Open heavy-flavour production in p-Pb collisions measured with ALICE at the LHC

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Outline

- Why heavy-flavour (HF) production studies in p-Pb collisions
- Open heavy-flavour reconstruction in ALICE
- Measurements in p-Pb collisions:
  - charmed-meson production
  - charmed-baryon production
  - leptons from heavy-flavour hadron decays
  - azimuthal correlations of D mesons and heavy-flavour decay electrons with charged particles
- Conclusions

Why heavy flavour in p-Pb collisions

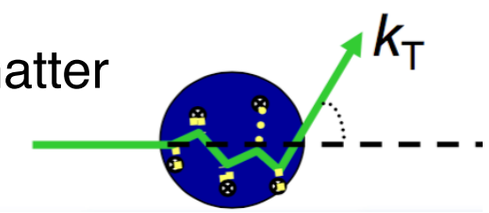
charm and beauty: effective probes of Quark-Gluon Plasma (QGP) in heavy-ion collisions

see X. Zhang talk

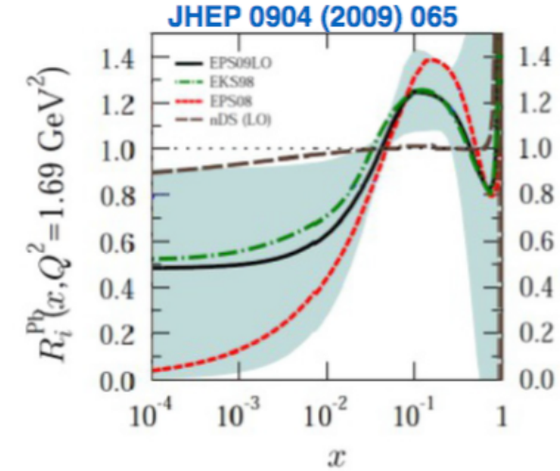
Interpretation of Pb-Pb results requires understanding of **cold nuclear matter (CNM) effects** in initial and final state:

- shadowing/gluon saturation at low Bjorken-*x*
- parton transverse momentum broadening, cold nuclear matter parton energy loss

constrain them by studying **p-Pb collisions**



JHEP 0904 (2009) 065



modification of gluon PDF in nuclear collisions: large uncertainties at low *x*

p-Pb collisions not only reference for CNM effects:
could collective effects in high-multiplicity p-Pb events modify HF particle production?

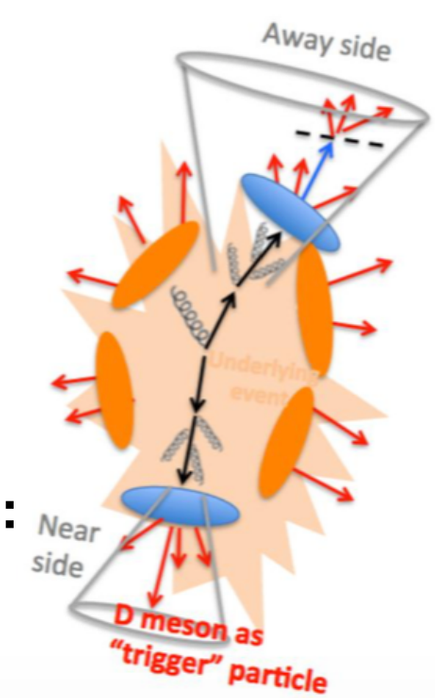
➡study role of collision geometry/particle density

Observables presented in this talk:

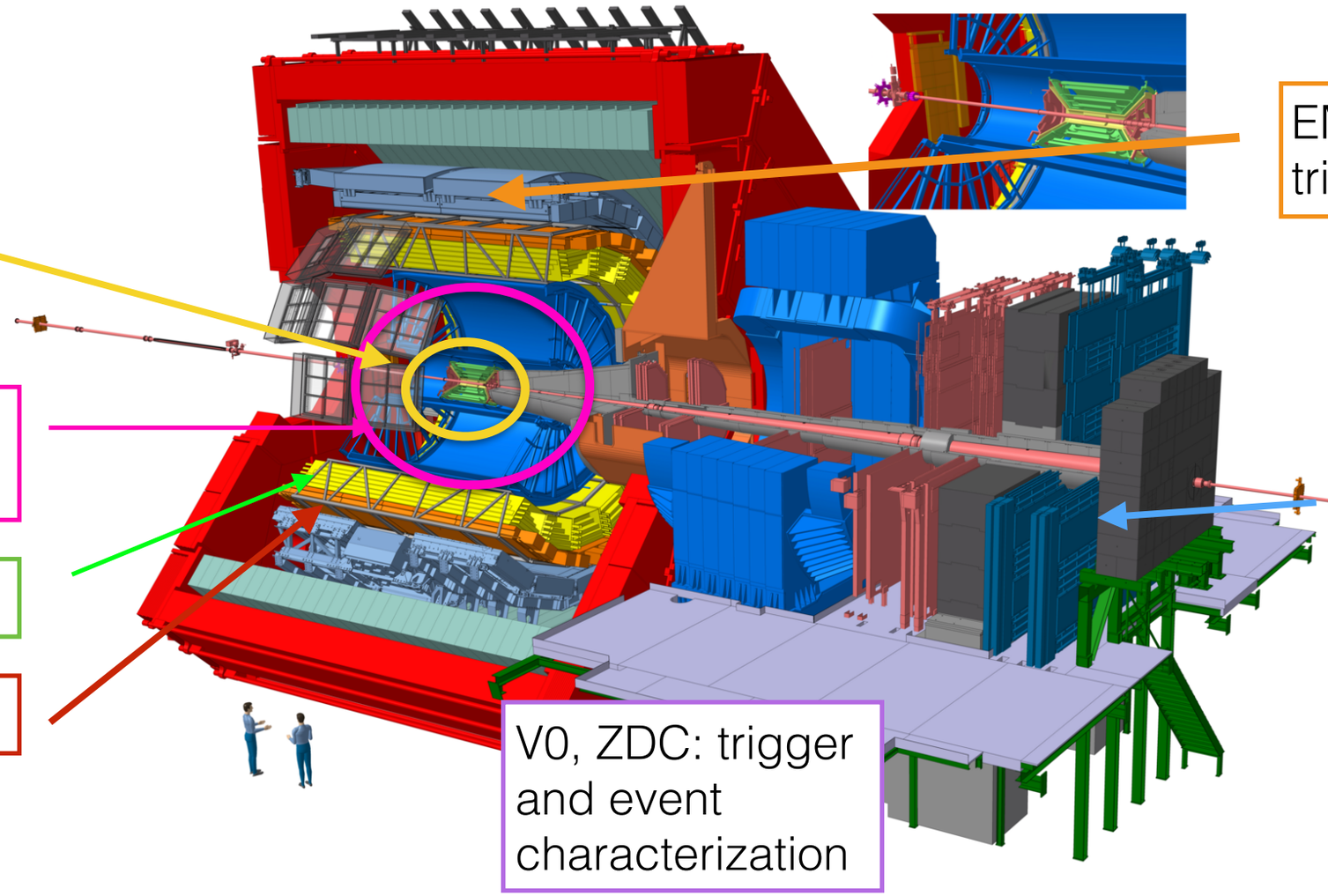
- **Nuclear modification factor:** modification in p-Pb w.r.t. pp collisions

$$R_{\mathrm{pA}} = \frac{1}{\langle T_{\mathrm{pA}} \rangle} \frac{\mathrm{d}N_{\mathrm{pA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

- Azimuthal correlations of **D mesons and HF decay electrons with charged particles:**
  - fragmentation of charm, properties of jets with charm content and possible collective effects in high-multiplicity p-Pb collisions



Open HF decay reconstruction



Selection and identification:

D-meson and Λ_c reconstruction: **ITS, TPC**, **TOF**

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

$\Lambda_c^+ \rightarrow \pi^+K^-p$, $\Lambda_c^+ \rightarrow pK^0_s$

Muons: **Forward Muon Spectrometer.** D,B —>$\mu^\pm$+X

Electrons: **ITS, TPC**, **TOF, EMCAL, TRD.** D,B —>$e^\pm$+X

Data Samples:

p-Pb collisions: $\sqrt{s_{NN}}$ =5.02 TeV

collected in 2013 ~100 M min.bias. events

L_{int}= 48.6 μb^{-1} (Run1)

L_{int} for muons analysis:

p-Pb: ~ 196 μb^{-1} (4.9 10^3 μb^{-1}) for low (high) p_T trigger

Pb-p: ~ 254 μb^{-1} (5.8 10^3 μb^{-1}) for low (high) p_T trigger

collected in 2016 ~600 M min.bias. events

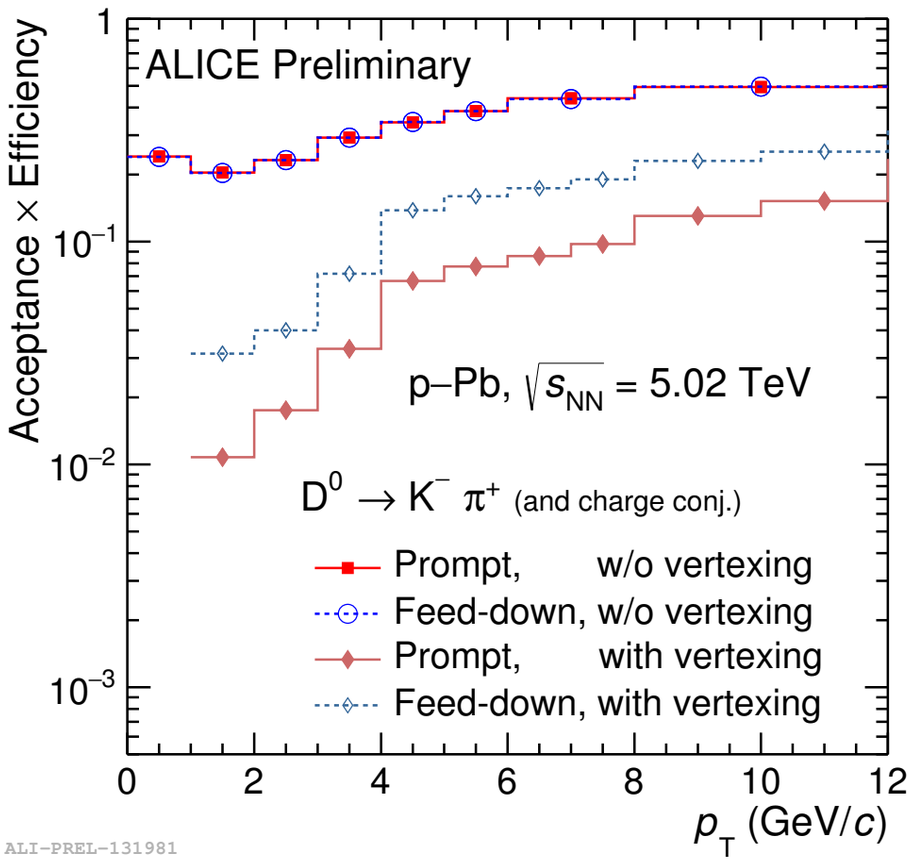
L_{int}= 292 μb^{-1} (Run2)

heavy-flavour hadron studies:
D-meson production in min. bias collisions
and as a function of event centrality in p-Pb collisions

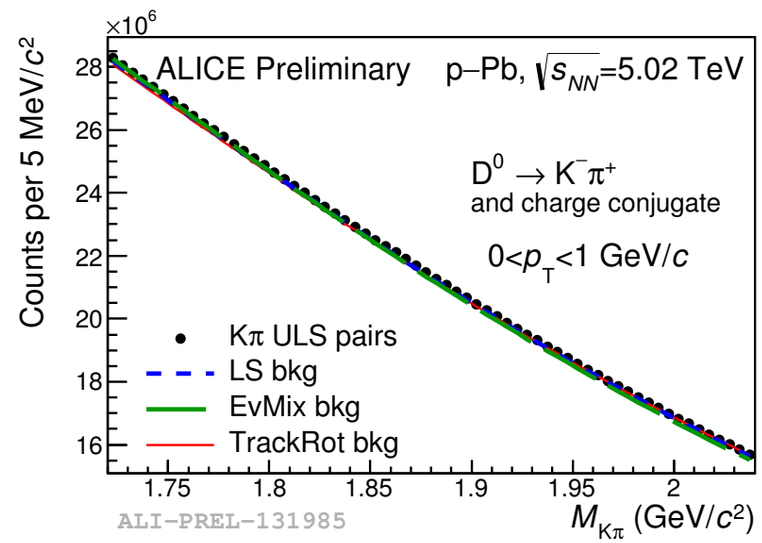
D^0 down to p_T= 0

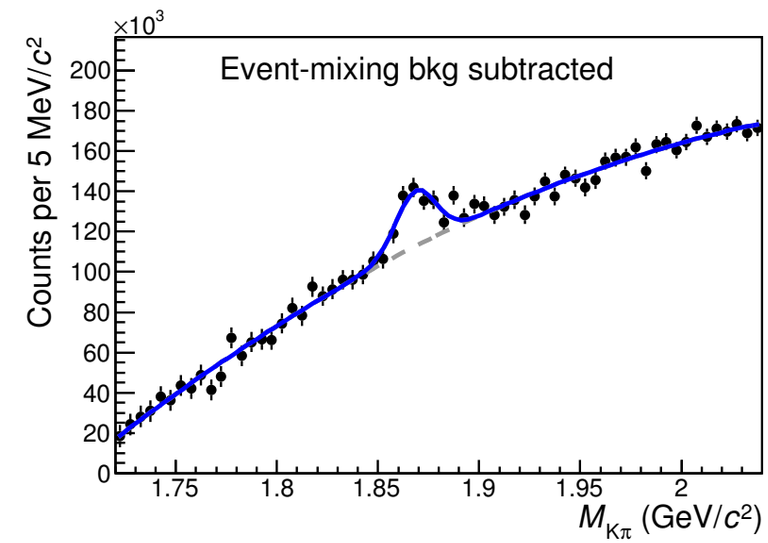
News from RUN2

ALICE-PUBLIC-2017-008



Run1 results: PRL113 n23 (2014) 232301, PRC94 n5(2016) 054908
Run2: 6x more statistics





Standard analysis reconstructs D mesons selecting on secondary vertex: inefficient for p_T<1 GeV/c

For D^0 low-p_T analysis:

PID selection, background subtraction method w/o reconstruction of D^0 decay vertex

- **efficiency larger by a factor of 20** at 1<p_T<2 GeV/c
- better significance than standard analysis for p_T<1 GeV/c

Combinatorial background subtraction via: event mixing, like sign, track rotation, side-band fit

D cross section in p-Pb collisions

News from RUN2

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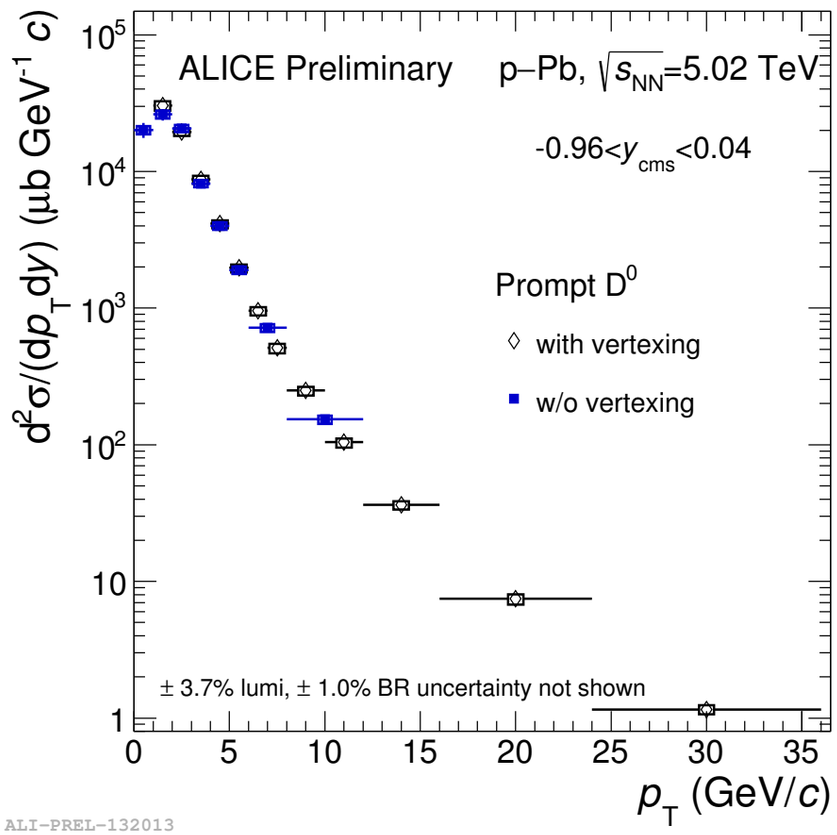

prompt D^0 p_T-differential cross section with and w/o vertexing method down to p_T=0

