Spin-Orbital Angular Momentum Interaction in Heavy-Ion Collisions

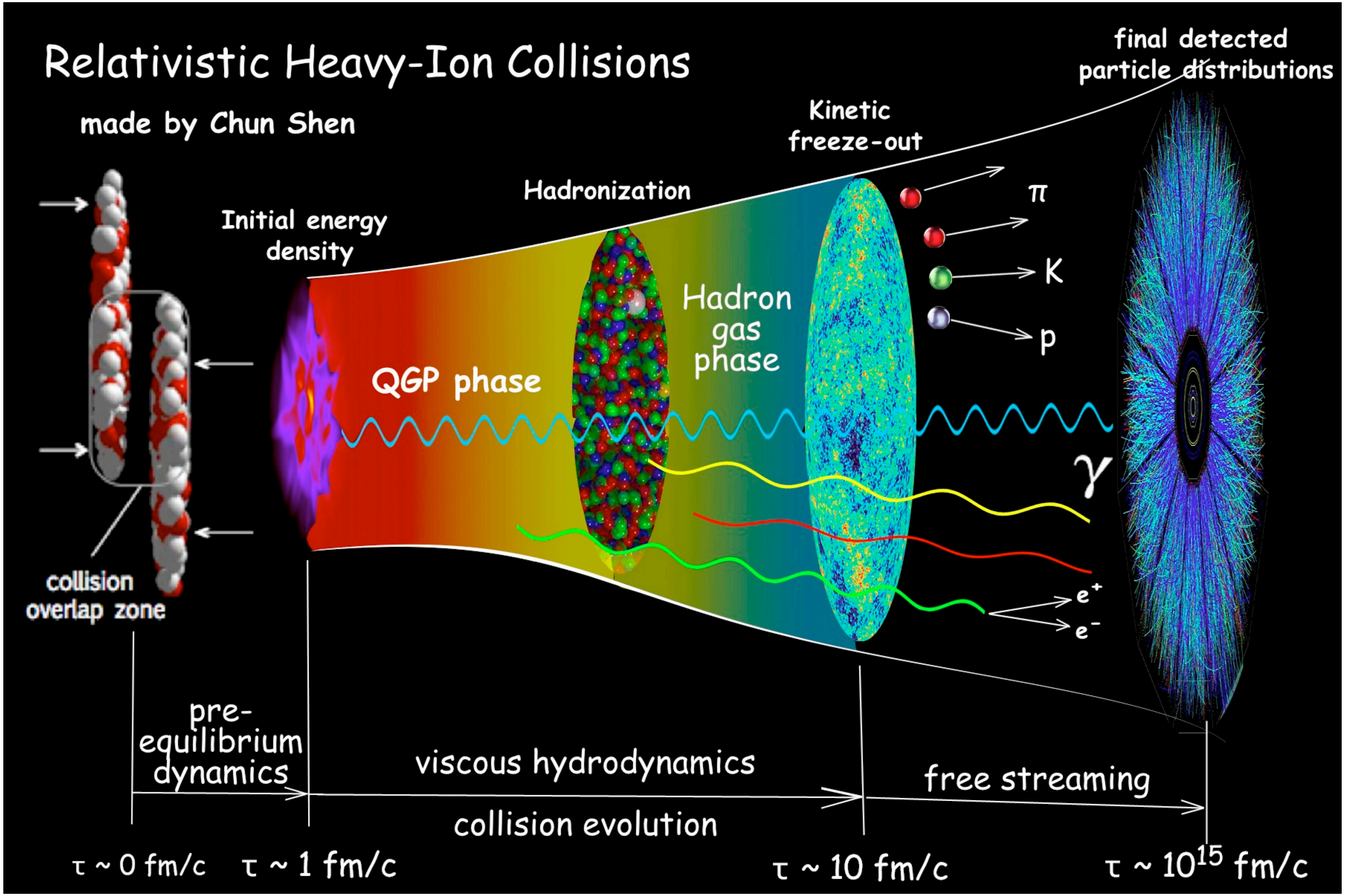
Bedanga Mohanty

NISER

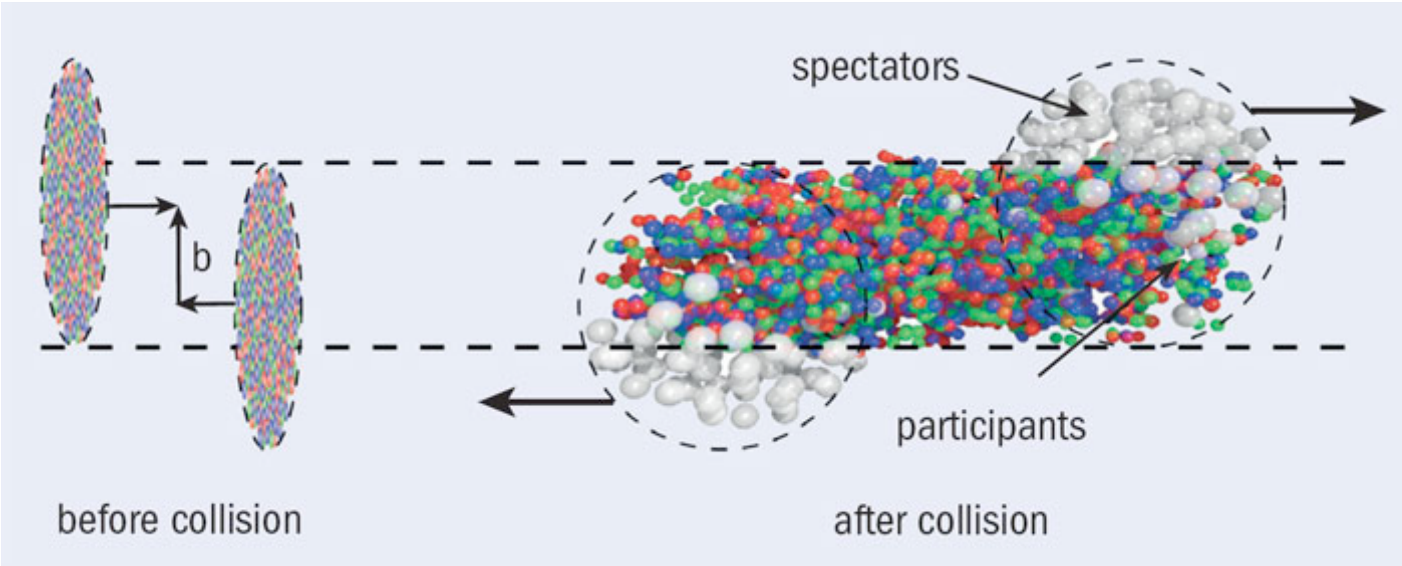
Based on : arXiv:1910.14408 (ALICE) and Nature 548, 62 (2017) (STAR)
*+ QM2019 talks by **Sourav Kundu** (ALICE) and **Subhash Singha** (STAR)*

Outline:
- ❑ High Energy Heavy-Ion Collisions
- ❑ Polarization of Lambda Baryons
- ❑ Spin Alignment of Vector Mesons (spin-1 particles)
- ❑ Summary

