Utrecht University

Measurements of D-meson production in p-Pb and Pb-Pb collisions with the ALICE detector at the LHC

Cristina Bedda
Utrecht University
On behalf of the ALICE Collaboration

ICNFP2017

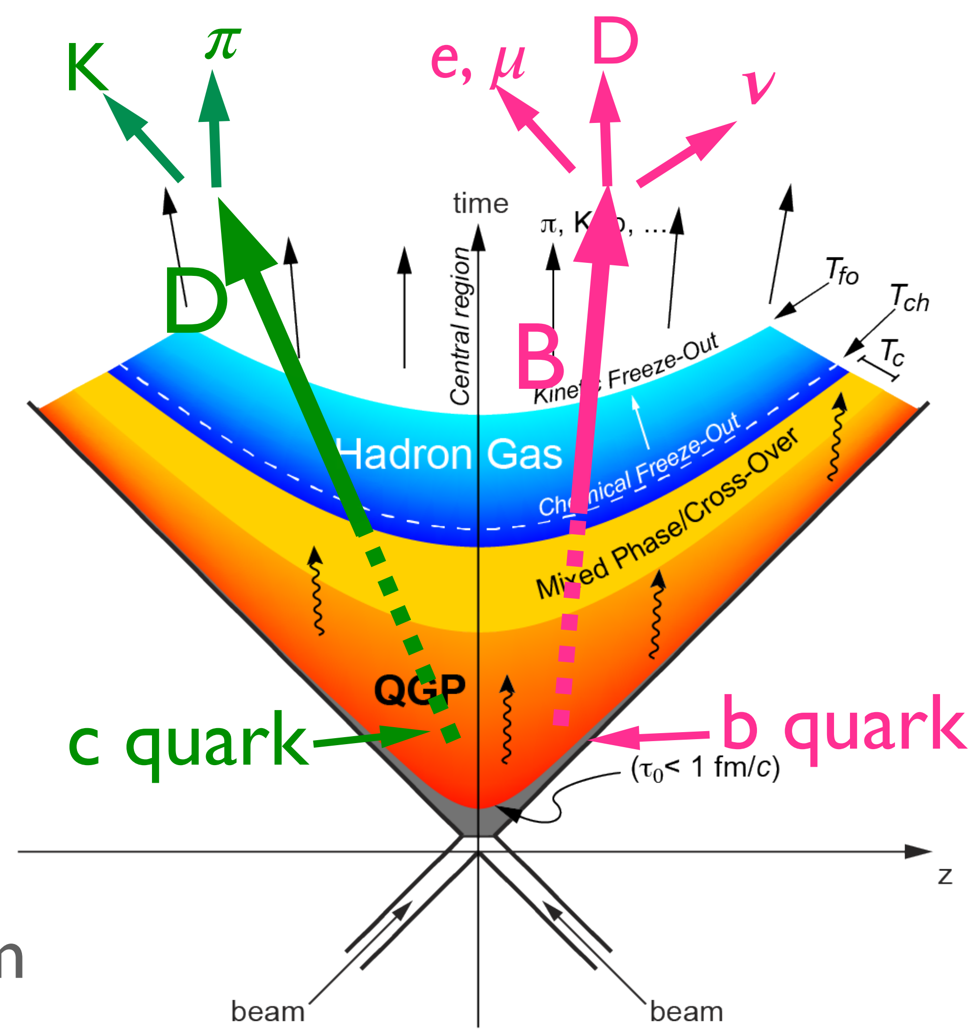
OUTLINE

- Physics motivation
- The ALICE detector
- D-meson reconstruction with ALICE
- Results in p-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV
  - Nuclear modification factor
  - Production vs event multiplicity
- Results in Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV
  - Nuclear modification factor
  - Azimuthal anisotropy (v_2)
- Conclusions

Physics Motivation

- Heavy quarks are produced in hard scattering processes in the initial stages of the collision
  - production time: Δt charm ~ 0.1 fm/c, beauty ~ 0.04 fm/c
  - QGP: ~0.3 fm/c

    F. M. Liu, S. X. Liu, Phys. Rev. C 89, 034906 (2014)



- They experience the whole evolution of the system

  ⟶ sensitive probe to study the QGP formation in Pb-Pb collisions

- Study of p-Pb collisions to disentangle cold nuclear matter effects and possible collective effects in high-multiplicity events

Physical observables

- **Nuclear modification factor**

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

Modification in p-Pb or Pb-Pb with respect to pp collisions

In Pb-Pb collisions allows to study:

- In-medium parton energy loss occurring via collisional and radiative processes
  - color-charge and quark-mass dependence $\longrightarrow \Delta E_g > \Delta E_{u,d} > \Delta E_c > \Delta E_b$
- Modification of hadronisation mechanism in presence of a medium: possible coalescence of charm with medium quarks

Physical observables

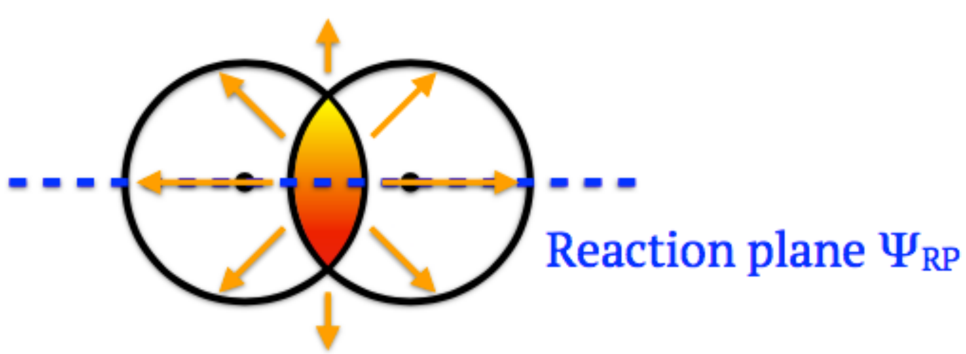
- **Nuclear modification factor**

  Modification in p-Pb or Pb-Pb with respect to pp collisions

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

  In Pb-Pb collisions allows to study:
  - In-medium parton energy loss occurring via collisional and radiative processes
    - color-charge and quark-mass dependence $\longrightarrow \Delta E_g > \Delta E_{u,d} > \Delta E_c > \Delta E_b$
  - Modification of hadronisation mechanism in presence of a medium: possible coalescence of charm with medium quarks

- **Azimuthal anisotropy**

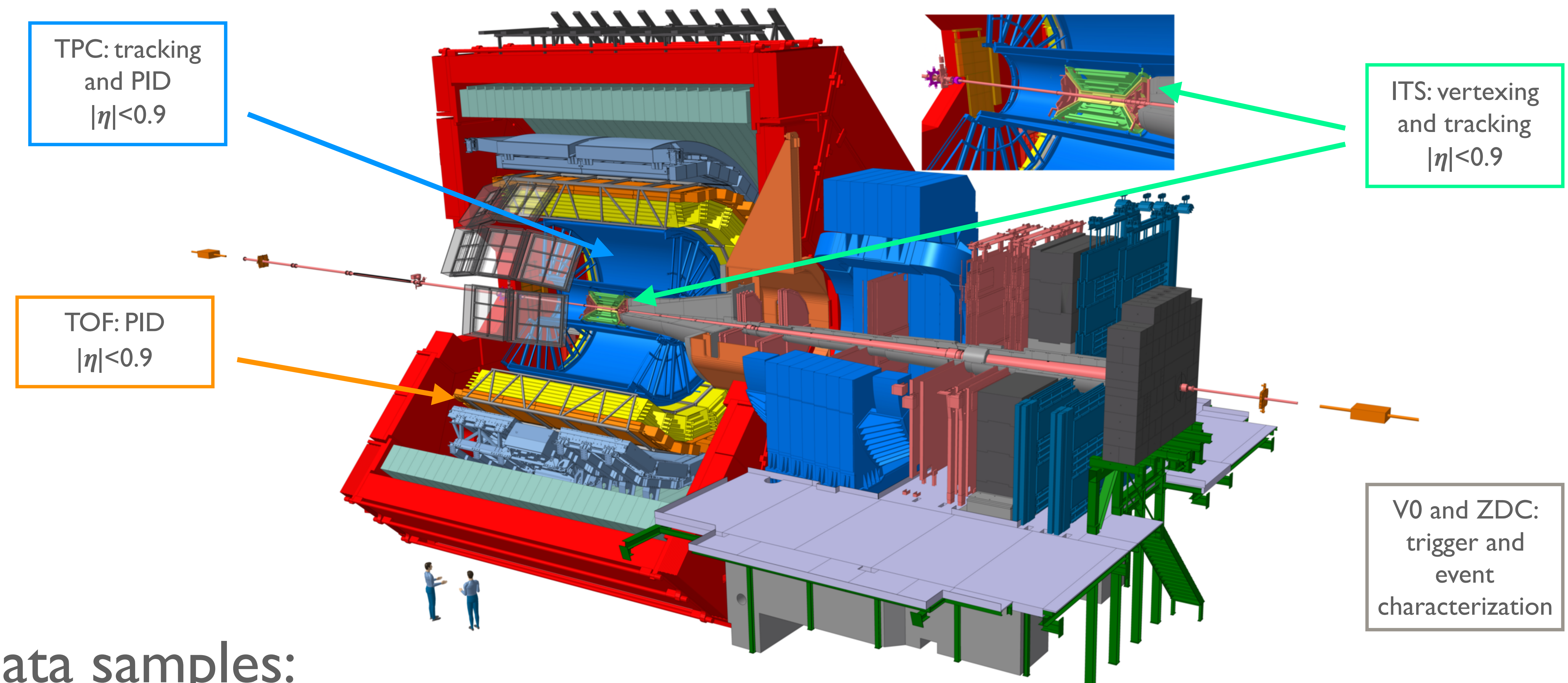


$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3p} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_{\mathrm{T}}\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\left\{1 + \sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_{\mathrm{RP}})]\right\}$$

Elliptic flow: $v_2 = \langle \cos[2(\varphi - \Psi_{\mathrm{RP}})] \rangle$

$v_2 > 0$
- at low p_{T}: thermalization/ collective motion of heavy quarks in the medium
- at high p_{T}: path length dependence of energy loss

The ALICE detector



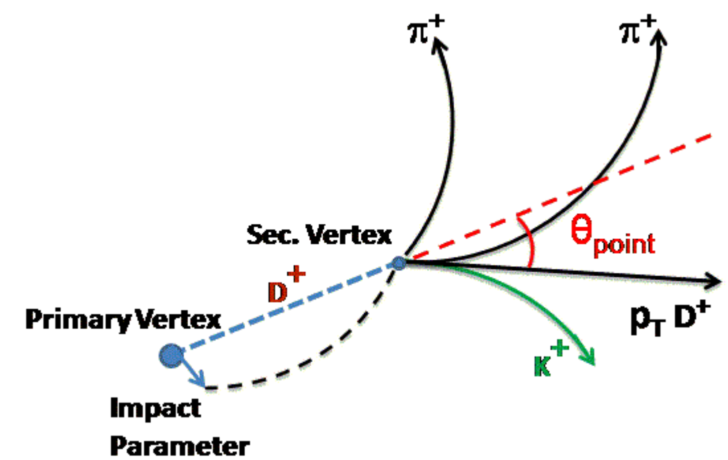
Data samples:

- p-Pb collisions (Run2): 600 M minimum bias events
- Pb-Pb collisions (Run2): 10 M events in the centrality class 0-10%, 20 M events in 30-50% and 20 M events in 60-80%

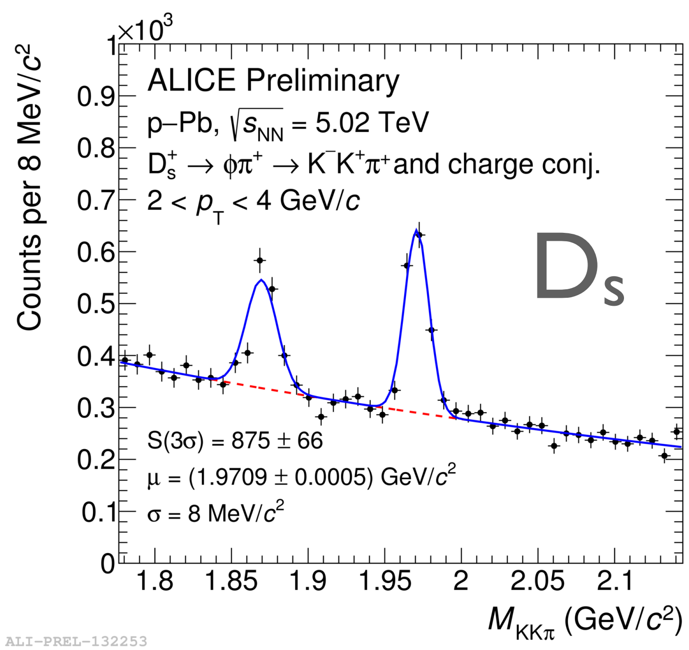
D-meson reconstruction

Reconstruction of **hadronic decay channels**

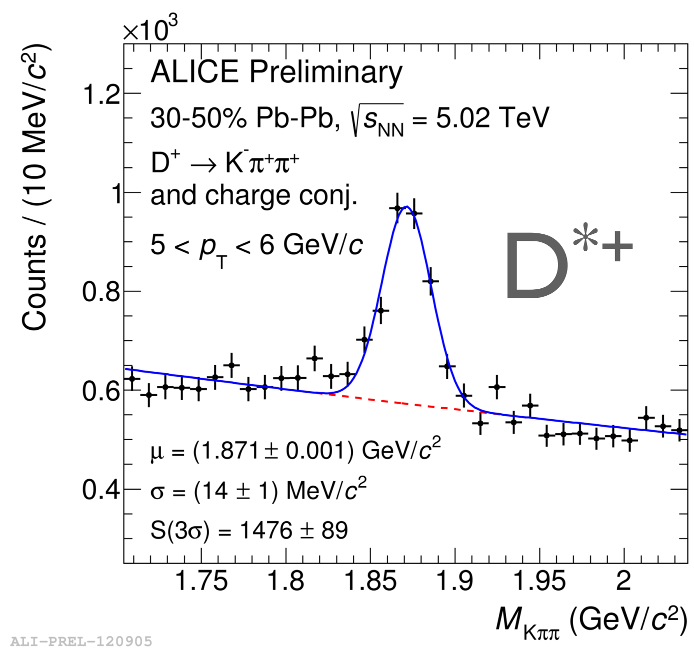
meson	M (GeV/c^2)	$c\tau$ (μm)	decay	BR (%)
D^0 ($c\bar{u}$)	1.865	123	$K^-\pi^+$	3.93
D^+ ($c\bar{d}$)	1.870	312	$K^-\pi^+\pi^+$	9.46
D^{*+} ($c\bar{d}$)	2.010	Γ = 83.3 KeV	$D^0(K^-\pi^+)\pi^+$	67.7 x 3.93
D^+_s ($c\bar{s}$)	1.968	150	$\Phi(K^-K^+)\pi^+$	2.27



- Signal extracted from invariant-mass distributions



ALICE-PUBLIC-2017-008



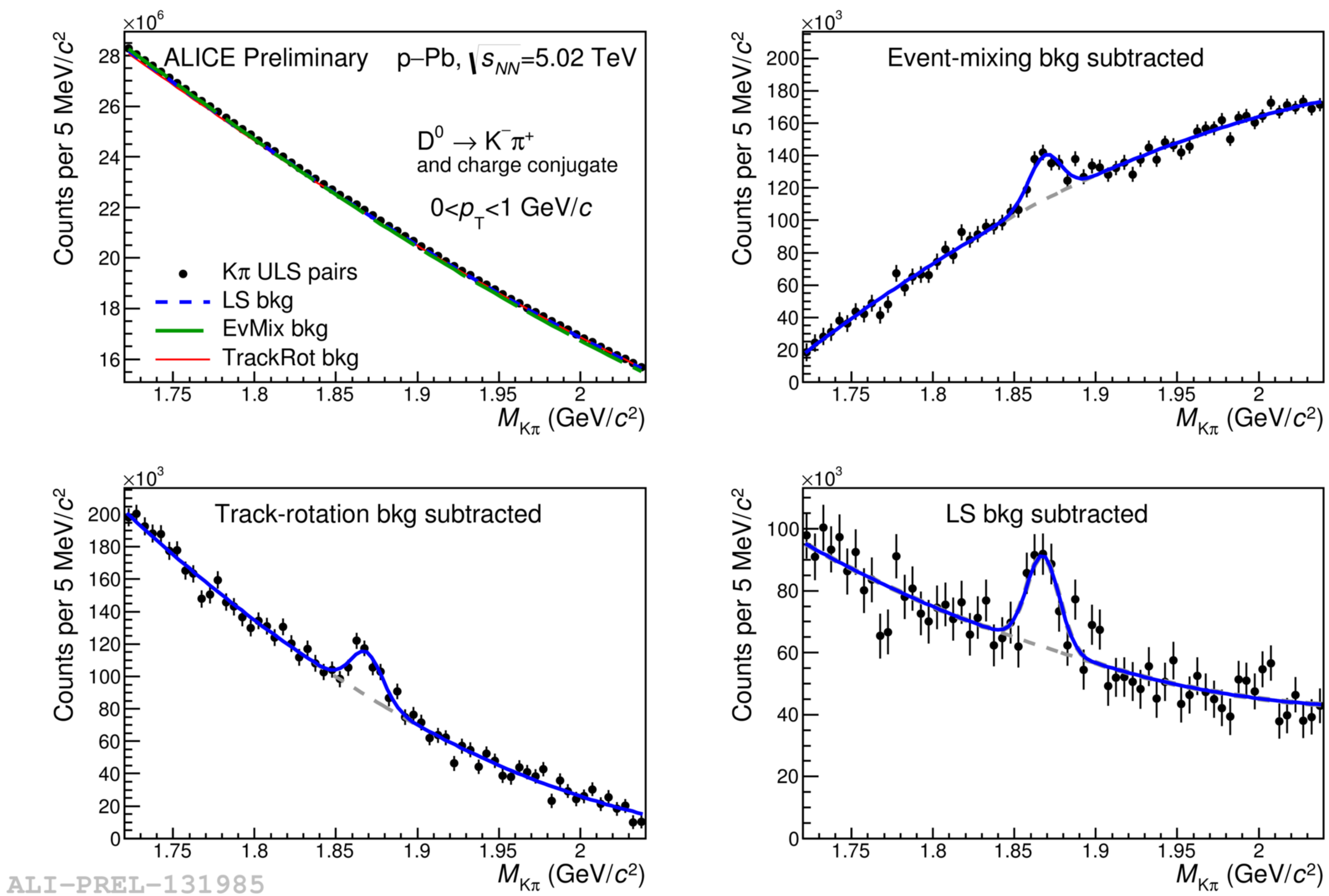
ALICE-PUBLIC-2017-005

Standard method:

- Identification of secondary vertices displaced few hundred μm from the primary vertices
- Topological selections and PID to reduce background

D-meson reconstruction

Background-subtraction method (D^0 only)



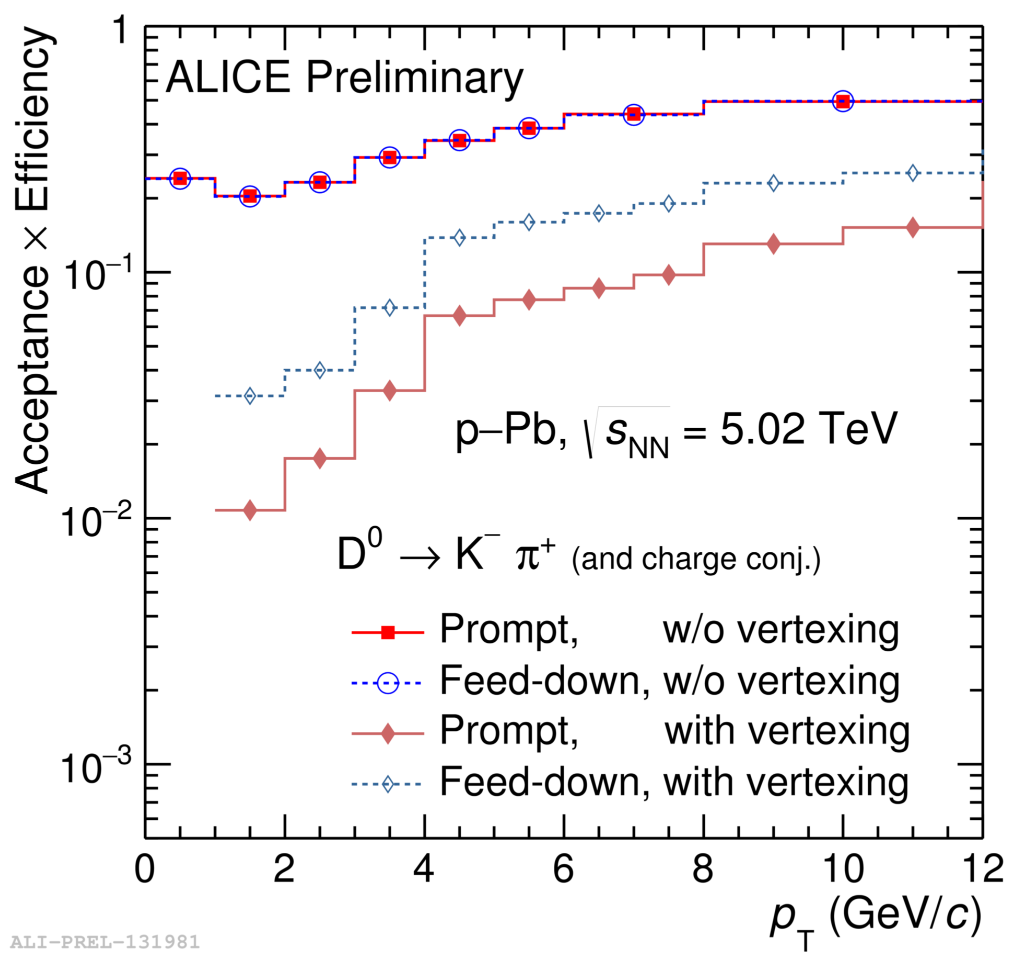
ALICE-PUBLIC-2017-008

- Without vertex reconstruction
- PID selection only
- Combinatorial background subtraction via: event mixing, like sign, track rotation, side-band fit
- Method effective for low p_T (<1 GeV/c), that decay very close to the primary vertex

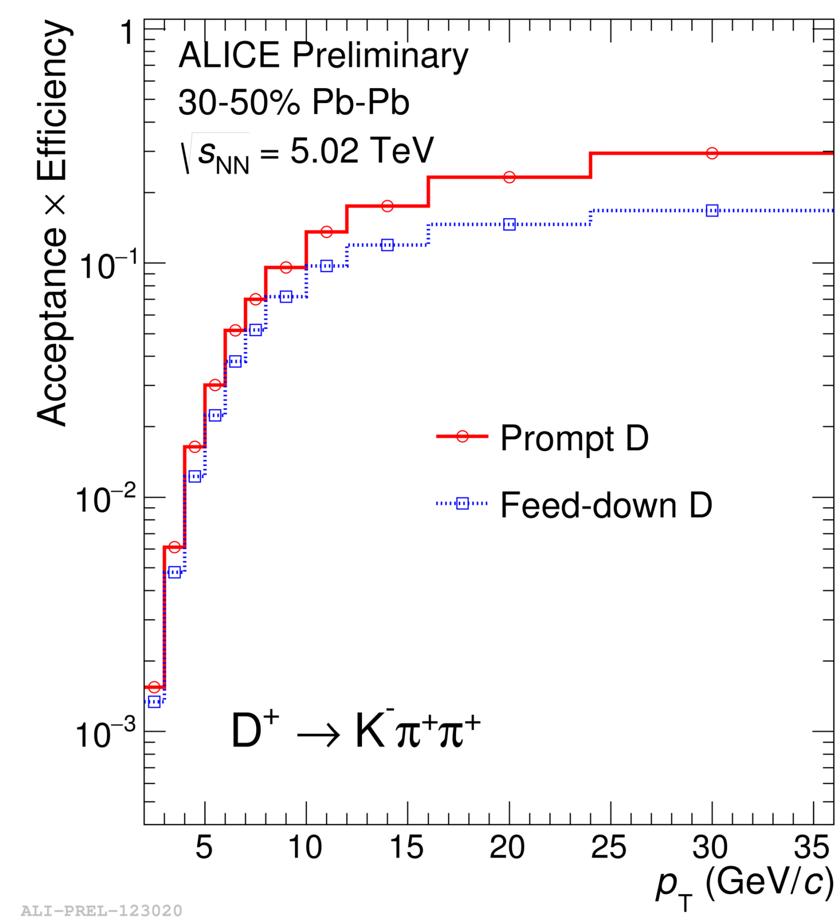
D-meson reconstruction

- Signal extracted corrected using Monte Carlo simulations for the acceptance of the detector and the selection efficiencies

p-Pb collisions



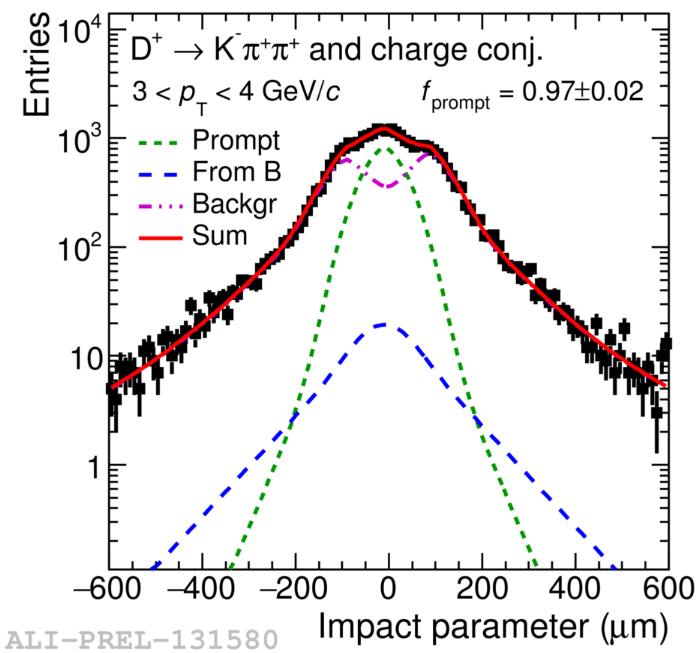
Pb-Pb collisions

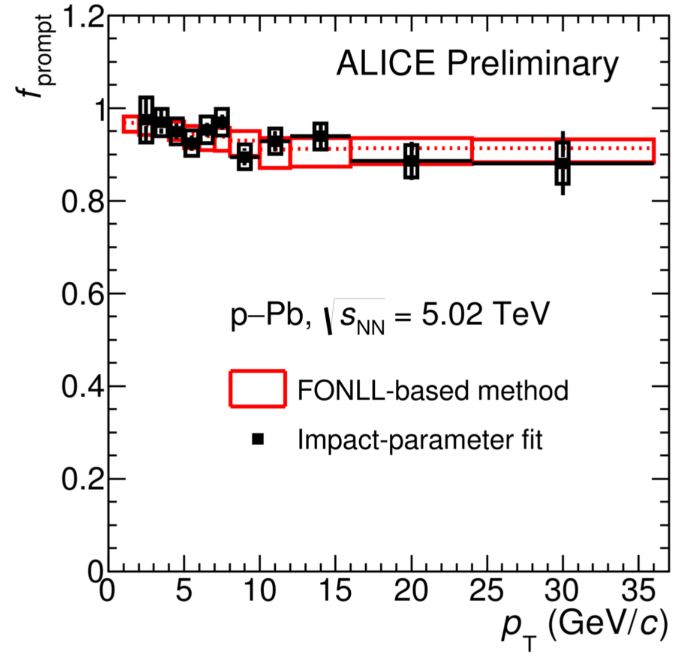


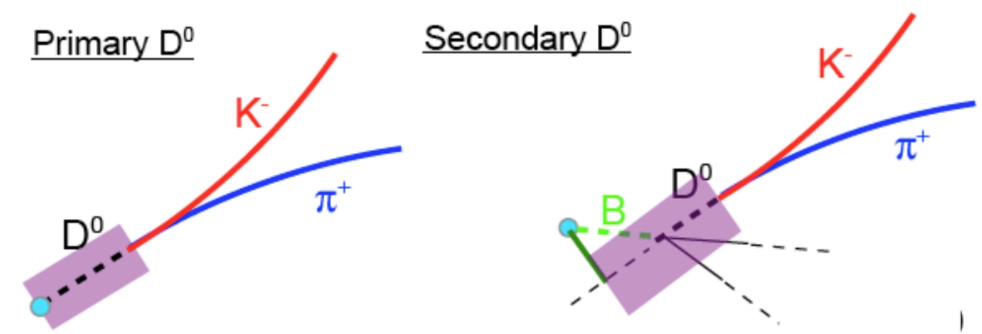
- Higher efficiency by a factor of 20 without vertex reconstruction for $1<p_T<2$ GeV/c
- Better S/B and significance with the "standard method" for $p_T>1$ GeV/c

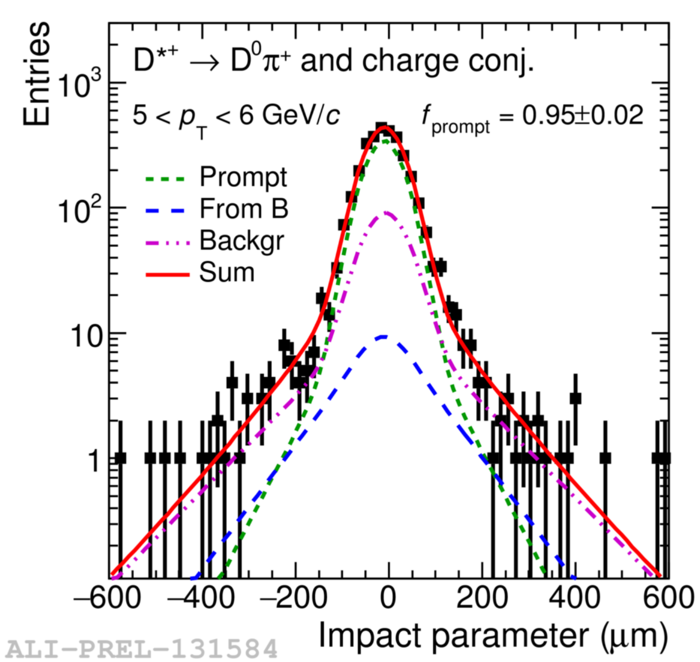
D-meson reconstruction

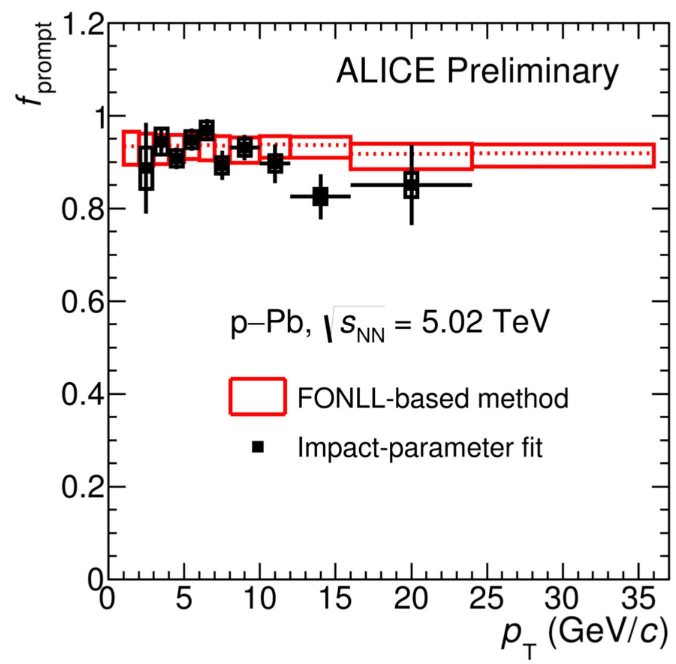
- Feed-down from b-hadrons subtracted with a FONLL-based method











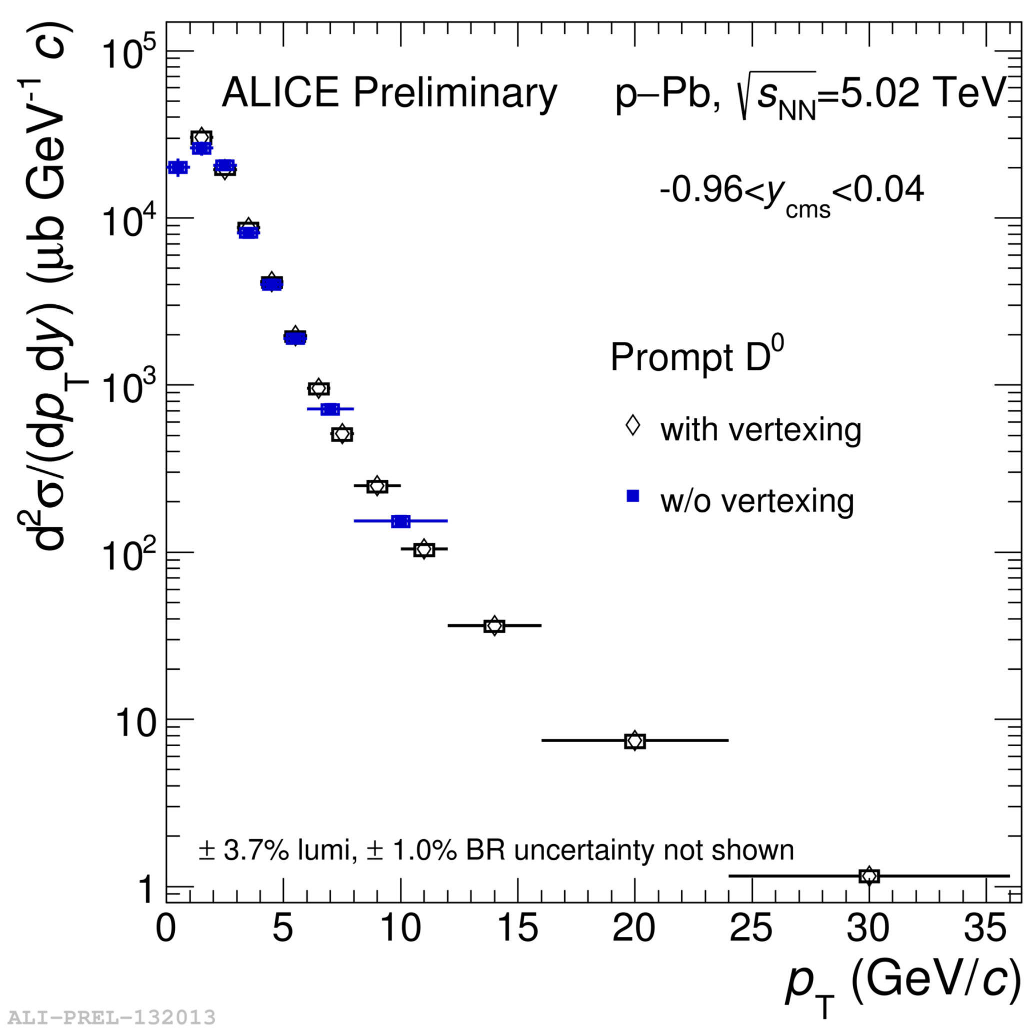
- Alternative data-driven method exploits the different shape of prompt and feed-down impact parameter distributions
- **Agreement between data driven and FONLL-based methods**

