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

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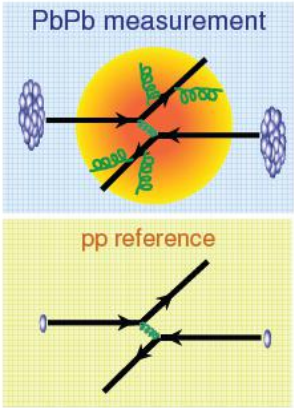
Outline

- ❑ Physics motivations
- ❑ Open heavy-flavour reconstruction in ALICE
- ❑ Open heavy-flavour nuclear modification factor
- ❑ Open heavy-flavour elliptic flow
- ❑ Model comparisons
- ❑ Conclusion and outlook

Hard Probes 2018,
1-5 October 2018, Aix-Les-Bains, France

Physics motivations

Charm and beauty quarks: sensitive probes of the medium properties



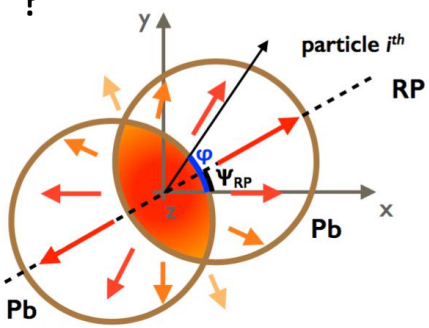
Open heavy flavours in nucleus-nucleus (AA) collisions

- In-medium parton energy loss:
  gluon radiation and elastic collisions
  - path length and medium density
  - color charge (Casimir factor)
  - quark mass (dead cone effect)

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

Is this reflected in: $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$?

- Heavy-quark participation in the collective expansion



Observables sensitive to the medium effects

✓ The nuclear modification factor, R_{AA}

$$R_{AA}(p_T) = \frac{1}{<T_{AA}>} \times \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T} = \frac{QCD\ \text{Medium}}{QCD\ \text{Vacuum}}$$

✓ If no nuclear effects: $R_{AA} = 1$

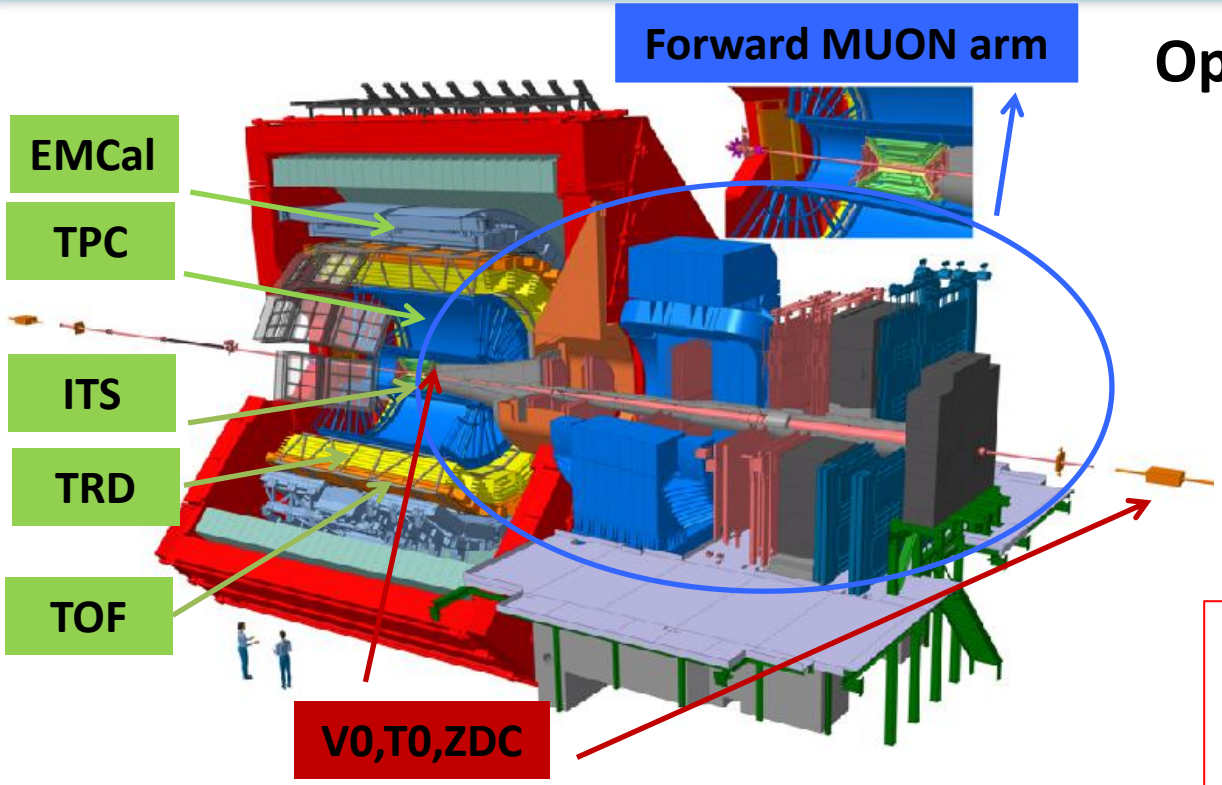
✓ Effects of the hot and dense medium produced in the collision breakup binary scaling: $R_{AA} \neq 1$

✓ Elliptic flow, v_2

$$v_2 = <\cos[2(\varphi - \psi_{RP})]>$$

✓ Second coefficient of the Fourier expansion of the azimuthal (φ) distribution w.r.t. to reaction plane angle (Ψ_{RP})

Open heavy-flavour reconstruction in ALICE



Open heavy flavours

Charmed hadrons (|y| < 0.5)

- $D^0 \rightarrow K^-\pi^+$
- $D^* \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$
- $D^+ \rightarrow K^-\pi^+\pi^+$

non-strange D mesons

- $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$
- $\Lambda_c^+ \rightarrow pK_s^0 \rightarrow p\pi^+\pi^-$

"Focus of this talk"

leptons

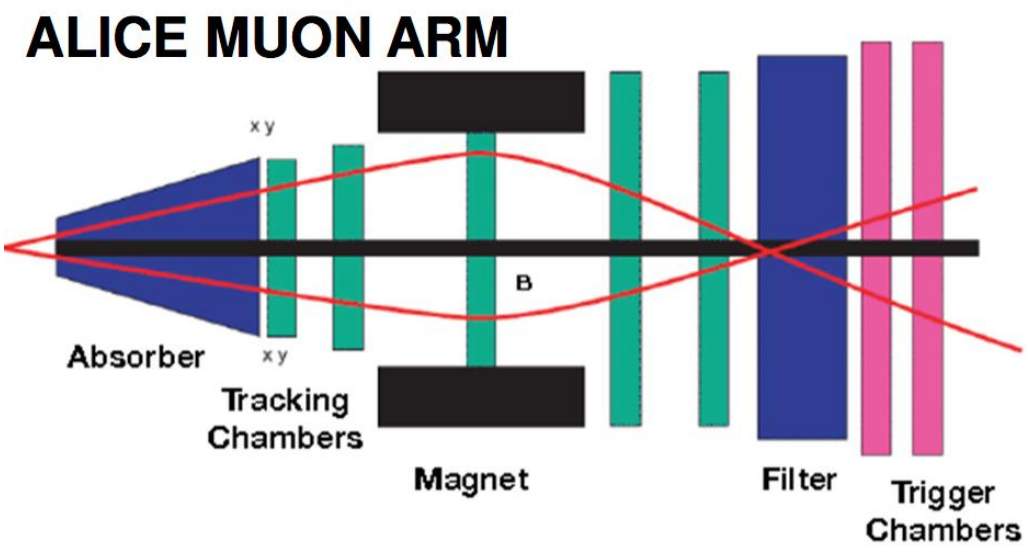
- **c,b → μX (2.5 < *y* < 4)**
- **c,b → eX (|*y*| < 0.8)**

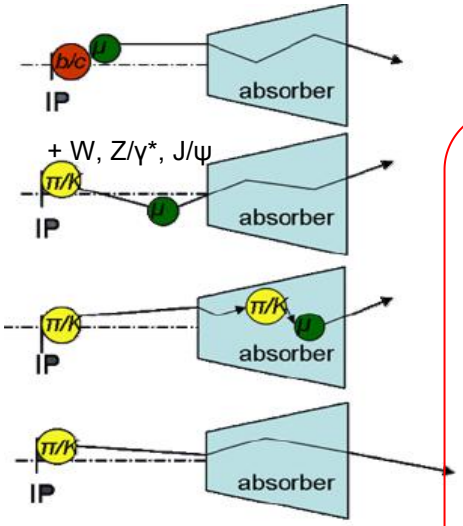
Forward MUON arm ($-4 < \eta < -2.5$)
- Muon trigger, tracking

Mid-rapidity ($|\eta|<0.9$)
- ITS, TPC, TOF, TRD: vertexing, tracking, PID
- EMCal: high-p_T electron trigger, PID

Forward detectors: V0, T0, ZDC
- Event trigger, centrality and event plane determination

Muons from heavy-flavour hadron decays





μ from heavy flavours

μ from primary π, K, W,Z/γ*, J/ψ

μ from secondary π, K

punch through hadrons

background ⇔

Muon track selection

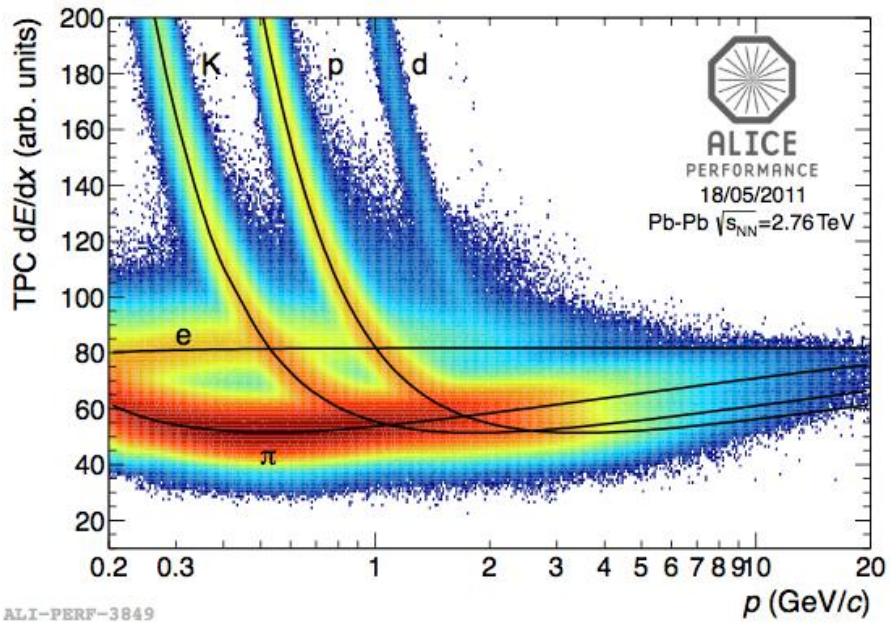
- **Acceptance & geometrical cuts**
  select tracks in the spectrometer acceptance
- **p_T cut at 3 GeV/*c***
  reject μ from secondary π, K
- **Muon tracking-trigger matching**
  reject hadrons crossing the front absorber
- **p × DCA (Dist. of Closest Approach) in 6σ**
  reject beam-gas interactions & particles produced in the absorber

