Measuring spin alignment of D^{*+} mesons in pp and Pb–Pb collisions with ALICE

Mingze Li (for the ALICE Collaboration)

Central China Normal University

26th International symposium on spin physics, 23rd Sep 2025

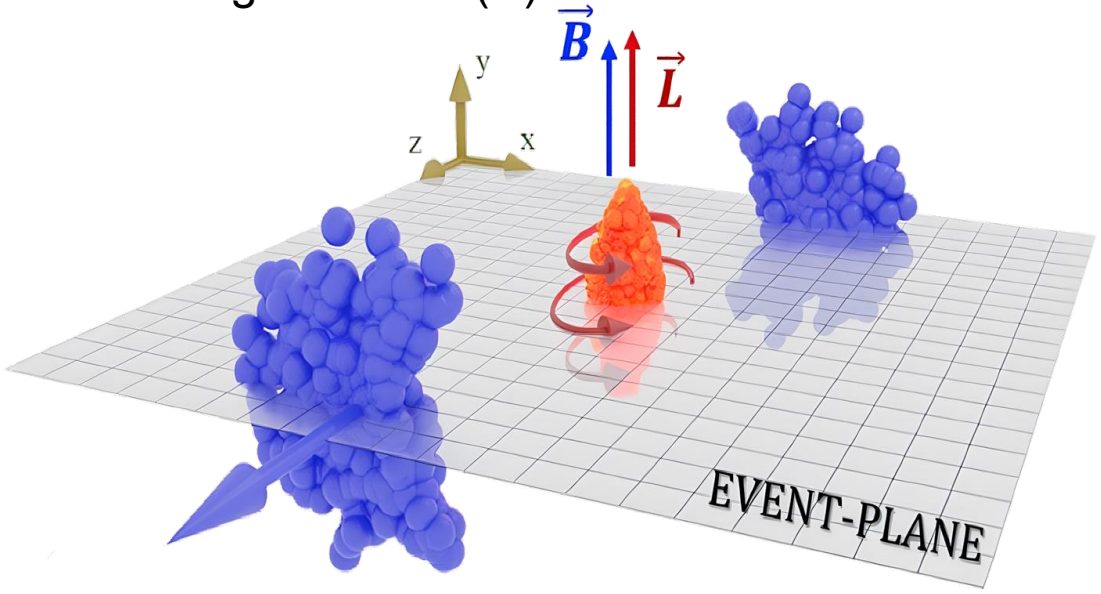
Polarization in AA collisions

Zuo-tang Liang, Xin-nian Wang
Phys.Rev.Lett. 94 (2005), 102301

ALICE

LBNL-56383

- Extreme conditions reached in non-central collisions:
  - A highly vortical system with orbital angular momentum (L), $\omega^* \sim 10^{22}$ s^{-1}
  - Charged spectator motion produces huge magnetic field (B) $\sim 10^{15}$ T



*ω: rotational speed (rotations/sec)

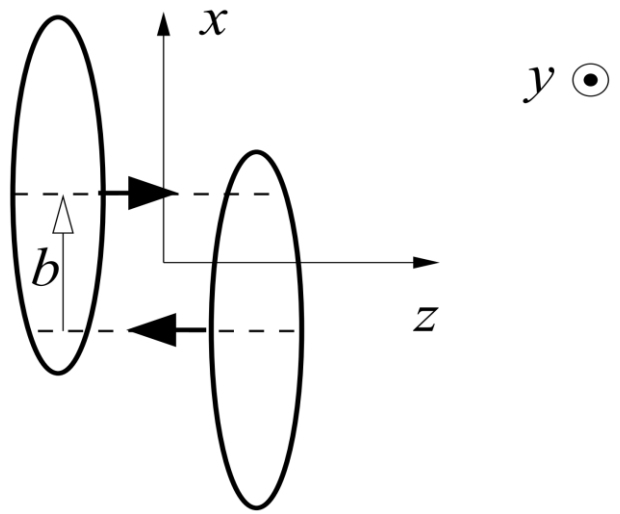
F. Becattini et al., Phys. Rev. C 95 (2017) 054902

Globally Polarized Quark-gluon Plasma in Non-central $A+A$ Collisions

Zuo-Tang Liang[1] and Xin-Nian Wang[2,1]
[1]*Department of Physics, Shandong University, Jinan, Shandong 250100, China*
[2]*Nuclear Science Division, MS 70R0319, Lawrence Berkeley National Laboratory, Berkeley, California 94720*
(Dated: October 18, 2004)

Produced partons have large local relative orbital angular momentum along the direction opposite to the reaction plane in the early stage of non-central heavy-ion collisions. Parton scattering is shown to polarize quarks along the same direction due to spin-orbital coupling. Such global quark polarization will lead to many observable consequences, such as left-right asymmetry of hadron spectra, global transverse polarization of thermal photons, dileptons and hadrons. Hadrons from the decay of polarized resonances will have azimuthal asymmetry similar to the elliptic flow. Global hyperon polarization is studied within different hadronization scenarios and can be easily tested.

PACS numbers: 25.75.-q, 13.88.+e, 12.38.Mh, 25.75.Nq



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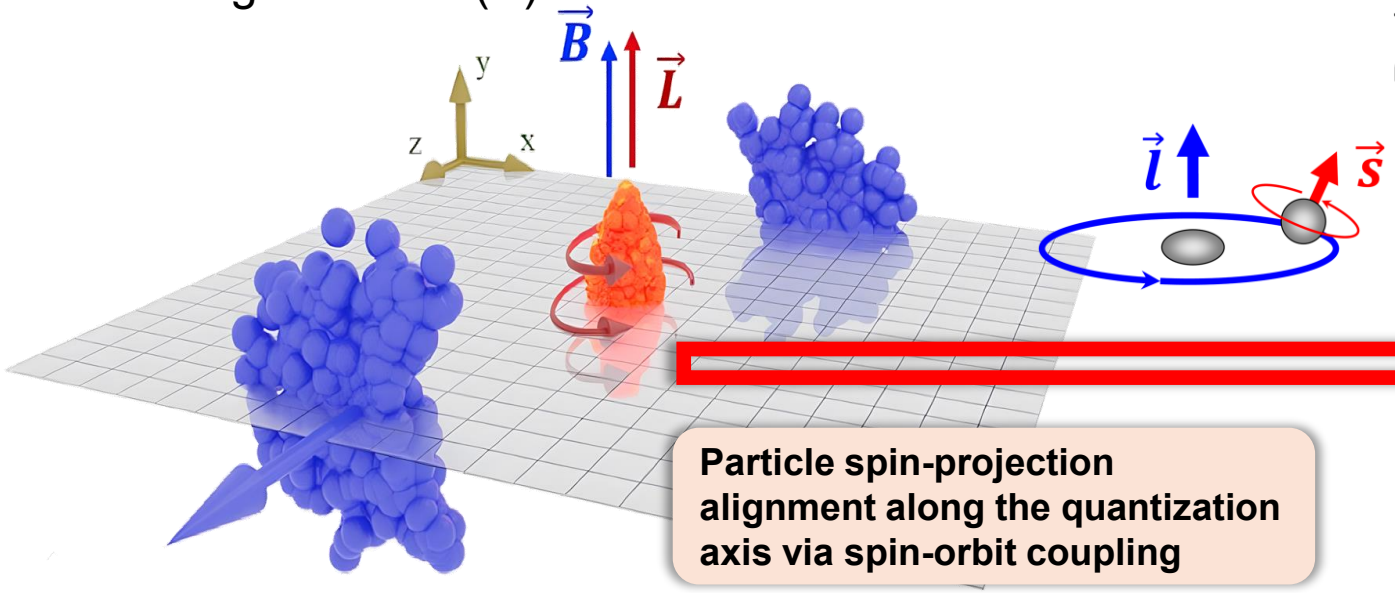


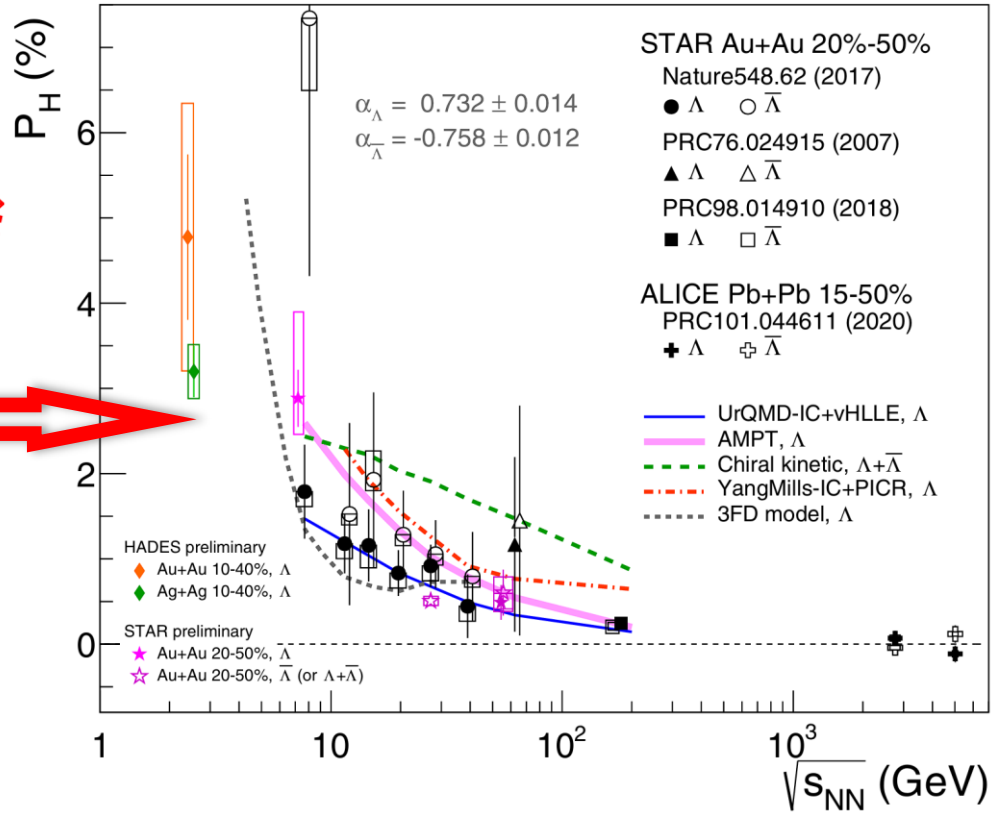
Particle spin-projection alignment along the quantization axis via spin-orbit coupling

*ω: rotational speed (rotations/sec)

F. Becattini et al., Phys. Rev. C 95 (2017) 054902

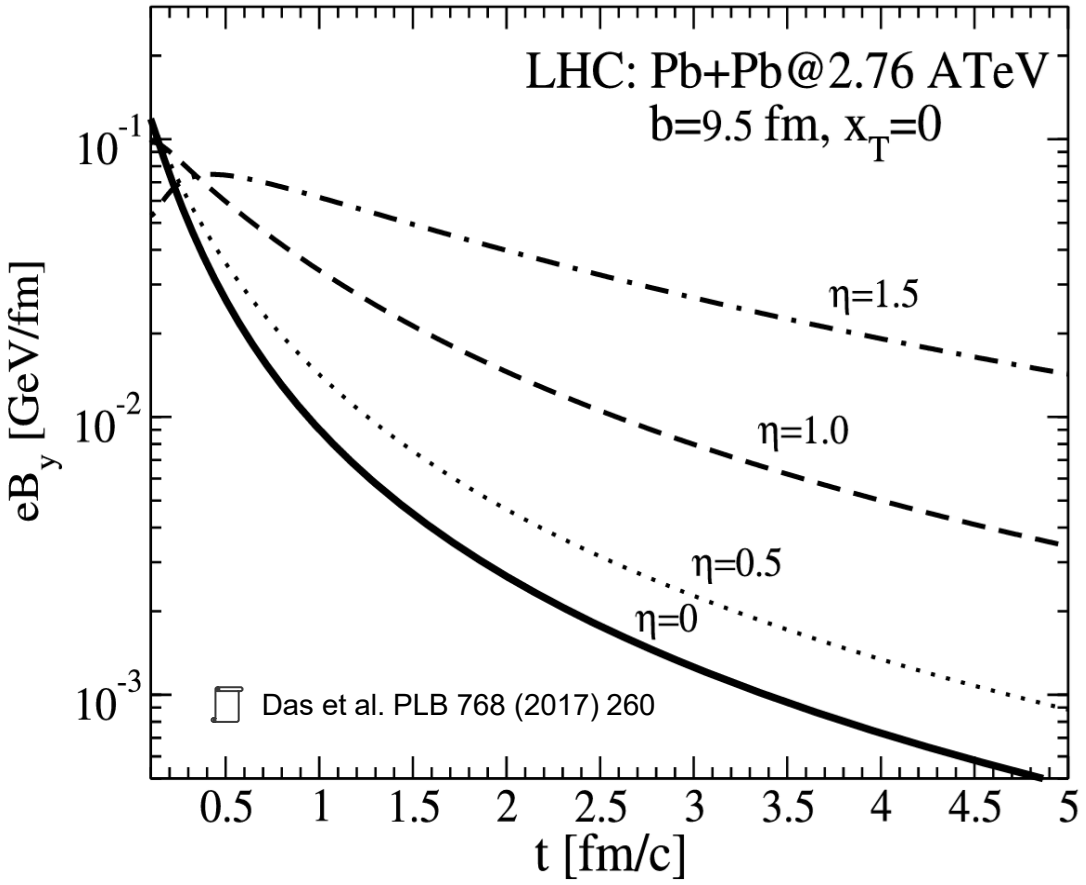
- Spin polarization: probability that the spin of a particle aligns in a given direction (quantization axis)

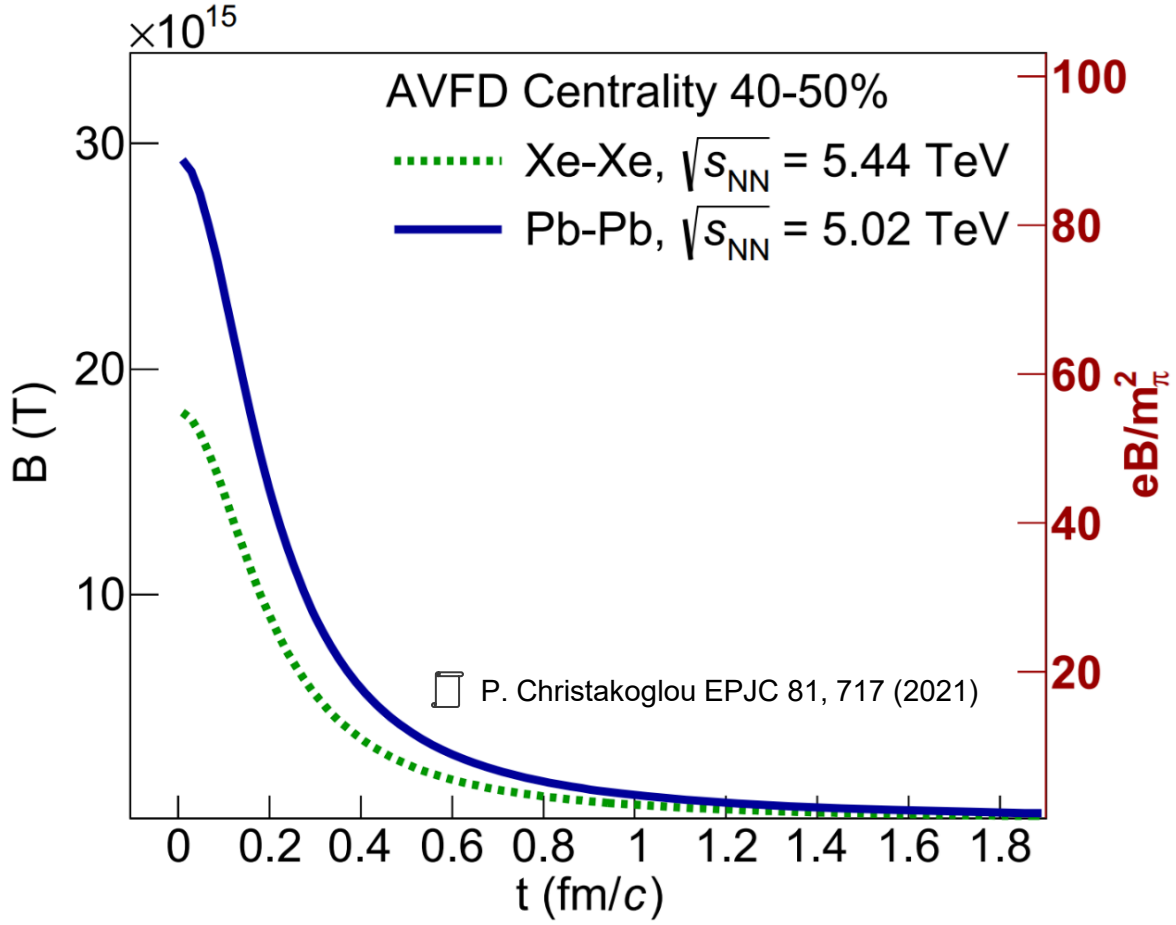
ALICE, PRC 101.044611 (2020) STAR, Nature 548 (2017) 62



Polarization in AA collisions

- Charged spectator motion produces magnetic field $(B) \sim 10^{15}$T
  - Decreases over time
  - Lifetime increases from mid to forward rapidity





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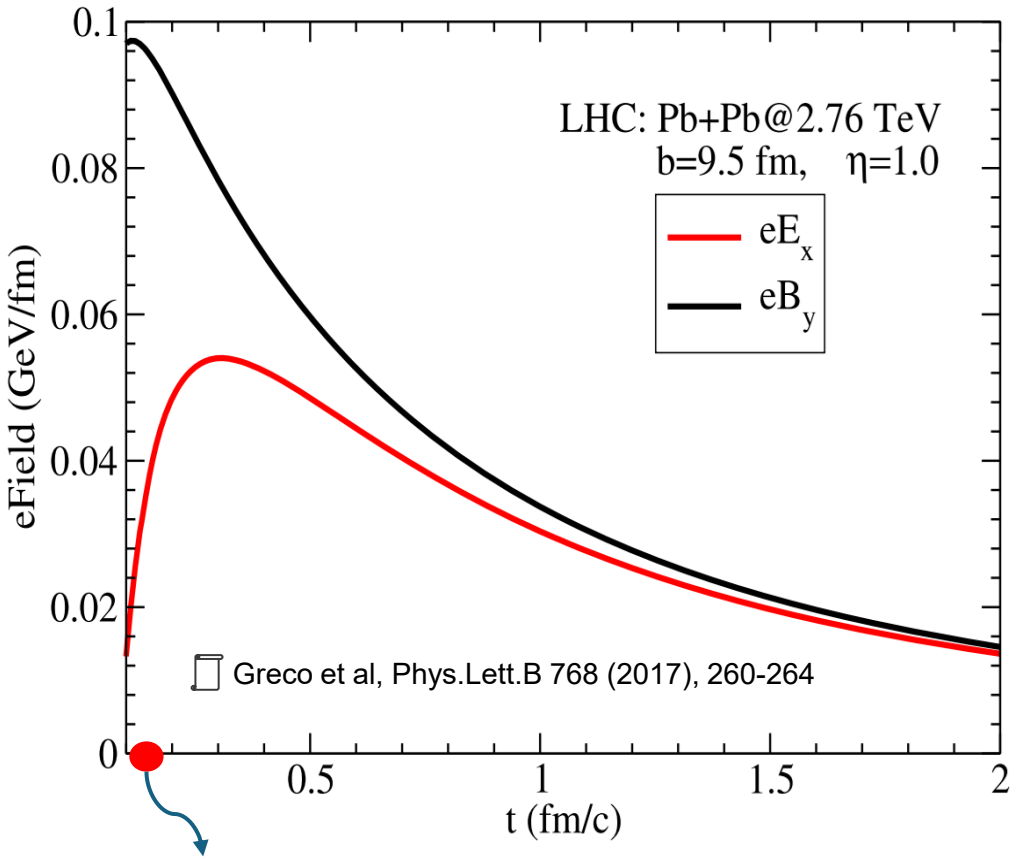
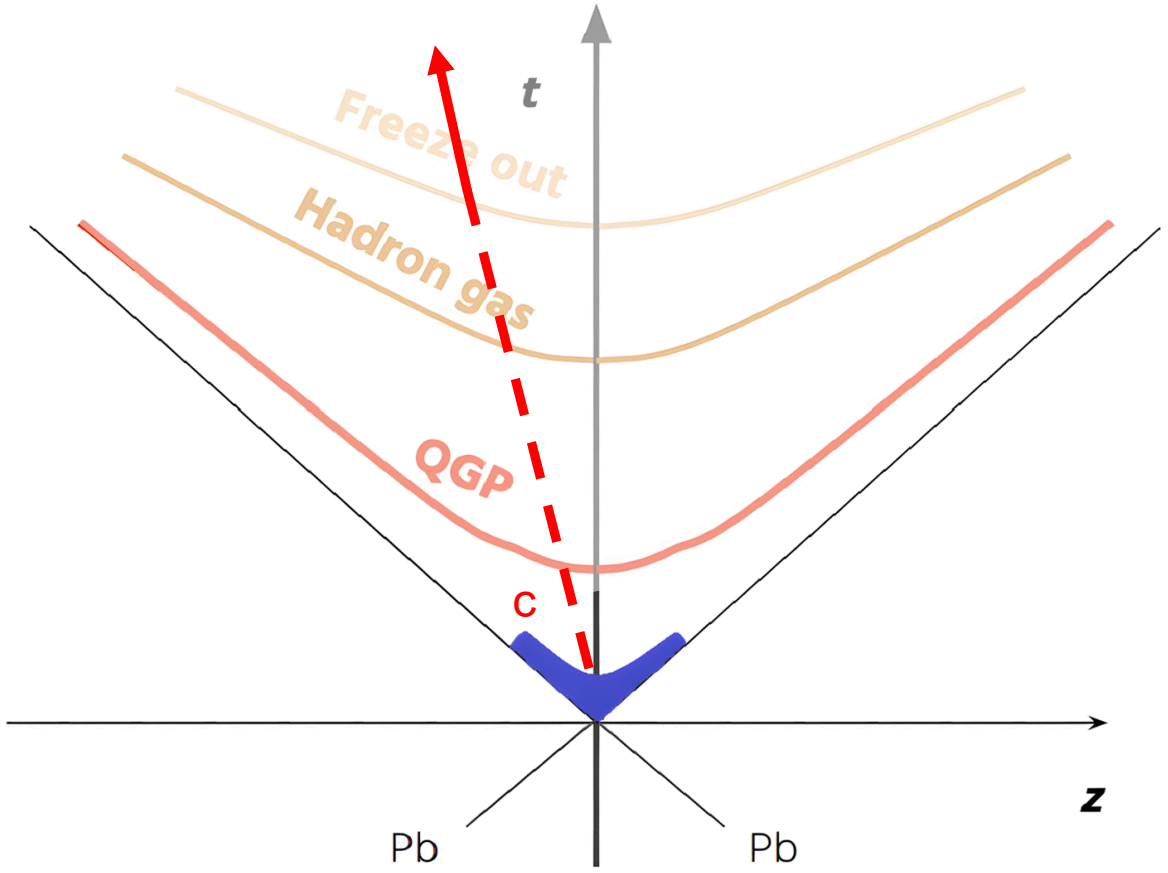


