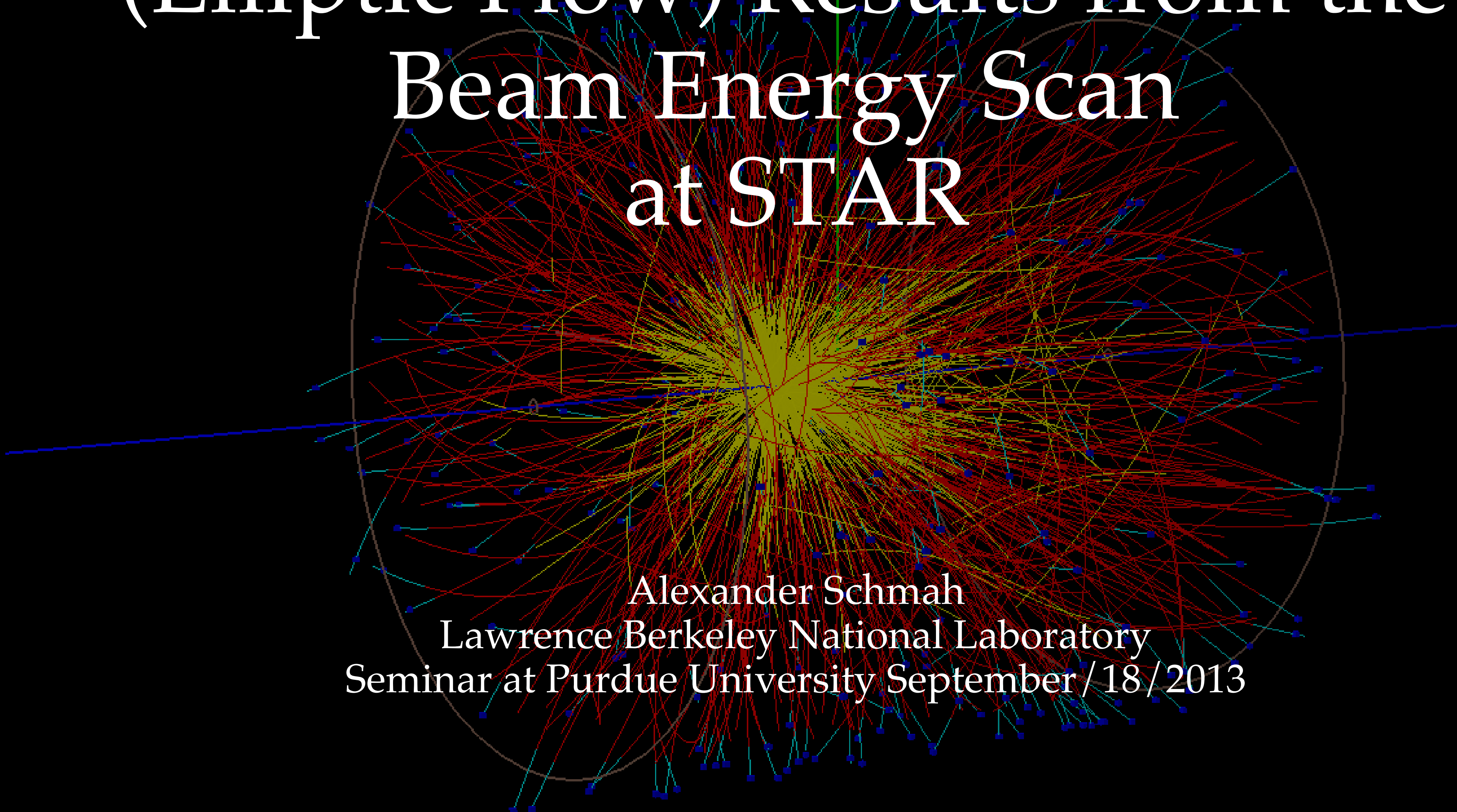
(Elliptic Flow) Results from the Beam Energy Scan at STAR



Alexander Schmah
Lawrence Berkeley National Laboratory
Seminar at Purdue University September/18/2013

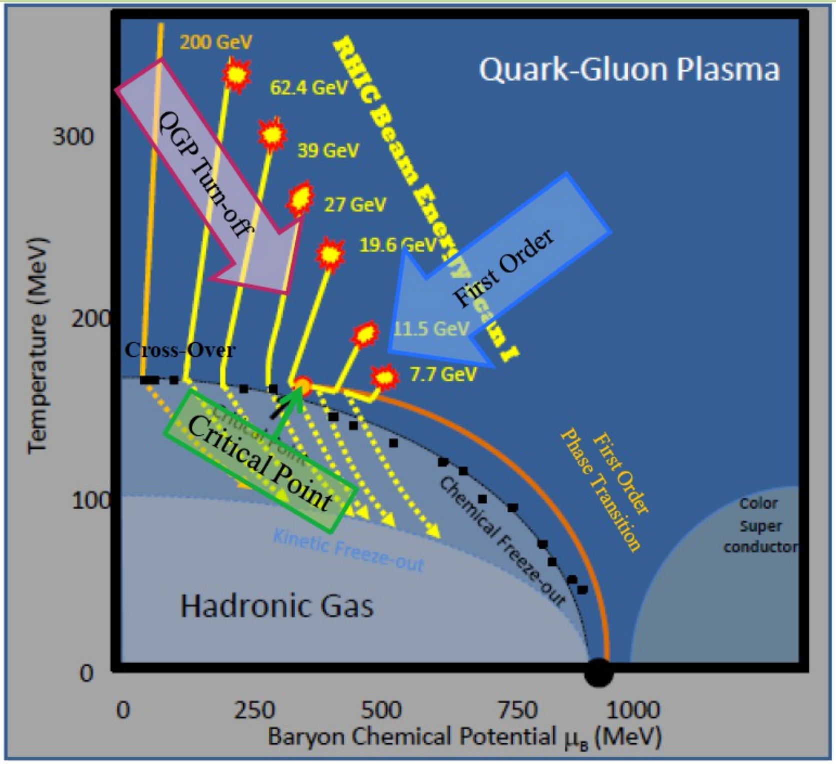
Berkeley Lab

U.S. DEPARTMENT OF ENERGY

Outline

- **Introduction to the Beam Energy Scan and the Experiment**
- **Selected highlights from the Beam Energy Scan**
- **Elliptic flow results from STAR**
- **Summary and Outlook**

The Beam Energy Scan at RHIC



D. Cebra

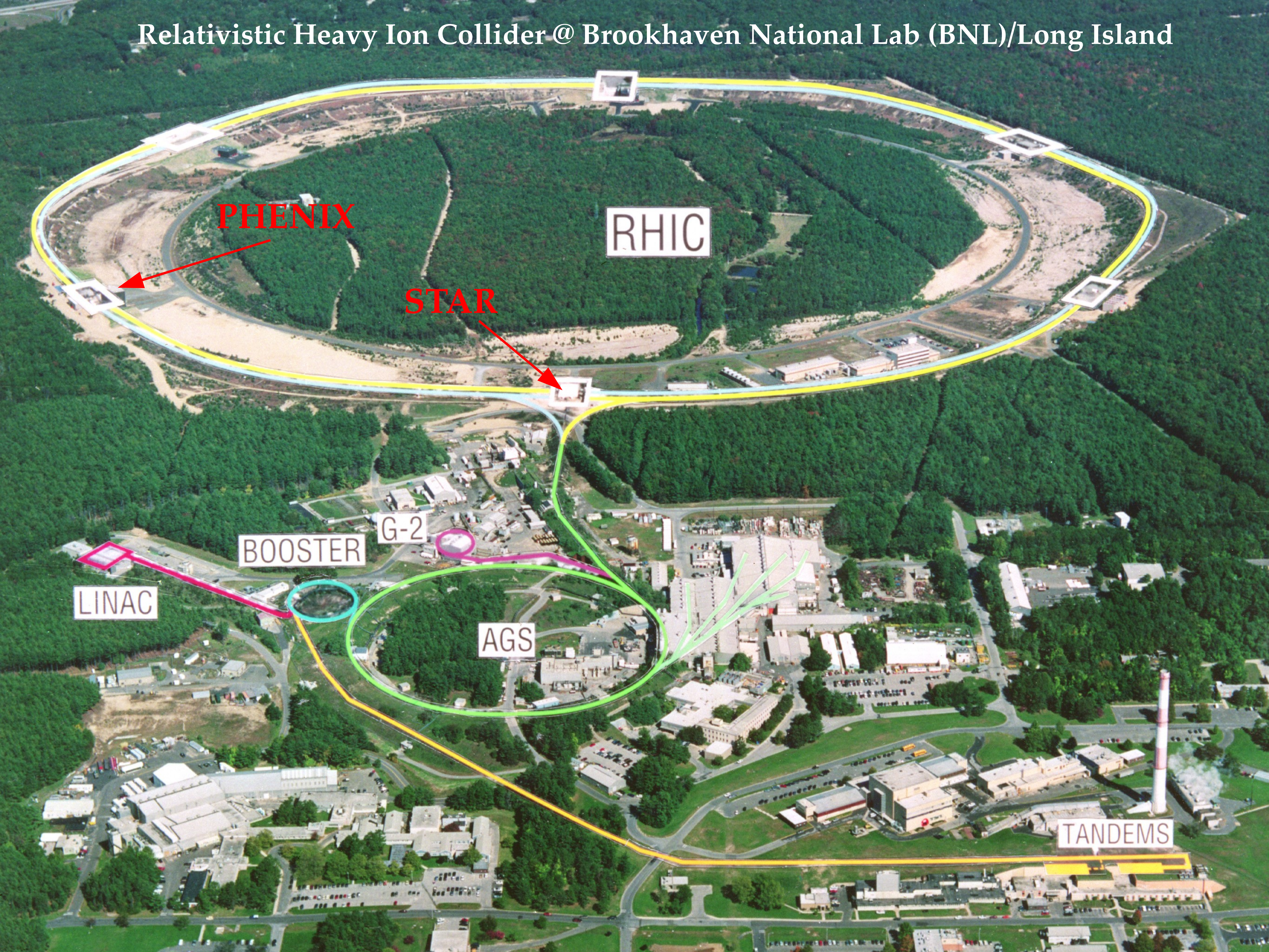
Methods to study the QCD phase space:

- QGP at high T and/or μ_B
  - → R_{AA}, NCQ scaling of v_2,...
- We expect from QCD lattice calculations a cross over at high energies
- First order phase transition?
  - → Azimuthal HBT, v_1 analyses
- Critical point?
  - → Fluctuation analyses (net-protons)
- Hadron gas phase at low T and/or μ_B

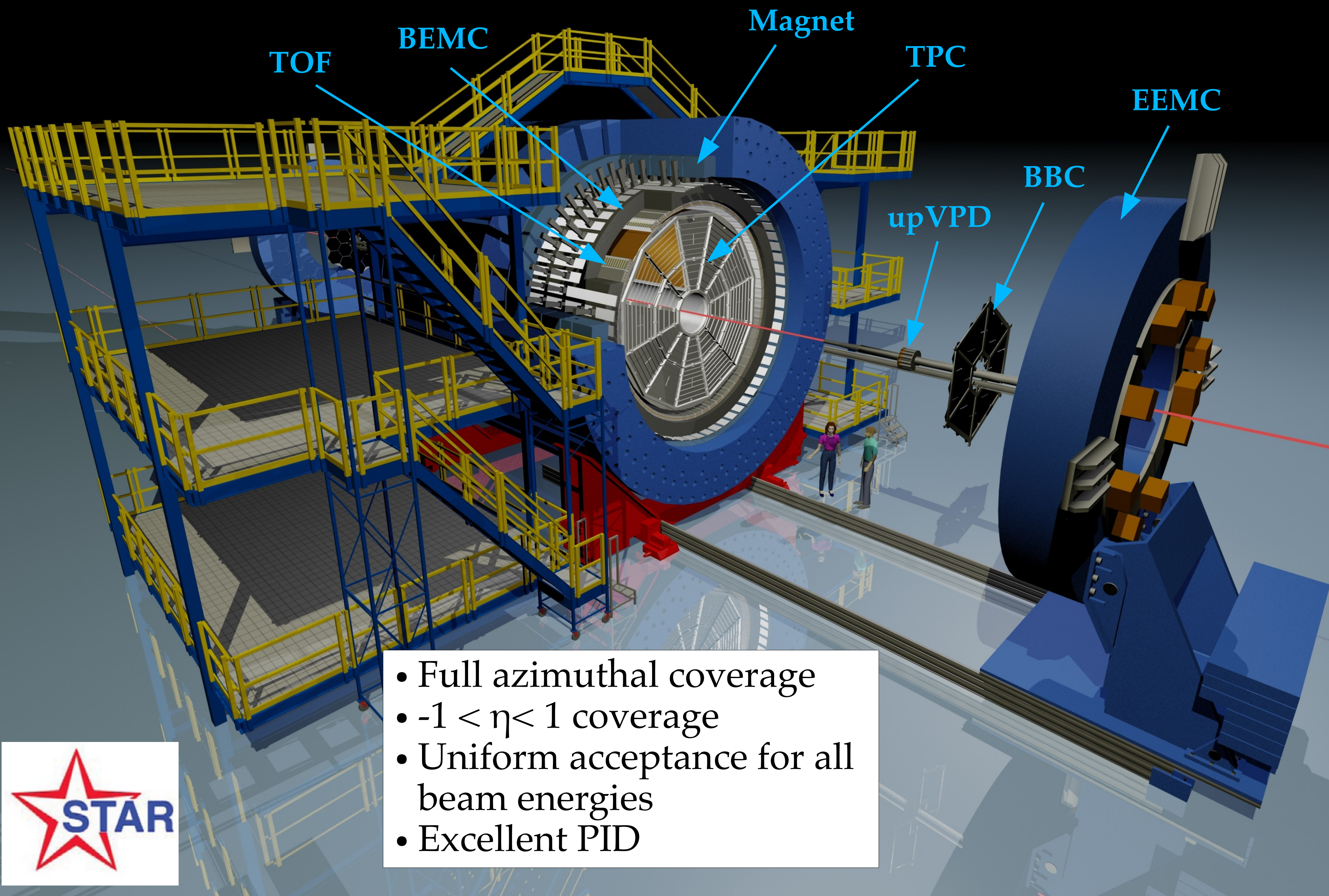
Disappearance of QGP signatures starts most likely before we reach the transition line!
→ The initial stage is in the QGP phase

$\sqrt{s_{NN}}$ (GeV)	MB Events in 10^6
7.7	4.3
11.5	11.7
19.6	35.8
27	70.4
39	130.4
62.4	67.3

*Au+Au minimum bias events at STAR usable for analysis


Relativistic Heavy Ion Collider @ Brookhaven National Lab (BNL)/Long Island
PHENIX
RHIC
STAR
G-2
BOOSTER
LINAC
AGS
TANDEMS

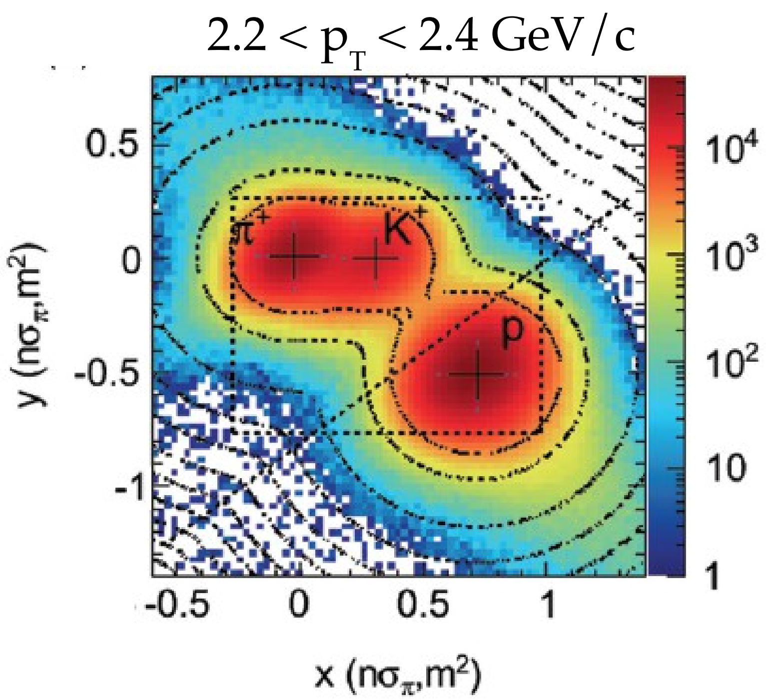
The Solenoidal Tracker At RHIC (STAR)



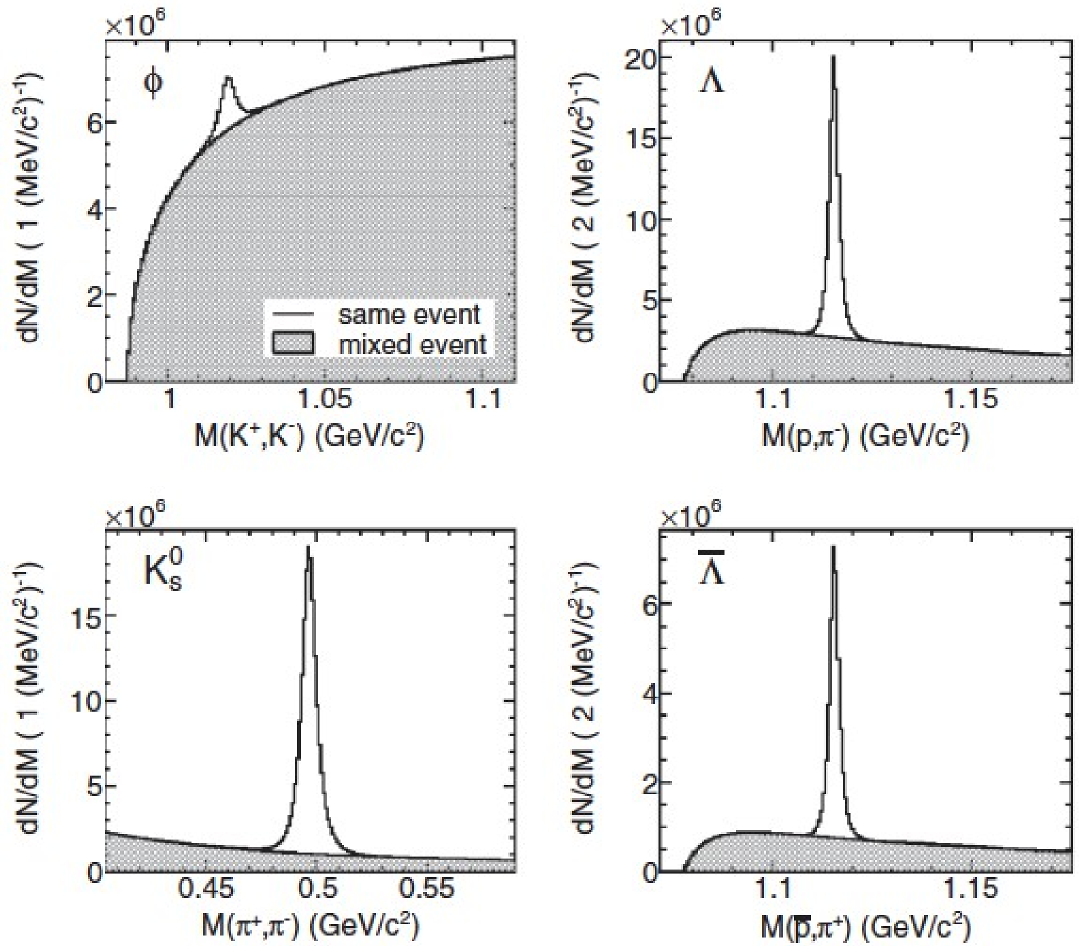
- Full azimuthal coverage
- $-1 < \eta < 1$ coverage
- Uniform acceptance for all beam energies
- Excellent PID

