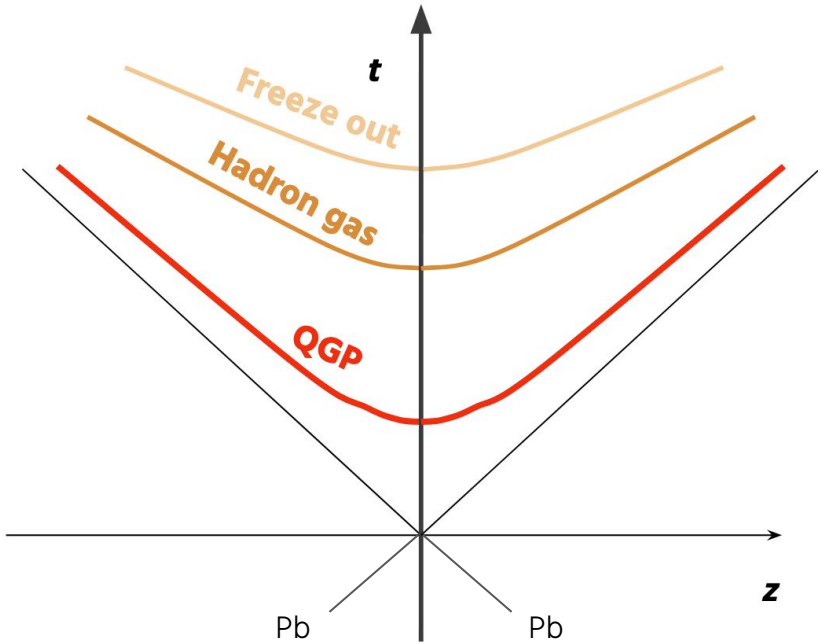
Investigation of early magnetic field and angular momentum in ultrarelativistic heavy-ion collisions via D^{*+}-meson spin alignment with ALICE

Himanshu Sharma, INFN Padova
On behalf of the **ALICE** Collaboration

Strangeness in Quark Matter, 2024

Motivation

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



"Simplified" spacetime evolution of heavy ion collisions

Motivation

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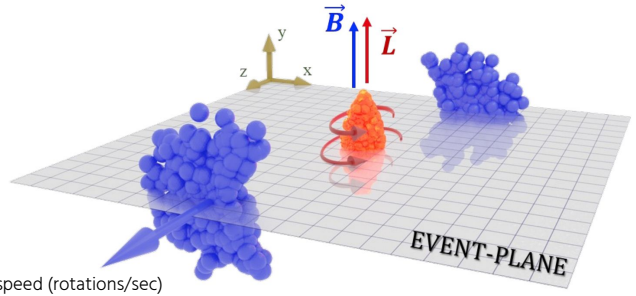
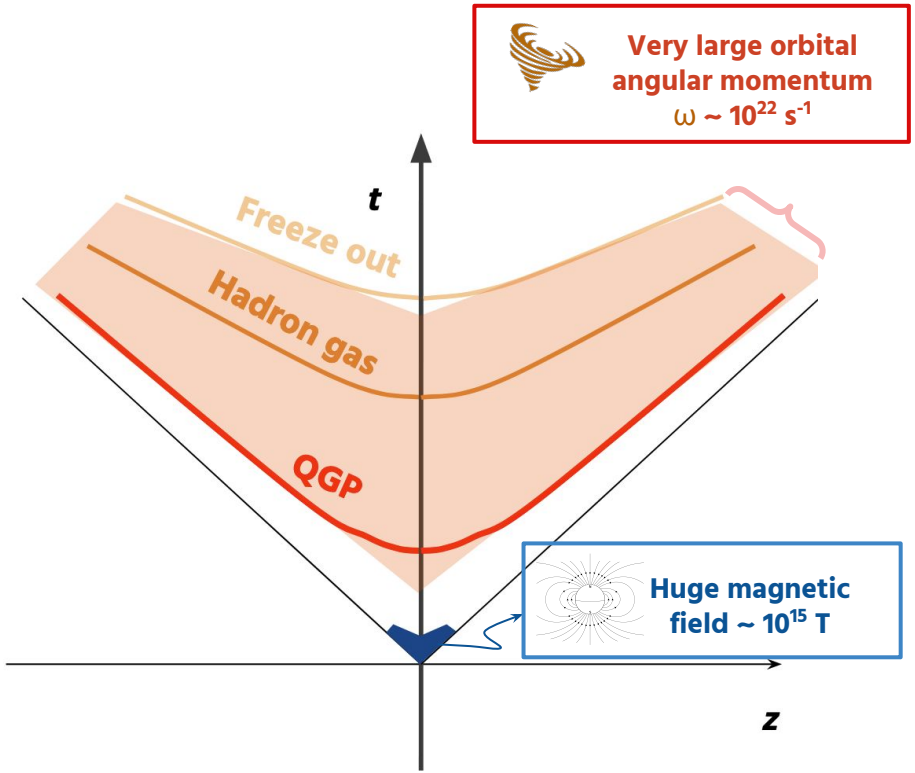
- In **non-central** collisions:
  - Charged spectator motion produces magnetic field (B) ~ **10^{15} T** †
    - Decreases with time
  - A highly vortical system with orbital angular momentum (L), ω* ~ **10^{22} s^{-1}** ★





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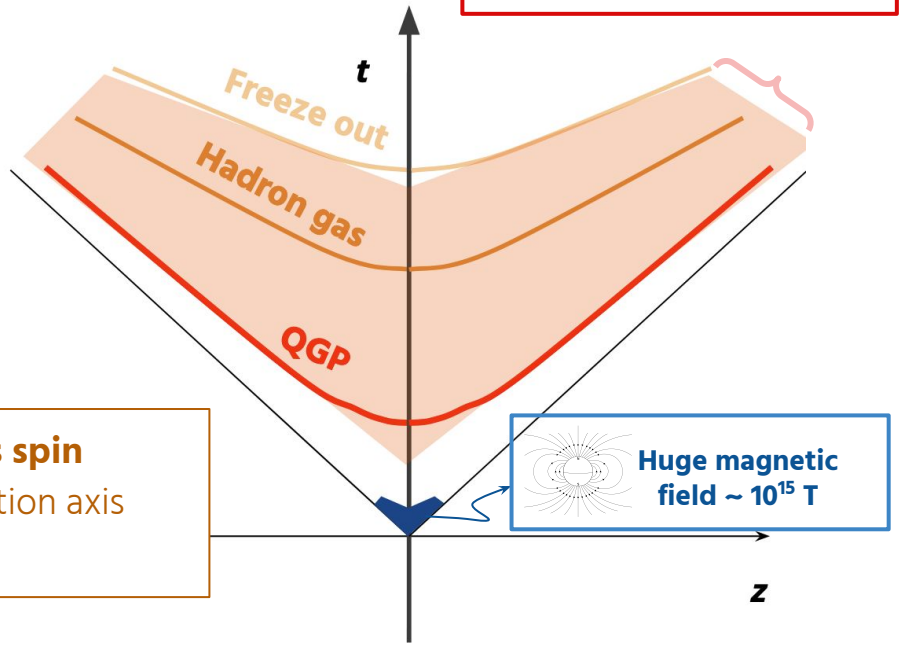
can preferentially **align** a **particle's spin projection** along the spin quantization axis through spin-orbit coupling



