_1
- …

(3) disappearance of signals of partonic degrees of freedom seen at 200 GeV

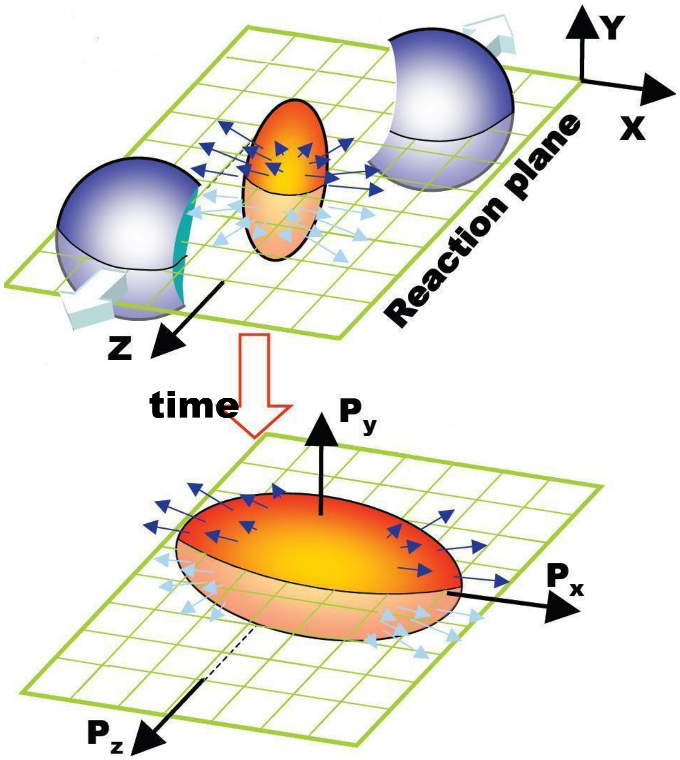
- disappearance of constituent-quark-number scaling of v_2
- disappearance of hadron suppression in central collisions
- dynamical charge fluctuations (old name: local parity violation)
- …

the easiest one …

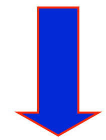
3. Turn off signatures of QGP

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

Anisotropic flow



Initial spatial anisotropy is determined by impact parameter and initial fluctuations



In early collision stages, spatial anisotropy is converted by gradient pressure and scattering to momentum anisotropy.

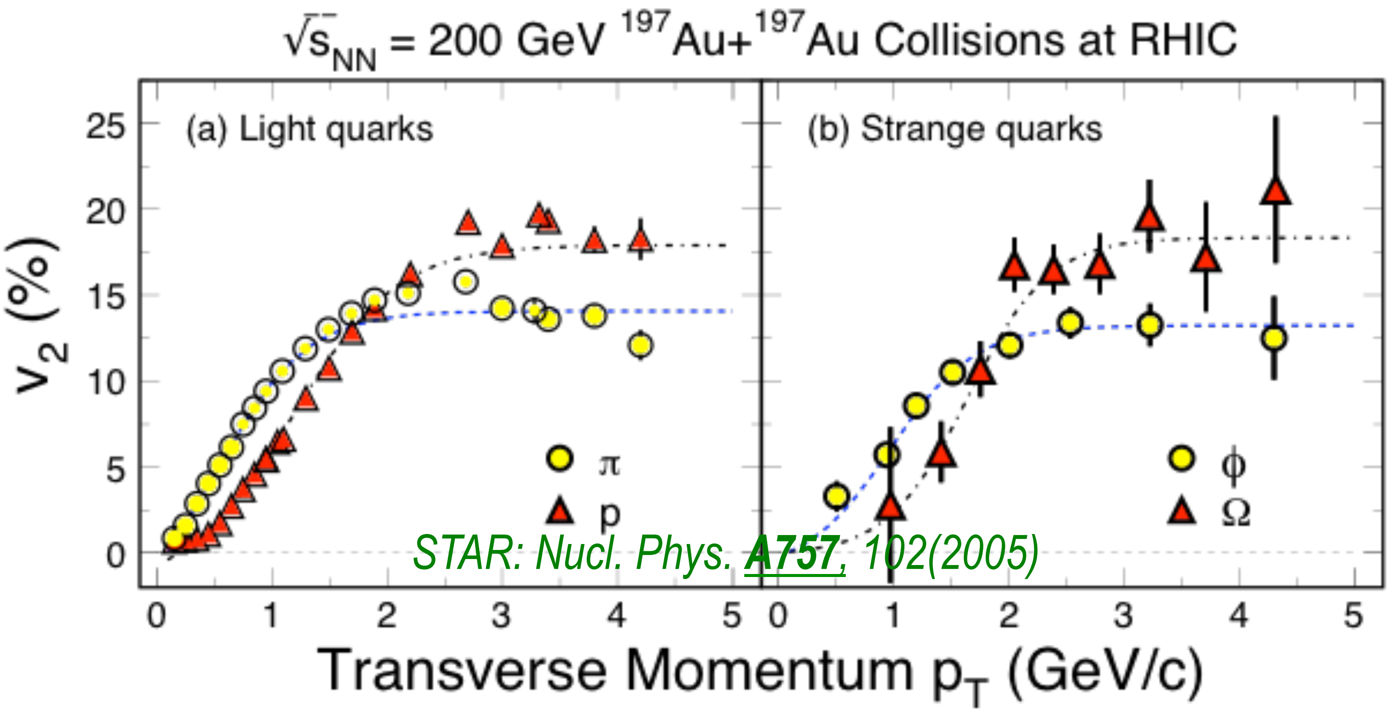
$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \psi_n)\right]\right)$$

$$v_{\mathrm{n}} = \left\langle \cos n\left(\varphi - \psi_n\right)\right\rangle, \quad n = 1,2,3..,$$

v_1: directed flow

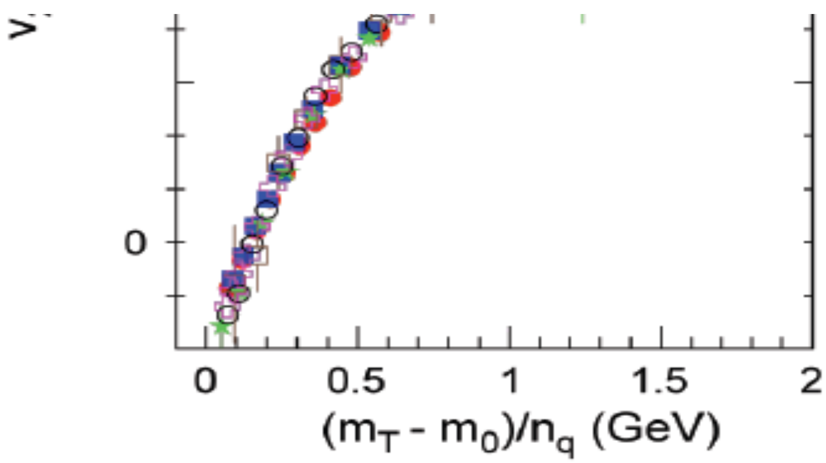
v_2: elliptic flow

v_3: triangular flow…..



t 200 GeV

ıeters by quark
s=3, mesons=2)
ıryon separation
ıns

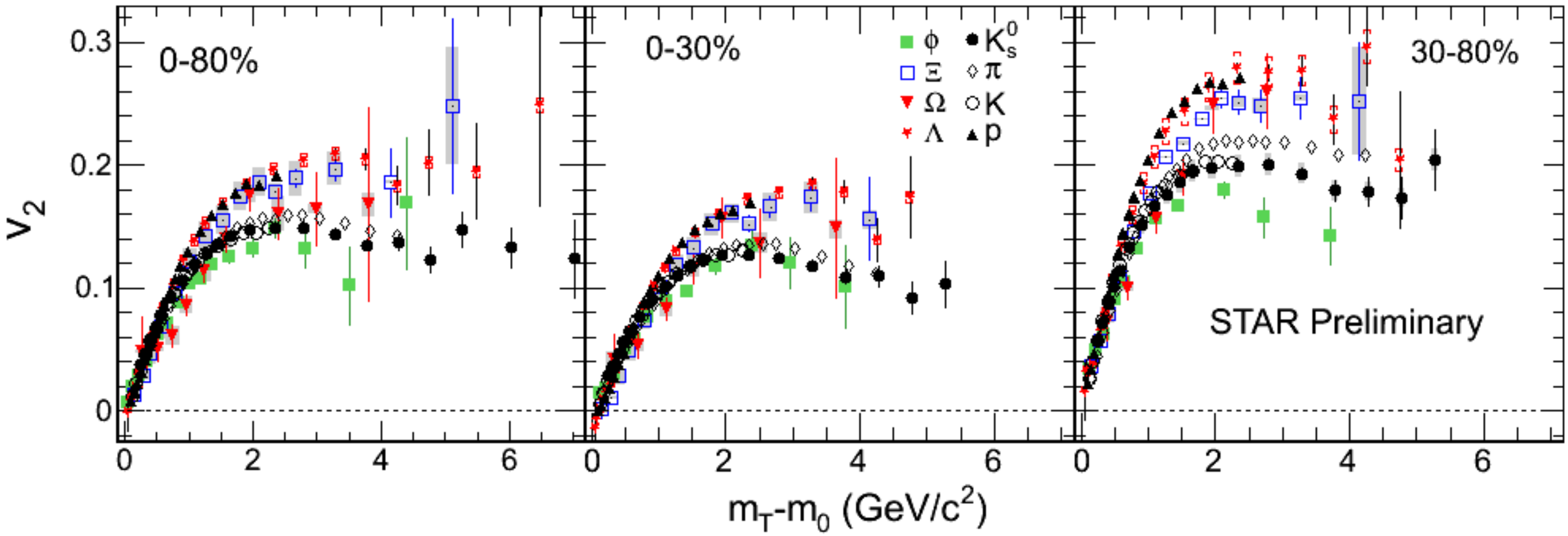


flow developed in pre-hadronic stage
DECONFINEMENT at RHIC

Identified Particle Elliptic Flow @ 200 GeV

QM 2012:

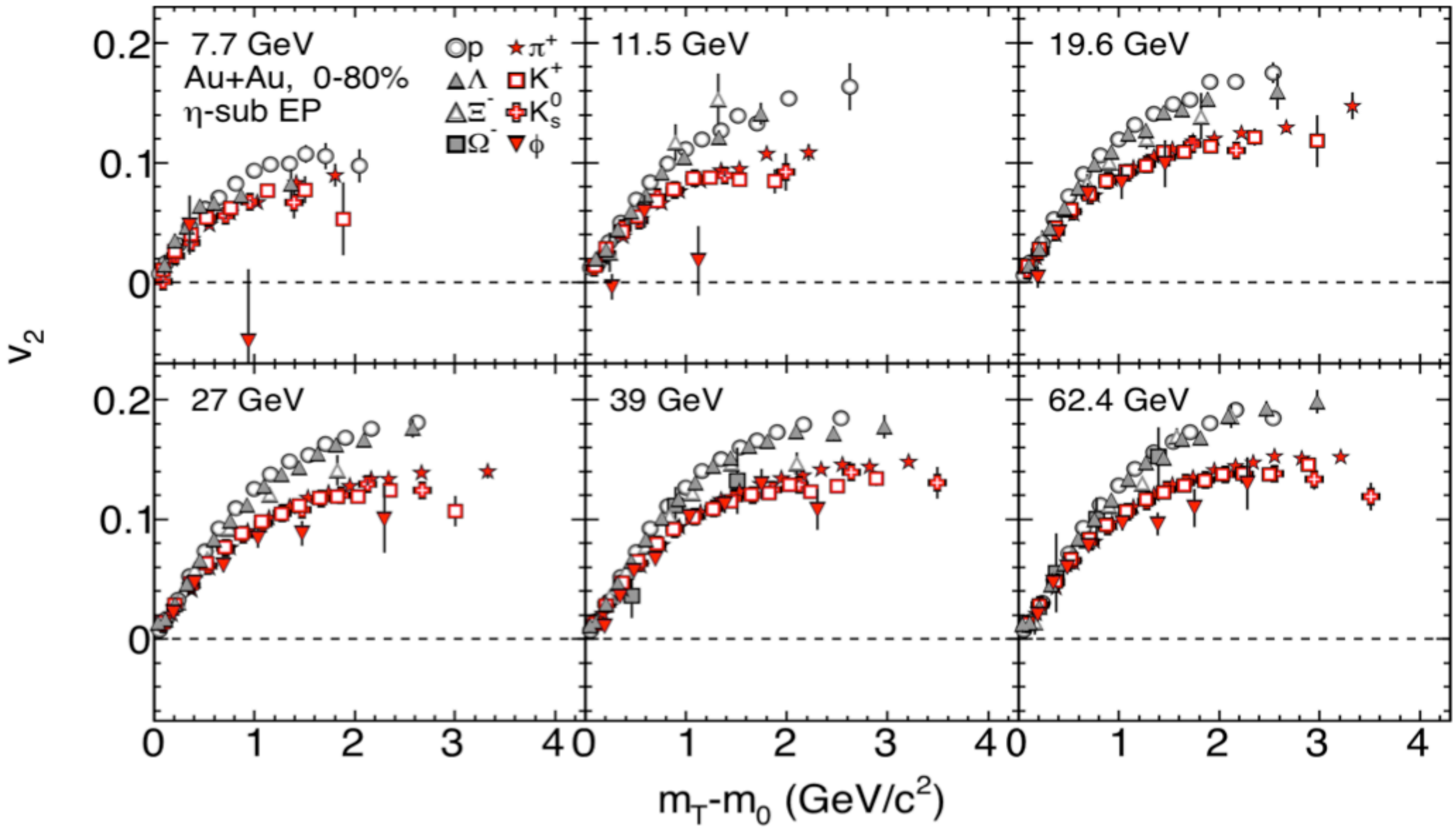
$\pi^+, \pi^-, K_s^0, p, \bar{p}, \phi, \Lambda, \bar{\Lambda}, \Xi^-, \bar{\Xi}^+, \Omega^-, \bar{\Omega}^+$



with lowering energy, disappearance of n_q scaling
(≈disaperance of partonic degree of freedom)
would suggest that we <u>exit partonic world</u>

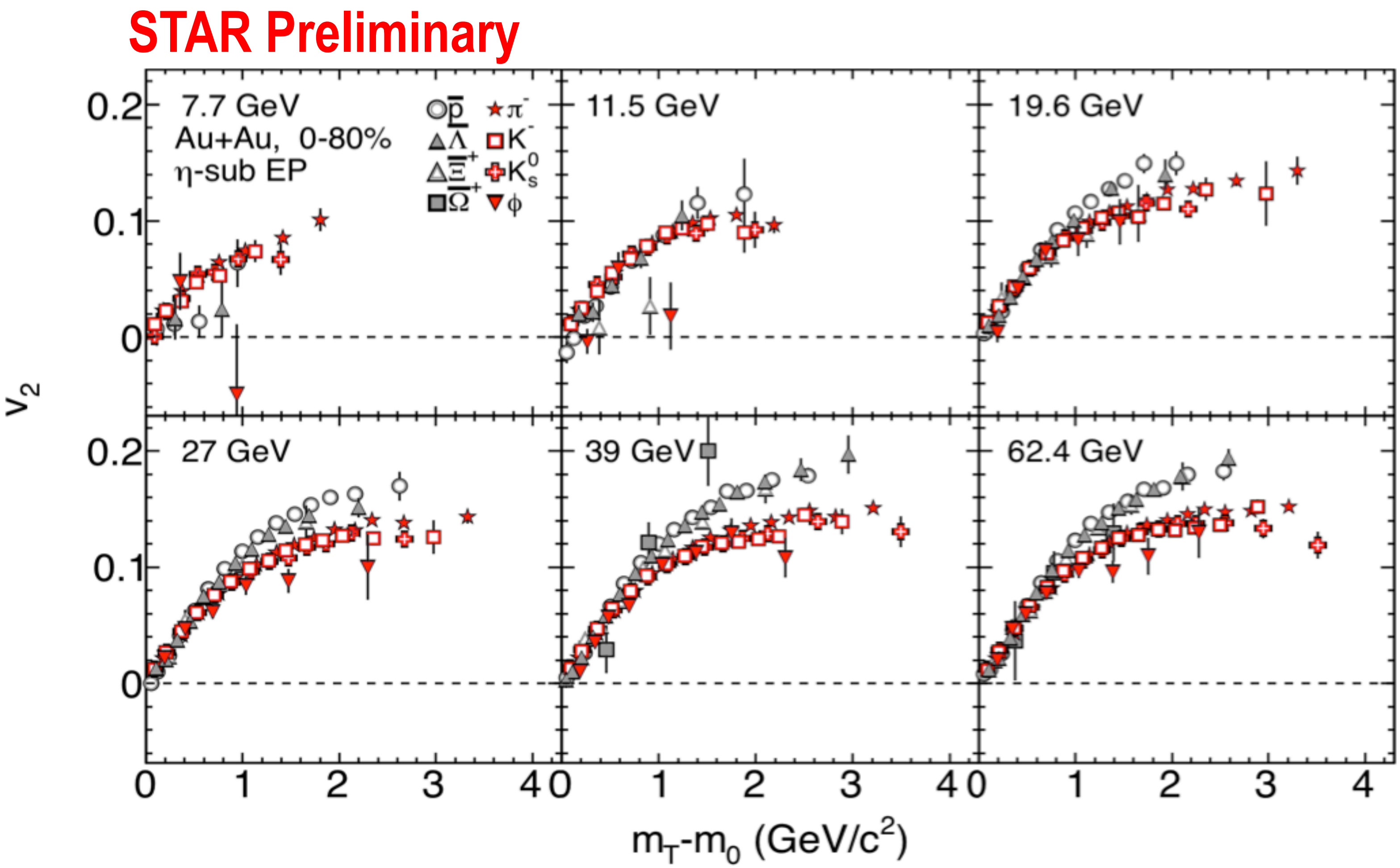
BES: v_2 of identified particles vs energy

