# What do we learn from the Beam Energy Scan at STAR?


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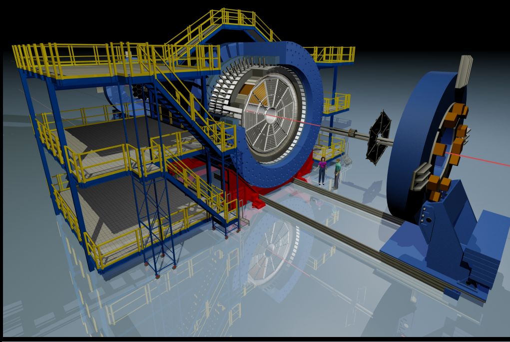
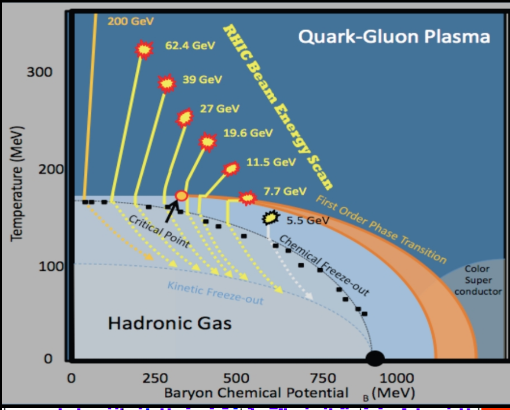
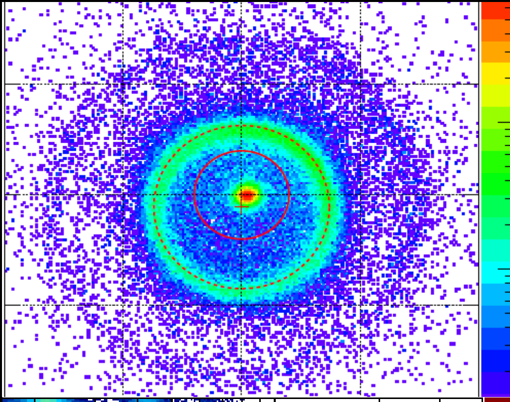
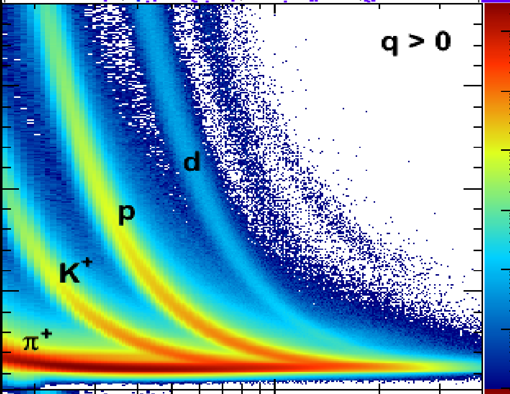
for the STAR Collaboration


**2012 RHIC & AGS Annual Users' Meeting**

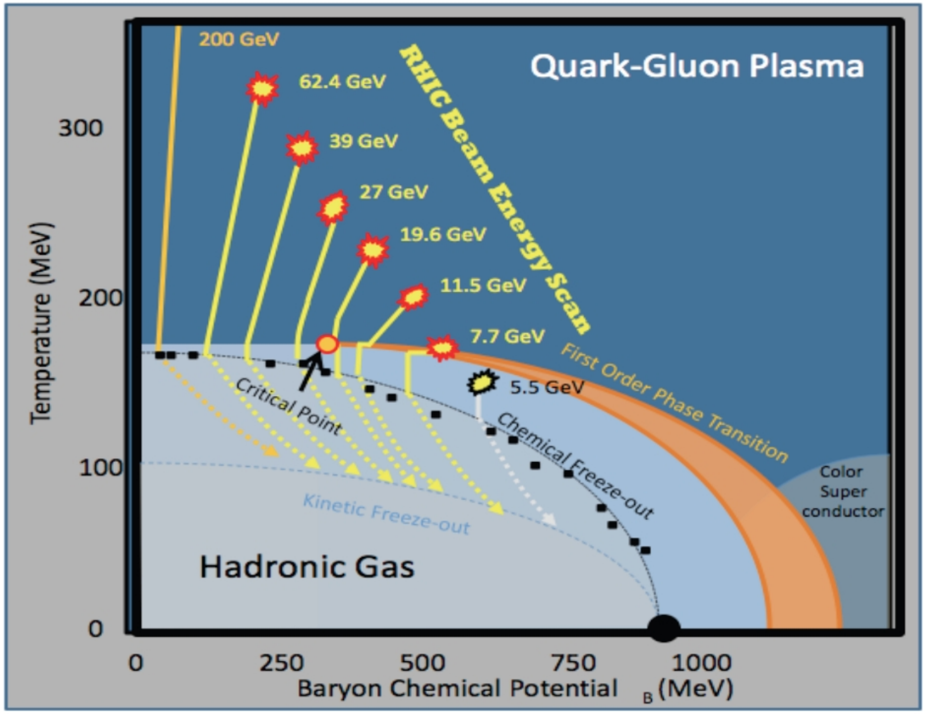
# Outline

- Introduction to the
  Beam Energy Scan program
- Spectra
- Fluctuations
- Flow
- Summary

# The Beam Energy Scan at RHIC/STAR




| $\sqrt{s_{NN}}$ (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

arXiv:1007.2613

**Main Goals:**
- Signatures for a possible phase transition
- Signatures for a possible critical point

**Strategy:**
- Almost equidistant steps in T-$\mu_B$: 7.7-62.4 GeV Au+Au reactions

**Methods:**
- Disappearance of QGP signals like $v_2$-ncq scaling, energy loss ($R_{CP}$),...
- Looking for non-monotonic behavior with energy (eccentricity, yields, slopes,...)
- Comparing to theory predictions
- Fluctuation analyses → critical point

# The Solenoid Tracker At RHIC (STAR)

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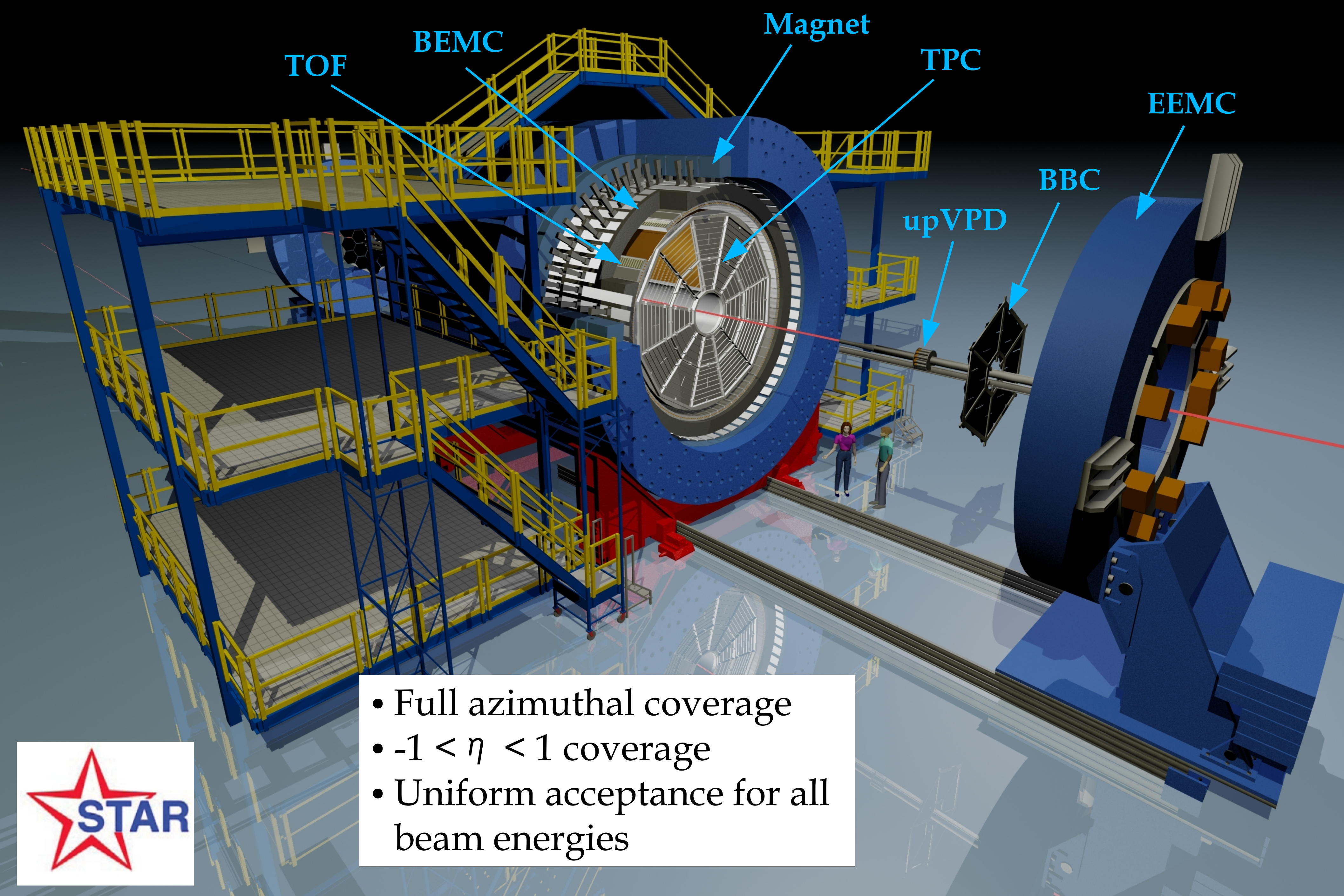
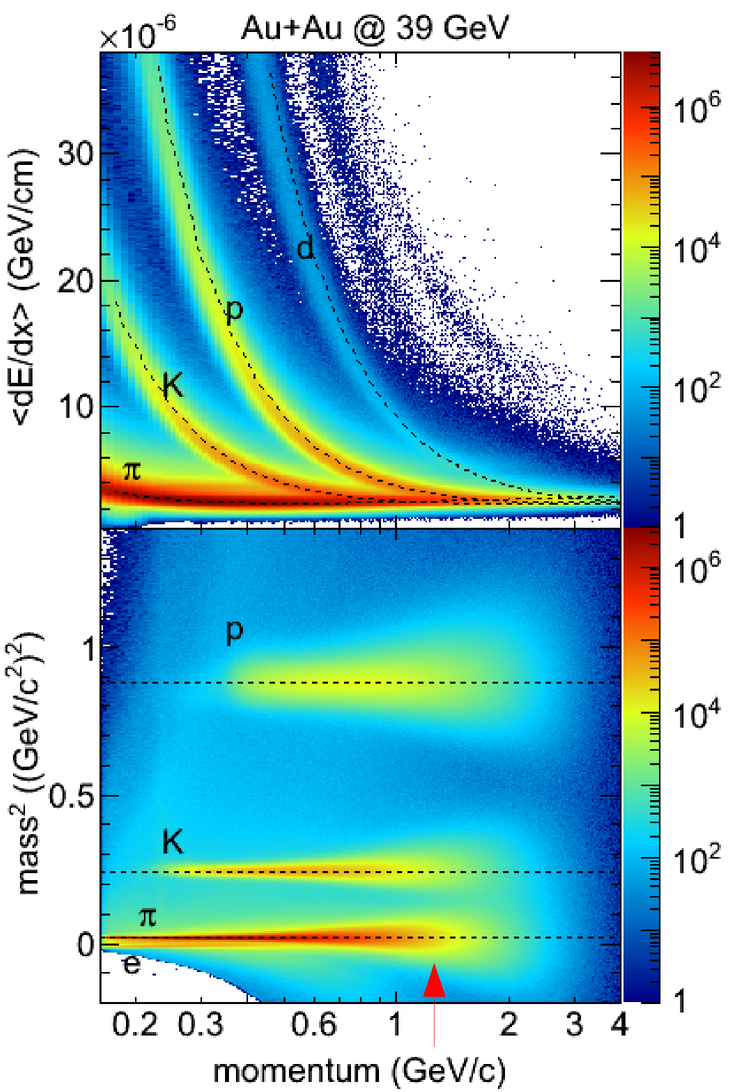
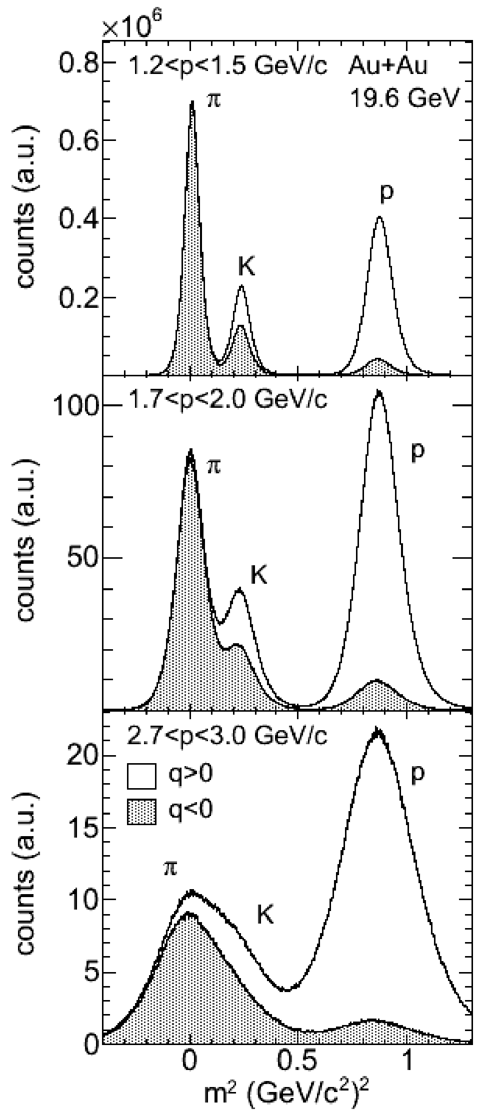



- Full azimuthal coverage
- $-1 < \eta < 1$ coverage
- Uniform acceptance for all beam energies

# Particle Identification

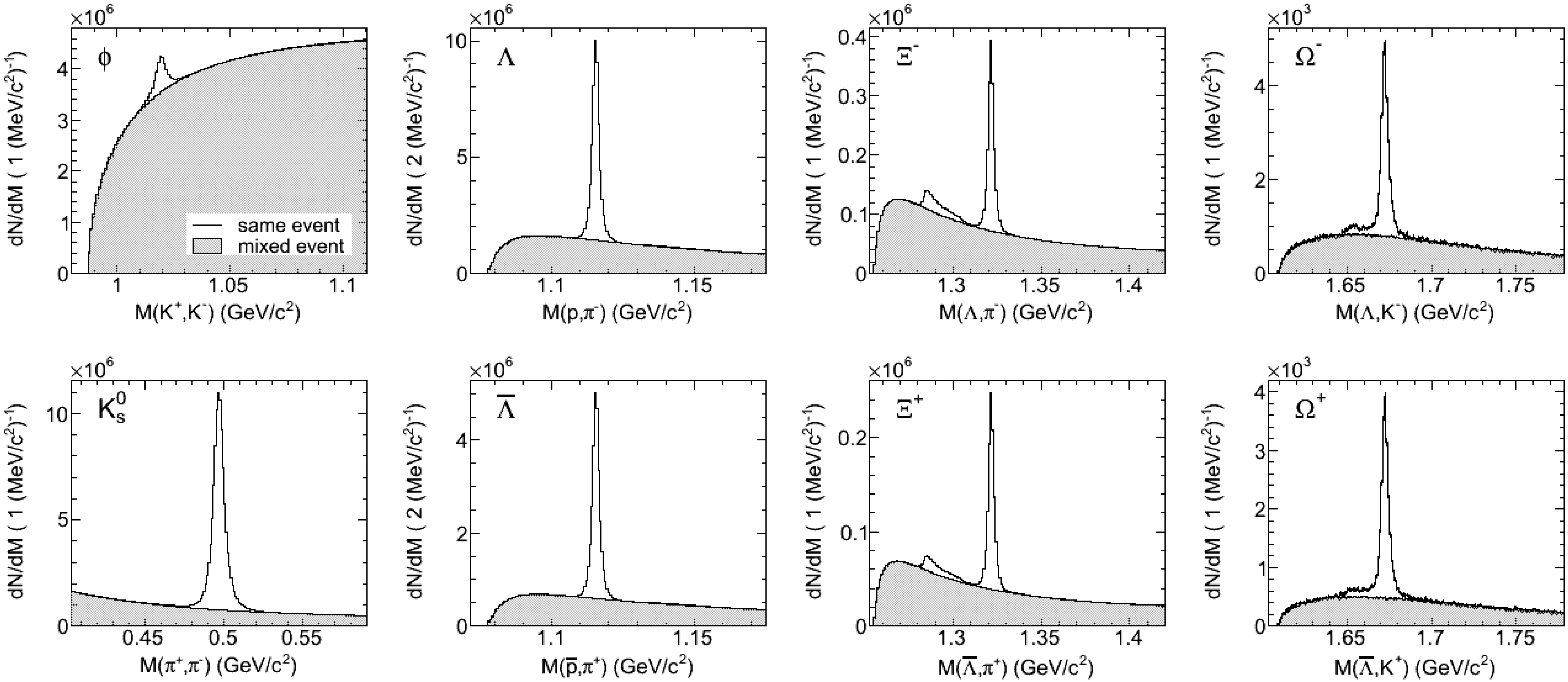


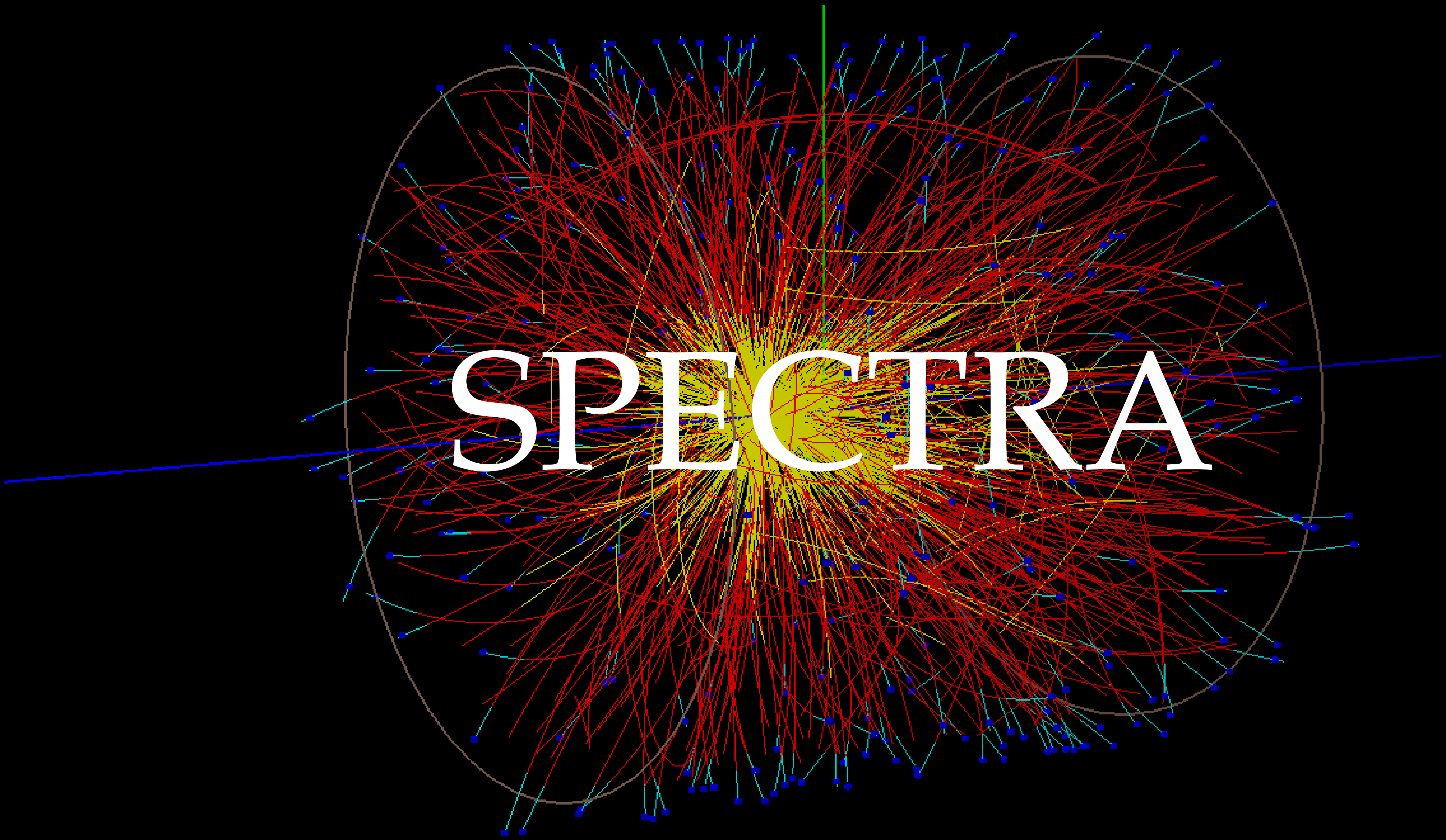

- Specific energy loss dE/dx from TPC
  → up to ~ 0.7 GeV/c clean PID for all particles
- $m^2$ from TOF
  → up to ~ 1.6 GeV/c clean PID for all particles
- Combination improves purity

