Results from STAR Beam Energy Scan Program

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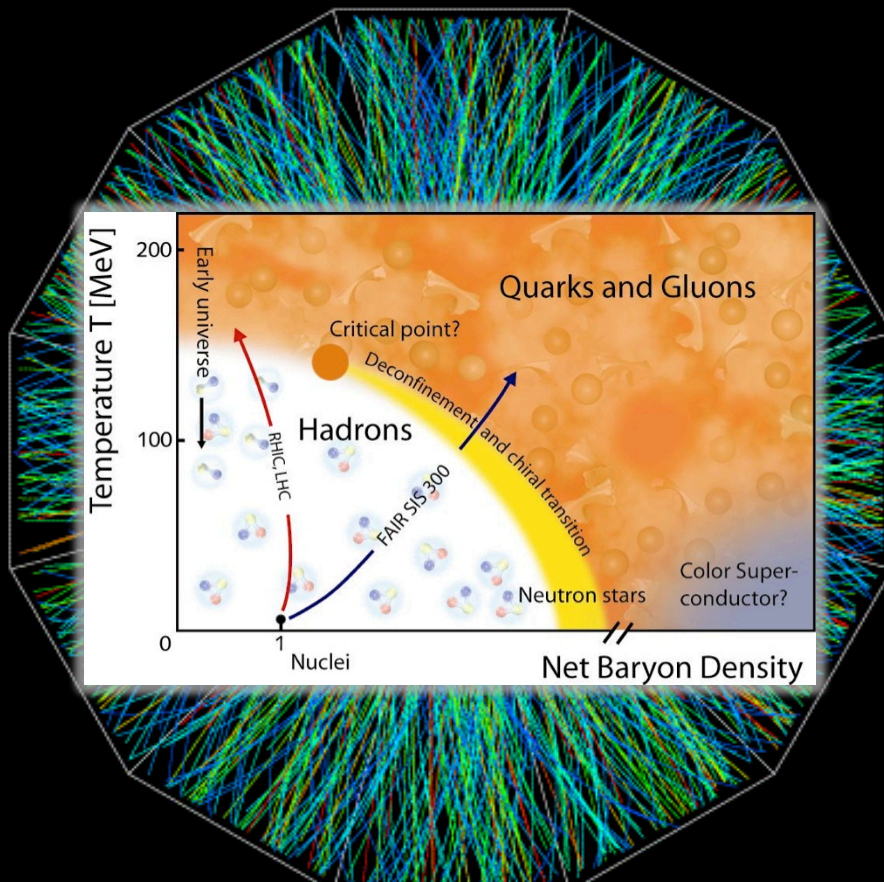
(for the STAR Collaboration)

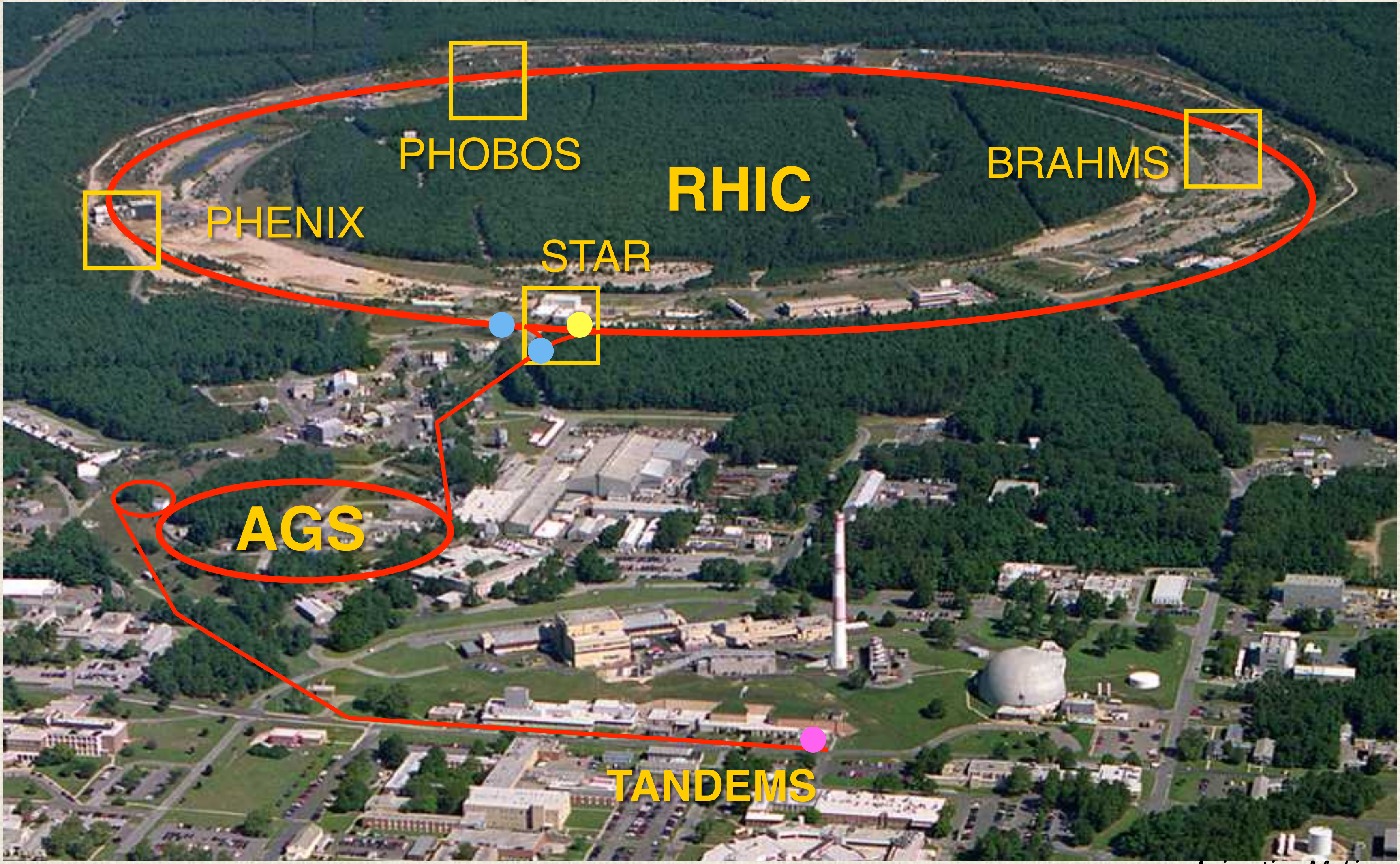


ISMD 2012

ISMD 2012

Relativistic Heavy Ion Collider

Brookhaven National Laboratory (BNL), Upton, NY



Animation M. Lisa

World's (second) largest operational heavy-ion collider

World's largest polarized proton collider

Relativ… …ider

Brookhave… …n, NY

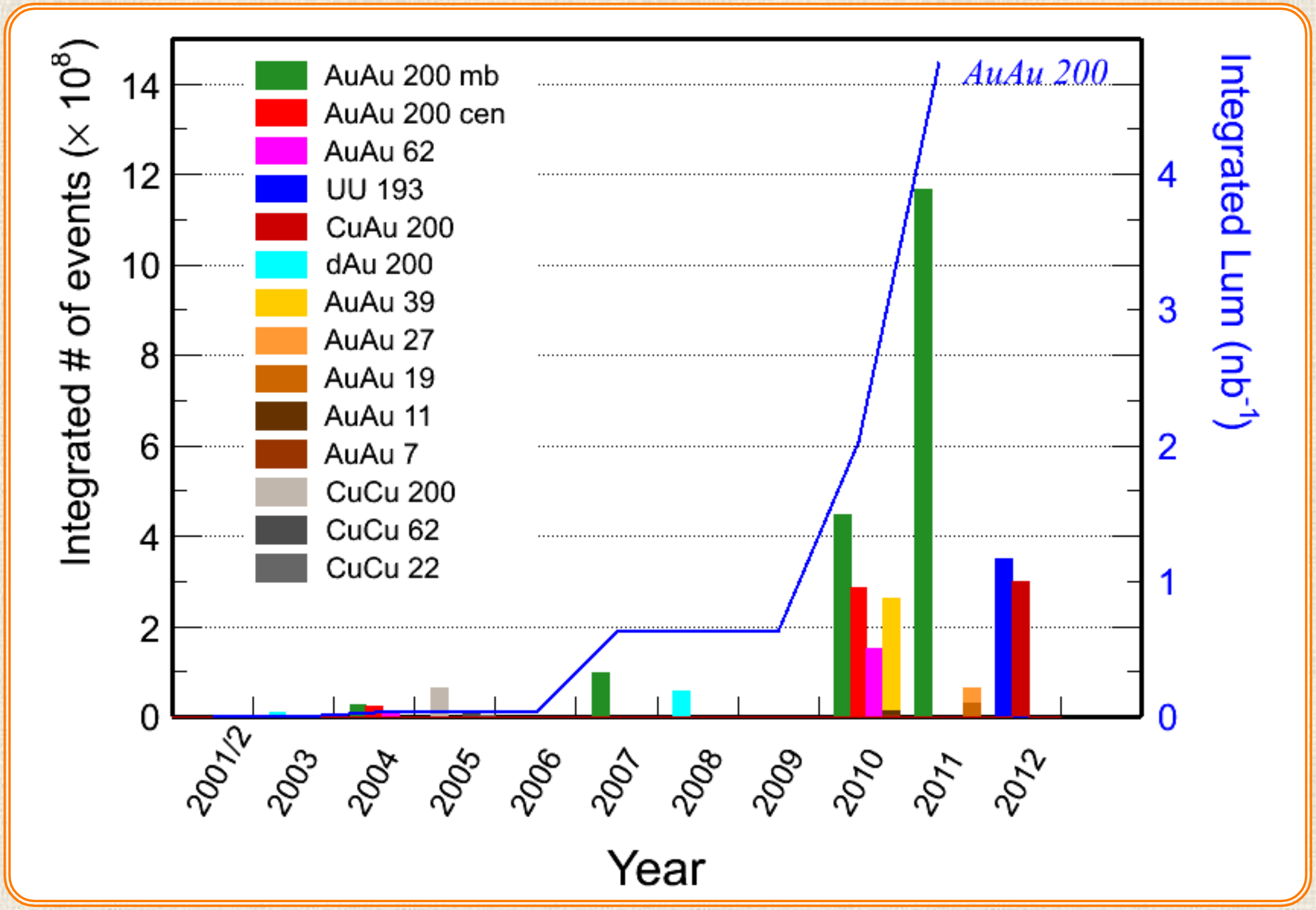
Year	System	$\sqrt{s_{NN}}$ [GeV]
2000	Au+Au	130
2001	Au+Au	200
2002	p+p	200
2003	d+Au	200
2004	Au+Au p+p	200, 62.4 200
2005	Cu+Cu	200, 62.4, 22
2006	p+p	62.4, 200, 500
2007	Au+Au	200
2008	d+Au p+p Au+Au	200 200 9.2
2009	p+p	200, 500
2010	Au+Au	200, 62.4, 39, 11.5, 7.7
2011	Au+Au p+p	200,19.6,27 500
2012	U+U Cu+Au p+p	193 200 200,510

Animation M. Lisa

World's (s… …ion collider

W… …der

Recorded Datasets



Fast DAQ + Electron Based Ion Source + 3D Stochastic cooling

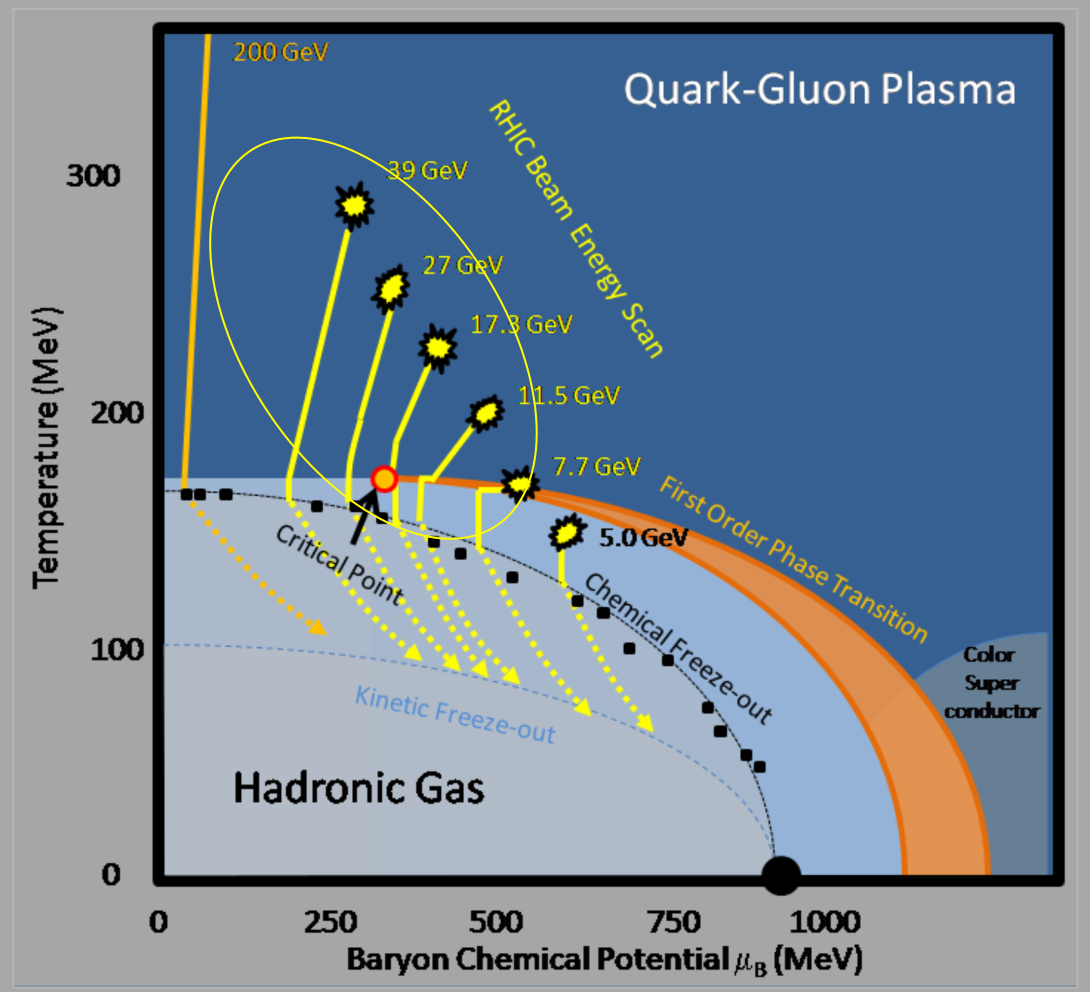
The RHIC Beam Energy Scan Project

- Since the original design of RHIC (1985), running at lower energies has been envisioned

- RHIC has studied the possibilities of running lower energies with a series of test runs: 19.6 GeV Au+Au in 2001, 22.4 GeV Cu+Cu in 2005, and 9.2 GeV Au+Au in 2008

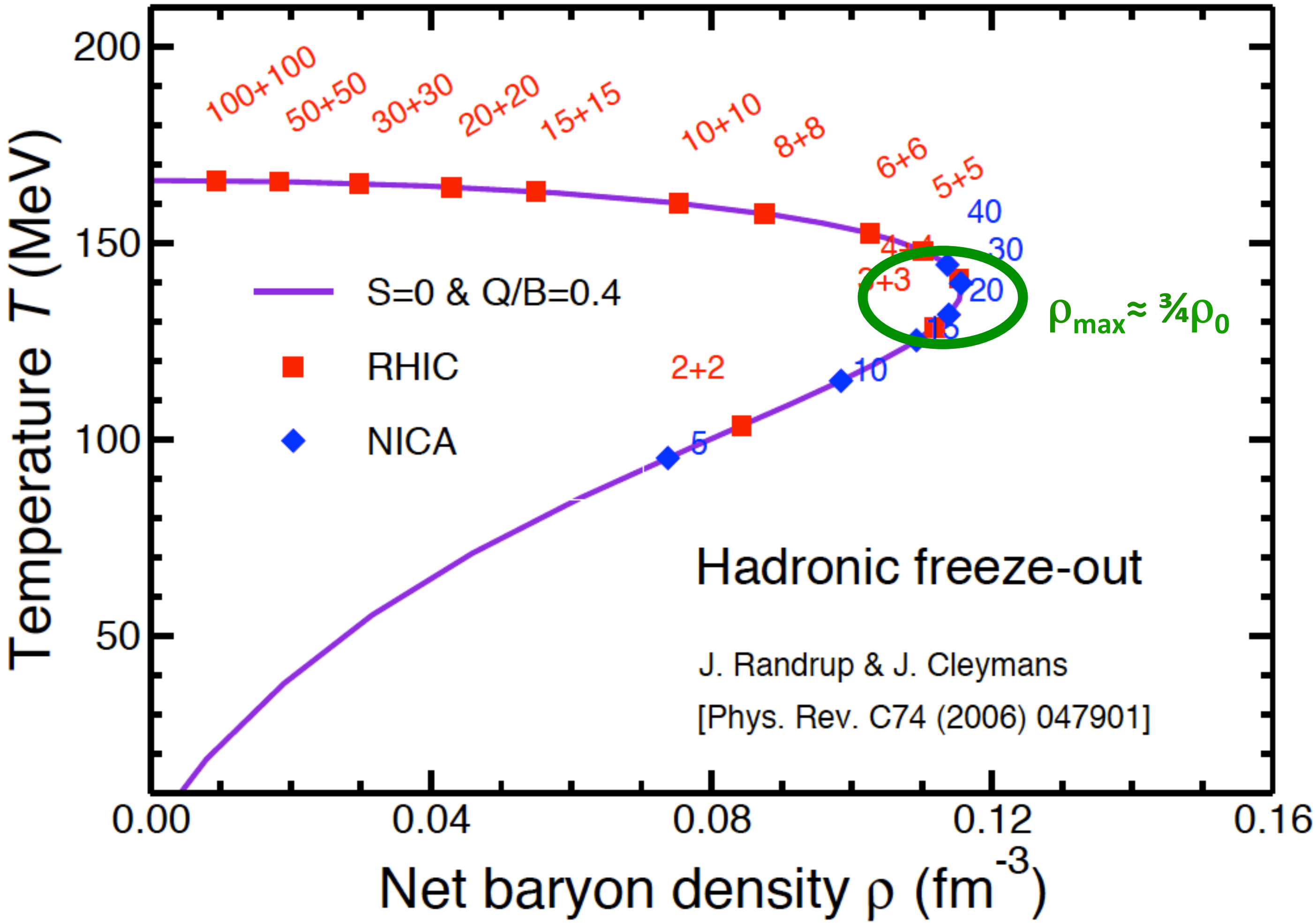
- In 2009 the RHIC PAC approved a proposal to run a series of six energies to search for the critical point and the onset of deconfinement.

- These energies were run during the 2010 and 2011 running periods.



