

# Global polarization of hyperons and spin alignment of vector mesons with ALICE at the LHC

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## Outline:

- ❖ Physics Motivation
- ❖ ALICE detector setup
- ❖ Results
  - Global polarization of  $\Lambda$ -hyperon
  - Spin alignment of  $K^{*0}$  vector meson
- ❖ Summary

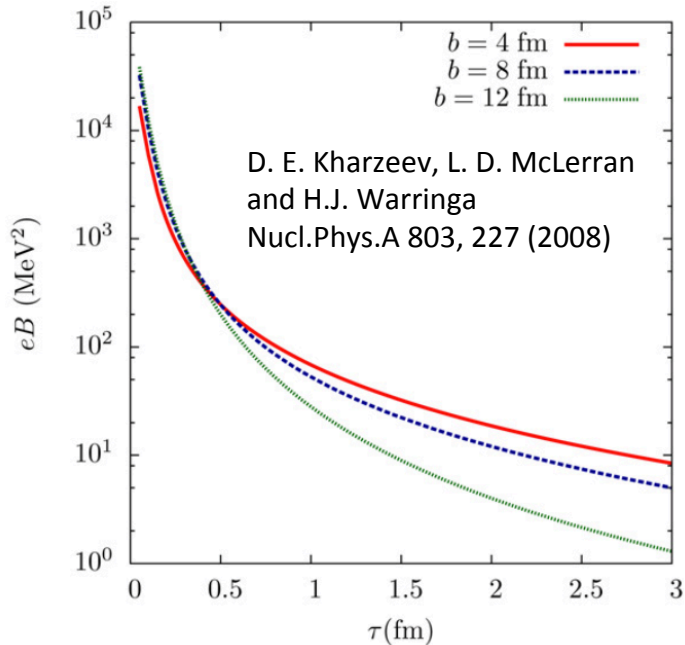
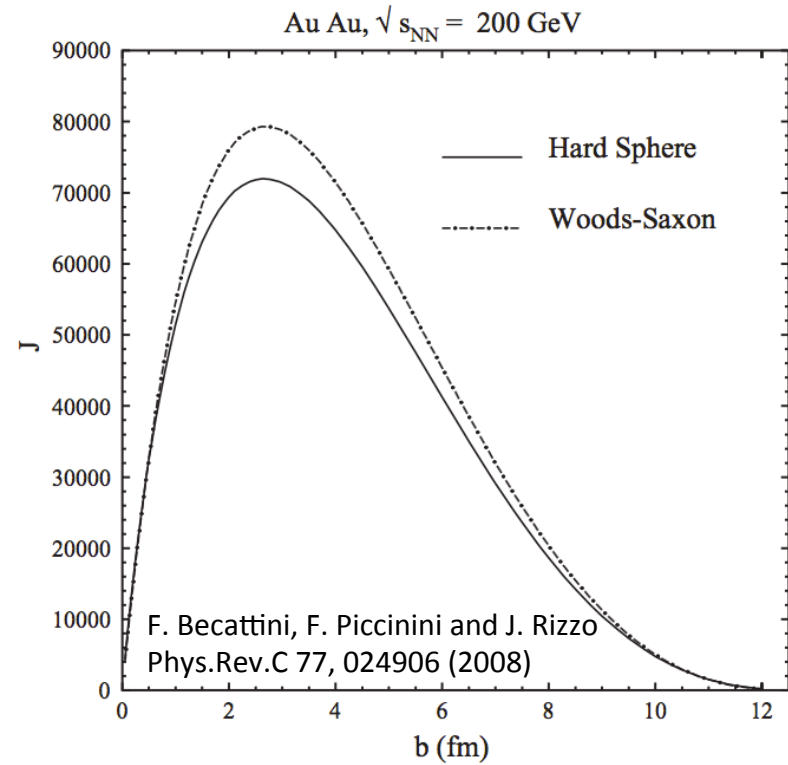
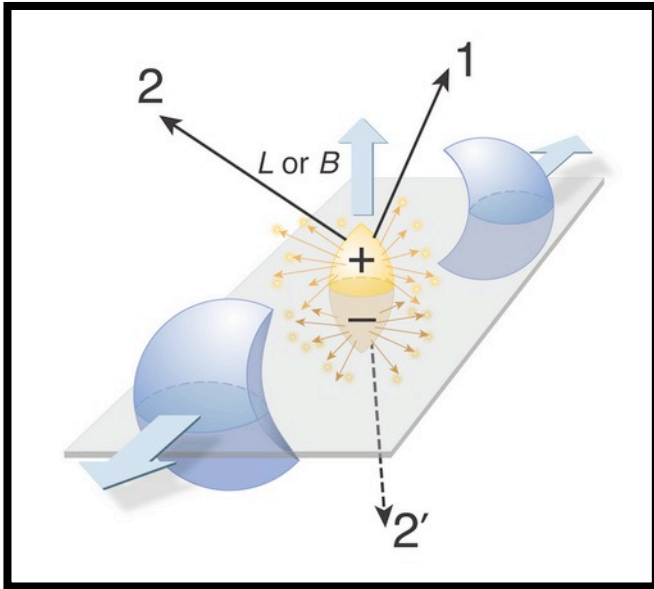


**The 5th Workshop on Chirality, Vorticity and  
Magnetic Field in Heavy Ion Collisions**

Tsinghua University, Beijing, China, April 8 – 12, 2019



# Motivation - I



Large angular momentum and magnetic field is expected to be produced in non-central heavy-ion collisions

Goal: Look for signature of these in measurements

$$M_{\pi}^2 \sim 2 \times 10^4 \text{ MeV}^2 \sim 3 \times 10^{14} \text{ Tesla} \sim 3 \times 10^{18} \text{ Gauss}$$

# Motivation - II

Effects to study:

i) Angular momentum of the heavy-ion collisions system (L)

ii) Vorticity of the fluid created in such collisions

$$\vec{\omega} = \frac{1}{2} \vec{\nabla} \times \vec{v}$$

iii) Strong Magnetic field (B) produced in such collisions

Possible experimental observable:

i) Global polarization of hyperons to probe the vorticity and magnetic field

$$\vec{P}_H \sim \vec{\omega}; \quad \vec{P}_H \sim \mu_H \vec{B}$$

ii) Spin alignment of vector mesons like  $K^{*0}$  and  $\phi$  to see the effect of initial angular momentum

# Angular distribution of vector mesons

$K^{*0}$  Vector meson

- Mass:  $896 \text{ MeV}/c^2$
- Lifetime:  $1.38 \times 10^{-23} \text{ s}$
- Spin: 1
- Decays to  $K^+$  and  $\pi^-$  (B.R.  $\sim 66.6\%$ )
- Quark content ( $d, \bar{s}$ )

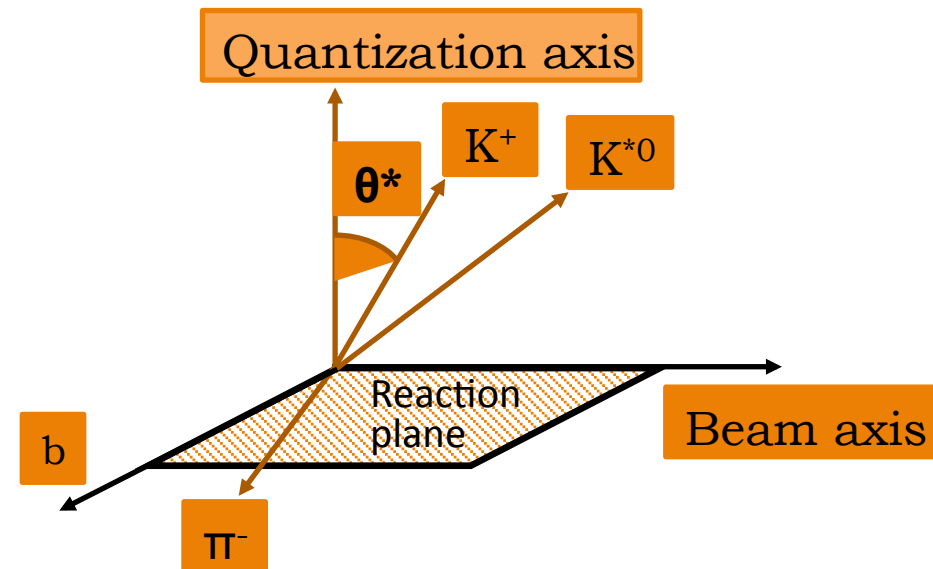
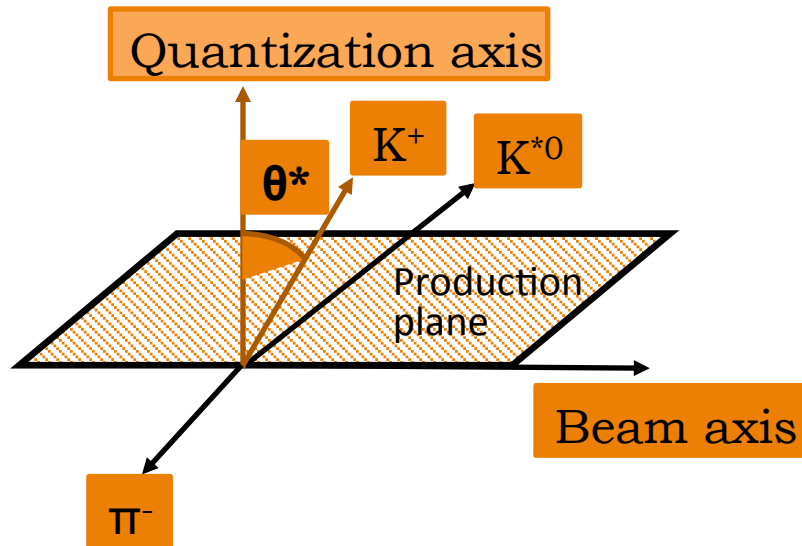
$\rho_{00}$  = Element of spin density matrix  
=  $1/3 \rightarrow$  No spin alignment

Quantization axis

- Normal to production plane
- Normal to reaction plane

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

K. Schilling, P. Seyboth and G. Wolf, Nucl. Phys. B 15, 397 (1970)



# Angular distribution of hyperons

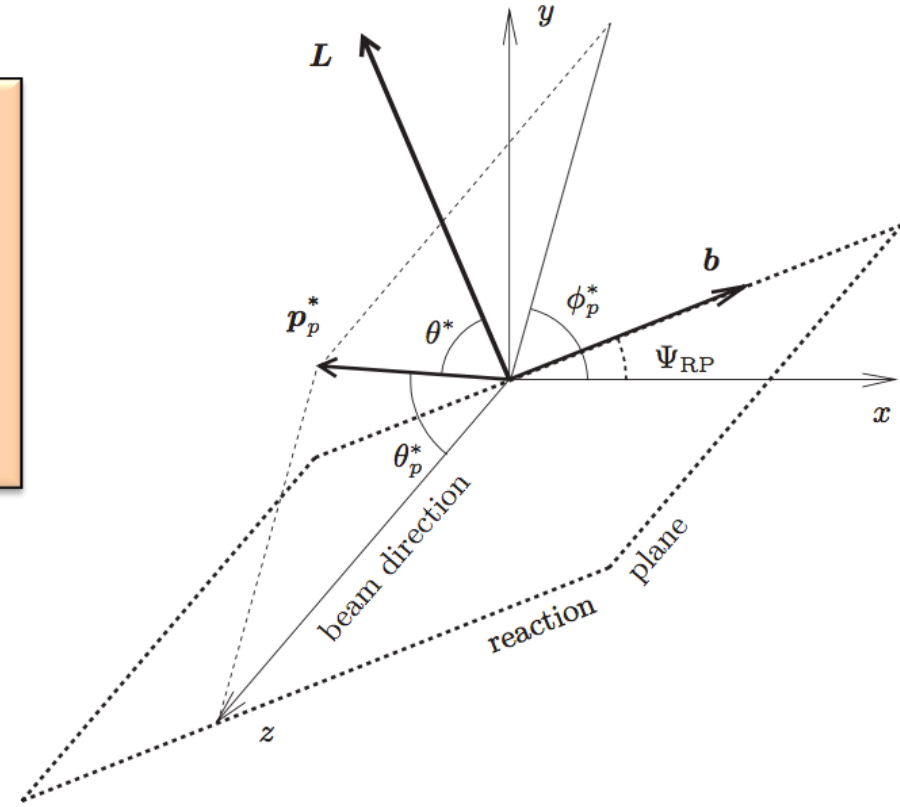
$\Lambda$  Hyperon

- Mass:  $1115 \text{ MeV}/c^2$
- Lifetime:  $2.632 \times 10^{-10} \text{ s}$
- Spin:  $1/2$
- Decays to  $p$  and  $\pi^-$  (B.R.  $\sim 63.9\%$ )
- Quark content (u,d,s)

