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

42nd International Conference on High Energy Physics

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18th July 2024

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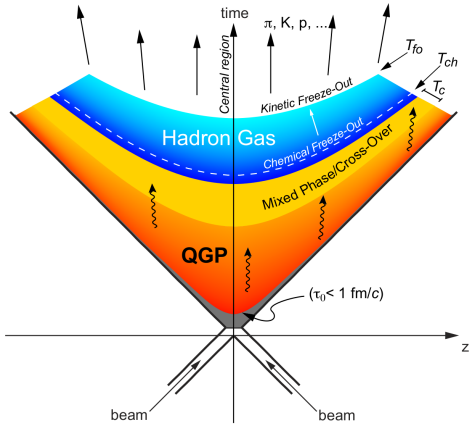
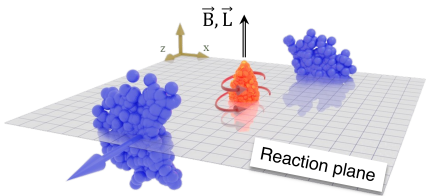
- Extreme conditions are obtained in non-central heavy-ion collisions



- Charged spectator motion produces large magnetic field (B) → $\sim 10^{16}$ T, decreasing with time

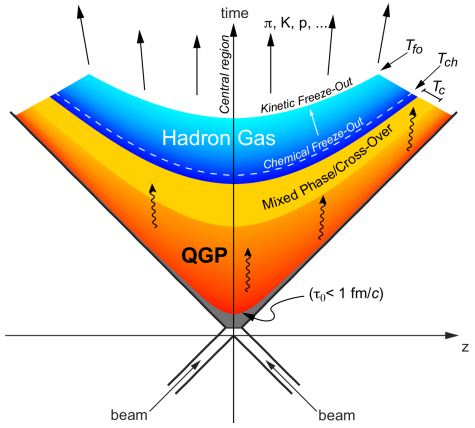
  Christakoglu et al. EPJC 81 (2021) 717

- A highly vortical system is formed → large orbital angular momentum (L) STAR, Nature 548 (2017) 62
  - rotational speed $\omega \sim 10^{22}$ s^{-1}



Physics motivations

- Extreme conditions are obtained in non-central heavy-ion collisions



- Charged spectator motion produces large magnetic field (B) → $\sim 10^{15}$ T, decreasing with time

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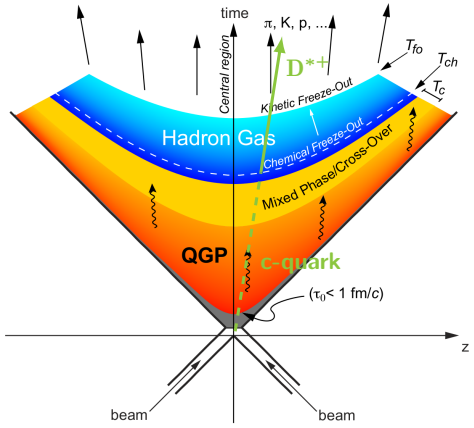
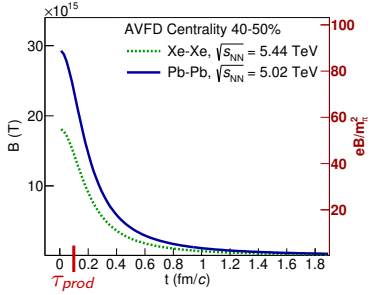
- A highly vortical system is formed → large orbital angular momentum (L) STAR, Nature 548 (2017) 62
  - rotational speed $\omega \sim 10^{22}$ s^{-1}
  - align particle spin projection along the spin quantisation axis through spin-orbit coupling

- Extreme conditions are obtained in non-central heavy-ion collisions



- Charm quarks are produced in the early stages
  - $\tau_{prod} \leq \hbar/m_c \sim 0.1$ fm/c
  - more sensitive to the high intensity of the EM fields than light quarks



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Polarisation measurements

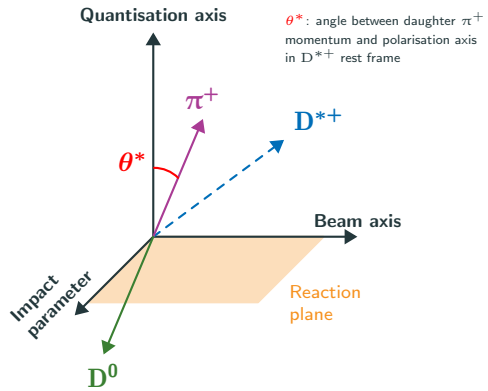
- For strongly-decaying vector mesons, rely on spin density matrix element ρ_{00}
  - $\rho_{00} = 1/3$ ➔ no spin alignment
  - $\rho_{00} \neq 1/3$ ➔ spin alignment