STAR

Particle Identification

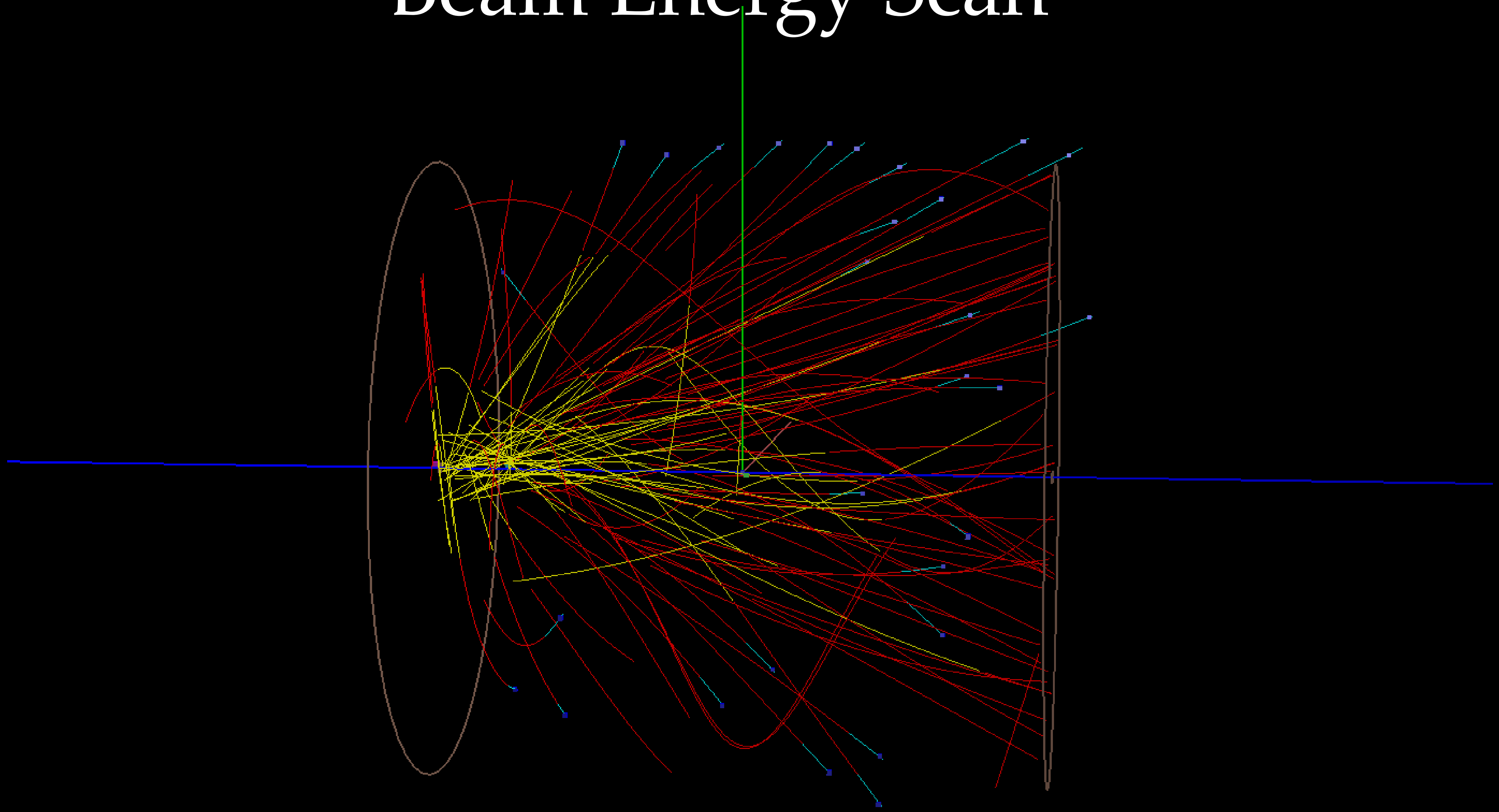


*rotated m2 vs. dE/dx distribution to get max. separation between pions and kaons

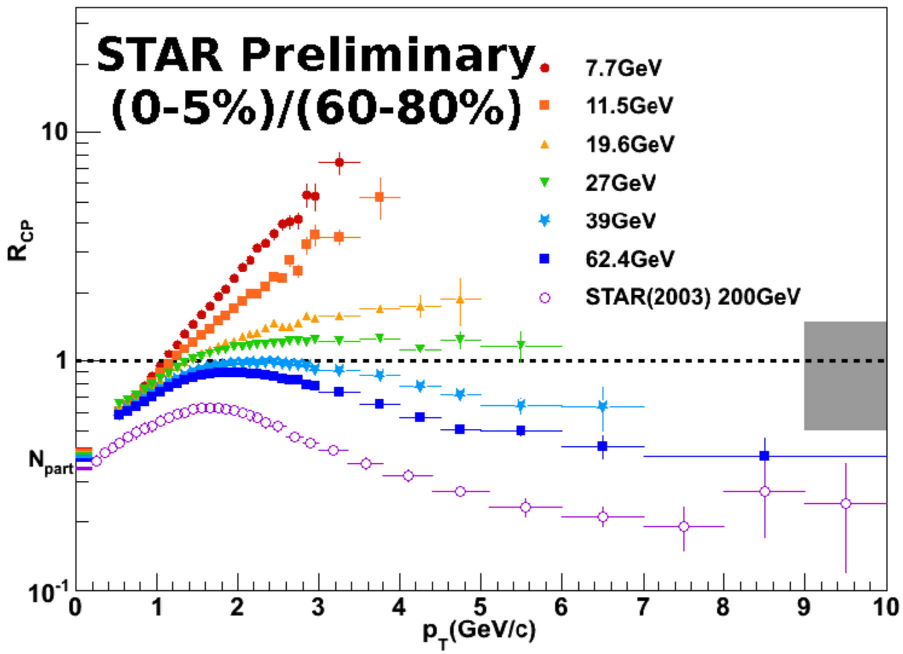


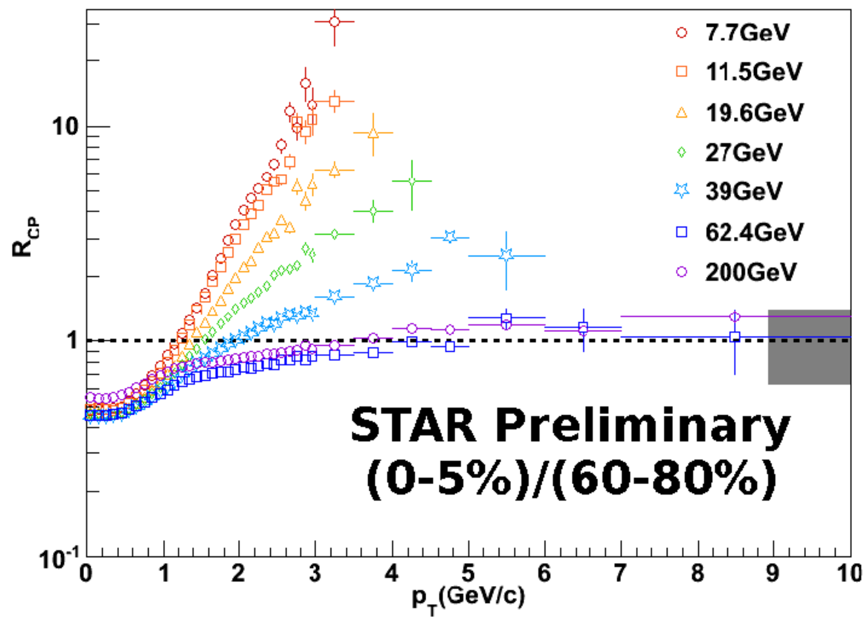
- Full time-of-flight detector for beam energy scan
  → 2D particle identification with dE/dx from TPC
- Neutral particle reconstruction via invariant mass
- Low mass setup → reduced conversion

Selected Highlights from the Beam Energy Scan



R_{CP} in Comparison to Hijing

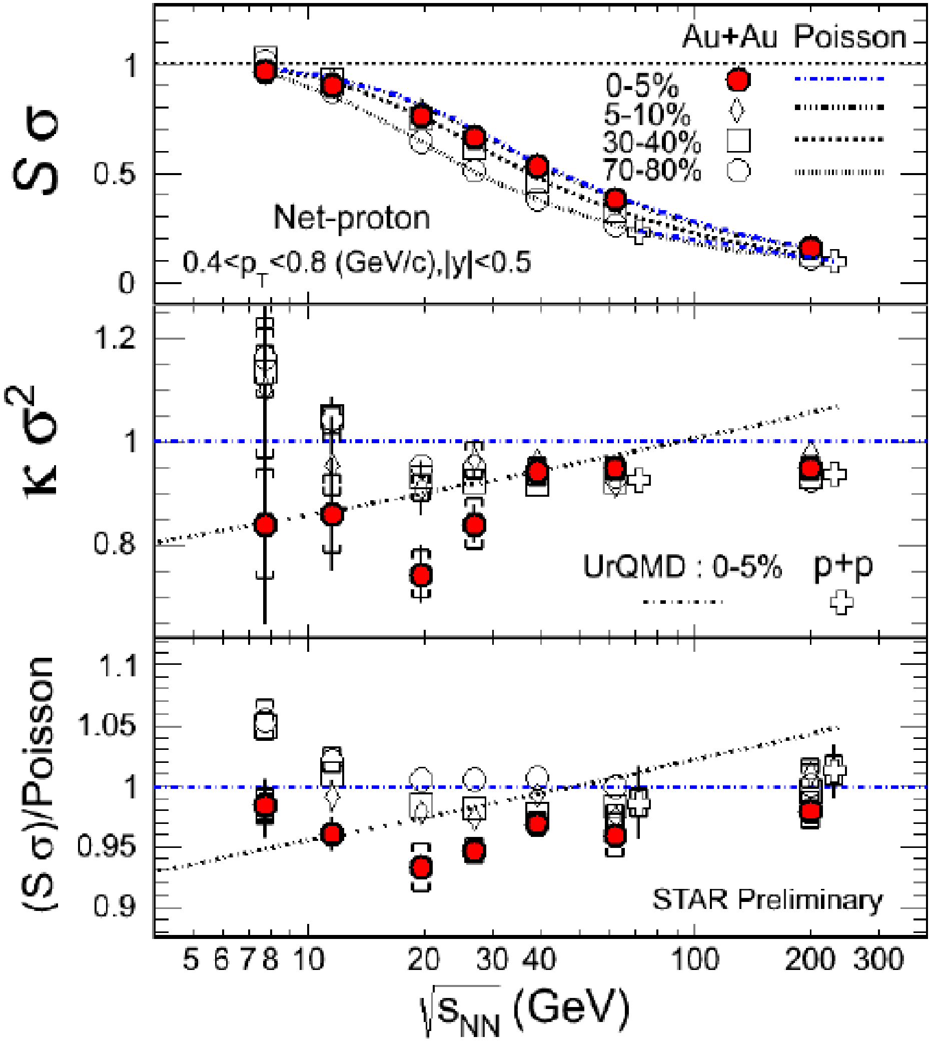




- Hard processes have very low cross section at lower energies
  → **probe disappeared?**
- Similar pattern for Hijing calculations with Cronin effect included
- No jet quenching included in calculation!
  → **Change of R_{CP} with energy eventually not related to energy loss / lack of energy loss in the QGP**

Higher Moments of Net-protons

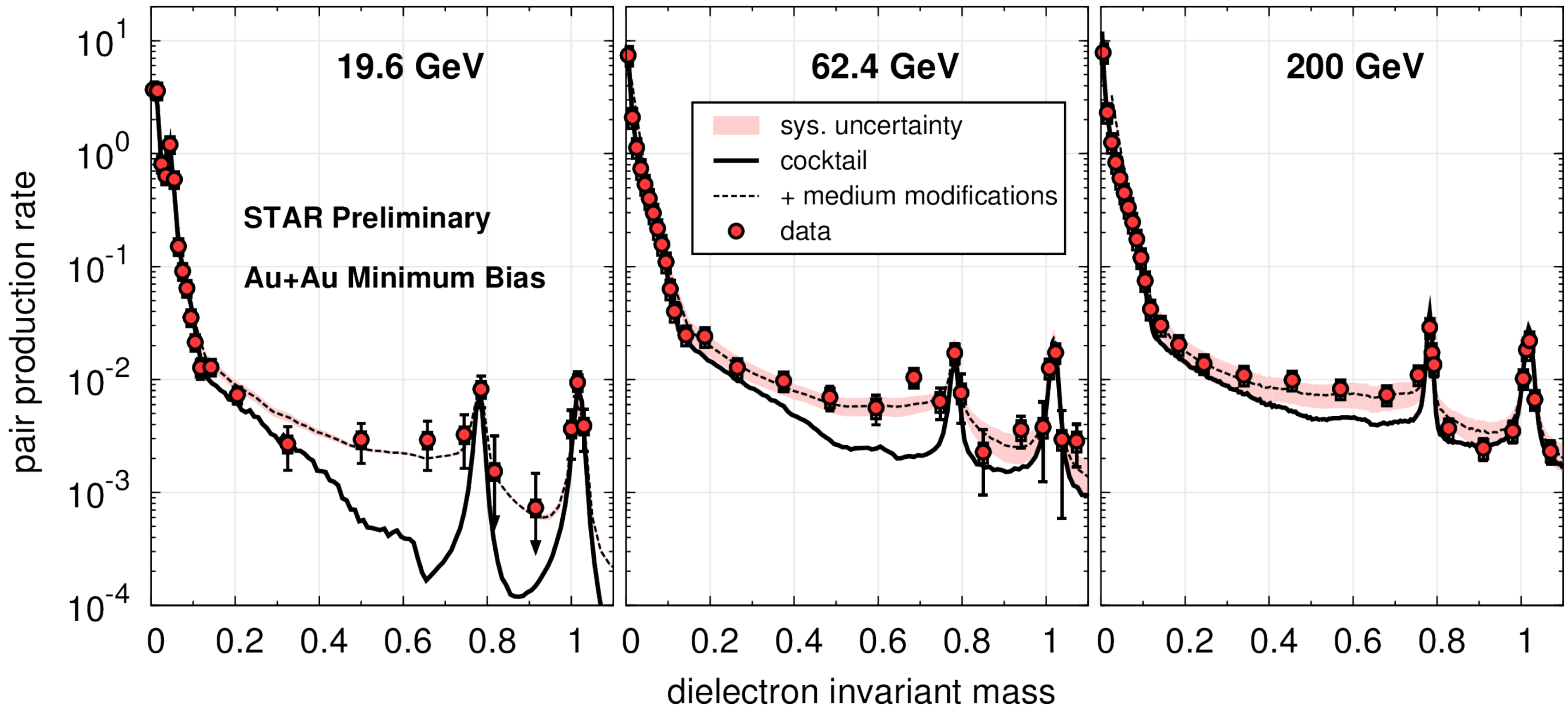
Xiaofeng Luo



- Deviations below Poisson expectations are observed beyond statistical and systematic errors in 0-5% most central collisions for $\kappa\sigma^2$ and $S\sigma$ above 7.7 GeV
- For peripheral collisions, the deviations above Poisson expectations are observed below 19.6 GeV
- UrQMD model show monotonic behavior for the moment products, in which non-CP physics, such as baryon conservation, hadronic scattering effects, are implemented

Di-Electron Spectra + Theory

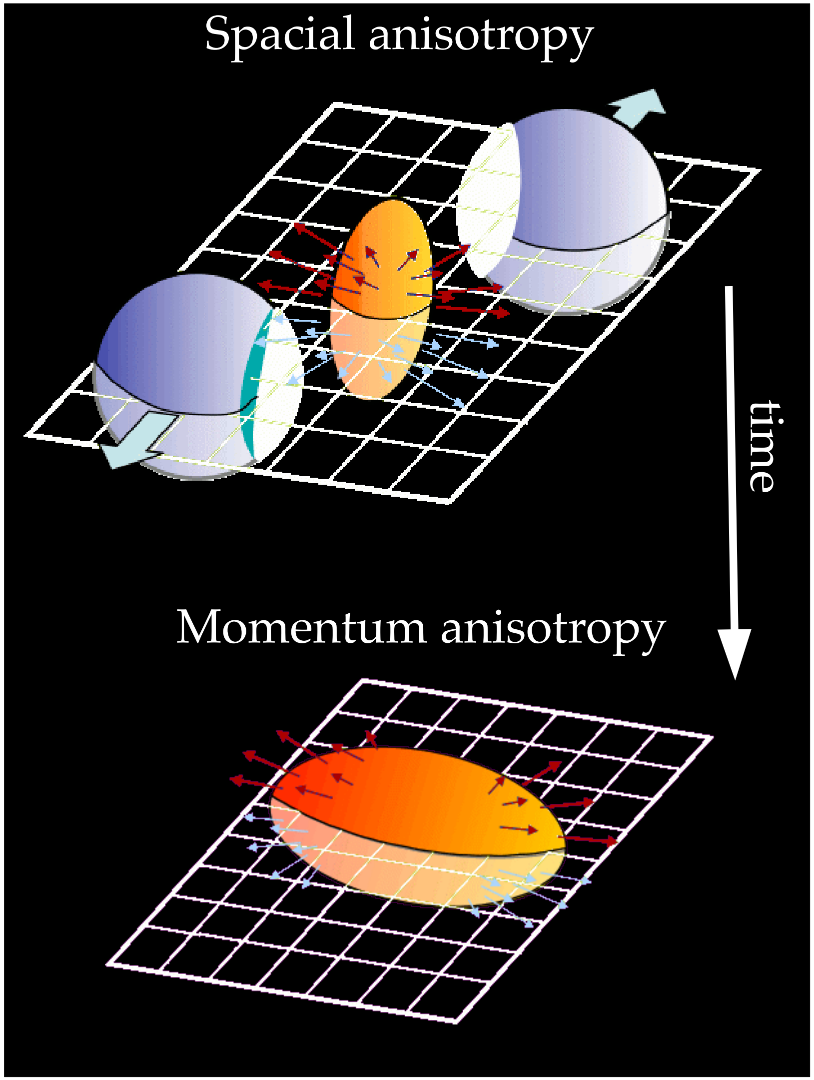
Patrick Huck, Jie Zhao



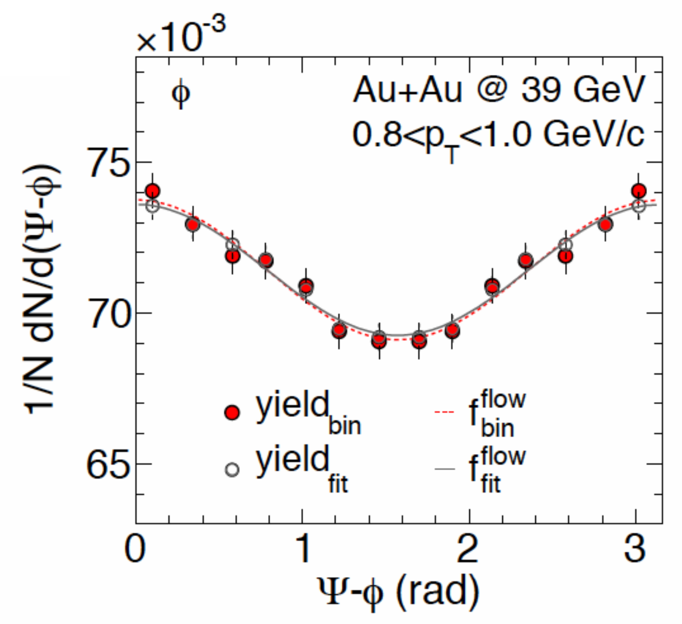
R. Rapp, private communication, R. Rapp Adv. Nucl. Phys. 25,1 (2000)