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

STAR: Phys.Rev.C 76, 024915 (2007)

$|P_H| \rightarrow$  Polarization  
 $= 0 \rightarrow$  No polarization  
 $\alpha_H \rightarrow$  Decay parameter



$L =$  system angular momentum (defined along the normal to the reaction plane)

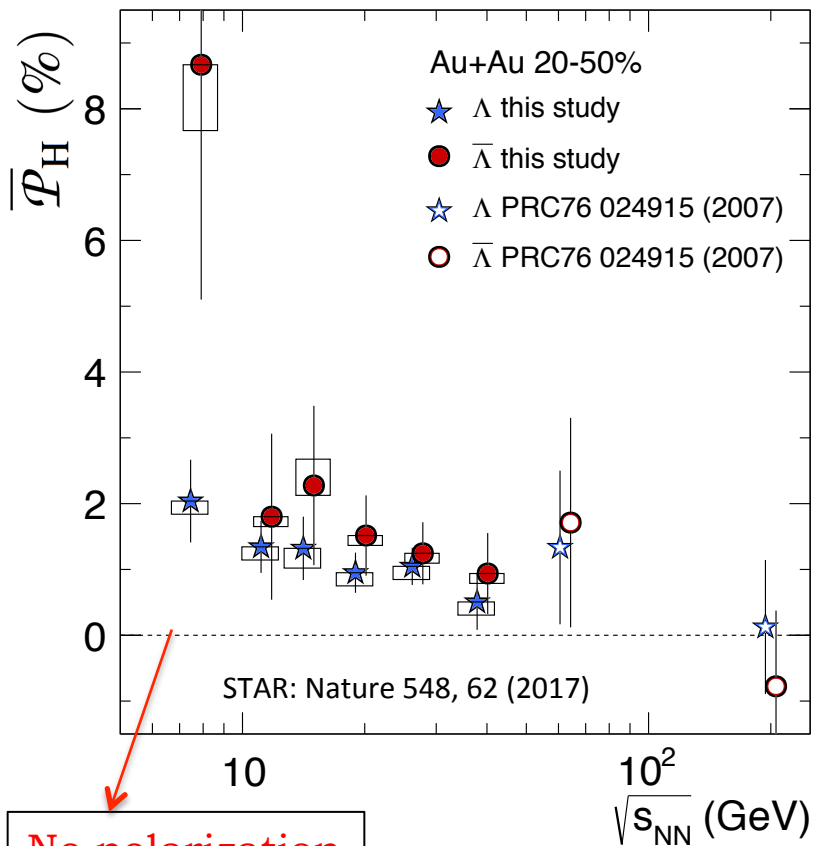
$p_p^* =$  three momentum of  $p(\bar{p})$  in hyperon rest frame

$\theta_p^* =$  polar angle of  $p(\bar{p})$  in hyperon rest frame

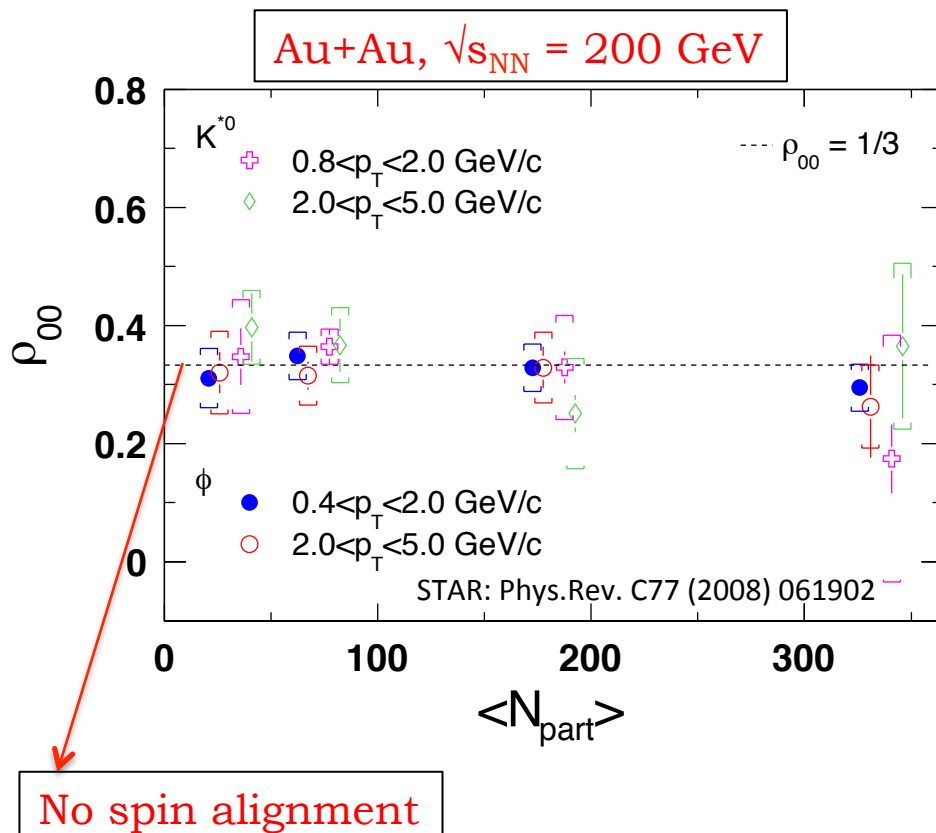
$\phi_p^* =$  azimuthal angle of  $p(\bar{p})$  in hyperon rest frame

# Global polarization and spin alignment results at RHIC

All results from the STAR Experiment



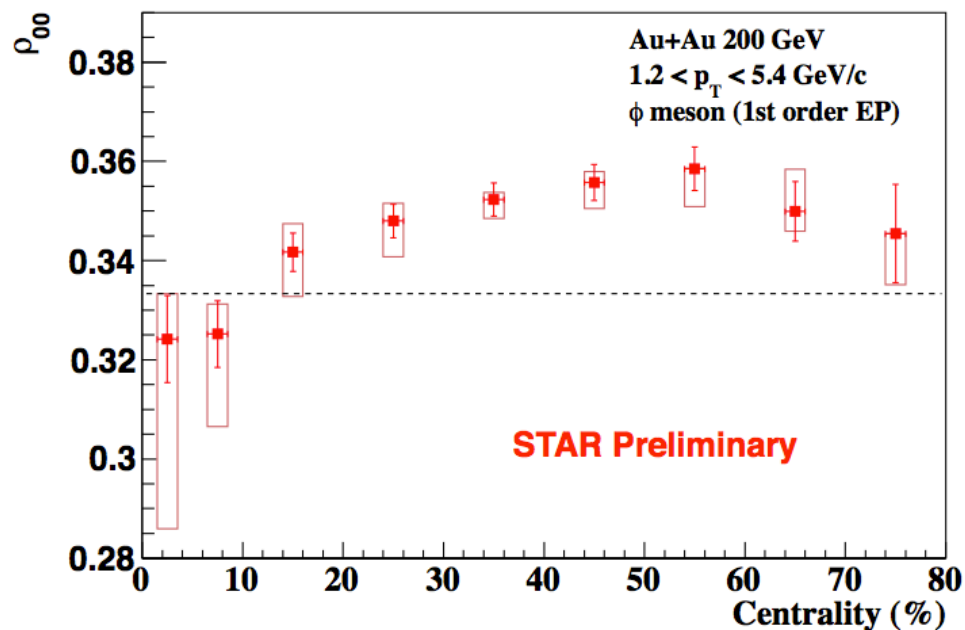
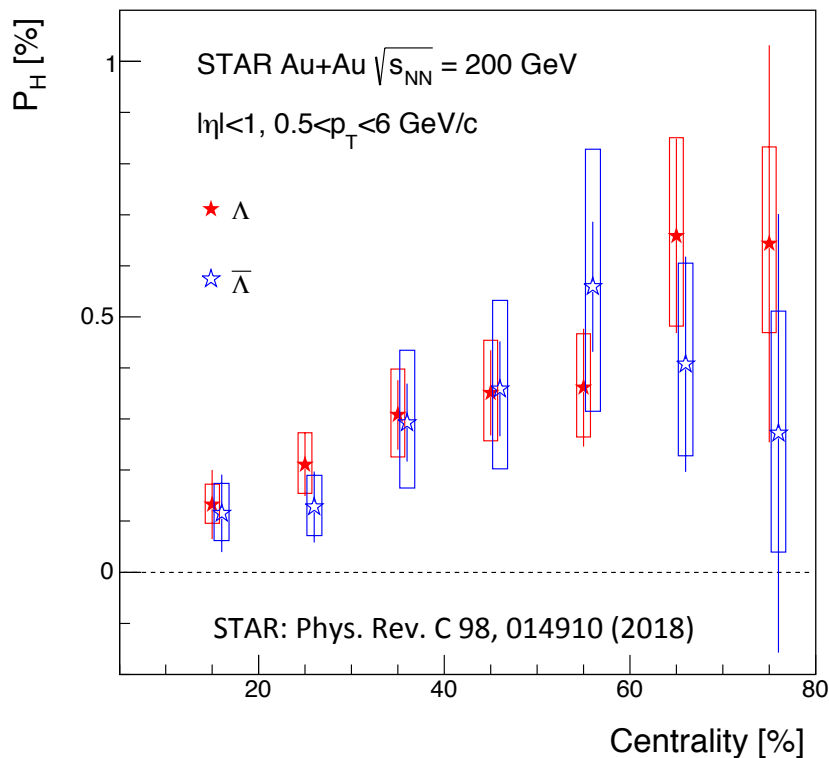
Global  $\Lambda$  hyperon polarization.  
Results w.r.t event plane.



Spin alignment of vector mesons.  
Results w.r.t event plane.

# Global polarization and spin alignment results at RHIC

All results from the STAR Experiment



STAR: QM2018 Proc. Nucl. Phys. A 982, 559 (2019)

