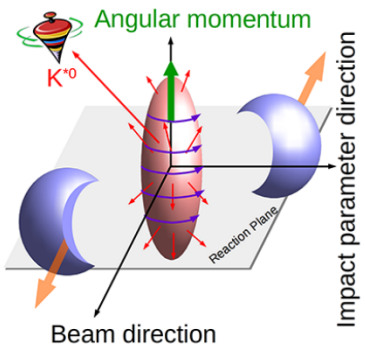
Spin alignment measurements of vector mesons with ALICE at LHC

Bedanga Mohanty
(On behalf of the ALICE Collaboration)

Outline:

- High energy heavy-ion collisions
  - Introduction
  - Initial conditions: Angular momentum & magnetic field
- Spin alignment of vector mesons
  - Observable and theory expectation
  - ALICE physics analysis
  - Results
- Discussion
- Summary and Outlook

Based on:



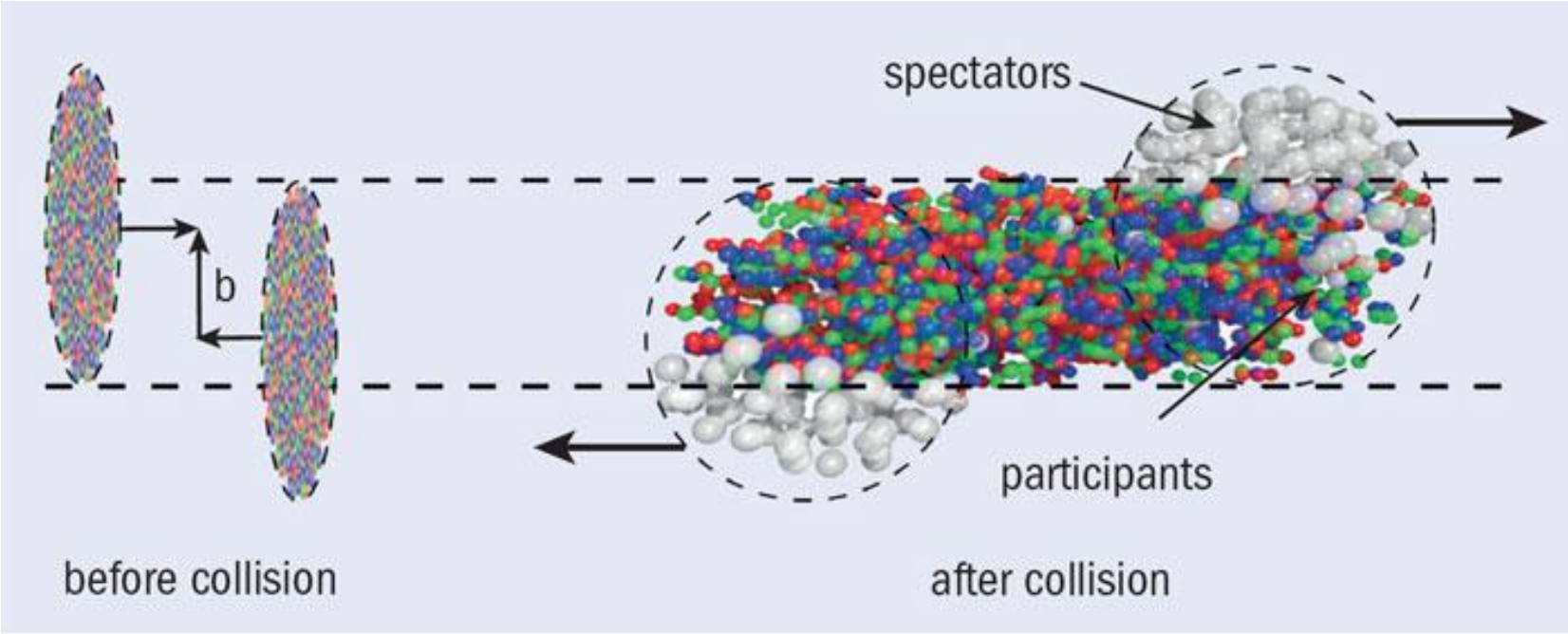
EDITORS' SUGGESTION

Evidence of Spin-Orbital Angular Momentum Interactions in Relativistic Heavy-Ion Collisions

The measured spin alignment of vector mesons in heavy-ion collisions is consistent with that expected from the spin-orbit coupling of quarks with the large angular momentum of the collision.

S. Acharya *et al.* (The ALICE Collaboration)
Phys. Rev. Lett. **125**, 012301 (2020)

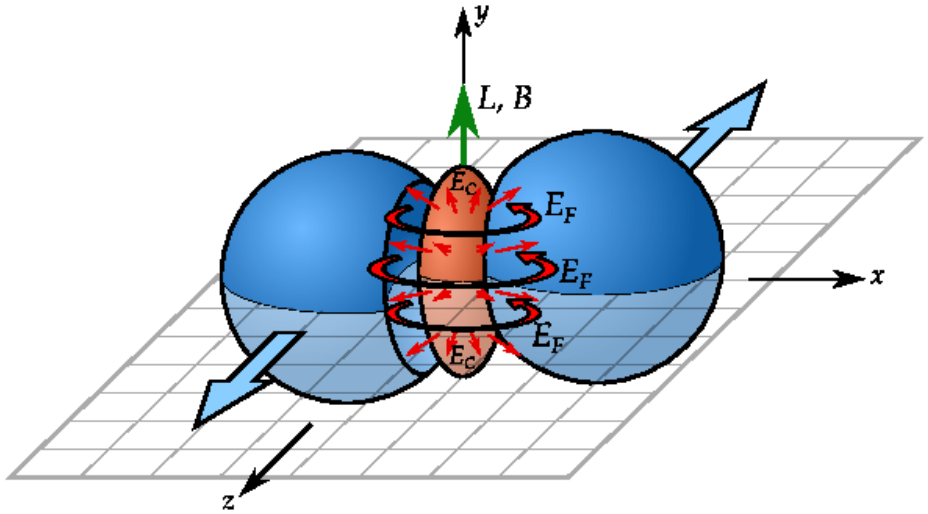
Heavy-ion collisions



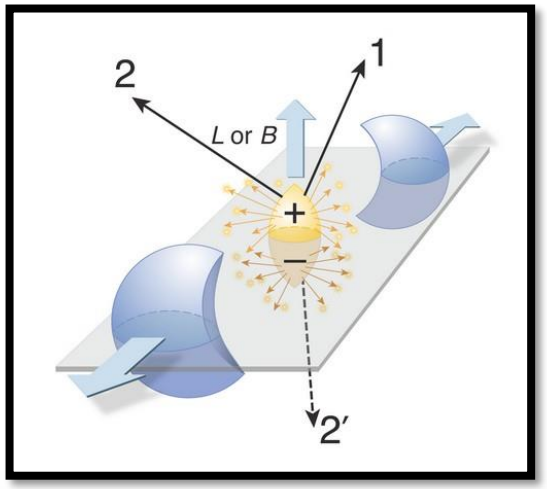
Reaction plane: Impact parameter and beam axis

L and B perpendicular to reaction plane

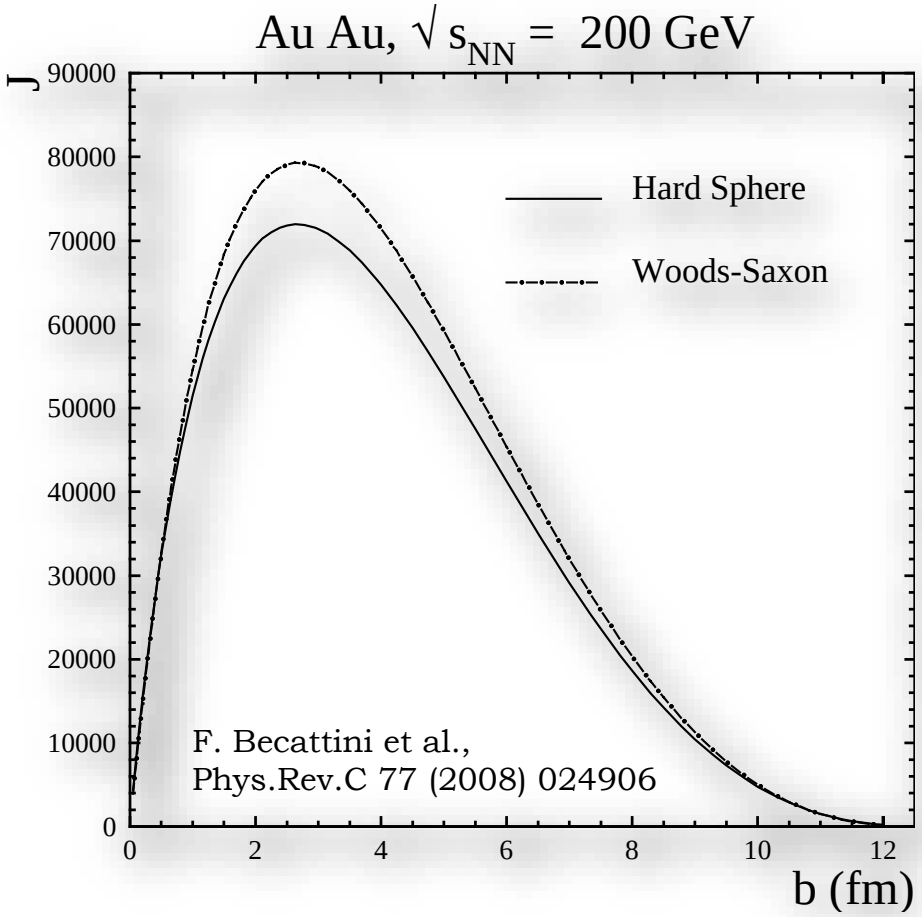
Spin-orbital angular momentum interaction could manifest as vorticity (ω) of the fluid.

