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Azimuthal correlations as a tool for testing of fundamental symmetries & searching for novel phenomena in heavy ion collisions

PARTICLE PHYSICS SEMINAR

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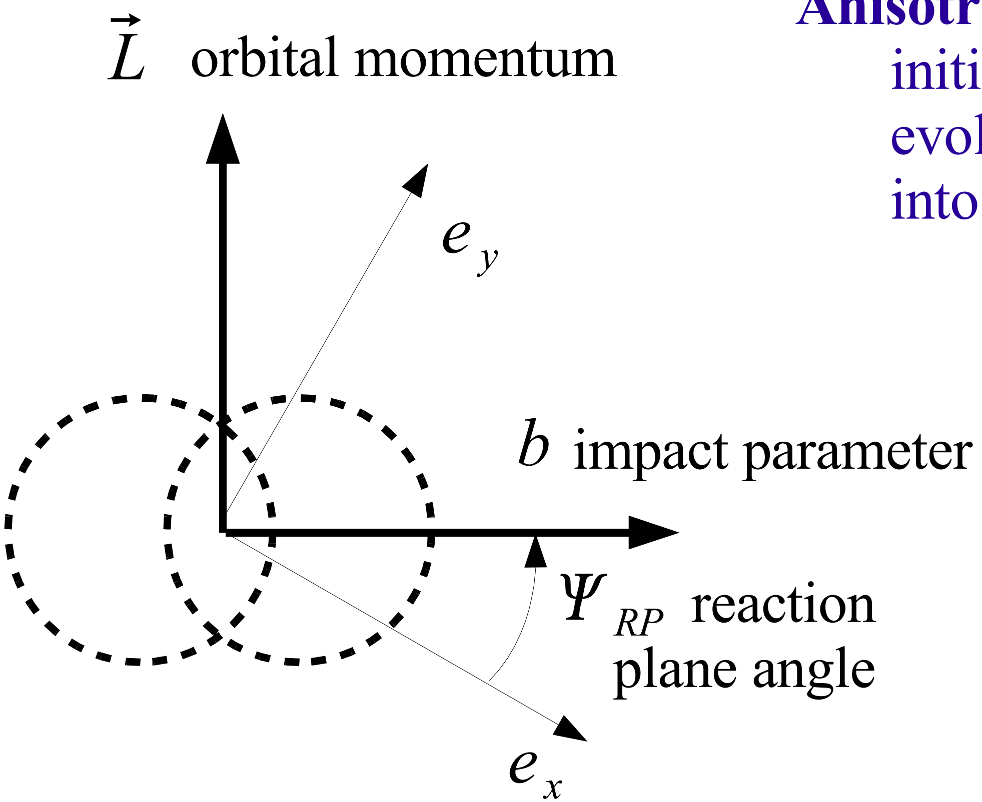
Asymmetries with respect to the reaction plane



e_z **beam direction pointing out of plane**

$[e_z, b]$ reaction plane

Anisotropic transverse flow

initial space anisotropy of the overlapped area evolves, due to interactions and pressure gradient, into momentum space anisotropy

Global polarization

preferential orientation of the spin of produced particles wrt the system orbital momentum

Strong parity violation in HIC

asymmetry in charge particle production with respect to the system orbital momentum

Azimuthal correlations

Reaction plane orientation is unknown

Estimated from azimuthal distribution of particles produced in HIC
Any analysis involves **a few particle azimuthal correlations**

Contribution from different competing effects into correlations

Asymmetries with respect to the reaction plane:
anisotropic flow, global polarization, parity violation

Other correlations not related to the reaction plane orientation:
Resonances, jets, effects of global momentum conservation

Detector acceptance

Produce spurious correlations,
bias the results with contribution from different effects

Anisotropic transverse flow

Anisotropic transverse flow

Sensitive to the early stage of the collision

Thermodynamics predictions, signature for QGP (Quark Gluon Plasma)

Anisotropic transverse flow

Coefficients in Fourier decomposition of particle azimuthal distribution in momentum space:

$$\frac{dN}{d\phi} \sim 1+2\sum_{n=1}^{\infty} v_n \cos\left[n\left(\phi-\Psi_{RP}\right)\right]$$

v_n is n-harmonic anisotropic flow: directed (n=1) and elliptic (n=2) flow

Immediate observable

$$v_n = \langle \cos n(\phi-\Psi_{RP})\rangle$$

reaction plane orientation is unknown in the experiment

How to define the reaction plane orientation?

Estimating the reaction plane orientation
from azimuthal distribution of produced particles

Single particle vector

$$u_n = \cos n\phi + i \sin n\phi = x_n + i y_n = \exp\{i n \phi\}$$

Event plane flow vector (and event plane angle)
defined with particles produced in the collision

$$Q_n = \sum_{EP} u_n$$

$$= X_n + i Y_n = \sum_{EP} \cos n\phi + i \sum_{EP} \sin n\phi$$

$$= |Q_n| \exp\{i n \Psi_{EP}\}$$

Event plane flow vector is proportional to the reaction plane angle.
Needs to correct on the **event plane resolution**

Observable for anisotropic flow

Two particle correlations

Average other all RP orientations and particle's azimuthal angles

$$\langle u_n Q_n \rangle = v_n \langle M v_n \rangle_{EP}$$

Event plane resolution (defined with random sub-events)

$$\langle M v_n \rangle_{EP} = 2\sqrt{\langle Q_n^a Q_n^b \rangle}$$

Observable expressed via event plane vector

$$v_n = \frac{\langle u_n Q_n \rangle}{2\sqrt{\langle Q_n^a Q_n^b \rangle}}$$

or →

$$v_n = \frac{\langle \cos n(\phi - \Psi_{EP}^{a,b}) \rangle}{\sqrt{\langle \cos n(\Psi_{EP}^{a} - \Psi_{RP}^{b}) \rangle}}$$

Normalizing event plane vector to unity

Detectors used to define the event plane vector

Time Projection Chamber (TPC)

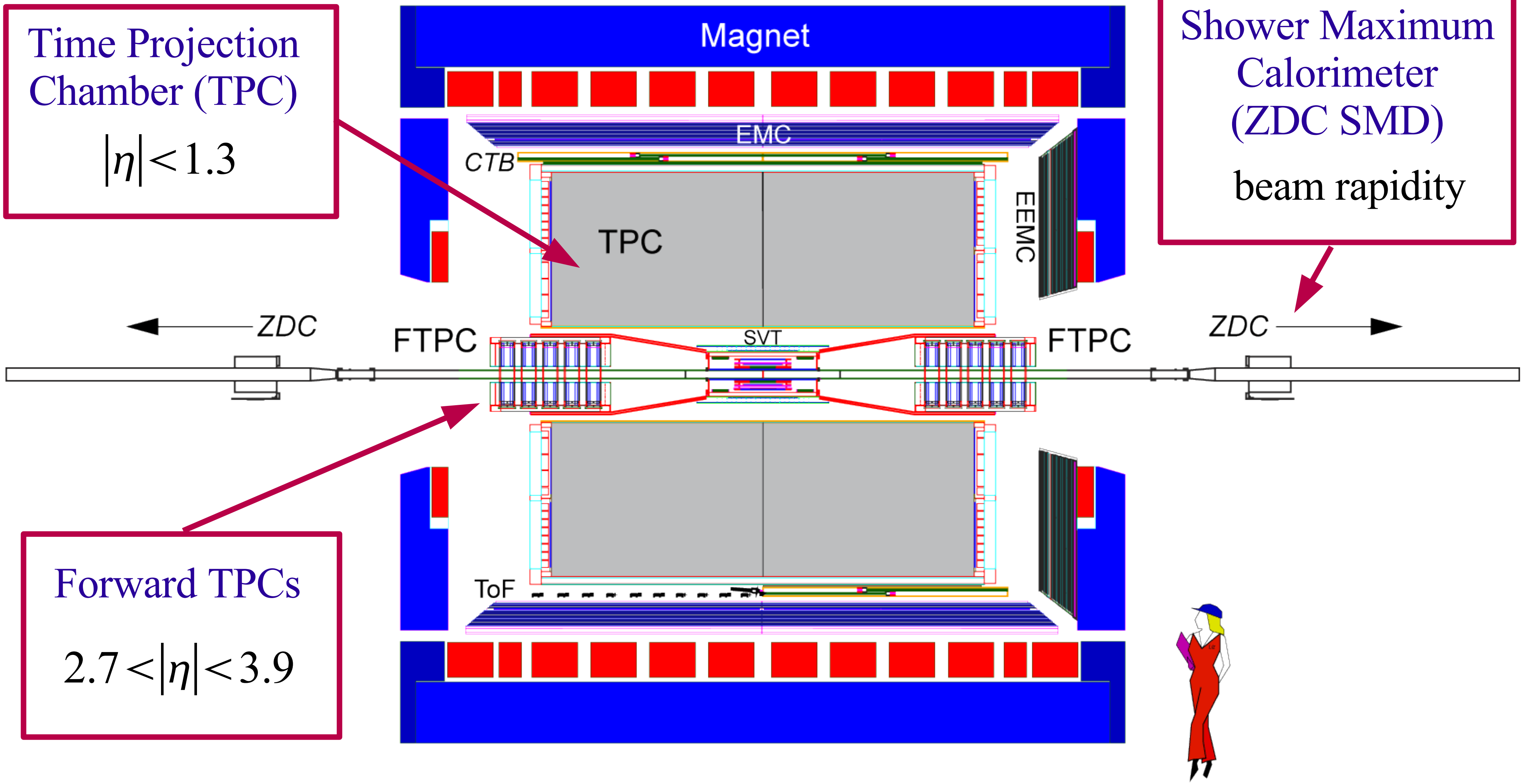
$|\eta| < 1.3$

Shower Maximum Calorimeter (ZDC SMD)

