Non-strange and strange D-meson and charm-baryon production in heavy-ion collisions measured with ALICE at the LHC

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On behalf of the ALICE Collaboration

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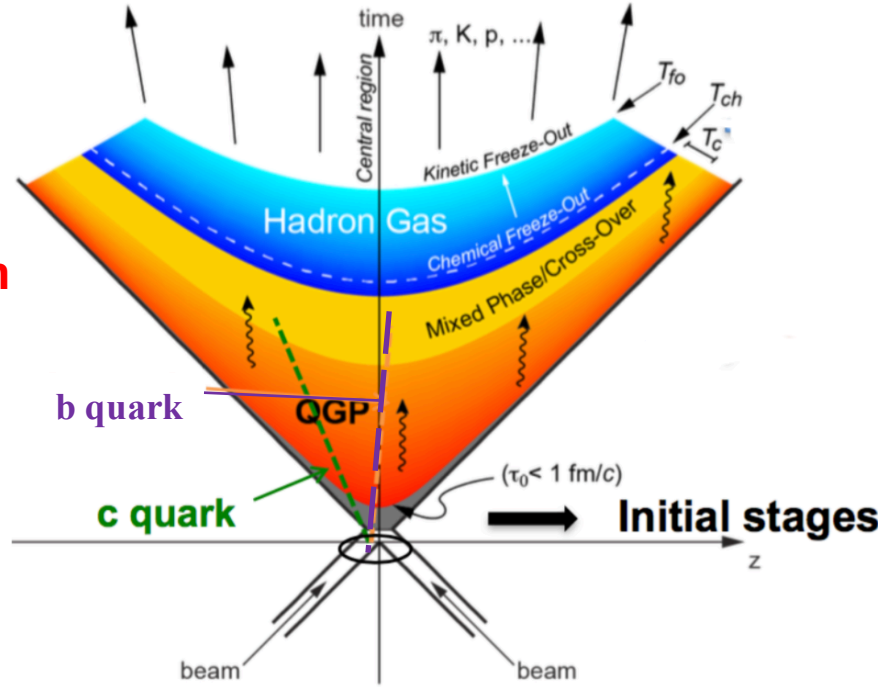
INFN & Univ. Padova, Italy

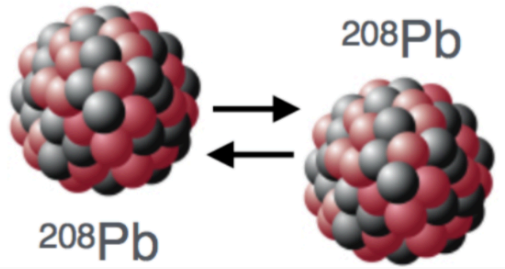
Heavy Flavour: effective probes of the QGP

- Produced in **initial hard scattering (high Q^2)** processes
  - Cross section calculable with pQCD ($m_{c/b} \gg \Lambda_{QCD}$) in hadronic collisions
- $\tau_{c/b} \sim 0.01 - 0.1$ fm/c < QGP formation time (~0.1-1 fm/c)
  - Experience the whole system evolution **interacting with the medium** formed in Pb-Pb collisions



In Pb-Pb collisions:

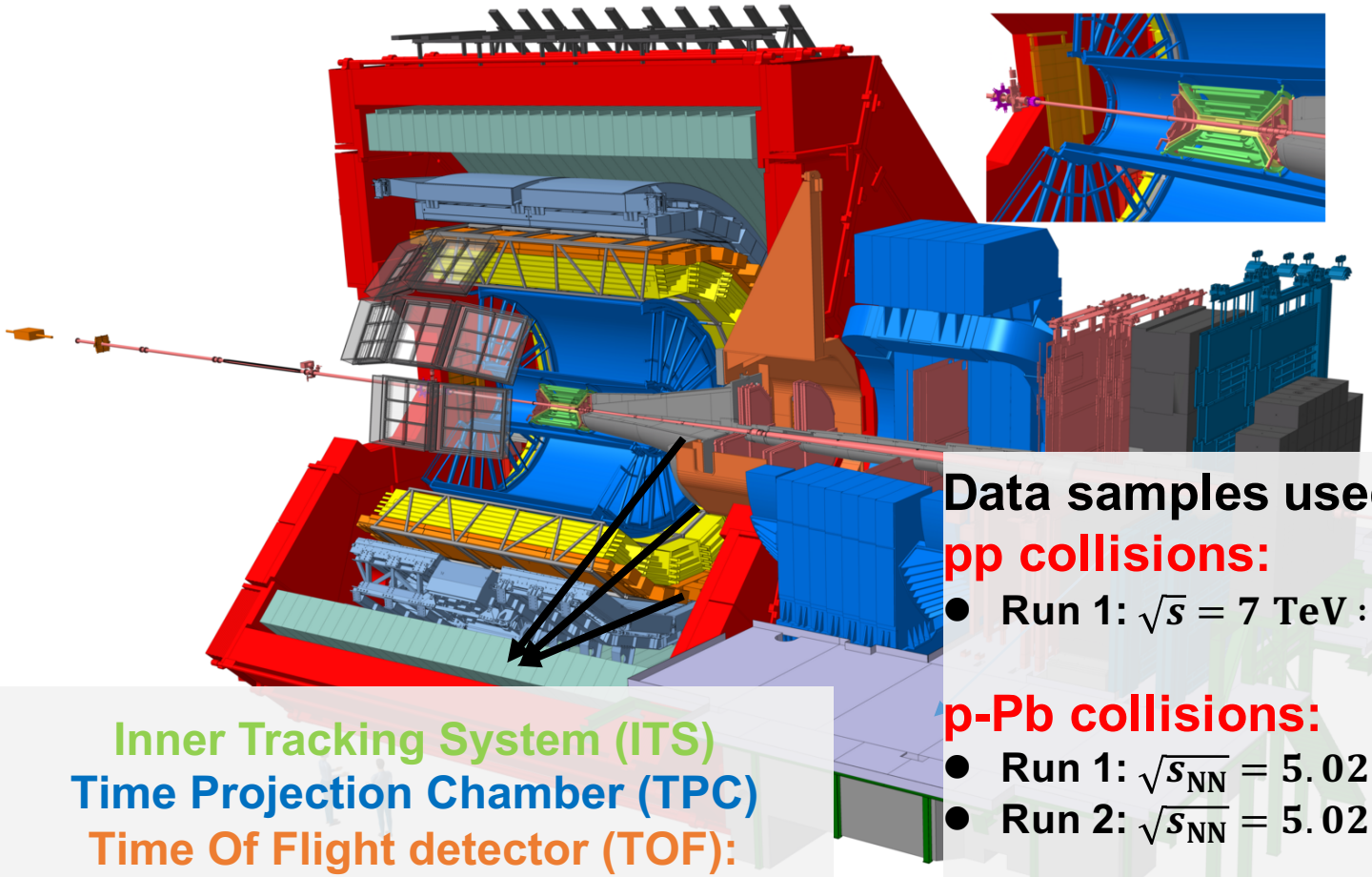
- Study of charm energy-loss mechanism in the medium
  - Colour-charge and quark-mass dependence
- Participate in the collective motion and thermalisation of the medium
- Modification of hadronisation mechanism in the medium
  - **Coalescence mechanism**?
  - **Diquark in medium?**



In pp and p-Pb collisions:

- Further investigate charm hadronisation mechanism

The ALICE detector



V0, ZDC:
Event plane, trigger and centrality/multiplicity determination

Inner Tracking System (ITS)
Time Projection Chamber (TPC)
Time Of Flight detector (TOF):
Vertexing, tracking and PID
$|\eta| < 0.9$

Data samples used for the analyses discussed:

pp collisions:

- **Run 1:** $\sqrt{s} = 7$ **TeV** : ~370*10^6 min.bias events, $L_{\mathrm{int}} = 6.0\ \mathrm{nb}^{-1}$

p-Pb collisions:

- **Run 1:** $\sqrt{s_{\mathrm{NN}}} = 5.02$ **TeV** : ~100*10^6 min.bias events, $L_{\mathrm{int}} = 48.6\ \mathrm{nb}^{-1}$
- **Run 2:** $\sqrt{s_{\mathrm{NN}}} = 5.02$ **TeV** : ~600*10^6 min.bias events, $L_{\mathrm{int}} = 292\ \mathrm{nb}^{-1}$

Pb-Pb collisions:

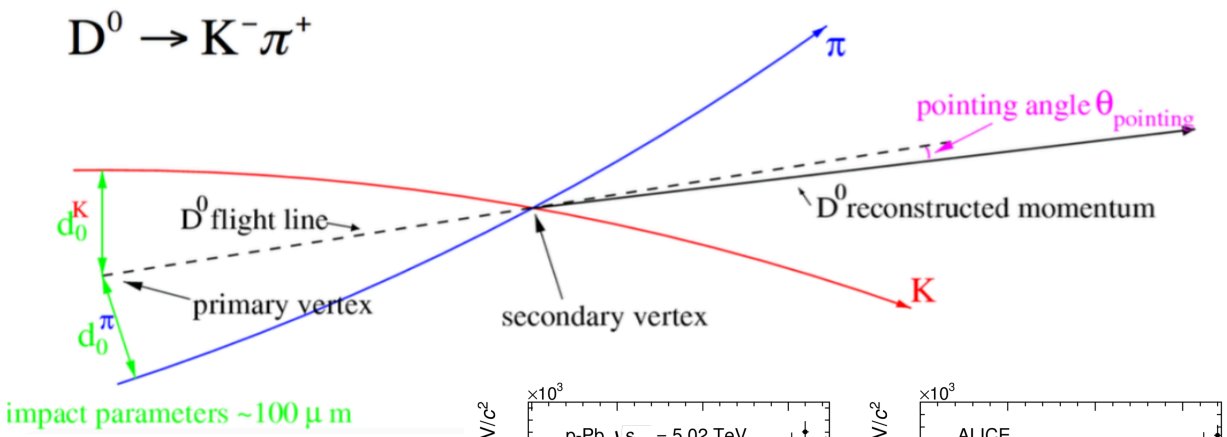
- **Run 2:** $\sqrt{s_{\mathrm{NN}}} = 5.02$ **TeV** : ~100*10^6 V0 min.bias events $L_{\mathrm{int}} = 13.4\ \mu\mathrm{b}^{-1}$

Poster ID: 37, 44, 45, 269 by J.Wilkinson, E.Meninno, F.Grosa, C.Hills

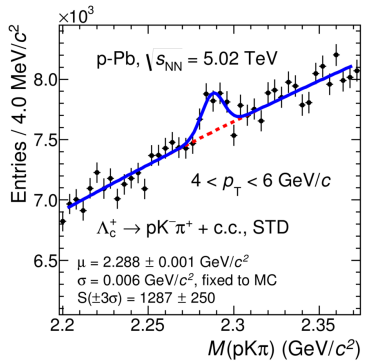
Hadronic decay channel reconstruction

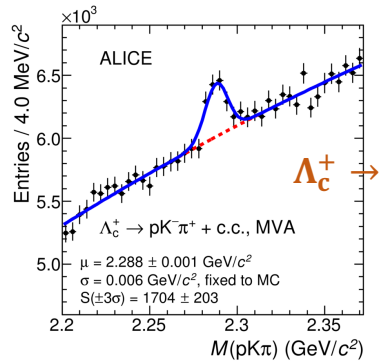
arXiv:1804.09083

$D^0 \to K^-\pi^+$	BR ~ 3.93%	$c\tau \sim 123\ \mu m$
$D^+ \to K^-\pi^+\pi^+$	BR ~ 9.46%	$c\tau \sim 312\ \mu m$
$D^{*+} \to D^0(K^-\pi^+)\pi^+$	BR ~ 2.66%	-
$D_s^+ \to \phi(K^-K^+)\pi^+$	BR ~ 2.27%	$c\tau \sim 150\ \mu m$
$\Lambda_c^+ \to pK^-\pi^+$	BR ~ 6.35%	$c\tau \sim 60\ \mu m$
$\Lambda_c^+ \to pK_S^0$	BR ~ 1.58%	"



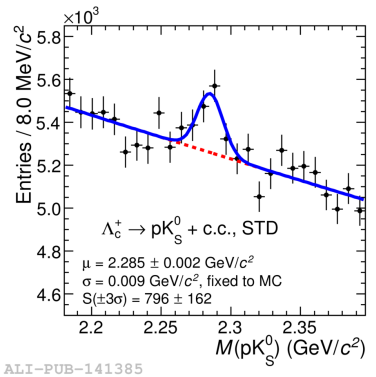
- Decay topology selections and PID used to reduce the combinatorial background
  - Multivariate approach (Boosted Decision Tree) also applied for Λ_c^+ in p-Pb
- Signal is extracted via an invariant-mass analysis
- Feed-down from beauty-hadron decays are subtracted exploiting FONLL calculations with assumptions on feed-down nuclear modification factor