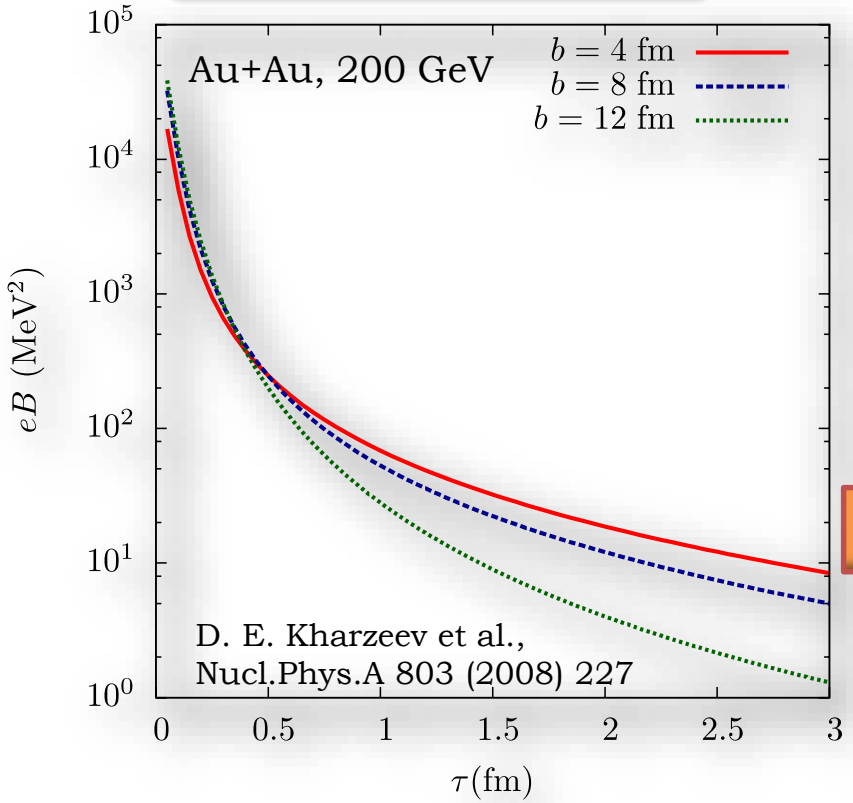


Angular momentum & magnetic field



Impact parameter dependence





Time dependence

Large magnetic field

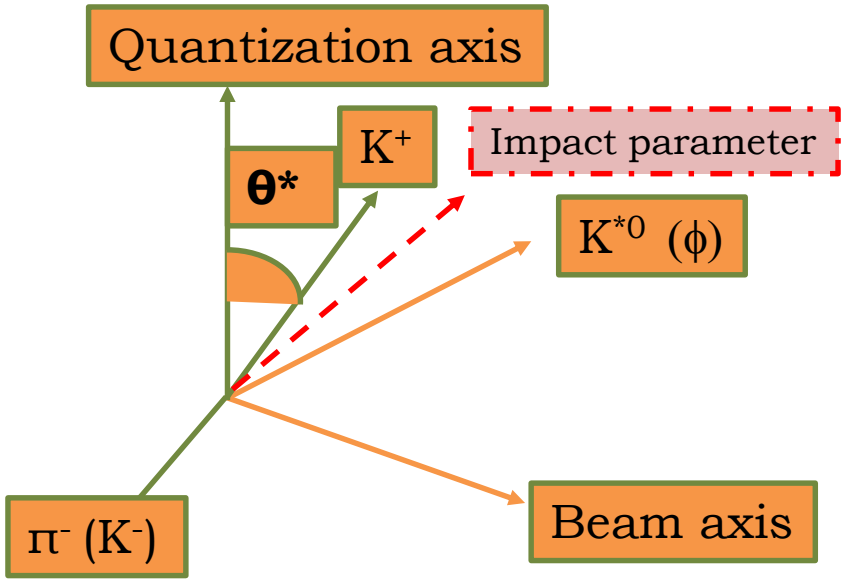
Large angular momentum (Conserved Quantity)

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

Angular distribution of vector mesons

K^{*0} Vector meson
- Mass – 896 MeV/c^2
- Lifetime – 4 fm/c
- Spin 1
- Decays to K^+ and π^- (B.R – 66%)
- Quark content (d,$\bar{s}$)

ϕ Vector meson
- Mass – 1019 MeV/c^2
- Lifetime – 42 fm/c
- Spin 1
- Decays to K^+ and K^- (B.R – 49%)
- Quark content (s,$\bar{s}$)



Quantization axis
- Normal to production plane (Momentum of vector meson and beam axis)
- Normal to reaction plane (Impact parameter and beam axis)

K. Schilling et al., Nucl. Phys. B 15 (1970) 397

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

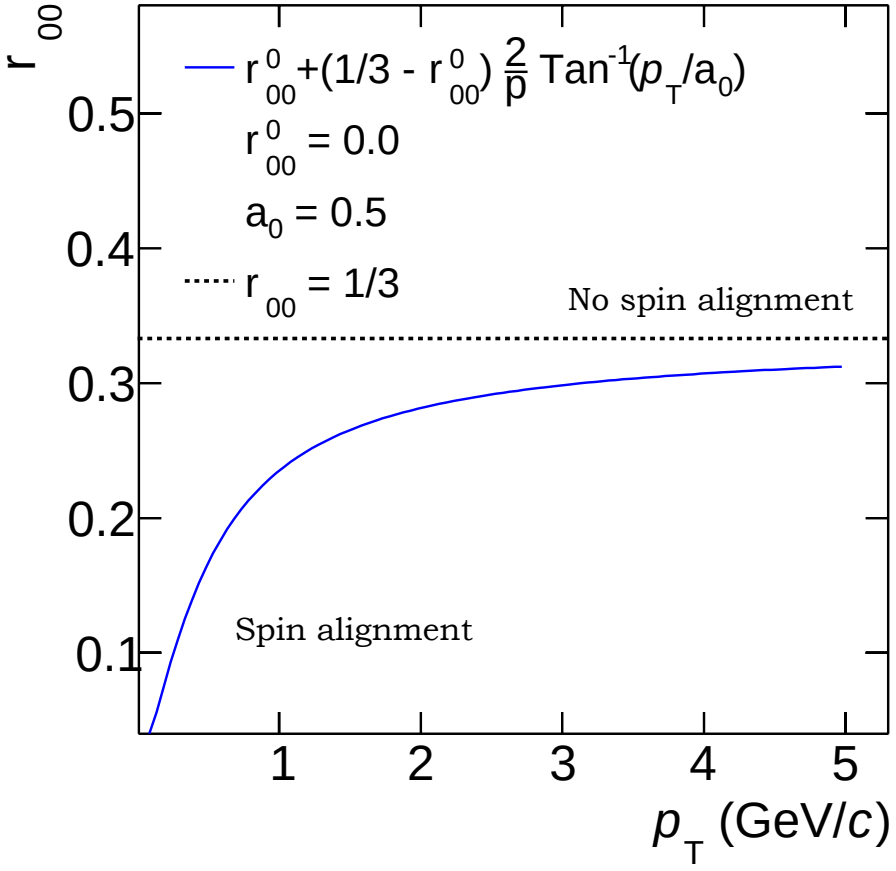
ρ_{00}: Probability vector meson is in spin state = 0

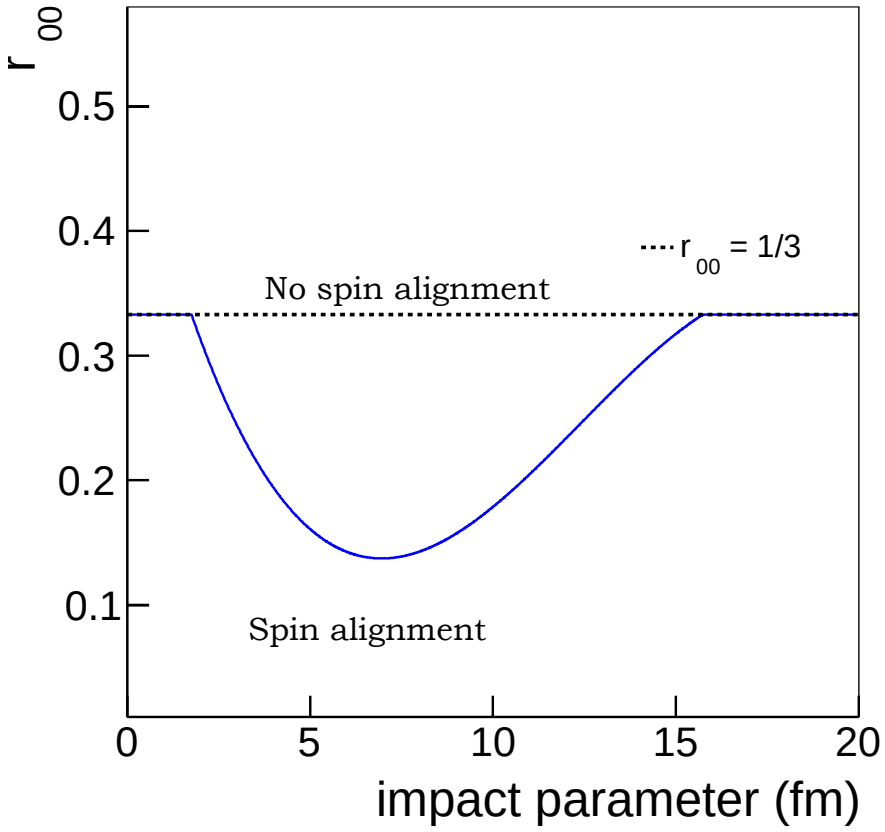
ρ_{00} = 1/3 → No spin alignment

Angular distribution of decay daughters of vector (spin=1) meson gets modified in presence of large angular momentum