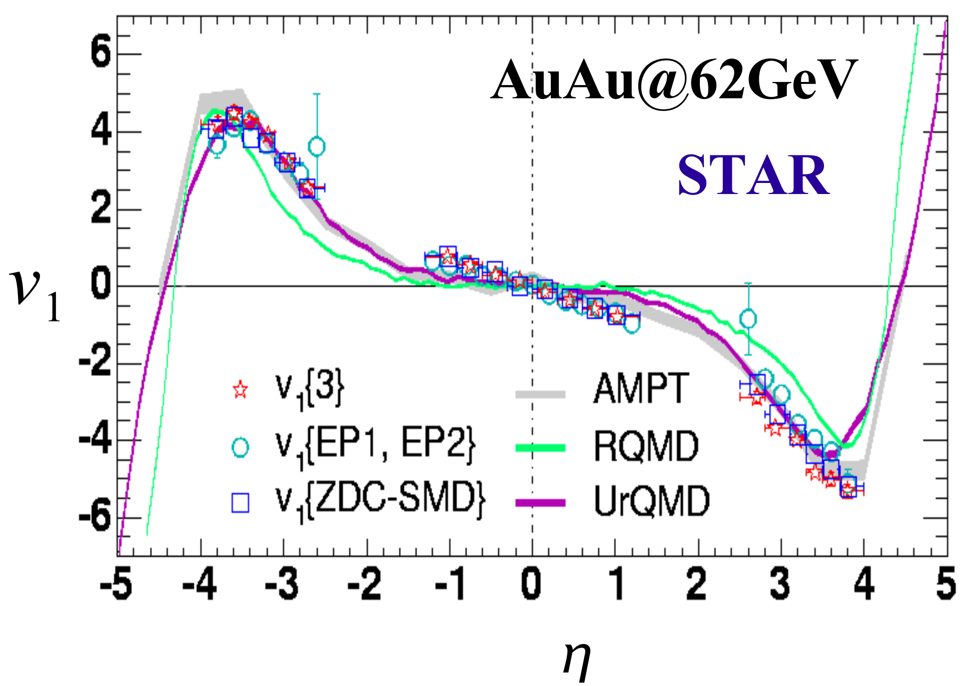
beam rapidity

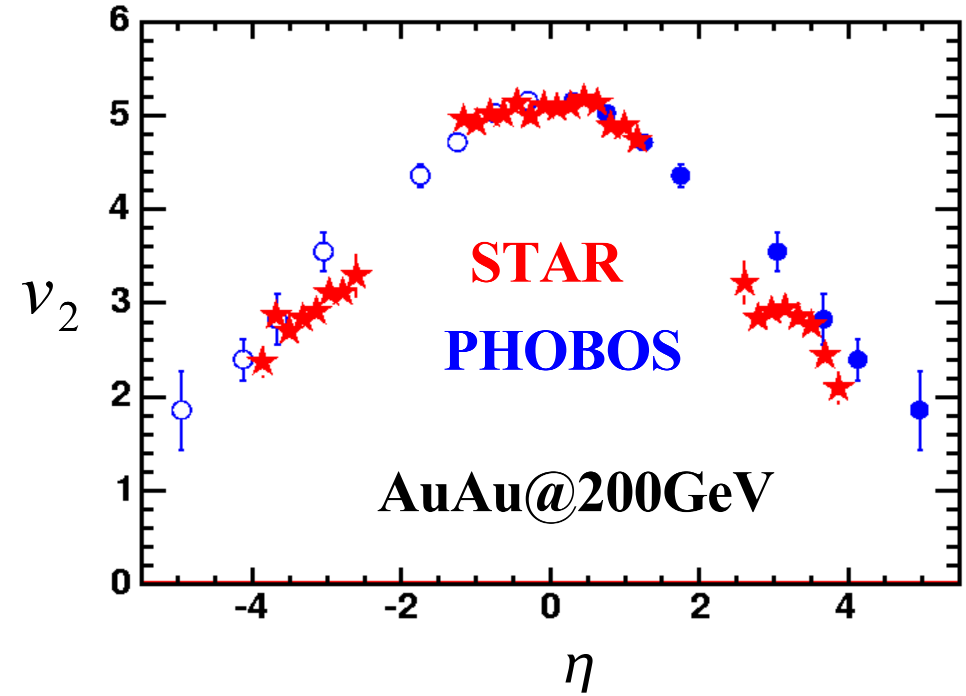
Forward TPCs

$2.7 < |\eta| < 3.9$



Strong anisotropic flow at RHIC





Directed flow
Anti-symmetric, increases with rapidity

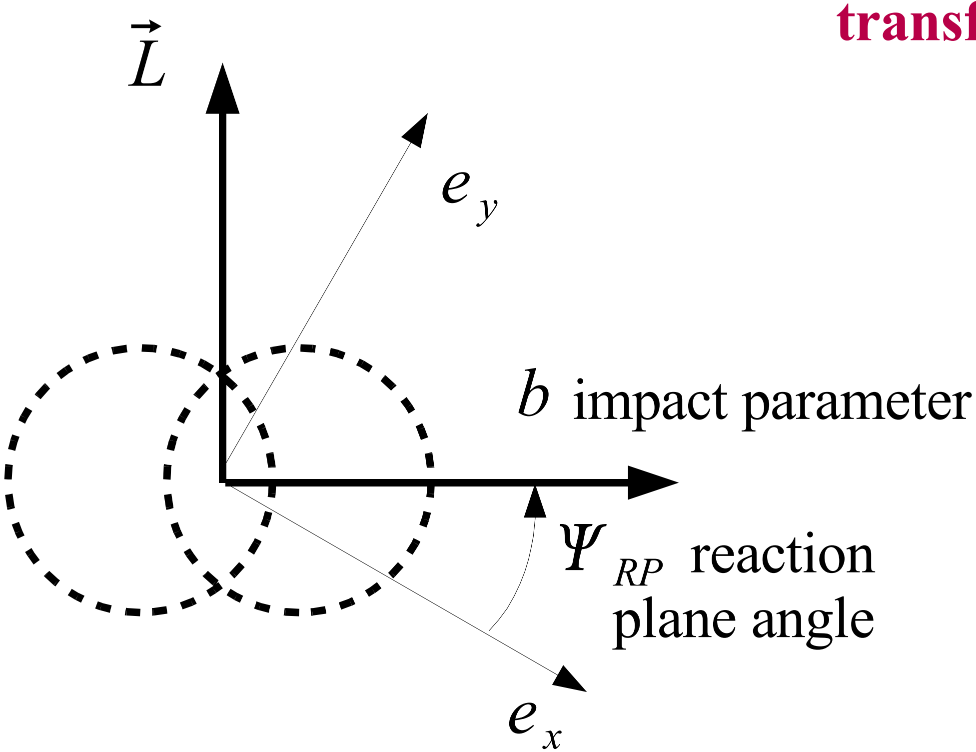
Elliptic flow
Symmetric strongest at mid-rapidity

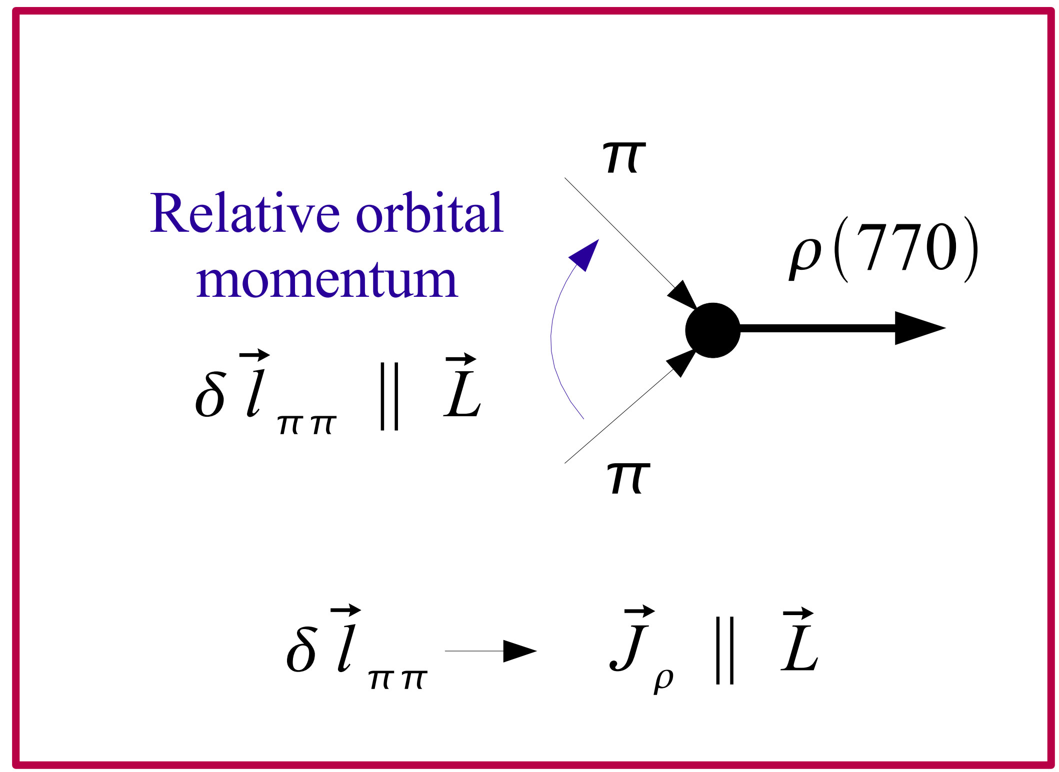
The stronger anisotropic flow within the detector coverage the closer event plane will be to the true reaction plane orientation

Global polarization of hyperons

Global polarization

large orbital momentum in non-central collisions → **spin-orbital transformation** → **Global polarization** preferential orientation of the spin of produced particles wrt the system orbital momentum





e_z **beam direction pointing out of plane**

Theoretical predictions for the global polarization

- Polarization of hyperon and vector meson spin alignment with respect to reaction plane orientation are first discussed in [1-3]

- Sensitive to the evolution of the system, hadronization mechanism, origin of hadronic spin

- Spin orbital transformation via polarized quark phase
  Calculations with static potential [1]

$$P_H = P_q \approx 0.3 \quad \text{Hyperons: } \Lambda, \Sigma, \Xi$$

Recent calculations with HTL (Hard Thermal Loop) gluon propagator [4]

$$-0.03 < P_q < 0.15$$

[1] **Z.-T. Liang and X.-N. Wang** PRL**94** 102301 (2005) [erratum: 039901(2006)]
[2] **Sergei A. Voloshin** nucl-th/0410089
[3] **Z.-T. Liang and X.-N. Wang** nucl-th/0411101
[4] **J-H. Gao, and Z. T. Liang** QM2006 satellite workshop (Xian, China, 2006)

Angular distribution for the global polarization

$$\frac{dN}{d\cos\theta^*} \sim 1+\alpha_H P_H \cos\theta^*$$

$P_H(\vec{p}_H;\vec{L})$ hyperon polarization wrt the reaction plane **(global polarization)**

α_H decay constant: $\alpha_{\Lambda(\bar{\Lambda})}=\pm 0.642$ for $\Lambda(\bar{\Lambda})\rightarrow p\pi^-(\bar{p}\pi^+)$

θ^* angle between the system orbital momentum and the hyperon decay baryon 3-momentum in the hyperon's rest frame

