NWO
Netherlands Organisation
for Scientific Research

Experimental review of Open Charm in p-A collisions

Alessandro Grelli

Utrecht University

Outline

- **pp collisions:**
  - Test pQCD calculations
  - Study hadronization mechanism
  - Set a reference for p-Pb and Pb-Pb
- **p-A 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-A collisions.
- **A-A collisions**
  - Heavy-quarks effective probe for the properties of the hot and dense QCD matter produced in heavy-ion collisions
    - Heavy-quark energy loss
    - Quarkonium dissociation/regeneration

Why 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

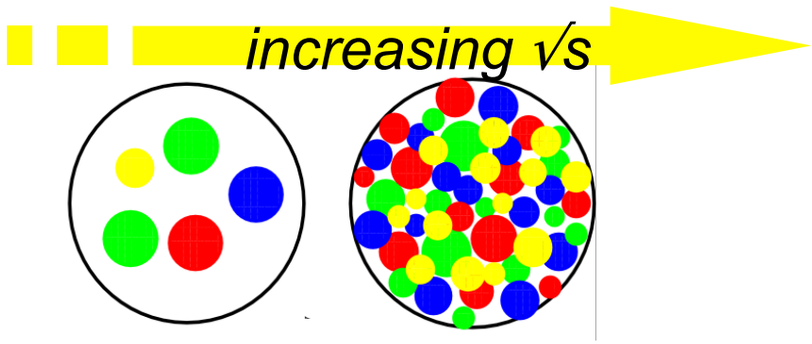
A-A

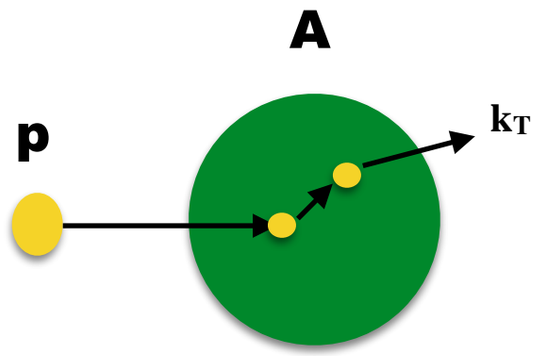
QCD medium

Why study pA: Canonical picture

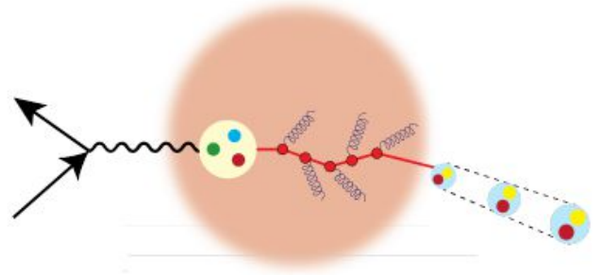
QCD vacuum

p-p



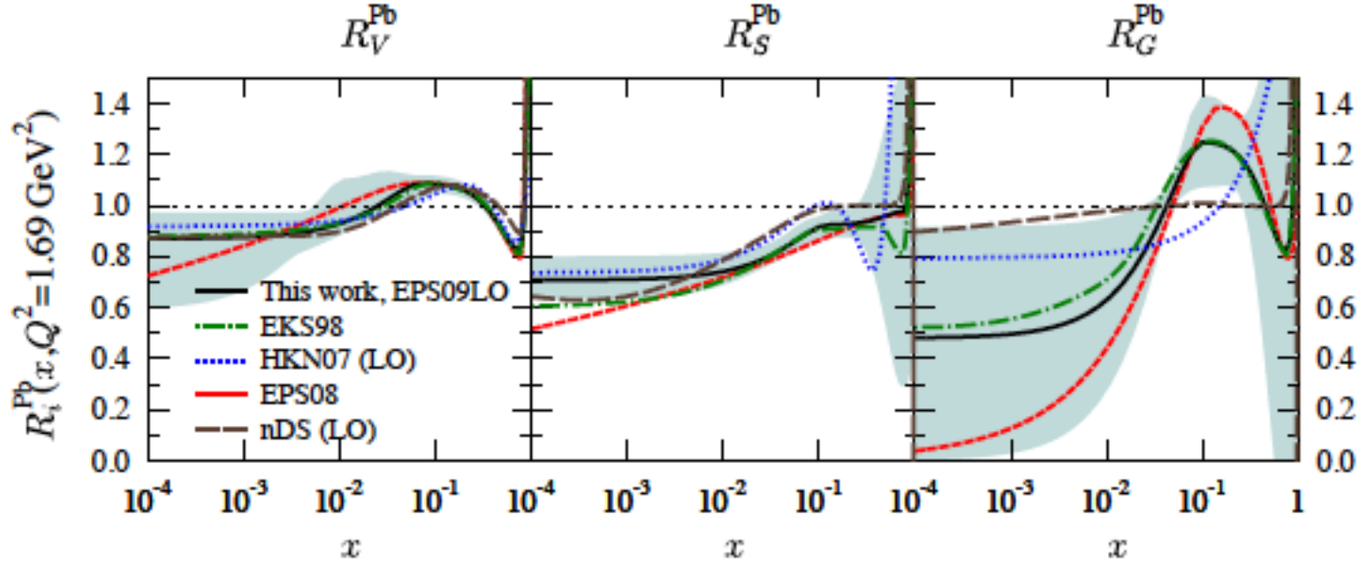


- Cold nuclear matter effects (nPDF, shadowing, gluon saturation, k_T-broadening, energy loss in CNM in the initial and final state)
- coherent/collective interactions of nuclear fragments, and QGP formation
- final-state interactions with QGP



A-A

QCD medium

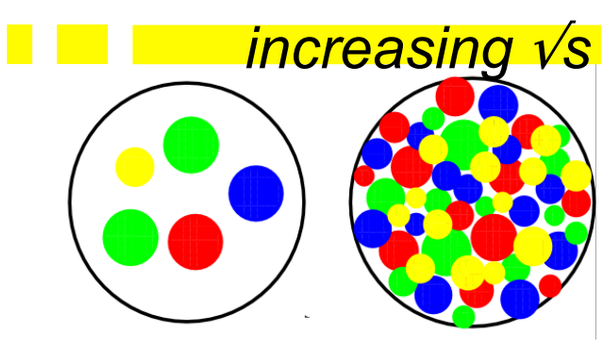


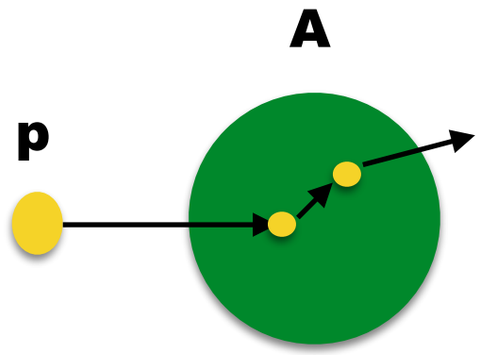
K.J. Eskola, H. Paukkunen, C. A. Salgado, JHEP 0904, 65 (2009)

Why study pA: Canonical picture

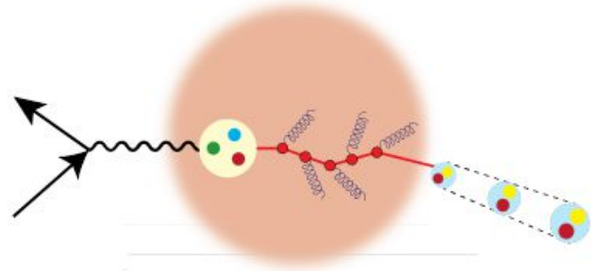
QCD vacuum

p-p



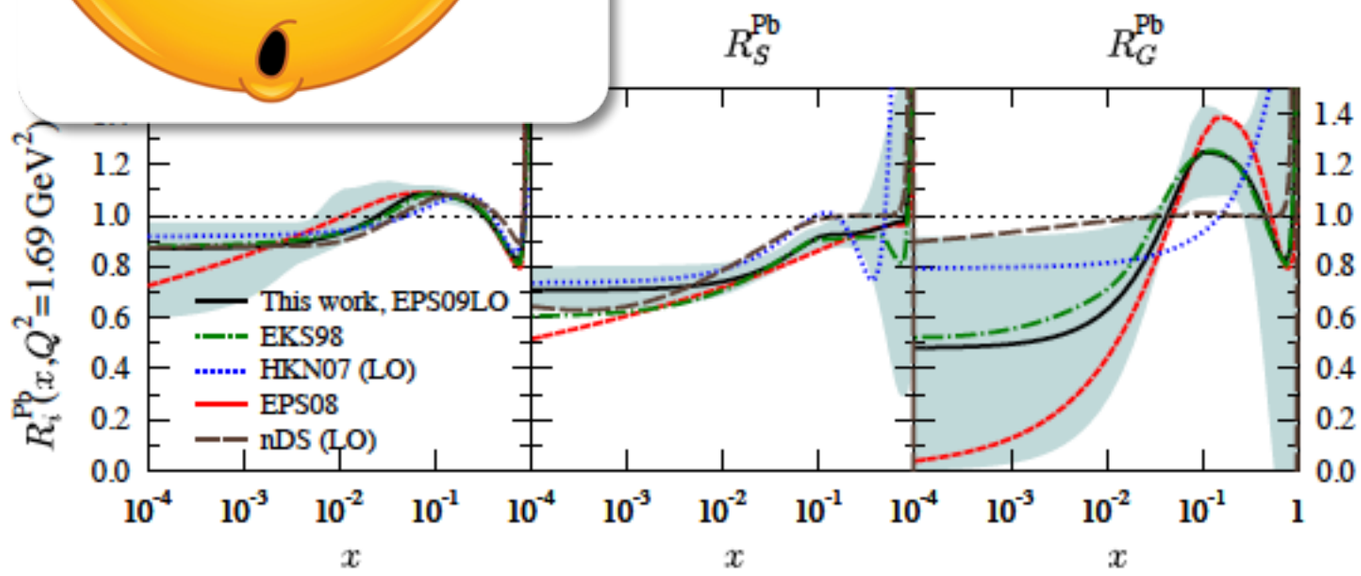


- Cold nuclear matt
  shadowing, gluon
  broadening, energ
  initial and final sta
- coherent/collectiv
  nuclear fragments
- final-state interact



A-A

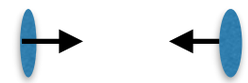
QCD medium



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

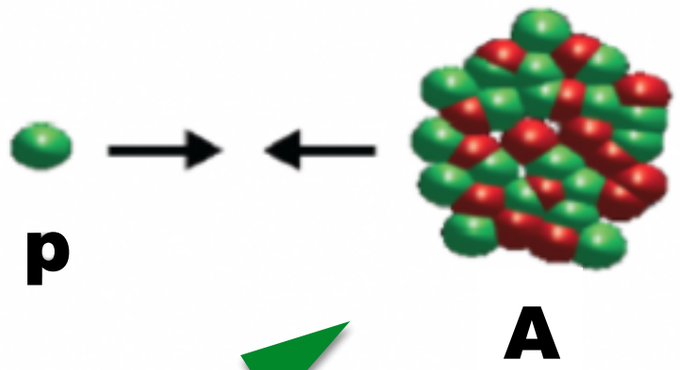
Why study pA: Canonical picture

QCD vacuum



p-p

- Probe Cold nuclear matter effects (nPDF, shadowing, gluon saturation, k_T-broadening, energy loss in the initial and final state)



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

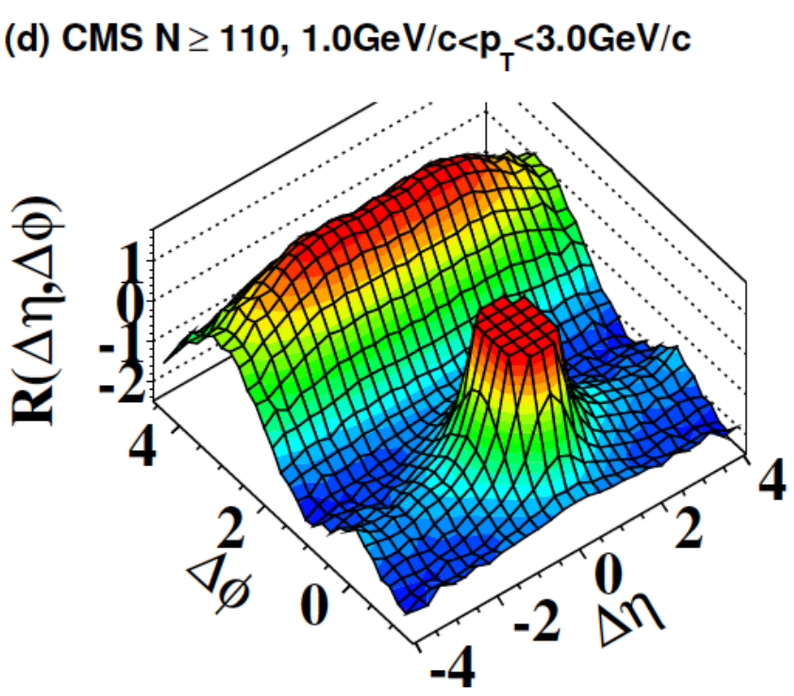
Outline

- **pp collisions:**
  - Test pQCD calculations
  - Study hadronization mechanism
  - Set a reference for p-Pb and Pb-Pb
- **p-A 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-A collisions.
- **A-A collisions**
  - Heavy-quarks effective probe for the properties of the hot and dense QCD matter produced in heavy-ion collisions
    - Heavy-quark energy loss
    - Quarkonium dissociation/regeneration

Collectivity in small systems

pp collisions

(CMS Collaboration) JHEP 09, (2010) 091



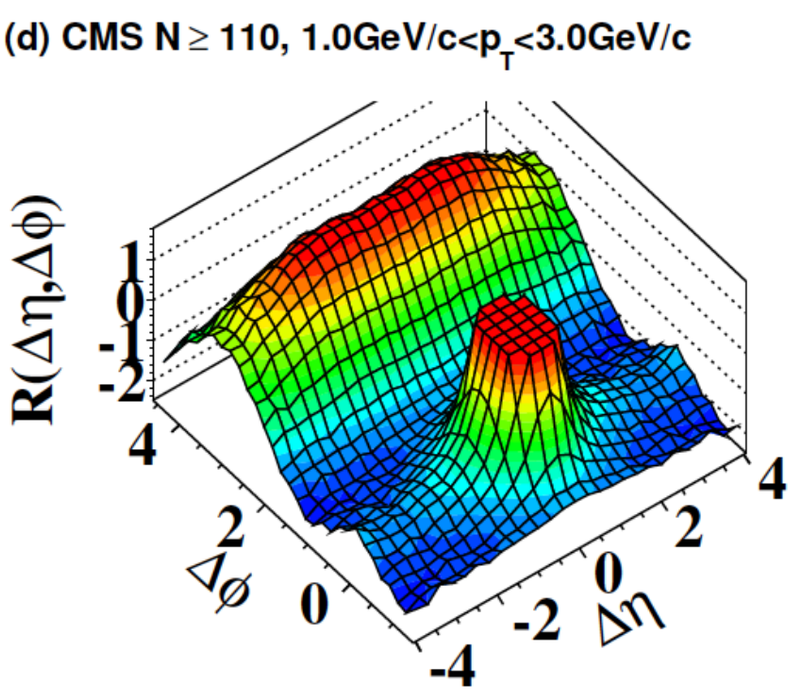
- ☑ LHC data opened a new hera: detailed study of high-multiplicity events (both in pp and p-A) become possible

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

Collectivity in small systems

pp collisions

(CMS Collaboration) JHEP 09, (2010) 091



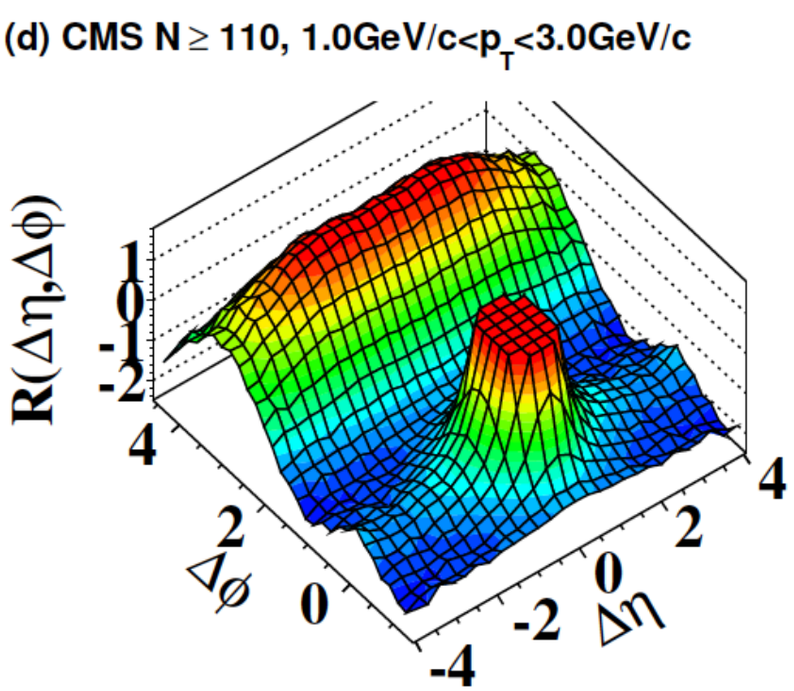
- ☑ LHC data opened a new hera: detailed study of high-multiplicity events (both in pp and p-A) becomes possible
- ☑ In 2010 CMS Collaboration publish a paper presenting the observation of a double-ridge structure high-multiplicity pp di-hadron correlation events

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

Collectivity in small systems

pp collisions

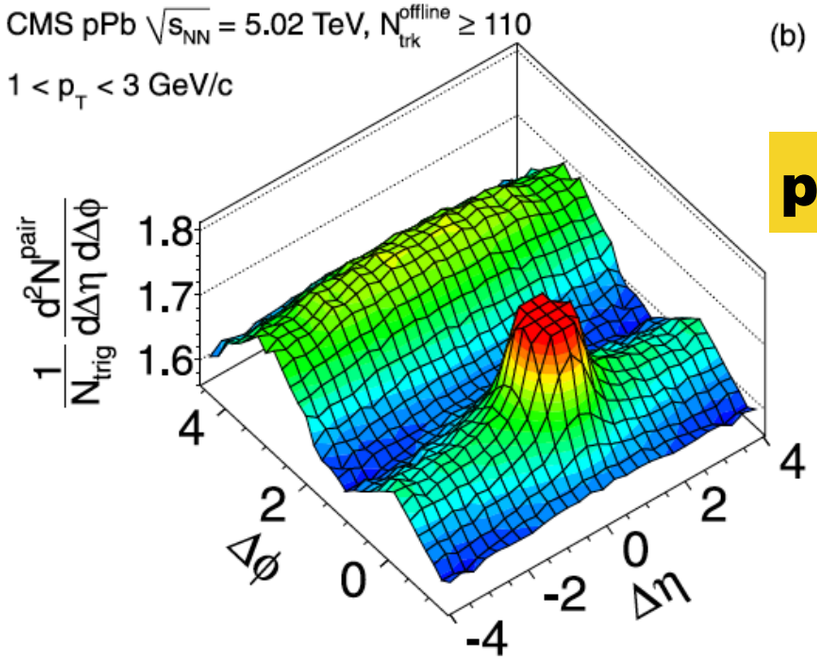
(CMS Collaboration) JHEP 09, (2010) 091



- ☑ LHC data opened a new hera: detailed study of high-multiplicity events (both in pp and p-A) becomes possible
- ☑ In 2010 CMS Collaboration publish a paper presenting the observation of a double-ridge structure high-multiplicity pp di-hadron correlation events

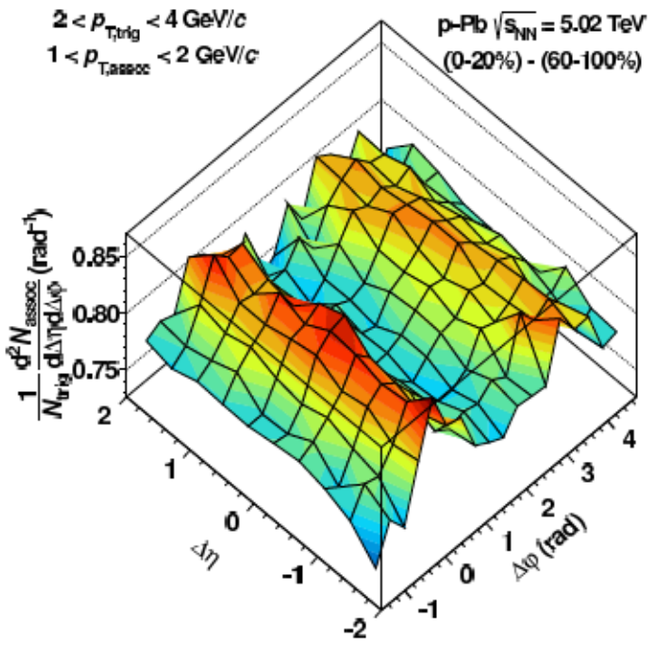
A collective QGP-like effect in pp and p-Pb?

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



p-Pb collisions

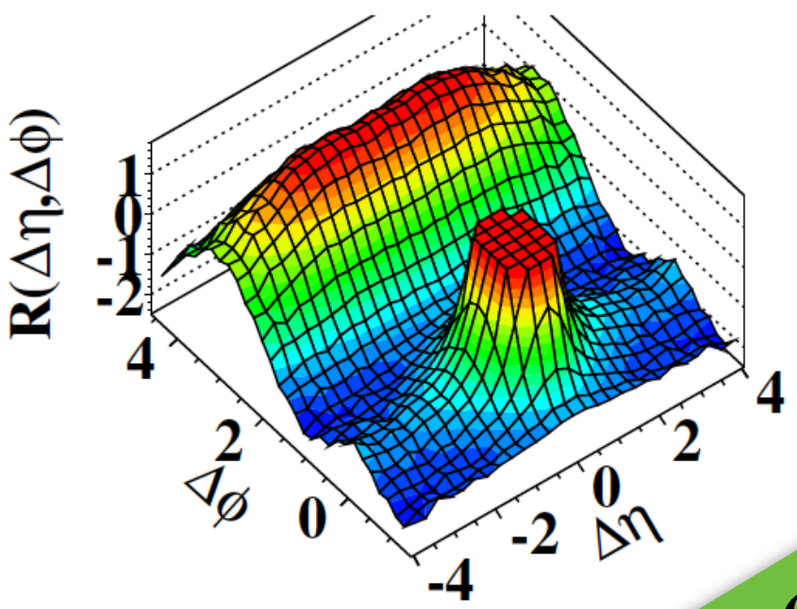
(ALICE Collaboration): Phys. Lett. B719, (2013) 29



Collectivity in small systems

pp collisions

(CMS Collaboration) JHEP 09, (2010) 091



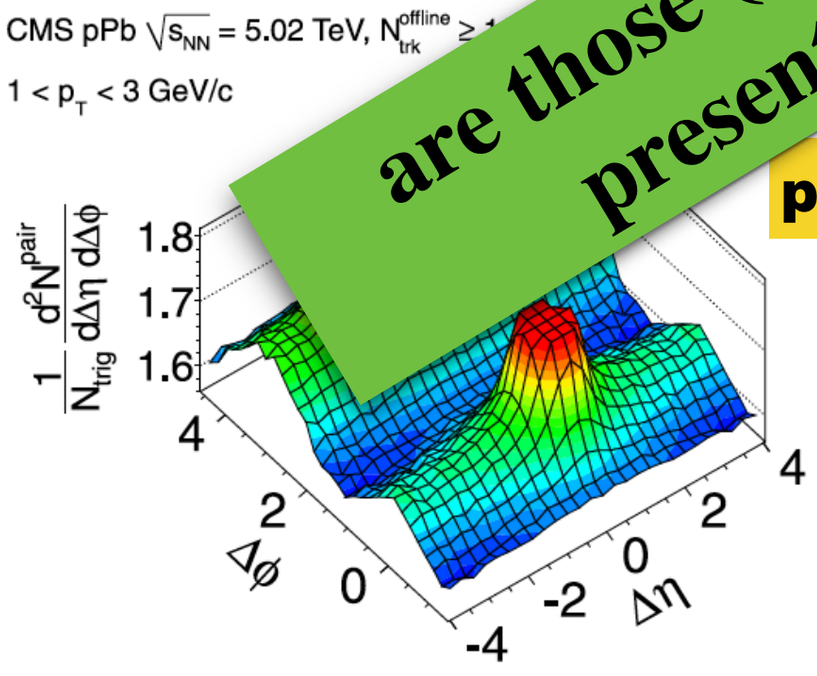
- ☑ LHC data opened a new hera: detailed study of high-multiplicity events (both pp and p-A) becomes possible
- ☑ In 2010 CMS Coll… a paper presenting th… double-ridge structur… pp di-hadron correlation ev…

…QGP-like effect in pp and p-Pb?