D cross section in p-Pb collisions

News from RUN2

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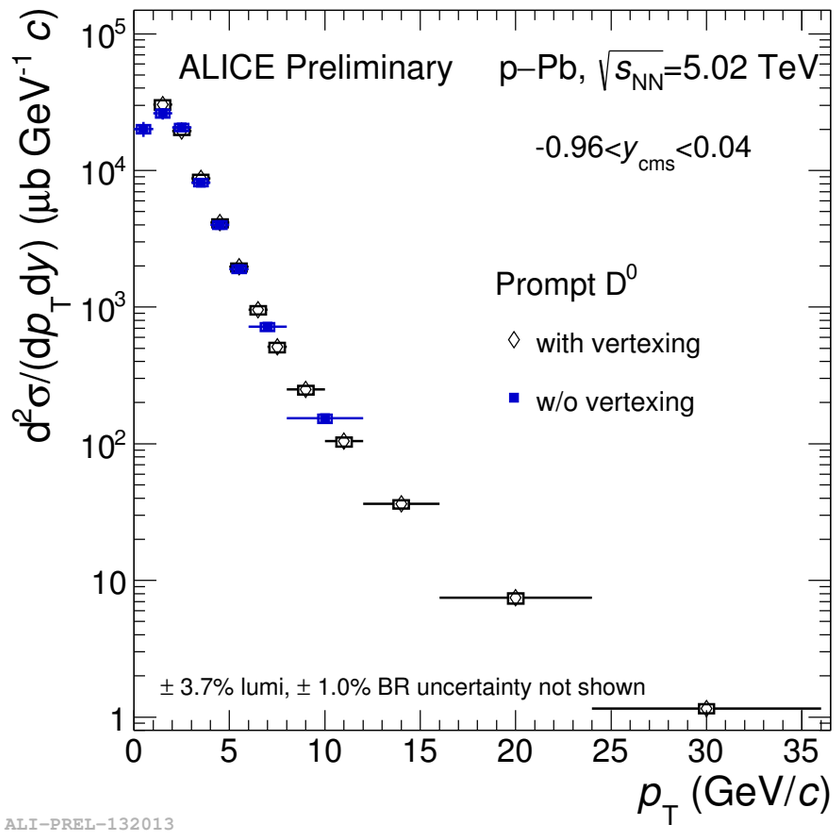
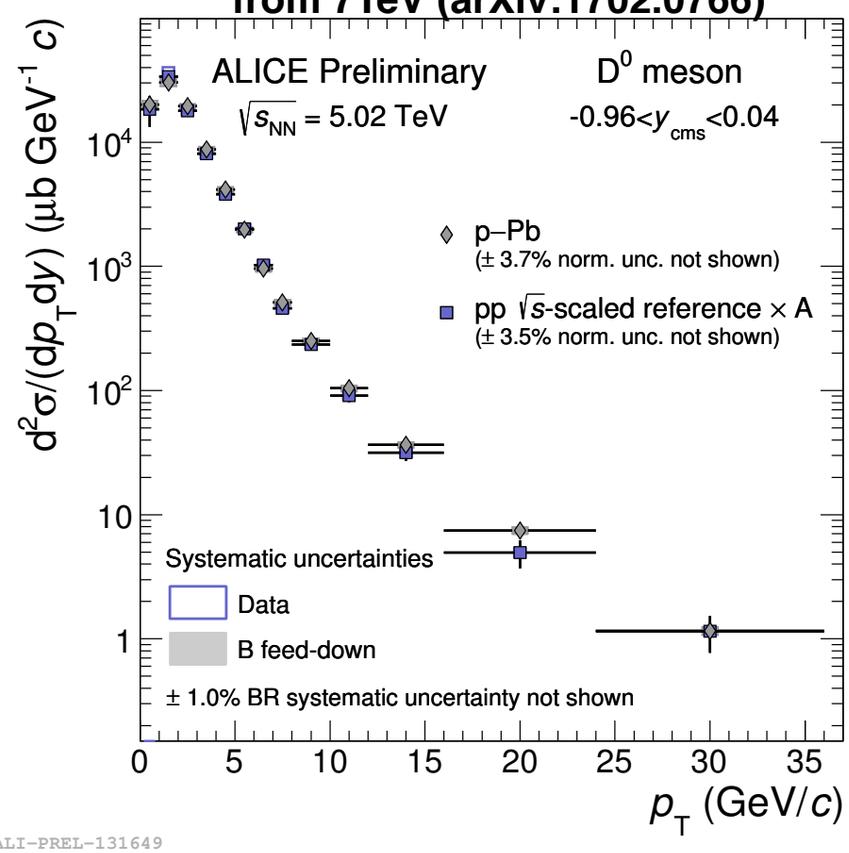


pp reference extrapolated from 7TeV (arXiv:1702.0766)



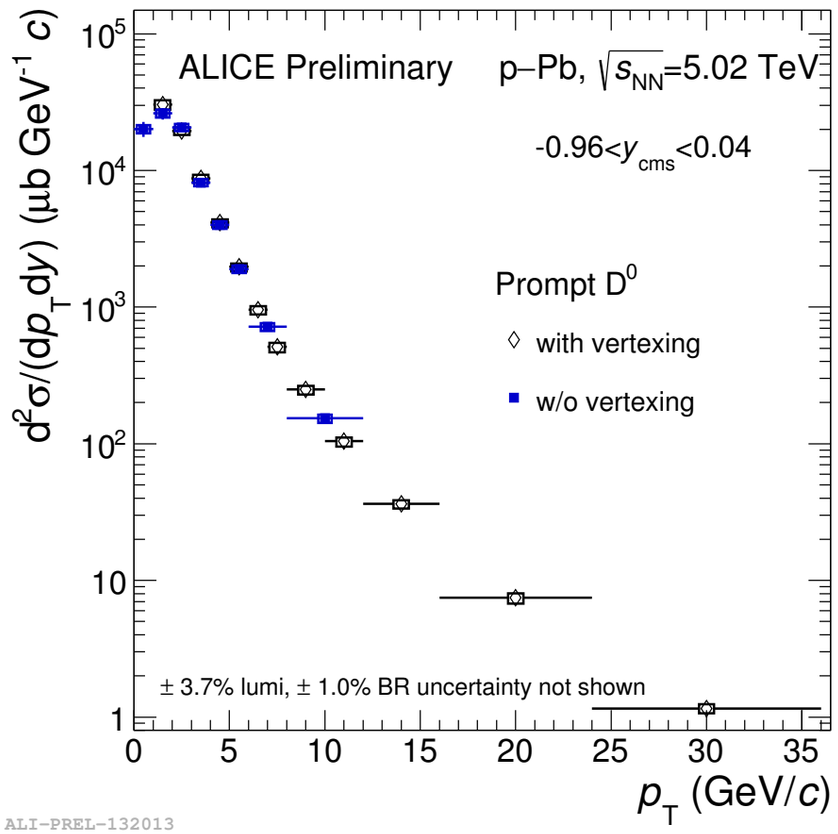
prompt D^0 p_T-differential cross section with and w/o vertexing method down to p_T=0

pp and **p-Pb** prompt D^0 p_T-differential cross sections: the most precise measurement obtained w/o vertexing for $0<p_T<1$ GeV/c and with vertexing for $p_T>1$ GeV/c method

D cross section in p-Pb collisions

News from RUN2

ALICE-PUBLIC-2017-008



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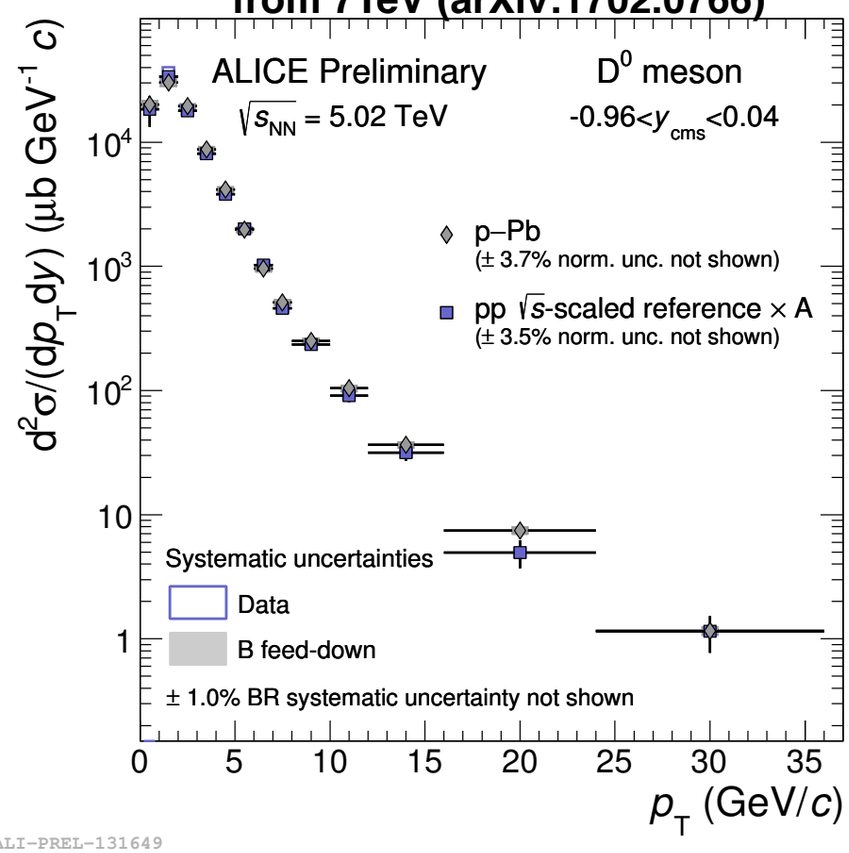
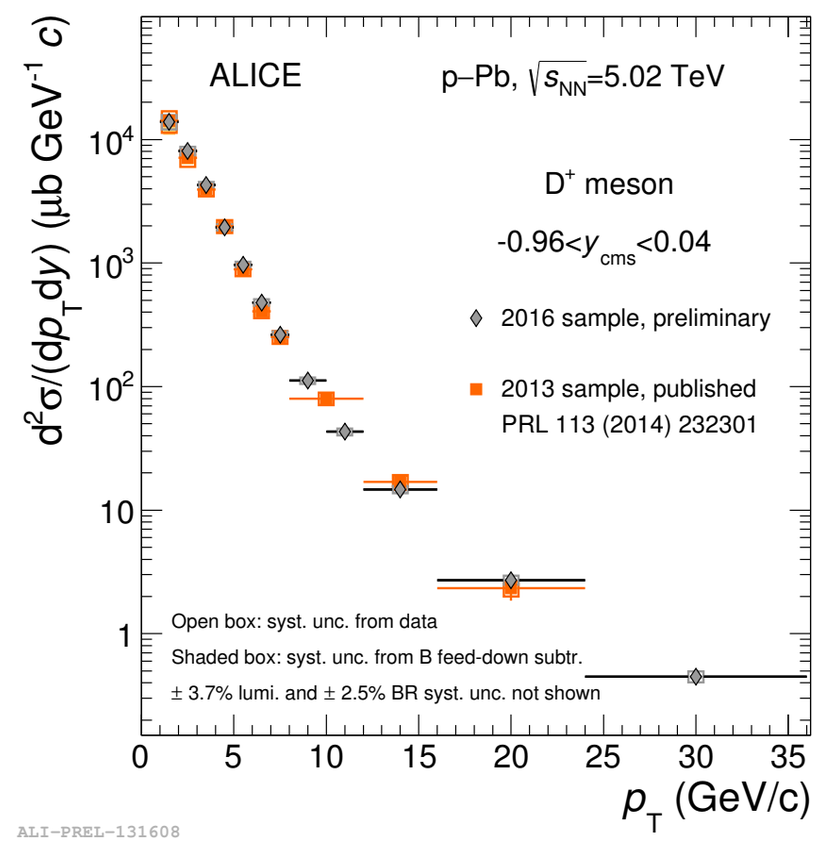


PRL113 n23 (2014) ,PRC94 n5(2016)



prompt D^0 p_T-differential cross section with and w/o vertexing method down to p_T=0

pp and **p-Pb** prompt D^0 p_T-differential cross sections: the most precise measurement obtained w/o vertexing for $0<p_T<1$ GeV/c and with vertexing for $p_T>1$ GeV/c method

prompt D^+ p_T-differential cross section with vertexing method in **Run1** vs **Run2** data:

- uncertainties reduced by a factor of ~2
- extended p_T coverage, for all D-meson species

D-meson R_{pPb}

$$R_{pPb} = \frac{\left(\frac{d\sigma}{dp_T}\right)_{pPb}}{A \times \left(\frac{d\sigma}{dp_T}\right)_{pp}}$$

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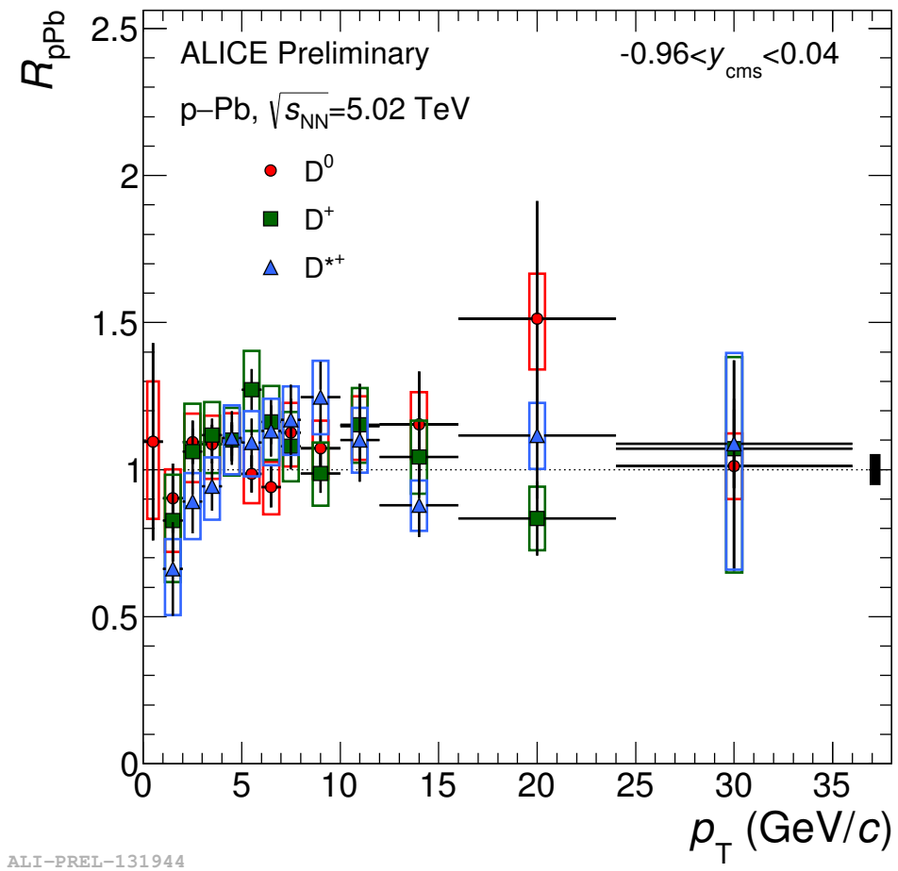
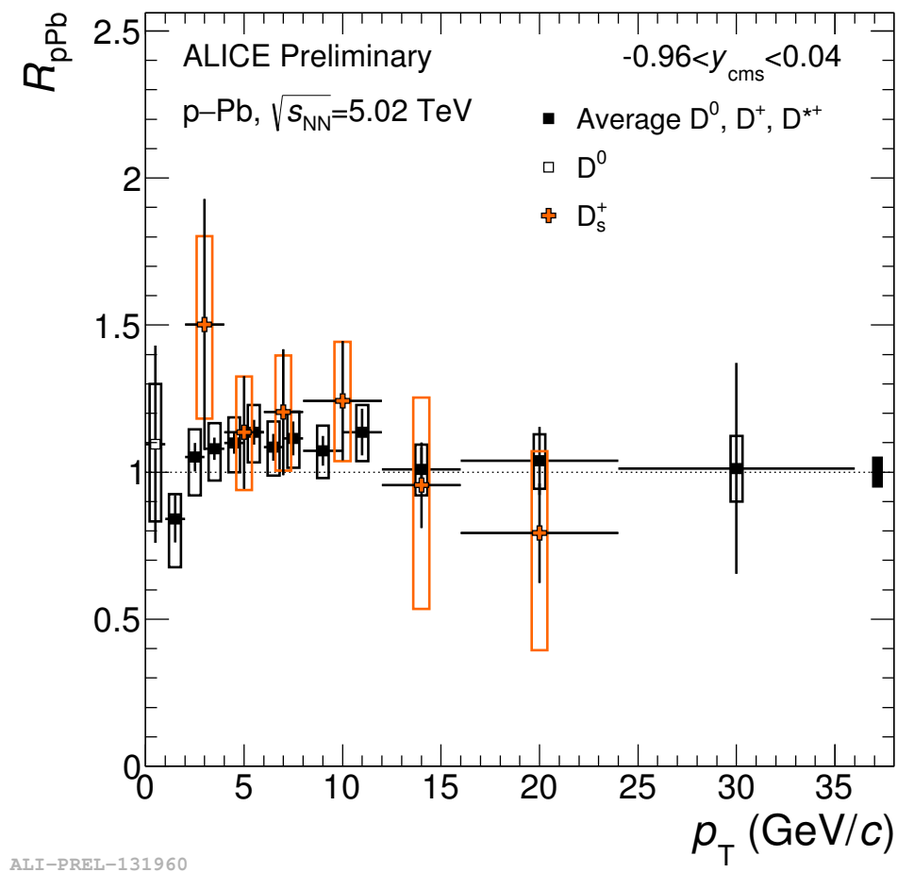
News from RUN2





Nuclear modification factor D^0,D^+,D^{*+} meson R_{pPb} compatible within uncertainties

