Spin alignment of vector mesons measured in Pb-Pb collisions with ALICE

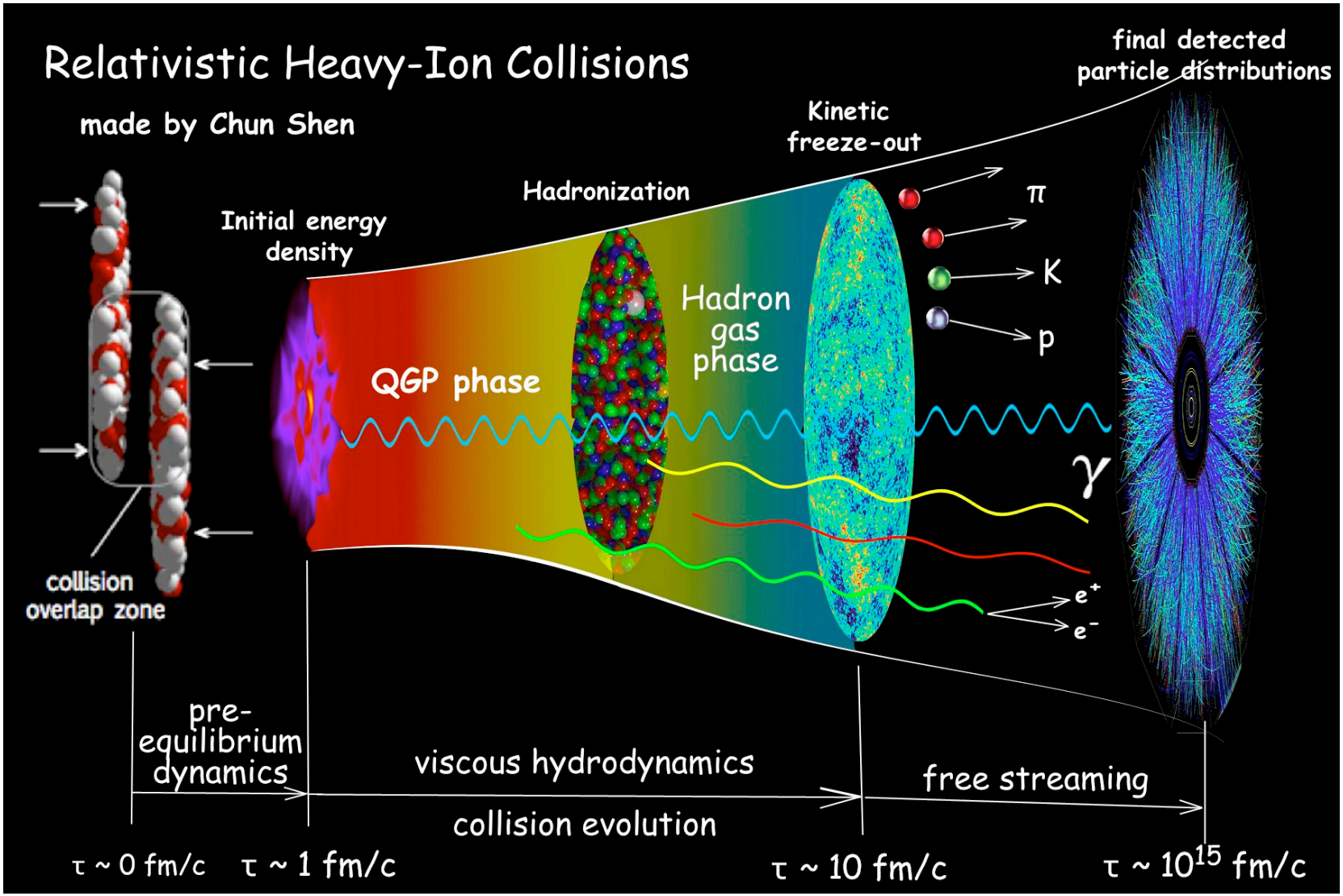
Bedanga Mohanty
(On behalf of the ALICE Collaboration)
CERN and NISER

Outline:

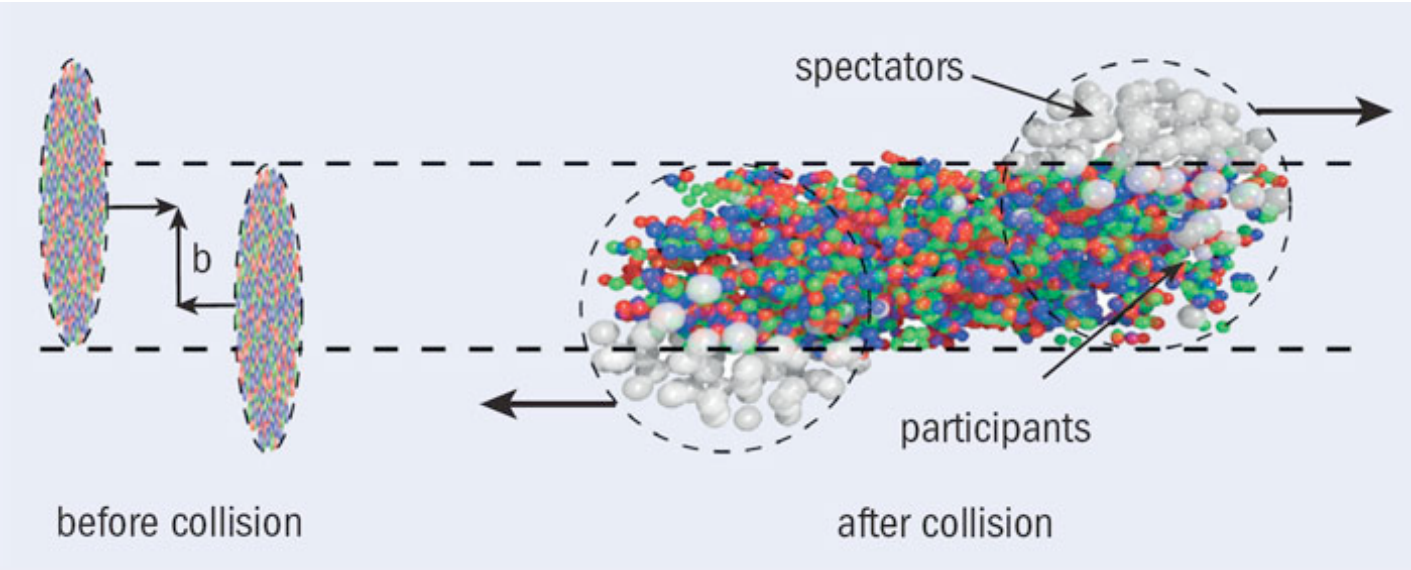
- High energy heavy-ion collisions
  - Introduction
  - Initial conditions: Angular momentum & magnetic field
- Spin alignment of vector mesons
  - Observable and theory expectation
  - ALICE physics analysis
  - Results
- Discussions: Comparison to theory expectation and RHIC results
- Summary
- Surprises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

Based on : arXiv:1910.14408 (ALICE)

Heavy-ion collisions

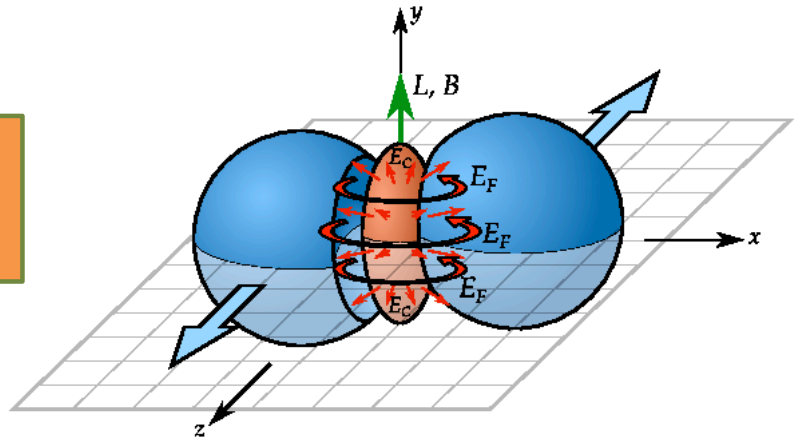


Heavy-ion collisions

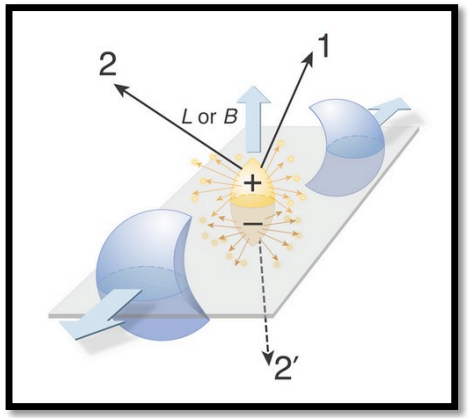


Reaction plane: Impact parameter and beam axis

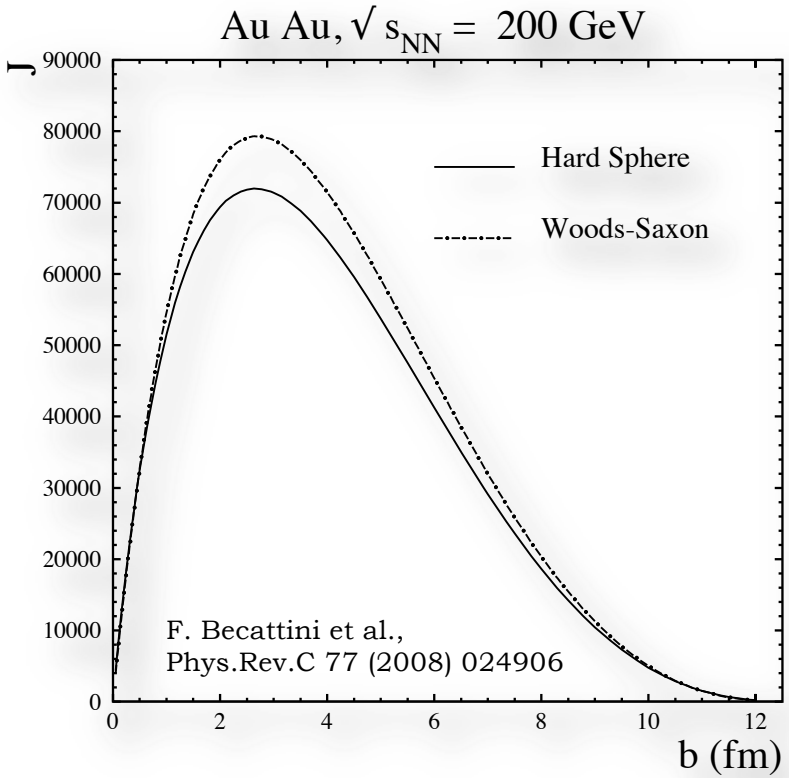
L and B perpendicular to reaction plane



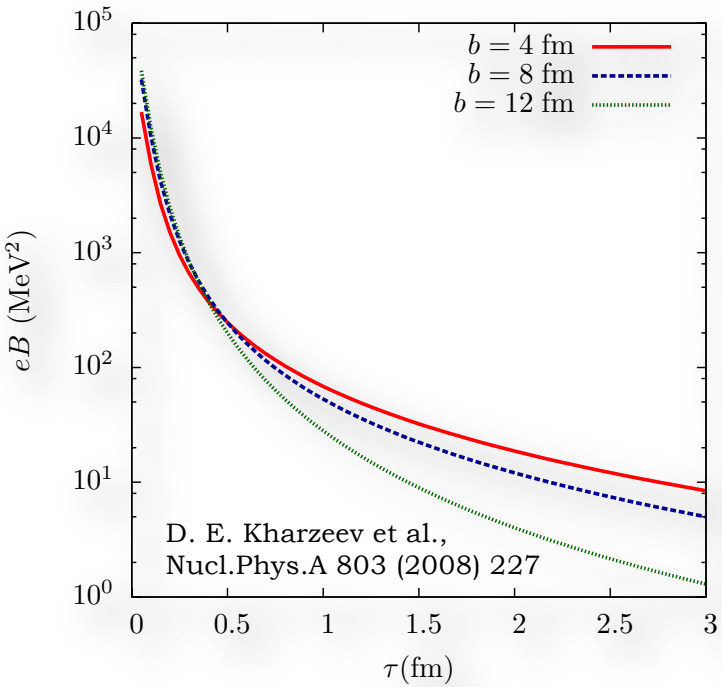
Angular momentum & magnetic field



Impact parameter dependence



Time dependence



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

System	Angular momentum ($h/2\pi$)
Electron in hydrogen atom	$\sqrt{l(l+1)}$
^{132}Ce (highest for nuclei)	70
Heavy-ion collisions	$10^4 - 10^5$

System	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 *STAR: Nature 548 (2017) 62*	**10^7 - 10^{21}**

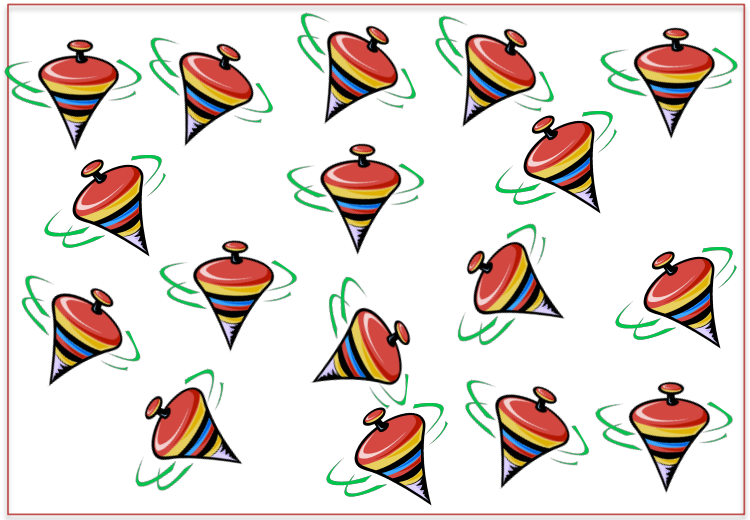
Focus of the study is to see the effect of large angular momentum and magnetic field in heavy-ion collisions

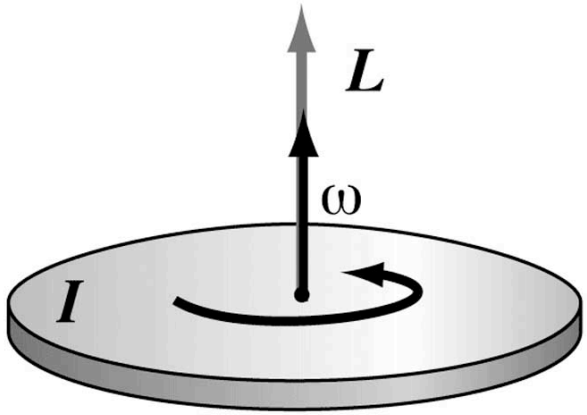
System	Magnetic Field in Tesla
Human brain	10^{-12}
Earth's magnetic field	10^{-5}
Refrigerator magnet	10^{-3}
Loudspeaker magnet	1
Strongest field in lab	10^3
Neutron star	10^6
Heavy-ion collisions	***10^{15} - 10^{16}***

Spin and angular momentum

Quarks (spin ½)
→
Vector mesons (spin 1)

What happens in presence of angular momentum ?

