Heavy-Flavour production from small systems to A-A collisions with ALICE

Alessandro Grelli

on behalf of the ALICE Collaboration

Utrecht University

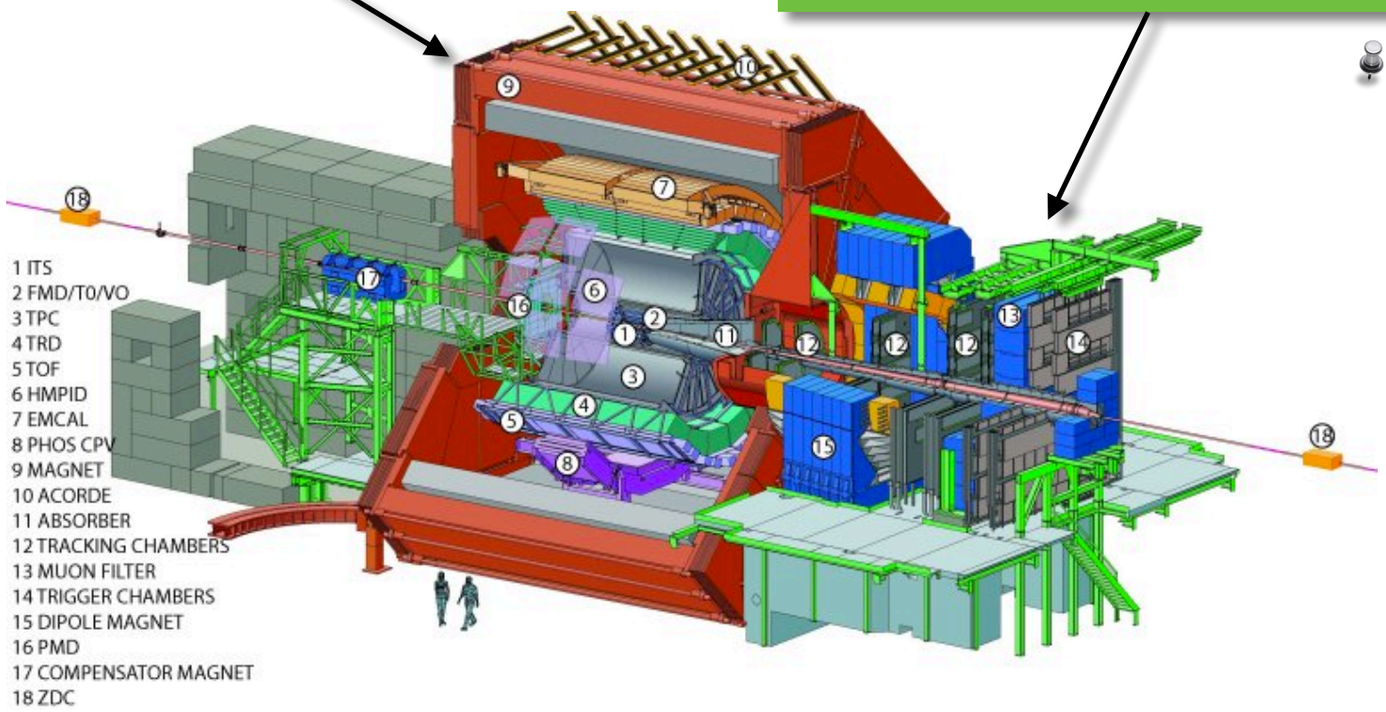
Outline

- **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.
- **A-A collisions**
  - Heavy-quark energy loss in-medium
  - Hadronization

Open heavy-flavours at ALICE

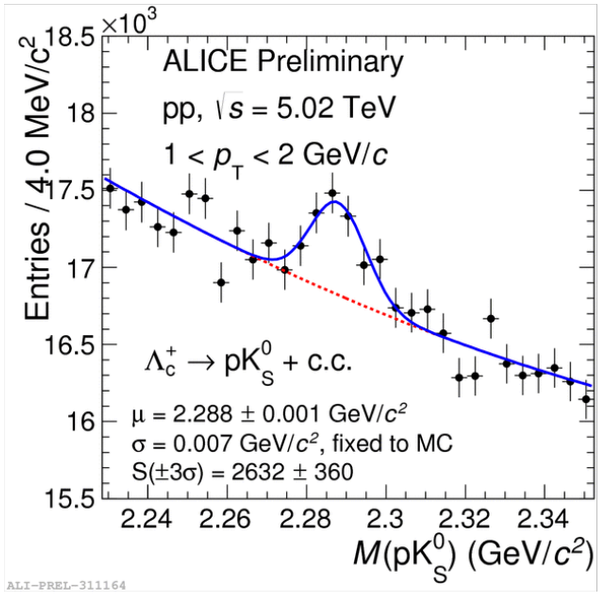
Central barrel (|y|<0.5)

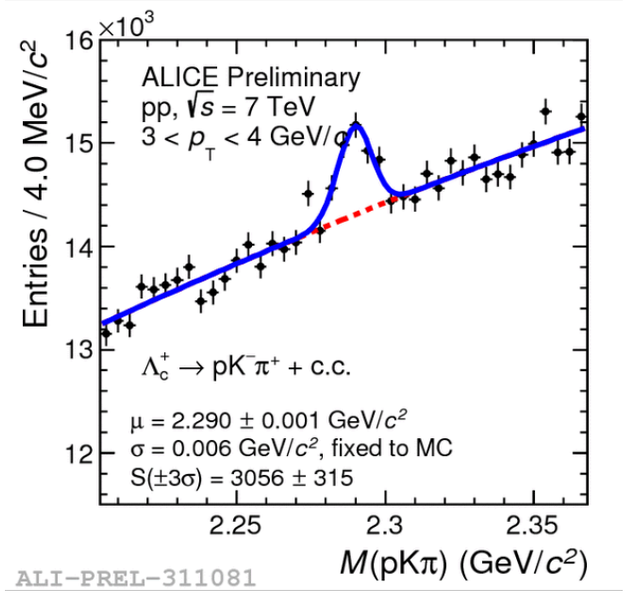
Forward muon spectrometer (2.5<y<4)



Central barrel measurements:

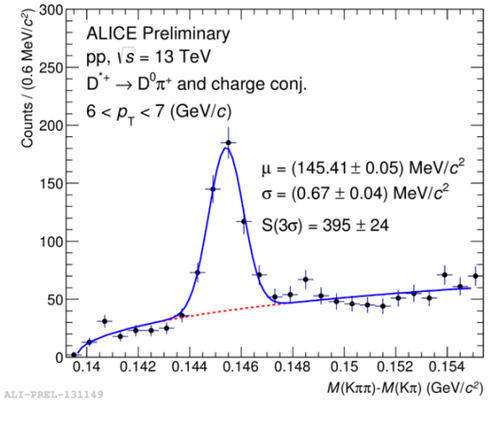
- ☑ Prompt D mesons (D^0,D^{*+}, D^+ and D_s) in hadronic channels
- ☑ Beauty via non-prompt D^0 and non-prompt J/Psi
- ☑ Charmed baryons (Λc, Ξc and Σc) in hadronic and semi-leptonic channels
- ☑ Electrons from charm and beauty hadron decays (HFe)
- ☑ Heavy-flavor jets

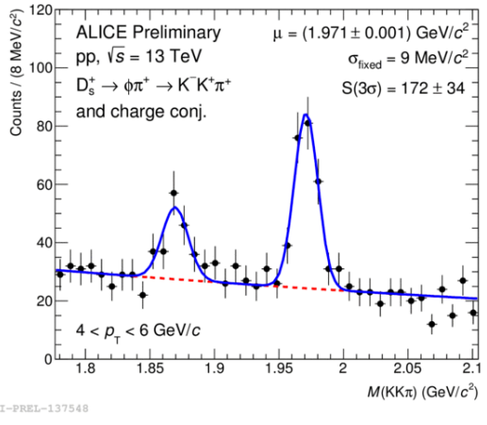




Forward rapidity measurements

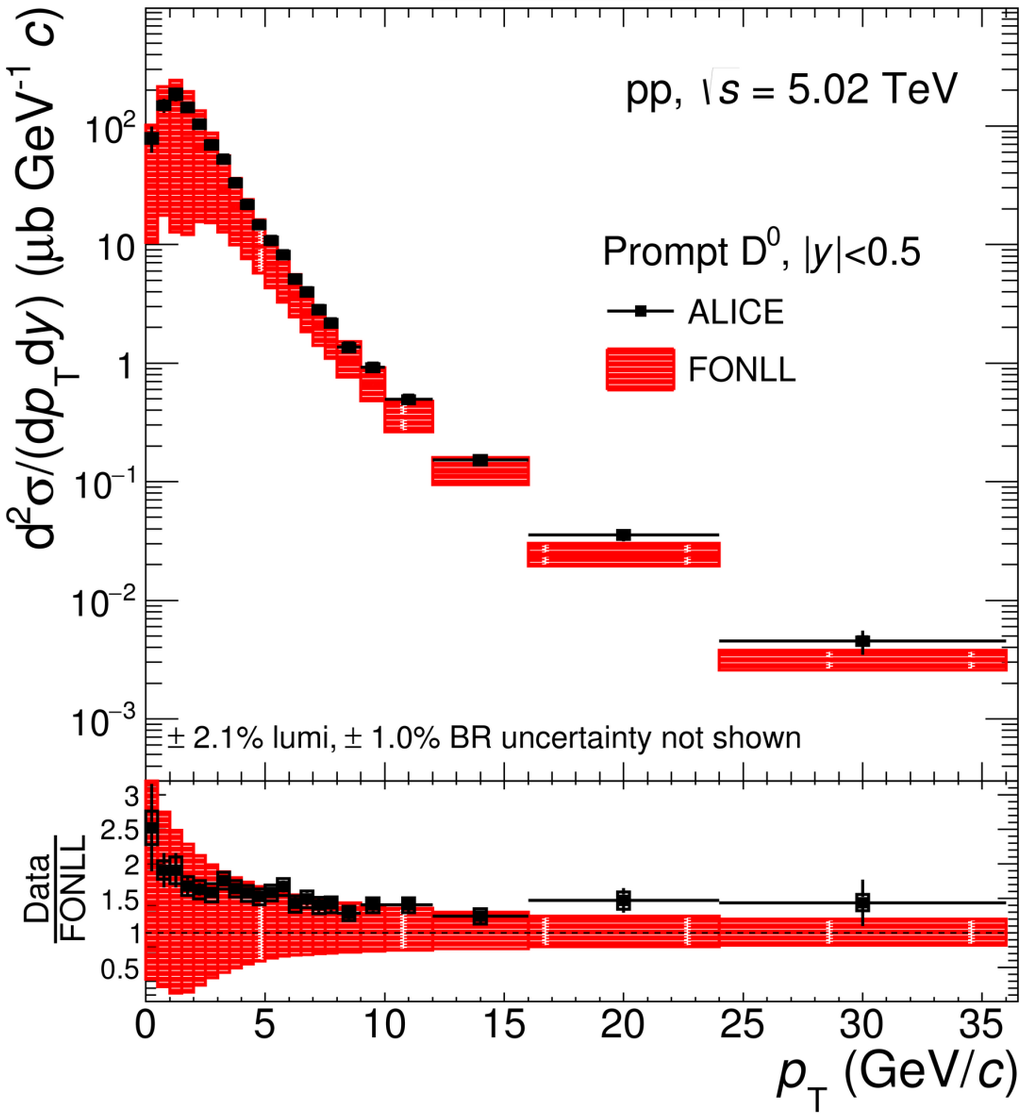
- ☑ Single muons from heavy-flavour hadron decays





HF production cross-sections at mid-rapidity

D⁰ at 5 TeV



ALI-PUB-314115

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

ALICE Coll, Eur.Phys.J. C77 (2017) no.8, 550

FONLL: JHEP 10 (2012) 137

HF production cross-sections at mid-rapidity

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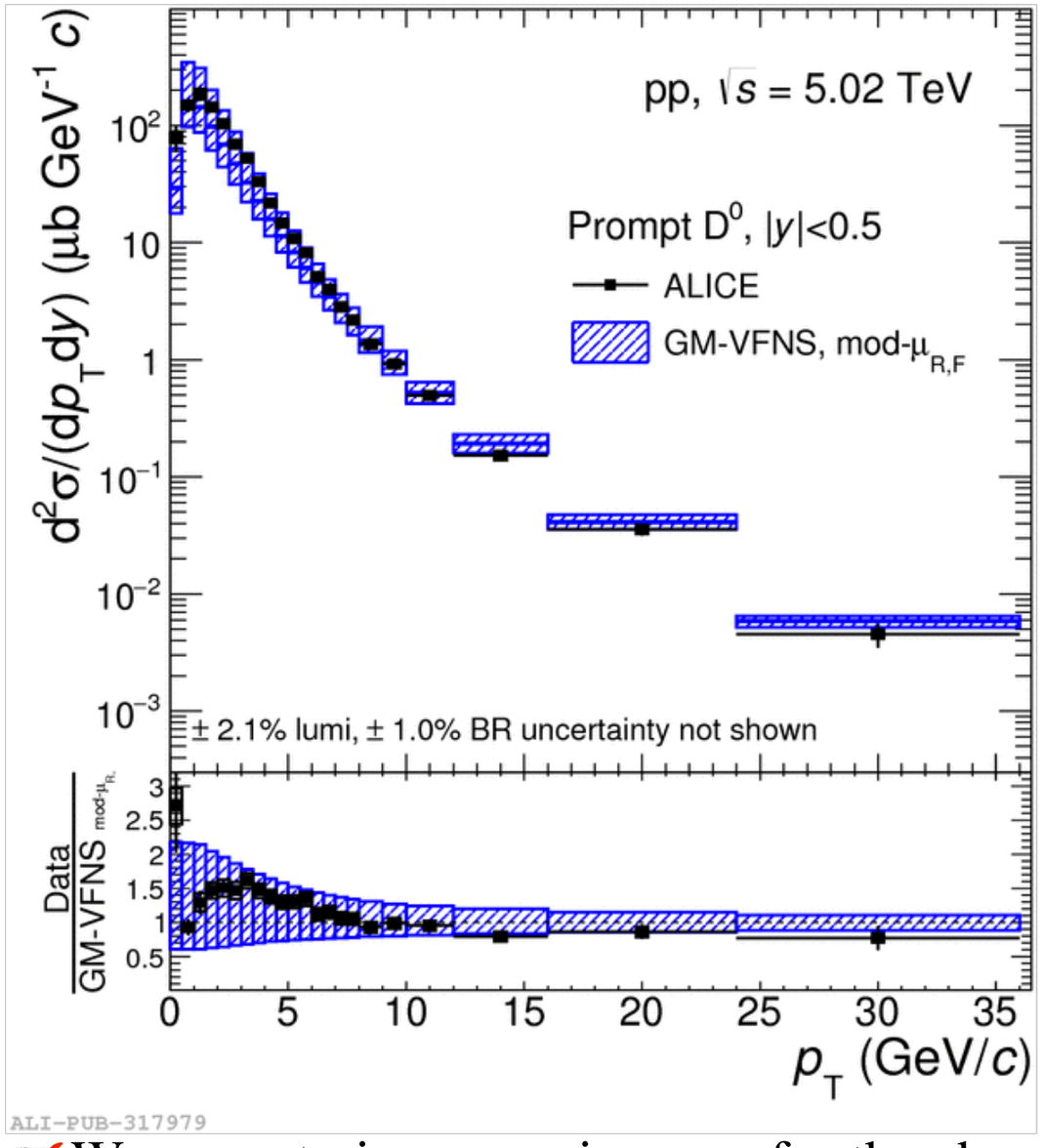
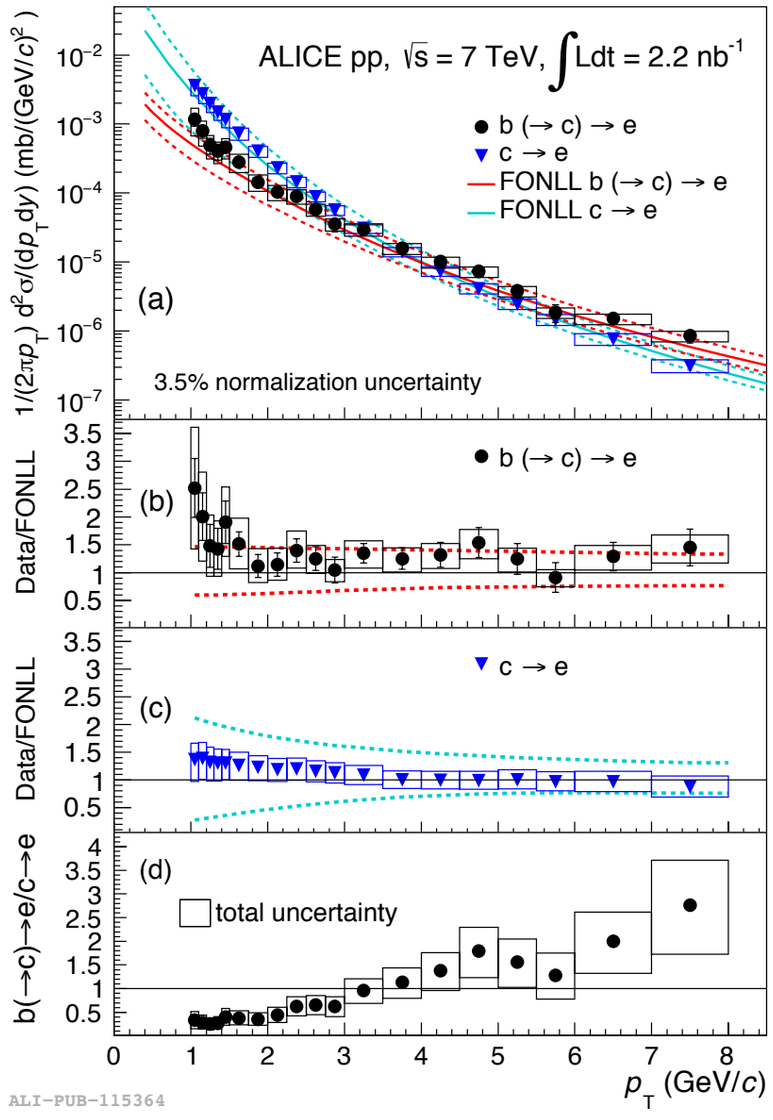


HFE at 7 TeV



Phys.Lett. B763 (2016) 507-509

JHEP 1509 (2015) 148

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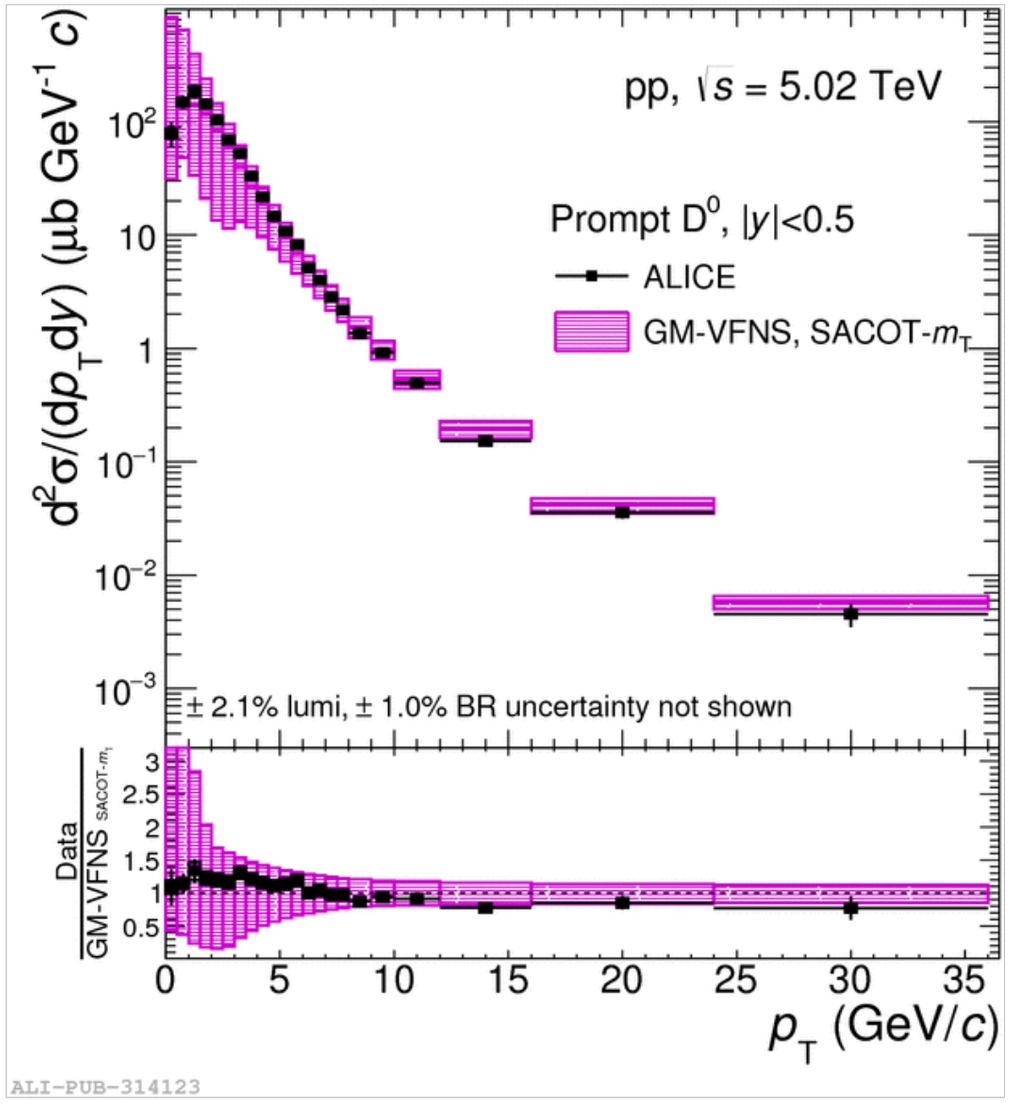
ALICE Coll, Eur.Phys.J. C77 (2017) no.8, 550

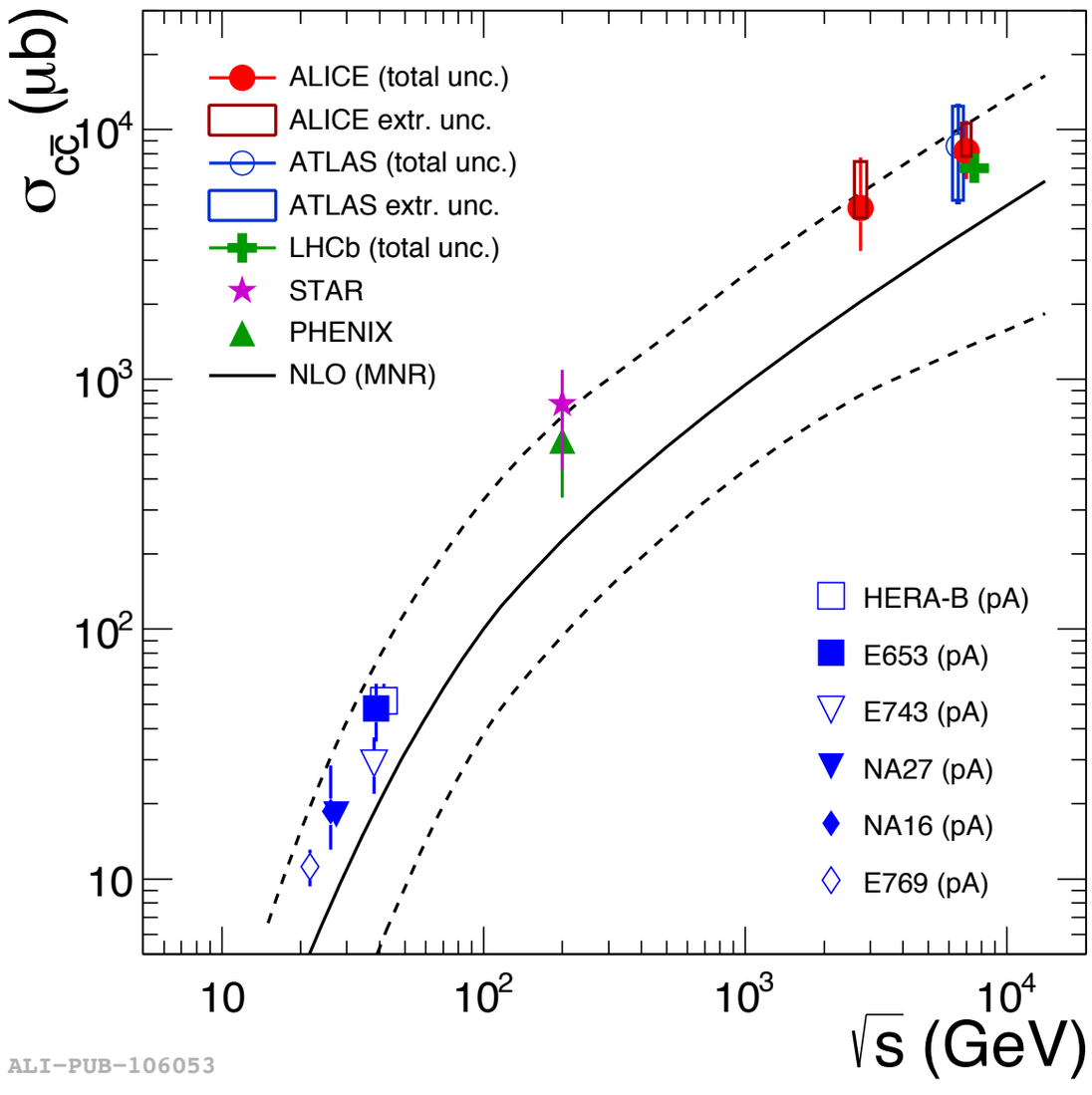
GM-VFNS: (Eur. Phys. J. C72 (2012) 2082

HF production cross-sections at mid-rapidity

D^0 at 5 TeV



Total charm cross-section



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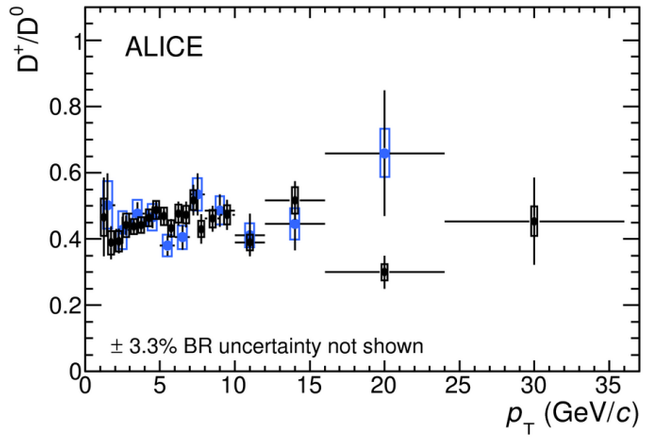
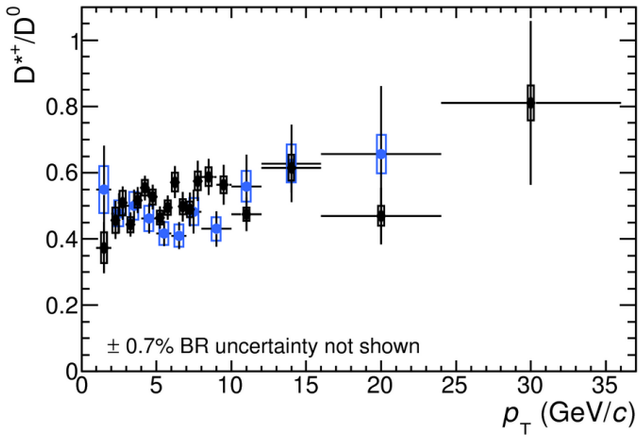
ALICE Coll, Eur.Phys.J. C77 (2017) no.8, 550

