Open-heavy-flavour production and elliptic flow in p-Pb collisions at the LHC with ALICE

Cristina Terrevoli
for the ALICE Collaboration
University of Houston

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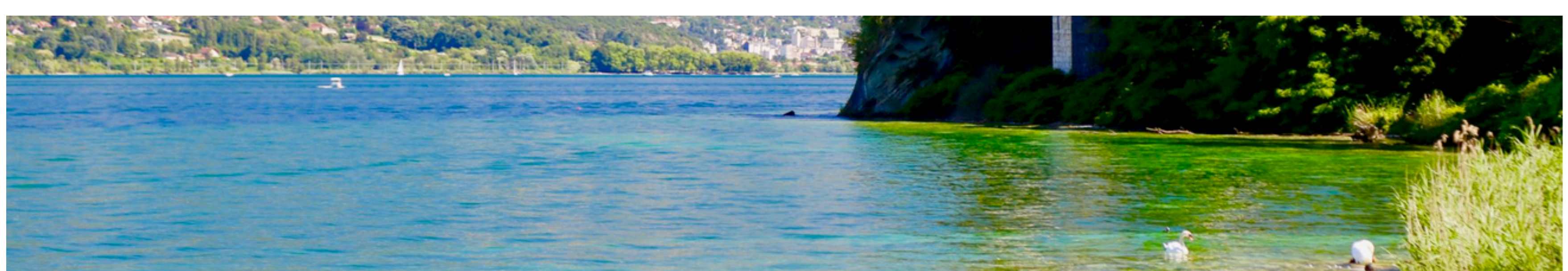
Aix-Les-Bains



Open heavy flavour in p-Pb collisions

ALICE

Heavy quarks effective probes of the Quark-Gluon Plasma in Pb-Pb collisions

Interpretation of Pb-Pb measurements
→ understanding of **cold nuclear matter (CNM) effects** in initial and final state
➡ **constrain them by studying p-Pb collisions**

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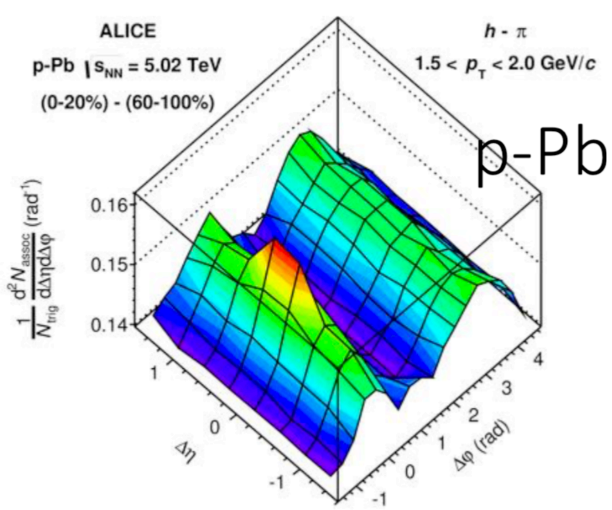
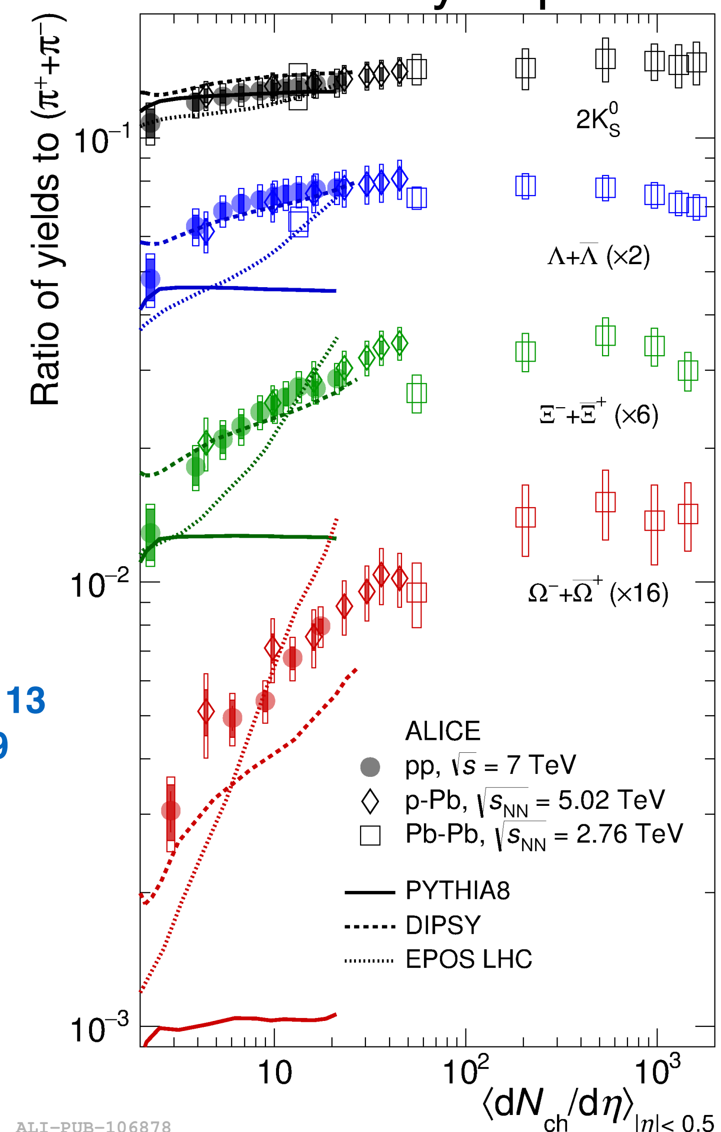
p-Pb collisions not only reference for CNM effects:
in high multiplicity p-Pb collisions, effects typically observed in A-A collisions
- ex. in the light flavour sector: long-range v_2-like angular correlations, enhancement of baryon production

Phys. Lett. B 726 (2013) 164-177



open questions:
- collective effects in high-multiplicity p-Pb events ?
- final-state effects also in p-Pb collisions?
- small-size QGP?

Nature Physics 13 535–539 (2017)



Open heavy flavour in p-Pb collisions

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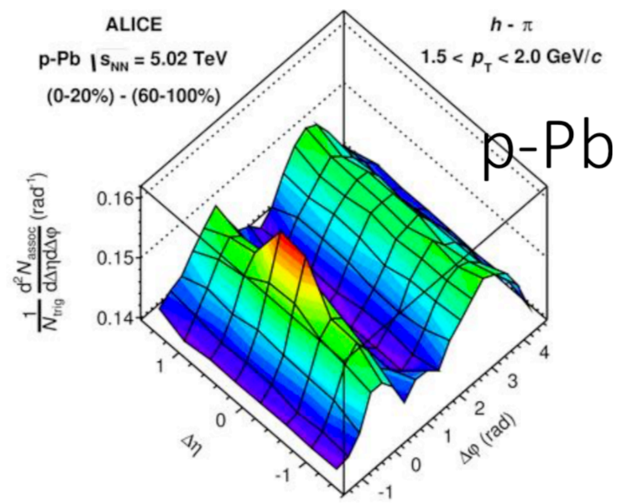

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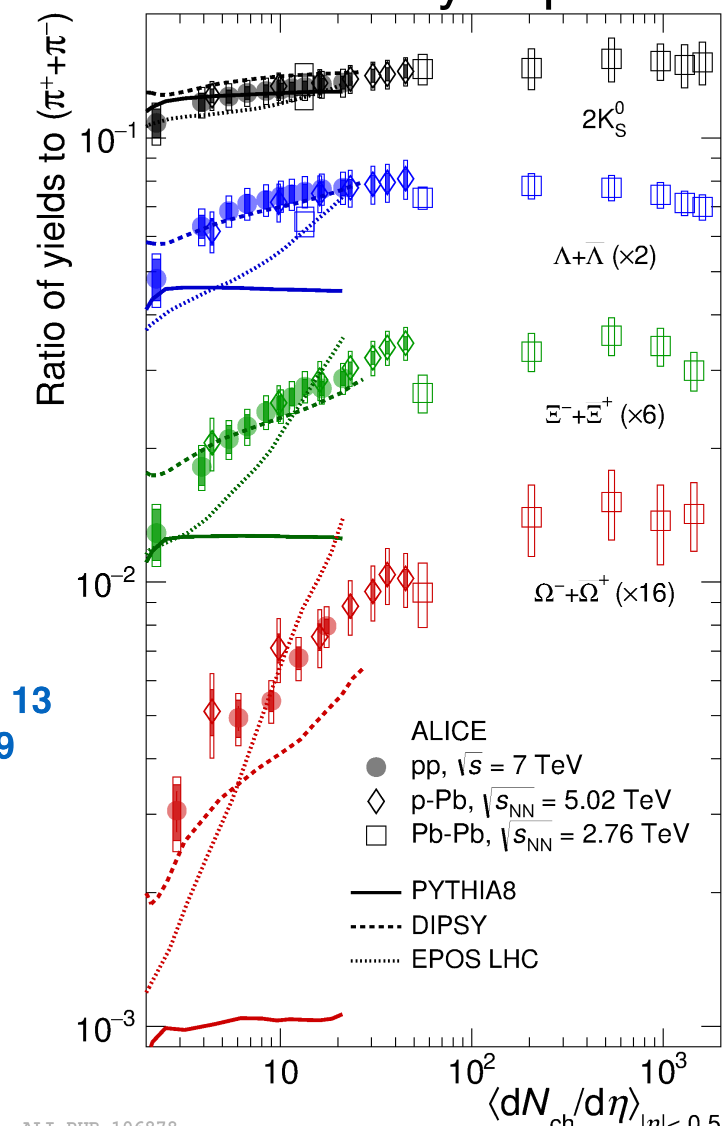


similar observations in the heavy-flavour sector?
News: more differential measurements to investigate high multiplicity p-Pb collisions

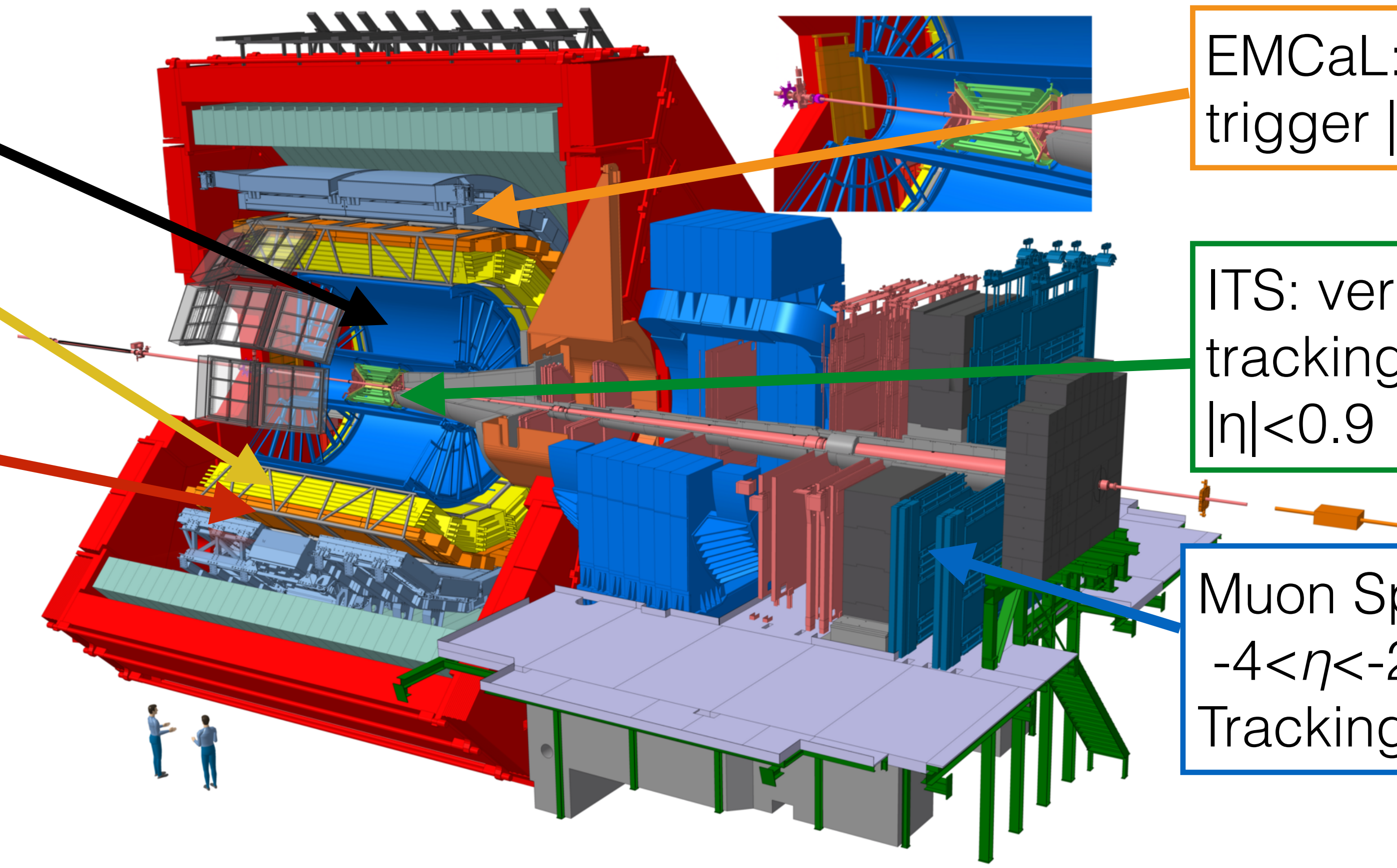
Open heavy-flavour reconstruction in ALICE

TPC: tracking, PID $|\eta|<0.9$

TRD: eID $|\eta|<0.9$

TOF: PID $|\eta|<0.9$

V0, ZDC: trigger and event characterization



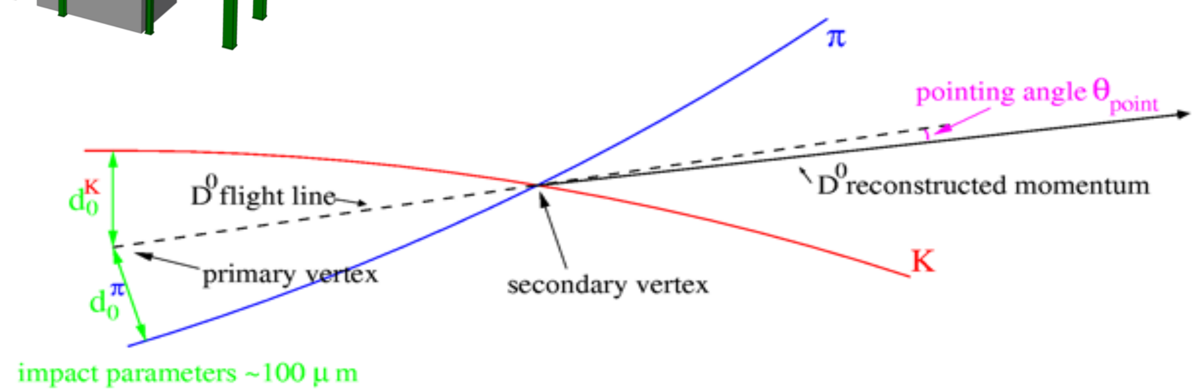
EMCaL: eID, trigger $|\eta|<0.7$

ITS: vertexing, tracking and PID $|\eta|<0.9$

Muon Spectrometer: $-4<\eta<-2.5$ Tracking, Trigger, μID

Fully reconstructed **D mesons and Λ_c** hadronic decays: **ITS**, **TPC**, **TOF**

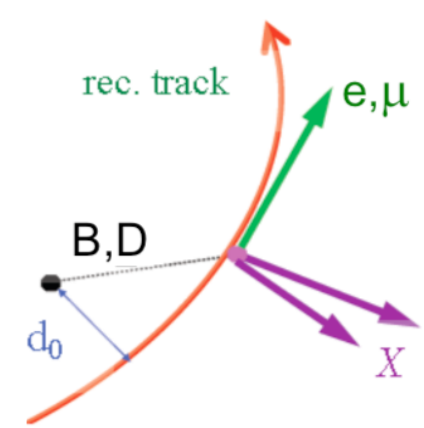
$D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D^{*+} \to D^0\pi^+$, $D_s^+ \to \Phi\pi^+ \to K^-K^+\pi^+$, $\Lambda_c^+ \to \pi^+K^-p$, $\Lambda_c^+ \to pK^0_s$



Partially reconstructed **semi-leptonic decays**

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

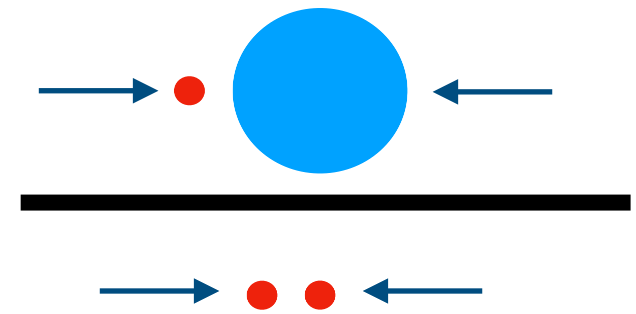
Electrons: **ITS**, **TPC**, **TOF**, **EMCAL**, **TRD**. D, B → $e^\pm$ + X

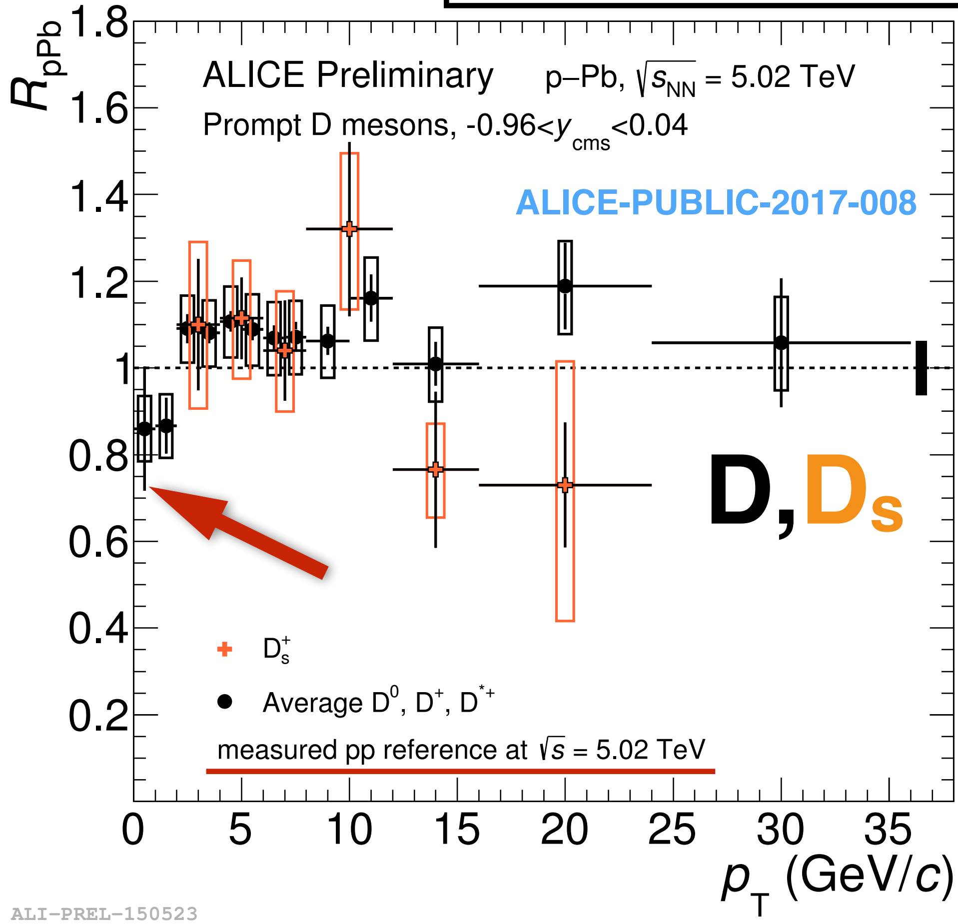


Nuclear modifications in p-Pb collisions

Nuclear Modification Factor: D-meson R_{pPb}

$$R_{pPb} = \frac{1}{A} \frac{d^2\sigma^{prompt\,D}_{pPb}/dp_T dy}{d^2\sigma^{prompt\,D}_{pp}/dp_T dy}$$





R_{pPb} compatible with unity within uncertainties

pp reference measured at 5.02TeV (NEW!)