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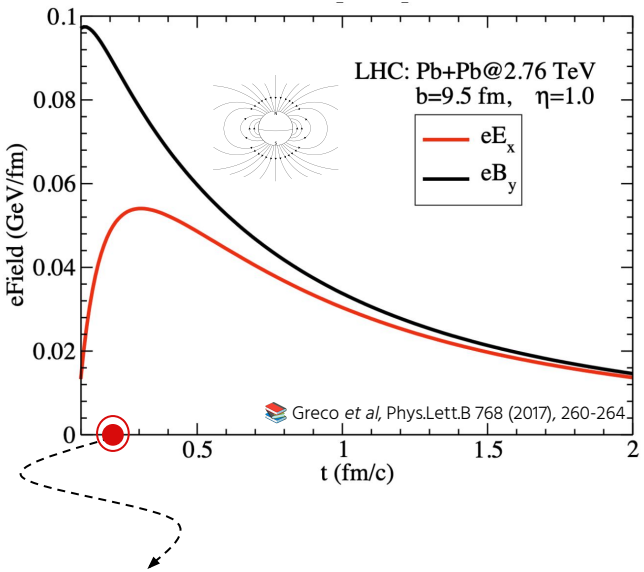
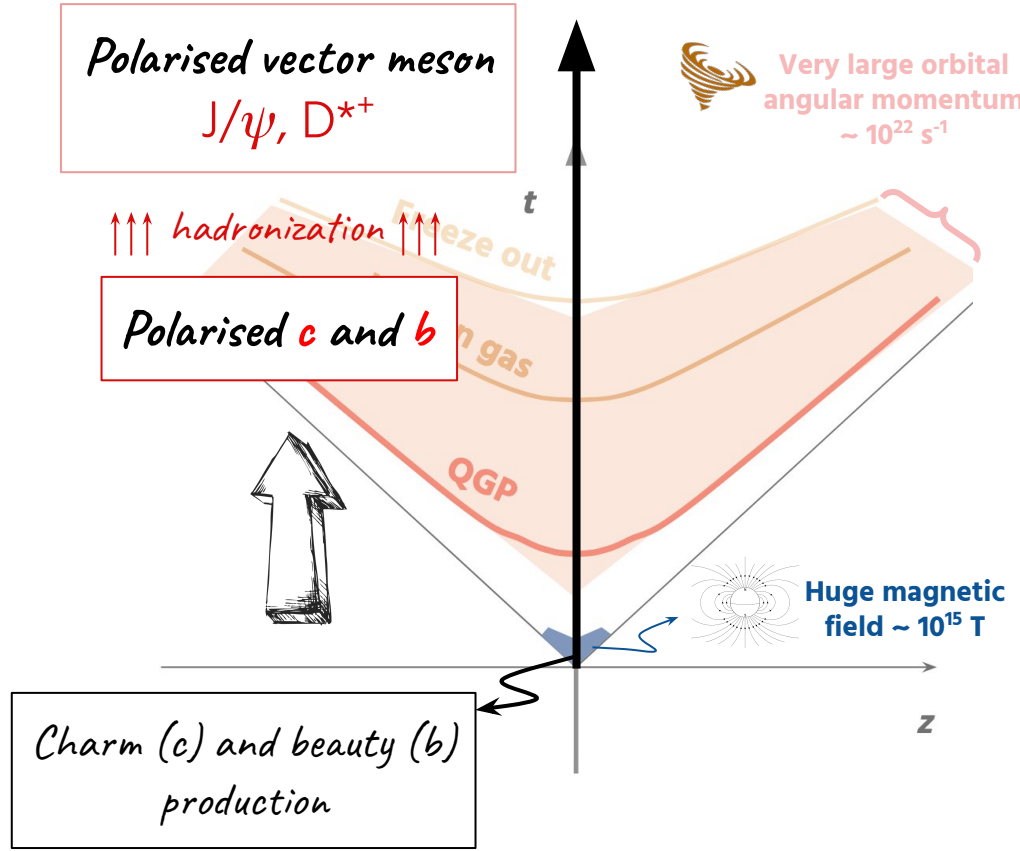


- Charm quarks produced in early stages,
  $t \sim 1/m_q \sim 0.1$ fm/c
  - **More sensitive to the high intensity of the EM fields than light quarks**



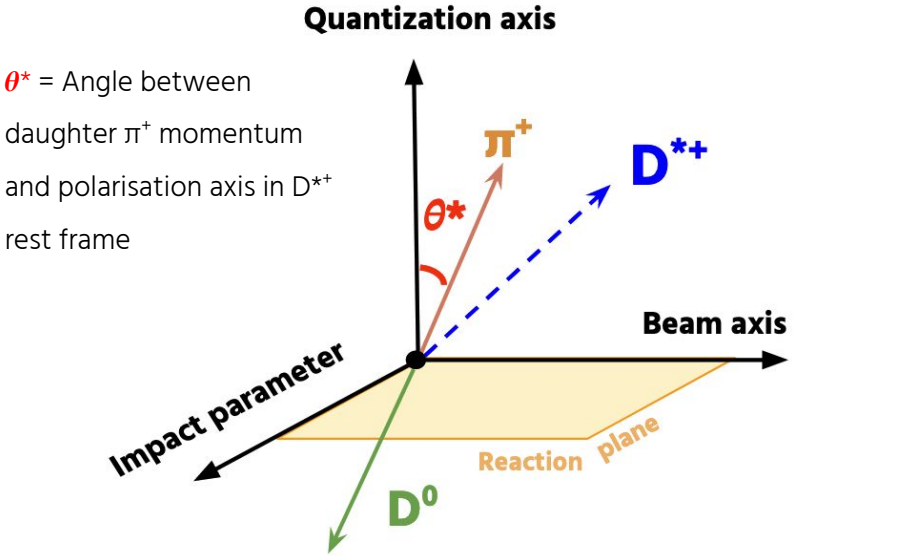
Spin alignment measurements

- 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:

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



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

- 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 — $\boldsymbol{p_T}$ **(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

