Measurements of heavy-flavor production as a function of multiplicity with ALICE at the LHC

Yoshini Bailung, for the ALICE Collaboration
Indian Institute of Technology Indore (IN)

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Physics Motivation

Heavy quarks (charm, beauty) due to their large masses (m_c~1.3 GeV/c^2, m_b~4.2 GeV/c^2) are produced at the early stages of the collision via hard scattering

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Inspect the role of multi-parton interactions and color reconnection in hadronization mechanisms
Interplay of soft and hard components in pp collisions
Collectivity in small systems?

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Test of perturbative QCD calculations
Baseline reference for heavy-ion studies

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Modification of heavy flavor yields due to cold nuclear matter (CNM) effects

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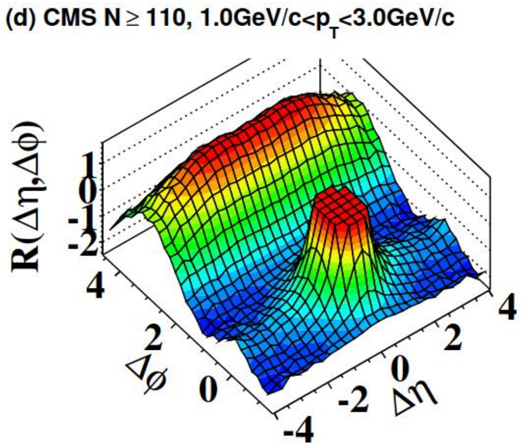
High multiplicity pp, p-Pb collisions show similarities to what is observed in heavy-ion collisions
- Ridge formation

†



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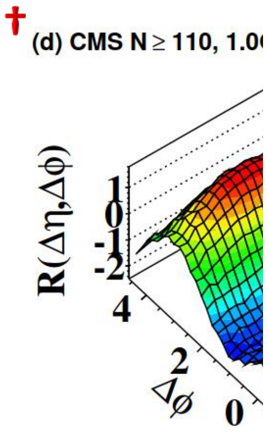

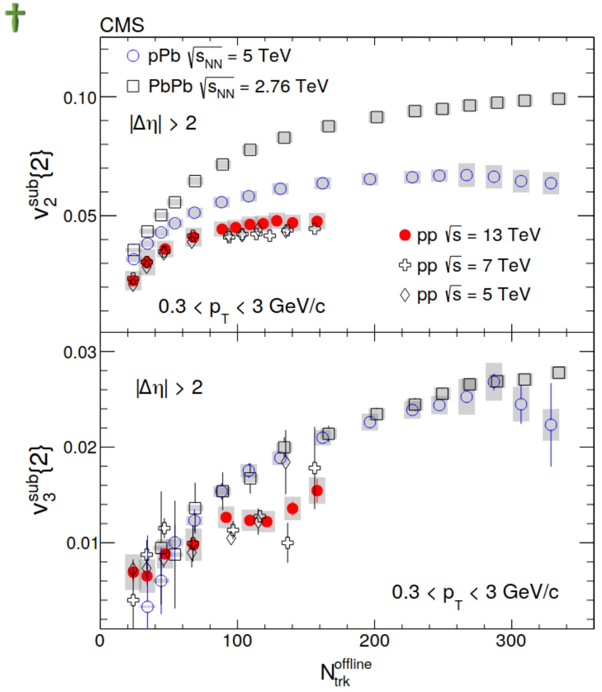

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High multiplicity pp, p-Pb collisions show similarities to what is observed in heavy-ion collisions

- Ridge formation
- Anisotropic flow
- Strange baryon enhancement

pp: Test of perturbative QCD calculations
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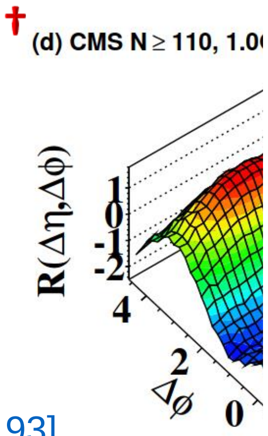
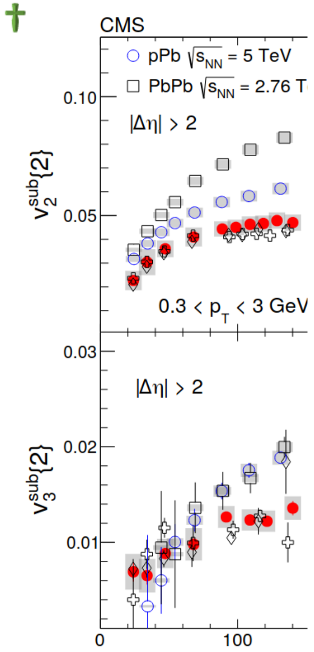
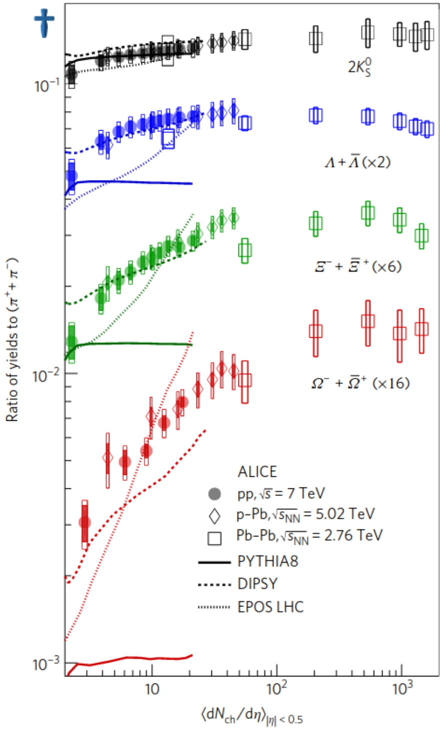
p-Pb: Modification of heavy flavor yields due to cold nuclear matter (CNM) effects

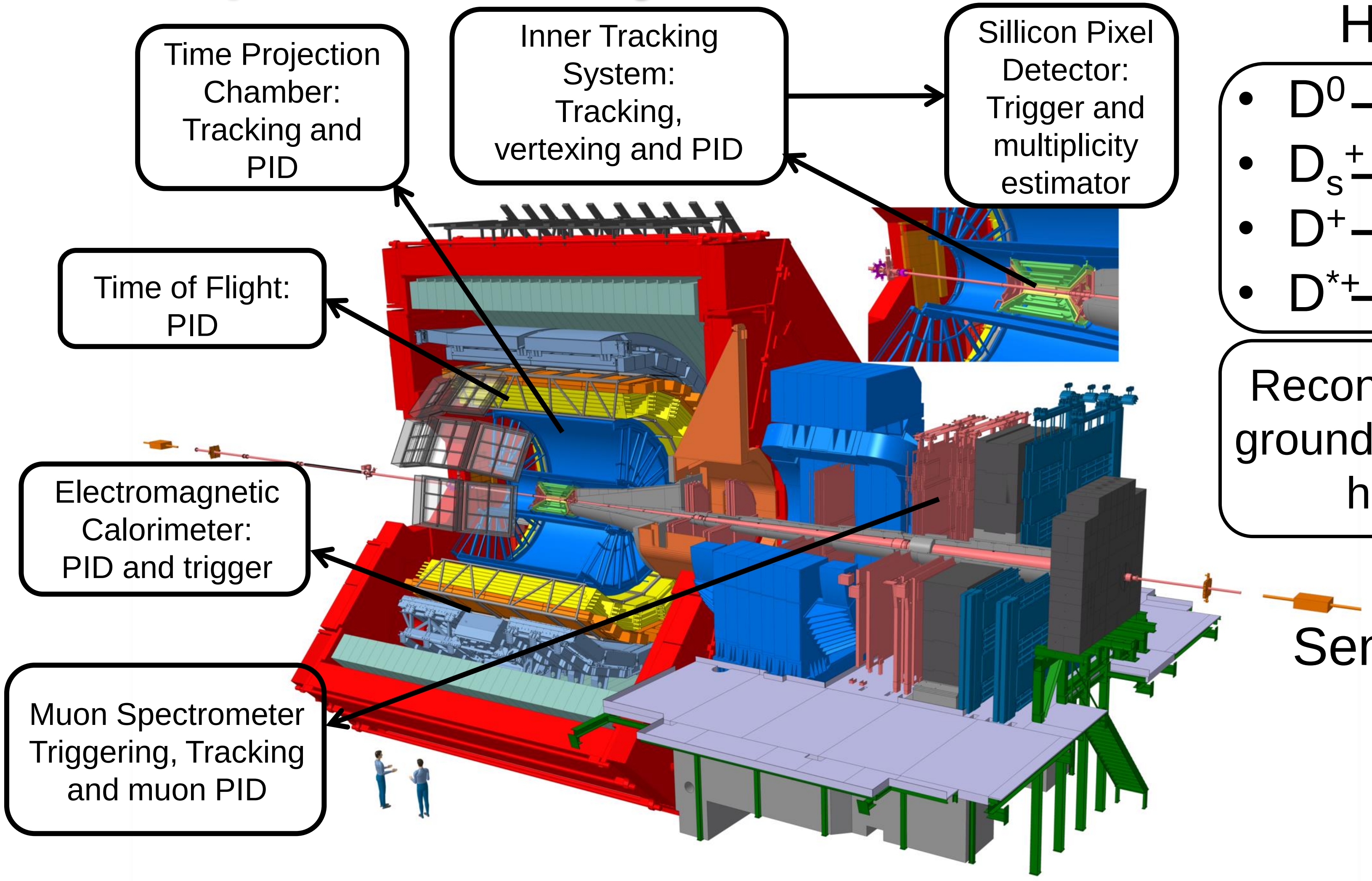






† [CMS, JHEP 09 (2010) 091]
† [CMS, Phys. Lett. B 765 (2017) 193]
† [Nature Physics 13 (2017) 535-539]

Open heavy-flavors with ALICE



Hadronic Decay Channels

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

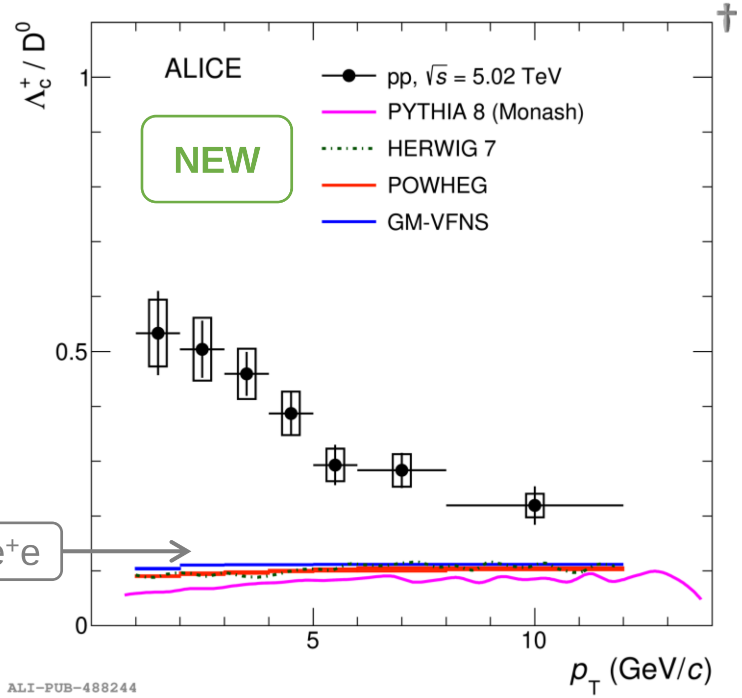
Reconstructing all ground state charm hadrons

- $\Lambda_c^+ \rightarrow pK^- \pi^+$
- $\Lambda_c^+ \rightarrow pK_s^0$
- $\Sigma_c^0 \rightarrow \Lambda_c^+ \pi^-$
- $\Sigma_c^{++} \rightarrow \Lambda_c^+ \pi^+$
- $\Xi_c^0 \rightarrow \Xi^- \pi^+$
- $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$
- $\Omega_c^0 \rightarrow \Omega^- \pi^+$

Semileptonic Decay Channels

$B,D \rightarrow e + X$
$B,D \rightarrow \mu + X$

Λ_c^+/D^0 in pp at $\sqrt{s} = 5.02$ TeV

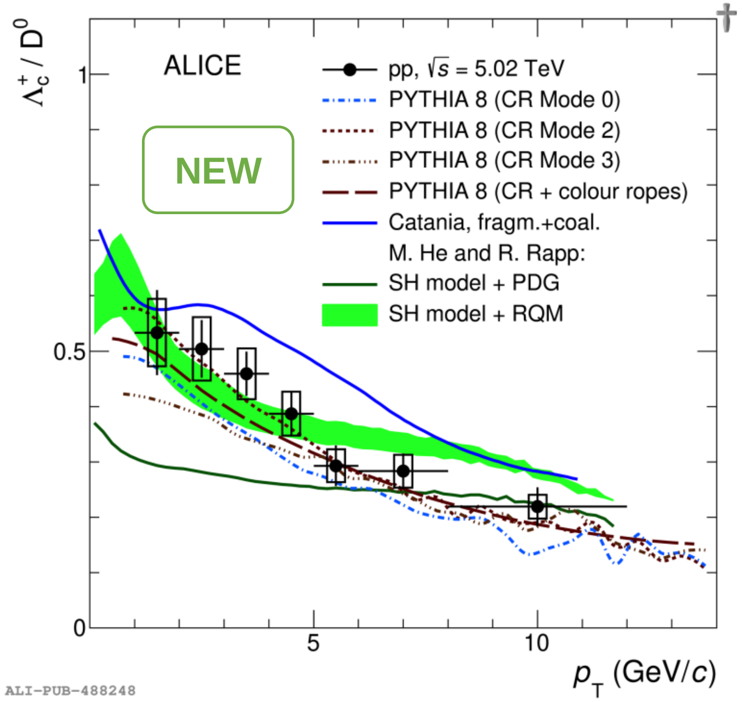


e⁺e

†

- PYTHIA8 Monash [EPJC 74 (2014) 3024]
- HERWIG 7 [EPJC 58 (2008) 639-707]
- POWHEG [JHEP 09 (2007) 126]
- GM-VFNS [PRD 101 (2020) 0114021]