- Angular distribution of decay products w.r.t. chosen direction

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

Polarisation/quantisation axis choice

- Orthogonal to reaction plane in Pb–Pb collisions ➔ same direction as L and B fields
- Direction of vector meson momentum in pp collisions ➔ helicity axis



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

Two different mechanisms for the production of polarised vector mesons in heavy-ion collisions

- Recombination of polarized quark in the QGP

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

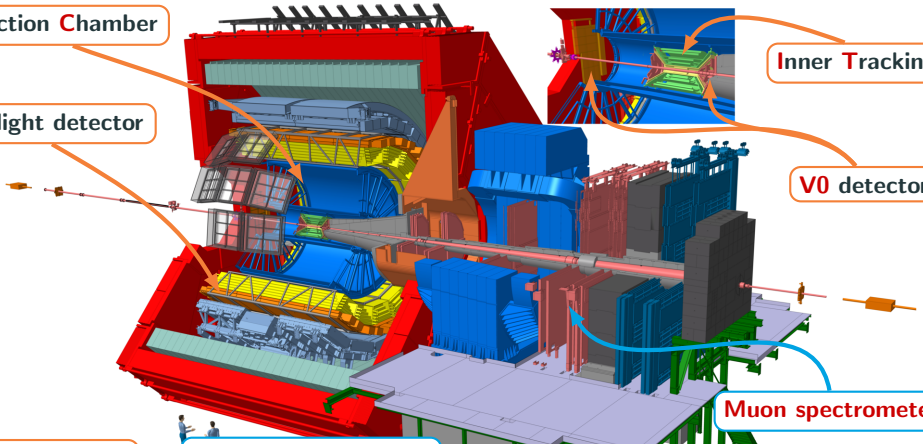
- Polarized quark fragmentation

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

P_q: quark polarisation
β: correlation among constituent quark and anti-quark
* $>$ for neutral mesons, $<$ for charged mesons

Liang et al. PLB 629 (2005) 20
Yang et al. PRC 97 (2018) 034917

A Large Ion Collider Experiment (LHC Run 2)



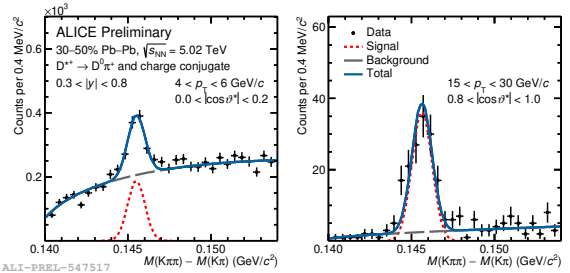
Measured at midrapidity ($|y| < 0.8$)

$\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+ \to \mathrm{K}^-\pi^+\pi^+$

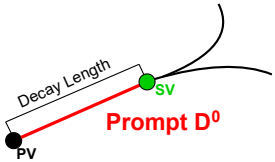
Measured at forward rapidity ($2.5 < y < 4$)

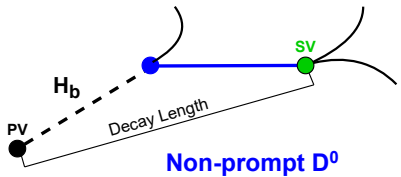
$\mathrm{J}/\Psi \to \mu^+\mu^-$

- Signal selection based on machine-learning multiclass classification algorithm
  - reduce combinatorial background
  - separate prompt and non-prompt D^{*+}-meson components



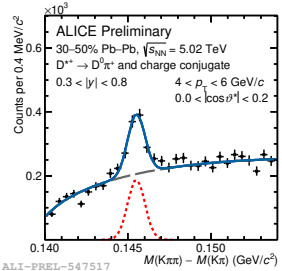
N.B.
D^{*+} measured via $D^{*+} \rightarrow D^0\pi^+$ strong decays

