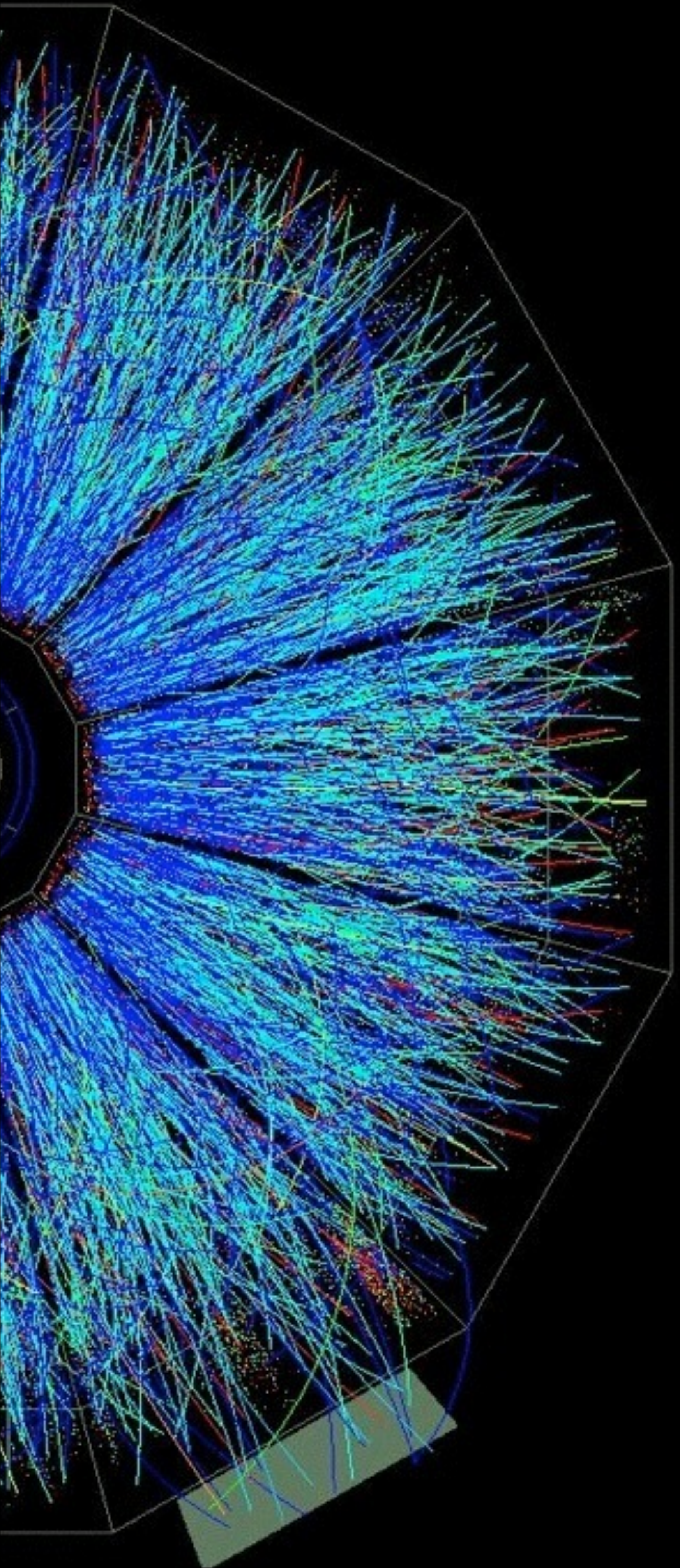


RHIC Beam Energy Scan @ STAR

Hiroshi Masui,
University of Tsukuba

HIM2013, Nov/2/2013

Outline

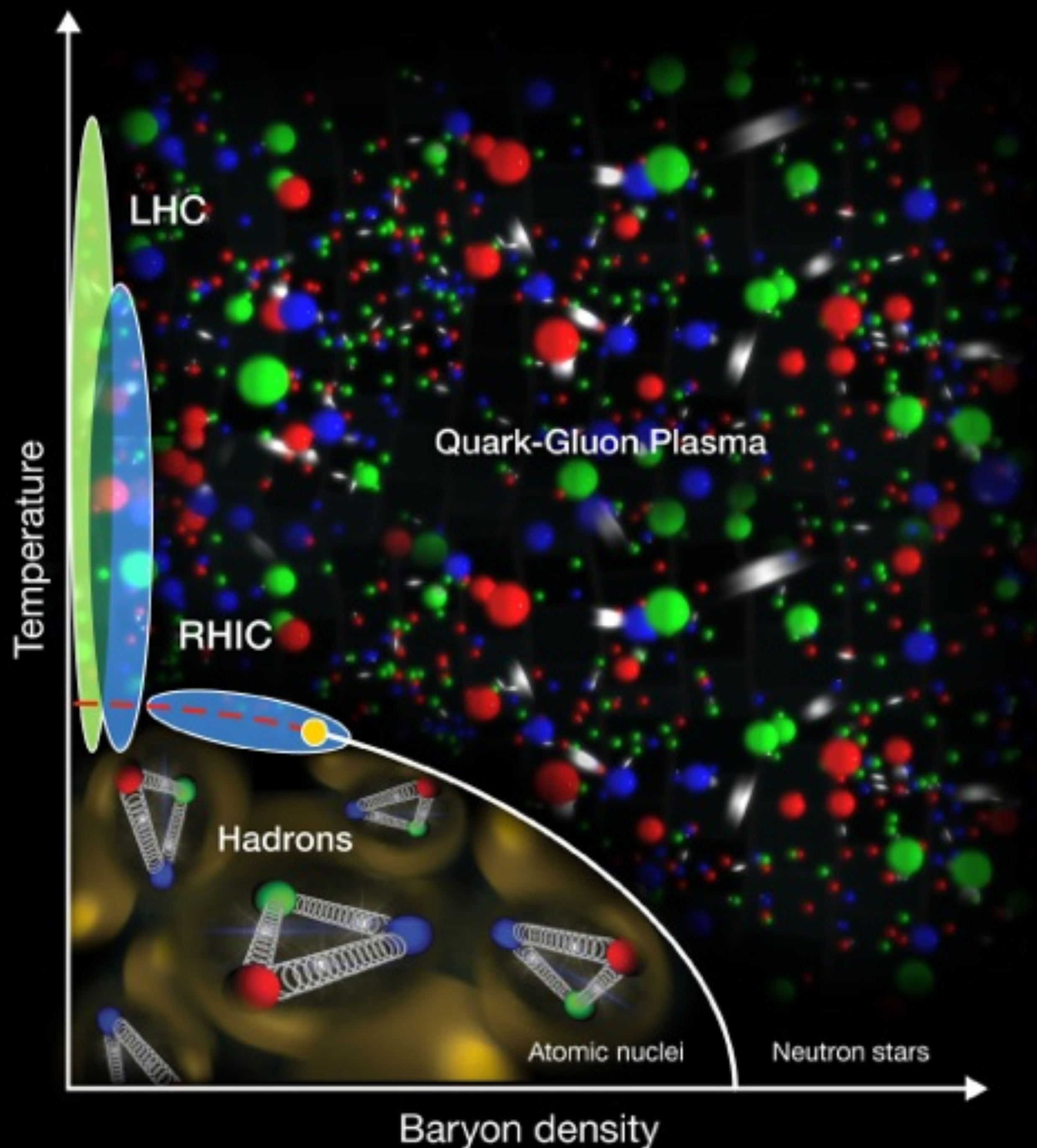
- Beam Energy Scan (BES) program at RHIC
  - Main goals at STAR
  - STAR detectors
- Results

  Step 0: Where are we in the phase diagram ?

  Step 1: Turn-off QGP signals

  Step 2: 1^{st} order phase transition & critical point search
- STAR upgrade plans related to BES Phase-II
  - iTPC, event plane detector (HALO)
- Conclusions

RHIC Beam Energy Scan (BES)

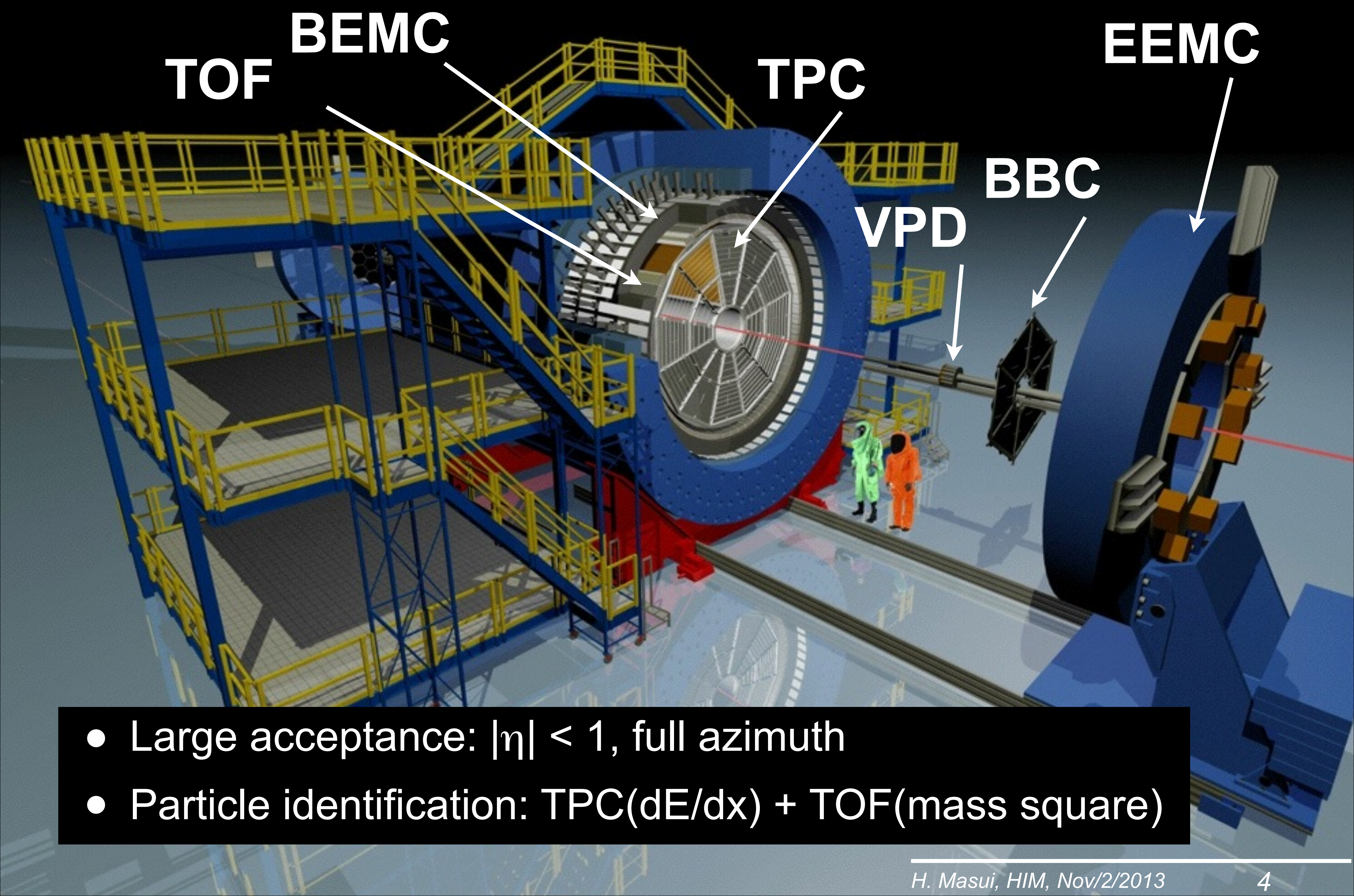


QCD phase diagram from BNL web site
http://www.bnl.gov/bnlweb/pubaf/pr/photos/2012/07/RHIC_Graphics_Fig1-HR.jpg

- 3 main goals
  - turn-off signals of QGP
  - Search for phase boundary
  - Search for QCD critical point

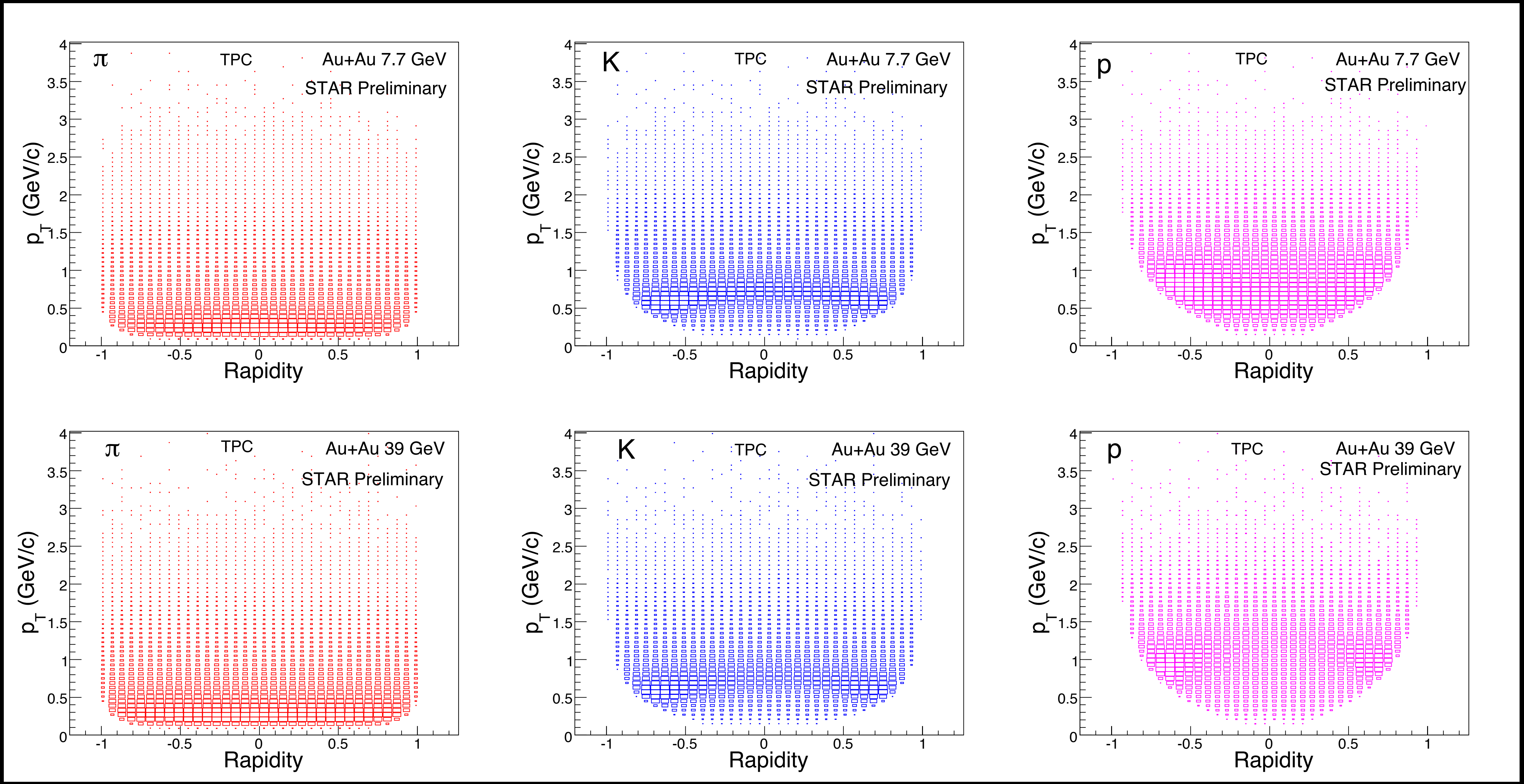
$\sqrt{s_{NN}}$ (GeV)	events (10^6)	year
62.4	67	2010
39	130	2010
27	70	2011
19.6	36	2011
11.5	12	2010
7.7	5	2010
5	-	2012

STAR - Solenoidal Tracker At RHIC



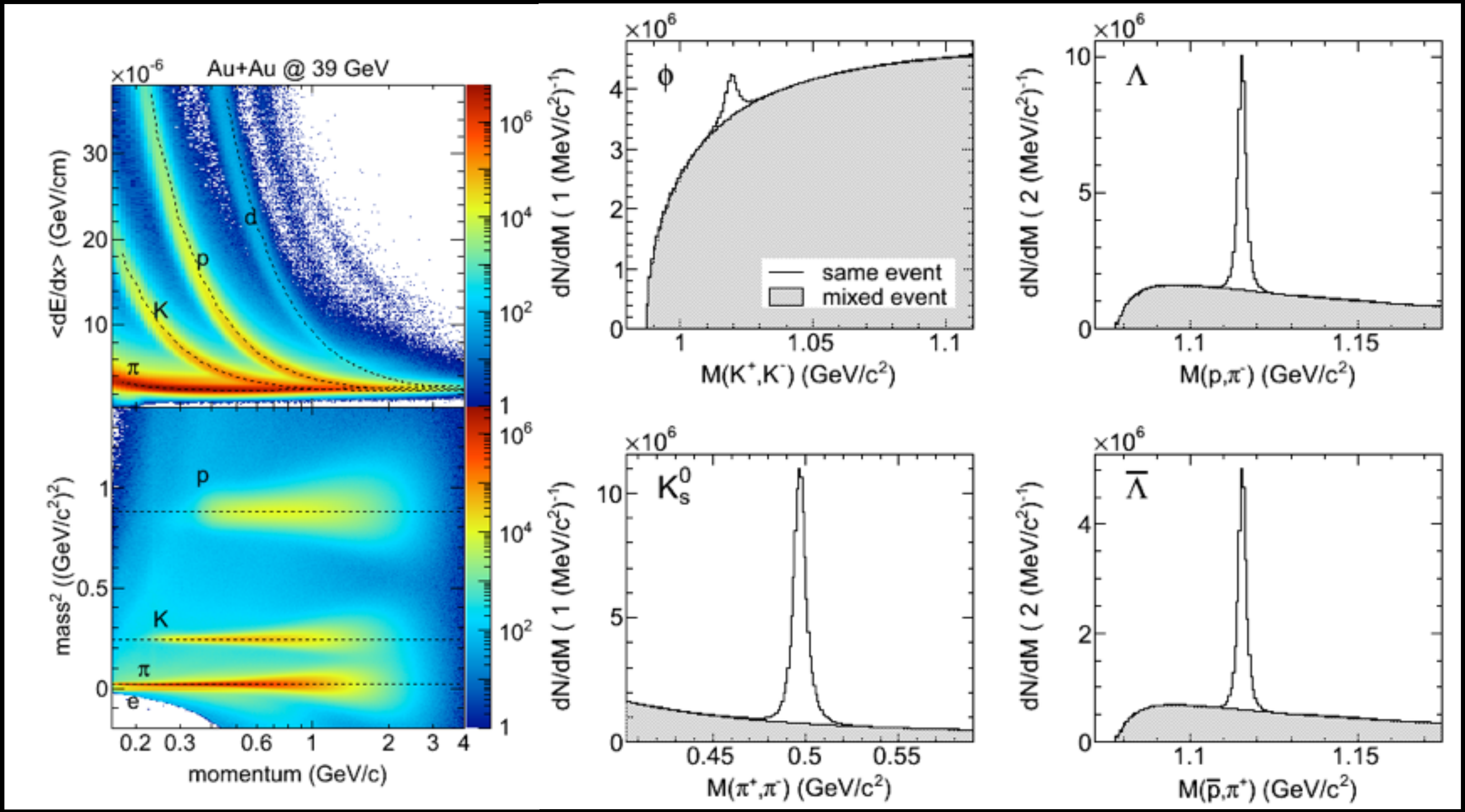
- Large acceptance: $|\eta| < 1$, full azimuth
- Particle identification: TPC(dE/dx) + TOF(mass square)