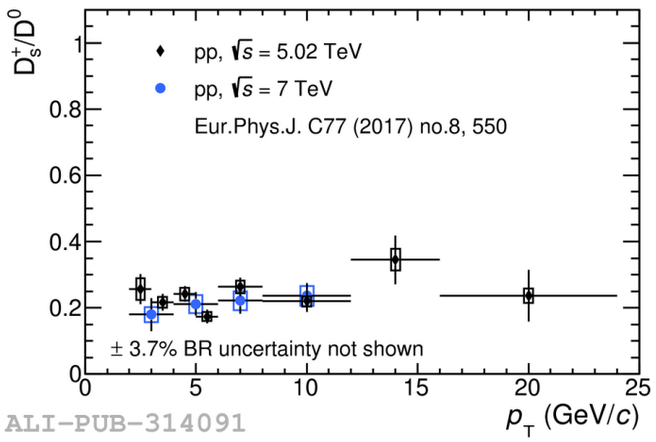
GM-VFNS, SACOT-m_T: JHEP 05(2018)196

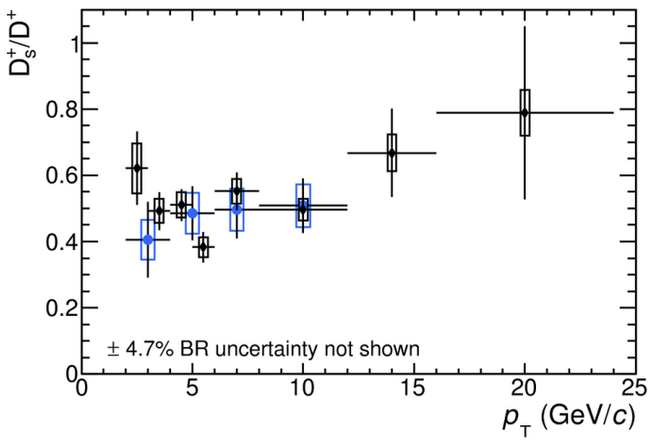
D meson ratios

Cross-section ratios

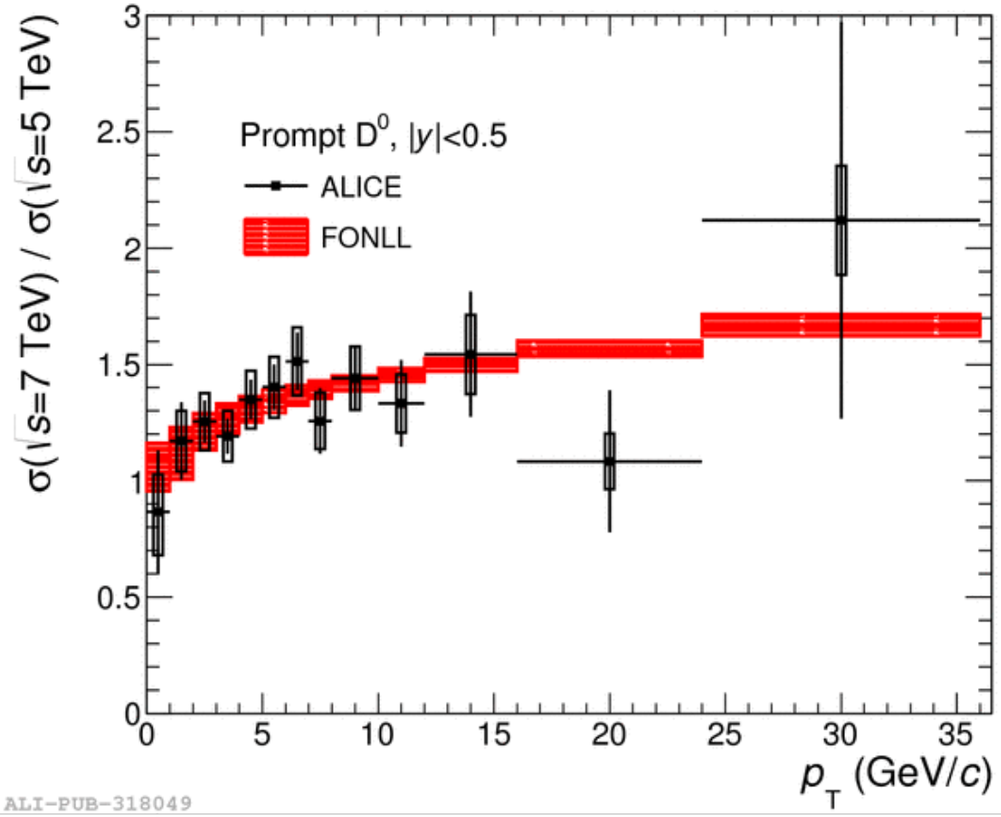








Energy ratios

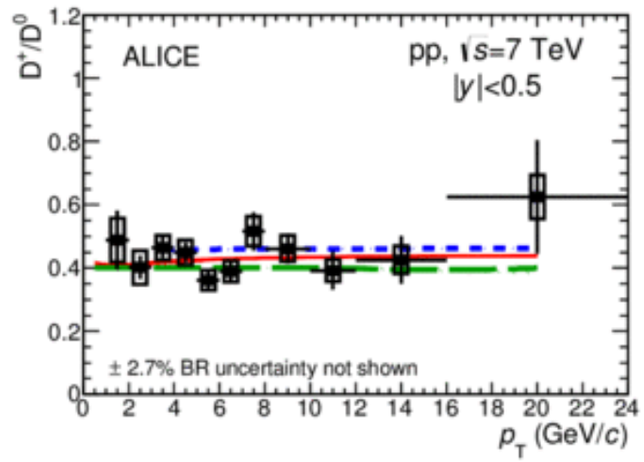


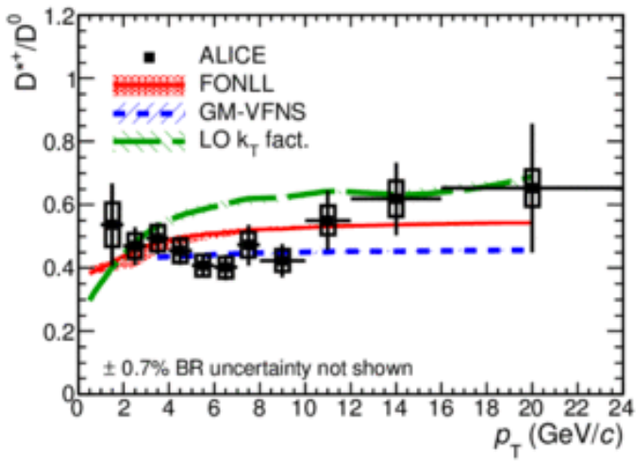
ALICE Coll, Eur.Phys.J. C79 (2019) no.5, 388

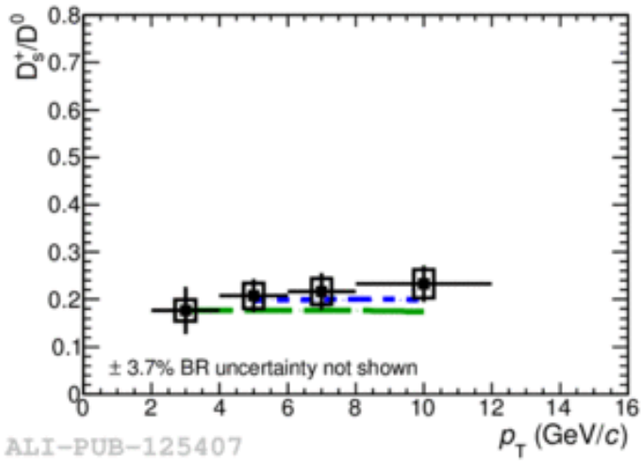
- ☑ D mesons are studied at the LHC at different collision energies (2.76, 5.02, 7, 8 and 13 TeV)
- ☑ Cross-section ratios do not show significant p_T dependence → not large difference between fragmentation to pseudoscalar (D^0, D^+ and D_s) and vector (D^{*+}) mesons, nor to strange and non-strange mesons

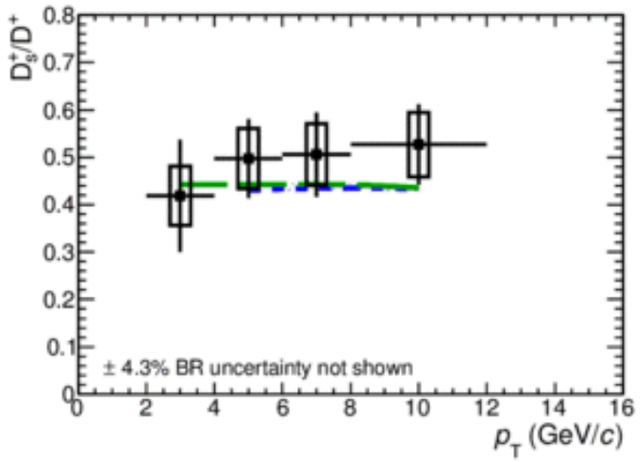
D meson ratios

Cross-section ratios



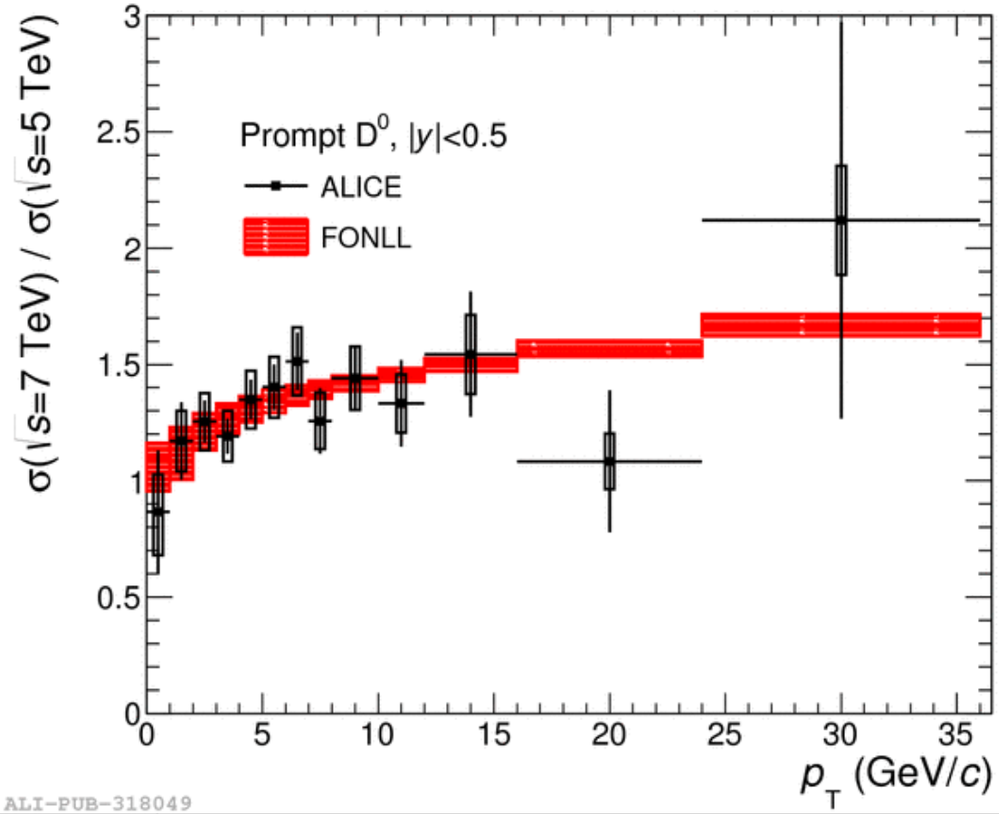






ALI-PUB-125407

Energy ratios



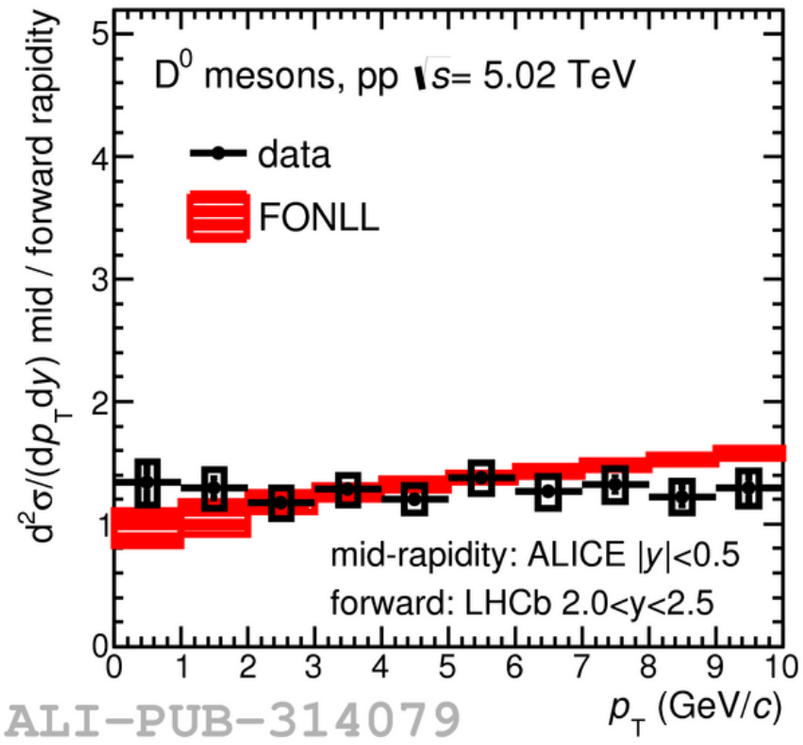
ALI-PUB-318049

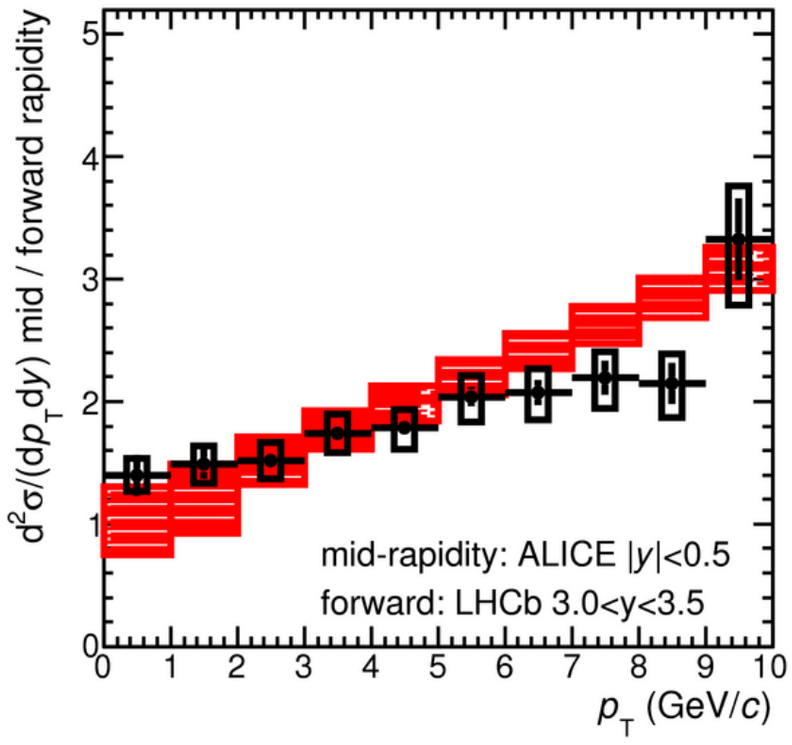
ALICE Coll, Eur.Phys.J. C79 (2019) no.5, 388

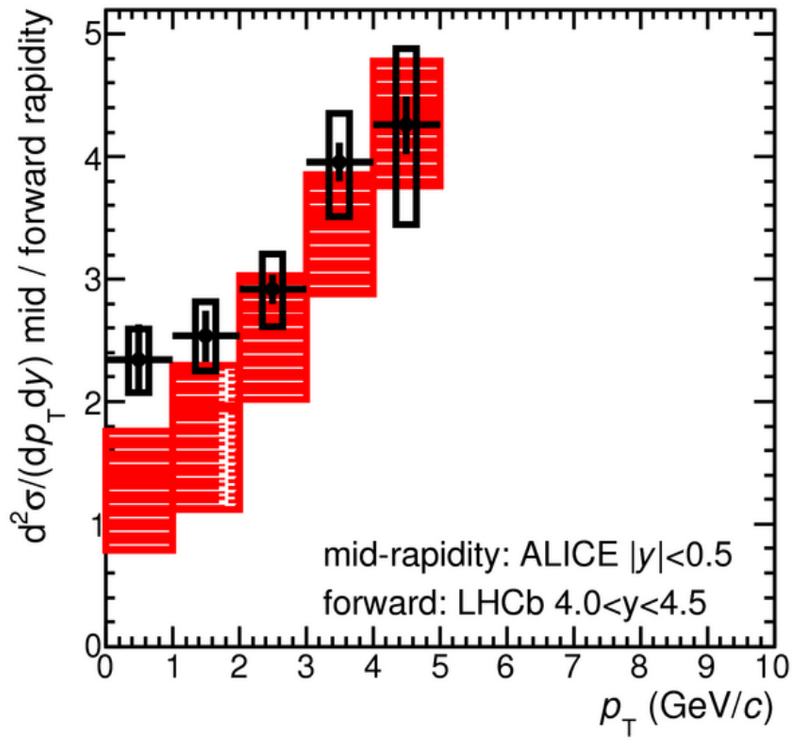
- ☑ D mesons are studied at the LHC at different collision energies (2.76, 5.02, 7, 8 and 13 TeV)
- ☑ Cross-section ratios do not show significant p_T dependence → not large difference between fragmentation to pseudoscalar (D^0, D^+ and D_s) and vector (D^{*+}) mesons, nor to strange and non-strange

Central to forward ratio

ALICE Coll, Eur.Phys.J. C79 (2019) no.5, 388



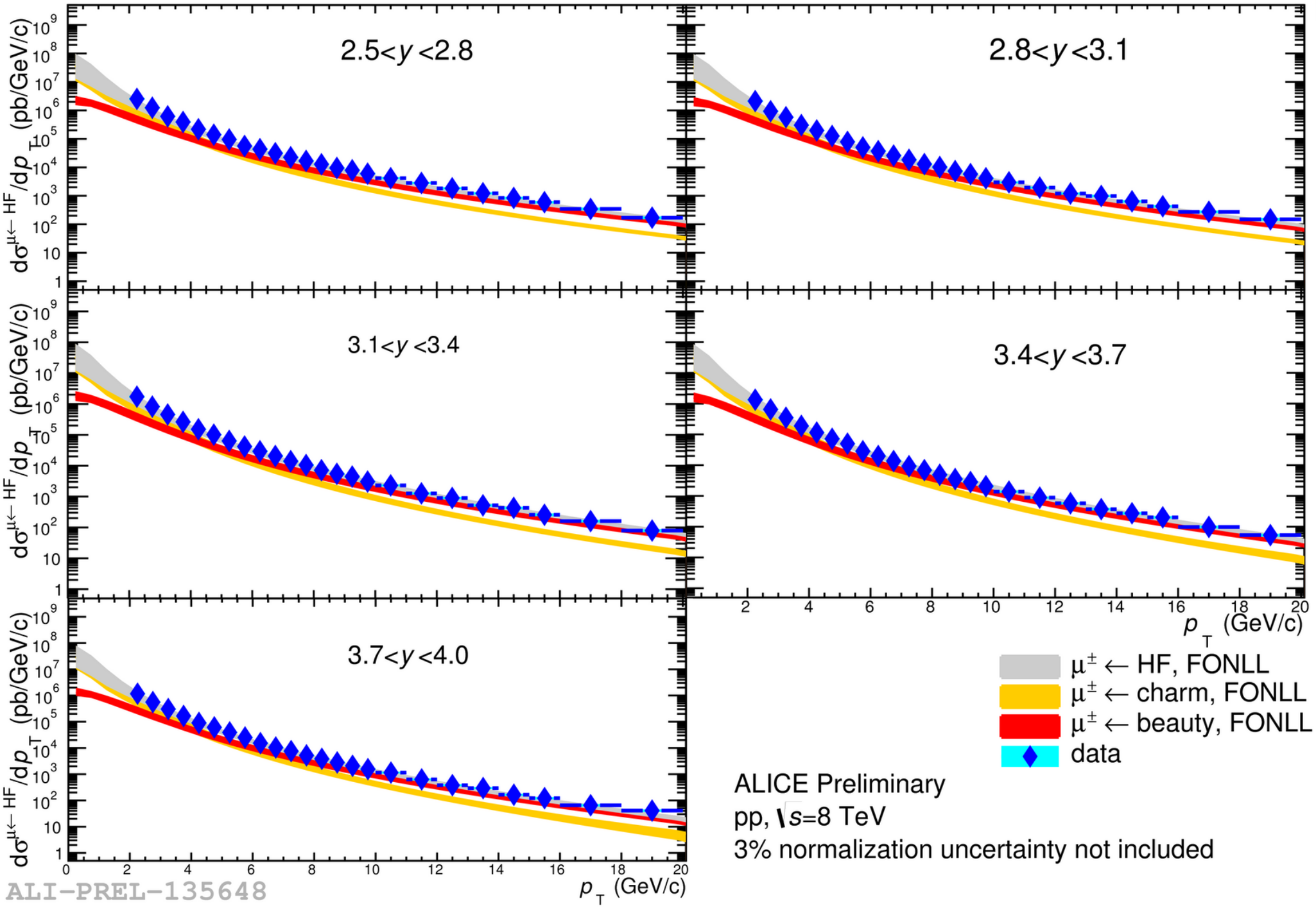




- ☑ Precise measurement down to ~0 p_T
- ☑ Mid- forward ratio can provide additional sensitivity to gluon PDF at small Bjorken-x (10^{-4}-10^{-5})
- ☑ Comparison with FONLL show compatibility but tend to hint a different slope

Muons at forward rapidity

ALICE Coll, JHEP 1909 (2019) 008



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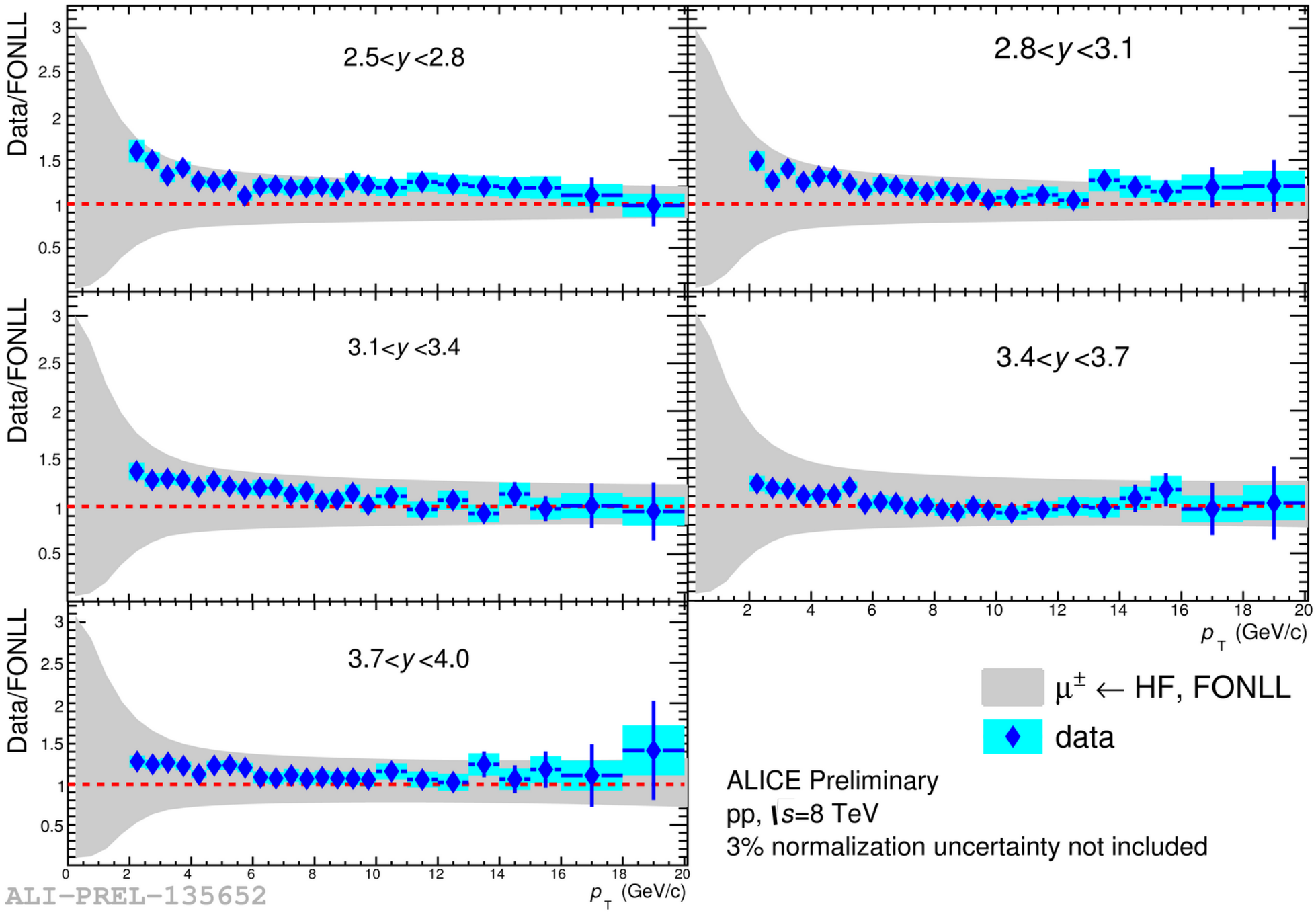