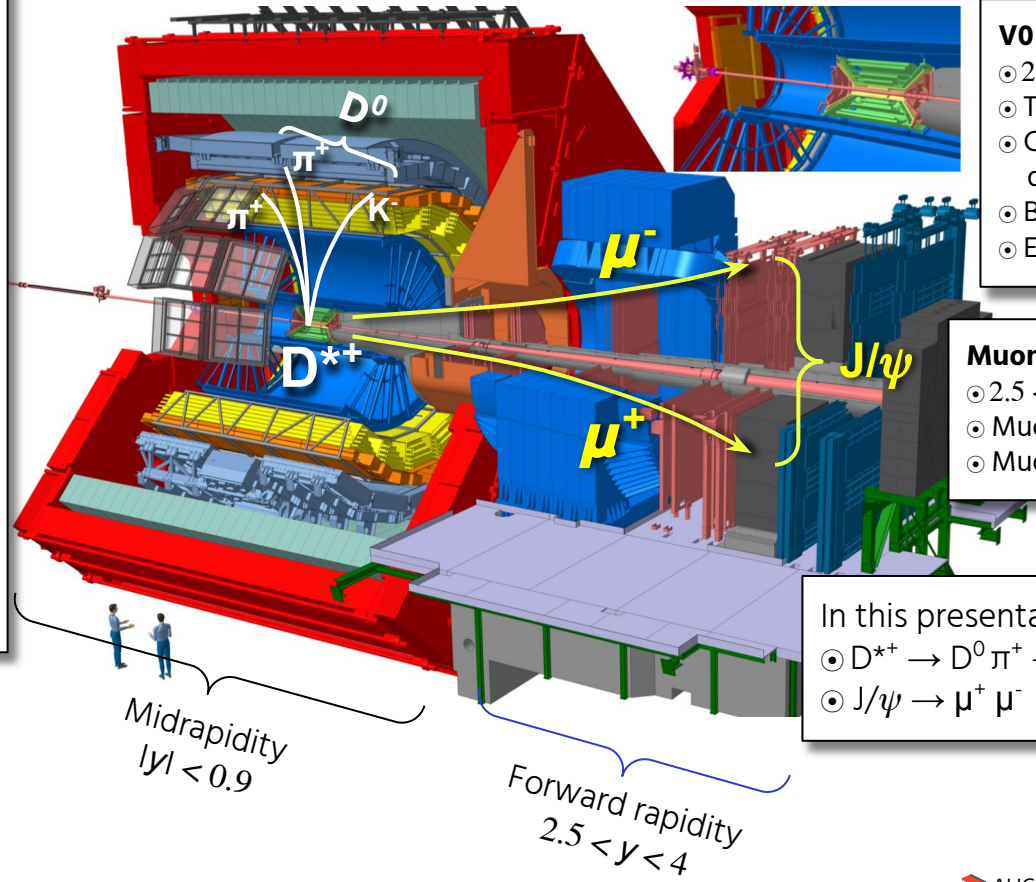
Central barrel detectors
$|\eta| < 0.9$

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



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

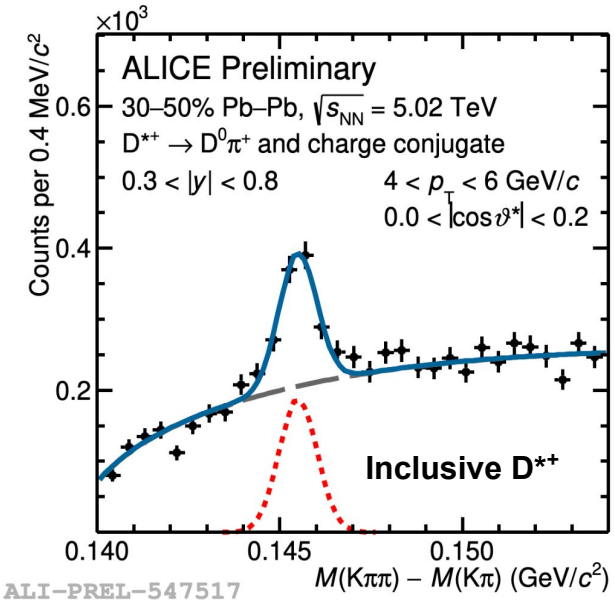
Muon spectrometer
- $2.5 < y < 4$
- Muon trigger
- Muon tracking down to very low p_T

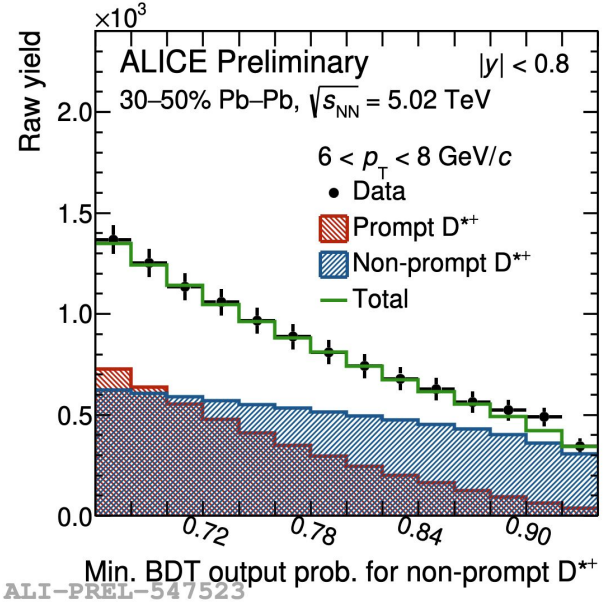
In this presentation, we focus on
- $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$
- $J/\psi \rightarrow \mu^+ \mu^-$

ALICE Collaboration, JINST (2008) S08002

D^{*+} yield extraction

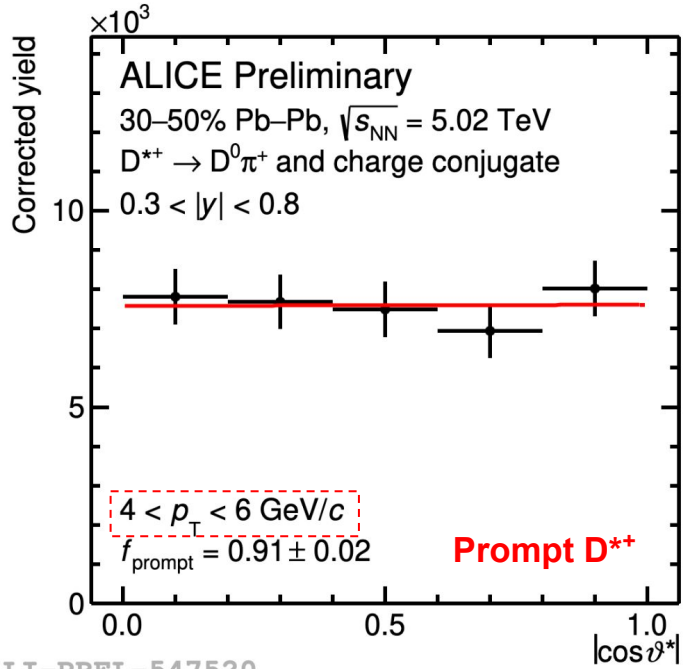
- For D^{*+} analysis in pp and Pb–Pb collisions, Boosted Decision Trees (BDT) are used to
  - Reduce the combinatorial background
  - Separate prompt and non-prompt D^{*+} components

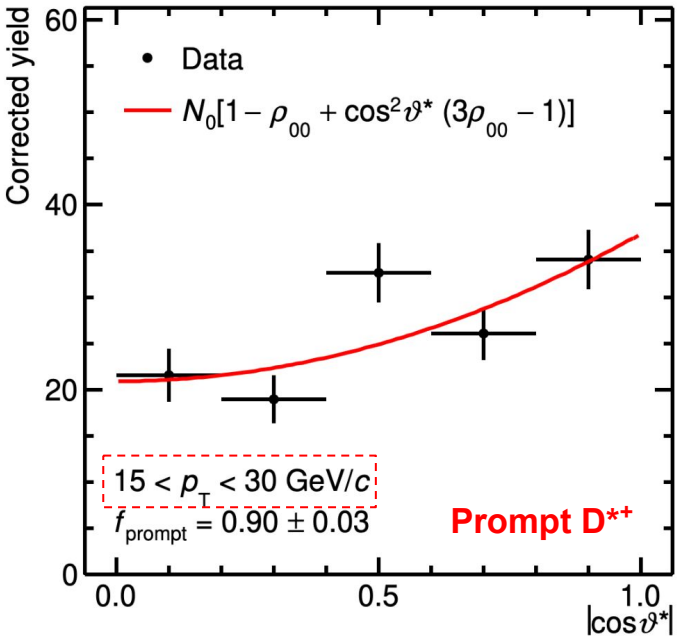




D^{*+} yield extraction

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

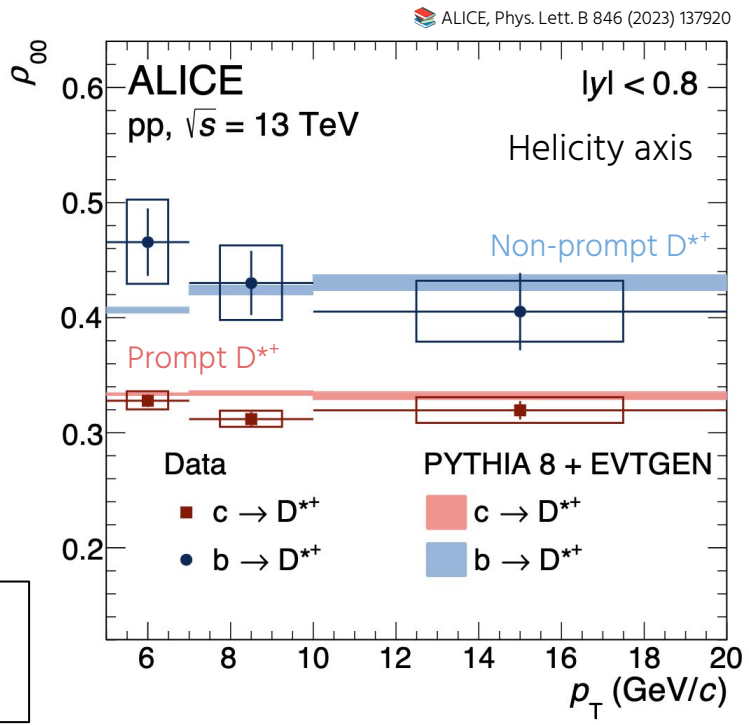




ALI-PREL-547520

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**
  - $\varrho_{00} = 1/3 \Rightarrow$ No spin alignment for prompt D^{*+}
  - $\varrho_{00} > 1/3 \Rightarrow$ 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