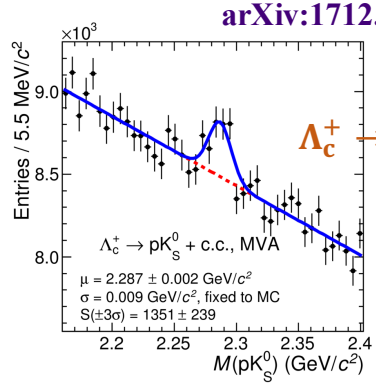




$\Lambda_c^+ \to pK^-\pi^+$

arXiv:1712.09581





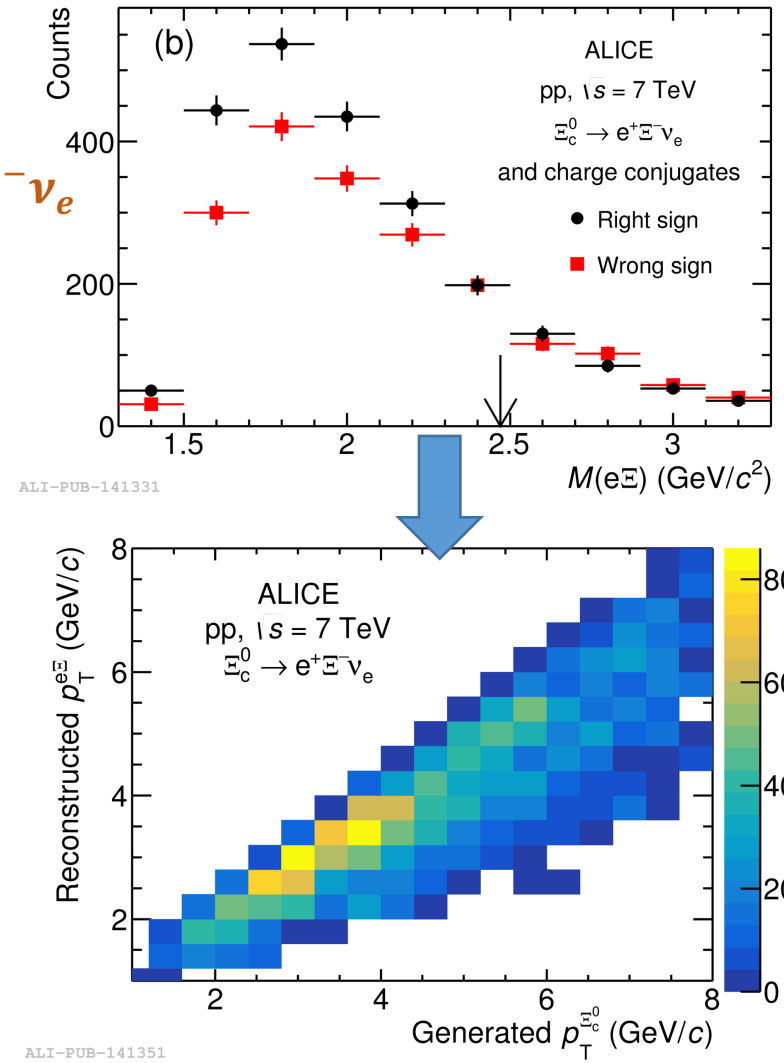
$\Lambda_c^+ \to pK_S^0$

ALI-PUB-141385

Semi-leptonic decay channel reconstruction

$\Lambda_c^+ \to e^+ \Lambda \nu_e$	BR ~ 3.6%
$\Xi_c^0 \to e^+ \Xi^- \nu_e$	BR unknown

$(\Xi_b \to) \Xi_c^0 \to e^+ \Xi^- \nu_e$



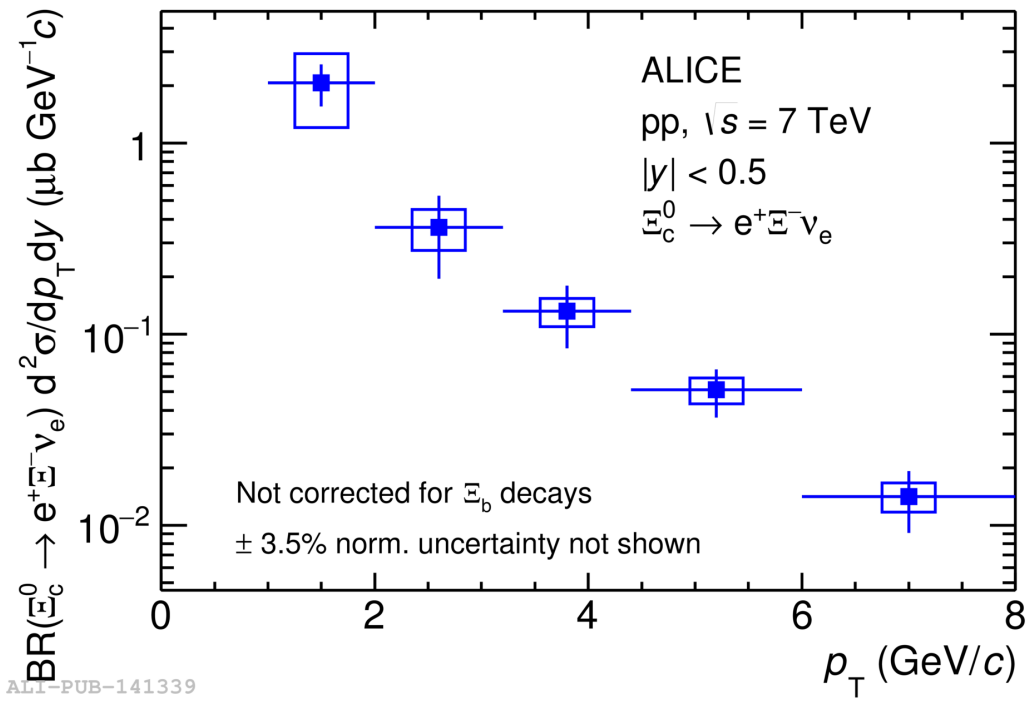
- PID is used to reduce the combinatorial background
- Wrong-sign $e^-\Lambda$ ($e^-\Xi^-$) pairs are subtracted from right-sign invariant mass distribution $e^+\Lambda$ ($e^+\Xi^-$)
- Unfold $e^+\Lambda$($e^+\Xi^-$) p_T spectrum to obtain the Λ_c^+(Ξ_c^0) spectrum
- Feed-down from beauty-hadron decays are subtracted for Λ_c^+ but not for Ξ_c^0

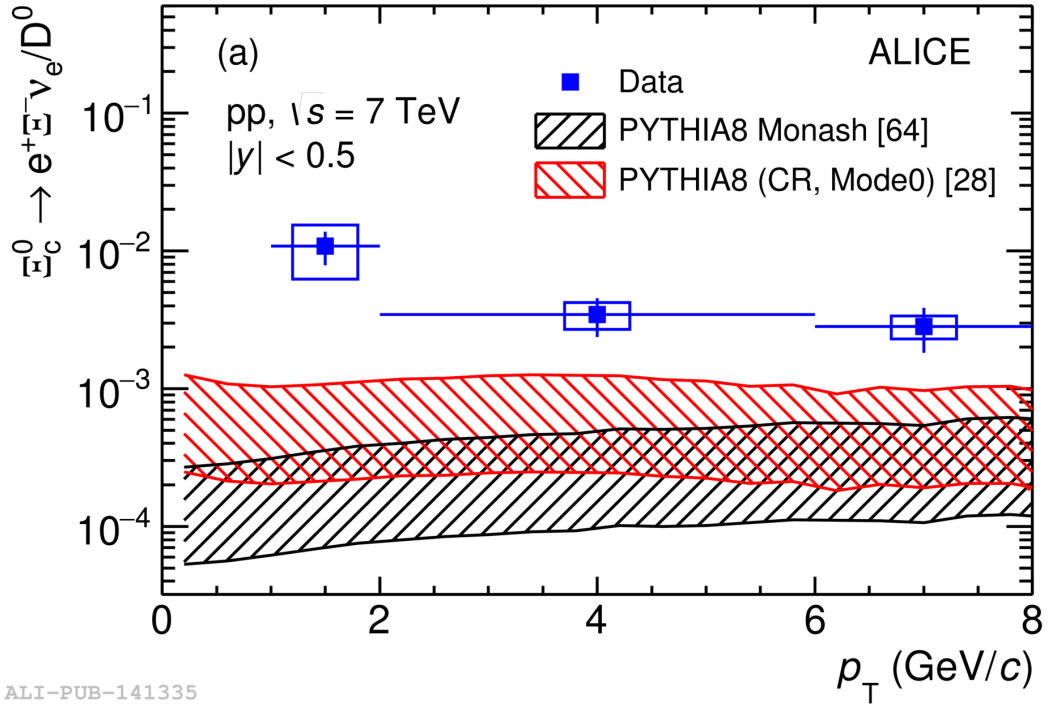
Phys.Lett. B 781 (2018) 8-19

$\Xi_c^0 \times$BR and Ξ_c^0/D^0

[1] Phys. Rev. D40 (1989) 2955, Phys. Rev. D43 (1991) 2939, Phys. Rev. D53 (1996) 1457
[64] PYTHIA 8 Monash: P. Skands, S. Carrazza, and J. Rojo, Eur. Phys. J. C74 (2014) 3024
[28] Colour reconnection: J. R. Christiansen and P. Z. Skands JHEP 08 (2015) 003

Published!





Phys.Lett. B 781 (2018) 8-19

- **First** measurement of $\Xi_c^0 \times$BR at the LHC (BR unknown)
- Baryon-to-meson ratio $\Xi_c^0 \to e^+\Xi^-\nu_e/D^0$ larger than predictions (BR range (0.83% - 4.2%) estimated from theory [1])

Poster ID: 37, 44, 269 by J.Wilkinson, E.Meninno, C.Hills

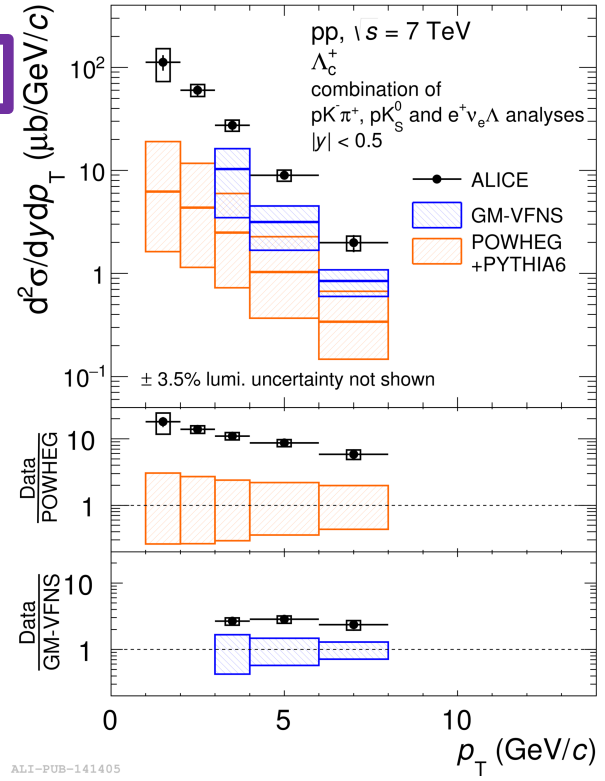
GM-VFNS: Eur. Phys. J. C72 (2012) 2082
PIWHEG+PYTHIA6: JHEP 09 (2007) 126
Shao et al.: Eur. Phys. J. C77 no. 1, (2017) 1

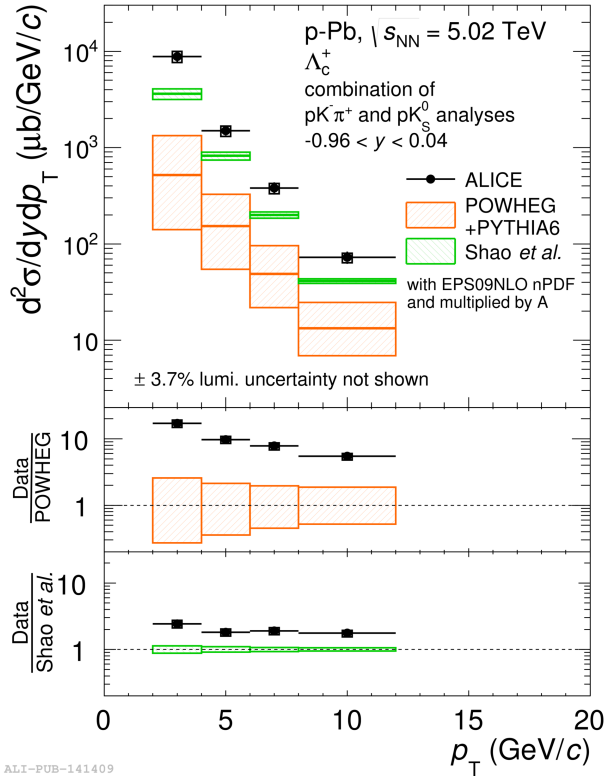
Λ_c^+ p_T-differential cross section

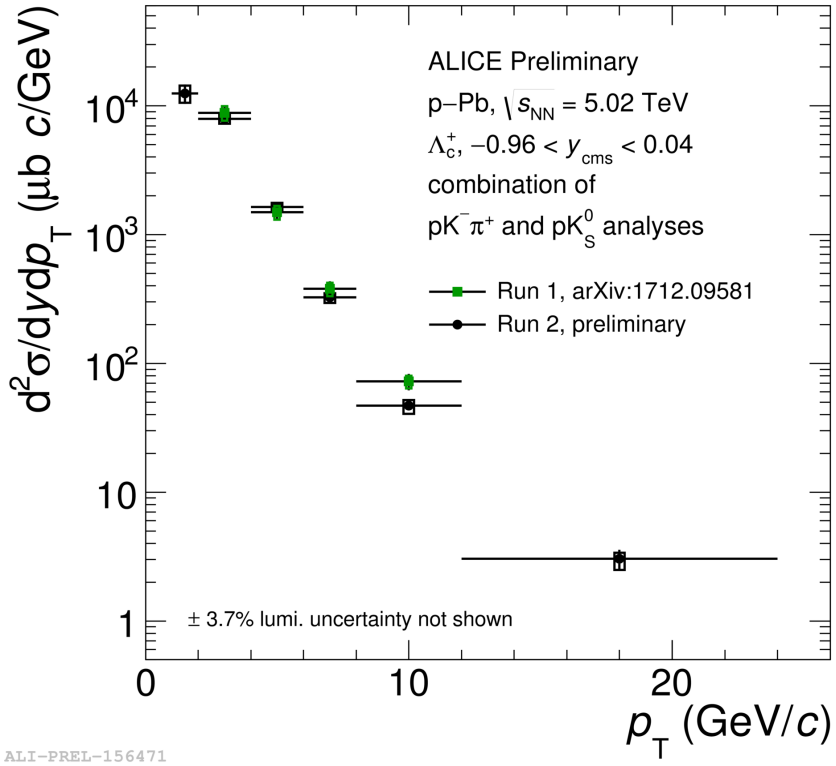
arXiv:1712.09581

Published!