Immediate observable

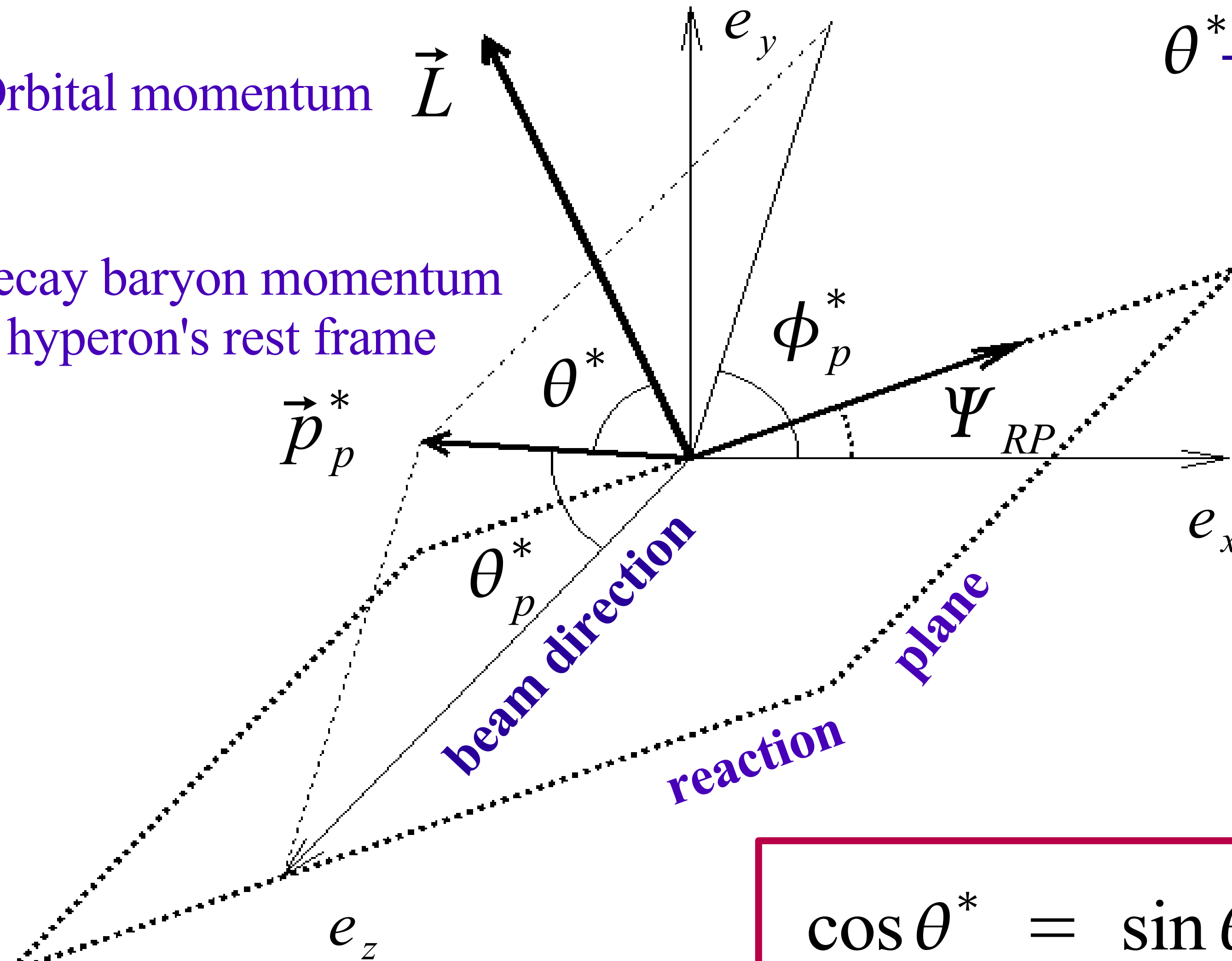
$$P_H=\frac{3}{\alpha_H}\langle\cos\theta^*\rangle$$

θ^* **is defined by the reaction plane orientation => flow measurement technique**

Angles definition and notations

Orbital momentum $\vec{L}$

Decay baryon momentum in hyperon's rest frame $\vec{p}_p^{\,*}$



θ^* - angle between $\vec{p}_p^{\,*}$ and $\vec{L}$

$\phi_p^*(\theta_p^*)$ decay baryon azimuthal (polar) angles

Ψ_{RP} reaction plane angle

$$\cos\theta^* = \sin\theta_p^* \sin(\phi_p^* - \Psi_{RP})$$

Observable for the global polarization

$$P_H(\vec{L}, \vec{p}_H) = P_H(\phi_H - \Psi_{RP}, \eta^H, p_t^H)$$

$$= \sum_{n=0}^{\infty} P_H^{(n)} \cos[2n(\phi_H - \Psi_{RP})]$$

$$P_H \equiv P_H^{(0)} = \frac{8}{\pi \alpha_H} \langle \sin(\phi_p^* - \Psi_{RP}) \rangle$$

similar to directed flow' observable => anisotropic flow technique!

ϕ_p^* decay baryon azimuthal angle in hyperon's rest frame

Ψ_{RP} reaction plane angle

$\langle ... \rangle$ - averaging over all reaction plane orientations and decay baryon 3-momentum directions in the hyperon's rest frame

Global polarization measurement technique

$$P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\phi_p^* - \Psi_{EP}^1) \rangle}{R_{EP}^1}$$

Ψ_{EP}^1 1st order event plane angle

R_{EP}^1 1st order event plane resolution

ϕ_p^* decay baryon azimuthal angle in hyperon's rest frame

Estimating reaction plane with measured particles - two particle correlations

Scalar product technique

$$P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin\phi_p^* X_{EP}^1 \rangle - \langle \cos\phi_p^* Y_{EP}^1 \rangle}{R_{EP}^1}$$

$$Q_{EP}^1 = (X_{EP}^1, Y_{EP}^1)$$ - 1st order event plane vector

Detector acceptance effects

Acceptance effects can bias the polarization signal

Due to detector acceptance higher harmonics ($P_H^{(n)}, n>0$) can contribute

$$\frac{8}{\alpha_H \pi} \langle \sin(\phi_p^* - \Psi_{RP}) \rangle = \frac{4}{\pi} \overline{\sin\theta_p^*} P_H^{(0)} - \frac{2}{\pi} \overline{\sin\theta_p^* \cos[2(\phi_H - \phi_p^*)]} P_H^{(2)}$$

Overall scale correction

Perfect acceptance $A_0 = 1$

$$A_0 = \frac{2}{\pi} \overline{\sin\theta_p^*} = \frac{4}{\pi} \int \frac{d\Omega_p^*}{4\pi} \frac{d\phi_H}{2\pi} A(\vec{p}_H, \vec{p}^*) \sin\theta_p^*$$

Higher harmonics (n=2) admixture

Perfect acceptance $A_2 = 0$

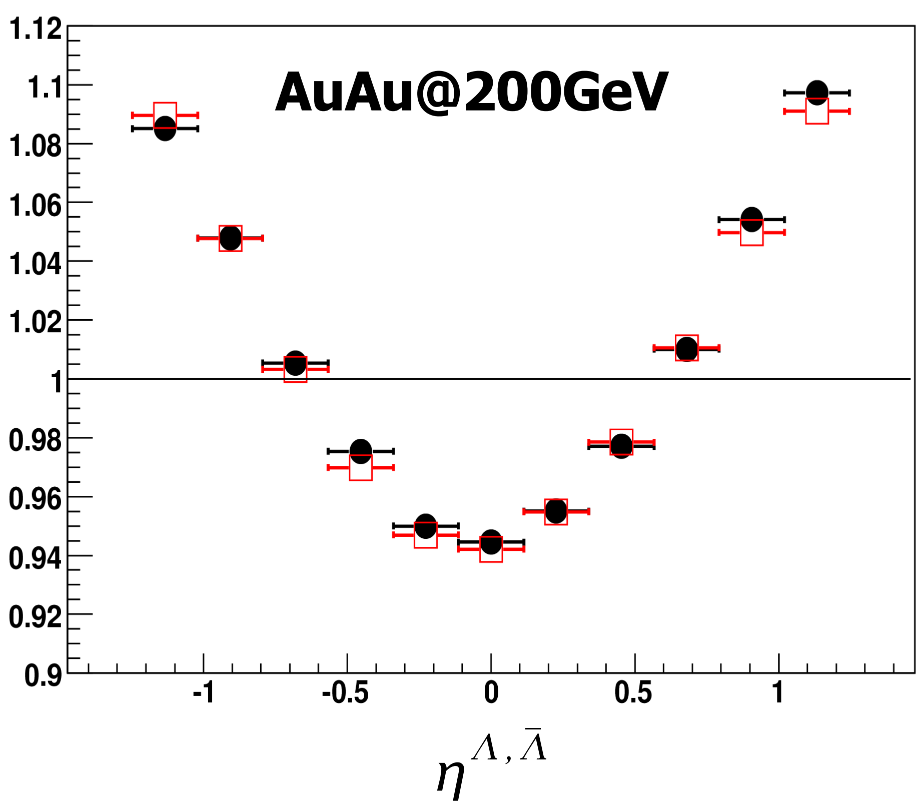
$$A_2 = \frac{2}{\pi} \overline{\sin\theta_p^* \cos[2(\phi_H - \phi_p^*)]}$$

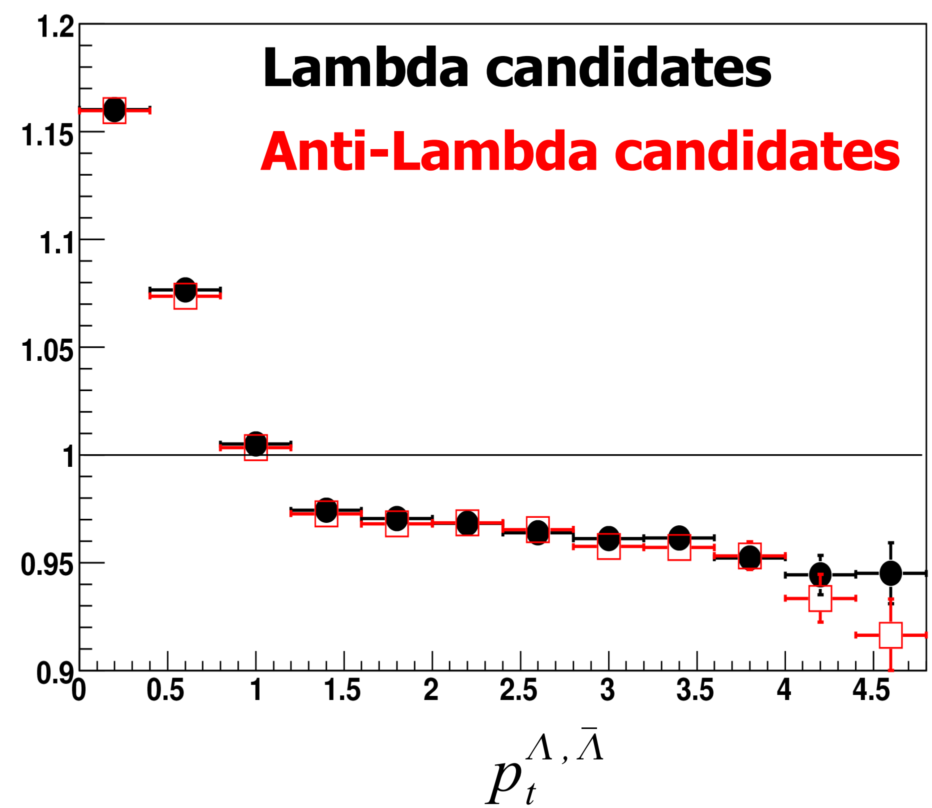
$A_{0,} A_2$ **can be calculated directly from the data**