ALICE-PUBLIC-2017-008

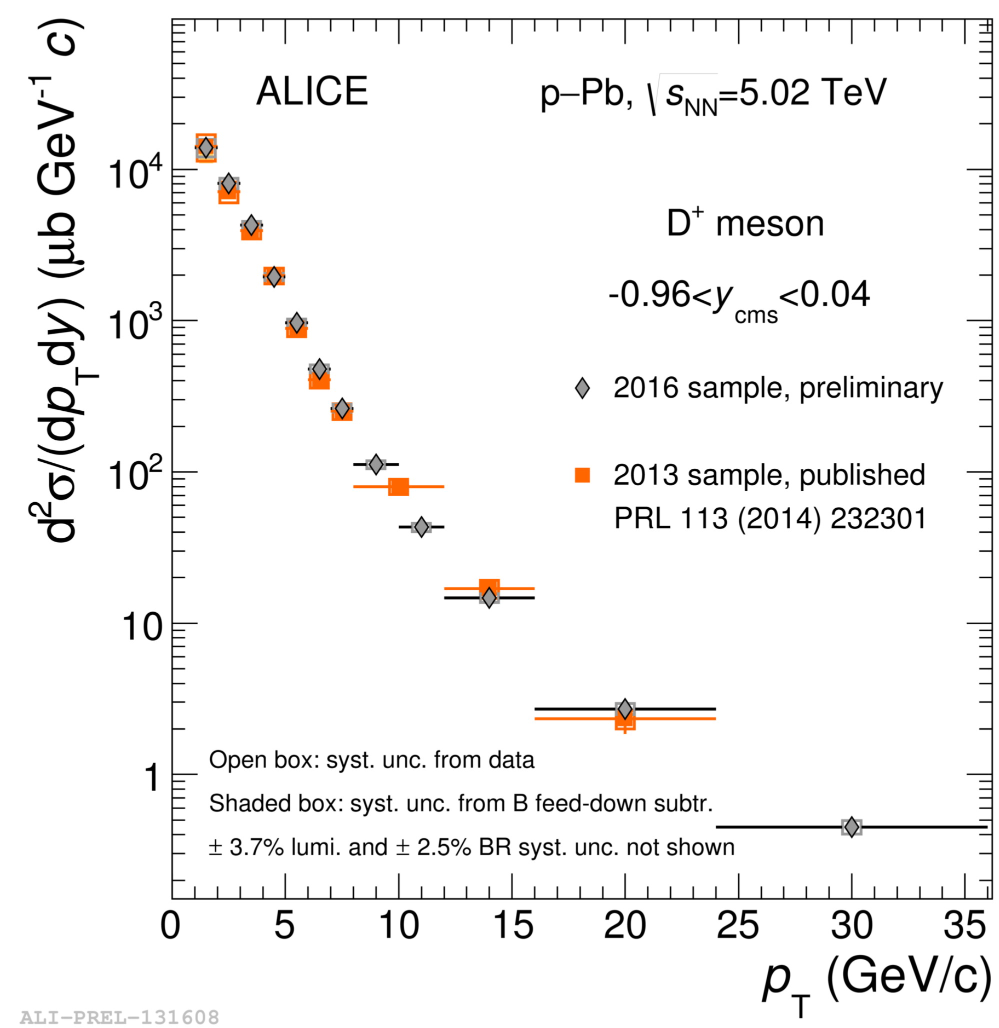
p-Pb collisions

D-meson cross section

ALICE-PUBLIC-2017-008



PRL113 n23 (2014) ,PRC94 n5(2016)

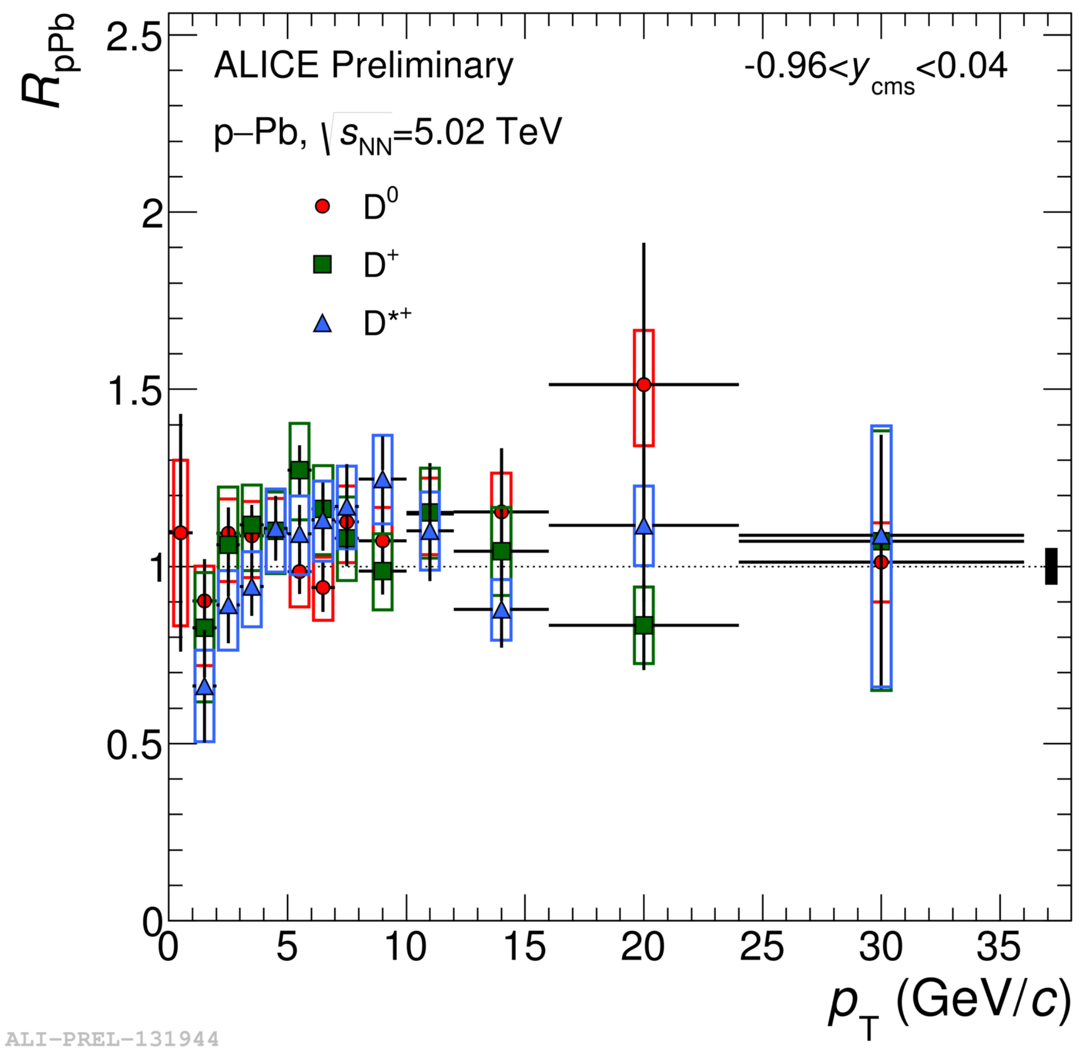


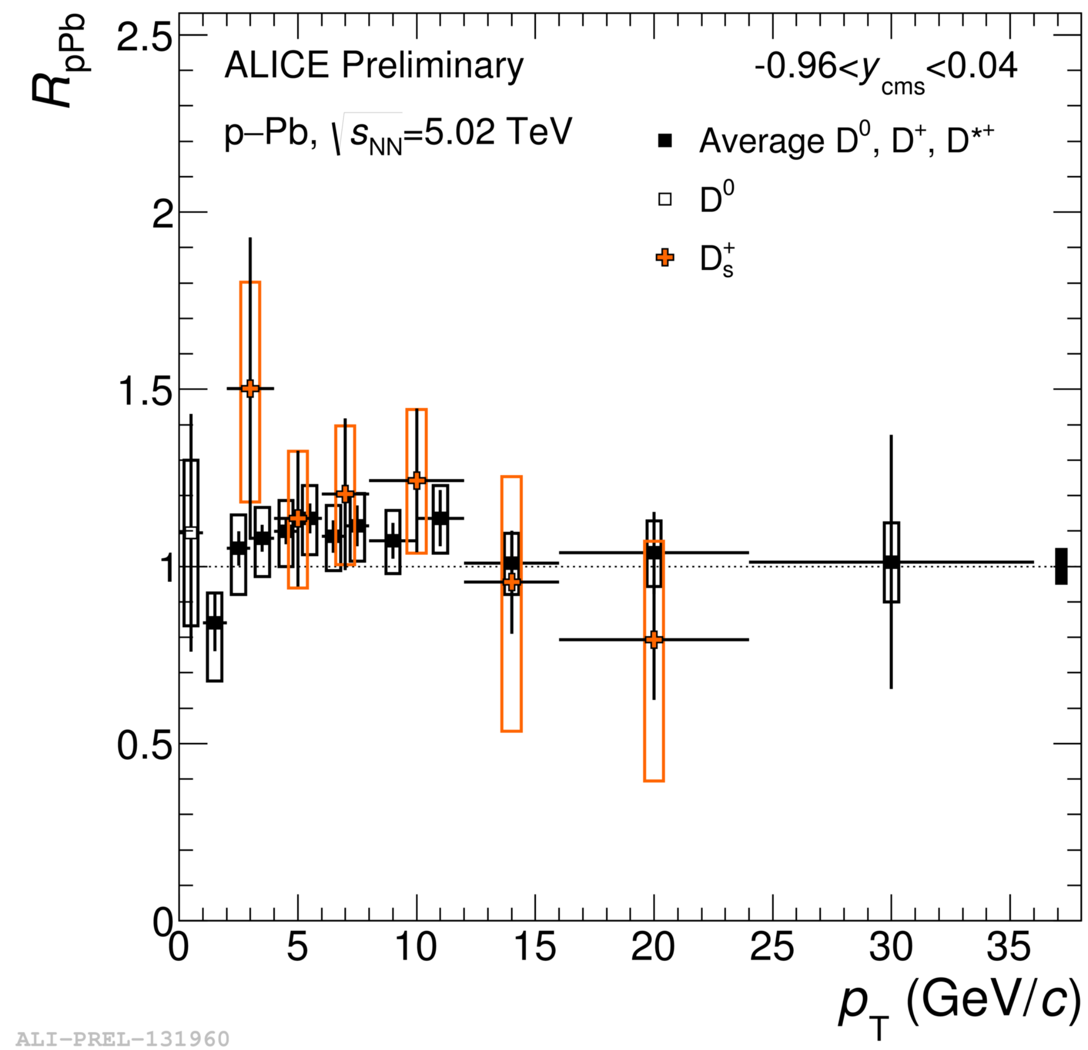
- **Prompt D^0 p_T-differential cross section** with and w/o vertexing method **down to p_T=0**, consistent results for p_T>1 GeV/c
- Prompt D-meson cross section **consistent between Run1 and Run2:**
  - reduced uncertainties and extended p_T coverage with Run2 data

D-meson R_{pPb}

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

ALICE-PUBLIC-2017-008



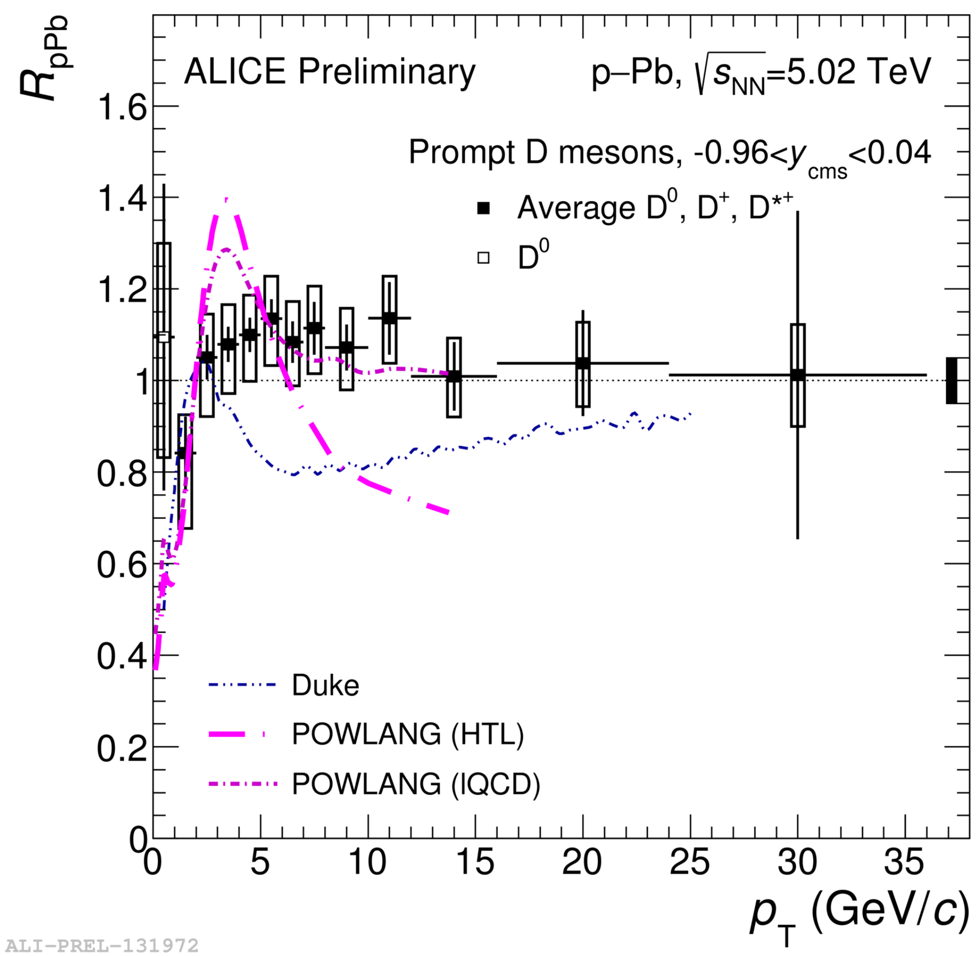


- Nuclear modification factor of D^0, D^+ and D^* mesons compatible within uncertainties
- **Non-strange D-meson R_{pPb} compatible with unity**
- **D_s R_{pPb} compatible with non-strange D mesons** within uncertainties

