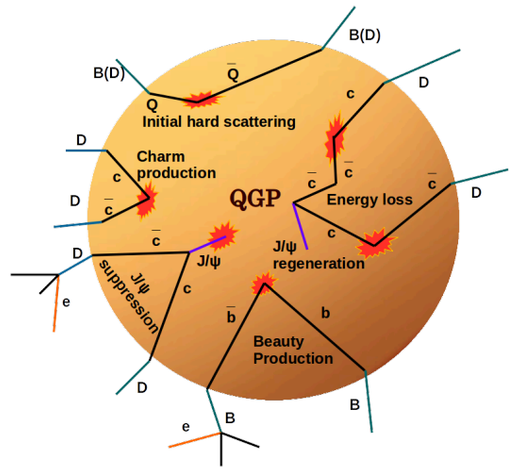
Heavy-Flavour production in small systems

Alessandro Grelli

Utrecht University



Open heavy-flavour production

pp collisions:

- Test pQCD calculations
- Study fragmentation and hadronisation, heavy-flavour jet properties
- Set a reference for p-Pb and Pb-Pb

p-Pb collisions

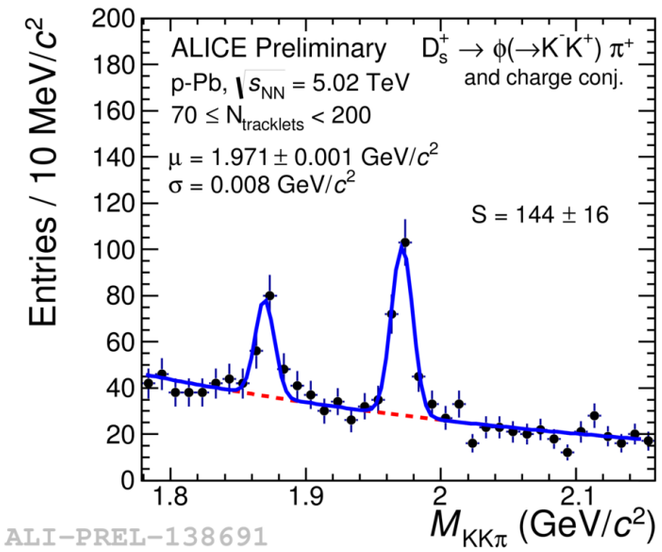
- Study cold nuclear matter (CNM) effects (nPDF, shadowing, gluon saturation, k_T-broadening, energy loss in CNM in the initial and final state)
- Address possible collective effects and effects related to the (possible) formation of a QGP in p-Pb collisions.

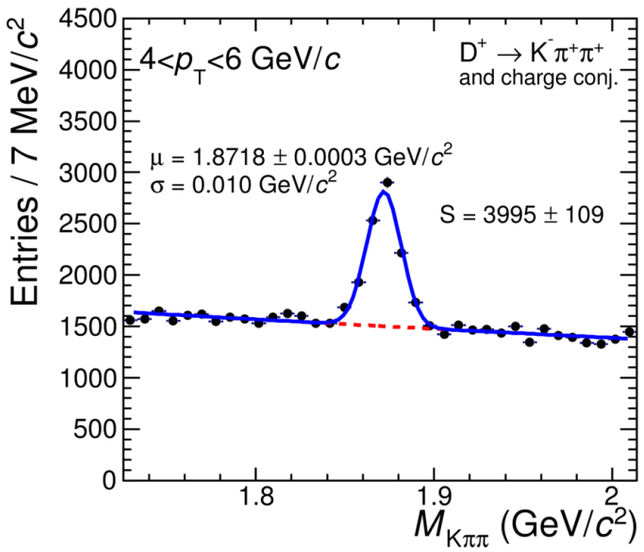
Charm hadronization in vacuum

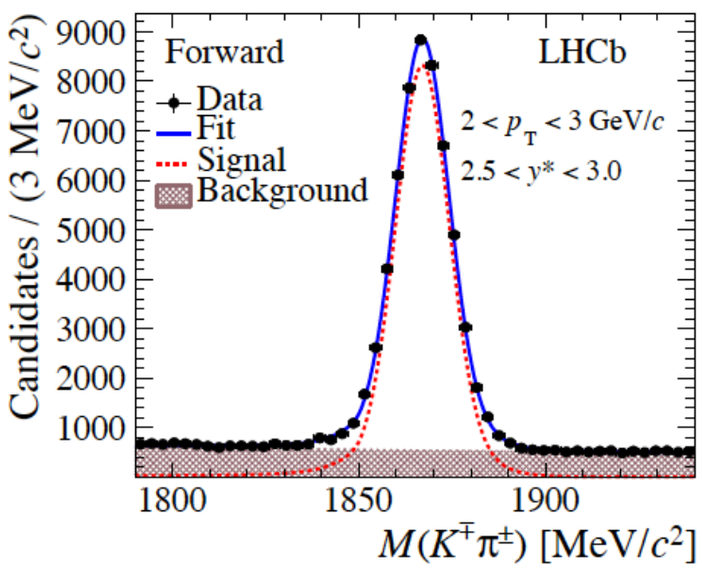
- Do we understand it?
  - Lc[Xic]/D0 ratio in pp and p-Pb: ALICE vs LHCb
  - Possible implications of the experimental result

Heavy-Flavours at LHC

- ☑ D mesons in hadronic decay channels (D^0, D^{*+}, D^+, D_s)

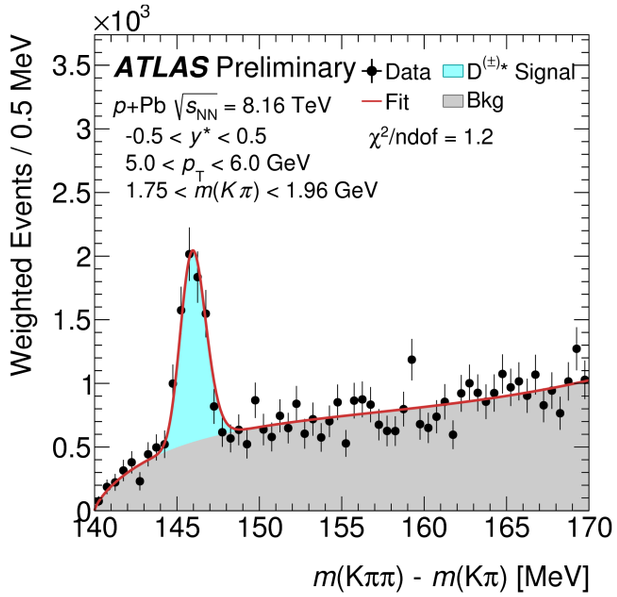






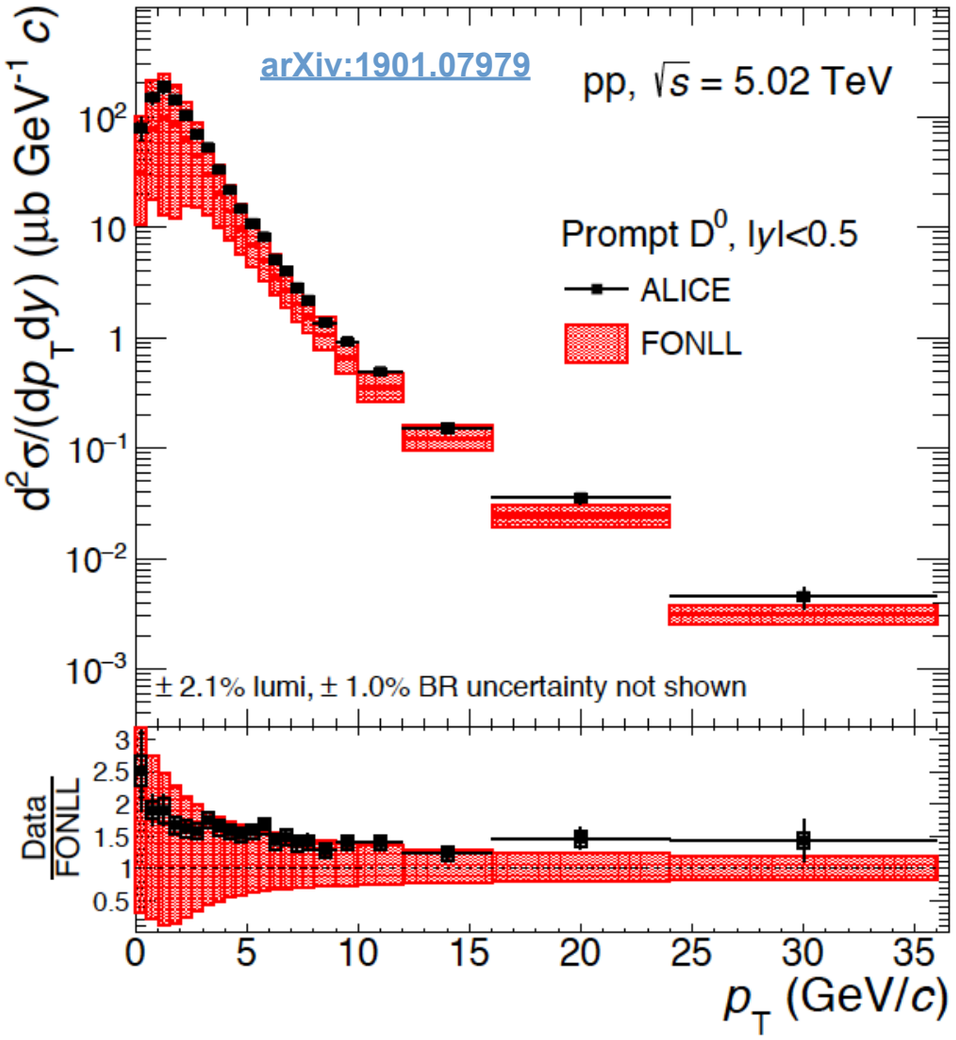
.. fairly similar reconstruction strategy among different experiments:
Invariant mass analysis after topological and PID cuts

- ☑ Charmed baryons in hadronic and semileptonic channels
- ☑ B mesons in hadronic decay channels
- ☑ Heavy-flavour decay leptons
- ☑ Heavy flavour jets

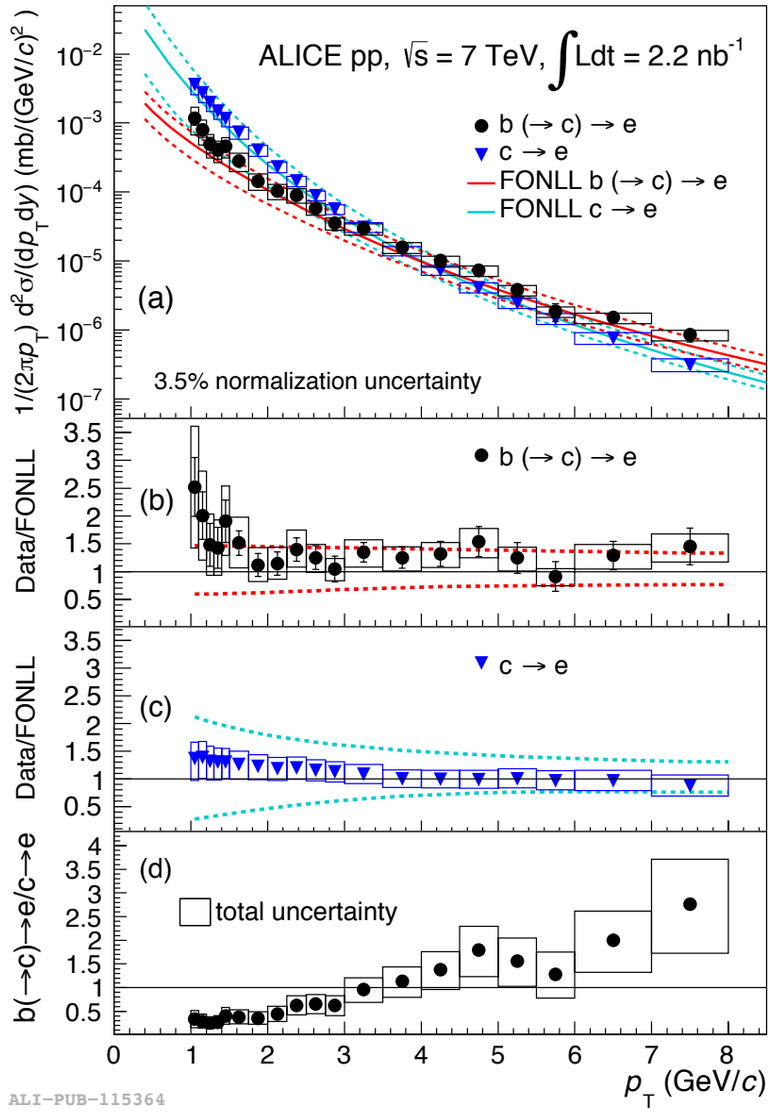


HF production cross-sections

ALICE: D^0 at 5 TeV



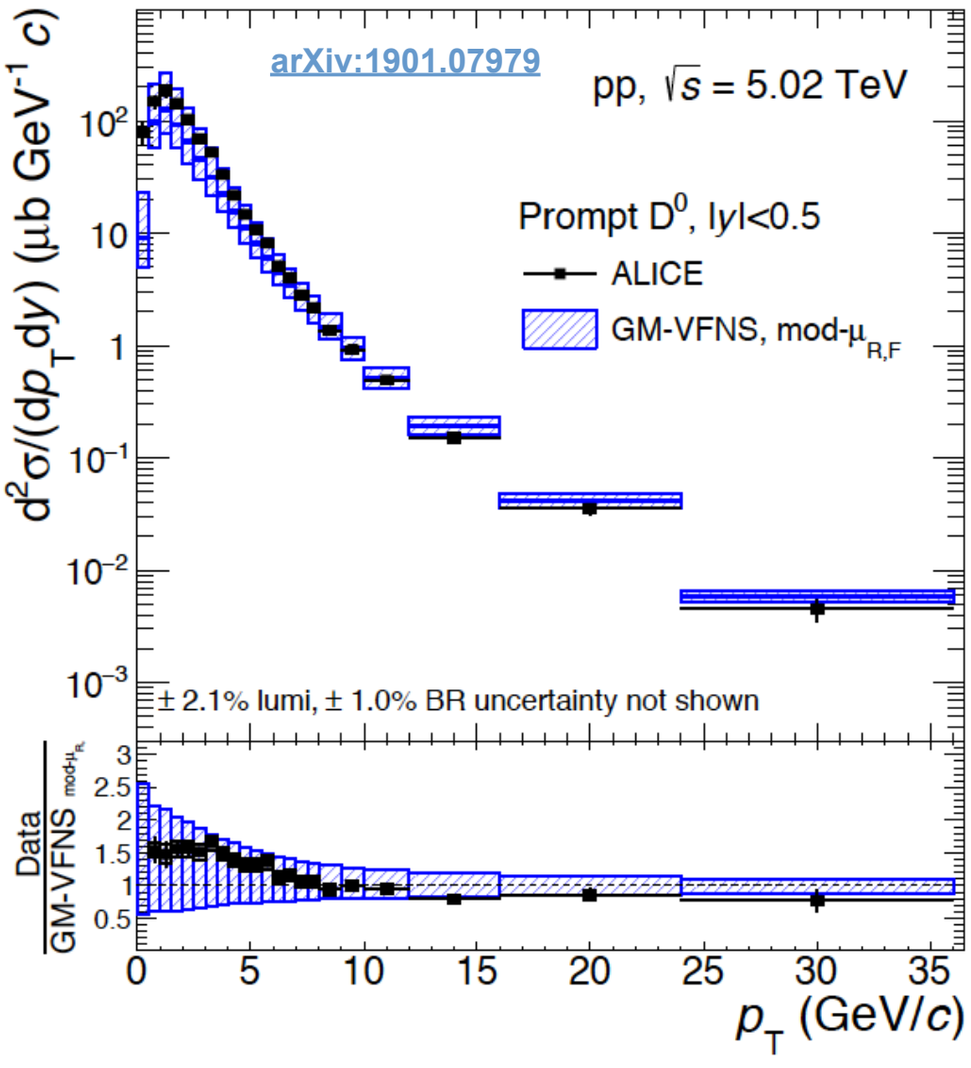
ALICE: HFE at 7 TeV



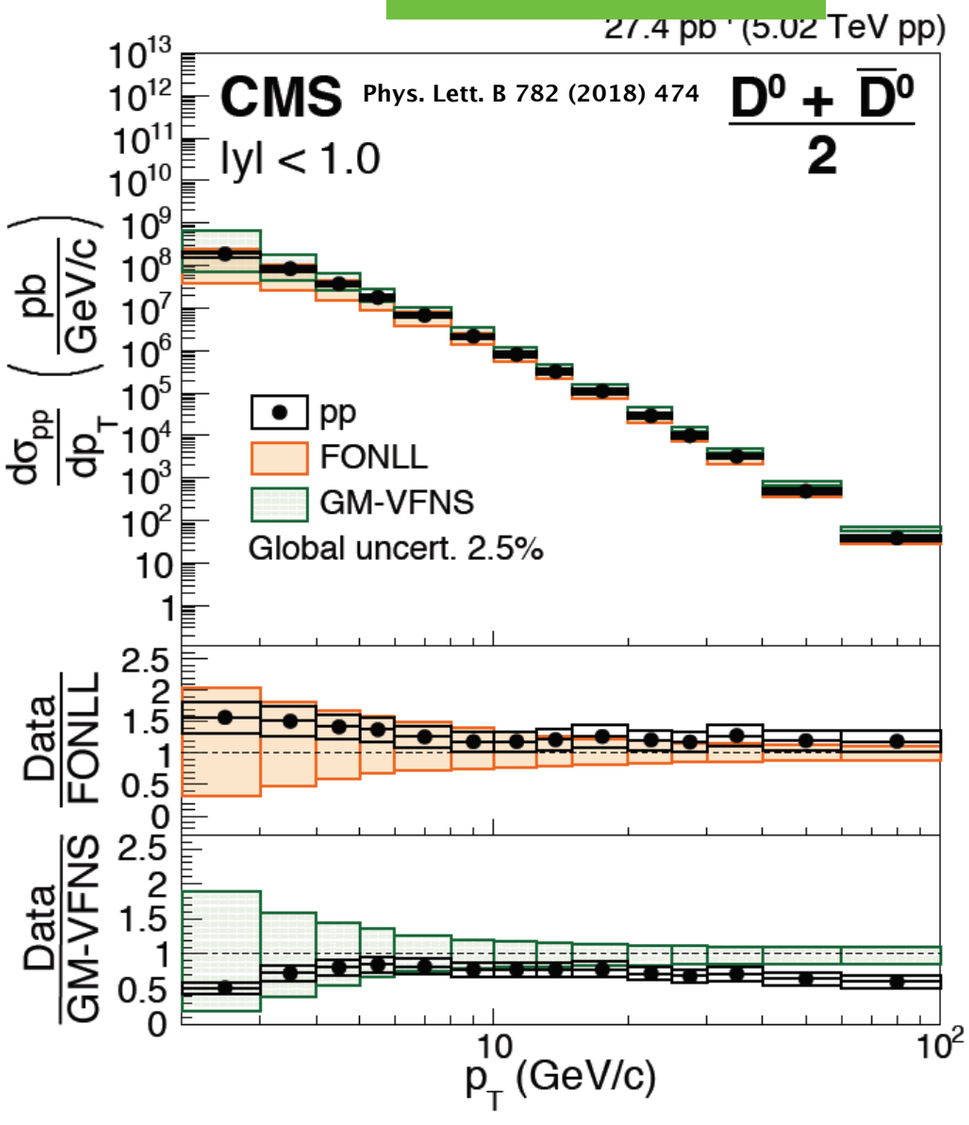
- ☑ We are entering a precison hera for the charm measurements in pp collisions.
- ☑ Data points, at few % level precision, start to pose strong constraints for pQCD based models

HF production cross-sections

ALICE: D⁰ at 5 TeV



CMS: D⁰ at 5 TeV



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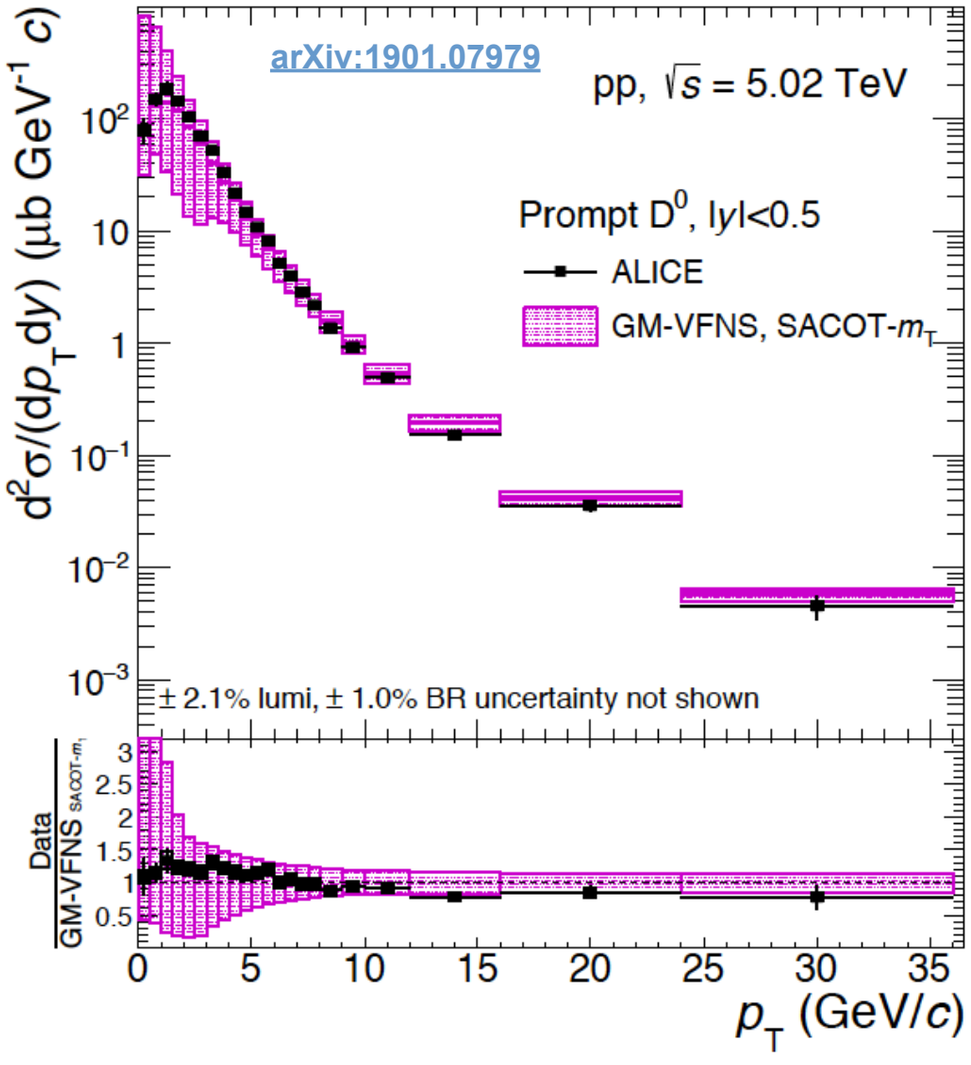
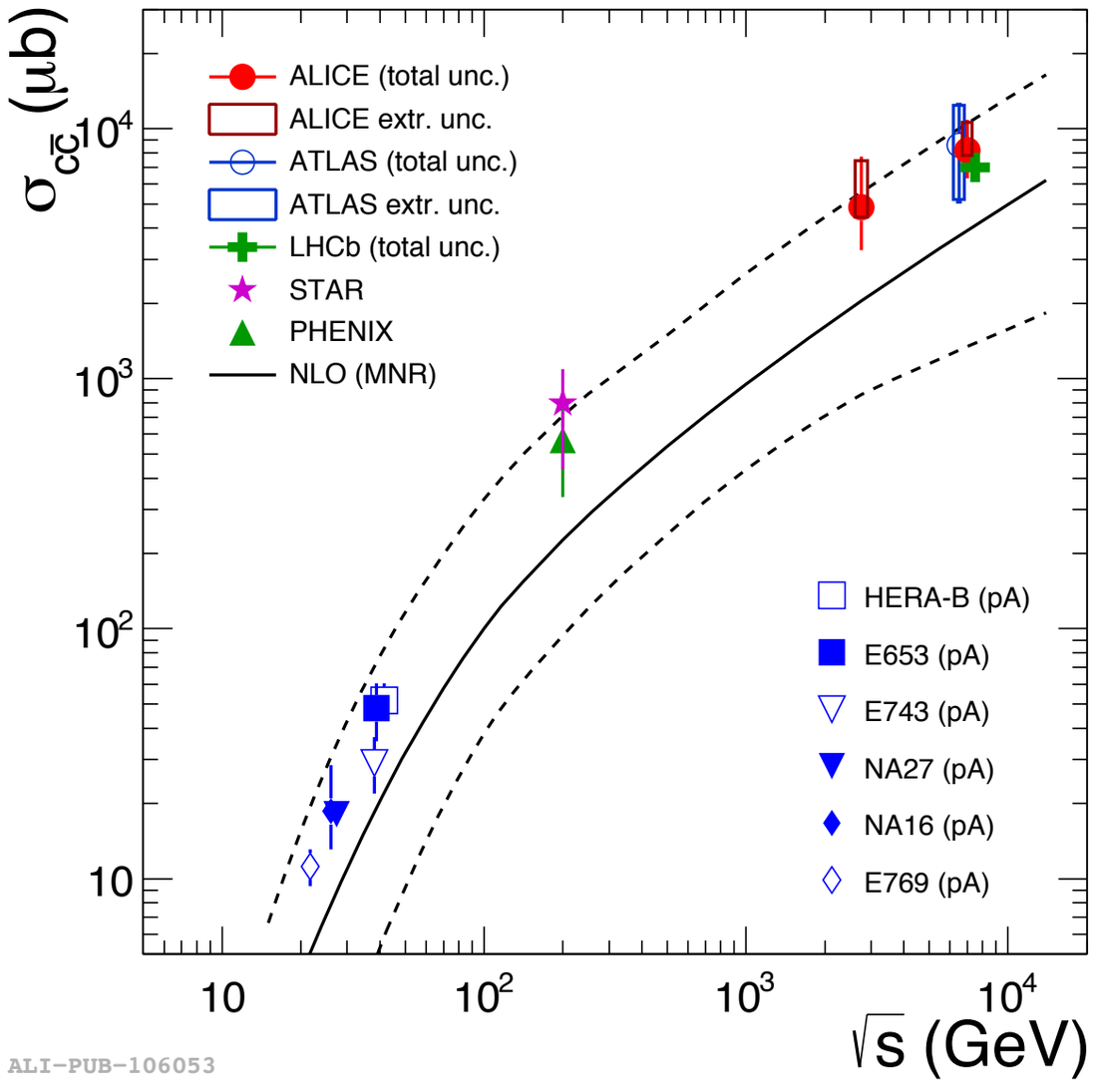