ALICE-PUBLIC-2018-006

- D^0 measured down to $p_T = 0$:
  - improved precision due to new reference
- D_s R_{pPb} compatible with **averaged non-strange D mesons**

Nuclear Modification Factor: D-meson, Λ_c R_{pPb}

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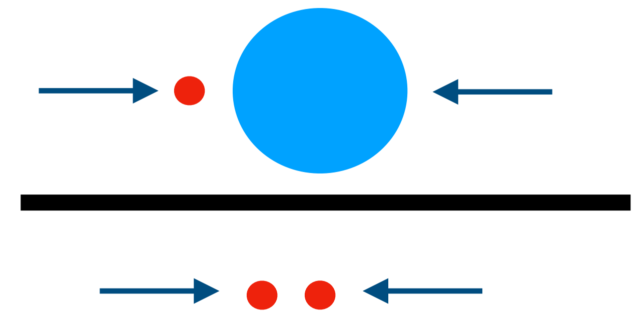

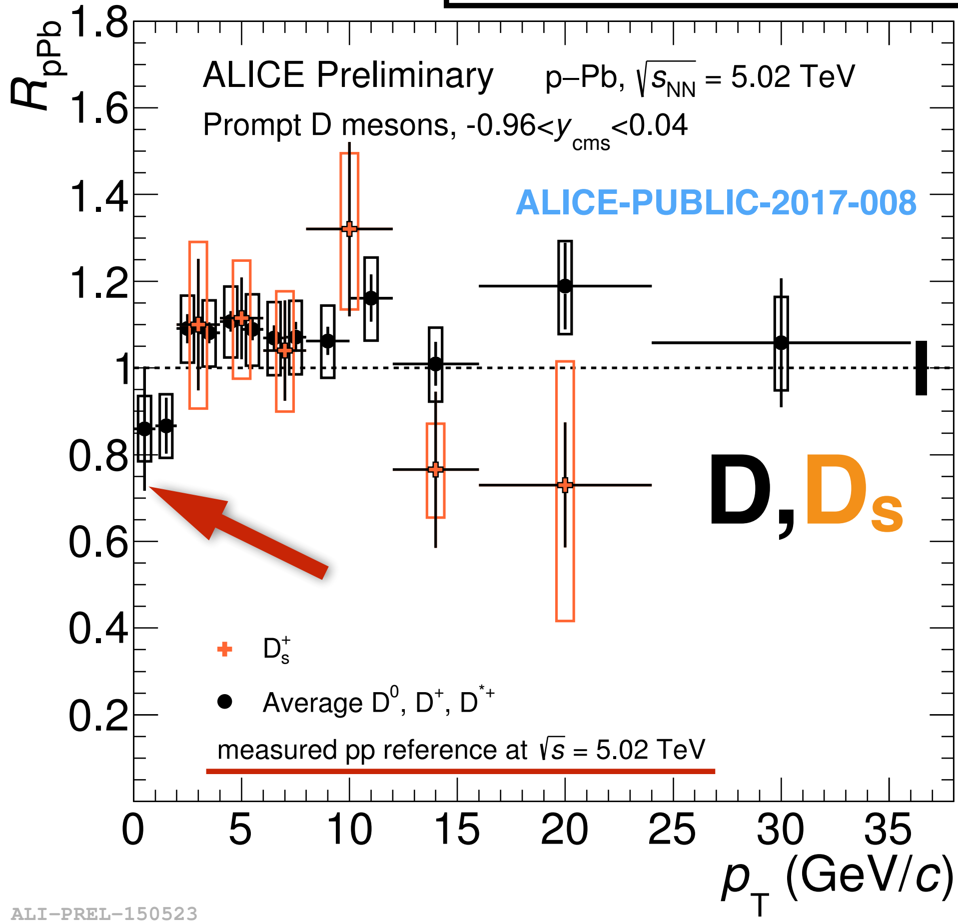

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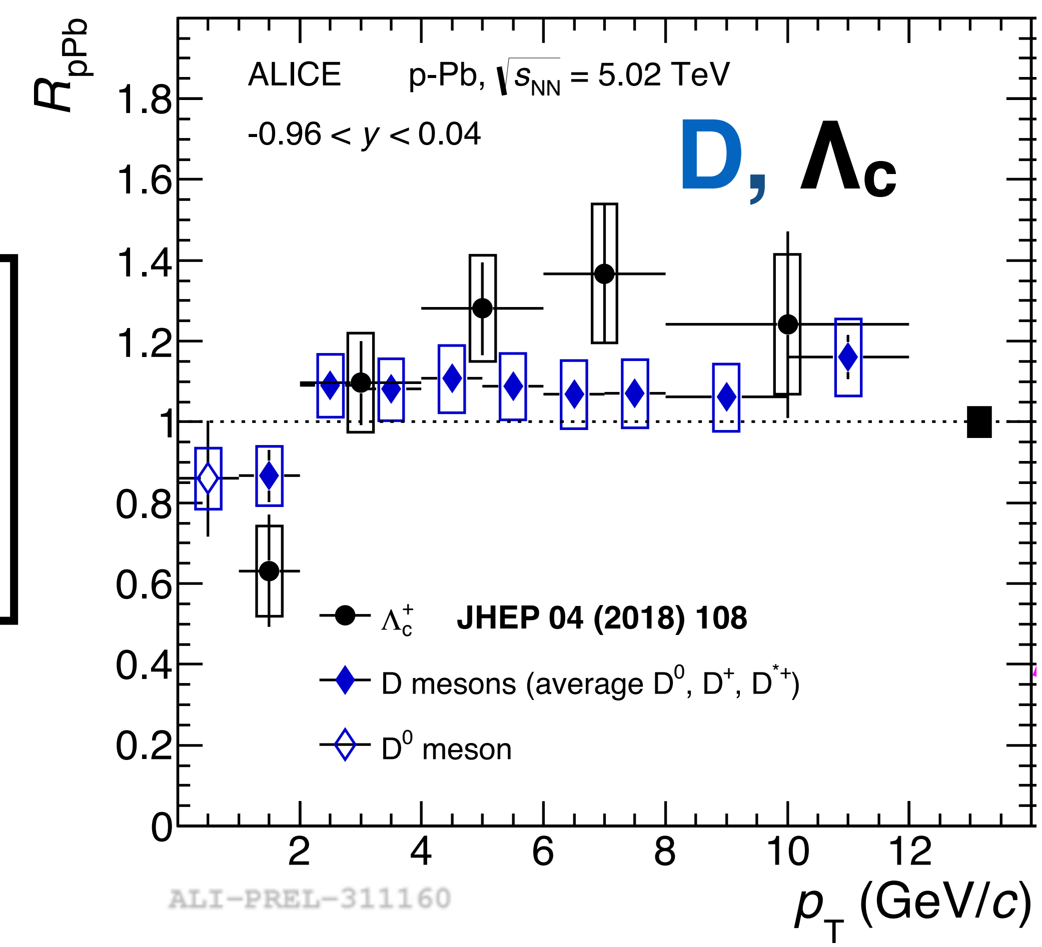


pp reference scaled from 7 TeV
Eur.Phys.J. C77 (2017) 550

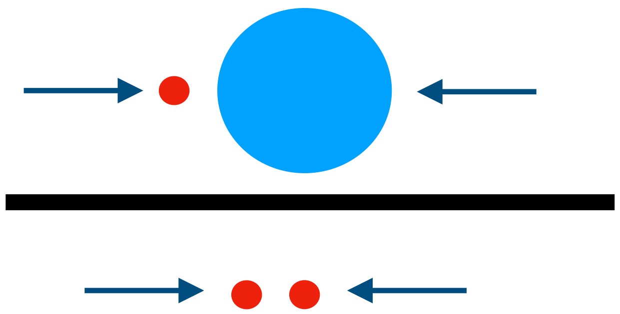
- **D^0 measured down to $p_T = 0$:**
  - **improved precision due to new reference**
- **D_s R_{pPb}** compatible with **averaged non-strange D mesons**

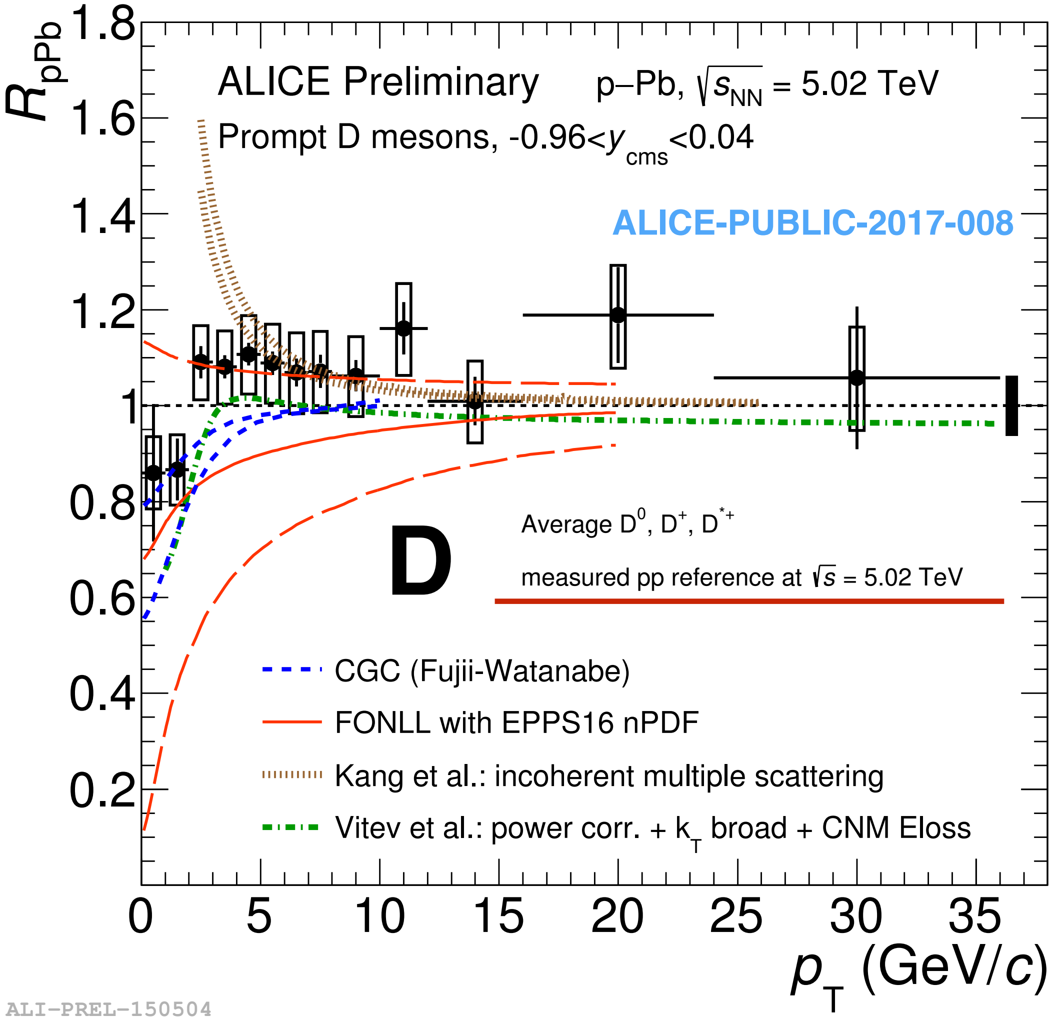
charmed baryon **Λ_c R_{pPb}** compatible with **D-meson R_{pPb}** and consistent with unity within uncertainties

Baryon measurements: E.Meninno's Talk

Nuclear Modification Factor: D-meson R_{pPb} vs models

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





- **Models** including **CNM effects only** are compatible with data
- a model including **incoherent multiple scattering** describes data within uncertainties for p_{T}> 5 GeV/c

Nuclear Modification Factor: D-meson R_{pPb} vs models

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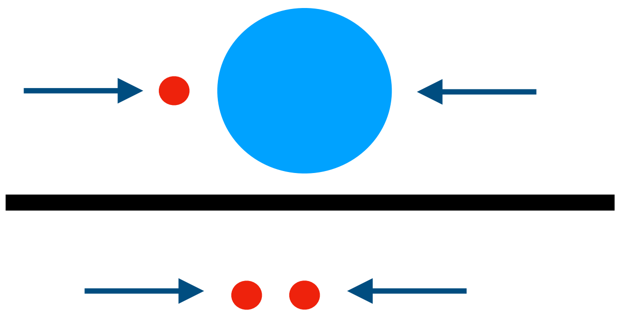

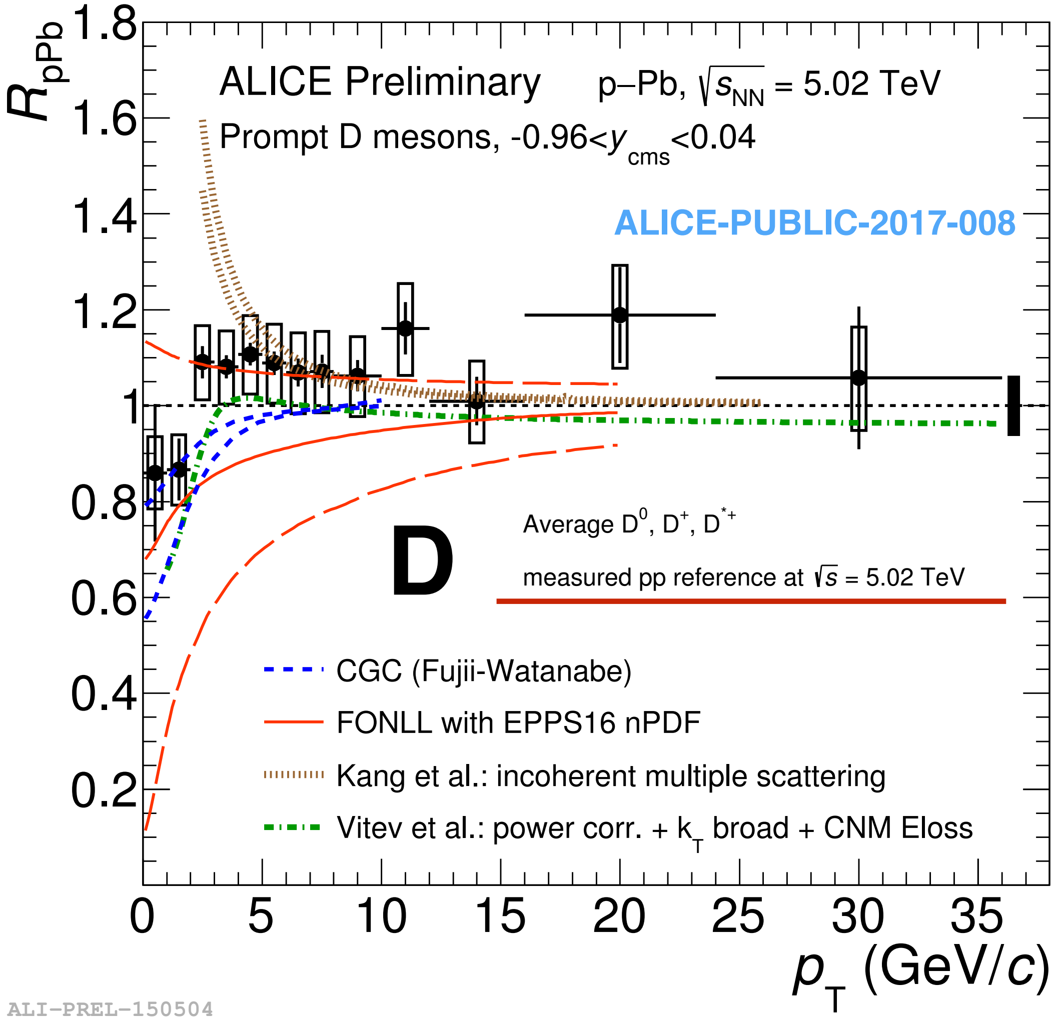

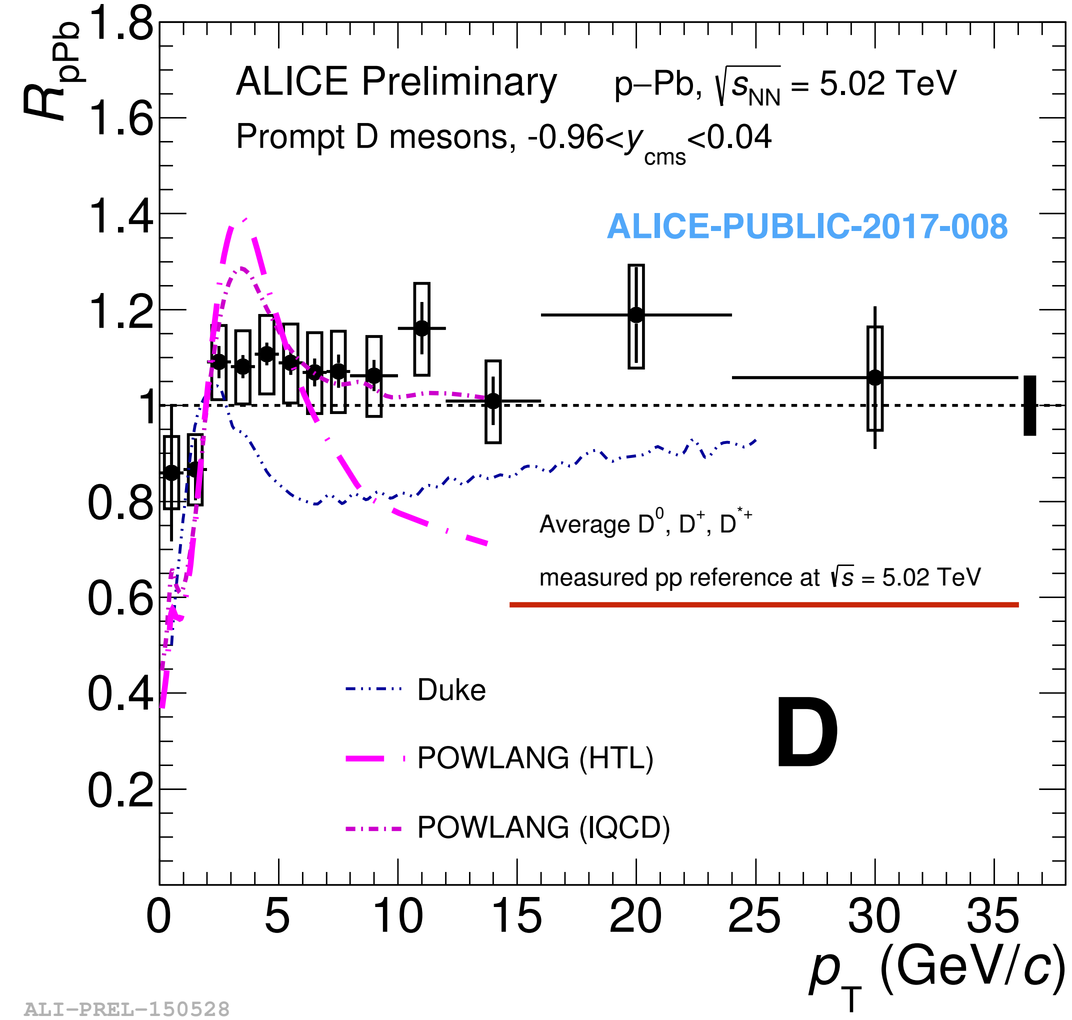

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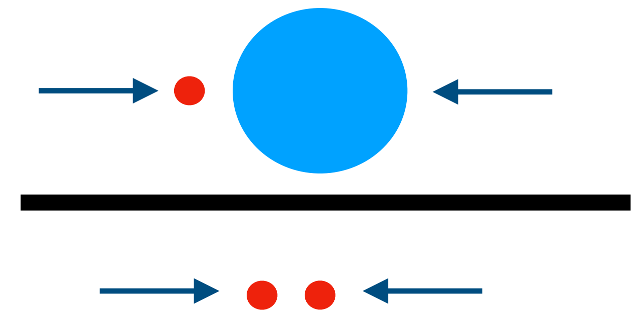
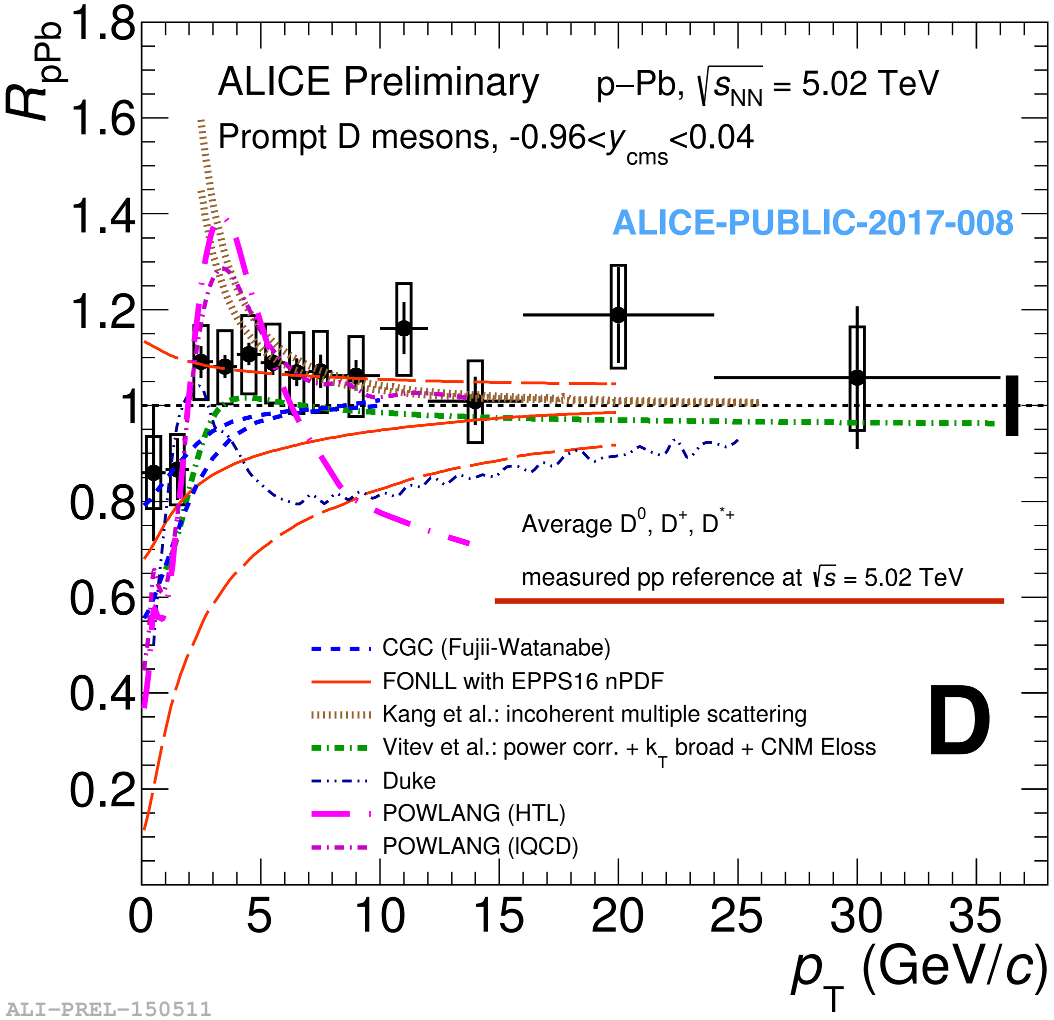
Models including **QGP formation** in p-Pb collisions can describe data up to p_T~6 GeV/c

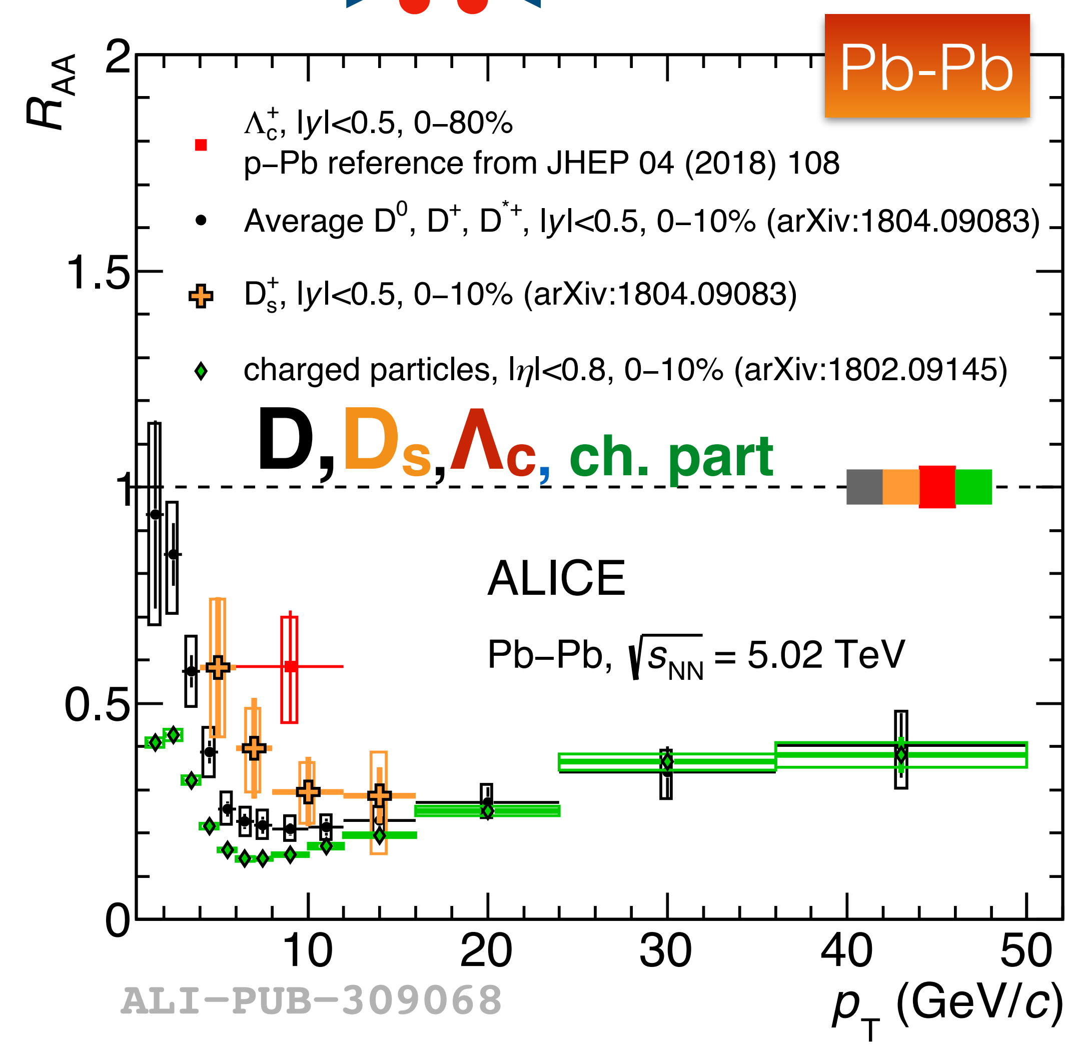
Data do not favour a suppression larger than 10-15% for 5<p_T<12 GeV/c