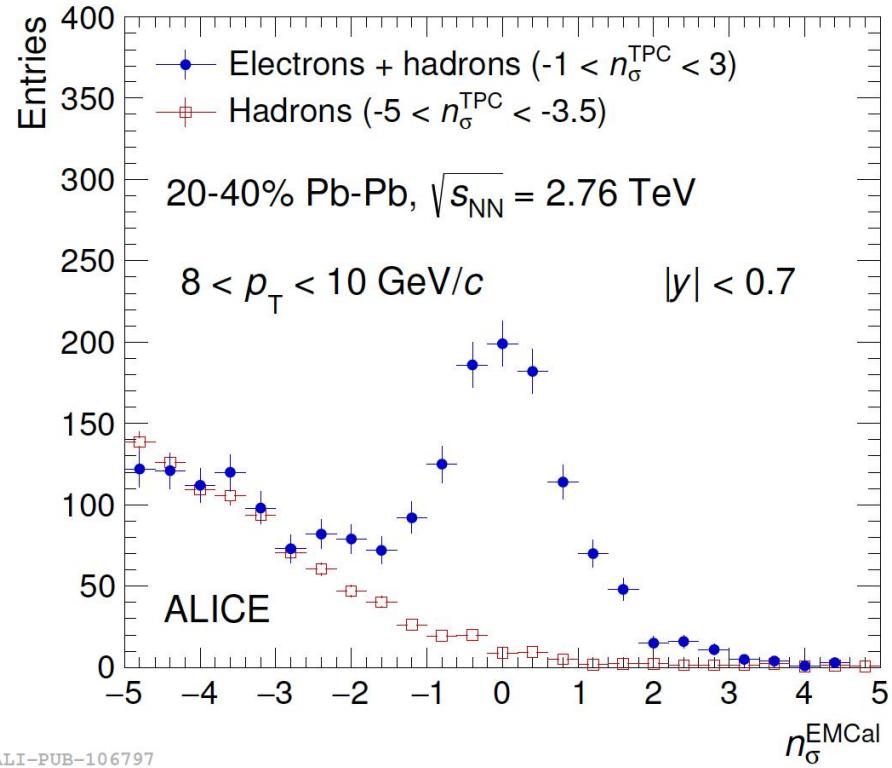
$\mu^{\pm} \leftarrow$ b, c studies

- **Background subtraction**
  μ ← **primary π, K** (main contribution at low p_T) **, J/ψ decays** (dominates at 5 GeV/*c*):
  data-tuned background cocktail
  μ ← **W, Z/γ* decays** (main contribution at high p_T):
  POWHEG simulation

Electrons from heavy-flavour hadron decays

-Low-p_T electrons: PID via TPC dE/dx complemented with TOF and ITS
-High-p_T electrons: PID using TPC, EMCal





Main background sources:

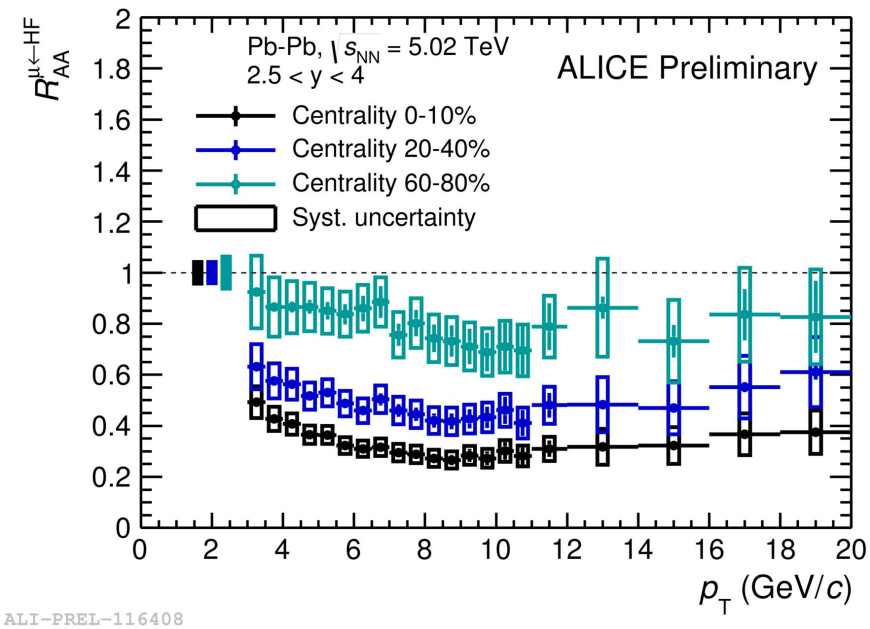
-γ conversions
-π^0 and η Dalitz decays

Background subtraction:

-Measured: photonic-electron tagging method (e^+e^- pairs)
-Calculated: data-tuned background cocktail

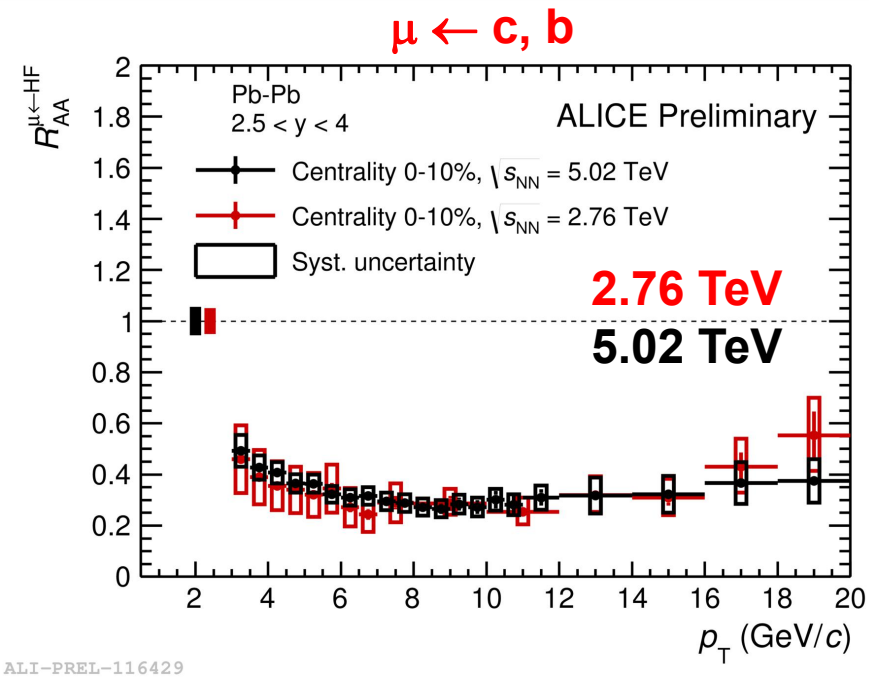
p_T-differential R_{AA} of muons ← c, b in Pb-Pb collisions

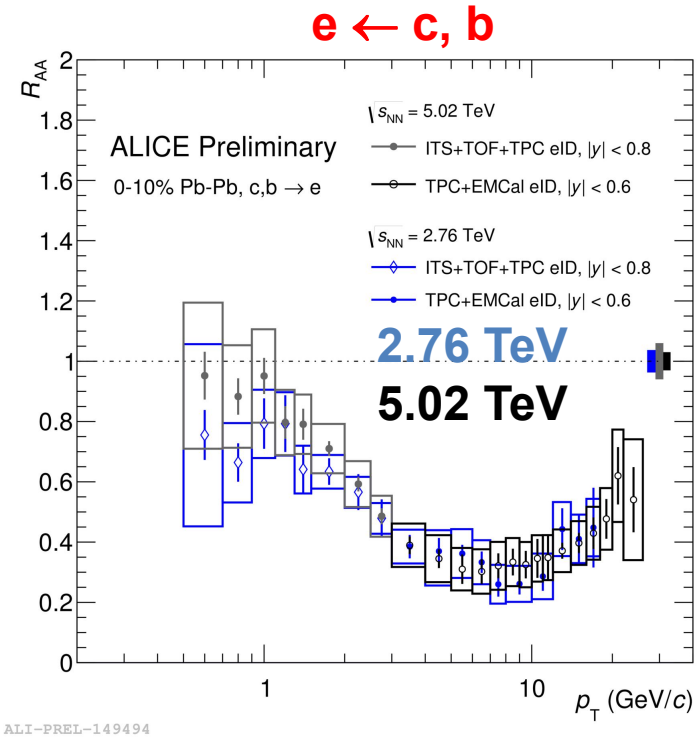
μ ← c, b



- Clear increase of the suppression for more central events: about a factor 3 at p_T~8 GeV/c in 0-10% Pb-Pb collisions
- High p_T, beauty component dominant, indication of beauty energy loss

