Investigation of early magnetic field and angular momentum in ultrarelativistic heavy-ion collisions via D*$^+$-meson spin alignment with ALICE

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On behalf of the **ALICE** Collaboration

Strangeness in Quark Matter, 2024

INFN PADOVA
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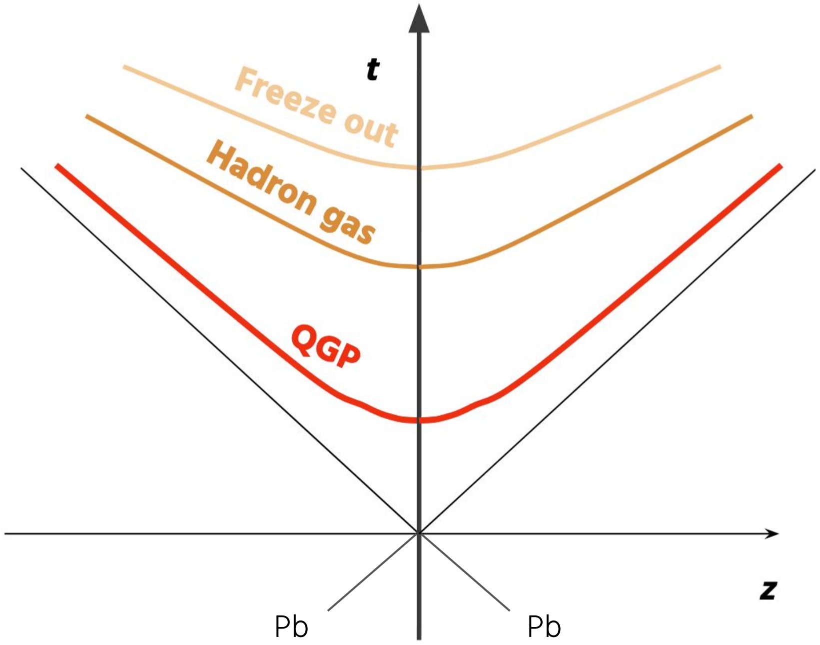
Sezione di Padova

SQM 2024
The 21st International Conference on Strangeness in Quark Matter
3-7 June 2024, Strasbourg, France

ALICE

Motivation

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

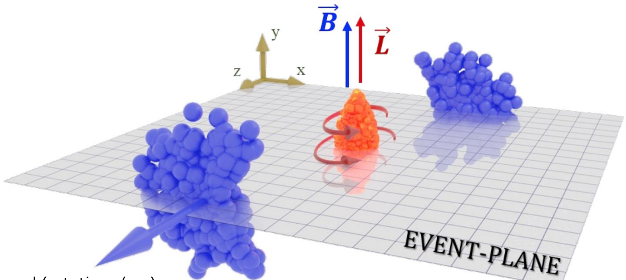


“Simplified” spacetime evolution of heavy ion collisions

Motivation

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

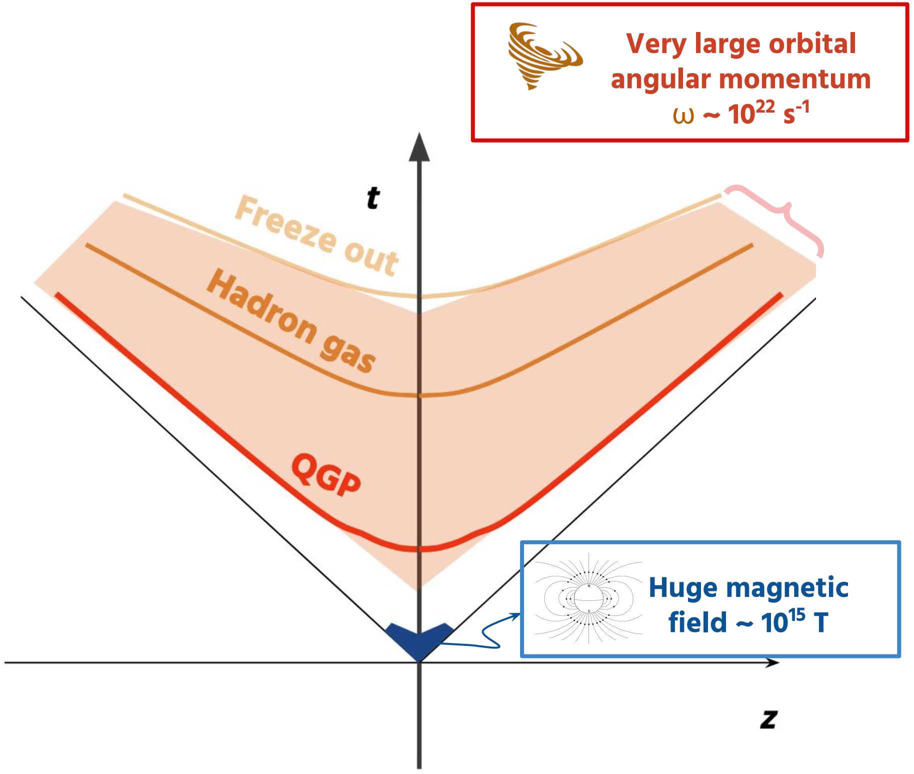
- In **non-central** collisions:
  - Charged spectator motion produces magnetic field (B) ~ $\mathbf{10^{15}}$ **T** †
    - Decreases with time
  - A highly vortical system with orbital angular momentum (L), ω* ~ $\mathbf{10^{22}\ s^{-1}}$ ★



*ω: rotational speed (rotations/sec)

† P Christakoglou *et al*, Eur. Phys. J. C (2021) 81: 717

★ STAR Collaboration, Nature 548, 62 (2017)



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ALICE

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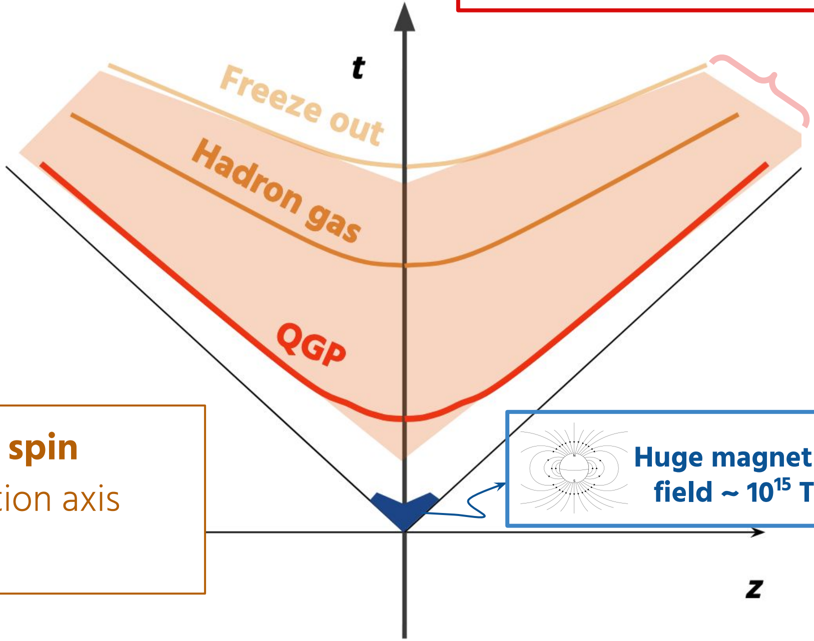
can preferentially **align** a **particle's spin projection** along the spin quantization axis through spin-orbit coupling