Heavy-Ion Collisions

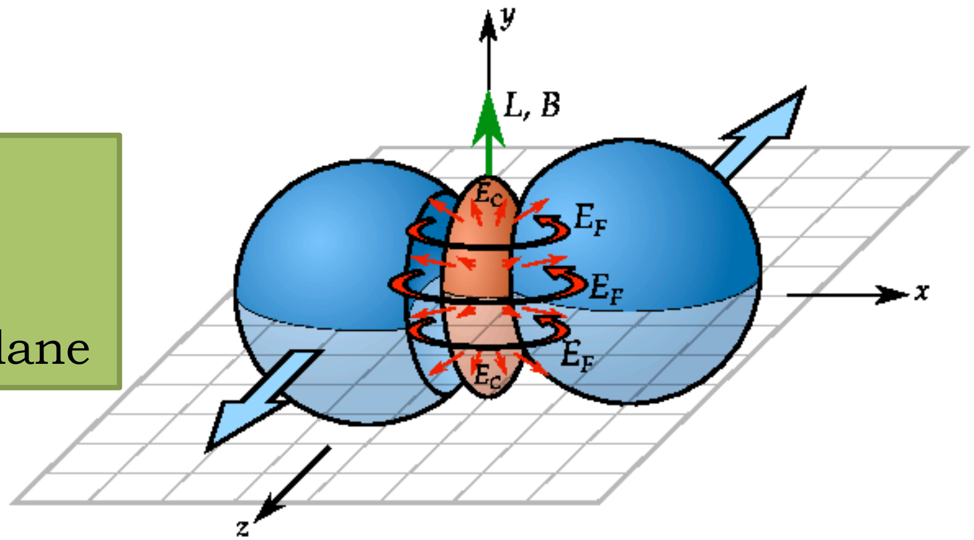


Heavy-Ion Collisions

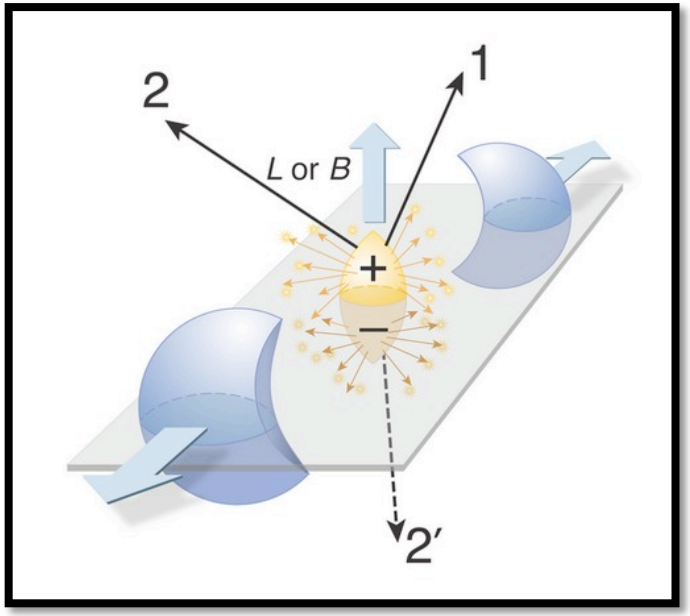


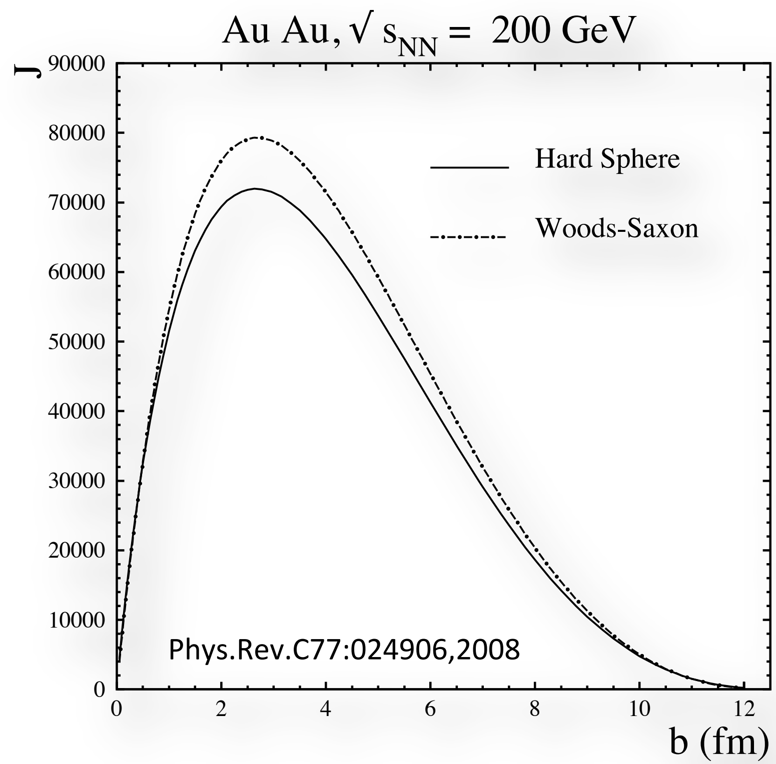
Reaction Plane: Impact Parameter and Beam Axis

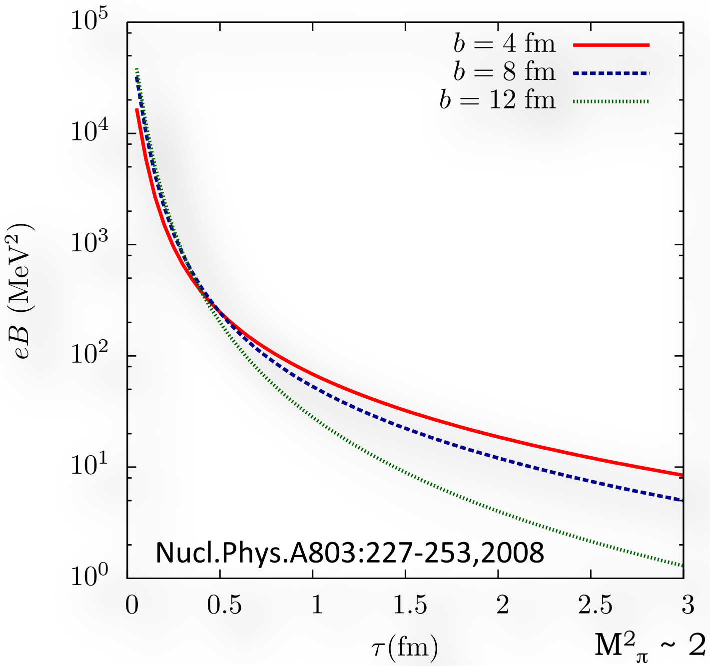
L and B perpendicular to Reaction Plane



Heavy-Ion Collisions







Large Angular Momentum (Conserved Quantity)

Large Magnetic Field

M^2_π ~ 2 x 10^4 MeV^2 ~ 3 x 10^{14} Tesla ~ 3 x 10^{18} Gauss

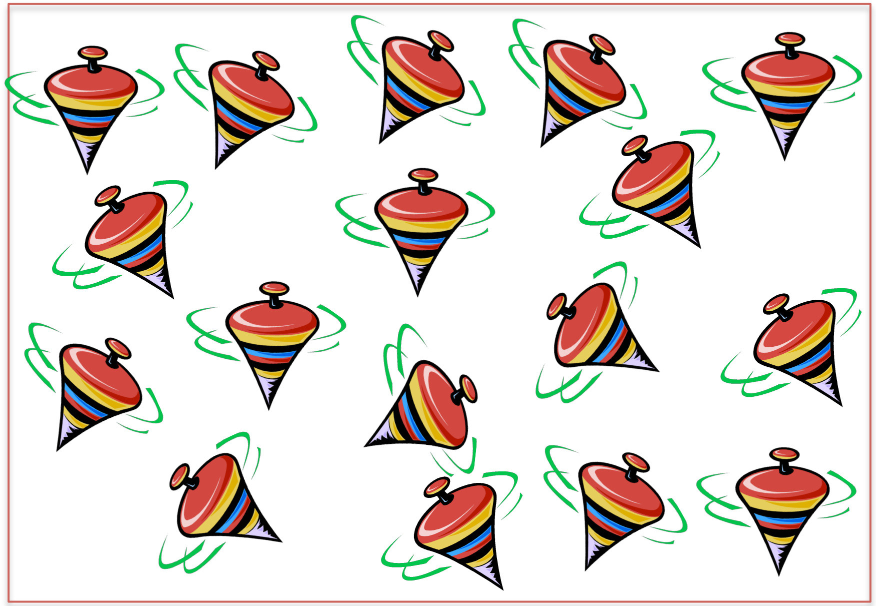
Angular Momentum & Magnetic Field in Nature

Nature	Angular Momentum in units of h/2π
Electron in hydrogen atom	$\sqrt{l(l+1)}$
^{132}Ce (highest for a nuclei)	70
Heavy Ion Collisions	***$10^4 - 10^5$***
Earth	10^6

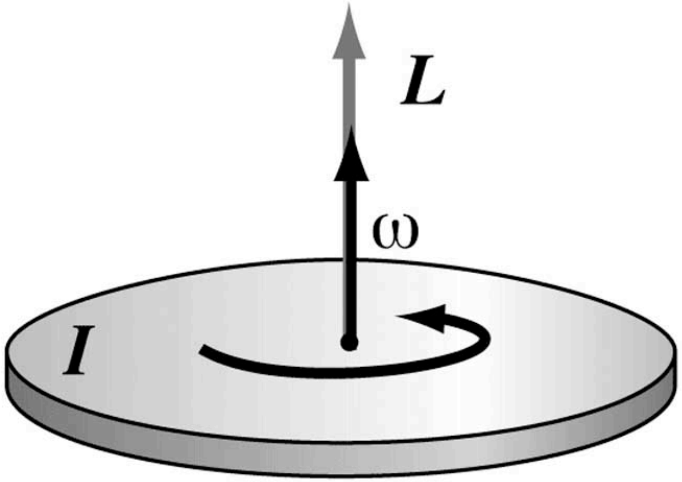
Want to focus on studies to see the effect of large Angular Momentum and Magnetic Field in Heavy-ion collisions

Nature	Magnetic Field in Tesla
Human Brain	10^{-12}
Earth's Magnetic field	10^{-5}
Refrigerator Magnet	10^{-3}
Loudspeaker Magnet	1
Strongest field in lab	10^3
Neutron Star	10^6
Heavy Ion Collisions	***10^{15} - 10^{16}***

Spin and Angular Momentum

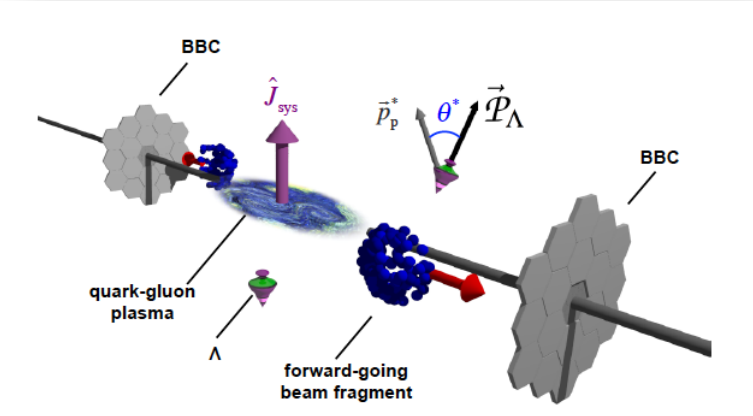


What happens in presence of Angular Momentum



Can we see experimentally the signature of spin-orbit angular momentum interactions for QCD matter produced in heavy-ion collisions ?