…QGP-like) collective effects … the Charm sector?

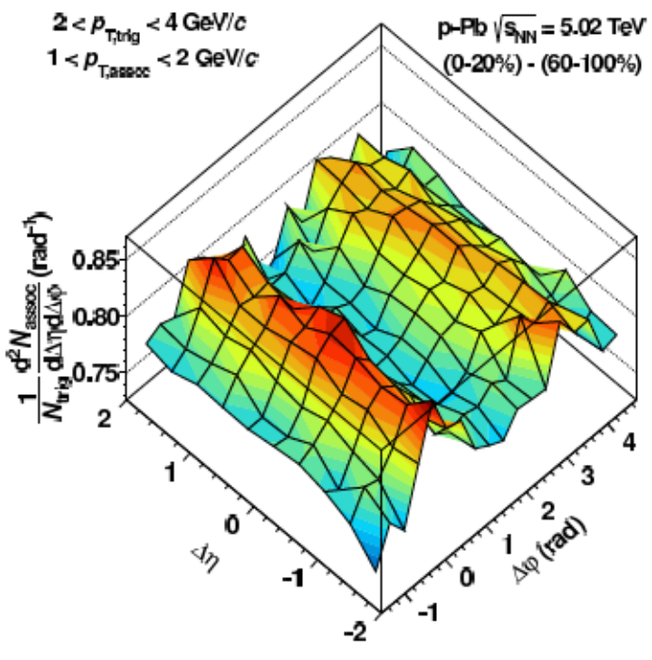
are those (QGP… present in the C…

(CMS Collaboration) Phys. Lett. B71…



p-Pb collisions

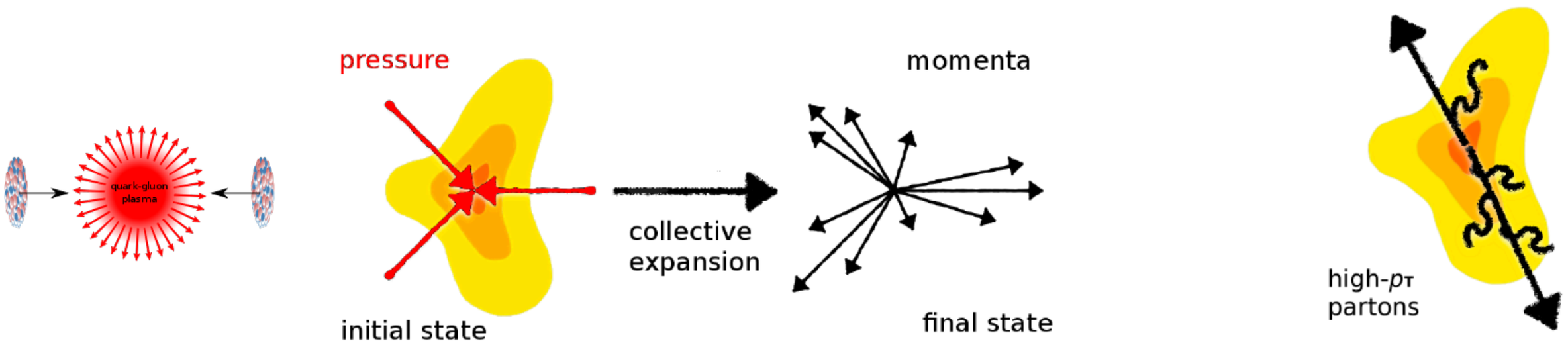
(ALICE Collaboration): Phys. Lett. B719, (2013) 29



Elliptic flow v_2 as a measure of collectivity

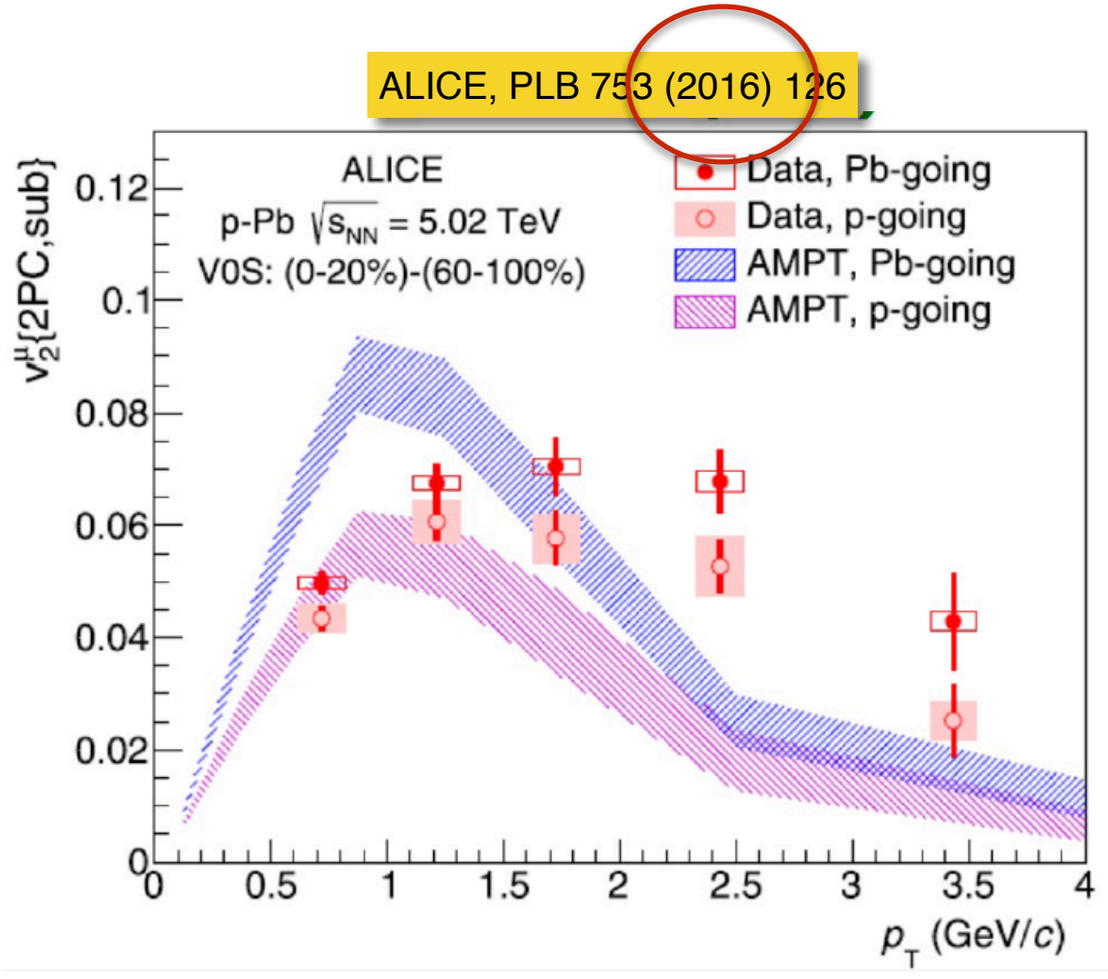
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \Psi_n)\right]$$

- Flow: momentum anisotropies in azimuthal angle, quantified by coefficients $\mathbf{v_n}$
  - ☑ 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 traverse)
  - ☑ 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

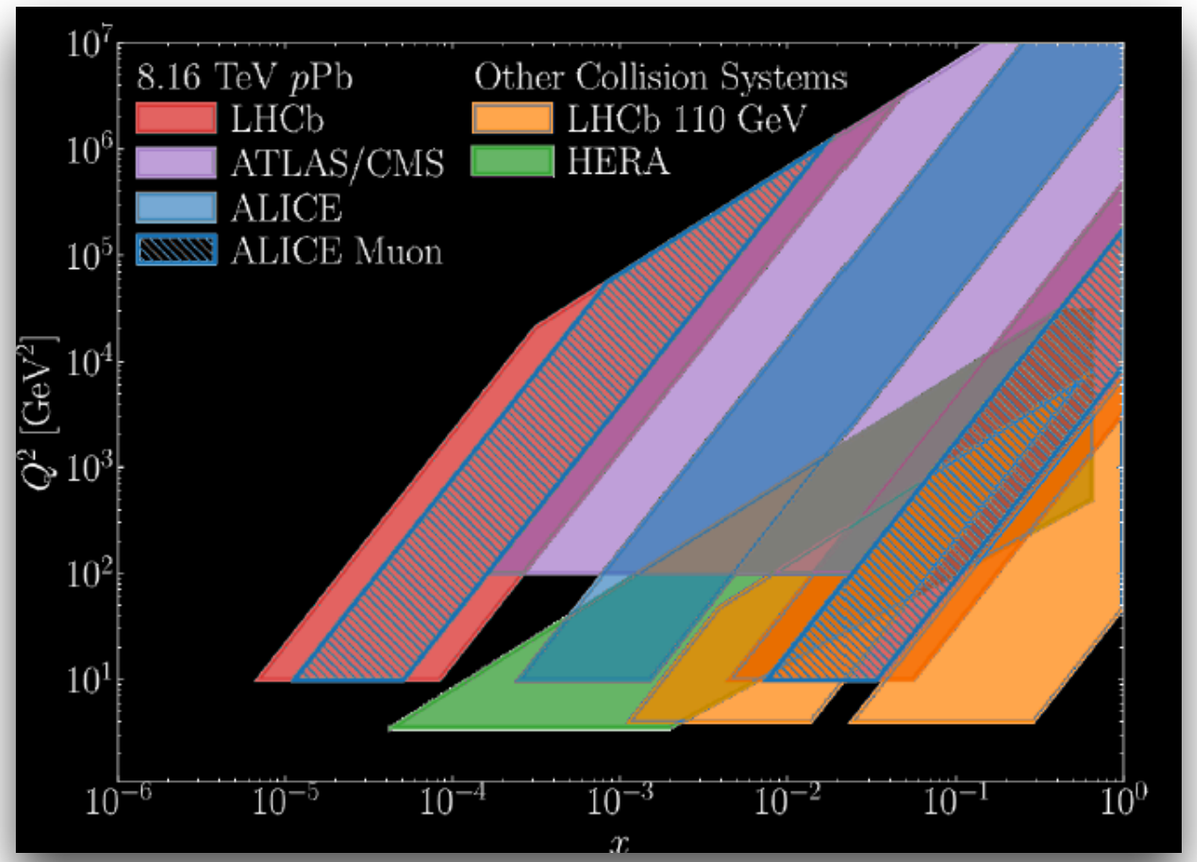


☑ **Indirect hint** of non-zero heavy flavour flow in p-Pb from inclusive muons at forward rapidity (p_T>2 GeV/c)

➡ High-p_T inclusive muons are HF dominated.

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

Open-charm production: review of recent results



LHCb:
Graphic by T. Boettcher

- ☐ Fully reconstructed hadronic decays of D mesons
- ☐ Fully reconstructed hadronic decays and semi-leptonic decays of charmed baryons
- ☐ Electrons from heavy-flavour hadrons decays
- ☐ Muons from heavy-flavour hadrons decays

Open-charm production: review of recent results

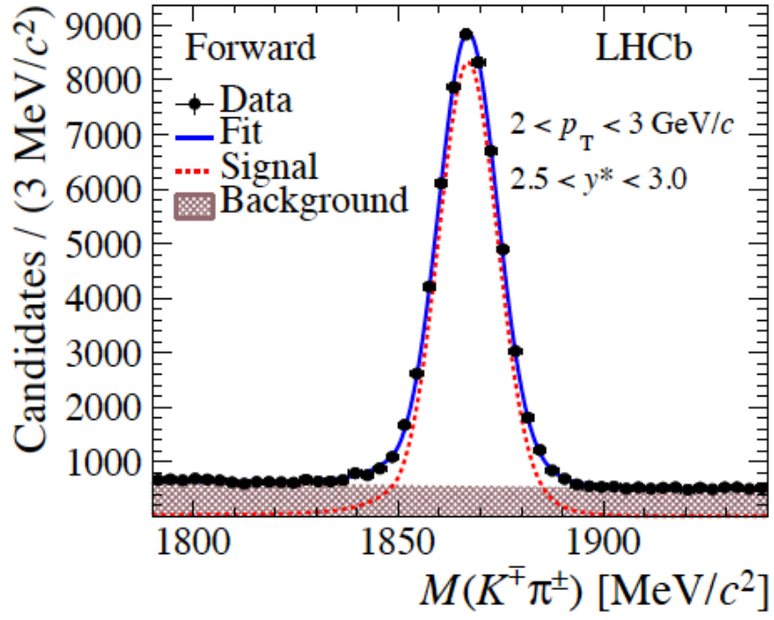
Sorry in advance if your favourite experiment/result is not covered!

- [x] Fully reconstructed hadronic decays of D mesons
- [x] Fully reconstructed hadronic decays and semi-leptonic decays of charmed baryons
- [ ] Electrons from heavy-flavour hadrons decays
- [ ] Muons from heavy-flavour hadrons decays

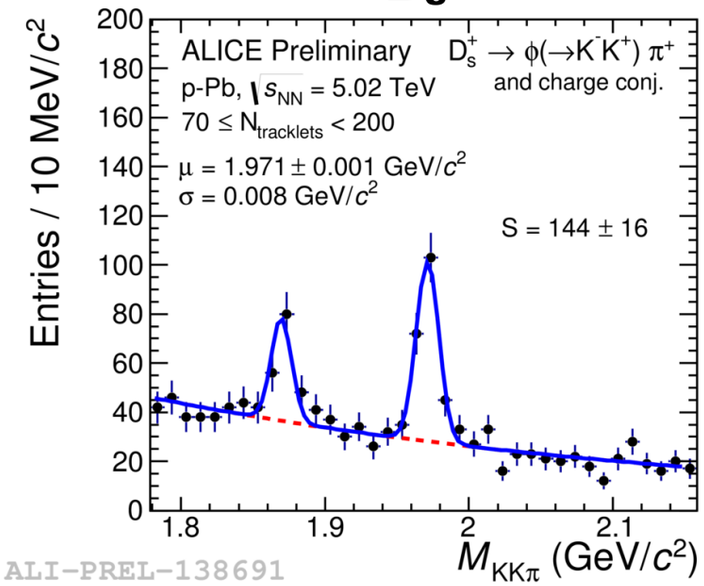
D-meson production in p-A

- ☑ Fairly similar reconstruction strategy among different experiments:
  - ➡ Reconstruct the displaced topology ($c\tau_D$ ~123-300 μm)
  - ➡ Apply selections on the reconstructed topology
  - ➡ Particle IDentification (PID) to further suppress background (ALICE, LHCb, STAR)
  - ➡ Use background simulation methods (mixing, rotational, like sign) to access the very low p_T (~0) (ALICE, STAR)

D^0

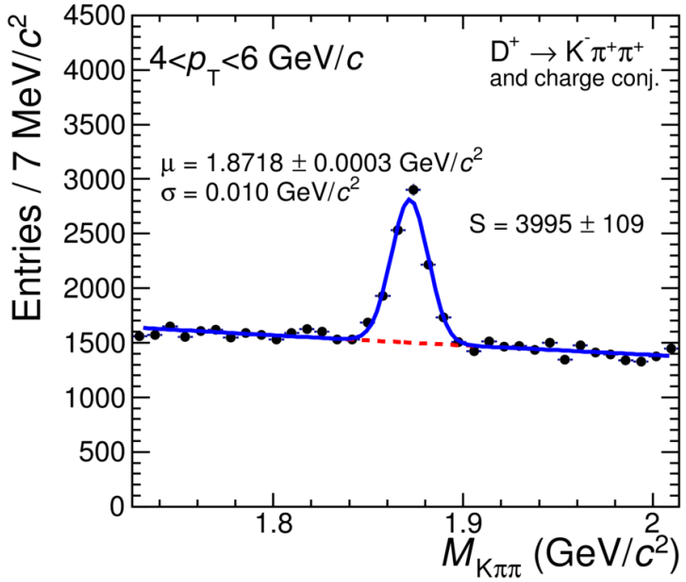


D_s

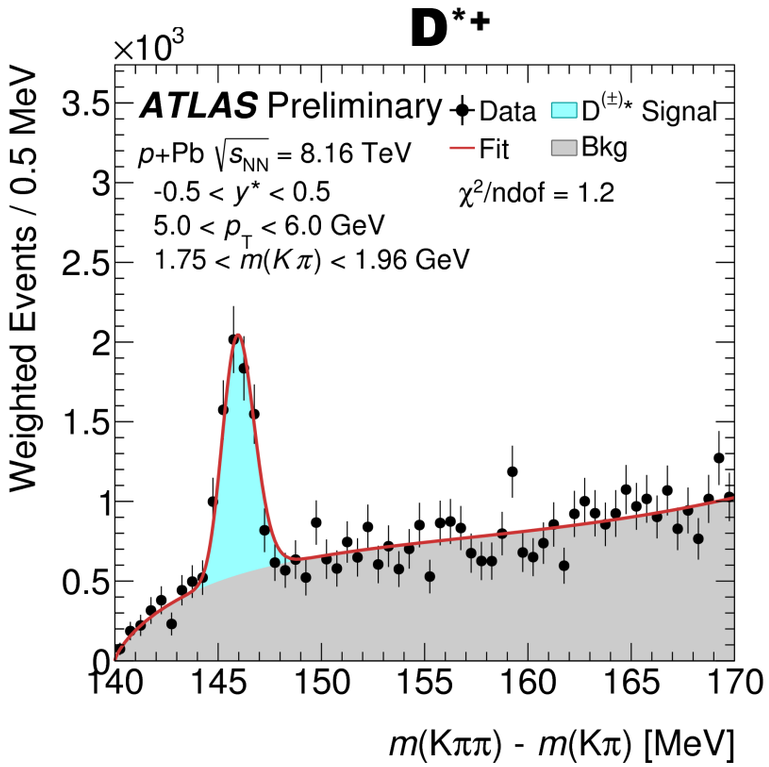


ALI-PREL-138691

D^+



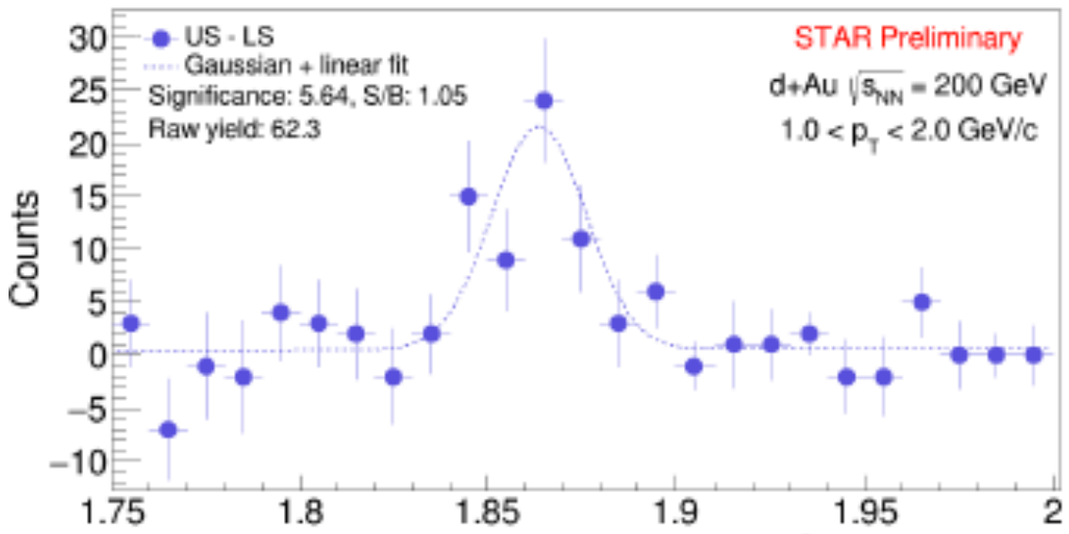
D^{*+}

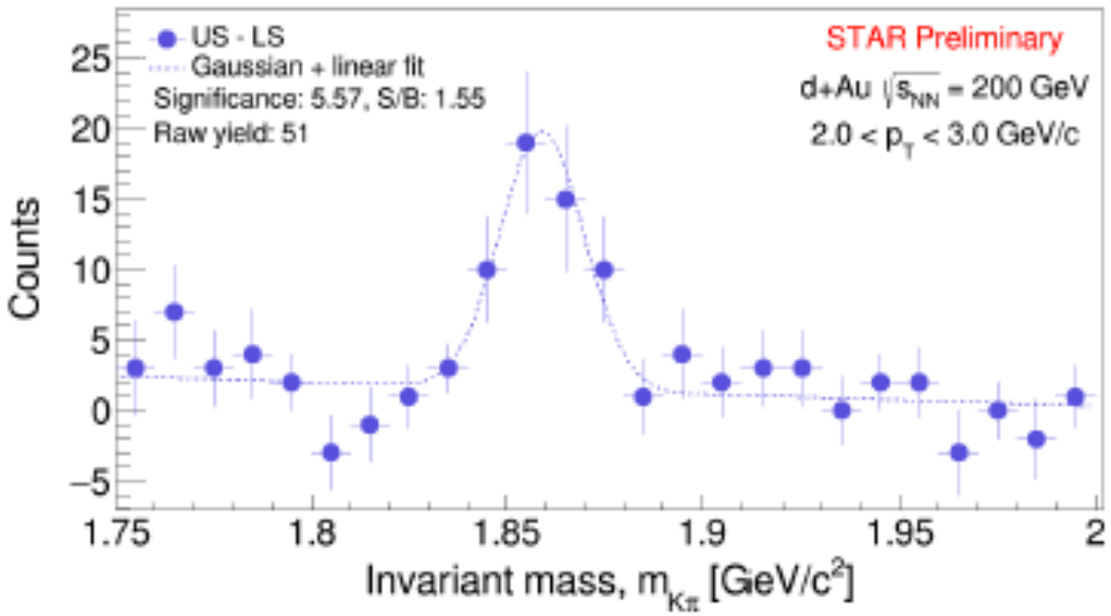


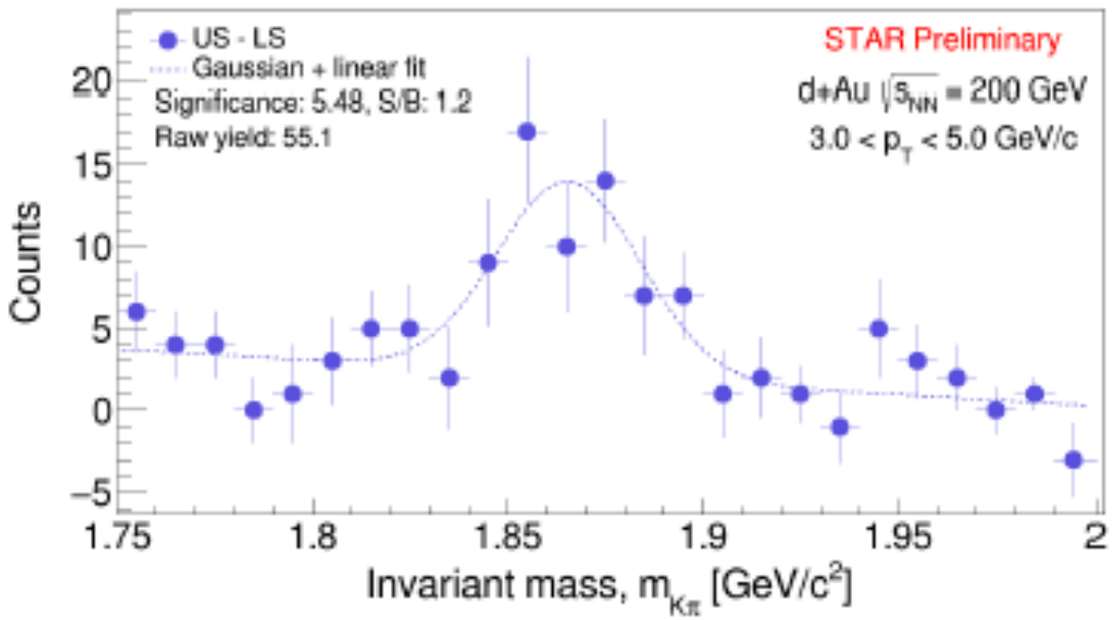
D-meson production at $\sqrt{s_{NN}}$ = 200 GeV