Very large orbital angular momentum ω ~ 10^{22} s^{-1}



Huge magnetic field ~ 10^{15} T

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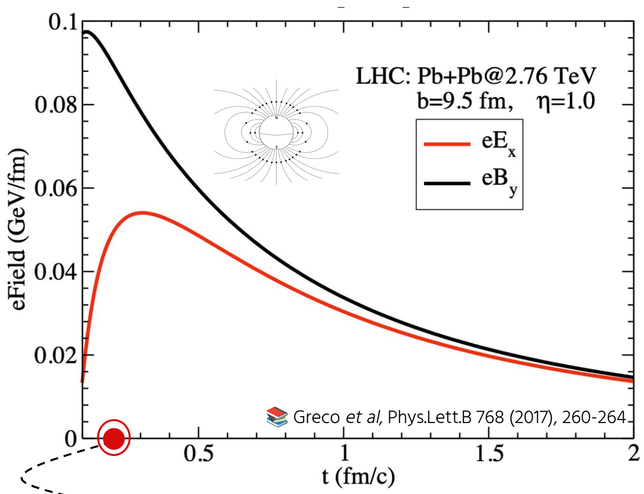
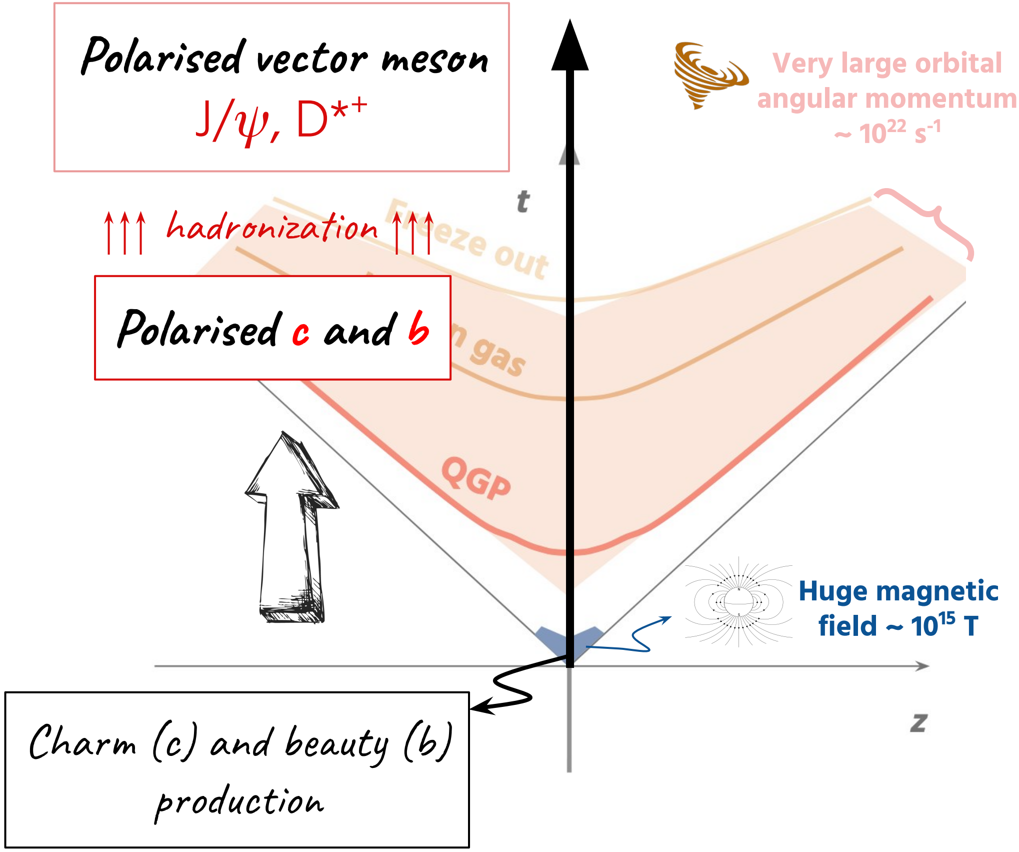


- Charm quarks produced in early stages,
  $t \sim 1/m_q \sim 0.1$ fm/c
  - **More sensitive to the high intensity of the EM fields than light quarks**



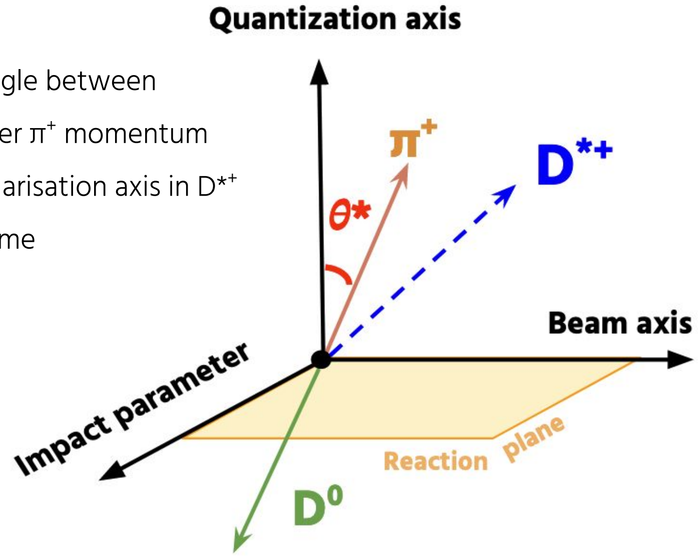
Spin alignment measurements

- Hadrons' spin alignment measurements rely on spin density matrix element (ϱ_{00})
  - ϱ_{00} = 1/3 ⇒ No spin alignment
  - ϱ_{00} ≠ 1/3 ⇒ spin alignment observed
- Polarisation/Quantization axis
  - **Orthogonal to event plane**: In the direction of **L** and **B** fields (in Pb–Pb collisions)
  - **Helicity**: In the direction of vector meson momentum, (considered in pp collisions)

Angular distribution of decay products:

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

θ^* = Angle between daughter π^+ momentum and polarisation axis in D^{*+} rest frame



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Angular distribution of decay products:

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

- Vector meson spin alignment governed by two mechanisms

Quark recombination

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

* **>** for Neutral meson, **<** for Charged meson

$\boldsymbol{P_q}$ = Polarisation of quark

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 anti-quark

Low p_T — **p_T (GeV/c)** — High p_T

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

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

ALICE experiment

Central barrel detectors
$|\eta| < 0.9$

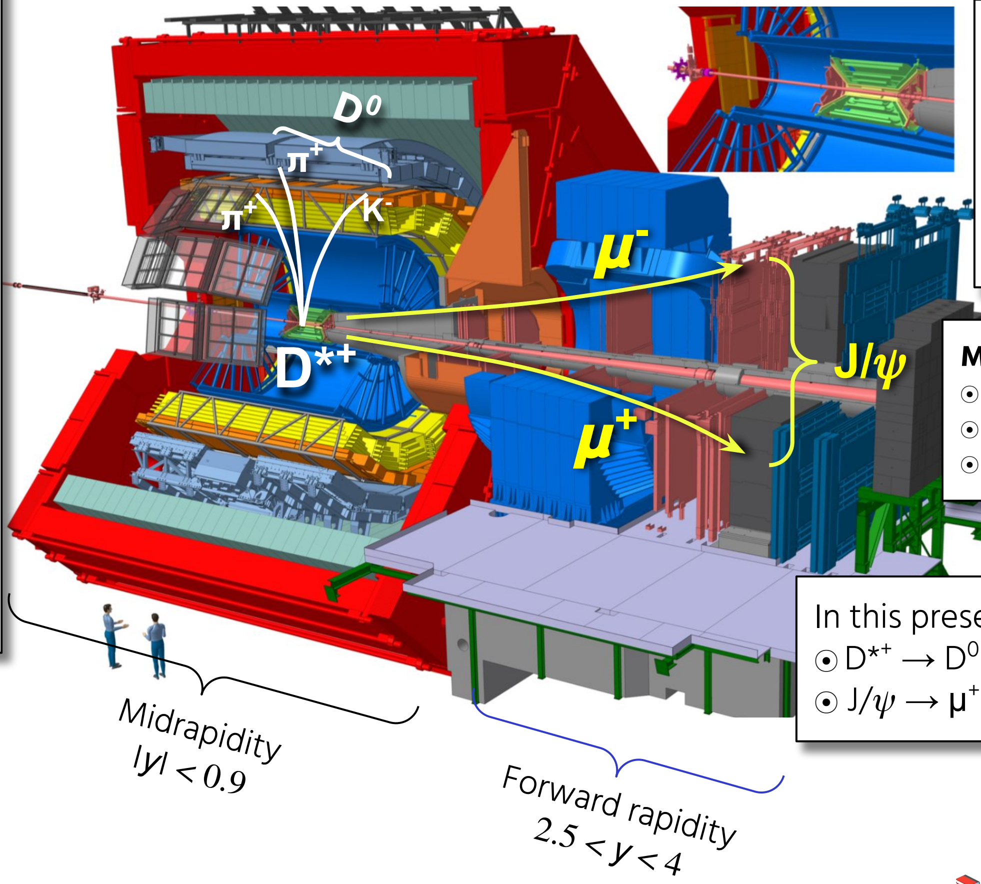
1) ITS
- Tracking
- Primary and secondary vertex reconstruction

2) TPC
- Tracking
- Particle identification

3) TOF
- Particle identification

Excellent tracking and PID capabilities down to very low momentum

ALICE:LHC Run 2



V0
- $2.8 < \eta < 5.1$ & $-3.7 < \eta < -1.7$
- Triggers
- Collision centrality determination
- Background rejection
- Event plane determination

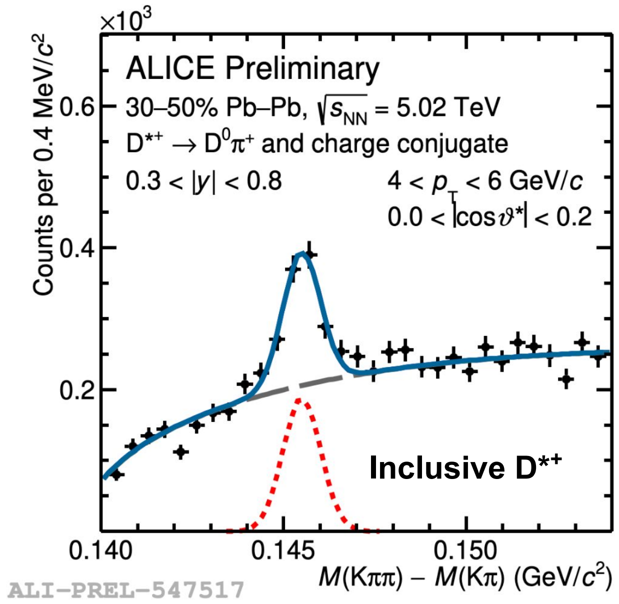
Muon spectrometer
- $2.5 < y < 4$
- Muon trigger
- Muon tracking down to very low p_T

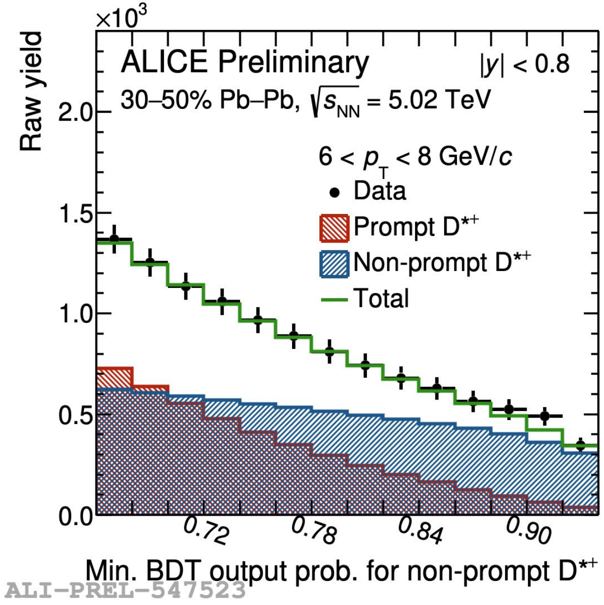
In this presentation, we focus on
- $D^{*+} \to D^0 \pi^+ \to K^- \pi^+ \pi^+$
- $J/\psi \to \mu^+ \mu^-$

ALICE Collaboration, JINST (2008) S08002

D*+ yield extraction

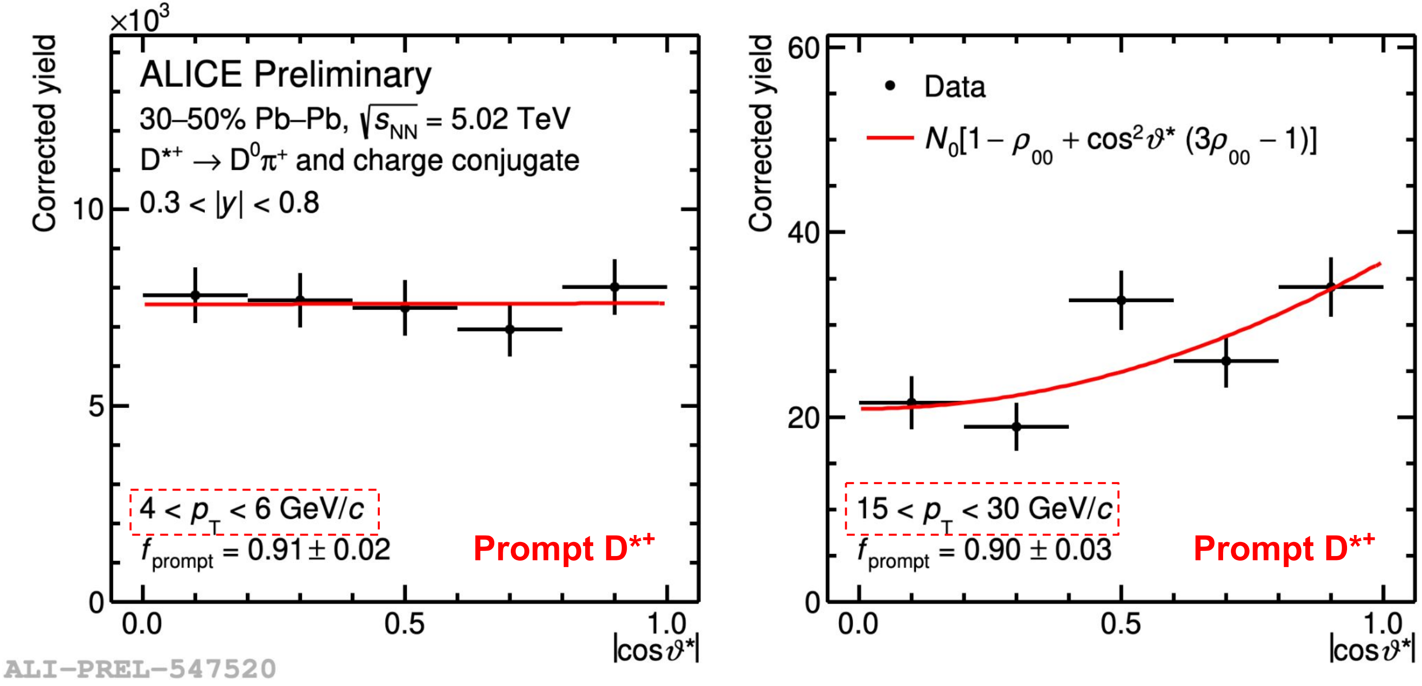
- For D*+ analysis in pp and Pb–Pb collisions, Boosted Decision Trees (BDT) are used to
  - Reduce the combinatorial background
  - Separate prompt and non-prompt D*+ components





