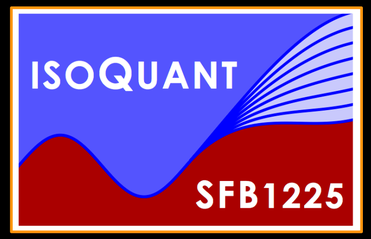


Heavy-flavour production via single electron and di-electron measurements

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

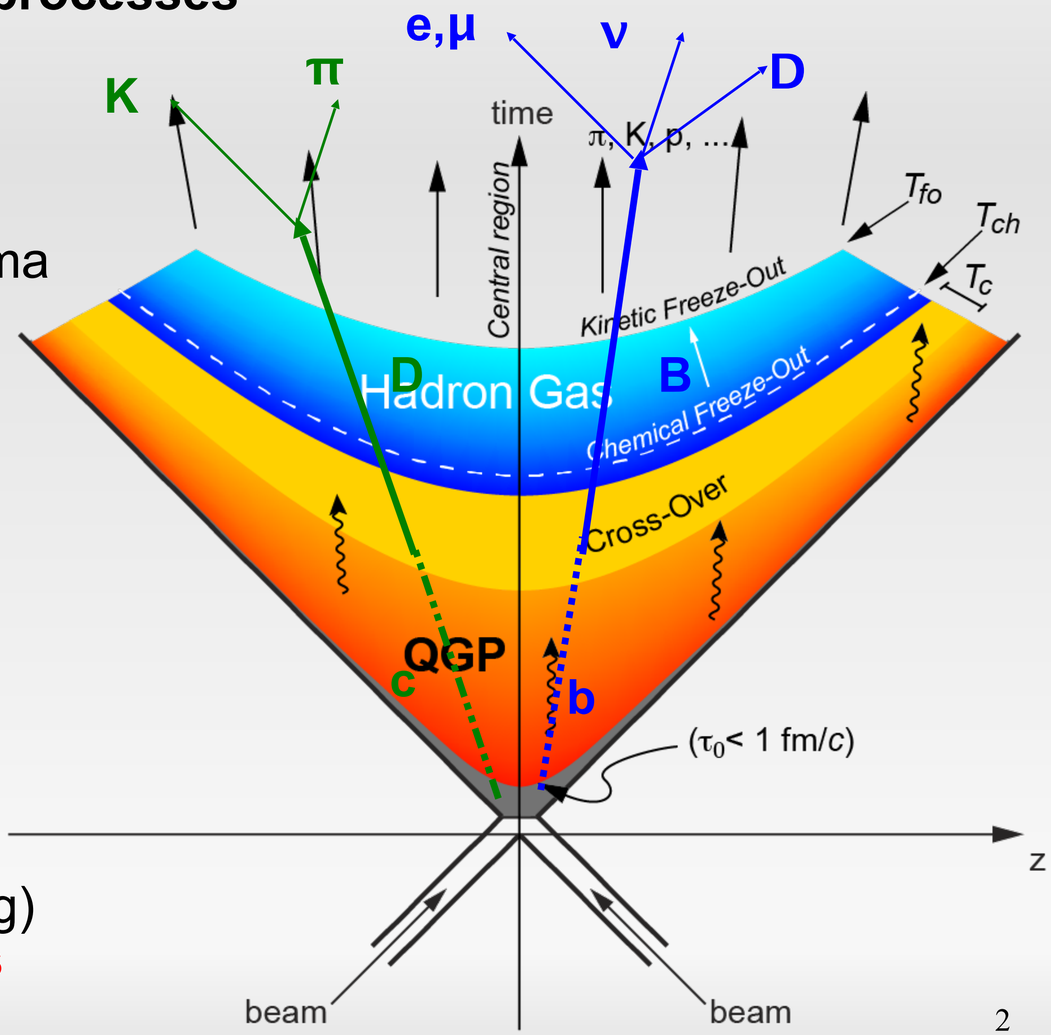
→ They experience the full evolution of the system
⇨ sensitive probes of the properties of the Quark-Gluon Plasma