total charm cross-section



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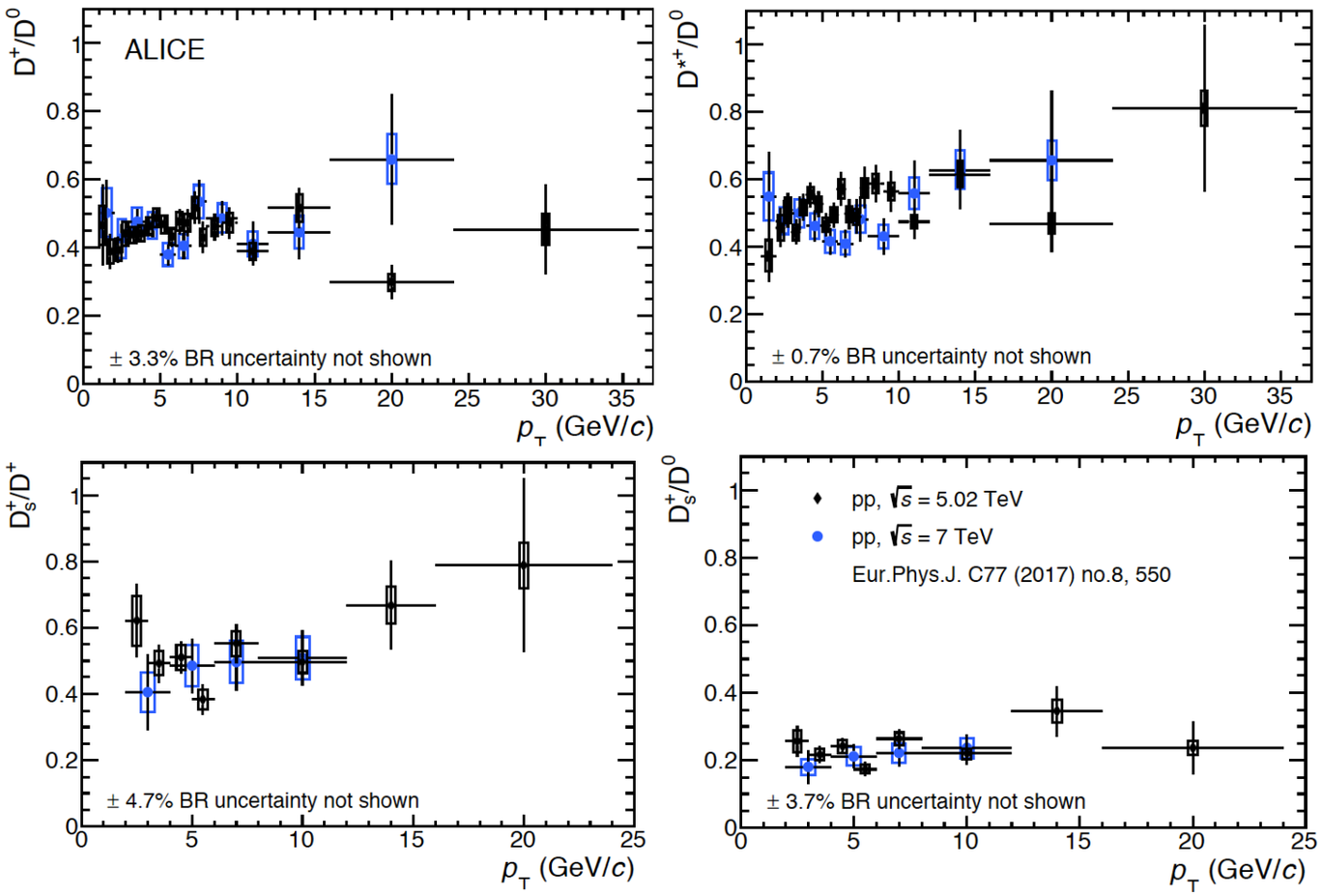
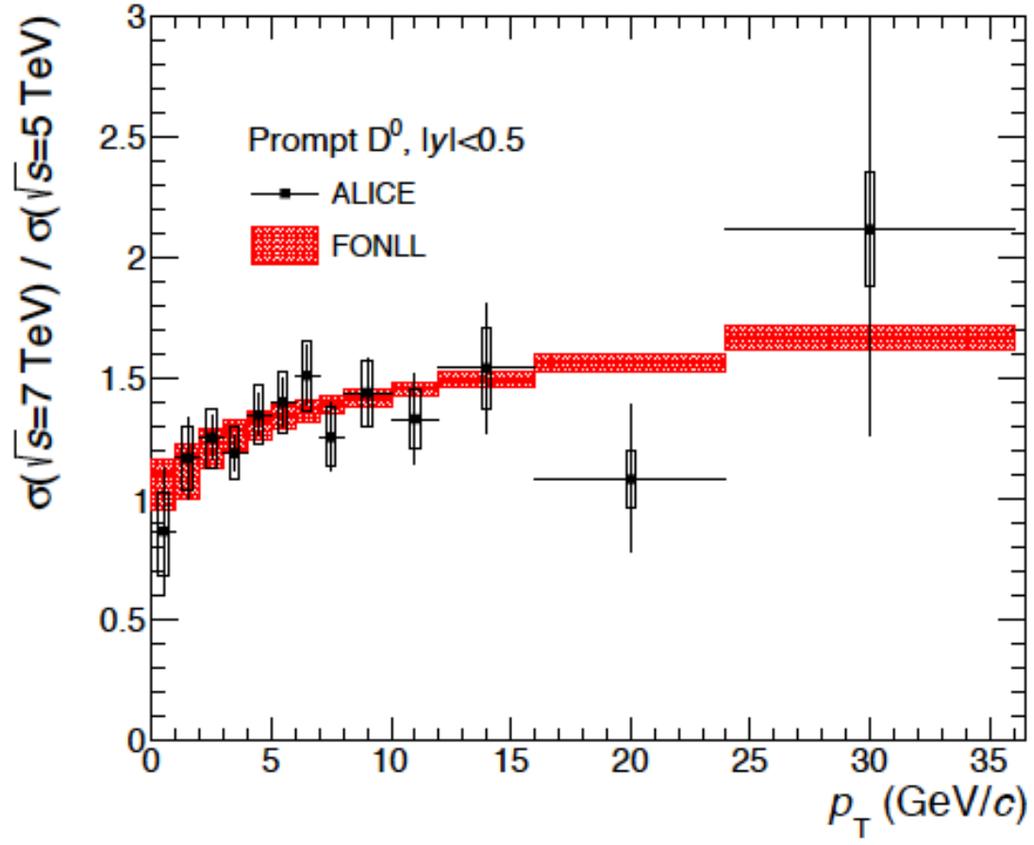
D meson ratios

Cross-section ratios

arXiv:1901.07979



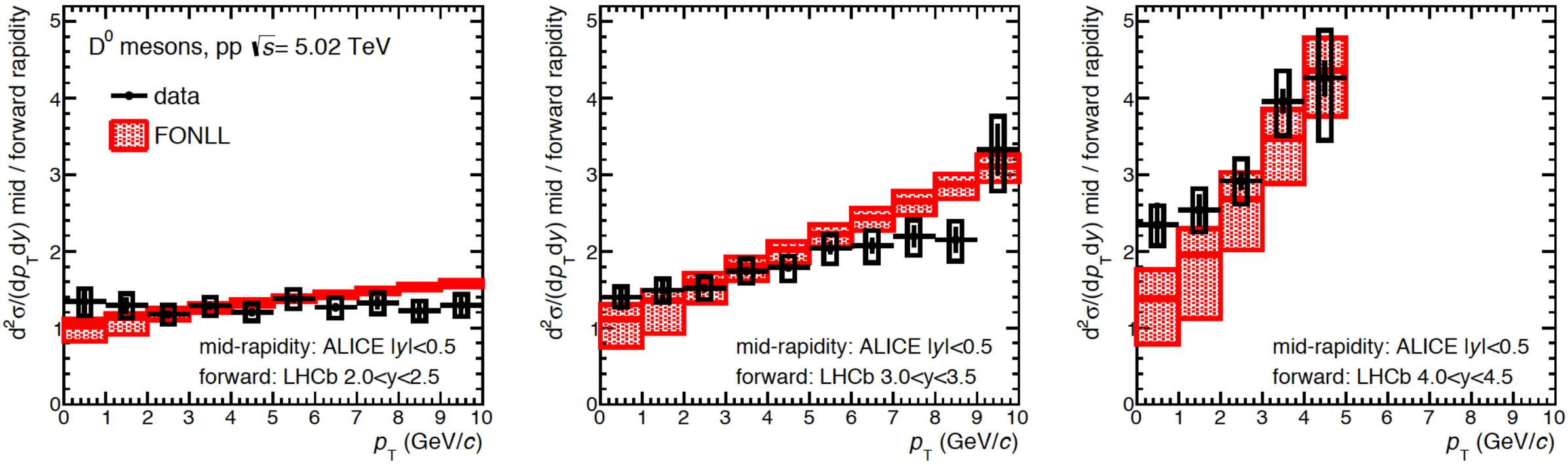
Energy ratios



- D mesons are studied at LHC at different collision energies (2.76, 5.02, 7, 8 and 13 TeV)
- Cross-section ratios do not show significant p_T dependence → not large difference between fragmentation to pseudoscalar (D^0, D^+ and D_s) and vector (D^{*+}) mesons and to strange non-strange mesons

ALICE vs LHCb: mid- forward ratio

arXiv:1901.07979

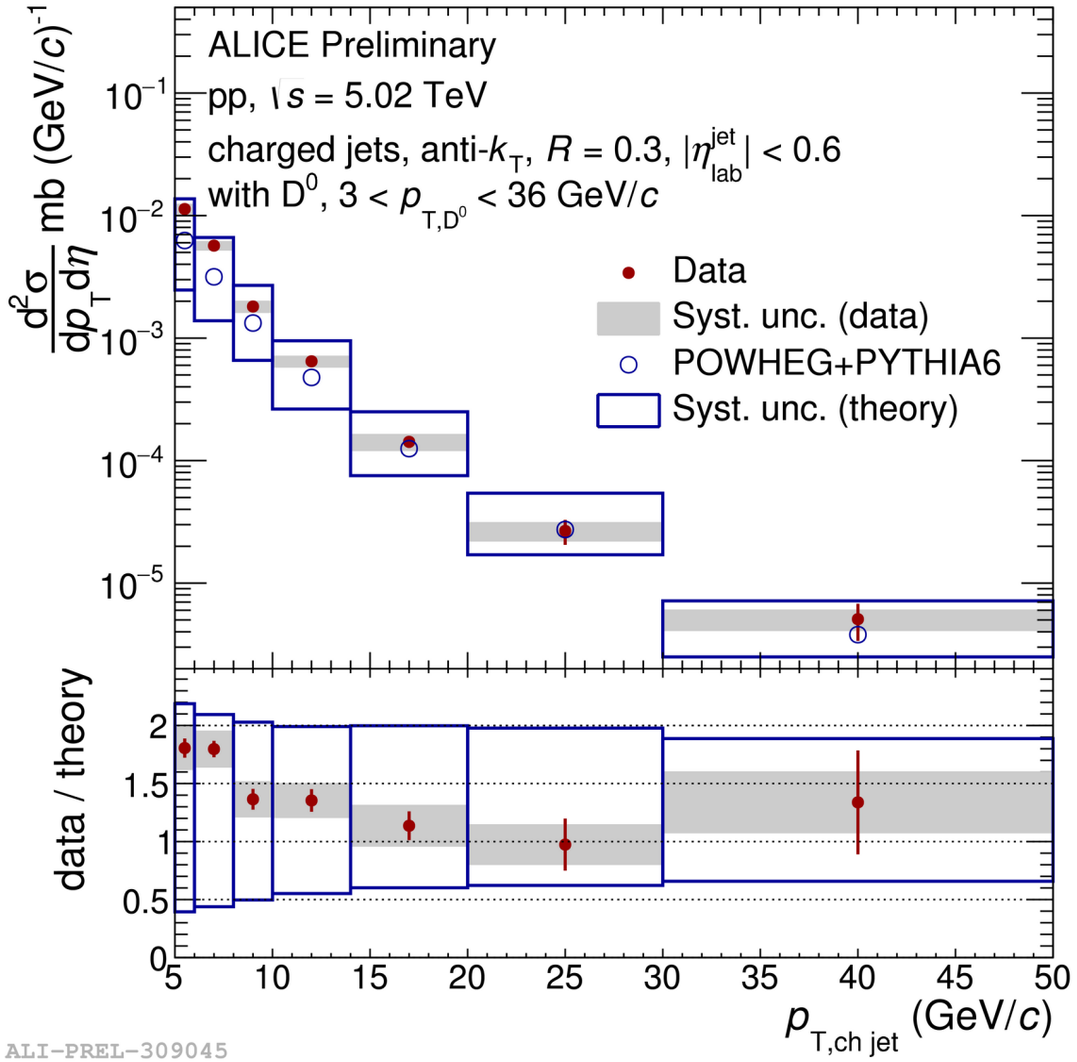


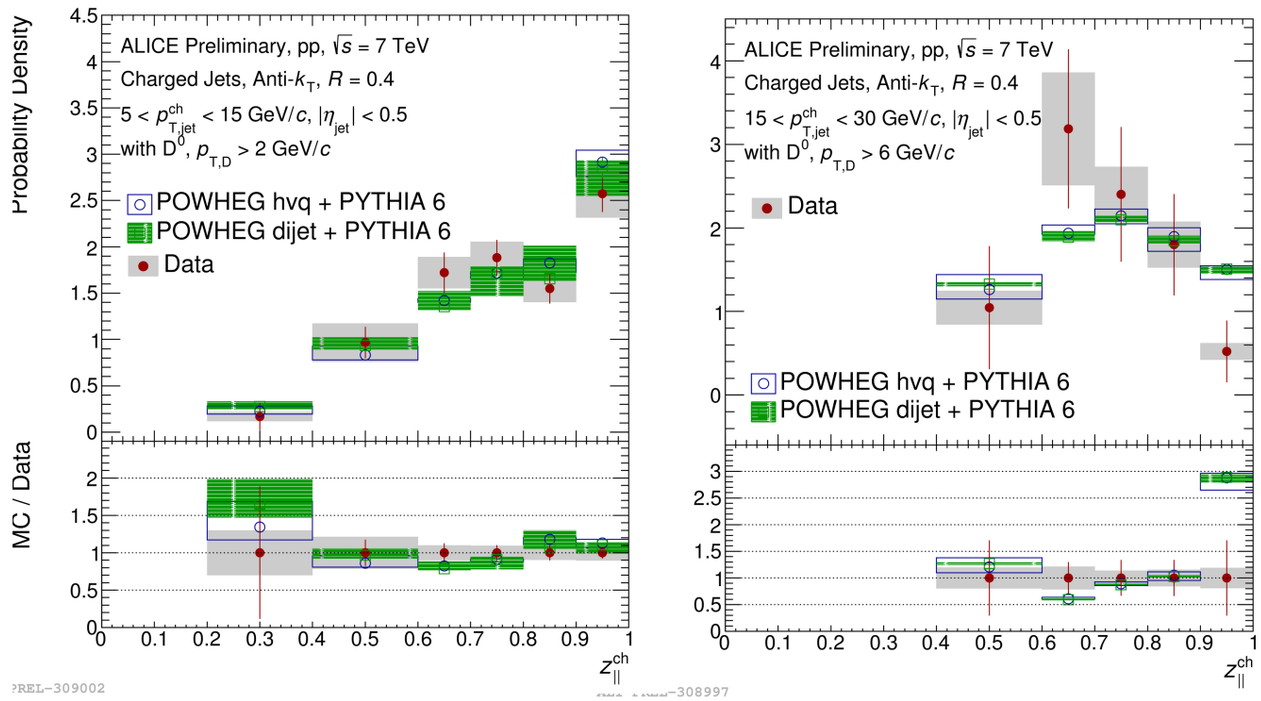
- Precise measurement down to ~0 p_T
- Mid- forward ratio can provide sensitivity to gluon PDF at small Bjorken-x (10^{-4}-10^{-5})
- Comparison with FONLL show compatibility but tend to hint a different slope

D tagged jets

- Charged jets containing a D meson as one of the constituents

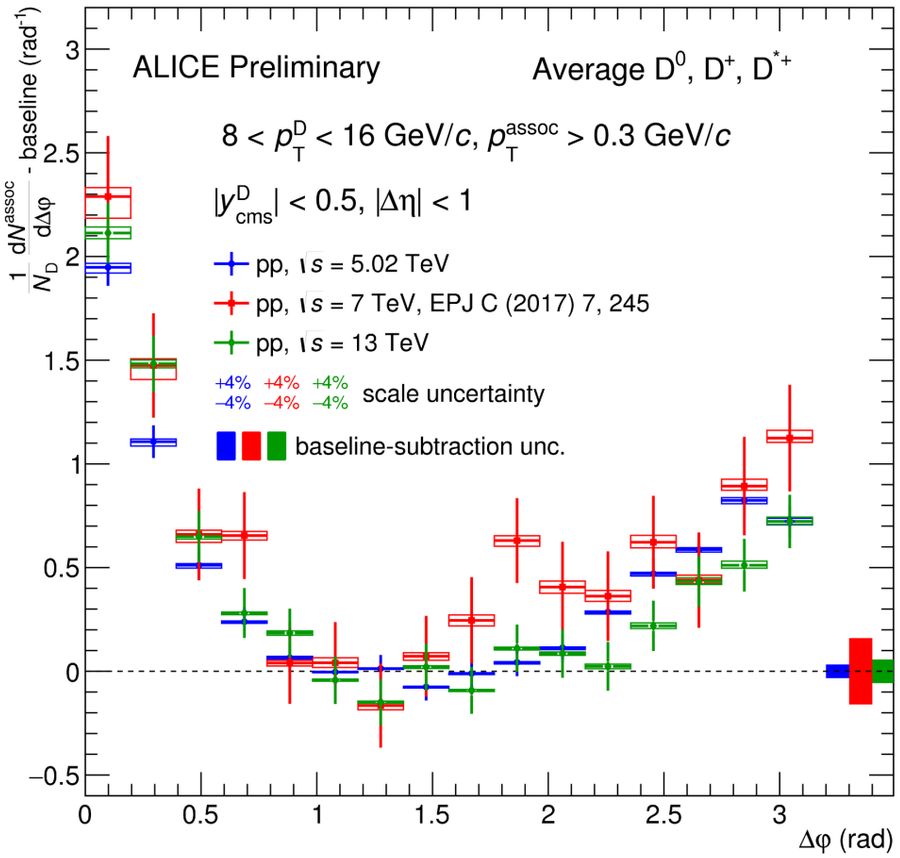
$$z_{||} = \frac{\vec{p}_{\mathrm{ch\,jet}} \cdot \vec{p}_{\mathrm{D}}}{\vec{p}_{\mathrm{ch\,jet}} \cdot \vec{p}_{\mathrm{ch\,jet}}}$$





- Cross-sections: Agreement with NLO pQCD POWHEG + PYTHIA6 predictions in both systems
  - ☑ D^{*+}-tagged jet result in p-Pb .. see backup
- Momentum fractions: Agreement with NLO pQCD POWHEG + PYTHIA6 predictions
  - ☑ Kinematics reach and precision can be extended with pp at 5.02 and 13 TeV

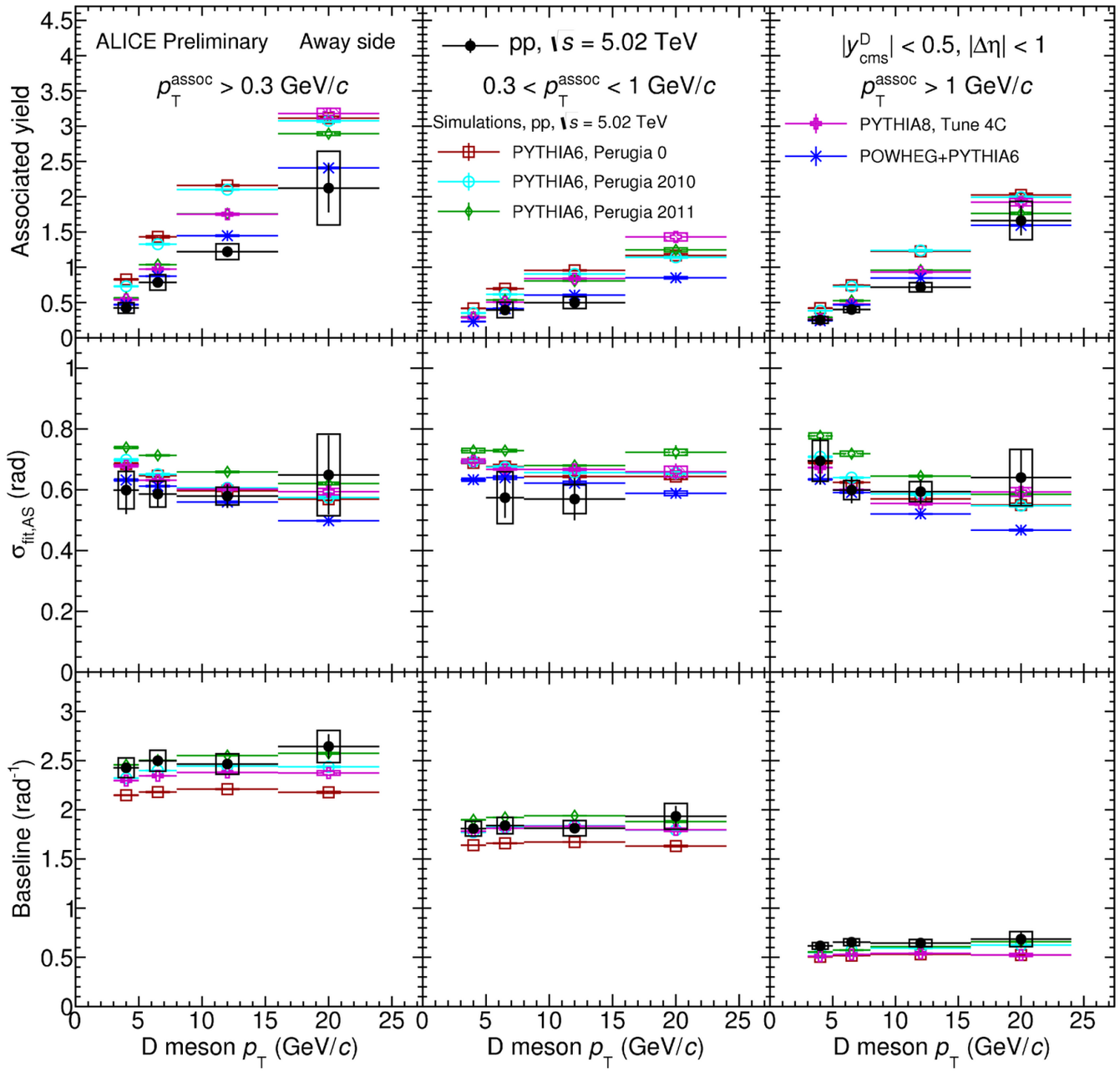
D-h correlations



ALI-PREL-307319

- Yields at high D p_T: tension with PYTHIA 6,8, while POWHEG closer to data
- Width: hint of smaller width than POWHEG+PYTHIA expectations at low assoc. p_T
- Yields: lower POWHEG predictions w.r.t. PYTHIA 6,8; closer to data