- Charm quarks produced in early stages
  $\mathbf{t \sim 1/m_q \sim 0.1\ fm/c}$



"Simplified" spacetime evolution of heavy-ion collisions

Polarization in AA collisions

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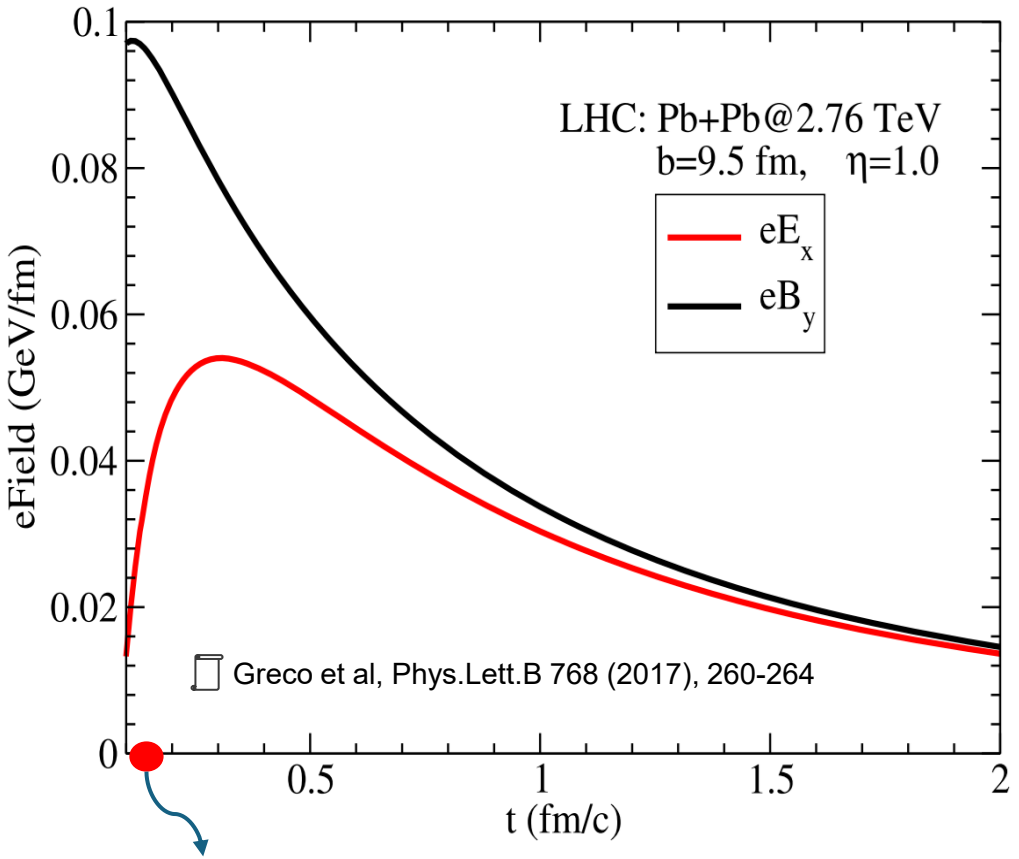

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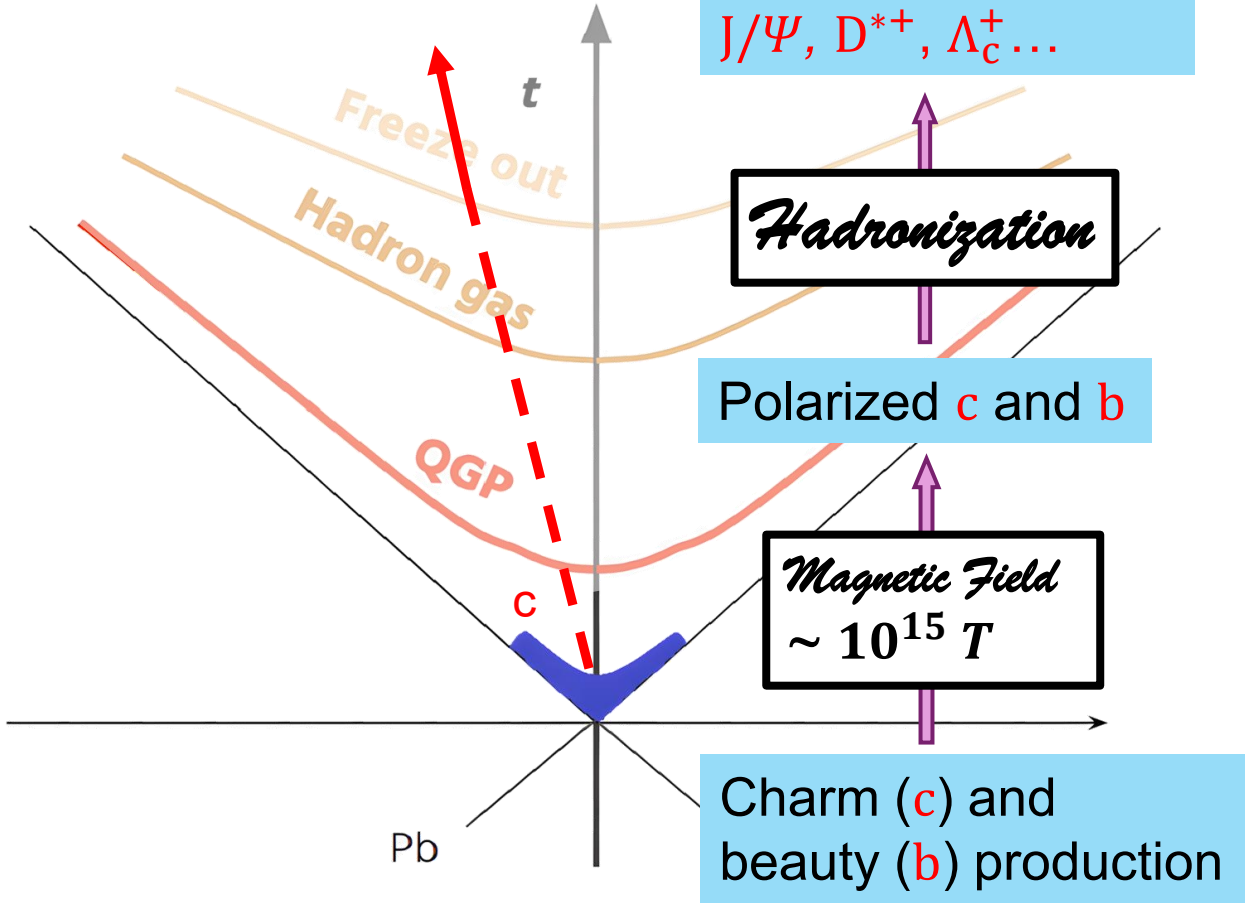


"Simplified" spacetime evolution of heavy-ion collisions

Polarization and spin alignment

$\Lambda_c^+ \rightarrow p\, K^{*0}$ $\rightarrow p\, K^- \pi^+$

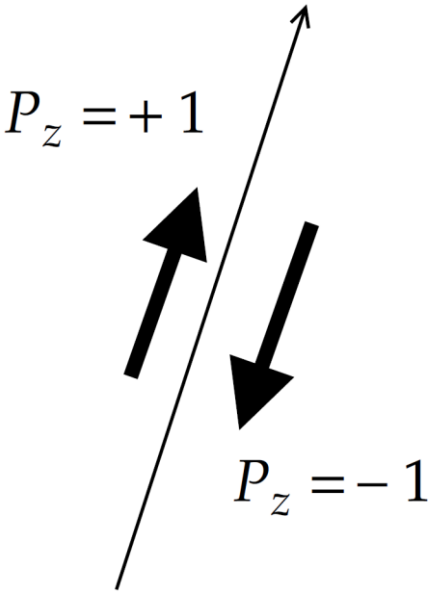
$J = 1/2$ fermion

Longitudinal polarization:

$$P_z = \rho_{\frac{1}{2},\frac{1}{2}} - \rho_{-\frac{1}{2},-\frac{1}{2}}$$

Deviation from 0 is polarization, i.e. preferential way for the particle spin (“up”, “down”)

$$\frac{dN}{d\cos\vartheta^*} = \int \frac{dN}{d\Omega} d\varphi^* = \frac{N}{2}(1 + \alpha_H P_z \cos\vartheta^*)$$



- Decay parameter $\alpha_{\Lambda_c^+} = -\alpha_{\overline{\Lambda_c^+}}$
- It quantifies the “sensitiveness” to the mother-particle polarization, i.e. the probability of the daughter momentum to align along a certain direction due to mother polarization
- It depends on the decay channel

$\Lambda_c^+ \rightarrow p\, K^{*0}$: $\alpha_{\Lambda_c^+} = -\alpha_{\overline{\Lambda_c^+}} = 0.873 \pm 0.010 \pm 0.023 \pm 0.003$ LHCb, Phys. Rev, D 108, 012023

$\Lambda_c^+ \rightarrow p\, K_S^0$: $\alpha_{\Lambda_c^+} = -\alpha_{\overline{\Lambda_c^+}} = -0.784 \pm 0.008 \pm 0.006$ LHCb, arXiv: 2409.02759v2 [hep-ex]

$\Lambda_c^+ \rightarrow \pi^+ \Lambda$: $\alpha_{\Lambda_c^+} = -\alpha_{\overline{\Lambda_c^+}} = -0.785 \pm 0.006 \pm 0.003$ LHCb, arXiv: 2409.02759v2 [hep-ex]

Polarization and spin alignment

$D^{*+} \rightarrow D^0 + \pi^+ \rightarrow (K^- + \pi^+) + \pi^+$

$J = 1$
vector meson

- For vector mesons the spin direction is unknown
- ~~Polarization~~ → spin alignment

$$\frac{dN}{d\cos\theta^*} = \int \frac{dN}{d\Omega} d\varphi^* = N\left[(1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2\theta^*\right]$$

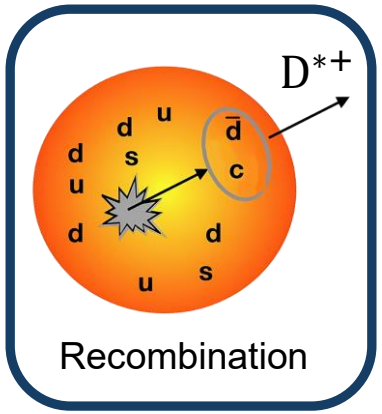
- Spin-density matrix element ρ_{00}
  - $\rho_{00} \neq 1/3 \Rightarrow$ Spin alignment observed, i.e. there is a preferential spin state
  - $\rho_{00} = 1/3 \Rightarrow$ Spin alignment not observed

In fact, we do not know anything about $\rho_{-1,-1}$ and $\rho_{+1,+1}$

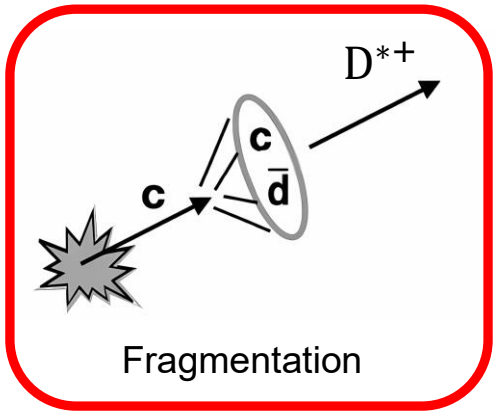
$$\rho = \begin{pmatrix} \rho_{-1,-1} & \rho_{-1,0} & \rho_{-1,1} \\ \rho_{0,-1} & \boldsymbol{\rho_{0,0}} & \rho_{0,1} \\ \rho_{1,-1} & \rho_{1,0} & \rho_{-1,1} \end{pmatrix}$$

Spin alignment in AA collisions

- Hadron spin-alignment measurements rely on spin density matrix element (ρ_{00})
  - $\rho_{00} = 1/3 \rightarrow$ No spin alignment
  - $\rho_{00} \neq 1/3 \rightarrow$ Spin alignment observed
- Vector meson spin alignment governed by two mechanisms:



Recombination



Fragmentation

Quark recombination

$$\rho_{00} = \frac{1 - P_q \cdot P_{\bar{q}}}{3 + P_q \cdot P_{\bar{q}}} = \begin{cases} \leqslant 1/3^* \Rightarrow \vec{\mathrm{B}} \\ < 1/3^* \Rightarrow \vec{\mathrm{L}} \end{cases}$$

*>⅓ q=0, < ⅓ q ≠ 0
P_q: Polarization of quark

Wang et al, Phys. Rev. C 97, 034917

Quark fragmentation

$$\rho_{00} = \frac{1 + \beta \cdot P_{\bar{q}}^2}{3 - \beta \cdot P_{\bar{q}}^2} > 1/3$$

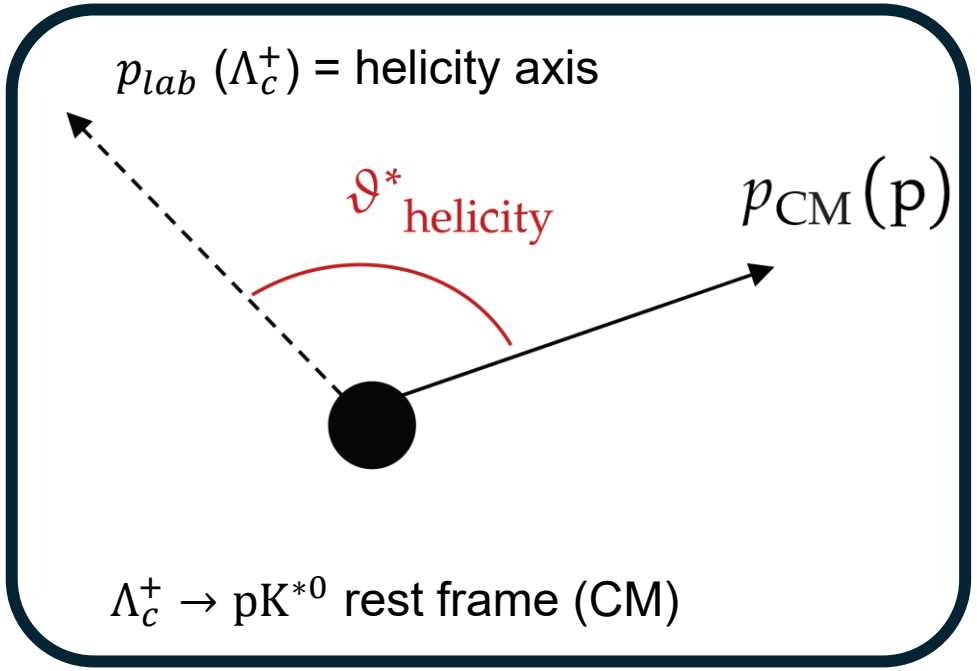
β: Correlation between constituent quark and antiquark

Liang et al, Physics Letters B 629 (2005) 20–26

Low p_{T} — $\boldsymbol{p_{\mathrm{T}}(\mathrm{GeV}/c)}$ — High p_{T}

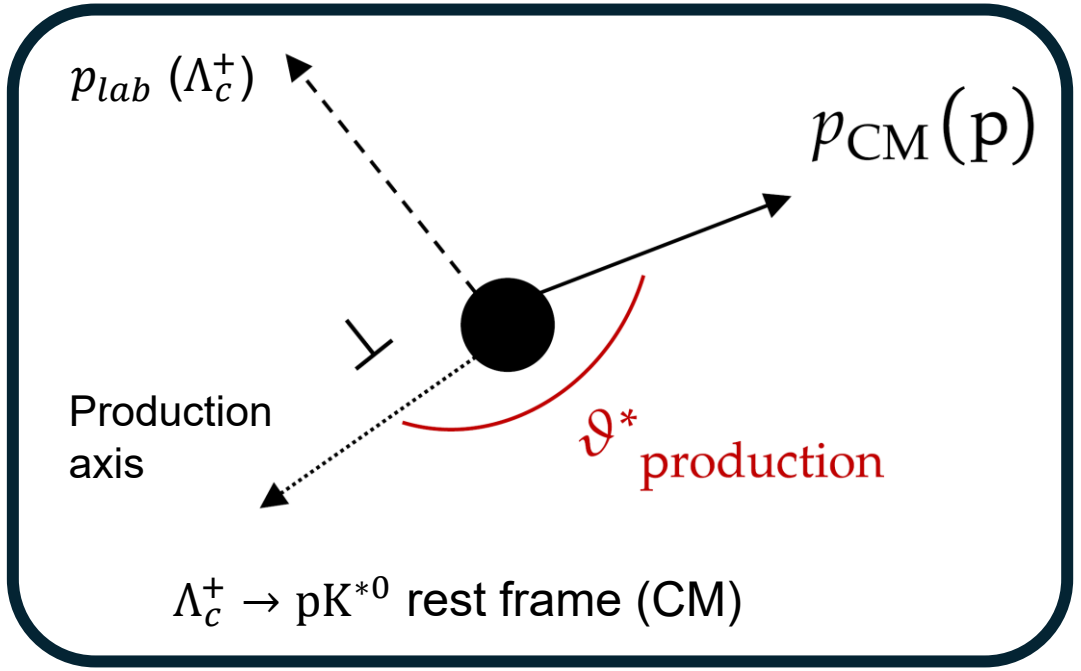
Analysis frames

Helicity frame



$\vartheta^*_{helicity}$: Angle between proton momentum in Λ_c^+ rest frame and the p_{lab} (Λ_c^+) direction

Production frame

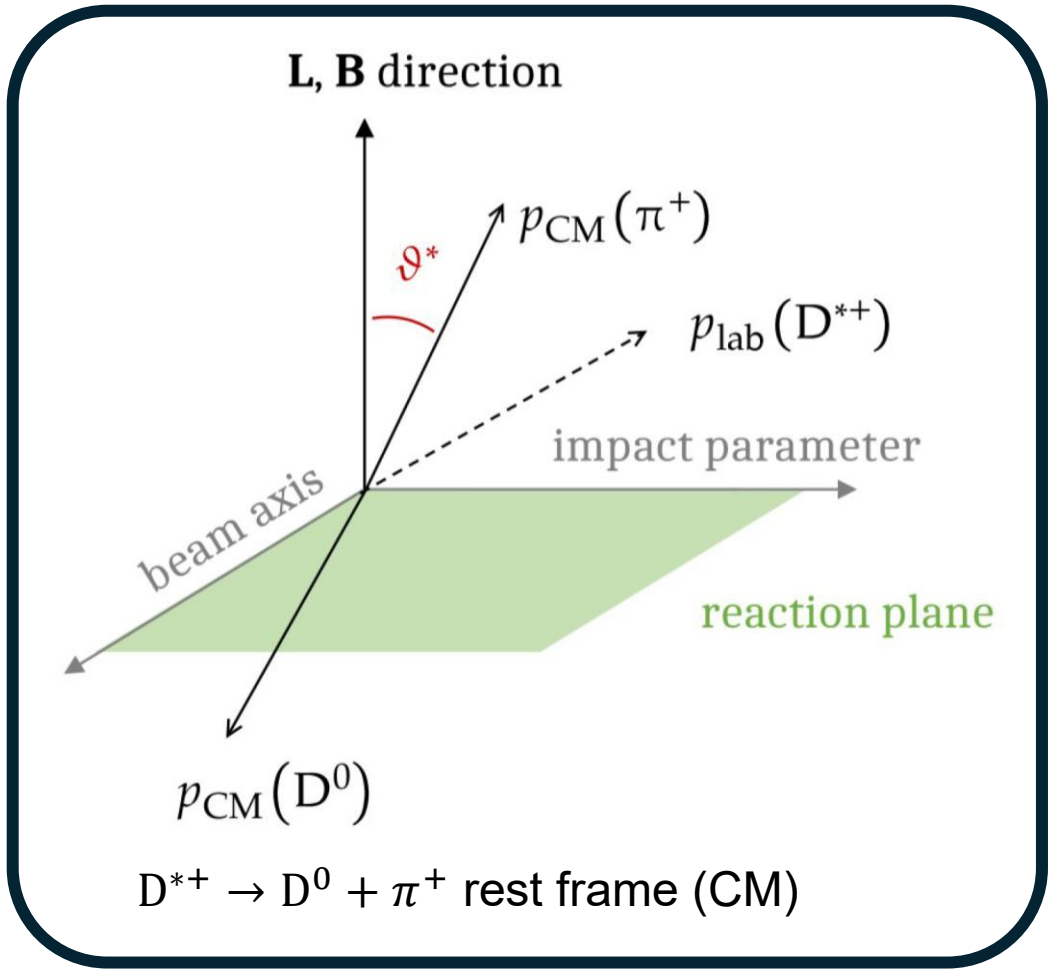


$\vartheta^*_{production}$: Angle between proton momentum in Λ_c^+ rest frame and the production axis direction