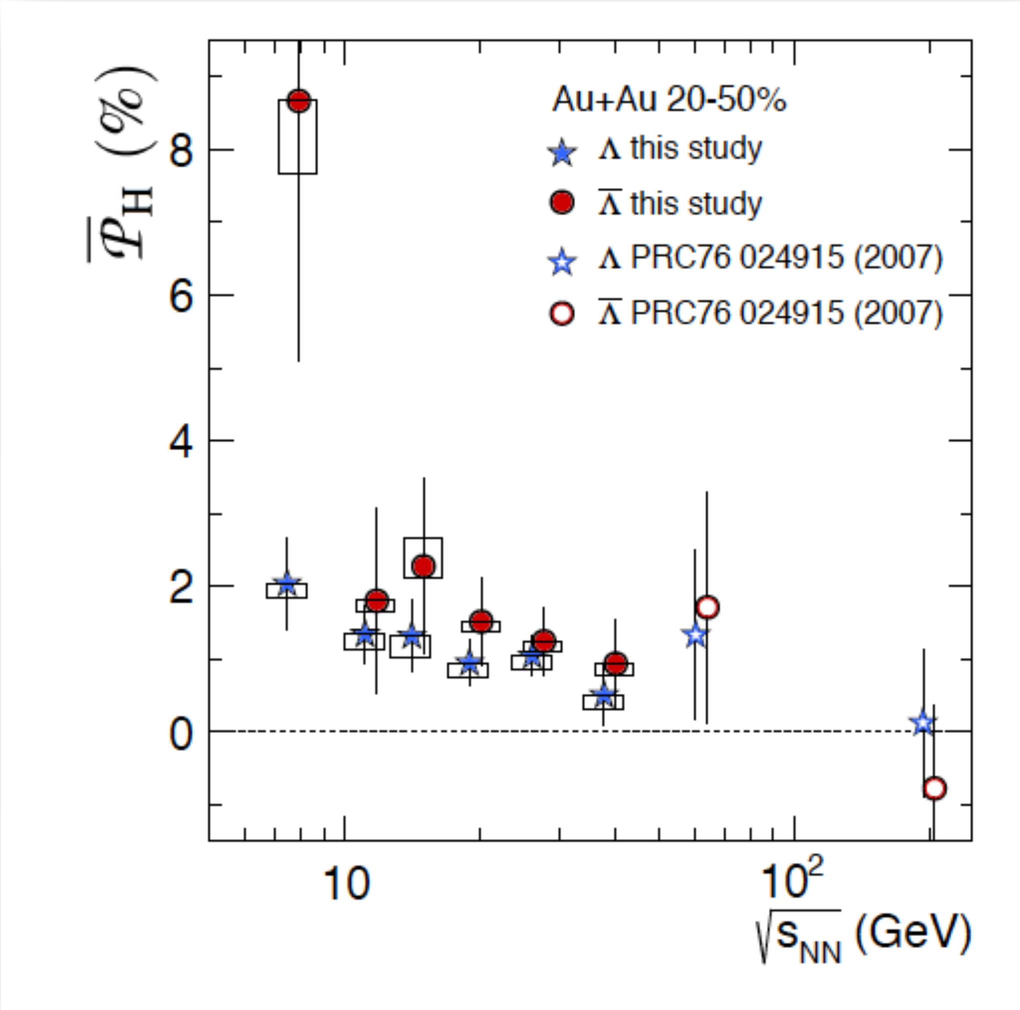
Λ polarization - RHIC



$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_H |\vec{\mathcal{P}}_H| \cos\theta^*\right)$$

decay parameter $\alpha_\Lambda = -\alpha_{\overline{\Lambda}} = 0.642 \pm 0.013$

$$\omega = k_B T \left(\overline{\mathcal{P}}_{\Lambda'} + \overline{\mathcal{P}}_{\overline{\Lambda}'}\right)/\hbar$$



$$\omega \approx (9 \pm 1) \times 10^{21}\ s^{-1}$$

Nature 548, 62 (2017) (STAR Collaboration)
Phys Rev C 98, 14910 (2018) (STAR Collaboration)

Conclusions

- ✓Lambda Polarization seen in RHIC Beam Energy Scan Program.

- ✓Polarization decreases with increase in beam energy

- ✓Polarization measurements of hadrons emitted from the fluid used to estimate the vorticity

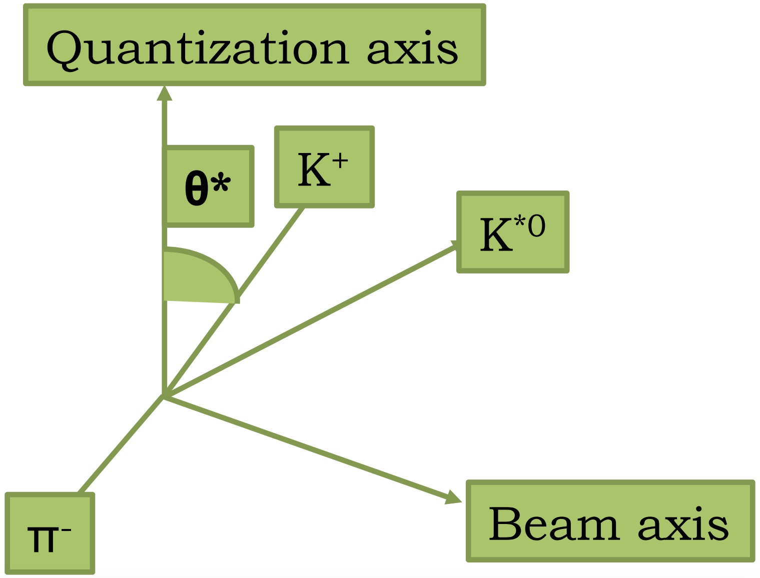
- ✓ First measurement of vorticity done in heavy-ion collisions

Vorticity in Nature

Nature	**Vorticity (s^{-1})**
Solar Sub-surface	10^{-7}
Terrestrial Atmosphere	10^{-5}
Great Red Spot of Jupiter	10^{-4}
Tornado Core	10^{-1}
Heated Soap Bubbles	100
Turbulent flow in superfluid He	150
Heavy Ion Collisions	***10^{7} - 10^{21}***

Angular Distribution of Vector Mesons

K^{*0} Vector Meson
- Mass – 896 MeV/c^2
- Life time – 4 fm/c
- Spin 1
- Decays to K^+ and π^- (B.R – 66%)
- Quark content (d,sbar)



Nucl. Phys. B 15 (1970) 397

$$\frac{dN}{dcos\theta d\phi} = \langle\theta,\phi,\lambda_1,\lambda_2|M\rho M^\dagger|\theta,\phi,\lambda_1,\lambda_2\rangle$$

$$= \sum_{\lambda_V}\sum_{\lambda_{V'}}\langle\theta,\phi,\lambda_1,\lambda_2|M|\lambda_V\rangle\langle\lambda_V|\rho|\lambda_{V'}\rangle\langle\lambda_{V'}|M^\dagger|\theta,\phi,\lambda_1,\lambda_2\rangle$$

λ = Helicities
ρ = spin density matrix
M = Decay amplitude

Quantization axis
- Normal to production plane
- Normal to reaction plane

Angular Distribution of Vector Mesons

In terms of spherical harmonics

$$\frac{dN}{dcos\theta d\phi} = |C|^2 \times \sum_{m_1,m_2} Y^*_{1,m_1}(\theta,\phi) Y_{1,m_2}(\theta,\phi) \rho_{m_1,m_2}$$

Integrating over azimuthal angle

$$\frac{dN}{dcos\theta} = |C|^2 \times \frac{3}{8\pi}\left[sin^2\theta\rho_{-1,-1} + 2cos^2\theta\rho_{0,0} + sin^2\theta\rho_{1,1}\right] \times 2\pi$$
$$= |C|^2 \times \frac{3}{4}\left[sin^2\theta\left(\rho_{-1,-1} + \rho_{1,1}\right) + 2cos^2\theta\rho_{0,0}\right]$$

Normalized spin density matrix – Trace = 1

$$\frac{dN}{dcos\theta} = N_0\left[1 - \rho_{0,0} + cos^2\theta\left(3\rho_{0,0} - 1\right)\right]$$