STAR Preliminary



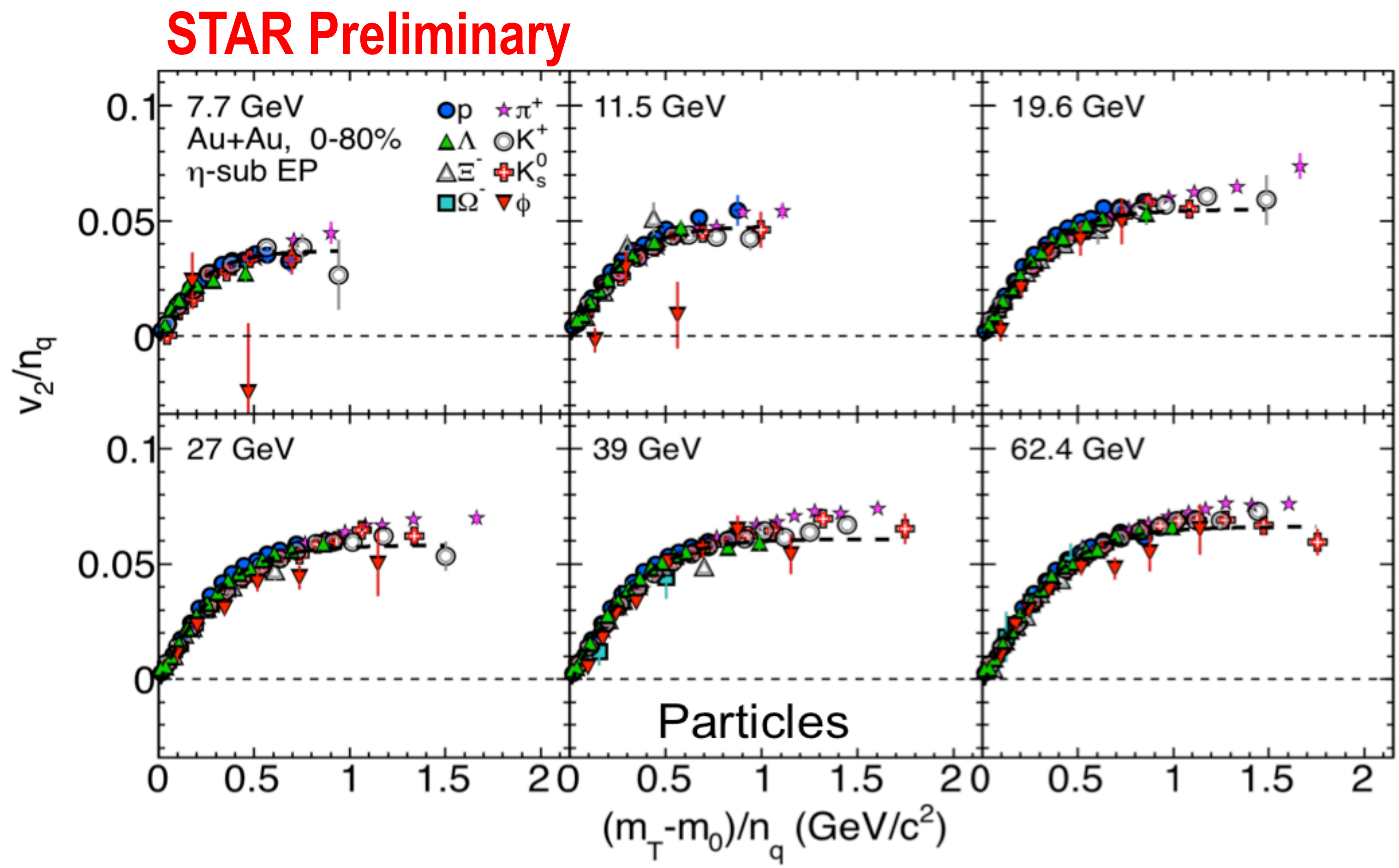
Baryon vs. meson splitting for particles decreases as we go down in $\sqrt{s_{NN}}$

BES: v_2 of identified *anti*particles vs energy



Baryon vs. meson splitting for ***anti***particles disappears at energies ≤11.5 GeV (within errors)

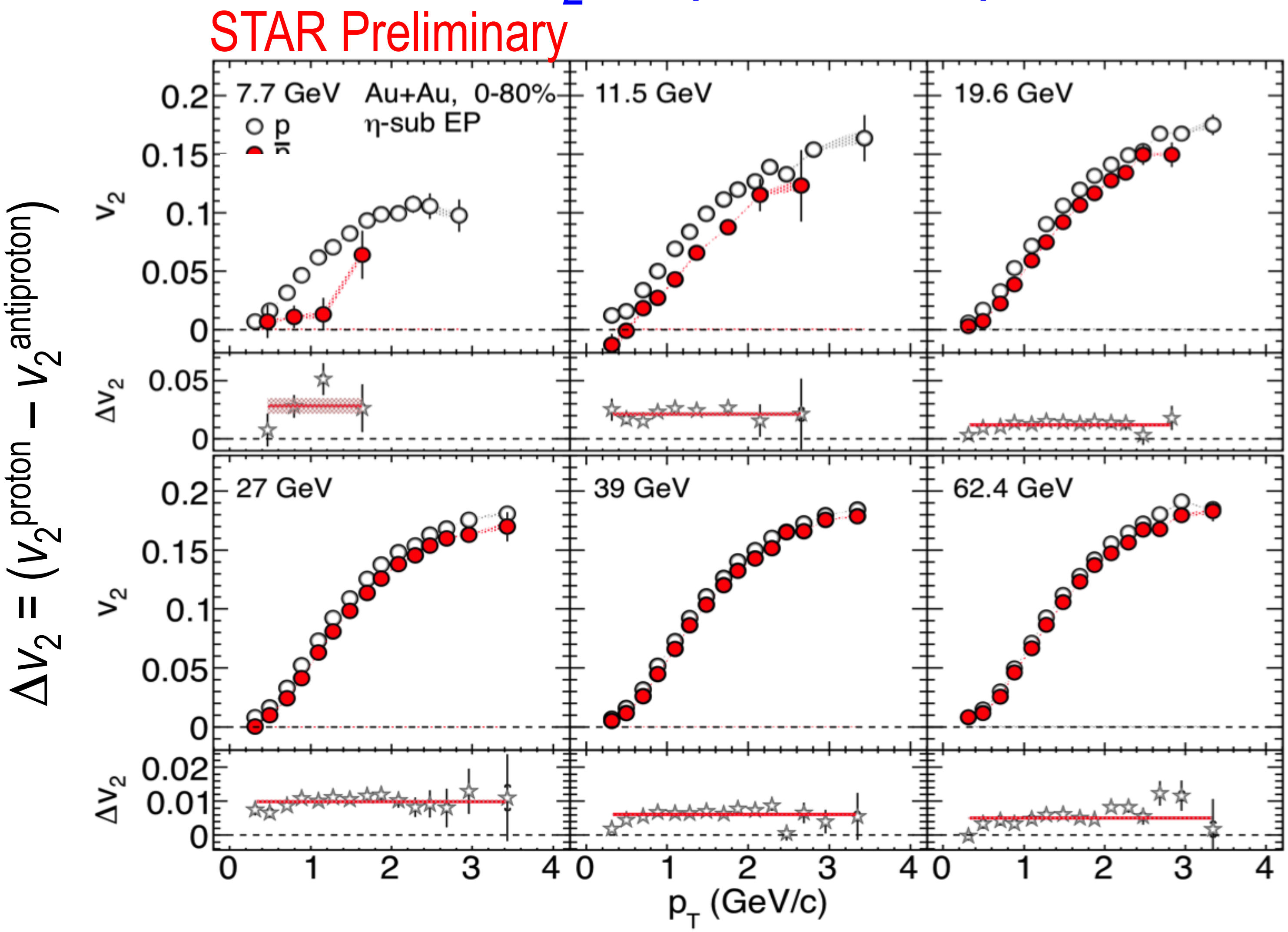
BES: n_q scaling with energy - particles



n_q scaling holds within ~10% separately for particles and *anti*particles, except ϕ

ϕ meson becomes outlier at lowest two energies – but large error bars

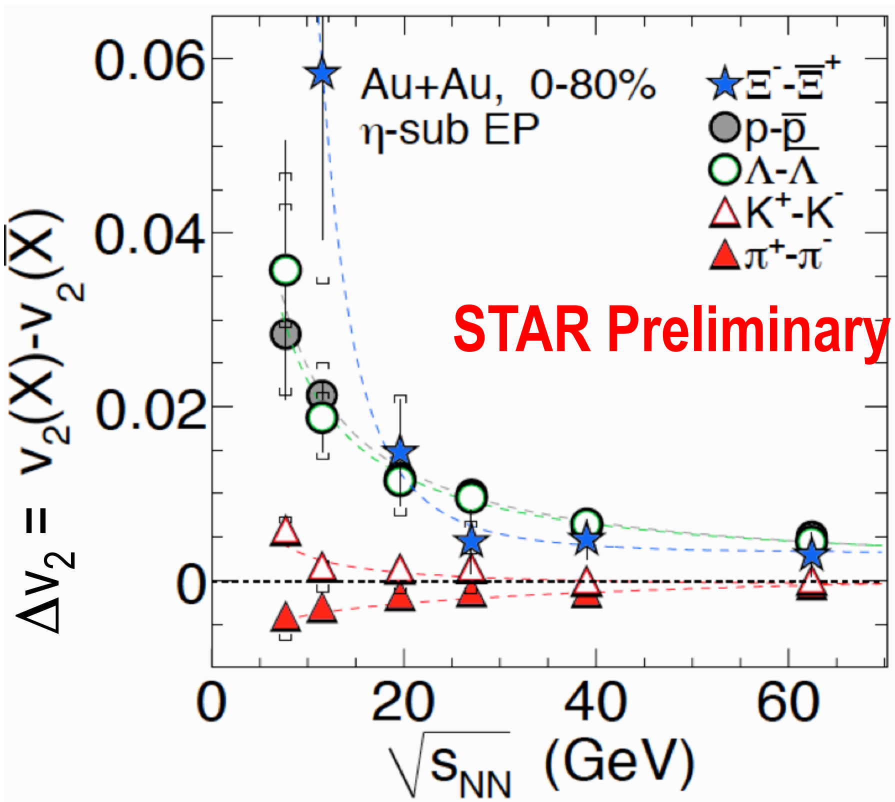
BES: v_2 for p and anti-p



Proton – antiproton difference increases with decreasing energy

(very little p_T dependence)

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



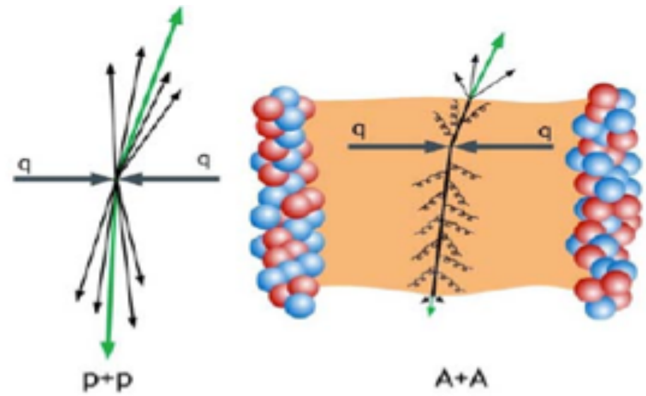
remarkable difference between particle and antiparticle is observed
-> break down of N_q scaling between particles and *anti*particles at lower energies

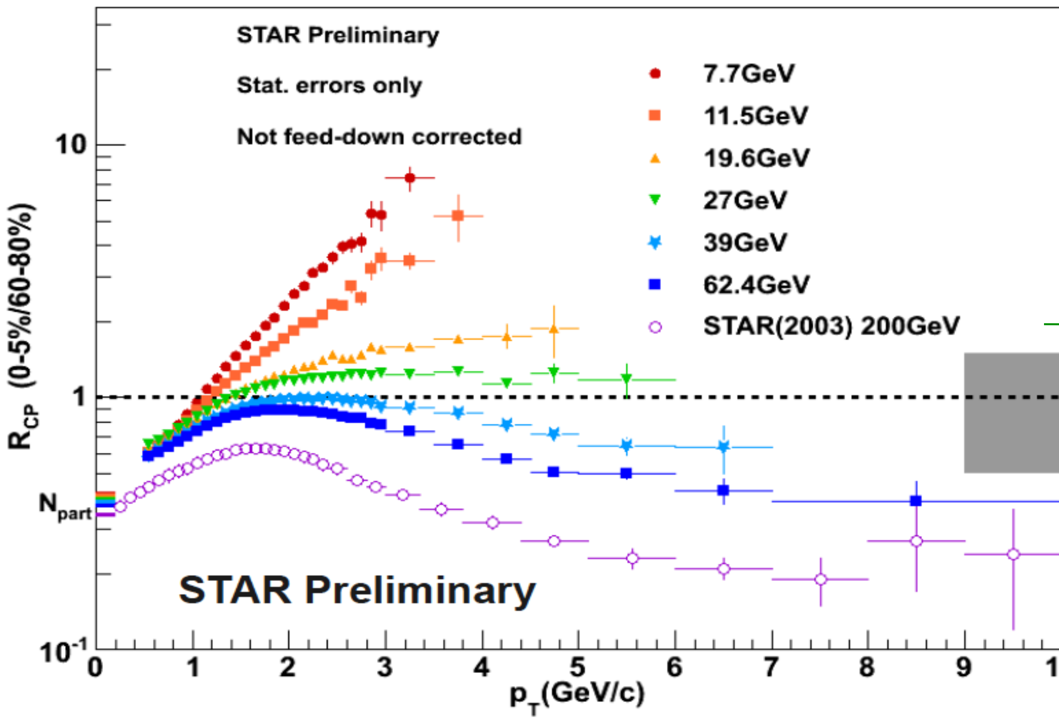
Δv_{2}:
- is larger for baryons than for mesons
- <u>nonlinear increase with decrease of $\sqrt{s_{NN}}$</u>
- study a role of baryon transport to mid-rapidity and hadronic potentials:

*J. Xu et al., PRC **85**, 041901 (2012)*
*J. Dunlop et al., PRC **84**, 044914 (2011).*