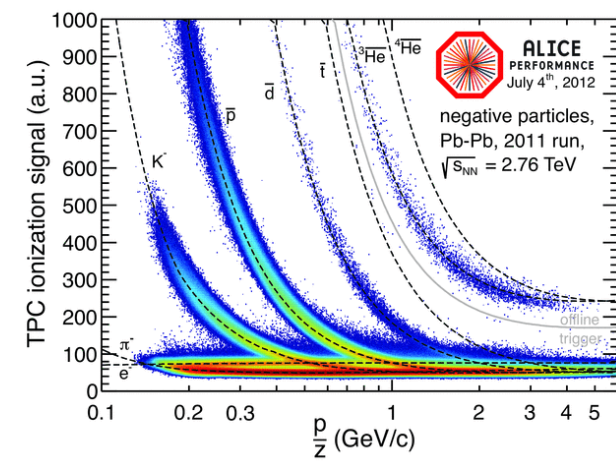
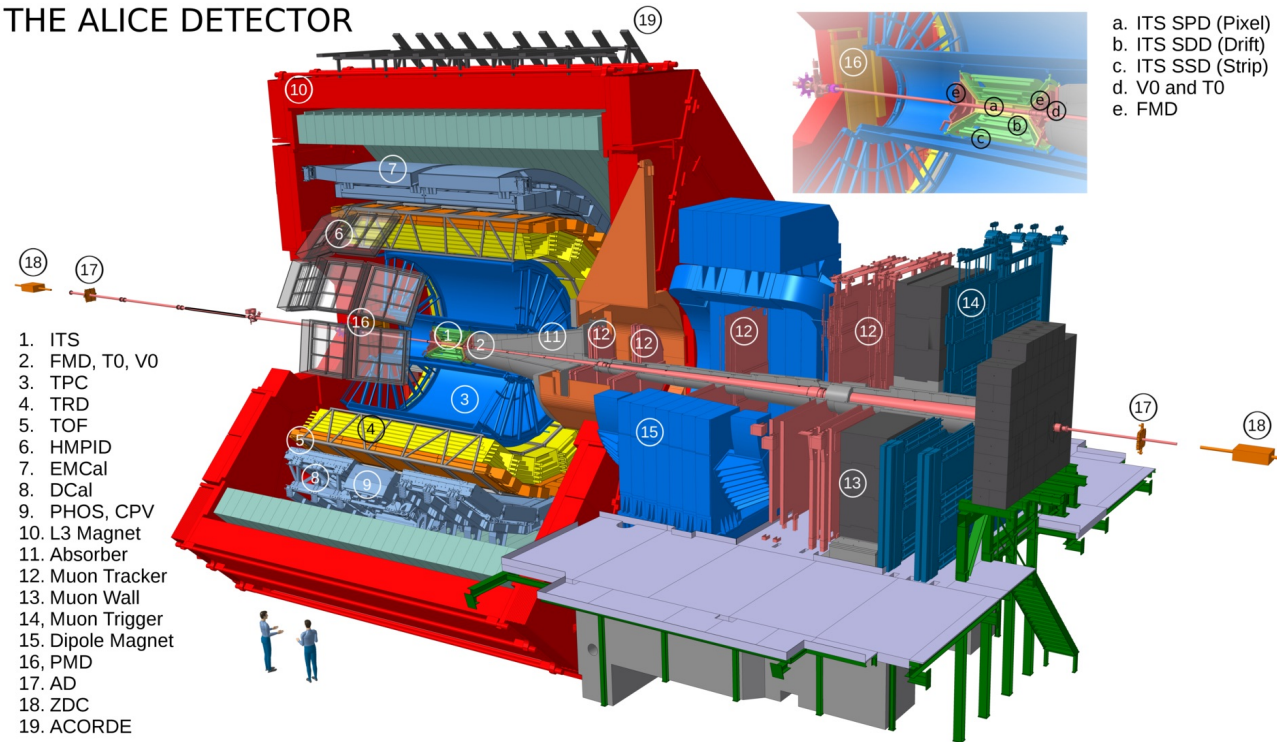
The centrality dependence of  $\Lambda$  hyperon polarization is observed. The magnitude of polarization is higher for peripheral collisions.

$\rho_{00}$  of  $\phi$  meson shows centrality dependence.  $\rho_{00} > 1/3$  for mid-central collisions

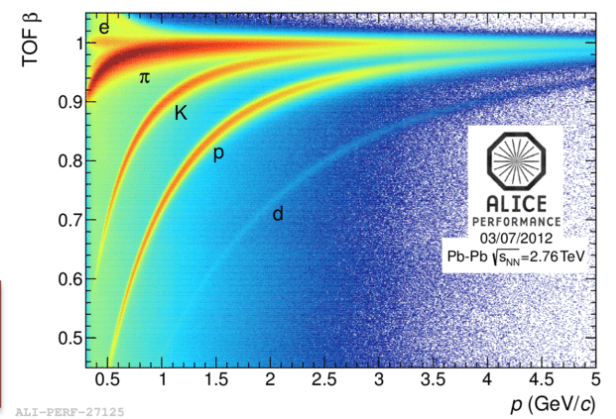
# ALICE detector



## THE ALICE DETECTOR



ITS+TPC:  $|\eta| < 0.9$ , Tracking  
 TPC: Particle identification



Time of Flight:  $|\eta| < 0.9$   
 Particle identification

V0 :  $-3.7 < \eta < -1.7$  and  $2.8 < \eta < 5.1$   
 Trigger and event centrality  
 Event plane estimation

ZDC :  $|\eta| > 8.7$   
 Event plane estimation

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



# Global polarization of $\Lambda$ hyperon

# Data set and analysis

Collision system and energy	Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV, Minimum bias
Rapidity	$ y  < 0.5$
No. of events	$\sim 49$ M
Collision centrality	5-15%, 15-50%
Hadrons	$\Lambda$ -hyperons
Background	Side bands
Quantization axis	First order event plane $\psi_{EP}^{(1)}$ from ZDC

Measurement observable

$$\frac{dW}{d\sin\theta_P^* d\phi_P^*} = \frac{1}{4\pi} (1 + \alpha_{\Lambda, \bar{\Lambda}} |\vec{P}_H| \cos\theta_P^*)$$

Angles are of daughter proton in rest frame of hyperon

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

Component perpendicular to reaction plane and averaged over all events

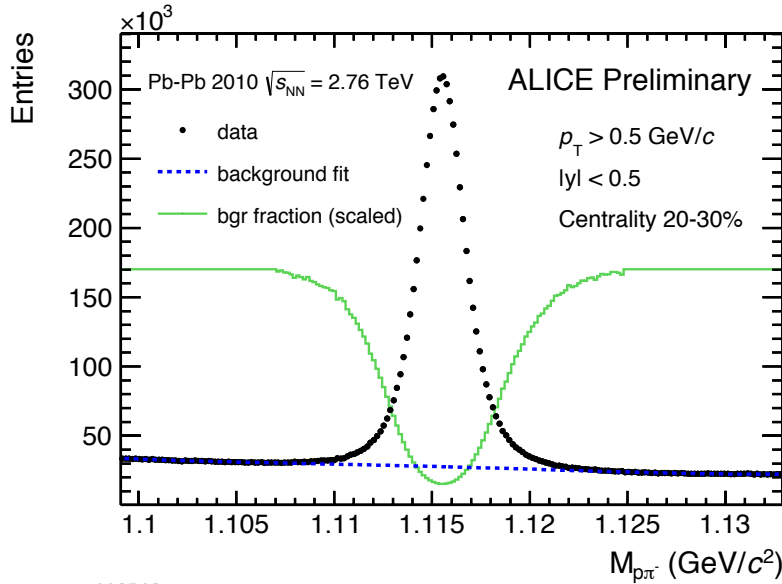
$$P_{\Lambda, \bar{\Lambda}} = \frac{8}{\pi \alpha_{\Lambda, \bar{\Lambda}}} \times \frac{\langle \sin(\phi_p^* - \psi_{EP}^{(1)}) \rangle}{R_{EP}^{(1)}}$$

Statistical uncertainty

$$\approx \frac{8}{\pi \alpha_{\Lambda, \bar{\Lambda}}} \times (2R_{EP}^{(1)} \sqrt{N_{\Lambda}})^{-1}$$

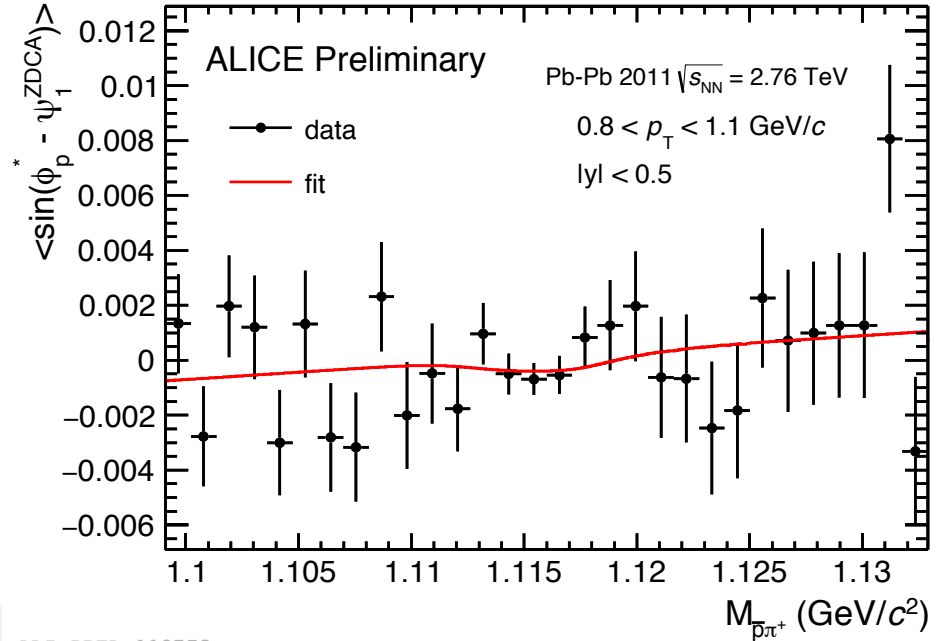
Event plane using the two neutron ZDCs

# Signal extraction and EP resolution



ALI-PREL-119748

$\Lambda$   $M_{inv}$  distribution and  
 $\Lambda$  background distribution



ALI-PREL-119753

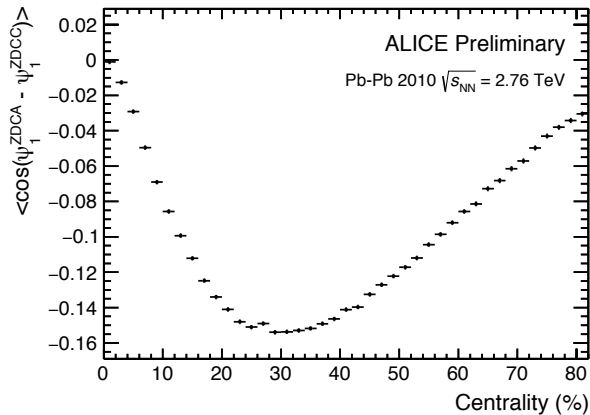
Fit distribution

$$(1 - f(M)) \times P_H + f(M) \times [\text{linear function}]$$

$P_H$  is the polarization signal

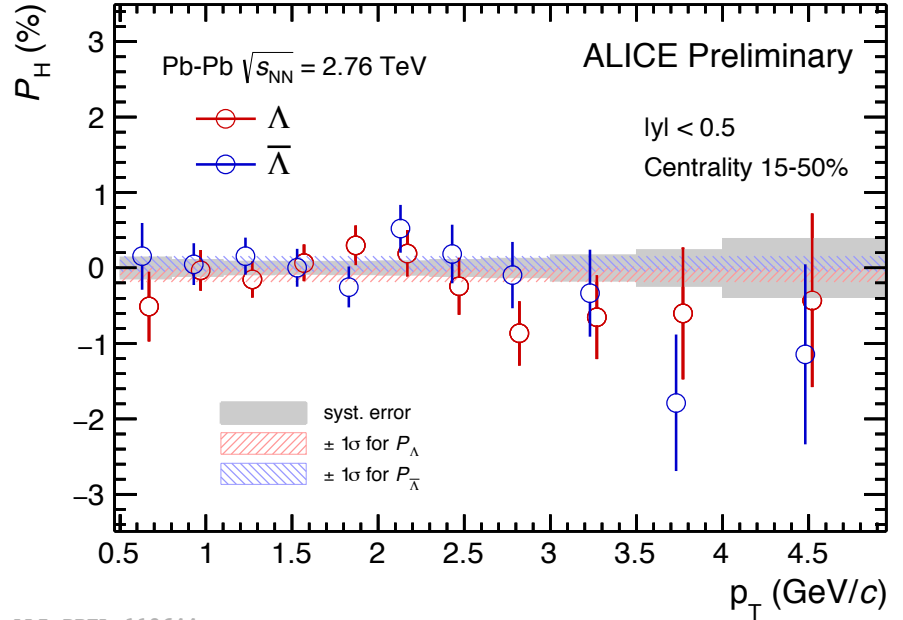
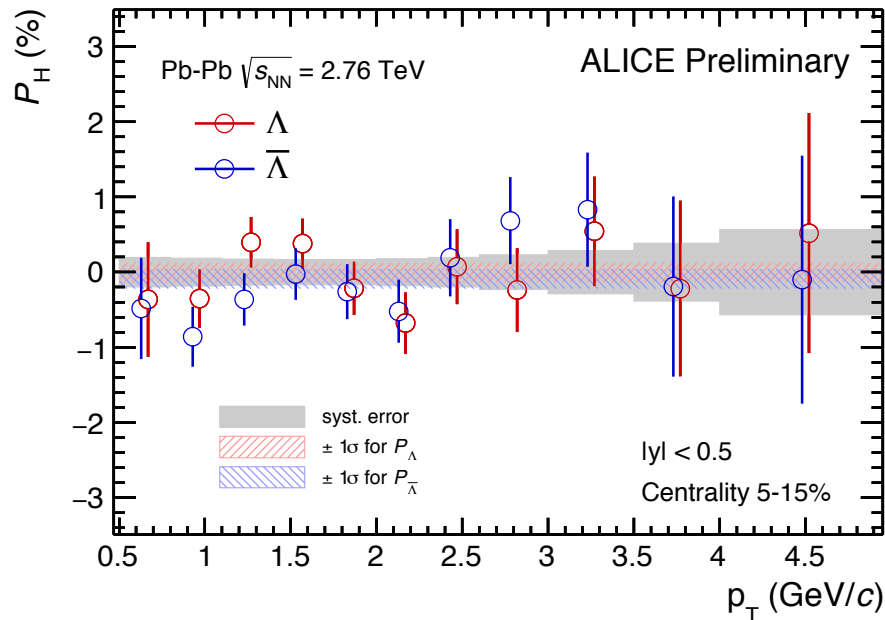
$$R_{EP}^{(1)} \approx \sqrt{-\langle \cos(\psi_1^{ZDCA} - \psi_1^{ZDCC}) \rangle}$$