Acceptance



- Acceptance is collision energy independent (thanks to RHIC)

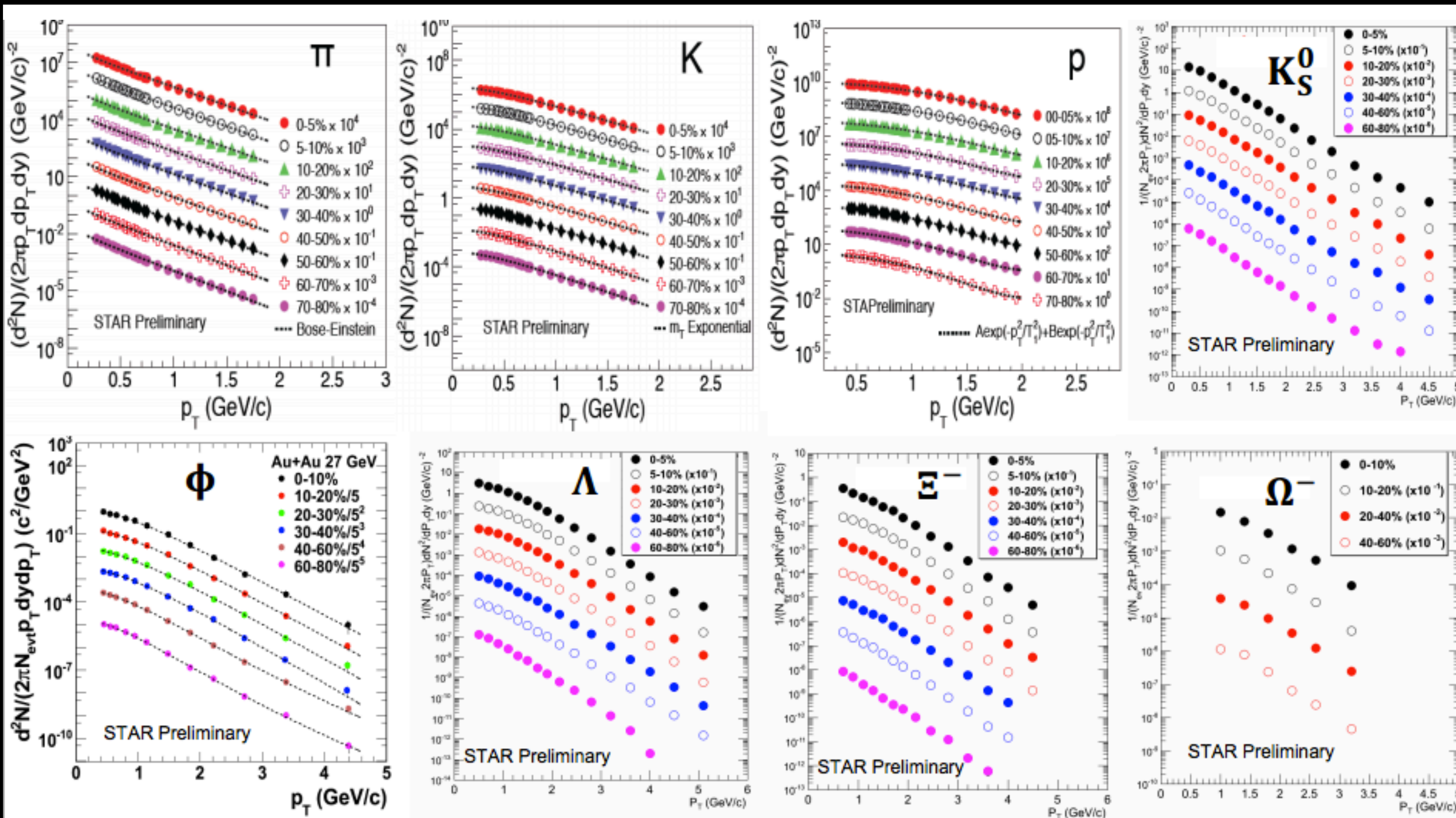
Particle identification



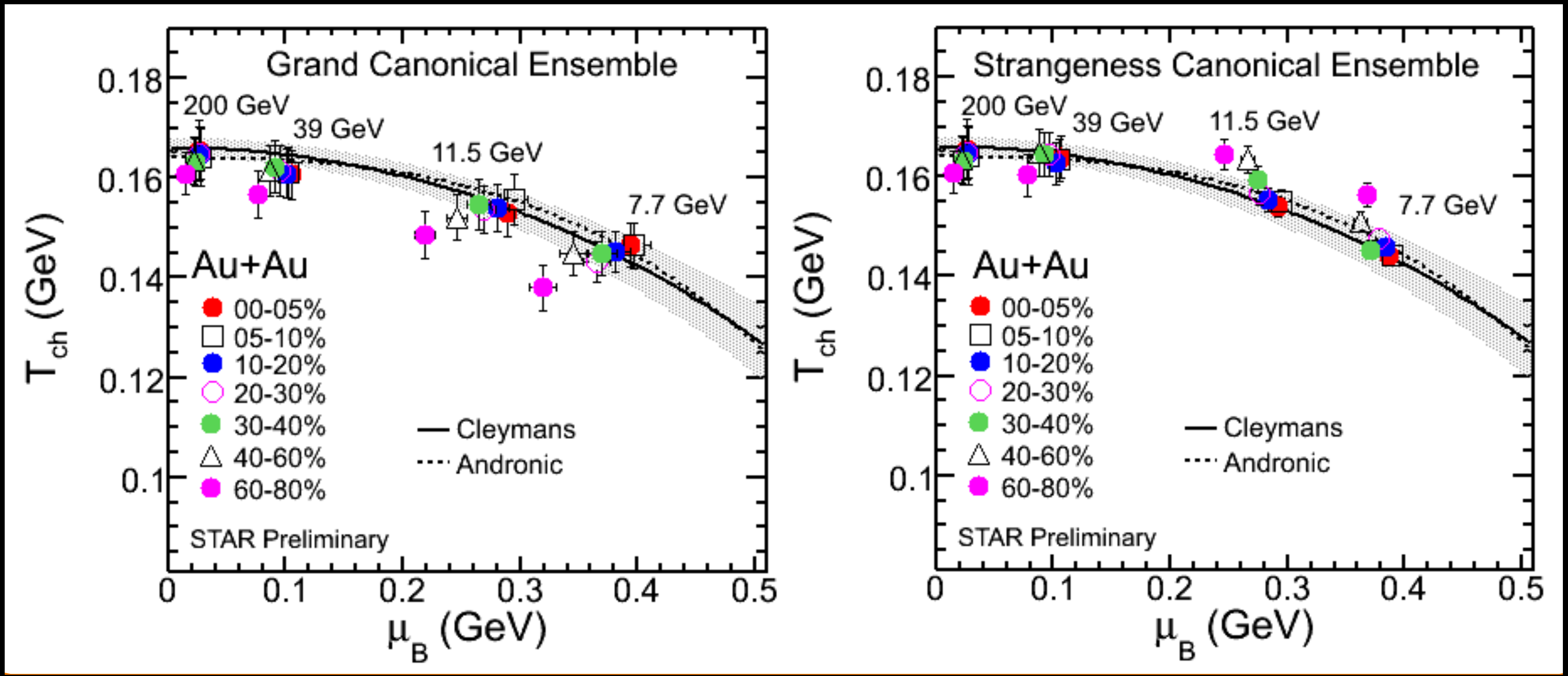
- TPC+TOF: π, K, p and φ
- Topological reconstruction of weak decays

Transverse momentum spectra

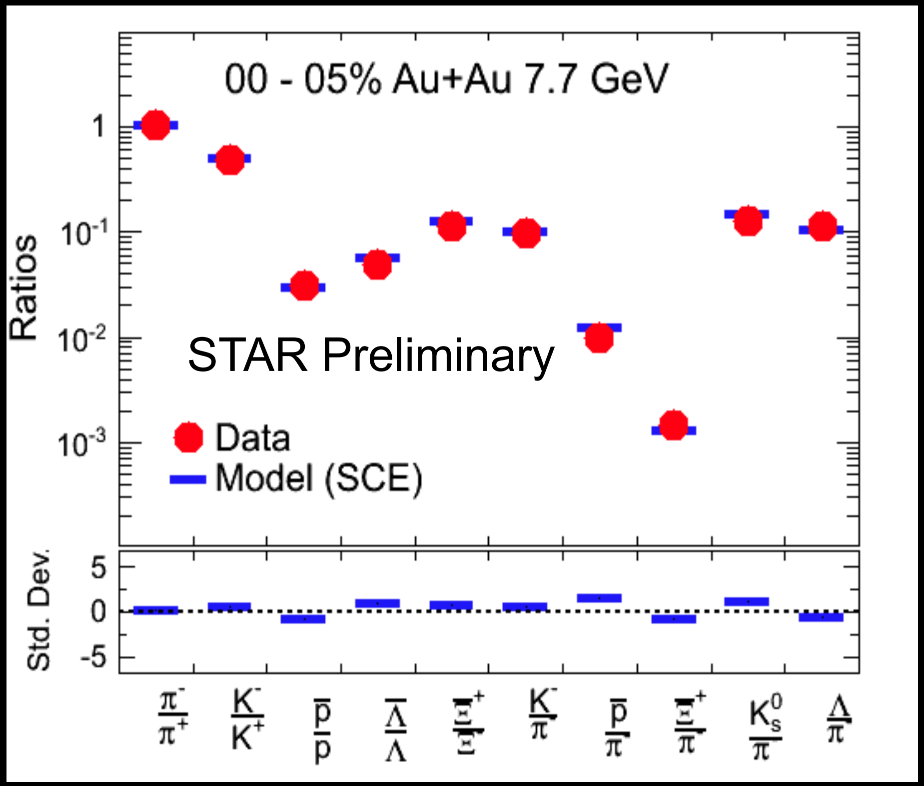
Au+Au at 27 GeV



We are at 100-400 MeV in μ_B

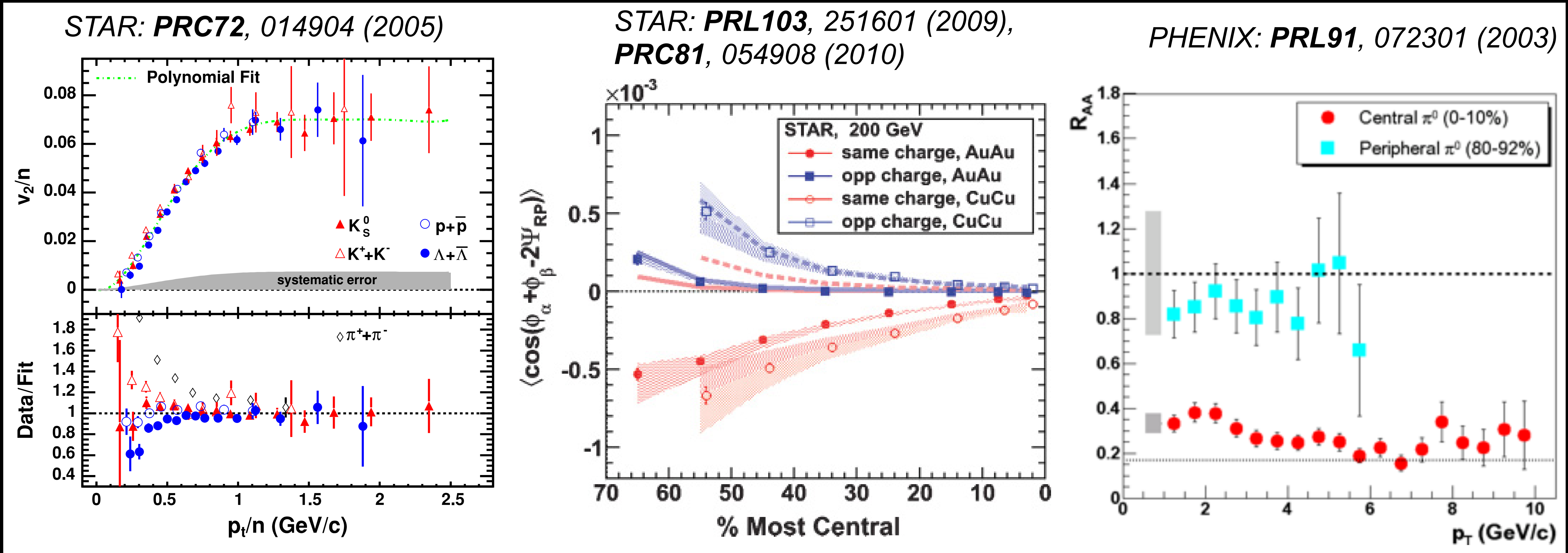


T_{ch}: chemical freeeze-out temperature
μ_B: baryon chemical potential



- Map (T_{ch}, μ_B)
- Fit particle ratio by statistical model
  - Test GCE and SCE ensembles
- BES covers up to ~ 400 MeV in μ_B
- Is QGP gone such high μ_B ?

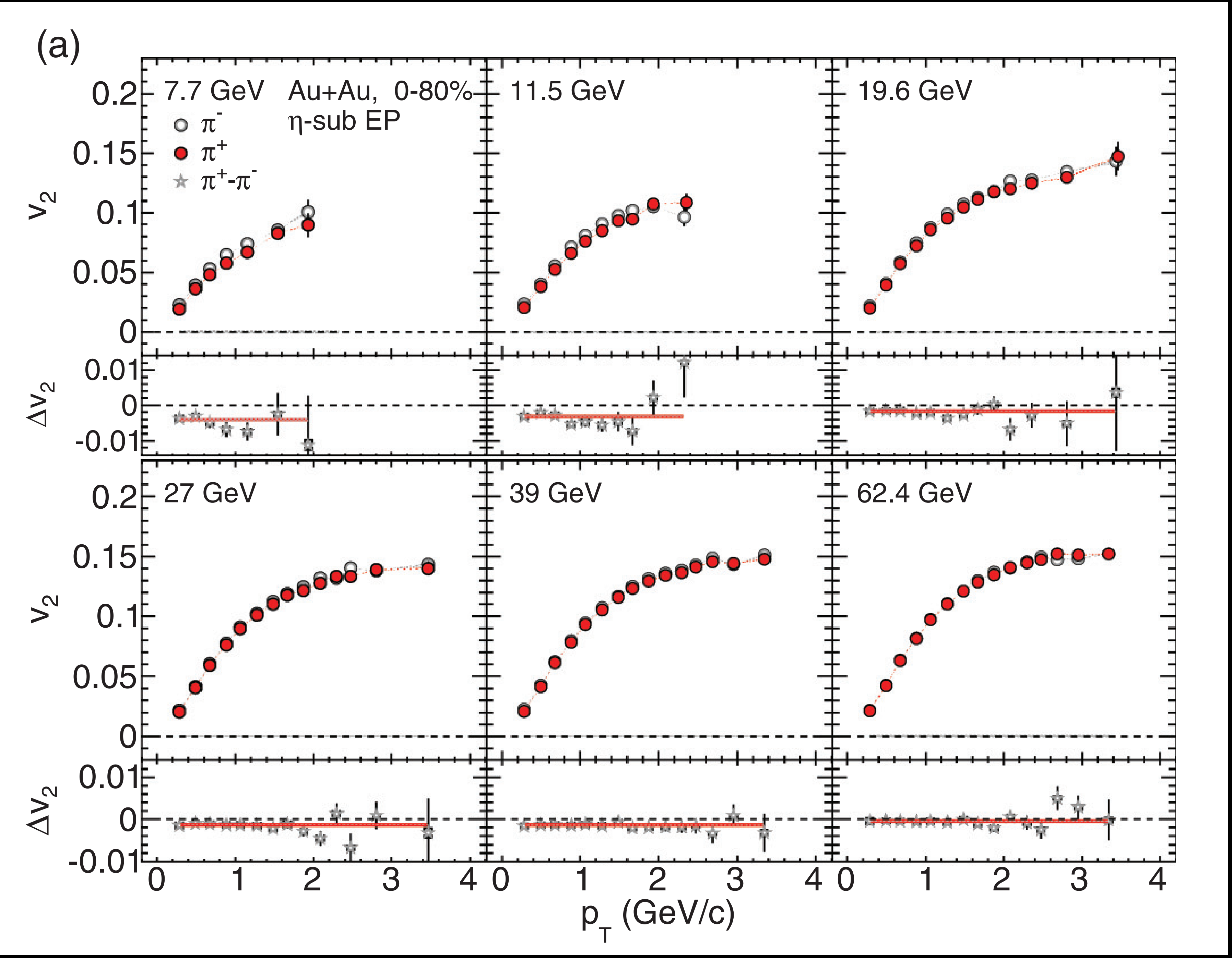
Next step - Turn-off QGP signals



- QGP signals at $\sqrt{s_{NN}}$ = 200 GeV
  - Number of Constituent Quark scaling - deconfinement
  - Charge separation - chiral magnetic effect ?
  - High p_T suppression - parton energy loss
- What happens on these observables if we decrease beam energies ?