D meson: “trigger” particle, correlated with charged tracks: associated particles



ALI-PREL-307380

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Why to study pA: Canonical picture

QCD vacuum

p-p

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- coherent/collective interactions of nuclear fragments, and QGP formation
- final-state interactions with QGP

A-A

QCD medium

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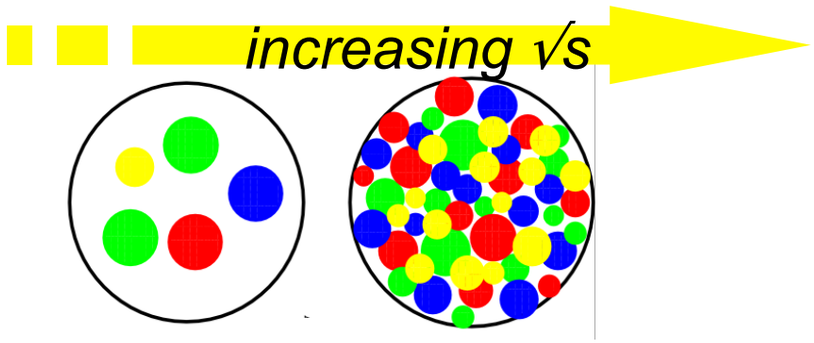

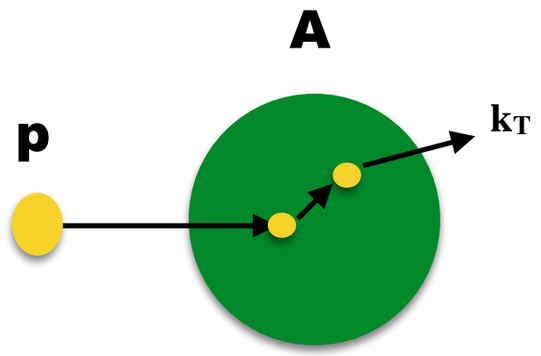

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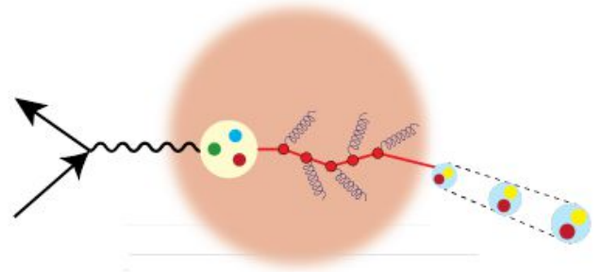
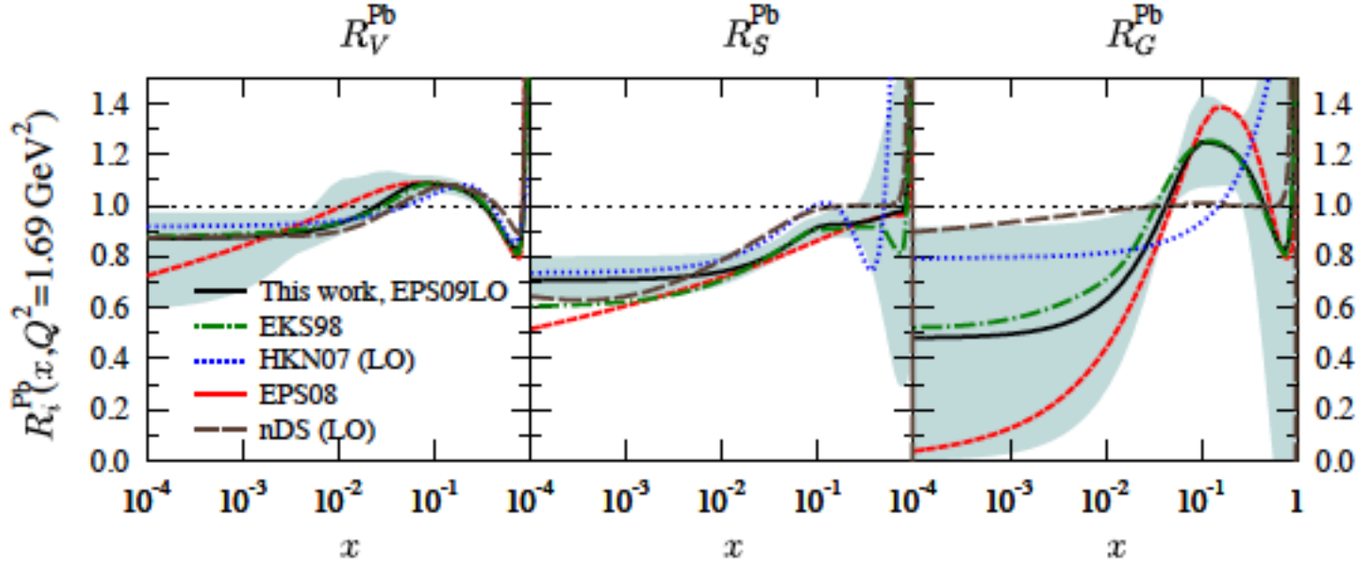


A-A

QCD medium



K.J. Eskola, H. Paukkunen, C. A. Salgado, JHEP 0904, 65 (2009)

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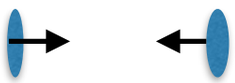
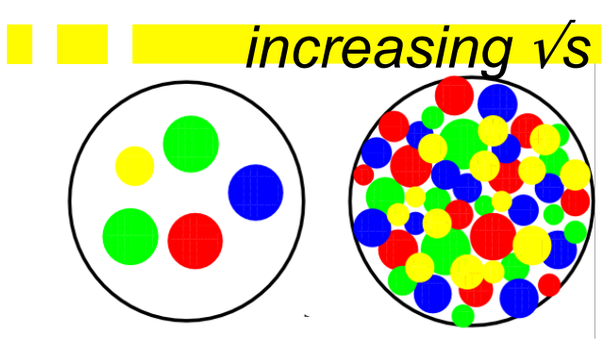
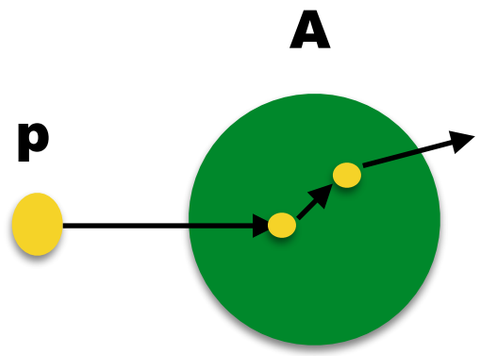


p-p





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  shadowing, gluon
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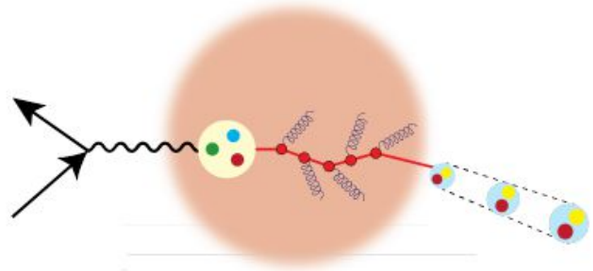

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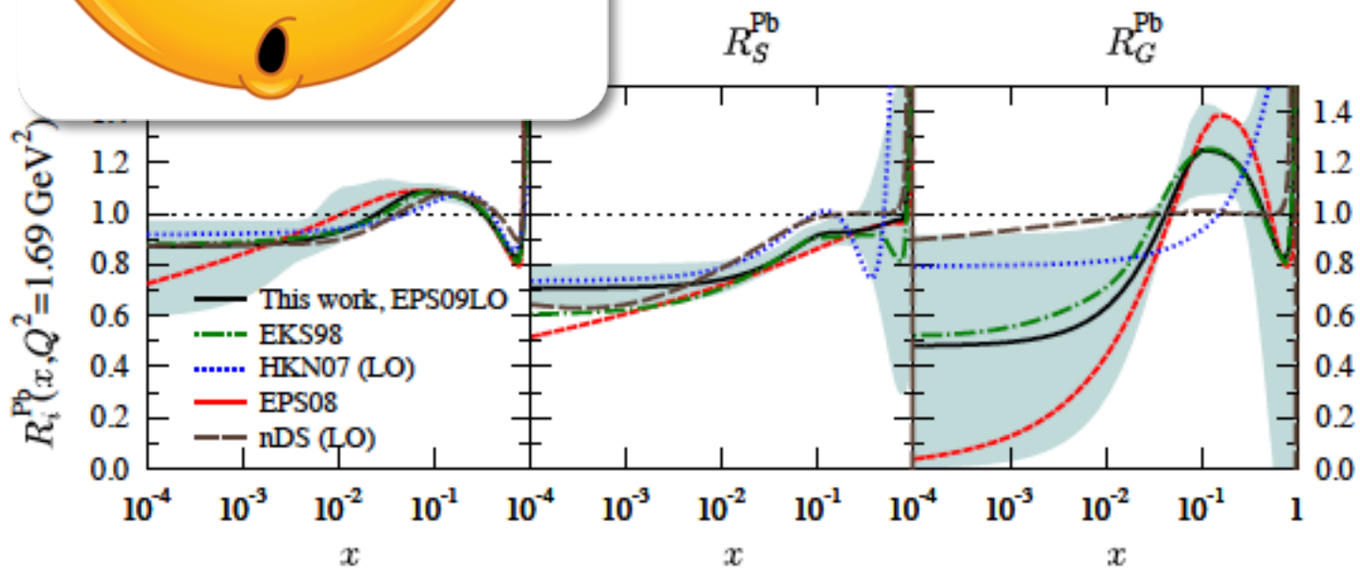

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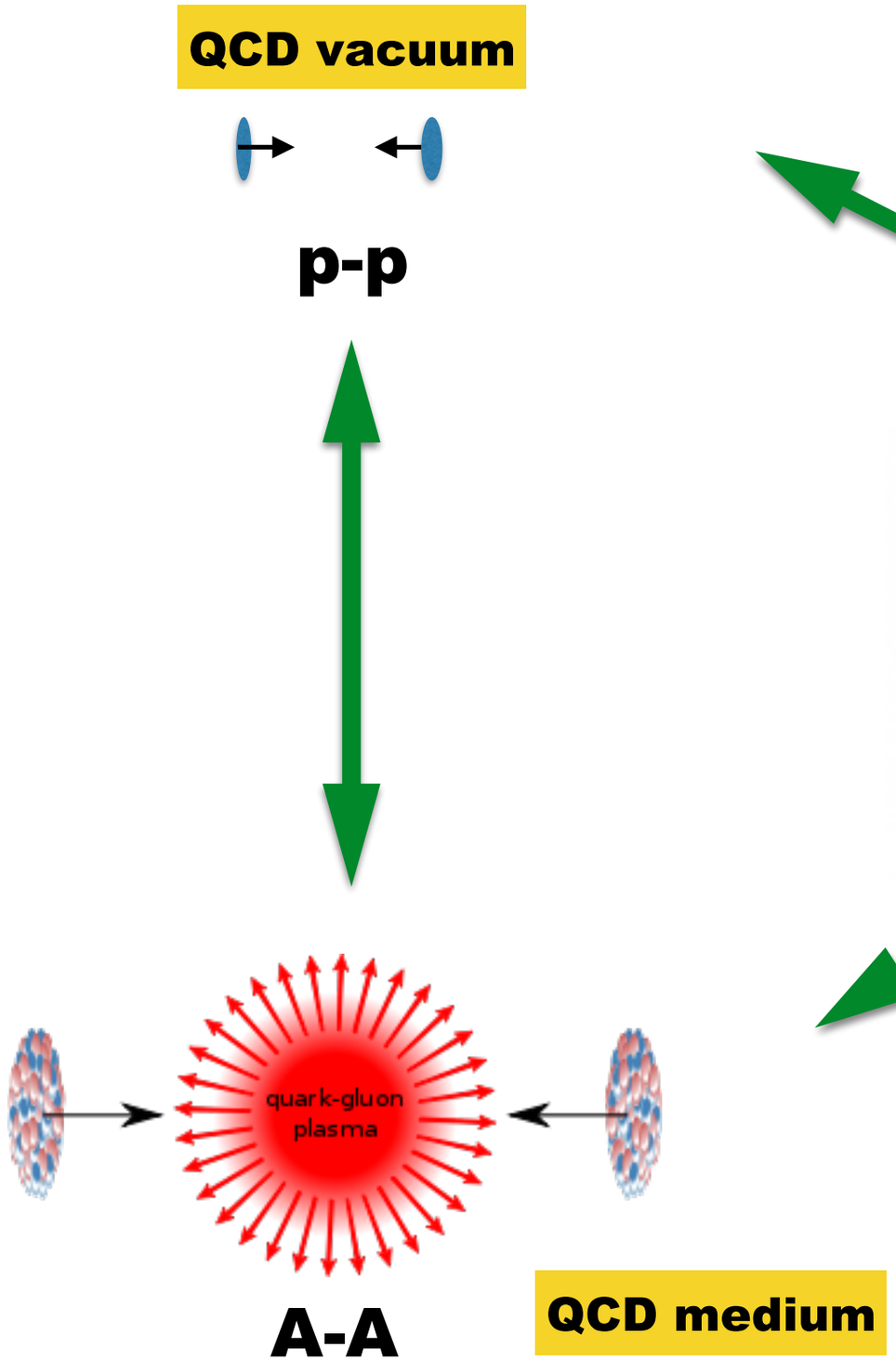

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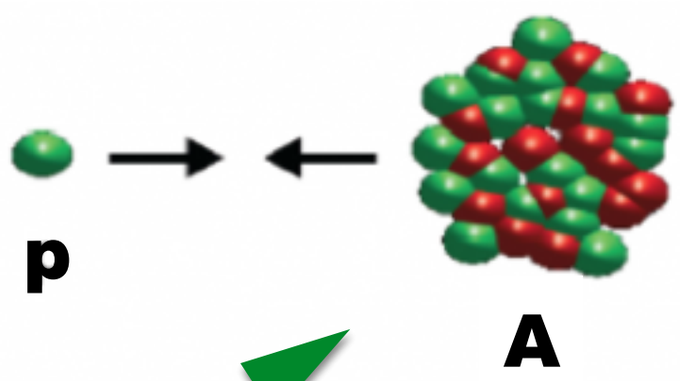
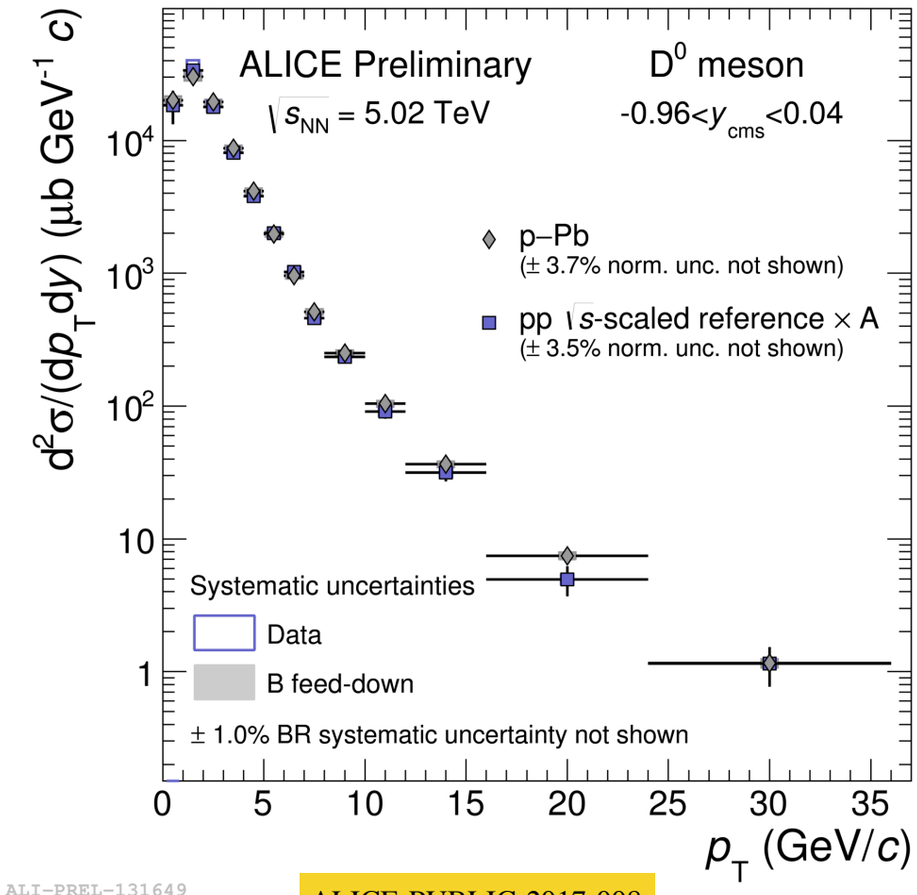


- Use what we learned in pp vs pA to ascribe differences pp(pA)-vs-AA to formation (and properties) of **Quark Gluon Plasma**

Phys. Rev. Lett. 118 (2017) 072001

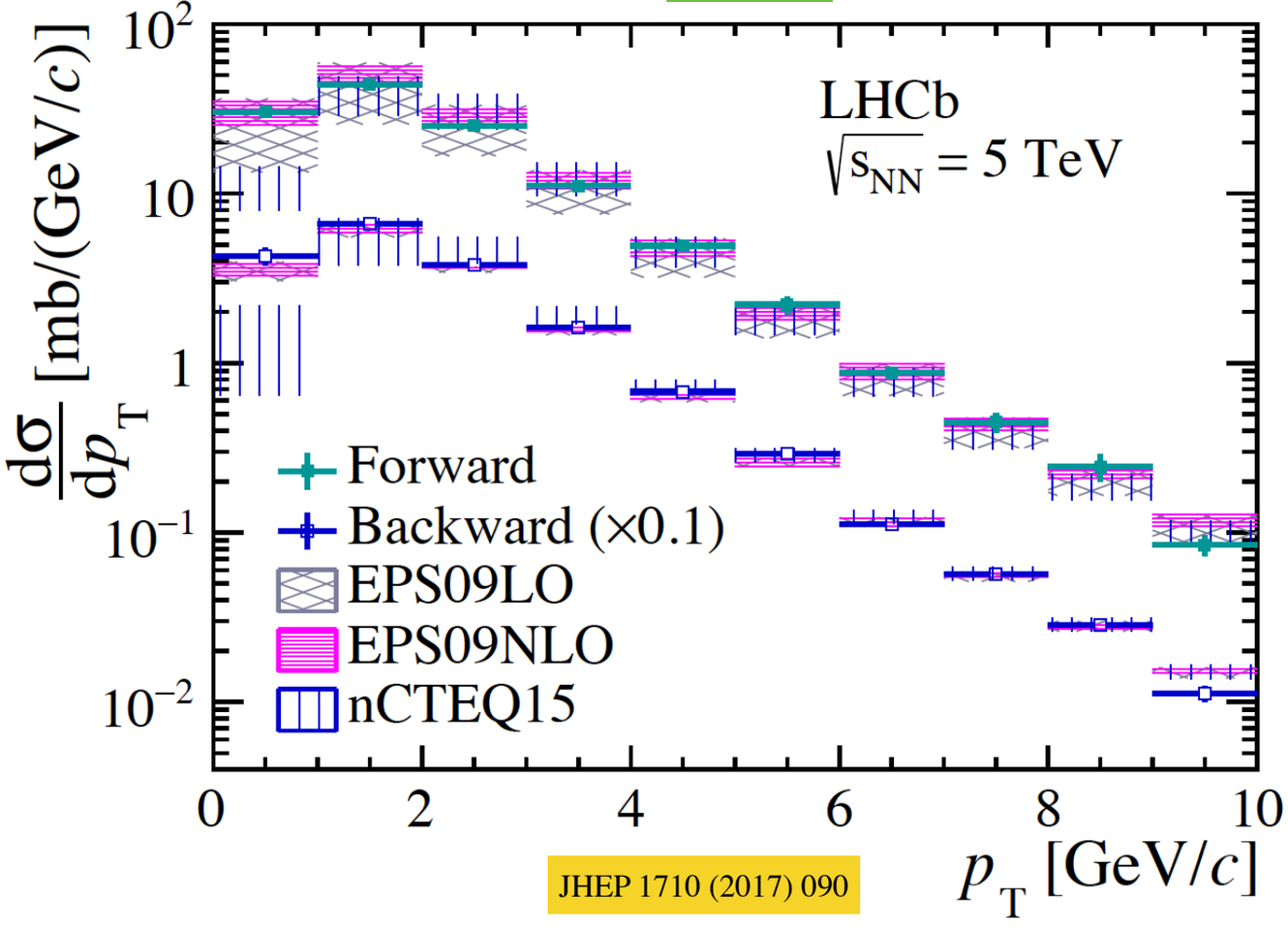
D-meson production: p-Pb @ 5.02 TeV

ALICE



ALICE-PUBLIC-2017-008

LHCb

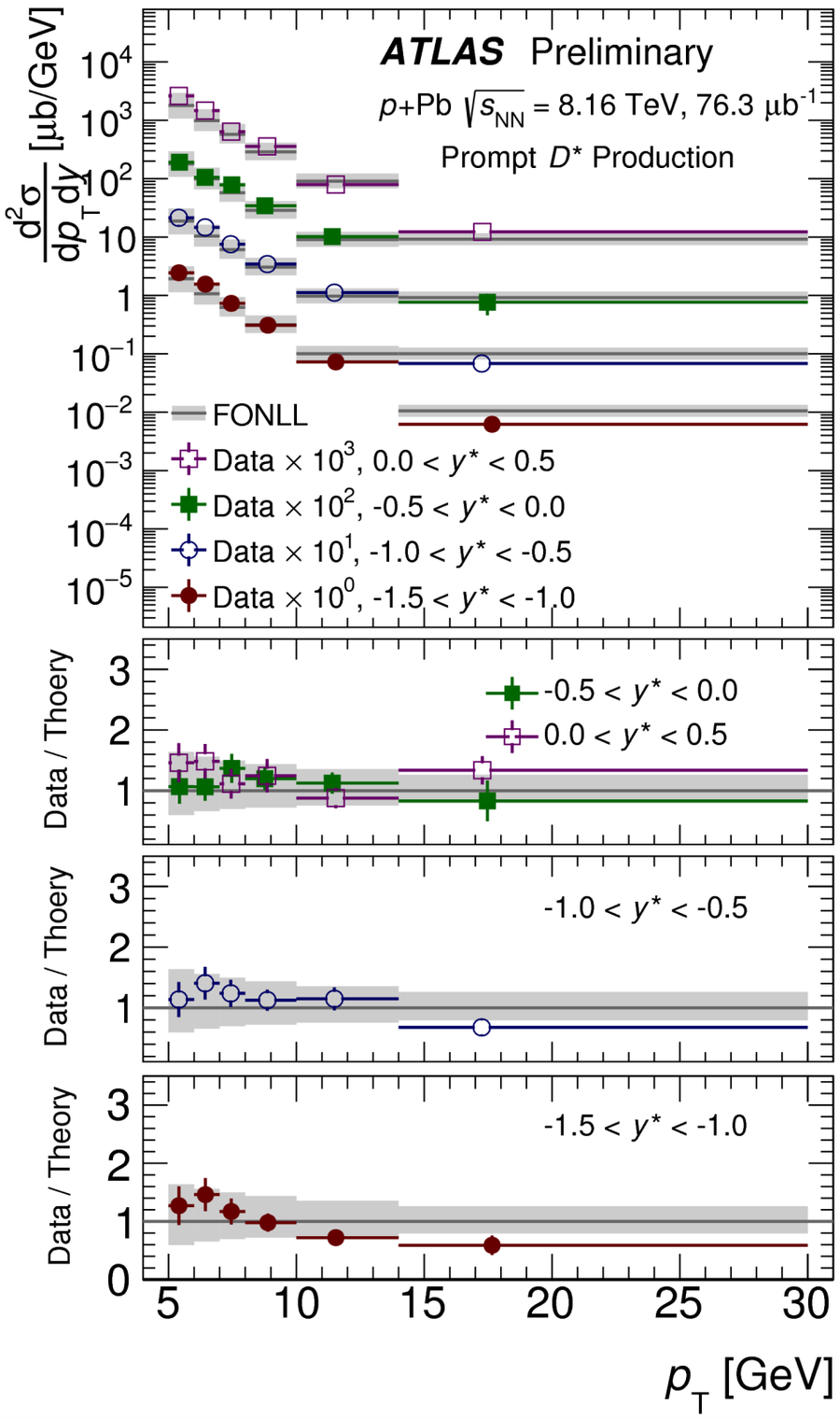


JHEP 1710 (2017) 090

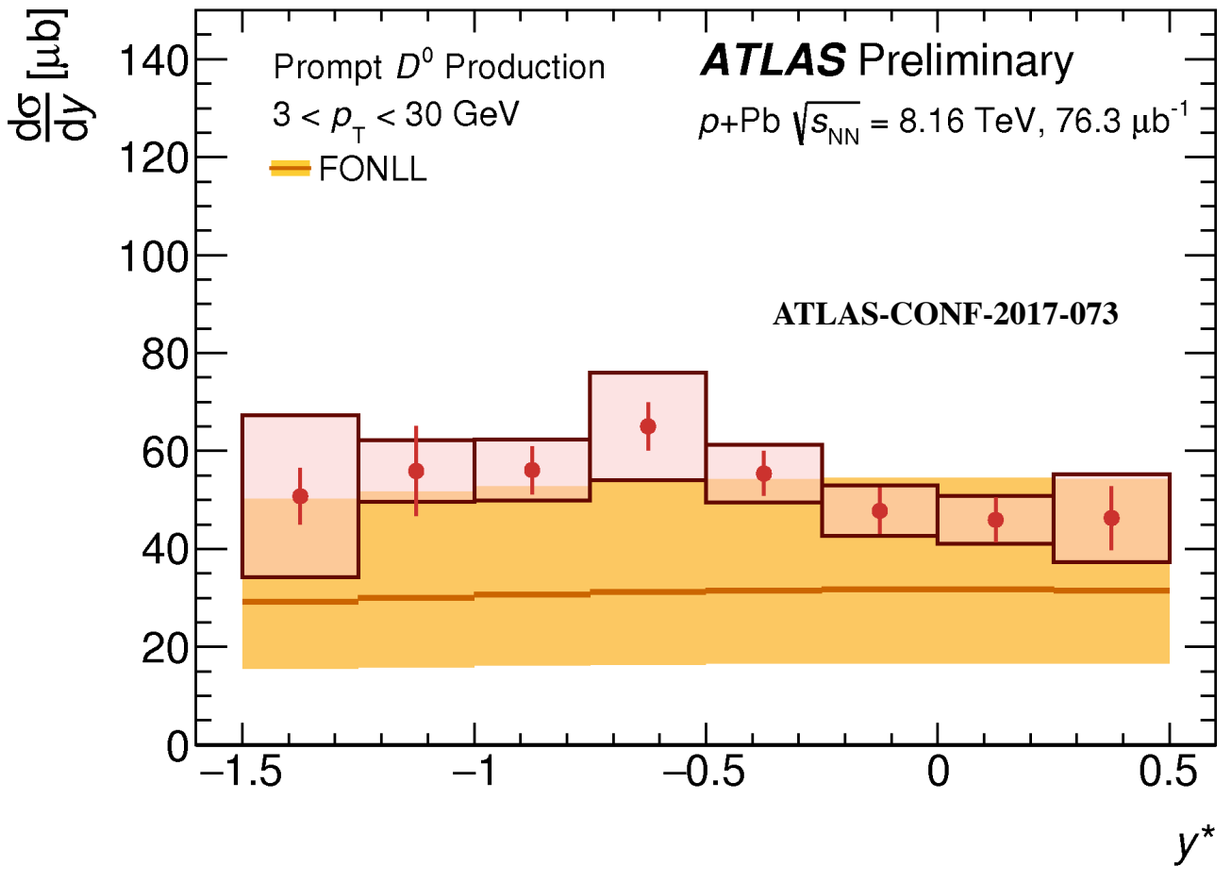
- ☑ Production cross-sections measured in a large rapidity interval and down to ~0 p_T
- ☑ ALICE results from LHC run II, LHCb from LHC run I (large improvement in statistic expected with run II data sample)
- ☑ General agreement with nPDF calculations

