Chirality and Vorticity at SQM 2019

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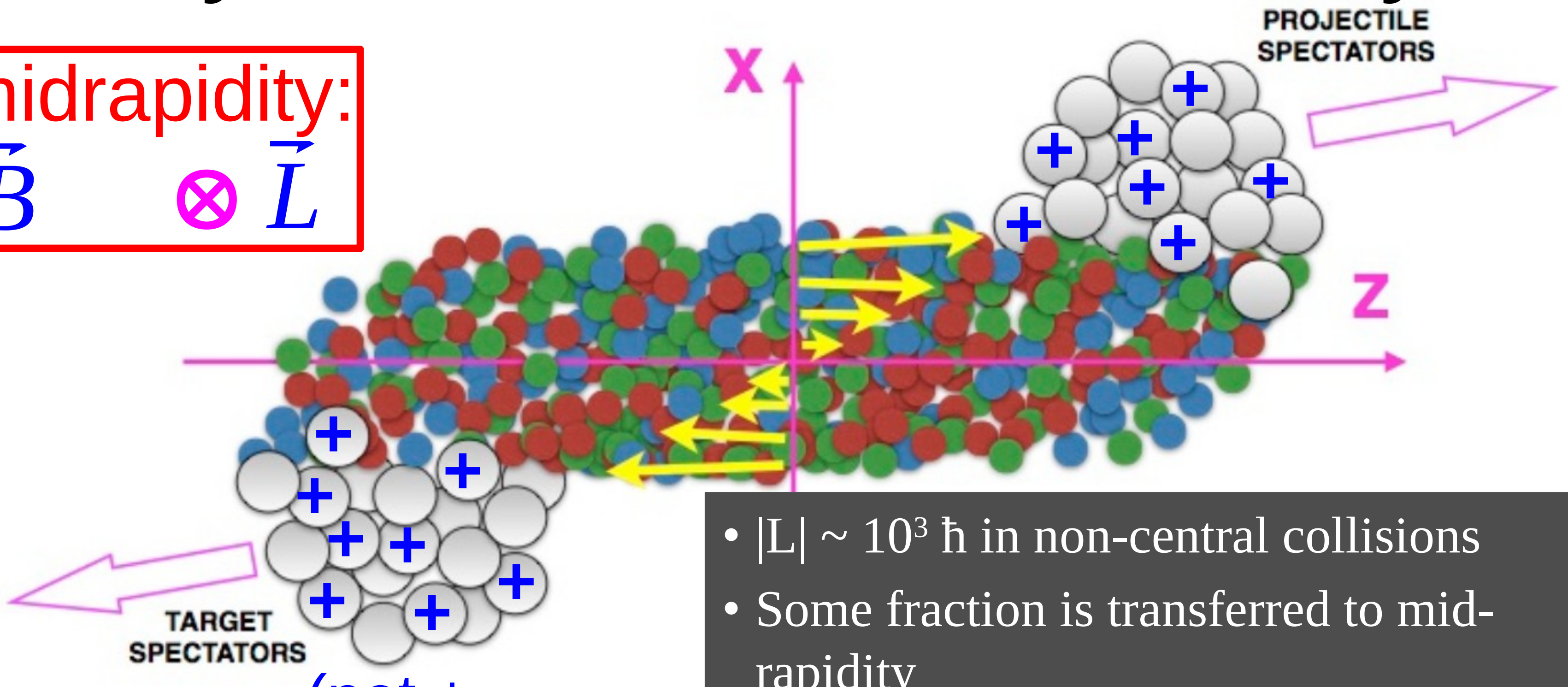
06/14/19

Vorticity

Very basic overview: Vorticity

At midrapidity:
$\otimes \vec{B}$ $\otimes \vec{L}$

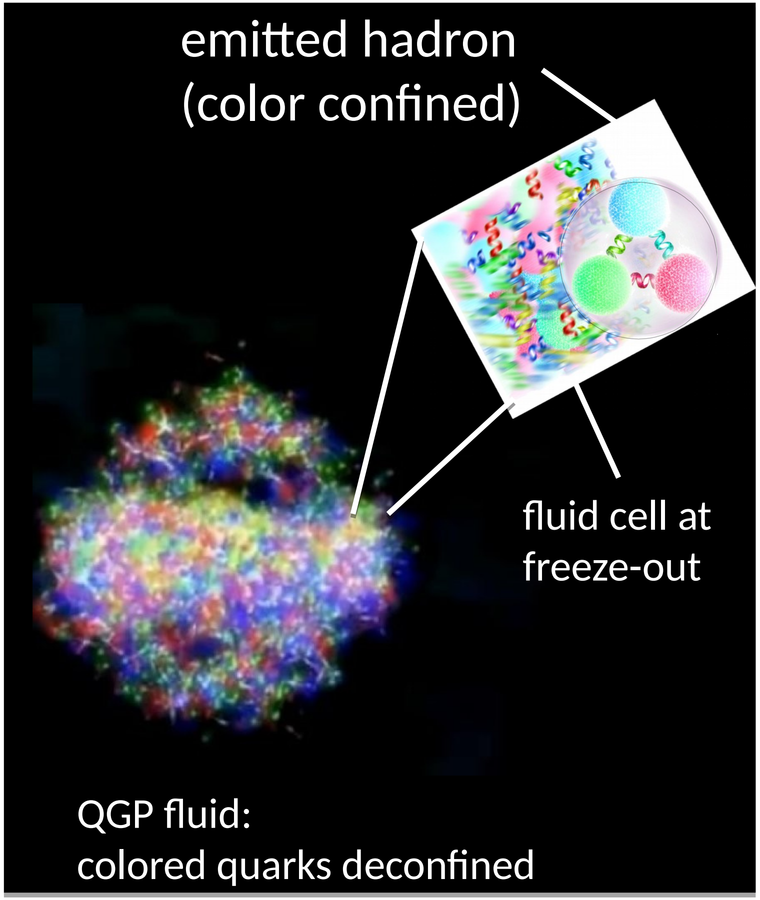


(net + charge)

- |L| ~ 10^3 ħ in non-central collisions
- Some fraction is transferred to mid-rapidity
- How does that affect fluid/transport?
  - Vorticity: $\vec{\omega} \equiv \frac{1}{2} \vec{\nabla} \times \vec{v}$
- How would it manifest itself in data?

Vorticity → particle spin

- In a transport model polarization comes from spin-orbit interaction of quarks with local relative velocities in cell
  - Analagous to Barnett effect
- In hydro
  - Vorticity part of second order hydro
  - Angular momentum is chemical potential
  - At freezeout (e.g. Cooper-Frye) particle momenta and spin must add to total L in cell
- In both fluid cells local vorticity statistically align to system L

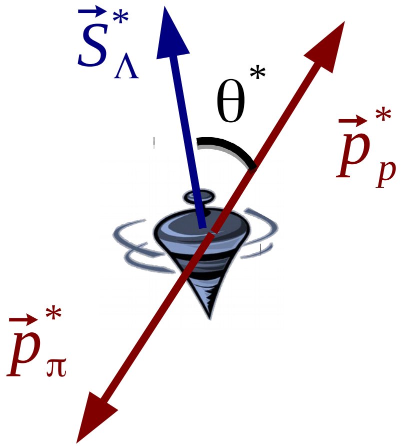


Experiment: measuring spin

- Spin ½ parity violating weak decays (e.g. Lambda) are "self-analyzing"
  - Reveal polarization by preferentially emitting daughter proton in spin direction

$$\frac{dN}{d\Omega^*}=\frac{1}{4\pi}\left(1+\alpha\vec{P}\cdot\hat{p}_p^*\right)=\frac{1}{4\pi}\left(1+\alpha P\cos\theta^*\right)$$

$$\alpha=0.642\pm0.013\quad\text{[measured]}$$

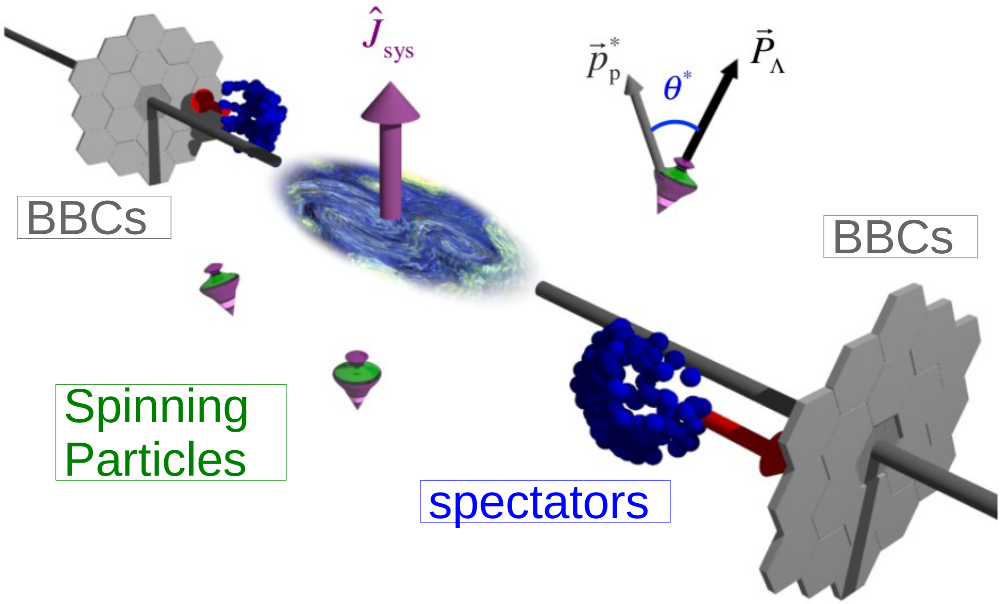


- Spin-1 vector mesons (e.g. phi, K*) also have coupling of spin to angular momentum
- Because there are now three possible spin states (+1, 0, -1) it is no longer as simple as projecting spin onto an axis, instead one has a 3x3 hermition spin density matrix, ρ, such that tr(ρ) = 1.
- Due to the trace constraint, spin alignment means that the diagonal elements of the matrix (ρ_{nn}) deviate from 1/3
- Vector mesons decay strongly so elements ρ_{11} and ρ_{-1-1} are degenerate, and only ρ_{00} is independent
- Therefore spin alignment means ρ_{00} > 1/3 or ρ_{00} < 1/3

$$\frac{dN}{d\cos\theta^*}=N_0\left(1-\rho_{00}\cos\theta^*\left(3\rho_{00}-1\right)\right)$$

Experiment: Angular momentum

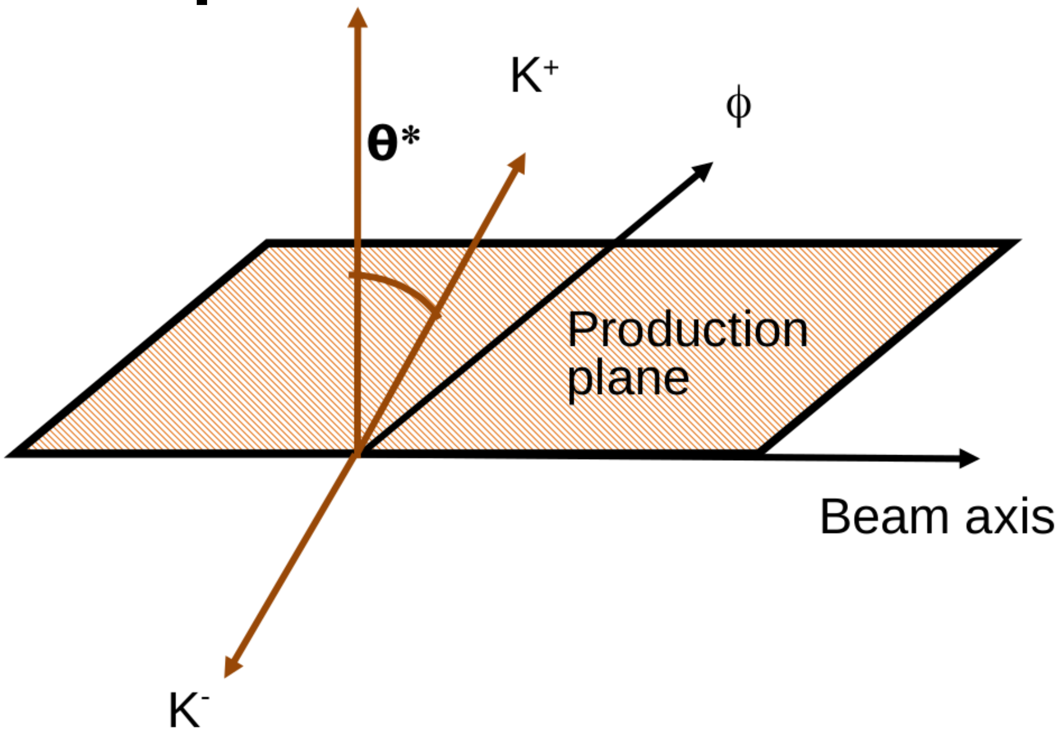
- For spin-½ particles L is perpendicular to first-order event plane (found with forward detectors)