Suppression of high p_t particles - R_{cp} for charged particles

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



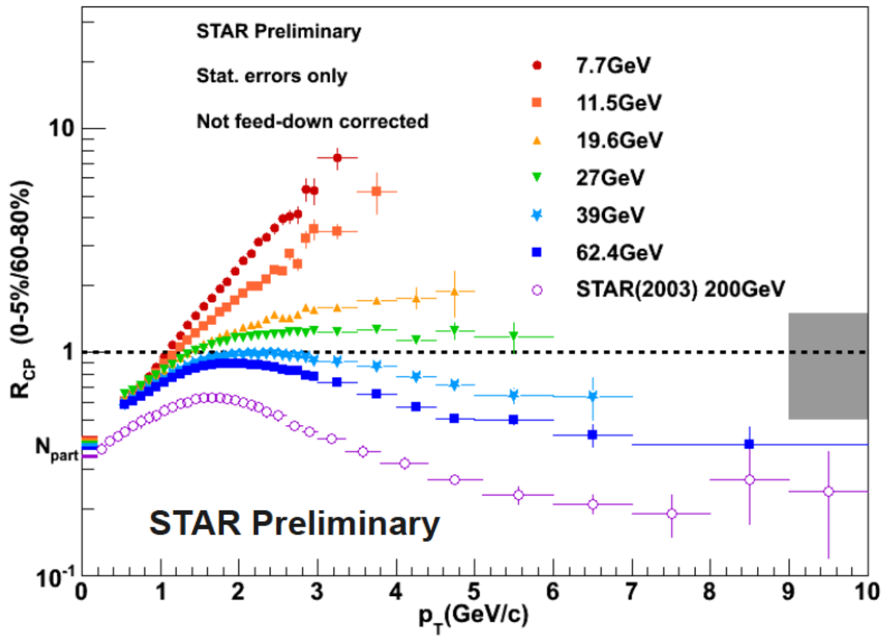


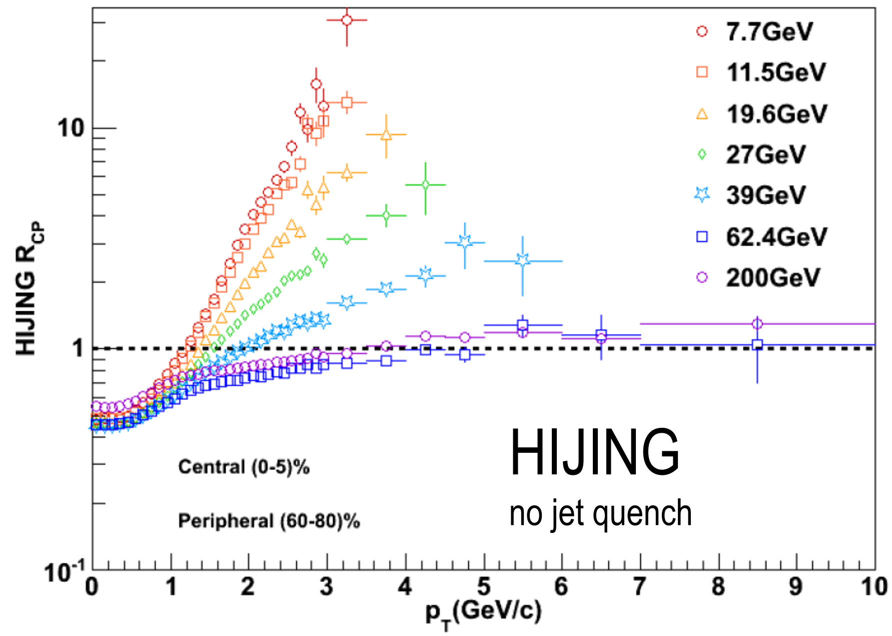
J.Adams et al., (STAR coll.)
PRL 91, 172302 (2003)

R_{CP}>1 for 27 GeV and below - high p_t suppression seen at 200 GeV is gone

BES: R_{cp} for charged particles

QM 2012:





HIJING <u>without jet quenching, but including Cronin effect</u> (though k_T broadening) resembles $\sqrt{s_{NN}}$ dependence at low energies

Change in QGP/HG/nuclear matter opacity vs. $\sqrt{s_{NN}}$?

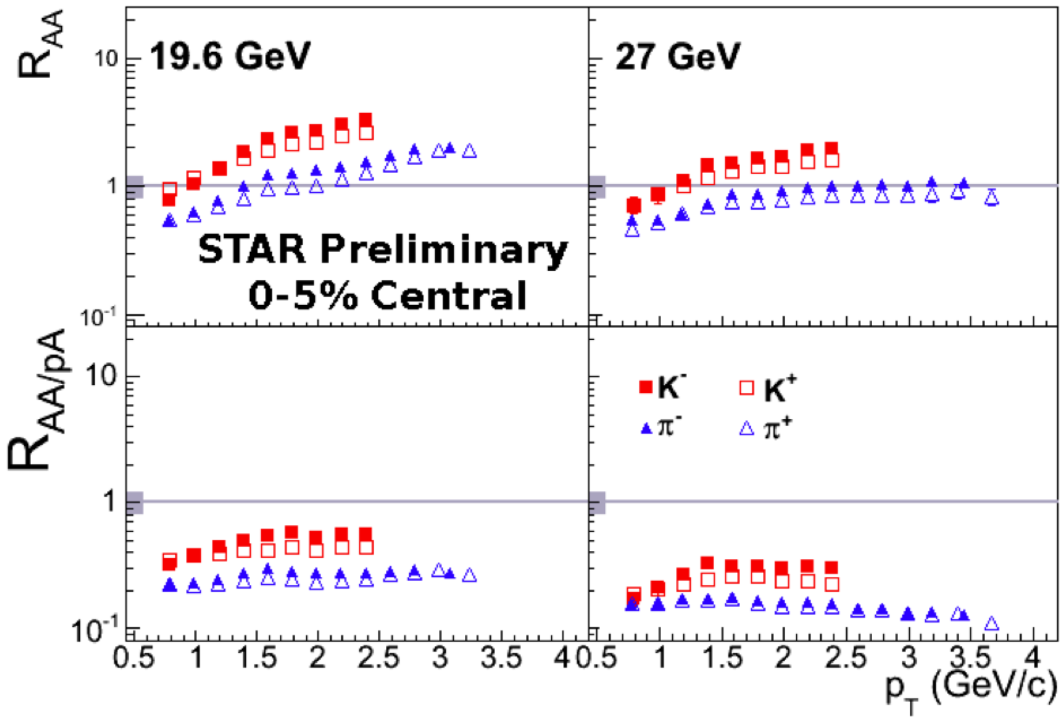
role of Cronin effect under investigation

impact of Cronin effect on nuclear modification factor …

(a qualitative illustration)

Particle ratios scaled by p+p(R_{AA}) and p+W ($R_{AA/pA}$):

QM 2012:



p+p, p+W data (Fermilab): D.Antreasyan et al., Phys.Rev.D19, 764 (1979)

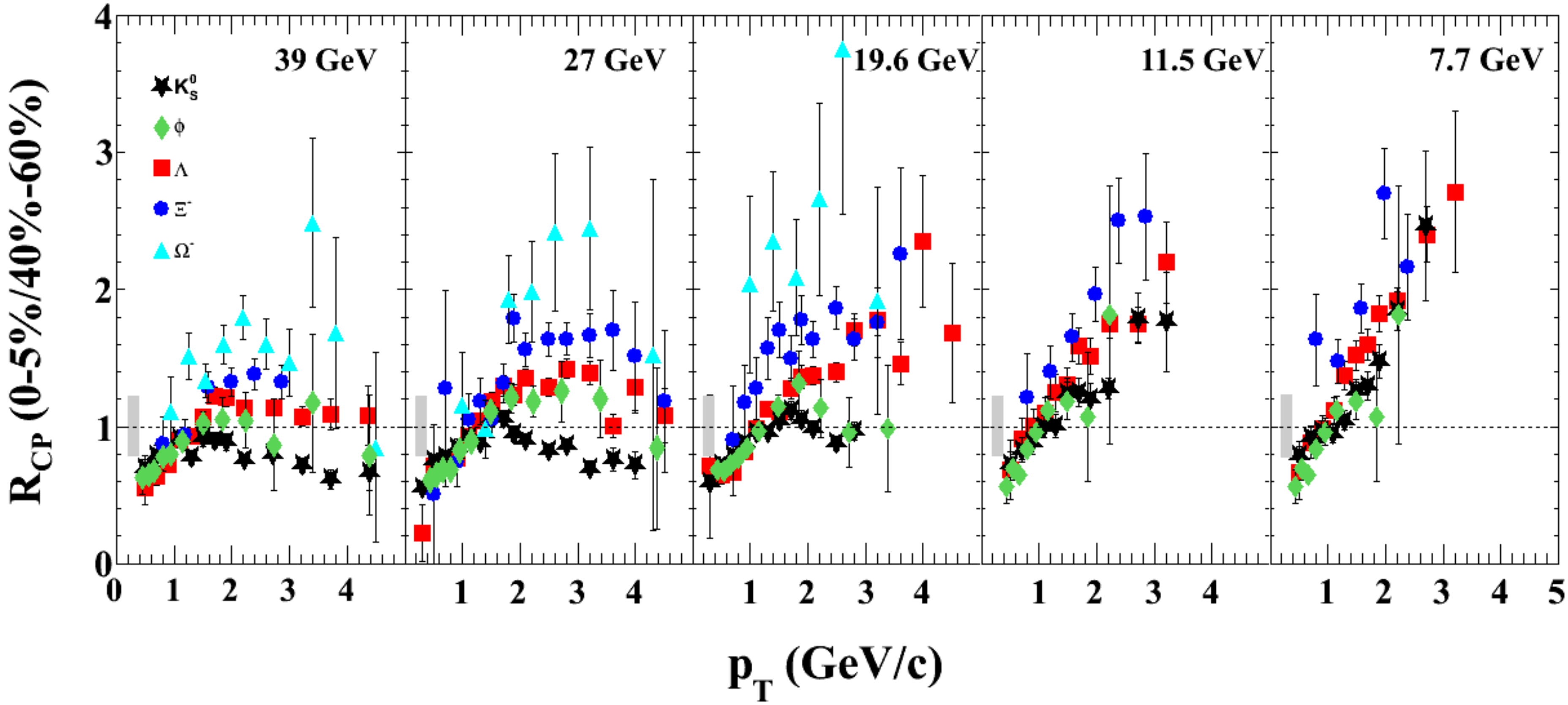
Cronin effect leads to apparent enhancement of R_{AA} at high pt

Similar effect on nuclear modification factor as lack of QGP energy loss

Work in progress

R_{CP} of various strange hadrons

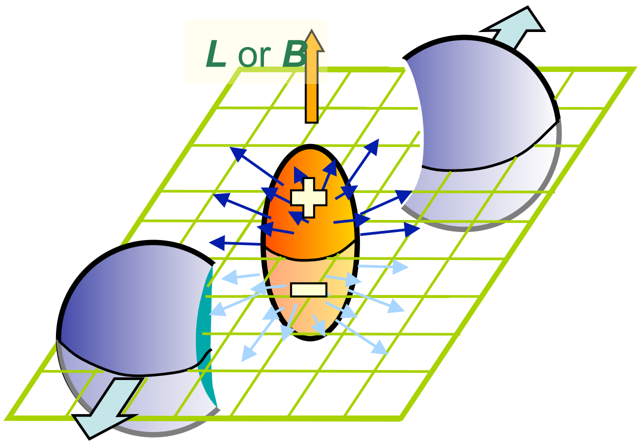
QM 2012 :

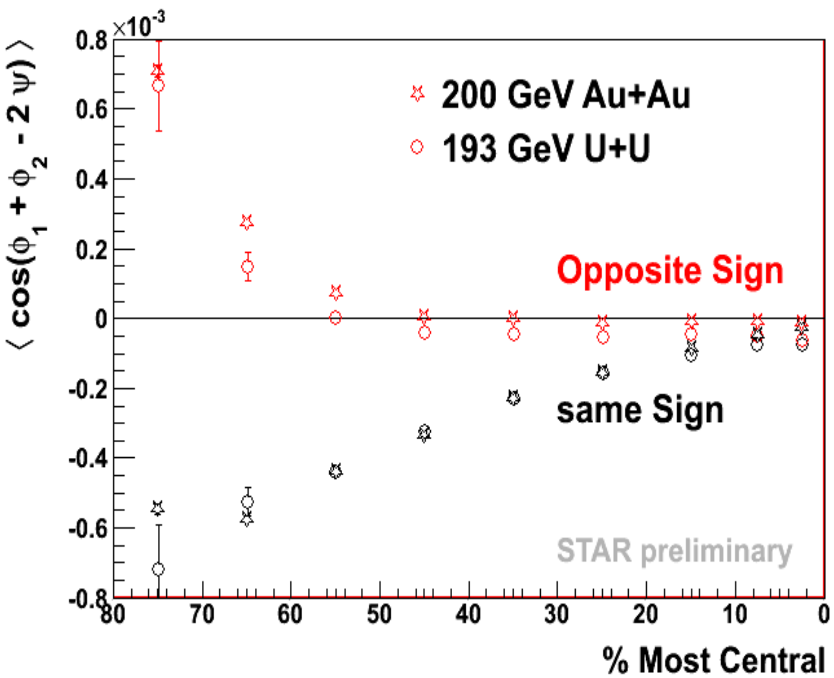


Baryon-meson splitting reduces with decrease of energy and at 7.7 is gone, indicating decreasing partonic effects at lower energies

For $K^0_{pt>2\ GeV/c}$: R_{CP}<1 for $\sqrt{s_{NN}}$> 19 GeV and >1 for $\sqrt{s_{NN}}$<11.5 GeV

Dynamical charge correlations ("local parity violation")





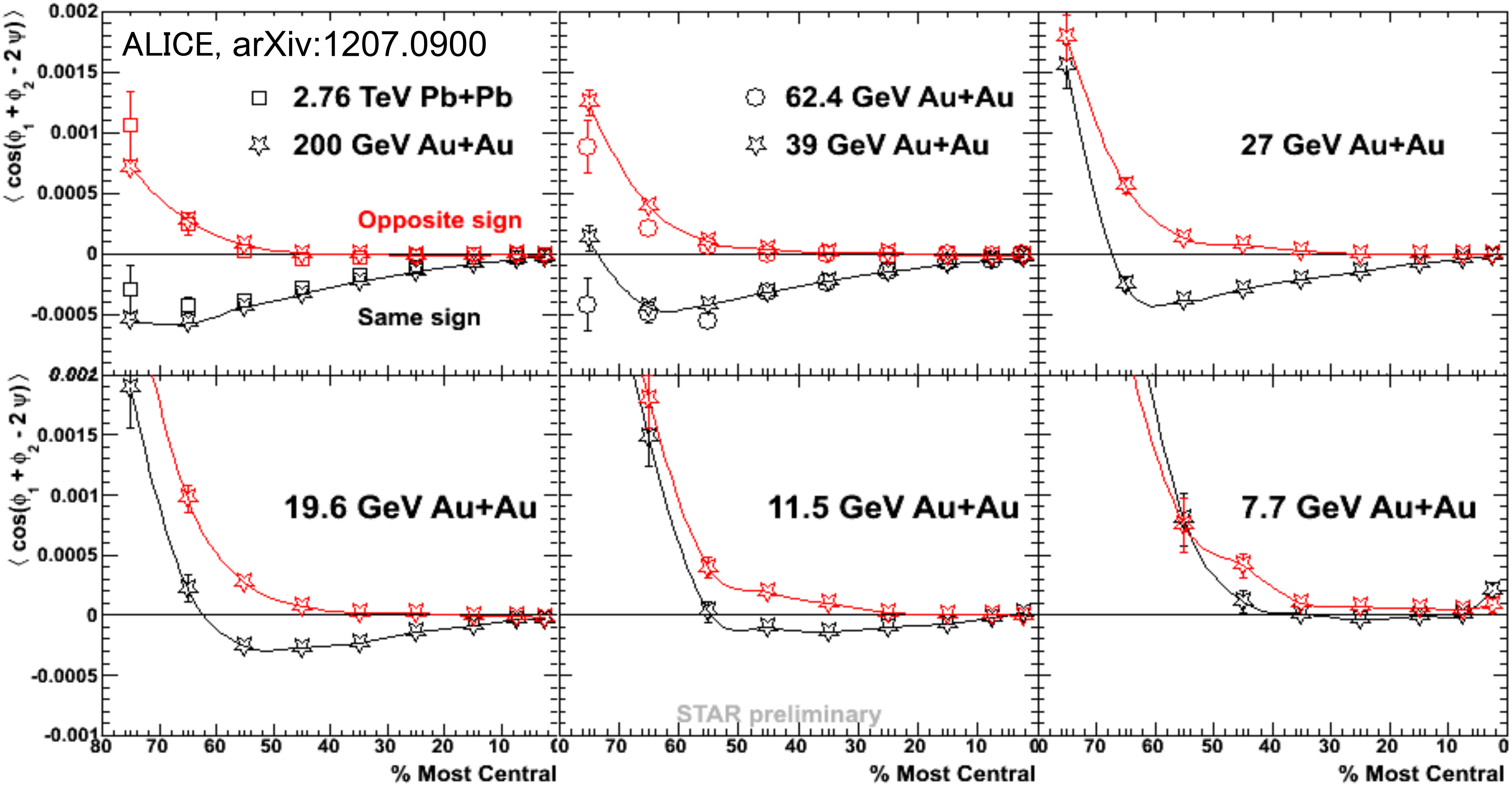
(1) Under strong magnetic field, when the system is in the state of deconfinement and chiral symmetry restoration is reached, local fluctuation may lead to local parity violation.