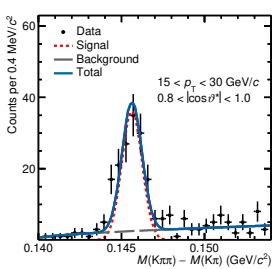


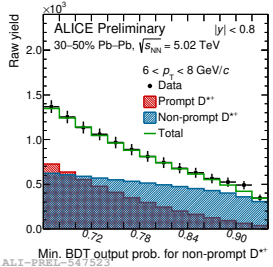


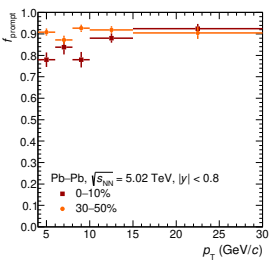
- Signal selection based on machine-learning multiclass classification algorithm
  - reduce combinatorial background
  - separate prompt and non-prompt D^{*+}-meson components

- Non-prompt contribution estimated using a data-driven approach
  - not requiring any model prediction as input

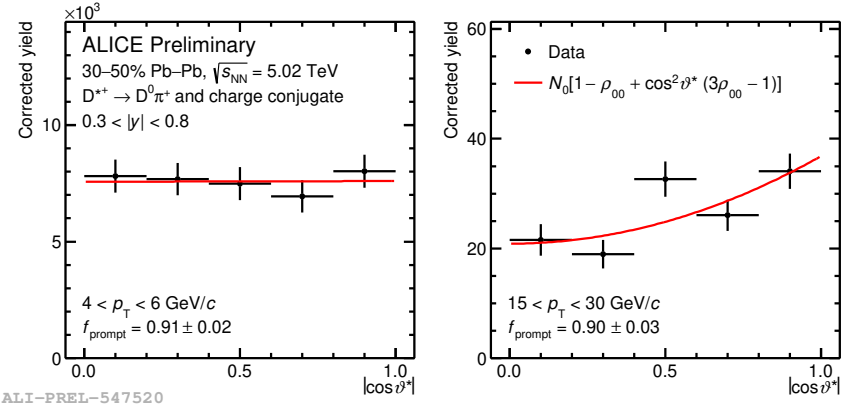




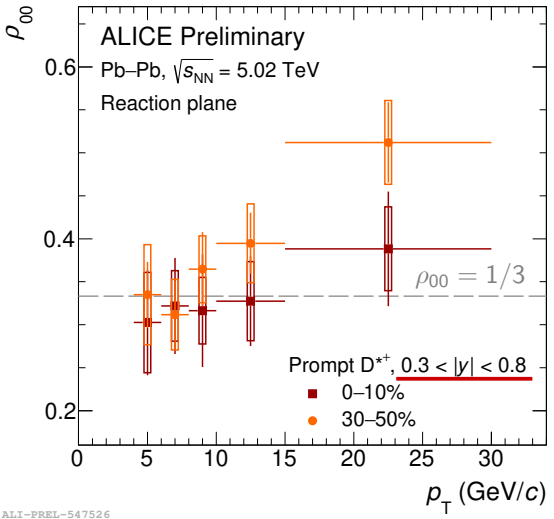




- ρ_{00} extracted in different centrality classes, p_T and rapidity intervals. Taking into account
  - event-plane finite resolution
  - non-prompt D^{*+}-meson contribution

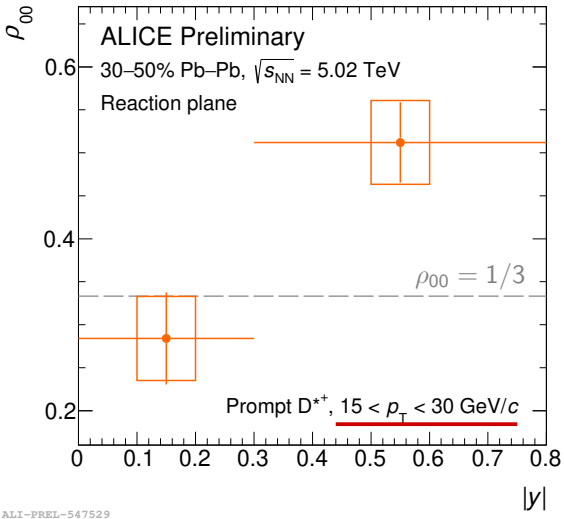


D^{*+} spin alignment in Pb–Pb collisions



- First measurement of prompt D^{*+} spin alignment w.r.t. the reaction plane in Pb–Pb collisions
- Hint of centrality and p_T dependence
  - 0–10% → ρ_{00} compatible with 1/3
  - 30–50% → $\rho_{00} > 1/3$ at high p_T
- Consistent with polarised charm-quark hadronisation via fragmentation