Lukáš Kramárik [poster] QM2018

https://indico.cern.ch/event/656452/contributions/2871089/



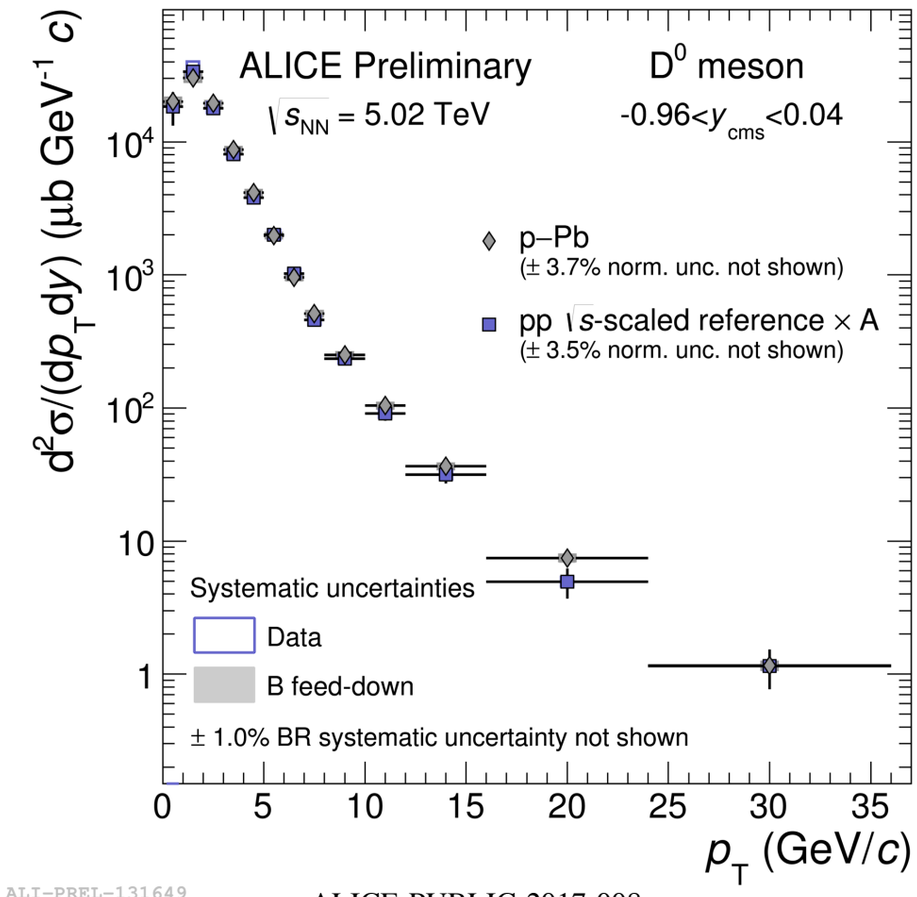




- ☑ STAR experiment at RHIC is analyzing the new 2016 **d-Au** run
  - ➡ Excellent performances of the Heavy-Flavour tracker allow for the investigation of charm in d-Au
  - ➡ D^0 accessible down to low p_T (~1 GeV/c)
  - ➡ Good significance (>5)

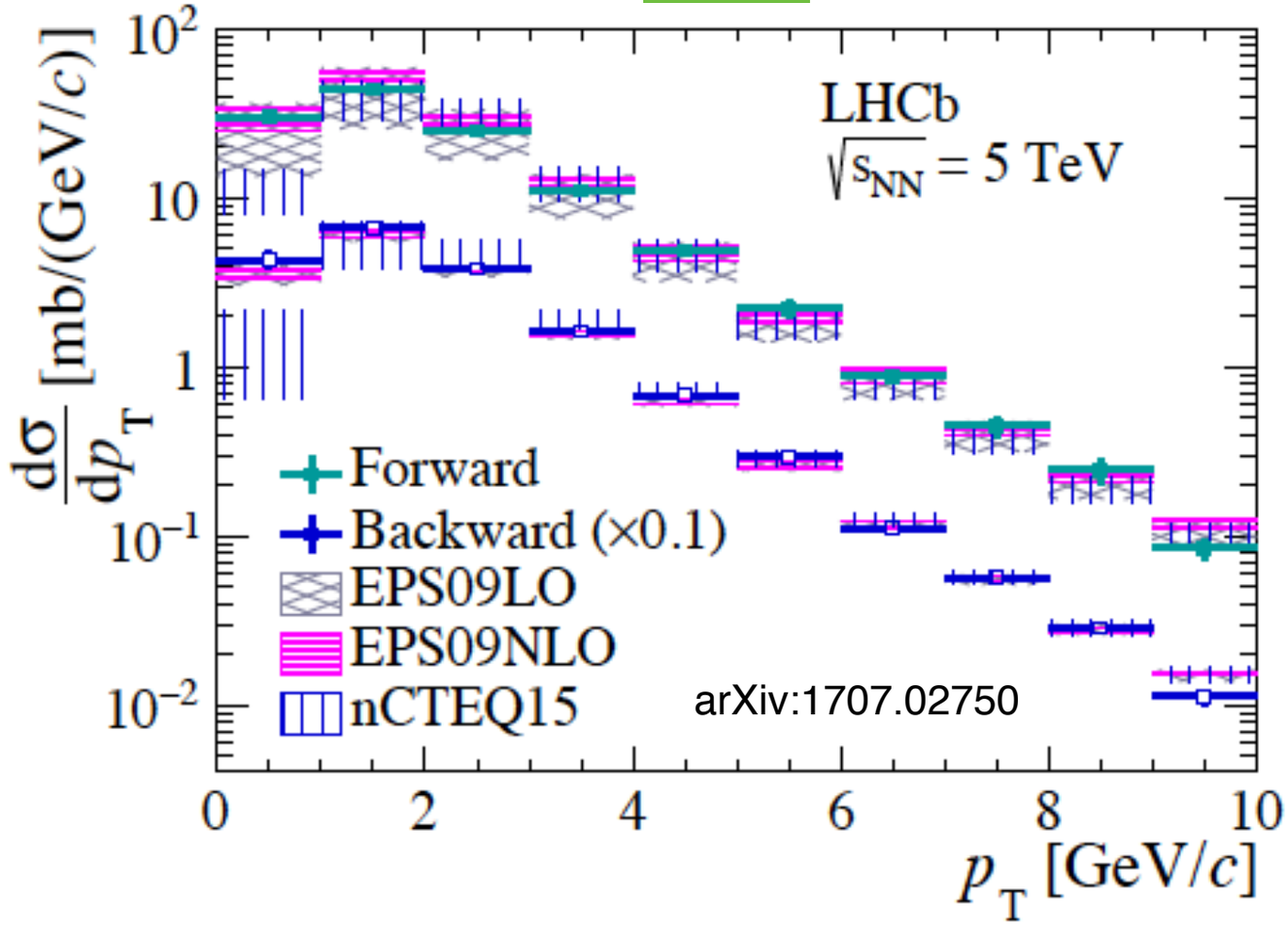
D-meson production: p-Pb @ 5.02 TeV

ALICE



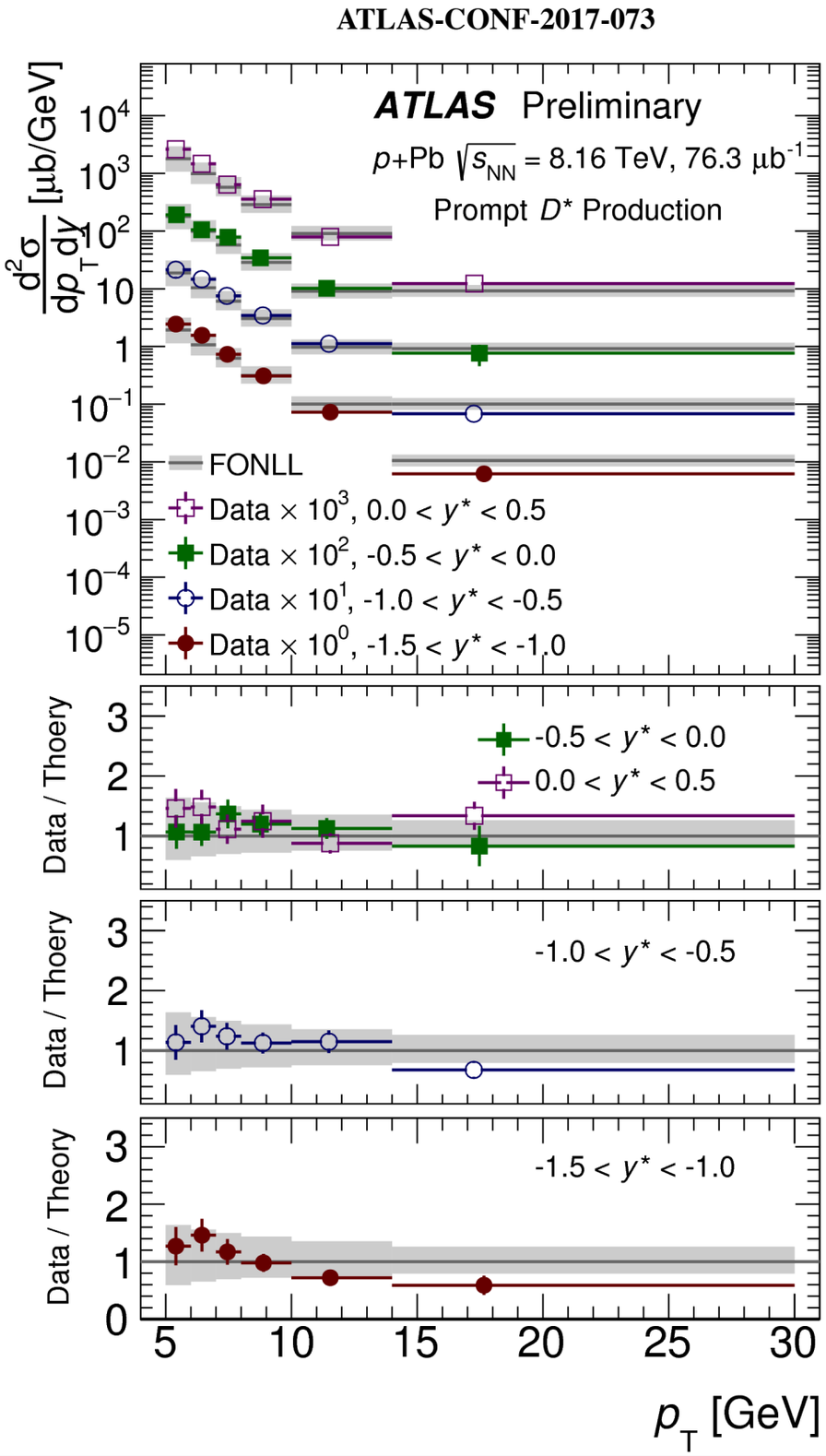
ALICE-PUBLIC-2017-008

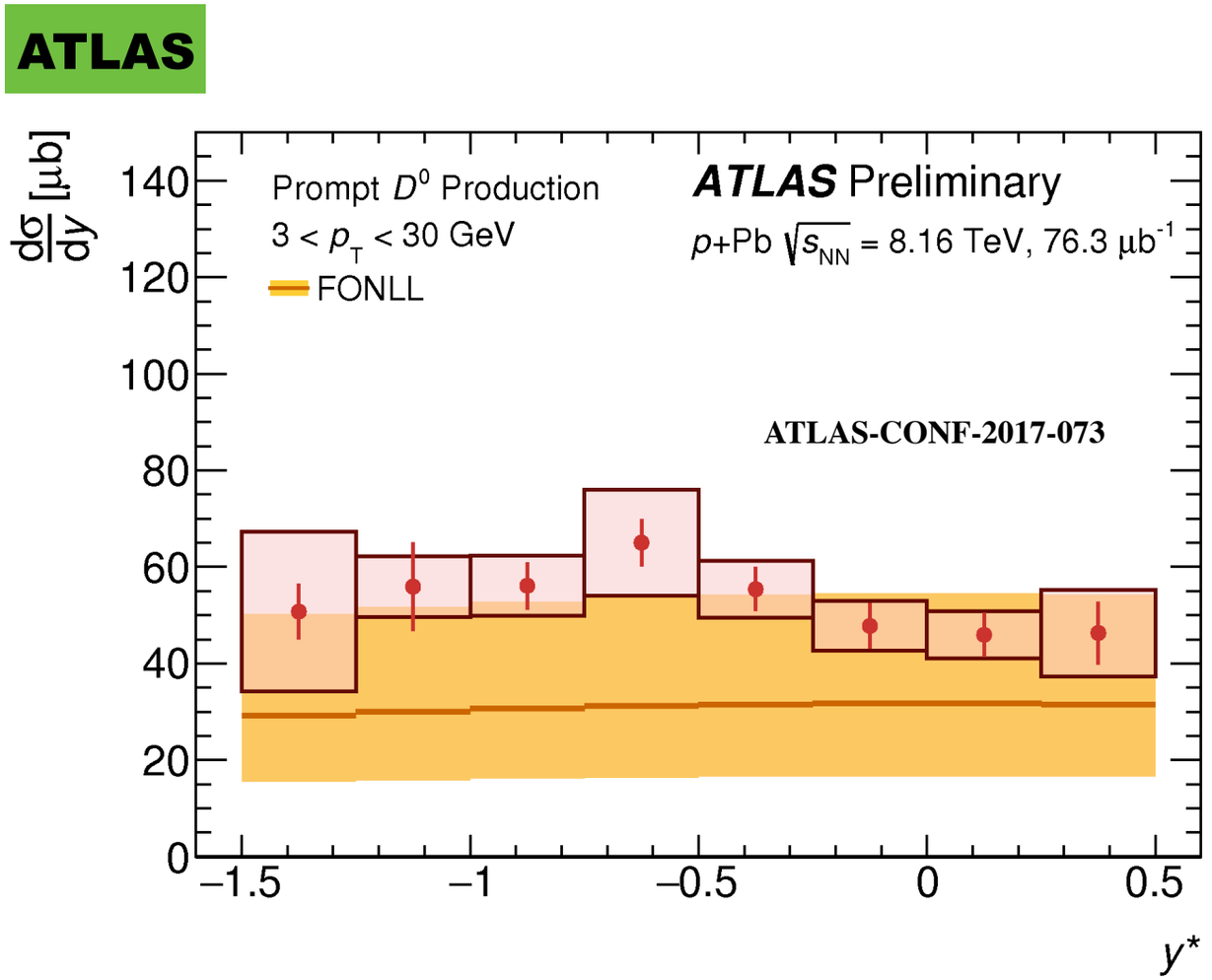
LHCb



- ☑ 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 pQCD calculations including nuclear modifications of PDF

D-meson production: p-Pb @ 8.16 TeV

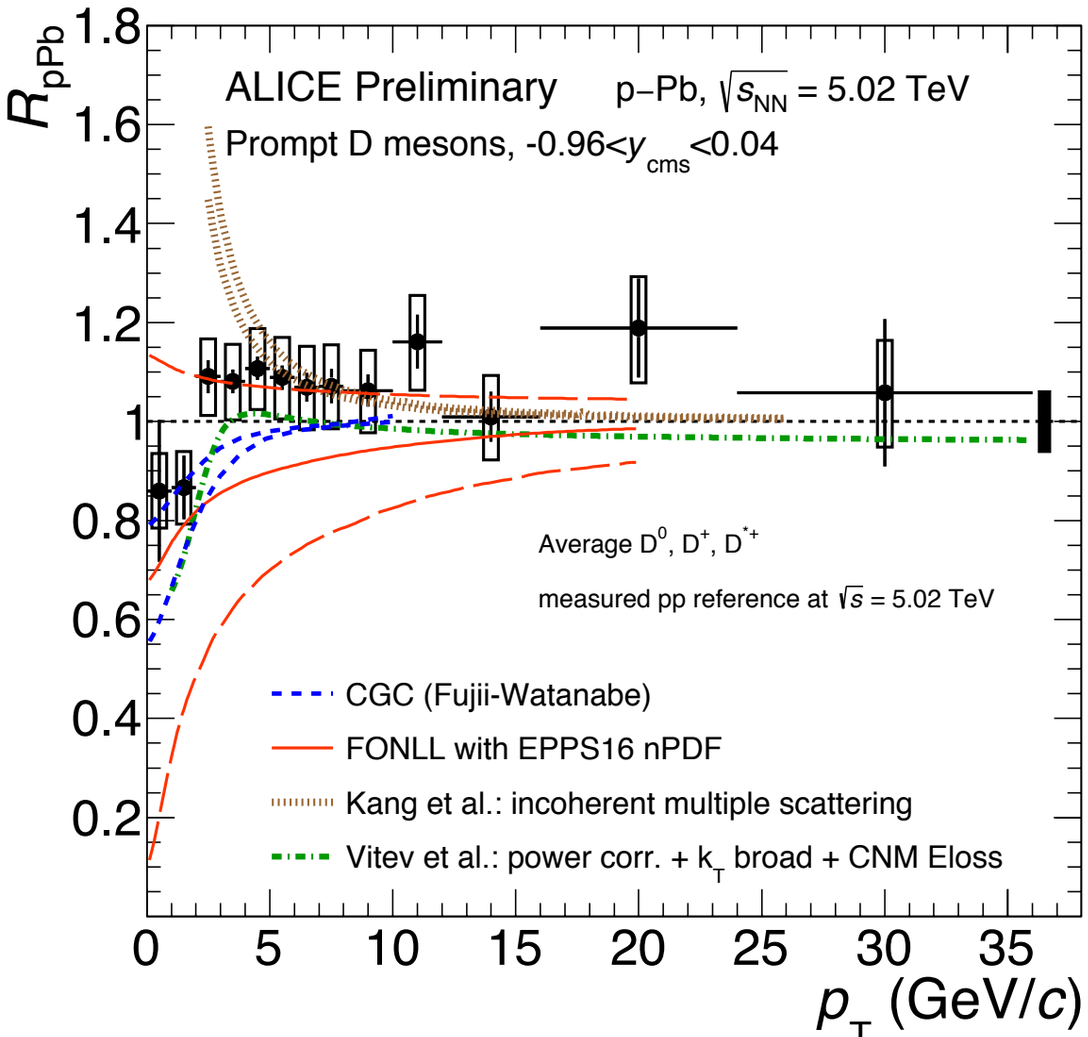




- ☑ Possibility to investigate 5.02 and 8.16 TeV energy regimes at LHC.
- ☑ Production well understood even if on the high side of the pQCD based calculations

D-meson R_{pA} - ALICE

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

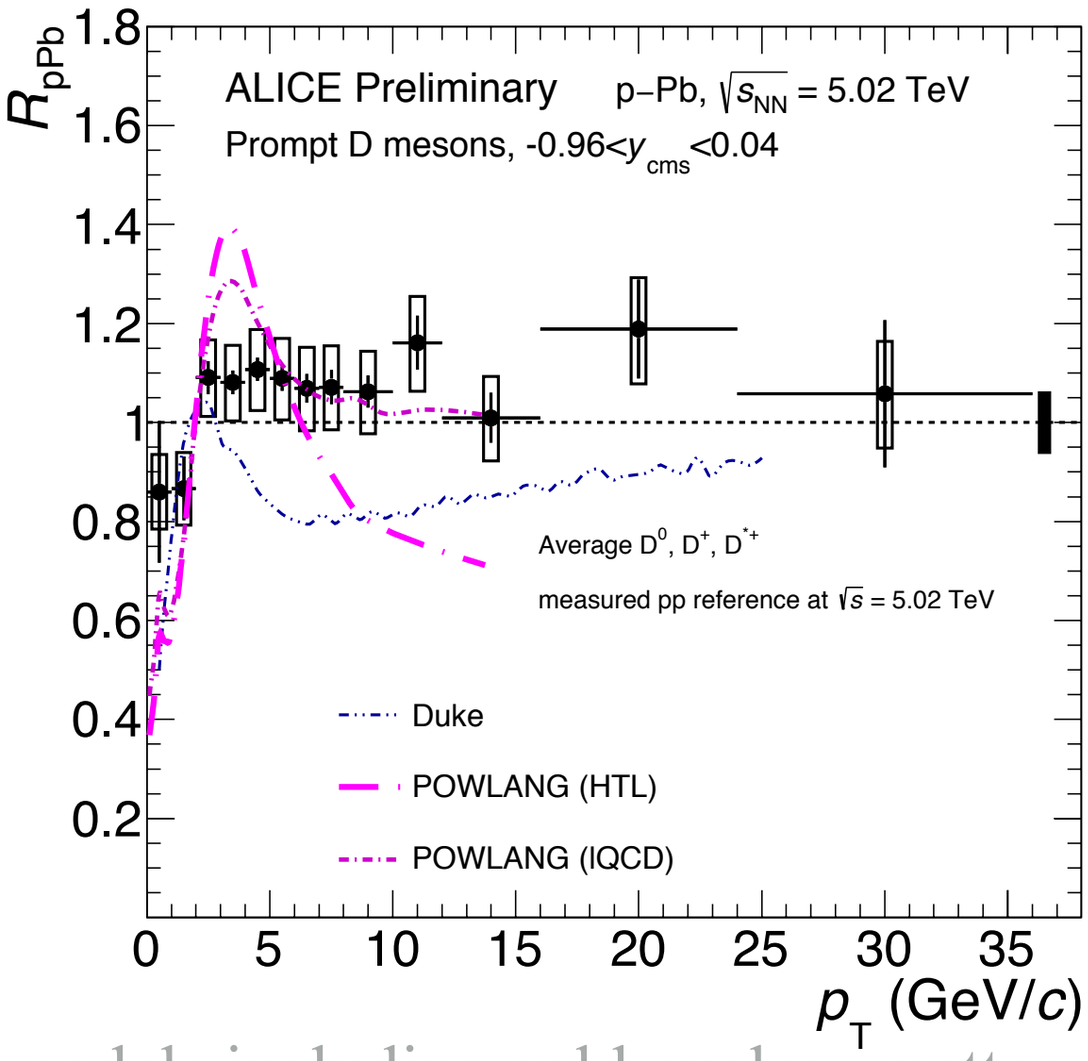


ALICE-PUBLIC-2017-008

- ☑ Described by models including cold nuclear-matter effects
- ☑ Described by 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 (or look at complementary observables (e.g. v2, multiplicity-differential studies)