D*+ yield extraction

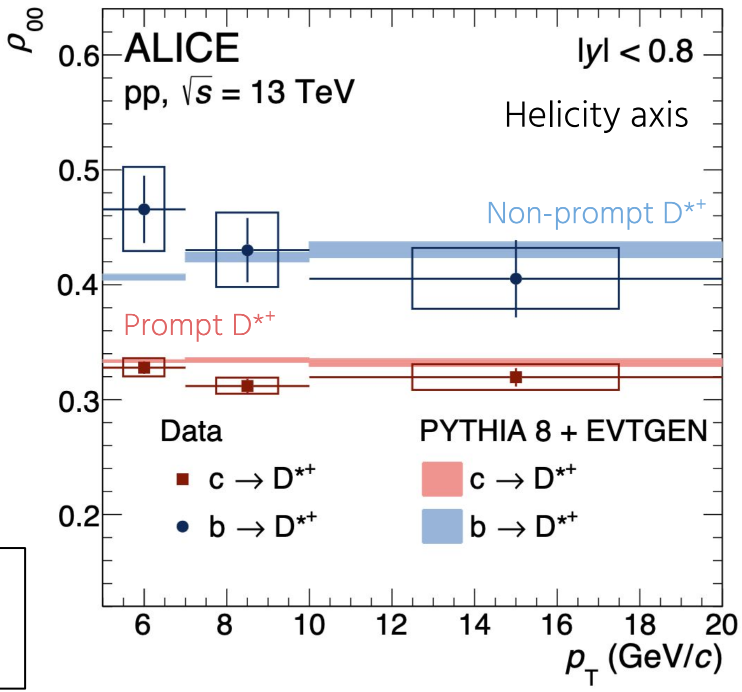
- For D*+ analysis in pp and Pb–Pb collisions
  - ϱ_{00} extraction for prompt and non-prompt D*+ in different p_T intervals



Spin alignment measurement in pp collisions

- First measurement of the prompt and non-prompt D^{*+} spin alignment at the LHC
- Measurements performed in the **Helicity axis**
  - $\rho_{00} = 1/3 \Rightarrow$ No spin alignment for prompt D^{*+}
  - $\rho_{00} > 1/3 \Rightarrow$ Spin alignment observed for non-prompt D^{*+}
    - Due to Helicity conservation in b-hadron decays
- "PYTHIA 8 (MC generator) + EVTGEN (decayer)" predictions are consistent with the measurements

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



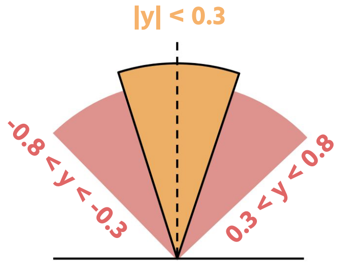
Serves as a benchmark for D^{*+} spin alignment measurements in Pb–Pb collisions

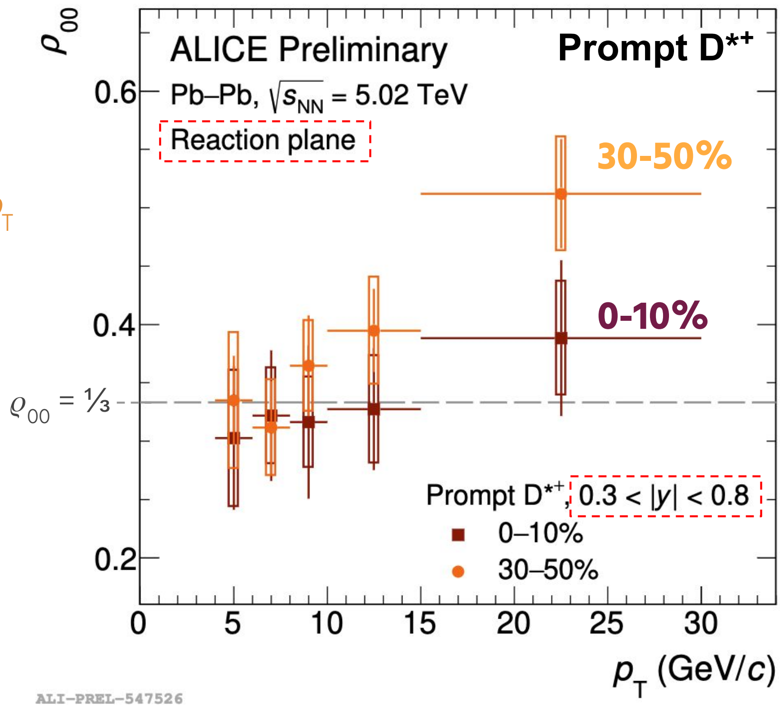
Prompt D^{*+} spin alignment in **Pb–Pb** collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

Spin alignment measurement

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

- Extracted ϱ_{00} parameter for **prompt D*+**
  - In two rapidity regions
  - Hint of rising trend with p_T
  - **0-10%: Consistent with ϱ_{00} = ⅓**
  - **30-50%**: Evidence of ϱ_{00} larger than ⅓ at high p_T
    ⇒ Hadronization by quark fragmentation





Spin alignment measurement in different rapidity region

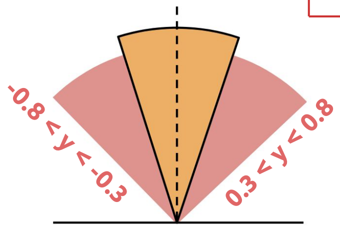
First measurement of D^{*+} spin alignment with respect to the reaction plane in Pb–Pb collisions

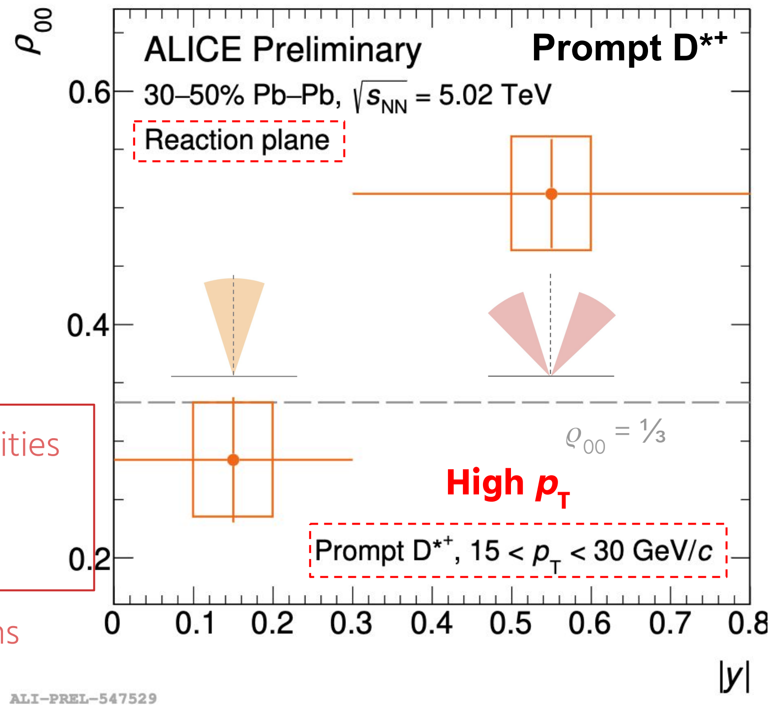
- Extracted ρ_{00} parameter for **prompt D^{*+}**
  - Hints of rising trend with p_T
  - **0-10%: Consistent with ρ_{00} = 1/3**
  - **30-50%: At high p_T ρ_{00} > ⅓**
    - ➢ **No significant deviation at midrapidity from ρ_{00} = 1/3**
    - ➢ **ρ_{00} > 1/3 at large rapidity, B effect?**

⇒ B decreases <u>slower in time</u> at large rapidities
⇒ Very early produced c quark (<u>large momentum</u>) are affected more by B fields

⇒ Spin-dependent fragmentation functions for charm?