Nuclear Modification Factor: R_{pPb} vs R_{AA}

$$R_{pPb} = \frac{1}{A}\frac{d^2\sigma_{pPb}^{prompt\,D}/dp_T dy}{d^2\sigma_{pp}^{prompt\,D}/dp_T dy}$$







Pb-Pb results: F.Grosa's Talk

Suppression observed at intermediate-high p_T in Pb-Pb collisions is due to final-state effects

Heavy-flavour hadron decay electron R_{pPb}

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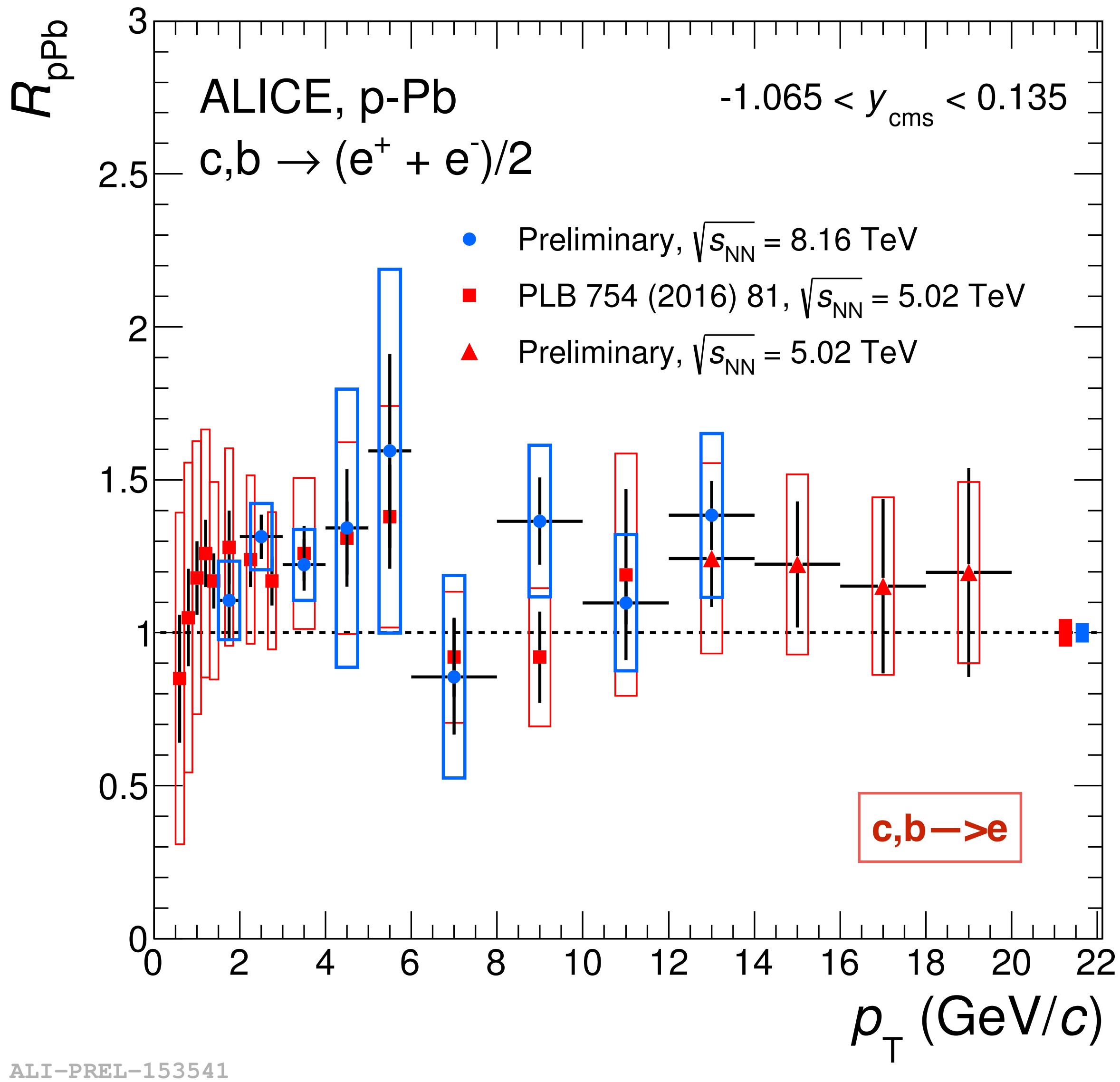
electrons from charm+beauty decays

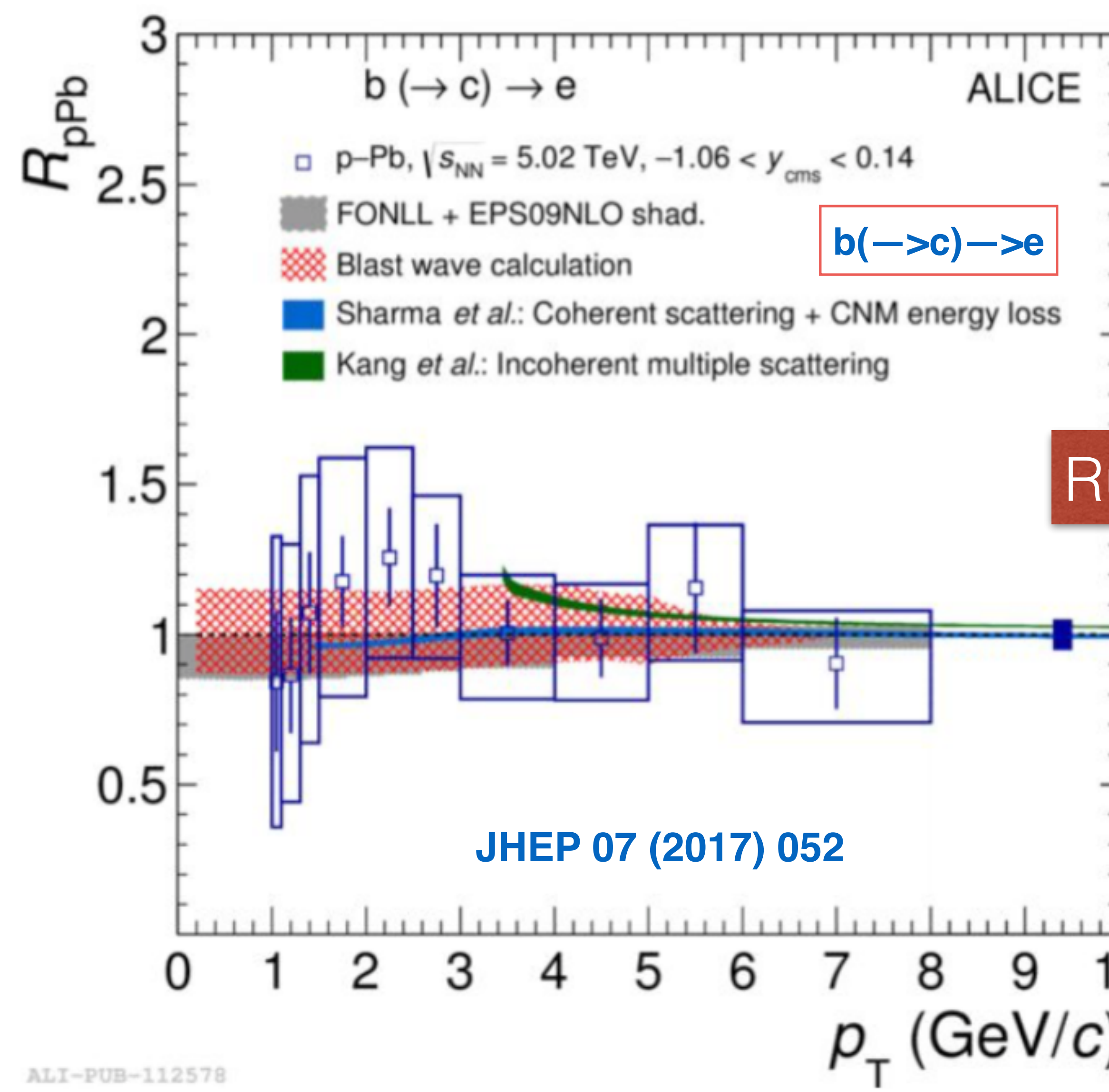


Run1, 5.02 TeV

Run2, 8.16 TeV

no energy dependency within uncertainties

electrons from beauty decays



- Beauty and beauty+charm electron results are compatible within uncertainties
- R_{pPb} described by models that include CNM

Heavy-flavour hadron decay electron (HF-e) R_{pPb} compatible with unity

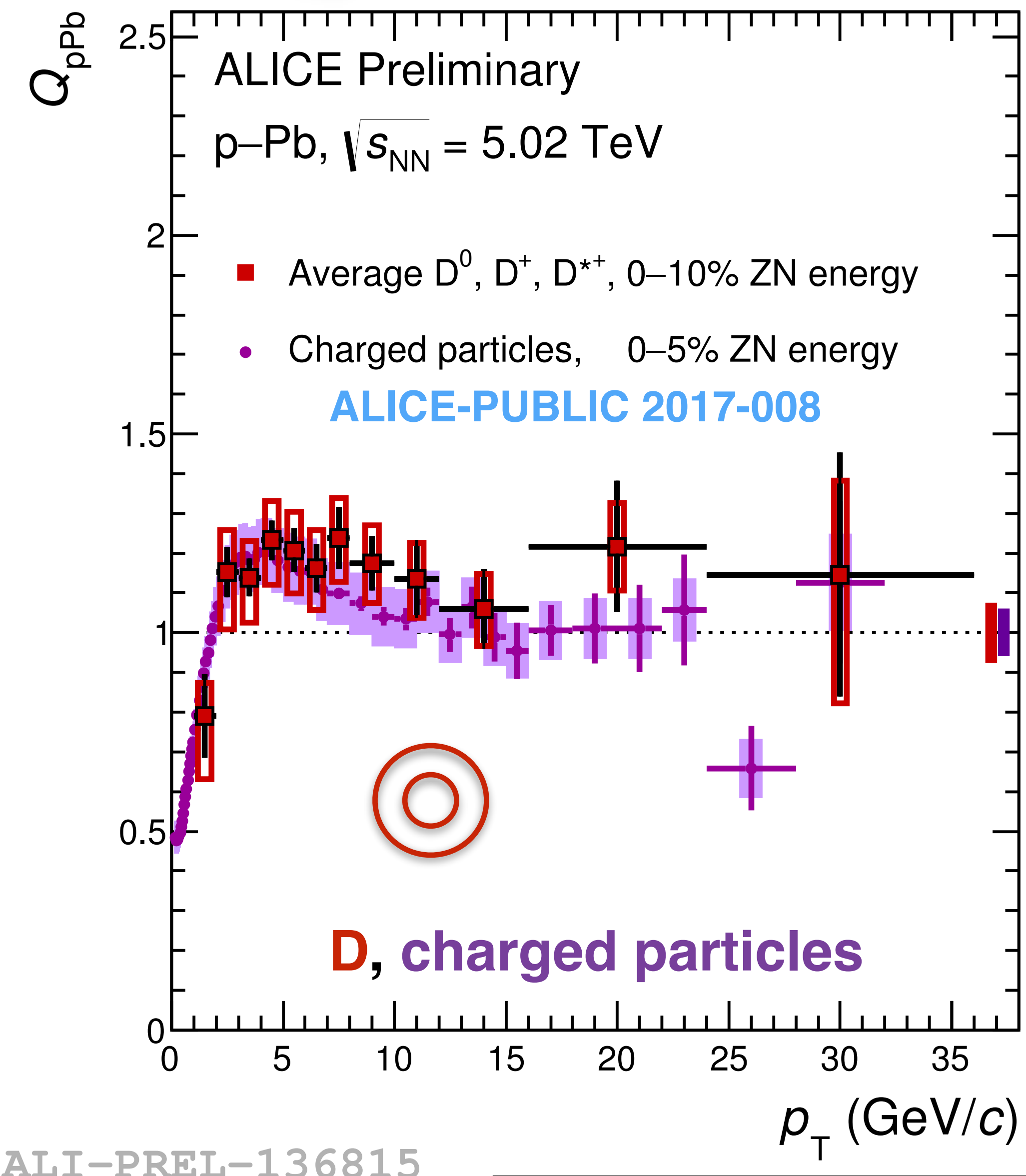
Nuclear modification factor in centrality classes: Q_{pPb}

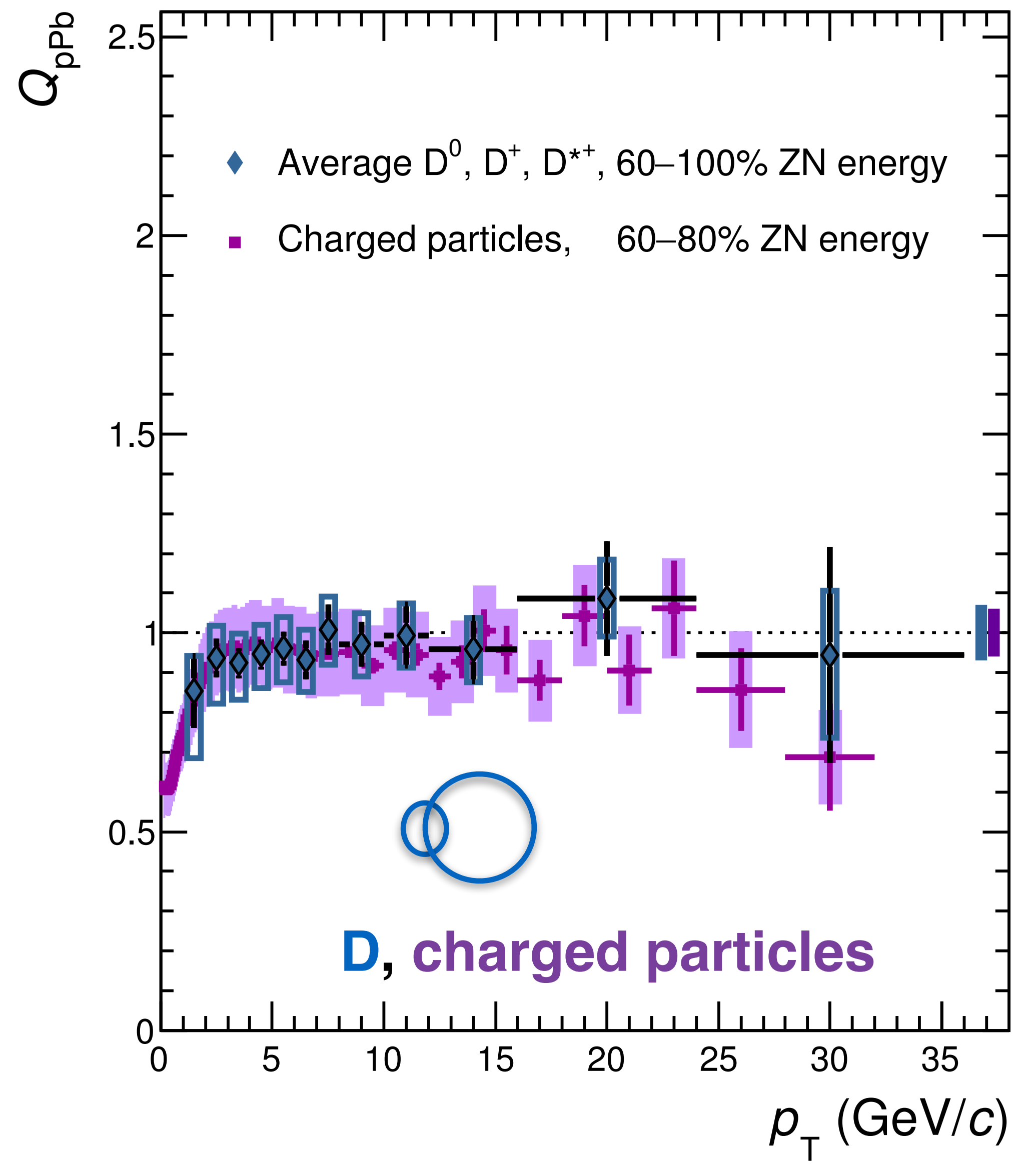
investigating the high multiplicity p-Pb collisions

$$Q_{pPb}^{cent} = \frac{(d^2N^{prompt\,D}/dp_T dy)_{pPb}^{cent}}{\langle T_{pPb}\rangle^{cent} \times (d^2\sigma_{pp}^{prompt\,D}/dp_T dy)}$$

Centrality classes: slicing the distribution of the energy deposited in the neutron calorimeter in the Pb-going side (ZNA)

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





Similar charged-particle Q_{cp}

Phys. Rev. C 91 (2015) 064905

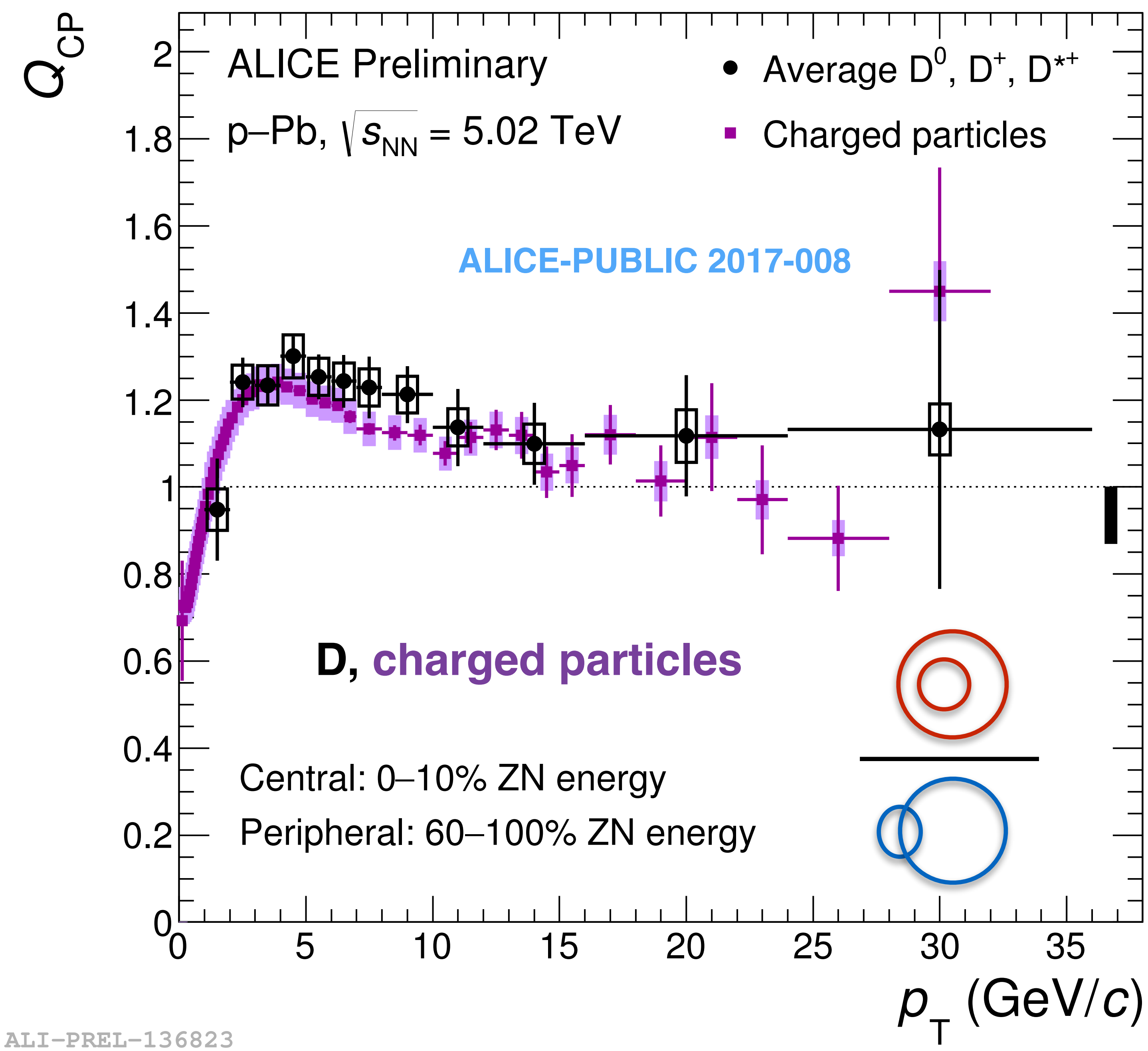
- **Q_{pPb} in most central (0-10%) and peripheral (60-100%) centrality classes** are compatible within uncertainties and consistent with unity.
- Hint of Q_{pPb}>1 in central 0-10% in 3<p_T< 8 GeV/c

Nuclear modification factor in centrality classes: Q_{cp}

investigating the high multiplicity p-Pb collisions

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

central/peripheral ratio



Similar as charged-particle Q_{cp}

Phys. Rev. C 91 (2015) 064905

Q_{cp} more precise measurement than Q_{pPb}

- independent from pp reference
- some sources of systematic uncertainties cancel in the ratio