A landmark of the QCD phase diagram

Maximum Net Baryon Density



$\rho_{max} \approx \frac{3}{4}\rho_0$

The maximum net baryon density at freeze-out expected for $\sqrt{s_{NN}}$≈6-8 GeV

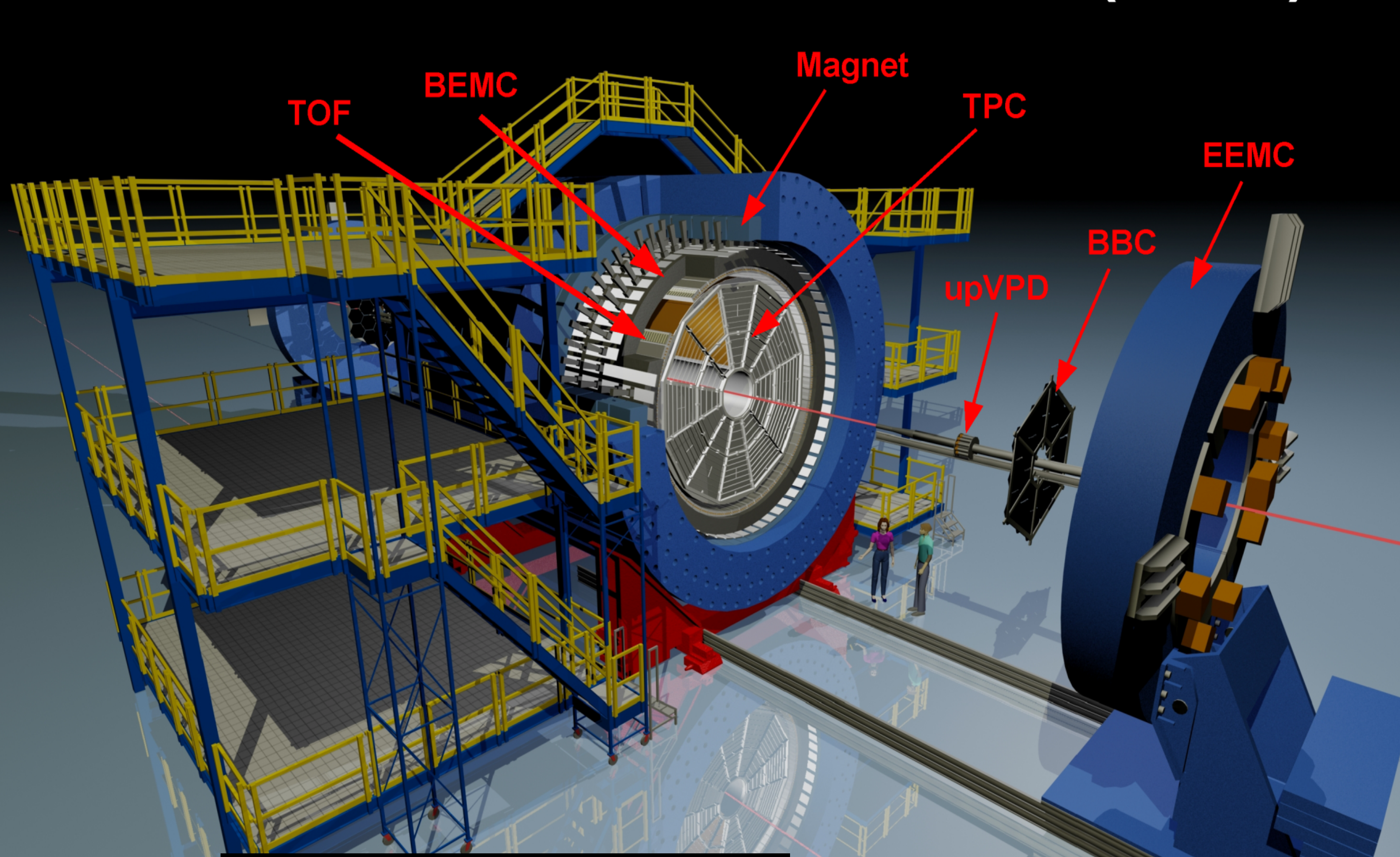
The RHIC Beam Energy Scan Motivation

0) Turn-off of sQGP signatures

1) Search for the signals of phase boundary

2) Search for the QCD critical point

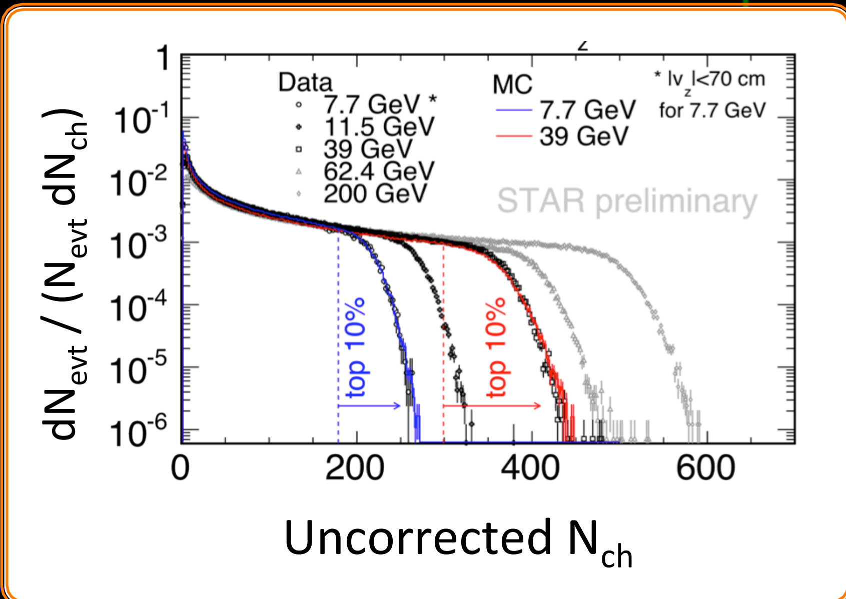
<u>See talks after the break:</u>
Nihar Sahoo: Higher moments of net-charge multiplicity distributions…
Zhiming Li: Dynamical higher cummulant ratios of net and total protons…



TPC:
Detects Particles in the $|\eta|<1$ range
π, K, p through dE/dx and TOF
K^0_s, Λ, Ξ, Ω, ϕ through invariant mass

Coverage: $0 < \phi < 2\pi$ $|\eta| < 1.0$
Uniform acceptance: All energies and particles

BES Data Taking



BES-I Data:

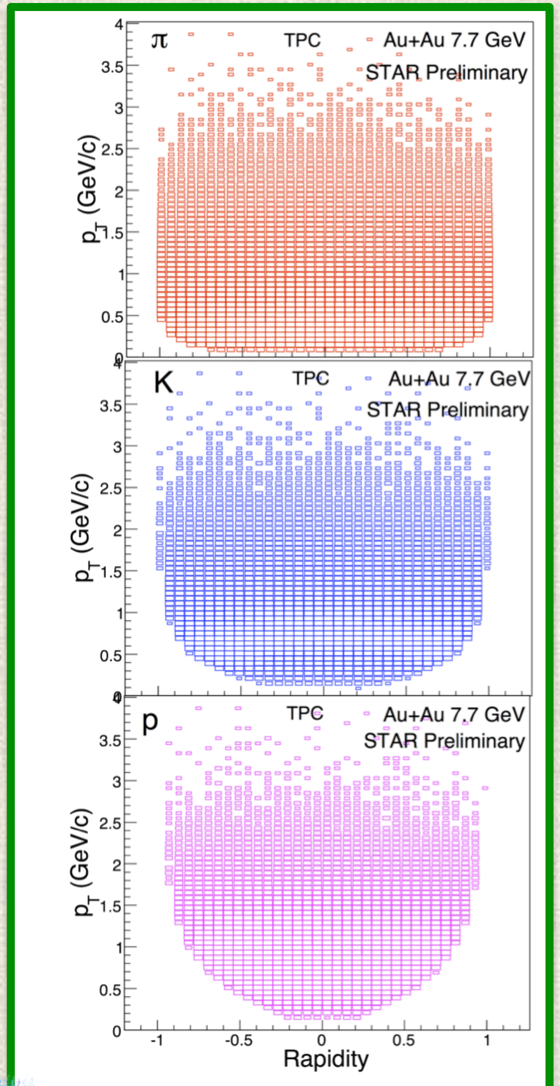
Year	$\sqrt{s_{NN}}$ [GeV]	events(10^6)
2010	39	130
2011	27	70
2011	19.6	36
2010	11.5	12
2010	7.7	5
2012*	5	Test Run

Detector performance generally improves at lower energies. Geometric acceptance remains the same, track density gets lower. Triggering required effort, but was a solvable problem.

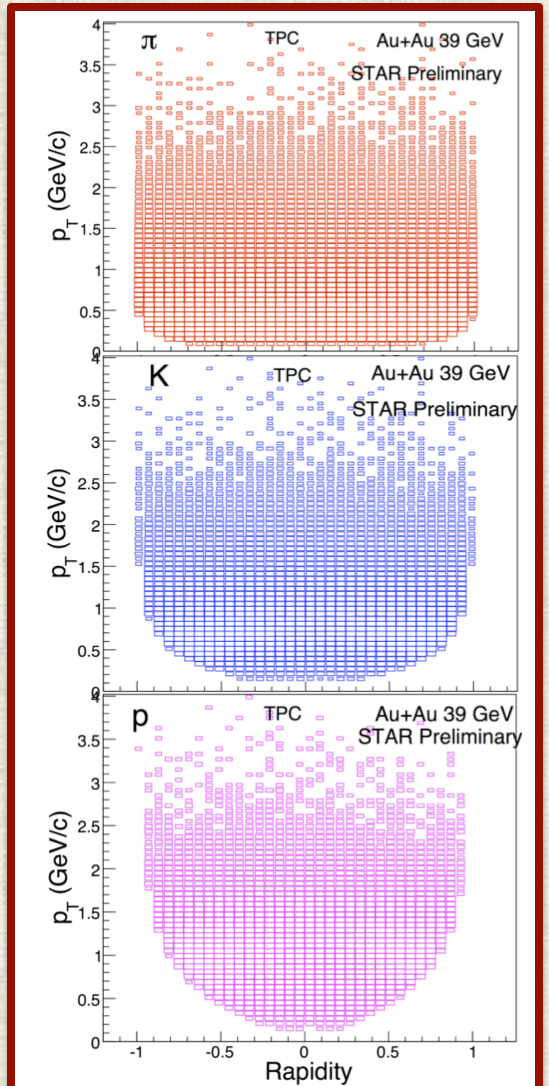
Central Au+Au at 7.7 GeV in STAR TPC

STAR TPC - Uniform Acceptance over all RHIC Energies

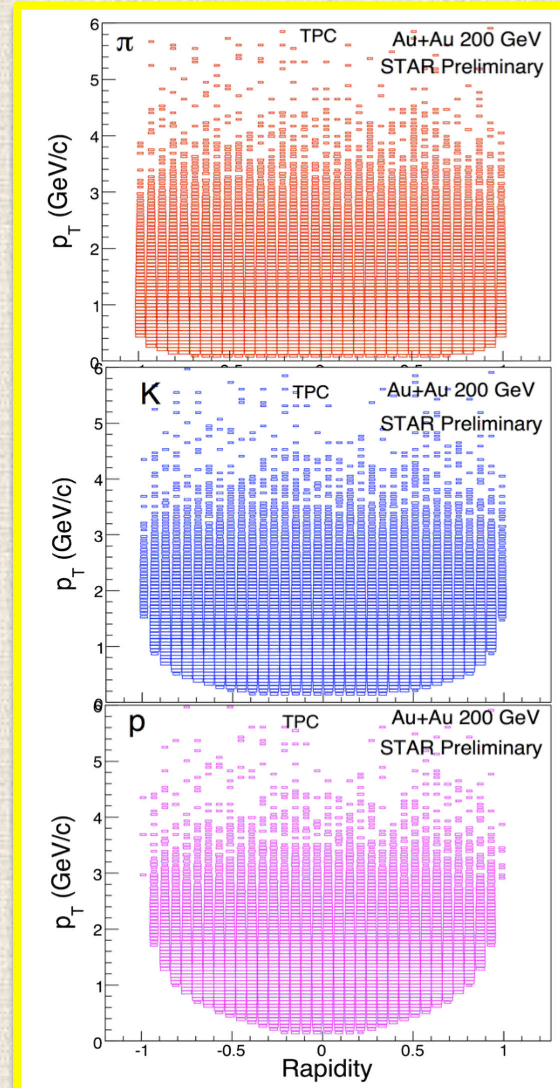
Au+Au at *7.7* GeV



Au+Au at *39* GeV

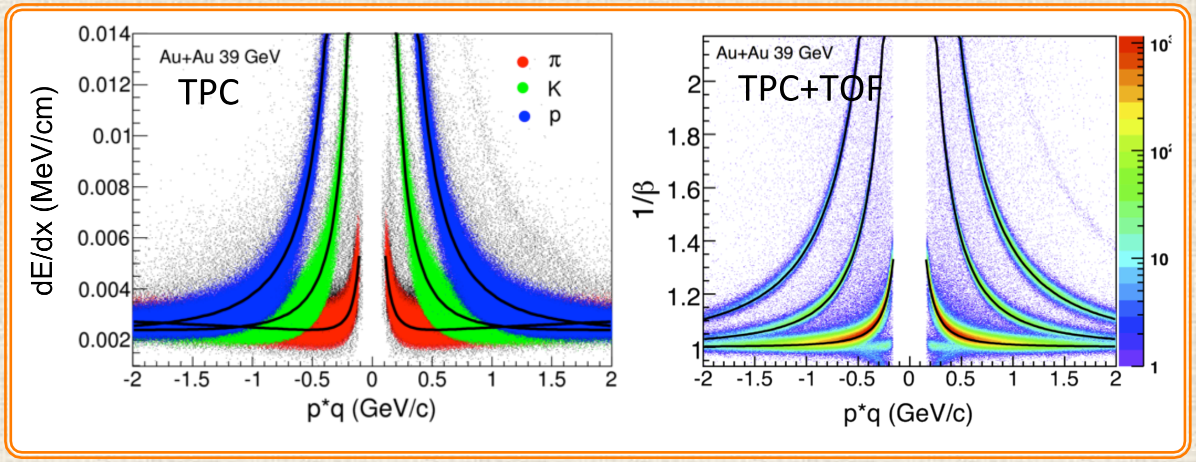


Au+Au at *200* GeV



- Crucial for all analyses

Particle Identification

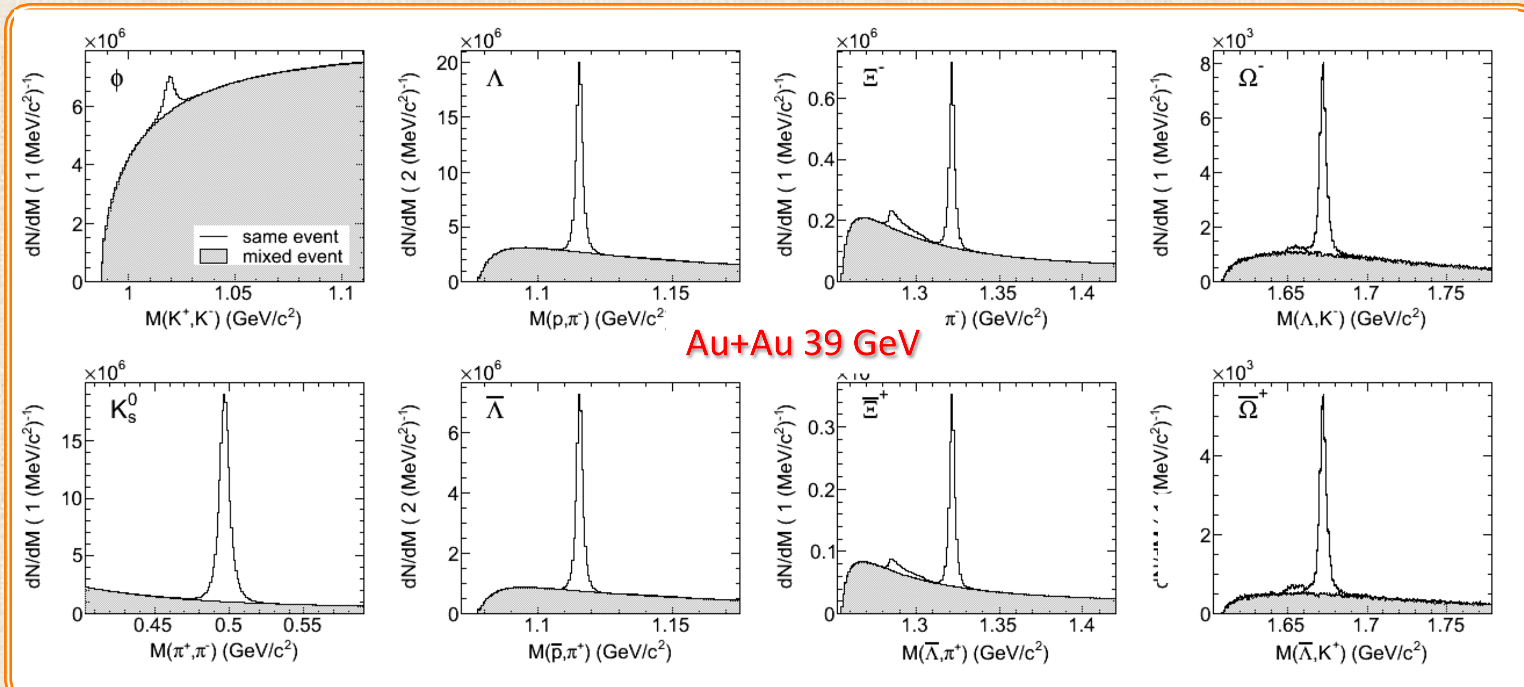


PID (TPC+TOF):

