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Measurements of heavy-flavour decay leptons in Pb-Pb, Xe-Xe and p-Pb collisions with ALICE at the LHC

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National Institute of Science Education and Research (NISER)

3rd Heavy—Flavour Meet 2019
Indian Institute of Technology Indore, India



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Outline

- Physics Motivation
- Observables
- Measurement of heavy-flavour decay lepton with ALICE
- Results :
 - p-Pb collisions
 - Pb-Pb collisions
 - Xe-Xe collisions
- Summary and outlook



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Motivation

➤ In Pb-Pb collisions:

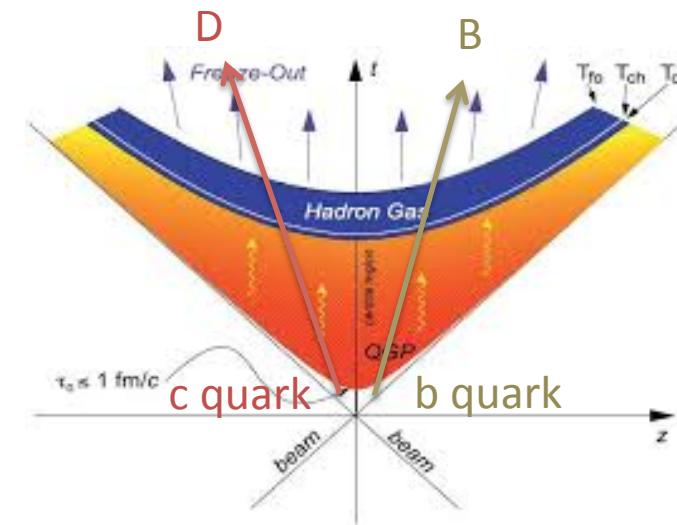
Heavy quarks, i.e. charm and beauty quarks are excellent probes to study the properties of the strongly-interacting medium created in heavy-ion collisions :

- ✓ Produced in the early stages of the collisions
- ✓ Witness entire space-time evolution of the system
- ✓ Interact with the hot and dense QCD matter
- ✓ Parton energy loss by radiative and elastic processes

➤ In p-Pb collisions:

Cold nuclear matter (CNM) effects :

- ✓ modifications of the parton distribution functions in nuclei (nPDF)
- ✓ Gluon saturation at low x (color glass condensate)
- ✓ k_T -broadening
- ✓ Energy loss
- ✓ Possibility of final-state effects



➤ In pp collisions:

- ✓ Test of perturbative QCD (pQCD) calculations
- ✓ Reference for p-Pb and Pb-Pb collisions
- ✓ Study the Multi-Parton interactions (MPIs)



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Observables: Nuclear modification factor

- Defined as :

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

- Quantify the energy loss in medium by collisional and radiative processes :
- ✓ Colour-charge dependence
- ✓ Dead-cone effect -> expected mass-dependent energy loss:

$$\Delta E (g) > \Delta E (u,d,s) > \Delta E (c) > \Delta E (b) \quad PLB 519 (2001) 199$$

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

- $R_{AA} = 1$ at high transverse momentum (p_T) indicates no medium effects
- $R_{AA} < 1$ at high p_T indicates a modification/softening of the spectra which can be related to parton energy loss.



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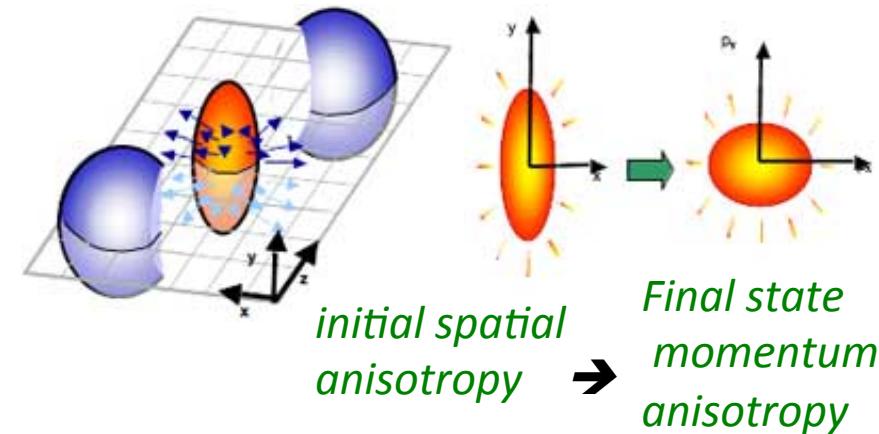
Observables: Anisotropic flow

- measures the momentum anisotropy of the final-state particles
- created due to the initial spatial anisotropy of the overlap region

- Fourier expansion of azimuthal distribution of produced particles:

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

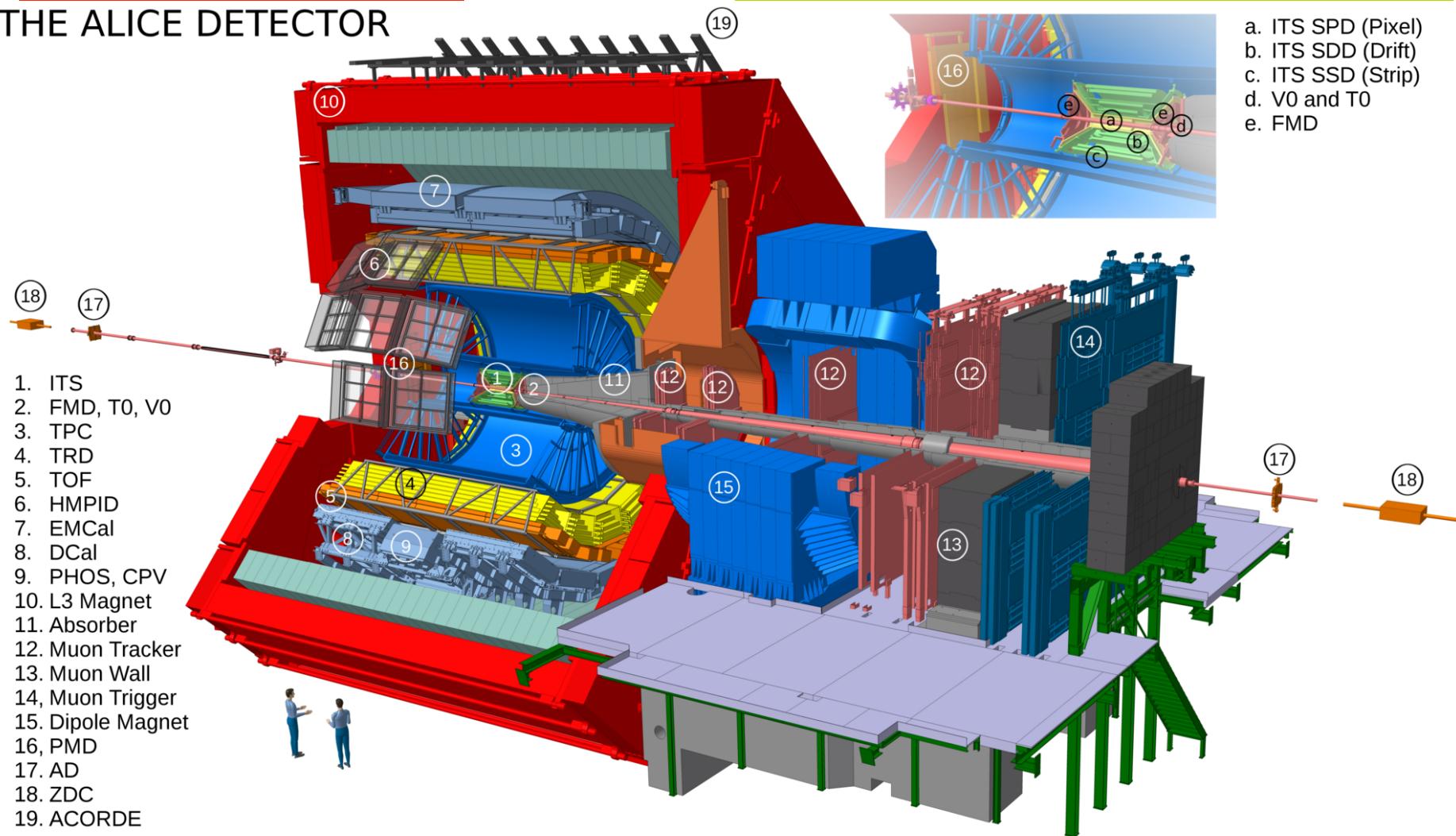
- quantified as the v_n , Ψ_{RP} is the reaction plane angle
- The second Fourier coefficient of the distribution is called elliptic flow (v_2).
- Elliptic flow of heavy-flavour particles provides information on:
 - ✓ Collective expansion and possible thermalization (low and intermediate p_T)
 - ✓ Path-length dependence of heavy-flavour energy loss (high p_T)





A Large Ion Collider Experiment (ALICE)