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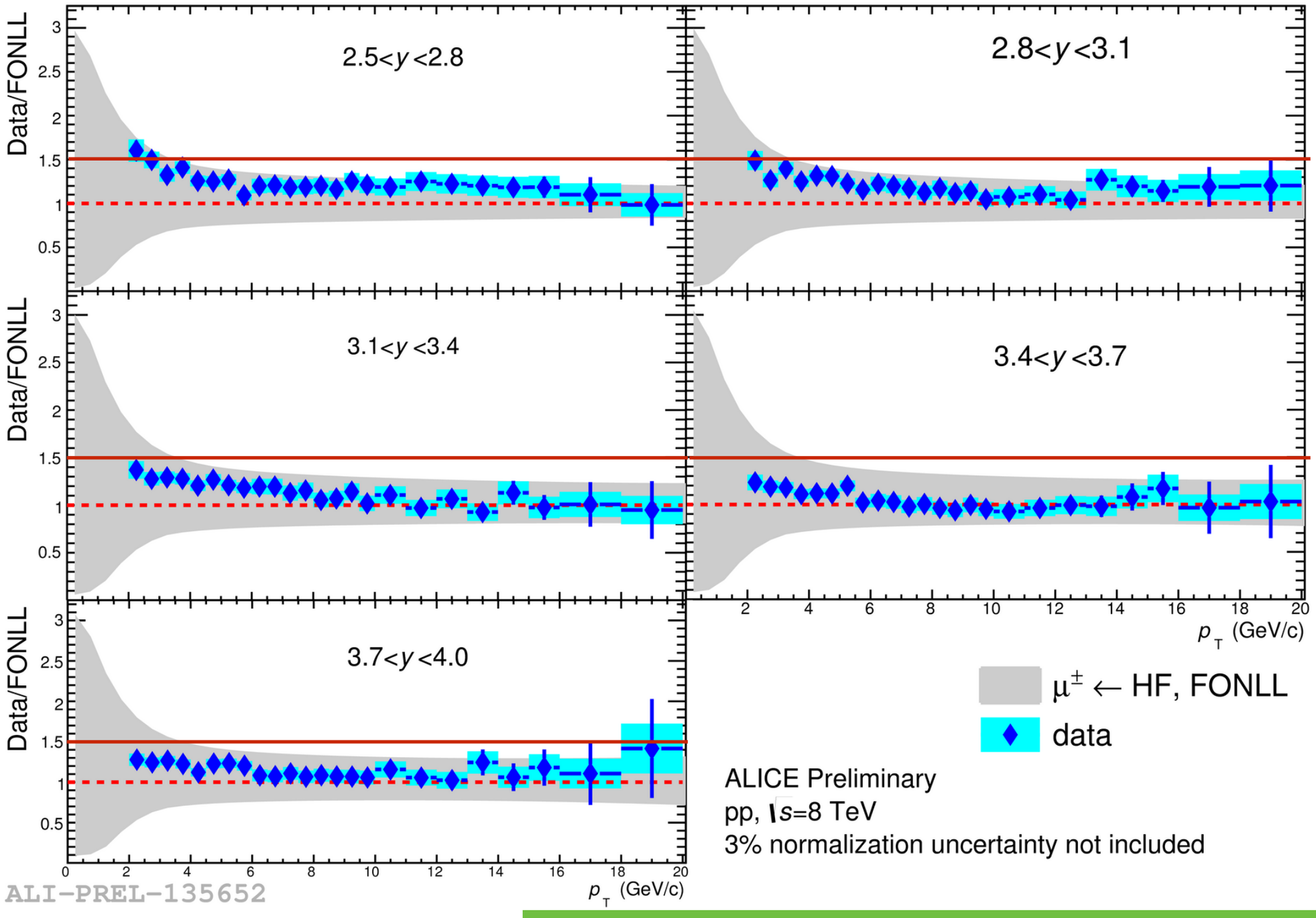
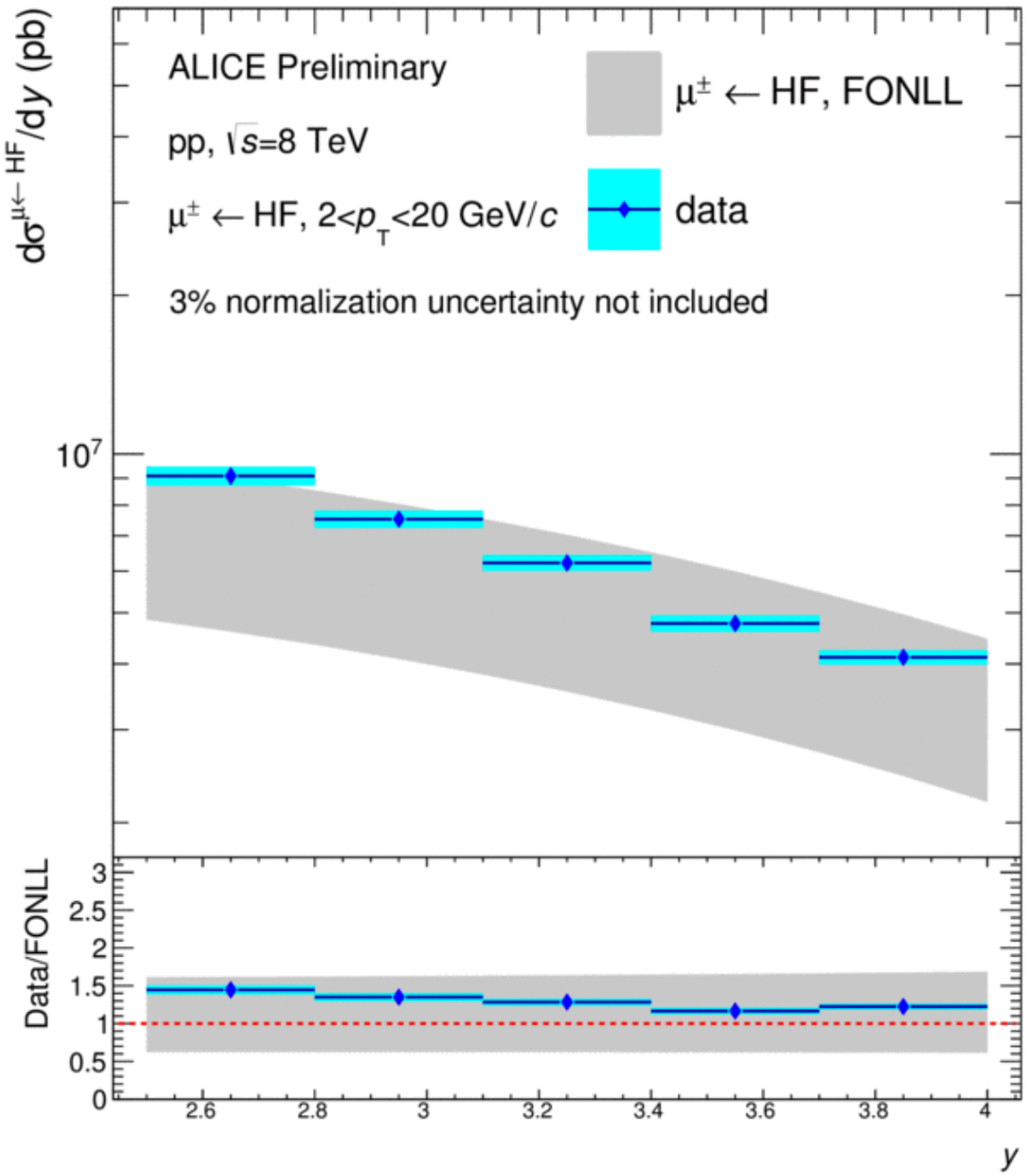


Tendency of a better agreement with FONLL going more forward

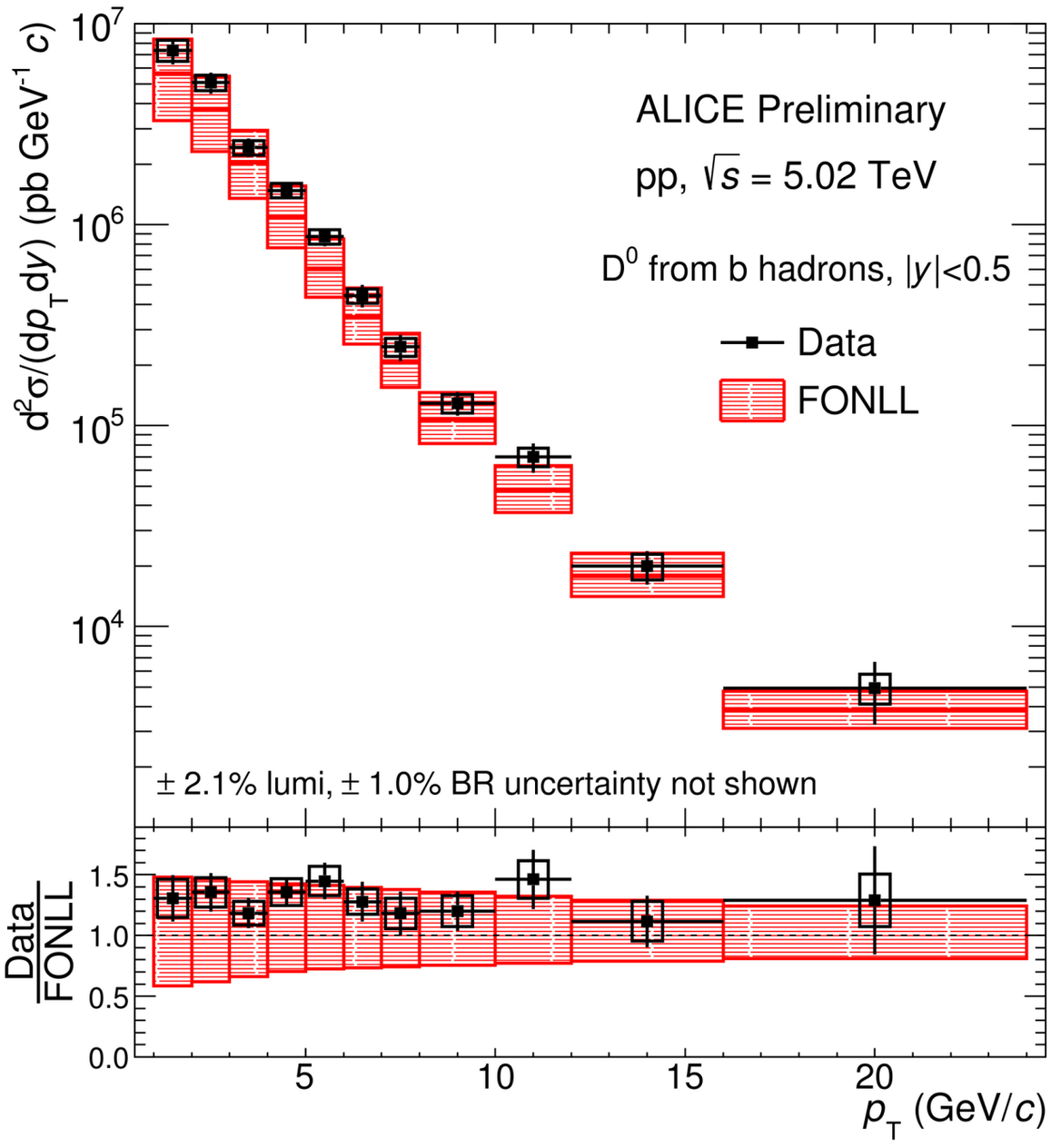
Muons at forward rapidity



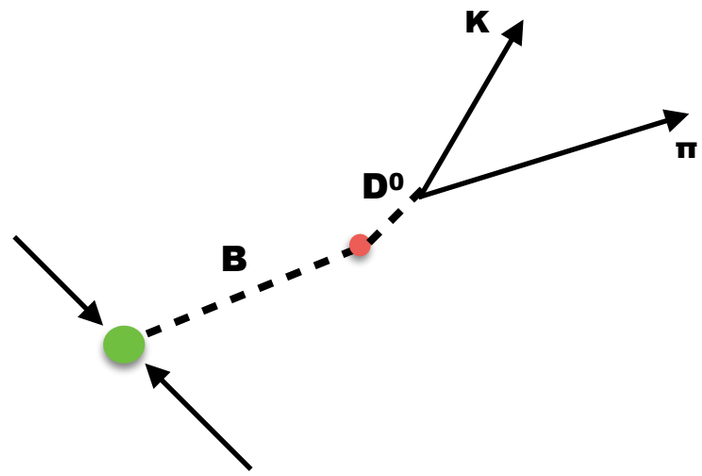
ALI-PREL-135656

- ☑ Data extremely precise -> strong test of pQCD
- ☑ Data in agreement with the model within model uncertainty, however, tendency of a better agreement at large rapidities

Beauty via non-prompt D^0

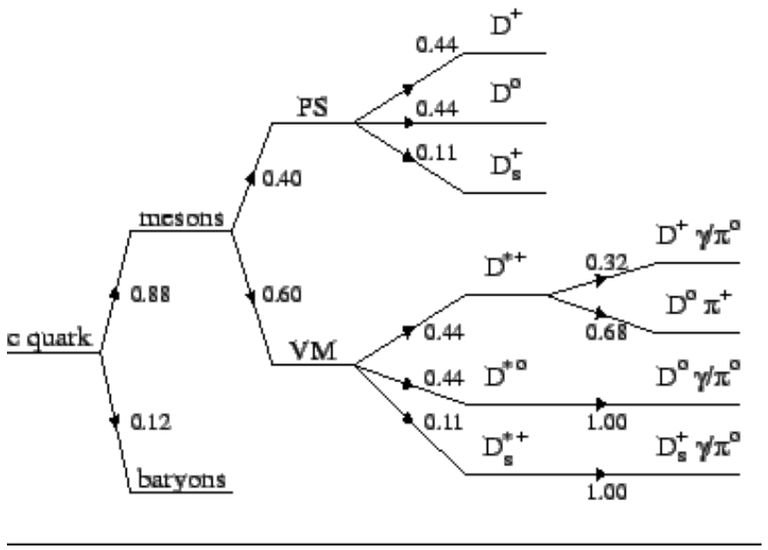


ALI-PREL-319648

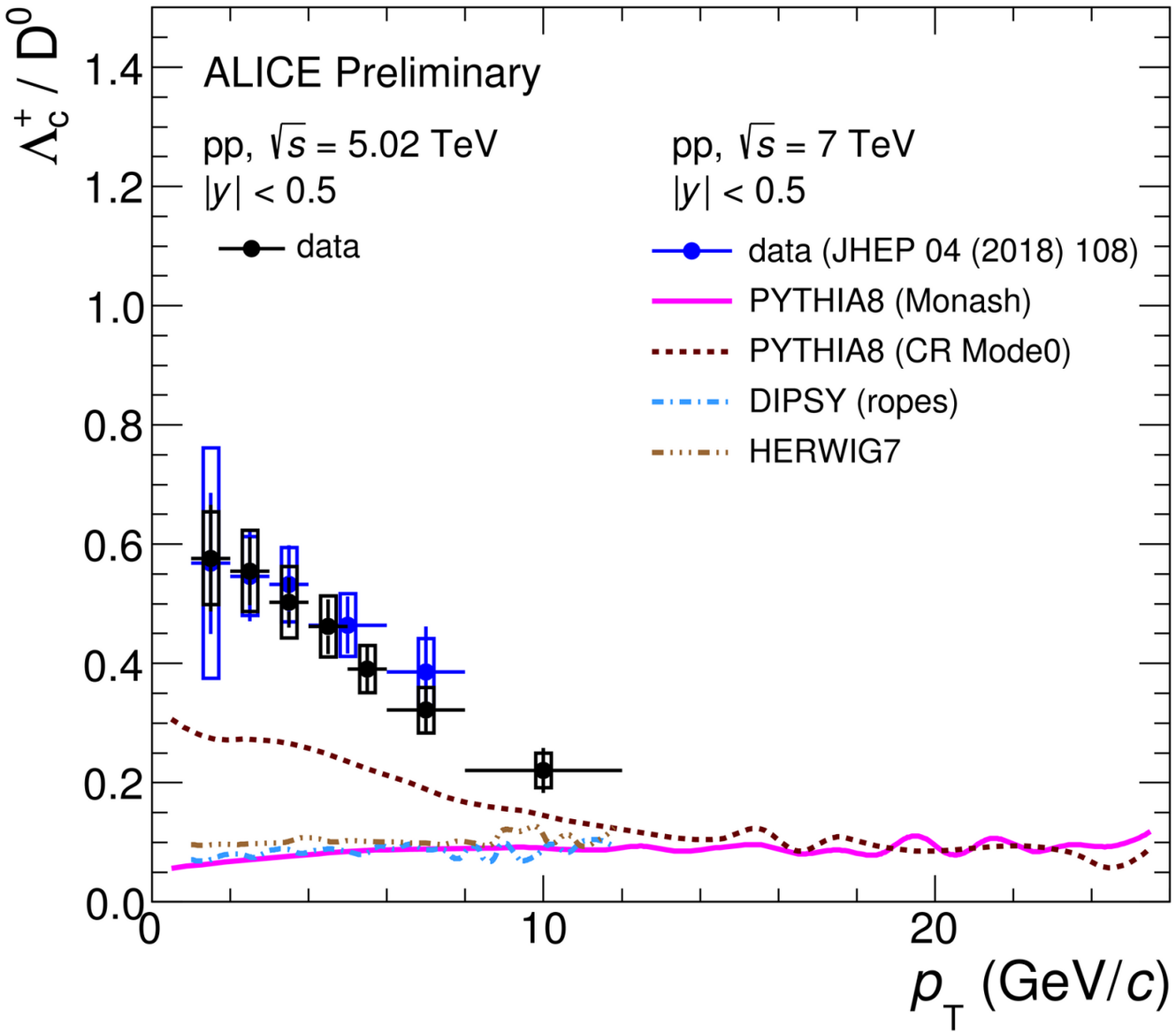


- ☑ Reasonably precise measurement down to $p_T \sim 1$ GeV/c
- ☑ Exploit Machine Learning algorithms
- ☑ Data in agremeent with model within model uncertainty, however, tendency to be at the upper limit.

Charm fragmentation and hadronization



Λ_c production in pp, p-Pb

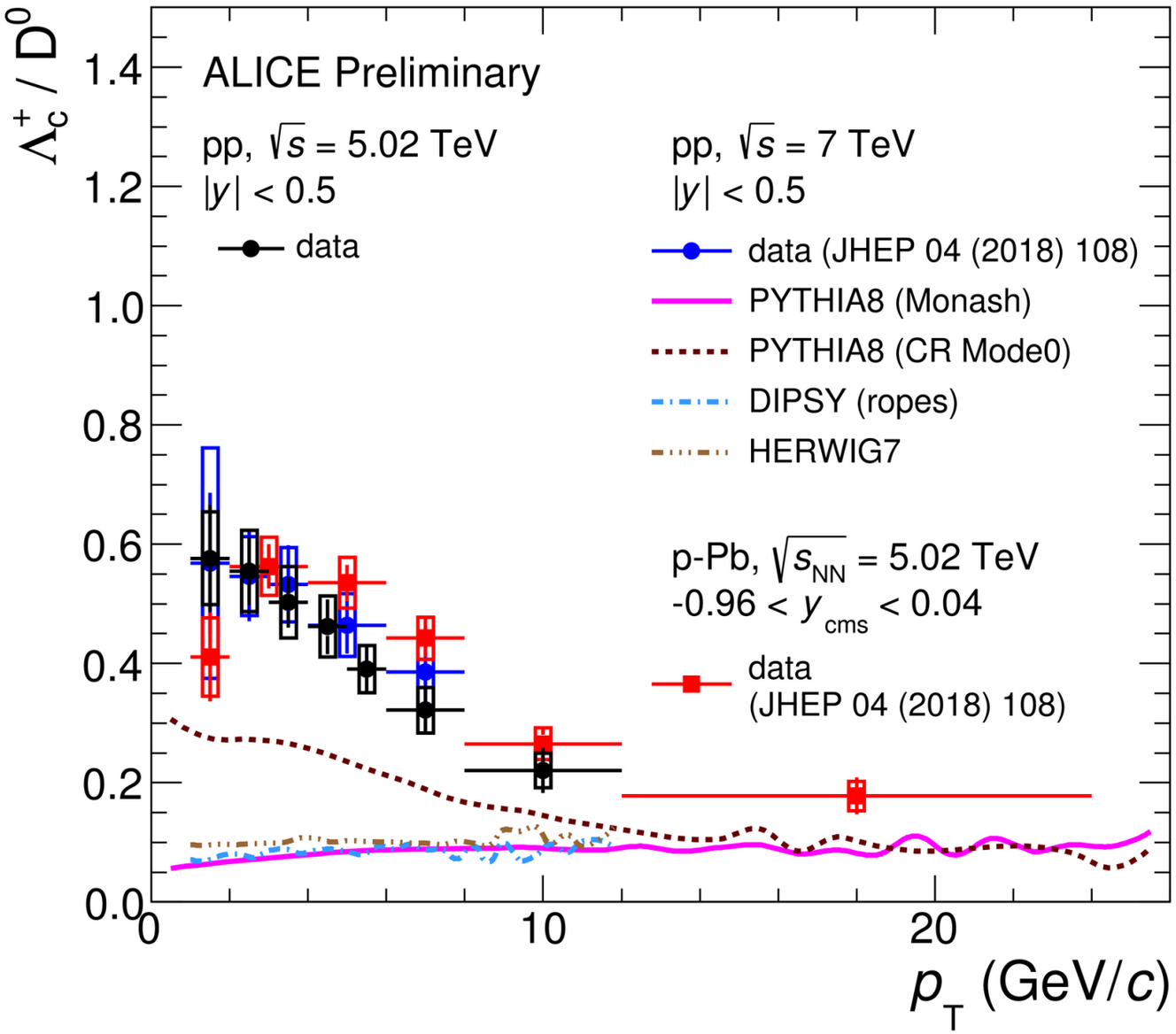


ALI-PREL-311156

- 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 p_T range, sits in the 0.1-0.2 region. Challenge the universality of the fragmentation functions? Need to measure the z value
- New analysis in pp at 5 TeV largely improves the precision (factor 2 in [1,2] GeV/c) and extends the p_T range

Zeus Collaboration, ArXiv:1306.4862

Λ_c production in pp, p-Pb

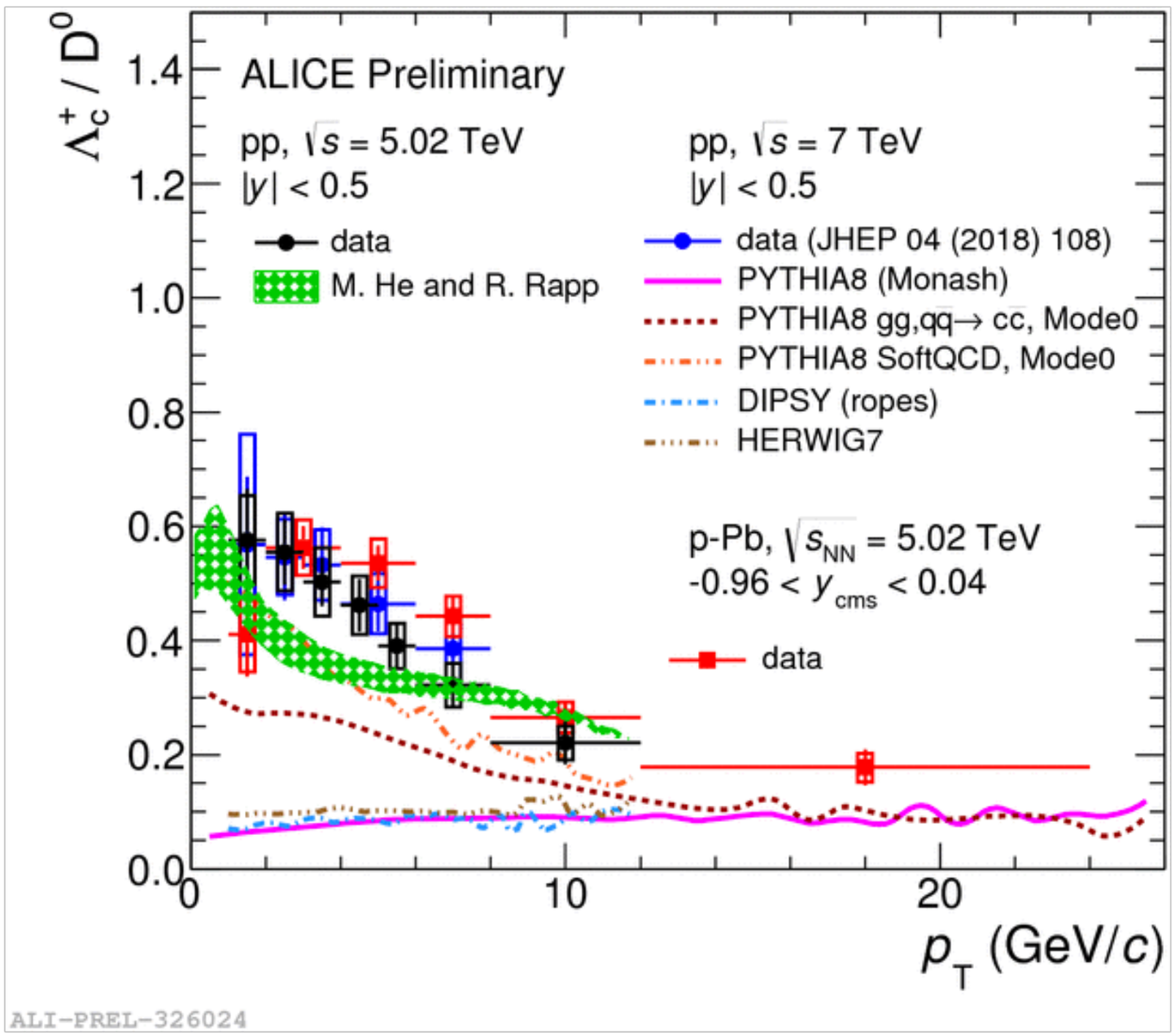


ALI-PREL-311152

- ☑ 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 p_T range, sits in the 0.1-0.2 region. Challenge the universality of the fragmentation functions? Need to measure the z value
- ☑ New analysis in pp at 5 TeV largely improves the precision (factor 2 in [1,2] GeV/c) and extends the p_T range
- ☑ Comparison with p-Pb result shows a similar (?) trend. Need more data to conclude

Zeus Collaboration, ArXiv:1306.4862

Λ_c production in pp, p-Pb



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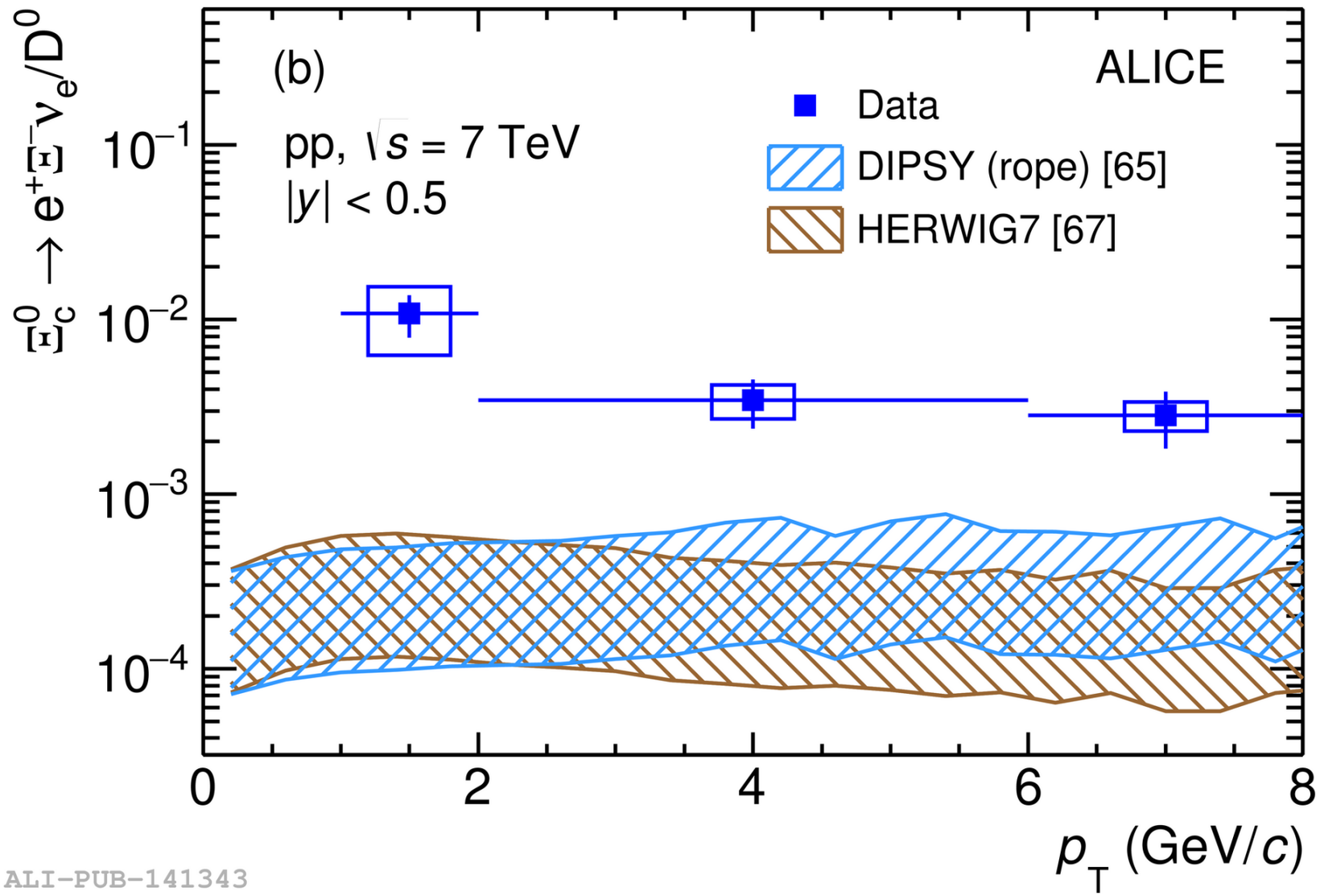
- New analysis in pp at 5 TeV largely improves the precision (factor 2 in [1,2] GeV/c) and extends the p_T range
- Comparison with p-Pb result shows a similar (?) trend. Need more data to conclude
- Pythia Mode 0 and M.He and R. Rapp can get the shape of the ratio but not yet the magnitude