π/K: p_T~1.6 GeV/c

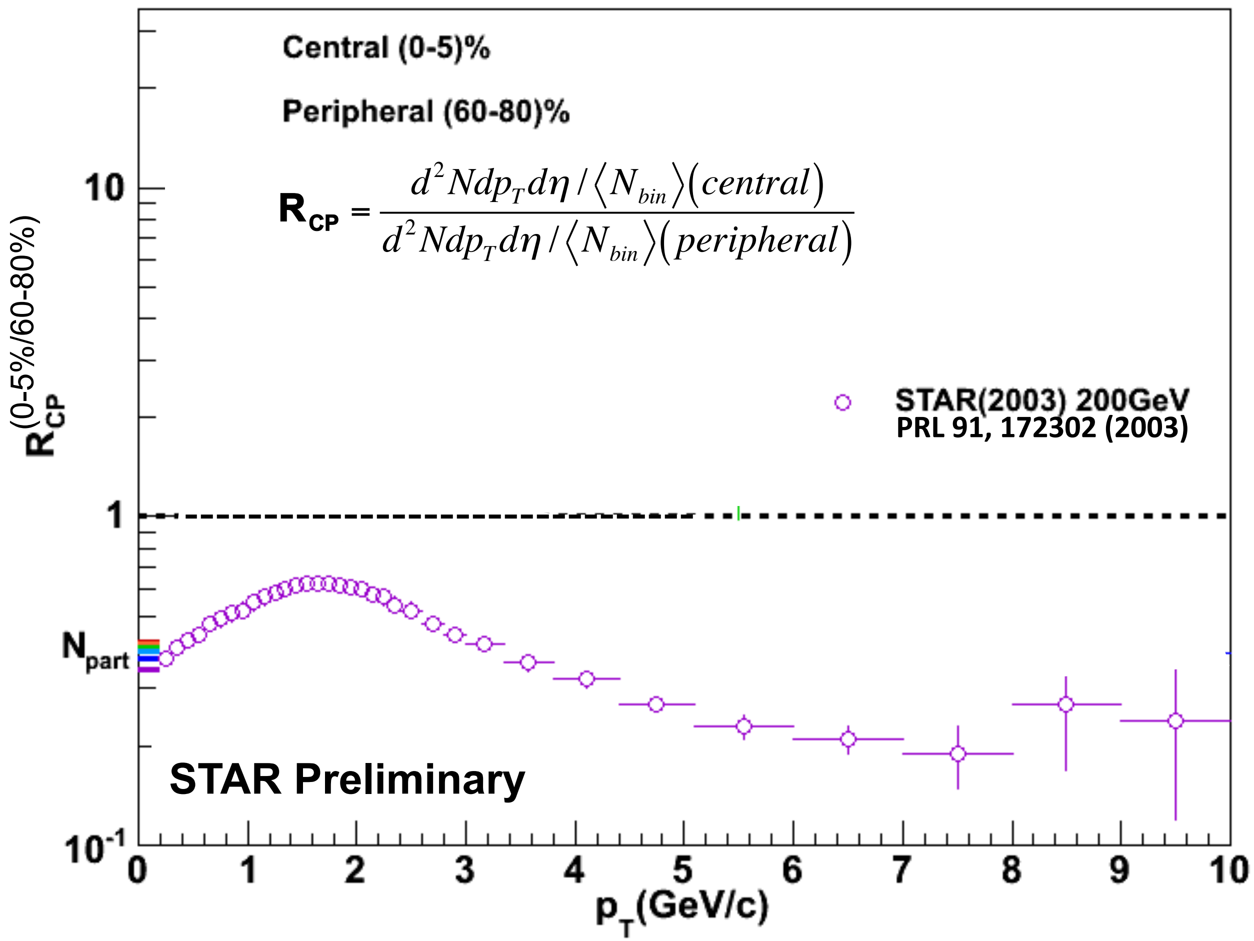
p: p_T~3.0 GeV/c

Strange hadrons: decay topology & invariant mass

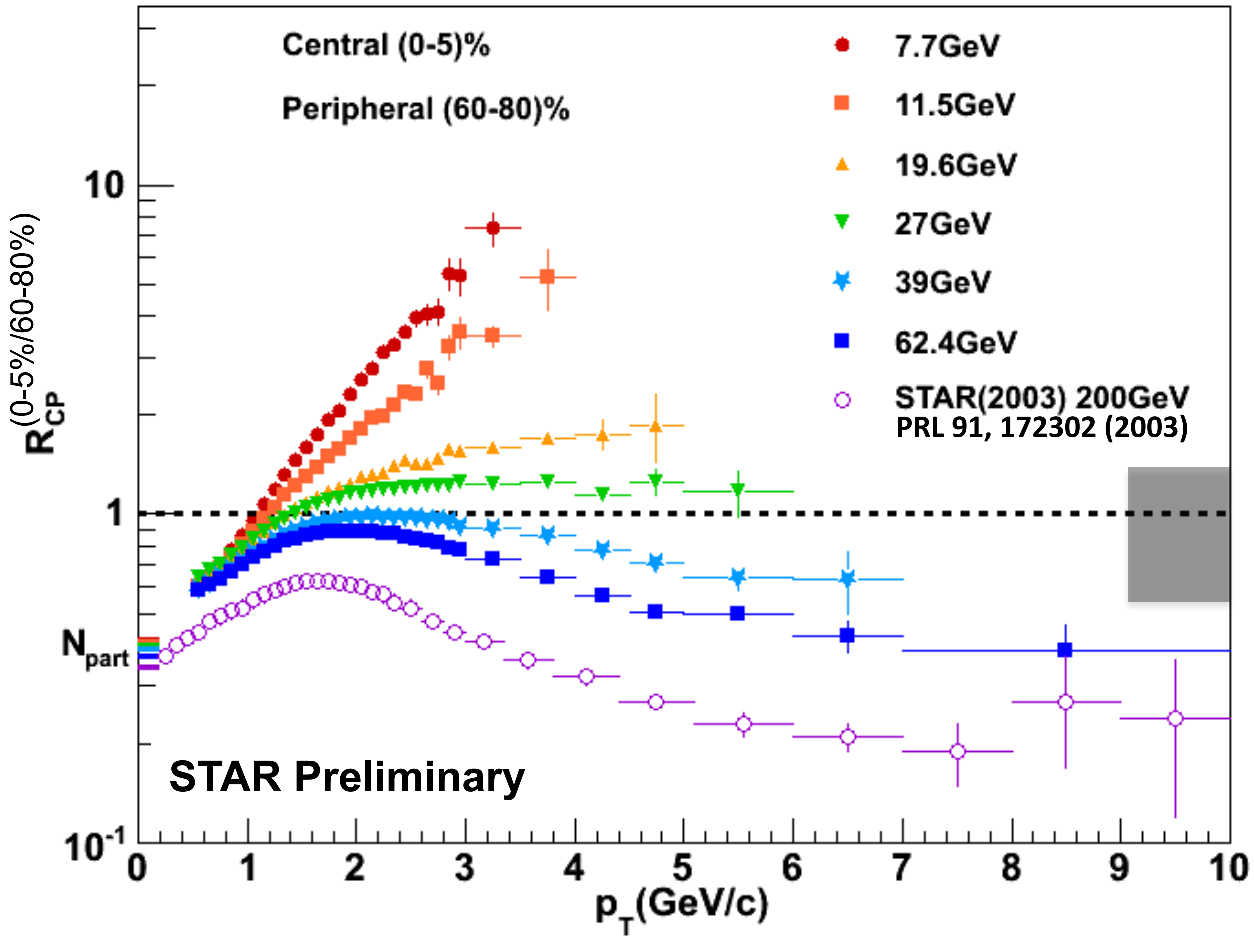


Selected Results

Suppression of Charged Hadrons …

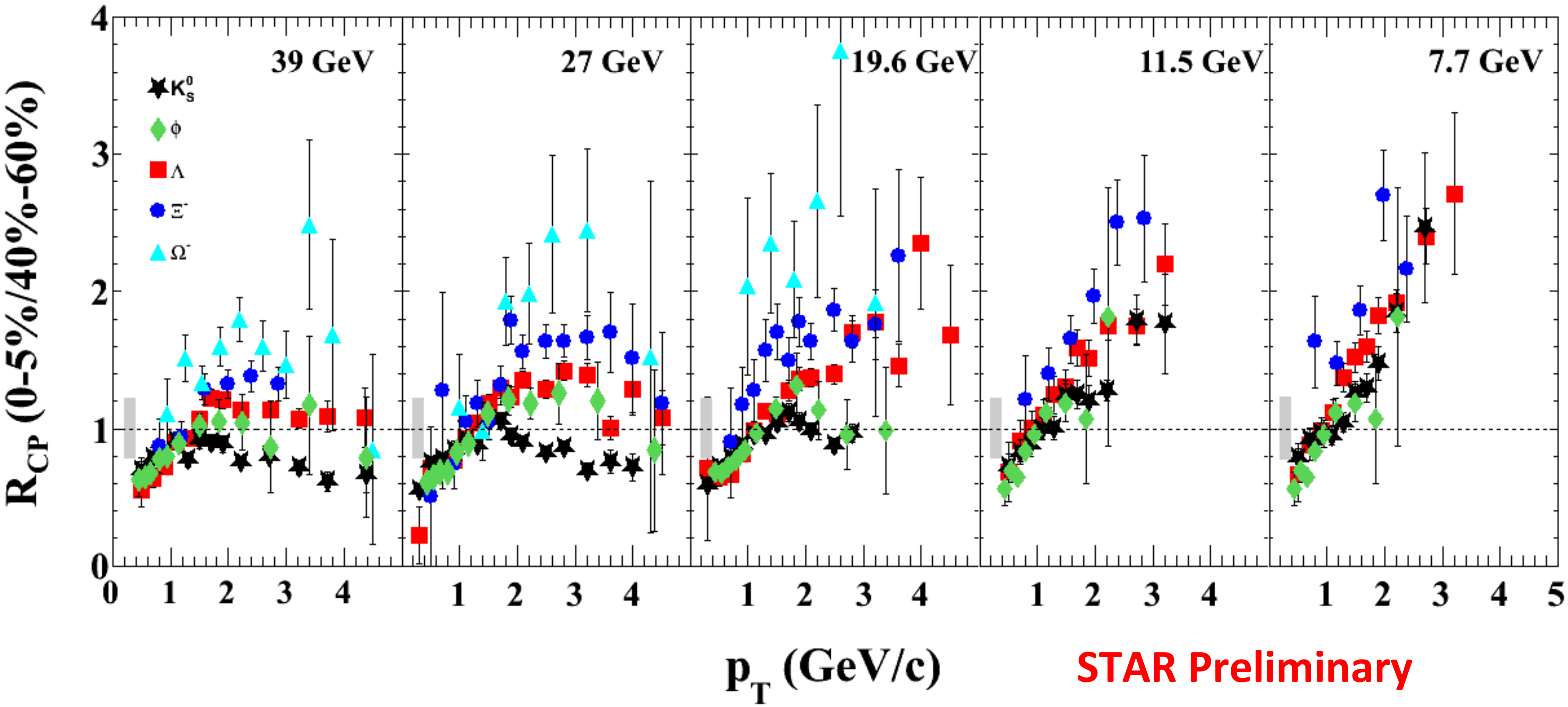


… and its Disappearance



$R_{CP} \geq 1$ at $\sqrt{s_{NN}} \leq 27$ GeV - Cronin effect?

R_{CP} : Identified Particles

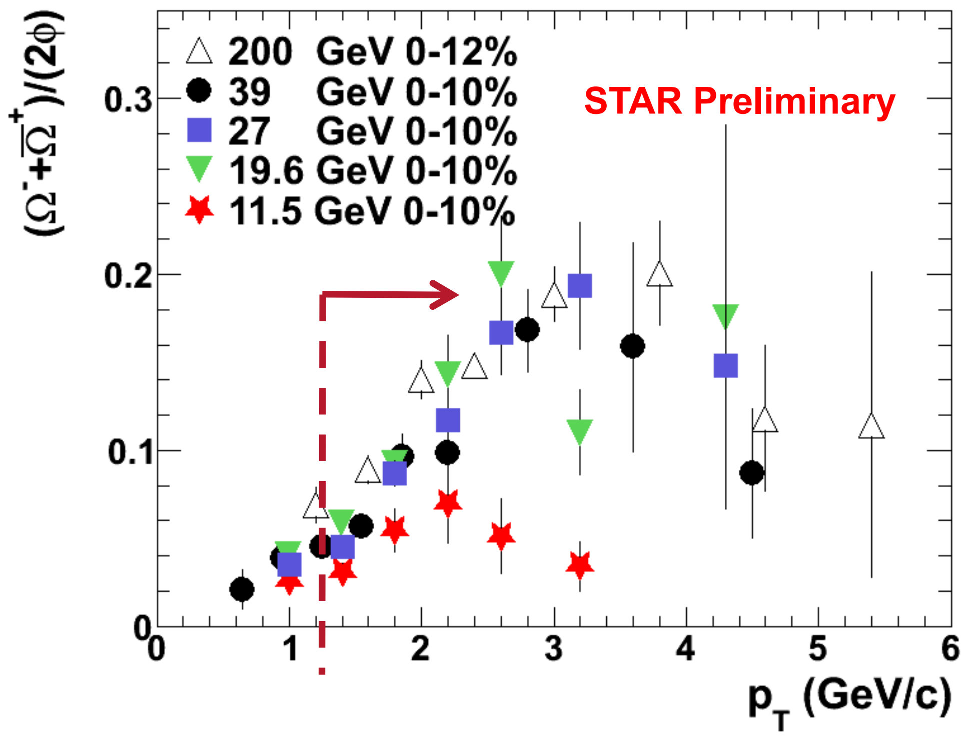


- Baryon-meson splitting reduces and disappears with decreasing energy

For p_T > 2 GeV/c:

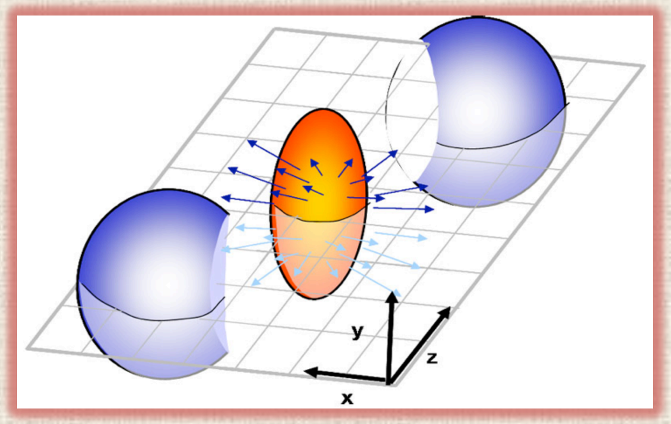
- R_{CP} ($K^0{}_s$) < 1 @ $\sqrt{s_{NN}}$ > 19.6 GeV
- R_{CP} > 1 @ $\sqrt{s_{NN}} \leq$ 11.5 GeV

Baryon/Meson Ratio



➢ Ω/ϕ ratio falls off at 11.5 GeV

Azimuthal Anisothropy



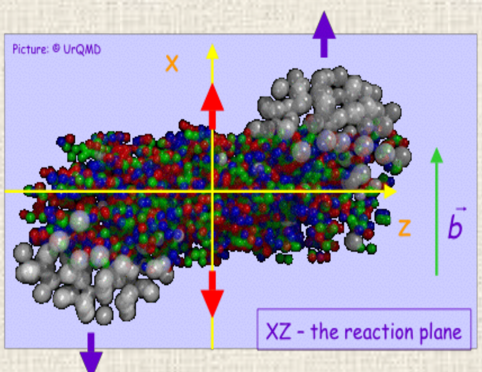
$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \psi_n)\right]\right)$$

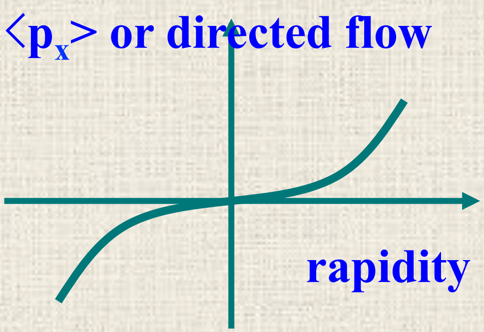
Directed flow is quantified by the first harmonic: $v_1 = \langle \cos(\phi - \Psi_r) \rangle$

$$\phi = \tan^{-1}\left(\frac{p_x}{p_y}\right)$$

- Directed flow is due to the sideward motion of the particles within the reaction plane.
- Generated already during the nuclear passage time ($2R/\gamma \approx .1$ fm/c@200GeV)

⇒ It probes the onset of bulk collective dynamics during thermalization (preequilibrium)

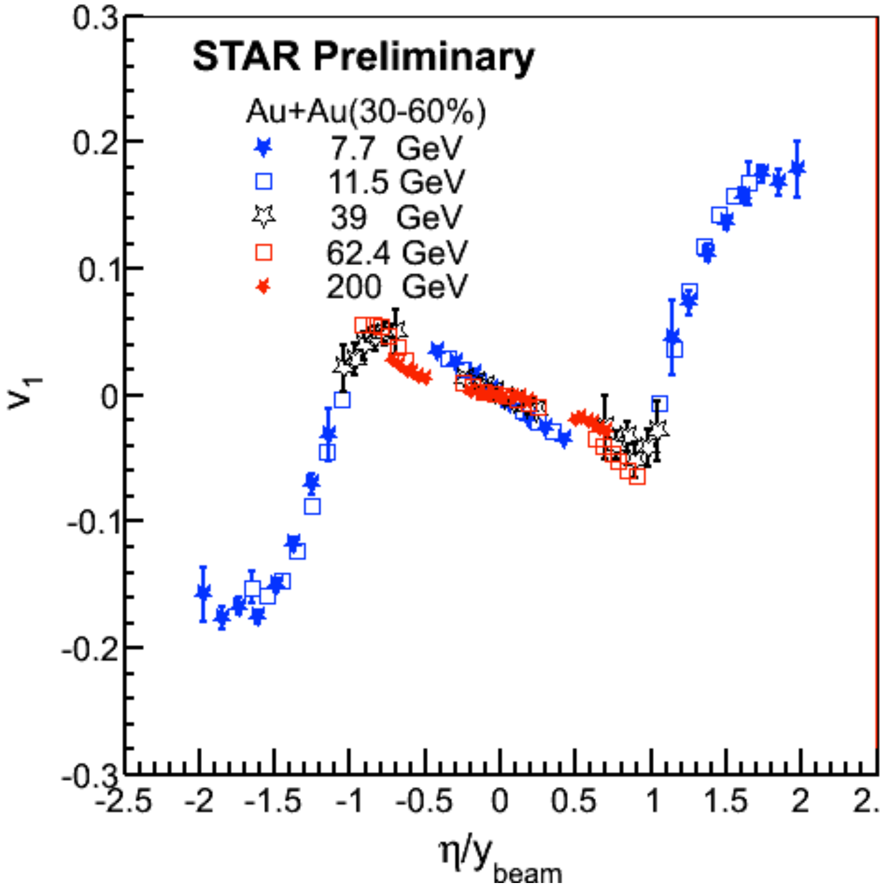


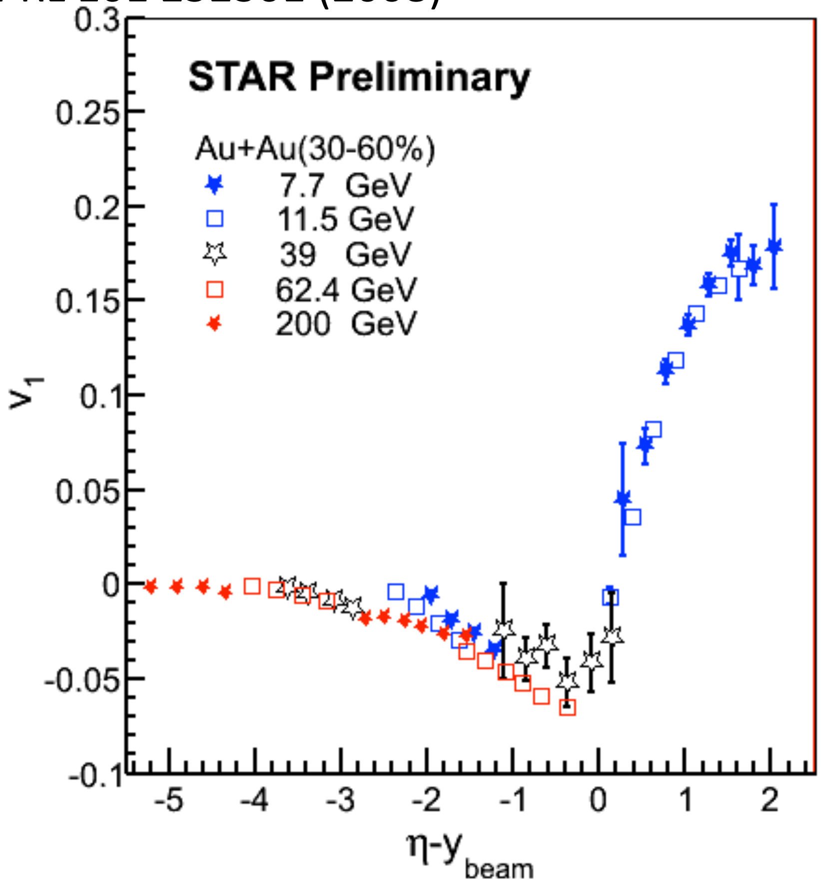


$v_1(y)$ is sensitive to baryon transport, space - momentum correlations and QGP formation