- For spin-1 particles using the second-order plane also works

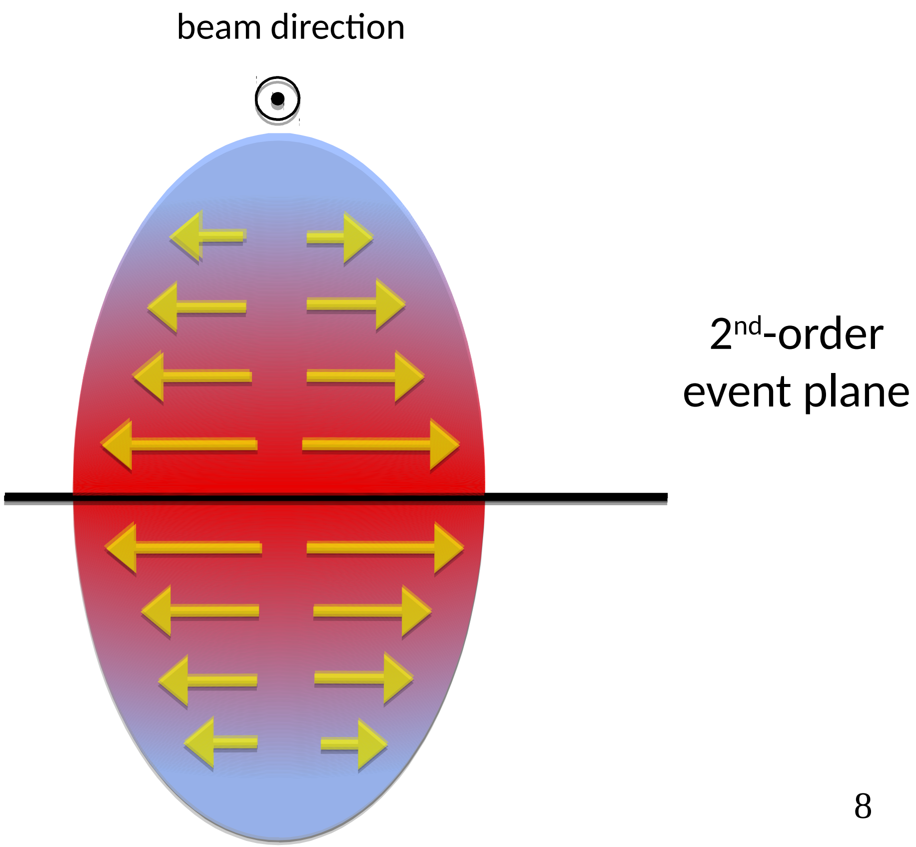
Additional considerations: production plane

- Particles may also be polarization along the direction of the production plane – the plane spanned by beam axis and the particle momentum
- Equally true for spin ½ and vector mesons



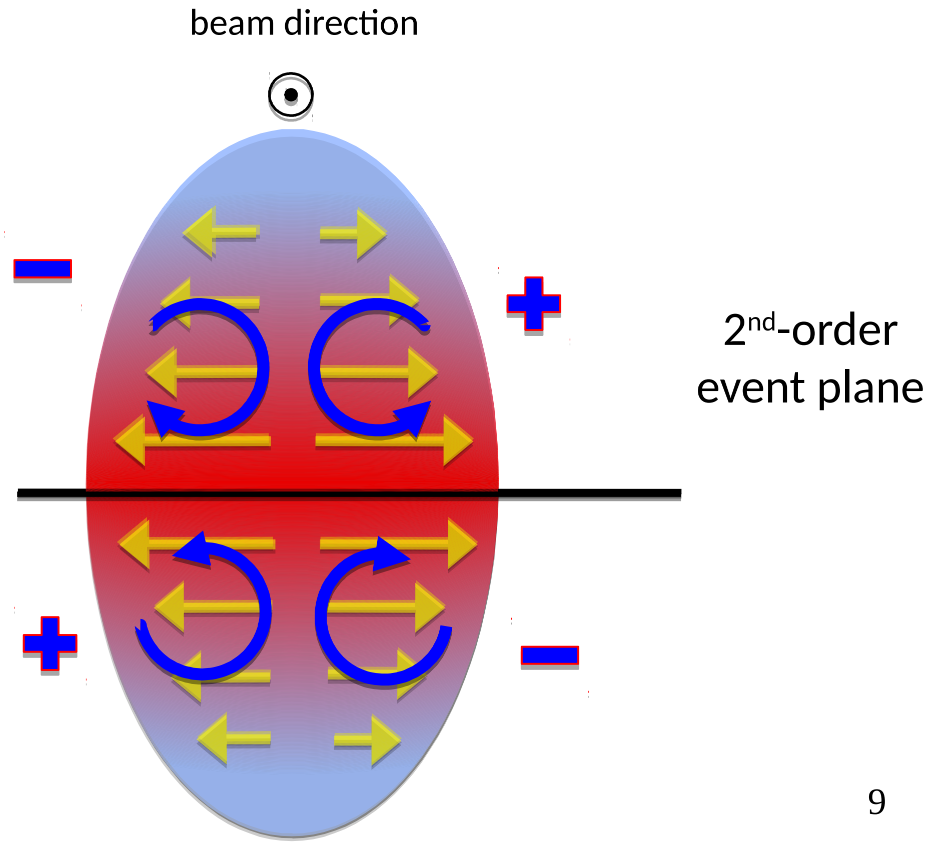
Additional considerations: Longitudinal polarization

- Elliptic flow → expansion is greater in-plane than out-of-plane



Additional considerations: Longitudinal polarization

- Elliptic flow → expansion is greater in-plane than out-of-plane
- This velocity gradiant → vortices
- Expect quadrupole structure of spin projected onto beam axis as a function of emission angle



Chirality

Chirality basics

- At sufficiently high temperatures quark masses are negligible, making them chiral fermions
- The QCD Lagrangian does not explicitly conserve Charge + Parity (CP), so, spontaneous excesses in chiral fermions are possible
- The strength of the CP violation is poorly constrained and is generally represented by the Chern-Simon’s number

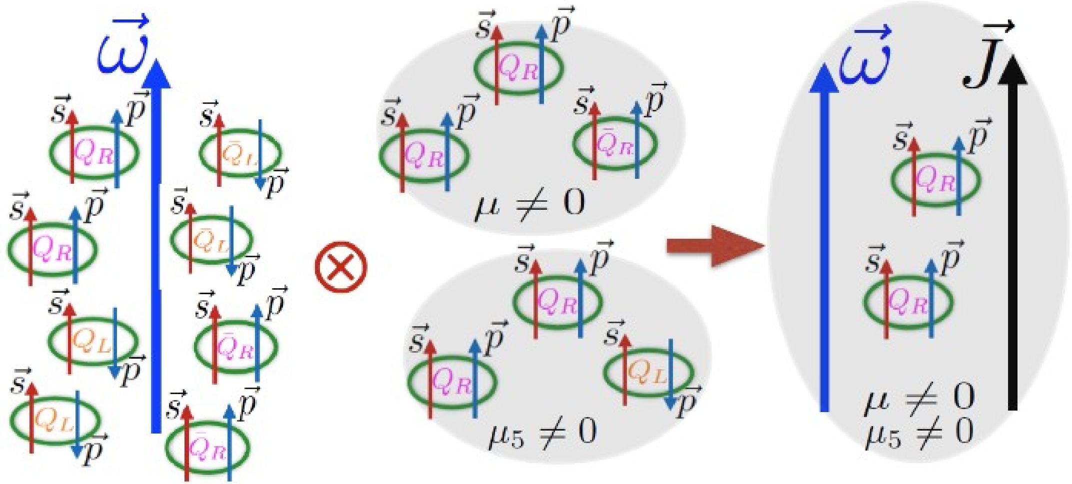
Chiral Vortical Effect

- At sufficiently high temperatures quark masses are negligible, making them chiral fermions
- The QCD Lagrangian does not explicitly conserve Charge + Parity (CP), so, spontaneous excesses in chiral fermions are possible
- The strength of the CP violation is poorly constrained and is generally represented by the Chern-Simon’s number

Chiral Vortical Effect (II)

- In a medium with nonzero chirality (characterized by μ_5) neutral baryons (e.g. Lambdas) will show a separation of baryon number along the direction of the vorticity

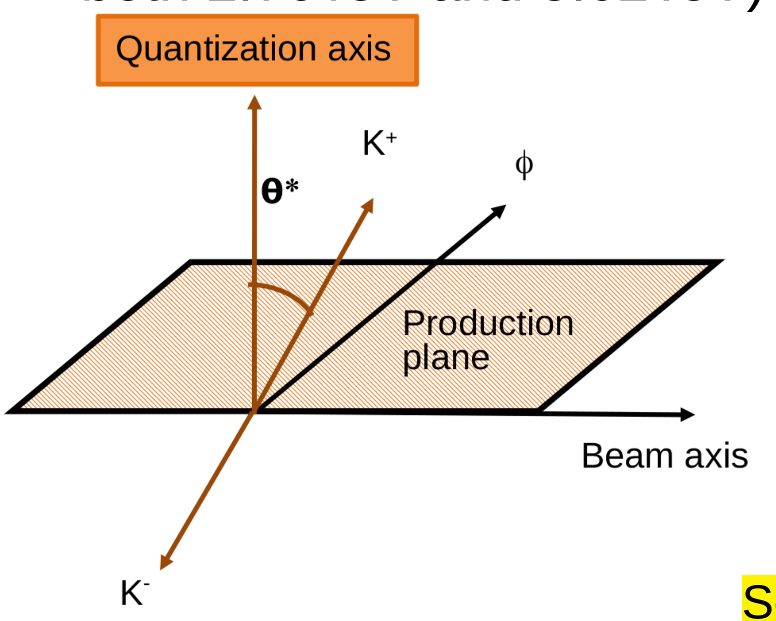
$$J_E = \frac{N_c \mu_5}{3\pi^2} \mu_B \omega$$