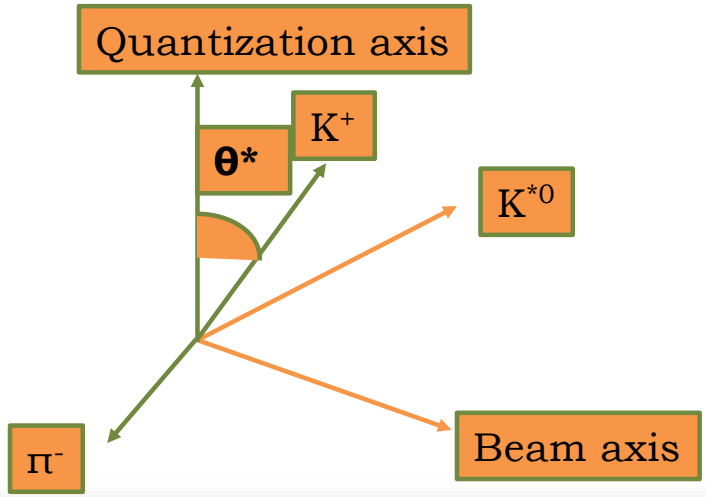




Can we see experimentally the signature of spin-orbit angular momentum interactions for QCD matter produced in heavy-ion collisions ?

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,$\bar{s}$)



K. Schilling et al., 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
  (Momentum of vector meson and beam axis)
- Normal to reaction plane
  (Impact parameter and beam axis)

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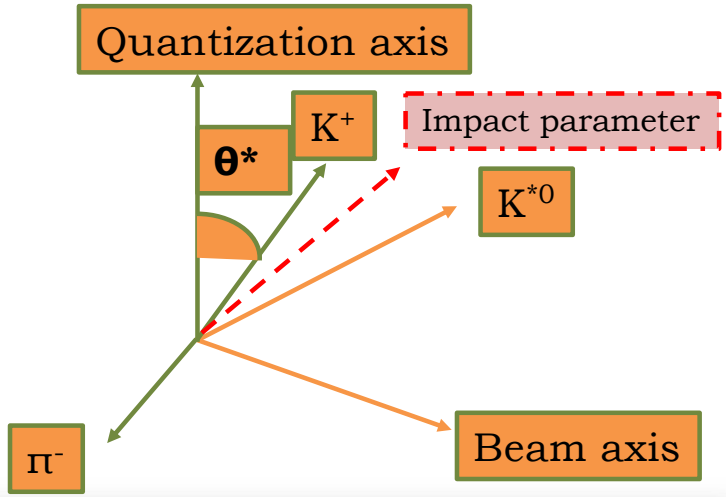

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Angular distribution of vector mesons

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

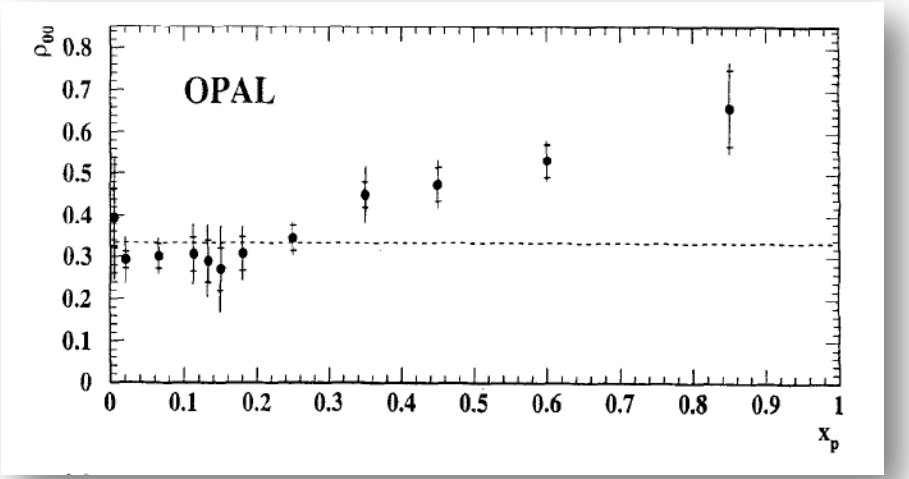
$$\frac{dN}{dcos\theta} = N_0\left[1 - \rho_{0,0} + cos^2\theta\left(3\rho_{0,0} - 1\right)\right]$$

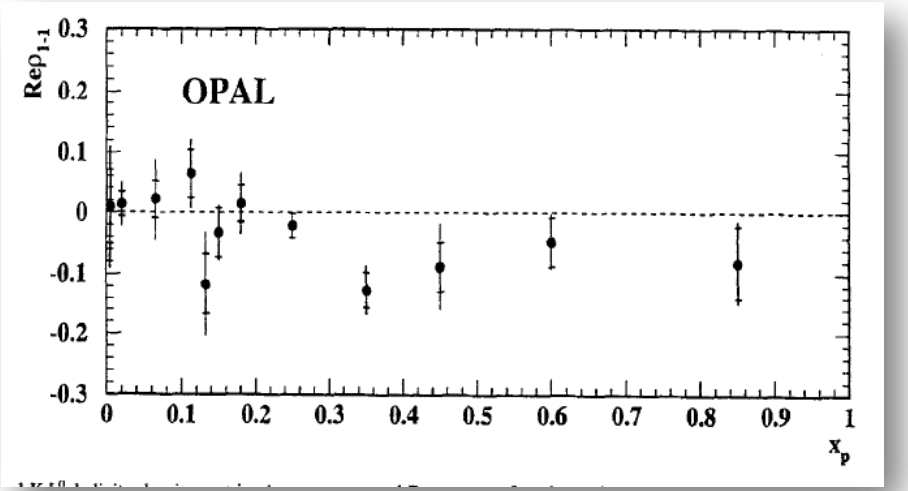
ρ_{00}: Probability vector meson is in spin state = 0

ρ_{00} = 1/3 → No spin alignment

Measurements in e^+e^- collisions

In e^+e^- experiments results exists. Goal was to study role of spin on production dynamics





Spin alignment of leading K*(892)0 mesons in hadronic Z0 decays **OPAL** Collaboration (K. Ackerstaff et al.). Phys.Lett. B412 (1997) 210-224

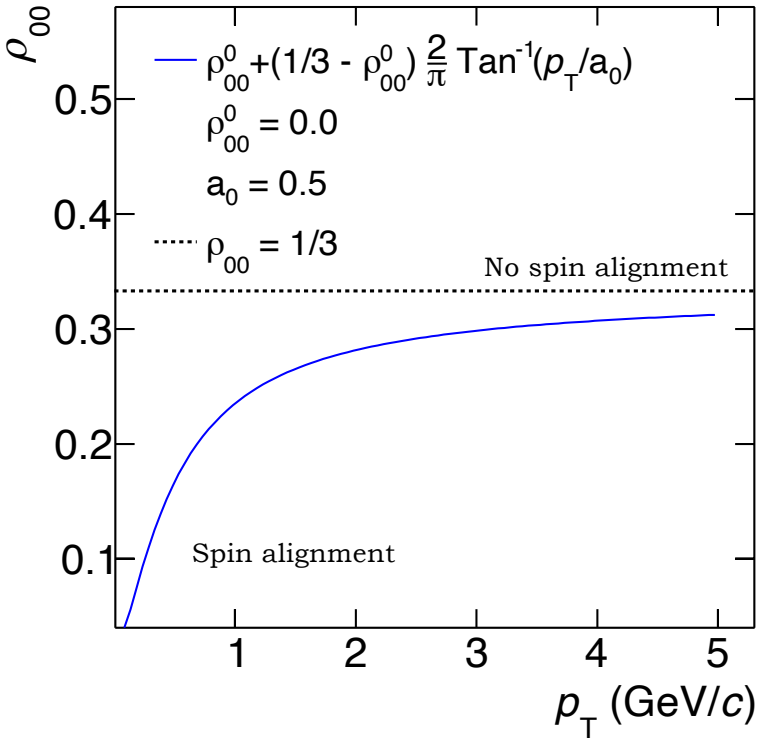
Study of phi (1020), D*+- and B* spin alignment in hadronic Z0 decays, **OPAL** Collaboration (K. Ackerstaff et al.). Z.Phys. C74 (1997) 437-449

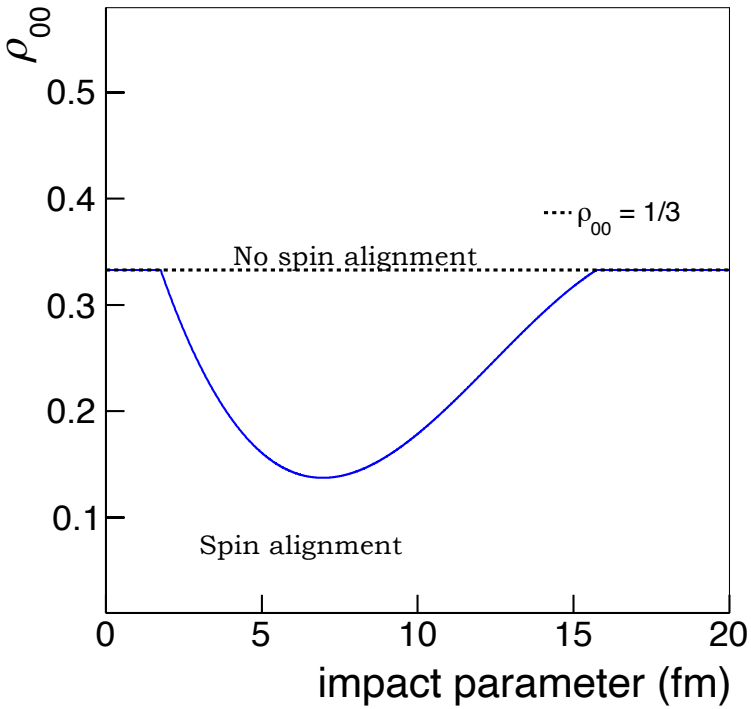
Measurement of the spin density matrix for the rho0, K*0 (892) and phi produced in Z0 decays **DELPHI** Collaboration (P. Abreu et al.).Phys.Lett. B406 (1997) 271-286

Our measurements are in heavy-ion collisions to probe spin-orbital angular momentum interactions in QCD matter

Qualitative theory expectation

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





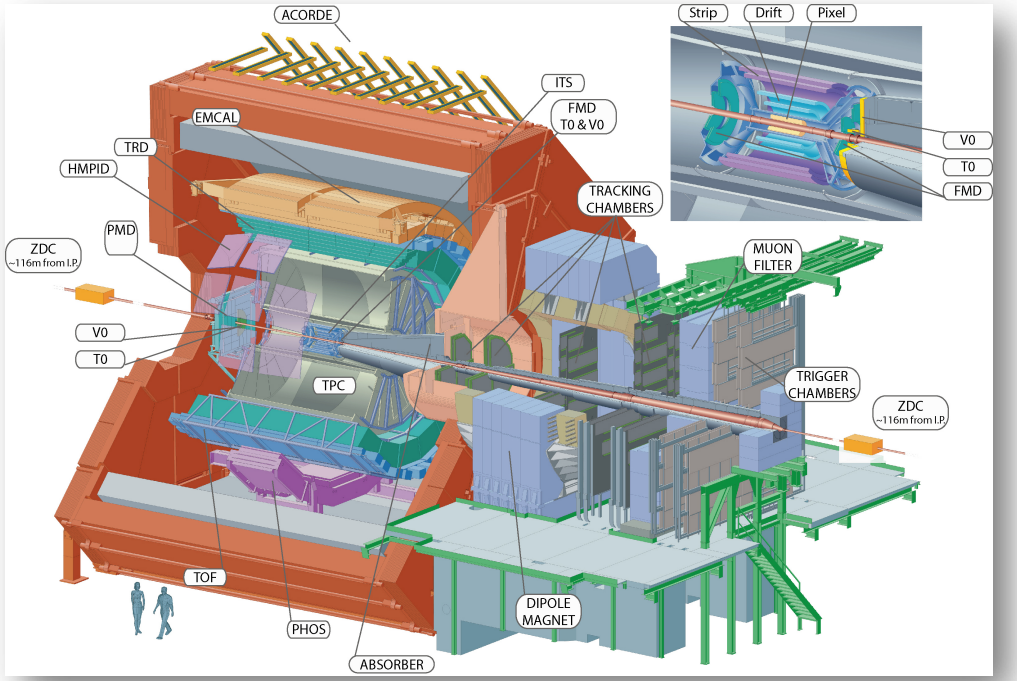
- Low p_T phenomena – Hadronization via recombination
- Small spin alignment for central.and peripheral collisions
- Maximum effect for mid-central (intermediate impact parameter) collisions
- Effect larger for K* than ϕ mesons (factor 10 lifetime difference, re-scattering effect, heavier mass of strange 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	$\rho_{00}(\text{rec}) < 1/3$ $\sim \frac{1-P_q P_q}{3+P_q P_q}$ $\rho_{00}(\text{frag}) > 1/3$ $\sim \frac{1+\beta P_q P_q}{3-\beta P_q P_q}$	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., arXiv:1910.13684*

