Investigation of charm hadronization and early magnetic field in ultrarelativistic heavy-ion collisions via D^{*+}-meson spin alignment with ALICE

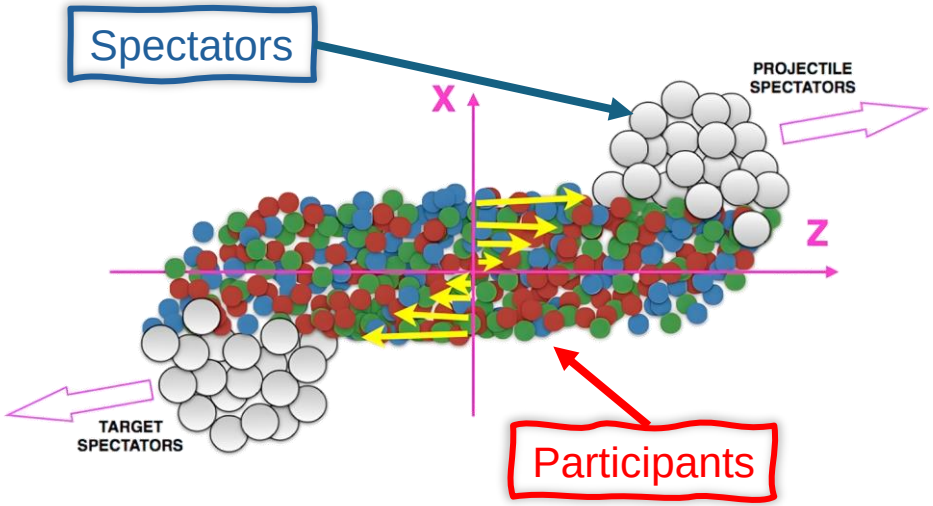
Mingze Li (for the ALICE Collaboration)
Central China Normal University

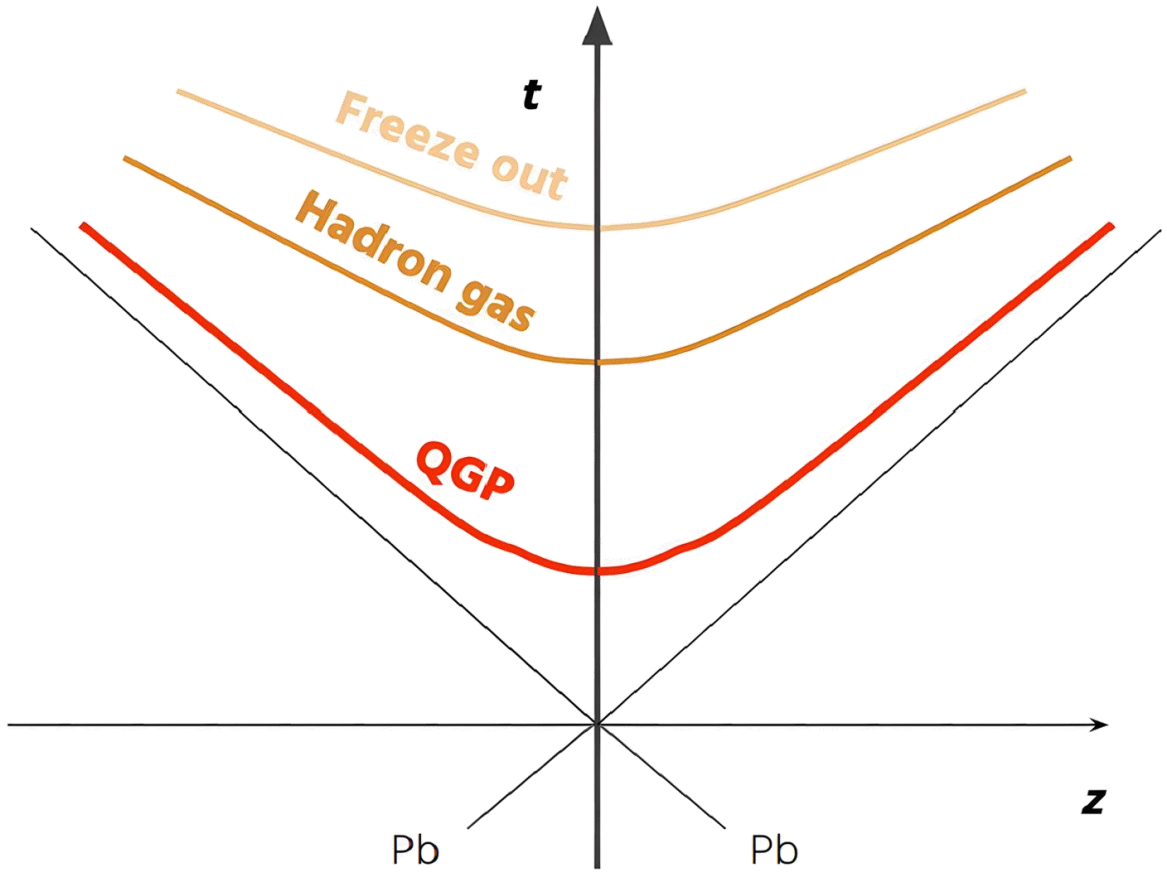
Hard Probes Conference, 24th Sep 2024

Motivation

- In heavy-ion collisions, system evolves through various phases

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





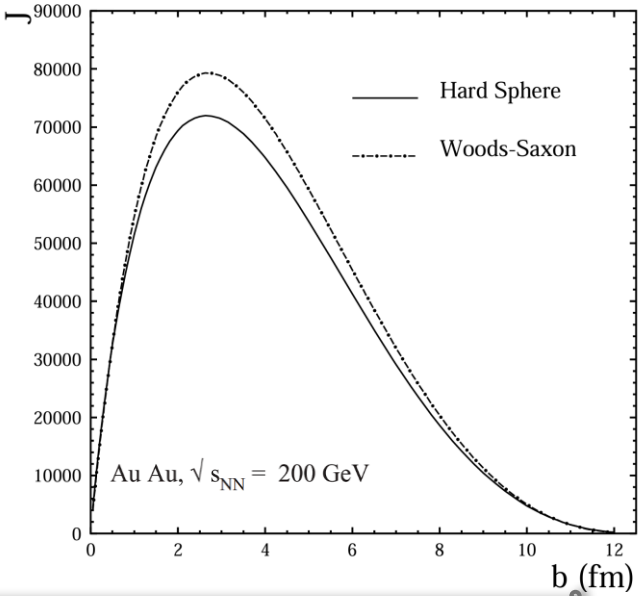
*ω: rotational speed (rotations/sec)

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

Motivation

- In heavy-ion collisions, system evolves through various phases
- In non-central collisions:
  - A highly vortical system with orbital angular momentum (L), $\omega \sim 10^{22} s^{-1}$
    - Strong b^* dependence
    - Affects system's evolution/hadronization process

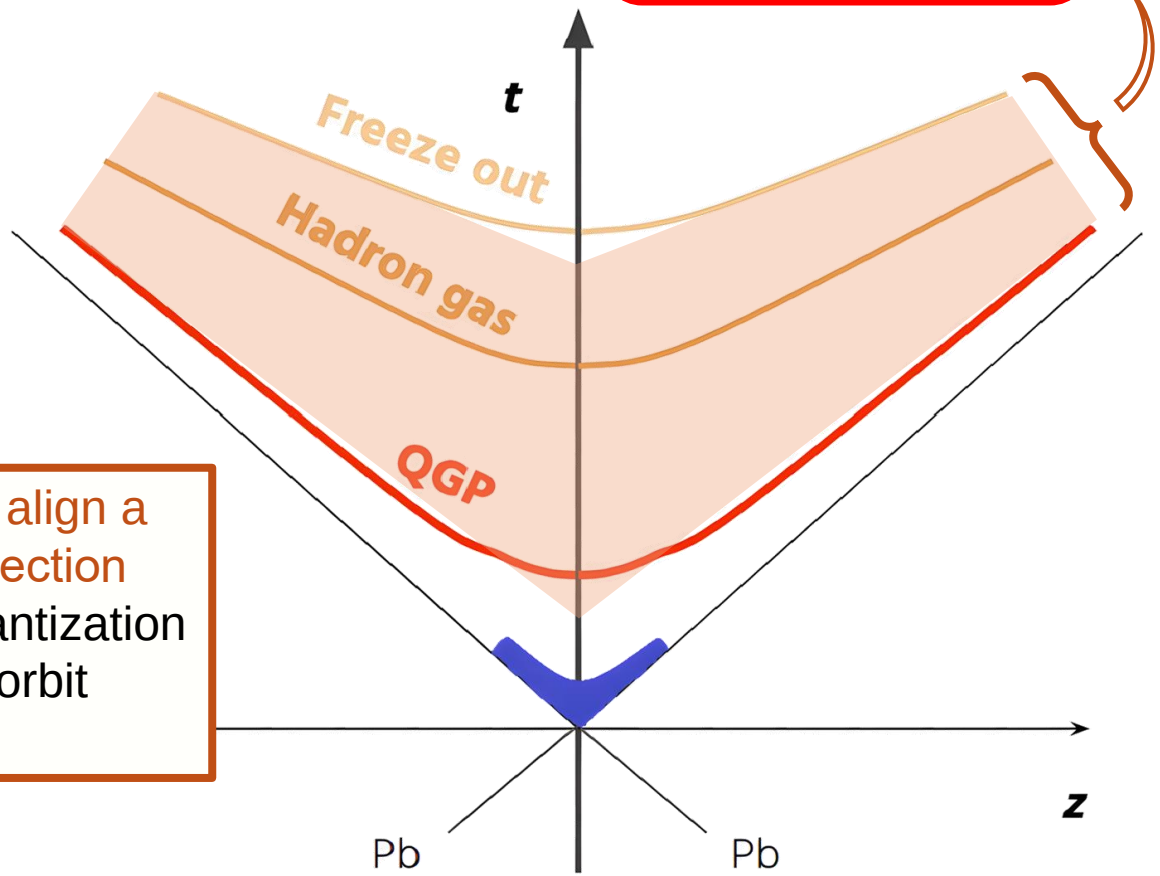
Becattini et al., PRC 77 (2008) 024906



Can preferentially align a particle's spin projection along the spin quantization axis through spin-orbit coupling

*b: impact parameter

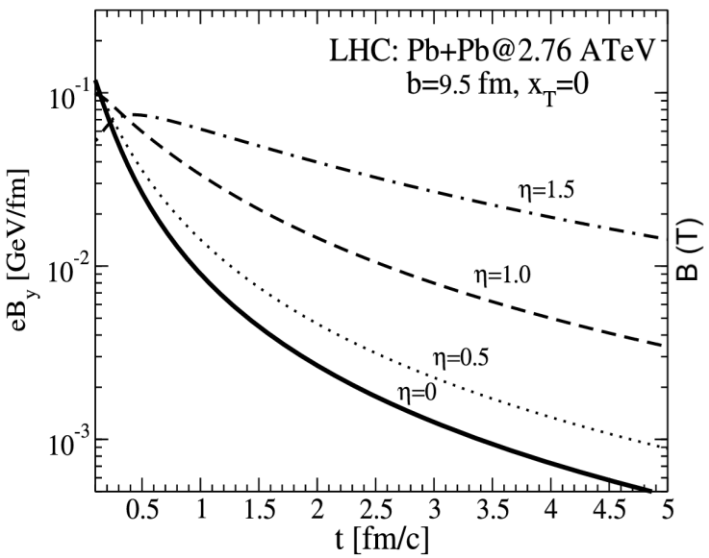
Very large orbital angular momentum $\omega \sim 10^{22} s^{-1}$



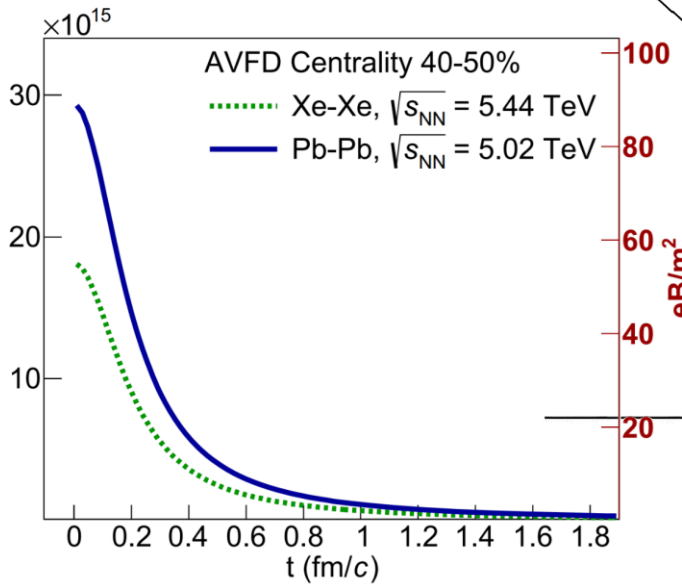
"Simplified" spacetime evolution of heavy-ion collisions