(2) Experimentally one would observe the separation of the charges in high-energy nuclear collisions.

(3) Observed signature at top RHIC energies has excellent statistical significance for AuAu, UU and CuCu

(4) If interpretation is correct, disappearance of signal would be new signature for turn-off of deconfinement

Dynamical charge correlation signal vs. $\sqrt{s_{NN}}$



Splitting between same and opposite-sign charges decreases with decreasing $\sqrt{s_{NN}}$ and disappears below $\sqrt{s_{NN}}$ = 11.5 GeV *what did we learned on #3 (turn off signatures of QGP):*

These observations:

- baryon/meson grouping for *anti*particles stars 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 exciting …

1. Critical Point

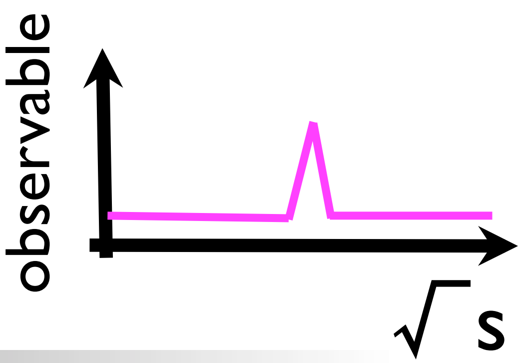
CP: Why fluctuations and correlations ?

Theory:

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

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

Fluctuations maximized at Critical Point



Fluctuations near CP

T. Andrews. Phil. Trans. Royal Soc., 159:575, 1869

CO_2 near
liquid-gas transition
(critical opalescence)

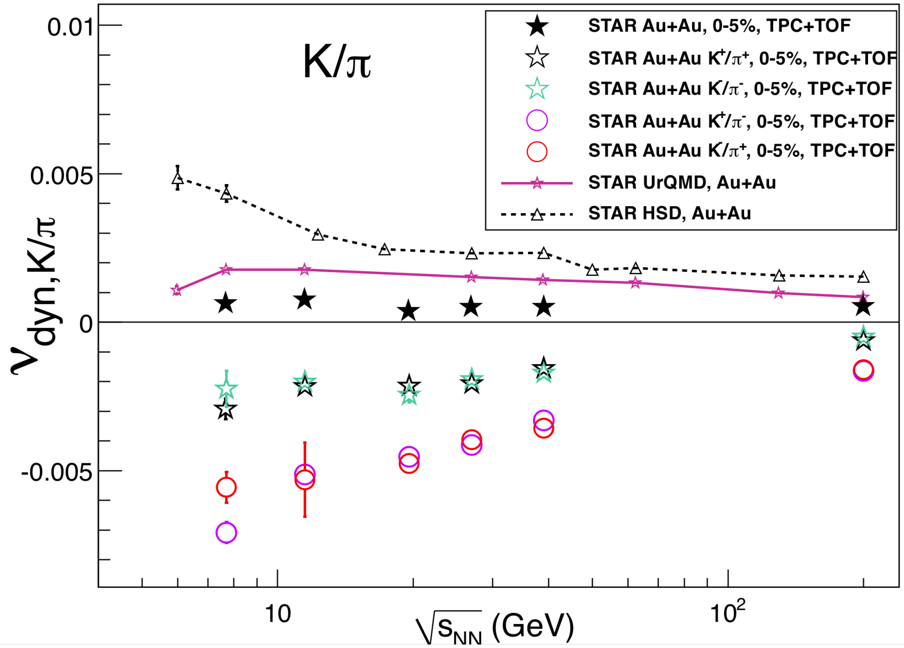
Promising observables:

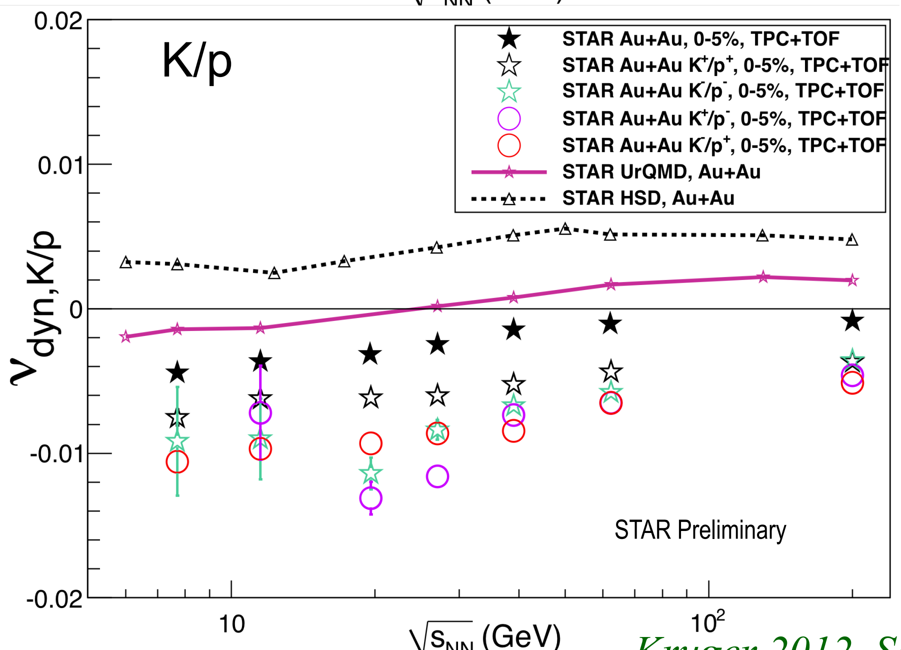
Particle ratio fluctuations: K/π, p/π, K/p

Conserved numbers (B,Q,S) fluctuations

- higher moments of net-protons and net-charge

event-by-event particle ratio fluctuations

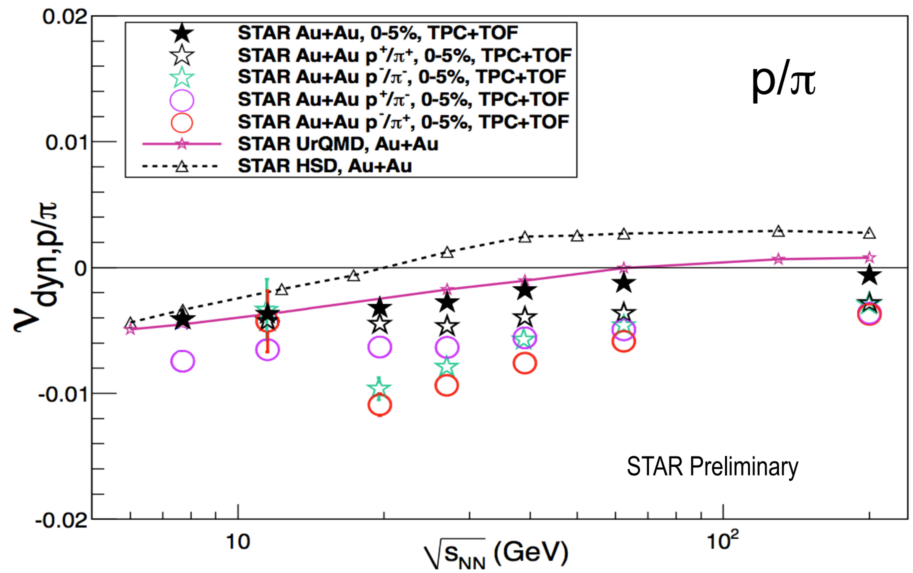




$$\nu_{dyn,K\pi} = \frac{\langle N_K(N_K-1)\rangle}{\langle N_K\rangle^2} + \frac{\langle N_\pi(N_\pi-1)\rangle}{\langle N_\pi\rangle^2} - 2\frac{\langle N_K N_\pi\rangle}{\langle N_K\rangle\langle N_\pi\rangle}$$

$$\sigma_{dyn} = sign(\sigma^2_{data} - \sigma^2_{mixed})\sqrt{\left|\sigma^2_{data} - \sigma^2_{mixed}\right|}$$

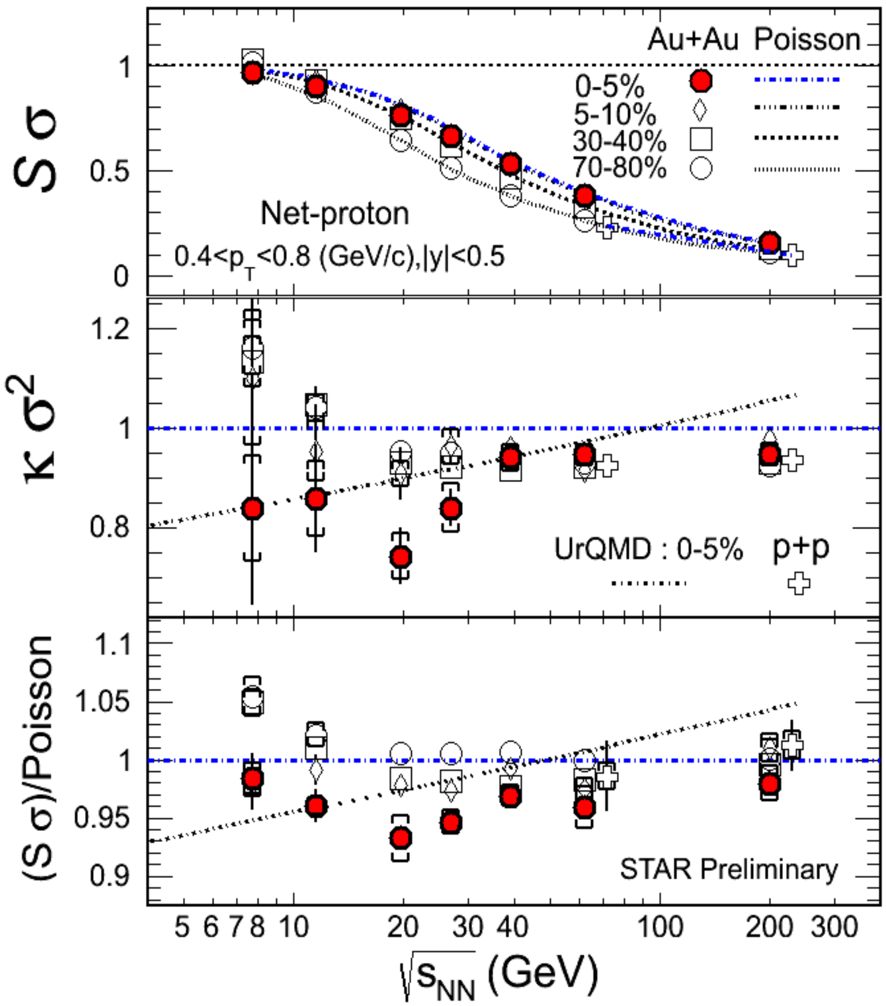
$$\sigma^2_{dyn} \approx \nu_{dyn}$$



Constant or monotonic trends observed in particle ratio fluctuations with energy

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)
- Non-monotonic behavior could be indicative of the QCD critical
- **Similar behavior at 39, 62 and 200 GeV**
- **Deviations below Poisson baseline in 0-5% central collisions, and above Poisson baseline in peripheral collisions below 19.6 GeV**

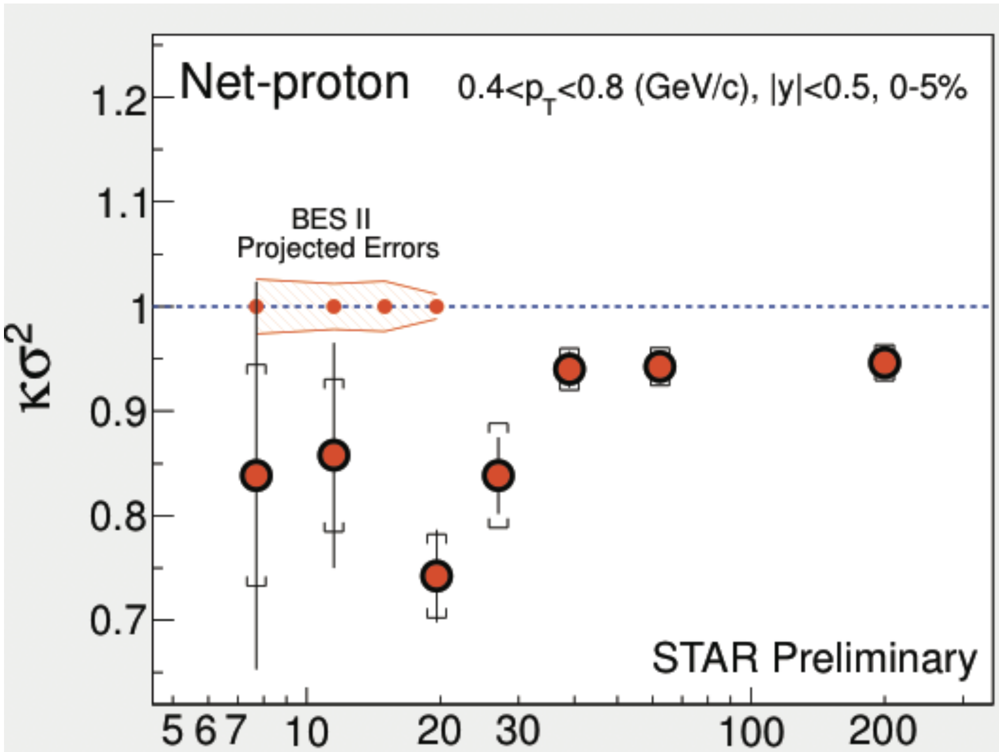
(could be due to other correlation sources)

- **UrQMD shows monotonic behavior vs √s**

- Data points below 19.6 GeV have large uncertainties -> prevents conclusions (presently)

→ for BES phase-II

Current and projected uncertainties on net-proton kurtosis x variance



BES phase II:

$\sqrt{s_{NN}}$ (GeV)	μ_B	BES I	BES II
19.6	206	36 (M)	**400** (M)
15	250		**100** (M)
11.5	316	12 (M)	**120** (M)
7.7	420	5 (M)	**80***** (M)

what did we learned on #1 (Critical Pont):

Deviations of moment products in central Au+Au collisions from Poisson expectations are observed

Uncertainties of current results on higher moments (particularly at 19.6 GeV and bellow) prevents us from drawing conclusions

⟶ more statistics – BES II

the equivalent of CP … (!)

2. Phase transition

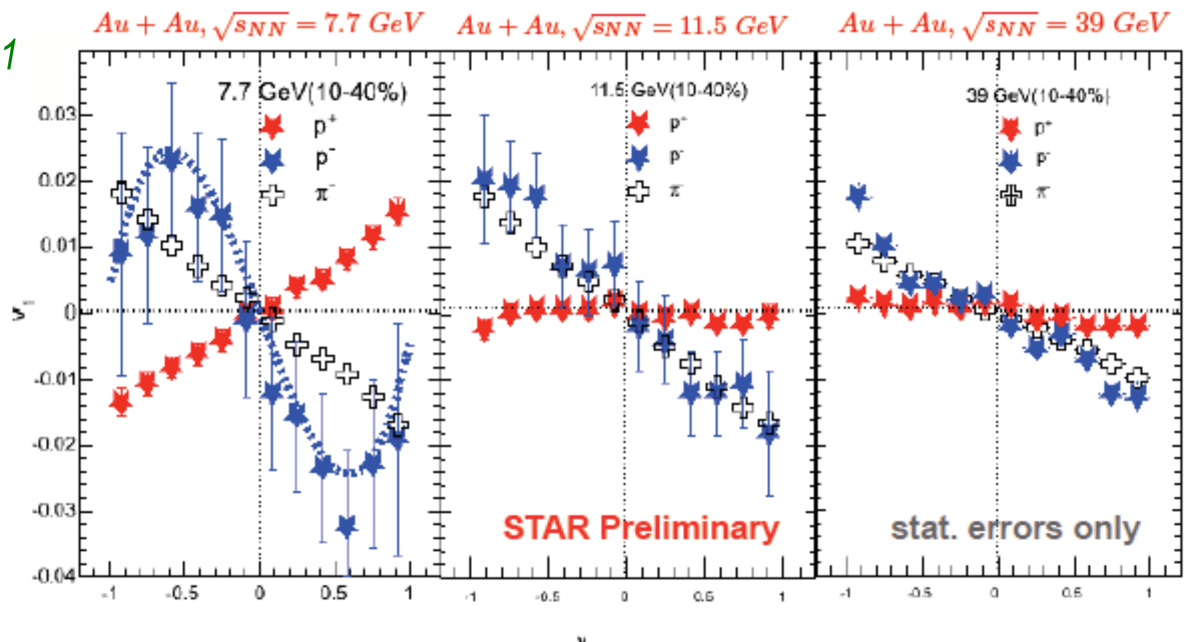
can we demonstrate the softening of EOS ?