$\rho_{00} = 1/3$ → No Spin Alignment

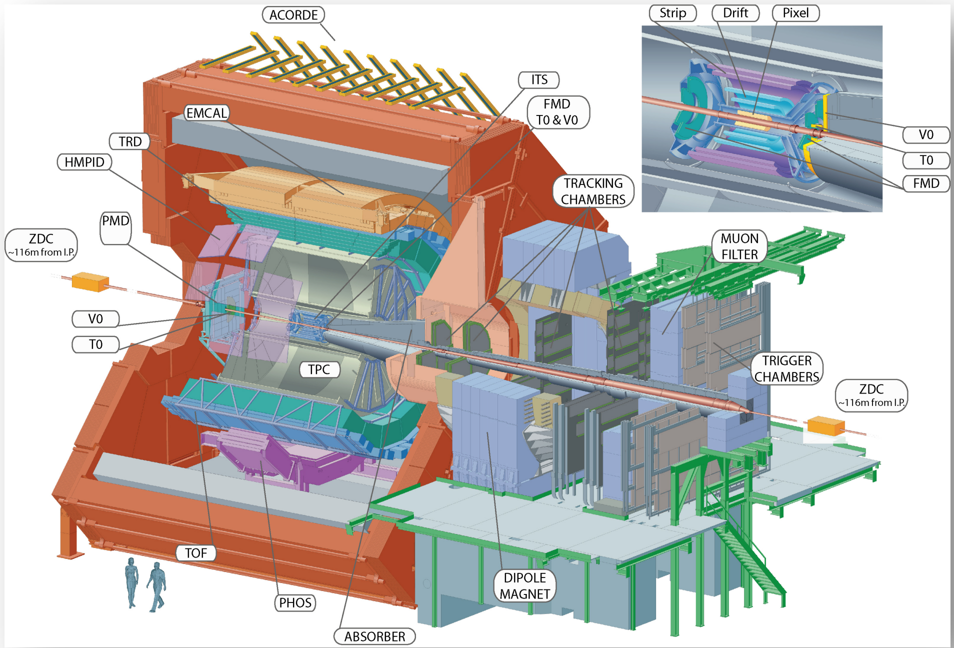
Difference between Lambda Baryon and Vector Mesons

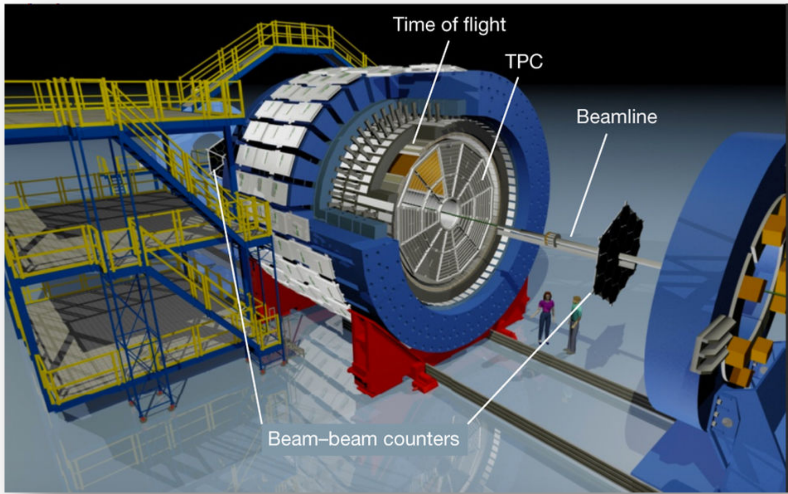
Species	K^{*0}	ϕ	Λ
Quark Content	d-bar s	s s-bar	uds
Mass (MeV/c^2)	896	1020	1115
Life time (fm/c)	4	45	Long
Spin (J^P)	1^-	1^-	$½^+$
Decays	$K\pi$	KK	$p\pi$
Branching Ratio	66%	49%	100 %
Feed-down	Negligible	Negligible	Substantial
Sign of direction of angular momentum	Not required 2^{nd} order EP	Not required 2^{nd} order EP	Required 1^{st} Order EP

Detectors

ALICE @ LHC

STAR @ RHIC



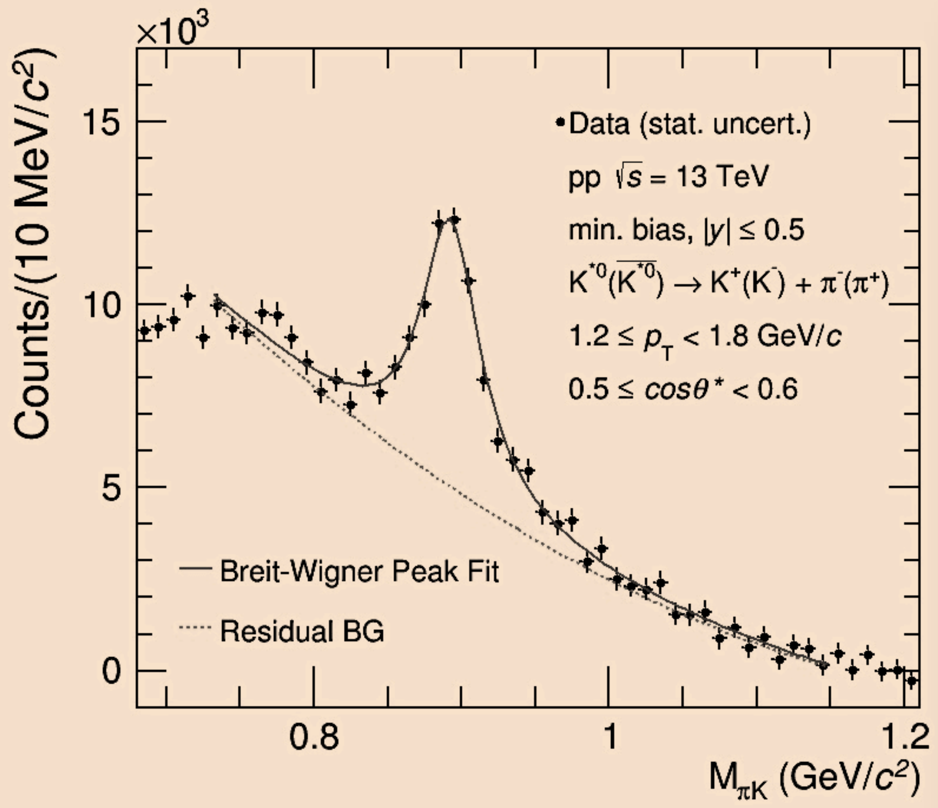


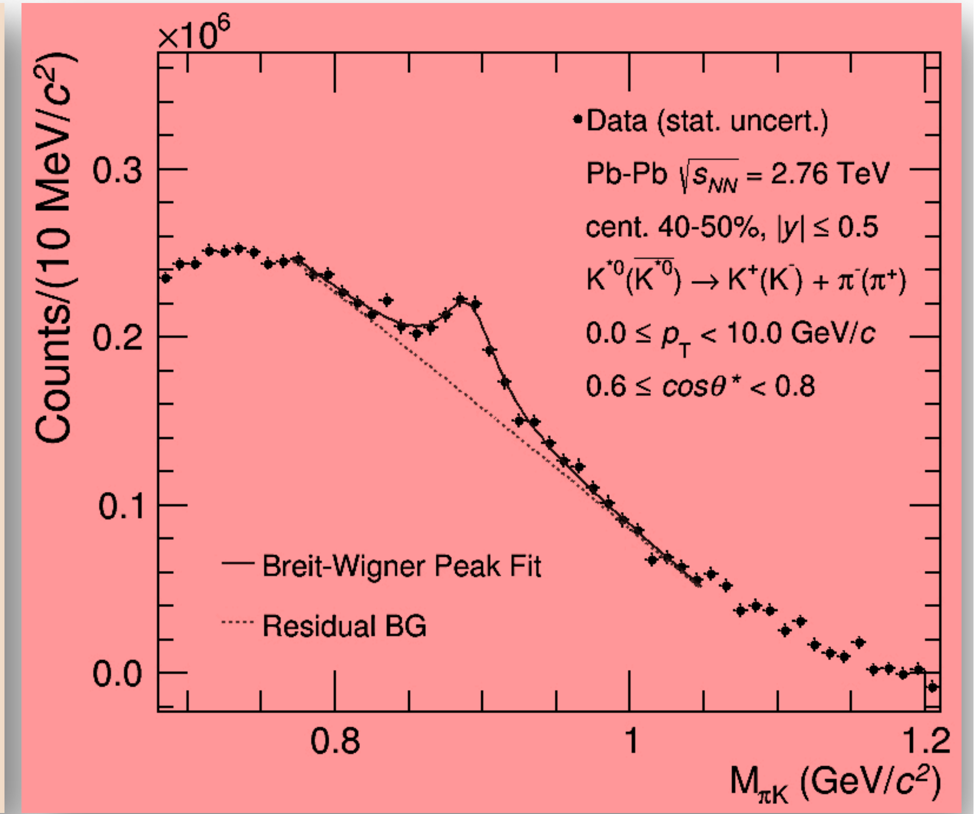
Particle identification: TPC + TOF
Momentum Measurement TPC (+ITS in ALICE)
Event Plane Angle Measurement (V0 in ALICE and TPC/ZDC in STAR

Data Set

Collision system	pp at 13 TeV, Pb-Pb at 2.76 TeV, Au+Au at 200 and 54.4 GeV
Rapidity	$\|y\| < 0.5$
No. of events	~ 43 M (pp), 14 M (Pb-Pb), 520 M (Au+Au 54.4 GeV) and 350 M (Au+Au 200 GeV)
Hadrons	pp: K^{*0} and ϕ Pb-Pb: K^{*0}, ϕ and K_S^0 Au+Au: K^{*0} and ϕ
Background	Mixed events (LHC) and Rotational Method (RHIC)
Efficiency x acceptance	Corrected
Quantization axis	pp: Normal to production plane (PP) Pb-Pb: Normal to production plane (PP), event plane (EP) and random event plane (RndEP: randomizing the event plane angle in azimuthal plane) Au+Au: Noraml to Event Plane and 3D random Event Plane