p_T-differential R_{AA} of leptons ← c, b in Pb-Pb collisions: energy dependence

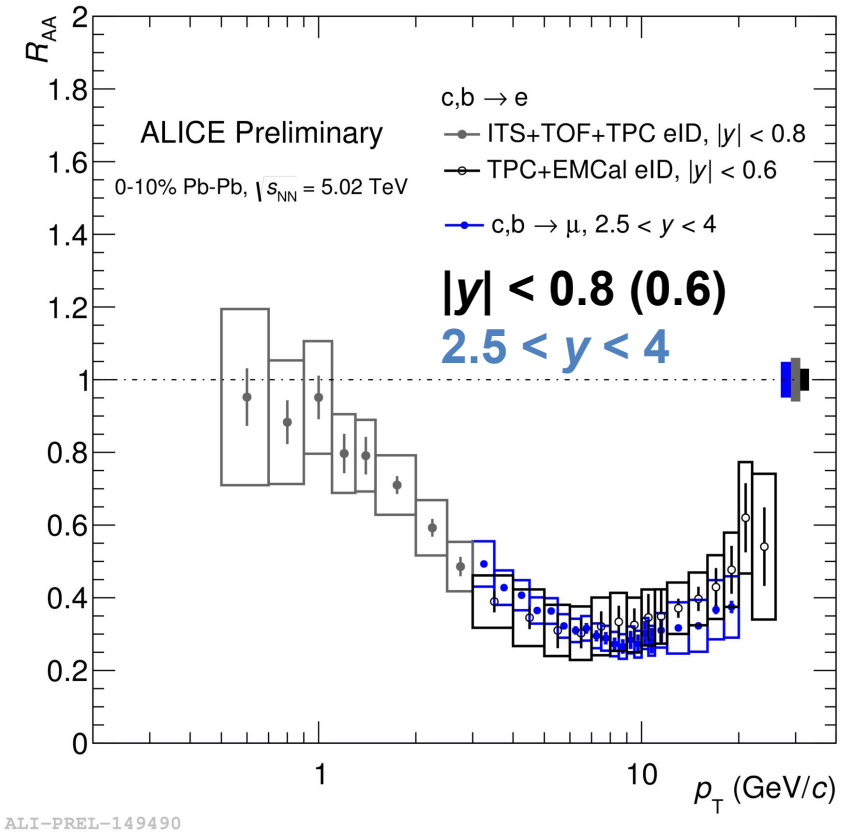




- Similar suppression at 5.02 TeV and at 2.76 TeV: described by model [1] at two energies → harder spectra and denser medium counterbalance
- e ← c, b R_{AA} measurements down to p_T = 0.5 GeV/c: low-p_T measurements crucial in all systems to test binary scaling of total cc-bar cross section and possible effect of initial-state effects like nuclear PDF (shadowing)
- Improved precision at 5.02 TeV

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

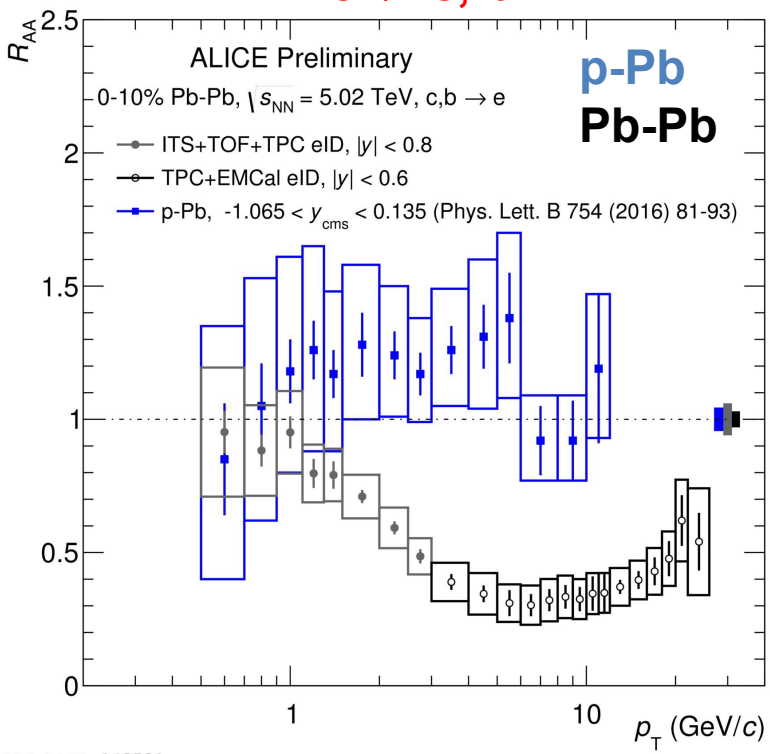
p_T-differential R_{AA} of leptons ← c, b in Pb-Pb collisions: rapidity dependence



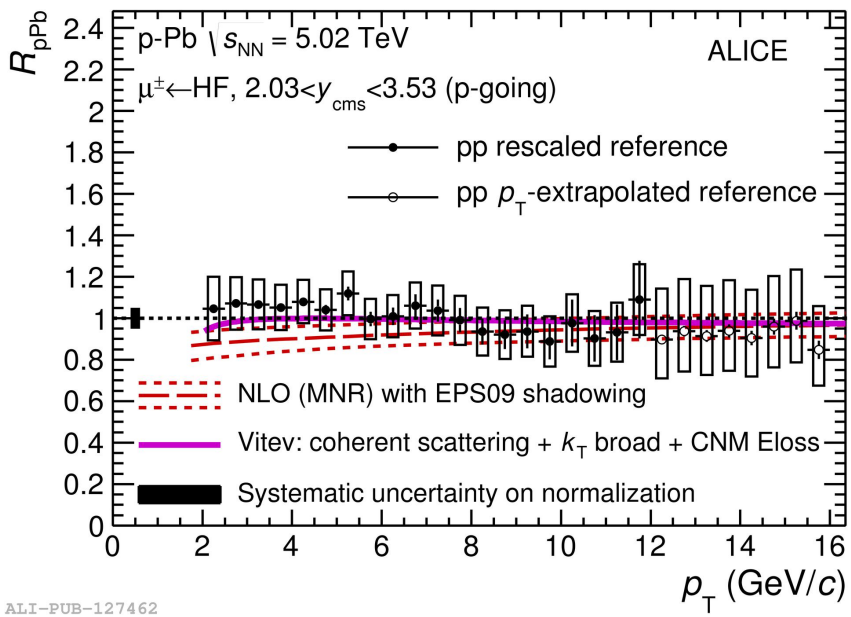
- Compatible results within uncertainties for heavy-flavour decay electrons ($|y| < 0.8$ (0.6)) and heavy-flavour decay muons ($2.5 < y < 4$) R_{AA}. Indication that heavy quarks suffer a strong in-medium energy loss in a wide rapidity interval

p_T-differential R_{AA} of leptons ← c, b in Pb-Pb and p-Pb collisions

e ← c, b



μ ← c, b

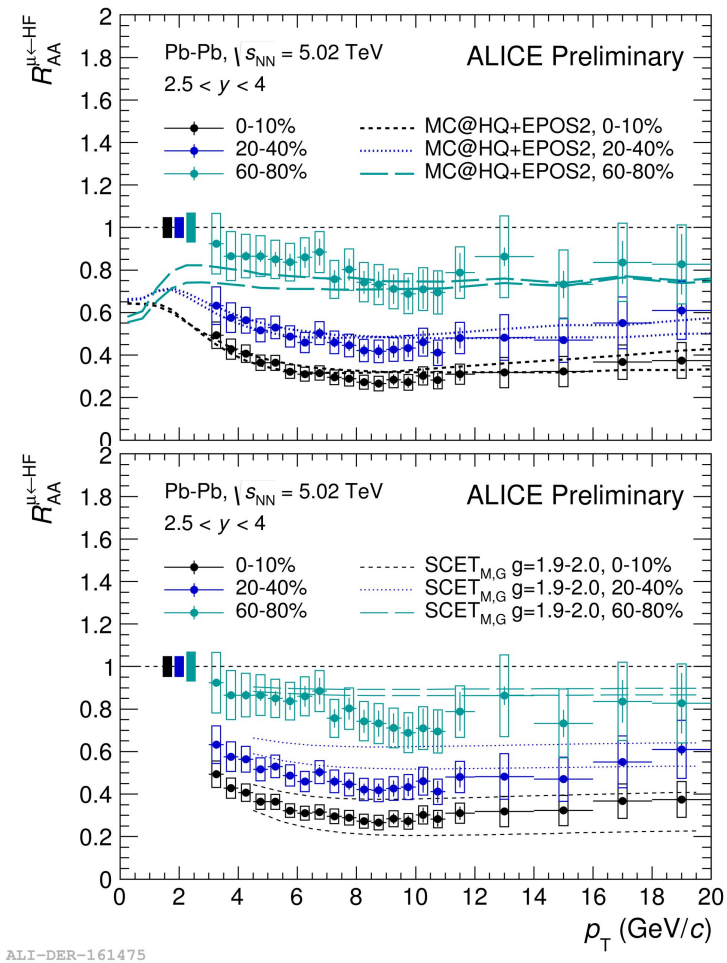


p-Pb: Phys. Lett. B 770 (2017) 459-472

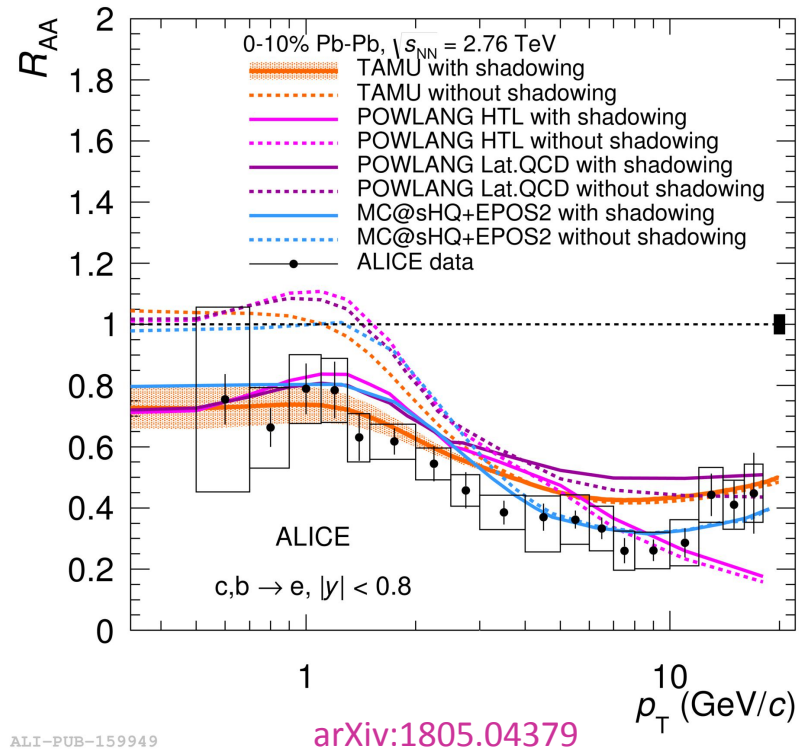
- R_{pPb} at mid- and forward rapidity: consistent with unity within uncertainties over the whole measured p_T interval
- The suppression observed at high p_T in central Pb-Pb collisions results from final-state effects related to parton energy loss