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



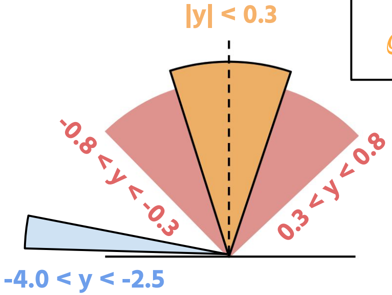


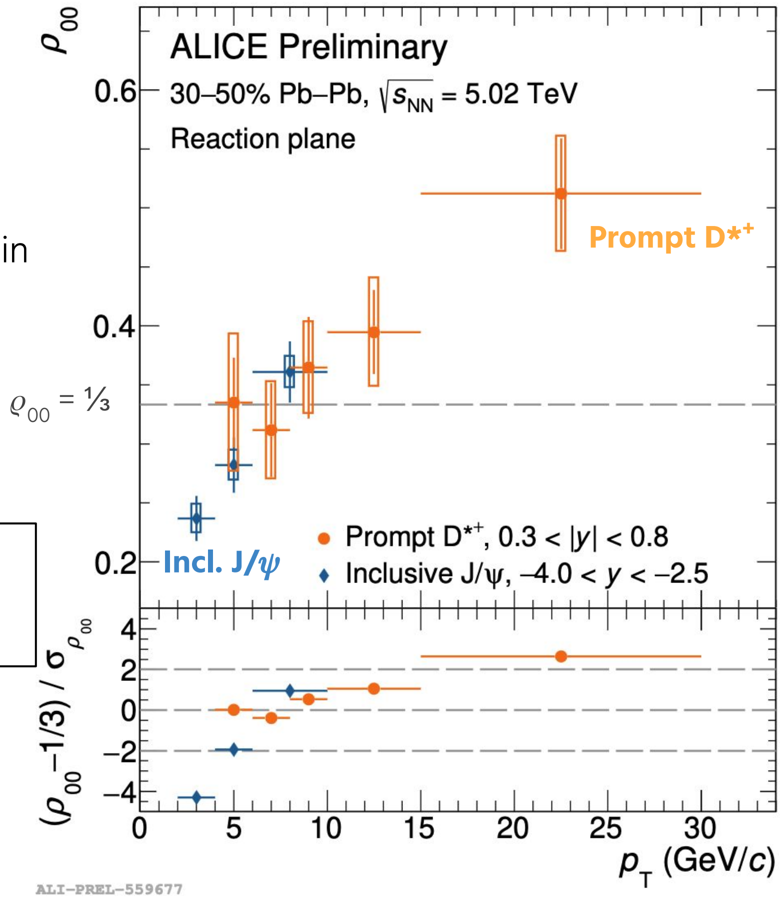
Spin alignment measurement: Prompt D^{*+} vs Inclusive J/ψ

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

$\varrho_{00} < ⅓$: Quark **recombination** at low p_T
$\varrho_{00} > ⅓$: Quark **fragmentation** at high p_T





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

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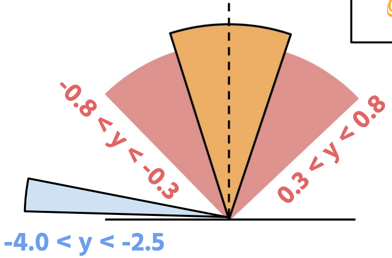
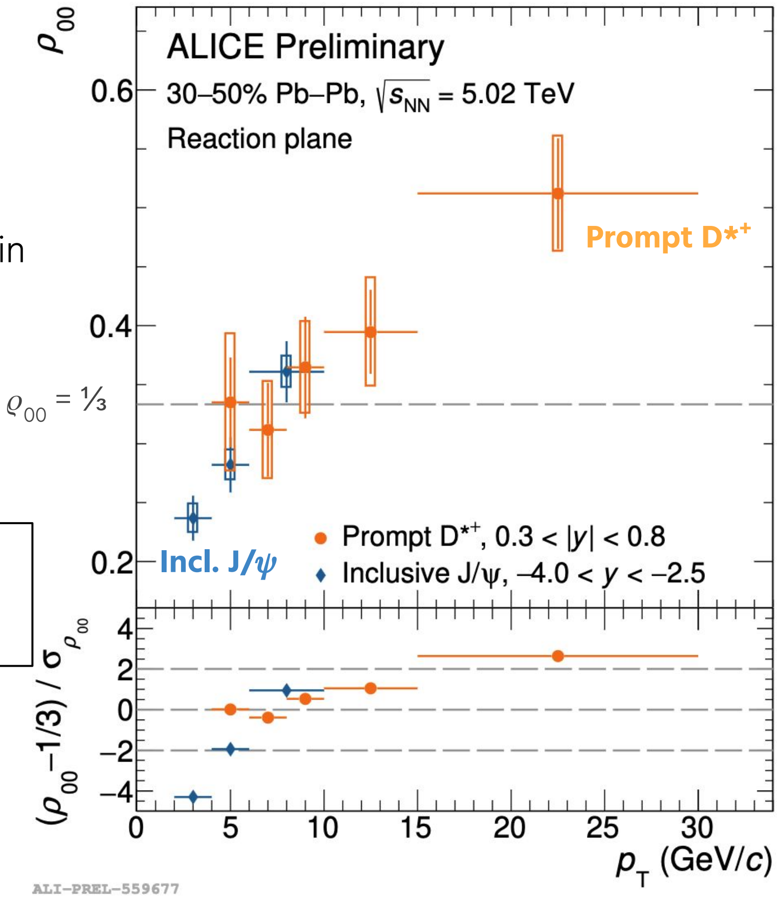


