Heavy-flavour hadron decay leptons in Pb-Pb and Xe-Xe collisions at the LHC with ALICE

- Electrons at mid-rapidity, $|y| < 0.7$
- Muons at forward-rapidity, $2.5 < y < 4$

Andrea Dubla
for the ALICE Collaboration

Physics motivation

→ **Charm and beauty** quarks are produced in **hard scattering processes** in the initial stages of the collisions

→ They experience the full evolution of the system
→ sensitive probes of the properties of the Quark-Gluon Plasma

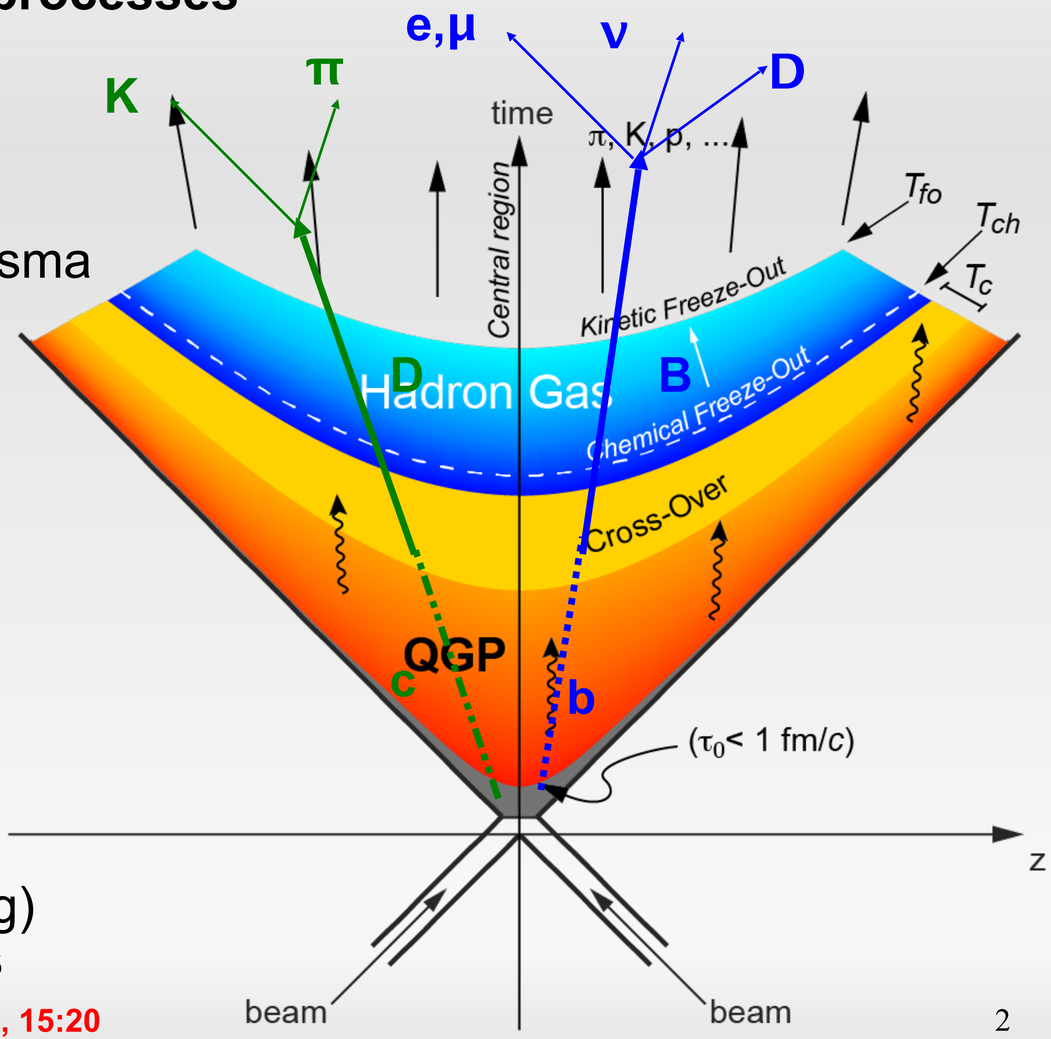
→ Expected to **lose energy** while traversing the medium

→ **Collective expansion** of the medium

→ **Hadronization**: fragmentation vs coalescence

→ **Cold Nuclear Matter effect**: modification of nPDF (shadowing)
- Need **reference measurements in pp and p-Pb collisions**

H. Zanoli: Wed 16th, 15:20

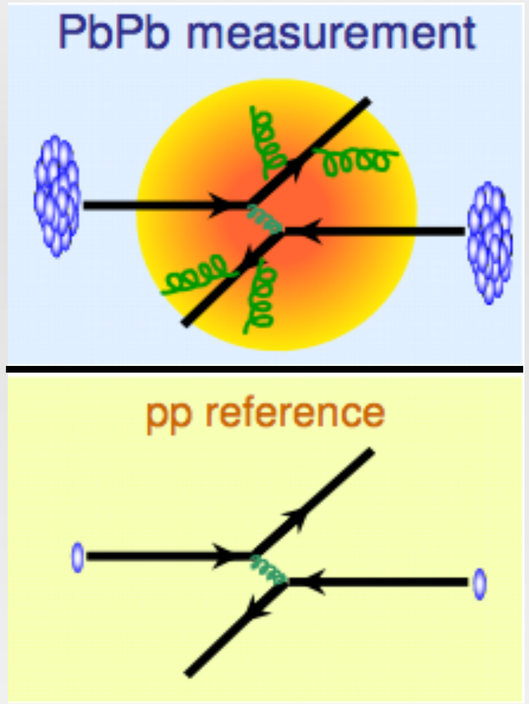


Nuclear modification factor

– Production of hard probes (heavy quarks, jets...) in AA collisions is expected to scale with the number of nucleon-nucleon collisions N_{coll} (**binary scaling**)

– **Observable**: nuclear modification factor

$$R_{AA}(p_T, y) = \frac{1}{\langle T_{AA} \rangle} \cdot \frac{d^2N_{AA}/dp_T dy}{d^2\sigma_{pp}/dp_T dy} \sim \frac{QCD\ medium}{QCD\ vacuum}$$



– If no nuclear effects are present → R_{AA} = 1

– **Cold Nuclear Matter** effects:
→ **shadowing** leads to a reduction of the heavy-flavour yield (important at **low p_T**)

– In-medium parton **energy loss** via **radiative** (gluon emission) and **collisional** processes depending on:
→ colour charge
→ quark mass (dead cone effect)
→ path length and medium density

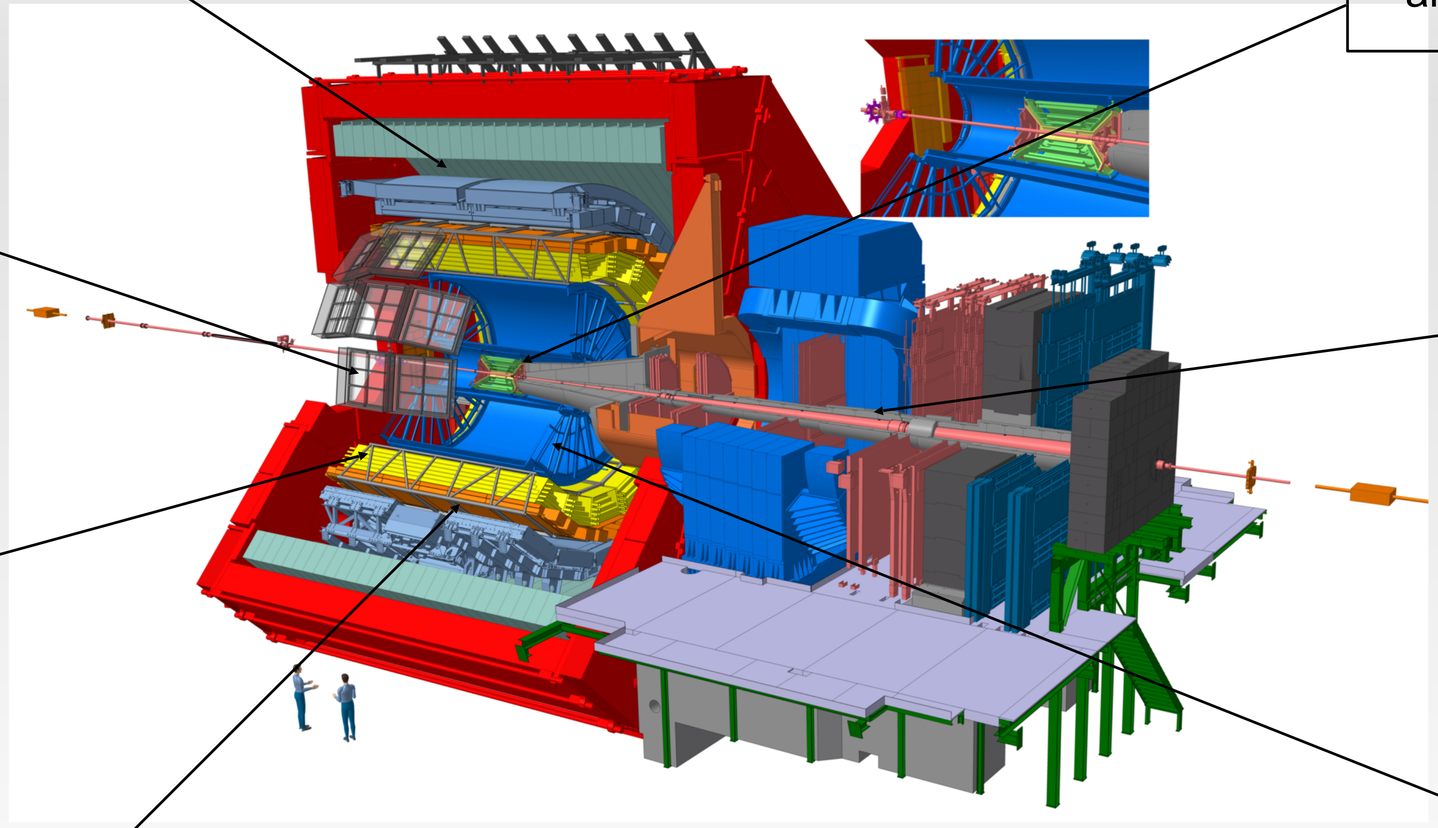
Dokshitzer and Kharzeev, PLB 519 (2001) 199
Wicks, Gyulassy, J.Phys. G35 (2008) 054001