THE ALICE DETECTOR





ALICE: heavy-flavour decay lepton reconstruction

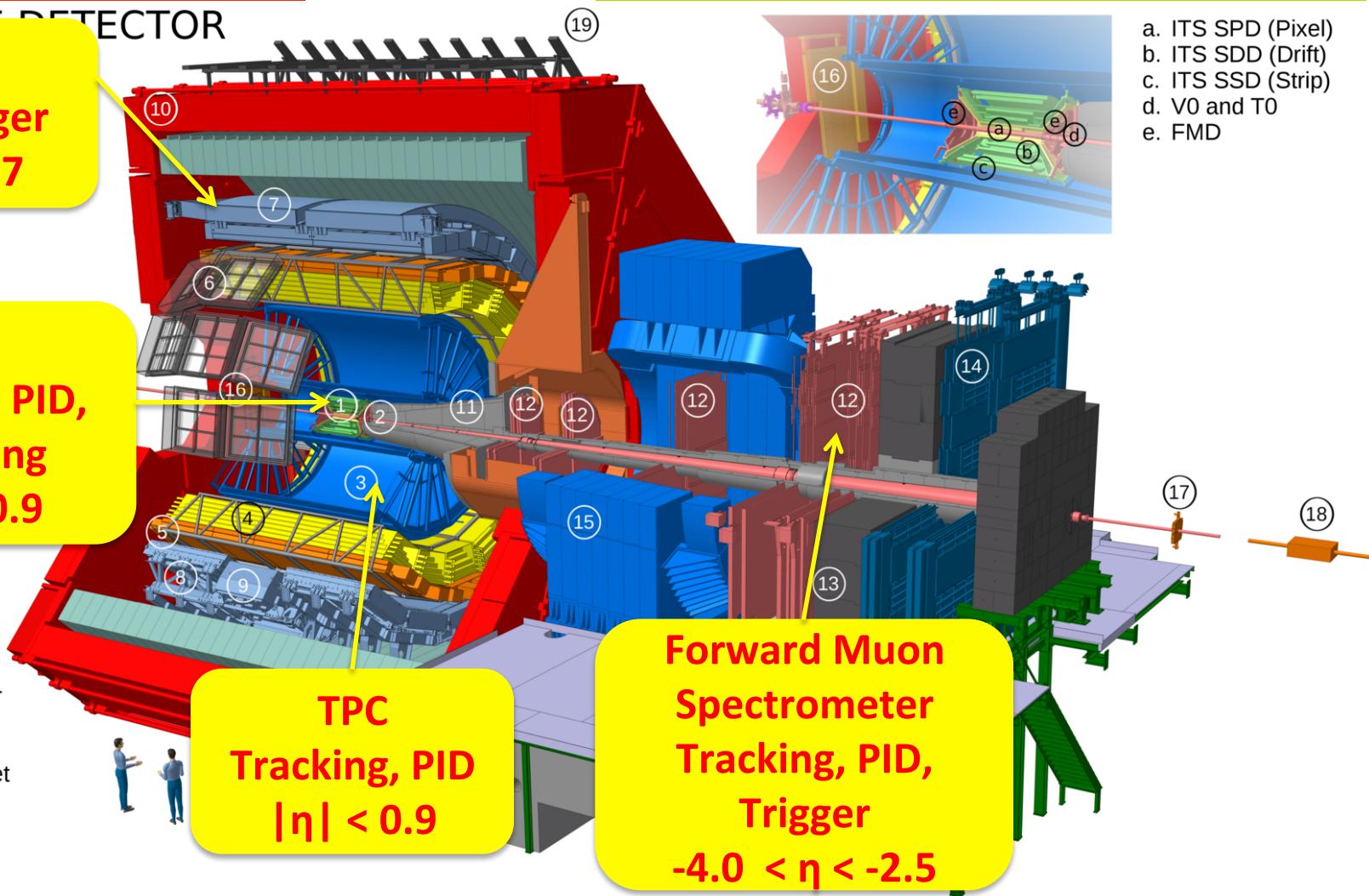
THE ALICE DETECTOR

EMCal
PID, Trigger
 $|\eta| < 0.7$

ITS
Tracking, PID,
vertexing
 $|\eta| < 0.9$

TPC
Tracking, PID
 $|\eta| < 0.9$

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

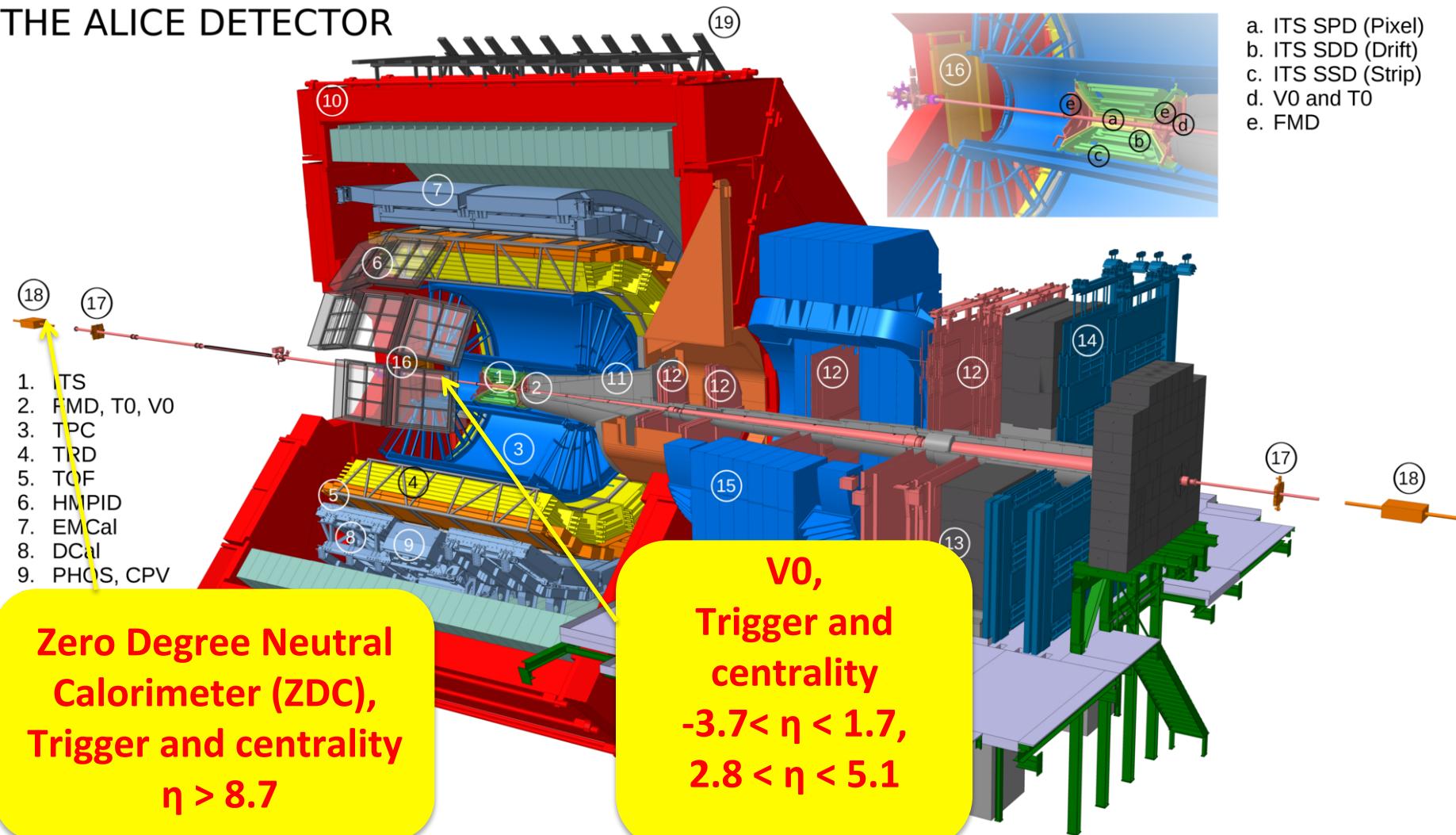




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ALICE: centrality selection

THE ALICE DETECTOR



Open heavy-flavour production in ALICE

- D-meson reconstruction via their hadronic decay channels with invariant mass method (ITS, TPC, TOF) ($|\eta| < 0.9$):

$D^0(c\bar{u}) \rightarrow K^-\pi^+$	BR -> 3.88%
$D^+ (c\bar{d}) \rightarrow K^-\pi^+\pi^+$	BR -> 9.13%
$D^{*+} (c\bar{d}) \rightarrow D^0(K^-\pi^+\pi^+) \pi^+$	BR -> 67.7%
$D_s^+ (c\bar{s}) \rightarrow \phi\pi^+(K^-K^+\pi^+)$	BR -> 2.28%
$\Lambda_c^+ (cud) \rightarrow pK^-K^+\pi^+, pK_s^0$	BR -> 6.23%, 1.58%

Focus of this talk:

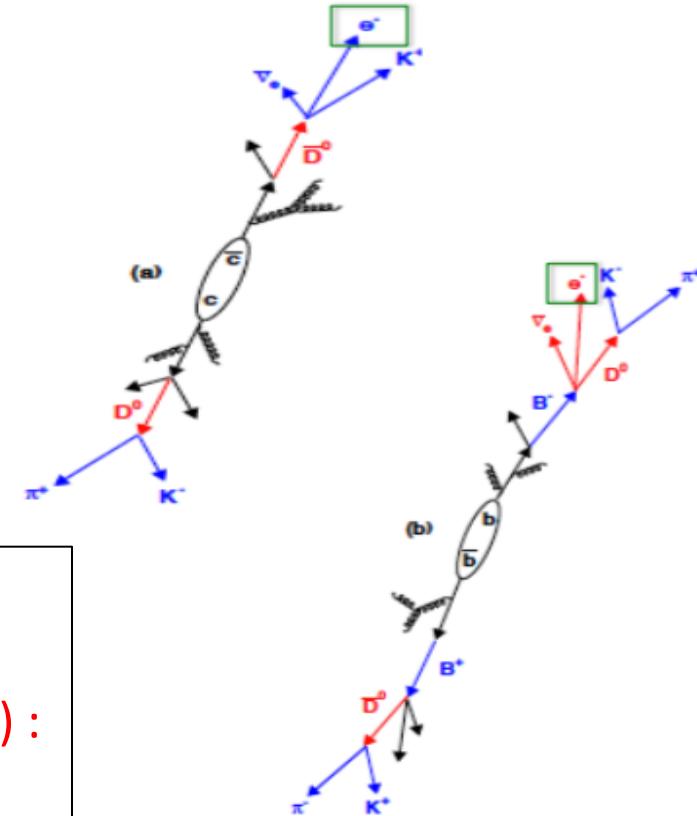
- Semi-leptonic decay:

Muons (Forward Muon Spectrometer) ($-4 < \eta < 2.5$) :