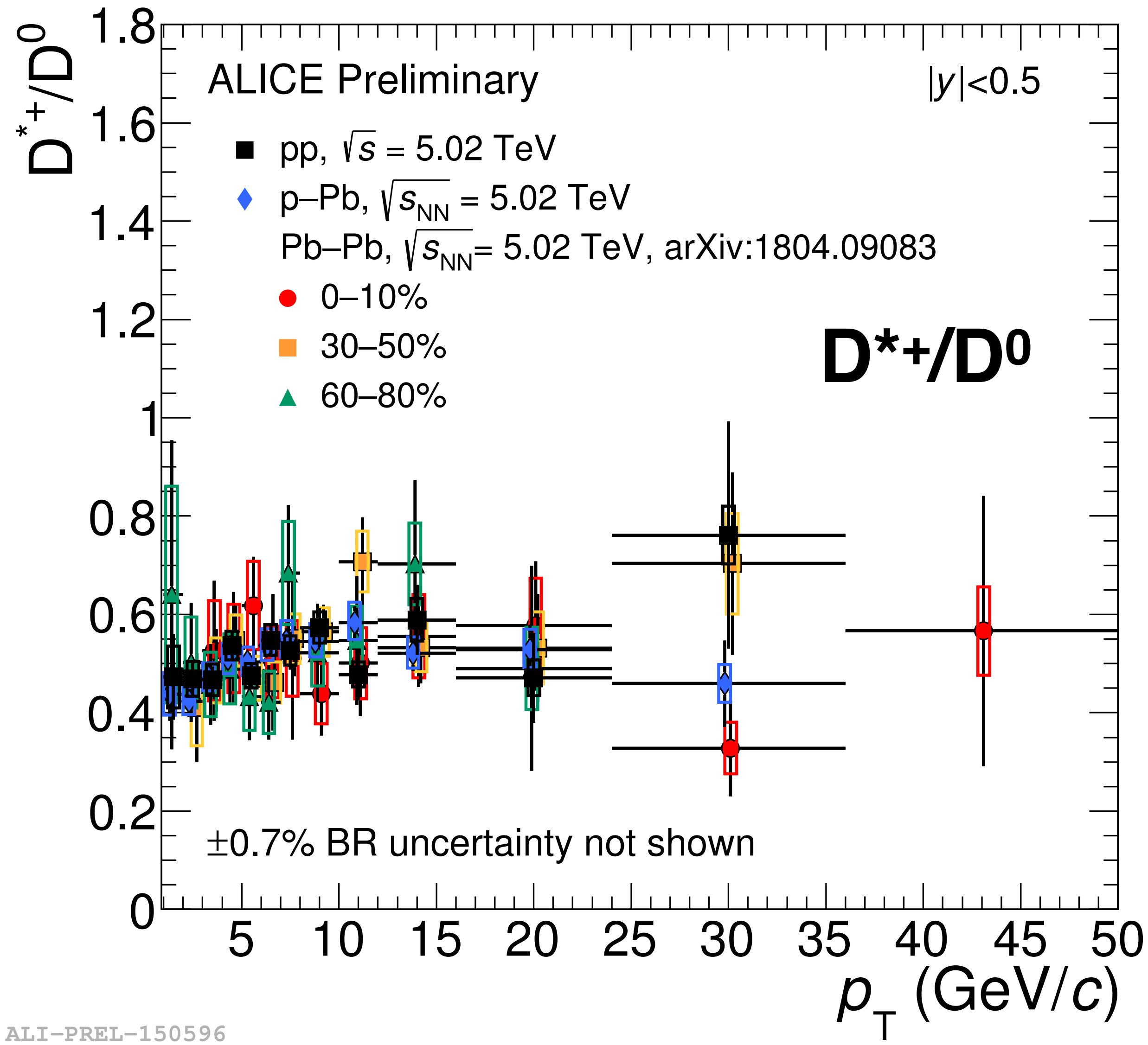
Hint of Q_{cp} > 1 in $3 < p_T < 8$ GeV/c **for D mesons with 1.5 σ** significance

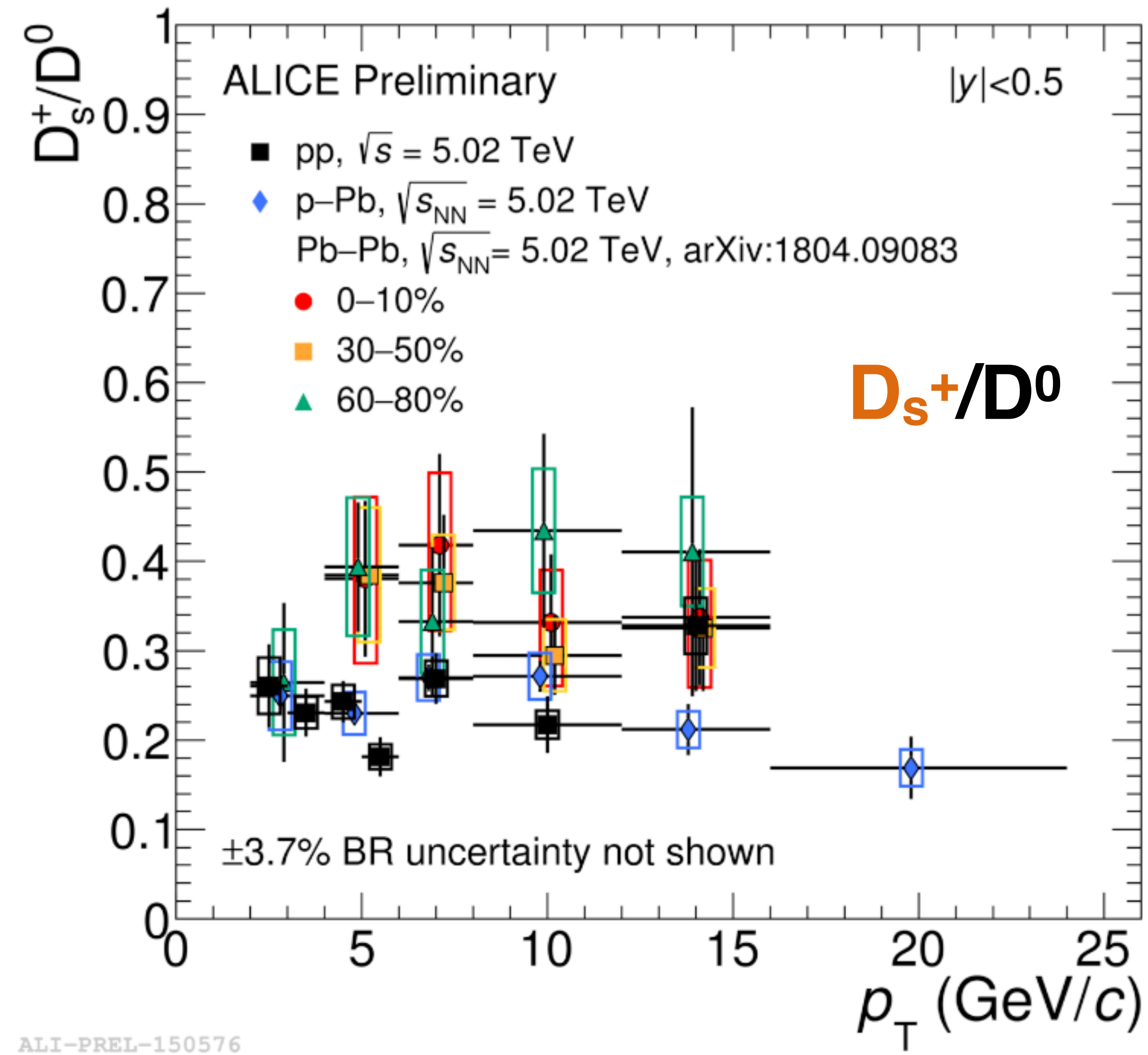
➡ Radial flow?

➡ Initial or final-state effect?

Charm-hadron ratios in small systems

Charm-hadron ratios





Relative abundances of **D^{*+}/D^0** and **D_s^+/D^0** compatible in **pp** and **p-Pb** collisions

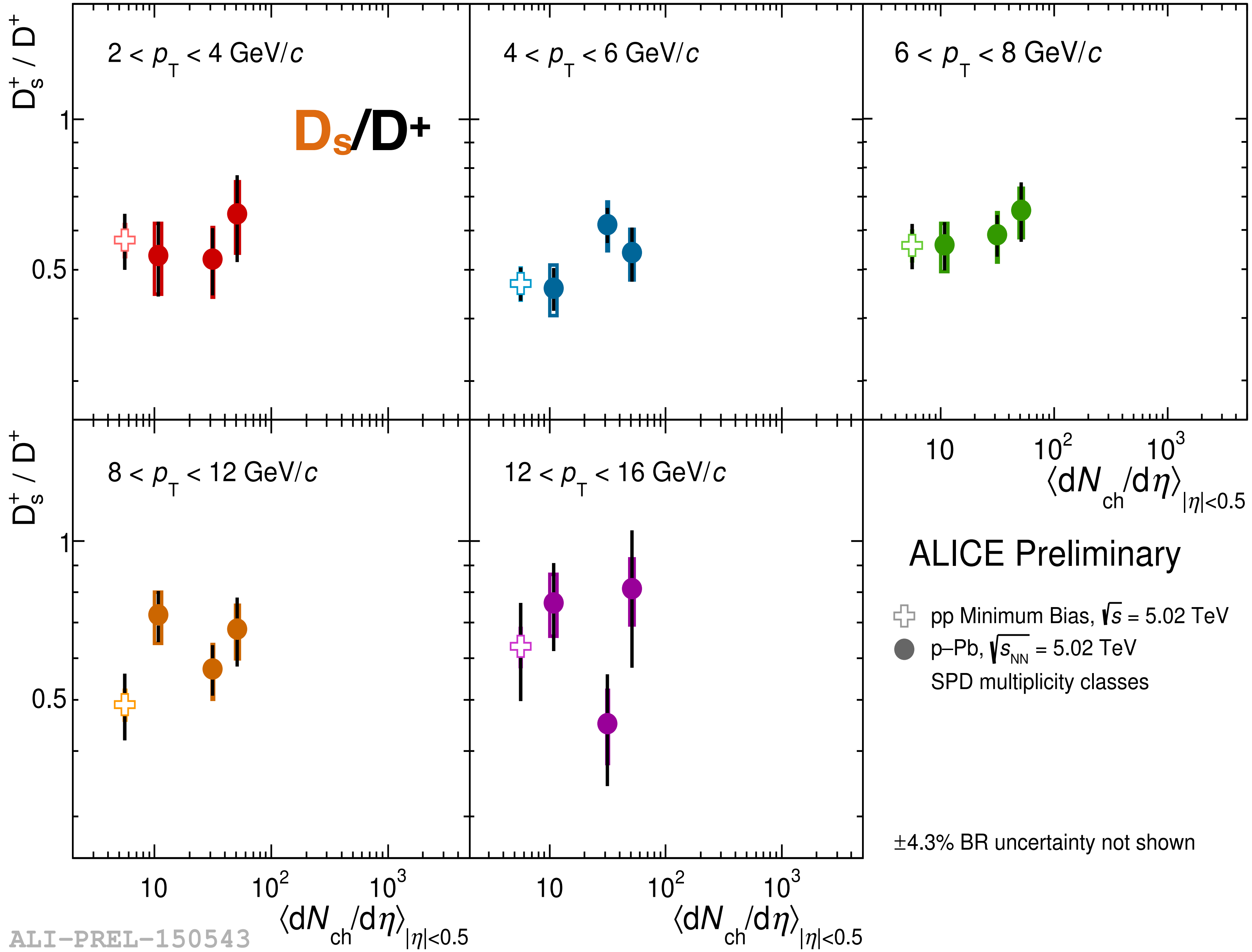
- and also consistent with measurements in e^+e^- collisions at LEP **Gladilin, EPJ C75 (2015) 19**

Hint of a enhanced production of **D_s** **w.r.t. non-strange D meson (D^0)** in **Pb-Pb** collisions

Charm-hadron ratio: strange/no-strange

investigating the high multiplicity p-Pb collisions

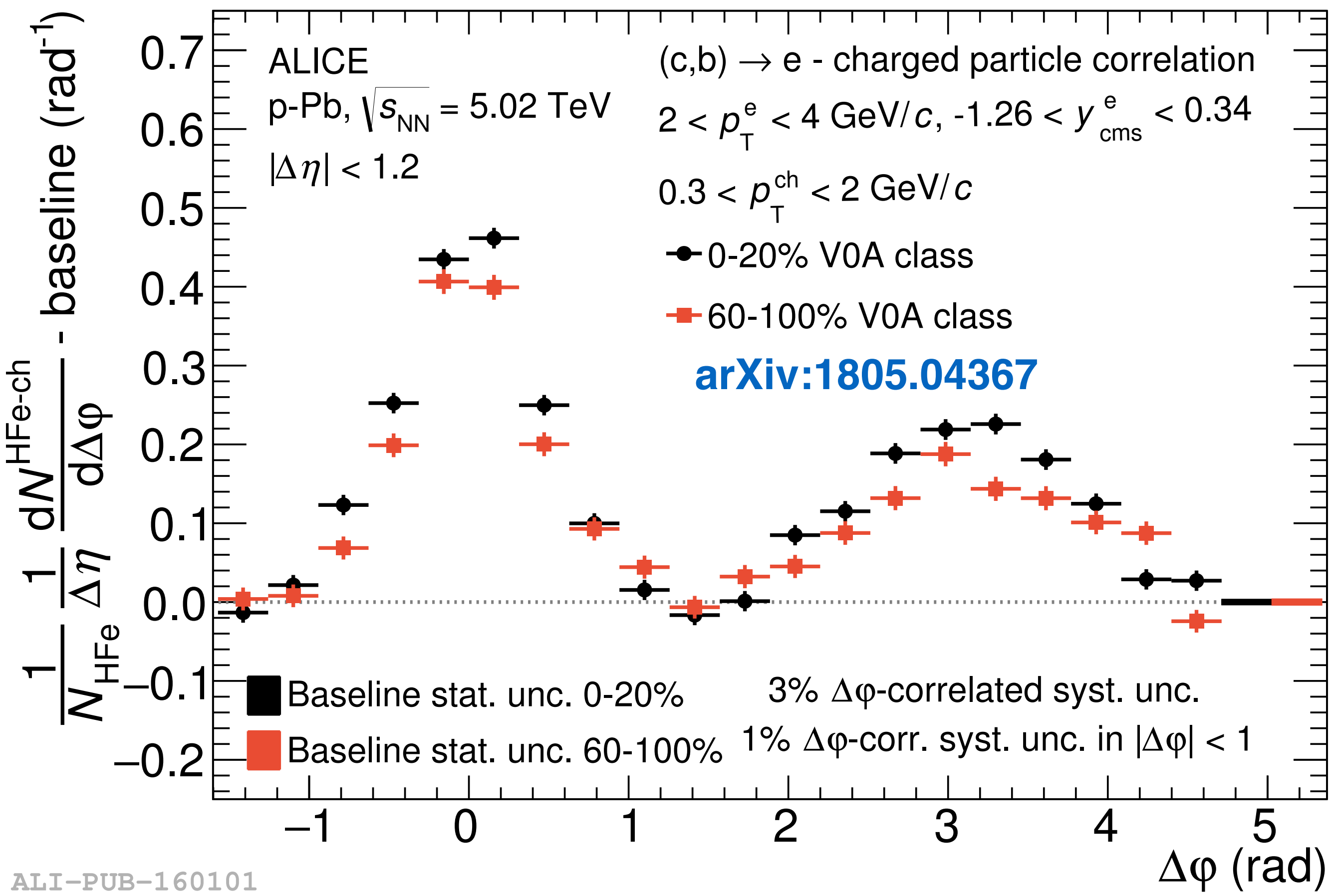
Light flavour sector: strangeness enhancement with multiplicity in small systems.
Heavy-flavour?



D_s/D^+ measured as a function of multiplicity in different p_T ranges
- compatible ratios in pp and p-Pb collisions
- no dependency vs multiplicity with the current uncertainties

collectivity in high-multiplicity p-Pb collisions?

HFe-hadron azimuthal correlations



Angular correlations between heavy-flavour decay electrons and charged particles at mid-rapidity **0-20%** and **60-100%**

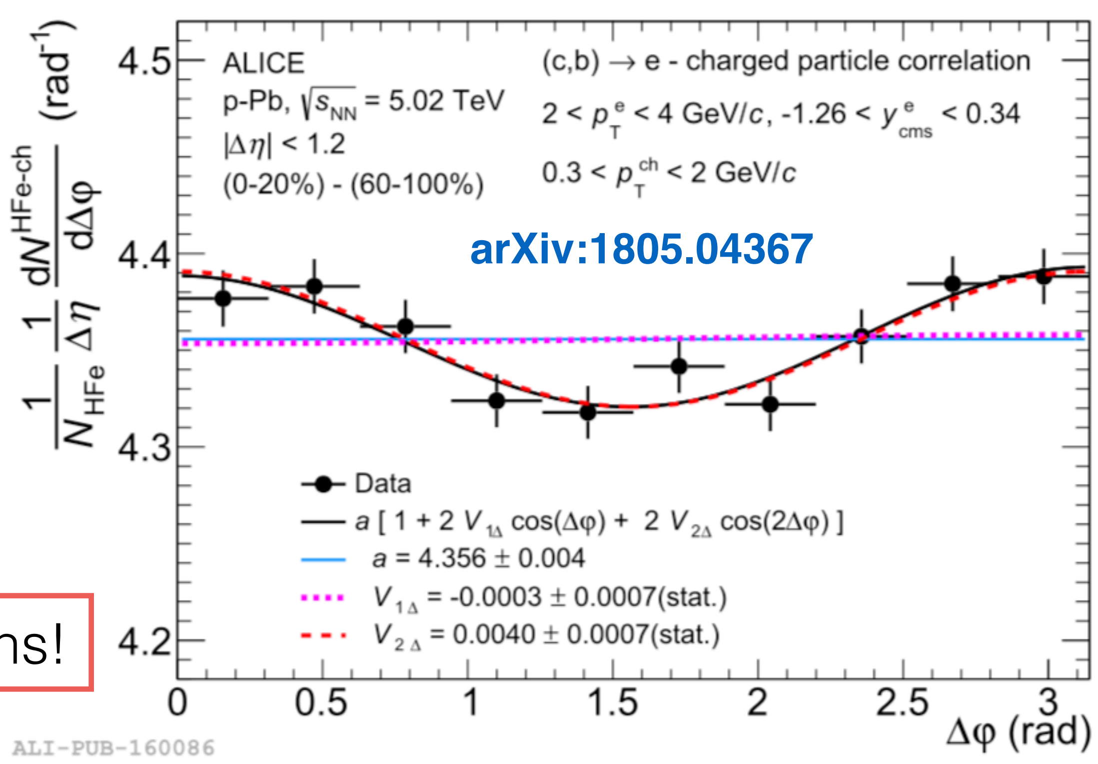
- multiplicity selected via V0A at forward rapidity $2.8 < \eta < 5.1$
- **hint of a enhancement** of near- and away-side peaks distribution **in central 0-20% p-Pb**

investigating the high multiplicity p-Pb collisions

➡ jet contribution subtracted: high-multiplicity - low-multiplicity events

$$\left(\frac{1}{N_a}\frac{dN^{ab}}{d(\Delta\varphi)}\right)^{HM} - \left(\frac{1}{N_a}\frac{dN^{ab}}{d(\Delta\varphi)}\right)^{LM}_{sub} = P\left(1 + \sum_{n=1}^{\infty} 2 \times v_n^a v_n^b \times \cos[n\Delta\varphi]\right)$$

Azimuthal modulation remains!