Compatible with e⁺e⁻



†

- PYTHIA 8 CR Modes [JHEP 08 (2015) 003]
- M. He and R. Rapp [PLB 795 (2019) 117-121]
- RQM [PRD 84 (2011) 014025]
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- † [arXiv:2011.06079]

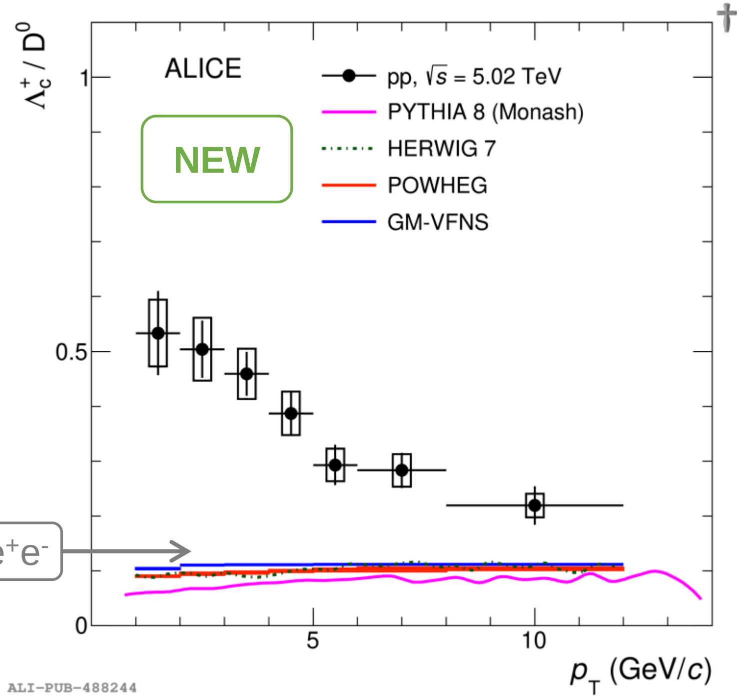
Compatible with pp

- PYTHIA8 (Monash tune)
- HERWIG 7 (hadronization via clusters)
- POWHEG (matched with PYTHIA 6 to generate parton showers)
- GM-VFNS pQCD calculations

- PYTHIA8 with Color Reconnection (CR) beyond leading color (BLC) approximation (Mode 0, Mode 2, Mode 3)
- Catania with coalescence+fragmentation
- M.He and R. Rapp + RQM (SHM approach)

Λ_c^+/D^0 in pp at $\sqrt{s} = 5.02$ TeV

See poster by **Tiantian Cheng** (13 July, 19:30 CEST) for more discussion on **charm-baryon enhancement**



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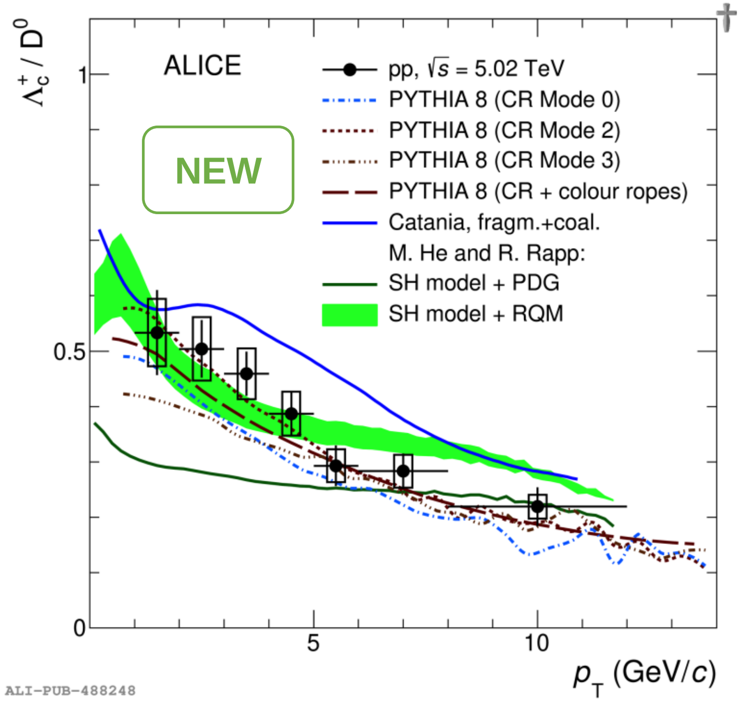
Compatible with e^+e^-



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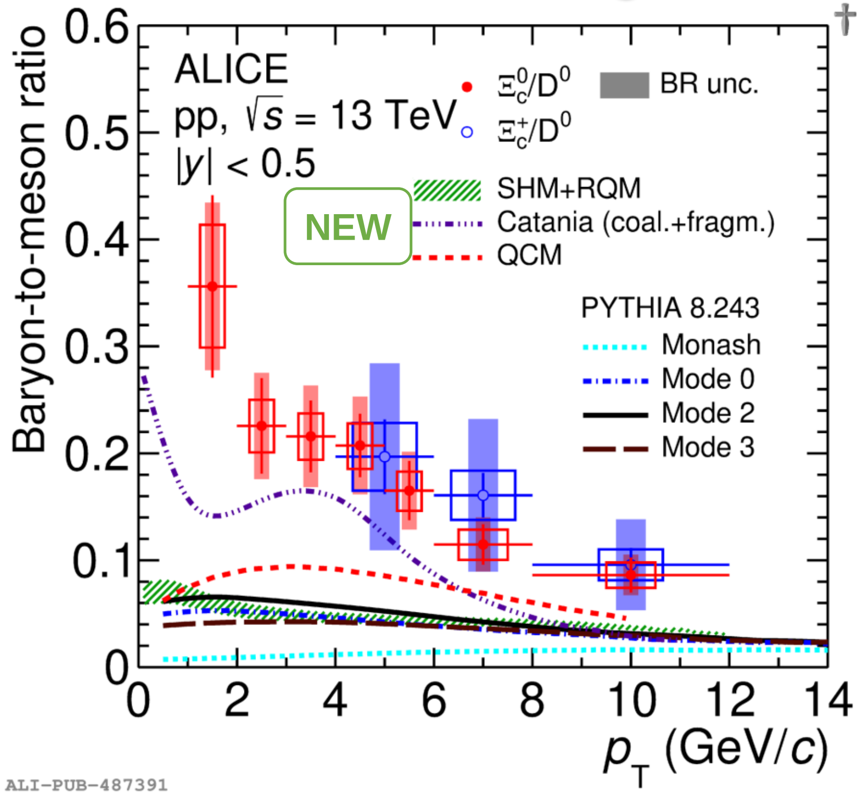
$\Xi_c^{0,+}/D^0$ and Ω_c^0/D^0 in pp at $\sqrt{s} = 13$ TeV

- PYTHIA 8 Monash [EPJC 74 (2014) 3024]
- PYTHIA 8 CR Modes(0,2,3) [JHEP 08 (2015) 003]
- SHM+RQM [PLB 795 (2019) 117-121]
- Catania [arXiv:2012.12001]
- QCM [EPJC 78 (2018) 344]



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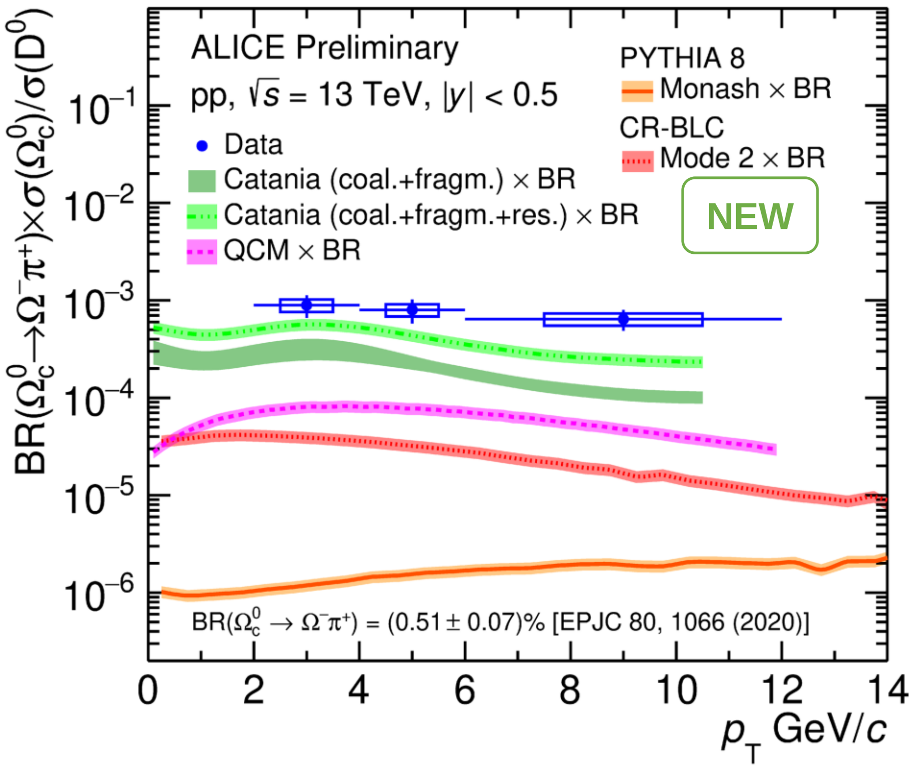


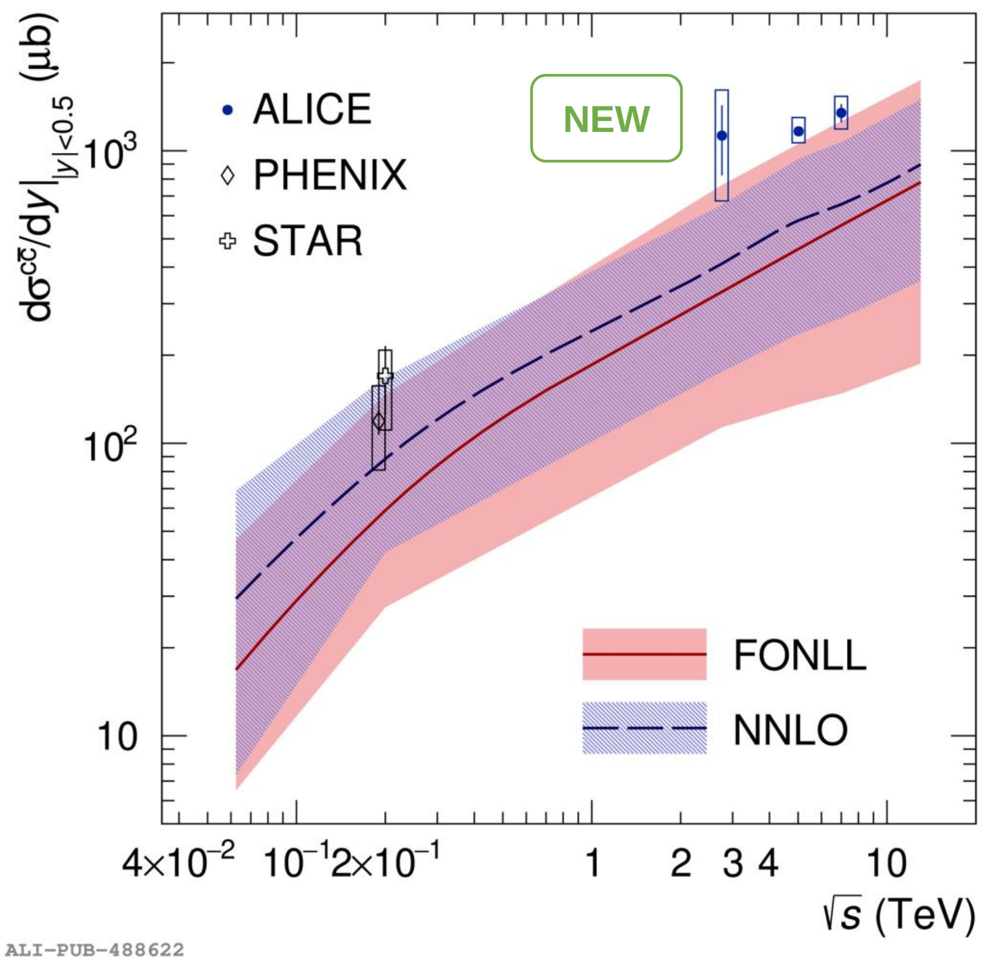
ALI-PREL-486632

- PYTHIA8 CR-BLC, SHM+RQM, Quark (re-)Combination Mechanism (QCM) ⟶ underestimate data
- Catania with coalescence + fragmentation ⟶ compatible with data

- PYTHIA8 CR-BLC, Catania with coalescence, QCM ⟶ underestimate data
- Catania with coalescence + fragmentation + resonances ⟶ compatible with data

- $\mathrm{BR}(\Omega_c^0 \to \pi^+\Omega^-)$ = (0.51±0.07%) theoretical calculation [EPJ 80, (2020) 1066]
- † [arXiv: 2105.05187]

Charm total production cross section



- New measurement of total charm cross section in pp at 5.02 TeV†

$$d\sigma^{c\bar{c}}/dy|_{|y|<0.5} = 1165 \pm 44(\text{stat.})^{+134}_{-101}(\text{syst.})\mu b$$

- Previous results in pp at 2.76† and 7† TeV updated with fragmentation fractions from 5.02 TeV analysis ⟶ 40% higher
- Results on the upper edge of FONLL and NNLO calculations