Qualitative theory expectation

Z. Liang et. al., Phys. Lett. B629, 20 (2005)





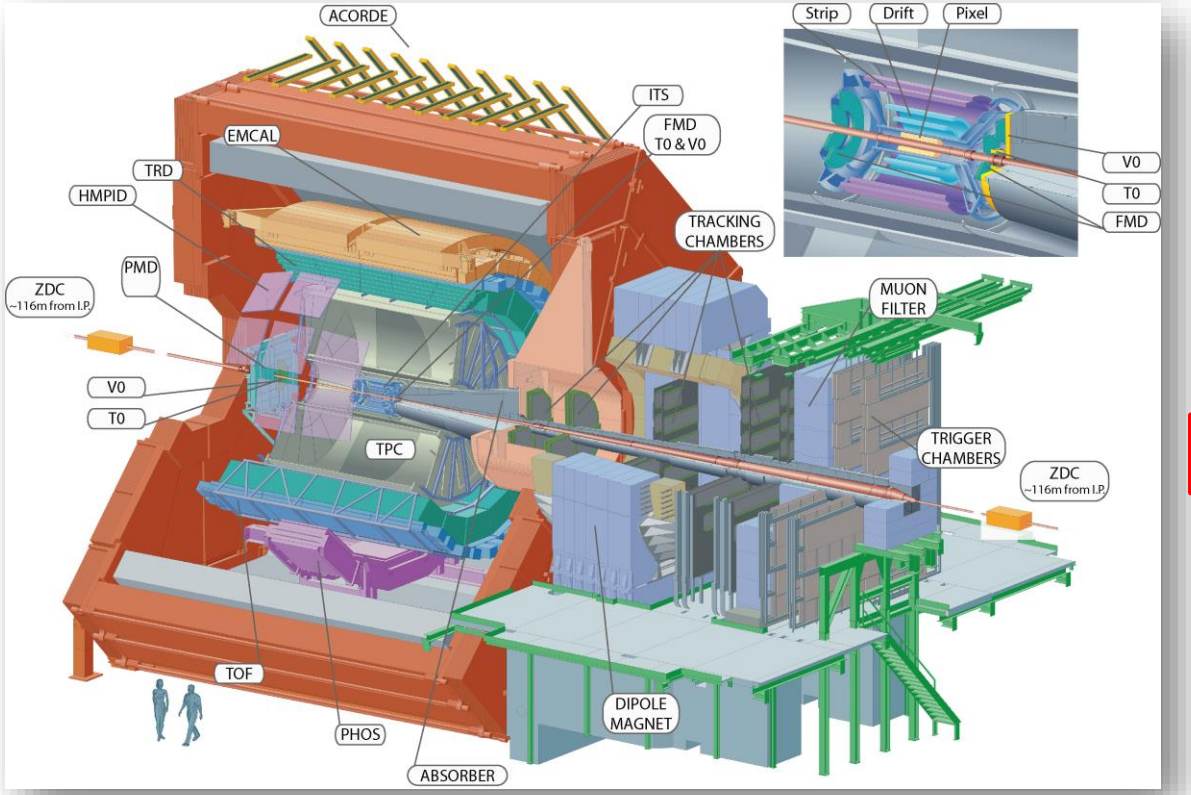
- Low p_T phenomena – Hadronization via recombination
- Small spin alignment for central and peripheral collisions
- Maximum effect for mid-central (intermediate impact parameter) collisions
- Effect larger for K* than ϕ mesons (factor 10 lifetime difference, re-scattering effect, heavier mass of strange quark, coherent field)

Physics process and theory expectation

Physics process	Theory	Remarks	Reference
Vorticity (ω)	$\rho_{00}(\omega) < 1/3$	$\rho_{00}(\omega) \sim \frac{1}{3} - \frac{1}{9}(\beta\omega)^2$	*F. Becattini et al., Phys. Rev. C 95 (2017) 054902*
Magnetic field (B)	$\rho_{00}(B) > 1/3$ $\sim \frac{1}{3} - \frac{1}{9}\beta \frac{q_1 q_2}{m_1 m_2} B^2$ $\rho_{00}(B) < 1/3$	Electrically neutral vector mesons Electrically charged vector mesons	*Y. Yang et. al., Phys. Rev. C 97 (2018) 034917*
Hadronization	$\rho_{00}(rec) < 1/3$ $\sim \frac{1-P_q P_q}{3+P_q P_q}$ $\rho_{00}(frag) > 1/3$ $\sim \frac{1+\beta P_q P_q}{3-\beta P_q P_q}$	Recombination Fragmentation	*Z. Liang et. al., Phys. Lett. B 629 (2005) 20 (2005)* *Z. Liang and X. N. Wang Phys.Rev.Lett. 94 (2005) 102301*
Coherent meson field	$\rho_{00} > 1/3$	ϕ mesons	*X. L. Sheng et. al., Phys.Rev.D 101 (2020) 096005*

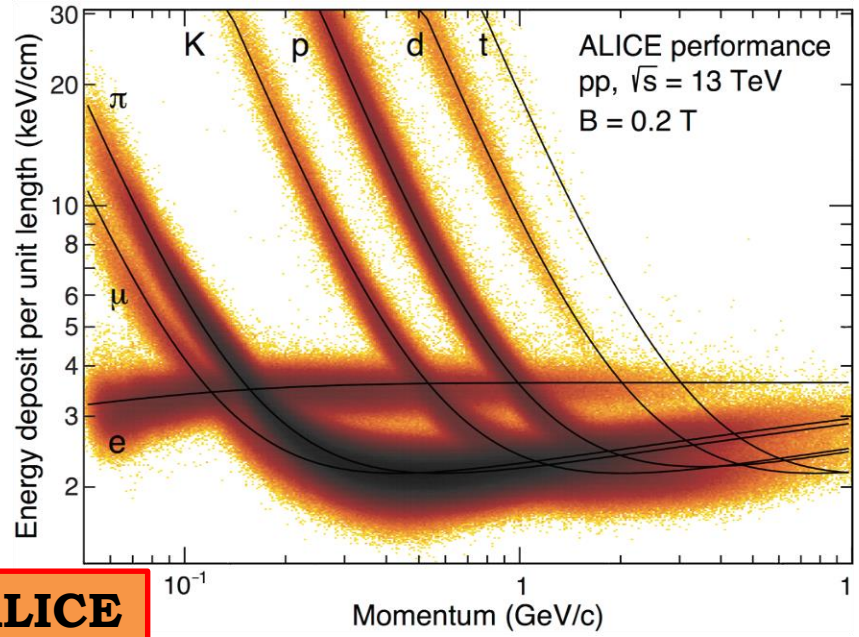
ALICE detector

ALICE @ LHC

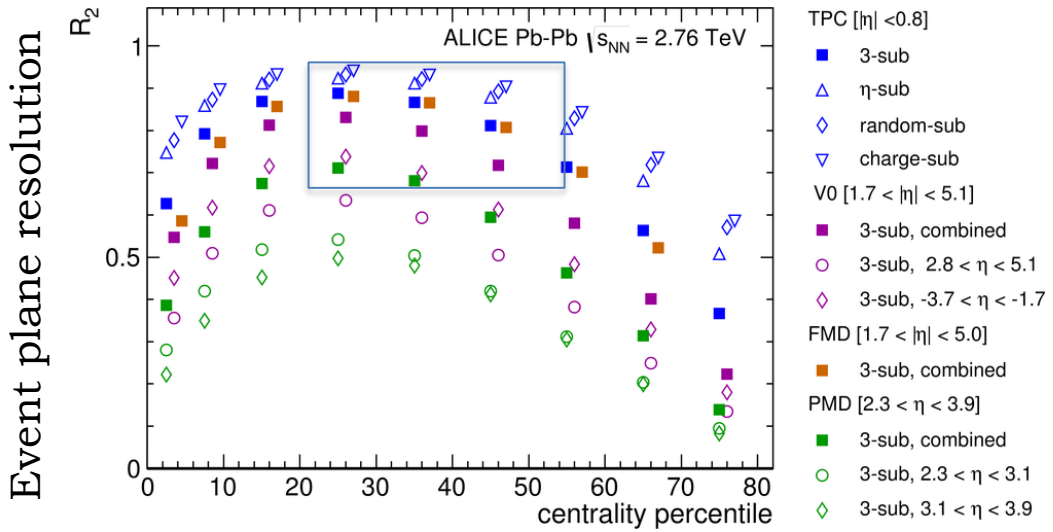


PID @ ALICE

PDG, 2018



Event Plane @ ALICE



ALICE: Int. J. Mod. Phys. A 29 (2014) 1430044

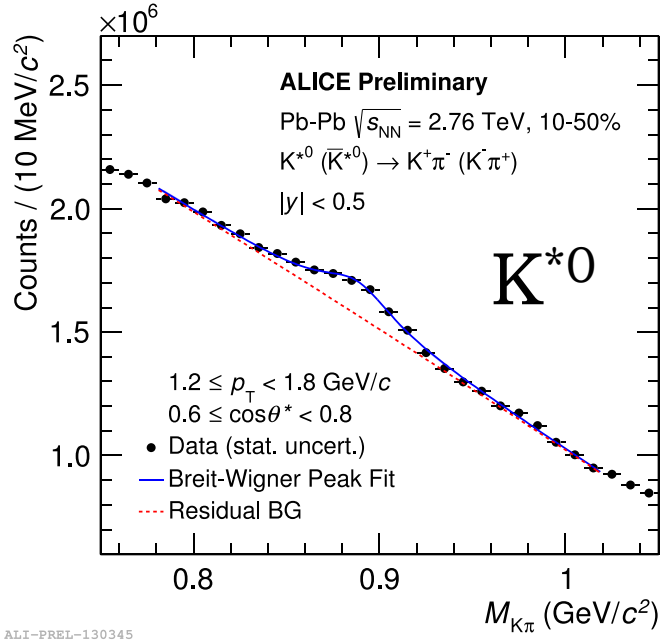
Particle identification: TPC + TOF
Momentum measurement TPC+ITS
Event plane angle measurement: V0