Zeus Collaboration, ArXiv:1306.4862

Rapp et al. PLB, 795, 10 August 2019, Pages 117-121

Ξ_c production in pp

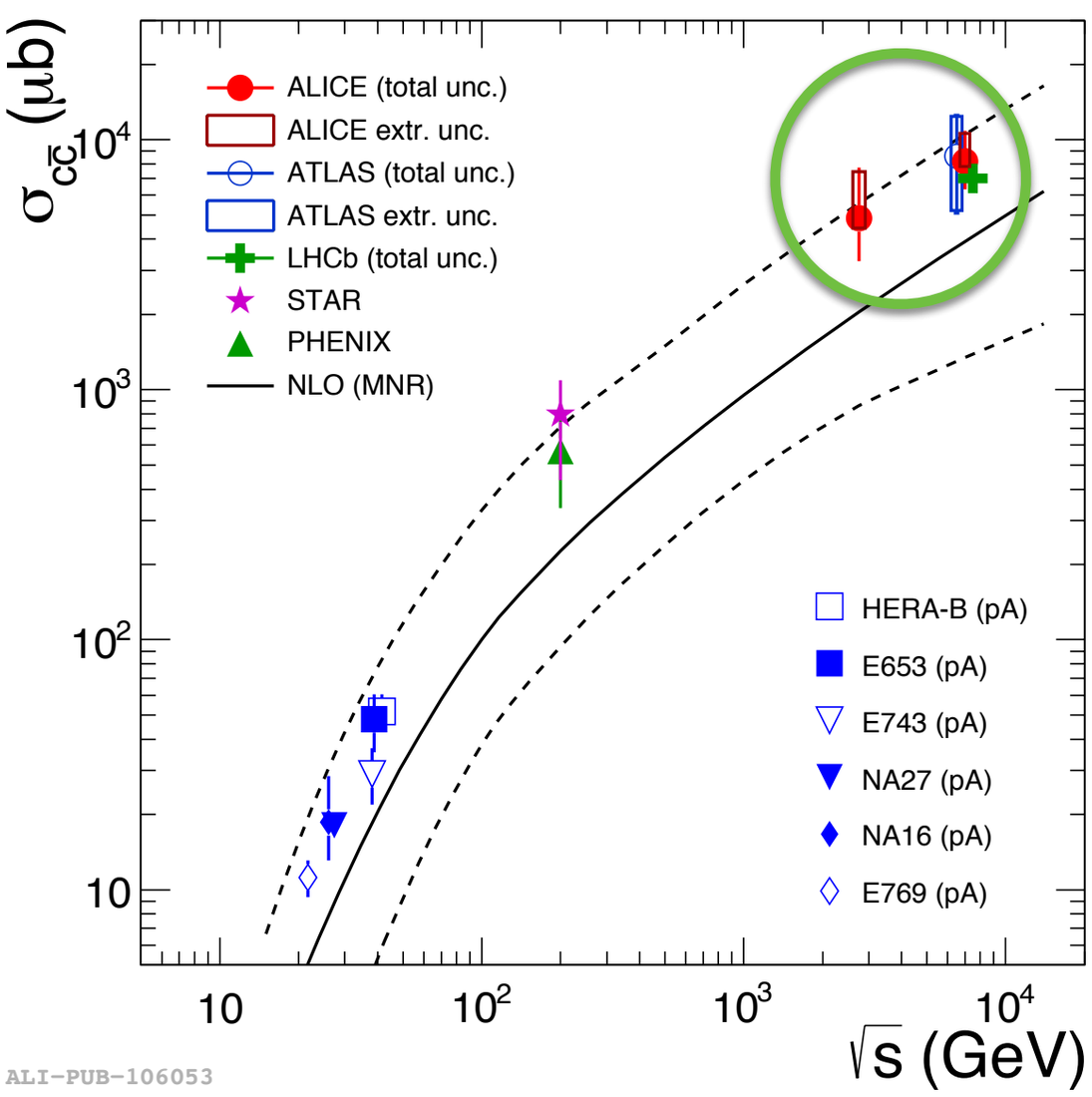
ALICE Coll, Phys.Lett. B781 (2018) 8-19



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

Going back to the total cross-section

ALICE Coll, Eur.Phys.J. C77 (2017) no.8, 550



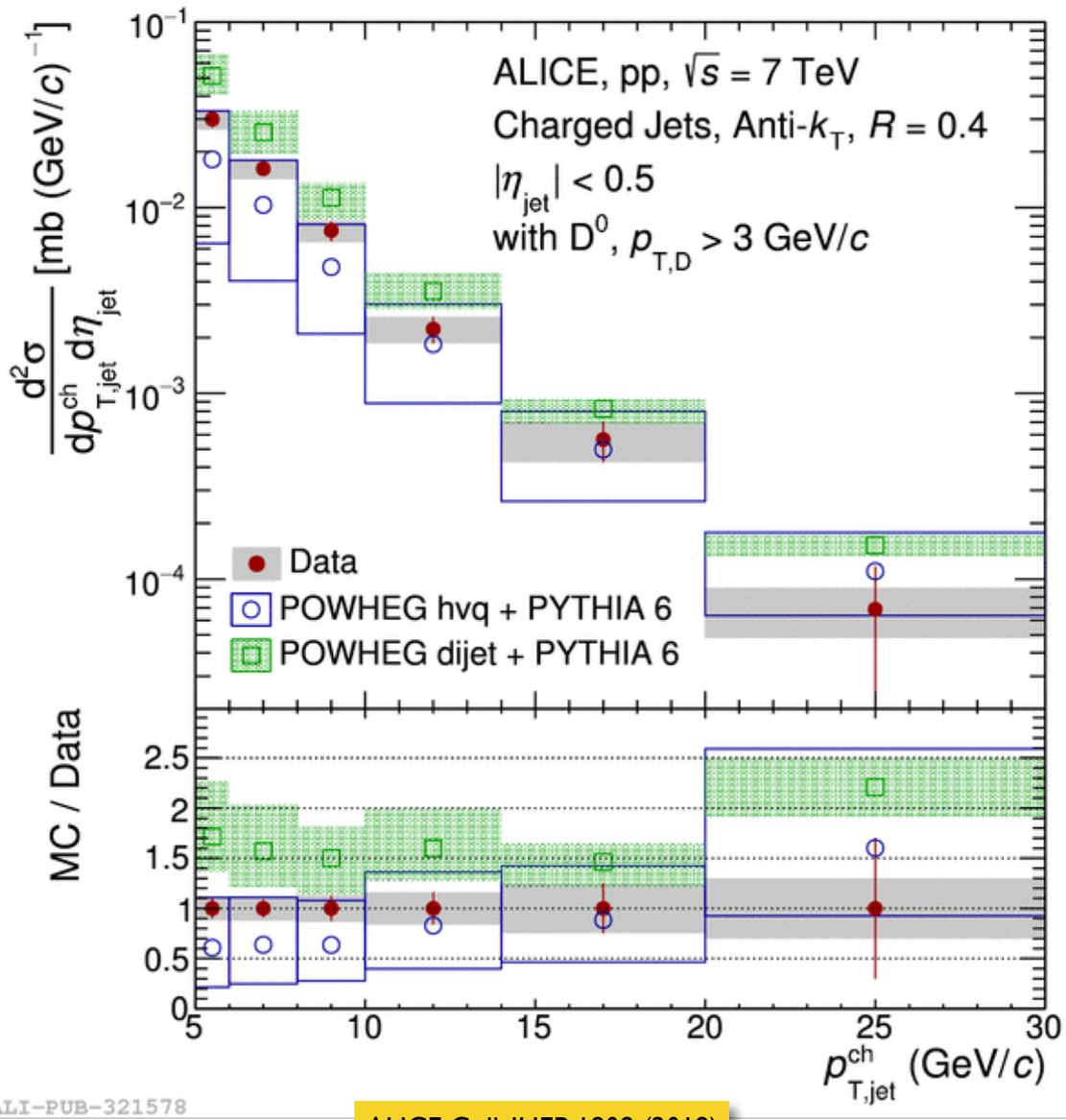
- ☑ Earlier measurements consider the Λ_c/D^0 ratio fixed to lepton-lepton and lepton-hadron colliders (unversality of the FF)
- ☑ The recent ALICE results call for a re-calculation of the total cross-section in view of the higher-than-expected Λ_c/D^0 ratio.
- ☑ The total cross section value will increase

Stay tuned!

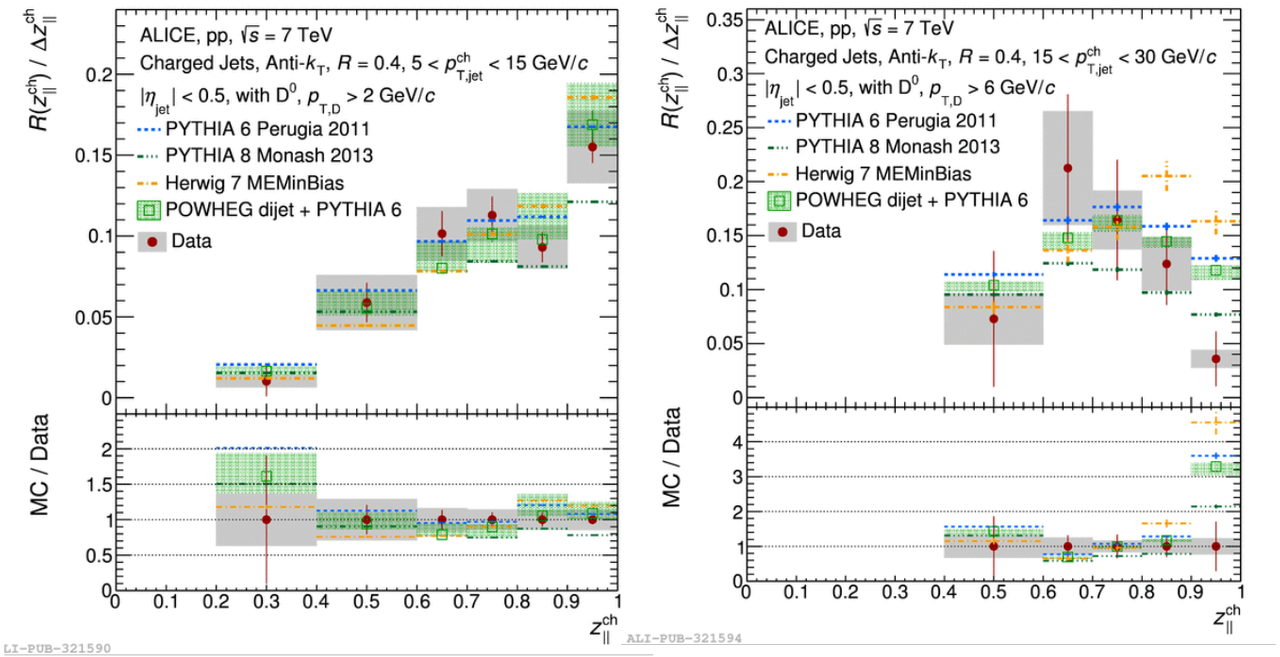
D tagged jets @ 5.02 TeV

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

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



ALICE Coll, JHEP 1908 (2019)

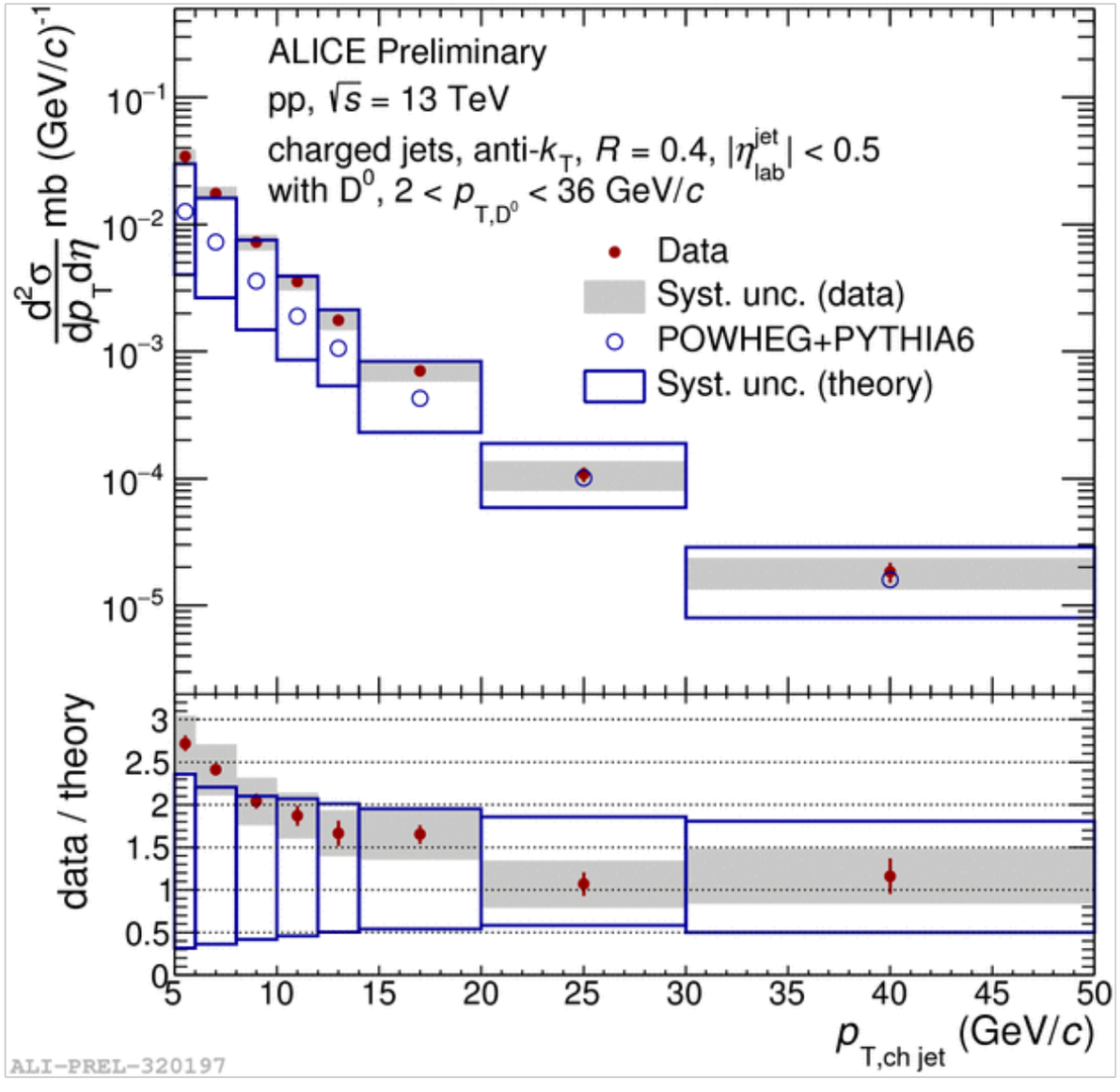


- Cross-sections: Agreement with NLO pQCD POWHEG hvq + PYTHIA6 predictions.
  - ☑ Some tension in the cross-section with POWHEG dijet

- 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 tagged jets @ 13 TeV

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



- Similar situation as for 7 TeV but now a hint of tension between data and model is building up at low jet p_T

Outline

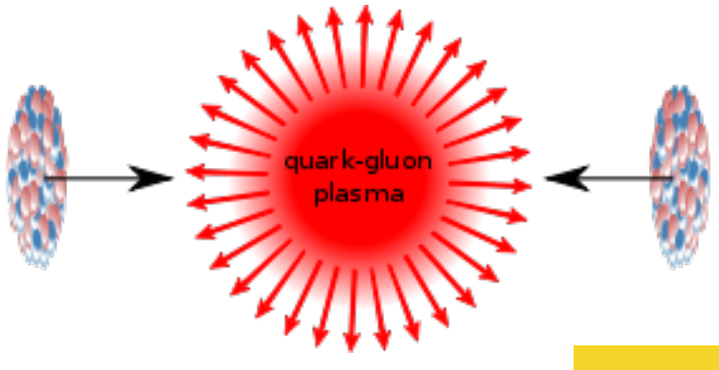
- **pp collisions:**
  - Test pQCD calculations
  - Study fragmentation and hadronisation, heavy-flavour jet properties
  - Set a reference for p-Pb and Pb-Pb
- **p-Pb collisions**
  - Study cold nuclear matter (CNM) effects (nPDF, shadowing, gluon saturation, k_T-broadening, energy loss in CNM in the 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

Why to study pA: Canonical picture

QCD vacuum

p-p

- Cold nuclear matter effects (nPDF, shadowing, gluon saturation, k_T-broadening, energy loss in CNM in the initial and final state)
- coherent/collective interactions of nuclear fragments, and QGP formation
- final-state interactions with QGP

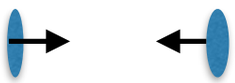


A-A

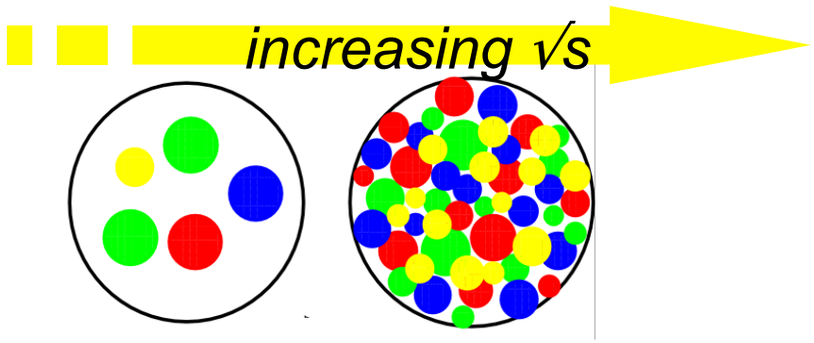
QCD medium

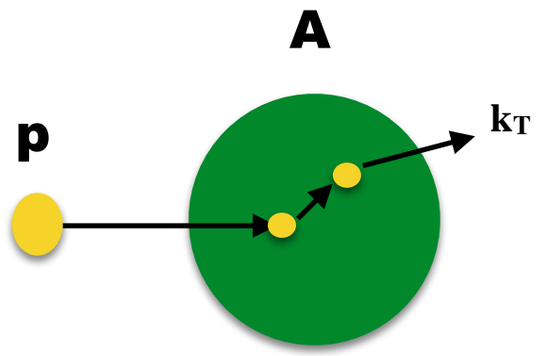
Why to study pA: Canonical picture

QCD vacuum

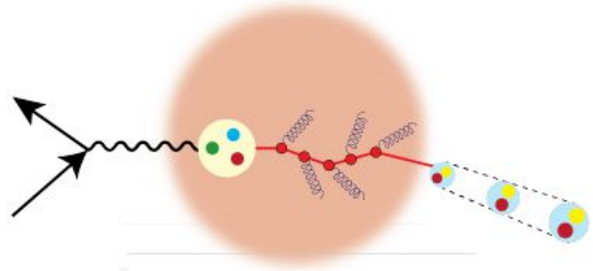


p-p



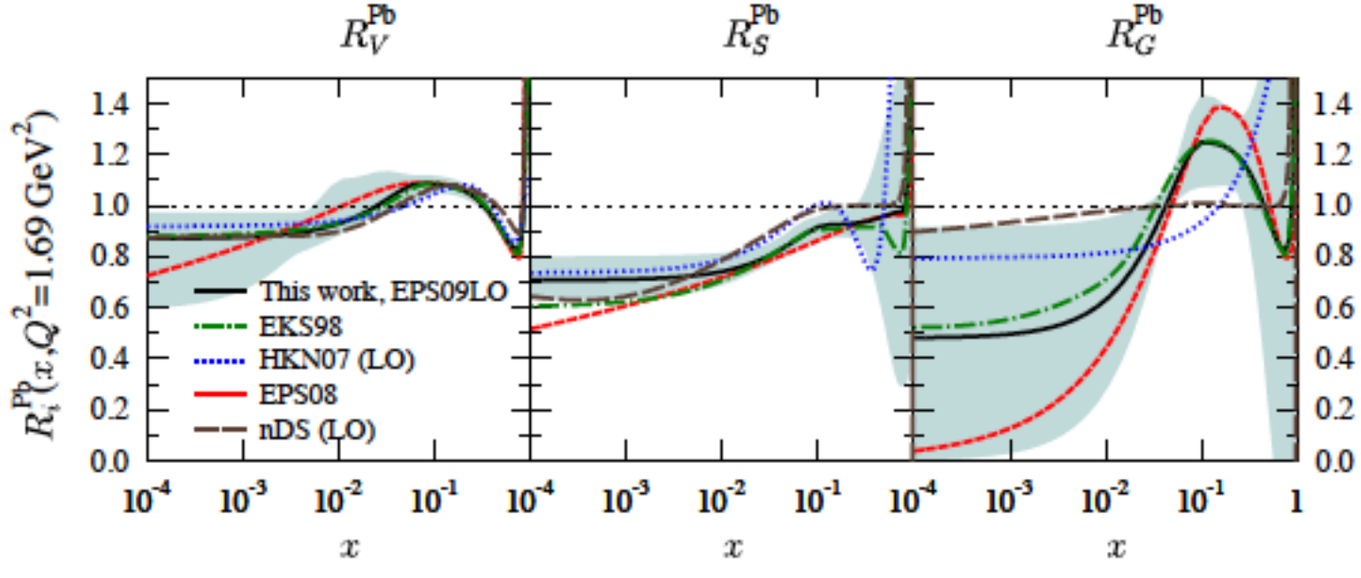


- Cold nuclear matter effects (nPDF, shadowing, gluon saturation, k_T-broadening, energy loss in CNM in the initial and final state)
- coherent/collective interactions of nuclear fragments, and QGP formation
- final-state interactions with QGP



A-A

QCD medium

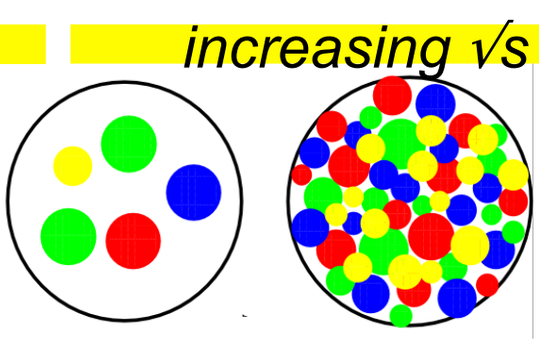


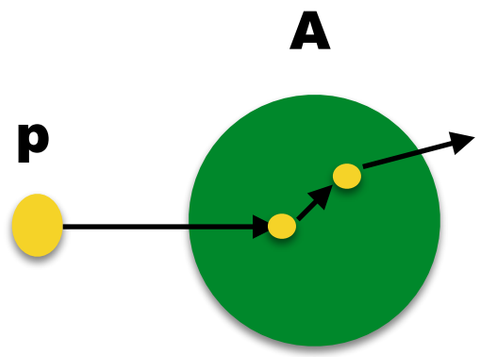
K.J. Eskola, H. Paukkunen, C. A. Salgado, JHEP 0904, 65 (2009)

Why to study pA: Canonical picture

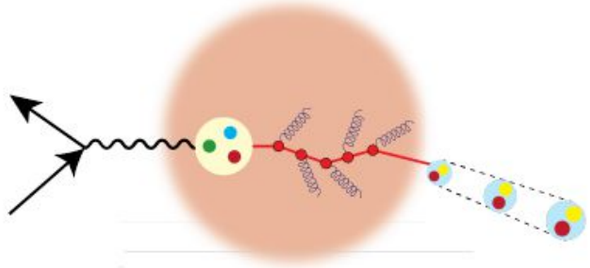
QCD vacuum

p-p



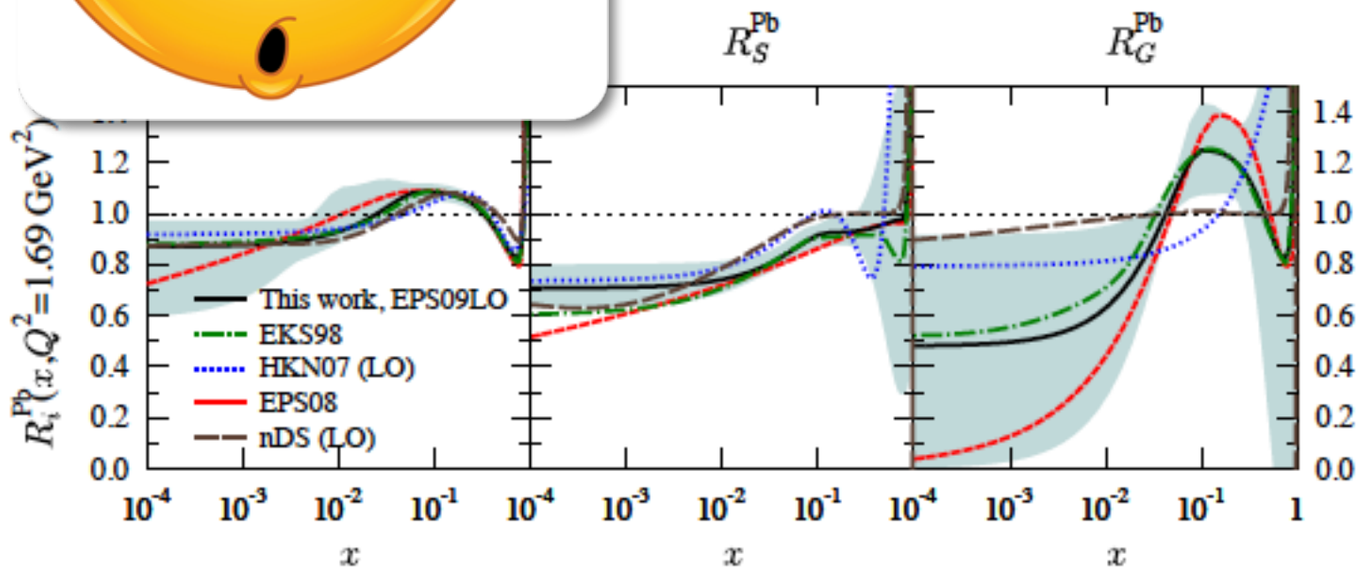


- Cold nuclear matt
  shadowing, gluon
  broadening, energ
  initial and final sta
- coherent/collectiv
  nuclear fragments
- final-state interact



A-A

QCD medium



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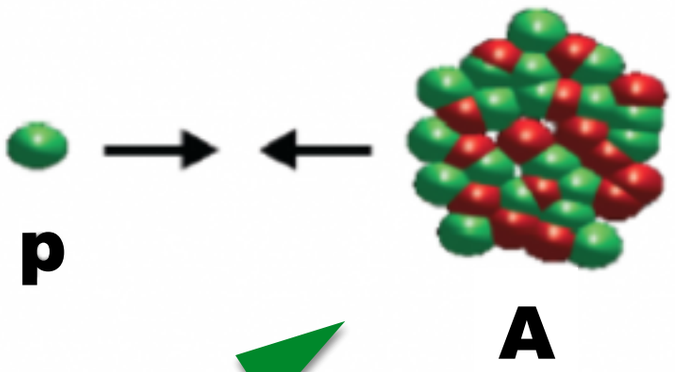