→ 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**

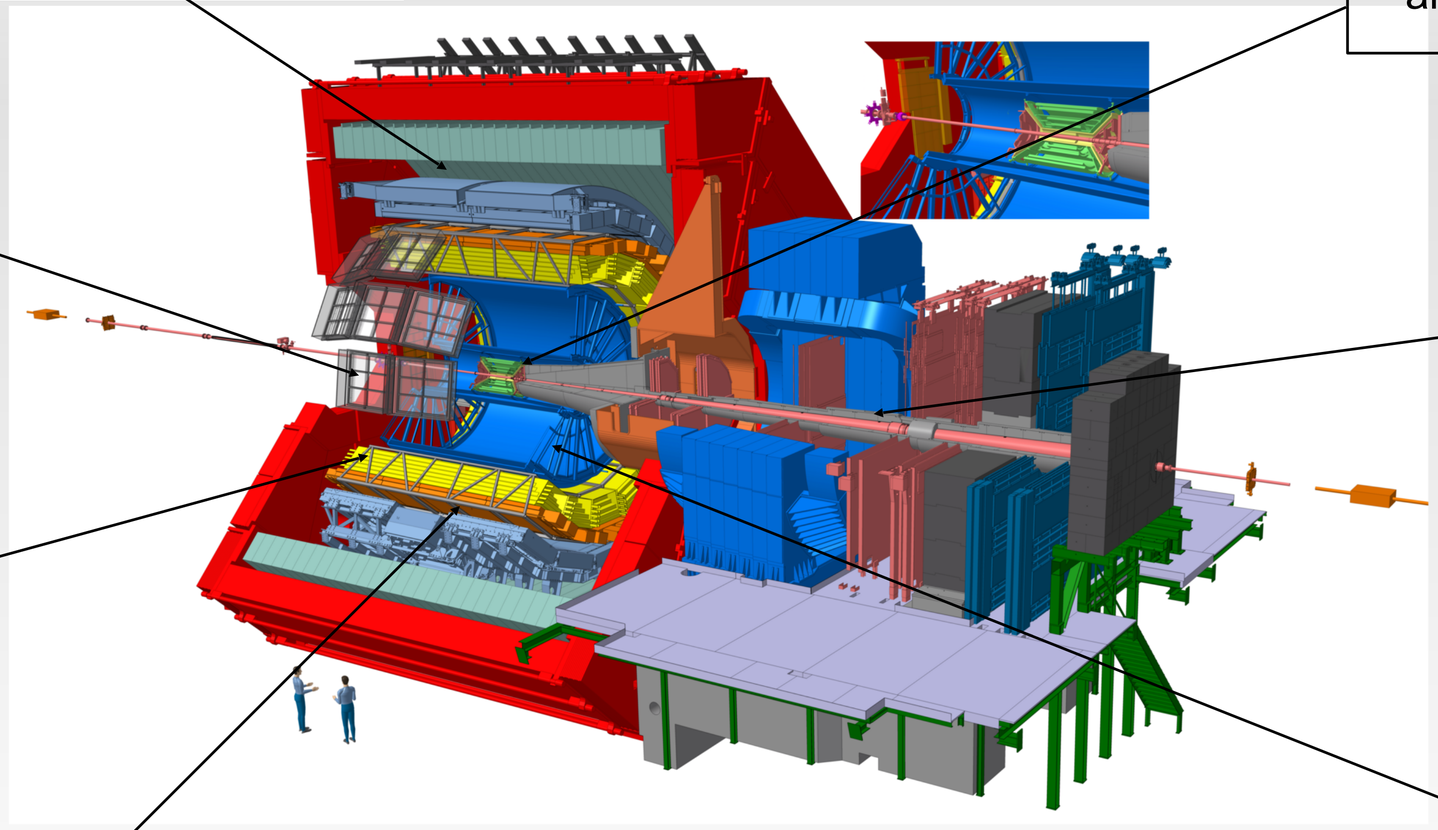


ALICE detector

EMCal: trigger, electron ID

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

V0: trigger, centrality and event plane determination



Forward muon spectrometer

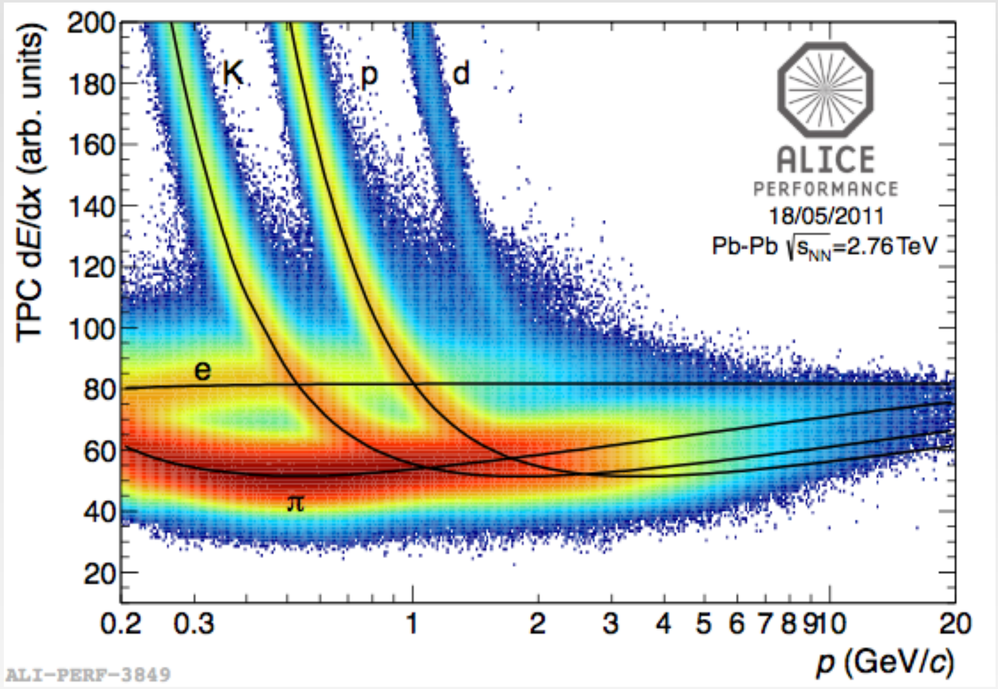
TRD: tracking, electron ID

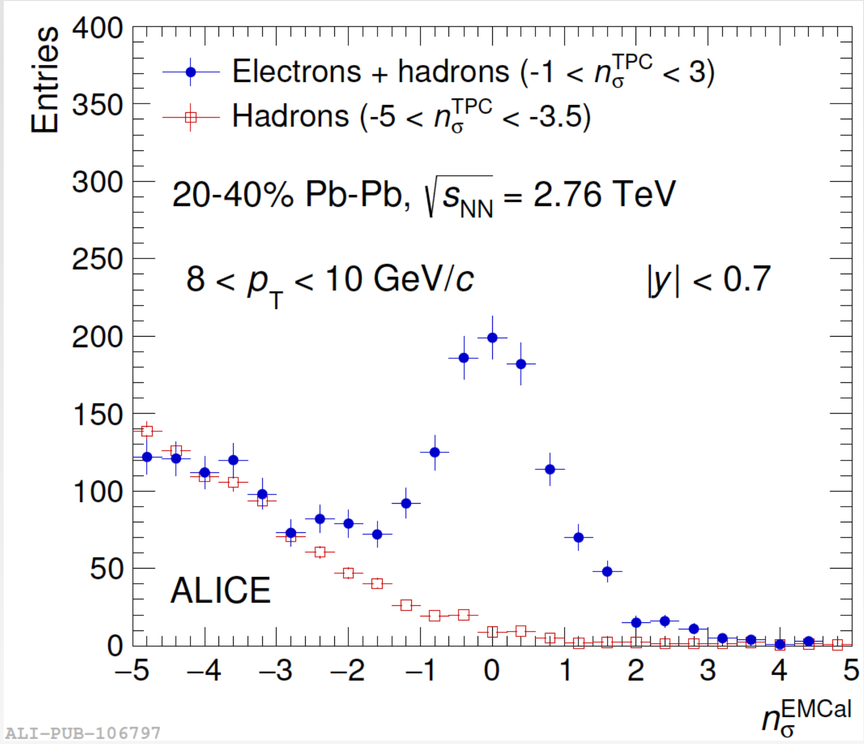
TPC: tracking, PID via d*E*/d*x*, event

TOF: PID via time of flight

Single-electron 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

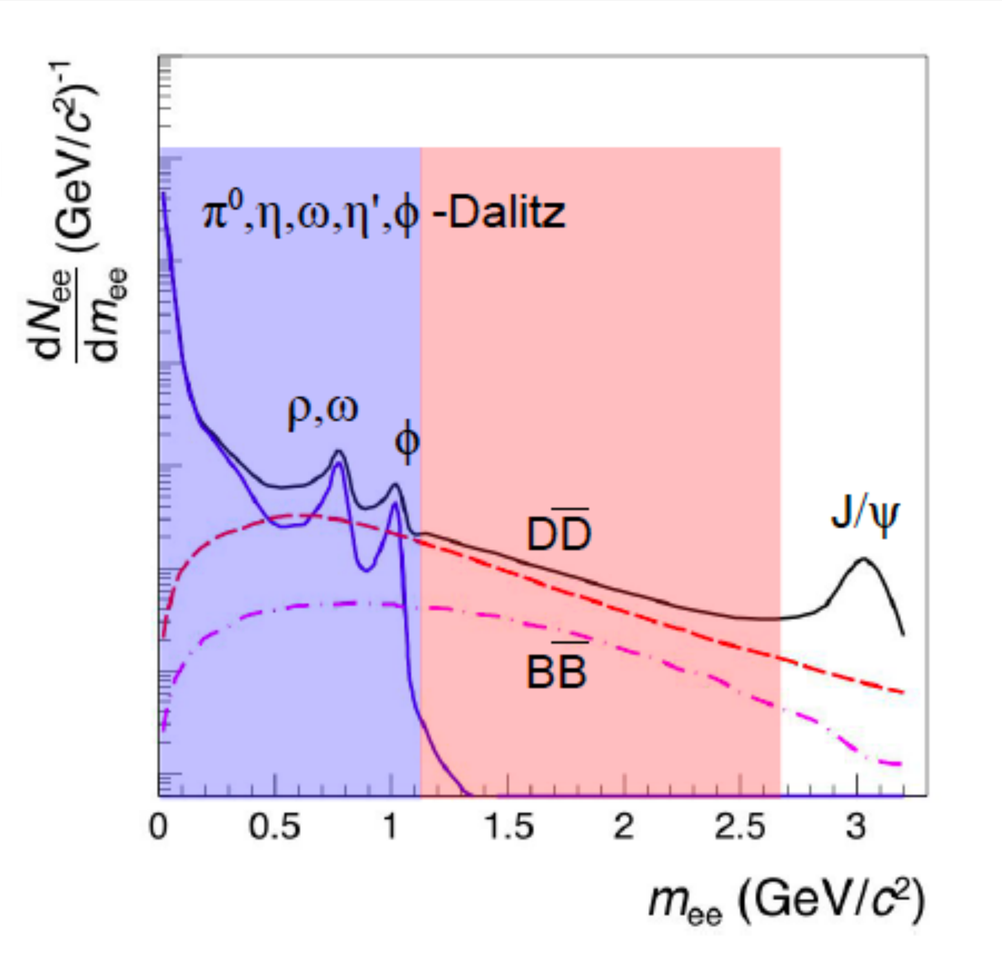




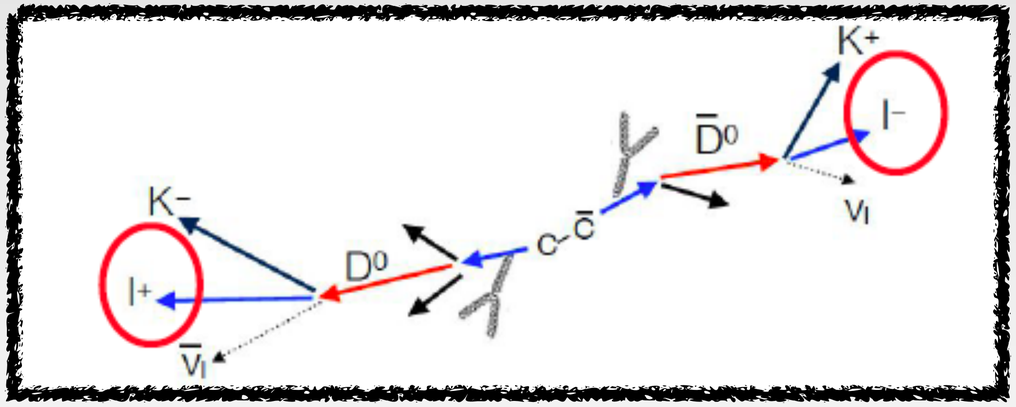
Main background sources:
- γ conversions
- π^0 and η Dalitz decays

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

Dielectron production



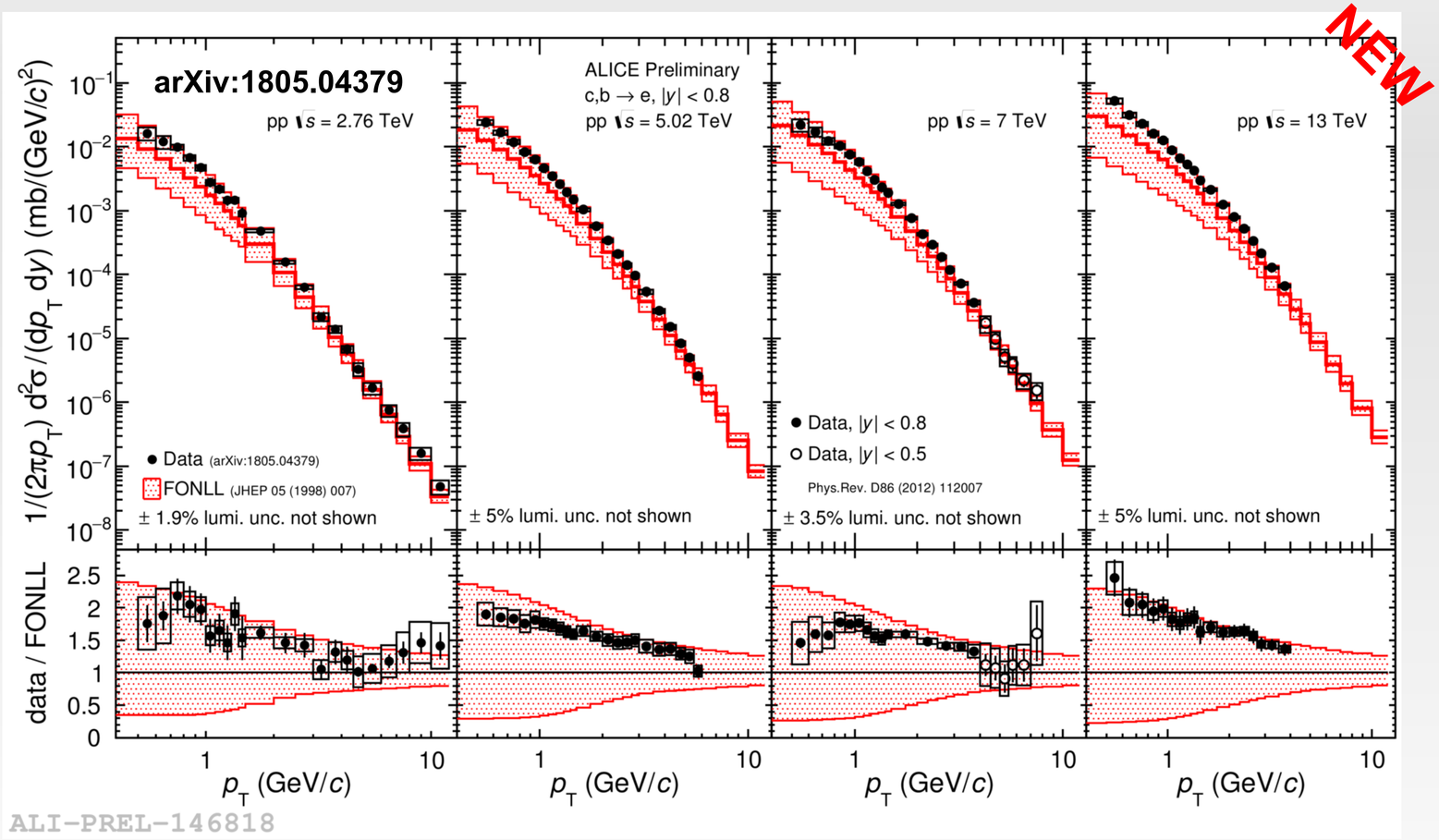
- Measure Dalitz decays ($\pi^0,\eta,\omega,\eta',\phi$) and 2-body decays ($\rho,\omega,\phi$) of mesons
- Study direct photons via internal conversion ($\gamma^{dir*}\rightarrow e^+e^-$) (Complementary to real photon measurements, test pQCD calculations)



