Open heavy-flavour measurements in p-Pb and Pb-Pb collisions with ALICE at the LHC

Cristina Terrevoli
University & INFN Padova
for the ALICE Collaboration

Outline

- Open heavy flavours in ALICE
  - Pb-Pb and p-Pb collisions: physics motivations
  - observables

- Open heavy-flavour reconstruction in ALICE

- Measurements in p-Pb collisions

- Measurements in Pb-Pb collisions

- Conclusions

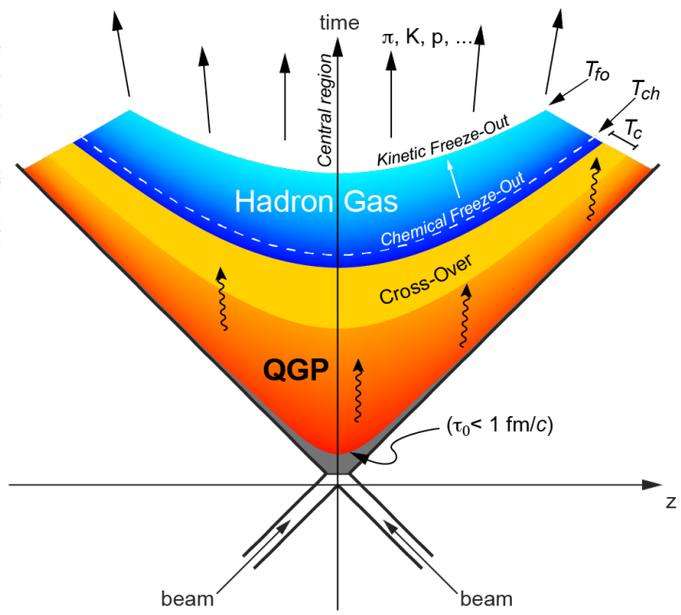
Measurements in pp collisions and in p-Pb collisions as a function of multiplicity: see F. Colamaria talk Tuesday 16.00 and J. Wagner Tuesday 17.00

Open heavy flavours in Pb-Pb and p-Pb collisions

charm and beauty: effective probes of the Quark-Gluon Plasma (QGP)

$m_c \sim 1.5$ GeV/c^2, $m_b \sim 5$ GeV/c^2

- produced at the early stage of the collision
- propagate and interact with medium constituents



Pb-Pb collisions:

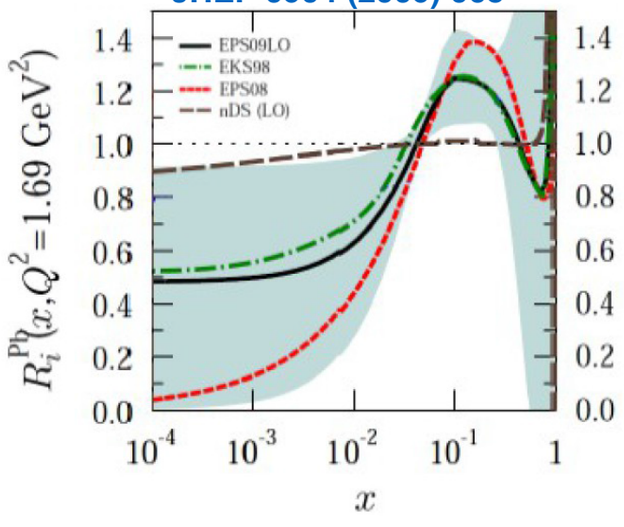
investigate the interaction of heavy quarks with the medium

- energy loss mechanisms
- colour-charge and mass dependence of parton energy loss
- do c and b quarks participate in the collective expansion of the system?

p-Pb collisions:

- quantify Cold Nuclear Matter (CNM) effects on charm production
  - modification of parton densities in nuclei via shadowing or saturation
  - k_T-broadening
  - parton energy loss in cold nuclear matter?
- possible final-state "medium" effects?
- access to low-x region and explore different x regimes in different rapidity ranges

JHEP 0904 (2009) 065



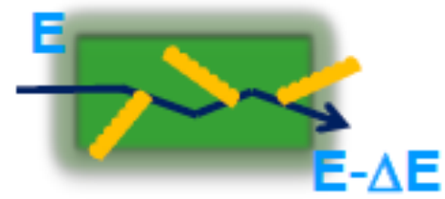
gluon nPDF: very large uncertainties at low x

QGP effects and observables

Energy loss via radiative and collisional processes:

Theoretical prediction: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$ colour-charge and mass dependence of energy loss

Observable: nuclear modification factor: $R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle T_{AA}\rangle d\sigma_{pp}/dp_T}$

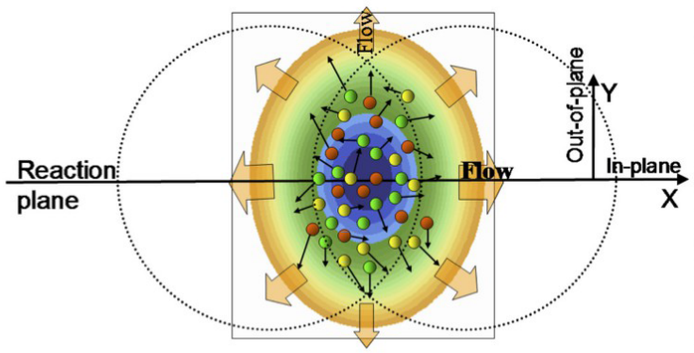


Expectation: $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$?

caveats: different production kinematics and fragmentation should be considered in the comparisons

Azimuthal anisotropy:

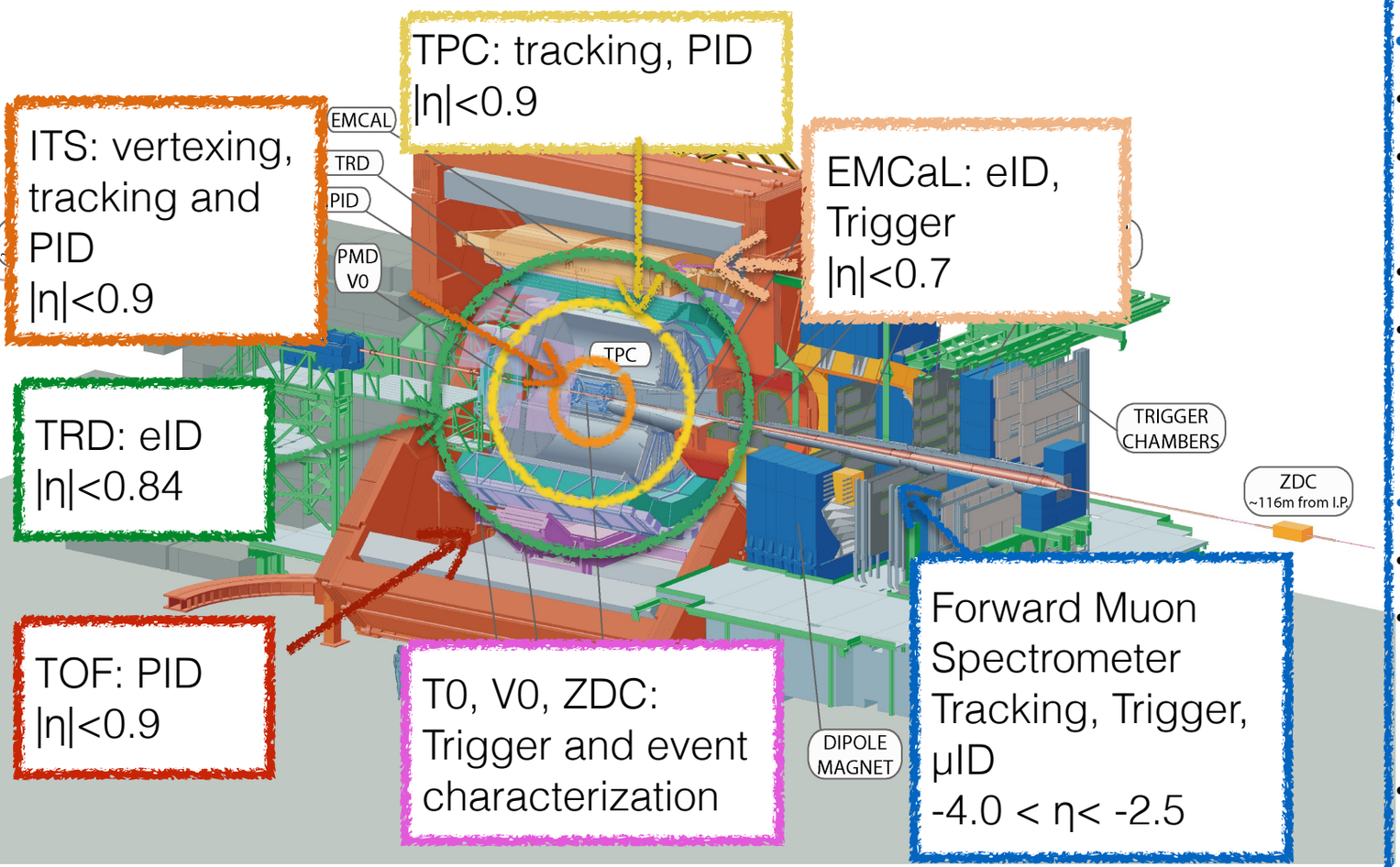
- in semi-central collisions, re-scattering among produced particles converts the initial geometrical anisotropy into momentum anisotropy
- path-length dependent energy loss induces an asymmetry in momentum space
- observable sensitive to the thermalization of c and b quarks in QGP



Observable: elliptic flow $v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_n)]\right)$$

Open heavy-flavour hadron decays



$D, B \rightarrow e^{\pm}, \mu^{\pm} + X$

$D^0 \rightarrow K^- \pi^+$	B.R. = 3.93±0.04%	cτ~123 μm
$D^+_s \rightarrow \phi\pi^+ \rightarrow K^- K^- \pi^+$	B.R. = 2.77±0.12%	cτ~150 μm
$D^+ \rightarrow K^- \pi^+ \pi^+$	B.R. = 9.13±0.19%	cτ~312 μm
$D^{*+} \rightarrow D^0 \pi^+$	B.R. = 67.7±0.05%	

[PDG 2015]

Selection and identification

- **Muons: Forward Muon Spectrometer**
- Acceptance and geometrical cuts
- Tracks matched with trigger
  - hadron rejection
- Pointing angle to the vertex
- background ($\mu \leftarrow \pi$,K and $\mu \leftarrow$W) subtracted with data-tuned MC cocktail and MC, respectively
- **Electrons: ITS, TPC, TOF, EMCAL, TRD**
- eID
- background subtraction with invariant mass e^-e^+ method or cocktail method based on data
- beauty-hadron decay electrons are measured using the impact parameter distribution
- **D-meson reconstruction: ITS, TPC, TOF**
- PID of decay products
- displaced vertex reconstruction and topological selection
- for low p_T D^0: background subtraction method w/o reconstruction of D^0 decay vertex

p-Pb collisions

collected in 2013 $\sqrt{s_{NN}}$ = 5.02 TeV

new w.r.t. SQM2015

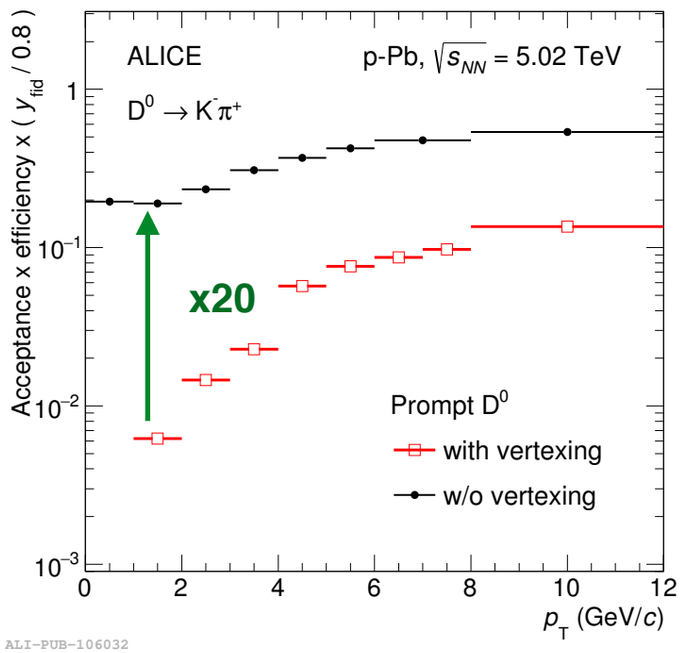
D^0 down to p_T = 0 and p_T-integrated cross section