Charged Hadrons v_1: Beam Energy Dependence

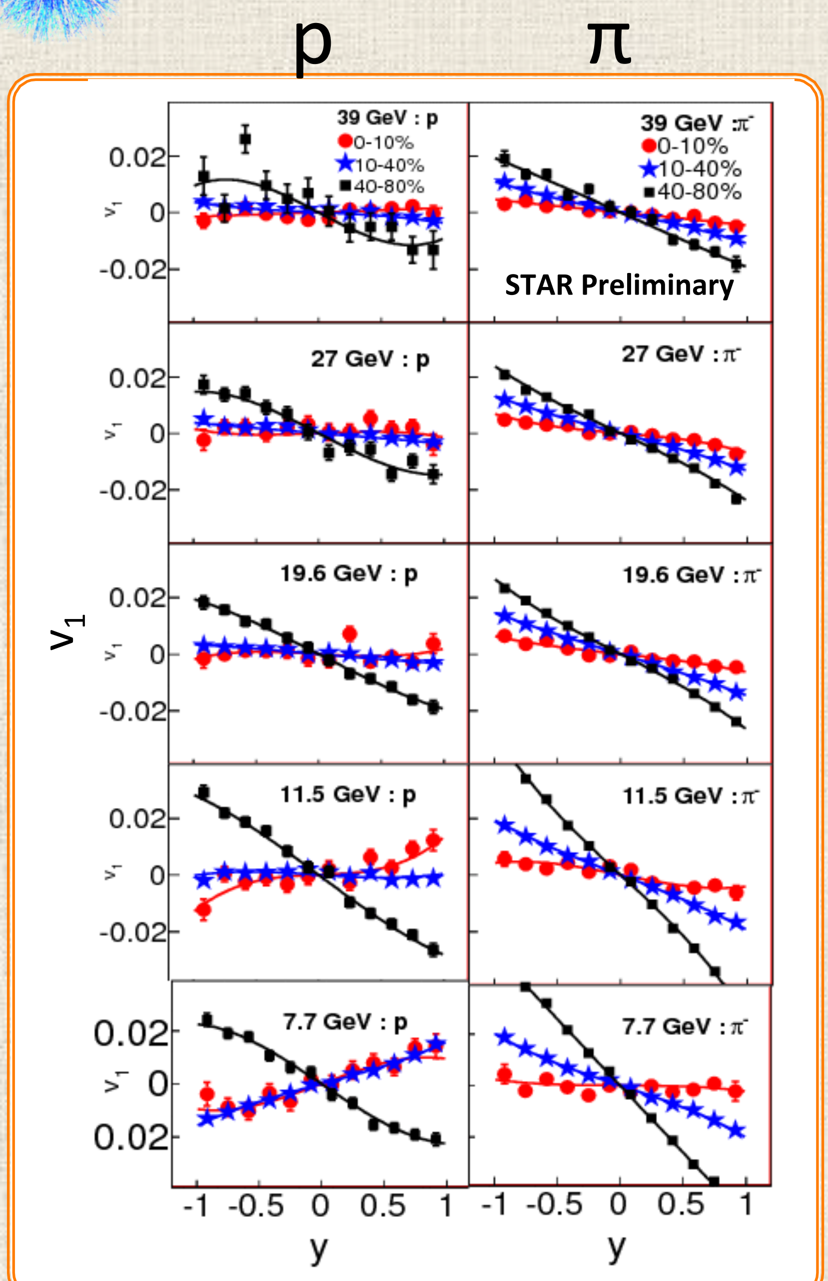
Data at 62.4&200GeV from STAR, PRL 101 252301 (2008)

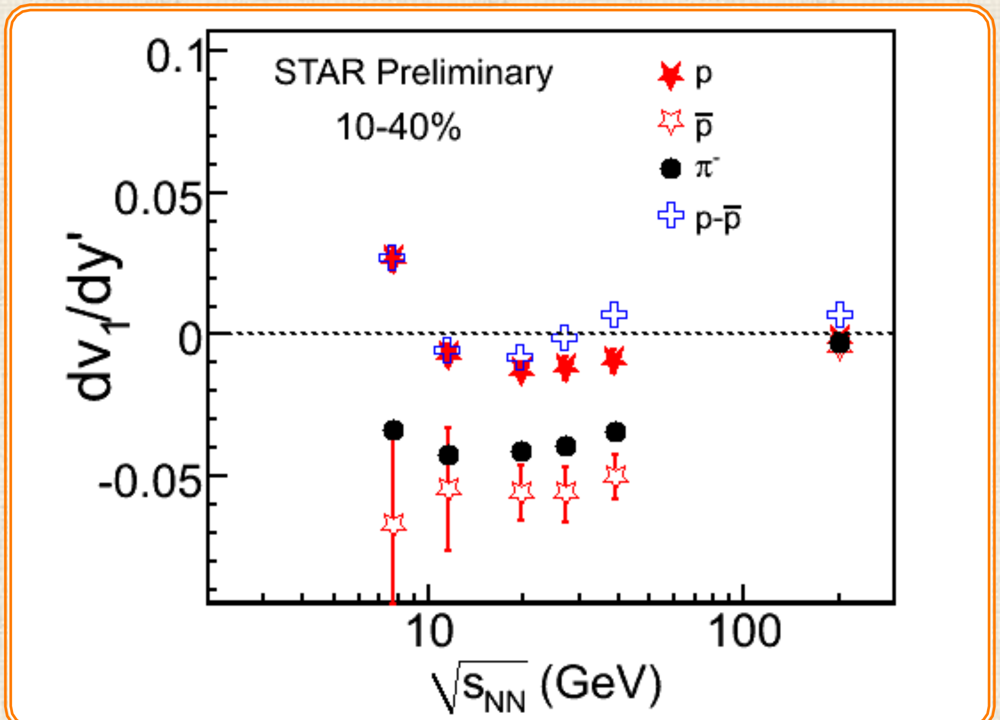




Scaling behavior in v_1 vs. η/y_{beam} and v_1 vs. $\eta' = \eta - y_{beam}$

Directed Flow of p and π



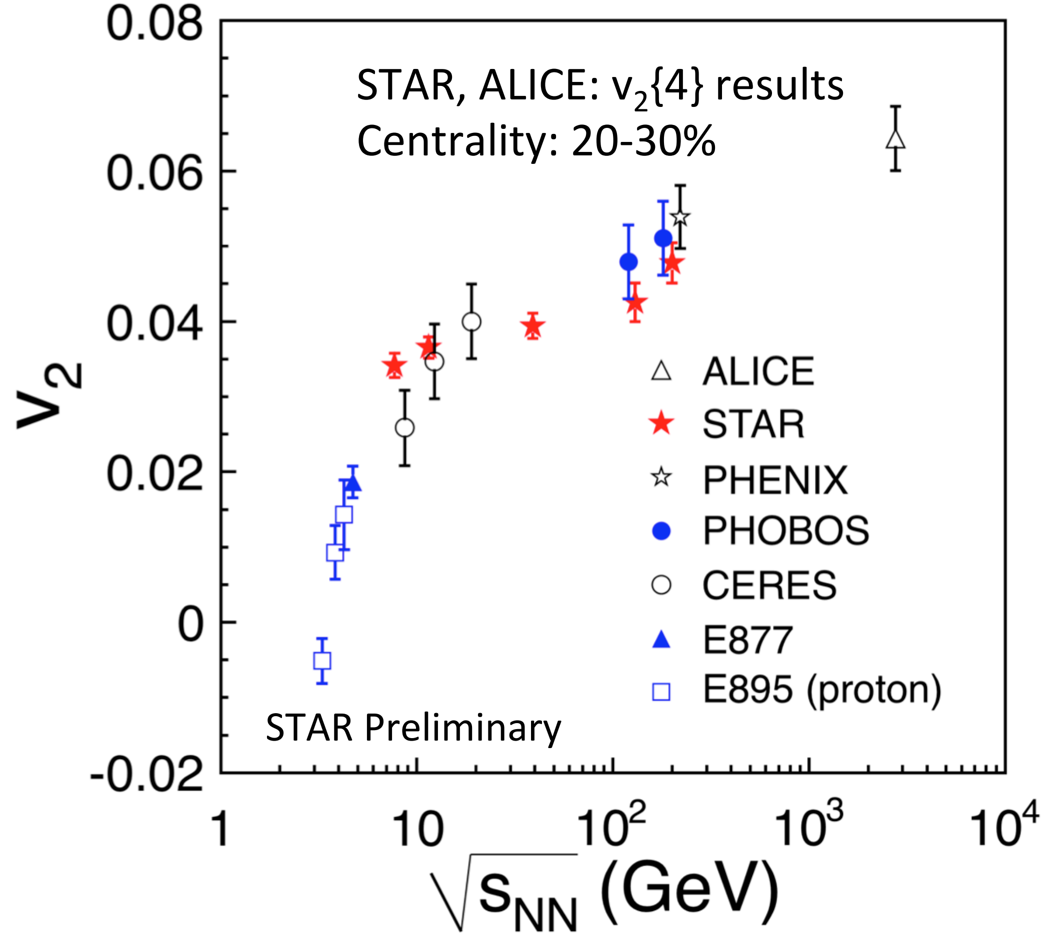


Mid-central collisions:

Pion v_1 slope: Always negative (7.7-39 GeV)

(Net)-proton v_1 slope: changes sign between 7.7 and 11.5 GeV - may be due to the contribution from the transported protons coming to midrapidity at the lower beam energies

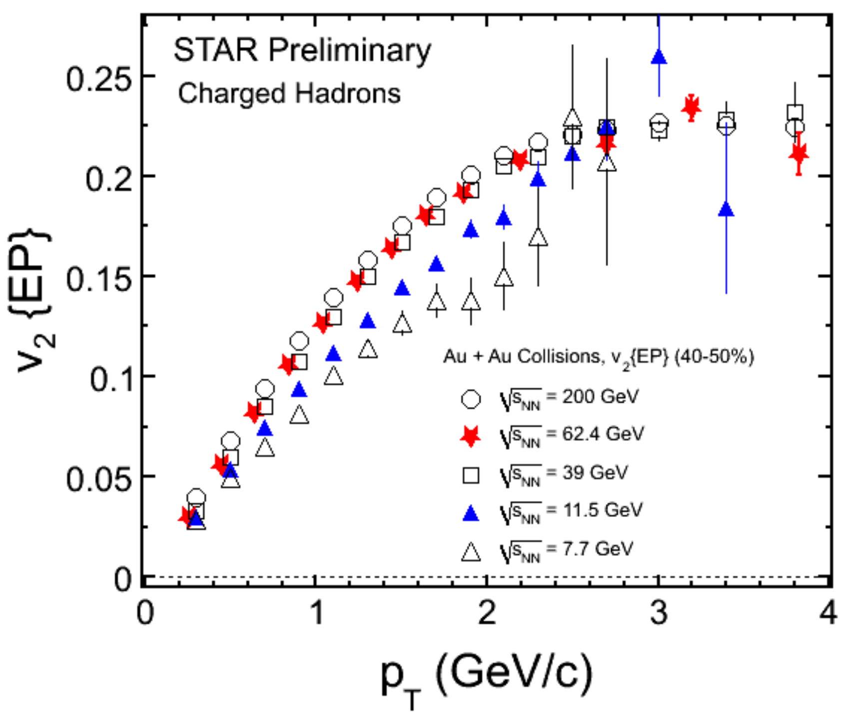
Energy Dependence of v_2

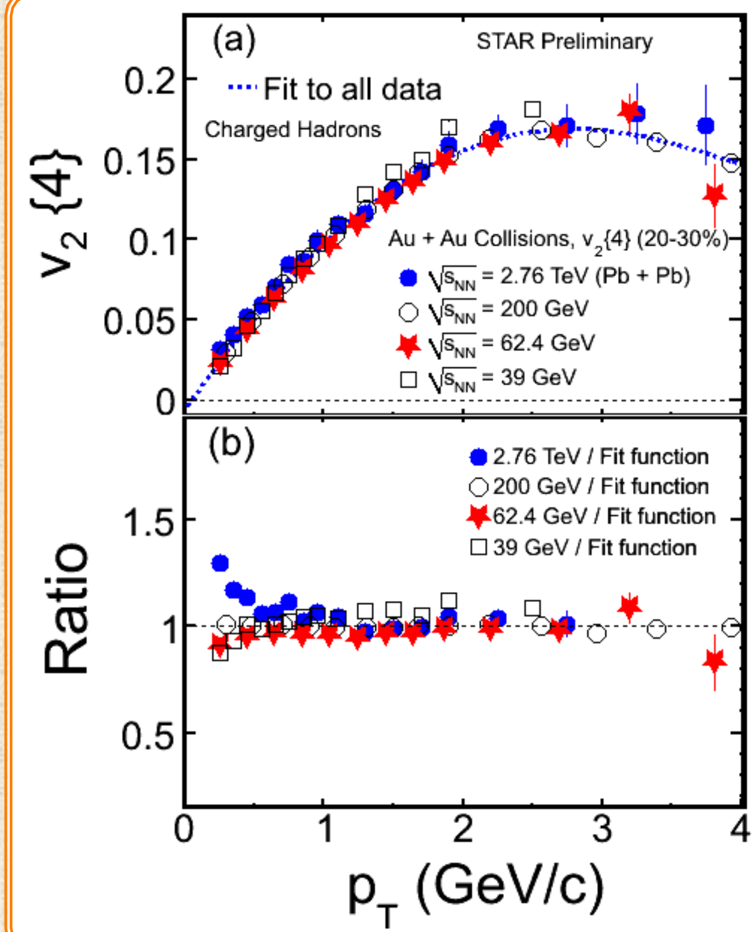


ALICE: PRL 105, 252302 (2010)
PHENIX: PRL 98, 162301 (2007)
PHOBOS: PRL 98, 242302 (2007)
CERES: Nucl. Phys. A 698, 253c (2002).
E877: Nucl. Phys. A 638, 3c(1998).
E895: PRL 83, 1295 (1999).
STAR 130 Gev:
Phys.Rev. C66,034904 (2002).
STAR 200 GeV:
Phys.Rev. C72,014904 (2005).

- The rate of increase with collision energy is slower from 7.7 to 39 GeV compared to that between 3 to 7.7 GeV

$v_2(p_T)$: First Result





STAR: Nucl.Phys. A862-863(2011)125

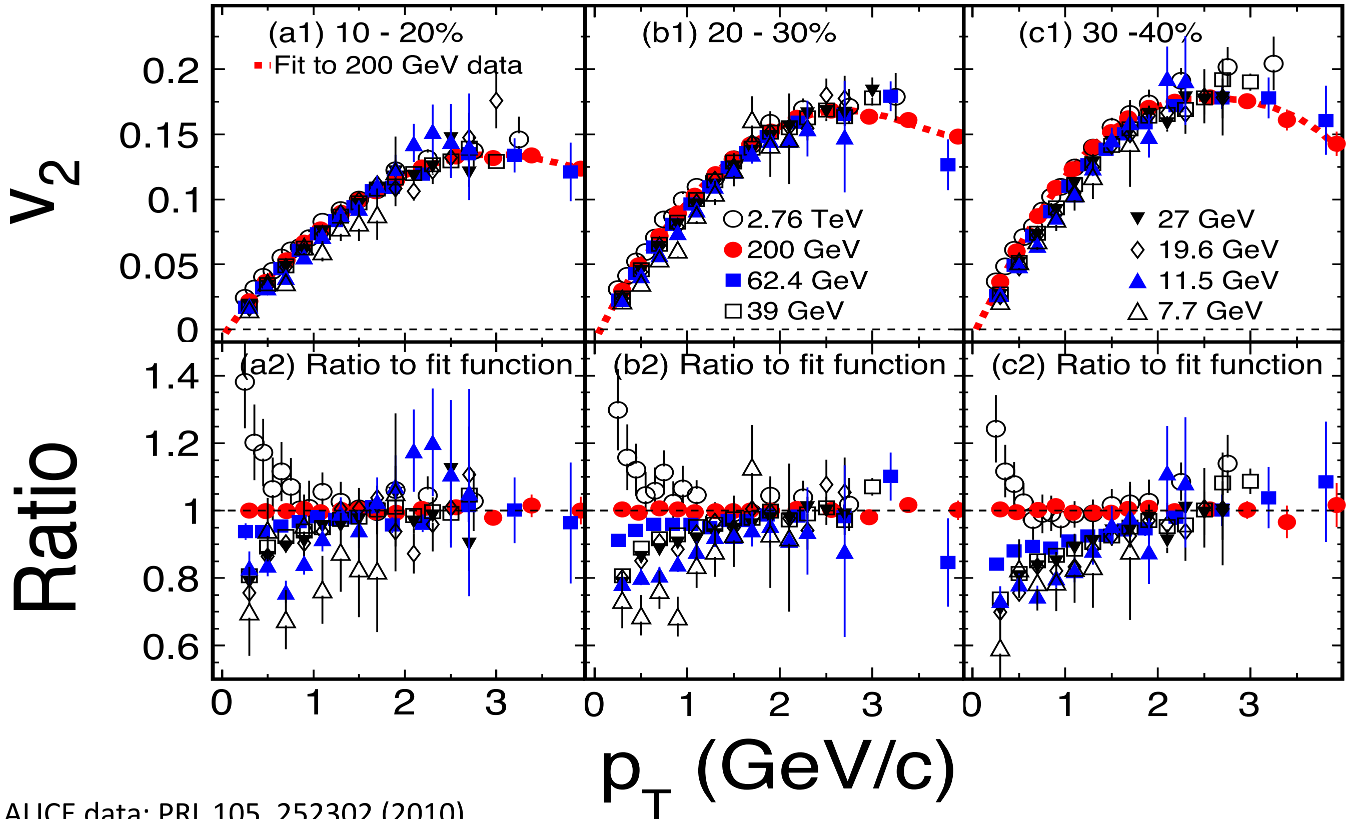
✓ v_2 (7.7 GeV) < v_2 (11.5 GeV) < v_2 (39 GeV)