A-A

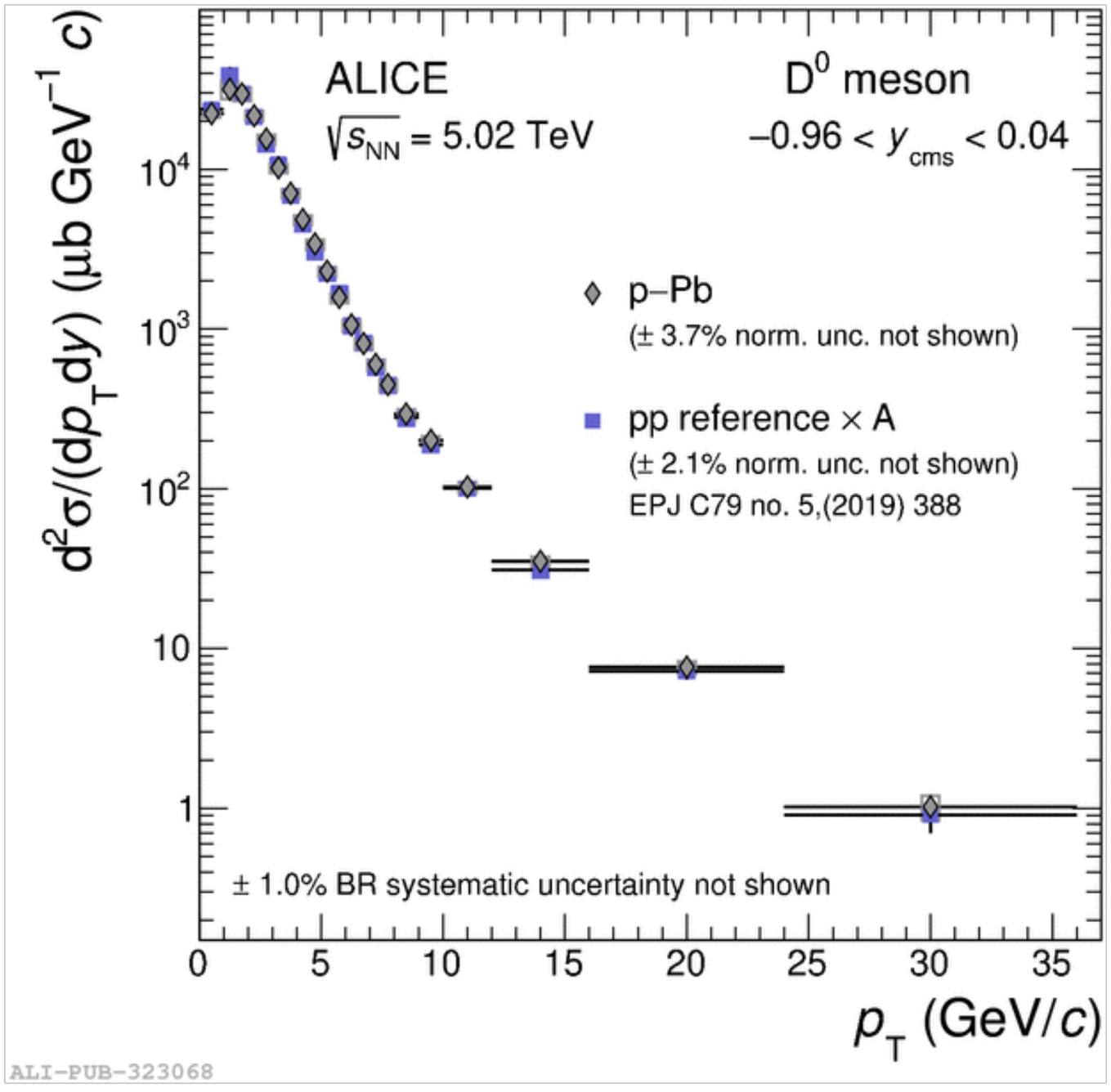
QCD medium

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

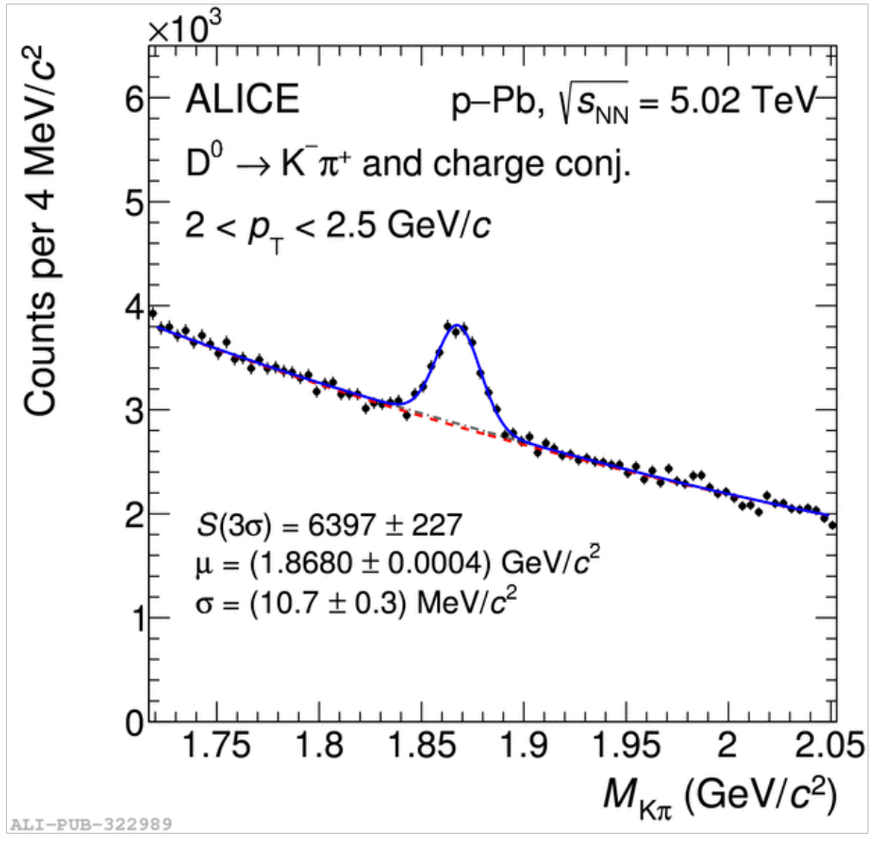
Phys. Rev. Lett. 118 (2017) 072001

D-meson production: p-Pb @ 5.02 TeV

arXiv:1906.034, Submitted to JHEP

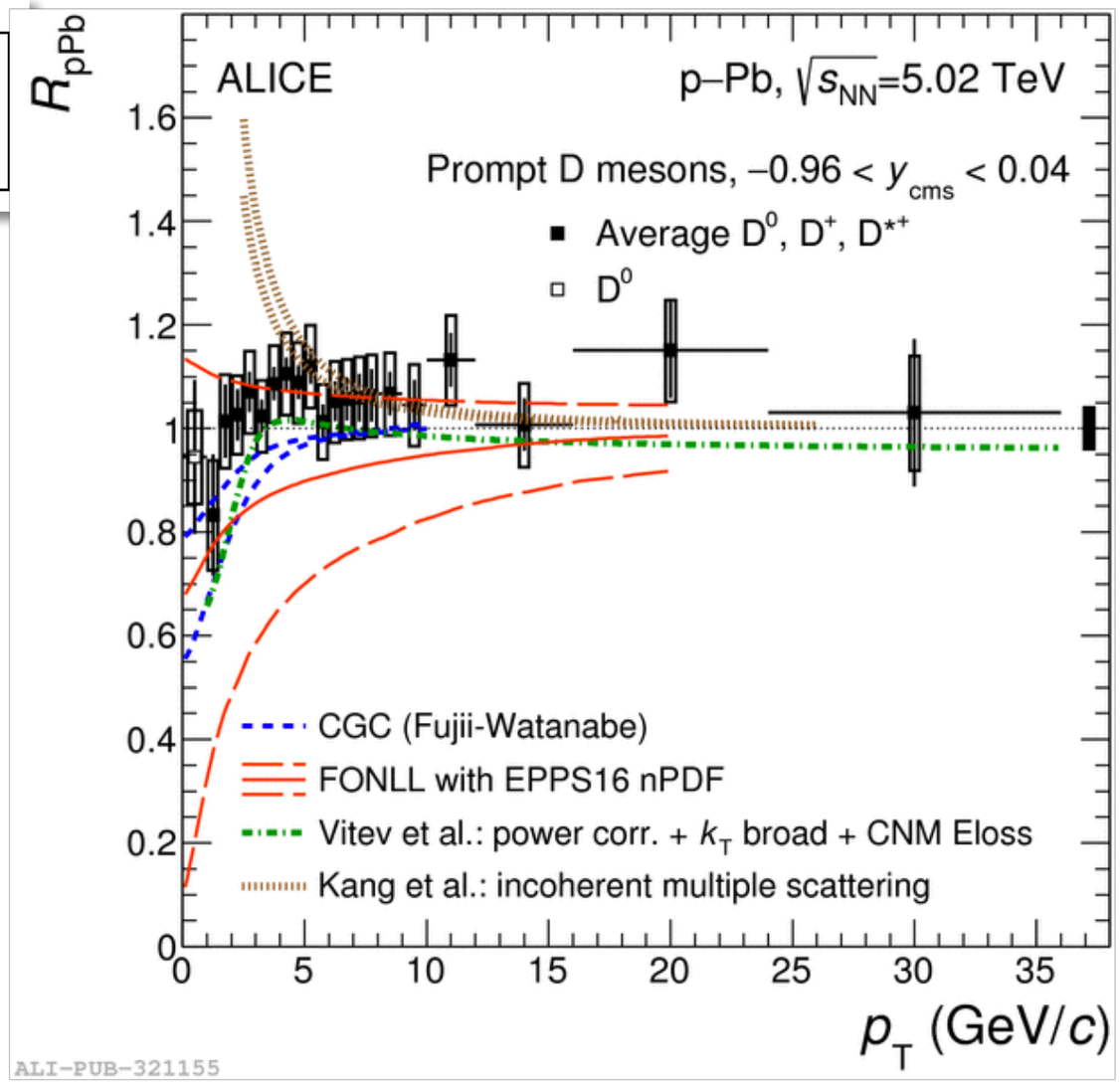


- ☑ Production cross-sections measured in a large rapidity interval and down to $p_T \sim 0$
- ☑ Precison measurement



D-meson R_{pA}

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



arXiv:1906.034, Submitted to JHEP

- ☑ Described by models including cold nuclear-matter effects
- ☑ Described by models including the formation of QGP in p-Pb:
  - ➡ data disfavour suppression >~10% at high-p_{T}
  - ➡ need to improve the precision of the measurement for a more conclusive statement

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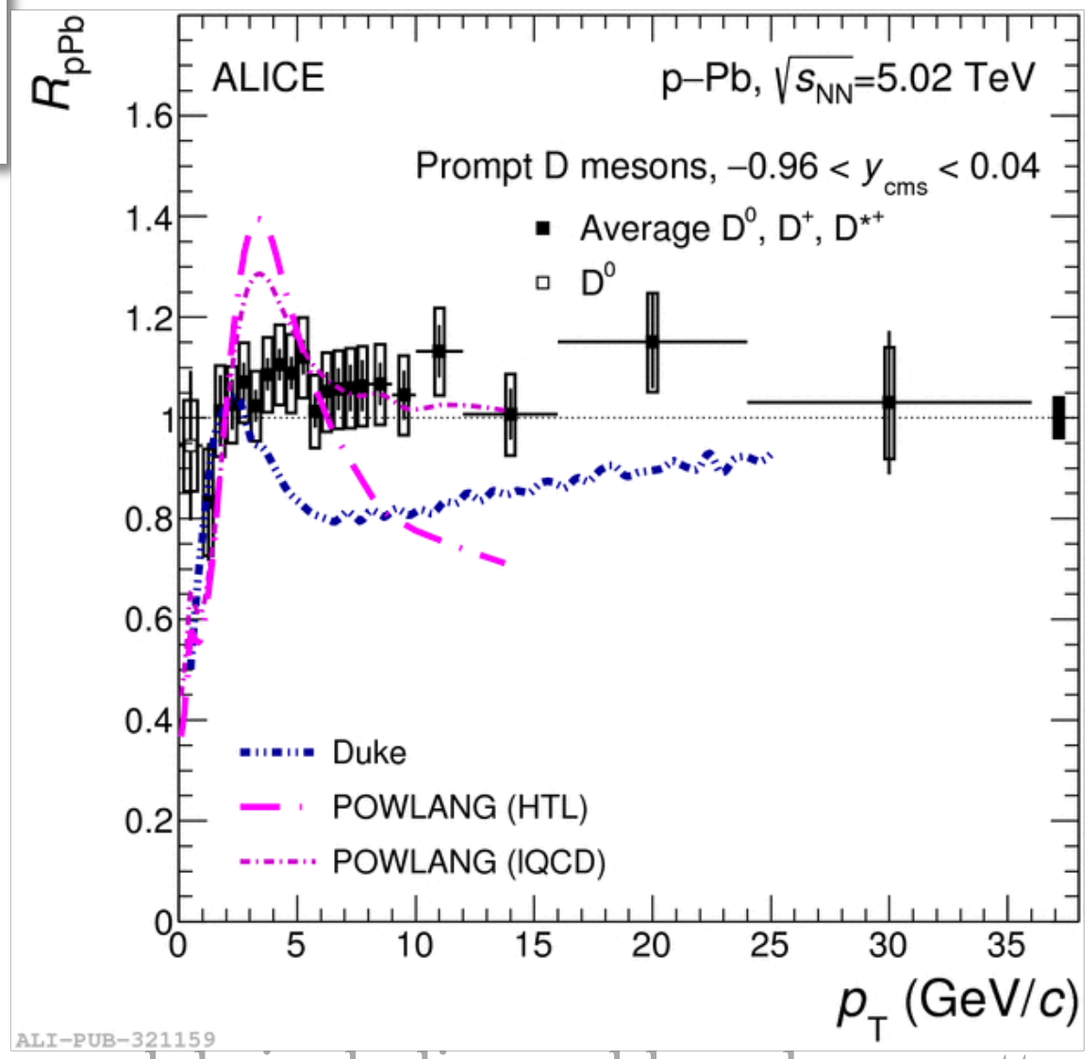

arXiv:1906.034, Submitted to JHEP

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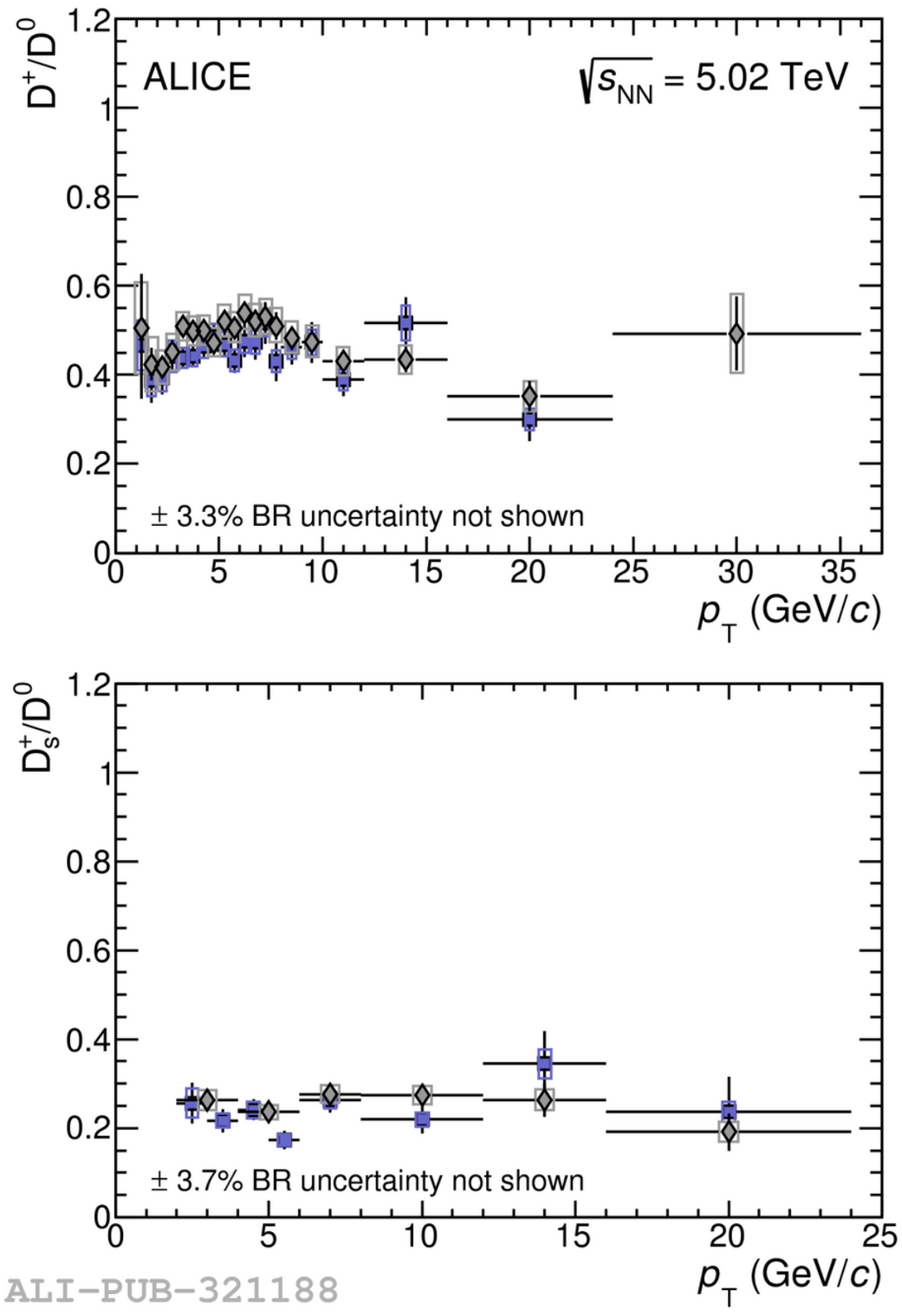
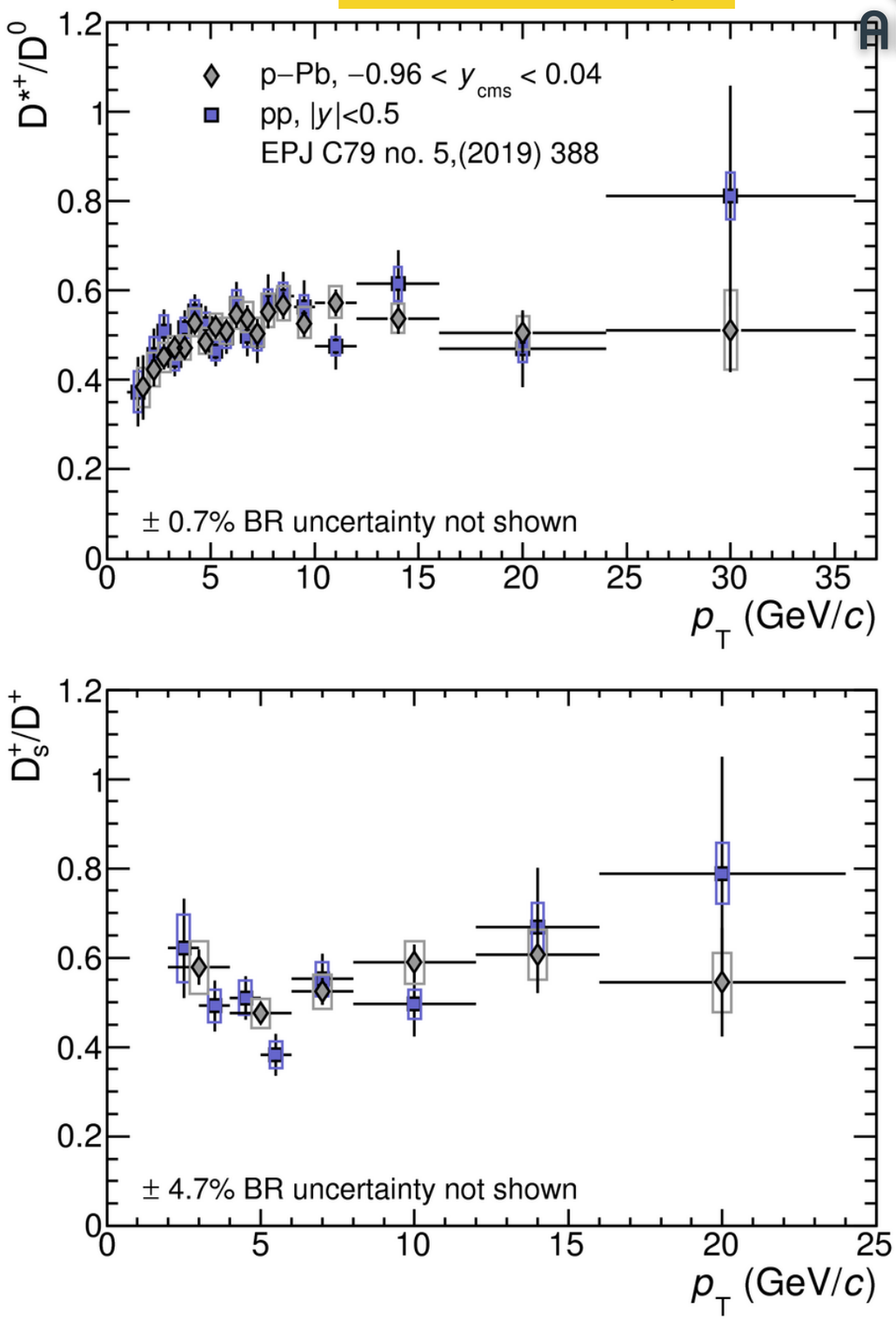
D-meson ratios: pp vs p-Pb

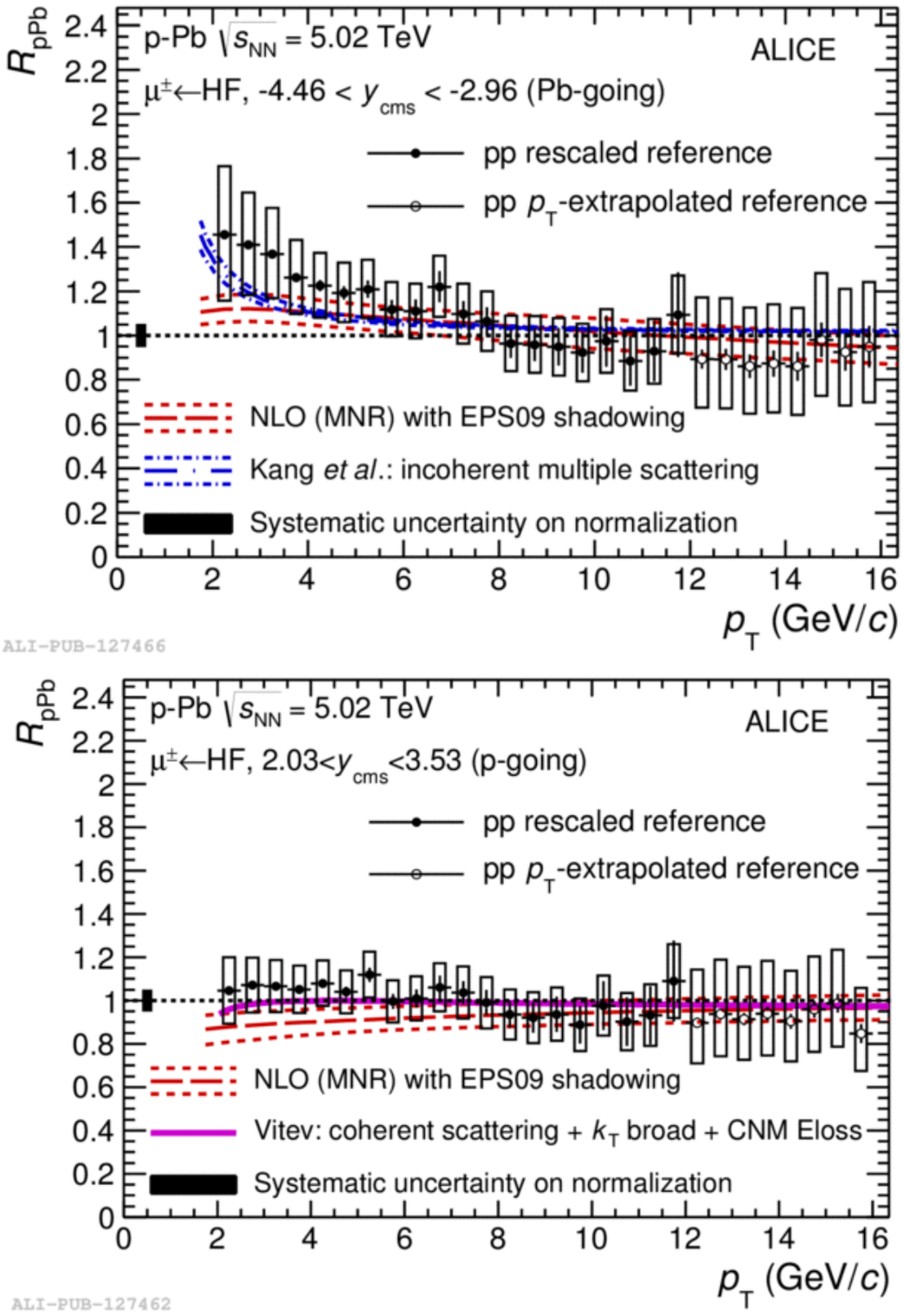


ALI-PUB-321188

arXiv:1906.034, Submitted to JHEP



Muons at forward rapidity



- R_{pPb} of muons from heavy-flavour decay hadrons measured in a large p_T internal and both, in the p-going and Pb-going sides
- Within the experimental precision pQCD based models agree with data
- In the Pb-going side, at low p_T data tend to favour "incoherent multiple scattering" based models. However more data are needed to conclude

ALICE Coll, Phys. Lett. B 770 (2017) 459-472

Outline

- **pp collisions:**
  - Test pQCD calculations
  - Study fragmentation and hadronisation, heavy-flavour jet properties
  - Set a reference for p-Pb and Pb-Pb
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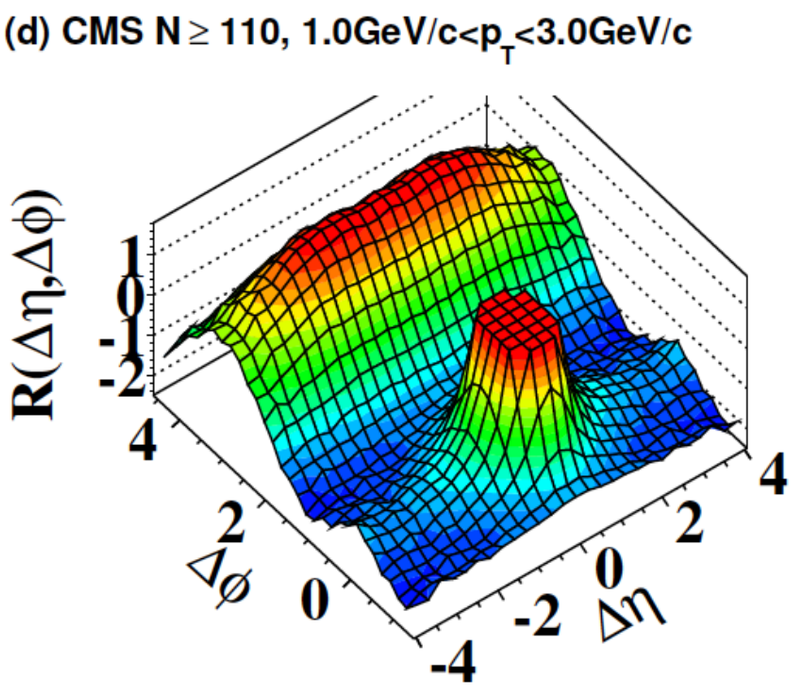
  - Address possible collective effects and effects related to the (possible) formation of a QGP in p-Pb collisions.
- **Charm hadronization in vacuum**
  - Do we understand it?
    - Lc[Xic]/D0 ratio in pp and p-Pb: ALICE vs LHCb
    - Possible implications of the experimental result

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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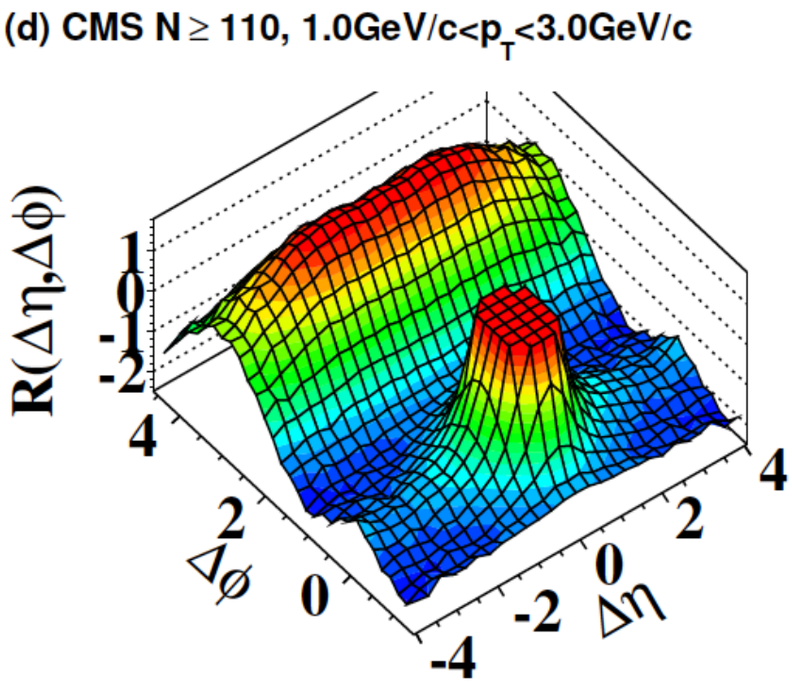

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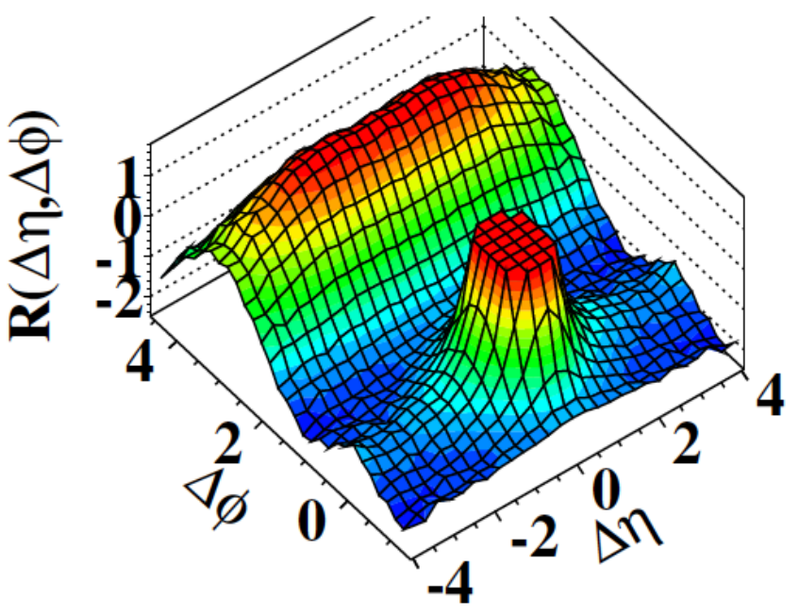

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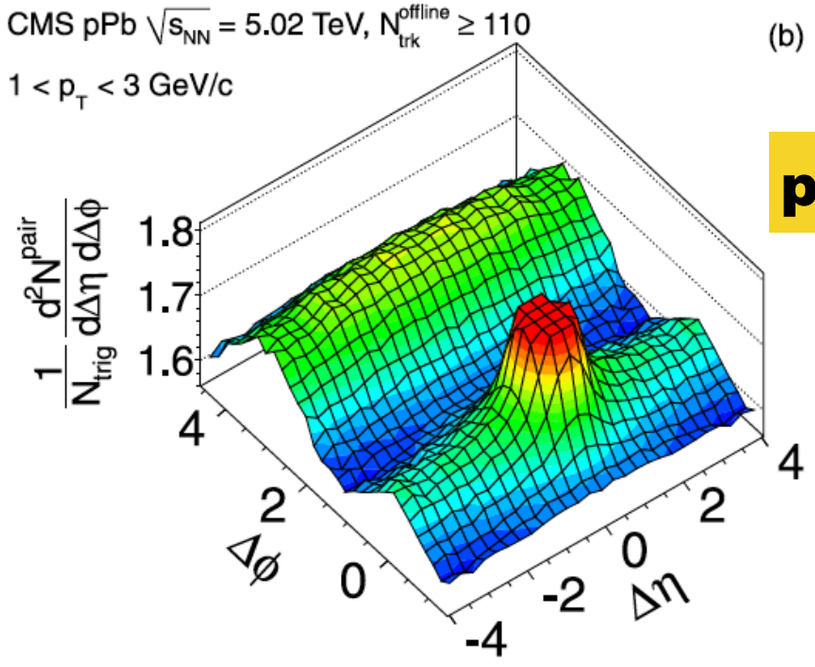
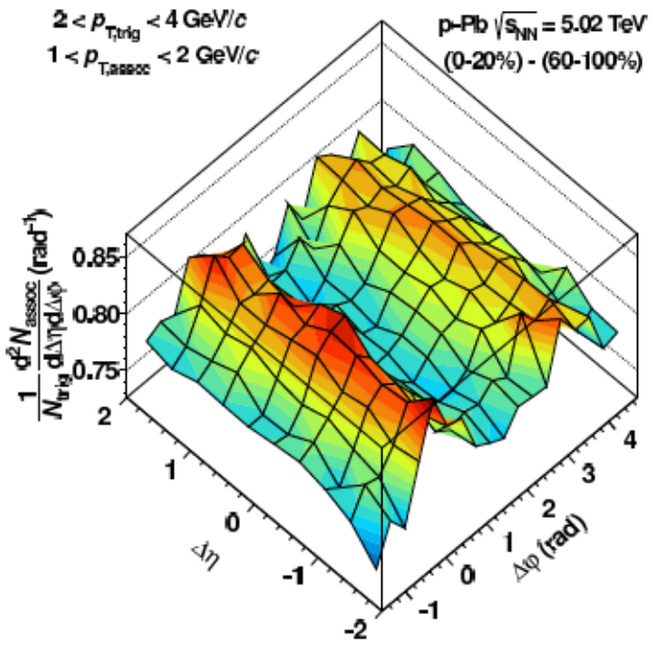
A collective QGP like effect in pp and p-Pb?