HF-decay lepton v_2 in p-Pb

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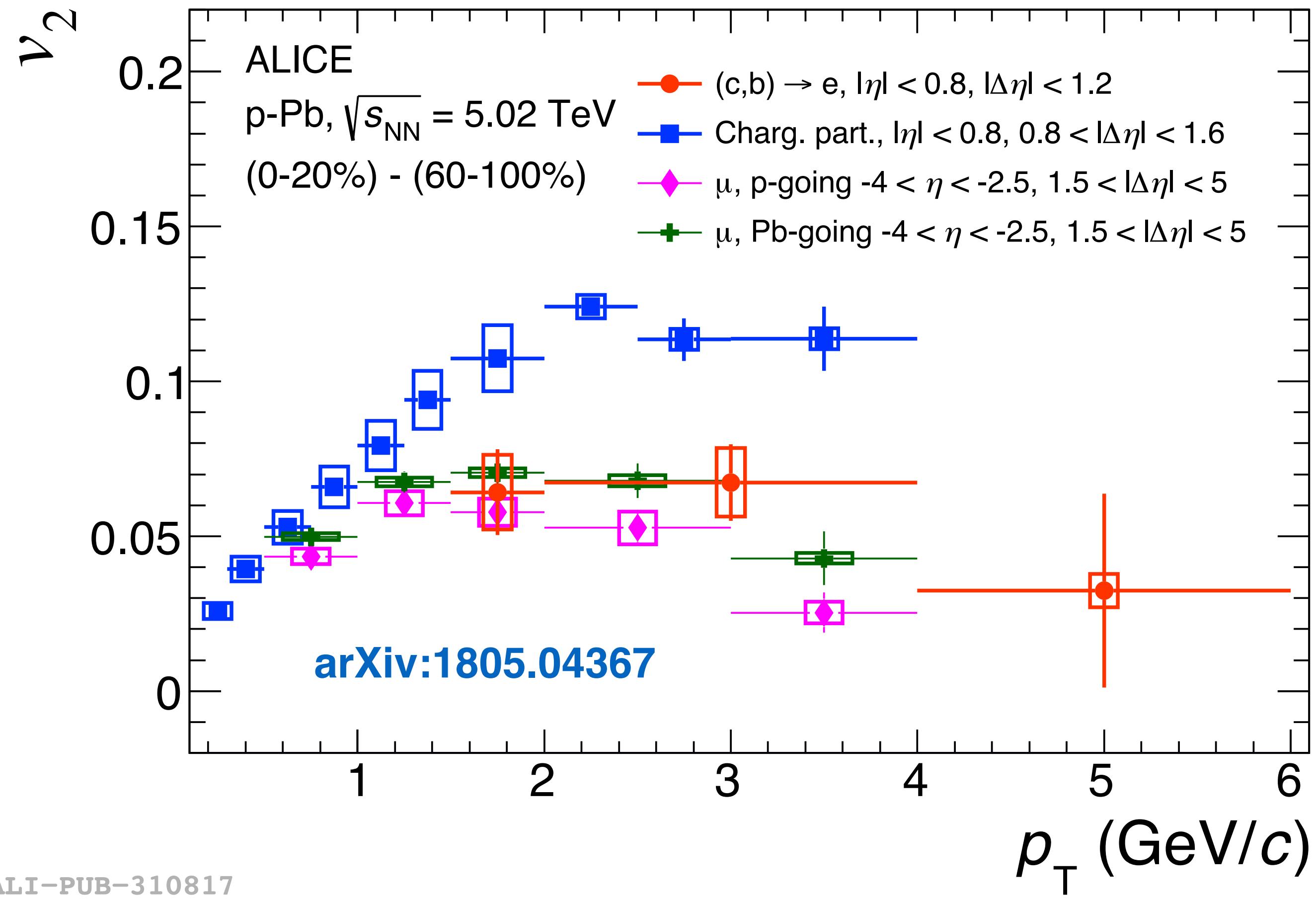
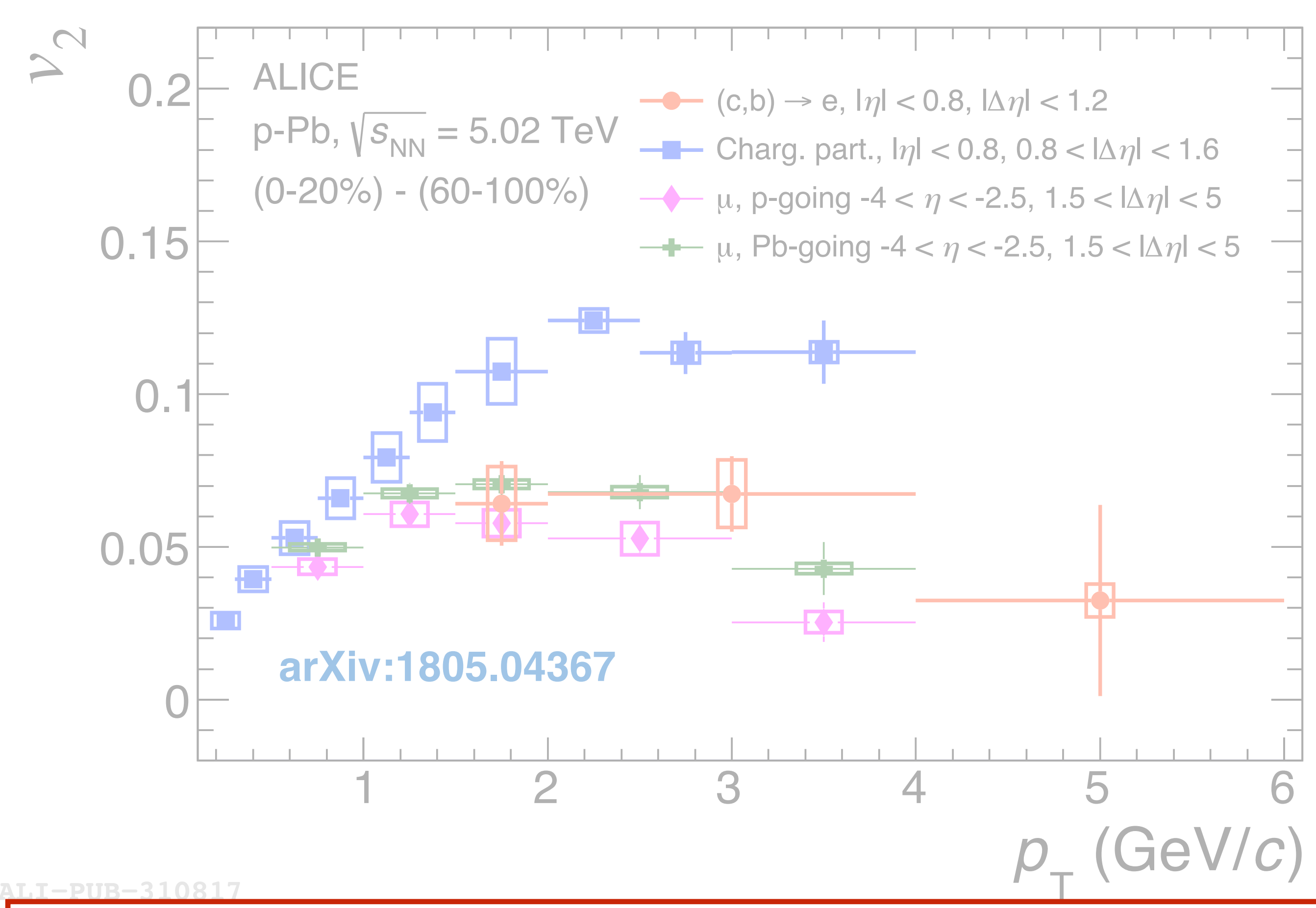
v_2: second-order coefficient of the Fourier expansion of the azimuthal distributions of particles

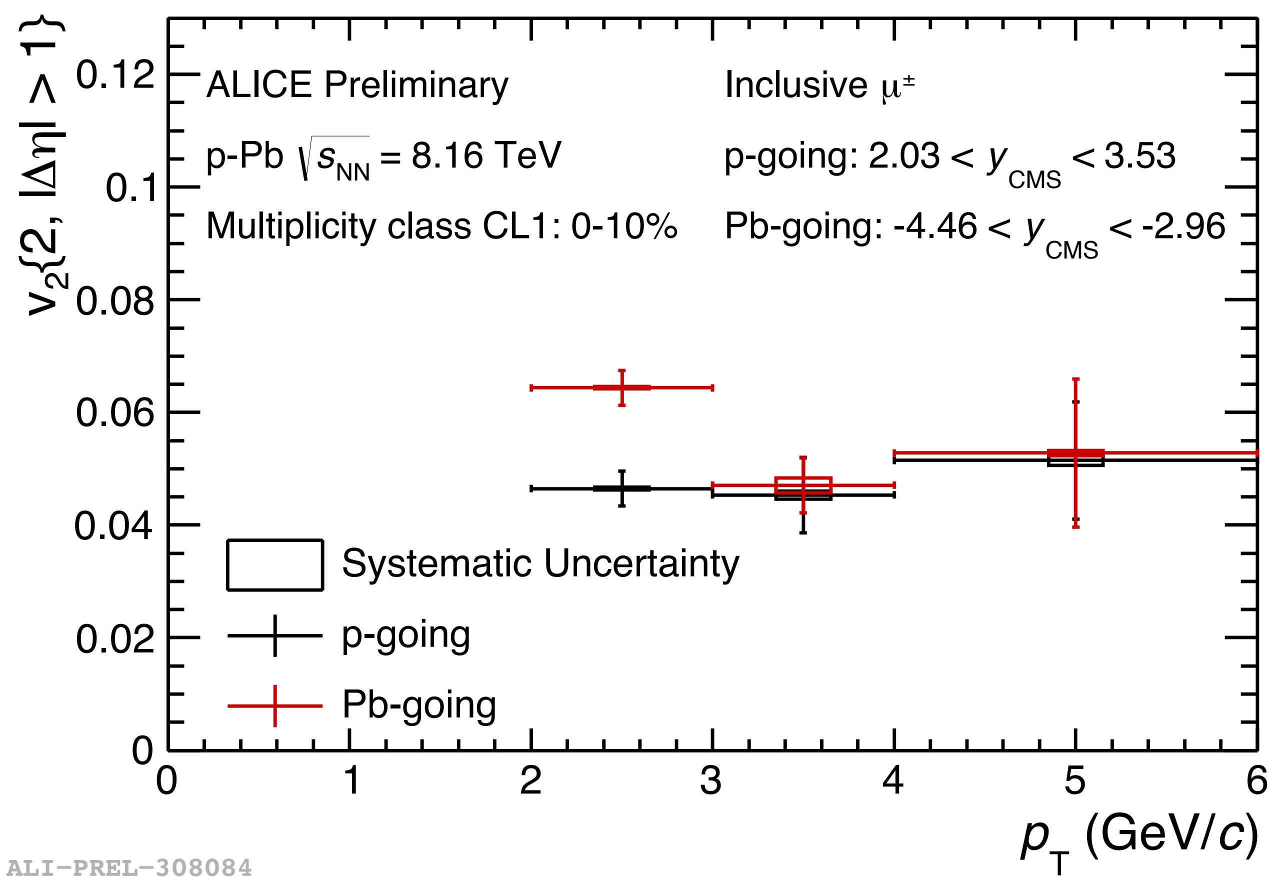


- **HF-e v_2>0** in 1.5<p_T<4 GeV/c in high multiplicity events **with significance > 5 σ**
- sizeable effect, possibly lower than **charged-particles maximum,** and similar to **inclusive muons** at large rapidities

HF-decay lepton v_2 in p-Pb

v_2: second-order coefficient of the Fourier expansion of the azimuthal distributions of particles

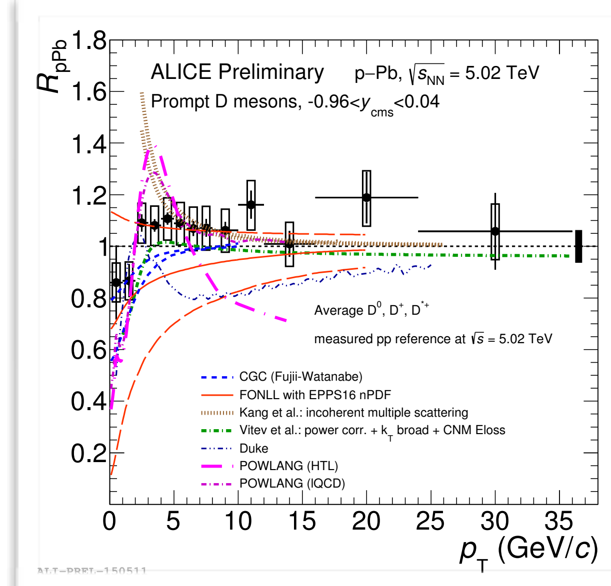




- **NEW! μ v_2** measured in different collision energy **$\sqrt{s_{NN}}$ = 8.16 TeV**, in an extended p_T range
  - where HF-μ components dominate
- **Analysis Strategy:** Q-cumulants with 2-particle correlations
- 0-10% high-multiplicity class: CL1, $N_{tracklets}$= # track segments in the two innermost layers of the ITS
- similar values at forward and backward rapidities
- **μ v_2>0** in 2<p_T<6 GeV/c in high multiplicity events **with significance > 3 σ**

- **compatible with HF-e and inclusive μ in p-Pb collisions at 5.02 TeV**

Conclusions



- ***R*$_{pPb}$ of heavy-flavour hadrons compatible with unity** and described by models including CNM effects
- Measured **D-meson R_{pPb} at high p_T disfavours** QGP models that predict a significant **suppression at high p_T in p-Pb collisions**
    - **suppression in Pb-Pb collisions at intermediate p_T is due to final-state effects**

- **Investigation of high-multiplicity p-Pb collisions:**
    - D-meson Q_{pPb} compatible with unity
    - Hint of D-meson $Q_{CP} > 1$ at low-intermediate p_T
    - No modification in the ratios of strange/non-strange mesons in different systems and vs multiplicity
    - Non-zero v_2 for HF-decay leptons in high multiplicity events

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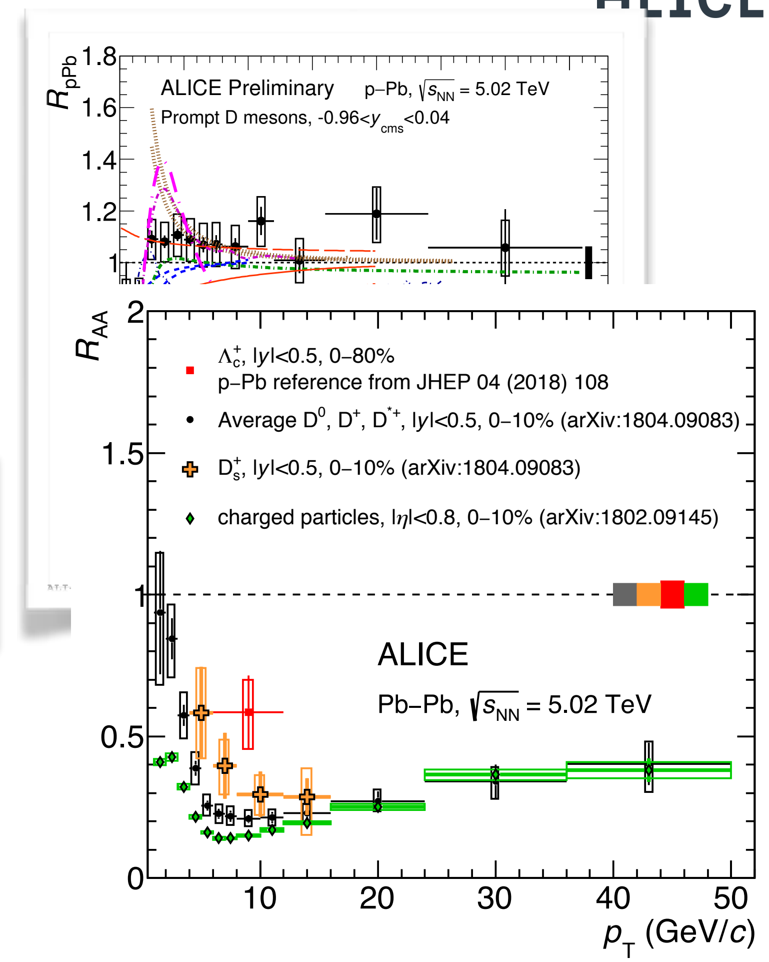

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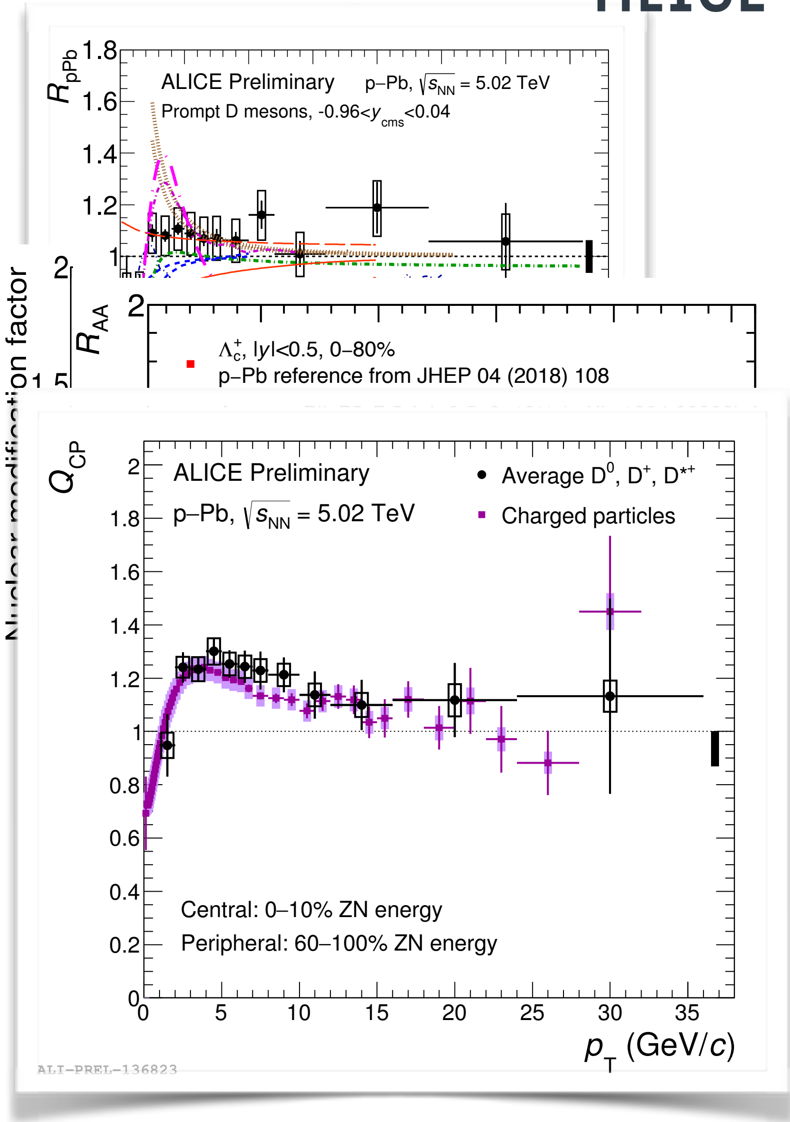

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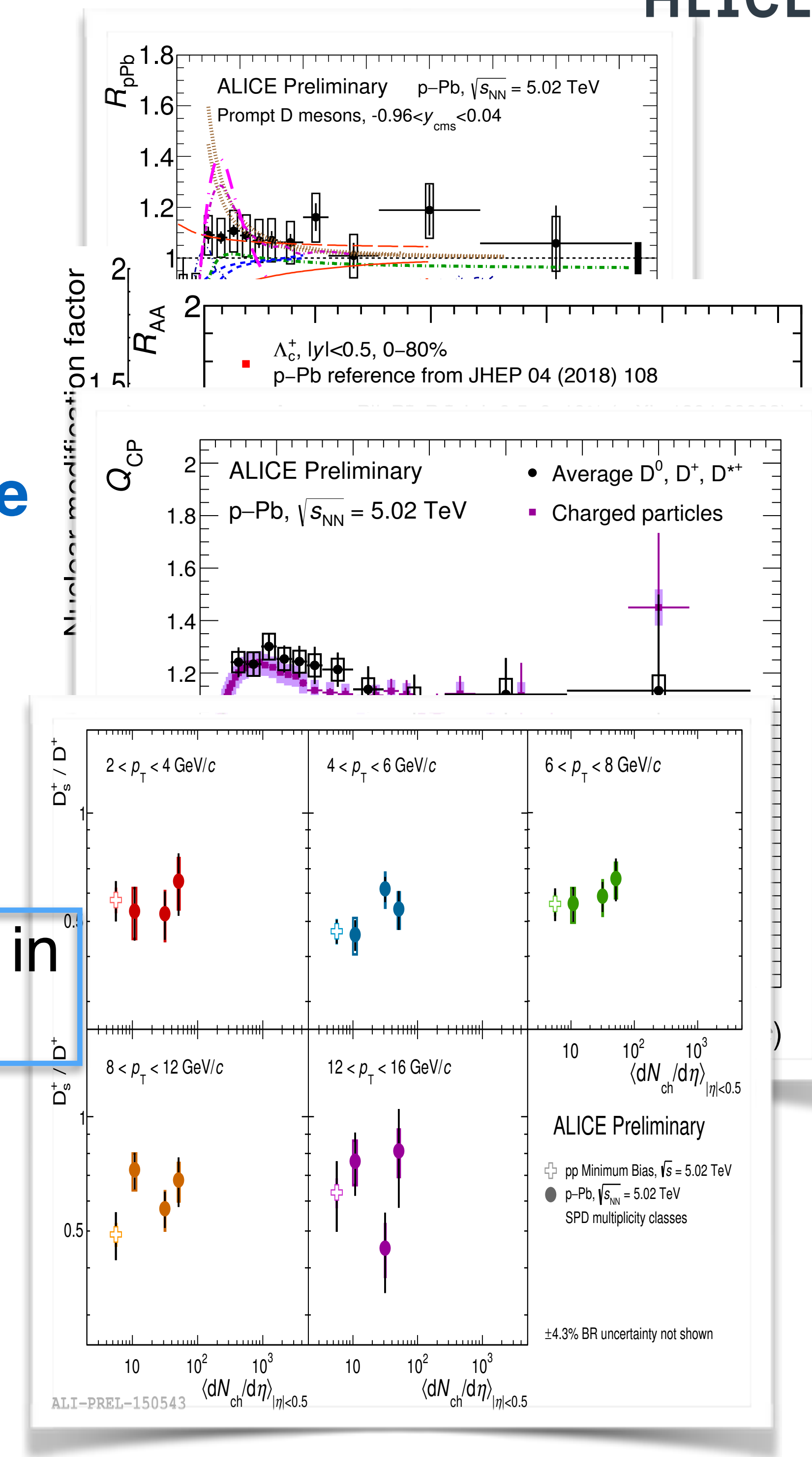

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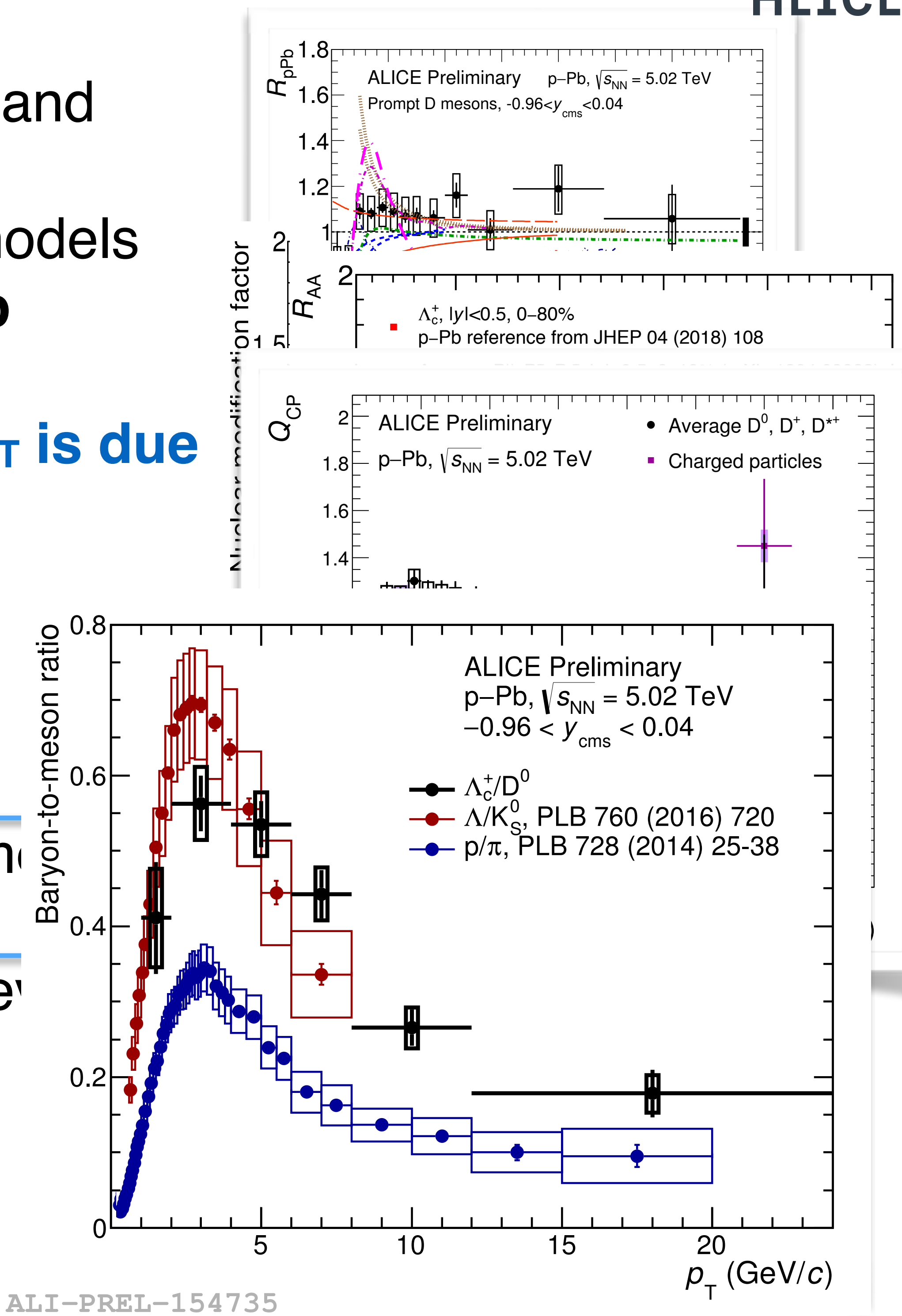