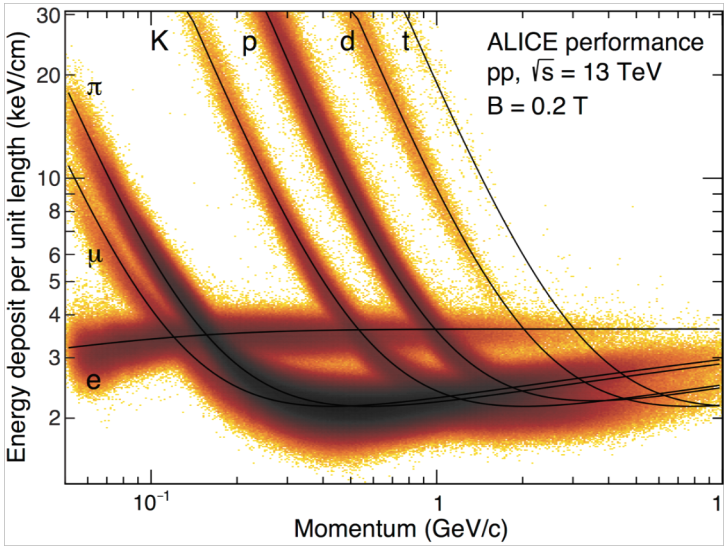
ALICE detector

ALICE @ LHC

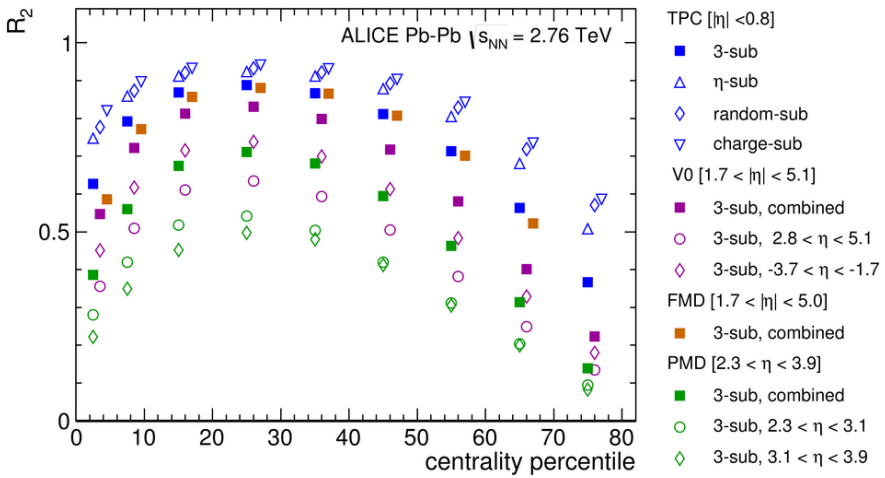


PID @ ALICE

PDG, 2018



EP @ ALICE



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

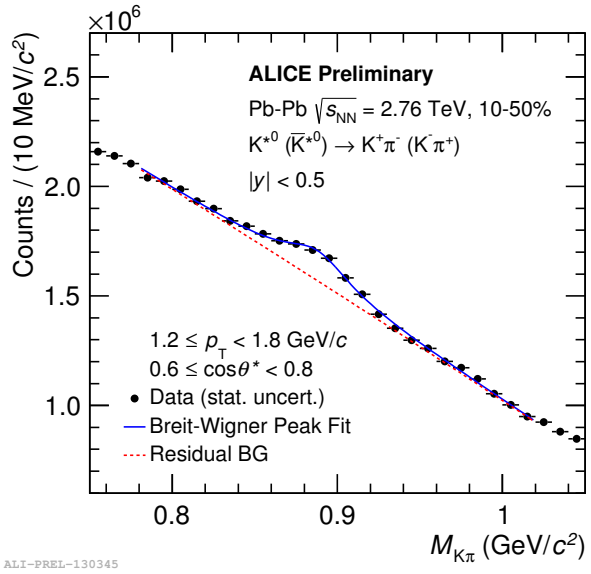
Particle identification: TPC + TOF
Momentum measurement TPC+ITS
Event plane angle measurement: V0

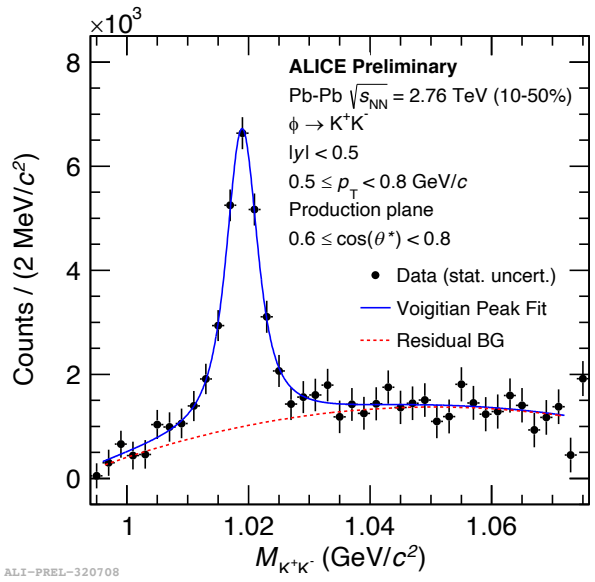
ALICE data set

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 $\rho_{00} - \frac{1}{3} = \frac{4}{1+3R}(\rho_{00}^{\mathrm{obs}} - \frac{1}{3})$ *A.H. Tang et al., Phys Rev C 98 (2018) 044907*

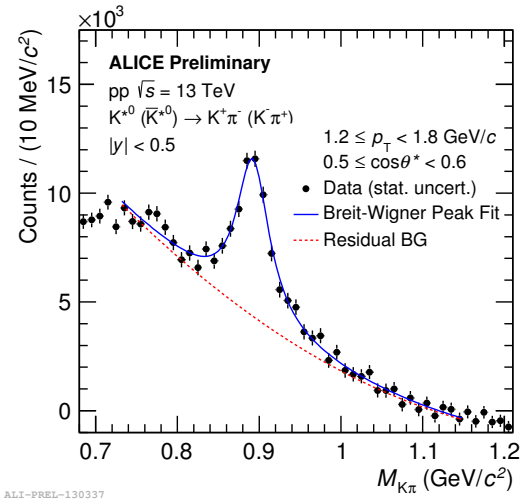
K^{*0} and ϕ vector meson

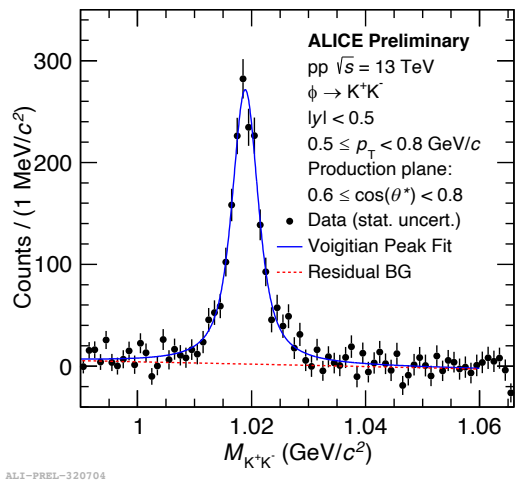
Pb-Pb





pp





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

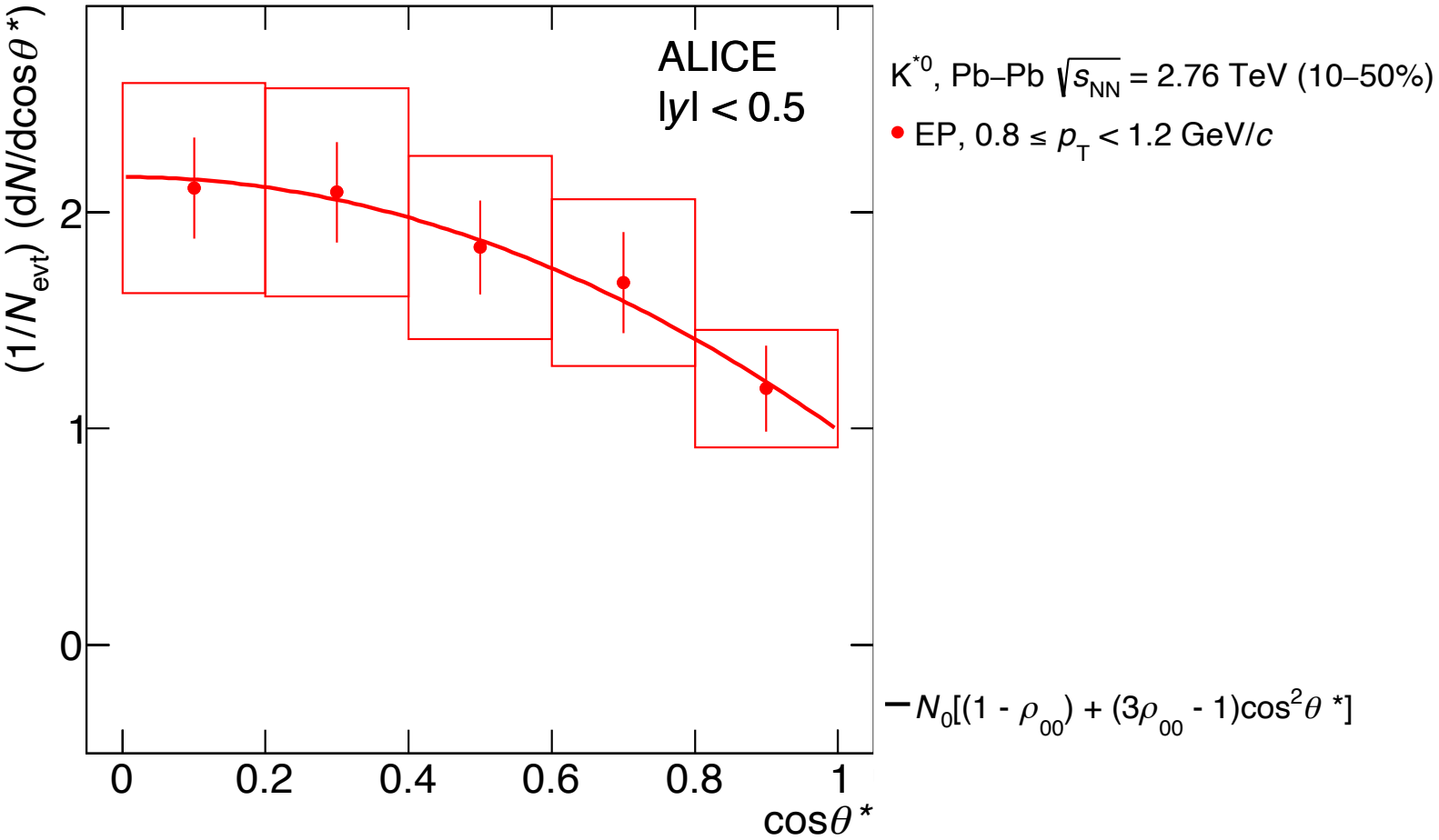
ϕ vector meson
- Mass – 1019 MeV/c^2
- Lifetime – 42 fm/c
- Spin 1
- Decays to K^+ and K^- (B.R – 49%)
- Quark content (s,$\bar{s}$)

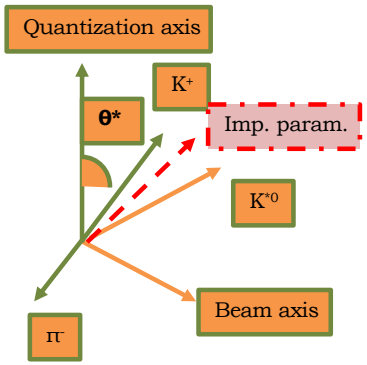
K^{*0}: Breit-Wigner
ϕ: Voigtian

Residual background: Polynomial function

arXiv:1910.14408 (ALICE)