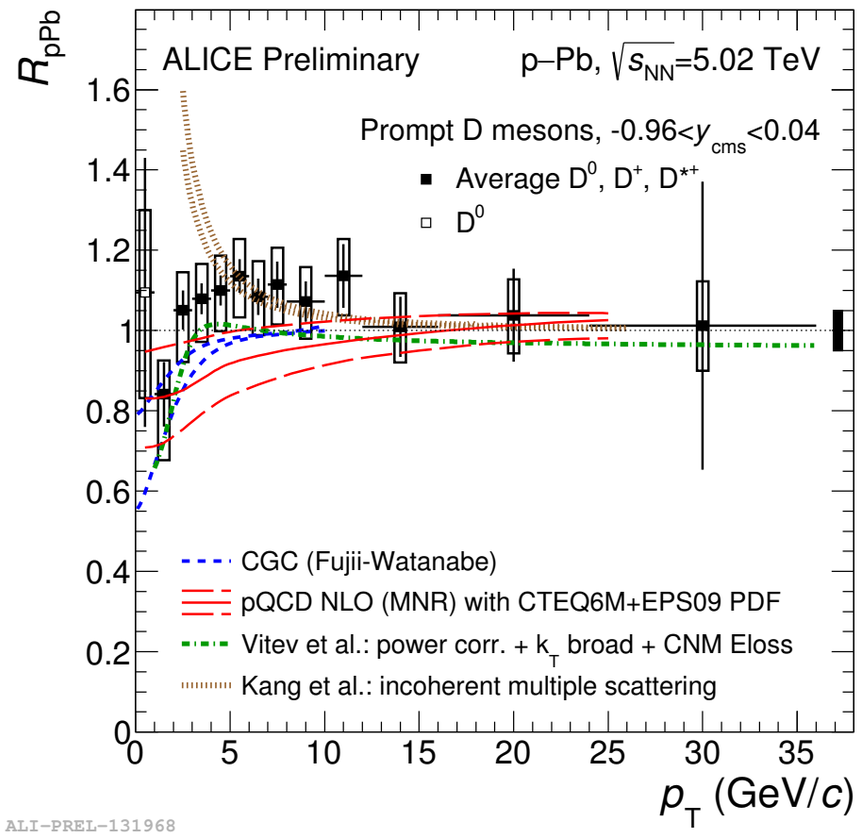
- R_{pPb} compatible with unity
  - but central values larger than 1 in $2<p_T<12$ GeV/c
- Average of non-strange D-meson R_{pPb} compared to D_s R_{pPb}: agreement within uncertainties

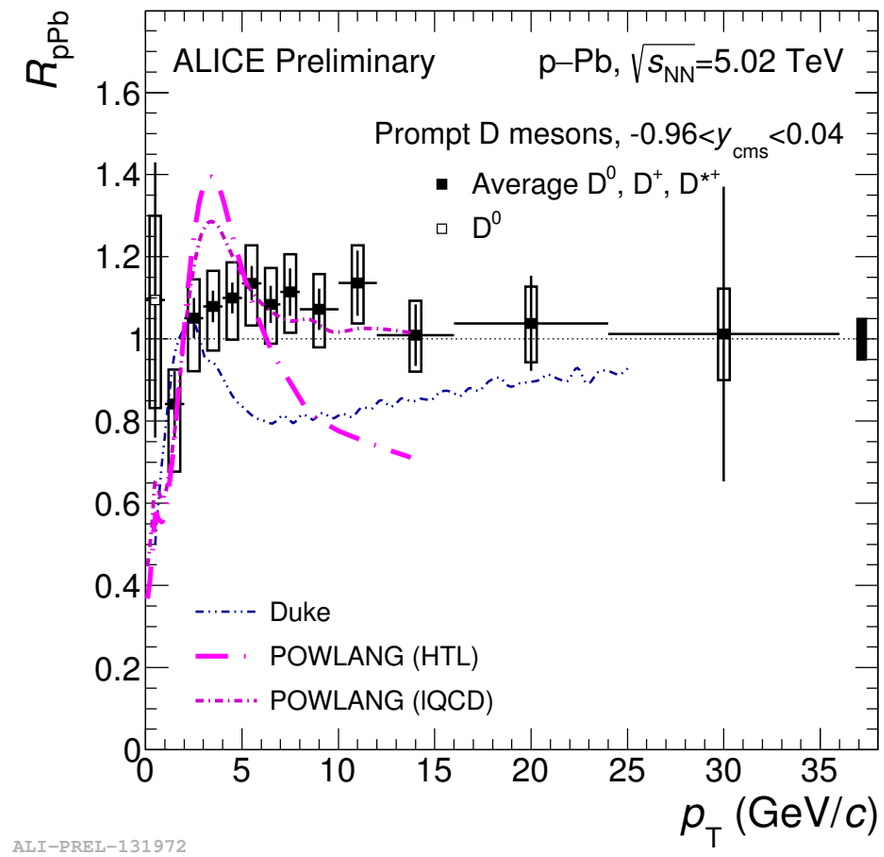
D-meson R_{pPb}

$$R_{pPb} = \frac{\left(\frac{d\sigma}{dp_T}\right)_{pPb}}{A \times \left(\frac{d\sigma}{dp_T}\right)_{pp}}$$

News from RUN2

ALICE-PUBLIC-2017-008





Models including
- **CNM effect only** are compatible with data
- **incoherent multiple scattering** describes data within uncertainties for p_T> 5 GeV/c

Models including
- **QGP formation** also in p-Pb can describe data at low-intermediate p_T

Data do not favor a suppression larger than 10-15% for 5<p_T<12 GeV/c

- larger differences between models at low p_T

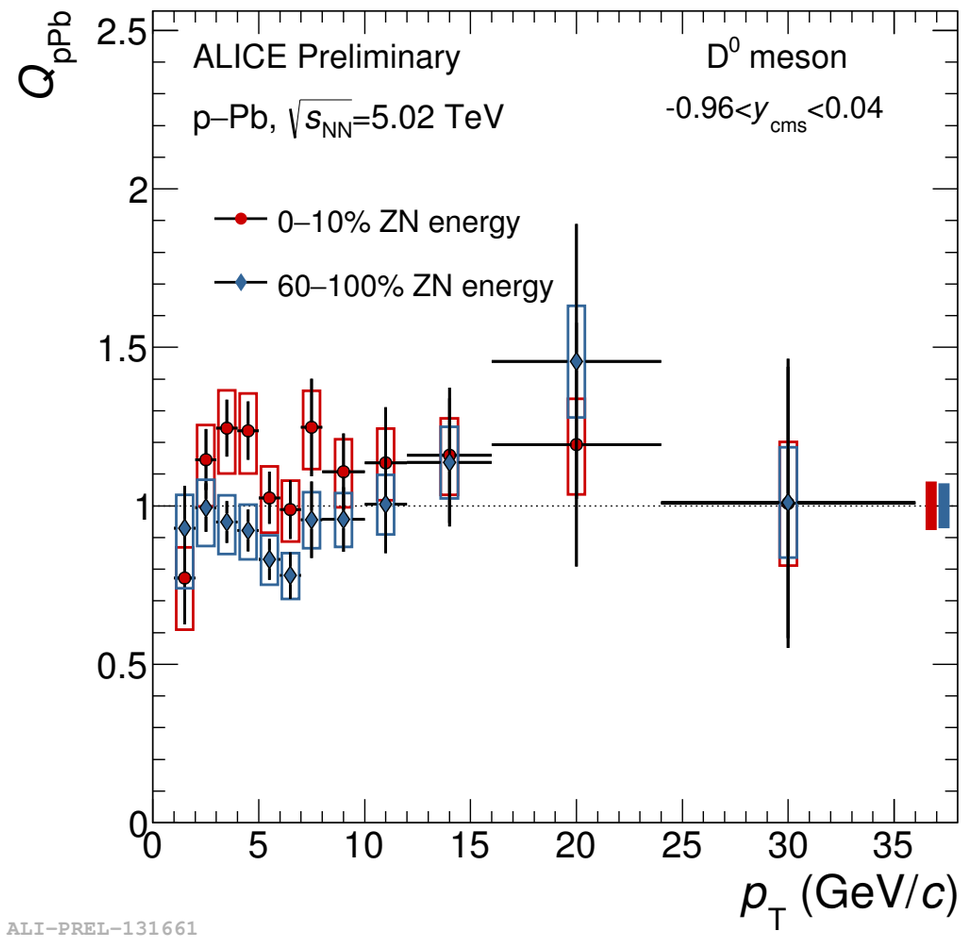
➡ need more precise pp reference at low p_T to disentangle between models

D-meson production vs multiplicity

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

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

News from RUN2



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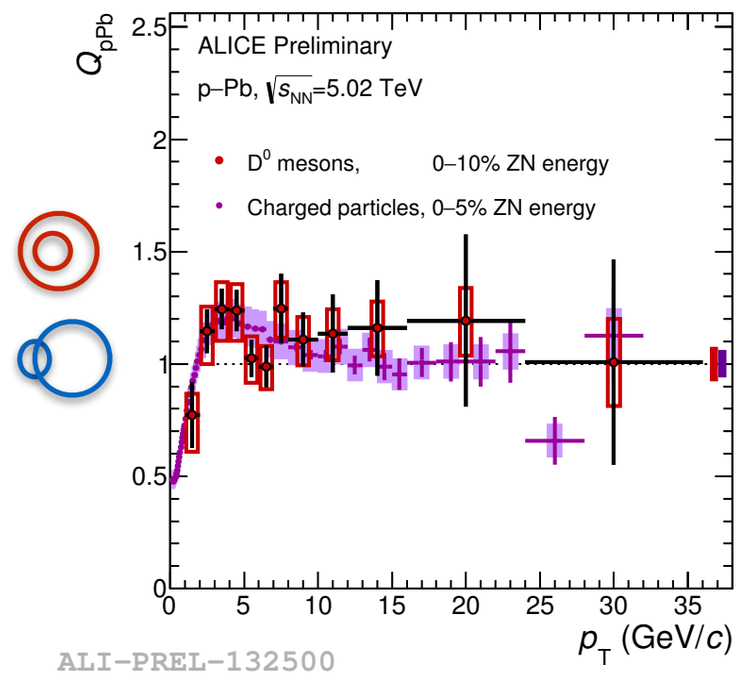
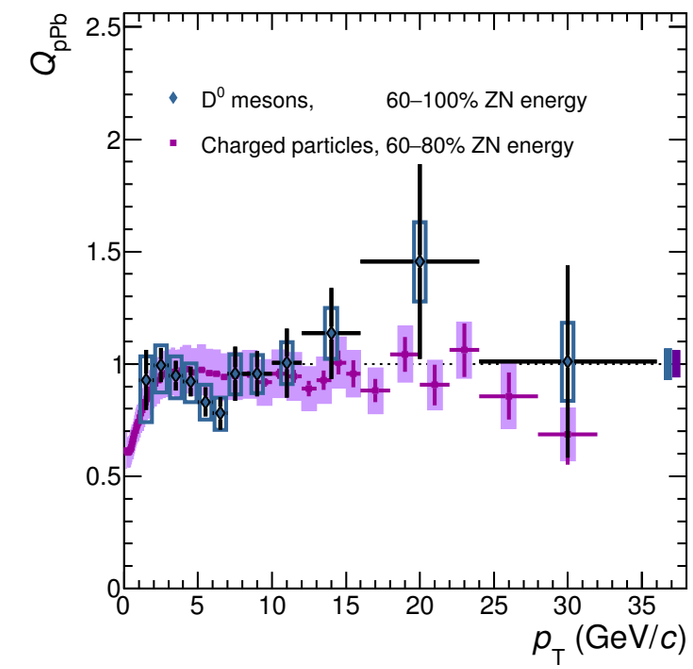
2017-008





Classes obtained slicing the energy deposited in neutron calorimeter on Pb-going side (ZNA)
Q_{pPb} in most central (0-10%) and peripheral (60-100%) centrality ranges are compatible within uncertainties and compatible with unity

D^0 Q_{pPb} in comparison with charge-particles Q_{pPb}
- slight different centrality range
- agreement within uncertainties

D-meson production vs multiplicity

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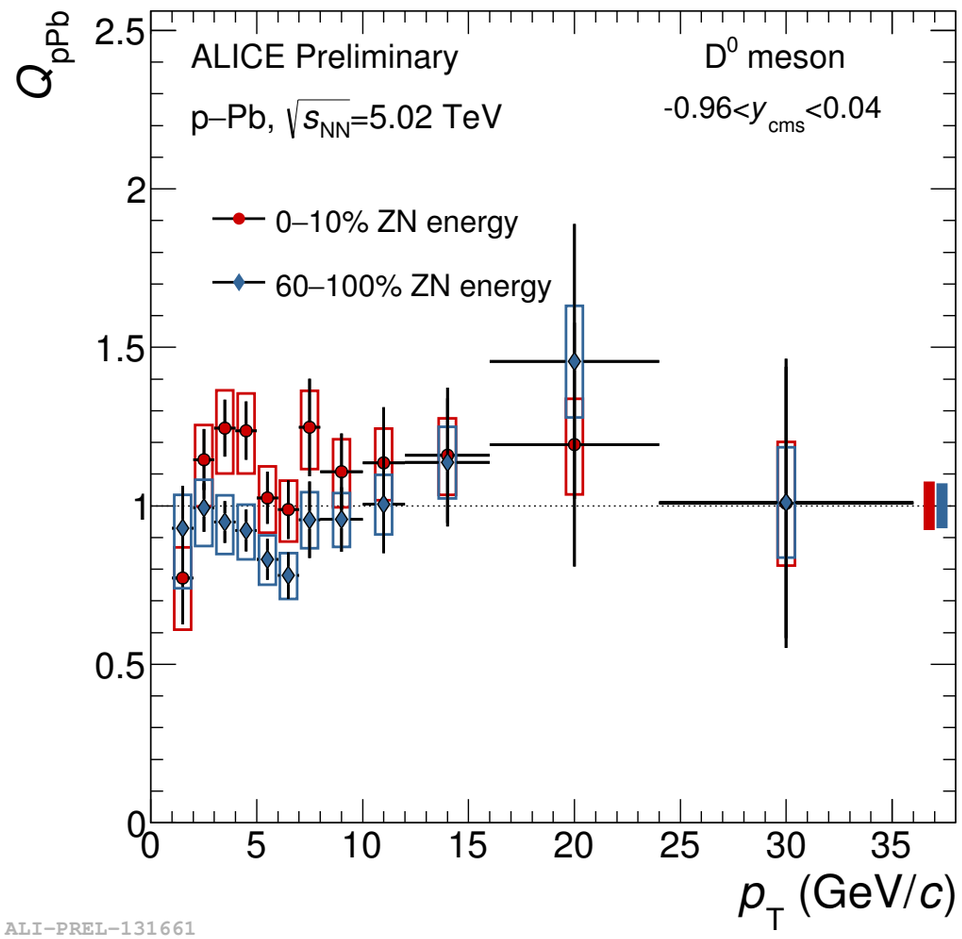
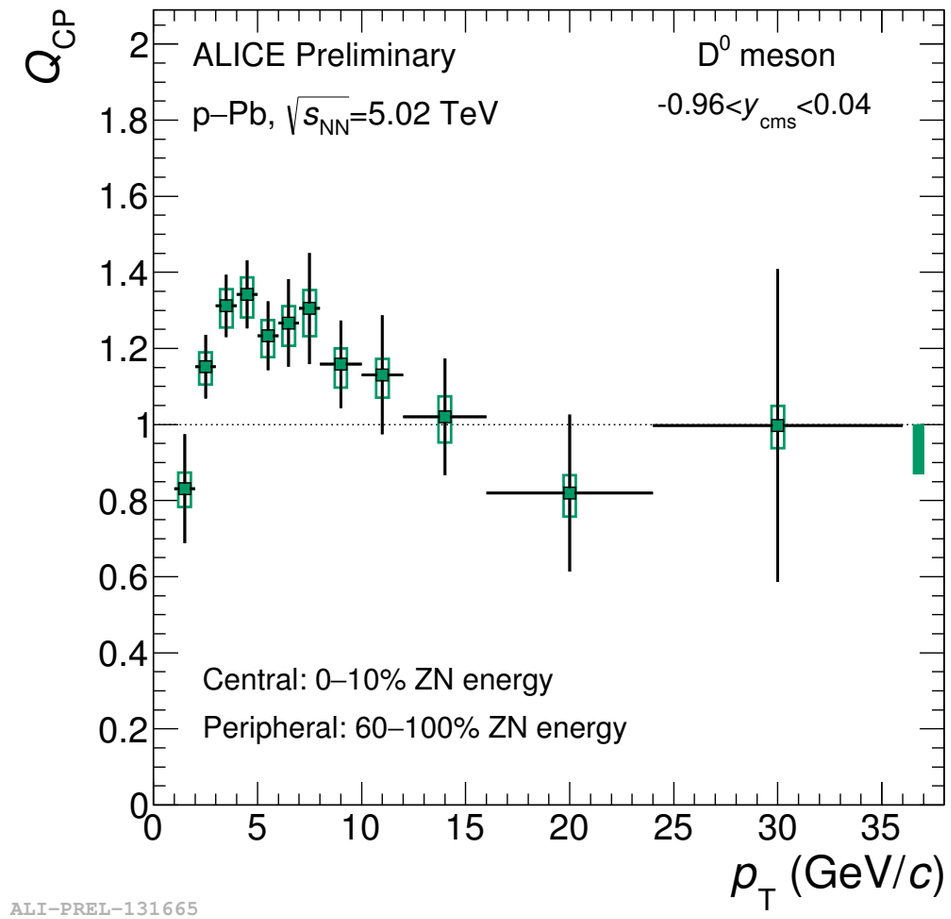
$$Q_{\mathrm{pPb}} = \frac{(\mathrm{d}N^{\mathrm{D}}/\mathrm{d}p_{\mathrm{T}})_{\mathrm{pPb}}}{\langle T_{\mathrm{pPb}}\rangle \times (\mathrm{d}\sigma^{\mathrm{D}}/\mathrm{d}p_{\mathrm{T}})_{\mathrm{pp}}} \qquad \langle T_{\mathrm{pPb}}\rangle = \frac{\langle N_{\mathrm{coll}}\rangle_i}{\sigma_{\mathrm{NN}}}$$