# Invariant Mass Distributions

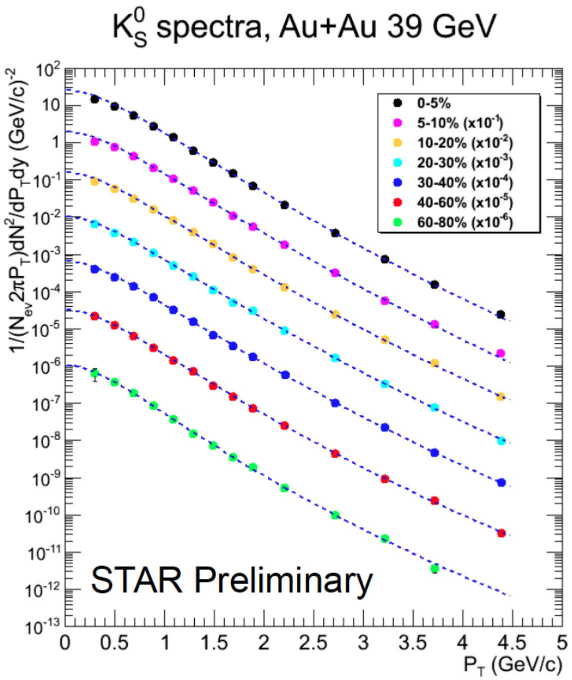
Au+Au @ 62.4 GeV

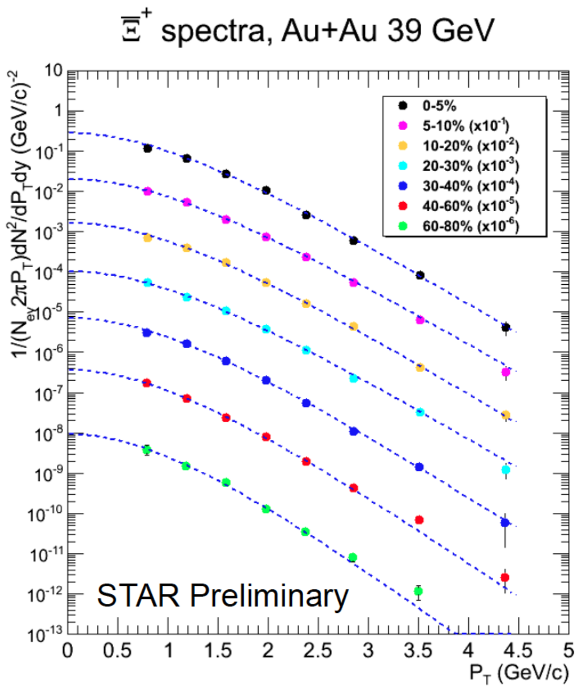


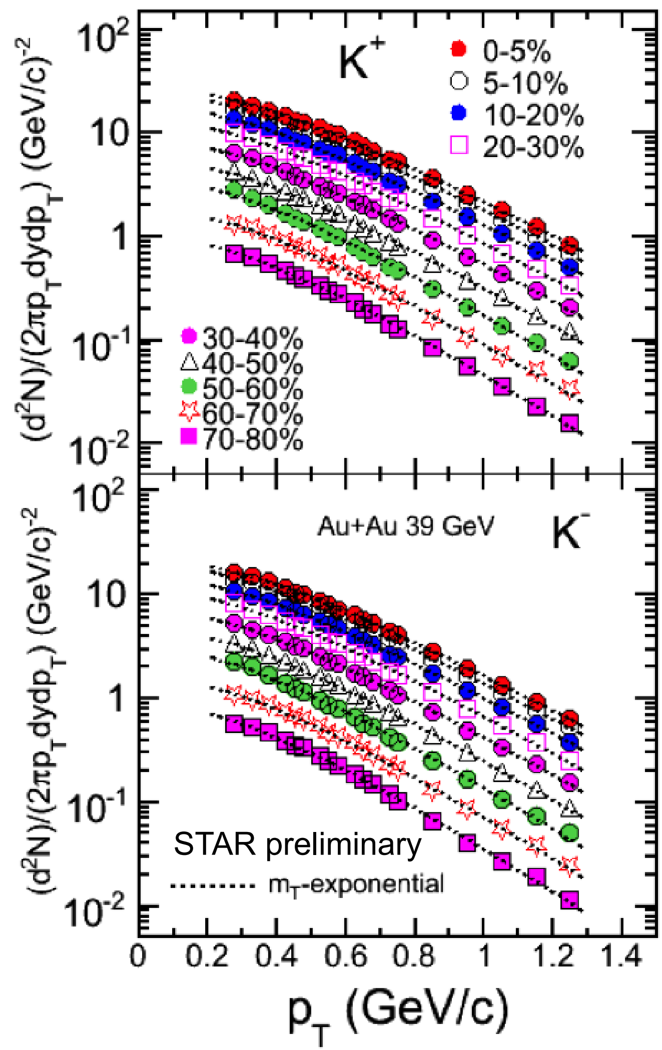

- Topological reconstruction of V0 particles, all daughter particles identified
- Mixed event technique for combinatorial background


SPECTRA

# Particle Spectra



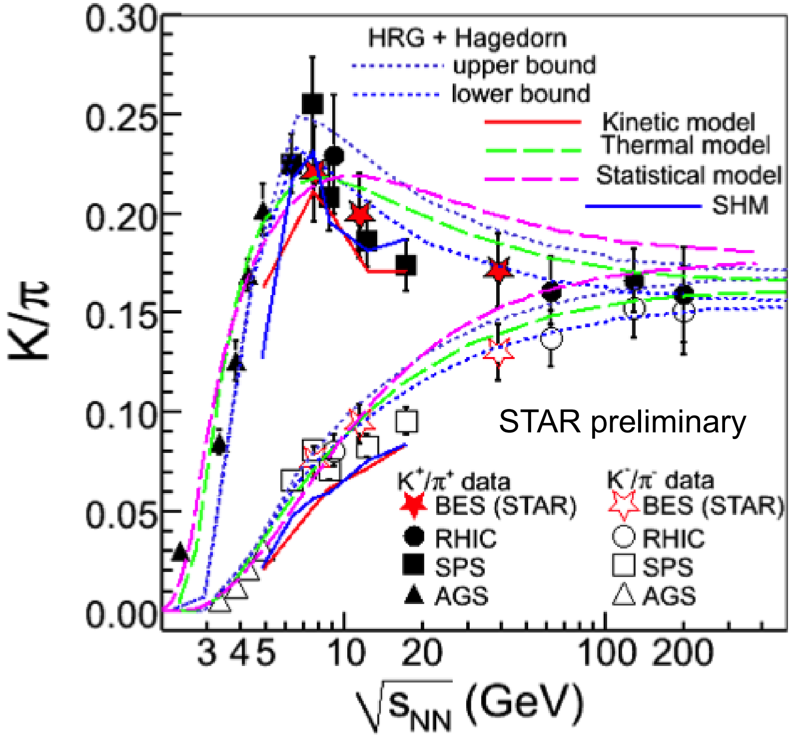



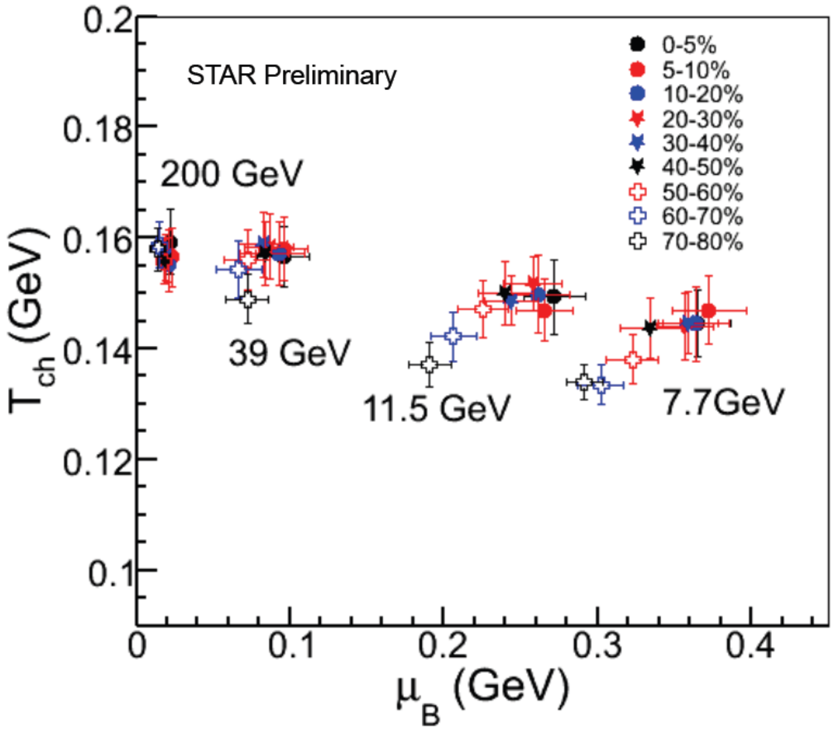

- Charged particles up to 1.3 GeV/c
  → higher $p_T$ in preparation
- $K^0$, $\Lambda$, $\overline{\Lambda}$, $\Xi^{+/-}$, $\Omega^{+/-}$ spectra up to $p_T$ = 4.5 GeV/c
- Corrected for feed down
- **Yields agree well with published results**

  (i.e. NA49: PRC66 (2002) 054902, E802: PRC 58 (1998) 3523)

# Particle Spectra Results

STAR CPOD 2011

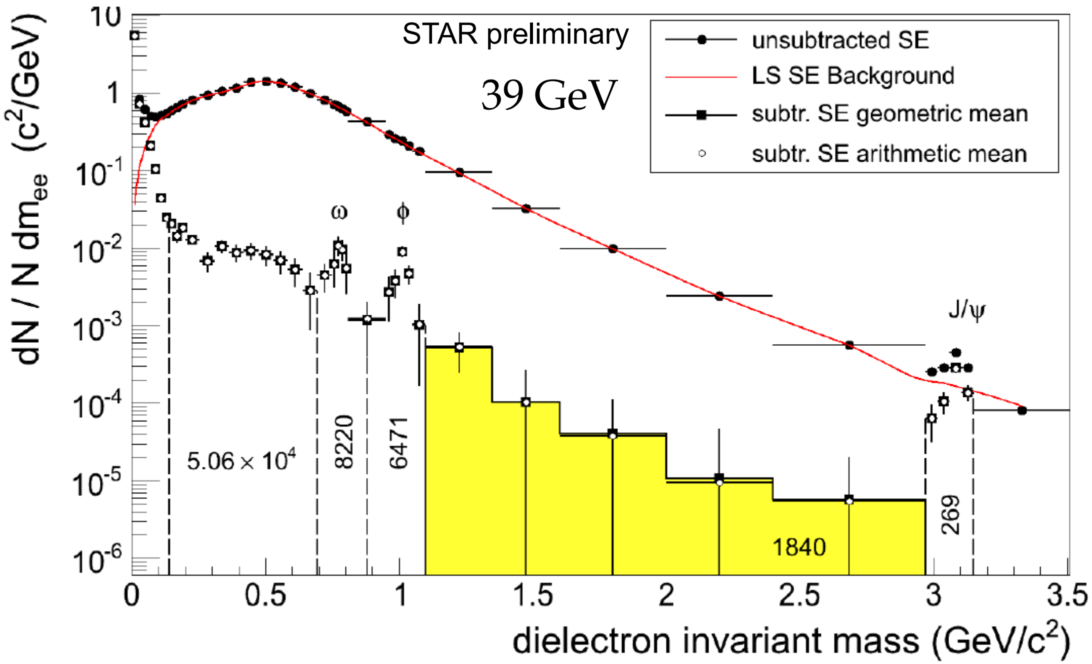


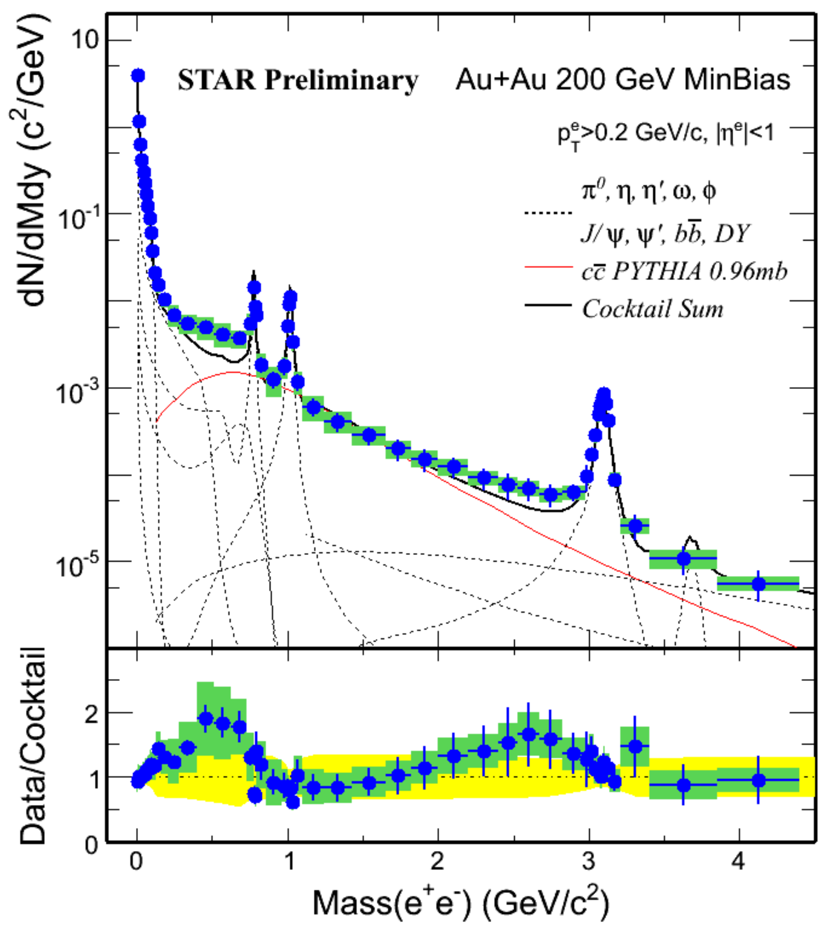




- Transverse momenta spectra contain fundamental information → freeze-out conditions
- K/π ratio as a signature for phase transition? → most likely not

- Grand canonical approach used
- Based on K, π, p ratios
- **Centrality dependence of chemical freeze-out parameters**
- For lower energies significant