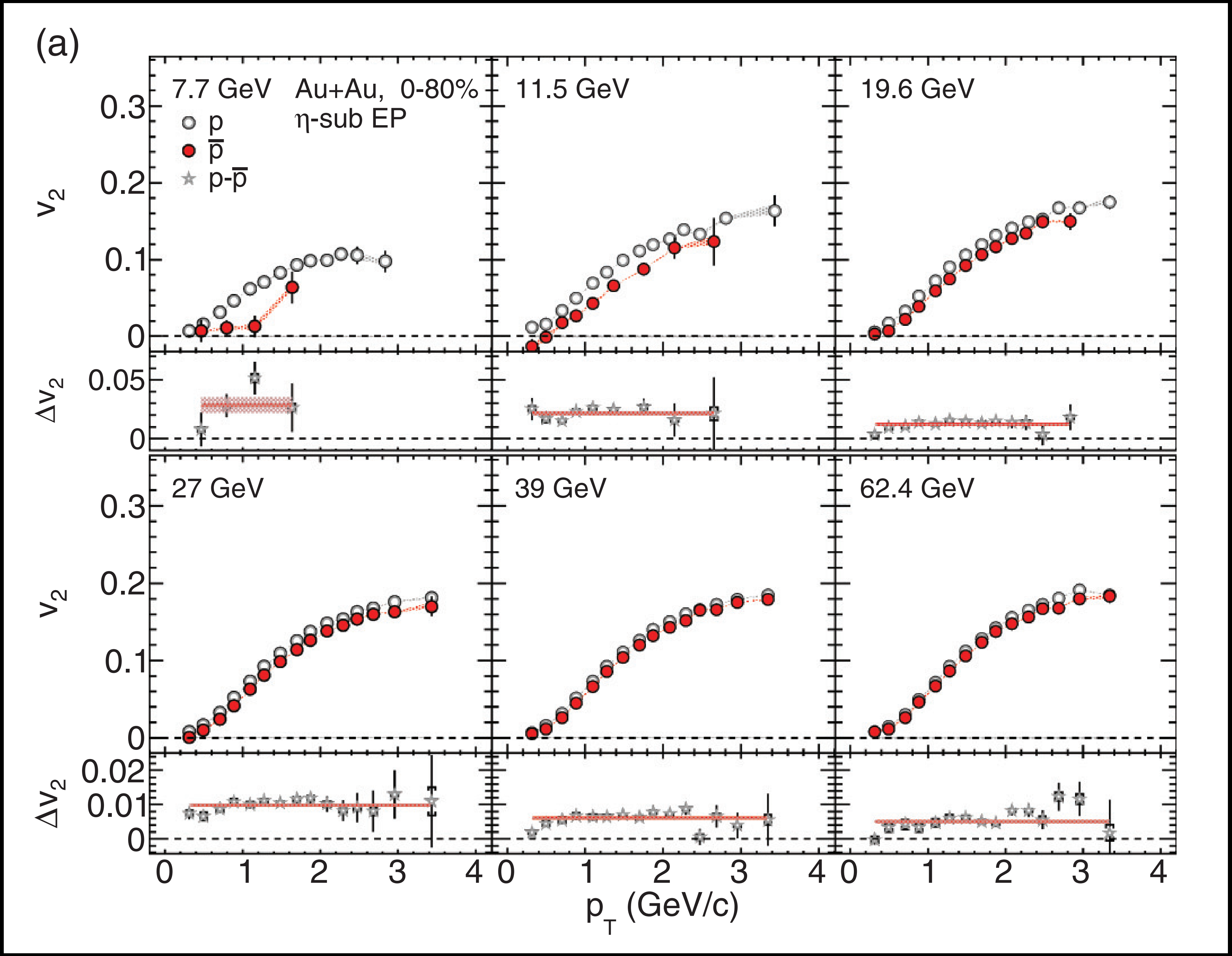
Particle vs anti-particle, mesons

*STAR: **PRC88**, 014902 (2013)*



- No difference between charged pions in high energies
- $v_2(\pi^+) < v_2(\pi^-)$ for all p_T in low energies

Particle vs anti-particle, baryons

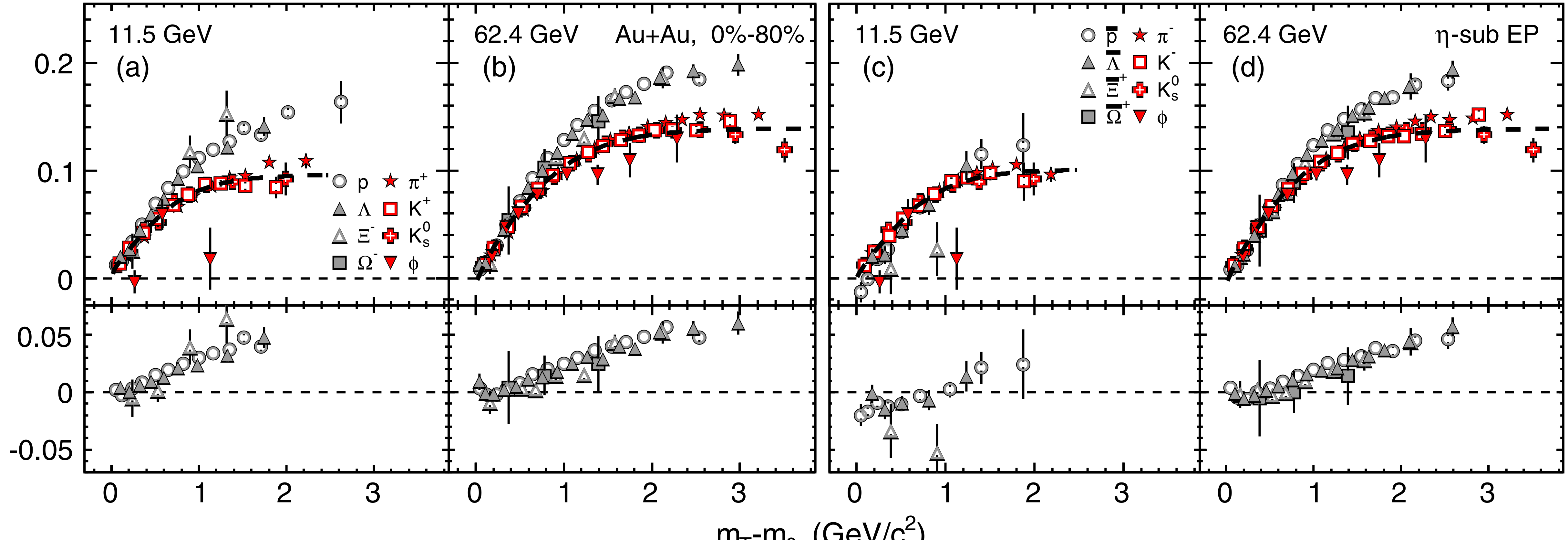


*STAR: **PRC88**, 014902 (2013)*

- $v_2(p) > v_2(\bar{p})$ at 62.4 GeV, difference increases in low energies
- Significant difference of v_2 (~50%) at 7.7 GeV

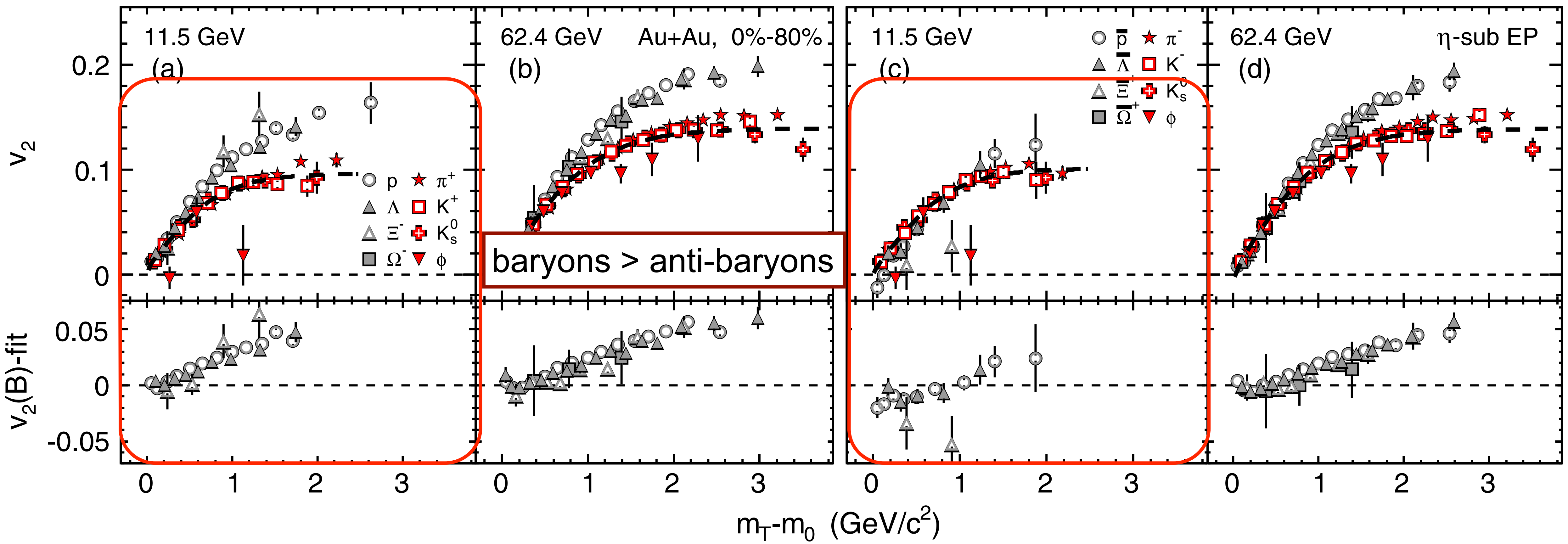
Break down of NCQ scaling

STAR: **PRL110**, 142301 (2013)



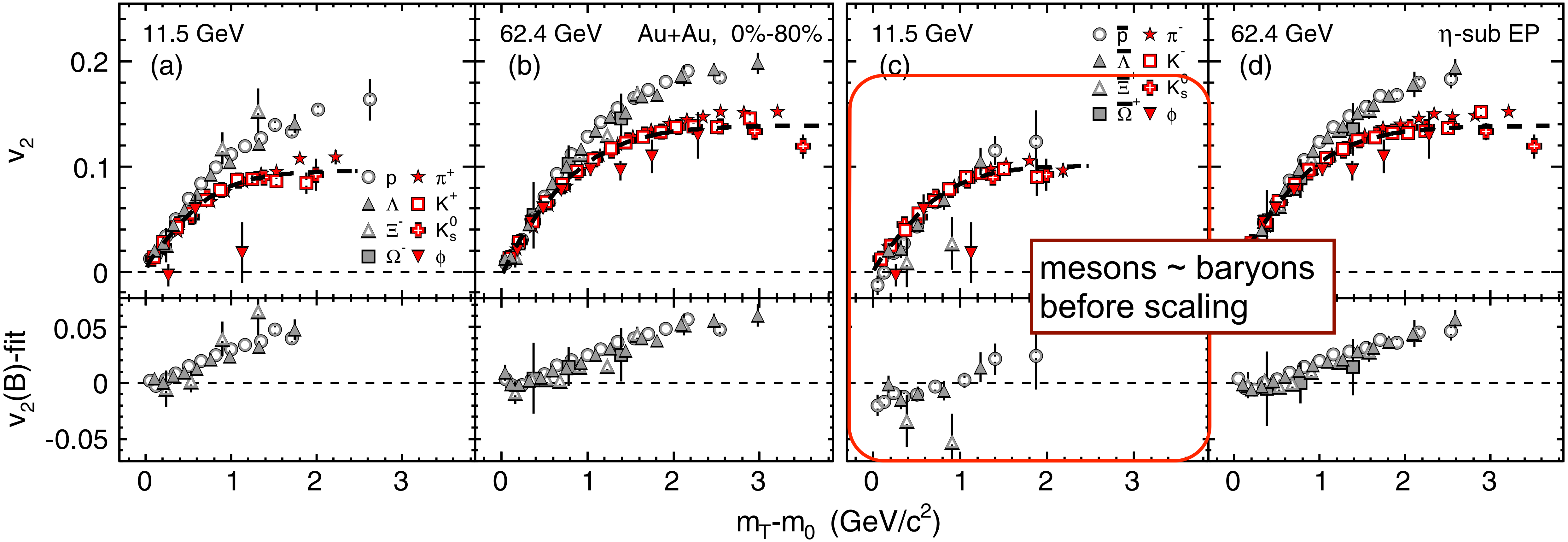
Break down of NCQ scaling

STAR: **PRL110**, 142301 (2013)



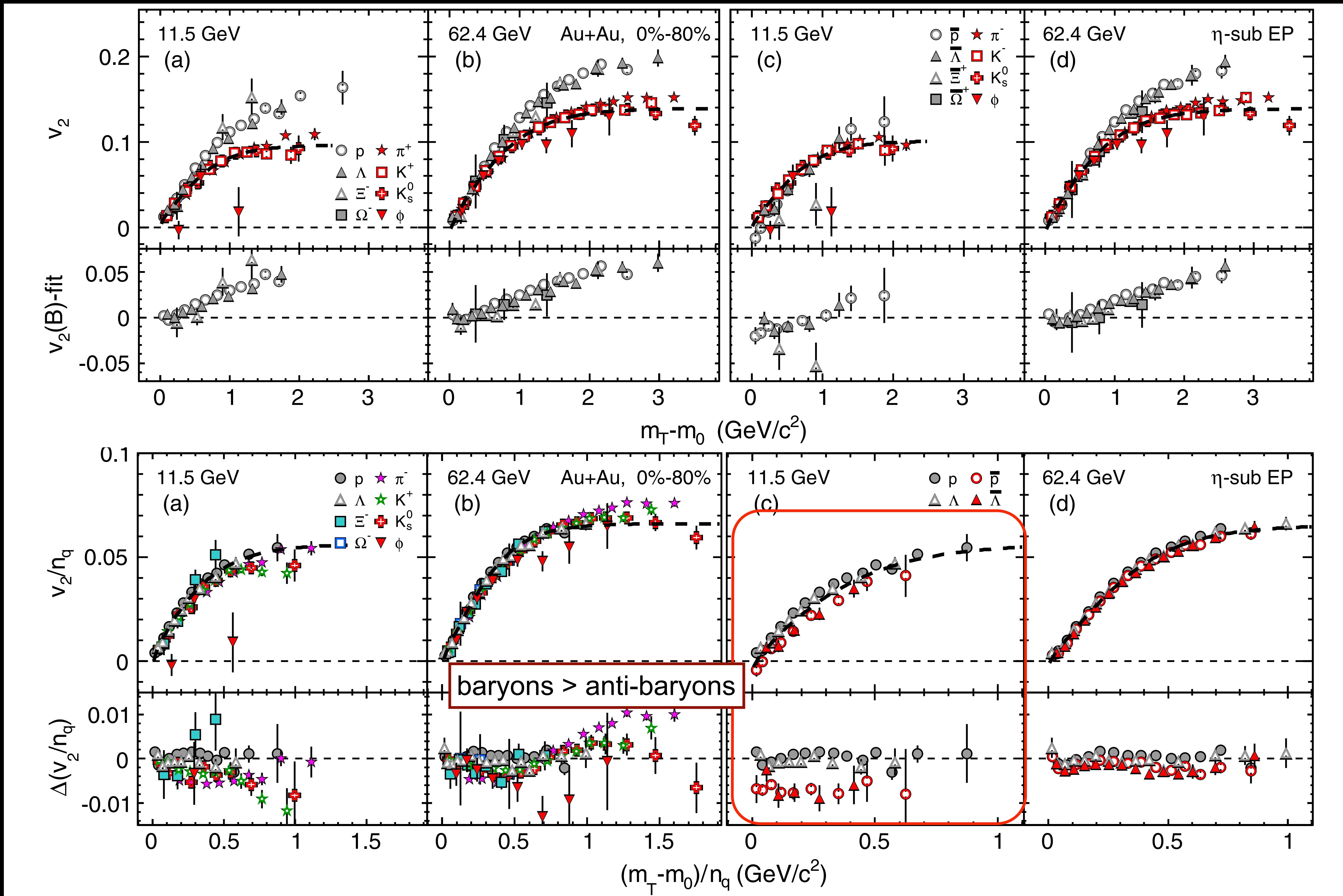
Break down of NCQ scaling

STAR: **PRL110**, 142301 (2013)



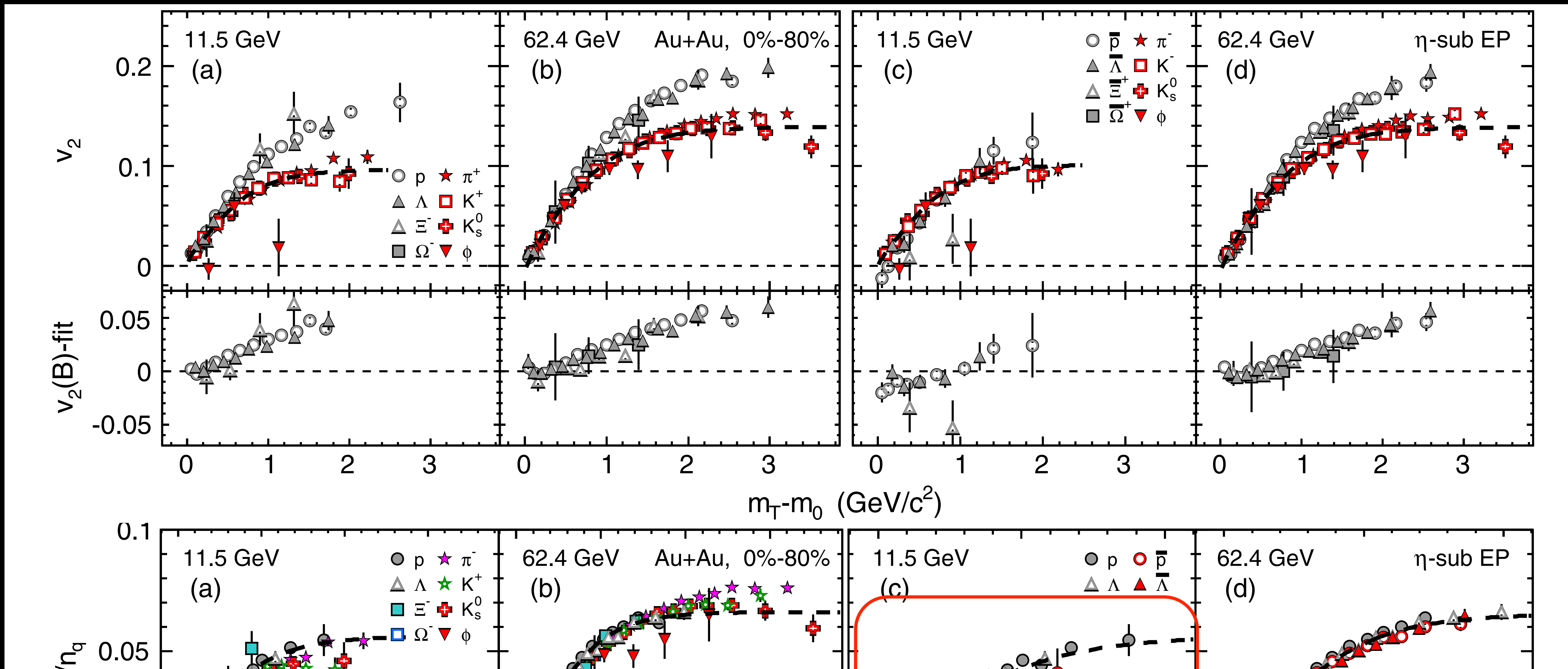
Break down of NCQ scaling

STAR: **PRL110**, 142301 (2013)