Motivation

- In heavy-ion collisions, system evolves through various phases
- In non-central collisions:
  - Charged spectator motion produces magnetic field (B) $\sim 10^{15}$T
    - Decreases over time
    - Lifetime increases from mid to forward rapidity

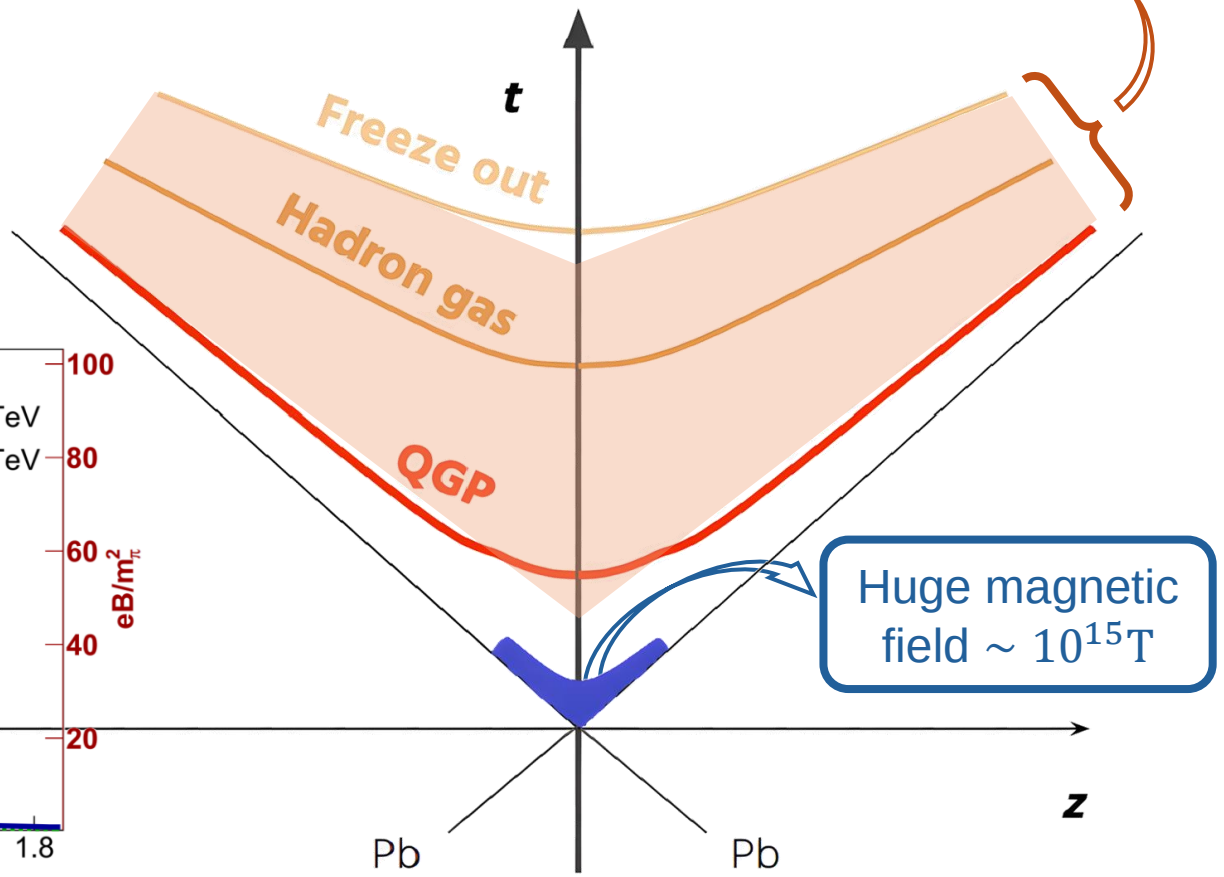


Das et al. PLB 768 (2017) 260



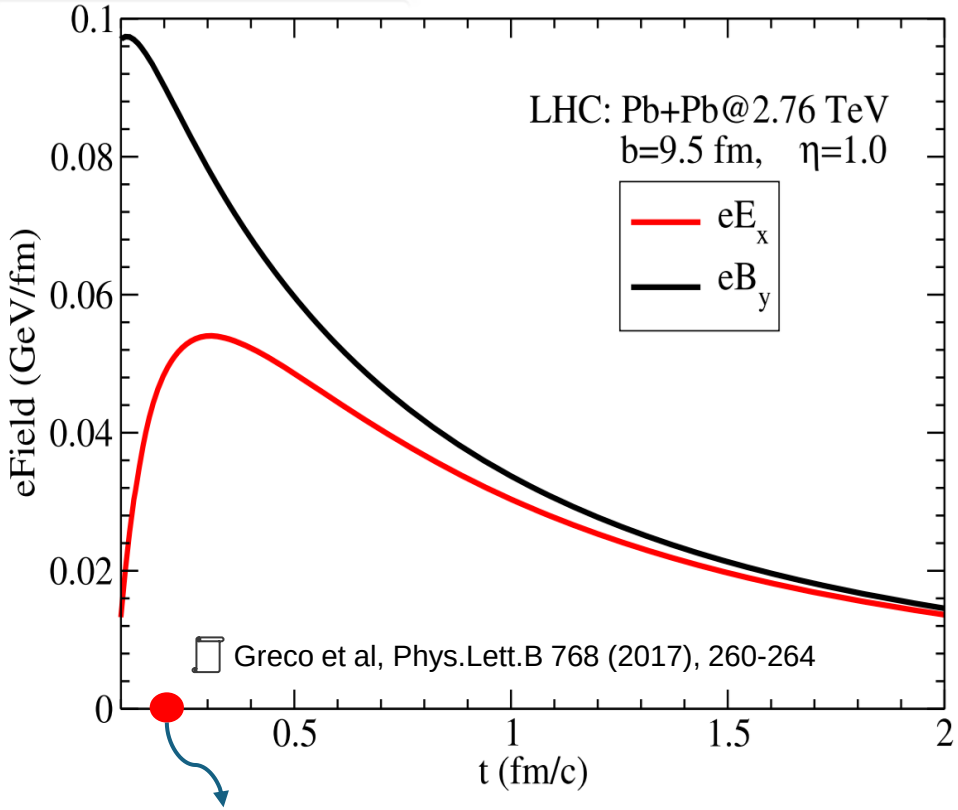
P. Christakoglou EPJC 81, 717 (2021)

Very large orbital angular momentum $\omega \sim 10^{22}\mathrm{s}^{-1}$



"Simplified" spacetime evolution of heavy-ion collisions

Motivation



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

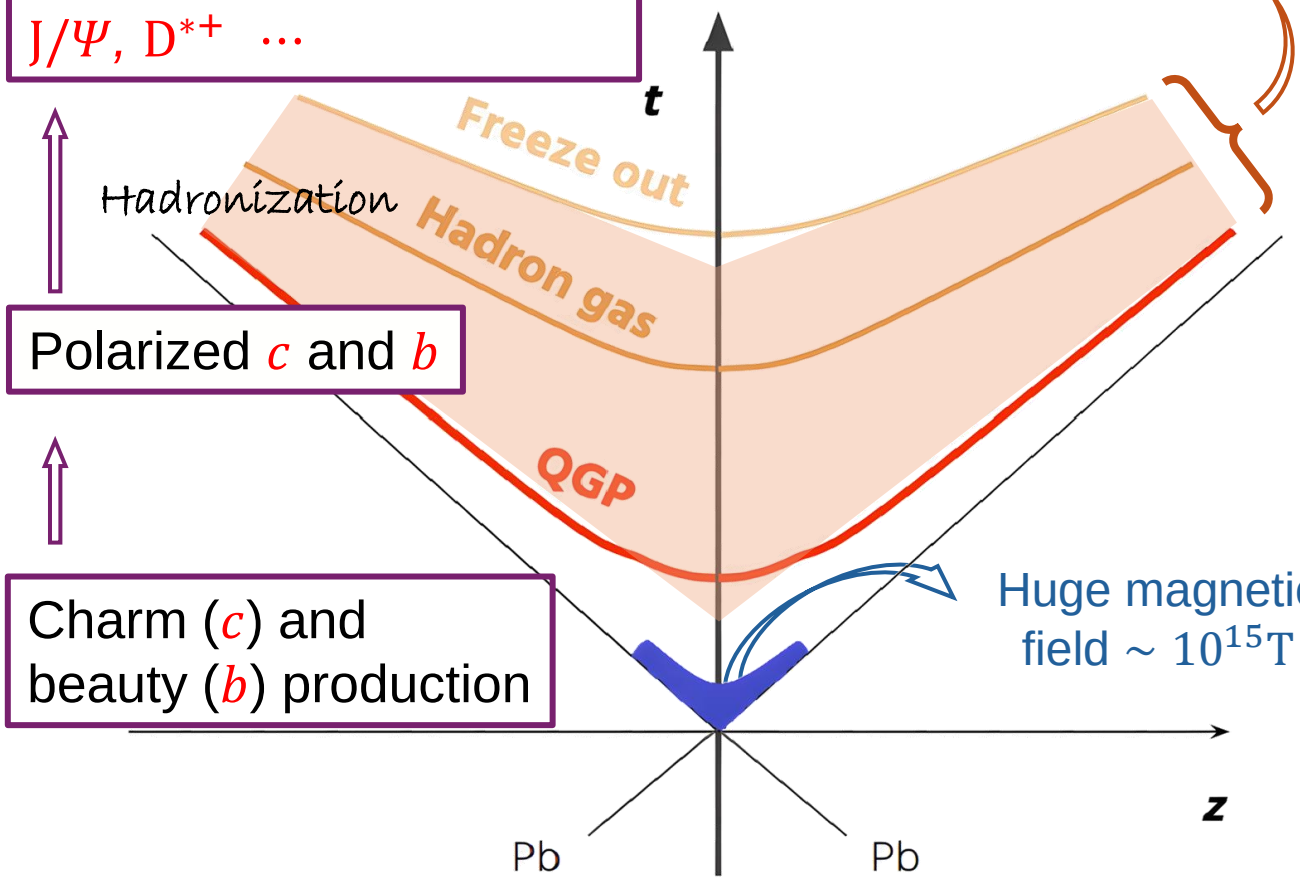
More sensitive to the high intensity of the EM fields compared to light quarks

Very large orbital angular momentum $\omega \sim 10^{22} s^{-1}$

Polarized vector meson J/Ψ, D^{*+} …

Polarized c and b

Charm (c) and beauty (b) production



"Simplified" spacetime evolution of heavy-ion collisions

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

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

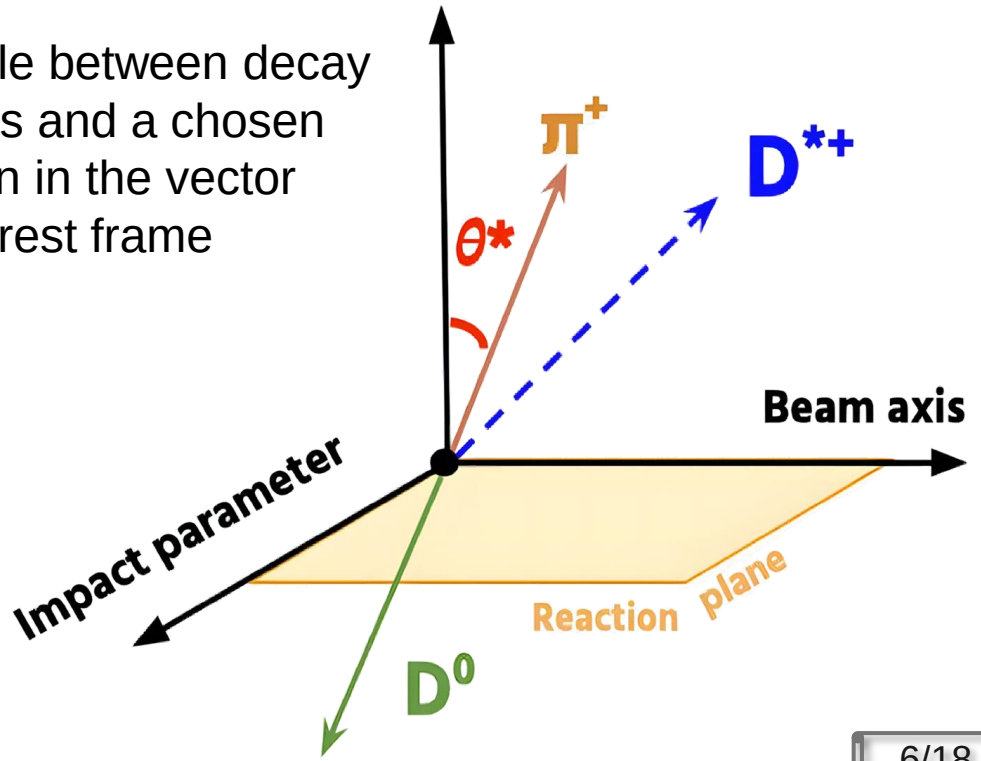
- Quantization axis

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



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Angular distribution of decay products