ALICE detector

EMCal: trigger, electron ID

ITS: tracking, vertexing and PID via d*E*/d*x*

V0: trigger, centrality and event plane determination



Forward muon spectrometer

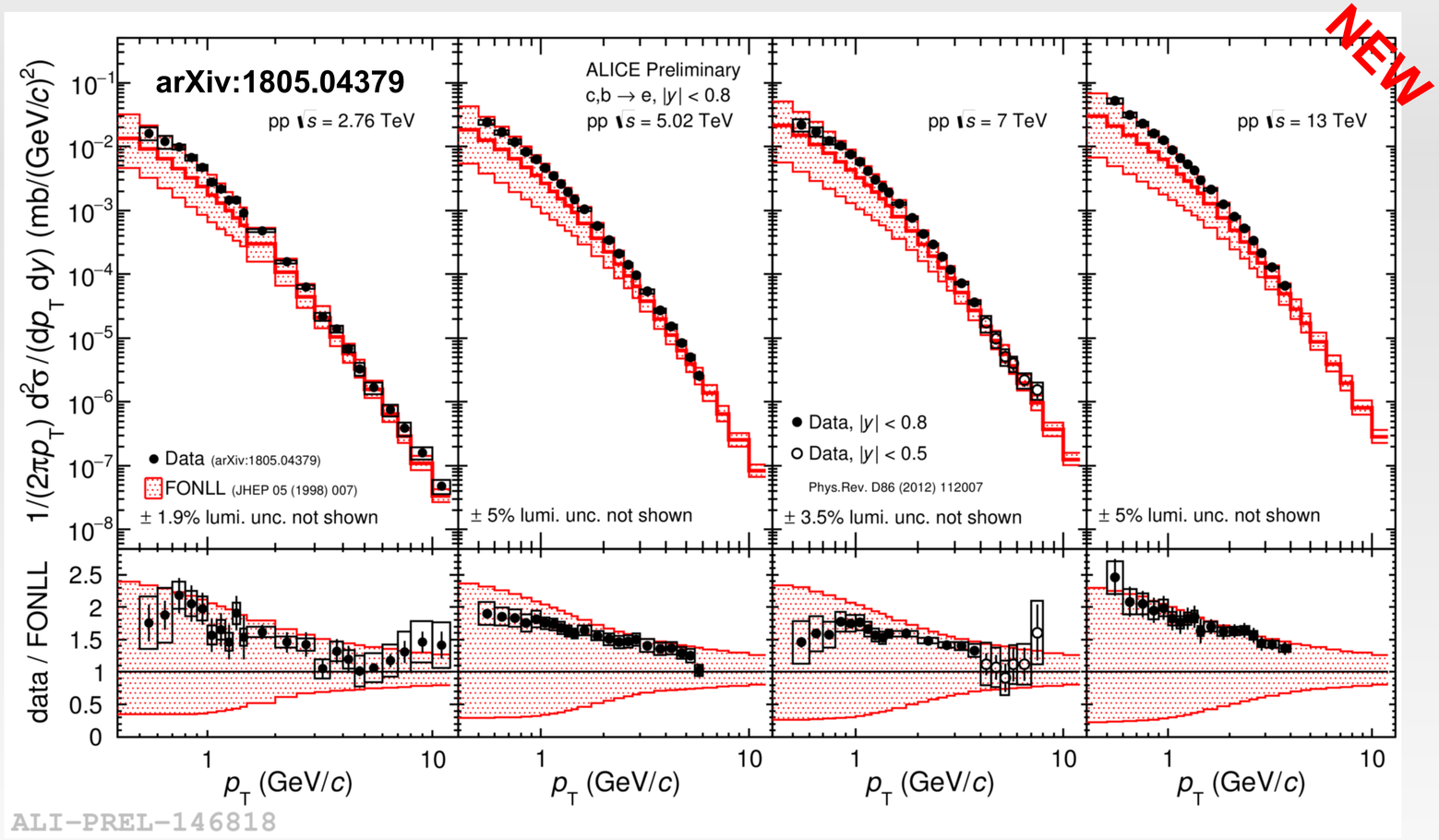
TRD: tracking, electron ID

TPC: tracking, PID via d*E*/d*x*, event

TOF: PID via time of flight

Heavy-flavour decay electrons in pp collisions

2.76 TeV → 5.02 TeV → 7 TeV → 13 TeV

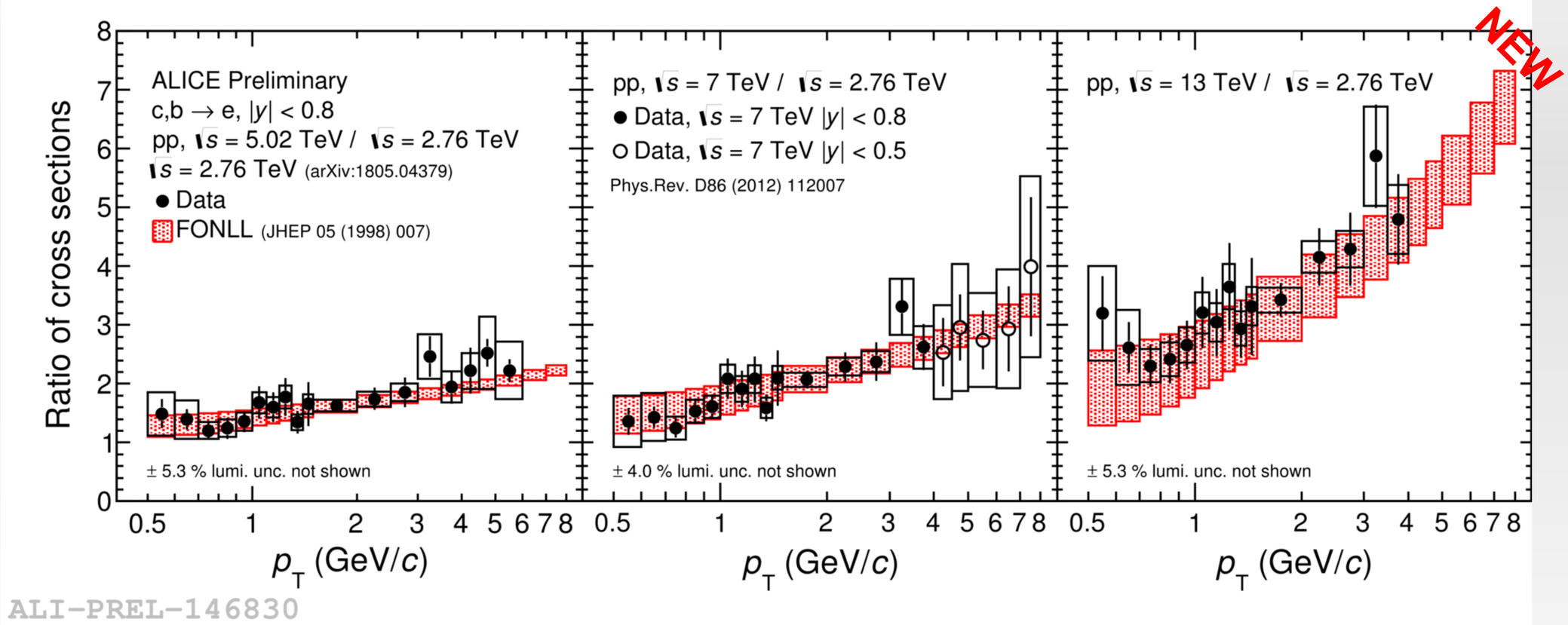


– Testing the **centre-of-mass energy dependence** down to p_T = 0.5 GeV/c

→ Large range of collision energy analysed, data consistently at the upper edge of FONLL calculation at all energies

→ Large **reduction of systematic uncertainty** in the measurements w.r.t. previous publications!

Heavy-flavour decay electrons in pp collisions

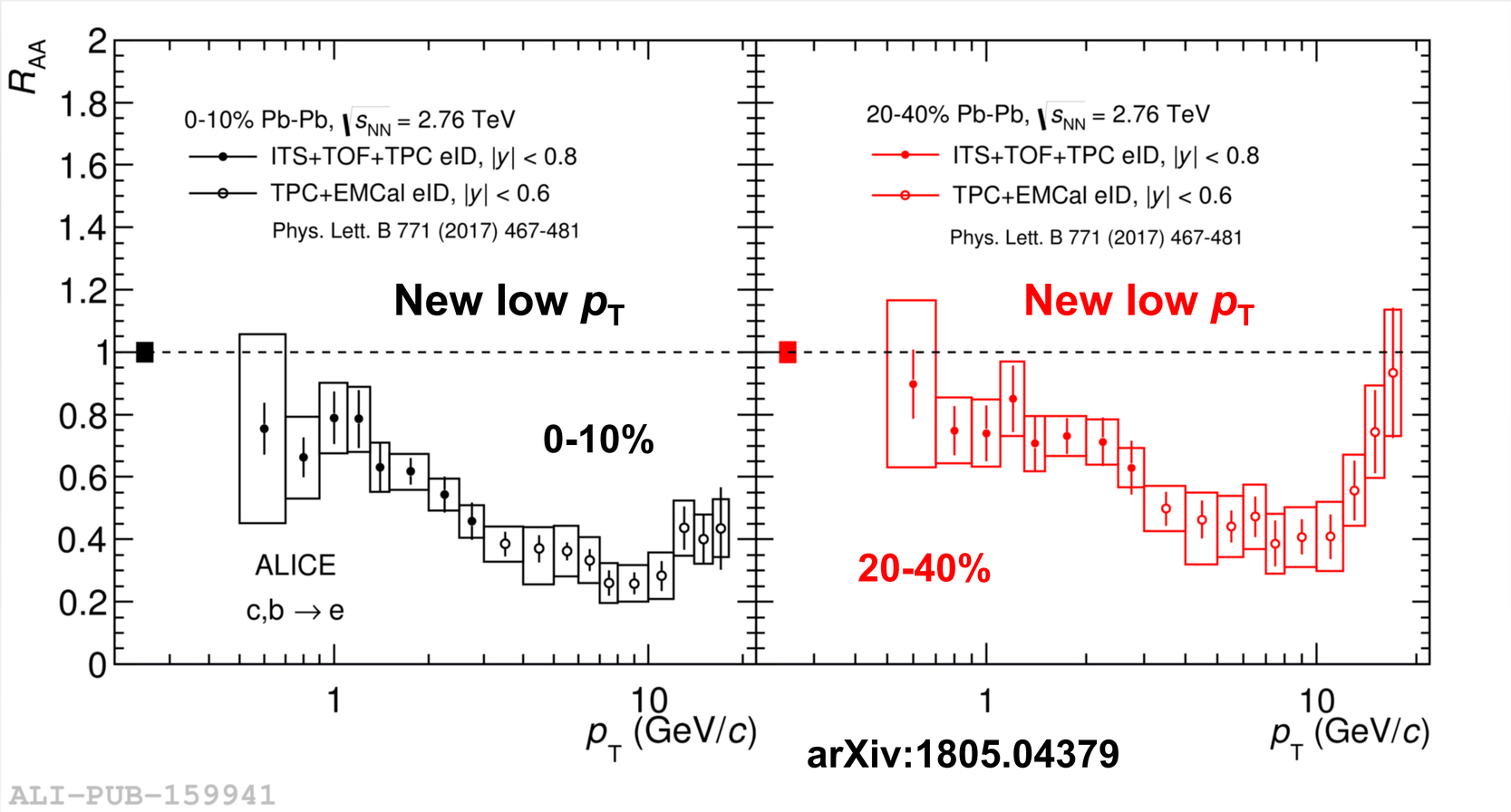


– Ratios of cross sections at different energies can be used in order to further test the pQCD FONLL calculation. In the ratios, part of the uncertainties cancel out

– at low p_T may help to set constraints to the gluon PDF → small values of Bjorken-x

Eur.Phys.J. C75 (2015) no.12, 610

Heavy-flavour hadron decay electron nuclear modification factor

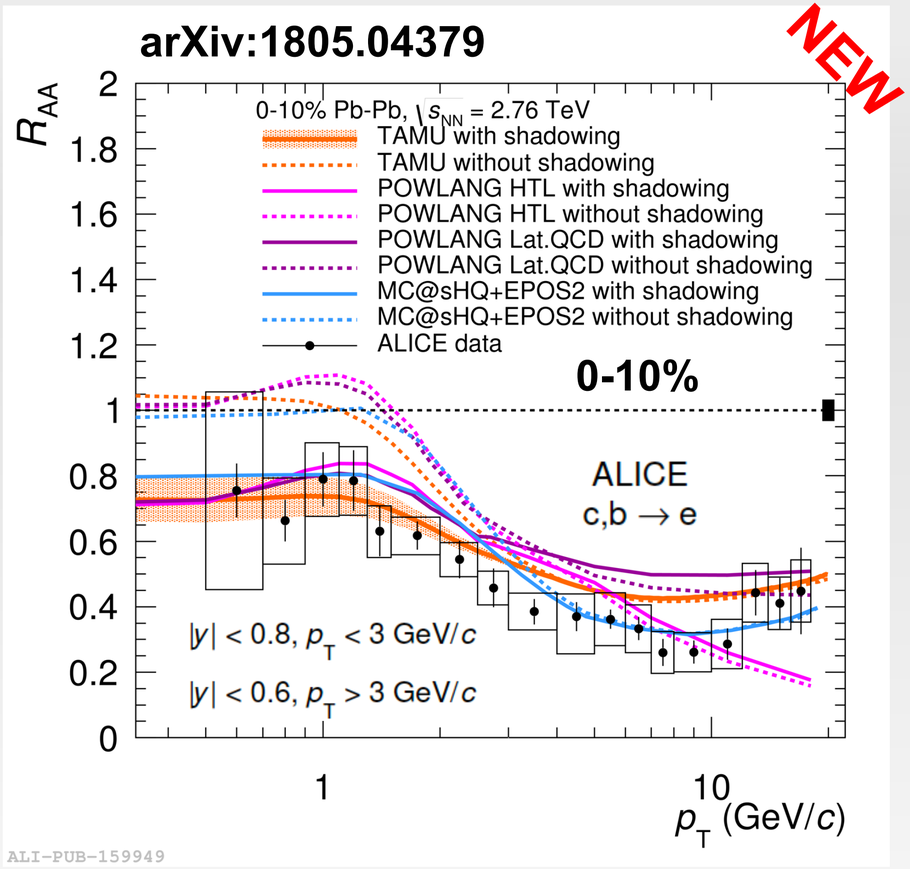


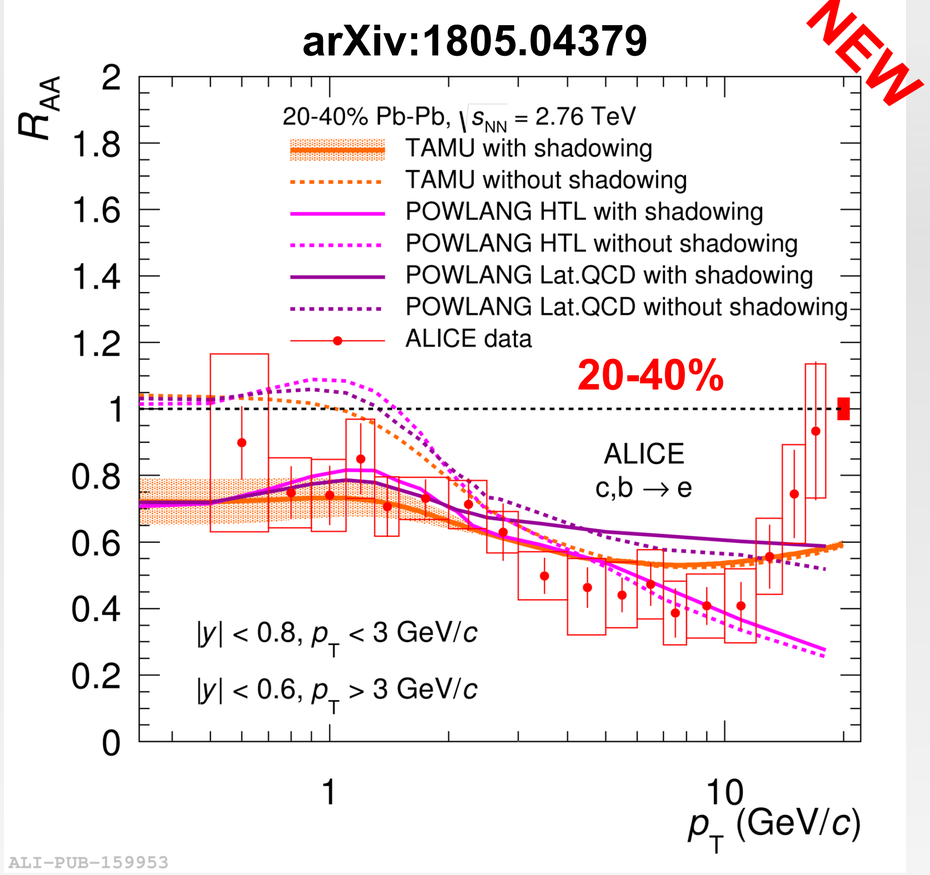
New R_{AA} measurements in Pb-Pb collisions at 2.76 TeV down to p_T = 0.5 GeV/c