- FONLL [JHEP 1210 (2012) 137]
- NNLO [PRL 118 (2017)] [JHEP 03 (2021) 029]
- PHENIX [PRC 84 (2011) 044905]
- STAR [PRD 86 (2012) 072013]
- † [arXiv:2105.06335]
- † [JHEP 07 (2012) 191]
- † [EPJC 77 (2017) 550]

Λ_c^+/D^0 in pp at $\sqrt{s} = 13$ TeV

- Multiplicity dependence of Λ_c^+/D^0 yield ratio

↓

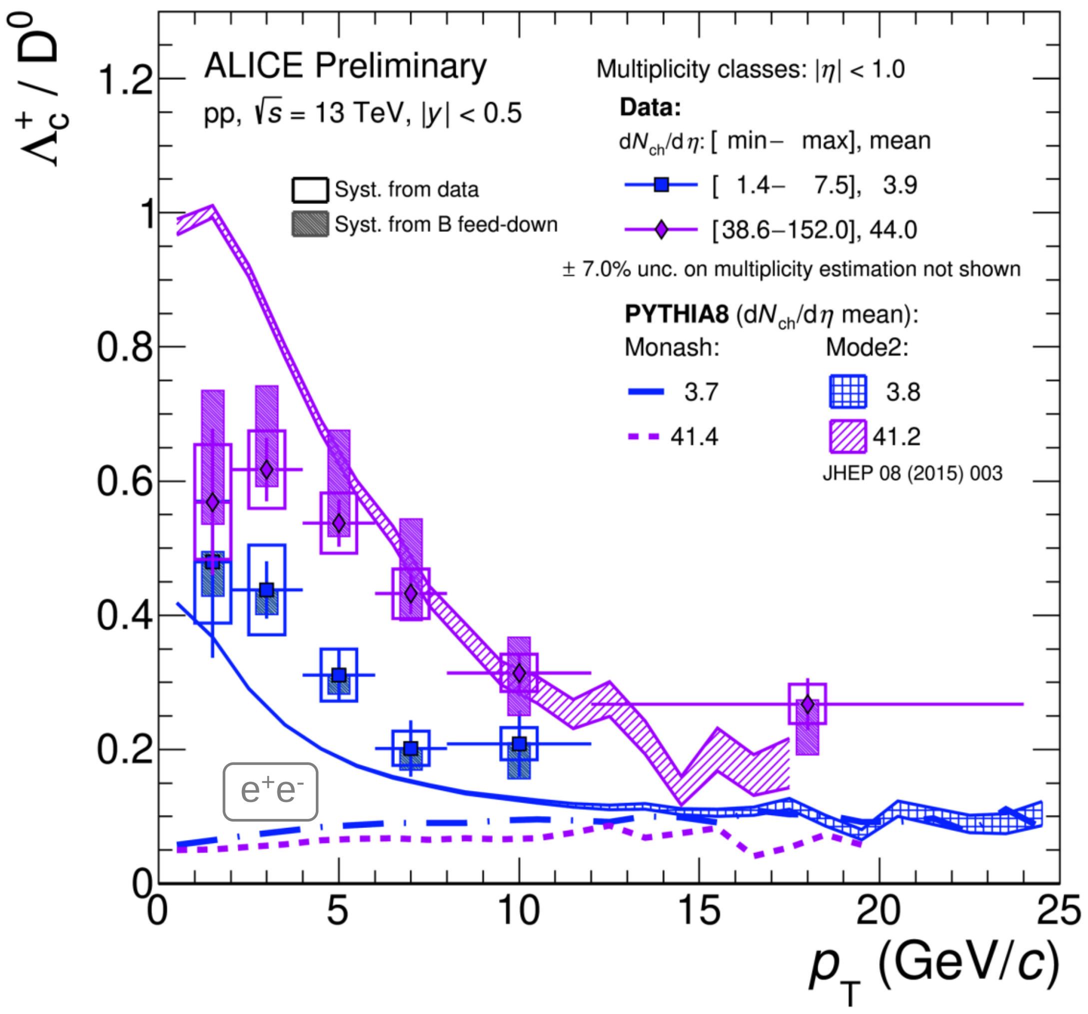
Modifications in hadronization mechanisms with multiplicity?

Radial flow in high multiplicity pp events?

- PYTHIA8 Monash tune fails to describe the results
- PYTHIA8 with CR Mode2 describes the measurements with p_T and multiplicity fairly well
- Measurements higher than values in e^+e^-† collisions

↓

Non-universality of charm fragmentation



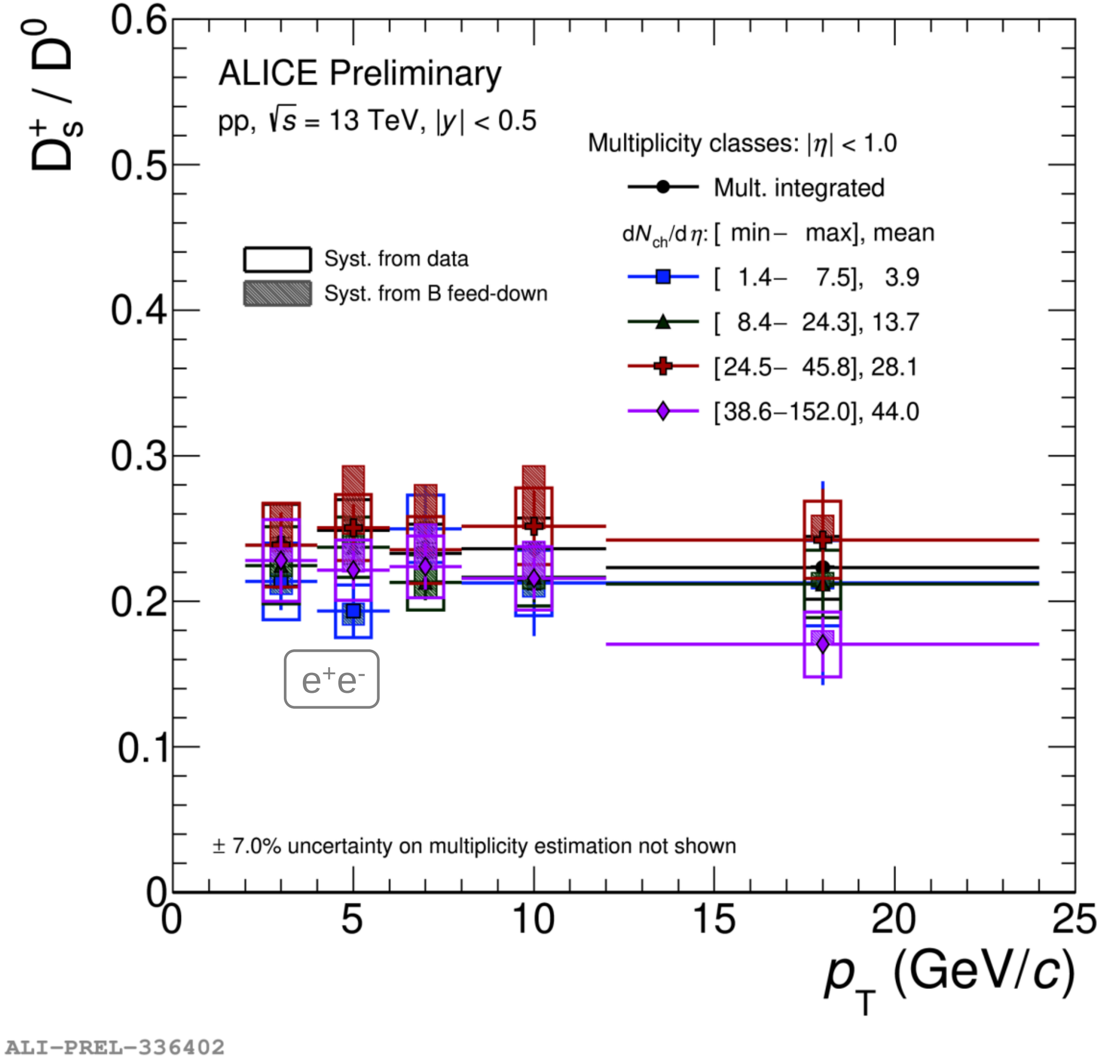
ALI-PREL-336442

- PYTHIA8 [Comput. Phys. Commun. 178 (2008) 852]
- PYTHIA8 Monash [Eur. Phys. J. C 74 (2014) 3024]
- PYTHIA8 Mode2 [JHEP 08 (2015) 003]
- † [L. Gladilin, Eur. Phys. J. C 75, 19 (2015)]

D_s^+/D^0 in pp at $\sqrt{s} = 13$ TeV

- No multiplicity dependence observed for D_s^+/D^0 ratio yields
- The results are comparable with the average of p_T integrated measurements performed at e^+e^-† collisions

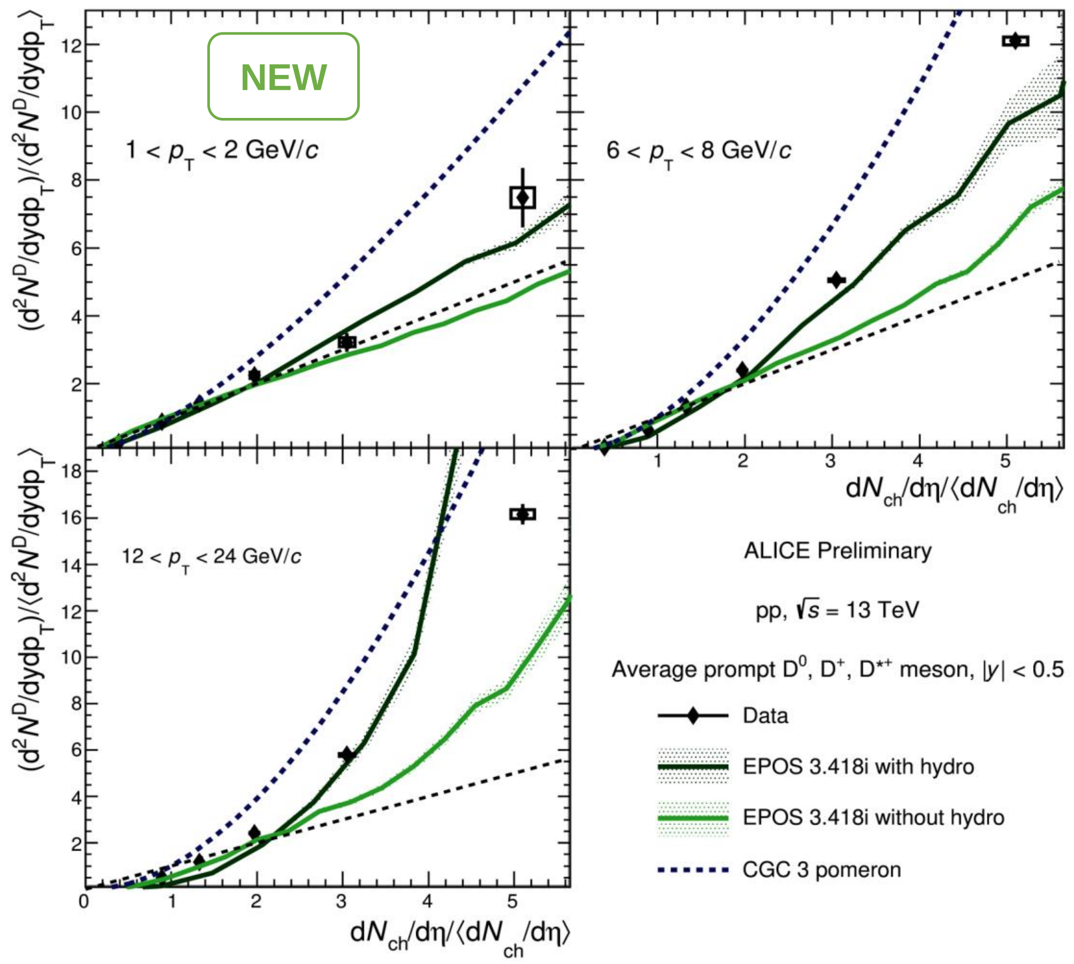
† [L. Gladilin, Eur. Phys. J. C 75, 19 (2015)]



D-meson self-normalised yields vs models in pp at $\sqrt{s} = 13$ TeV

- EPOS3† generator assuming initial conditions followed by a hydrodynamical evolution
- EPOS3 without the hydro component
- CGC Pomeron3†, with three-pomeron fusion correction

† [PRC 89, (2014) 064903]
† [PRD 101, (2020) 094020]



ALI-PREL-488879

D-meson self-normalised yields vs models in pp at $\sqrt{s} = 13$ TeV

- EPOS3† generator assuming initial conditions followed by a hydrodynamical evolution