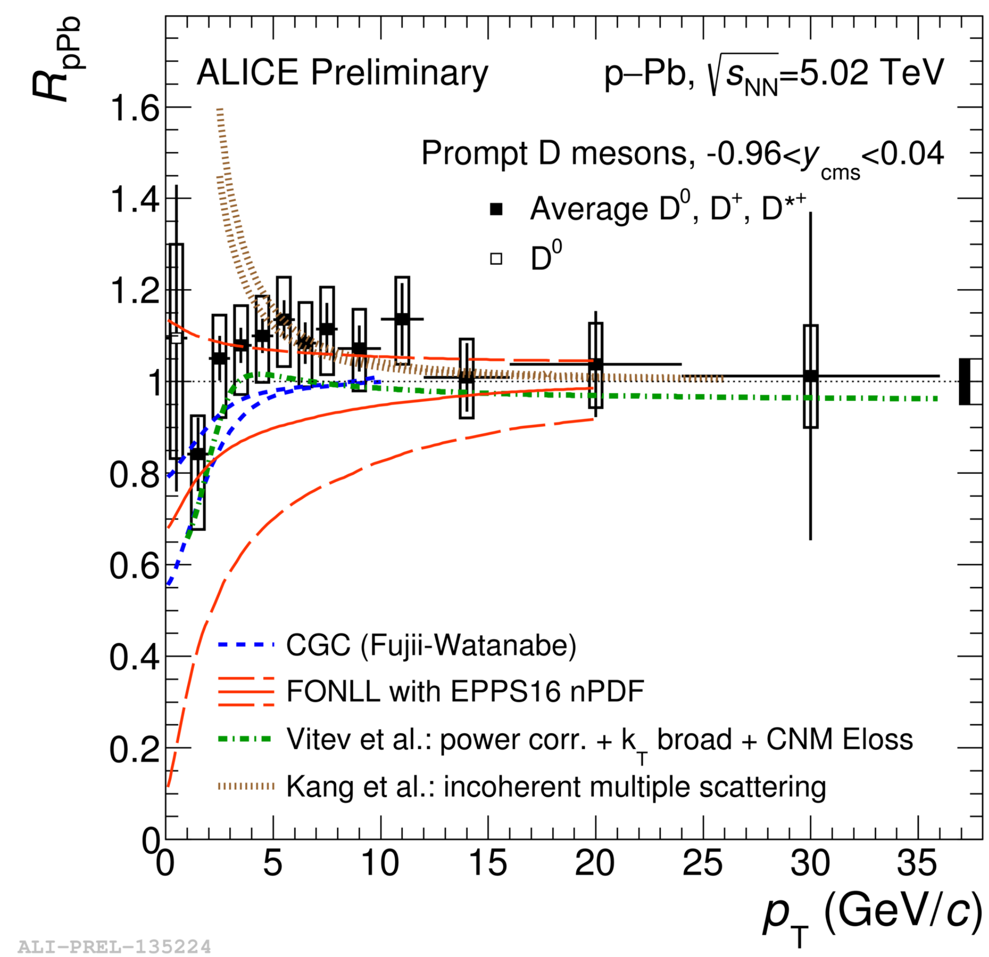
D-meson R_{pPb}

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

Models including QGP formation in p-Pb collisions



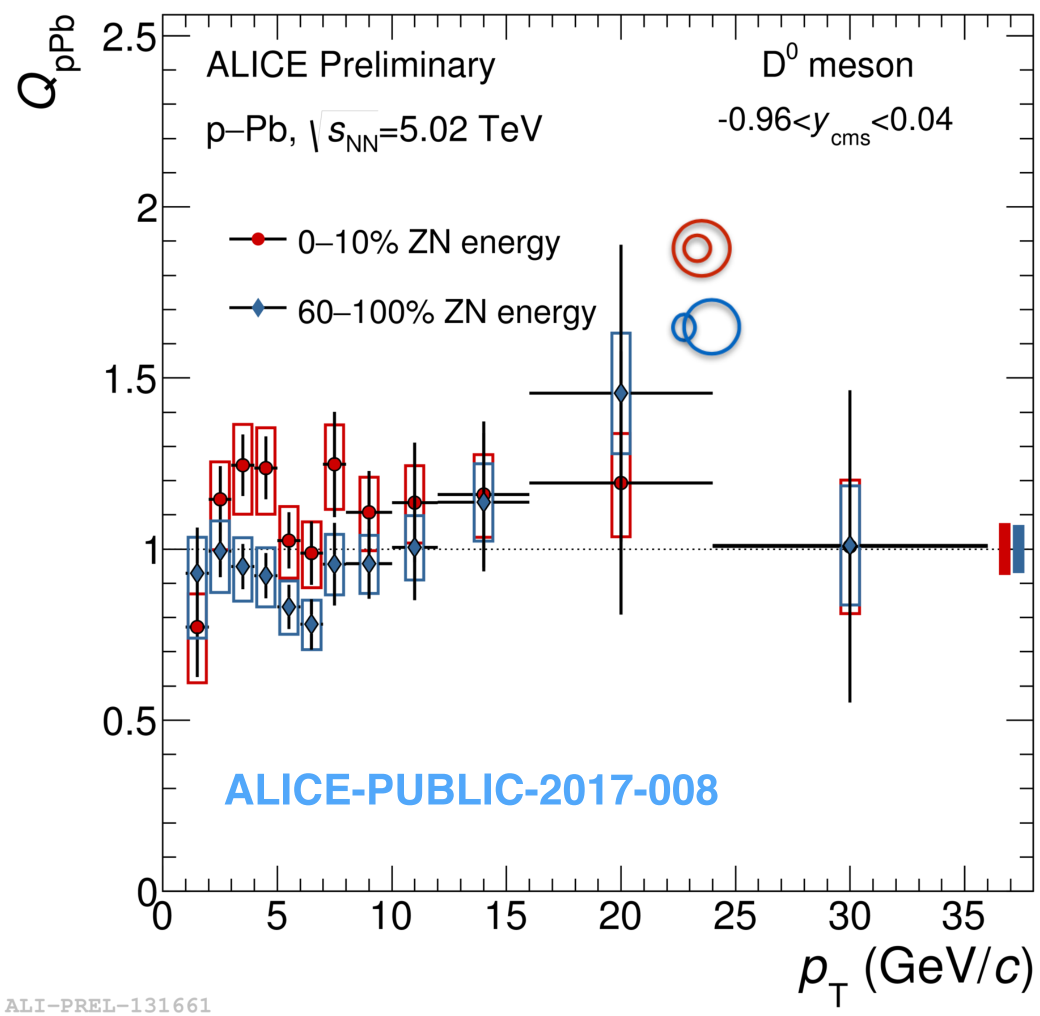
Models including CNM effects and incoherent multiple scattering



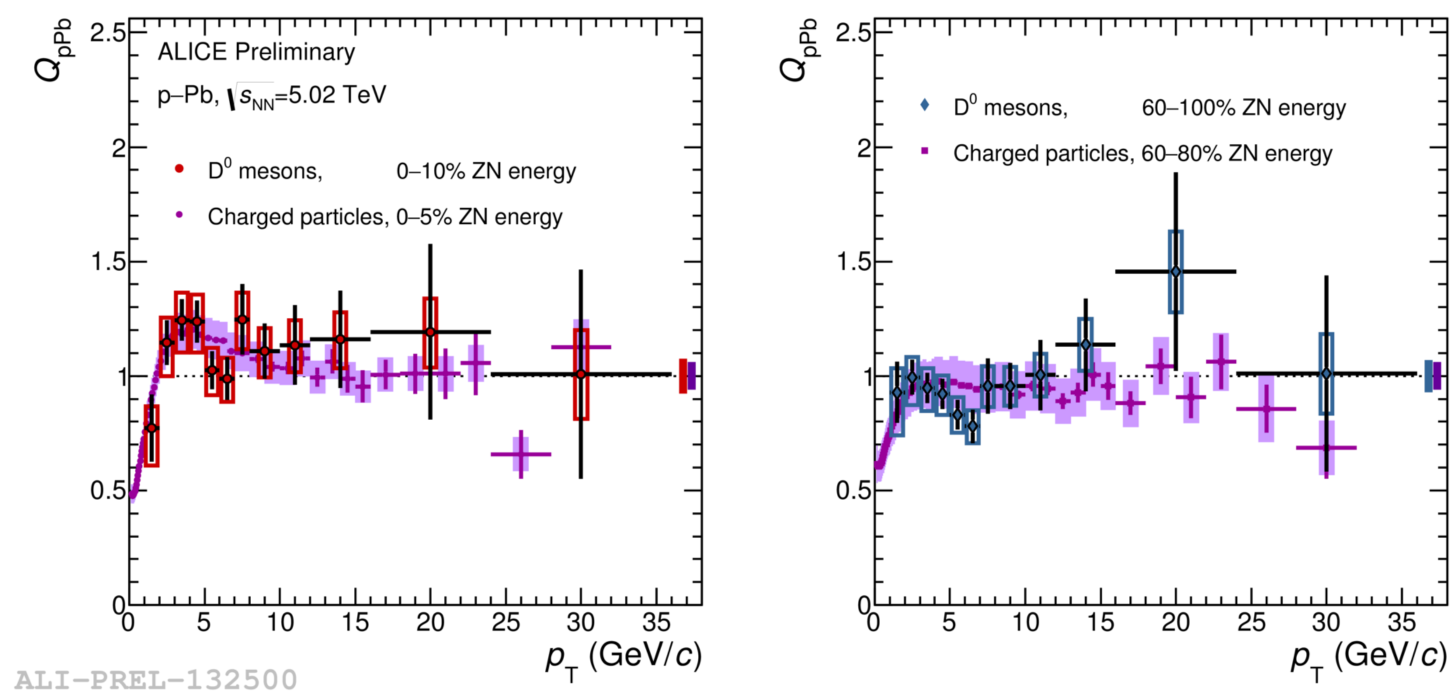
ALICE-PUBLIC-2017-008

- Data described by models including CNM effects, as well as effects deriving from the formation of QGP in p-Pb collisions
- Disfavour QGP models that predict suppression >10-15% at high p_T

D-meson production vs centrality



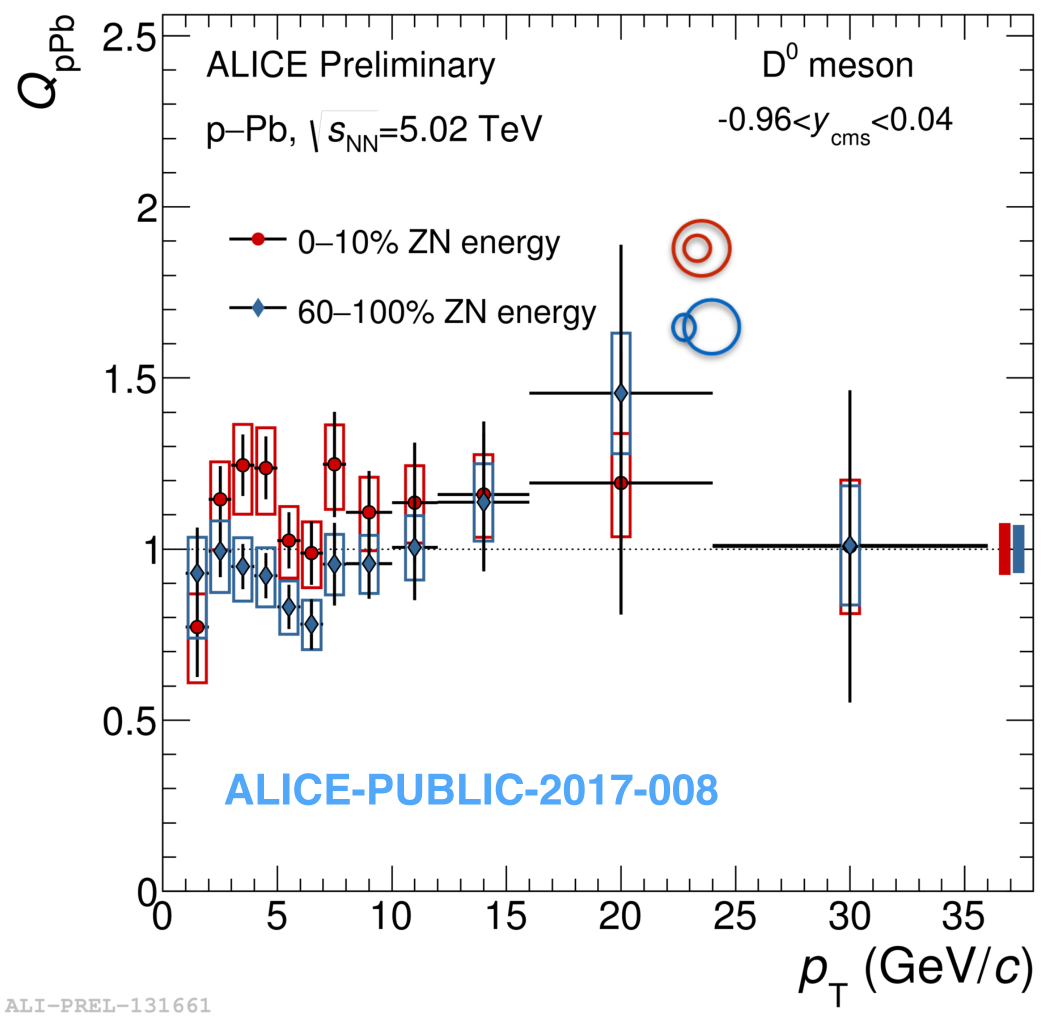
$$Q_{pPb} = \frac{\left(\frac{dN^D}{dp_T}\right)_{pPb}}{T_{pPb} \times \left(\frac{d\sigma^D}{dp_T}\right)_{pp}} \qquad \langle T_{pPb} \rangle = \frac{\langle N_{coll} \rangle}{\sigma_{NN}}$$



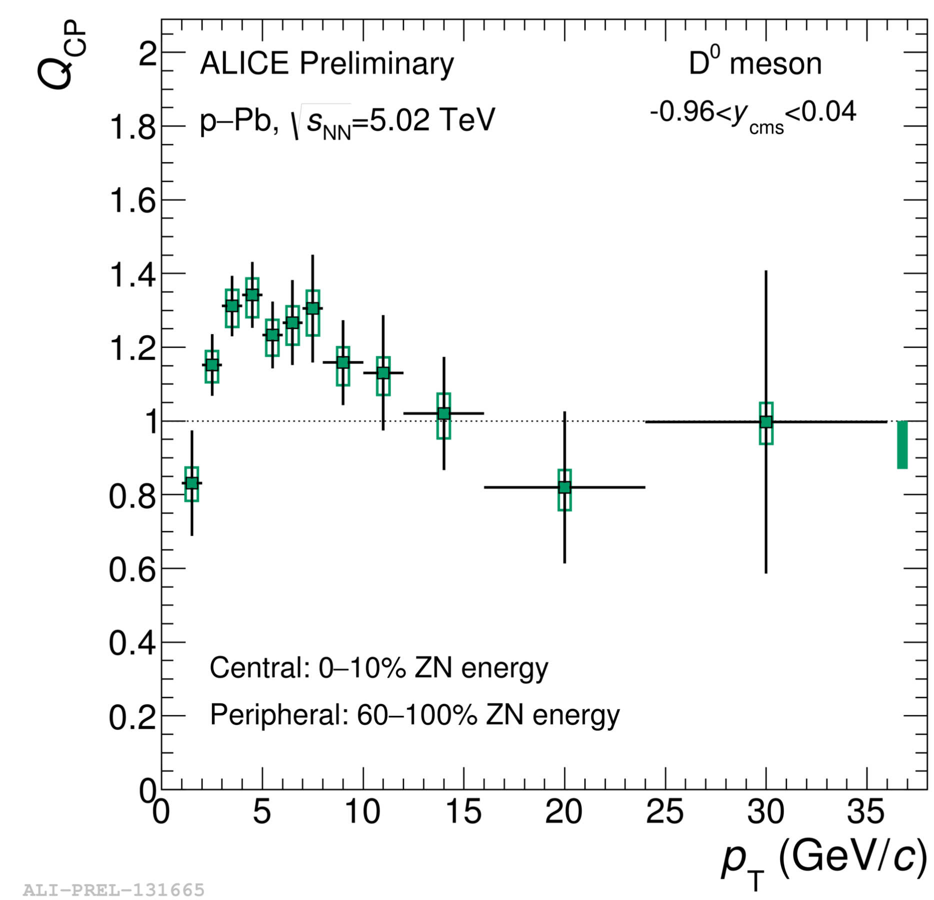
- Centrality classes obtained from the energy deposited in the neutron calorimeter on Pb-going side (ZNA)
- Q_{pPb} in most central and peripheral centrality ranges are compatible within uncertainties

- **D^0 Q_{pPb} in agreement with charge-particles Q_{pPb}**
  - caveat: slightly different centrality ranges

D-meson production vs centrality



Q_{CP}: ratio central/peripheral
more precise measurement



ALICE-PUBLIC-2017-008

- Centrality classes obtained from the energy deposited in the neutron calorimeter on Pb-going side (ZNA)
- Q_{pPb} in most central and peripheral centrality ranges are compatible within uncertainties

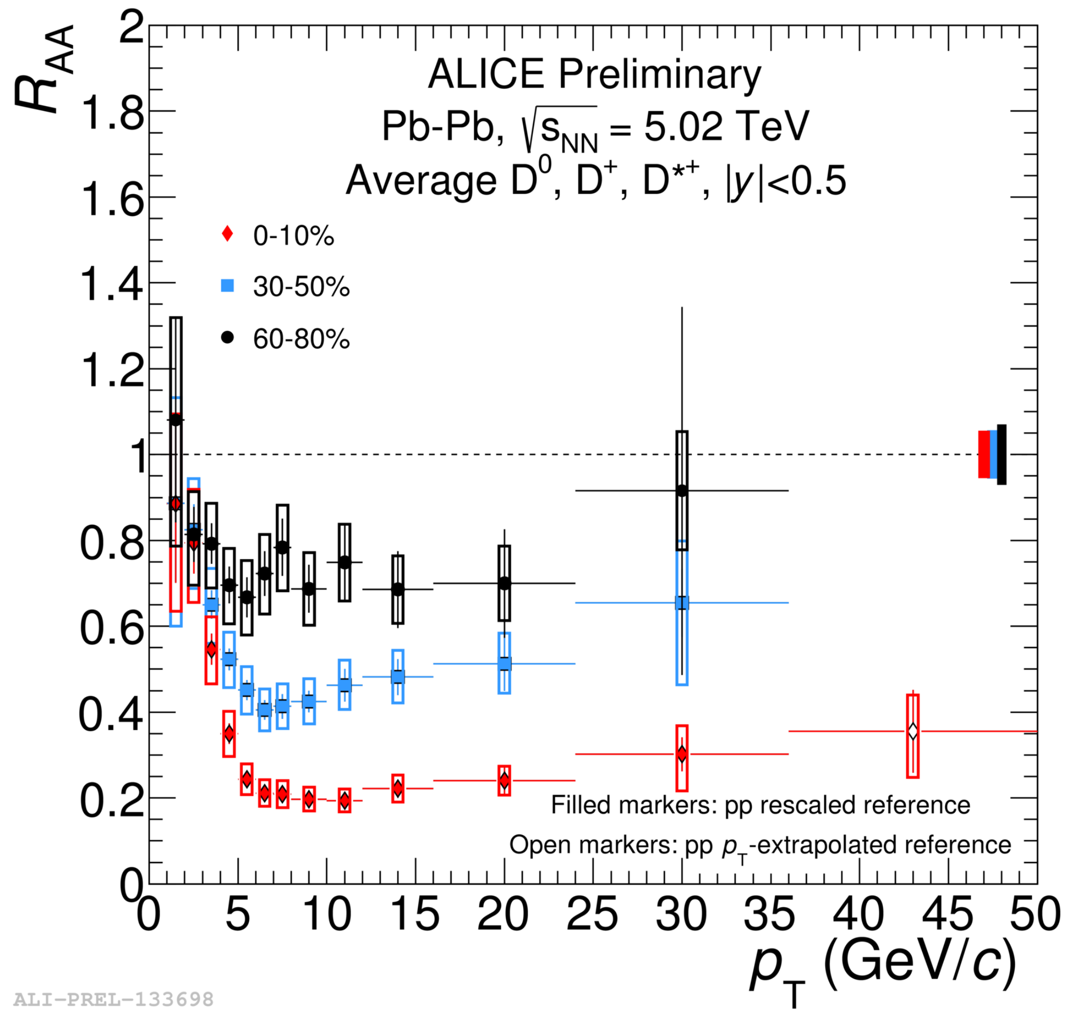
- **Hint of Q_{CP} >1 in 3-8 GeV/c with 1.7σ**
  - Initial or final state effect?
  - Possible influence of radial flow on heavy-flavour hadrons in p-Pb collisions