★ v_2 (39 GeV) ≈ v_2 (62.4 GeV) ≈ v_2 (200 GeV) ≈ v_2 (2.76 TeV)

⇒ sQGP from 39 GeV to 2.76 TeV

$v_2(p_T)$: Final Result

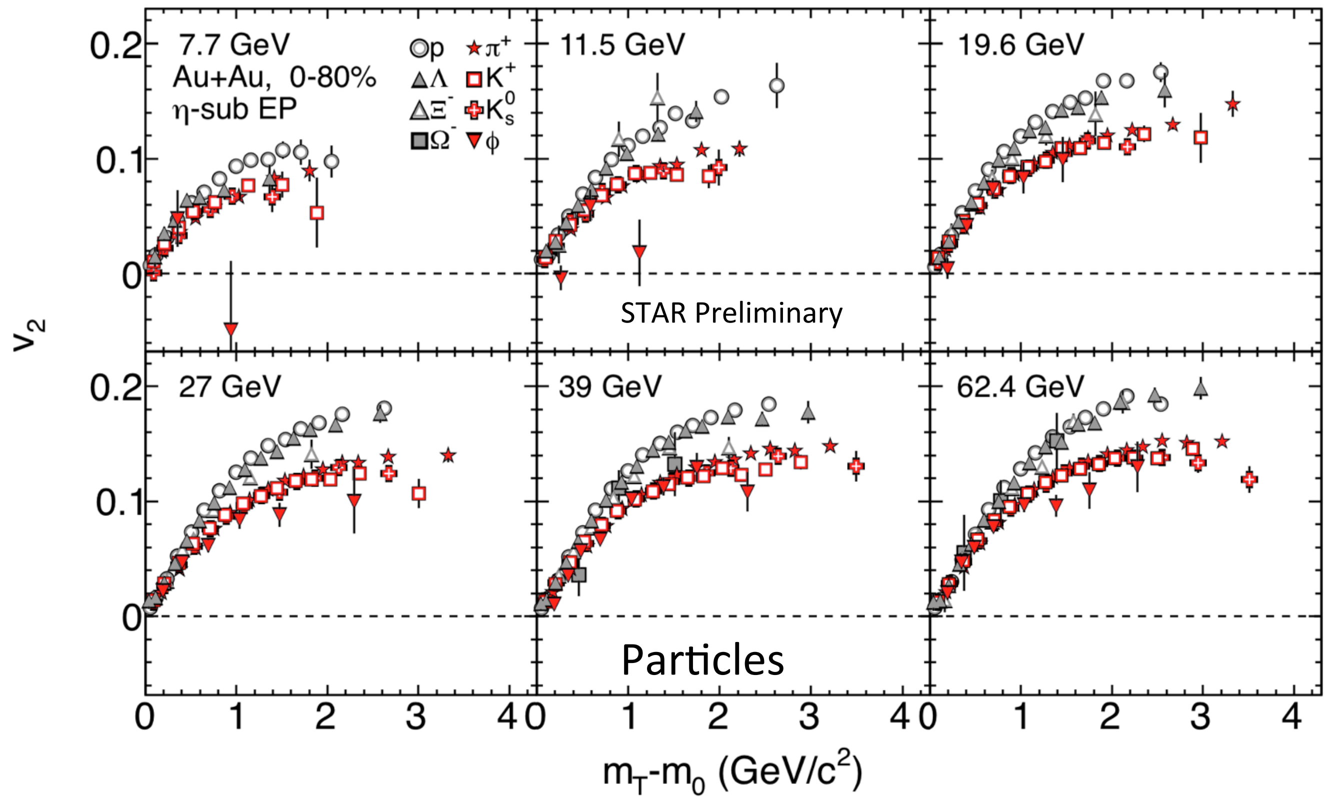
STAR Coll.: e-Print arXiv:1206.5528



ALICE data: PRL 105, 252302 (2010)

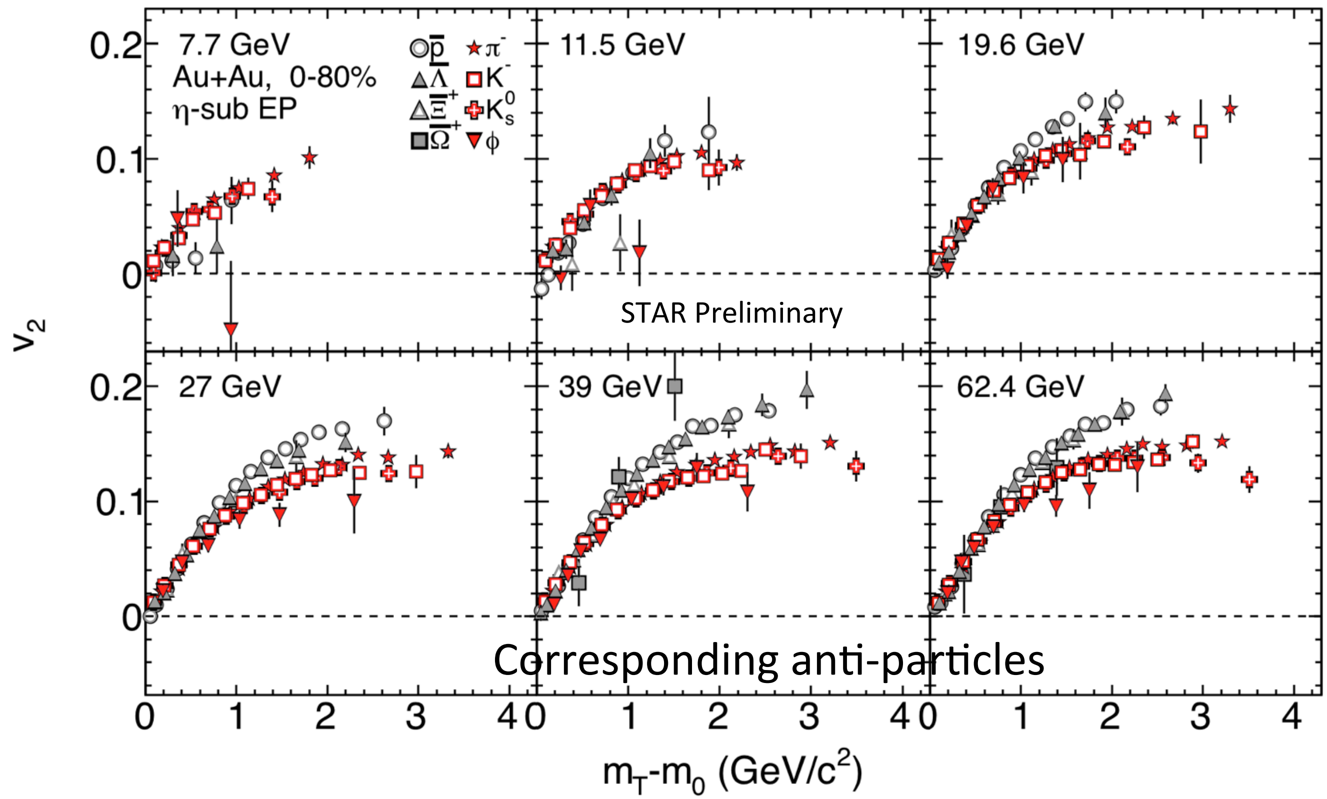
For $p_T < 2$ GeV/c: v_2 values rise with increasing $\sqrt{s_{NN}}$
For $p_T \geq 2$ GeV/c: v_2 values are (within stat. errors) comparable
The increase of v_2 with $\sqrt{s_{NN}}$, could be due to change of chemical composition and/or larger collectivity at higher collision energy.

v_2 vs. m_T-m_0



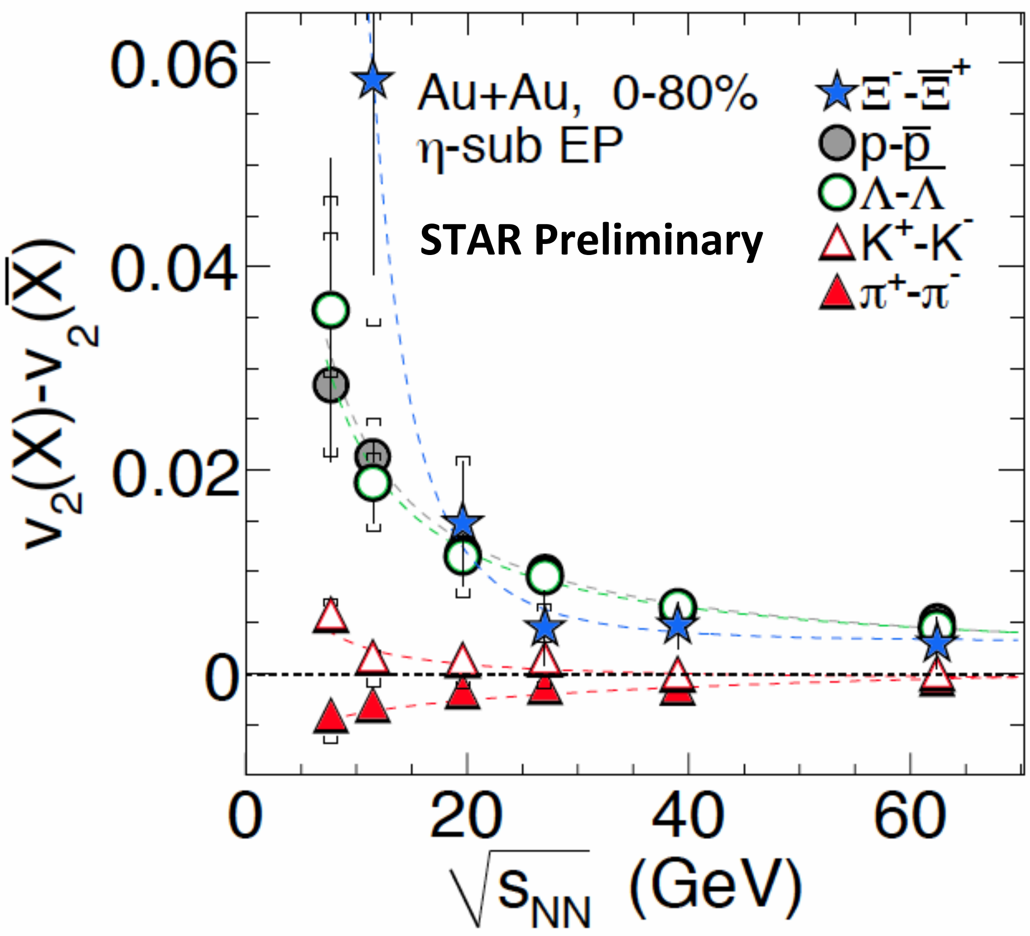
- Baryon–meson splitting is observed when collisions energy ≥ 19.6 GeV for both particles and the corresponding anti-particles
- For anti-particles the splitting is almost gone within errors at 11.5 GeV

v_2 vs. m_T-m_0



- Baryon–meson splitting is observed when collisions energy ≥ 19.6 GeV for both particles and the corresponding anti-particles
- For anti-particles the splitting is almost gone within errors at 11.5 GeV

Particles vs. Anti-particles



- **Beam energy ≥ 39 GeV**
  - Δv_2 for baryon and anti-baryon within 10%
  - Almost no difference for mesons
- **Beam energy < 39 GeV**
  - The difference of baryon and anti-baryon v_2

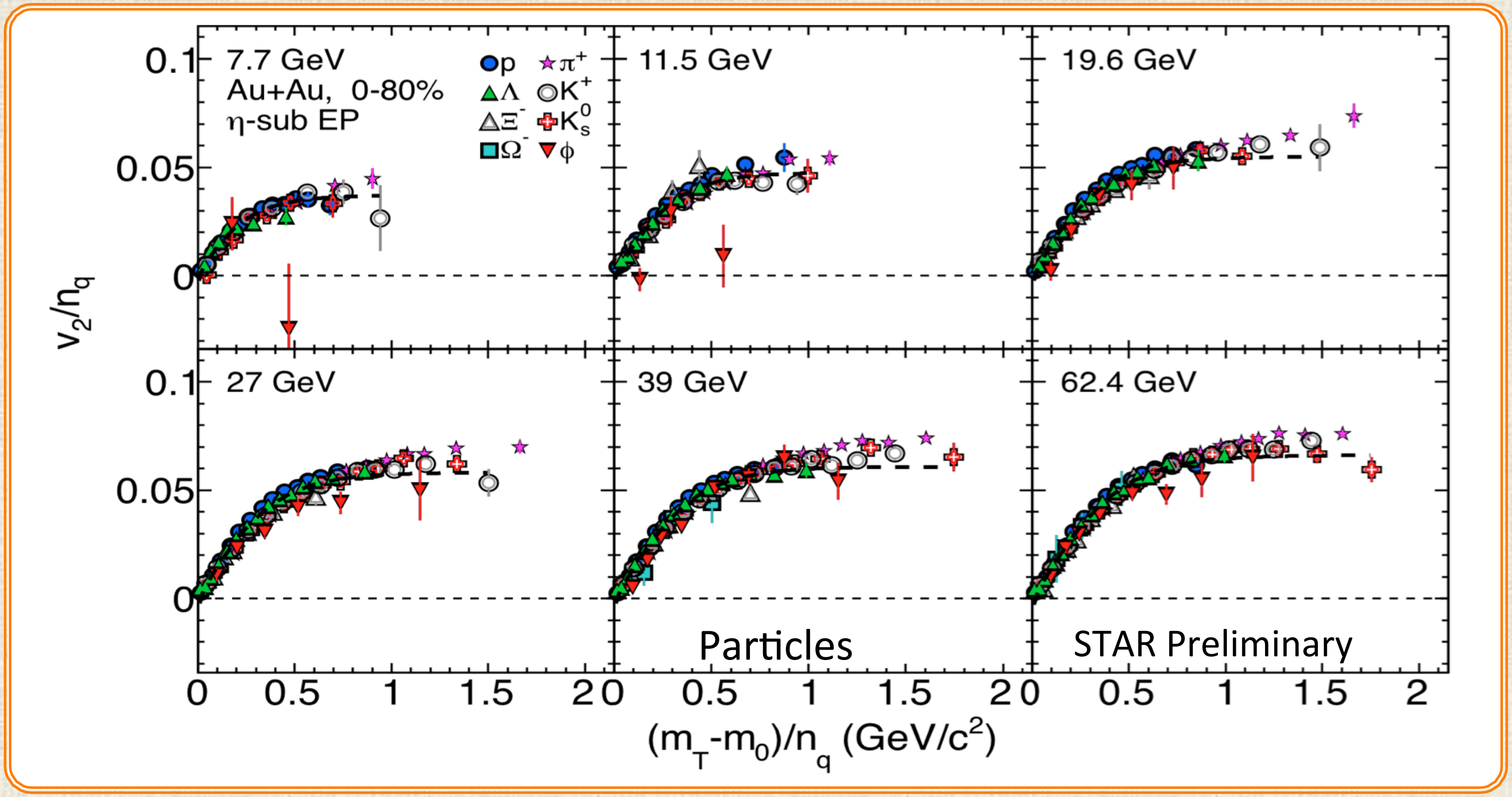
  → Increasing with decrease of beam energy
- **At $\sqrt{s_{NN}}$ = 7.7 - 19.6 GeV**
  - $v_2(K^+)>v_2(K^-)$
  - $v_2(\pi^-) >v_2(\pi^+)$
- **Possible explanation(s)**
  - Baryon transport to midrapidity?

    ref: J. Dunlop et al., PRC 84, 044914 (2011)
  - Hadronic potential?

    ref: J. Xu et al., PRC 85, 041901 (2012)

The difference between particles and anti-particles is observed

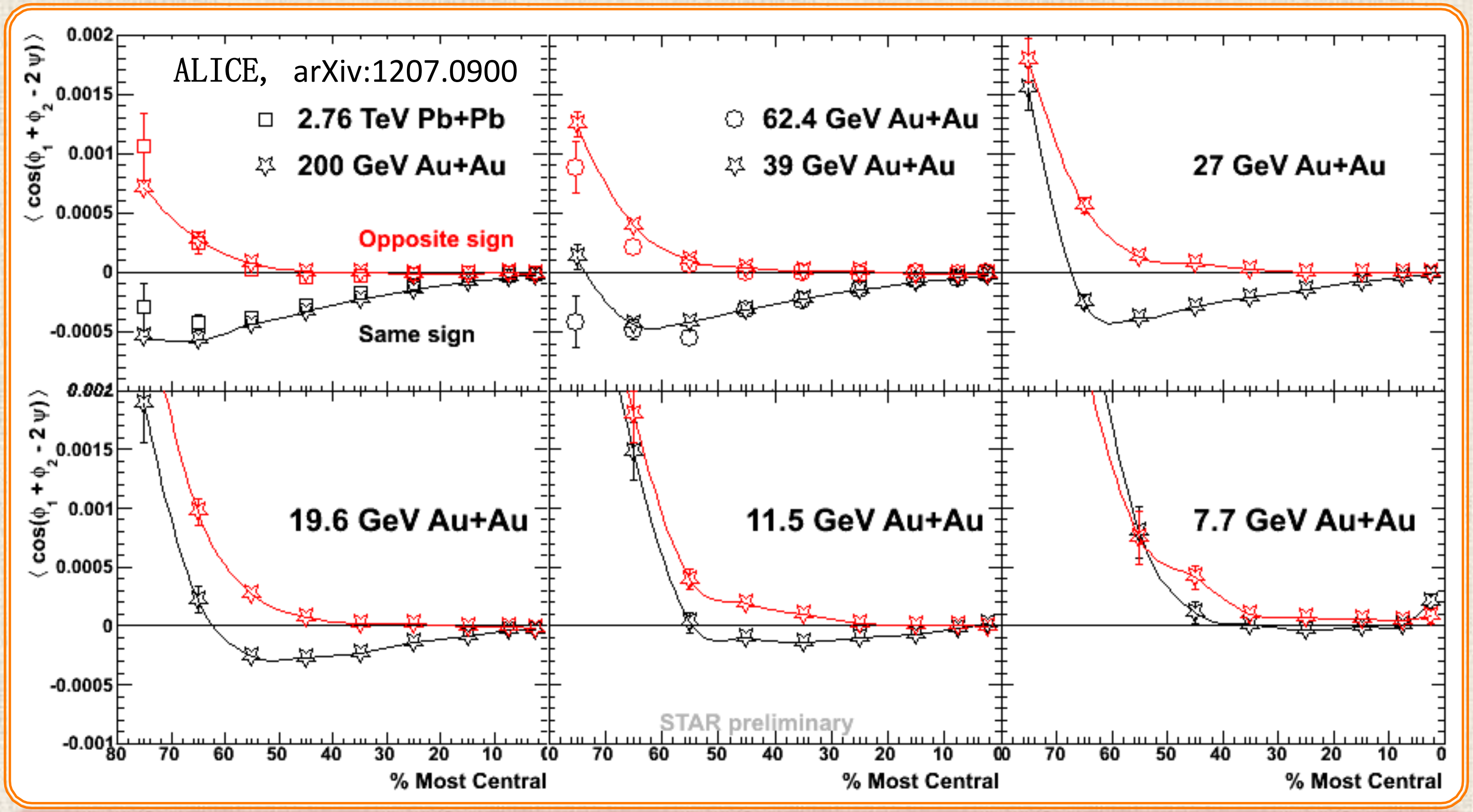
NCQ Scaling Test



- ✓ Universal trend for most of particles – n_{cq} scaling not broken at low energies
- ✓ ϕ meson v_2 deviates from other particles in Au+Au@(11.5 & 7.7) GeV: ~ 2σ at the highest p_T data point