↓

Comparable to data

Deviates at high multiplicities

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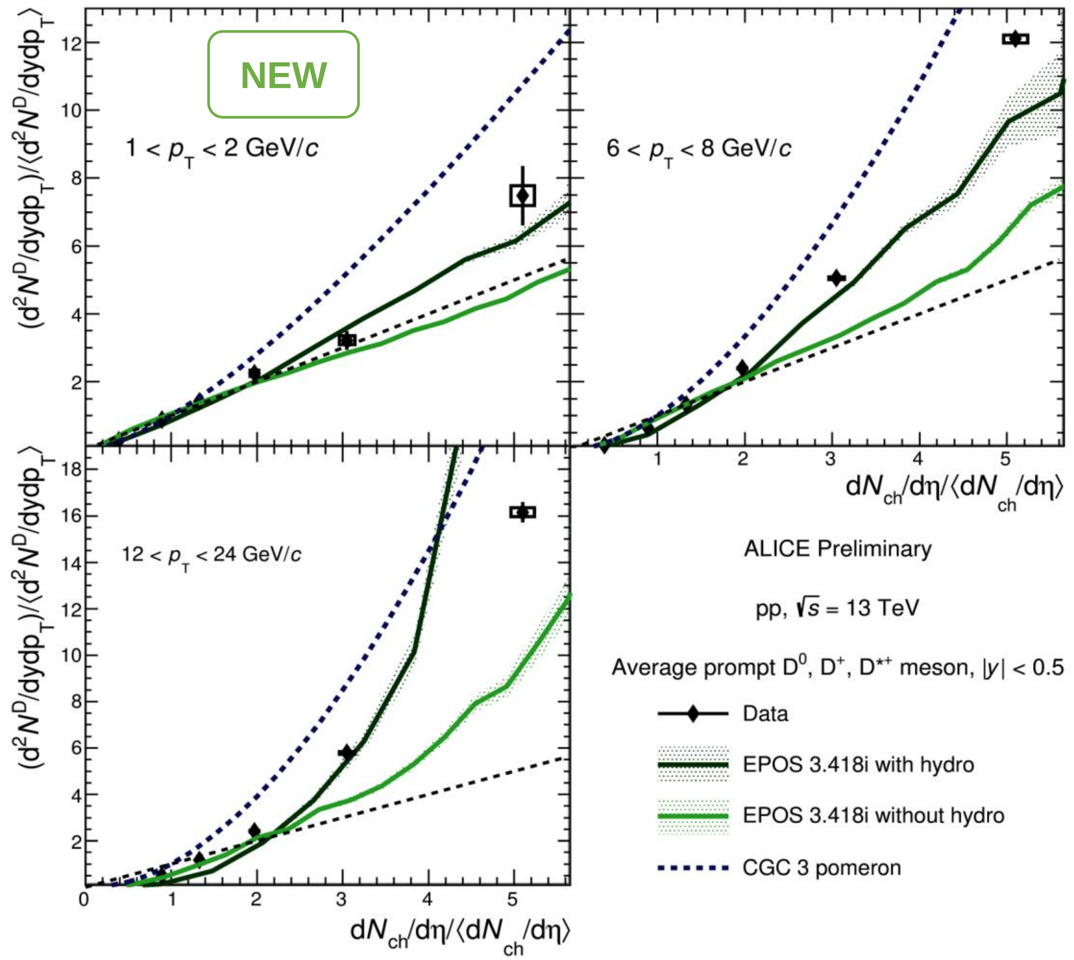

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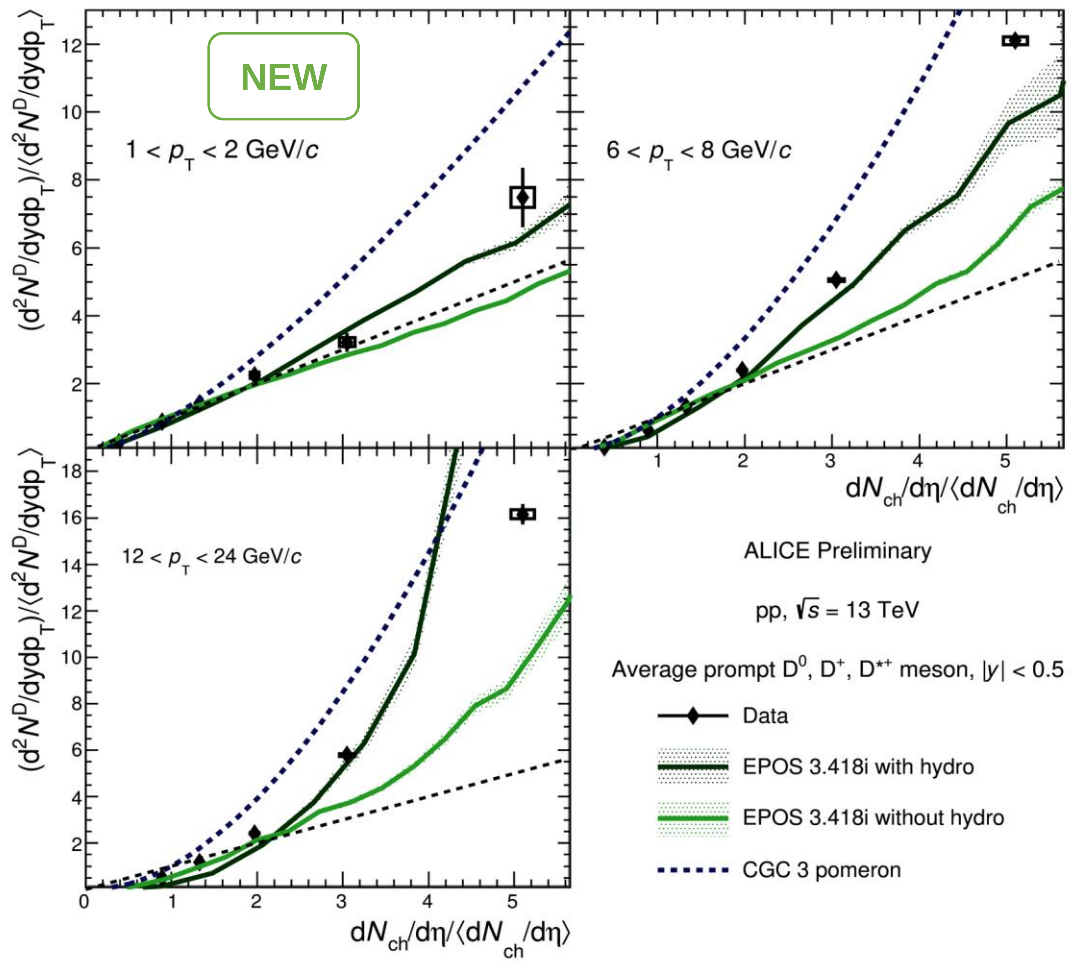

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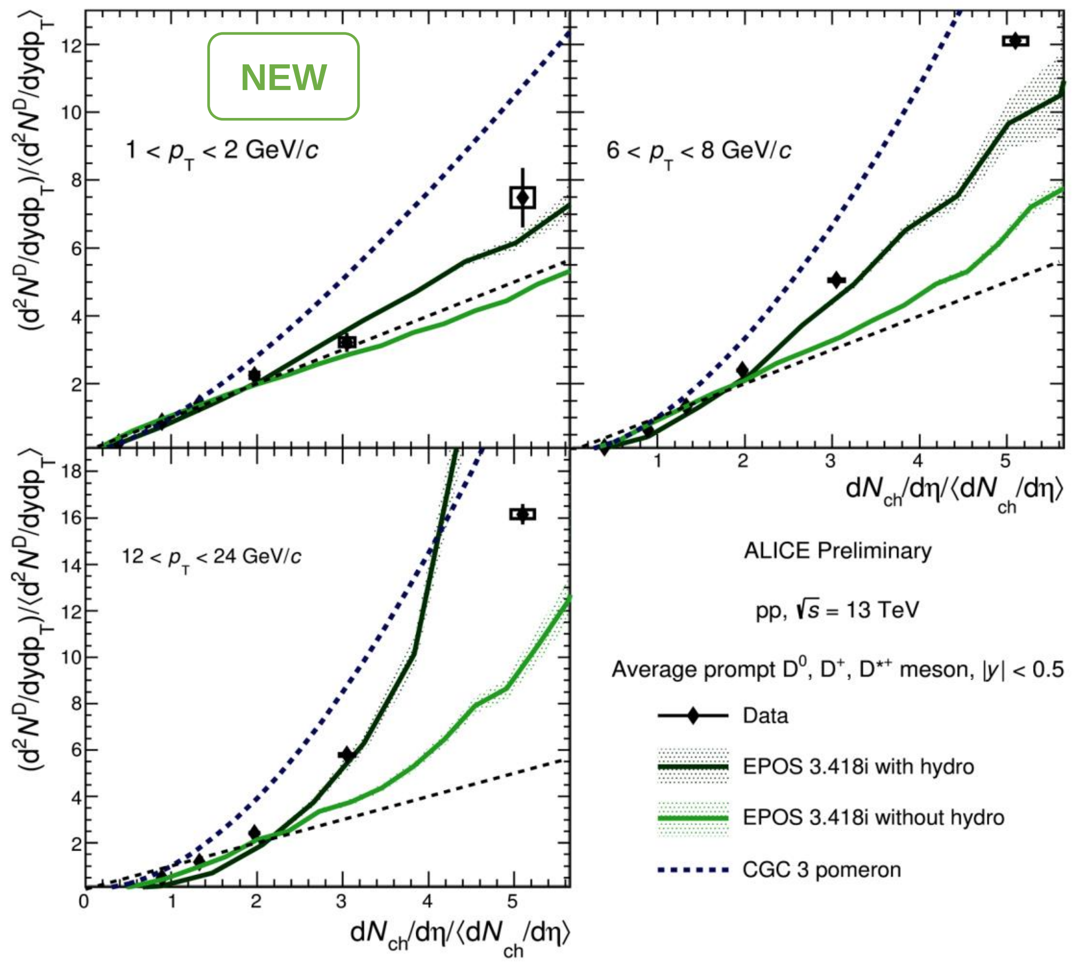

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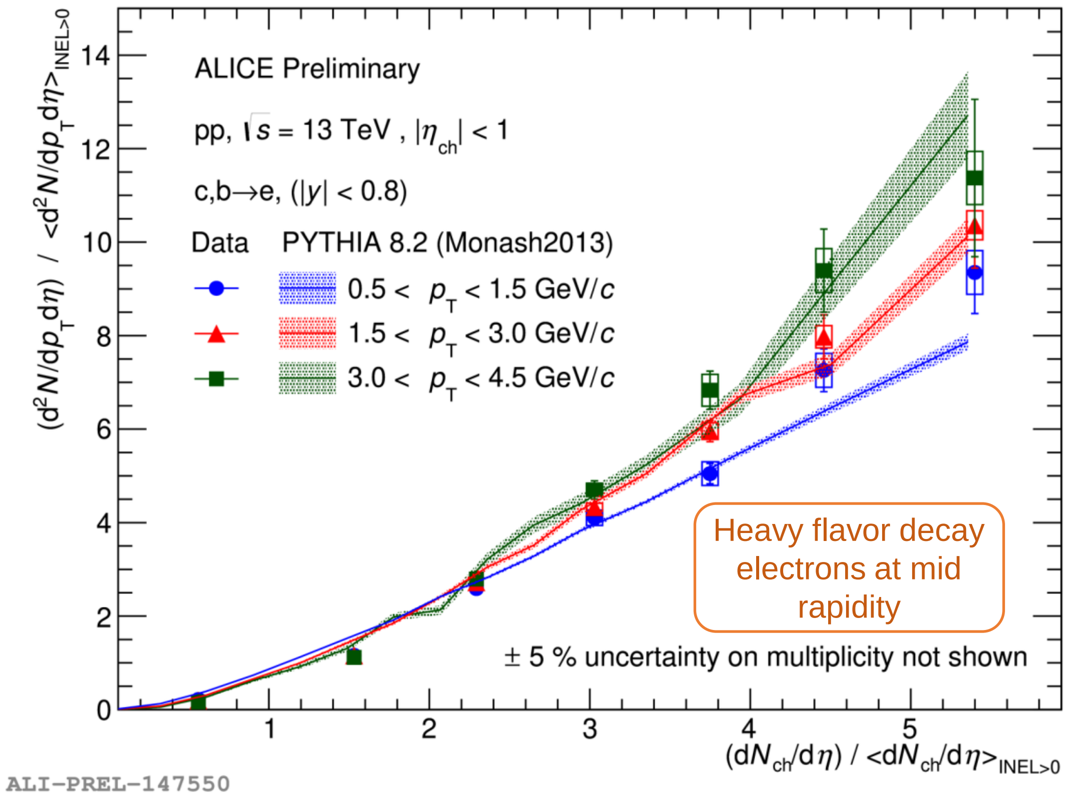
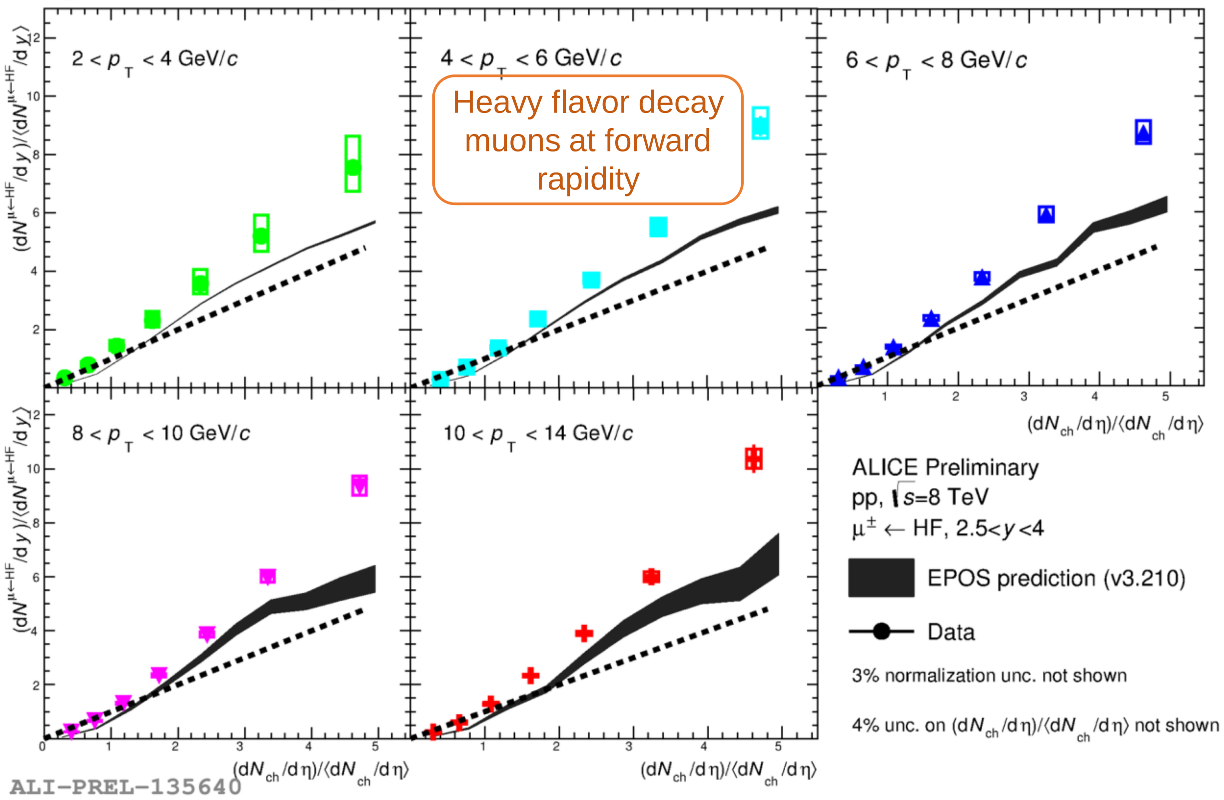
Heavy flavor decay lepton production