$c, b \rightarrow \mu^\pm + X$ BR->11%

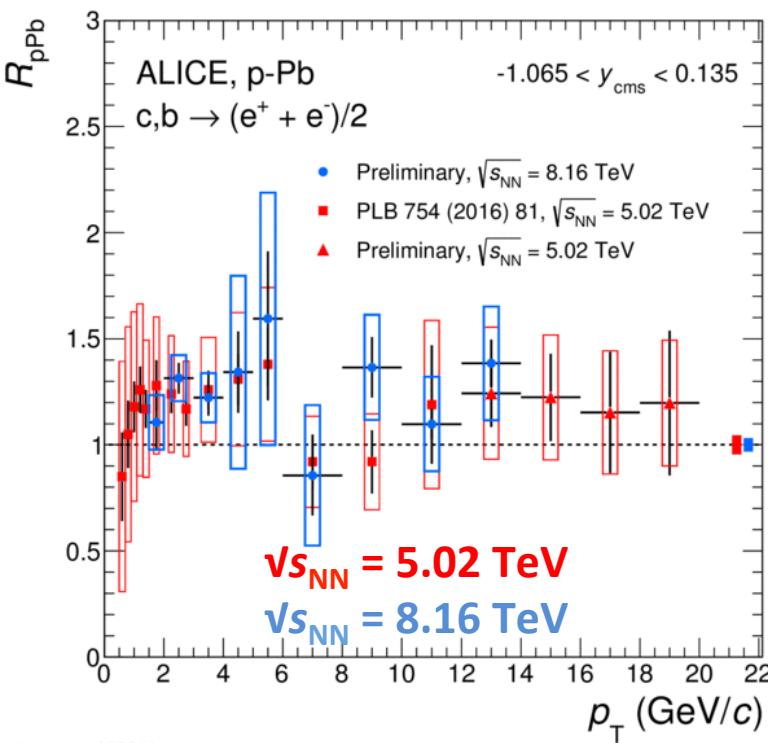
Electrons (ITS, TPC, TOF, EMCal, TRD) ($|\eta| < 0.9$)

$c, b \rightarrow e^\pm + X$ BR->11%

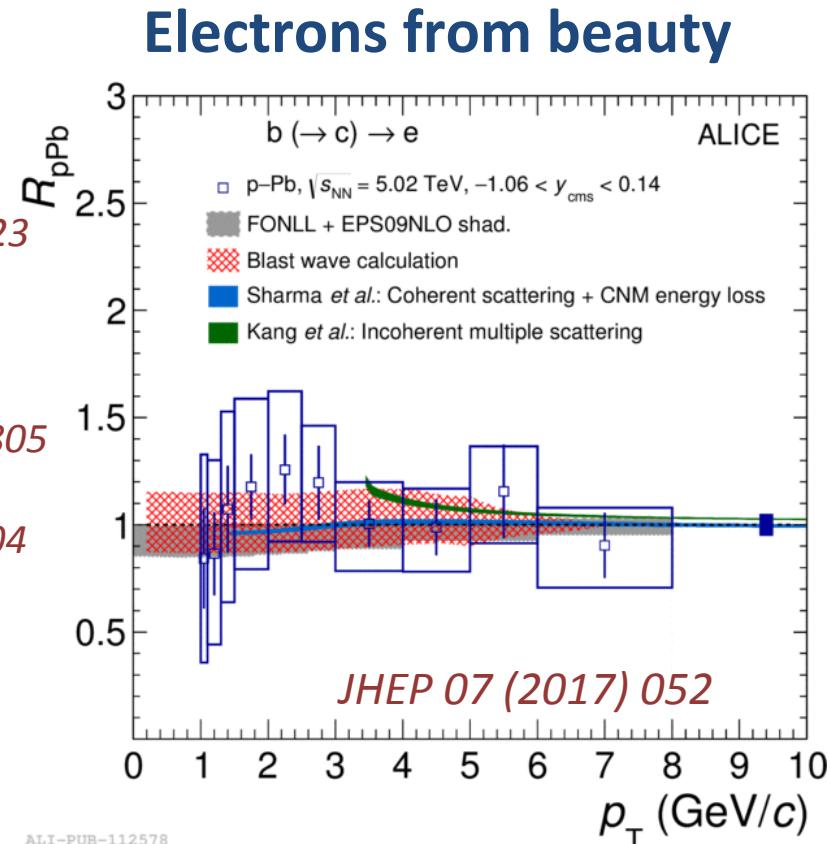


Heavy-flavour hadron decay electron R_{pPb}

Electrons from charm+beauty

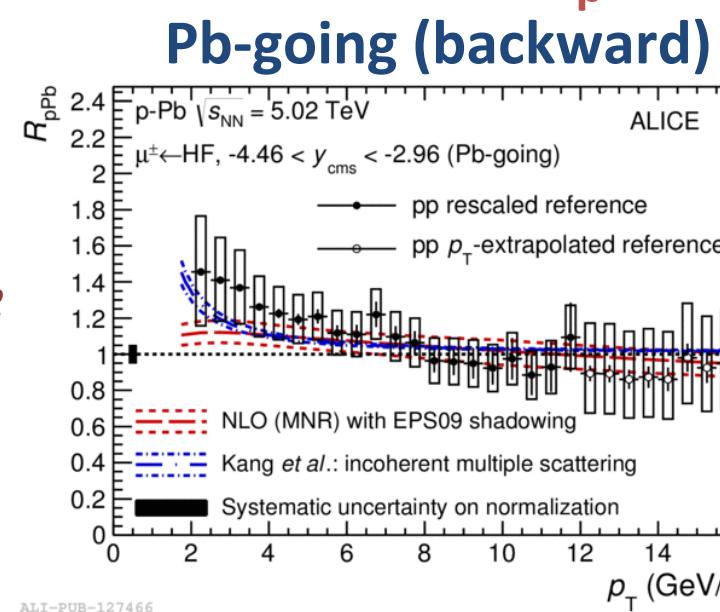
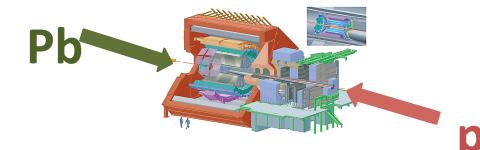
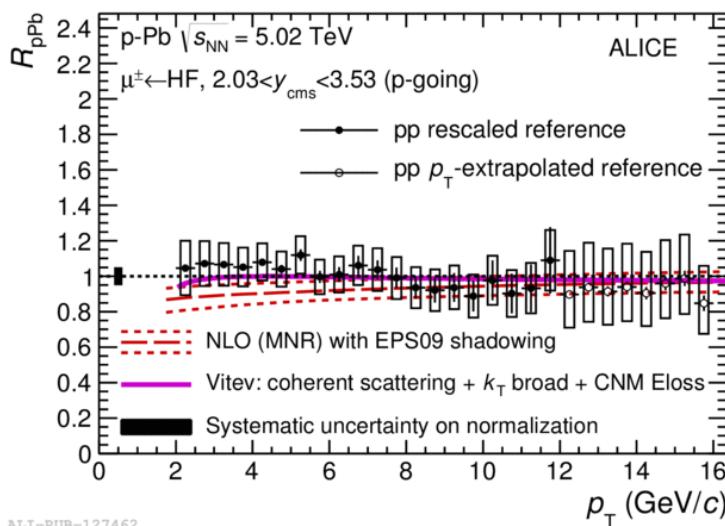
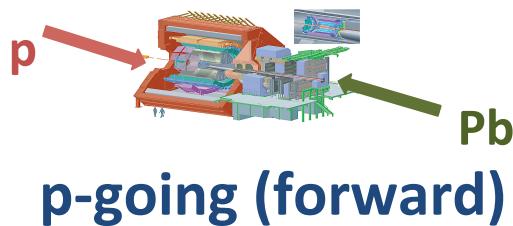


Kang et al:
PLB 740(2015)23
Sharma et al:
PRC 80(2009) 054902
FONLL: *JHEP 9805 (1998)007*
EPOS09: *JHEP 04 (2009)065*



- No energy dependence within uncertainty
- charm+beauty and beauty electron results are compatible within uncertainties
- Results are well described by the models including CNM effects

Heavy-flavour hadron decay muon $R_{p\text{Pb}}$

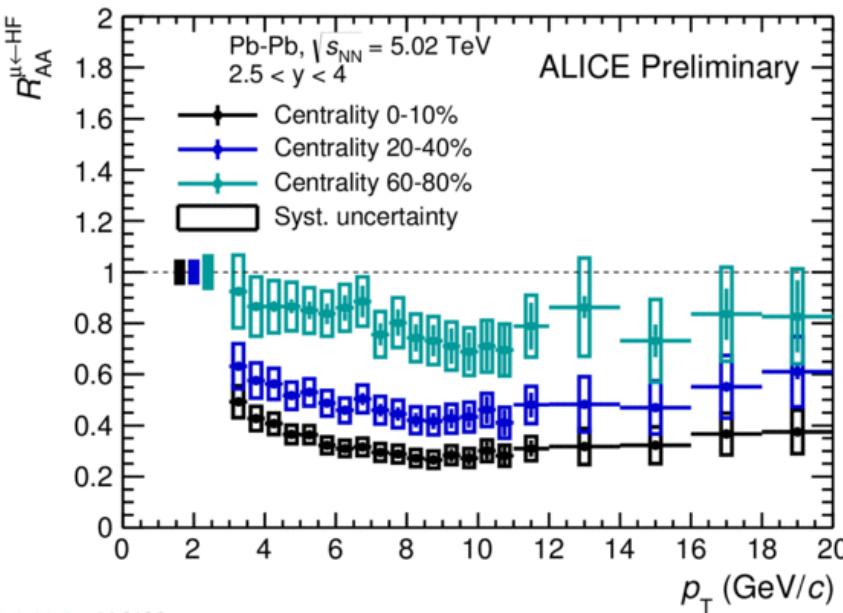


- EPOS09:
JHEP 0904(2009)065
- Vitev et al.:
PRC 80(2009)054902
- Z.B.Kang et al.:
PLB 740(2015)23
- ALICE data:
PLB 770 (2017) 459

- Study in different rapidity ranges allows us to explore different x regimes
- $R_{p\text{Pb}}$ of heavy-flavour decay muons is consistent with unity at forward rapidity
- Hint of enhancement at backward rapidity at low p_T ($2 < p_T < 4 \text{ GeV}/c$)
- Models including CNM effects describe the data within uncertainties