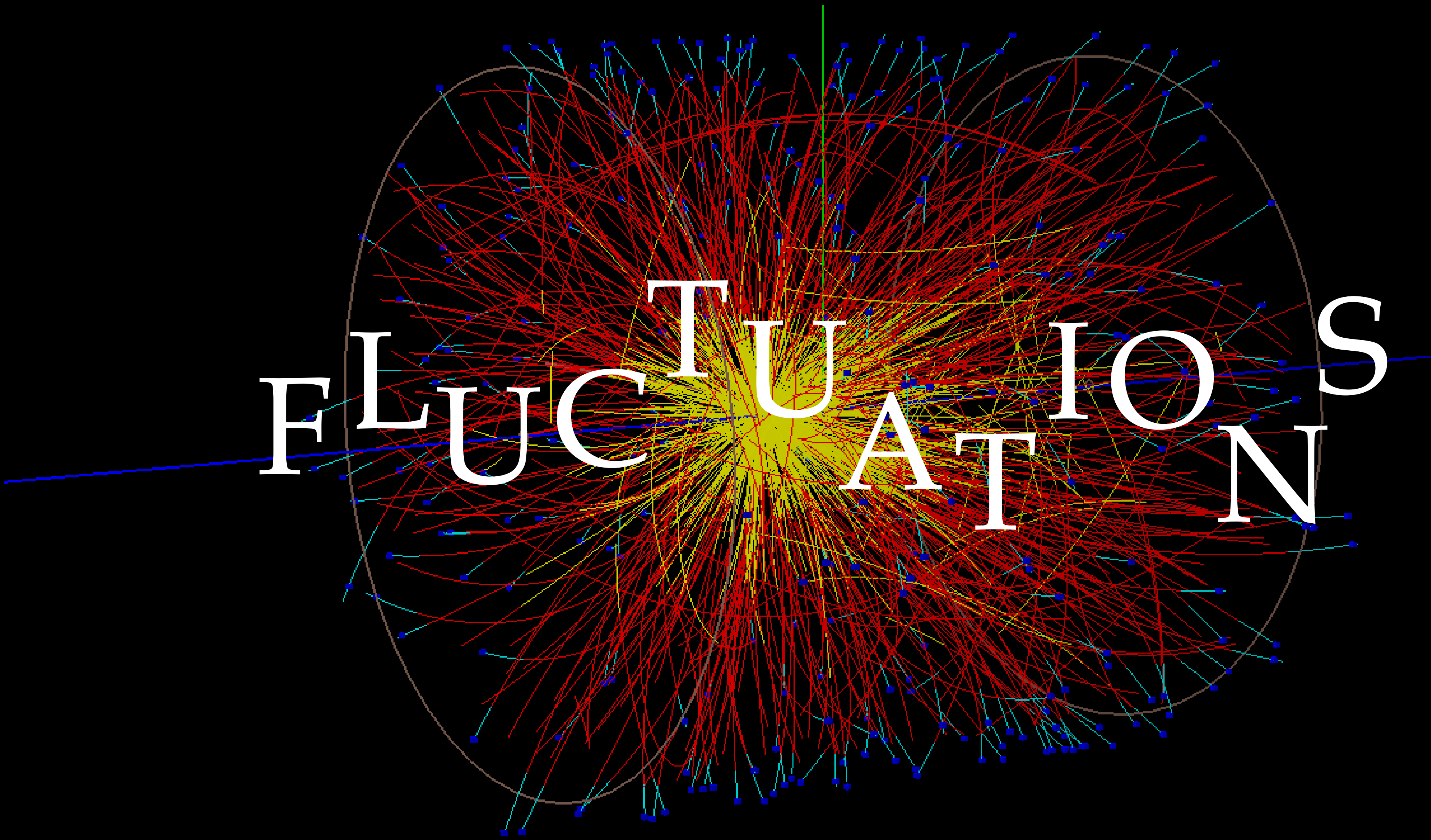
# Di-Lepton Spectroscopy



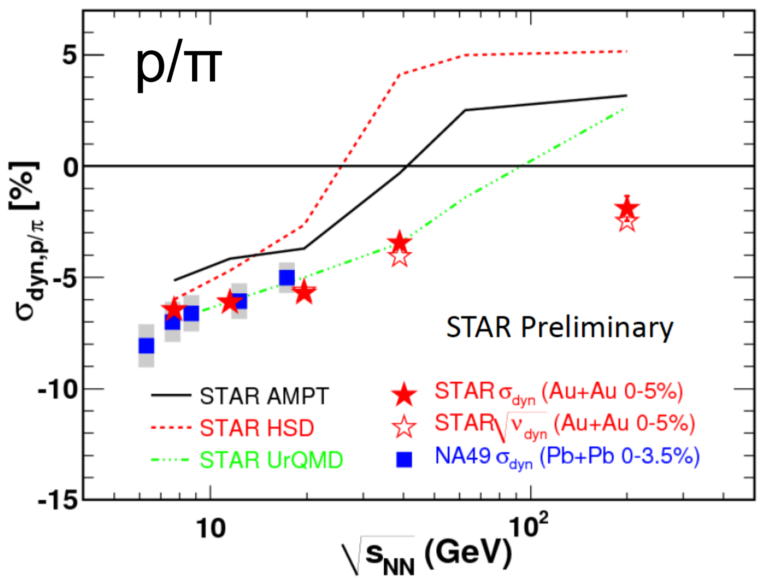



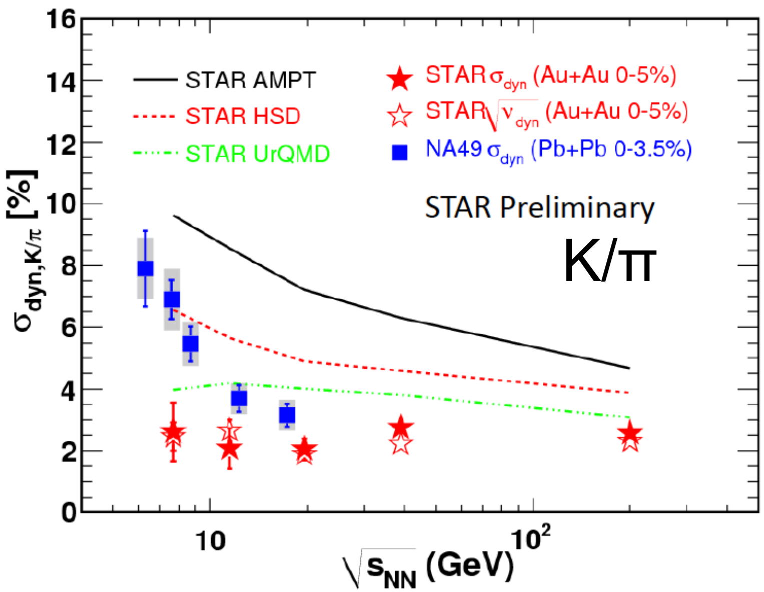

- Prominent peaks for ϕ, ω and J/Ψ
- Enough statistics for differential $p_T$
- 200 GeV "enhancement" observed at low $M_{ee}$
  - → smaller compared to PHENIX results
  - → energy dependence? (19.6, 27, 39, 62.4 GeV)

**STAR CPOD 2011**


FLUCTUATIONS

# K(p)/π Event-by-Event Fluctuations



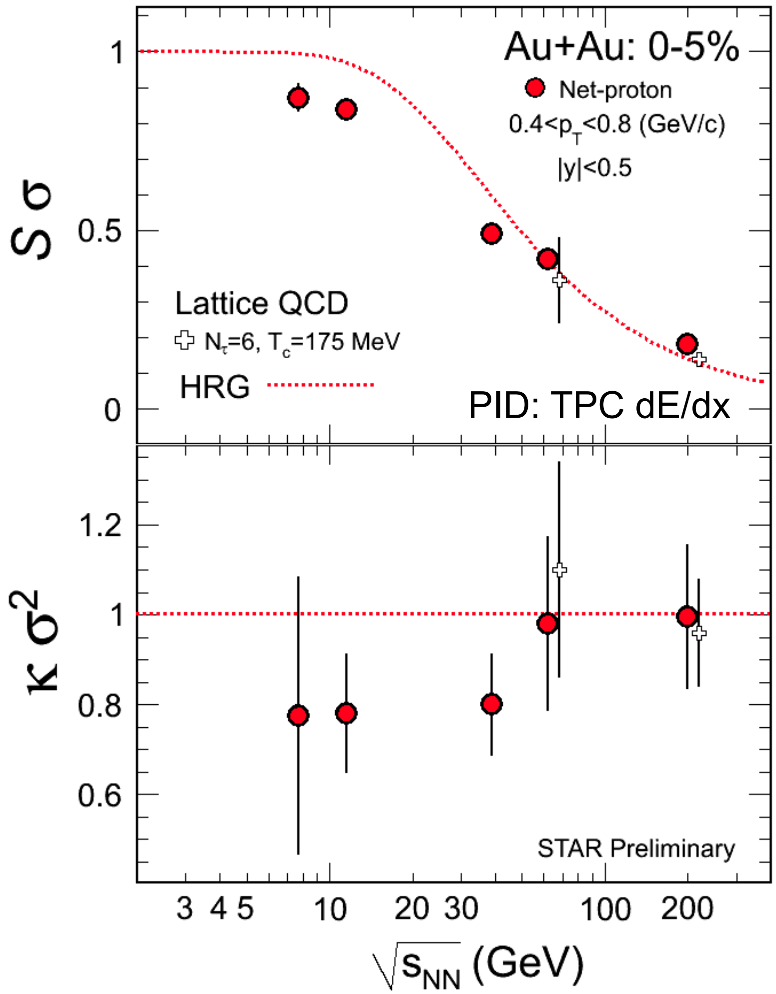




- **STAR observes a monotonic increase for the p/π dyn. fluctuations vs. $\sqrt{s_{NN}}$**
- **Almost constant value for K/π vs. $\sqrt{s_{NN}}$**
- UrQMD can describe the trend for the STAR results
- Good agreement between STAR and NA49 results for $\sigma_{dyn,p/\pi}$
- Significant difference for $\sigma_{dyn,K/\pi}$ especially at 7.7 GeV
- Different acceptance most likely not the reason for the difference
- PID is different for the two experiments

NA49: Phys.Rev.C79 044910 (2009)

STAR CPOD 2011

# Higher Moments of Net-Proton Distributions




The 62.4 and 200 GeV data are published in PRL 105 (2010) 022302

F. Karsch and K. Redlich, Phys. Lett. B 695, 136 (2011)

STAR CPOD 2011

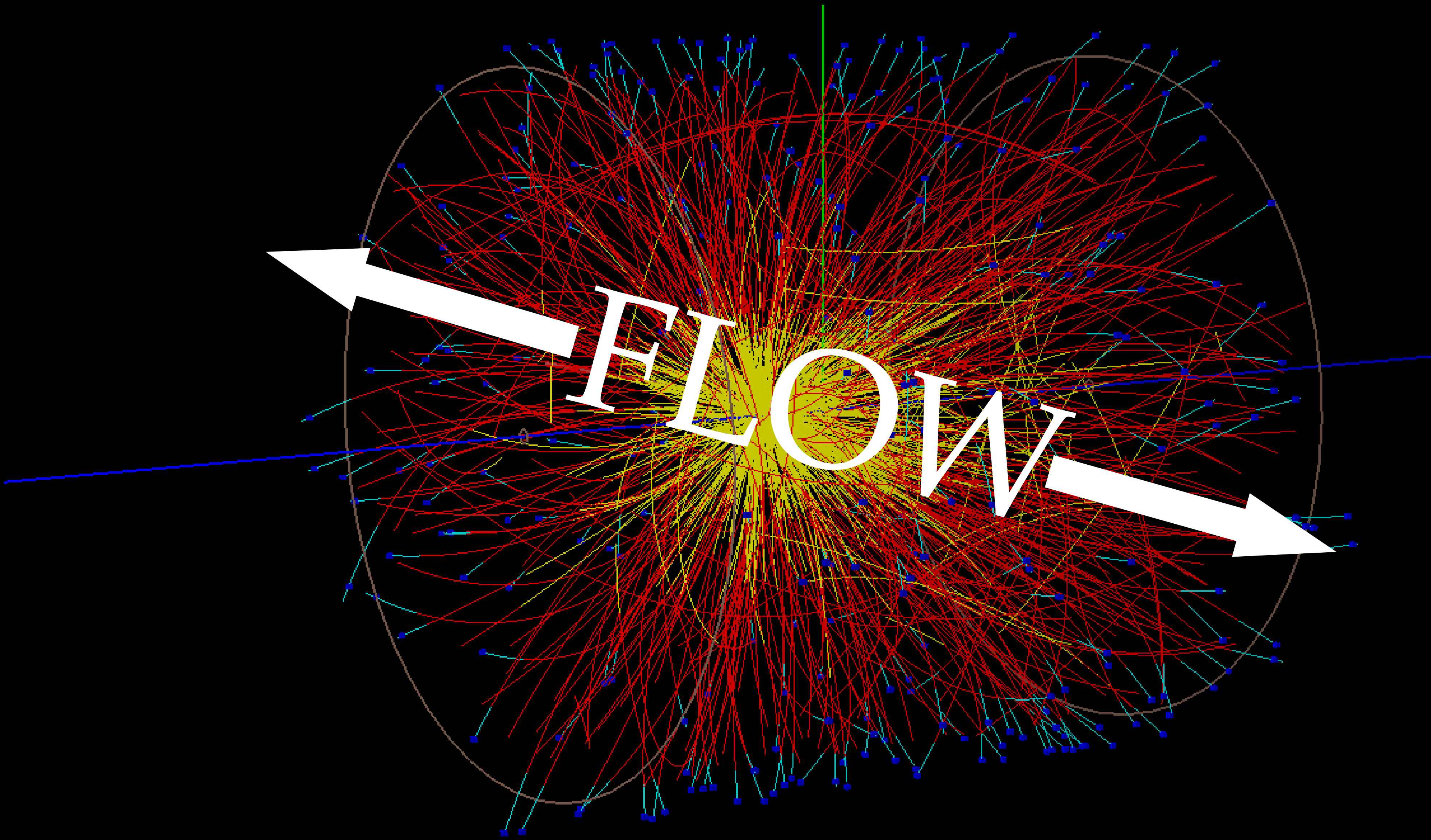
→ Today: Daniel McDonald, 15:20

- Conserved quantity: ~Baryons
- Product of moments cancels out volume effects
- Data are consistent with HRG model at high energies
- No indication for a non-monotonic behavior so far
- Analysis for 19.6 and 27 GeV is ongoing
- Autocorrelation between centrality definition window and analysis window is being studied → more important at the lower energies!
- PID methodology (rapidity, $p_T$ cuts, PID method) studies are ongoing
- More accurate statistical error propagation is ongoing

$\kappa\sigma^2 \sim \chi^{(4)}/\chi^{(3)}$ $S\sigma \sim \chi^{(3)}/\chi^{(2)}$ $\sigma^2/M=\chi^{(2)}/\chi^{(1)}$

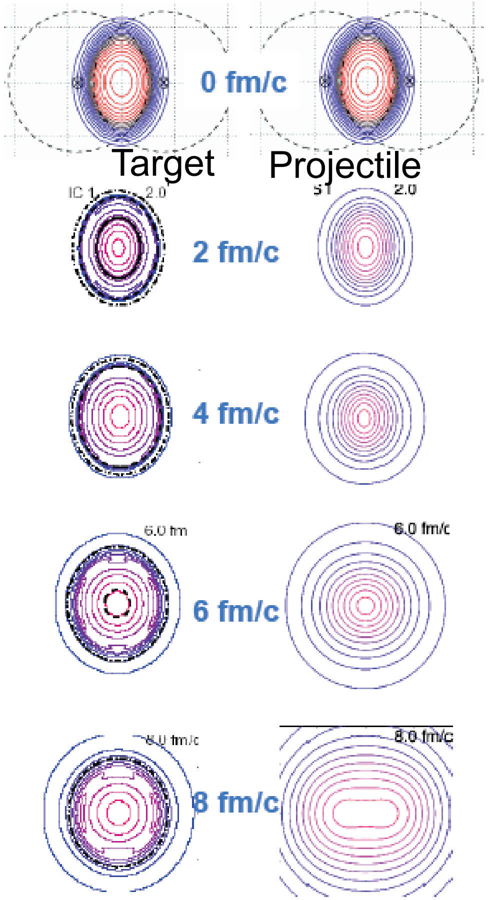
Product of moments cancel volume effect

F. Karsch et al, Phys. Lett. B 695, 136 (2011).
M.Cheng et al, Phys. Rev. D 79, 074505 (2009)5


FLOW

# Freeze out Eccentricity from Azimuthal HBT

Spatial eccentricity:



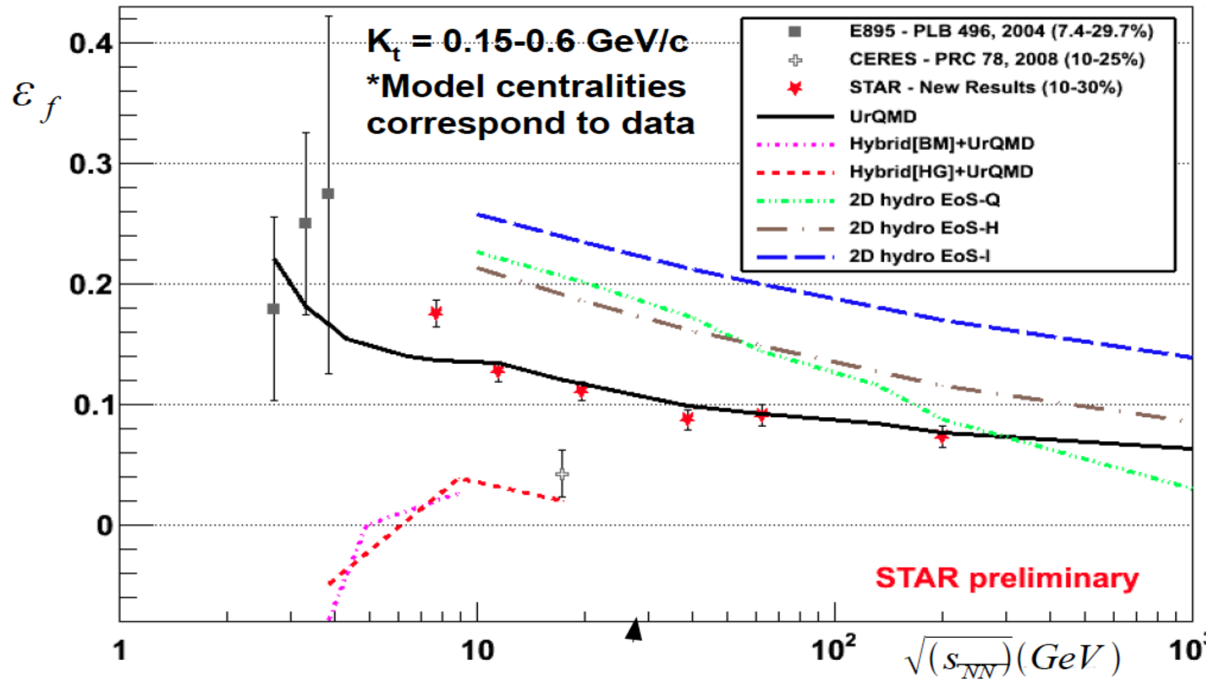

With 1st order P.T.

Without 1st order P.T.