News from RUN2





ALICE-PUBLIC 2017-008

Classes obtained slicing the energy deposited in neutron calorimeter on Pb-going side (ZNA)
Q_{pPb} in most central (0-10%) and peripheral (60-100%) centrality ranges are compatible within uncertainties and compatible with unity

Ratio central/peripheral: **more precise measurement**

- independent from pp-reference and several systematics uncertainties cancel in the ratio

Q_{cp}>1 in 3-8 GeV/*c* with 1.7 σ

- Initial- or final-state effect?
- Possible influence of radial flow on HF particles in p-Pb?

heavy-flavour hadron studies: Λ_c production in p-Pb collisions

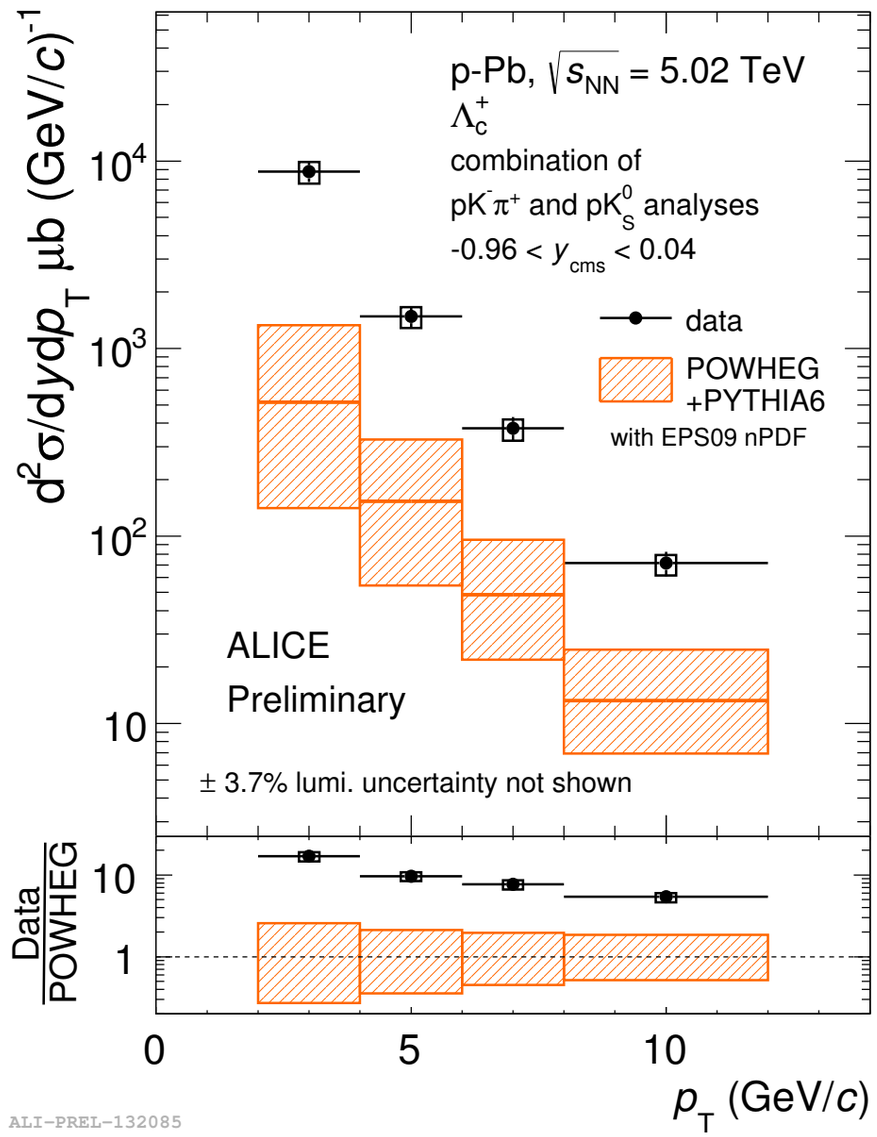
Λ_c measurement in p-Pb

News from RUN1

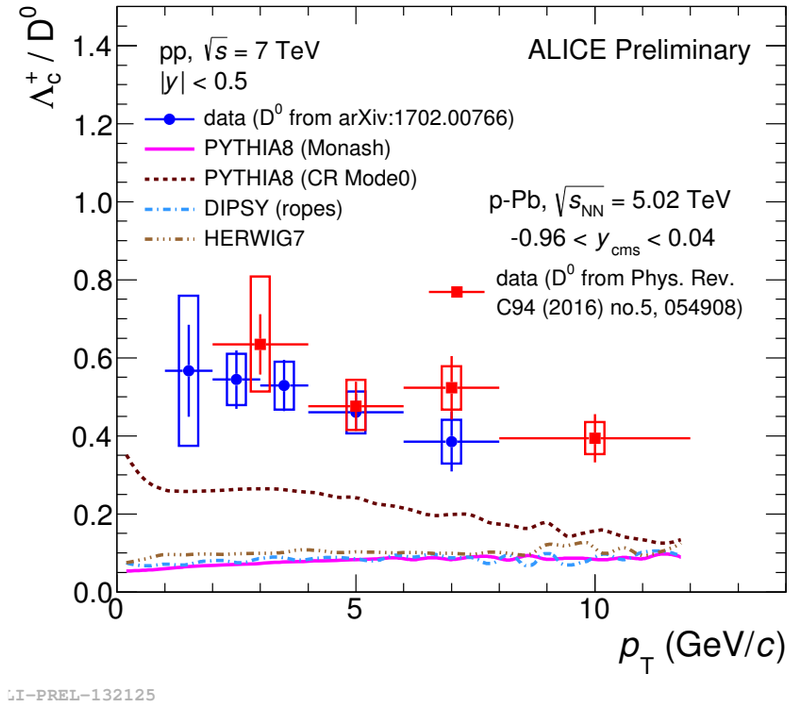
Λ_c cross section measured with 2 different techniques in 2 different decay channels: $pK\pi$, pK^0_S

see A. De Caro talk today QCD morning session

Λ_c cross section



Ratio Λ_c/D^0



Ratio Λ_c/D^0: agreement in pp and in p-Pb collisions

- models well describe D^0 cross section

Tension comparing with models

- caveat: tuned on previous measurements

Λ_c measurement in p-Pb

News from RUN1

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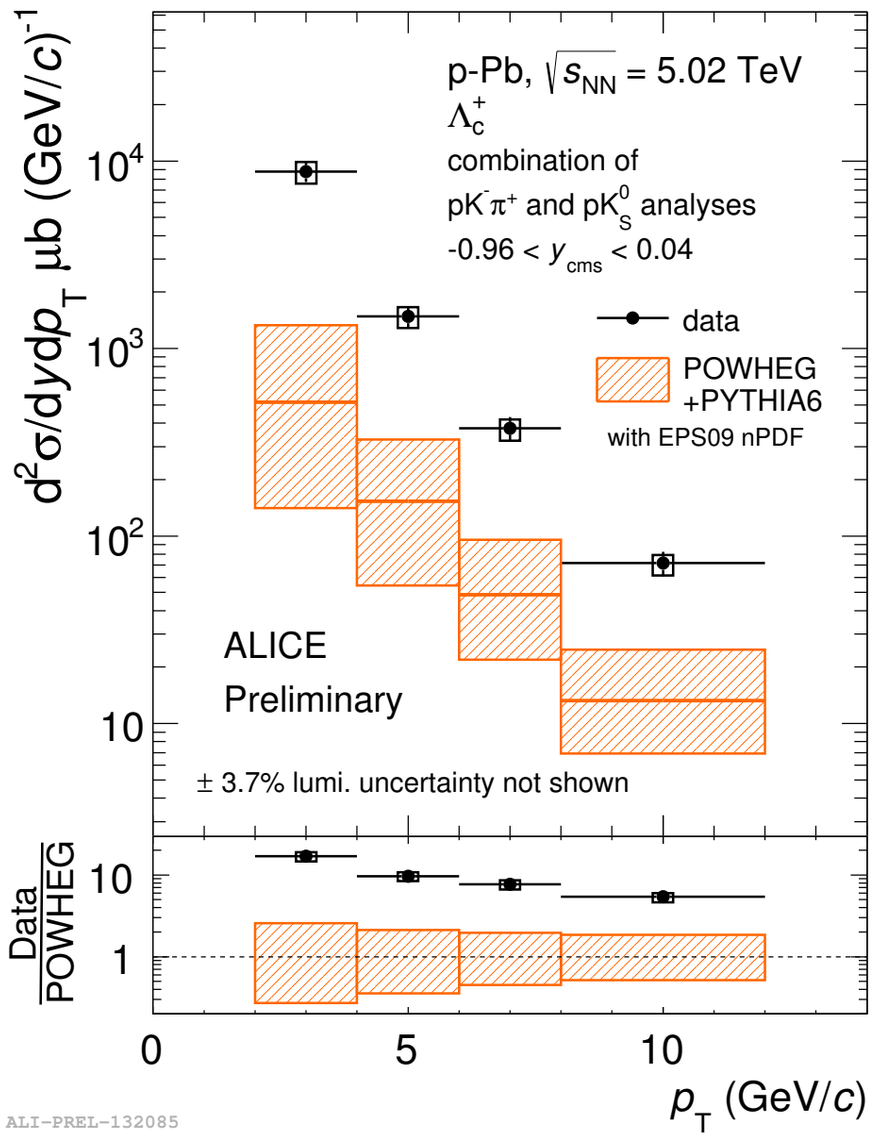
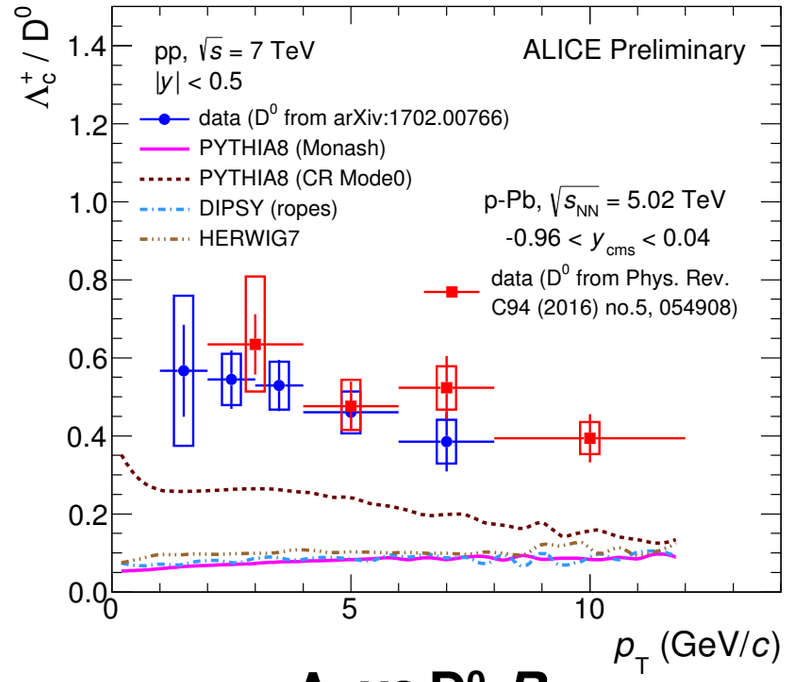
Λ_c cross section



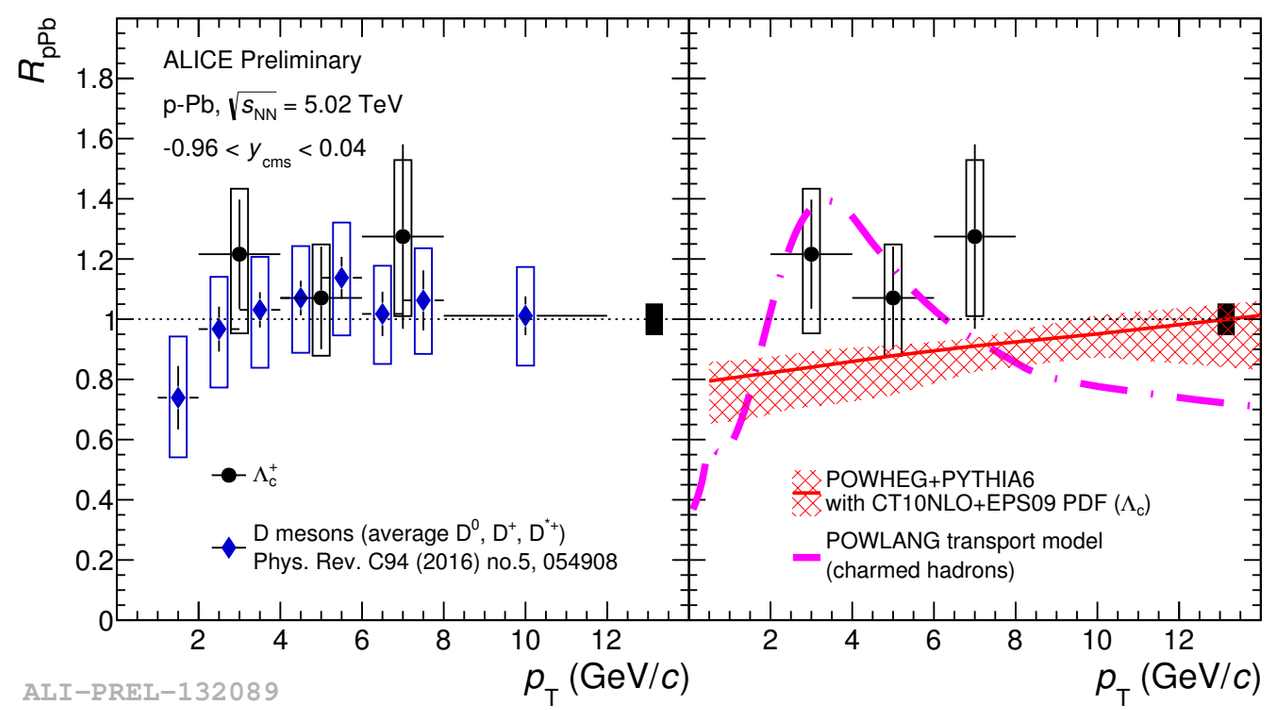
Ratio Λ_c/D^0



Ratio Λ_c/D^0: agreement in pp and in p-Pb collisions

- models well describe D^0 cross section

Λ_c vs D^0 R_{pPb}



Λ_c R_{pPb} compatible with unity within uncertainties

Tension comparing with models

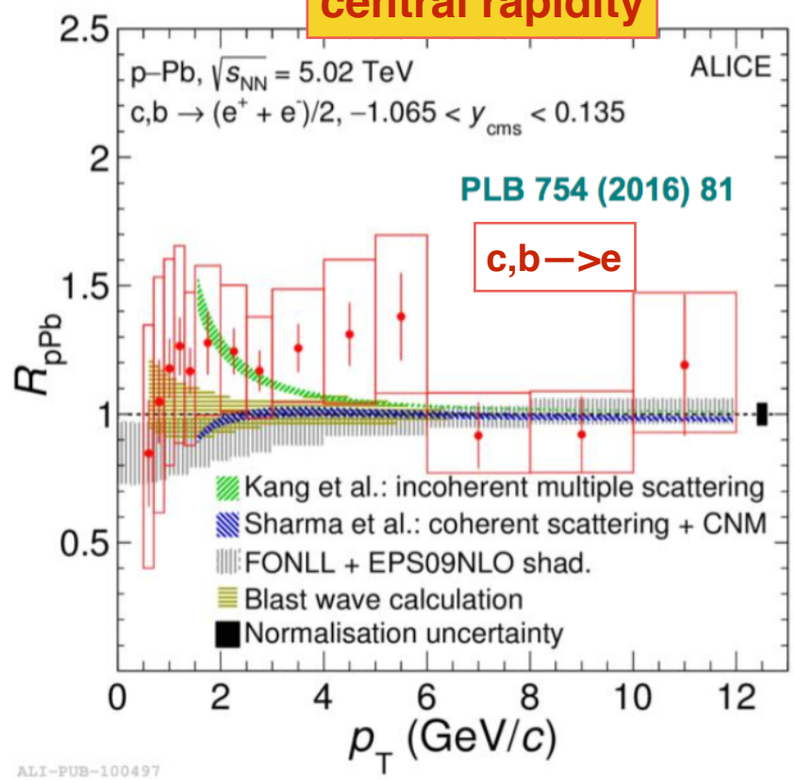
- caveat: tuned on previous measurements

electrons and muons from heavy-flavour hadron decays

Heavy-flavour hadron decay lepton R_{pPb}

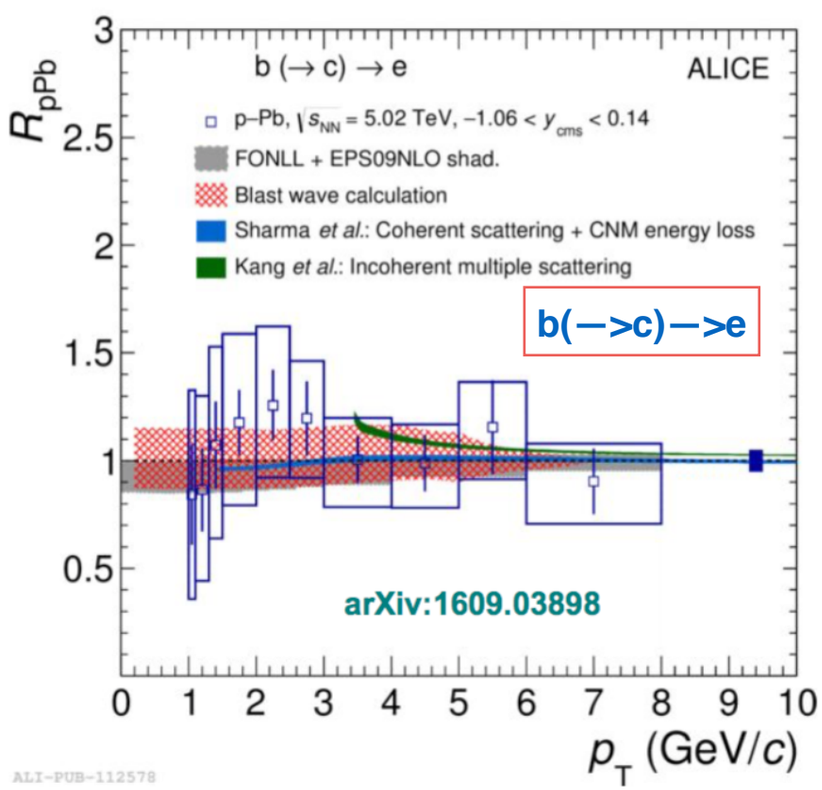
RUN1

central rapidity



R_{pPb} consistent with unity

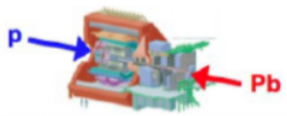
- also consistent with enhancement in $1 < p_T < 6$ GeV/c as seen in d-Au at $\sqrt{s_{NN}}$ =200 GeV **(PRL 109 (2012) 242301)**
- described by models including initial-state effects or with radial flow within uncertainties