Model comparison: R_{AA} in Pb-Pb collisions (1/2)

μ ← c, b



e ← c, b



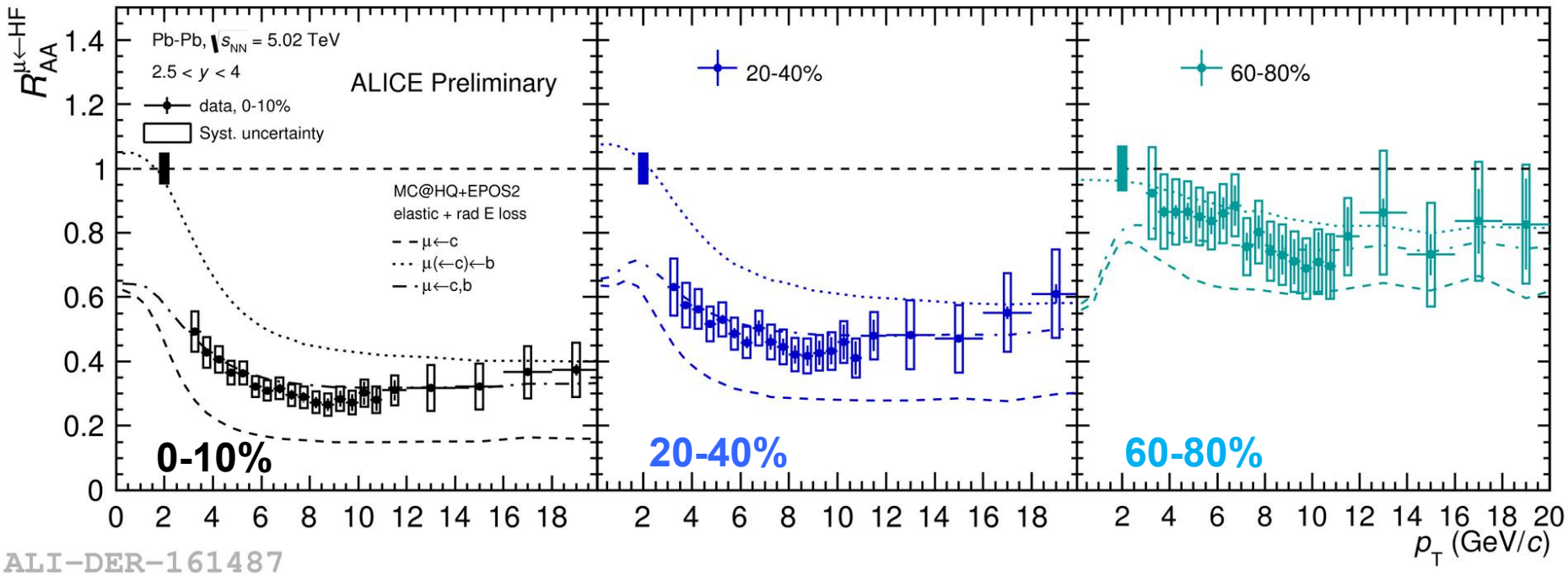
arXiv:1805.04379

MC@sHQ: Phys.Rev. C89, (2014) 014905;
SCET: Phys. Rev. C 80 (2009) 054902
POWLANG: EPJ C73 (2013) 2481;
TAMU: PLB735 (2014) 445–450;

- R_{AA} measurements at $\sqrt{s_{NN}}$ = 5.02 TeV provide new constraints on energy loss models
- Data are better described by models when nuclear PDF (EPS09) are used

Model comparison: R_{AA} in Pb-Pb collisions (2/2)

μ ← b and μ ← c predictions, separately !

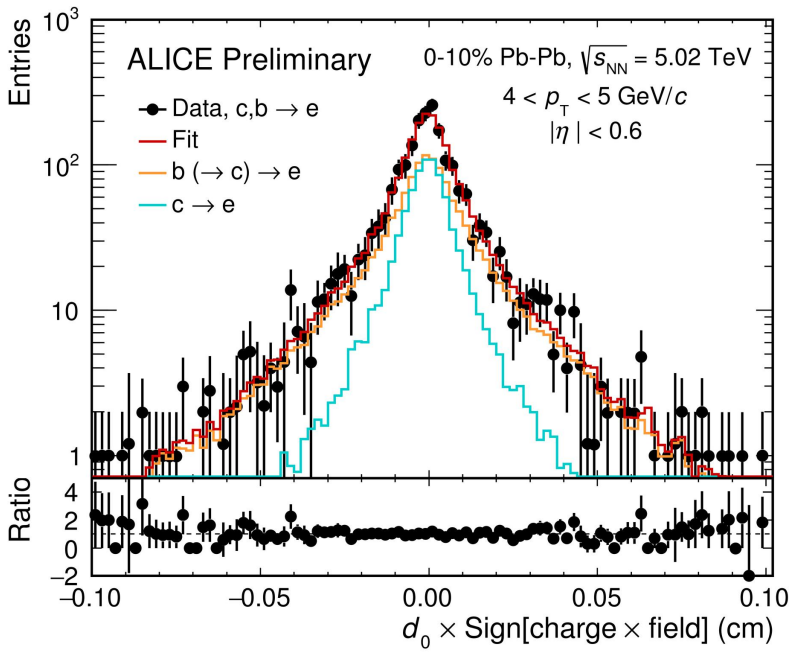


- Data at high p_T very close to μ ← b MC@sHQ+EPOS2 predictions in different centrality classes
- MC@sHQ+EPOS2, which reproduces well μ←c,b R_{AA}, expects μ←b R_{AA} > ~ 2 x μ←c R_{AA}

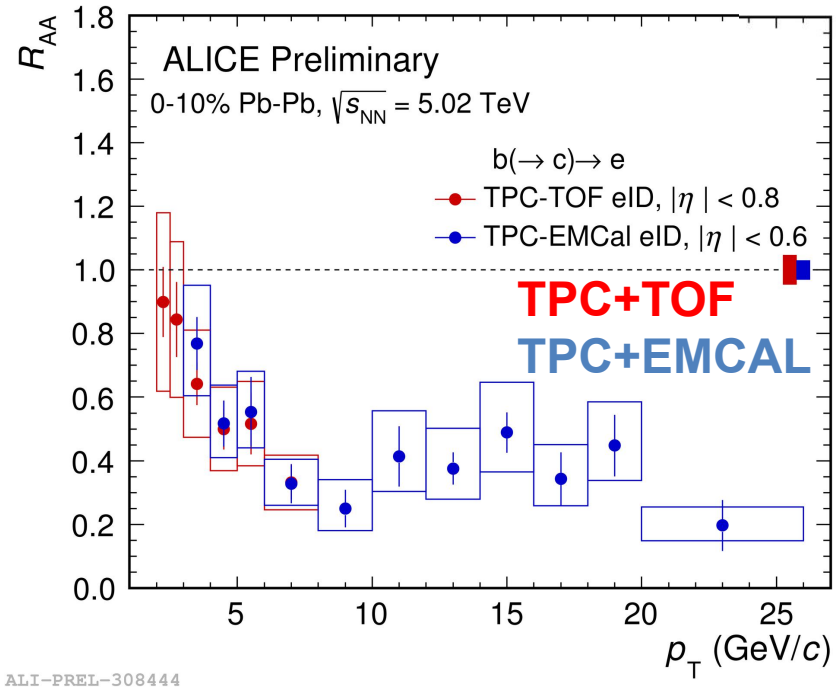
MC@sHQ: Phys.Rev. C89, (2014) 014905

R_{AA} of $e^{\pm} \leftarrow b$ in Pb-Pb collisions (1/2)