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

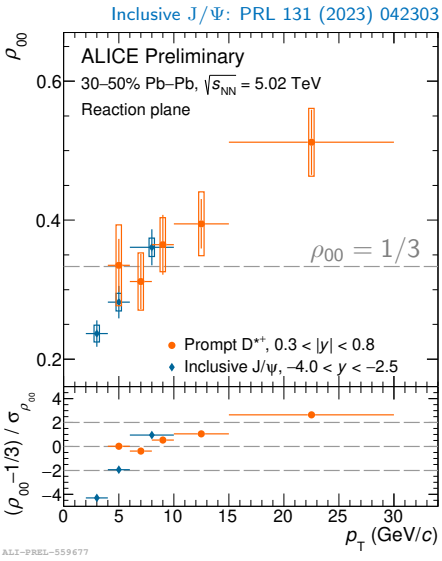


ALI-PREL-547529

- Rapidity dependence at high p_T in semicentral collisions
  - no spin alignment observed for $|y| < 0.3$
  - deviation from 1/3 in forward-backward region $0.3 < |y| < 0.8$
- Compatible with longer-lasting magnetic field at larger rapidities
  - earlier-produced c quarks (larger momentum) are affected more by B field
- Effect of spin-dependent fragmentation functions for charm, unrelated to QGP?

Chen et al. PRD 102 (2020) 034001

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



- Spin-alignment measurements of prompt D^{*+} and inclusive J/Ψ mesons in good agreement within the uncertainties
- Rising trend for inclusive J/Ψ with p_T
  - ρ_{00} below 1/3 for $p_T < 5$ GeV/c
- Qualitative agreement with
  - $\rho_{00} < 1/3$ → quark recombination and orbital angular momentum at low p_T
  - $\rho_{00} > 1/3$ → quark fragmentation at high p_T

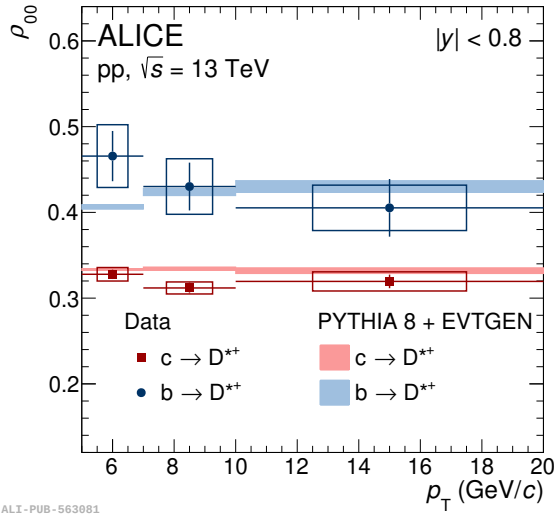
D^{*+} spin alignment in pp collisions

- First measurements of prompt and non-prompt D^{*+} spin alignment at the LHC
- Measurements performed w.r.t. helicity axis
  - prompt D^{*+} → no evidence of spin alignment
  - non-prompt D^{*+} → $\rho_{00} > 1/3$, due to helicity conservation in b-hadron decays

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

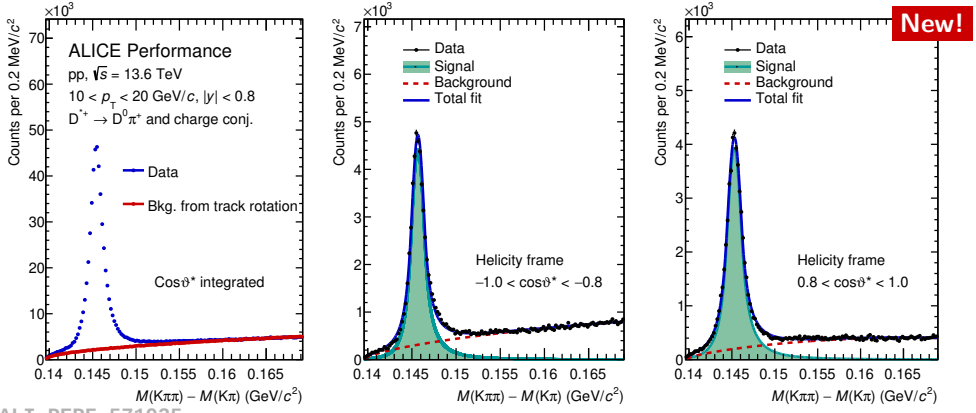
- Measurements in agreement with PYTHIA 8 + EVTGEN calculations
- Baseline for studies performed in Pb–Pb