Charm Baryons-to-meson ratios in E. Meninno's Talk

Conclusions

- R_{pPb} **of heavy-flavour hadrons compatible with unity** and described by models including CNM effects
- Measured **D-meson R_{pPb} at high p_T disfavours** QGP models that predict a significant **suppression at high p_T in p-Pb collisions**
    - **suppression in Pb-Pb collisions at intermediate p_T is due to final-state effects**

- **Investigation of high-multiplicity p-Pb collisions:**
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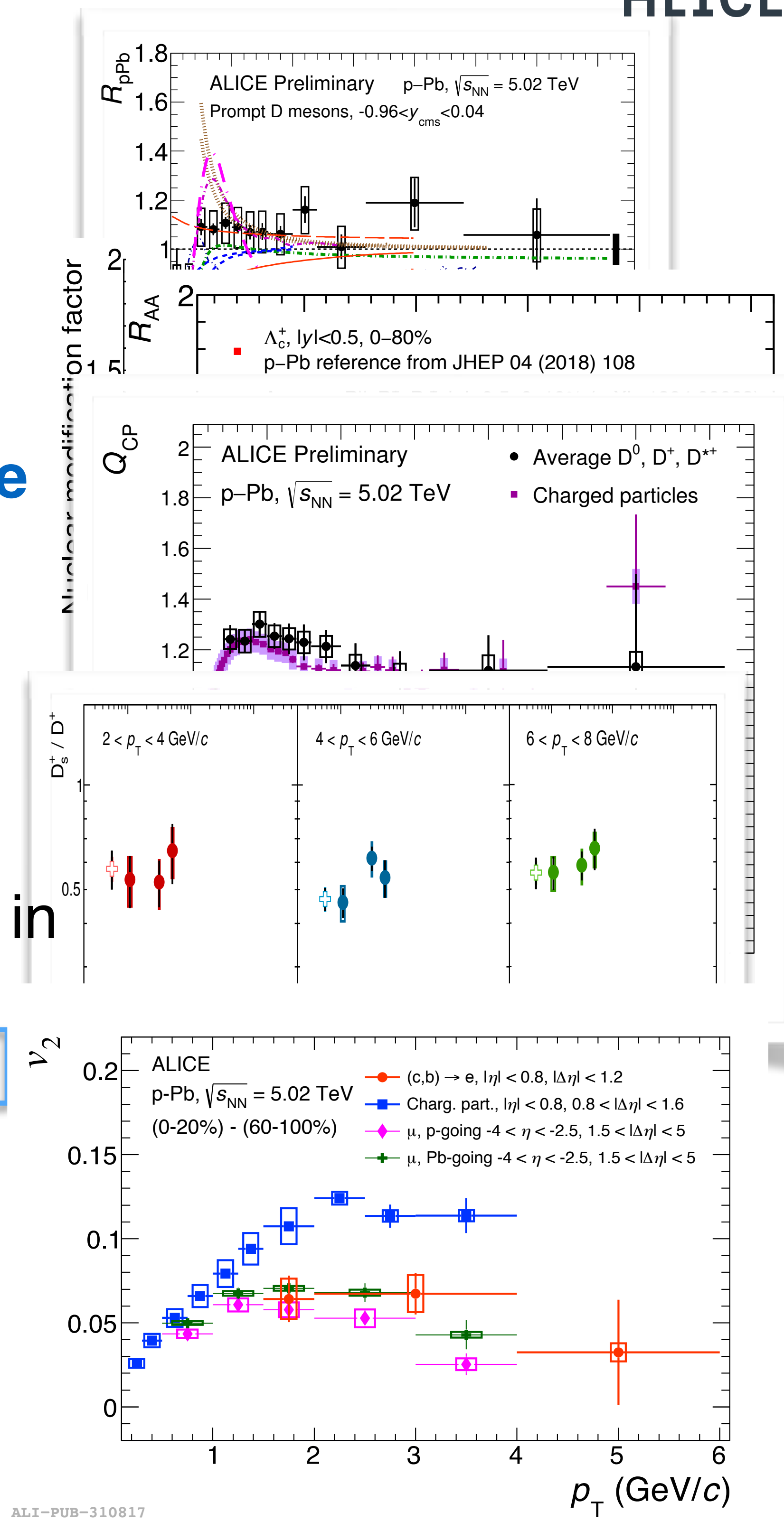

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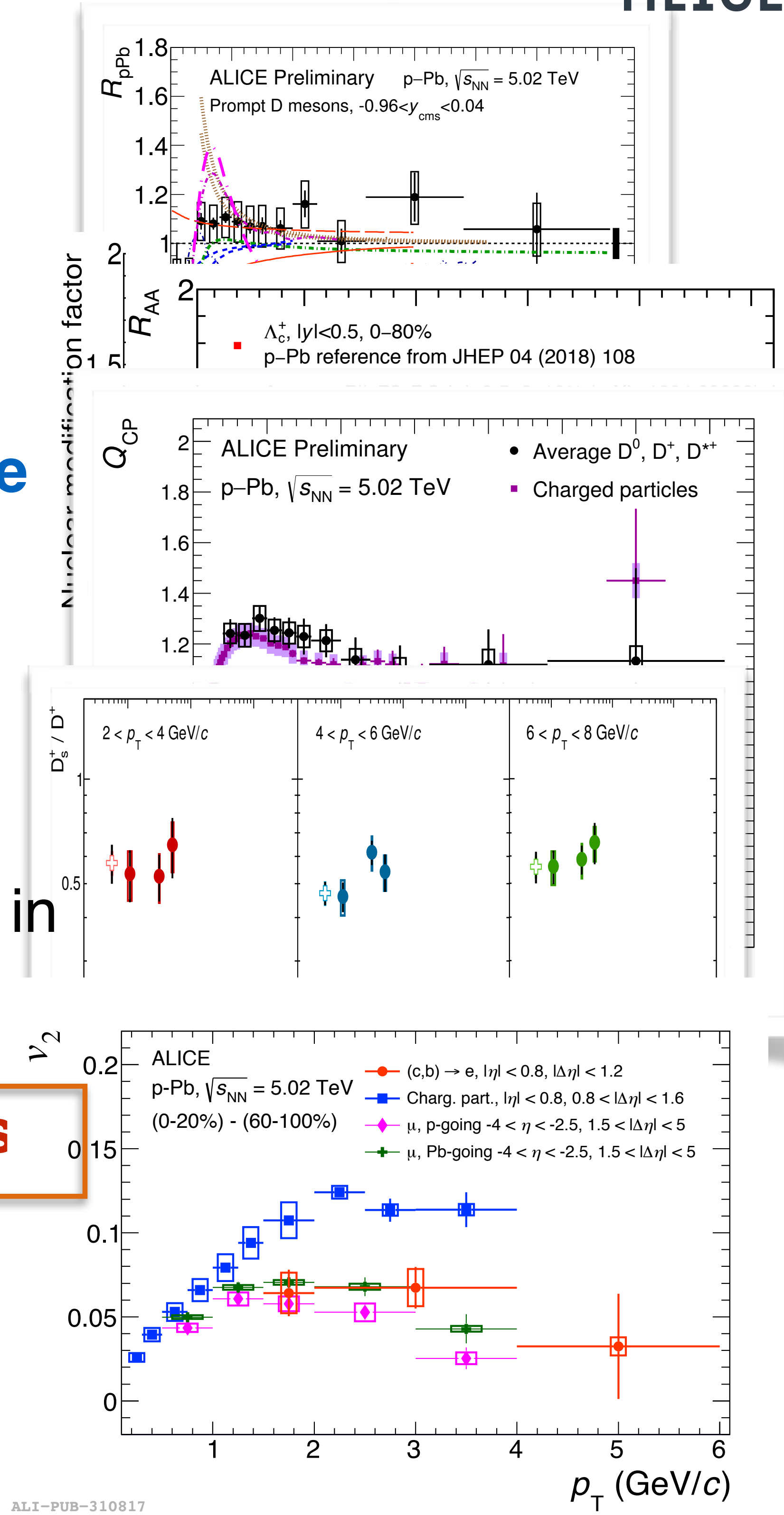
Collective effects in p-Pb: origin? Initial- or final-state effects



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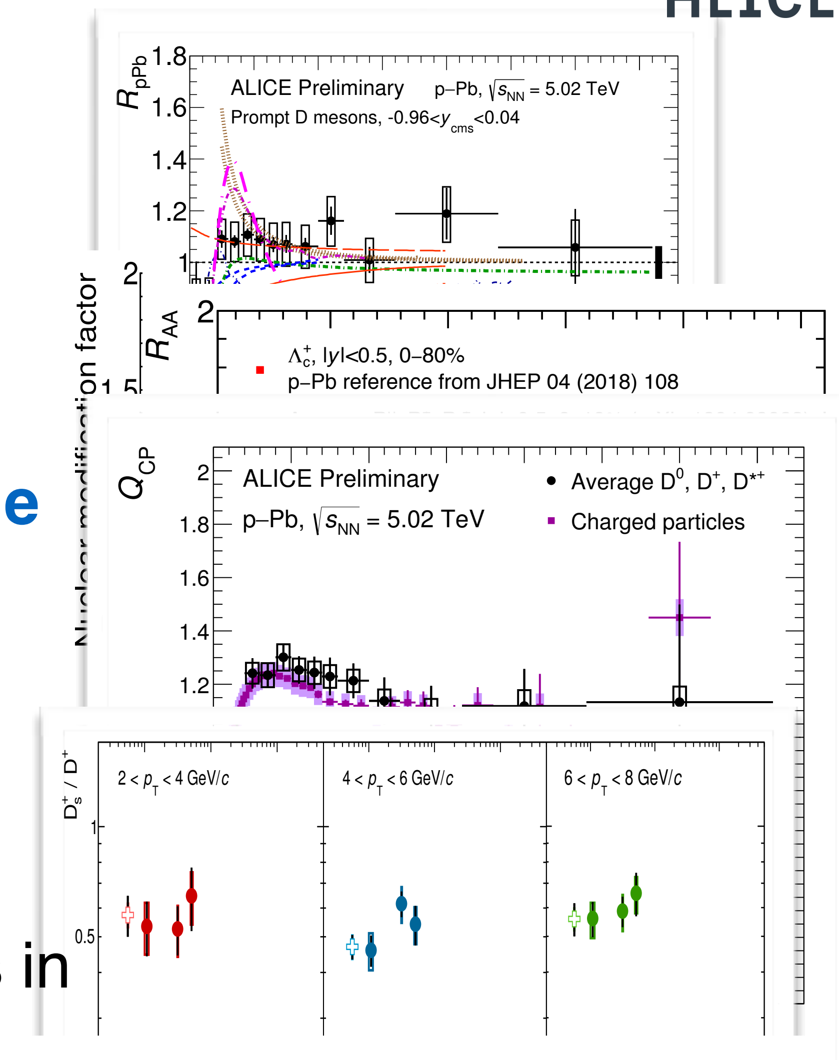

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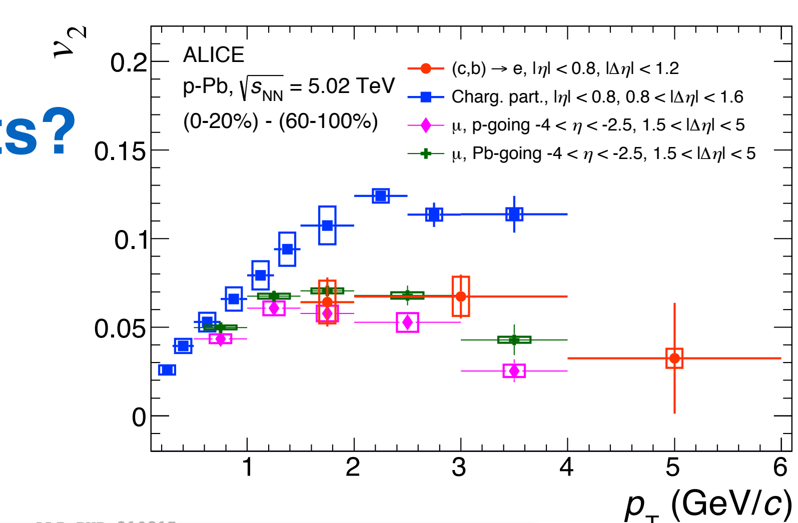


➡ More in HF-jets, D-h correlation results in p-Pb **S. Aiola Talk**

Upgrades of ALICE in LHC Run 3-4

- improved precision and extended p_T reach for HF measurements

Upgrade prospects: C. Bedda's Talk

backup

Data Samples

p-Pb collisions, data samples:

Min. bias **$\sqrt{s_{NN}}$=5.02 TeV min.bias**
Run1 2013 100 M L_{int}= 47.8 μb^{-1}
Run2 2016 600 M L_{int}= 292 μb^{-1}

electrons (2016) **$\sqrt{s_{NN}}$=8.16 TeV min. bias**
Trig.1(p_T>10 GeV/c) L_{int} = 599 μb-1

Trig.2 (p_T>5 GeV/c) L_{int} = 34.6 μb-1

≈20M MB events L_{int} = 10.1 μb^{-1}

Muons (2013) **$\sqrt{s_{NN}}$=5.02 TeV min. bias**

Trigger MSL (p_T > 0.5 GeV/c) p-Pb L_{int} = 196 μb^{-1}, Pb-p L_{int} = 254 μb^{-1}

Trigger MSH (p_T > 4.2 GeV/c) p-Pb L_{int} = 4.9 · 10^3 μb^{-1} , Pb-p L_{int} = 5.8 · 10^3 μb^{-1}

Muons (2016) **$\sqrt{s_{NN}}$=8.16 TeV min. bias**

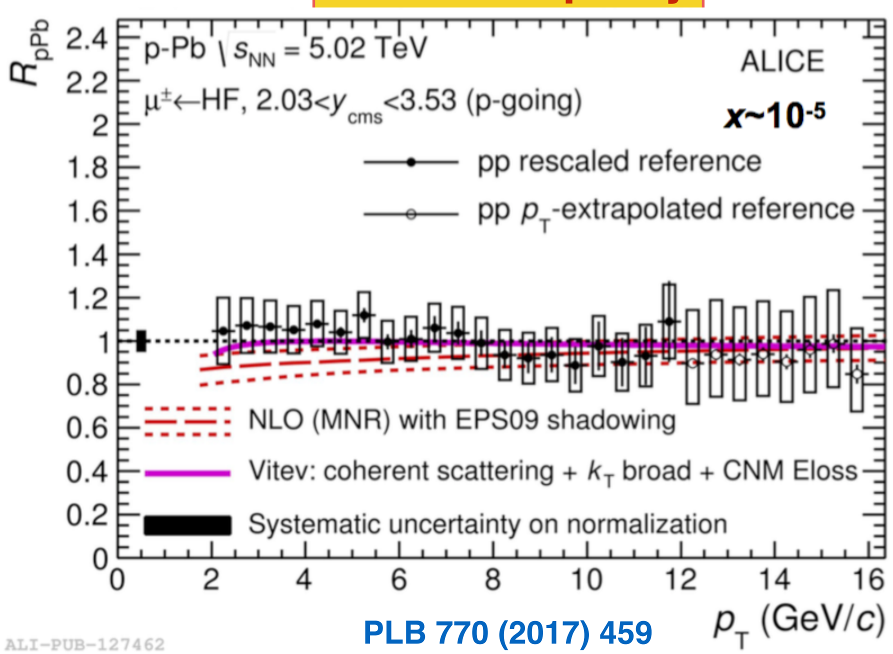
Trigger MSL (p_T > 0.5 GeV/c) p-Pb L_{int} = 22 M, Pb-p L_{int} = 3.4M

Trigger MSH (p_T > 4.2 GeV/c) p-Pb L_{int} = 17M , Pb-p L_{int} =34M

Heavy-flavour hadron decay lepton R_{pPb}

ALICE

forward rapidity



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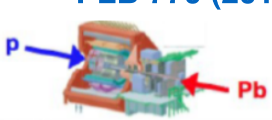
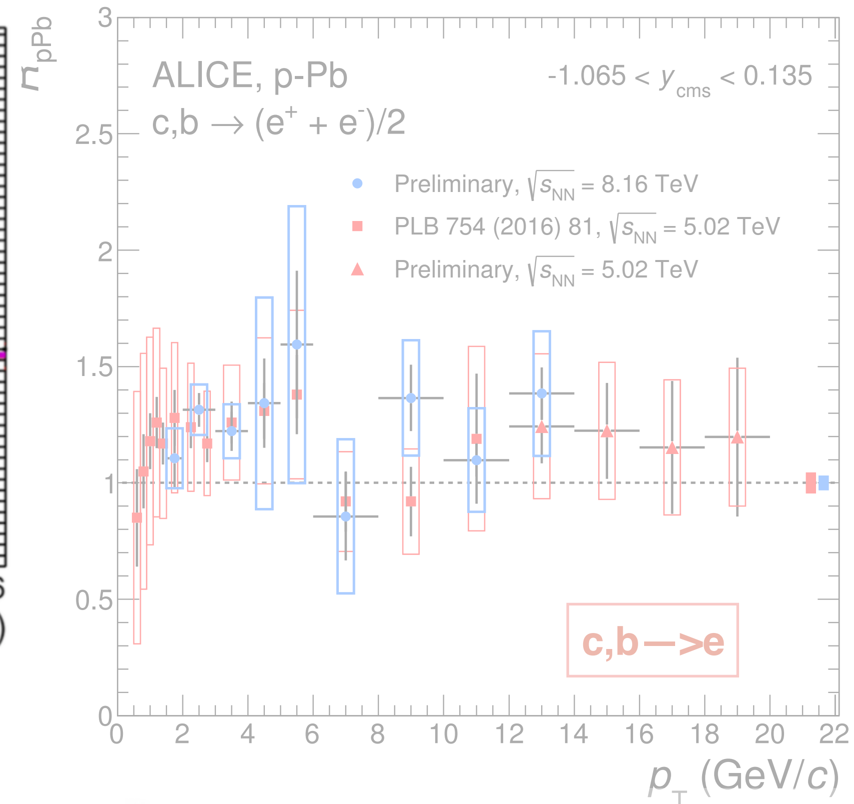


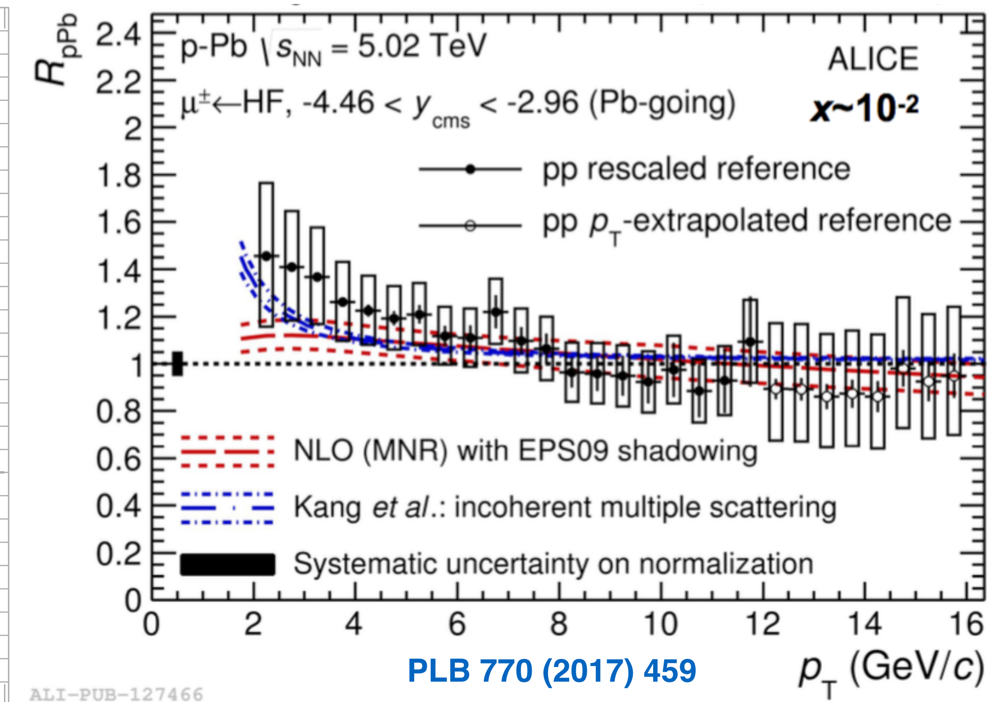
Forward: p-going

Run1

central rapidity



backward rapidity



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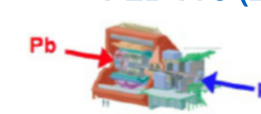
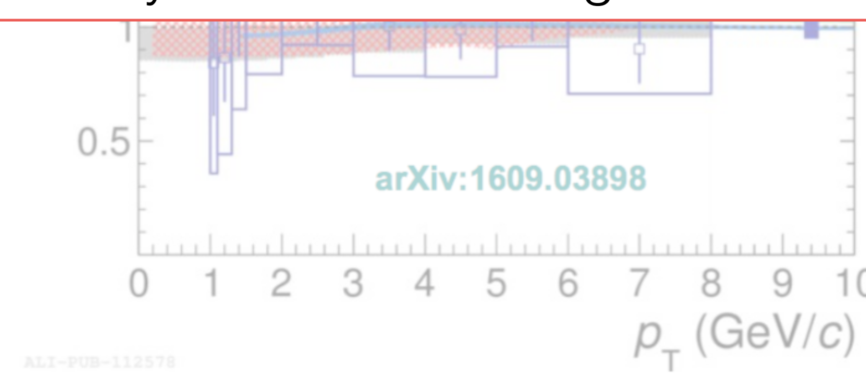