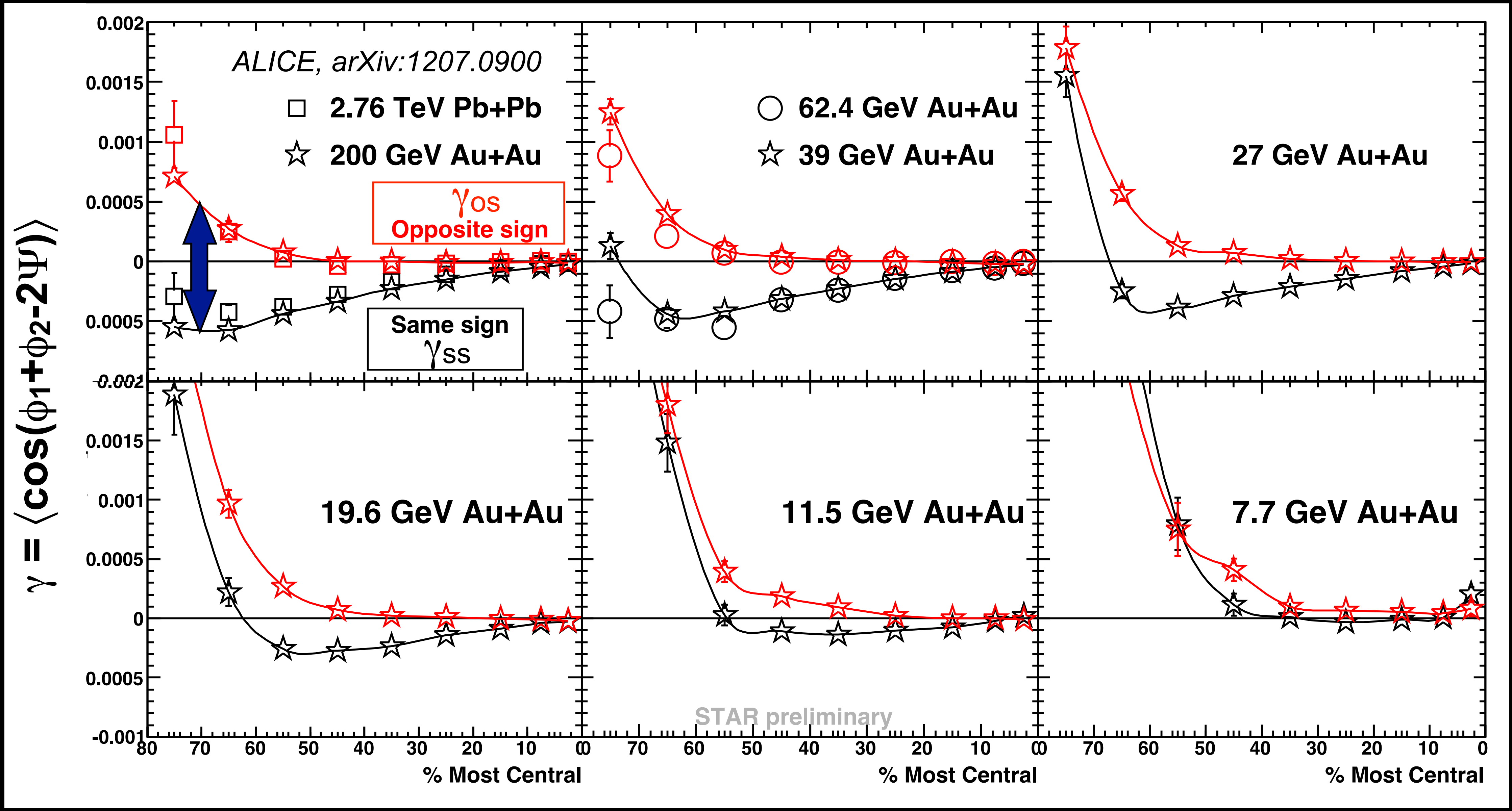
Break down of NCQ scaling

STAR: **PRL110**, 142301 (2013)



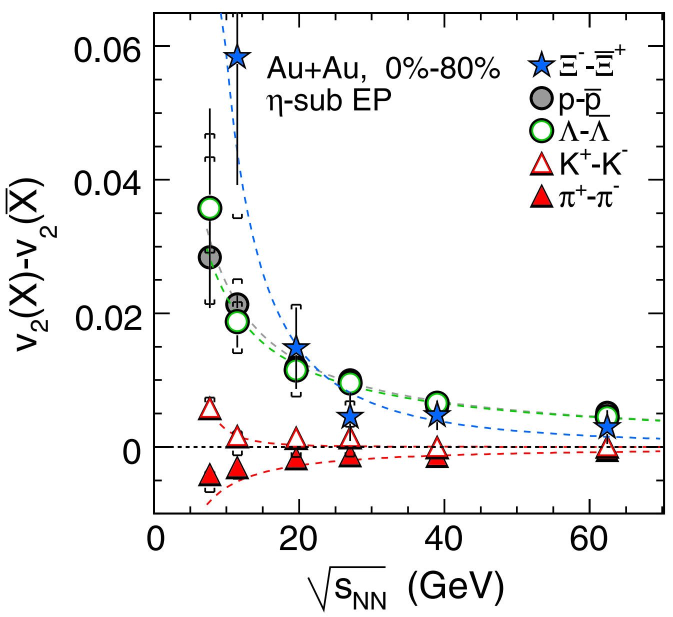
- ***NCQ scaling of v_2 breaks down between particles and anti-particles***
  - Interpretations; baryon stopping, mean-field potentials in AMPT, hydro+UrQMD, NJL model + coalescence, ….
  - Qualitative agreements. No quantitative explanations yet

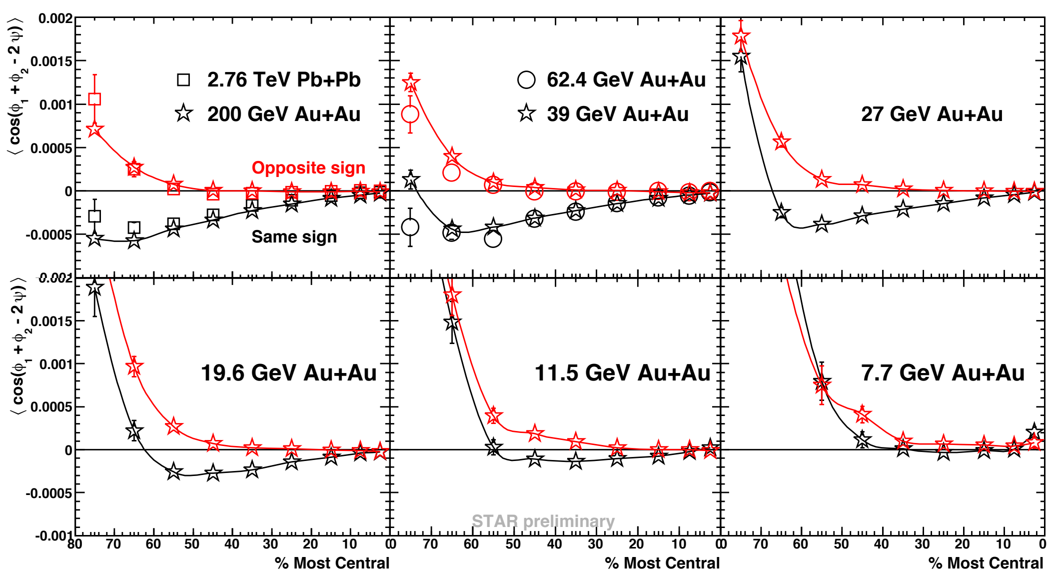
Disappear charge separation ?

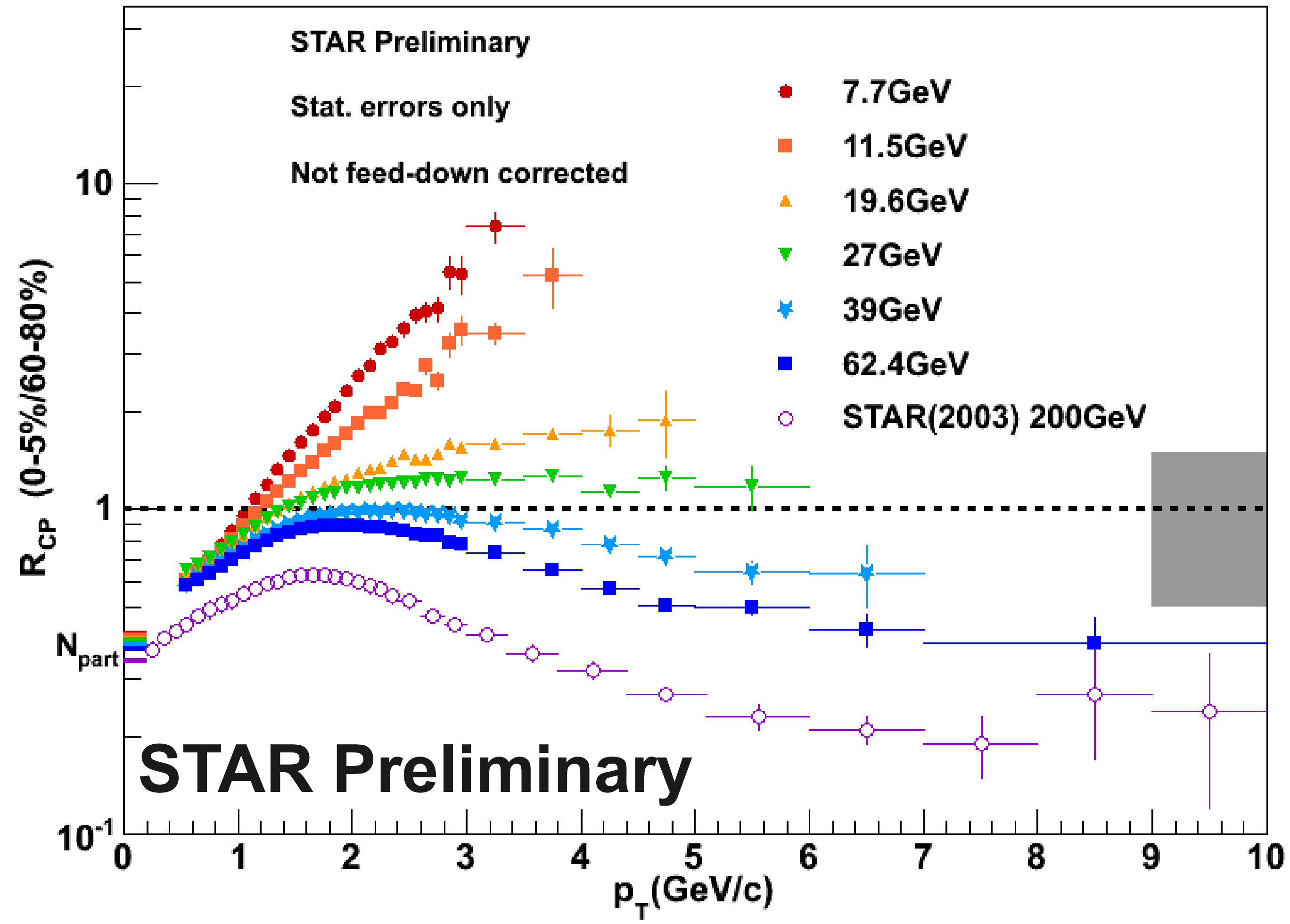


- Chiral magnetic effect induces charge separation orthogonal to the reaction plane
  - requires deconfinement + chiral symmetry restoration
- Charge separation (γ_{OS}-γ_{SS}) decreases with decreasing beam energies, seems to disappear at $\sqrt{s_{NN}}$ = 7.7-11.5 GeV

Below 39 GeV



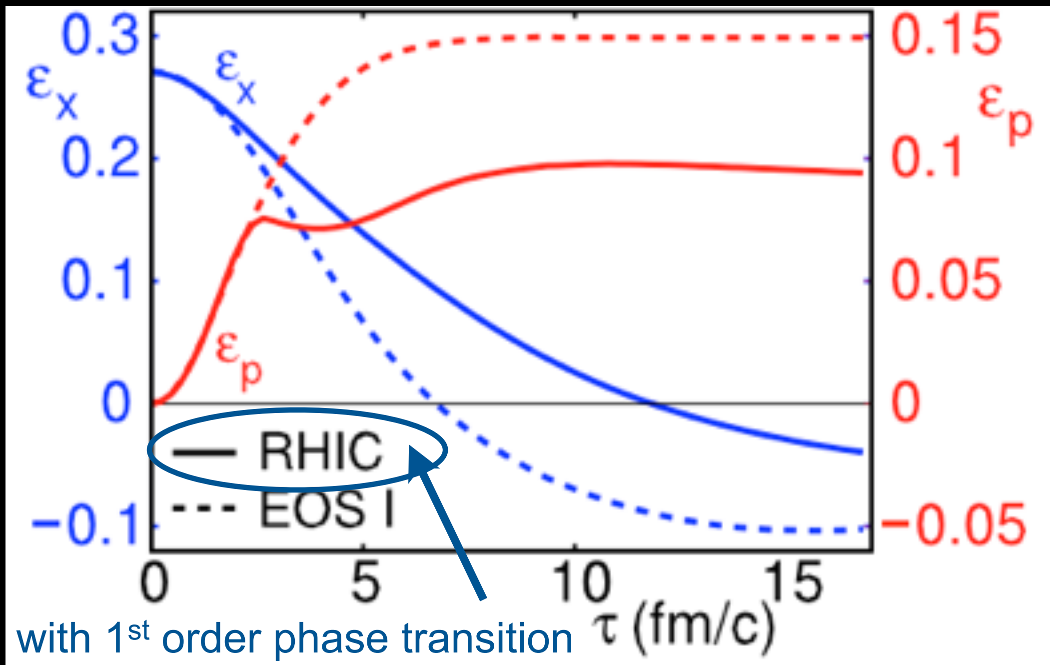




- Observe change in behavior of v_2, charge separation and high p_T suppression pattern below 11.5-39 GeV
  - 1st order phase transition ?

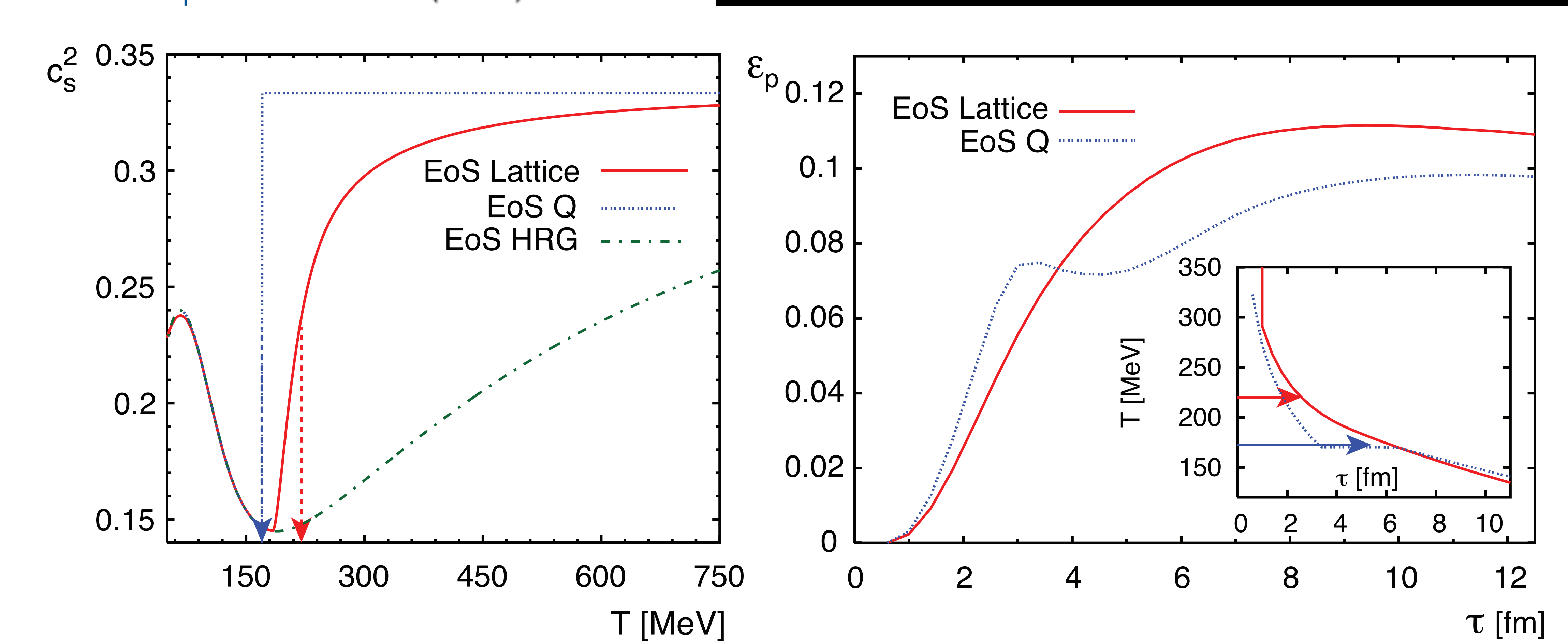
Equation of state → flow systematics

*P. F. Kolb et al, **PRC62**, 054909 (2000)*



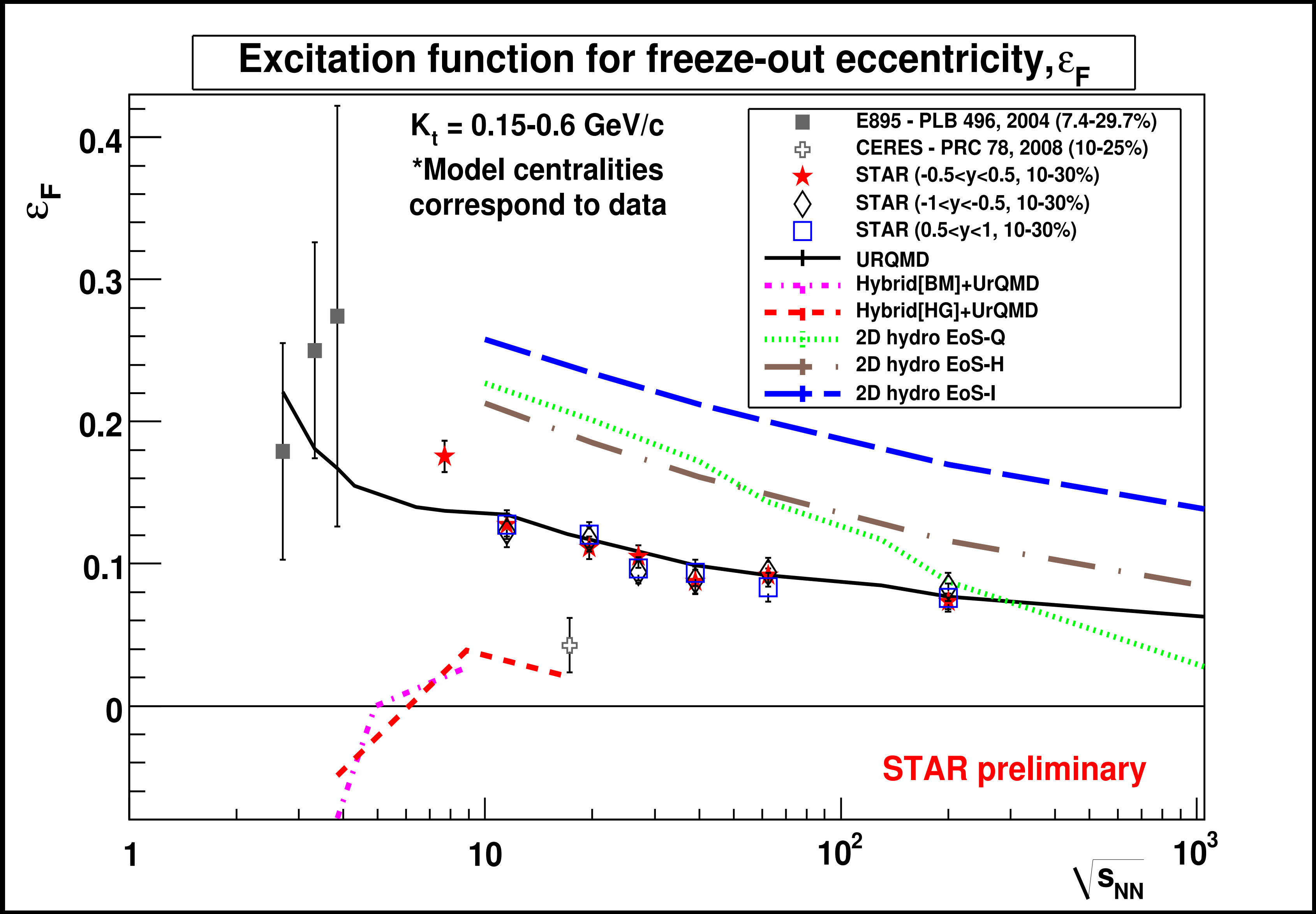
- 1st order phase transition affects the build up of ***spatial & momentum anisotropy***