K^{*0} Vector Meson

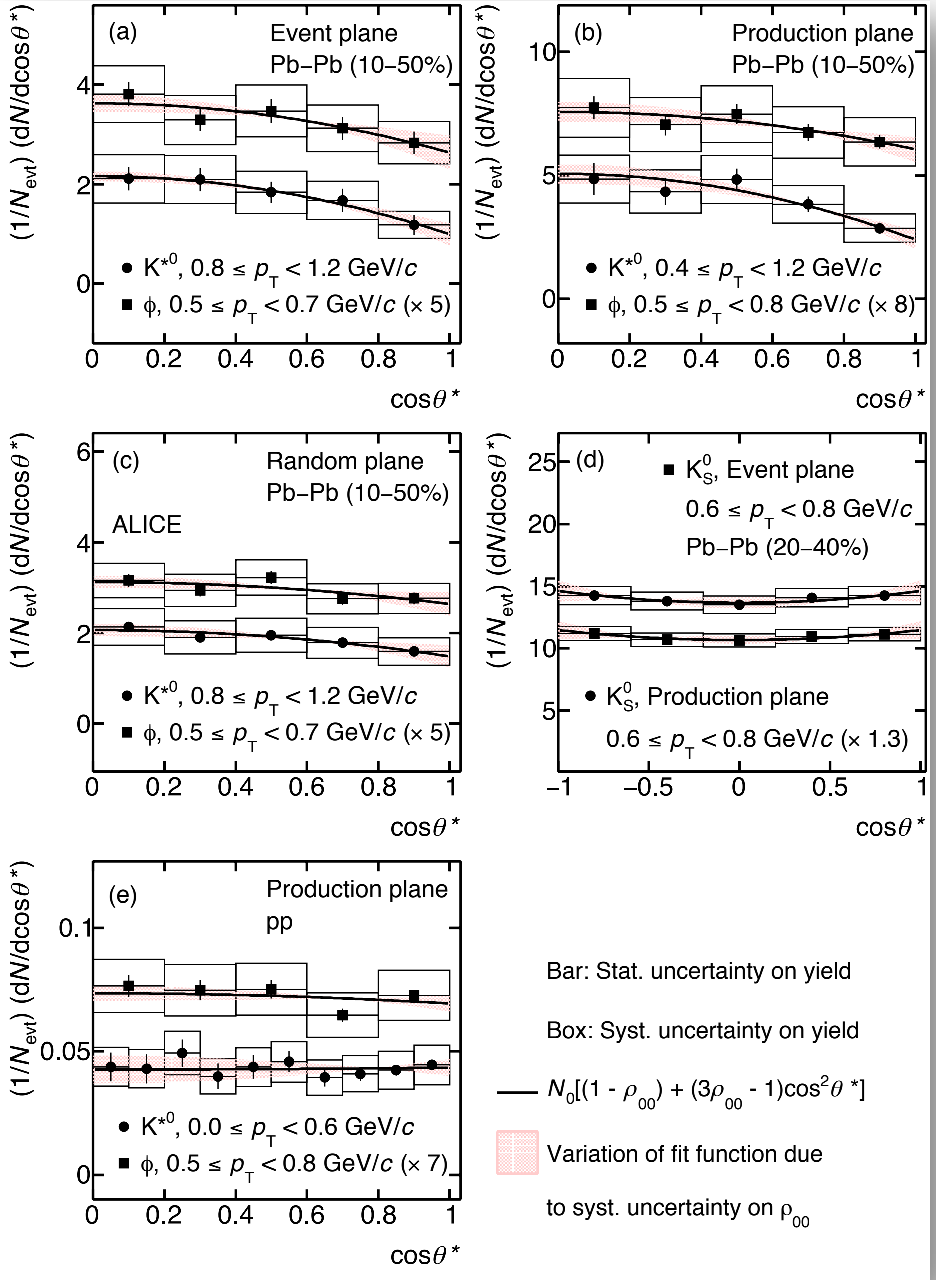




pp collisions

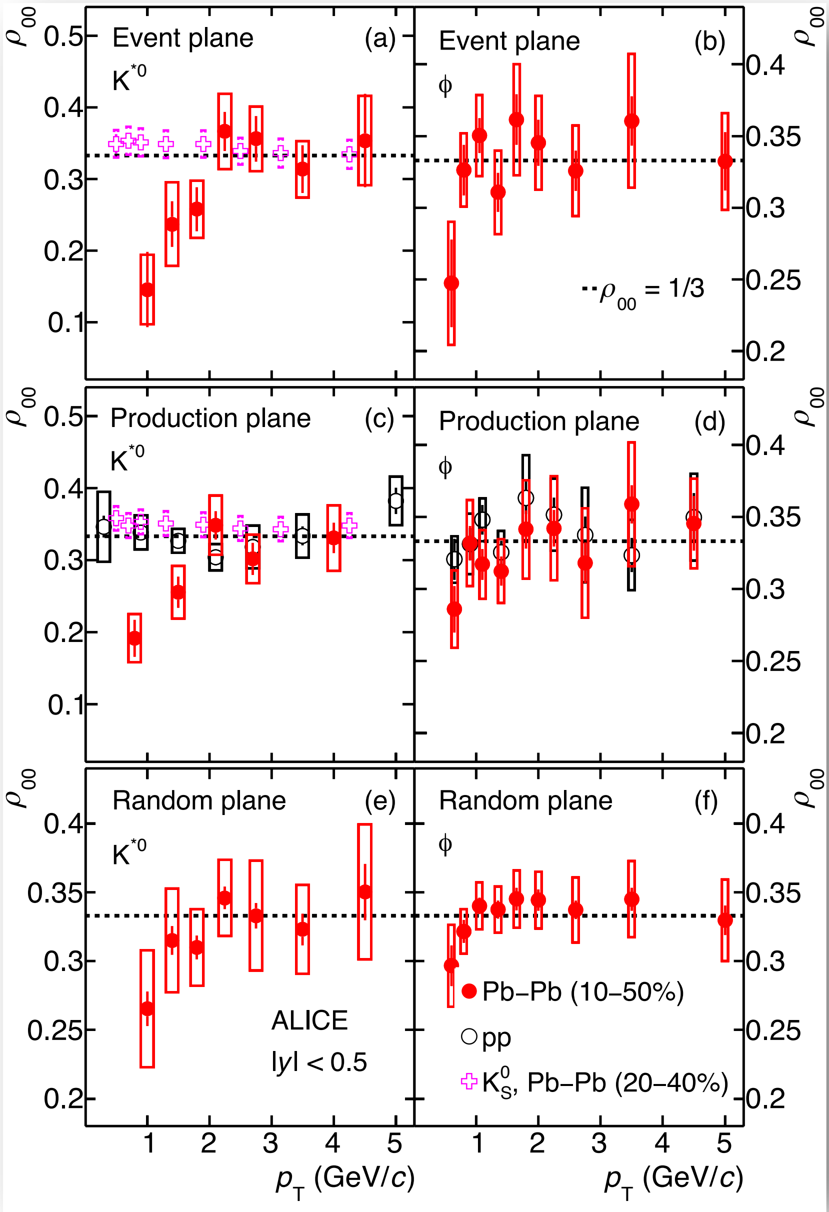
Heavy-Ion collisions

Angular Distribution of Vector Mesons



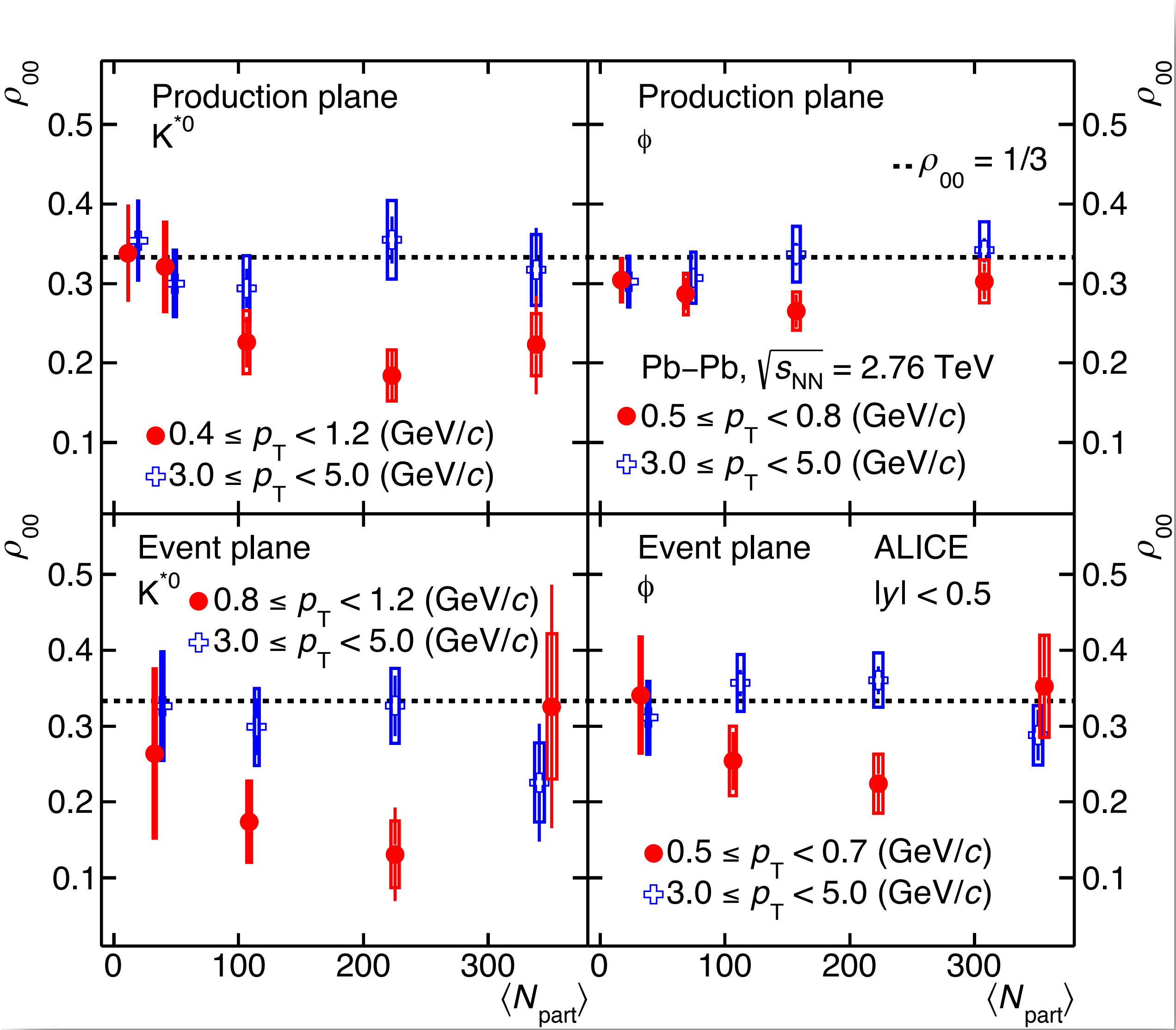
1. Angular distribution NOT flat for Vector mesons with respect to quantization axis in heavy-ion collisions
2. Angular distribution FLAT for vector mesons with respect to random quantization axis
3. Angular distribution FLAT for spin-0 mesons K0s in heavy-ion collisions
4. Angular distribution FLAT for vector mesons in proton-proton collisions