D-meson R_{pA} - ALICE

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

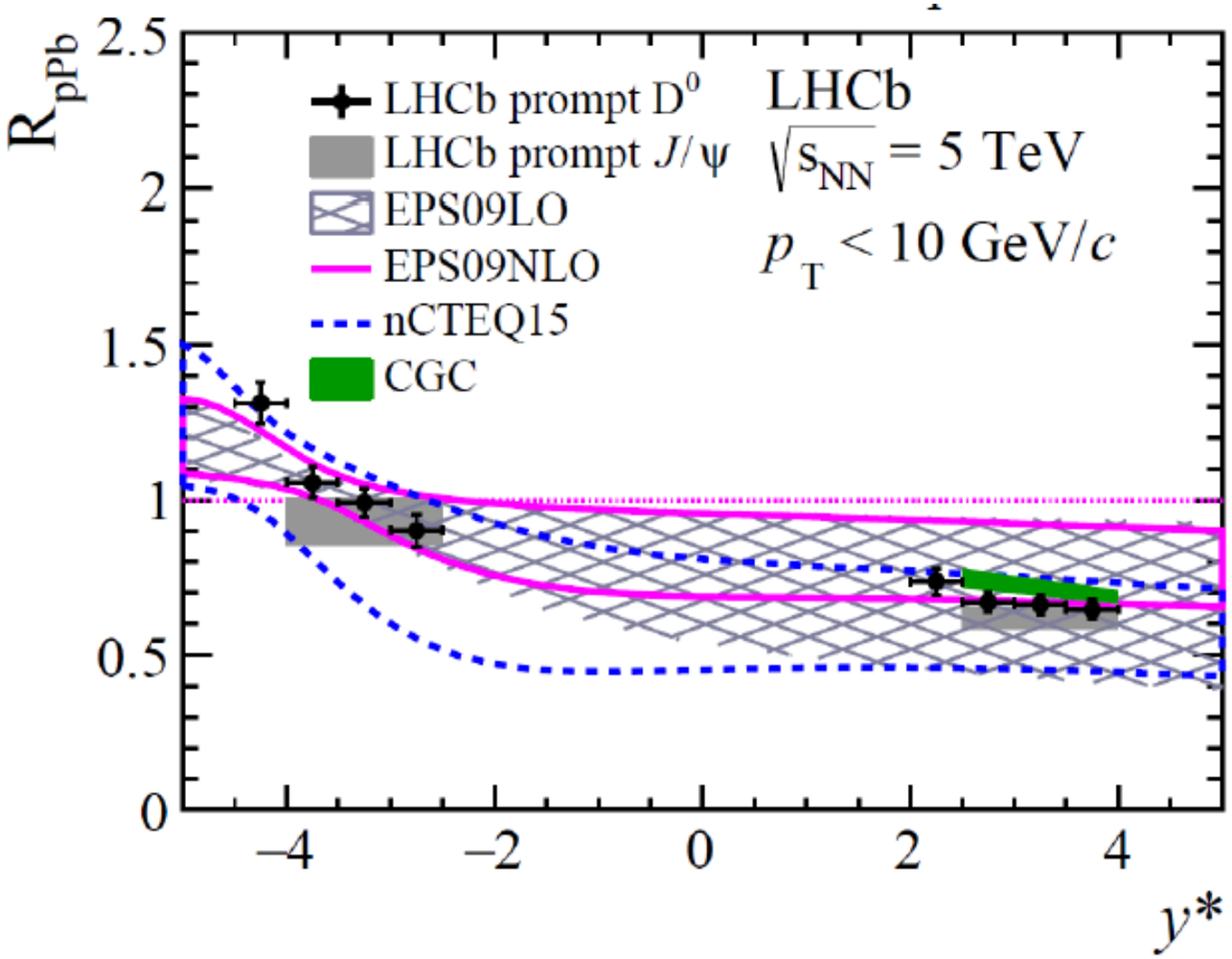


ALICE-PUBLIC-2017-008

- ☑ Described by models including cold nuclear-matter effects
- ☑ Described by 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 (or look at complementary observables (e.g. v2, multiplicity-differential studies)

D-meson R_{pPb} - LHCb

arXiv:1707.02750



EPS09LO

Eur. Phys. J. C77 (2017) 1, arXiv:1610.05382.

EPS09NLO

Comput. Phys. Commun. 184 (2013) 2562

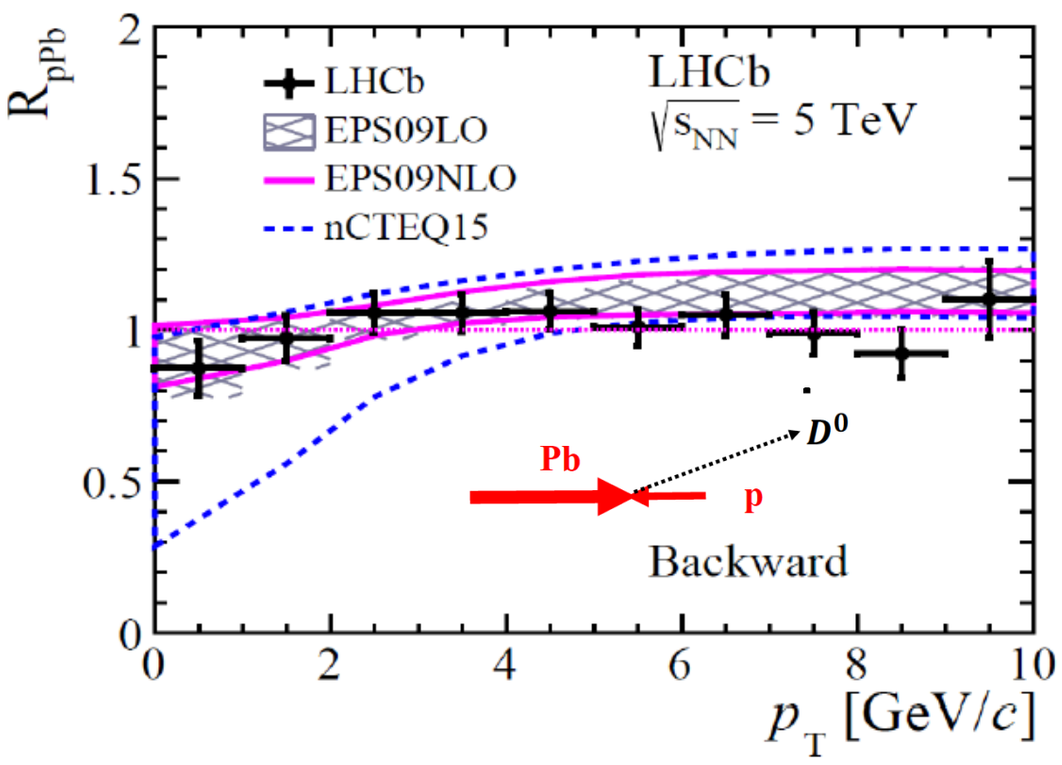
nCTEQ15

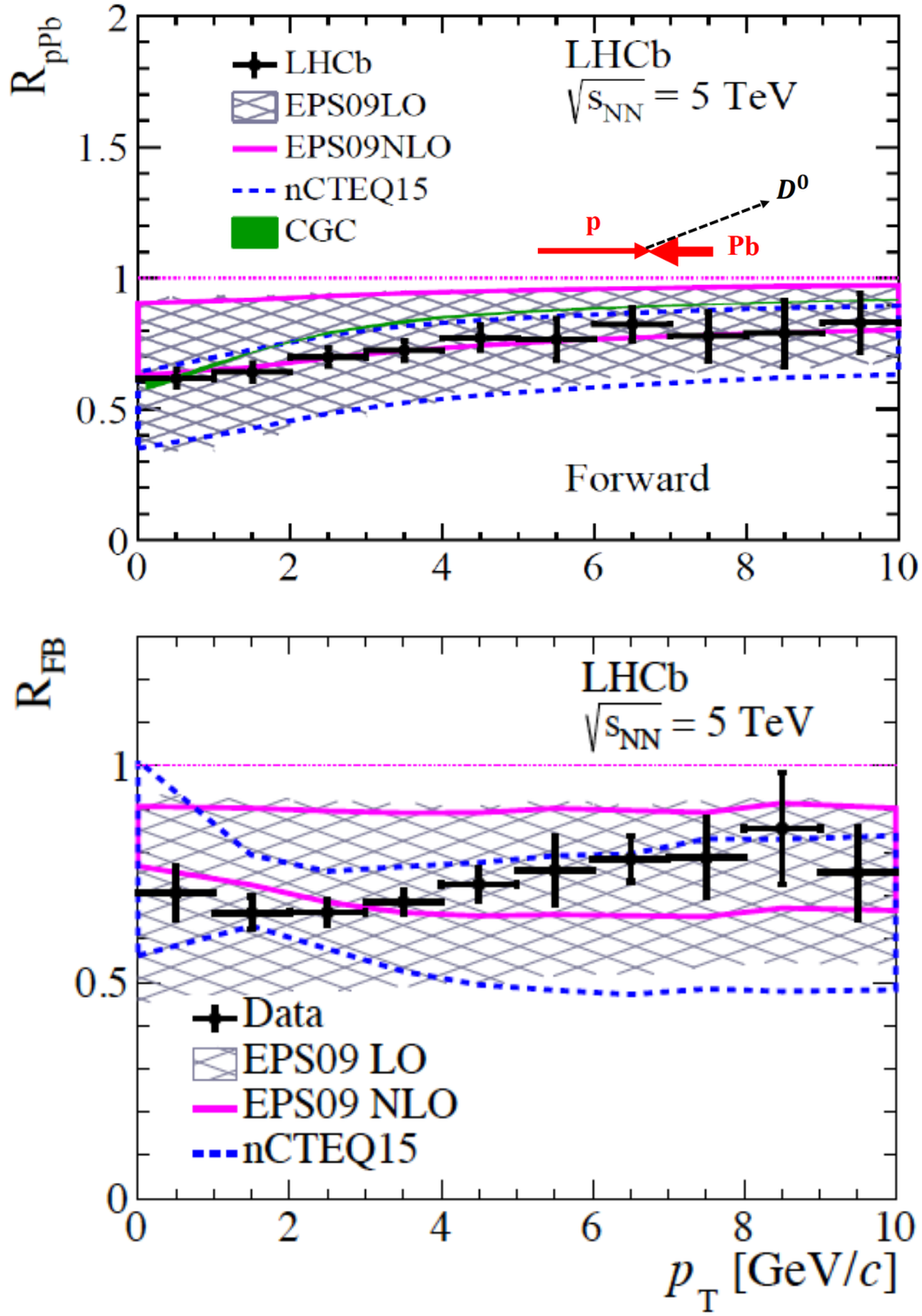
Comput. Phys. Commun. 198 (2016) 238,

- Data agree with nPDF and CGC but experimental precision starts to be much better than theoretical one:
  - Data sample used for the analysis: 1.58±0.02 nb^{-1} (2013)
  - Large data sample from 2016 still to be analyzed will grant significantly larger precision

D-meson forward to backward ratio - LHCb

arXiv:1707.02750





☑ Data agree with nPDF and CGC but experimental precision much better than the theory one.

CGC:

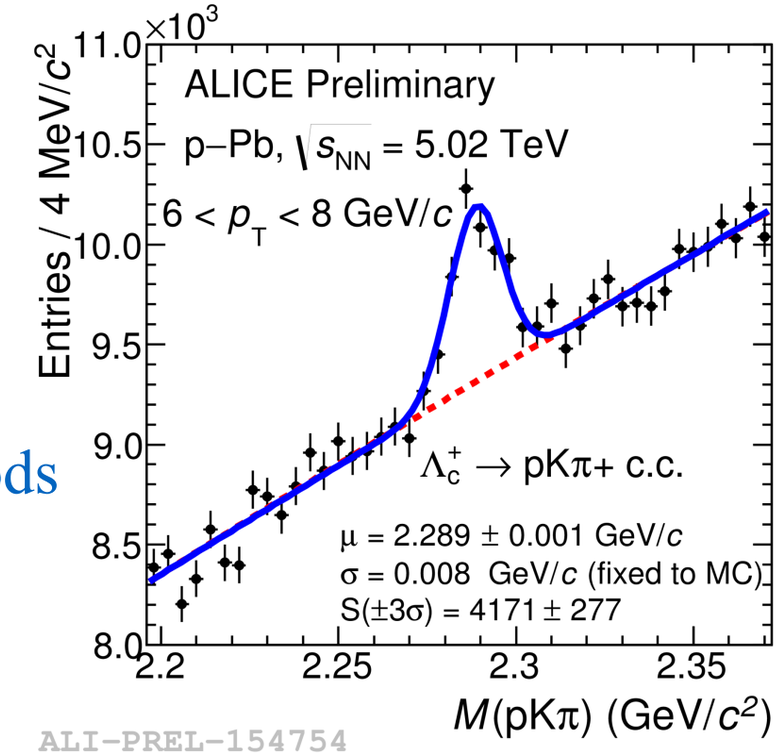
Phys. Rev. D91 (2015) 114005,

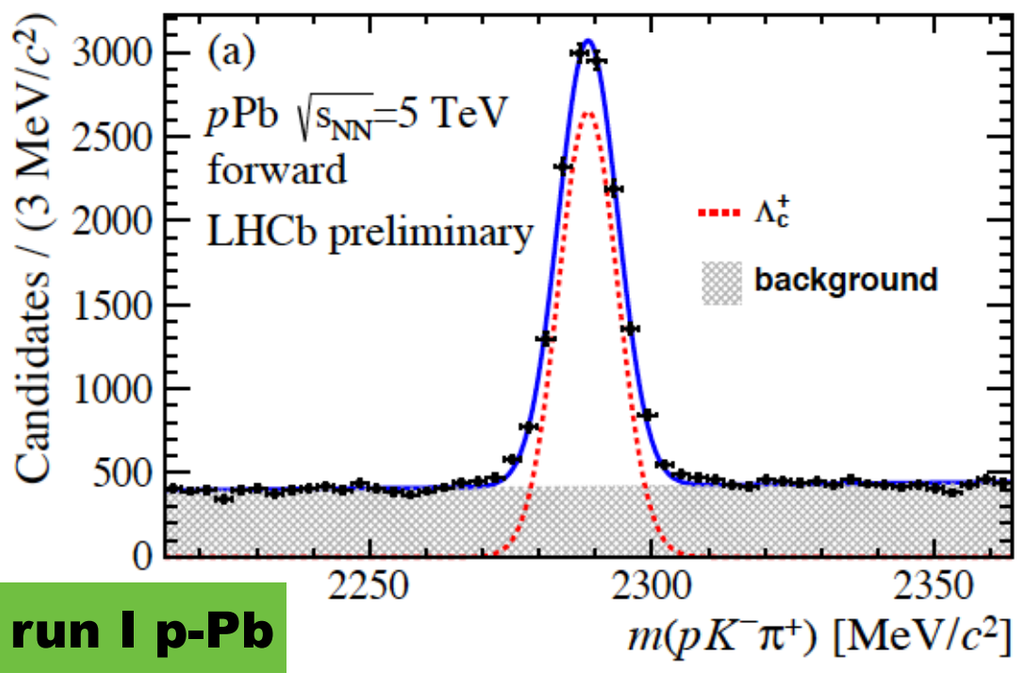
Λ_c production at LHC

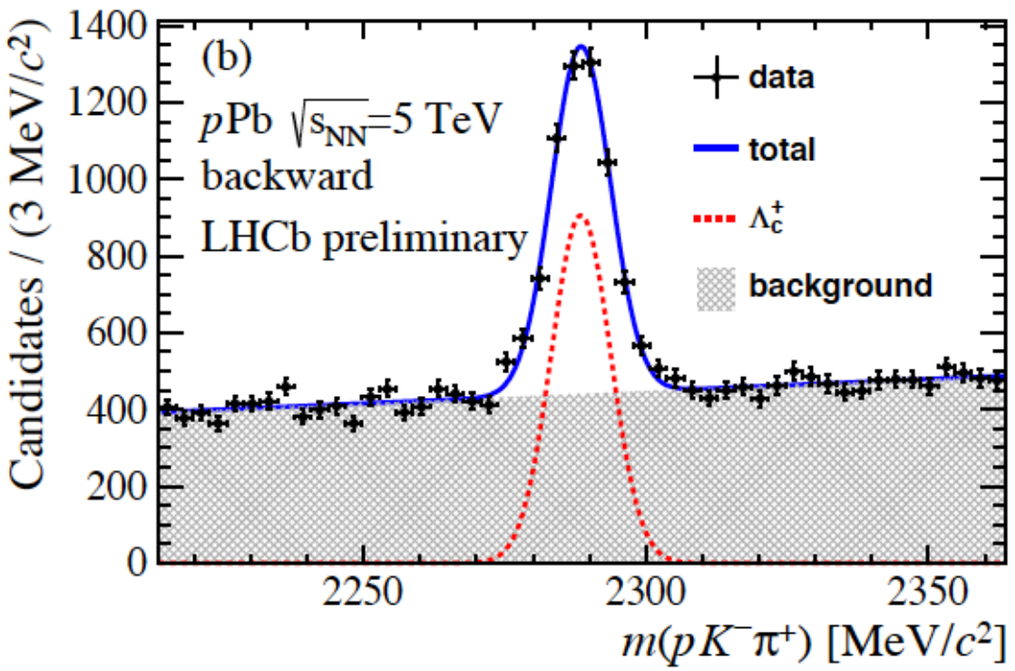
- Λ_c baryon reconstructed via hadronic and semi-leptonic decay channels:
  - Hadronic: Λ^+_c->pKπ (ALICE, LHCb), Λ^+_c->pK^0_s (ALICE)
  - Semileptonic: Λ^+_c->$e^+\Lambda\ \nu_e$ (ALICE)
  - In addition ALICE analyzes the hadronic decay channels both with standard and multivariate methods

$\Lambda_c^+ \to pK^-\pi^+$	BR ~ 6.35%	$c\tau \sim 60\ \mu m$
$\Lambda_c^+ \to pK_s^0$	BR ~ 1.58%	''

LHC run II p-Pb



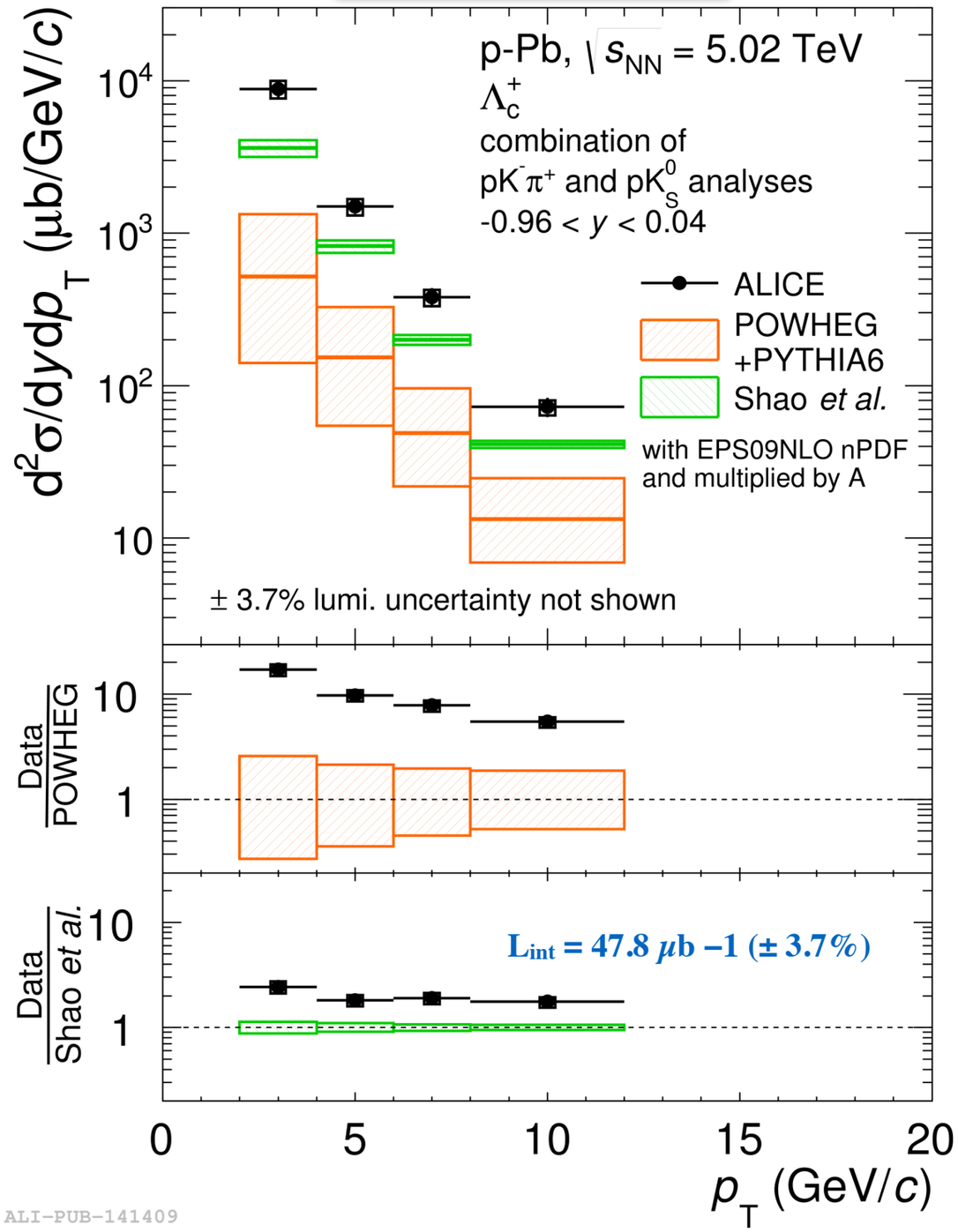




LHC run I p-Pb

Λ_c production at LHC run I (ALICE, LHCb)