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



p-Pb collisions

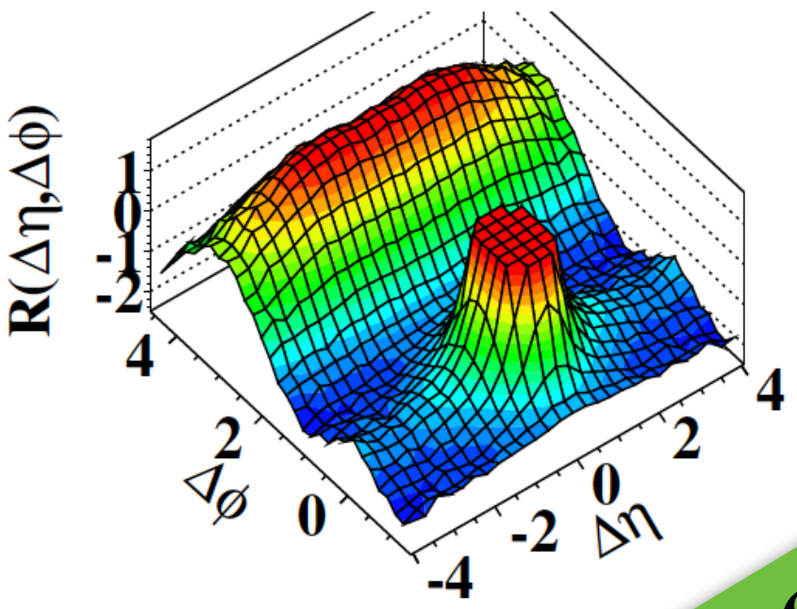
(ALICE Collaboration): Phys. Lett. B719, (2013) 29



Collectivity in small systems

pp collisions

(CMS Collaboration) JHEP 09, (2010) 091



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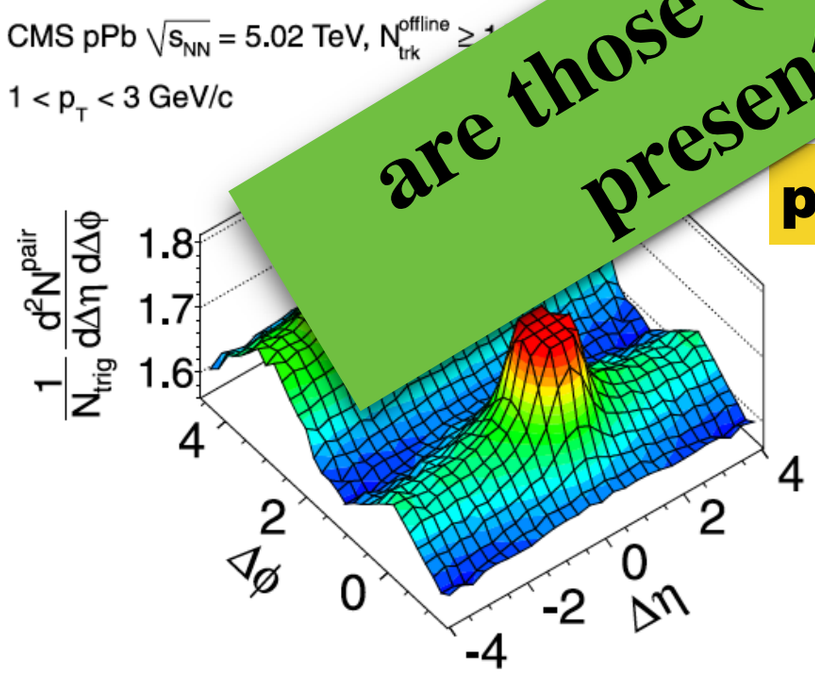
Are those (QGP-like) collective effects present in the Charm sector?

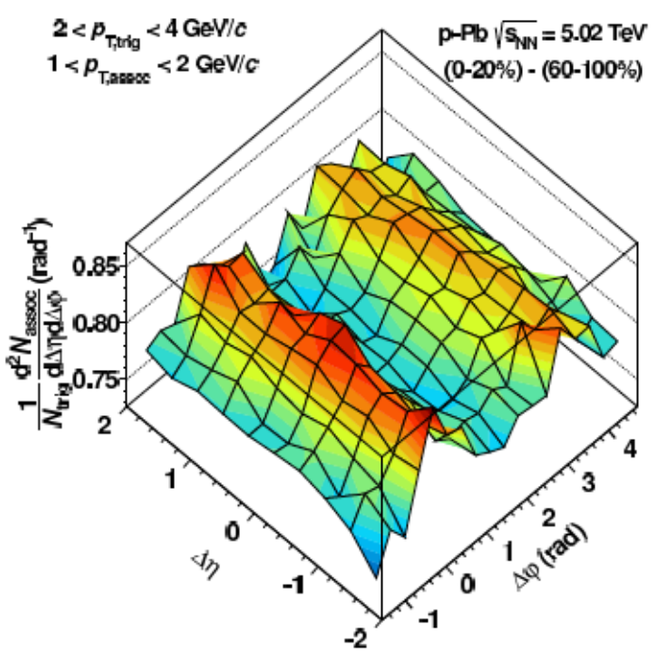
Is QGP like effect in pp and p-Pb?

(CMS Collaboration) Phys. Lett. B71



p-Pb collisions

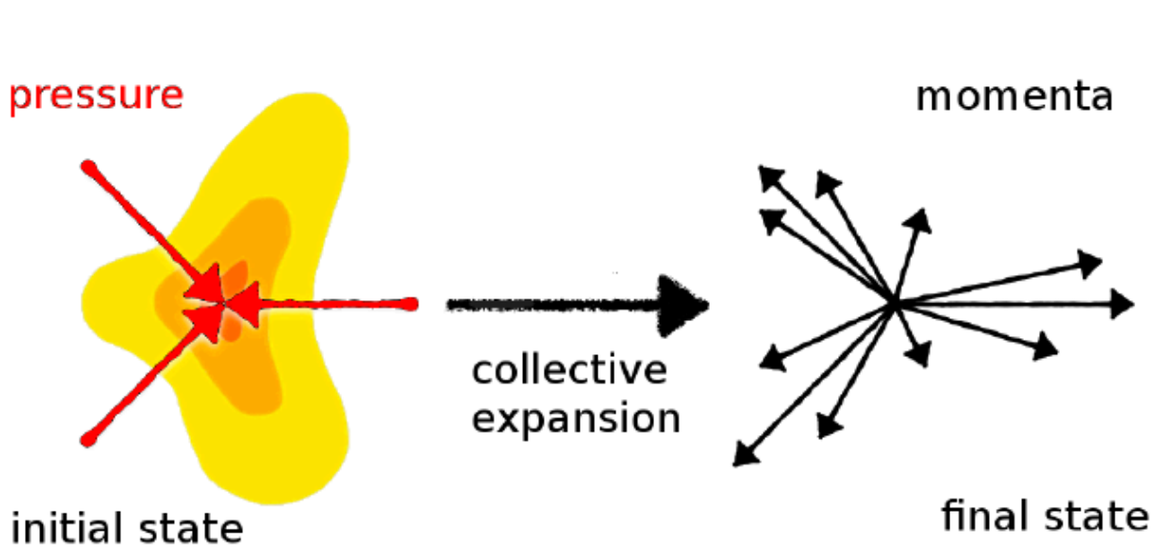
(ALICE Collaboration): Phys. Lett. B719, (2013) 29



Elliptic flow v_2 as a measure of collectivity

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

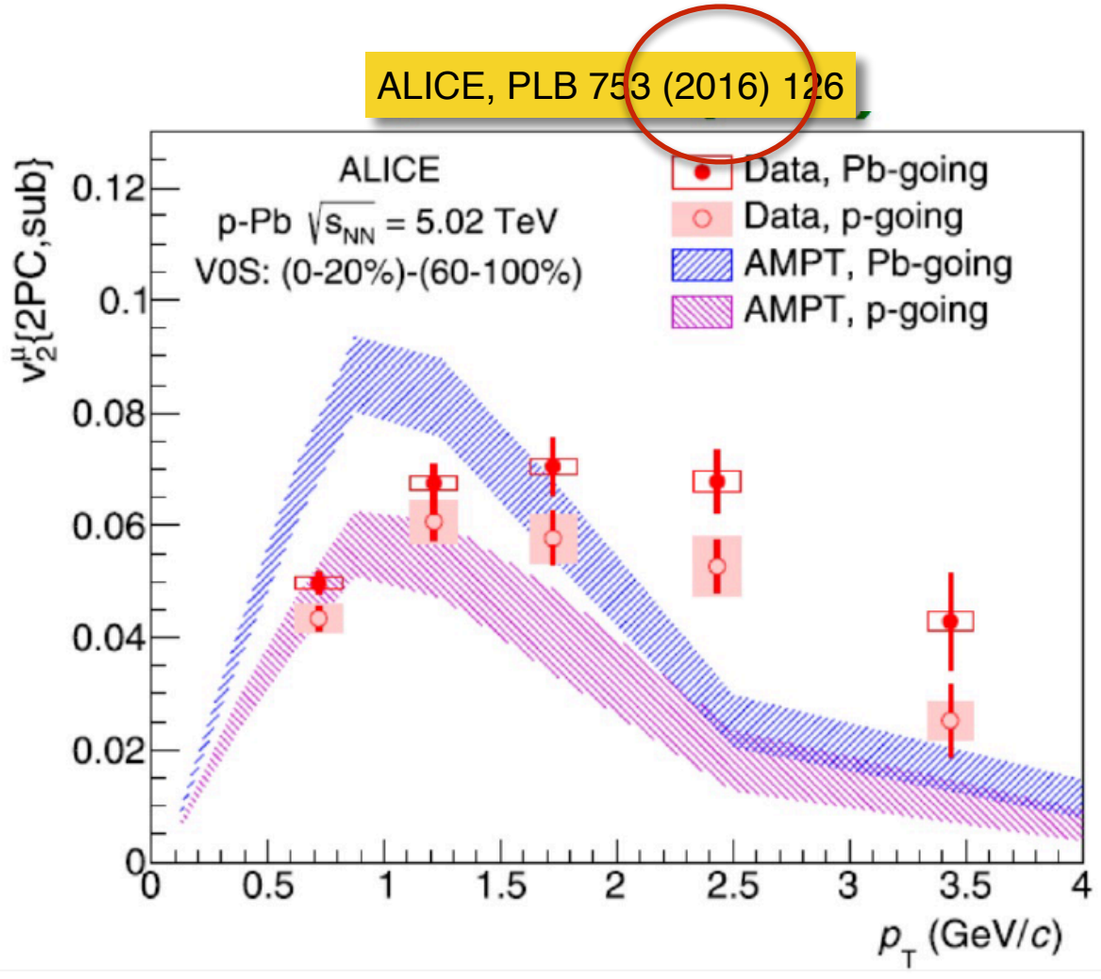
- Flow: momentum anisotropies in azimuthal angle, quantified by coefficients v_n
  - ☑ Soft sector (low-p_T < 2 GeV/c): multiple interactions between partons (a.k.a. collectivity") convert initial-state (IS) spatial anisotropies into final-state momentum ones
  - ☑ Hard sector (high-p_T, > 10 GeV/c): 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



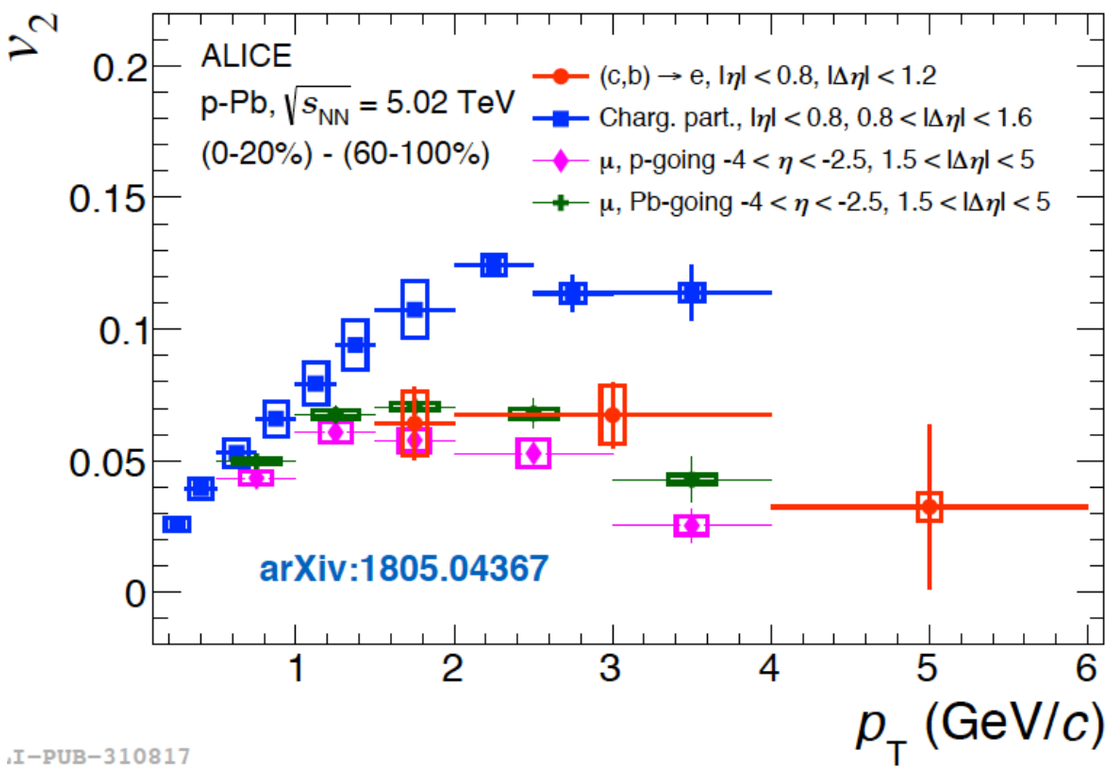
☑ **Indirect hint** of non-zero heavy-flavour flow in p-Pb from inclusive muons at forward rapidity (p_T>2 GeV/c)

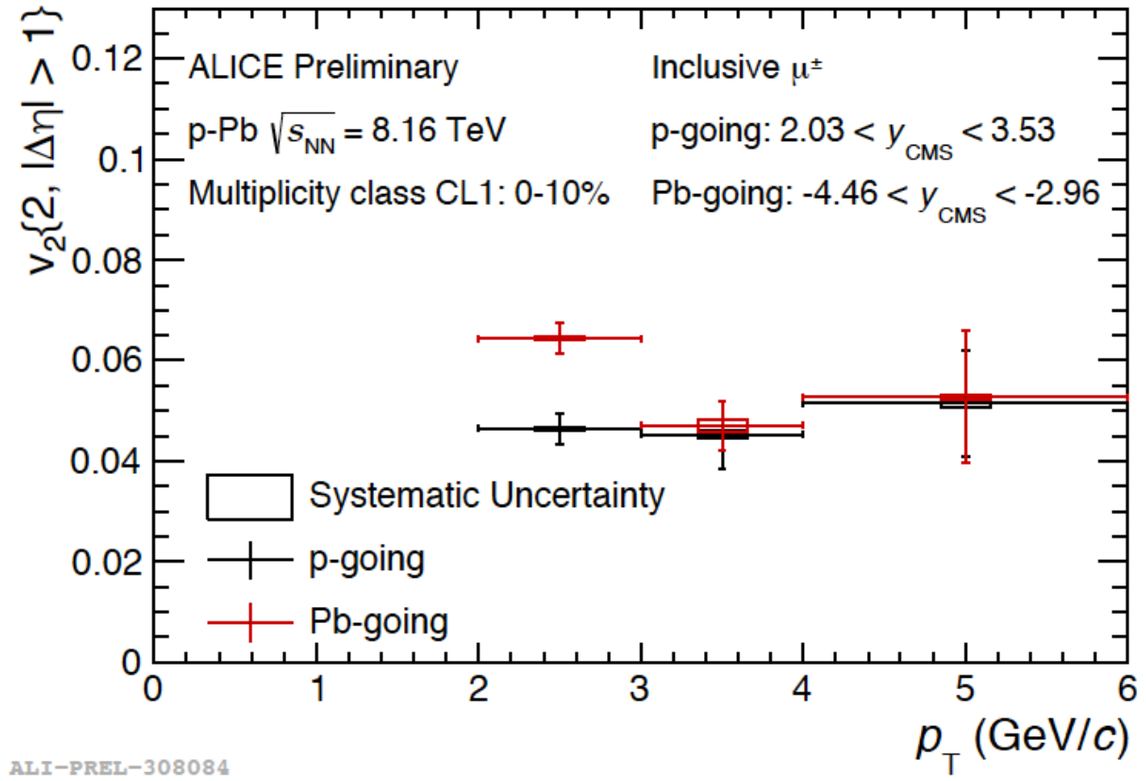
➡ High-p_T inclusive muons are HF dominated.

➡ Need direct proof (Prompt D mesons, heavy-flavour hadron decay leptons)

HF-decay leptons flow in p-Pb

ALICE Coll, 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?

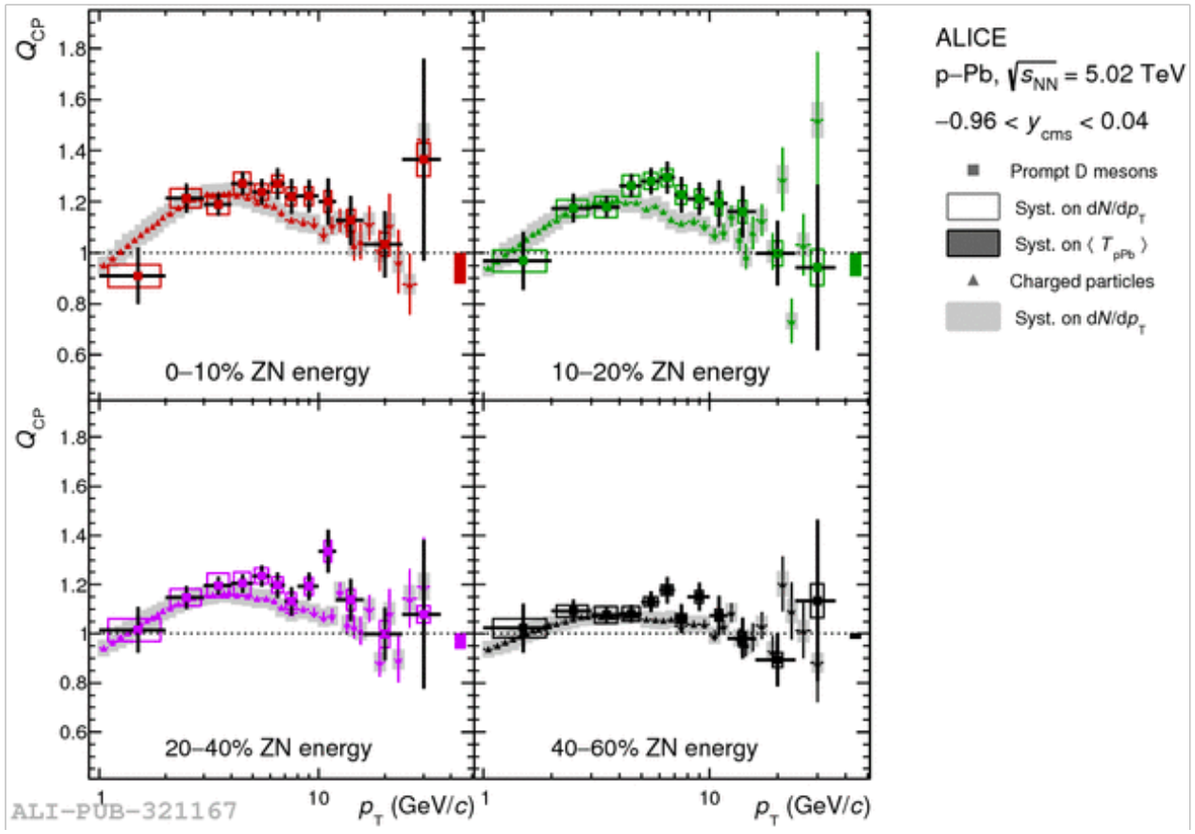
Heavy-flavour decay muons (forward rapidity)

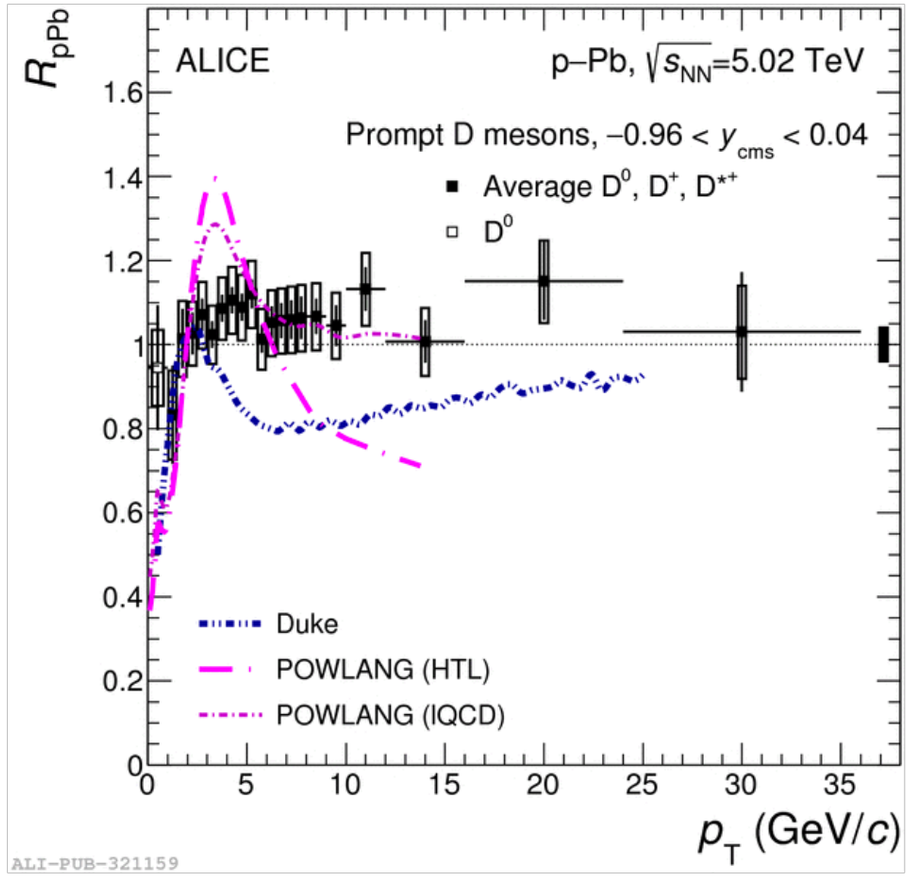
- ☑ Effect is qualitatively similar to the one observed for electrons

Collectivity in the D-meson sector?