→ **low-p_T** measurements **crucial** in all systems to **test binary scaling** of total charm cross section and possible effect of initial-state effects like nuclear PDF (**shadowing**)

→ systematic uncertainty largely reduced thanks to the new pp reference at 2.76 TeV

Heavy-flavour hadron decay electron nuclear modification factor



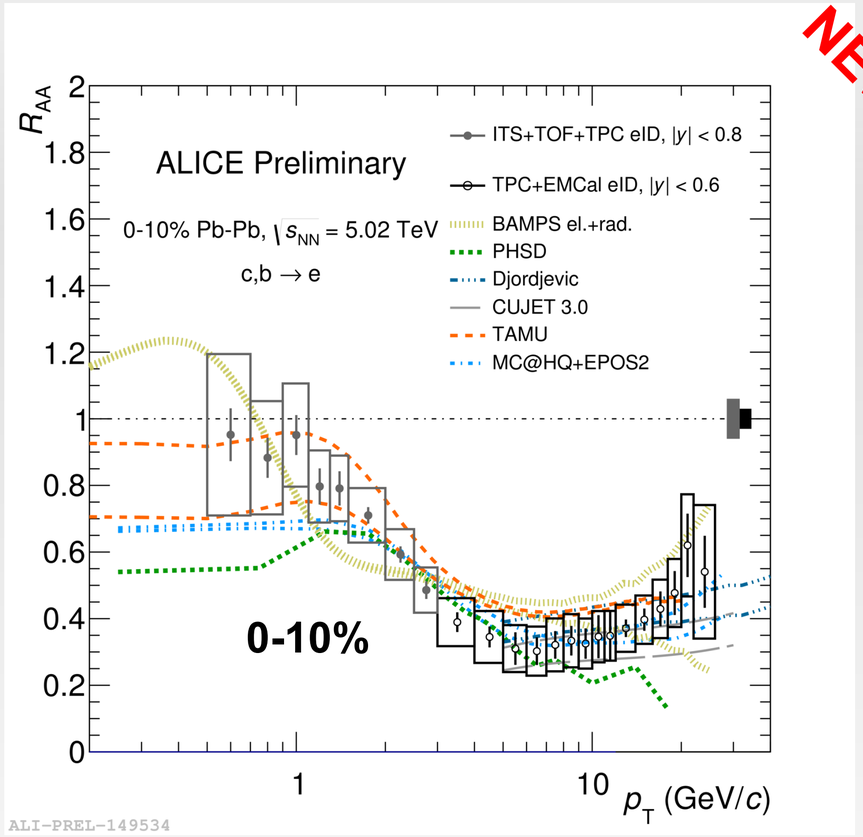


– Data are better described when the nuclear PDFs **(EPS09)** are included in the model calculation (**TAMU**, **POWLANG** and **MC@sHQ+EPOS2**) in both centrality intervals

– POWLANG: Eur.Phys.J. C73 (2013) 2481;
– TAMU: Phys.Lett. B735 (2014) 445–450;
– MC@HQ+EPOS: PRC 89 (2014) 014905;

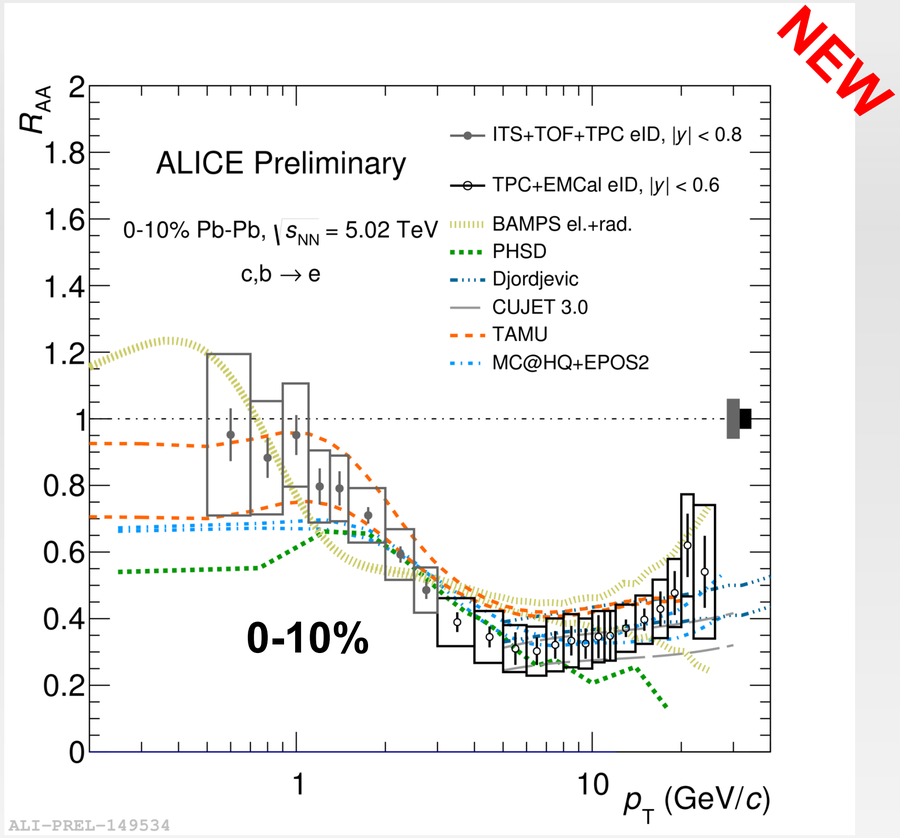
– Suppression at intermediate/high p_T is better described by models that include both **radiative** and **collisional energy loss** processes

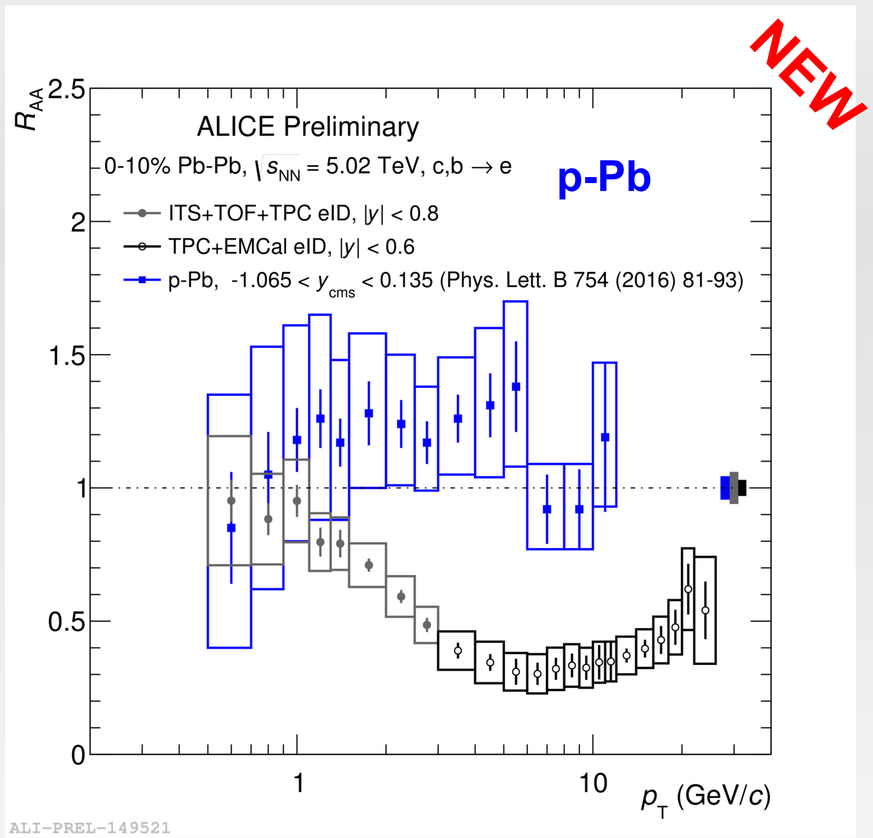
Heavy-flavour hadron decay electron nuclear modification factor



– **New R_{AA}** measurements in Pb-Pb collisions at **5.02 TeV** down to p_T = 0.5 GeV/c

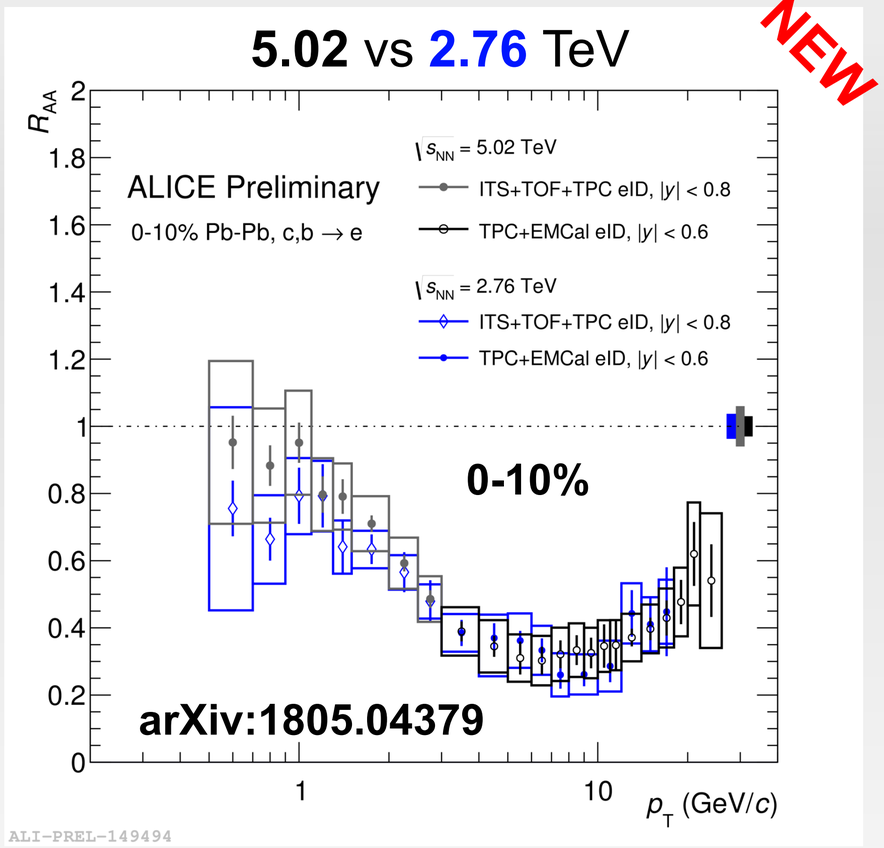
Heavy-flavour hadron decay electron nuclear modification factor





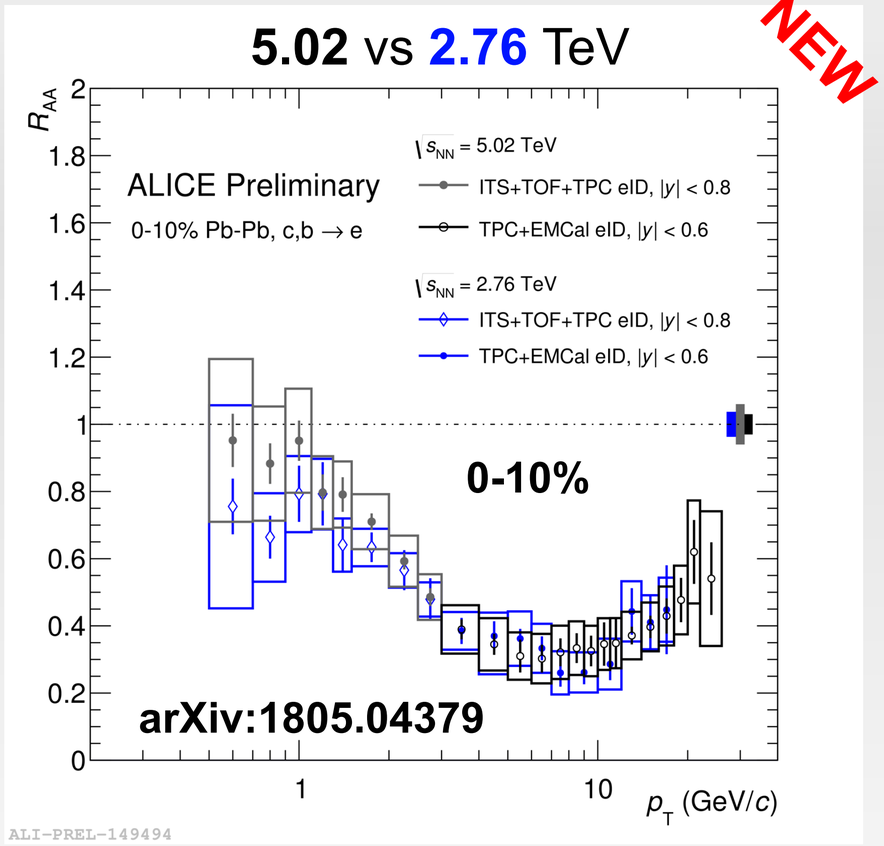
- **New R_{AA}** measurements in Pb-Pb collisions at **5.02 TeV** down to p_T = 0.5 GeV/c
- **R_{pPb} consistent with unity (PLB 754 (2016) 81)** → no strong modification of heavy-flavour decay electron spectra in p-Pb collisions relative to pp collisions
- **Large suppression** at high p_T in **Pb-Pb** collisions
  → **final-state effect** due to heavy-quark in-medium energy loss