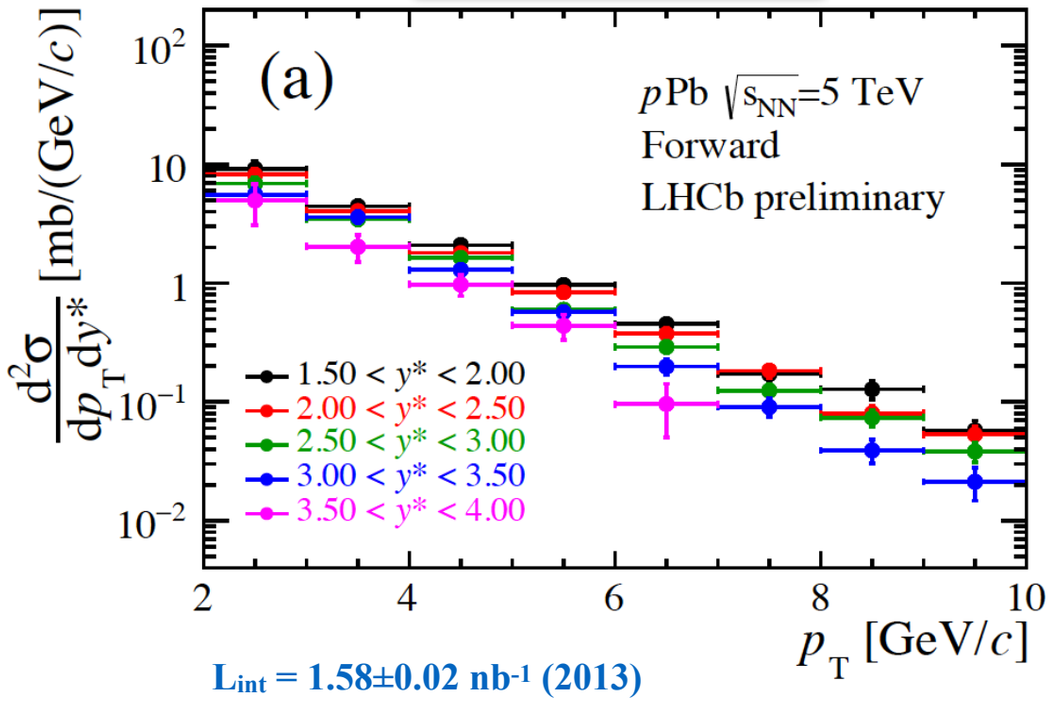
ALICE: arXiv:1712.09581



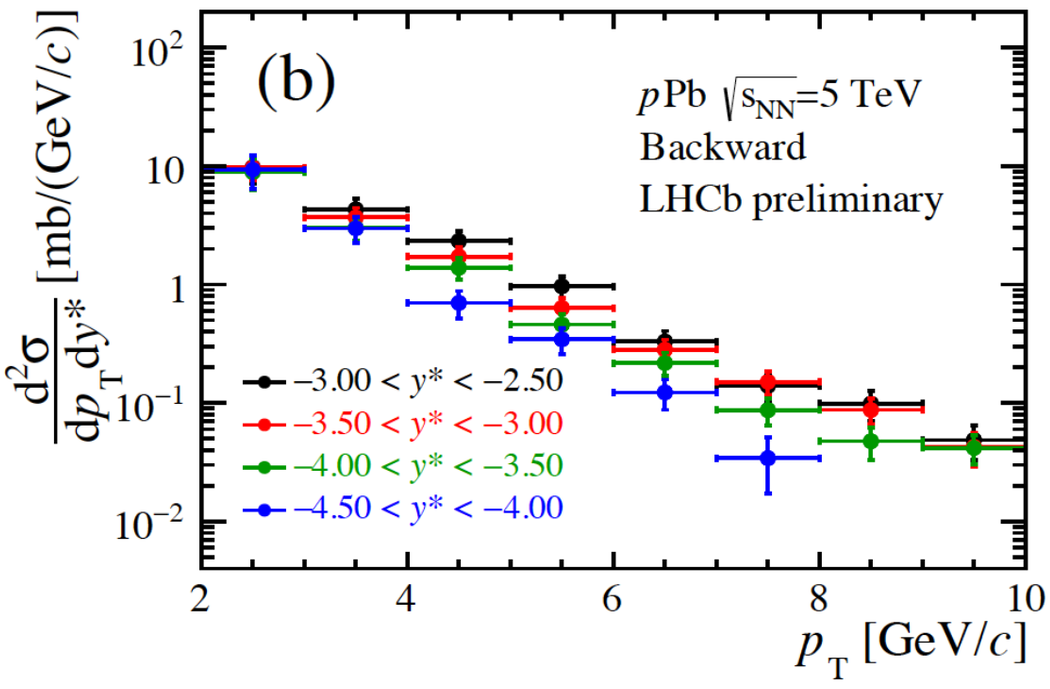
PIWHEG+PYTHIA6: JHEP 09 (2007) 126

Shao et al.: Eur. Phys. J. C77 no. 1, (2017) 1

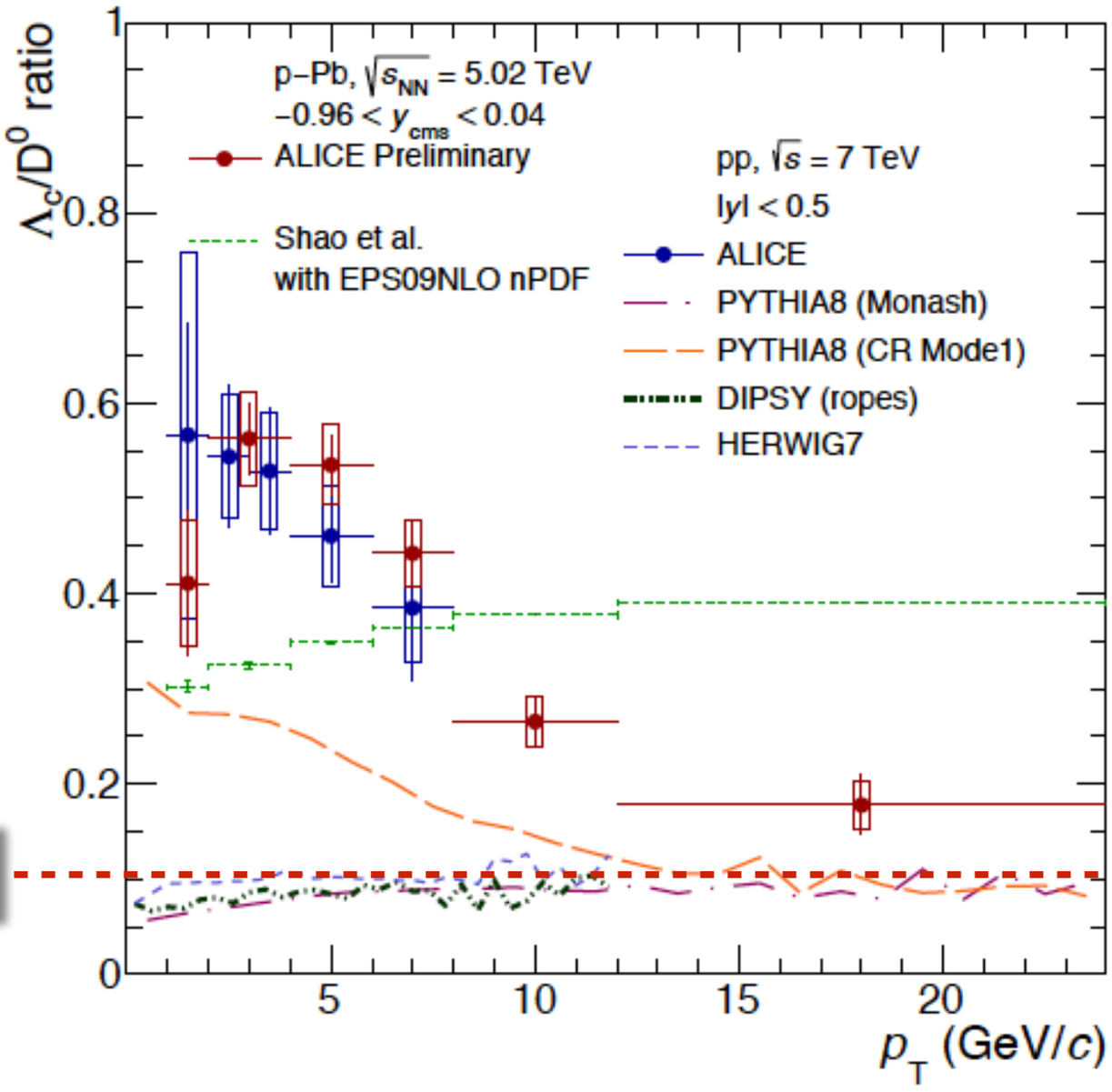
LHCb-CONF-2017-005



L_{int} = 1.58±0.02 nb^{-1} (2013)



Charmed baryon-to-meson ratio (ALICE)



LHC run II (New)

$$R_{\Lambda_c^+/D^0} = \frac{\sigma_{\Lambda_c^+}(y^*, p_T)}{\sigma_{D^0}(y^*, p_T)}$$

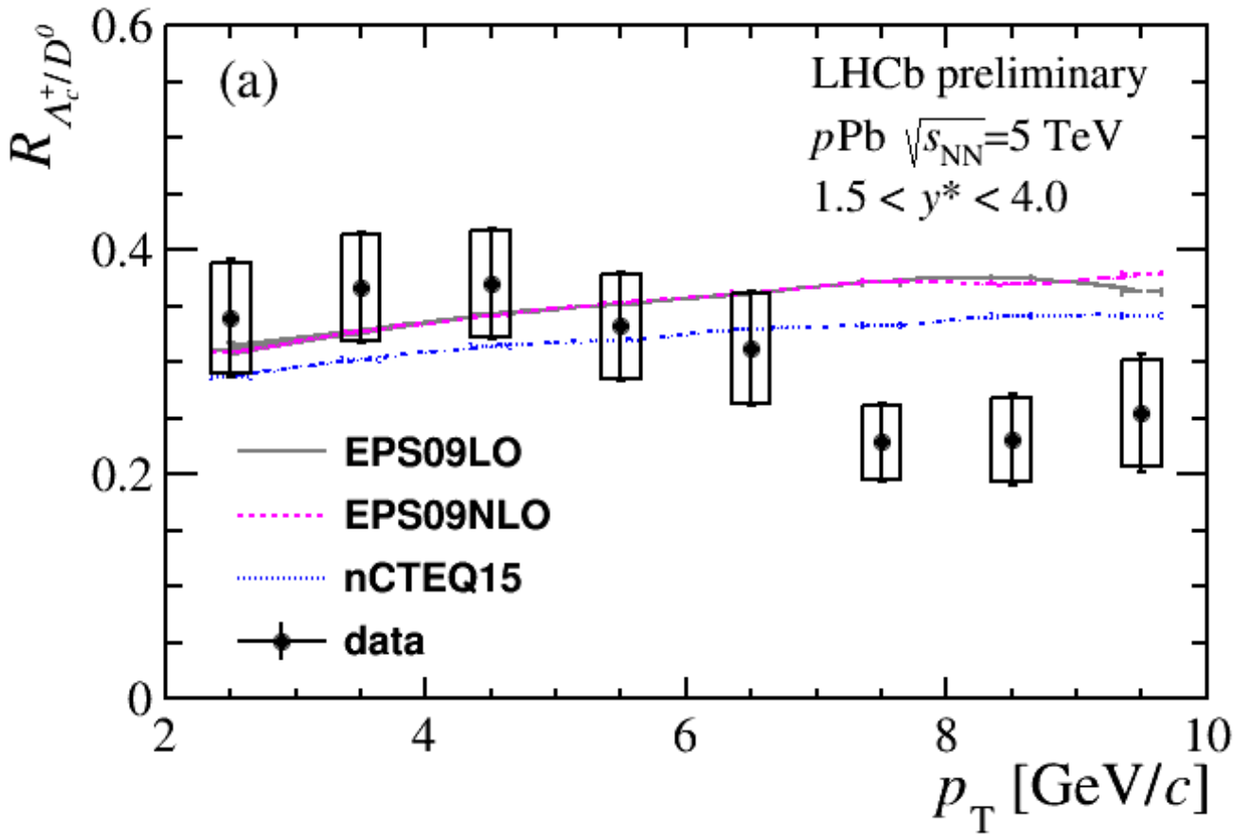
e-p from Desy

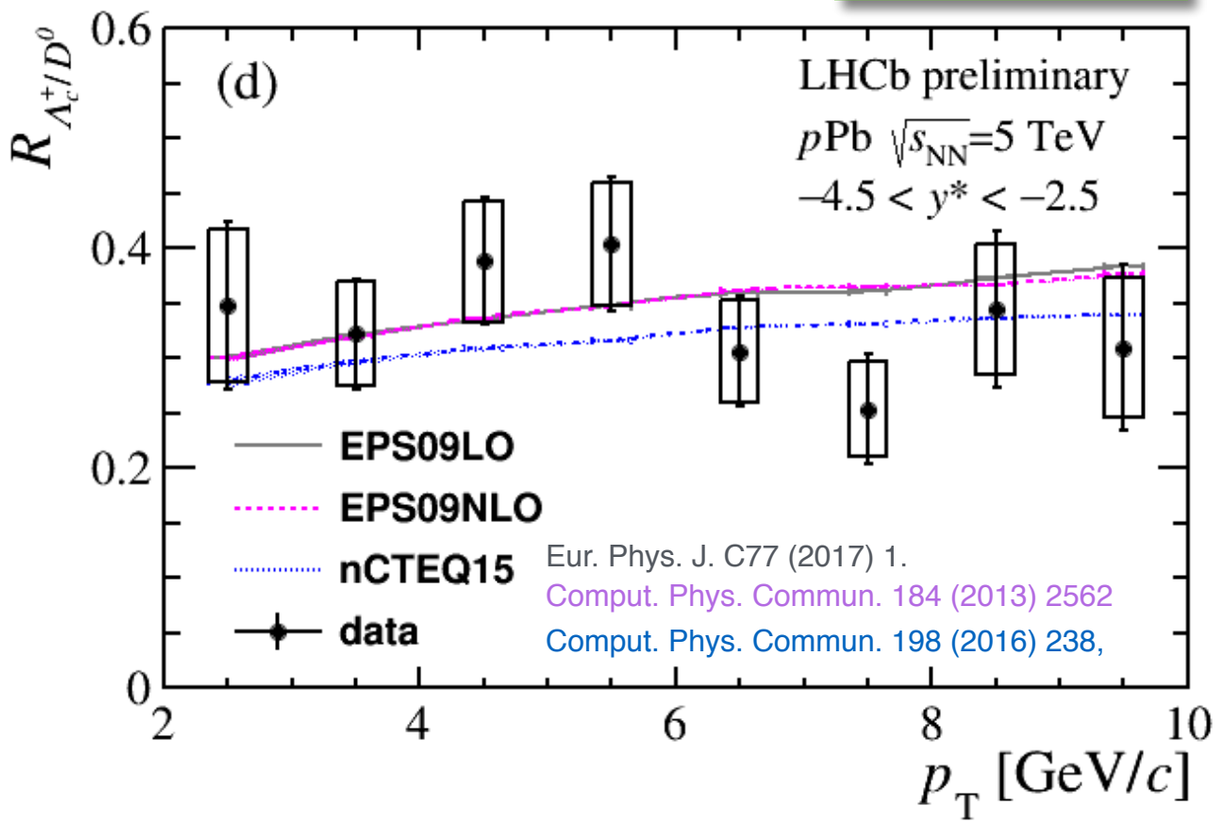
- Λ_c/D^0 ratio underestimated by models up to factor 5. At intermediate/low p_T the value of the ratio ranges between 0.4-0.5. Significantly larger than values found at electron-hadron colliders. *Something not understood in charm fragmentation?*

similar behavior pp and p-Pb

Charmed baryon-to-meson ratio (LHCb)

LHC run I





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

- ☑ Sensitive to charm hadronisation mechanisms
- ☑ Model based on measured *pp* cross-section
- ☑ nPDFeffects mostly cancel
  - EPS09LO & EPS09NLO similar
  - nCTEQ15 slightly lower.
- ☑ Slight increase with increasing p_T

Forward:
- **Consistent at lower p_T**
- **Below theories at higher p_T**

Backward:
- **Consistent for all p_T**

See Jiayin Sun talk at QM2018
https://indico.cern.ch/event/656452/

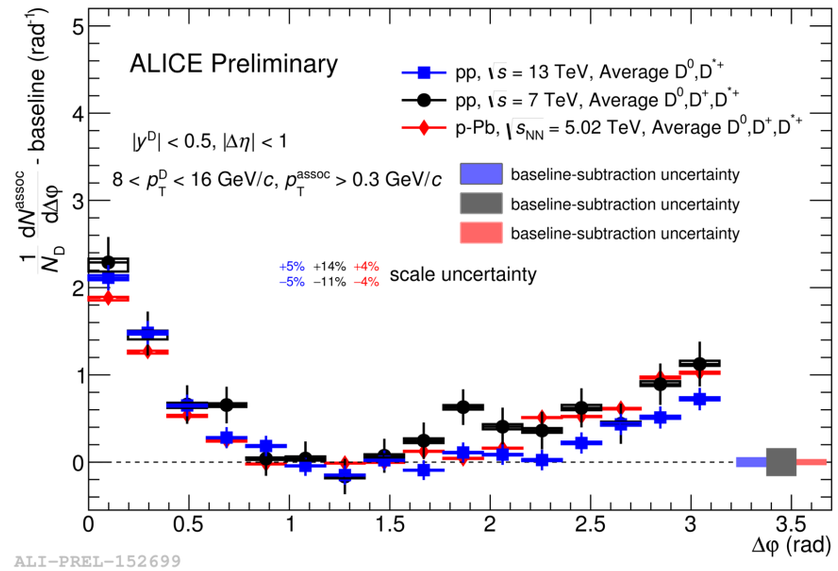
Charm correlations and jets

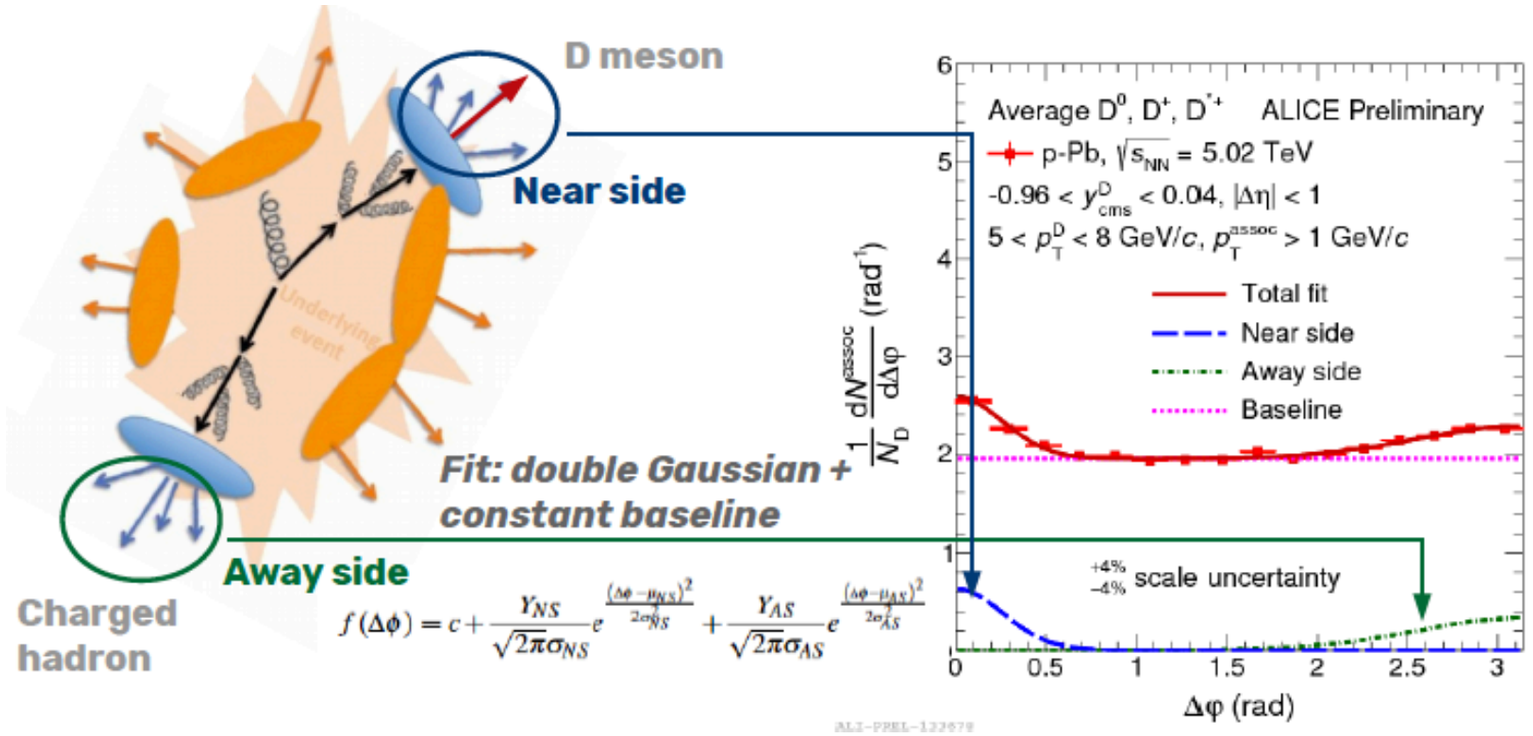
D-h correlations - ALICE

- D^0, D^+, D^{*+} results: fully reconstructed via the hadronic decays and averaged
- D meson: "*trigger*" particle, correlated with other charged tracks: *associated particles*
- Contribution from the B feed-down subtracted