Kolb and Heinz, 2003, nucl-th/0305084

STAR: DNP2011

Lisa, Frodermann, Graef, Mitrovski, Mount, Petersen, Bleicher, *New J. Phys.* 2011, arxiv: 1104.5267




- **Monotonic decrease of $\varepsilon_f$ from 7.7 to 200 GeV of the STAR data**
- UrQMD appears to predict the STAR data most closely

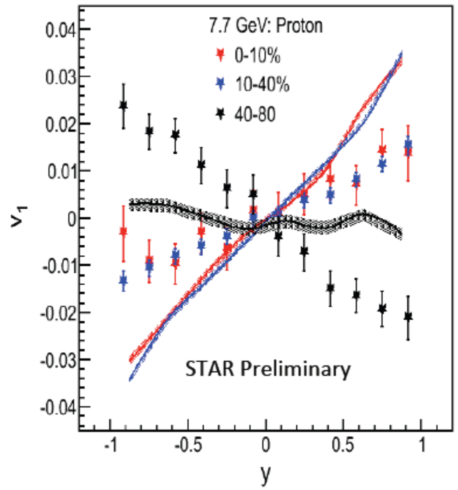
# Directed Flow of Protons

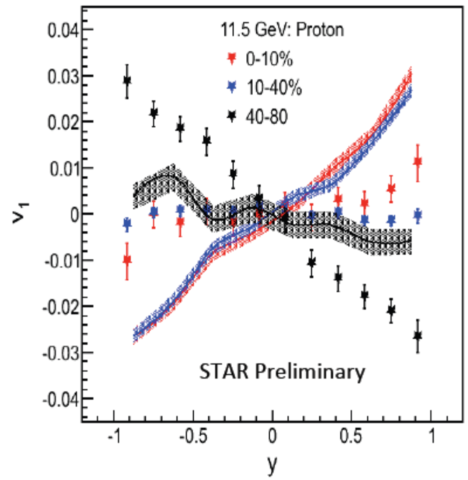
**STAR SQM 2011**

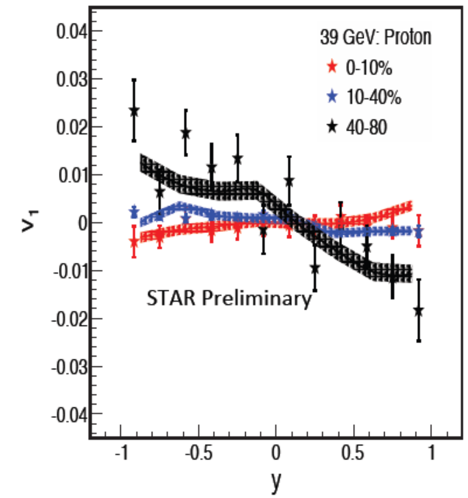
- **$dv_1 / dy$ of protons for 10-40% most central collisions shows a sign change between 7.7 and 11.5 GeV**

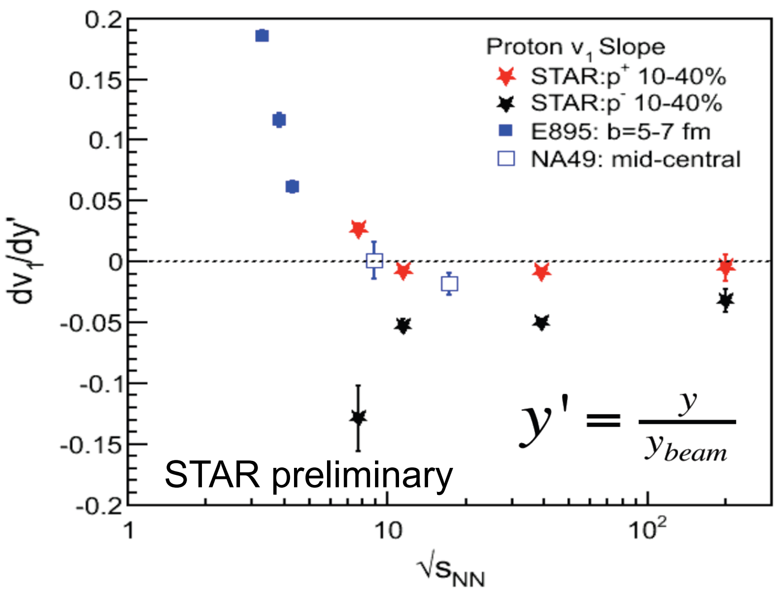
  → effect from transported quarks at lower energies?

- UrQMD (bands) predicts the correct trend but not the magnitude

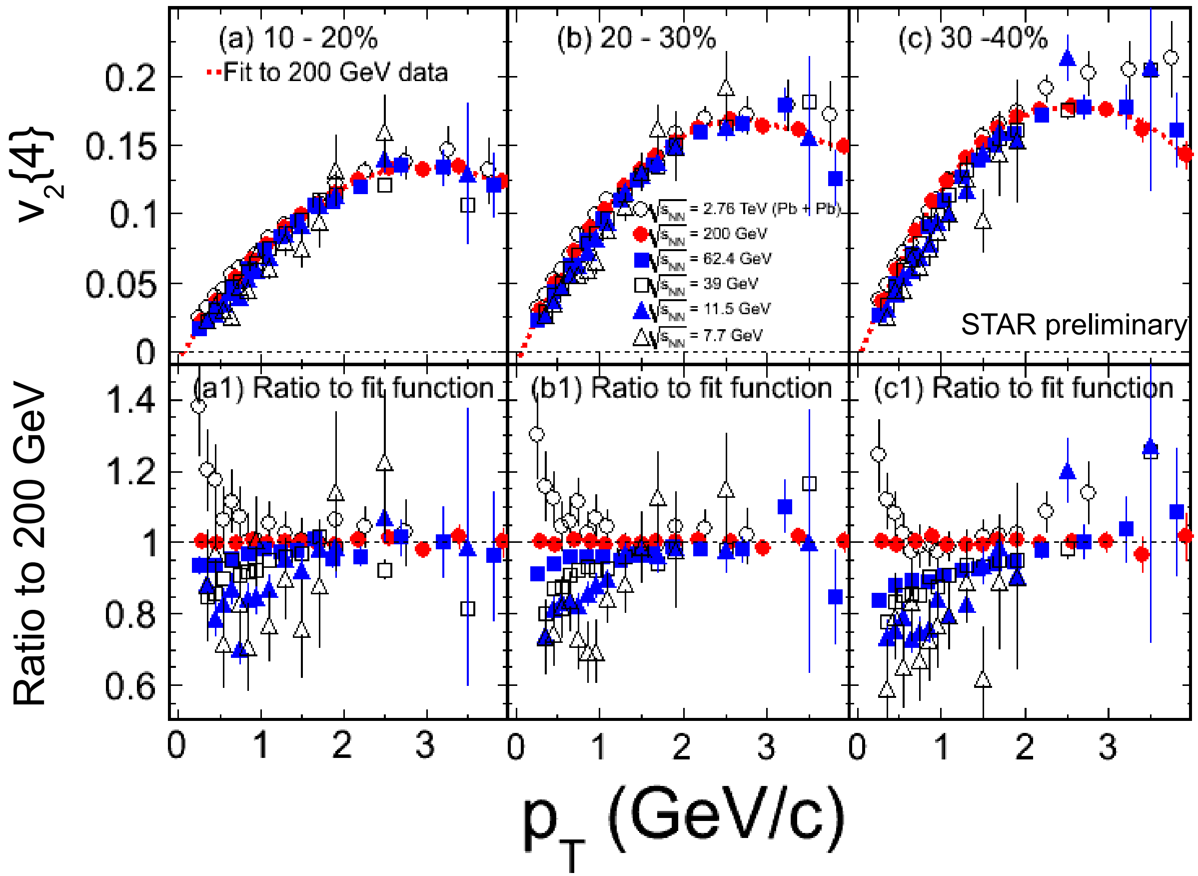


# Elliptic Flow of Charged Hadrons

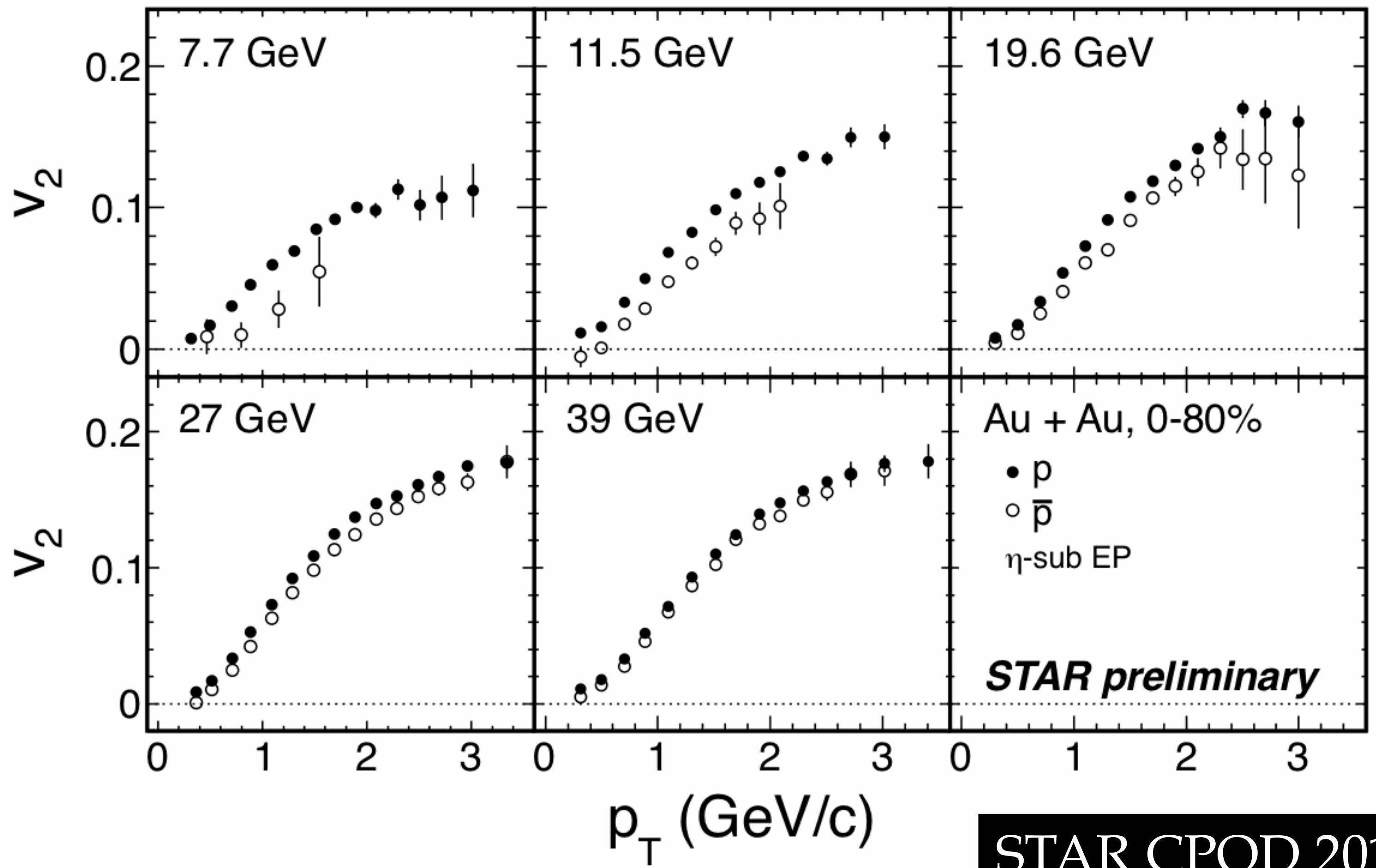



STAR SQM 2011

ALICE data: Phys. Rev. Lett. 105, 252302 (2010)

- $v_2\{4\}$ cumulant method $\rightarrow$ 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 $\sqrt{s_{NN}}$
- Baseline measurement for identified particle $v_2$

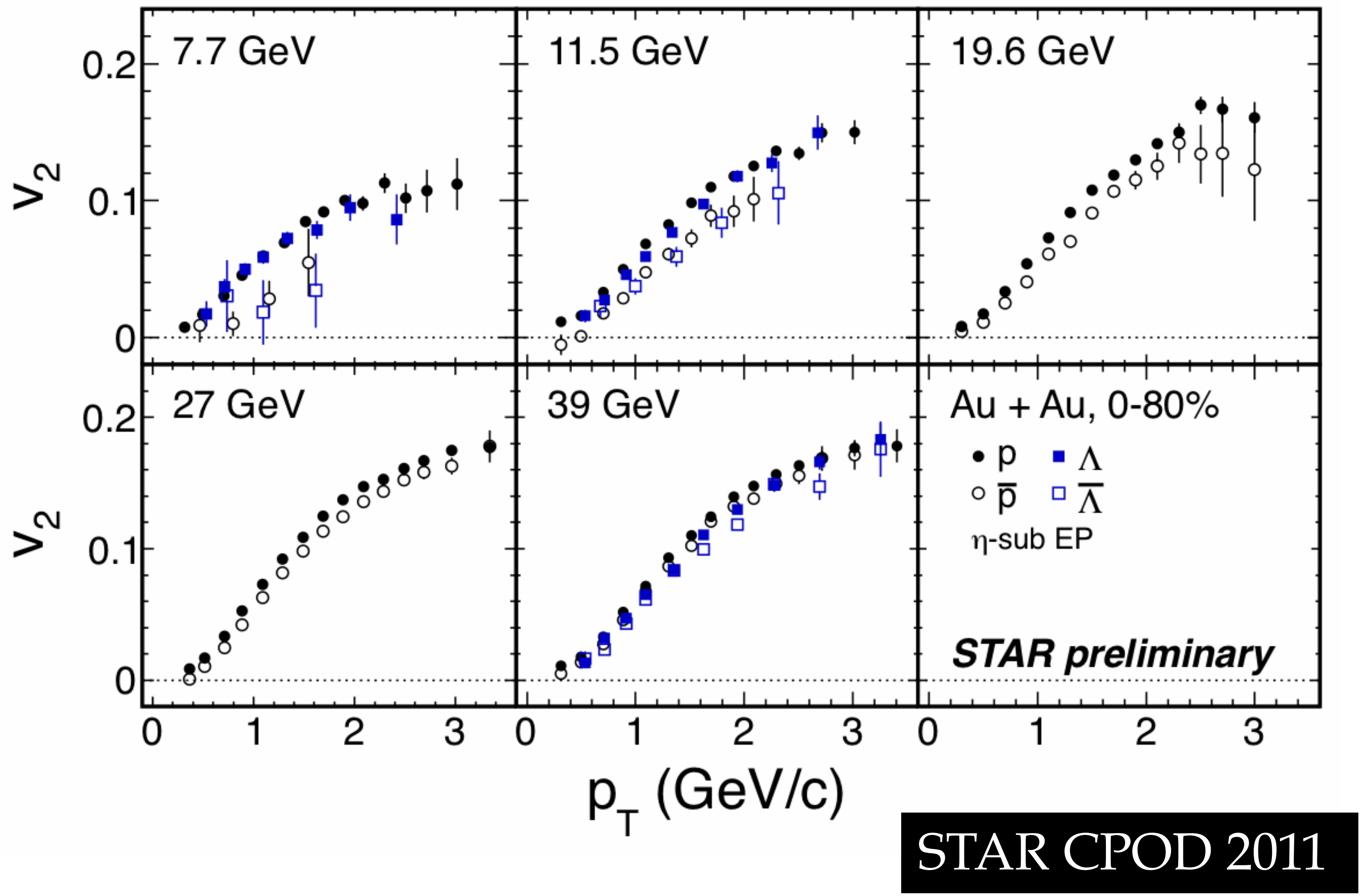
# Elliptic Flow of p and $\bar{p}$




STAR CPOD 2011

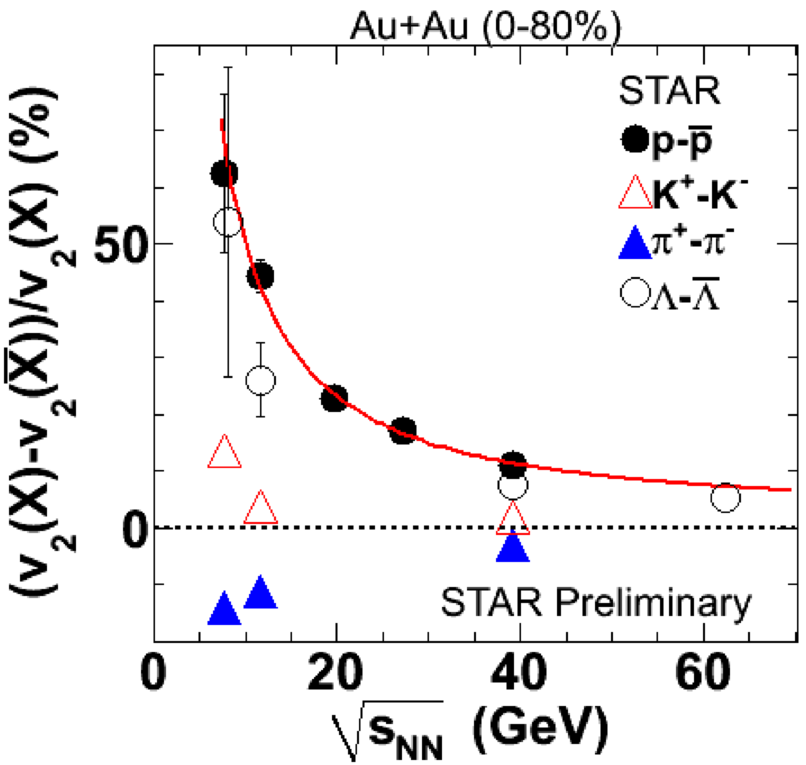
- Increasing larger difference between p and $\bar{p}$ with decreasing energy
- $v_2(p) > v_2(\bar{p})$

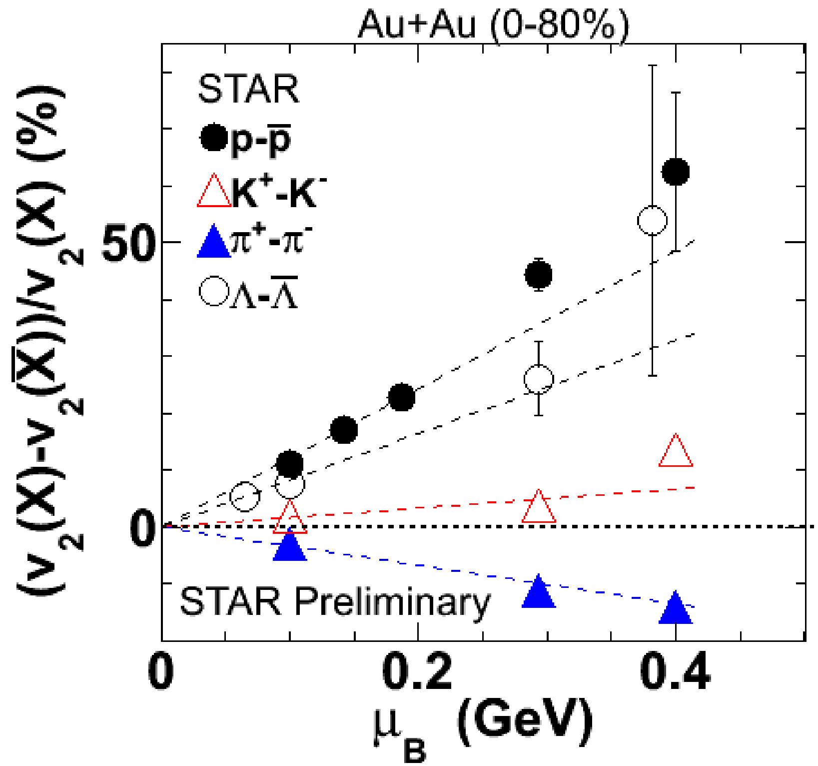
# Elliptic Flow of $\Lambda$, $\overline{\Lambda}$




- **Very similar to protons and anti-protons**
- Systematically higher $v_2$ of $\Lambda$ compared to $\overline{\Lambda}$ at lower energies

# $v_2$ Difference vs. $\sqrt{s_{NN}}$ and $\mu_B$




$\mu_B$* values obtained from central reactions

$\sqrt{s_{NN}} \rightarrow \mu_B$ from: http://arxiv.org/pdf/1111.2406v1.pdf

- **Small difference at higher energies, large increase at lower energies**
- Difference increases with $\mu_B$