Production axis: The transverse direction perpendicular to both the beam and helicity axes

Analysis frames

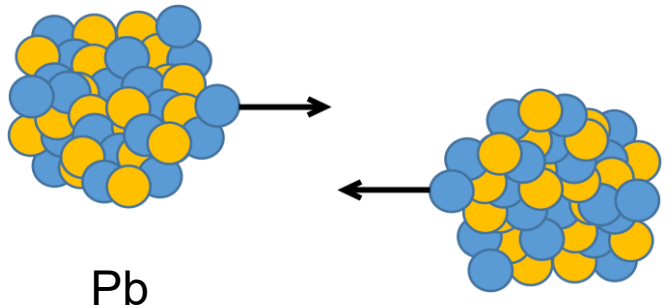
Event-plane frame



$\mathrm{D}^{*+} \rightarrow \mathrm{D}^0 + \pi^+$ rest frame (CM)

ϑ^*: Angle between the pion momentum in the D^{*+} rest frame and the quantization axis orthogonal to reaction plane, i,e. along the L, B direction

Well defined only in heavy-ion collisions



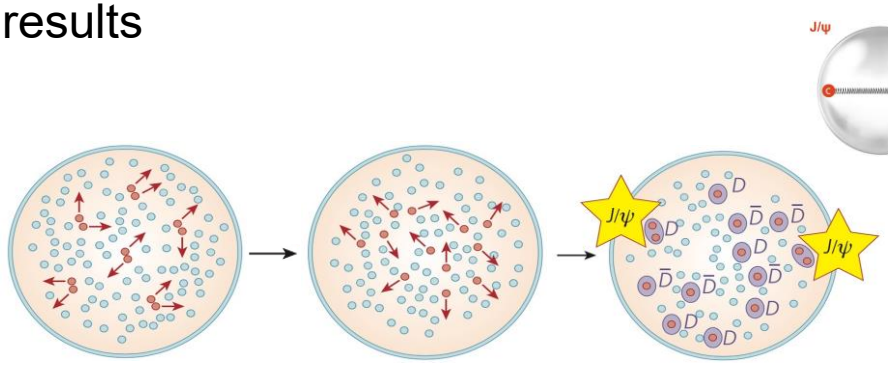
J/ψ polarization measurement

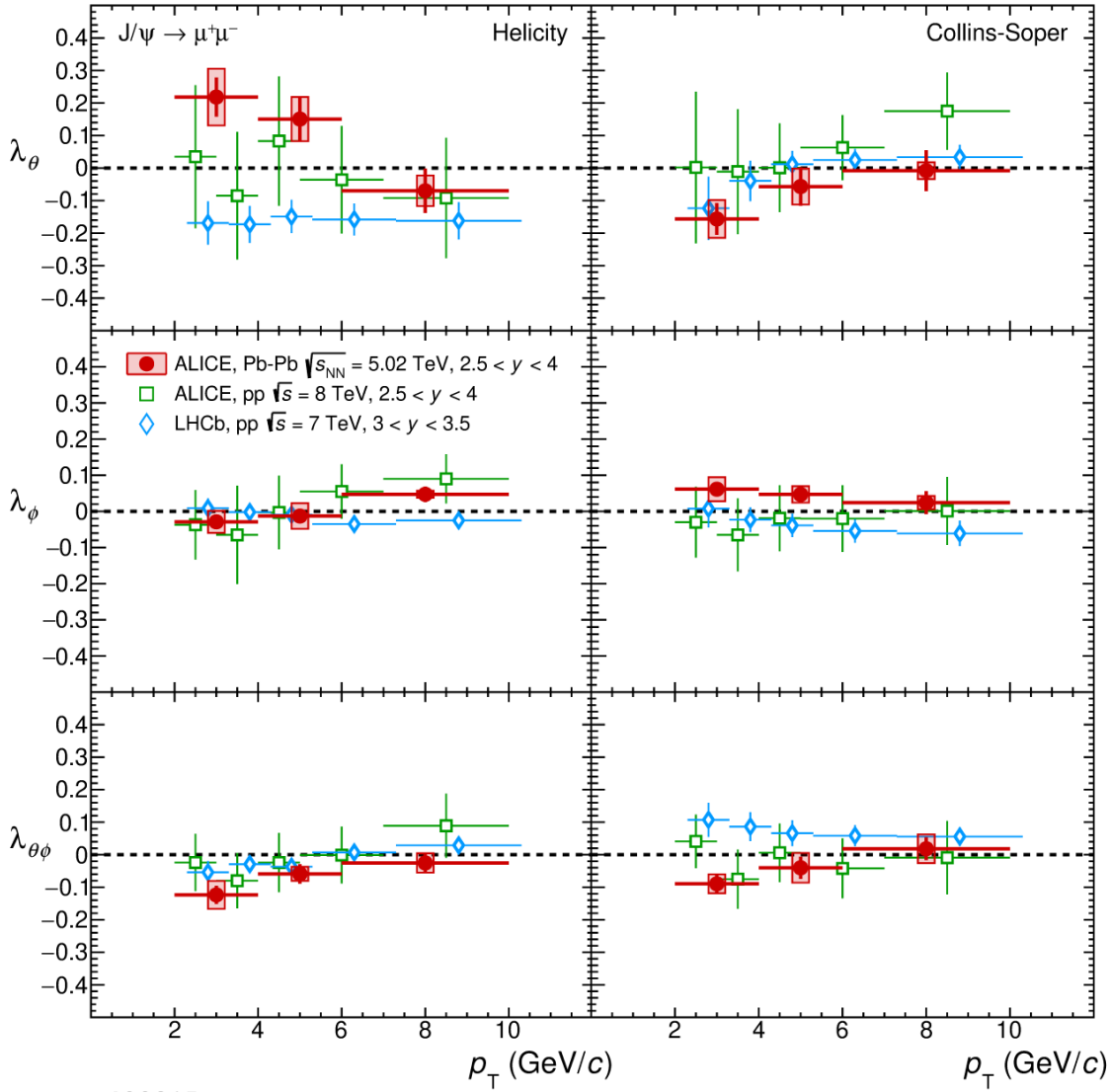
$$\lambda_\theta = \frac{1-3\rho_{00}}{1+\rho_{00}}$$

Xiaozhi's presentation

- First measurement of the polarization parameters for J/ψ production in Pb–Pb collisions at LHC energies
- Dominant contribution from (re-)generation in Pb–Pb collisions at LHC energies
- Significant difference in $\lambda_\theta^{\mathrm{HE}}$ with respect to the LHCb results

High (LHC) energy





ALI-PUB-490215

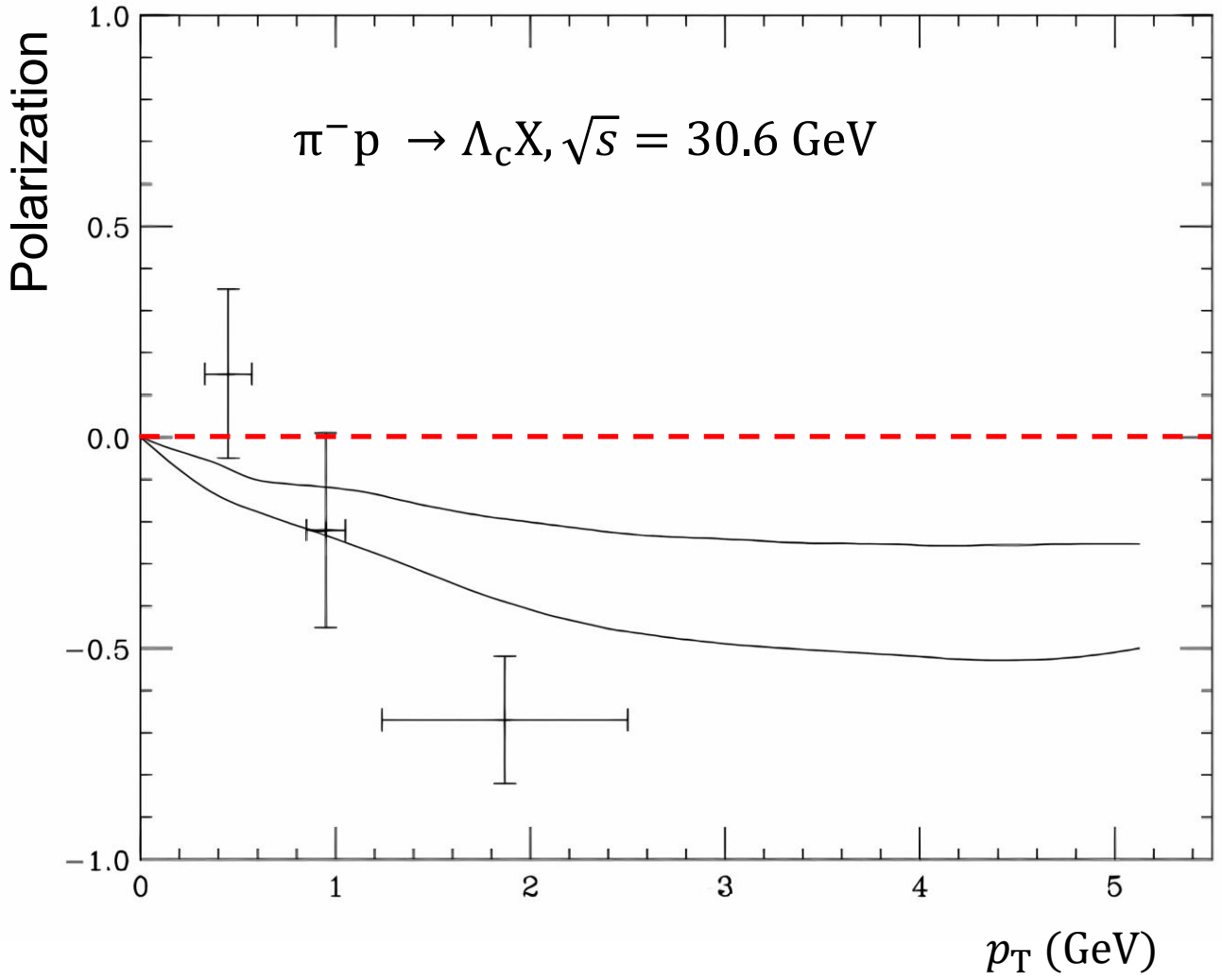
ALICE Collaboration, Phys. Lett. B 815 (2021) 136146

Polarization in pp collisions

- Hint of Λ_c^+ polarization at high p_T in $\pi^- p$ collisions with $p(\pi^-) = 500\ \mathrm{GeV}/c$ by E791 experiment at Fermilab

- Λ_c^+ polarization predicted by quark-diquark model calculations with spin-dependent fragmentation functions.

What about Λ_c^+ at LHC?



E791 Collaboration, Phys. Lett. B471: 449-459, 2000

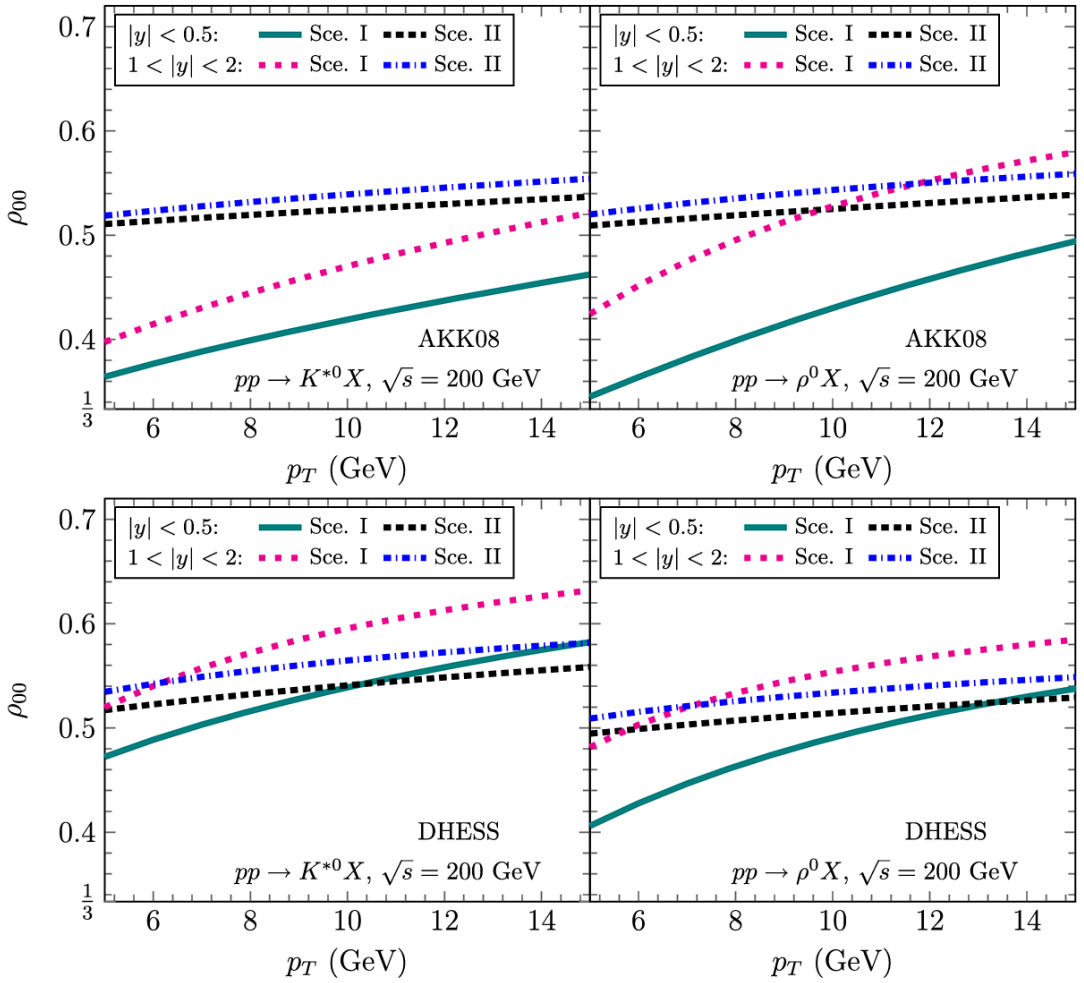
Polarization in pp collisions

- For vector mesons the spin direction is unknown: Polarization now well defined
  - Hadron spin-alignment measurements rely on spin density matrix element (ρ_{00})

K. Chen, Z. Liang, Y. Song, S. Wei, Phys. Rev. D 102, 034001

- Spin-dependent fragmentation functions (FFs) extracted from ρ_{00} measurements of K^{*0} and ρ^0 vector mesons in $\mathrm{e}^+\mathrm{e}^-$ collisions
- Used to predict ρ_{00} in ultrarelativistic pp collisions
- Significant ρ_{00} predicted at high p_T, and strongly dependent on FFs assumptions

What about D^{*+} at LHC?



ALICE detector

Central barrel detectors
$|\eta| < 0.9$

1) **ITS**
- **Tracking**
- **Primary and secondary vertex reconstruction**

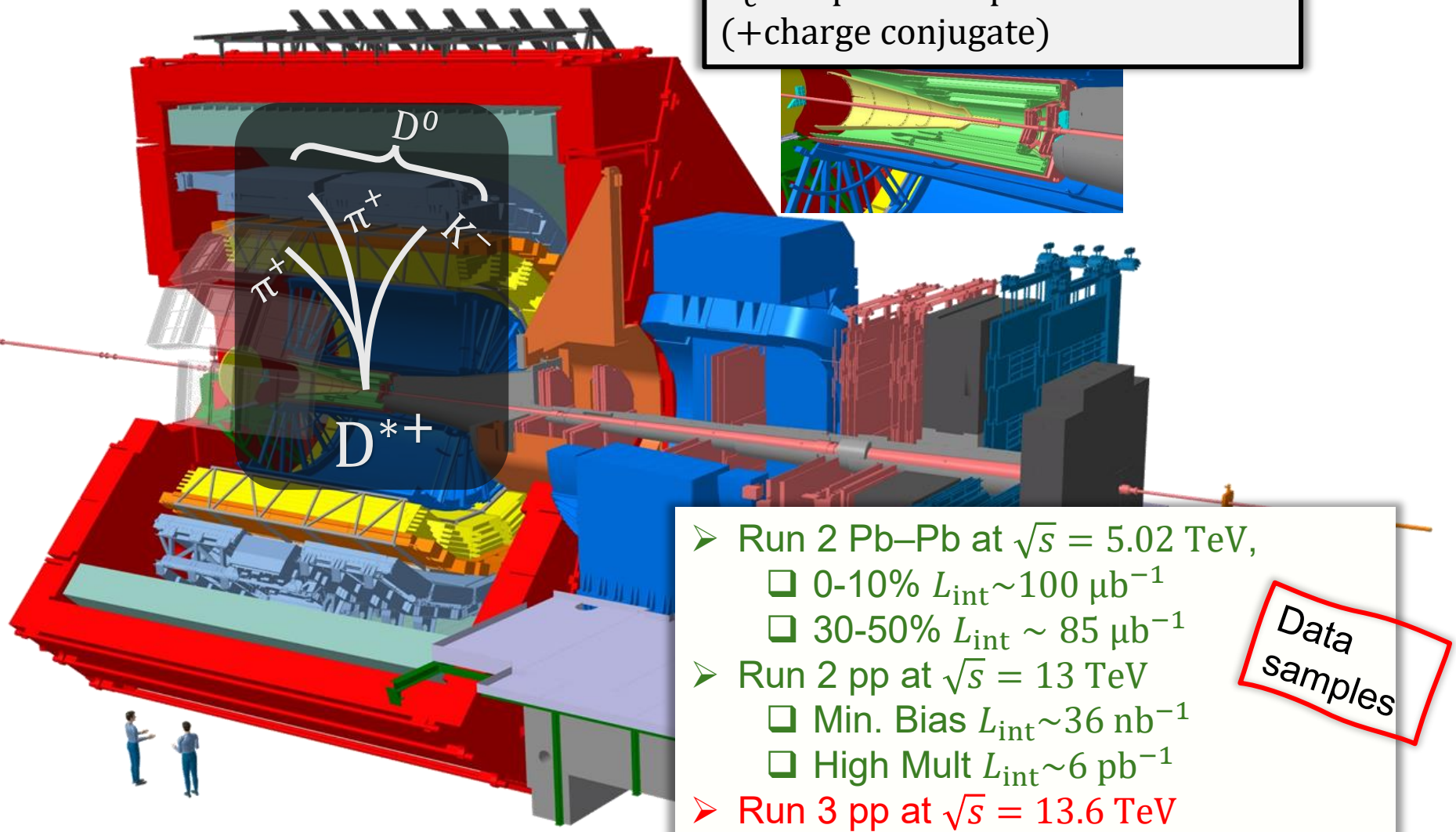
2) **TPC**
- **Vertexing**
- **Tracking**
- **Particle identification**

3) **TOF**
- **Particle identification**

Excellent tracking and PID capabilities down to very low momentum

ALICE: LHC Run 3

$D^{*+} \to D^0 + \pi^+ \to (K^- + \pi^+) + \pi^+$
$\Lambda_c^+ \to p\ \bar{K}^{*0} \to p\ K^-\ \pi^+$
(+charge conjugate)