- The scenario of a broadened rho spectral function can **consistently describe the LMR excess yield from $\sqrt{s_{NN}}$=19.6 up to 200 GeV**

Azimuthal Anisotropy



Measured particle emission relative to event plane (Ψ)

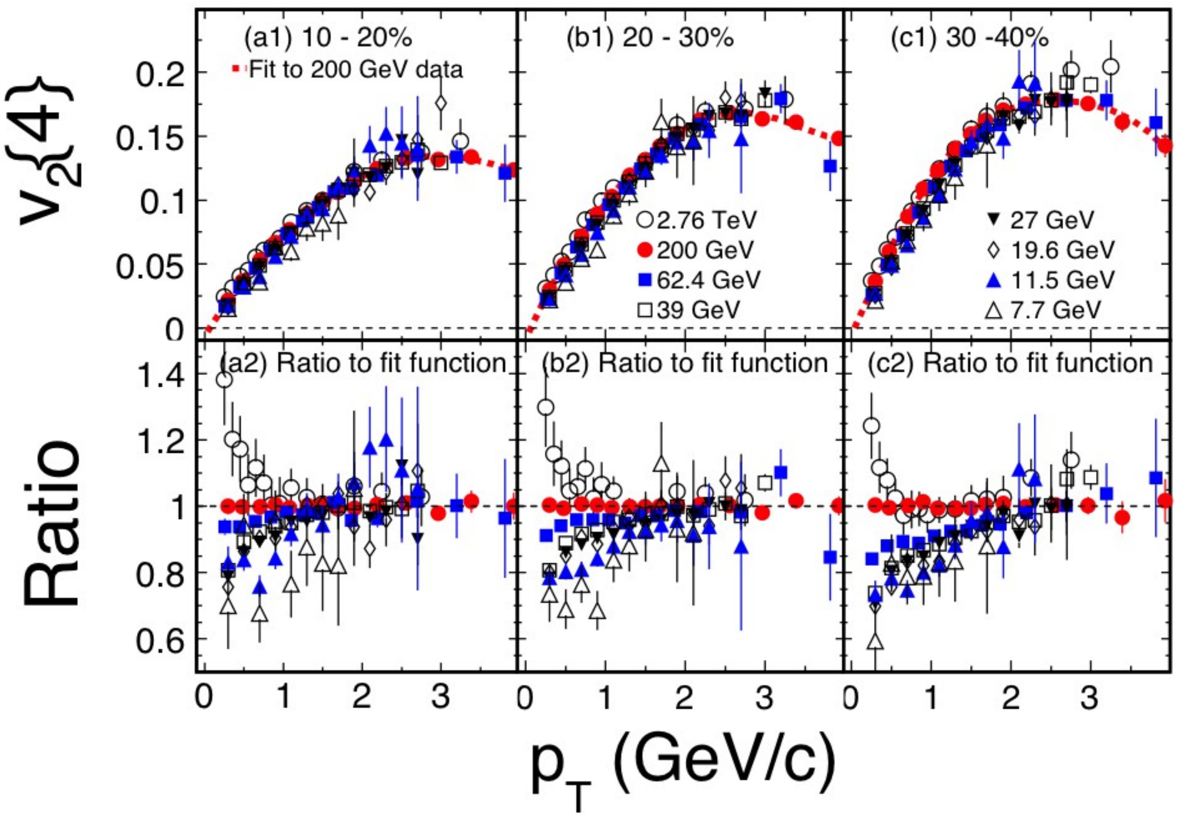


Characterization with Fourier decomposition:

$$\frac{dN}{d(\Psi_m - \phi)} \approx 1 + 2\sum_{n\geq 1} v_n \cos\left[n(\Psi_m - \phi)\right]$$

- Sensitive to early evolution → partonic stage
- Sensitive to Equation-of-State

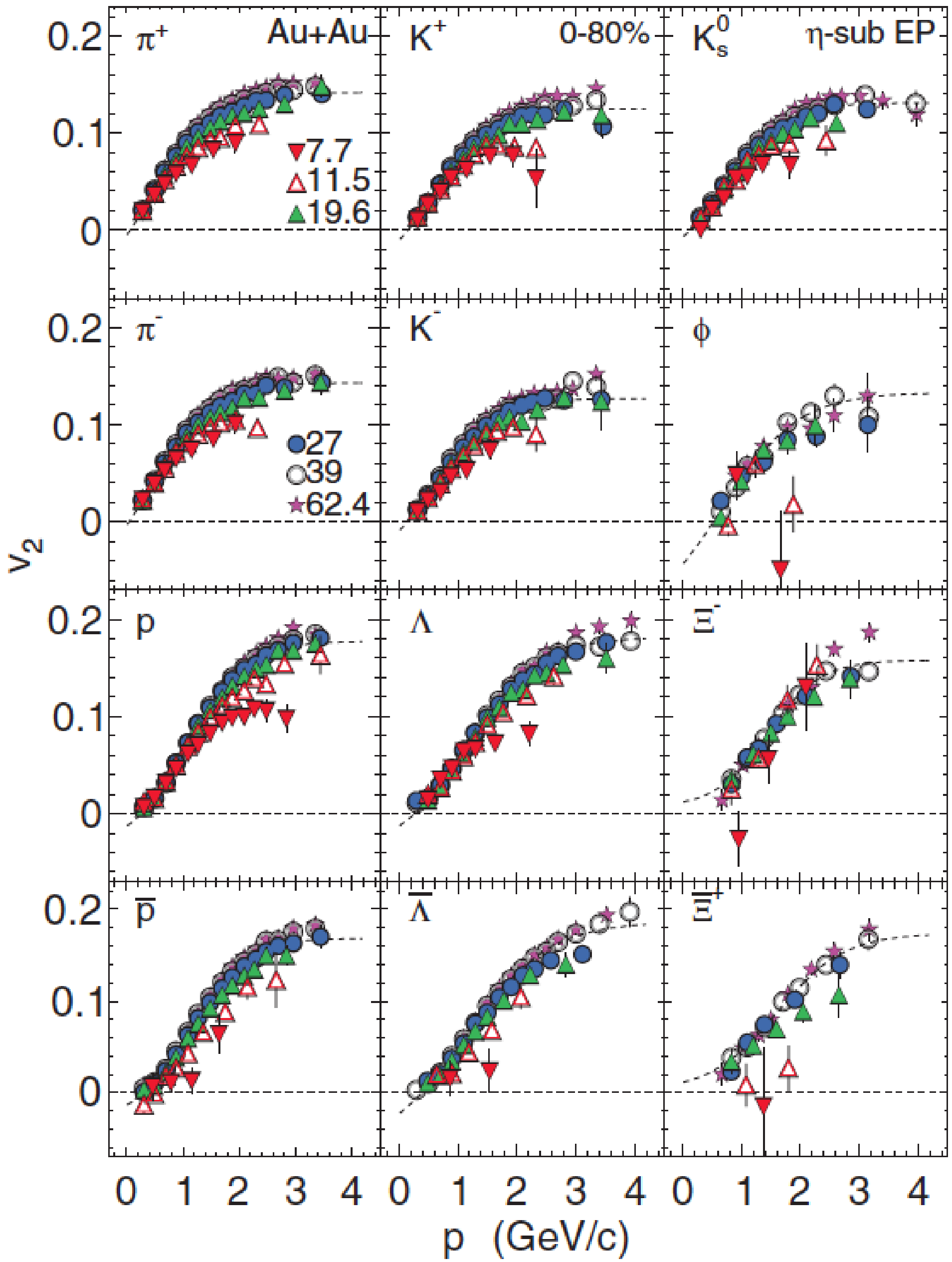
Elliptic Flow (v_2) of Charged Hadrons



STAR: Phys.Rev. C86, 054908 (2012)
ALICE: Phys. Rev. Lett. 105, 252302 (2010)

- $v_2\{4\}$ cumulant method
  → insensitive to non-flow
- General shape and magnitude of $v_2\{4\}(p_T)$ is similar for all energies between 7.7 GeV – 2.76 TeV
- In detail: at $p_T < 2$ GeV/c the $v_2\{4\}$ increases with increasing $\sqrt{s_{NN}}$
- Large collectivity? Particle composition?
- Baseline measurement for identified particle v_2

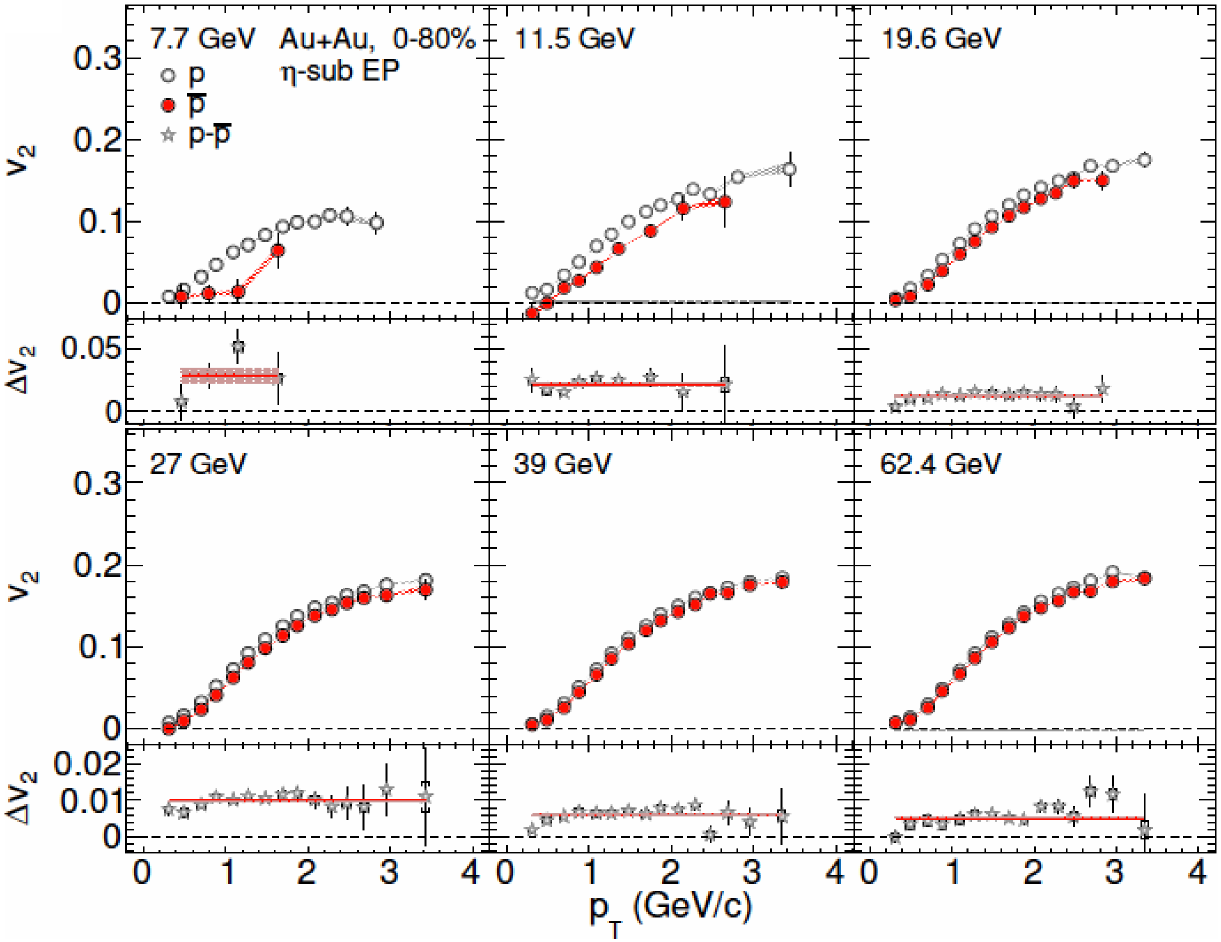
Energy and PID Dependence of v_2



Phys. Rev. C 88, 014902 (2013)

- v_2 up to $p_T = 4$ GeV/c
- v_2(Baryons) > v_2(Mesons)
- v_2 is increasing with energy

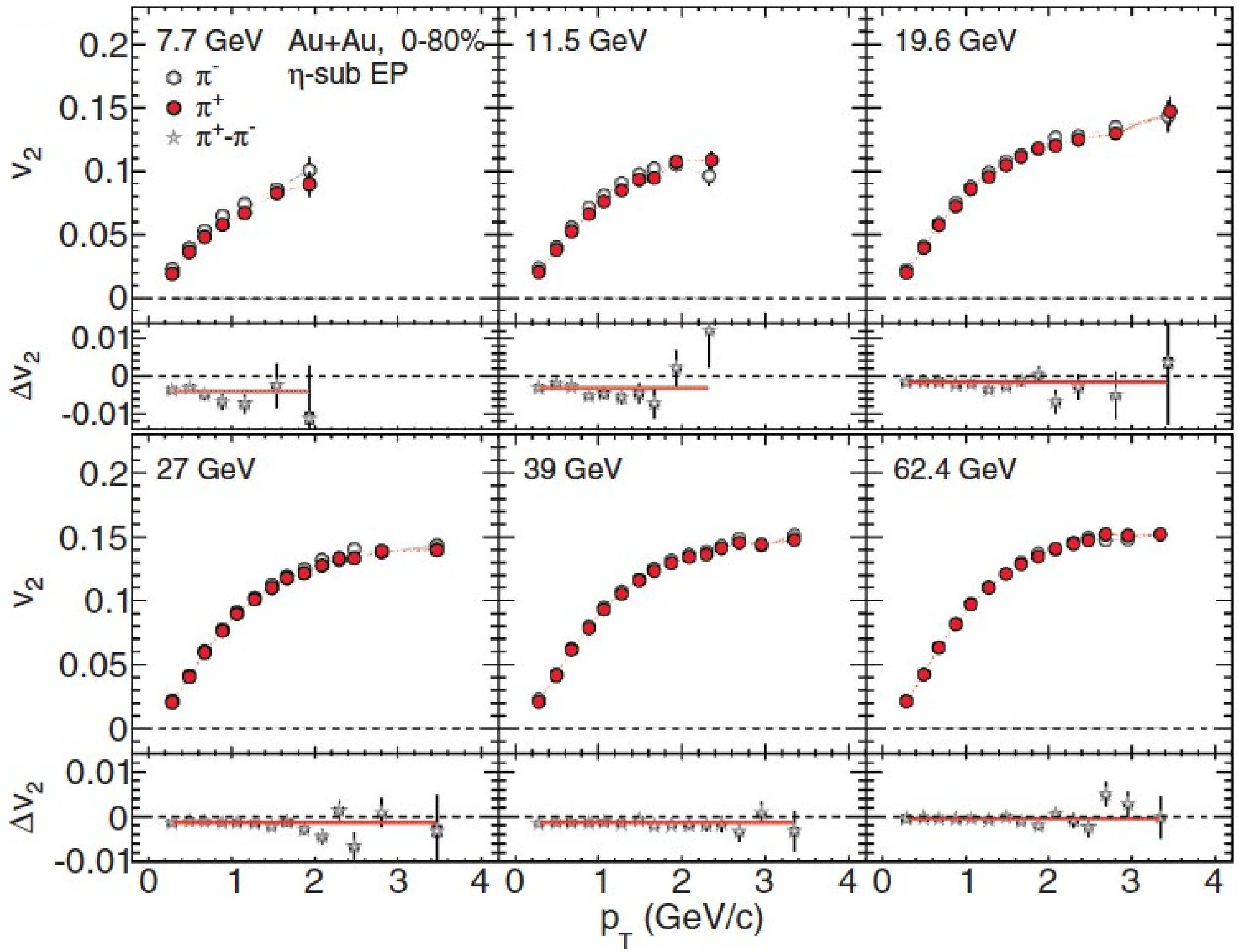
v_2 for Protons: 0%-80%



Phys. Rev. C 88, 014902 (2013)

- Difference in v_2 between particles and anti-particles is constant as a function of p_T
- Δv_2 is increasing with decreasing energy

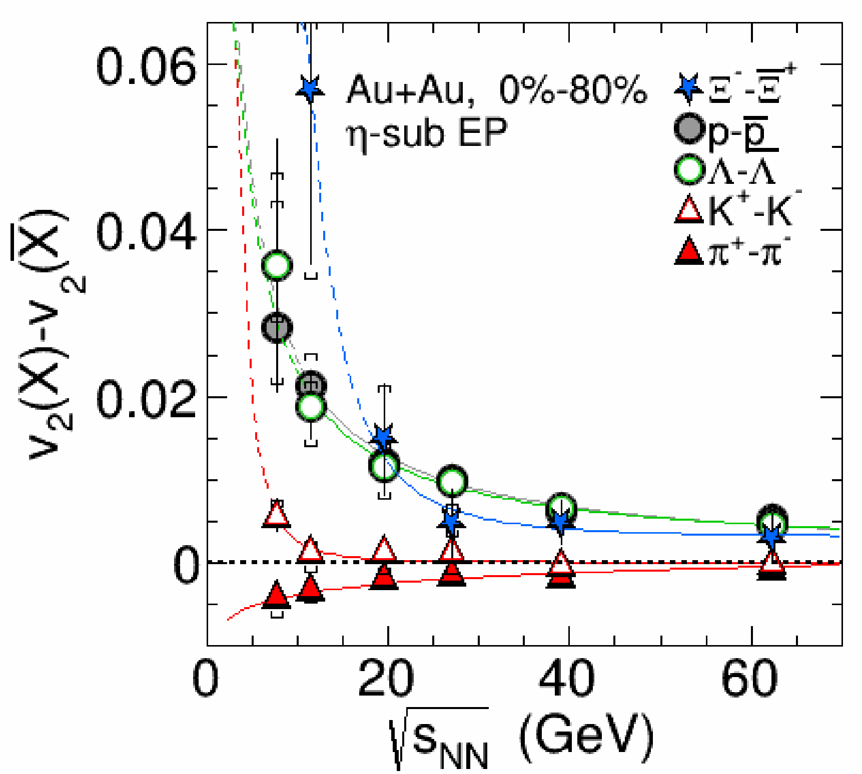
v_2 for Pions: 0%-80%

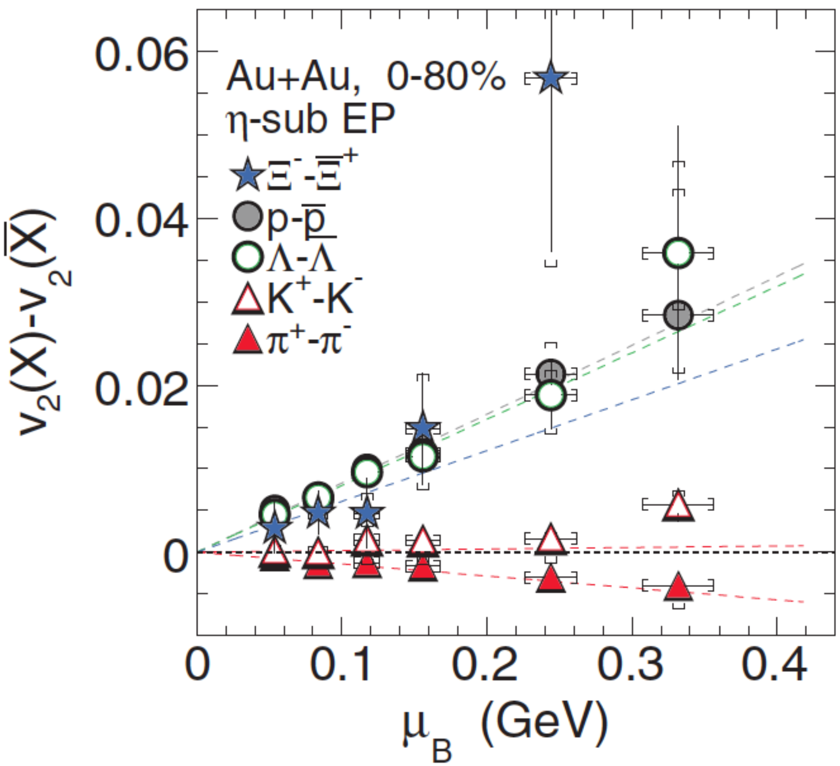


Phys. Rev. C 88, 014902 (2013)