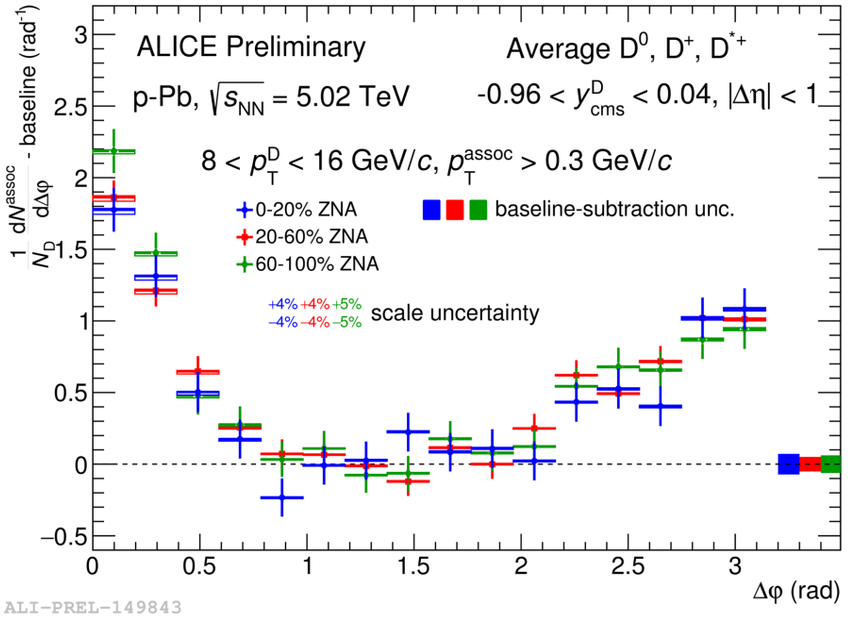
based on FONLL beauty cross section and correlation template from PYTHIA

p-Pb vs pp





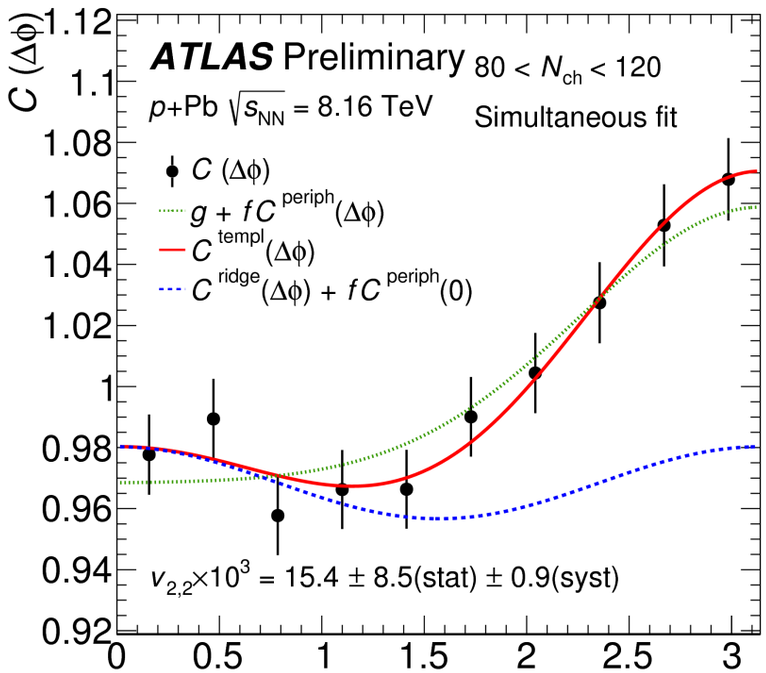
p-Pb vs multiplicity

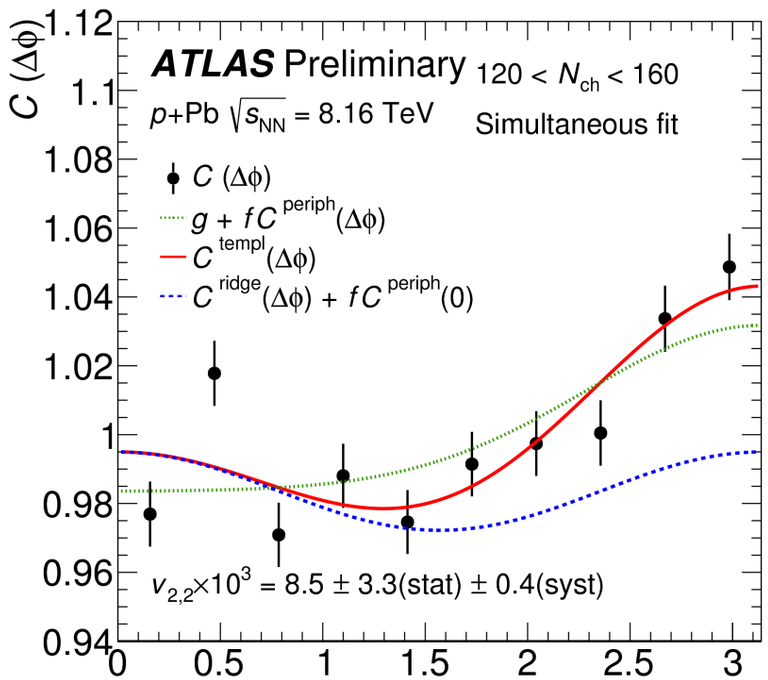


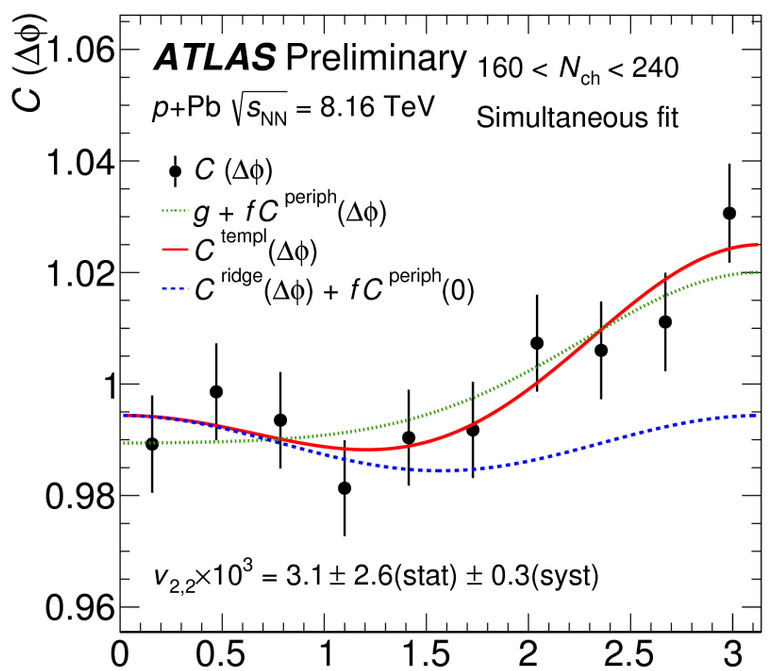
D-h correlations - ATLAS

ATLAS-CONF-2017-073

N_{ch}



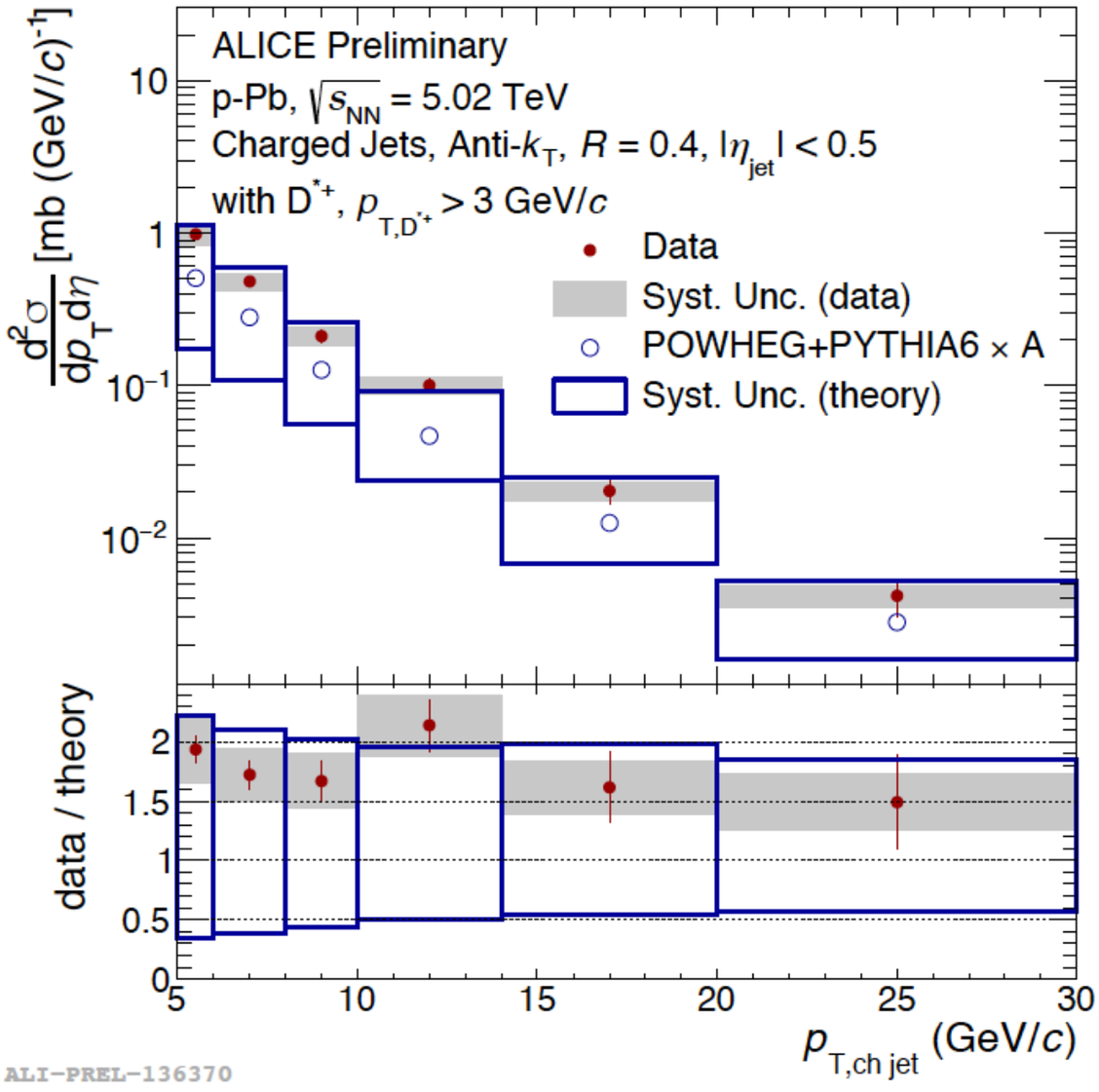


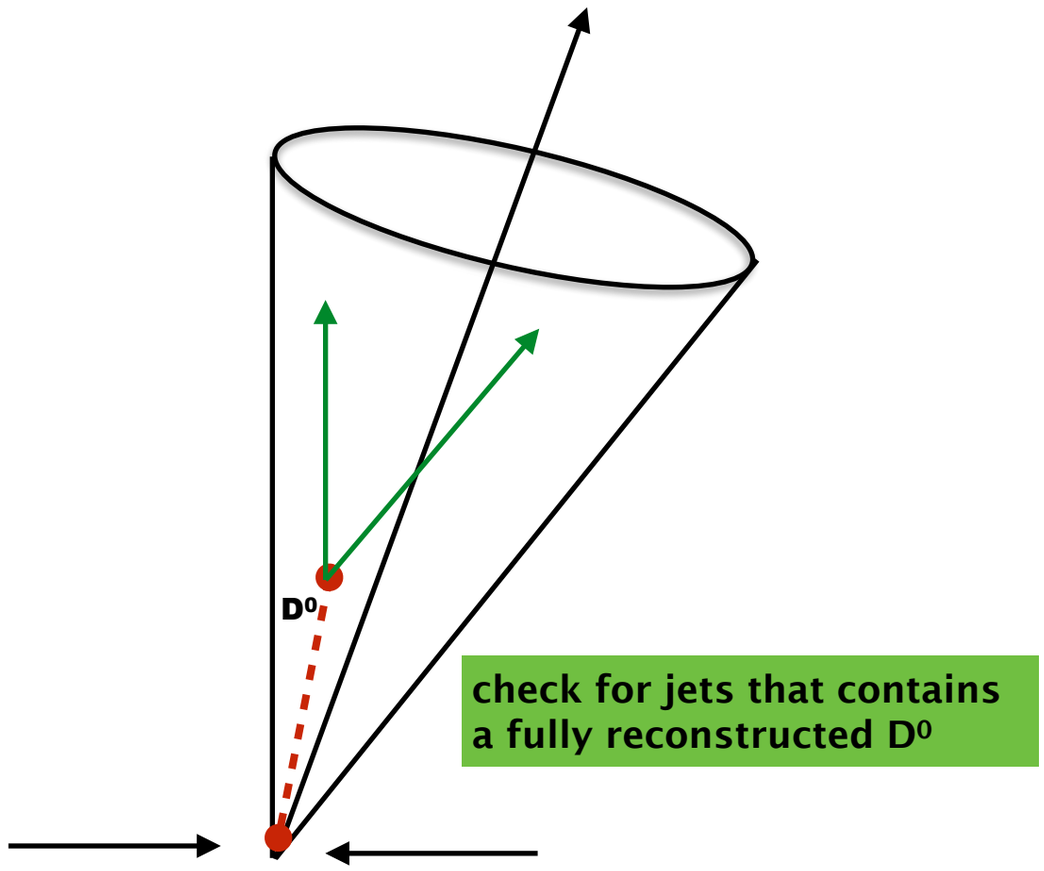


$L_{int} = 76.3\mu b{-}1$ (2016)

$$v_{2,2}(80 < N_{ch} < 120) = (15.4 \pm 8.5(\text{stat}) \pm 0.9(\text{syst})) \times 10^{-3},$$
$$v_{2,2}(120 < N_{ch} < 160) = (8.5 \pm 3.3(\text{stat}) \pm 0.4(\text{syst})) \times 10^{-3},$$
$$v_{2,2}(160 < N_{ch} < 240) = (3.1 \pm 2.6(\text{stat}) \pm 0.3(\text{syst})) \times 10^{-3}.$$

Study of Charm jet production in p-Pb (ALICE)

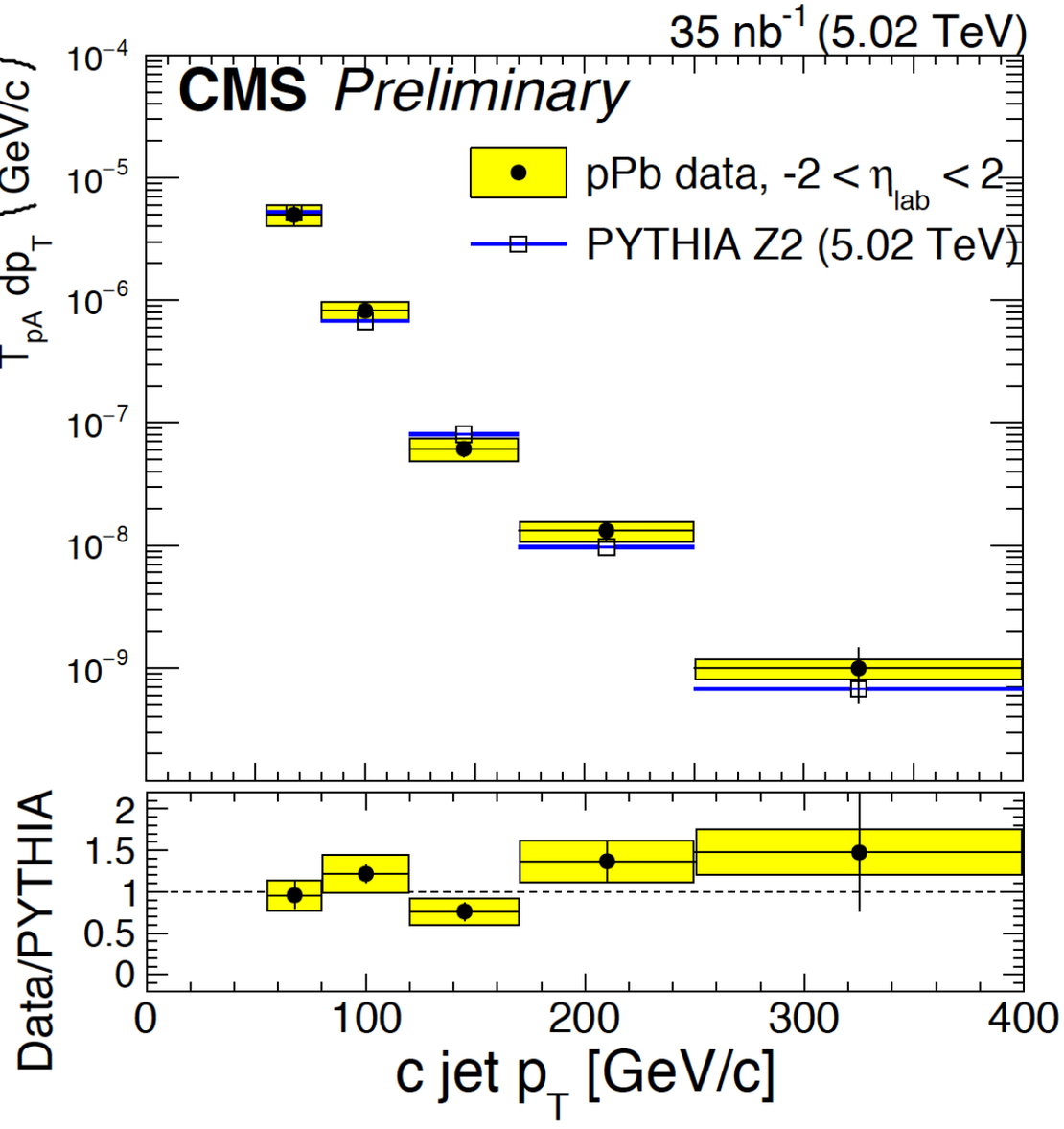




- ☑ D-jet spectrum measured down to $p_T = 5$ GeV/c → *Important constraint for theory*
- ☑ Described by POWHEG+PYTHIA6 (Perugia 2011 tune) simulation within uncertainty
- ☑ Unique opportunity to study charm jet properties and structure (… in Pb-Pb)

Study of Charm jet production in p-Pb (CMS)

CMS-PAS-HIN-15-012



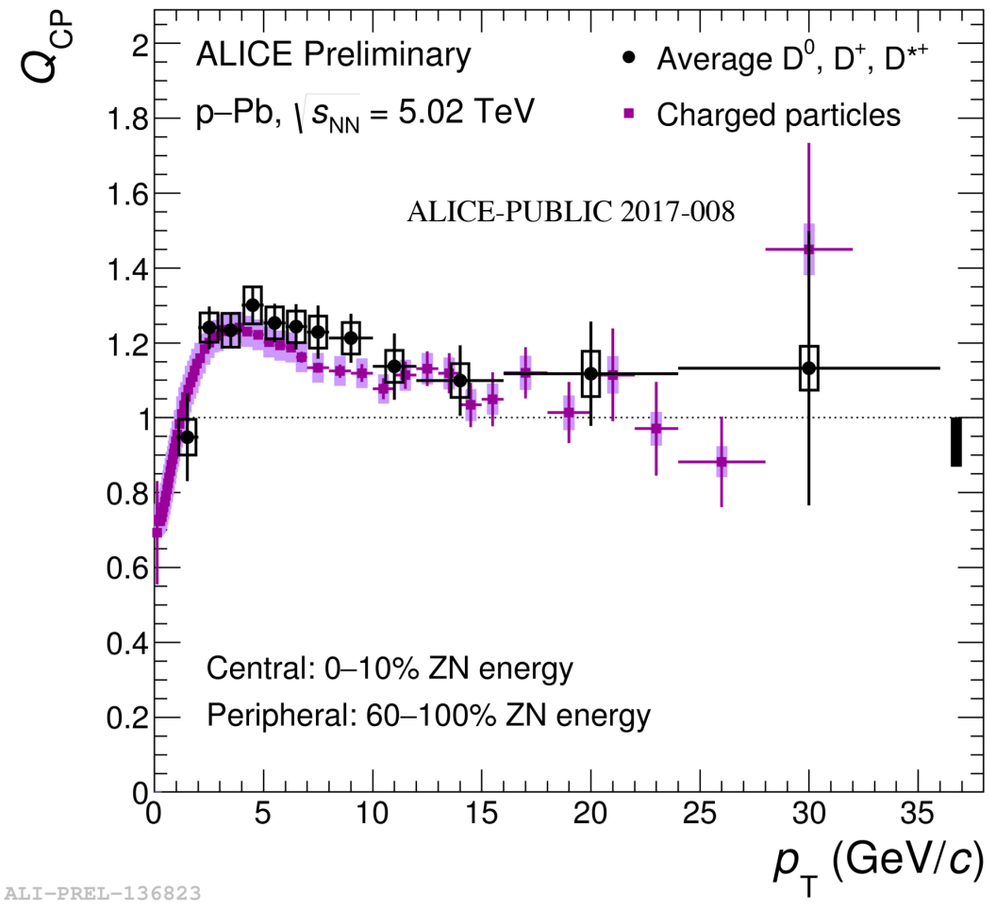
☑ p_T differential cross section compatible with PYTHIA up to very high jet p_T

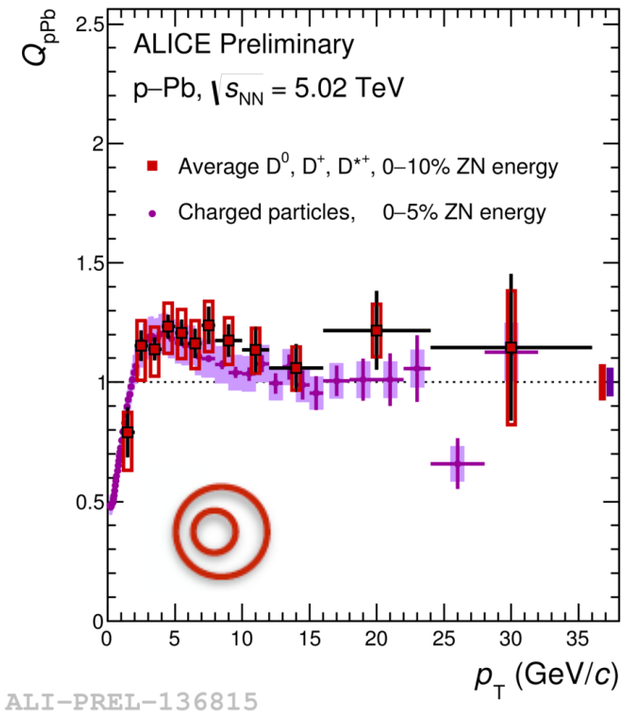
Collectivity in the heavy-flavour sector?