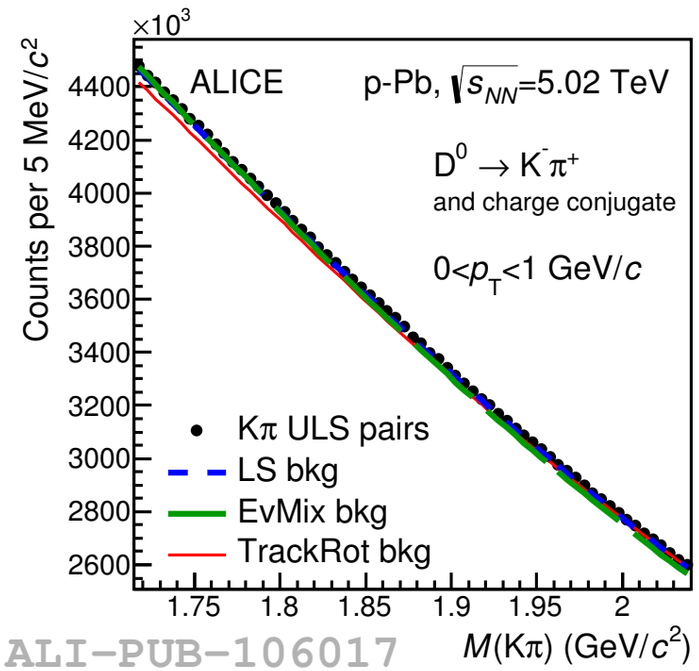
arXiv:1605.07569

open heavy-flavour decay electron R_{pPb}

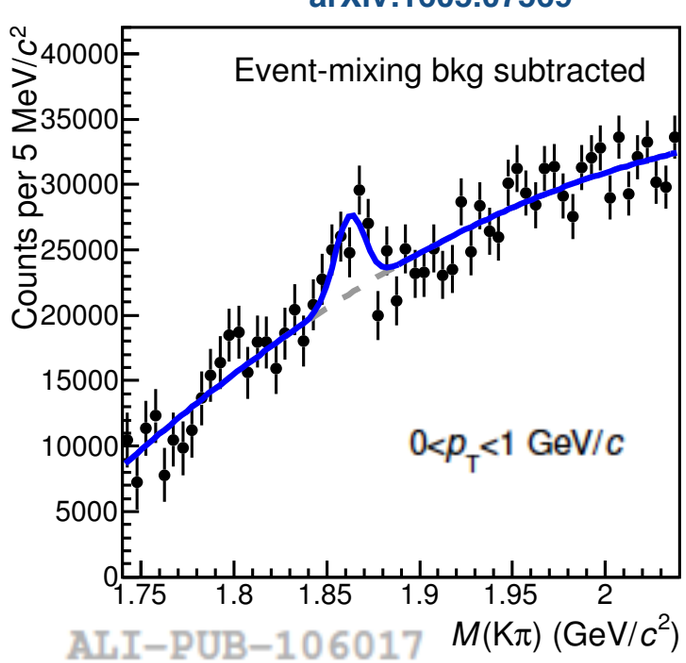
Phys. Lett. B 754 (2016) 81-93

D^0 down to $p_T = 0$: background subtraction method





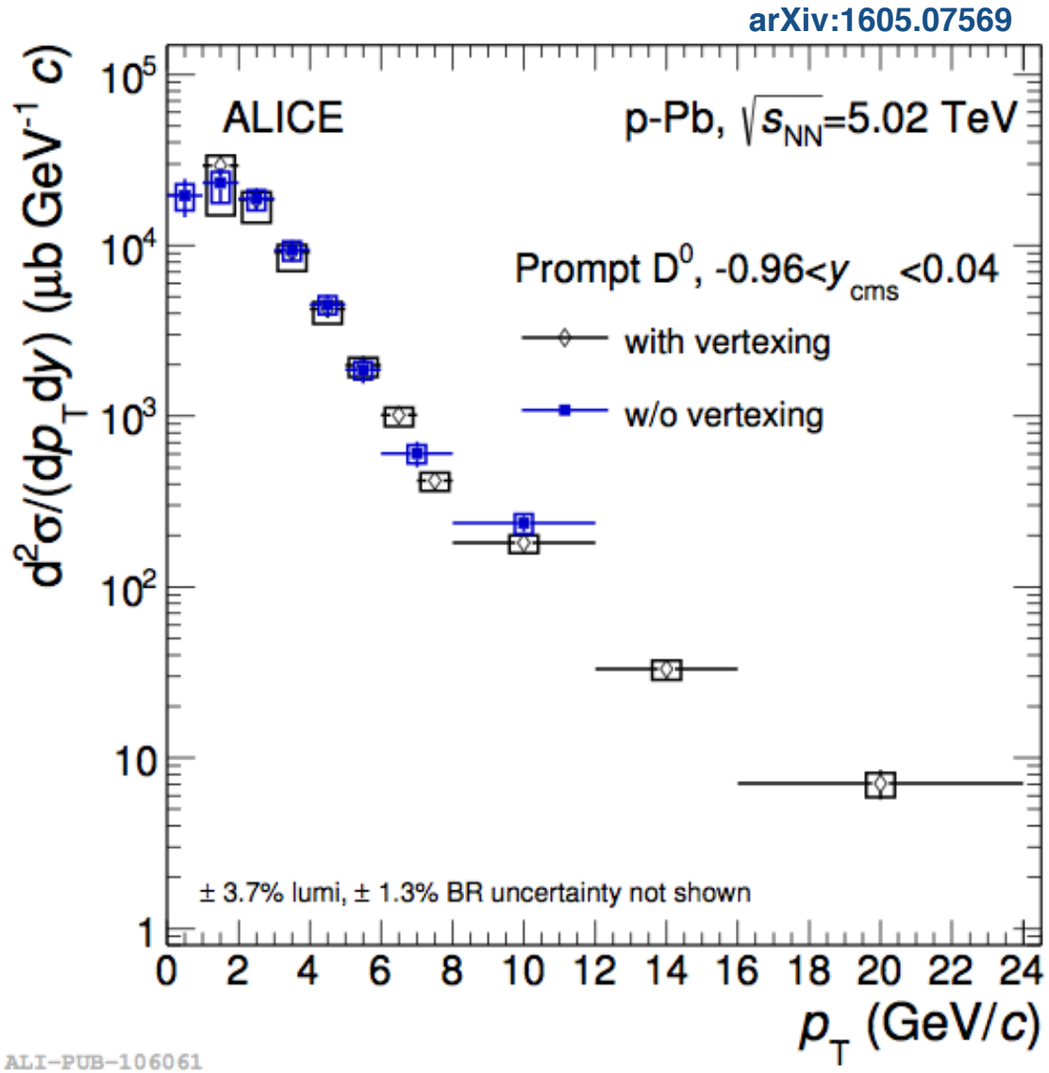
arXiv:1605.07569

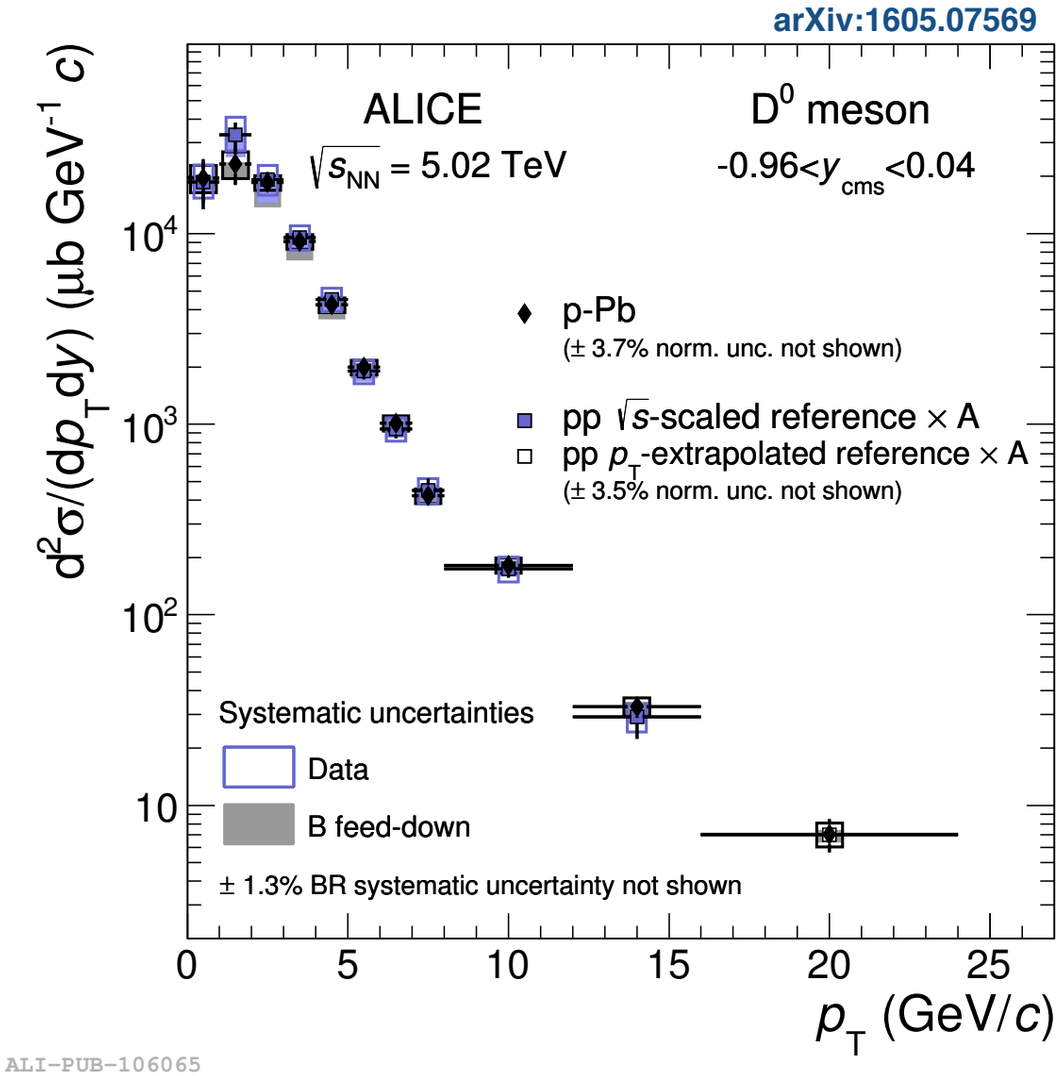


L_{int}= 48.6 μb^{-1}

- Standard D-meson analysis with secondary vertex separation cuts is inefficient below 1-2 GeV/c (small Lorentz boost)
- Developed procedure based only on PID, without vertexing cuts
  - efficiency larger by x20 → better significance than with vertexing for $p_T < 2$ GeV/c
  - also small feed-down → reduced systematic uncertainties
- **Combinatorial background subtraction via**: event mixing, like sign, track rotation, side-band fit

D^0 cross section in p-Pb collisions down to $p_T = 0$





pp results: see F. Colamaria talk Tuesday 16.00

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

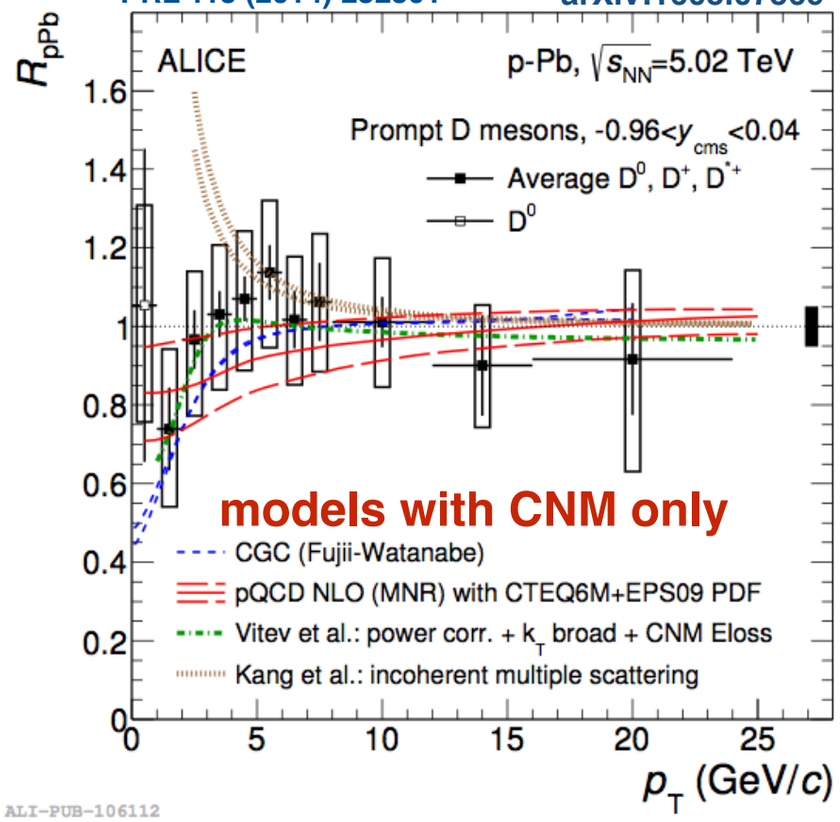
pp and **p-Pb** prompt D^0 p_T-differential cross section: the most precise measurement obtained with the "w/o vertexing" method for $0<p_T<2$ GeV/c and with "vertexing method" for $p_T>2$ GeV/c

p_T-integrated D^0 production cross section in p-Pb collisions

$$\mathrm{d}\sigma^{\mathrm{prompt}\,D^0}_{\mathrm{p-Pb},5.02\,\mathrm{TeV}}/\mathrm{dy} = 79.0 \pm 7.3\,(\mathrm{stat.})^{+\,7.1}_{-13.4}\,(\mathrm{syst.}) \pm 2.9\,(\mathrm{lumi.}) \pm 1.0\,(\mathrm{BR})\ \mathrm{mb}$$

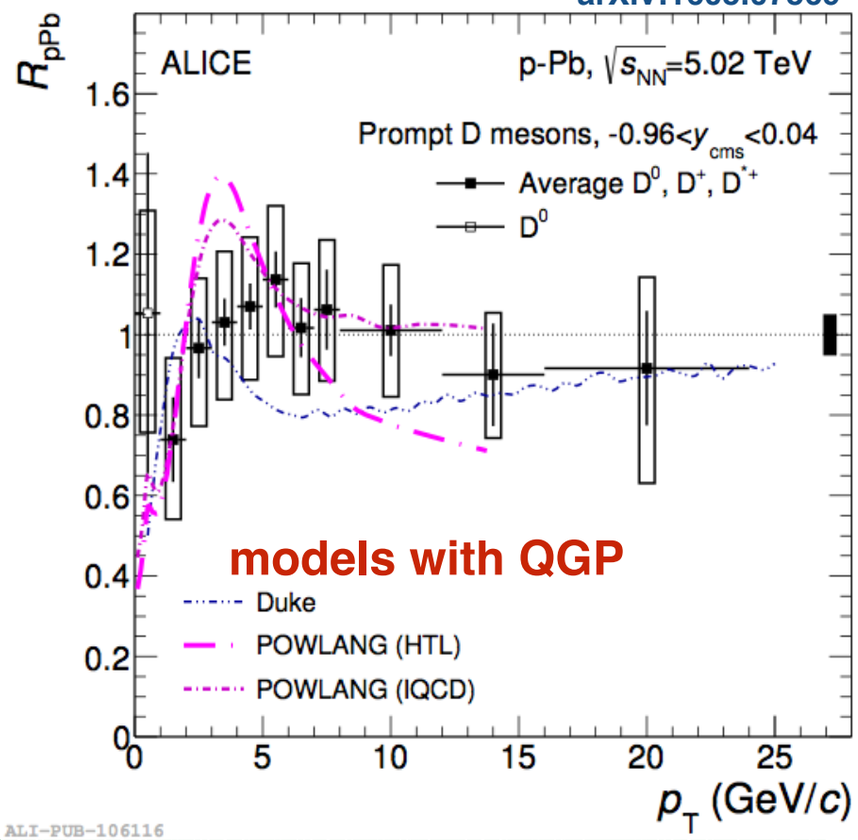
D-meson R_{pPb}

PRL 113 (2014) 232301 arXiv:1605.07569



ALI-PUB-106112

arXiv:1605.07569



ALI-PUB-106116

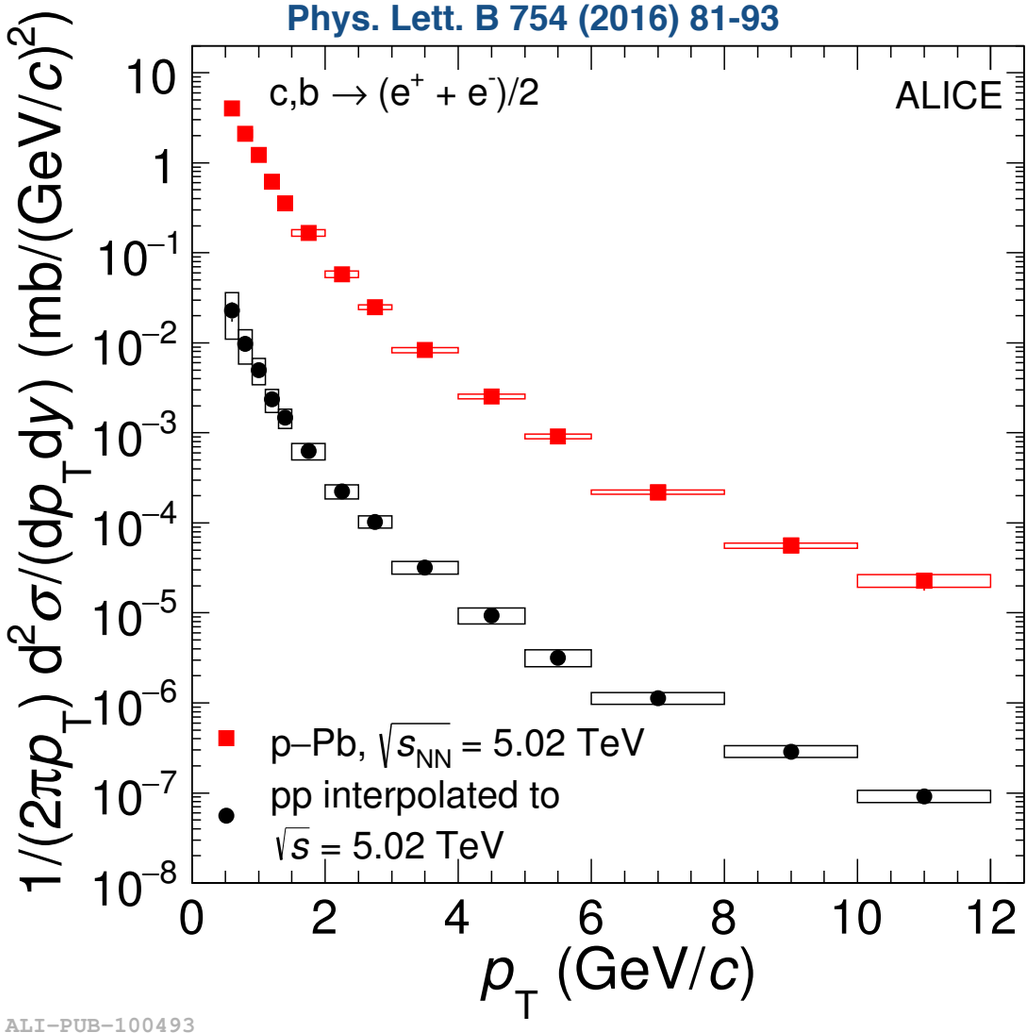
$$R_{\mathrm{pPb}}^{\mathrm{prompt\,D^0}}(p_{\mathrm{T}} > 0, -0.96 < y_{\mathrm{cms}} < 0.04) = 0.89 \pm 0.11\,(\mathrm{stat.})^{+0.13}_{-0.18}\,(\mathrm{syst.})$$

R_{pPb} **consistent with unity** for all D-meson species

- no indication for suppression at intermediate/high p_T
- data do not favour a suppression larger than 20% at p_T~5-10 GeV/c
- R_{pPb} described within uncertainties by models including initial-state and final-state effects
- uncertainties still too large to distinguish between the existing models—> will be improved with 2016 p-Pb collisions

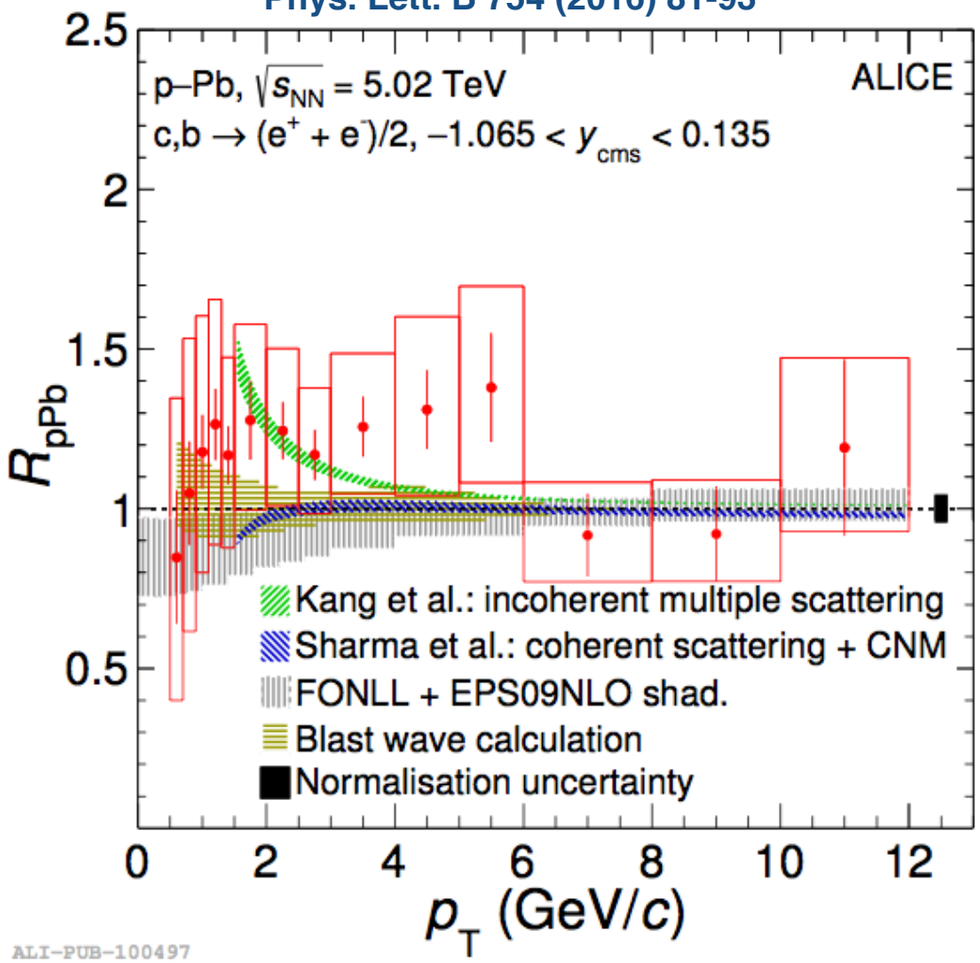
Heavy-flavour hadron decay electron R_{pPb}