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

- Vector meson spin alignment governed by two mechanisms:

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}

ALICE detector

ALICE: LHC Run 3

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

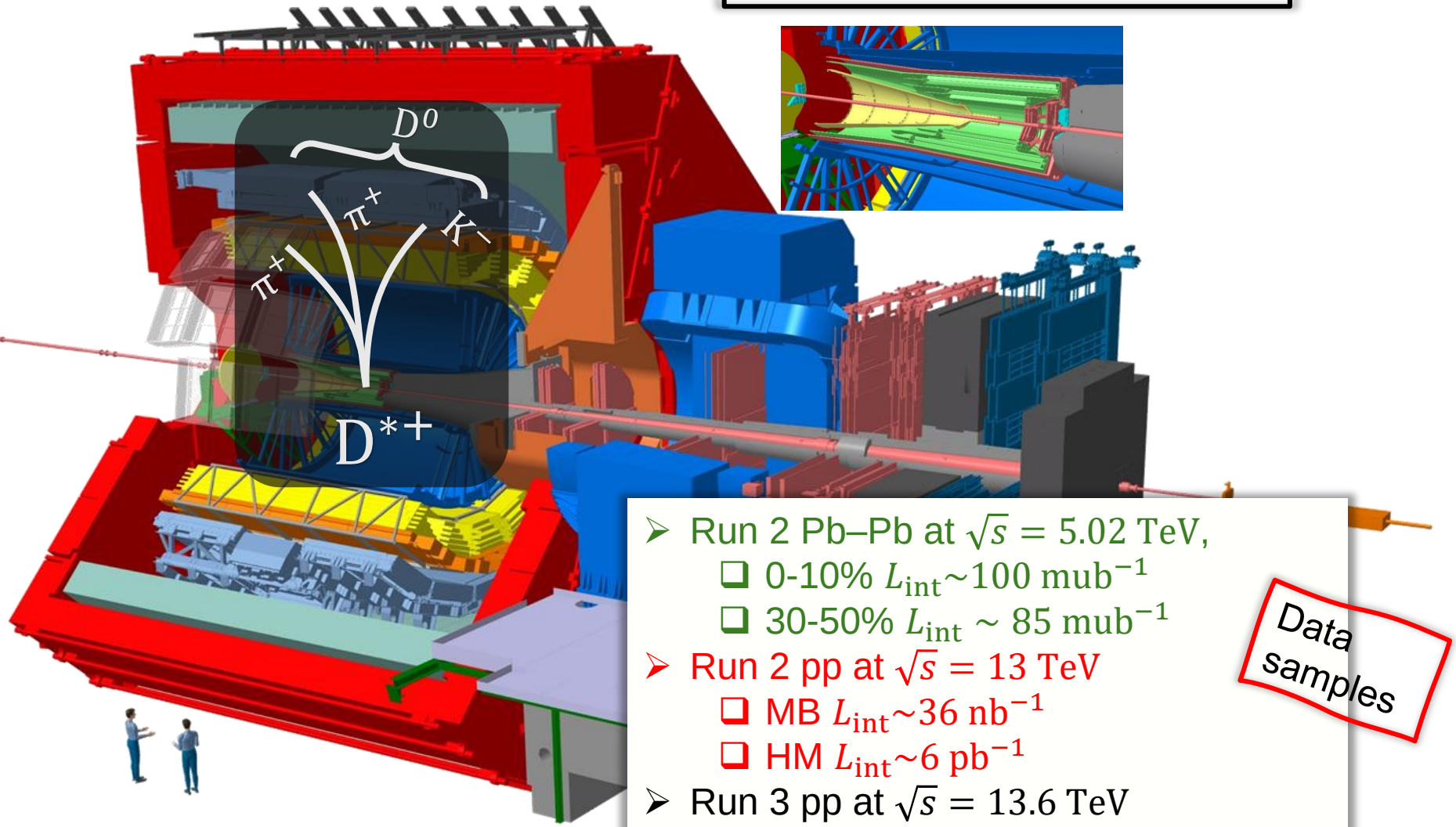
Central barrel detectors
$|\eta| < 0.9$

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



Data samples

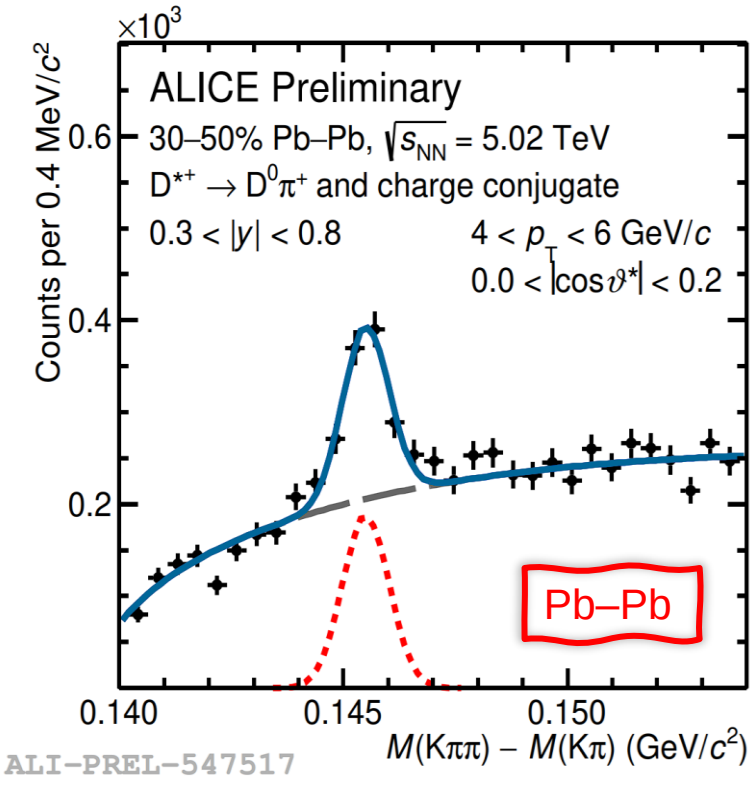
- Run 2 Pb–Pb at $\sqrt{s} = 5.02$ TeV,
  - 0-10% $L_{\text{int}} \sim 100\ \text{mub}^{-1}$
  - 30-50% $L_{\text{int}} \sim 85\ \text{mub}^{-1}$
- Run 2 pp at $\sqrt{s} = 13$ TeV
  - MB $L_{\text{int}} \sim 36\ \text{nb}^{-1}$
  - HM $L_{\text{int}} \sim 6\ \text{pb}^{-1}$
- Run 3 pp at $\sqrt{s} =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

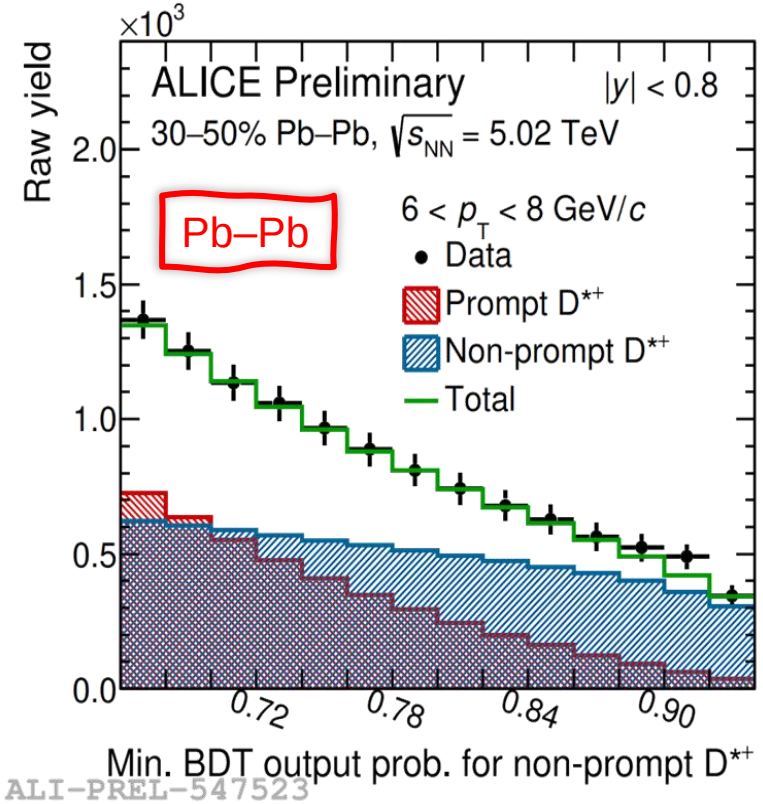
ALICE Collaboration, JINST (2008) S08002

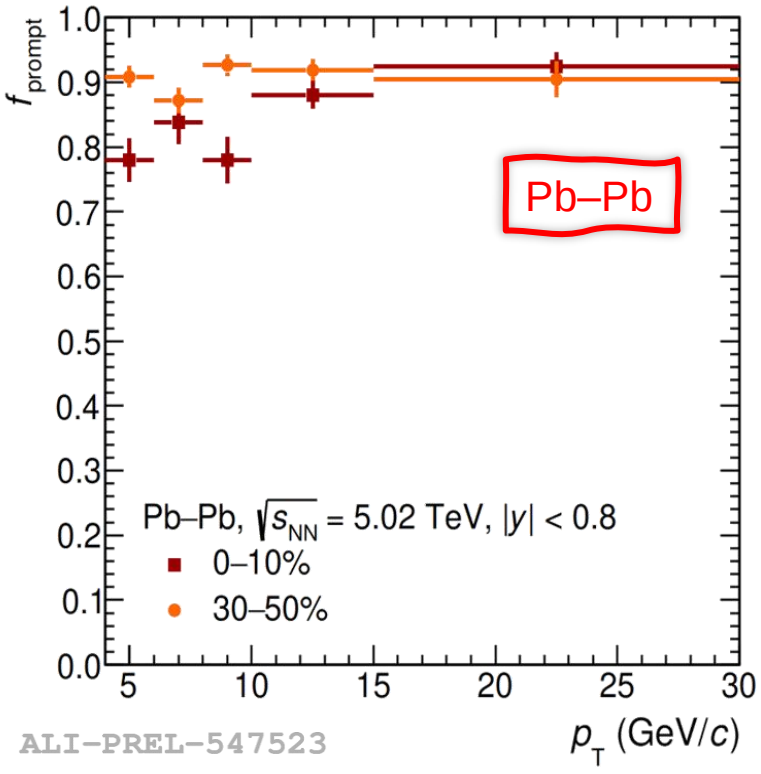
D^{*+} yield extraction

For D^{*+} analysis in pp and Pb–Pb collisions, Boosted Decision Trees (BDT) are used to

- Reduce the combinatorial background
- Separate prompt and non-prompt D^{*+} components