Reduction of v_2 for ϕ meson and absence of n_{cq} scaling ➔ during the evolution the system remains in the hadronic phase [B. Mohanty and N. Xu: J. Phys. G 36, 064022(2009)]

Disappearance of Charge Separation w.r.t. EP



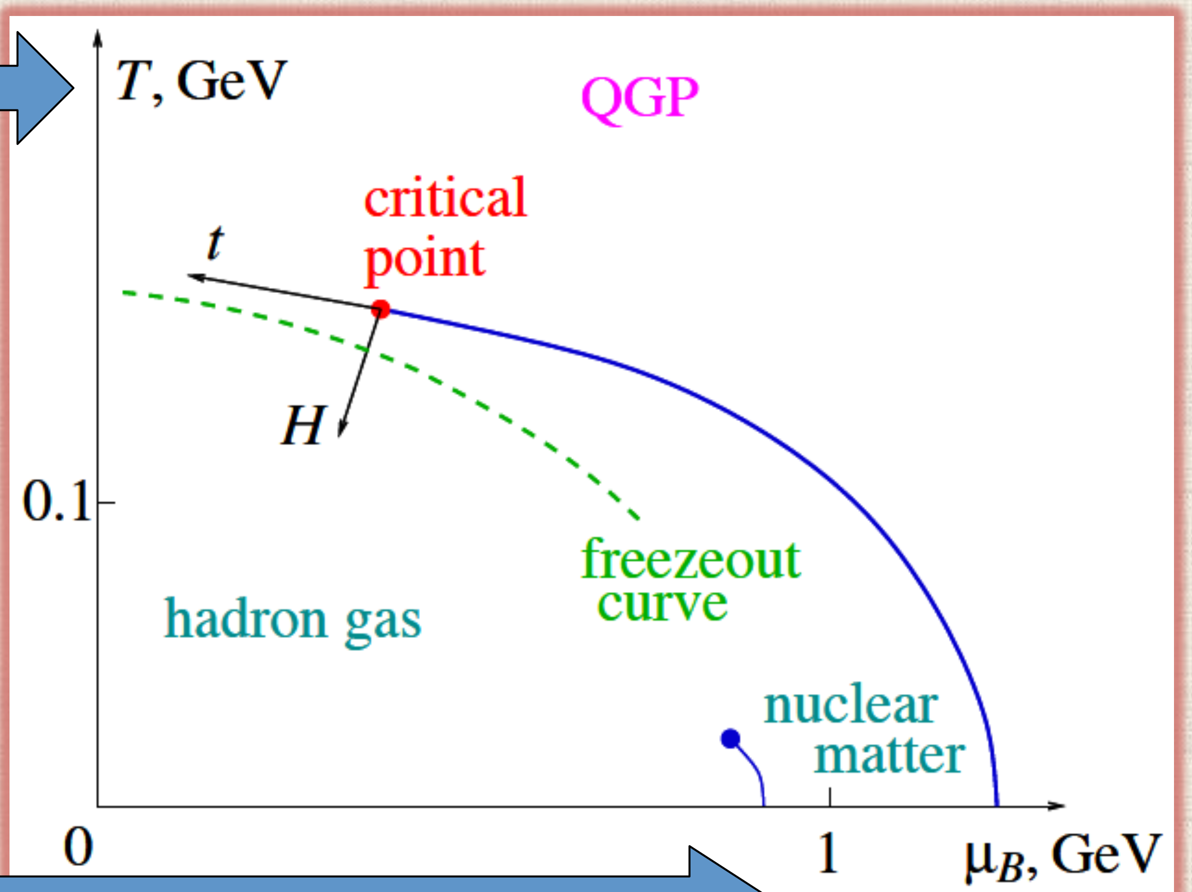
$$\langle\cos(\phi_1 + \phi_2 - 2\Psi)\rangle = \langle\cos(\phi_1 - \Psi)\cos(\phi_2 - \Psi)\rangle - \langle\sin(\phi_1 - \Psi)\sin(\phi_2 - \Psi)\rangle$$

- Motivated by search for local parity violation. Require sQGP formation.
- The splitting between OS and LS correlations (charge separation) seen in top RHIC energy Au+Au collisions.

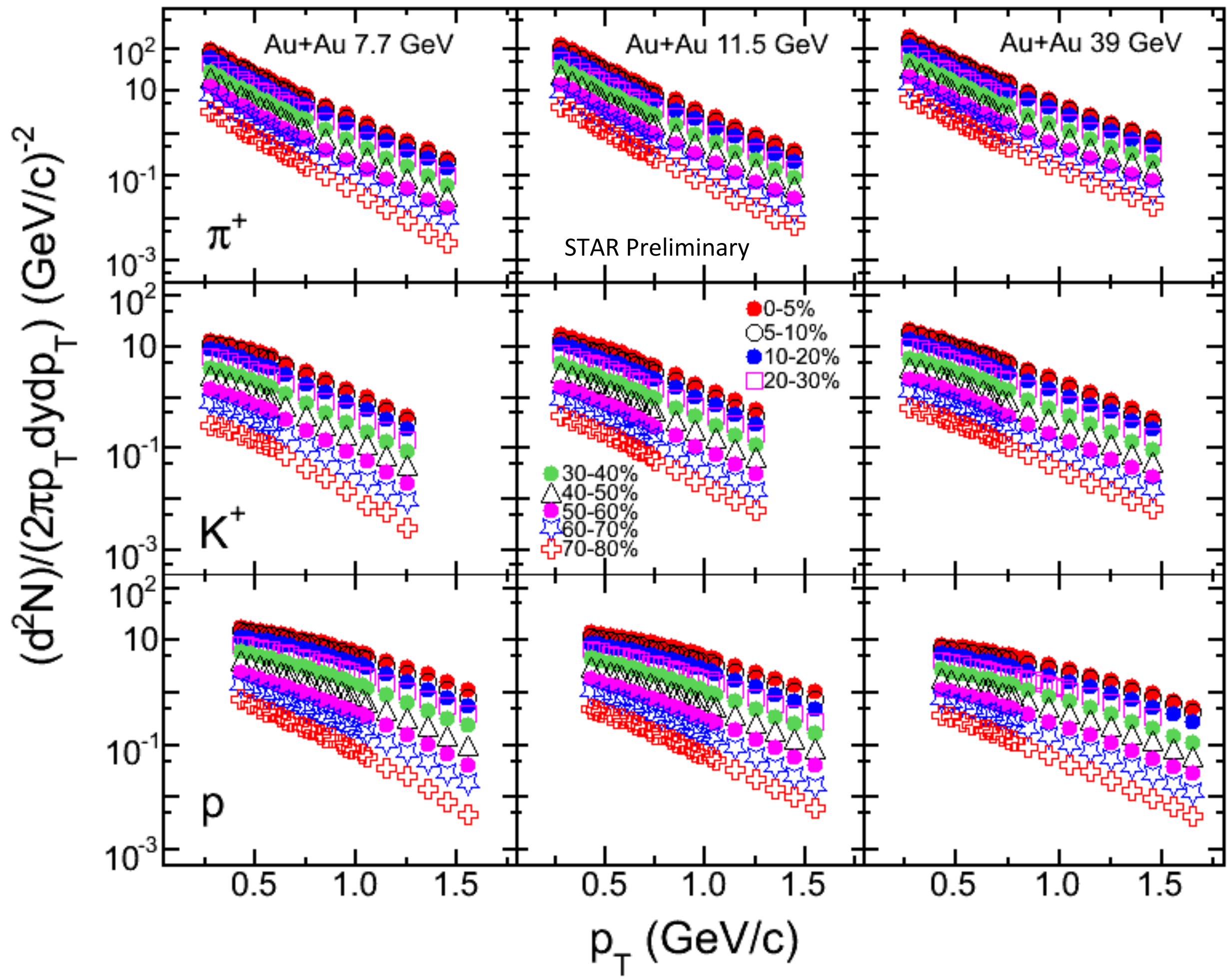
Charge separation signal disappears at lower energies (≤ 11.5 GeV)!

Accessing Phase Diagram

T-μ_B:
From spectra and ratios

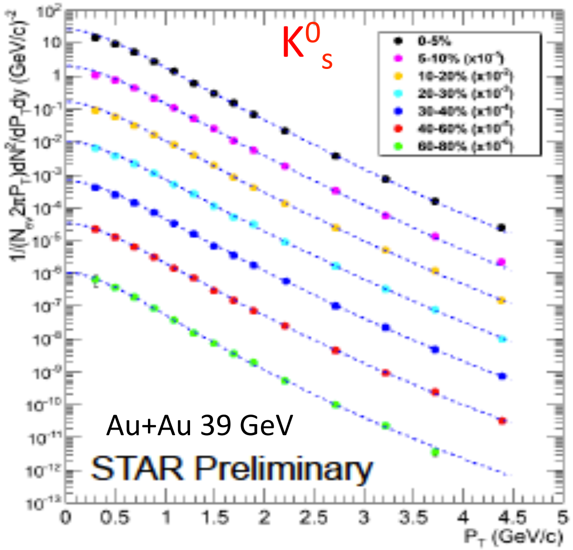


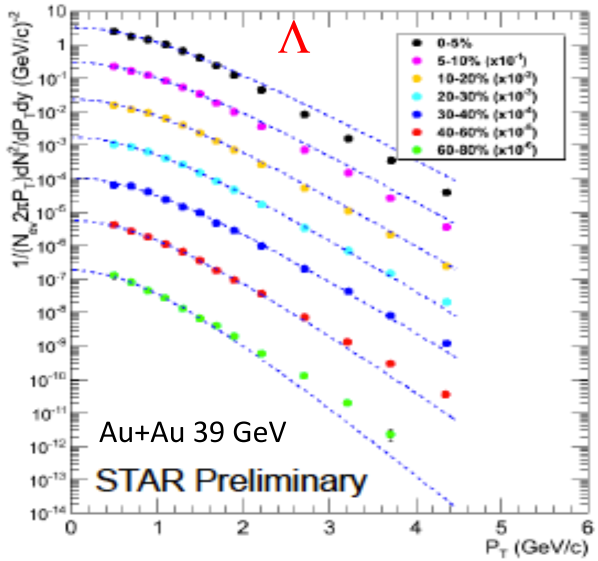
π, K, p Spectra

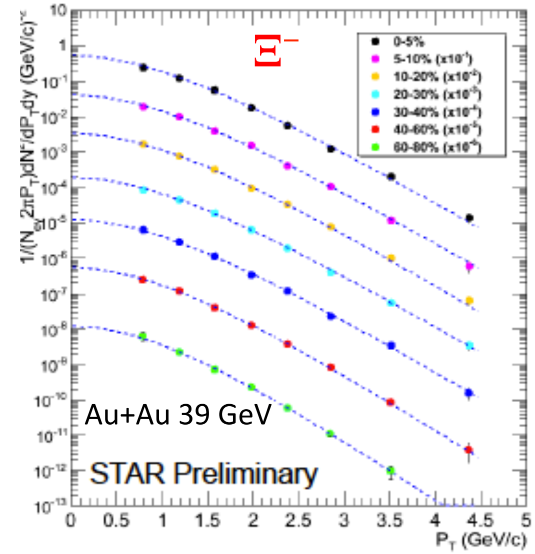


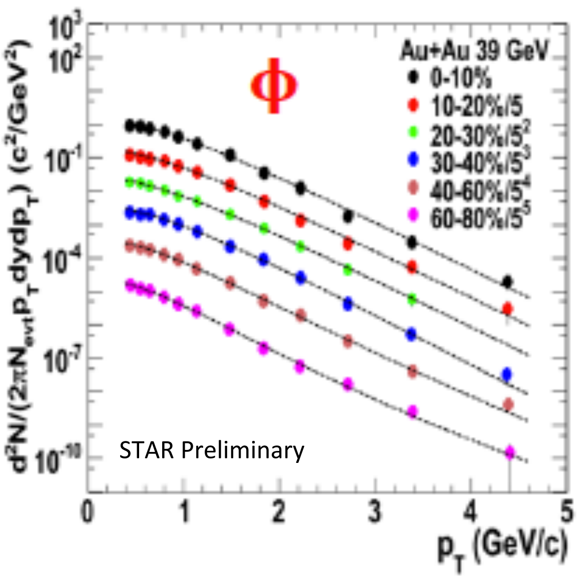
Slopes: π > K > p. Proton spectra: without feed-down correction
π,K,p yields within measured p_T ranges: 70-80% of total yields

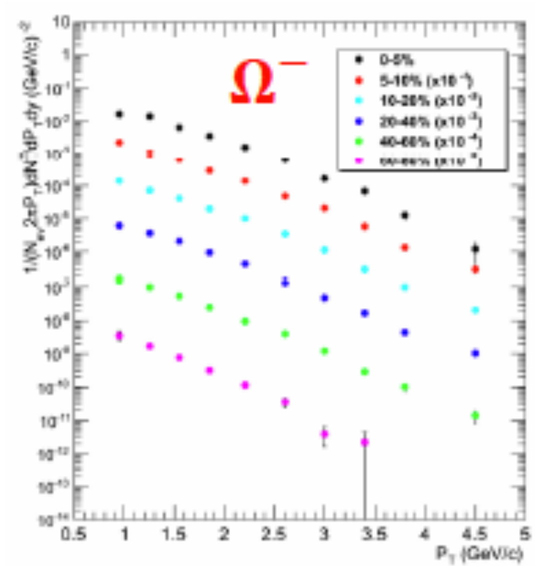
Strange Hadron Spectra









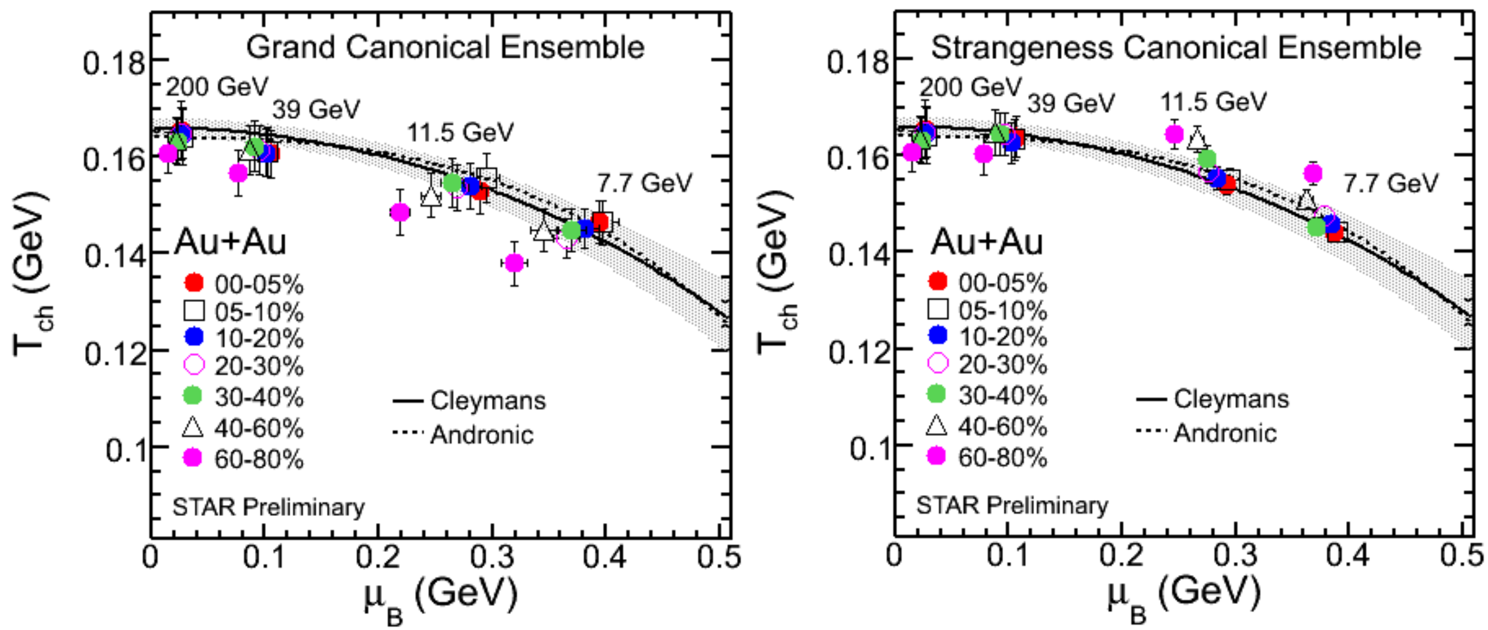


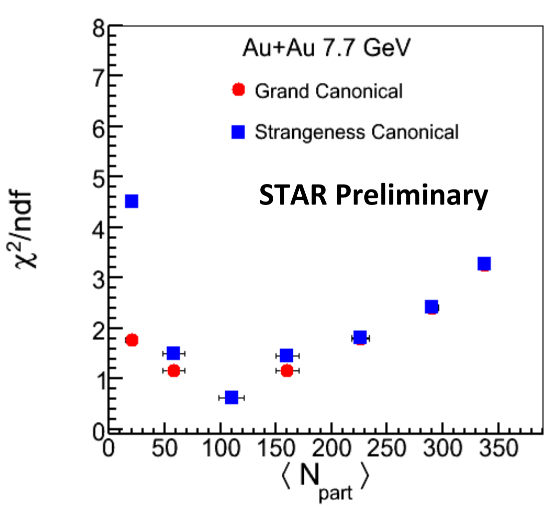
ϕ, K^0_s: Levy function fit

Λ, Ξ : Boltzmann fit

Λ: feed-down corrected

Chemical Freeze-out Parameters





THERMUS* Model:
T_{ch} and μ_B

Particles used:
π, K, p, Λ, K^0_s, Ξ

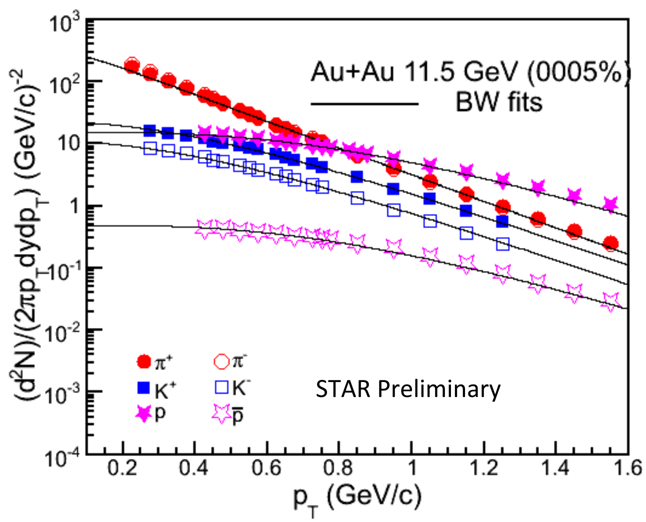
✧ Centrality dependence of freeze-out temperature with baryon chemical potential observed for first time at lower energies