Event plane resolution  $\sim$   
 0.39 (Max)



ALI-PREL-119757

# Hyperon polarization measurements: $p_T$ dependence



ALI-PREL-119628

ALI-PREL-119644

## $p_T$ integrated results

5-15%

$$P_{\Lambda}(\%) = -0.01 \pm 0.13(stat) \pm 0.04(syst)$$

$$P_{\bar{\Lambda}}(\%) = -0.09 \pm 0.13(stat) \pm 0.08(syst)$$

15-50%

$$P_{\Lambda}(\%) = -0.08 \pm 0.10(stat) \pm 0.04(syst)$$

$$P_{\bar{\Lambda}}(\%) = 0.05 \pm 0.10(stat) \pm 0.03(syst)$$

Feed down corrections underway (model dependent)  $\sim 1.7 \pm 0.5$

# Summary: Global polarization results



- ✓  $P_H$  consistent with zero for Pb-Pb collisions at midrapidity for  $\sqrt{s_{NN}} = 2.76$  TeV
- ✓ Expected significance of the combined  $\Lambda$  and anti- $\Lambda$  result is at a  $1\sigma$  level
- ✓ 10 times more event statistics needed for a  $3\sigma$  significance result

# Spin alignment of $K^{*0}$ vector meson

# Data set and analysis

## pp collisions

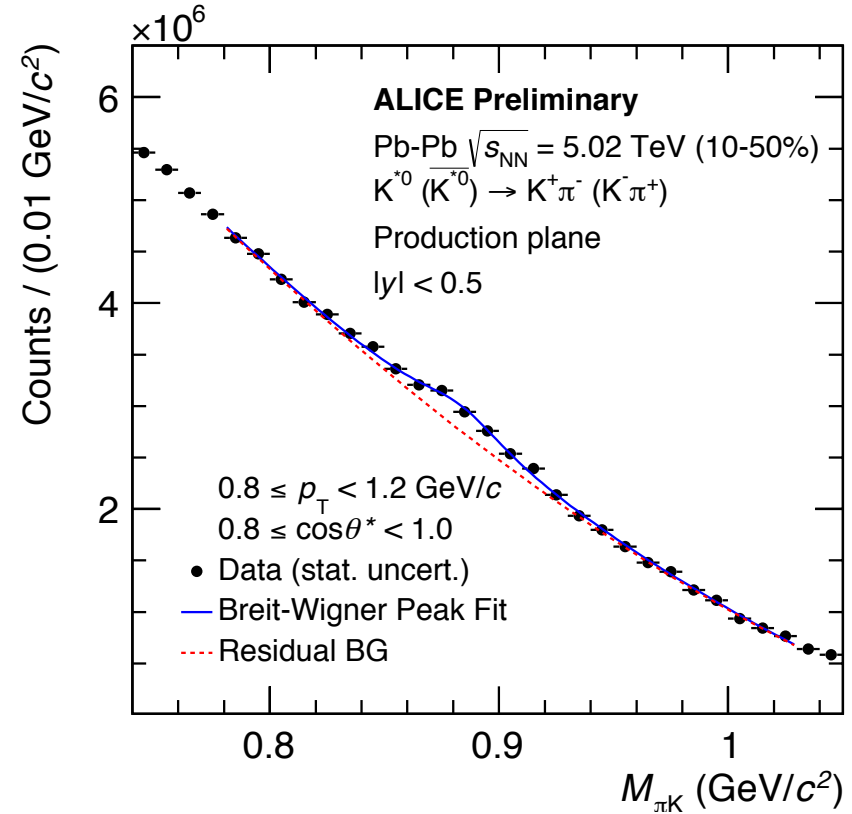
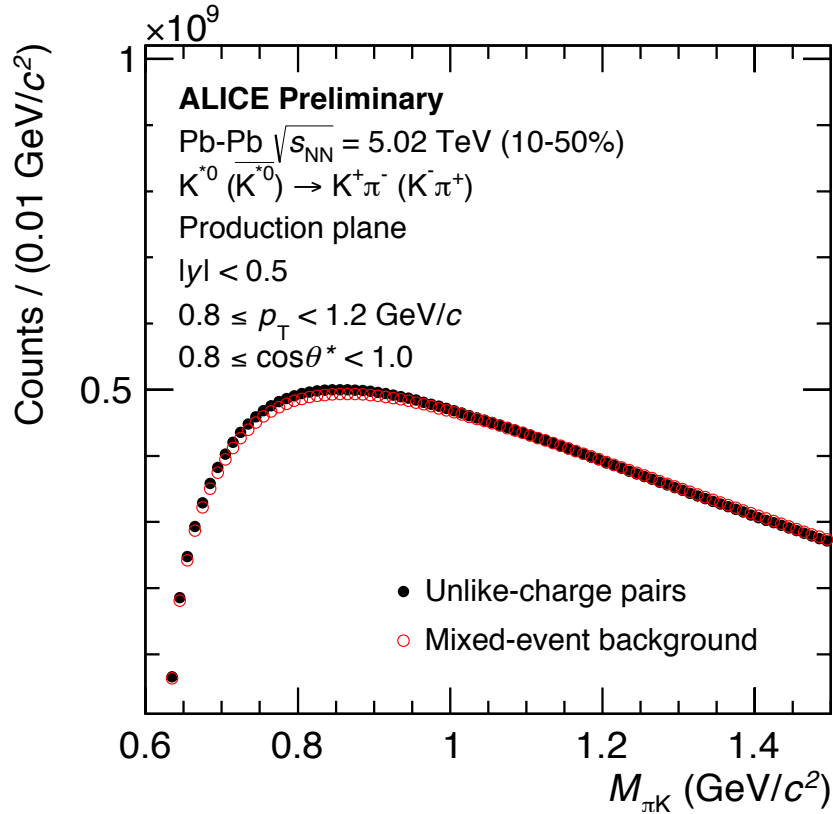
Collision system and energy	pp at 13 TeV, Minimum bias
Rapidity	$ y  < 0.5$
No. of events	$\sim 43$ M
Hadrons	$K^{*0}$
Background	Mixed events
Efficiency x acceptance	Corrected
Quantization axis	Normal to Production plane

## Heavy-ion collisions

Collision system and energy	Pb-Pb at 2.76 and 5.02 TeV, Minimum bias
Rapidity	$ y  < 0.5$
No. of events	$\sim 14$ M (2.76 TeV), $\sim 30$ M (5.02 TeV)
Collision Centrality	$K^{*0}$ :10-50, 0-10, 10-30, 30-50, 50-70, 70-90 and 50-80%, $K_s^0$ :20-40%
Hadrons	$K^{*0}$ and $K_s^0$
Background	Mixed events
Efficiency x acceptance	Corrected
Quantization axis	Normal to Production plane and Event plane

Goal: Measure  $dN/d\cos\theta^*$  vs.  $\cos\theta^*$  and extract  $\rho_{00}$  value as a function of  $p_T$  and centrality of  $K^{*0}$ .

# $K^{*0}$ vector meson reconstruction in Pb-Pb collisions in Production Plane method



Same event (sig+bgr) and mixed event (bgr) distributions

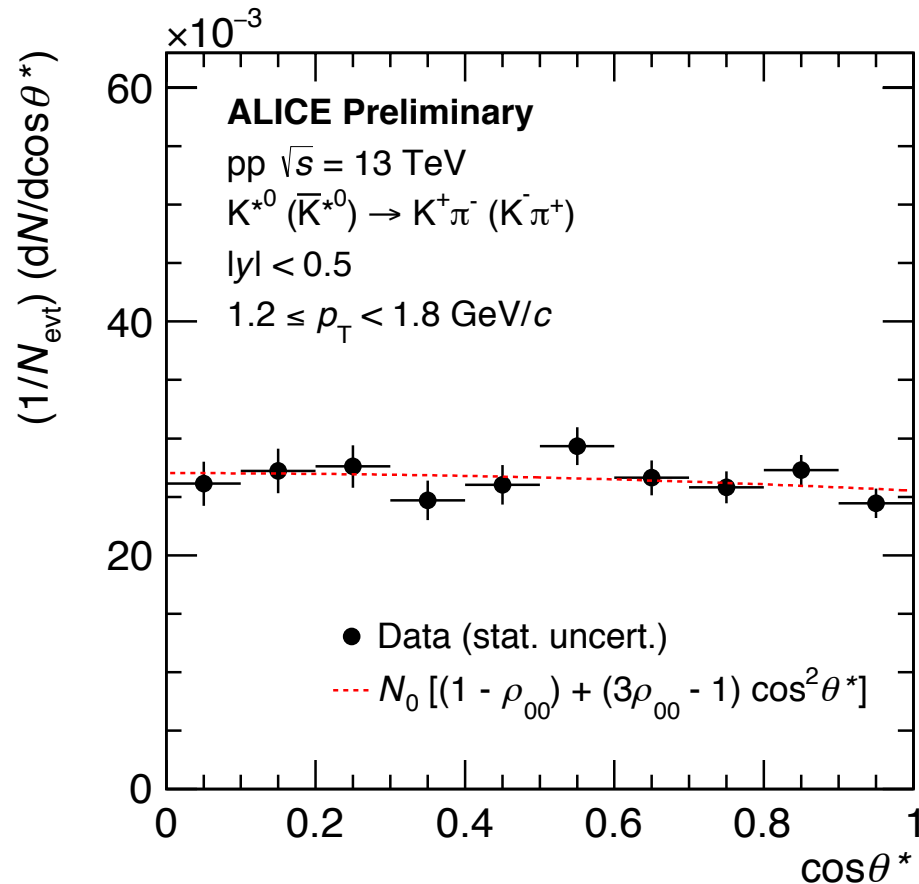
Same event distribution after mixed event background subtraction