➡ Look at ***flow systematics***

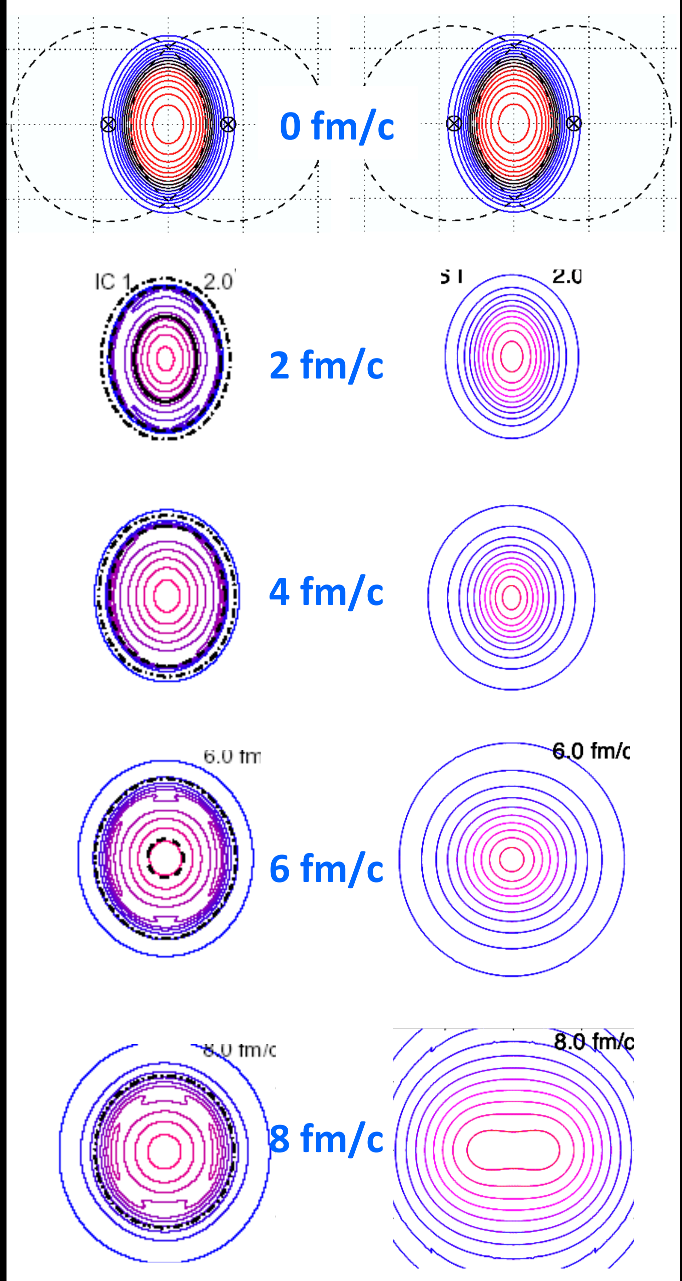


R. Snellings, New J. Phys.13, 055008 (2011)

Spatial anisotropy (eccentricity)



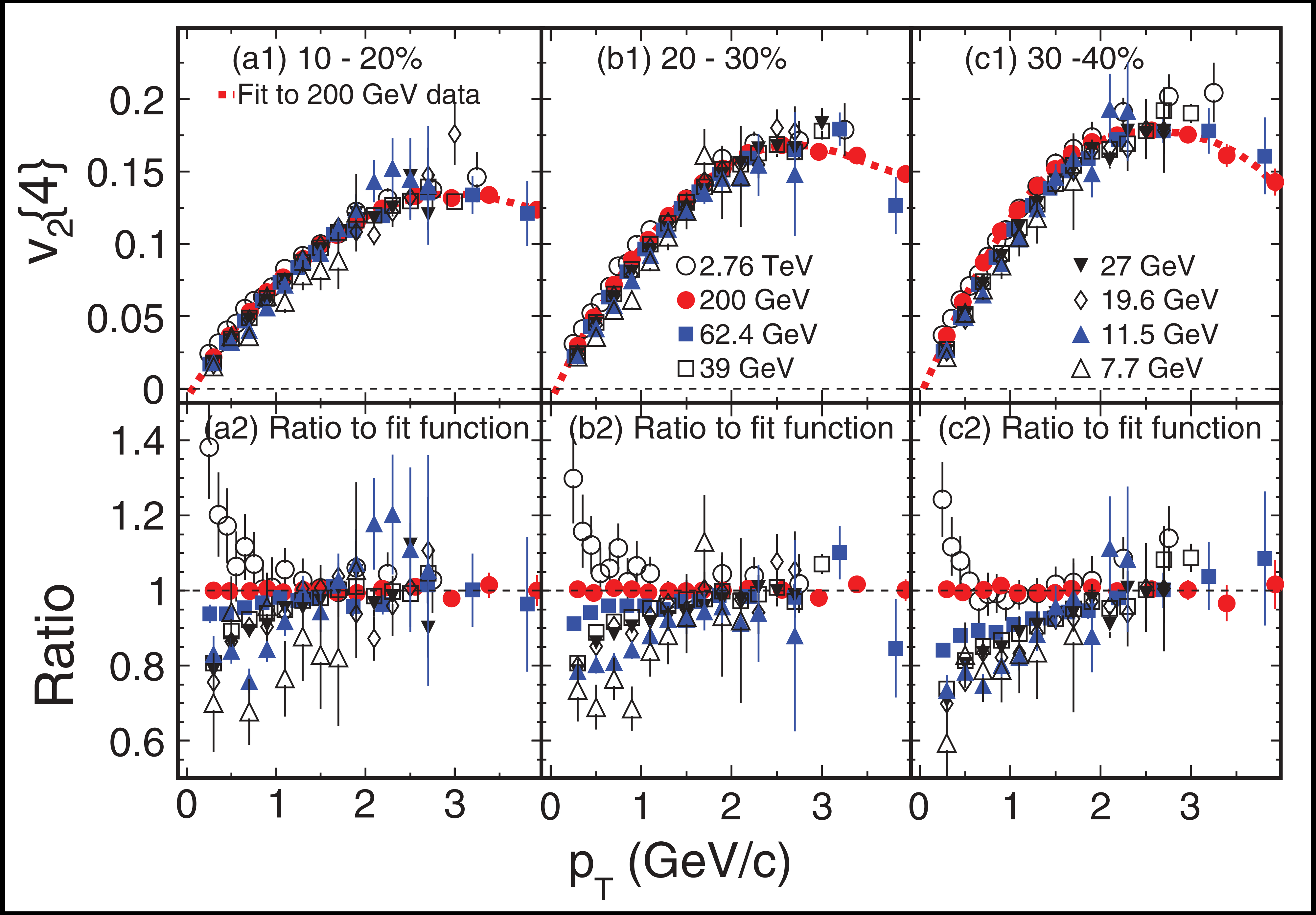
M. Lisa



Ideal hydro calculations - Kolb & Heinz

- No sudden change on spatial anisotropy
  - except for the CERES data point
- Data agree with pure hadronic cascade UrQMD

Momentum anisotropy - elliptic flow

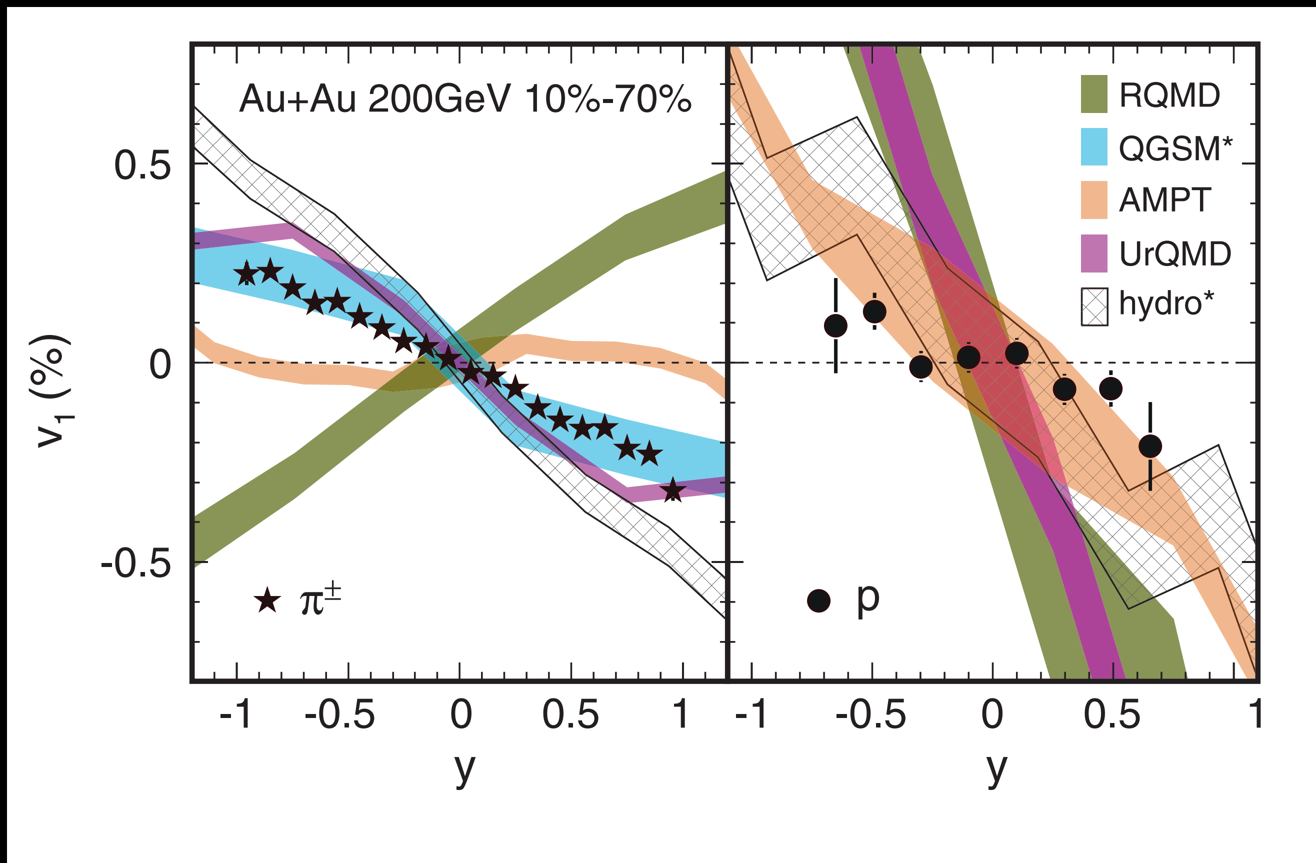


*STAR: **PRC86**, 054908 (2012)*

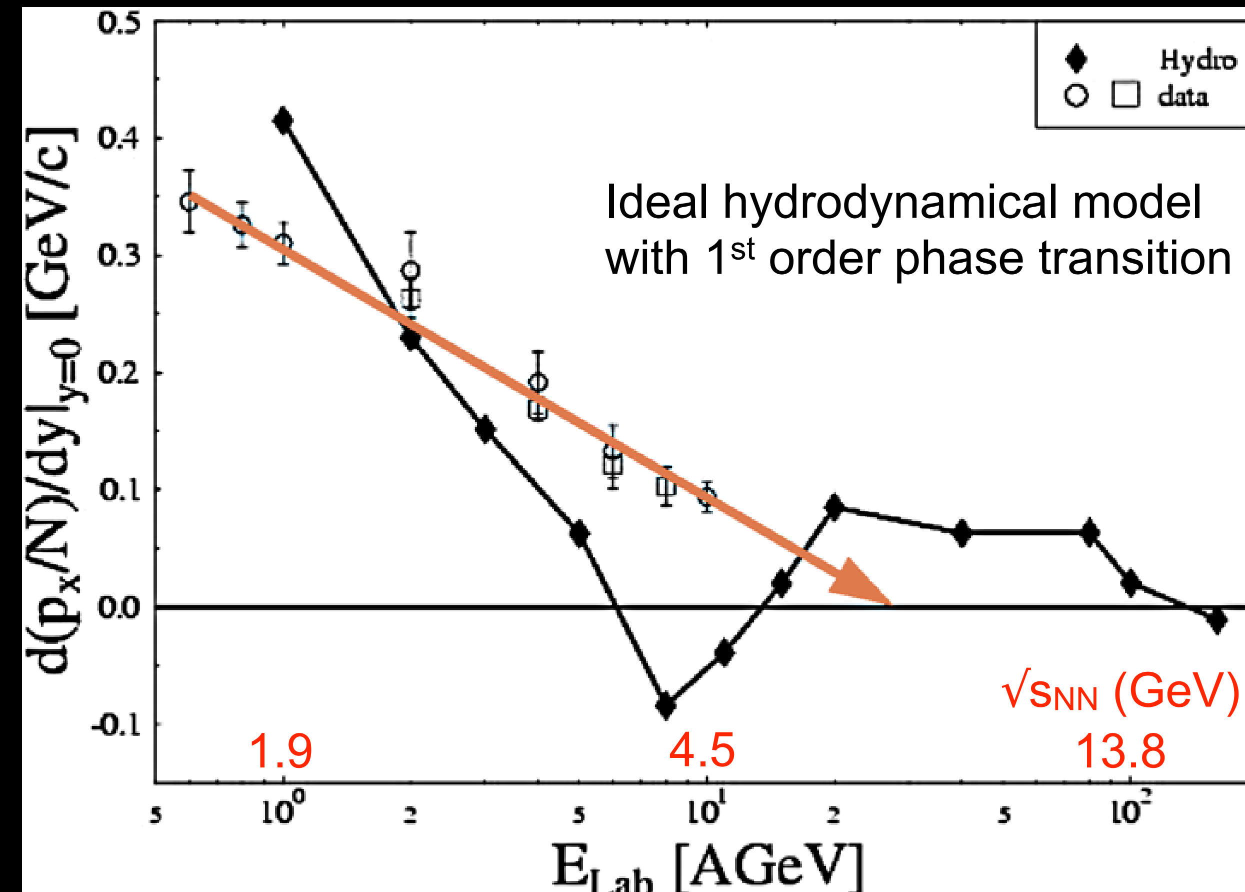
- No sudden change on $v_2\{4\}$, smooth increase as a function of energy