Phys. Lett. B 754 (2016) 81-93



ALI-PUB-100493

Phys. Lett. B 754 (2016) 81-93

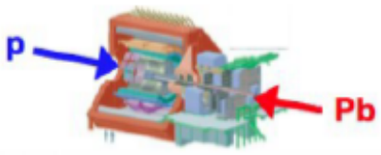


ALI-PUB-100497

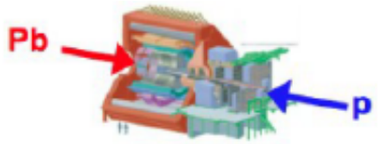
- p-Pb analysis: systematic uncertainties smaller than in pp collisions
  - p-Pb: estimation of the electron background via the e^+e^- invariant mass technique
  - pp: background subtracted via cocktail method

- R_{pPb} **consistent with unity** within uncertainties
- also consistent with enhancement in $1<p_{\mathrm{T}}<6$ GeV/c as seen in d-Au at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV **PRL109 (2012) 242301**
- described by models including initial-state effects or with radial flow within uncertainties

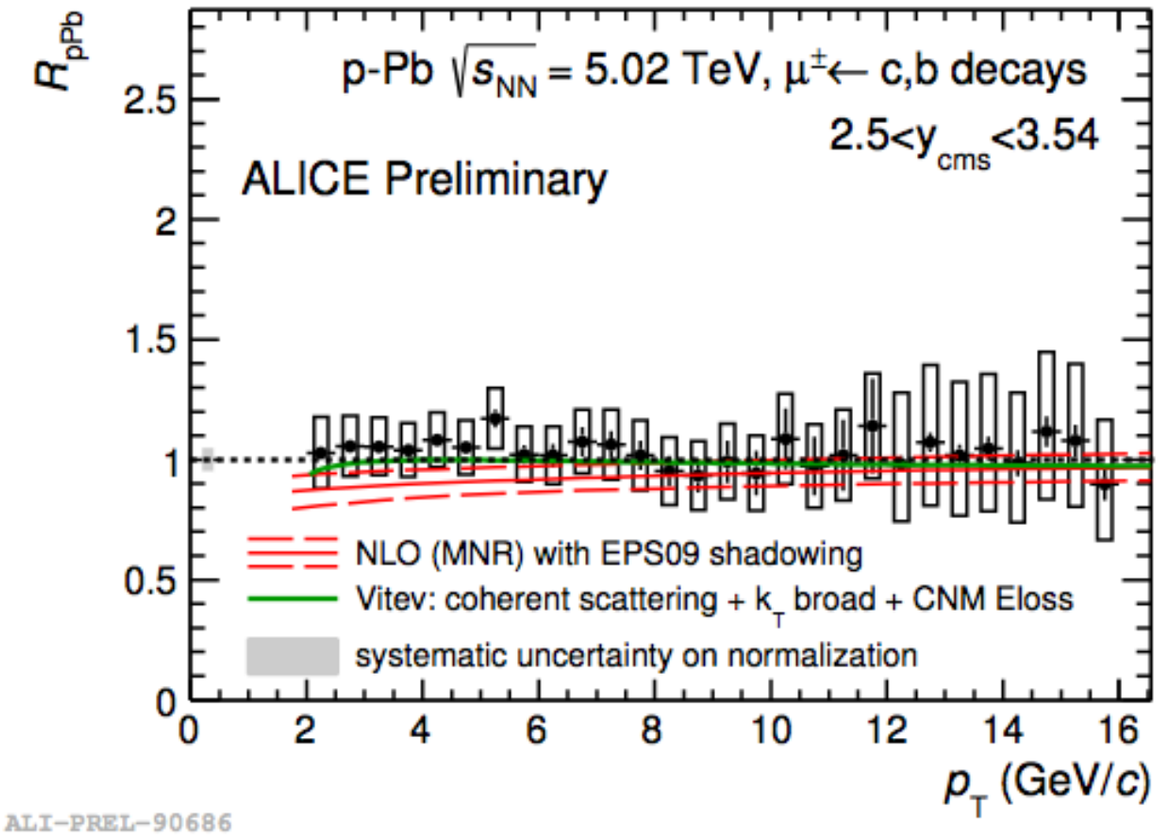
Heavy-flavour hadron decay muon R_{pPb}



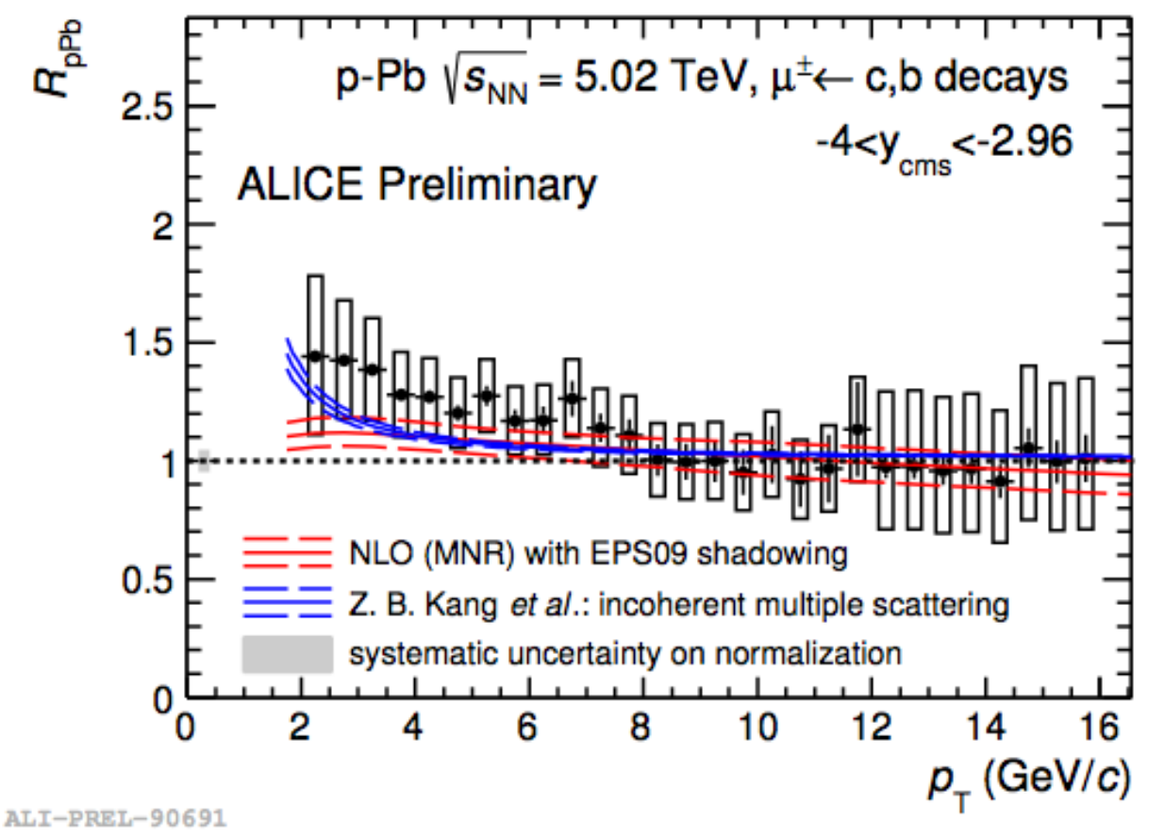
Forward: p-going



Backward: Pb-going



ALI-PREL-90686



ALI-PREL-90691

- Different rapidity ranges allow to access to different *x* regimes
- R_{pPb} of open heavy-flavour decay muons is **consistent with unity** at forward rapidity and **slightly larger than unity** at backward rapidity for $2 < p_T < 4$ GeV/c
  - described within uncertainties by models including cold nuclear matter effects

Pb-Pb collisions

collected in 2010+2011 $\sqrt{s_{NN}}$ = 2.76 TeV

new w.r.t. SQM2015

D-meson R_{AA} in 0-10% and 30-50%

JHEP1603(2016) 081

D_s R_{AA}

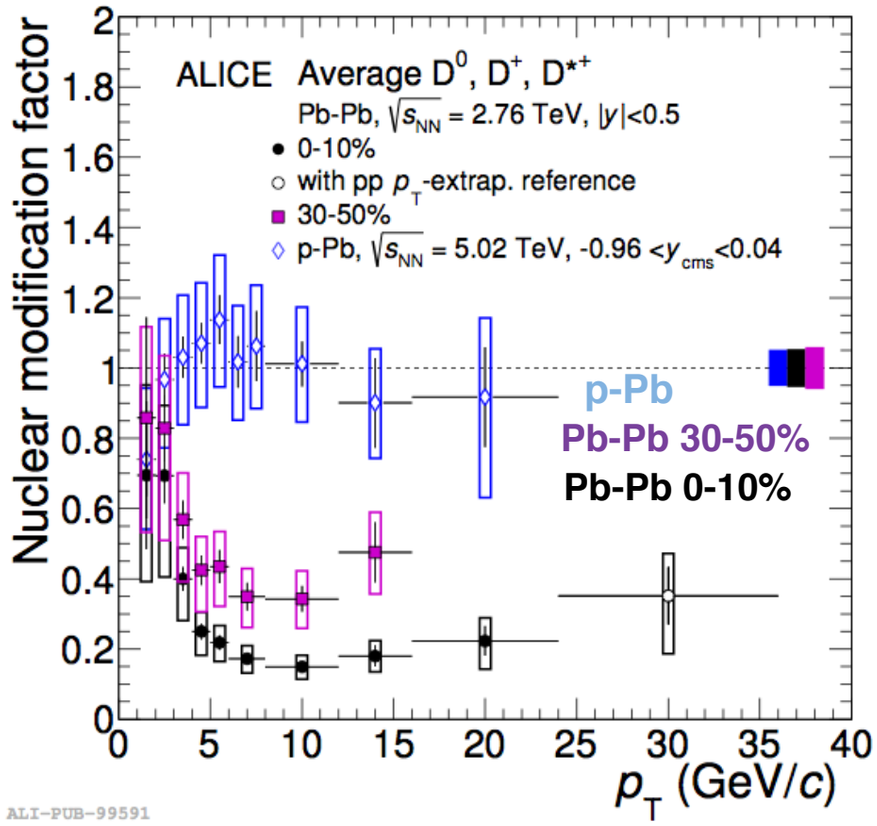
JHEP1603(2016) 082

v_2 of electrons from open heavy-flavour hadron decays

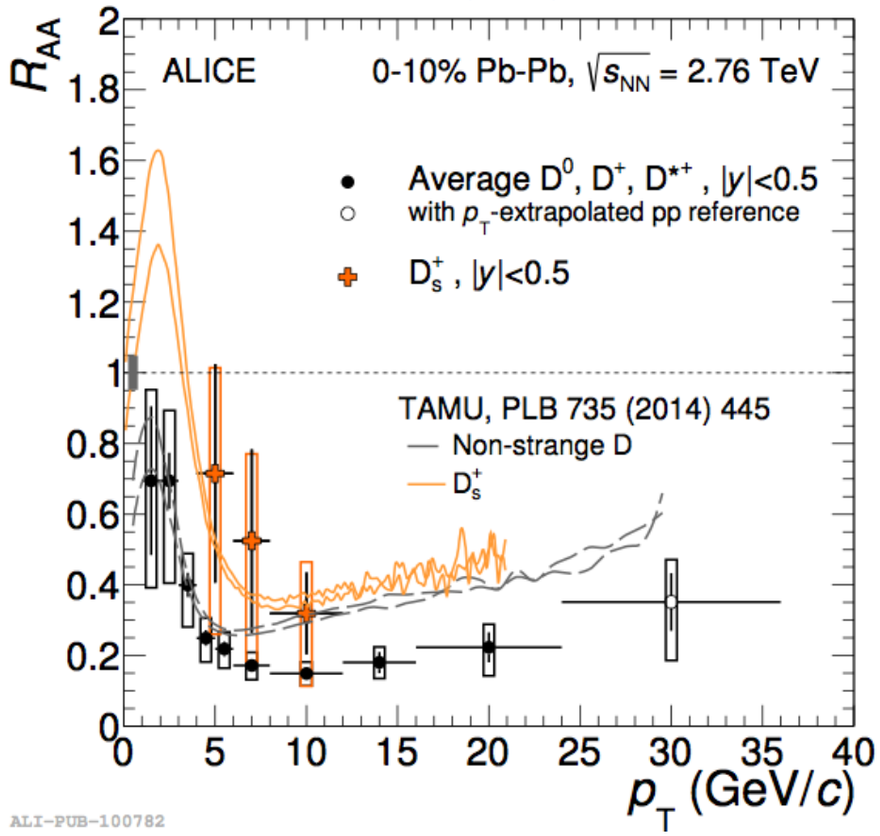
arXiv:1606.00321

D-meson R_{AA}

JHEP1603(2016) 081



JHEP1603(2016) 082



Strong suppression of D mesons for central and semi-central Pb-Pb collisions at intermediate and high-p_T

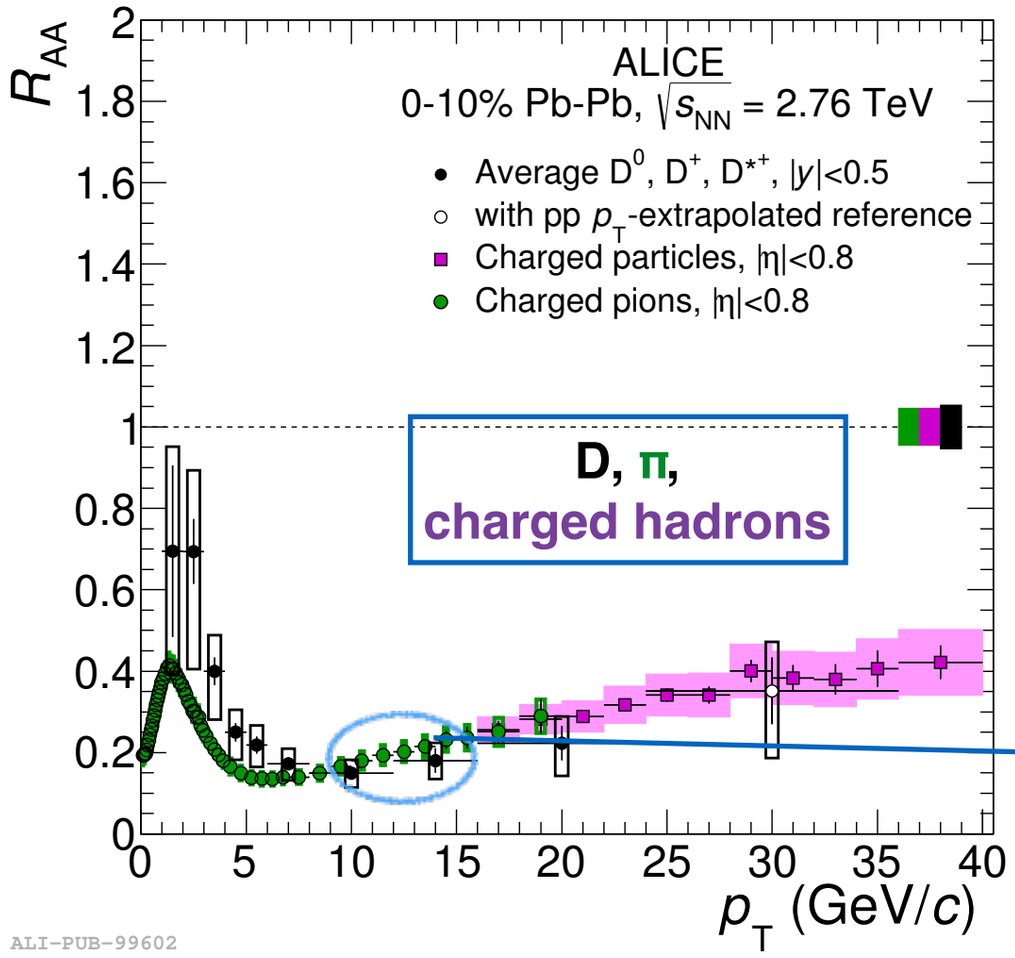
Less suppression for D_s?