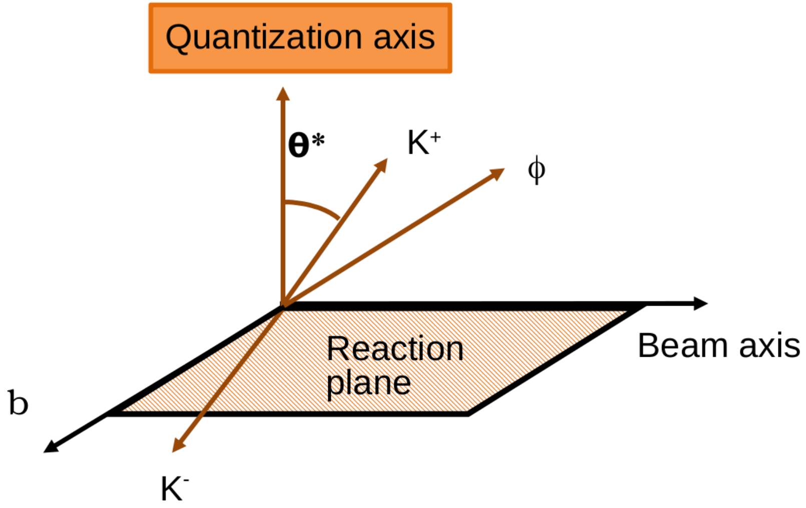


Spin alignment measurements of vector mesons with ALICE detector at the LHC

Analysis procedure

- Look for deviation of ρ_{00} from 1/3 for
  - Vector mesons K* and φ
  - Production plane (pp), production plane (PbPb), event plane (PbPb, both 2.76TeV and 5.02TeV)

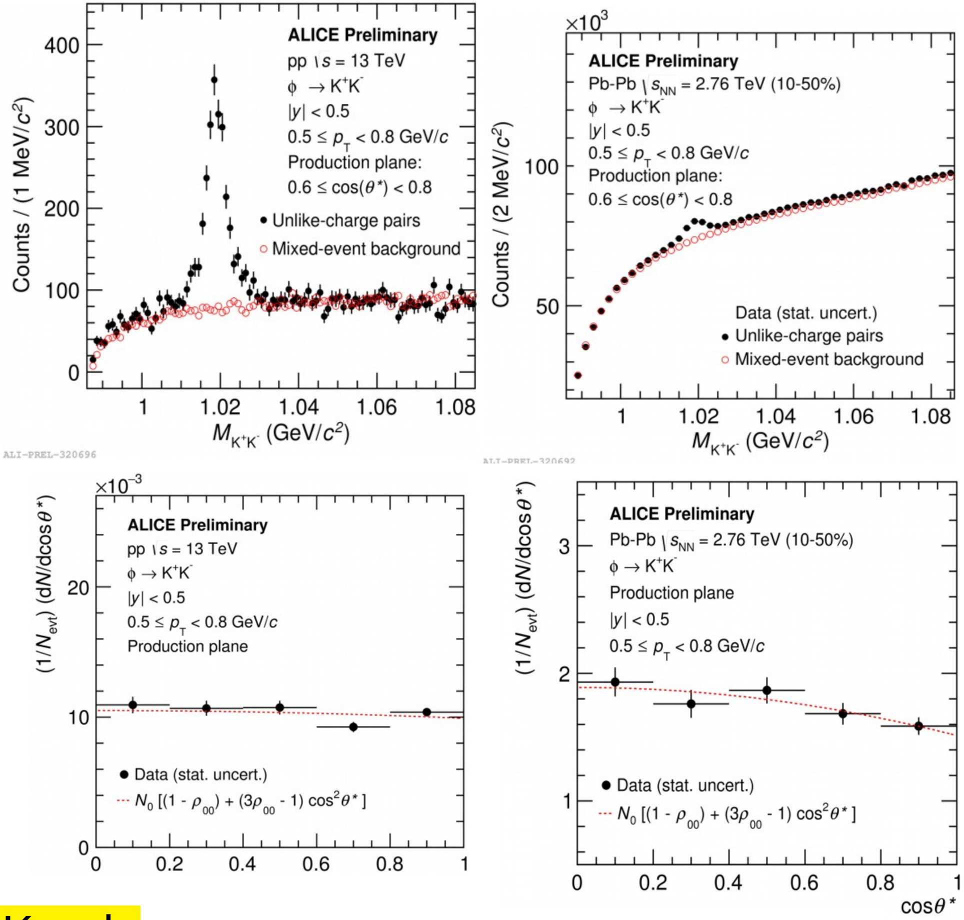




General approach

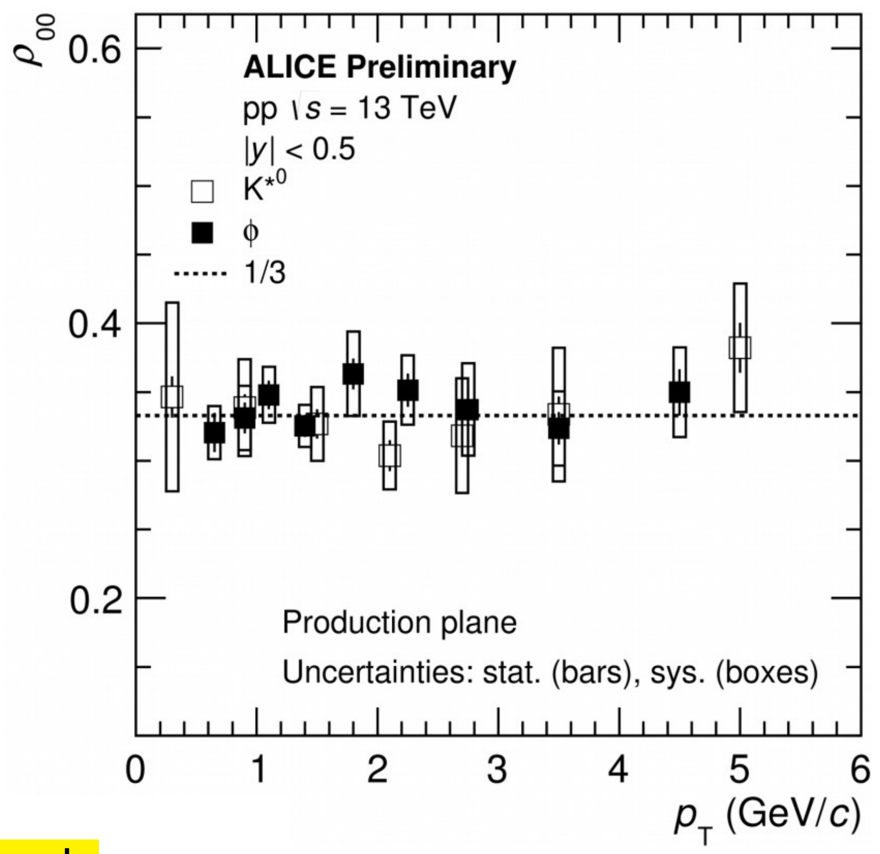
- Find vector mesons and estimate mass background with mixed-event
- Extract ρ_{00} by fitting $\cos(\theta^*)$ distribution with

$$\frac{dN}{d\left(\cos\theta^*\right)} = N_0 \times \left[\left(1-\rho_{00}\right) + (1/R)\left(3\rho_{00}-1\right)\cos^2\theta^*\right]$$



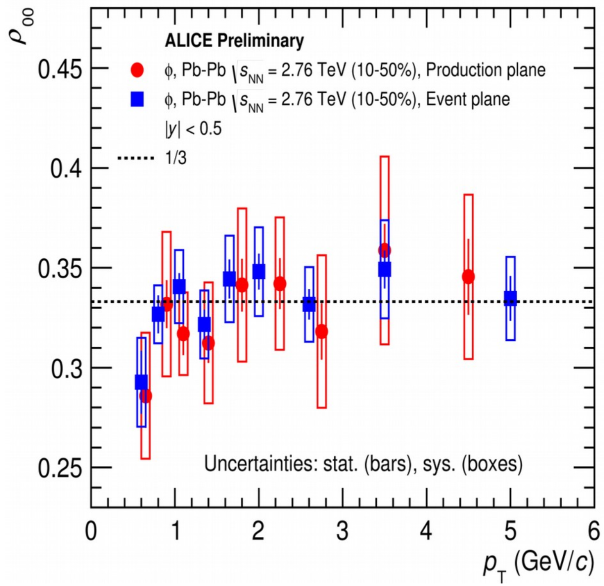
Results: pp production plane

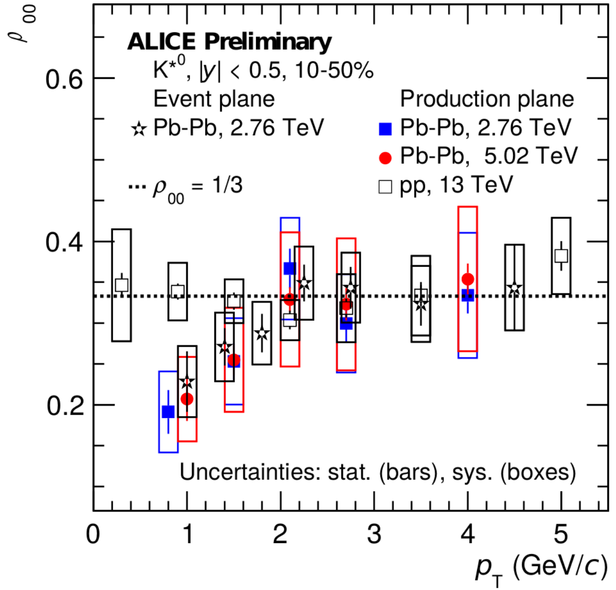
- No spin alignment for pp production plane



Results: PbPb

- Hint of deviation seen for PbPb production plane and PbPb event plane at lowest pT bin for both particles
- Production plane results are consistent with event plane results
- K* deviation from 1/3 is larger than that for φ.
  - φ deviation is 1.3σ and 1.4σ for production and event plane
  - K* deviation is 2.5σ and 1.8σ for production and event plane



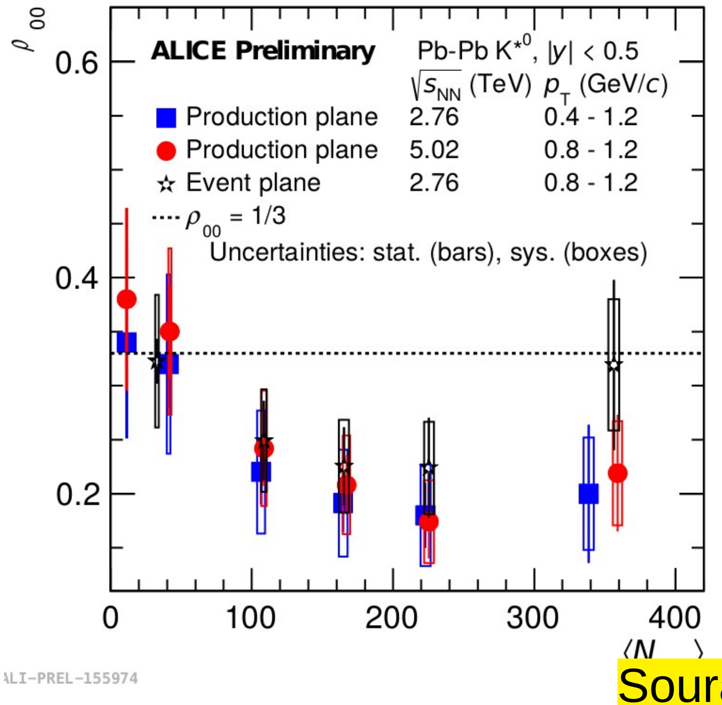


Sourav Kundu

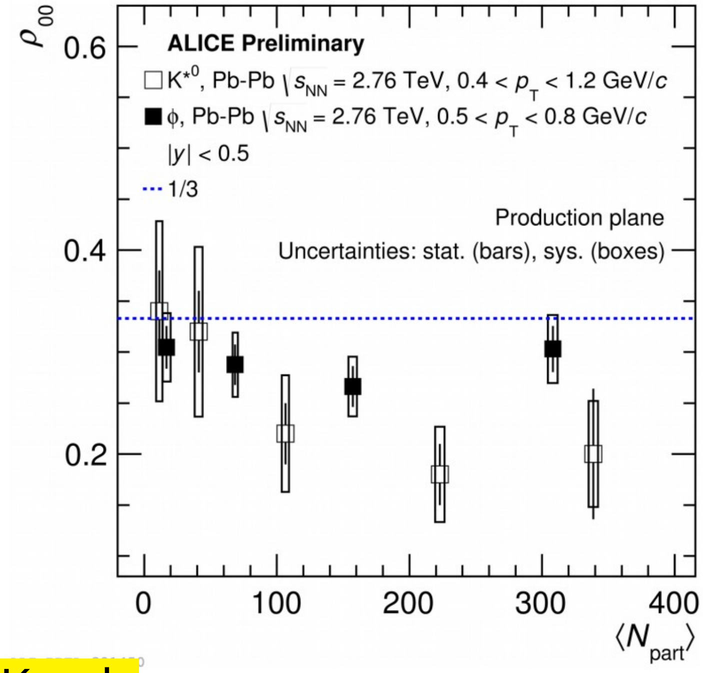
PbPb centrality dependence

- Centrality dependence of the deviation of the first pT bin from zero is consistent