New!





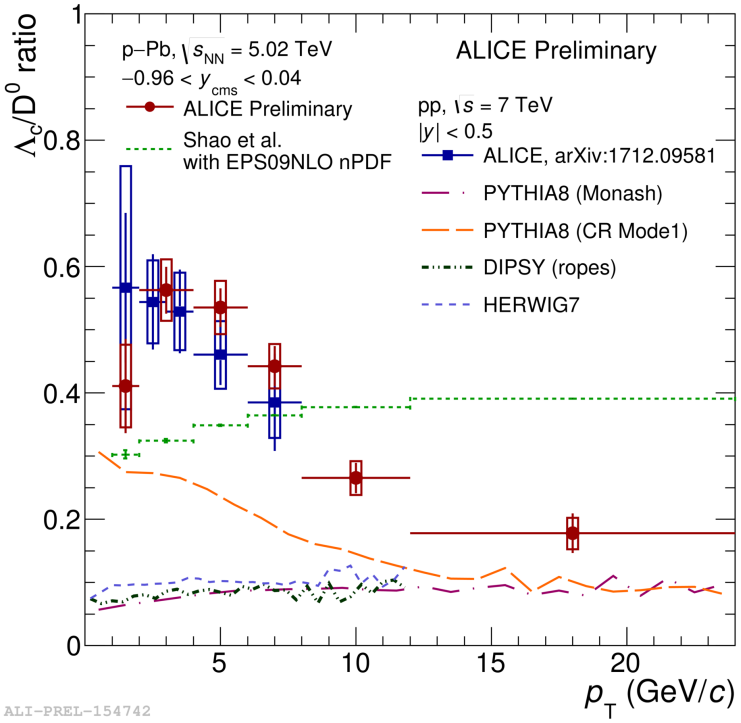


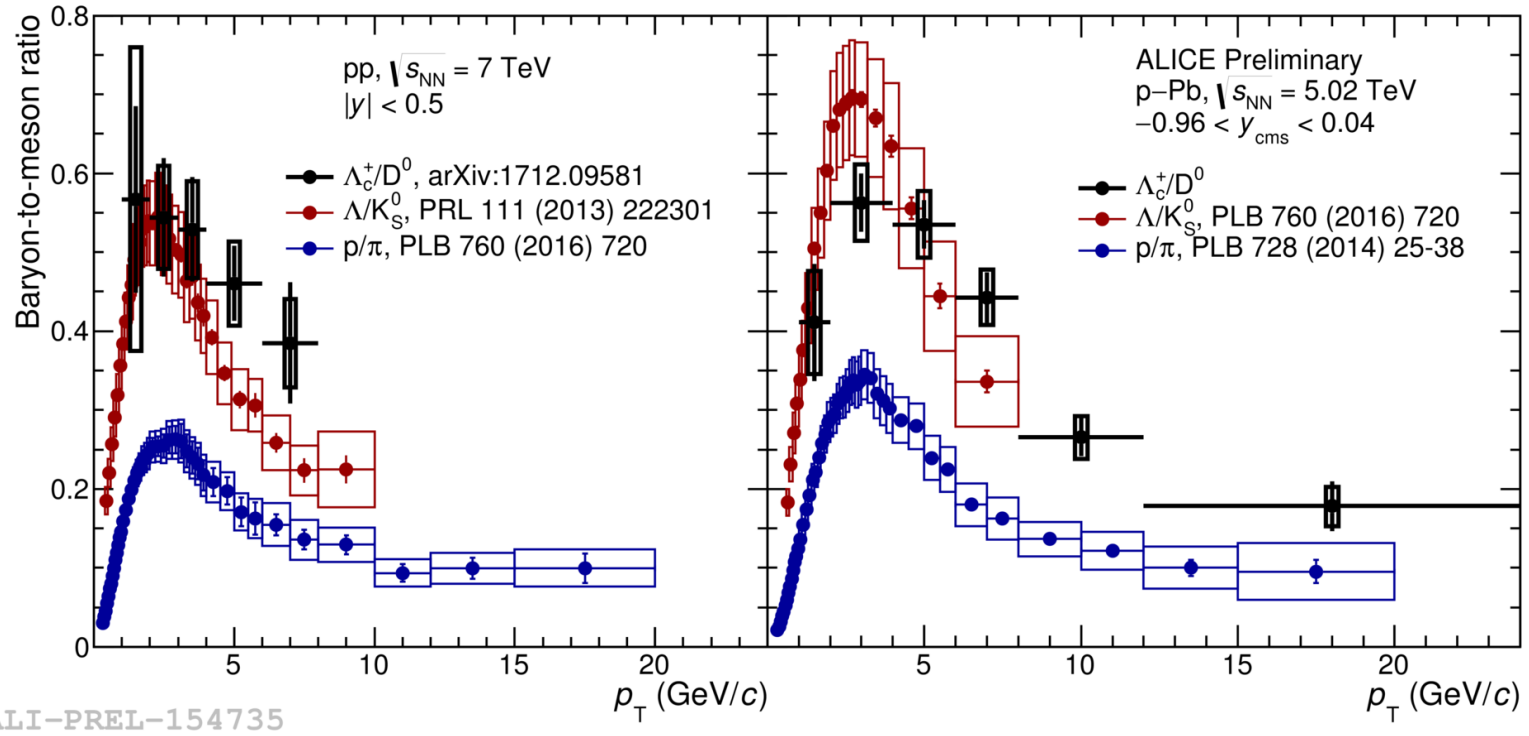
Improved precision and extended p_T range with Run 2 data!

- p_T-differential cross section of Λ_c^+ **underestimated** by theoretical models in both pp and p-Pb collisions
  - ➢ Fragmentation function is tuned to reproduce results from lower energy e^+e^- collisions

Λ_c^+/D^0 ratio in pp and p-Pb

New!



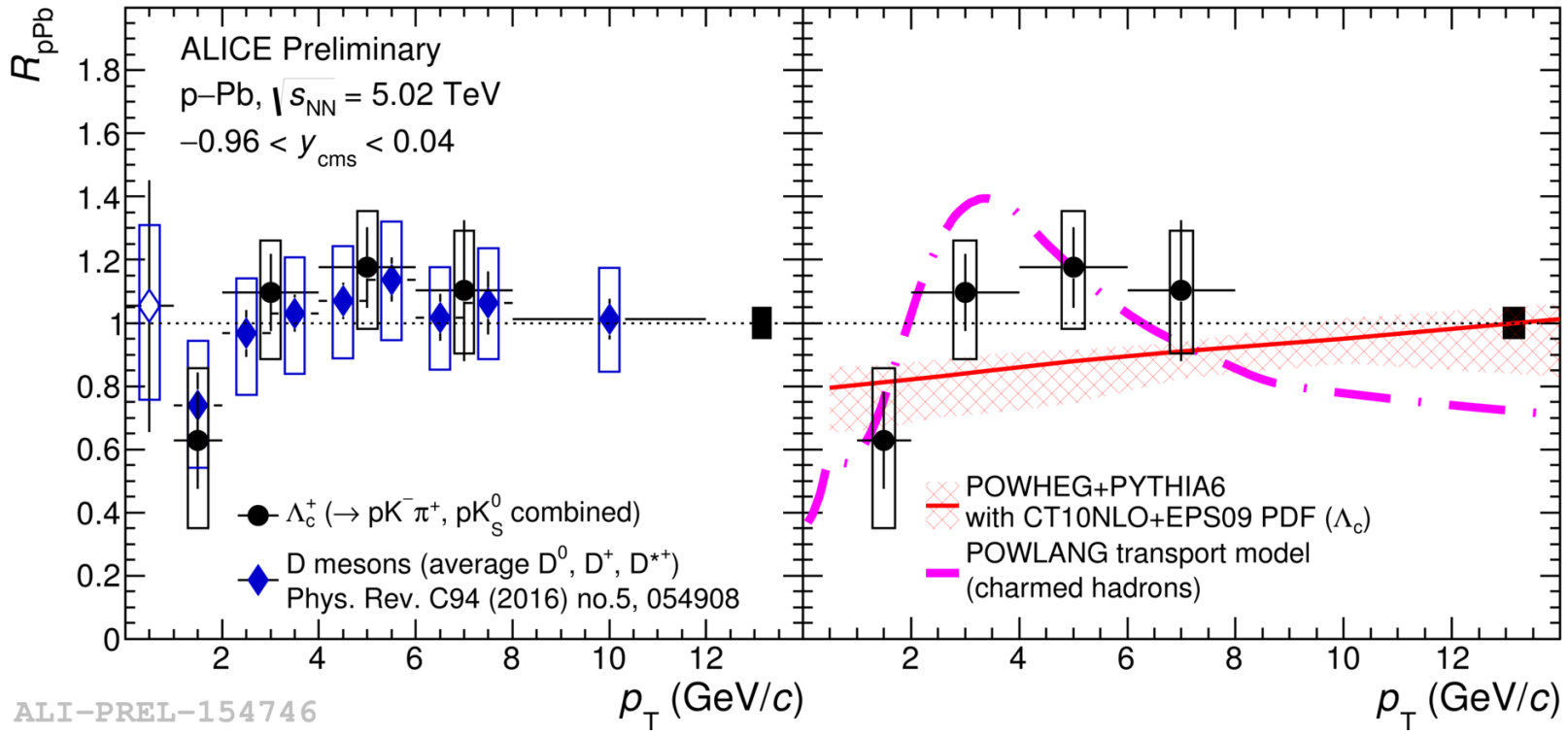


- Λ_c^+/D^0 compatible within uncertainties in pp and p-Pb collisions
- Λ_c^+/D^0 ratio **higher than expectation** from MC (PYTHIA8 with enhanced colour reconnection closer to data)
- New, more precise, preliminary result in p-Pb collisions shows decreasing values from p_T = 4 GeV/*c*. Trend similar to baryon-to-meson ratio in the light-flavour sector

Λ_c^+ R_{pPb}

POWHEG+PYTHIA6 with CT10NLO+EPS09
PDF: JHEP 09 (2007) 126, Phys. Rev. D82 (2010) 074024, JHEP 04 (2009) 065
POWLANG: JHEP 03 (2016) 123

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



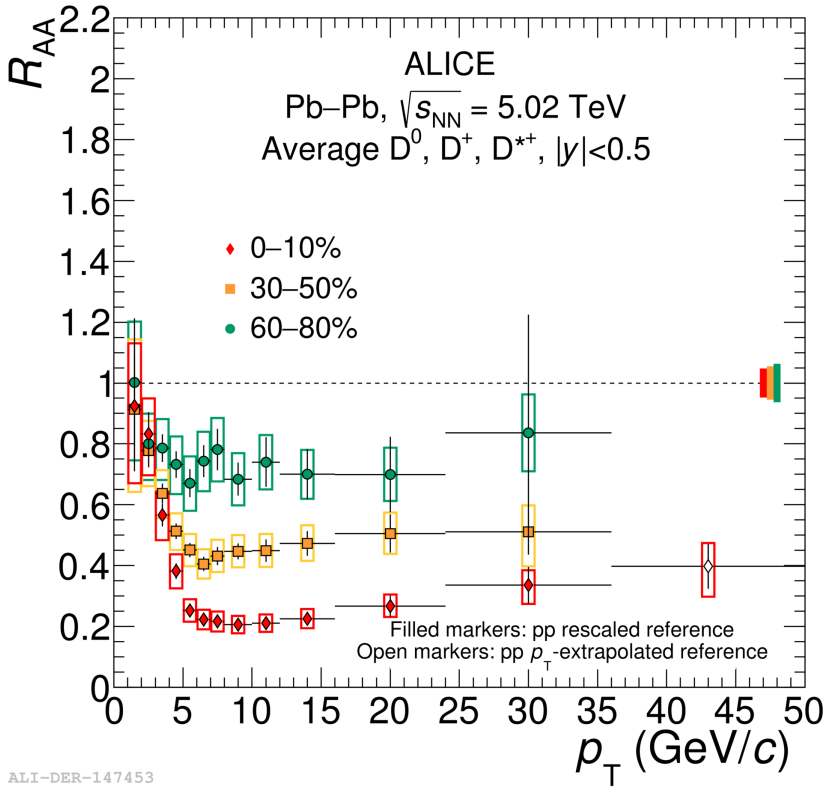
New!