PLB 846 (2023) 137920

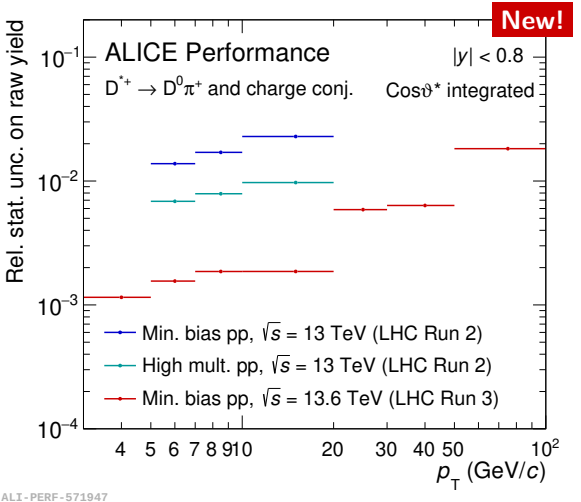


ALI-PUB-563081

- Large datasets are being collected by the ALICE experiment during LHC Run 3
  - high data taking rates: 500 kHz in pp and 50 kHz in Pb–Pb collisions
  - improved detector performances



- Large datasets are being collected by the ALICE experiment during LHC Run 3
- Enabling more differential measurements in $\cos\theta^*$ and transverse momentum
  - up to $p_{\mathrm{T}} \sim 100\ \mathrm{GeV}/c$
  - will allow us to test charm spin-dependent fragmentation functions
- Statistical uncertainties will be reduced by at least a factor 10 w.r.t Run 2 results

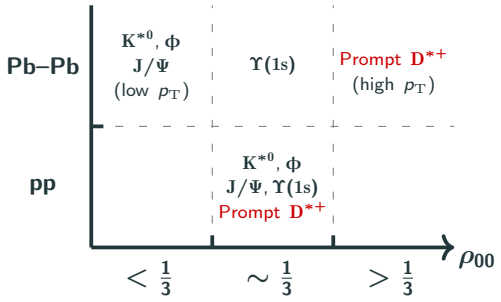


Summary

- First results of D^{*+} spin alignment in pp and Pb–Pb collisions are presented
- Significant polarisation observed for prompt D^{*+} in semicentral Pb–Pb collisions at high p_{T}
  - larger effect at forward-backward rapidity compared to midrapidity
  - consistent with quark fragmentation scenario
- Theoretical predictions are required for conclusive remarks!

More on polarisation by ALICE:
C. De Martin, 18th Jul 15:19
R. Lavicka, 18th Jul 15:36

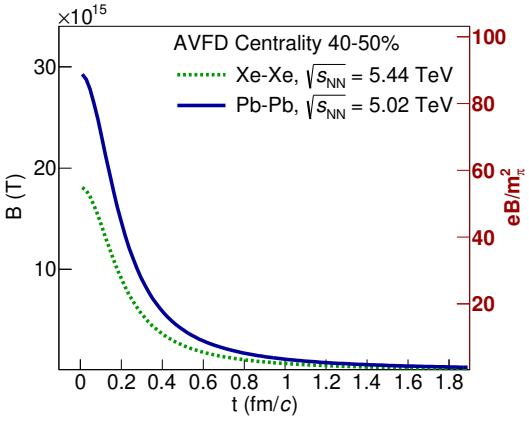
Summary of spin alignment/polarisation for different vector mesons in ALICE

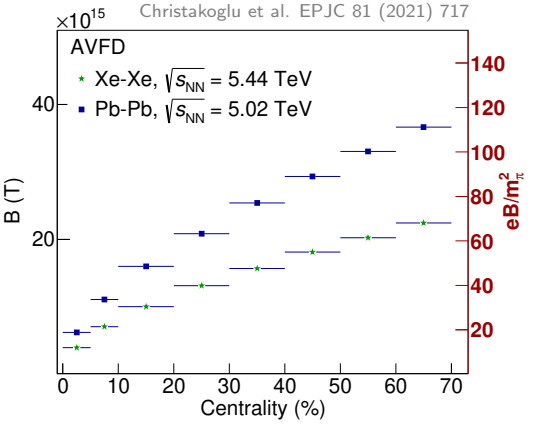


	pp	Pb–Pb
D^{*+}	PLB 846 (2023) 137920	ALICE Preliminary
J/Ψ	EPJC 78 (2018) 562	PRL 131 (2023) 042303
$\Upsilon(1s)$	ALICE Preliminary	PLB 815 (2021) 136146
K^{*0}, ϕ	PRL 125 (2020) 012301	PRL 125 (2020) 012301