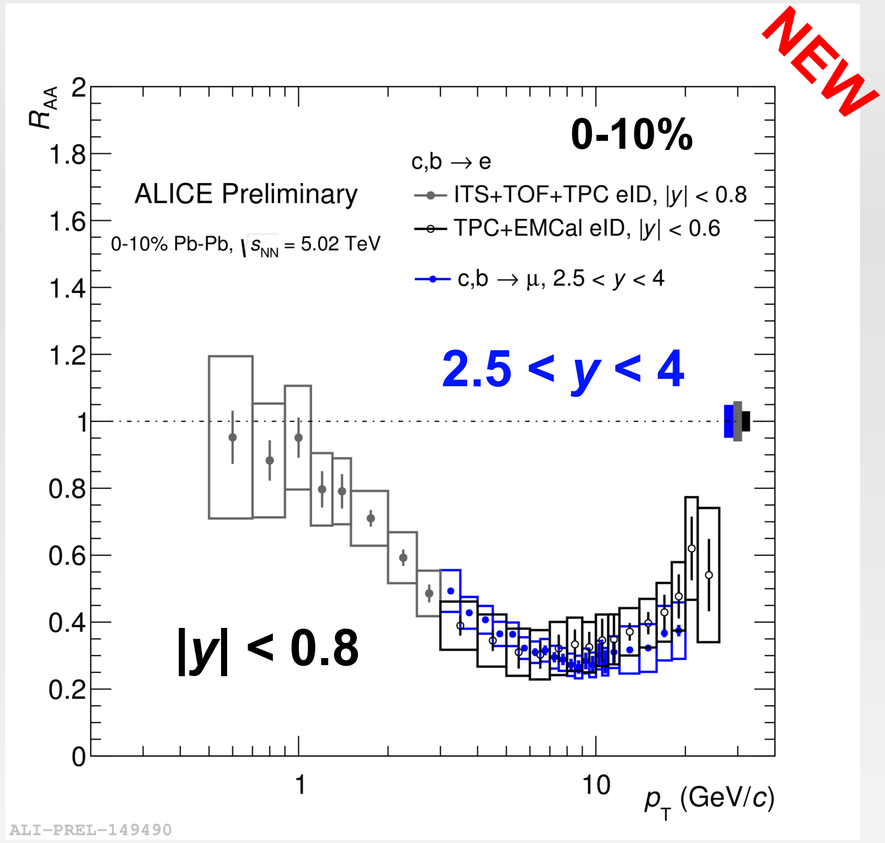
Heavy-flavour hadron decay electron nuclear modification factor



– Similar R_{AA} is measured between the two collision energies.
→ interplay between **harder p_T spectra** and **larger energy loss** at 5.02 TeV w.r.t 2.76 TeV
- modulo different charm/beauty fraction

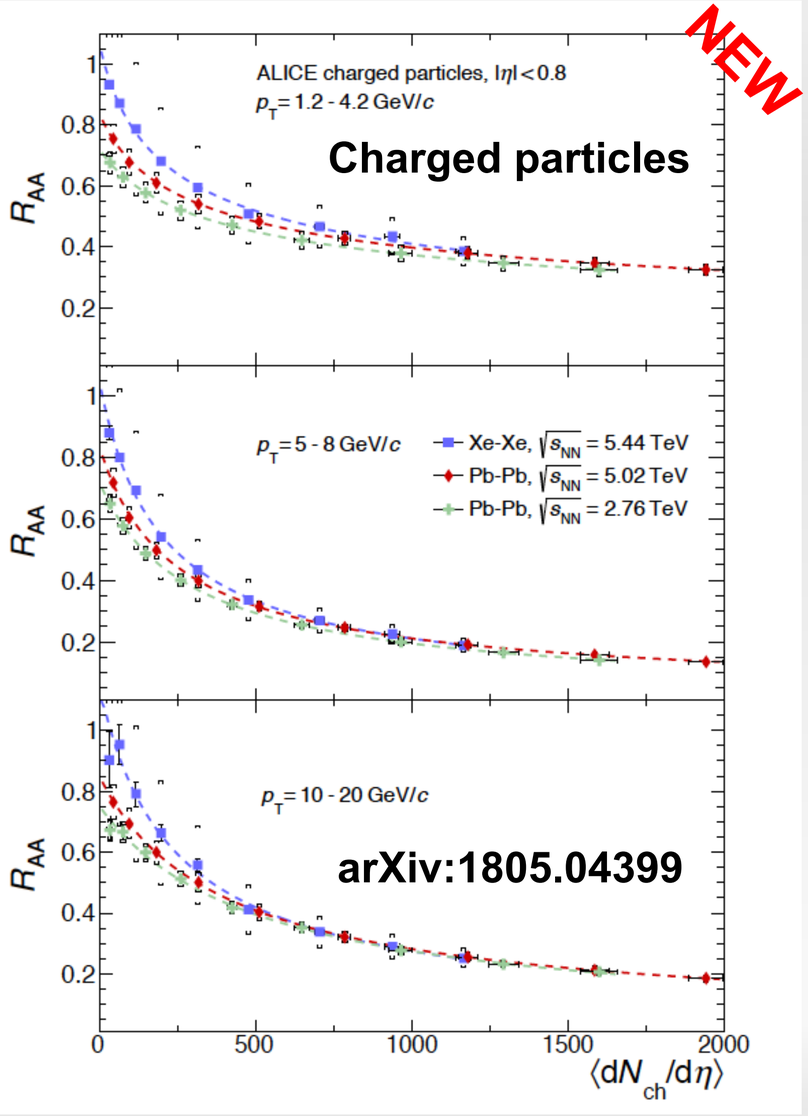
Heavy-flavour hadron decay electron nuclear modification factor





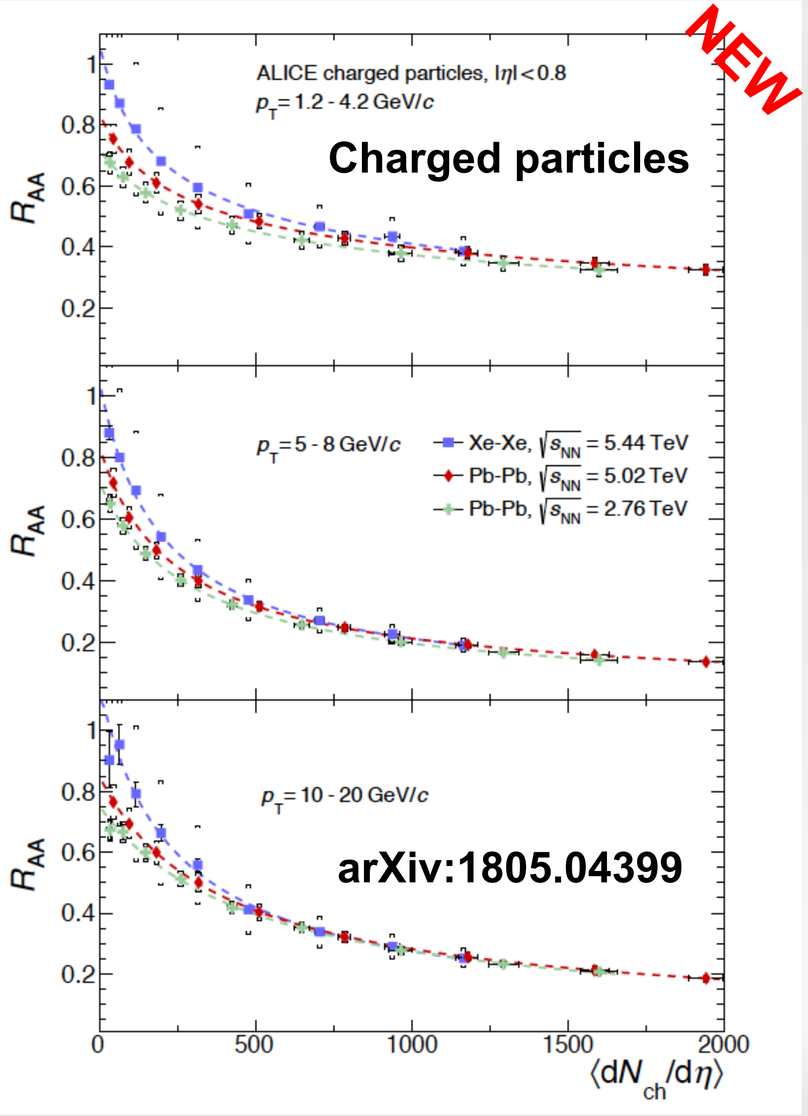
– Similar R_{AA} is measured between the two collision energies.
  → interplay between **harder p_T spectra** and **larger energy loss** at 5.02 TeV w.r.t 2.76 TeV
    - modulo different charm/beauty fraction
– Suppression compatible with the one observed for **muons** from heavy-flavour hadron decay at forward rapidity at the same collision energy

Nuclear modification factor in Xe-Xe collisions at 5.44 TeV

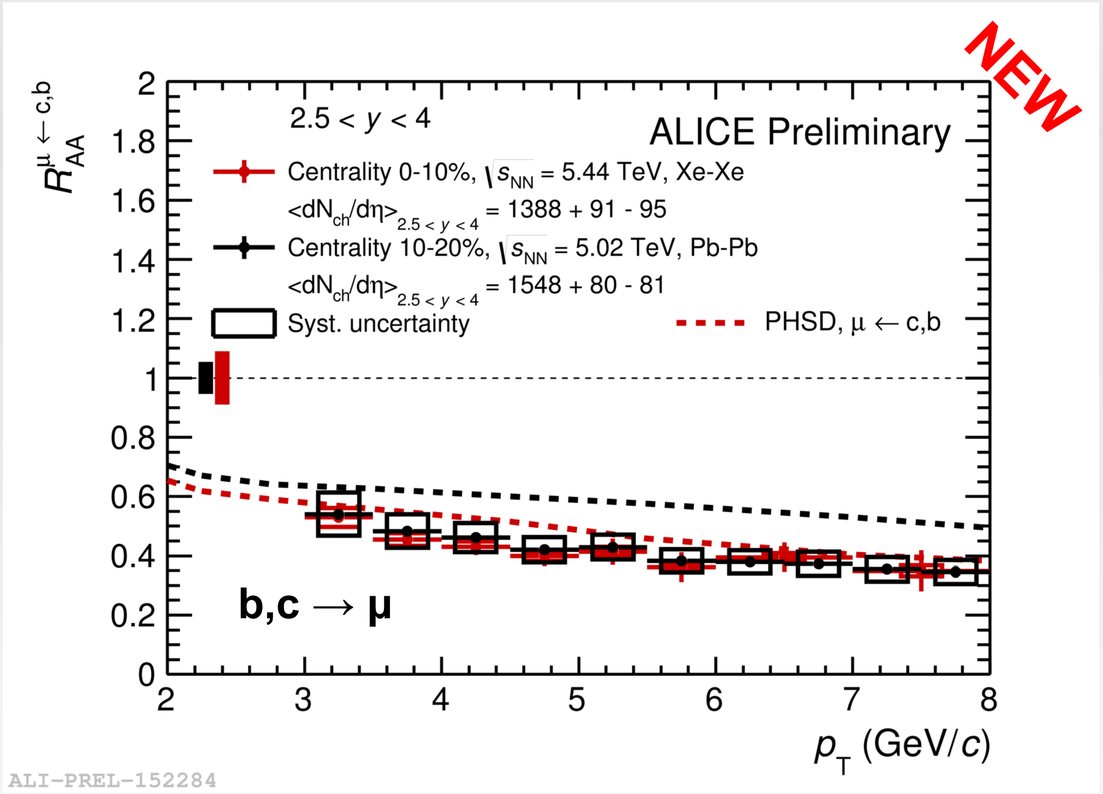


Similar R_{AA} is observed in Xe-Xe and Pb-Pb when compared at similar $\langle dN/d\eta \rangle$