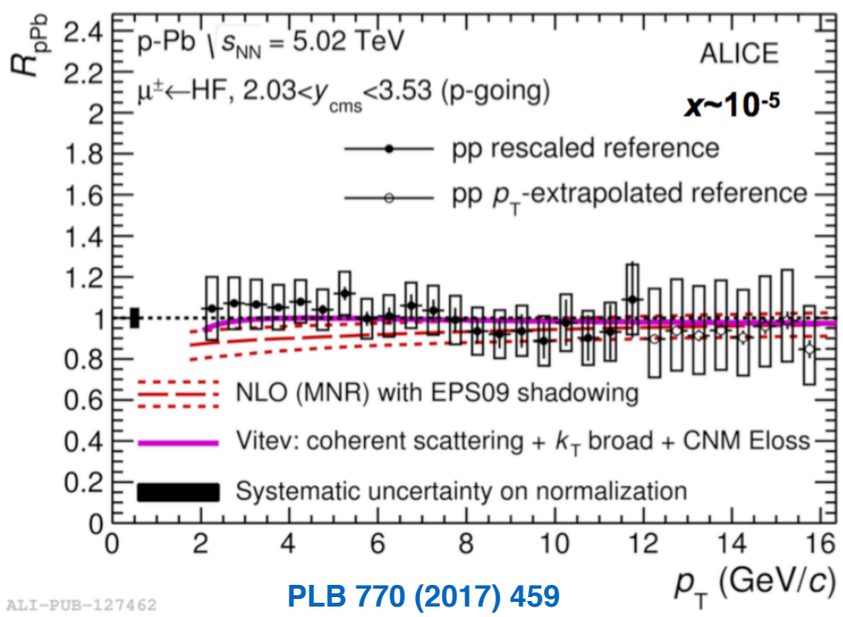


Heavy-flavour hadron decay lepton R_{pPb}

RUN1

forward rapidity





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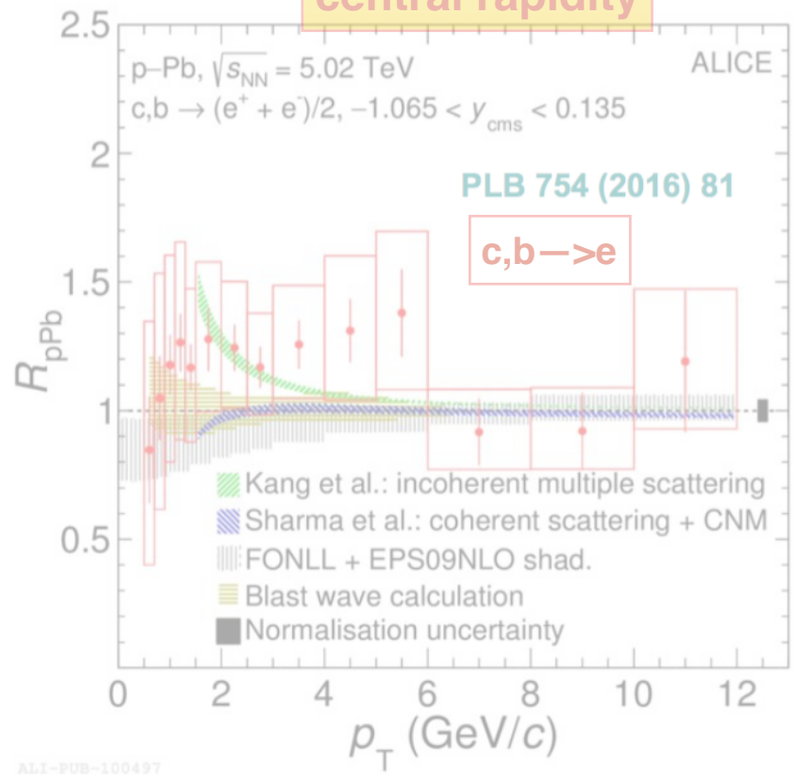
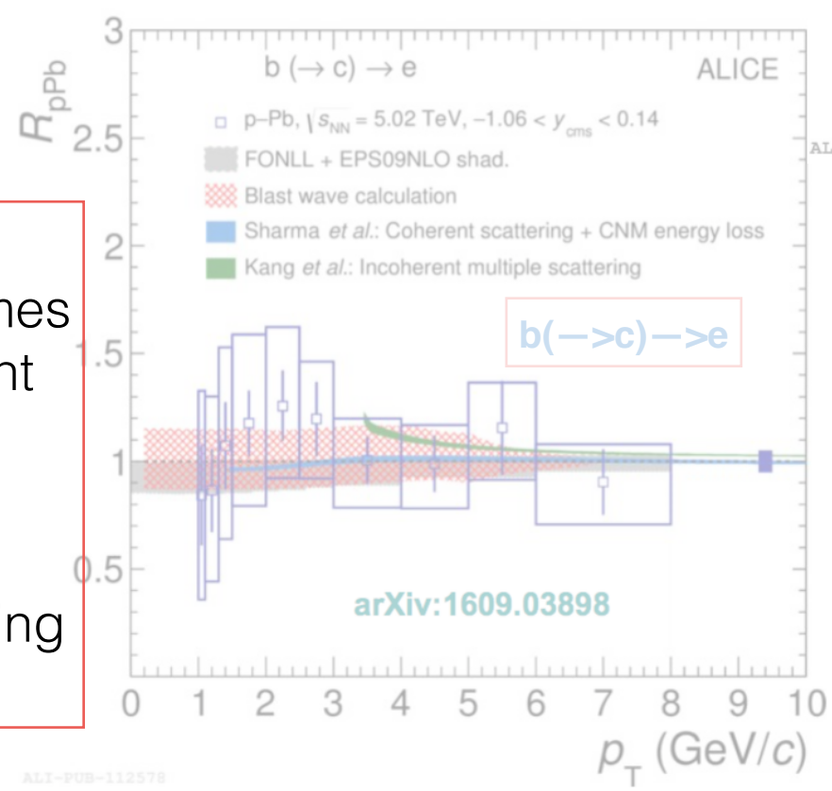
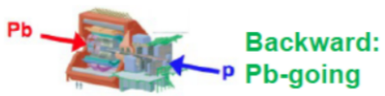
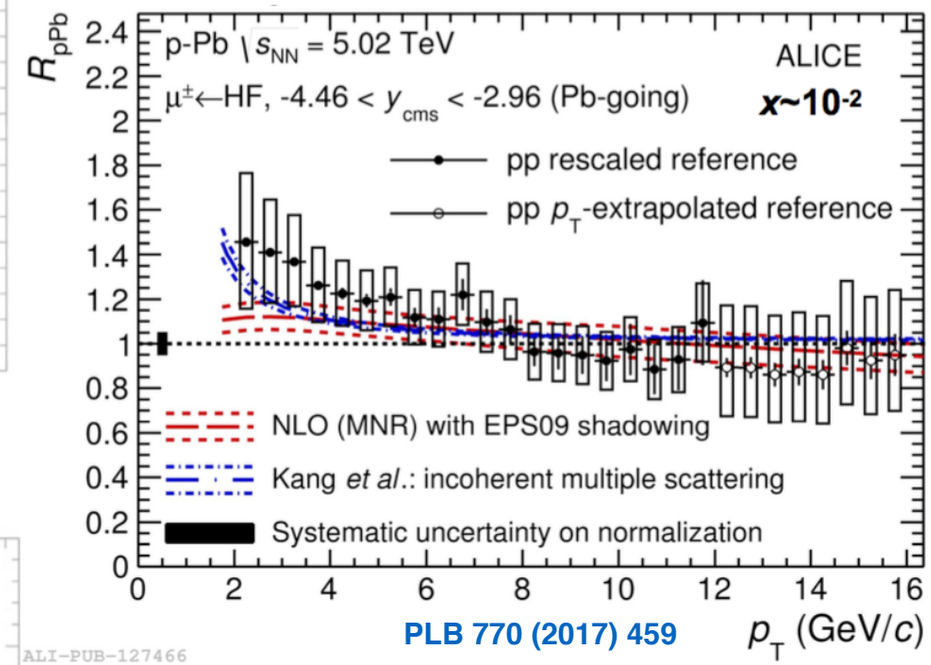
central rapidity





backward rapidity





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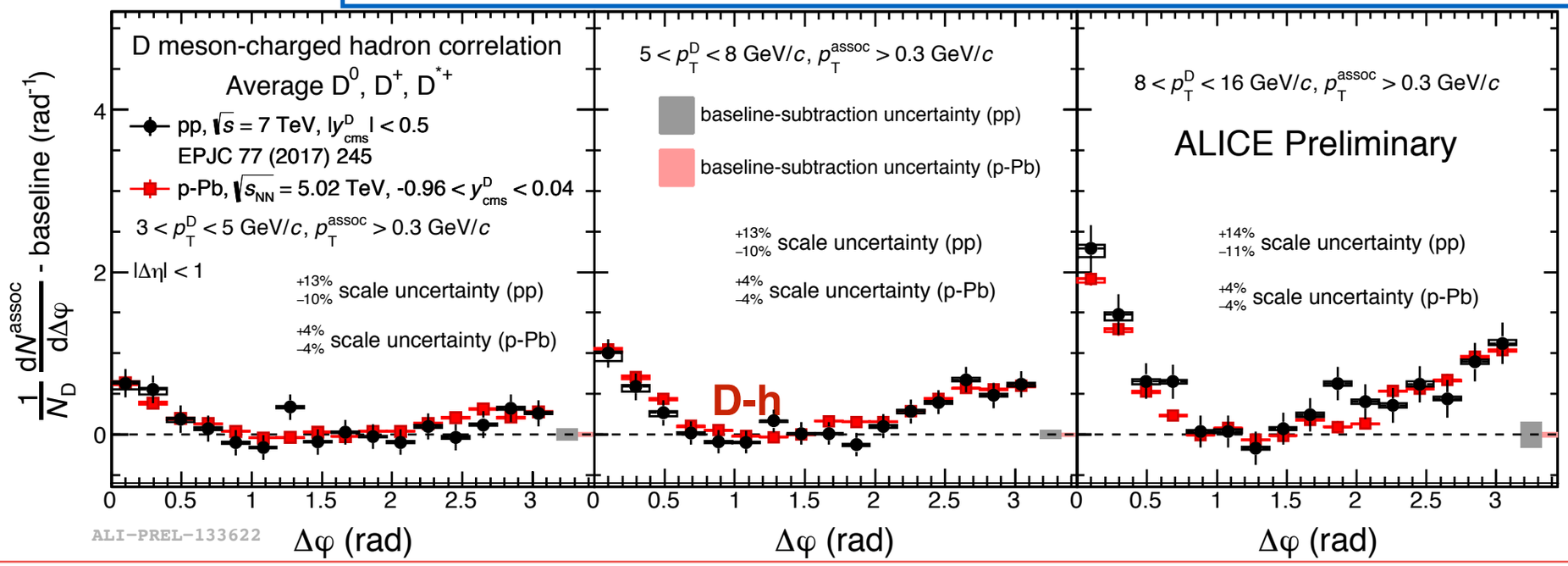
Different rapidity ranges allow access to different Bjorken-x regimes

- forward production consistent with no nuclear modification
- hint of enhancement at backward rapidity at low p_T
- described by models including CNM effects

D-hadron azimuthal correlations

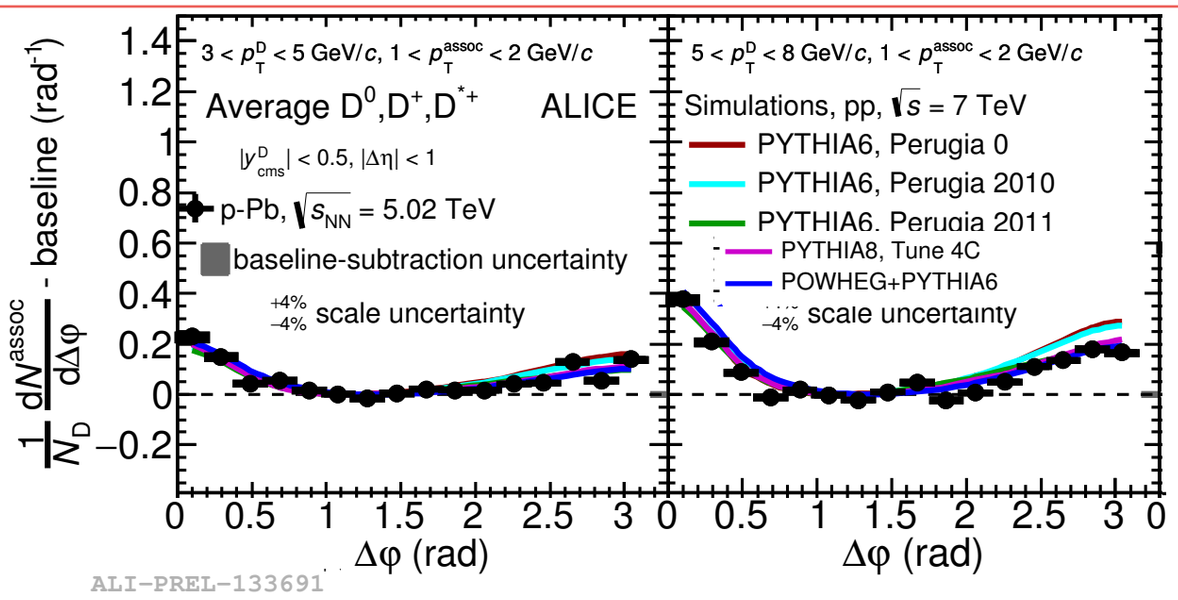
Azimuthal correlations of D mesons and HF decay electrons with charged particles access charm fragmentation and jet properties in presence of nucleus

News from RUN2



Very promising reference in view of Pb-Pb studies
Near side: modification of parton fragmentation
Away side: look for yield suppression, path-length dependence of energy loss

No modification observed in **p-Pb** compared to a **pp reference** after baseline subtraction