Directed flow

STAR: ***PRL108***, *202301 (2012)*

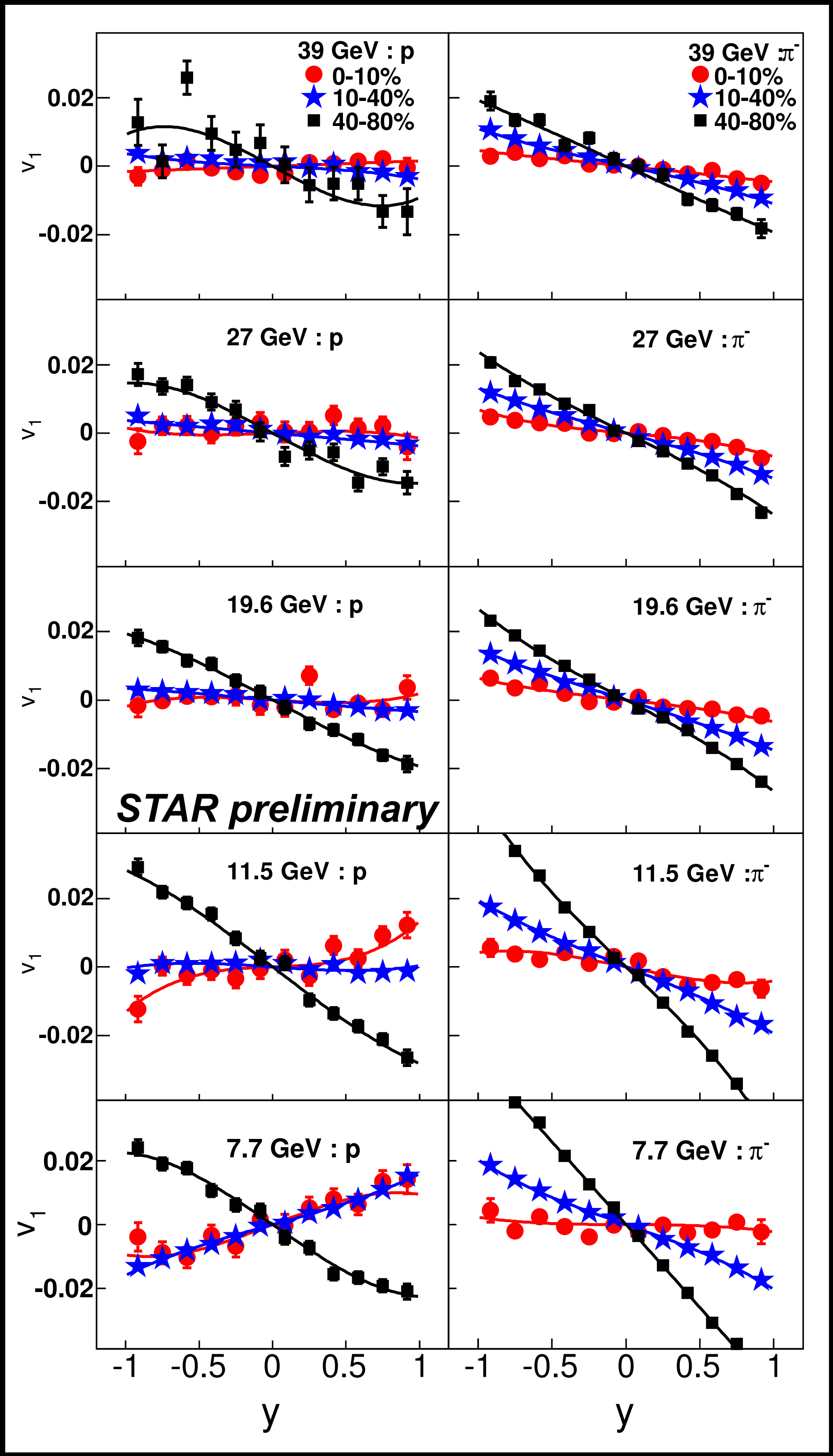


H. Stocker, ***NPA750***, *121 (2005)*



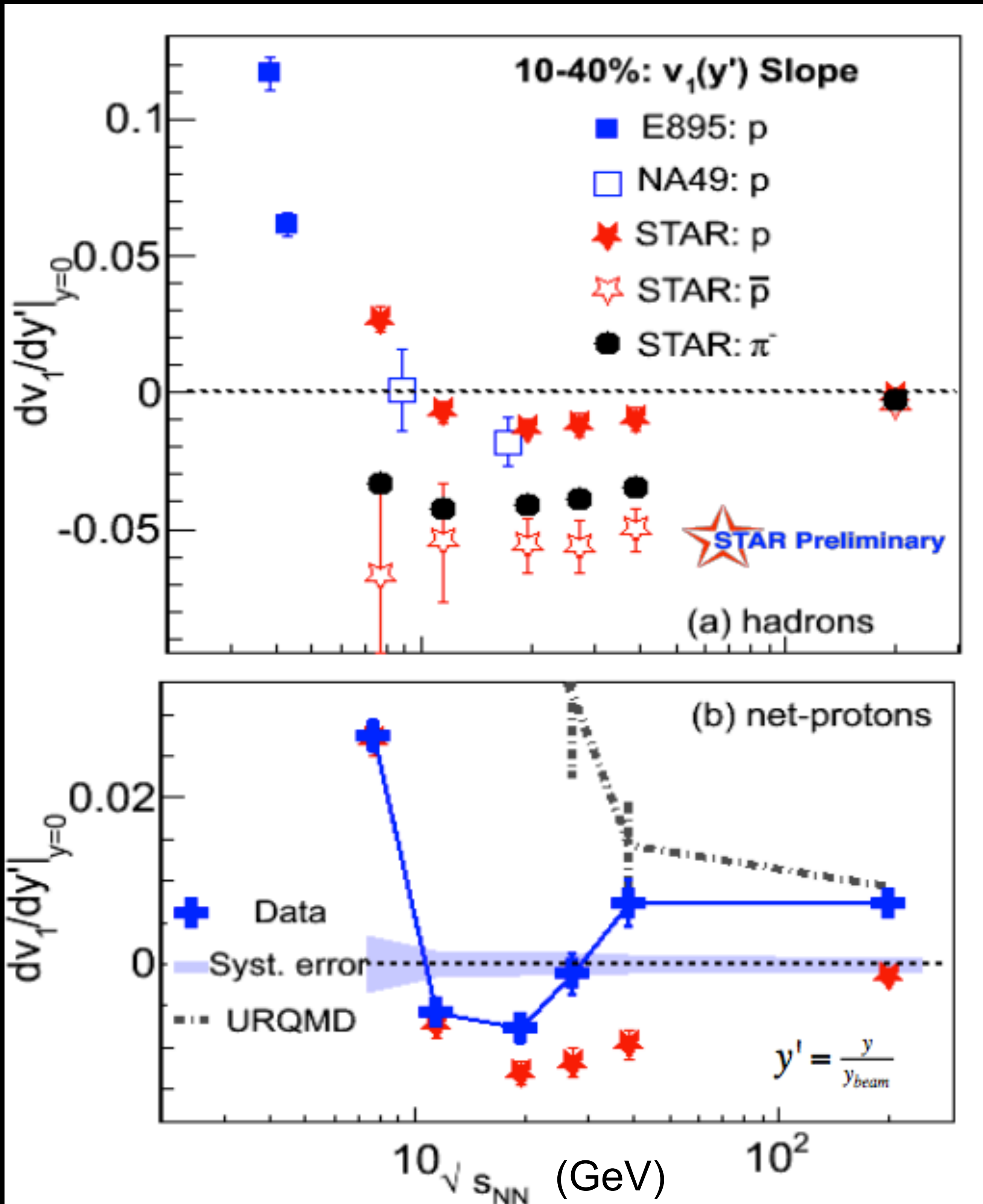
- Less focus on high energies
  - Signal is small, large non-flow (momentum conservation)
  - Need 3D models - challenge to transport (and hydro) models
- Directed flow is also sensitive to 1st order phase transition
  - Especially slope of v_1
  - Very non-trivial energy dependence (prediction)

Directed flow at BES



- v_1 slope is all negative for protons and pions
  - except for protons at 7.7 and 11.5 GeV
- Slope is generally steeper in lower energies in peripheral collisions
- No sudden change on v_1 slope would be expected from this results

Net-proton v_1 slope



- Smooth energy dependence for hadrons
  - consistent with trends from NA49 and E895
- However, net-proton v_1 slope shows non-monotonic behaviour
  - Minimum around 10-20 GeV, double sign change around 10 and 30 GeV
- Transport calculations UrQMD & AMPT cannot reproduce the results
- Interesting to see other net-hadron v_1 slope (not studied yet)

Fluctuations diverge at CP

- At critical point (with infinite system)
  - susceptibilities and correlation length diverge
    - both quantities cannot be directly measured
- Experimental observables
  - Moment (or cumulant) of conserved quantities: net-baryons, net-charge, net-strangeness, ...
  - Moment product (cumulant ratio) ↔ ratio of susceptibility

$$\kappa_2 = \left\langle (\delta N)^2 \right\rangle \sim \xi^2, \kappa_3 = \left\langle (\delta N)^3 \right\rangle \sim \xi^{4.5}, \kappa_4 = \left\langle (\delta N)^4 \right\rangle - 3 \left\langle (\delta N) \right\rangle^2 \sim \xi^7$$

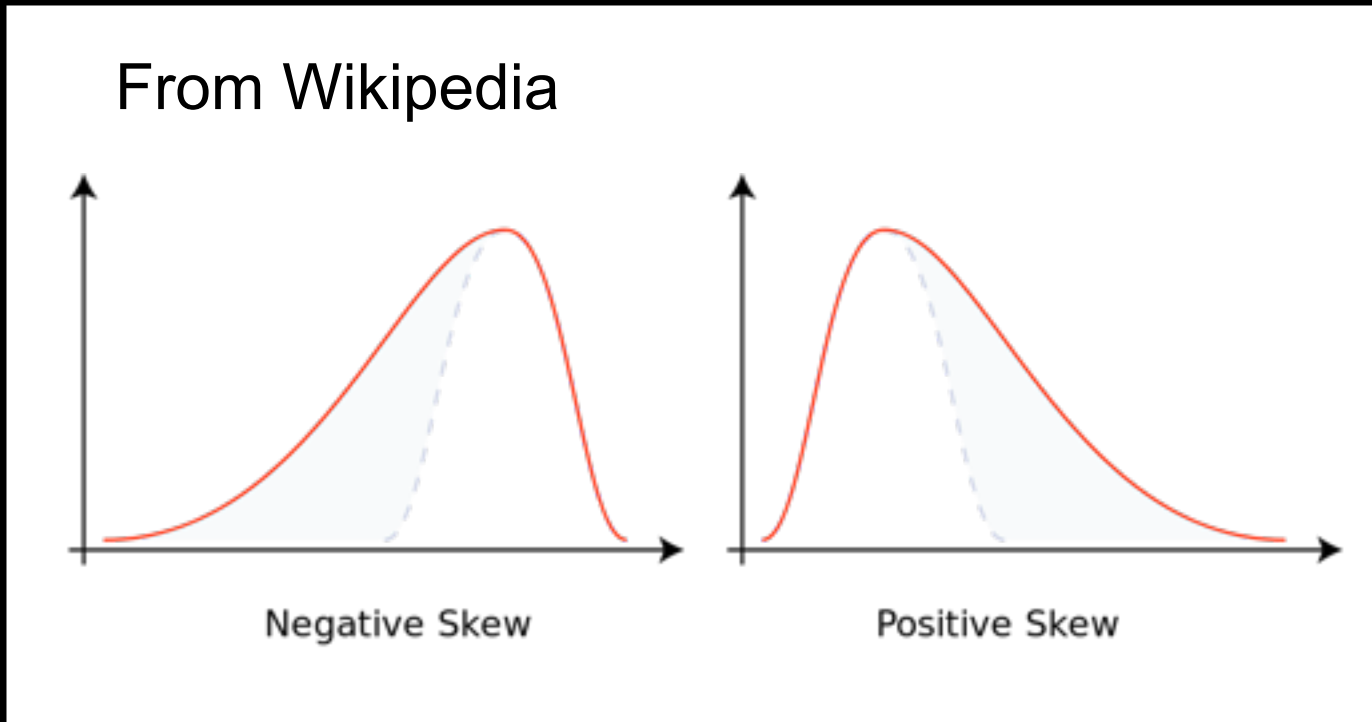
$$S\sigma = \frac{\kappa_3}{\kappa_2} \sim \frac{\chi_3}{\chi_2}, \ K\sigma^2 = \frac{\kappa_4}{\kappa_2} \sim \frac{\chi_4}{\chi_2}$$

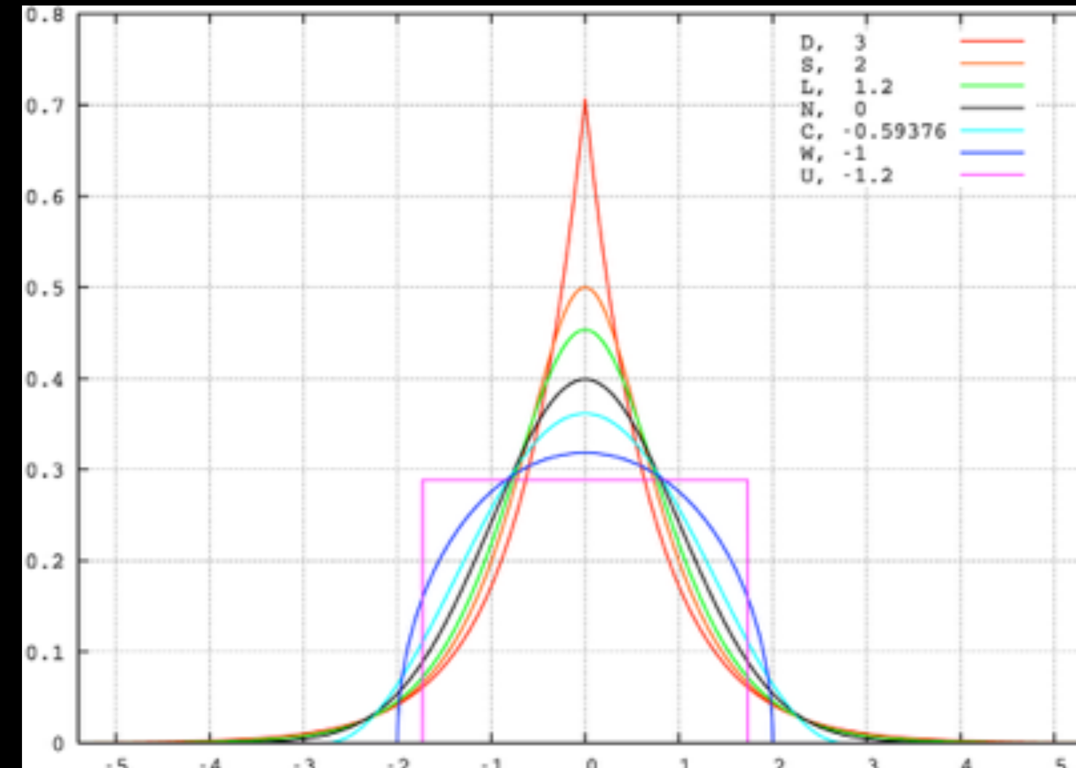
- directly related to the susceptibility ratios (Lattice QCD)
- higher moments (cumulants) have higher sensitivity to correlation length

*M. A. Stephanov, **PRL102**, 032301 (2009)*

- ***Signal = Non-monotonic behavior of moment products (cumulant ratios) vs beam energy***

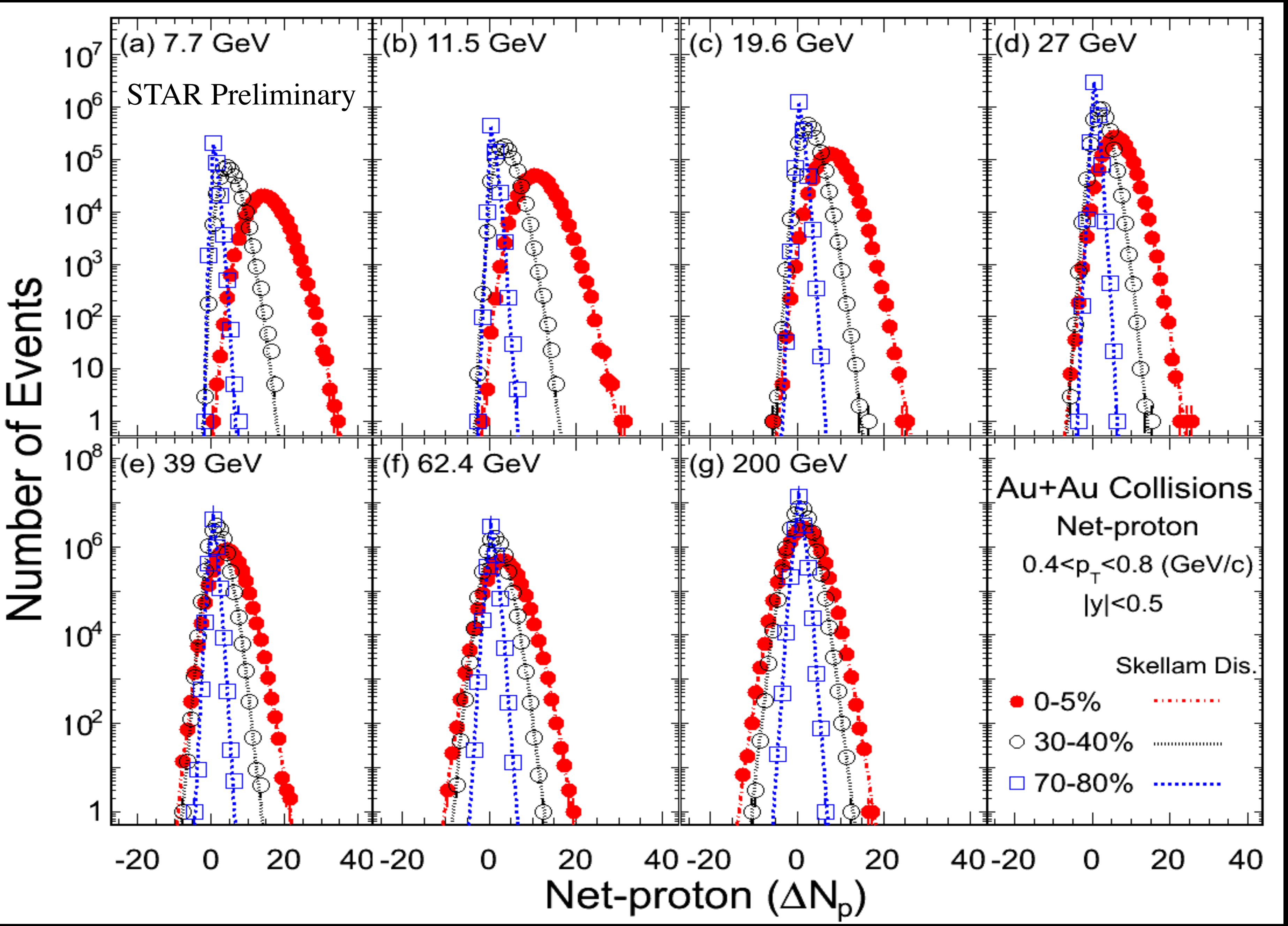
Non-gaussian fluctuations





- 3rd moment = Skewness *S*
  - Asymmetry
- 4th moment = Kurtosis *K*
  - Peakedness
- Both moments = 0 for gaussian distribution
- Critical point induces non-gaussian fluctuations

Net-proton distributions

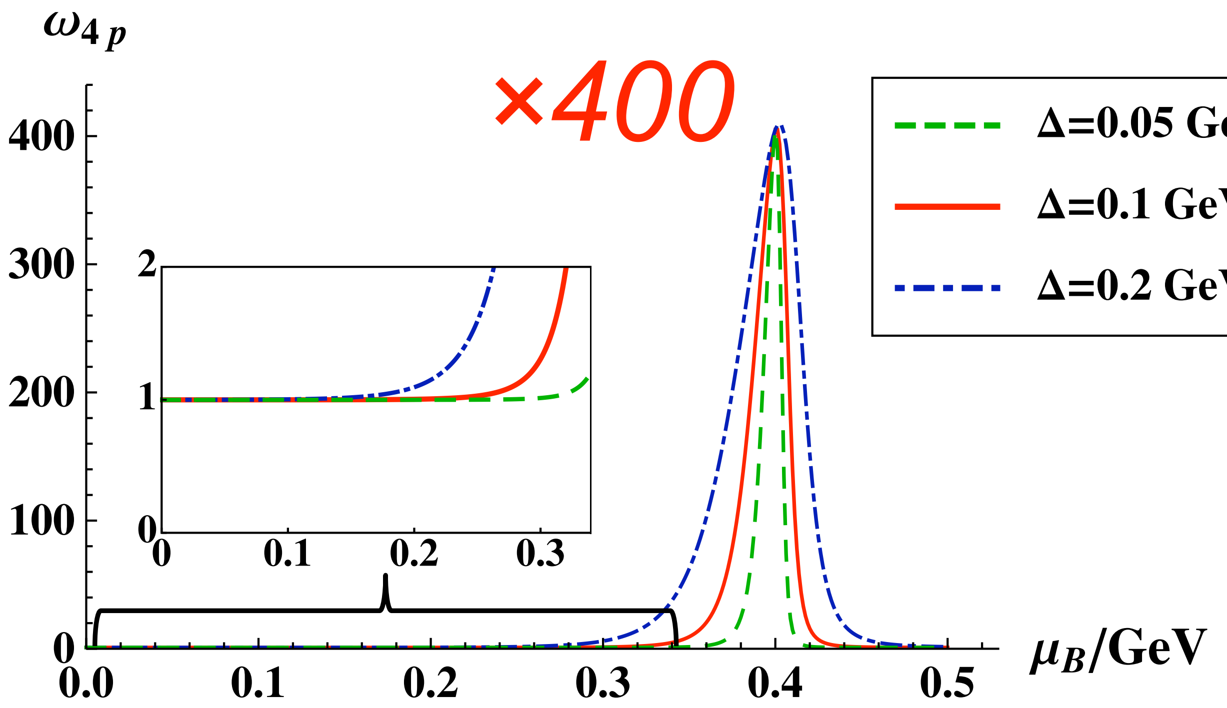


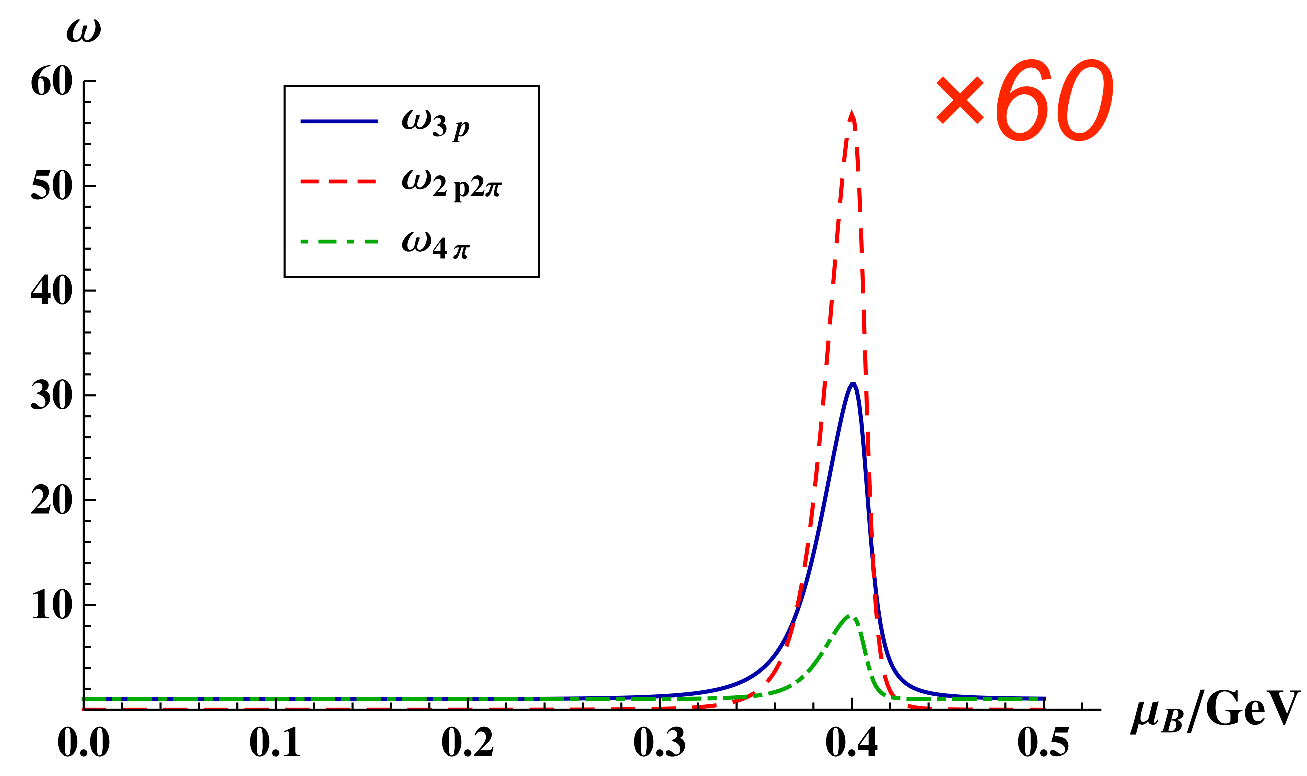
- Distributions look like gaussian or poisson by eyeball
- Information of higher moments are mostly encoded in the tail
- We are dealing with tiny signals