† [Eur. Phys. J. C (2019) 79: 36]





Stronger than linear dependence with charged-particle multiplicity with increasing p_T dependence

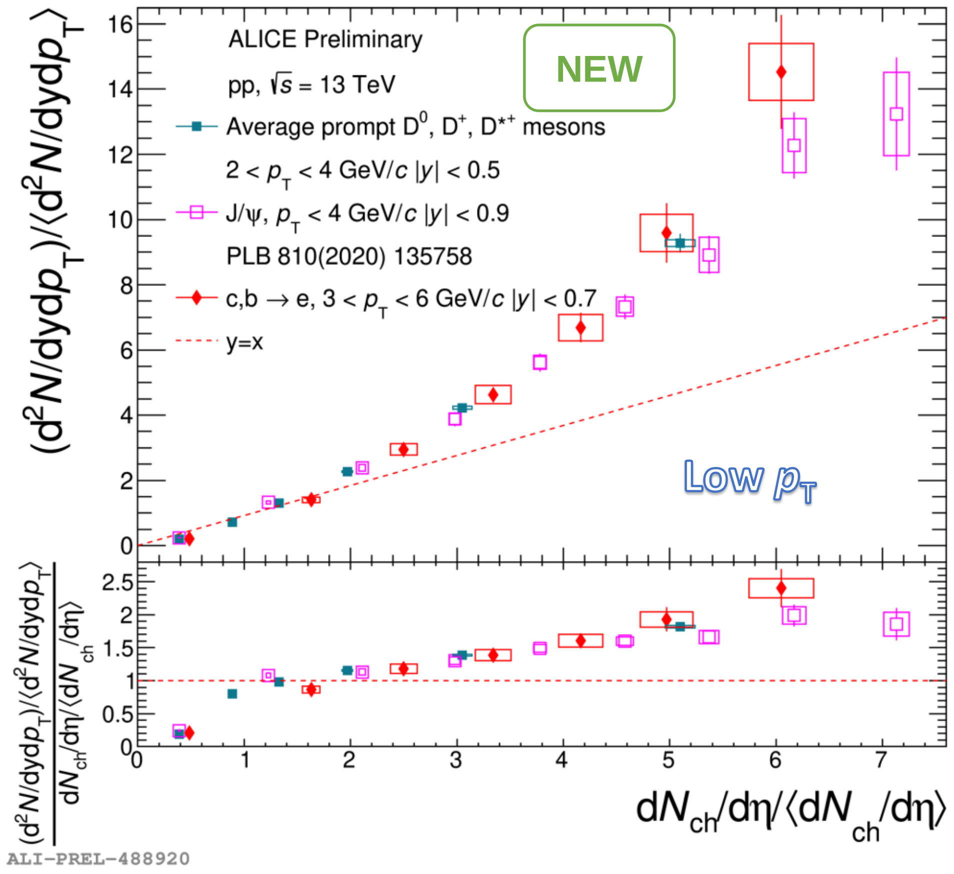
PYTHIA 8.2 Monash 2013 tune ⟶ comparable with data.
Role of auto-correlation effects in stronger than linear trend†

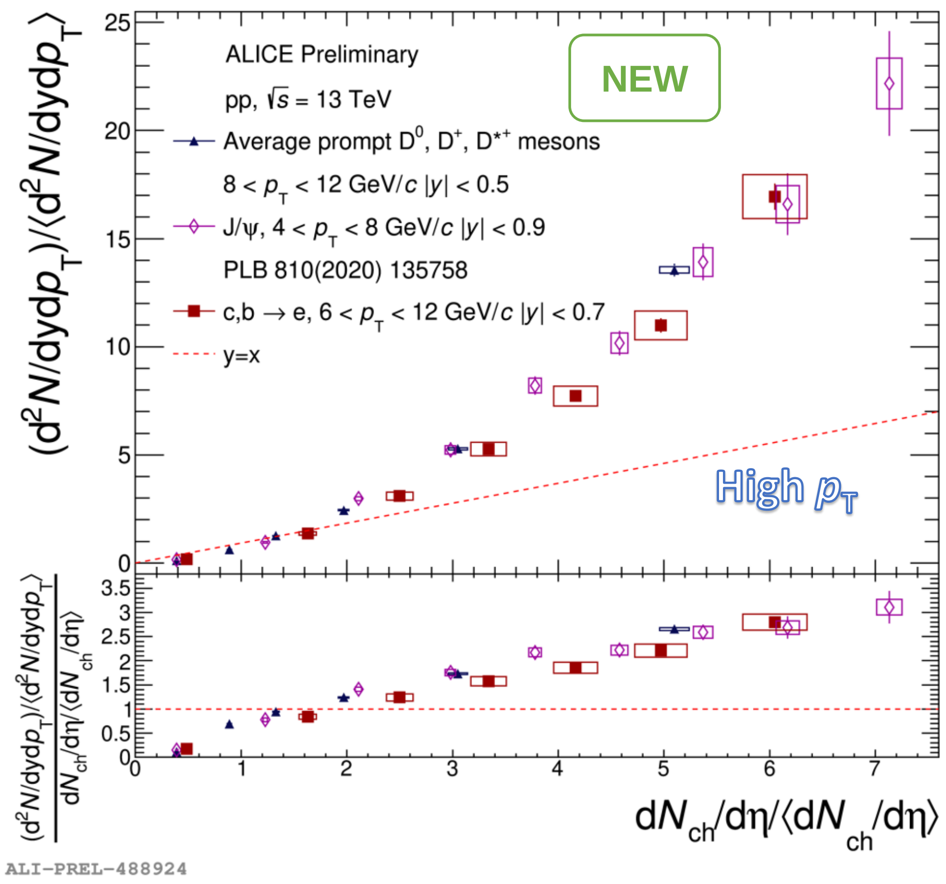
Similar dependence with charged-particle multiplicity with a weaker p_T dependence.

EPOS3 predictions (without hydro) ⟶ underestimates data

More comparisons!

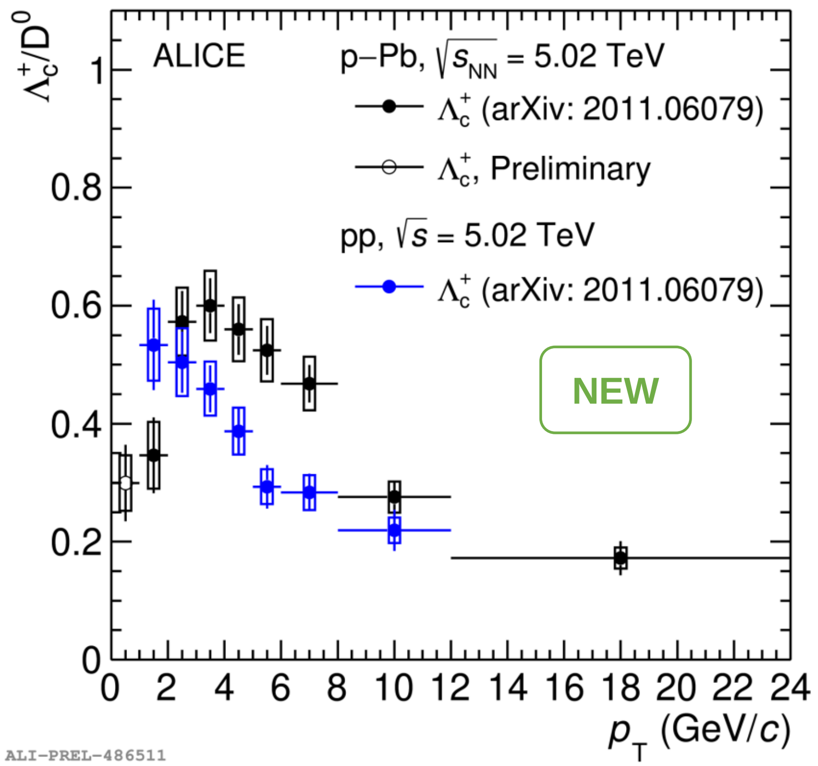
† [PLB 810 (2020) 135758]



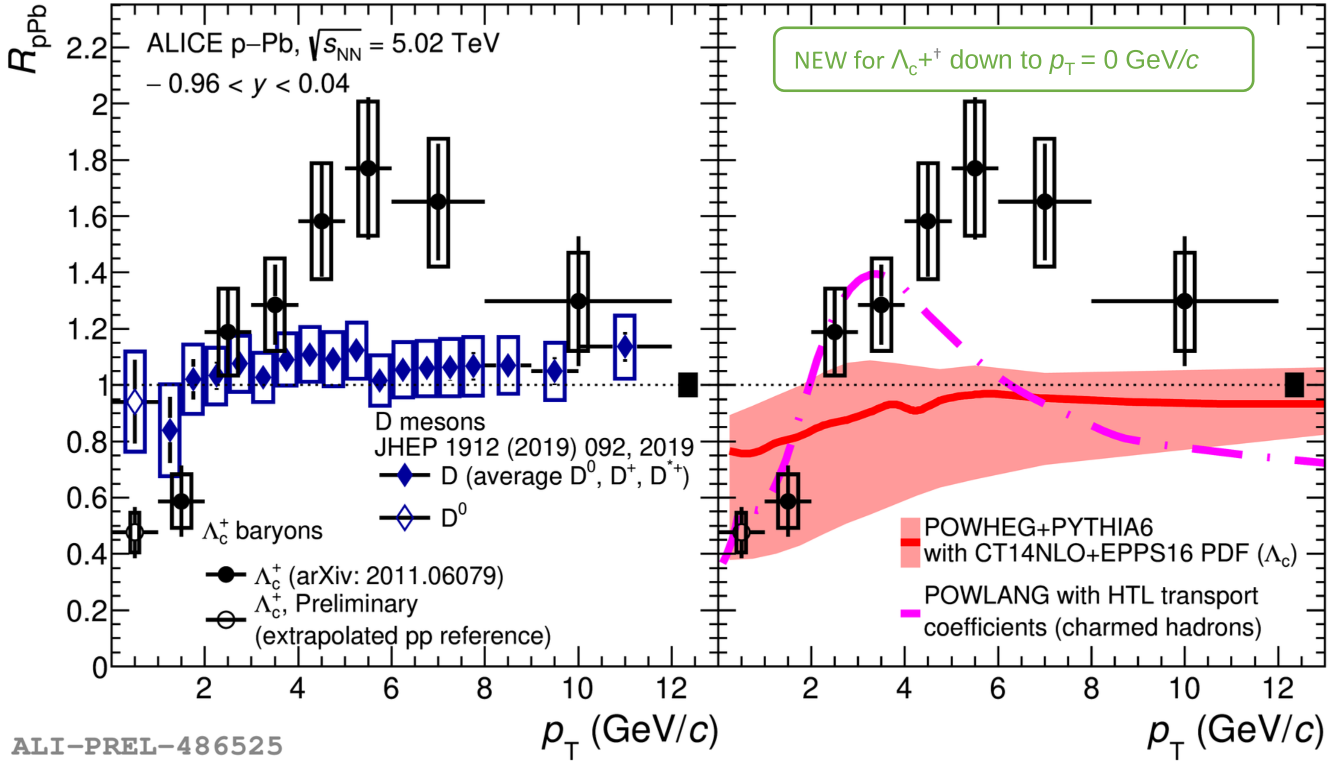


Similar trend of self-normalised yield for D-meson, electrons from heavy-flavor hadron decays, and J/Ψ† at mid rapidity, both at low and high p_T

Open charm measurements in p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV



Λ_c^+/D^0 comparisons ⟶ higher in mid-p_T and lower in $p_T < 2$ GeV/c for p-Pb w.r.t. pp collisions



- R_{pPb} (D^0) ≈ 1 across all p_T
- R_{pPb} (Λ_c^+) ⟶ Suppression at $p_T < 2$ GeV/c above unity elsewhere

- POWHEG [EPJC 77 no. 3, (2017) 163]
- PYTHIA6 [JHEP 09 (2007) 126]
- POWLANG [JHEP 03 (2016) 123]
- † [arXiv:2011.06079]

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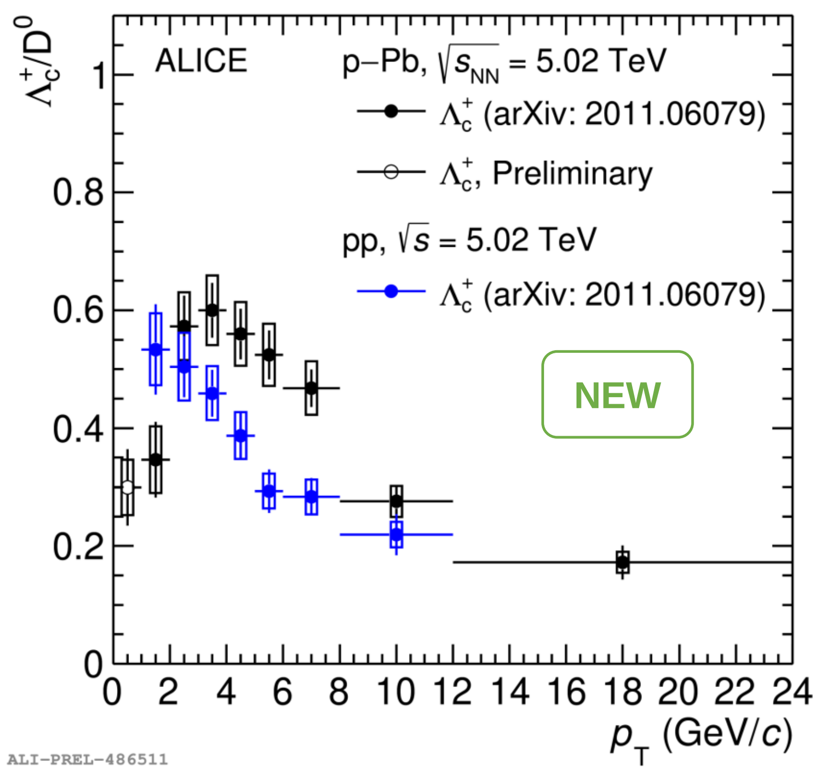