New



ALI-PREL-308464

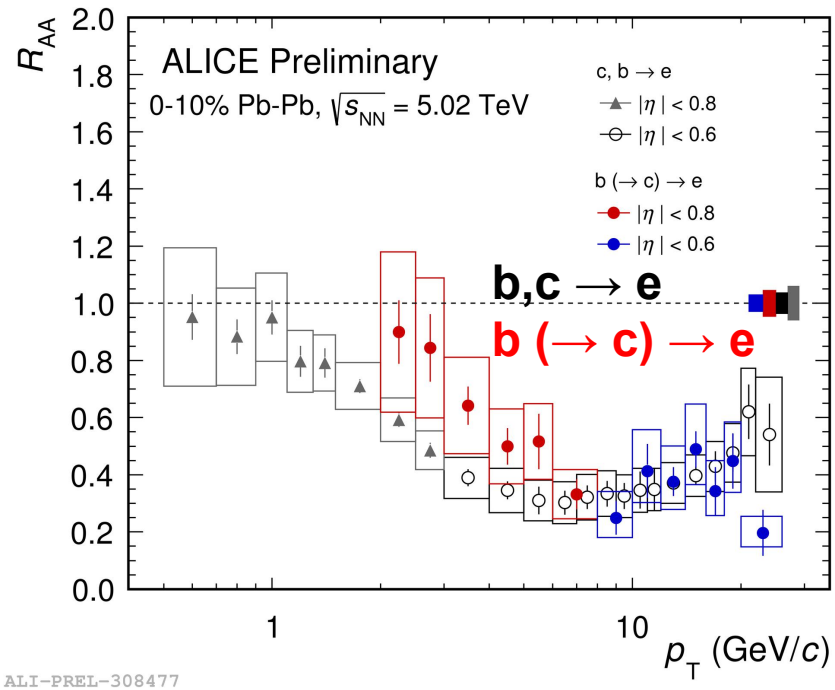


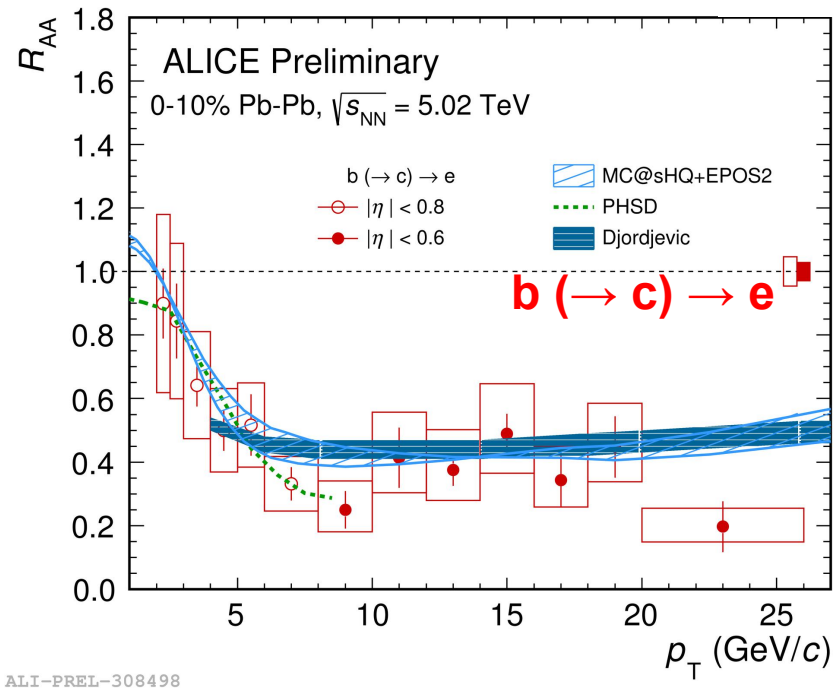
ALI-PREL-308444

- Analysis of $e^{\pm} \leftarrow b$ based on the electron impact parameter distribution. Beauty-decay electron yield measured up to 26 GeV/c using EMCAL-triggered data
- Consistent result with TPC-TOF based analysis and EMCAL-TPC based analyis in overlapping p_T interval

R_{AA} of $e^{\pm} \leftarrow b$ in Pb-Pb collisions (2/2)

New



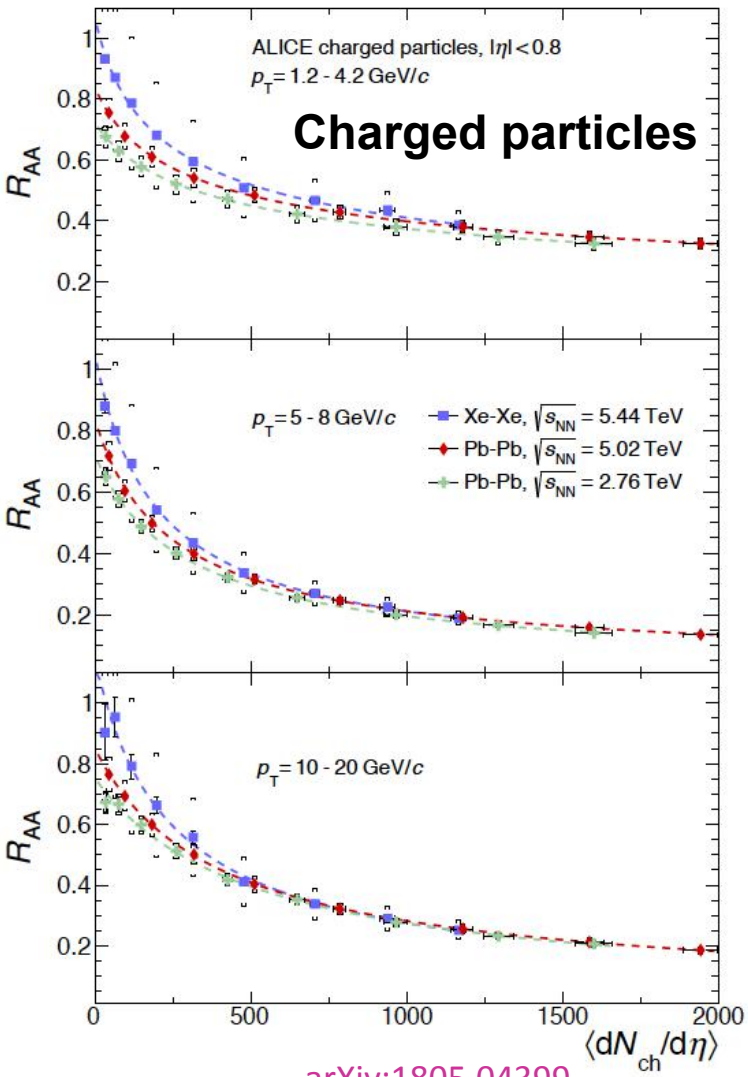


- Hint of a smaller suppression for beauty-decay electron for p_T < 6 GeV/c
- Data are reproduced by models within uncertainties, implementing mass-dependent energy loss

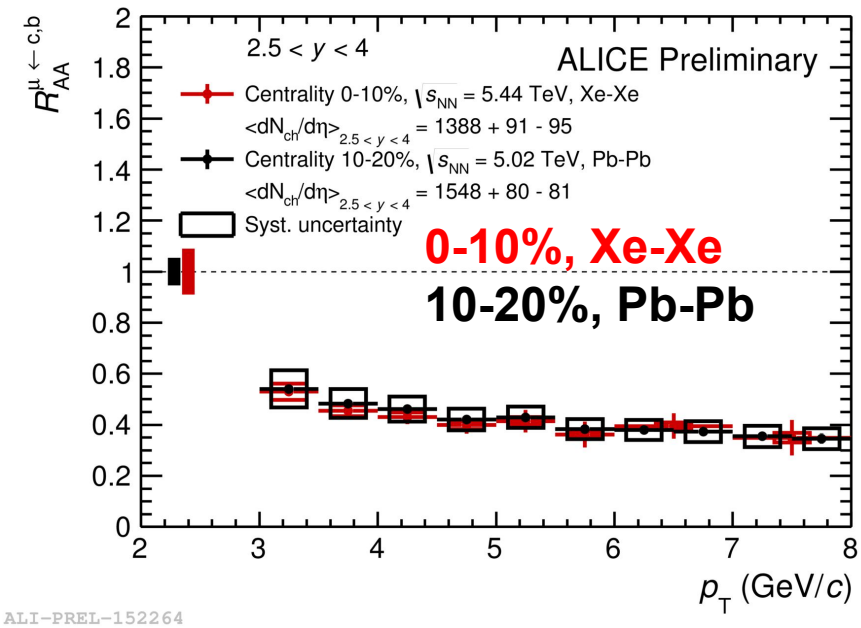
MC@sHQ: Phys.Rev. C89 no. 1, (2014) 014905
PHSD: Phys. Rev. C93 no. 3, (2016) 034906
Djordjevic: Phys. Rev. C92 (2015) 024918

p_T-differential R_{AA} of leptons ← c, b in Xe-Xe collisions: geometry and path-length dependence

Charged particles: similar R_{AA} is observed in Xe-Xe and Pb-Pb at similar <dN/dη>



arXiv:1805.04399

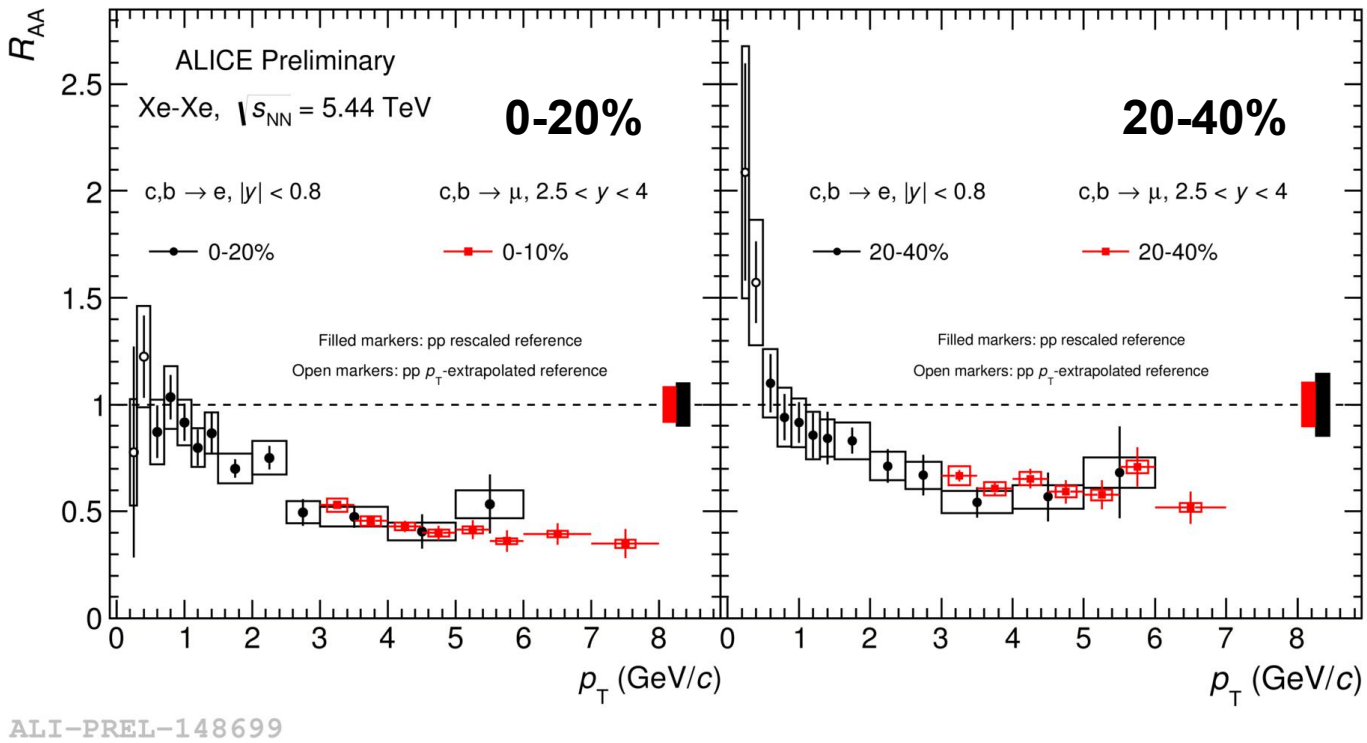


- Similar heavy-flavour hadron decay muon R_{AA} observed in 0-10% Xe-Xe and 10-20% Pb-Pb collisions at similar <dN/dη>
  - ✓ Possible interplay of geometry and path-length dependence