- Sensitive to the charm hadronization processes in heavy-ion collisions
- But large uncertainties, no conclusive interpretation at the moment

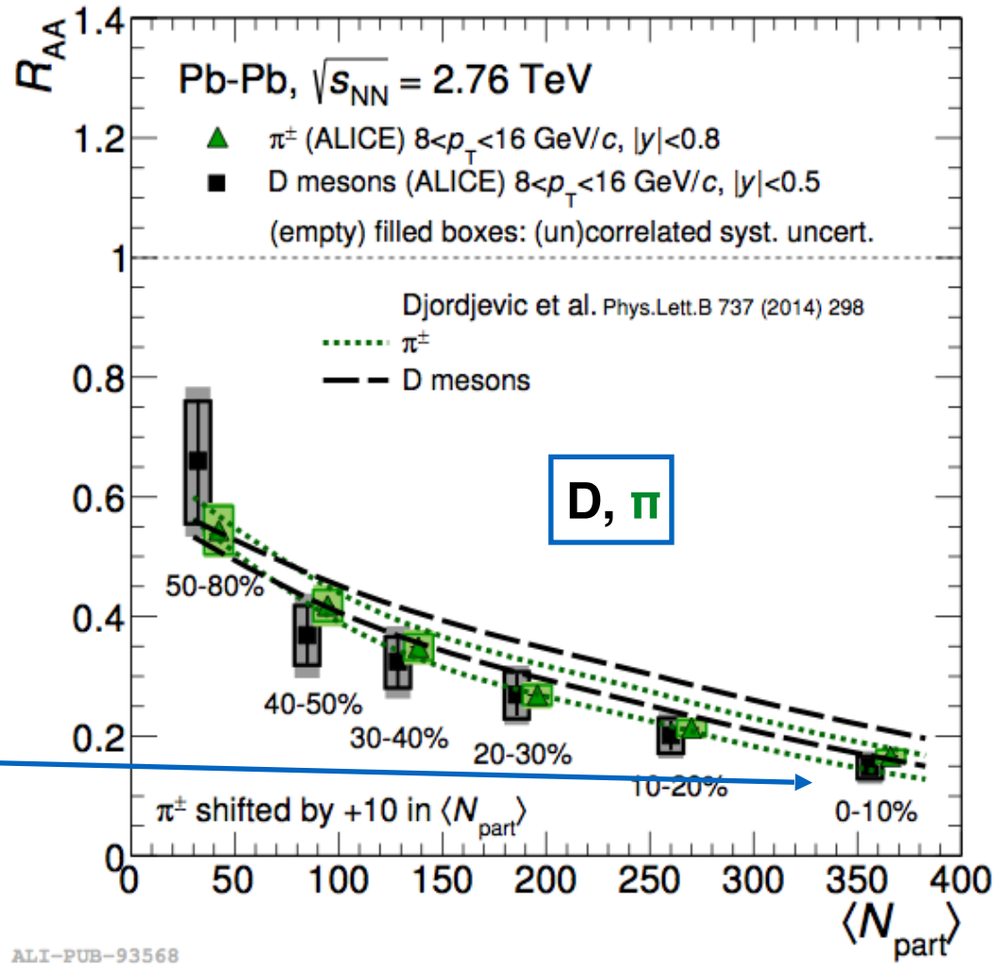
R_{pPb} consistent with unity indicates that the suppression in Pb-Pb collisions is not due to initial-state effects
Significant energy loss of heavy quarks in the medium

D-meson R_{AA}

JHEP: 03 (2016) 081



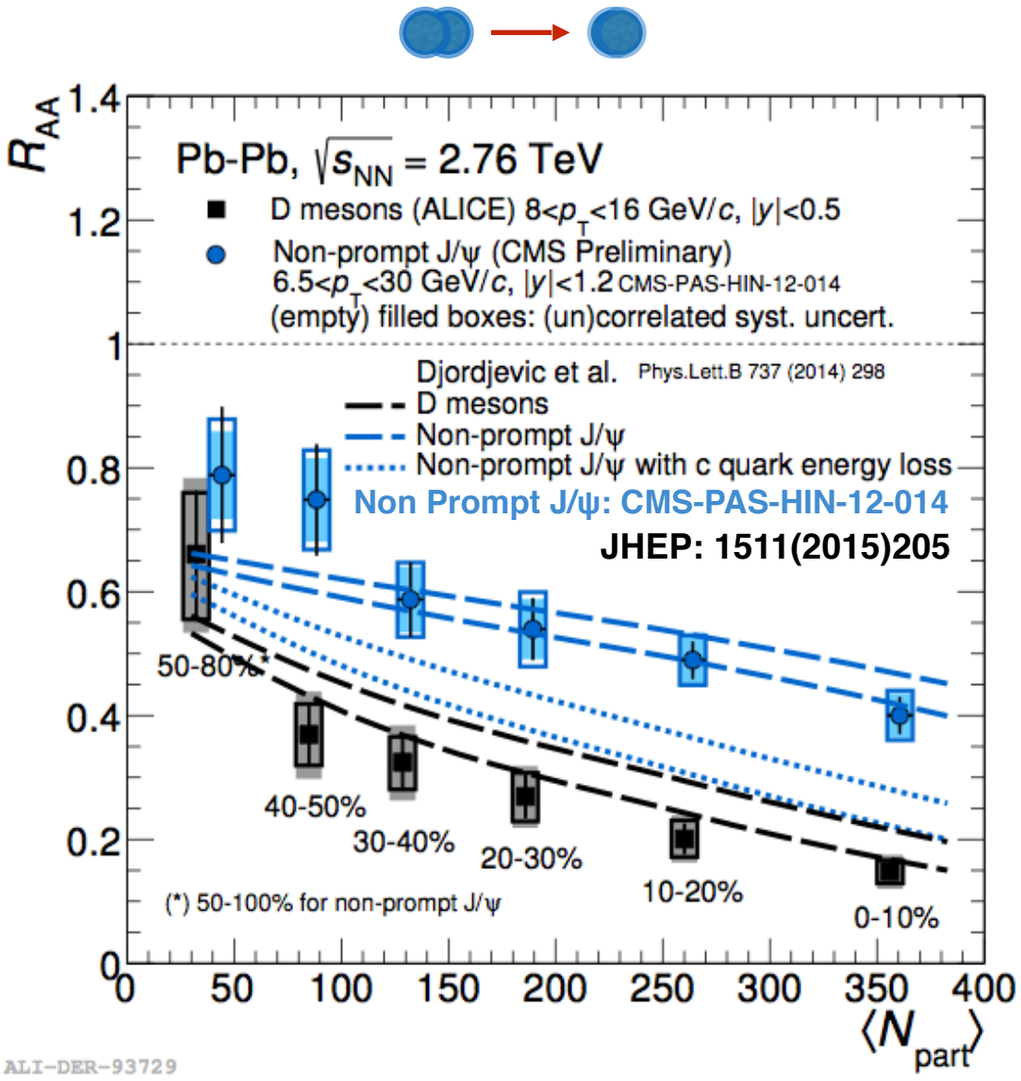
JHEP: 1511(2015)205



R_{AA}(D)~R_{AA}(light flavours)

- R_{AA}(D) slightly larger than R_{AA}(π) for $p_T < 6$ GeV/c
- consistent R_{AA} for $p_T > 6$ GeV/c
  - described by models that take into account colour-charge dependence of energy loss and softer fragmentation and p_T spectrum of gluons w.r.t. c quarks Djordjevic, PLB 734 (2014) 286; Wicks, Horowitz, Djordjevic, NPA 872 (2011) 265

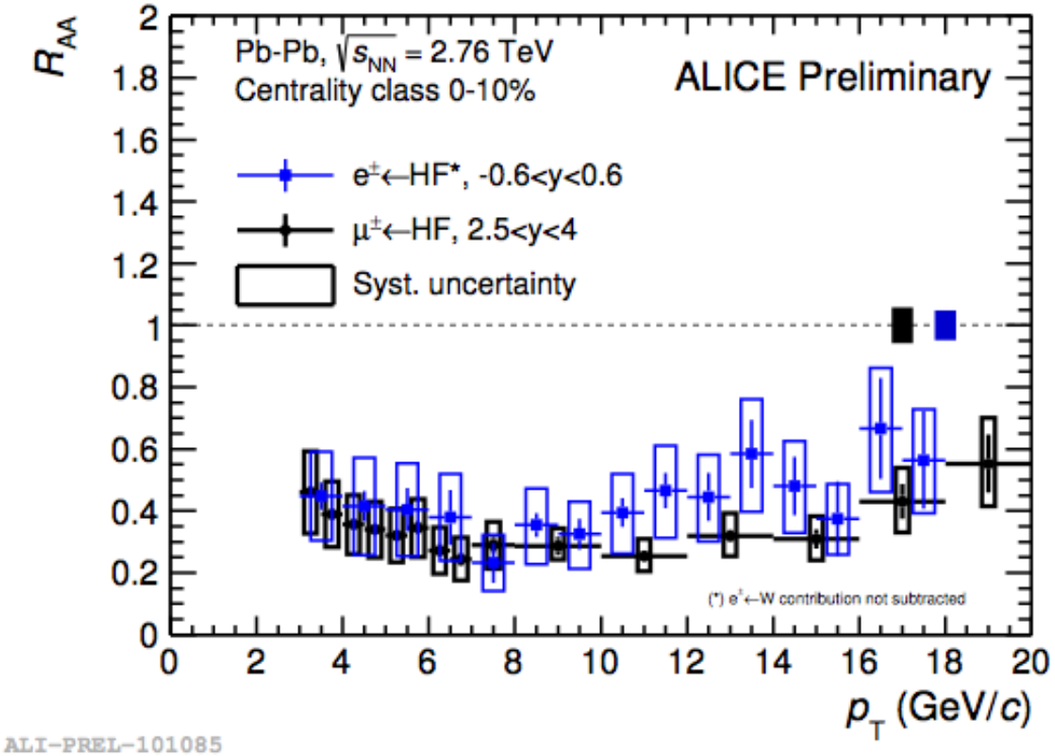
D-meson R_{AA}



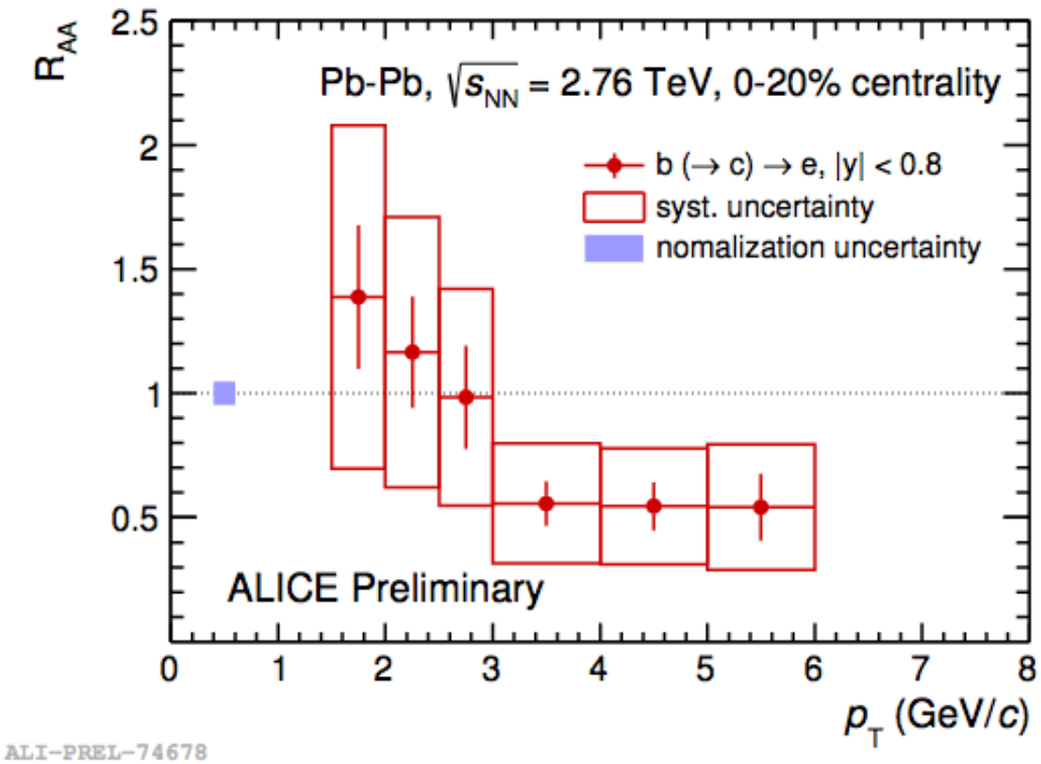
R_{AA}(D) < R_{AA}(B—>J/Ψ)

- indication for mass hierarchy of the R_{AA}
- described by model including mass-dependent radiative and collisional energy loss
- similar patterns from MC@sHQ+EPOS2 and TAMU
  Phys. Rev. C 89 (2014) 014905; arXiv: 1401.3817;

Heavy-flavour hadron decay lepton R_{AA}



ALI-PREL-101085



ALI-PREL-74678

Similar suppression for open heavy-flavour decay electrons (|y|<0.6) and muons (2.5 < y< 4)

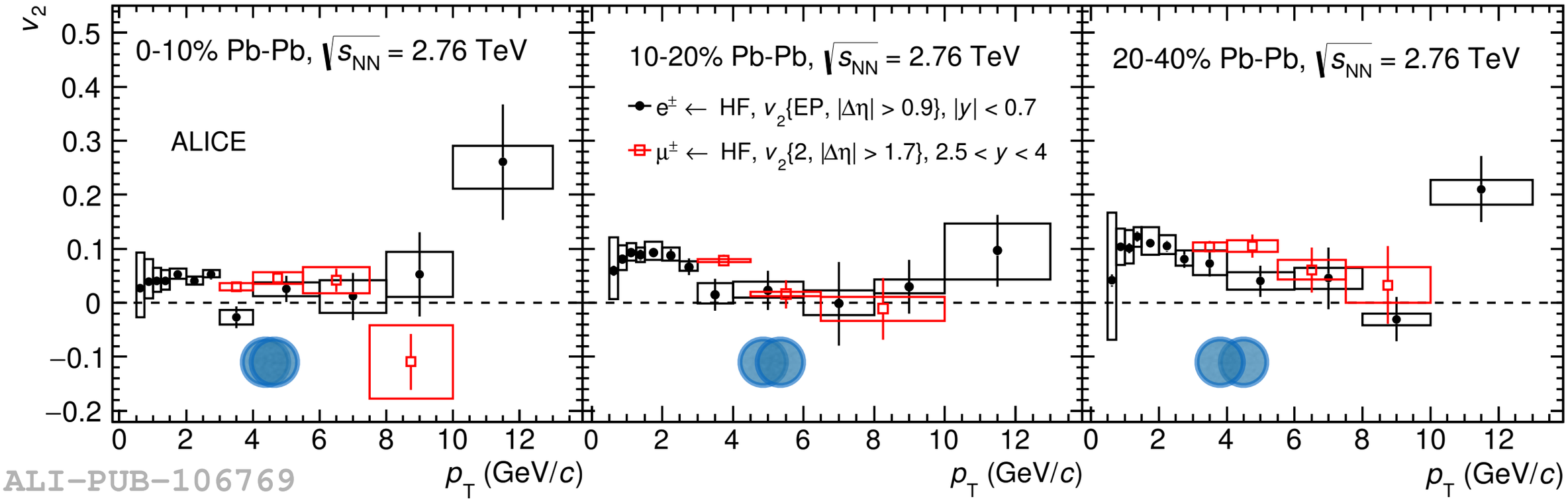
Hint of suppression is observed at $p_T > 3$ GeV/c for beauty-decay, measurement based on DCA distributions

R_{pPb} ~1 indicates that the suppression in Pb-Pb collisions is not due to initial-state effects —> hot and dense medium effects

v_2 of leptons from heavy-flavour hadron decays

- **v_2 of electrons from open heavy-flavour hadron decays**
  - measured with the event plane method
  - obtained from the measurement of the inclusive electron elliptic flow by subtracting the elliptic flow of electrons from background

e: arXiv:1606.00321 **μ: PLB: 753(2016)41**



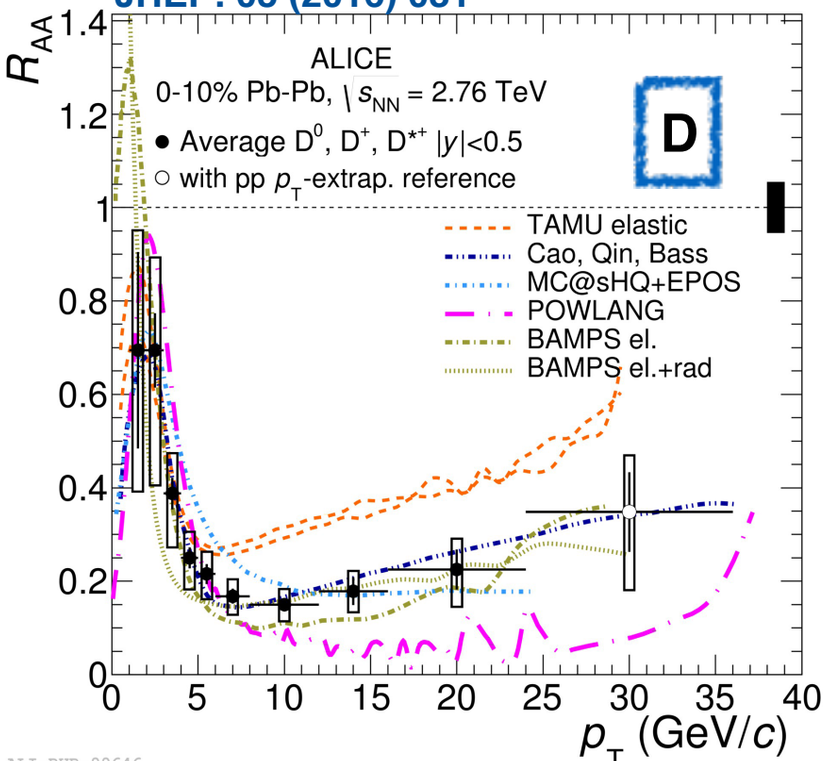
$v_2 > 0$ for open heavy-flavour decay electrons in all centrality classes with maximum significance of 5.9σ in (20-40%) for $2 < p_T < 2.5$ GeV/c

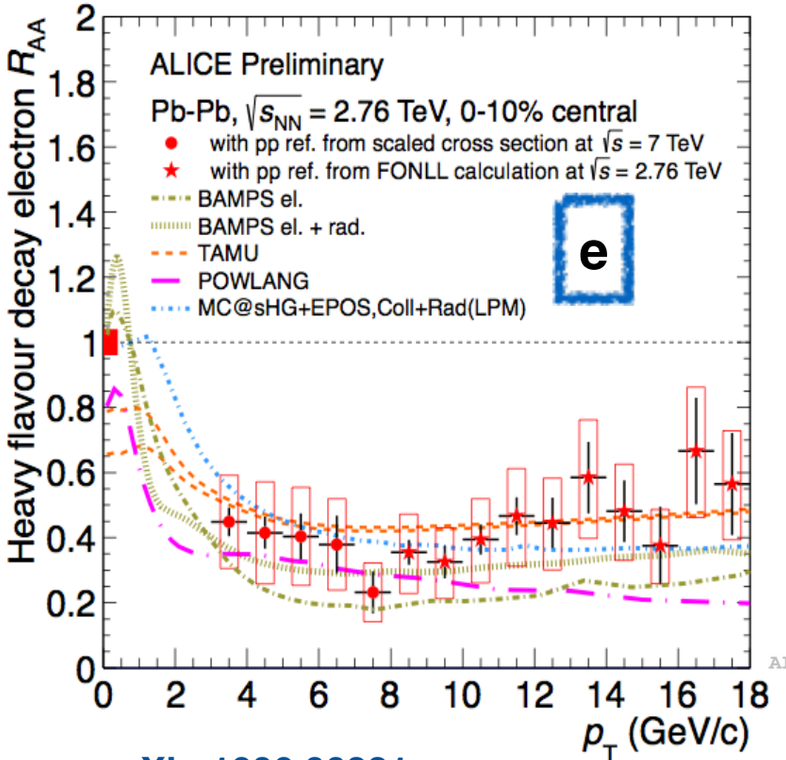
- **Similar v_2 of open heavy-flavour decay electrons** (at mid-rapidity) **and muons** (at forward rapidity)
- Hint for an **increase of v_2 from central to semi-central collisions**