Spin Alignment of Vector Mesons (Spin 1) and K^0_s(Spin 0)



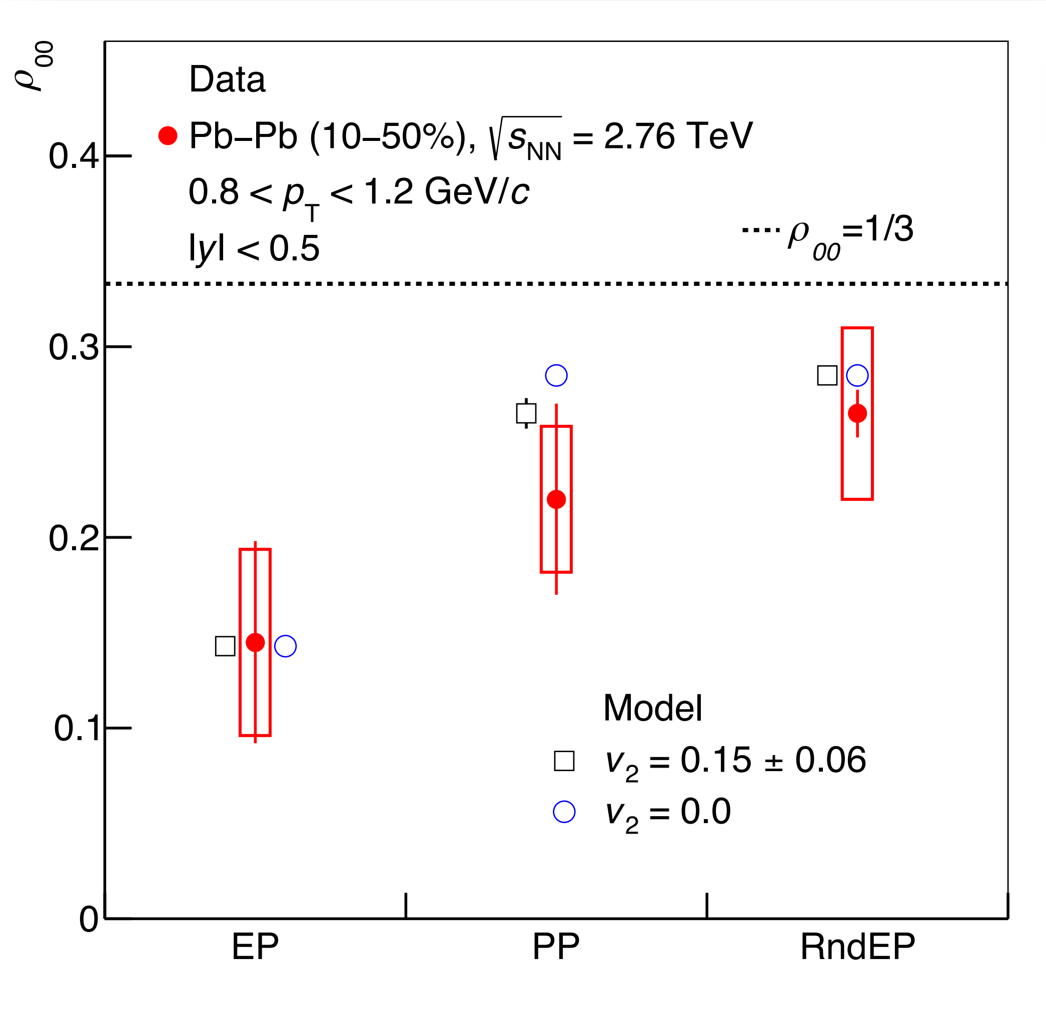
1. Spin Alignment (ρ_{00} < 1/3) observed for Spin 1 particle at Low momentum
2. No spin alignment (ρ_{00} ~ 1/3) observed for Spin 0 particle
3. No spin alignment (ρ_{00} ~ 1/3) observed in proton+proton collisions
4. No spin alignment (ρ_{00} ~ 1/3) observed for random planes

Spin Alignment of Vector Meson



1. Maximum spin alignment observed for mid-central collisions in low p_T (3σ for K^{*0} and 2σ for ϕ)
2. $\rho_{00} \sim 1/3$ for high p_T vector mesons
3. $\rho_{00} \sim 1/3$ for peripheral collisions and deviation from 1/3 small for central collisions

Relation Between EP and PP



$$\rho_{00}(\mathrm{PP}) - \frac{1}{3} = \left(\rho_{00}(\mathrm{EP}) - \frac{1}{3}\right) \times \frac{1 + 3v_2}{4}.$$

The physical picture is that spin alignment with respect to the event plane is coupled to that in the production plane through the elliptic flow of the system.

The ρ_{00}(RndEP) is lower than 1/3 as the quantization axis is always perpendicular to the beam axis, resulting in a residual effect.

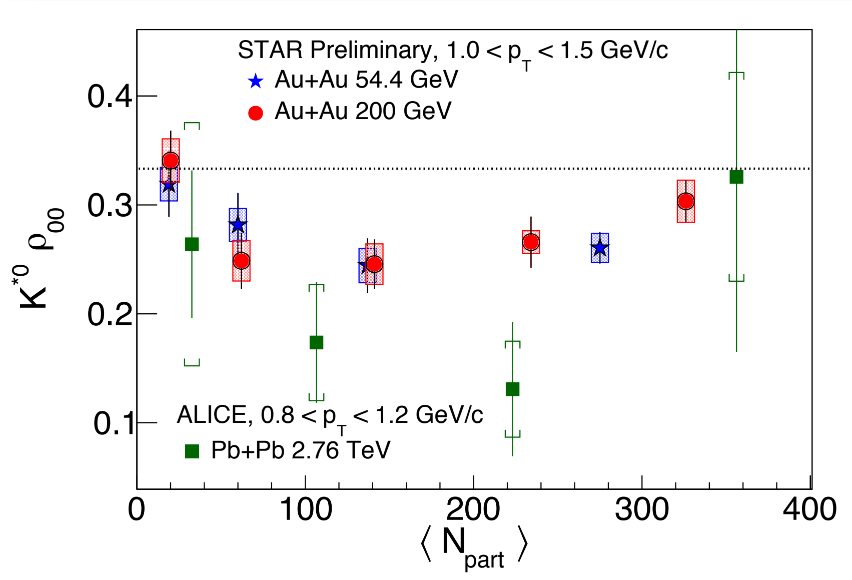
Physics Process and Theory Expectation

Physics Process	Theory expectation	Remarks
Vorticity	$\rho_{00}(\omega) < 1/3$	
Magnetic Field	$\rho_{00}(B) > 1/3$	Electrically Neutral Vector Mesons
	$\rho_{00}(B) < 1/3$	Electrically charged vector mesons
Hadronization	$\rho_{00}(rec) < 1/3$	Recombination
	$\rho_{00}(frag) > 1/3$	Fragmentation