M. Djordjevic et al, arXiv: 1805.04030

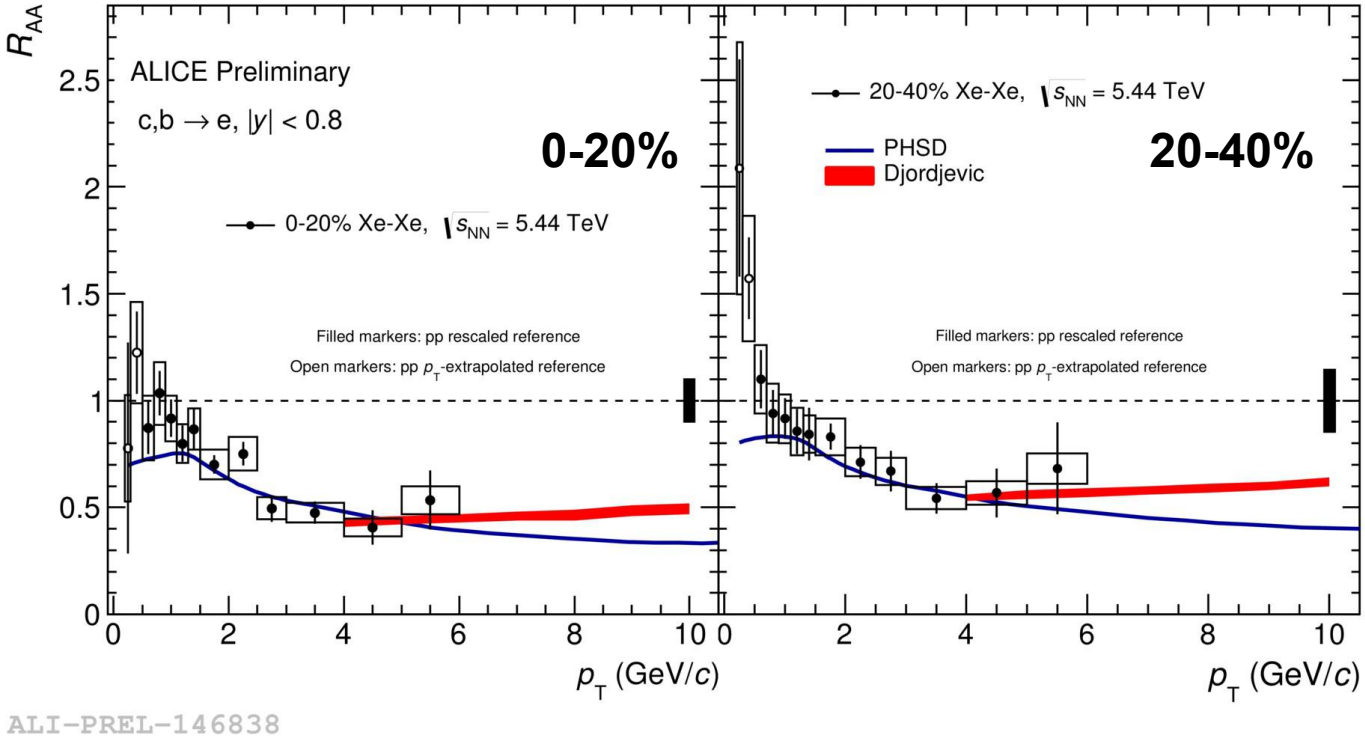
p_T-differential R_{AA} of leptons ← c, b in Xe-Xe collisions: rapidity dependence

Heavy-flavour decay electron R_{AA} measured down to p_T = 0.2 GeV/c thanks to the low B field used during the Xe-Xe data taking!



- Compatible results within uncertainties for heavy-flavour decay electrons ($|y| < 0.8$) and heavy-flavour decay muons ($2.5 < y < 4$) R_{AA} in central and semi-central collisions

Model comparison: R_{AA} in Xe-Xe collisions

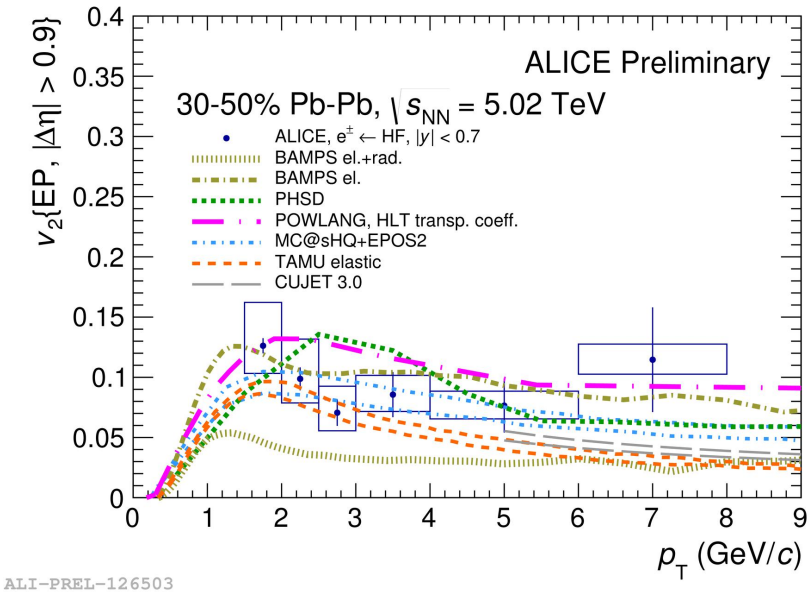


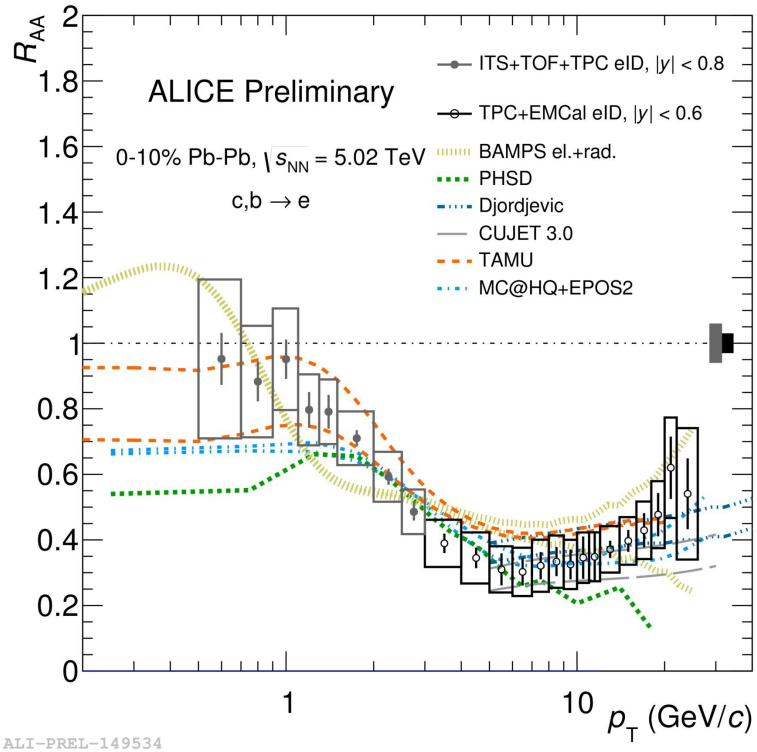
- Data are reproduced by models in Xe-Xe collisions within uncertainties

PHSD: Phys. Rev. C93 no. 3, (2016) 034906
Djordjevic: Phys. Rev. C92 (2015) 024918

v_2 of leptons ← c, b in Pb-Pb collisions

MC@sHQ: Phys.Rev. C89 no. 1, (2014) 014905
TAMU: Phys. Lett. B 735 (2014) 445
BAMPS: J. Phys. G42 no. 11, (2015) 115106
POWLANG: Eur. Phys. J. C75 no. 3, (2015) 121
PHSD: Phys. Rev. C93 no. 3, (2016) 034906
CUJET: arXiv:1207.6020 [hep-ph], (2012)





- e ← c, b measured at mid-rapidity in $|y| < 0.7$ exhibit a positive v_2, confirmation of significant interaction of heavy quarks with the medium
- Set constraints to models able to calculate both quenching (R_{AA}) and collectivity (v_2) of open heavy flavours

Conclusion

- R_{AA} of open heavy-flavour decay leptons in heavy-ion collisions
  - ✓ Strong suppression in 0-10% centrality class. The measured suppression is due to final-state effects (R_{pPb} ~ 1)
  - ✓ Similar R_{AA} at mid and forward rapidity
  - ✓ Similar heavy-flavour hadron decay muon R_{AA} observed in 0-10% Xe-Xe and 10-20% Pb-Pb collisions

- Set constraints to models able to calculate both quenching (R_{AA}) and collectivity (v_2) of open heavy flavours

More differential measurements will come soon with new data from the incoming Pb-Pb run

Other presentations/posters session !

Please have a look the presentations/posters on open heavy flavours in heavy-ion collisions !