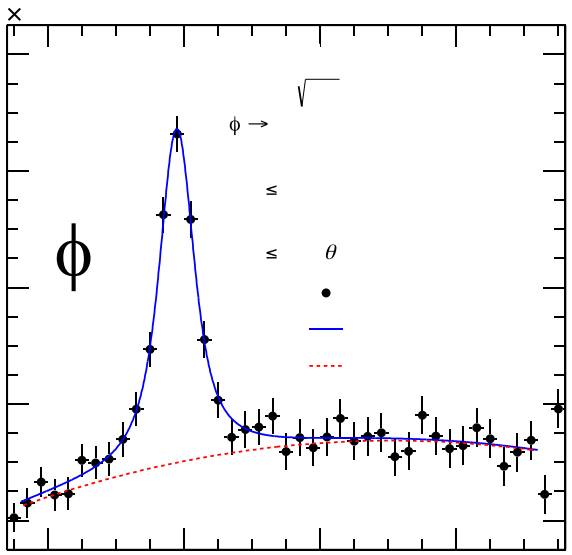
ALICE data set

Collision system	pp at 13 TeV, Pb-Pb at 2.76 TeV
Rapidity	$\lvert y \rvert < 0.5$
No. of events	~ 43 M (pp), 14 M (Pb-Pb)
Hadrons	pp: K^{*0} and ϕ Pb-Pb: K^{*0}, ϕ and K_S^0
Background	Mixed events
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)
Event plane resolution (R)	Corrected for EP analysis $\rho_{00} - \frac{1}{3} = \frac{4}{1+3R}(\rho_{00}^{\mathrm{obs}} - \frac{1}{3})$ *A.H. Tang et al., Phys Rev C 98 (2018) 044907*

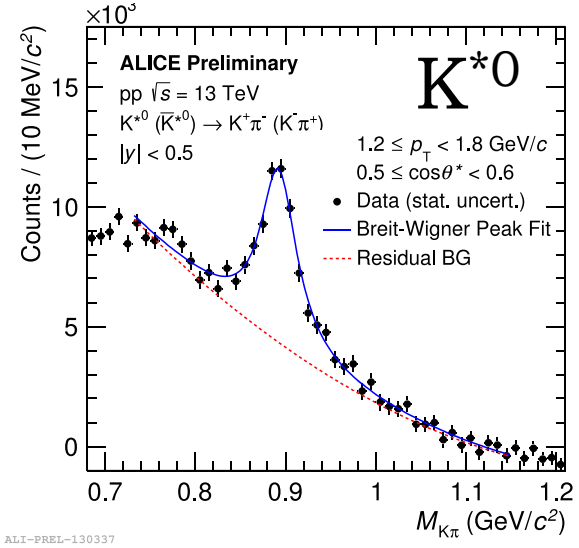
K^{*0} and ϕ vector meson

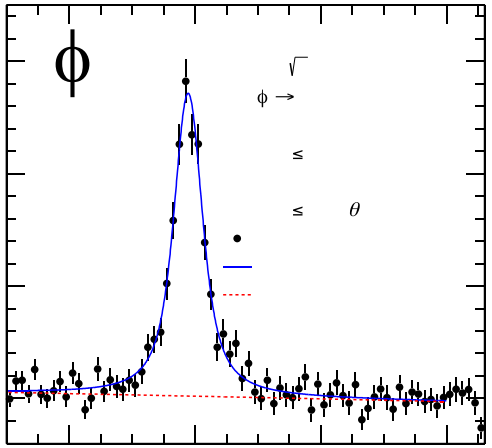
Pb-Pb





pp





K^{*0} vector meson
- Mass – 896 MeV/c^2
- Lifetime – 4 fm/c
- Spin 1
- Decays to K^+ and π^- (B.R – 66%)
- Quark content (d,$\bar{s}$)

ϕ vector meson
- Mass – 1019 MeV/c^2
- Lifetime – 42 fm/c
- Spin 1
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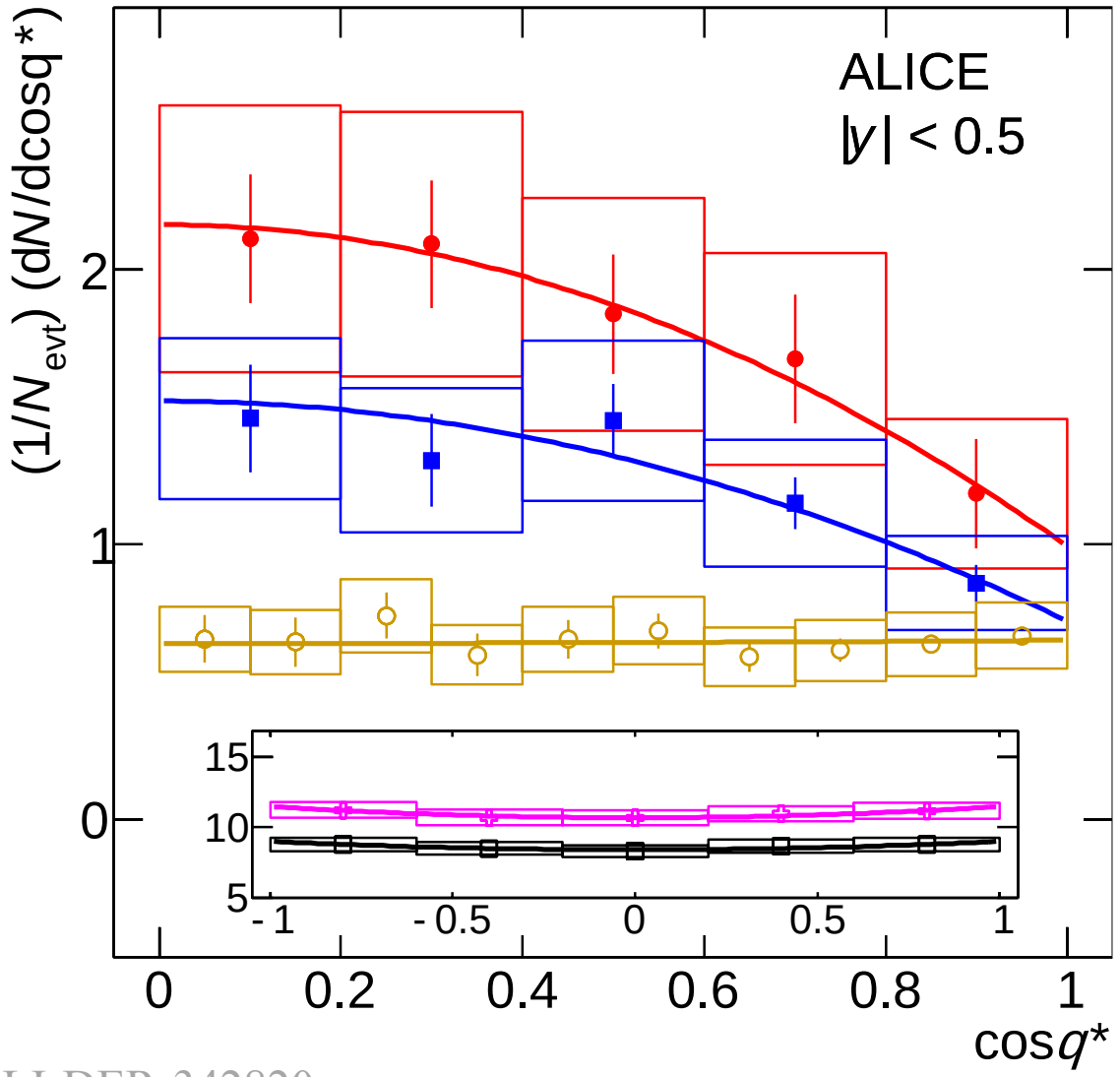
- Quark content (s,$\bar{s}$)

K^{*0}: Breit-Wigner
ϕ: Voigtian
Residual background:
Polynomial function

Phys. Rev. Lett. 125, 012301 (2020) - ALICE

Angular distribution of vector mesons



K^{*0}, Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV (10-50%)

● EP, $0.8 \le p_T < 1.2$ GeV/c

■ PP (´ 0.3), $0.4 \le p_T < 1.2$ GeV/c

K^{*0}, pp $\sqrt{s}$ = 13 TeV

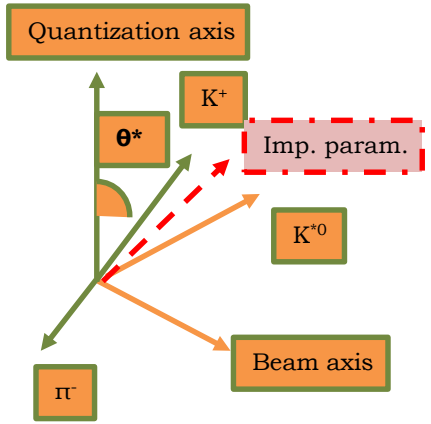
○ PP (´ 15), $0.0 \le p_T < 0.6$ GeV/c

K^0_S, Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV (20-40%)

✚ EP, $0.6 \le p_T < 0.8$ GeV/c

□ PP (´ 0.8), $0.6 \le p_T < 0.8$ GeV/c

— $N_0[(1 - r_{00}) + (3r_{00} - 1)\cos^2 q^*]$



ALI-DER-342820

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Spin alignment of vector mesons: p_T dependence