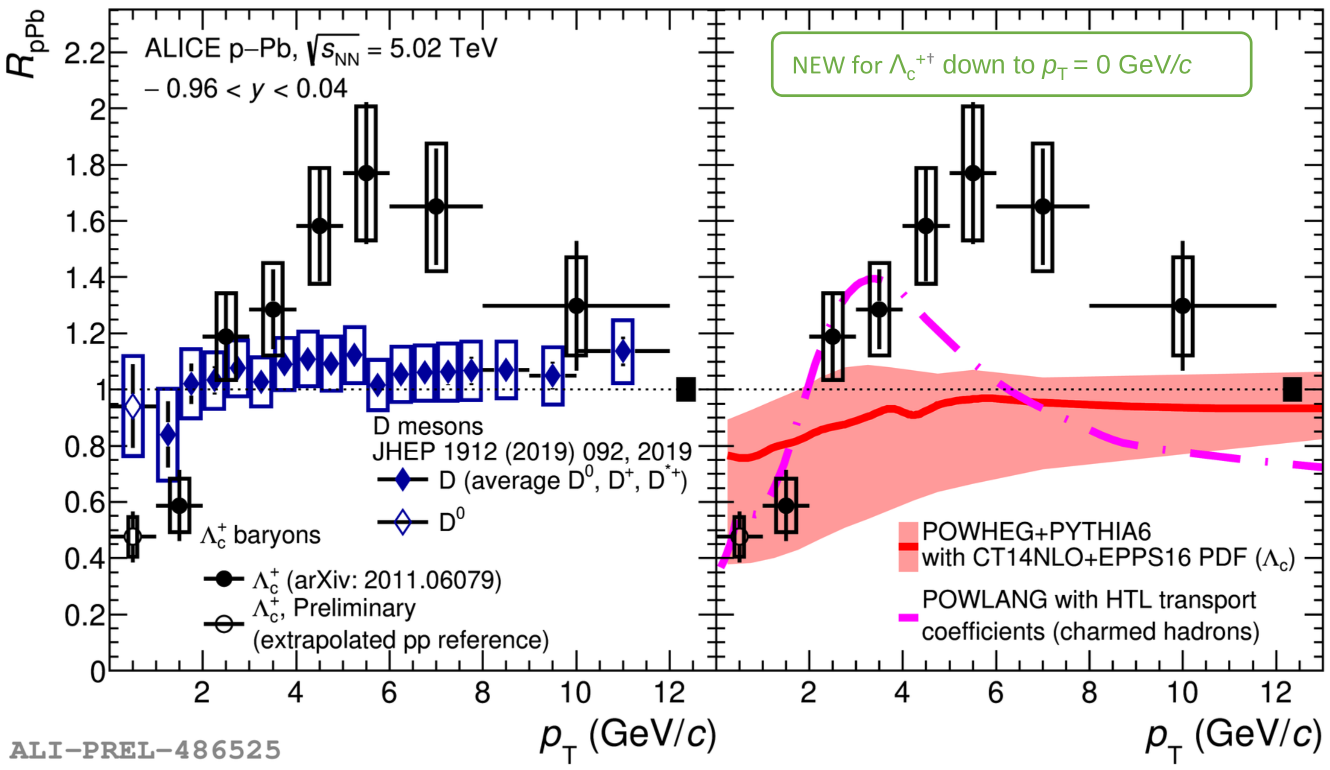

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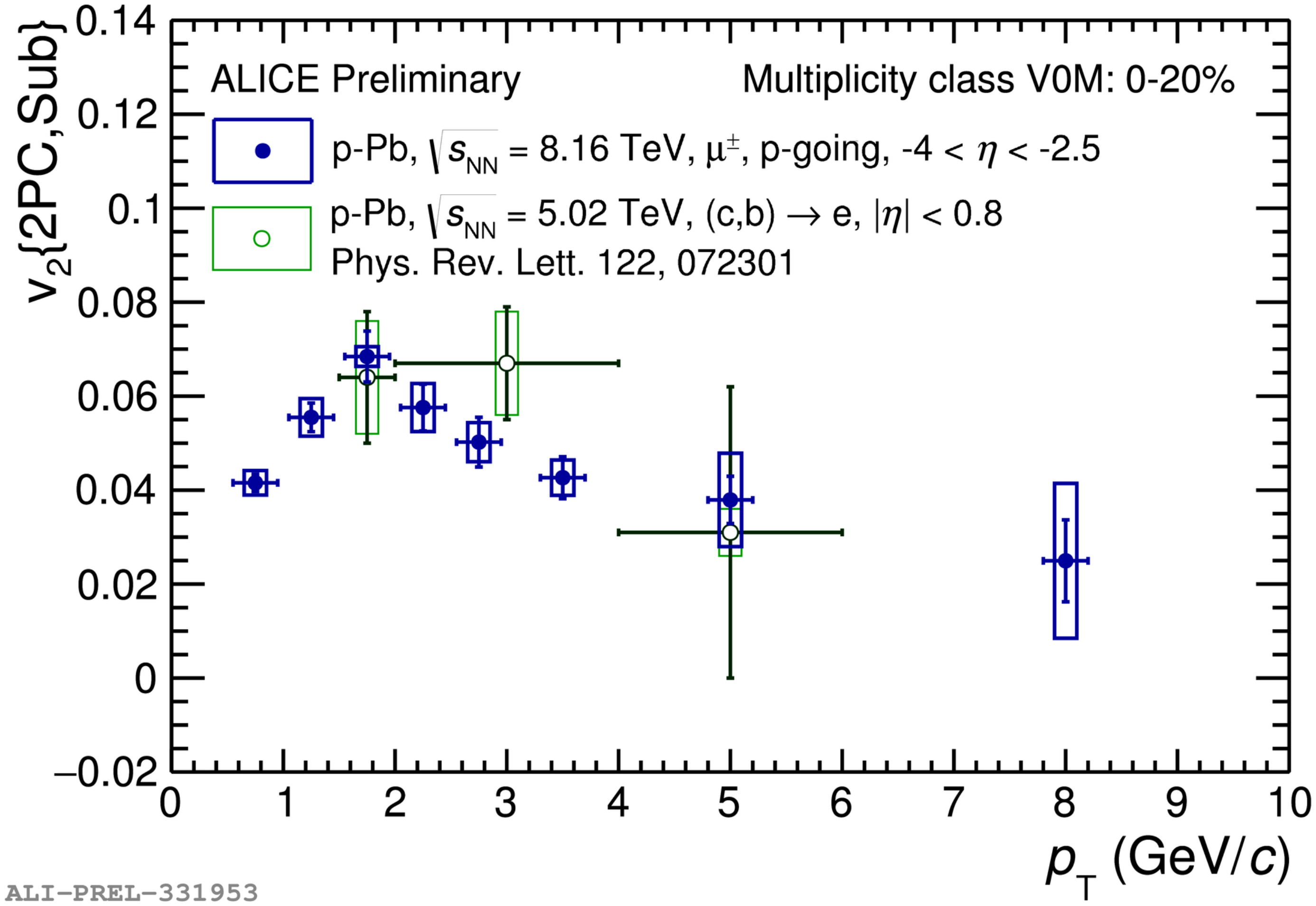
Radial flow or modification of hadronization mechanism in p-Pb systems?

Elliptic flow of heavy flavor leptons in p-Pb collisions



- v_2 of heavy flavor decay electrons† and muons measured at mid and forward rapidity respectively are compatible
- Indication of collectivity in the collision system

† [PRL 122, (2019) 072301]

Summary

pp

- Λ_c^+/D^0 in pp at 5.02 TeV show enhancement compared to e^+e^-. Clear $\boldsymbol{p}_T$ and **multiplicity dependence** observed (Not seen for D_s^+/D^0)
- Λ_c^+/D^0 in pp at 5.02 TeV, $\Xi_c^{0,+}/D^0$ and Ω_c^0/D^0 in pp at 13 TeV measurements compared to various model predictions
- Total charm cross section in pp at 5.02 TeV measured using all charm hadron states
- Average D-mesons, J/Ψ and heavy flavor lepton self-normalised yields in pp at 13 TeV are compatible with the stronger than linear trend with multiplicity and steeper p_T dependence in similar p_T bins ⟶ Weak p_T dependence for muons
- EPOS3 with hydro component reproduce the average D-meson production and PYTHIA8 Monash 2013 reproduce heavy flavor electrons data **fairly well**. EPOS3 without hydro **fails** to reproduce the D-meson and muon production

p-Pb

- **First** measurement of Λ_c^+ down to p_T = 0 GeV/c in p-Pb at 5.02 TeV
- R_{pPb} measurements ⟶ ≈1 for D^0 , <1 for Λ_c^+ at p_T < 2 GeV/c and >1 elsewhere. POWHEG+PYTHIA6 and POWLANG predictions are in **good** agreement at low and intermediate p_T but **deviates** at high p_T for Λ_c^+ measurements
- **Positive** v_2 observed for heavy flavor leptons (muons at forward rapidity and electrons at mid-rapidity)

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→

- **Enhancement** of all charm-baryon production in pp collisions than e^+e^- collisions
- Charm fragmentation **non universal**
- Multi-parton interactions, color reconnection mechanism and auto- correlation effects in play
- **Collectivity** in high multiplicity pp collisions?
- Hint of **modification of hadronization mechanisms** vs multiplicity

p-Pb

- **First** measurement of Λ_c^+ down to p_T = 0 GeV/c in p-Pb at 5.02 TeV
- R_{pPb} measurements → ≈1 for D^0 , <1 for Λ_c^+ at p_T < 2 GeV/c and >1 elsewhere. POWHEG+PYTHIA6 and POWLANG predictions are in **good** agreement at low and intermediate p_T but **deviates** at high p_T for Λ_c^+ measurements
- **Positive** v_2 observed for heavy flavor leptons (muons at forward rapidity and electrons at mid-rapidity)

Summary

pp

- Λ_c^+/D^0 in pp at 5.02 TeV show enhancement compared to e^+e^-. Clear $\boldsymbol{p}_\mathbf{T}$ and **multiplicity dependence** observed (Not seen for D_s^+/D^0)
- Λ_c^+/D^0 in pp at 5.02 TeV, $\Xi_c^{0,+}/D^0$ and Ω_c^0/D^0 in pp at 13 TeV measurements compared to various model predictions
- Total charm cross section in pp at 5.02 TeV measured using all charm hadron states
- Average D-mesons, J/Ψ and heavy flavor lepton self-normalised yields in pp at 13 TeV are compatible with the stronger than linear trend with multiplicity and steeper p_T dependence in similar p_T bins → Weak p_T dependence for muons
- EPOS3 with hydro component reproduce the average D-meson production and PYTHIA8 Monash 2013 reproduce heavy flavor electrons data **fairly well**. EPOS3 without hydro **fails** to reproduce the D-meson and muon production

→

- **Enhancement** of all charm-baryon production in pp collisions than e^+e^- collisions
- Charm fragmentation **non universal**
- Multi-parton interactions, color reconnection mechanism and auto- correlation effects in play
- **Collectivity** in high multiplicity pp collisions?
- Hint of **modification of hadronization mechanisms** vs multiplicity

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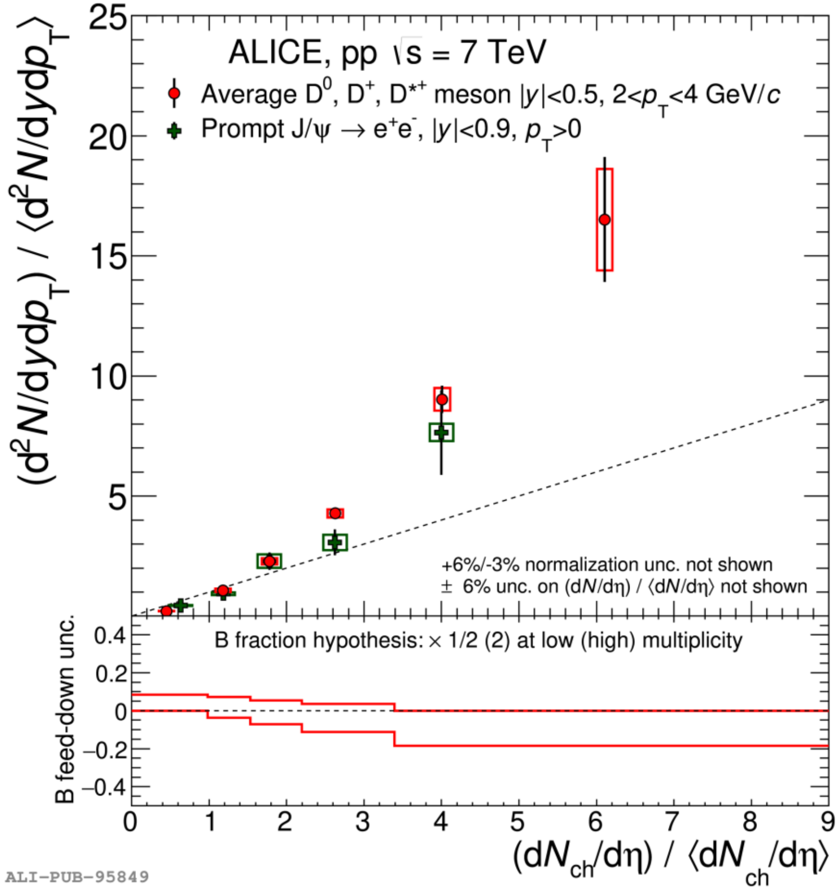
Collectivity in high multiplicity p-Pb collision systems?