Angular distribution of vector mesons





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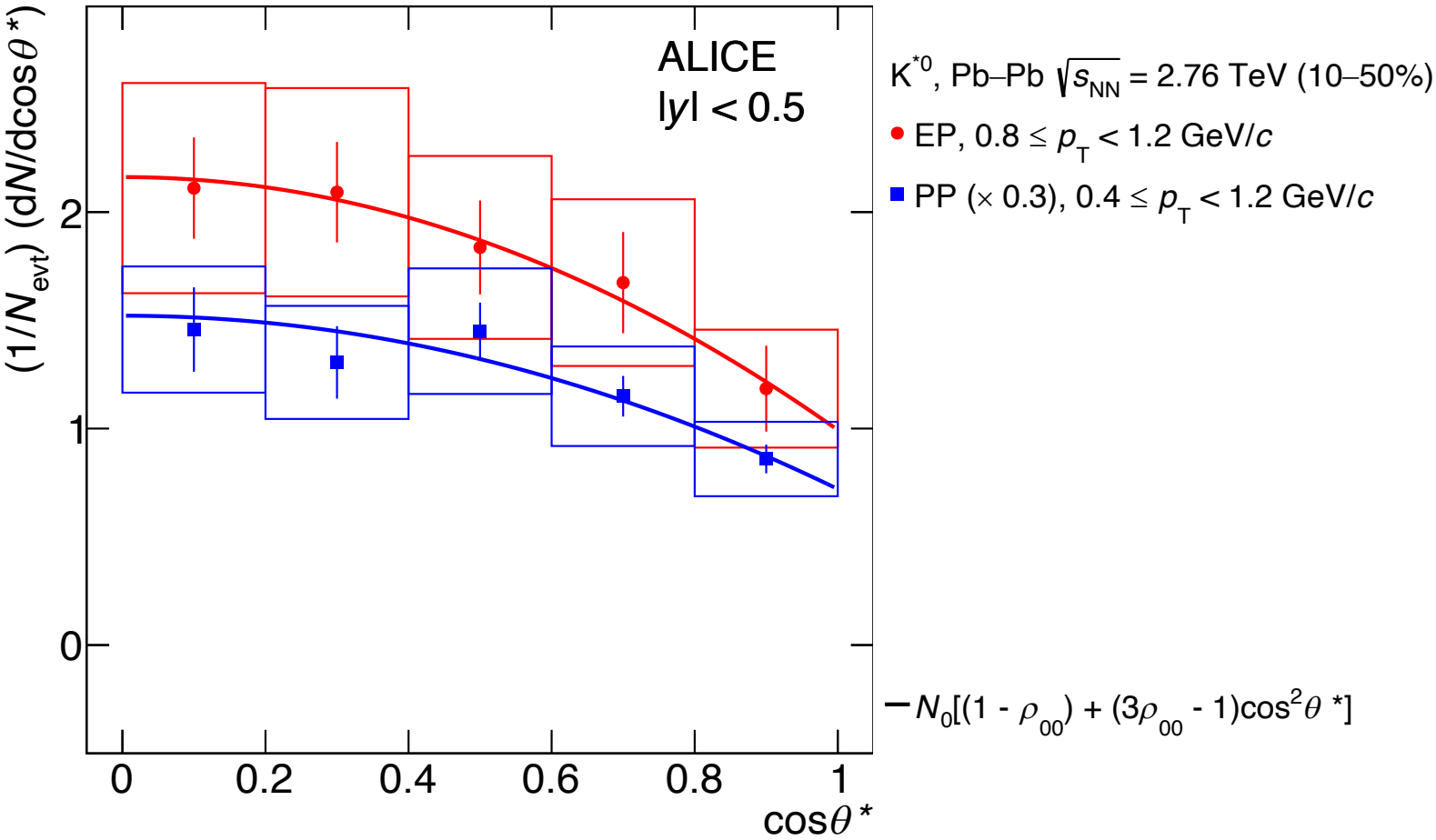

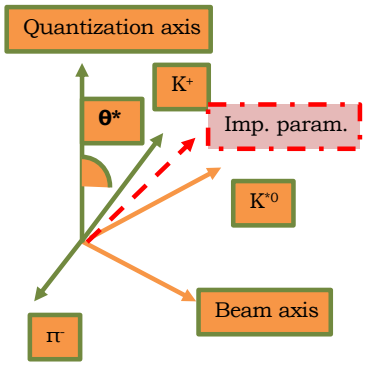

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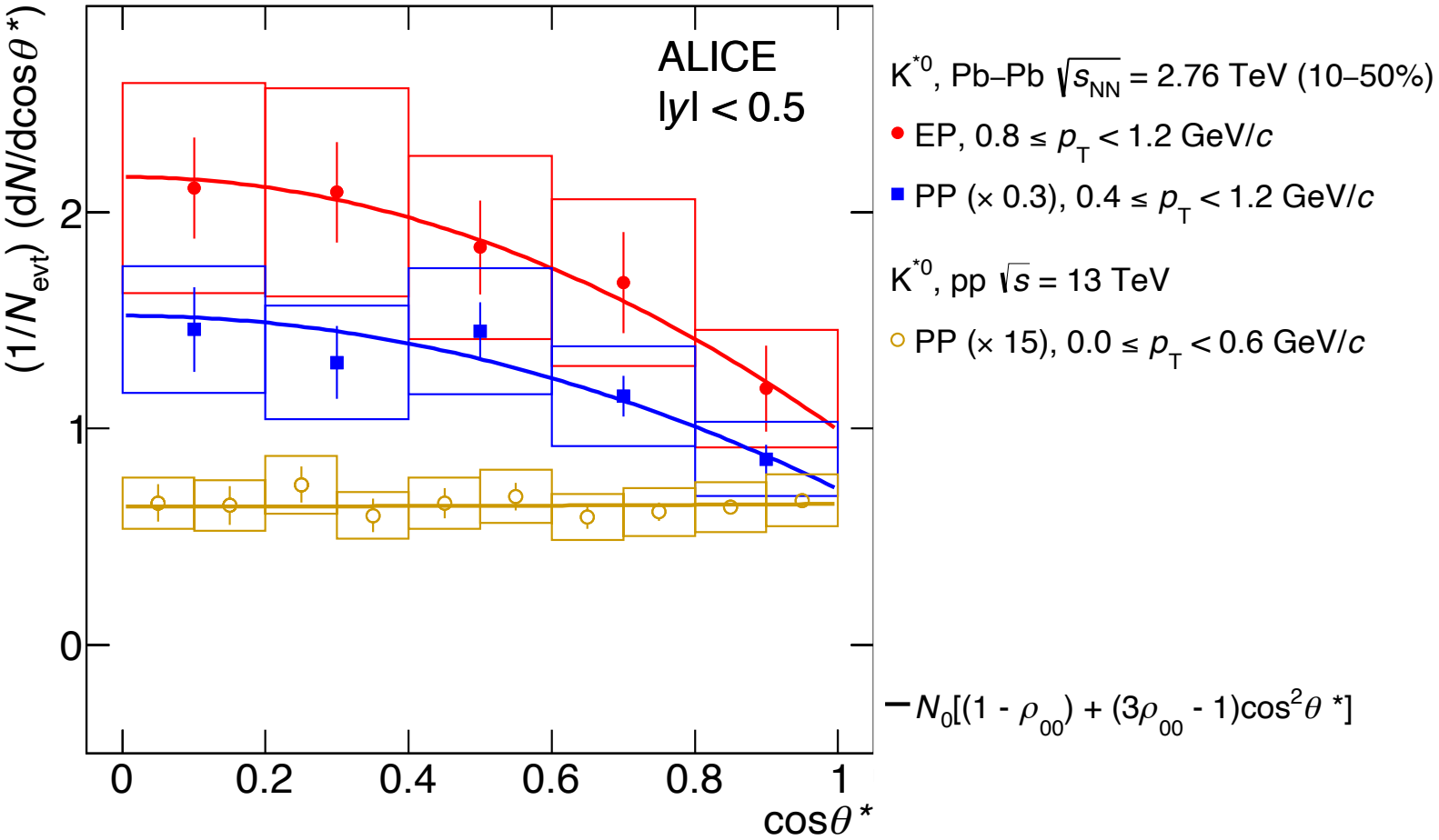

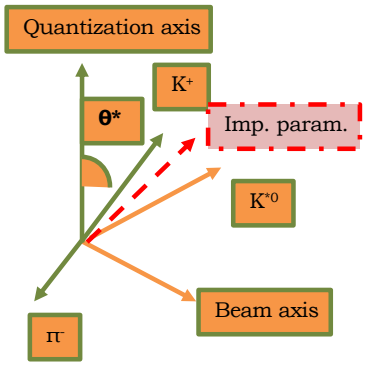

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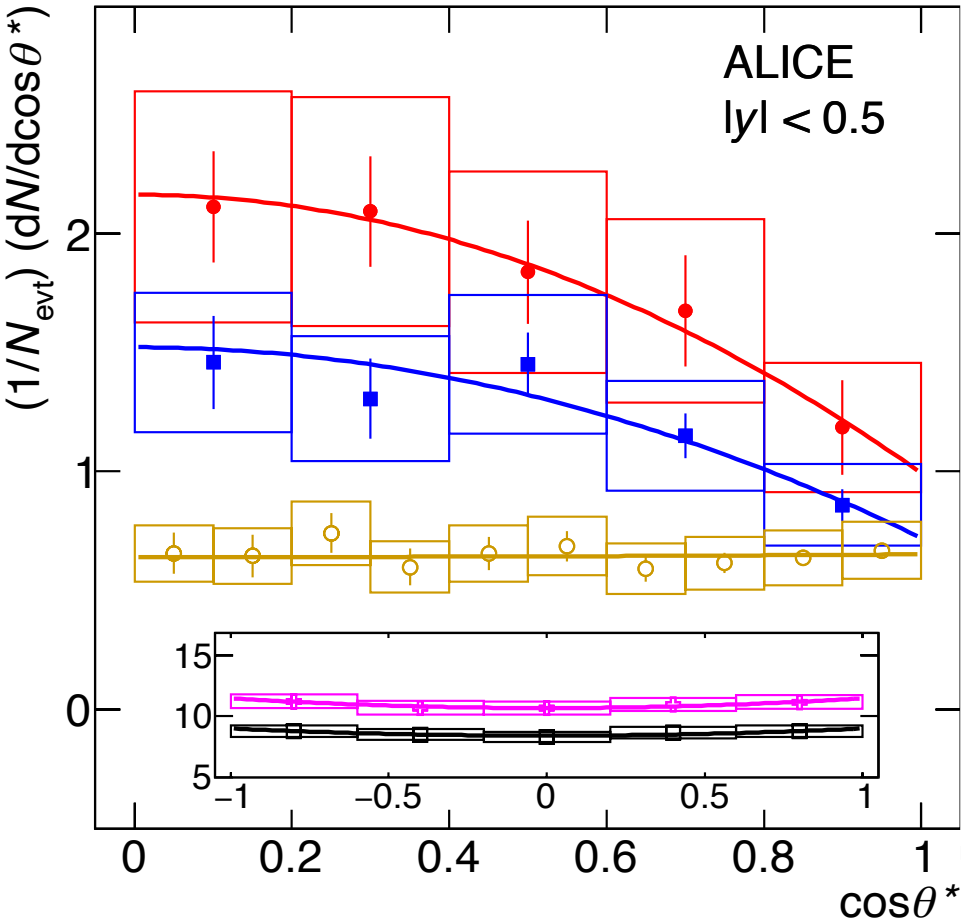


K^{*0}, Pb–Pb $\sqrt{s_{NN}}$ = 2.76 TeV (10–50%)

- EP, $0.8 \le p_T < 1.2$ GeV/c
- PP (× 0.3), $0.4 \le p_T < 1.2$ GeV/c

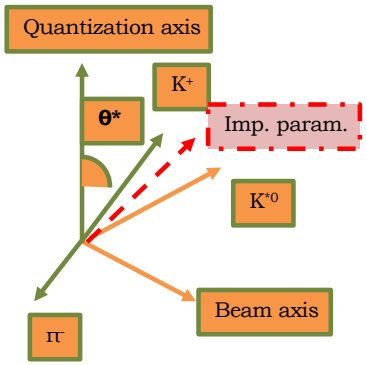
K^{*0}, pp $\sqrt{s}$ = 13 TeV

- 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

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



ALI-DER-342820

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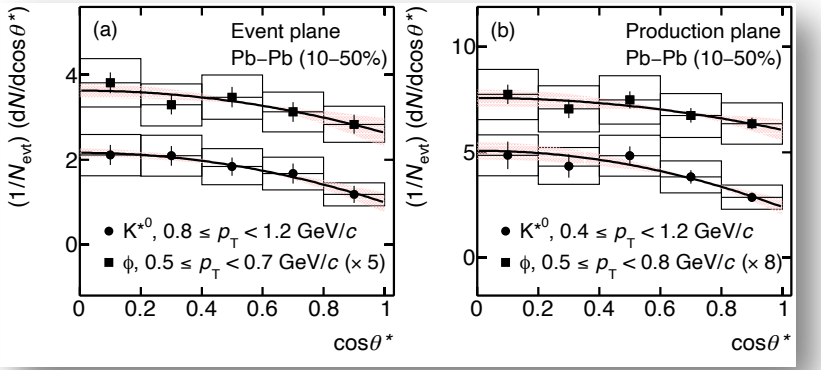
Systematics uncertainties and checks

On ρ_{00}

Source	K^{*0} Low p_T	K^{*0} High p_T	ϕ Low p_T	ϕ 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