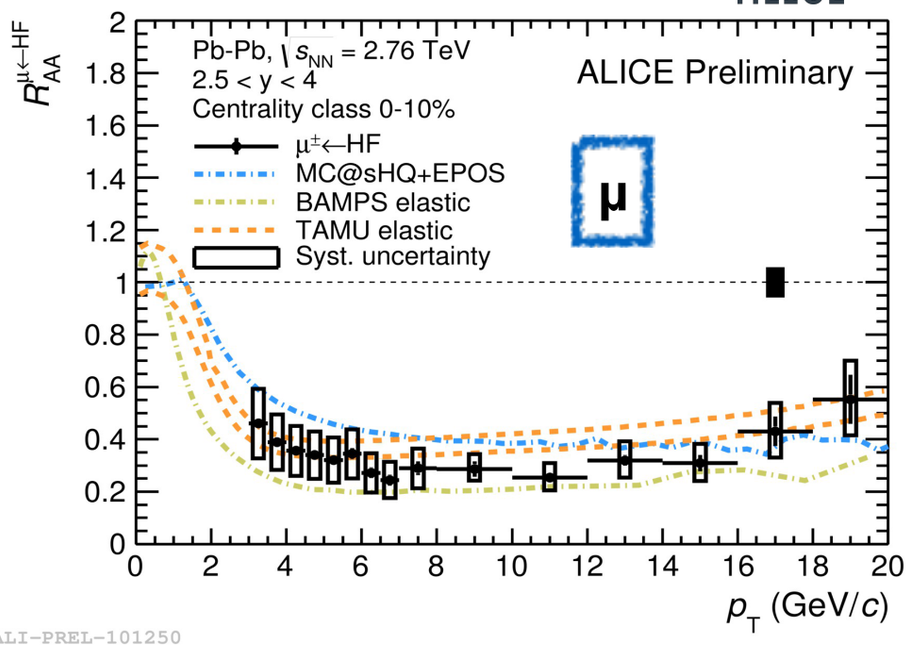
Confirm significant interaction of heavy quarks with the medium
Suggest collective motion at low p_T in the expanding fireball

Comparison with models

JHEP: 03 (2016) 081

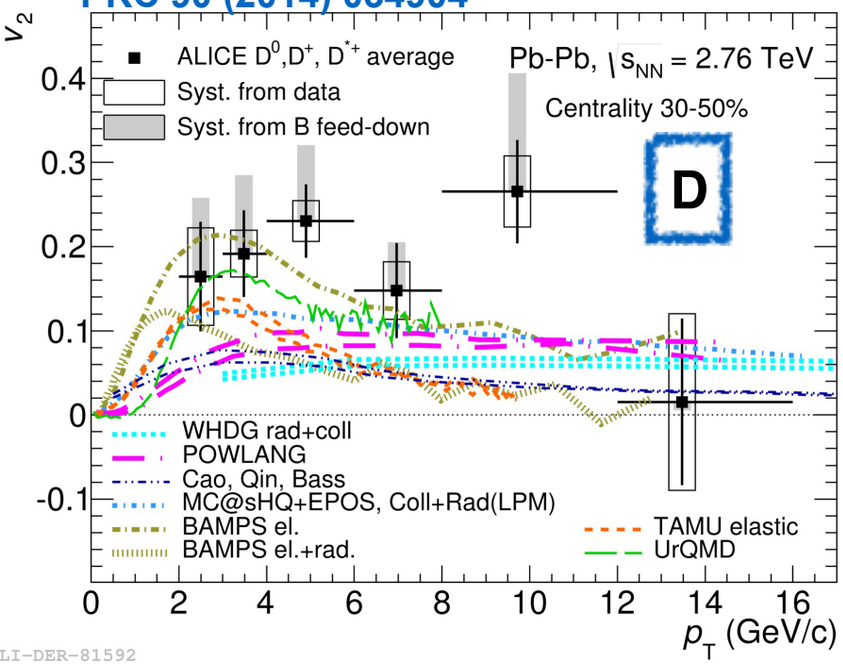






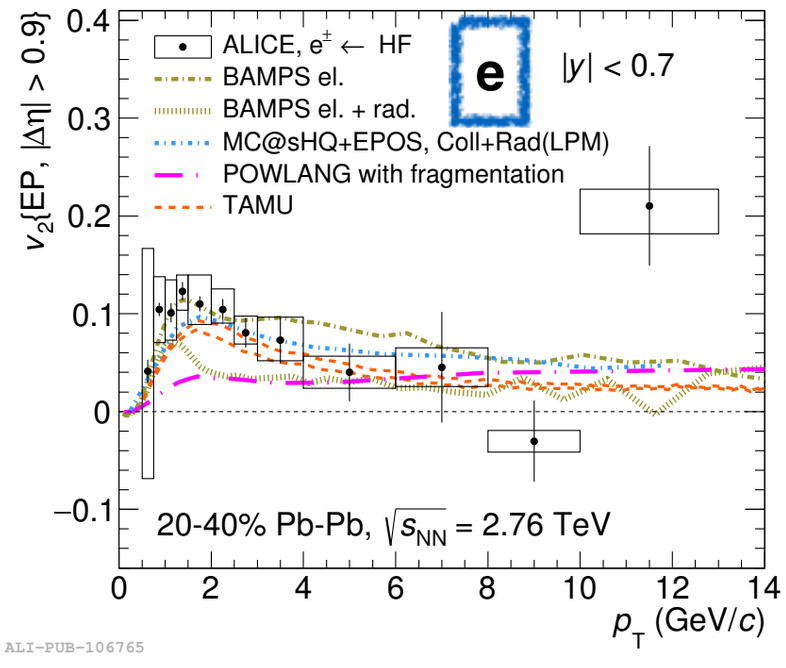
ALI-PUB-99646

PRC 90 (2014) 034904



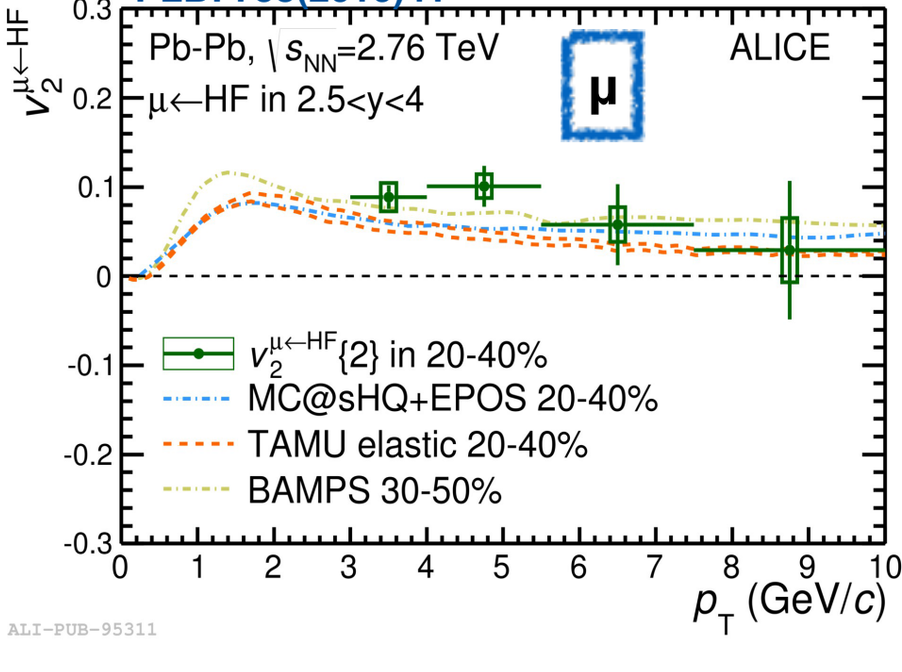
ALI-DER-81592

arXiv:1606.00321



ALI-PUB-106765

PLB: 753(2016)41



ALI-PUB-95311

Description of v_2 and R_{AA} together is challenging!
Measurements start to provide constraints for models

WHDG: Nucl. Phys. A 872 (2011) 265; Cao, Qin, Bass: Phys. ReV. C 88 (2013) 044907; TAMU elastic: arXiv: 1401.3817;
POWLANG: Eur. Phys. J. C 71 (2011) 1666, J. Phys. G 38 (2011) 124144; BAMPS: Phys. Lett. B 717 (2012) 430;
MC@ sHQ+EPOS, Coll + Rad (LPM): Phys. Rev. C 89 (2014) 014905; UrQMD: arXiv:1211.6912

Conclusions

ALICE results on open heavy-flavour production

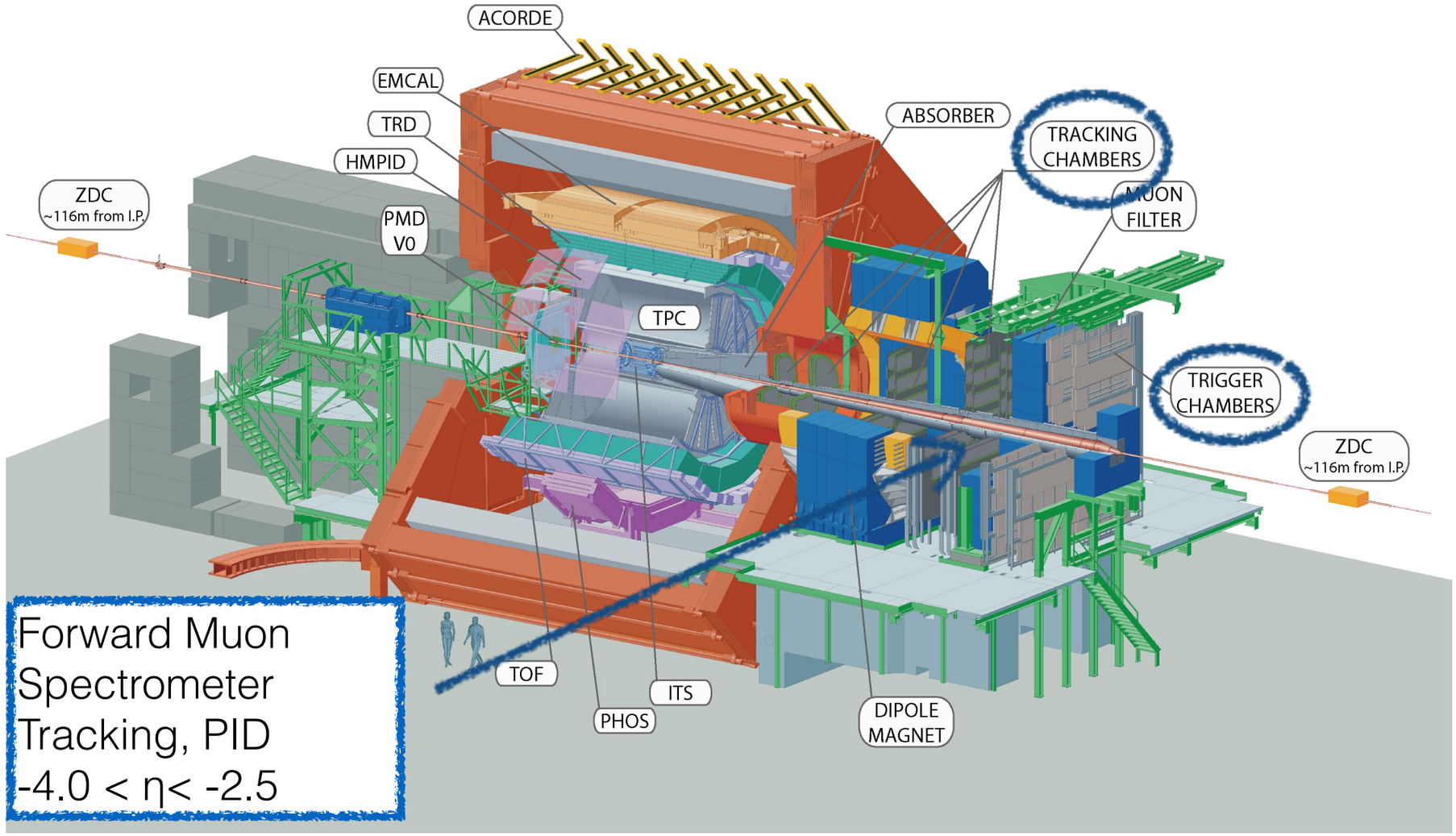
- **R_{pPb} consistent with unity** and **models including cold nuclear matter** (CNM) effects, that appear to be small for $p_T > 2$ GeV/c
- **Strong suppression in Pb-Pb collisions** for $p_T > 3$ GeV/c is due to final-state effects, consistent with collisional and radiative energy loss mechanisms
- High-p_T suppression of D mesons and J/Ψ from B decays consistent with mass-dependent energy loss for D and B mesons
- **Positive elliptic flow** measured for open heavy-flavour particles
  - **heavy flavours participate to the collective expansion at low p_T**

Looking forward to more precise measurements with the LHC run 2 data and run 3 with the ALICE upgrade

ALICE upgrade: see D. Silvermyr talk Friday 9.00

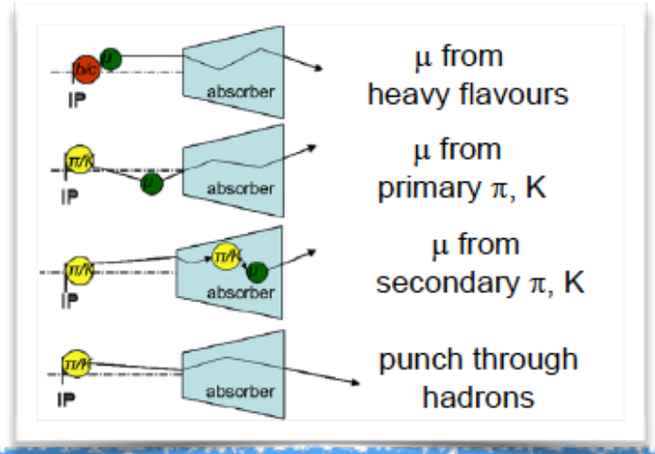
Backup

μ± from open heavy-flavour hadron decays



Forward Muon Spectrometer
Tracking, PID
$-4.0 < \eta < -2.5$

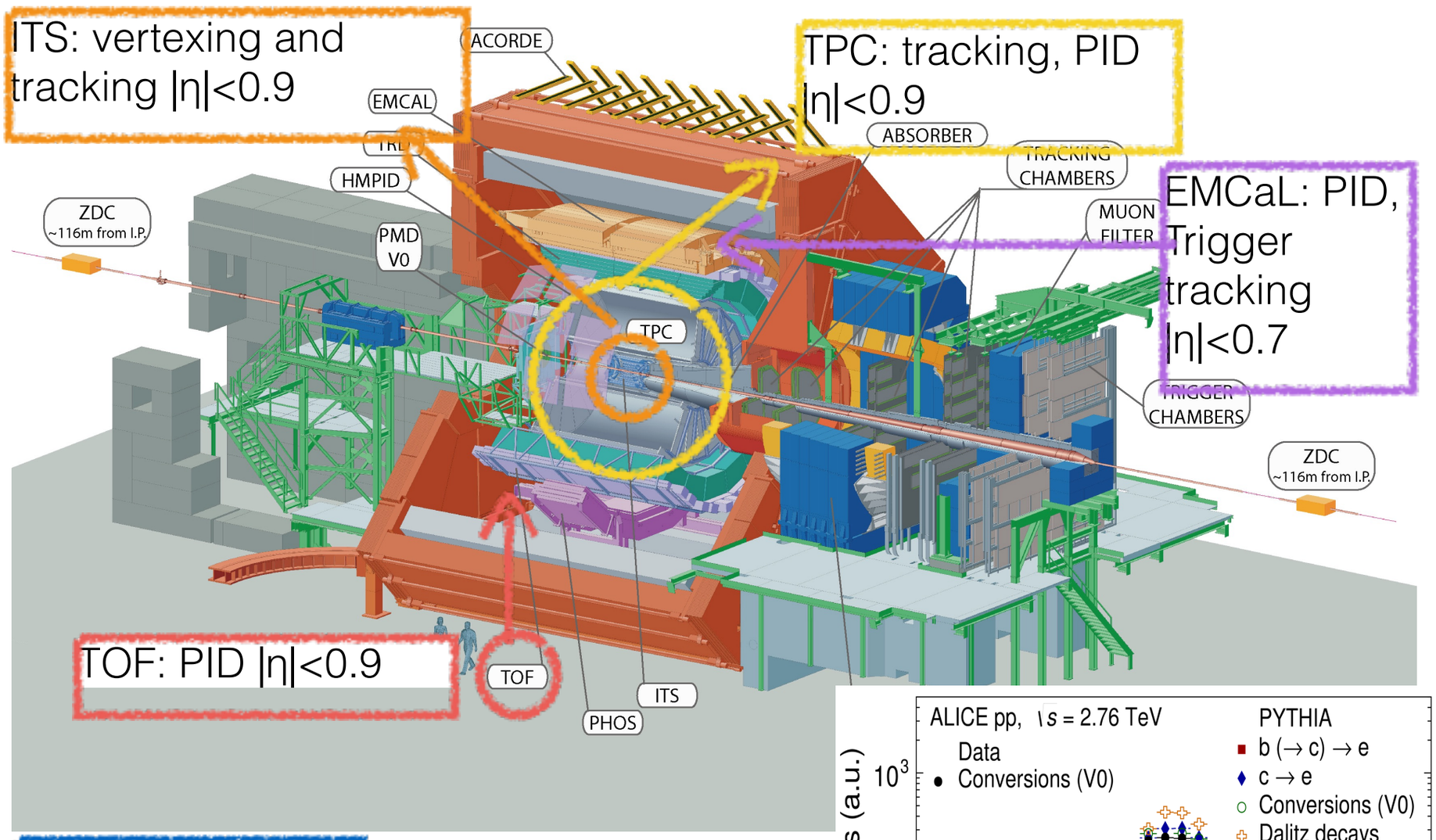
$D, B, \Lambda_c \rightarrow \mu^- + X$



Muon track selection and identification

- Acceptance and geometrical cuts
- Tracks matched with trigger: hadron rejection
- Pointing angle to the vertex:
  - rejection of beam-gas interactions and background from particles produced in the absorber
- Remaining background: from primary pions and kaons estimated via data-tuned MC cocktail