- R_{pPb} of Λ_c^+ consistent with unity, D-meson R_{pPb} and models within uncertainties:
  - **CNM effects**: POWHEG+PYTHIA with CT10NLO+EPS09 PDF
  - **Hot medium effects**: POWLANG with 'small-size' QGP formation, collisional energy loss

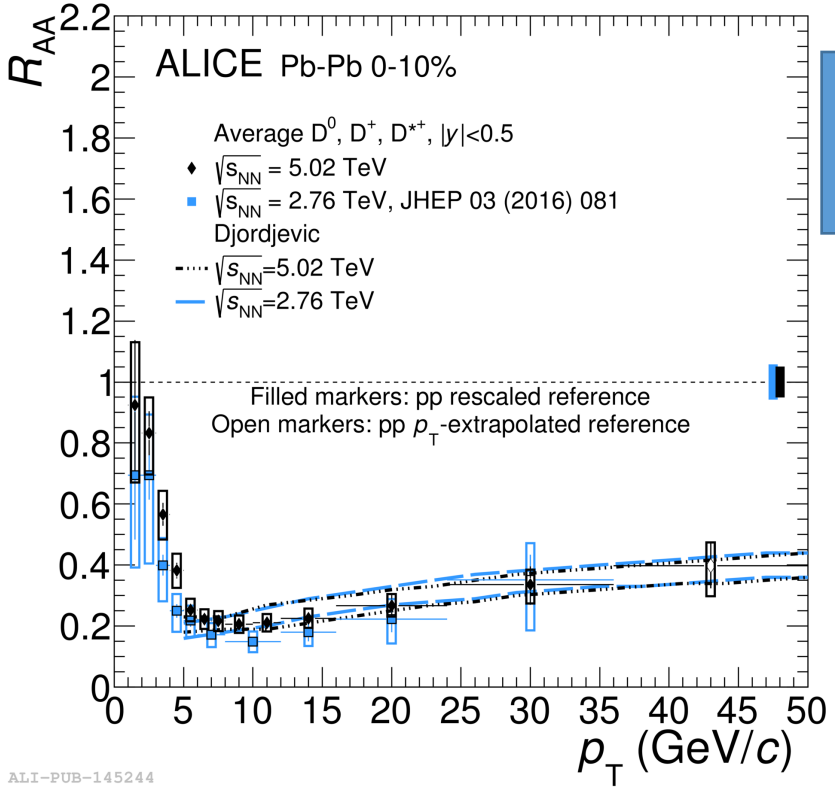
Poster ID: 45 by F.Grosa

[1] Djordjevic, Phys. Rev. C92 (2015) 024918

D meson R_{AA} in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV



60-80%
30-50%
0-10%



Improved precision in Run-2 with respect to Run-1 measurements

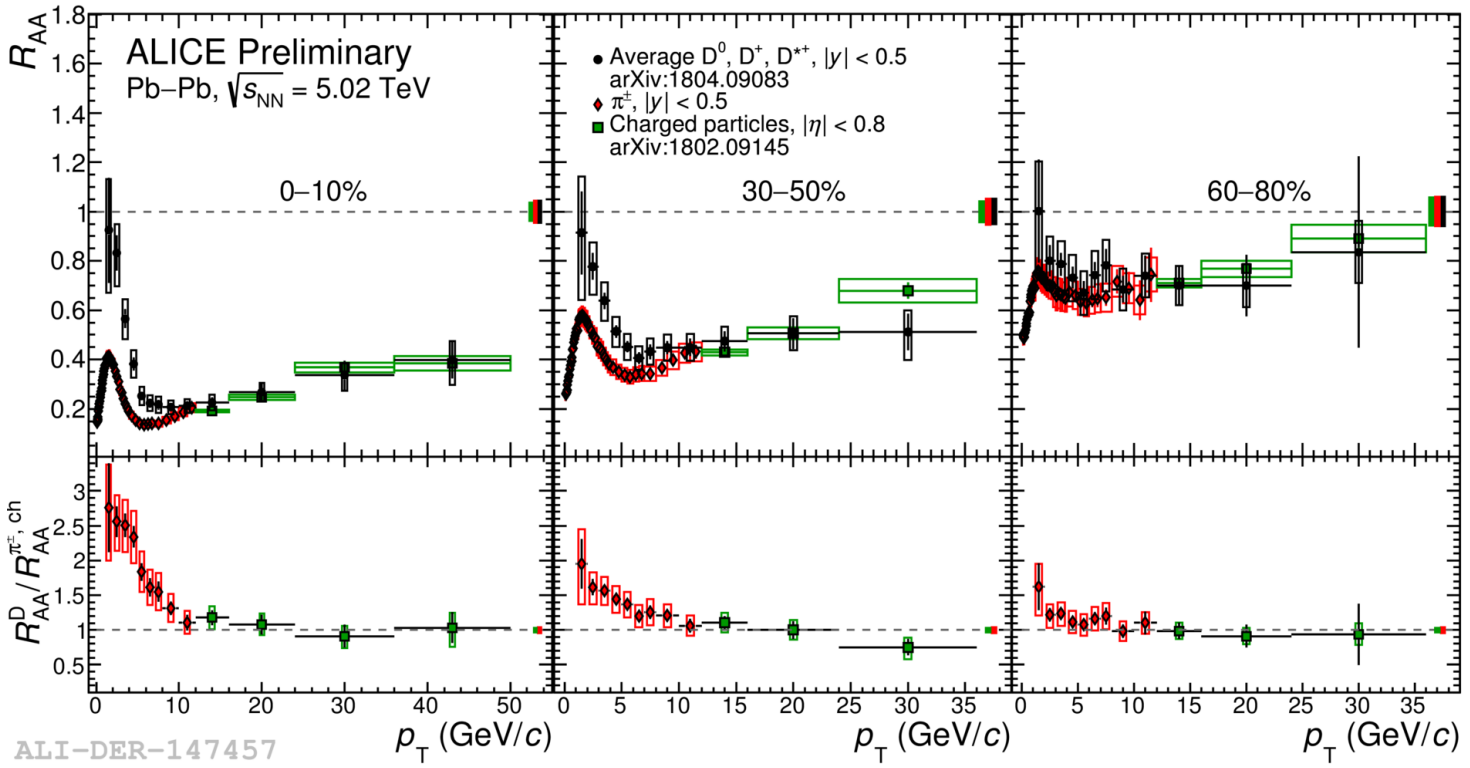
Submitted!

0-10%

arXiv:1804.09083

- **Strong suppression** of non-strange D meson in Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV, increasing with centrality
- Similar suppression between $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV
  - Described by model [1] at two energies -> **harder spectra and denser medium counterbalance**

D-meson and charged-particle R_{AA} comparison



Submitted!

$\pi^{\pm}$ ALICE preliminary

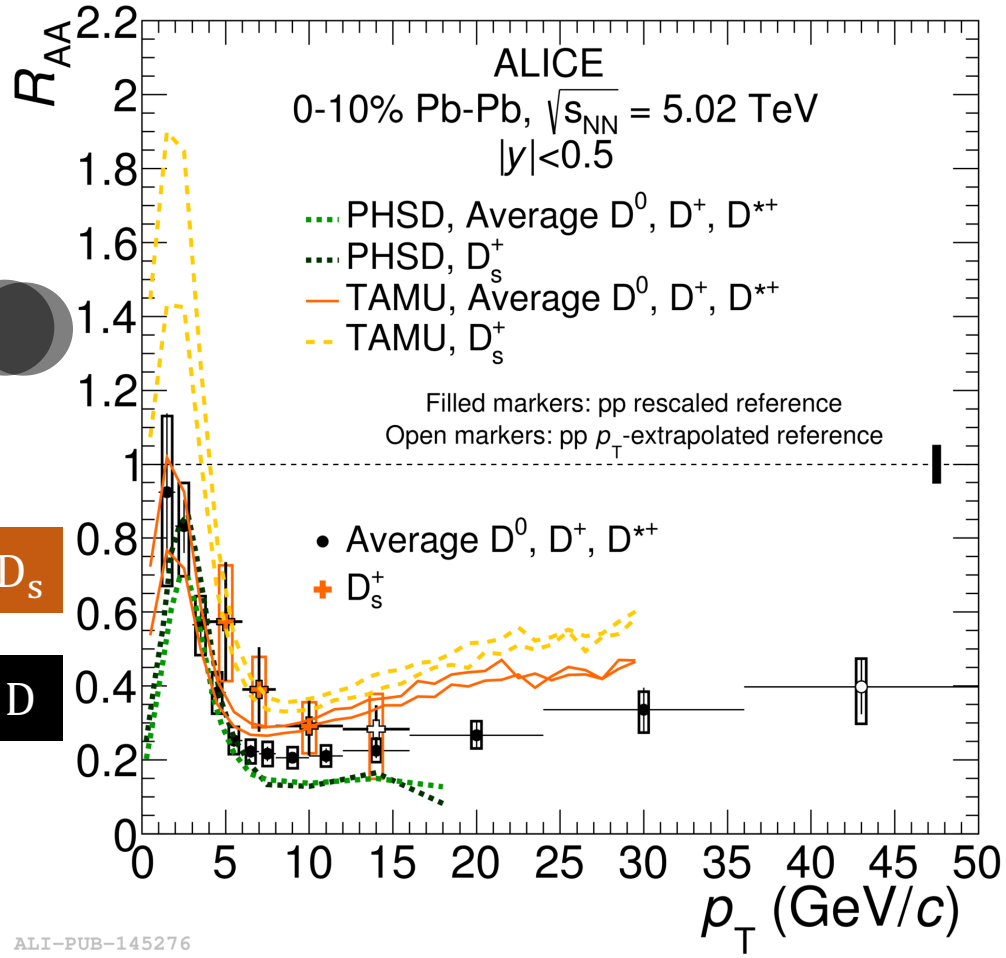
Charged-particle: arXiv:1802.09145

arXiv:1804.09083

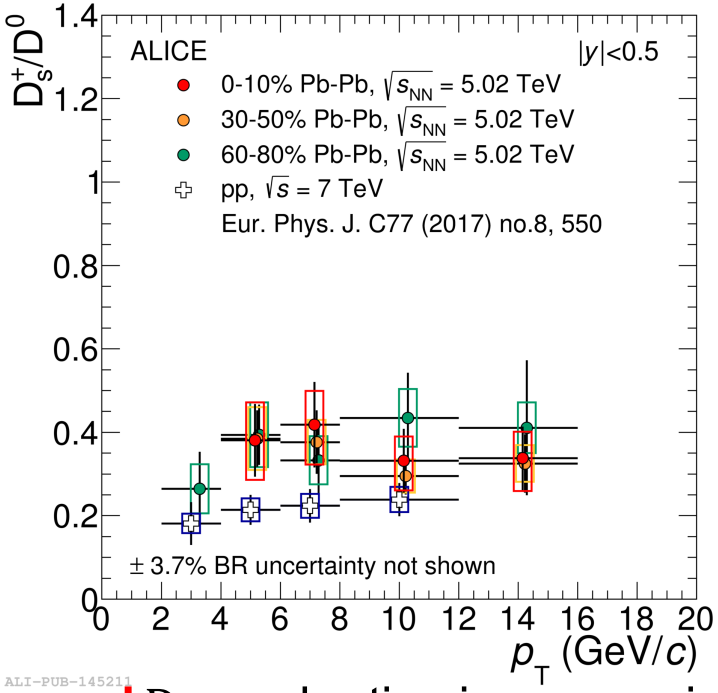
- Similar D-meson, $\pi^{\pm}$ and charged-particle R_{AA} result for $p_T > 10$ GeV/c in 0-10% and 30-50%, compatible results in 60-80% for $p_T > 1$ GeV/c
- D-meson R_{AA} larger than that of charged pions at low p_T for 0-10% and 30-50% centrality classes
  - Not straightforward interpretation: N_{part} vs N_{coll} scaling at low p_T, different fragmentation and initial spectra shapes, possible mass and Casimir factor effects, different impact of coalescence and radial flow

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

PHSD: Phys. Rev. C93 no. 3, (2016) 034906
TAMU: Phys.Lett. B735 (2014) 445–450
Catania: Eur.Phys.J.C (2018) 78:348



arXiv:1804.09083



Submitted!