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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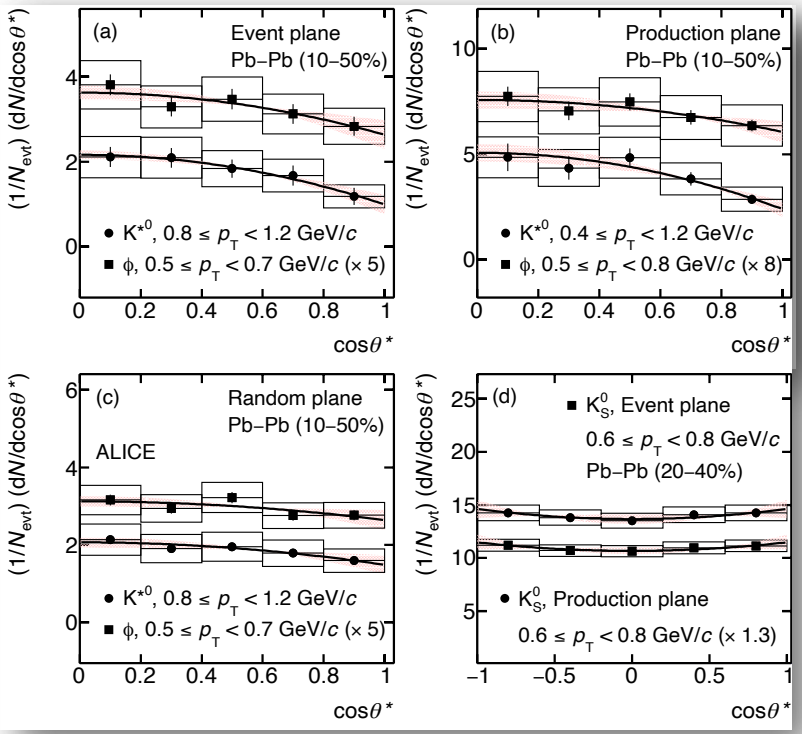
Angular distribution of vector mesons



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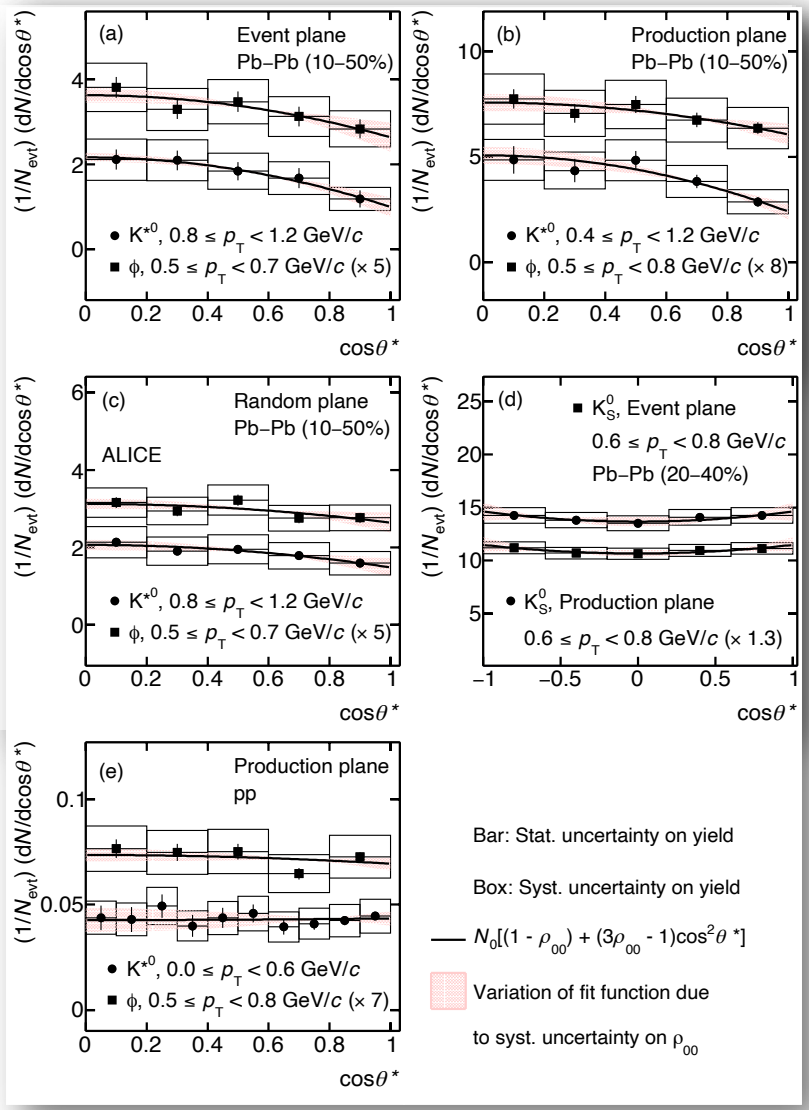

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Spin alignment of vector mesons: p_T dependence

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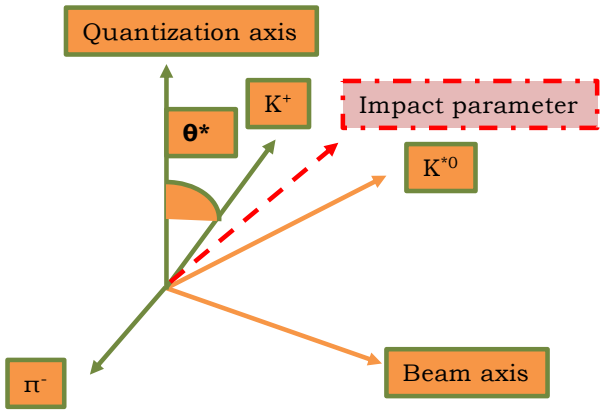

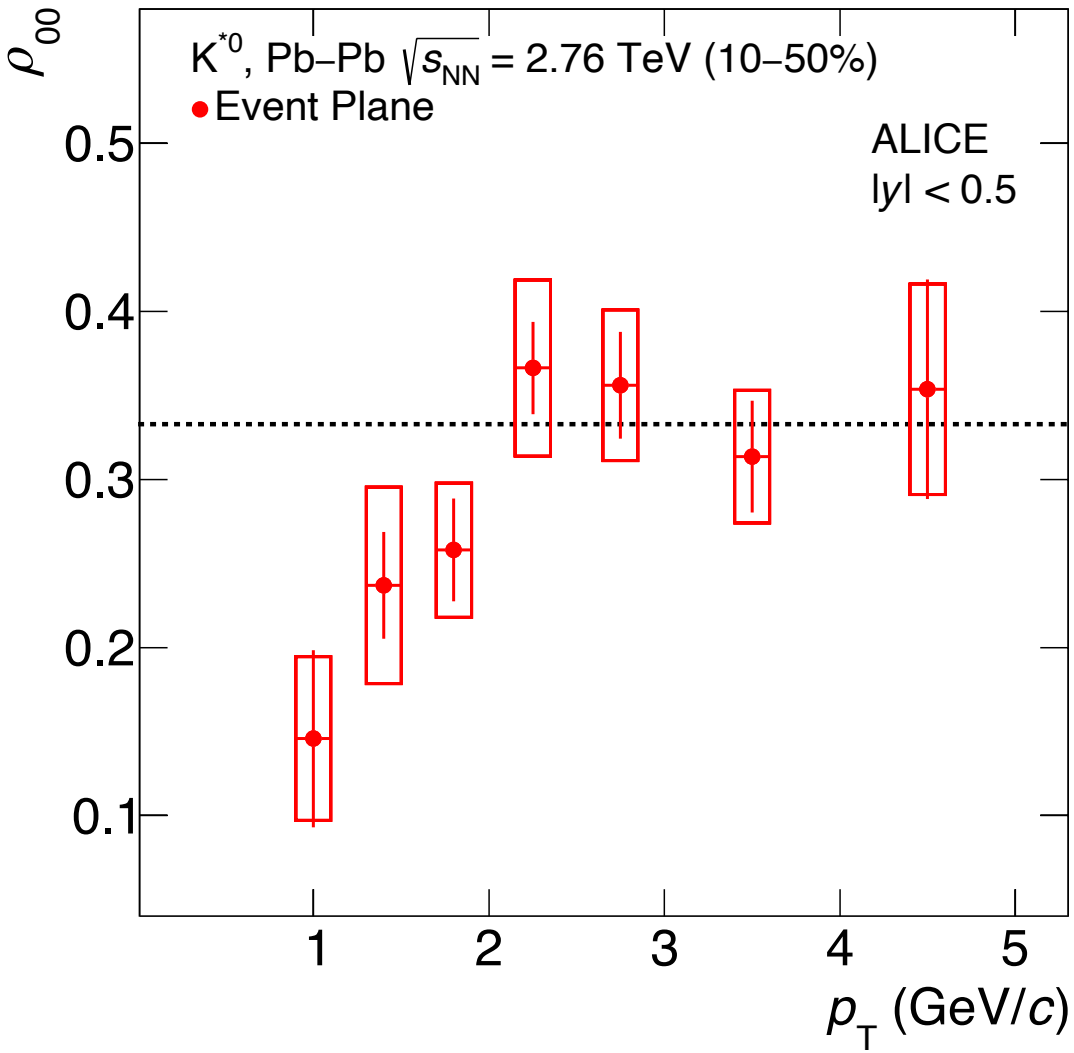

No spin alignment

Spin alignment of vector mesons: p_T dependence

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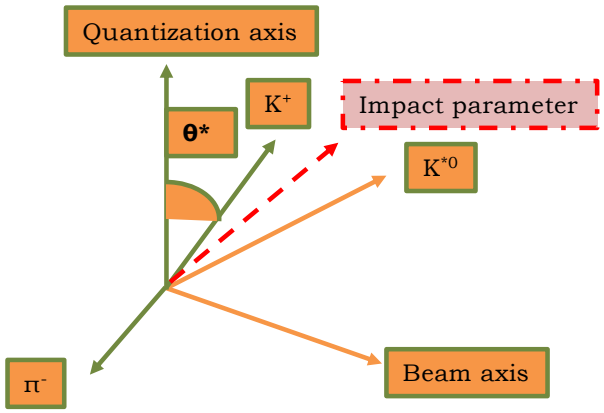

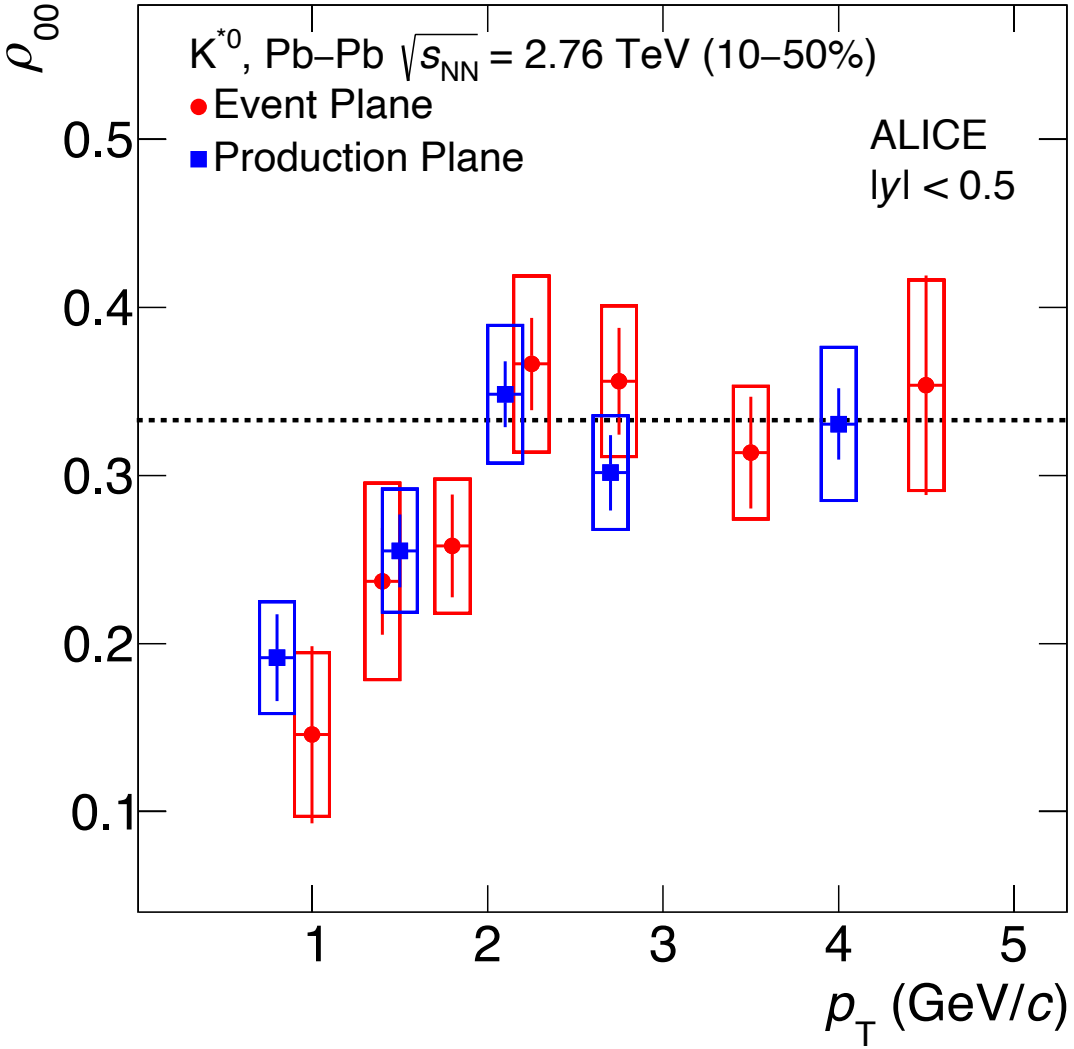

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Spin alignment of vector mesons: p_T dependence