- Difference in v_2 between particles and anti-particles is also constant for mesons as a function of p_T
- Δv_2 is much smaller for mesons compared to baryons

Δv_2 vs. $\sqrt{s_{NN}}$: all Particles

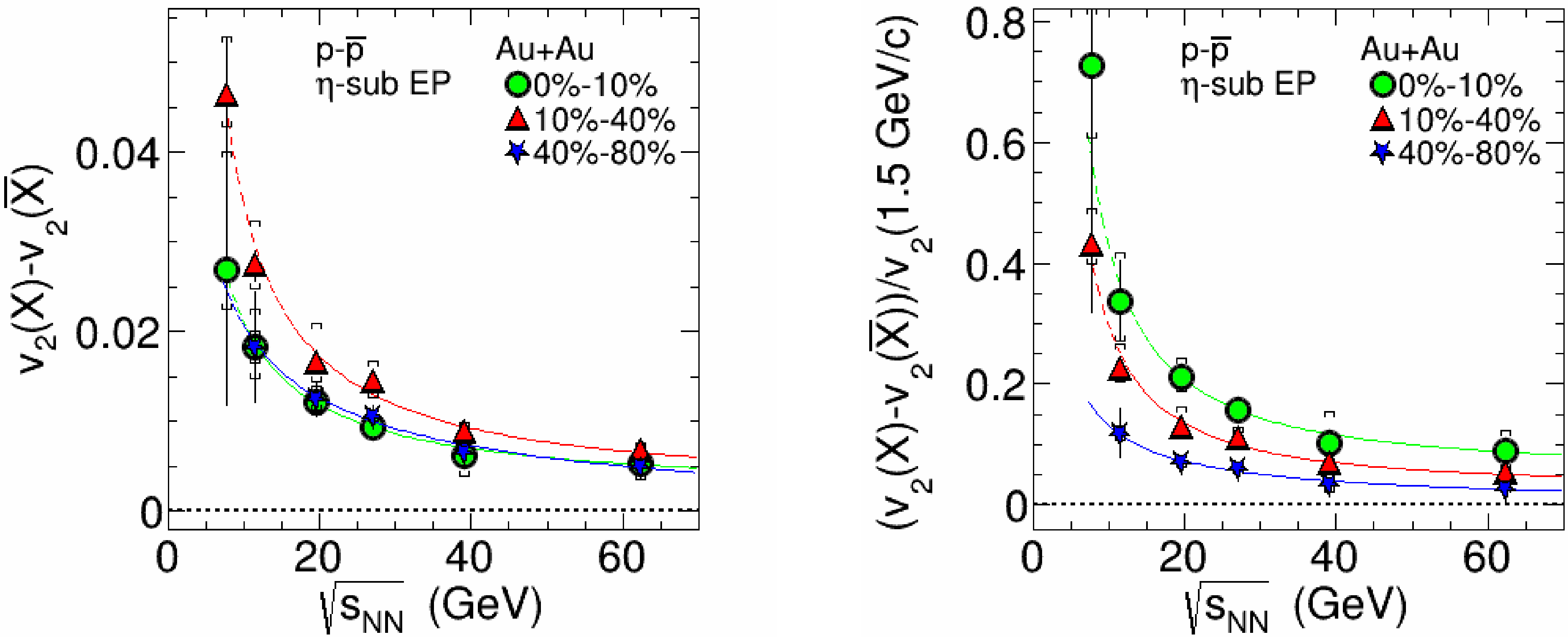




Phys. Rev. Lett. 110, 142301 (2013)

- Energy dependence of Δv_2 looks similar for all baryons
- Much smaller Δv_2 for mesons, inverted for pions
- Δv_2 is increasing linearly with μ_B
  → suggests a direct connection of the two quantities
  → quark transport?

Centrality Dependence Δv_2 vs. $\sqrt{s_{NN}}$: Protons

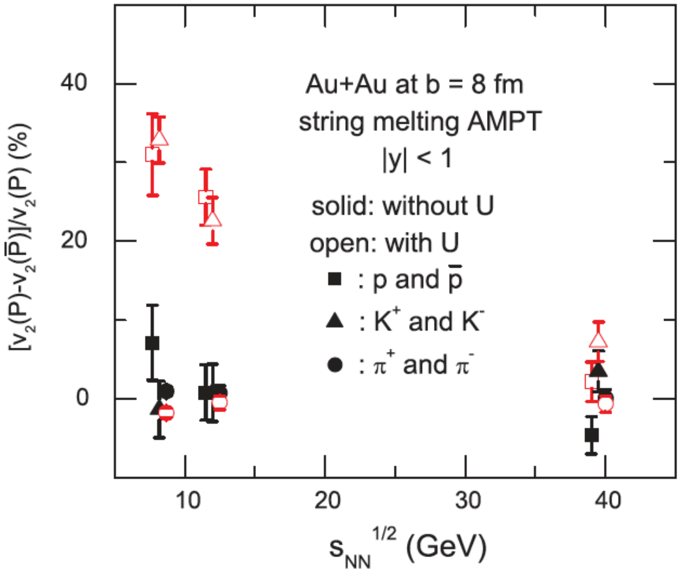


- Similar trend of Δv_2 for all centralities

- Relative difference shows a clear centrality ordering of $\Delta v_2/v_2$(1.5 GeV/c), with Δv_2(0%-10%) > Δv_2(40%-80%)

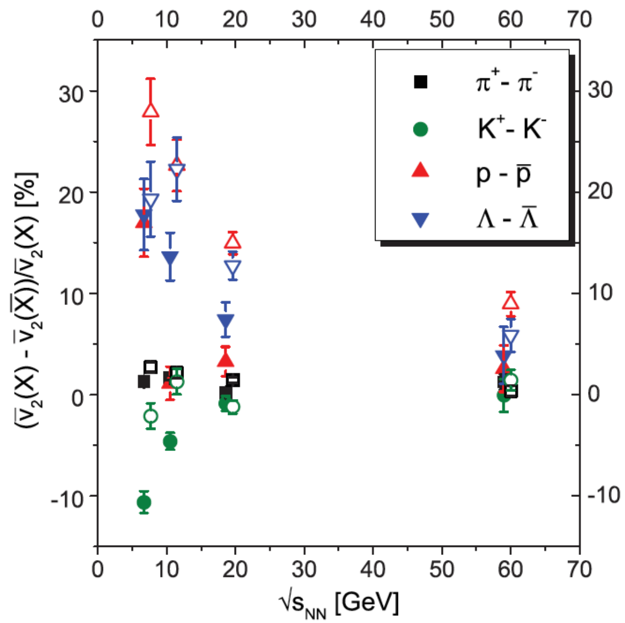
Theory Explanations for Δv_2

Phys. Rev. C 85, 041901(R) (2012)



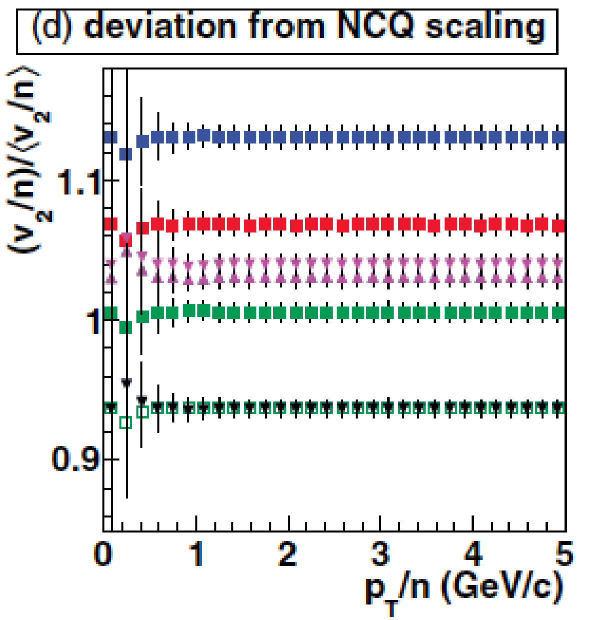
- Hadronic potentials are different for different particle species
  → changes the flow pattern

Phys. Rev. C 86, 044903 (2012)



- Baryon chemical potential changes with energy
  → pressure different for particles and anti-particles

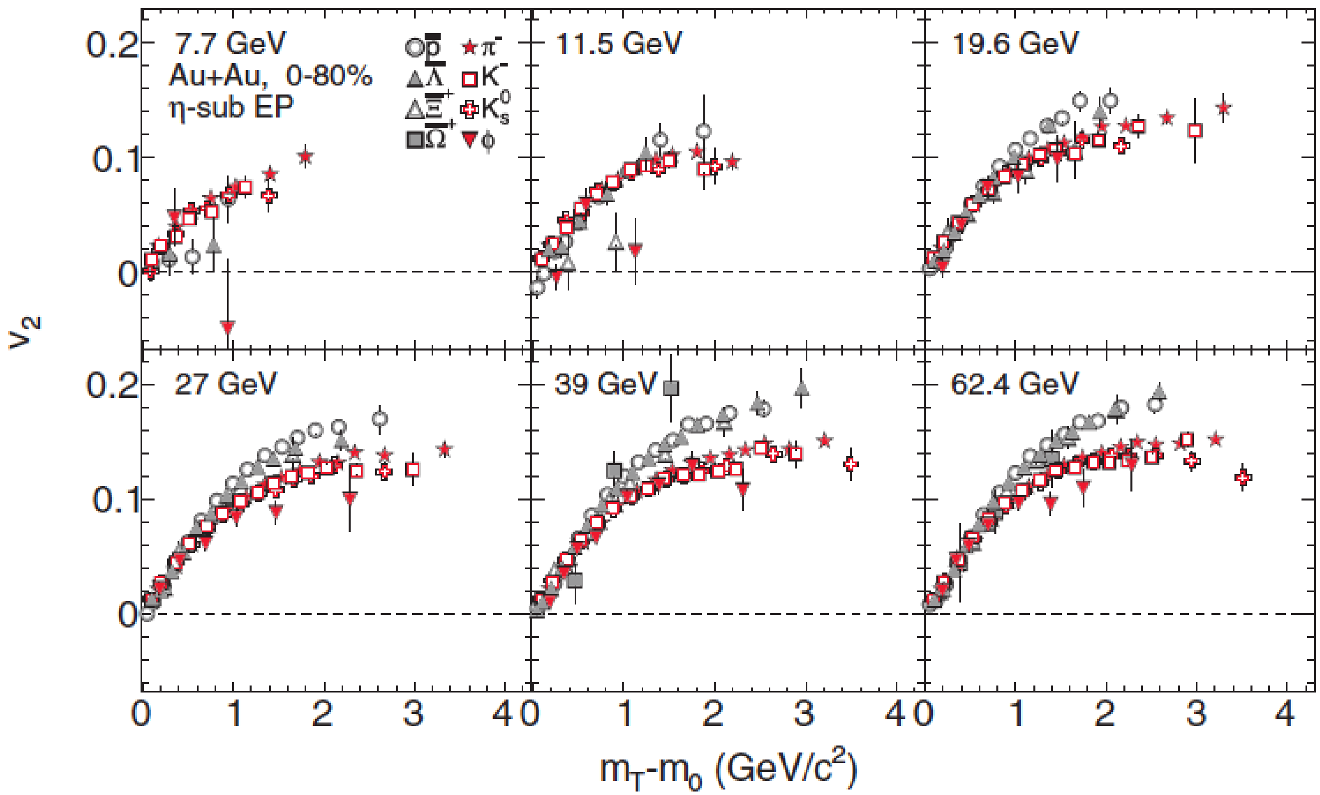
Phys. Rev. C 84, 044914 (2011)



- Transported quarks have larger v_2 than produced quarks

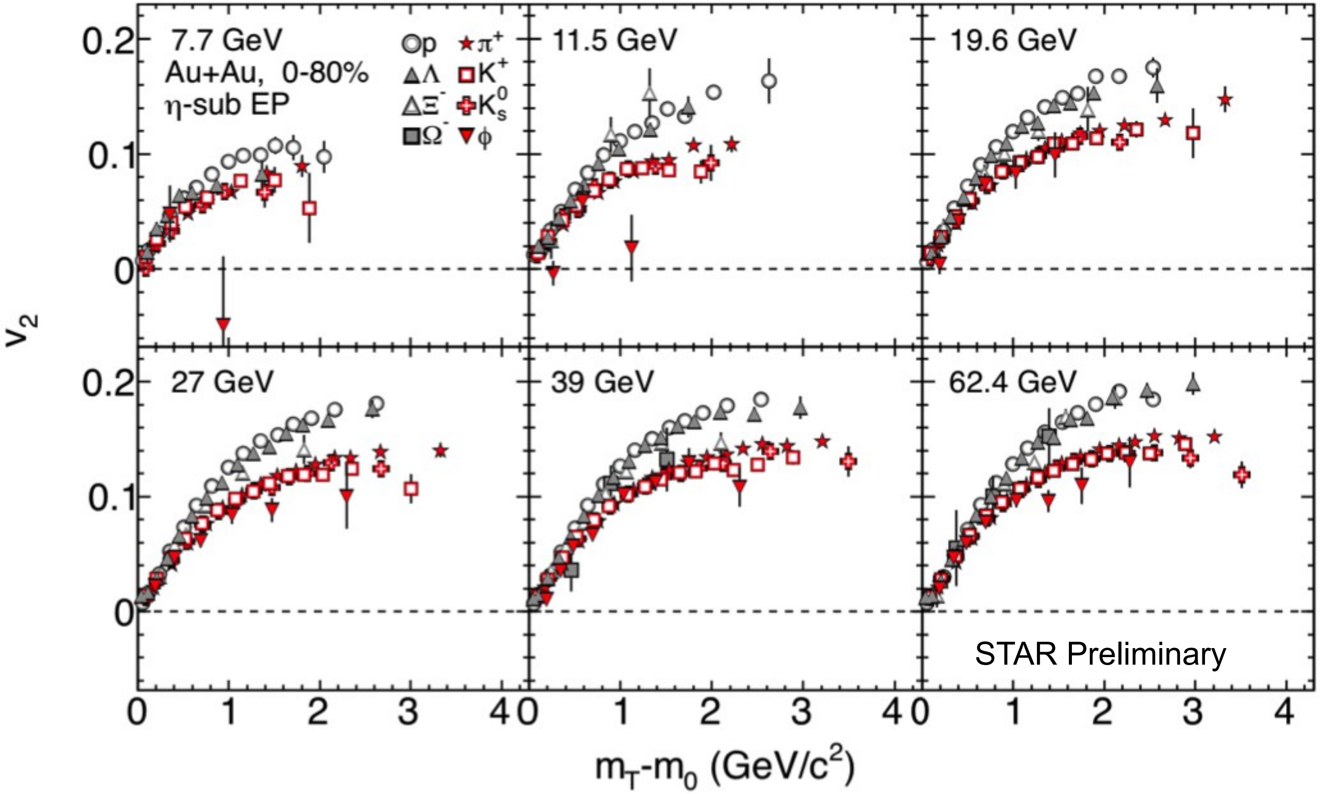
→ Approximately explains the measured patter, not related to QGP → hadron gas transition

Elliptic Flow (v_2) of anti-Particles



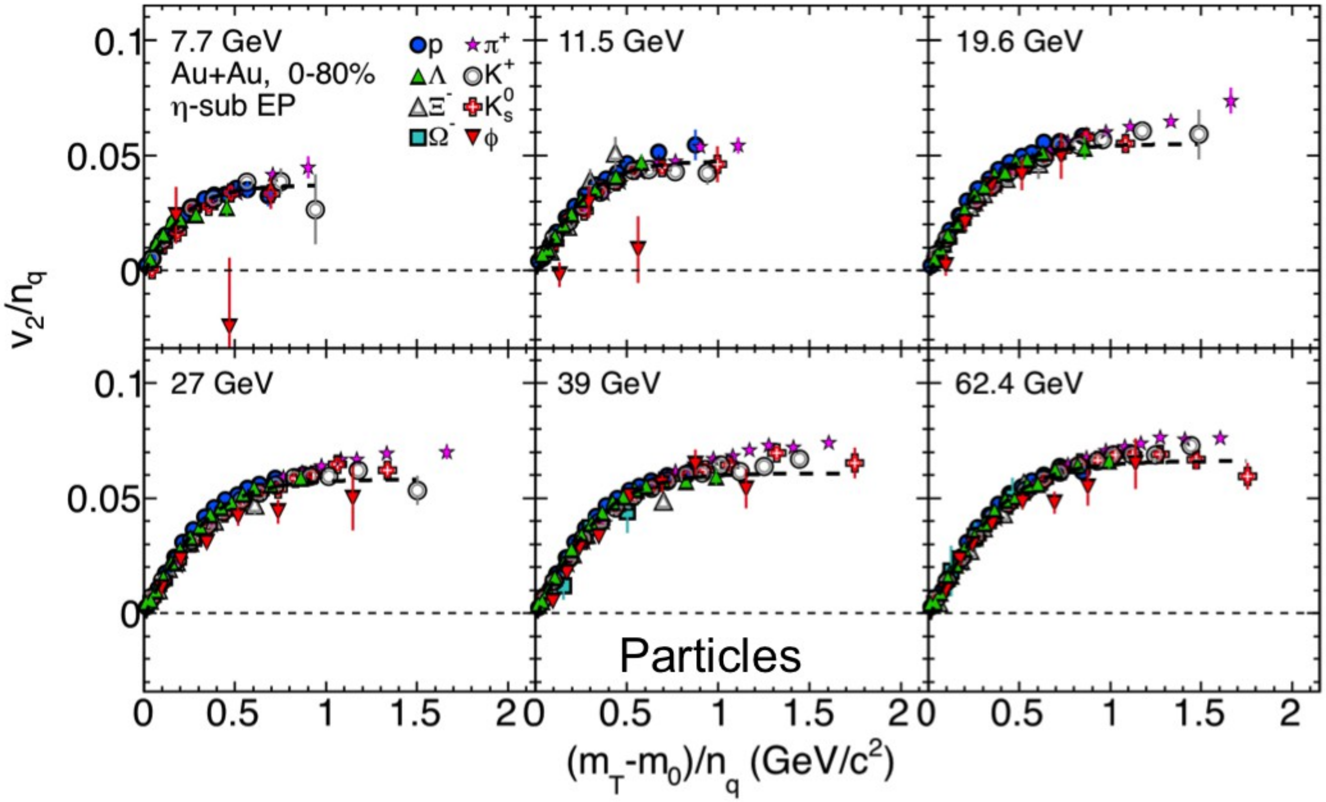
- Clear baryon ↔ meson splitting at $\sqrt{s_{NN}}$ >= 11.5 GeV
- Splitting at 7.7 GeV, ϕ at 7.7 and 11.5 GeV?
  → More statistics needed