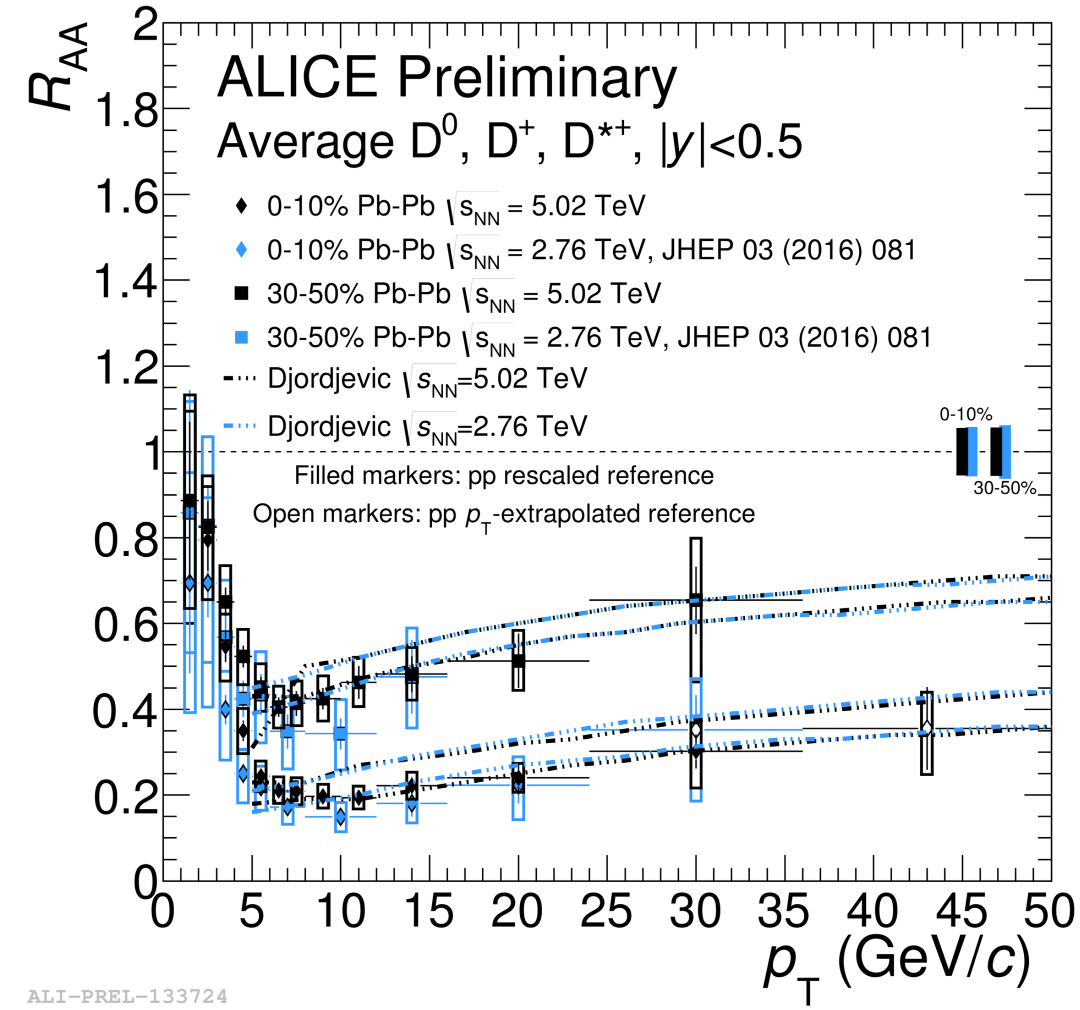
Pb-Pb collisions

D-meson R_{AA}

$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

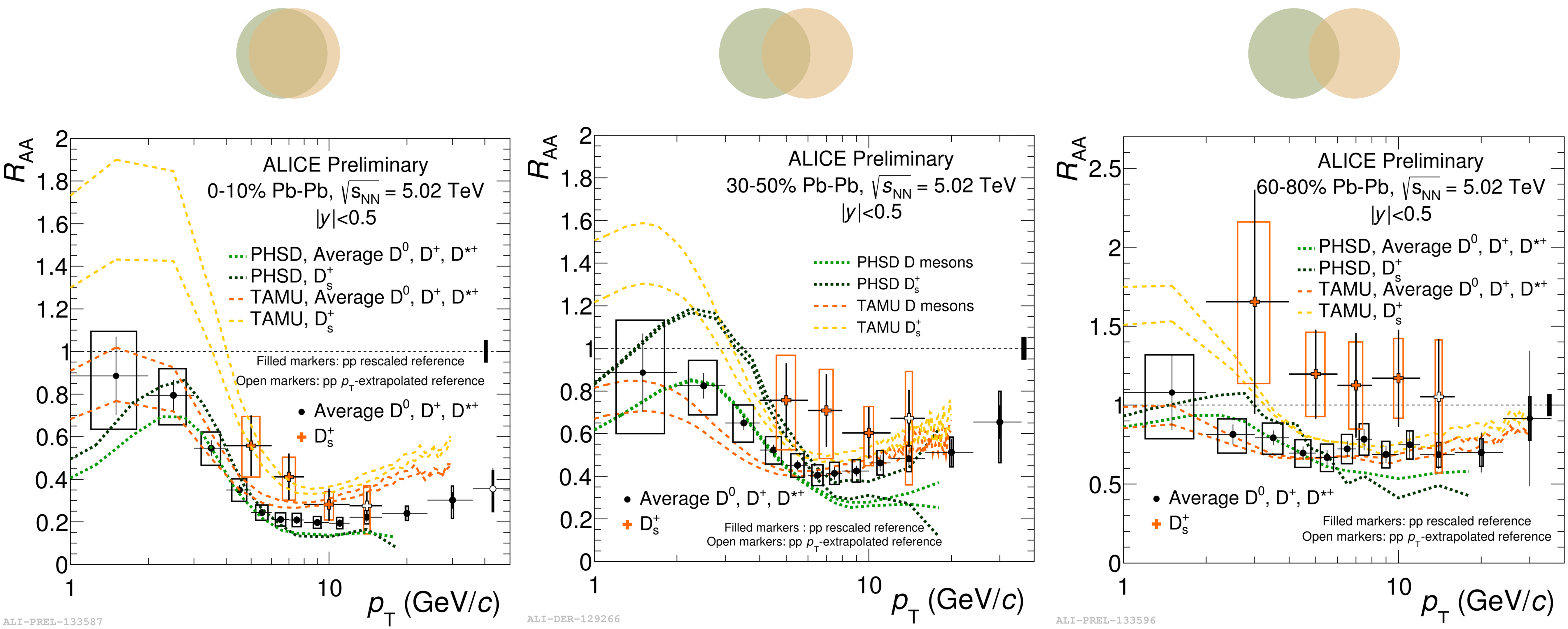
ALICE-PUBLIC-2017-005





- **Increasing suppression from peripheral** (60-80%) **to central** (0-10%) **collisions**
- **Similar D-meson R_{AA} at $\sqrt{s_{NN}}$=5.02 TeV and $\sqrt{s_{NN}}$=2.76 TeV,** consistent with theoretical predictions
- Improved precision in Run2

D_s and non-strange D-meson R_{AA}



ALICE-PUBLIC-2017-005

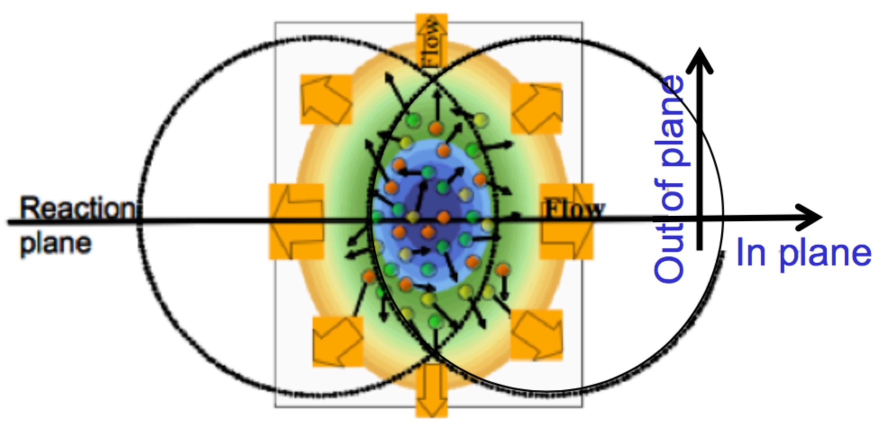
- **Hint of higher D_s with respect to non-strange D-meson R_{AA}**
- Still large uncertainties to conclude

TAMU: Phys. Lett. B 735, 445-450 (2014)
PHSD: Phys. Rev. C 92, 014910 (2015)

Elliptic Flow

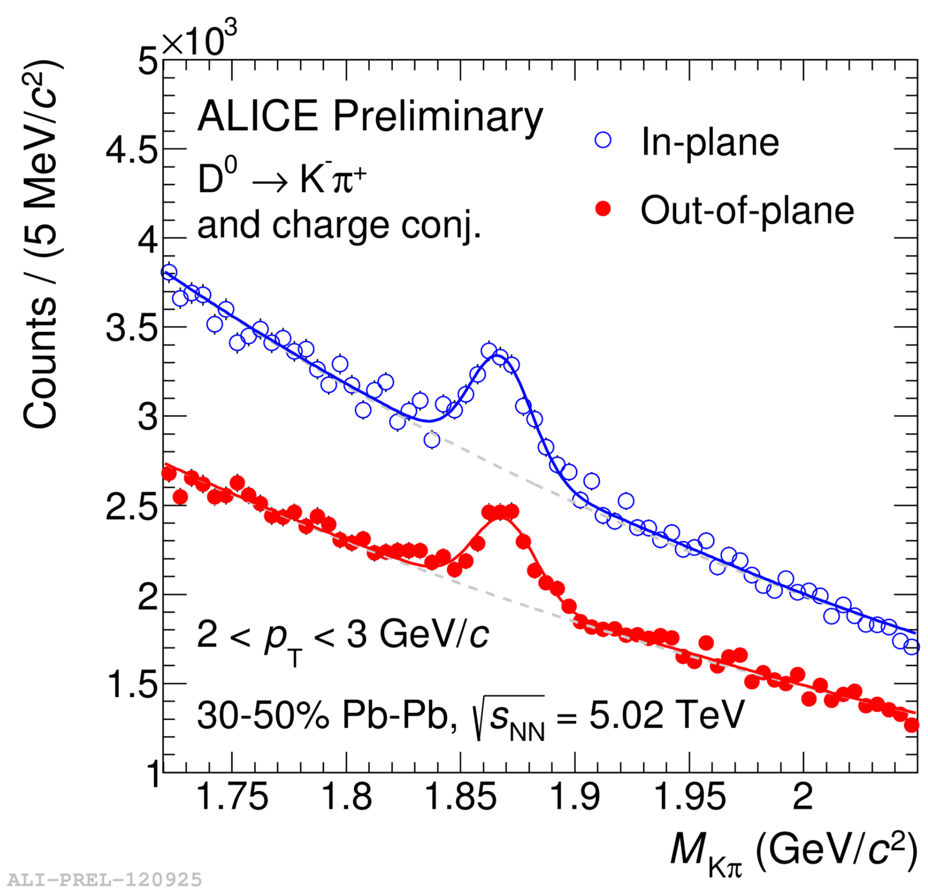
Event plane method: estimation of the Reaction Plane

(using **V0** detector: **−3.7 < η < −1.7 U 2.8 < η < 5.1**)



D-meson candidates divided in 2 categories:

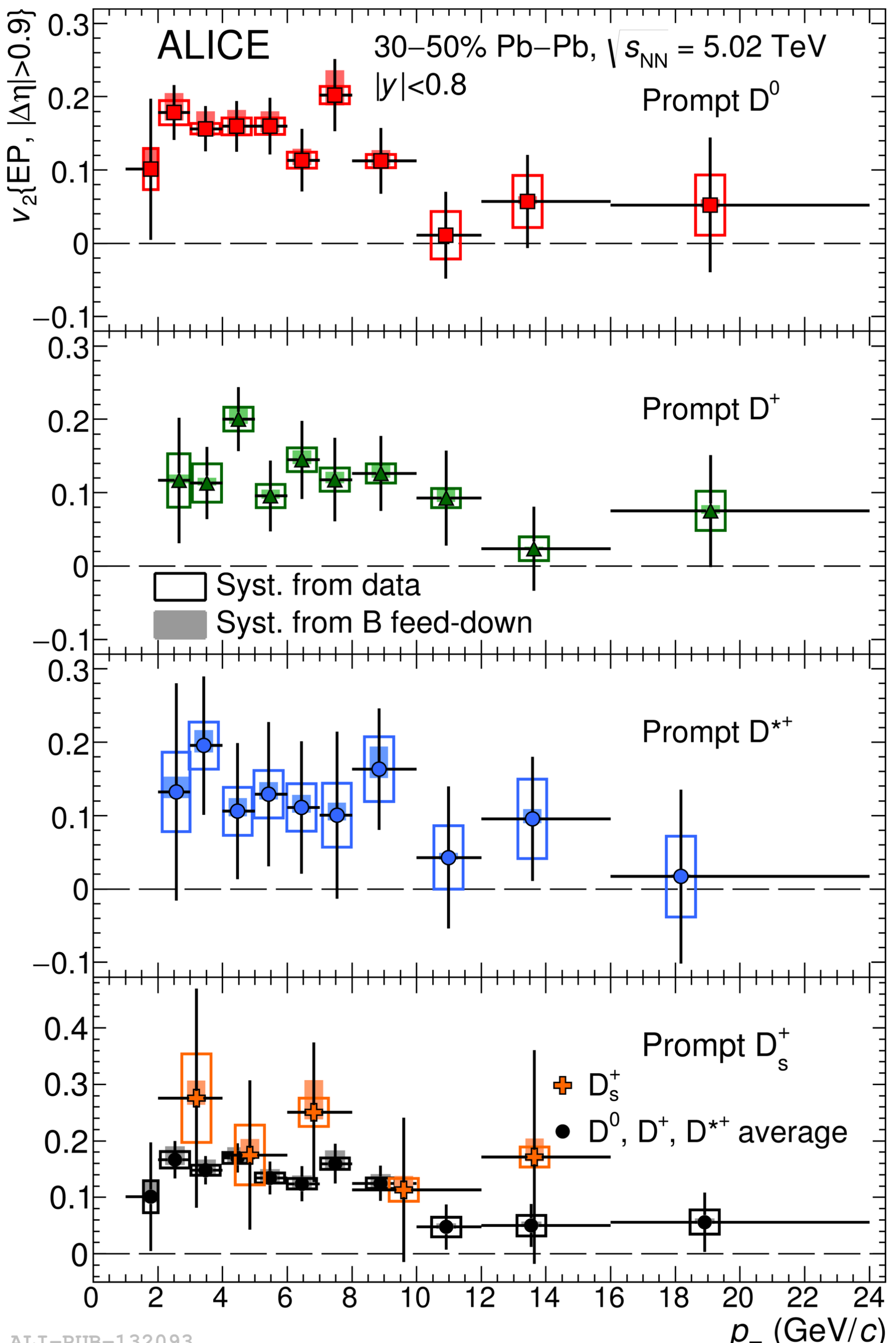
in-plane and out-of-plane particles



$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{\text{in-plane}} - N_{\text{out-of-plane}}}{N_{\text{in-plane}} + N_{\text{out-of-plane}}}$$