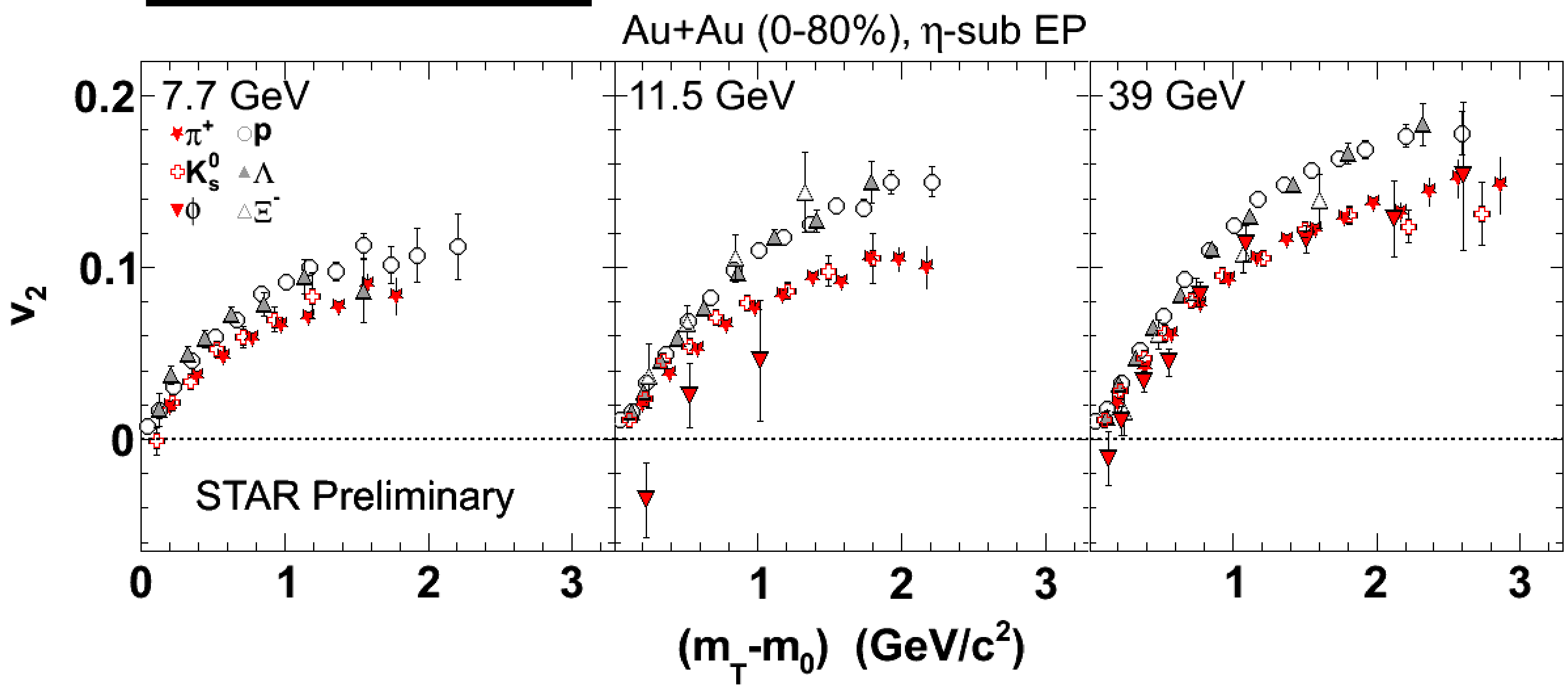
- Dominance of hadronic phase?
- Baryon/quark transport?*
- Hadronic potentials?**

STAR CPOD 2011

** J. C. Dunlop et al., **PRC84**, 044914 (2011)*
*** J. Xu et al., arXiv:1201.3391 [nucl-th]*

# Elliptic Flow of Particles vs. $m_T$

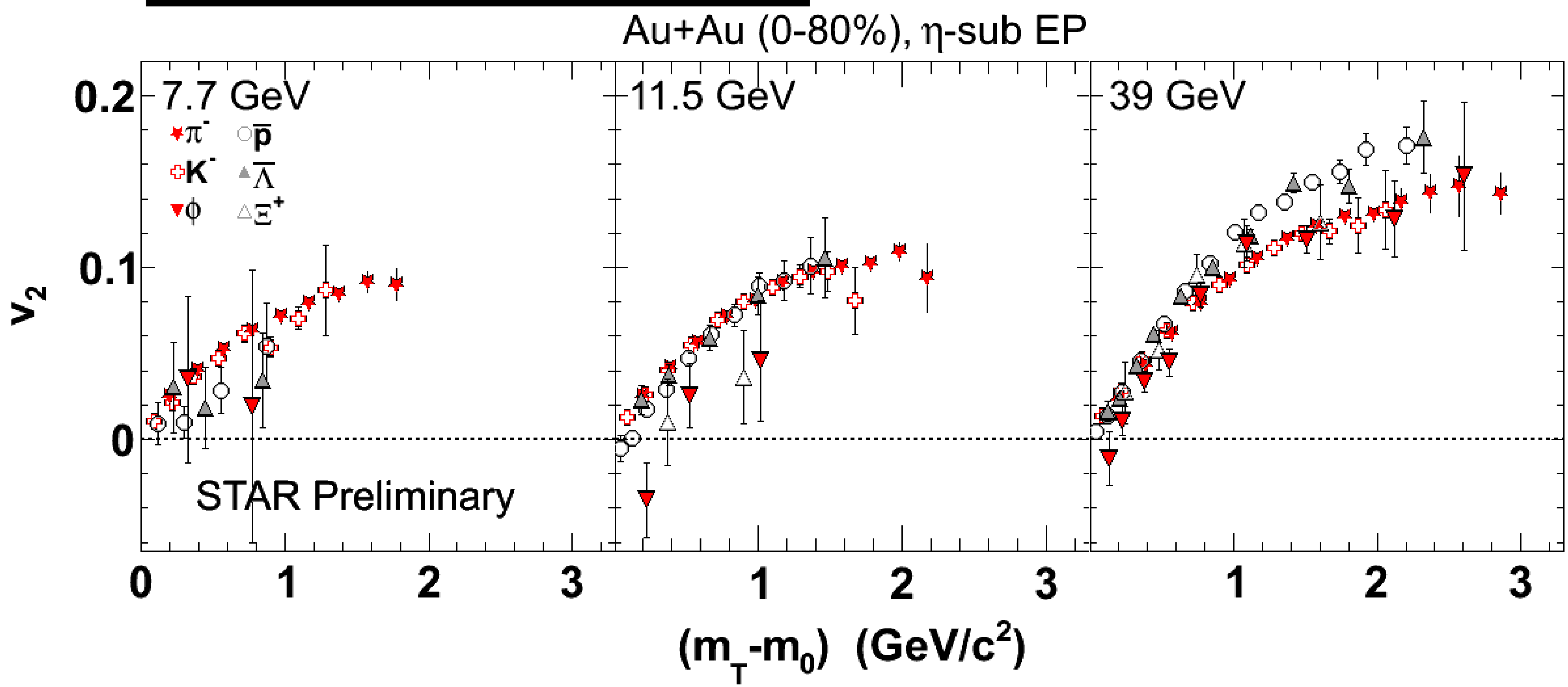
STAR CPOD 2011




- Clear baryon ↔ meson splitting at 11.5 and 39 GeV
- Splitting smaller at 7.7 GeV, $\phi$ at 11.5 GeV → different?

# Elliptic Flow of anti-Particles vs. $m_T$

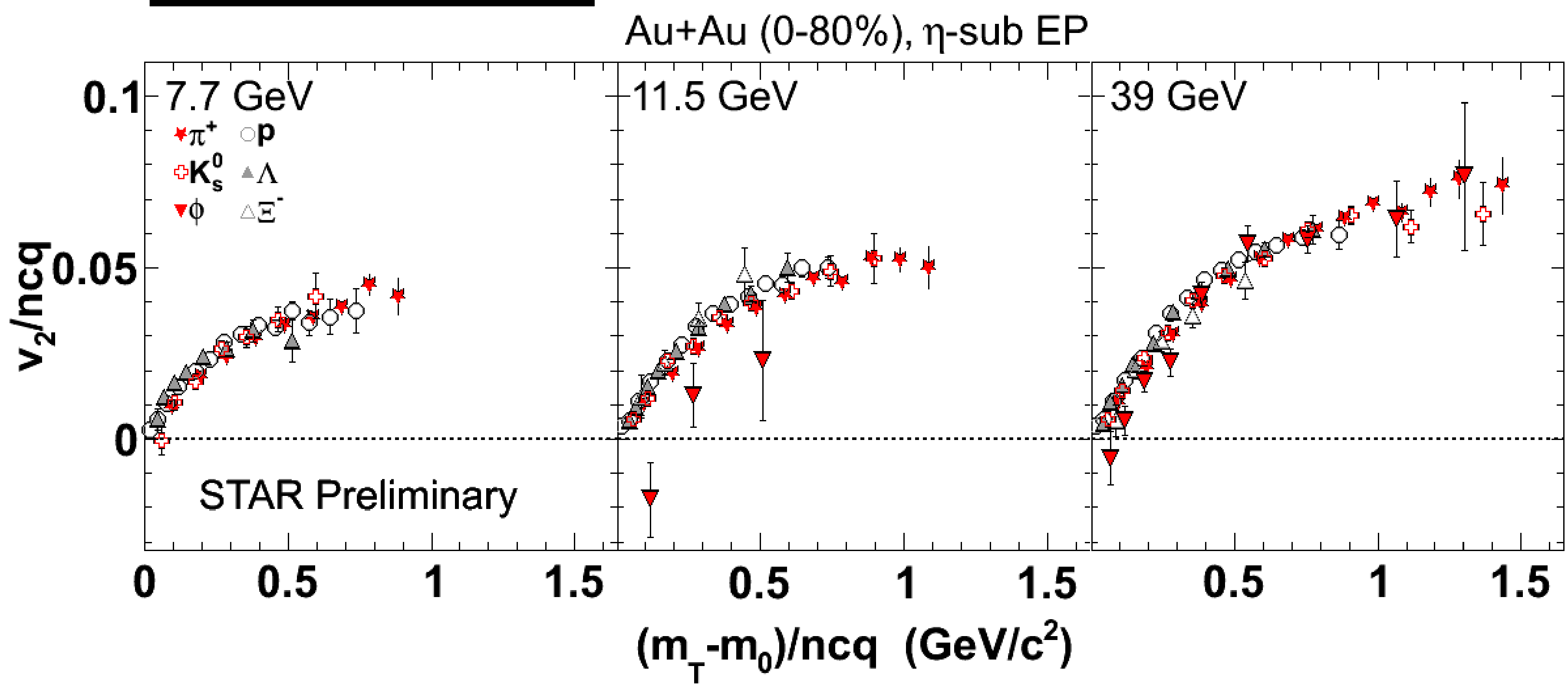
STAR CPOD 2011/QM 2011




- Clear baryon ↔ meson splitting at 39 GeV
- **At 7.7 and 11.5 GeV the splitting is small/gone?**

# NCQ Scaling of Particles vs. $m_T$

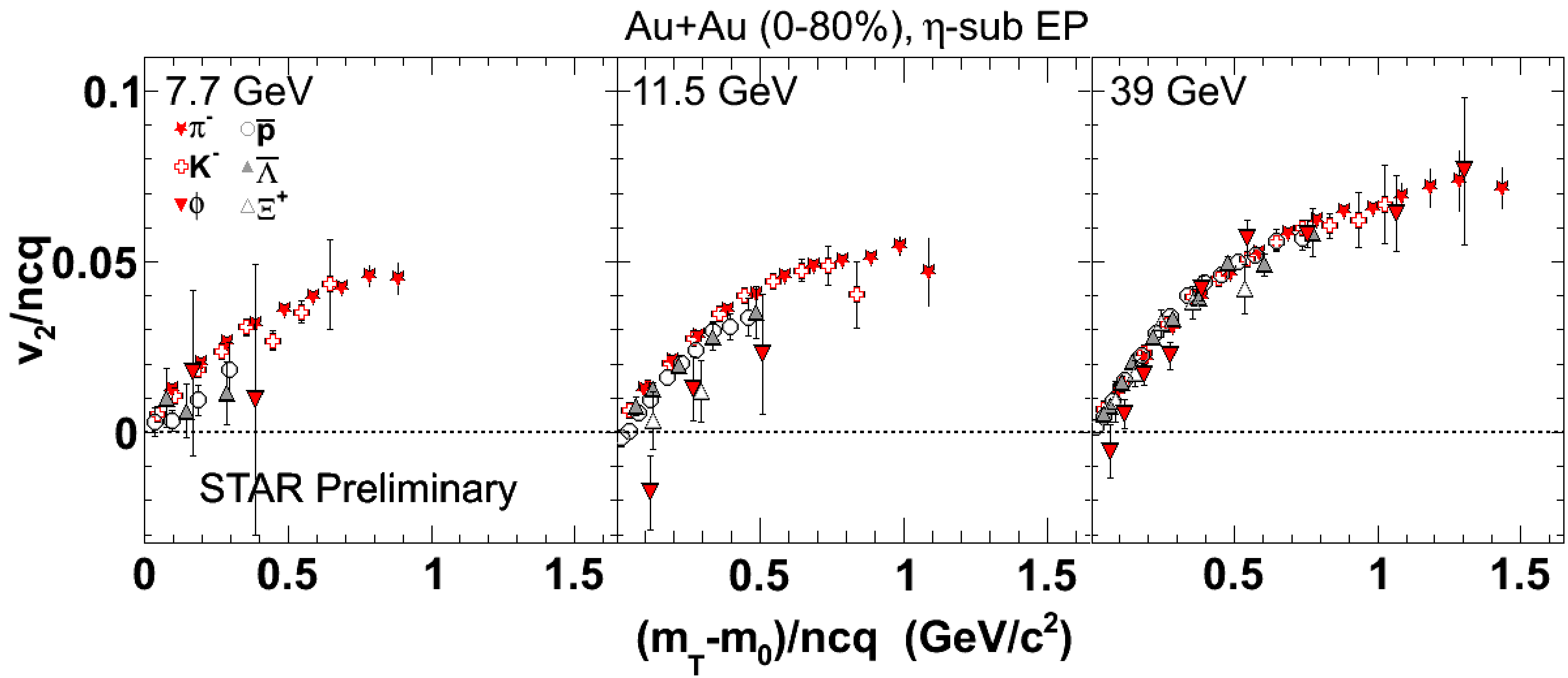
STAR CPOD 2011




- **Number-of-Constituent Quark scaling holds for particles**
- $\phi$ -mesons show different trend at 11.5 GeV, but no statistics at high $m_T$

# NCQ Scaling of anti-Particles vs. $m_T$

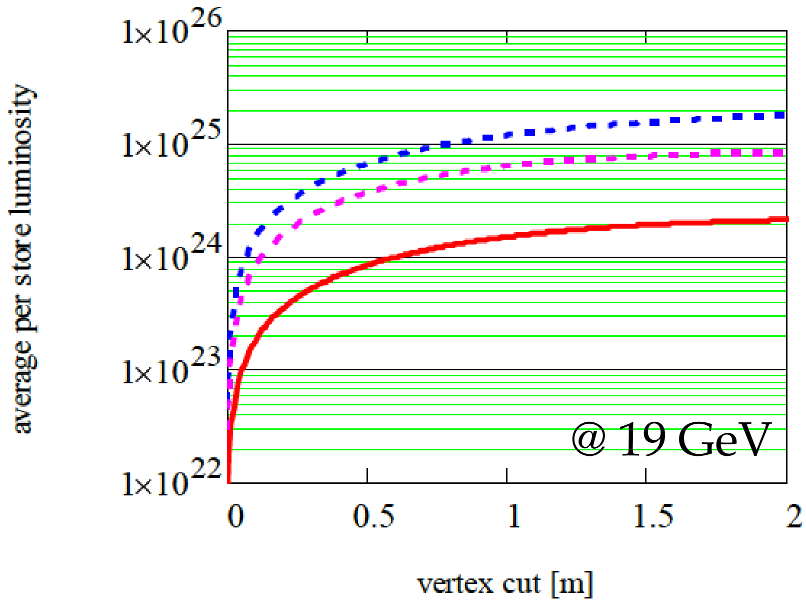
STAR CPOD 2011/QM2011




- **Number-of-Constituent Quark scaling holds at 39 GeV, looks different at 7.7 and 11.5 GeV compared to particles**
- $\phi$ -mesons show different trend, but no statistics at high $m_T$

# Outlook and Future Perspectives

- Most analyses will be finalized soon for all BES energies
- $R_{CP}$, centrality dependence, di-lepton $p_T$ spectra, higher order cumulants, LPV, $v_3$, $v_n$...
- Take data at an additional energy (15 GeV)?
- 5 GeV in collider mode, lower energies in fixed target mode?
- BES Phase II with electron cooling + longer bunch lengths $\rightarrow$ more statistics at 7.7 and 11.5 GeV




Luminosity upgrade with electron cooling + longer bunch lengths

*Alexei Fedotov and Mike Blaskiewicz*
*C-AD, Brookhaven National Laboratory*
***POTENTIAL FOR LUMINOSITY IMPROVEMENT FOR LOW-ENERGY RHIC OPERATION WITH LONG BUNCHES***

# Summary

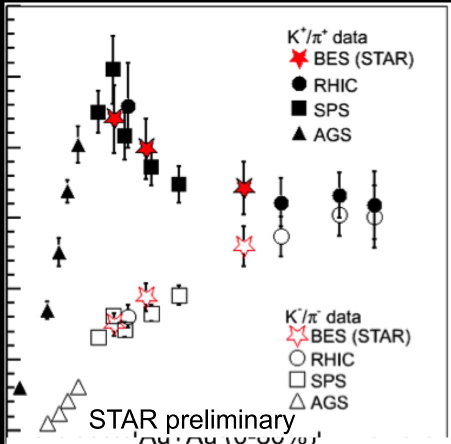
**Spectra results:** - Excellent agreement with published results
- Centrality dependence of freeze-out parameters

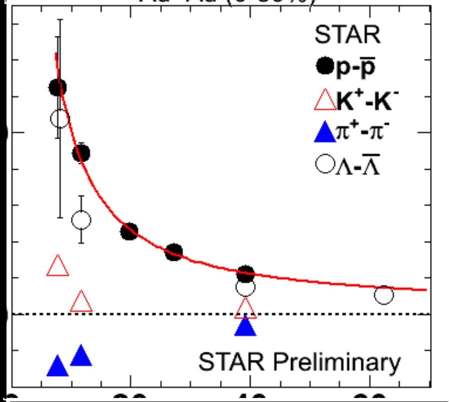
**Event anisotropy:** -Difference between particles and corresponding anti-particles in $v_2$
-ϕ-meson $v_2$ deviates from other hadrons at 11.5 GeV
→ partonic phase becomes less important?