Elliptic Flow (v_2) of Particles



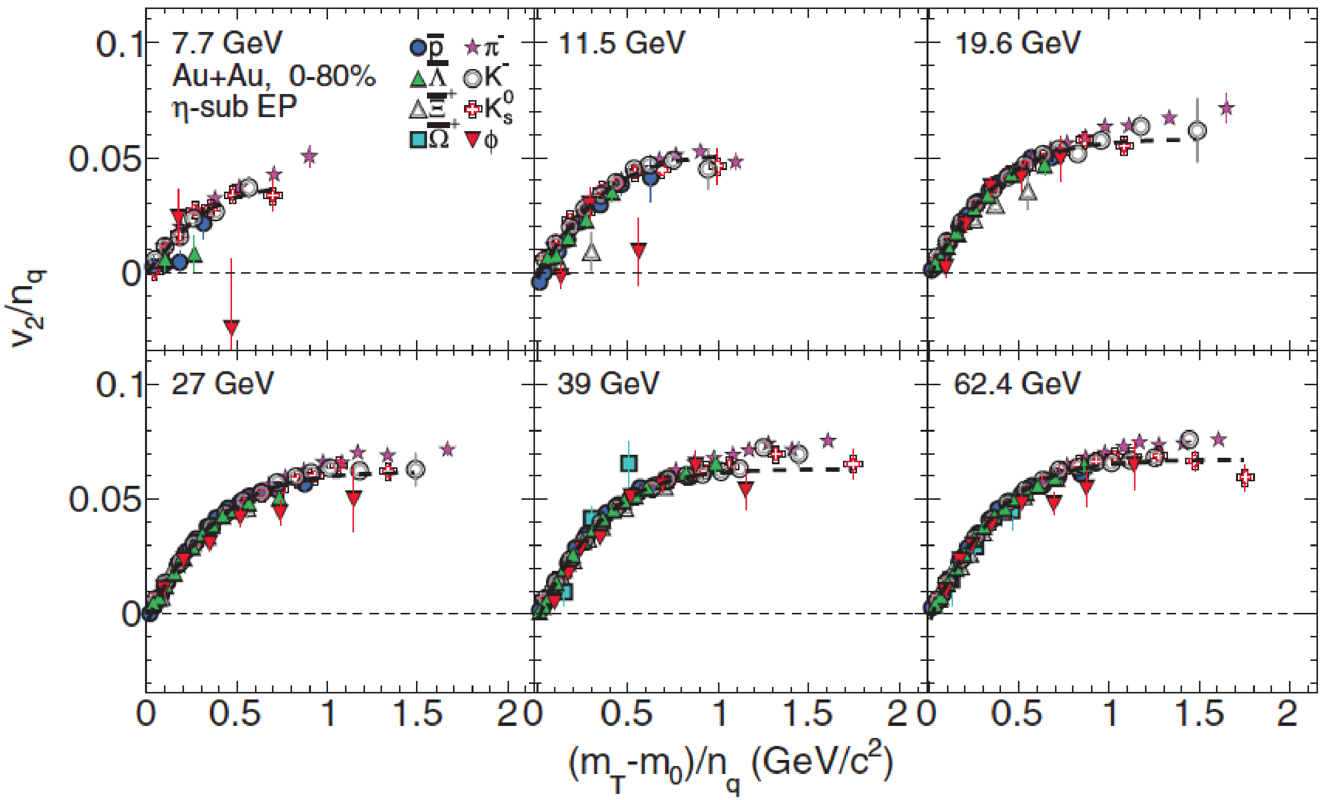
- Clear baryon ↔ meson splitting at $\sqrt{s_{NN}}$ >= 11.5 GeV
- Splitting smaller at 7.7 GeV, ϕ at 7.7 and 11.5 GeV different?
  → More statistics needed

NCQ Scaling of Particles



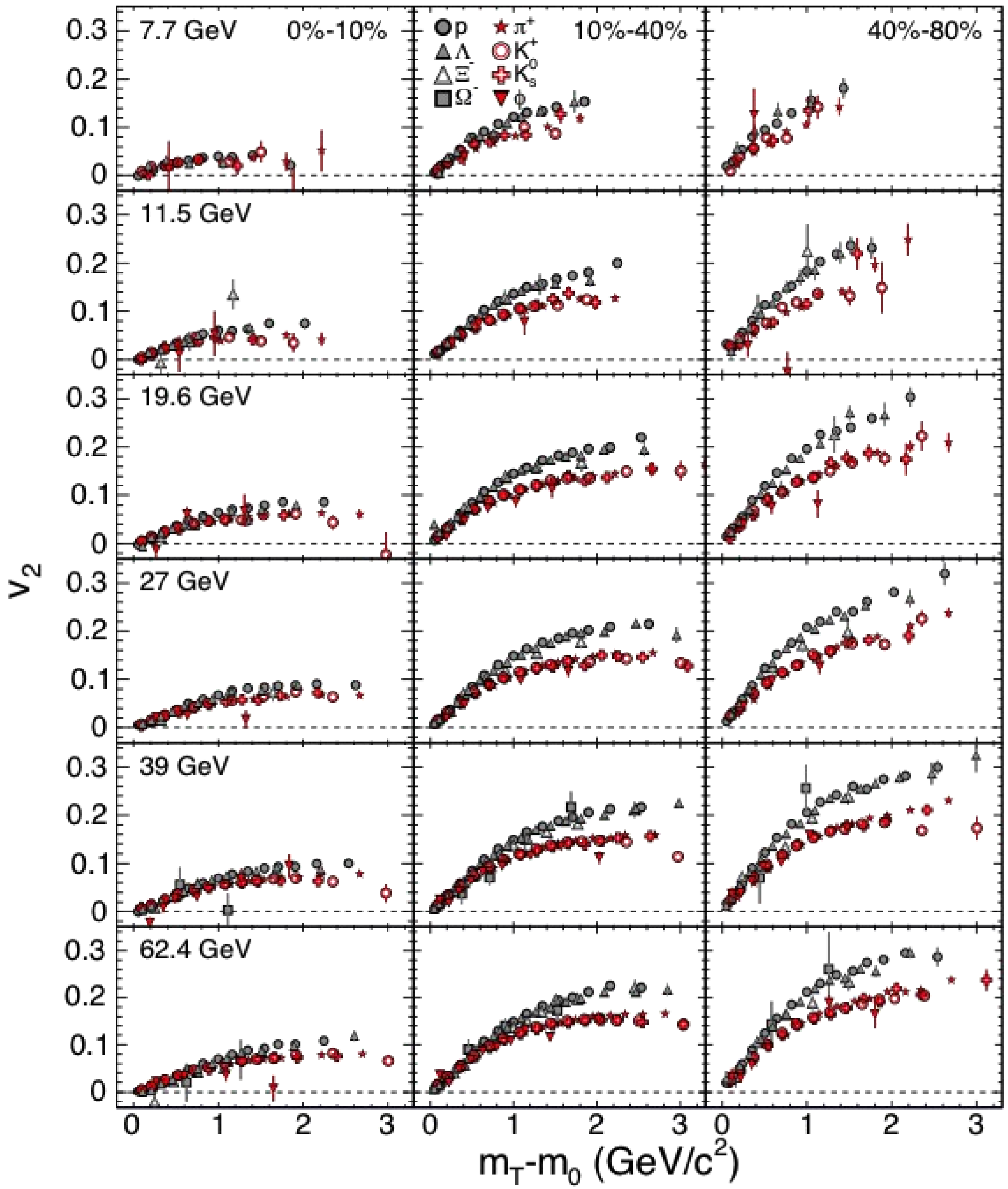
- NCQ-scaling holds for particles within 10%
- Only $v_2(\phi)$ deviates by ~2σ at 7.7 and 11.5 GeV from general trend

NCQ Scaling of anti-Particles



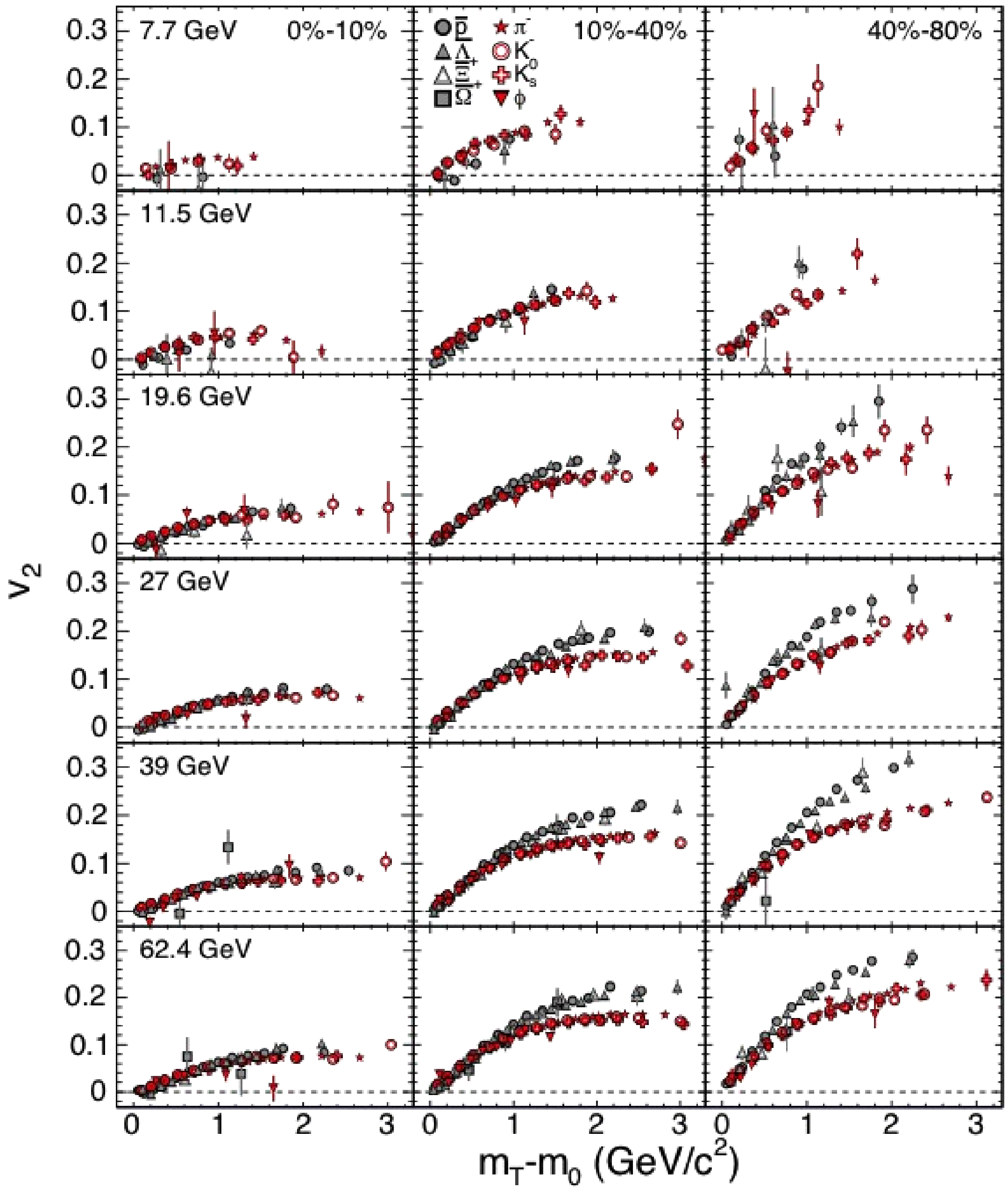
- NCQ-scaling holds for anti-particles within 10%
- Only $v_2(\phi)$ deviates by ~2σ at 7.7 and 11.5 GeV from general trend

v_2 vs. m_T-m_0: Particles



- v_2 is increasing with decreasing centrality and increasing energy
- Similar baryon-meson splitting observed at 10%-40% and 40%-80% for all energies
- Almost no splitting at 0%-10%

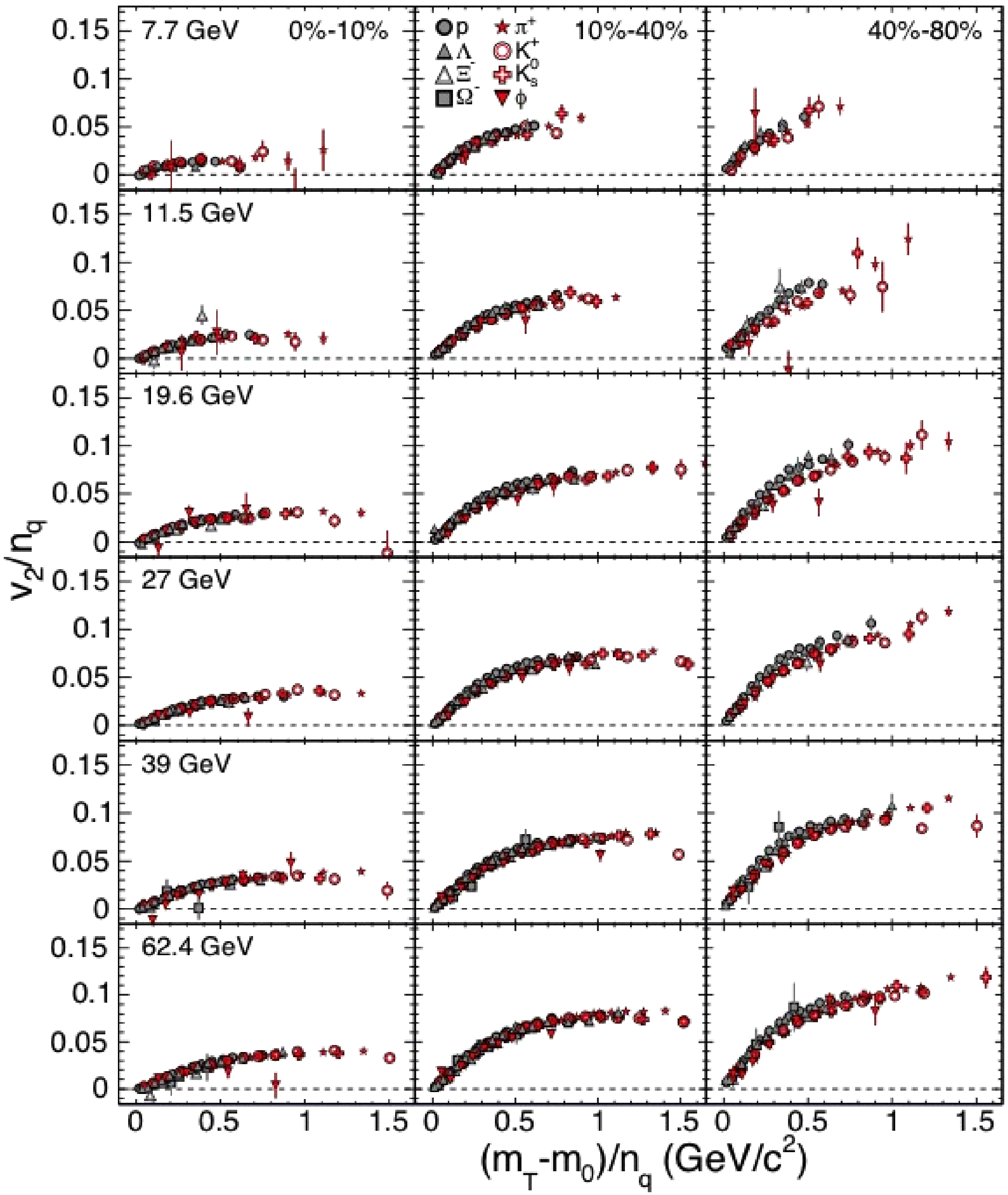
v_2 vs. m_T-m_0: anti-Particles



- Smaller baryon-meson splitting observed at 10%-40% and 40%-80% for lower energies compared to higher energies
- No splitting at 0%-10%!

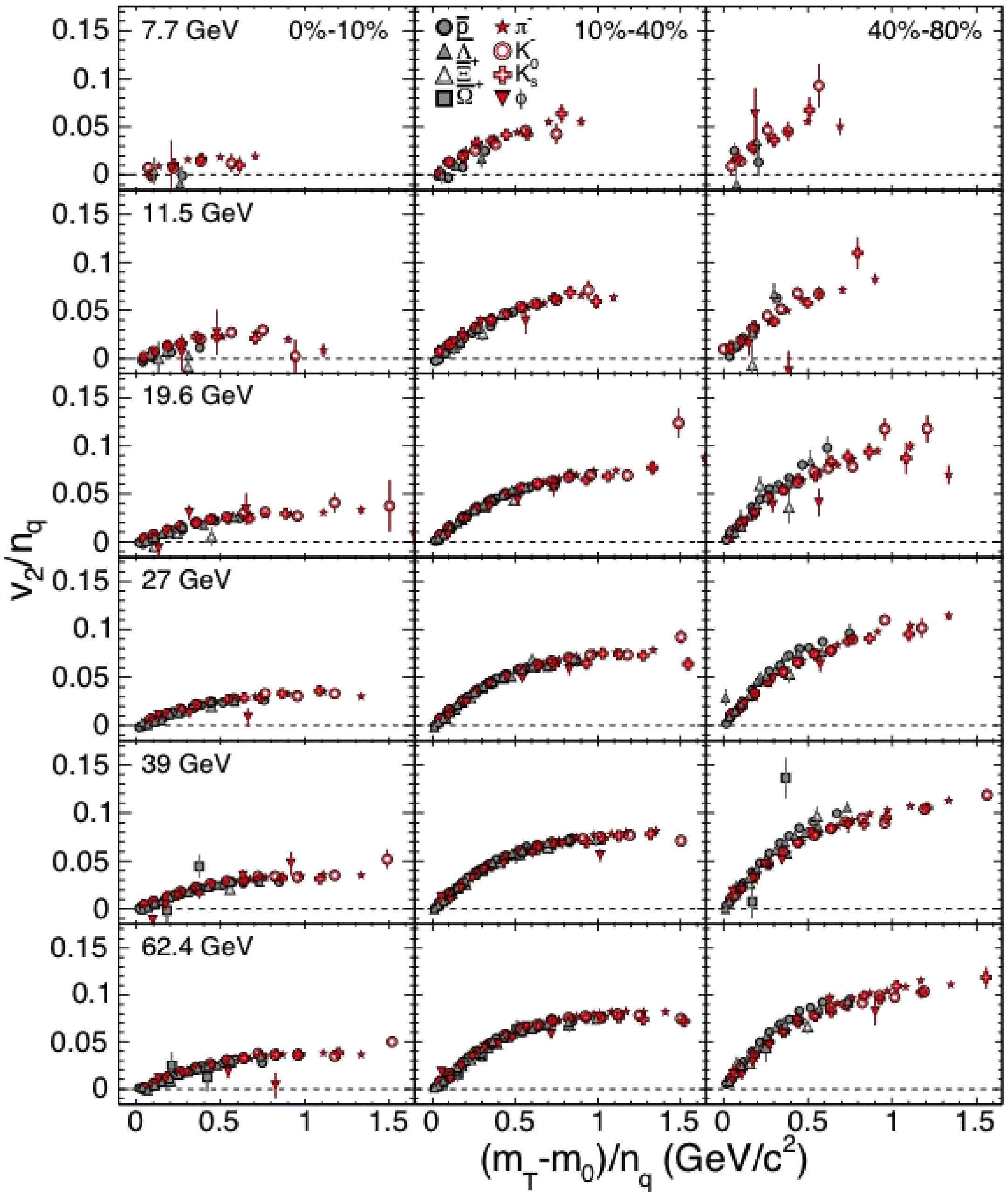
→ anti-baryons go down in v_2 or baryon are going up in v_2?

v_2/n_q vs. $(m_T-m_0)/n_q$: Particles



- NCQ-scaling is very good for 0%-10% and 10%-40%
- Significant difference between baryons and mesons at 40%-80%