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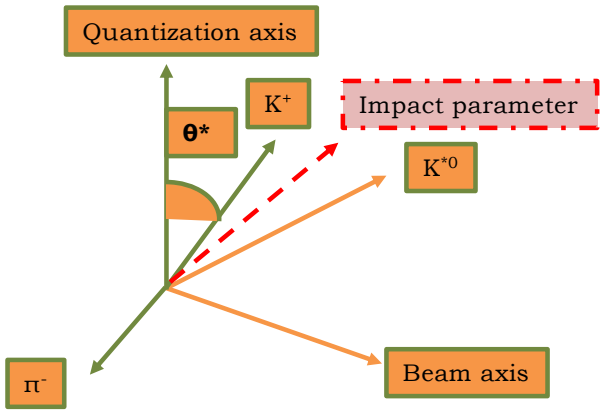

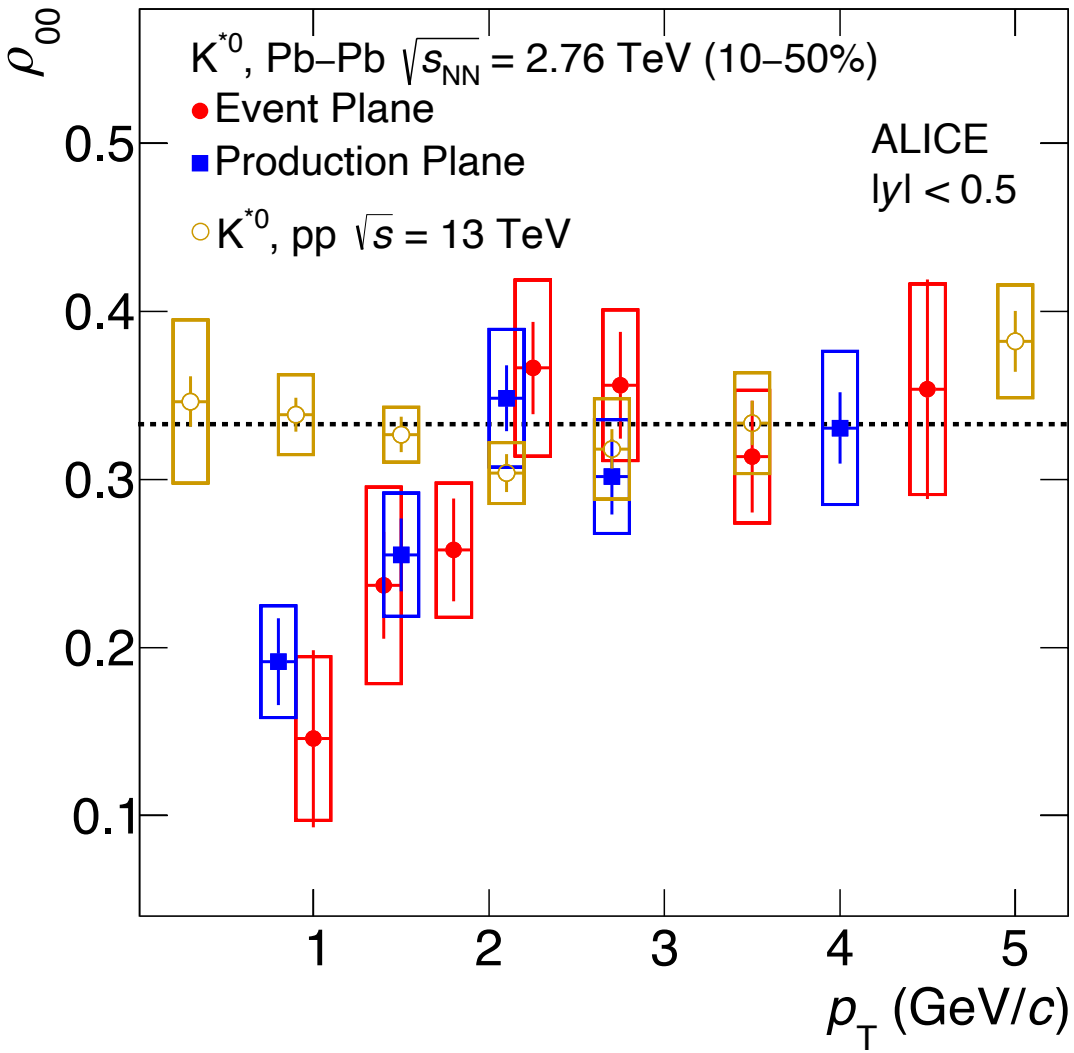

No spin alignment

Spin alignment of vector mesons: p_T dependence

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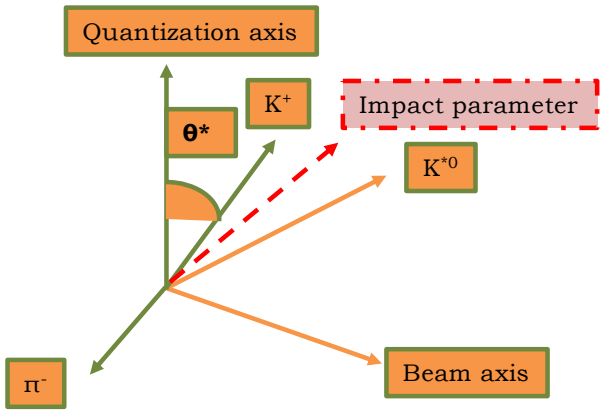
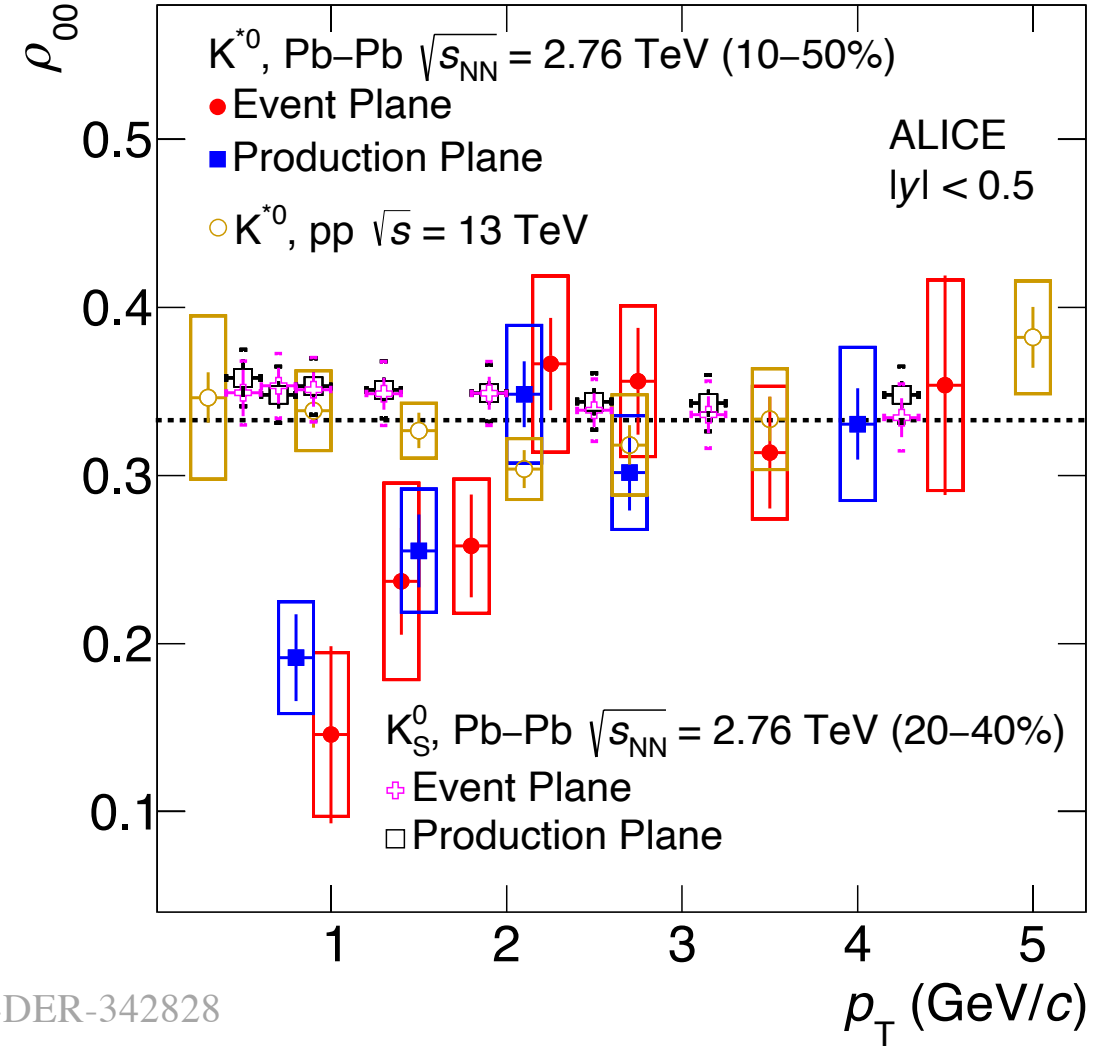
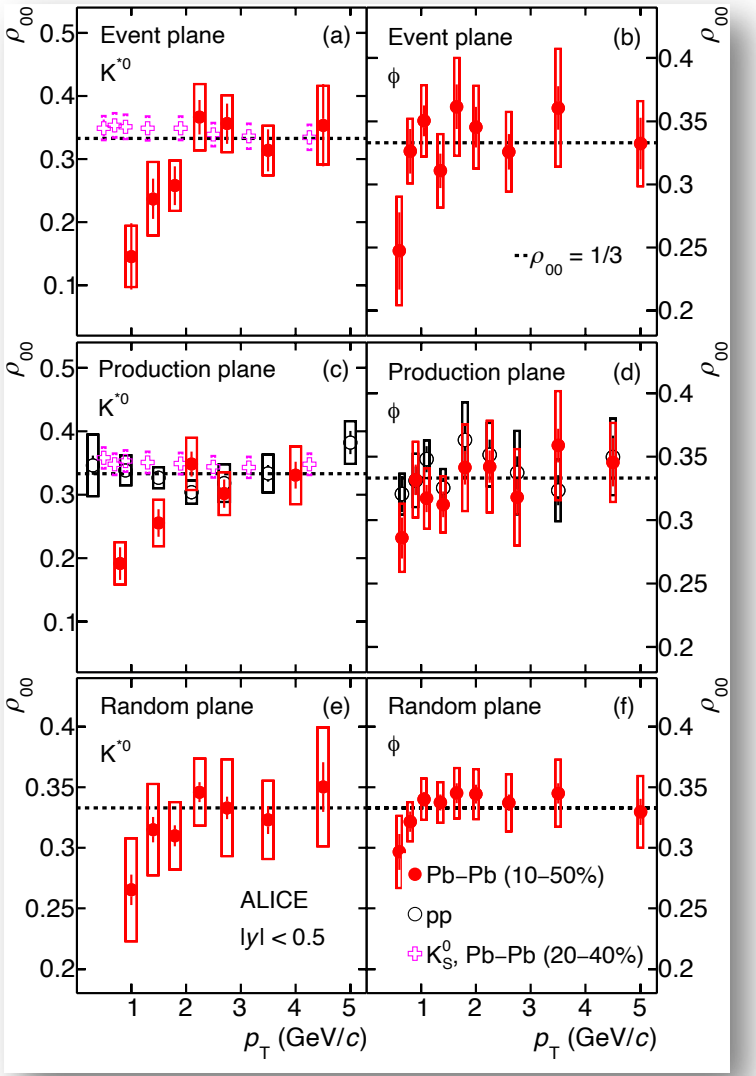