Nuclear modification factor in Xe-Xe collisions at 5.44 TeV



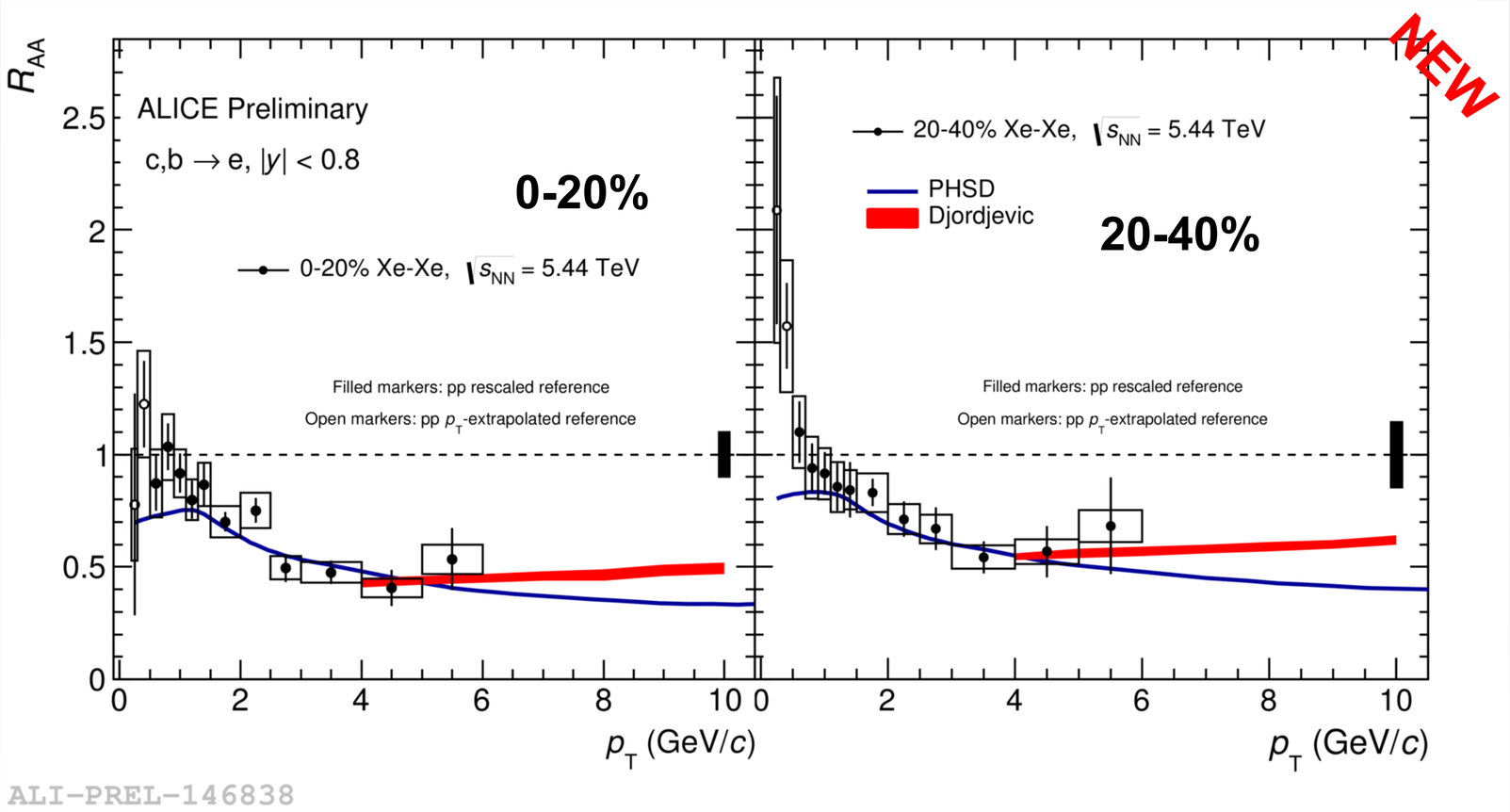
Similar R_{AA} is observed in Xe-Xe and Pb-Pb when compared at similar $\langle dN/d\eta \rangle$



– Comparison of **Pb-Pb** and **Xe-Xe** collisions at different N_{part} or N_{ch} may add sensitivity to probe the path-length dependence of energy loss
→ both radiative and collisional processes relevant for heavy-flavour
→ constraints to model calculations

Nuclear modification factor in Xe-Xe collisions at 5.44 TeV

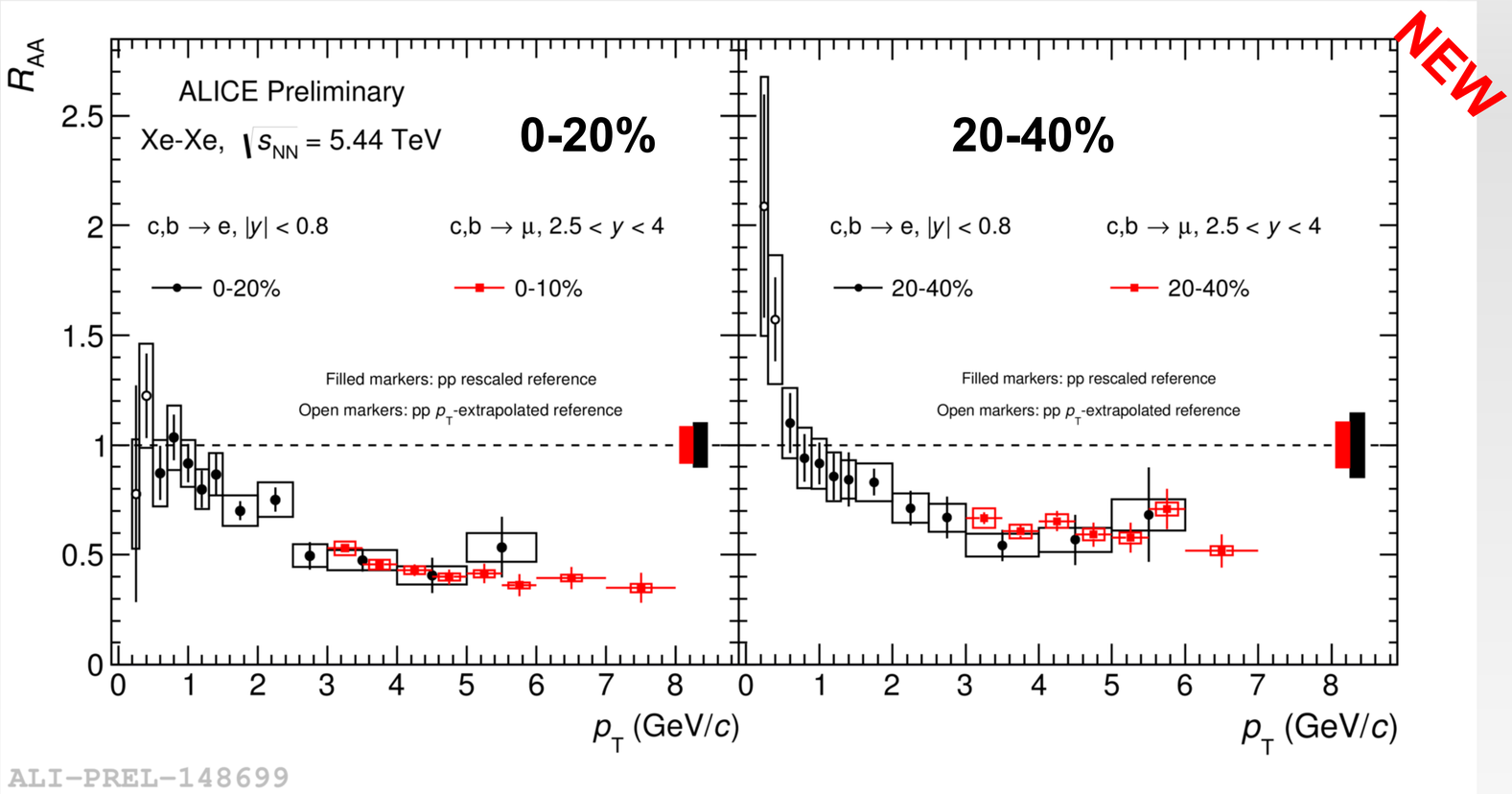
– **New R_{AA}** measured down to **p_T = 0.2 GeV/c** thanks to the low B field used in ALICE during the Xe-Xe data taking!



– Possible future measurement of total charm cross section in heavy-ion collisions
– Data are reproduced by model calculations

Nuclear modification factor in Xe-Xe: rapidity dependence

– **New R_{AA}** measured down to **p_T = 0.2 GeV/c** thanks to the low B field used in ALICE during the Xe-Xe data taking!



– Also in this collision system a similar suppression is observed with the **muons** from heavy-flavour hadron decay at forward rapidity

– Hint of a smaller suppression in 0-10% with respect to 20-40% centrality

Beauty-decay electrons R_{AA}

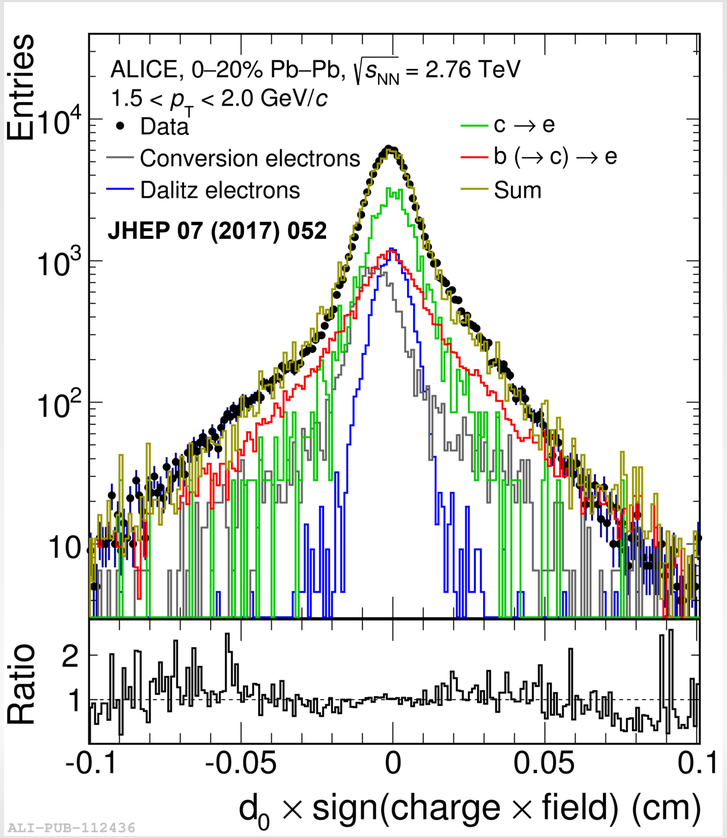
– Analysis based on the electron impact parameter distribution

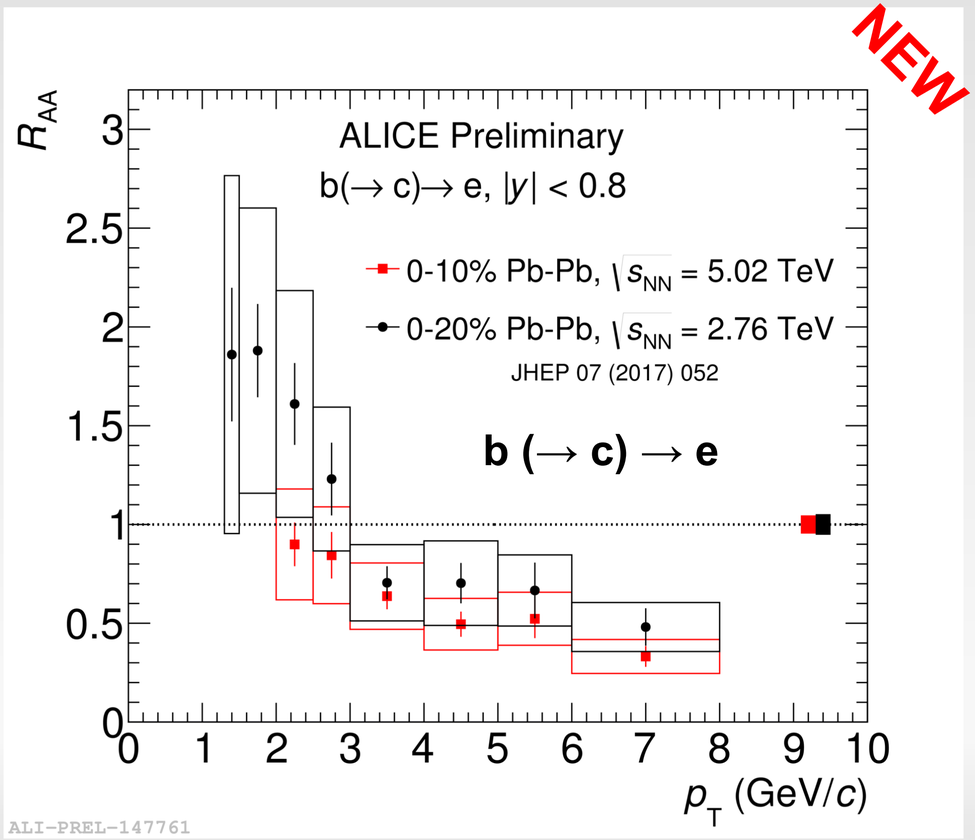
JHEP 07 (2017) 052

– **First R_{AA}** measurement of beauty-decay electrons in **0-20%** centrality at **2.76 TeV**

– **New R_{AA}** measurement of beauty-decay electrons in **0-10% centrality at 5.02 TeV**

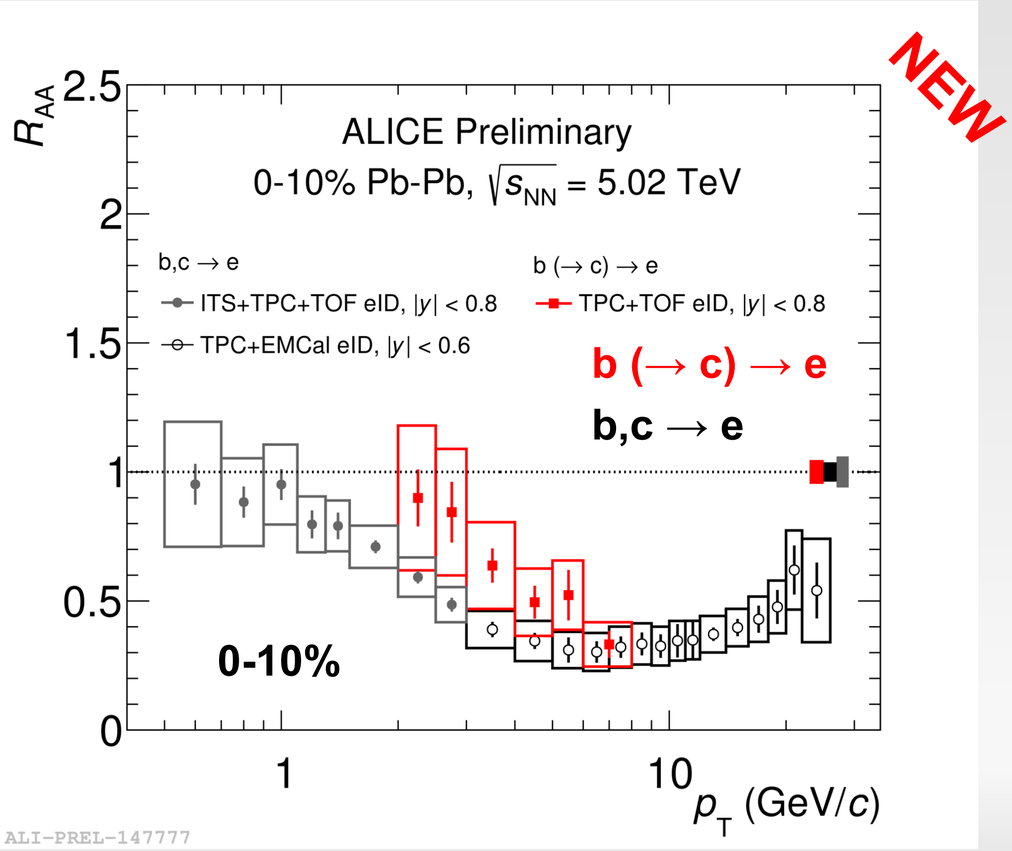
→ $R_{AA} < 1$ for $p_T > 3$ GeV/c and compatible with the R_{AA} measured at 2.76 TeV