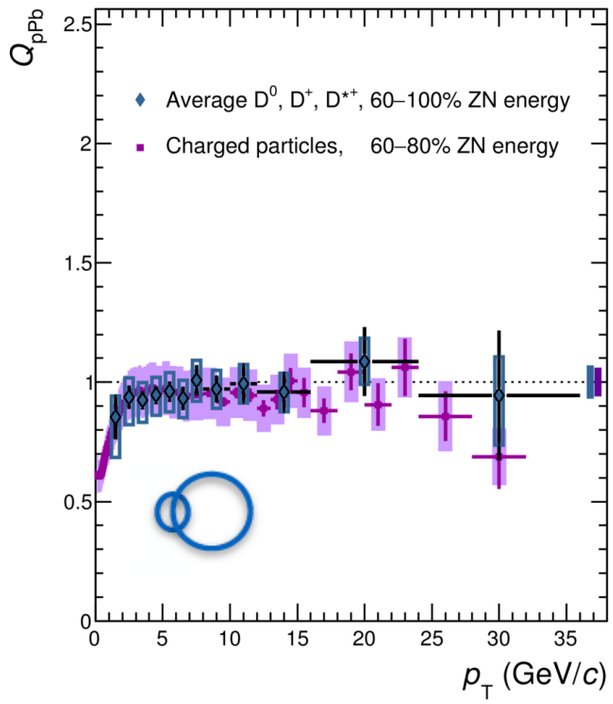
D-meson production vs centrality (ALICE)

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

$$Q_{\mathrm{pPb}}^{0-10\%}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{pPb}}^{0-10\%}/\mathrm{d}p_{\mathrm{T}}}{\langle T_{\mathrm{AA}}\rangle_{0-10\%} \times \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}} \qquad \langle T_{\mathrm{pPb}}\rangle = \frac{\langle N_{\mathrm{coll}}\rangle_i}{\sigma_{\mathrm{NN}}}$$







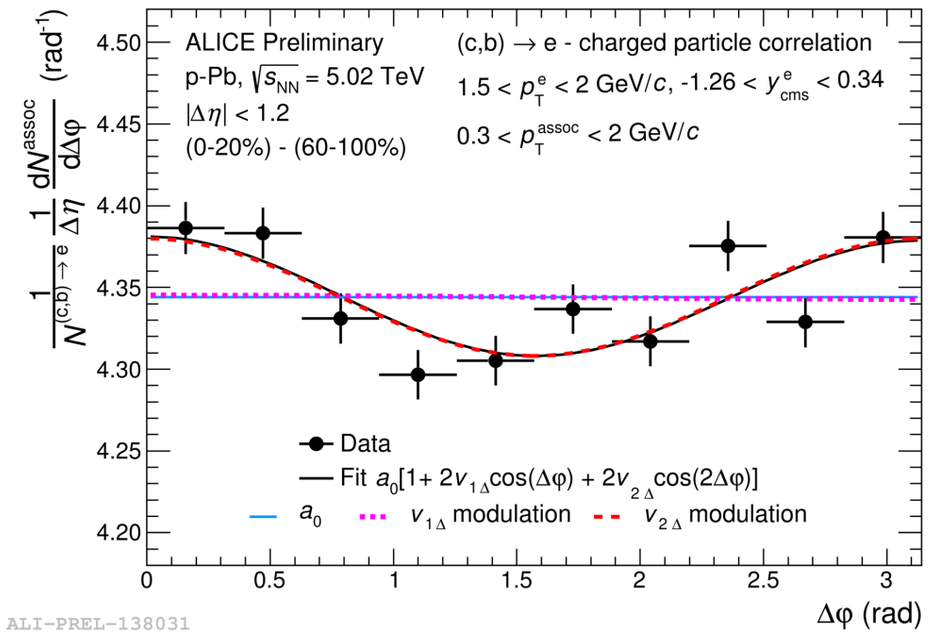
- Hint for D-meson "Central-to-peripheral" ratio (Q_{CP}) larger than unity
  - ✓ 1.5σ in $3<p_{\mathrm{T}}<8$ GeV/c
- Very similar to charged pion Q_{CP}

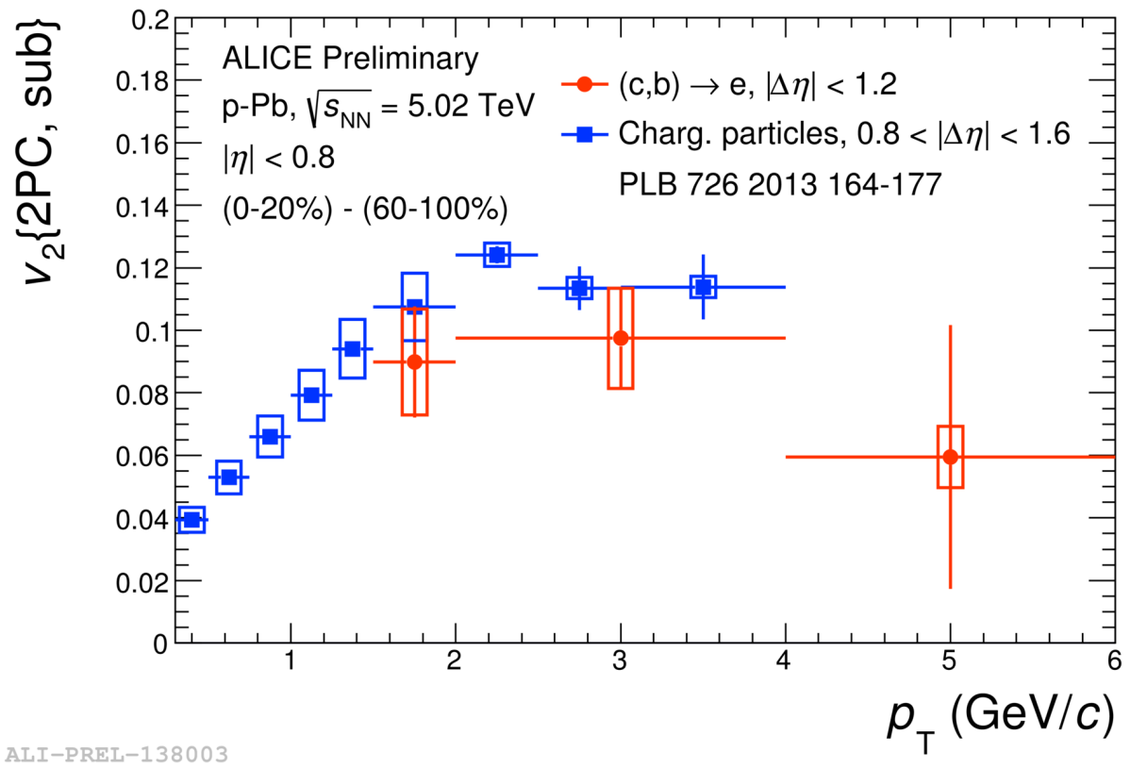
  Initial-state effect? Mass effect? Radial flow?

  … need comparison with theoretical calculations

Heavy-flavour hadron decay electrons v_2 (ALICE)

$$C^{HM} - C^{LM}_{sub} = P\left(1 + \sum_{n=1}^{2} 2 \times v_{n\Delta} \times \cos[n\Delta\varphi]\right)$$

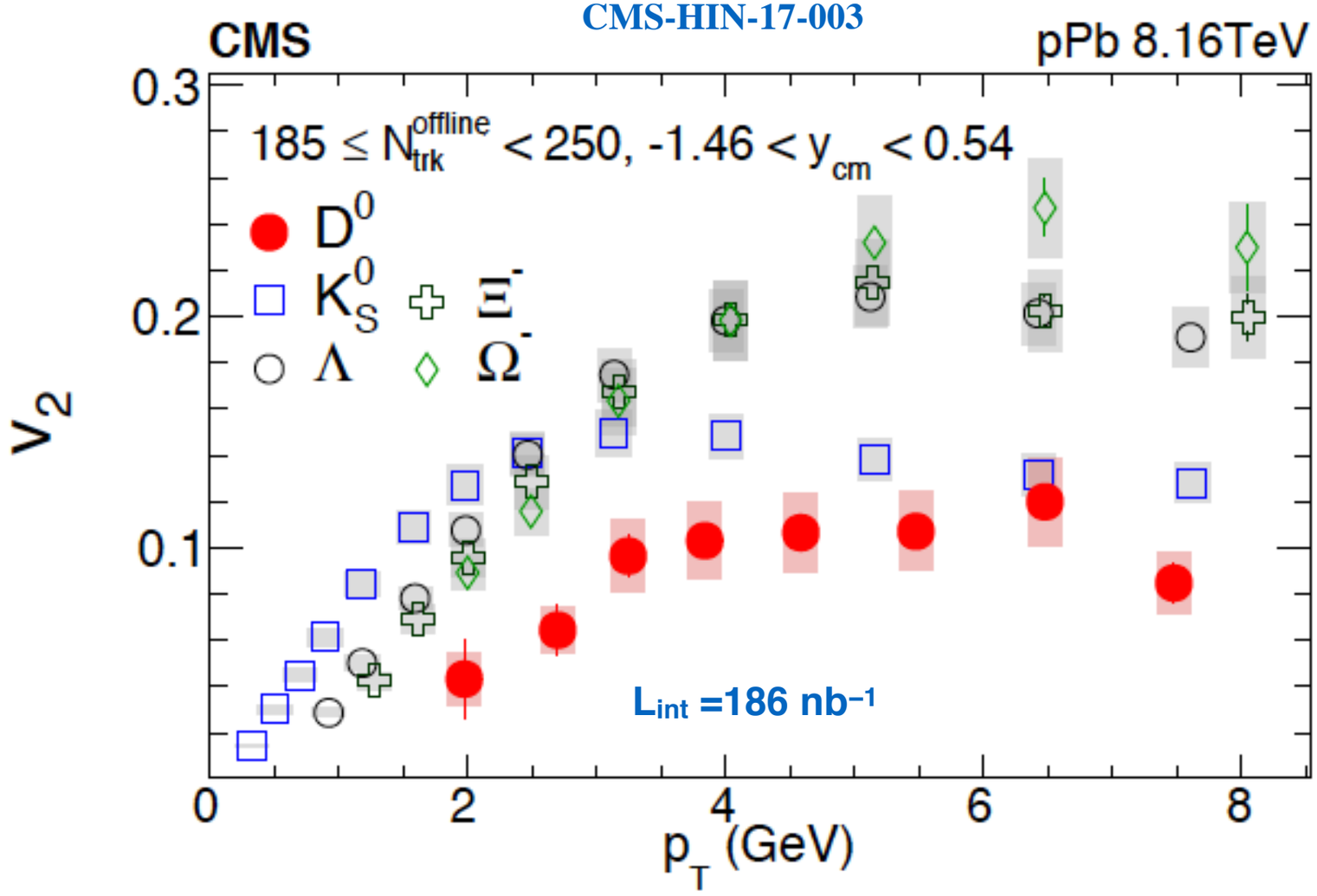




- Positive v_2 measured for heavy-flavour decay electrons at ~5σ:
  - ☑ Initial-state effects, collective effects?
  - ☑ Data suggest a v_2 comparable with the one of charged particles

D-meson v_2 (CMS)

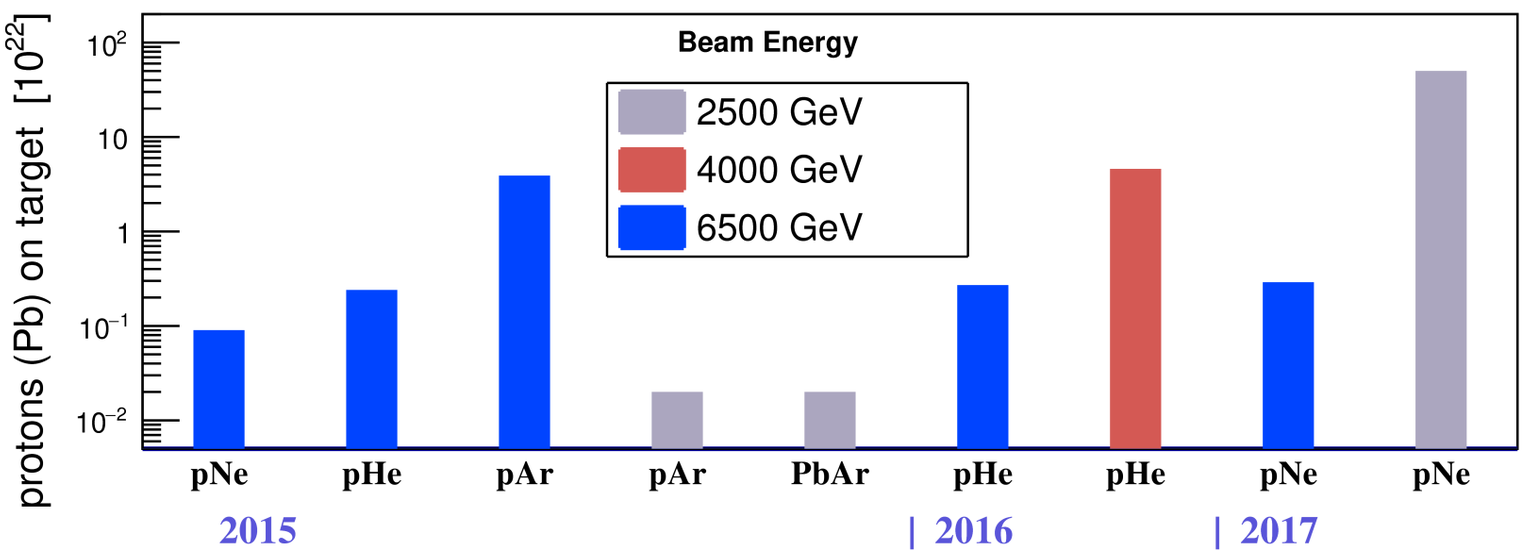
CMS-HIN-17-003



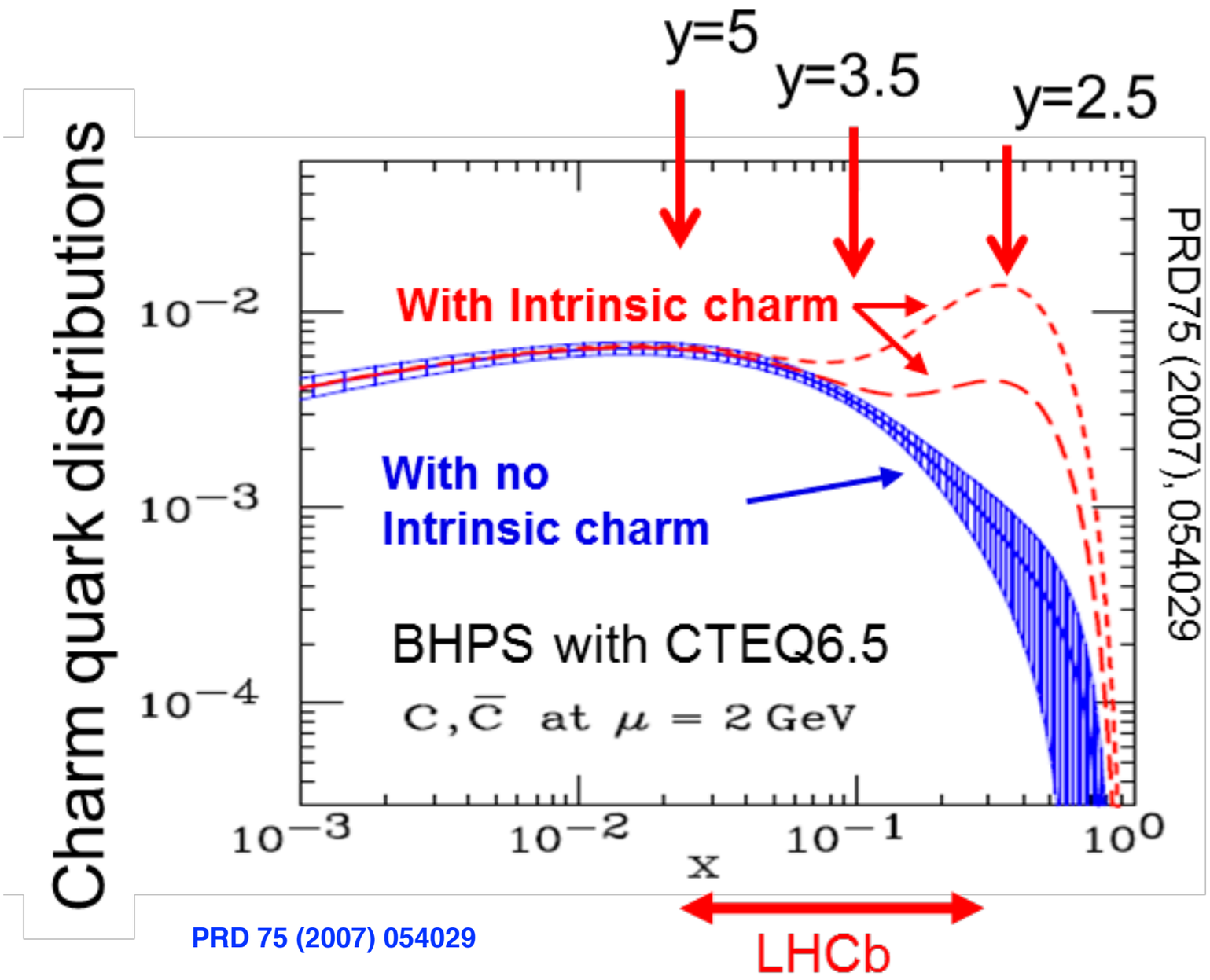
- Comparing to strange-hadron results, the D^0 v_2 values are smaller at a given p_T, or at similar transverse kinetic energy per constituent quark, after normalizing v_2 by the number of constituent quarks.
- This indicates that in high-multiplicity pPb collisions, the collective behavior of charm quarks is weaker than that of the light-flavor quarks. This effect is not seen in heavy-ion (Pb-Pb) collisions.

More than p-Pb at LHC

LHCb



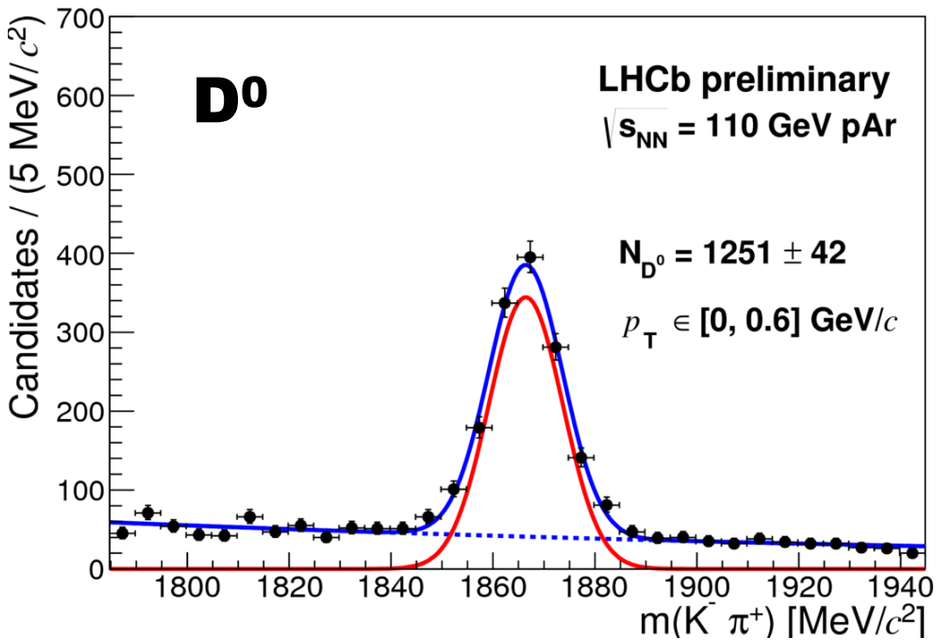
Charm production at fixed target with LHCb



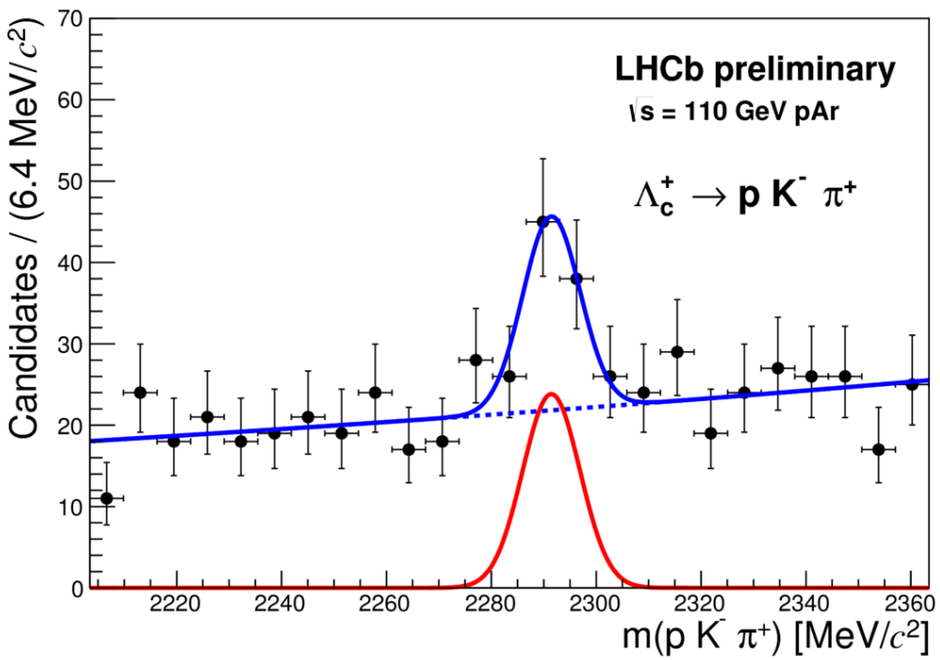
☑ Unique opportunity to constraint nPDF and intrinsic charm