- Study **heavy-flavour (HF) production** via simultaneous semi-leptonic decays of D and B mesons
  - Complementary to single HF measurements

Heavy-flavour decay electrons in pp collisions

2.76 TeV → 5.02 TeV → 7 TeV → 13 TeV

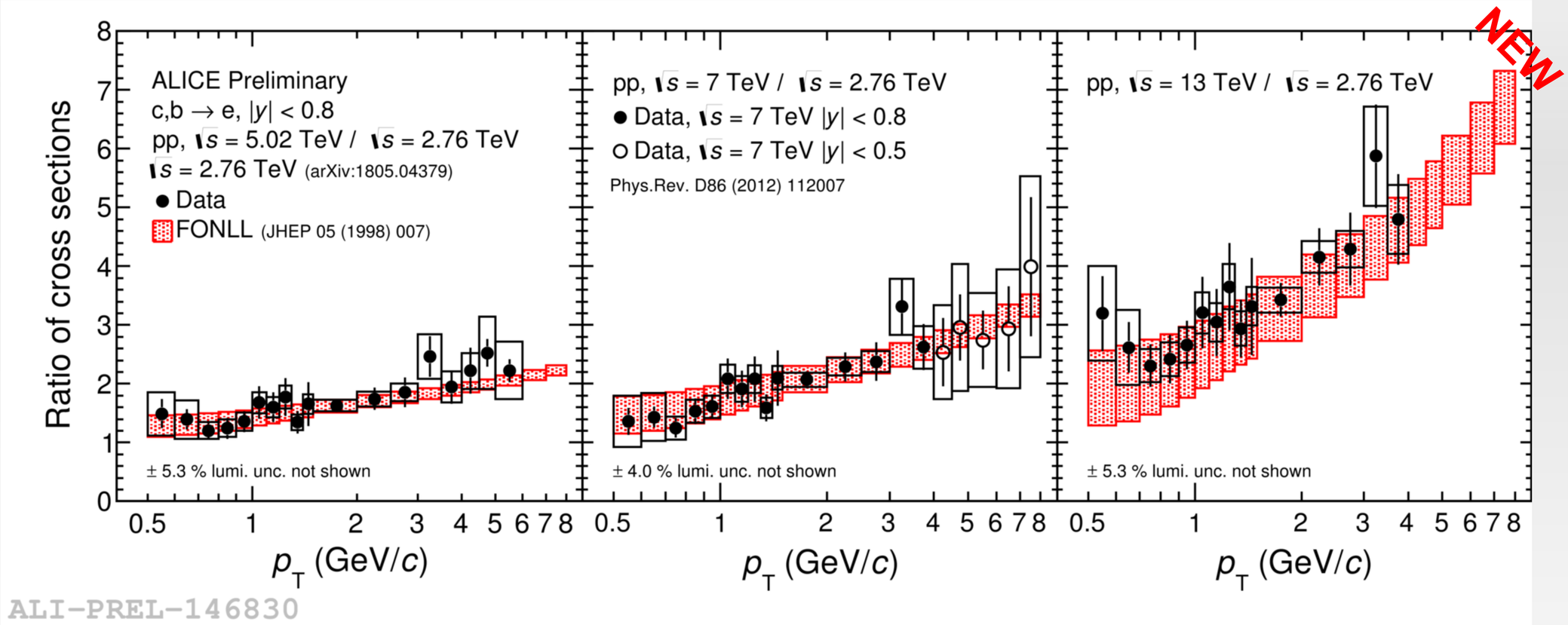


– Testing the **centre-of-mass energy dependence**

⇨ testing pQCD based calculations down to $\boldsymbol{p_T}$ **= 0.5 GeV/*c***: at the upper edge of FONLL calculation at all energies

⇨ Large improvement in the measurement precision!

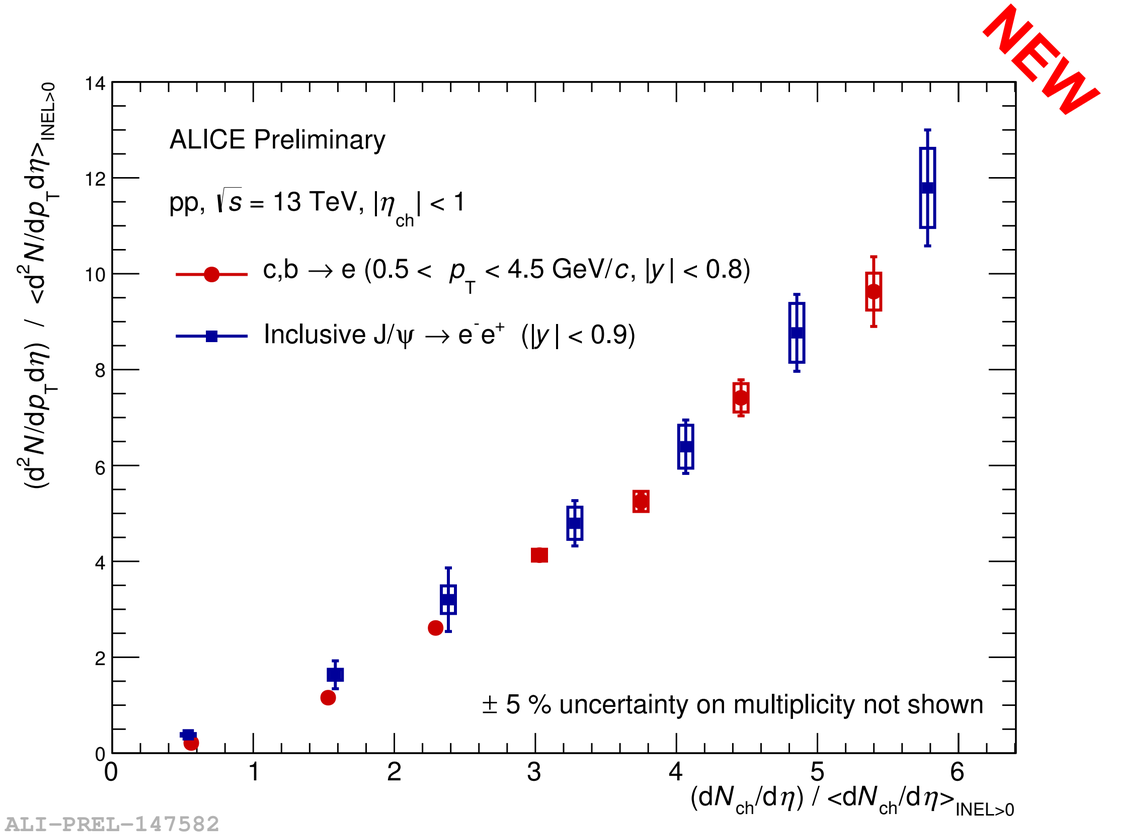
Heavy-flavour decay electrons in pp collisions

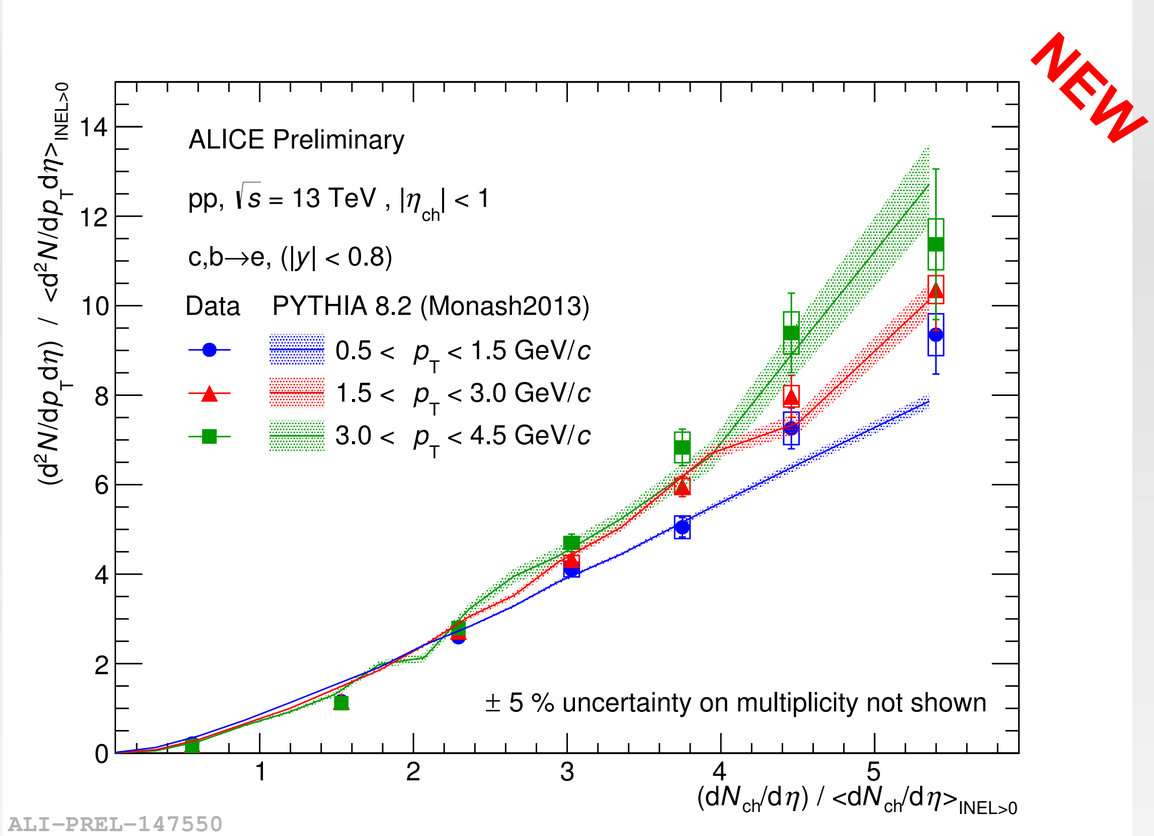


– Ratios of cross sections at different energies can be used in order to further test the pQCD FONLL calculation. In the ratios, part of the uncertainties cancel out

– It may helps to set additional constraints to model calculations
Eur.Phys.J. C75 (2015) no.12, 610