Yield is the area under Breit-Wigner distribution

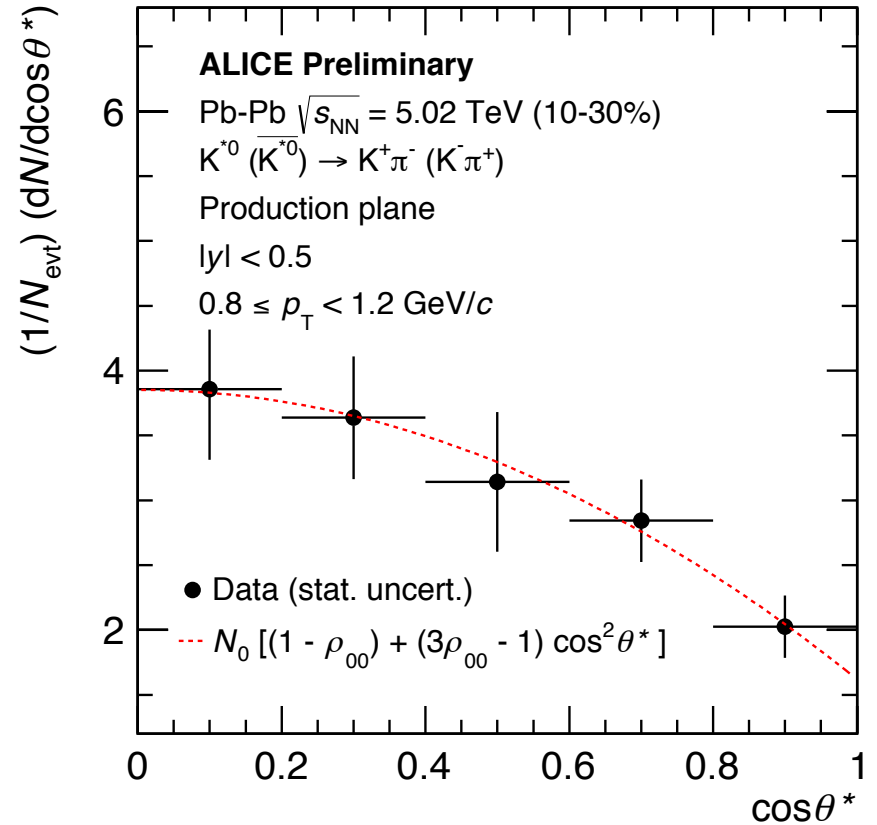


# Angular distribution: Production plane

pp collisions

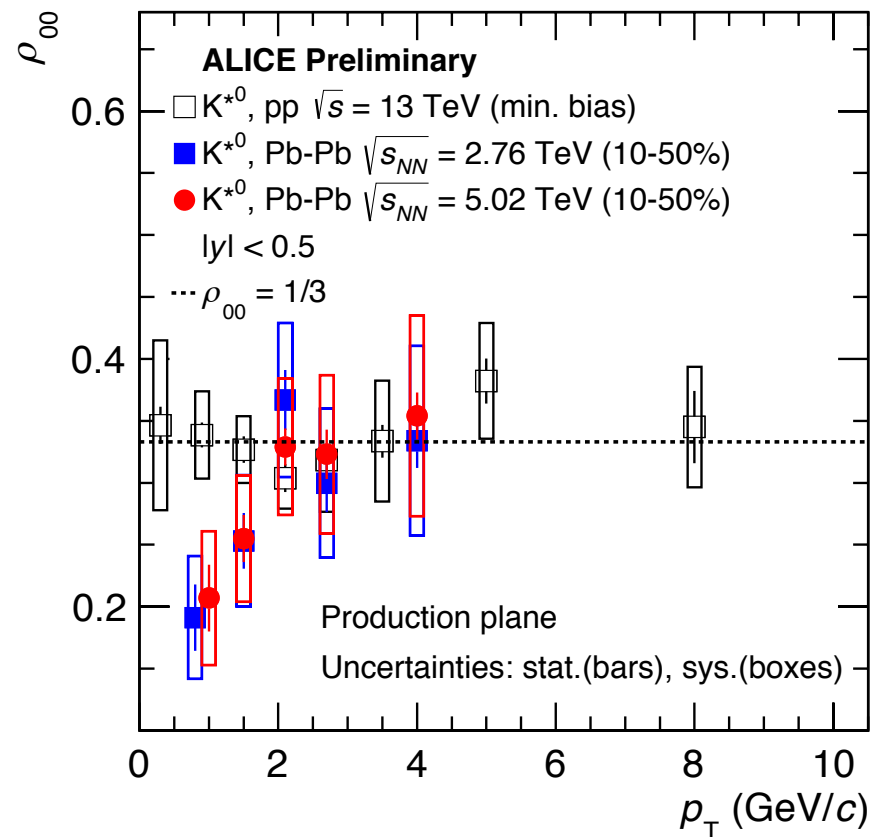
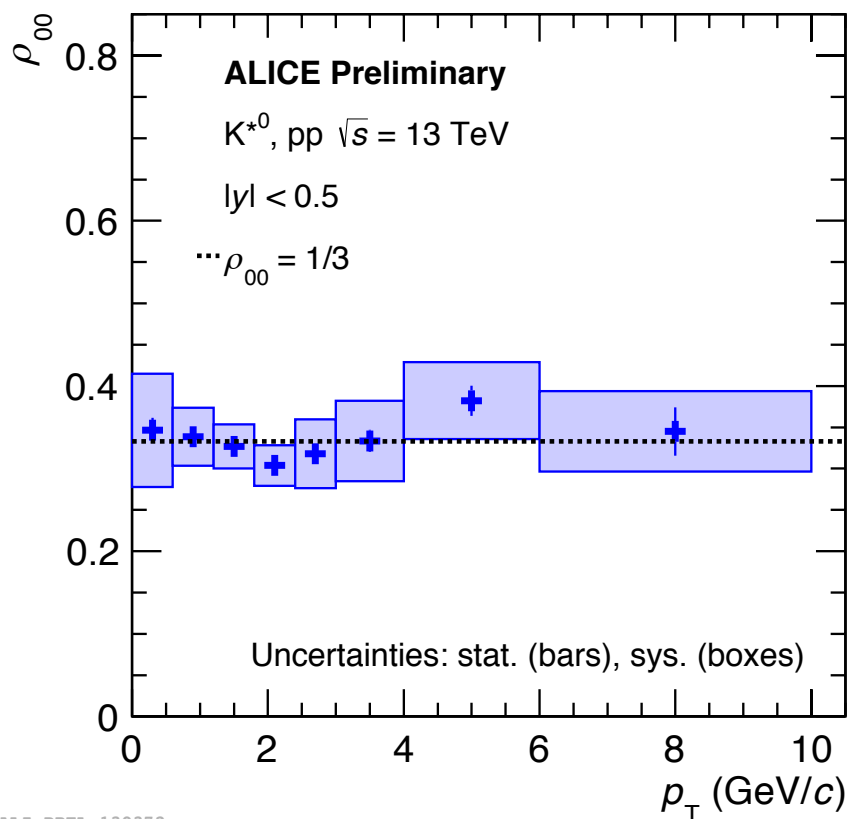


Heavy-ion collisions



Two parameters ( $N_0$  and  $\rho_{00}$ ) fit to  $\cos\theta^*$  distributions measured in different  $p_T$  bins

# Spin density matrix element ( $\rho_{00}$ ) vs. $p_T$ : Production Plane

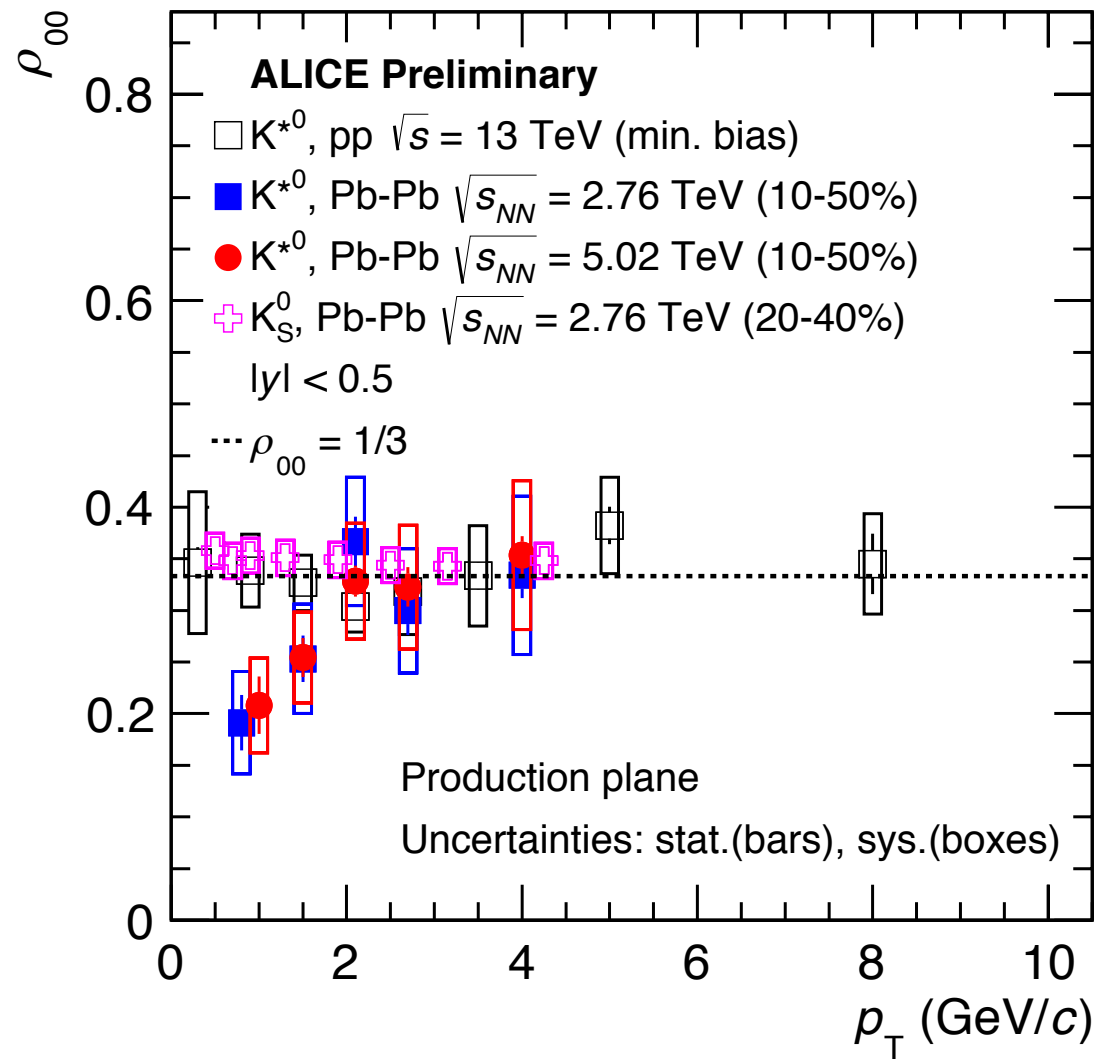


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pp collisions:  $\rho_{00} = 1/3$

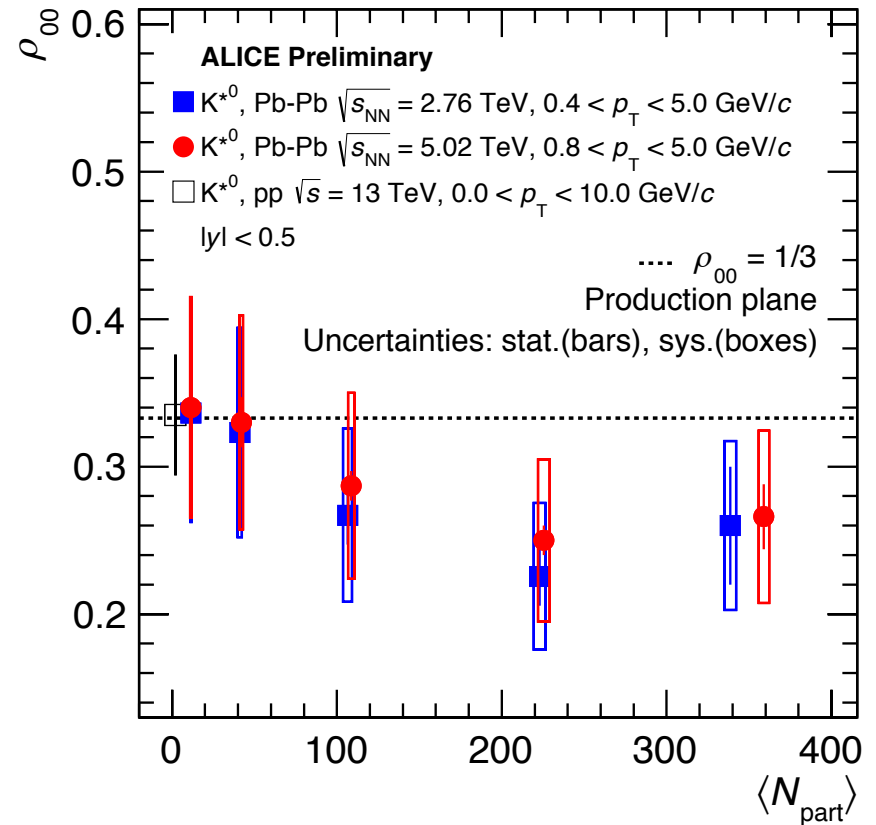
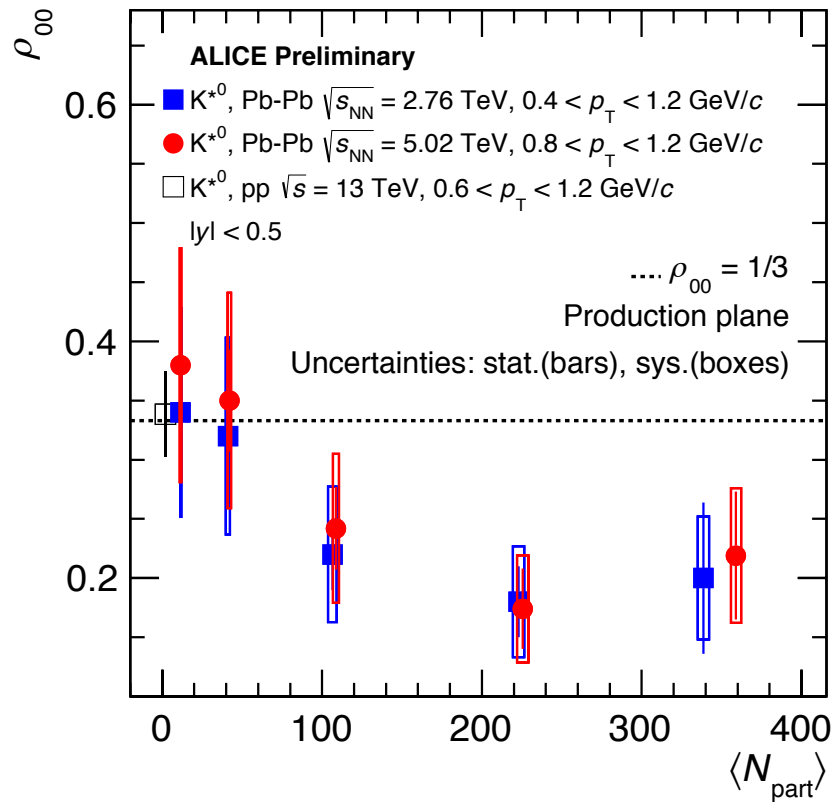
Pb-Pb collisions: For 1<sup>st</sup>  $p_T$  bin,  $\rho_{00}$  values about  $2.5\sigma$  and  $2.3\sigma$  below  $1/3$  in 2.76 TeV and 5.02 TeV respectively