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 …

L.P.Csernai, D.Rohrich, PLB 458,454 (1999)
H.Stocker, NP A750, 121 (2005)
J.Brachmann et al., PRC 61, 24909(2000)

STAR, QM 2011



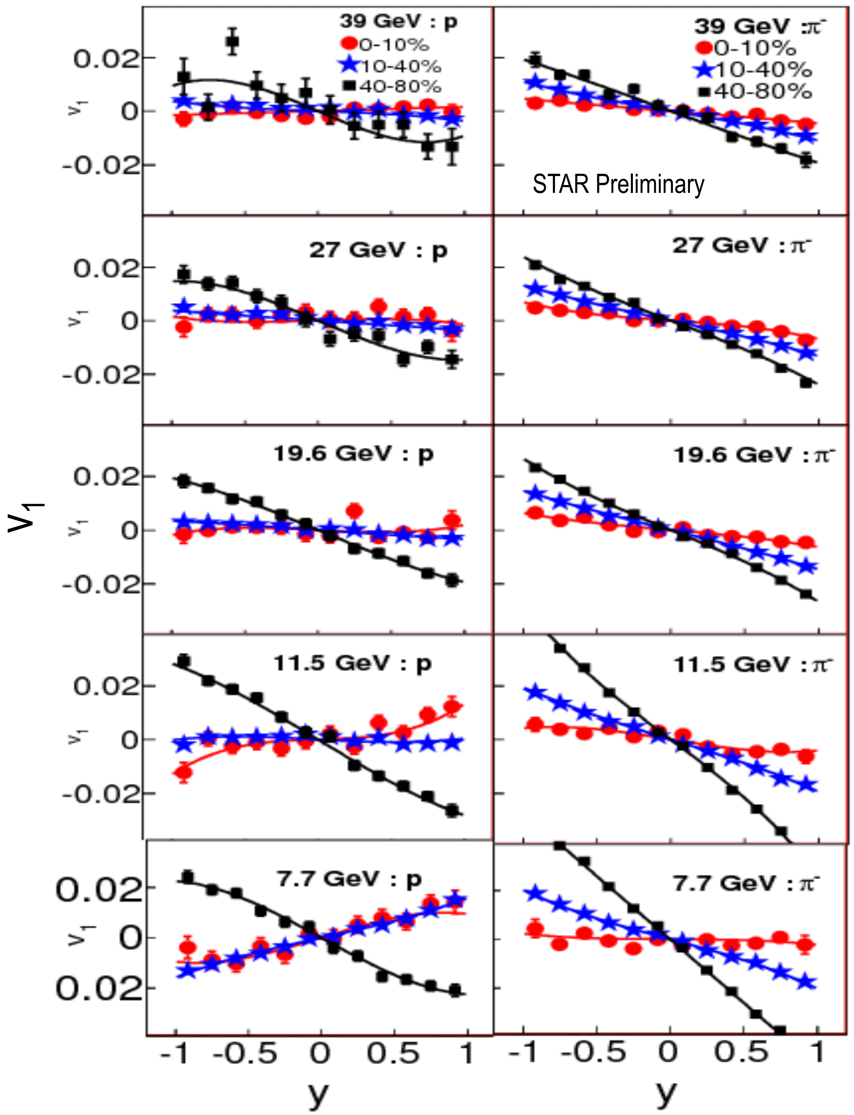
Proton v_1 slope at midrapidity changes sign (7.7 and 11.5 GeV) → softening of EOS (1st order PT?)

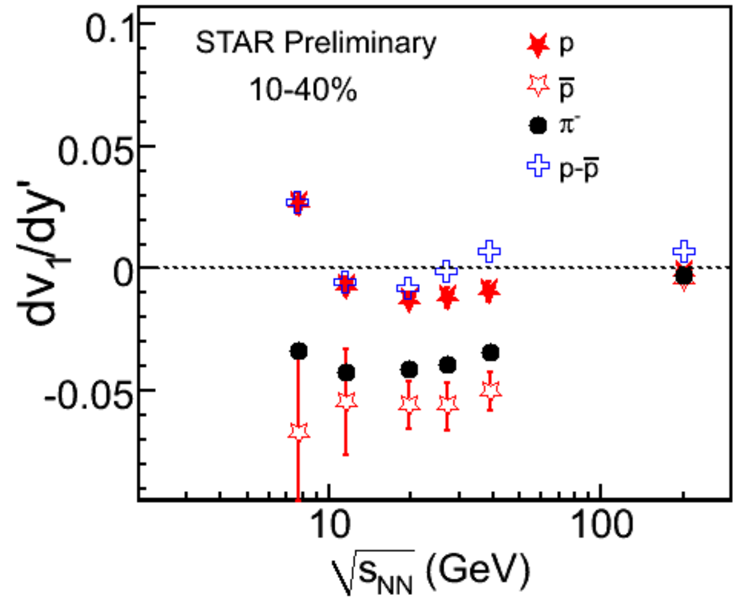
@ 39 GeV all measured v_1 values follow trend observed at higher RHIC energies

Note, the difference between protons and antiprotons

Search for softening of EOS – directed flow

STAR, QM 2012

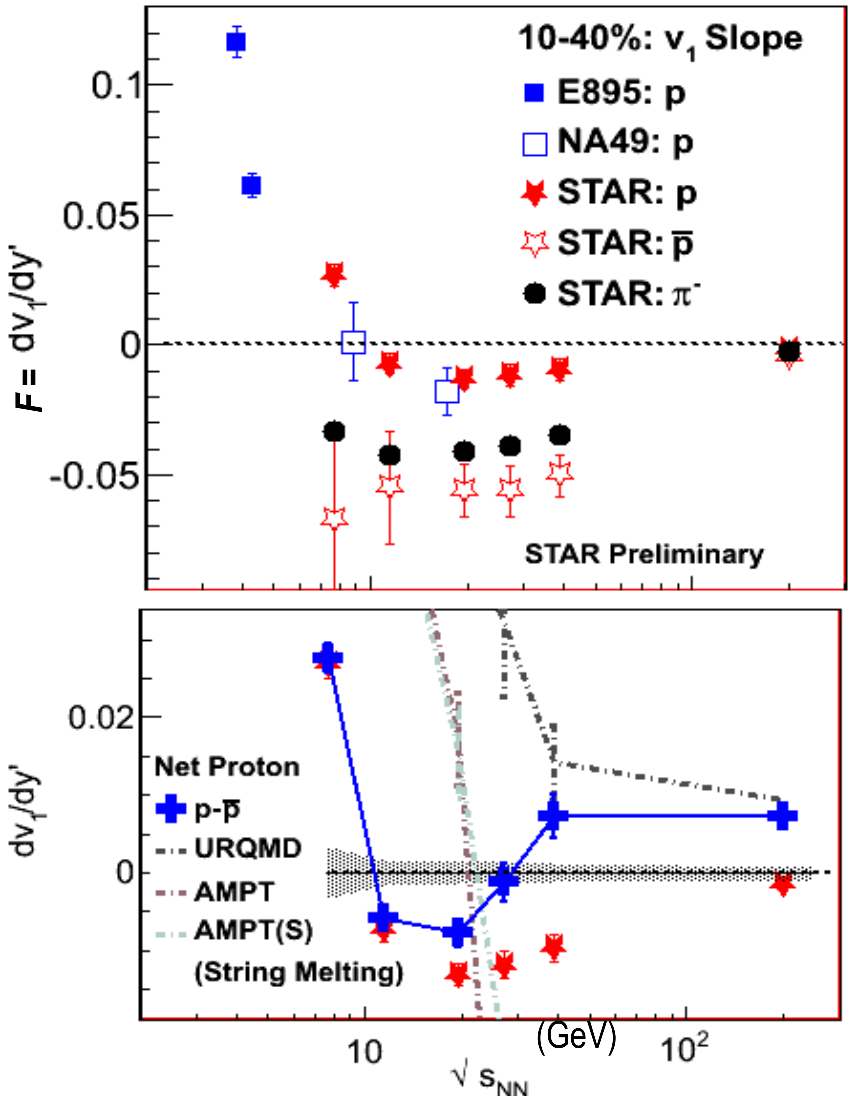




@ mid-central (10-40%) Au+Au collisions :
pions (+,-), kaons (+,-) and anti-p slope is always negative (7.7-39 GeV)
proton slope changes sign from positive to negative between 7.7 and 11.5 GeV, it remains small but negative up to 200 GeV

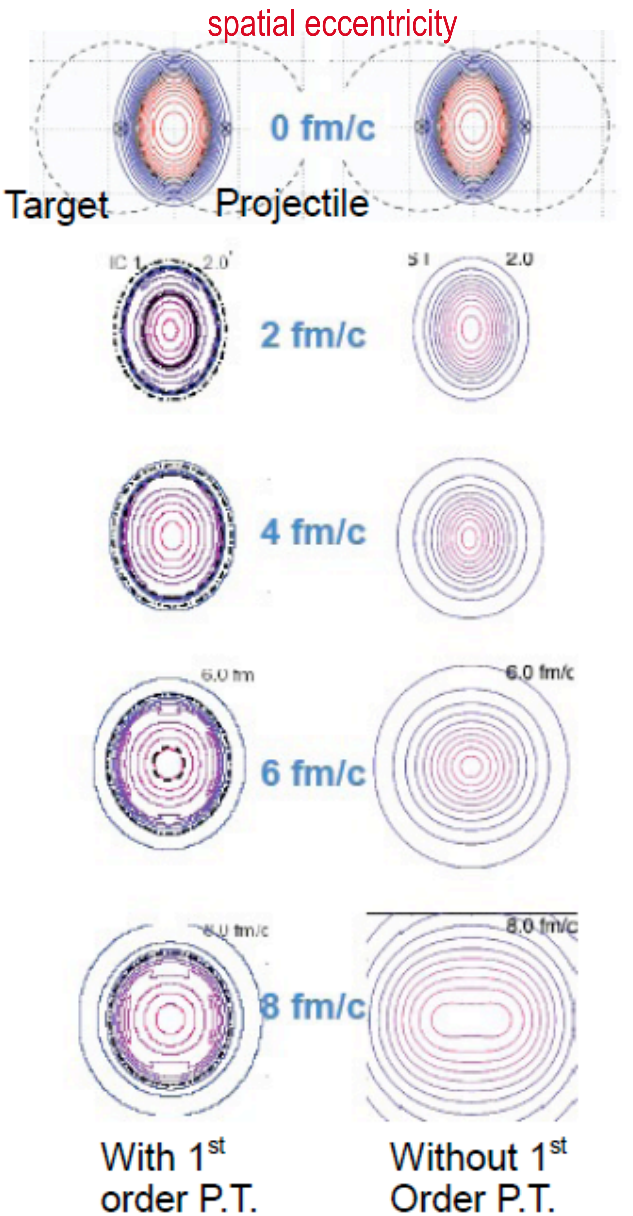
EOS softening ? – comparison with transport models

F = net-protons ($p-\bar{p}$) v1 slope: dv_1/dy



- Protons v_1 consistent with "collapse" hydro predictions
- Net-protons signal should correspond to only stopped participants
- **<u>Net-proton v_1 changes sign twice</u>** in the measured energy region, and shows a minimum around 11.5-19.6 GeV, coming up ~ 27 GeV, suggestive of a **<u>change in compressibility</u>**
- Transport models UrQMD and AMPT can not reproduce observed net-proton v_1 slope
- Other physics sources are under investigation

<u>Theory:</u> more input
<u>Experiment</u>: BES Phase II – more statistics, centrality dependence, …



Reference: Kolb and Heinz, 2003, nucl-th/0305084

azimuthal – HBT

provides info about shape of particle emitting source

Freeze-out shape of participant zone in non-central collisions is sensitive to EOS:

- Initial out-of-plane eccentricity
- Stronger in-plane pressure gradients drive in-plane expansion (-> more spherical freeze-out shape)
- Measure eccentricity at freeze-out as function of energy:

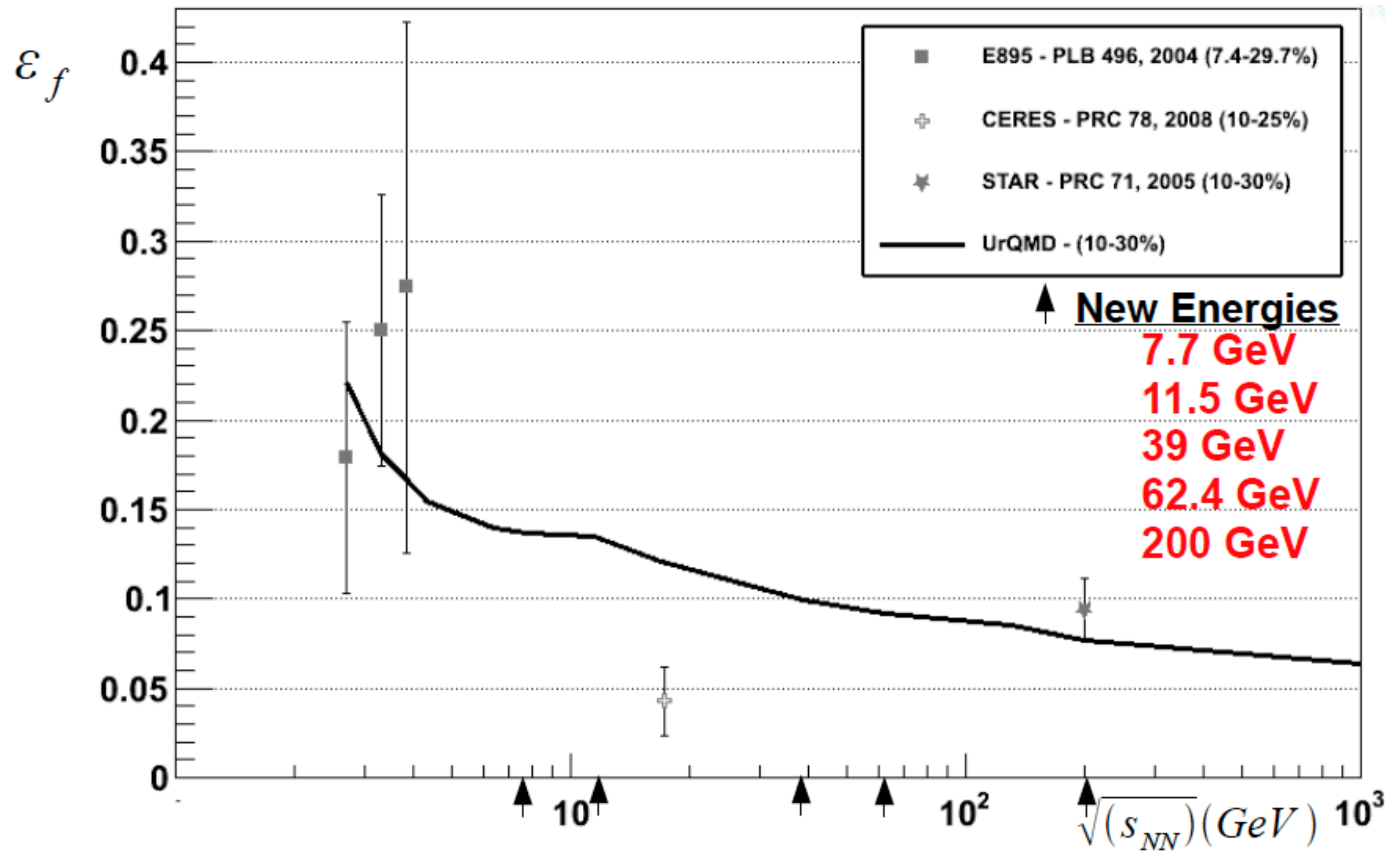
$$\varepsilon_F = \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2}$$