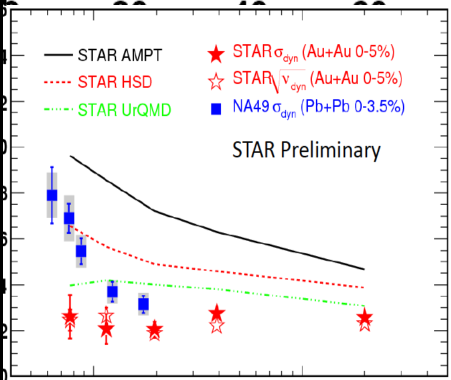
**Azimuthal HBT**: Smooth decrease with increasing energy

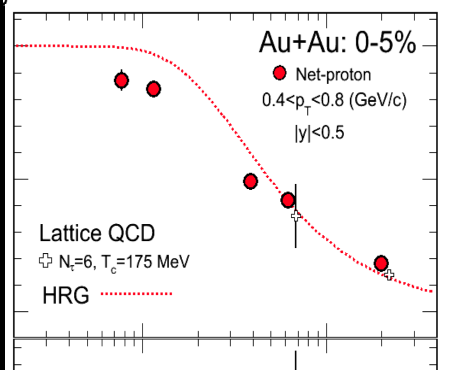
**K/π fluctuations**: Flat as a function of $\sqrt{s_{NN}}$, discrepancy at lower energies with NA49 results

**Higher moments:** In agreement with HRG model at higher energies.



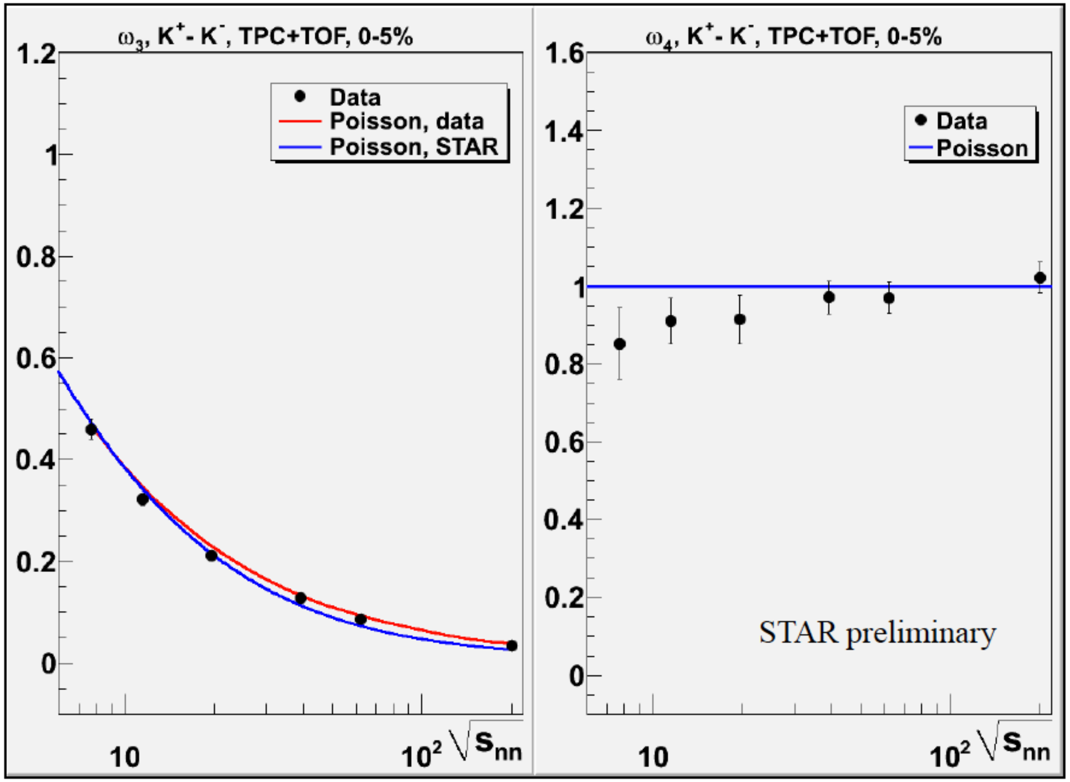



# BACKUP

# Higher Moments of Net-Kaon Distributions

STAR APS Fall Meeting 2011
$\longrightarrow$ Today: Daniel McDonald, 15:20

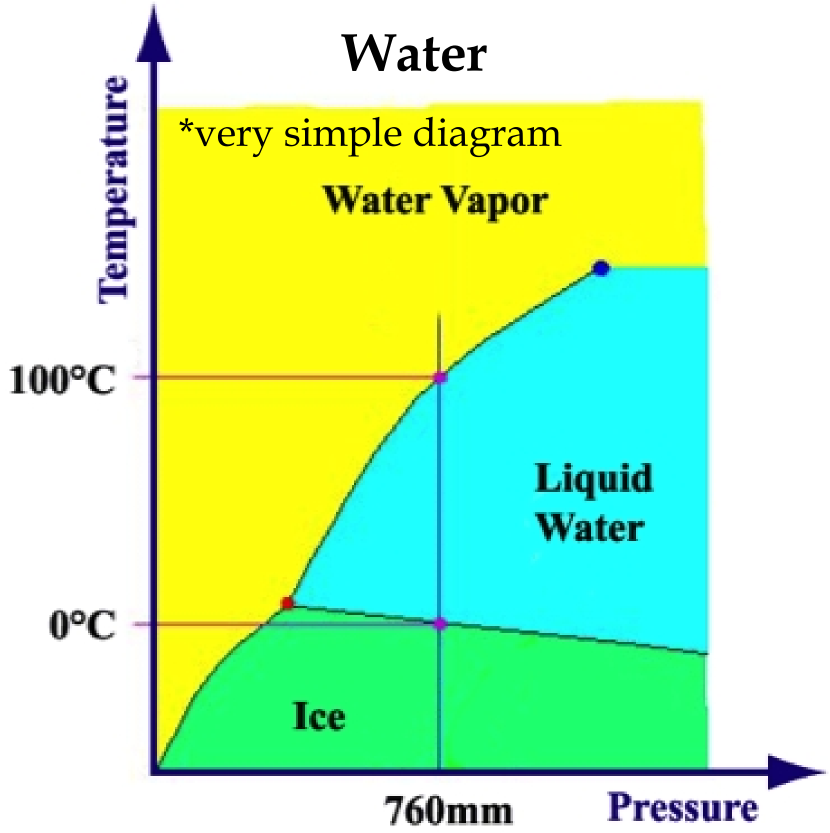
$$\kappa_{2x} \equiv \langle\langle x^2 \rangle\rangle \qquad \omega_{ip} \equiv \frac{\kappa_{ip}}{\langle N_p \rangle}$$
$$\kappa_{3x} \equiv \langle\langle x^3 \rangle\rangle$$

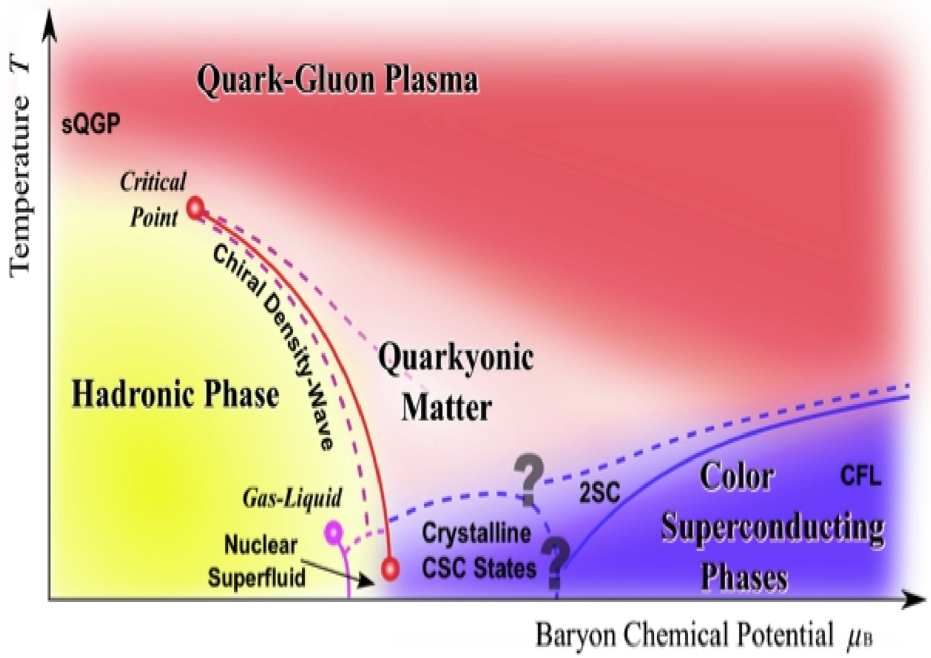



- Conserved quantity: ~Strangeness
- Intensive normalized cumulants
- Use of time-of-flight
- Different acceptance used for centrality definition and analysis
- **No dramatic enhancement with respect to Poisson so far**

*Poisson, STAR = efficiency corrected

# What do we want to learn?

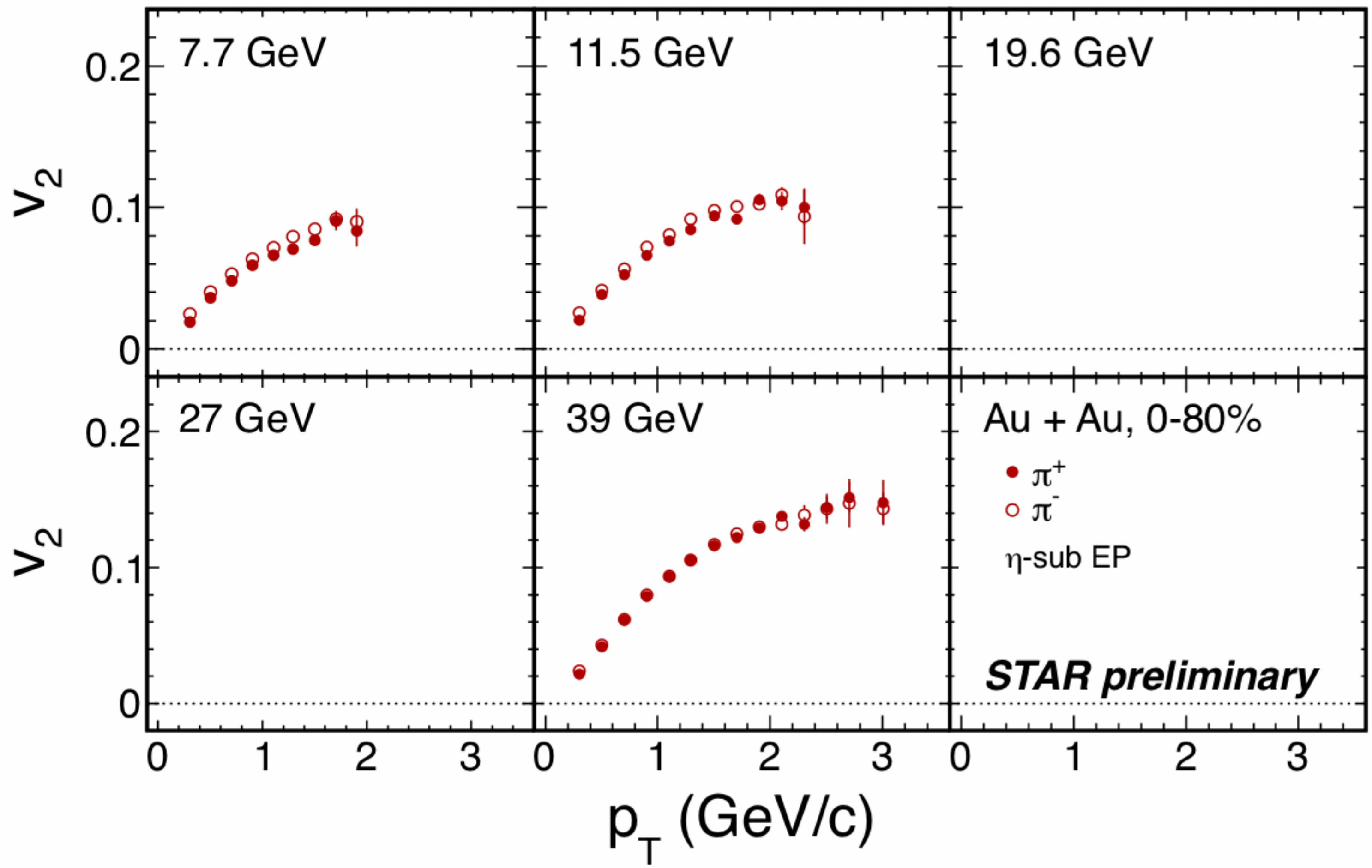



K. Fukushima and T. Hatsuda, Rept. Prog. Phys., 014001(2011); arXiv: 1005.4814

- Only very few points and lines are known on the QCD phase diagram
  → phase transition line: not known
  → critical point: not known
- Use Heavy-Ion reactions to study the diagram!

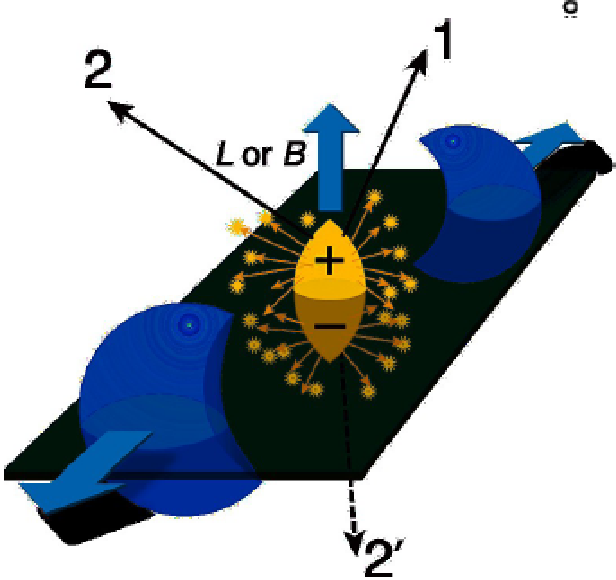
# Elliptic Flow of $\pi^+$, $\pi^-$



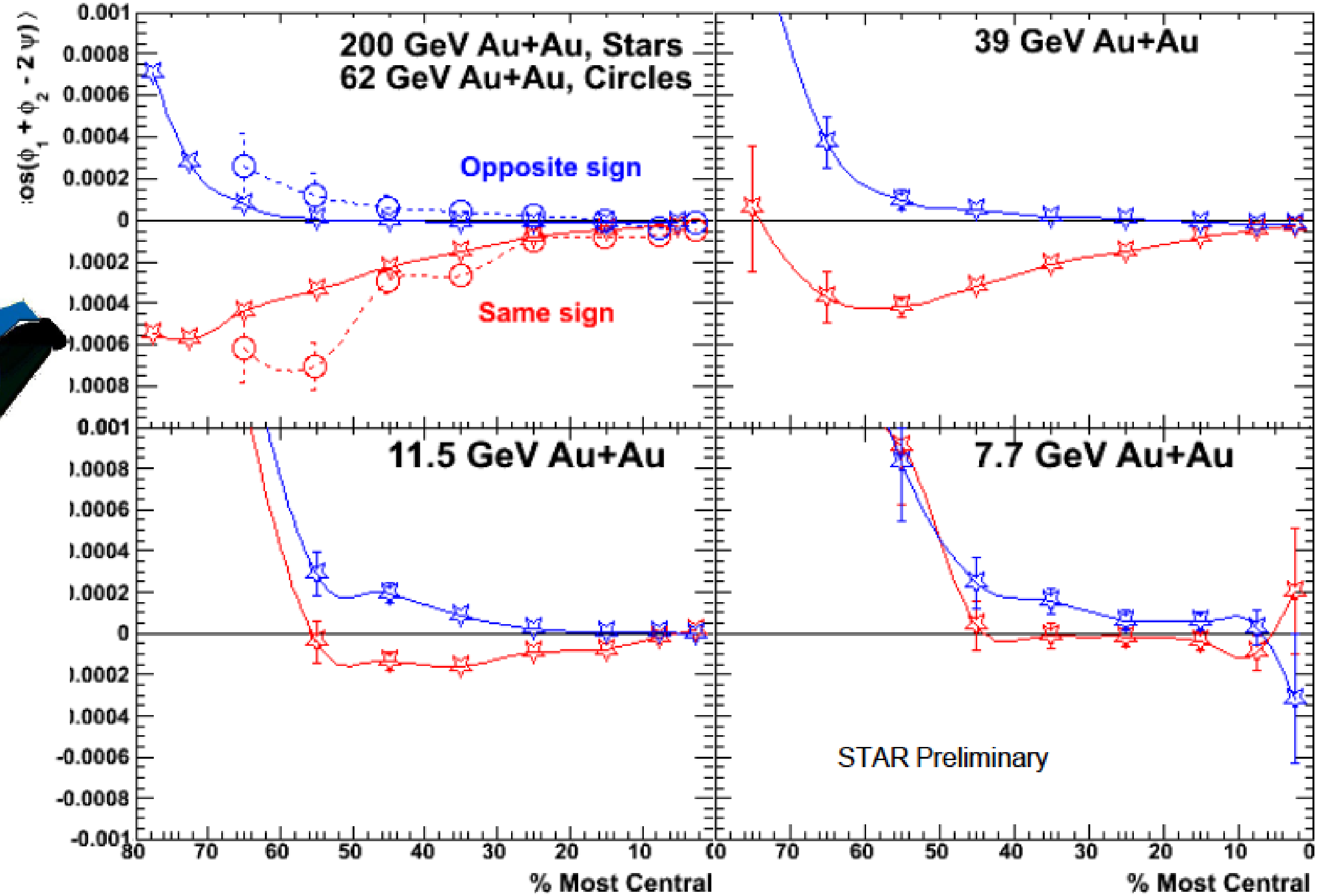

- Almost no difference at 39
- Systematical higher $v_2$ of $\pi^-$ compared to $\pi^+$ at lower energies