Studies of heavy-flavour production as a function of multiplicity

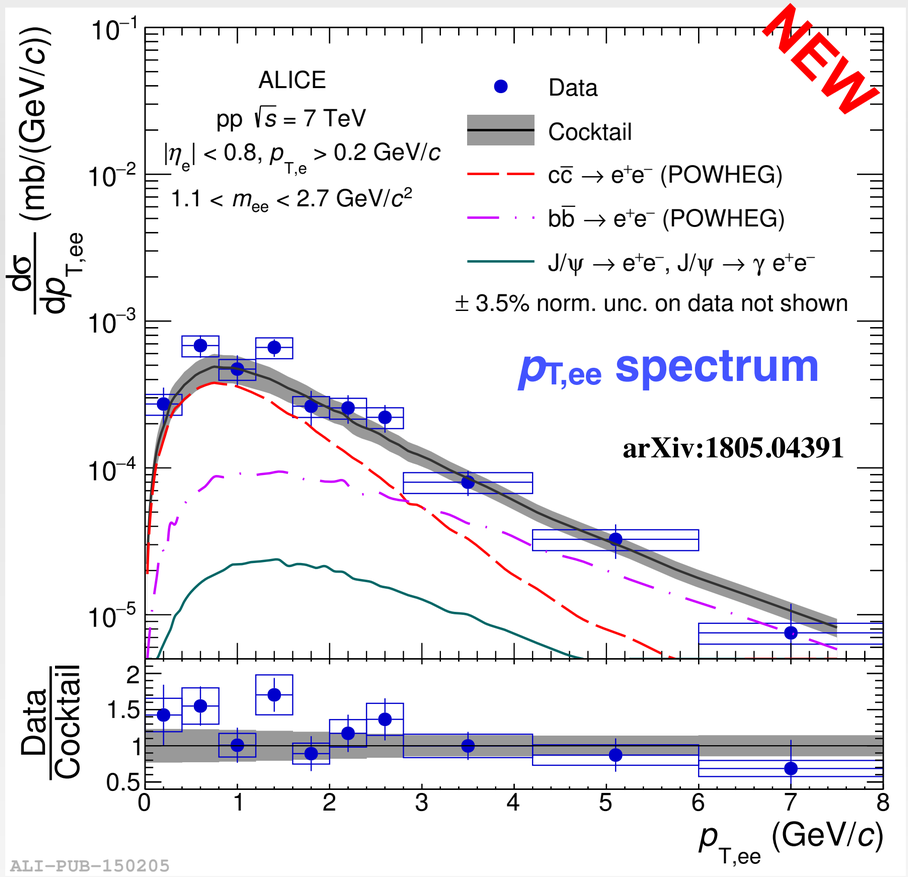


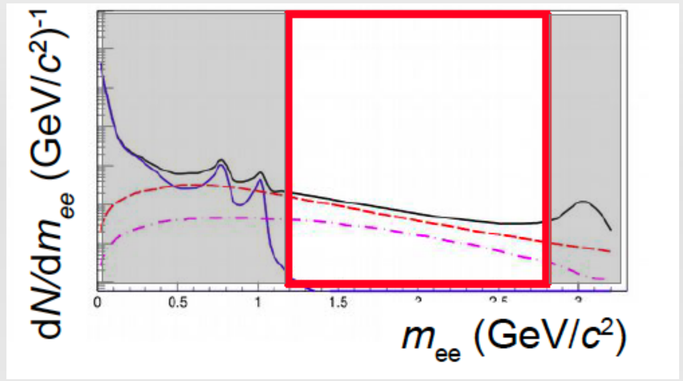


– Heavy-flavour production in pp collisions provides **insight into** their **production mechanisms** and into the interplay between **hard and soft processes** in particle production

– The self-normalized yield shows a **faster than linear increase** trend and are **comparable with J/ψ measurements and PYTHIA8.2 predictions**

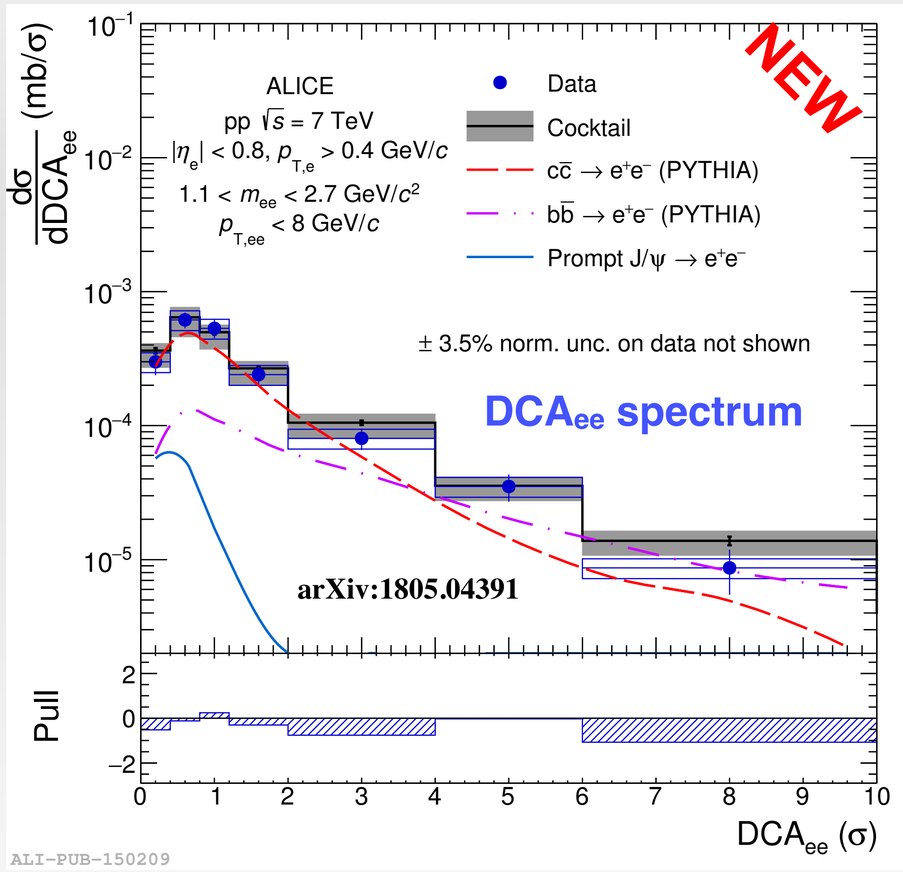
$p_{T,ee}$ and DCA_{ee} analyses in pp at $\sqrt{s}$ = 7 TeV





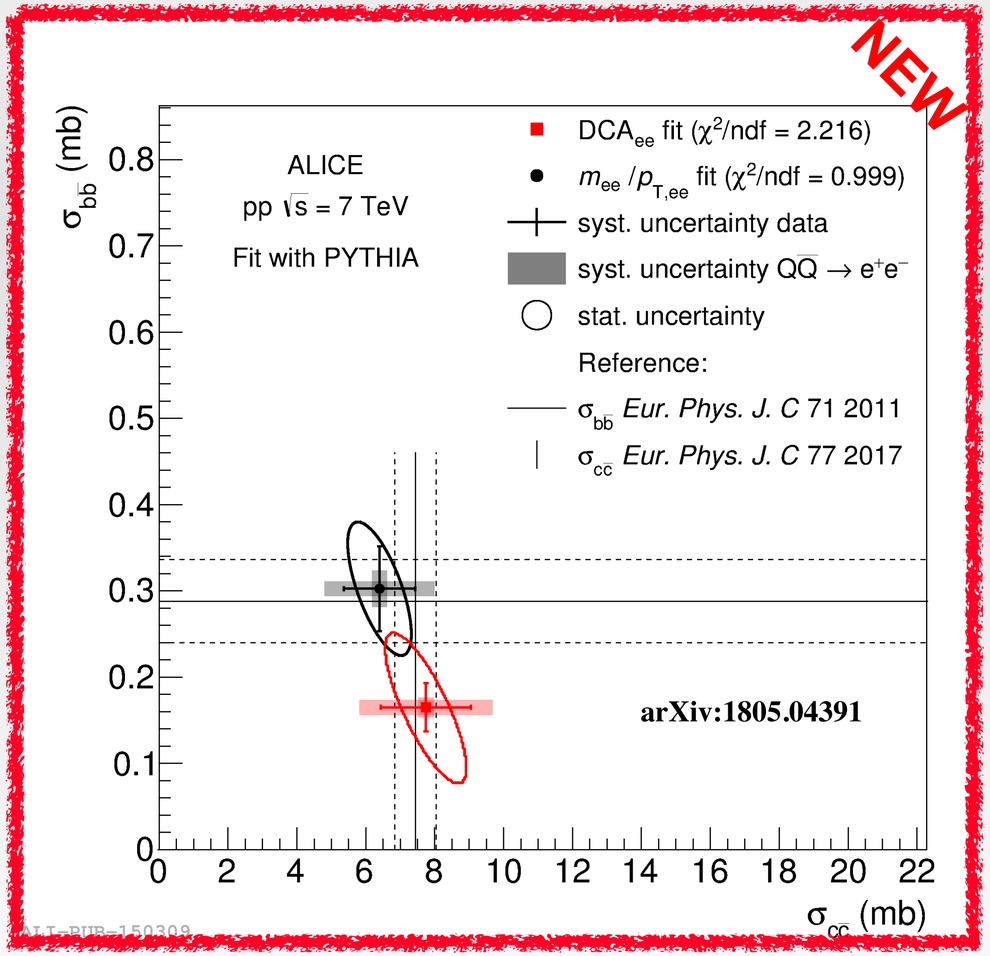
Intermediate-mass region

- **Charm** dominates at low $p_{T,ee}$ ($p_{T,ee} < 3$ GeV/c) and small DCA_{ee}
- **Beauty** dominates at large $p_{T,ee}$ ($p_{T,ee} > 4$ GeV/c) and large DCA_{ee}