Acceptance corrections A_0

$$A_0 = \frac{2}{\pi}\overline{\sin\theta_p^*}$$

Corrections < 20% percent

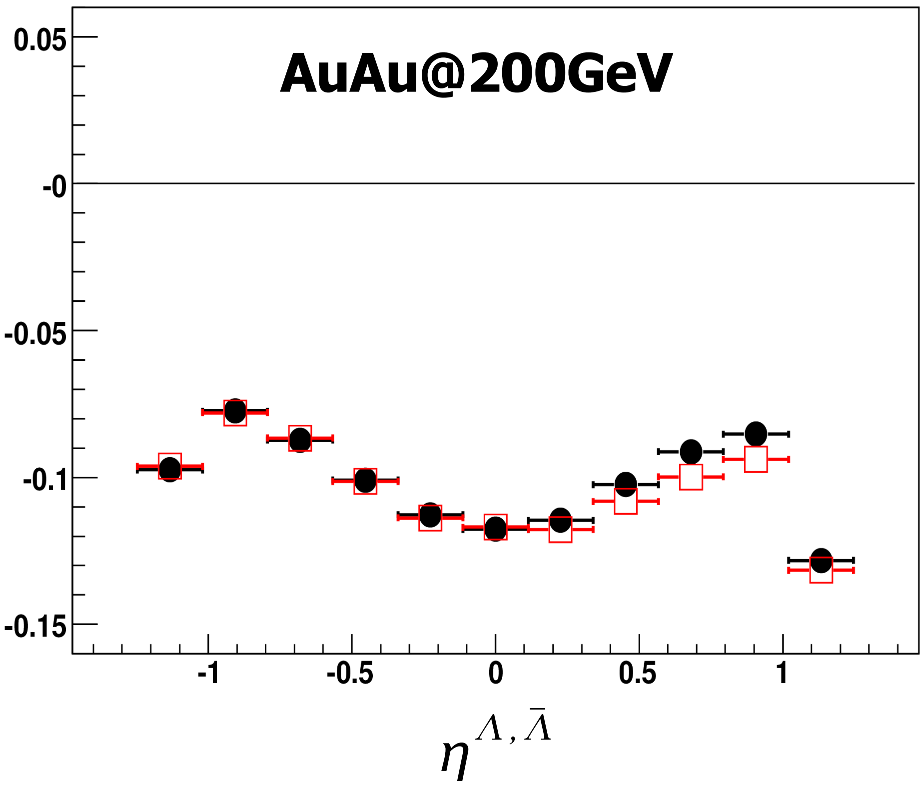


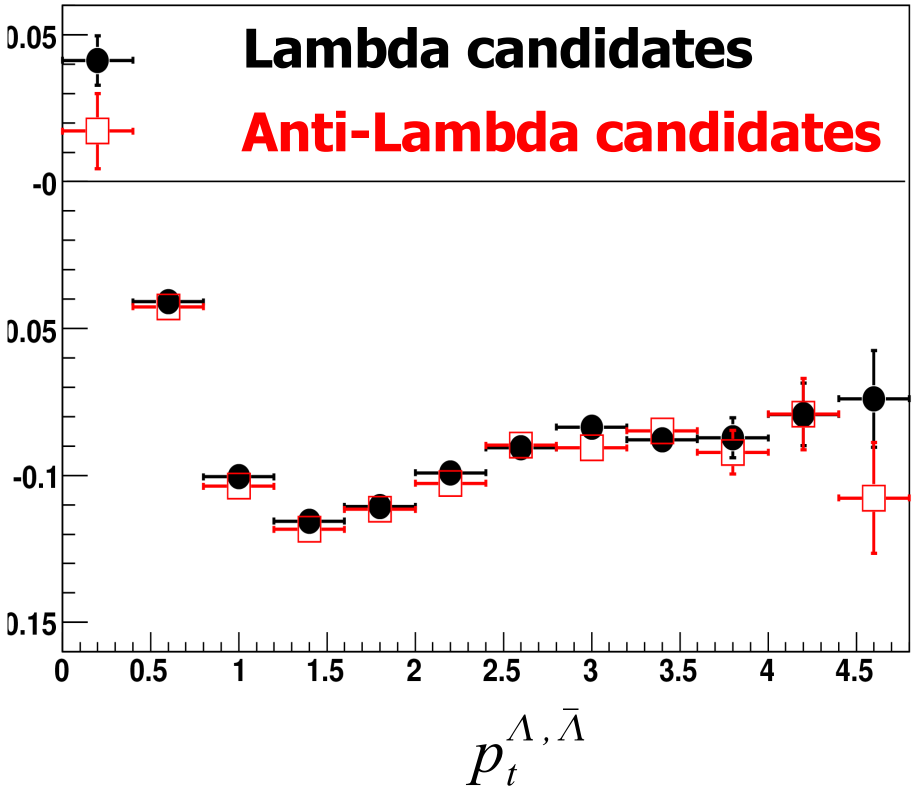


Higher harmonics contribution A_2

$$A_2 = \frac{2}{\pi} \overline{\sin\theta_p^* \cos[2(\phi_H - \phi_p^*)]}$$

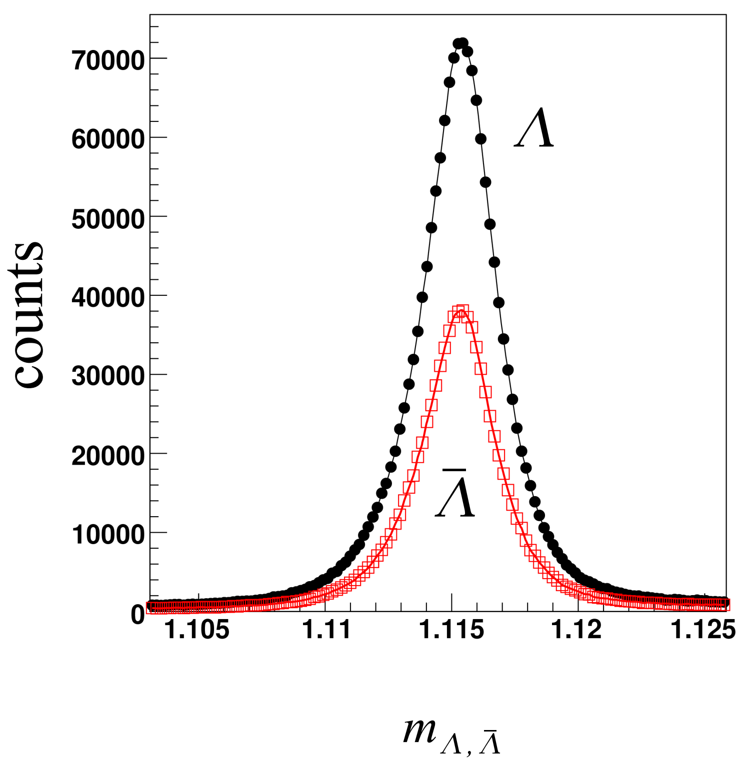
effect < 20% percent





Global polarization systematics study

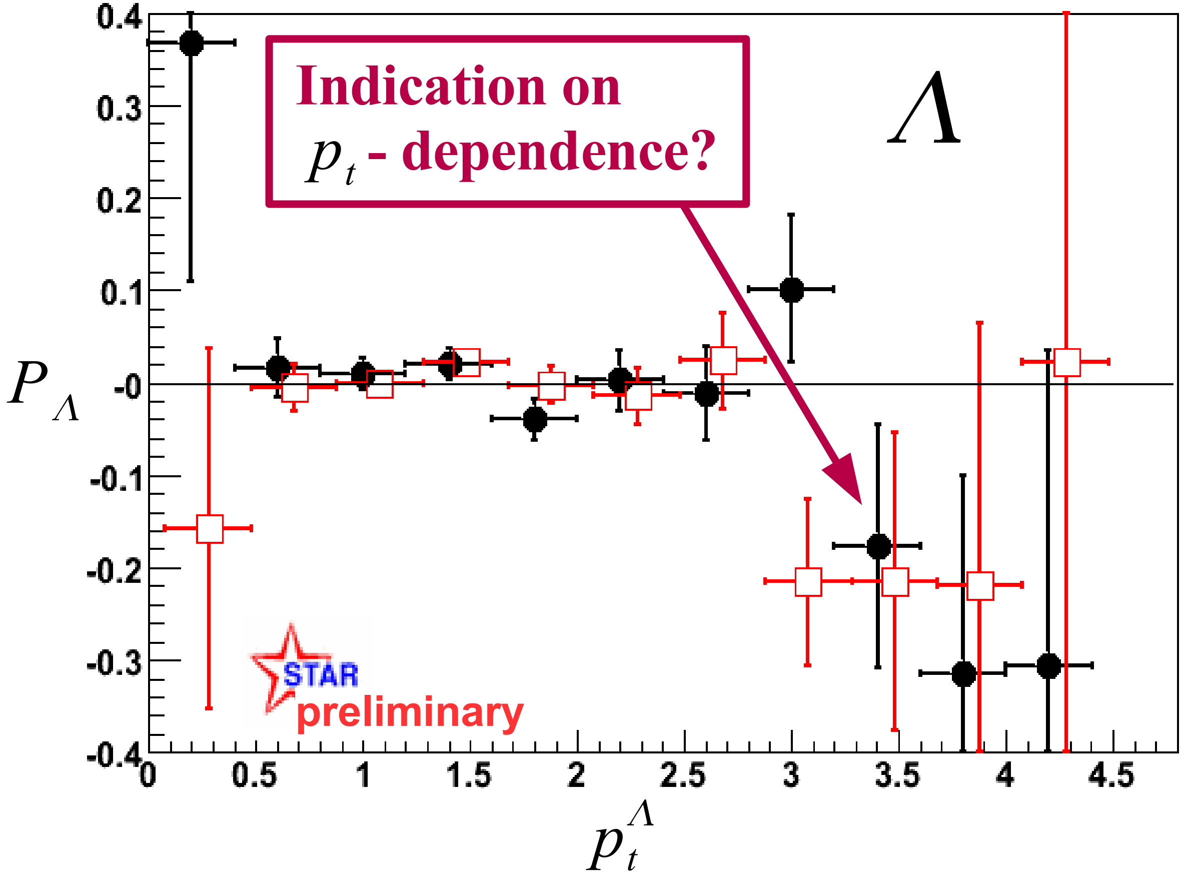
AuAu@62GeV



- Background, K_S^0 contamination (<8%)
- Non uniform detector acceptance (<20%)
- Higher harmonics contribution (<20%)
- Reaction plane reconstruction (30%)
- Spin precession (<0.1%)
- Multi-strange feed-down (<15%)
- Σ^0 feed-down (<30%)
- Hyperon directed flow contribution (<1%)
- Comparison between $\bar{\Lambda}$ and Λ results Statistics is smaller by 20% (40%) for AuAu@200GeV (AuAu@62GeV)
- Monte-Carlo simulations

Lambda global polarization vs transverse momentum

RHIC Run IV data



AuAu@200GeV (20-70%)

AuAu@62GeV (0-80%)