No spin alignment

ALI-DER-342828

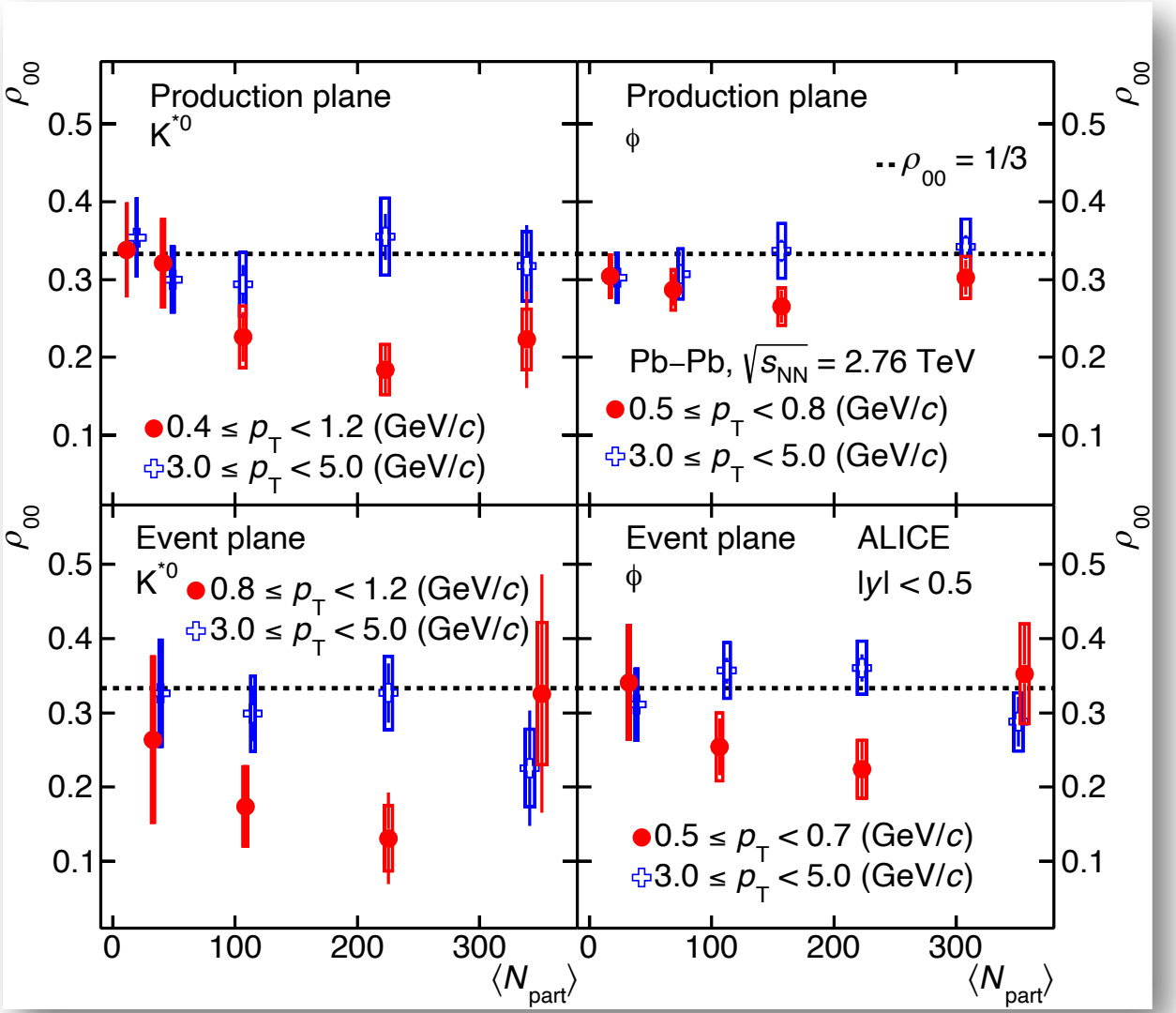
Spin alignment of vector mesons



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

arXiv:1910.14408 (ALICE)

Spin alignment: centrality dependence



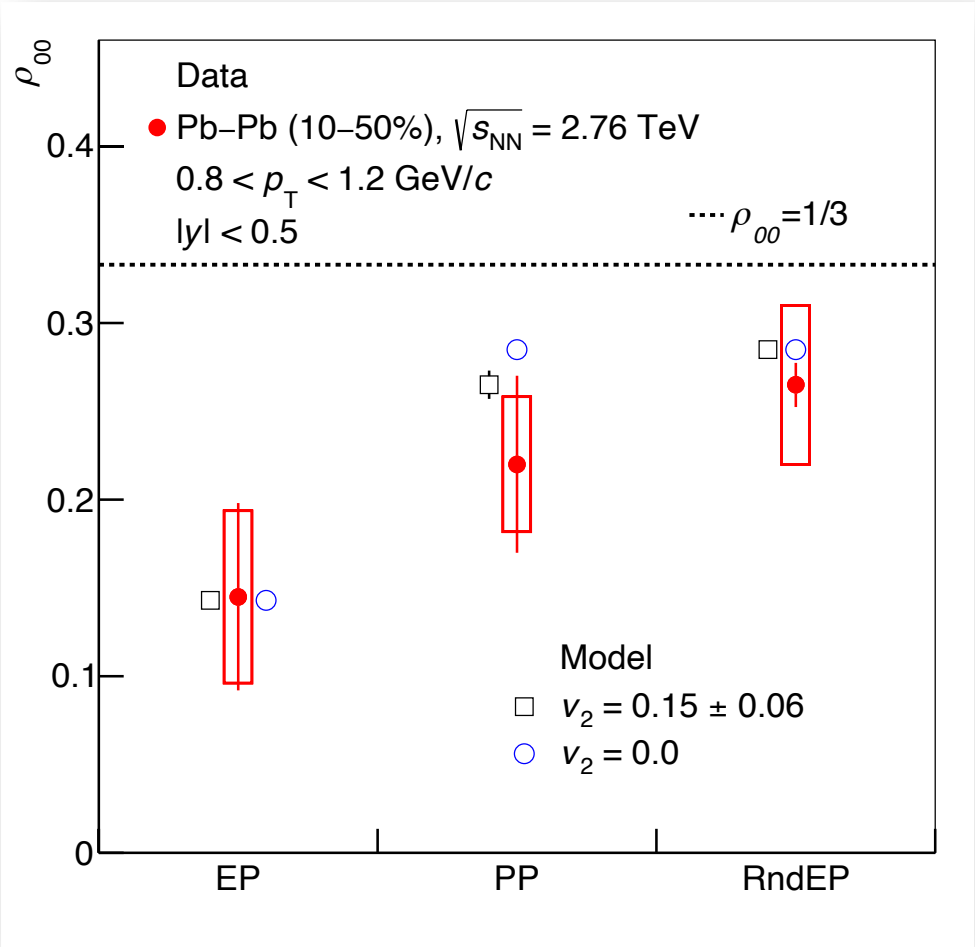
1. Maximum spin alignment observed for mid-central collisions in low p_T (3σ for K^{*0} and 2σ for ϕ)

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

arXiv:1910.14408 (ALICE)

Relation between EP and PP



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

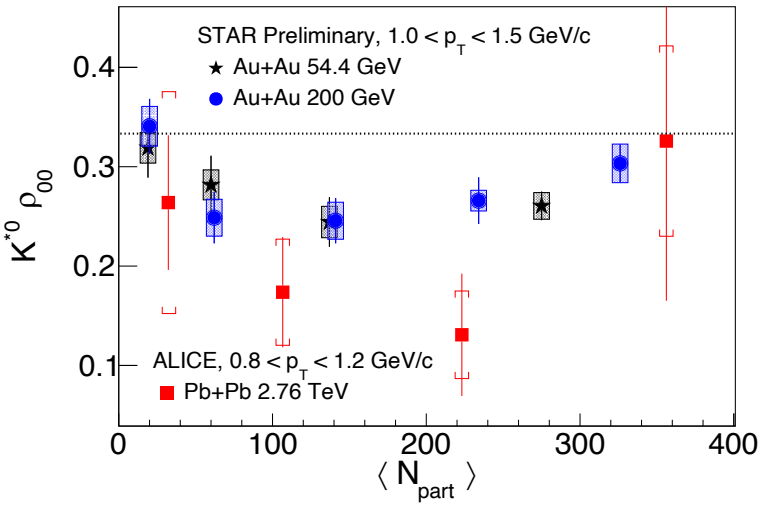
The physical picture is that spin alignment with respect to the event plane is coupled to that in the production plane through the elliptic flow of the system.

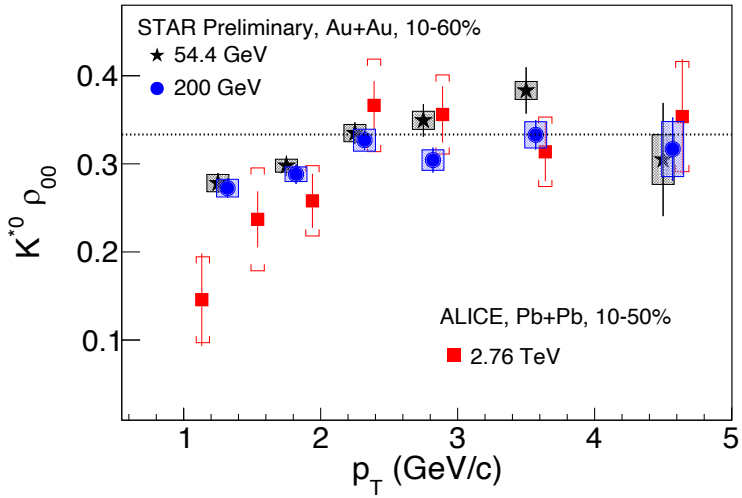
The ρ_{00}(RndEP) is lower than 1/3 as the quantization axis is always perpendicular to the beam axis, resulting in a residual effect.

arXiv:1910.14408 (ALICE)

Theoretical expectation & comparison to RHIC

Centrality dependence

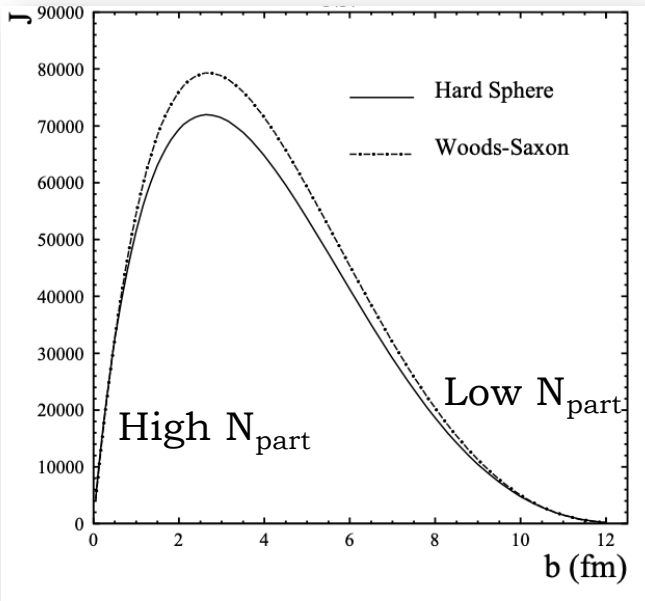




Centrality dependence of angular momentum

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

arXiv:1910.14408 (ALICE)

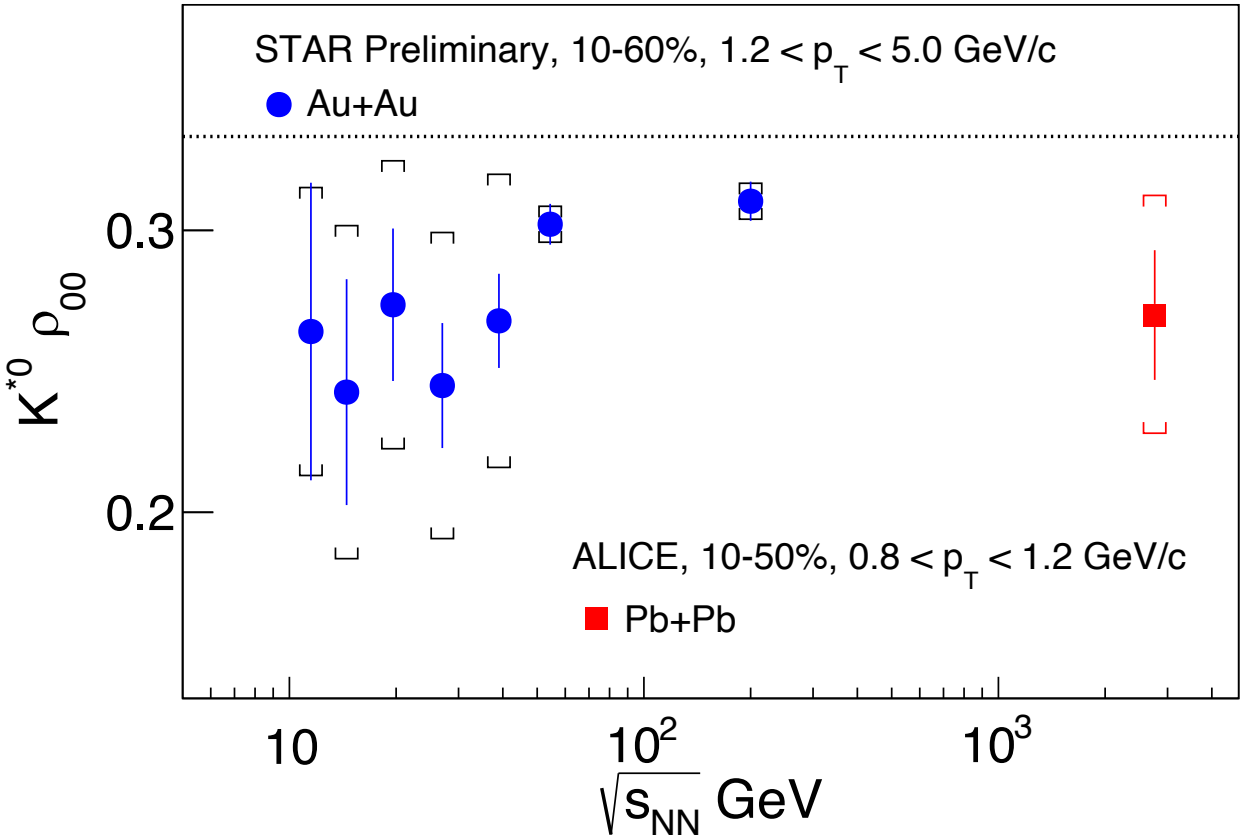


Transverse momentum dependence

Transverse dependence of ρ_{oo} 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

STAR: S. Singha, QM2019

Collision energy dependence



arXiv:1910.14408 (ALICE)