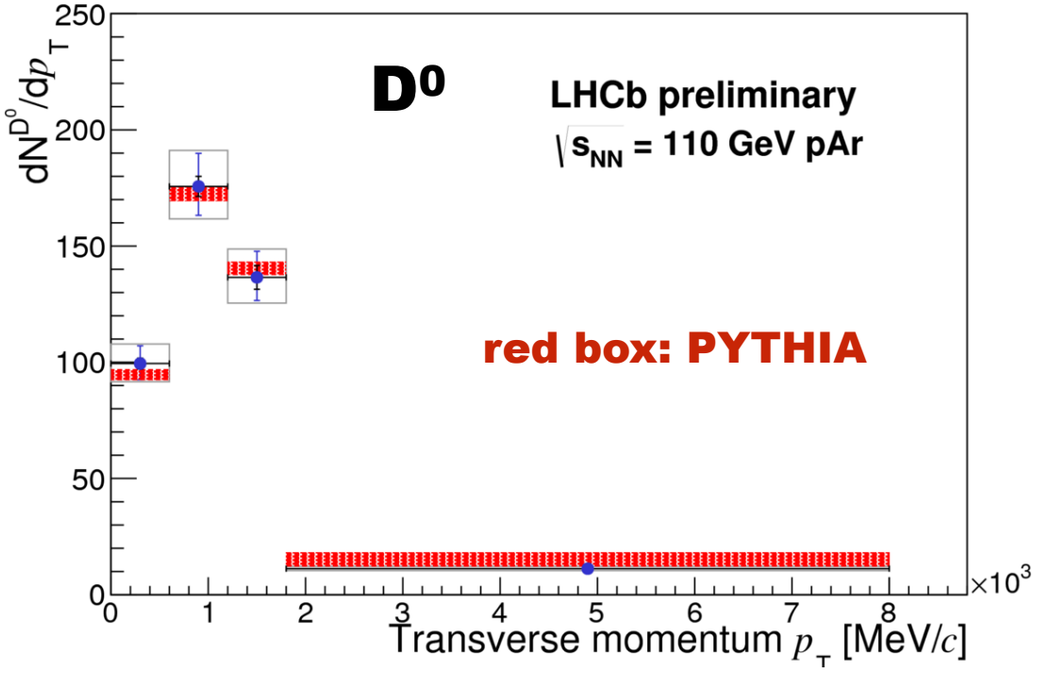
p-Ar results from LHCb

LHCb-CONF-2017-001

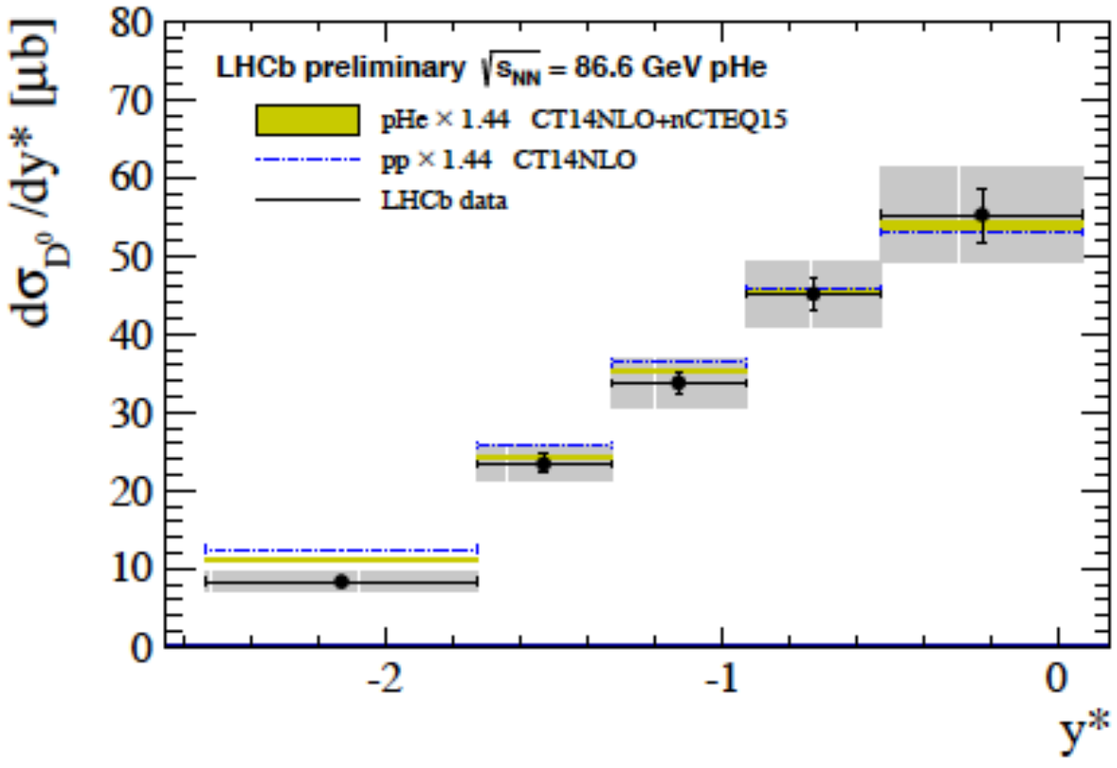


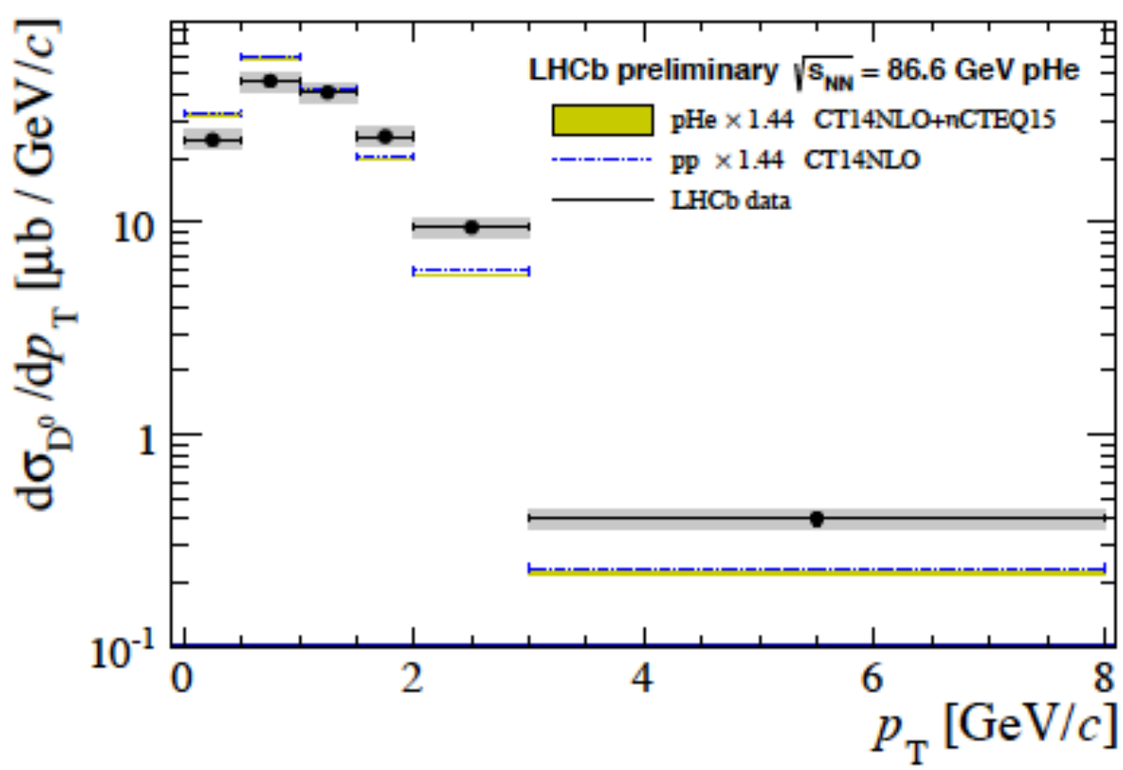
- ☑ Thanks to the SMOG detector LHCb can collide protons with different nuclei
- ☑ Similar statistic on tape for p-He and about factor 10 higher for p-N
- ☑ The large variety of targets will provide stringent constraints on models.





p-He results from LHCb





See Shanzhen Chen talk at QM2018

https://indico.cern.ch/event/656452/

- ☑ D^0 in p-He at 86.6 GeV.
- ☑ HELAC-ONIA [EPJC 77:1 (2017)] predictions for pp (blue line) and p-He (yellow box) overlaid with measurement
- ☑ No strong intrinsic charm contribution is observed
- ☑ Reasonable agreement with theoretical expectations

Summary

- 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
- The combined results of the LHC experiments allow measuring charm jets in a wide momentum range ~5-500 GeV/c
- LHCb has large samples still to be analyzed. Additional constraints on nPDF, D-D correlations, …?
- New d-Au sample (2016) from RHIC at BNL to be analyzed to complete the picture

☑ Some open question:

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

Extra Slides

a.grelli@uu.nl

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:

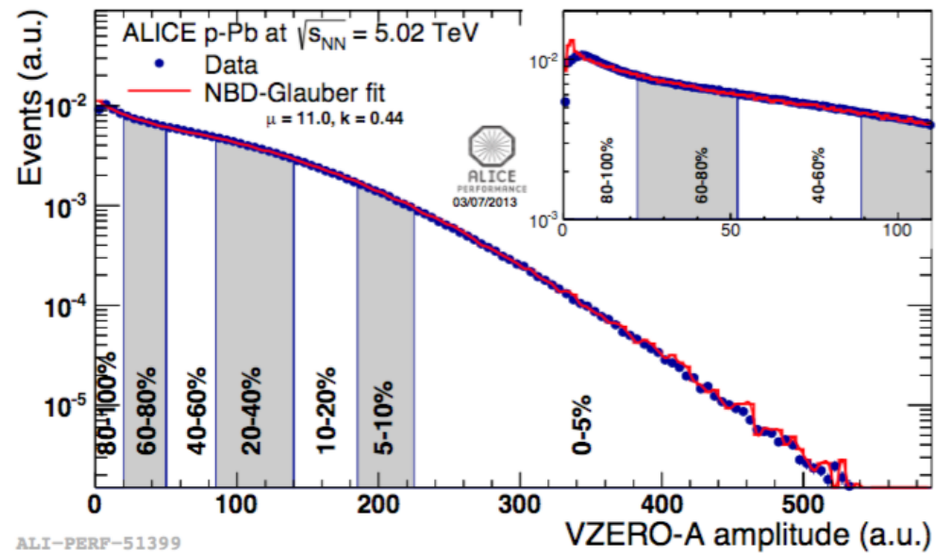
V0A: $\langle N_{coll} \rangle$ determined by Glauber fit of V0 amplitude

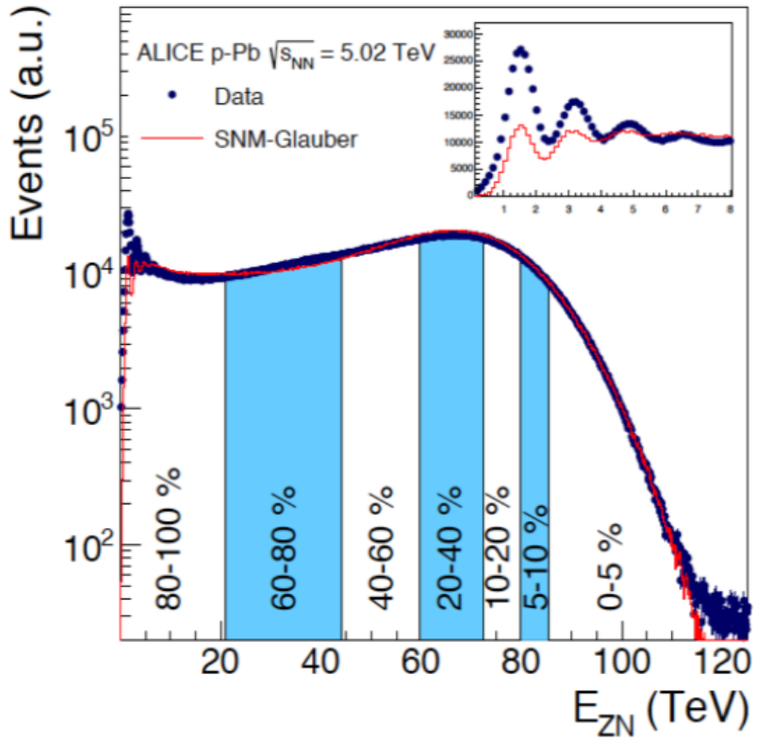
ZNA: $\langle N_{coll} \rangle$ obtained with a "Hybrid method"

- 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

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

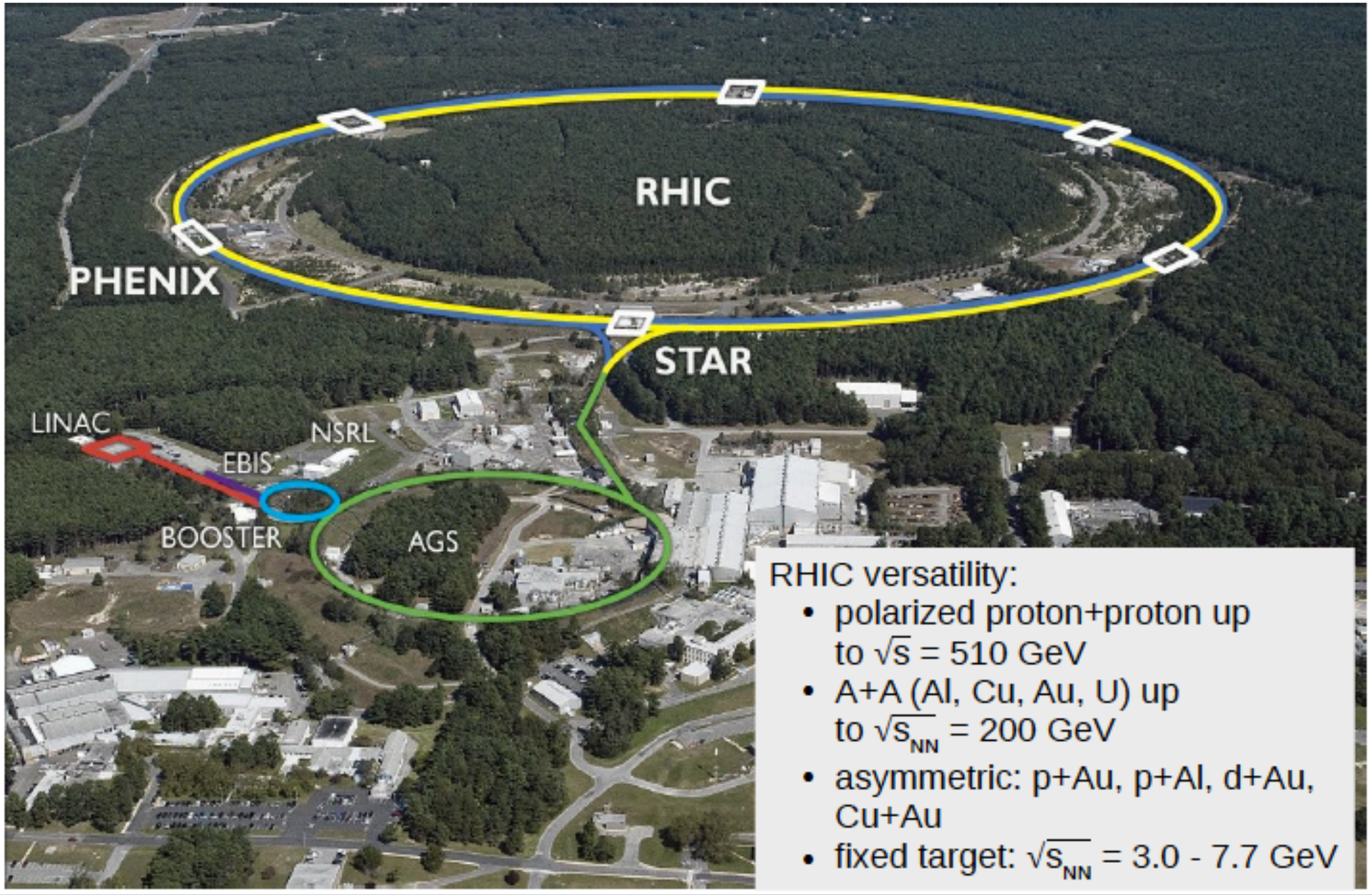
investigate charm production in p-Pb collisions w.r.t. pp collisions: possible multiplicity dependent modification of the p_T spectra in p-Pb?





a.grelli@uu.nl

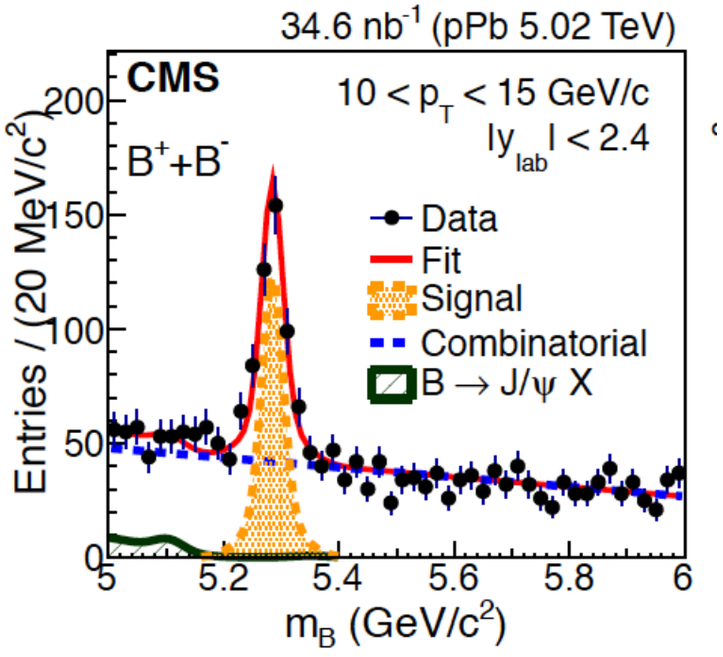
Total cross-section



RHIC versatility:

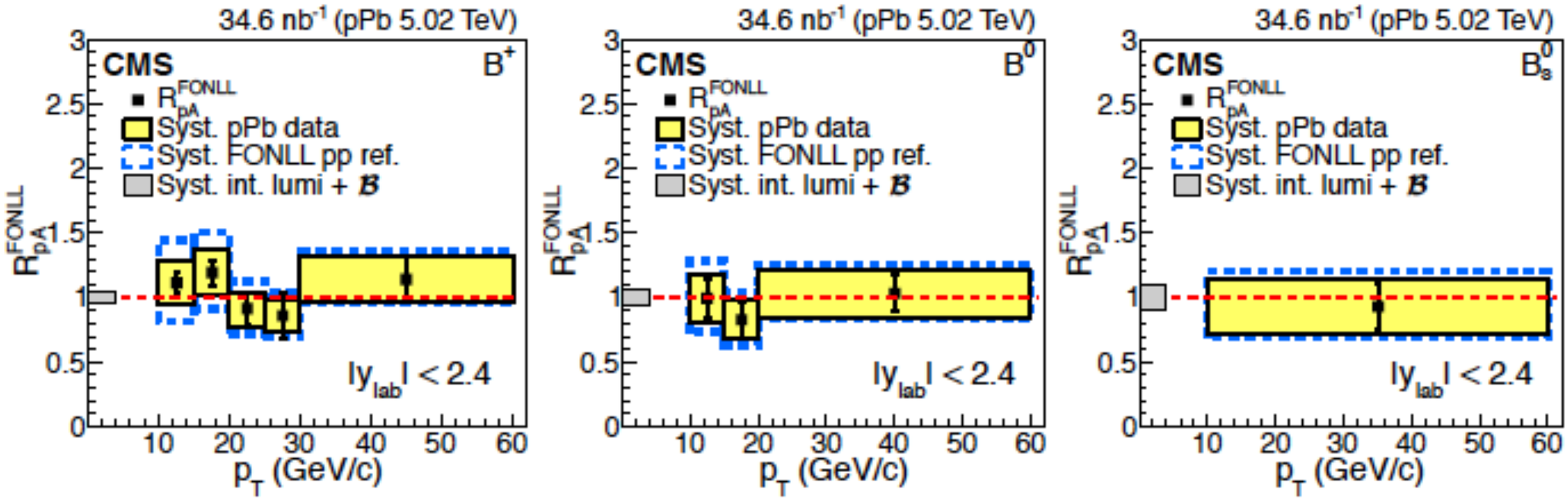
- polarized proton+proton up to $\sqrt{s}$ = 510 GeV
- A+A (Al, Cu, Au, U) up to $\sqrt{s_{NN}}$ = 200 GeV
- asymmetric: p+Au, p+Al, d+Au, Cu+Au
- fixed target: $\sqrt{s_{NN}}$ = 3.0 - 7.7 GeV

Fully reconstructed B mesons with CMS



PRL 116 (2016 032301

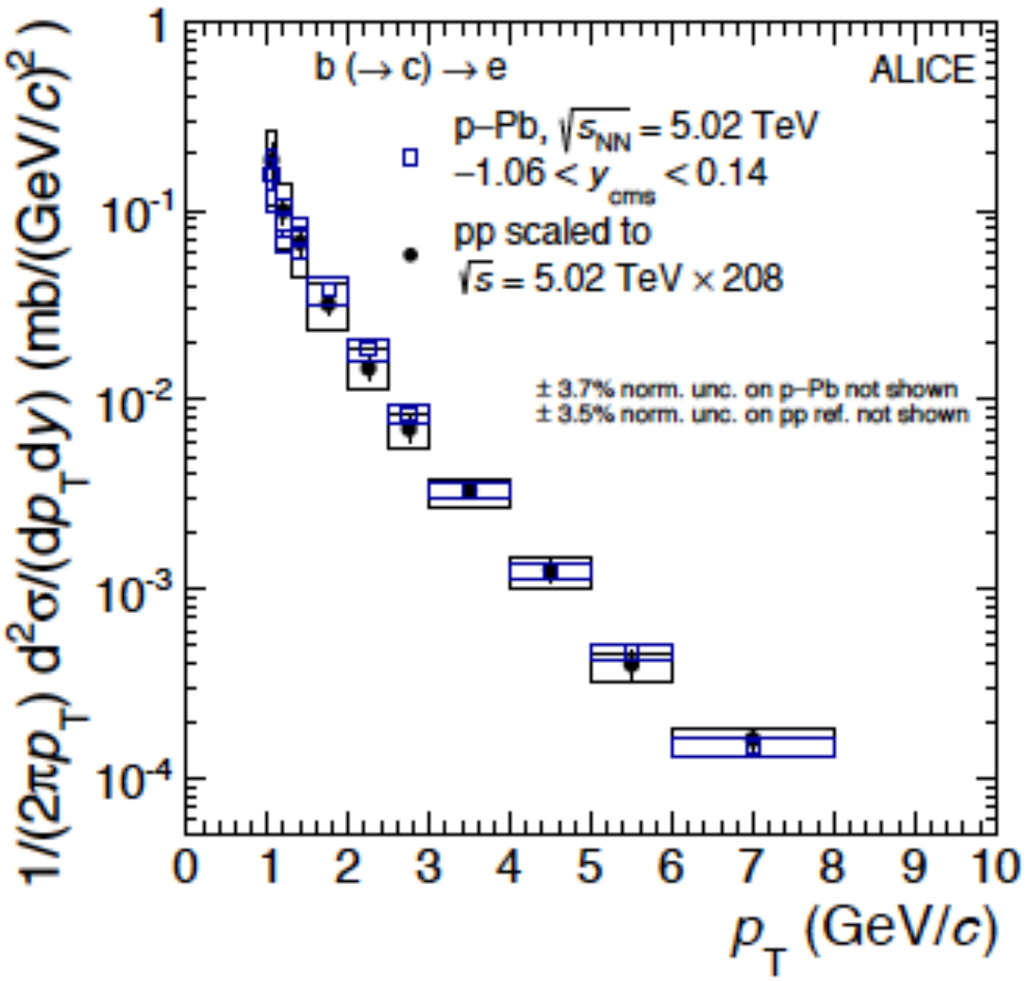
- ☑ Fully reconstructed B (B+, B0, Bs) mesons
- ☑ pp reference from FONLL pQCD calculation
- ☑ Only high-pT accessible
- ☑ R_{pPb} consistent with unity

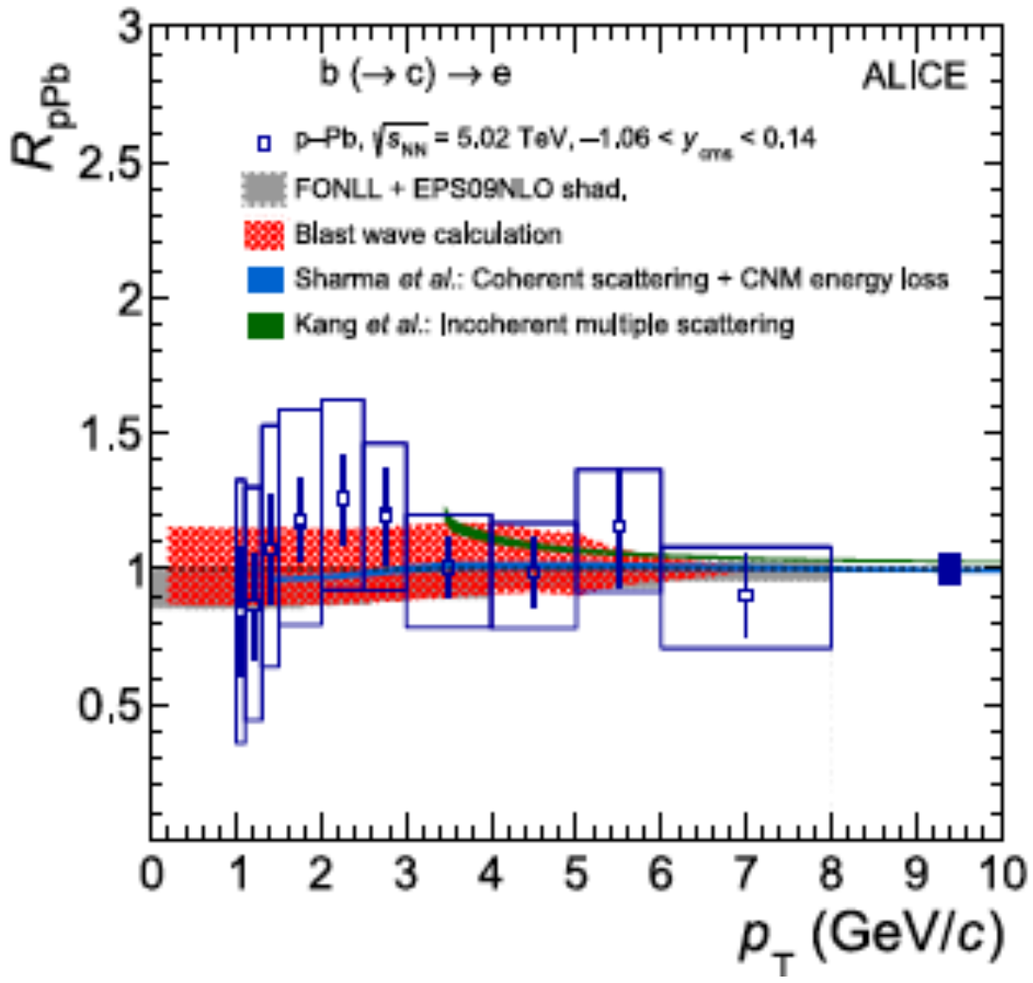


a.grelli@uu.nl

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