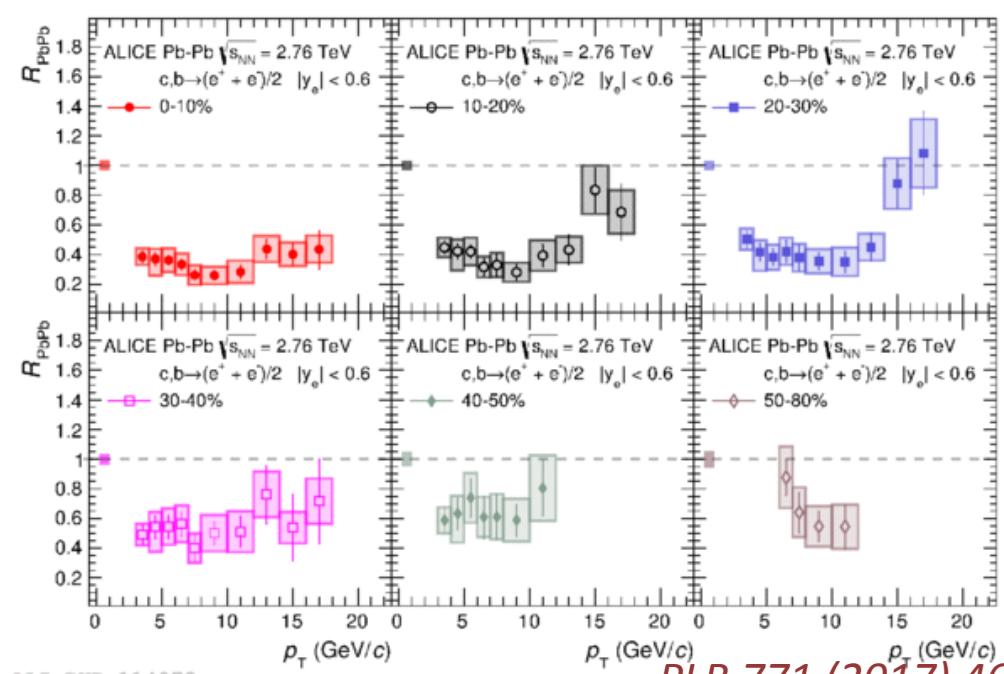
Heavy-flavour hadron decay lepton R_{AA} : centrality dependence

$c,b \rightarrow \mu$



ALI-PREL-116408

$c,b \rightarrow e$



ALI-PUB-114073

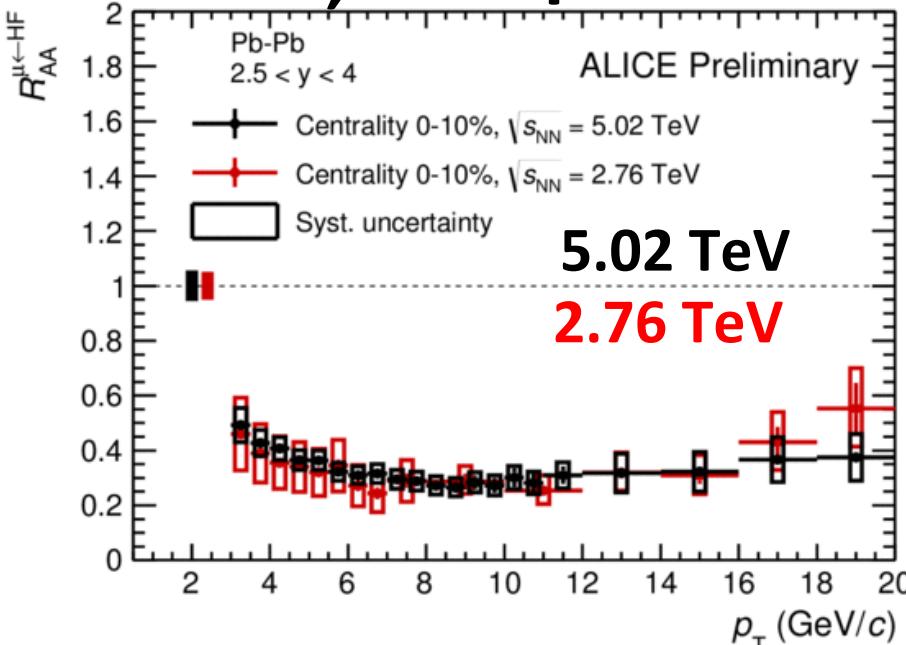
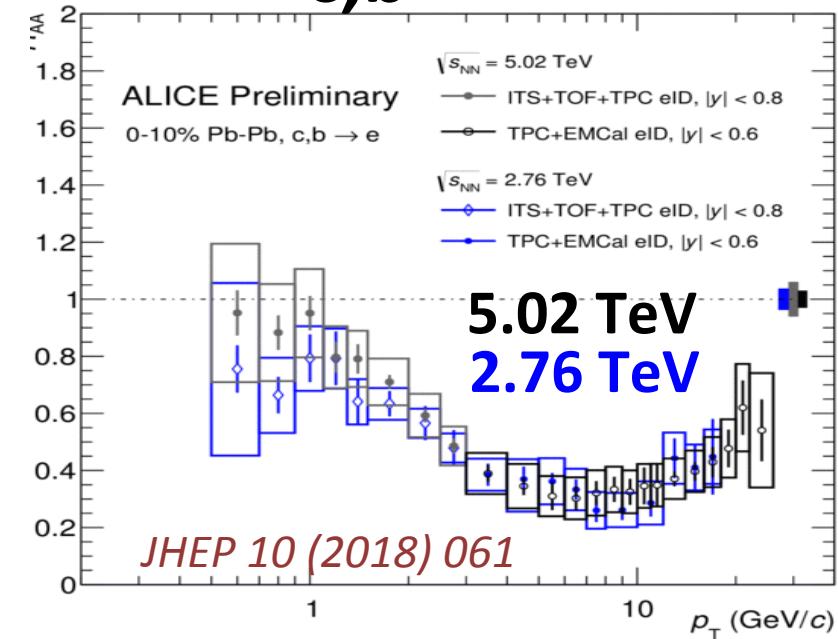
PLB 771 (2017) 467

- Strong suppression observed at high p_T for most central collisions
- Suppression increases towards more central collisions
- high- p_T leptons are dominated by beauty electrons \rightarrow indication of beauty energy loss



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Heavy-flavour hadron decay lepton R_{AA} : center-of-mass energy dependence

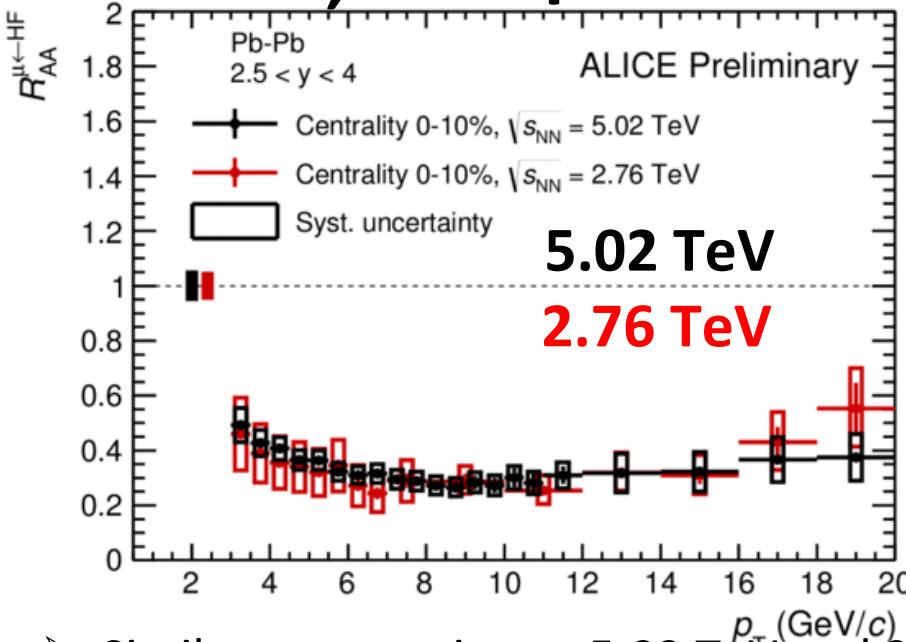
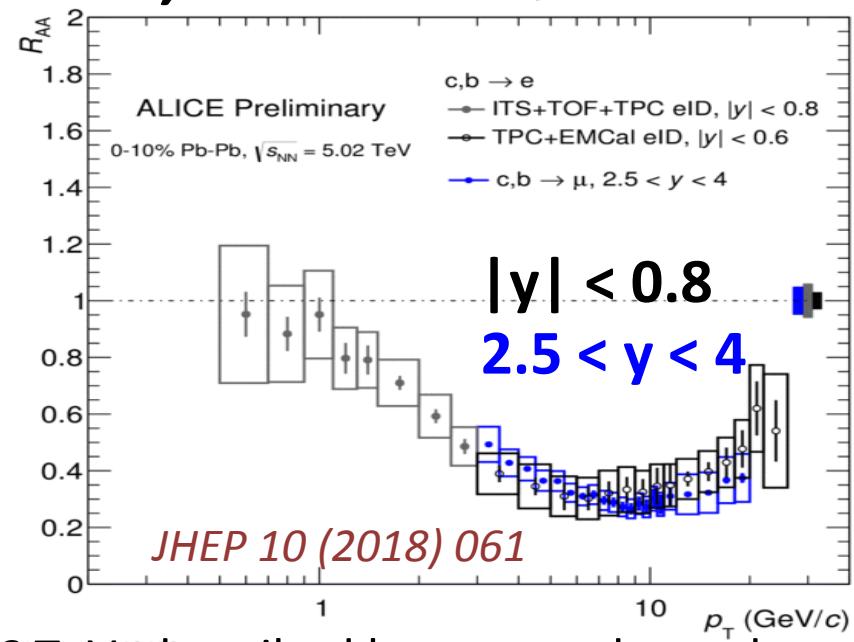
c,b → μ**c,b → e**

- Similar suppression at 5.02 TeV and 2.76 TeV: described by energy-dependent model (*Djordjevic, Phys. Rev. C92 (2015) 024918*): harder spectra and denser medium balance each other
- Measurements down to low p_T (0.5 GeV/c at mid rapidity): sensitive to probe initial-state effects



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Heavy-flavour hadron decay lepton R_{AA}