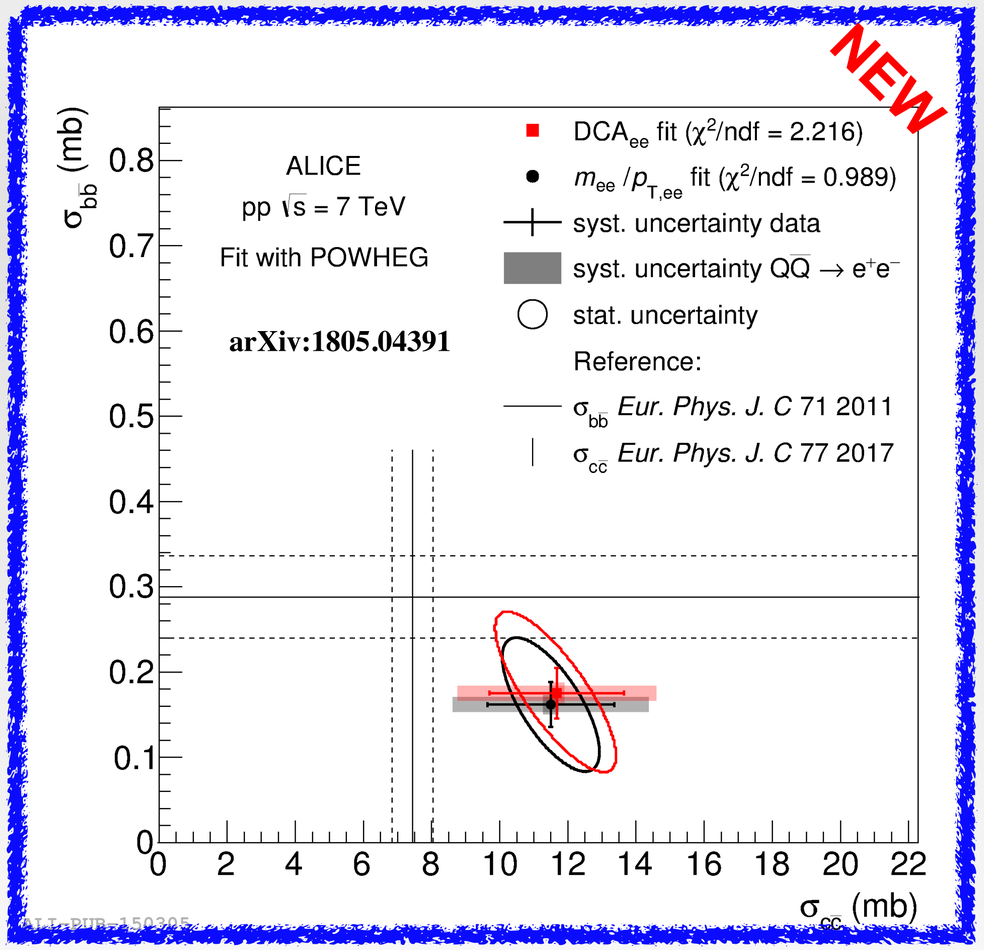
- Let the normalization of the charm and beauty contributions free in the cocktail
- Fit m_{ee}/$p_{T,ee}$ and DCA_{ee} spectra independently to extract the total charm and beauty cross sections

Model dependence



PYTHIA 6 Perugia 2011 tune (LO with parton shower)

POWHEG (NLO) + PYTHIA 6 parton shower

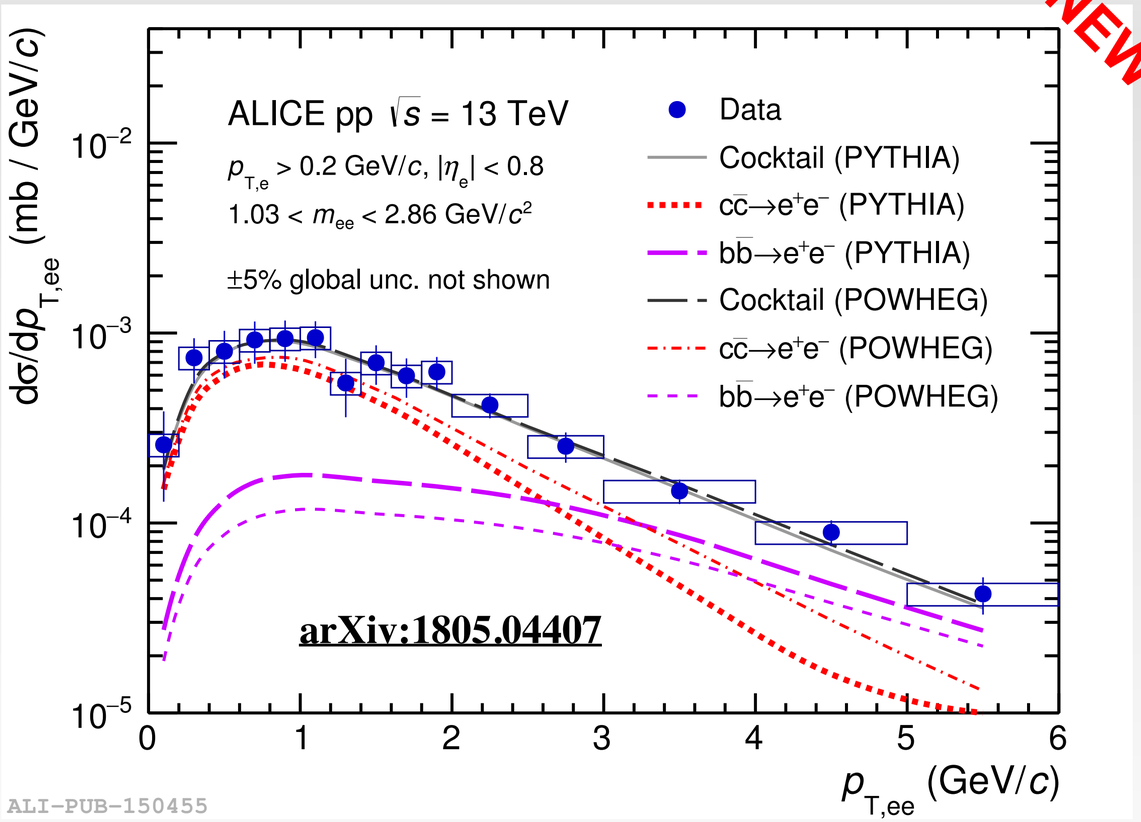


⇨ Significant **model dependence** of the extracted total charm and beauty cross section

⇨ **Sensitivity** to the different implementation of **heavy-quark production mechanisms**

Heavy-flavour production in pp at $\sqrt{s}$ = 13 TeV

$p_{T,ee}$ spectrum in the intermediate-mass region



First measurement of $d\sigma_{c\bar{c}/b\bar{b}}/dy|_{y=0}$ in pp collisions at $\sqrt{s}$ = 13 TeV

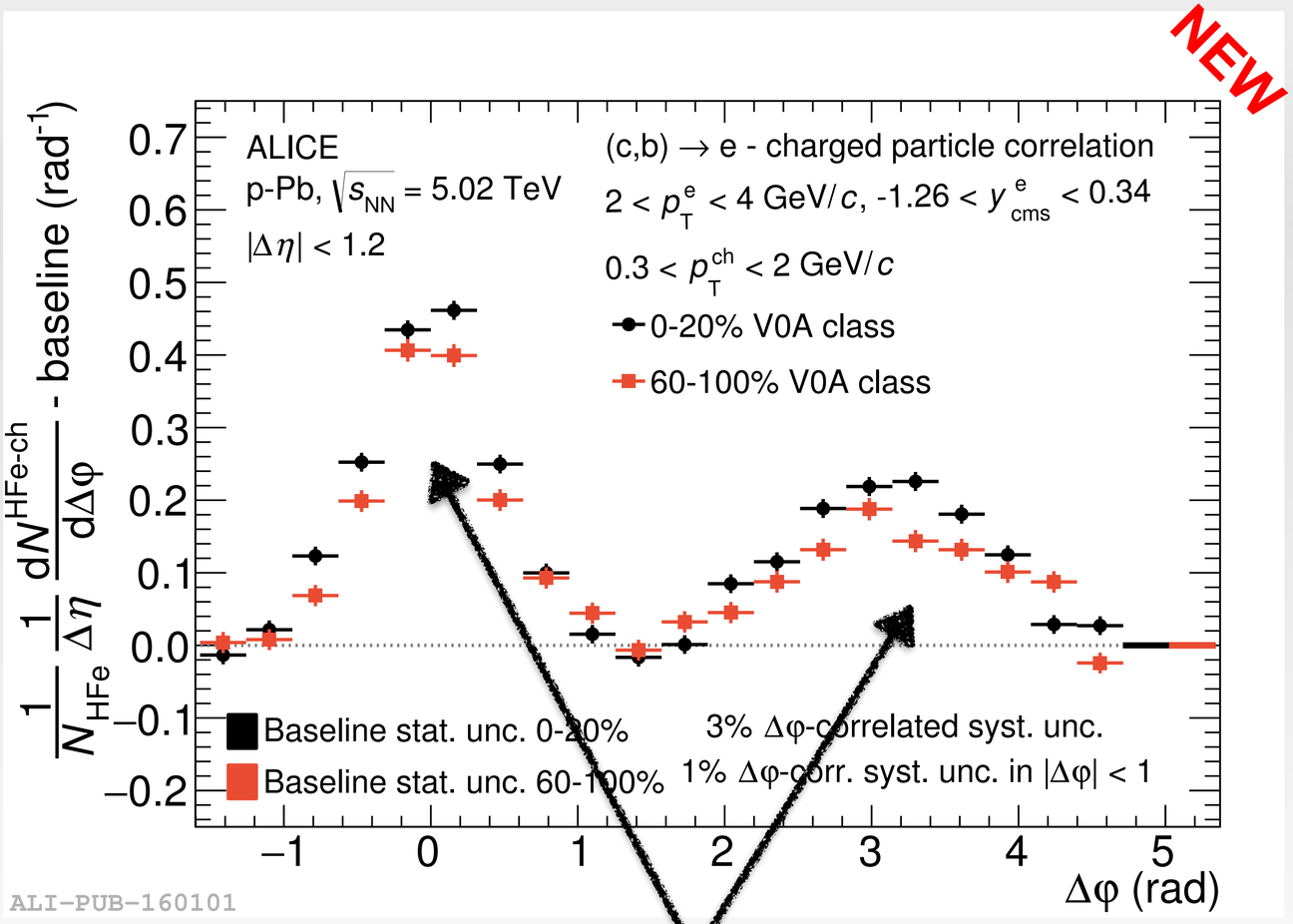
	PYTHIA 6 Perugia 2011 tune (LO with parton shower)	POWHEG (NLO) + PYTHIA 6 parton shower
$d\sigma_{c\bar{c}}/dy\|_{y=0}$	$974 \pm 138\,(\text{stat.}) \pm 140\,(\text{syst.})$ µb	$1417 \pm 184\,(\text{stat.}) \pm 204\,(\text{syst.})$ µb
$d\sigma_{b\bar{b}}/dy\|_{y=0}$	$79 \pm 14\,(\text{stat.}) \pm 11\,(\text{syst.})$ µb	$48 \pm 14\,(\text{stat.}) \pm 7\,(\text{syst.})$ µb