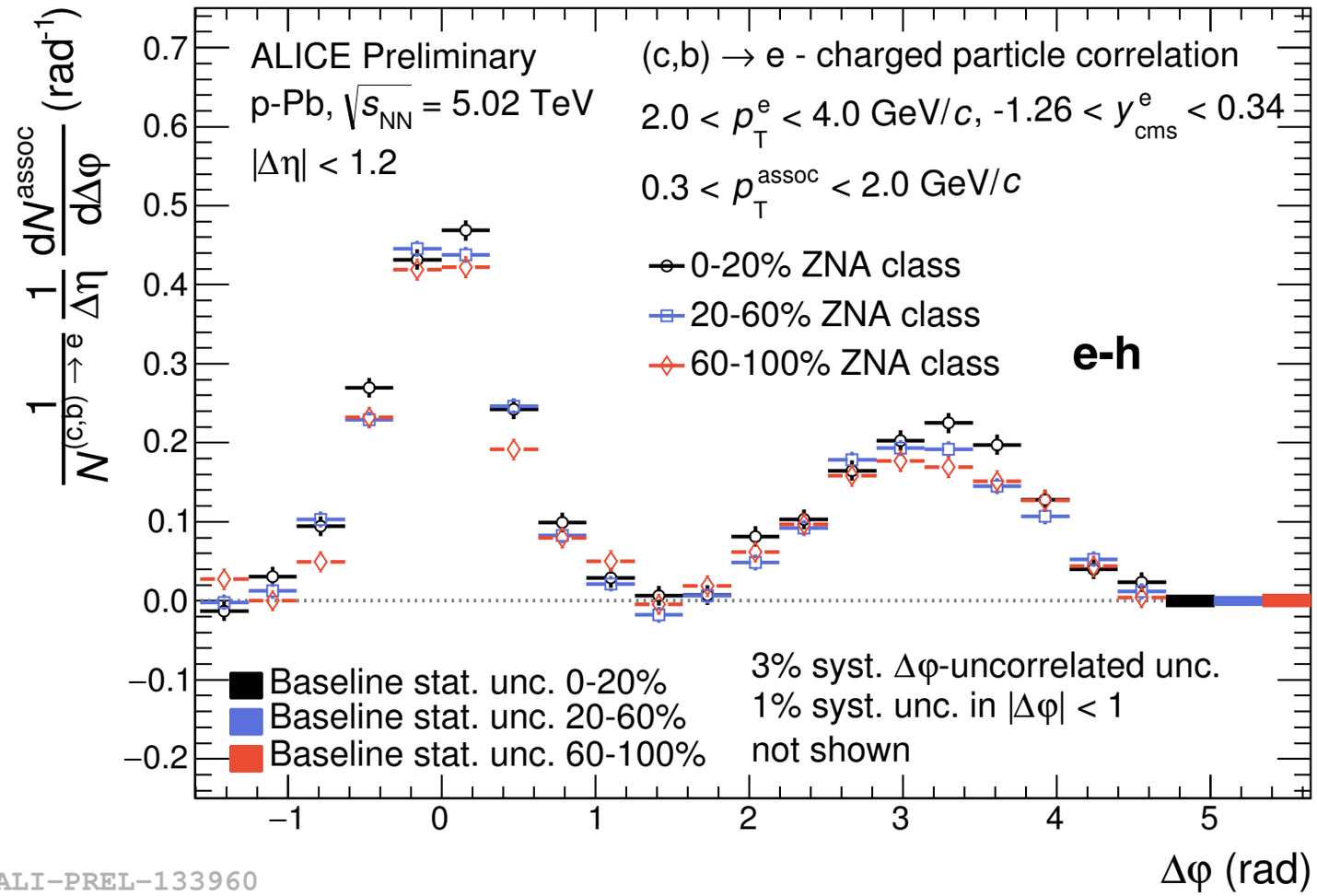
Run1 results:
EPJC (2017) 77: 245
Run2: significant increase of precision + access new p_T intervals (see backup)

Correlation distributions and their p_T trend well described by models

HFe-hadron azimuthal correlations

Azimuthal correlations of D mesons and HF decay electrons with charged particles access charm fragmentation and jet properties in presence of nucleus

News from RUN2



- distributions corrected for efficiencies
- electrons from background (main sources: gamma conversion and π^0 dalitz decays) subtracted with invariant mass technique

Increased statistics of Run-2 sample allows us to study **correlation in classes of centrality** (ZN slicing) and **look forward for possible flow modulation in central events** —> **stay tuned!**

Conclusions

ALICE results on open heavy-flavour production in p-Pb collisions at $\sqrt{s_{NN}}$ =5.02 TeV

- Compatible results with Run1 analysis, **better precision, extended p_T coverage**
- R_{pPb} of charm mesons, baryon and leptons **consistent with unity and models** including CNM
- **D R_{pPb} central values >1** in $2<p_T<12$ GeV/c and described by CNM; disfavour QGP models that predict a significant suppression at high p_T
- Multiplicity dependent measurement: **Q_{cp}>1** at 1.7σ 0-10%/60-100%. From initial- or final-state effects? radial flow in p-Pb?
- No significant difference between pp and p-Pb collisions for azimuthal correlations of D mesons with charged particles in minimum-bias p-Pb, precise measurement, good reference for next Pb-Pb runs

More differential measurements are ongoing
We are looking forward to the pp run at 5 TeV in December to perform a high-precision measurement of the pp reference

Backup

p-Pb collisions: event-activity estimator

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

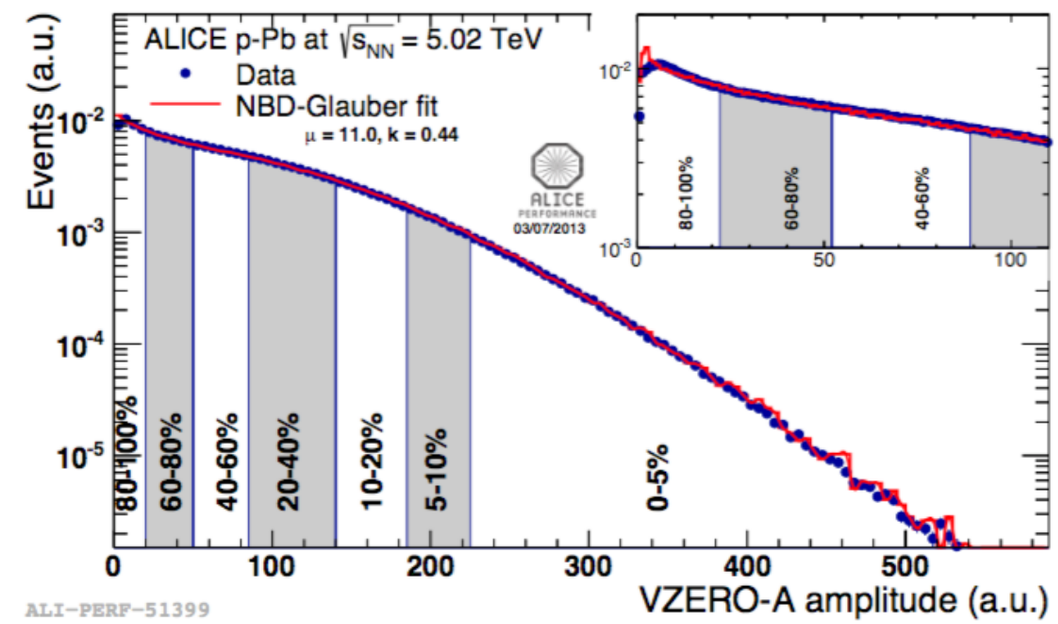
Experimentally:

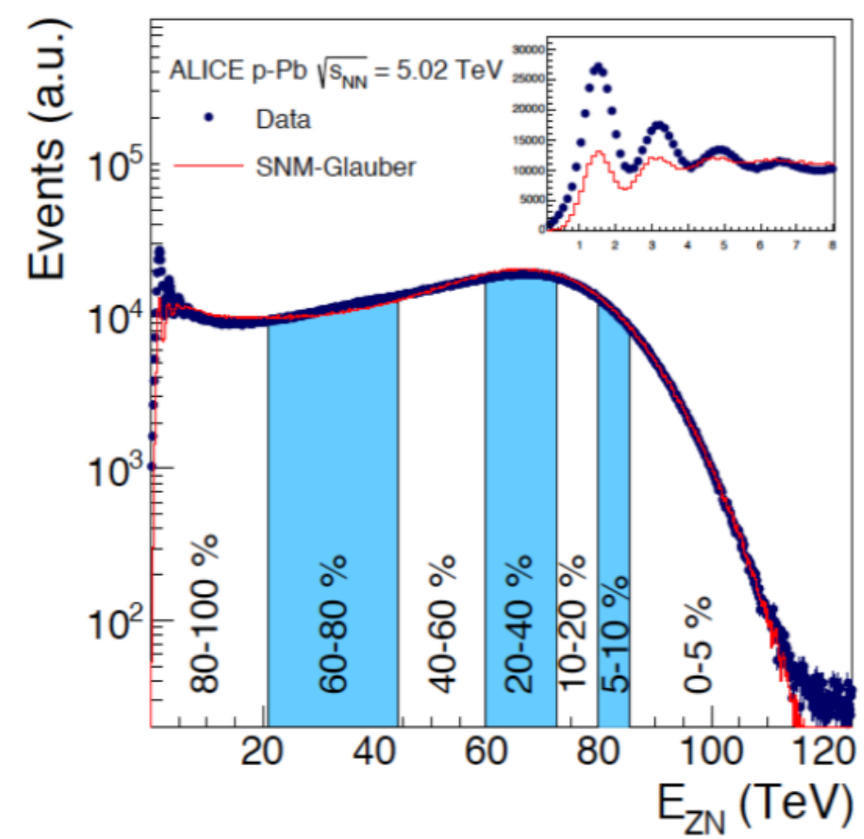
V0A: $\langle N_{coll} \rangle$ determined by Glauber fit of V0 amplitude

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

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



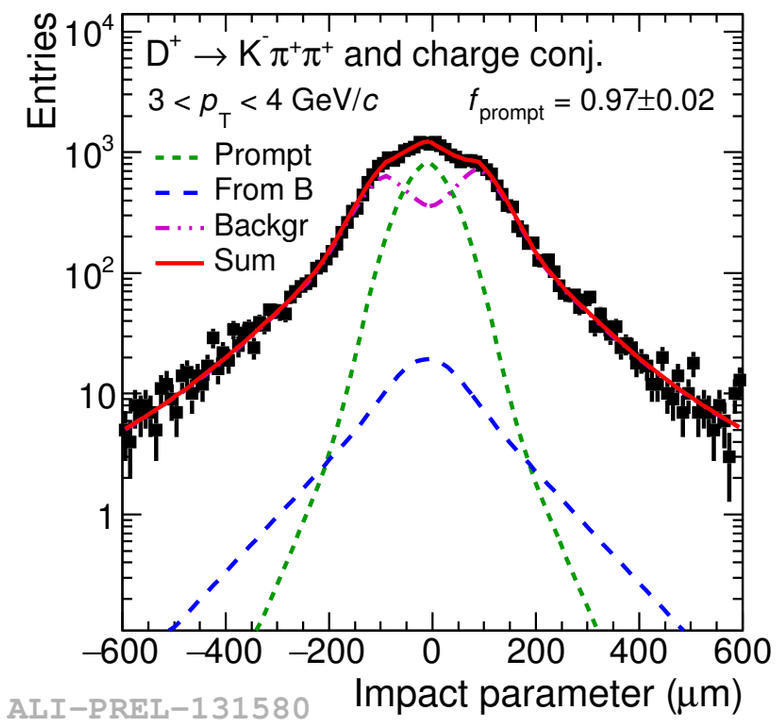


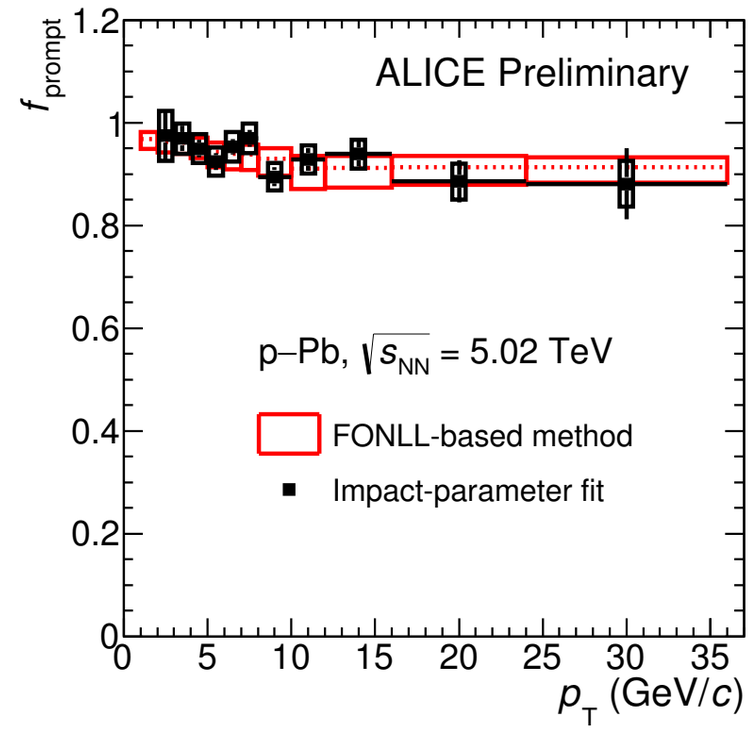
investigate charm production in p-Pb collisions w.r.t. pp collisions: possible multiplicity dependent modification of the p_T spectra in p-Pb?

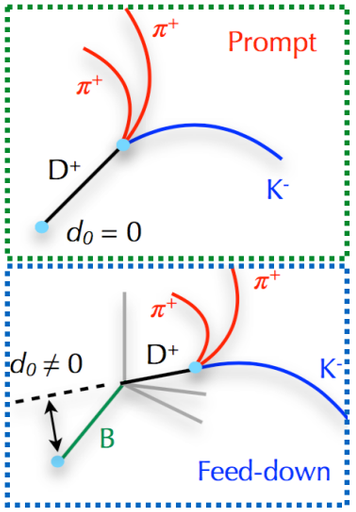
Feed down: data driven method

News from RUN2

ALICE-PUBLIC-2017-008







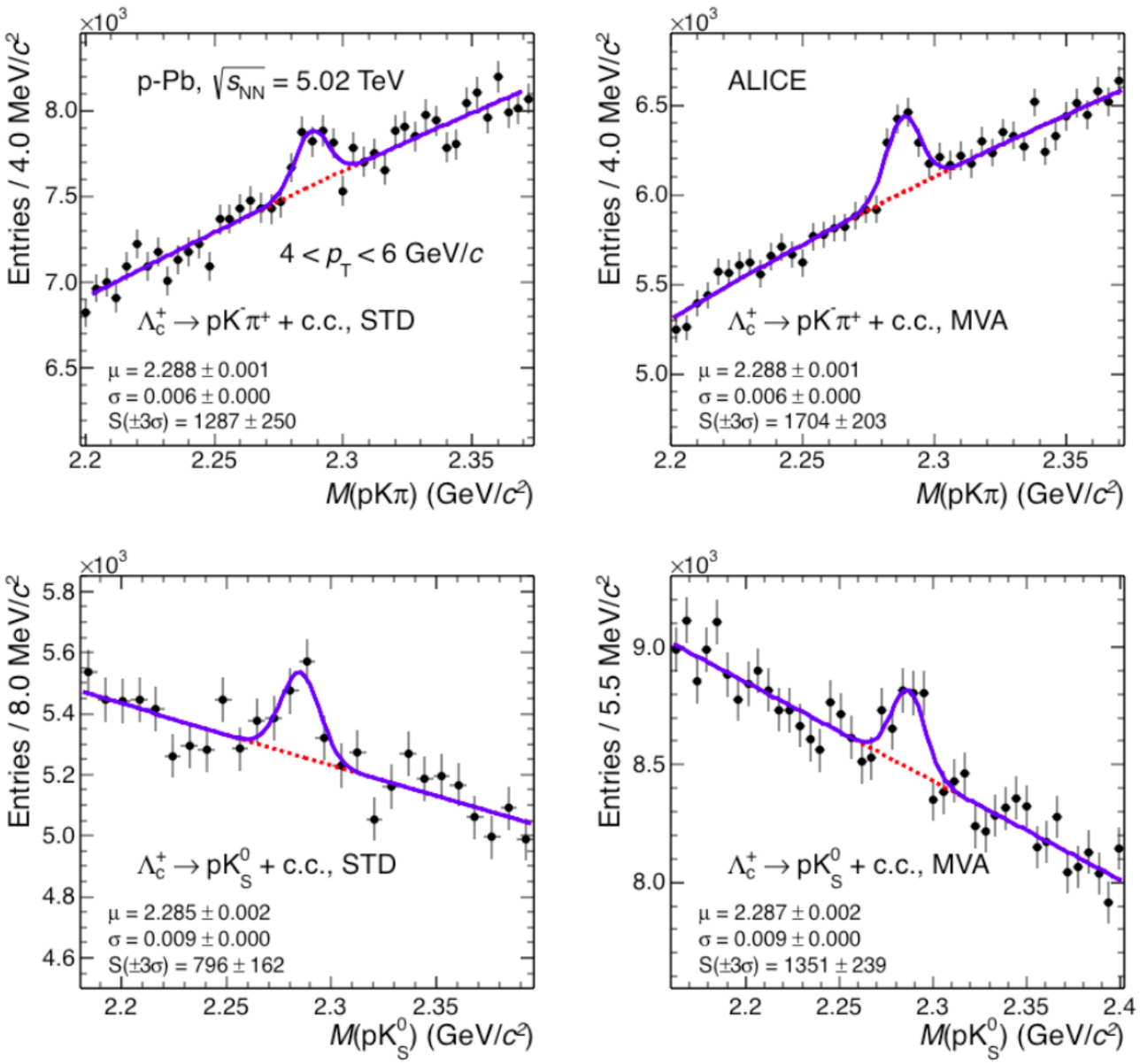
Measured raw yield includes **prompt D** and **feed-down D**