R_2=resolution term

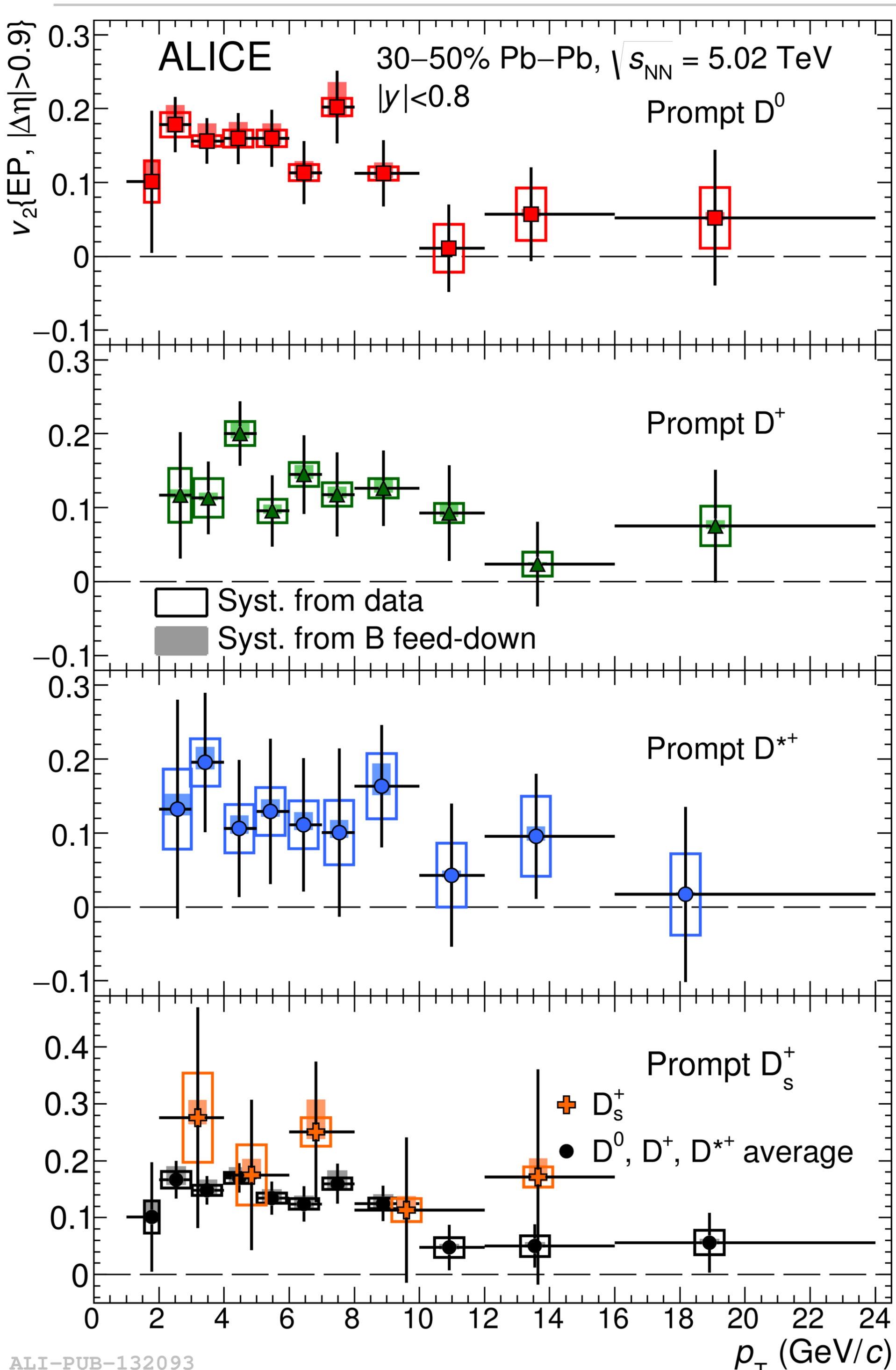
D-meson v_2



arXiv:1707.01005

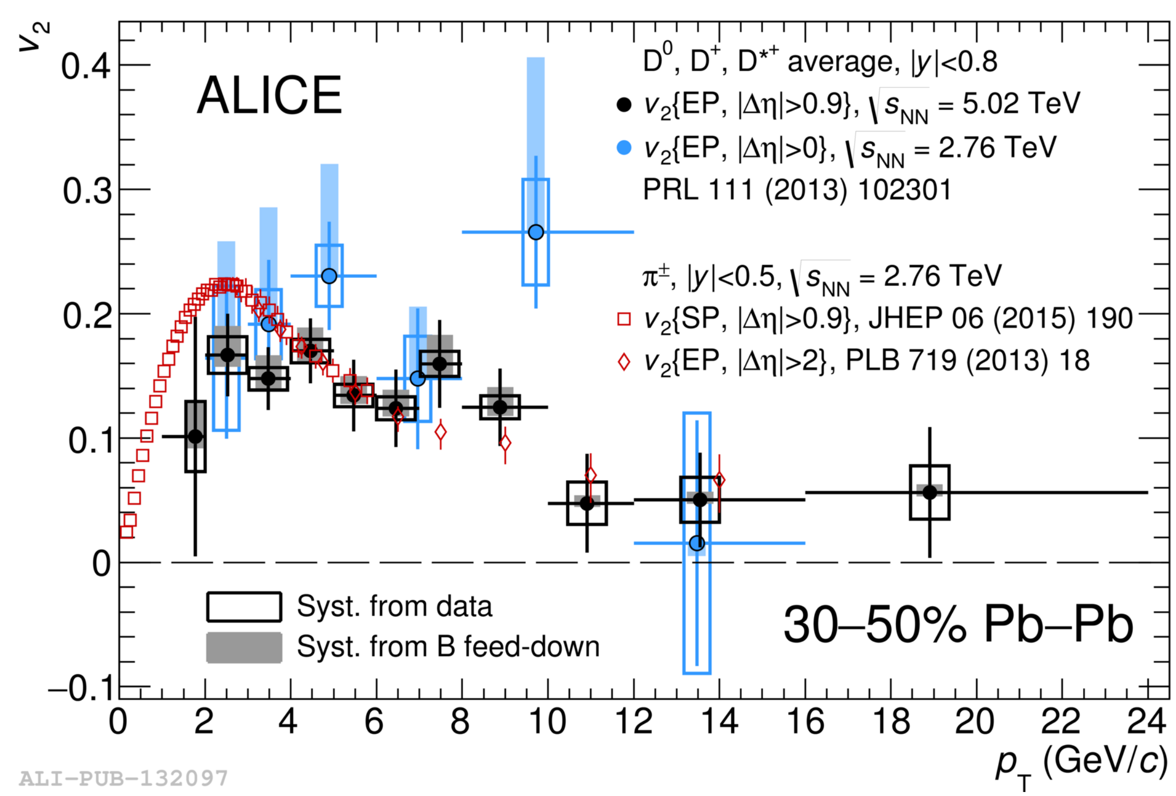
- **Non strange D-meson v_2 larger than 0** for $2 < p_T < 10$ GeV/c
- **D^+_s v_2 compatible with non strange D-meson v_2**

D-meson v_2



arXiv:1707.01005

- **Non strange D-meson v_2 larger than 0** for $2<p_T<10$ GeV/c
- **D^+_s v_2 compatible with non strange D-meson v_2**
- **D-meson v_2 compatible at $\sqrt{s_{NN}}$=5.02 TeV and $\sqrt{s_{NN}}$=2.76 TeV**
- **D-meson v_2 similar to $\pi^\pm$ v_2**
  - hint of difference at low p_T but more statistics needed to conclude

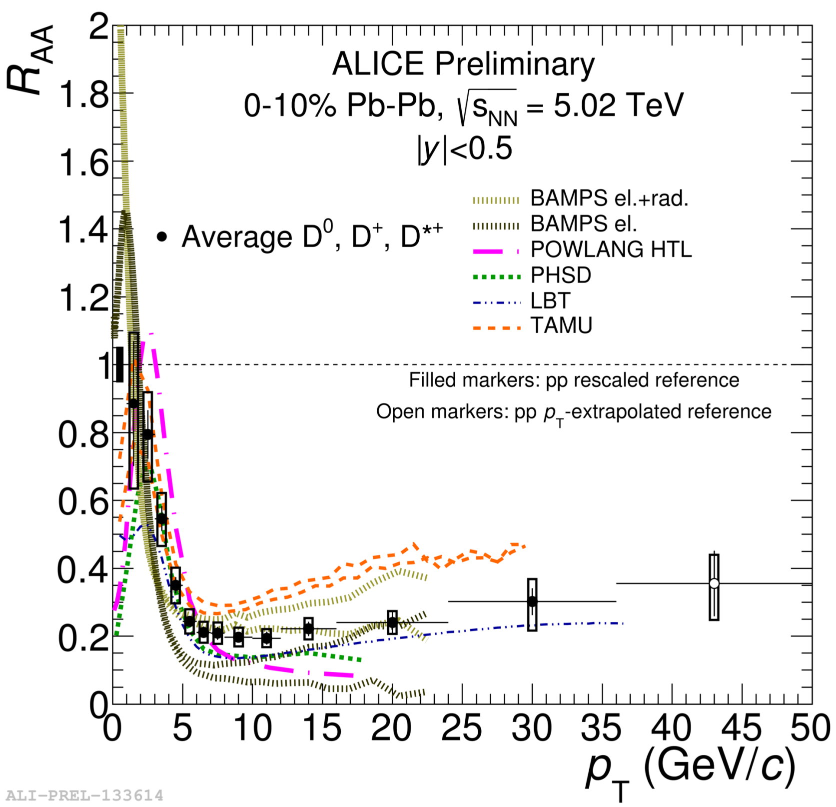


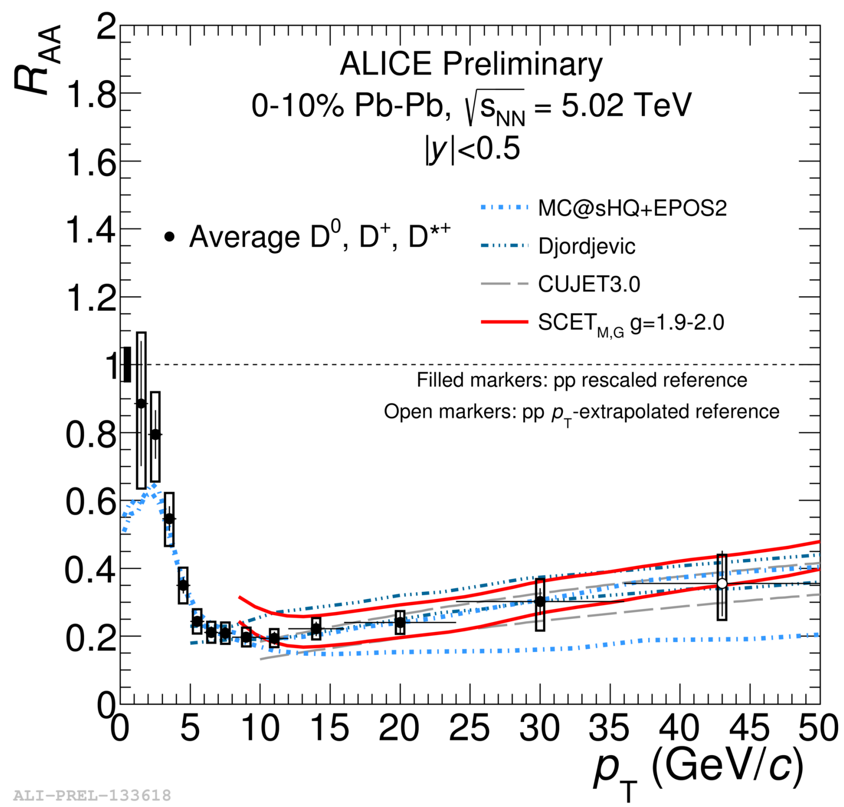
Comparison with models

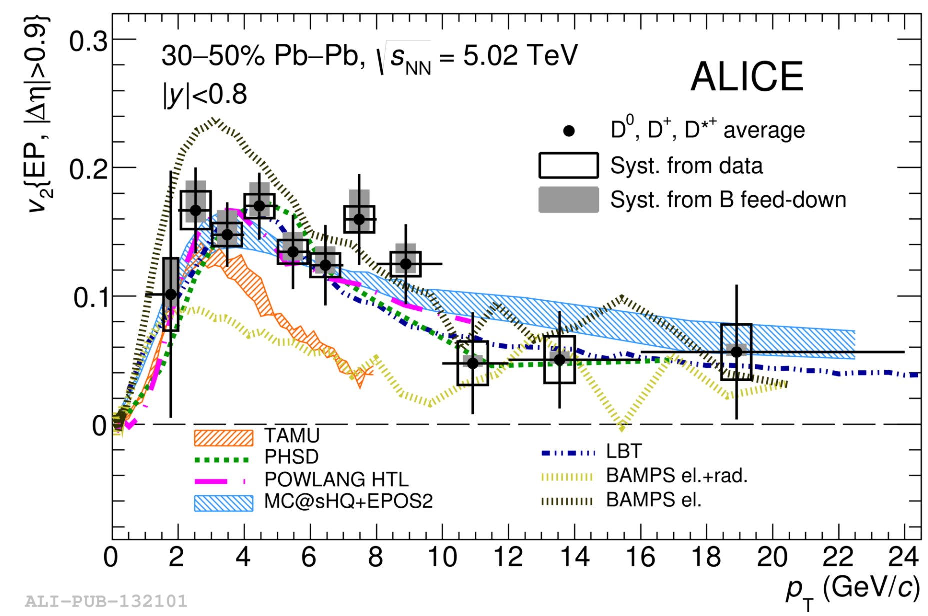
Heavy-quark transport models

pQCD energy loss based models

ALICE-PUBLIC-2017-005







arXiv:1707.01005

TAMU: Phys. Lett. B 735, 445-450 (2014)
PHSD: Phys. Rev. C 92, 014910 (2015)
POWLANG: EPJC 75,121(2015)
BAMPS: JPG 42,115106 (2015)
LBT: arXiv:1703:00822

Djordjevic: PRC 92,024918 (2015)
SCET: JHEP 03, 146 (2017)
MC@sHQ+EPOS: PRC 89, 014905 (2015)
CUJET: JHEP 02,169 (2016)

- Measurement of D-meson R_{AA} and v_2 provide important constraints to theoretical predictions thanks to the improved precision

D-meson v_2 (Event-shape engineering)

The second-harmonic reduced flow vector q_2 can be used to quantify the eccentricity (average v_2) of the events

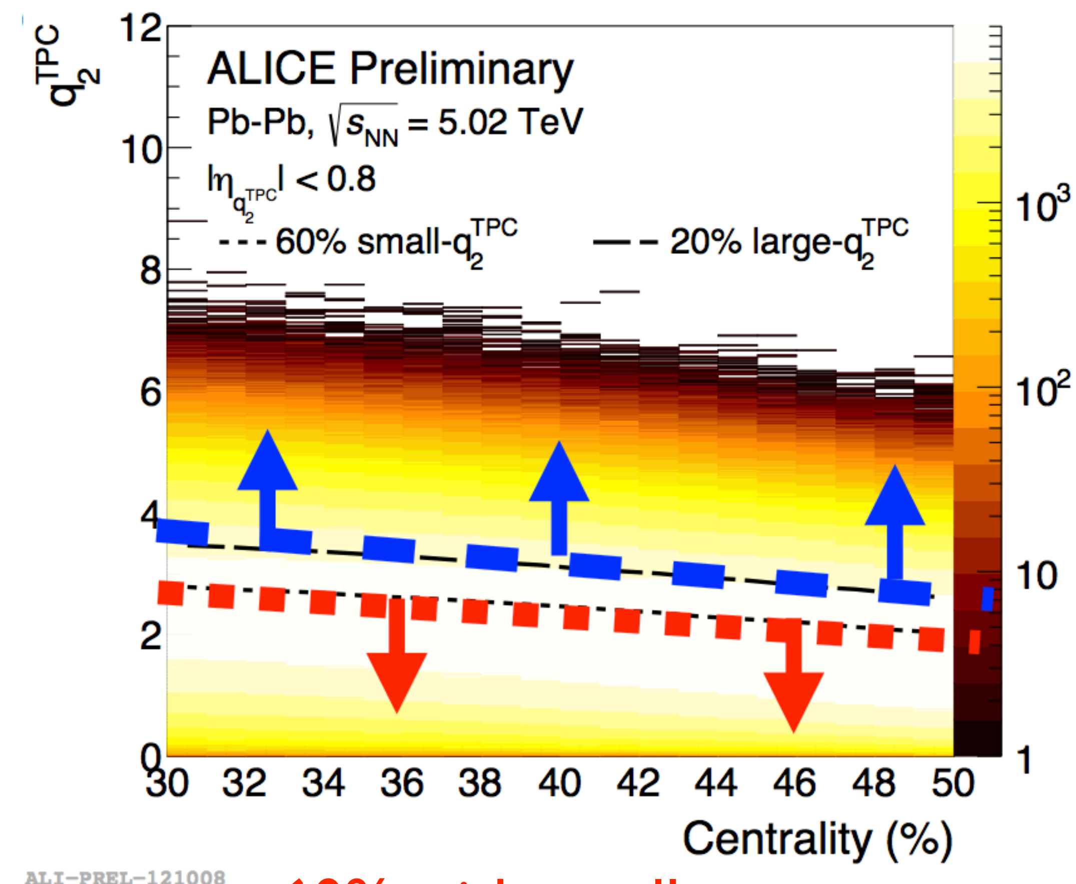
$$q_2 = \frac{|\boldsymbol{Q}_2|}{\sqrt{M}},$$