D-meson production: p-Pb @ 8.16 TeV

ATLAS-CONF-2017-073



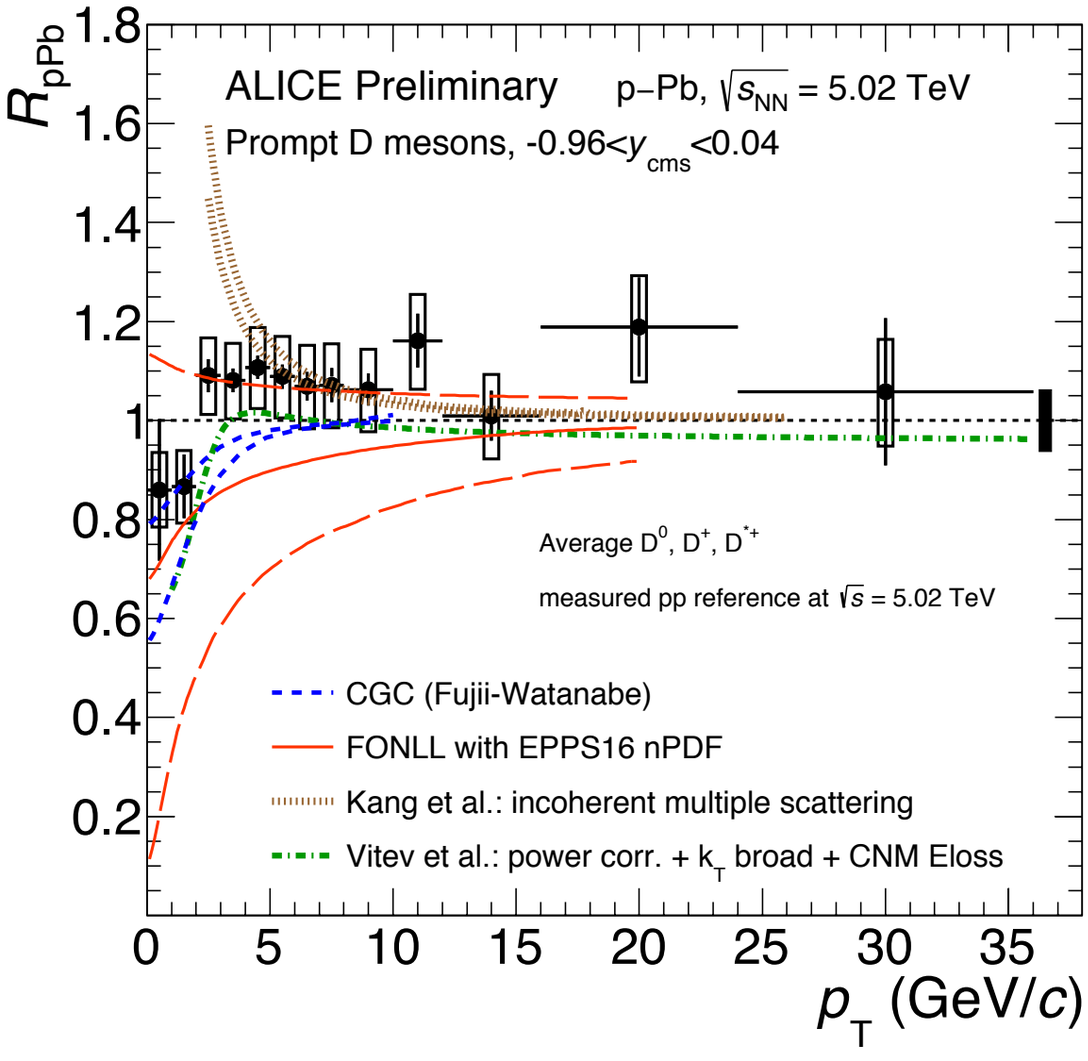
ATLAS



- Possibility to investigate 5.02 and 8.16 TeV energy regimes at LHC.
- Production well understood even if on the high side of the pQCD based calculations

D-meson R_{pA} - ALICE

$$R_{\mathrm{pA}} = \frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{pA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$



ALICE-PUBLIC-2017-008

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- ☑ Described my models including the formation of QGP in p-Pb:
  - ➡ data disfavour suppression >~15% at high-p_T
  - ➡ need to improve the precision of the measurement for a more conclusive statement

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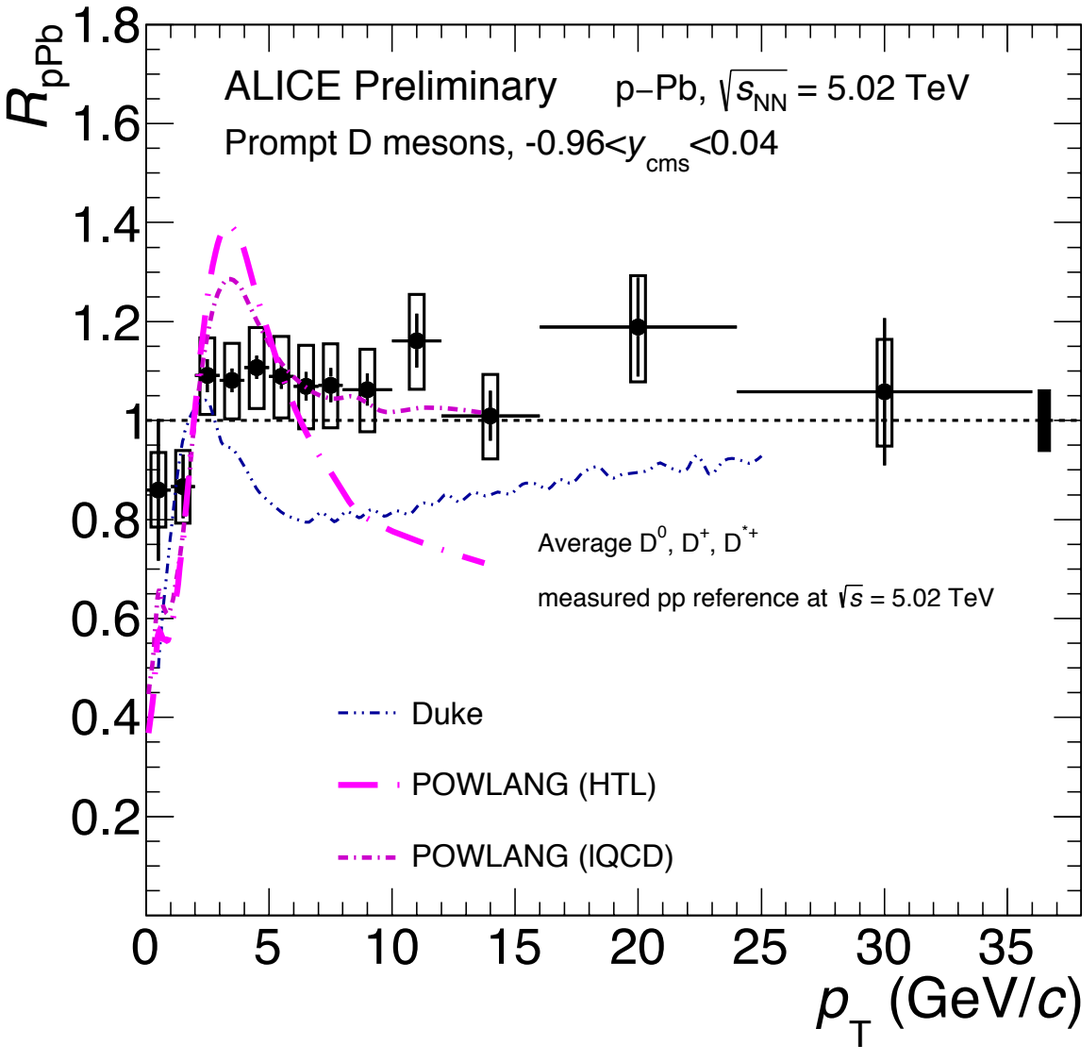

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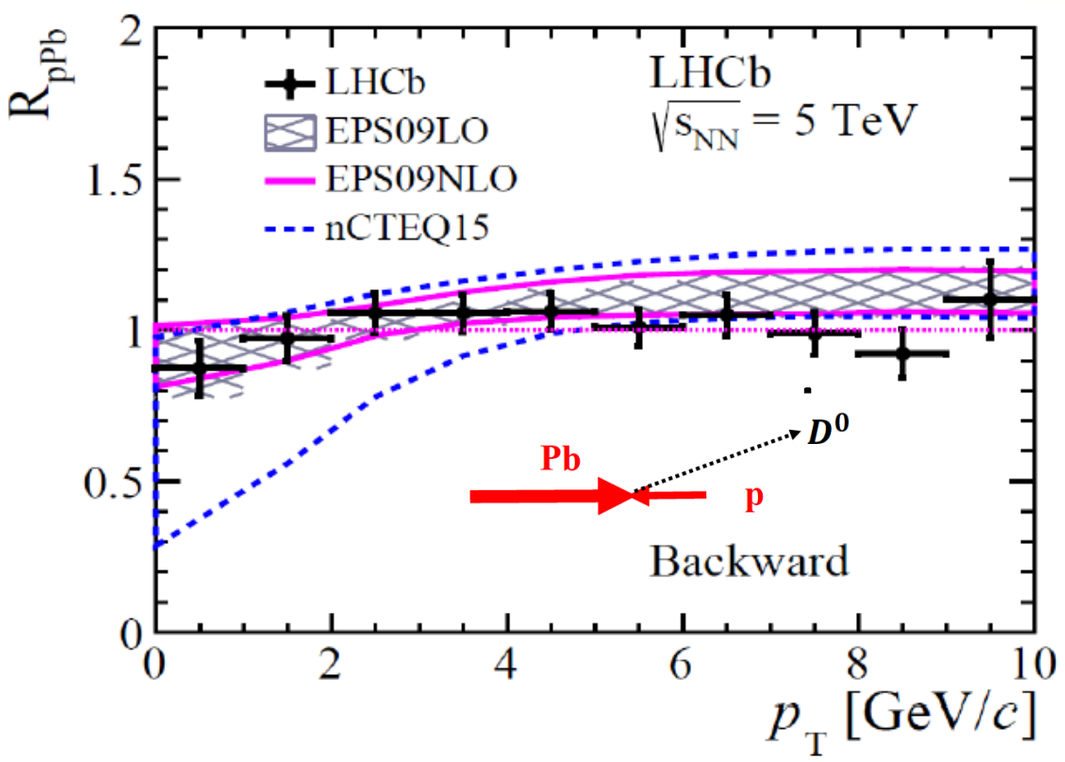
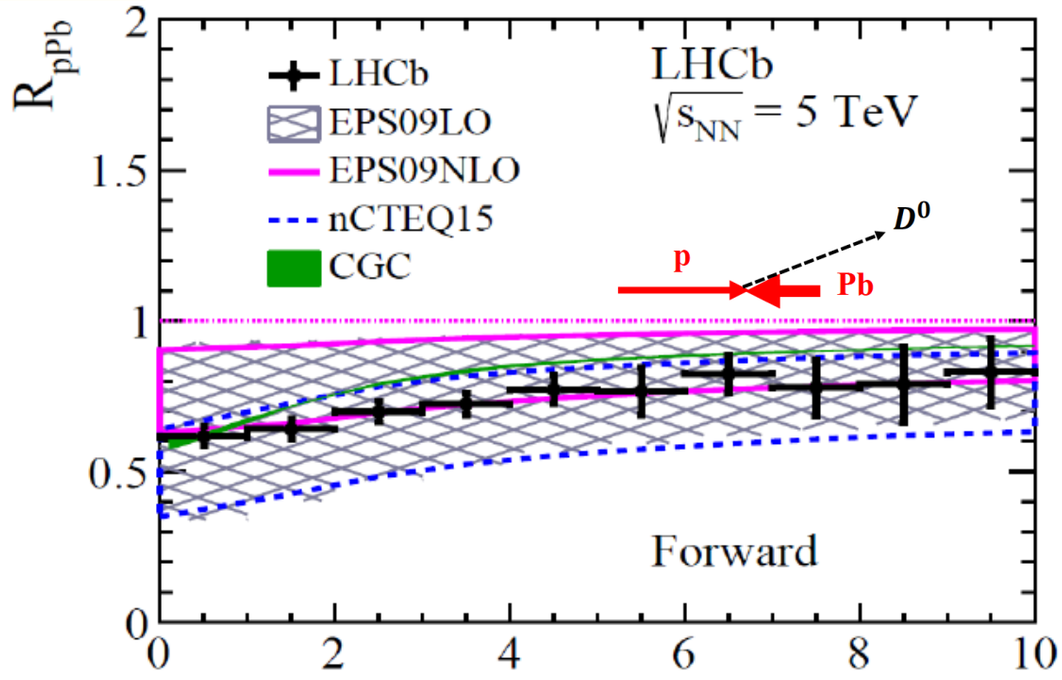
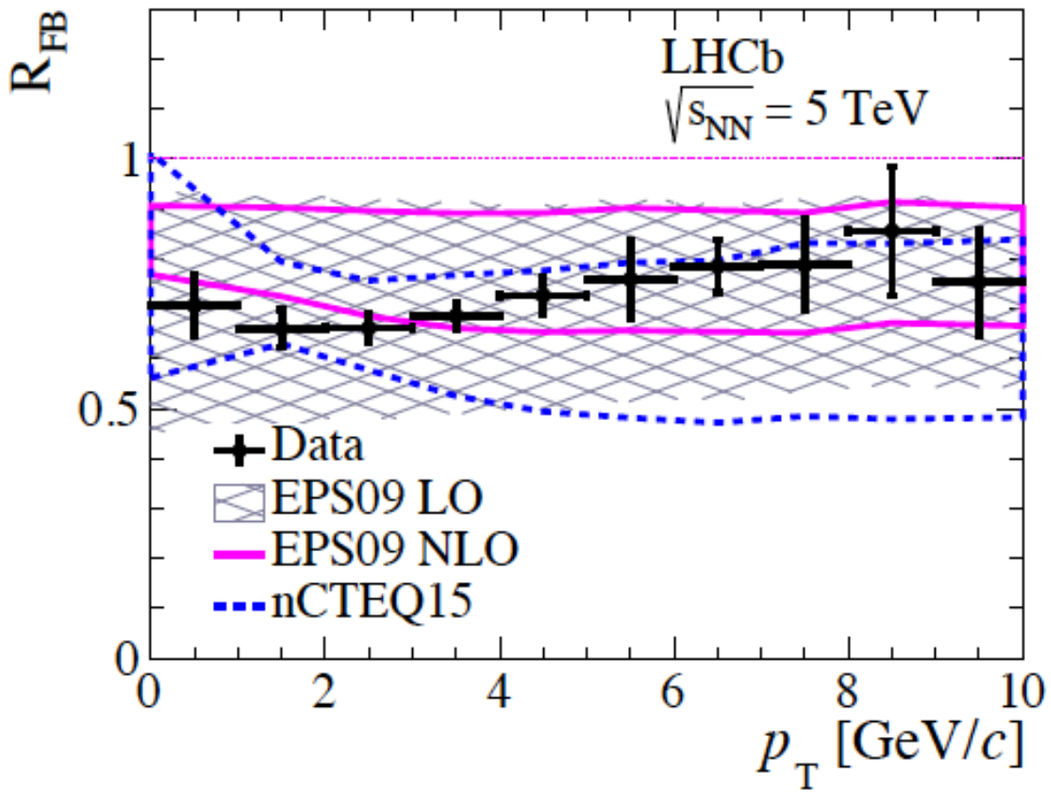
D-meson forward to backward ratio - LHCb

JHEP 1710 (2017) 090







- Data agree with nPDF or CGC but experimental precision much better than the theory one.

CGC:

Phys. Rev. D91 (2015) 114005,

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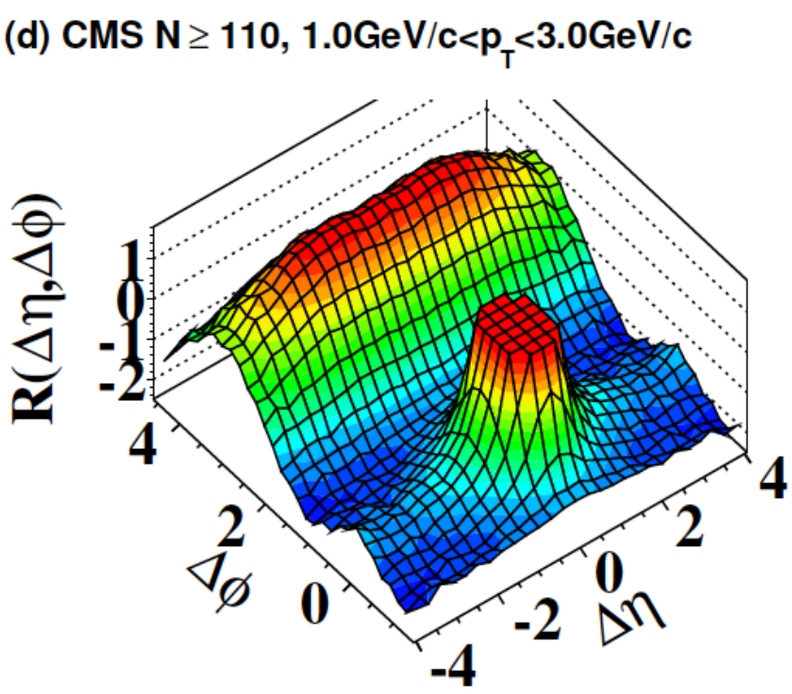
Collectivity in small systems

pp collisions

(CMS Collaboration) JHEP 09, (2010) 091



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M. He, R. J. Fries and R. Rapp, arXiv:1204.4442 [nucl-th].

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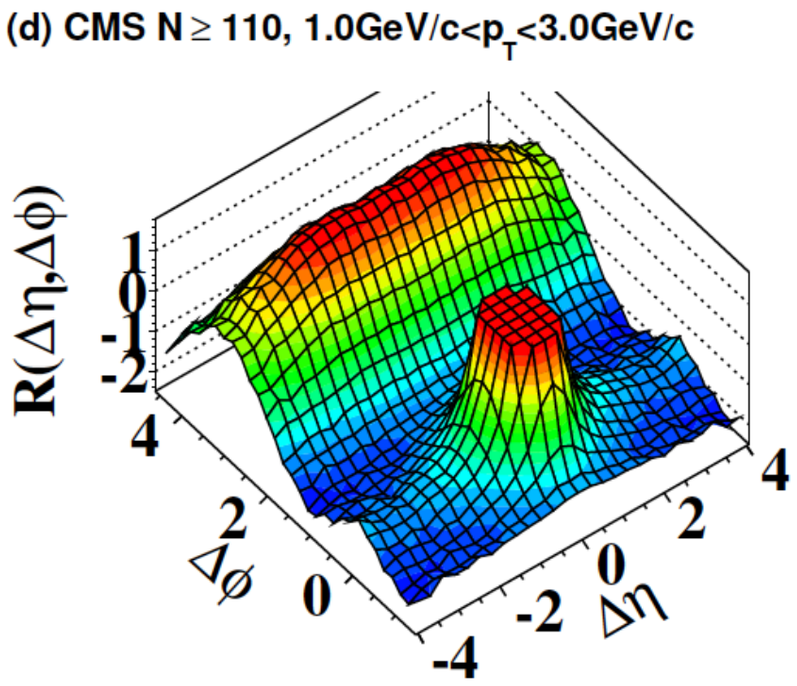

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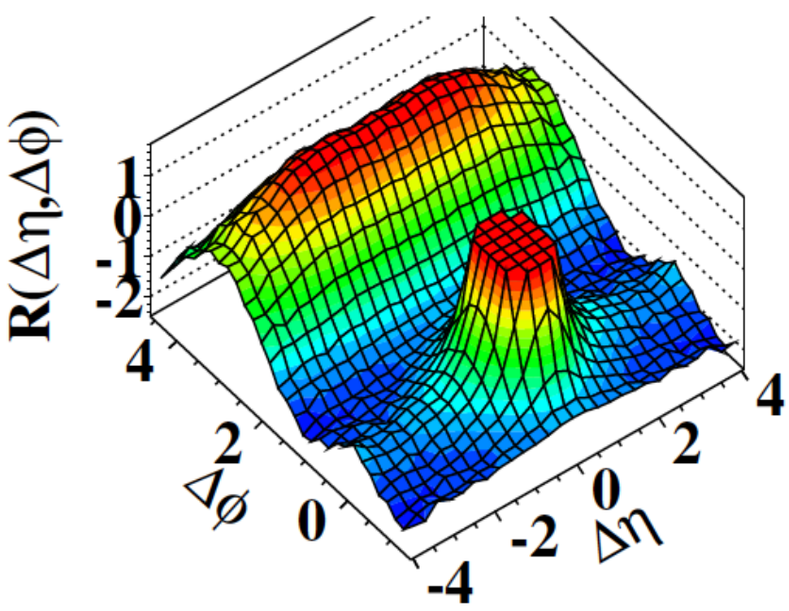

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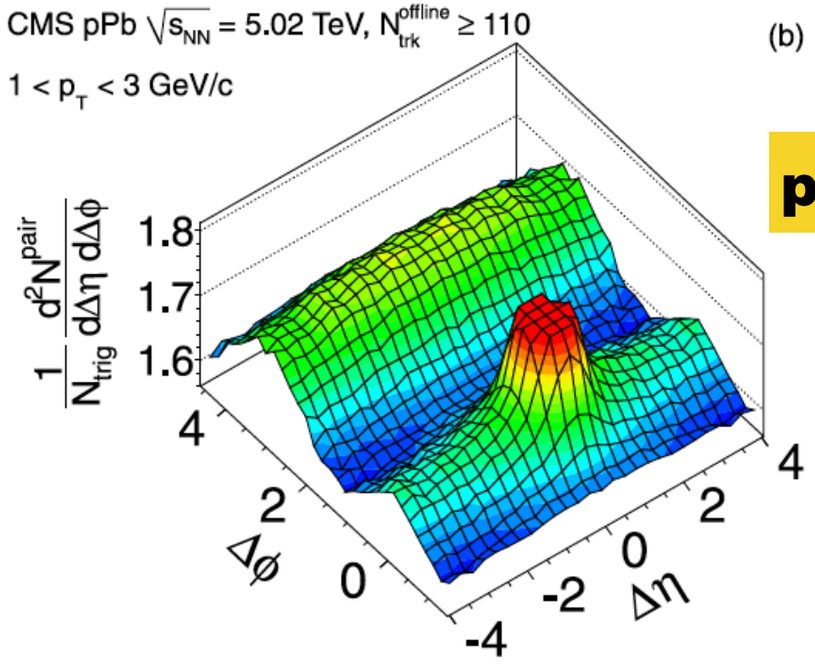
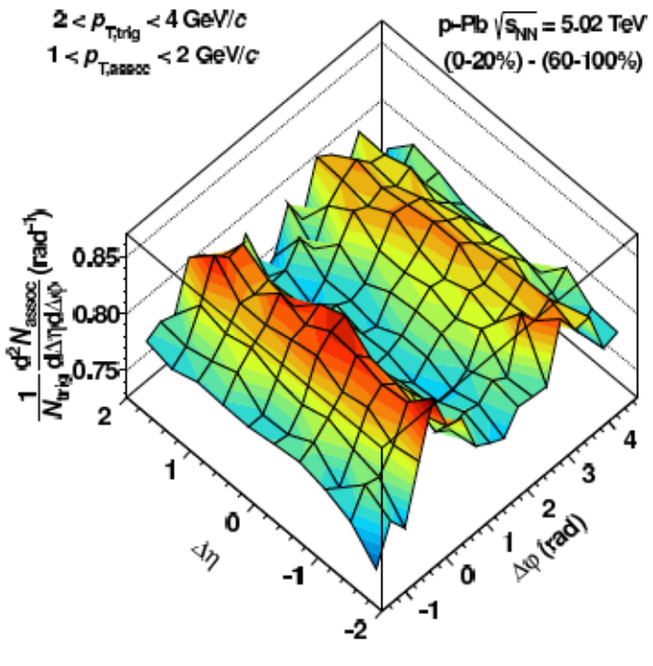
A collective QGP like effect in pp and p-Pb?