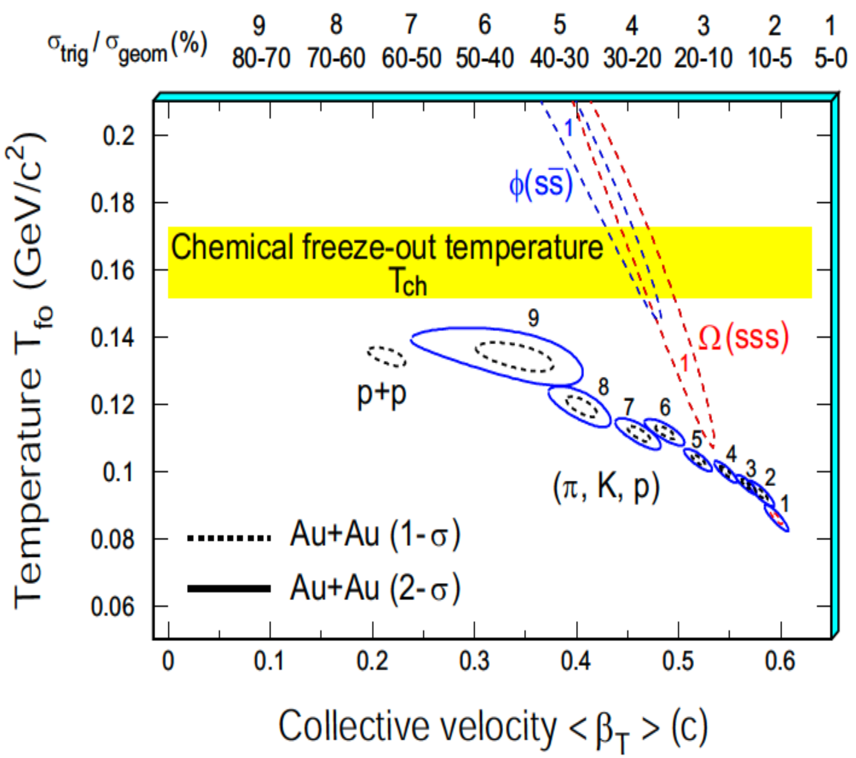
v_2/n_q vs. $(m_T-m_0)/n_q$: anti-Particles



- NCQ-scaling is very good for 0%-10% and 10%-40%
- Significant difference between baryons and mesons at 40%-80%

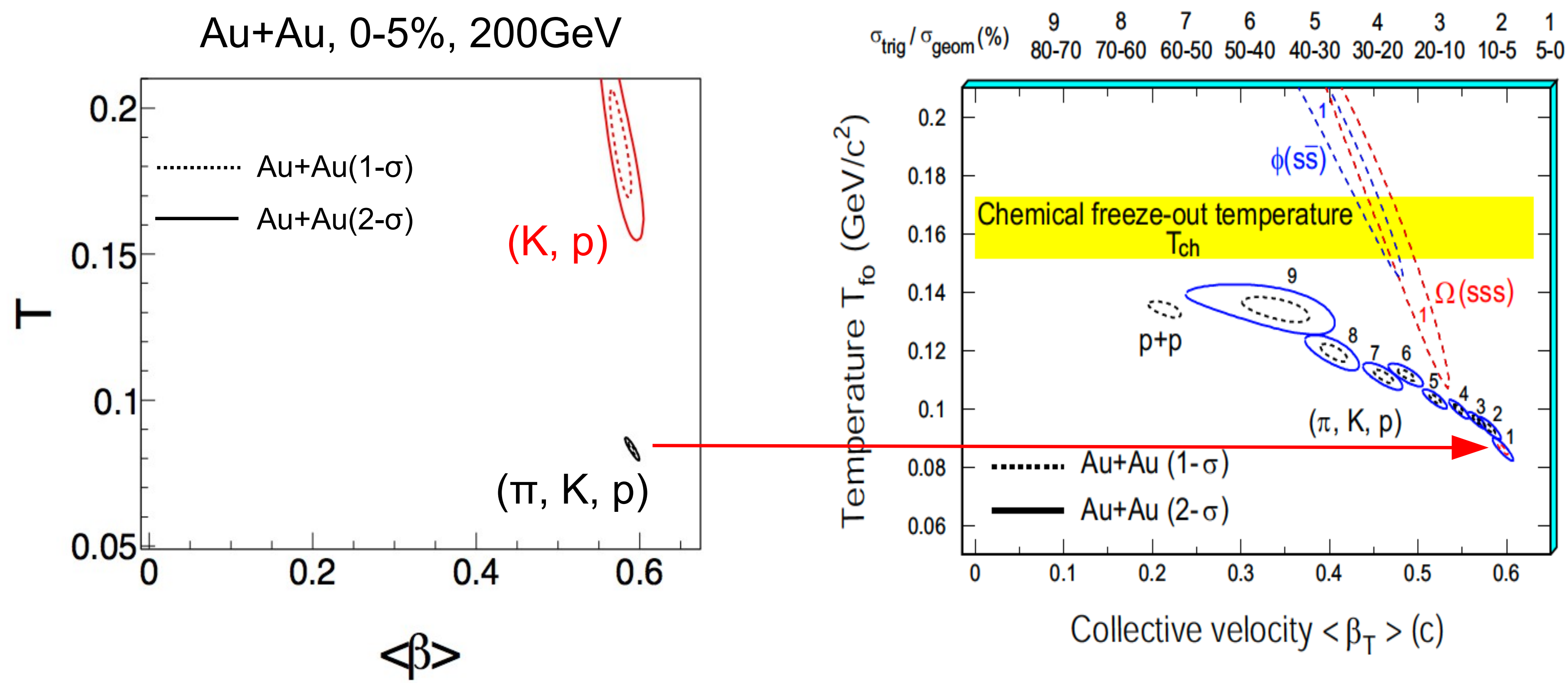
What about Blast Wave?

- Simple, old but still effective parametrization for radial flow in heavy-ion collisions
- Difference between multi-strange hadron radial flow and π, K, p?
- Beam energy dependence of radial flow?



Nucl.Phys.A757:102-183,2005

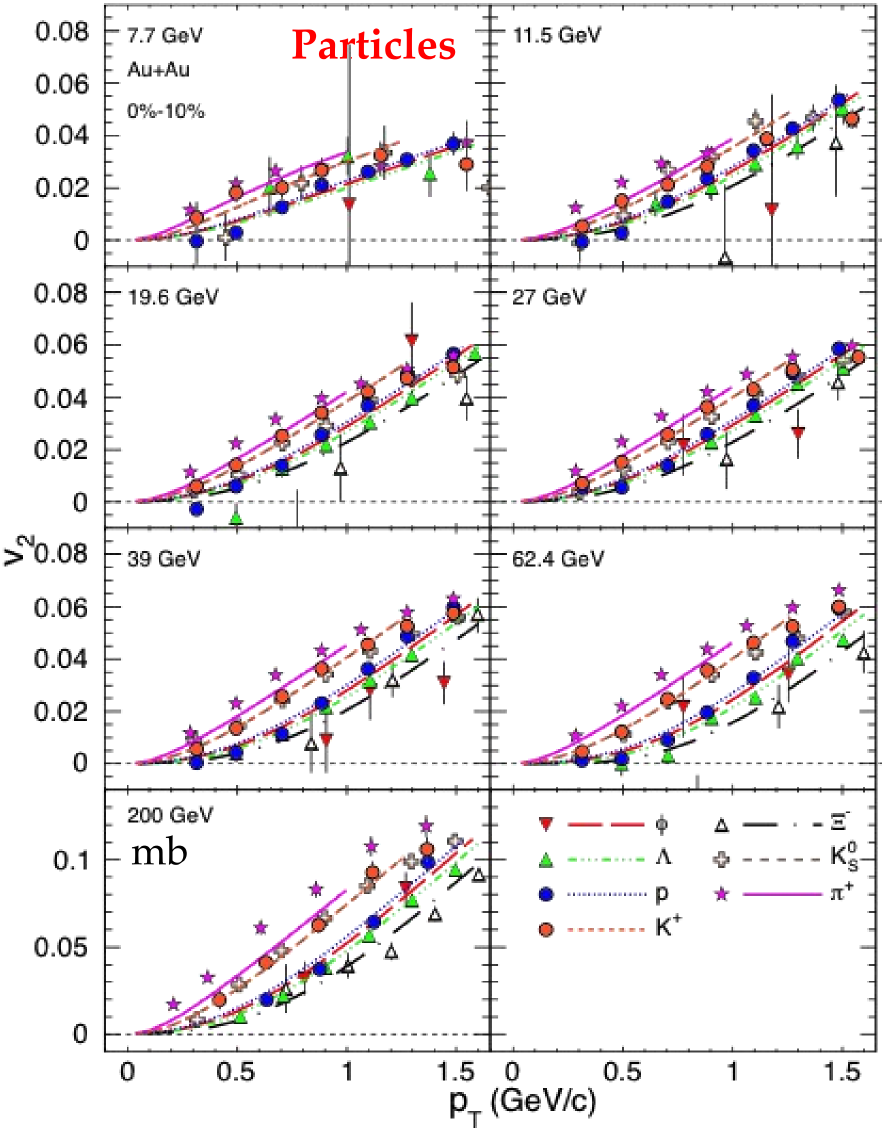
Excluding the Pions

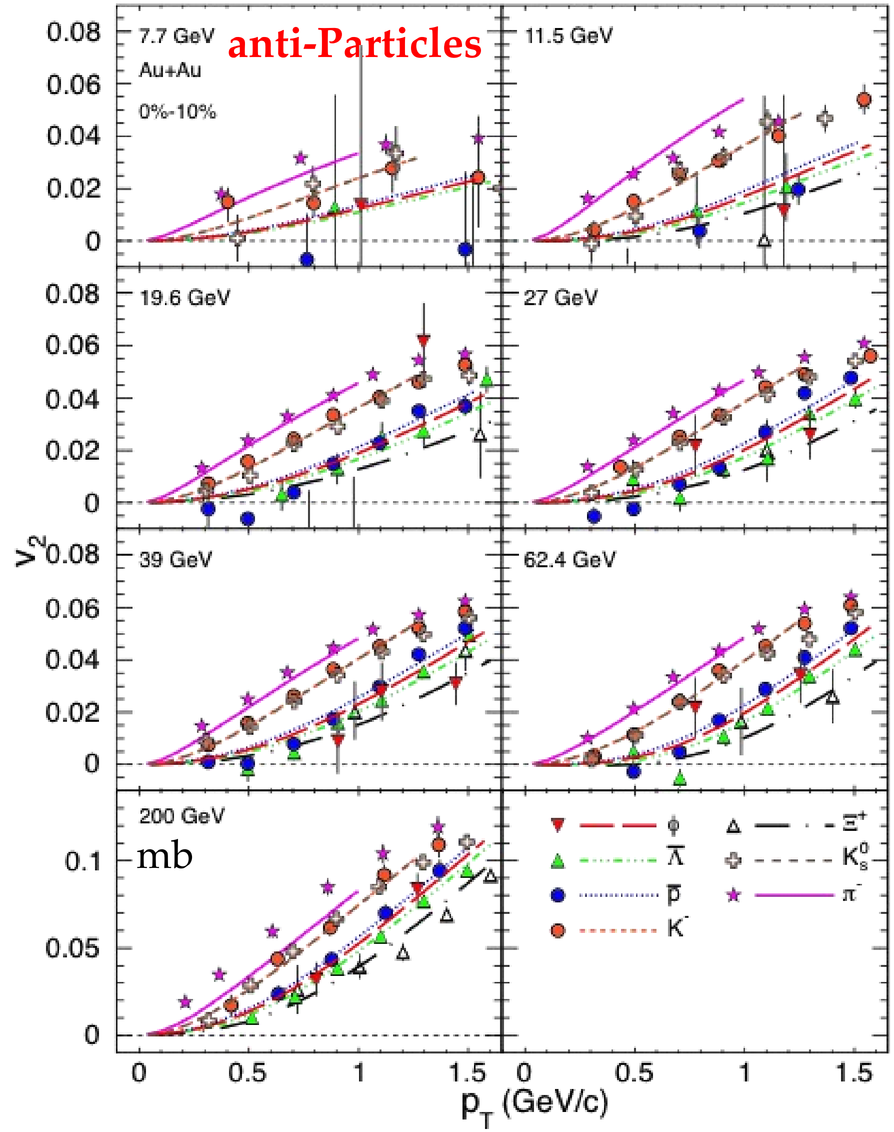


Nucl.Phys.A757:102-183,2005

- Apparently not the phi mesons are different, the pions seem to be off
  → dominated by Delta decays

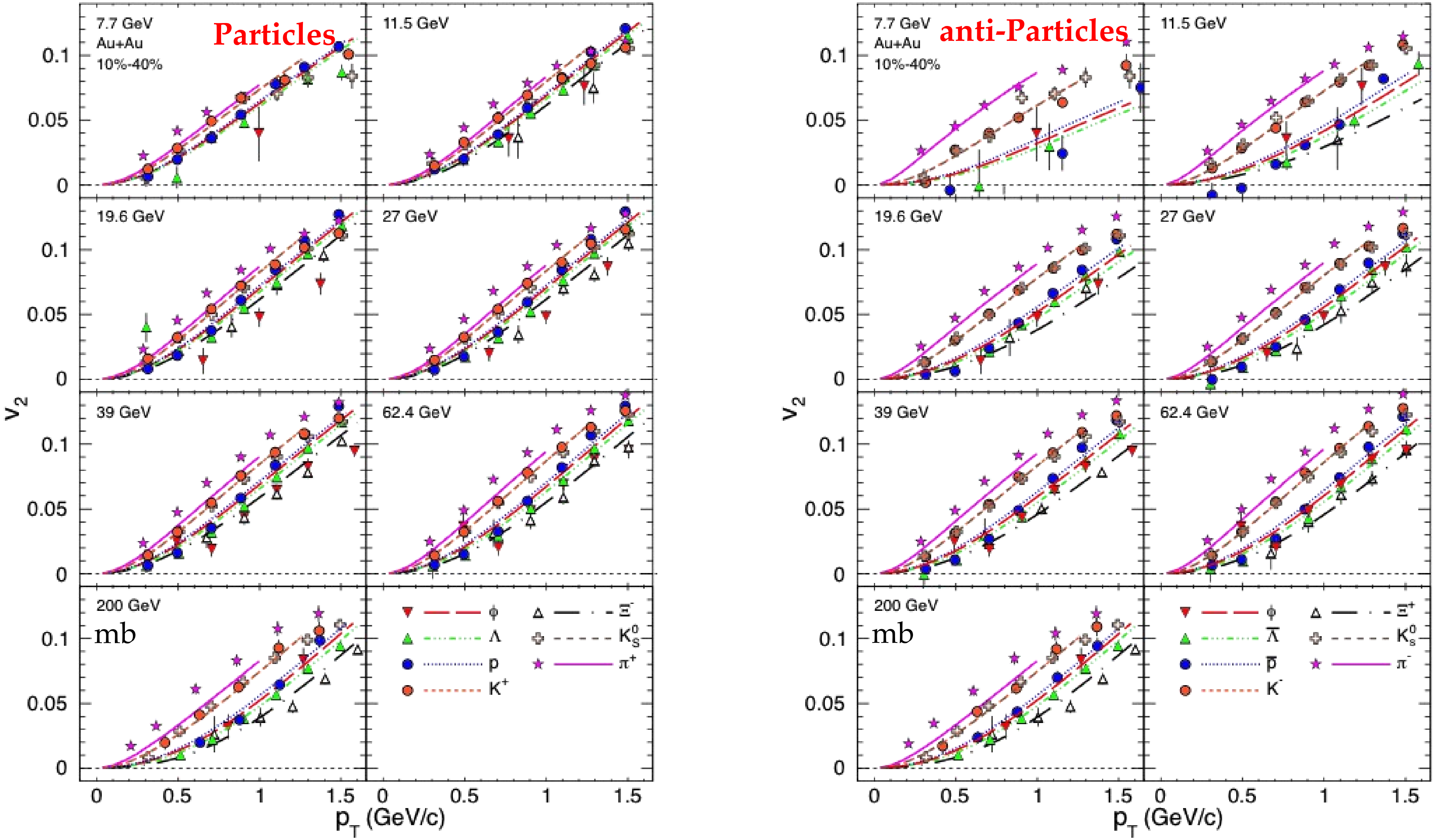
Blast Wave Fits for v_2 vs. p_T: 0%-10%





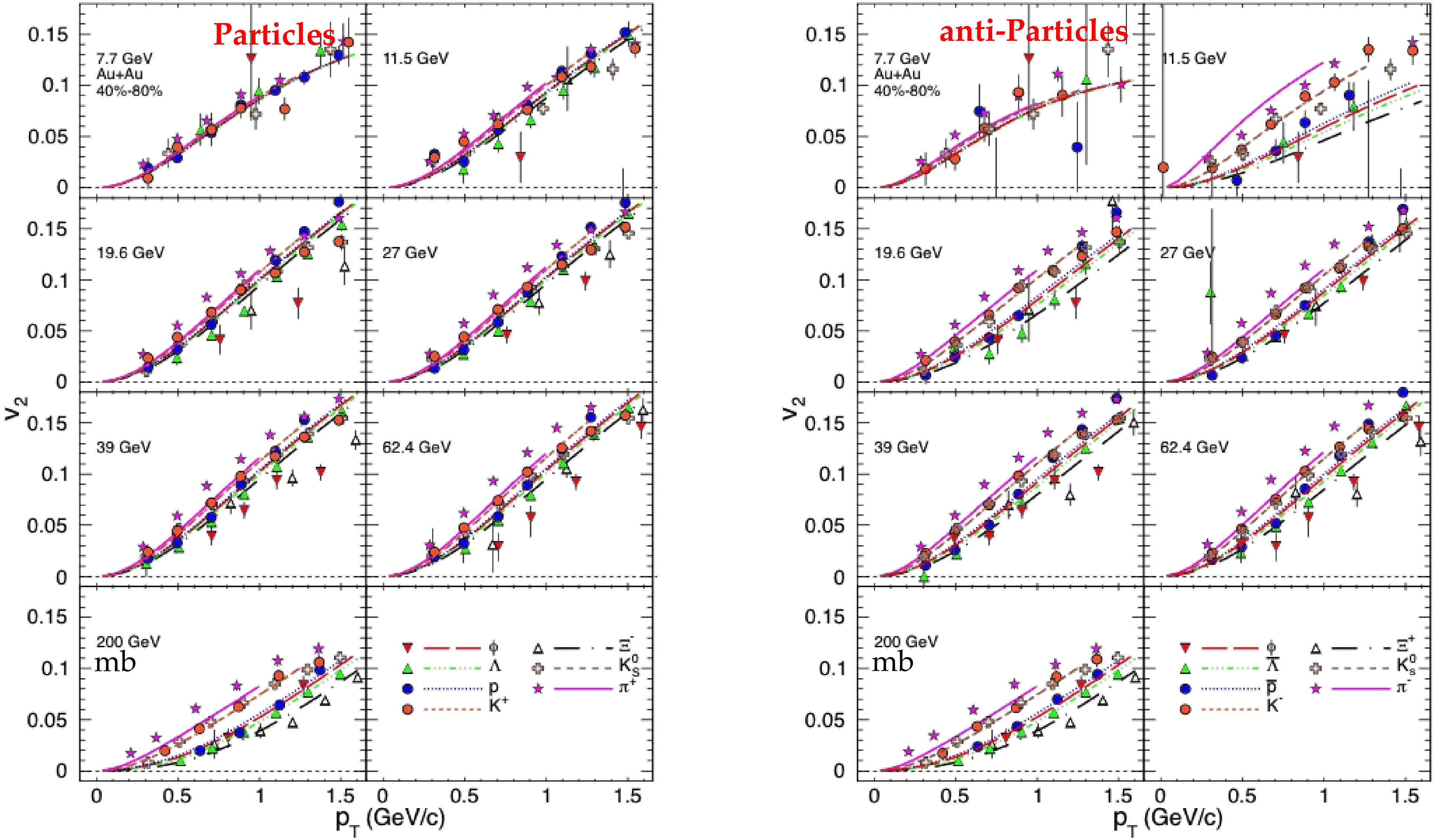
- Mass ordering well described by blast wave fits