ALICE Collaboration, JINST (2008) S08002

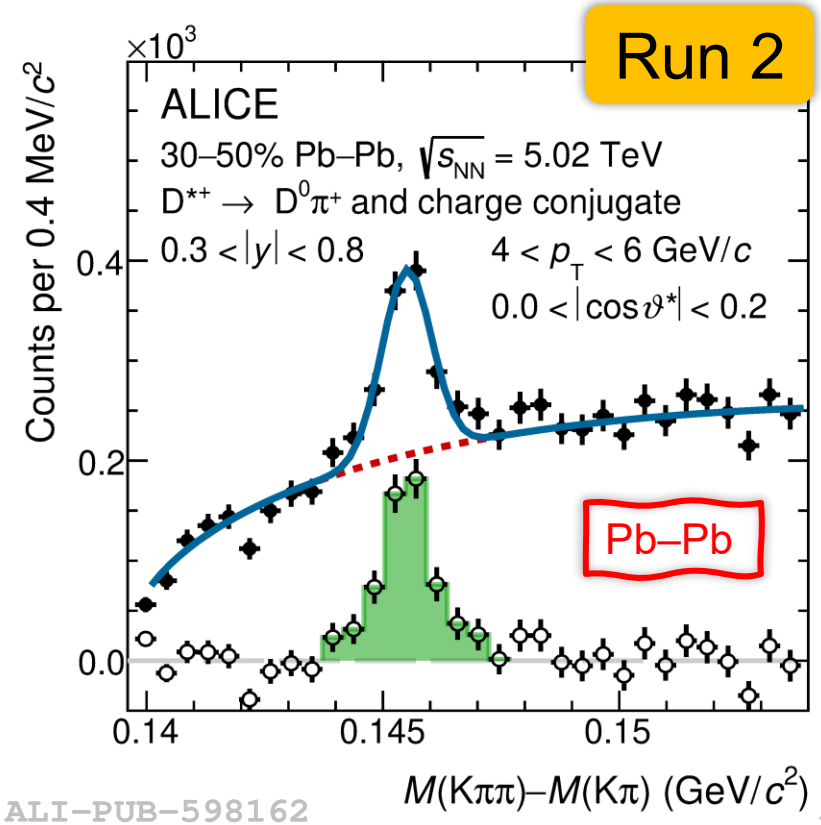
Data samples

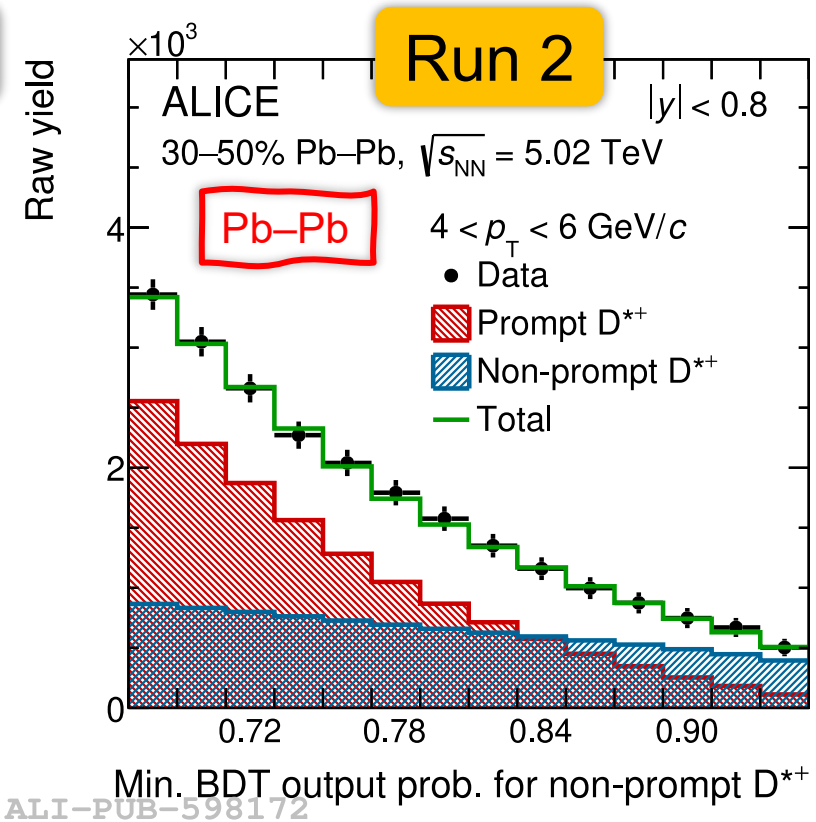
- Run 2 Pb–Pb at $\sqrt{s} = 5.02$ TeV,
  - 0-10% $L_{\text{int}} \sim 100\ \mu b^{-1}$
  - 30-50% $L_{\text{int}} \sim 85\ \mu b^{-1}$
- Run 2 pp at $\sqrt{s} = 13$ TeV
  - Min. Bias $L_{\text{int}} \sim 36\ nb^{-1}$
  - High Mult $L_{\text{int}} \sim 6\ pb^{-1}$
- Run 3 pp at $\sqrt{s} = 13.6$ TeV
  - MB $L_{\text{int}} \sim 10\ pb^{-1}$

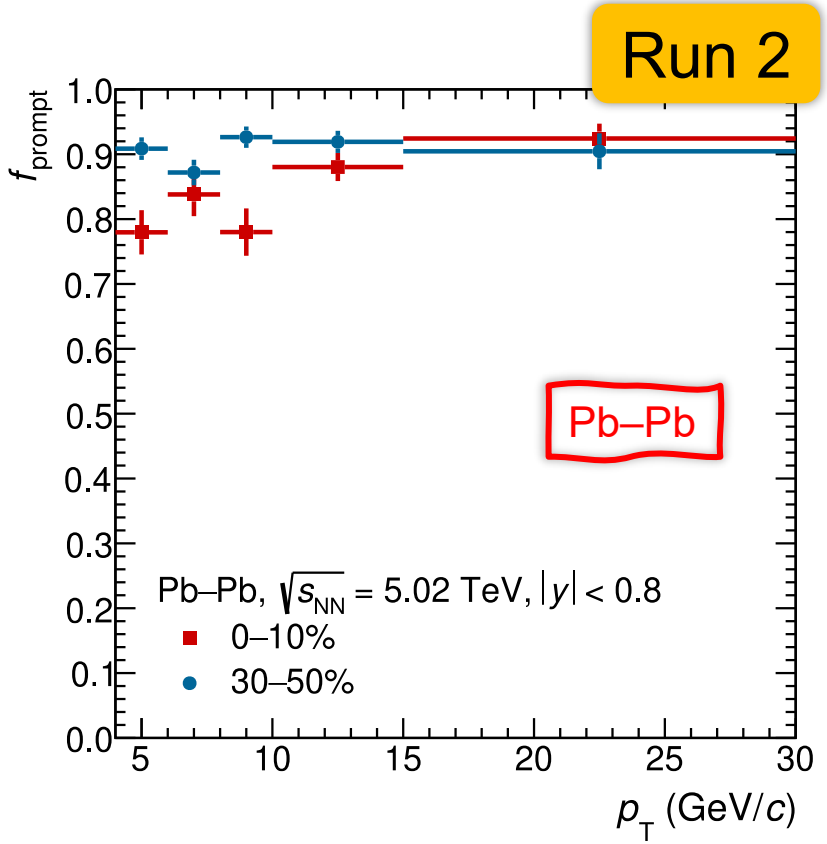
D^{*+} yield extraction

For D^{*+} analysis in pp and Pb–Pb collisions, Boosted Decision Trees (BDT) with 3-class (prompt, non-prompt, background) classification are used to:

- Reduce the combinatorial background
- Separate prompt and non-prompt charm hadrons





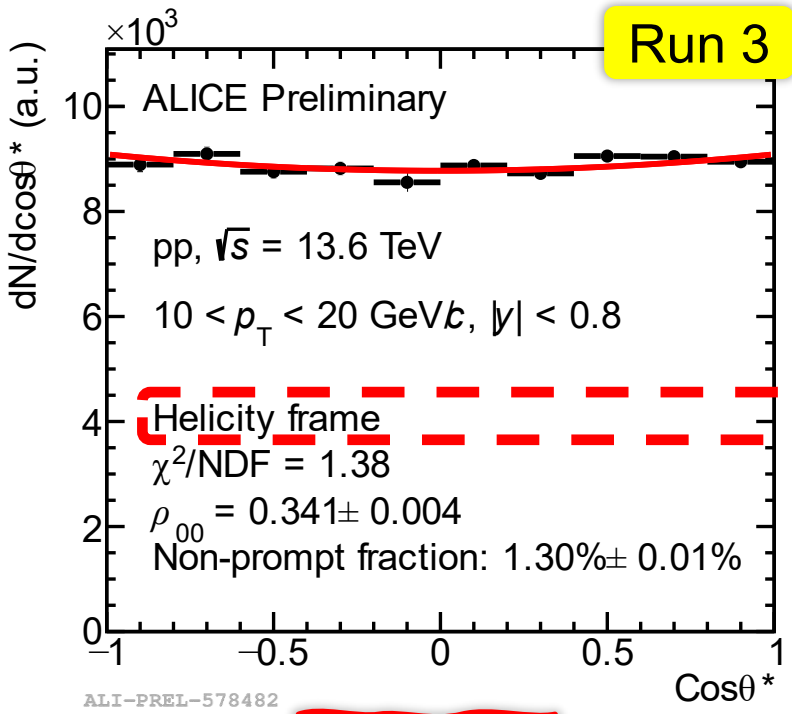


ρ_{00} extraction

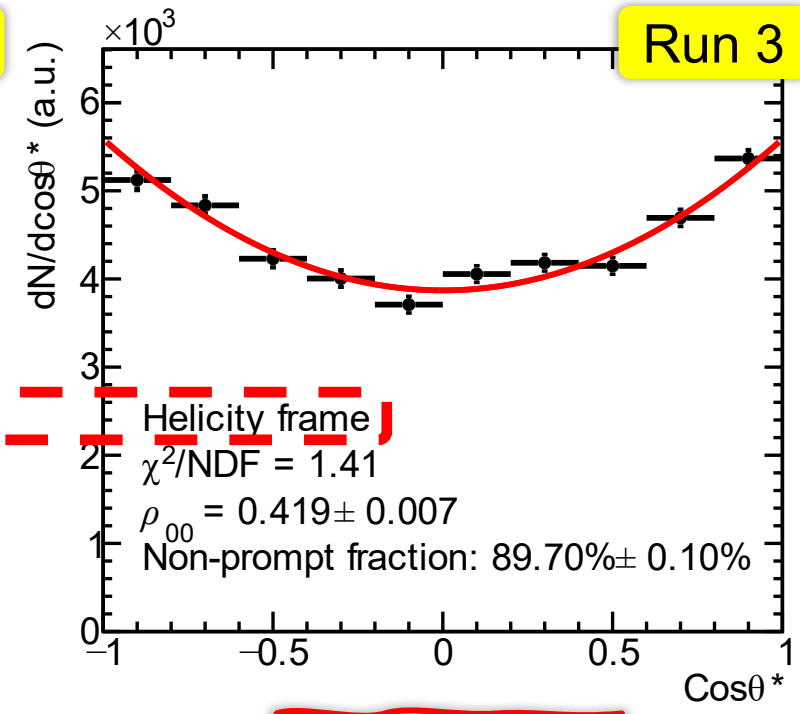
- **Helicity:** Direction of vector meson momentum
- **Production:** Direction perpendicular to vector meson momentum and beam axis

Spin alignment:

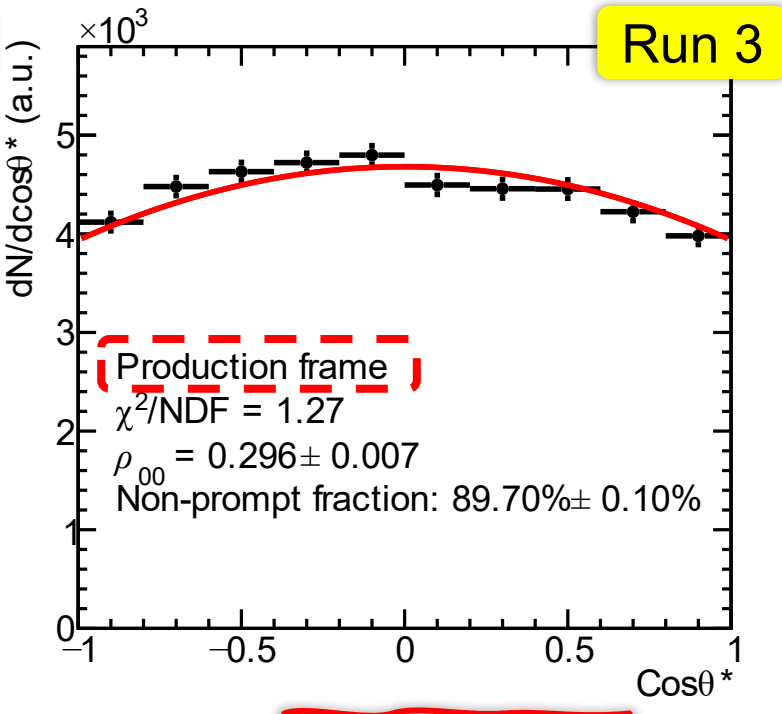
$$\frac{dN}{d\cos\theta^*} = N_0[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*]$$



Prompt D^{*+}



Non-prompt D^{*+}



Non-prompt D^{*+}

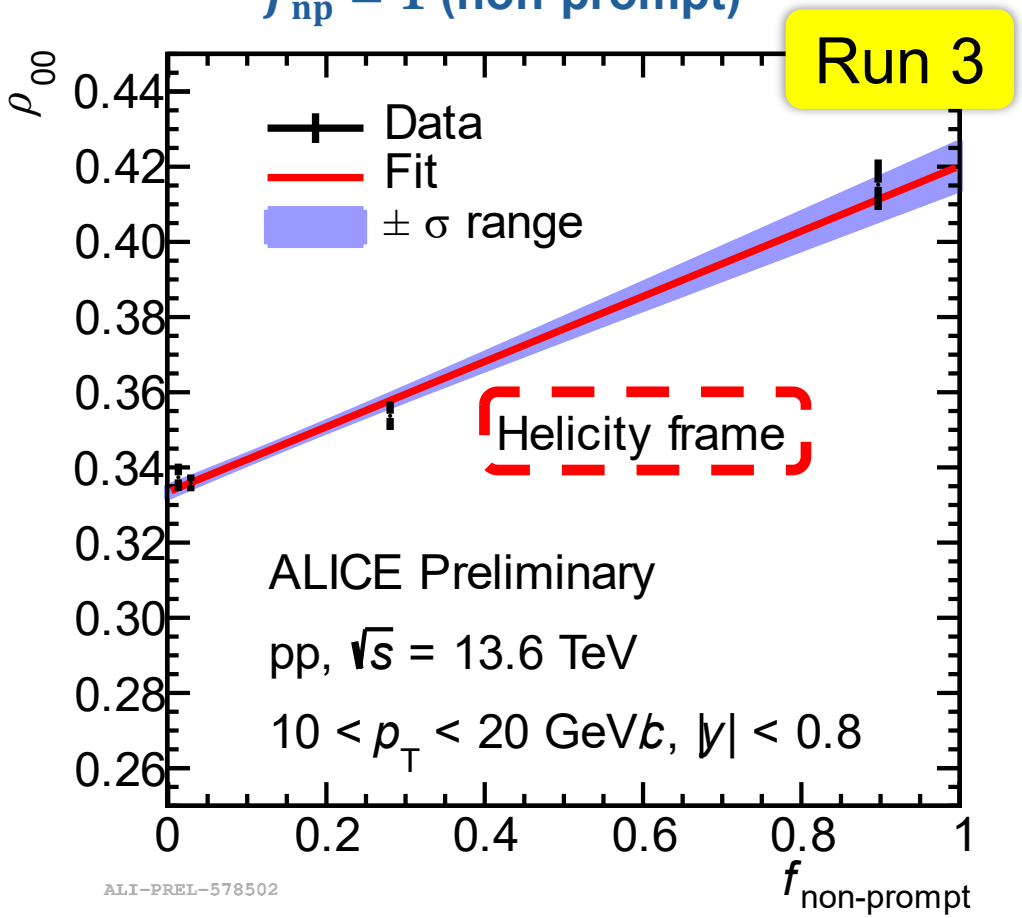
ρ_{00} extraction

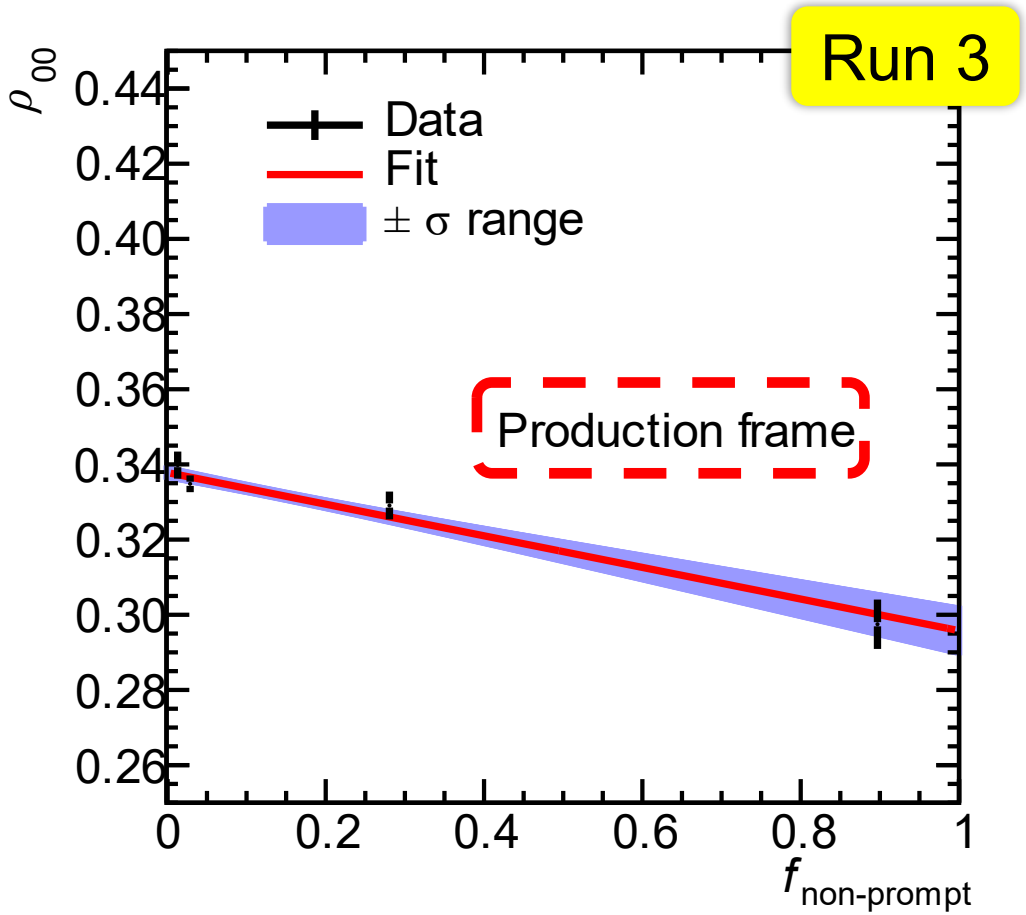
- **Analysis repeated vs. f_{np}** in each p_{T} interval
- **Extrapolation to $f_{np} = 0$ (prompt)** and

  $f_{\mathrm{np}} = 1$ (non-prompt)

Extrapolation:

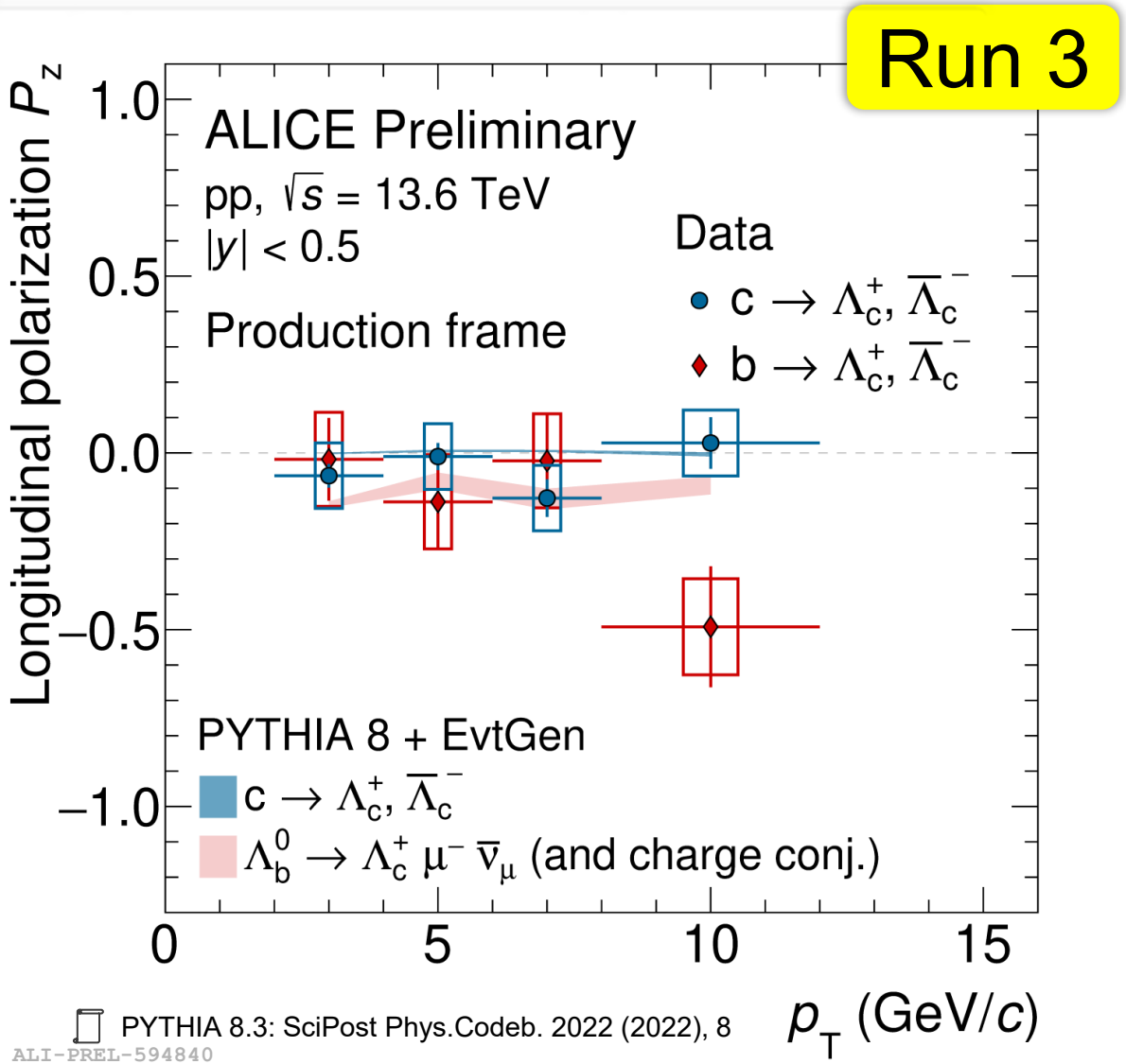
$$\rho_{00} = f_{\mathrm{prompt}} \cdot \rho_{00}^{\mathrm{prompt}} + f_{\mathrm{non-prompt}} \cdot \rho_{00}^{\mathrm{non-prompt}}$$