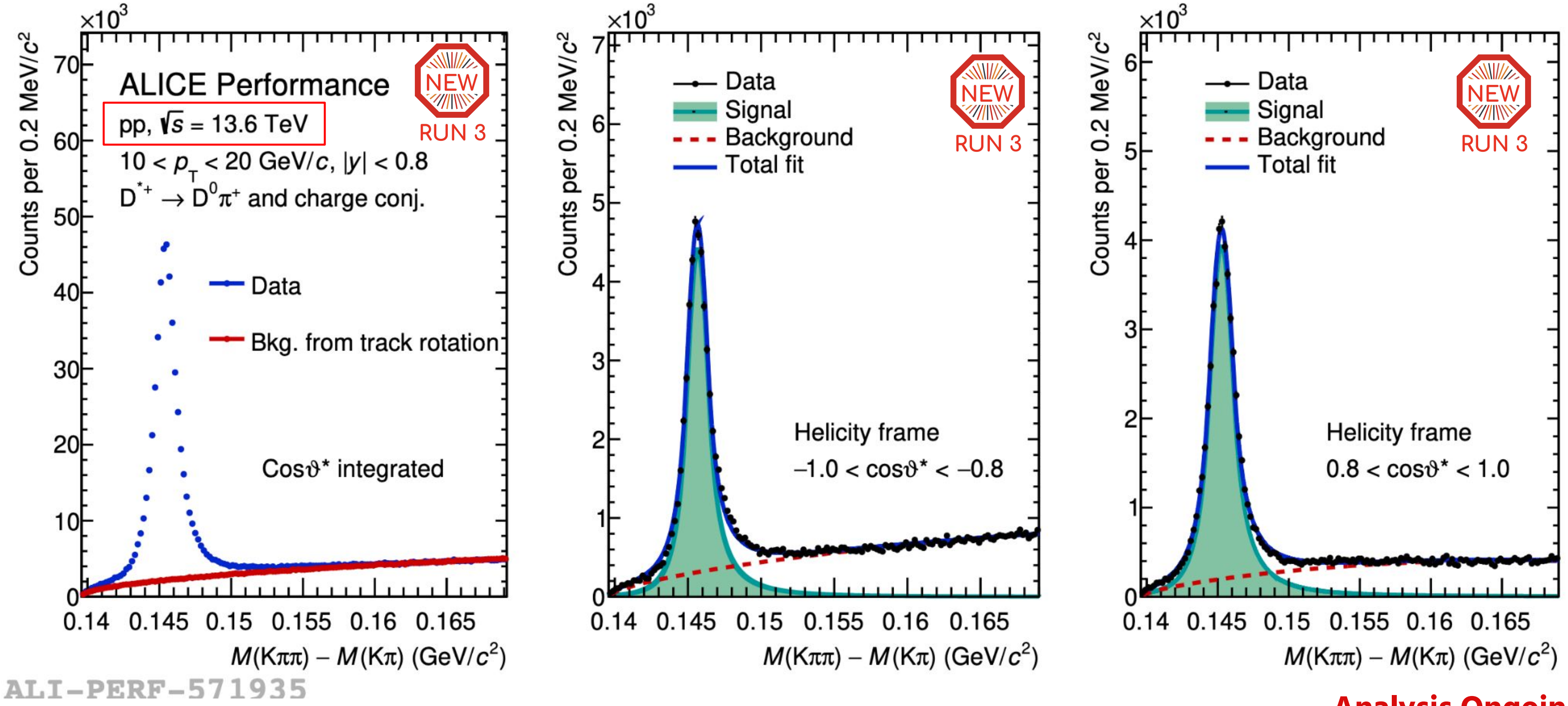
J/ψ polarisation in ALICE

by D. Mallick's on 5th June @ 10:40



Outlook

- Large datasets are collected by the ALICE during LHC Run 3 (Ongoing)
  - Large data taking rates: **500 kHz in pp** and **50 kHz in Pb–Pb** collisions



Analysis Ongoing

Outlook

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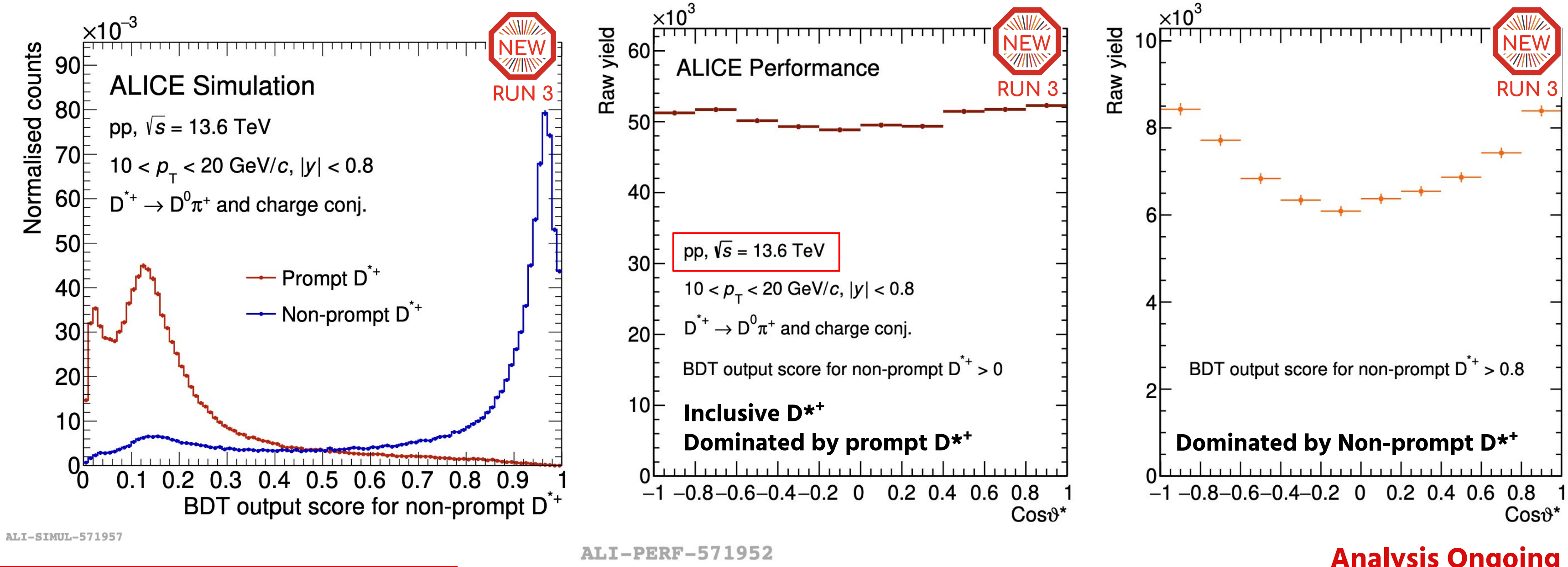
  - Large data taking rates: **500 kHz in pp** and **50 kHz in Pb–Pb** collisions

- More differential measurements in p_T and cos θ^*, up to $p_T \sim$ **100 GeV/c** in pp collisions

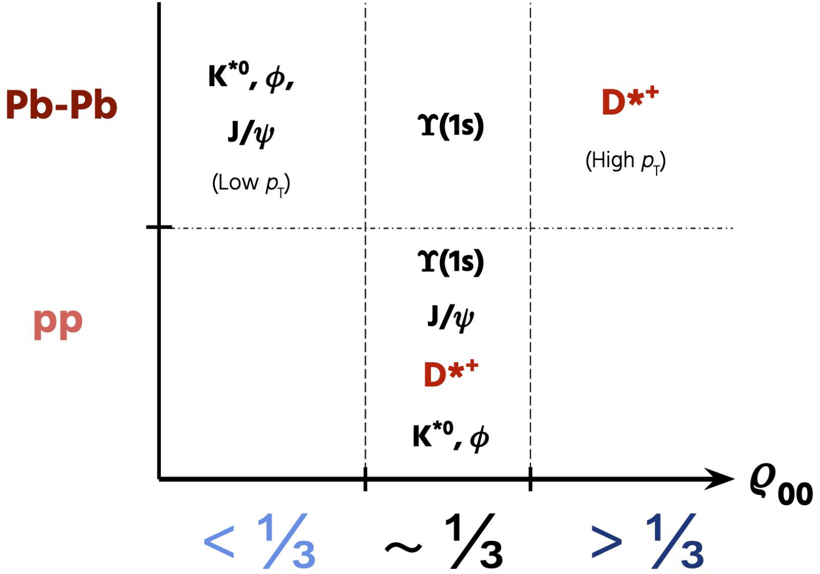


Analysis Ongoing

Summary

- First results of prompt D^{*+} spin alignment with respect to the reaction plane in Pb–Pb collisions are presented
- Significant spin alignment observed in prompt D^{*+} in semicentral collisions at high p_T.
  - Larger effect at forward-backward rapidity compared to midrapidity
    - Consistent with quark fragmentation scenario
- Results consistent with inclusive J/ψ polarization in the overlapping p_T region in semicentral collisions
- Theoretical predictions are required for conclusive remarks!