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

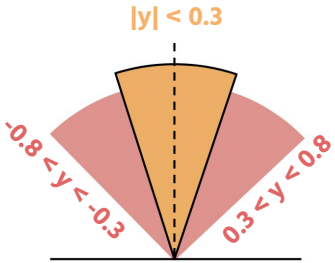
Prompt D^{*+} spin alignment in **Pb–Pb** collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

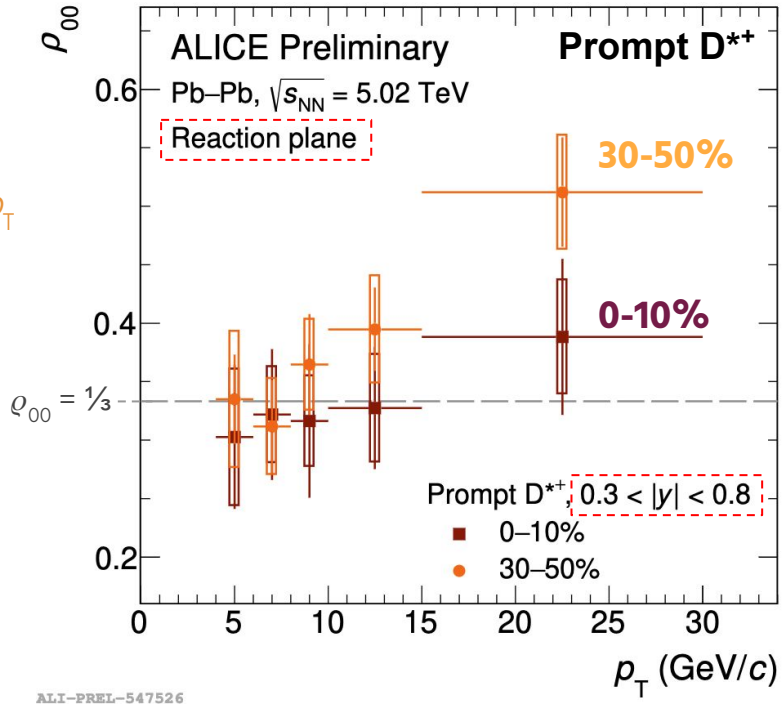
Spin alignment measurement

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 $\varrho_{00} = 1/3$**
  - **30-50%**: Evidence of ϱ_{00} larger than 1/3 at high p_T

    ⇒ Hadronization by quark fragmentation





Spin alignment measurement in different rapidity region

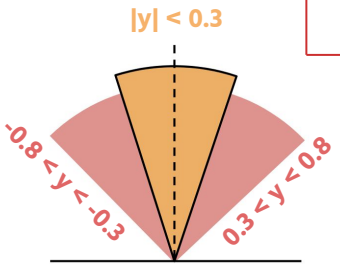
First measurement of D^{*+} spin alignment with respect to the reaction plane in Pb–Pb collisions

- Extracted ϱ_{00} parameter for **prompt D^{*+}**
  - Hints of rising trend with p_T
  - **0-10%: Consistent with $\varrho_{00} = 1/3$**
  - **30-50%: At high p_T $\varrho_{00} > 1/3$**

➢ **No significant deviation at midrapidity from $\varrho_{00} = 1/3$**

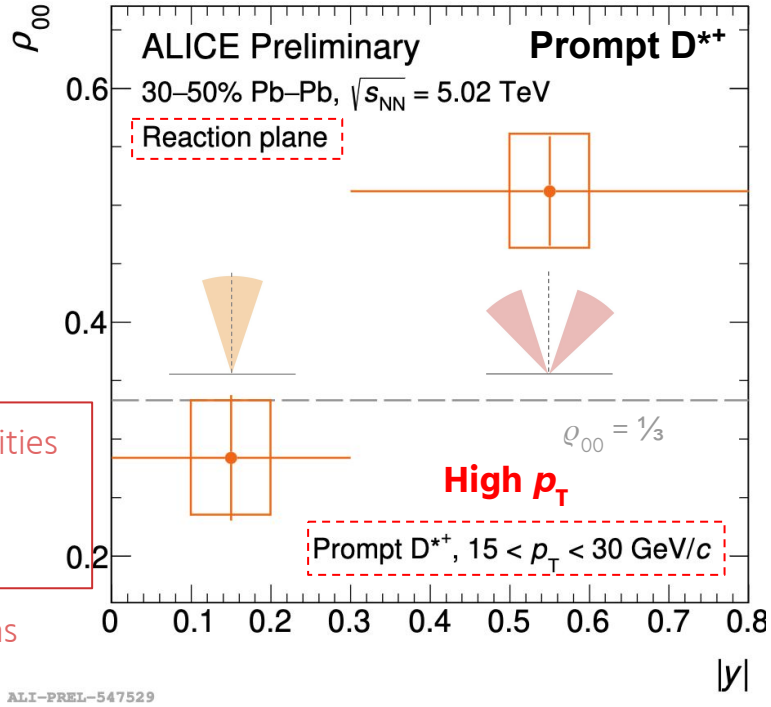
➢ **$\varrho_{00} > 1/3$ at large rapidity, B effect?**

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



⇒ Spin-dependent fragmentation functions for charm?

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

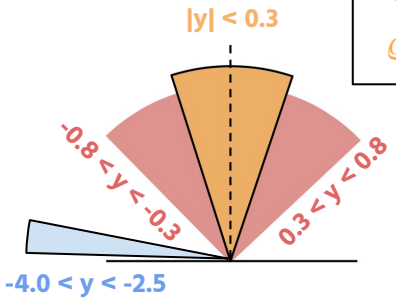


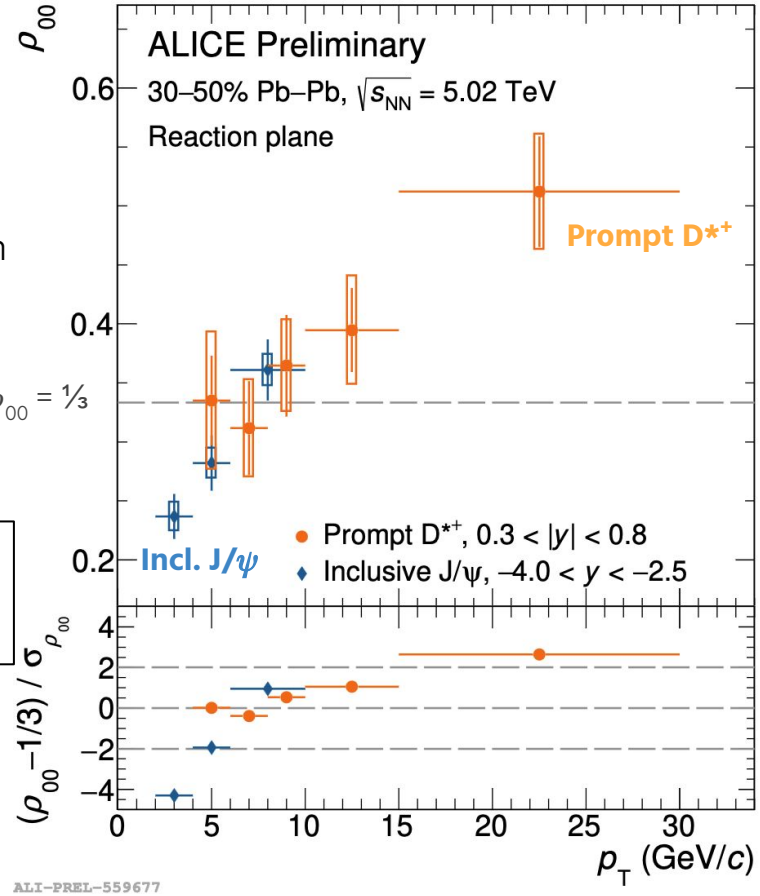
ALI-PREL-547529

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

$\varrho_{00} < 1/3$: Quark **recombination** at low p_T
$\varrho_{00} > 1/3$: Quark **fragmentation** at high p_T