Results

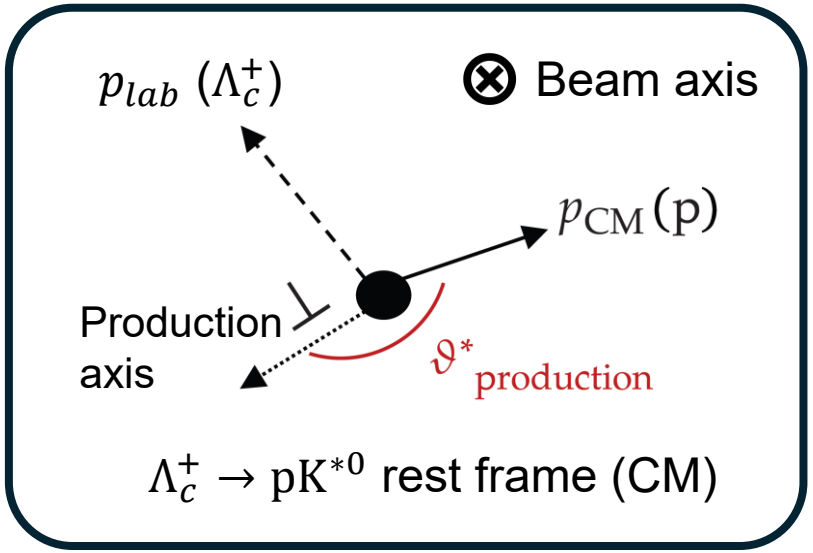
Λ_c^+ polarization in pp collisions



PYTHIA 8.3: SciPost Phys.Codeb. 2022 (2022), 8

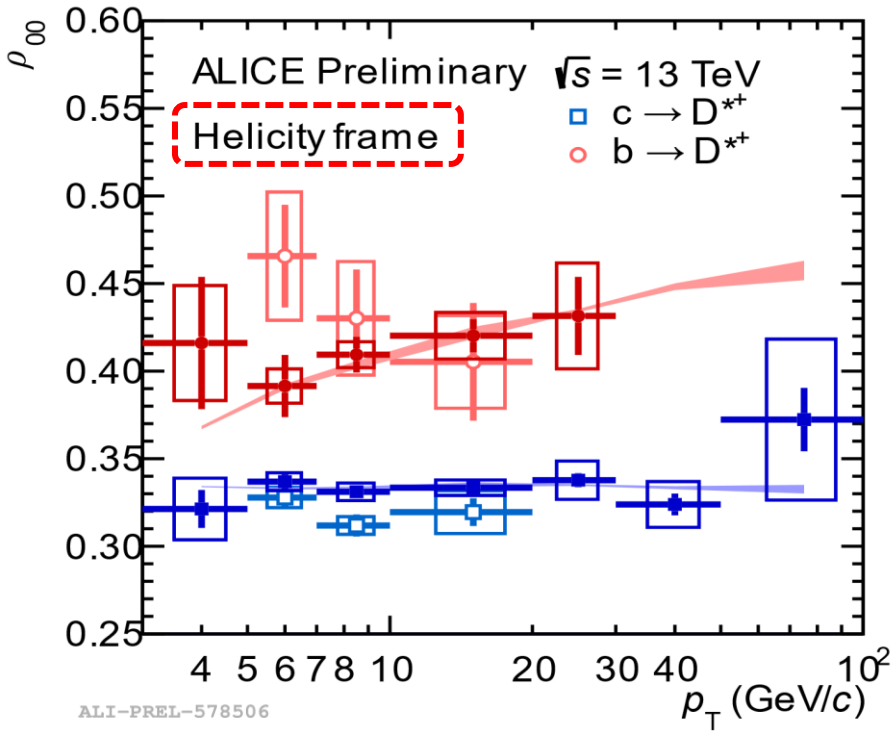
ALI-PREL-594840

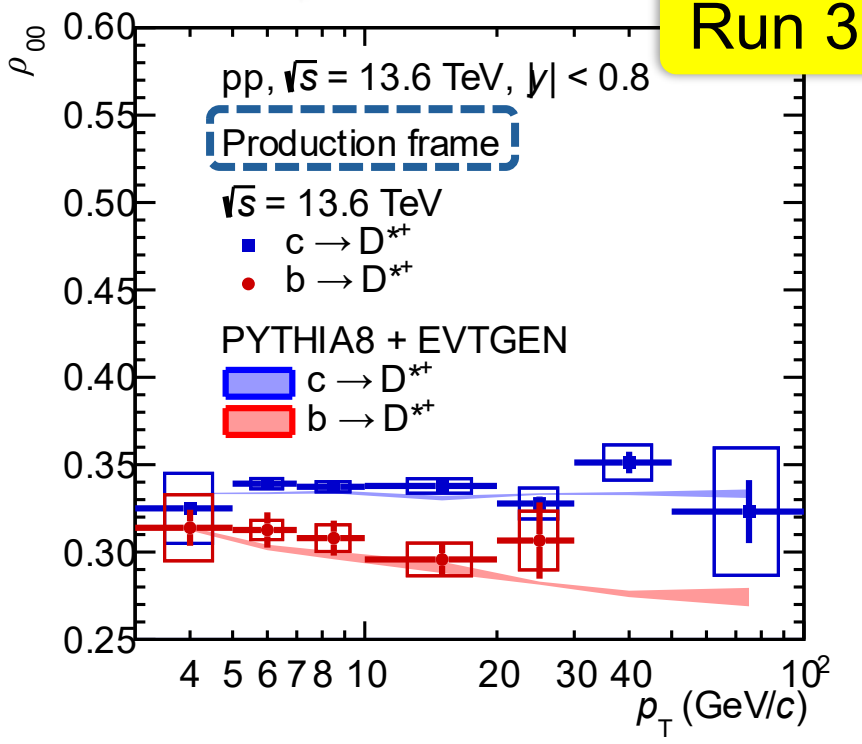
EVTGEN: EPJ Web Conf. 295 (2024), 03012



- First measurement of longitudinal polarization (P_z) of prompt Λ_c^+ (and charge conjugated) in pp collisions at LHC
- No significant (P_z) observed for prompt in the production frame
- Measurement are compatible with PYTHIA8 + EvtGen predictions

D^{*+} spin alignment in pp collisions





Measurement in agreement with prediction of PYTHIA 8.3+EVTGEN

PYTHIA 8.3: SciPost Phys.Codeb. 2022 (2022), 8

EVTGEN: EPJ Web Conf. 295 (2024), 03012

- **Prompt D^{*+}**
  - ⇒ No significant deviation from ρ_{00}= ⅓
  - ⇒ Not supporting any hadronization scenario employing spin-dependent FFs
- **Non-prompt D^{*+}**
  - ⇒ ρ_{00} larger than ⅓ for helicity frame
  - ⇒ Helicity conservation in weak decays of beauty hadrons

D^{*+} spin alignment in pp collisions

Extracted ρ_{00} parameter for

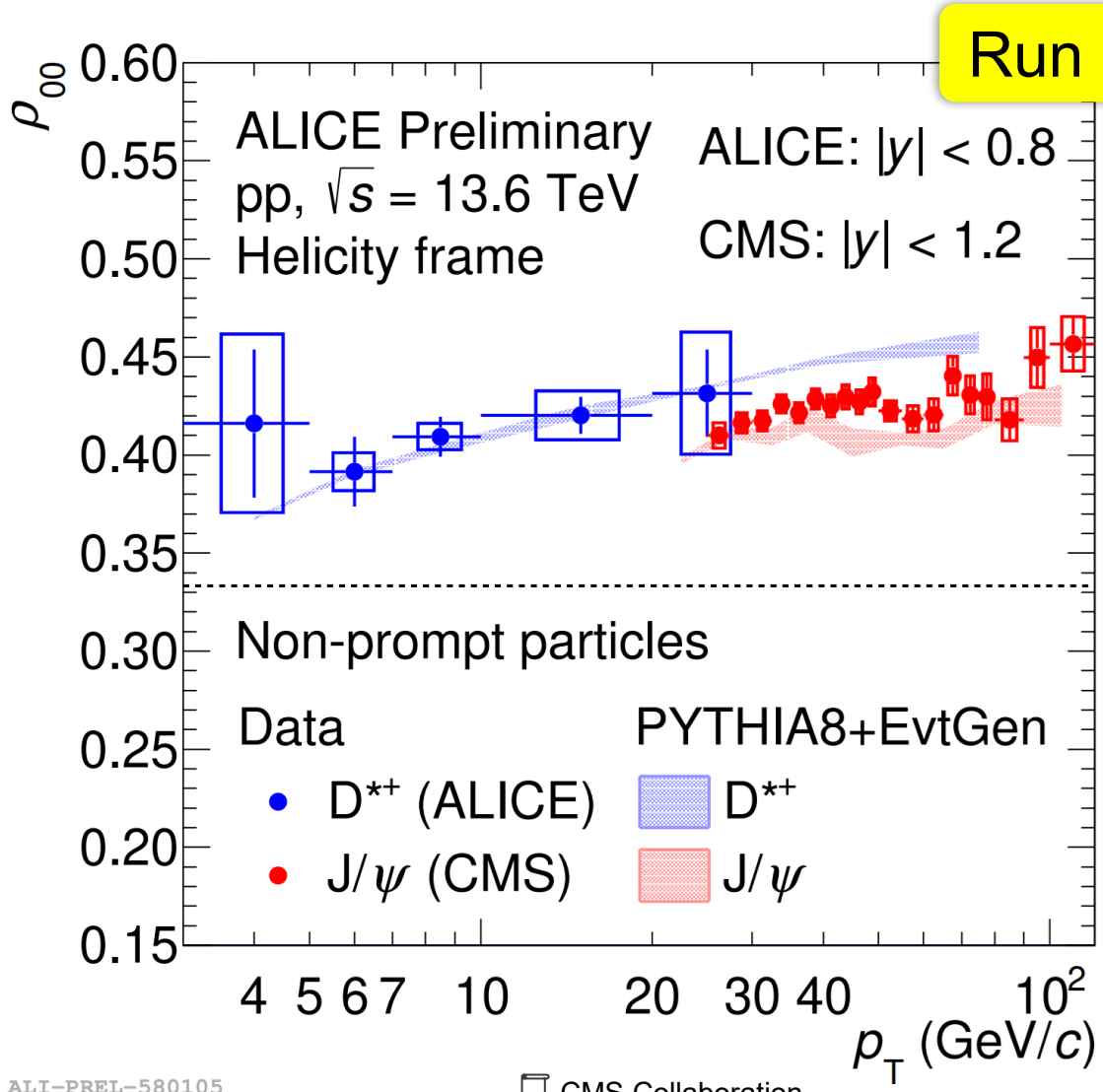
- **Non-prompt D^{*+}**

  ⇒ ρ_{00} larger than ⅓ in helicity frame

The ρ_{00} of non-prompt D^{*+} is compared with the polarization measurement of J/ψ from CMS

- Results are compatible within the uncertainties in the overlapping p_T region

Measurement in agreement with prediction of PYTHIA 8.3+EVTGEN



PYTHIA 8.3: SciPost Phys.Codeb. 2022 (2022), 8

EVTGEN: EPJ Web Conf. 295 (2024), 03012

CMS Collaboration

ALICE Preliminary

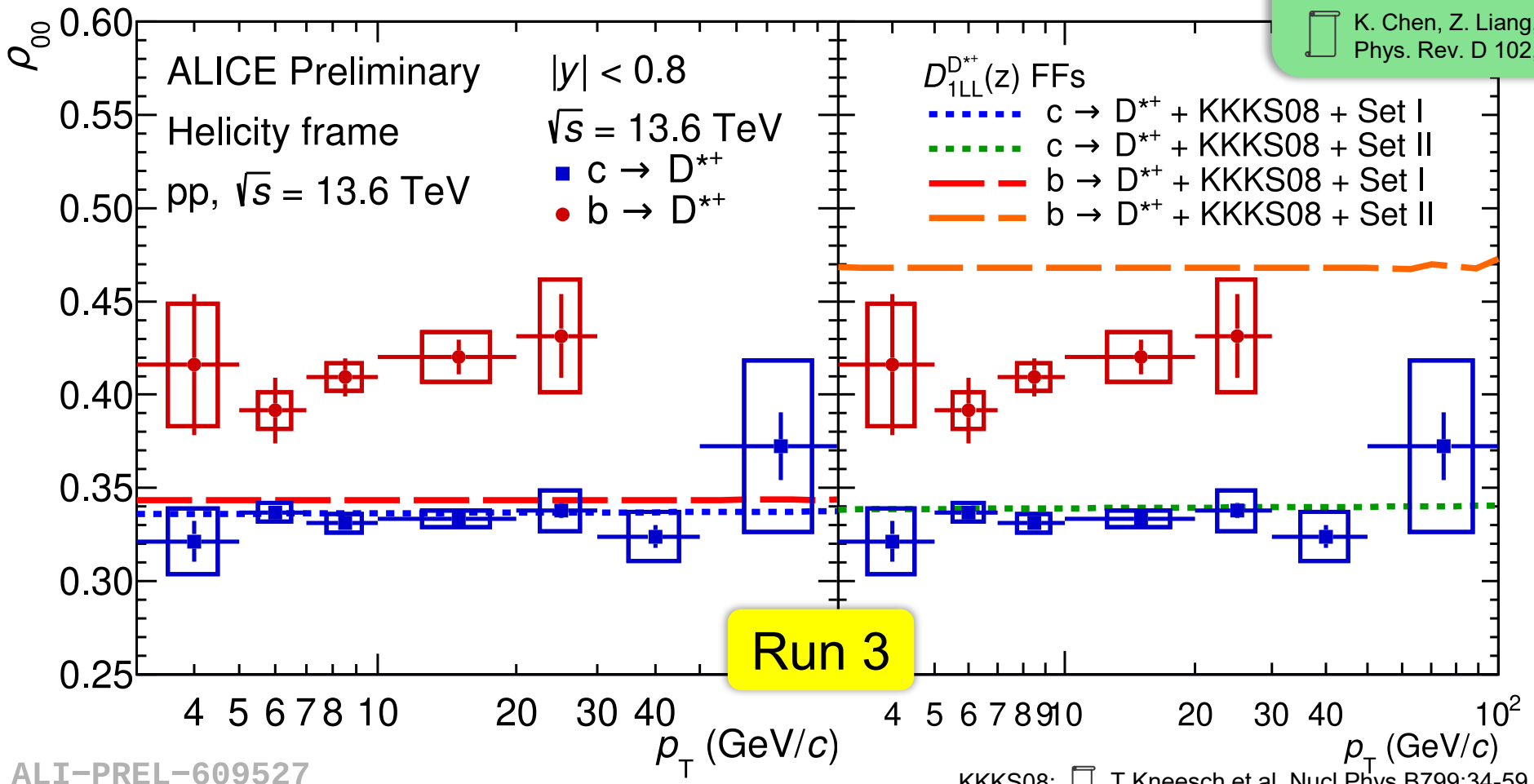
ALICE, Eur. Phys. J. C 78 (2018) 562

D^{*+} spin alignment in pp collisions

- Comparison with model employs spin-dependent fragmentation functions, tuned on e^+e^- measurements
  - Set I includes data from CLEO II, HRS, TPC, SLD and OPAL
  - Set II excludes the OPAL data for the $b \to D^{*+}$ process

For details of the theoretical framework, see:

K. Chen, Z. Liang, Y. Song, S. Wei, Phys. Rev. D 102, 034001



ALI-PREL-609527

KKKS08: T.Kneesch et al. Nucl.Phys.B799:34-59,2008

D^{*+} spin alignment in Pb–Pb collisions

First measurement of D^{*+} spin alignment with respect to the reaction plane in Pb–Pb collisions

Extracted ρ_{00} parameter for **prompt D^{*+}**

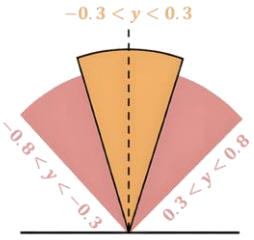
- In less central rapidity regions $0.3 < |y| < 0.8$
  - Central collisions (0-10%):

    Consistent with $\rho_{00} = 1/3$
  - Non-central collisions (30-50%):

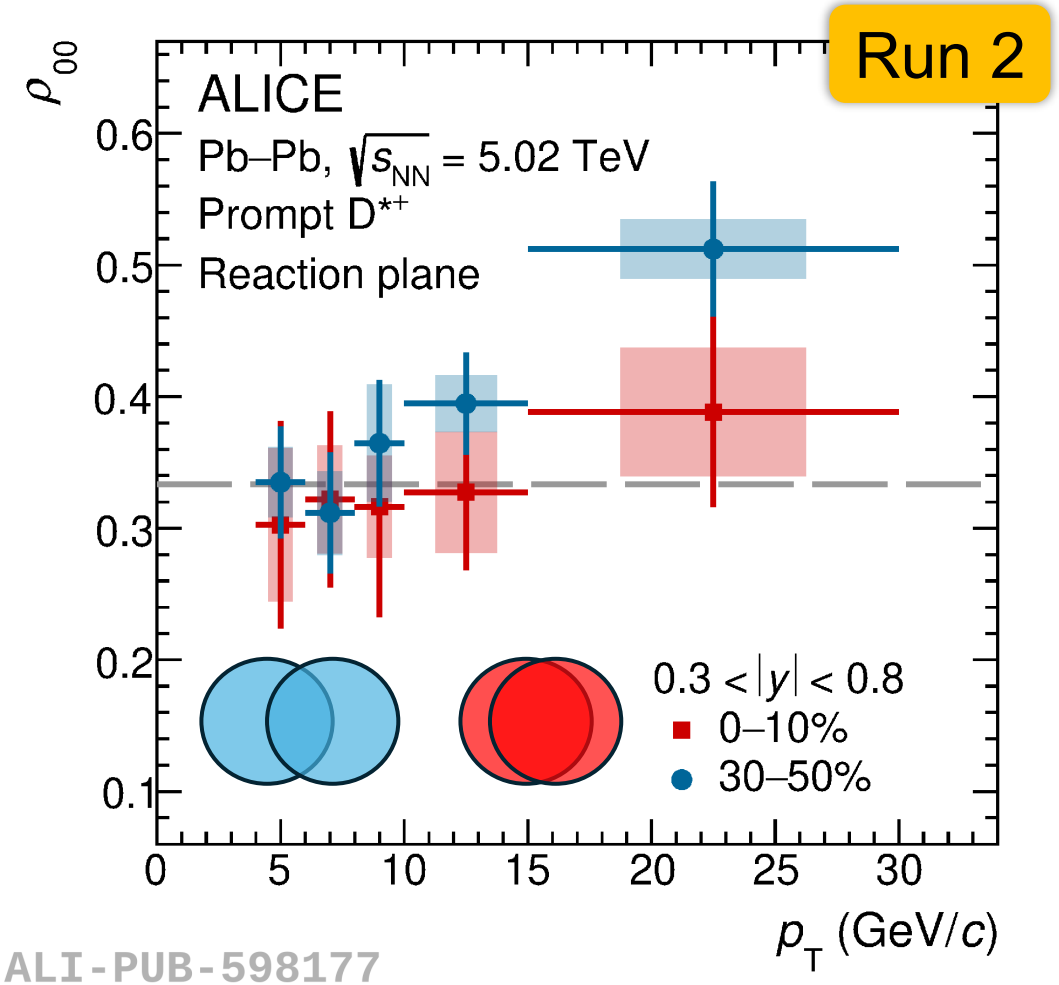
    Evidence of ρ_{00} larger than 1/3 at high p_T

    ⇒ Consistent with the scenario of polarized charm quarks hadronizing via fragmentation

$$\rho_{00} = \frac{1 + \beta \cdot P_q^2}{3 - \beta \cdot P_q^2} > 1/3$$



Liang et al, Physics Letters B 629 (2005) 20–26

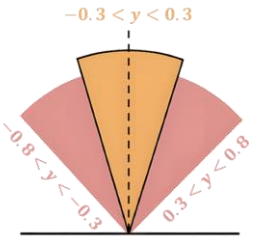


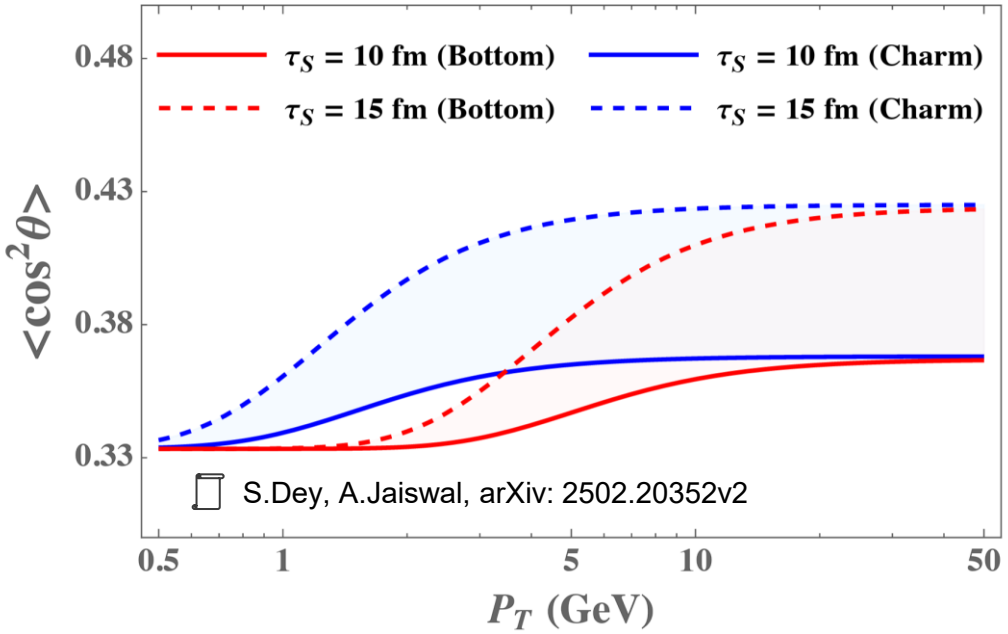
ALICE, arxiv: 2504.00714, accepted by JHEP