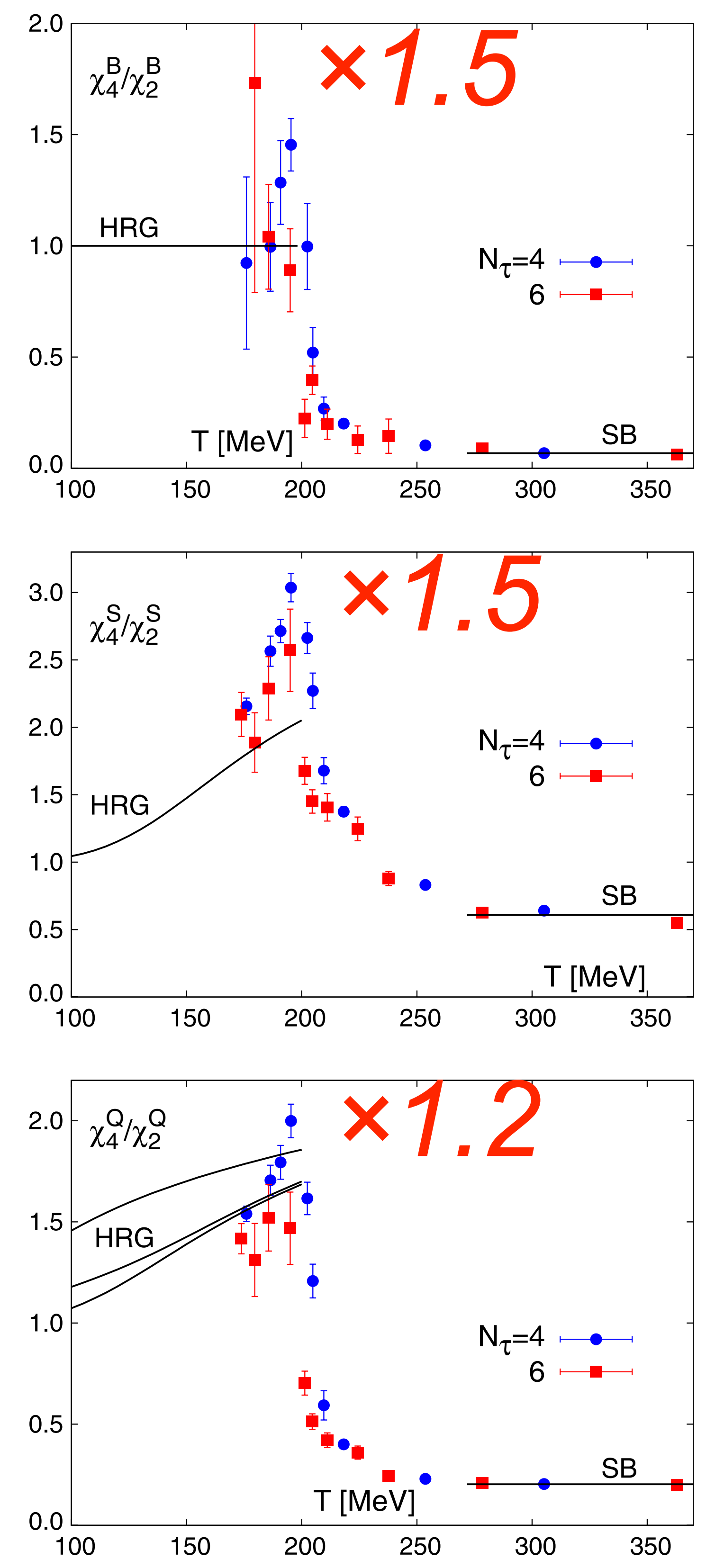
Predictions

M. Cheng et al, PRD**79**, 074505 (2009)
Lattice QCD

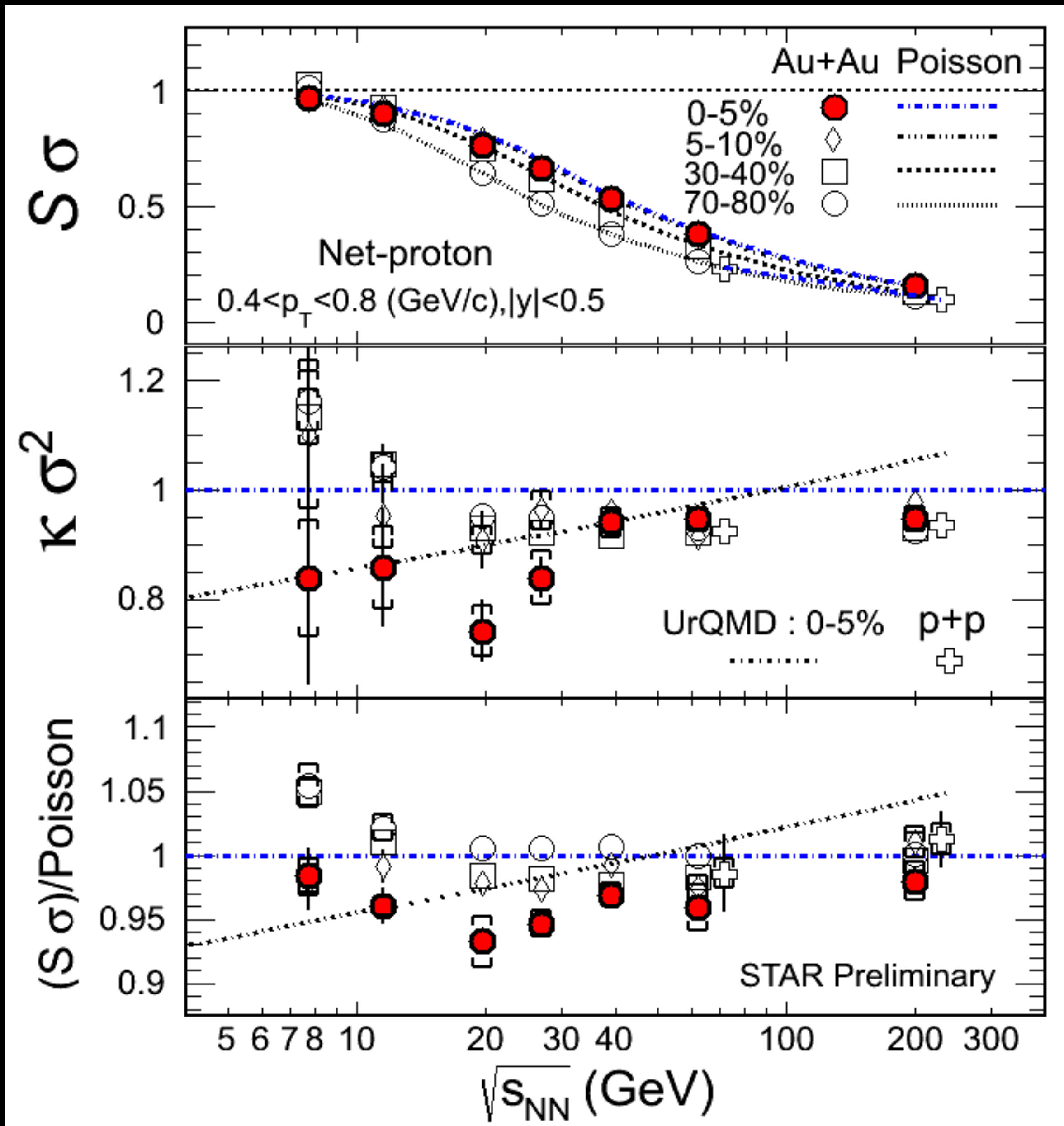
C. Athanasiou et al, PRD**82**, 074008 (2010)
Non-linear sigma model

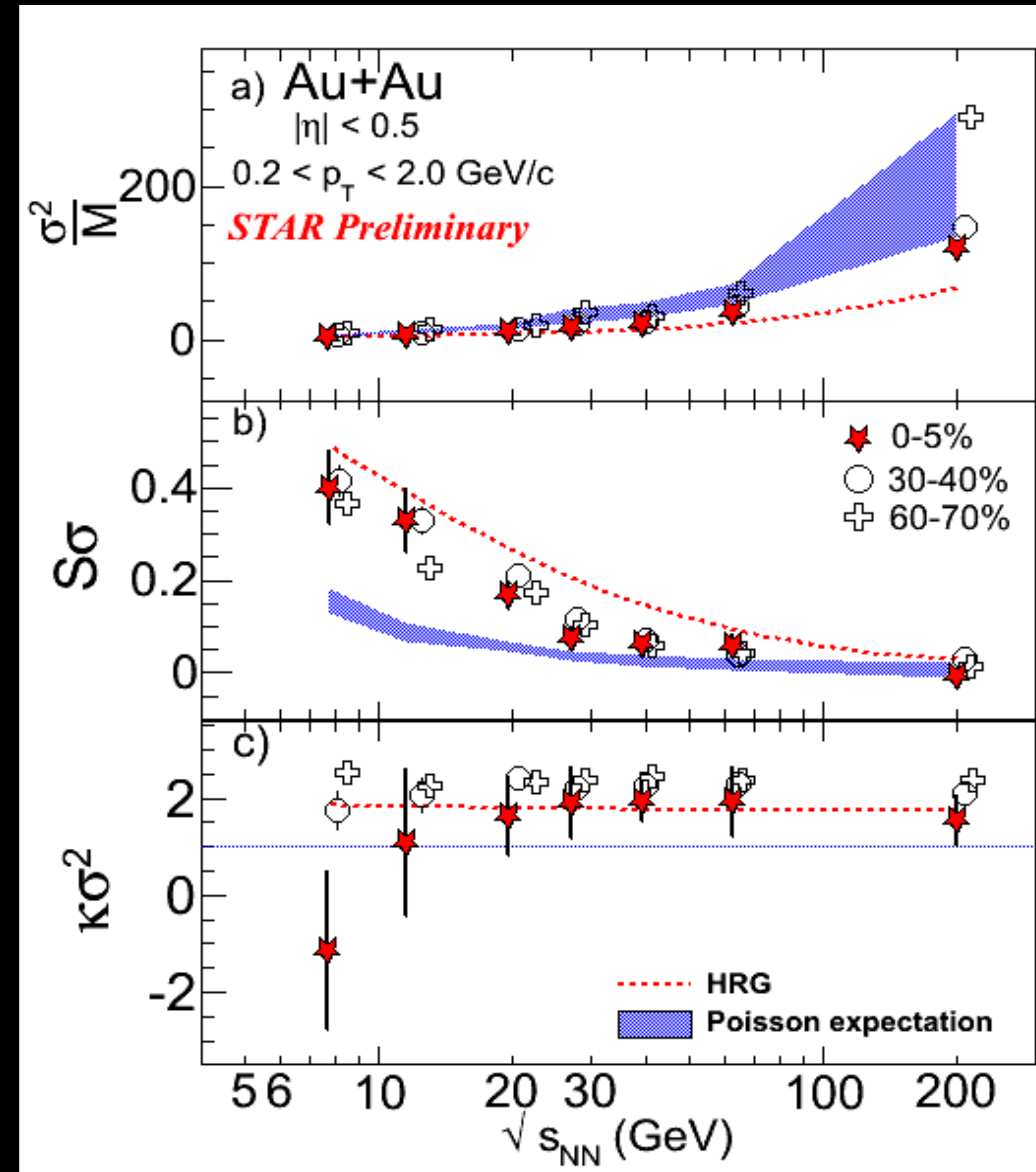






Net-protons & Net-charge





- No significant excess observed for both net-protons & net-charge
  - Something happened below 30-40 GeV ?

Current issues

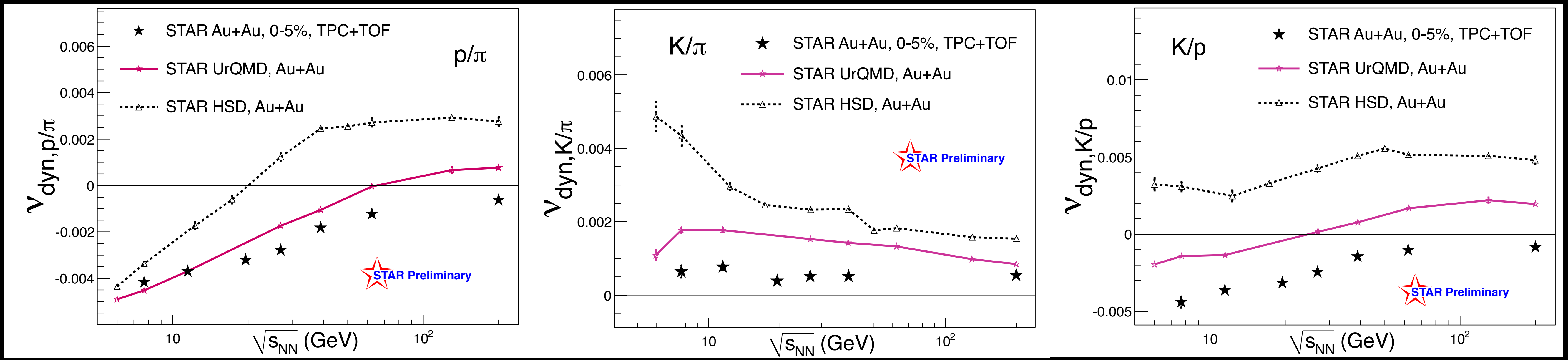
- Net-proton is not net-baryon
  - Net-charge might be better

*A. Bzdak and V. Koch, **PRC86**, 044904 (2012),*
*M. Kitazawa and M. Asakawa, **PRC86**, 024904 (2012)*

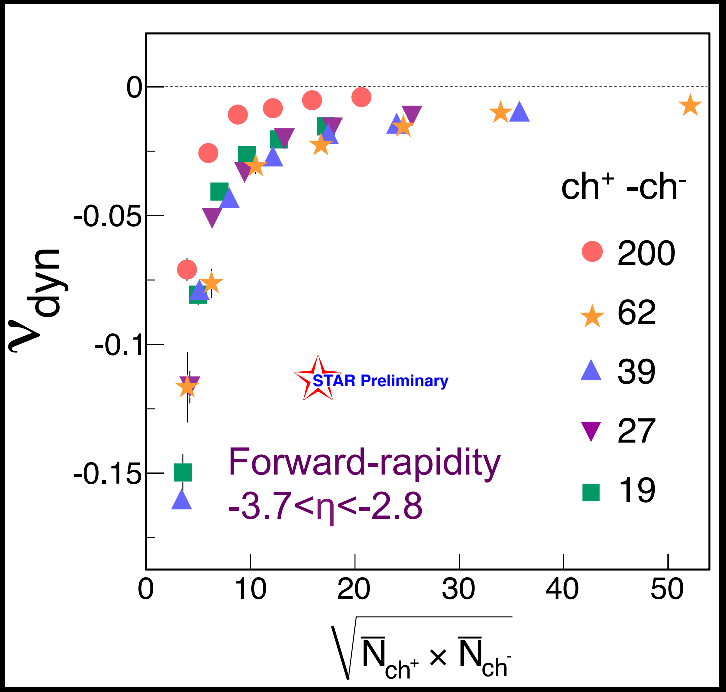
- Efficiency correction is important
  - Under investigation
- Is Poisson baseline reliable ? How about (Negative-) Binomial distribution ?
  - Under investigation
- 100 MeV gap in μ_B between 11.5 and 19.6 GeV
  - 15 GeV is planed in 2014
- Need more statistics at 7.7 and 11.5 GeV
  - BES phase-II in 2018-2019

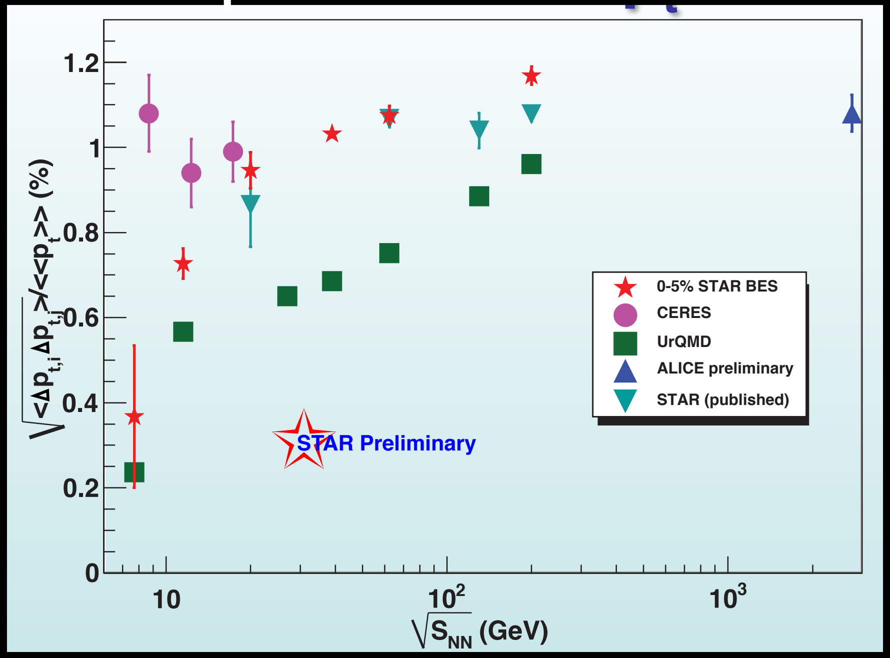
Other fluctuation observables

Particle ratio fluctuations



p_T correlation





- None of fluctuation observables show significant excess
  - No sensitivity to CP ? Signal is weak ? No CP ?