# Spin alignment of $K^{*0}$ (spin 1) and $K^0_s$ (spin 0)



Control Experiment:  
No spin alignment observed  
for spin 0 hadron  $K^0_s$

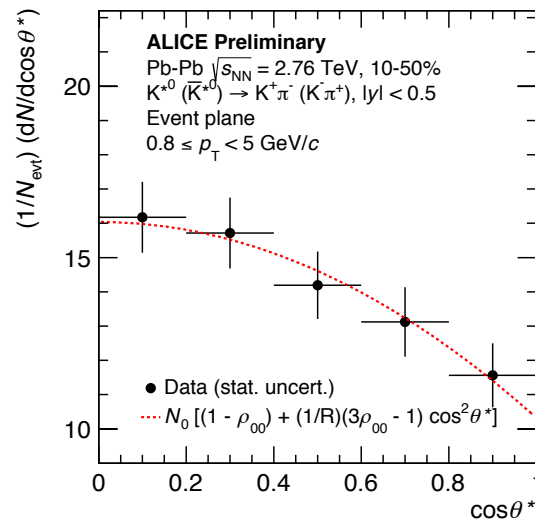
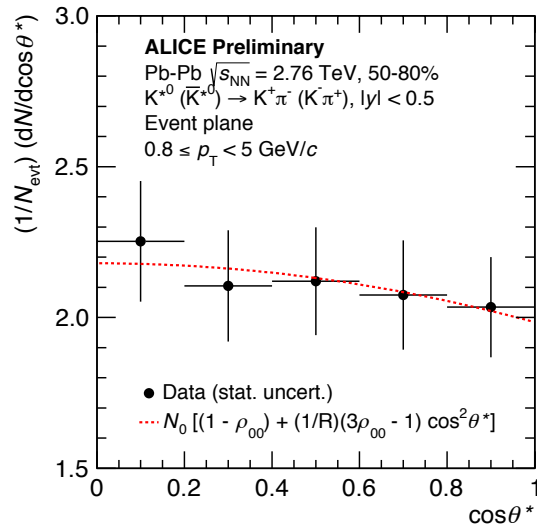
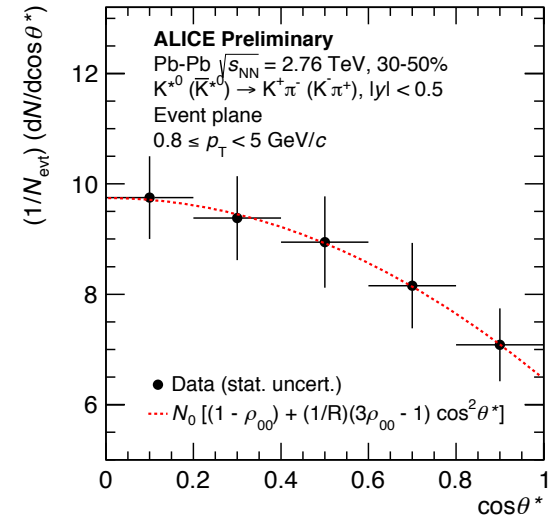
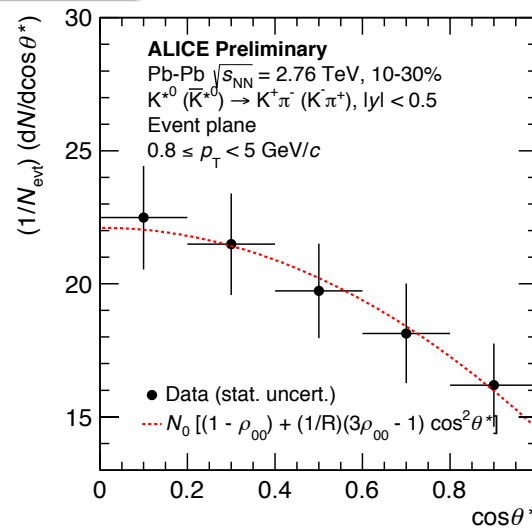
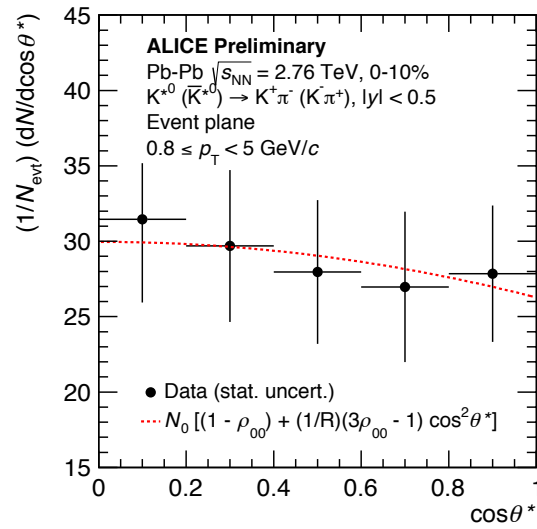
# Centrality & energy dependence of $\rho_{00}$ : Production plane



- $\rho_{00}$  shows centrality dependence and maximum deviation from 1/3 for centrality class 10-30%
- Similar values of  $\rho_{00}$  are observed at both the energies

# Angular distribution: Event Plane

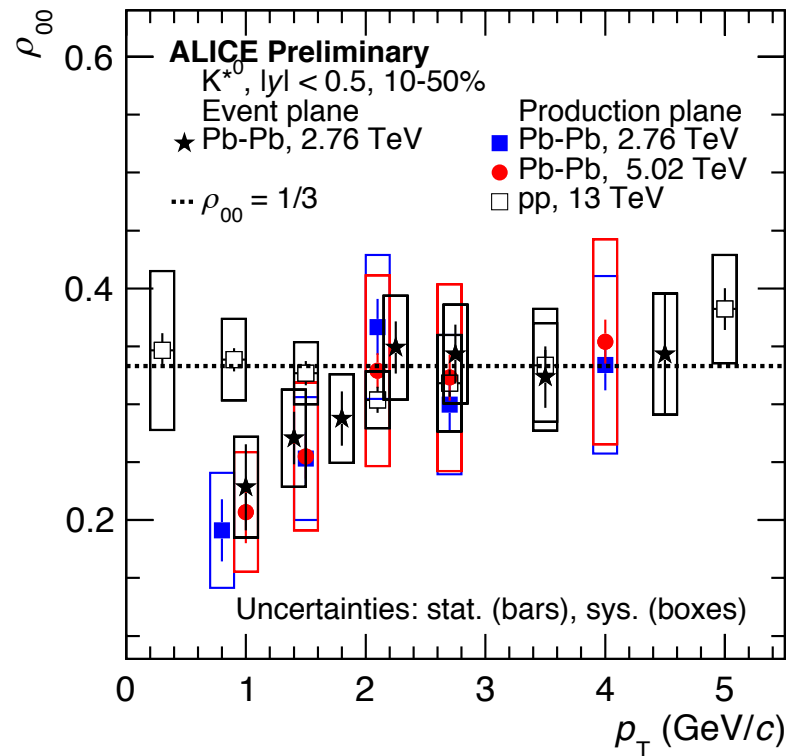
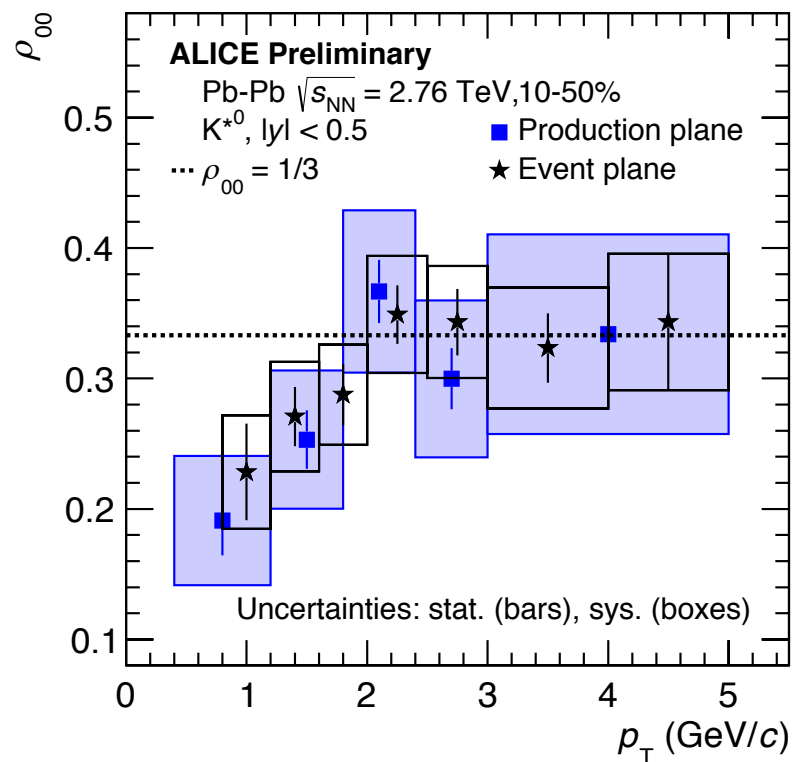
Pb-Pb at  $\sqrt{s_{NN}} = 2.76$  TeV



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

- Two parameters ( $N_0$  and  $\rho_{00}$ ) from fit to  $\cos\theta^*$
- $R$  is the second order event plane resolution.