- Expectation: excitation function for freeze-out eccentricity to fall monotonically with increasing energy

Non-monotonic behavior could indicate a change in EOS (softening ?) -> 1st order phase transition

M.Lisa et al., New J.Phys. 13 (2011) 065006

Measurements prior to BES



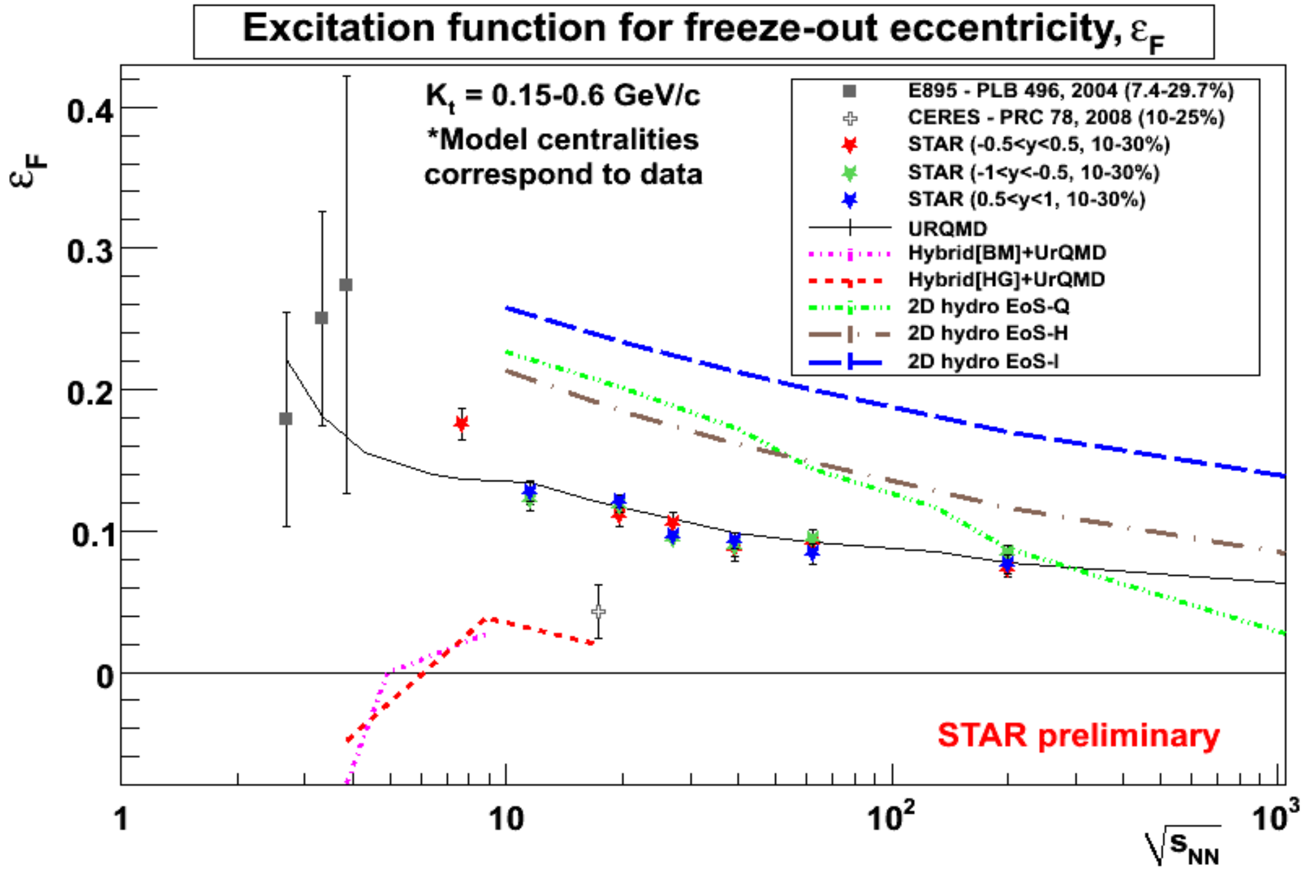
possible minimum follow by the rise ?

speculations/explanations: softening of EOS due to entrance into mixed phase above some energy, observed as plateau or minimum in excitation function

M.Lisa et al., New J.Phys. 13 (2011) 065006

Excitation function (BES points included)

Azimuthal HBT for freeze-out eccentricity



Measured freeze-out eccentricity parameters show a smooth decrease from low to high energies

consistent with monotonically decreasing shape

So, what have we learned from BES Phase-I

STAR and RHIC excellent performance down to 7.7 GeV (5 ?)

BES Phase-I data sets (39, 27, 19.6, 11.5 and 7.7 GeV) cover important region of QCD phase diagram with sufficient statistics for initial survey

but it is rather coarse coverage

Several key sQGP signatures NOT seen at low energies:

- $v_2(m_T - m_0)$ exhibits well-known baryon-meson splitting, but splitting is smaller at low $\sqrt{s_{NN}}$
- v_2 for particles & antiparticles diverges strongly at low $\sqrt{s_{NN}}$
- high p_t suppression R_{CP} disappears at low $\sqrt{s_{NN}}$, under investigation
- charge separation signal disappears at low $\sqrt{s_{NN}}$, interpretation unclear

Interesting hints:

- fluctuations are constant or monotonic with energy from 7.7 to 200 GeV
- higher moments of net-protons deviates from Poisson baseline
- dv_1/dy of net-protons (directed flow) changes sign with $\sqrt{s_{NN}}$: softening of EOS ?
- freeze-out eccentricity (aHBT) monotonically decreases with energy

RHIC's energy range is special …

RICH sits at a "sweet spot" in energy, in which rapid changes occur in a number of signatures for energies up to approximately 30 GeV, while remaining surprisingly stable beyond that over the two orders of magnitude to the LHC

→ so, did we answer our "three" questions ?

1. turn-off of QGP signatures ? **clear evidence** no need to search above 19.6
2. Evidence of the first order phase transition ? **hints** lower end of range
3. Search for the critical point ? **? !** **MORE** statistics !!!

Good chance for Au Au at $\sqrt{s_{NN}}$ = 15 GeV in 2013

Answering remaining questions - BES II

→ **STAR will have BES Phase-II program of precision measurements to map out QCP phase structure** with order of magnitude increase in data samples

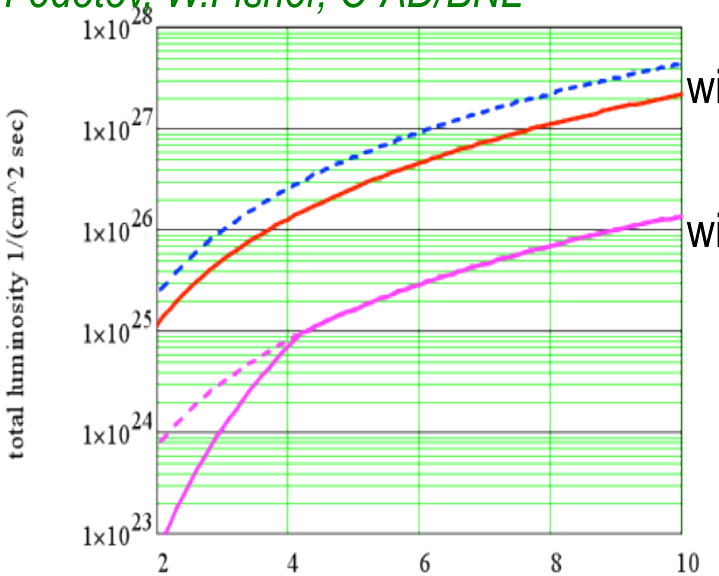
$\sqrt{S_{NN}}$ (GeV)	19.6	15	11.5	7.7
μ_B (GeV)	205	250	315	420
BES I (MEvts)	36	---	12	5
BES II (MEvts)	**400**	**100**	**120**	**80**

But that's a lot of data… at current rates, this would take ~70 weeks of RHIC operations!

→ needed electron cooling device for RHIC HI beams

Improvements for BES phase II

A.Fedotov, W.Fisher, C-AD/BNL



with e- cooling

without e-cooling

(1) Electron cooling at RHIC will raise luminosity by factor 3-10 in range $\sqrt{s_{NN}}$ 5-20 GeV

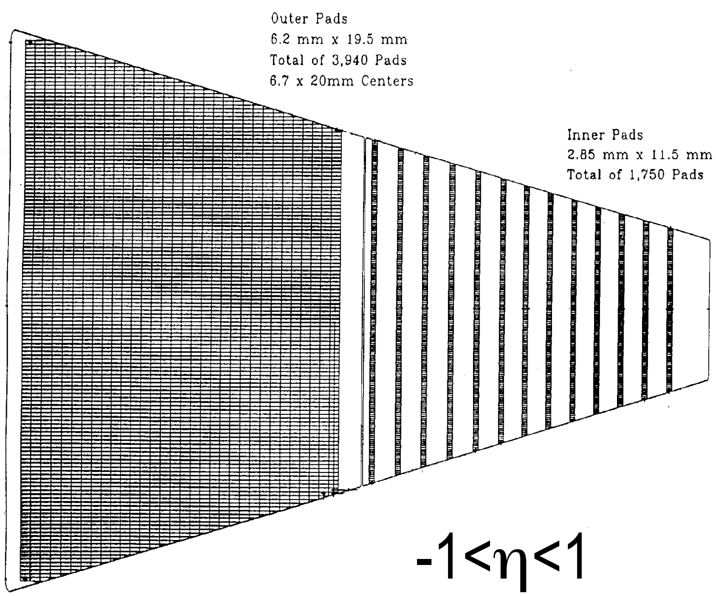
Phase I (2017) $\sqrt{s_{NN}}$ = 5-9 GeV

Phase II (2018+) $\sqrt{s_{NN}}$ = 9-20 GeV

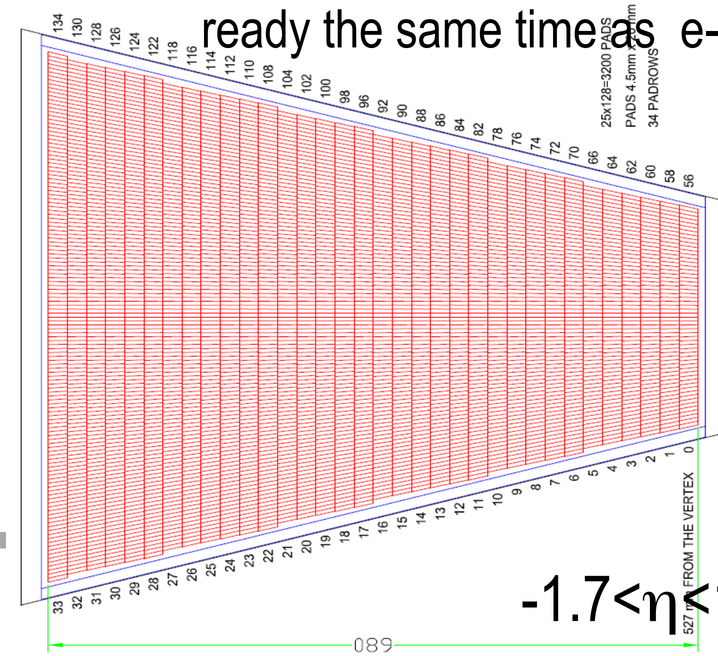
~5 M $ and would not be ready before 2017