A summary of spin alignment/polarisation for different vector mesons in ALICE

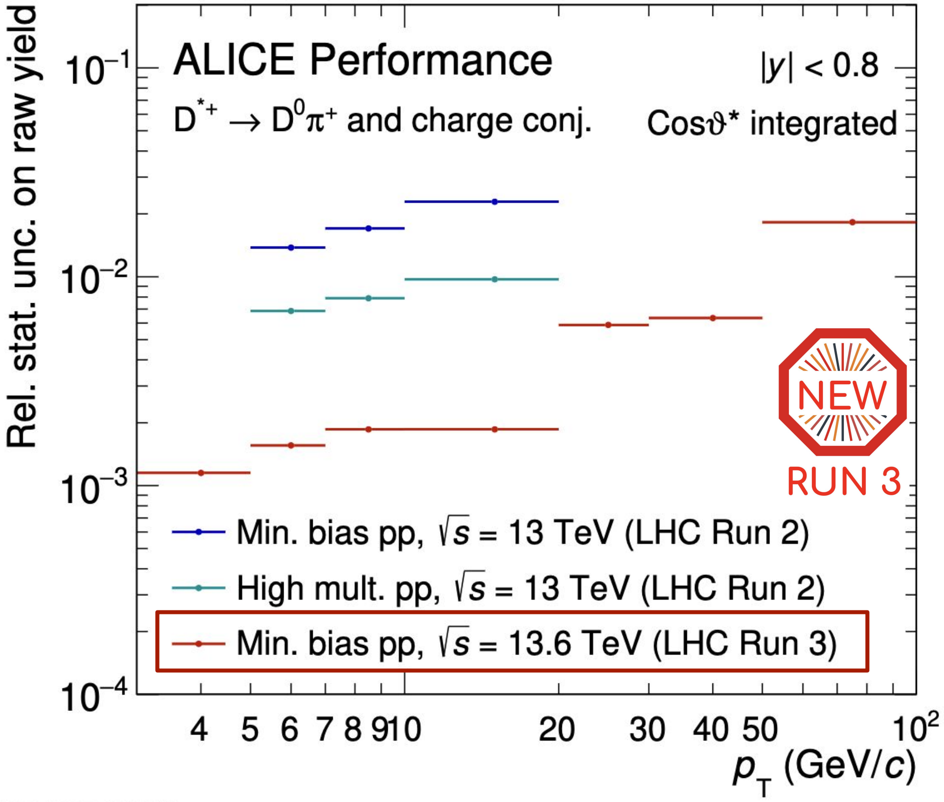


	pp	Pb–Pb
D^{*+}	ALICE, Phys. Lett. B 846 (2023) 137920	ALICE Preliminary
J/ψ	ALICE, Eur. Phys. J. C 78 (2018) 562	ALICE, Phys. Rev. Lett. 131, 042303
Y(1s)	ALICE Preliminary	ALICE, Phys. Lett. B 815 (2021) 136146
K^{*0}	ALICE, EPJ Web of Conf 171, 16008	ALICE, Phys. Rev. Lett. 125 (2020) 012301

Additional slides

Run 3 performance for D*⁺

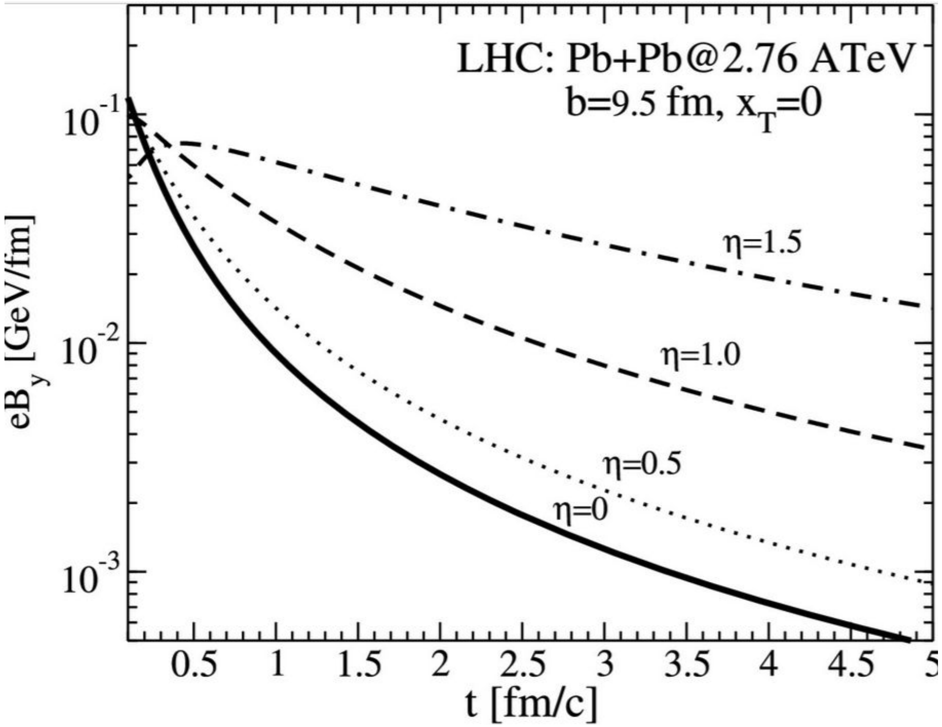
- A comparison of relative uncertainties on raw yields of D^{*+}