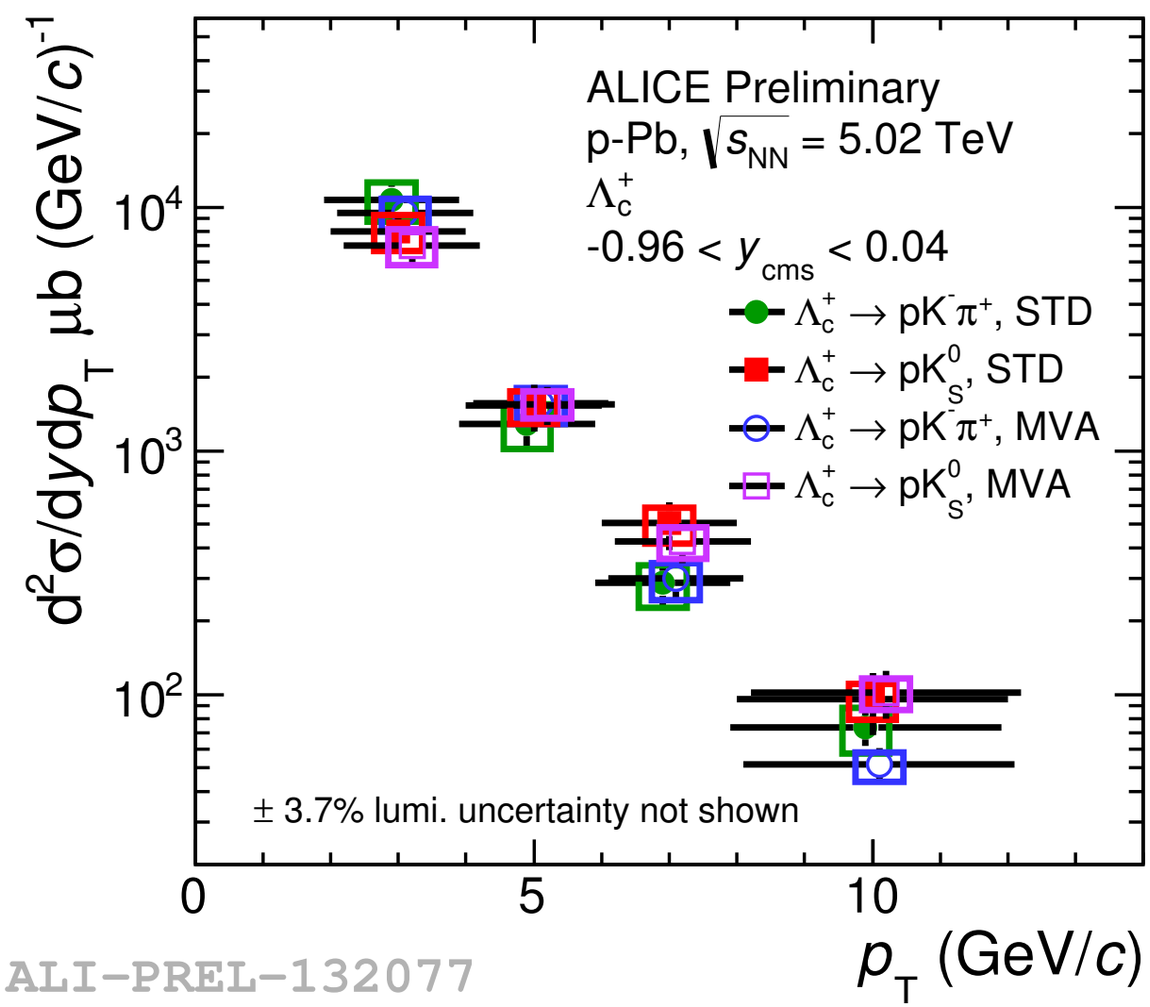
- Fraction of prompt D mesons usually estimated using theoretical predictions of production cross section for prompt and feed-down D mesons
- An alternative **data-driven approach** exploits the **different shape** of the distributions of the **transverse-plane impact parameter** to the primary vertex (***d*0**)
- **Fraction of prompt D+ measured** via an **unbinned log-likelihood fit** of the ***d*0 distributions** of D+ candidates in the invariant-mass region of the signal

Agreement between data driven method and FONLL-based method.

Comparable uncertainties $3<p_T<16$ GeV/c

Λ_c signal extraction in p-Pb





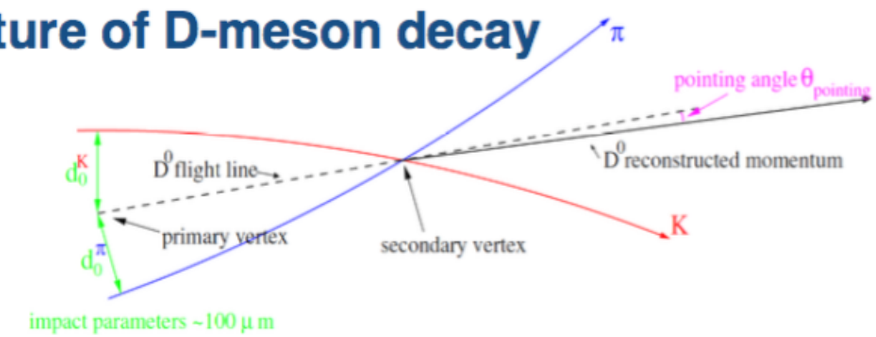
D-meson reconstruction

full reconstruction of D meson hadronic decays at mid rapidity

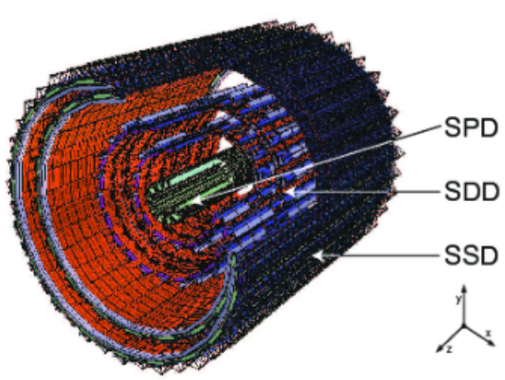
- signal extraction through invariant mass analysis
- particle identification to reduce combinatorial background

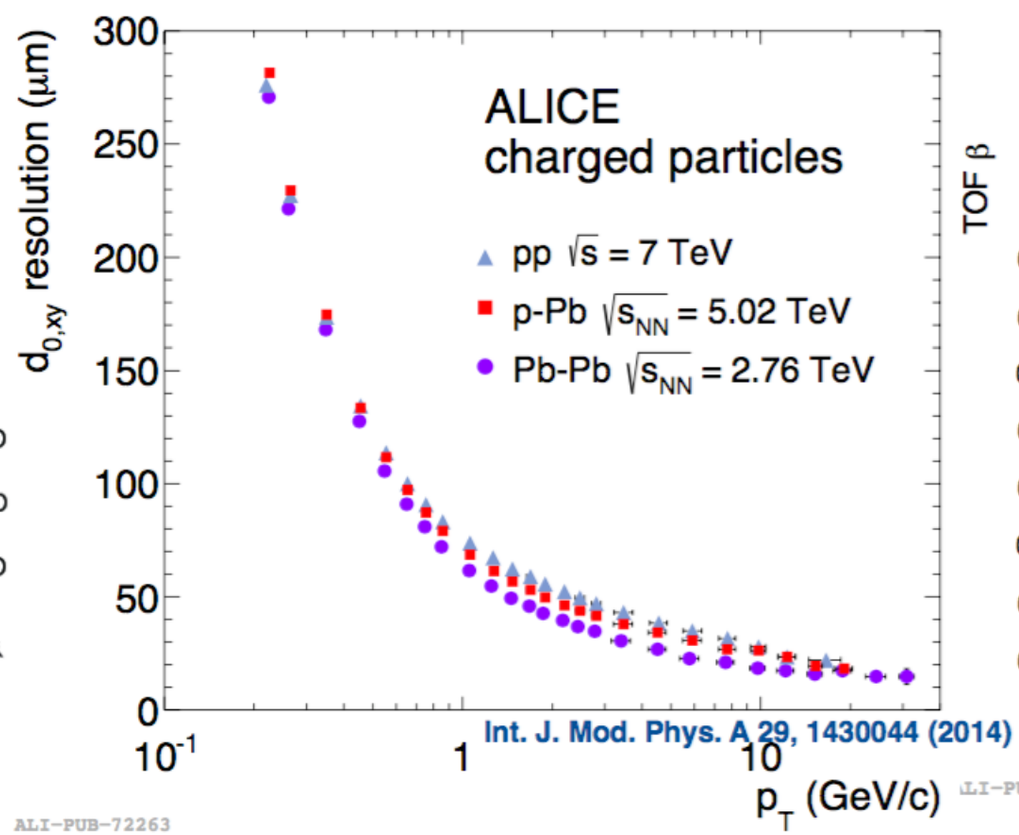
cτ ~100-300 μm: **displaced decay vertex is a signature of D-meson decay**

tracking and vertexing precision
crucial for heavy-flavour analysis



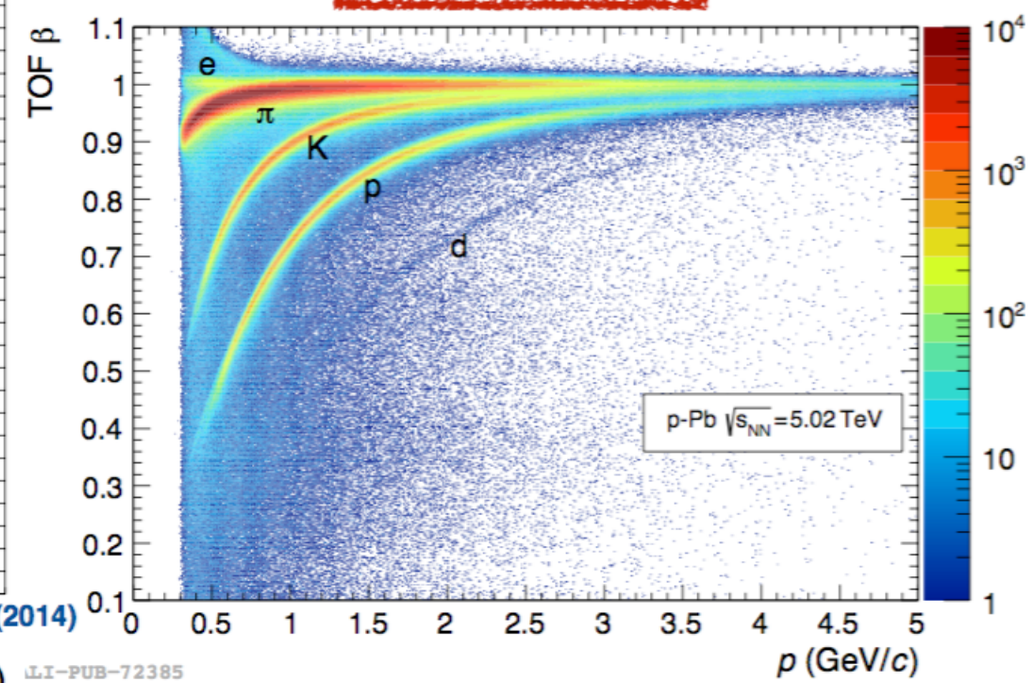
ITS: vertexing, tracking
|η|<0.9





Int. J. Mod. Phys. A 29, 1430044 (2014)

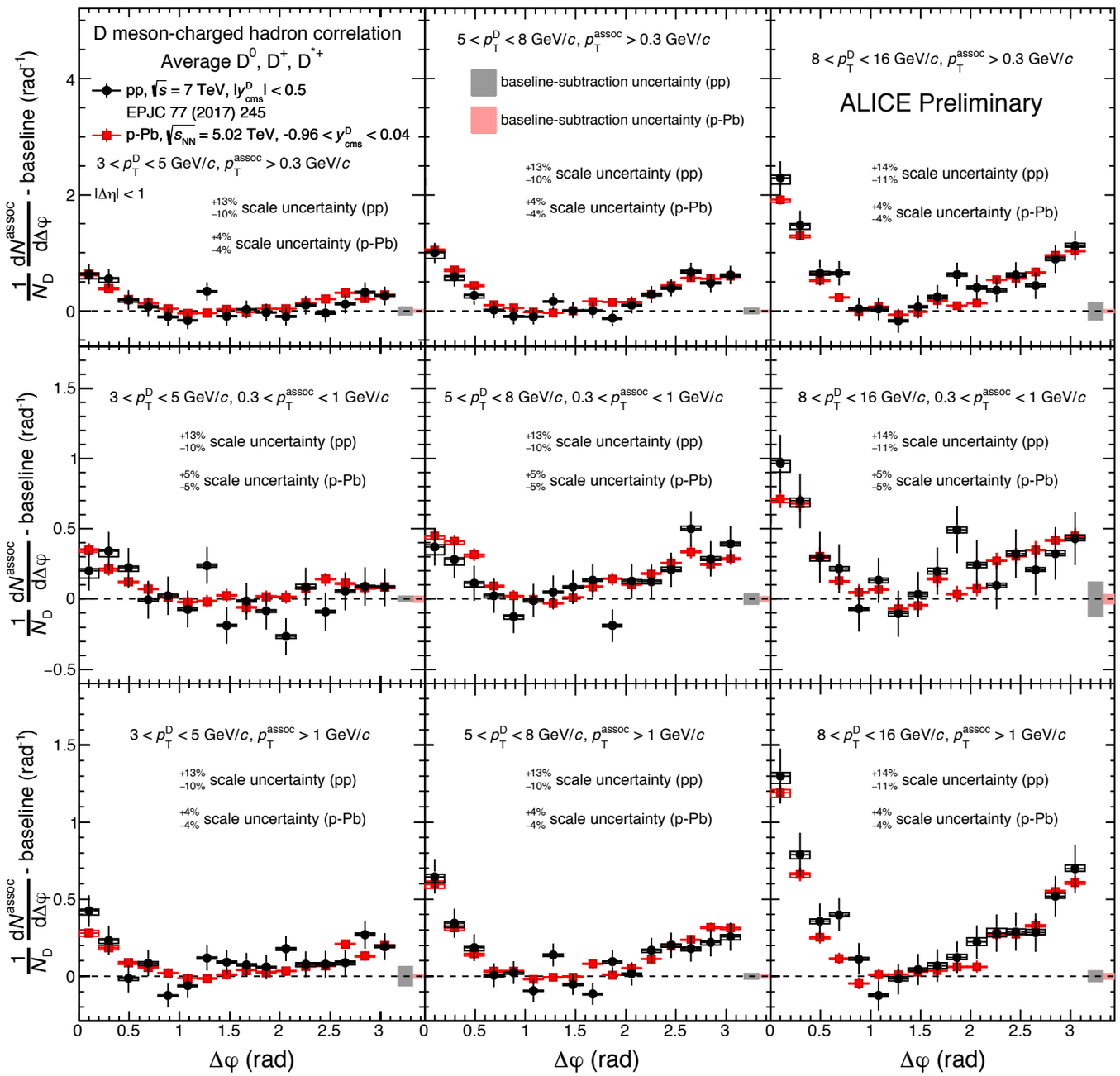
TOF: PID |η|<0.9



D-hadron azimuthal correlations

Azimuthal correlations of D mesons and HF decay electrons with charged particles access charm fragmentation and jet properties in presence of nucleus

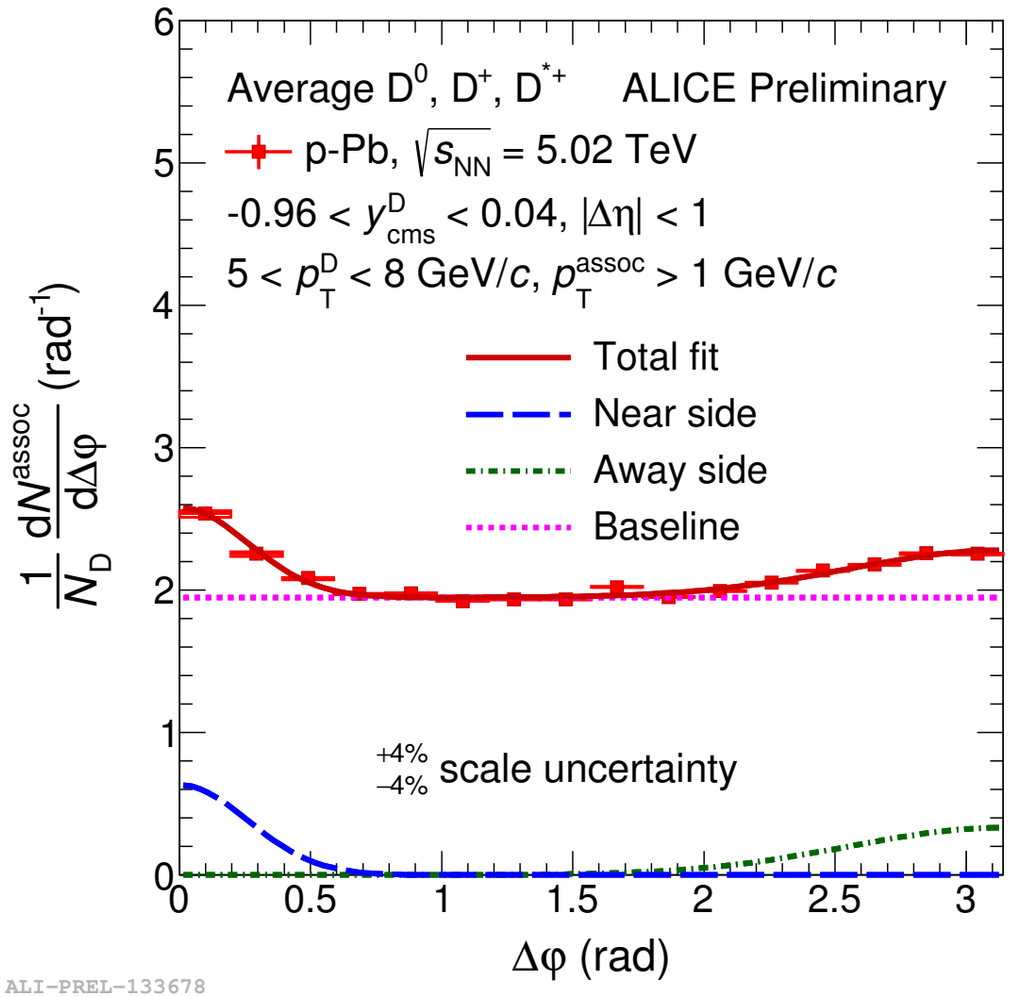
News from RUN2



Very promising reference in view of Pb-Pb studies
Near side: modification of parton fragmentation
Away side: look for yield suppression, path-length dependence of energy loss

Run1 results:
EPJC (2017) 77: 245
Run2: significant increase of precision + access new p_T intervals