(2) iTPC: extends η range to 1.7

ready the same time as e-cooling

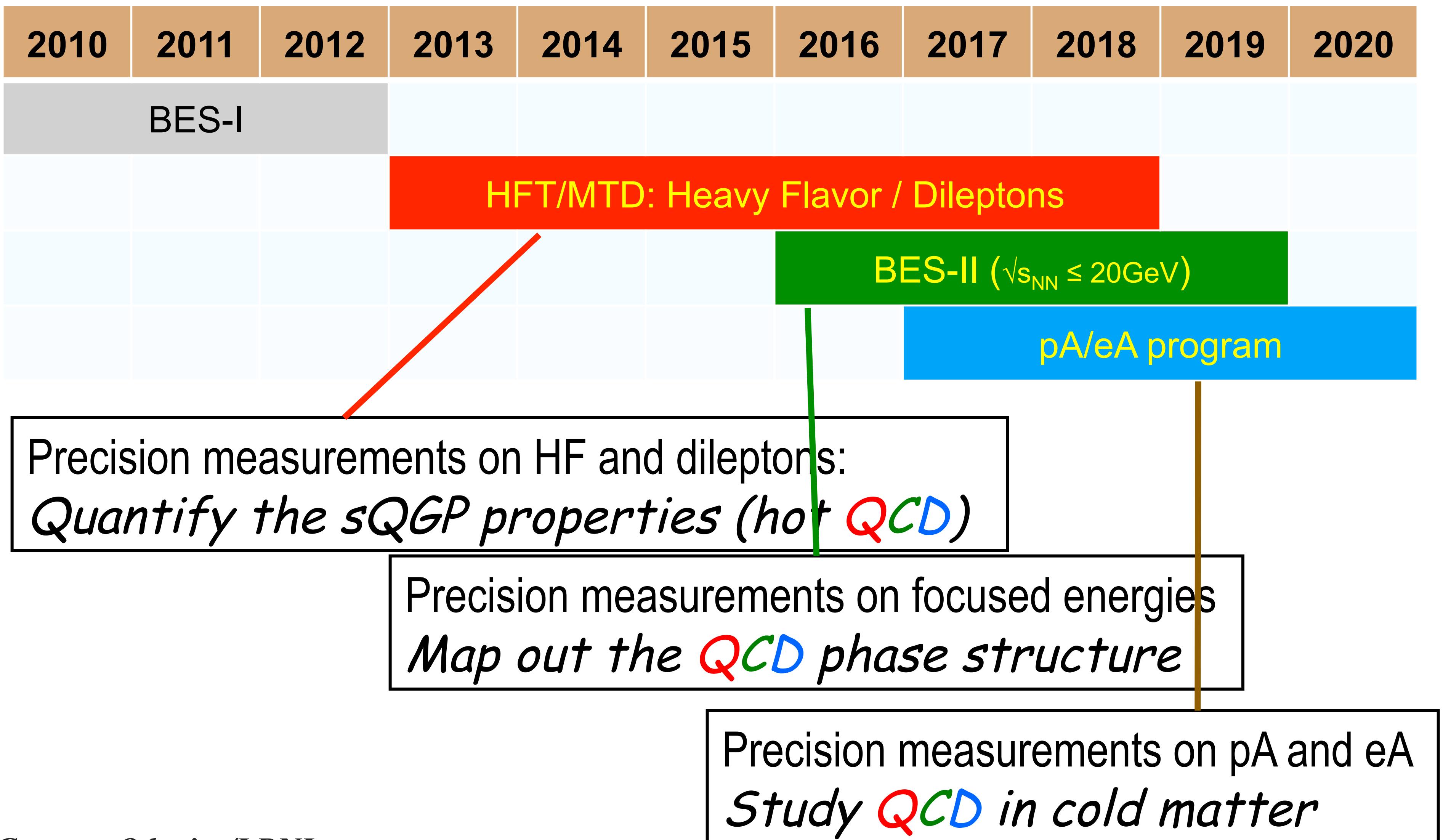


$-1<\eta<1$

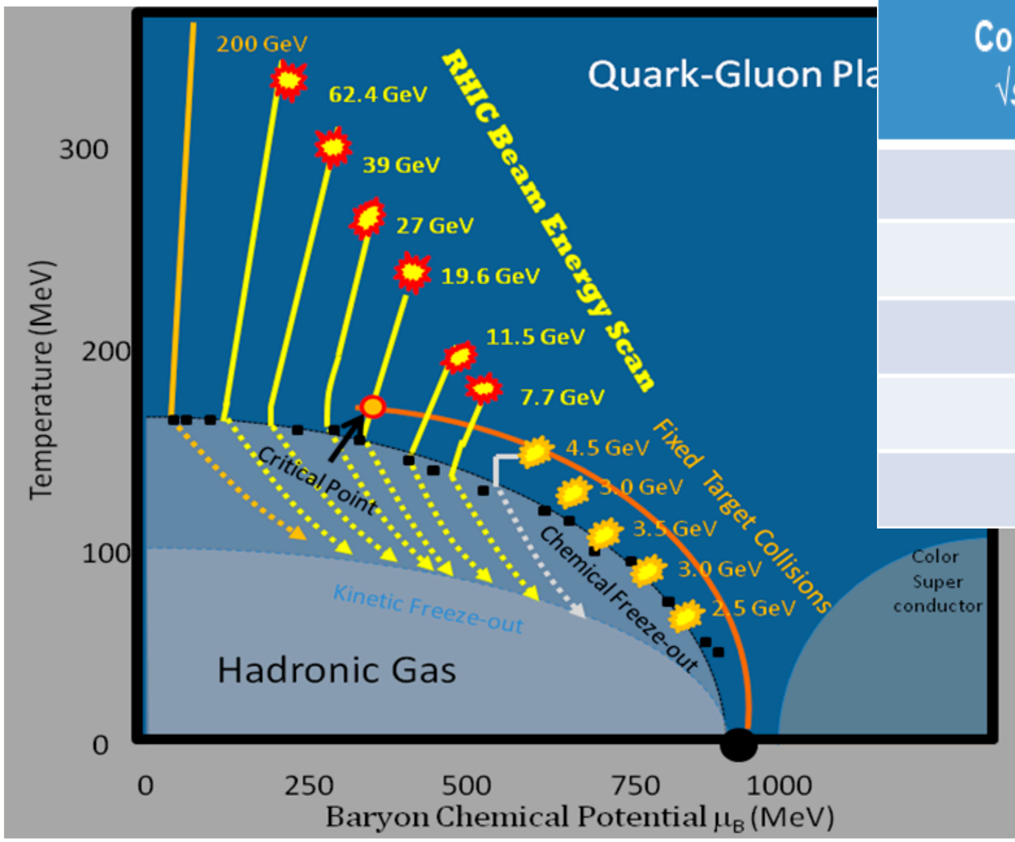


$-1.7<\eta<1.7$

but, BES Phase-II will not happen very soon …



μ_B extended range in STAR due to fixed target program

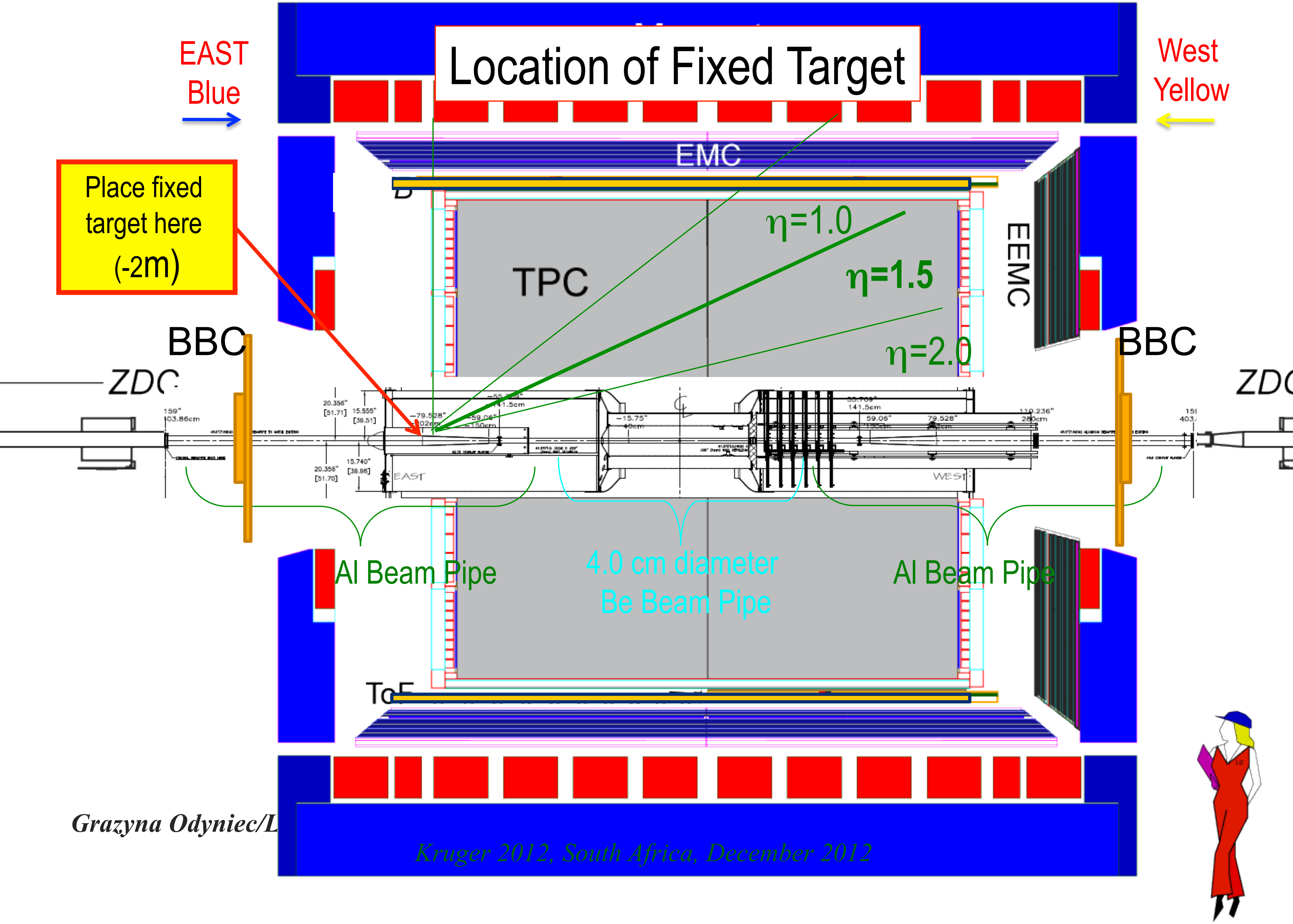


Collider mode $\sqrt{s_{NN}}$ (GeV)	Fixed-target mode $\sqrt{s_{NN}}$ (GeV)	Fixed-target mode μ_B (MeV)
19.6	4.5	585
15	4.0	625
11.5	3.5	670
7.7	3.0	720
5	2.5	775

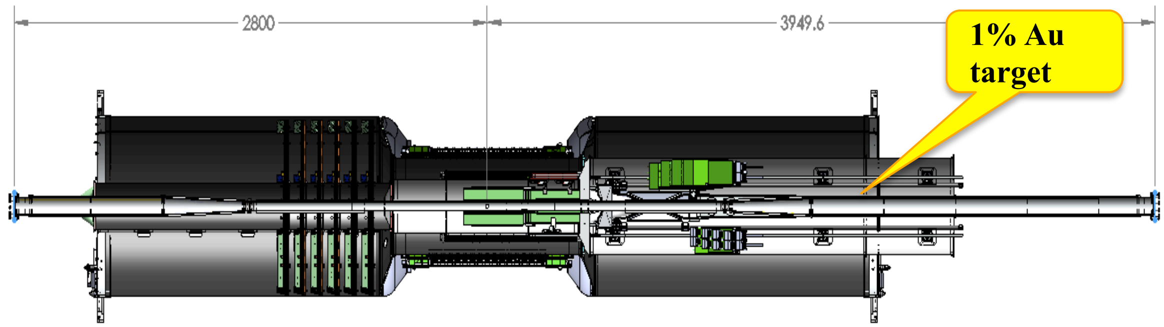
Fixed-target running allows much higher rates without e-cooling at lower energies

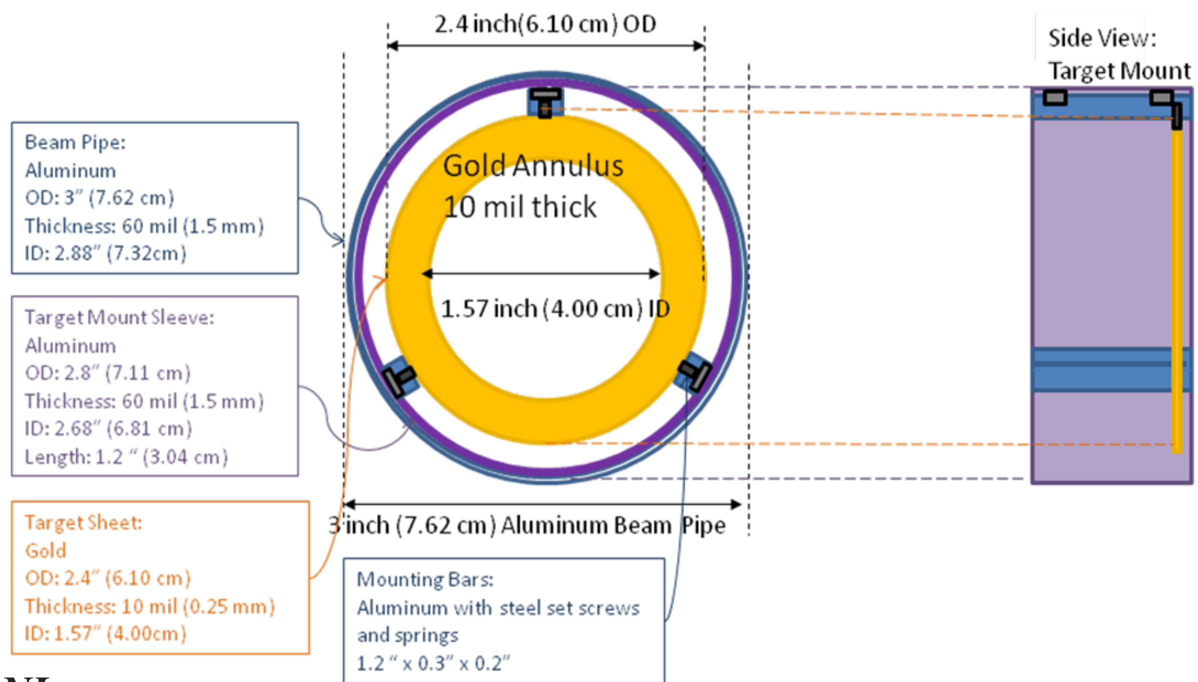
Minimal impact on concurrent operation

Location of Fixed Target

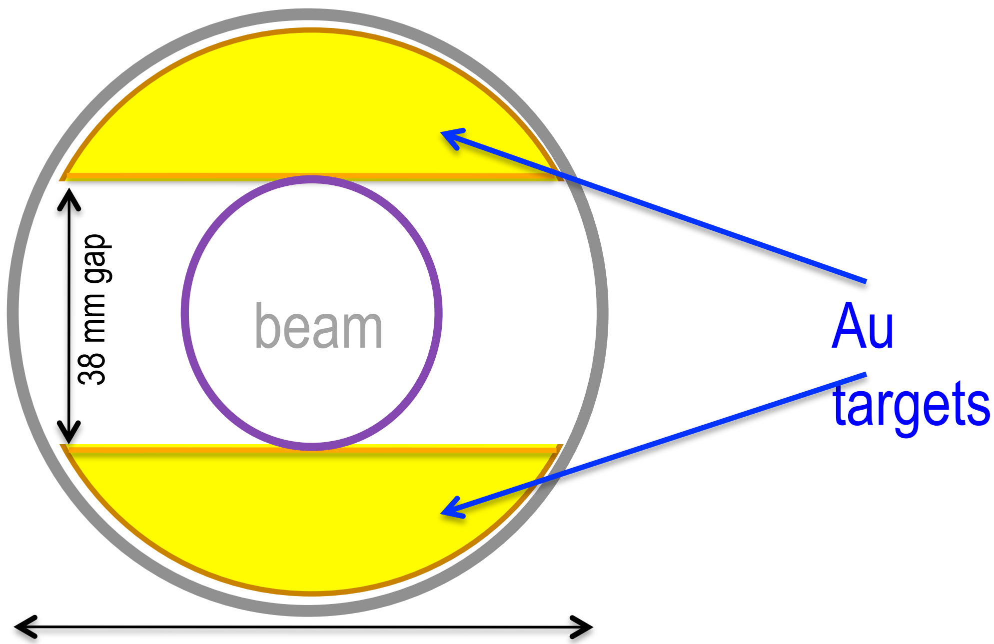


On much faster scale: **Fixed target in STAR**



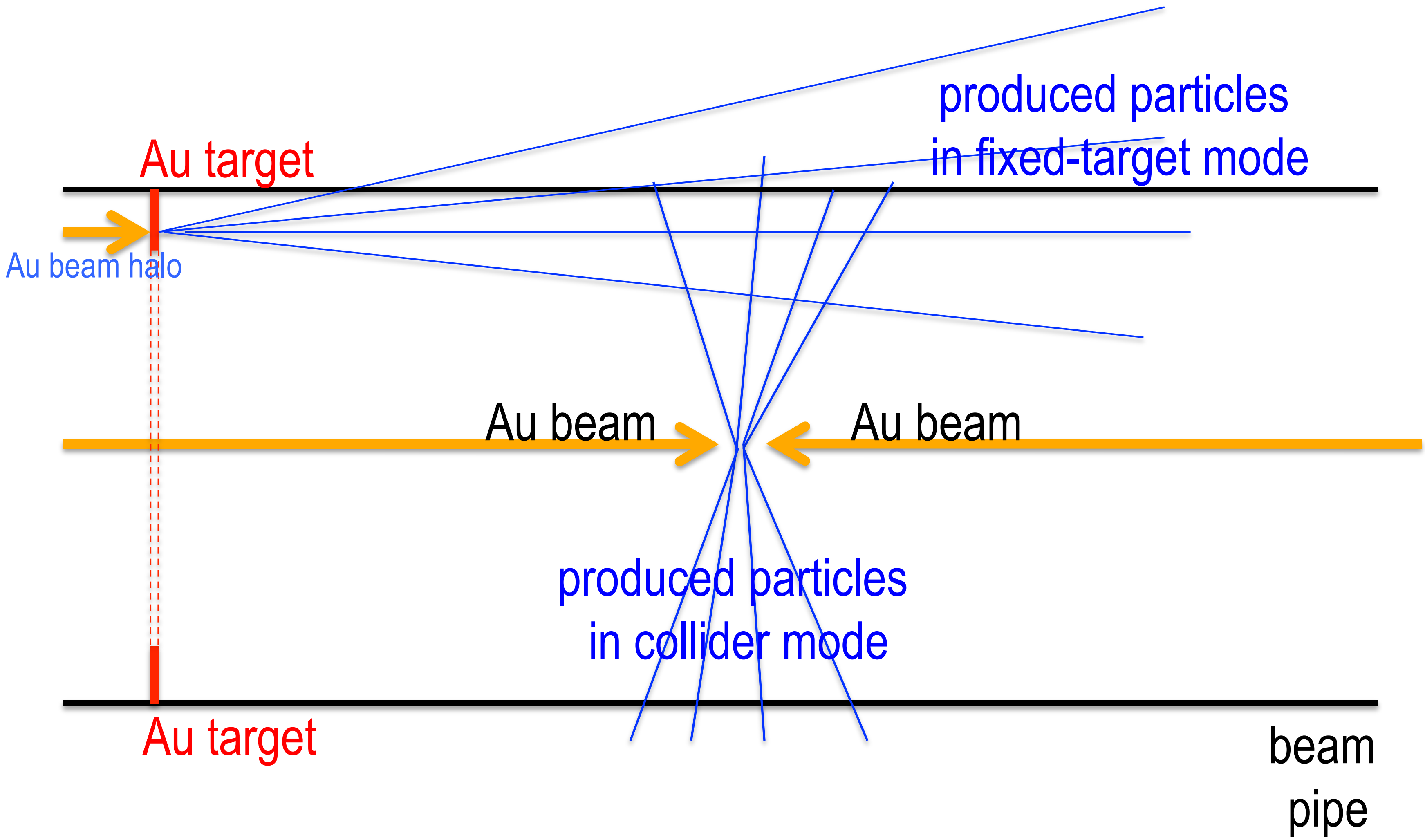


the real design:



because kicker magnet, used to dump the beam, works in horizontal plane

Concurrent running in STAR



fixed-target events taken while waiting for collider mode collisions

Fixed-target

we already have experience with running STAR in the fixed-target mode (!) and with analyzing data