Backup

B field in heavy-ion collisions





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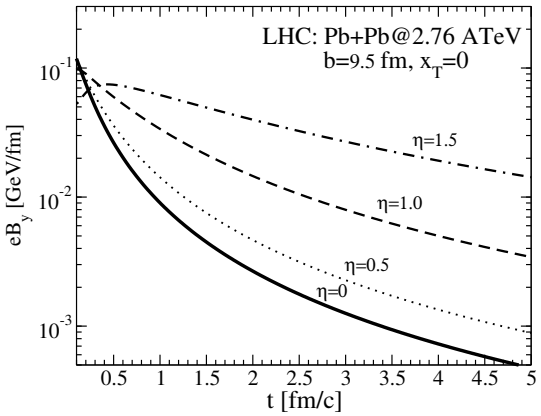
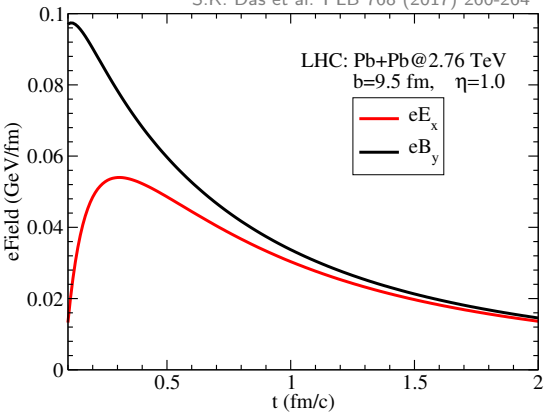
EM field in heavy-ion collisions

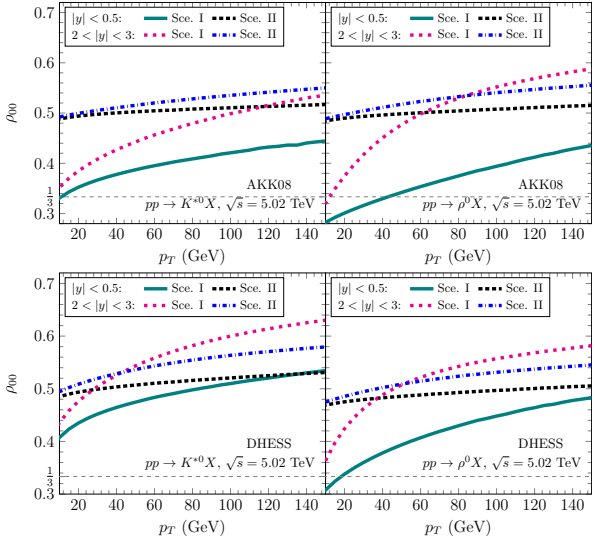


S.K. Das et al. PLB 768 (2017) 260-264

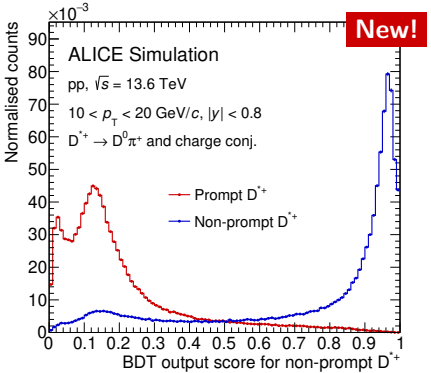


Spin alignment vs p_{T} — pp collisions

Chen et al. PRD 102 (2020) 034001



D^{*+} spin alignment in pp collisions — Run 3



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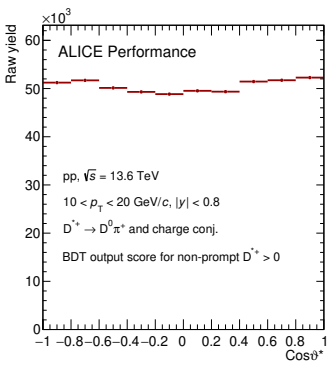

ALI-PERF-571952