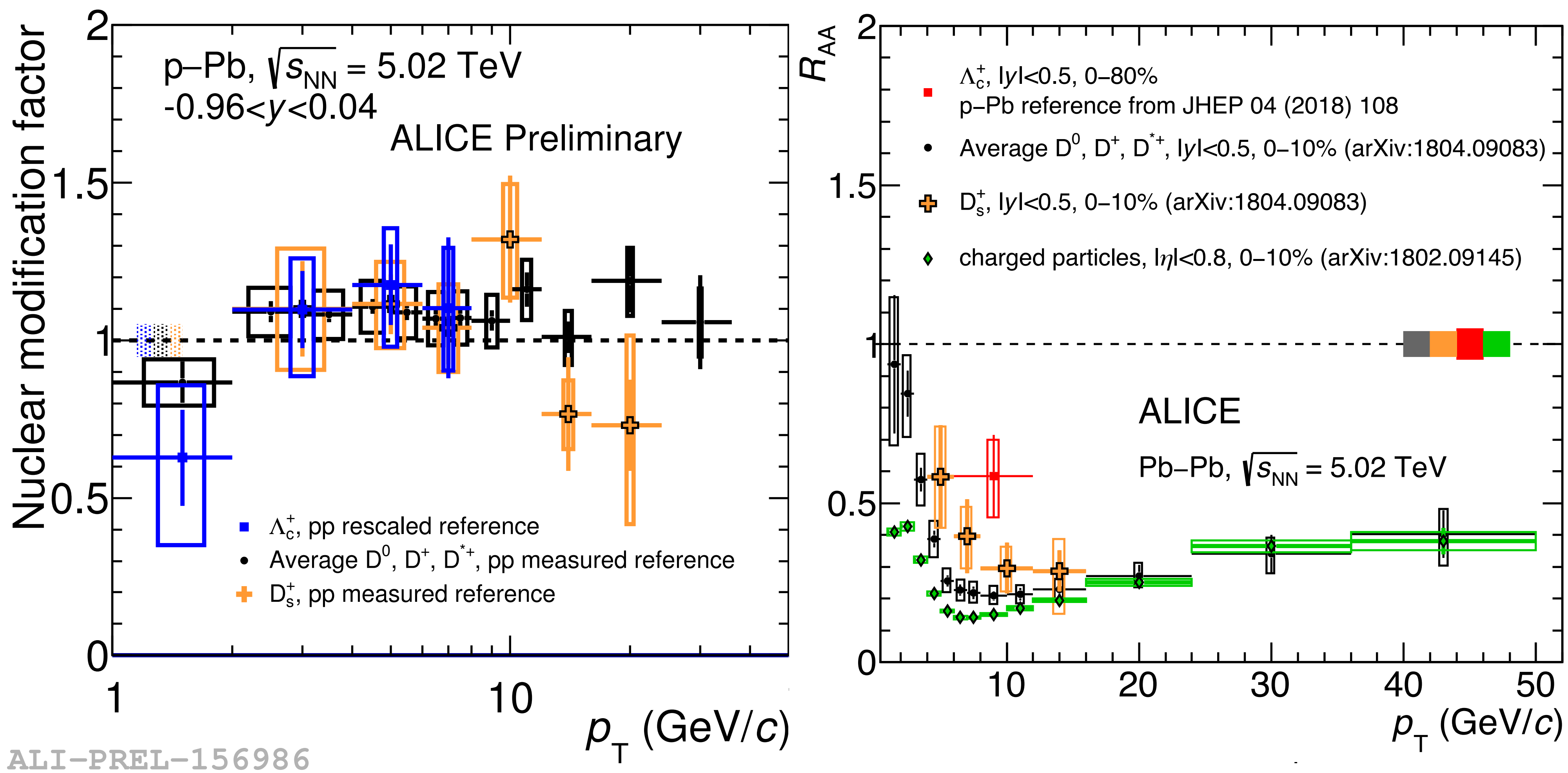
Backward: Pb-going

Different rapidity ranges allow access to different Bjorken-*x* regimes

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



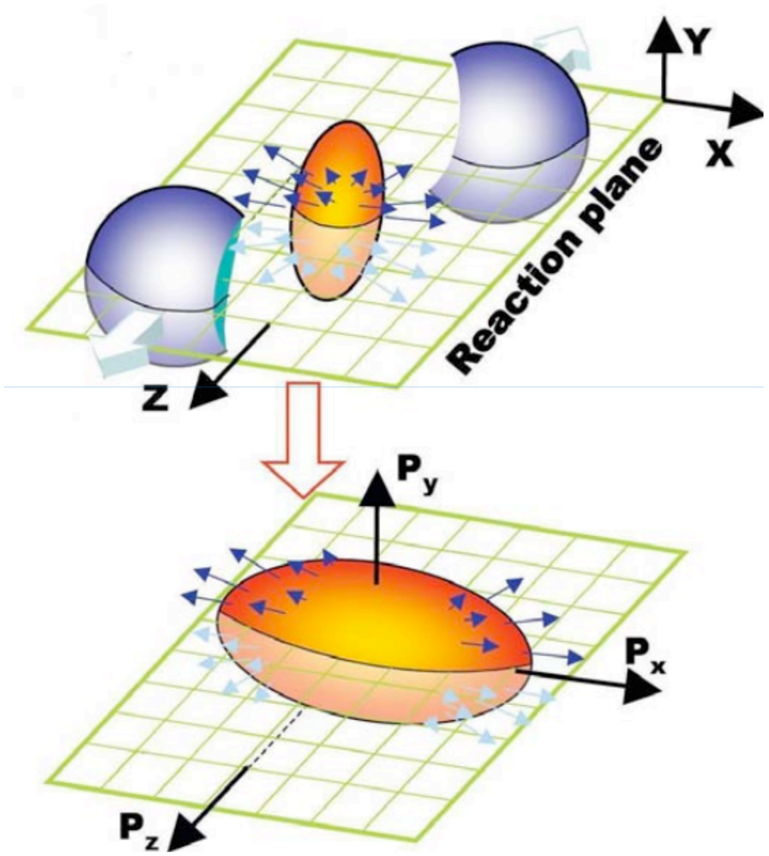
charm hadrons: Family Portrait in p-Pb and Pb-Pb



Azimuthal Flow

In Pb-Pb

- Signature of collective motion in heavy-ion collisions, due to presence of QGP
- Provide experimental information on the equation of state and the transport properties of the created QGP



Initial spatial anisotropy of peripheral collisions

- "almond shaped" of the overlap region:
  - larger pressure gradient in x-z plane than in y direction
  - particle re-scattering: *convert the initial spatial anisotropy into a momentum anisotropy*

Observable: elliptic flow v_2

Second coefficient of the Fourier expansion of the azimuthal distributions of particles

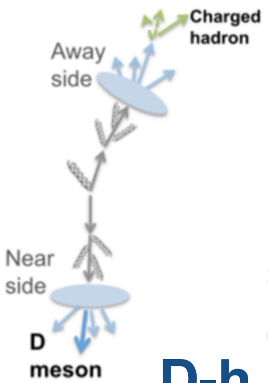
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{+\infty} v_n \cos[n(\varphi - \psi_n)]$$

low p_T: multiple interactions between partons (collectivity)

positive v_2 for HF hadrons —> charm participates to the collective effects in the QGP

D-hadron and e-hadron azimuthal correlations

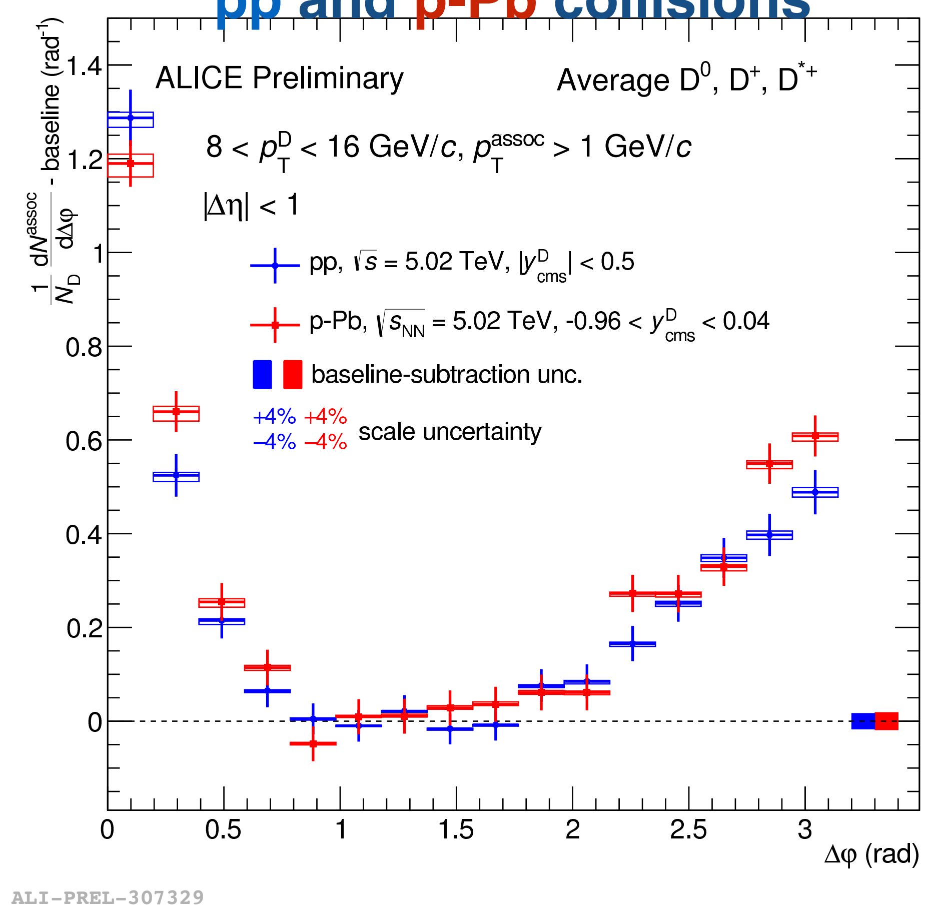
ALICE



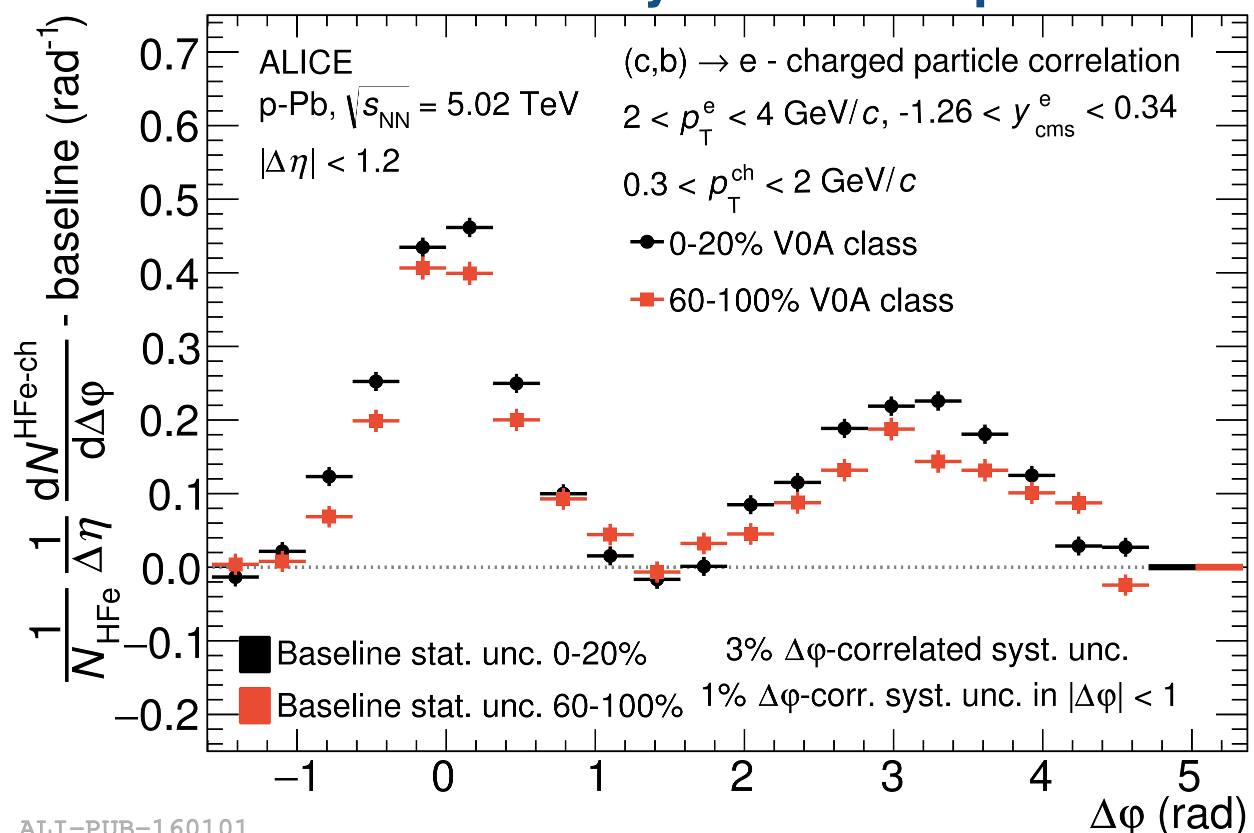
Azimuthal correlations of D mesons and HF decay electrons with charged particles: $\Delta\varphi=\varphi_{e/D}-\varphi_{ch}$ distributions access charm fragmentation and jet properties

investigating the high multiplicity p-Pb collisions

D-h correlation in minimum bias pp and p-Pb collisions



e-h correlation: different centrality classes in p-Pb



arXiv:1805.04367

- **No evidence of modification** of charm quark production and fragmentation **in different collisions systems.**
- references for future Pb-Pb measurements

hint of a enhanced of near and away side peaks distribution in central 0-20% p-Pb collisions than in 60-100%

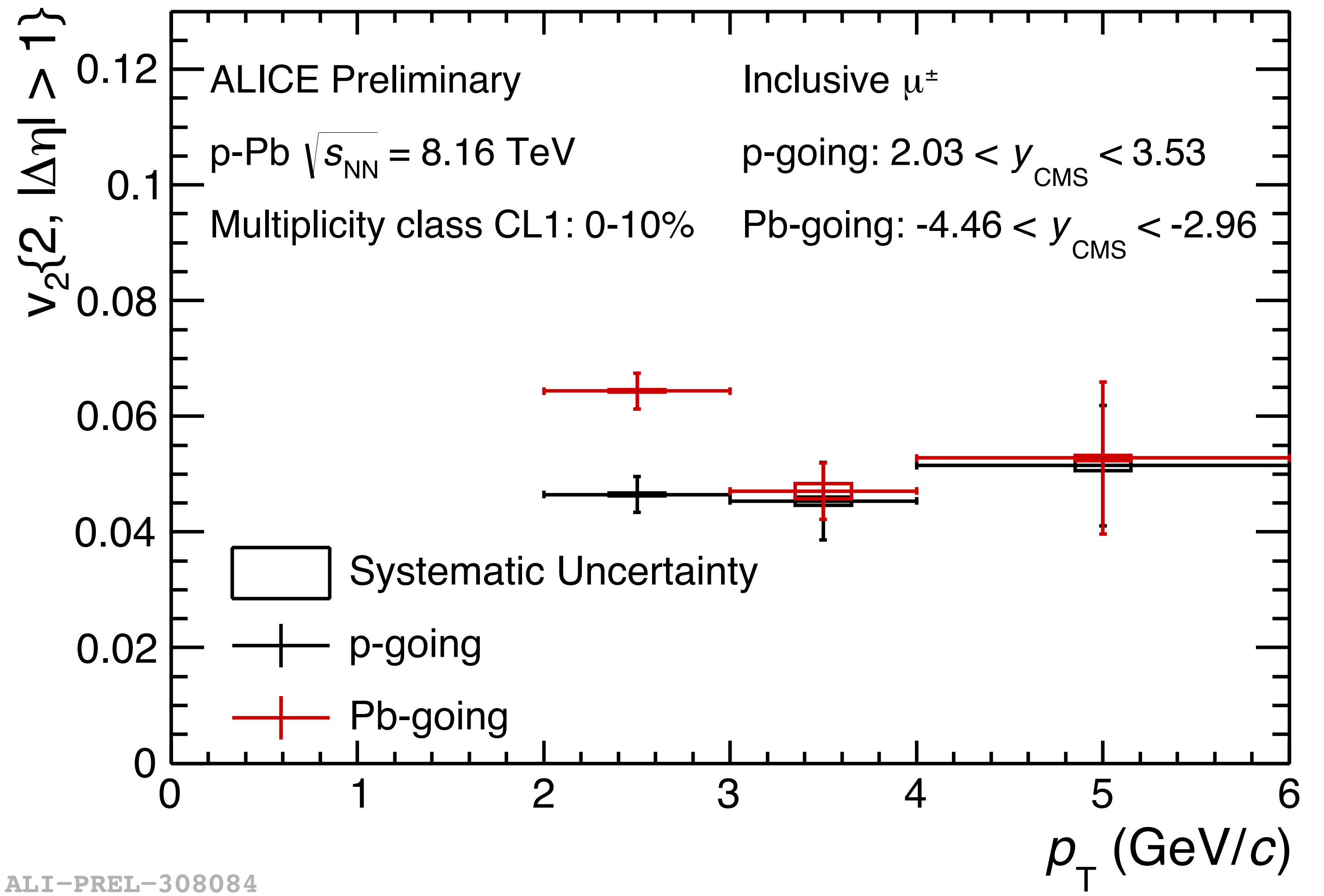
muon v_2

2-particle correlation $\langle\langle 2\rangle\rangle_n = \langle\langle \cos n(\varphi_1 - \varphi_2)\rangle\rangle$

Cumulants expressed in terms of azimuthal corr. $c_n\{2\} = \langle\langle 2\rangle\rangle_n$

Cumulants are directly related to the Fourier coefficients

$$v_n\{2\} = \sqrt{c_n\{2\}}$$



- Rapidity gap between **Particle of interests (P**
  Particles: muons (forward rapidity)

v_2 calculation:

- reference flow $v_2^{ref} = \sqrt{c_n\{2\}}$
- $d_2\{2\}$: differential cumulants (POI correlated with 1 reference particle)

$$v_2\{2\}(p_T, \eta) = \frac{d_2\{2\}}{\sqrt{c_2\{2\}}}$$

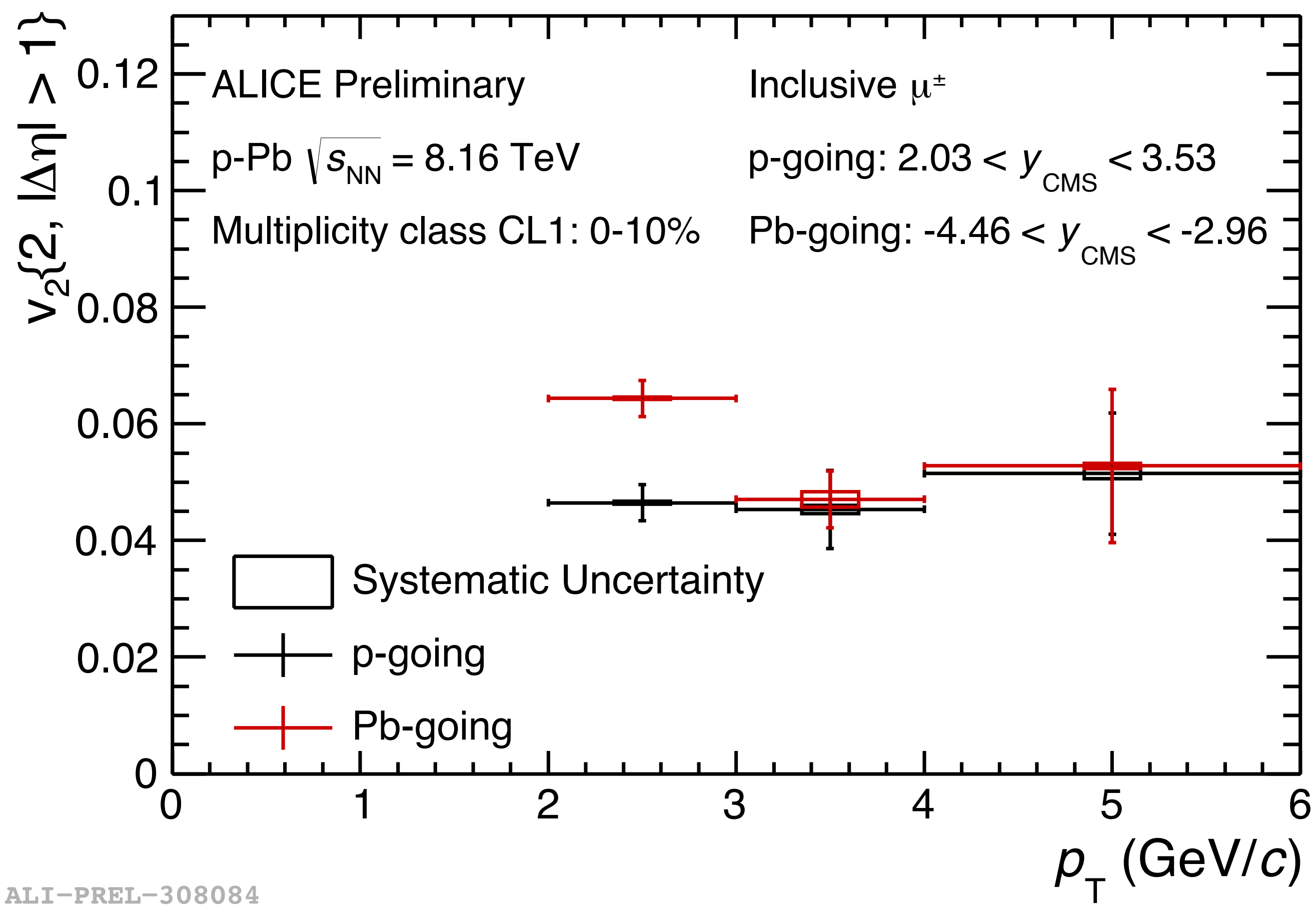
- Non-flow subtracted: few particle correlations not associated to the common symmetry plane
  - Correlations between particles in jets, or from resonance decays, etc.
  - **Non-flow subtraction:** estimated in pp at 13 TeV

$$v_2^{pPb,sub}(p_T) = \frac{d_2^{pPb}(p_T) - k \cdot d_2^{pp}(p_T)}{\sqrt{c_2^{pPb} - k \cdot c_2^{pp}}} \qquad k = \frac{<M>^{pp}(0-100\%)}{<M>^{pPb}(cent)}$$