- M: multiplicity
- $|\boldsymbol{Q}_2| = \sqrt{Q_{2,x}^2 + Q_{2,y}^2}$

$$Q_{2,x} = \sum_{i=1}^{M} \cos 2\varphi_i \ , \ Q_{2,y} = \sum_{i=1}^{M} \sin 2\varphi_i$$

$$\langle q_2^2 \rangle \simeq 1 + \langle (M-1) \rangle \langle (v_2^2 + \delta_2) \rangle$$

S. A. Voloshin, A. M. Poskanzer, and R. Snellings, Relativistic Heavy Ion Physics, Vol. 1/23 (Springer- Verlag, 2010), pp. 5–54

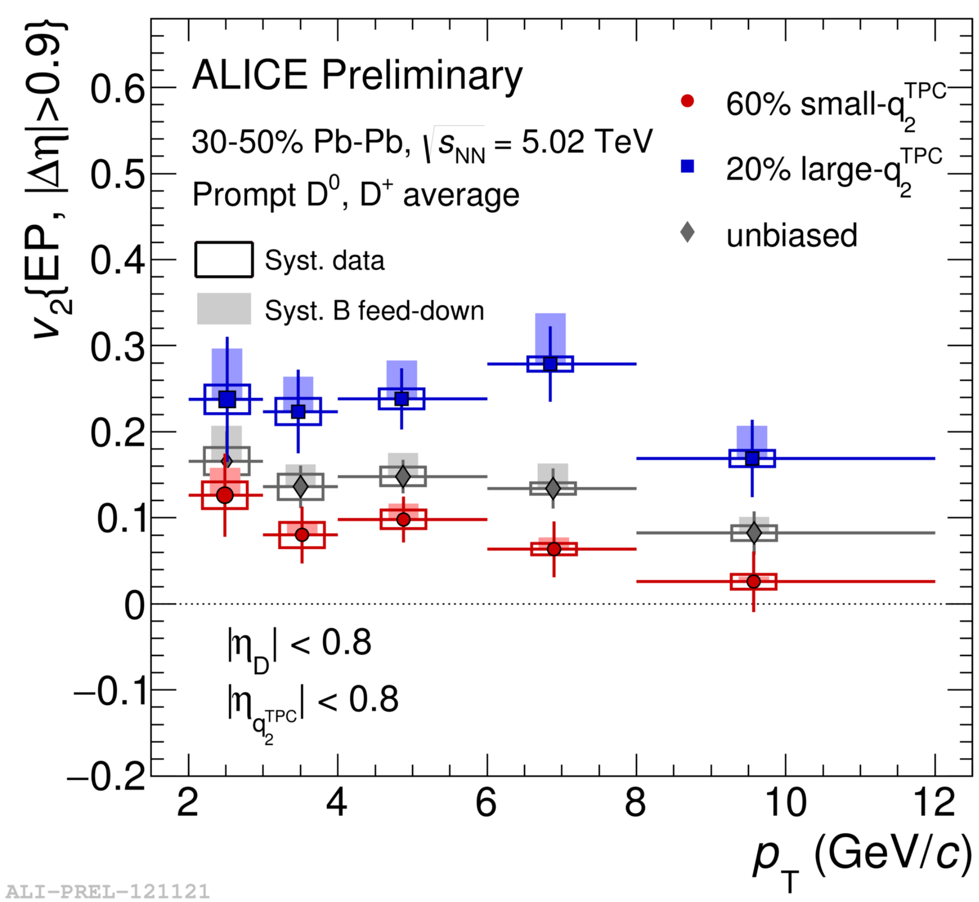


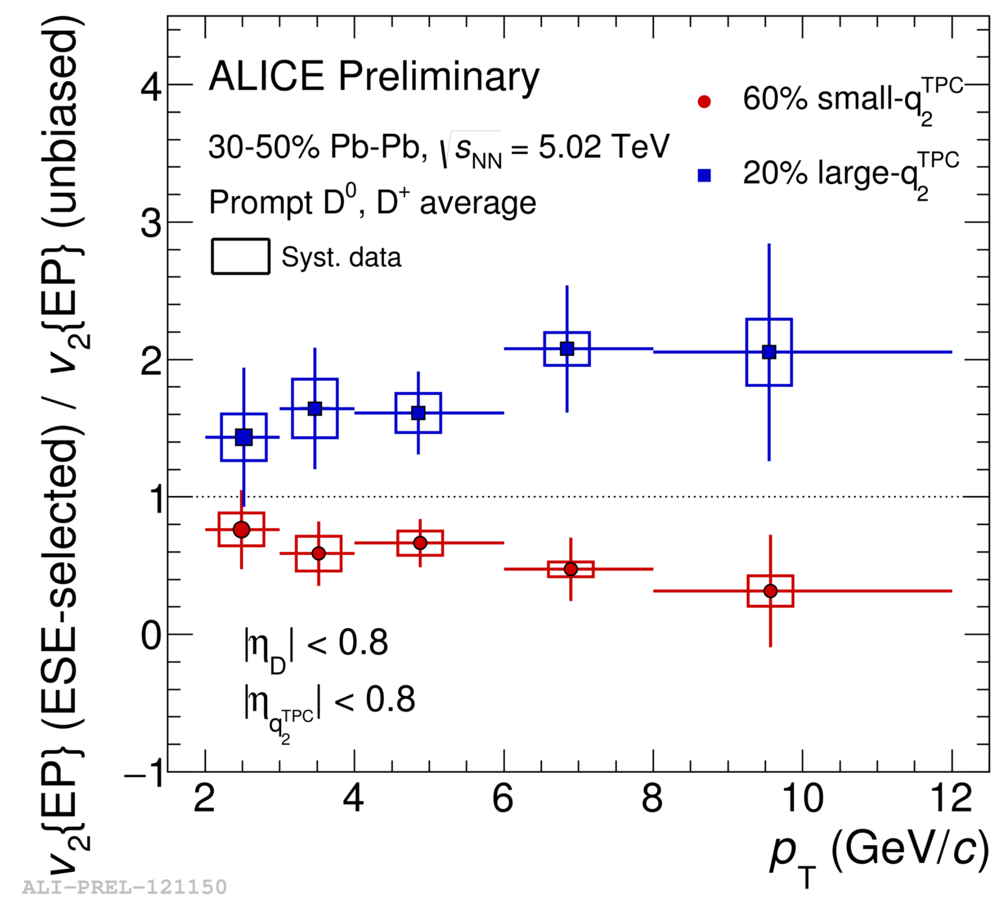
60% with smaller q_2

20% with larger q_2

- Opportunity to study the coupling of c quarks to the bulk of light quarks from the underlying medium by measuring the D-meson v_2 for different values of q_2

D-meson v_2 (Event-shape engineering)





- **Larger D-meson v_2 for events with larger q_2 and smaller D-meson v_2 for events with smaller q_2**
- Auto-correlations between q_2 and D mesons v_2 present
- Sensitivity of D mesons to the light quarks collectivity and event-by-event fluctuations

Conclusions

Large collection of new ALICE results on D-meson production in p-Pb and Pb-Pb collisions from Run2 at $\sqrt{s_{NN}}$=5.02 TeV

- Compatible results with Run1 analyses but better precision and extended p_T range
- p-Pb collisions
  - R_{pPb} of D mesons consistent with unity
  - central/peripheral: Q_{CP} >1 in 3-8 GeV/c with 1.7σ, radial flow? initial- or final-state effects?
- Pb-Pb collisions
  - Increasing suppression from peripheral to central collisions for D-meson R_{AA}
  - Hint of coalescence+strangeness enhancement comparing strange and non-strange D mesons
  - D-meson elliptic flow in semi-peripheral Pb-Pb collisions larger than 0 (even for D_s)
    $\longrightarrow$ strong coupling of charm quark with the medium
  - Event-Shape Engineering for the D-meson elliptic flow
    $\longrightarrow$ sensitivity of charm quark to the light-quark collectivity and to the event-by-event initial fluctuations

Backup

Theoretical models

BAMPS: Boltzman equation with collisional energy loss in expanding QGP
*[Phys. Rev. C **84** (2011) 024908; JPG 42,115106 (2015); Phys. Lett. B **717** (2012) 430]*
TAMU: HQ transport with coll. e.loss only, resonant scattering and coalescence+hydro
[Phys.Lett. B735 (2014) 445-450]

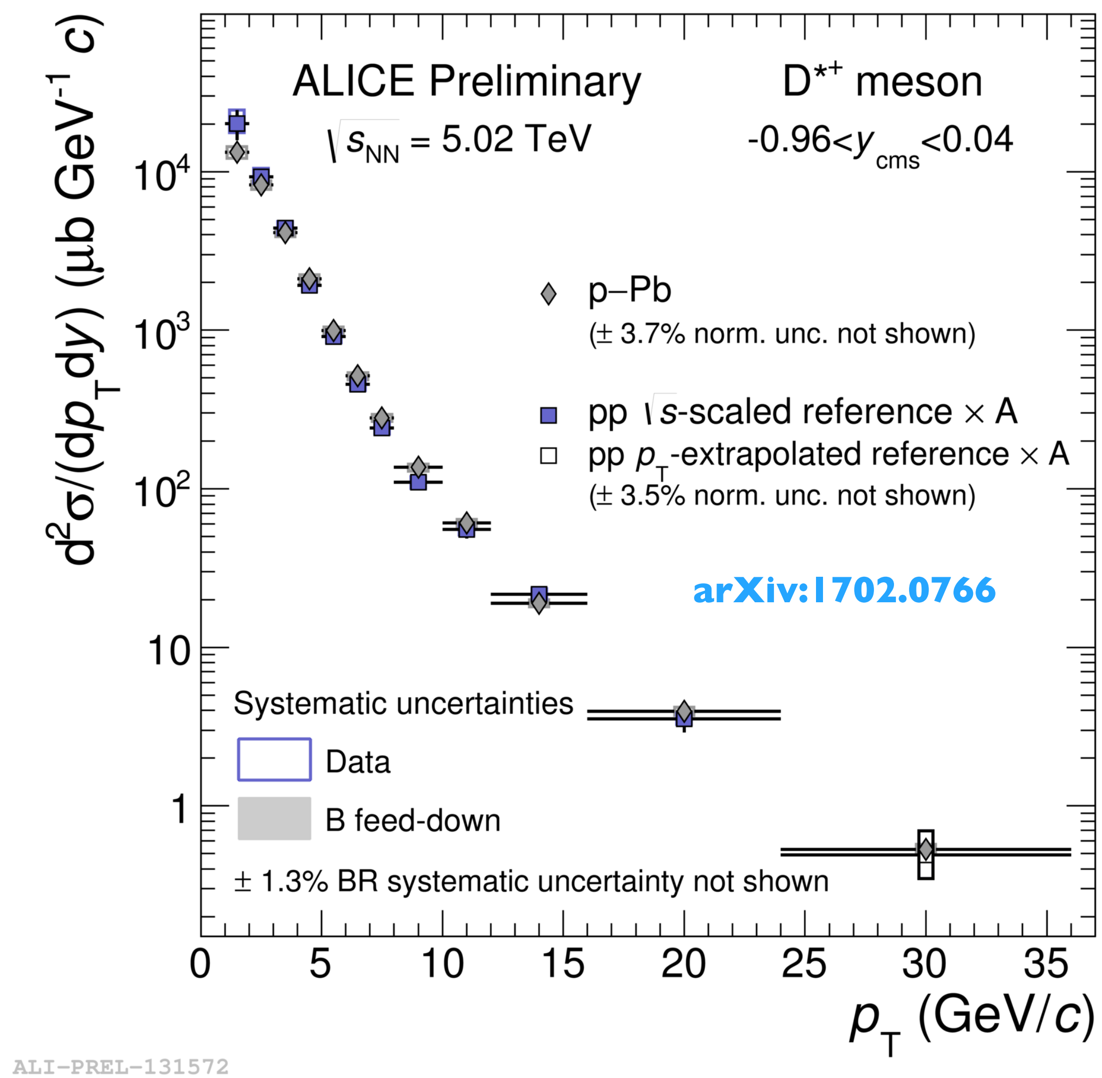
POWLANG HTL: HQ transport with Langevin equation with collisional energy loss and, recombination, viscous hydrodynamic expansion. Transport coeff. dependence on quark momentum
*[EPJC 75,121(2015); J. Phys. G **38** (2011) 124144]*
Djordjevic: energy loss due to both radiative and collisional, processes in a finite size dynamical QCD medium *[Phys. Rev. C 92 (2015) 024918]*

Ads/CFT: energy loss fluctuations included in a realistic strong coupling energy loss model from AdS/CFT
[arXiv:1610.02043, arXiv:1605.09285]
SCET$_{M,G}$ NLO: in-medium formation and dissociation of D and B, ideal fluid with Bjorken expansion
[JHEP 03, 146 (2017)]

Xu, Cao, Bass: Langevin with coll. and rad. term and recombination+hydro
*[Phys. Rev. C **88** (2013) 044907]*

PHSD: Parton-Hadron-String Dynamics transport approach, coalescence
[Phys.Rev. C92 (2015) no.1, 014910, Phys.Rev. C93 (2016) no.3, 034906]
MC@sHQ+EPOS: coll. and rad. e.loss in expanding medium based on EPOS model, recombination
*[Phys. Rev. C **89** (2014) 014905]*