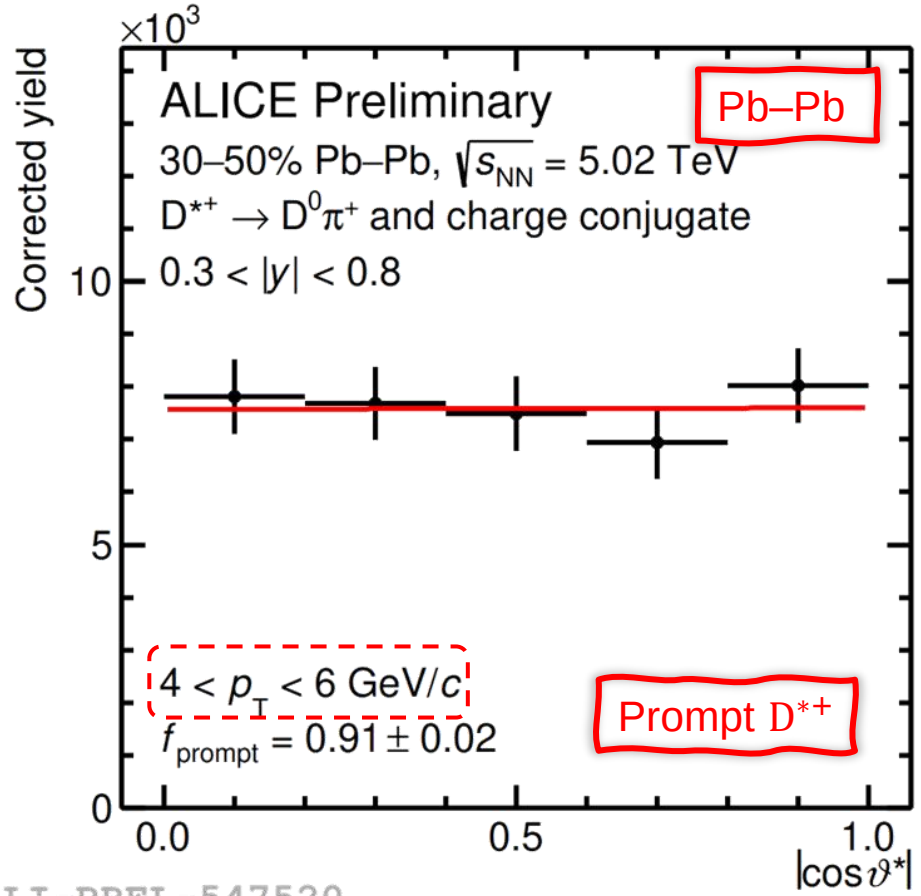


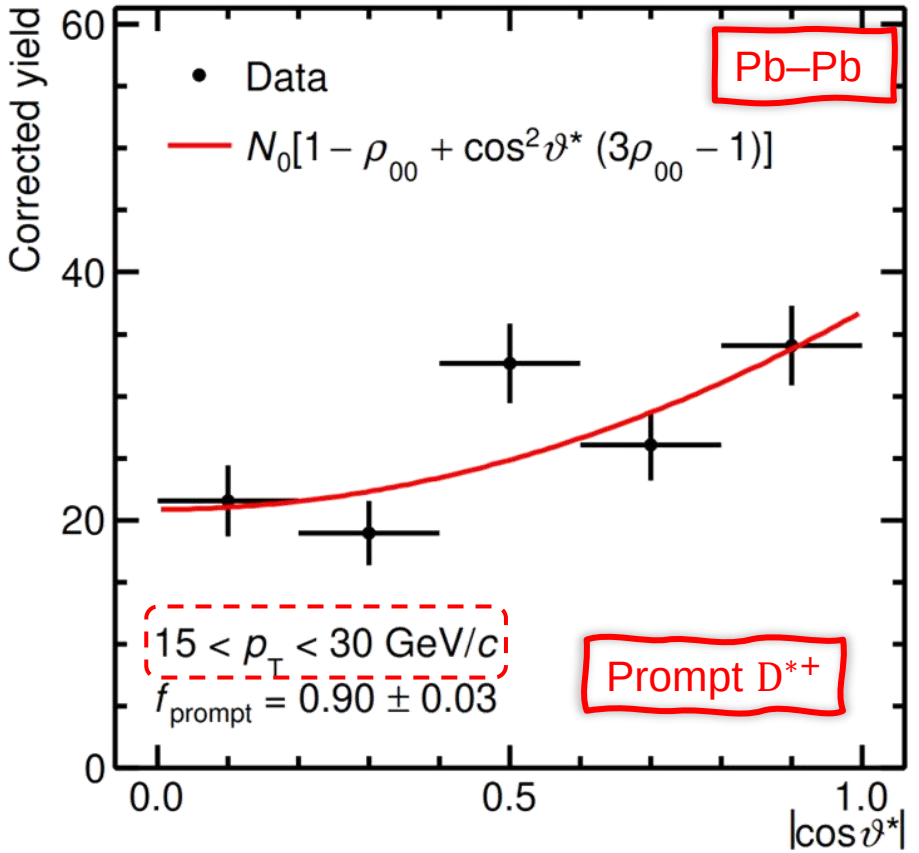


ρ_{00} extraction

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

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





ALI-PREL-547520

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

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

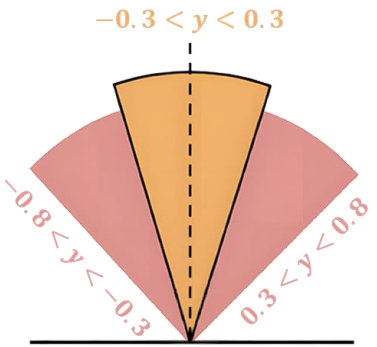
Extracted ρ_{00} parameter for **prompt D^{*+}**

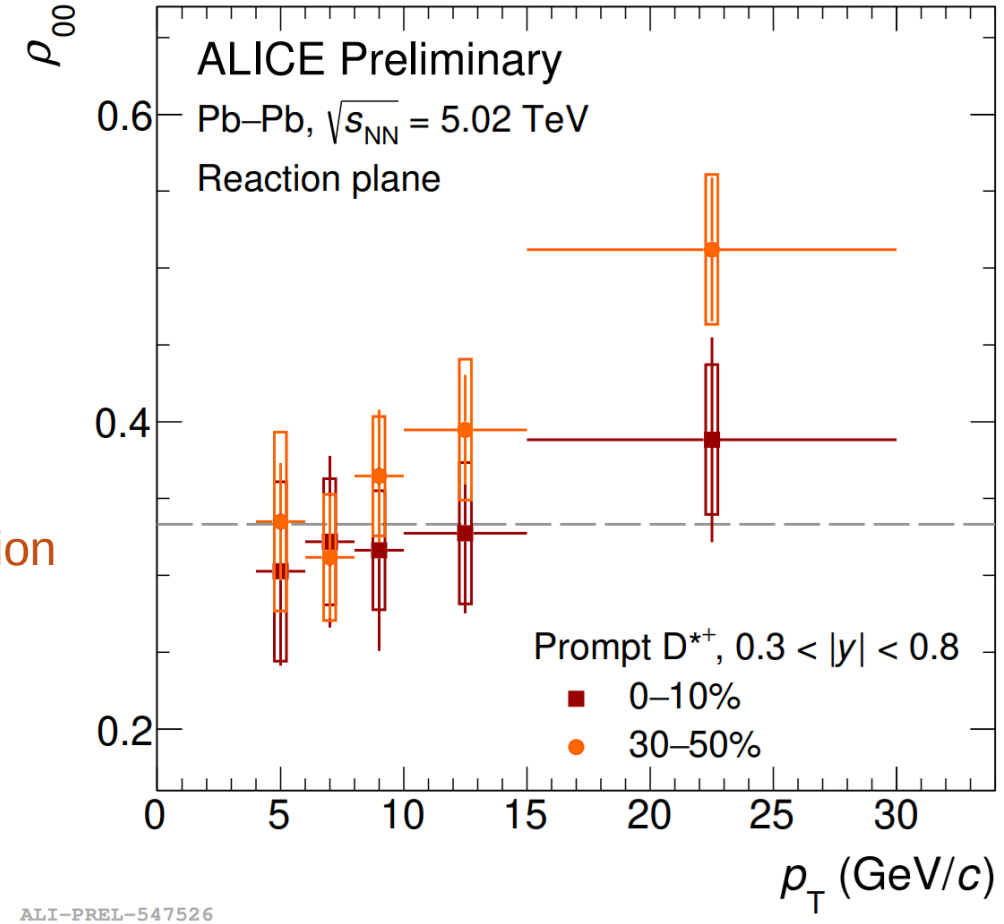
- In less central rapidity regions $0.3 < |y| < 0.8$
  - Central collisions (0-10%):

    Consistent with $\rho_{00} = ⅓$
  - Non-central collisions (30-50%):

    Evidence of ρ_{00} larger than ⅓ at high p_T

    ⇒ Hadronization by quark fragmentation



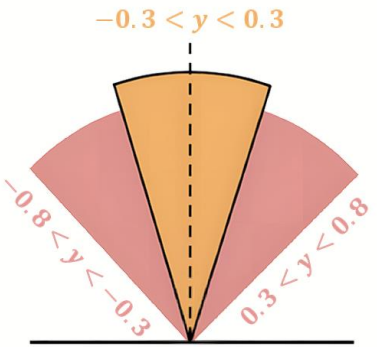


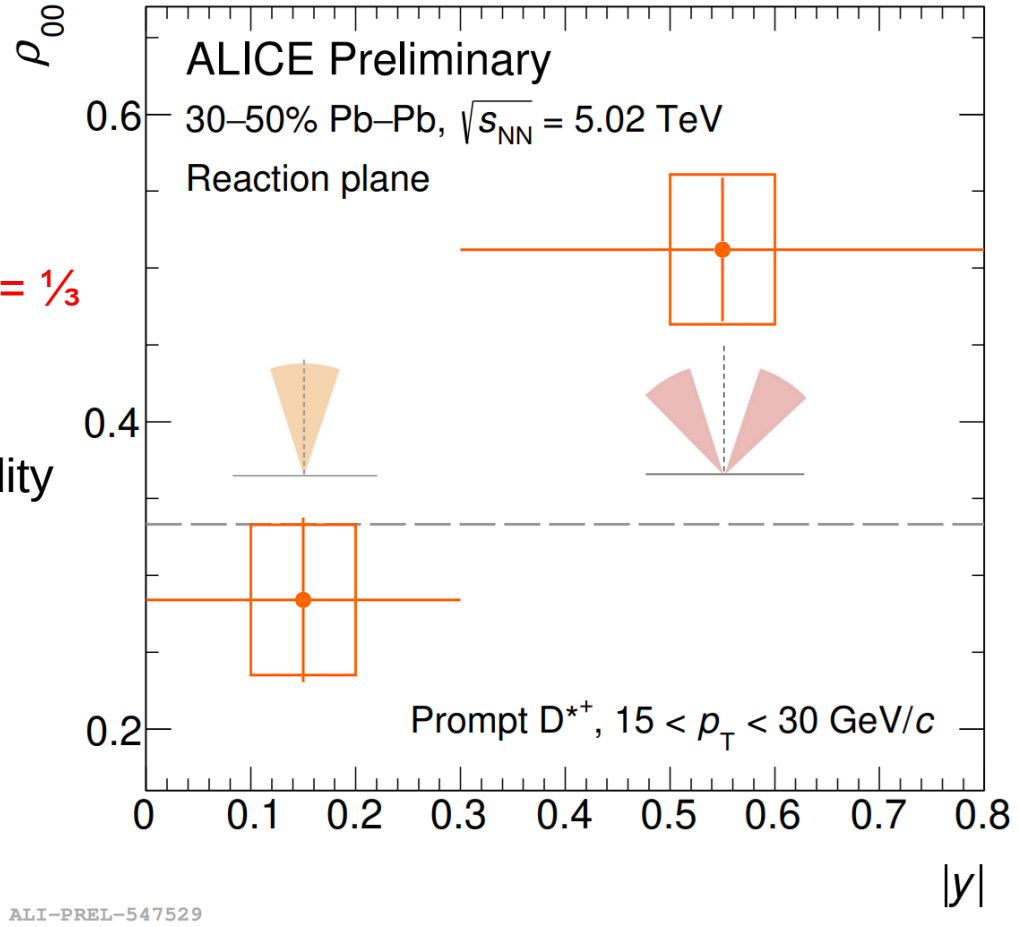
D^{*+} spin alignment in Pb–Pb collision

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 quark (large momentum) are affected more by $\vec{B}$ fields
    - ⇒ Spin-dependent fragmentation functions for charm