(CMS Collaboration) Phys. Lett. B718, (2013) 795



p-Pb collisions

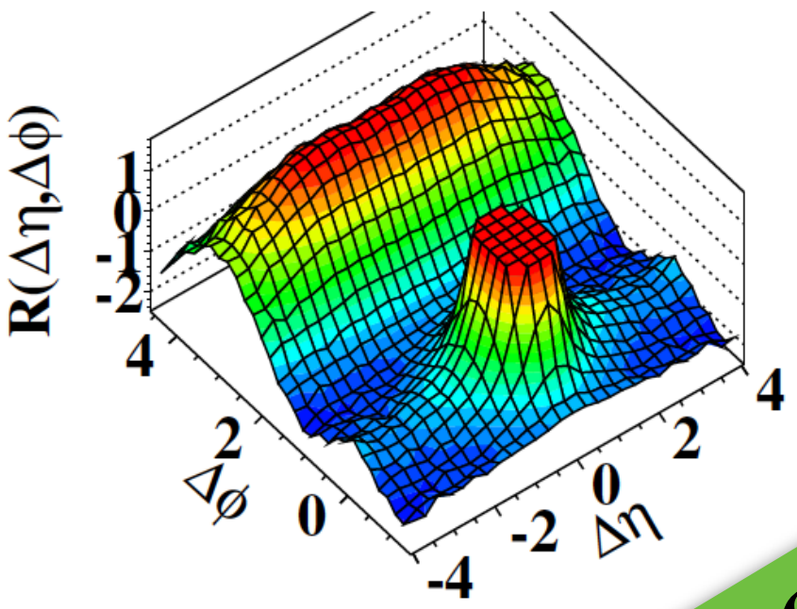
(ALICE Collaboration): Phys. Lett. B719, (2013) 29



Collectivity in small systems

pp collisions

(CMS Collaboration) JHEP 09, (2010) 091

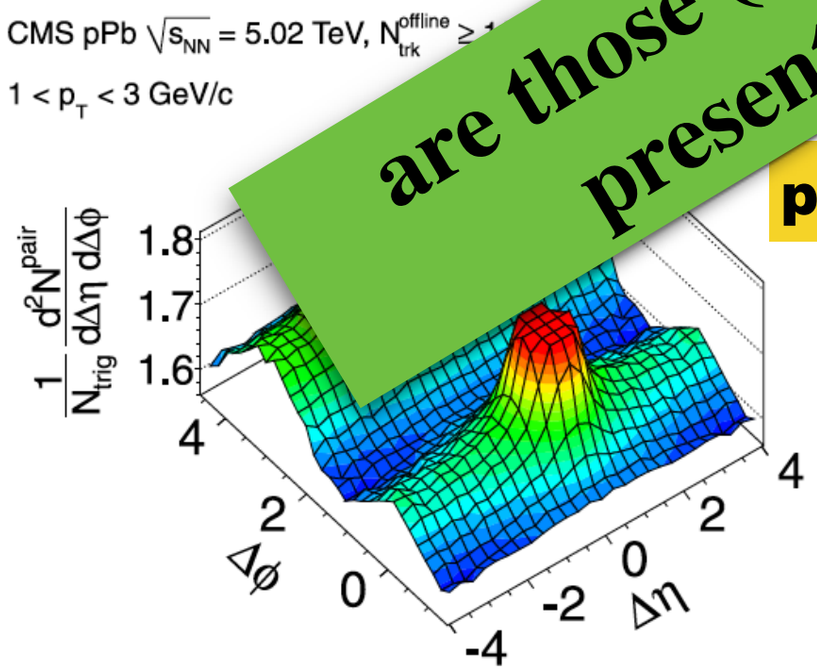


- ☑ LHC data opened a new hera: detailed study of high-multiplicity events (both pp and p-A) become possible
- ☑ In 2010 CMS C… ish a paper highlighti… structure in high-multi… -hadron correaltions

QGP like effect in pp and p-Pb?

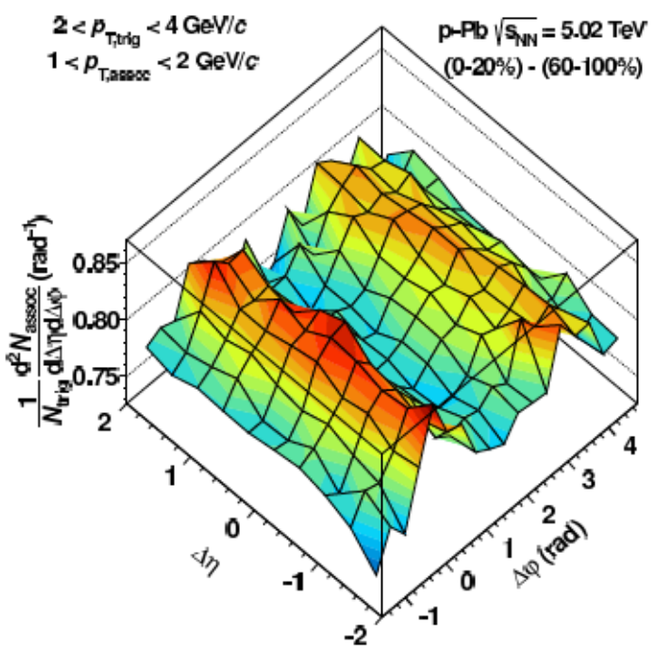
(QGP-like) collective effects are those present in the Charm sector?

(CMS Collaboration) Phys. Lett. B71…



p-Pb collisions

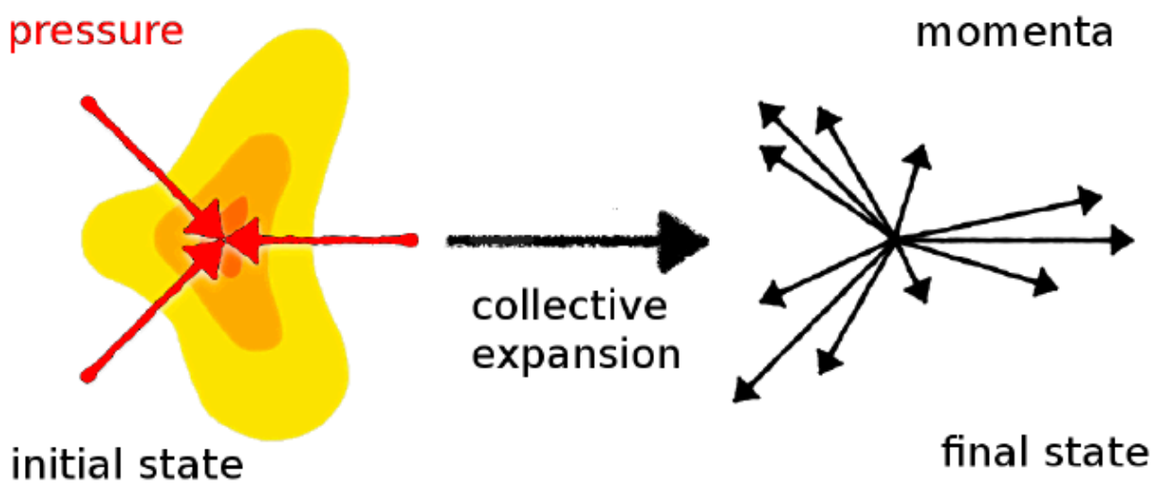
(ALICE Collaboration): Phys. Lett. B719, (2013) 29



Elliptic flow v_2 as a measure of collectivity

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \Psi_n)\right]$$

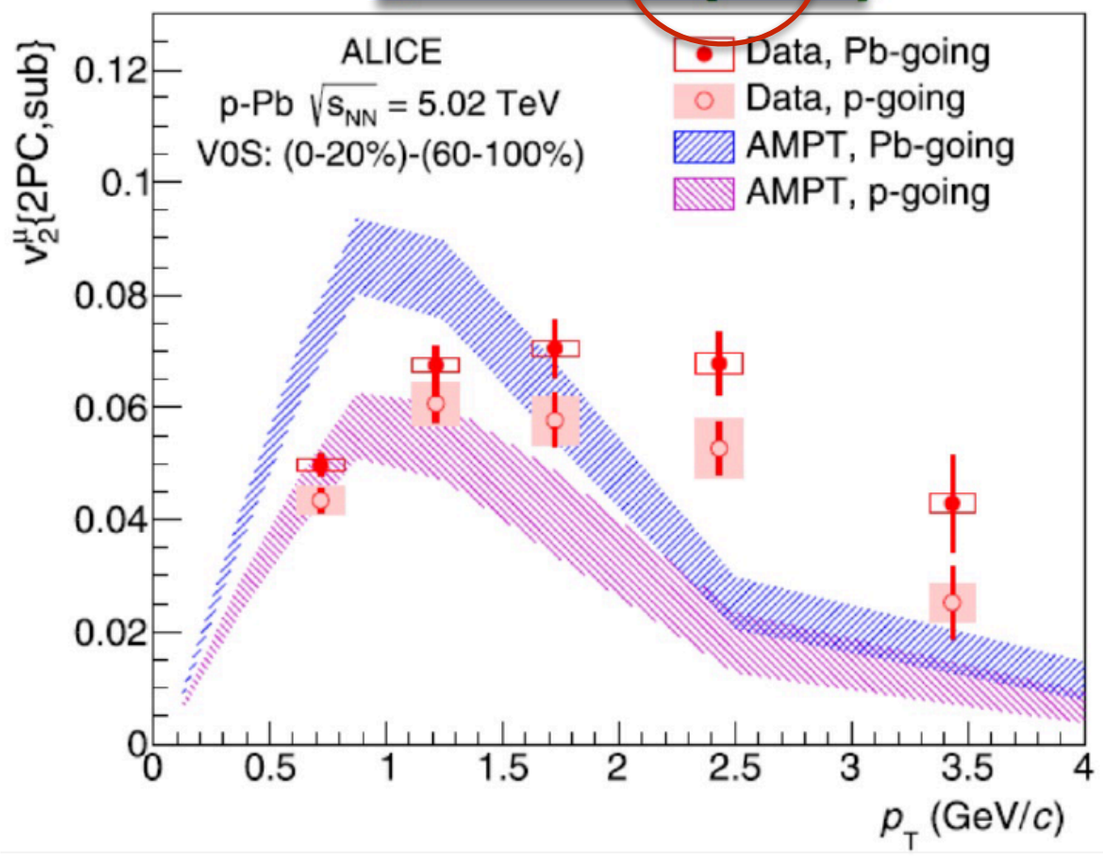
- Flow: momentum anisotropies in azimuthal angle, quantified by coecients $\mathbf{v_n}$
  - ☑ Soft sector (low-$p_T < 2$ GeV/c): multiple interactions between partons (a.k.a. collectivity") convert initial-state (IS) spatial anisotropies into final-state momentum ones
  - ☑ Hard sector (high-p_T, > 10 GeV/c): path-length dependent parton energy loss (partons loose energy differently according to how much medium they transverse)
  - ☑ Common origin: spatial anisotropies from geometry of the collision and IS fluctuations



Heavy-flavour collectivity in p-Pb?

- ☑ Non zero elliptic flow (v_2) as a measure of collectivity

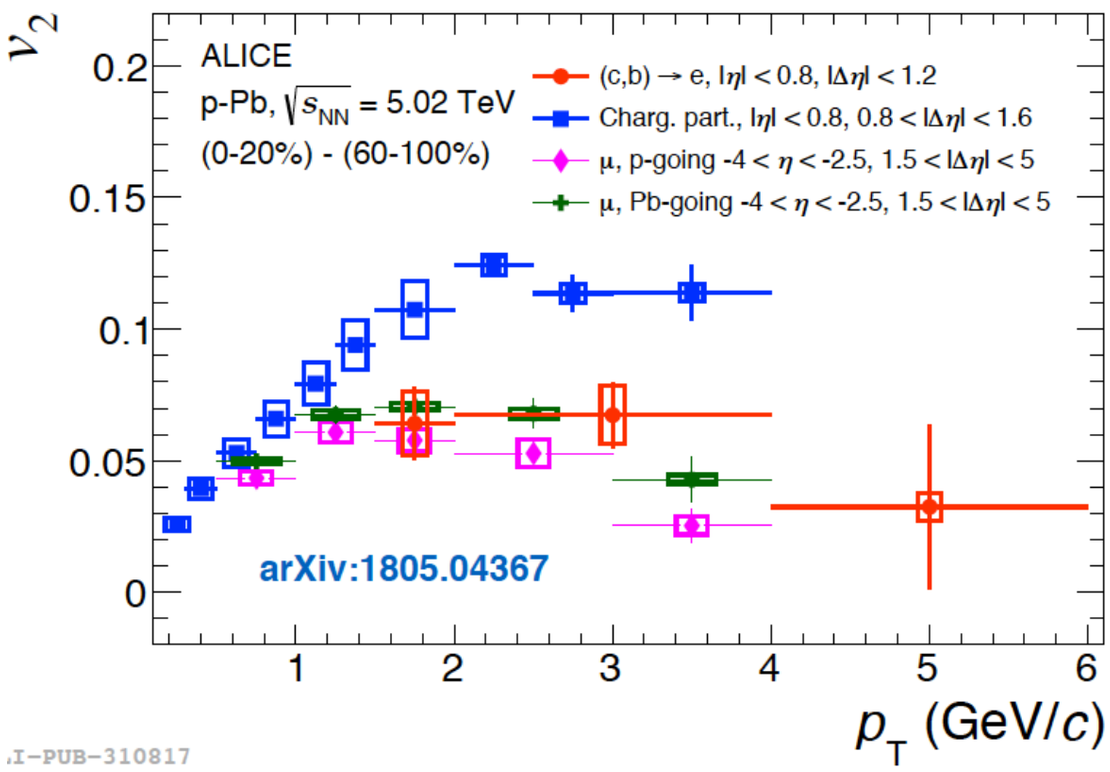
ALICE, PLB 753 (2016) 126

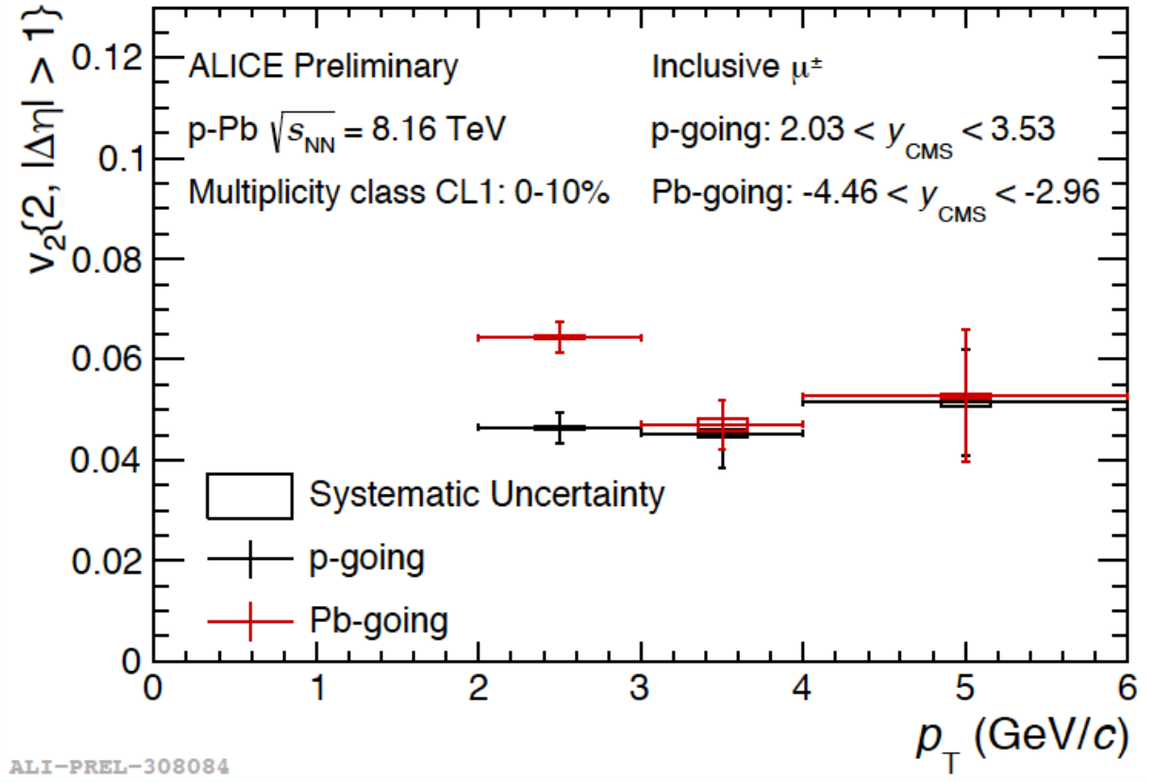


- ☑ **Indirect hint** of non-zero heavy flavour flow in p-Pb from inclusive muons at forward rapidity (p_T>2 GeV/c)
  - ➡ High-p_T inclusive muons are HF dominated.
  - ➡ Need direct proof (Prompt D mesons, heavy-flavour hadron decay leptons)

HF leptons flow in p-Pb

Phys. Rev. Lett. 122, 072301 (2019)





Heavy flavour decay electrons (mid-rapidity)

- ☑ Effect is qualitatively similar to the one observed for inclusive muons
- ☑ Significance: >5σ for 1.5< p_{Te}< 4 GeV/c
- ☑ Initial or final state effect?

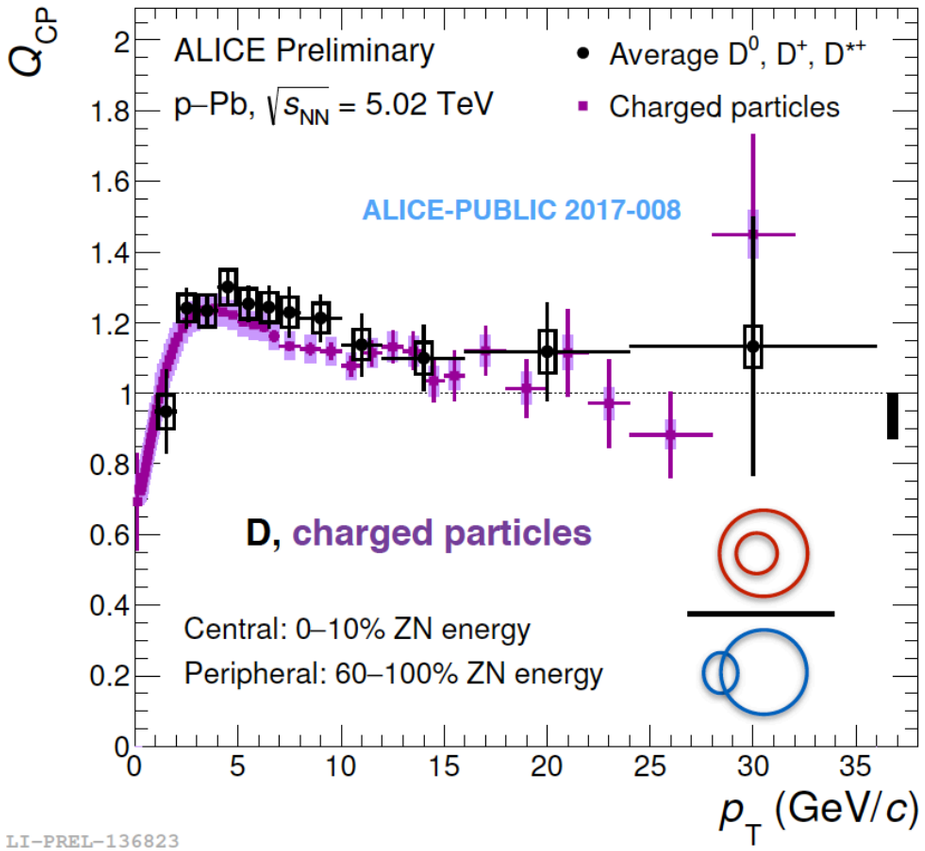
Heavy flavour decay muons (forward rapidity)

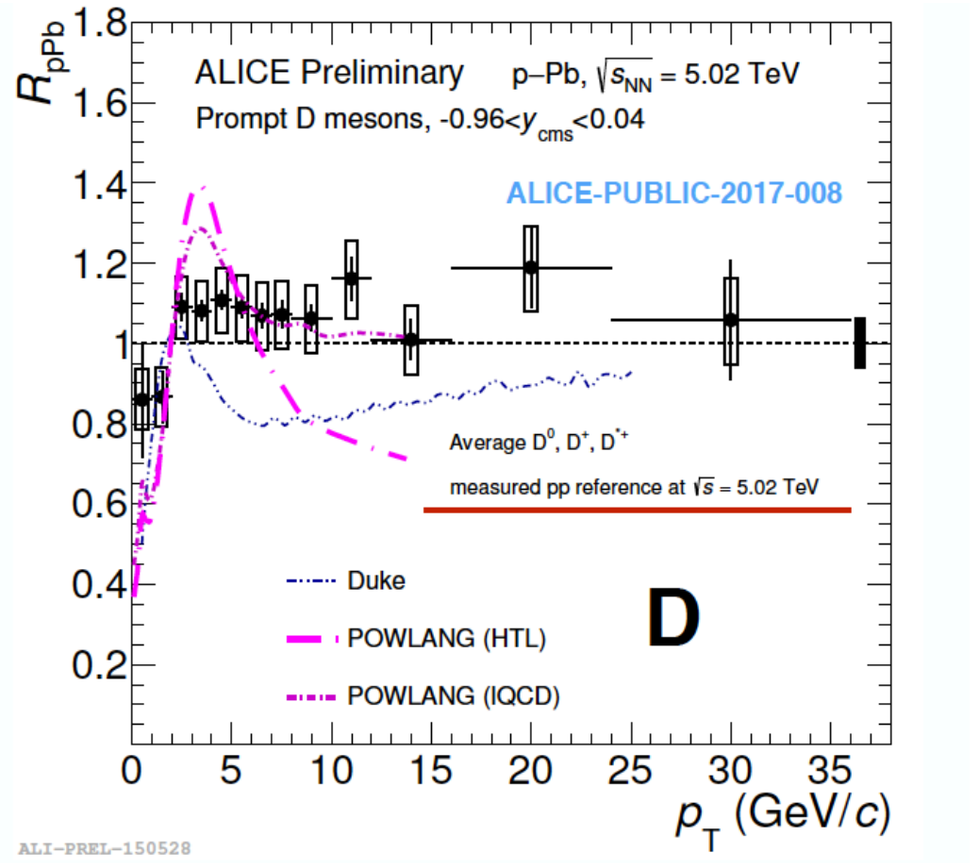
- ☑ Effect is qualitatively similar to the one observed for HFe

Collectivity in the D meson sector?

$$Q_{\mathrm{CP}} = \frac{(\mathrm{d}^2N^{\mathrm{prompt\,D}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y)^{0-10}_{\mathrm{pPb}} \big/ \langle T_{\mathrm{pPb}}\rangle^{0-10}}{(\mathrm{d}^2N^{\mathrm{prompt\,D}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y)^{60-100}_{\mathrm{pPb}} \big/ \langle T_{\mathrm{pPb}}\rangle^{60-100}}$$

$$R_{\mathrm{pPb}} = \frac{1}{A}\frac{\mathrm{d}^2\sigma^{\mathrm{prompt\,D}}_{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\mathrm{d}^2\sigma^{\mathrm{prompt\,D}}_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$