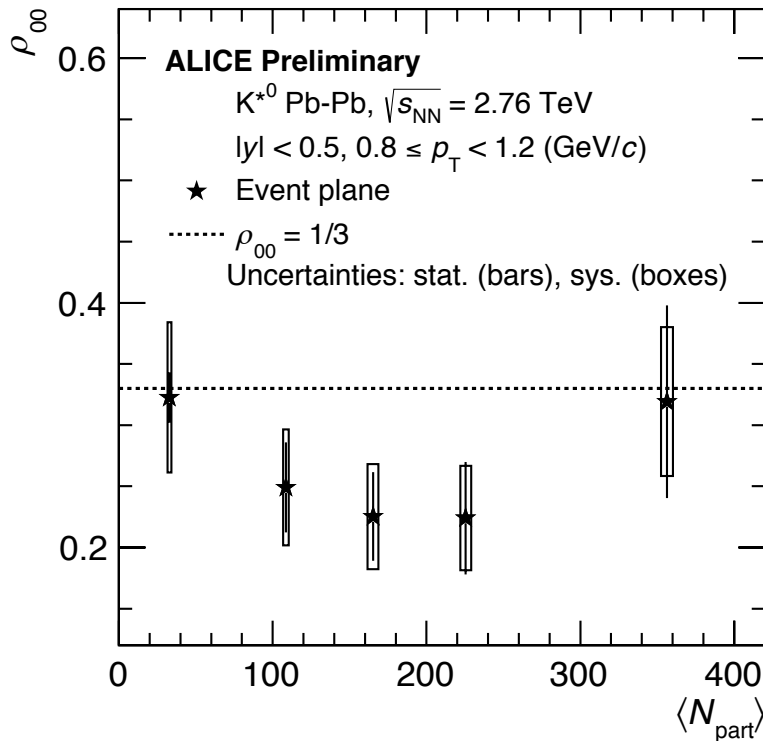
# Spin density matrix element ( $\rho_{00}$ ) vs. $p_T$ : Event vs. Production Plane



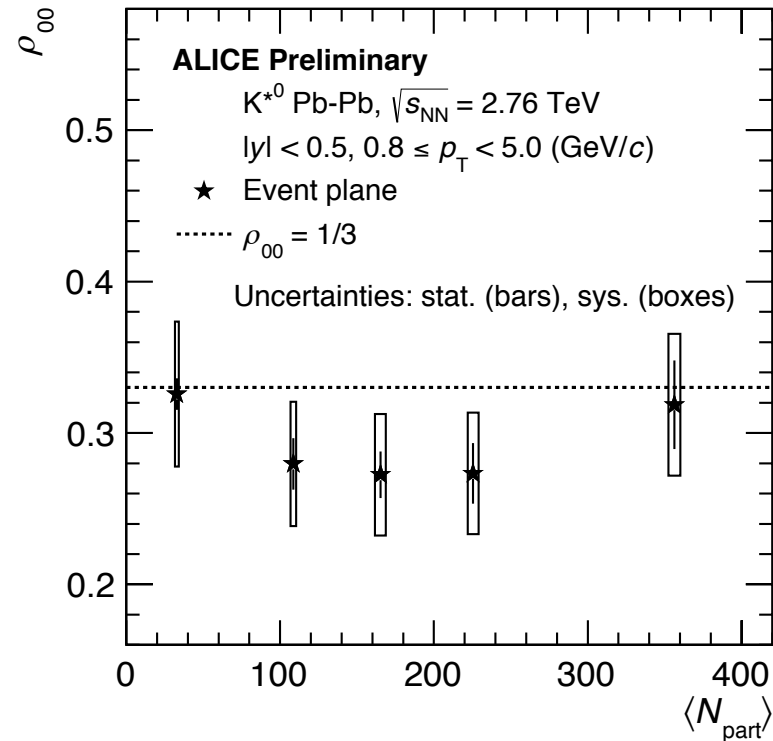
- $\rho_{00} < 1/3$  for  $p_T < 2.0$  GeV/c in both Event and Production plane
- Within statistical and systematic uncertainties  $\rho_{00}$  values are similar in both Production and Event plane method

# Centrality dependence of $\rho_{00}$ : Event plane

First  $p_T$  bin



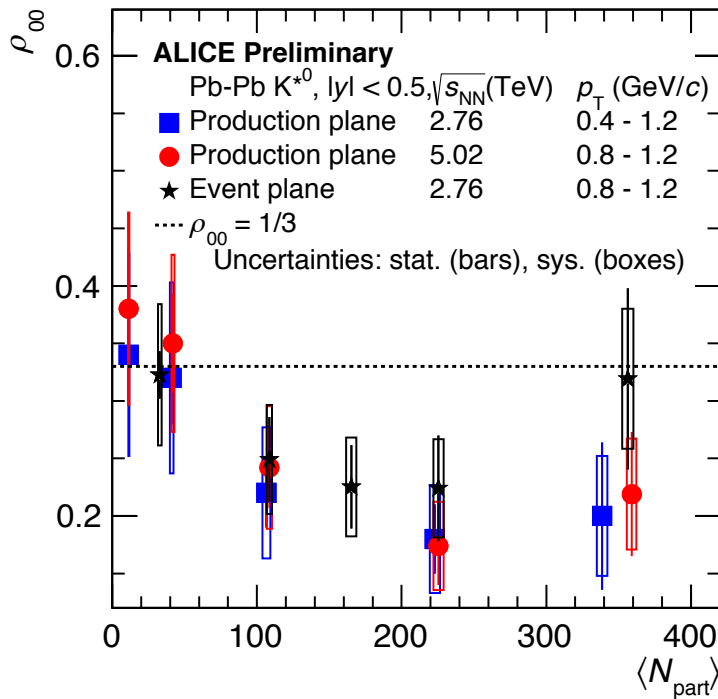
Integrated  $p_T$



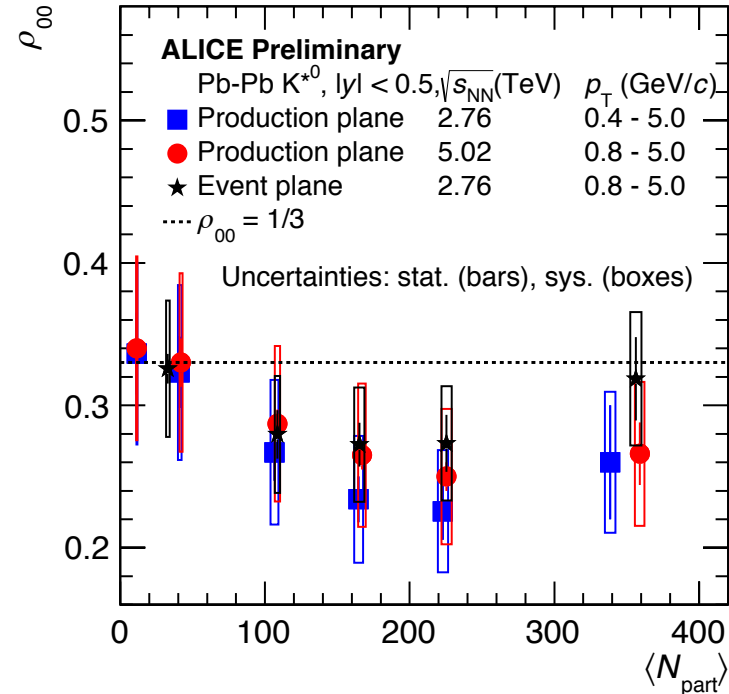
- $\rho_{00}$  shows centrality dependence and maximum deviation from 1/3 for centrality class 10-30% - First  $p_T$  bin is at  $\sim 1.74 \sigma$  and integrated  $p_T$  is at  $\sim 1.35 \sigma$   
(Event plane resolution (10-30%) = 0.72)

# Centrality dependence of $\rho_{00}$ : Event plane vs. Production plane vs. Production plane

First  $p_T$  bin



Integrated  $p_T$

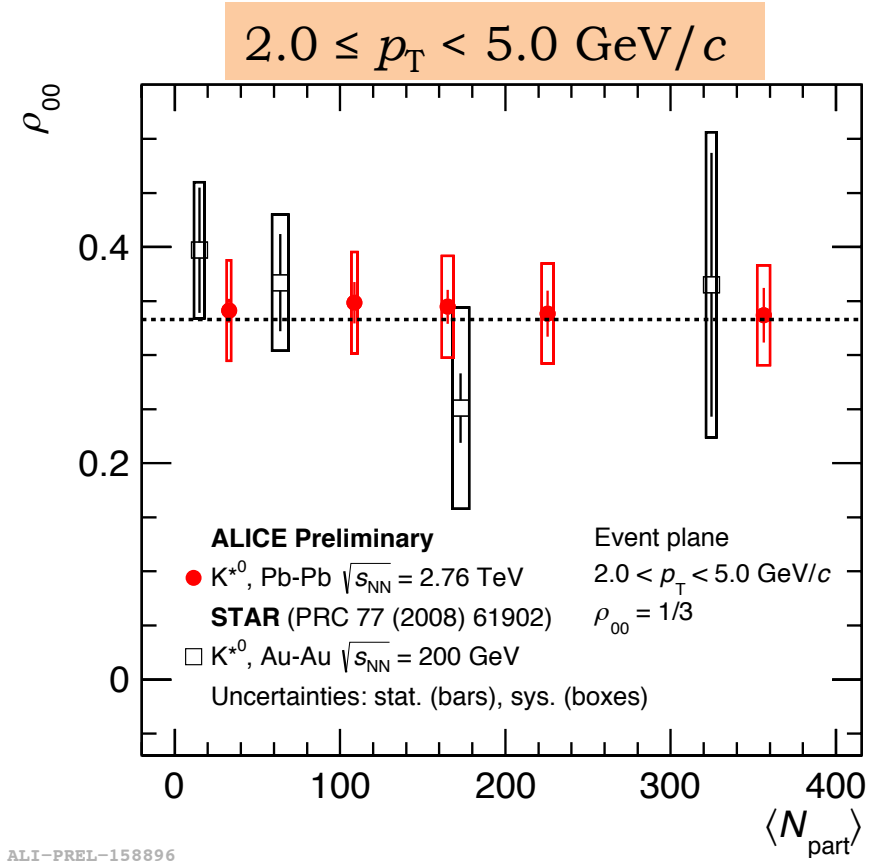
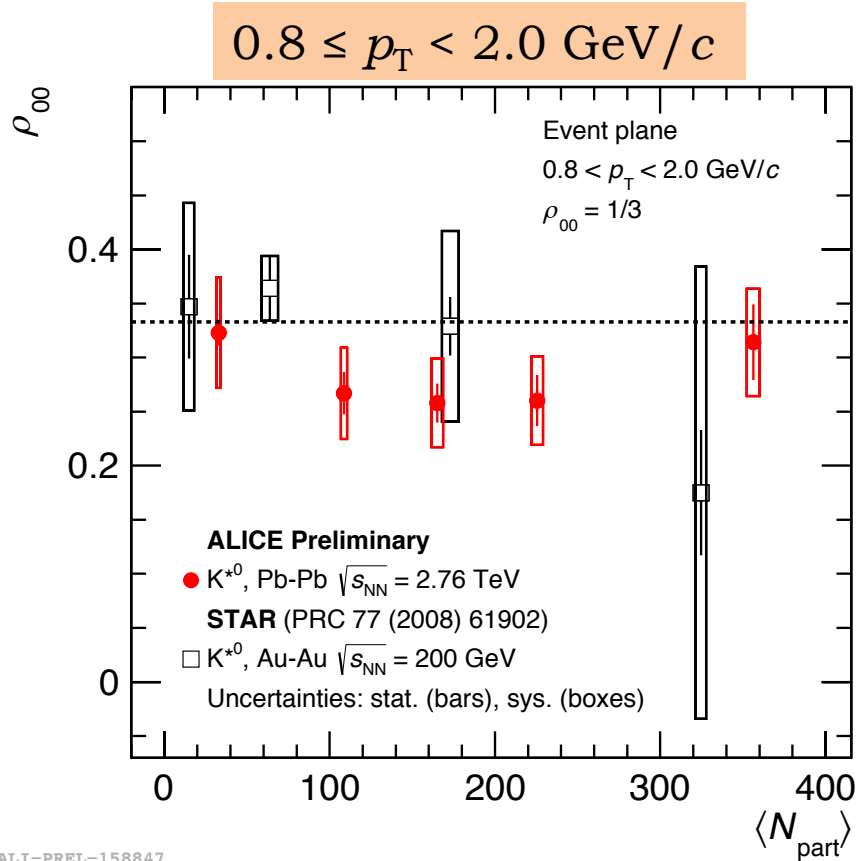


- $\rho_{00}$  shows centrality dependence in both Production and Event plane and maximum deviation from  $1/3$  for centrality class 10-30%
- Within statistical and systematic uncertainties  $\rho_{00}$  values are similar in both Production and Event plane method



# $\rho_{00}$ vs. $\langle N_{part} \rangle$ : Comparison with STAR results in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV

All results are w.r.t. Event plane



- ❑ For low  $p_T$ :  $\rho_{00}$  shows centrality dependence for Pb-Pb 2.76 TeV
- ❑ For high  $p_T$ : Both STAR and ALICE results are consistent with  $\rho_{00} = 1/3$  (Uncertainties are smaller in ALICE)