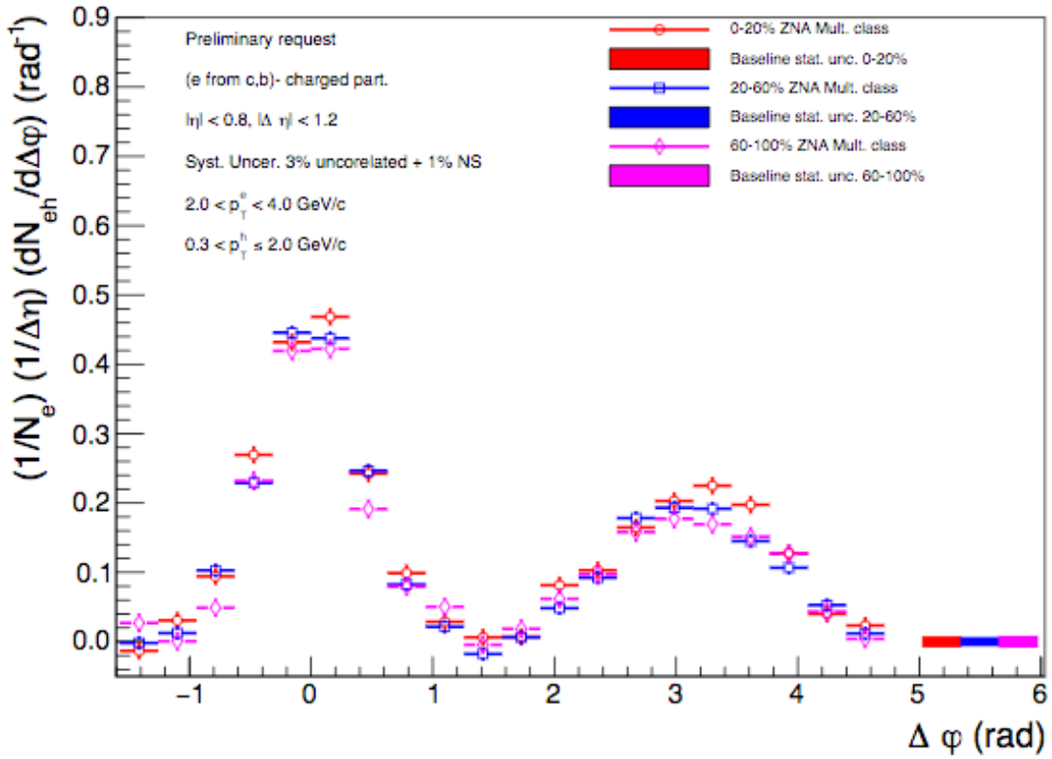
D-hadron azimuthal correlations



Quantitative observables extracted from the fit:

- Near-side yield
- Near-side width
- Baseline value

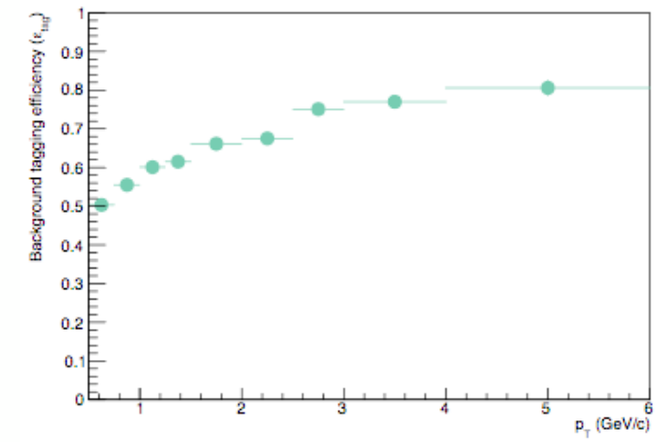
e-hadron azimuthal correlations

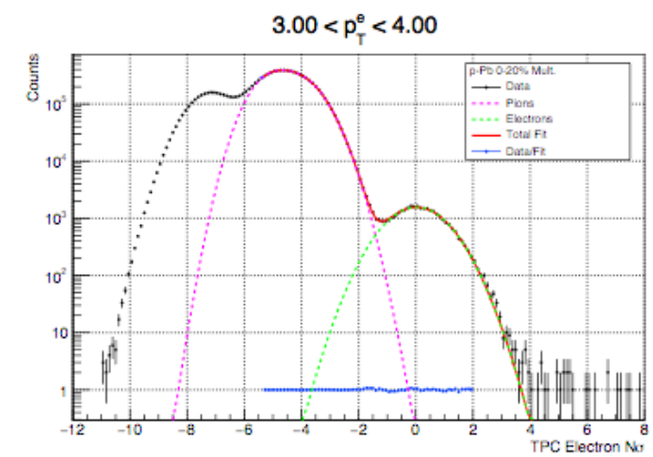


Tagging efficiency

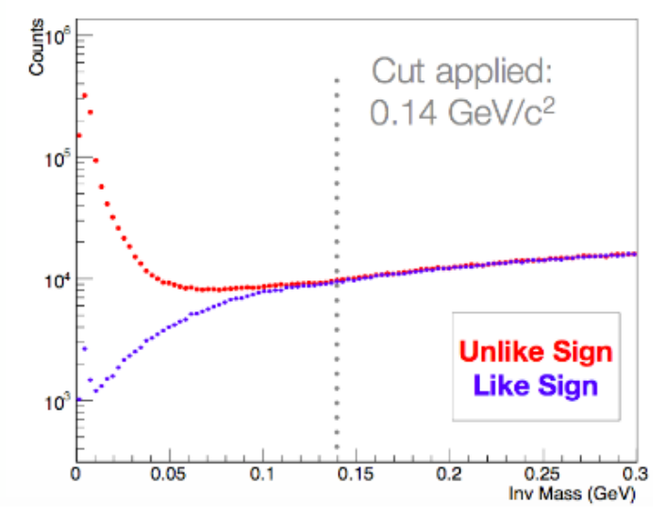
TPC Nσ fits used for hadron contamination estimation

Invariant mass





- Main background sources are electrons from π^0 and η (Photon conversions in the detector material and Dalitz decays)
- Background subtraction is performed using the invariant mass method: pair with low invariant mass are selected (<140 MeV/c^2). Like sign pairs are used to subtract the combinatorial background



HFe-hadron azimuthal correlations

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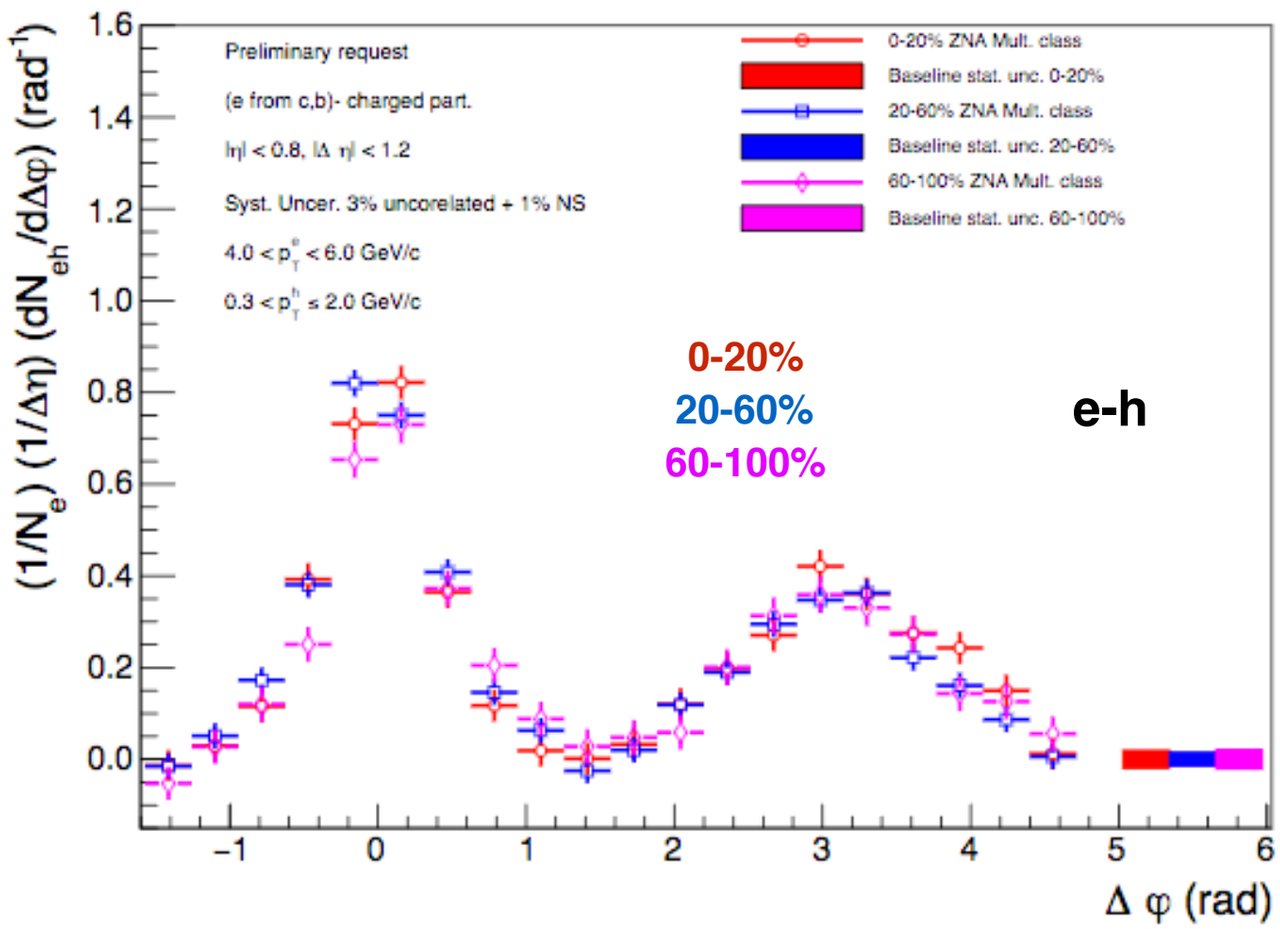
News from RUN2



- distributions corrected for efficiencies
- electrons from background (main sources: so called “photonic”) subtracted with invariant mass technique

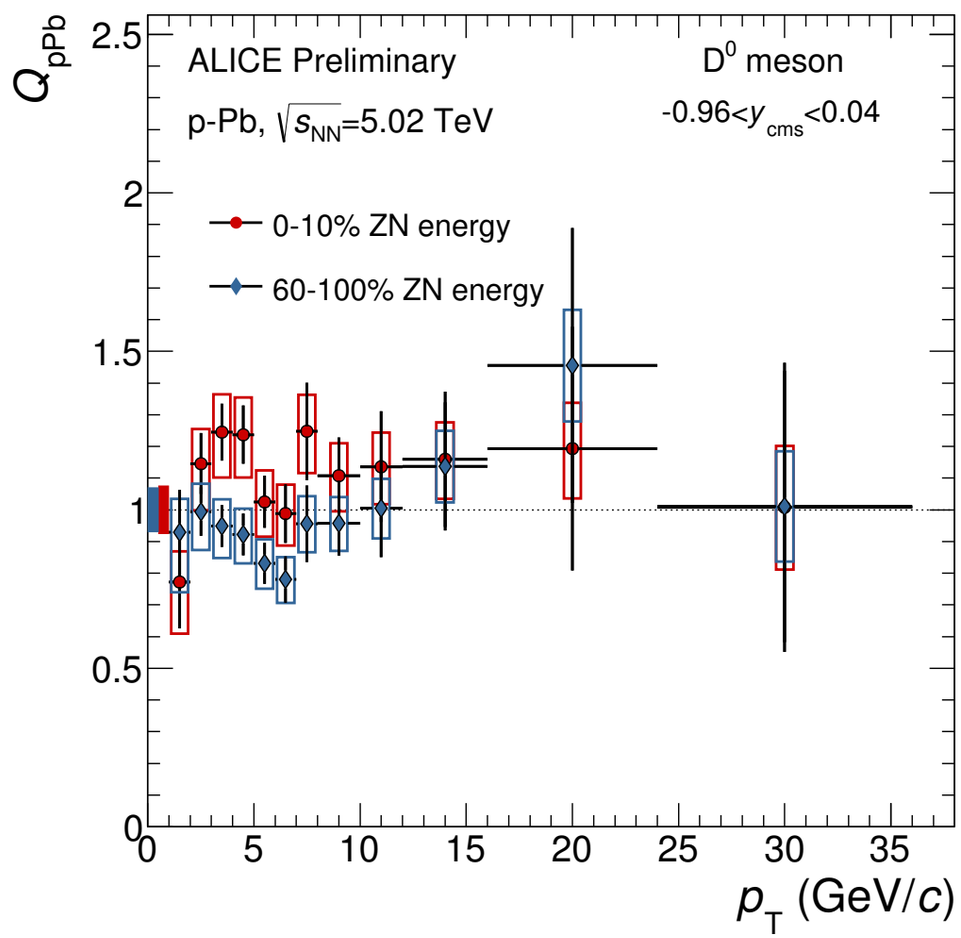
Increased statistics of Run-2 sample allows us to study **correlation in classes of centrality** (ZN slicing) and **look forward for possible flow modulation in central events** —> **stay tuned!**

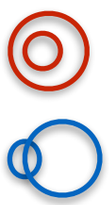
D-meson production vs multiplicity

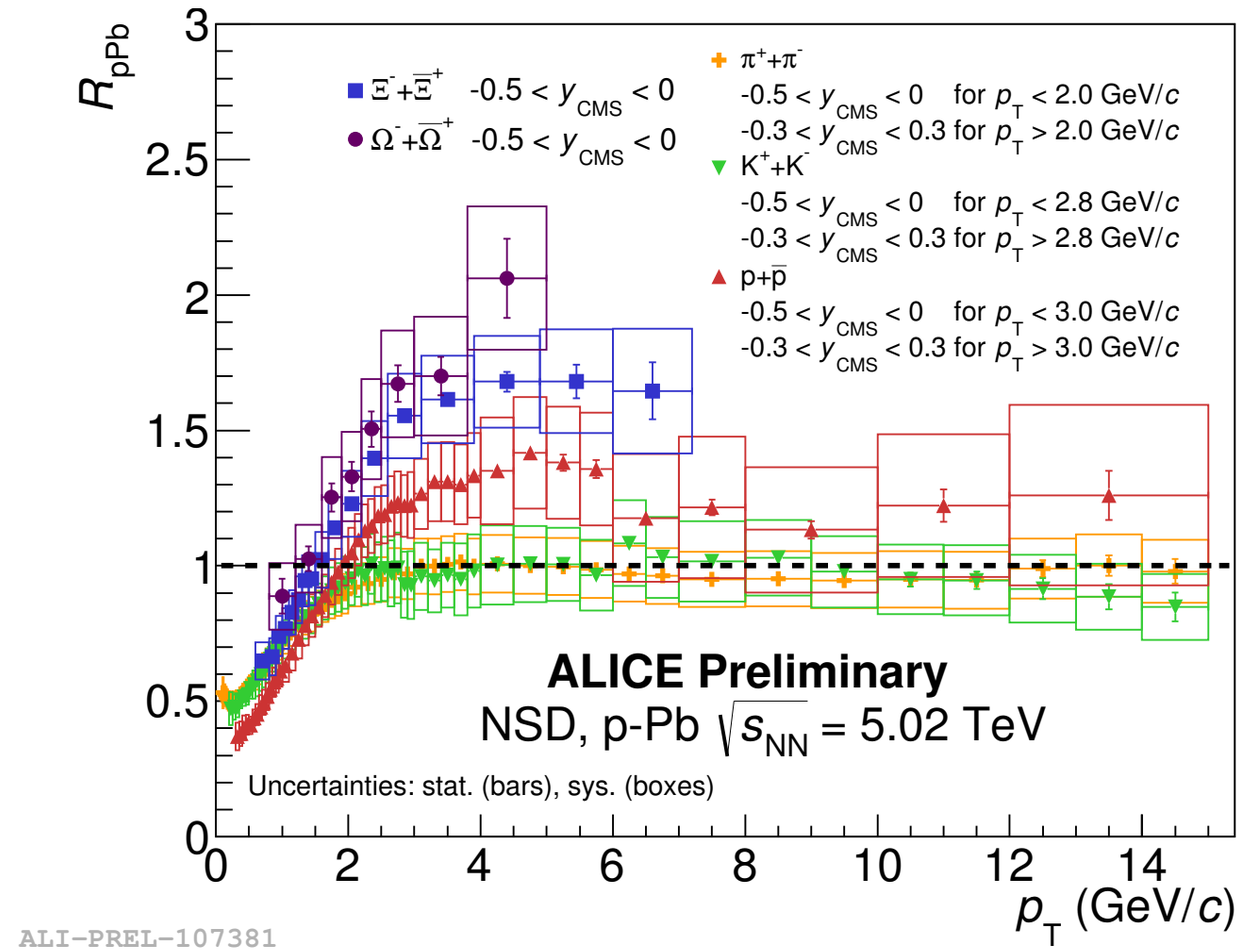
Centrality determination in p-Pb
Phys. Rev. C 91 (2015) 064905

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

News from RUN2







Classes obtained slicing the energy deposited in neutron calorimeter on Pb-going side (ZNA)
Most central (0-10%) and peripheral (60-100%) centrality ranges are compatible within uncertainties and compatible with unity

***R_{pPb}* of of primary charged** π, K, p and multi-strange baryons Ξ and Ω at mid-rapidity measured in p–Pb collisions at √ sNN = 5.02 TeV:

- hint of mass dependence of the R_{pPb}