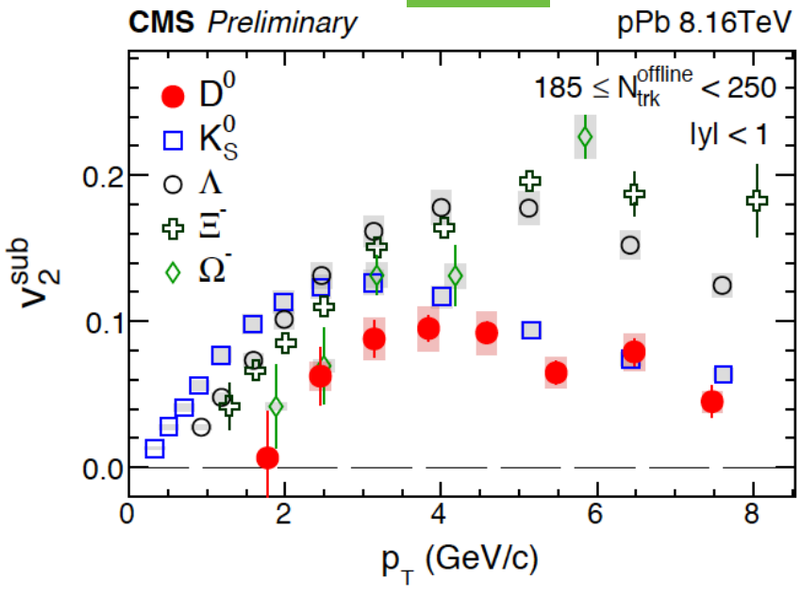


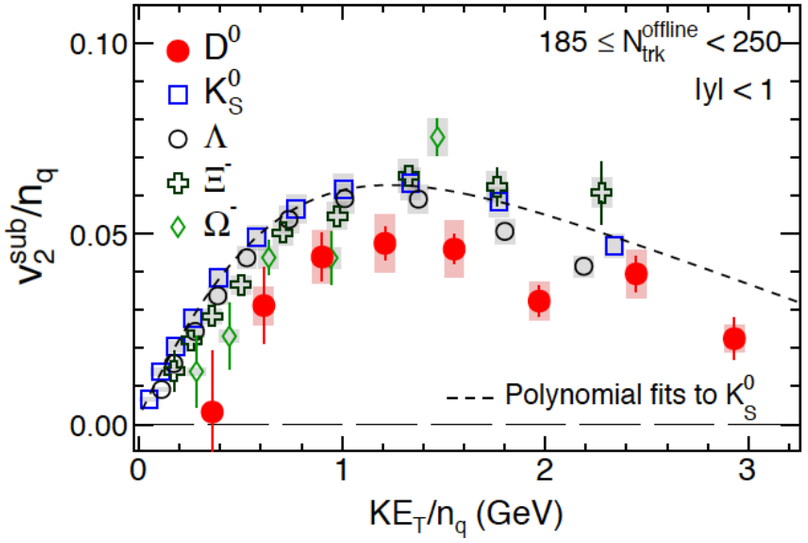
- ☑ Hint for D-meson "Central-to-peripheral" ratio (QCP) larger than unity (1.5σ in $2 < p_{\mathrm{T}} < 8$ GeV/c)
- ☑ Initial-state effect? Mass effect? Radial flow? … early to say, need comparison with theoretical calculations.
- ☑ However, models that contemplate the production of a small QGP in p-Pb tend to predict a suppression on the D mesons R_{pPb} at high p_{T}. At present our results tend to disfavour suppressions larger than 10-20%

D-meson v_2 in p-Pb at 8.16 TeV (CMS)

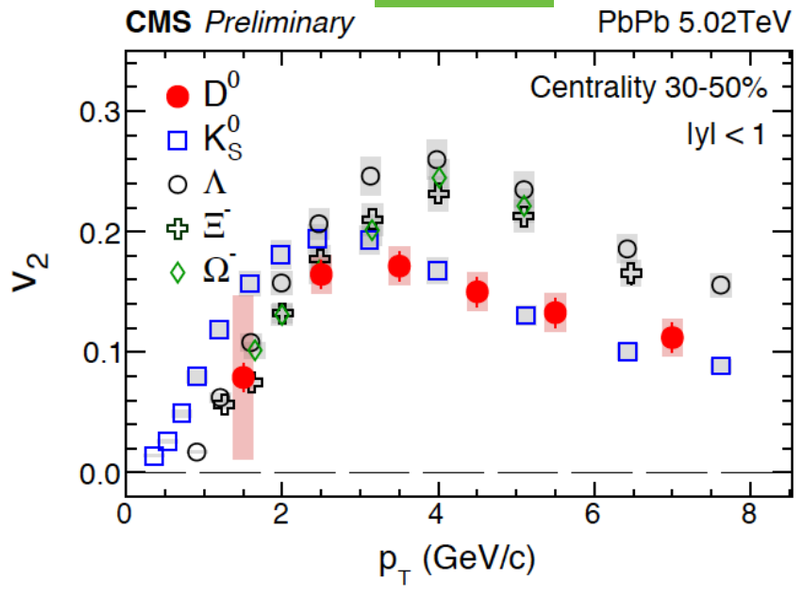
CMS-HIN-17-003

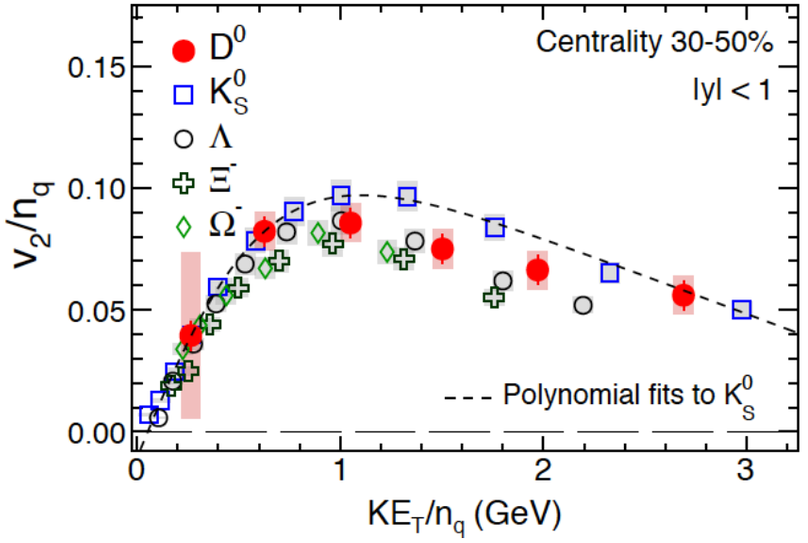
p-Pb





Pb-Pb





☑ Comparing to strange-hadron results, the D^0 v_2 values are smaller at a given p_T, or at similar transverse kinetic energy per constituent quark, after normalizing v_2 by the number of constituent quarks.

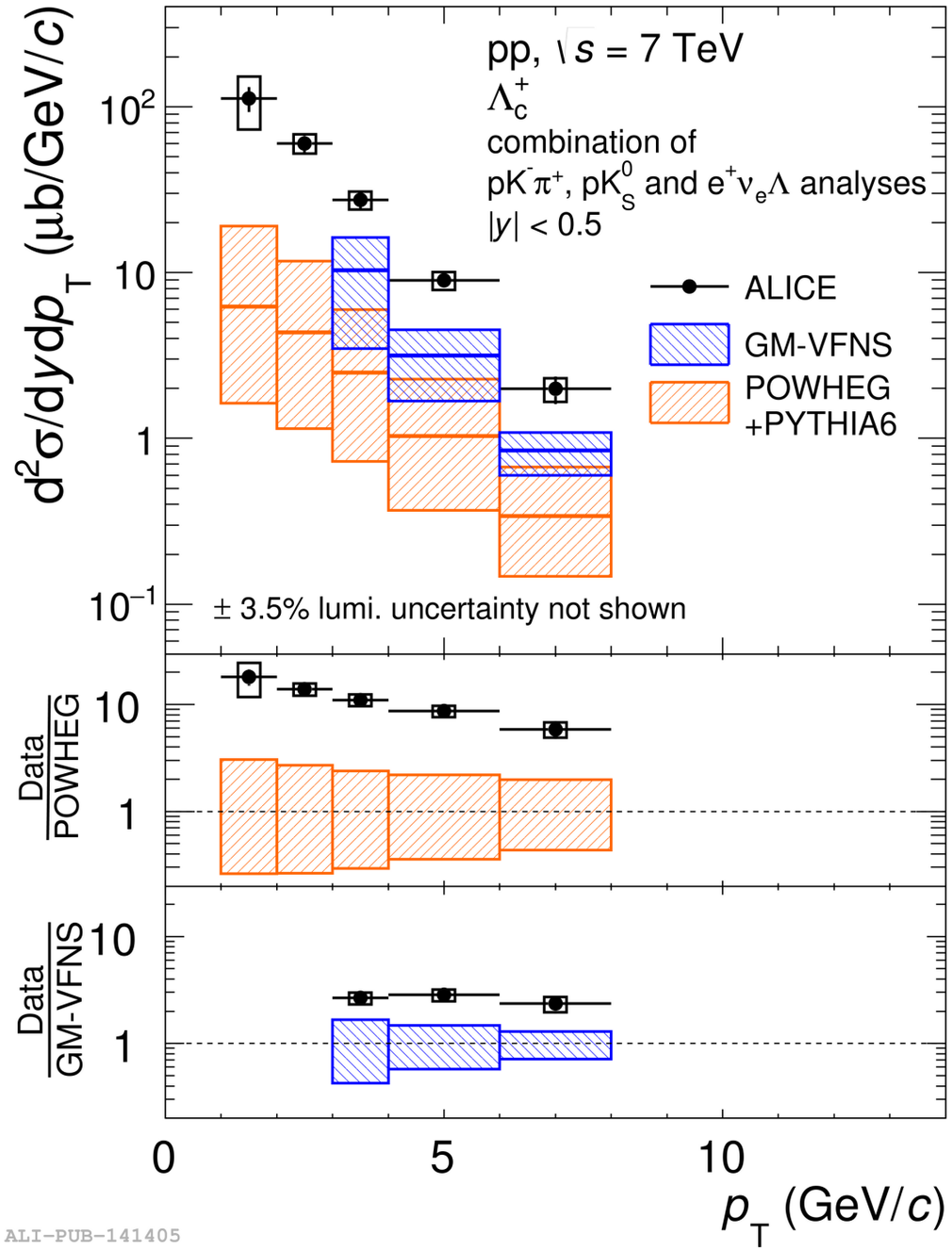
☑ The collective behavior of charm quarks is weaker than that of the light-flavor quarks. This effect is not seen in heavy-ion (Pb-Pb) collisions.

Open heavy-flavour production

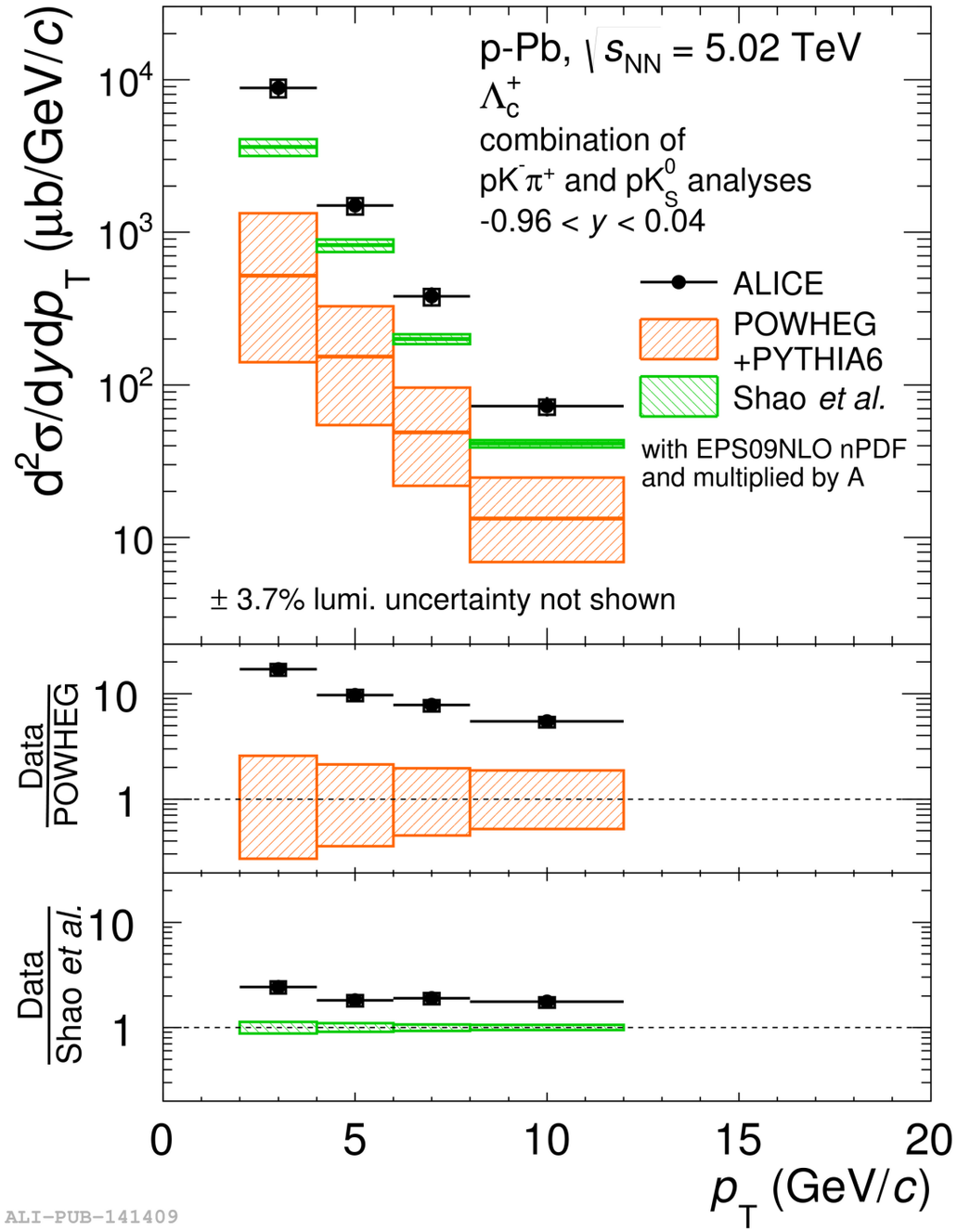
- **pp collisions:**
  - Test pQCD calculations
  - Study fragmentation and hadronisation, heavy-flavour jet properties
  - Set a reference for p-Pb and Pb-Pb
- **p-Pb collisions**
  - Study cold nuclear matter (CNM) effects (nPDF, shadowing, gluon saturation, k_T-broadening, energy loss in CNM in the initial and final state)
  - Address possible collective effects and effects related to the (possible) formation of a QGP in p-Pb collisions.
- **Charm hadronization in vacuum**
  - Do we understand it?
    - $\Lambda_c[\Xi_c]/D^0$ ratio in pp and p-Pb: ALICE vs LHCb
    - Possible implications of the experimental result

Λ_c production in pp, p-Pb (ALICE)

pp



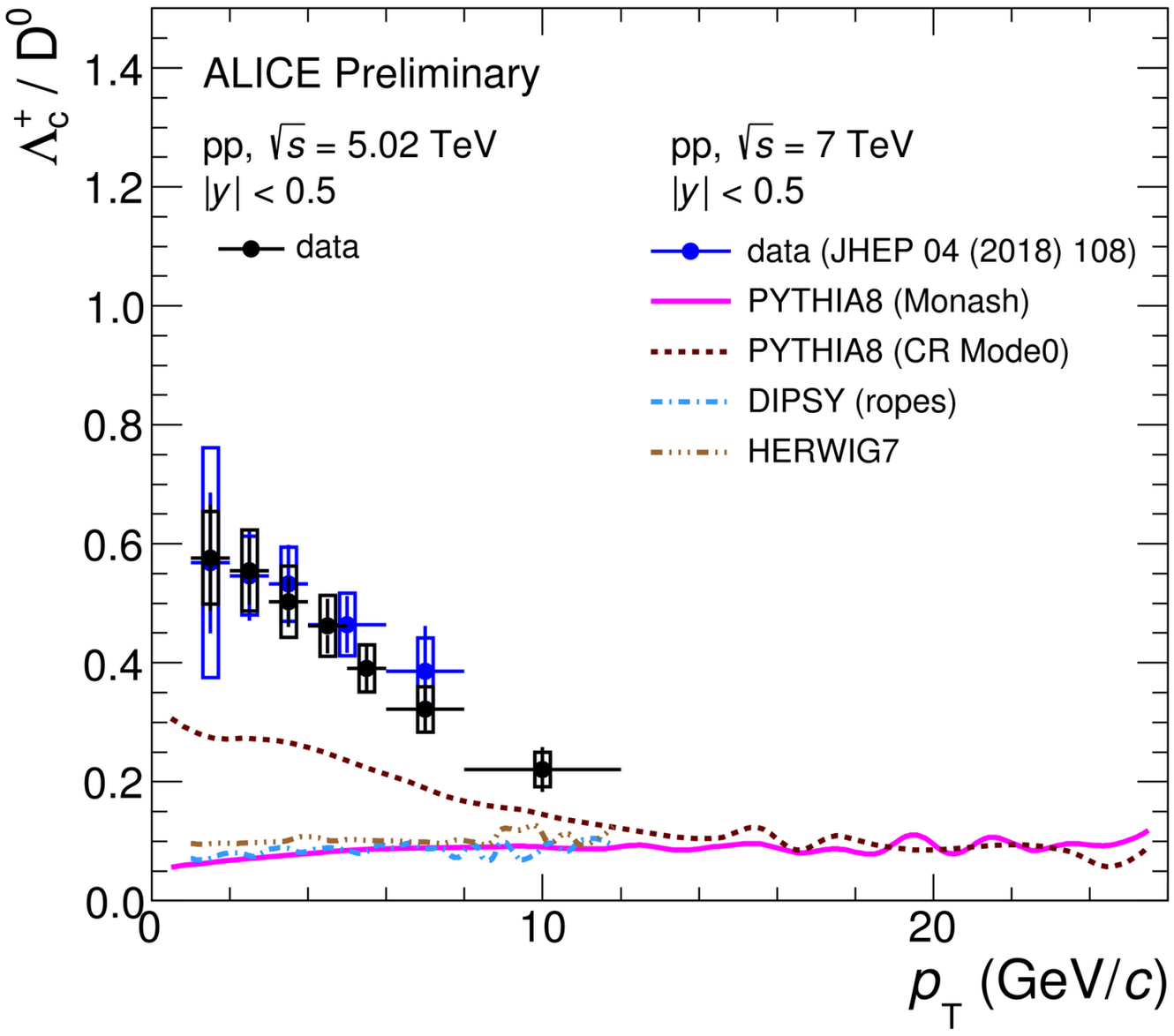
p-Pb



JHEP 1804 (2018) 108

Λ_c production in pp, p-Pb (ALICE)

LHC run II data



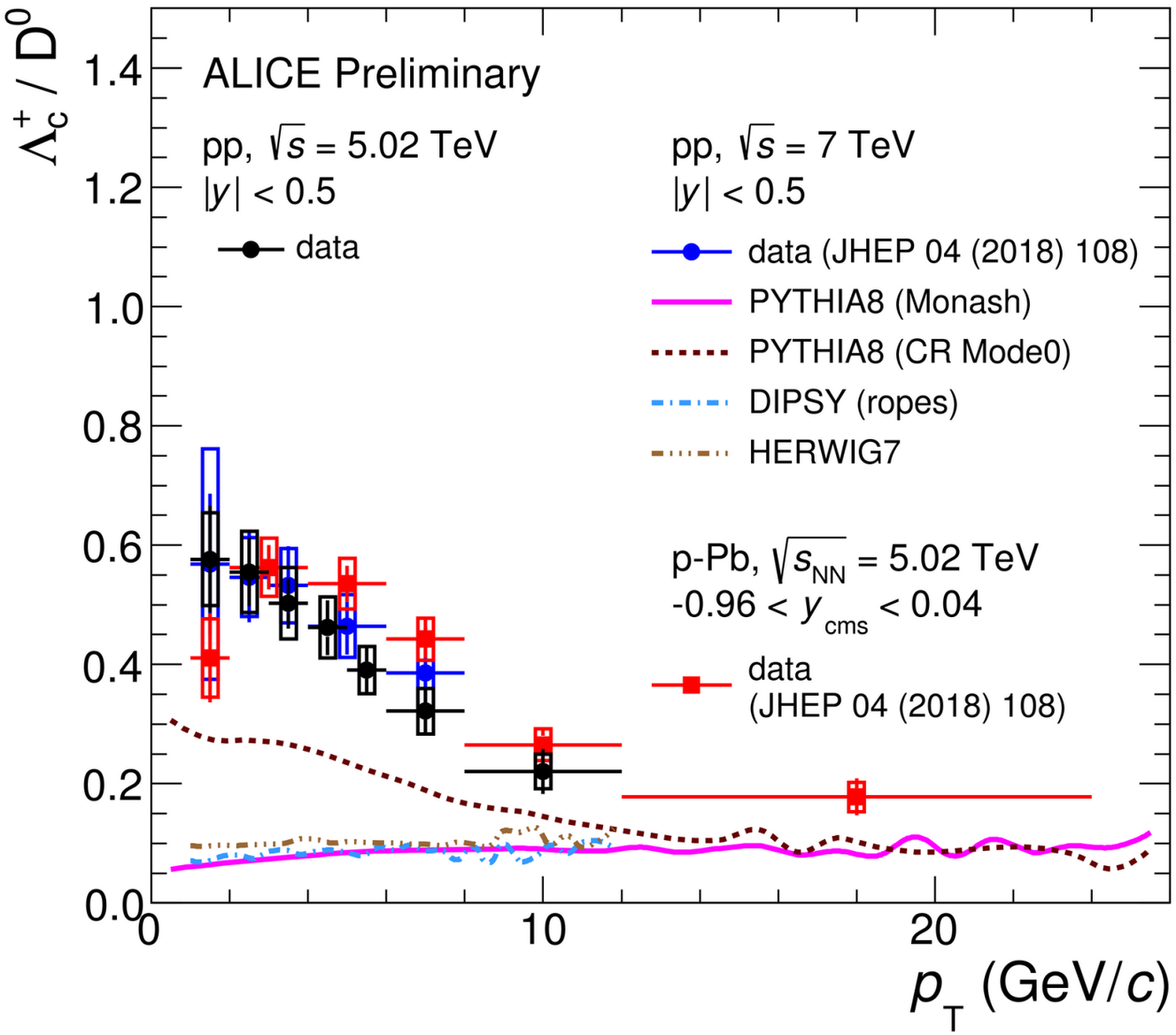
ALI-PREL-311156

- ☑ Λ_c/D^0 largely understimated by models, only Pythia with CR get the shape but not the magnitude
- ☑ Result from HERA, obtained in a similar pt range, sits in the 0.1 region. Challenge for the universalità of the fragmentation functions
- ☑ New analysis in pp at 5 TeV largely improve the precision (factor 2 in [1,2] GeV/c) and extend the p_T range

JHEP 1804 (2018) 108

Λ_c production in pp, p-Pb (ALICE)

LHC run II data



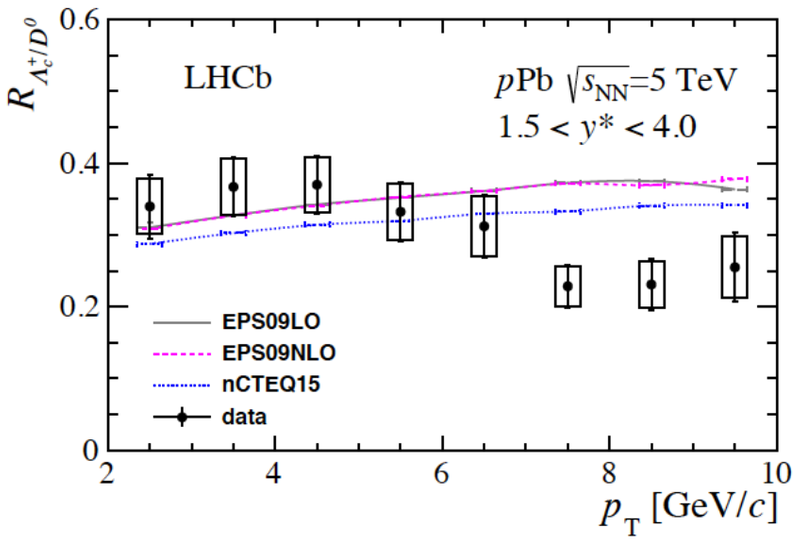
ALI-PREL-311152

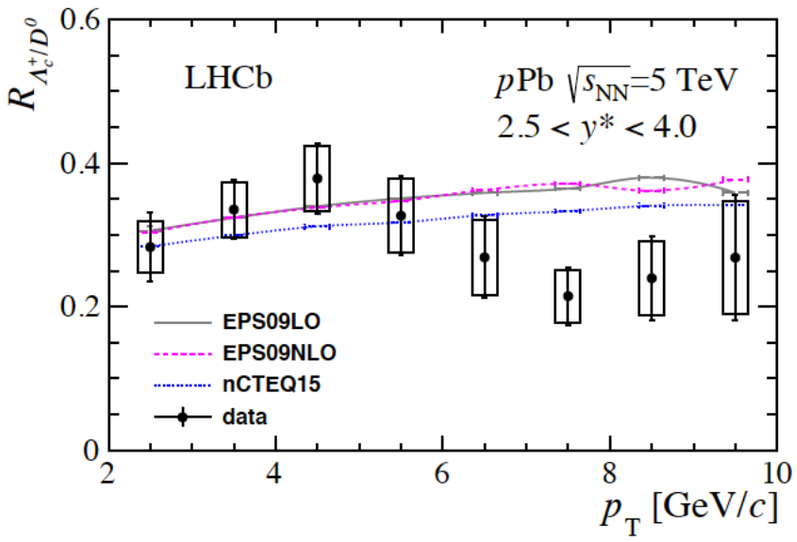
- ☑ Λ_c/D^0 largely understimated by models, only Pythia with CR get the shape but not the magnitude
- ☑ Result from HERA, obtained in a similar pt range, sits in the 0.1 region. Challenge for the universalità of the fragmentation functions
- ☑ New analysis in pp at 5 TeV largely improve the precision (factor 2 in [1,2] GeV/c) and extend the p_T range
- ☑ Comparison with p-Pb result shows a similar (?) trend. Need more data to conclude