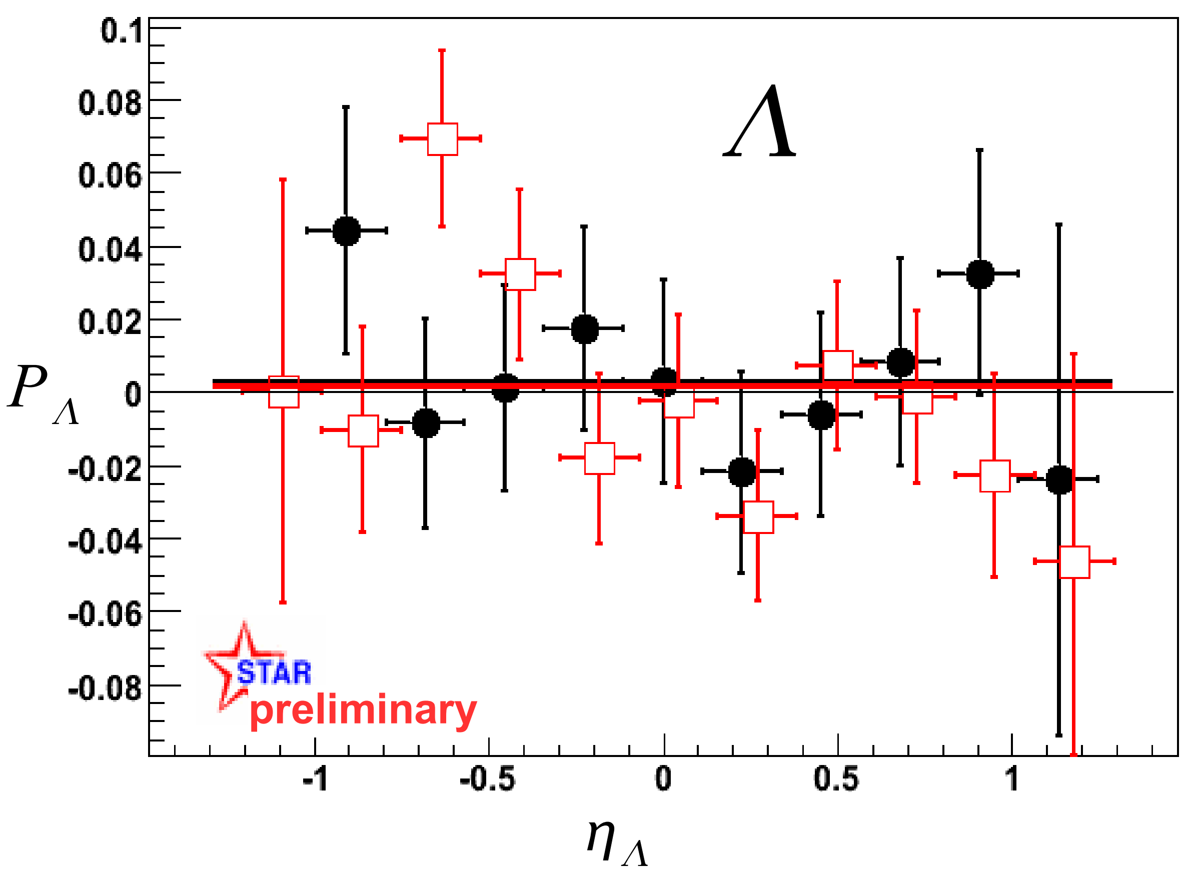
Global polarization is zero for small Lambda p_t

No theory curves on p_t dependence for the moment

I. Selyuzhenkov QM2006 (nucl-ex/0701034)

Lambda global polarization vs pseudo-rapidity

RHIC Run IV data



AuAu@200GeV (20-70%)

AuAu@62GeV (0-80%)

Line fit for AuAu@200GeV

$$P_\Lambda = (2.6 \pm 9.5) \times 10^{-3}$$

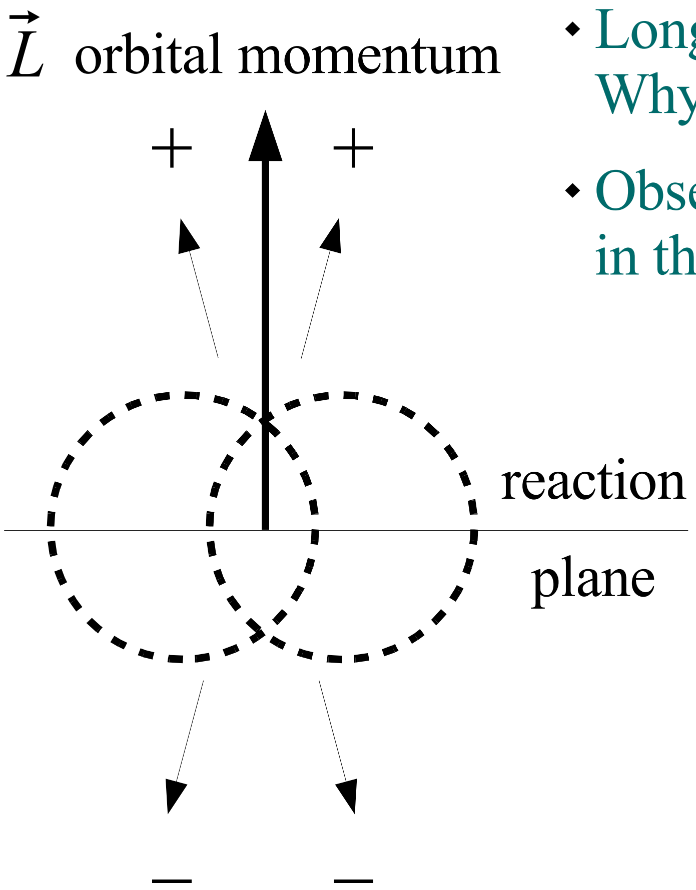
Line fit for AuAu@62GeV

$$P_\Lambda = (1.9 \pm 8.0) \times 10^{-3}$$

$\bar{\Lambda}$ **results are in agreement with those for** Λ

Strong parity violation

Strong parity violation



- Long standing puzzle of the standard model: Why C and CP invariance are preserved in strong interactions?
- Observation can explain matter and antimatter asymmetry in the Universe which appears at the QCD phase transition

Not forbidden in HIC: formation of CP-odd domains [1]

Preferential emission of the same charge particles in the direction along the orbital momentum [2,3]

Orientation can be changed from event to event what requires a correlation analysis

[1] **D. Kharzeev**, *et. al* PRL**81** 512 (1998), PRD**61** 111901 (2000)
[2] **D. Kharzeev** hep-ph/0406125 (2004)
[3] **S.A. Voloshin** PRC**70** 057901 (2004)

Parity violation angular distribution

$$\frac{dN}{d\varphi_{\pm}} \sim 1 + 2a_{\pm} \sin(\varphi_{\pm} - \Psi_{RP})$$

$\varphi_{\pm}$ particle emission azimuthal angle

$a_{\pm} = \pm\frac{4}{\pi}\frac{Q}{N_{\pm}}$ asymmetry in charged particle production proportional to the topological charge $Q \geq 1$ and charge multiplicity $N_{\pm}$

Estimated asymmetry at RHIC [1] is of the order of 1%

[1] **D. Kharzeev** hep-ph/0406125 (2004)

"Non-parity" correlations and how to suppress them

- **Correlations wrt the reaction plane**

Directed flow	symmetric eta region
Global polarization	zero signal

- **"Non-flow" correlations**

Resonances, jets, etc	3-particle correlations
	TPC, Forward TPCs event plane
Coulomb	Different charge combinations

- **Detector effects**

Track merging, etc	eta sub-events

- **What else? Needs more input**

Observable from three particle correlations

$$\langle \cos(\varphi_i + \varphi_j - 2\Psi_{RP}) \rangle = -a_i a_j$$

+ Non-parity **3 particle correlations**

Suppressed by:

symmetric pseudo-rapidity region
three particle correlation itself
differently charged event plane
eta sub-events
TPC and Forward TPC event planes

Similar to mixed harmonic in directed flow measurement

i, j (+/-) charged particles

Ψ_{RP} reaction plane angle

Theory expectations:

$$a_+ a_+ = a_- a_- = -a_+ a_- > 0$$

[2] **S.A. Voloshin** PRC**70** 057901 (2004)

Notations used in the plots

$$[a_i a_j]_{[\Psi_{EP}]} = -\frac{\langle \cos(\varphi_i + \varphi_j - 2\Psi_{EP}) \rangle}{\sqrt{\langle \cos 2(\Psi^a_{EP} - \Psi^b_{EP}) \rangle}}$$

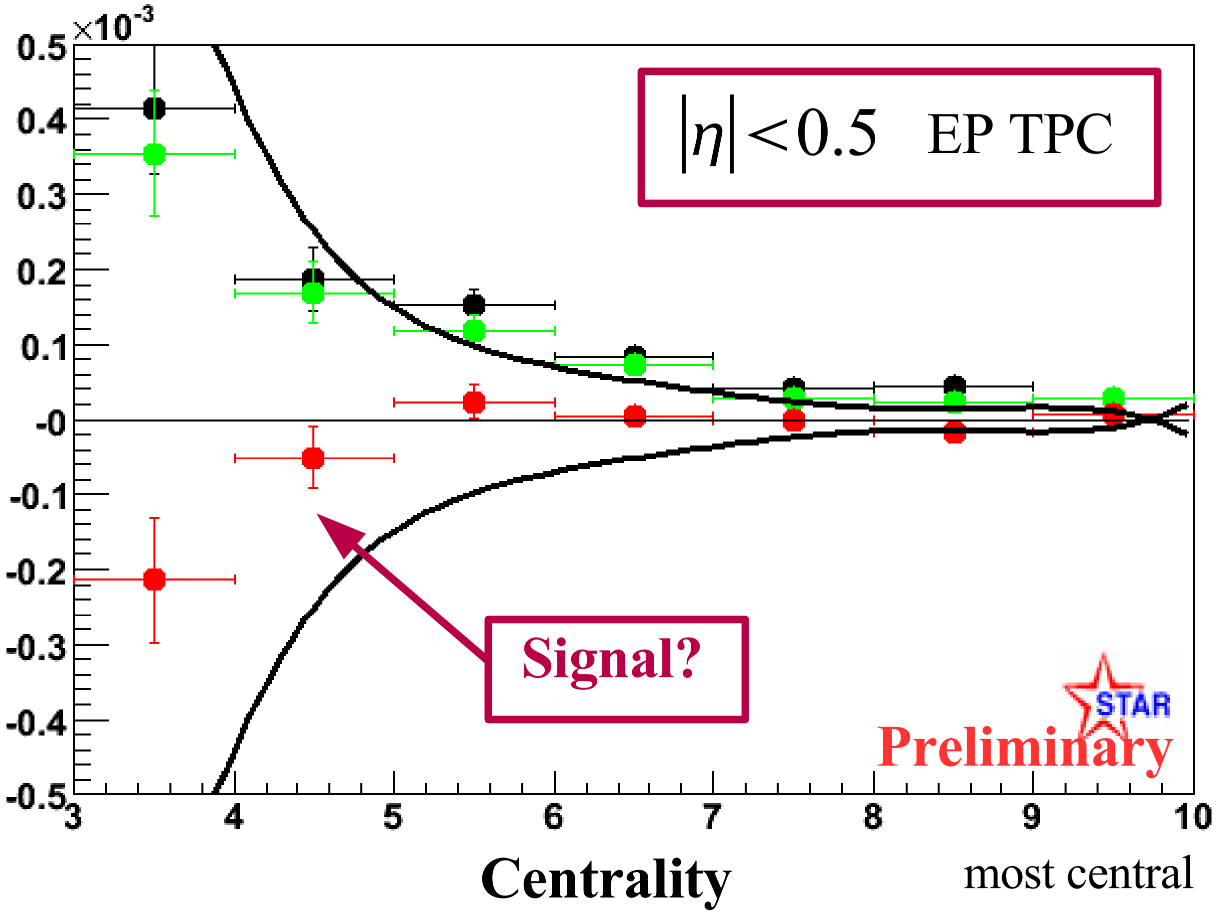
$i, j = +, -$ charge of the particles i and j

$\Psi_{EP} = +, -, ch$ charge of the particles used to obtain the second order event plane

Sample $[a_+ a_-]_{[ch]}$ 3-particle correlations with opposite charged particles and event plane calculated from all charge particles

AuAu@62GeV: TPC event plane $|\eta| < 0.5$

Lines are theory predictions
with topological charge Q=1



TPC event plane all charges

$[a_- a_-]_{[ch]}$	**black**
$[a_+ a_+]_{[ch]}$	**green**
$[a_+ a_-]_{[ch]}$	**red**

Very promising result

Main question

Do we see signal?
Is it robust with respect to different systematic checks?