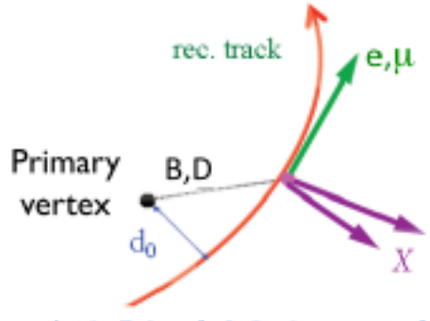
e± from open heavy flavour hadron decays

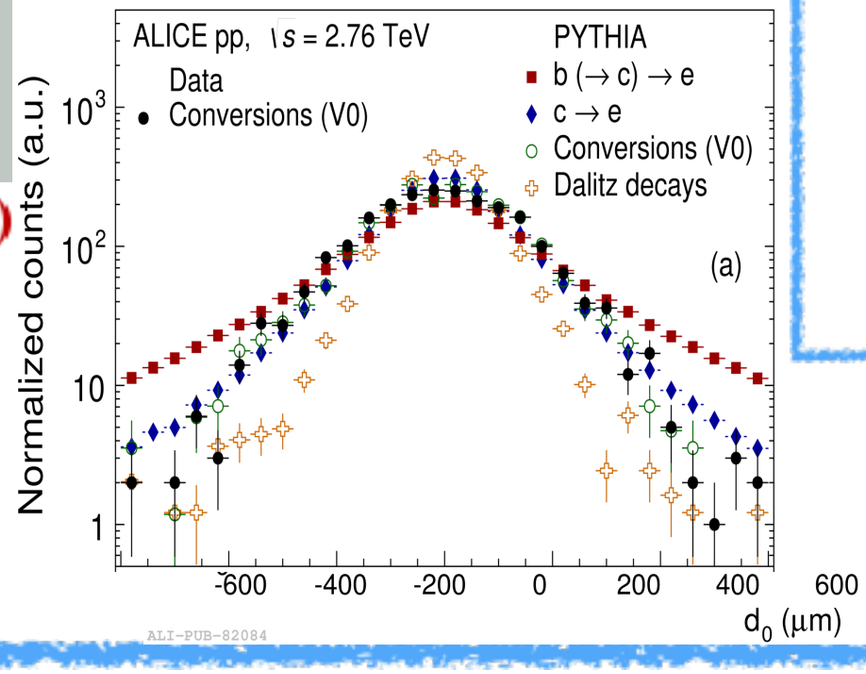


- **e^- ID** with TPC and TOF for low p_T and EMCaL for high p_T
- background subtraction with invariant mass e^-e^+ method or cocktail method based on data
- **beauty-hadron decay electrons** are measured using the impact parameter distribution: broader than **charm-hadron decay** due to their longer life time

D, B, $\Lambda_c \rightarrow e^- + X$

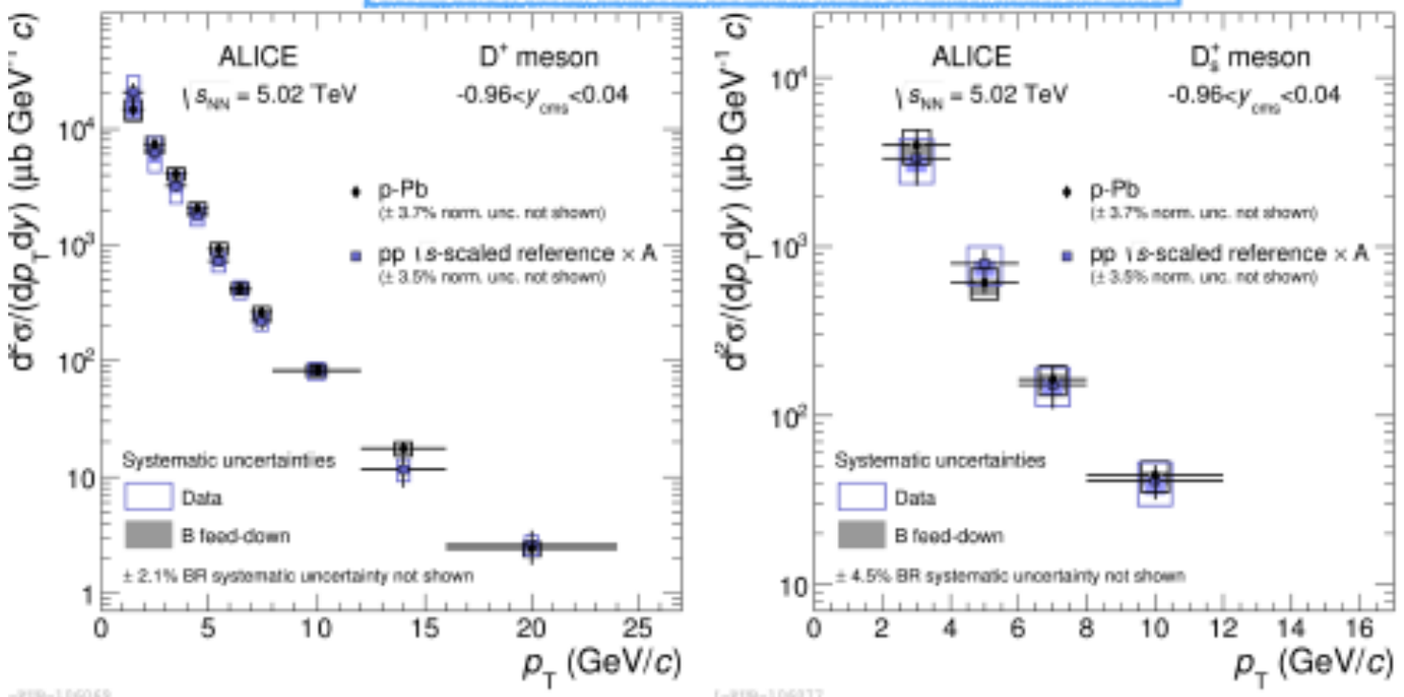
Semi-leptonic decays (c,b)



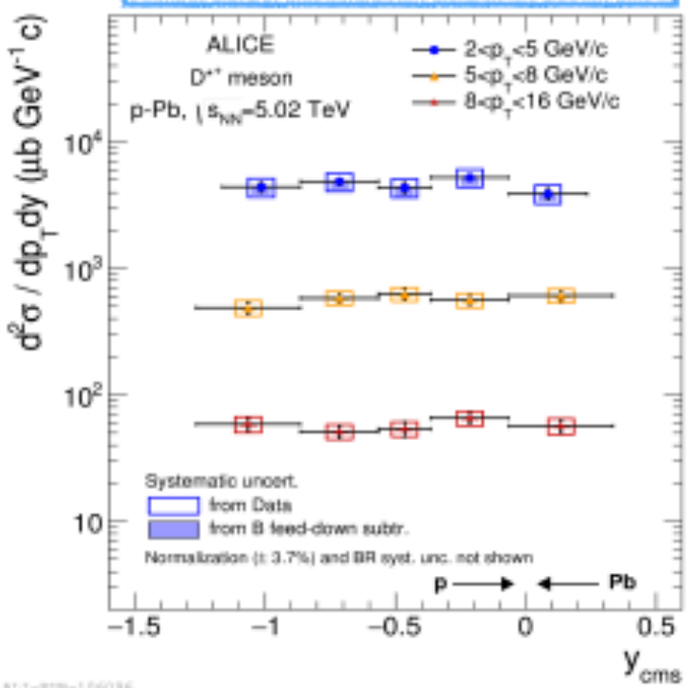


Open HF p_T-differential cross section in p-Pb

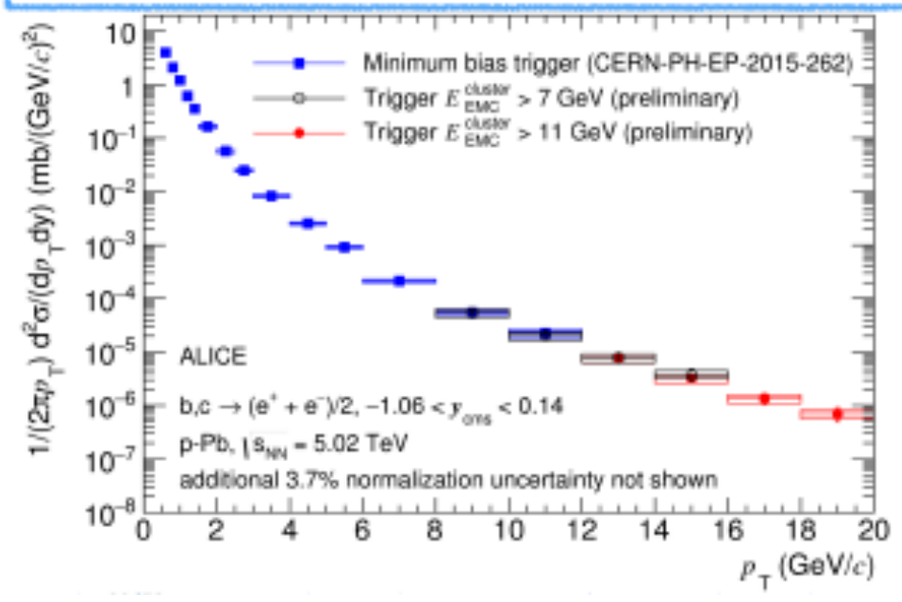
D+ and D_s cross section in pp and p-Pb



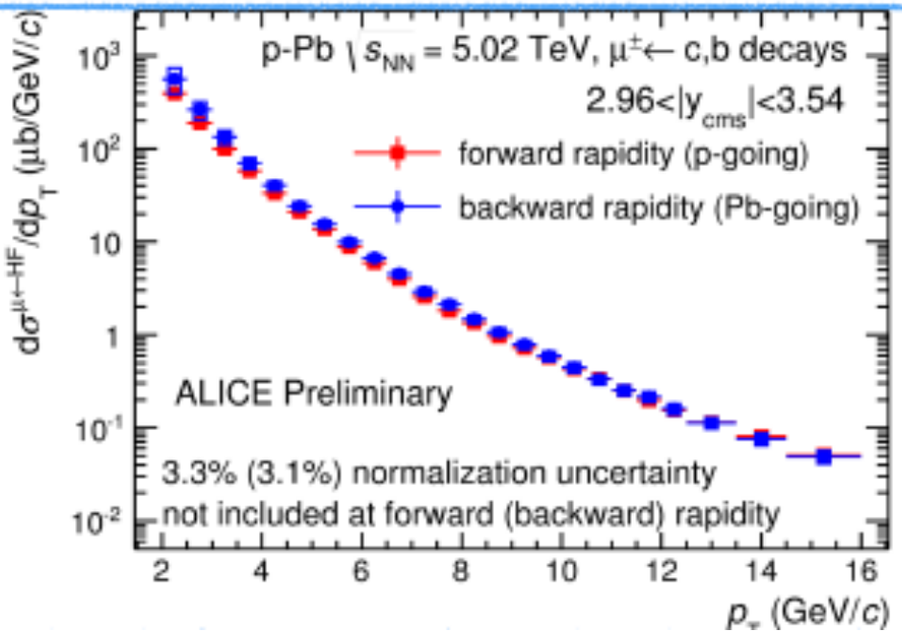
D*cross section vs rapidity



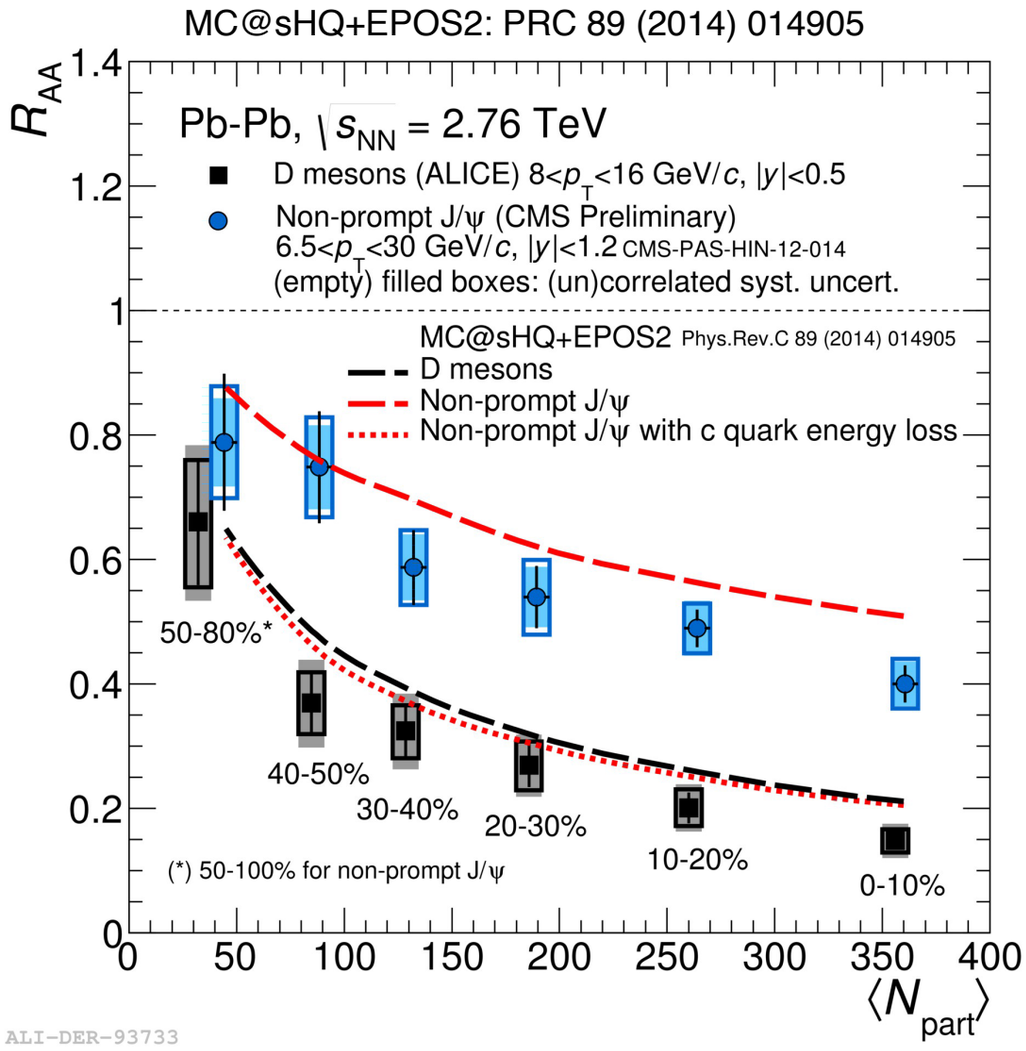
HF decay electrons cross section with MB results and extended p_T range with EMCal trigger