STAR: S. Singha, QM2019

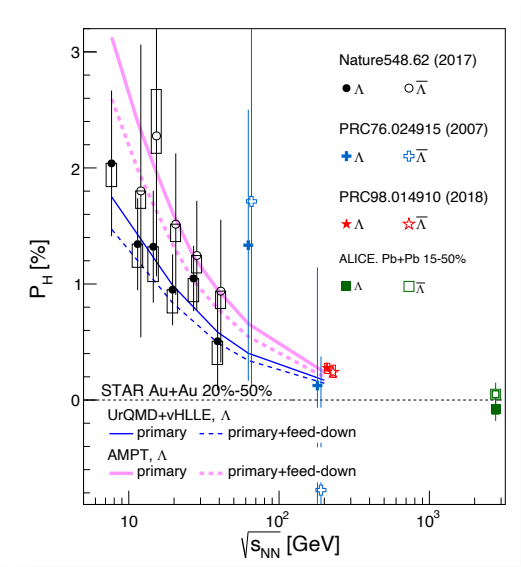
- *Looks like no energy dependence of ρ_{00}.*
- *High statistics data at LHC and RHIC will clarify the picture.*
- *ALICE Pb-Pb analysis at 5.02 TeV under progress.*

Summary so far

- ✓First evidence of spin alignment in vector mesons in high energy **heavy-ion collisions**. Both RHIC and LHC observe the phenomenon.
- ✓ Measurement **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

Surprises

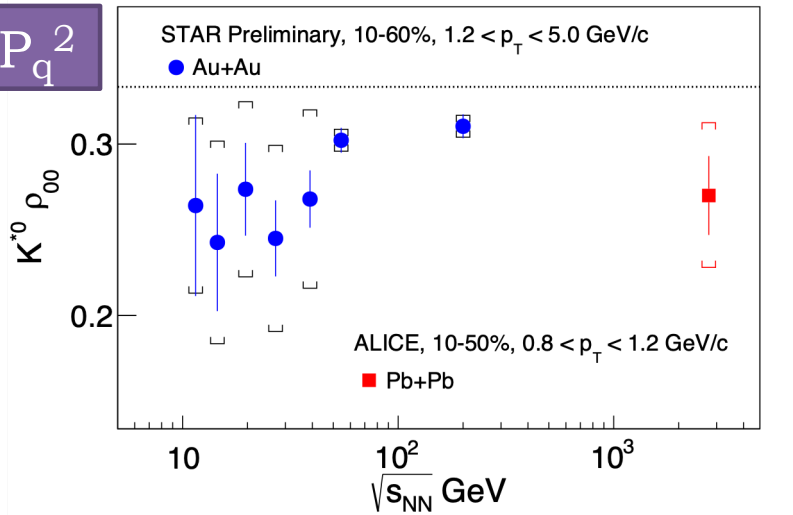
1.



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

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

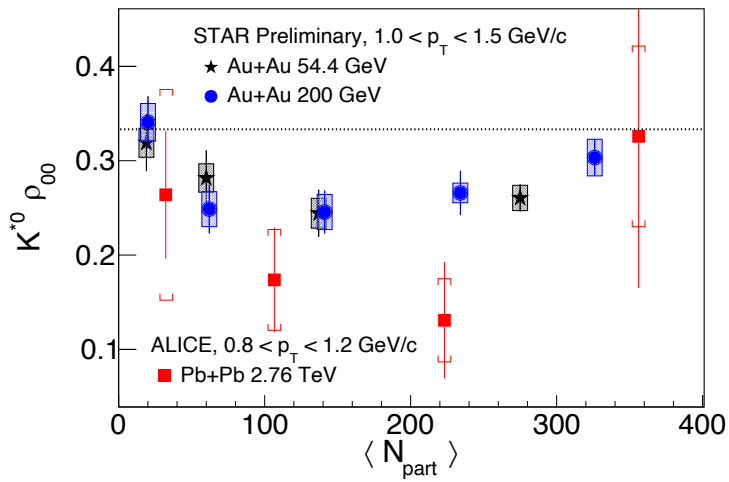
ρ_{00} **no energy dependence ?**



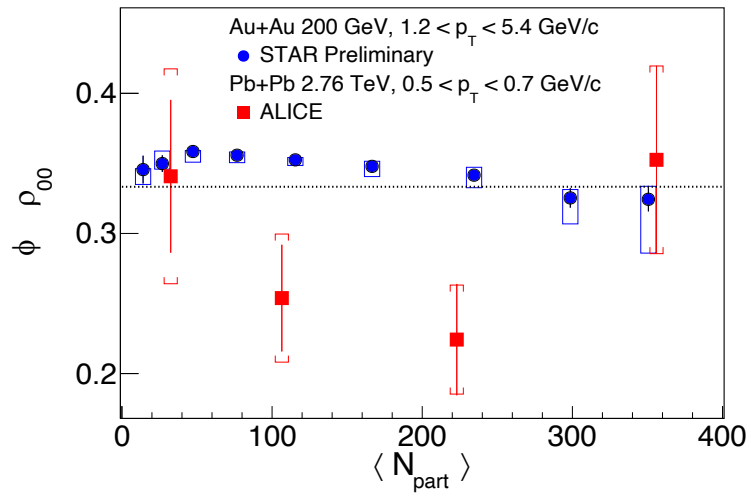
STAR: S. Singha, QM2019

arXiv:1910.14408 (ALICE)

2.

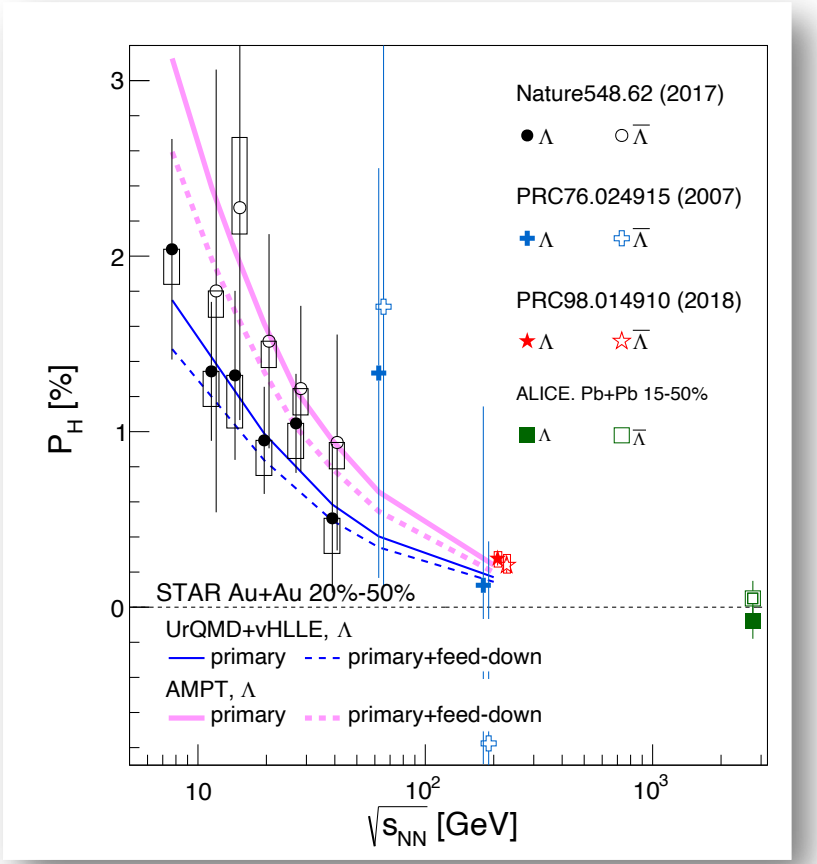


K^{*0} versus ϕ meson at RHIC and LHC



Polarization

Model	Polarization
Angular momentum polarizes the quark, they coalesce to form vector mesons $\rho_{00}(\text{rec}) \sim \frac{1-P_q P_q}{3+P_q P_q}$ *Z. Liang et. al., Phys. Lett. B 629 (2005) 20*	Quark polarization $P_s = 0.25$ +/- 0.07 $P_d = 0.80$ +/- 0.57
Thermal approach and non-relativistic limit $\rho_{00}(\omega) \sim \frac{1}{3} - [(\omega/T)^2]\frac{1}{9}$ $P_V \sim \frac{2}{3}\left(\frac{\omega}{T}\right)$ *F. Becattini et al., Phys. Rev. C 95, 054902 (2017)*	Vector meson polarization $P_{K^*} = 0.61$ +/- 0.17 $P_\phi = 0.28$ +/- 0.11



Estimates based on simple models with assumptions

Outlook

A. Theoretical Side:

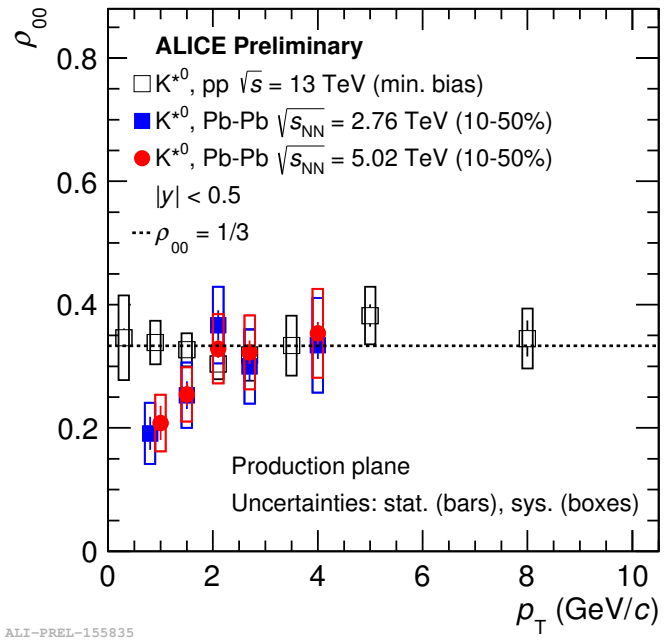
- The experimental measurements → challenges to theory

1. Explain Lambda and vector mesons results simultaneously
2. Explain the difference in ρ_{00} values of K* (< 1/3) and ϕ (> 1/3 at RHIC and < 1/3 at LHC) meson
3. Development of proper relativistic spin hydrodynamics
4. Models with conservation of angular momentum, fraction of initial angular momentum transferred to QCD matter, how to convert L or ω of fluid → spin of particles

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

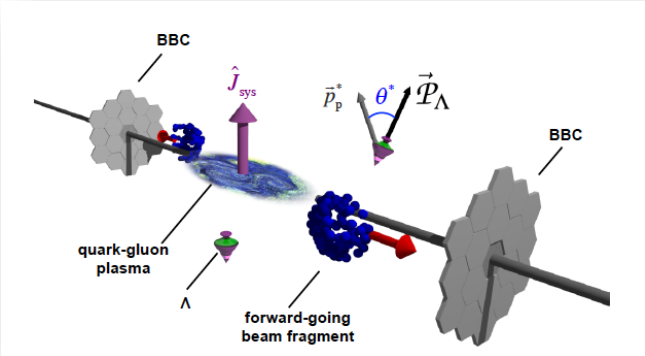


Pb-Pb 5.02 TeV - 2015

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

BACK UP

Λ polarization - RHIC

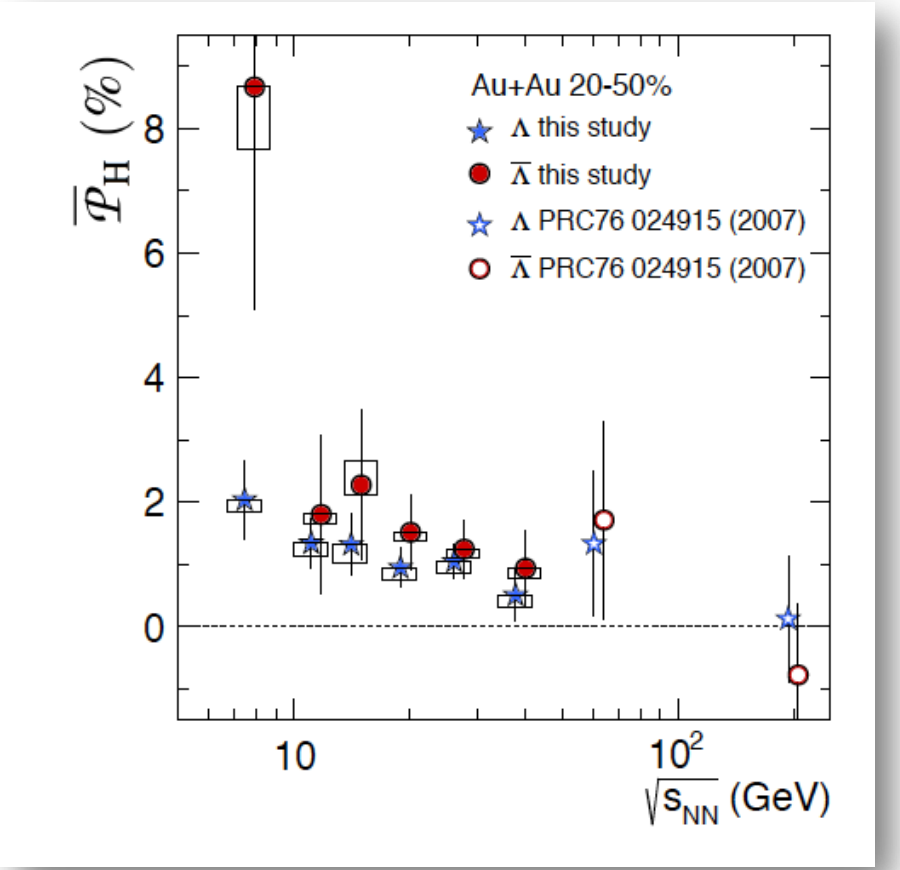


$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_H |\vec{\mathcal{P}}_H| \cos\theta^*\right)$$

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

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

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



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

STAR RESULTS