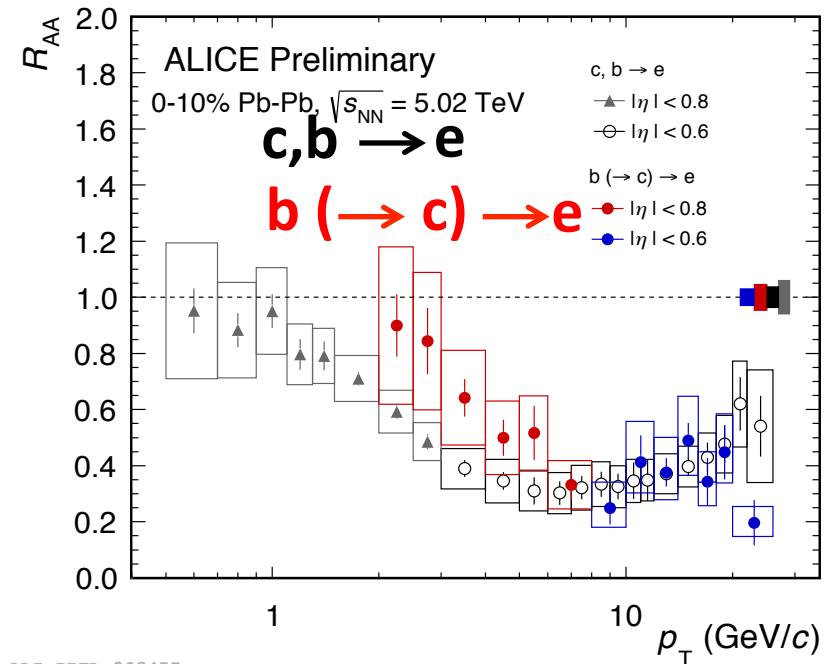
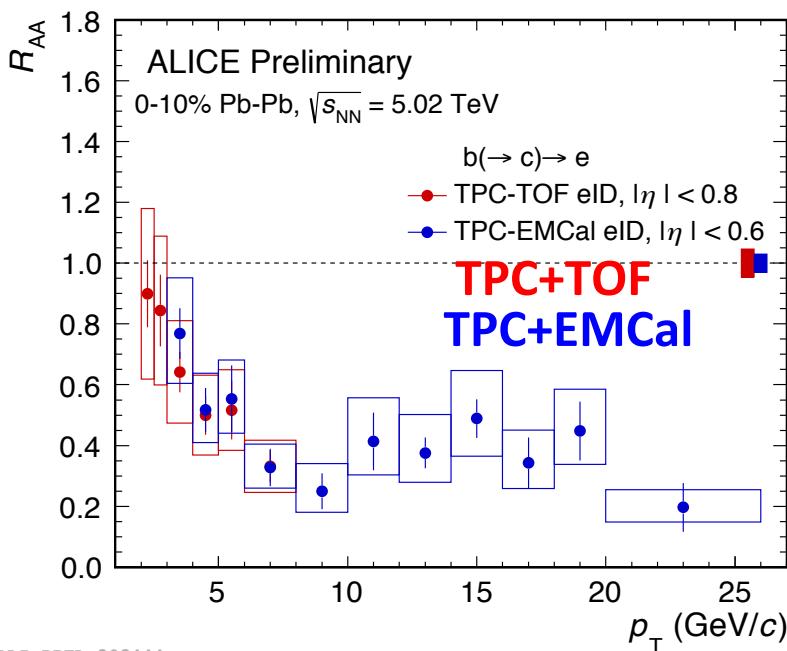
 $c,b \rightarrow \mu$  $c,b \rightarrow e$ $c,b \rightarrow \mu$ 

- Similar suppression at 5.02 TeV and 2.76 TeV: described by energy-dependent model (*Djordjevic, Phys. Rev. C92 (2015) 024918*): harder spectra and denser medium balance each other
- Measurements down to low p_T (0.5 GeV/c at mid rapidity): sensitive to probe initial-state effects
- Rapidity-independent in-medium energy loss observed



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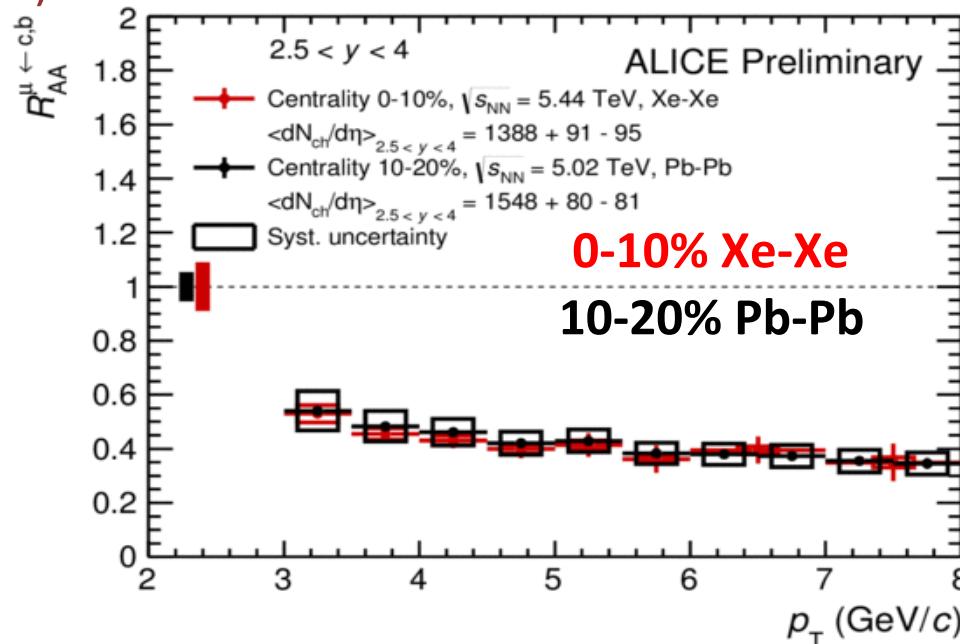
Beauty-hadron decay electron R_{AA}



- Low p_T with TPC + TOF and high p_T (up to $p_T = 26$ GeV/c) using TPC + EMCal (using EMCal-triggered data) -> results are consistent -> large suppression observed at high p_T
- Hint of smaller suppression of beauty-decay electron for $p_T < 6$ GeV/c

Heavy-flavour hadron decay lepton R_{AA} in Xe-Xe collisions

- Comparison of R_{AA} in different collisions systems->different system size
- Constraints on the path-length dependent energy-loss (*M. Djordjevic et al,*
arxiv 1805.04030)



c,b → μ

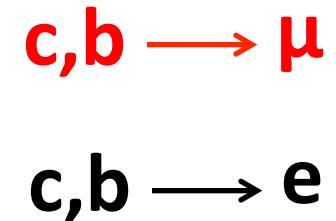
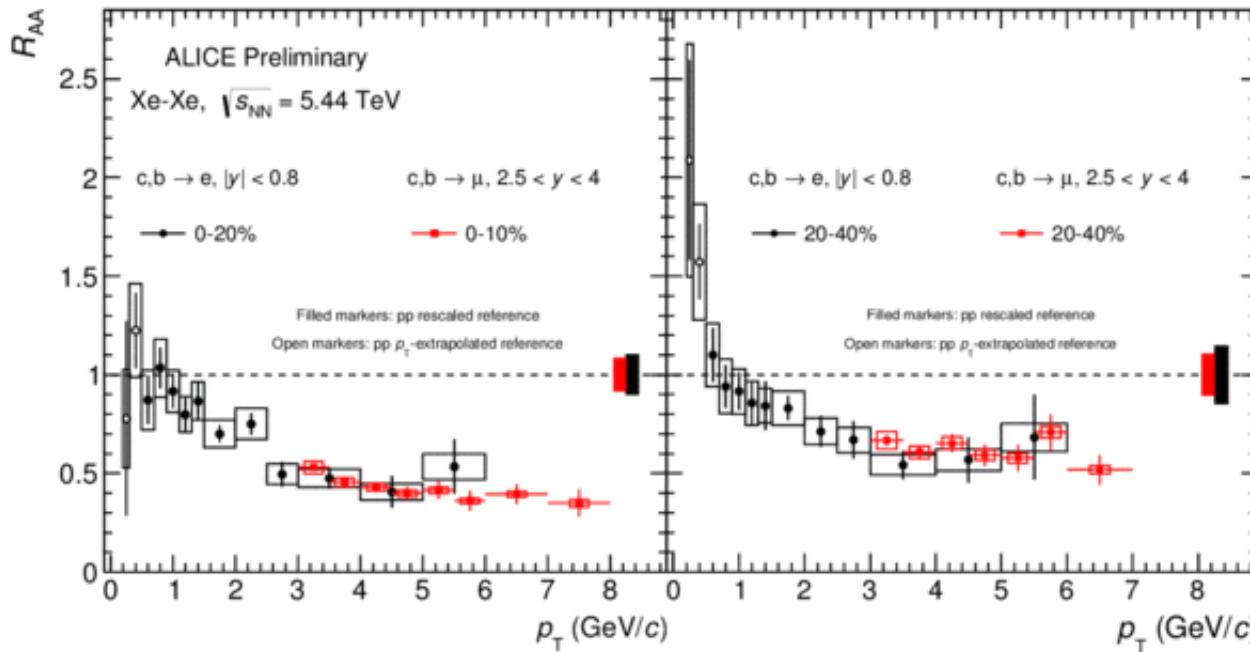
- Similar heavy-flavour hadron decay muon R_{AA} for 0-10% Xe-Xe and 10-20% Pb-Pb
 - N_{ch} and N_{part} values are similar for both cases
- Similar results are also observed for charged particles (*PLB 788 (2019) 166*)



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Heavy-flavour hadron decay lepton R_{AA} in Xe-Xe collisions