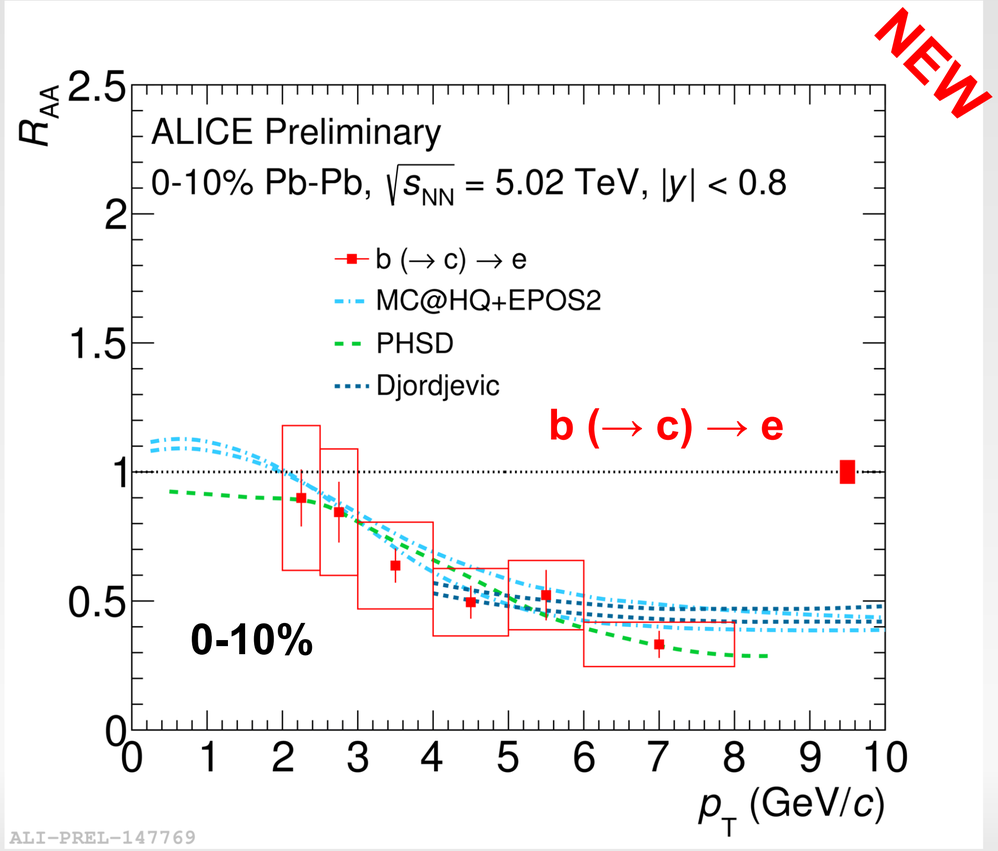




Beauty-decay electron R_{AA}

– **New R_{AA}** measurement of **beauty-decay electron in 0-10% centrality at 5.02 TeV**
→ hint of a smaller suppression for beauty than charm+beauty decay electrons at the same electron p_T
→ large contribution to the systematic uncertainties from the rescaled pp cross section
→ agreement within the uncertainties with models implementing **mass-dependent** energy loss





Conclusion

→ Strong **suppression** of **heavy-flavour** yields at high p_T → **final-state effect**
  – Described by theoretical models implementing **mass-dependent** energy loss

→ Low p_T measurements highlight the importance of **initial-state effects** like shadowing

→ New R_{AA} measurements in **Xe-Xe** collisions
  – Similar R_{AA} is observed in Xe-Xe and Pb-Pb when compared at identical $\langle dN/d\eta \rangle$, scenario consistent with the quadratic path length dependent of medium-induced radiative energy loss
  – R_{AA} down to p_T **= 0.2 GeV/*c***, possible future measurement of total charm cross section in heavy-ion collisions

→ Hint for R_{AA} **< 1** for beauty decay electrons at $p_T > 3$ GeV/c

→ R_{AA} measurements at **different energies and for different collision systems** continue to provide constraints to theory model calculations

Poster Session!!!

Don’t miss the details in the poster session!

→ **[168] – Mattia Faggin –** Measurement of low transverse momentum electrons from heavy-flavour hadron decays in Pb-Pb collisions at 5.02 TeV with ALICE
→ **[92] – Camila De Conti –** Production of electrons from beauty-hadron decays in Pb-Pb collisions at 5.02 TeV with ALICE
→ **[163] – Sebastian Hornung –** Production of electrons from heavy-flavour hadron decays in proton-proton and Xe-Xe collisions with ALICE at the LHC
→ **[111] – Martin Voelkl –** Production and azimuthal anisotropy of beauty decay electrons in Pb-Pb collisions at 2.76 TeV with ALICE

BACKUP

Data Samples

Xe-Xe@5.44 TeV

1 Million of MB events

Pb-Pb@2.76 TeV

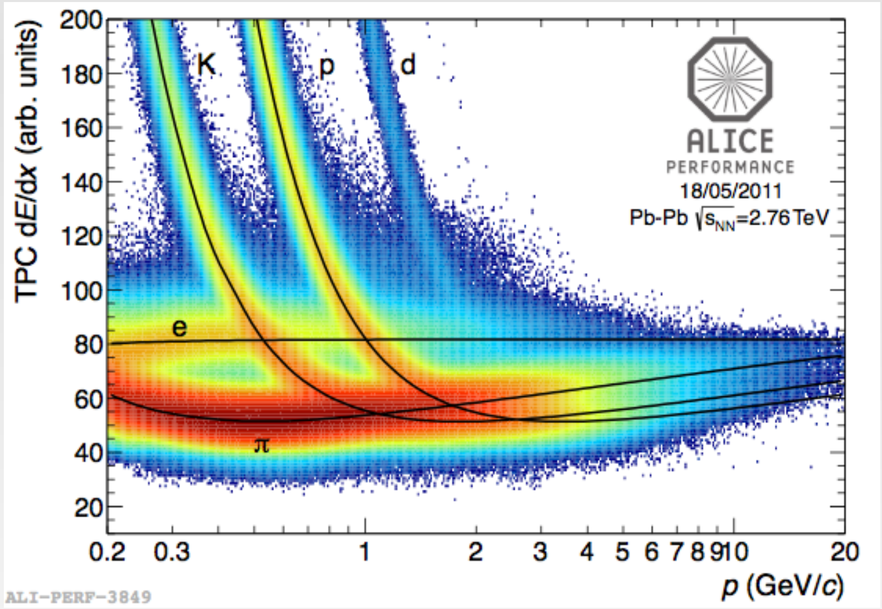
Centrality class	$\langle T_{AA} \rangle$ (mb^{-1})	N_{events}	L_{int} (μb^{-1})
0–10%	23.44 ± 0.76	16.4×10^6	21.3 ± 0.7
30–50%	3.87 ± 0.18	9.0×10^6	5.8 ± 0.2

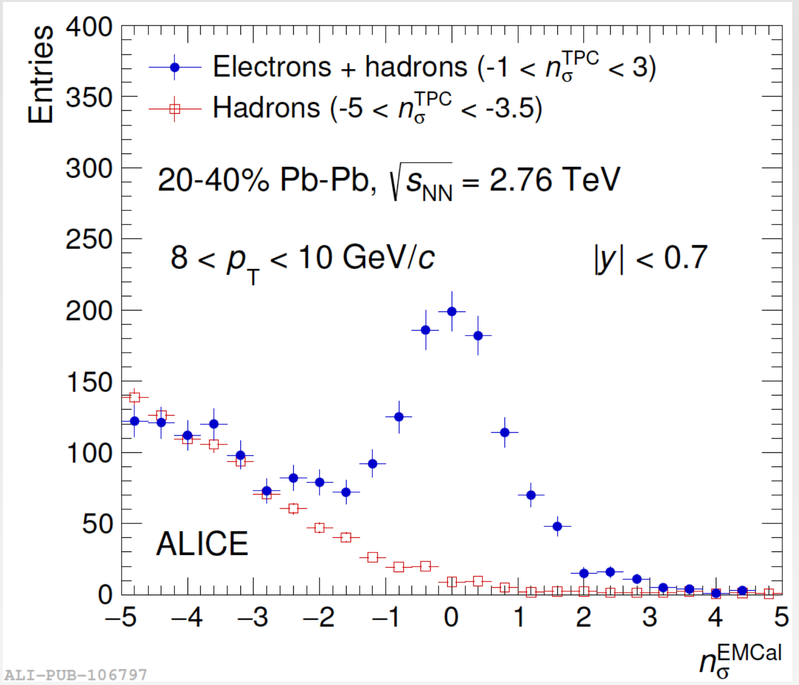
Pb-Pb@5.02 TeV

Centrality class	$\langle T_{AA} \rangle$ (mb^{-1})	N_{events}
0–10%	23.42 ± 0.75	10.4×10^6
30–50%	3.82 ± 0.14	20.8×10^6
60–80%	0.404 ± 0.017	20.8×10^6

Electrons from heavy-flavour hadron decays

– **Low-p_T** electrons ($p_T < 3$ GeV/c): PID via TPC dE/dx complemented with TOF and ITS
– **High-p_T** electrons ($p_T > 3$ GeV/c): PID using TPC, EMCal



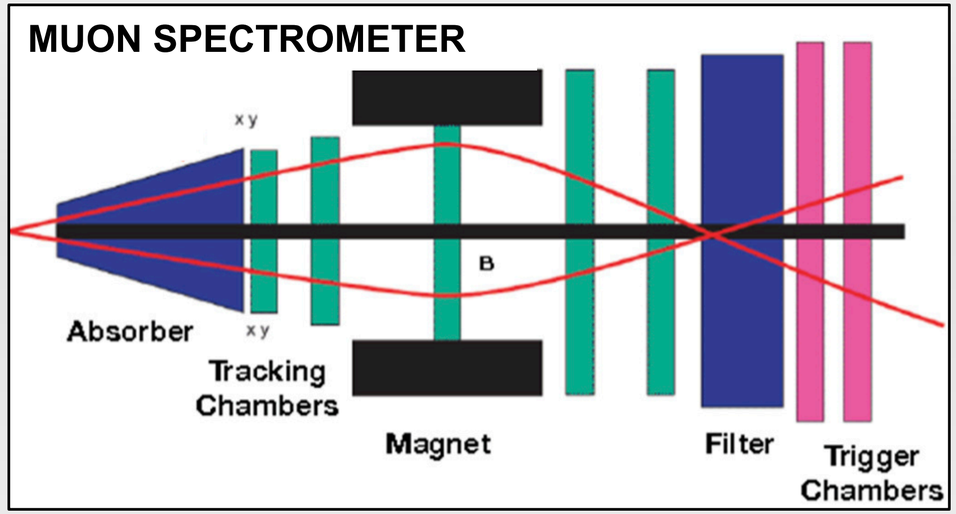


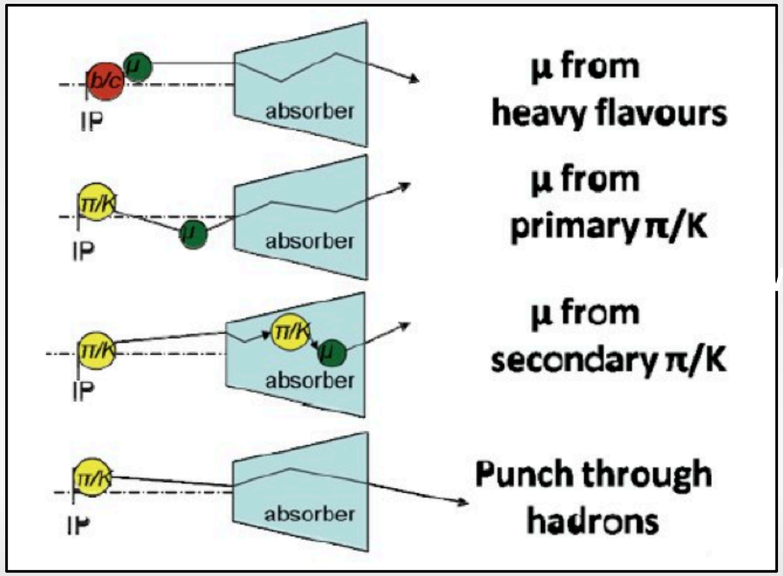
Main background sources:
– γ conversions
– π^0 and η Dalitz decays

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

Muons from heavy-flavour hadron decays

$-4 < \eta < -2.5$





Track selection:

– Acceptance and geometrical cuts

– Muon trigger matching:
reject the hadrons that cross the absorber

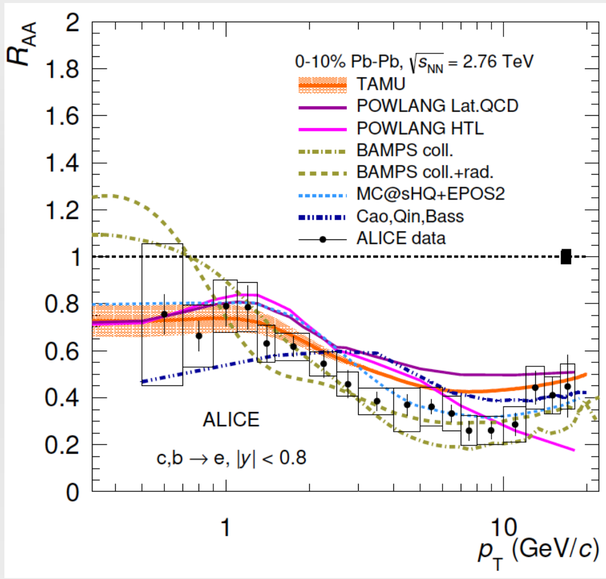
– Select tracks pointing back to the vertex:
Remove tracks from beam-gas interactions

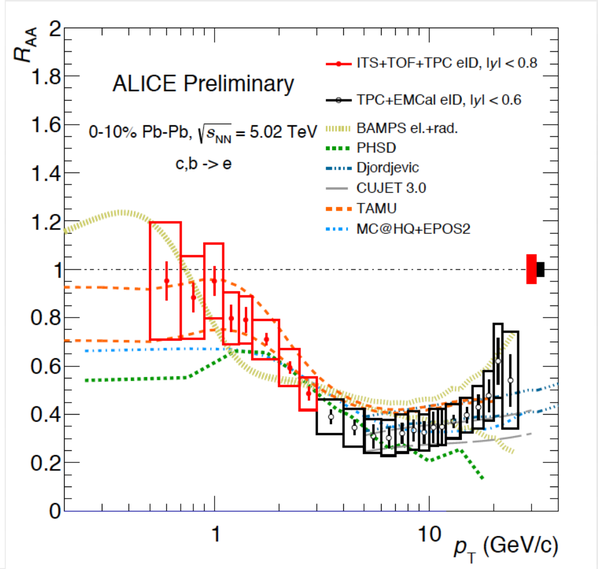
Remaining main background:

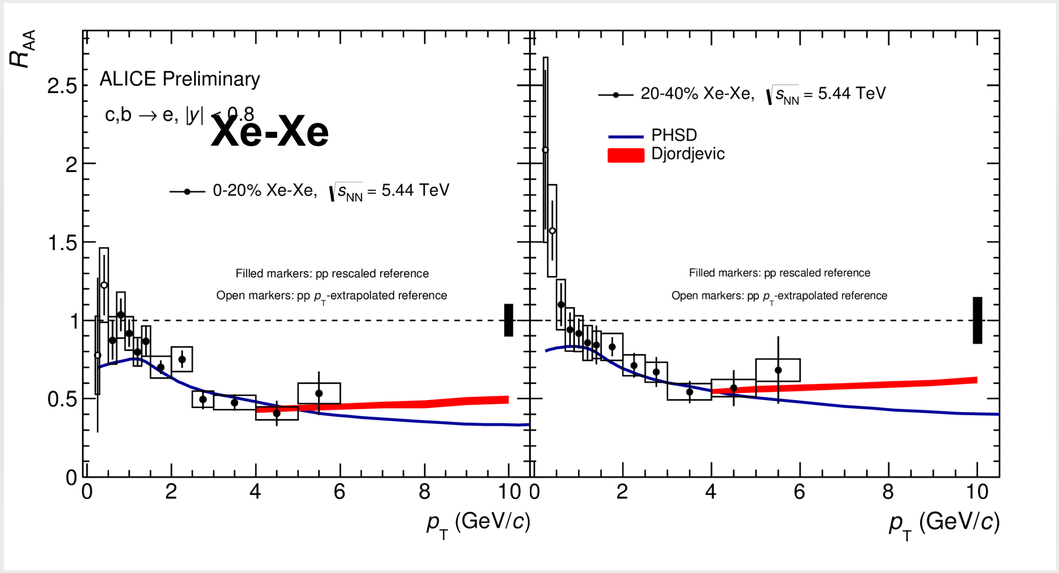
– μ from primary π and K decays (subtracted with MC-tuned on π, K spectra measured at mid-rapidity)

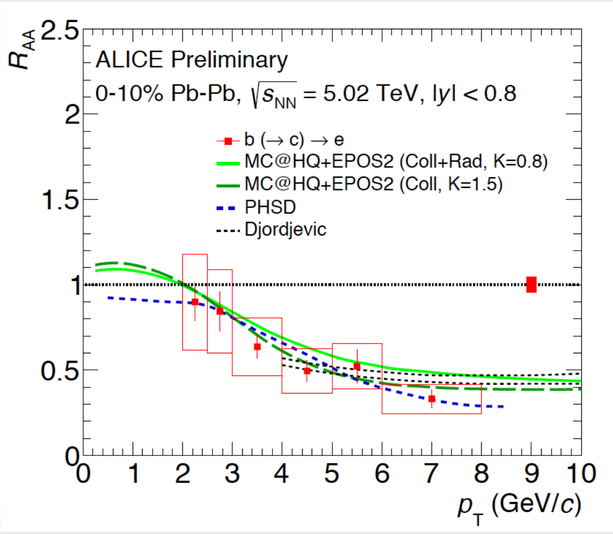
– μ from J/ψ/W/Z/γ* decays at high p_T

Model predictions:









– **POWLANG: Eur.Phys.J. C73 (2013) 2481;**
– **TAMU: Phys.Lett. B735 (2014) 445–450;**
– **MC@HQ+EPOS: PRC 89 (2014) 014905;**
– **WHDG: Nucl. Phys. A 872 (2011) 256;**
– **BAMPS: PLB 717 (2012) 430; arXiv:1310.3597v1[hep-ph];**
– **UrQMD: arXiv:1211.6912[hep-ph]; J.Phys. Conf. Ser. 426 (2013) 012032; – Cao,Quin, Bass: PRC 88 (2013);**
– **Vitev:: PRC 80 (2009) 054902;**
– **Djordjevic: PRL 737 (2014) 298**

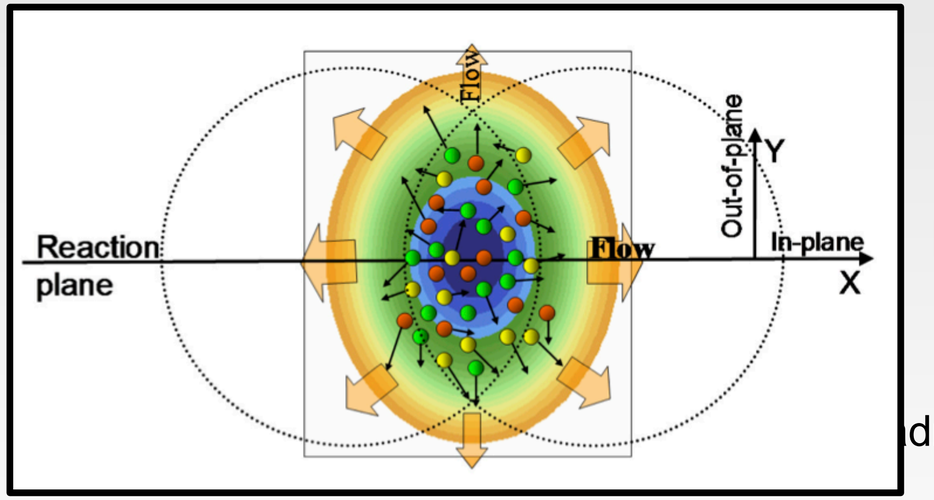
– R_{AA} measurements at different collision systems and energies, and for different heavy-flavour decay channels start to provide constraints for models

Collectivity: azimuthal anisotropy

– Re-scatterings among produced particles convert the initial **geometrical anisotropy** into an observable **momentum anisotropy**

– In addition, path-length dependent energy loss induces an asymmetry in momentum space

– **Observable**: **elliptic flow v_2 =** 2nd Fourier coefficient of the particle azimuthal distribution



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

Heavy-flavour v_2 measurements probe:

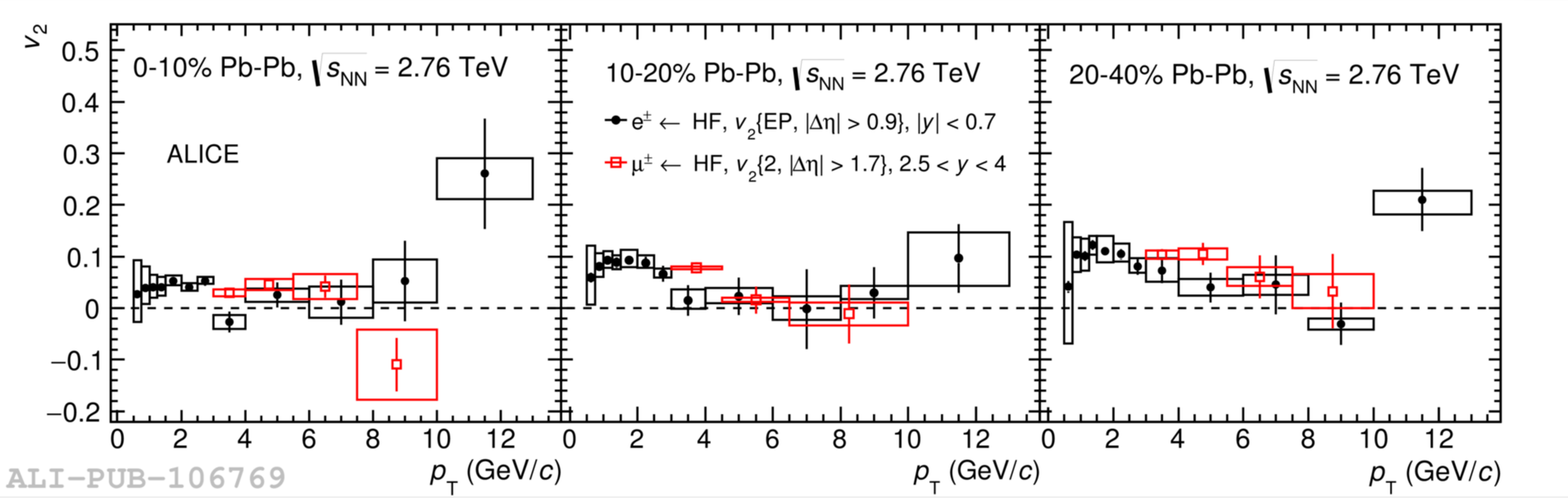
– **Low/intermediate p_T:** collective motion, degree of thermalization of heavy quarks and hadronization mechanism (recombination)