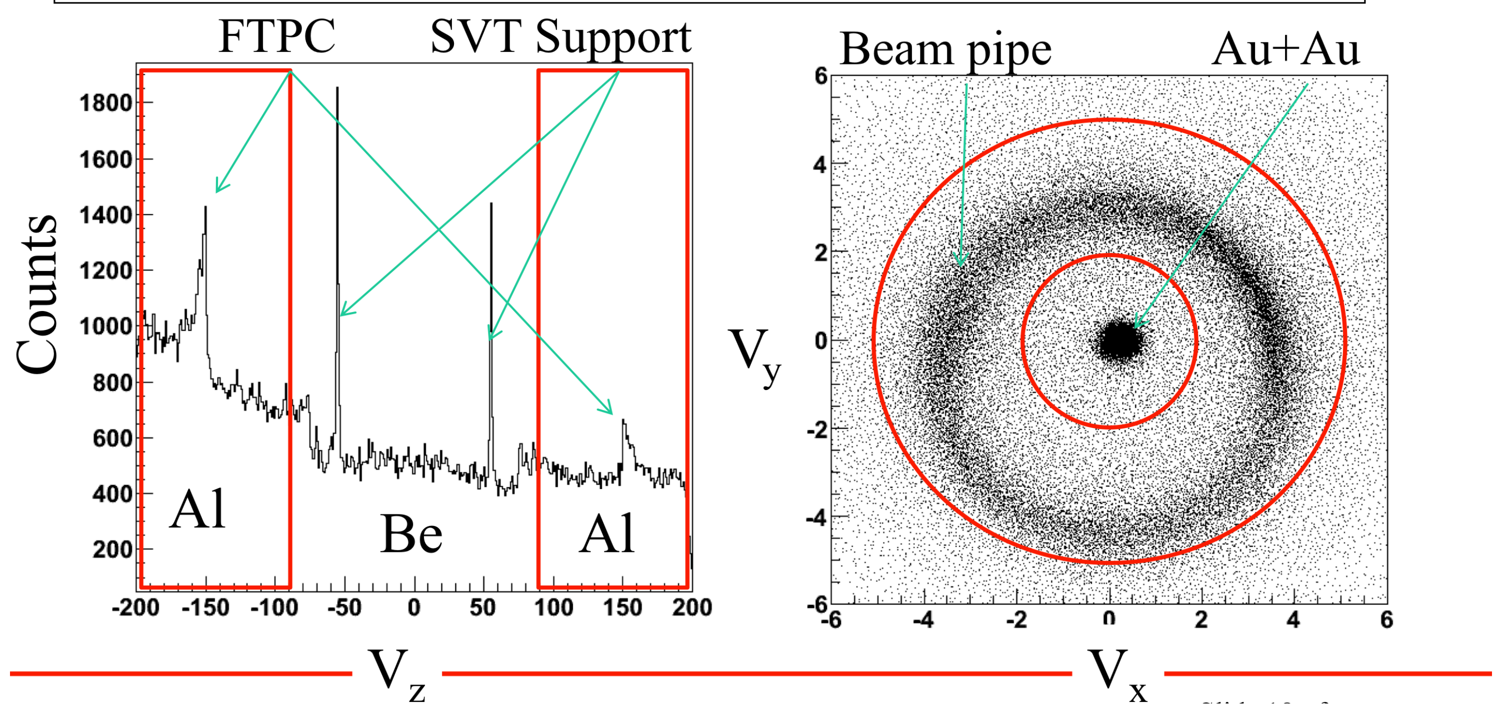
STAR capabilities

Data driven performance study

Au+Al at 3.85 GeV/c (from data set Au+Au at 7.7 GeV) – Samantha Brovko/UC Davis

Samantha's studies: Acceptance, PID, Spectra, vertexing, etc

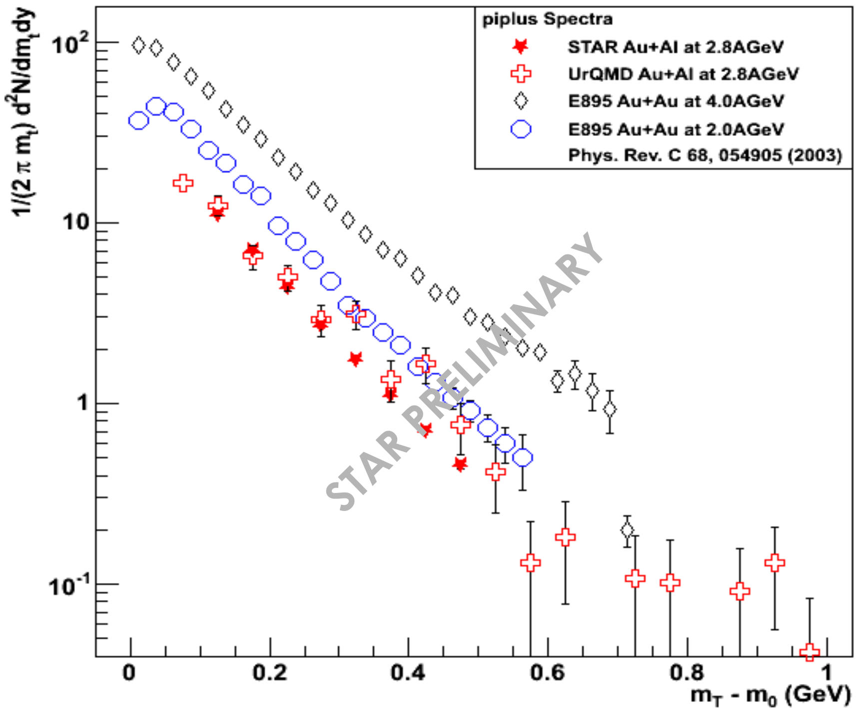
"7.7 GeV" Data set:
Select Events with $100 < |V_z| < 200$ and $2 < V_r < 5$ cm

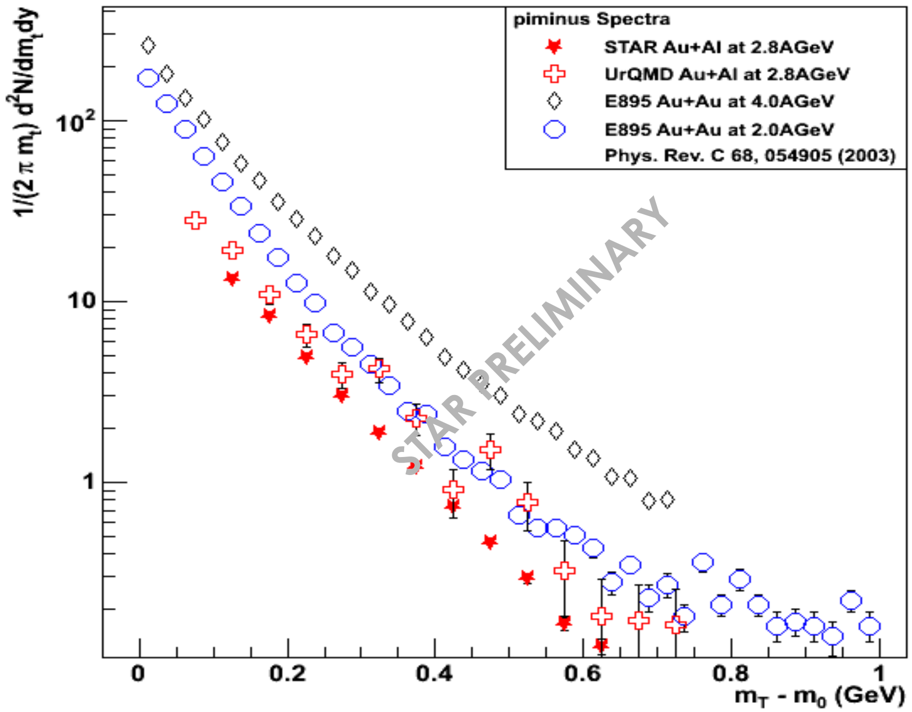


Remember, the BES trigger was designed to eliminate triggers like Au+Al events
BBC coincident should not allow for it

Au+Al (Au of 3.85 GeV on beam-pipe) -> $\sqrt{s}_{Fixed\text{-}Target}$ =2.98 GeV

2.8 AGeV Au+Al: Spectra π^+ and π^-





- No efficiency or acceptance corrections
  - Currently in progress
- Comparison to UrQMD suggests high efficiency for $\pi^{+/-}$

Sam Brovko

needs embedding for fixed target

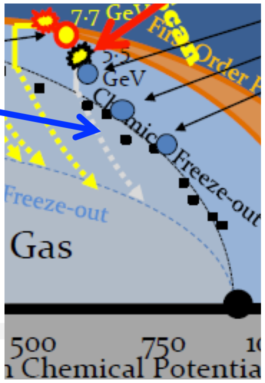
Fixed target at STAR

STAR will have adequate coverage (from mid-rapidity to target rapidity) in fixed-target mode, which is sufficient for some BES studies (detailed analysis of limitations in progress)

Main detectors TPC and TOF tested, work in progress on EEMC/BEMC, and trigger
Tracking, vertexing, PID reasonable, may be improved with optimization

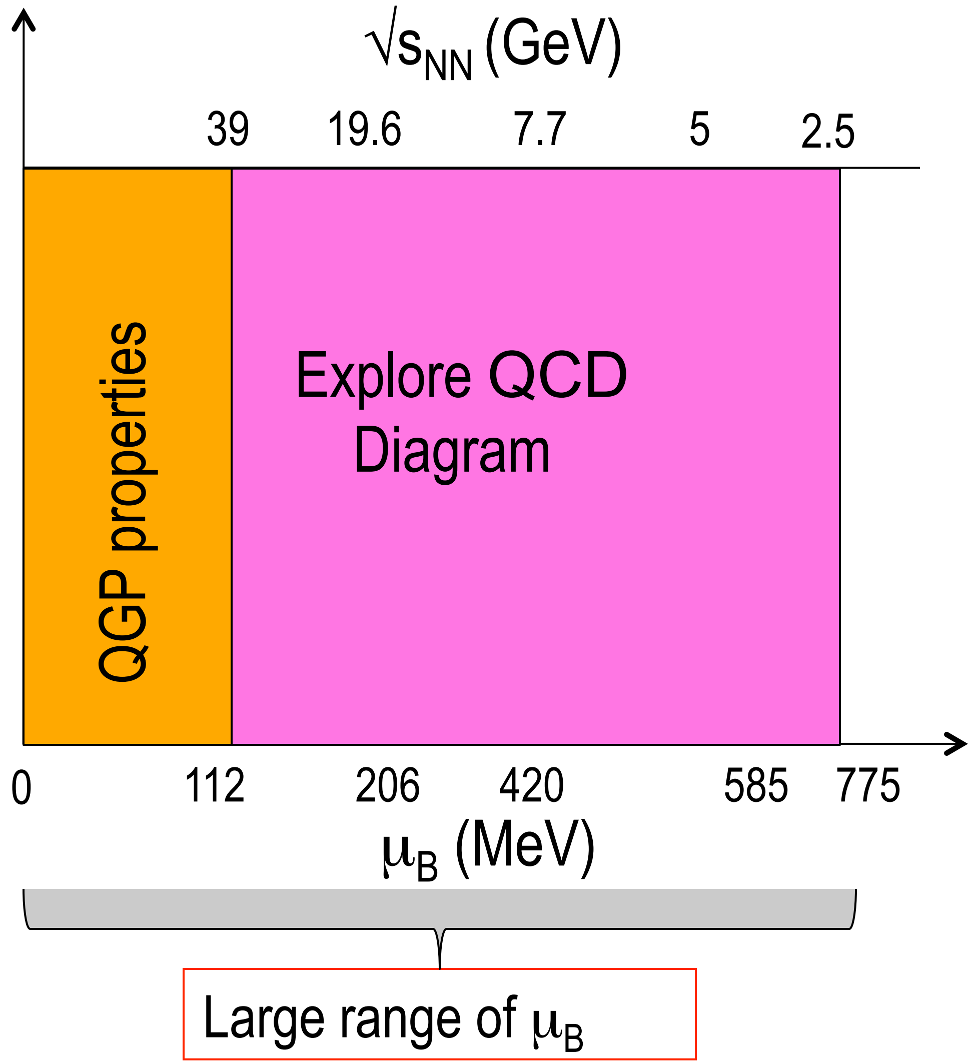
An internal fixed target can be used to take collisions with beam halo at injection energy, which will provide collisions at approximately $\sqrt{s_{NN}}$ of 5 GeV (data point missing from existing BES data)

If successful – this may open a way for fixed target runs with other beams used in BES program in collider mode experiments ($\sqrt{s_{NN}}$= 3.5 and 3 GeV, μ_B up to 800 MeV)

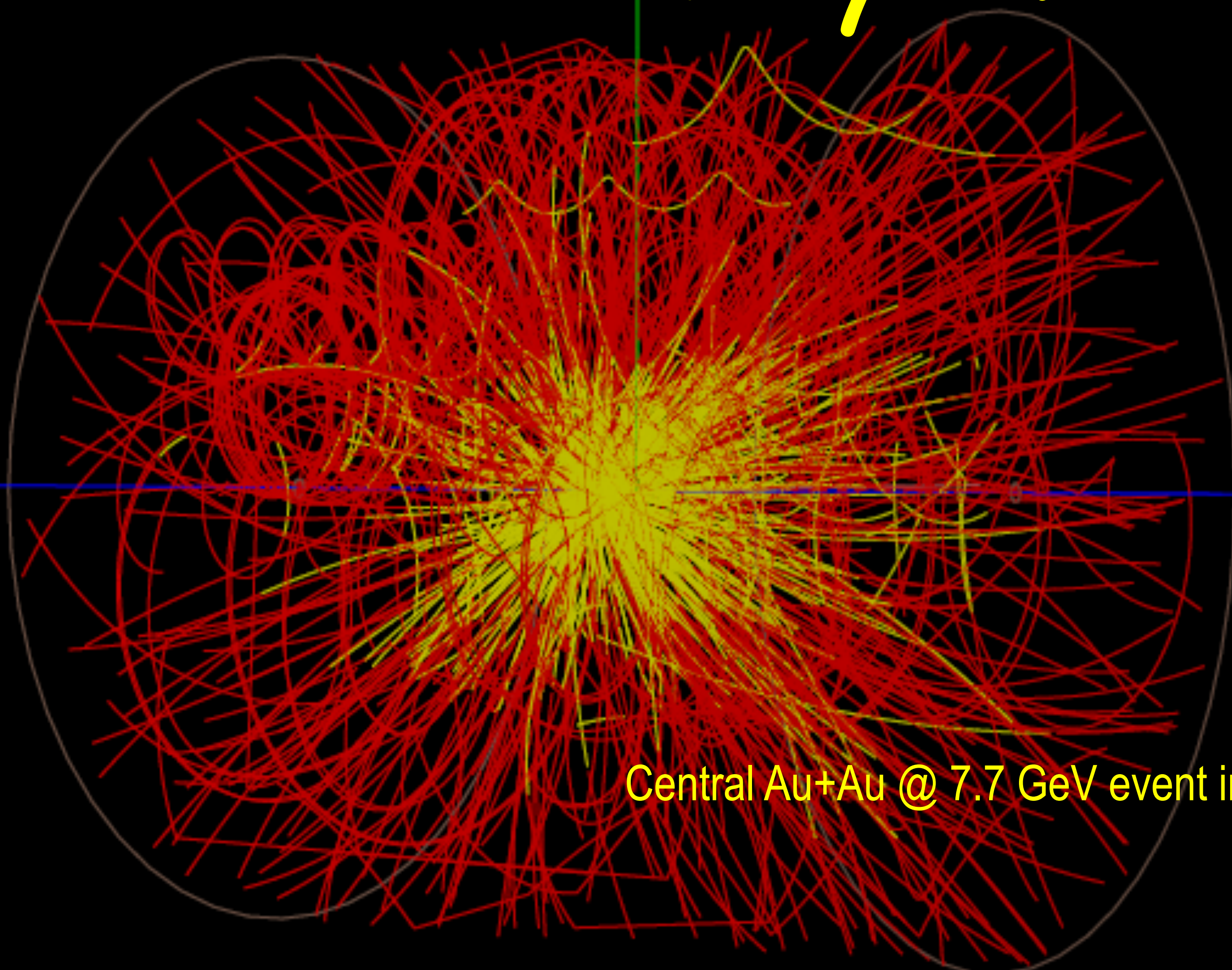


BES: analysis focused on evolution of trends with $\sqrt{s_{NN}}$ (not a single energy results)
with fixed target runs: $0 < \mu_B < \sim 800$ MeV !

Exploration of QCD phase diagram is in VERY good shape !



Thank you !



Central Au+Au @ 7.7 GeV event in STAR TPC