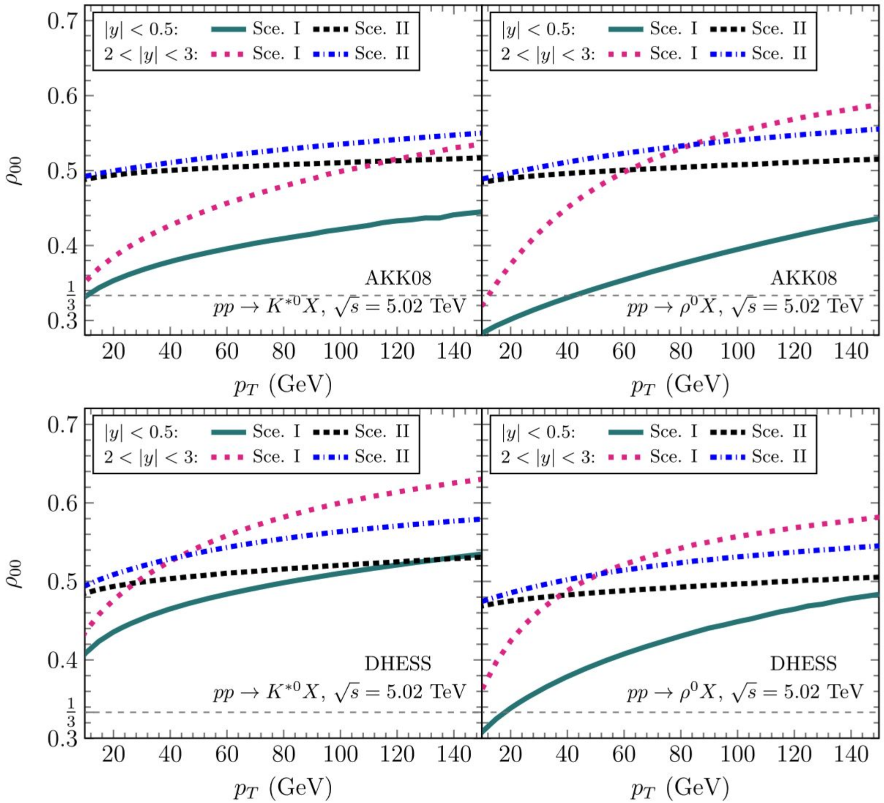
ALI-PERF-571947

EM field evolution vs rapidity

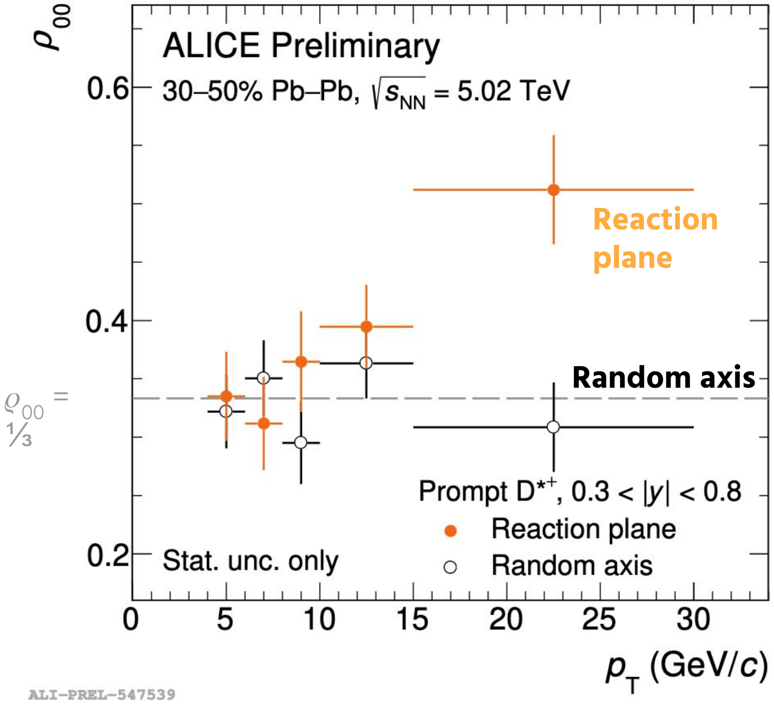
📚 Greco *et al*, Phys.Lett.B 768 (2017), 260-264

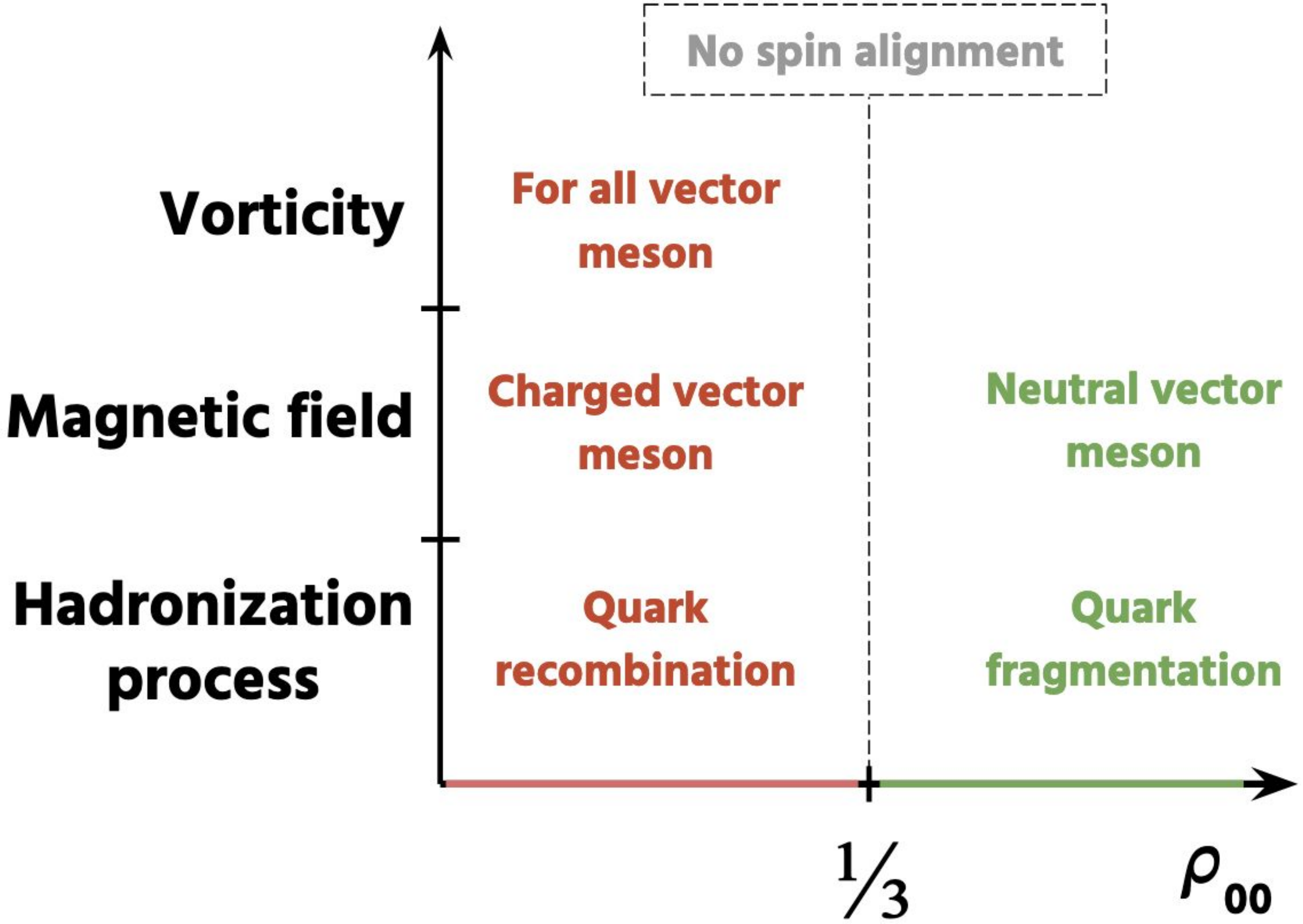


Spin dependent FF for light flavour vector meson



Spin alignment in **Reaction plane vs Random axis**




No spin alignment
Vorticity
Magnetic field
Hadronization process
For all vector meson
Charged vector meson
Neutral vector meson
Quark recombination
Quark fragmentation
$1/3$
ρ_{00}

Quark recombination

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

* **>** for Neutral meson, **<** for Charged meson

$\boldsymbol{P_q}$ = Polarisation of quark

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 anti-quark

Low p_T .... p_T (GeV/c) .... High p_T

- Quark charge and quark polarisation has same sign
  - B field effect:
    - In case of neutral meson (c-cbar), ϱ_{00} is always > ⅓
    - In case of, charged meson (D^{*+}), ϱ_{00} is always < ⅓
- Quark charge doensn't affect spin alignment originating from L

- Quark charge is squared so the charge signs do not matter here...