- Heavy-flavour decay electron R_{AA} measured down to $p_T = 0.2$ GeV/c



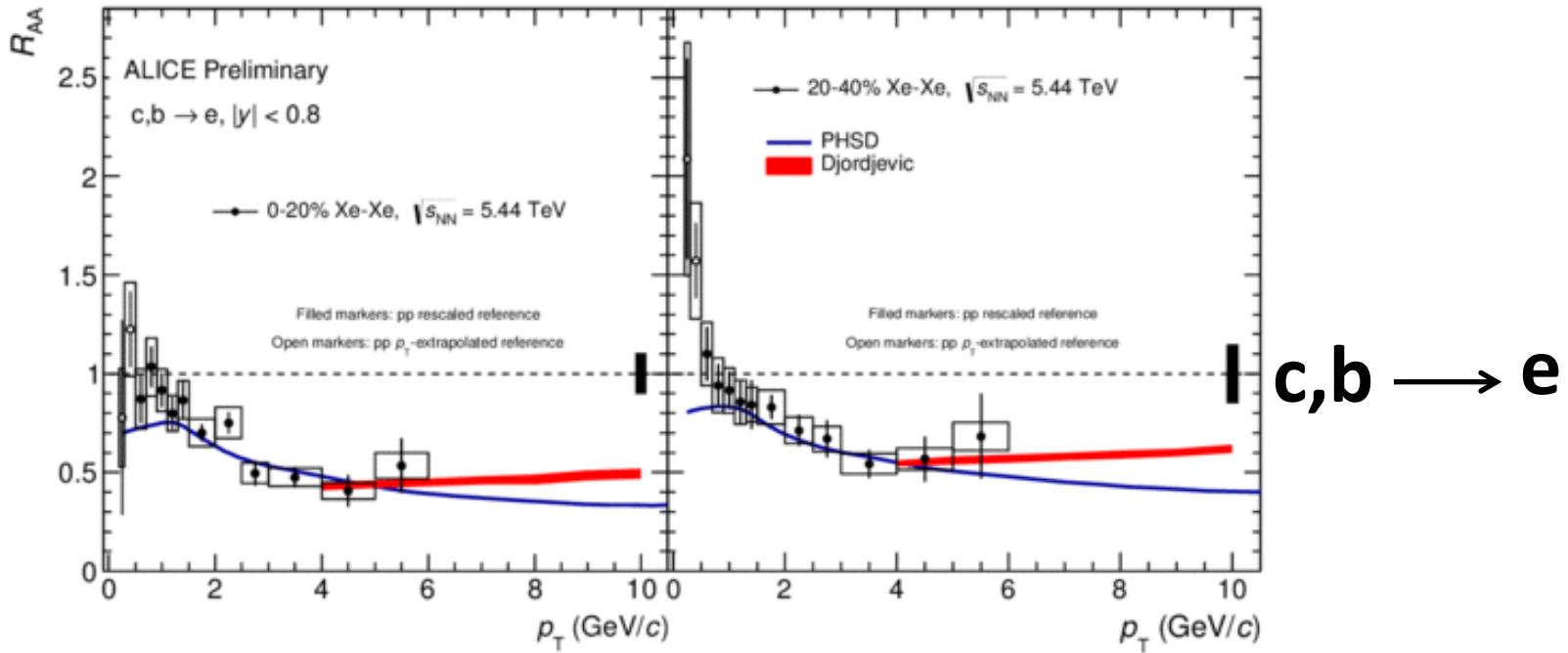
- ALI-PREL-148699
- Similar heavy-flavour hadron decay electron ($|y| < 0.8$) and muon ($2.5 < y < 4$) R_{AA}
 - Hint of stronger suppression for most central collisions



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Heavy-flavour hadron decay lepton R_{AA} in Xe-Xe collisions

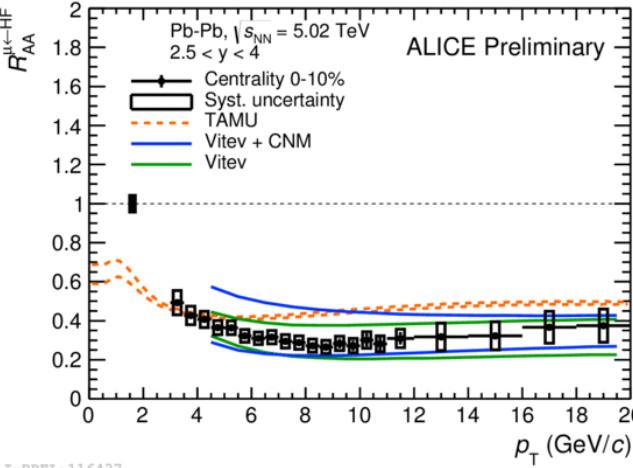
- Heavy-flavour decay electron R_{AA} measured down to $p_T = 0.2 \text{ GeV}/c$



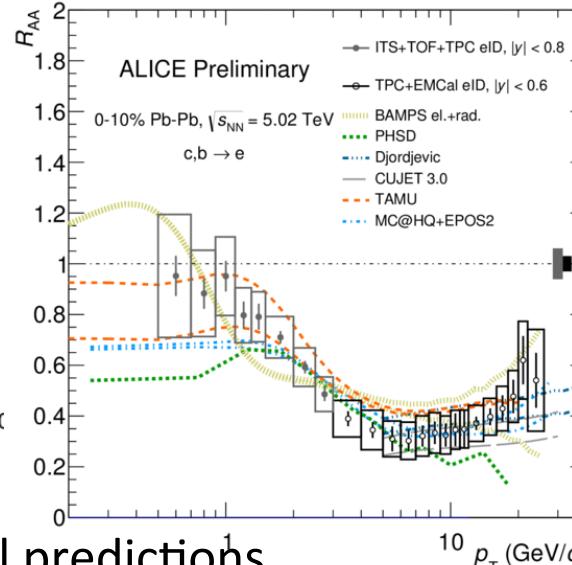
- Similar heavy-flavour hadron decay electron ($|y| < 0.8$) and muon ($2.5 < y < 4$) R_{AA}
- Hint of stronger suppression for most central collisions
- Data are well described by the model predictions (PHSD: Phys. Rev. C no.3 (2016) 034034, Djordjevic: Phys. Rev. C92 (2015) 024918)

Heavy-flavour hadron decay lepton R_{AA} : comparison with models

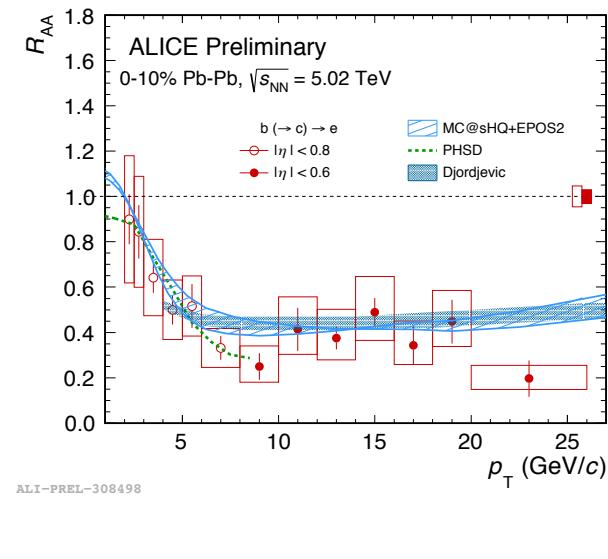
$c,b \rightarrow \mu$



$c,b \rightarrow e$



$b (\rightarrow c) \rightarrow e$



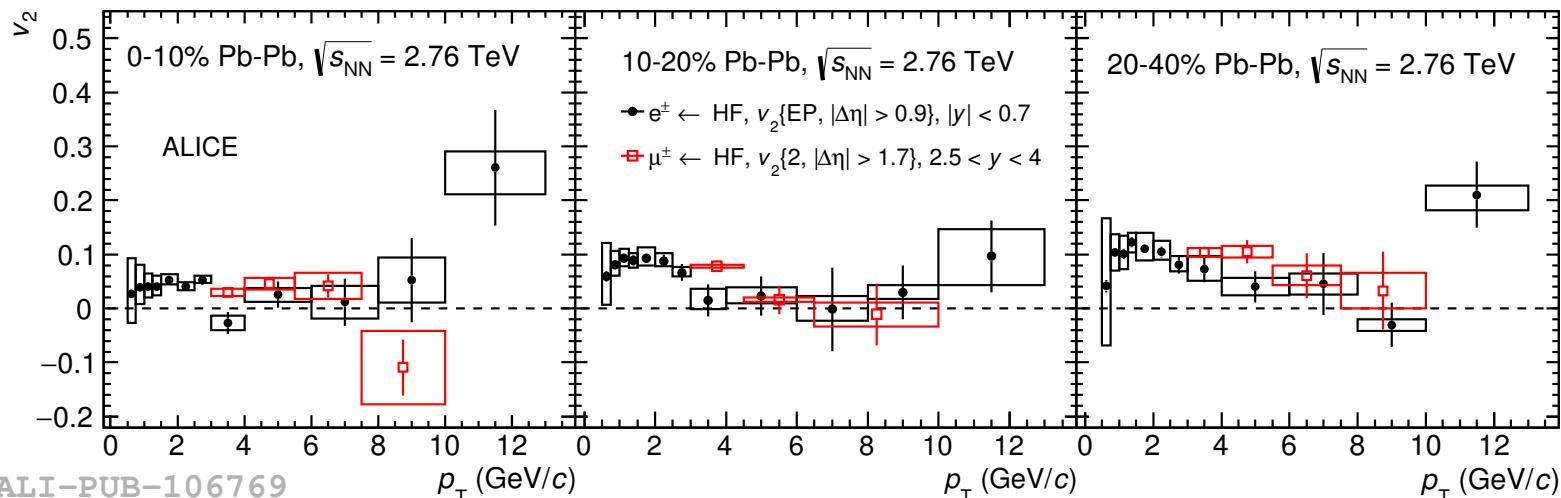
- Consistent with the model predictions (rad. + Coll. Energy loss) within the uncertainties
- Data are reproduced by mass-dependent energy loss within the uncertainties for beauty-hadron decay electrons
- Provide new constraints on energy loss models

MC@sHQ: Phys.Rev. C89 no. 1, (2014) 014905
TAMU: Phys. Lett. B 735 (2014) 445
BAMPS: J. Phys. G42 no. 11, (2015) 115106
PHSD: Phys. Rev. C93 no. 3, (2016) 034906
CUJET: arXiv:1207.6020 [hep-ph], (2012)
Djordjevic: Phys. Rev. C92 (2015) 024918

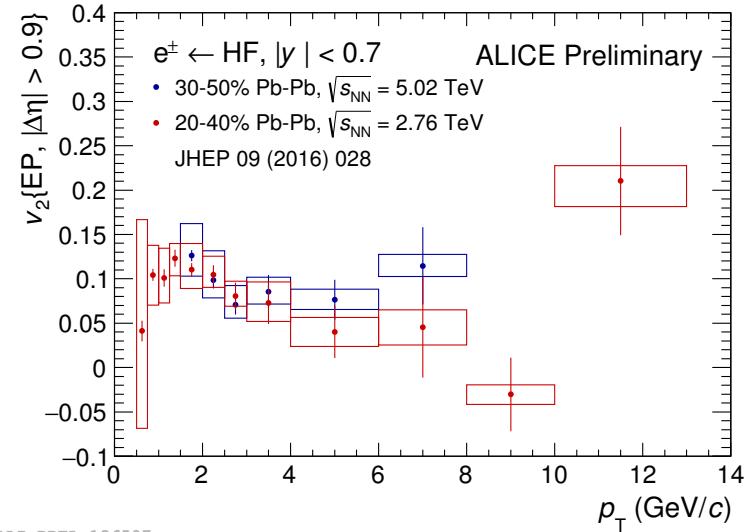


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Heavy-flavour hadron decay lepton ν_2