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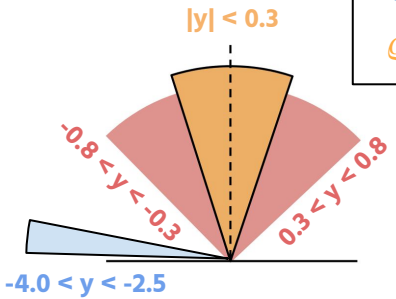
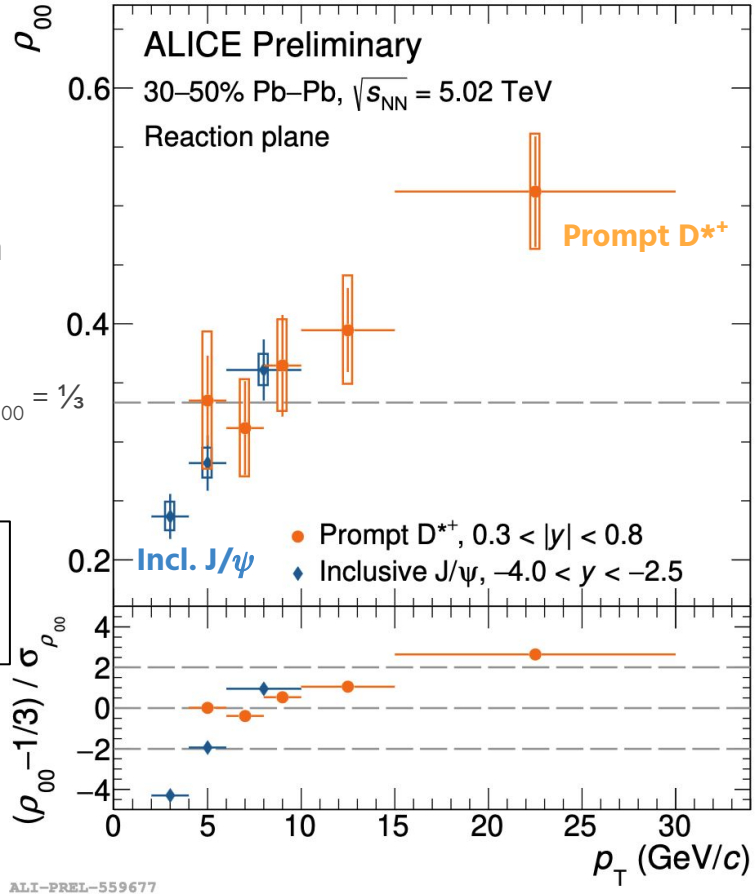
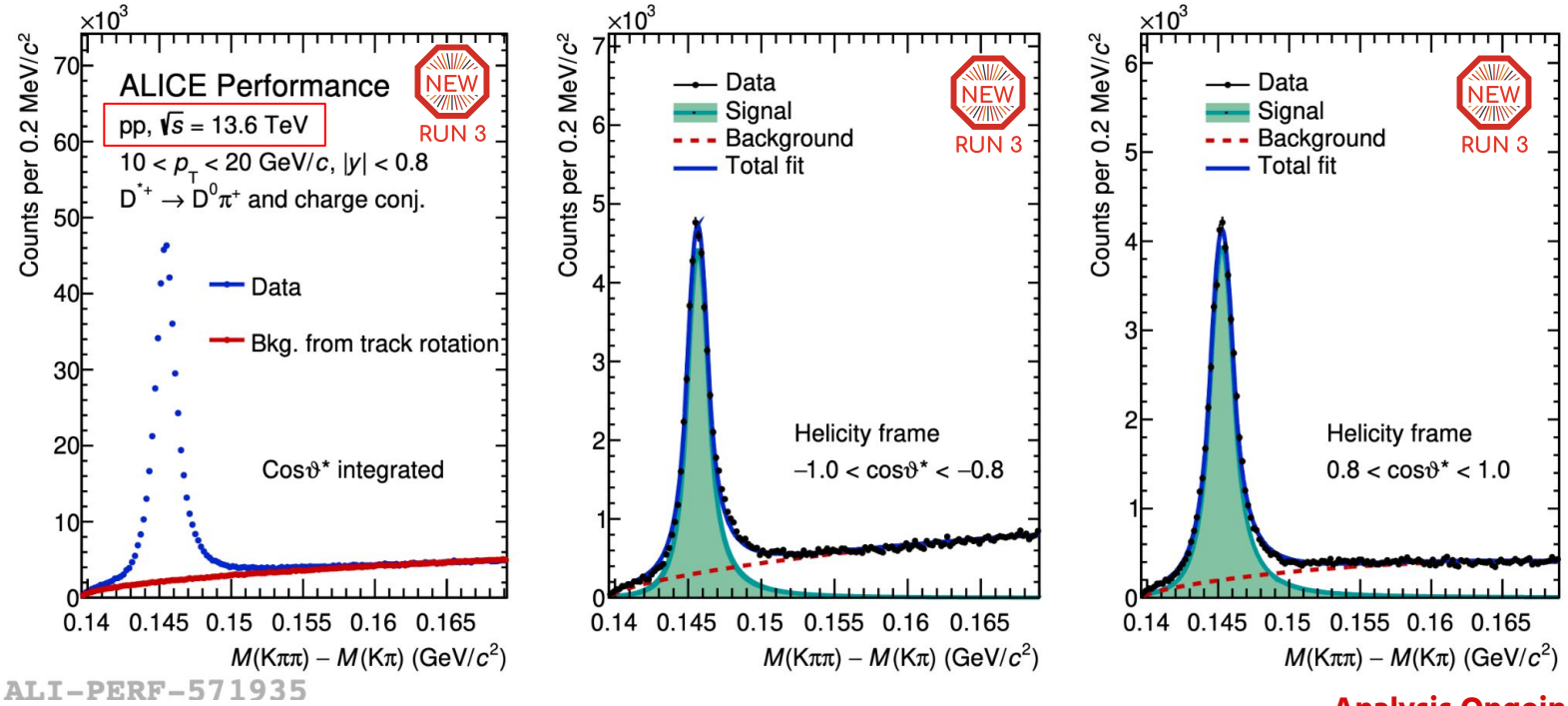