PRESENTATION:

(1) Fabrizio Grosa, Measurement of D-meson nuclear modification factor and flow in Pb-Pb collisions with ALICE at the LHC, 11:25 - 11:45, 10/02/2018

POSTERS:

(1) Erin Frances Gauger, Nuclear modification factor of beauty-decay electrons in Pb-Pb collisions at 5.02 TeV with ALICE , 18:25 - 20:00, 10/02/2018

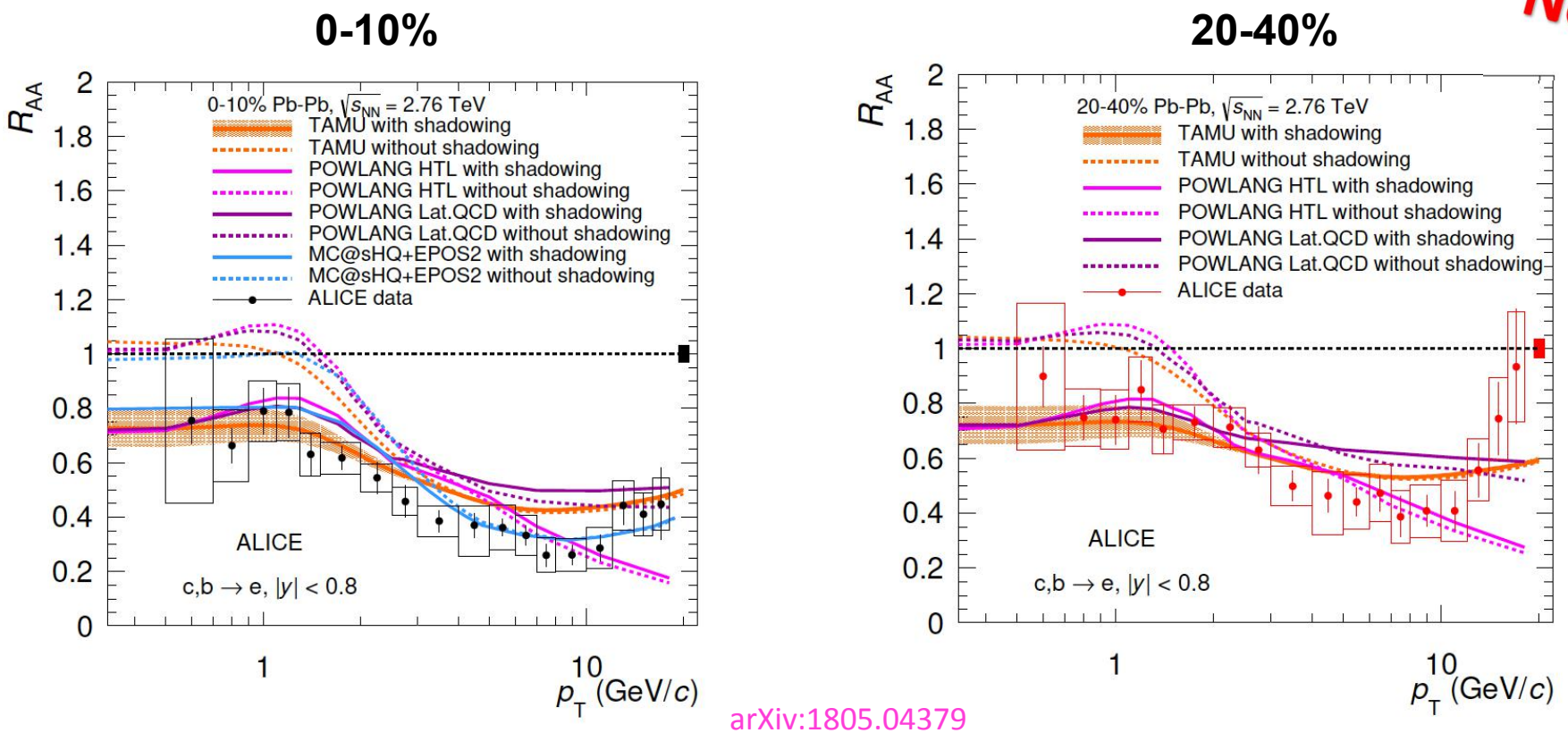
(2) Andrea Dubla, D-meson directed flow in Pb-Pb collisions with the ALICE detector, 18:25 - 20:00, 10/02/2018


Thank you for your attention

Backup

Model comparison: R_{AA} in Pb-Pb collisons (2/2)

New



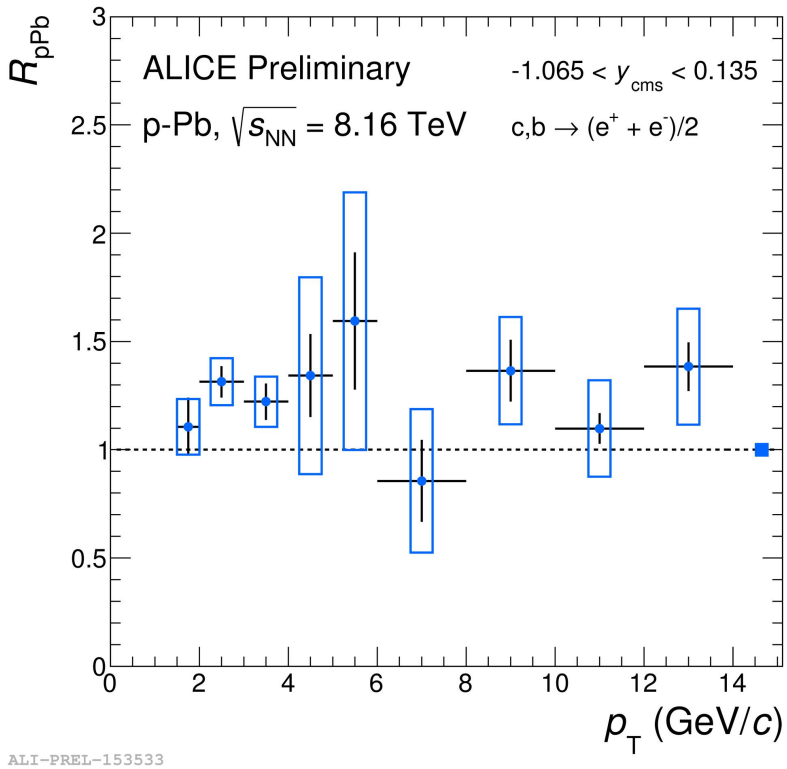
arXiv:1805.04379

- Data are better described when the nuclear PDFs (EPS09) are included in the model calculation (TAMU, POWLANG and MC@sHQ+EPOS2) in both centrality intervals
- Suppression at intermediate/high p_T is better described by models that include both radiative and collisional energy loss processes

MC@sHQ: Phys.Rev. C89 no. 1, (2014) 014905
TAMU: Phys. Lett. B 735 (2014) 445
POWLANG: Eur. Phys. J. C75 no. 3, (2015) 121

p_T-differential R_{AA} of leptons ← c, b in p-Pb collisions

e ← c, b



- R_{pPb} at mid- and forward rapidity: consistent with unity within uncertainties over the whole p_T range

R_{AA} of $e^{\pm} \leftarrow b$ in Pb-Pb collisions

Photonic background estimation ($N^{\mathrm{phot}}(p_{\mathrm{T}})$)

Main background, referred to as photonic electrons, comes from:

- $\pi^0, \eta \rightarrow \gamma e^+ e^-$ (Dalitz decays);
- $\gamma \rightarrow e^+ e^-$ (photon conversions).

- Background is estimated using invariant mass of ee pairs .
- The reconstructed amount of photonic electrons is

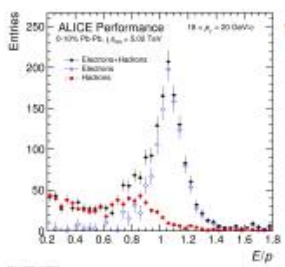
$$N^{\mathrm{phot}}_{\mathrm{reco}}(p_{\mathrm{T}}) = N^{\mathrm{ULS}}(p_{\mathrm{T}}) - N^{\mathrm{LS}}(p_{\mathrm{T}})$$

within $m_{\mathrm{ee}} \leq 140\ \mathrm{MeV}/c^2$.

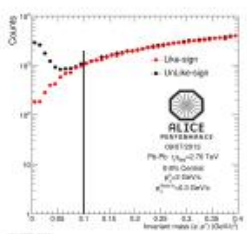
- The total photonic yield is obtained by correcting for tagging efficiency calculated using Monte-Carlo simulations:

$$\varepsilon^{\mathrm{tag}}(p_{\mathrm{T}}) = \frac{N^{\mathrm{true}}_{\mathrm{ULS}}(p_{\mathrm{T}}^{\mathrm{rec}})}{N^{\mathrm{true}}_{\mathrm{phot,incl}}(p_{\mathrm{T}}^{\mathrm{gen}})}$$

Selecting heavy-flavor electrons (high-p_{T})



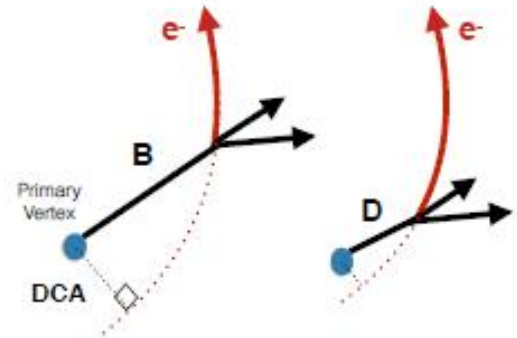
- Hadrons were subtracted from the sample using a data-driven method:
  1. Hadrons were selected with $n\sigma_{\mathrm{TPC-dE/dx}} < -4$
  2. Hadron E/p was scaled to match electron candidate E/p in the region $0.2 < E/p < 0.4$.
  3. Integrating the scaled hadron E/p in the signal region gives the hadron contamination.