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

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





- ☑ Hint for D-meson "Central-to-peripheral" ratio (QCP) larger than unity (~3σ in $2 < p_{\mathrm{T}} < 10$ GeV/c, *20-40%)*
- ☑ 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%

arXiv:1906.034, Submitted to JHEP

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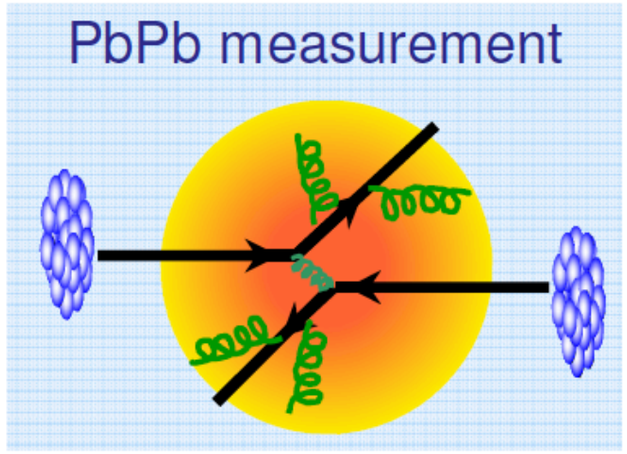
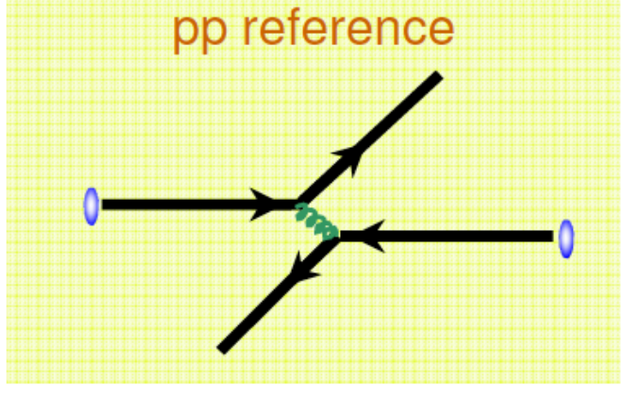
- **A-A collisions**
  - Heavy-quark energy loss in-medium
  - Hadronization

Observable: R_{AA}

- ☑ Production of hard probes in AA expected to scale with the number of nucleon-nucleon collisions N_{coll} (binary scaling)
- ☑ Observable: Nuclear Modification Factor

$$R_{AA}^{D}(p_T) = \frac{dN_{AA}^{D}/dp_T}{\langle T_{AA} \rangle \times d\sigma_{pp}^{D}/dp_T} = \frac{QCD\ Medium}{QCD\ vacuum}$$





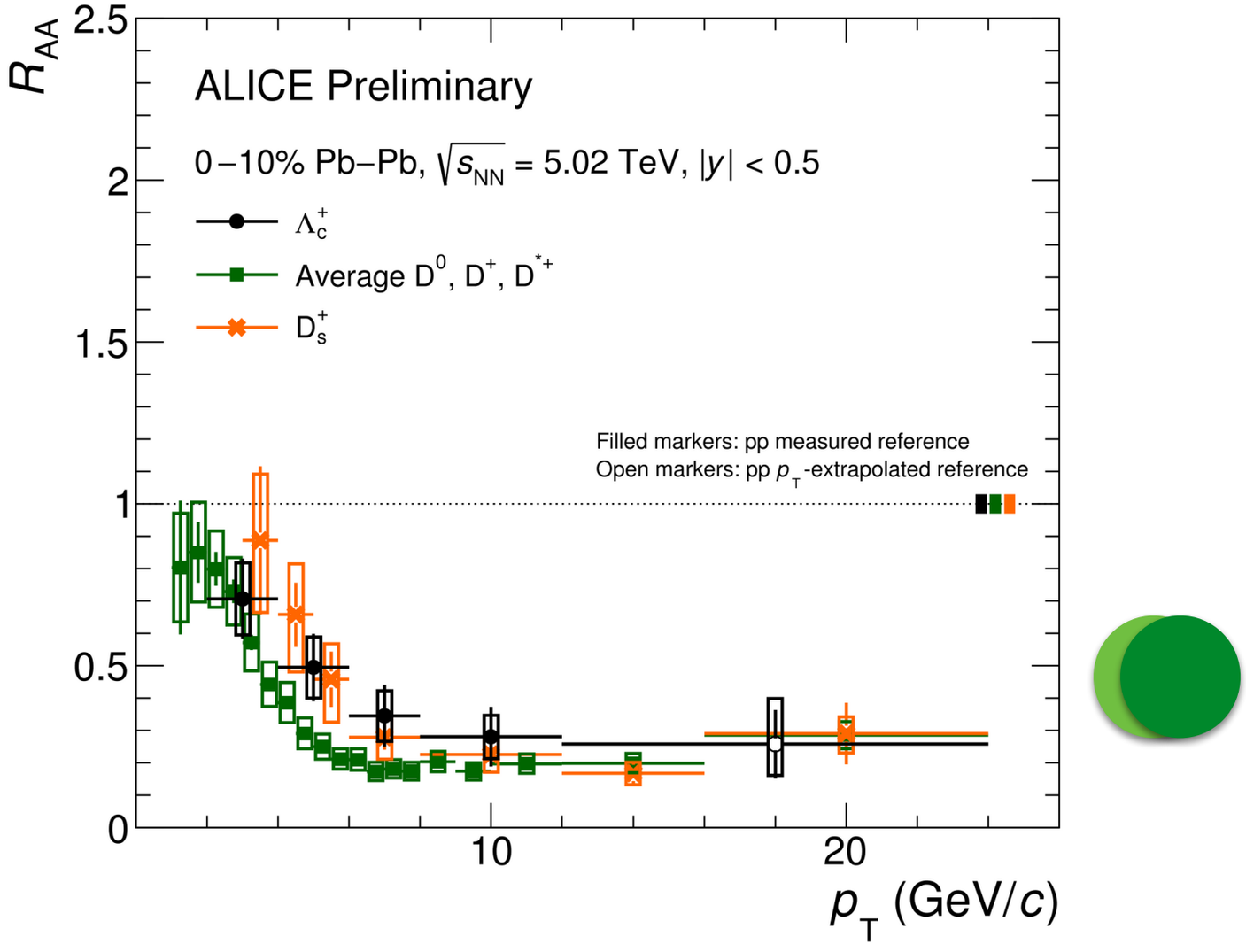
- ☑ What are the possibilities?
  - If no nuclear effects present: $R_{AA}=1$
  - Effects of the hot and dense medium produced in the collision breakup binary scaling: $R_{AA} \neq 1$

$R_{AA}(c,b,s)<R_{AA}(c)<R_{AA}(b)$

several caveat to take into account!!

- ☑ But also cold nuclear matter effects may lead to $R_{AA} \neq 1$ (needs solid pA reference)

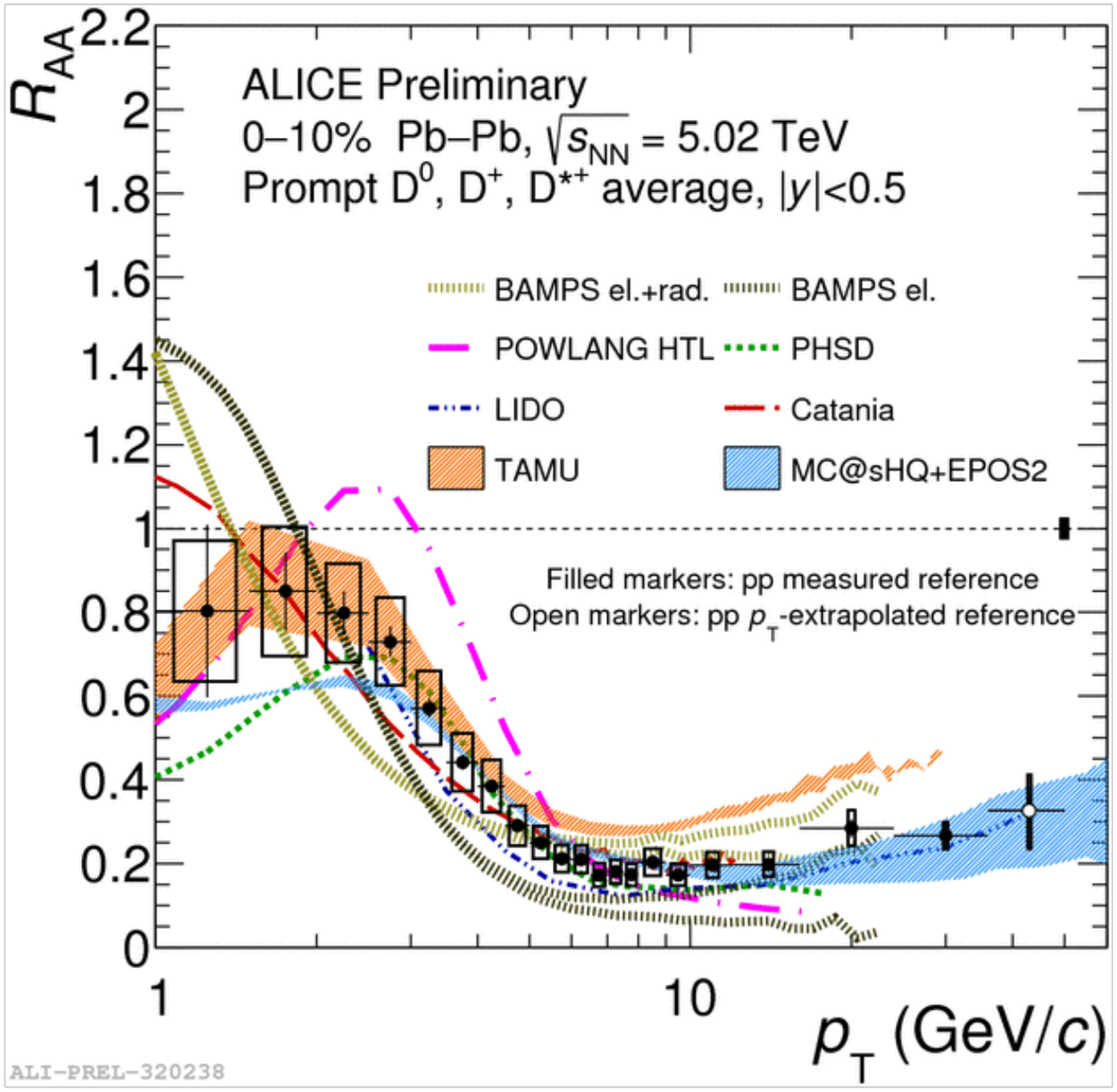
R_{AA} measurements



- R_{AA} of charm mesons and baryons show a large suppression, up to factor 5 for non-strange D mesons at 10 GeV/c that can be attributed to final state effects.
  - Hint of a smaller suppression of D_s and Λ_c with respect non-strange D mesons: Enhancment of D_s in a strangness rich environment and coalescence for Λ_c?

R_{AA} measurements

- ☑ In general models with collisional energy loss and shadowing work better at low p_T while models with radiative energy loss work better at high p_T



Transport models

PHSD **PRC 93 (2016) 034906** (collisional + radiative energy loss, recombination, hydro and nPDF)

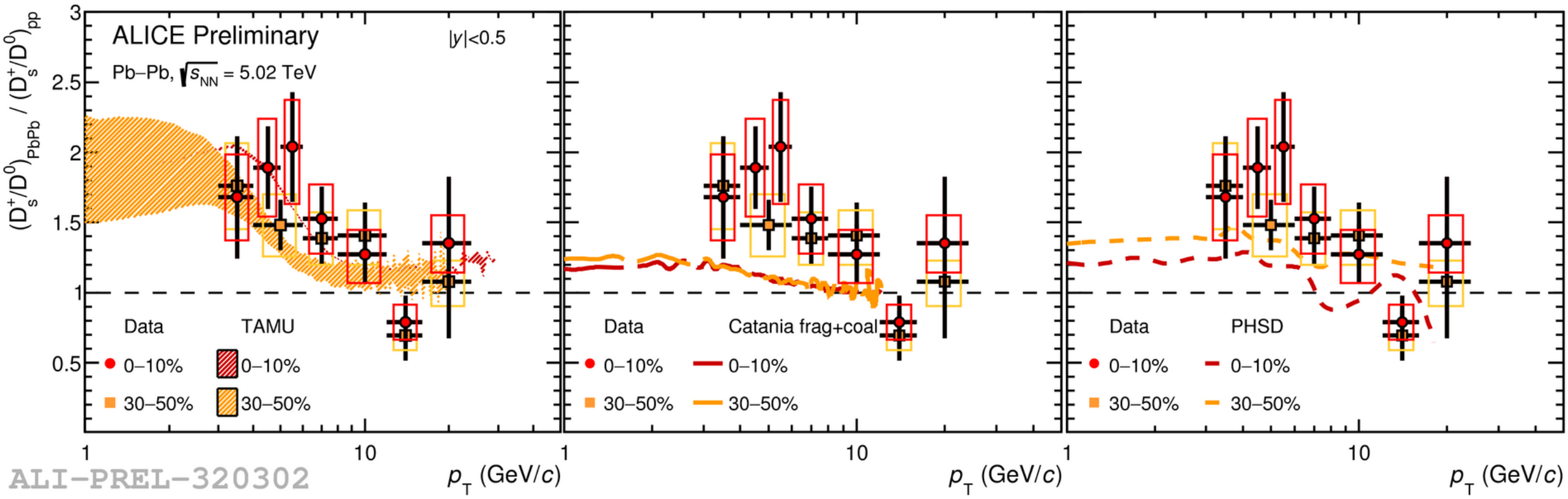
LBT **arXiv:1703.00822** (collisional + radiative energy loss, recombination, hydro and nPDF)

BAMPS **J. Phys. G42 (2015) 115106** (collisional + radiative energy loss, hydro)

POWLANG **EPJC 75 (2015) 121** (collisional energy loss, recombination, hydro + nPDF)

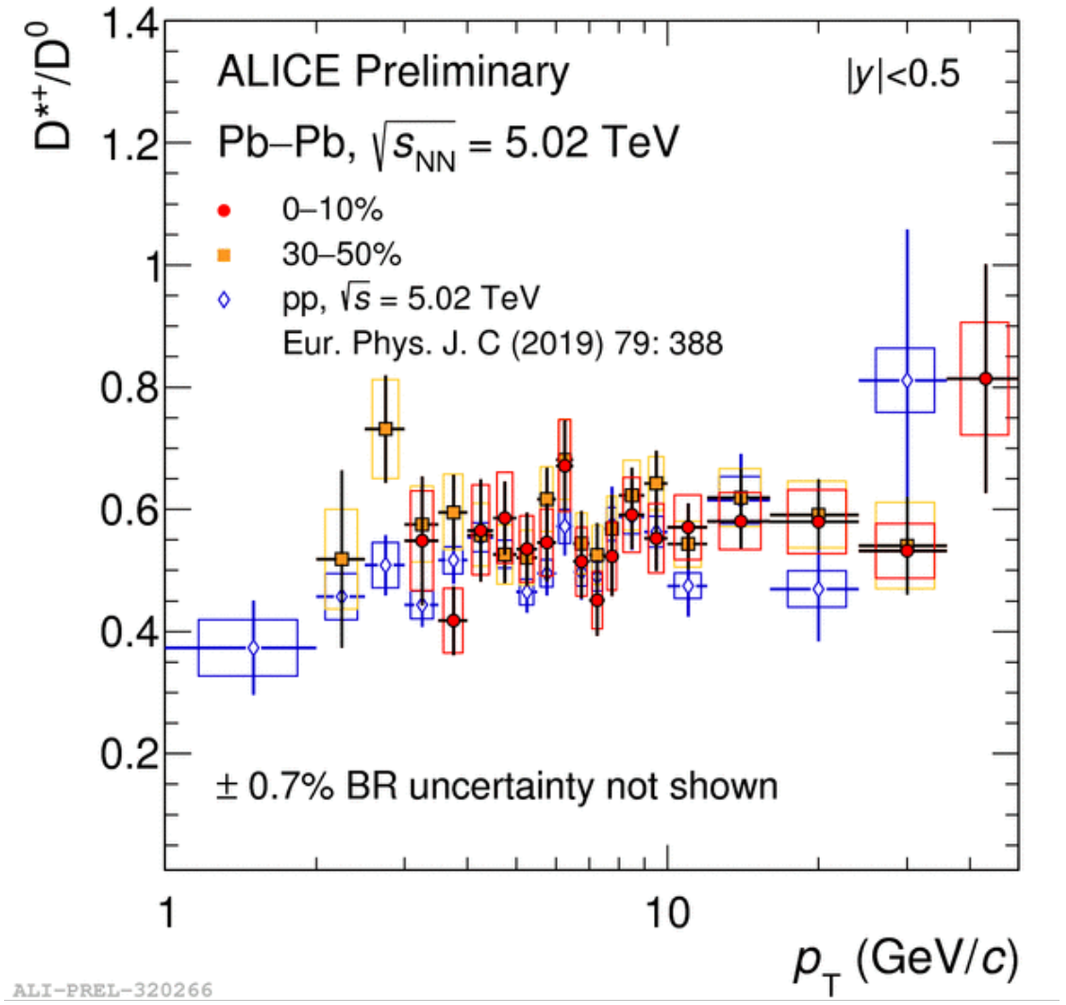
TAMU **Phys. Lett. B735 (2014) 445** (collisional energy loss, recombination, hydro + nPDF)

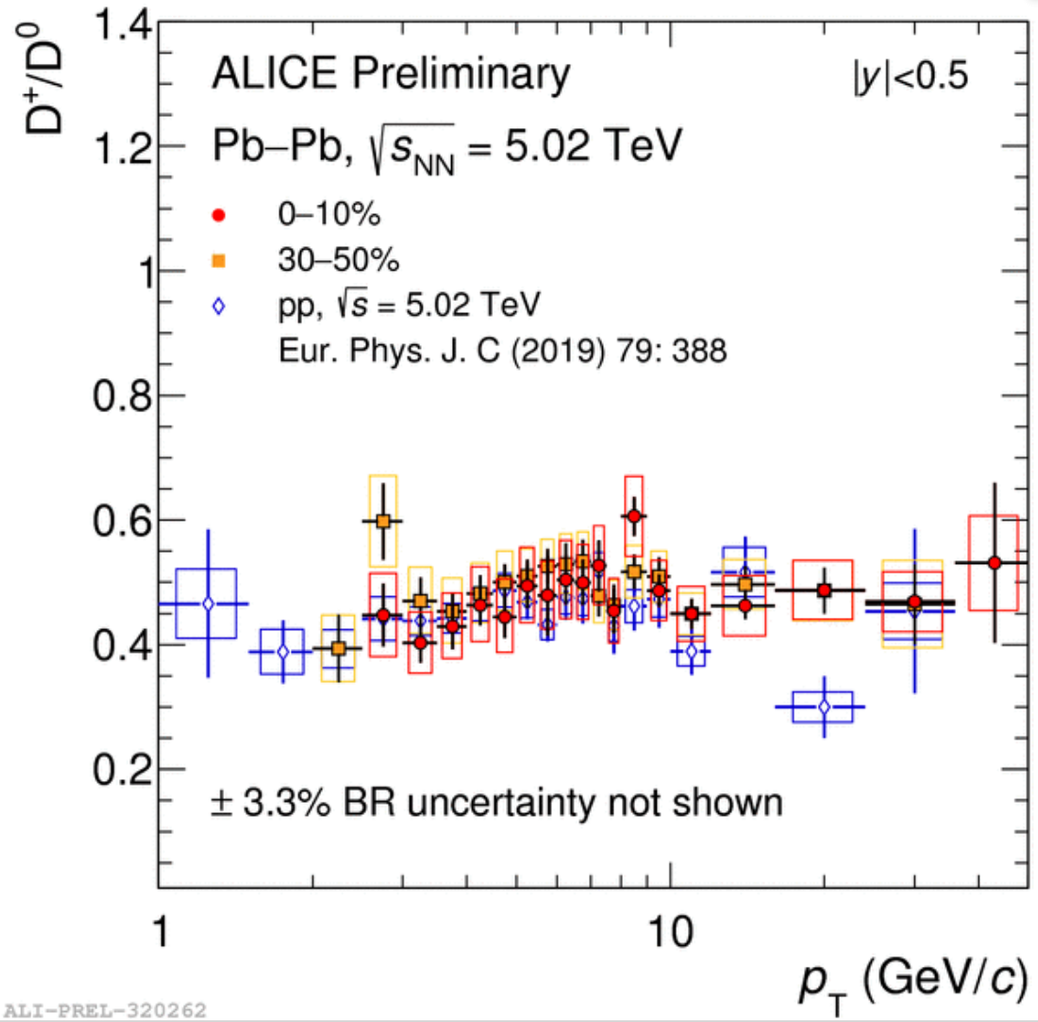
Double ratio: $(D_s/D^0)_{Pb\text{-}Pb}/(D_s/D^0)_{pp}$



- The double ratio $(D_s/D^0)_{Pb\text{-}Pb}/(D_s/D^0)_{pp}$ indicates an enhancement of D_s production in Pb-Pb in the region p_T<10 GeV/c that can be attributed to the strangeness-rich environment of Quark Gluon Plasma
- Models expectations are in qualitative agreement with data.

Non-strange D-meson ratios

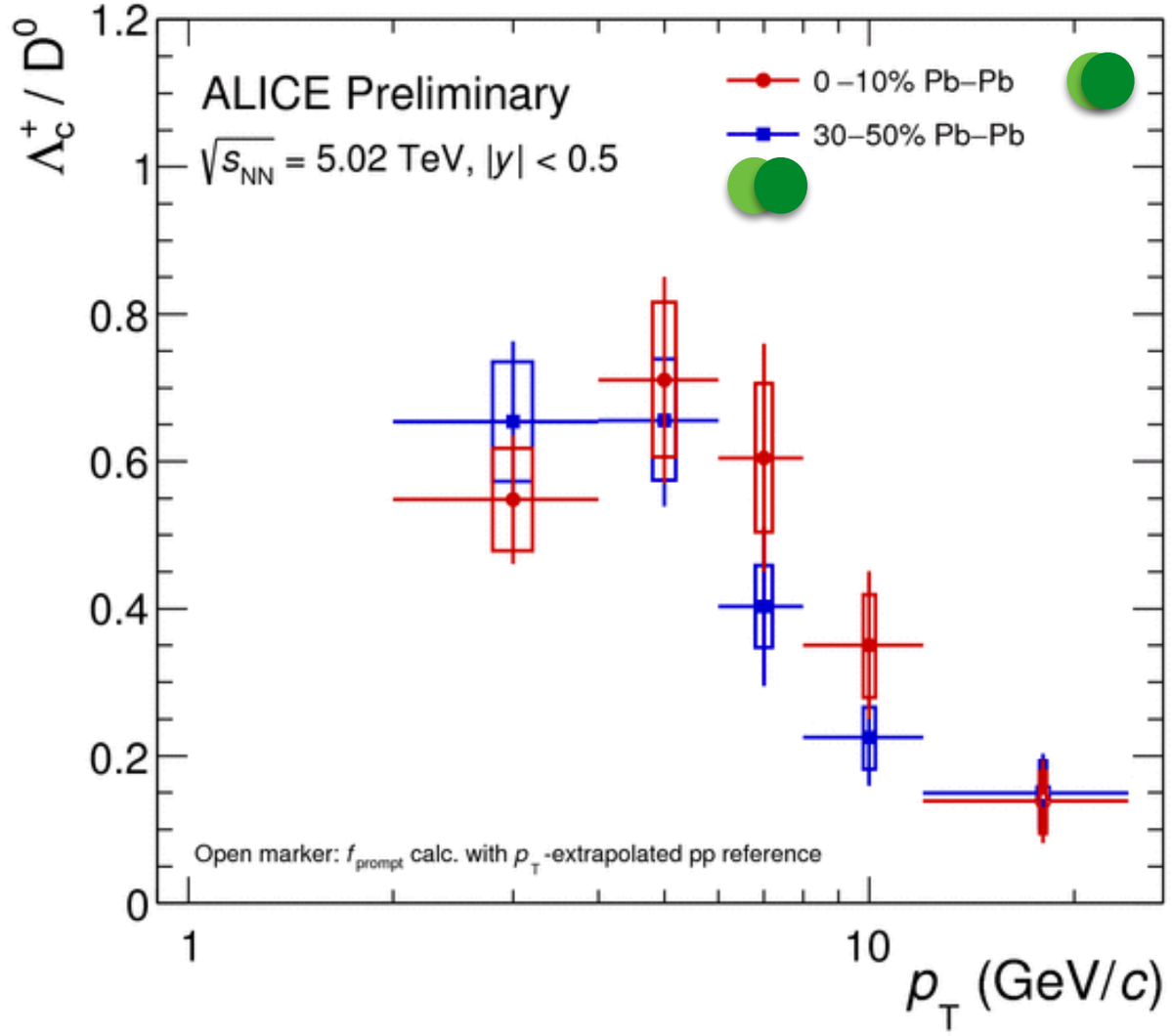




☑ Particle species ratio seems independent of the centrality of the Pb-Pb collision and even of the collision system

What about baryon-to-meson ratio?

- The investigation of the Λ_c/D^0 ratio in heavy-ion collisions allow investigating the possible modification of the charm fragmentation in-medium. Ratio enhanced with respect pp baseline if:
  - ☑ Charm quark hadronize via recombination with the light quarks in QGP
  - ☑ di-quark bound states can enhance further the ratio



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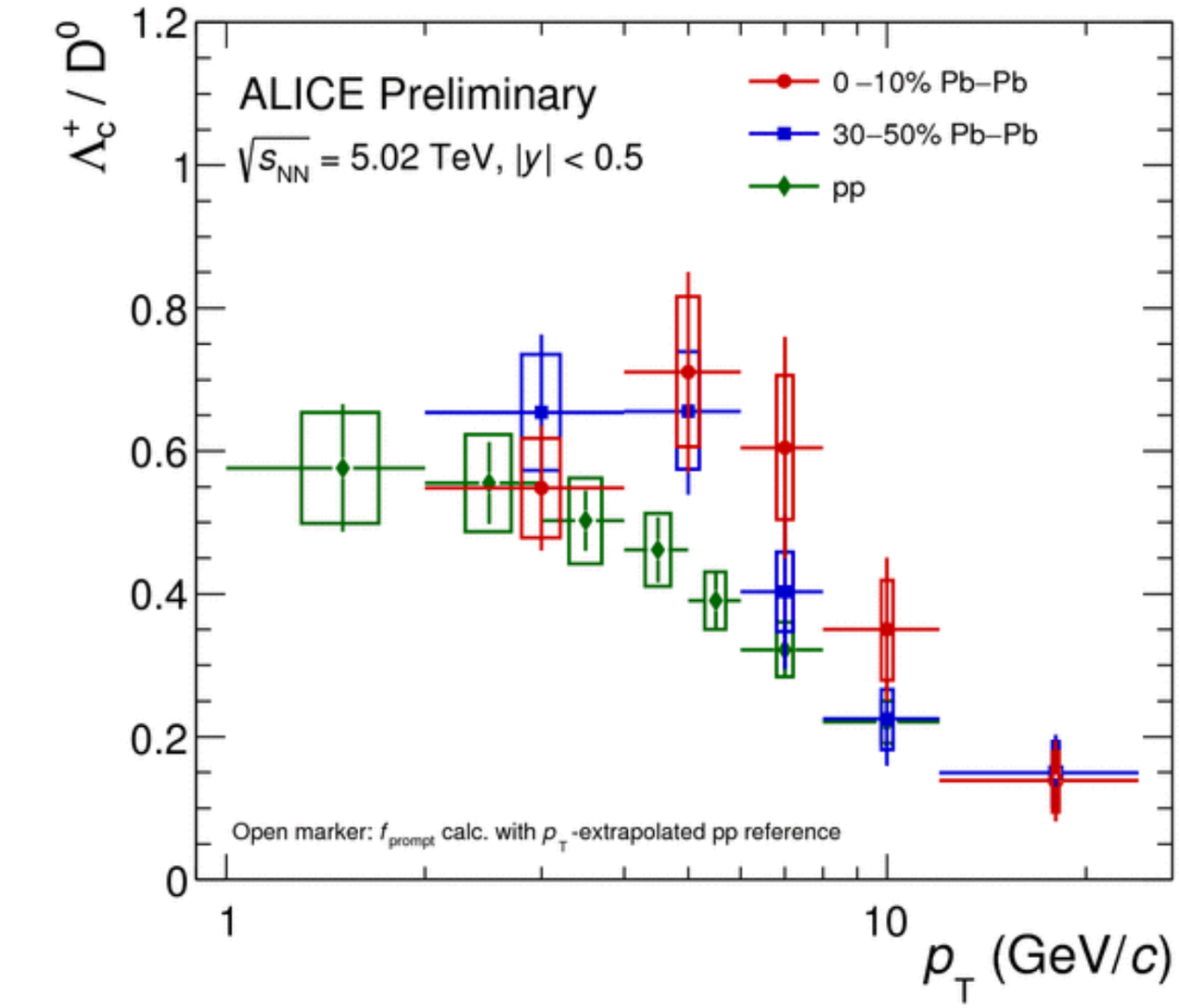
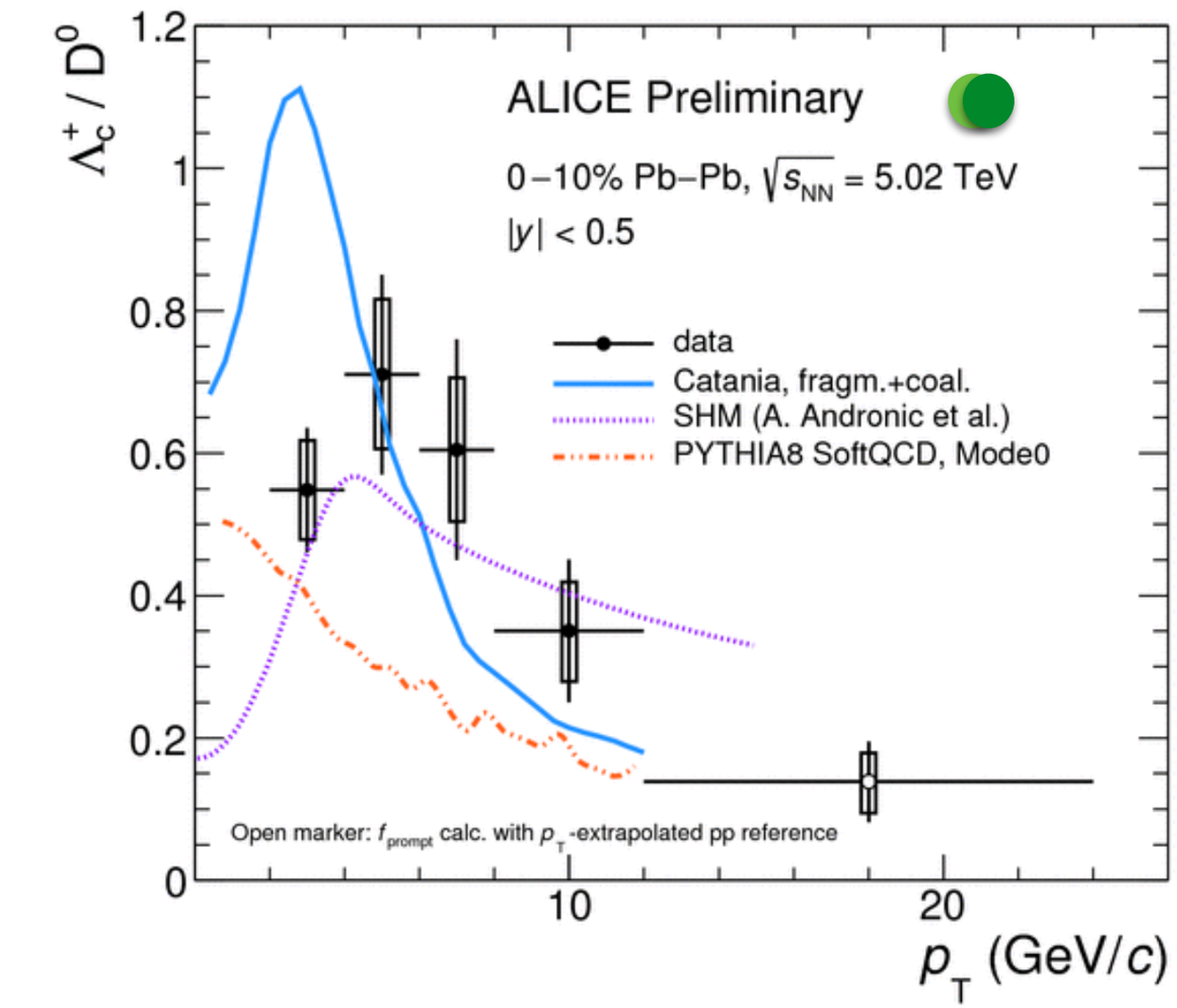
  - ☑ di-quark bound states can enhance further the ratio



What about baryon-to-meson ratio?