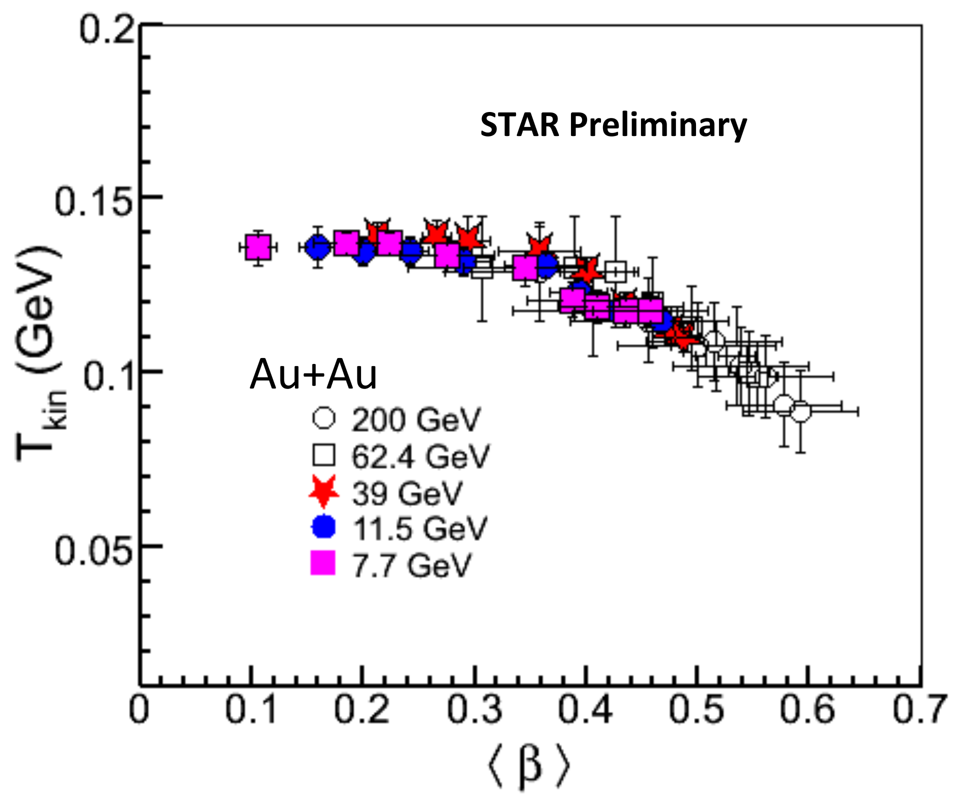
★ S. Wheaton & J.Cleymans, Comput. Phys. Commun. 180: 84, 2009.

Kinetic Freeze-out Parameters

Blast Wave: T_{kin} and $<\beta>$

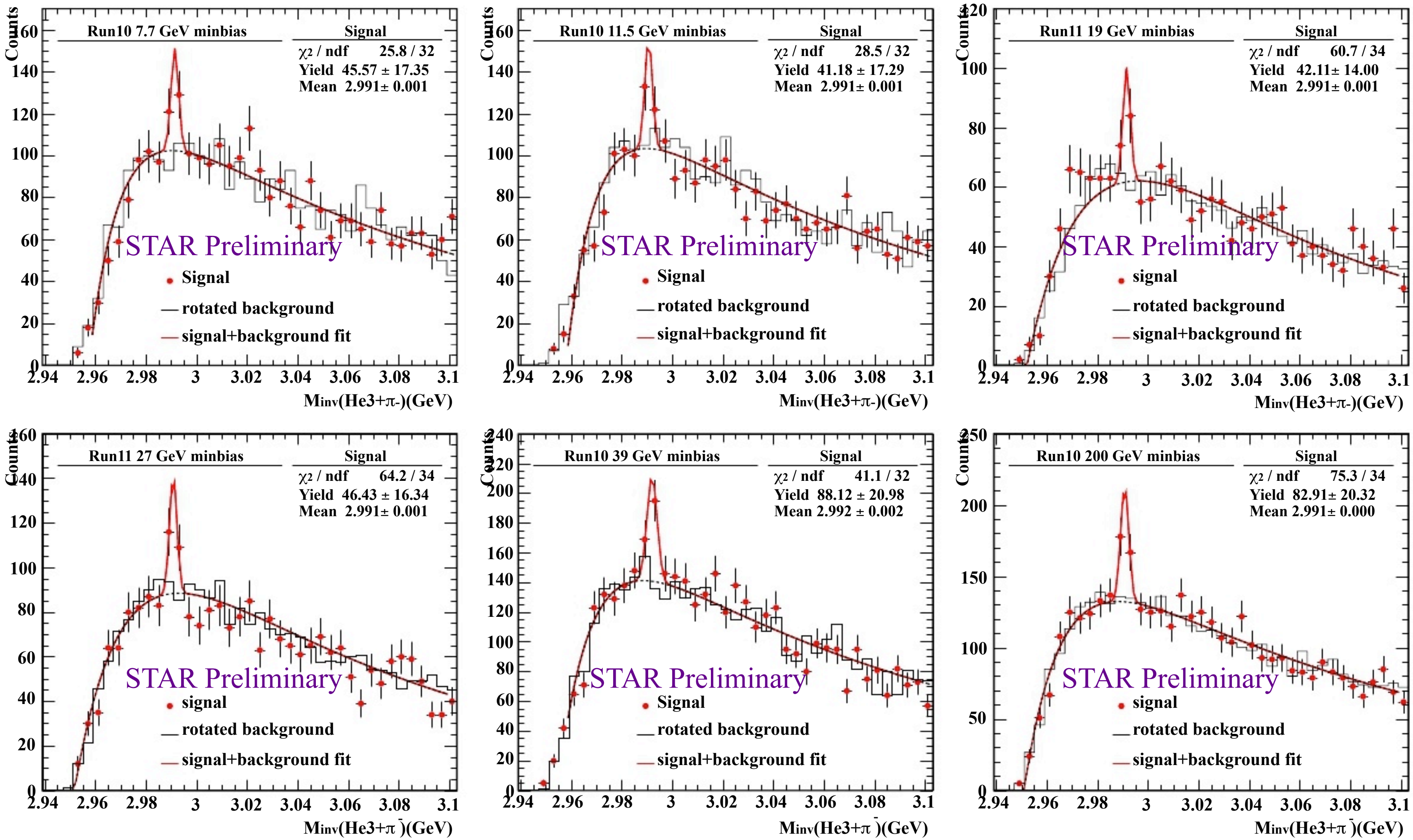
Particles used: π,K,p





✧ Higher kinetic temperature corresponds to lower value of average flow velocity and vice-versa

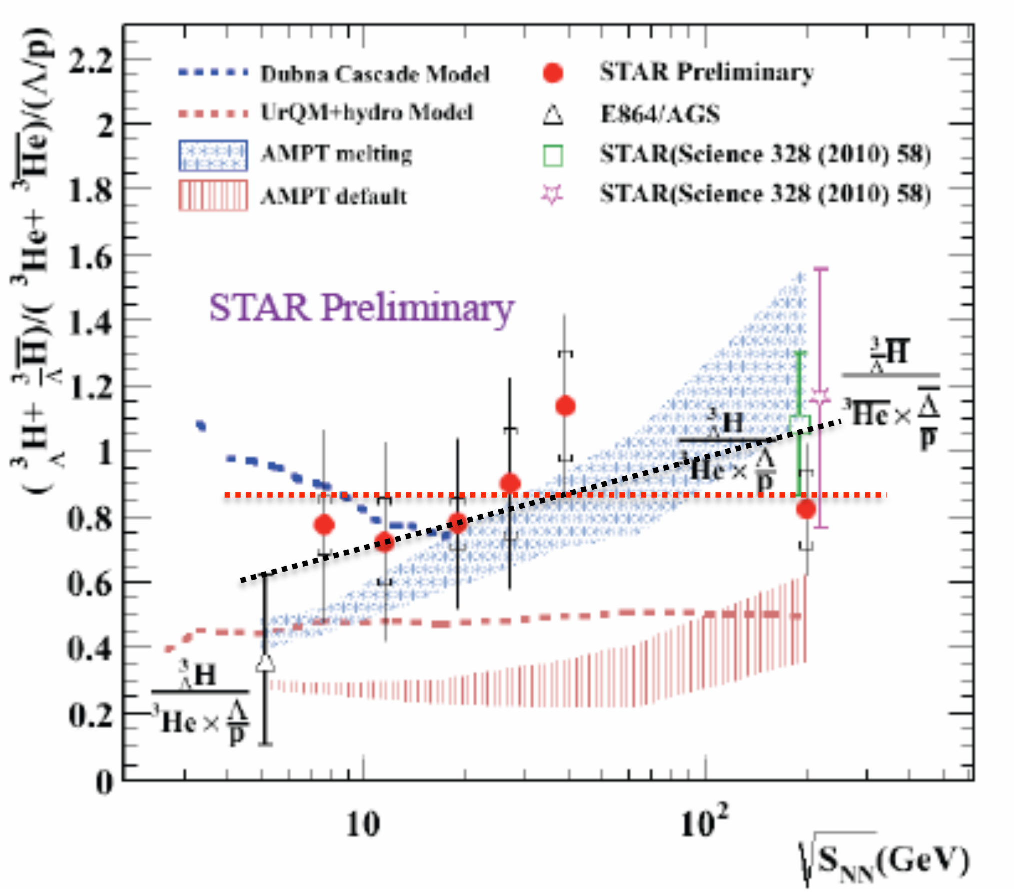
Hypertriton Production



$^{3}_{\Lambda}H + ^{3}_{\bar{\Lambda}}\bar{H}$ produced at $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, 39, 200 GeV (minbias)

Phase Boundary Search With Nuclei

Strangeness Population Factor: $S_3 = {}^{3}_{\Lambda}\mathrm{H}/({}^{3}\mathrm{He} \times \Lambda/p)$



Beam energy dependence of S_3 behaves differently in QGP and pure hadron gas

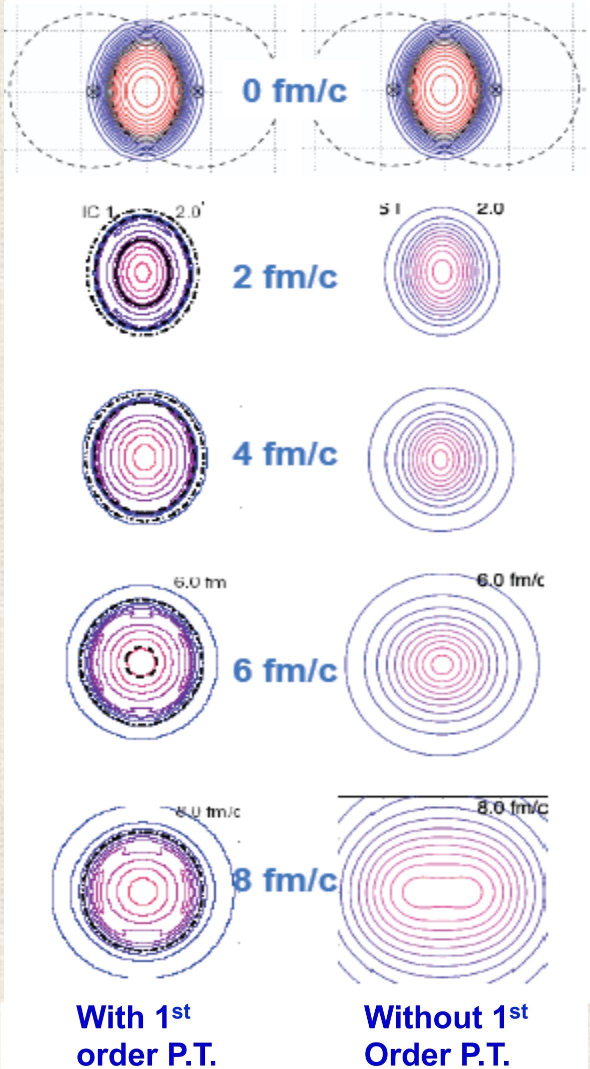
- S. Zhang et al., PLB 684 (2010) 224
- J. Steinheimer et al.,PLB 714 (2012) 85

S_3 indicates (with 1.7σ) an increasing trend

Needs higher statistics to make conclusive statement

Time evolution of the collision geometry

Spatial eccentricity



Kolb and Heinz, 2003, nucl-th/0305084

- Initial out-of-plane eccentricity
- Stronger in-plane pressure gradients drive preferential in-plane expansion
- Longer lifetimes or stronger pressure gradients cause more expansion and more spherical freeze-out shape

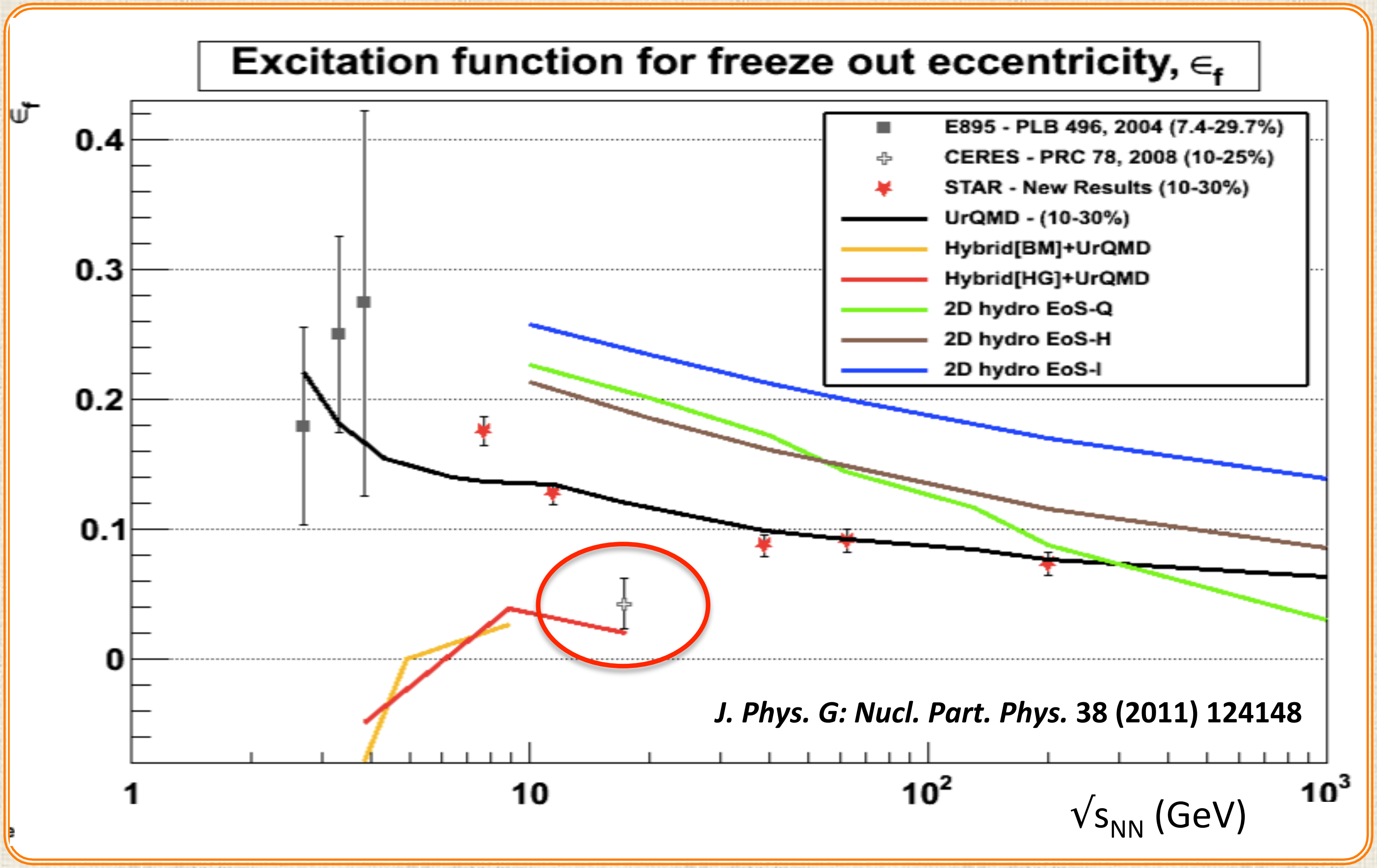
- We want to measure the eccentricity at freeze out, ε_F, as a function of energy using azimuthal femtoscopic radii R_x and R_y:

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

- Evolution of the initial shape depends on the pressure anisotropy
  - \- Freeze-out eccentricity sensitive to the 1st order phase transition.