– **High p_T:** path-length dependence of heavy-quark energy loss

Leptons from heavy-flavour hadron decays

HF-decay muons
2.5 < *y* < 4
PLB 753, (2016) 41

HF-decay electrons
|*y*| < 0.7
JHEP 09 (2016) 028

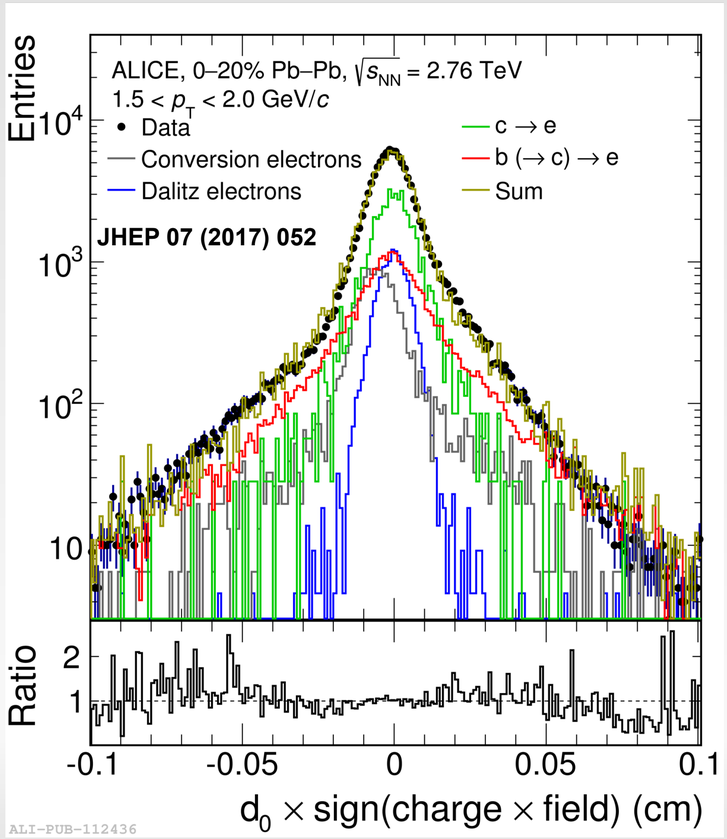


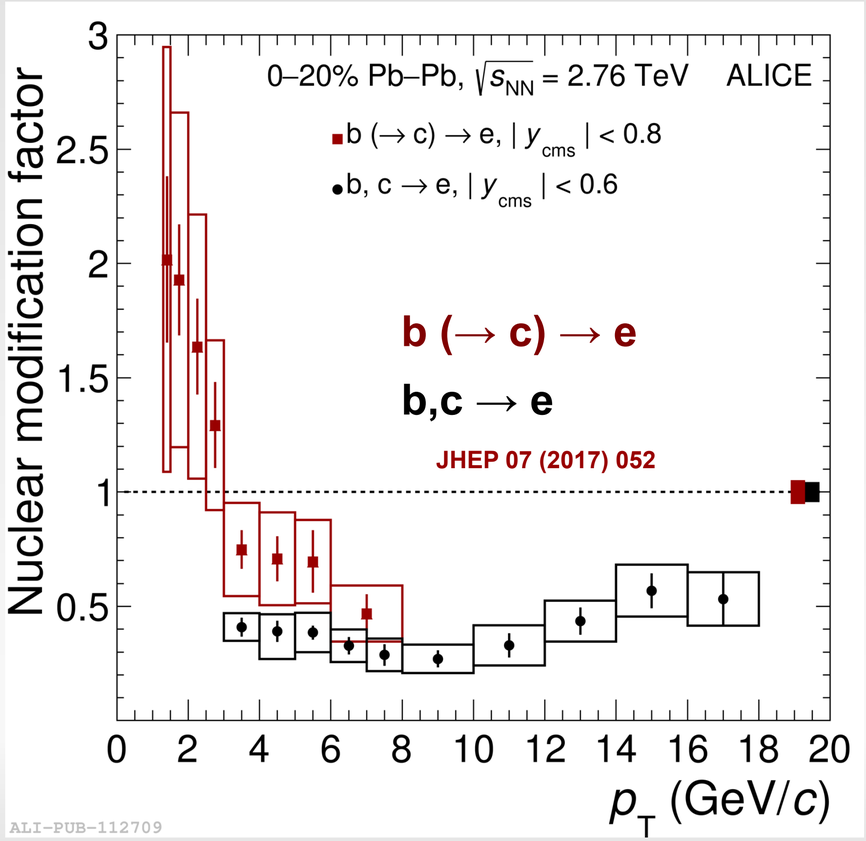
v_2 of heavy-flavour decay **electrons** (at mid-rapidity) and **muons** (at forward rapidity) are similar in the different centrality classes. Positive v_2 observed → 5.9σ effect for $2 < p_T < 2.5$ GeV/*c* in 20-40% centrality class for the heavy-flavour decay electrons.
Hint for an increase of v_2 from central to semi-central collisions as observed for D mesons
Suggests collective motion of low-p_T charm quarks in the expanding fireball

Beauty-decay electron R_{AA}

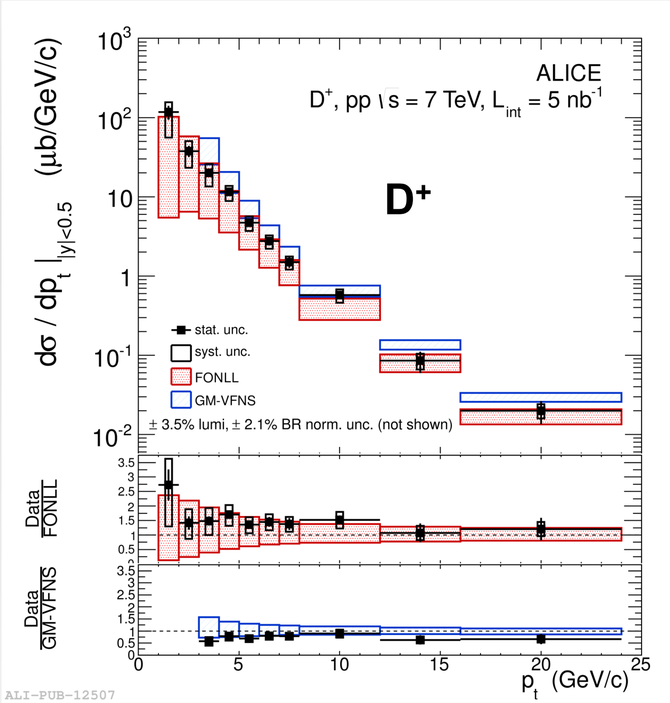
– Analysis based on the electron impact parameter distribution.

– First R_{AA} measurement of beauty-decay electron at 2.76 TeV in the 0-20% centrality interval:
→ $R_{AA} < 1$ for $p_T > 3$ GeV/c
→ consistent with the picture of **mass-dependent radiative and collisional energy loss**

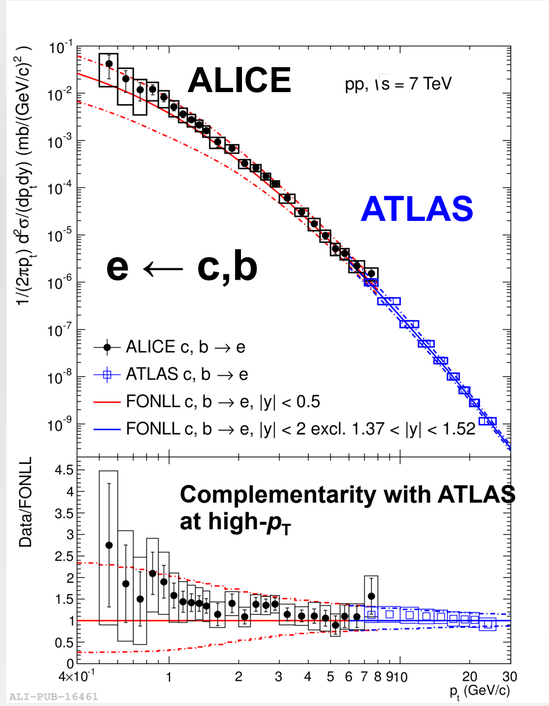




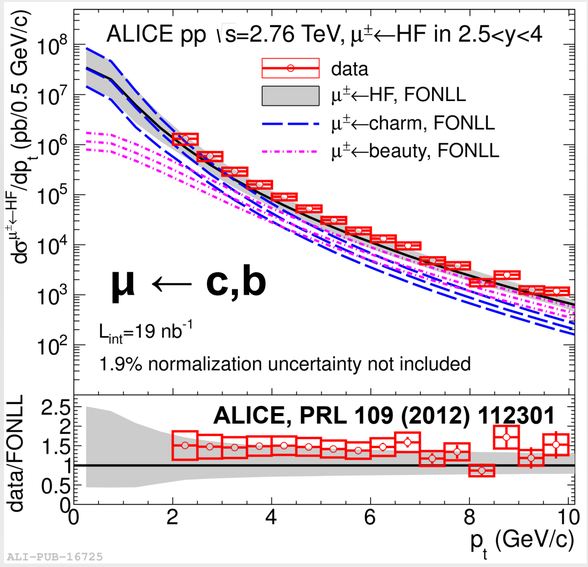
p_T-differential cross section

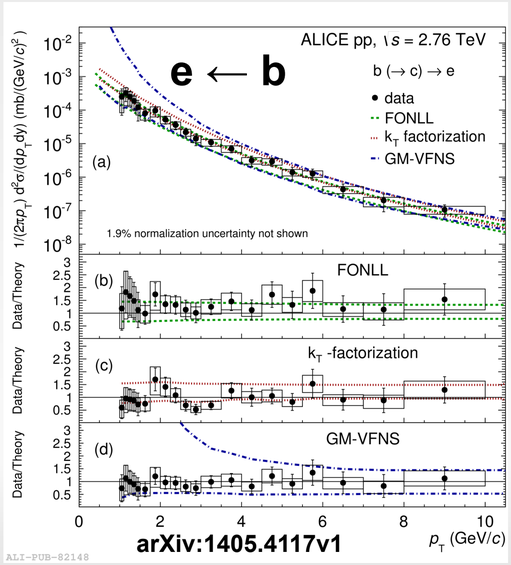


ALICE, JHEP 1201 (2012)



(ATLAS) PLB 707 (2012) 438
(ALICE) Phys. Rev. D86 (2012) 112007

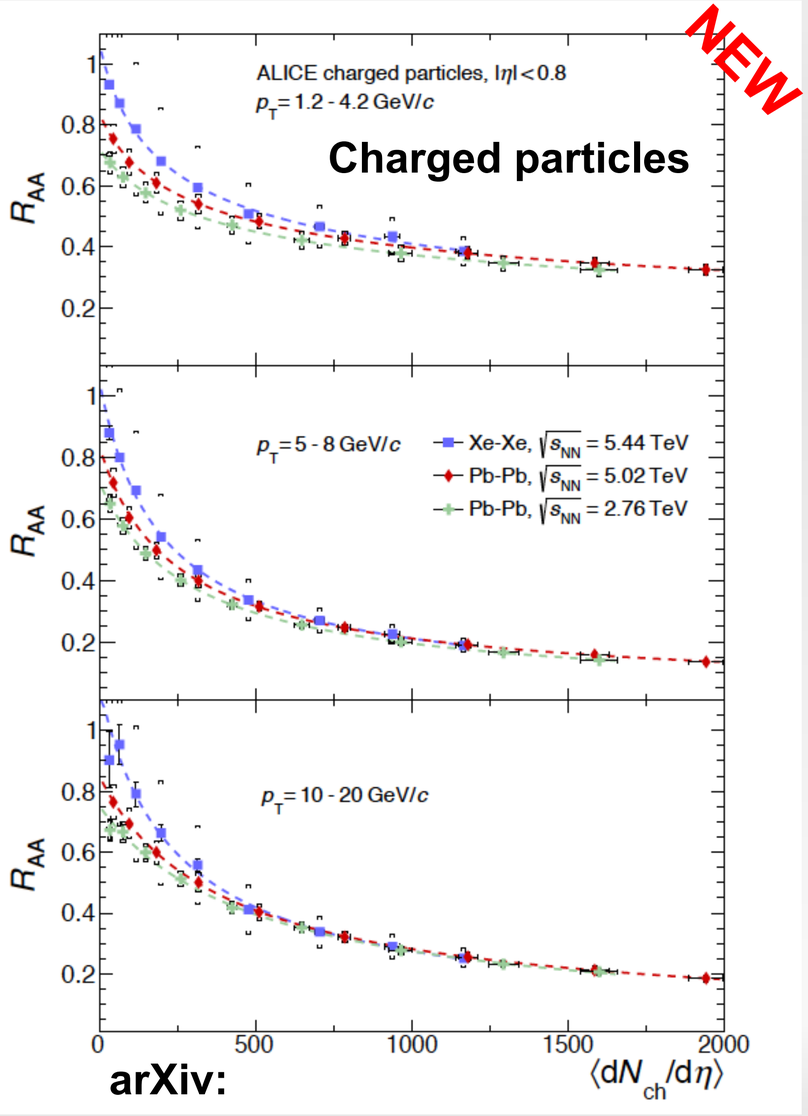




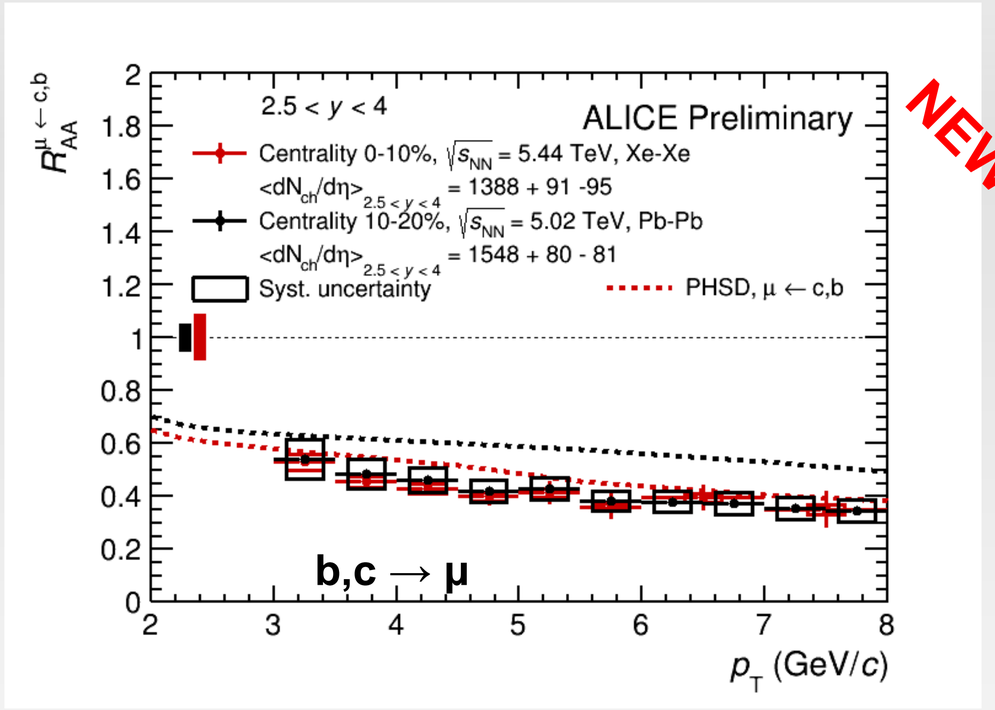
FONLL: JHEP 9805 (1998) 007
GM-VFNS: PRL 96 (2006) 012001
k_T Fact: PRD 62 (2000) 071502

Heavy-flavour p_T-differential cross sections well described by pQCD calculations at both energies (7 and 2.76 TeV)

Nuclear modification factor in Xe-Xe collisions at 5.44 TeV



Similar R_{AA} is observed in Xe-Xe and Pb-Pb when compared at similar $\langle dN/d\eta \rangle$



– Scenario consistent with the quadratic path length dependence of medium-induced **radiative energy loss**

$$\langle \Delta E \rangle \propto \varepsilon \cdot L^2$$

– Pb-Pb and Xe-Xe systems give excellent control over the path length
→ stringent constraints to all model calculations.