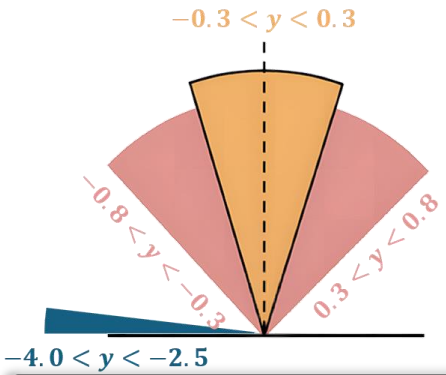


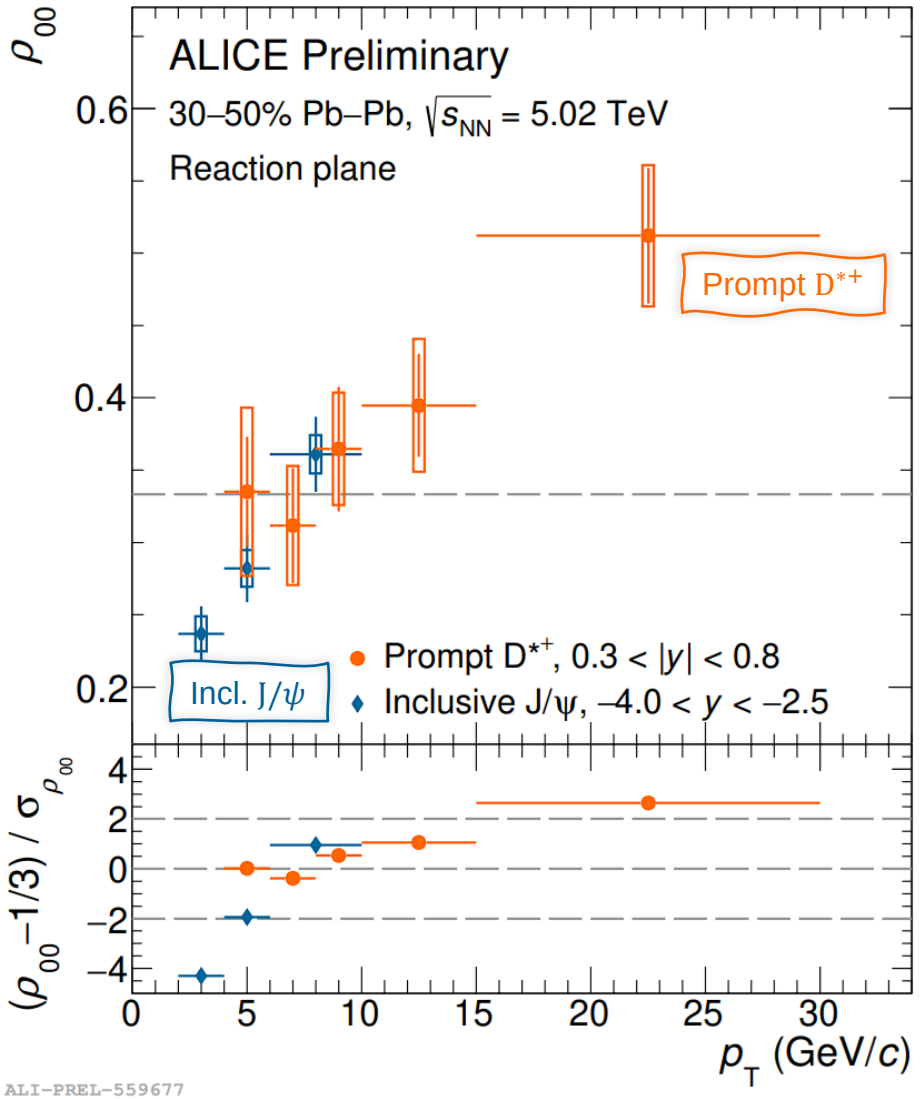


Spin alignment: Prompt D^{*+} vs inclusive J/ψ

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

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





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^{*+}

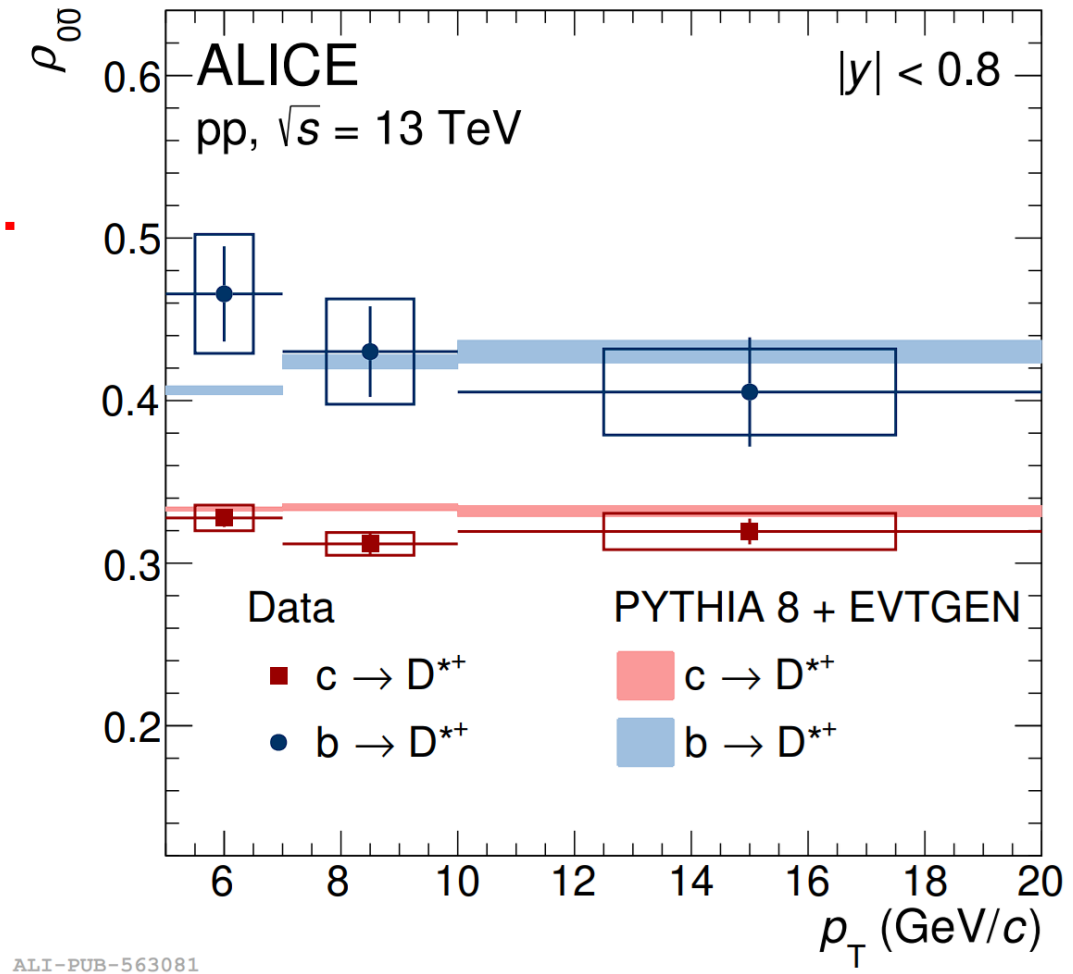
New ALICE preliminary results

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

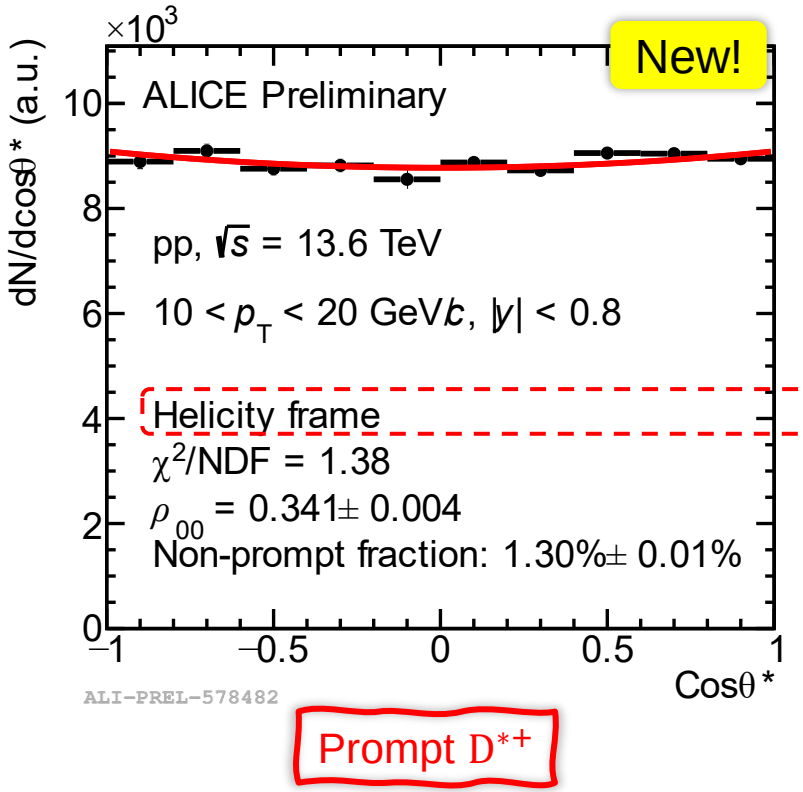
ALICE, Phys. Lett. B 846 (2023) 137920



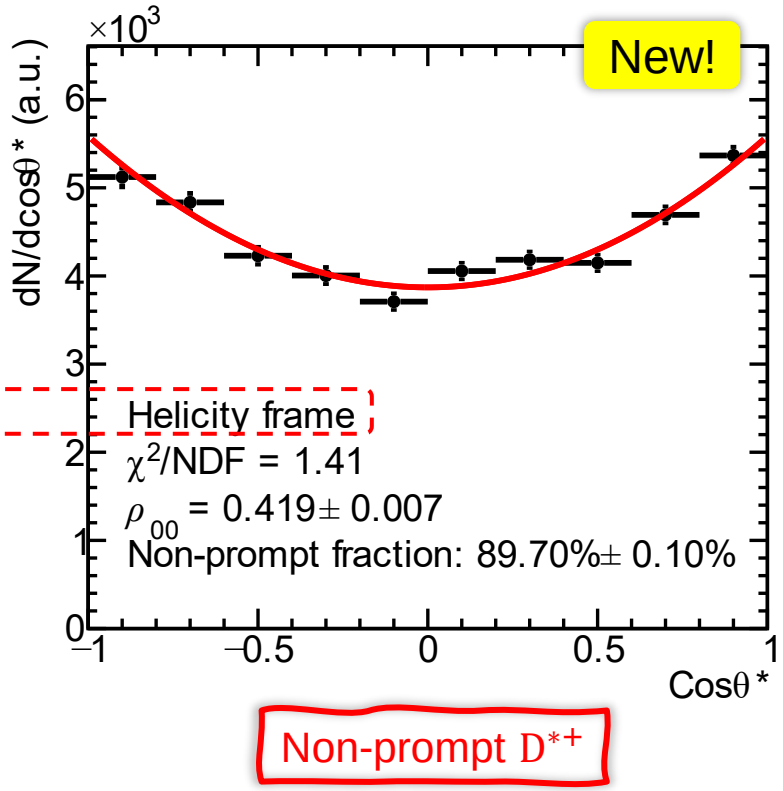
ρ_{00} extraction in pp collision

Measurement of D^{*+} spin alignment in pp collisions with respect to

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



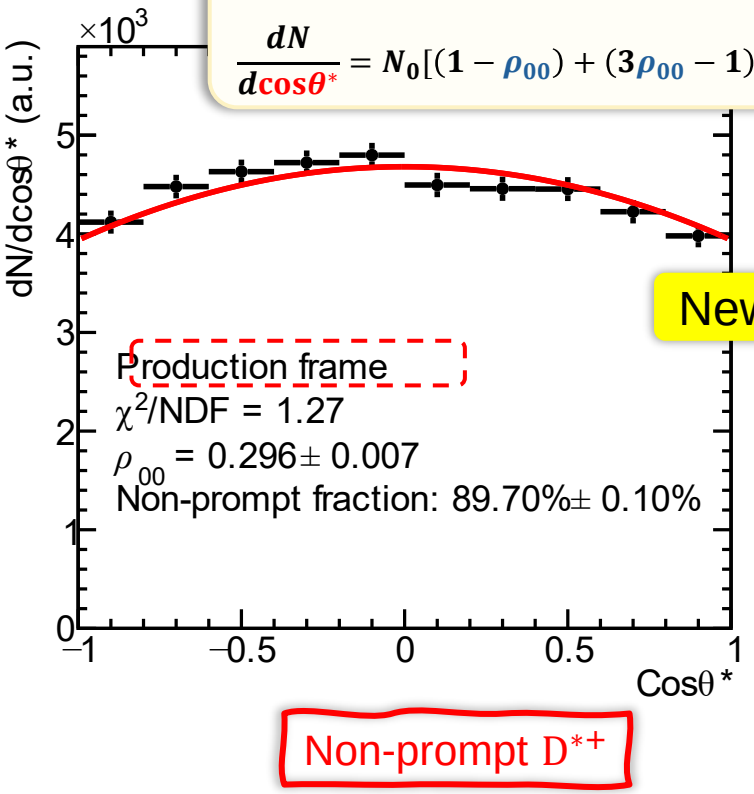
Prompt D^{*+}



Non-prompt D^{*+}

Fit function:

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



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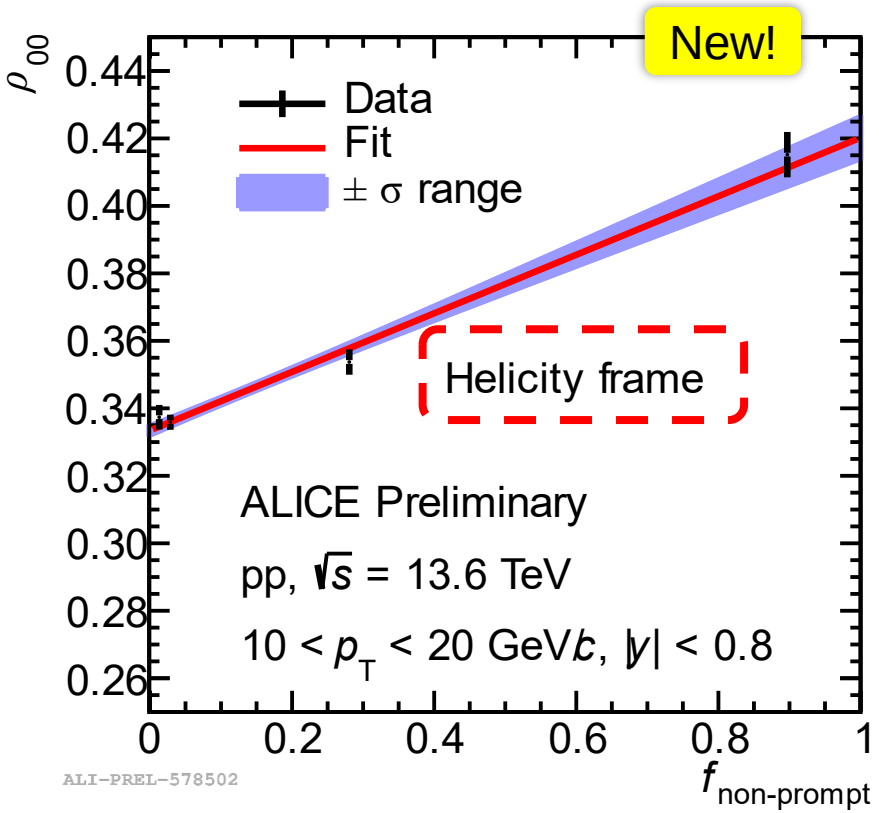
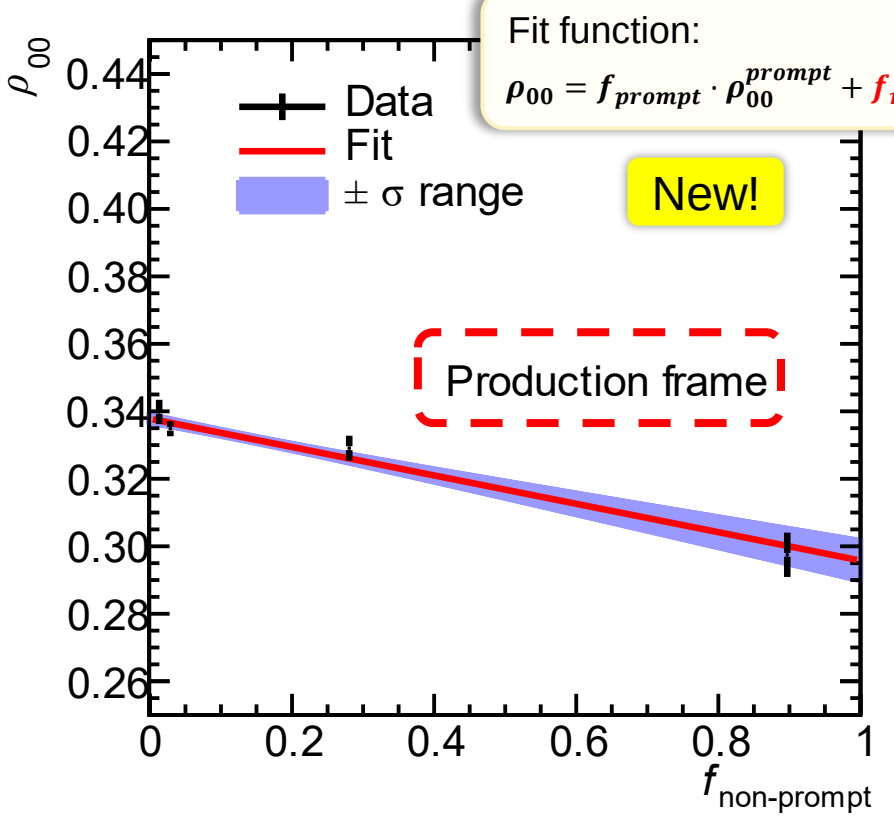




D^{*+} spin alignment in pp collision

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

Extracted ρ_{00} parameter for

- **Prompt D^{*+}**

  ⇒ No significant deviation from ρ_{00}= ⅓

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

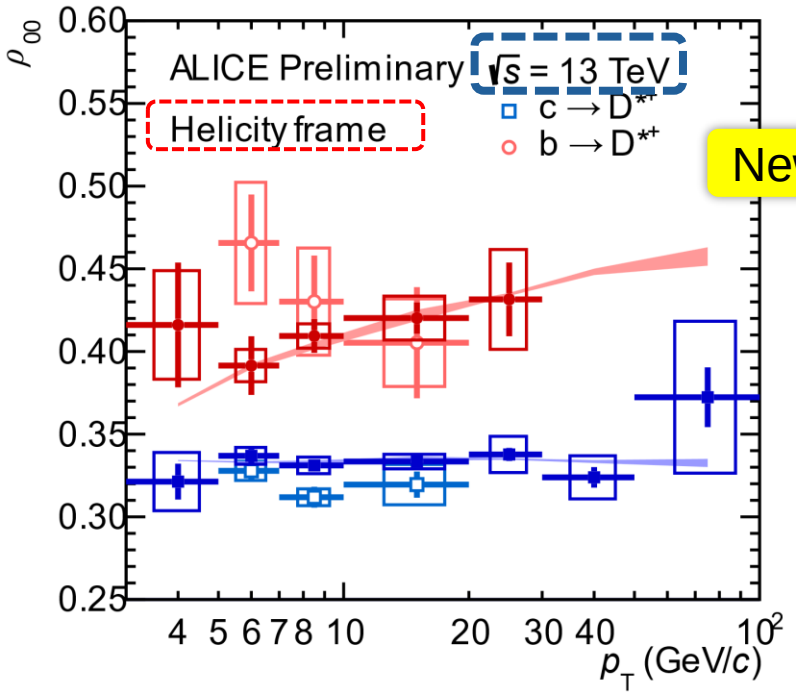
  ⇒ ρ_{00} larger than ⅓ for helicity frame

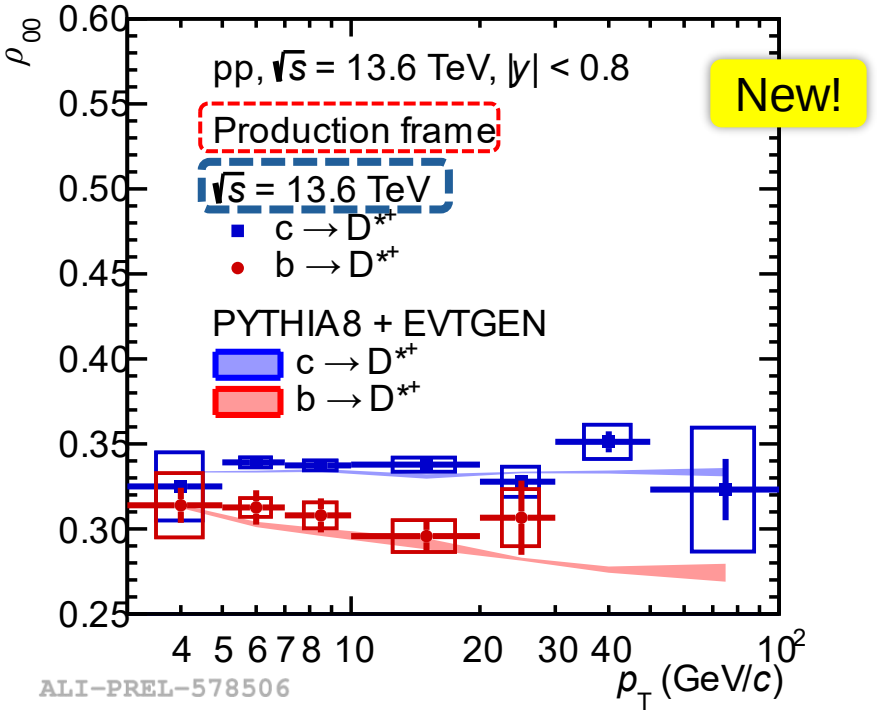
  Helicity conservation

  ⇒ ρ_{00} less than ⅓ at production frame

i. Measurement in agreement with prediction of PYTHIA 8.3+EVTGEN

ii. Reference for measurements in Pb–Pb collisions



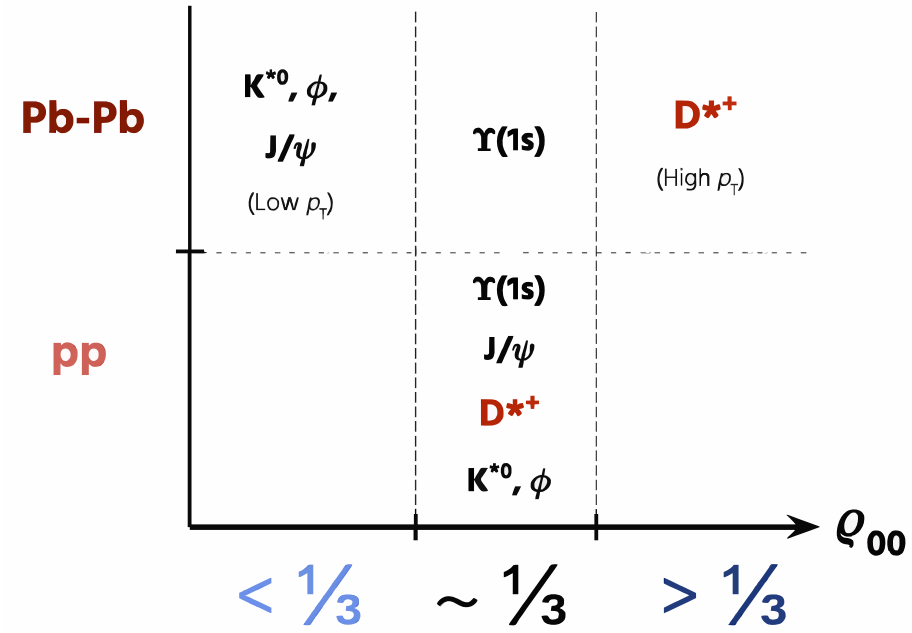


PYTHIA 8.3: SciPost Phys.Codeb. 2022 (2022), 8

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

Summary

- **pp collisions:**
  - light flavors, prompt D^{*+} and J/ψ are compatible with **zero polarization**
- **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 & forward rapidity ⇒ quark fragmentation scenario
- Theoretical predictions are required for conclusive remarks