K^{*0} : production and event plane



K^{*0} and ϕ: production plane



Sourav Kundu

Λ Polarization in Au+Au collisions at $\sqrt{s_{NN}}$ = 2.4 GeV Measured With HADES

Frederic Kornas

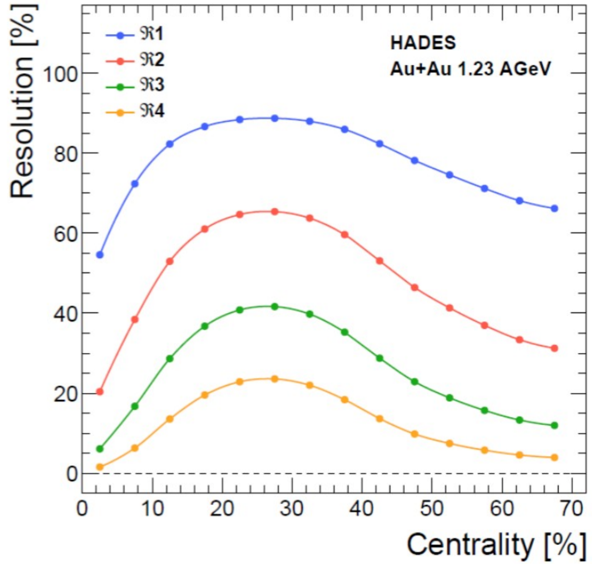
HADES 2.4GeV Lambda Polarization

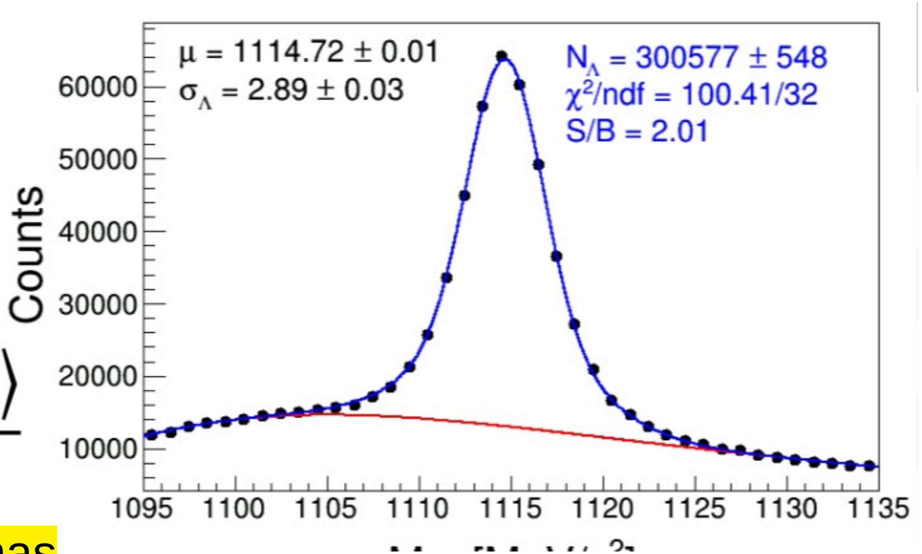
- Previous positive results have been at STAR ($\sqrt{s_{NN}}$ = 7.7-200GeV) which have been shown to rise with decreasing collision energy (there is also an important NULL result at ALICE)
  - Currently theory calculations predict an increasing trend as beam-energy decreases
    - These predictions do not specifically include HADES $\sqrt{s_{NN}}$
  - In principal, at some sufficiently low $\sqrt{s_{NN}}$ the polarization might decrease as the interplay between the effectiveness of the spin-orbit coupling and the dropping system angular momentum changes
- This is an important test of the model trend
- Strangeness production is significantly decreased at these energies, making the measurement difficult

Ingredients

- Very high-resolution first-order event plane
- Sophisticated neural-net Lambda reconstruction
- Ultimately correlate spin to angular momentum:

$$P_{\Lambda}(centrality) = \frac{8}{\pi \alpha_{\Lambda}} \frac{\langle sin(\Psi_{EP} - \phi_p^*) \rangle}{R_{EP}}$$





Frederic Kornas

Methodology: EP vs. Invariant mass

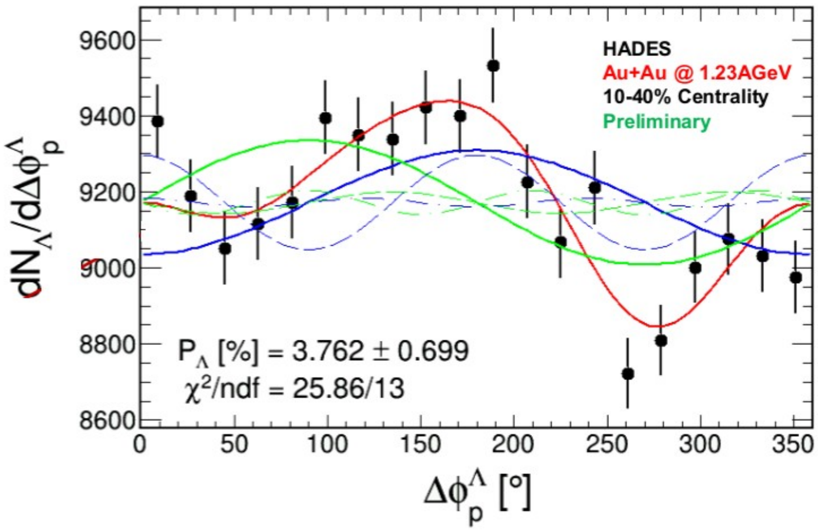
	(1) Event plane method	(2) Invariant mass fit method
General procedure	➤ Get $\mathrm{dN}/\mathrm{d}M_{inv}$ in a certain $\Delta\phi_p^*$-bin ➤ Get net amount of Λs in that bin ➤ Plot distribution of $N_\Lambda(\Delta\phi_p^*)$ ➤ Fit this distribution to get $\langle \sin(\Delta\phi_p^*)\rangle$ ➤ Calculate P_Λ	➤ Plot the distribution of $\langle sin(\Delta\phi_p^*)\rangle_{tot}$ as a function of M_{inv} ➤ Get S/B-ratio in each bin: $f(M_{inv})$ ➤ Make assumption for $\langle sin(\Delta\phi_p^*)\rangle_{BG}$ ➤ Fit the distribution to get $\langle sin(\Delta\phi_p^*)\rangle_{SG}$ ➤ Calculate P_Λ
Correction for R_{EP}	➤ Final result is corrected by $1/R_{EP}$ while $R_{EP}^{10-40\%}$ is used	➤ $1/R_{EP}^{10\%}$ in 10% centrality bins is weighted event-by-event when filling $\langle sin(\Delta\phi_p^*)\rangle_{tot}$
Advantage/ Drawback	➤ **D:** second decomposition in $\Delta\phi_p^*$-bins ➤ **A:** no background assumption	➤ **A:** direct extraction of $\langle sin(\Delta\phi_p^*)\rangle_{SG}$ ➤ **D:** background assumption needed

Frederic Kornas

Results: EP

- Only sine terms should contribute

Fit the distribution of the polarization angle $\Delta\phi_p^* = \Psi_{EP} - \phi_p^*$



Green: **Sin-Terms**
Blue: **Cos-Terms**

$$\frac{dN}{d\Delta\phi_p^\Lambda} = N_0\left[1 + 2b_1 \sin(\Delta\phi_p^*) + 2c_1 \cos(\Delta\phi_p^*) + 2b_2 \sin(2\Delta\phi_p^*) + 2c_2 \cos(2\Delta\phi_p^*) + \cdots\right]$$

First order event plane resolution

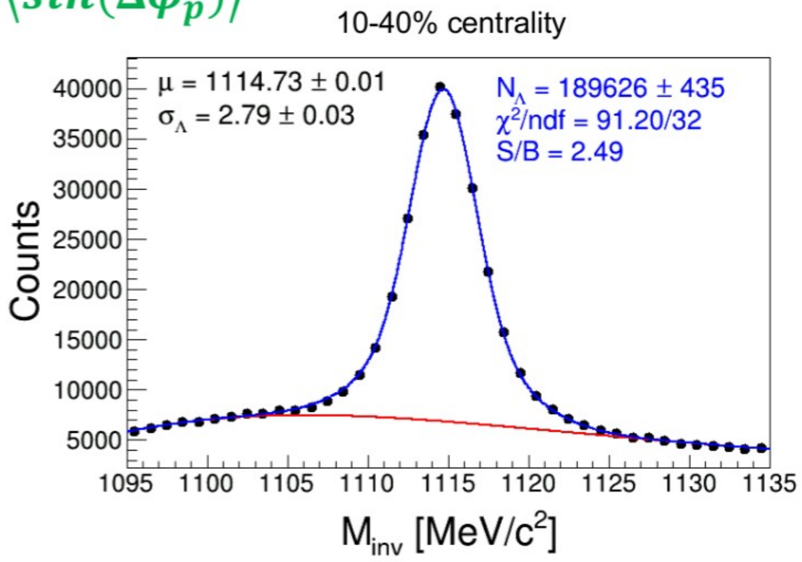
$$\Rightarrow P_\Lambda\,[\%] = 3.762 \pm 0.699\ (stat.)$$

$$P_\Lambda = \frac{8}{\pi\alpha_\Lambda}\frac{b_1}{R_1}$$

Results: invariant mass

Fit the distribution of $\langle sin(\Delta\phi_p^*)\rangle$

- Make assumption for $<\sin(\Delta\varphi_p^*)>_{BG}$
- Results consistent with EP