THANK YOU

BACKUP

Measurements in pp at $\sqrt{s} = 7$ TeV



† [JHEP 09 (2015) 148]

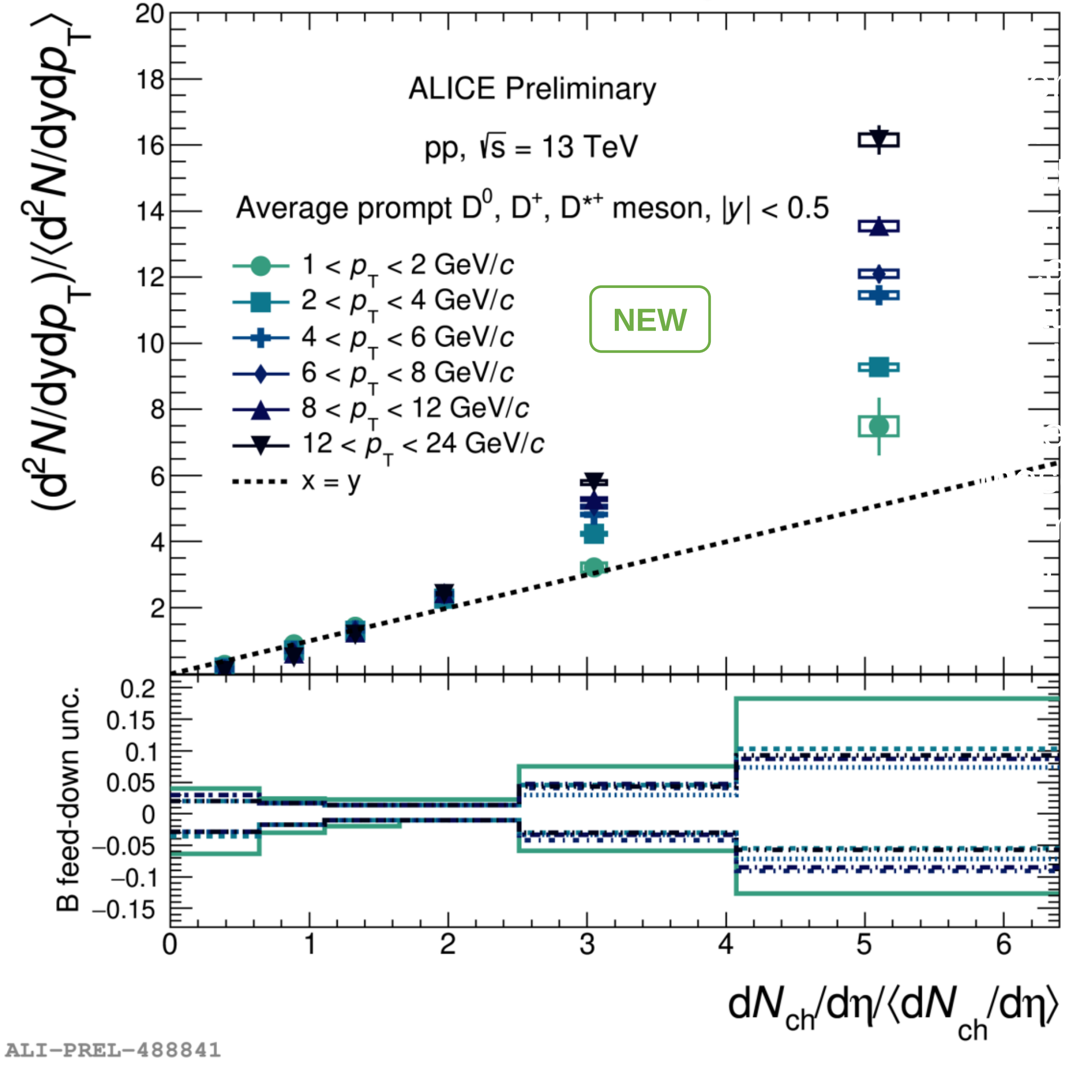
- Self-normalised yields are calculated as

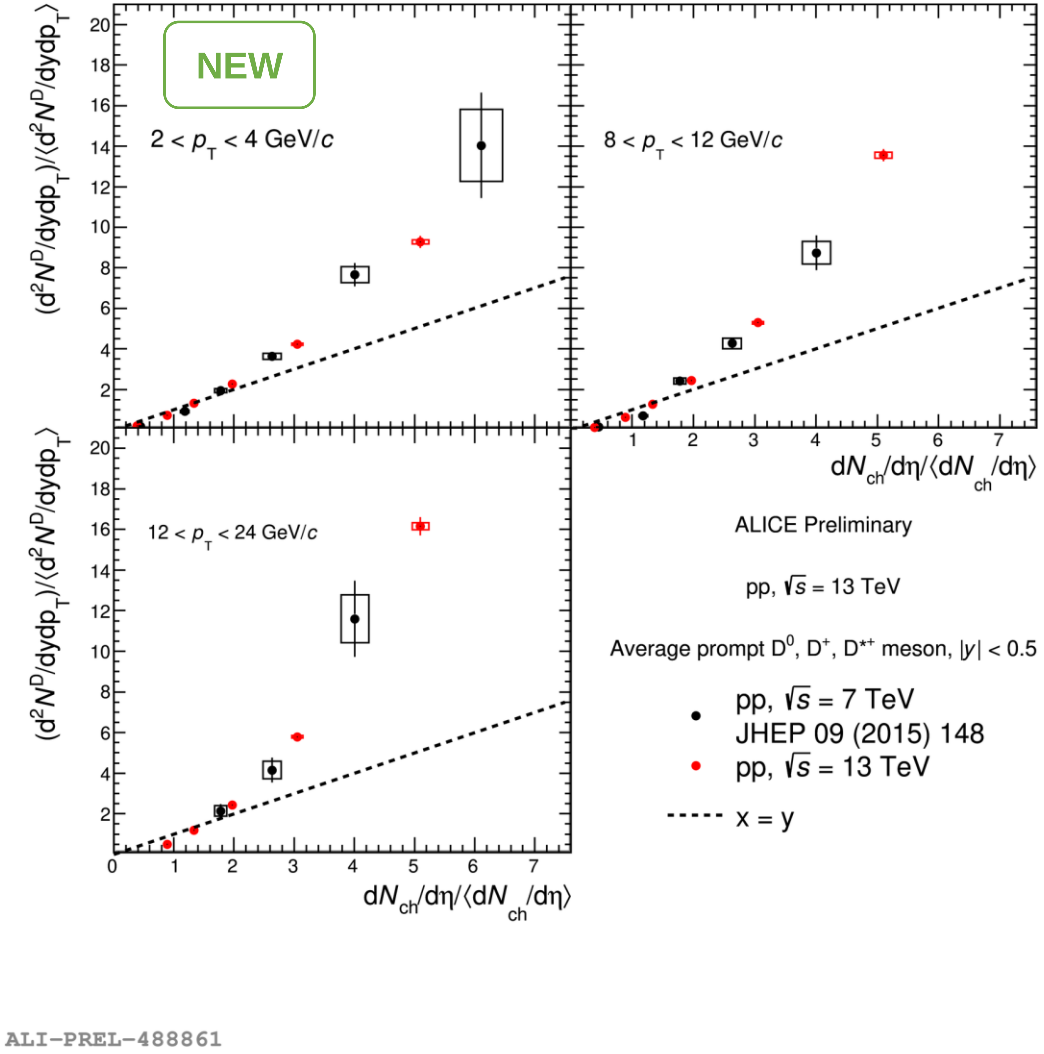
$$Y^{mult}_{corr} = \left(\frac{Y^{mult}}{(\epsilon^{mult} \times N^{mult}_{event}) / \epsilon^{trg}_{mult}} \right) \Bigg/ \left(\frac{Y^{mult}_{int}}{(\epsilon^{mult}_{int} \times N^{mult\ int}_{event}) / \epsilon^{trg}_{int}} \right)$$

Y^{mult} is the extracted raw yield, $\mathcal{E}^{mult}$ is the Acc × Eff value, N^{mult}_{event} is the number of events, and $\mathcal{E}^{trg}_{mult}$ is the trigger efficiency for a particular multiplicity bin. The numerator is normalised to the corresponding quantity for INEL > 0

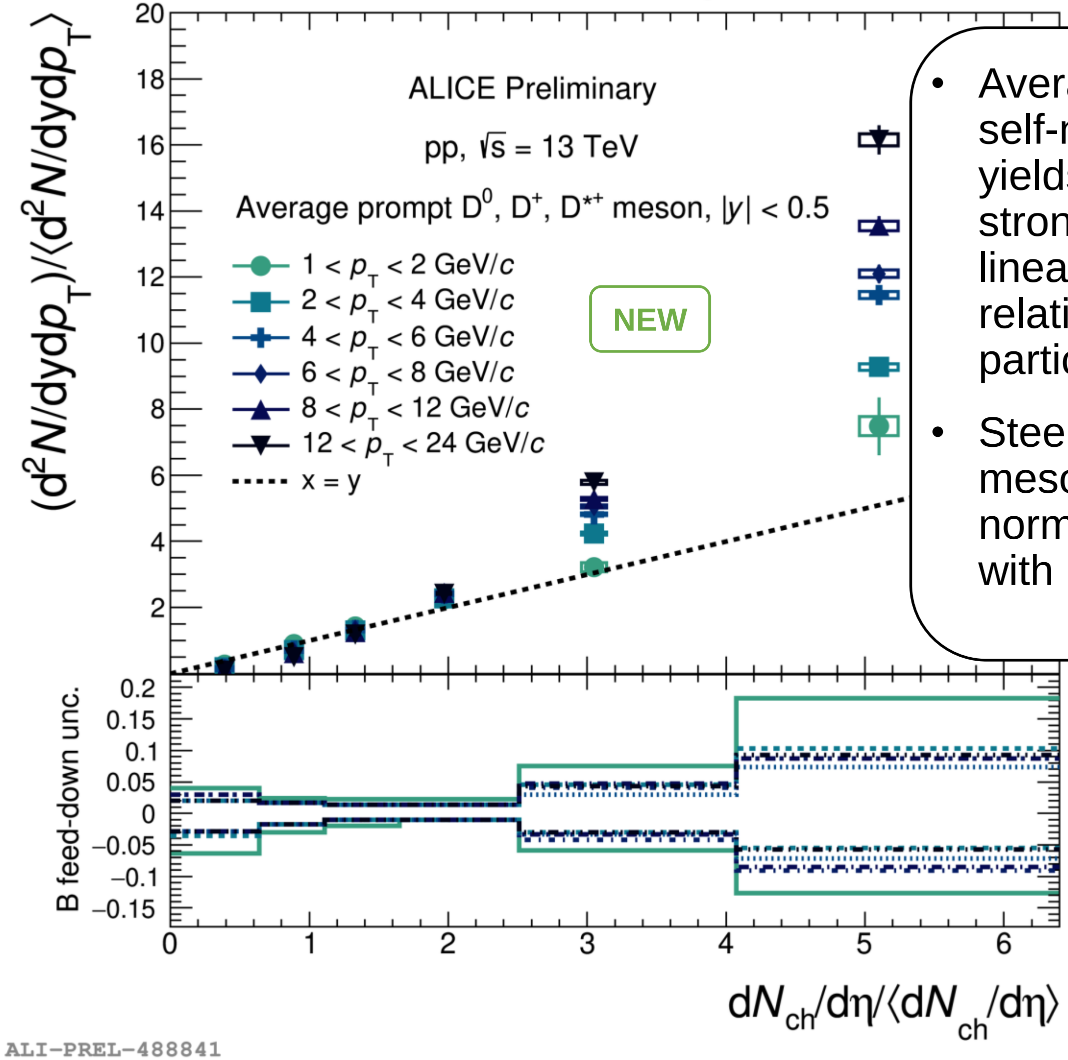
- D-meson and J/Ψ measurements at $\sqrt{s} = 7$ TeV† show a stronger than linear trend.