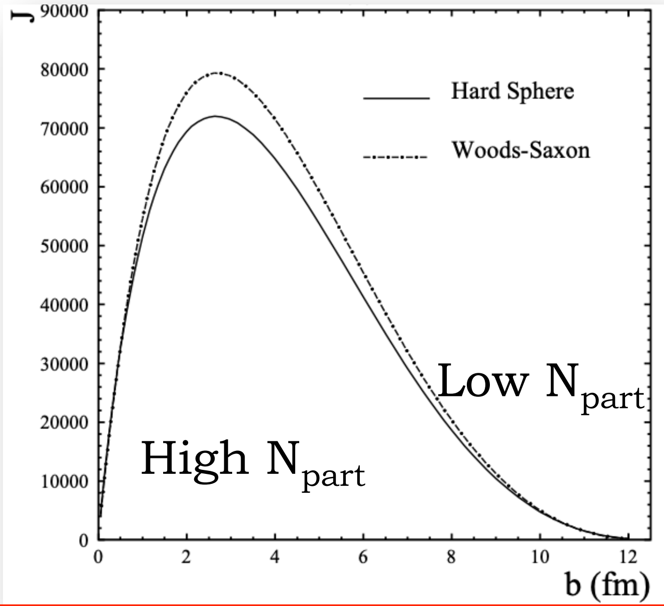
Z. Liang et. al., Phys. Lett. B629, 20 (2005) Y. Yang et. al., Phys. Rev. C 97, 034917 (2018)

Data and Theoretical Expectation

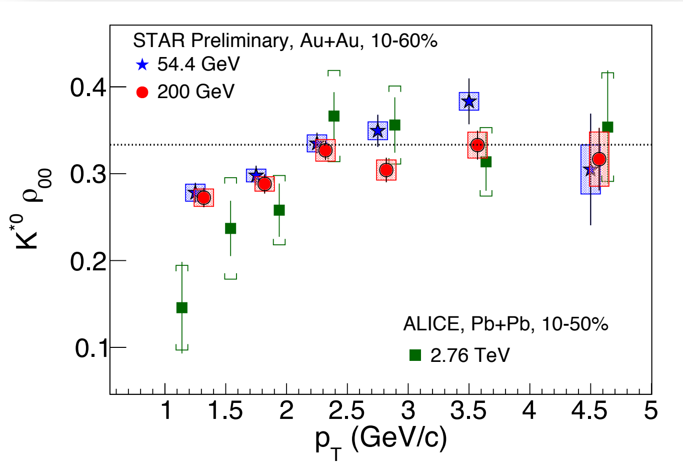
Centrality dependence



Centrality dependence of Angular Momentum



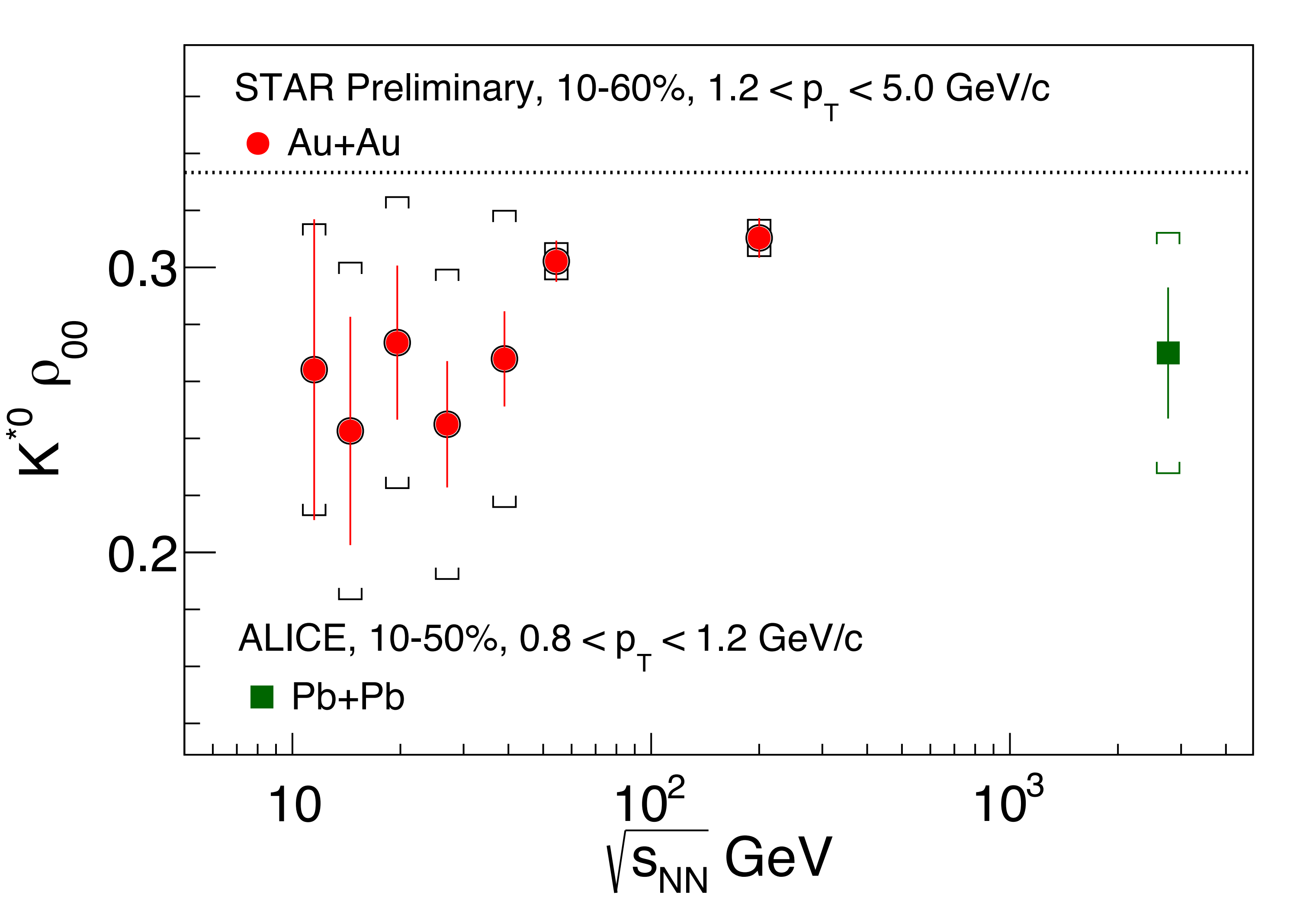
Centrality dependence of ρ_{00} similar to centrality dependence of angular momentum



Transverse Momentum dependence

Transverse dependence of ρ_{00} consistent with polarization of quarks in the presence of large initial angular momentum in heavy-ion collisions and a subsequent hadronization by the process of recombination

Energy Dependence



Looks like no energy dependence of ρ_{oo}
High statistics Beam Energy Scan Phase – II data will clear the picture.

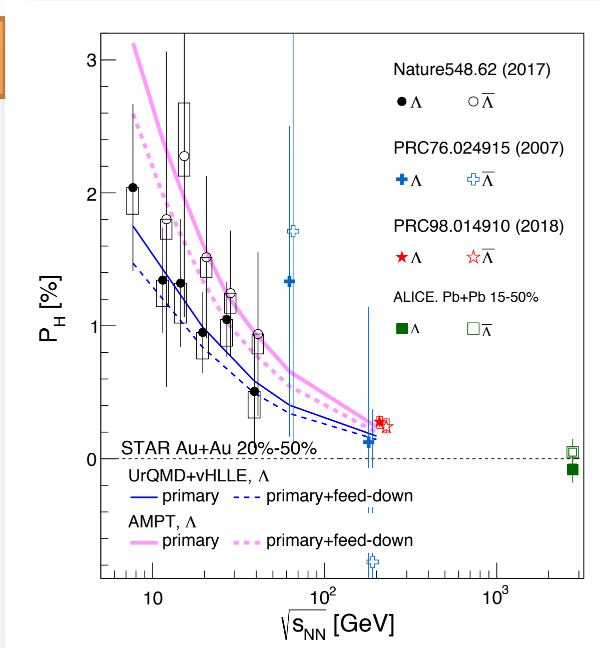
Summary

- ✓First evidence of spin alignment in vector mesons in high energy heavy-ion collisions. Both RHIC and LHC observes it.
- ✓ Measurement **coupled to** Event Plane – vanishes for random Event Plane
- ✓Spin alignment **not** observed in proton-proton collisions
- ✓Spin alignment **not** observed for spin 0 particles in heavy-ion collisions

Surprises

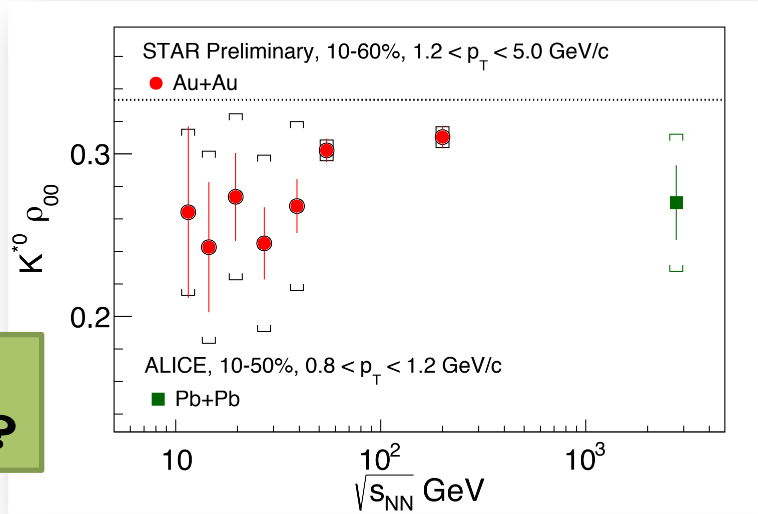
$P_H \sim P_q$ and $\rho_{00} \sim P_q^{\,2}$

1.