- Hint of **enhanced** D_s production in comparison to non-strange D mesons in Pb-Pb collisions. Expected from models
  - ➢ **Effect of coalescence + strangeness enhancement?**

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

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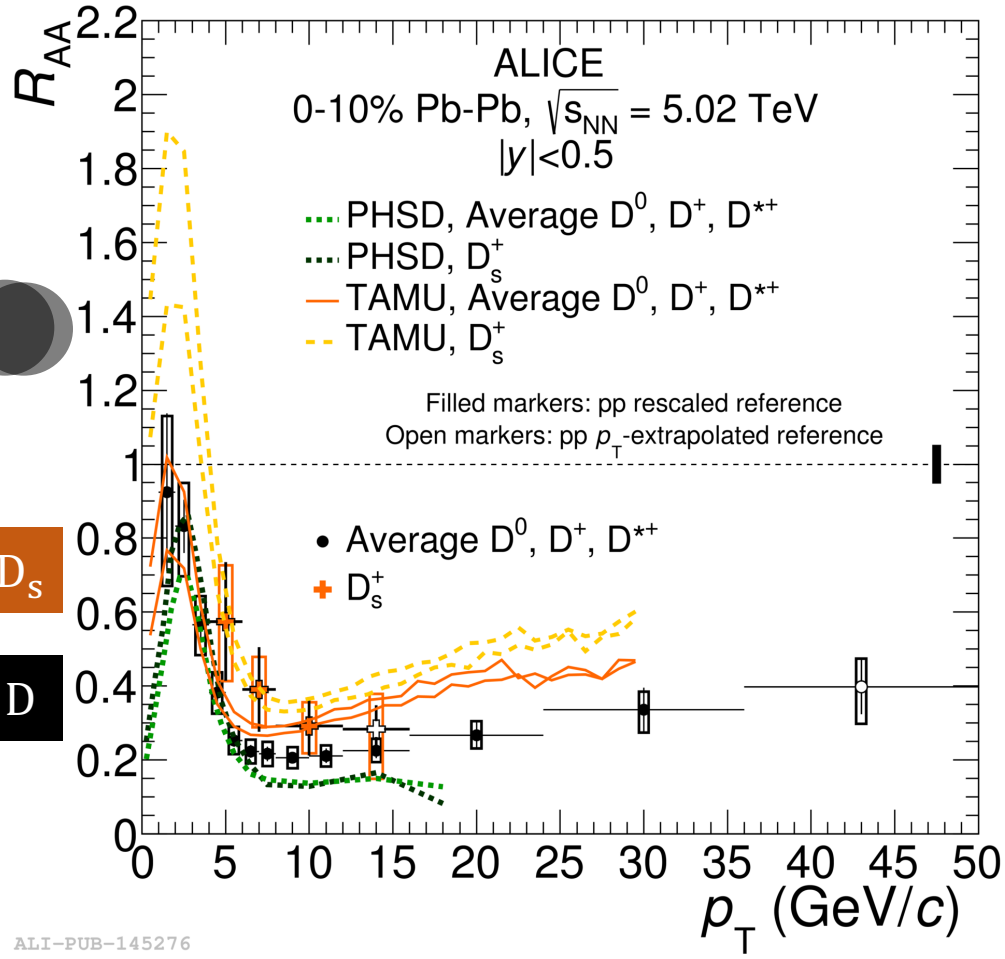
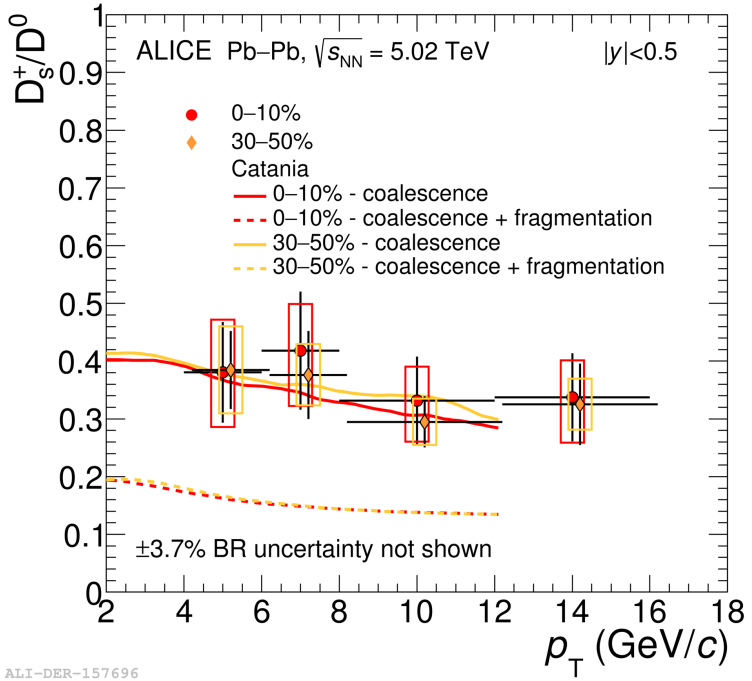


D_s

D



Submitted!

- Hint of **enhanced** D_s production in comparison to non-strange D mesons in Pb-Pb collisions. Expected from models
  - ➢ **Effect of coalescence + strangeness enhancement?**
- D_s/D^0: no evidence for centrality dependence within uncertainties
  - ➢ Negligible centrality-dependence expected by pure-coalescence scenario

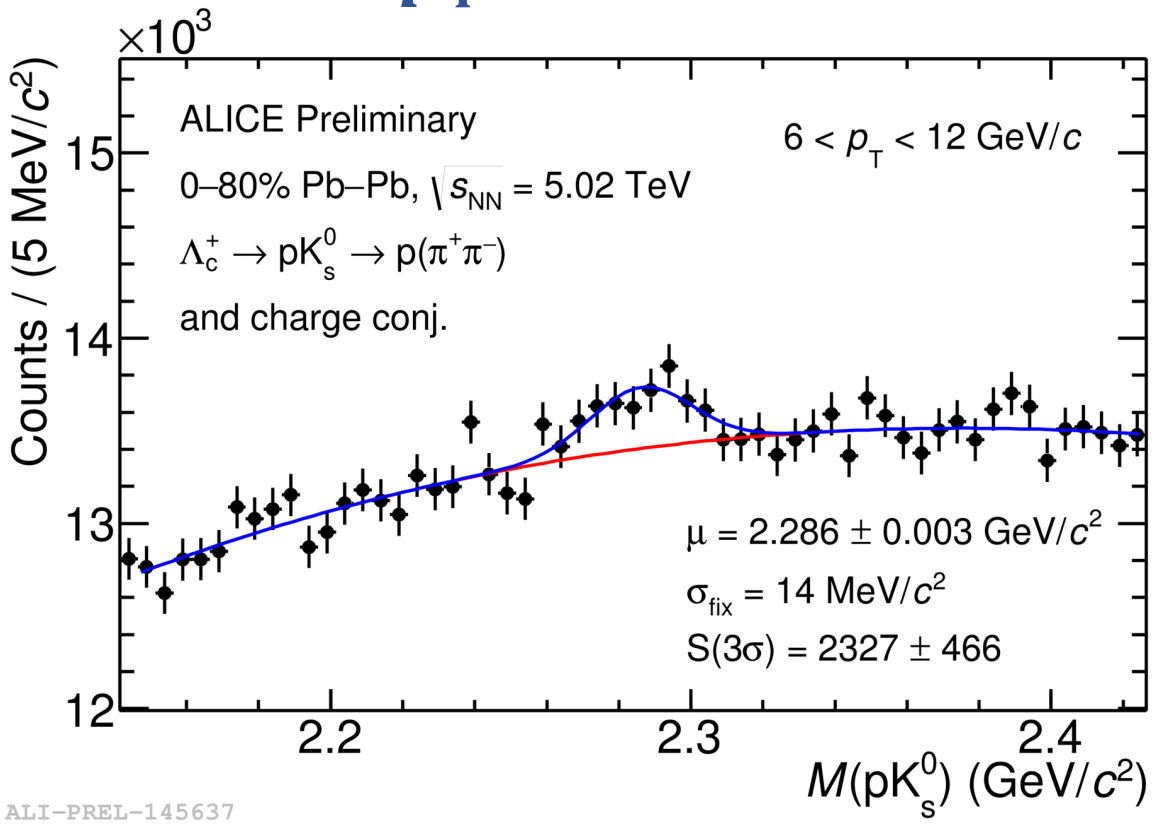
arXiv:1804.09083

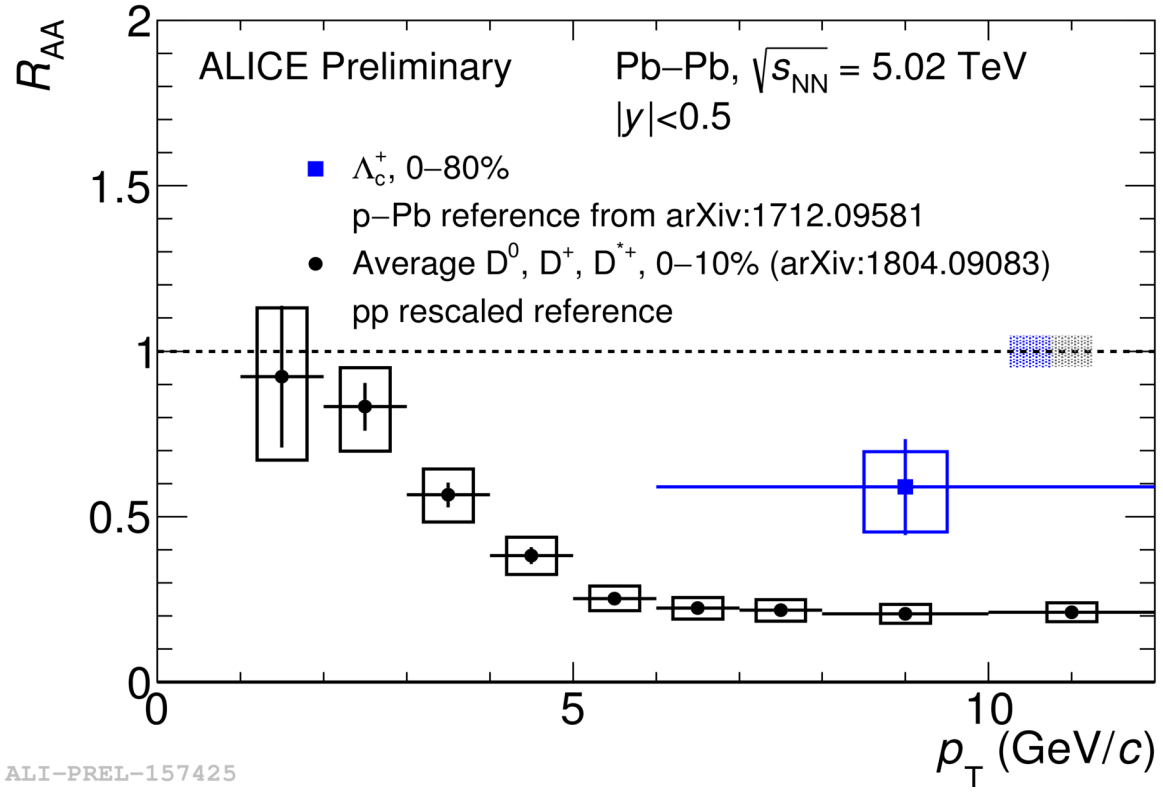
Poster ID: 132 by Y.Watanabe

Λ_c^+ invariant mass and R_{AA} in Pb-Pb

$6 < p_T < 12$ GeV/c 0-80%

New!





- Hint of larger R_{AA} for Λ_c^+ at 0-80% than D meson at 0-10%

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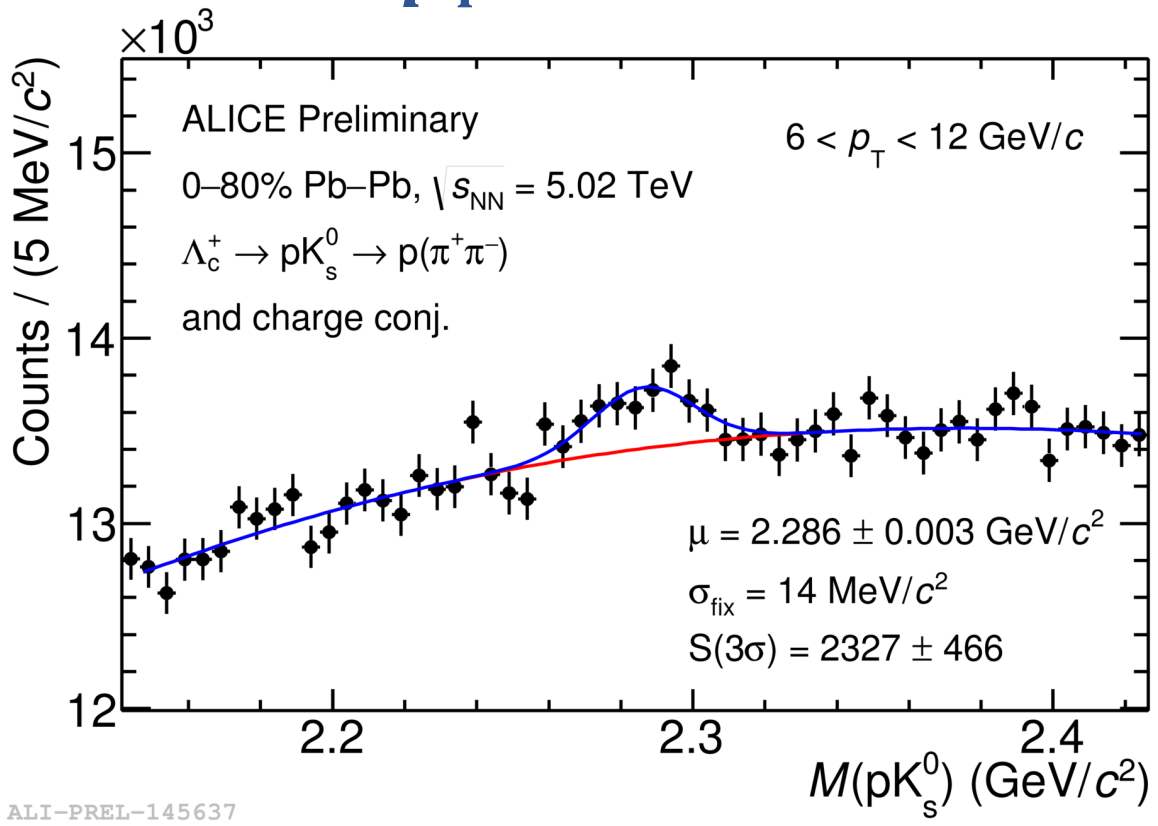
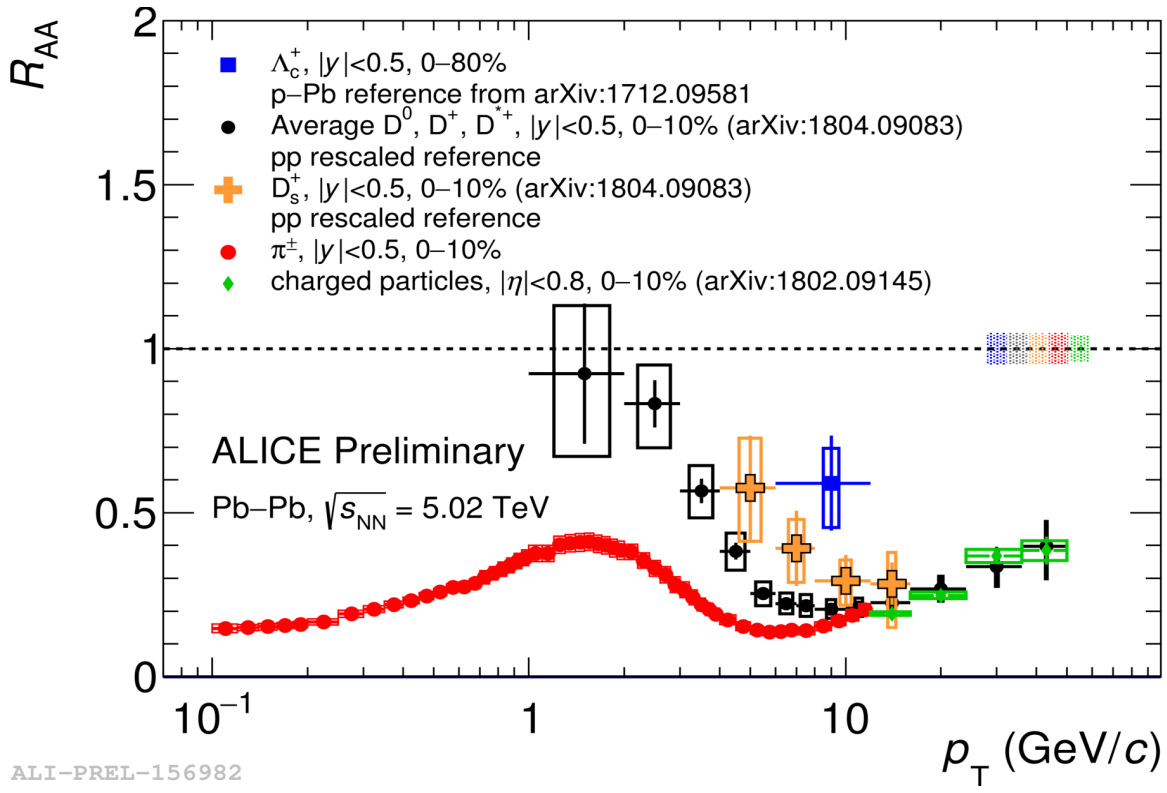