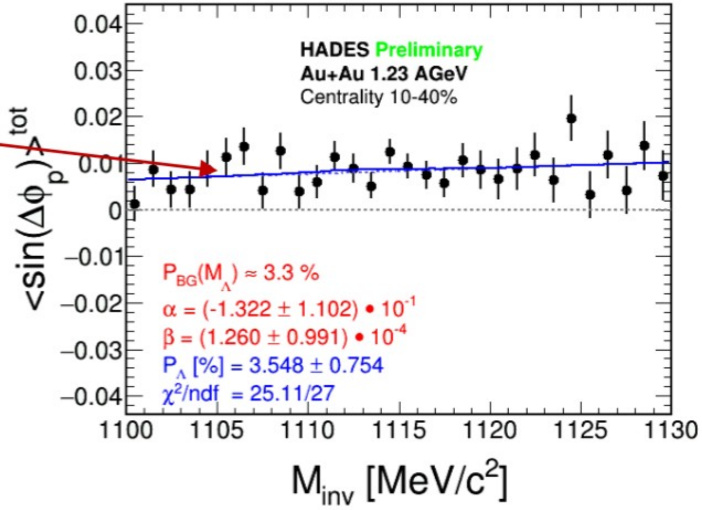


$$\langle\sin(\Delta\phi_p^*)\rangle_{tot} = f(M_{inv})\langle\sin(\Delta\phi_p^*)\rangle_{SG} + (1 - f(M_{inv}))\langle\sin(\Delta\phi_p^*)\rangle_{BG}$$

$$\langle\sin(\Delta\phi_p^*)\rangle_{BG} = \alpha + \beta \cdot M_{inv}$$

$$P_\Lambda = \frac{8}{\pi\alpha_\Lambda}\langle\sin(\Delta\phi_p^*)\rangle_{SG}$$

$$\Rightarrow \boldsymbol{P_\Lambda[\%] = 3.548 \pm 0.754(stat.)}$$

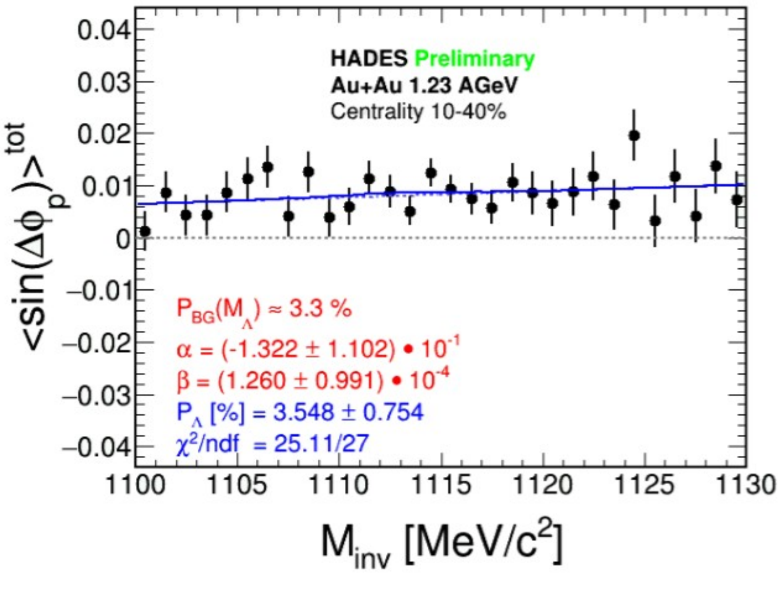


- **Background shows non-zero correlations with magnitude similar to the Λ signal!**

Frederic Kornas

Background polarization

- Unfortunately, no deviation from background is seen in HADES, unlike same method in STAR



Comparison to STAR @ $\sqrt{s_{NN}} = 200GeV$:

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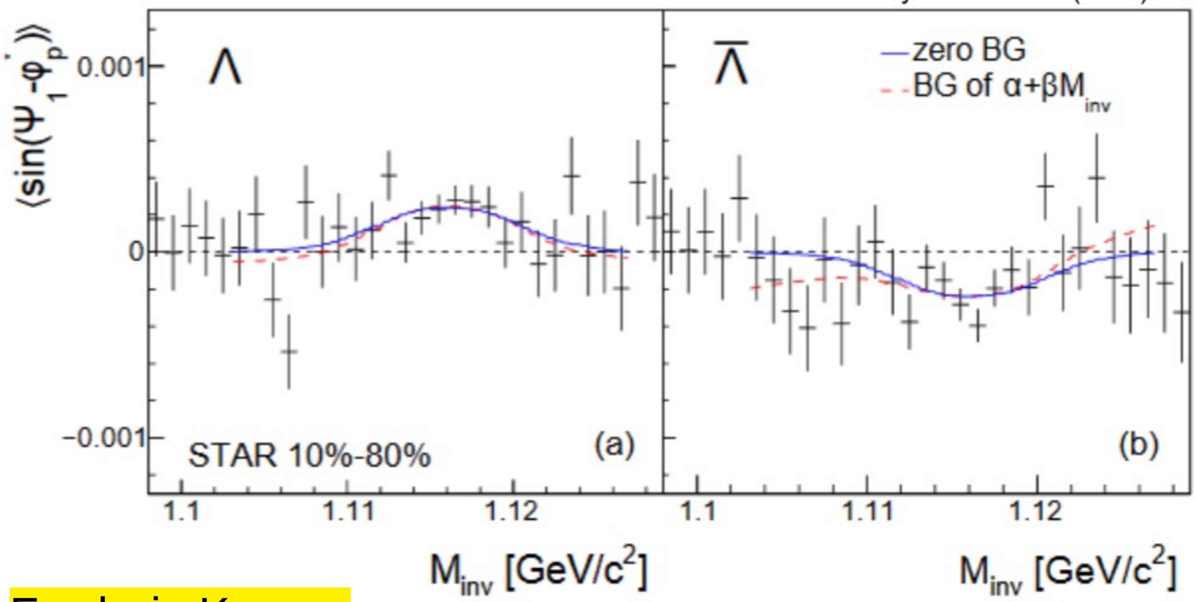

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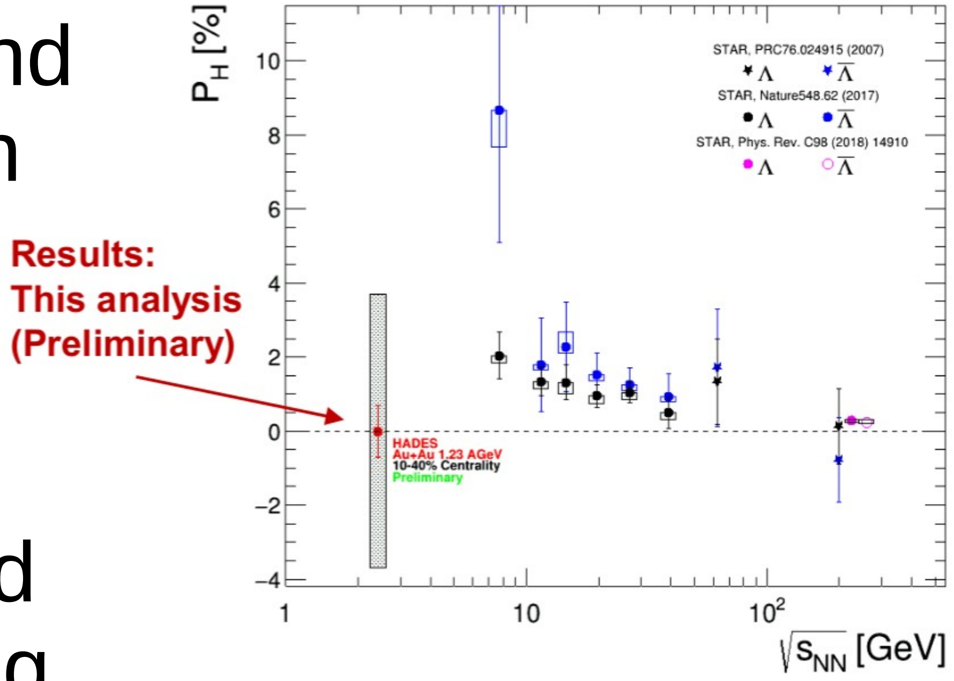
Conclusion

- Due to large background signal, after subtraction polarization is zero
- Systematic errors and further studies to understand background polarization are ongoing



Frederic Kornas

Directed flow, Vorticity and Λ Polarization in HIC

Oleksandr Vitiuk

General outline

- Understand the mechanisms that take angular momentum → particle polarization
- Use UrQMD with black disk approximation
- Monte Carlo method for probing time evolution of the various phase space densities of particle species.
- Lambdas and AntiLambdas are produced at and emitted from different positions in fireball
  - This will have some effect on the flow and polarization of these particles

Thermal vorticity → particle spin → polarization

In local thermal equilibrium, the ensemble average of the spin vector for spin-1/2 fermions with four-momentum p at space-time point x is obtained from the statistical-hydrodynamical model as well as the Wigner function approach and reads

$$S^\mu(x,p) = -\frac{1}{8m}(1-n_F)\,\epsilon^{\mu\nu\rho\sigma} p_\nu \varpi_{\rho\sigma}(x),$$

where the thermal vorticity tensor is given by

$$\varpi_{\mu\nu} = \frac{1}{2}\left(\partial_\nu \beta_\mu - \partial_\mu \beta_\nu\right),$$

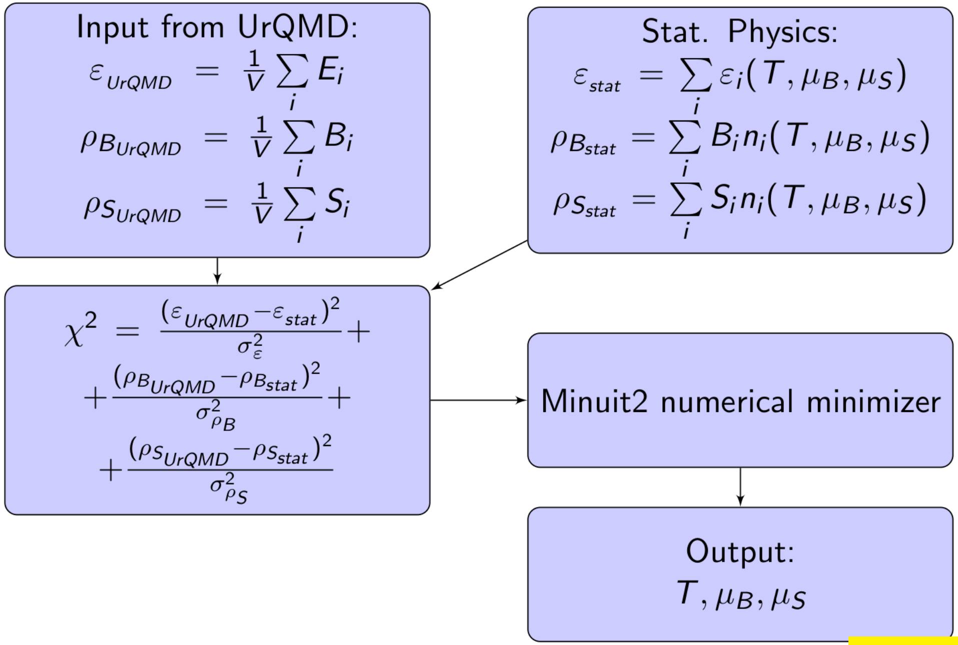
After some simplification one can get global polarization measure from statistical quantities

$$S^0(x,p) = \frac{1}{4m}\mathbf{p}\cdot\varpi_S, \quad \mathbf{S}(x,p) = \frac{1}{4m}(E_p \varpi_S + \mathbf{p}\times\varpi_T) \quad \Rightarrow \quad P = \frac{\langle \mathbf{S}^* \rangle \cdot \mathbf{J}}{|\langle \mathbf{S}^* \rangle||\mathbf{J}|}$$