J/ψ polarisation in ALICE
by D. Mallick's on 5th June @ 10:40



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

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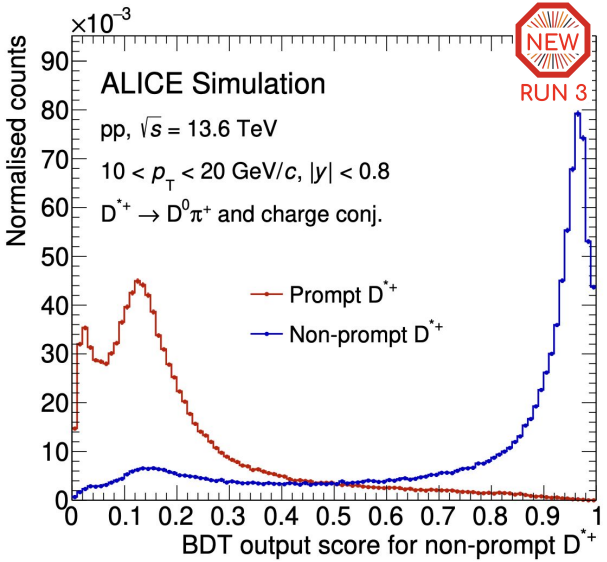
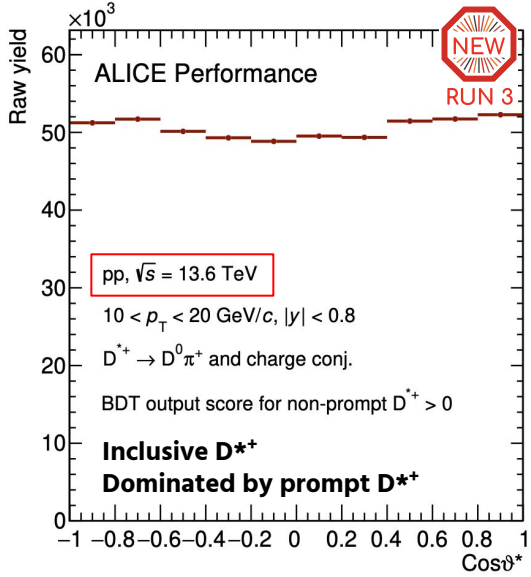
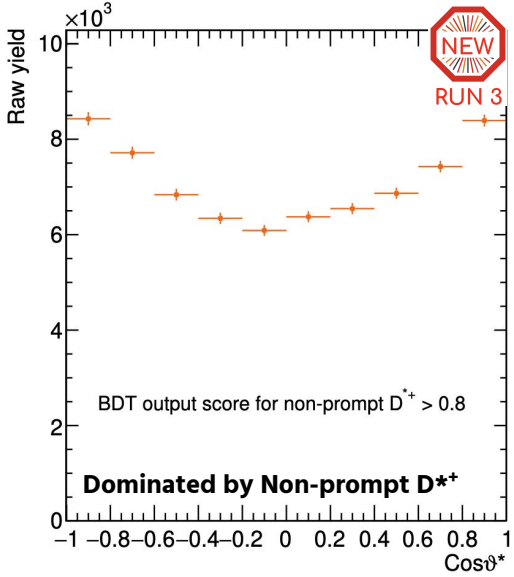
  - Large data taking rates: **500 kHz in pp** and **50 kHz in Pb–Pb** collisions

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



ALI-SIMUL-571957





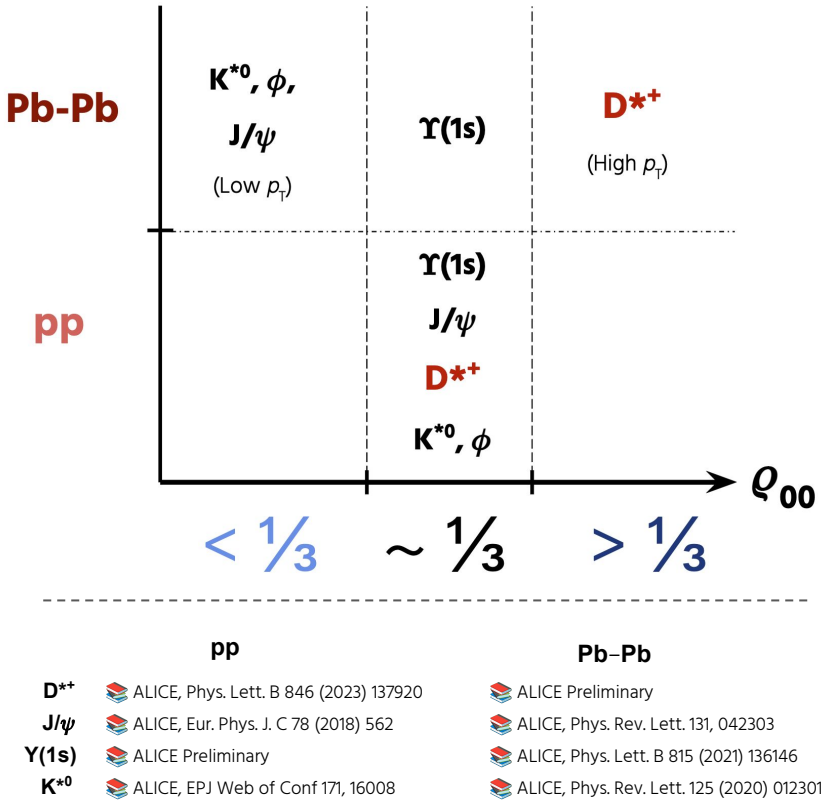
ALI-PERF-571952

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

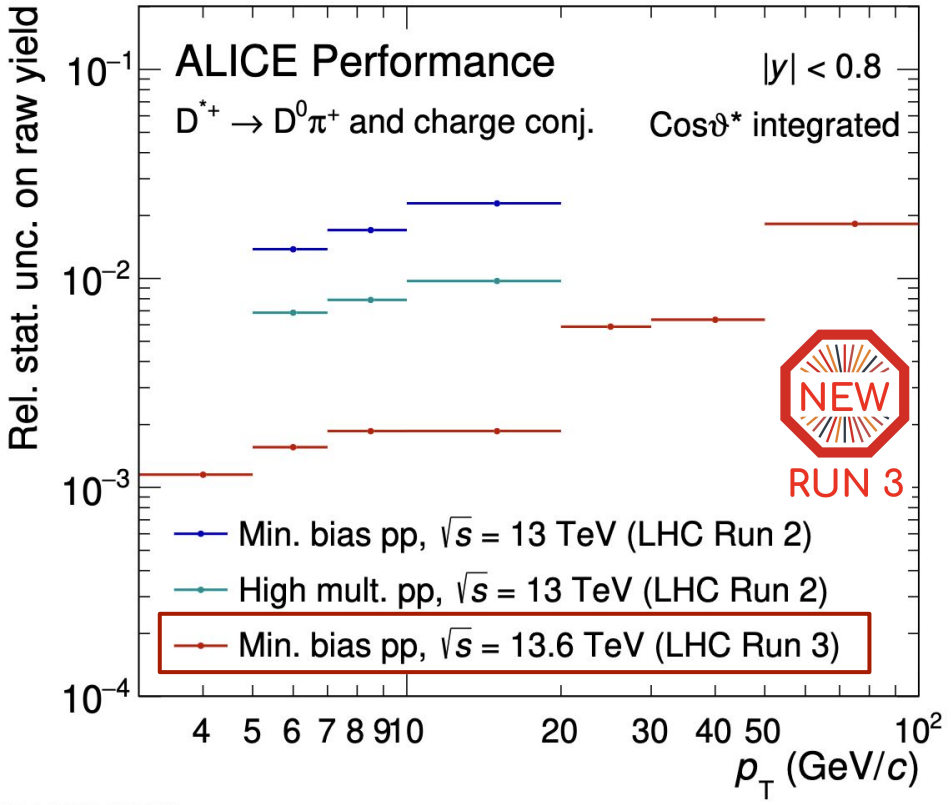


	pp	Pb–Pb
D^{*+}	ALICE, Phys. Lett. B 846 (2023) 137920	ALICE Preliminary
J/ψ	ALICE, Eur. Phys. J. C 78 (2018) 562	ALICE, Phys. Rev. Lett. 131, 042303
Y(1s)	ALICE Preliminary	ALICE, Phys. Lett. B 815 (2021) 136146
K^{*0}	ALICE, EPJ Web of Conf 171, 16008	ALICE, Phys. Rev. Lett. 125 (2020) 012301