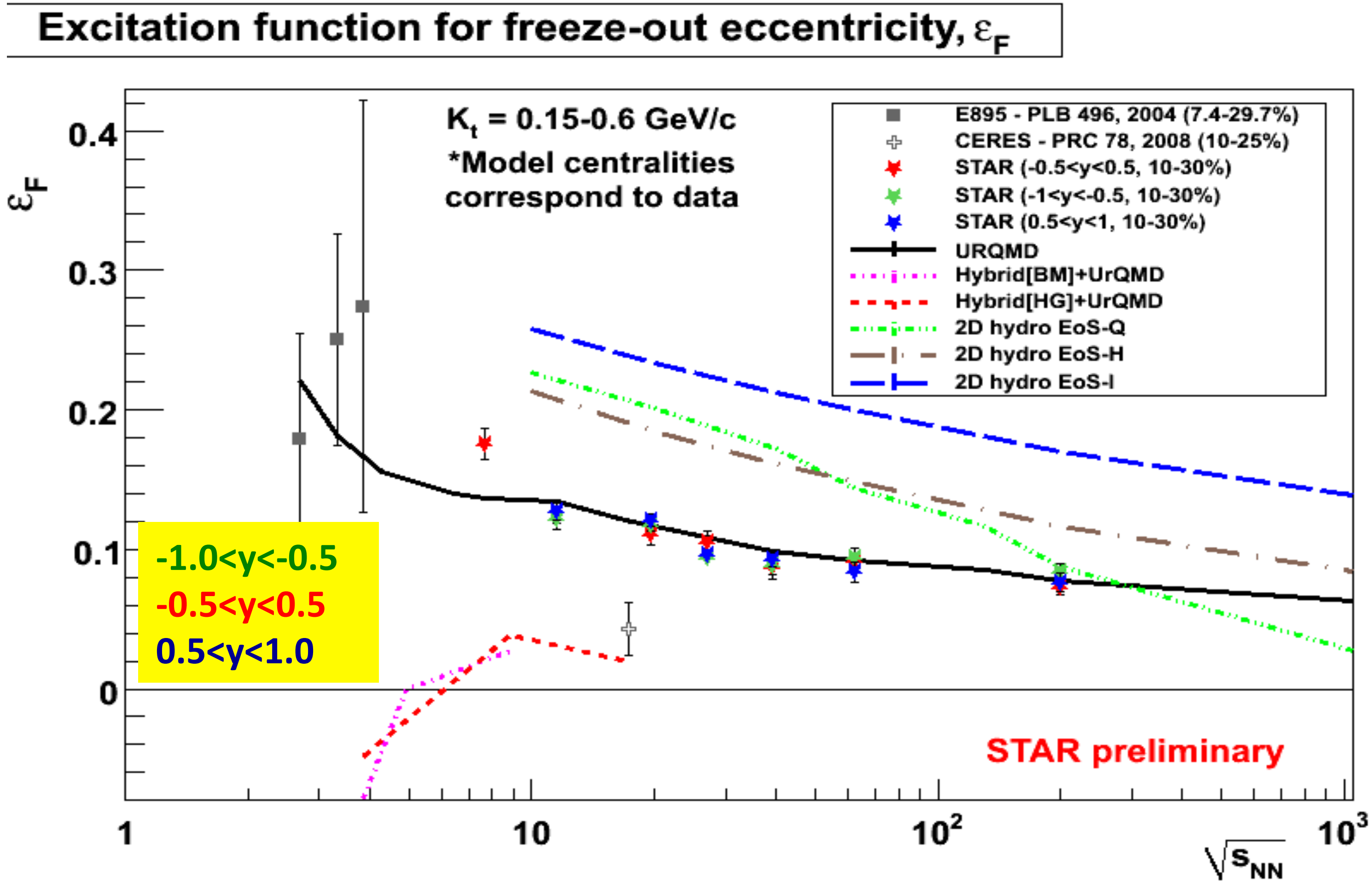
- Non-monotonic behavior could indicate a soft point in the equation of state.

Azimuthal HBT: First result



Is there a non-monotonic behavior?

Azimuthal HBT: More Data



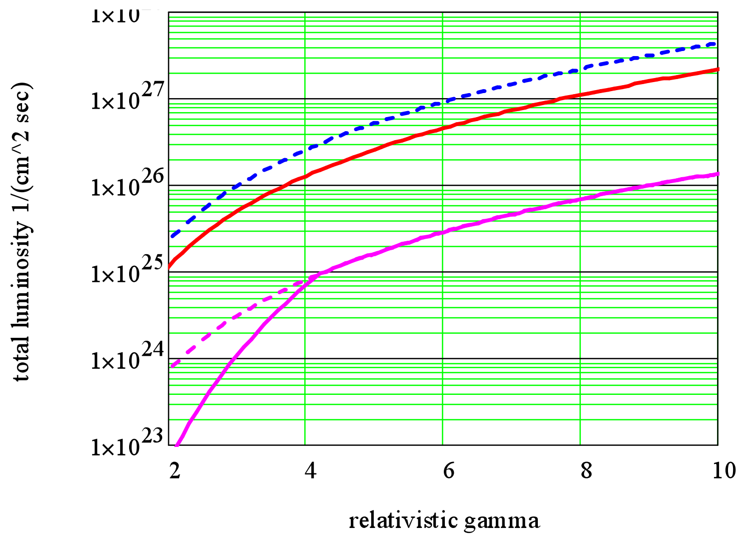
Is the discrepancy due to centrality or rapidity range? - NO

Beam Energy Scan Phase- II

BES Phase-II proposal

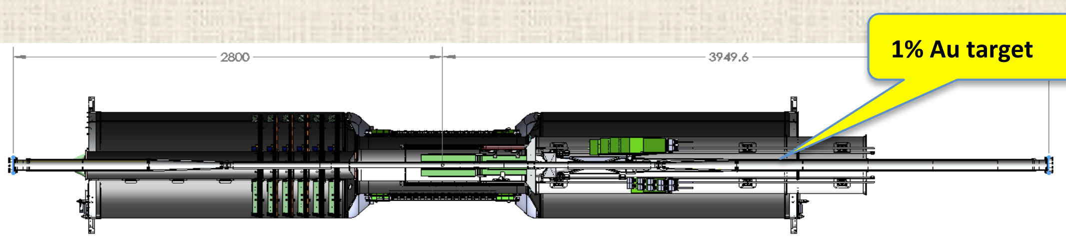
✧ Electron cooling will provide increased luminosity ~ 10 times

A. Fedotov, W. Fischer, private discussions, 2012.



Proposal BES-II (Years 2015-2017):

$\sqrt{s_{NN}}$ [GeV]	μ_B [MeV]	Requested Events(10^6)
Au+Au 19.6	206	150
Au+Au 15	256	150
Au+Au 11.5	316	50
Au+Au 7.7	420	70
U+U: ~20	~200	100

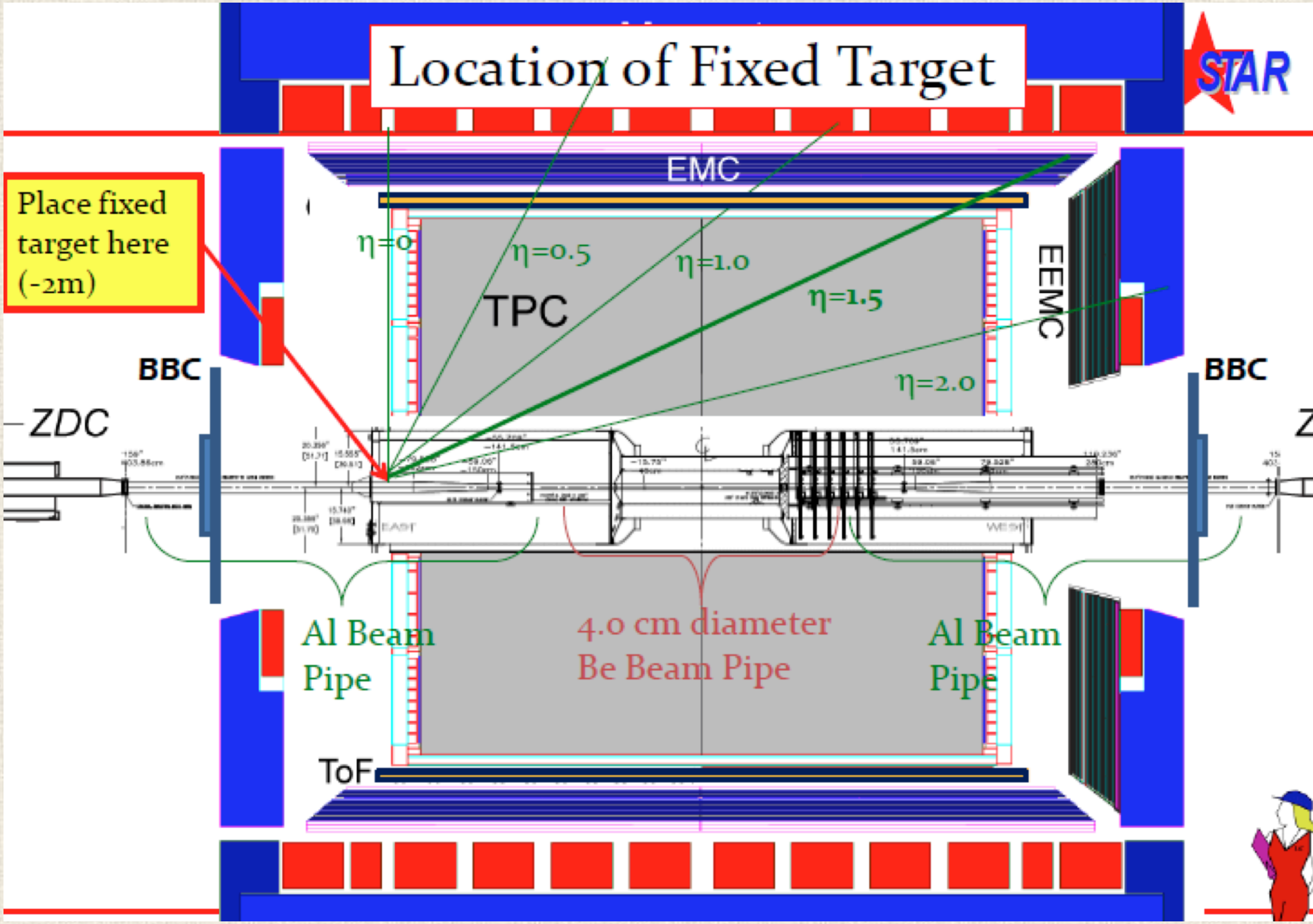


Fixed Target Proposal:

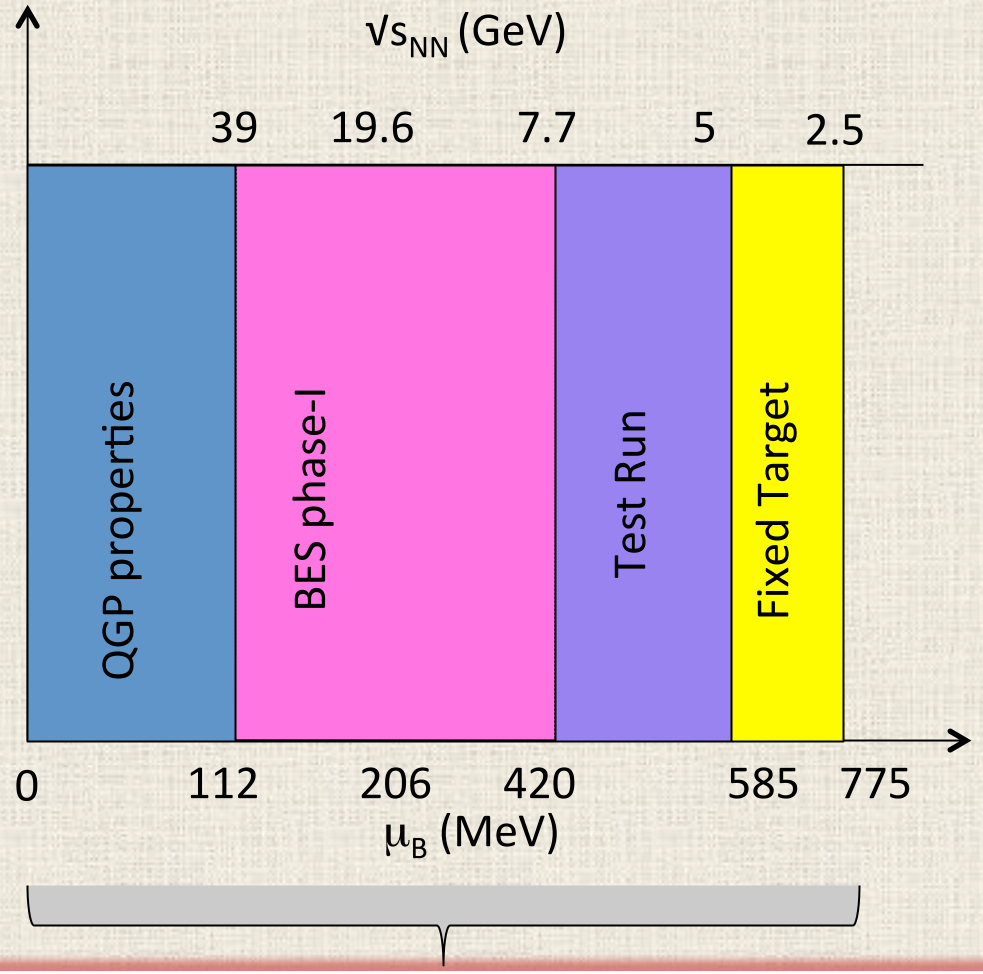
- Annular 1% gold target inside the STAR beam pipe
- 2m away from the center of STAR
- Data taking concurrently with collider mode at beginning of each fill

No disturbance to normal RHIC running

Fixed Target Set-up

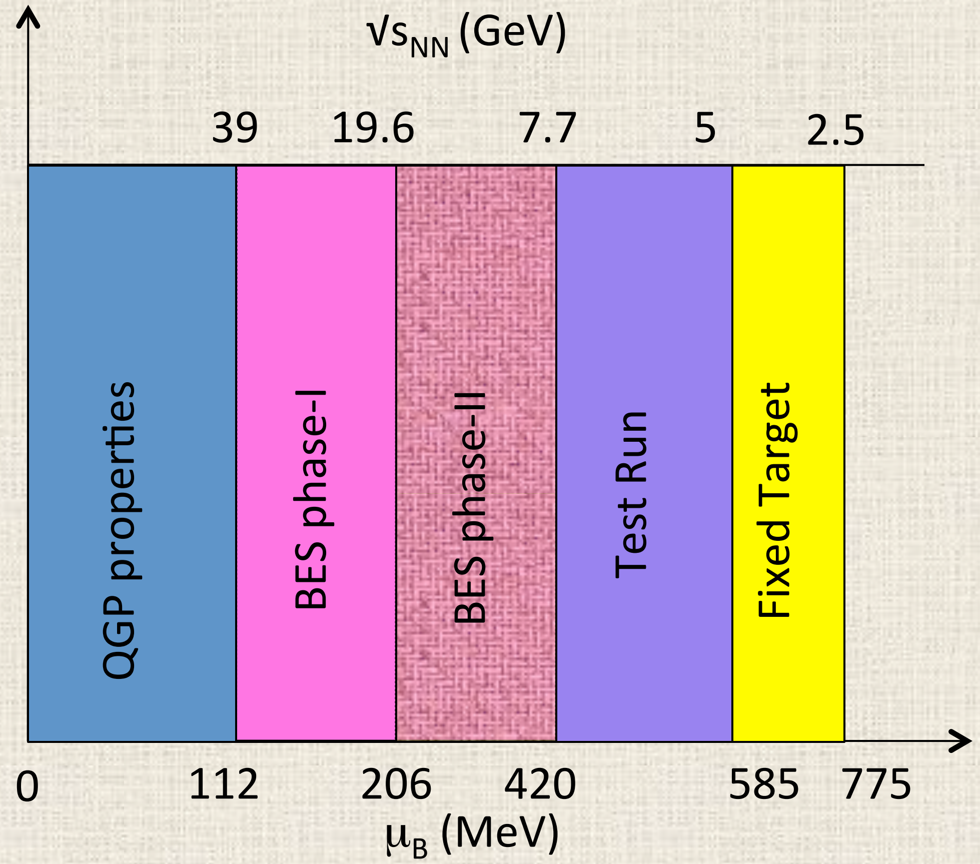


STAR BES Program Summary



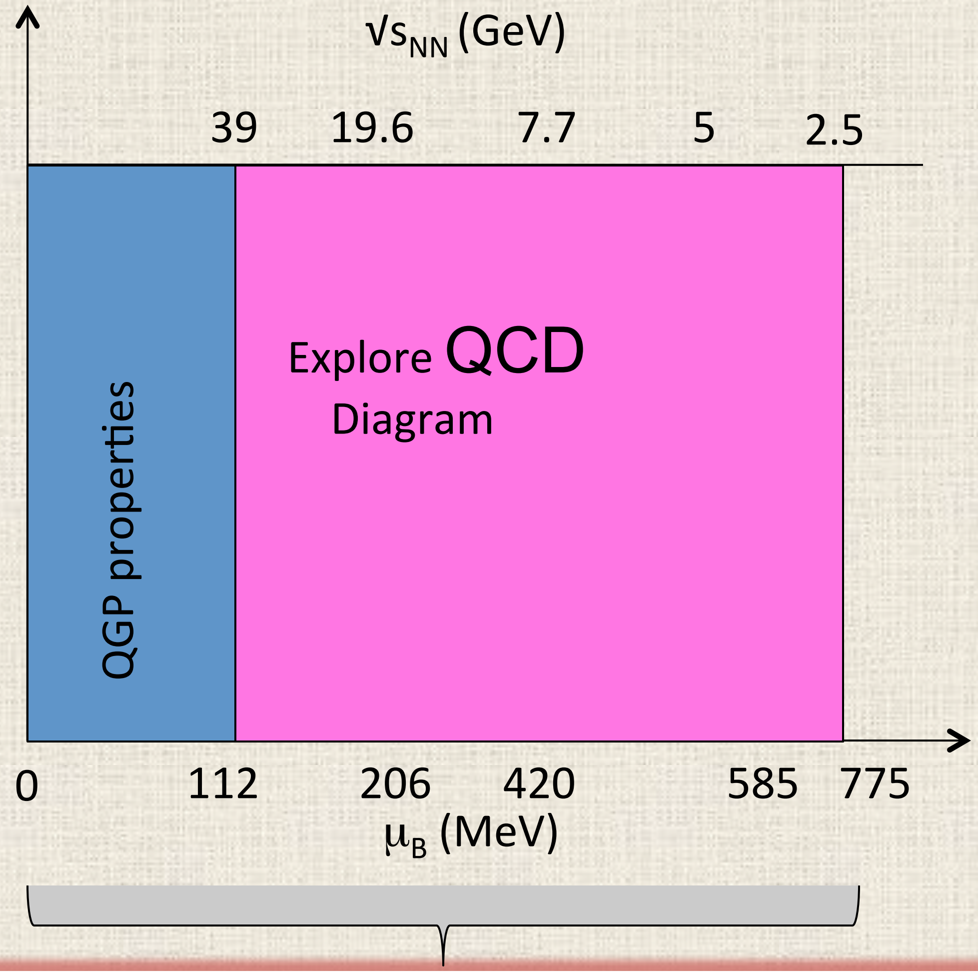
Large range of μ_B in the phase diagram !!!

STAR BES Program Summary



Large range of μ_B in the phase diagram !!!

STAR BES Program Summary



Large range of μ_B in the phase diagram !!!

Summary

- ★ STAR results from BES program covering large μ_B range provide important constraint on QCD phase diagram.

- ★ Different features show up:
  - **Proton v_1 slope changes sign between 7.7 GeV and 11.5 GeV**
  - **Particles-antiparticles v_2 difference increases with decreasing $\sqrt{s_{NN}}$**
  - **ϕ-meson v_2 deviates from others for $\sqrt{s_{NN}} \leq 11.5$ GeV**

- ★ Search for the critical point continues:
  - **Proposed BES-II program**
  - **Fixed target proposal to extend μ_B coverage up to 800 MeV**

STAR Collaboration

Thank You

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