- The main sources of non-heavy flavour electron background are:
  1. Dalitz decay:
     $$\pi^0 \rightarrow e^+ e^- \gamma$$
  2. Photon conversion:
     $$\gamma \rightarrow e^+ e^-$$

- These sources all have small masses, so we can use an invariant mass analysis:
  1. Flag electrons that form an unlike-sign pair with mass < 0.1 GeV/c^2
  2. Flag electrons that form a like-sign pair with mass < 0.1 GeV/c^2 (to account for combinatorial background)
  3. Subtract the DCA of the ULS-flagged electrons from the LS-flagged electrons to get the non-HFe DCA distribution

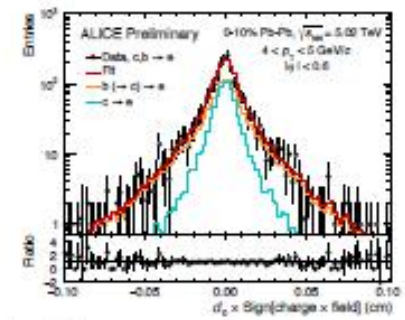
Extracting beauty electrons

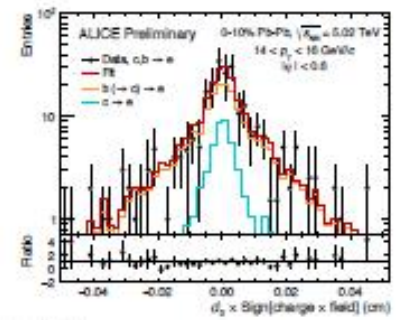


beauty hadrons $c\tau$ ~ 500 μm

charm hadrons $c\tau$ ~ 60-300 μm

- Electron sources have different lifetimes
- This makes the distributions of the distance of closest approach (DCA) of their decay electrons different



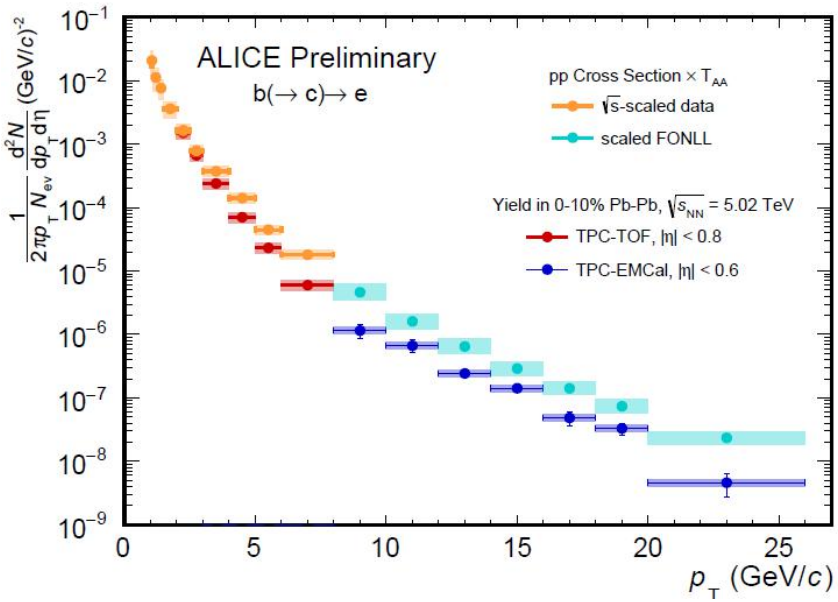


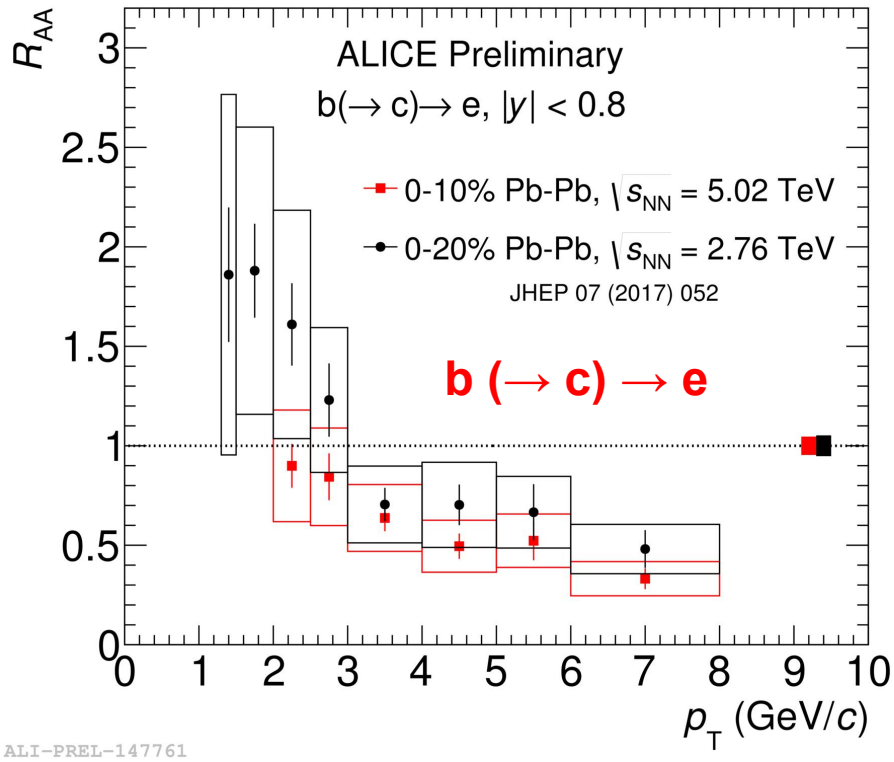
- Since their DCA shapes are different, we can use "templates" for different electron sources
  - Low-p_{T}: beauty, charm, Dalitz, and photonic conversion templates
  - High-p_{T}: beauty and charm fitted to heavy-flavor electron sample
- Templates are obtained from a Monte-Carlo simulation made by injecting PYTHIA6 pp events containing a charm or beauty quark in acceptance on a Pb-Pb event simulated with HIJING
- At high-p_{T} , fit heavy-flavor electron DCA with the following function using log-likelihood fit method

$$\mathrm{Fit} = \mathrm{a} \times \mathrm{Template}_{\mathrm{beauty}} + (\mathrm{N}_{\mathrm{HFe}} - \mathrm{a}) \times \mathrm{Template}_{\mathrm{charm}}$$

- Parameter *a* is the raw beauty yield

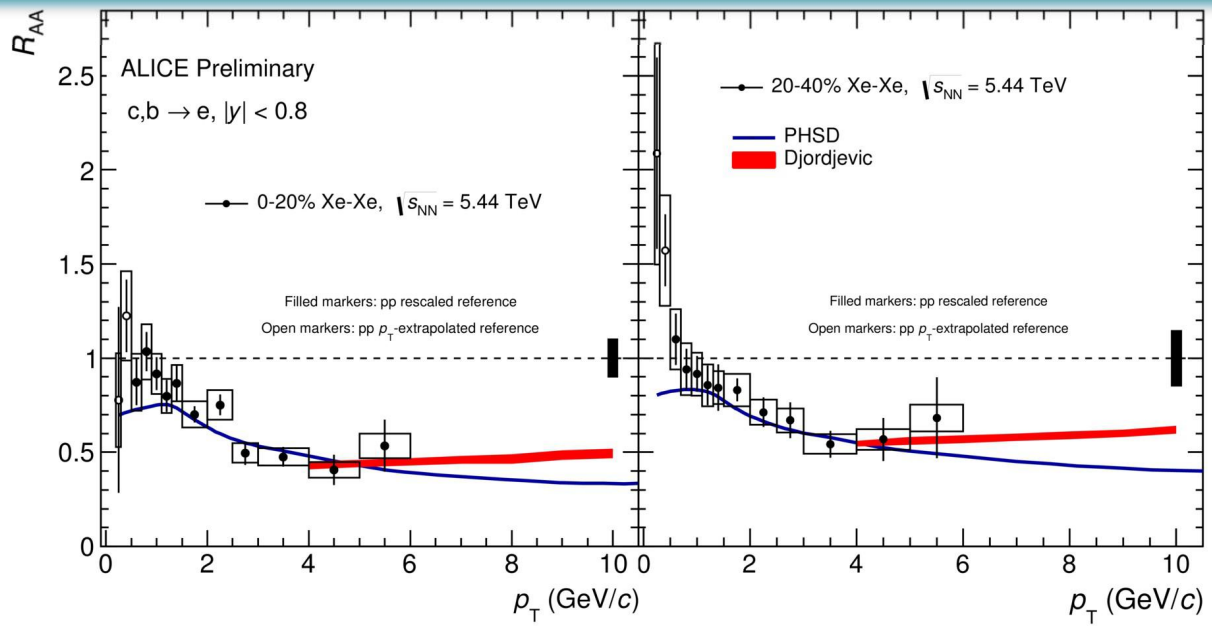
R_{AA} of $e^{\pm} \leftarrow b$ in Pb-Pb collisions

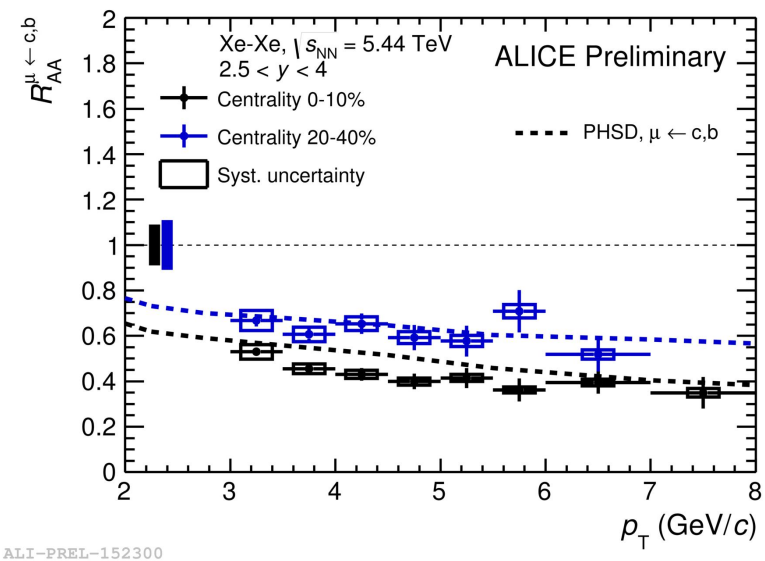




R_{AA} of leptons ← c, b in Xe-Xe collisions

New





- Data are reproduced by models in Xe-Xe collisions within uncertainties

PHSD: Phys. Rev. C93 no. 3, (2016) 034906
Djordjevic: Phys. Rev. C92 (2015) 024918

Transport and perturbative QCD (pQCD) energy loss models

Transport models	Heavy quark interactions	Hadronization	hydrodynamic	nPDF
TAMU	Collisional	Fragmentation+Recombination	√	√
PHSD	Collisional+Radiative energy loss	Fragmentation+Recombination	√	√
MC@sHQ+EPOS2	Collisional+Radiative energy loss	Fragmentation+Recombination	√	√
pQCD Eloss models	**Heavy quark interactions**	**Hadronization**	**hydrodynamic**	**nPDF**
SCET	Collisional+In-medium meson dissociation	Fragmentation	×	√