Additional slides

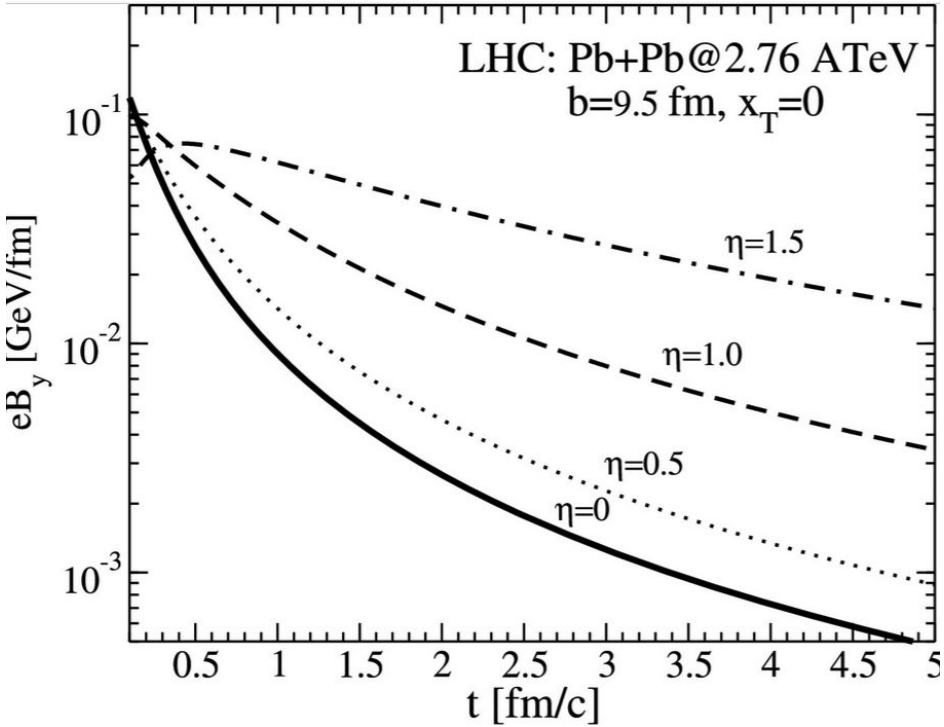
Run 3 performance for D*+

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

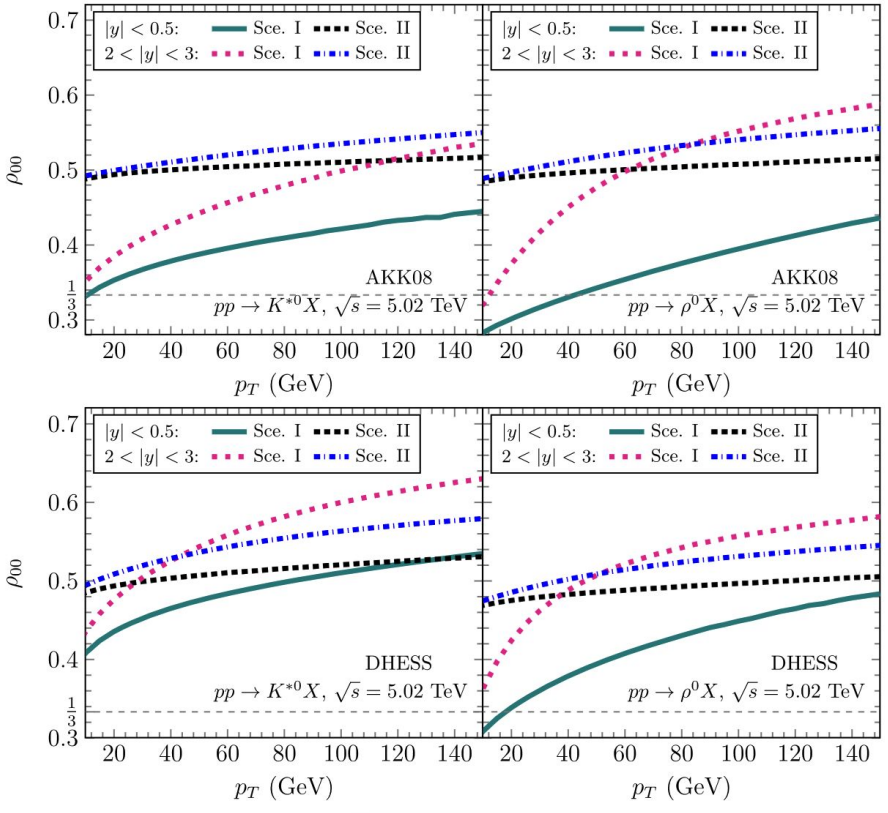


EM field evolution vs rapidity

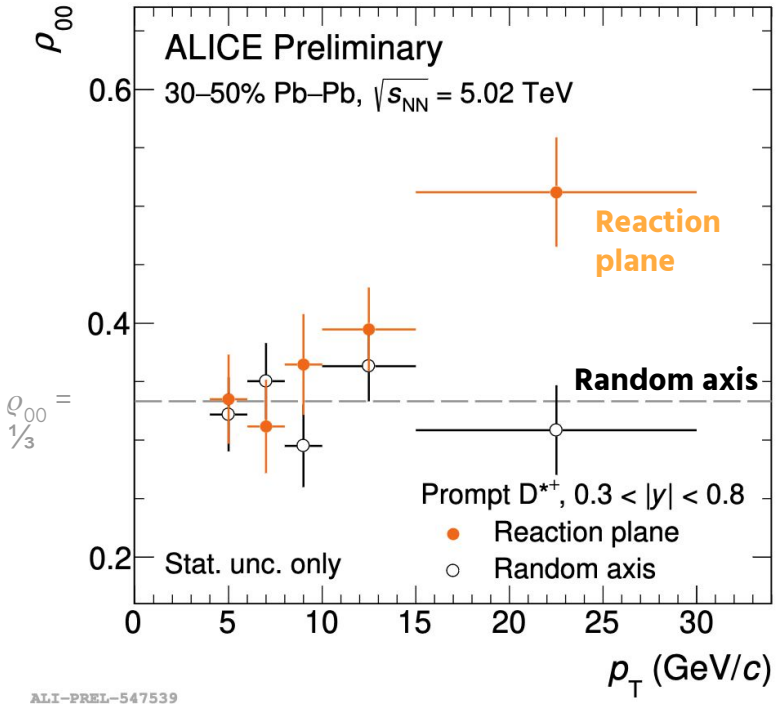
Greco *et al*, Phys.Lett.B 768 (2017), 260-264