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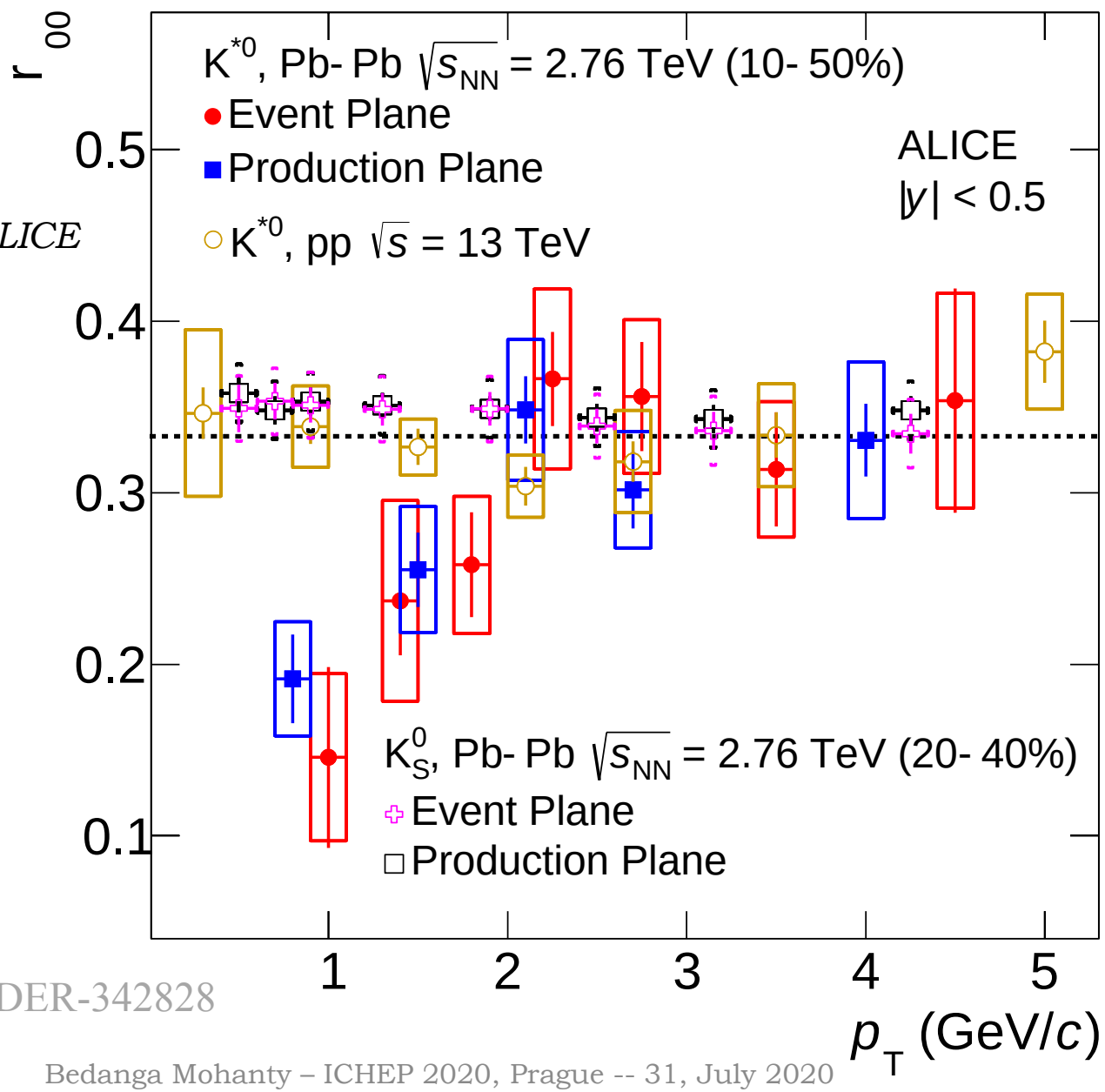
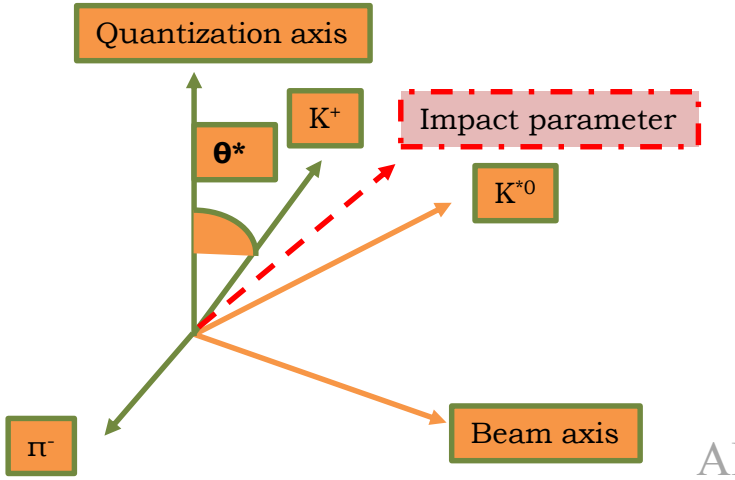


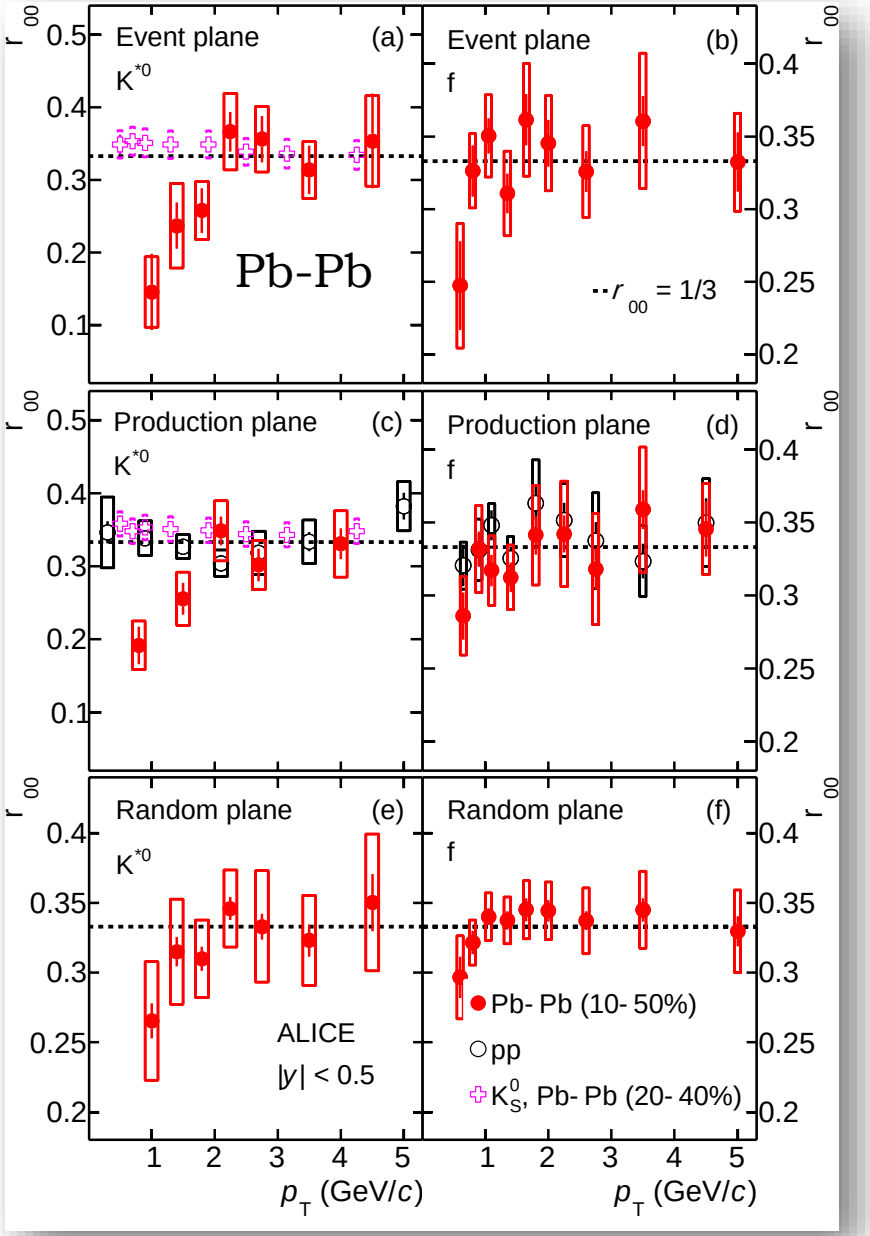
No spin alignment



ALI-DER-342828

Spin alignment of vector mesons

K^{*0}



ϕ

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

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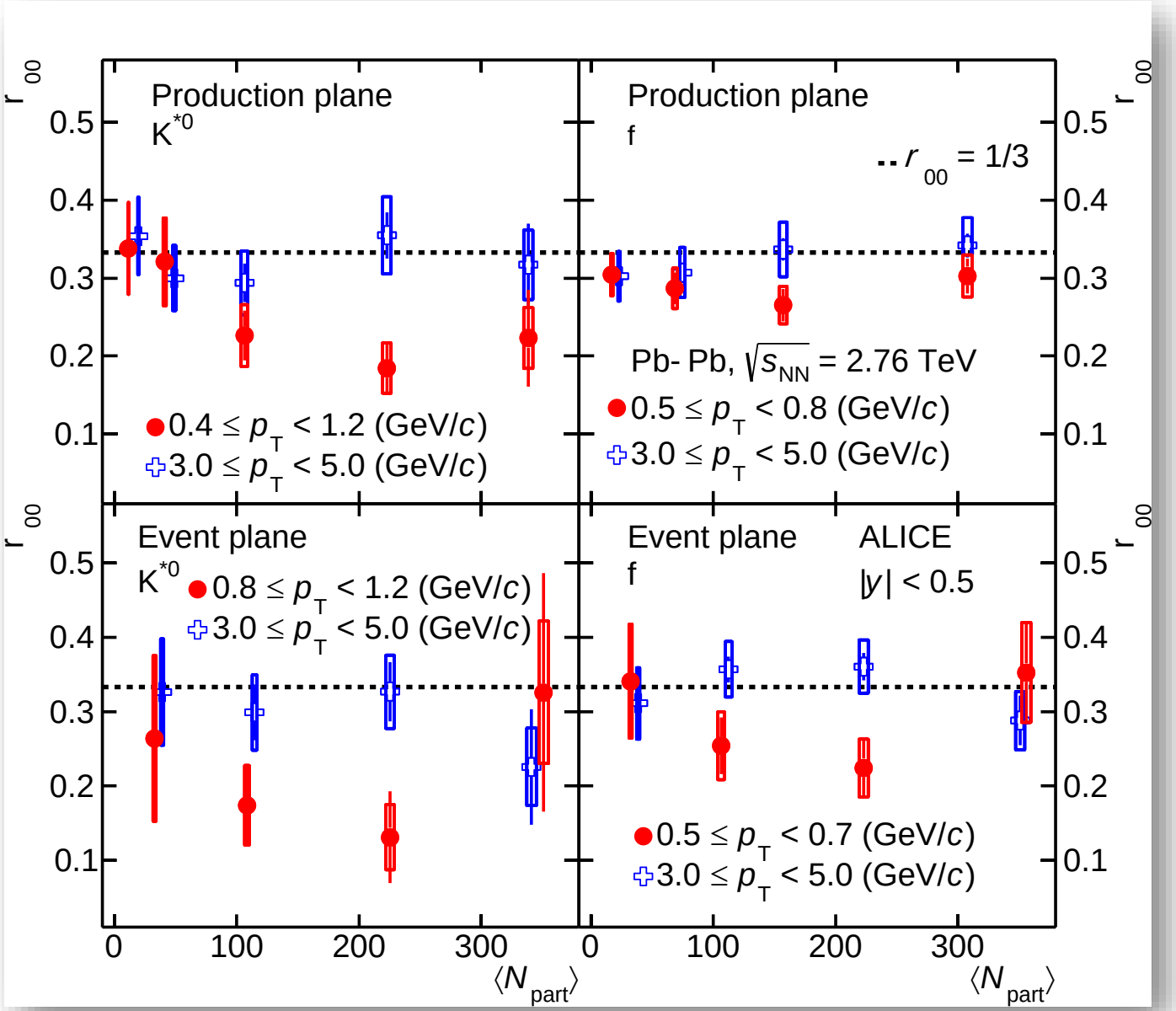
Spin alignment: centrality dependence