- ⇨ **Fit 2D** $p_{T,ee}$ and m_{ee} spectra to extract $d\sigma_{cc/bb}/dy|_{y=0}$
- ⇨ Similar **model dependence** observed as at $\sqrt{s}$ = 7 TeV
- ⇨ Further studies of charm production mechanisms

Heavy-flavour elliptic flow in p-Pb collisions

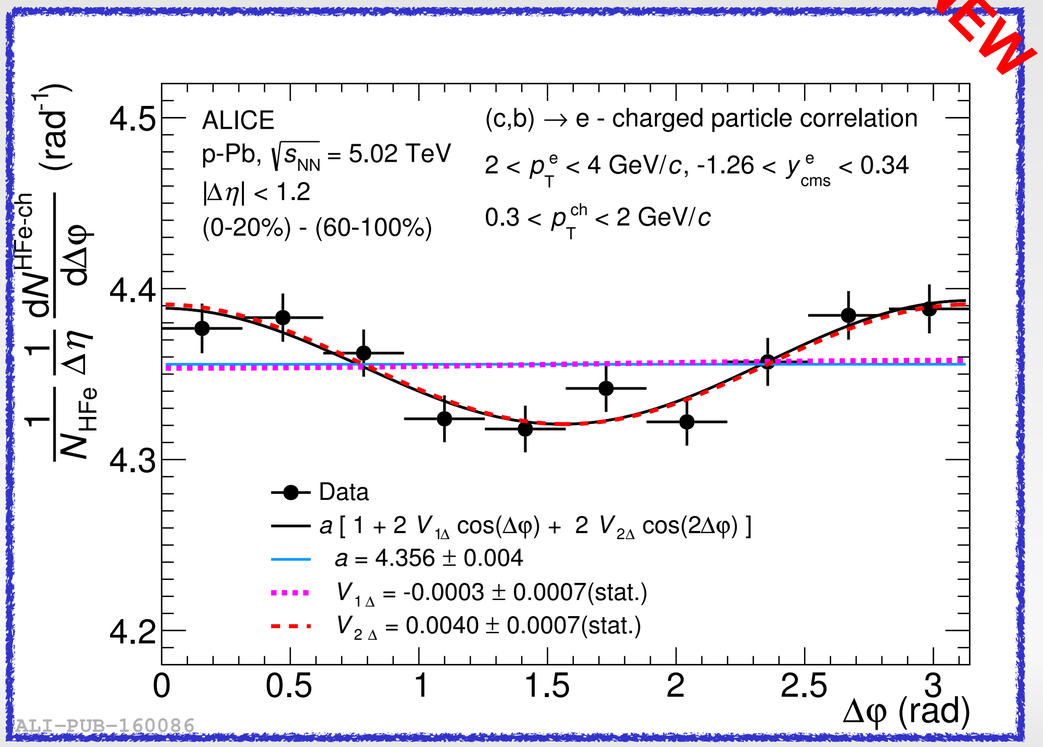
– **Two-particle correlations** of HFe with charged particles in **high multiplicity** and **low multiplicity** events

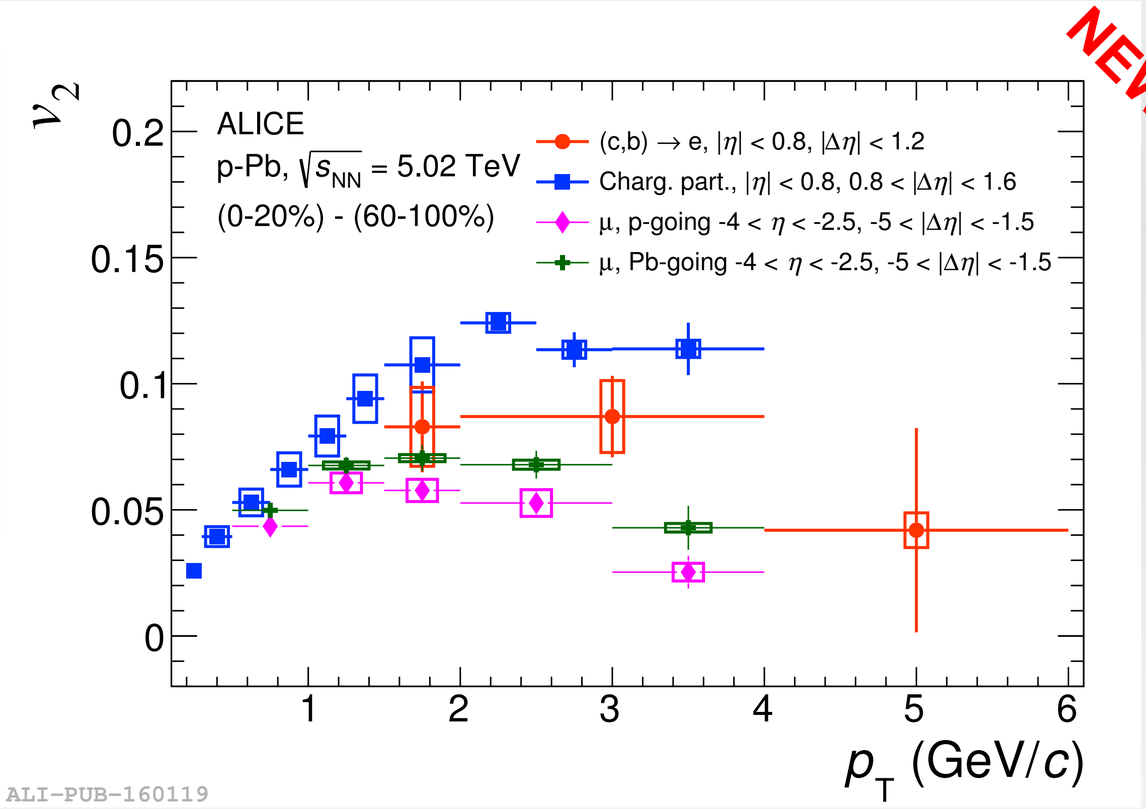
– Near and away side **modification** from low multiplicity to high multiplicity



Heavy-flavour elliptic flow in p-Pb collisions

- Jet subtraction: high mult. - low mult.
- **Modulation present!** Collective effects Initial- or final-state effect





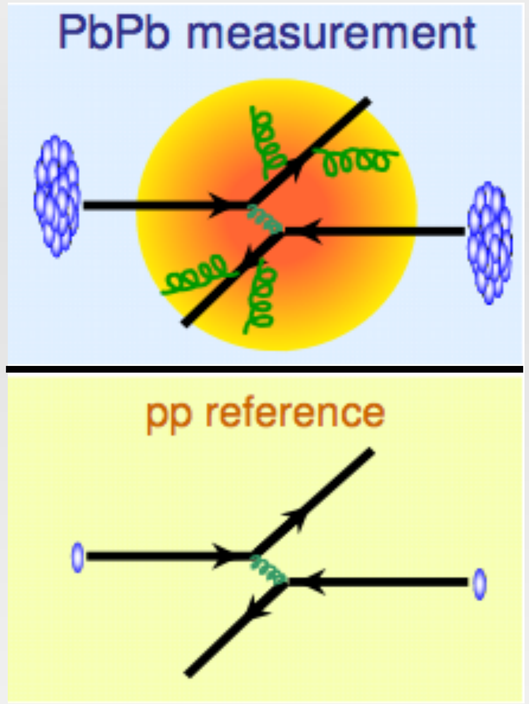
- Significance: **5.1σ for 1.5< p_{Te}< 4 GeV/c**
- Effect is qualitatively similar to the one observed for light flavours and inclusive muons