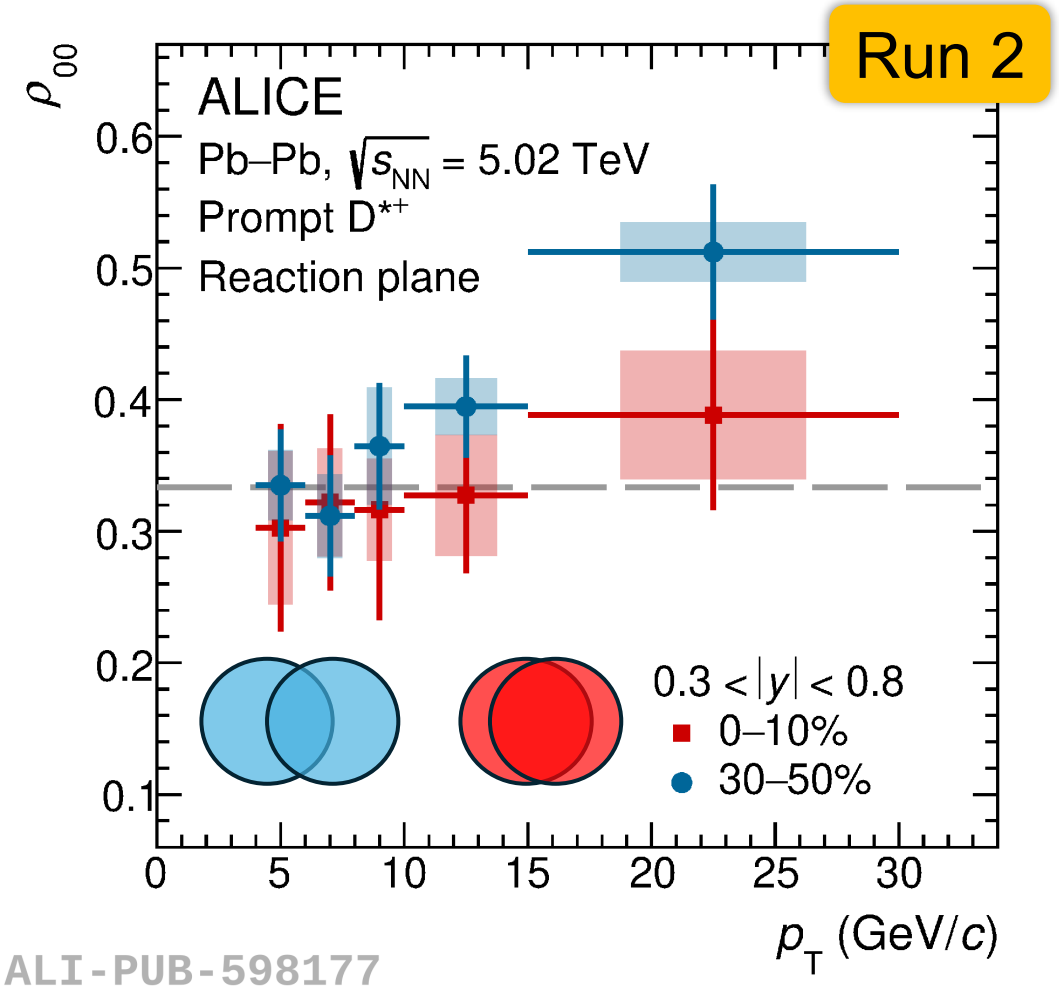
D^{*+} spin alignment in Pb–Pb collisions

- Spin alignment induced by initial B field?

  - High-p_T quarks retain greater polarization, since they exit the fireball more quickly
  - The lower the spin relaxation time, the less quarks retain polarization when traversing the medium
  - HF polarization useful to constrain charm-quark spin relaxation time







ALICE, arxiv: 2504.00714, accepted by JHEP

D^{*+} spin alignment in Pb–Pb collisions

First measurement of D^{*+} spin alignment with respect to the reaction plane in Pb–Pb collisions

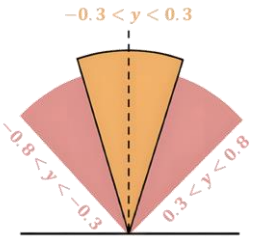
Extracted ρ_{00} parameter for **prompt D^{*+}**

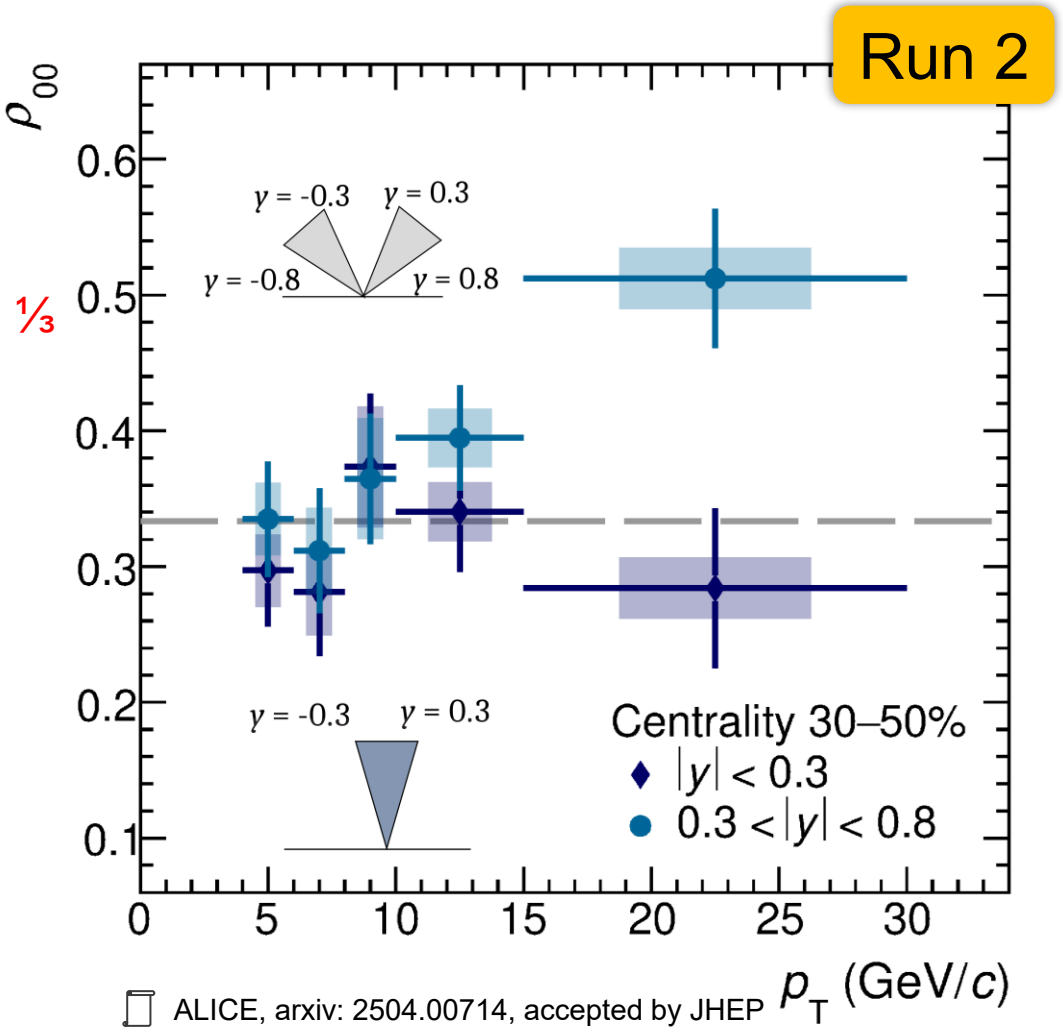
- In large p_T interval $15 < p_T < 30$ GeV/c and non-central collisions (30-50%):
  - No significant deviation at midrapidity from ρ_{00}= ⅓
  - Evidence of ρ_{00} larger than ⅓ at larger rapidity

⇒ $\vec{B}$ decreases slower in time at larger rapidity

⇒ Very early produced c quarks (large momentum) are affected more by $\vec{B}$ field

⇒ Spin-dependent fragmentation functions for charm



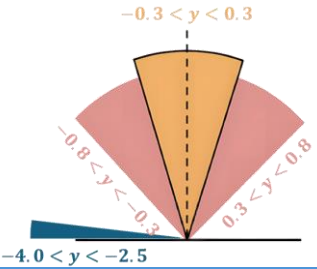


ALICE, arxiv: 2504.00714, accepted by JHEP

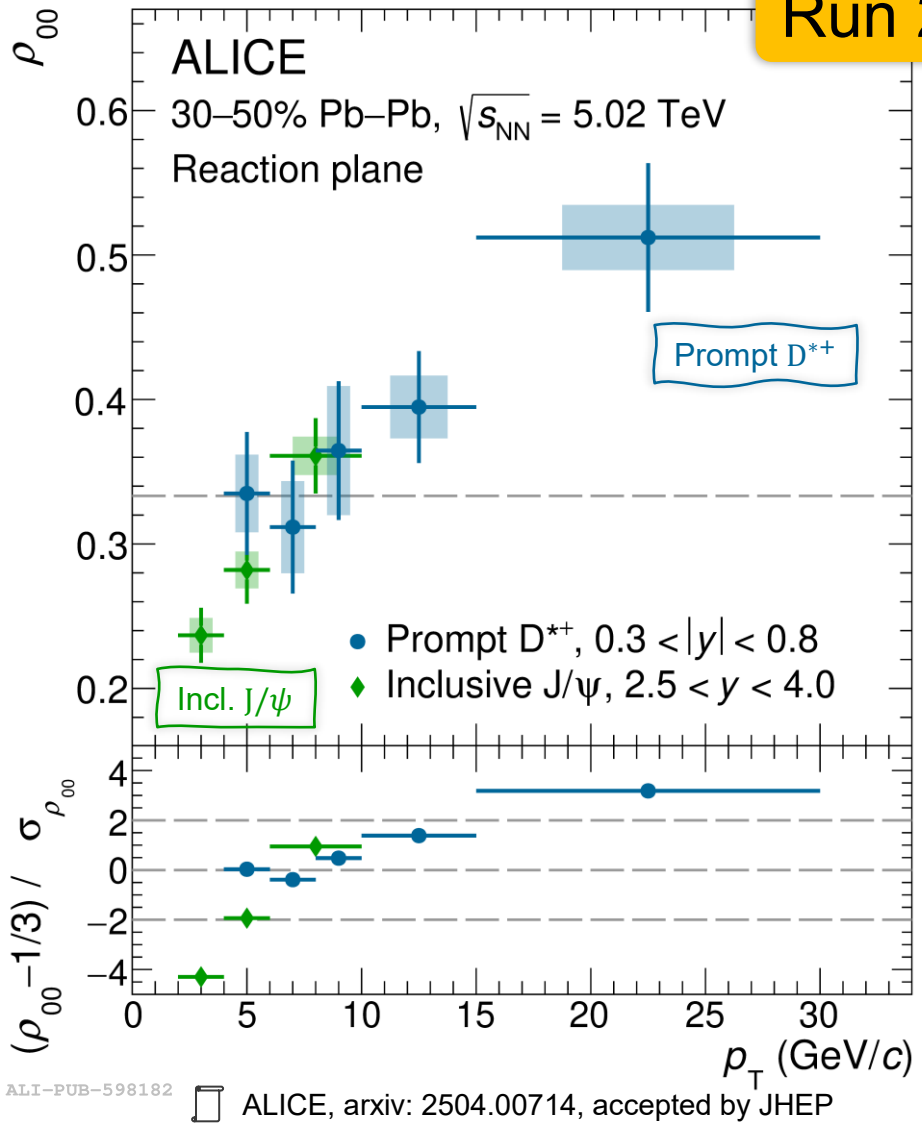
Spin alignment: prompt D^{*+} vs. inclusive J/ψ

ρ_{00} for prompt D^{*+} is compared with the inclusive J/ψ measurement

- Data are compatible within the uncertainties in overlapping p_T region
- ρ_{00} significantly smaller than ⅓ at p_T< 5 GeV/c
  - ⇒ J/ψ dominantly produced by recombination
- At high p_T, does the fragmentation of heavy quarks polarized by the magnetic field translates to $\rho_{00} > ⅓$?
  - ⇒ Need to constrain charmonium production mechanisms in hadronic collisions



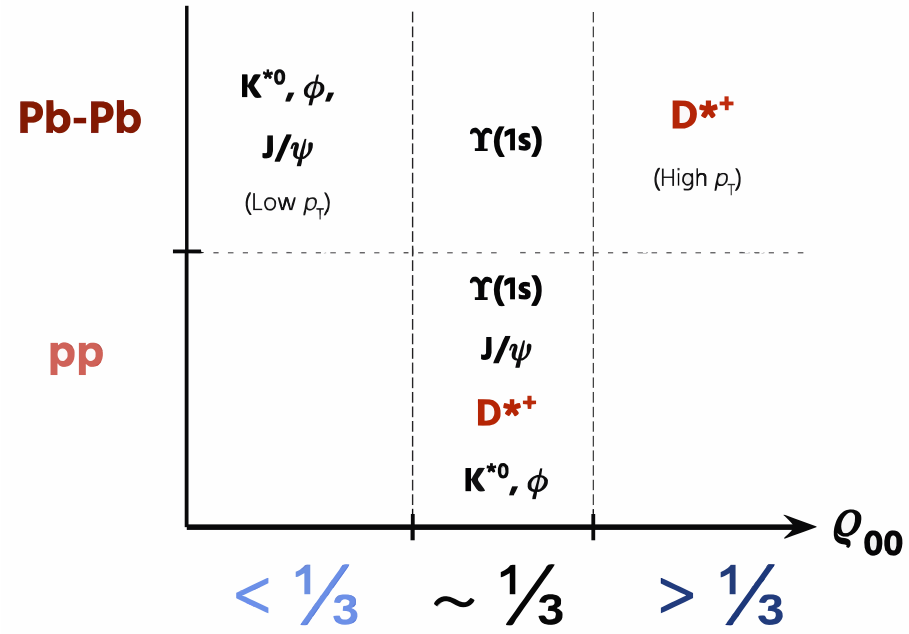
Run 2



ALICE, arxiv: 2504.00714, accepted by JHEP

Summary

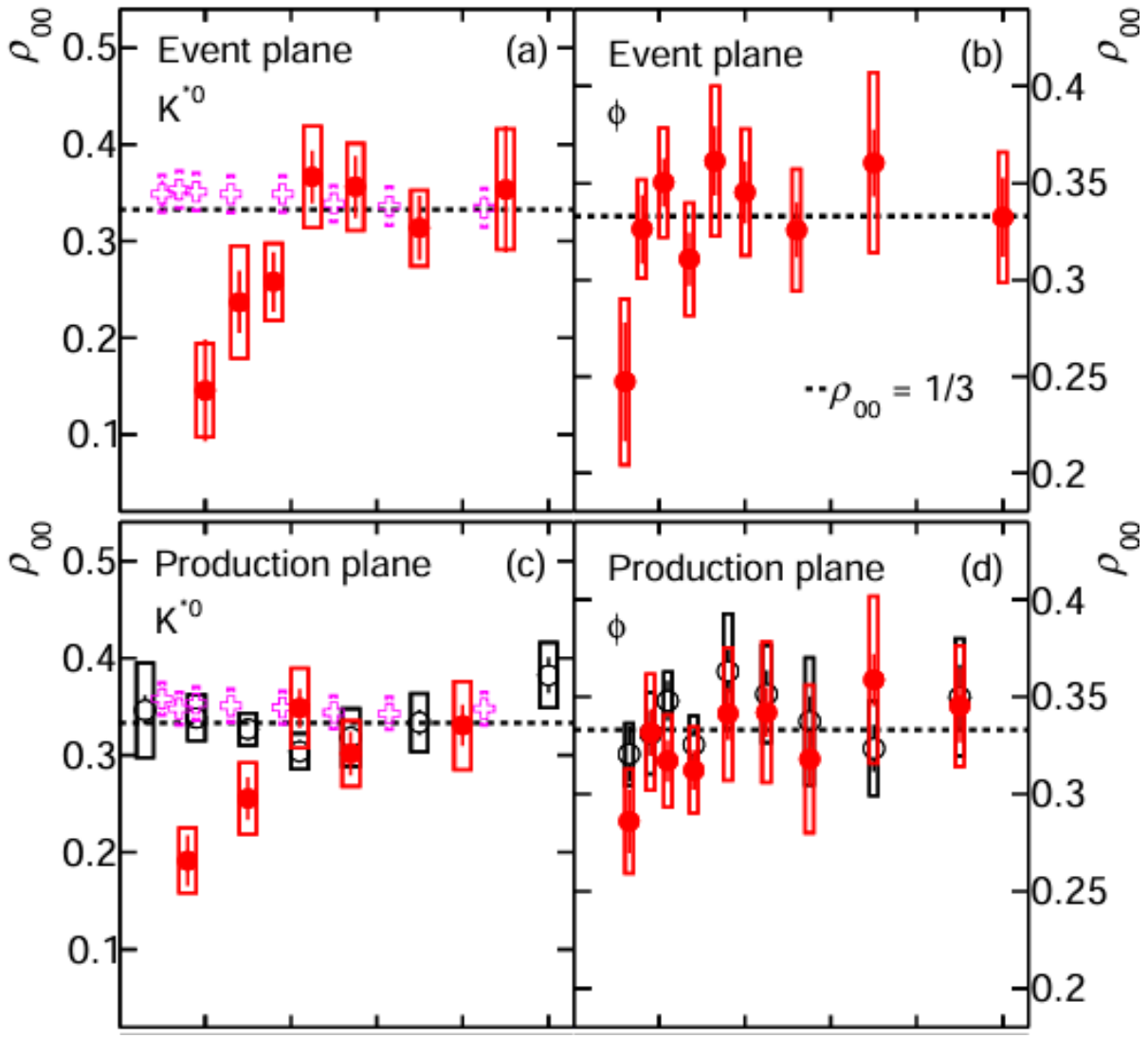
- **pp collisions:**
  - light flavors, prompt D^{*+} and J/ψ polarization are compatible with **zero**
- **Pb–Pb collisions:**
  - $\rho_{00} < 1/3$ for light flavors, J/ψ at low p_{T} ⇒ recombination scenario
  - $\rho_{00} > 1/3$ for prompt D^{*+} at high p_{T} & less central rapidity ⇒ quark fragmentation scenario
- Theoretical predictions are required for conclusions

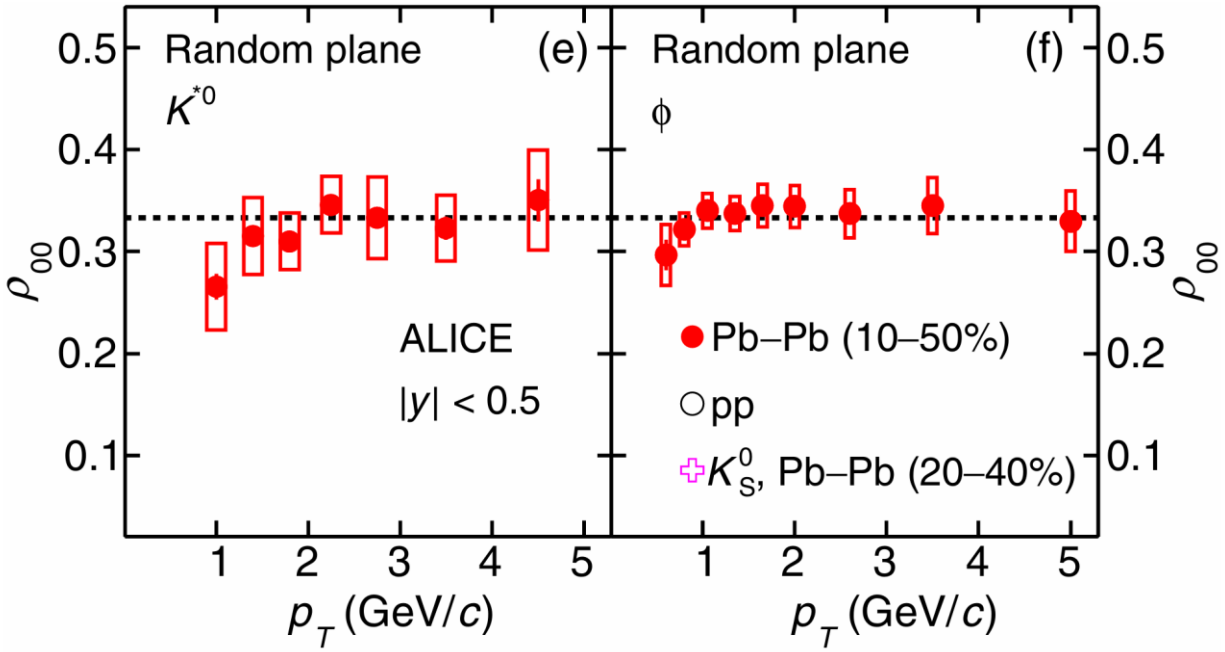


	pp	Pb–Pb
D^{*+}	ALICE, PLB 846 (2023) 137920	ALICE, CERN-EP-2025-072
J/Ψ	ALICE, EPJ. C 78 (2018) 562	ALICE, PRL. 131, 042303
K^{*0}	ALICE, EPJ 171, 16008	ALICE, PRL. 125 (2020) 012301