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

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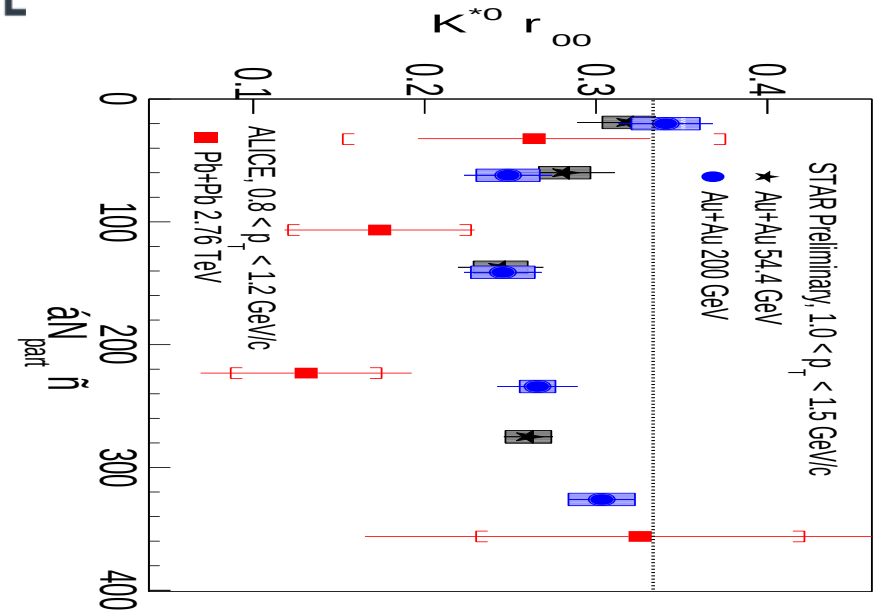
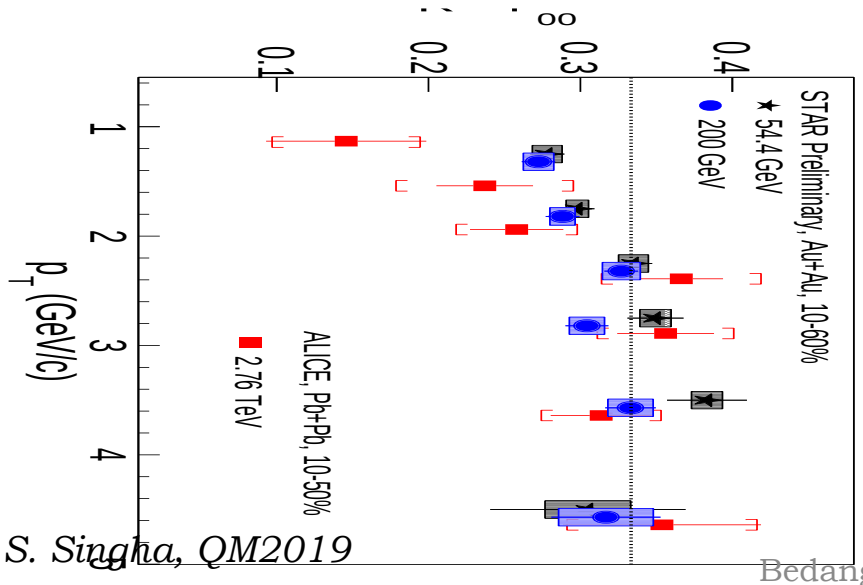
Theoretical expectation & comparison to RHIC

Centrality dependence



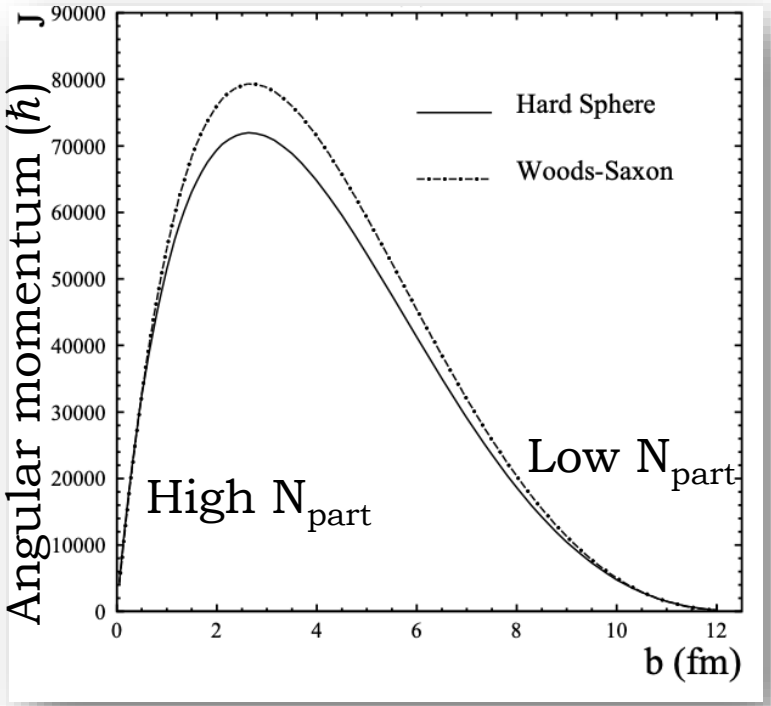


STAR: S. Singha, QM2019

Centrality dependence of angular momentum

Centrality dependence of ρ_{00} like centrality dependence of angular momentum

arXiv:1910.14408 (ALICE)

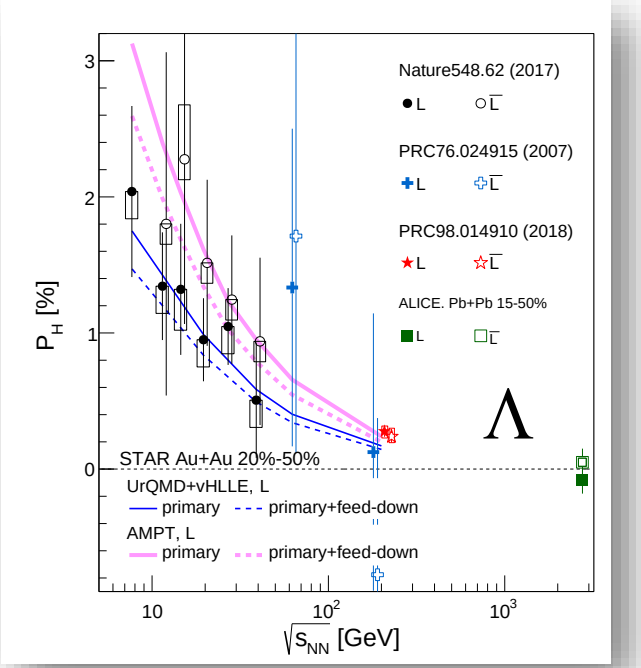


Transverse momentum dependence

Transverse momentum 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

Discussion

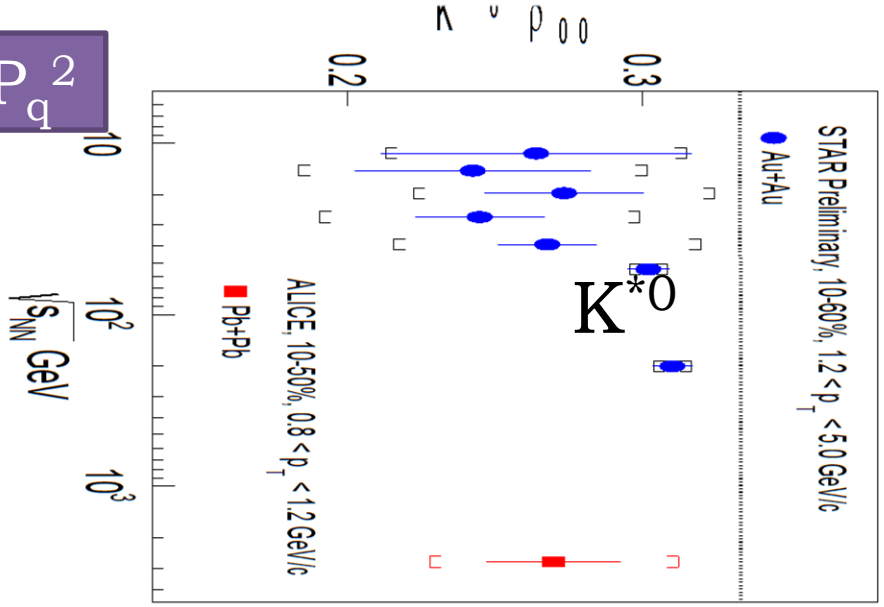
1.