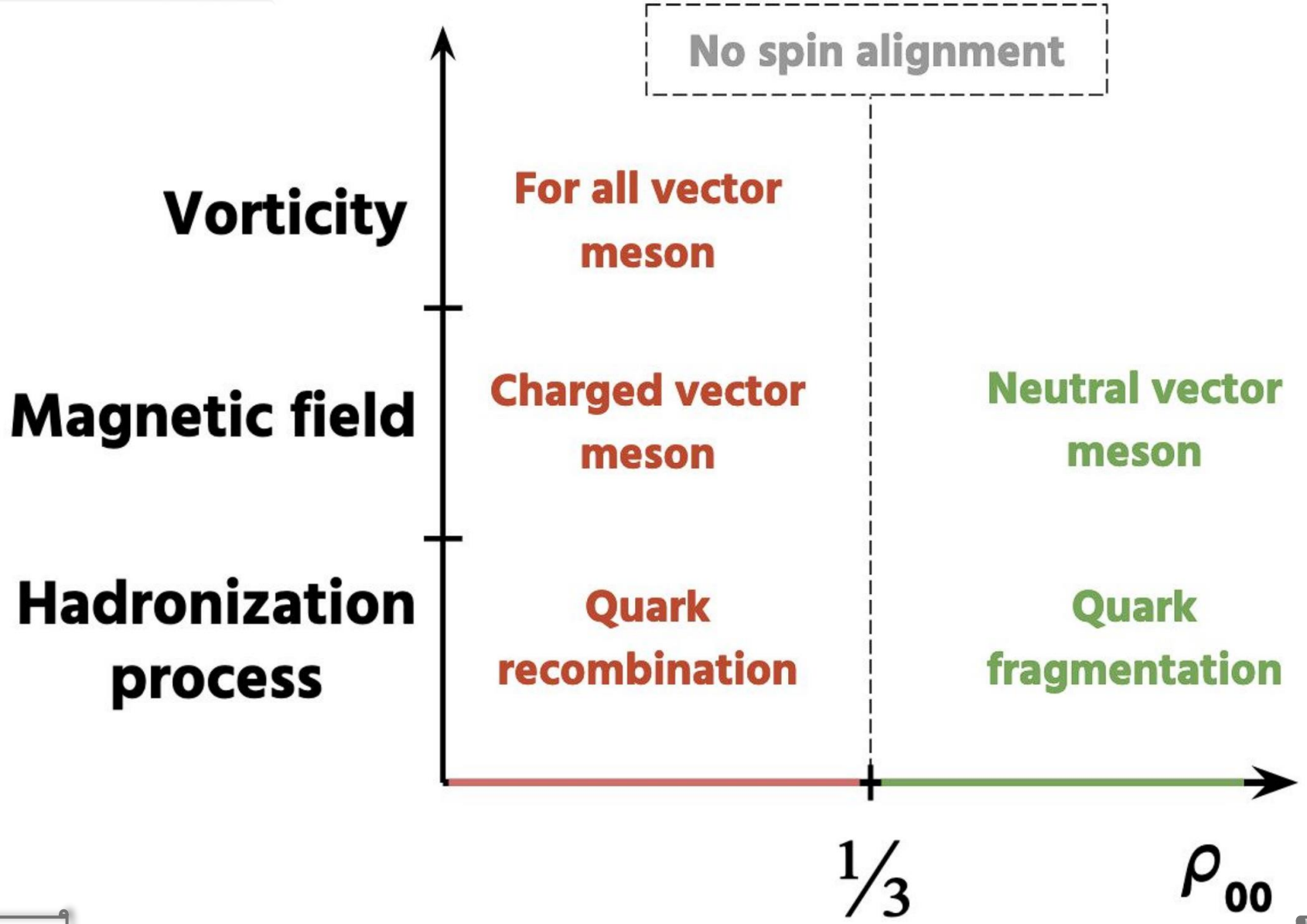


	pp	Pb–Pb
D^{*+}	ALICE, PLB 846 (2023) 137920	ALICE Preliminary
J/Ψ	ALICE, EPJ. C 78 (2018) 562	ALICE, PRL. 131, 042303
K^{*0}	ALICE, EPJ 171, 16008	ALICE, PRL. 125 (2020) 012301

Additional Slides

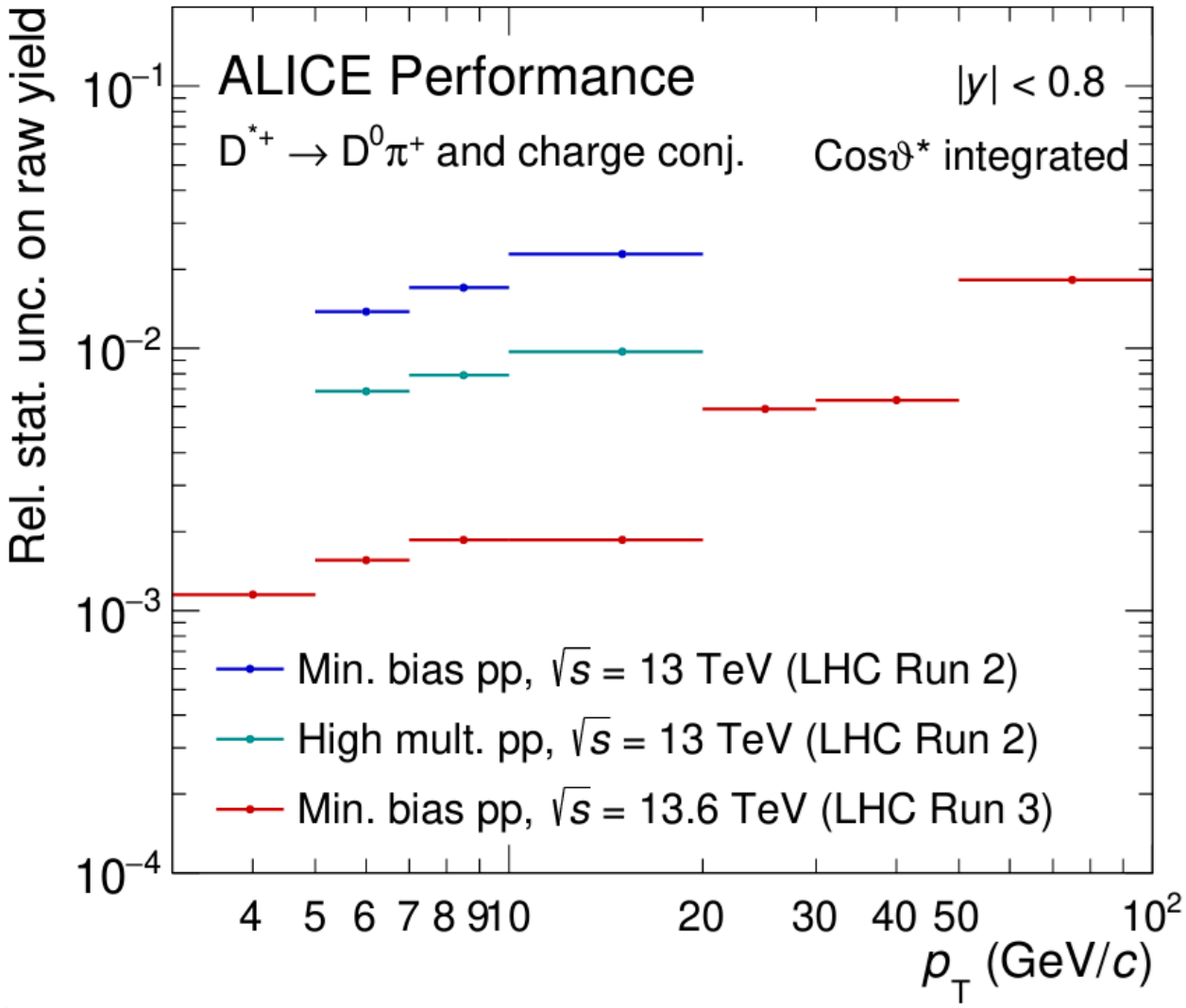
Theory expectation for ρ_{00}

Physics process and theory expectation



Run 3 performance for D^{*+}

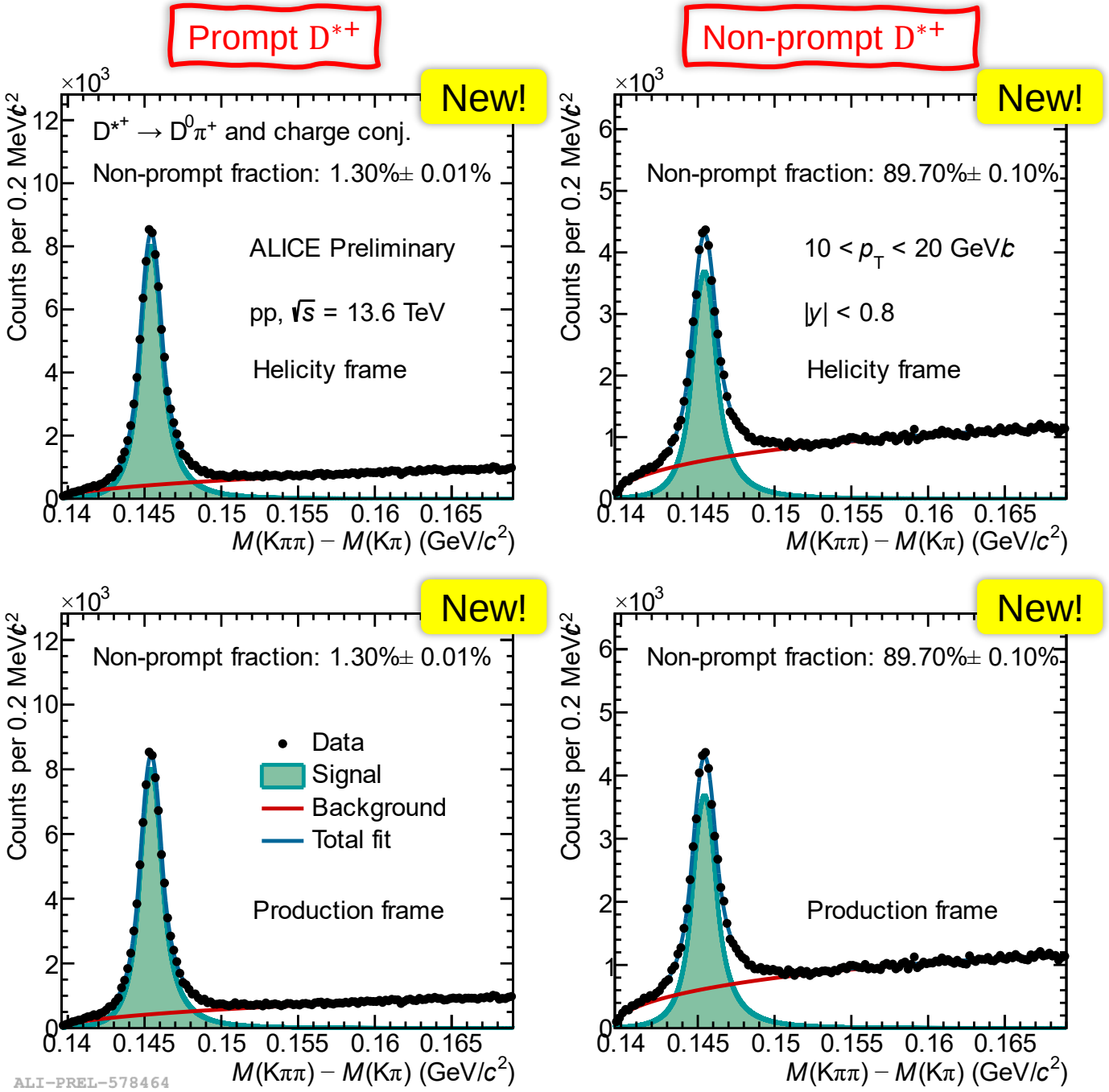
A comparison of relative uncertainties on raw yields of D^{*+}