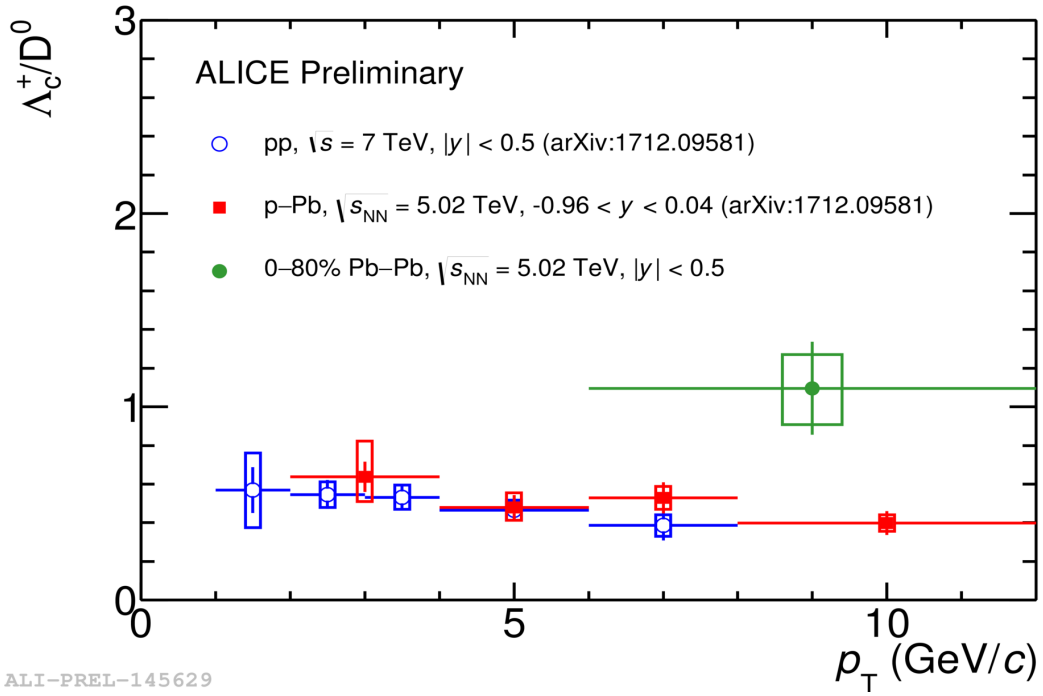


- Hint of larger R_{AA} for Λ_c^+ at 0-80% than D meson at 0-10%
  - Hierarchy Λ_c^+ R_{AA} > D_s^+ R_{AA} > non-strange D-meson R_{AA} > pion R_{AA}?

Λ_c^+/D^0 ratio in Pb-Pb

Oh et al.: Phys.Rev. C79(2009) 044905
Ghosh et al: Phys.Rev. D90 no. 5, (2014) 054018
Das et al: Phys.Rev. D94 no. 11, (2016) 114039
Plumari et al: Eur.Phys.J.C (2018) 78:348
STAR Preliminary: Nucl. Phys. A967, 928 (2017), 1704.04353

New!



- Λ_c^+/D^0 ratio measured in Pb-Pb, hint of enhancement w.r.t pp and p-Pb

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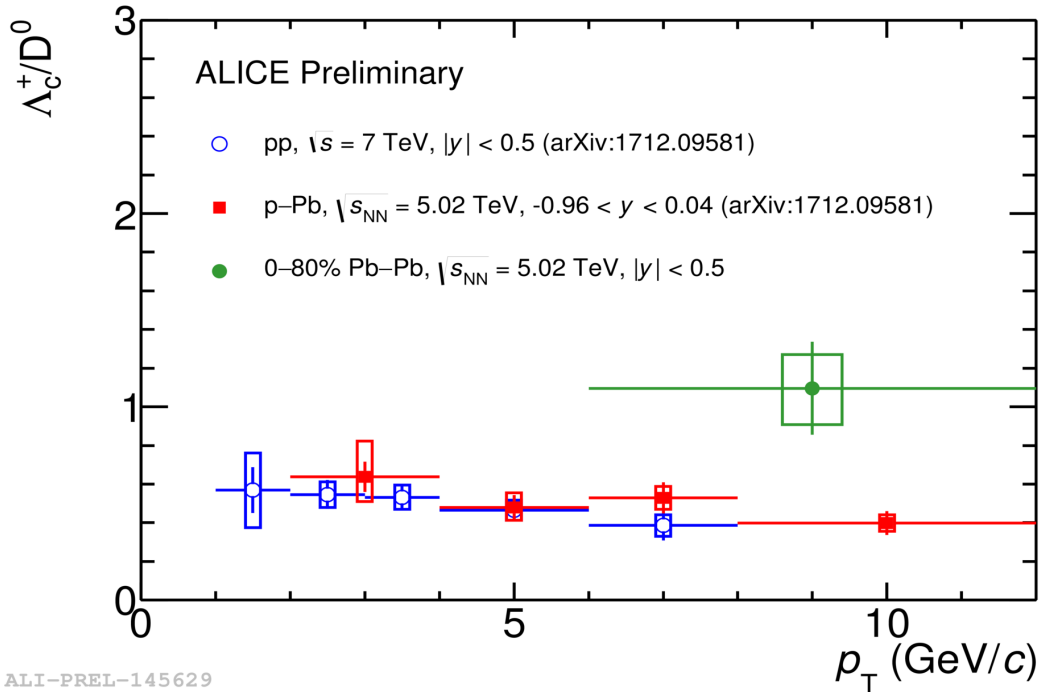

New!

Models	System energy	Λ_c^+/D^0
Oh et al.	Au-Au (central) 200 GeV	~0.35 (p_T = 6 GeV/c)
Ghosh et al.	RHIC and LHC	0.15-0.2 (p_T = 9 GeV/c)
Das et al.	Pb-Pb (0-20%) 5.5 TeV	~0.2 (p_T = 9 GeV/c)
Plumari et al.	Pb-Pb (0-20%) 2.76 TeV	0.1-0.5 (p_T = 8 GeV/c)

- Λ_c^+/D^0 ratio measured in Pb-Pb, hint of enhancement w.r.t pp and p-Pb
- Models tend to **underestimate** the data

Λ_c^+/D^0 ratio in Pb-Pb

Oh et al.: Phys.Rev. C79(2009) 044905
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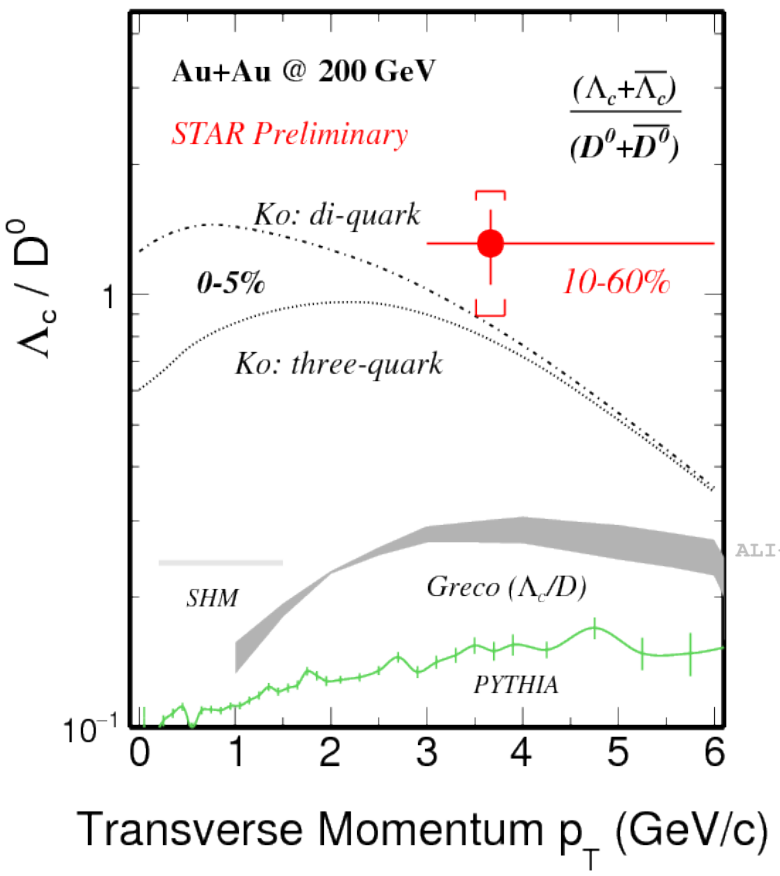