Blast Wave Fits for v_2 vs. p_T: 10%-40%



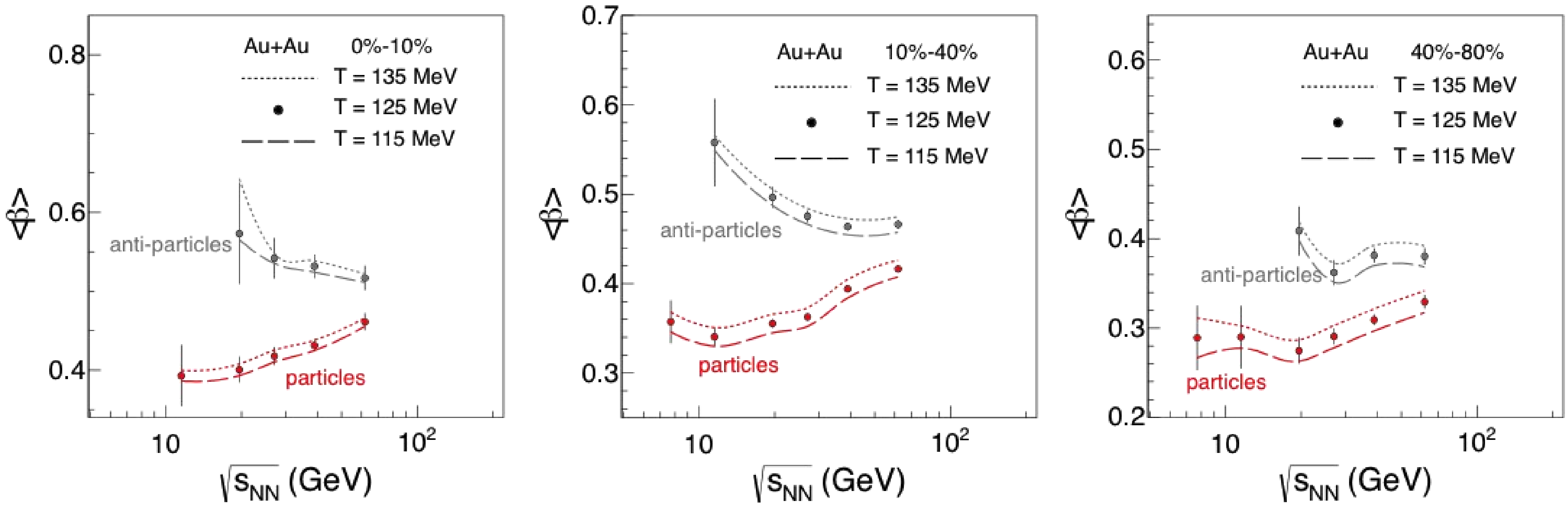
- Pions (not included in fit) are significantly off
- ϕ mesons are off for particles (lower energies) but not for anti-particles

Blast Wave Fits for v_2 vs. p_T: 40%-80%



- Pions (not included in fit) are significantly off
- ϕ mesons are off for particles but not for anti-particles

Blast Wave <β> vs. $\sqrt{s_{NN}}$



- Significant difference between particle and anti-particle <β> vs. $\sqrt{s_{NN}}$
- Larger <β> for higher centralities → **higher energy density?**
- <β> starts to merge at higher energies → **mainly produced particles**
- <β> decreases with increasing $\sqrt{s_{NN}}$ for anti-particles, opposite trend for particles
- Simultaneous fit with spectra in the future

Summary and Outlook

Beam Energy Scan

- High quality data at energies between 7.7 and 62.4 GeV
  → di-lepton spectra, R_{AA}, net-protons, flow,...
- No conclusive picture about phase transition

Elliptic flow

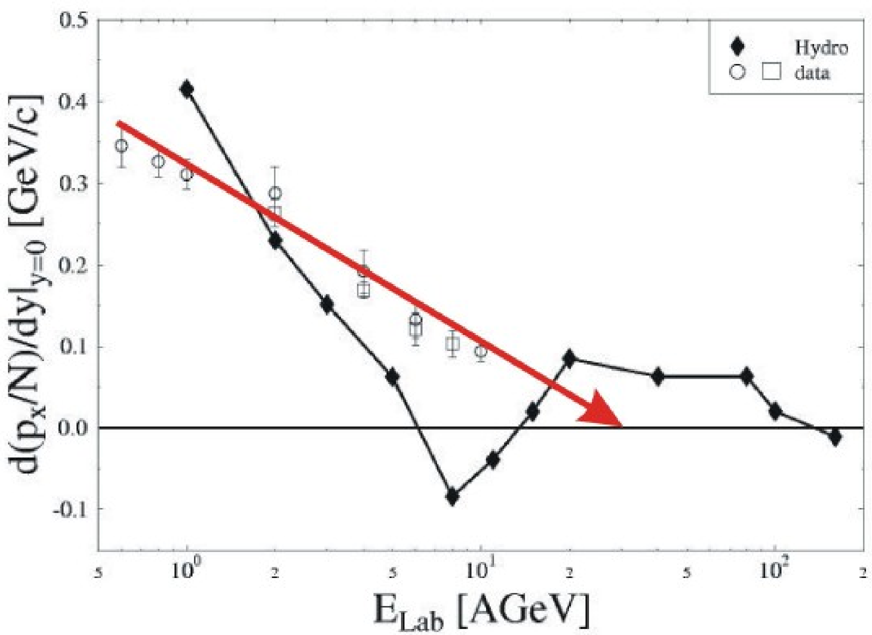
- Difference in v_2 between particles and anti-particles observed
  → NCQ scaling between particles and anti-particles is broken
  but holds for particles and anti-particles separately!
- Δv_2 is increasing with muB → transported quarks?
- Blast wave model can fit anti-particle v_2 data at all energies
  → multi-strange hadrons do not deviate

Outlook

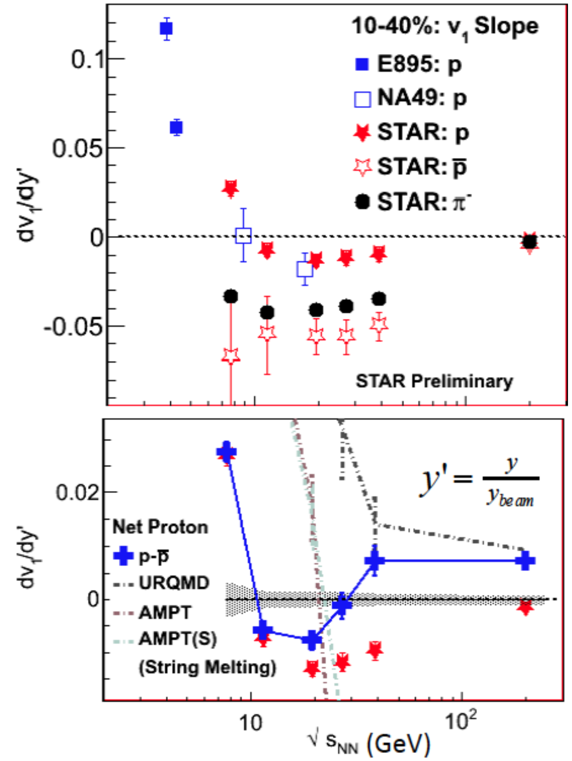
- Much more statistics in the interesting energy region (BES II)
  → precise and differential measurements of observables possible
- Lower energy data points with fixed target reactions
  → initial system not in QGP anymore?


Thanks!

Directed Flow (v_1)



H. Stoecker, Nucl. Phys. A 750 (2005)



- A non-monotonic behaviour of net proton v_1 slope is observed
- UrQMD and AMPT cannot explain even the sign of the net proton data
- Need more input from theory and more statistics to accurately measure centrality dependence to fully understand underlying physics

Blast Wave Equations

$$\frac{dN}{p_T dp_T} \sim \int_0^{2\pi} d\phi_s \int_0^R r dr m_T I_0[\alpha_t(r,\phi_s)] K_1[\beta_t(r,\phi_s)][1+2s_2 cos(2\phi_s)]$$

Spectra

$$v_2(p_t) = \frac{\int_0^{2\pi} d\phi_s \int_0^R r dr m_T cos(2\phi_s) I_2[\alpha_t(r,\phi_s)] K_1[\beta_t(r,\phi_s)][1+2s_2 cos(2\phi_s)]}{\int_0^{2\pi} d\phi_s \int_0^R r dr m_T I_0[\alpha_t(r,\phi_s)] K_1[\beta_t(r,\phi_s)][1+2s_2 cos(2\phi_s)]}$$

Elliptic flow

$$\alpha_t(r,\phi_s) = \frac{p_T}{T} sinh[\rho(r,\phi_s)]$$

mass enters here

$$\beta_t(r,\phi_s) = \frac{m_T}{T} cosh[\rho(r,\phi_s)]$$

$$\rho(r,\phi_s) = tanh^{-1}[\beta_0 \frac{r}{R}] + tanh^{-1}[\beta_a \frac{r}{R}] cos2\phi_s$$

$$\beta_0 = tanh\rho_0$$

$$\beta_a = tanh\rho_a$$

Phys. Lett. B. 503 (2001) 58–64
Phys. Rev. C. 48. (1993) 2462

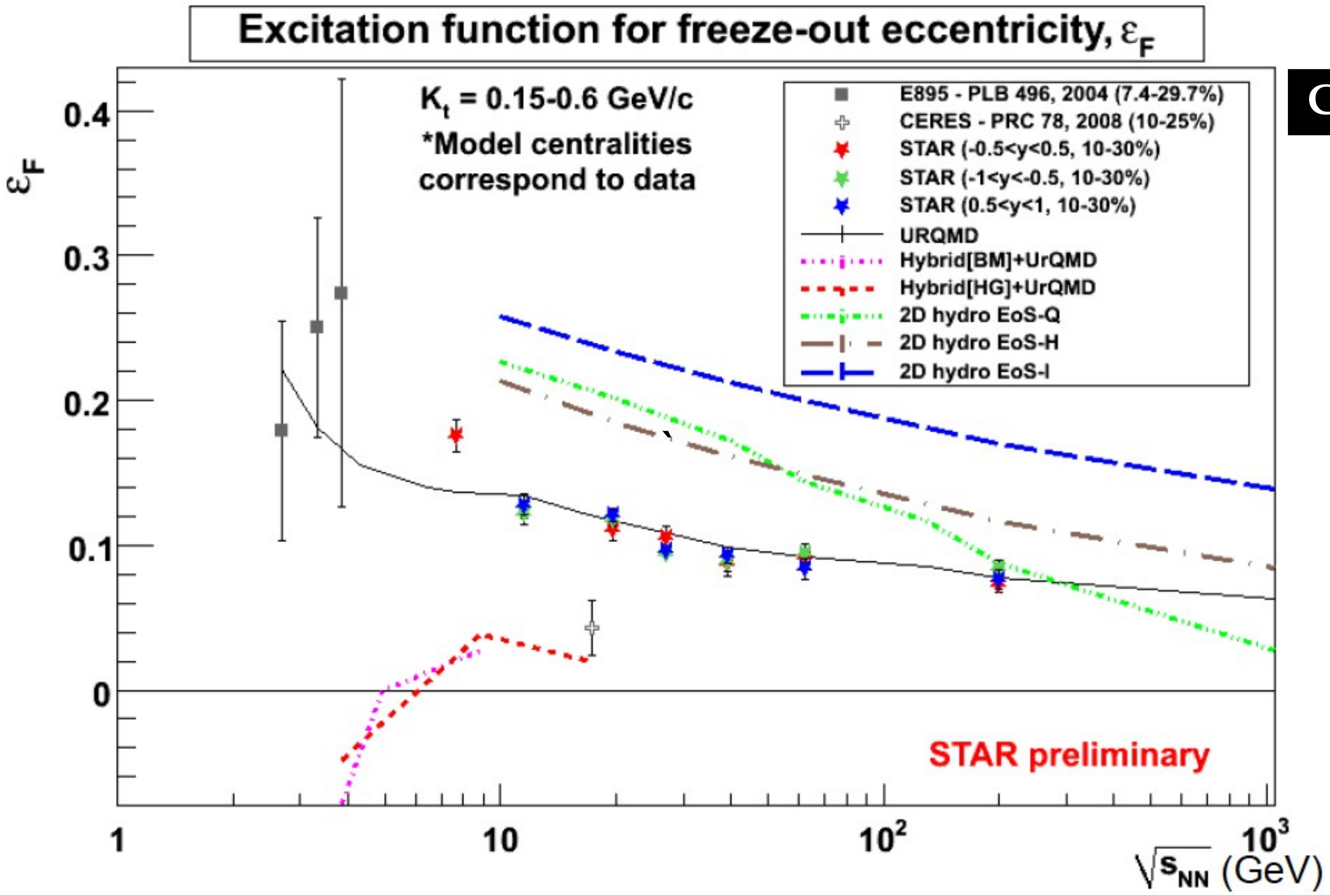
<u>Fit Parameters:</u>

- T – kinetic freeze-out temperature
- ρ_0 – surface transverse expansion rapidity
- ρ_a – the momentum space variation in the azimuthal density
- s_2 – the coordinate space variation in the azimuthal density
- R – maximum freeze-out radius
- Mass parameter as external input

<u>For v_2 fits:</u>

- T fixed to 135 MeV, varied +/- 10 MeV
- Pions excluded from fit (dominated by Δ decays at low p_T)
- Only low p_T fitted, higher p_T → NCQ scaling

Azimuthal HBT for Freeze-out Eccentricity

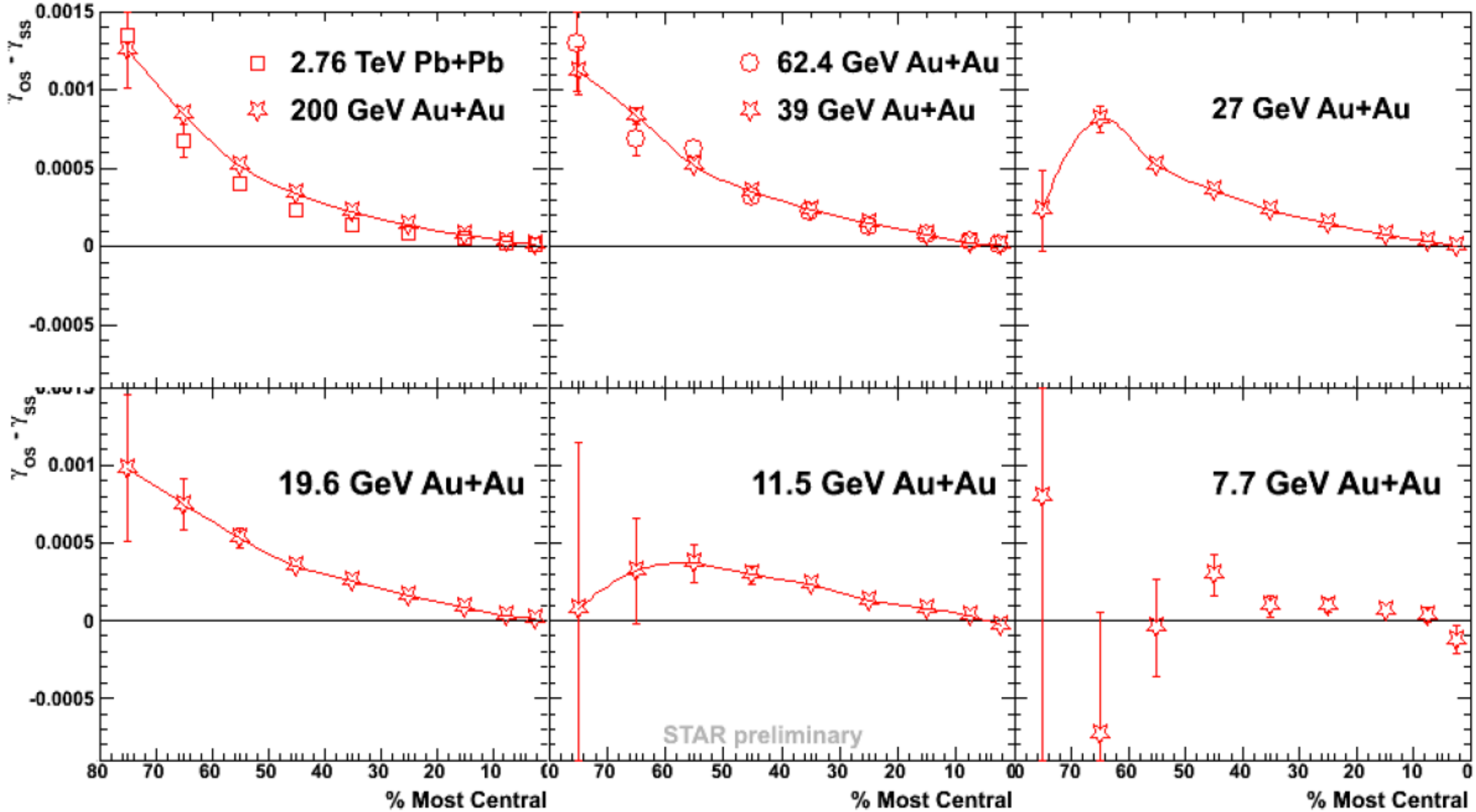


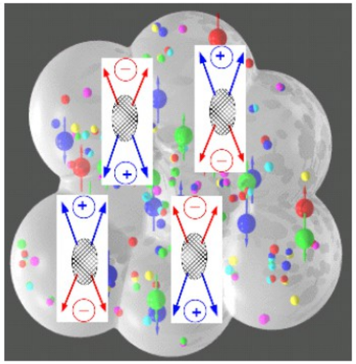
Christopher Anson

- Evolution of the initial shape depends on the pressure anisotropy
- Freeze-out eccentricity sensitive to the 1st order phase transition
- Measured freeze-out eccentricity parameters show a smooth decrease from low to high energies

Define $\gamma_{OS} - \gamma_{SS}$ as the Signal

$$\gamma = \langle \cos(\phi_\alpha + \phi_\beta - \Psi_{RP}) \rangle$$

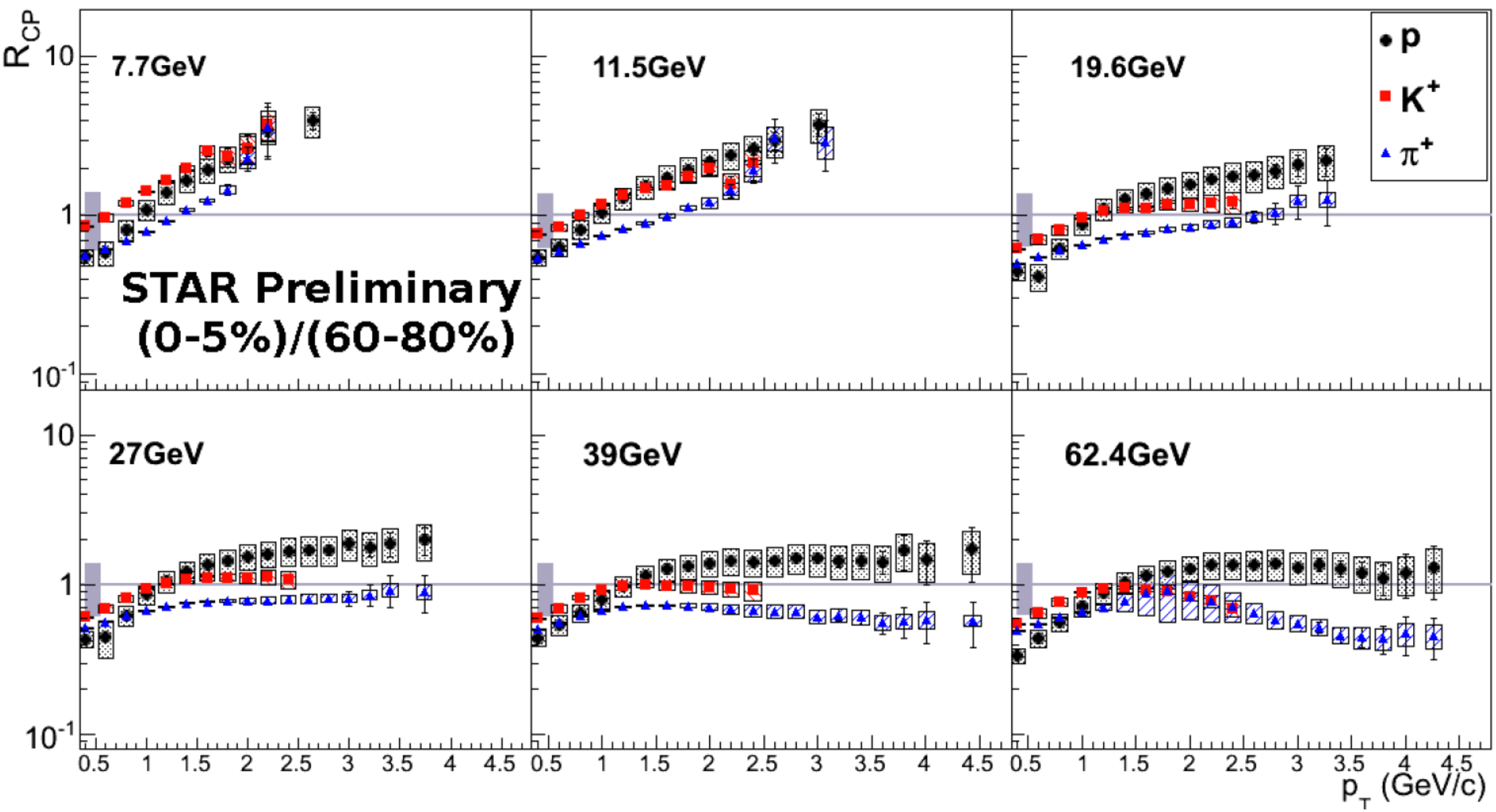




Local Parity Violation (LPV)