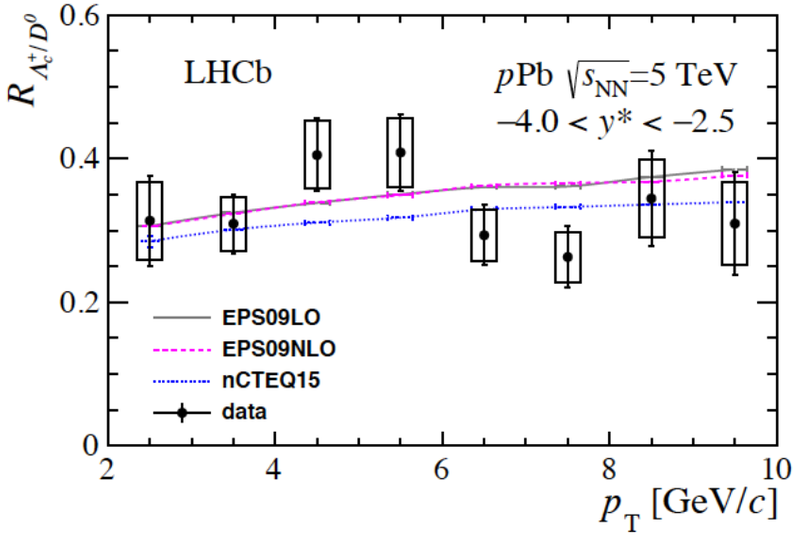
JHEP 1804 (2018) 108

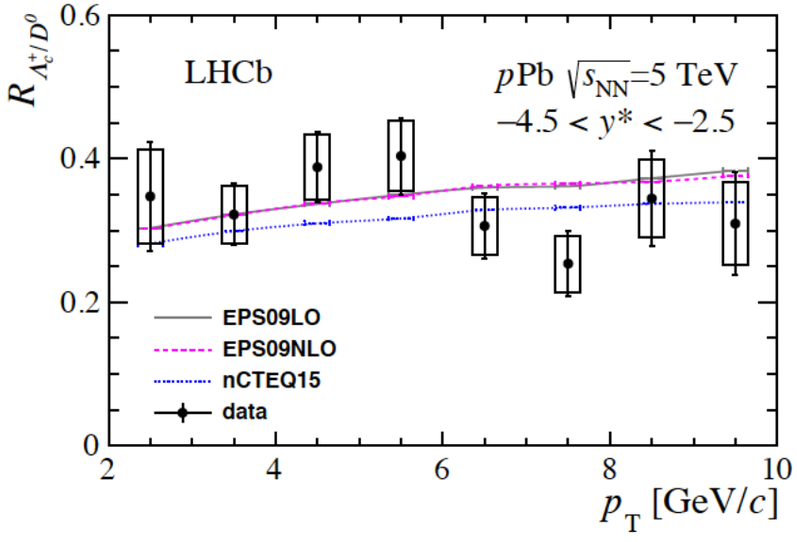
Λ_c production in p-Pb (LHCb)

JHEP 02 (2019) 102









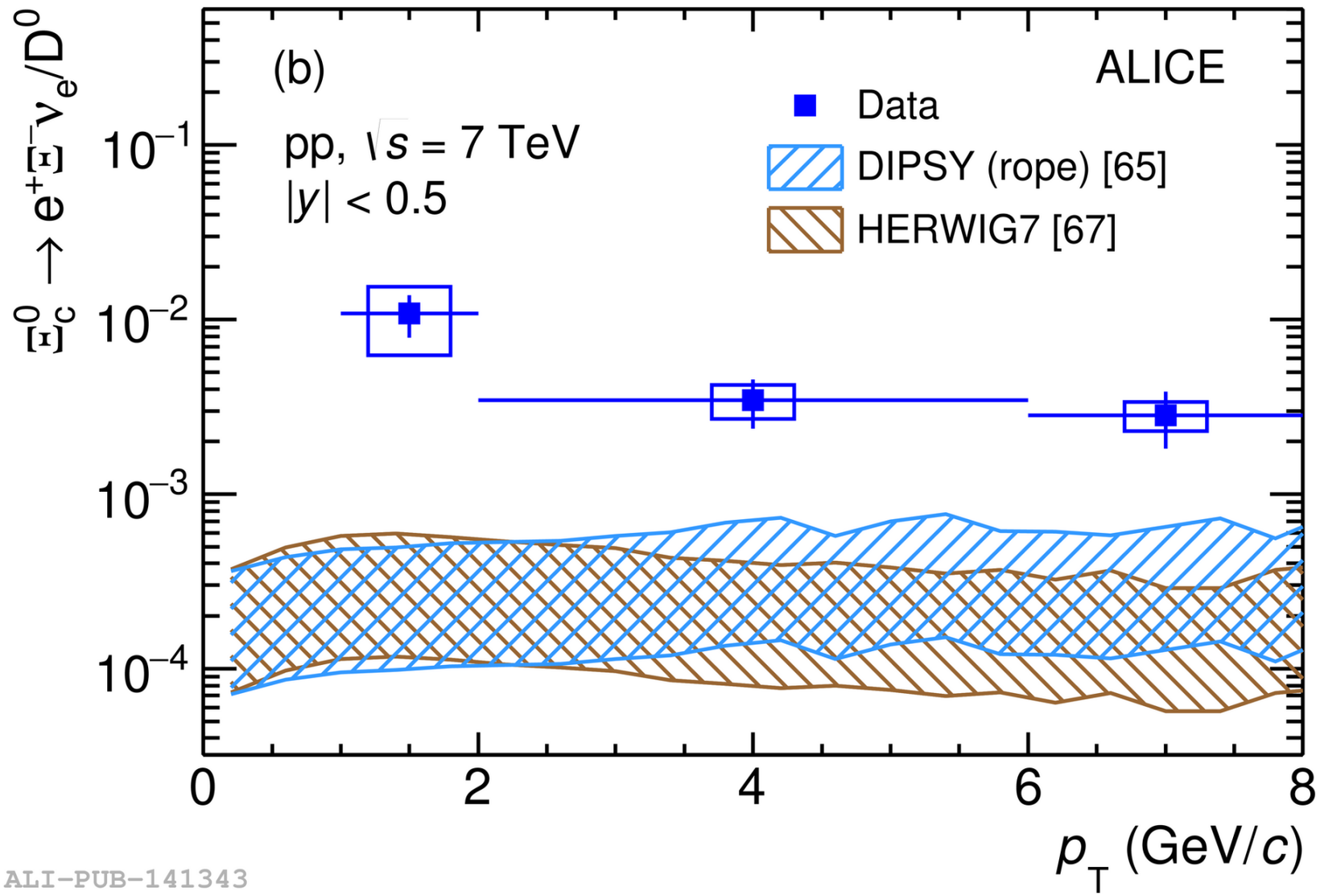
LHCb

- ☑ Data points agrees with nPDF calculations
- ☑ Different p_T dependence?
  - Need run II data to verify

Eur. Phys. J. C77 (2017) 1, arXiv:1610.05382.
Comput. Phys. Commun. 184 (2013) 2562
Comput. Phys. Commun. 198 (2016) 238,

Ξ_c production in pp (ALICE)

Phys.Lett. B781 (2018) 8-19



☑ Ξ_c/D^0 largely understimated by models. Similar situation as for Λ_c

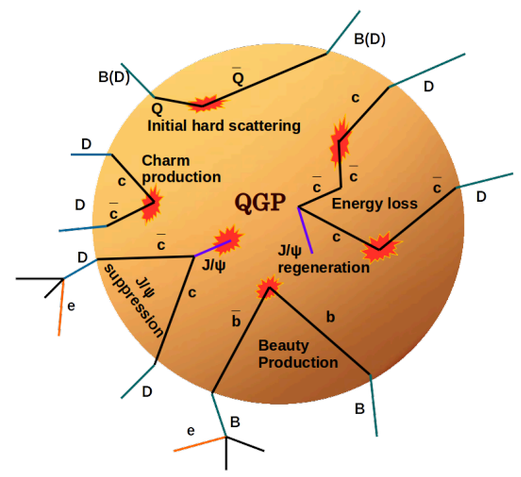
Summary

- pp measurements as a test of pQCD: we are entering a precision here, constraints to calculations become stringent
- p-Pb measurements to investigate initial state effects. Very good experimental precision ⇒ stringent test for CNM effects
- D meson results evidence possible collectivity in p-Pb collisions.
- Λ_c results are entering a precision hera. Unexpected behavior of baryon-to-meson ratio
- LHCb have large samples still to be analyzed. Additional constraints on nPDF, D-D correlations, …?

☑ Some open question:

- ☐ What is the nature of these collettive-like effects?
- ☐ Are the Λ_c/D^0 results a challenge for the universality of the FF?

Extra Slides



Centrality in p-Pb collisions (ALICE)

Centrality in p-Pb collisions: Phys. Rev. C 91 (2015) 064905

biases in the determination of $\langle N_{coll} \rangle$

- multiplicity fluctuations, jet-veto bias, geometrical bias

➡ Lose correlations between N_{part}, multiplicity and impact parameter *b*

➡ bias depends on estimator used for multiplicity determination

Experimentally:

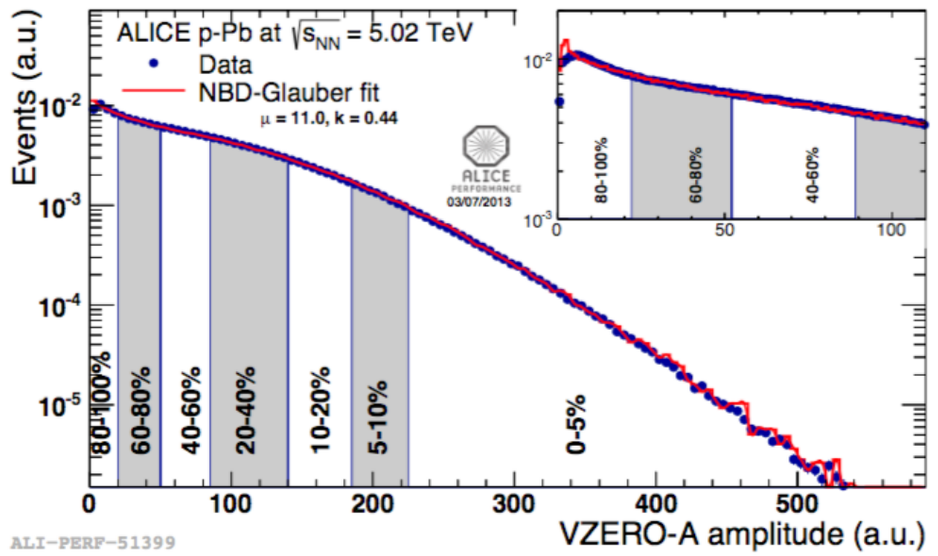
V0A: $\langle N_{coll} \rangle$ determined by Glauber fit of V0 amplitude

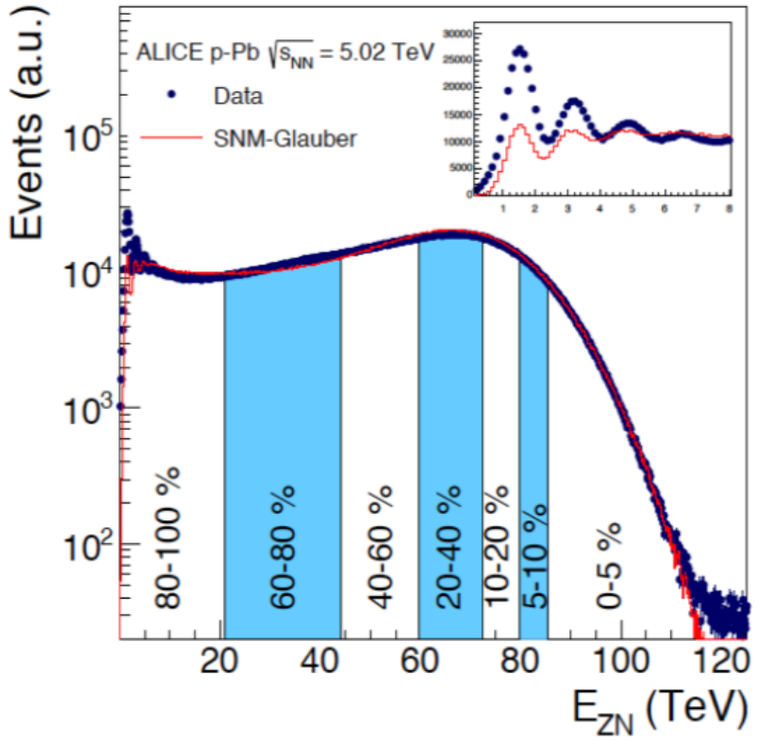
ZNA: $\langle N_{coll} \rangle$ obtained with a "Hybrid method"

- slice events in ZN energy (Pb going side)
- $\langle N_{coll} \rangle$ in ZN energy class obtained by scaling the minimum bias value with the ratio between the average charged-particle multiplicity at mid rapidity in the same class and that measured in the minimum bias sample

$$Q_{\mathrm{pPb}} = \frac{(\mathrm{d}N^{\mathrm{D}}/\mathrm{d}p_{\mathrm{T}})_{\mathrm{pPb}}}{\langle T_{\mathrm{pPb}} \rangle \times (\mathrm{d}\sigma^{\mathrm{D}}/\mathrm{d}p_{\mathrm{T}})_{\mathrm{pp}}} \qquad \langle T_{\mathrm{pPb}} \rangle = \frac{\langle N_{\mathrm{coll}} \rangle_i}{\sigma_{\mathrm{NN}}}$$

investigate charm production in p-Pb collisions w.r.t. pp collisions: possible multiplicity dependent modification of the p_T spectra in p-Pb?





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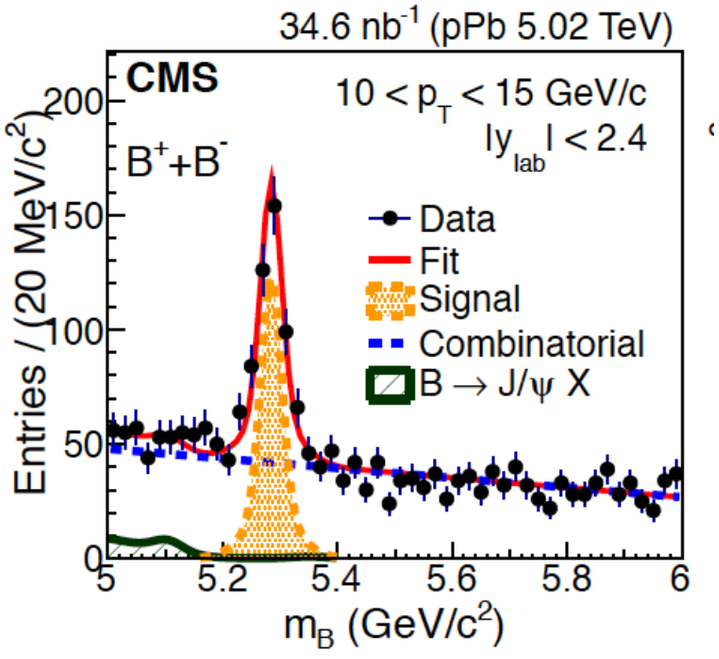
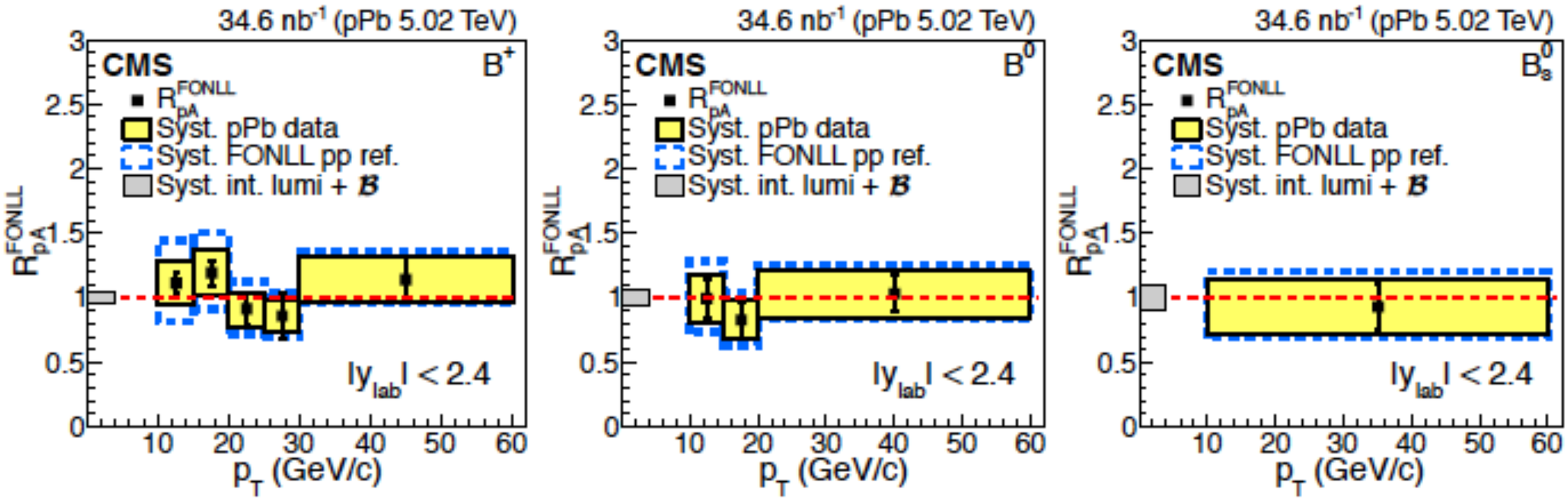
Fully reconstructed B mesons with CMS



PRL 116 (2016 032301

- ☑ Fully reconstructed B (B+, B0, Bs) mesons
- ☑ pp reference from FONLL pQCD calculation
- ☑ Only high-pT accessible
- ☑ R_{pPb} consistent with unity



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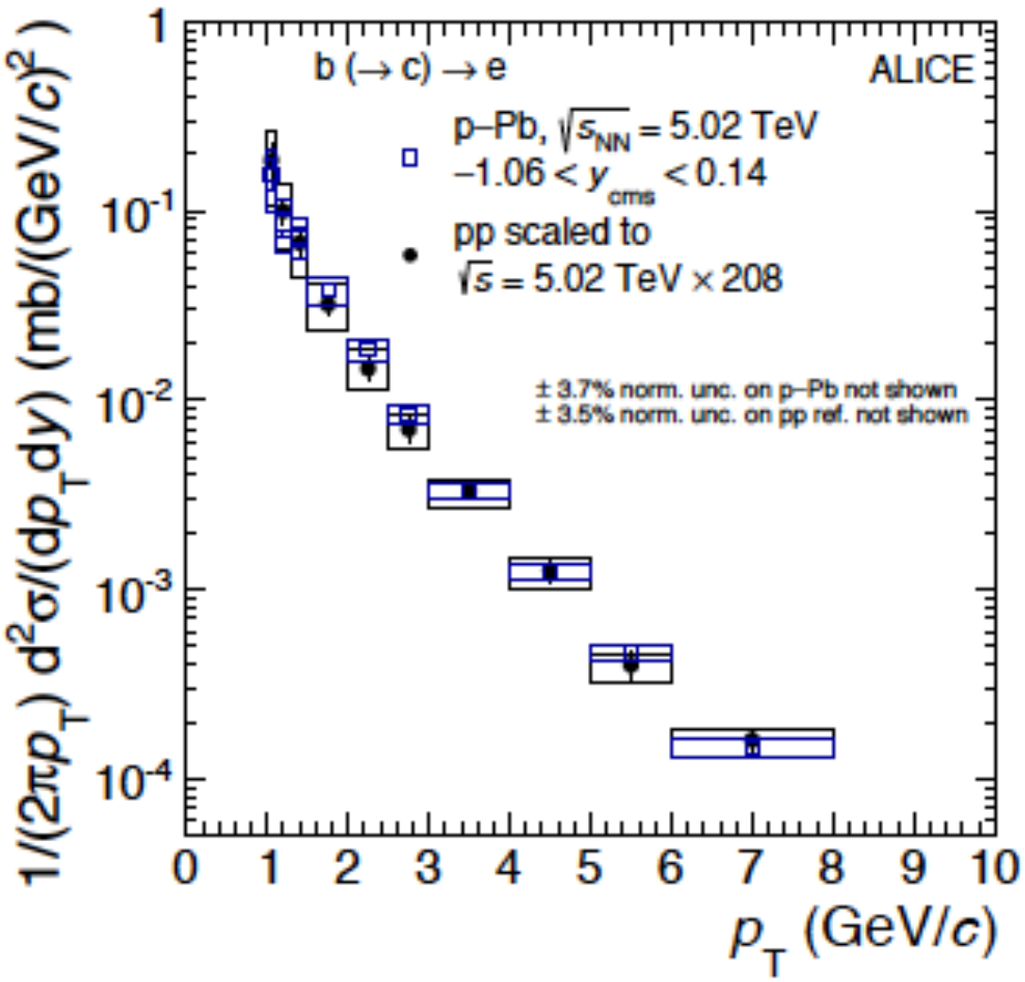
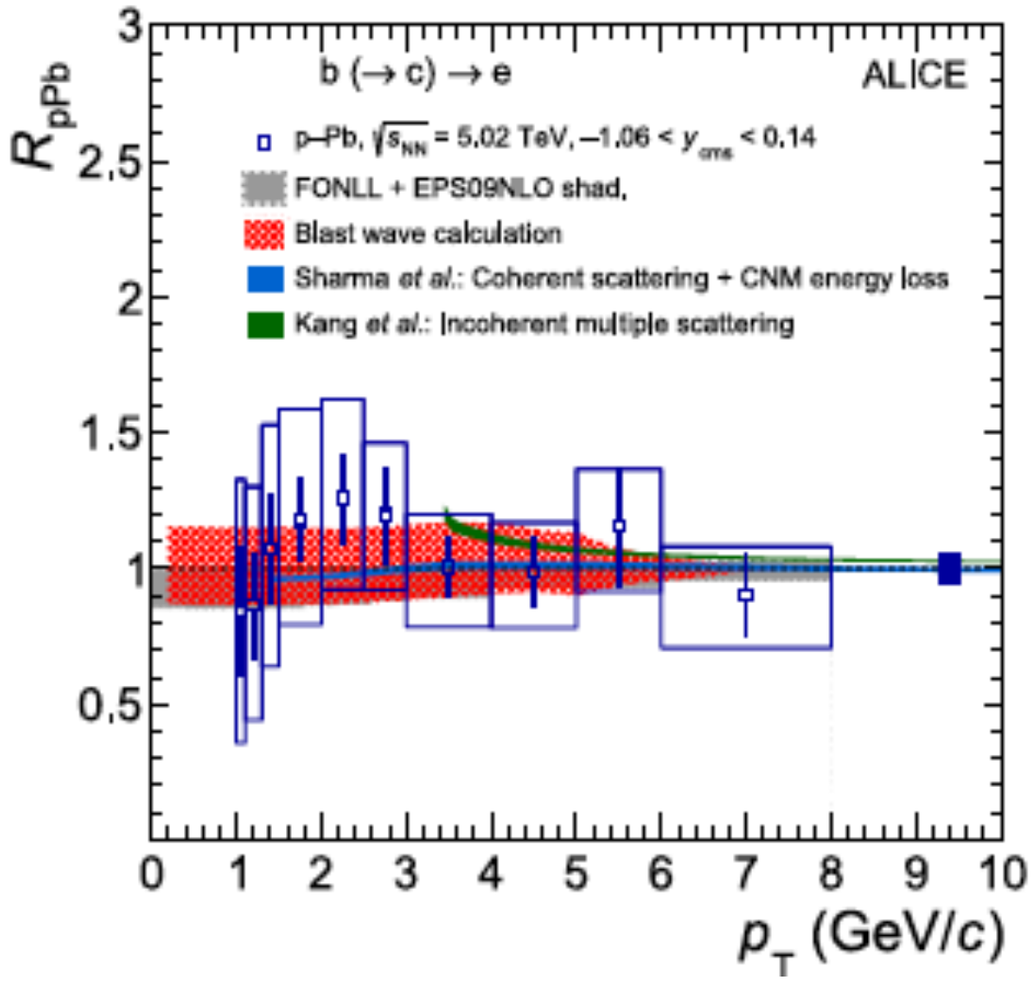
Open-beauty with ALICE