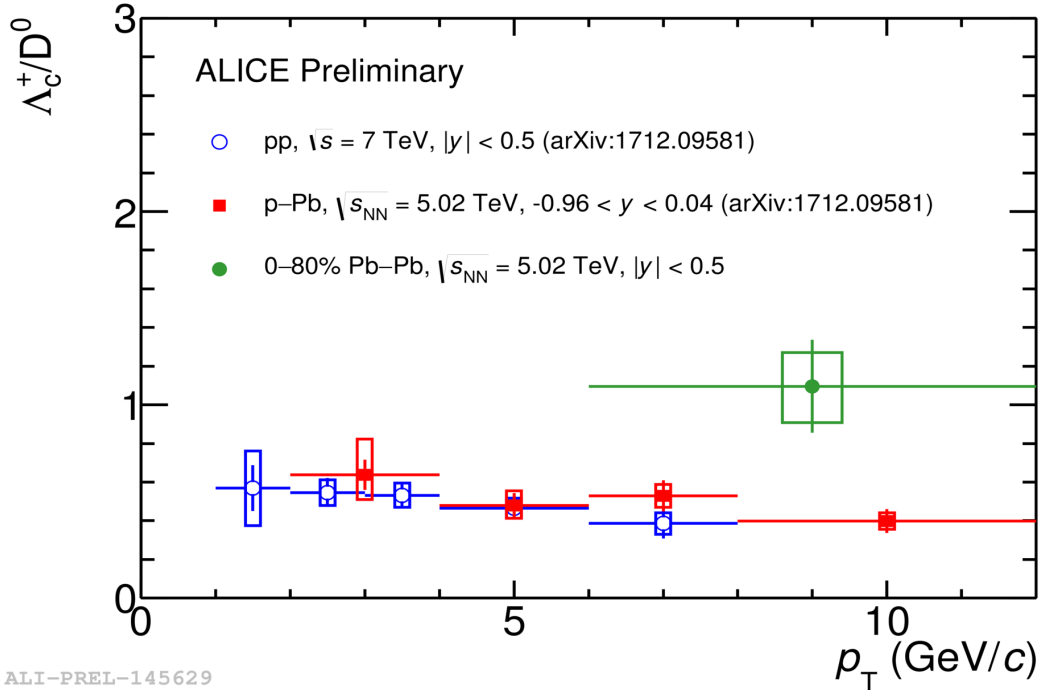

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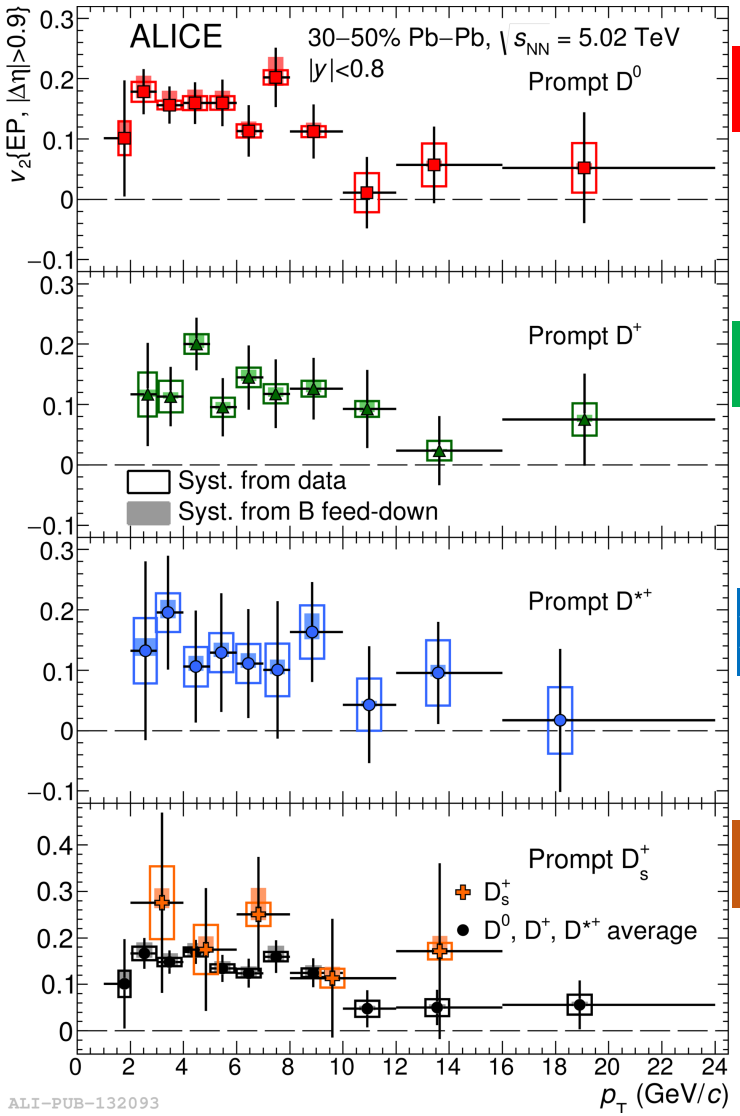
- Λ_c^+/D^0 ratio measured in Pb-Pb, hint of enhancement w.r.t pp and p-Pb
- Models tend to **underestimate** the data
- Similar value than that measured by STAR at low p_T in Au-Au @ 200 GeV

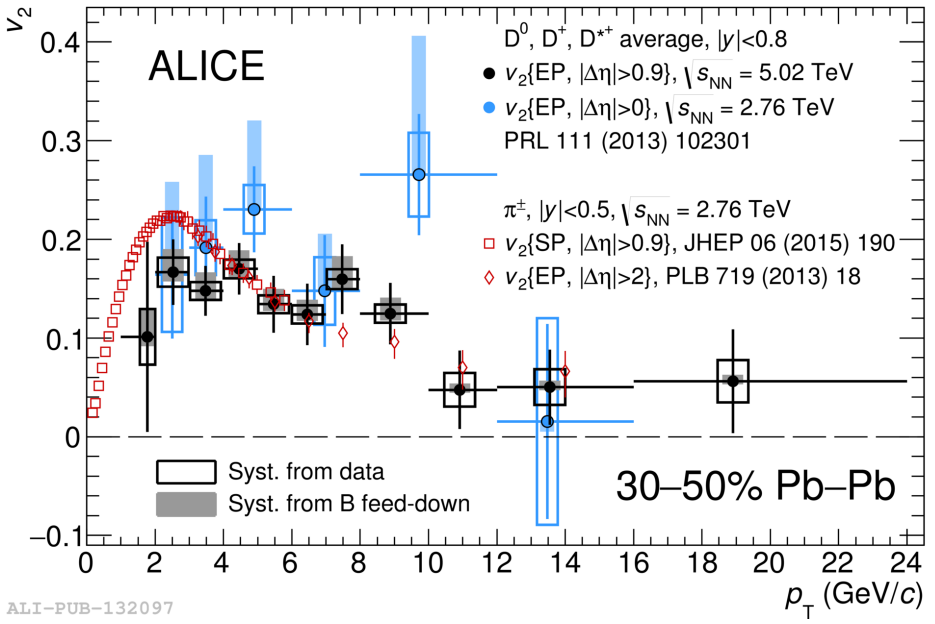
Poster ID: 424 by G.Luparello

D-meson v_2

Phys. Rev. Lett. 120 (2018) 102301



D^0 D$^+$ D^{*+} D$_s$



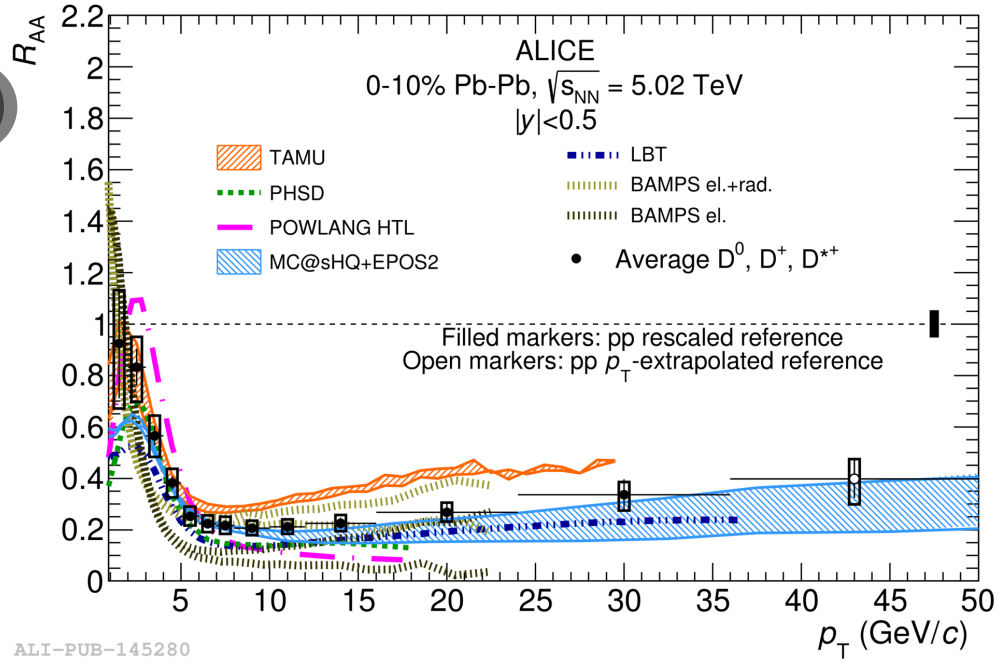
D Run 2
D Run 1
$\pi^{\pm}$

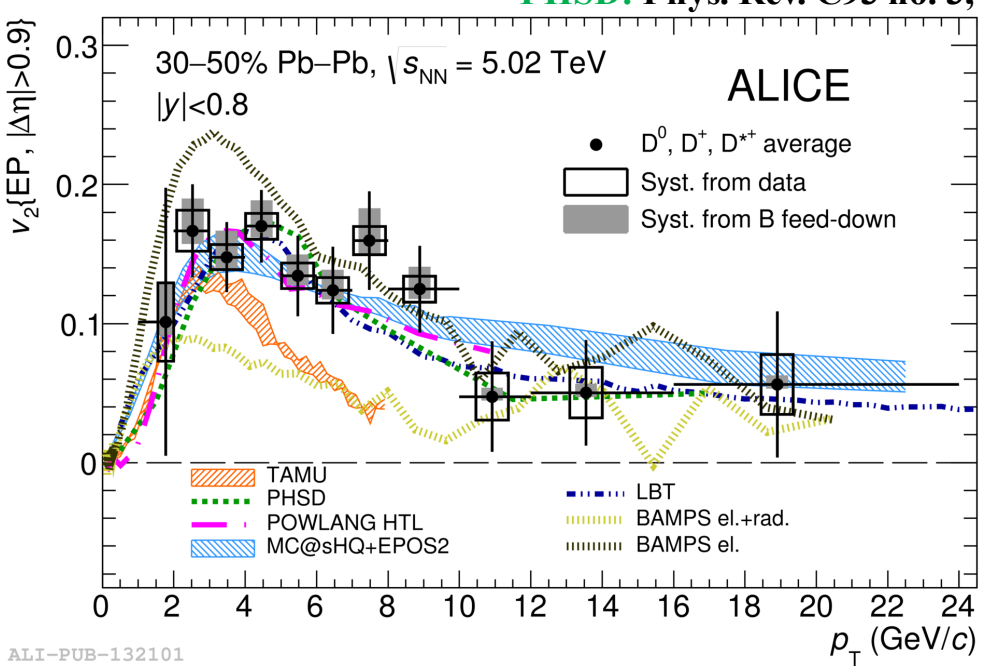
Published!

- **Positive** D-meson v_2 in $2 < p_T < 10$ GeV/c
  - Charm quark sensitive to medium collective motion
- **First** measurement of D_s^+ v_2
  - Compatible with that of non-strange D mesons
- D-meson v_2 compatible between $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV
- D-meson v_2 is similar to that of charged pions
  - Hint of **larger** pion v_2 at $p_T < 4$ GeV/c

Comparison with models

POWLANG: Eur. Phys. J. C75 no. 3, (2015) 121
MC@sHQ: Phys.Rev. C89 no. 1, (2014) 014905
LBT: Phys. Lett. B777 (2018) 255–259
BAMPS: J. Phys. G42 no. 11, (2015) 115106
PHSD: Phys. Rev. C93 no. 3, (2016) 034906





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- Models in which charm quarks pick up collective flow via **recombination or subsequent elastic collisions in expanding medium** better describe both v_2 and R_{AA} at low p_T (**LBT**, **MC@sHQ**, **PHSD**, **POWLANG**)
- Improved precision of the measurement can provide **important constraints** on models and help to extract information about the medium properties. For models describing reasonably the data
  - v_2 -> Diffusion coefficient $1.5 < 2\pi T D_s(T) < 7$ at T_c -> Charm thermalisation time τ_{charm} = 3-14 fm/c

Summary

- **New charmed-baryon measurements:**
  - Ξ_c^0, Λ_c^+ cross section in pp and Λ_c^+ in p-Pb collisions **underestimated** by models
  - **Λ_c^+/D^0 in pp and p-Pb collisions higher than MC predictions**
    - **Similar p_T-trend than baryon-to-meson ratio in light flavour sector**
  - **Λ_c^+/D^0 in Pb-Pb collisions, hint of enhancement w.r.t pp and p-Pb collisions**
- **D mesons results in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV :**
  - D^0, D^+, D^{*+}, D_s^+ R_{AA}: **increasing suppression** from peripheral to central collisions
  - Ratio of D_s^+ w.r.t non-strange D-meson results: **hint of enhancement in Pb-Pb w.r.t pp → coalescence and strangeness enhancement?**
  - D^0, D^+, D^{*+}, D_s^+ v_2 : **strong coupling of charm quark with the medium**
    - First measurement of D_s^+ v_2

Don’t miss the details in the poster session!

D meson results in Pb-Pb results

- **[45] F.Grosa:** Measurement of $\mathrm{D_s^+/D^+}$ as a function of transverse momentum and charged particle multiplicity in pp, p--Pb and Pb--Pb collisions with ALICE
- **[116] A.Festanti:** Event shape engineering for the D-meson elliptic flow in Pb--Pb collisions at 5.02 TeV with ALICE at the LHC
- **[424] G.Luparello:** D-meson v2 measurement in Pb-Pb collisions at 5.02 TeV with ALICE

Λ_c^+ baryon in run 2 p-Pb and Pb-Pb results

- **[37] J.Wilkinson:** TMVA methods to reconstruct $\Lambda_c^+ \rightarrow \mathrm{pK_s^0}$ in p--Pb collisions with ALICE at the LHC
- **[44] E.Meninno:** Studies of Λ_c^+ to $\mathrm{pK_s^0}$ in p-Pb collisions with the ALICE experiment at the LHC
- **[132] Y.Watanabe:** Measurement of Lambdac/D0 ratio in Pb-Pb collisions at 5.02 TeV with ALICE
- **[269] C.Hills:** Measurement of Λ_c^+ production via $\Lambda_c^+ \rightarrow \mathrm{pK^-\pi^+}$ channel in pPb collisions at 5.02 TeV