# Dynamical Charge Correlations

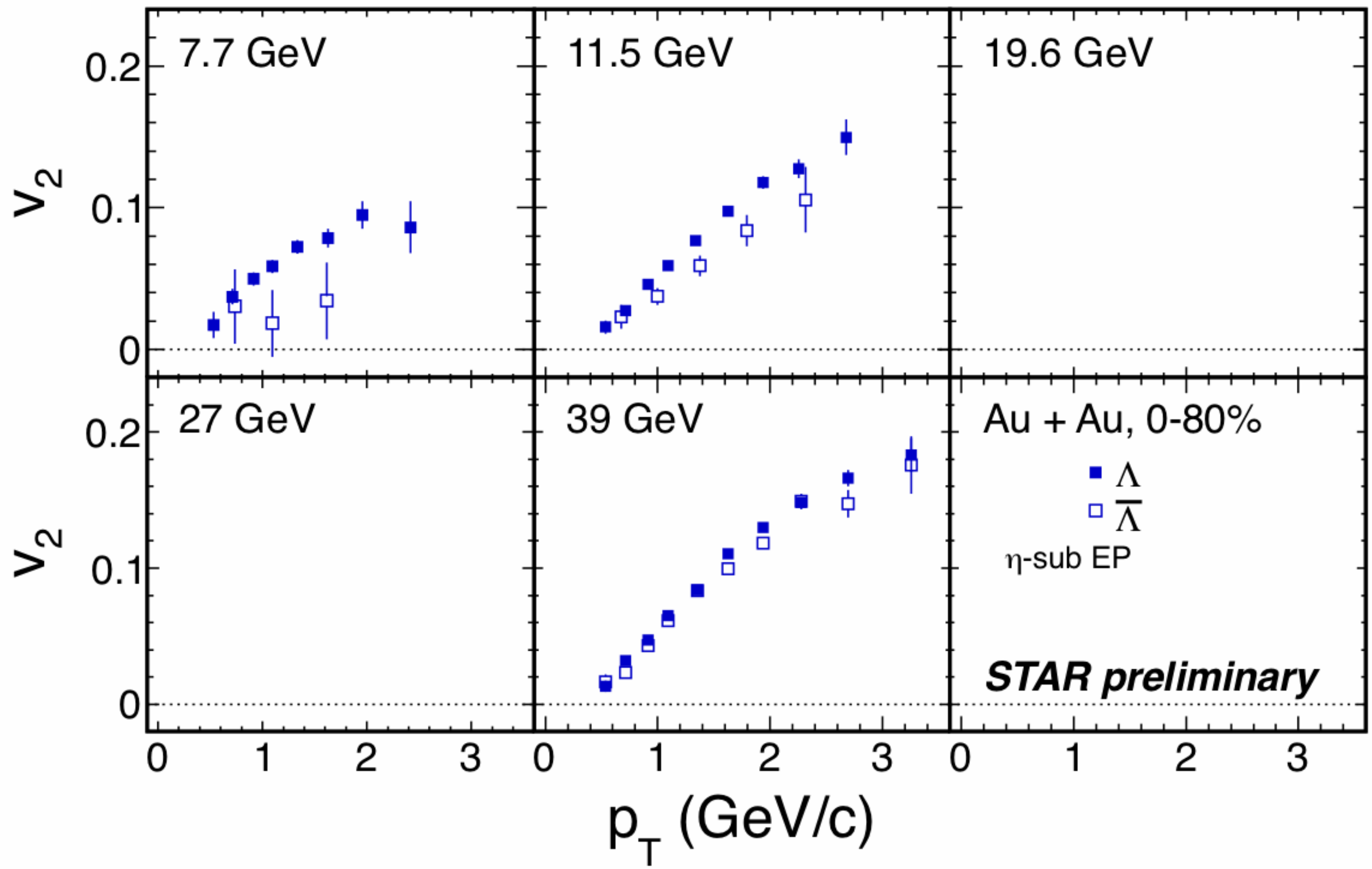
## Observations:




Measurement of charge correlations with respect to event plane

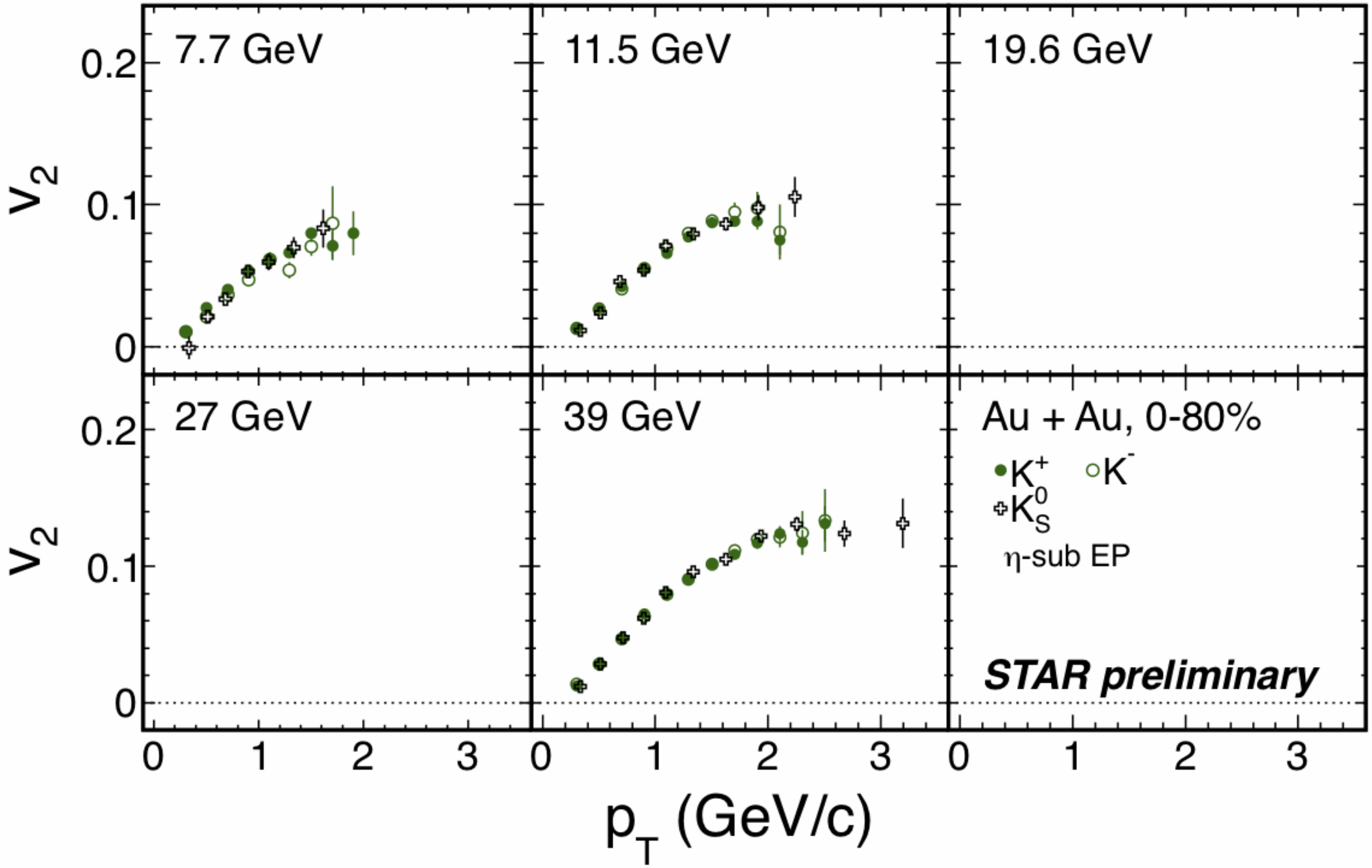


# Elliptic Flow of $\Lambda$, $\bar{\Lambda}$



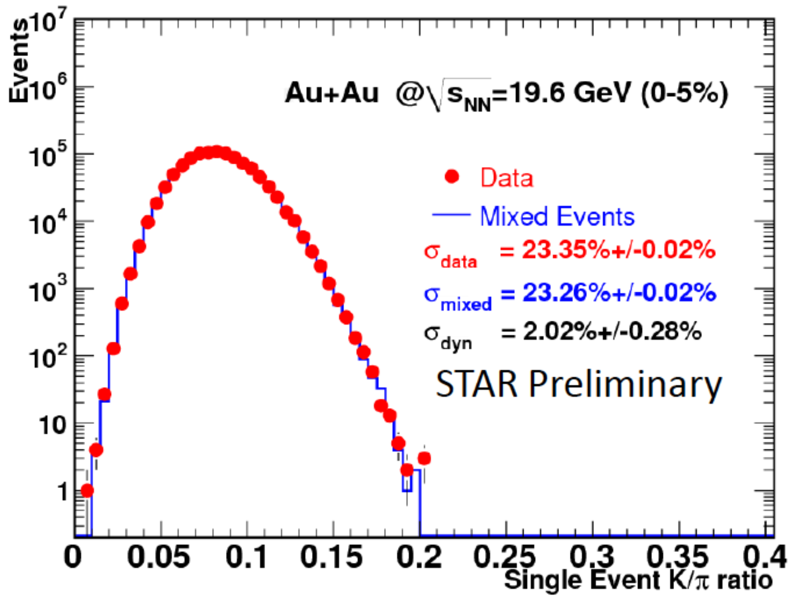

- Very similar to protons and anti-protons
- Systematical higher $v_2$ of $\Lambda$ compared to $\bar{\Lambda}$ at lower energies

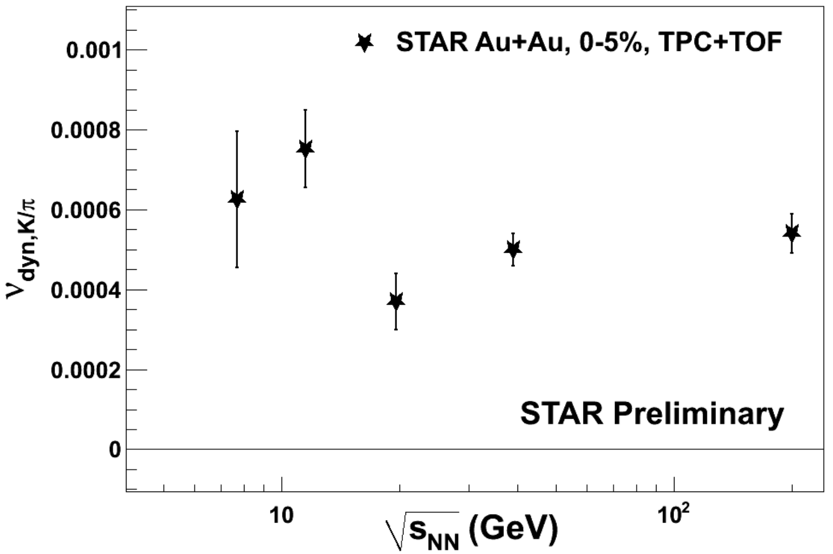
# Elliptic Flow of Kaons




- Different kaon species are very similar at 39 GeV
- At 7.7 and 11.5 GeV a small difference can be observed: $v_2(K^+) > v_2(K^-)$

# K/π Event-by-Event Fluctuations




**STAR: DNP2011**

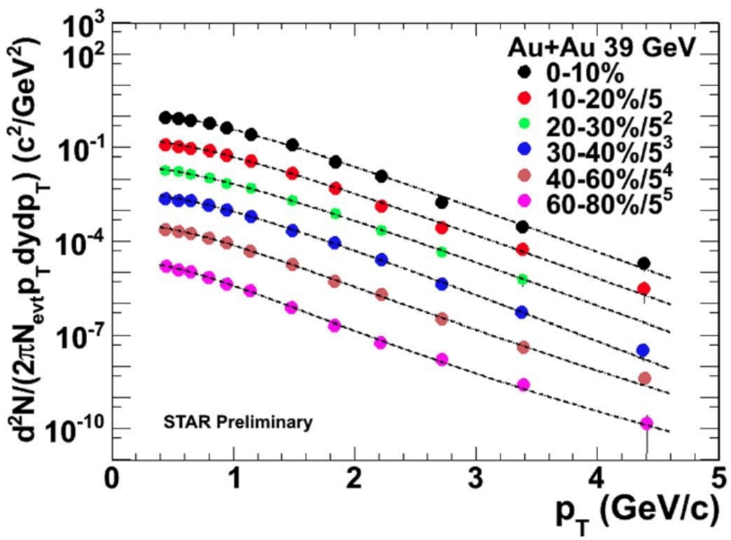
- Fluctuations in particle numbers can be related to critical behavior such as an increase in susceptibility
- Non monotonic behavior ($\sqrt{s_{NN}}$) of event-by-event particle ratios → critical point

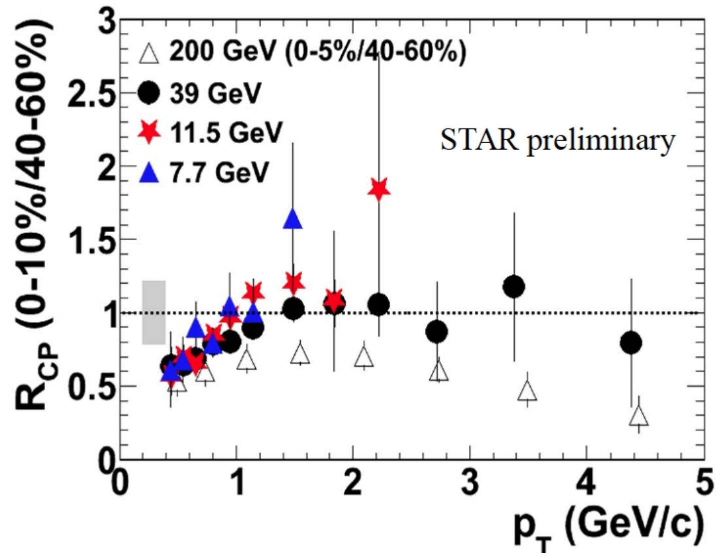
$$\sigma_{dyn} = sign\left(\sigma^2_{data} - \sigma^2_{mixed}\right)\sqrt{\left|\sigma^2_{data} - \sigma^2_{mixed}\right|}$$

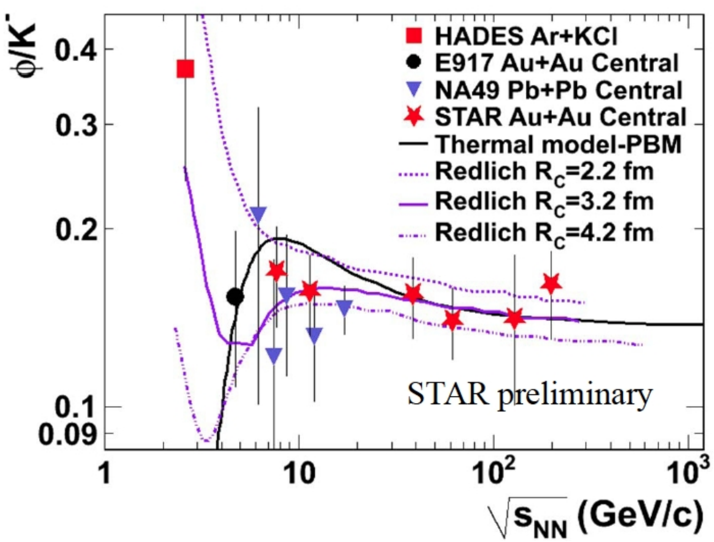
$$\nu_{dyn,K\pi} = \frac{\langle N_K(N_K-1)\rangle}{\langle N_K\rangle^2} + \frac{\langle N_\pi(N_\pi-1)\rangle}{\langle N_\pi\rangle^2} - 2\frac{\langle N_K N_\pi\rangle}{\langle N_K\rangle\langle N_\pi\rangle}$$

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

# ϕ-Meson Spectra from $\phi \rightarrow K^+K^-$



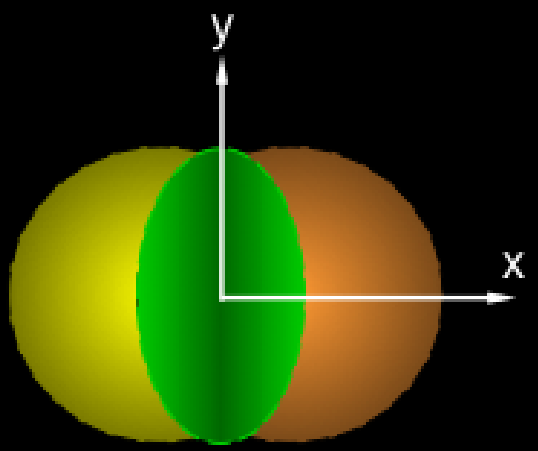



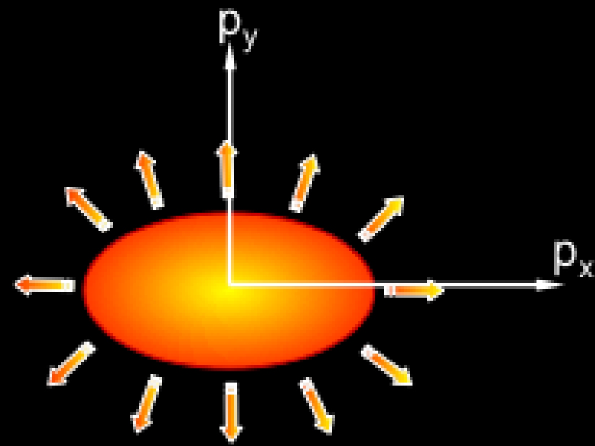

- Reconstruction up to 4.5 GeV in $p_T$
- $\phi/K^-$ ratio is used to test strangeness production mechanism
- $R_{CP}$ at 39 GeV is consistent with unity at $p_T > 1$ GeV/c

*error bars are combined stat. + syst.