J. High Energ. Phys. (2017) 2017: 52





- ☑ Beauty electrons results are compatible with unity within uncertainties
- ☑ Models describe well the R_{pPb}

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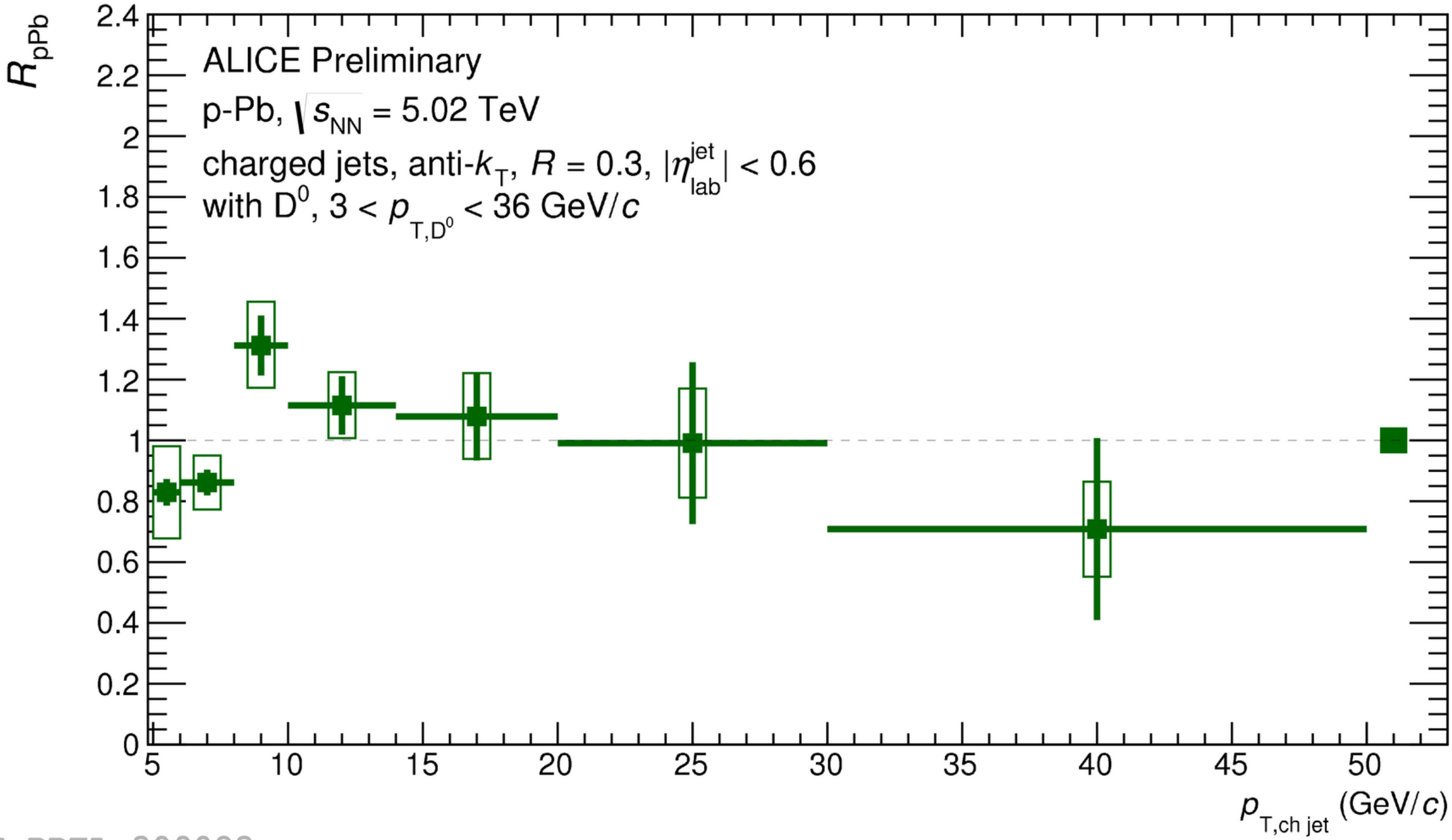
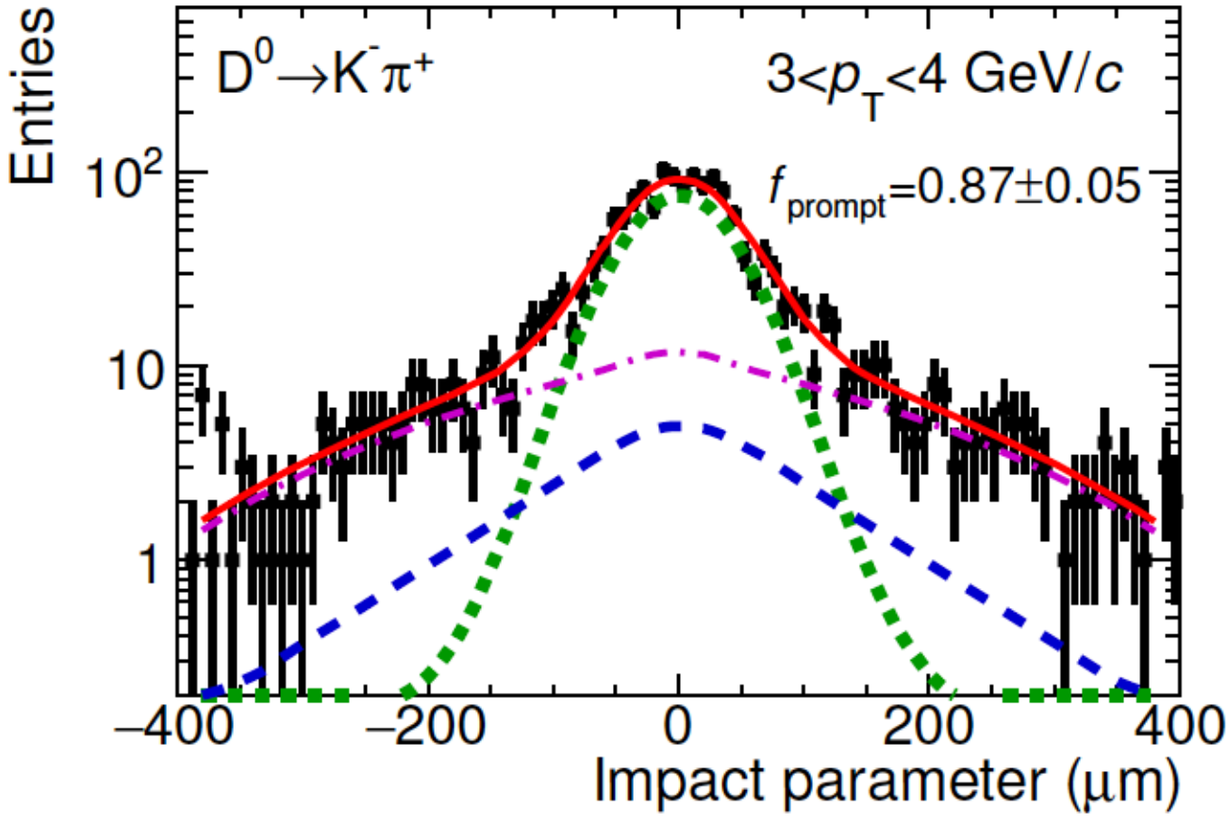
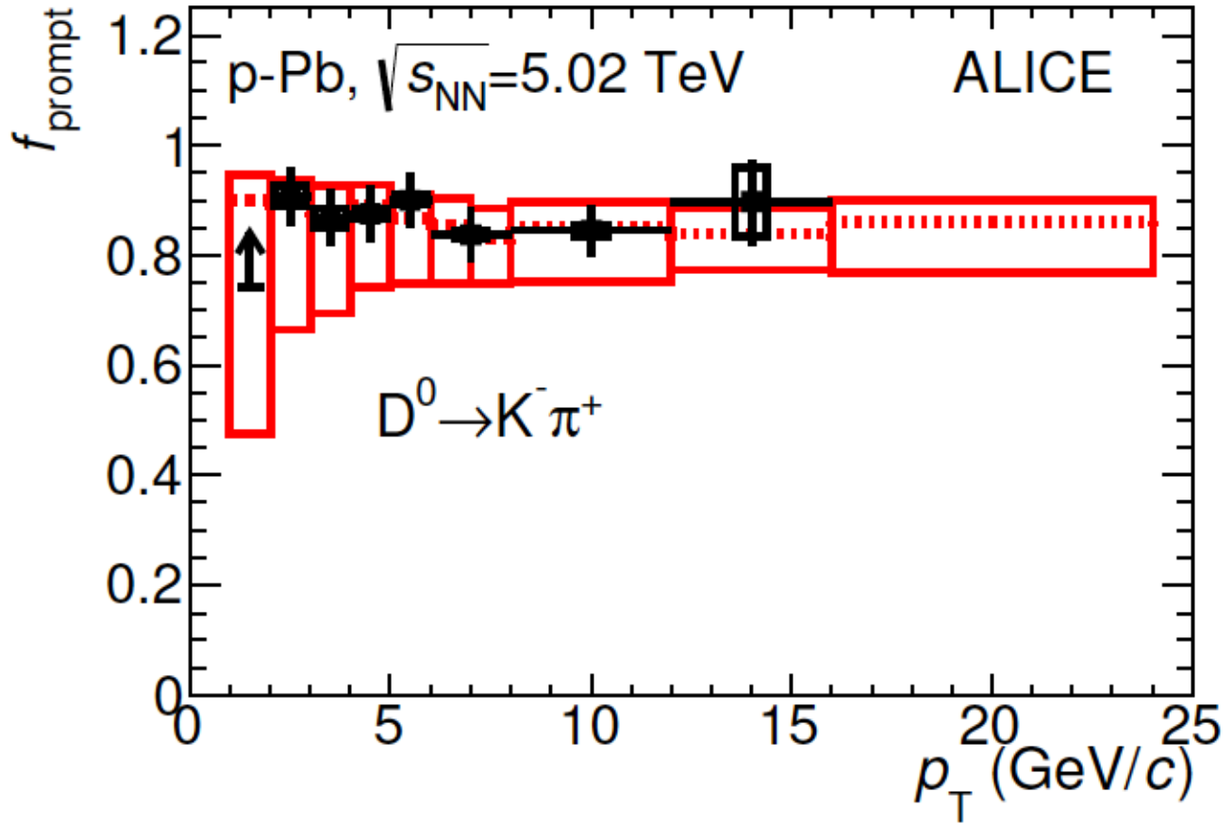
D tagged jets R_{pPb}



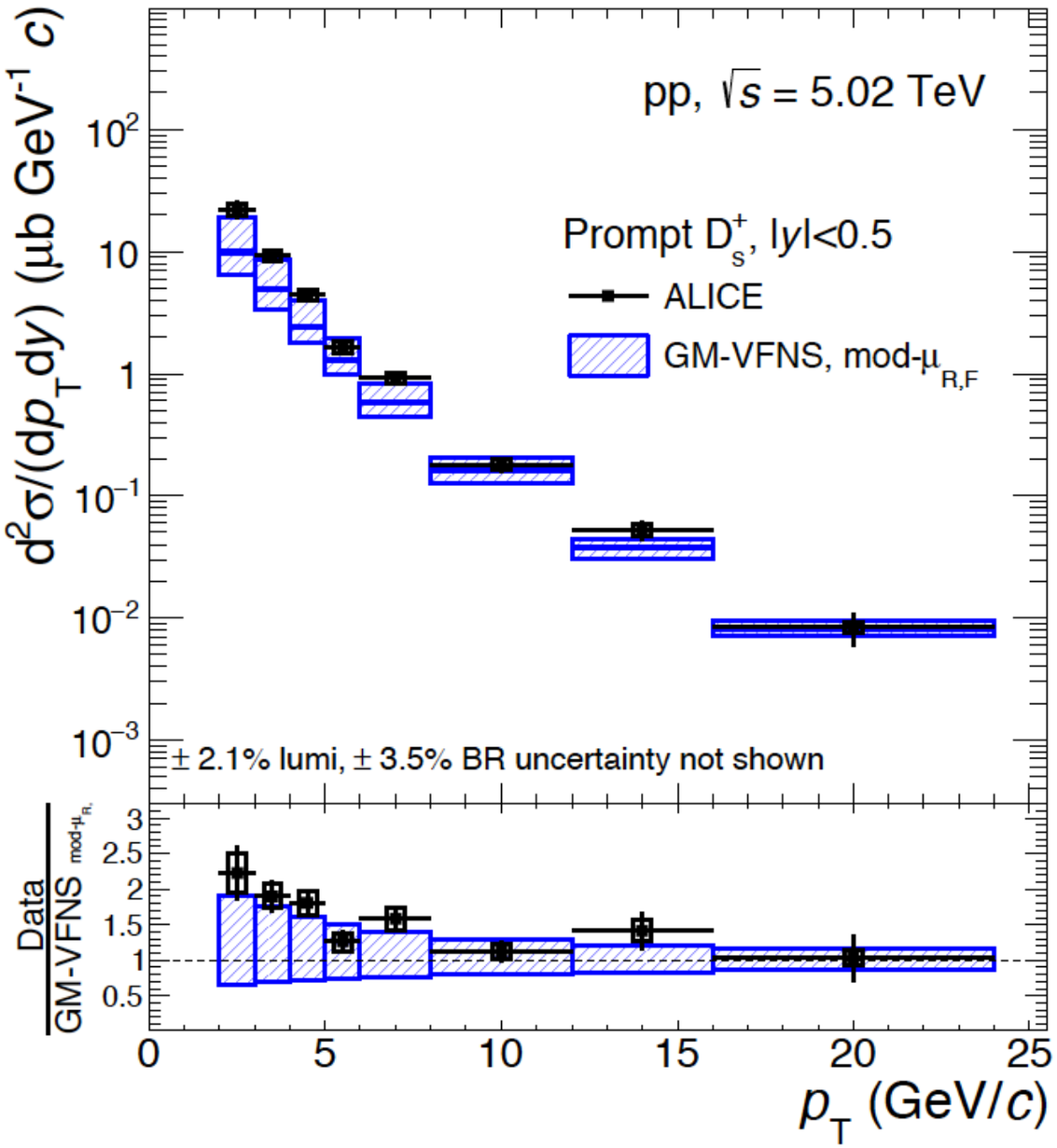
ALI-PREL-309083

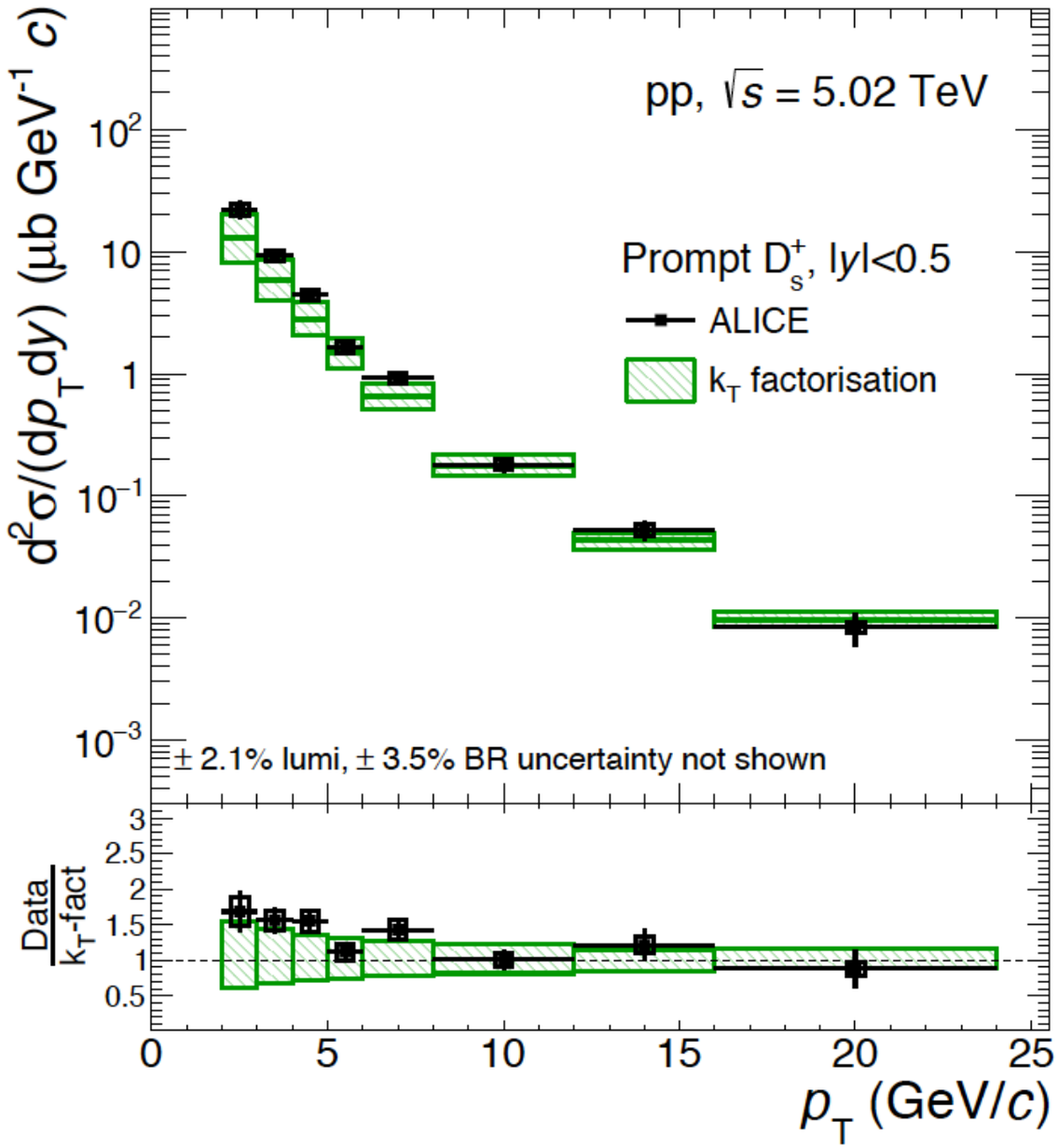
D mesons prompt fraction



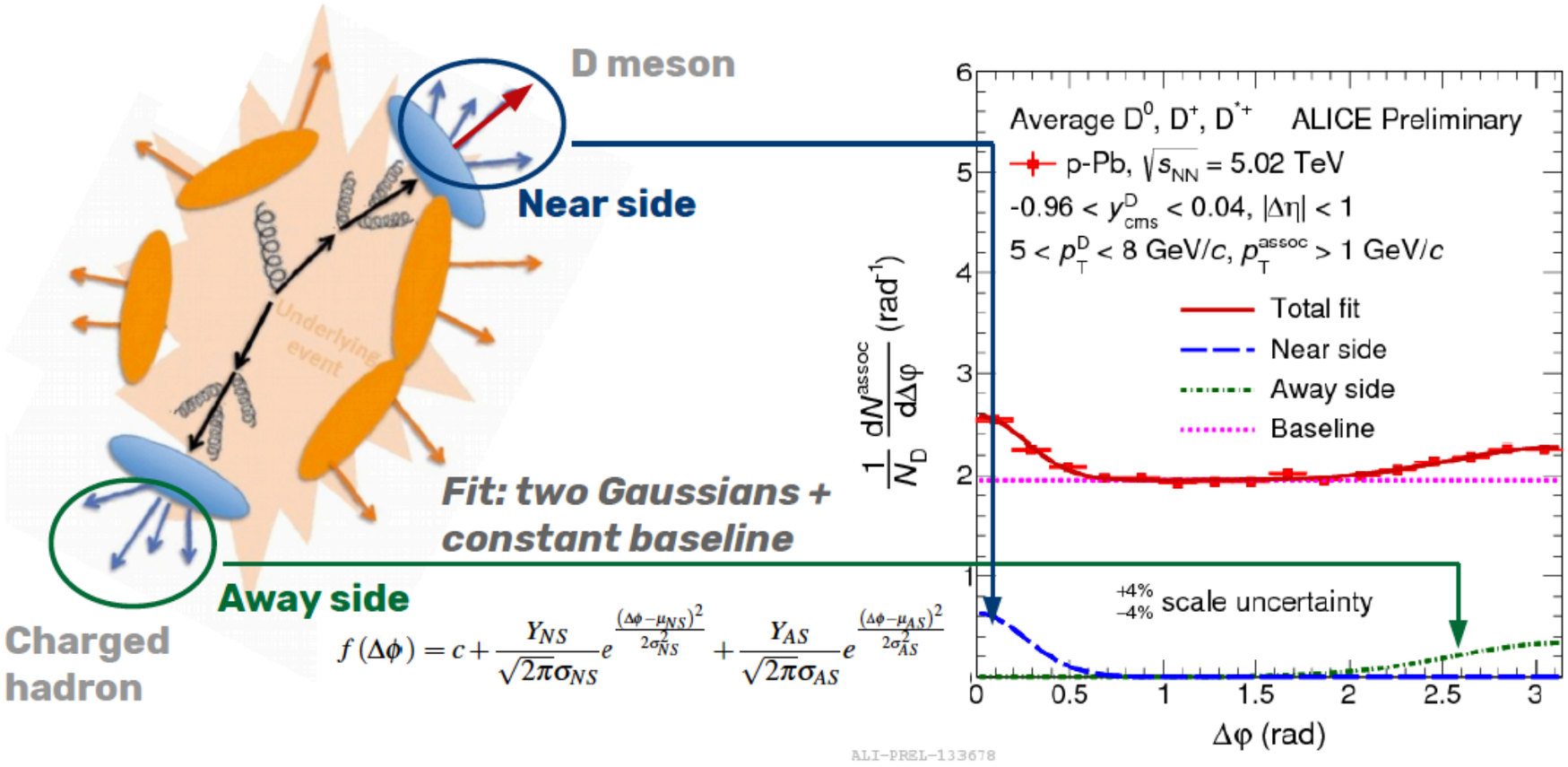


Ds production in pp at 5.02 TeV





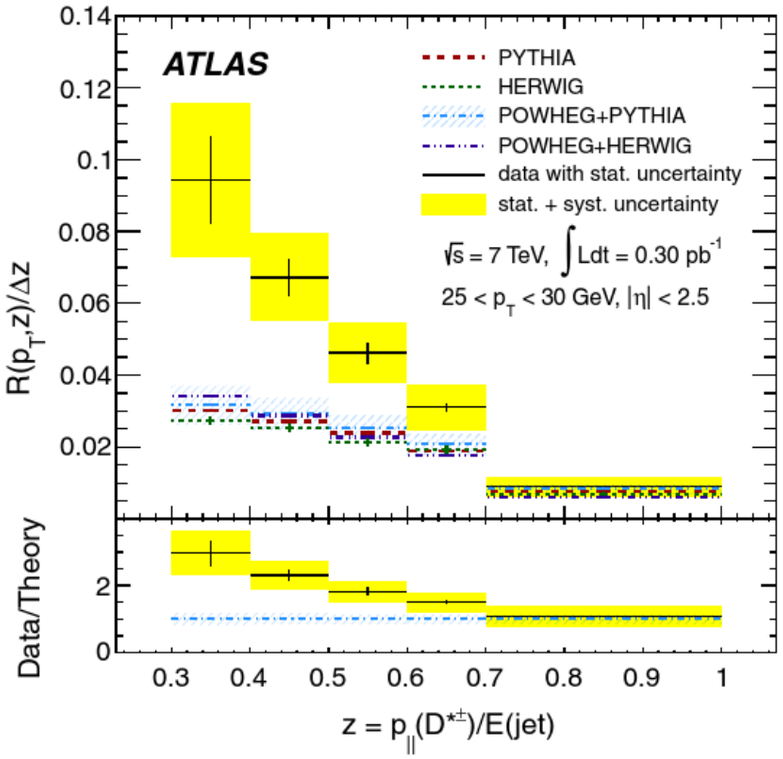
D-h correlations



- Average of D^0, D^+, D^{*+} results
- D meson: “trigger” particle, correlated with charged tracks: associated particles
- Contribution from the B feed-down subtracted
  - ✓ Based on FONLL beauty cross section and correlation templates from PYTHIA

D-tagged jets

PRD 85, 052005 (2012)



pp collisions:

- Sensitive probes of pQCD
- Further constraints on the heavy-favour uark production mechanism and fragmentation

p-Pb collisions: cold nuclear matter efects, collectivity ?

D-tagged jets in p-Pb