- Data well reproduced by statistical hadronization model. Catania coalescence model gives a reasonable comparison with some hint of tension at low momentum.
- Pythia Mode 0 (enhanced color reconnection) underestimates the magnitude of the data result



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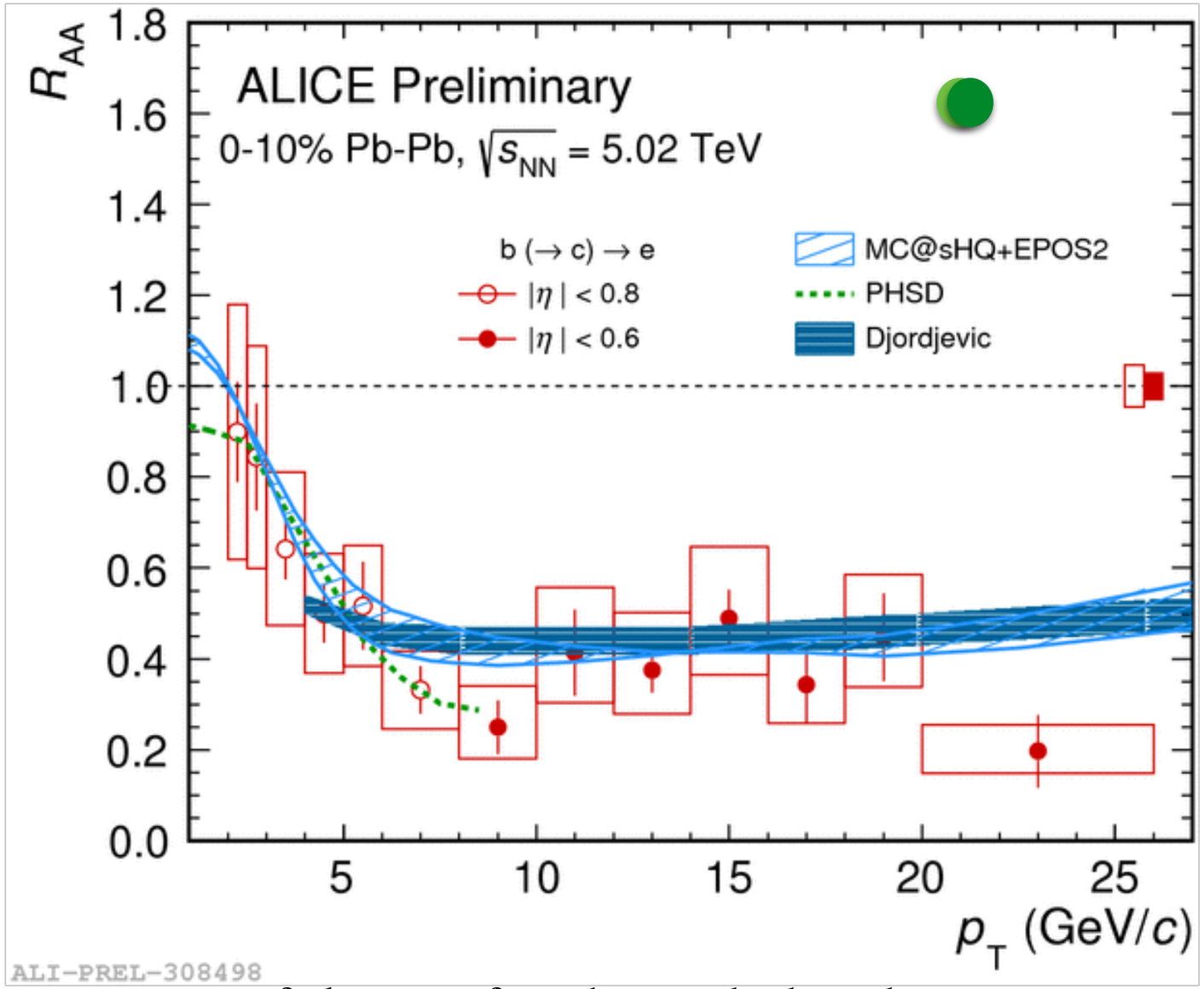
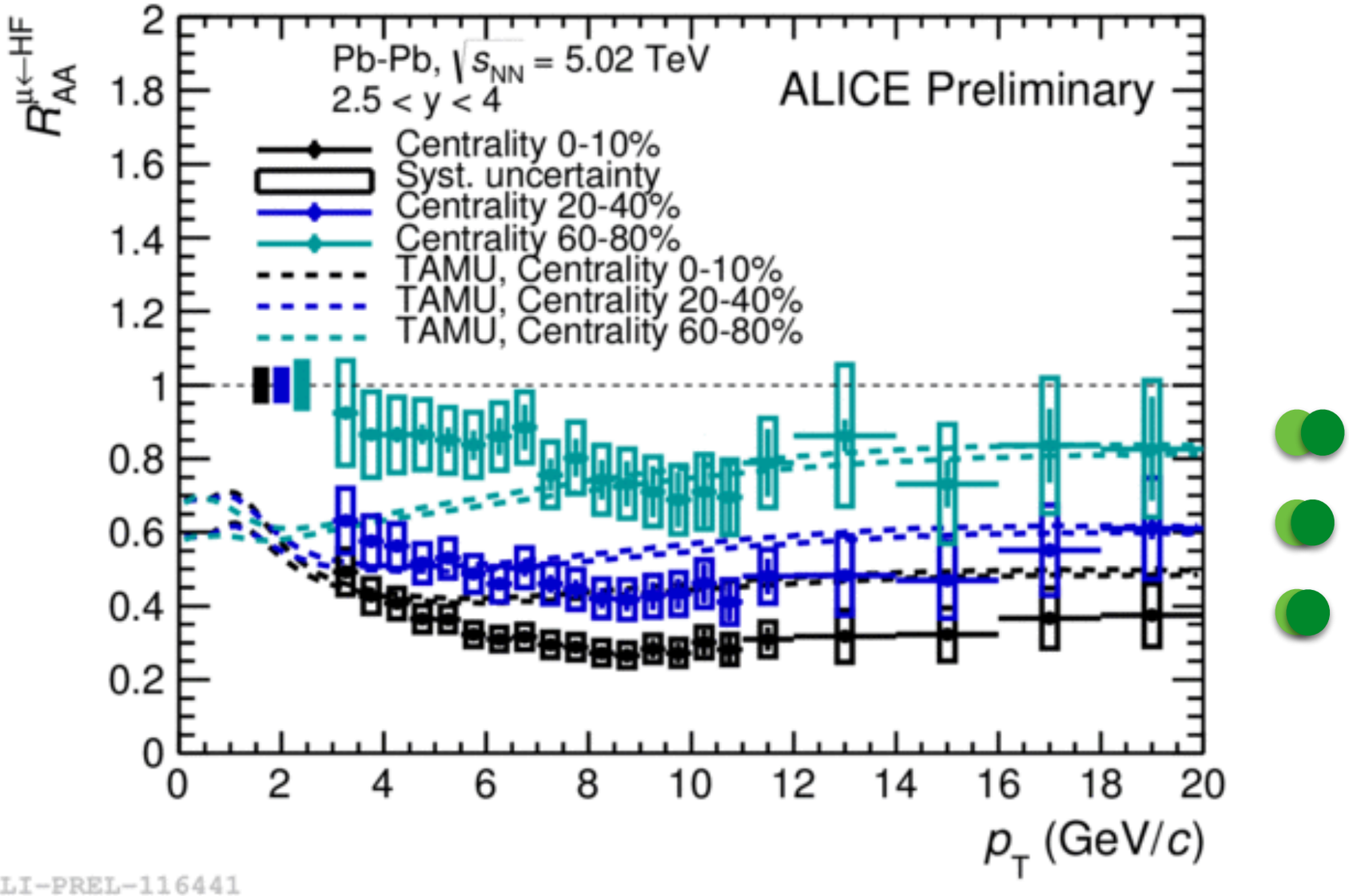
Beauty production



- ☑ Beauty via the measurement of electrons from beauty-hadron decays
- ☑ Large suppression measured in central Pb-Pb collisions
- ☑ Models including in-medium energy loss can reproduce well the data (within the large uncertainties)

Muons at forward rapidity



- ☑ Precision measurement! .. specially in 0-10% centrality
- ☑ Large suppression, similar in magnitude to the one found at central rapidity
- ☑ Very challenging for models.

Summary

- pp measurements as a test of pQCD: we are entering a precision era, 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 era. Unexpected behavior of baryon-to-meson ratio
- Pb-Pb results show a clear evidence of final-state effects. Large suppression -> R_{AA}<<1

☑ Some open question:

- ☐ What is the nature of these collettive-like effects in p-Pb?
- ☐ 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:

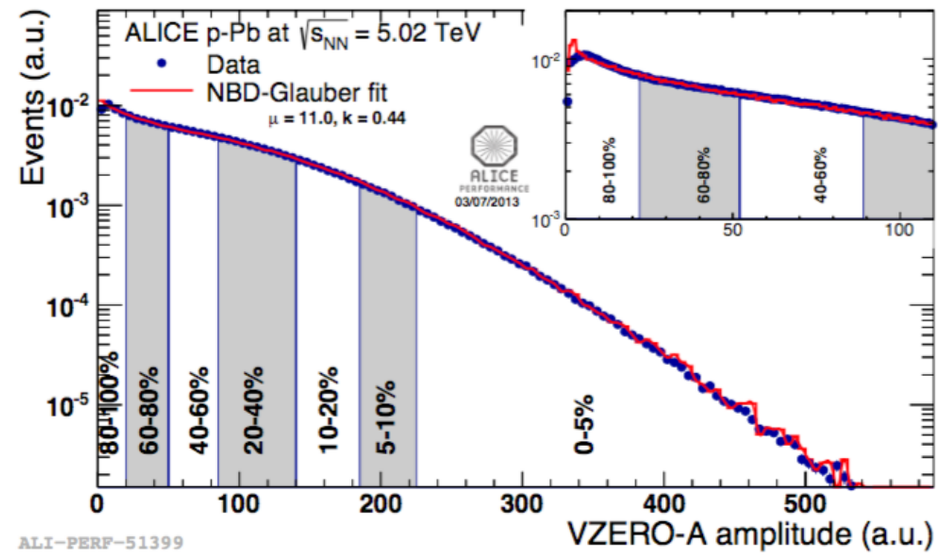
V0A: $\langle N_{coll} \rangle$ determined by Glauber fit of V0 amplitude

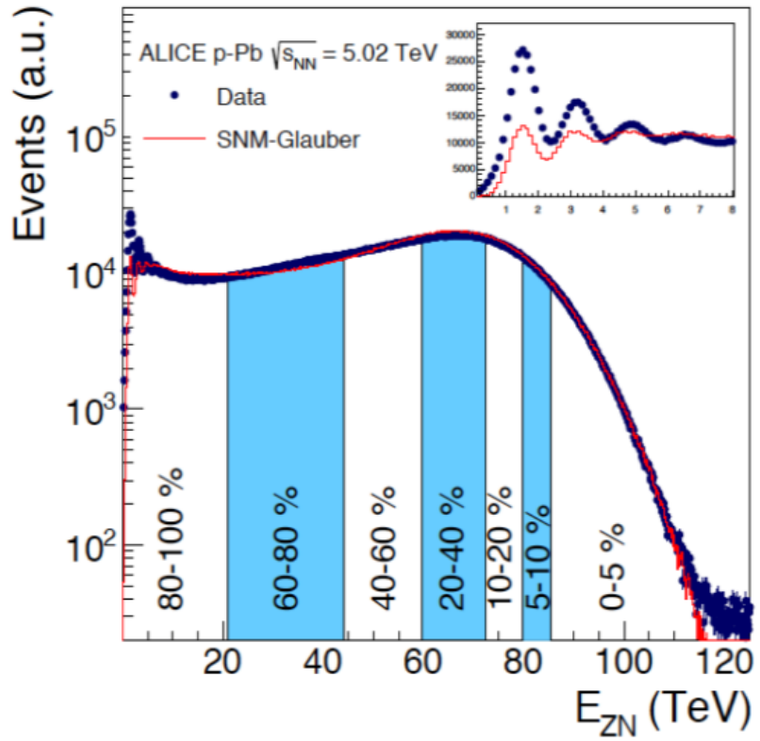
ZNA: $\langle N_{coll} \rangle$ obtained with a "Hybrid method"

- 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

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

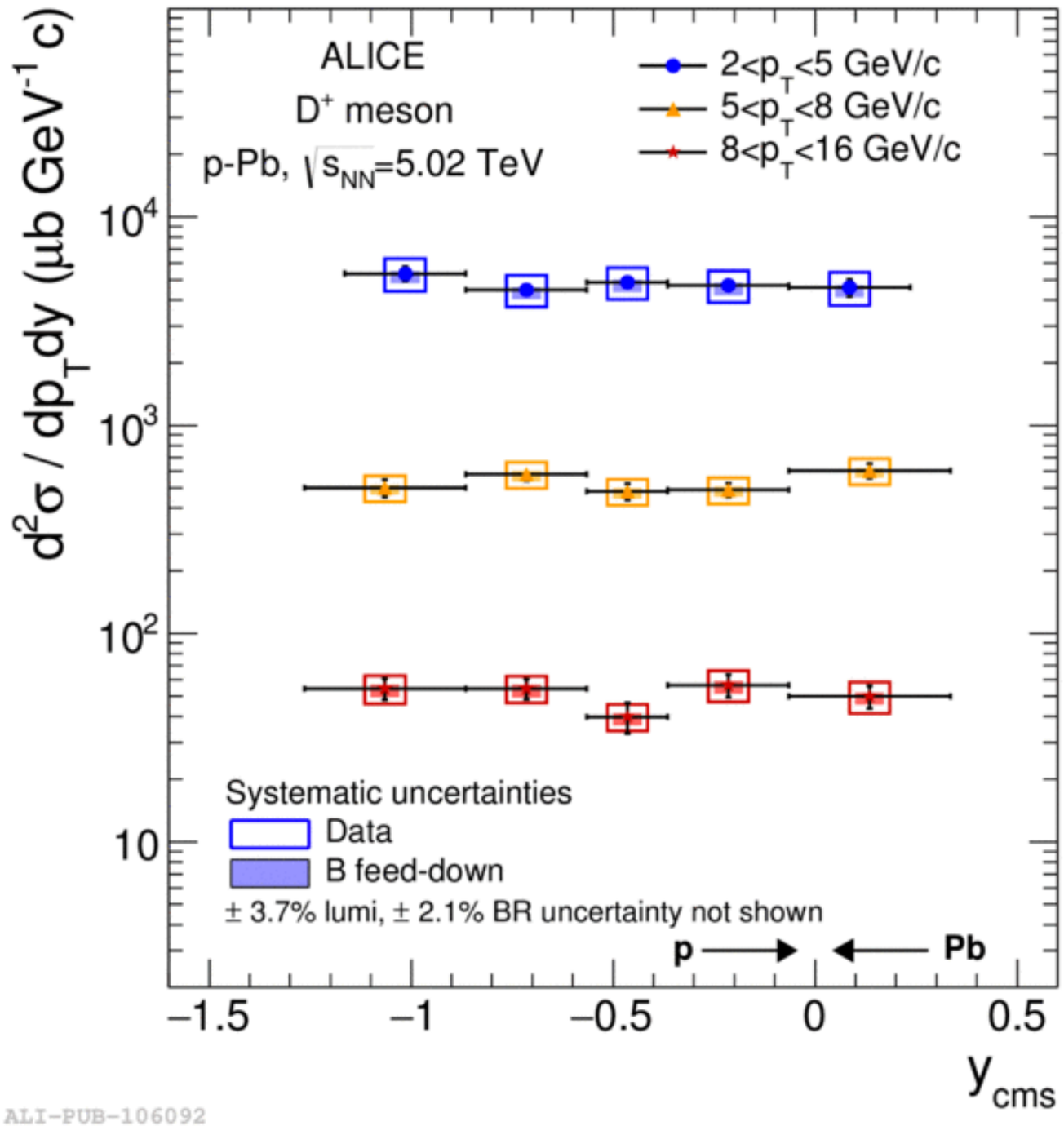
investigate charm production in p-Pb collisions w.r.t. pp collisions: possible multiplicity dependent modification of the p_T spectra in p-Pb?





a.grelli@uu.nl

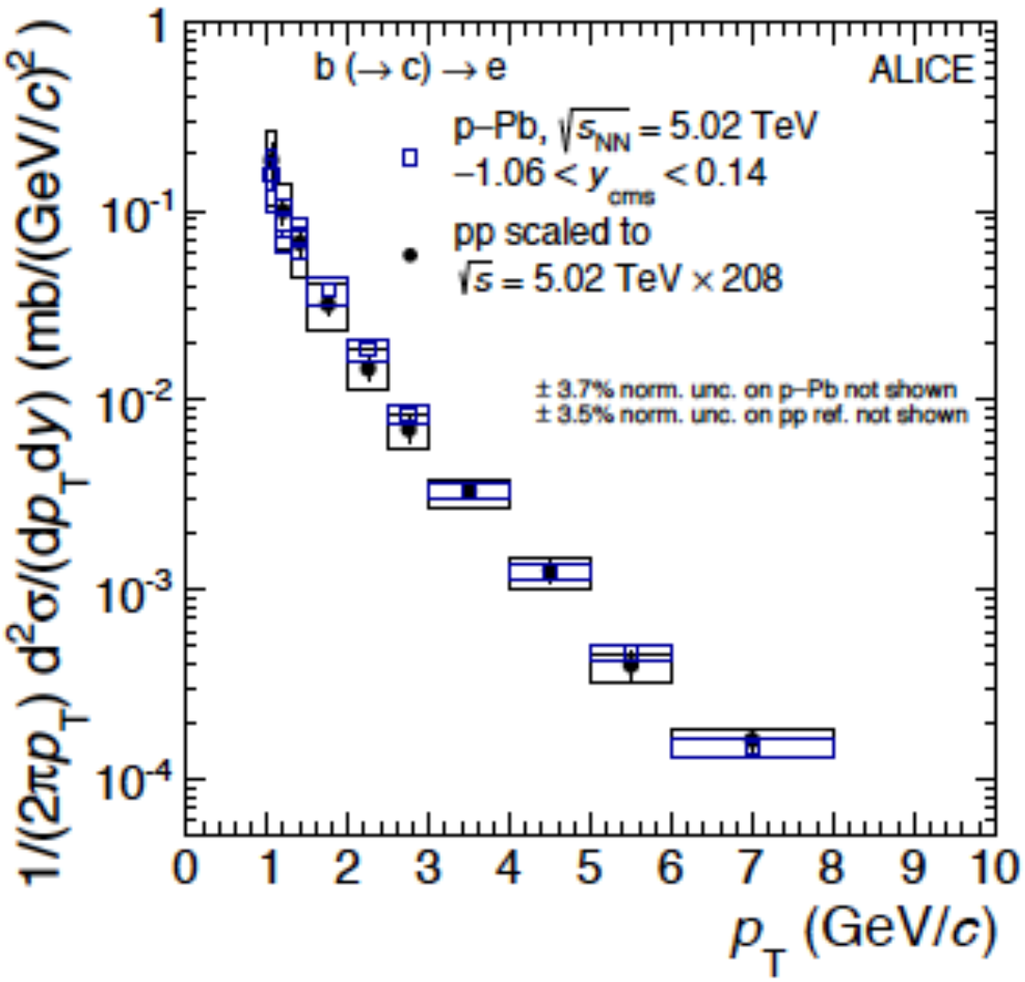
D mesons production vs rapidity at mid-rapidit

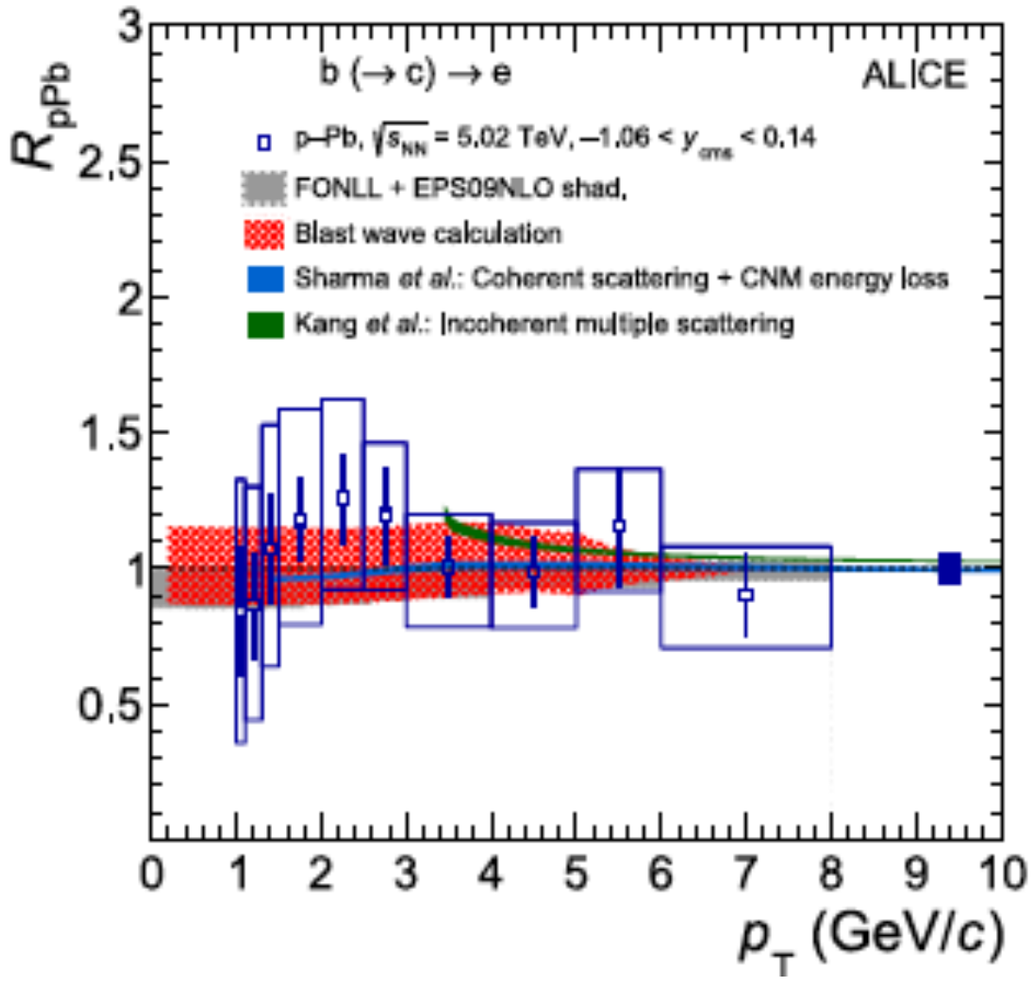


a.grelli@uu.nl

Open-beauty with ALICE

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

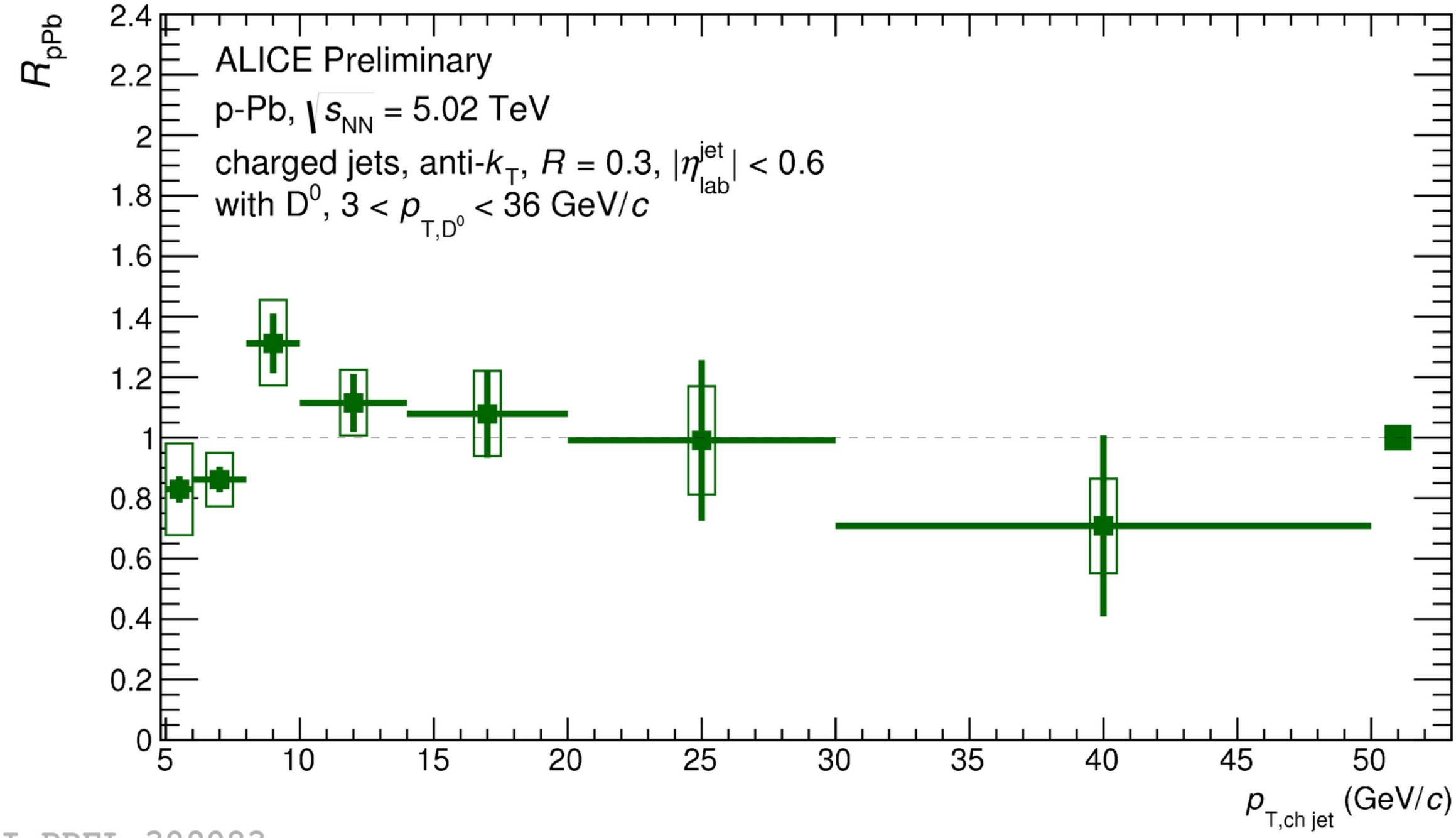




- ☑ Beauty electrons results are compatible with unity within uncertainties
- ☑ Models describe well the R_{pPb}

a.grelli@uu.nl

D tagged jets R_{pPb}



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D mesons prompt fraction