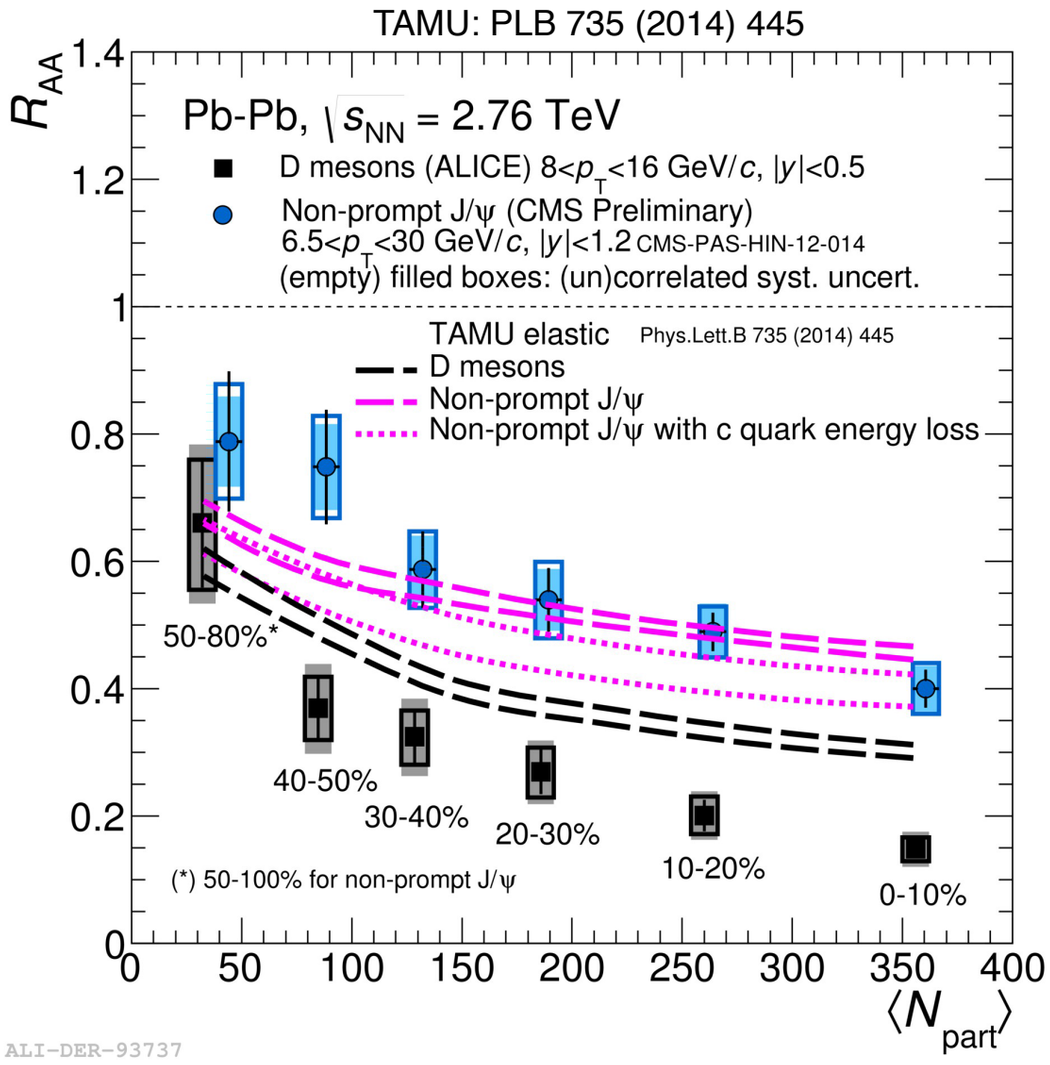


HF decay muon cross section at forward and backward rapidity



D-meson R_{AA} and models



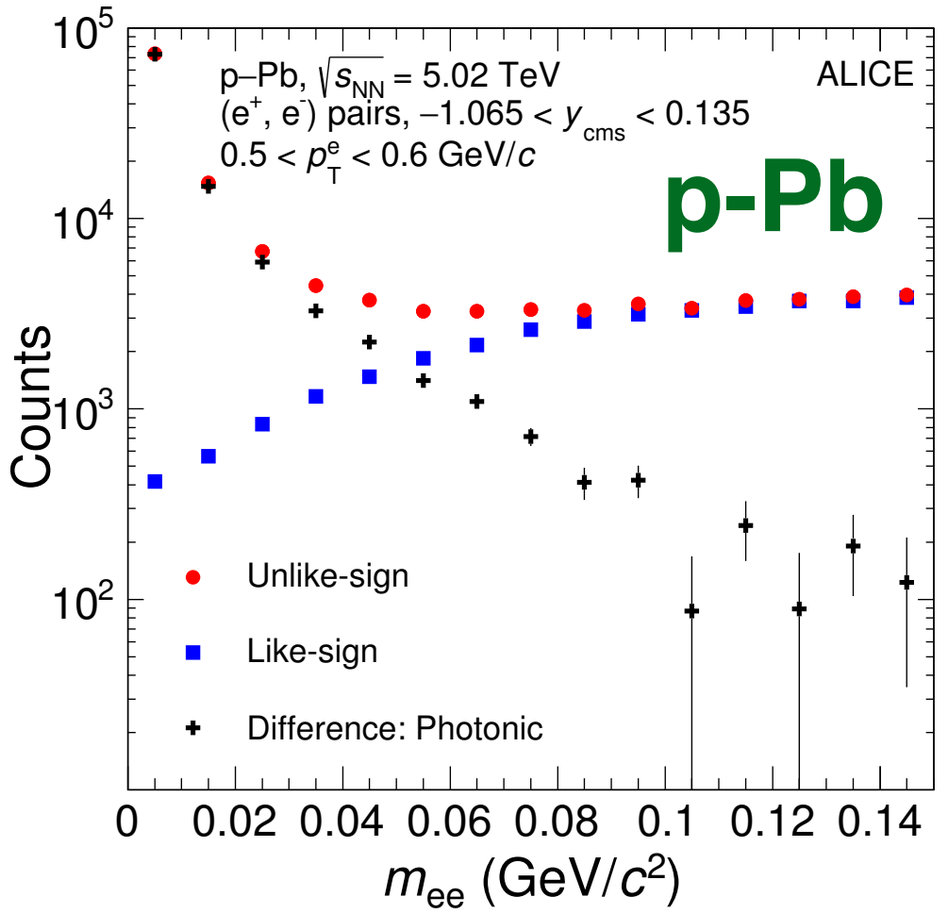


R_{AA}(D) < R_{AA}(B—>J/Ψ)

- indication for mass hierarchy of the R_{AA}
- described by model including mass-dependent radiative and collisional energy loss

Inclusive HF electrons in p-Pb and pp: yield extraction

main background sources: decay of neutral mesons and gamma conversion

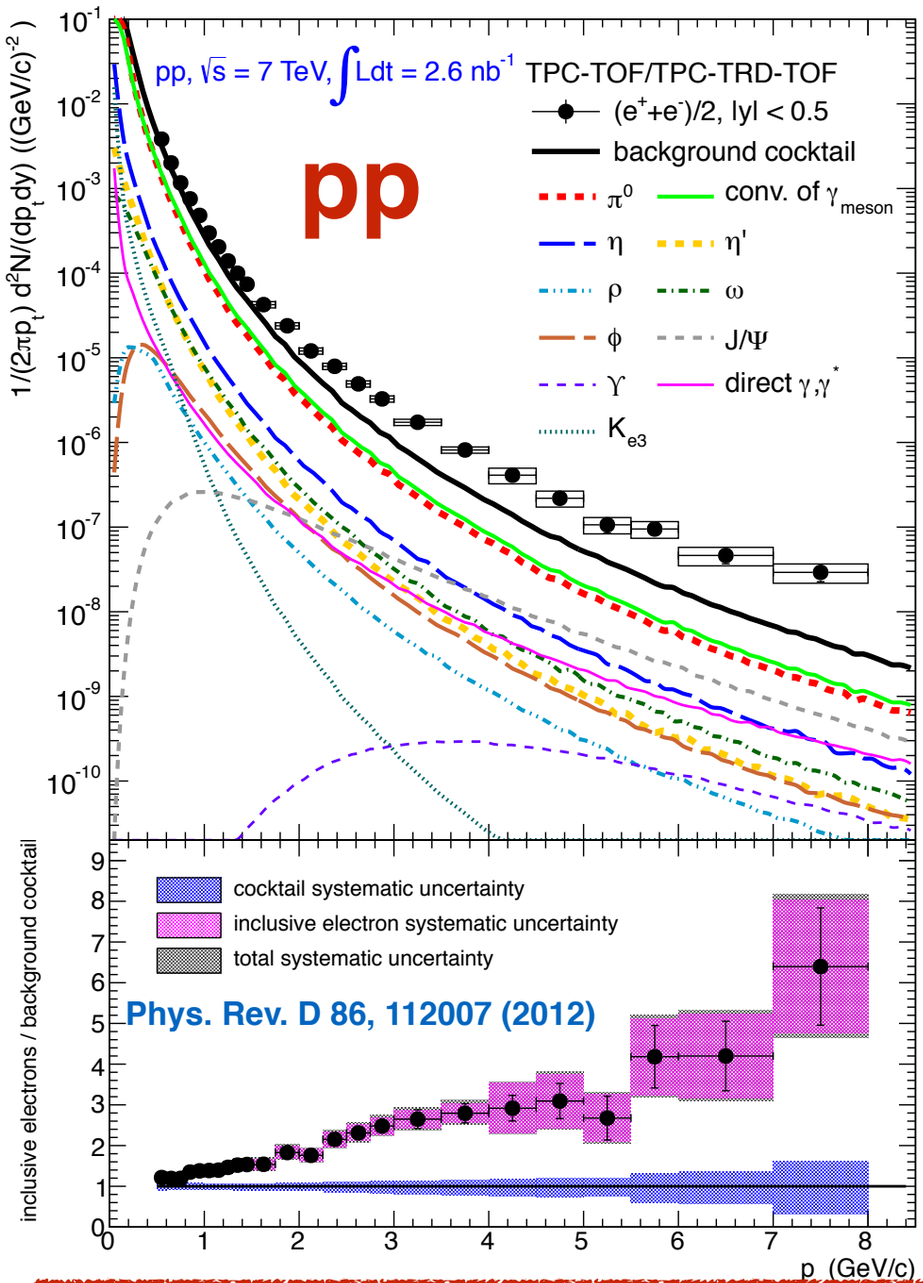


Invariant mass distributions of unlike-sign and like-sign pairs for the inclusive electron.

- Like-sign distr. estimates uncorrelated pairs
- Difference between the distributions = photonic contribution to the background

Subtraction of background from:

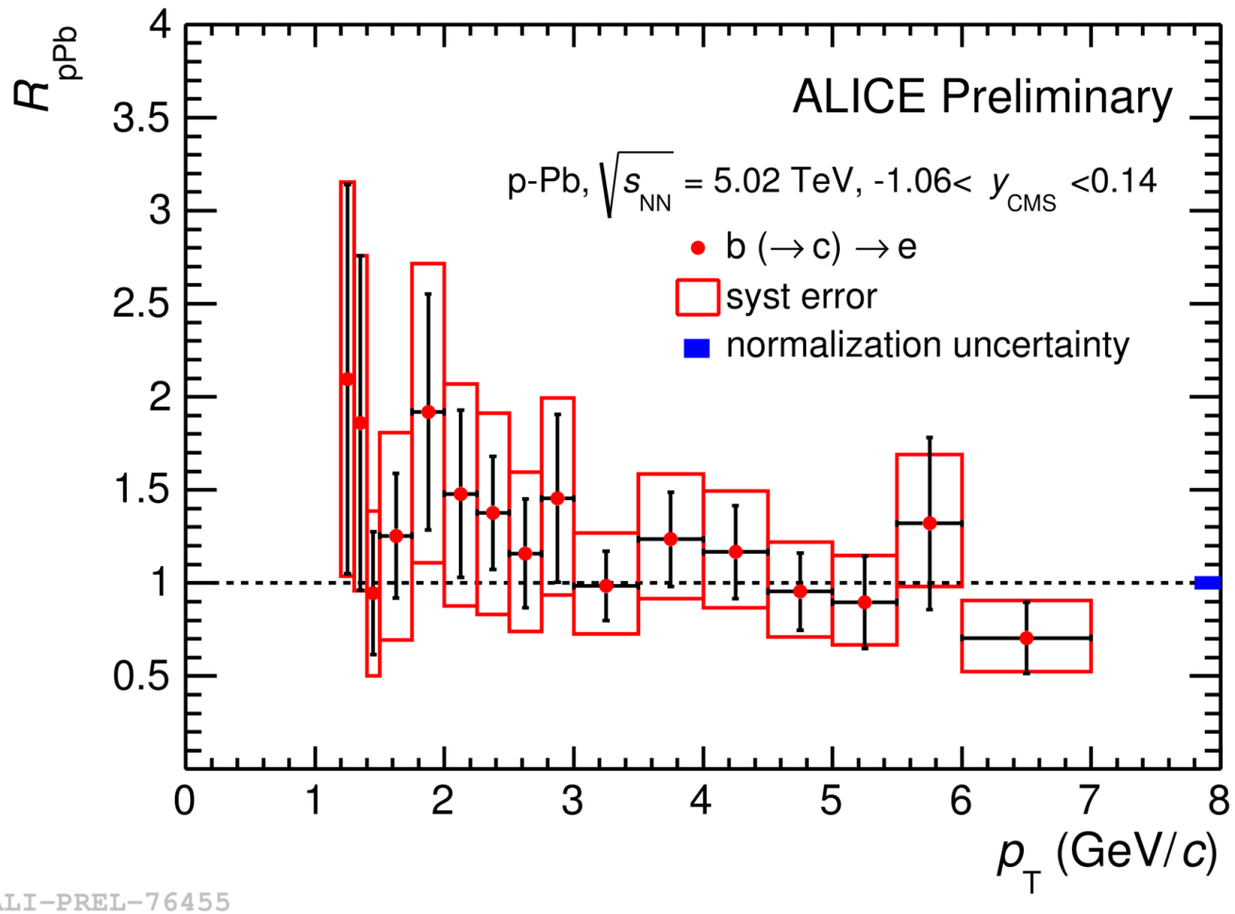
- Conversion γ
- Neutral-meson Dalitz decays
- J/ψ decays



data-tuned MC cocktail:
inclusive electron yield per min.bias pp@7TeV collision in comparison with background electron estimated within MC cocktail approach

HF electron from beauty hadron decay in p-Pb and Pb-Pb collisions

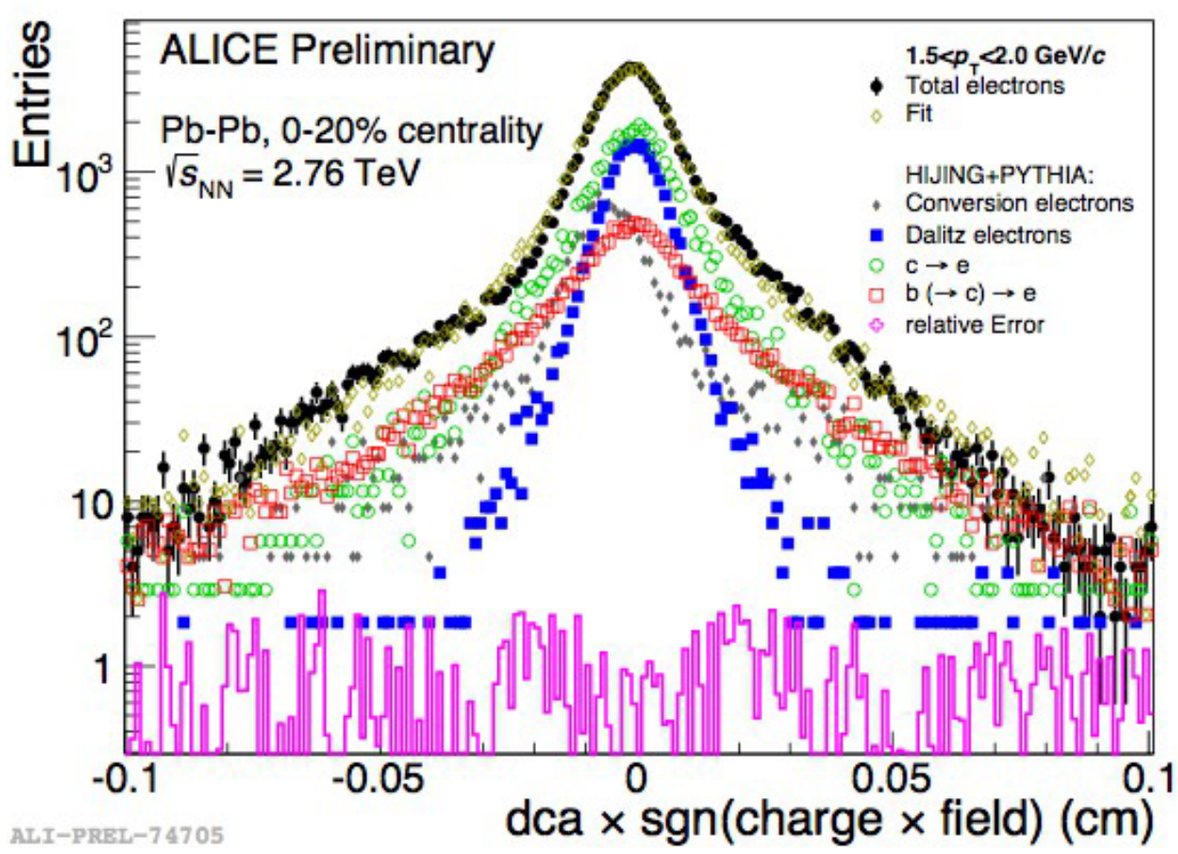
p-Pb



ALI-PREL-76455

R_{pPb} of beauty hadron decay electrons consistent with unity within uncertainties

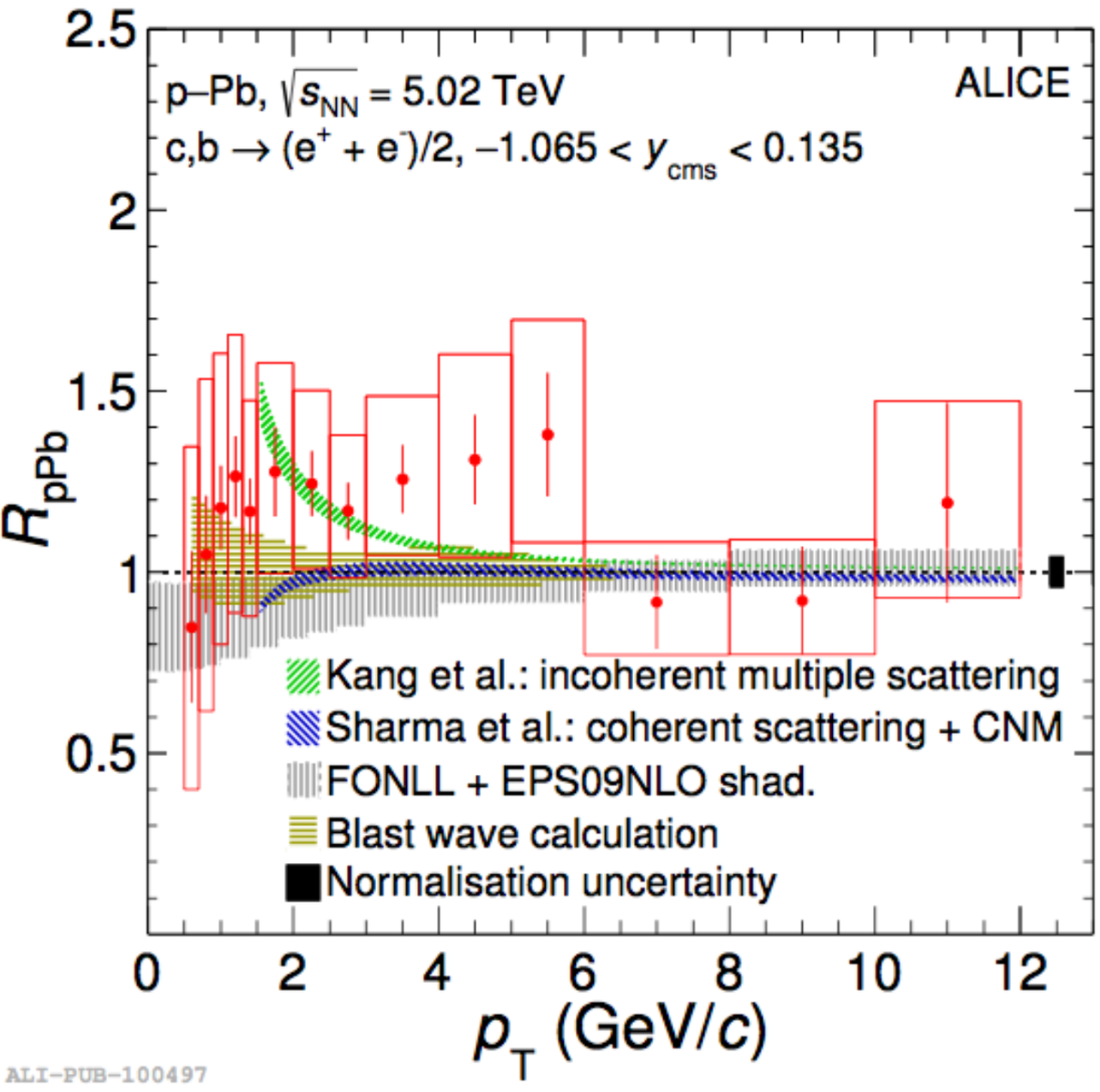
Pb-Pb



ALI-PREL-74705

Analysis based on the maximum-likelihood fit to the electron impact parameter distribution. **b —> e, c —> e** and other background sources