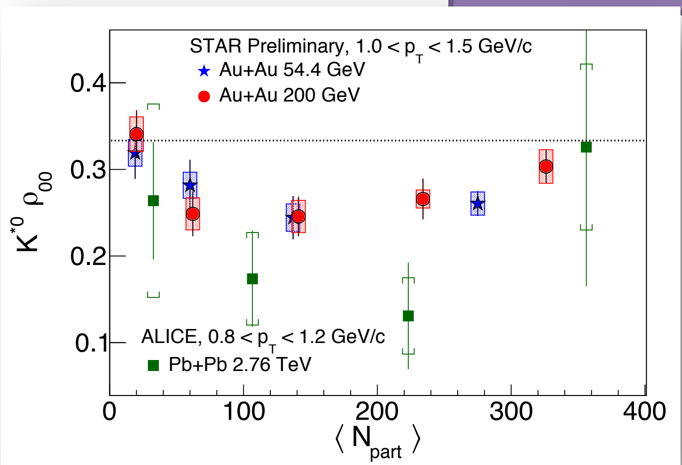
$\rho_{00} \sim 1/3$

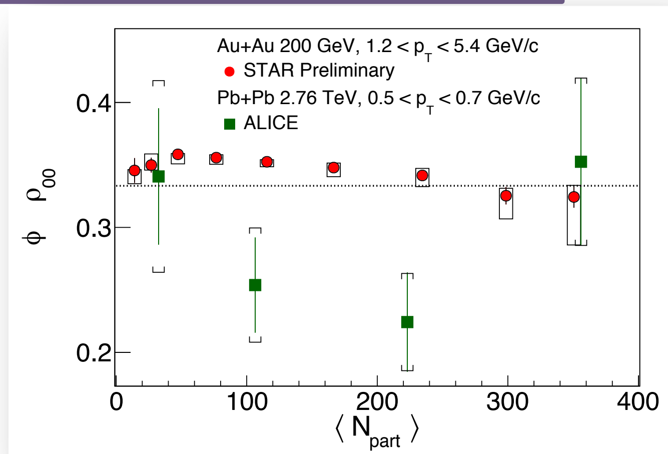
ρ_{00} no energy Dependence ?



K^{*0} versus ϕ meson at RHIC and LHC

2.





Outlook

A. **Theoretical Side**:

- The experimental measurements has thrown open challenges to theory

1. Cannot explain Lambda and vector mesons results simultaneously
2. Cannot explain the difference in ρ_{00} values of K* (< 1/3) and ϕ (> 1/3 at RHIC and < 1/3 at LHC) meson at RHIC and LHC
3. Development of proper relativistic spin hydrodynamics
4. Models with conservation of angular momentum, L or ω → spin

B. **Experimental Side**:

- Precision measurements will allow to also see the signatures of initial magnetic field

1. Lambda and anti-lambda polarization magnitude should be different
2. Charged K* and neutral K* ρ_{00} magnitude should be different

Establishing & proper treatment of initial conditions in heavy-ion collisions could have impact on the physics and discoveries in the area

Prof. Rajiv Gavai

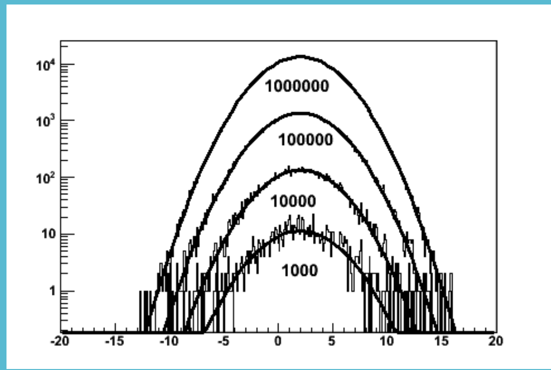
1. Constant source of support for my work

2. Physics link: Critical Point Search in the QCD Phase Diagram

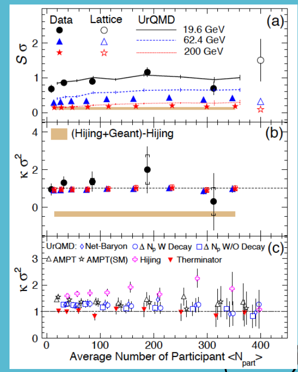
From: Bedanga Mohanty bedanga@gmail.com
Date: Thu, Jun 25, 2009 at 7:16 PM
Subject: Net proton - event statistics
To: <gavai@theory.tifr.res.in>

Dear Prof. Gavai,

We were discussing how the event statistics will affect the net-proton distribution.
.....



1004.4959 (PRL)

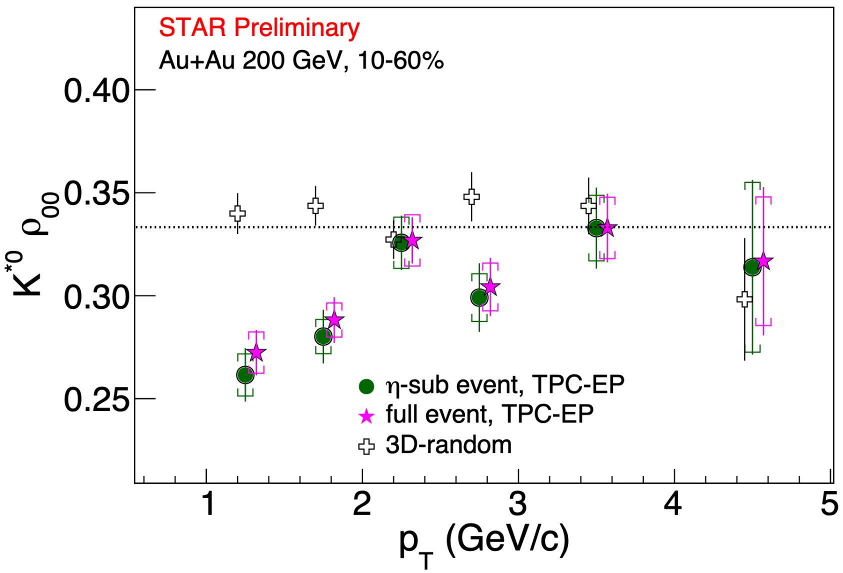


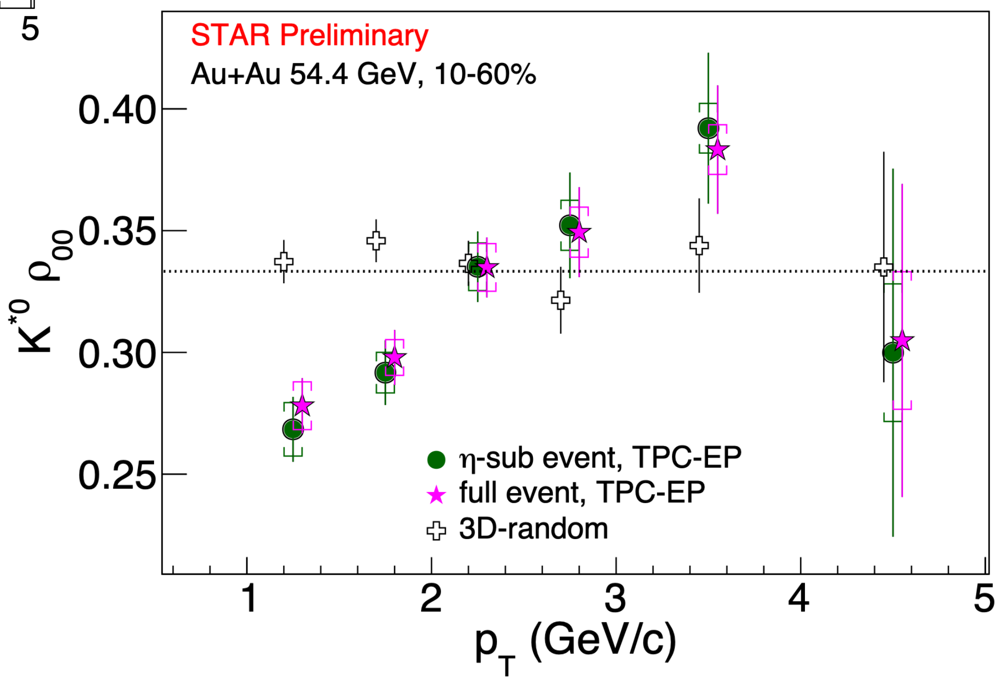
2. Great Support towards building up the QGP group at NISER

3. Borrowed the following quote of Nelson Mandela –
"I HAVE WALKED THAT LONG ROAD TO FREEDOM. I have tried not to falter; I have made missteps along the way. But I have discovered the secret that after climbing a great hill, one only finds that there are many more hills to climb. I have taken a moment here to rest, to steal a view of the glorious vista that surrounds me, to look back on the distance I have come. But I can only rest for a moment, for with freedom come responsibilities, and I dare not linger, FOR MY LONG WALK IS NOT YET ENDED"

- *From his autobiography Long Walk to Freedom, published in 1994.*

Back Up


STAR Preliminary
Au+Au 200 GeV, 10-60%
0.40
0.35
0.30
0.25
K^{*0} ρ_{00}
η-sub event, TPC-EP
full event, TPC-EP
3D-random
1
2
3
4
5
p_T (GeV/c)


STAR Preliminary
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0.40
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η-sub event, TPC-EP
full event, TPC-EP
3D-random
1
2
3
4
5
p_T (GeV/c)