# Anisotropy Parameter $v_2$

coordinate-space-anisotropy ⇨ momentum-space-anisotropy

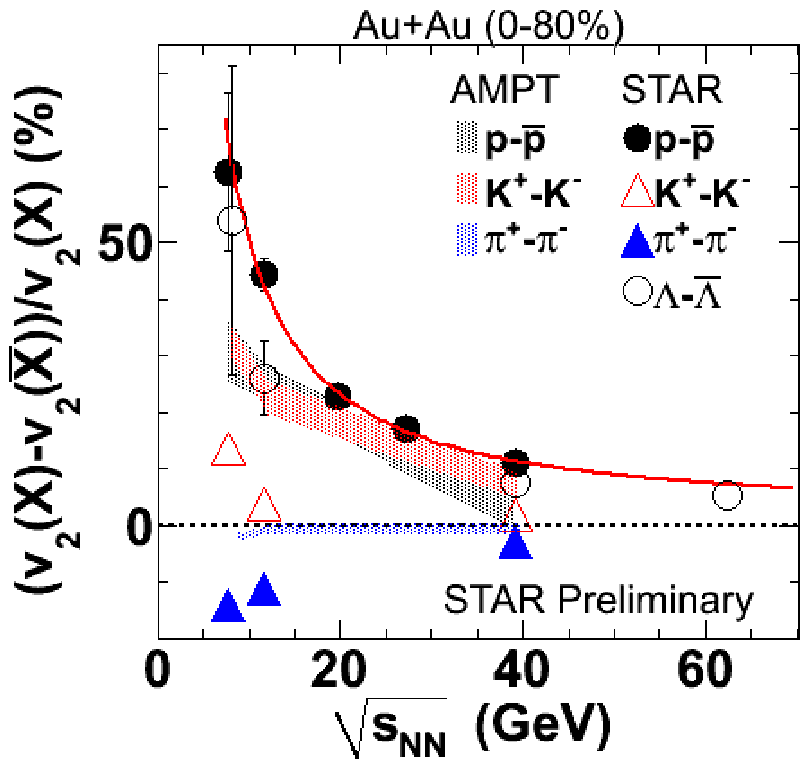


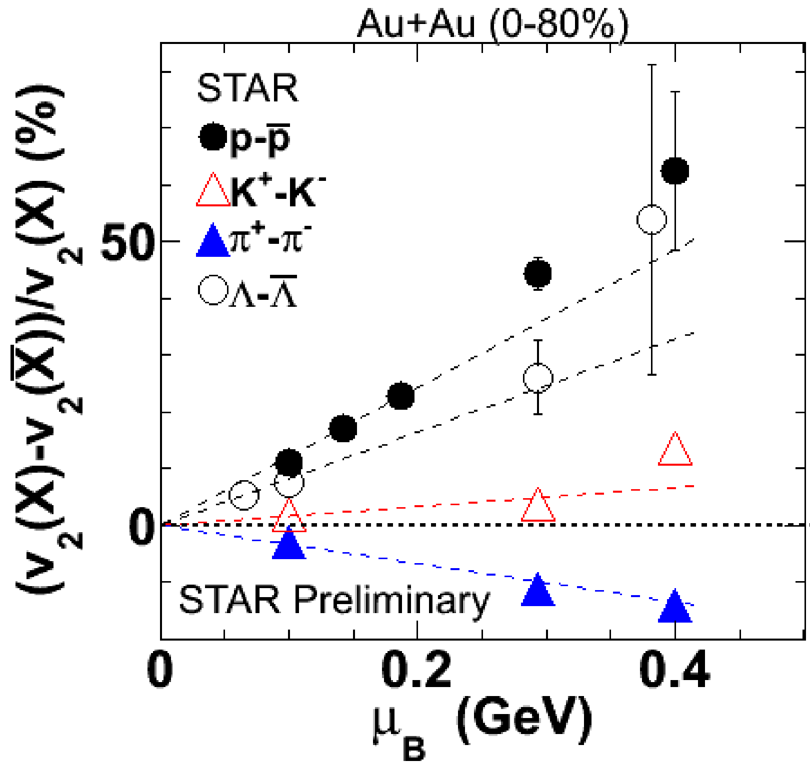




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \ \ \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

**Initial/final conditions, EoS, degrees of freedom**

# $v_2$ Difference vs. $\sqrt{s_{NN}}$ and $\mu_B$



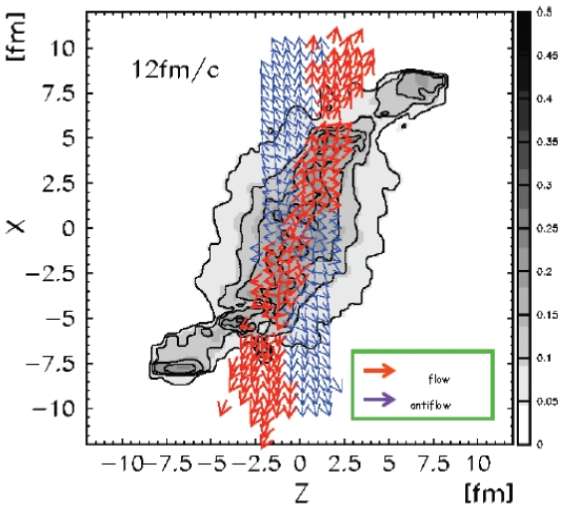




- Small difference at higher energies
- $(1/\sqrt{s_{NN}})^a$ increase at lower energies
- Difference increases almost linear with $\mu_B$

- Dominance of hadronic phase?
- Baryon/quark transport?*
- Hadronic potentials?**

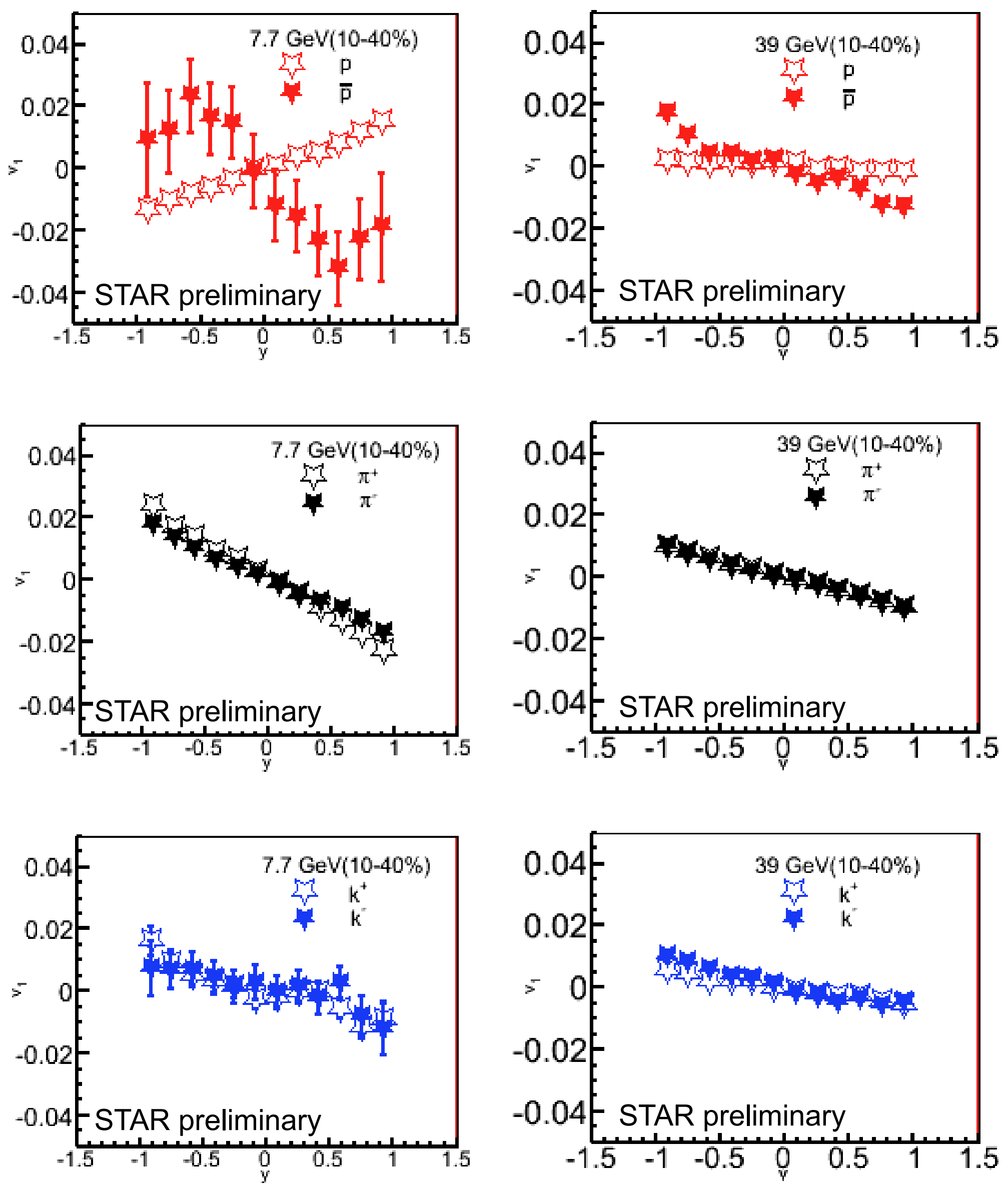
** J. C. Dunlop et al., **PRC84**, 044914 (2011)*
*** J. Xu et al., arXiv:1201.3391 [nucl-th]*

$\sqrt{s_{NN}} \rightarrow \mu_B$ from: http://arxiv.org/pdf/1111.2406v1.pdf

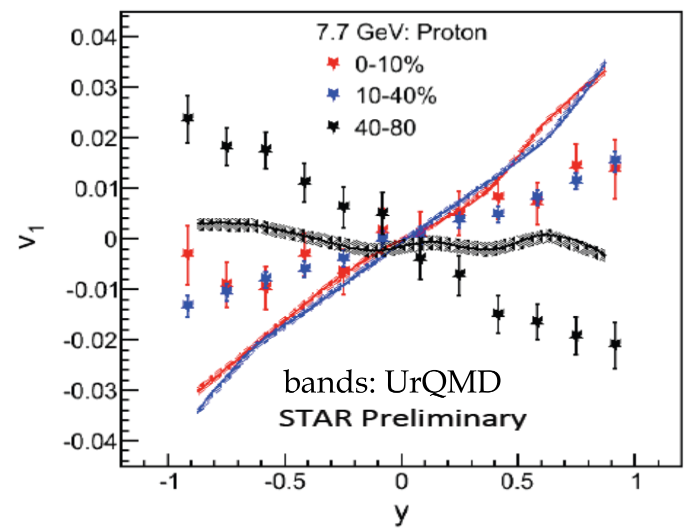



J. Brachmann et al., PRC 61, 24909 (2000).

# Directed Flow from Identified Hadrons



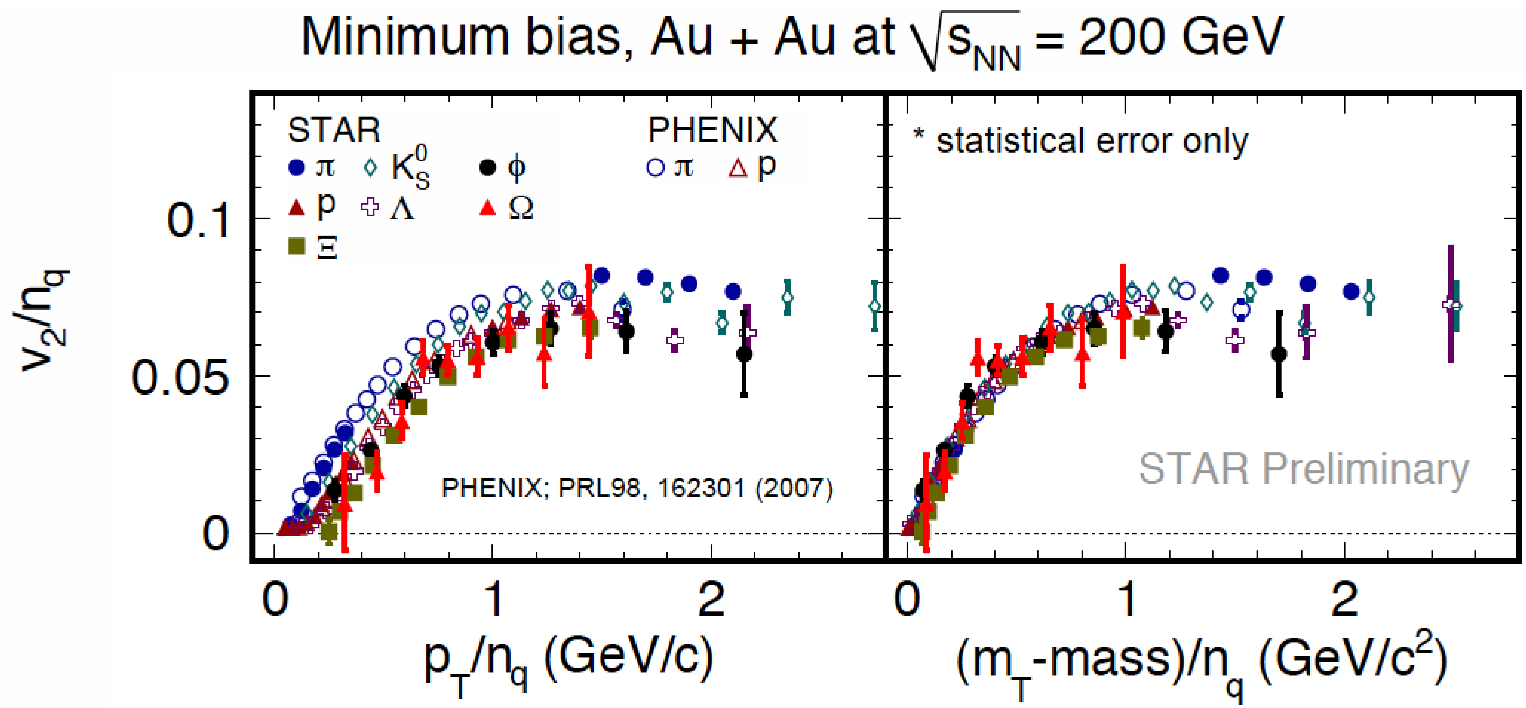

STAR: SQM2011




- $0.2 < p_T < 2.8$ for protons
- $0.2 < p_T < 1.6$ for pions and kaons
- Change of the proton $dv_1/dy$ from 39 to 7.7 GeV at mid-central collisions → maybe due to transported protons to mid-rapidity
- No change in the slope for other particle species
- UrQMD predicts the right trend

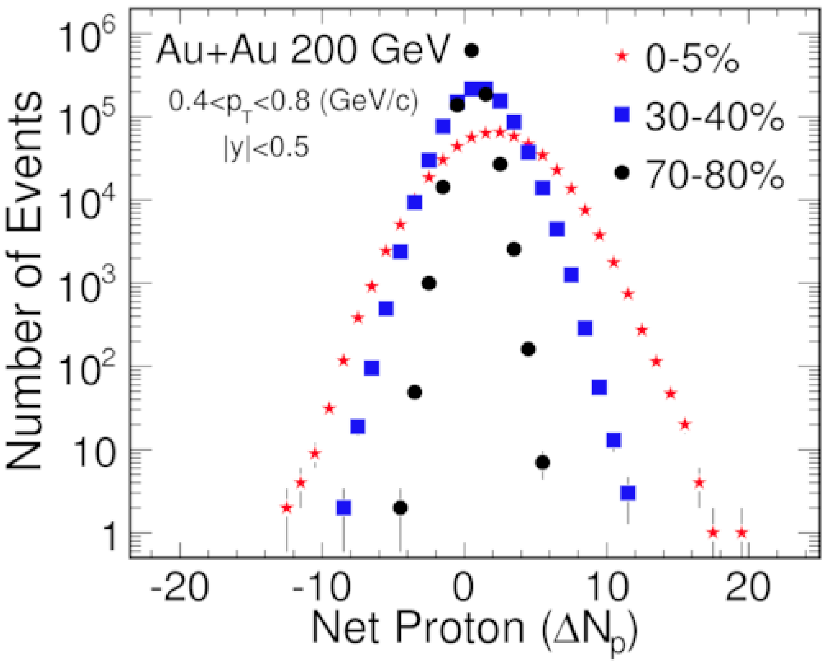
# NCQ-Scaling

Number-of-Constituent (NCQ) Scaling




- Shows partonic degrees of freedom
- How does it look like at lower energies?

# Higher Moments of Net-Proton Distributions




**Mean:** $M = < N >$

**Sigma:** $\sigma = \sqrt{< (N - < N >)^2 >}$

**Skewness:** $S = \frac{< (N - < N >)^3 >}{\sigma^3}$

**Kurtosis:** $\kappa = \frac{< (N - < N >)^4 >}{\sigma^4} - 3$

$$\chi_B^{(n)} = \left. \frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n} \right|_T$$

$$\chi_B^4 / \chi_B^2 = (\kappa\sigma^2)_B$$
$$\chi_B^3 / \chi_B^2 = (S\sigma)_B$$

F. Karsch et al, Phys. Lett. B 695, 136 (2011)
M.Cheng et al, Phys. Rev. D 79, 074505 (2009)

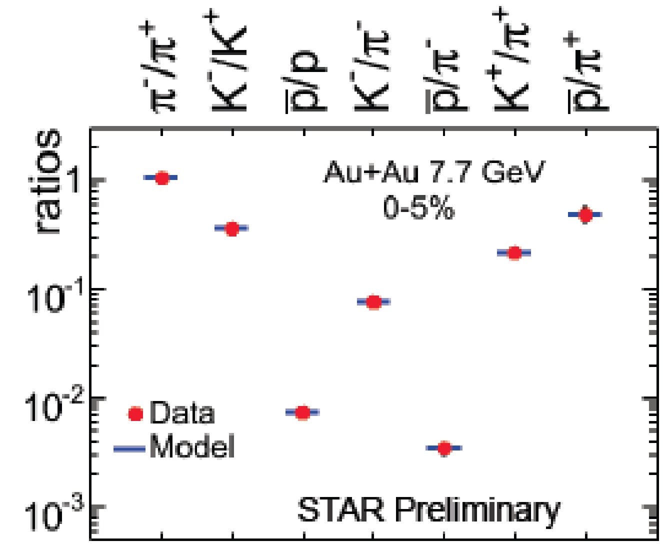
- Link between susceptibilities (e.g. from lattice QCD) and products of higher moments
- Volume effect cancels out
- Net-proton number fluctuations can reflect baryon number fluctuations
- High fluctuations predicted close to the critical point

# Chemical Freeze-out

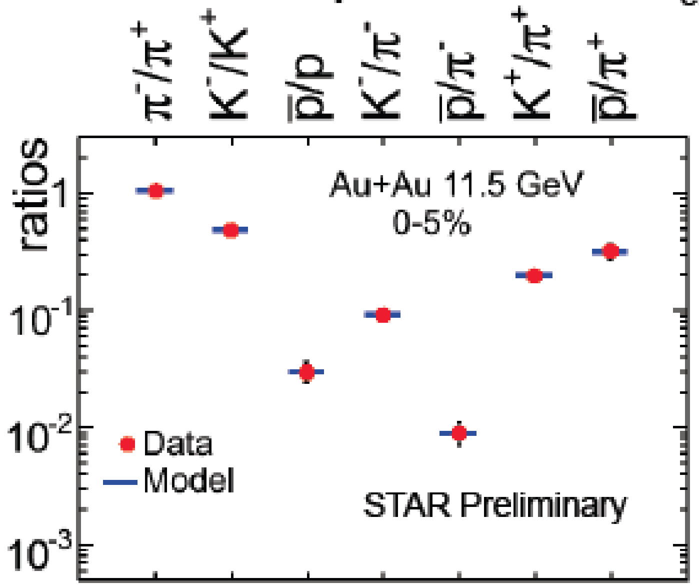
## Statistical-Thermal Model (THERMUS):

$$n = \frac{1}{V}\frac{\partial(T\ln Z)}{\partial\mu} = \frac{VTm_i^2 g_i}{2\pi^2}\sum_{k=1}^{\infty}\frac{(\pm1)^{k+1}}{k}\left(e^{\beta k\mu_i}\right)K_2\left(\frac{km_i}{T}\right)$$

β=1/T; -1(+1) for fermions (bosons), Z=partition function; $m_i$ = mass of hadron species i; V = volume; T = Temperature; $K_2$= 2nd order Bessel function; $g_i$ = degeneracy; $\mu_i$ = chemical potential




- ✧Fitted particle ratios with THERMUS
- ✧Used grand-canonical approach
- ✧Two main parameters: $T_{ch}$ and $\mu_B$




Try to use strange particles also in future

S. Wheaton & J. Cleymans, hep-ph/0407174;
S. Wheaton, J. Cleymans & M. Hauer, comp. phys. Comm. 180 (2009) 84.

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