Additional Slides

Vector meson spin alignment





D^{*+} spin alignment in pp collision

First measurement of D^{*+} spin alignment in pp collisions

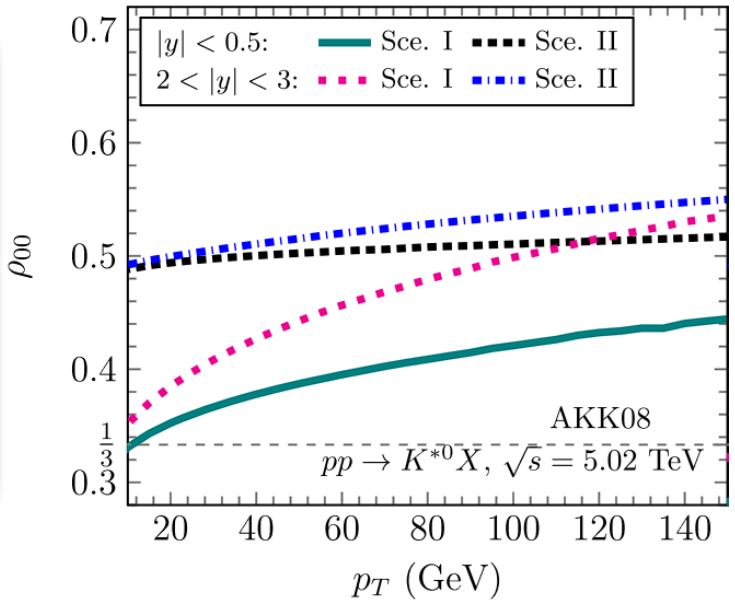
(During LHC Run 2, $\sqrt{s} = 13$ TeV)

- p_T up to 20 Gev/c for prompt and non-prompt D^{*+}
- Prompt D^{*+} no evidence of polarization
- Non-prompt D^{*+} $\rho_{00} > 1/3$

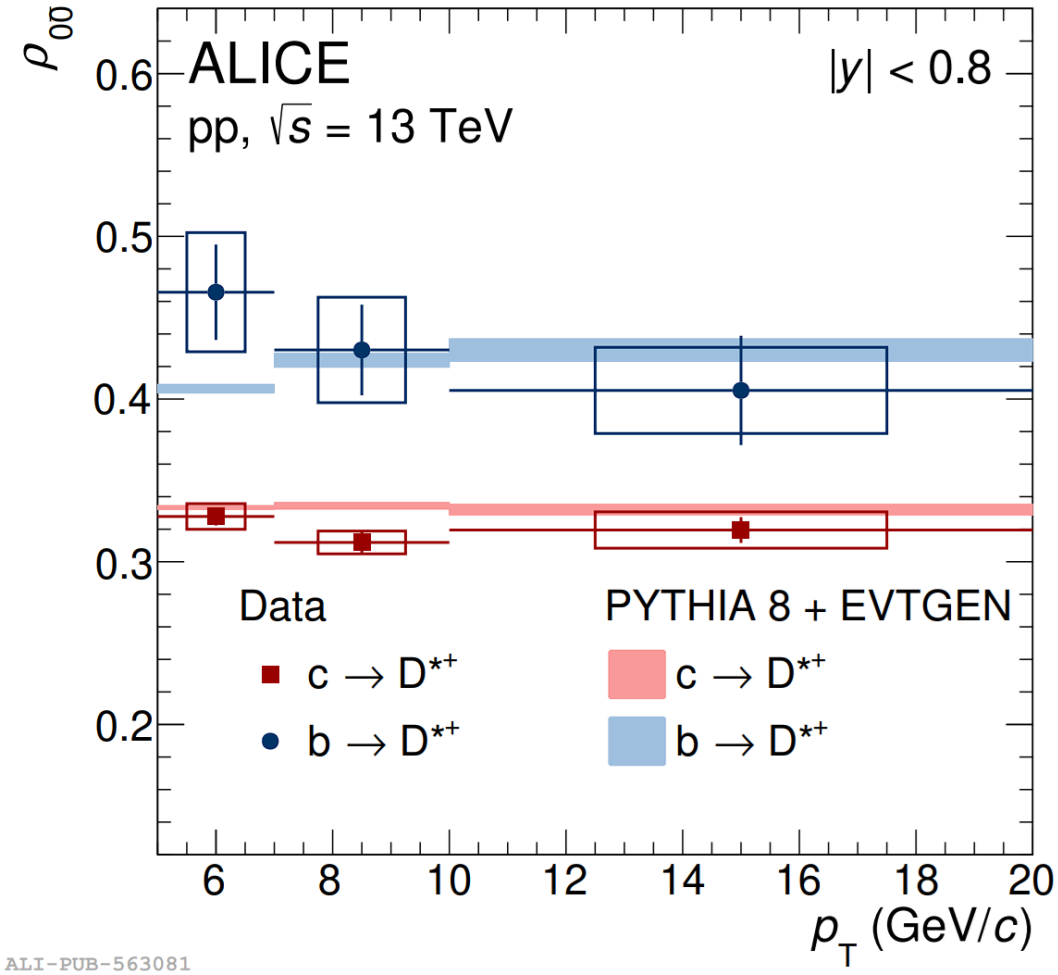
Polarization from spin-dependent fragmentation functions?

Need to reach higher p_T region!

Chen et al, Phys. Rev. D 102, 034001



ALICE, Phys. Lett. B 846 (2023) 137920



D^{*+} spin alignment in pp collision

First measurement of D^{*+} spin alignment in pp collisions

(During LHC Run 2 , $\sqrt{s} = 13$ TeV)

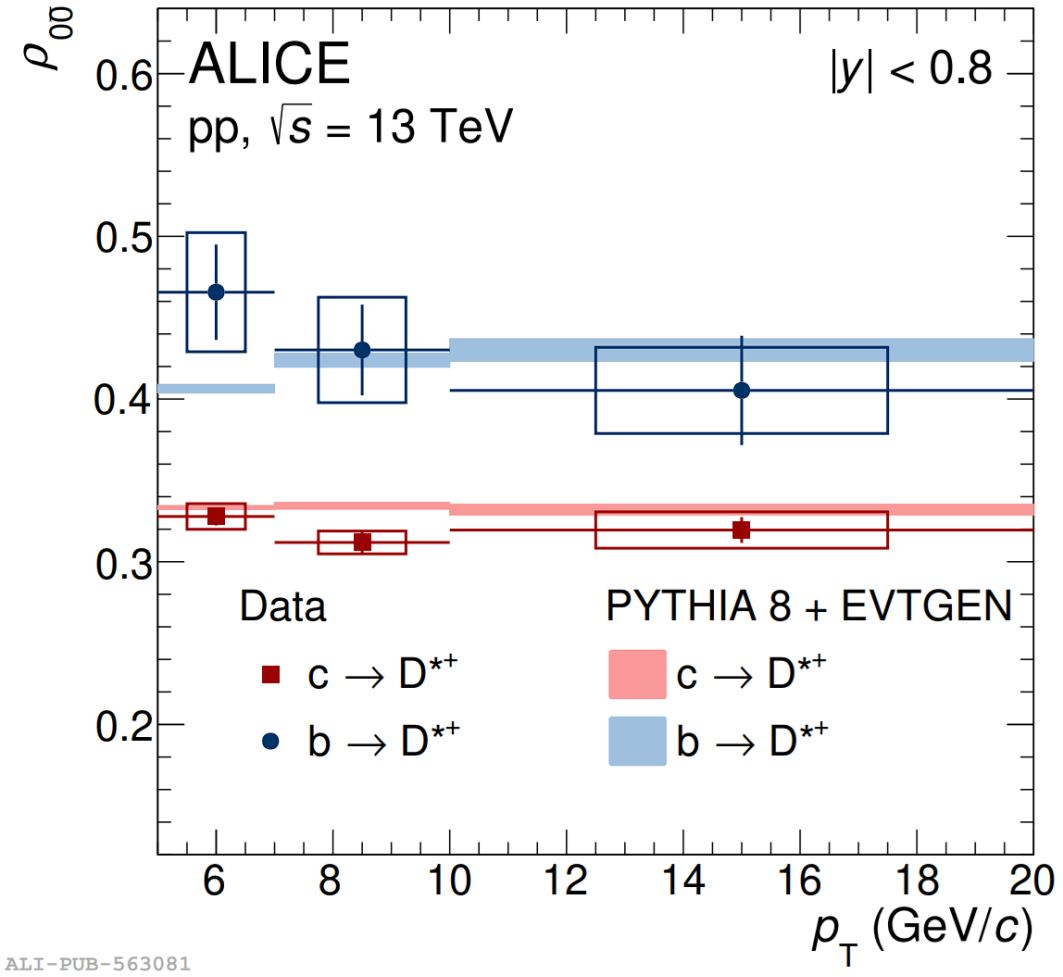
- p_T up to 20 GeV/c for prompt and non-prompt D^{*+}

New ALICE preliminary results

Larger data taking rates during LHC Run 3 ($\sqrt{s} = 13.6$ TeV)

(500 kHz in pp and 50 kHz in Pb–Pb)

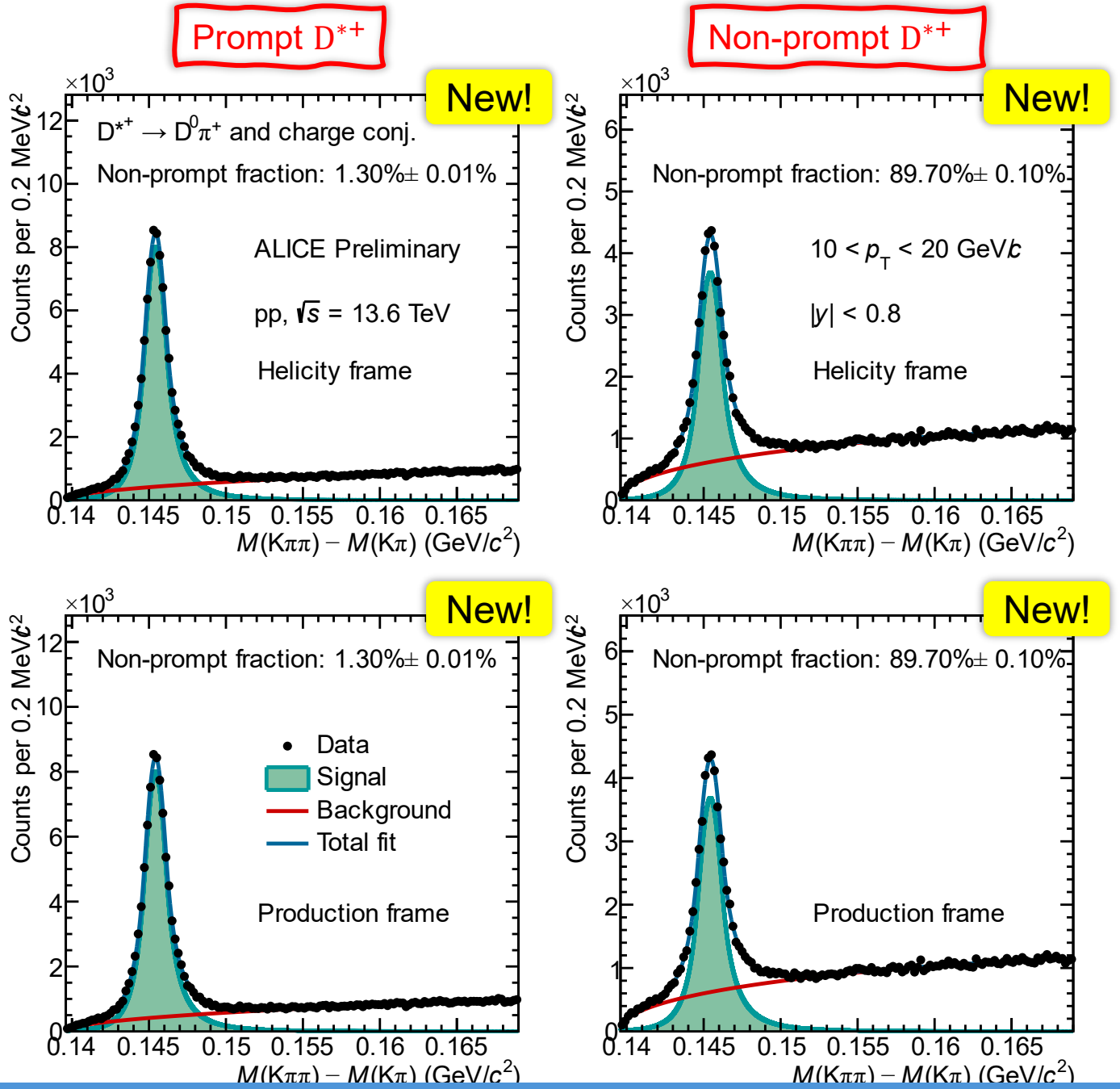
- Larger data samples for more accurate results
- p_T increased from maximum 20 up to 100 GeV/c
- Reference for measurements in Pb–Pb collisions