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

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

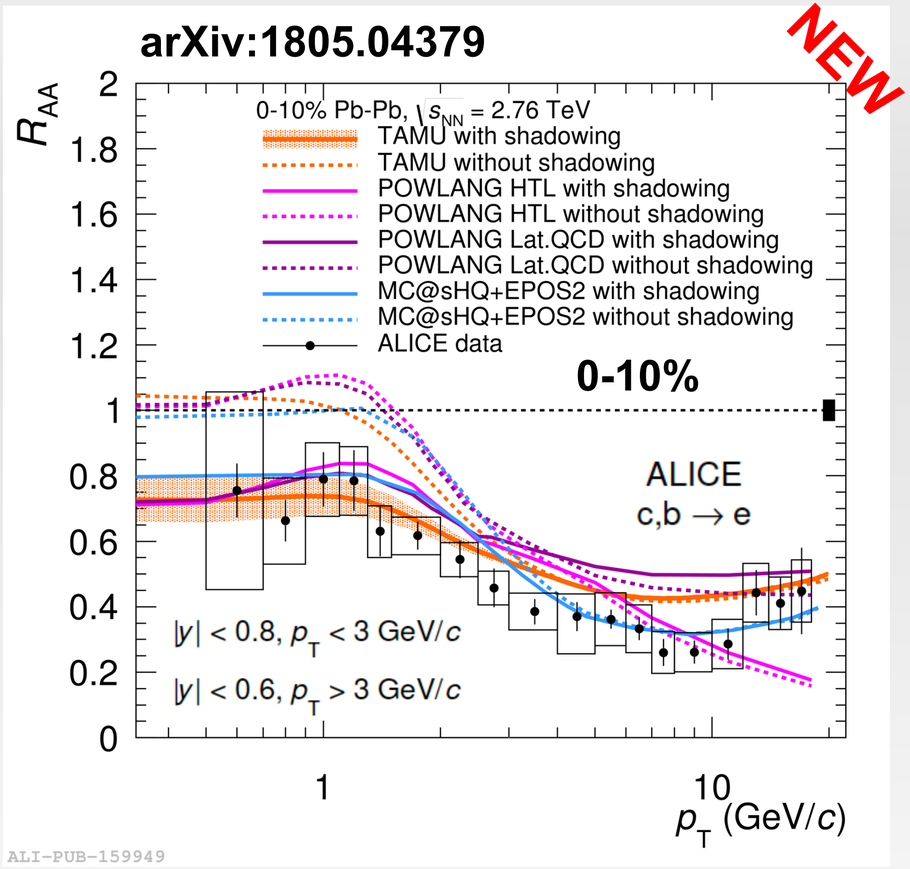


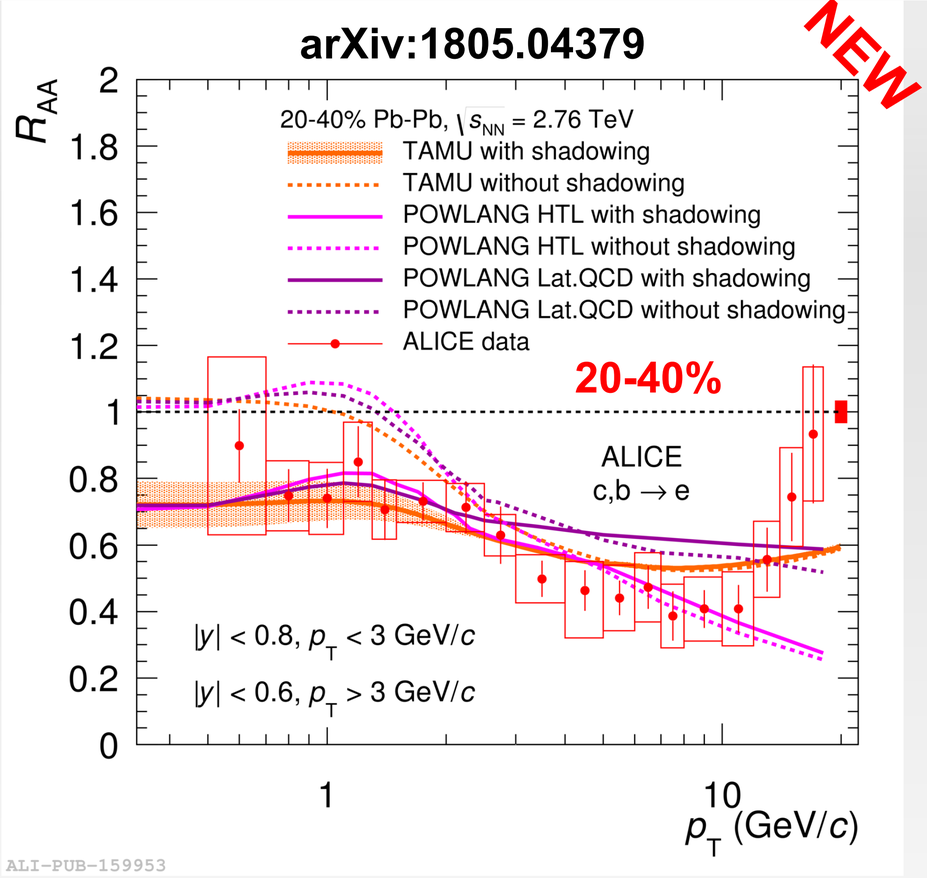
- If no nuclear effects are present → R_{AA} = 1

- **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

Heavy-flavour hadron decay electron nuclear modification factor



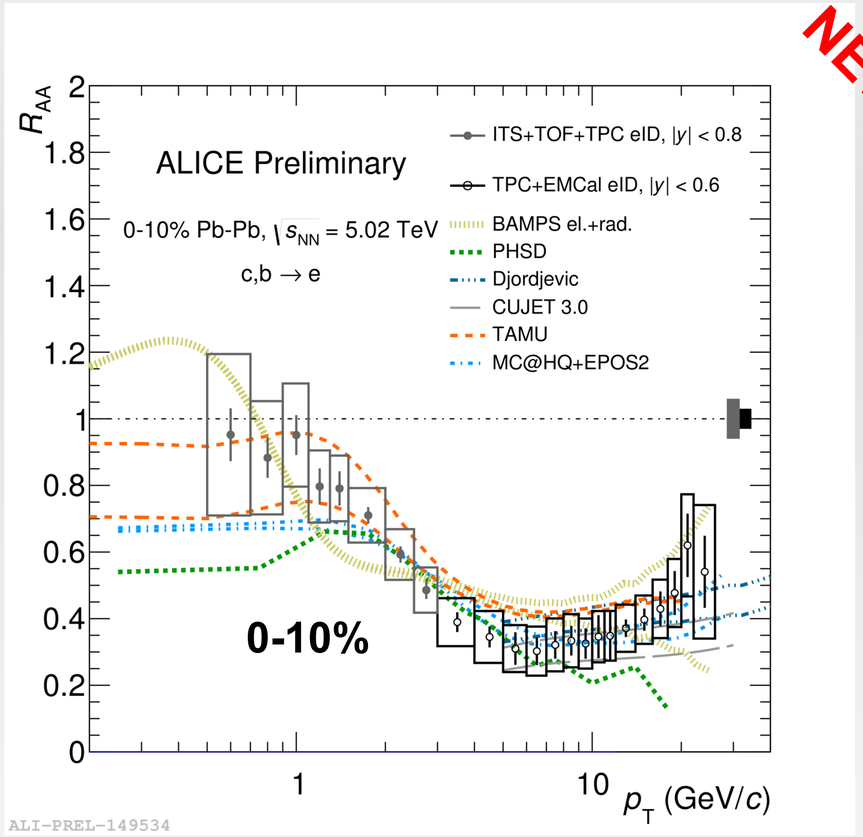


– Data are better described when the nuclear PDFs **(EPS09)** are included in the model calculation (**TAMU**, **POWLANG** and **MC@sHQ+EPOS2**) in both centrality intervals

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

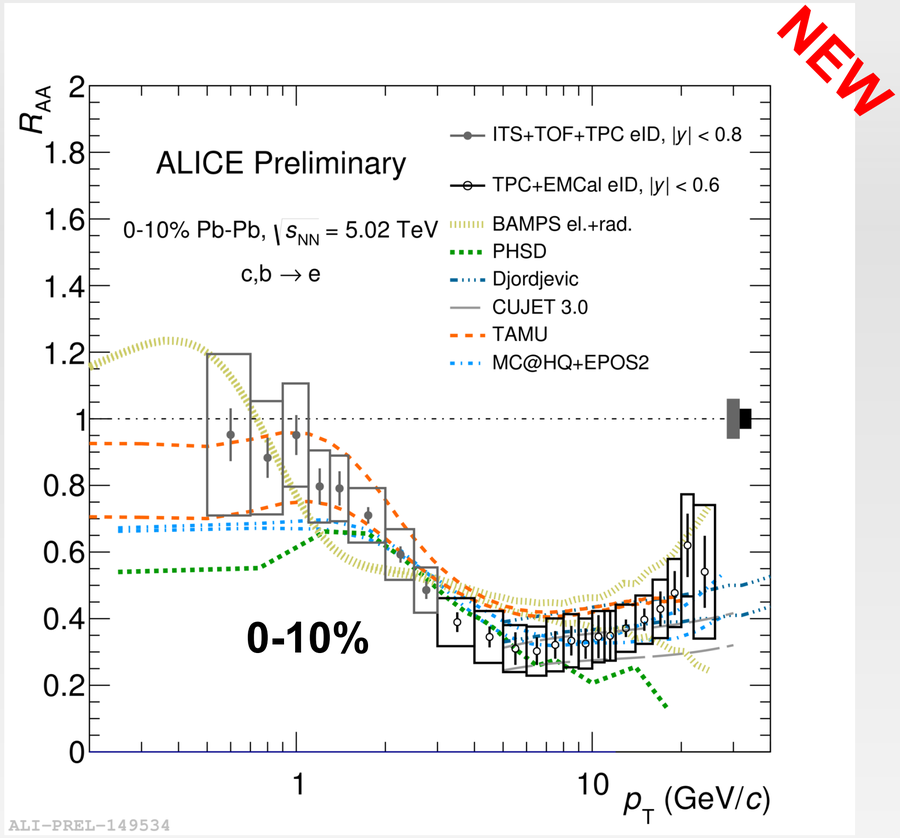
– Suppression at intermediate/high p_T is better described by models that include both **radiative** and **collisional energy loss** processes

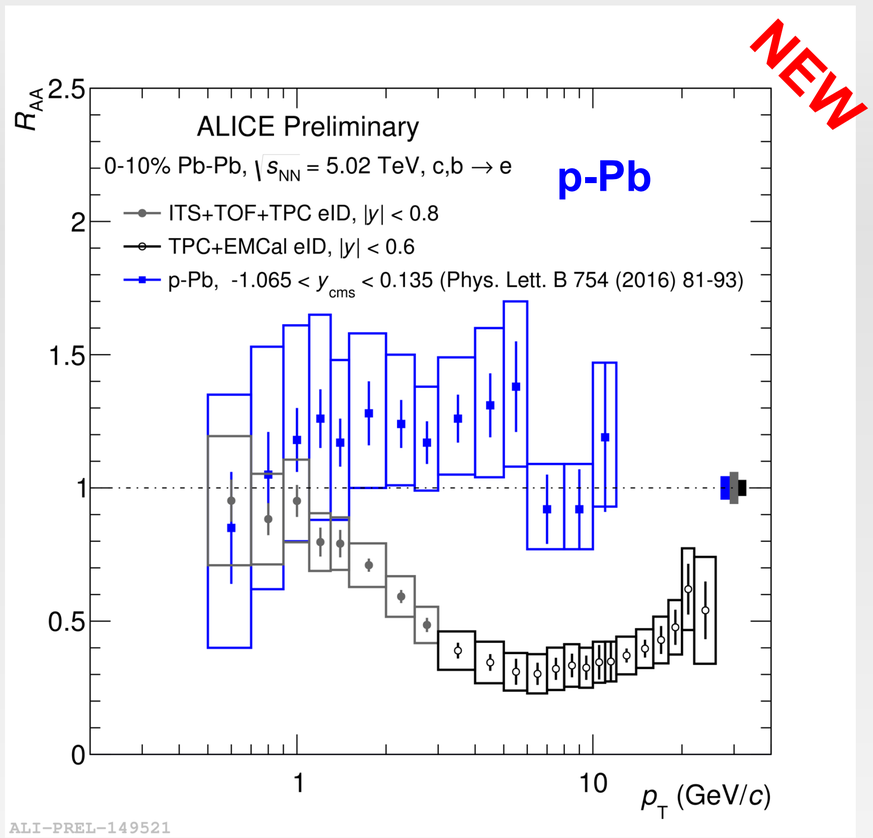
Heavy-flavour hadron decay electron nuclear modification factor