# Summary: Spin alignment results

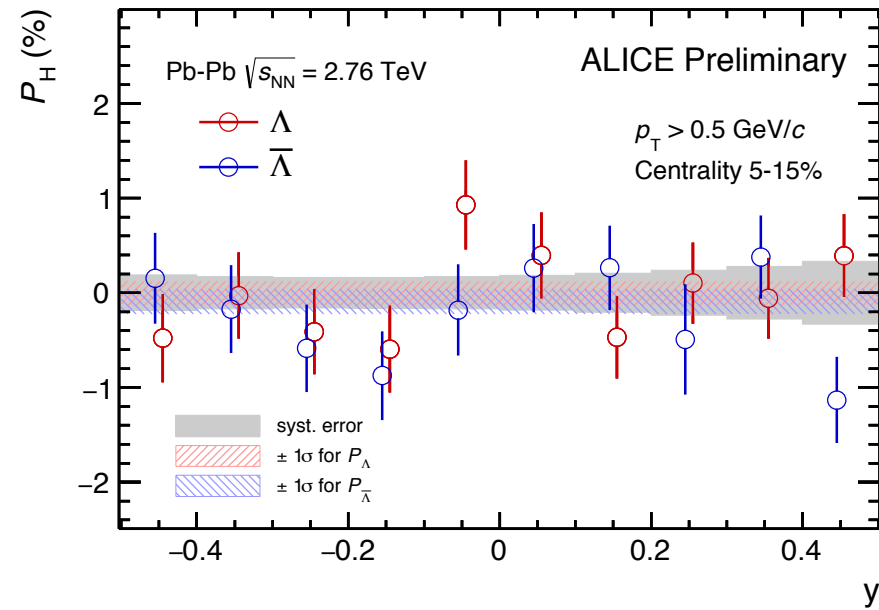
- ✓  $\rho_{00} < 1/3$  w.r.t. both Event and Production plane in Pb-Pb collisions. For first  $p_T$  bin, deviation is about  $2.5\sigma$  and  $3.0\sigma$  w.r.t. Production plane at 2.76 and 5.02 TeV respectively, about  $1.7\sigma$  w.r.t. Event plane at 2.76 TeV
- ✓  $\rho_{00}$  consistent with  $1/3$  for higher  $p_T$  in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  and 5.02 TeV in ALICE @ LHC
- ✓  $\rho_{00}$  shows centrality dependence and maximum deviation for mid-central collisions in both Event and Production plane
- ✓  $\rho_{00}$  values are similar at both  $\sqrt{s_{NN}} = 2.76$  and 5.02 TeV
- ✓  $\rho_{00} \sim 1/3$  : Spin alignment **not** observed in pp collisions and for  $K_s^0$  (spin 0) particle in Pb-Pb collisions

- ✓ Analysis with Pb-Pb 5.02 TeV data with higher statistics underway
- ✓ Spin alignment studies of  $\phi$  meson in pp collisions at  $\sqrt{s} = 13$  TeV and Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  and 5.02 TeV

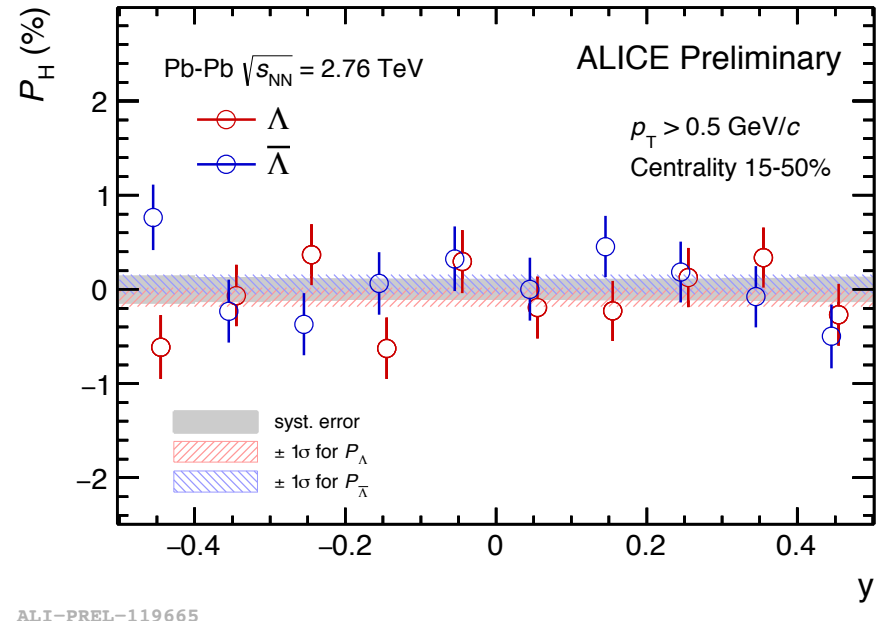
# BACKUP

# Hyperon polarization measurements: Rapidity dependence

5-15%



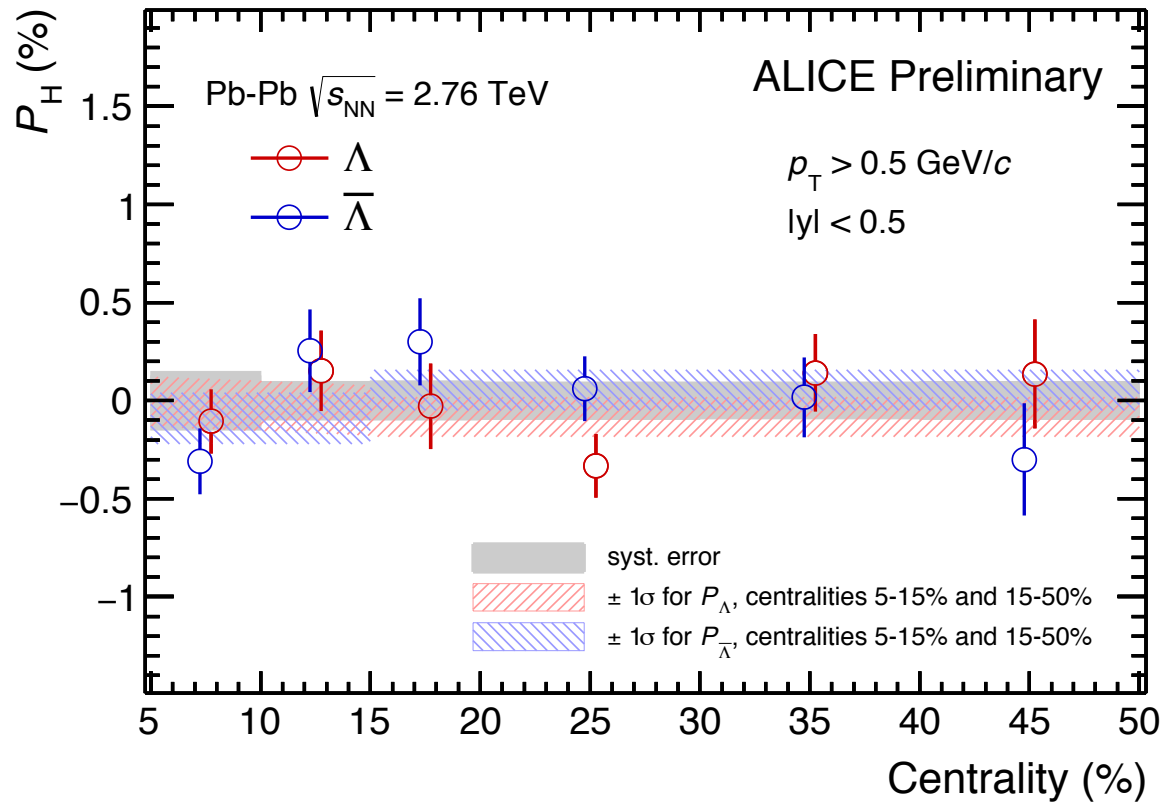
15-50%



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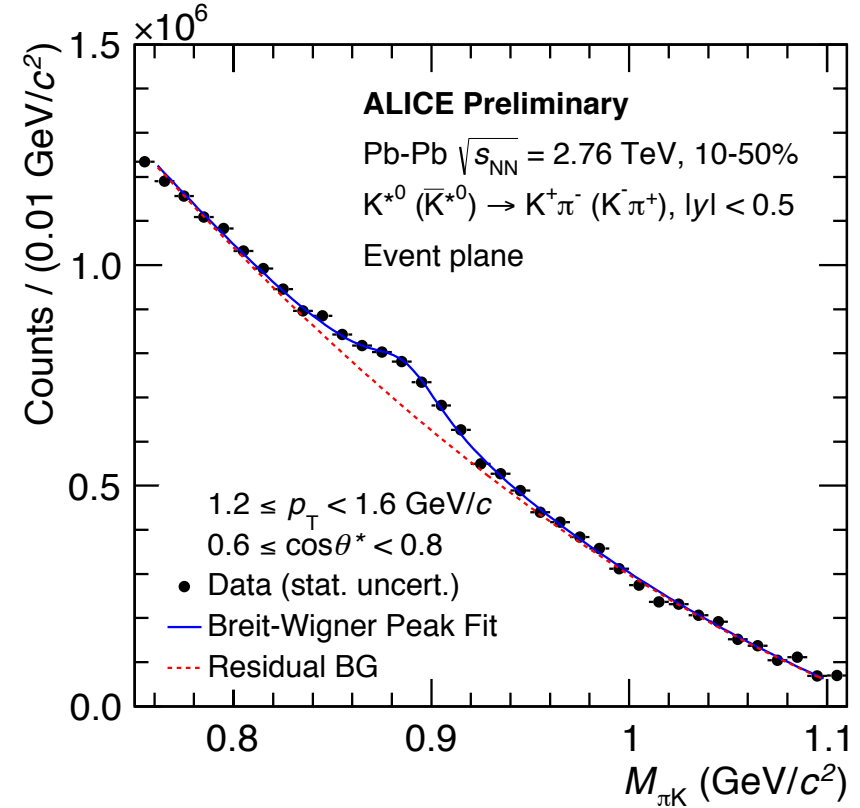
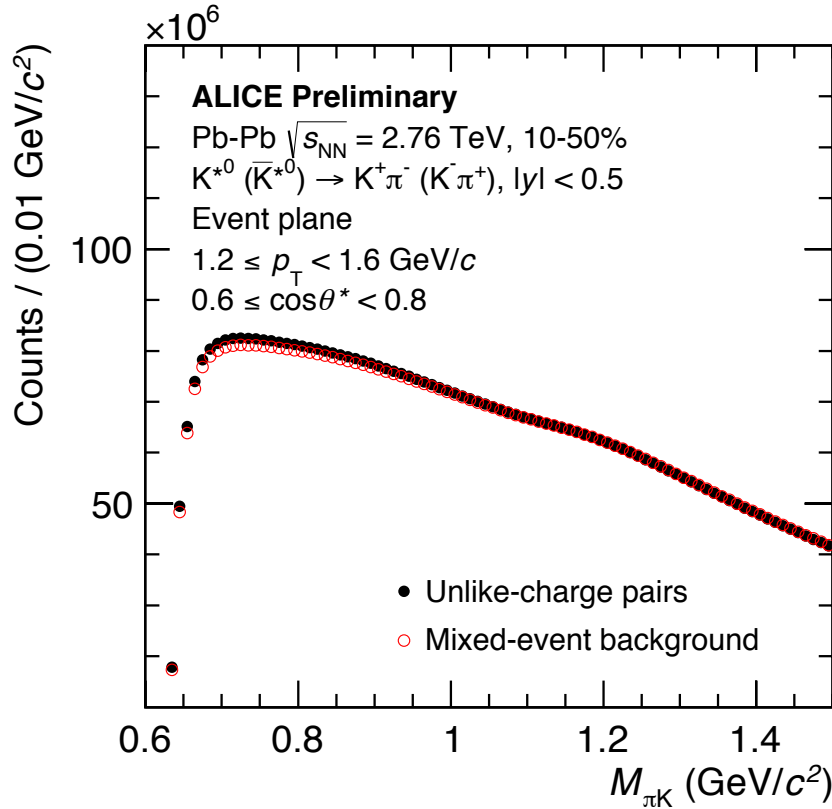
ALI-PREL-119665

# Hyperon polarization measurements: Centrality dependence



ALI-PREL-119599

# $K^{*0}$ vector meson reconstruction in Pb-Pb collisions in Event Plane method



Same event (sig+bgr) and mixed event (bgr) distributions

Same event distribution after mixed event background subtraction

Yield is the area under Breit-Wigner distribution