Heavy-flavour hadron decay electron R_{pPb} and models



- described by model including initial-state effects (FONLL + EPS09NLO)
- CNM energy loss, nuclear shadowing and coherent scattering at the partonic level
- incoherent multiple scattering suggest increasing at low p_T
- blast wave calculation including agrees with data

Heavy-flavour hadron decay muon R_{pPb}

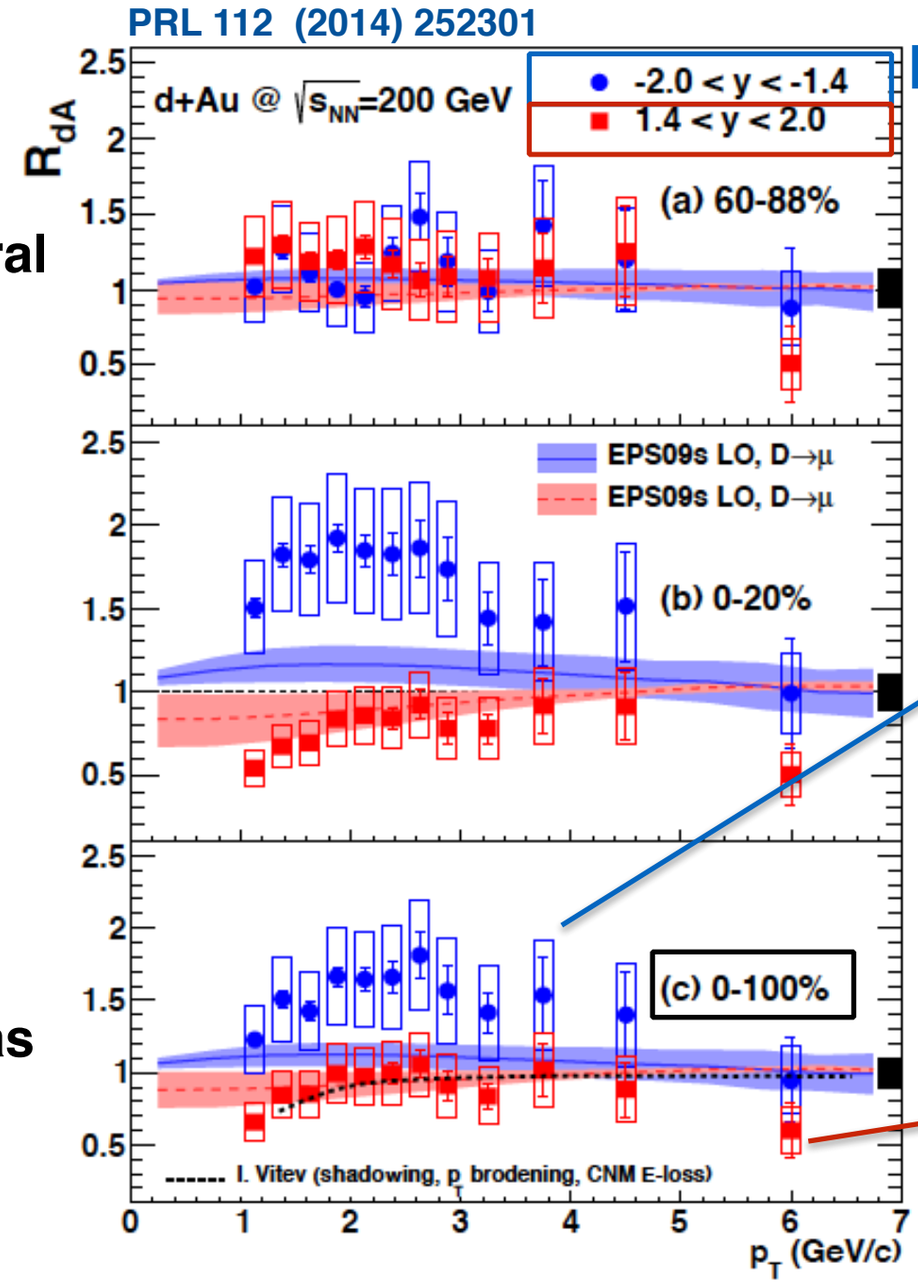
compared with PHENIX results

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

peripheral

central

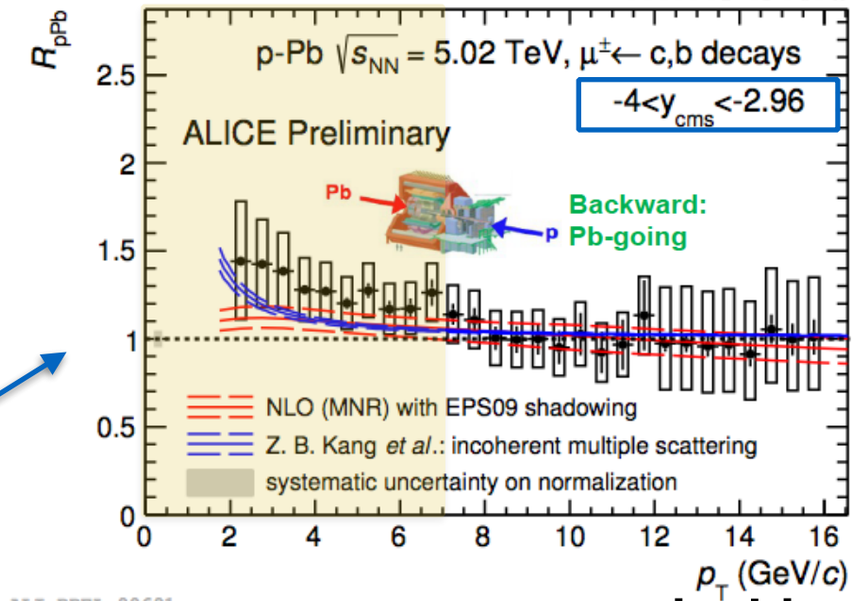
min. bias



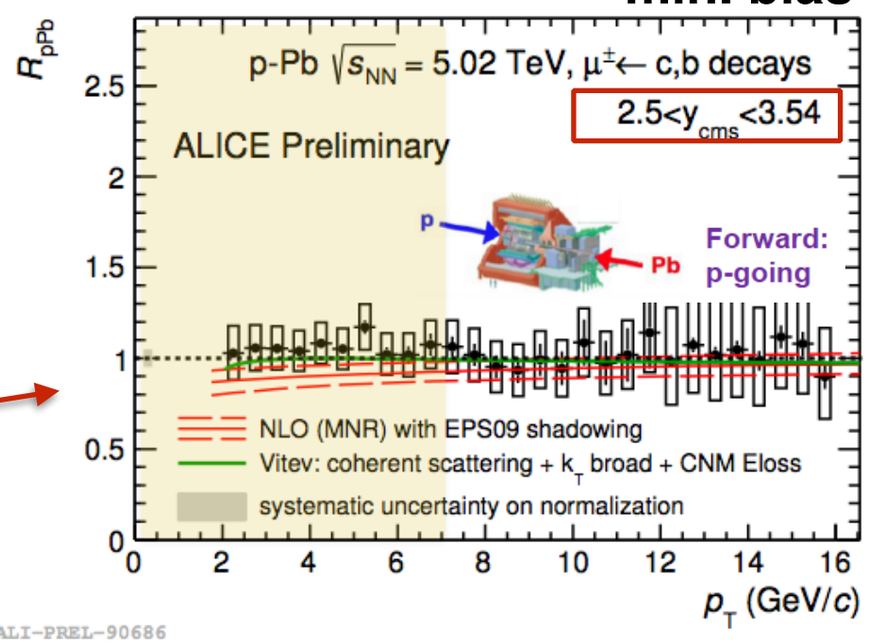
Backward

Forward

min. bias



min. bias



R_{pPb} of open heavy-flavour-decay muons is **consistent with unity** at forward rapidity and **slightly larger than unity** at backward rapidity for $2 < p_T < 4$ GeV/*c*

v_2 of leptons from heavy-flavour hadron decays

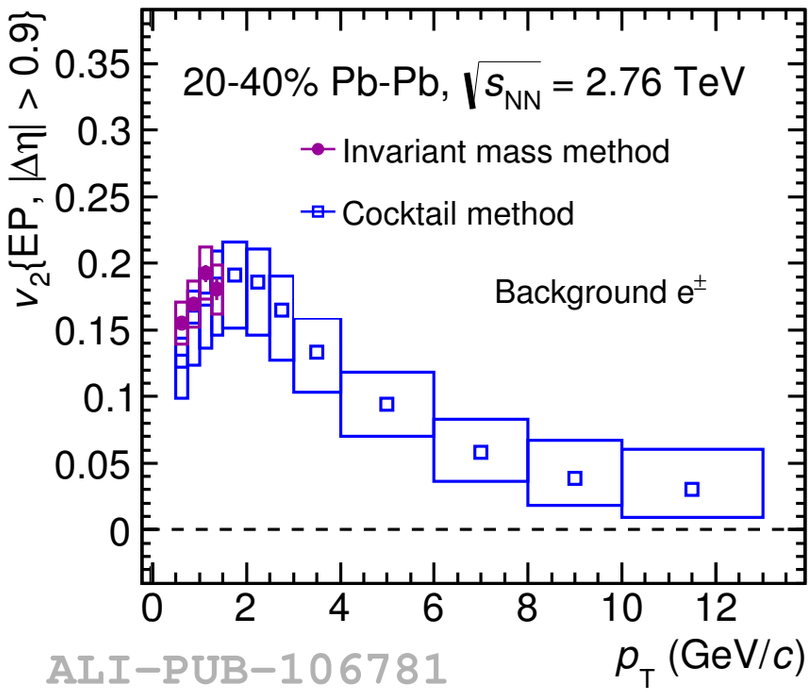
v_2 electrons

arXiv:1606.00321

$$v_2^{HFE} = \frac{(1+R_{SB})v_2^{incl} - v_2^{back}}{R_{SB}}$$

v_2 of inclusive electron measured with different methods:
- scalar product
- event plane

background subtraction:
- invariant mass method p_T<1.5 GeV/c
- cocktail method p_T>1.5 GeV/c



v_2 muons

PLB: 753(2016)41

$$v_2^{\mu\leftarrow HF} = \frac{v_2^{\text{incl }\mu} - f_{\text{decay }\mu}\, v_2^{\text{decay }\mu}}{1 - f_{\text{decay }\mu}}$$

Measured $v_2^{\text{Incl }\mu}$ of inclusive muon

Estimate $f_{\text{decay }\mu}$ and $v_2^{\text{decay }\mu}$

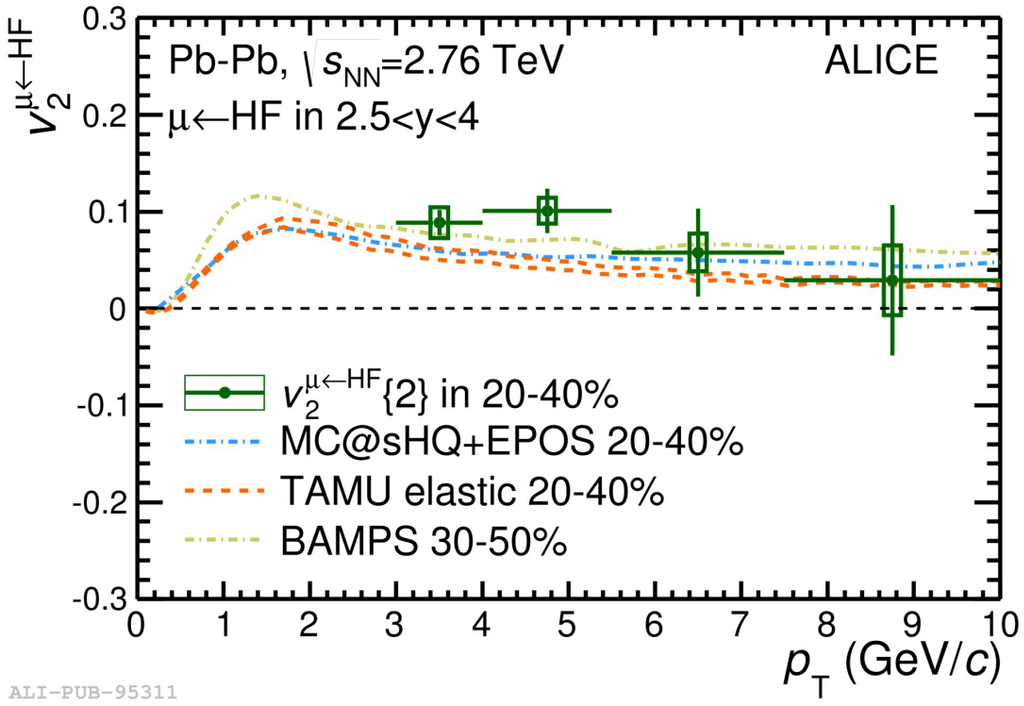
→ muon background fraction: ratio of yield of muons from primary π ,k.

$f_{\text{decay }\mu}$ ~15%(5%) at p_T = 3(10) GeV/c based on extrapolation of π/K spectra at mid-rapidity

→ $v2^{\text{decay }\mu}$ cocktail method based on data

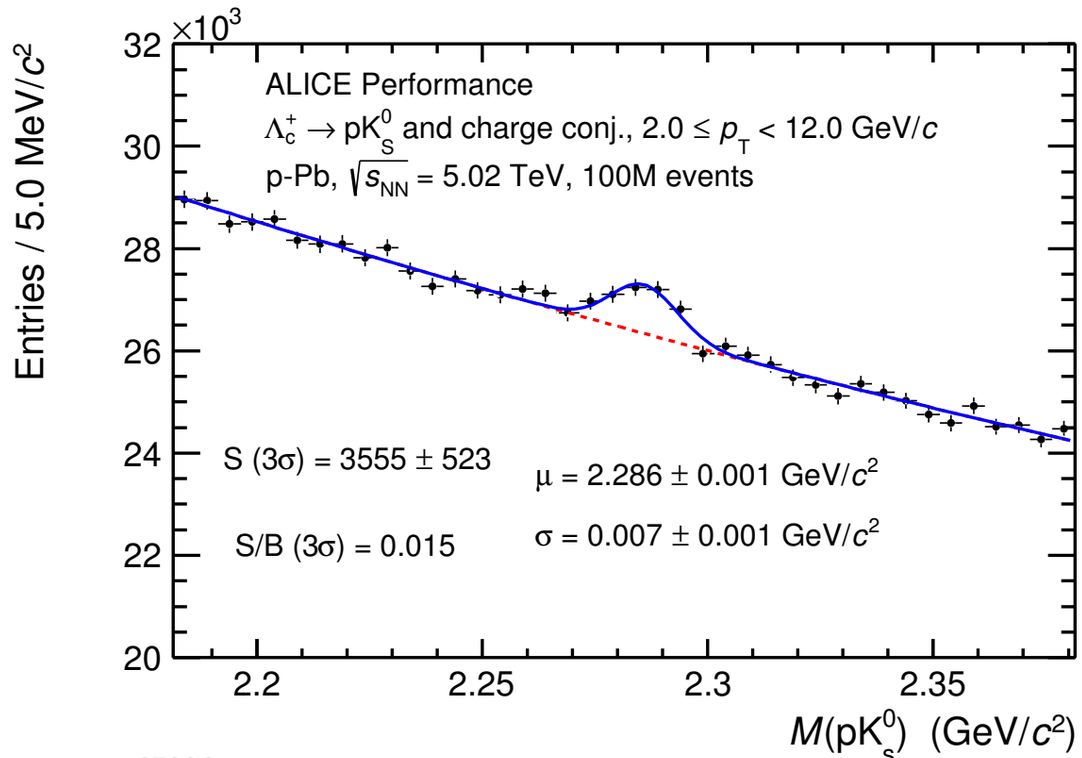
positive v_2 at intermediate p_T with significance > 3σ

measured with different methods:
- scalar product
- two- and four- particle Q cumulants
- Lee-Yang zeros



Λ_c in p-Pb

$\Lambda_c \longrightarrow pK^0_s$



10^8 events in p-Pb collisions

- Λ_c is reconstructed in a wide momentum range
- Good S/B separation
- Waiting for more statistics