Summary of BES phase-I

- Several turn-off signals observed in 10-30 GeV
  - Break down of NCQ scaling of v_2 between particles and anti-particles
  - Disappearance of charge separation
  - Disappearance of high p_T suppression
- No conclusive observations for 1st order phase transition and critical point search yet
  - Spatial and momentum anisotropy with respect to second harmonic event plane show monotonic energy dependence
  - Net-proton v_1 slope shows non-monotonic behavior
  - Fluctuation observables essentially show monotonic energy dependence
    - we need precision measurements below 20 GeV, especially for higher moments

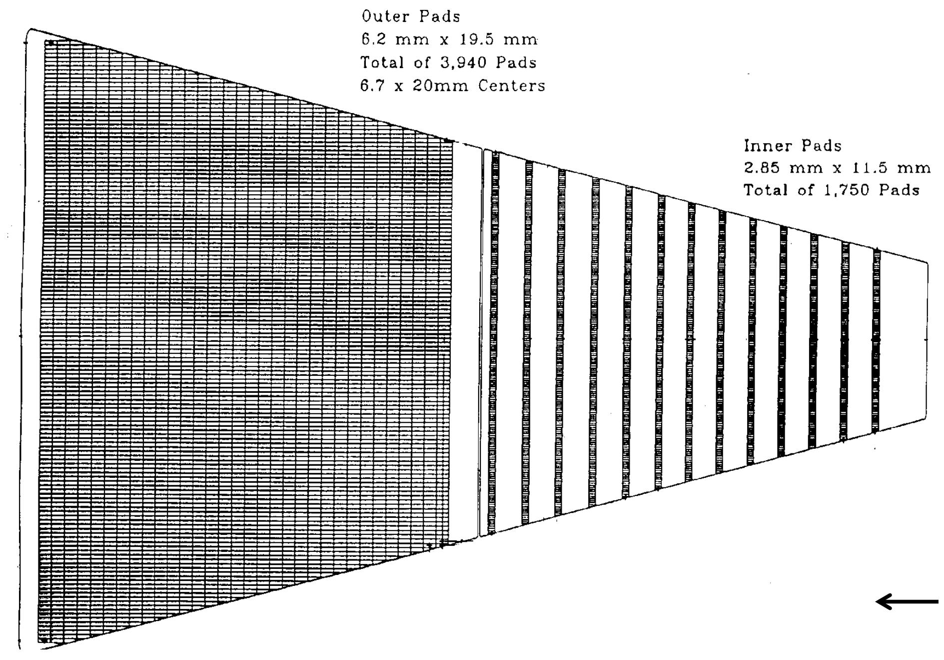
Future perspective

- Near term: 2014-2015
  - Complete HFT installation (2014)
    - Open charm, di-leptons at 200 GeV - sQGP properties
  - ***15 GeV for critical point search***
- Middle term: -2019
  - ***Electron cooling at RHIC (luminosity)***
  - ***Inner TPC upgrade*** - acceptance, efficiency, pid
  - ***Forward tracking upgrade*** - better event plane determination
- Middle and long term: 2016-
  - Forward upgrade towards eRHIC, eSTAR

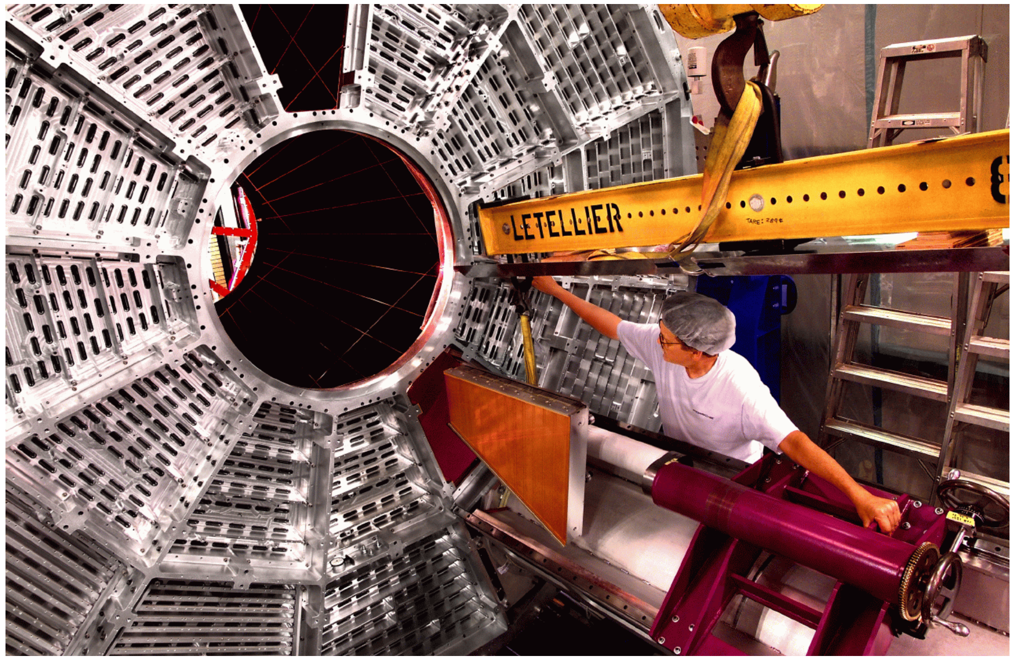
inner TPC (iTPC) upgrade

- Current pad plane layout with 13 rows and gaps
  - only 13 maximum possible points
  - only reads ~20% of possible gas path length
    - Inner sectors essentially not used in dE/dx
- Essentially limits effective acceptance to $|\eta|<1$

Z. Ye,
RHIC/AGS users meeting



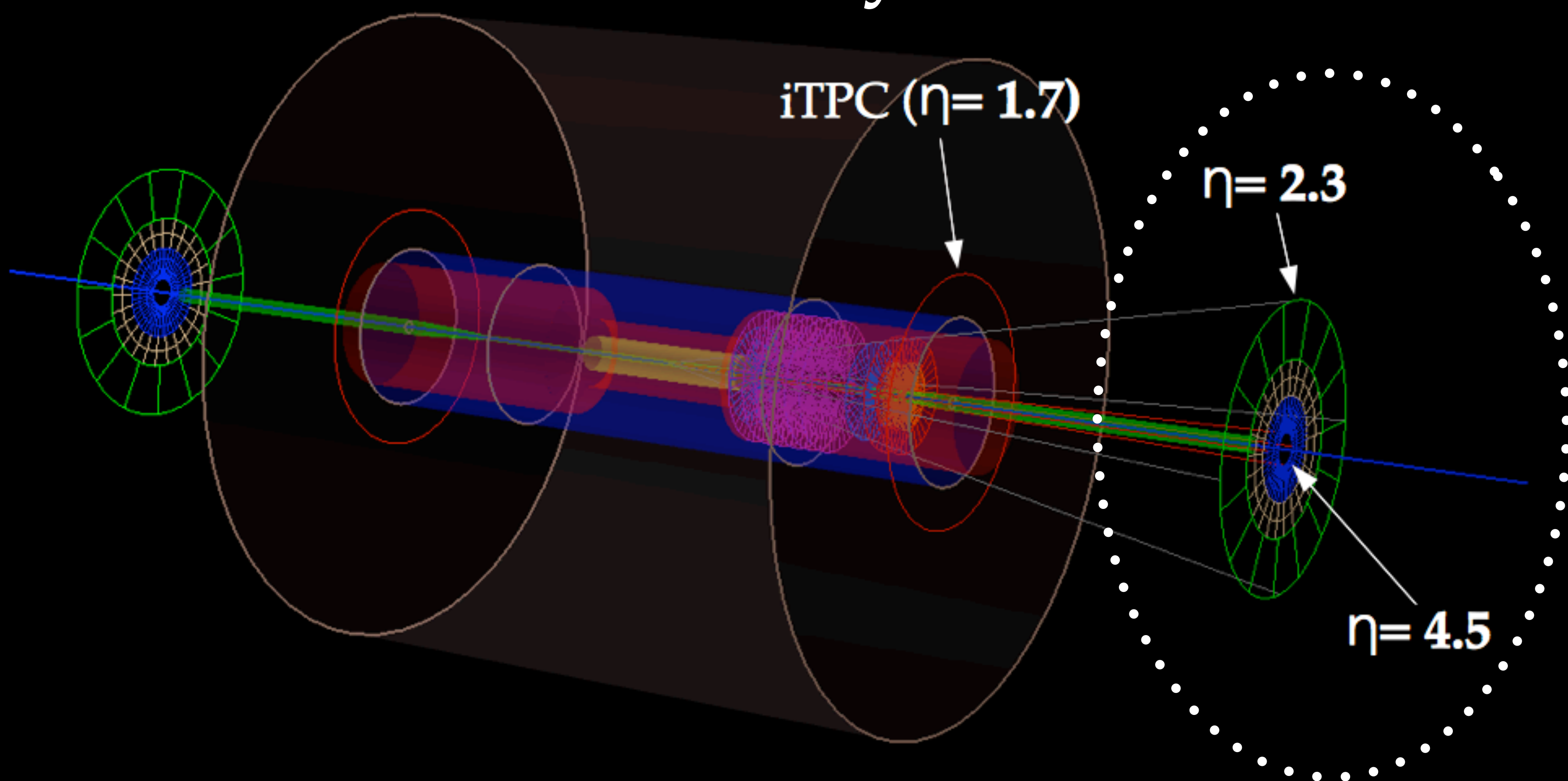
$\eta=\pm1$ $\eta=\pm1.2$ $\eta=\pm2$



- Rebuild inner sectors of the TPC
  - pseudorapidity coverage extend from 1 to 1.7
  - Improve dE/dx - better PID
  - Better efficiency, transverse momentum resolution

Event plane detector

HALO by A. Schmah (LBNL)

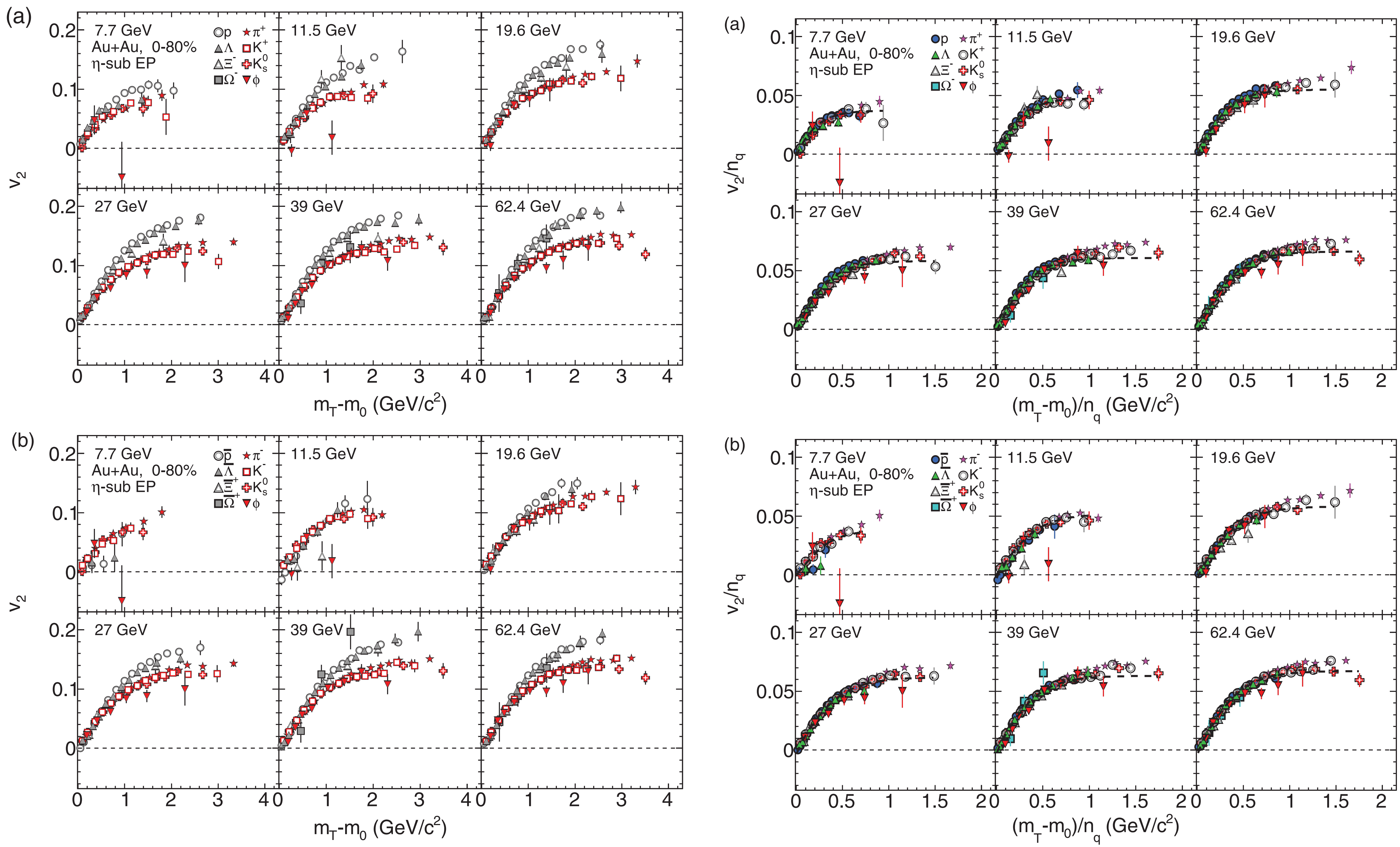


- Provide better event plane resolution
- Important as trigger detector (~95% events are background at 7.7 GeV in our current trigger)
- Provide independent centrality determination
- Evaluation is on-going for detector implementation

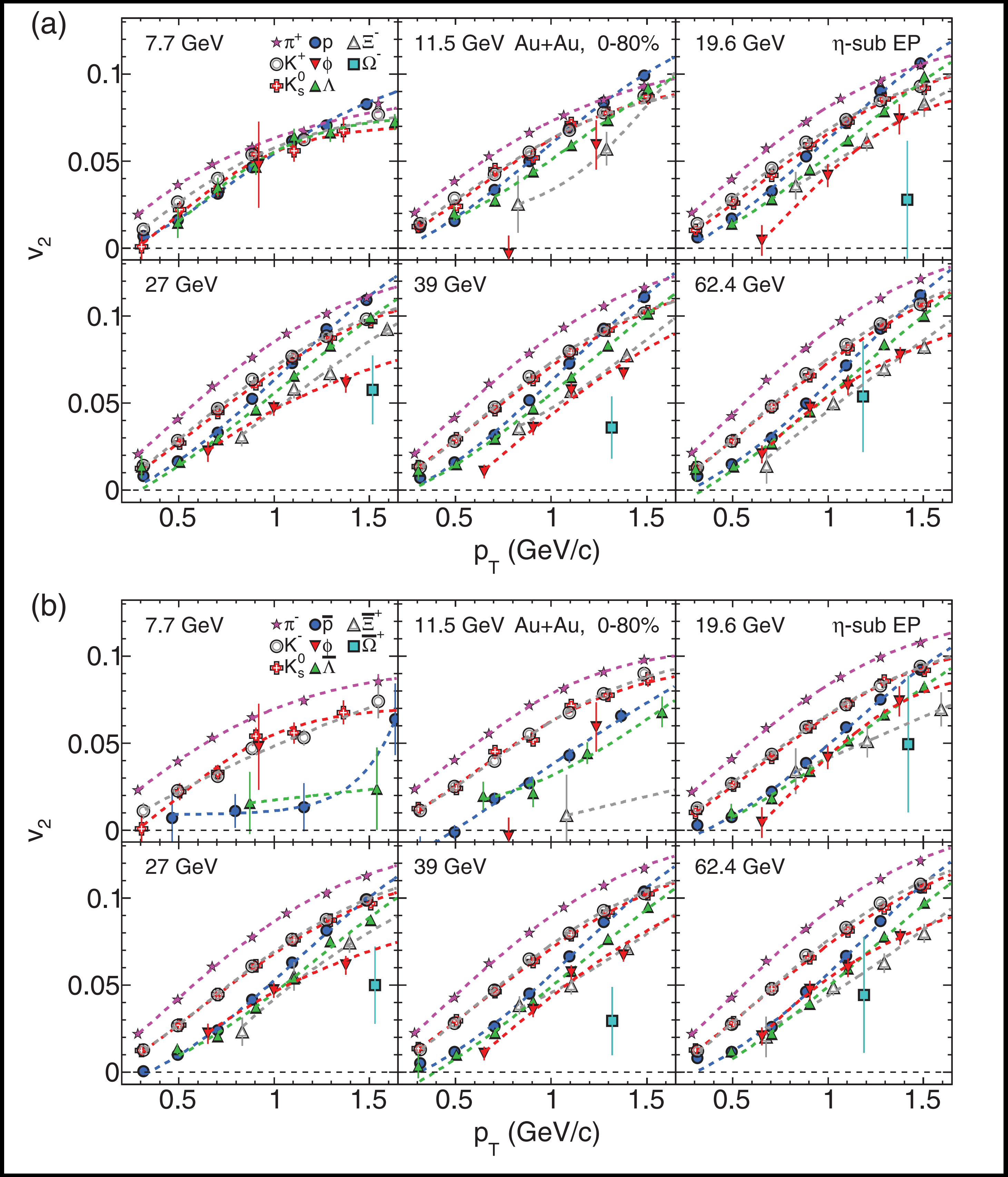
Conclusions

- RHIC BES-I
  - Turned off several key signals at 200 GeV
  - No conclusive evidence for 1st order phase transition and critical point search
  - Therefore, we proposed BES phase-II with 10-20 times better statistics
- RHIC BES-II (2018-2019)
  - Focus on $\sqrt{s_{NN}}$ < 20 GeV
  - Electron cooling + longer bunch lengths will increase luminosity
  - iTPC upgrade will extend pseudorapidity coverage, better pid, efficiency, p_T resolution
  - Event plane detector is being evaluated to improve flow measurements (and forward tracking in p+p)
  - (Fixed target mode is also considered at STAR in order to reach lower energies down to ~ 3 GeV)

Back up



STAR: ***PRC88***, *014902 (2013)*


(a)
7.7 GeV
11.5 GeV Au+Au, 0-80%
19.6 GeV
η-sub EP
27 GeV
39 GeV
62.4 GeV
v_2
p_T (GeV/c)
(b)
7.7 GeV
11.5 GeV Au+Au, 0-80%
19.6 GeV
η-sub EP
27 GeV
39 GeV
62.4 GeV
v_2
p_T (GeV/c)