I. Selyuzhenkov QM2005 (nucl-ex/0510069)

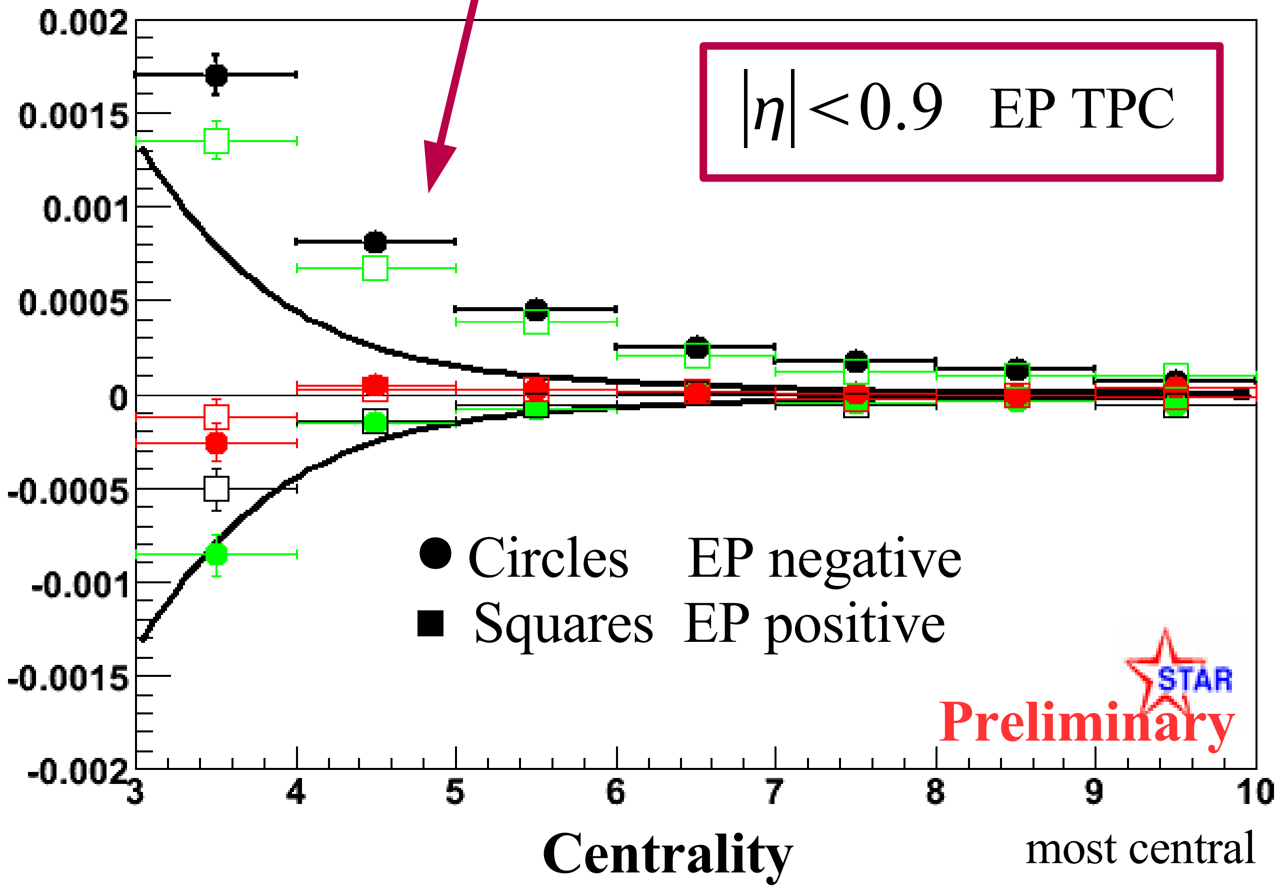
Systematics study

$$[a_i a_j]_{[\Psi_{EP}]}$$

- Results for AuAu@62GeV: $|\eta_{i,j}| < 0.5$, Ψ_{EP} from TPC
- Eta gap $\eta = 0.2$ between all 3 particles (small effect)
- AuAu@62GeV vs AuAu@200GeV: more statistics with $|\eta_{i,j}| < 0.9$
- Magnetic field in TPC:
  All plots are shown for Reversed FF,
  but data for FF reveals the same behavior
- Ψ_{EP} from different charges
- Large pseudo-rapidity gap: Ψ_{EP} from Forward TPCs

AuAu@62GeV: different charge TPC event plane

Three particles with the same charge



$[a_- a_-]_{[\pm]}$	**black**
$[a_+ a_+]_{[\pm]}$	**green**
$[a_+ a_-]_{[\pm]}$	**red**

Question

What is the origin of the same charge 3-particle correlations?

Conclusion

- **The $\Lambda(\bar{\Lambda})$ global polarization** has been measured in Au+Au collisions at the center of mass energies 62 and 200 GeV with the STAR detector at RHIC. Including systematic errors, an upper limit for the global polarization is obtained:

$$\left|P_{\Lambda,\bar{\Lambda}}\right| \leq 0.02$$

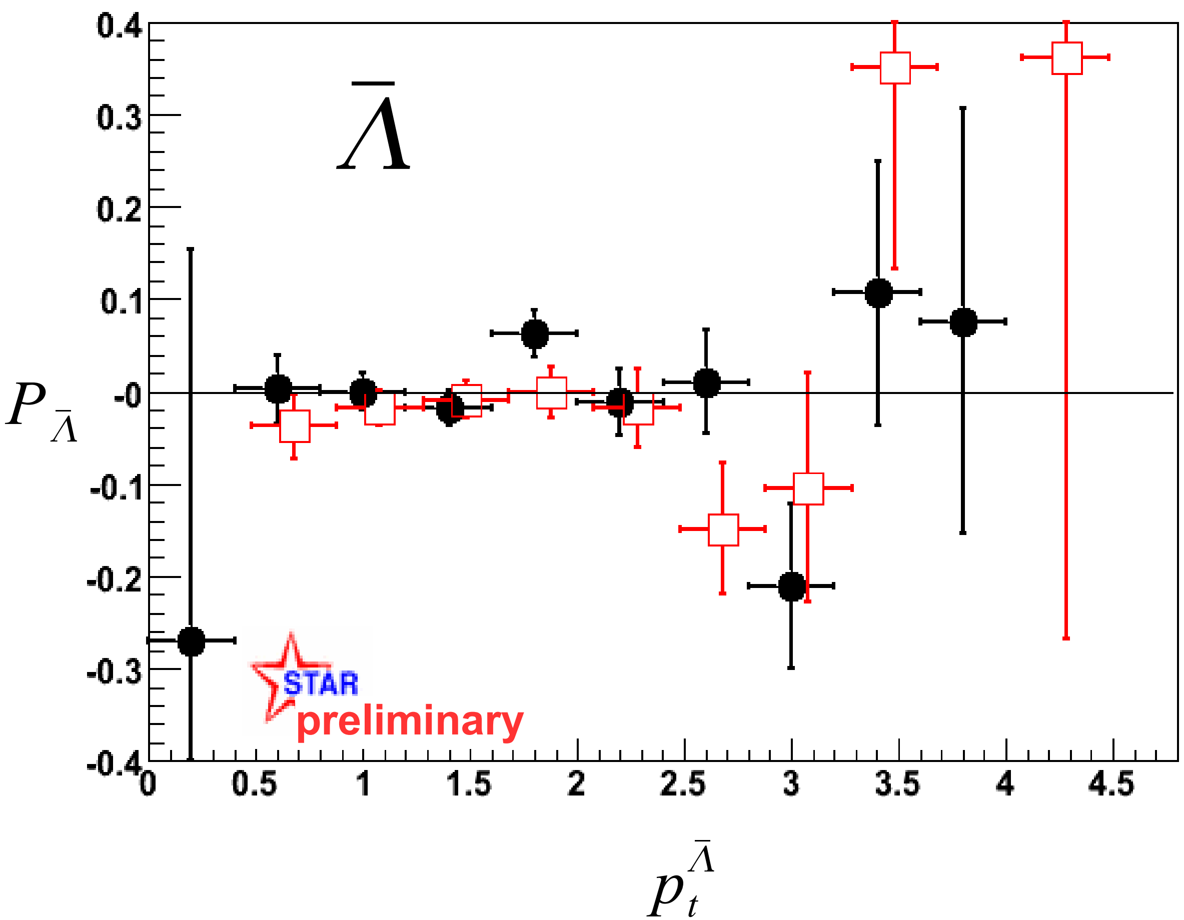
- **Parity violation in heavy ion collisions** study is in progress
  Available statistics is enough to be sensitive to the signal
  Systematic uncertainties are dominant:
  - No signal for the opposite charges
  - What is the origin of three same charge particle correlations
  - Difference between results for AuAu@62GeV and AuAu@200GeV

  Needs more systematics study:
  - Resonance contribution, detector effects: net charge in TPC, FTPC East/West separately, ZDC SMD event plane

Backup slides

Anti-lambda global polarization vs transverse momentum

RHIC Run IV data



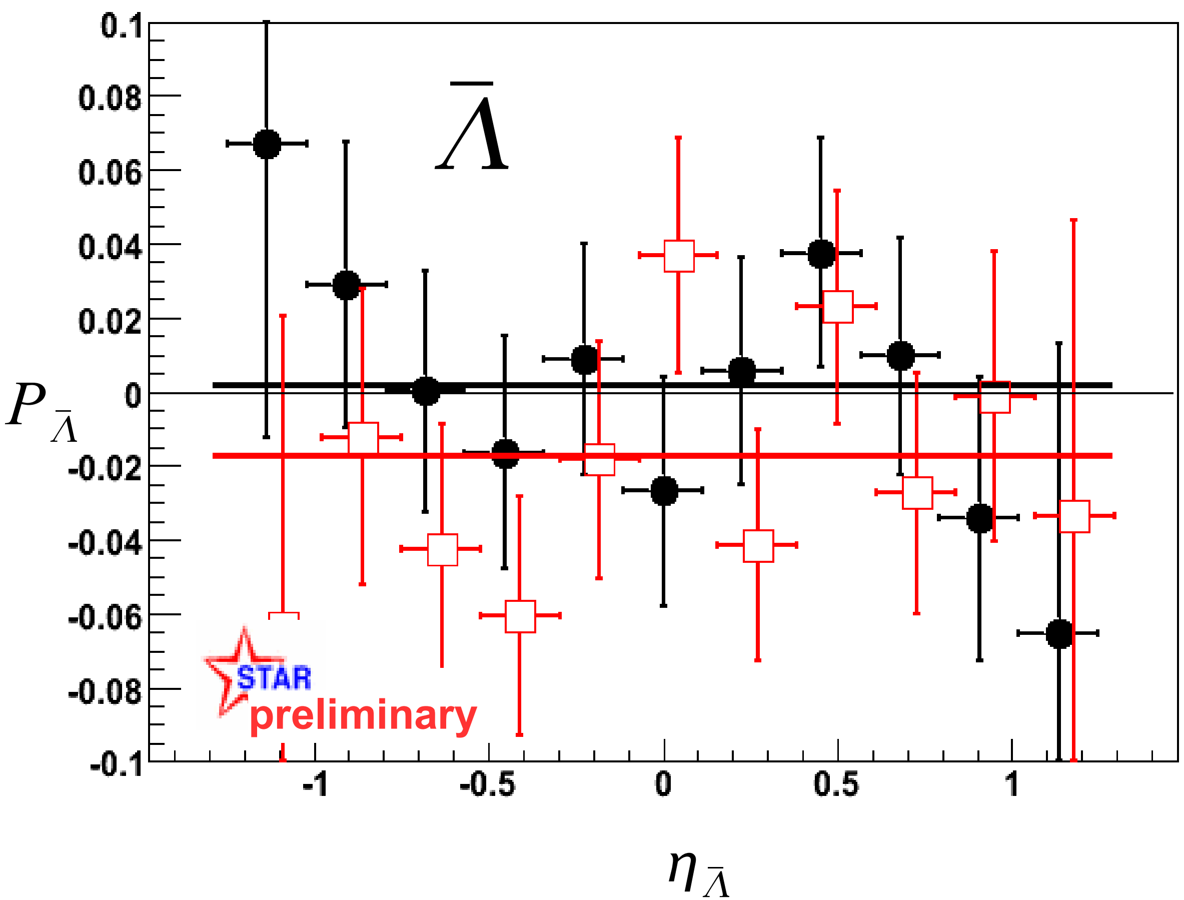
AuAu@200GeV (20-70%)