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

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

ρ_{00} **energy dependence ?**



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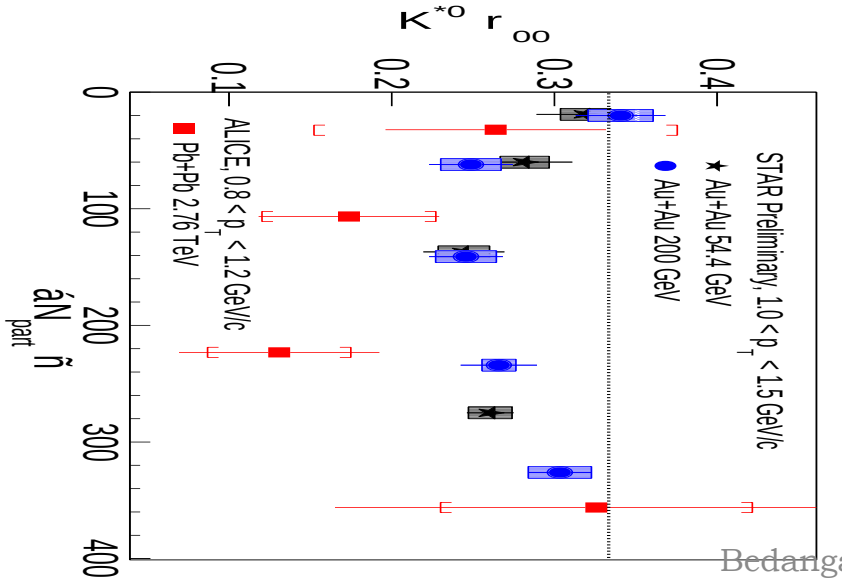
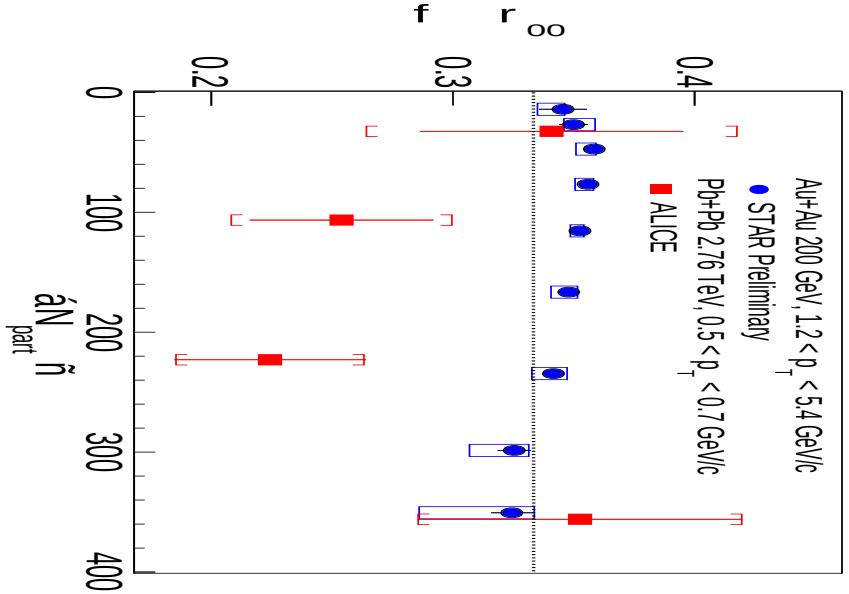
2.

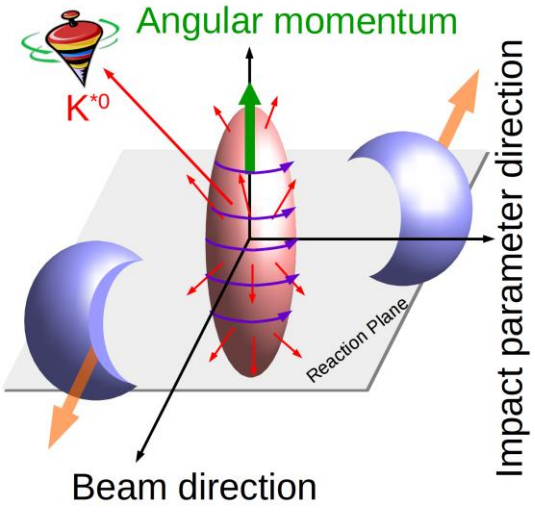


K^{*0} versus ϕ meson at RHIC and LHC

Role of coherent meson field



Summary



- ✓ First evidence of spin alignment in vector mesons in high energy **heavy-ion collisions**. Both RHIC and LHC observe the phenomenon.
- ✓ Measurements **coupled to** event plane – vanishes for random event plane ➔ related to **initial angular momentum**
- ✓ Spin alignment **not** observed in **proton-proton collisions**
- ✓ Spin alignment **not** observed for **spin 0 particles** in heavy-ion collisions

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Outlook

A. Theoretical Side:

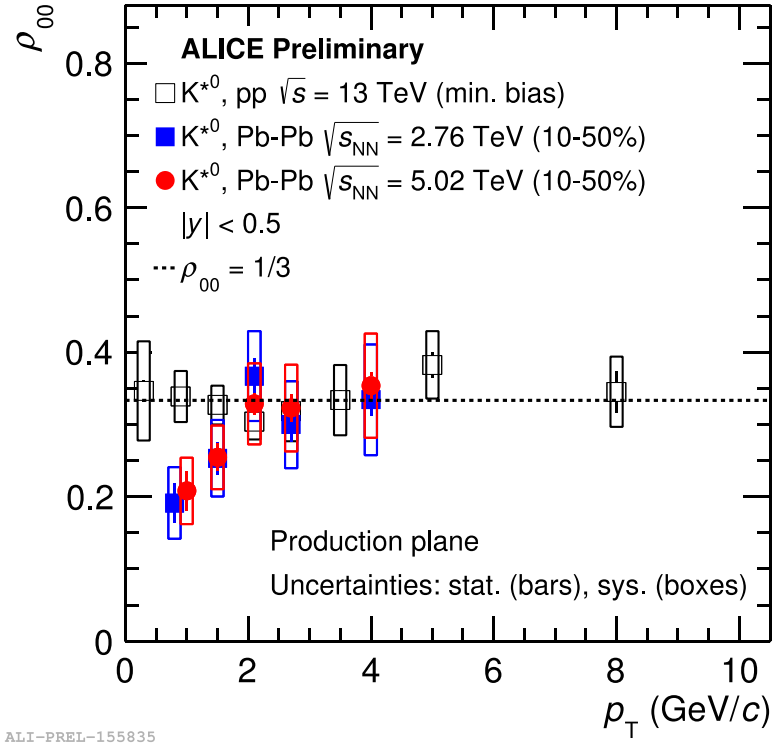
- The experimental measurements → challenges to theory

1. Explain Lambda and vector meson results simultaneously
2. Explain the difference in ρ_{00} values of ϕ (> 1/3 at RHIC and < 1/3 at LHC) meson
3. Relativistic spin hydrodynamics
4. Models with conservation of angular momentum.

B. **Experimental Side**:

- Precision measurements may allow sensitivity to initial magnetic field

1. Lambda and anti-Lambda polarization
2. Charged K* and neutral K* ρ_{00}
3. Working on 2015+2018 Pb-Pb 5.02 TeV data set in ALICE

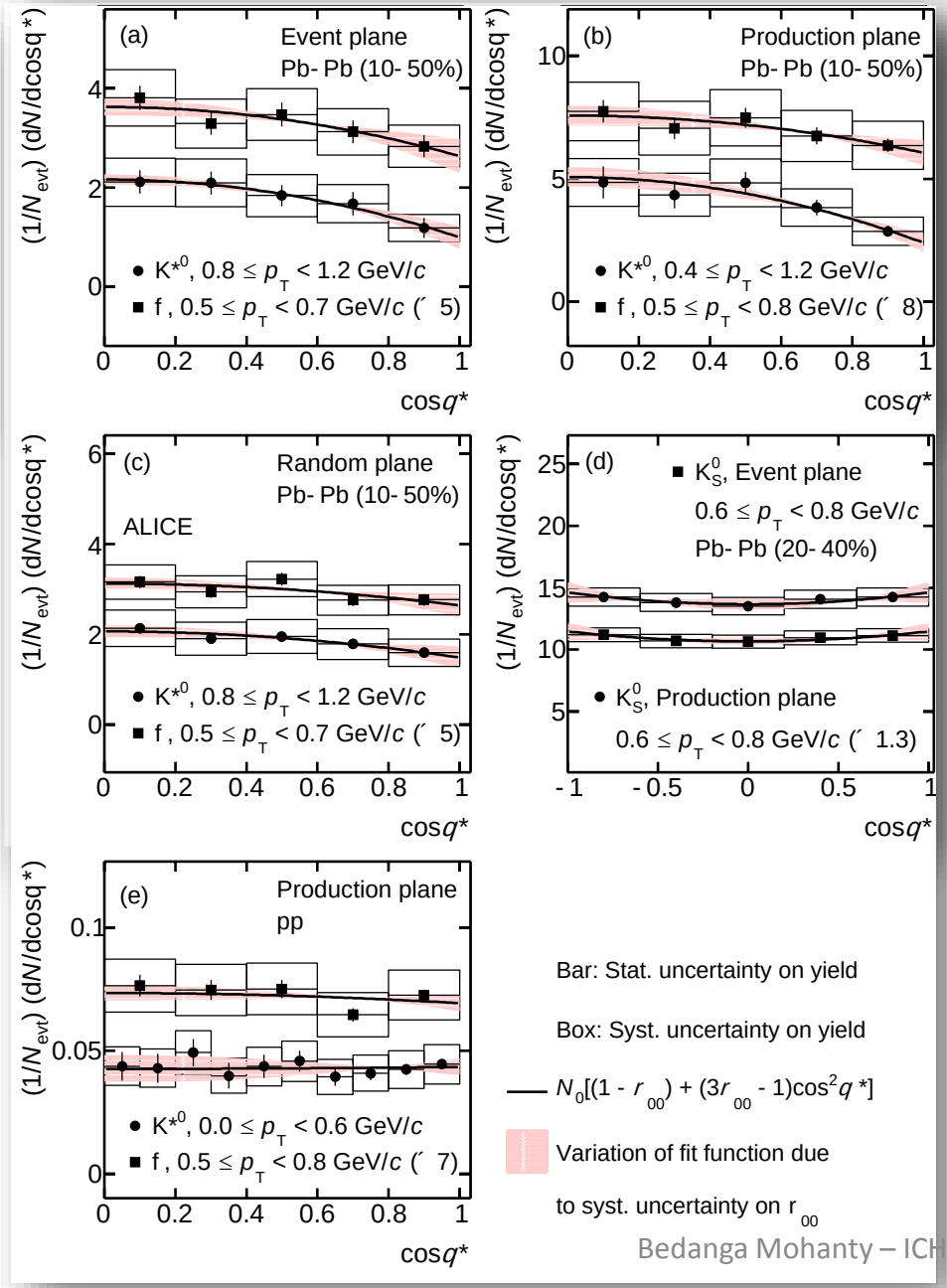


Pb-Pb 5.02 TeV - 2015

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

BACK UP

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 K^0_s in heavy-ion collisions
4. Angular distribution FLAT for vector mesons in proton-proton collisions