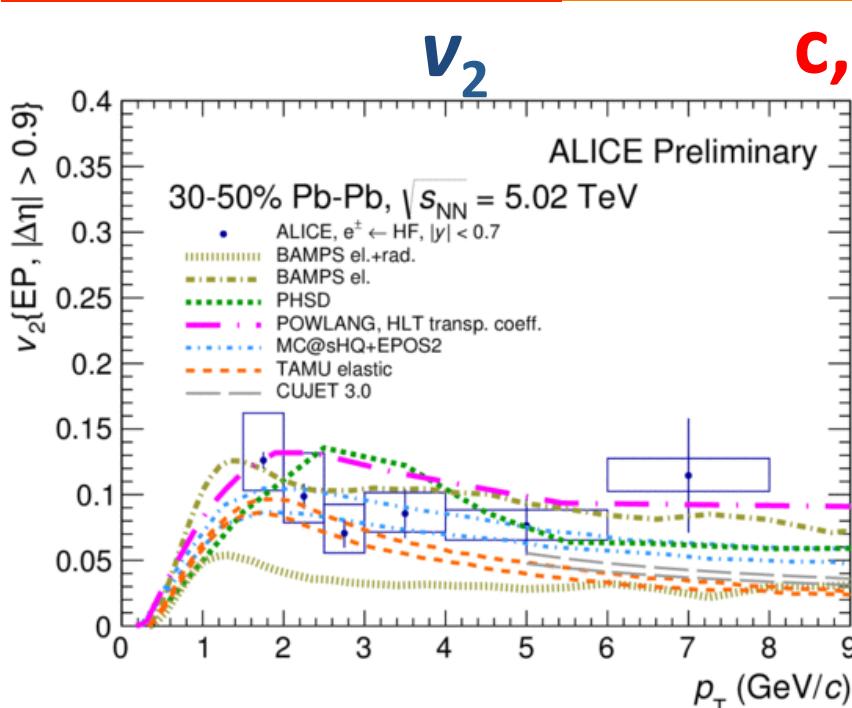
- Positive v_2 observed -> indication of collective motion of heavy quarks in the expanding medium
- v_2 increases from central to semi-central collisions
- v_2 is rapidity and center-of-mass energy independent



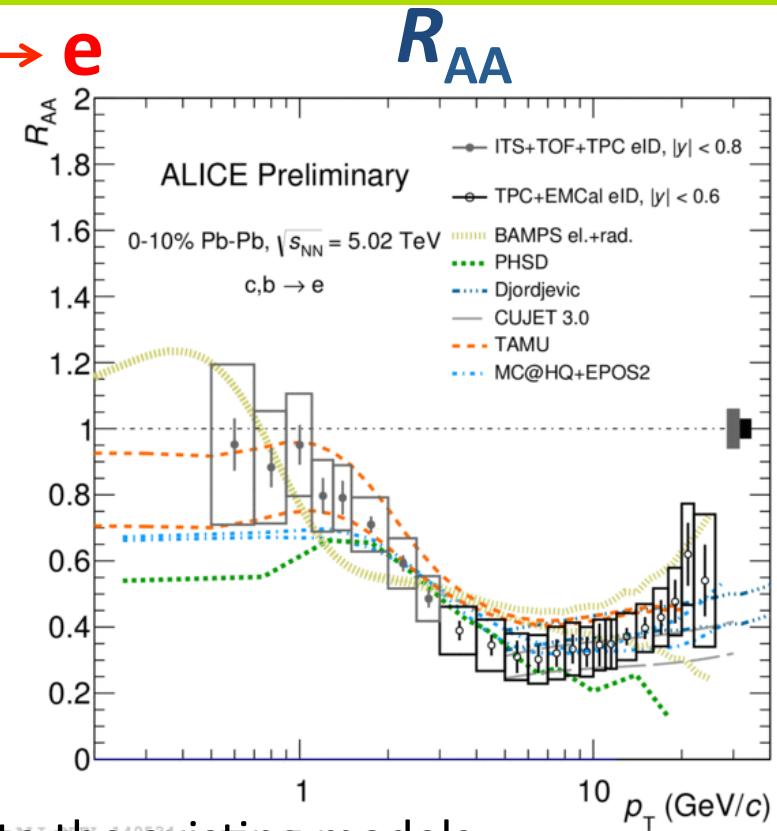


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Simultaneous description of v_2 and R_{AA}



POWLNG: *Eur. Phys. J. C75 no. 3, (2015) 121*



- R_{AA} and v_2 results provide constraints to the existing models
- Simultaneous model description of heavy-flavour R_{AA} and v_2 is still challenging.



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Summary

In p-Pb collisions

- ✓ $R_{p\text{Pb}}$ of heavy-flavour hadron decay lepton compatible with unity and described by the models which include CNM effects

In Pb-Pb collisions

- ✓ Strong suppression observed for most central (0-10%) collisions → charm and beauty quark energy loss → final-state effect (as $R_{p\text{Pb}} \sim 1$)
- ✓ Similar R_{AA} at mid and forward rapidity as well as at different center-of-mass energies
- ✓ Similar R_{AA} observed in 0-10% Xe-Xe collisions and 10-20% Pb-Pb collisions → constraints the path-length dependent energy loss
- ✓ Hint of smaller suppression of beauty-decay electrons at $p_T < 6 \text{ GeV}/c$ → mass-dependent energy loss
- ✓ Suppression is consistent with collisional and radiative energy loss models
- ✓ Positive v_2 of heavy-flavour hadron decay leptons is measured → collective motion of heavy quarks



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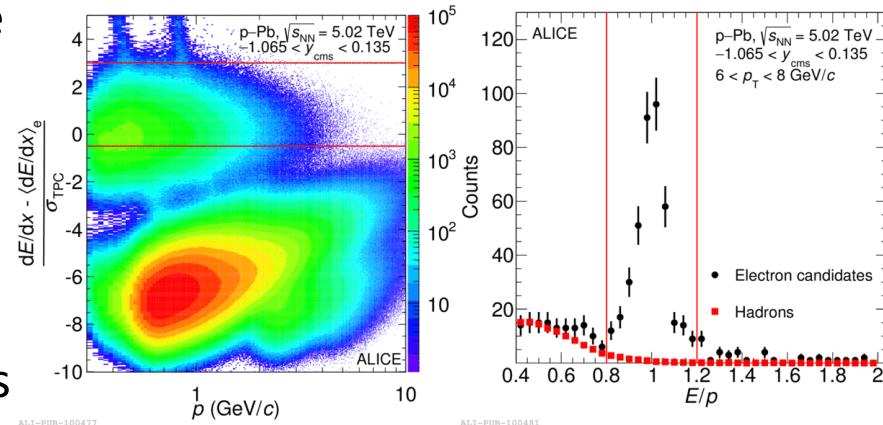
Back up



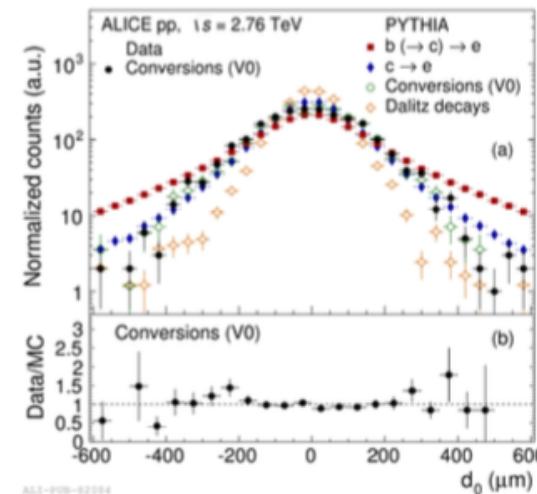
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Reconstruction of heavy-flavour hadron decay electrons

- Heavy-flavour hadron decay electrons are identified using TPC and TOF for low p_T and TPC and EMCal For high p_T
- Non heavy-flavour background (Dalitz decay from neutral mesons and photon conversion) removed using invariant mass method i.e. reconstruction of e^+e^- pairs or cocktail method
- Beauty-hadron decay electrons are separated using the impact parameter distribution
- ✓ Beauty-hadron decay electrons have broader track impact parameter distribution due to the longer life time of the beauty hadrons



PLB 754 (2016) 81-93



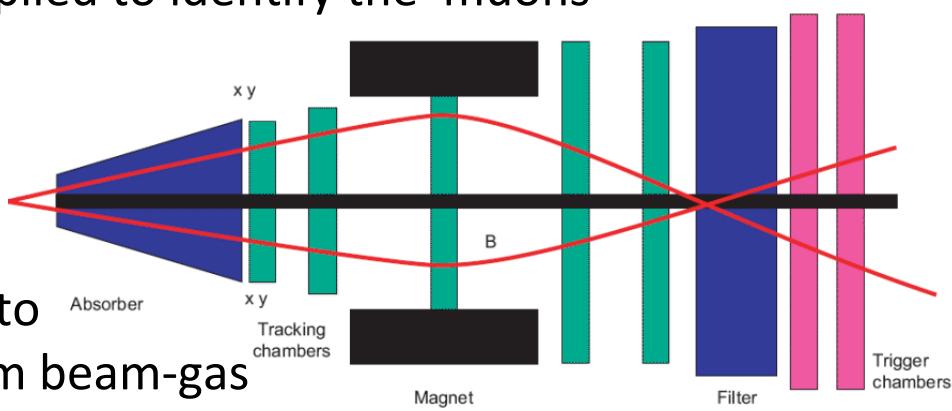
PLB 738 (2014) 97



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Reconstruction of heavy-flavour hadron decay muons