D-meson production in pp at √s = 13 TeV



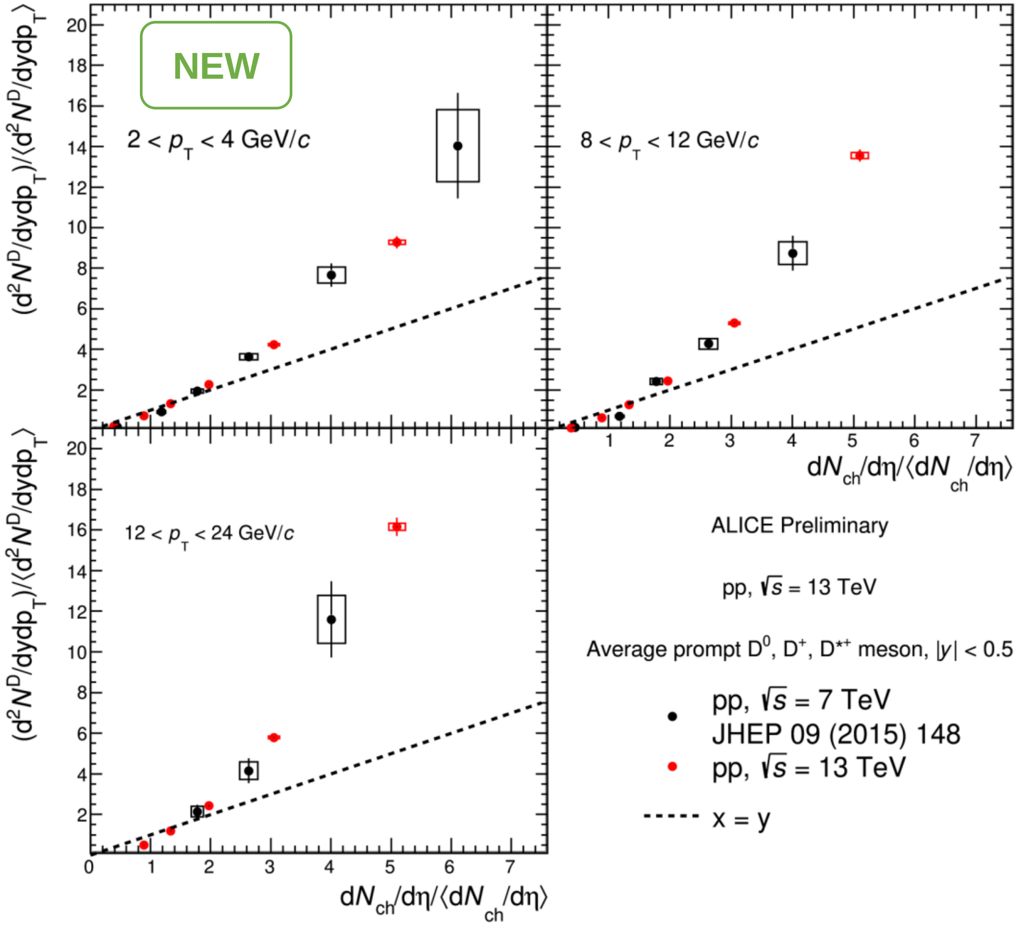


D-meson production in pp at $\sqrt{s}$ = 13 TeV



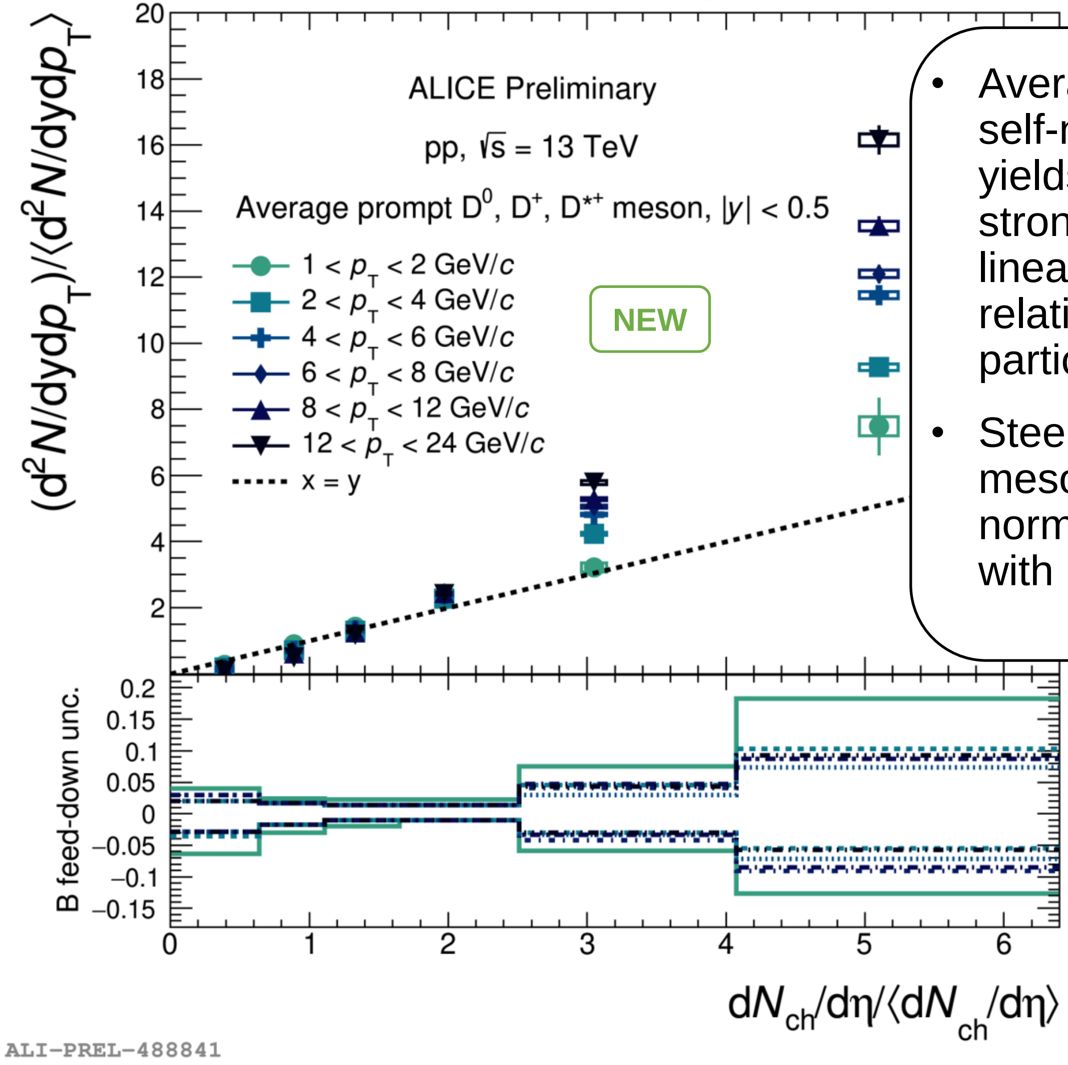
ALI-PREL-488841

- Average D-meson self-normalised yields show stronger than linear increase with relative charged-particle multiplicity
- Steeper rise of D-meson self-normalised yield with increasing p_T



ALI-PREL-488861

D-meson production in pp at $\sqrt{s}$ = 13 TeV



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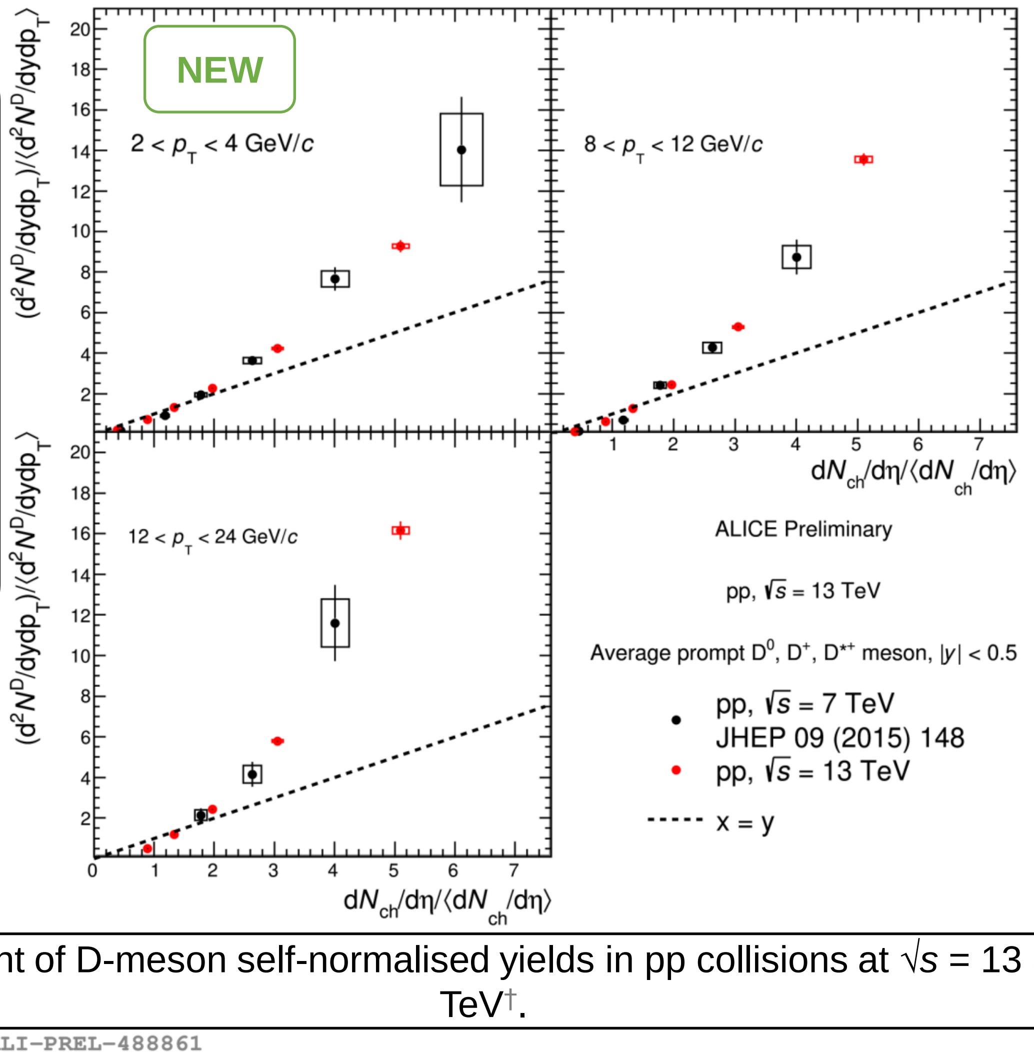


Agreement of D-meson self-normalised yields in pp collisions at $\sqrt{s}$ = 13 and 7 TeV†.

† [JHEP 09 (2015) 148]

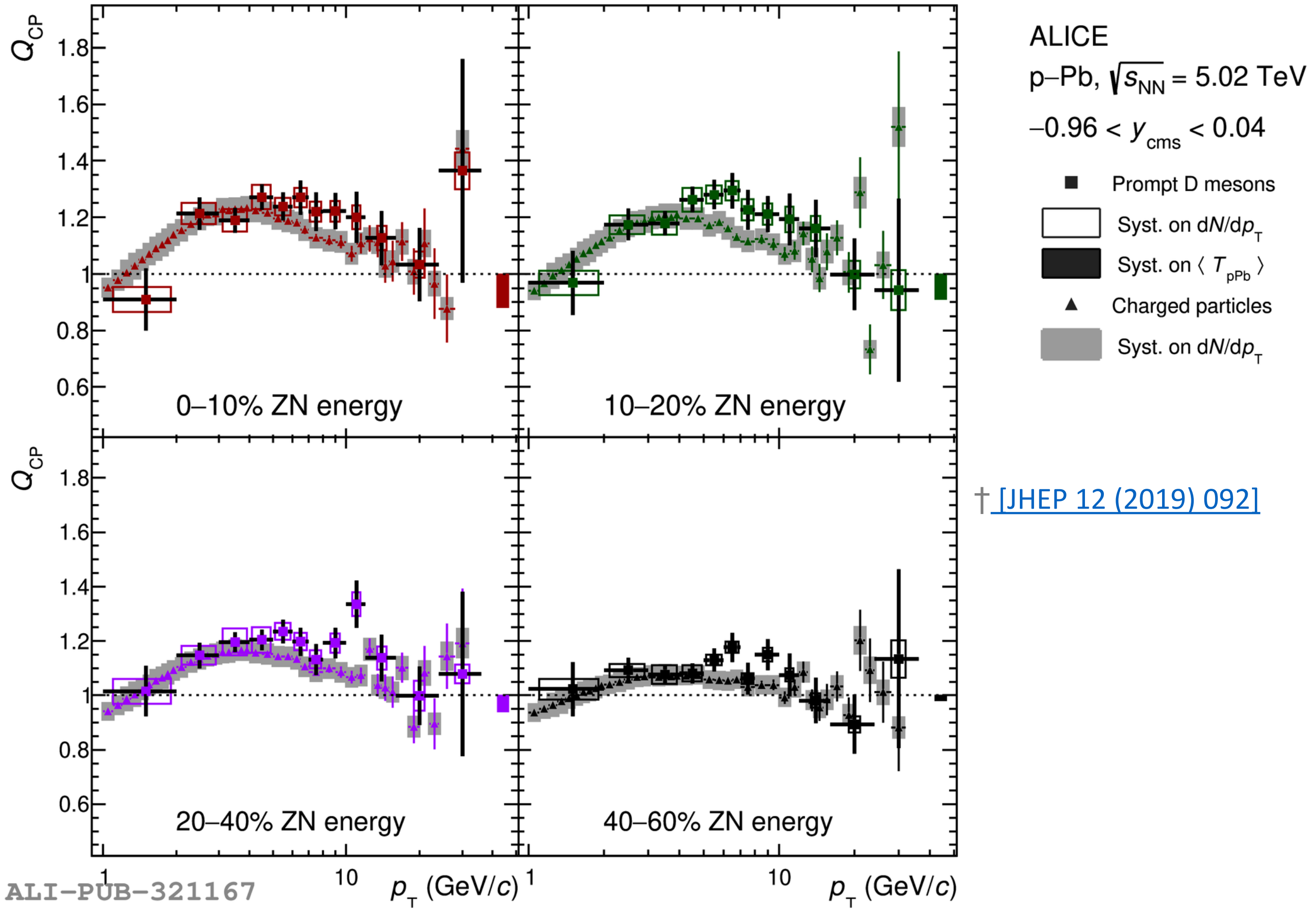
D-meson Q_{cp} in p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

- Q_{CP}† of D-meson yield ratios to the yield measured in the 60-100% centrality class are shown

$$Q_{CP} = \frac{(d^2 N^{prompt\,D}/dp_T dy)^{i}_{p-Pb} / \langle T_{pPb} \rangle_i}{(d^2 N^{prompt\,D}/dp_T dy)^{60-100\%}_{p-Pb} / \langle T_{pPb} \rangle_{60-100\%}},$$

where $\langle T_{pPb} \rangle$ is the nuclear overlap function

- The enhancement of Q_{CP} at intermediate p_T hint of radial flow



† [JHEP 12 (2019) 092]