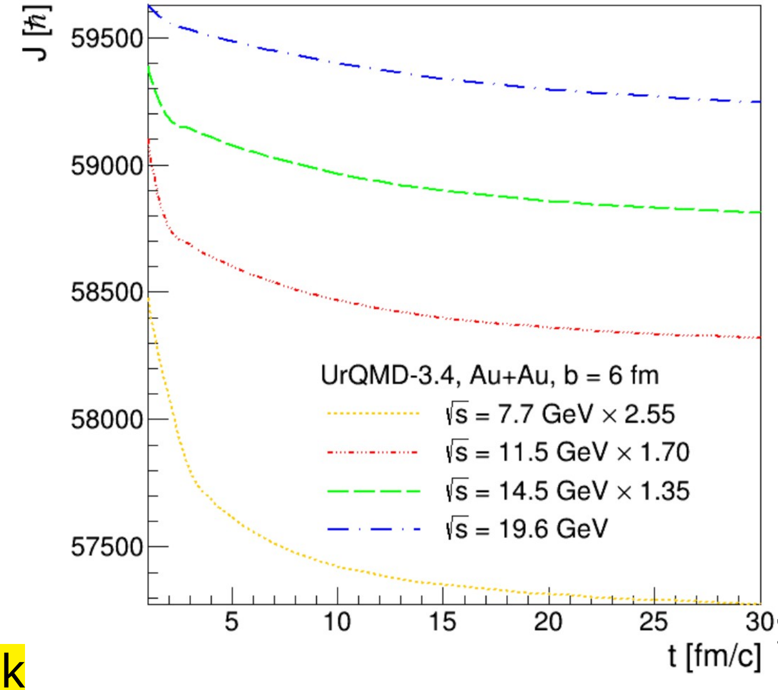
Oleksandr Vitiuk

Local thermal equilibrium w/ UrQMD

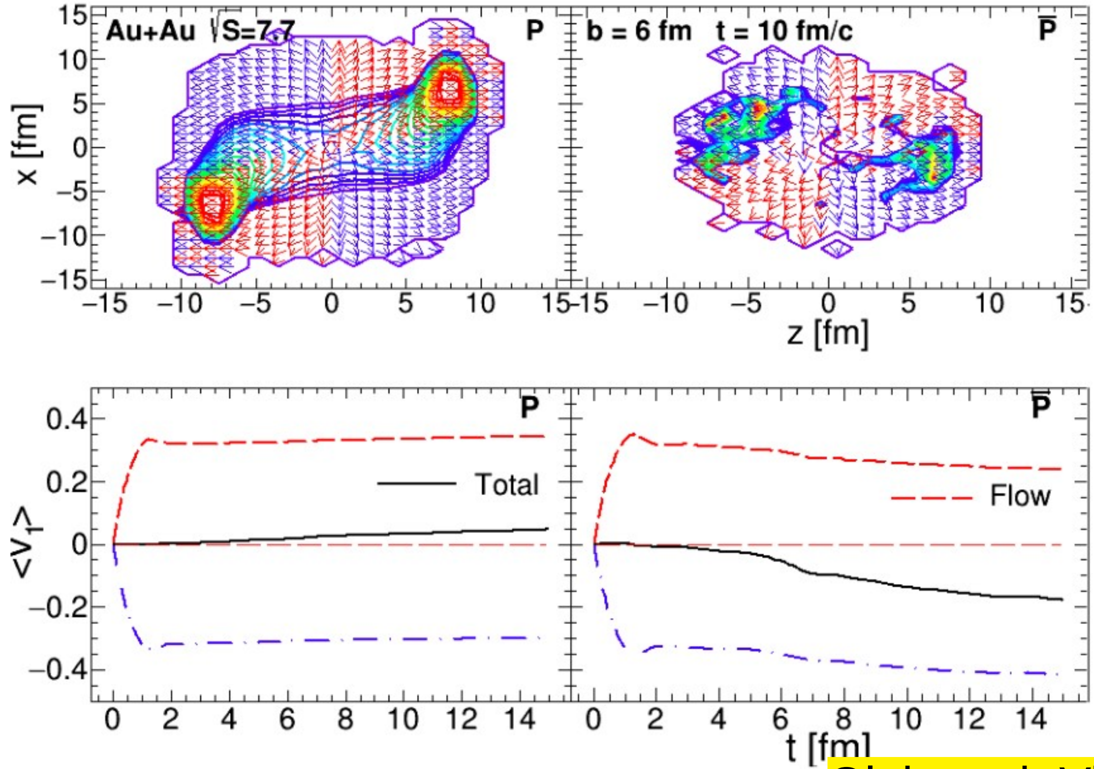
Parameters can be found via



Total angular momentum is not conserved, but deviation is ~ 2%



Flow difference due to emission regions

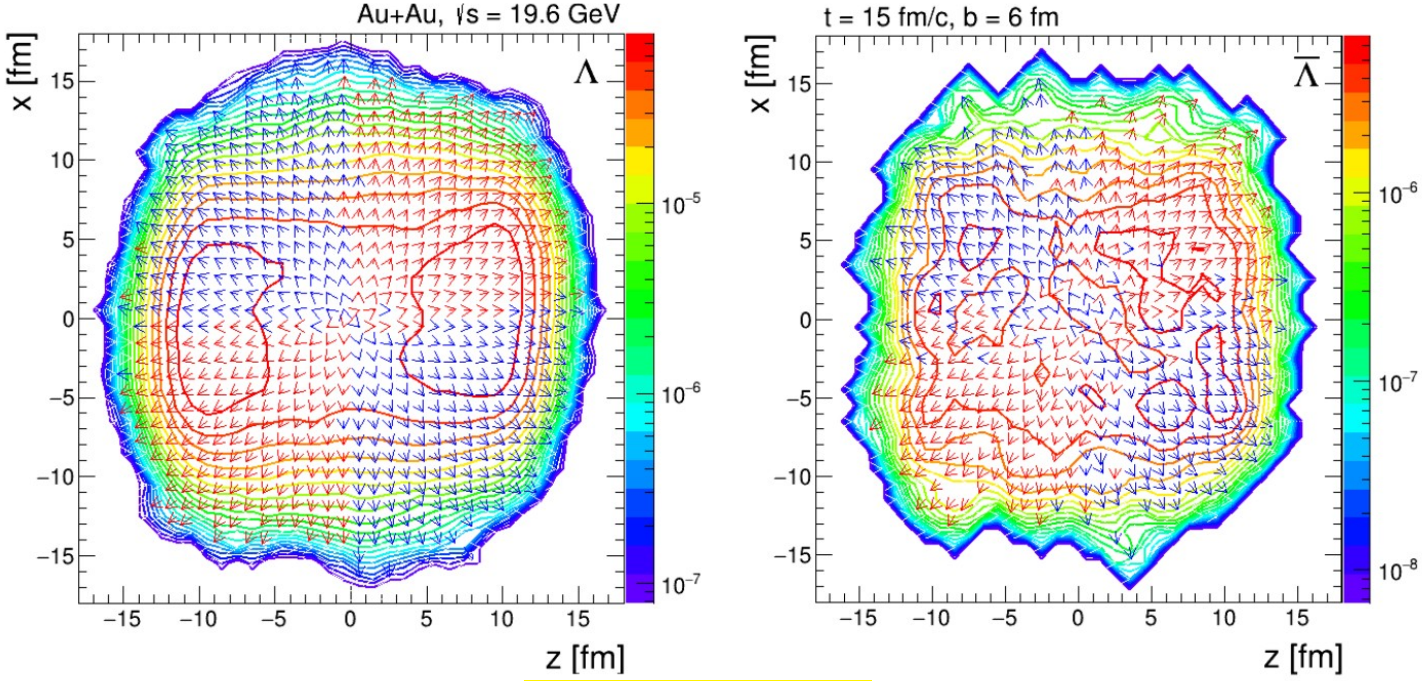


At low energies Λ and $\bar{\Lambda}$ are produced and emitted from the same regions as protons and antiprotons respectively. Λ's are concentrated also near hot and dense spectators, whereas $\bar{\Lambda}$'s are mostly produced in central region.

Oleksandr Vitiuk

Spatial distribution of Lambdas

At $\sqrt{s} = 19.6\,GeV$ Λ are mostly located near hot and dense regions and $\bar{\Lambda}$ are distributed more uniformly near system center.



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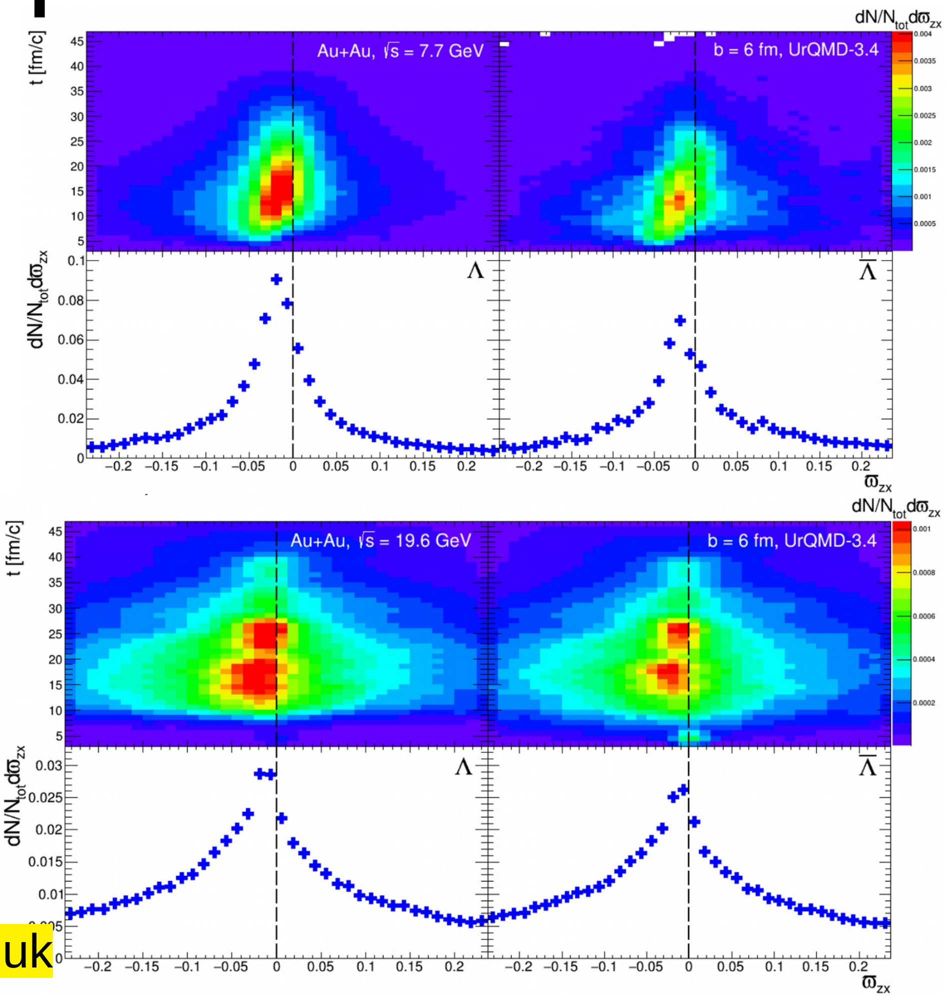
Vorticity comparison

- At 7.7GeV the zx projection of thermal vorticity is -0.04 and -0.017 for AntiLambda and Lambda (respectively)
- At 19.6GeV this is -0.011 and -0.009 for AntiLambda and Lambda (respectively)
- Note that negative projection of vorticity is a sign choice, it means positive polarization