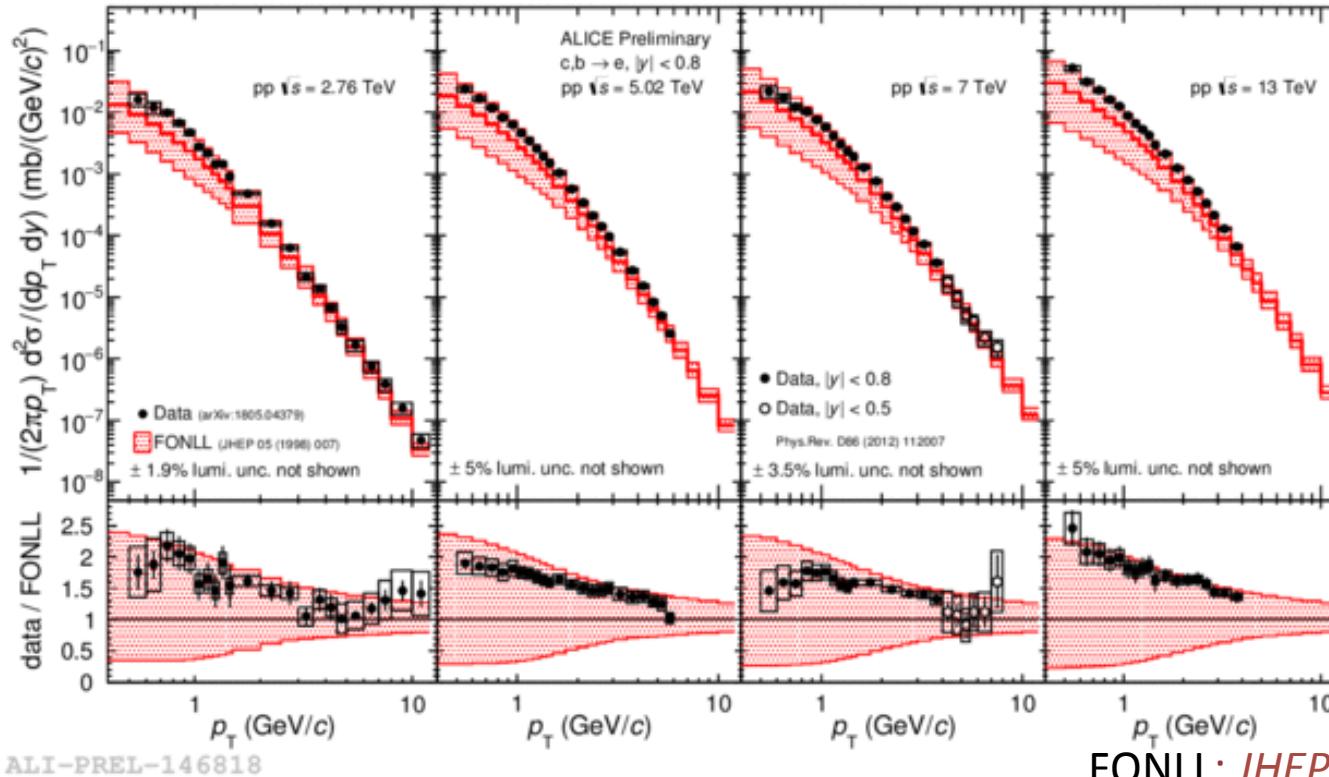
- Heavy-flavour hadron decay muons are reconstructed using forward muon spectrometer
- Acceptance and geometrical cuts are applied to identify the muons
- Track matching with trigger chambers is applied to reject hadrons
- Cut on the distance of closest approach to the primary vertex to remove tracks from beam-gas interactions
- Background (mainly coming from primary K and π decays) is estimated via data-tuned MC cocktail in pp, p-Pb, Xe-Xe and Pb-Pb collisions
- High p_T background from W decays are estimated using MC simulations





Heavy-flavour hadron decay electron production cross section

2.76 TeV 5.02 TeV 7 TeV 13 TeV



ALI-PREL-146818

FONLL: *JHEP 1210(2012)37*

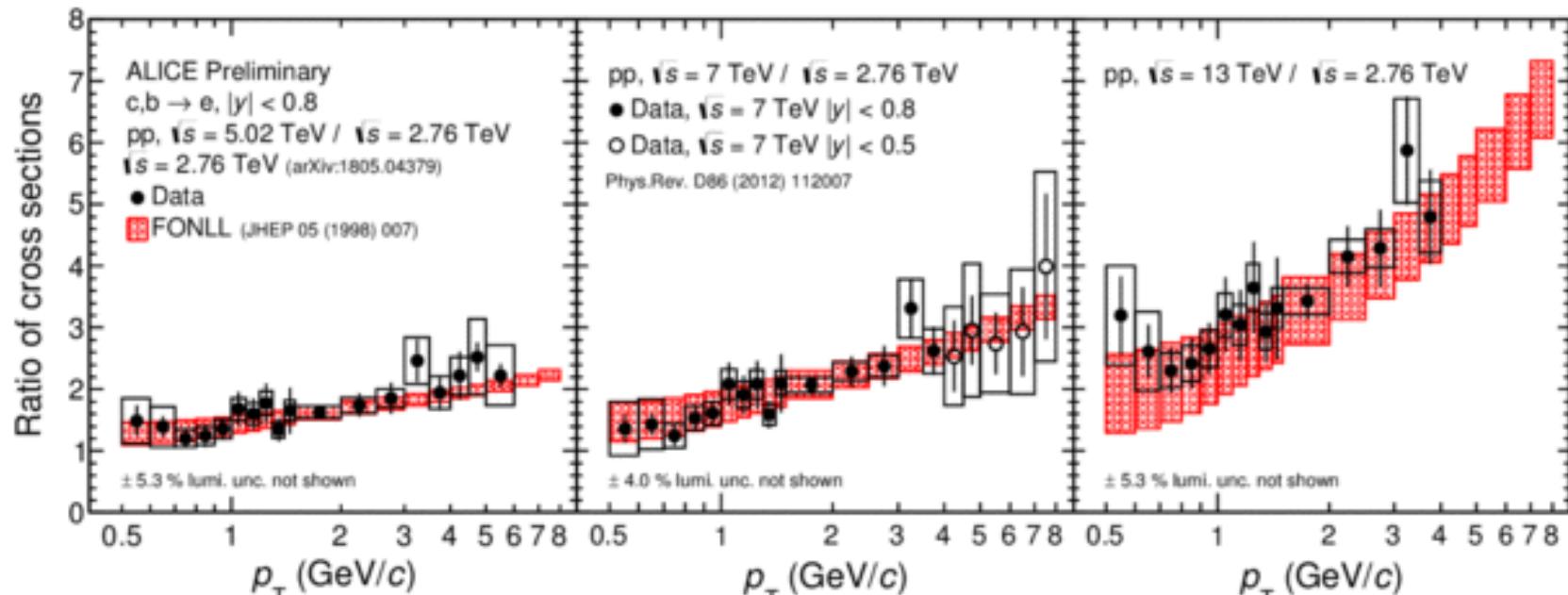
- Precise measurements of p_T -differential cross sections of heavy-flavour decay electrons at various energies ($\sqrt{s} = 2.76, 5.02, 7$ and 13 TeV)
- All measurements are compatible with the pQCD calculations within uncertainties



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pp collisions: ratio of cross section

5.02 TeV/2.76 TeV 7 TeV/2.76 TeV 13 TeV/2.76 TeV



ALI-PREL-146830

- Testing the center-of-mass energy dependence
- Some systematic uncertainties are cancelled out ➔ further testing of pQCD FONLL calculation



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Models

Kang et al., incoherent multiple scattering: Phys. Lett. B 740, 23 (2015)

Both initial-state and final-state interaction

Sharma et al., coherent multiple scattering: Phys. Rev. C 80, 054902 (2009)

Energy loss in cold nuclear matter and shadowing

FNOLL + EPOS09NLO: JHEP 9805, 007 (1998) + JHEP 0904, 065 (2009)

Initial state-effects (nuclear shadowing)

Blast-wave calculation: Phys. Lett. B 731, 51 (2014)

Hydrodynamic expansion

MC@sHQ+EPOS2: PR C89 (2014) 014905

Coll+Rad Eloss, recombination, EPOS-expansion

PHSD: PR C92 (2015) 1, 014910, PR C93 (2016) 3, 034906

Parton-Hadron-String Dynamics transport, coalescence

Xu, Cao, Bass: PR C88 (2013) 044907

Langevin with Coll+Rad Eloss, recombination+hydro

SCETM,G NLO: arXiv: 1610.02043

Soft Collinear Effective Theory, Bjorken expansion

Djorkevic: PR C92 (2015) 024918

Coll+Rad Eloss, recombination, finite-size hydro

POWLANG HTL: EPJ C71 (2011) 1666; JP G38 (2011) 124144

Langevin transport, Coll Eloss, recombination, hydrodynamics

AdS/CFT: JHEP 1411 (2014) 017; PR D91 (2015) 8, 085019;

AdS/CFT correspondence, Langevin Eloss + fluctuations, hydro

BAMPS: JP G 38 (2011) 124152; PL B 717 (2012) 430

Boltzmann transport, Coll. Eloss, expansion

TAMU: PL B735 (2014) 445-450

Transport, Coll. Eloss, resonant scatt. and coalescence+hydro



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Models

<u>TRANSPORT MODELS</u>	<u>Collisional Energy loss</u>	<u>Radiative Energy loss</u>	<u>Coalescence</u>	<u>Hydro</u>	<u>nPDF</u>
BAMPS + rad. J. Phys. G42 (2015) 115106	✓	✓	✗	✓	✗
LBT arXiv:1703.00822	✓	✓	✓	✓	✓
PHSD PRC 93 (2016) 034906	✓	✓	✓	✓	✓
POWLANG EPJC 75 (2015) 121	✓	✗	✓	✓	✓
TAMU Phys. Lett. B735 (2014) 445	✓	✗	✓	✓	✓
MC@sHQ+EPOS PRC 89 (2014) 014905	✓	✓	✓	✓	✓
<u>pQCD Eloss MODELS</u>	<u>Collisional Energy loss</u>	<u>Radiative Energy loss</u>	<u>Coalescence</u>	<u>Hydro</u>	<u>nPDF</u>
CUJET3.0 JHEP 02 (2016) 169	✓	✓	✗	✗	✗
Djordevic PRC 92 (2015) 024918	✓	✓	✗	✗	✓
SCET JHEP 03 (2017) 146	✓	✓	✗	✗	✓