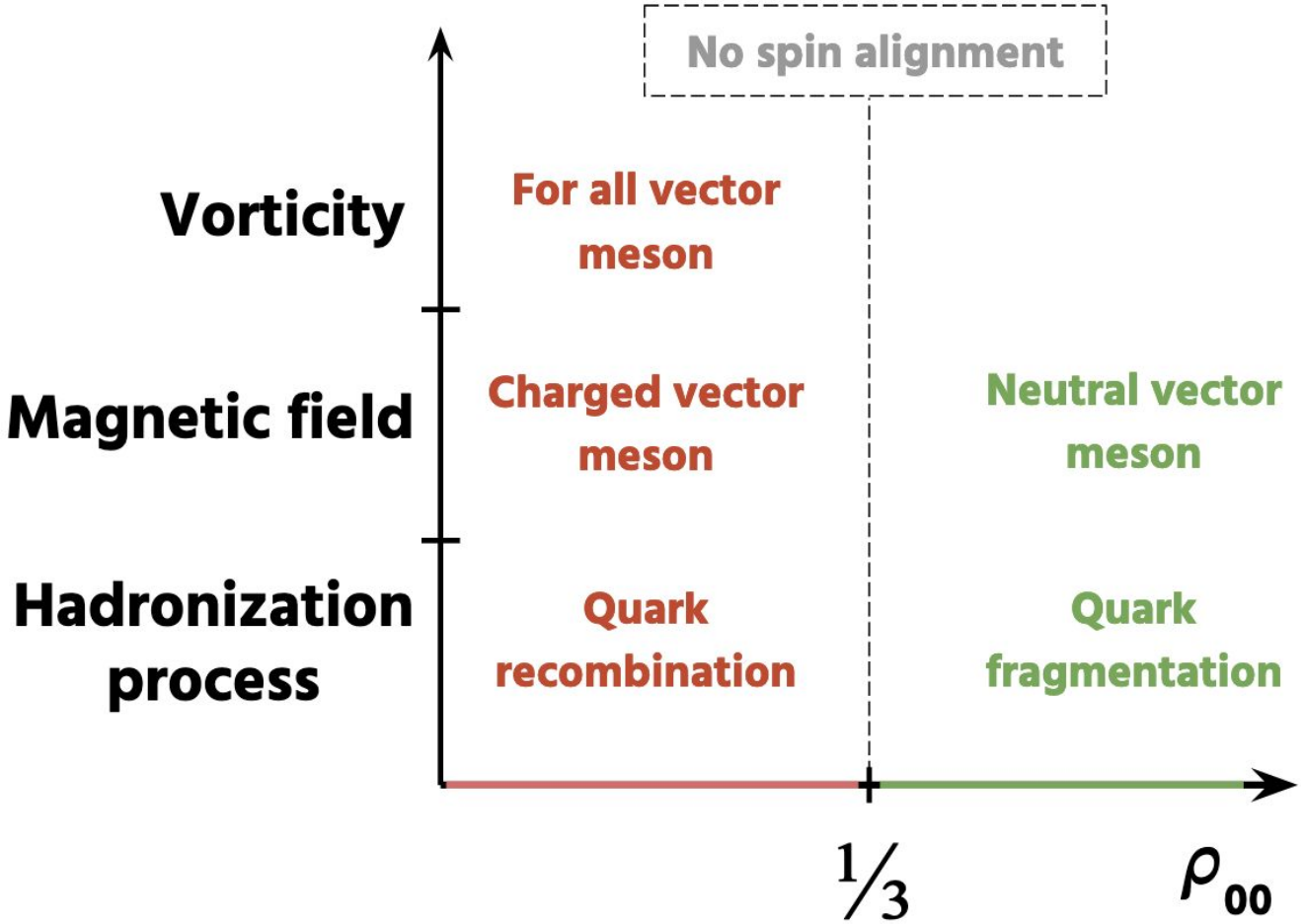


Spin dependent FF for light flavour vector meson



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




No spin alignment
Vorticity
For all vector meson
Magnetic field
Charged vector meson
Neutral vector meson
Hadronization process
Quark recombination
Quark fragmentation
1/3
ρ00

Quark recombination

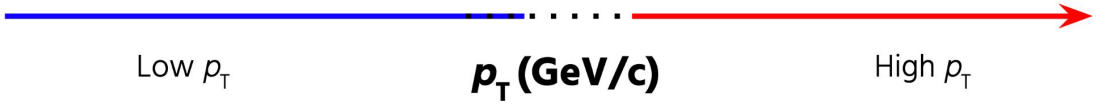
$$\rho_{00} = \frac{1 - P_q \cdot P_{\bar{q}}}{3 + P_q \cdot P_{\bar{q}}} = \begin{cases} \lesseqgtr 1/3^* \Rightarrow \vec{B} \\ < 1/3 \Rightarrow \vec{L} \end{cases}$$

* **>** for Neutral meson, **<** for Charged meson
P_q = Polarisation of quark

Quark fragmentation

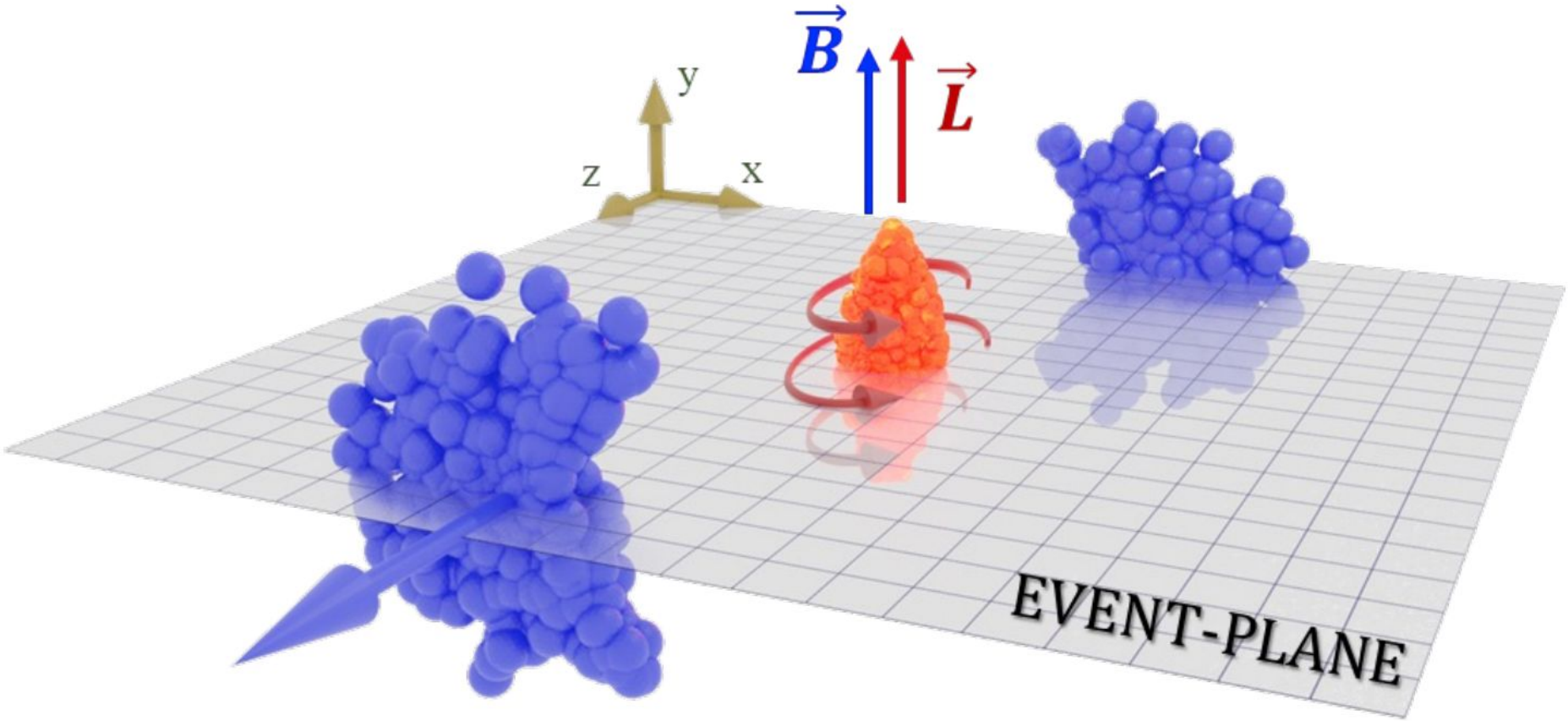
$$\rho_{00} = \frac{1 + \beta \cdot P_{\bar{q}}^2}{3 - \beta \cdot P_{\bar{q}}^2} > 1/3$$

β: Correlation between constituent quark and anti-quark



- 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...


$\vec{B}$
$\vec{L}$
y
z
x
EVENT-PLANE