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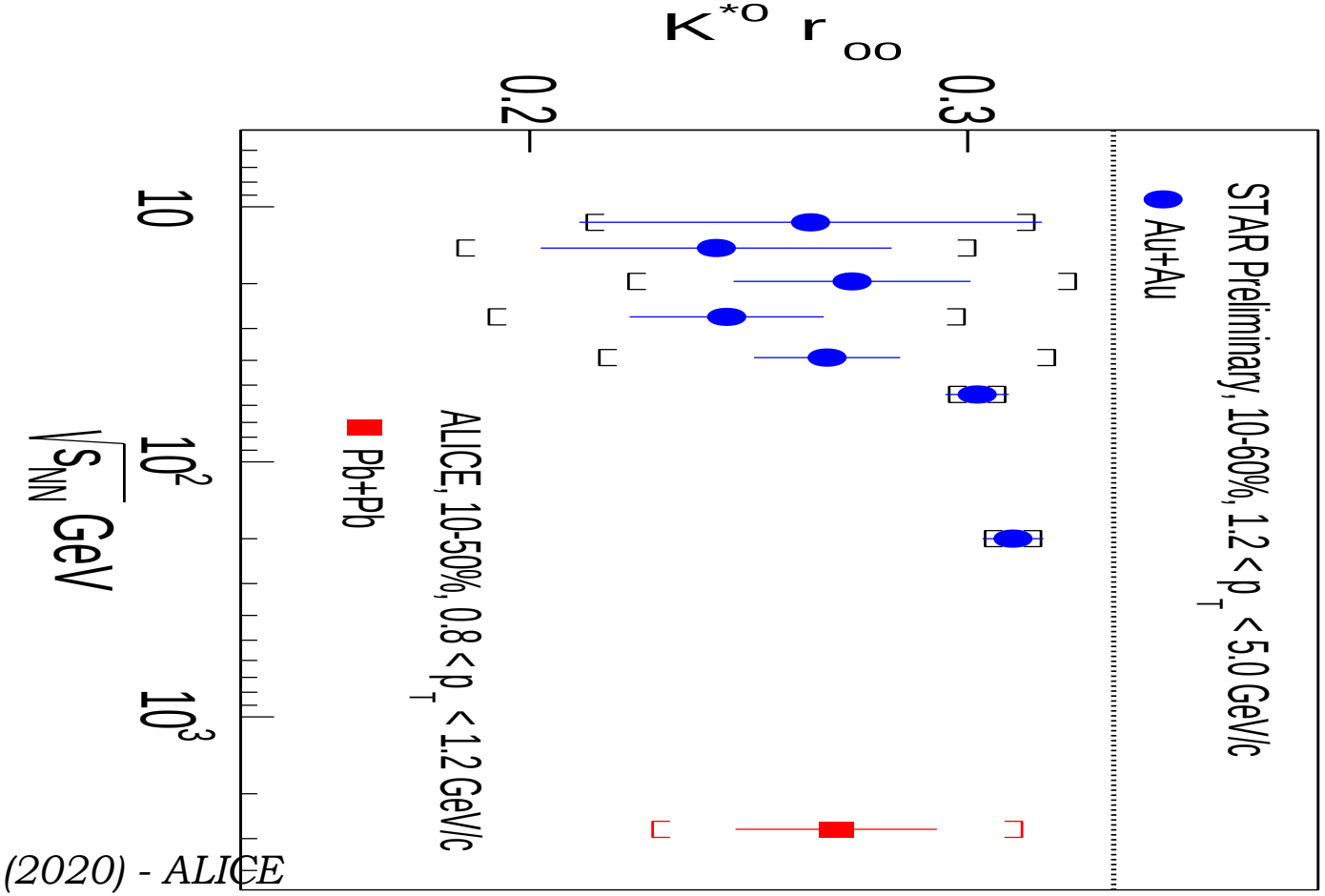
arXiv:1910.14408 (ALICE)

Collision energy dependence



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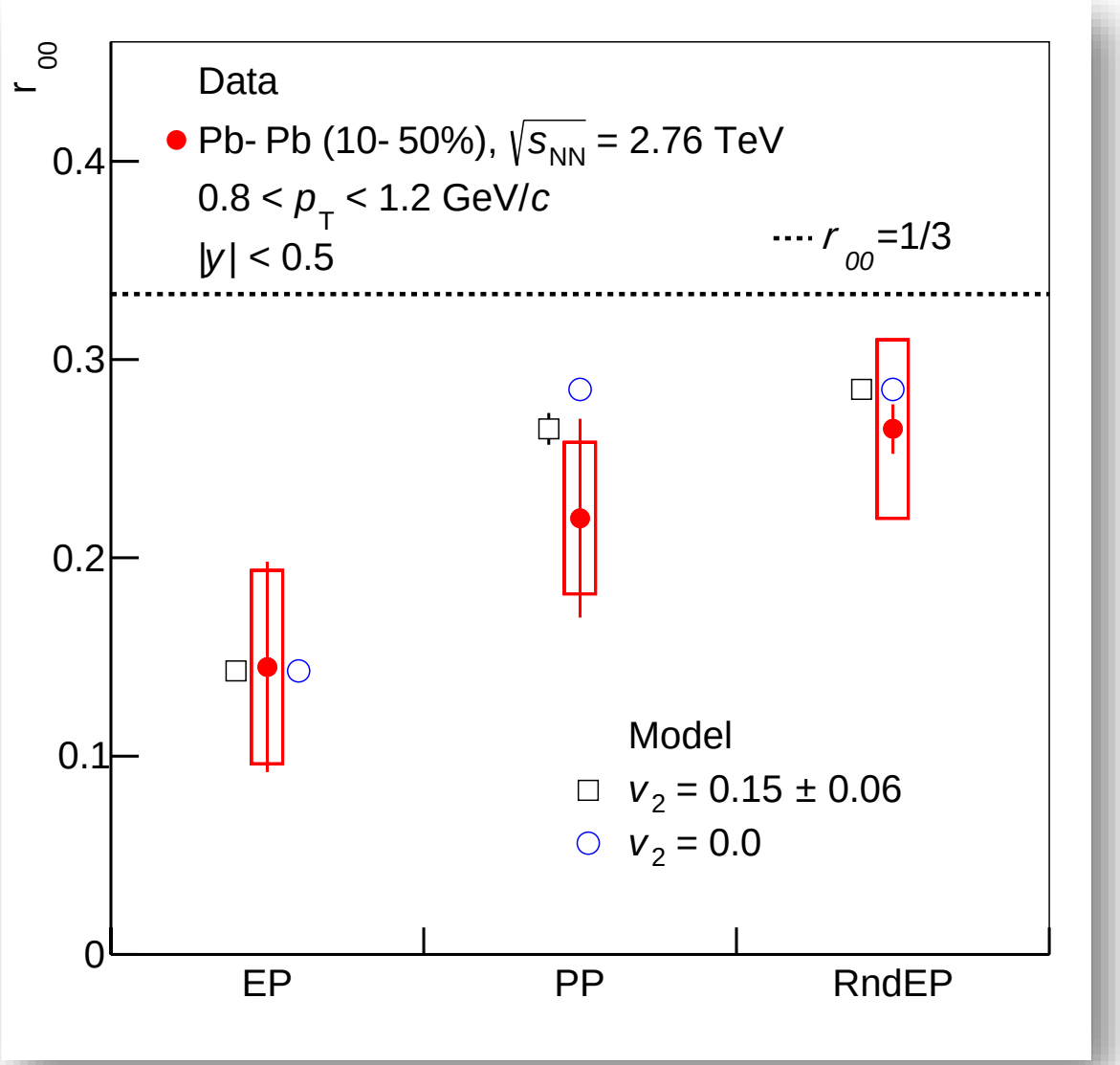
- *Looks like no energy dependence of ρ_{00}.*
- *High statistics data at LHC and RHIC will clarify the picture.*
- *ALICE Pb-Pb analysis at 5.02 TeV under progress.*

Relation between EP and PP



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

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.

arXiv:1910.14408 (ALICE)

Systematic uncertainties and checks

On ρ_{00}

Source	**K^{*0}**		**ϕ**	
	Low p_T	**High p_T**	**Low p_T**	**High p_T**
Yield extraction procedure	13%.	5%	8%	3%
Track selection criteria	14%	13%	6%	5%
Particle identification procedure	7%	8%	3%	5%

- Closure test (data and MC)
- Data samples with two different magnetic field polarities
- Positive ($0 < y < 0.5$) and negative ($-0.5 < y < 0$) rapidity
- K^{*0} and anti-K^{*0}
- Two different event generators are used to determine the reconstruction efficiency