AuAu@62GeV (0-80%)

Global polarization is zero for small Anti-lambda p_t

Anti-lambda global polarization vs pseudo-rapidity

RHIC Run IV data



AuAu@200GeV (20-70%)

AuAu@62GeV (0-80%)

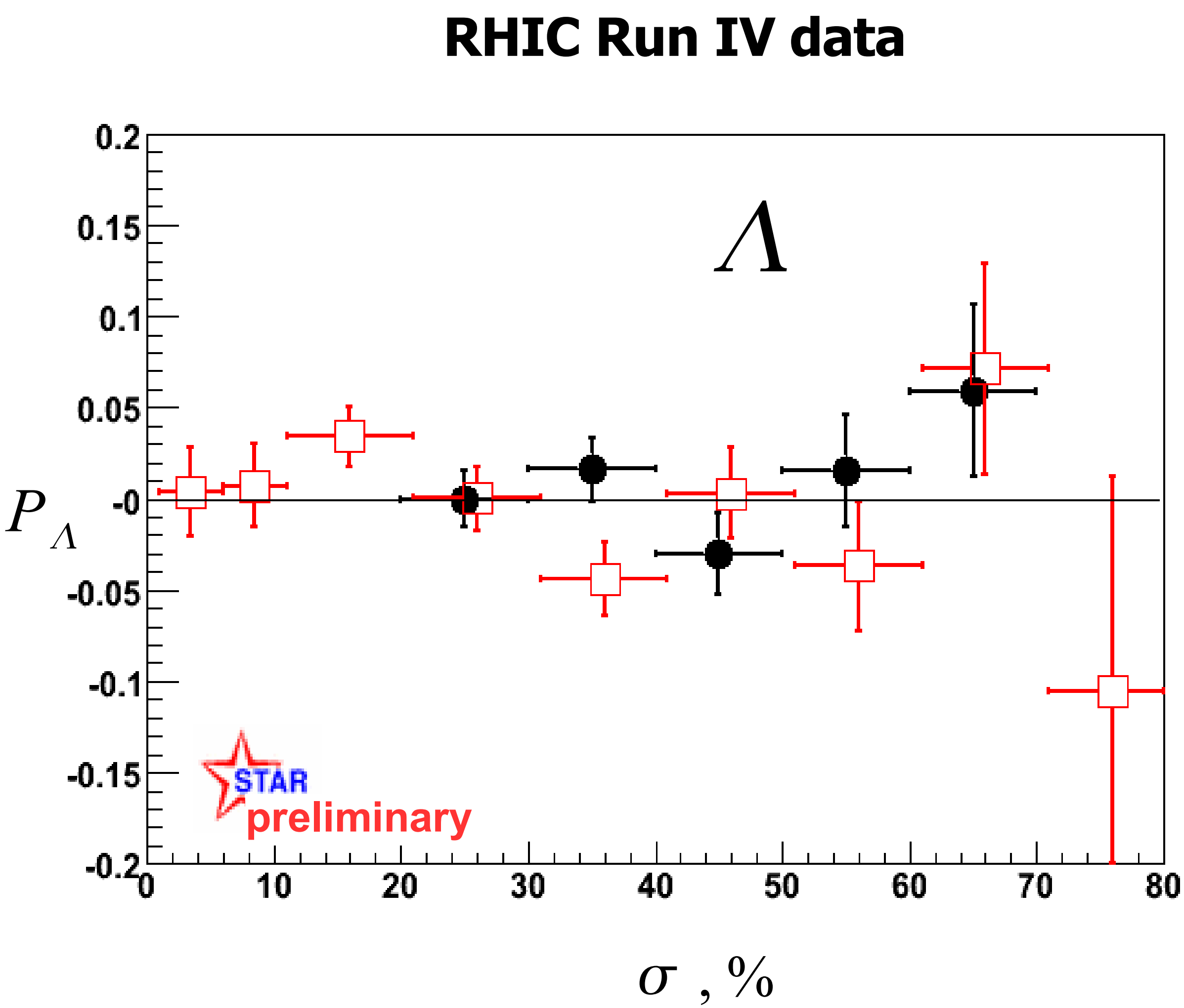
Line fit for **AuAu@200GeV**

$$P_{\bar{\Lambda}} = (1.7 \pm 10.7) \times 10^{-3}$$

Line fit for **AuAu@62GeV**

$$P_{\bar{\Lambda}} = (-17.3 \pm 11.0) \times 10^{-3}$$

Lambda global polarization vs centrality



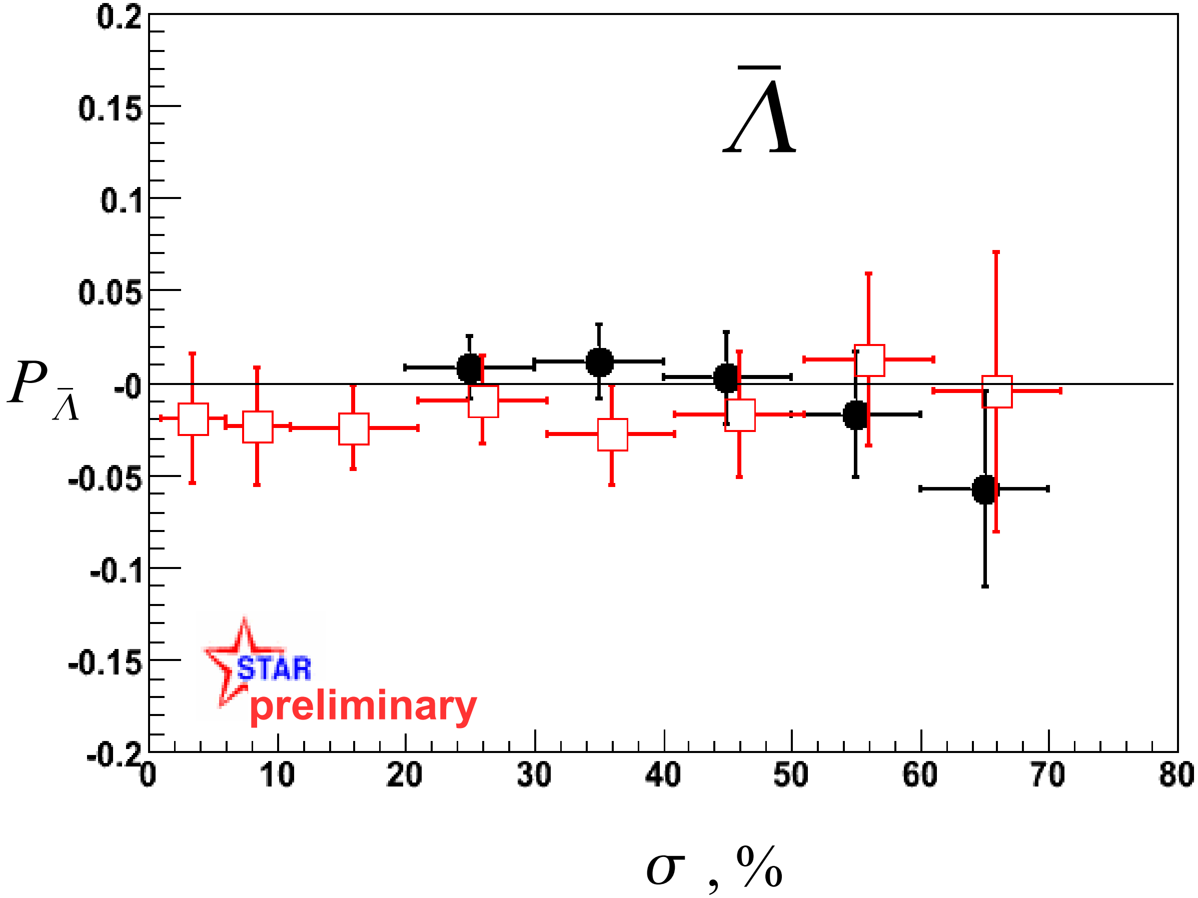
AuAu@200GeV (20-70%)

AuAu@62GeV (0-80%)

No centrality dependence observed

Anti-lambda global polarization vs centrality

RHIC Run IV data



AuAu@200GeV (20-70%)