- Significant difference between OS and SS at higher energies
- **Signal almost identical to 0 at 7.7 GeV**

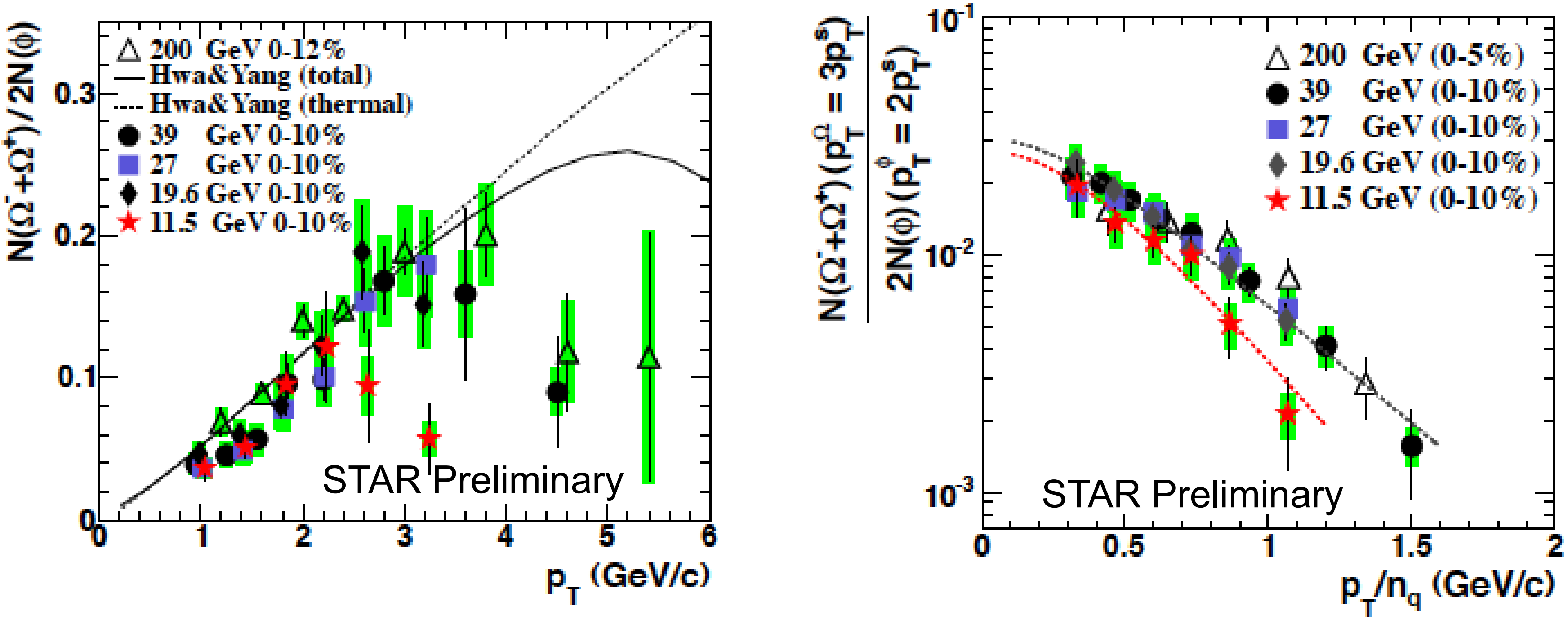
R_{CP} of Identified Charged Hadrons



- High p_T suppression of π and K at 39 and 62.4 GeV
- No suppression for protons at any energy
- Suppression decreases/disappears to lower energies

→ Disappearance of QGP signature

Strange Quark Dynamics

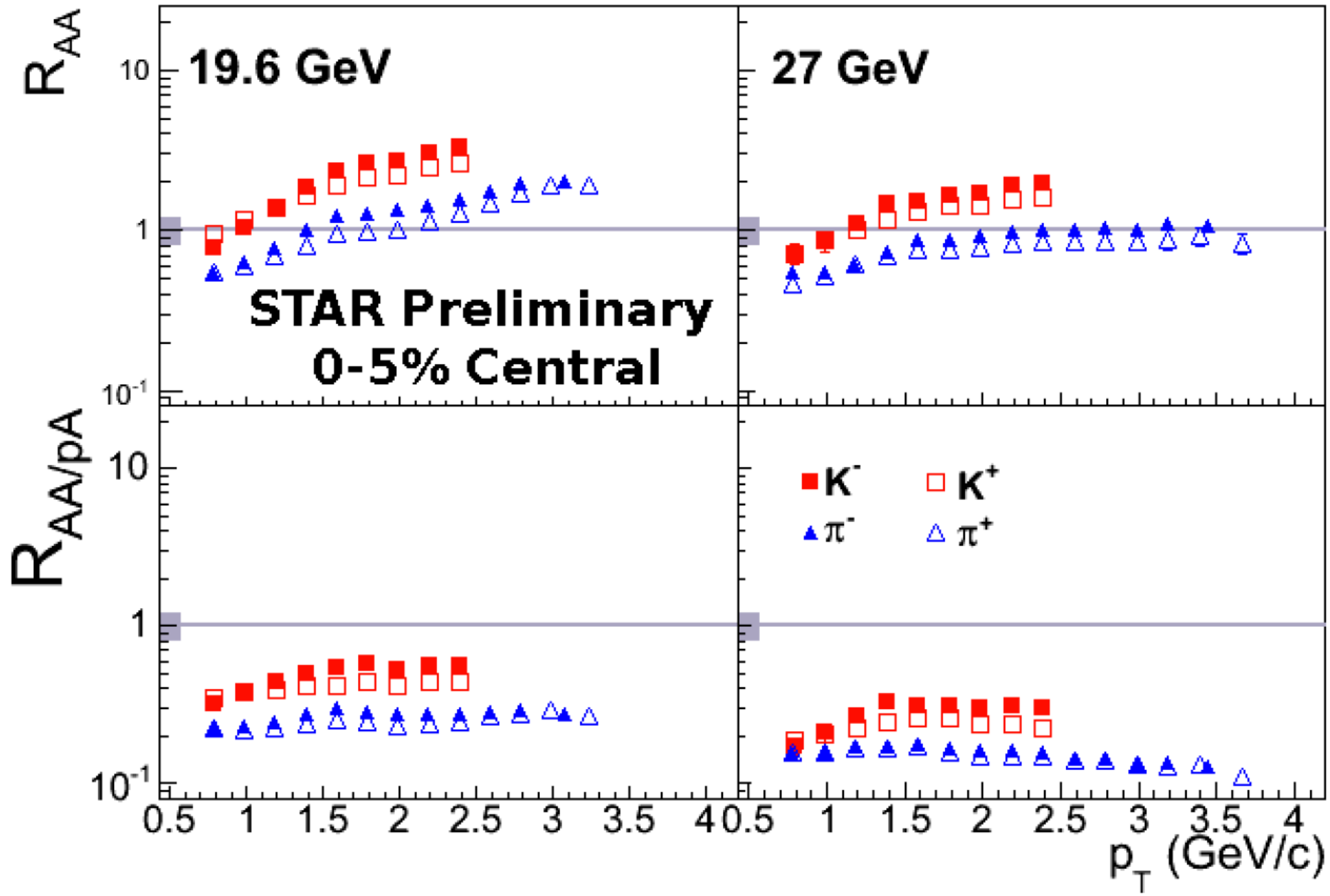


- Intermediate p_T Ω/ϕ ratios: Indication of separation between ≥ 19.6 and 11.5 GeV

- Derived strange quark p_T distributions show a trend of separation between ≥ 19.6 and 11.5 GeV.

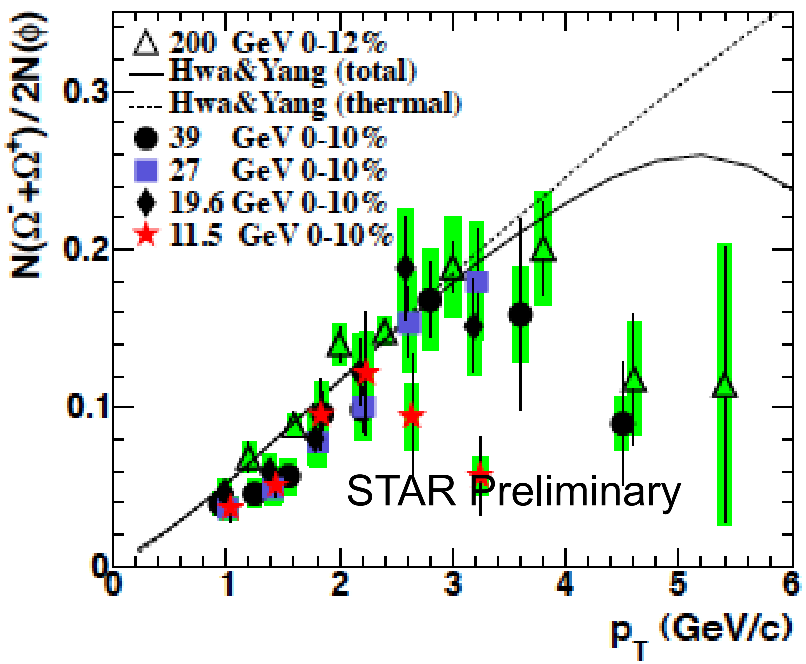
→ **Change of Ω production mechanism ? Parton recombination fails at 11.5 GeV?**

The Role of Cronin for R_{AA}



- Cronin effect changes the slope of R_{AA}
  → **The rise with p_T is eventually not related to energy loss, or the lack of energy loss in the medium**

Strange Quark Dynamics



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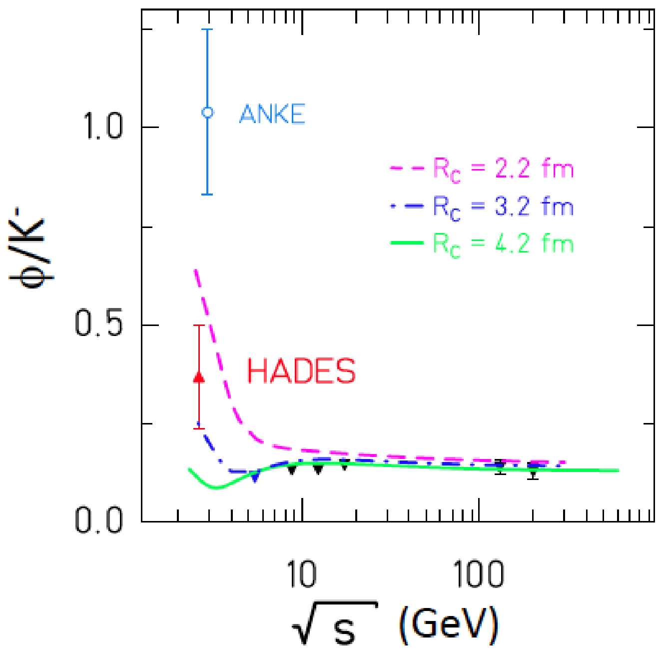
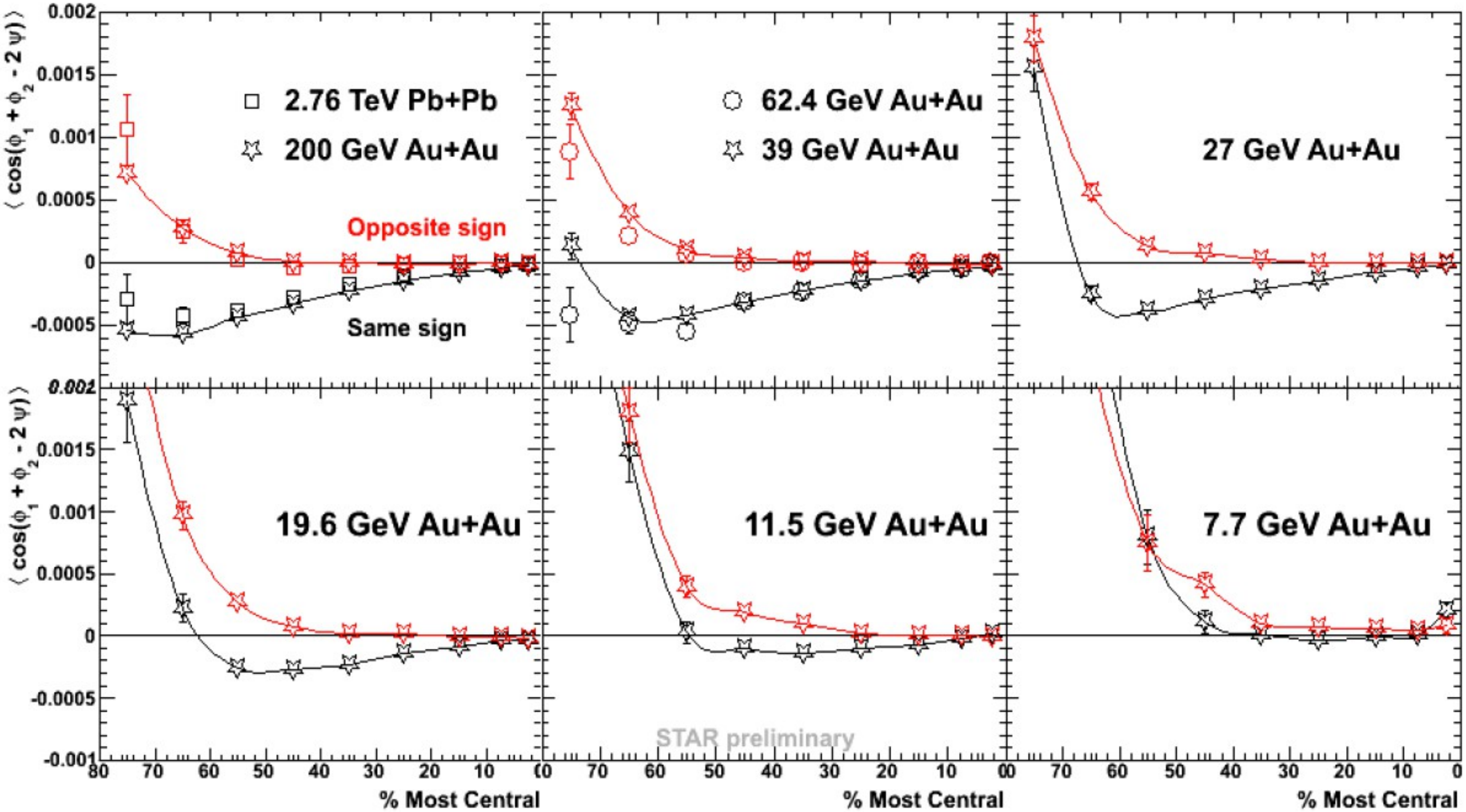


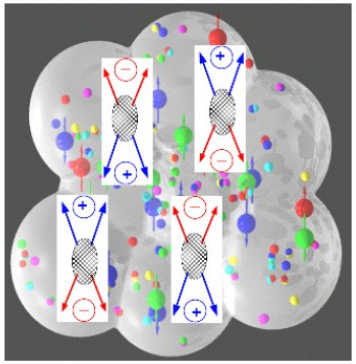
- Similar effects observed at other experiments

→ **canonical suppression of strangeness at lower energies?**

γ_{OS} and γ_{SS} in Beam Energy Scan

$$\gamma = \langle \cos(\phi_\alpha + \phi_\beta - \Psi_{RP}) \rangle$$





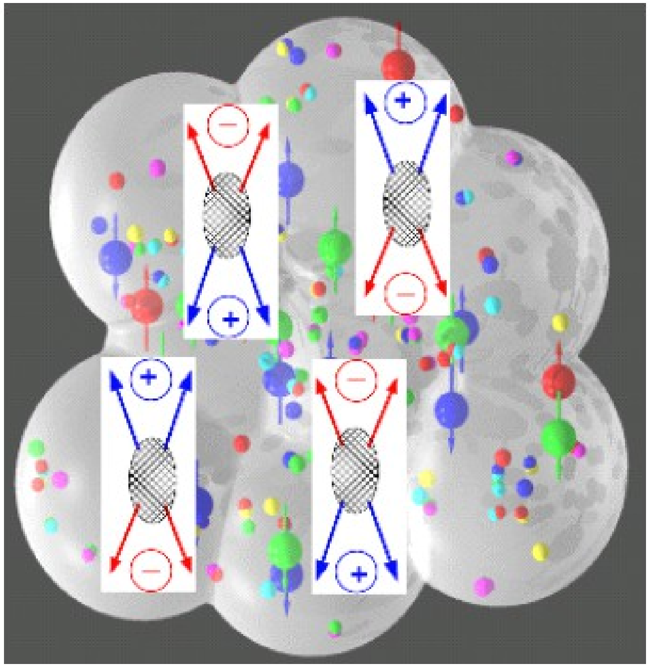
Local Parity Violation (LPV)

- Opposite sign (OS) is positive for all energies, increase with decreasing centrality
- Same sign (SS) is negative for higher energies, almost identical with OS at 7.7 GeV

Chiral Magnetic Effect

- Charge particle azimuthal angle distribution
  - $\frac{dN_\alpha}{d\phi} \propto 1 + 2v_{1,\alpha}\cos(\Delta\phi) + 2v_{2,\alpha}\cos(2\Delta\phi) + \cdots$

    $+ 2a_{1,\alpha}\sin(\Delta\phi) + 2a_{2,\alpha}\sin(2\Delta\phi) + \cdots$
  - Correlations $\langle a_\alpha a_\beta \rangle$ can be measured
  - $\alpha, \beta = +, -$



- Three-particle correlation
  - $\gamma = \langle \cos(\phi_\alpha + \phi_\beta - \Psi_{RP}) \rangle$

    $= [\langle v_{1,\alpha} v_{1,\beta} \rangle + B_{in}] - [\langle a_\alpha a_\beta \rangle + B_{out}]$
  - Direct flow term $\langle v_{1,\alpha} v_{1,\beta} \rangle$ is small and expected to be the same of SS and OS
  - In plane (B_{in}) and out-of-plane (B_{out}) correlations largely cancel out
  - $\langle a_\alpha a_\beta \rangle$ is sensitive to charge separation

$$\gamma_{os} > 0, \alpha \neq \beta$$

$$\gamma_{ss} < 0, \alpha = \beta$$

S. A. Voloshin, Parity violation in hot qcd: How to detect it, Phys. Rev. C **70**, 057901 (2004)