BACK UP

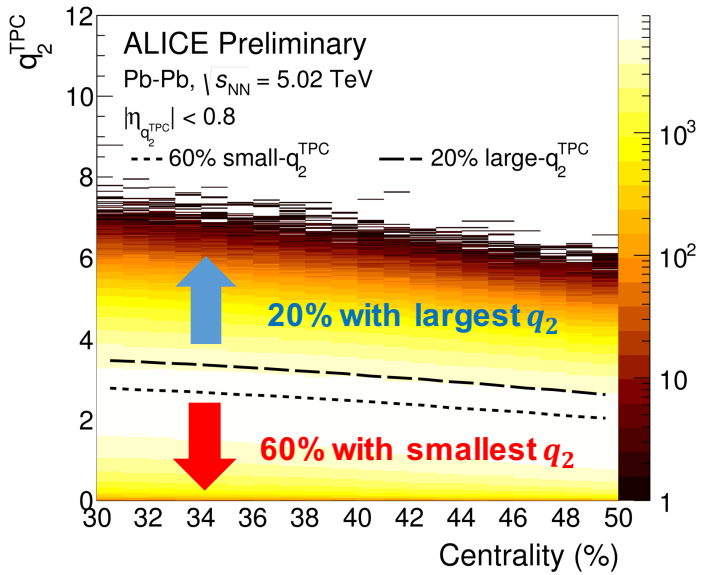
Poster ID: 116 by A.Festanti

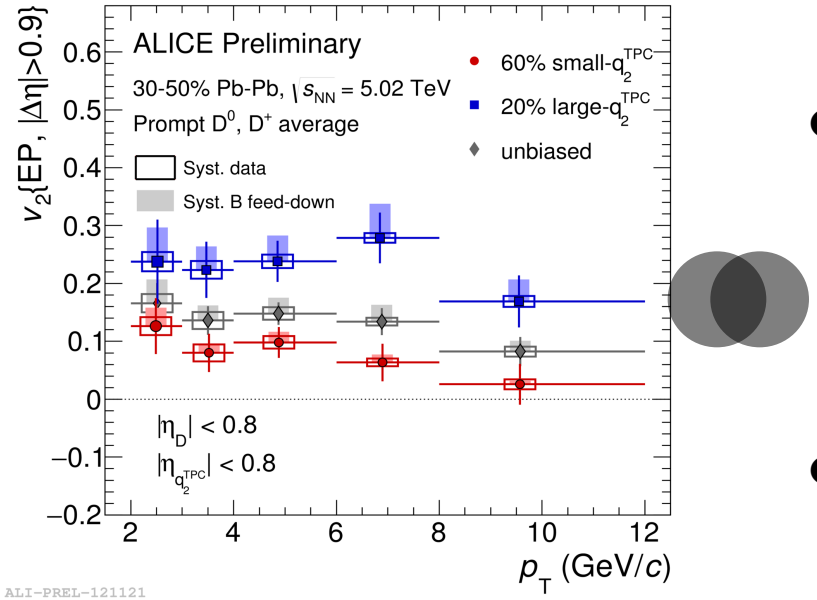
Event Shape Engineering Analysis

- Event eccentricity quantified by q_2 which depends on **multiplicity** and **strength of the flow**

$$\langle q_2^2 \rangle \approx 1 + \langle (\mathbf{M} - 1) \rangle \langle (\boldsymbol{v_2^2} - \delta_2) \rangle$$

- **Opportunity to study the charm-quark coupling to the bulk of light quarks** by measuring v_2 in events with different q_2 values



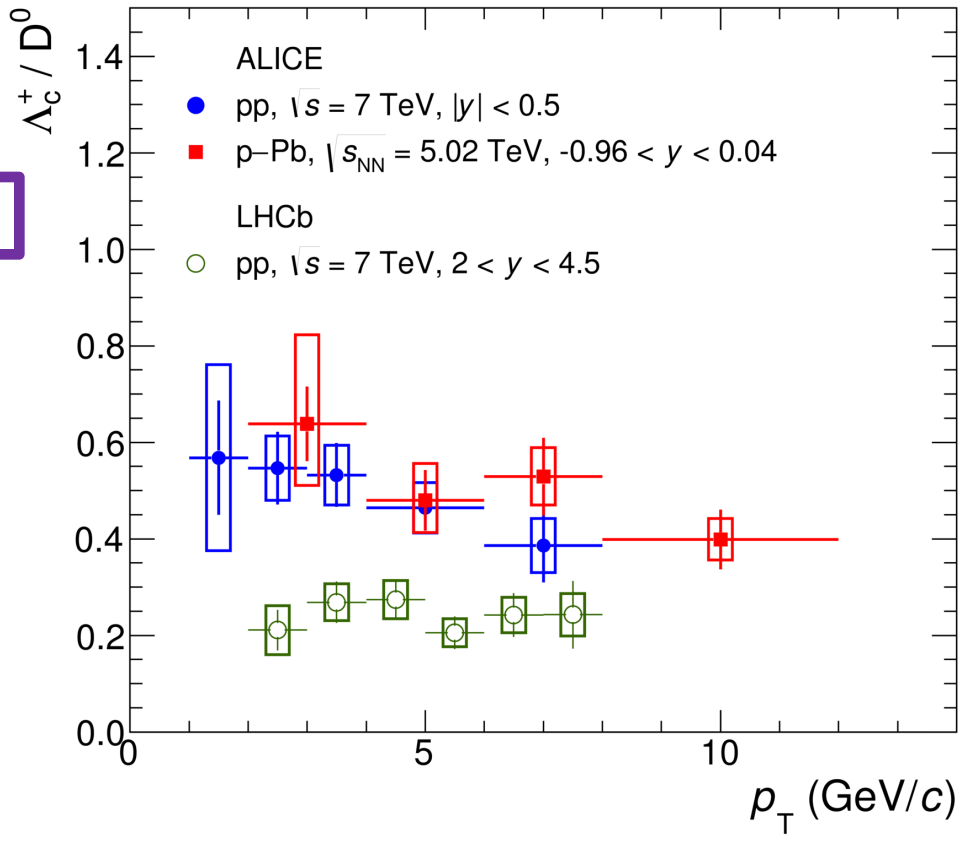


- **Significant separation** of D-meson v_2 in events with **large** and **small** q_2
  - ➢ Charm quarks are sensitive to the light-hadron **bulk collectivity** and event-by-event **initial condition fluctuations**
- Auto-correlations between q_2 and D mesons not removed completely

Λ_c^+/D^0 ratio compared with LHCb

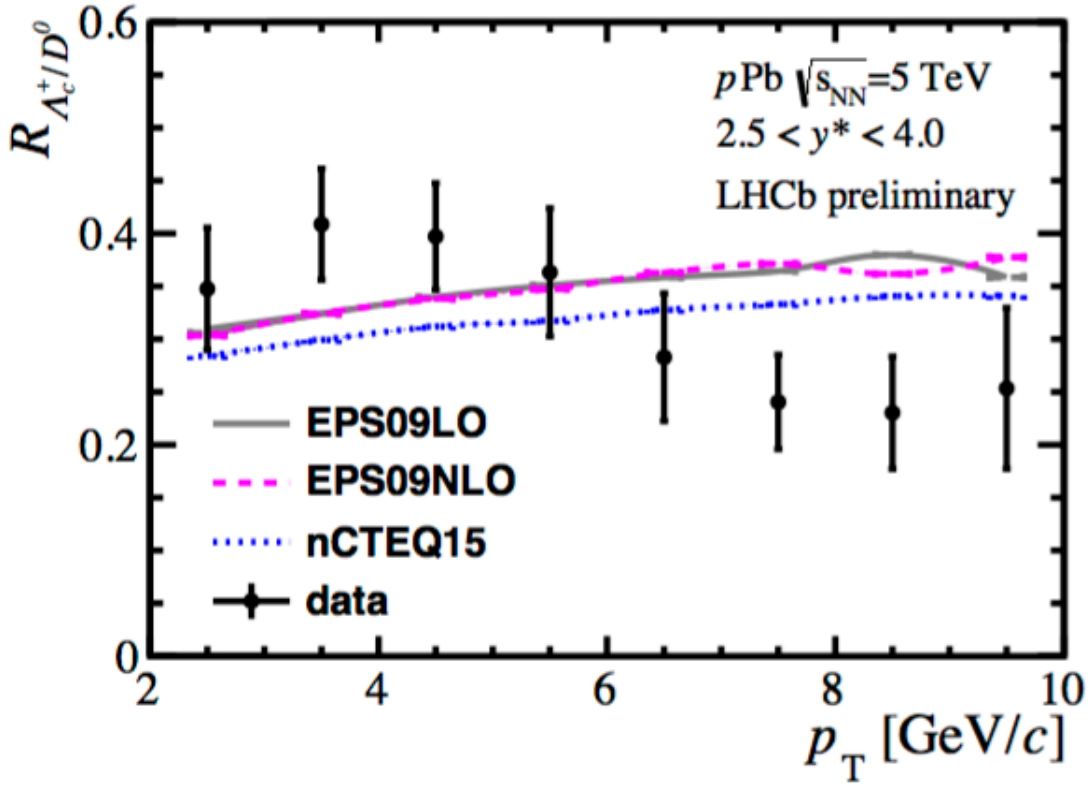
Published!

arXiv:1712.09581



LHCb:Nucl. Phys. B871 (2013) 1–20

p-Pb LHCb:CERN-LHCb-CONF-2017-005 (2017)



- ALICE measurement systematically **higher** than LHCb

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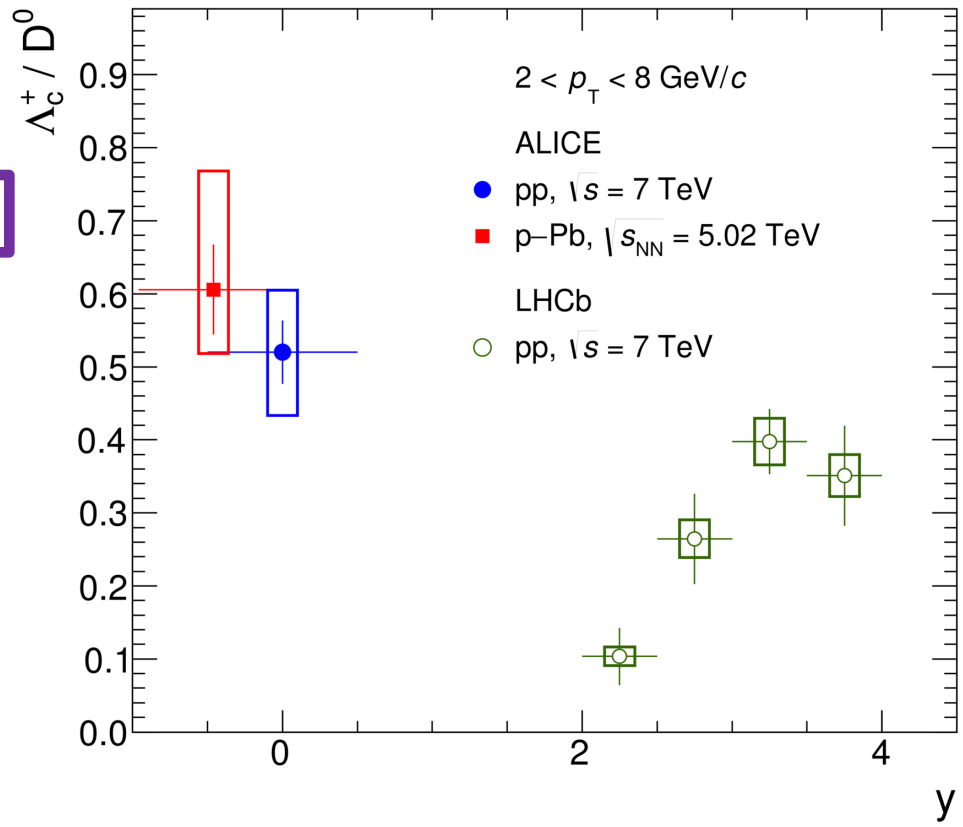

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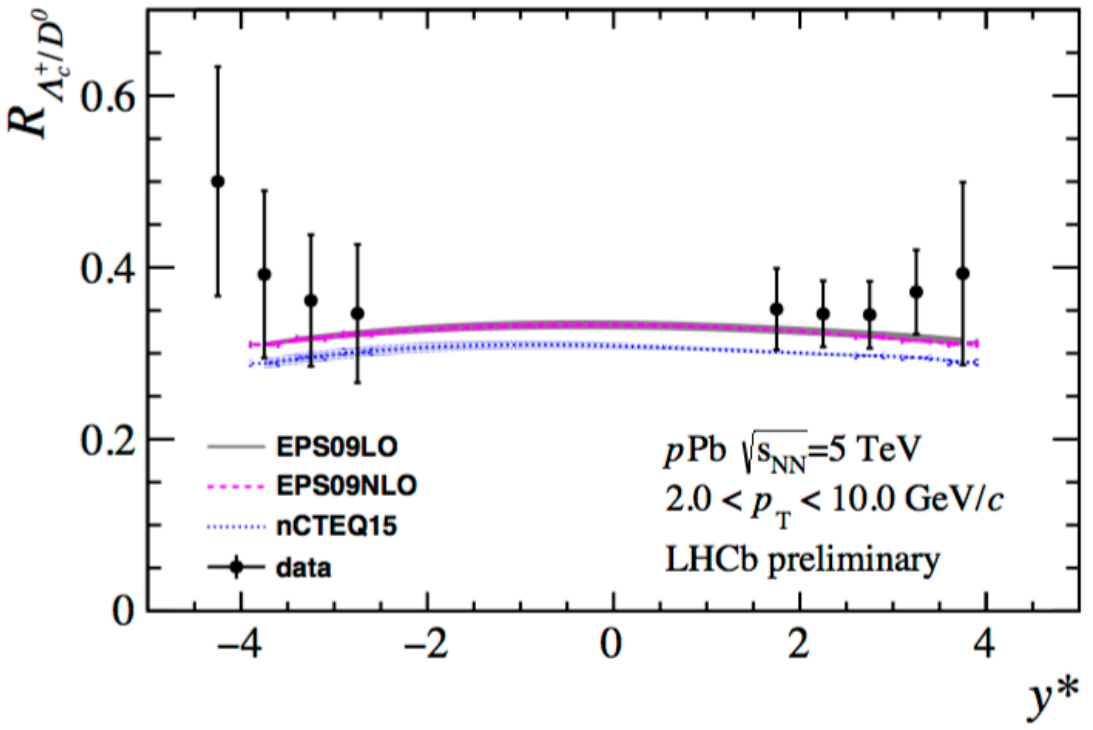
LHCb:Nucl. Phys. B871 (2013) 1–20

p-Pb LHCb:CERN-LHCb-CONF-2017-005 (2017)



- ALICE measurement systematically **higher** than LHCb

Λ_c^+ production in Pb-Pb compared with models