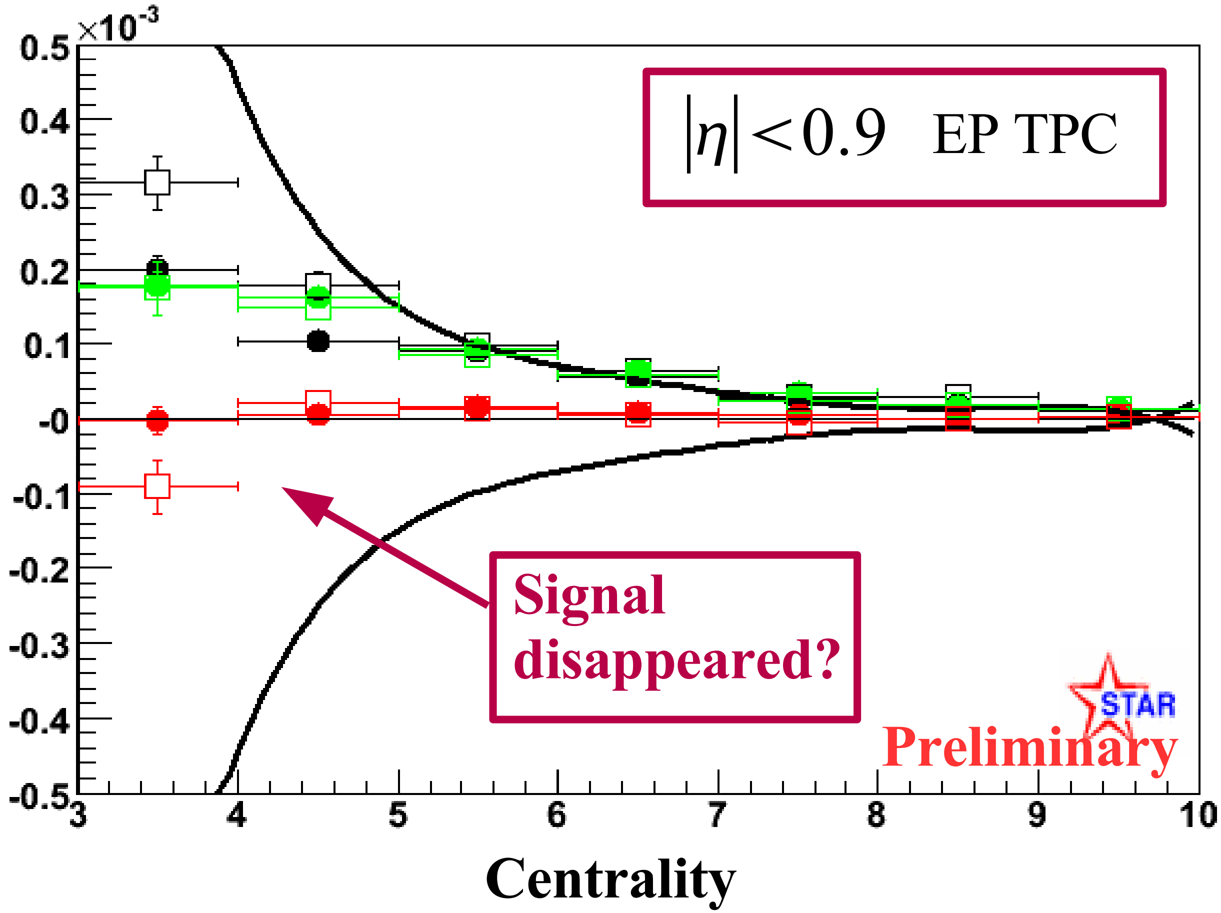
AuAu@62GeV (0-80%)

No centrality dependence observed

Consistent with Λ results

62 vs 200GeV: more statistics with $|\eta| < 0.9$

● Circles AuAu@200GeV
■ Squares AuAu@62GeV



$[a_- a_-]_{[ch]}$	**black**
$[a_+ a_+]_{[ch]}$	**green**
$[a_+ a_-]_{[ch]}$	**red**

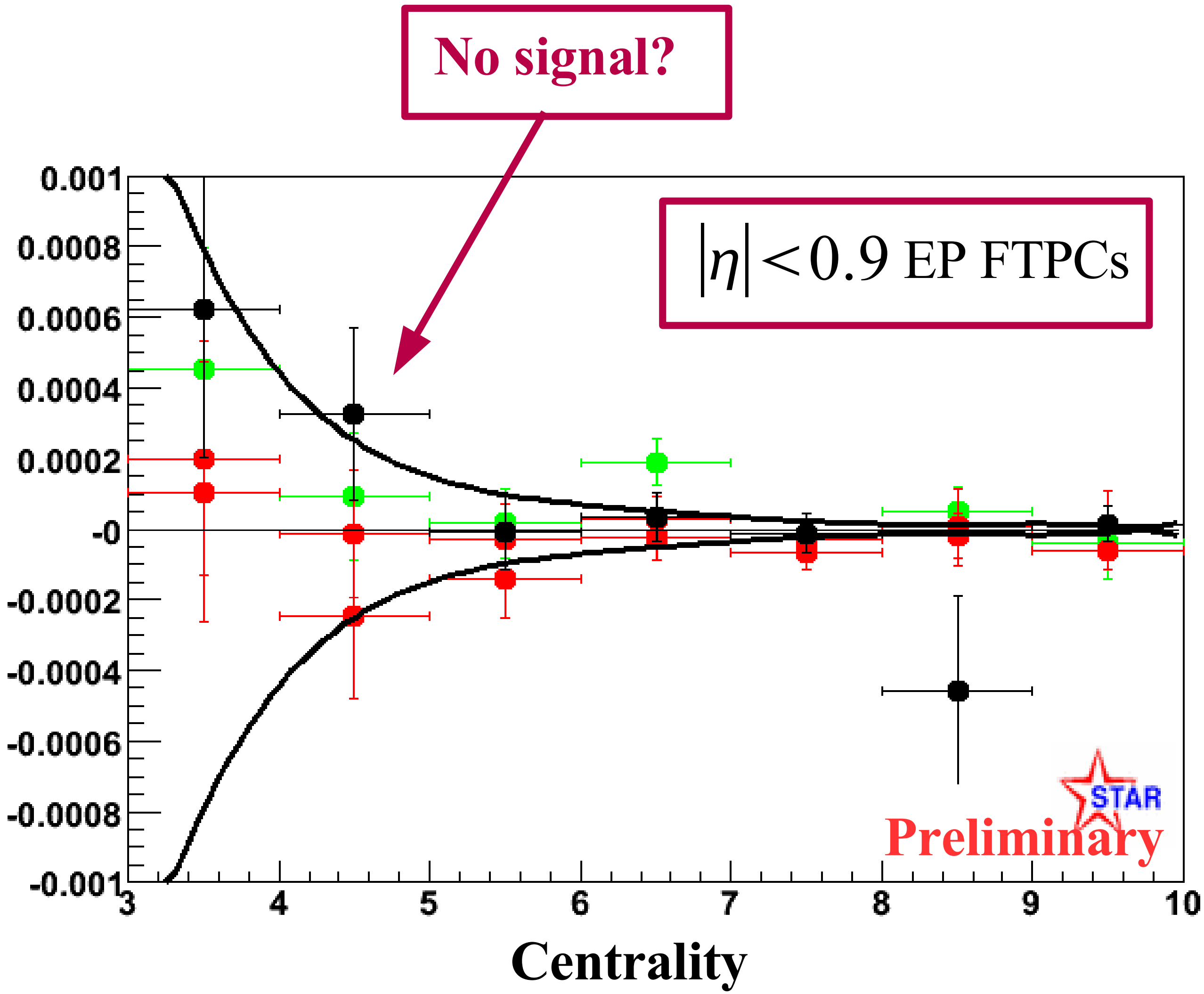
Questions

Do we see signal for the same charge particles?

Why there is nothing for opposite charges?

Are 62&200 results consistent?

AuAu@62GeV: Forward TPCs event plane



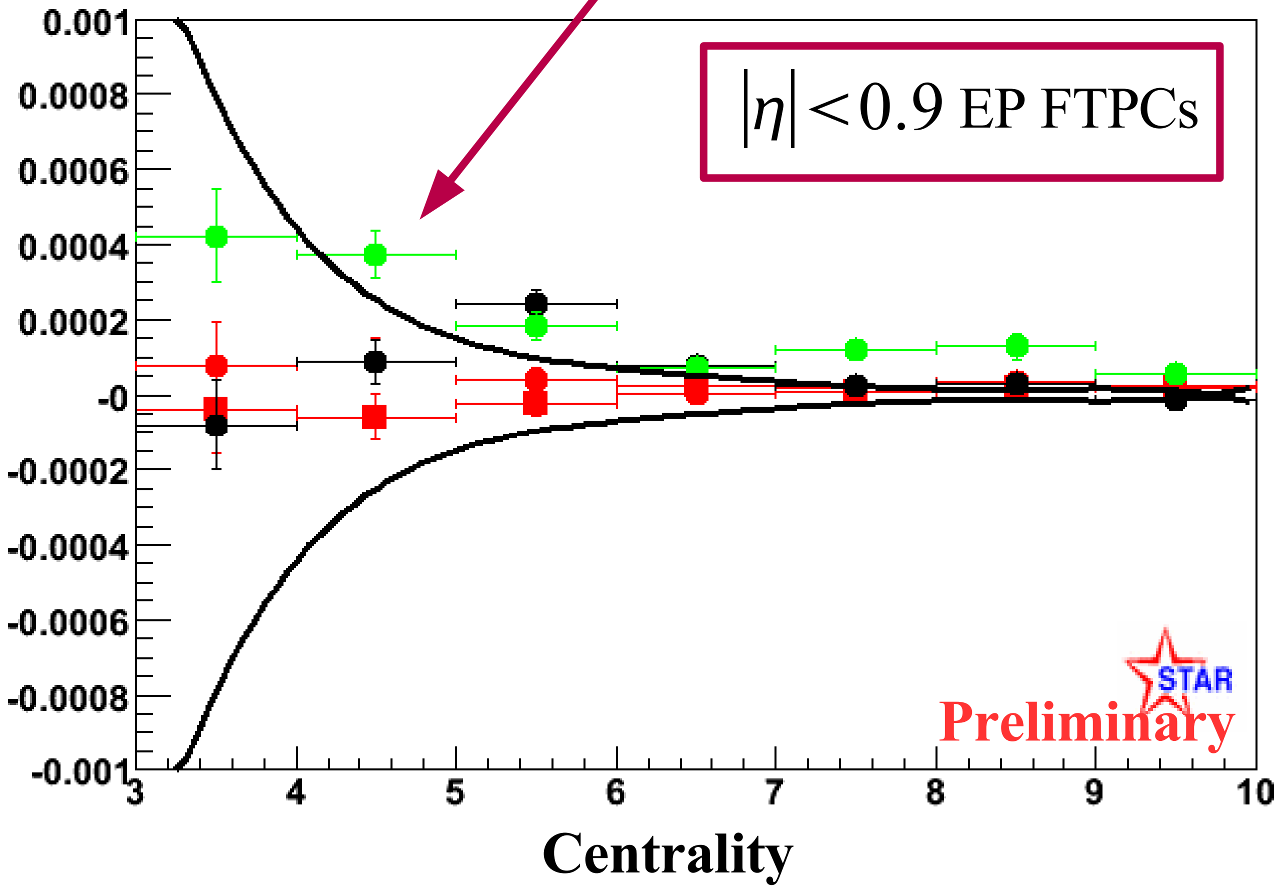
$[a_- a_-]_{[+]}$	**black**
$[a_+ a_+]_{[-]}$	**green**
$[a_+ a_-]_{[\pm]}$	**red**

FTPCs event plane inrroduce large pseudorapidity gap between particles

Out of statistics with FTPC event plane for AuAu@62GeV

AuAu@200GeV: Forward TPCs event plane

“Strange” TPC+FTPCs correlations



$[a_- a_-]_{[+]}$ black

$[a_+ a_+]_{[-]}$ green

$[a_+ a_-]_{[\pm]}$ red

More statistics that for 62GeV

problem with FTPCs in AuAu@200GeV

Outline

Asymmetries with respect to the reaction plane
- Anisotropic transverse flow
- Global polarization and spin alignment
- Strong parity violation

Why azimuthal correlations?

Anisotropic transverse flow
- Background effect in novel phenomena studies
- Measurement technique and sample results from RHIC

Global polarization of hyperons
- Theory and observable (2 particle correlations)
- Upper limit and systematic uncertainties

Strong parity violation in heavy ion collisions
- Theory and observable (3 particle correlations)
- Preliminary results and systematic study

Summary and outlook