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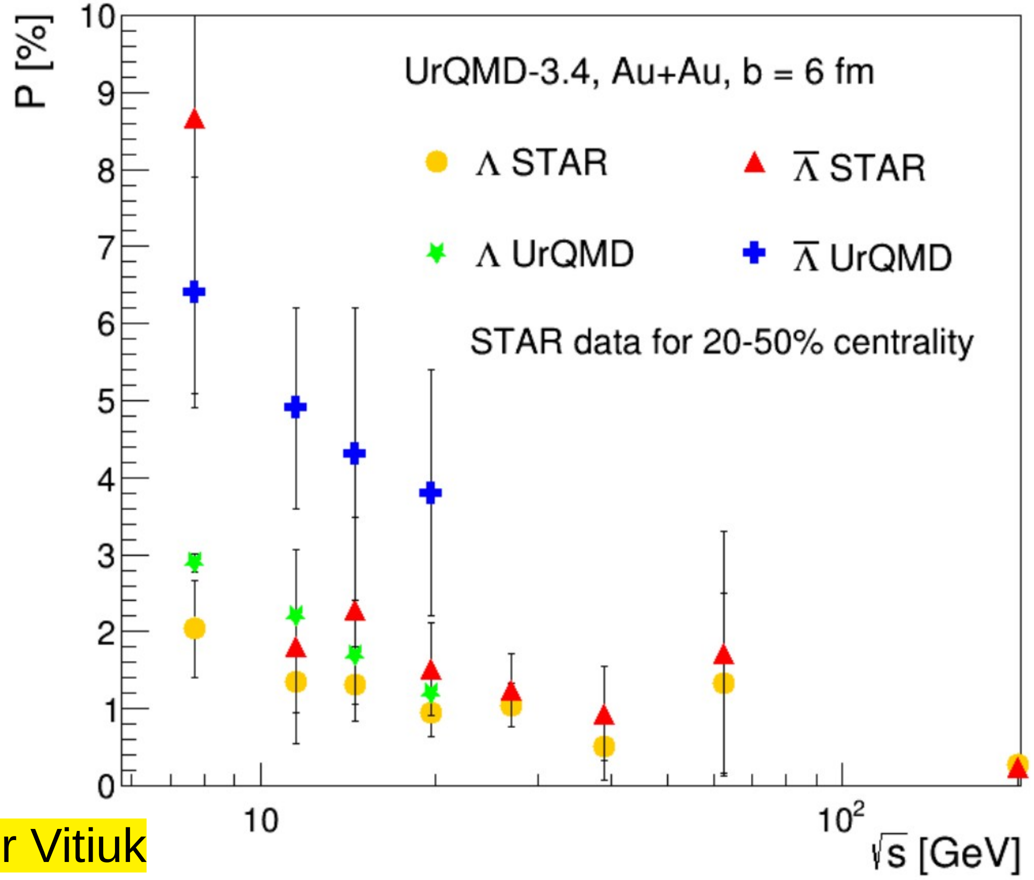
Conclusion

- Model predicts increasing gap of Lambda-AntiLambda polarization system as beam energy decreases (something hinted at in data)
- This is somewhat overpredicted, but general trend of data is captured



Oleksandr Vitiuk

Polarization of quarks and hadrons in heavy-ion collisions

This talk also references the following posters:

CHIRAL VORTICAL EFFECT AT A FINITE MASS AND UNRUH EFFECT FOR FERMIONS

George Prokhorov

Vorticity structure and helicity separation in heavy-ion collision.

Aleksei Zinchenko

Outline

- Touches on wide array topics, including:
- Mechanism for transference of angular momentum to quark polarization (using 4-velocity as gauge field)
- Why is the polarization so small?
- Should the polarization of Lambdas equal that of AntiLambdas?
- Structure of vorticity in PHSD and QGSM transport models

Oleg Teryaev

Strength of polarization

- Polarization proportional to anomalously induced axial current

$$j_A^\mu \sim \mu^2 \left(1 - \frac{2\,\mu\,n}{3\,(\epsilon + P)}\right) \epsilon^{\mu\nu\lambda\rho}\, V_\nu\, \partial_\lambda V_\rho$$

- Here n and ϵ correspond the charge and energy densities and P is the pressure
- Therefore, the μ-dependence of the polarization has to be more strong than that of CVE leading to the effect rapidly increasing with decreasing energy

Quark polarization → hadron polarization

- Axial charge here plays a role analagous to Cooper-Frye freezeout in hydro
  - Polarization of quarks is achieved via triangle anomaly
  - Axial current: charge → polarization vector

$$< p_n|j^0(0)|p_n >= 2p_n^0 Q_n \qquad < Q >\equiv \frac{\sum_{n=1}^{N} Q_n}{N} = \frac{\int d^3x\, j^0_{class}(x)}{N}$$

  - After boost helicity changes sign above/below RP

$$\Pi^{\Lambda,lab} = (\Pi_0^{\Lambda,lab}, \Pi_x^{\Lambda,lab}, \Pi_y^{\Lambda,lab}, \Pi_z^{\Lambda,lab}) = \frac{\Pi_0^{\Lambda}}{m_\Lambda}(p_y, 0, p_0, 0)$$

$$< \Pi_0^{\Lambda} >= \frac{m_\Lambda \Pi_0^{\Lambda,lab}}{p_y} =< \frac{m_\Lambda}{N_\Lambda p_y} > Q_5^s \equiv < \frac{m_\Lambda}{N_\Lambda p_y} > \frac{N_c}{2\pi^2}\int d^3x\, \mu_s^2(x)\gamma^2\epsilon^{ijk}v_i\partial_j v_k$$

Oleg Teryaev

Species dependence

- From the last slide, polarization is proportional to total axial charge and the inverse of number

$$< \Pi_0^\Lambda >= \frac{m_\Lambda \Pi_0^{\Lambda,lab}}{p_y} = < \frac{m_\Lambda}{\boxed{N_\Lambda} p_y} > \boxed{Q_5^s}$$

- Anti-hyperons have the same axial charge, but smaller number, thus they should have larger polarization than hyperons
  - This effect increases and beam energy is decreased

Size of polarization gap

- At very low energies this number discrepency is much too large and would lead to too big a gap
- Strange axial charge may be also carried by K* mesons
- Λ - accompanied by (+,anti 0) K* mesons with two sea quarks – small corrections
- Anti Λ – more numerous (-,0) K* mesons with single(sea) strange antiquark
- So, gap is mitigated by existence of vector mesons
- Note that STAR BES data shows just the slightest hint of a gap (at ~1.5σ averaged over the BES data)

Higher orders of the Chiral vortical effect

- CVE is the appearance of axial current in a rotating medium, directed along the vorticity

$$j^5_\mu = (\frac{T^2}{6} + \frac{\mu^2}{2\pi^2})\omega_\mu$$

- This can be generalized to include acceleration and higher moments of the vorticity at zero mass

$$\langle j^5_\mu \rangle = \left(\frac{1}{6}\left[T^2 - \frac{\omega^2}{4\pi^2}\right] + \frac{\mu^2}{2\pi^2} - \frac{a^2}{8\pi^2}\right)\omega_\mu + \mathcal{O}(\varpi^5). \quad (4)$$

In red: new terms in comparison to standard CVE in Eq. (1).

Higher order CVE (II)

- Comparisons with hydro coefficients allow George to generalize the finite mass case

$$\langle j^5_\mu \rangle = \int \frac{d^3p}{(2\pi)^3} \Big\{ n_F\Big(E_p - \mu - \frac{|\omega|}{2}\Big) - n_F\Big(E_p - \mu + \frac{|\omega|}{2}\Big) + n_F\Big(E_p + \mu - \frac{|\omega|}{2}\Big) - n_F\Big(E_p + \mu + \frac{|\omega|}{2}\Big) \Big\} \frac{\omega_\mu}{|\omega|}\,, \quad |\omega| = \sqrt{-\omega^2}\,. \tag{6}$$

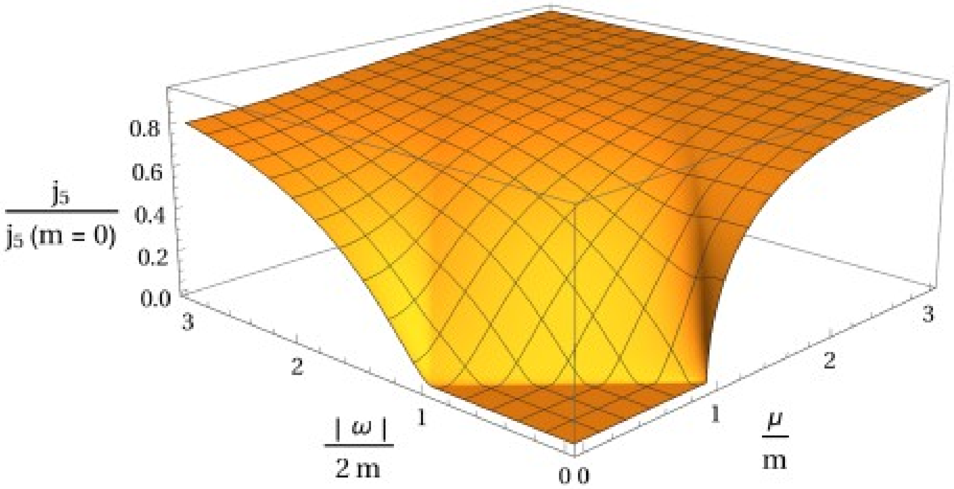
All the dependence of CVE on mass is accumulated in energy $E_p = \sqrt{p^2 + m^2}$.

Higher order CVE (III)

- If angular velocity enters as a chemical potential

$$\mu \to \mu \pm \frac{|\omega|}{2}$$

one can see the axial current dissapear for small angular momentum and chemical potiaal



The appearance of the angular velocity as a chemical potential leads to the vanishing of axial current in the limit $T \to 0$ *in the region* $|\omega| < 2(m - |\mu|)$.

Oleg Teryaev and George Prokhorov

Transport model calculations

- Vortex sheet surrounding fireball is seen in both PHSD and QGSM

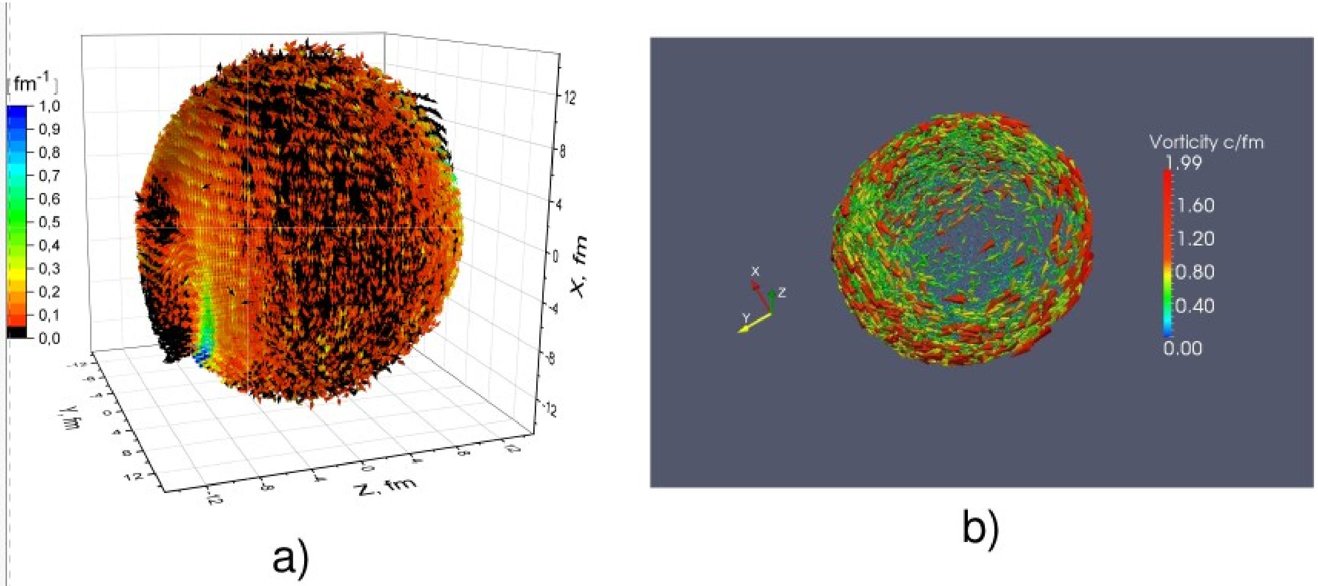


Figure: 1. Vortex sheet in PHSD a) and QGSM b).