- Non-Uniform-Acceptance corrections

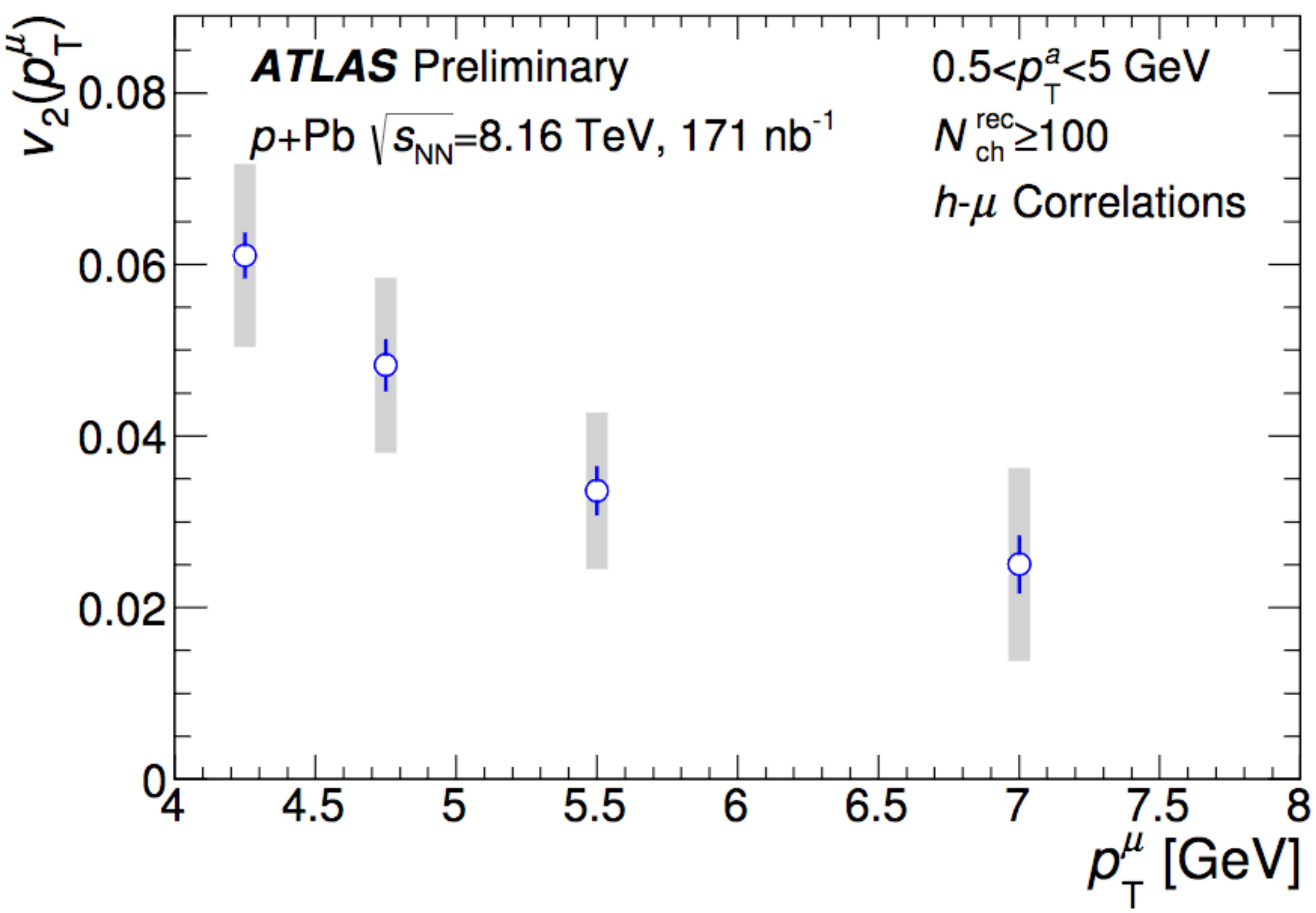
muon v_2

ALICE



ATLAS

https://cds.cern.ch/record/2244808

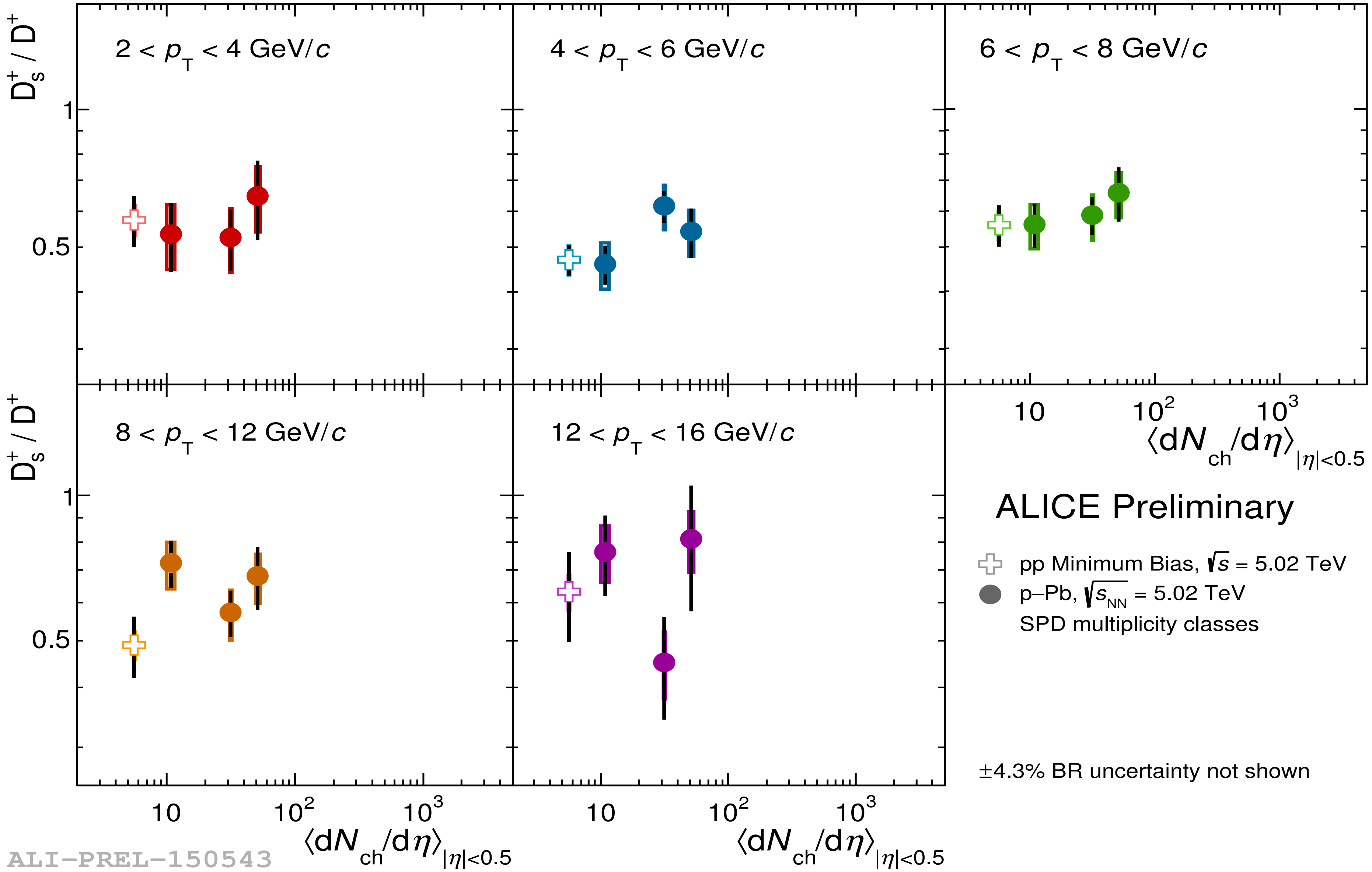


muon v_2
azimuthal correlation with charged particles and muons

$|\eta|<2.5$

Charm hadron ratio: strange/no-strange

investigating the high multiplicity pp and p-Pb collisions

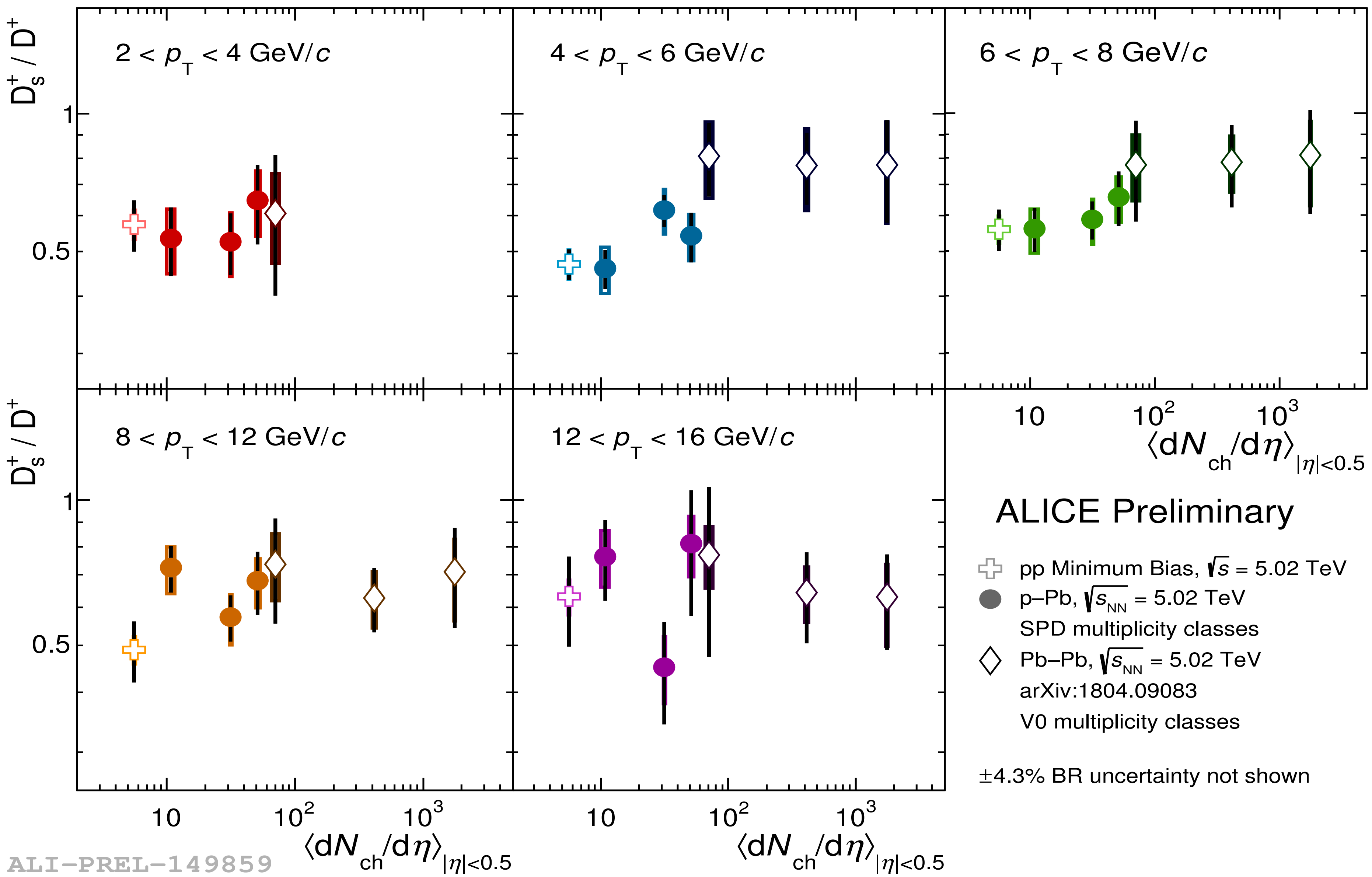


D_s/D^+ measured as a function of multiplicity in different p_T ranges

- ratios compatible in pp and p-Pb collisions
- no dependency with the current uncertainties

Charm hadron ratio: strange/no-strange

investigating the high multiplicity pp and p-Pb collisions



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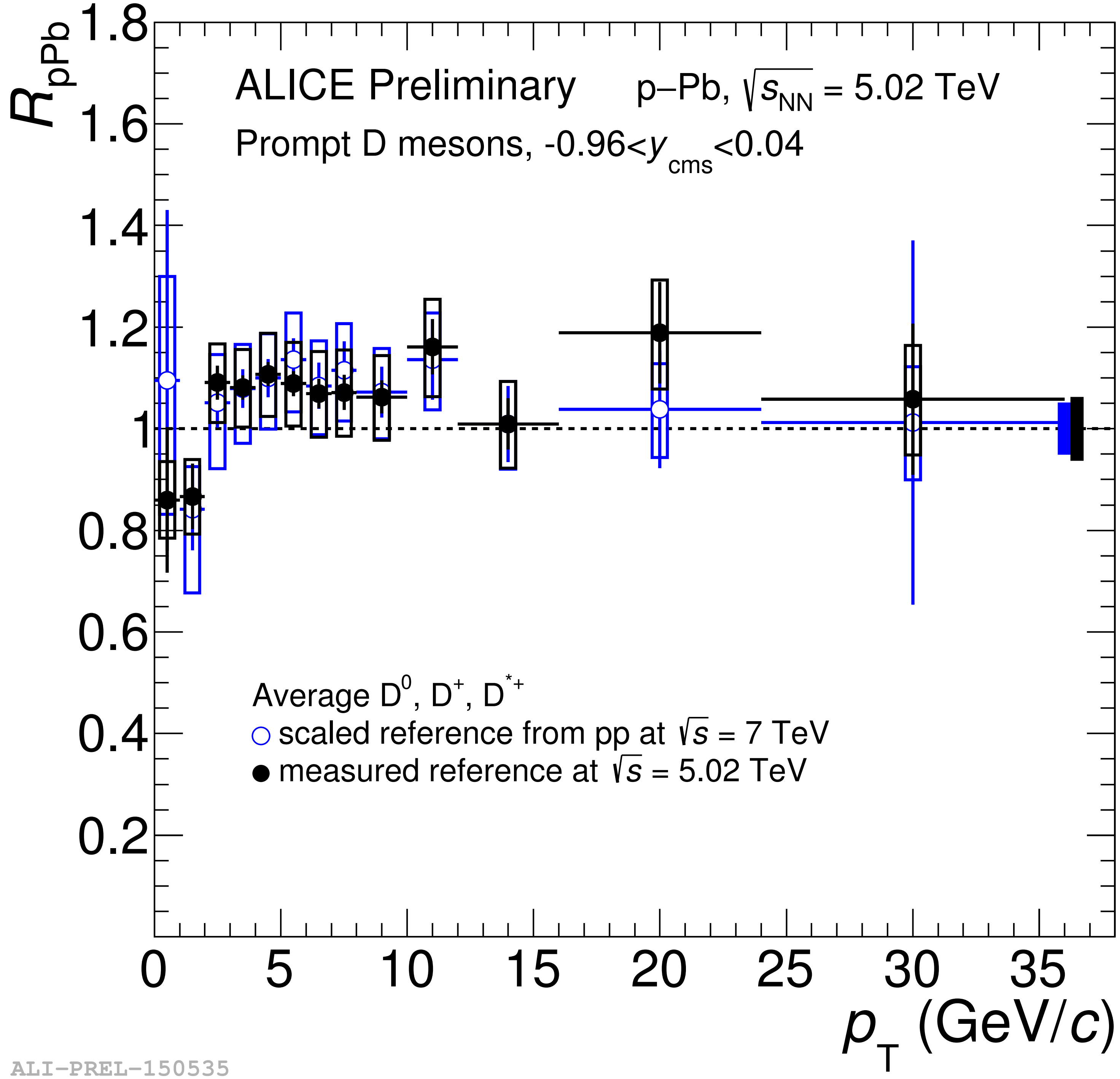
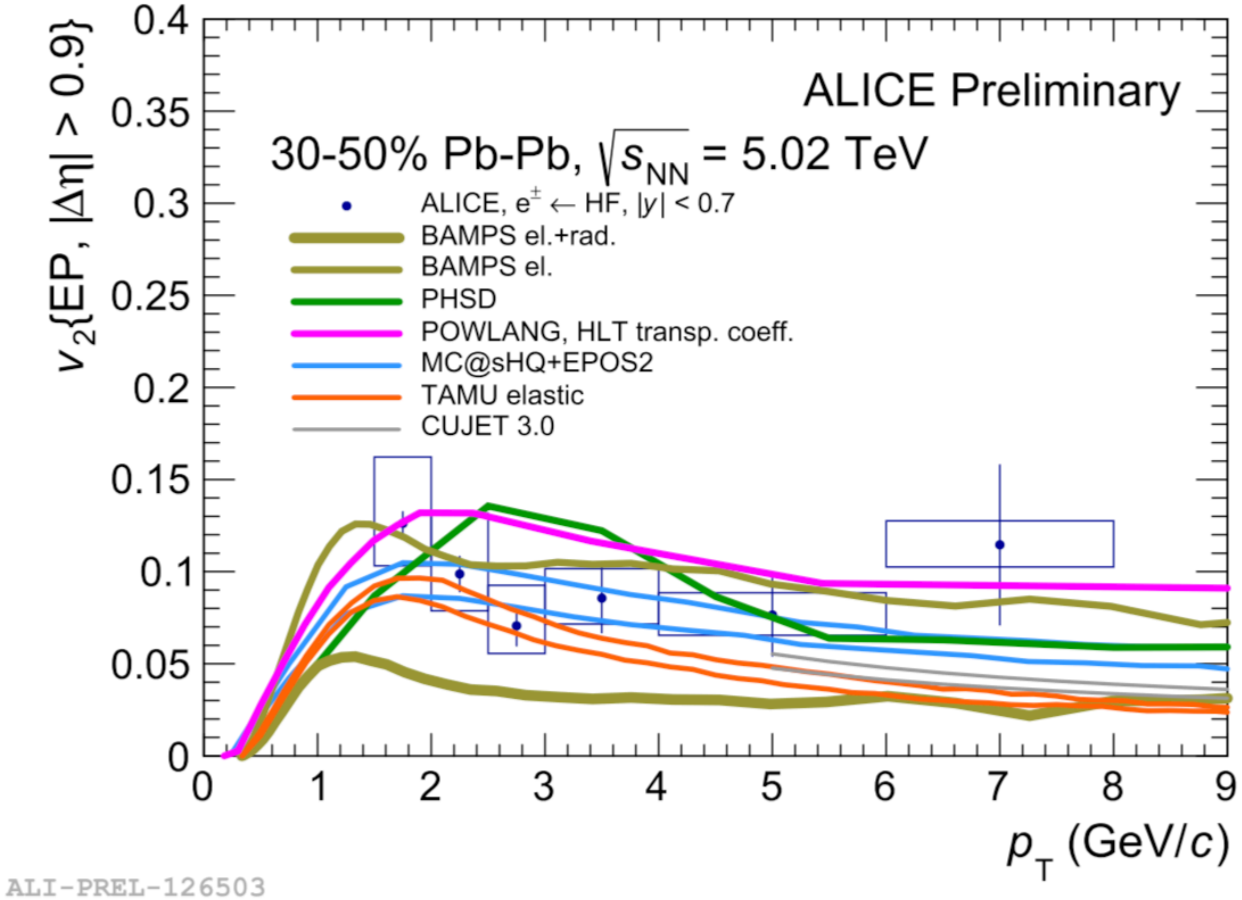
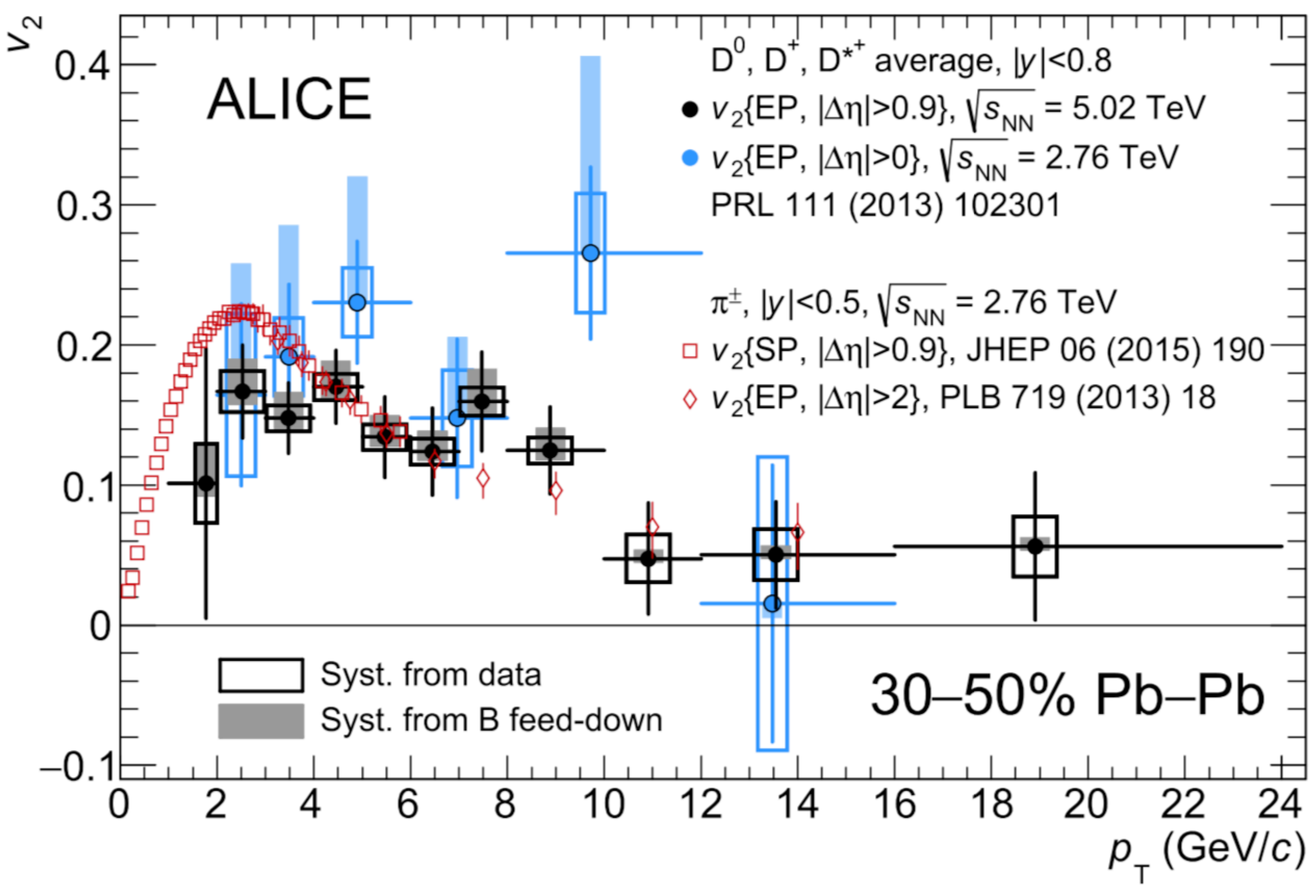
New pp reference: better precision at low pt



HF hadron v_2 in Pb-Pb





Phys. Rev. Lett. 120, 102301

R_{pPb} models

- **CGC**: arXiv:1706.06728
- **FONLL** (JHEP 1210 (2012) 137, arXiv:1205.6344) **with EPPS16 nPDFs** (Eur. Phys. J. C77 no. 3, (2017) 163, arXiv:1612.05741).
- **Vitev et al**: Phys.Rev. C80 (2009) 054902, arXiv: 0904.0032.
- **Kang et al.**: Phys. Lett. B740 (2015) 23–29, arXiv: 1409.2494.
- **Duke**: Nucl. xPart. Phys. Proc. 276-278 (2016) 225–228, arXiv:1510.07520.
- **POWLANG**: JHEP 03 (2016) 123, arXiv: 1512.05186.
- **FONLL** (JHEP 1210 (2012) 137, arXiv:1205.6344 [hep- ph]) with **EPS09NLO** (JHEP 04 (2009) 065, arXiv:0902.4154)
- **Blast wave calculation:** Phys. Lett. B 728 (2014) 25, arXiv:1307.6796
- **Sharma et al:** Phys. Rev. C 80 (2009) 054902, arXiv:0904.0032