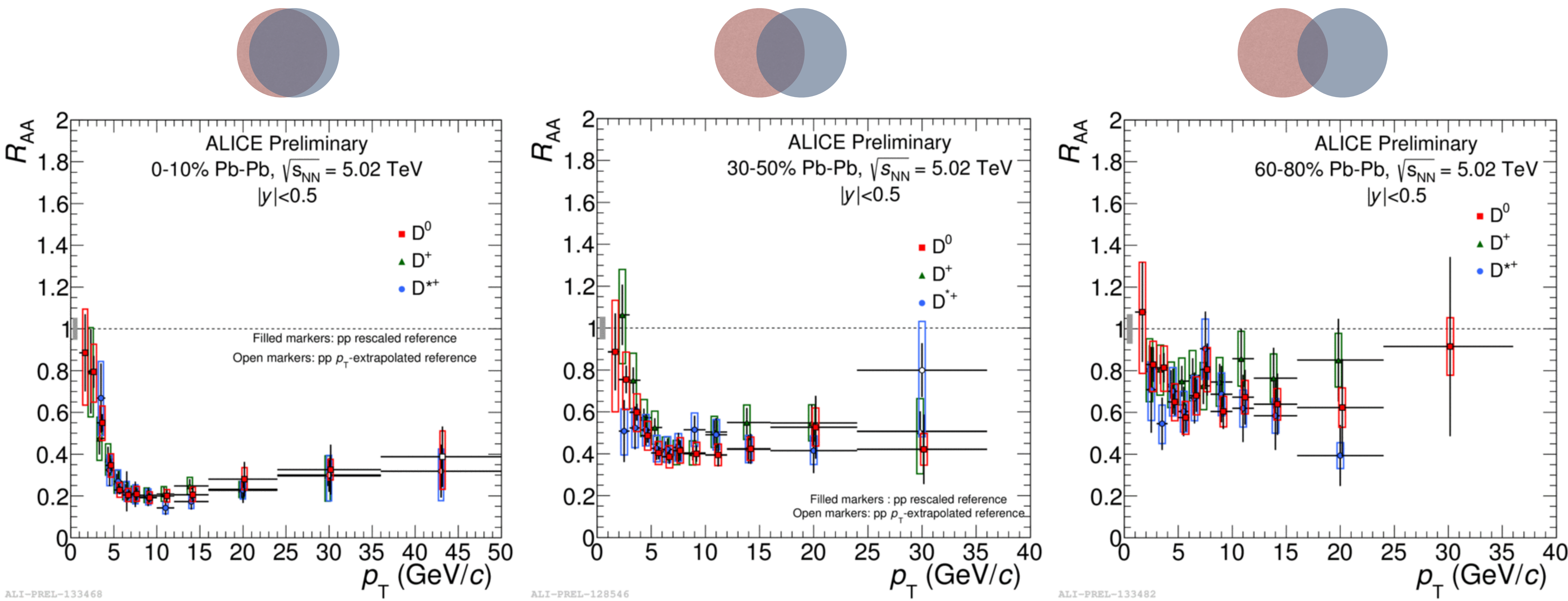
pp reference



- Reference obtained scaling 7 TeV pp collisions, reduced uncertainties

D-meson R_{AA}

$$R_{AA} = \frac{1}{< T_{AA} >} \frac{dN_{AA} / dp_T}{d\sigma_{pp} / dp_T}$$

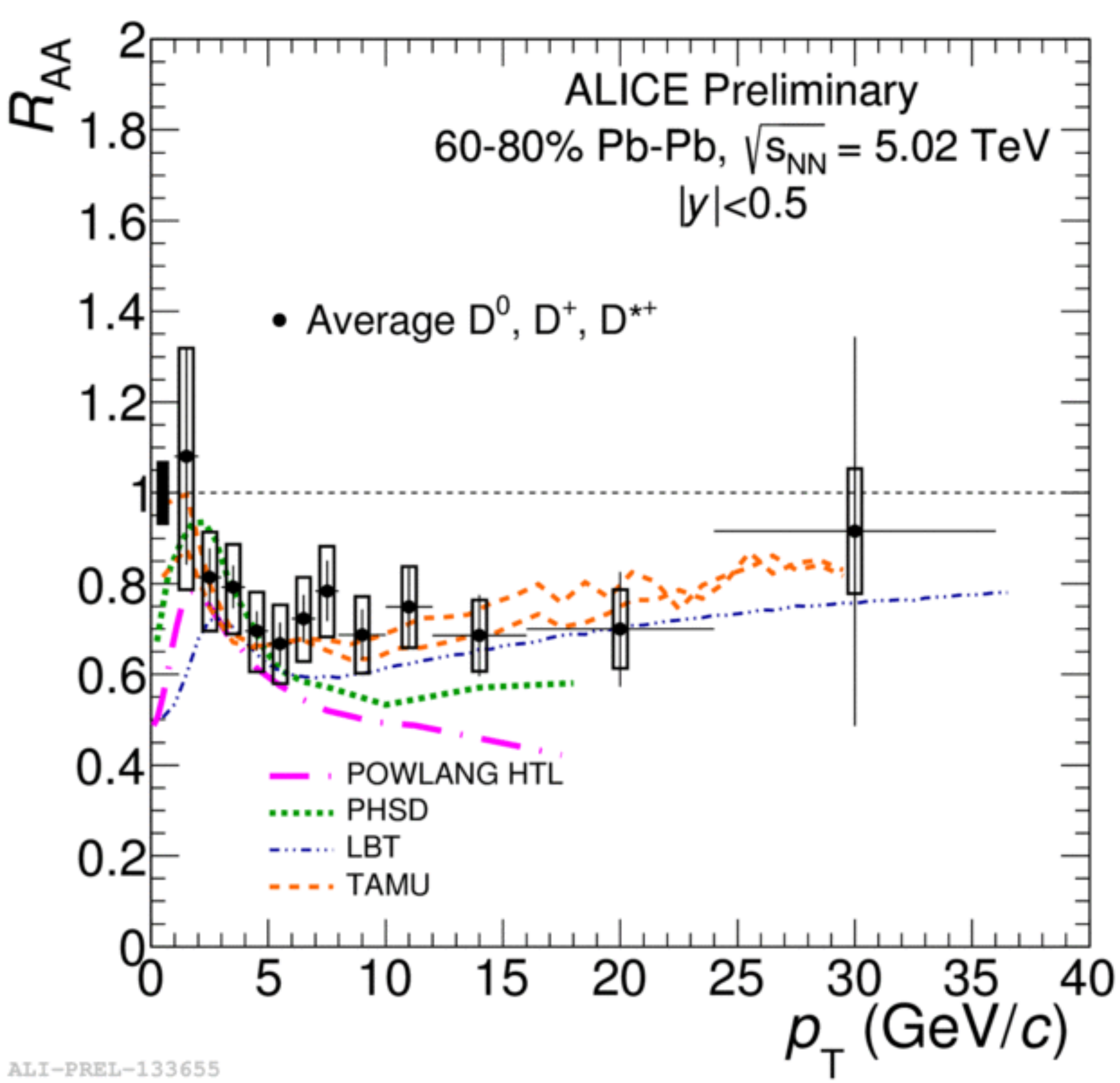


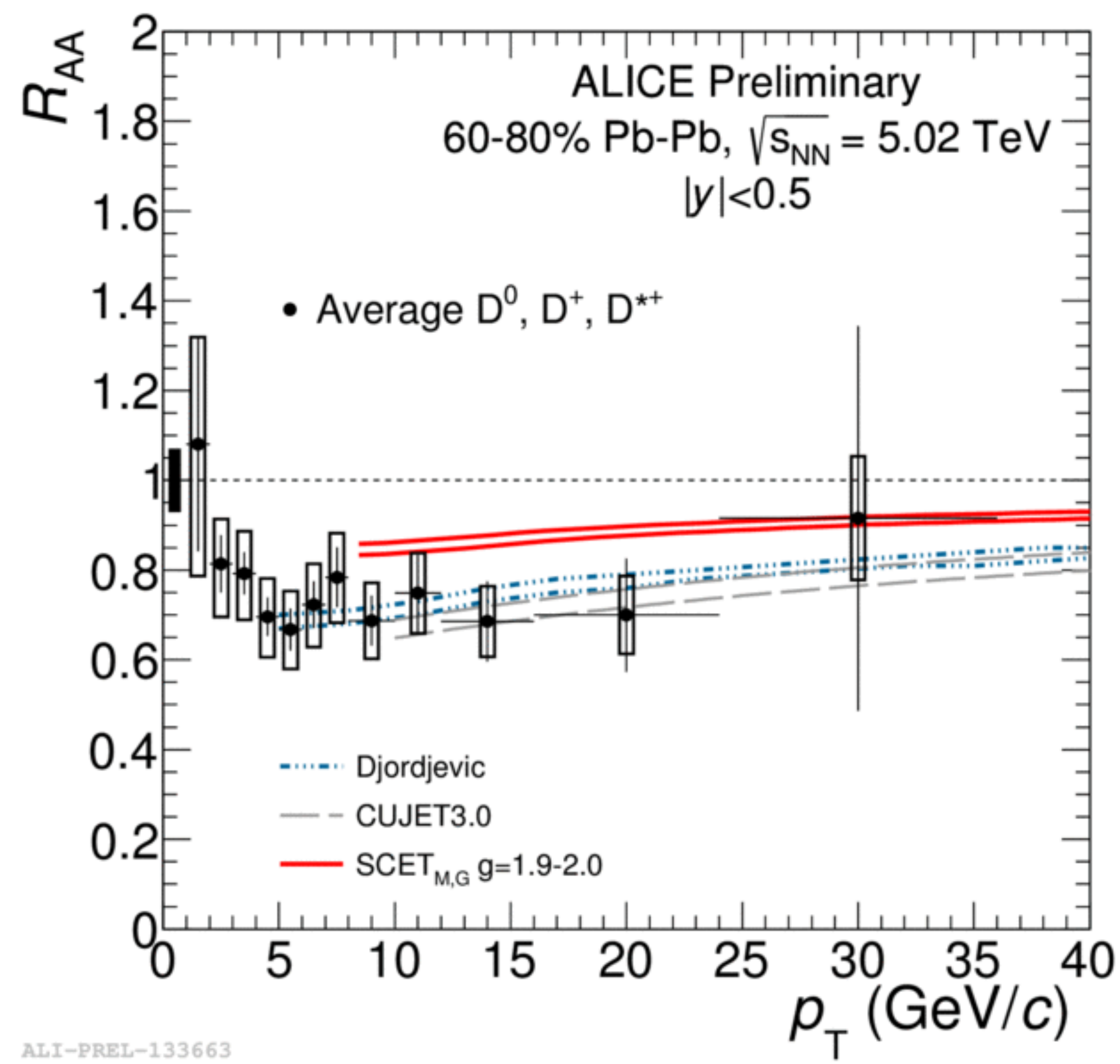
ALICE-PUBLIC-2017-005

- Non-strange D-meson R_{AA} compatible within uncertainties
- **Increasing suppression from peripheral** (60-80%) **to central** (0-10%) **collisions**

D-meson R_{AA} comparison with models

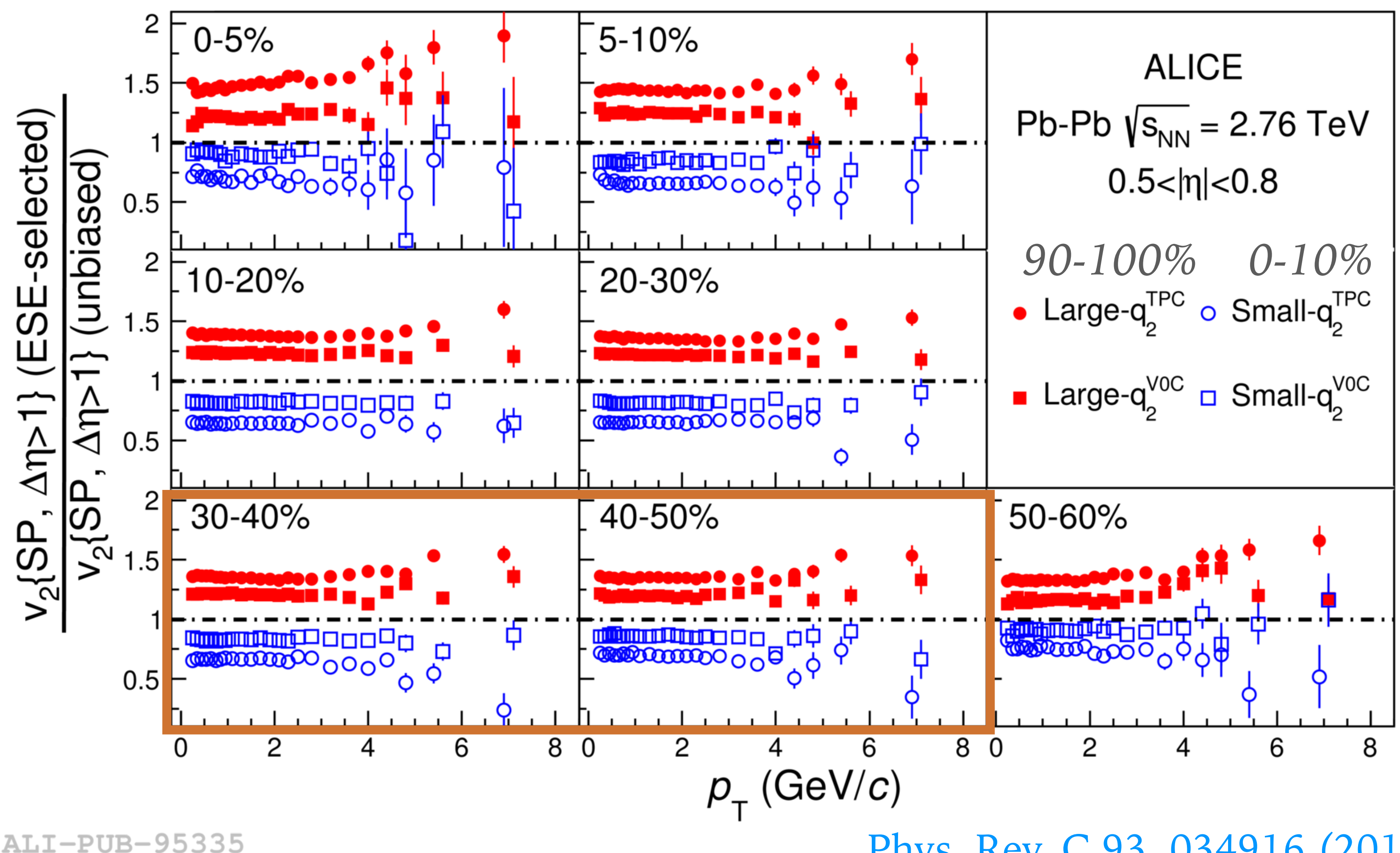
Peripheral centrality class



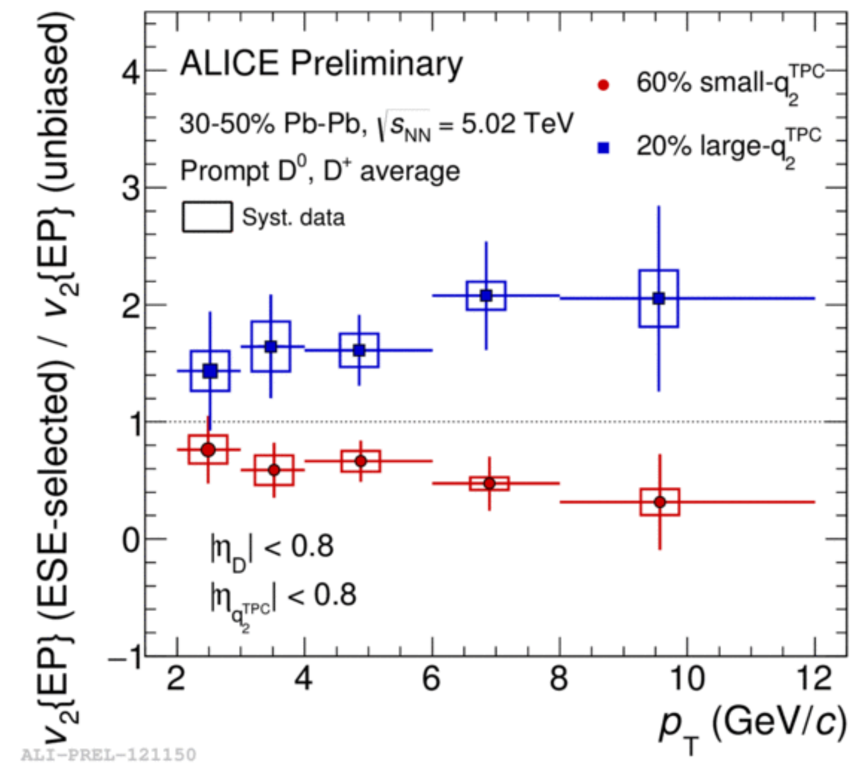


Pb–Pb COLLISIONS: EVENT SHAPE

Charged particles



D meson



Phys. Rev. C 93, 034916 (2016)

$$f_{\text{prompt}} = 1 - \frac{N_{\text{raw}}^{\text{D feed-down}}}{N_{\text{raw}}^{\text{D}}} = 1 - A \cdot \left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\right)_{\text{feed-down}}^{\text{FONLL}} \cdot R_{\text{pPb}}^{\text{feed-down}} \cdot \frac{(\text{Acc} \times \varepsilon)_{\text{feed-down}} \cdot \Delta y \Delta p_{\mathrm{T}} \cdot \text{BR} \cdot L_{\text{int}}}{N^{\mathrm{D}+\overline{\mathrm{D}},\text{raw}}/2}$$

prompt fraction of D mesons

signal extracted from invariant mass distributions

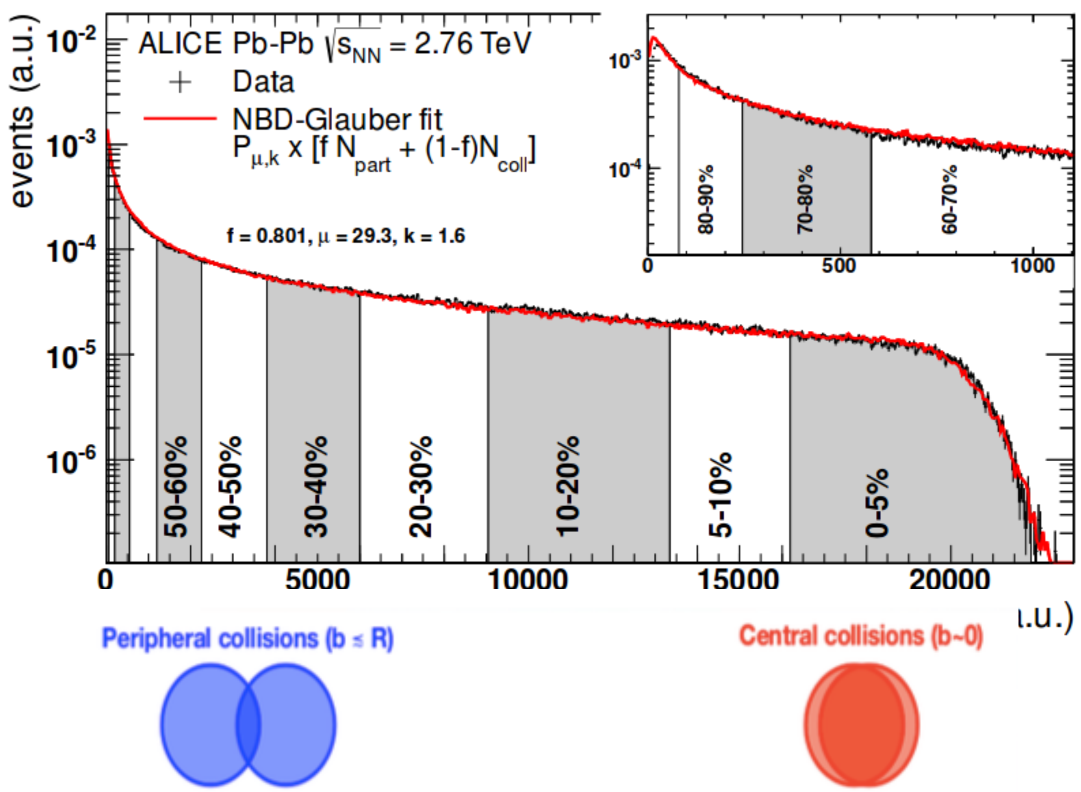
$$\left.\frac{dN^{\mathrm{D}^+}}{dp_{\mathrm{T}}}\right|_{|y|<0.5} = \frac{1}{2}\frac{1}{\Delta y \Delta p_{\mathrm{T}}}\frac{f_{prompt} \cdot \left.N^{\mathrm{D}^+ \text{raw}}\right|_{|y|<y_{fid}}}{(Acc \times \varepsilon)_{prompt} \cdot BR \cdot N_{ev}}$$

Acceptance times efficiency

- N_{ev} = number of events
- Δy = rapidity interval
- Δp_T = transverse momentum interval
- BR = branching ratio

CENTRALITY RANGES DEFINITION

Pb-Pb collisions



p-Pb collisions