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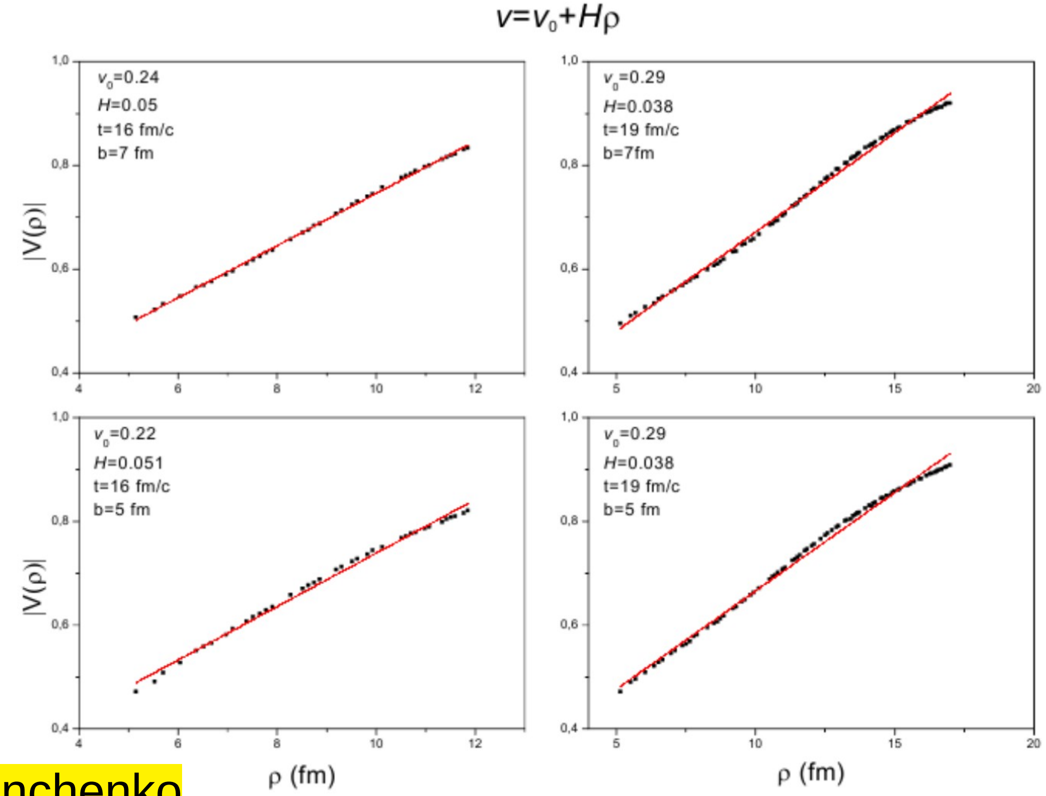
Hubble expansion

- PHSD evolution follows general Hubble expansion



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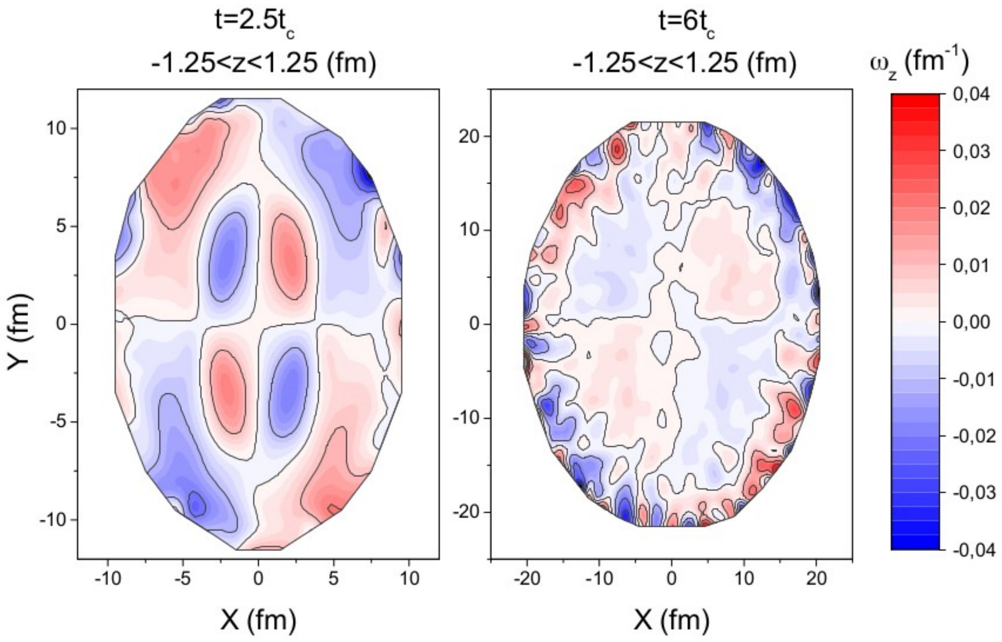
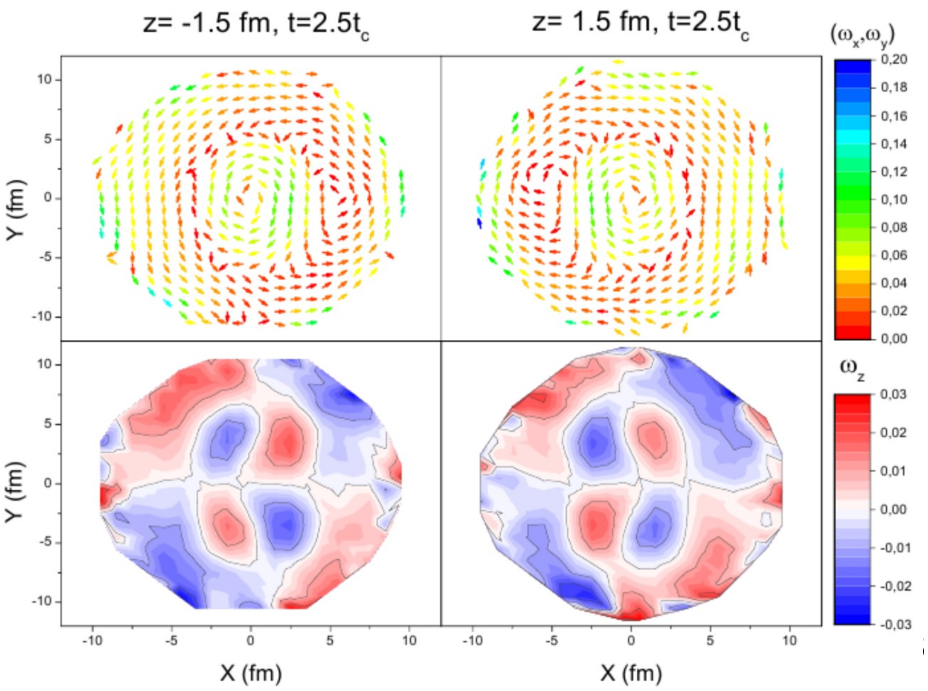
Quadrupole structures

- Seen for longitudinal polarization (as expected)





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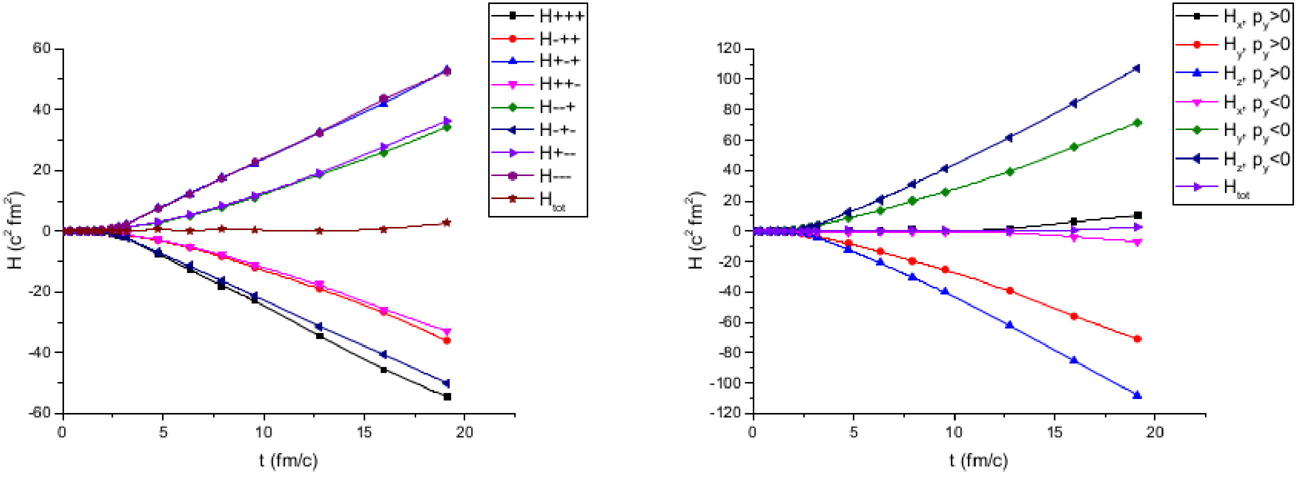
PHSD helicity separation

- Helicity separation in octants of fireball increases with time

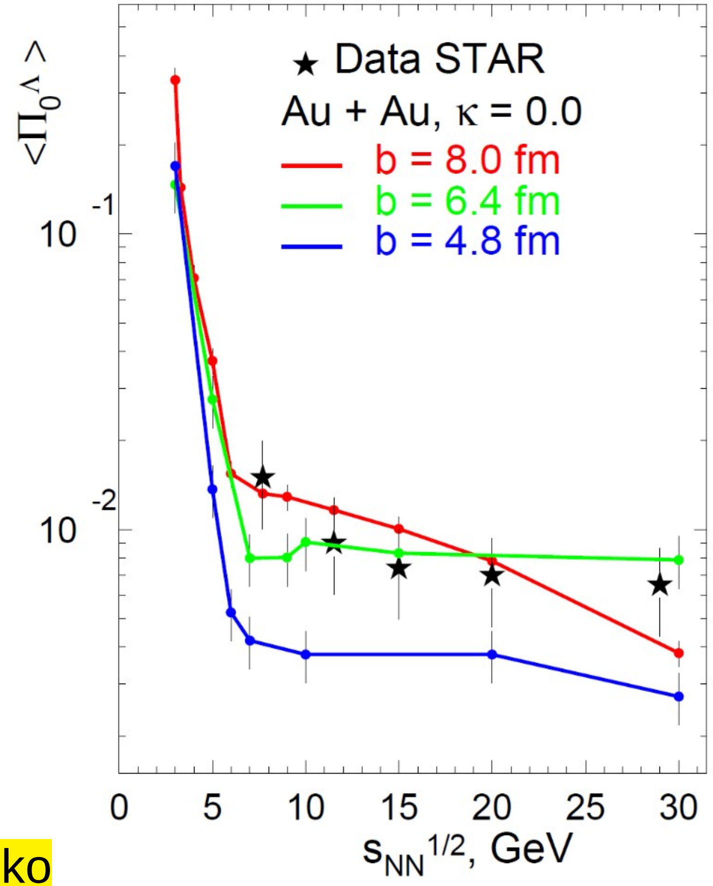


a) b)

Figure: 10. a) Helicity (H (***fm***^{2} ***c***^{2})) separation relative to spatial octants (impact parameter $\boldsymbol{b} = \mathbf{7}$ fm). +++ means that integration is in octant $\boldsymbol{x} > \mathbf{0}$, $\boldsymbol{y} > \mathbf{0}$, $\boldsymbol{z} > \mathbf{0}$ and — — — - $\boldsymbol{x} < \mathbf{0}$, $\boldsymbol{y} < \mathbf{0}$, $\boldsymbol{z} < \mathbf{0}$ respectively. b) Helicity (H (***fm***^{2} ***c***^{2})) separation relative to ***y***- component of momentum (impact parameter $\boldsymbol{b} = \mathbf{7}$ fm).

QGSM calculation

- In QGSM calculation polarization is well described
- PHSD in progress
- Does this rapid rise match HADES data?



Aleksei Zinchenko

END