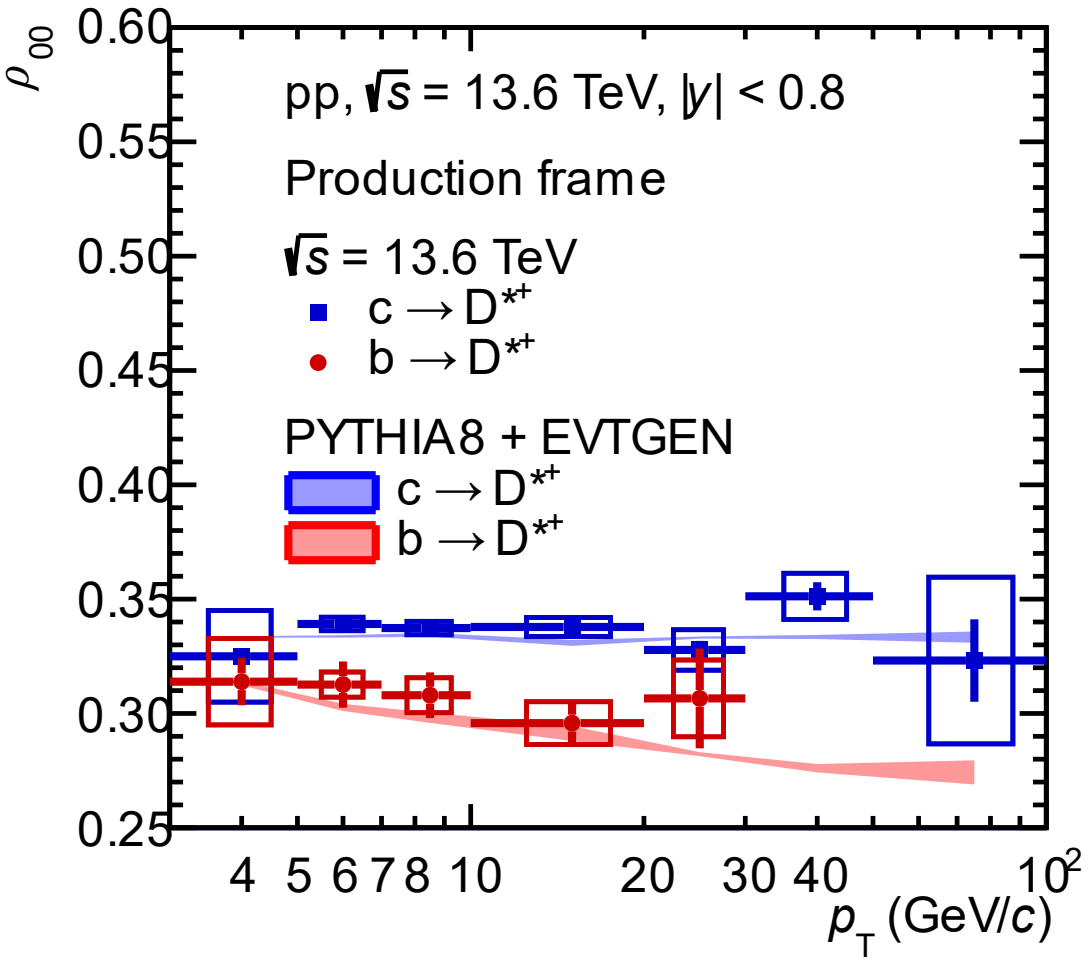
ALICE, Phys. Lett. B 846 (2023) 137920

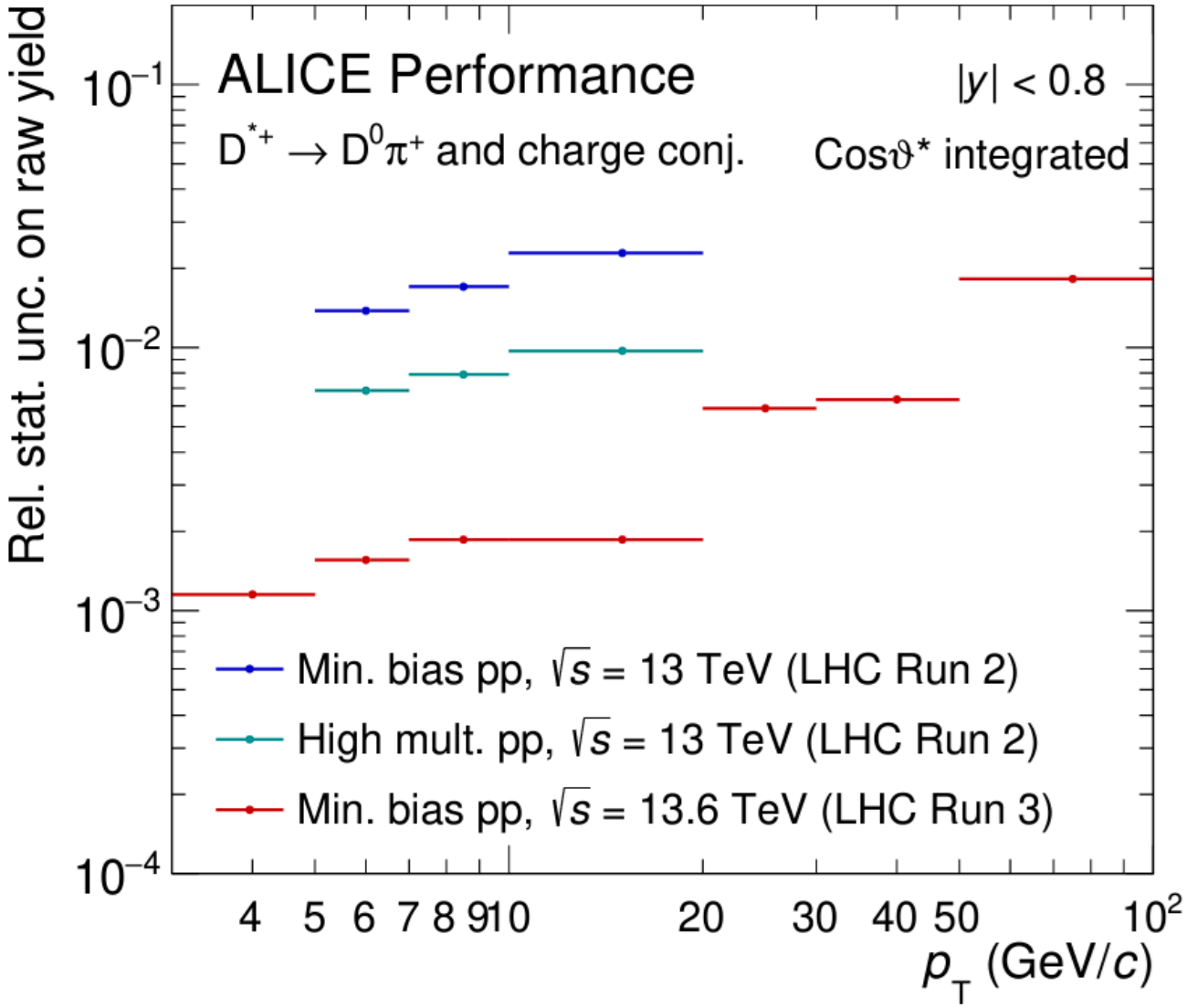
D^{*+} extraction

D^{*+} extraction in pp collision at $\sqrt{s} = 13.6$ TeV



Run 3 performance for D^{*+}



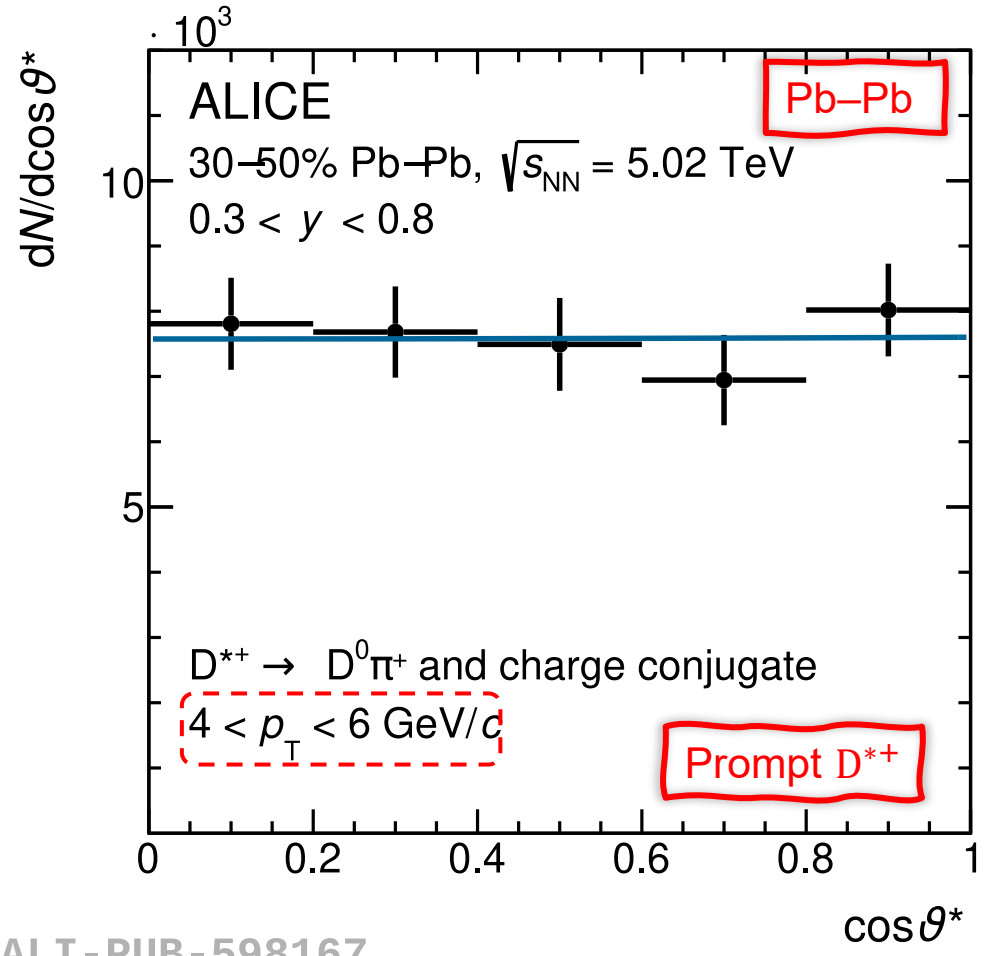


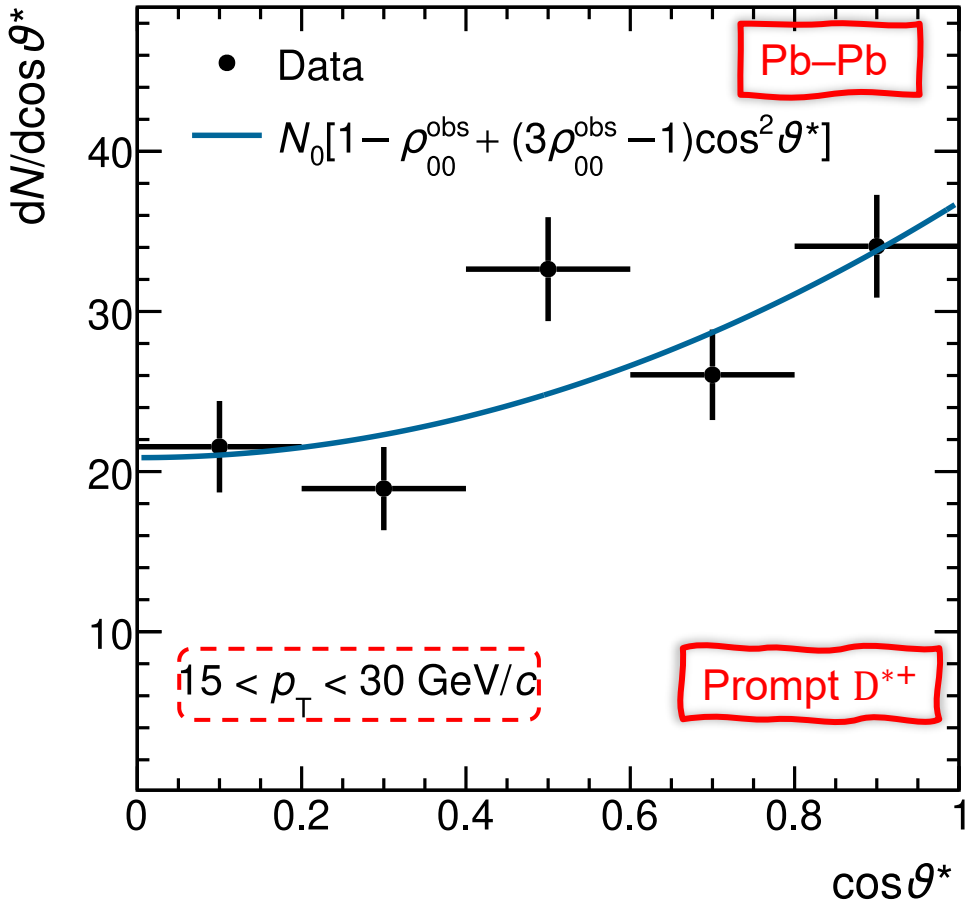
ALI-PERF-571947

ρ_{00} extraction in Pb–Pb collisions

For D^{*+} analysis in pp and Pb–Pb collisions

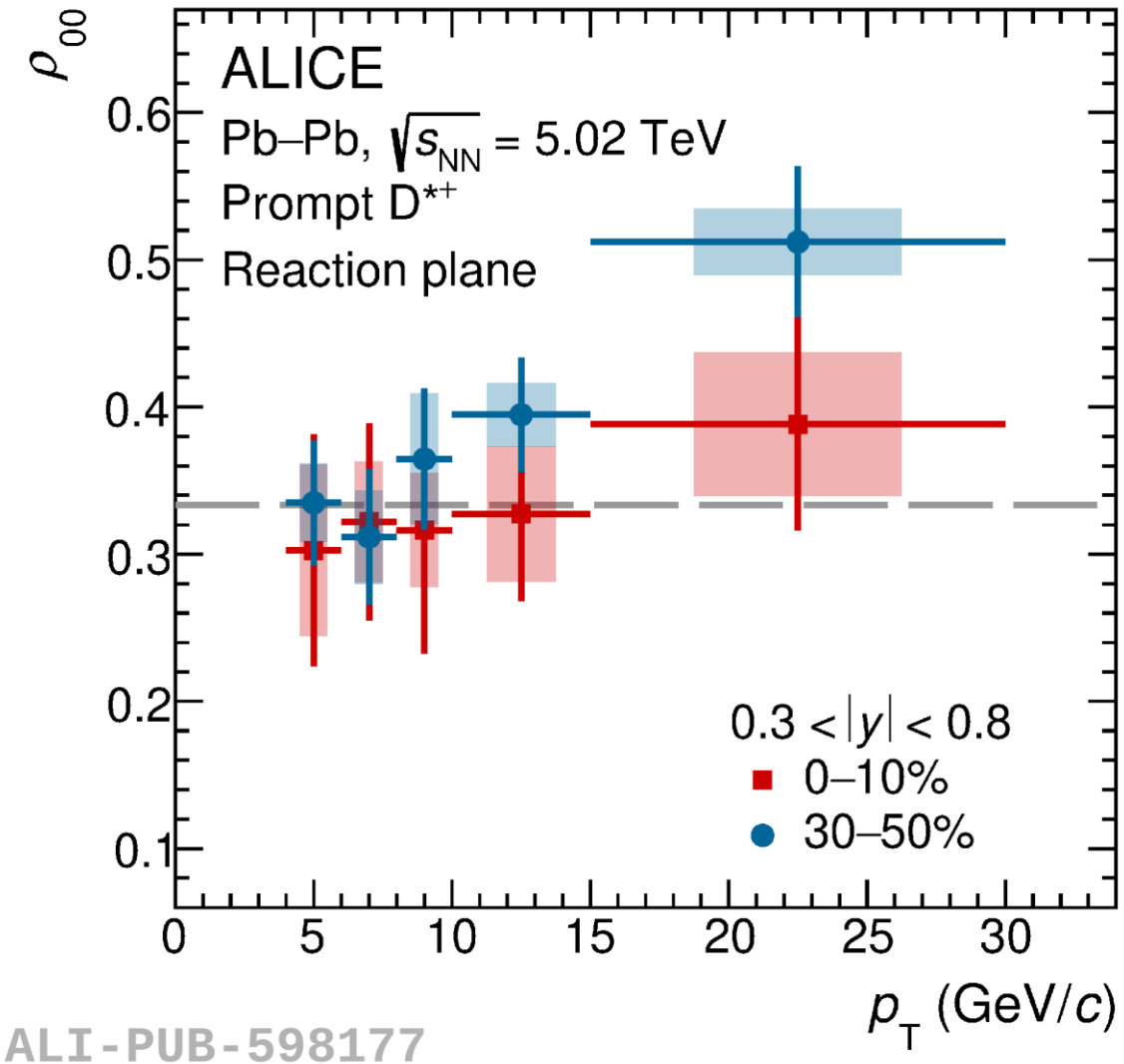
- ρ_{00} extraction for prompt and non-prompt D^{*+} in different p_{T} intervals

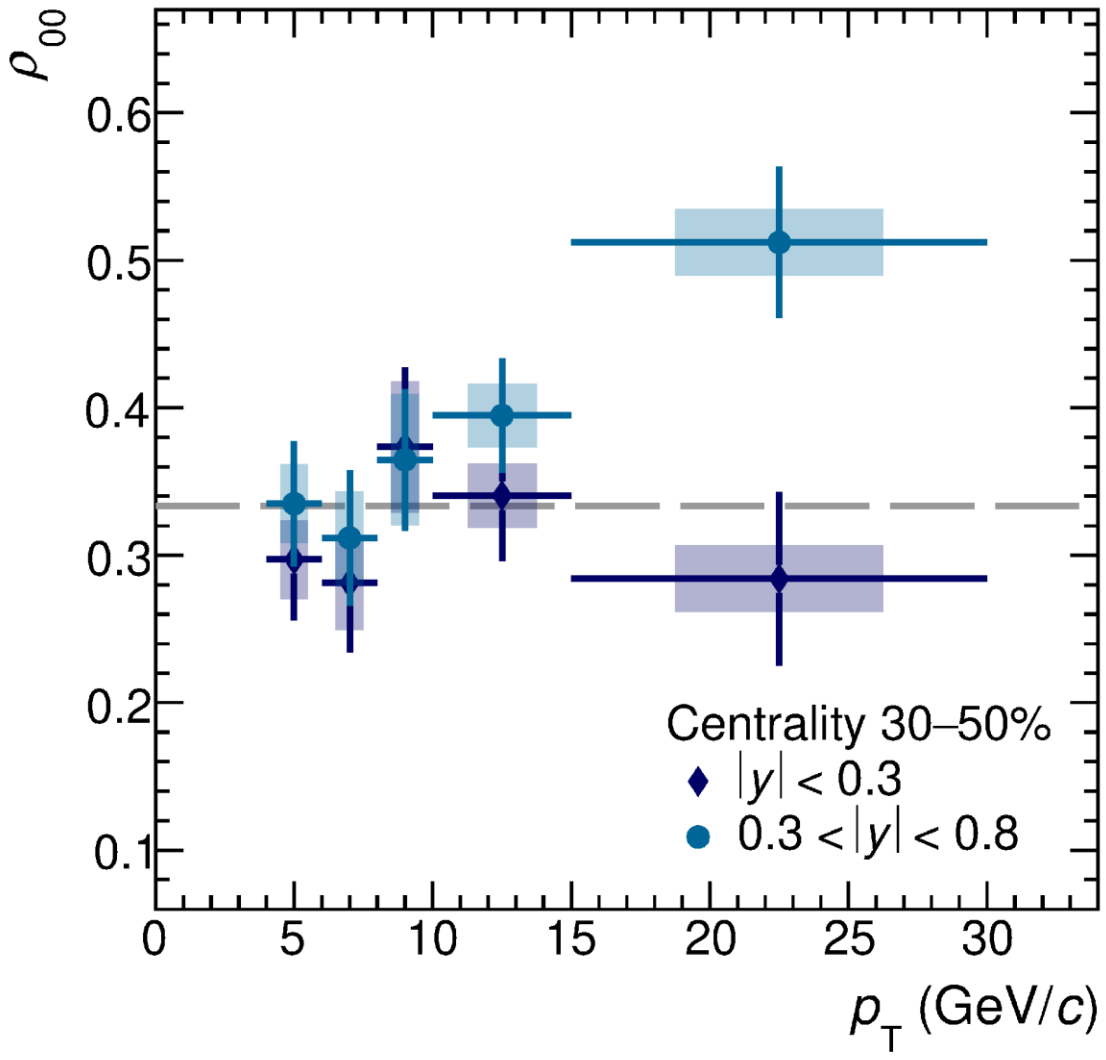




ALI-PUB-598167

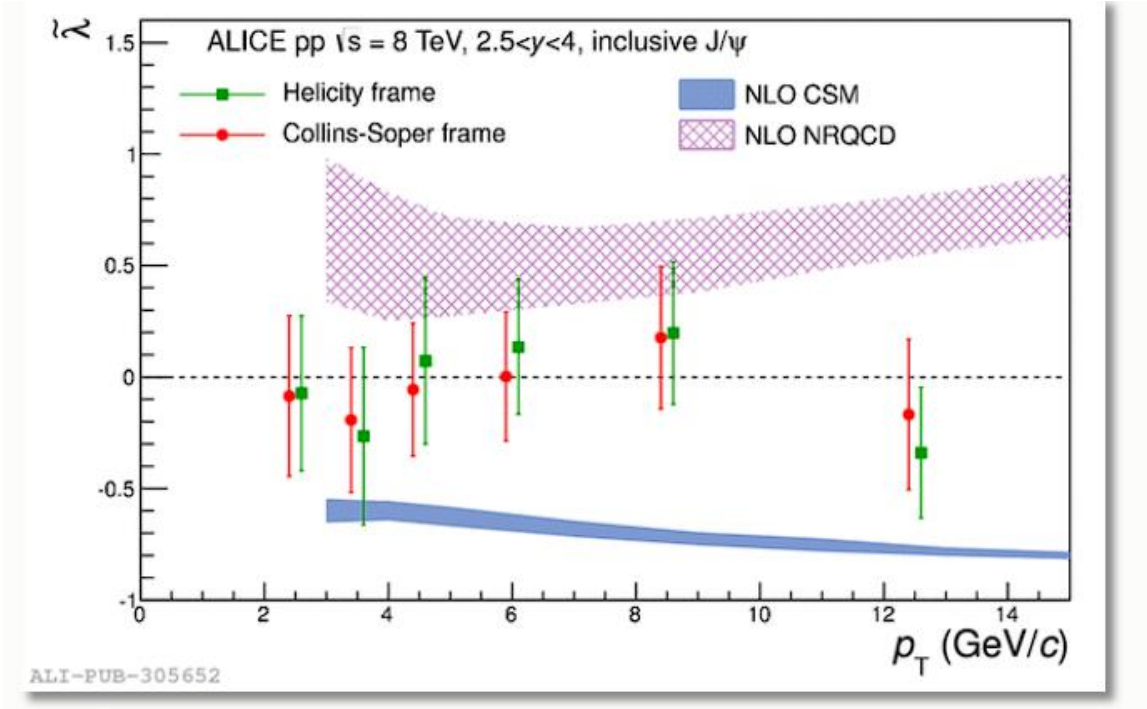
D^{*+} spin alignment in Pb–Pb collision

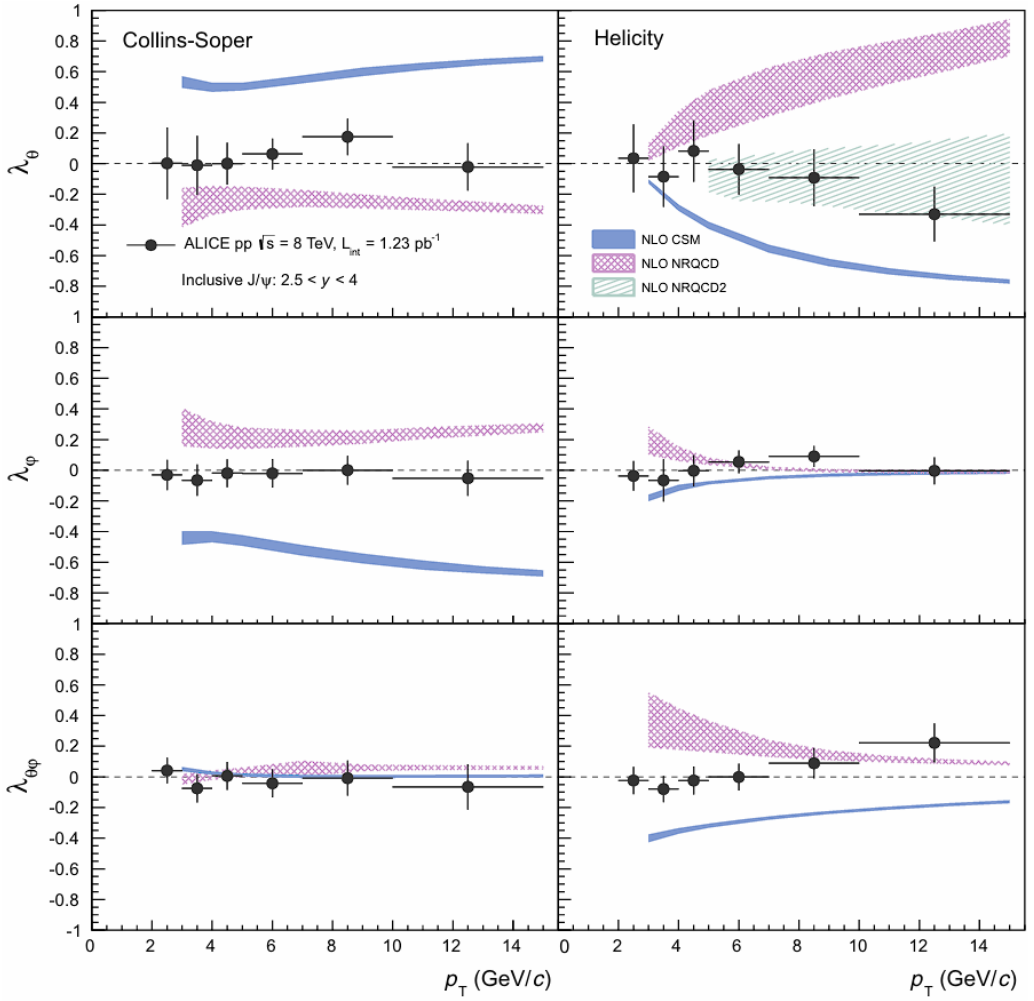




ALI-PUB-598177

J/ψ polarization





Polarization measurements

- Hadrons' spin alignment measurements rely on spin density matrix element (ρ_{00})
  - $\rho_{00} = 1/3 \rightarrow$ No spin alignment
  - $\rho_{00} \neq 1/3 \rightarrow$ Spin alignment observed

Angular distribution of decay products

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

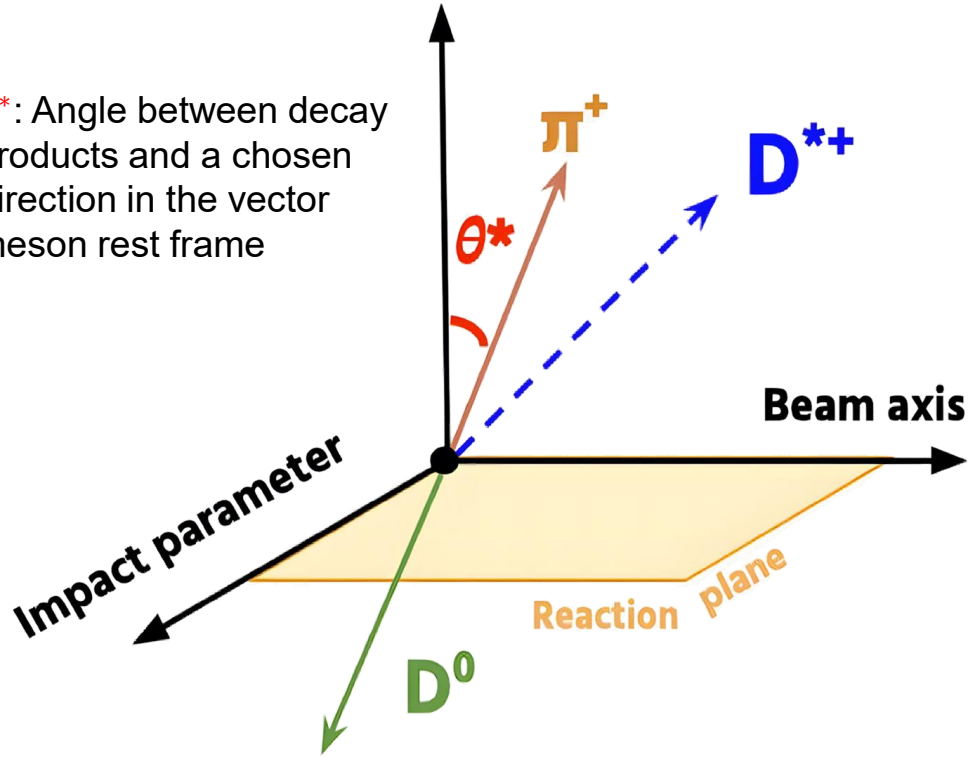
- Quantization axis

Orthogonal to event plane (Heavy-ion):
Direction of **L** and **B** fields

Helicity (pp):
Direction of vector meson momentum

Production (pp):
Direction perpendicular to vector meson momentum and beam axis

θ^*: Angle between decay products and a chosen direction in the vector meson rest frame



Theory expectation for ρ_{00}

Physics process and theory expectation