ALI-PERF-571947

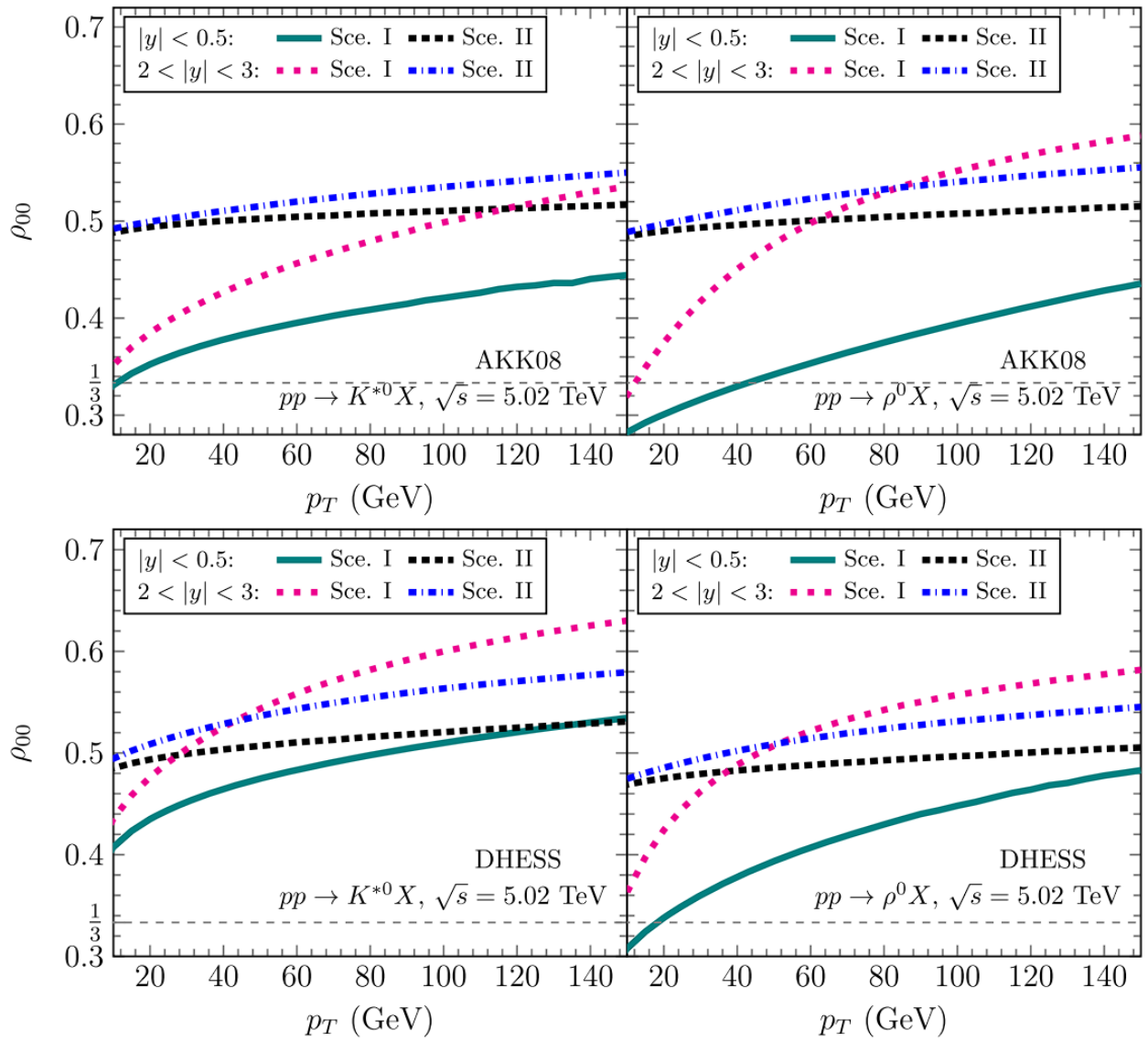
D^{*+} extraction

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



Spin dependent FF for light vector meson

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



Spin alignments of vector mesons in pp collisions at the LHC energy $\sqrt{s} = 5.02$ TeV for K^{*0} and ρ^0 in two rapidity regions as functions of p_{T}.

D^{*+} spin alignment in pp collision

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

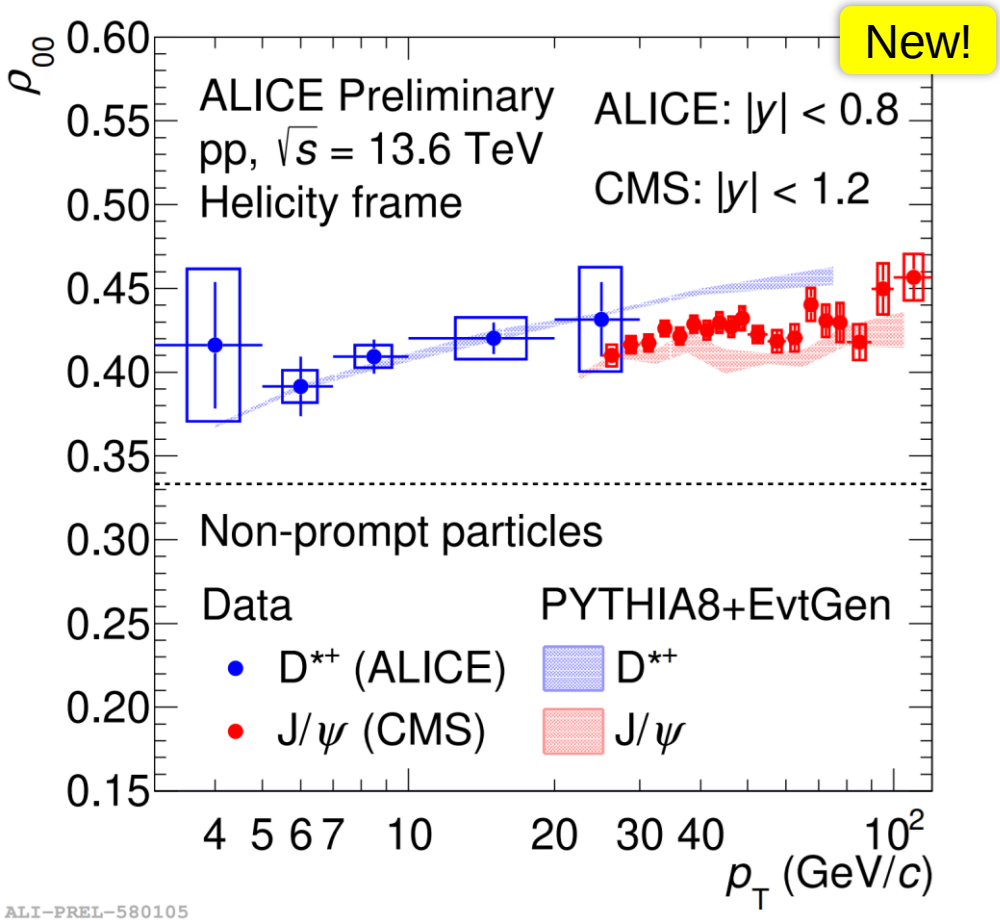
Extracted ρ_{00} parameter for

- **Prompt D^{*+}**
  - ⇒ No significant deviation from ρ_{00}= ⅓
- **Non-prompt D^{*+}**
  - ⇒ ρ_{00} larger than ⅓ at helicity frame
    - Helicity conservation
  - ⇒ ρ_{00} less than ⅓ at production frame

i. Measurement in agreement with prediction of PYTHIA 8+EVTGEN

ii. Reference for measurements in Pb–Pb collisions

pp collision: Results are compatible within the uncertainties in the overlapping p_T region



CMS Collaboration

ALICE Preliminary

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

D^{*+} spin alignment in pp collision

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

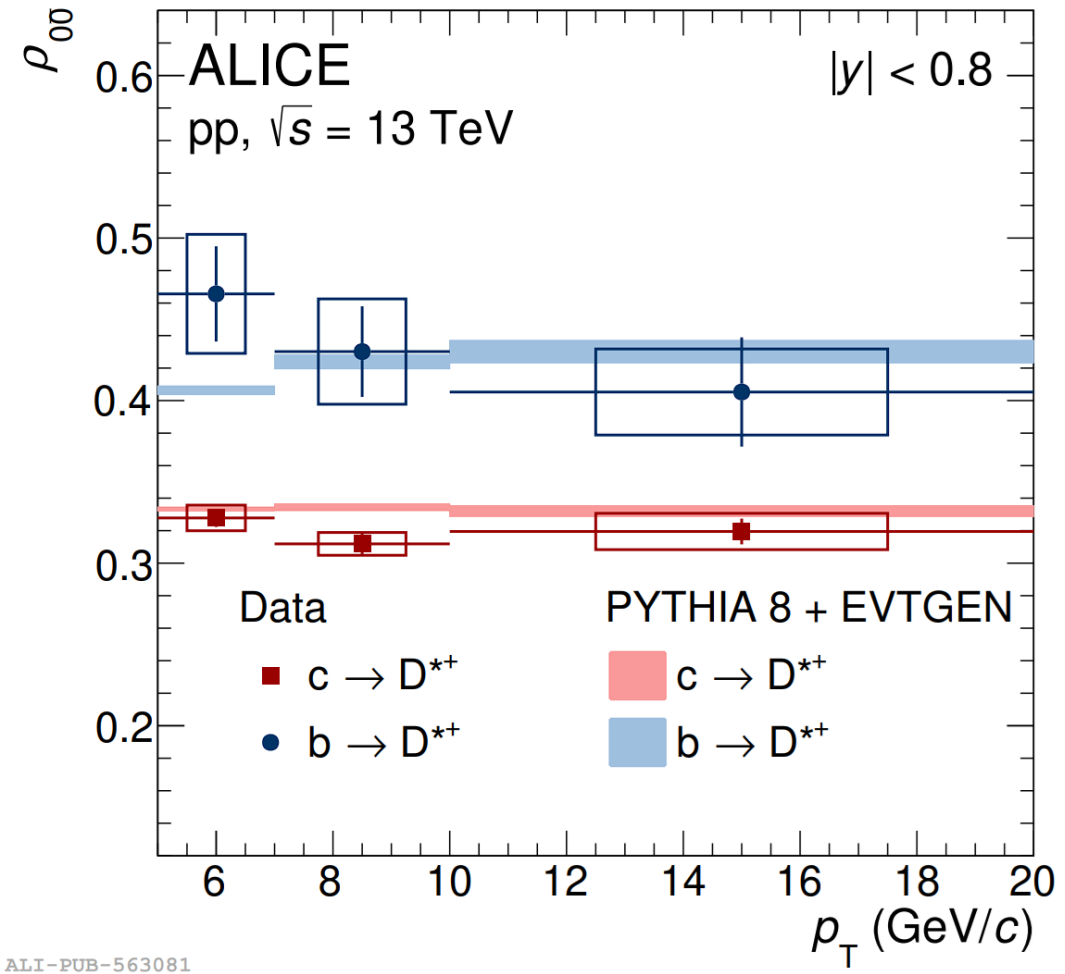
(During LHC Run 2, $\sqrt{s} = 13$ TeV)

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

Due to the helicity conservation

$B(S = 0) \rightarrow D^{*+}(S = 1) + X$

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



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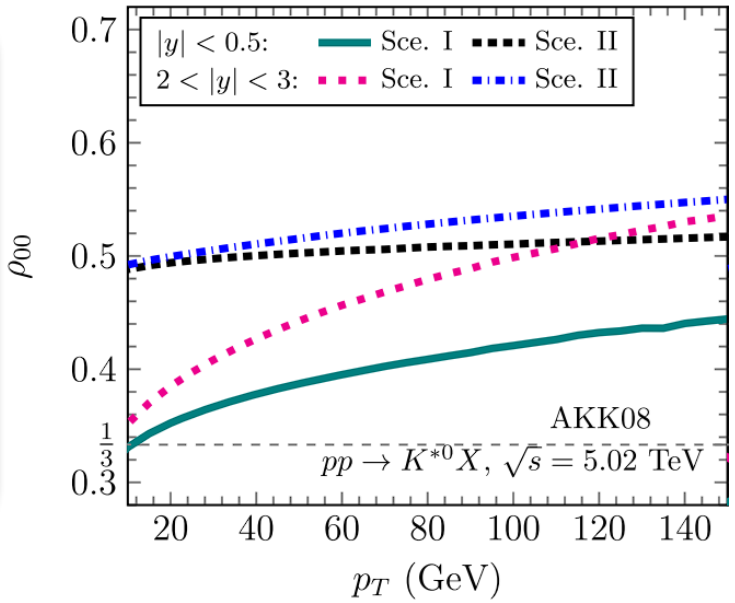
Polarization from spin-dependent fragmentation functions?

Need to reach higher p_T region!

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



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