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

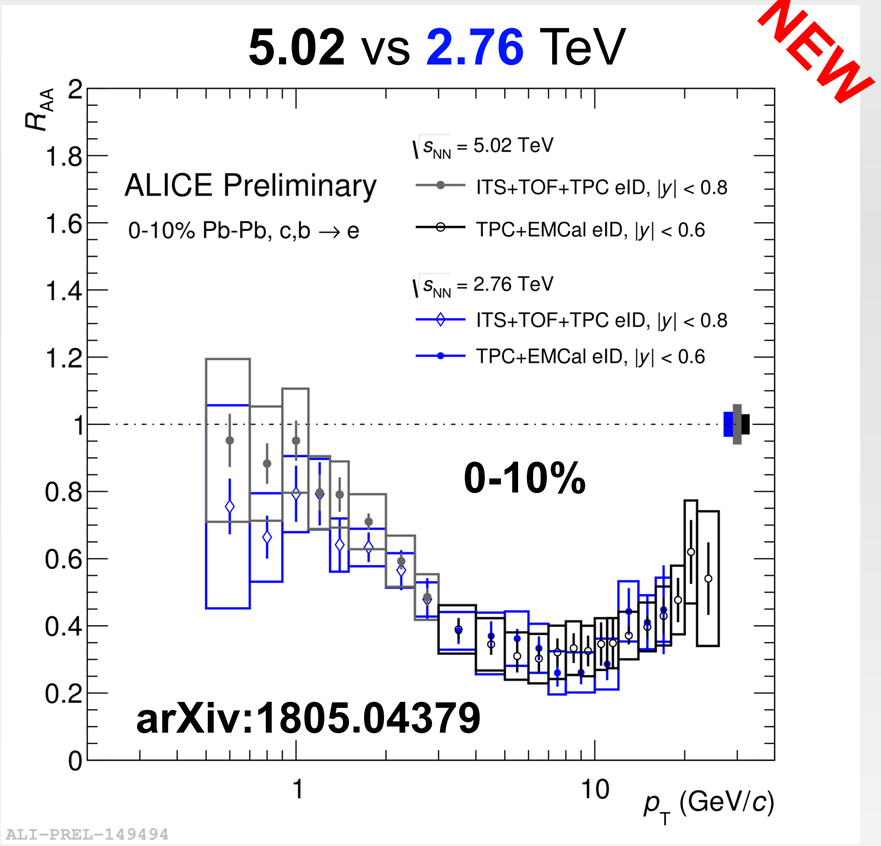
Heavy-flavour hadron decay electron nuclear modification factor





- **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

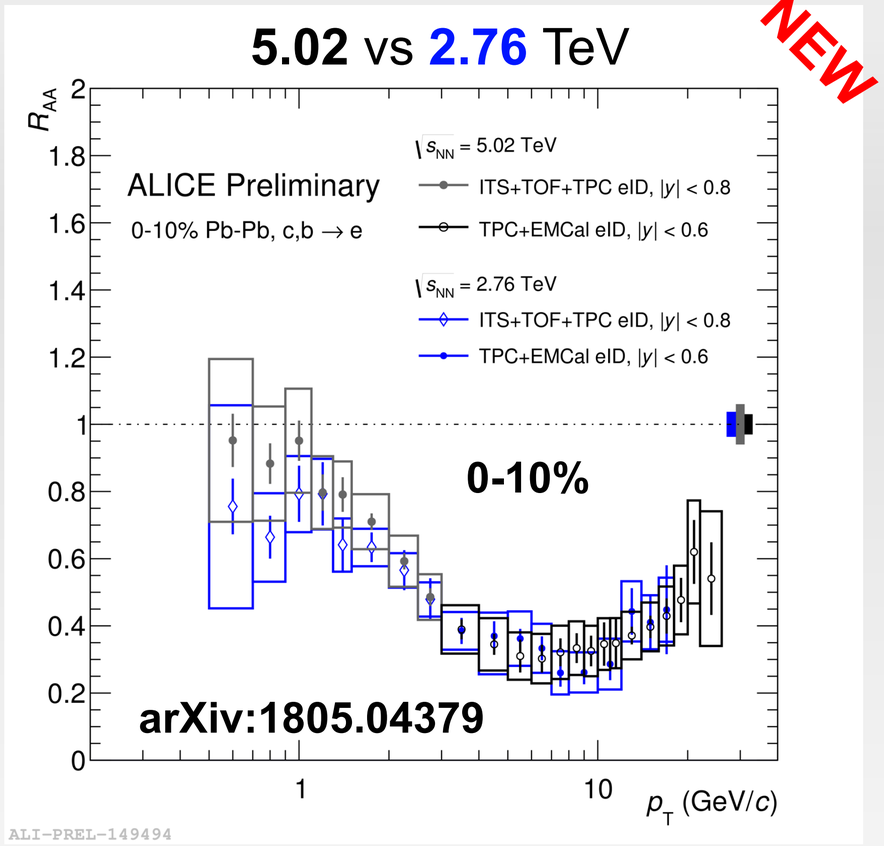


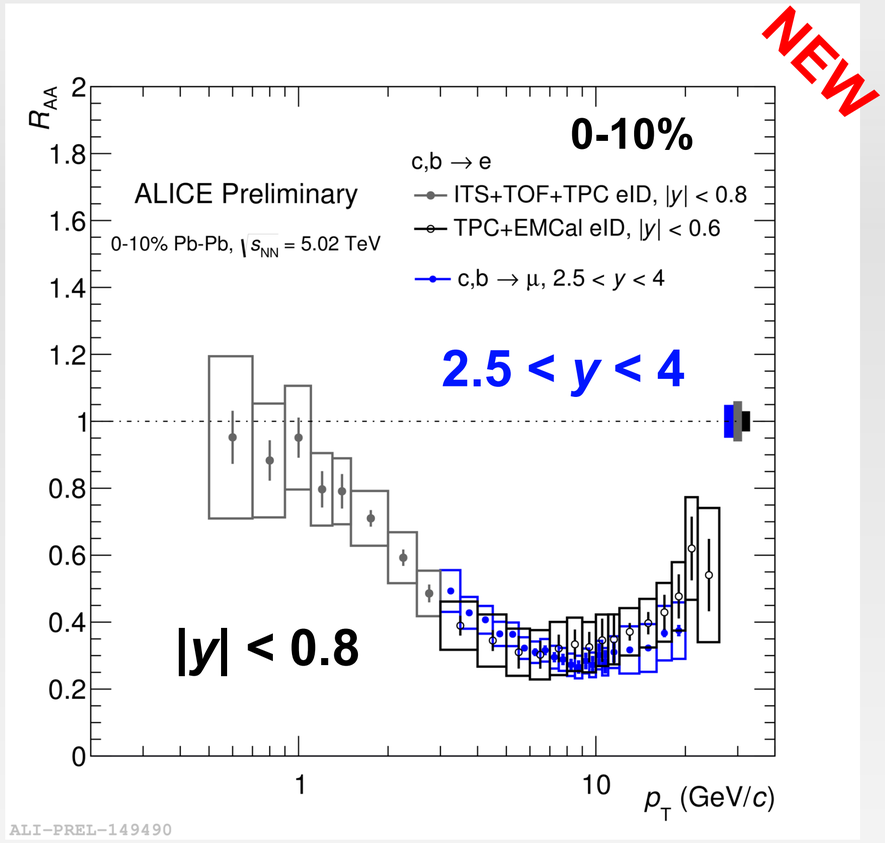
– Similar R_{AA} is measured between the two collision energies.

⇨ 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

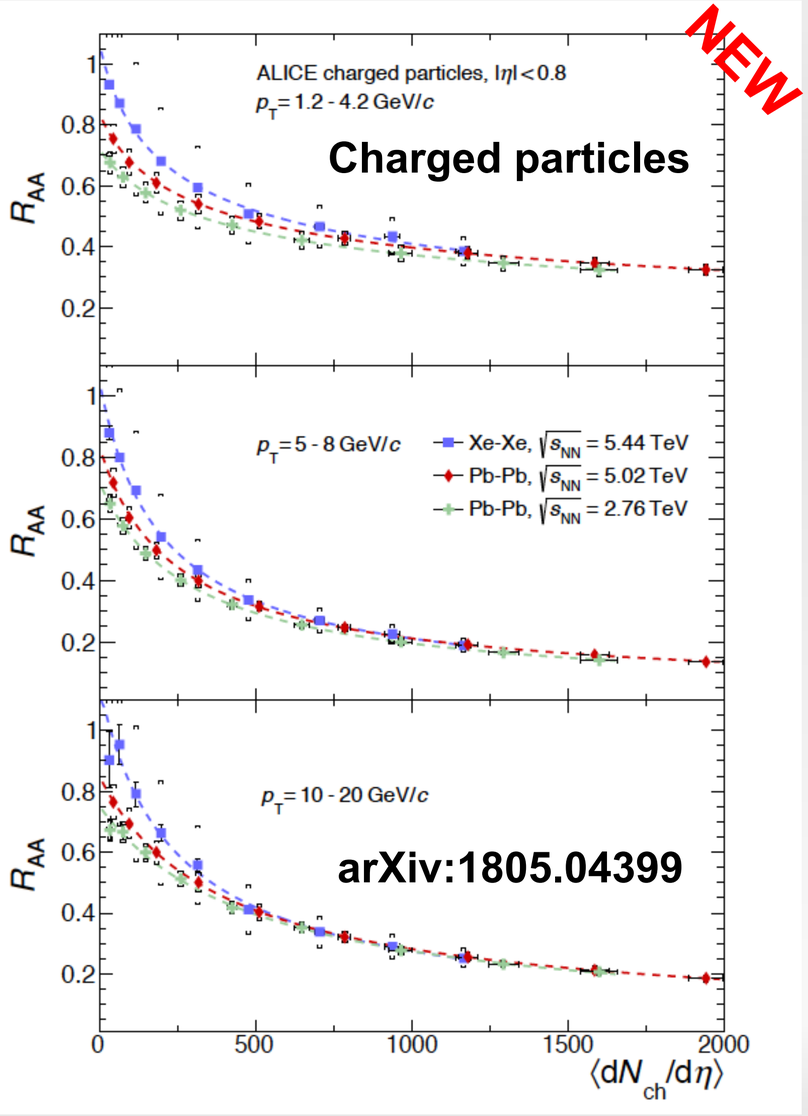
Heavy-flavour hadron decay electron nuclear modification factor





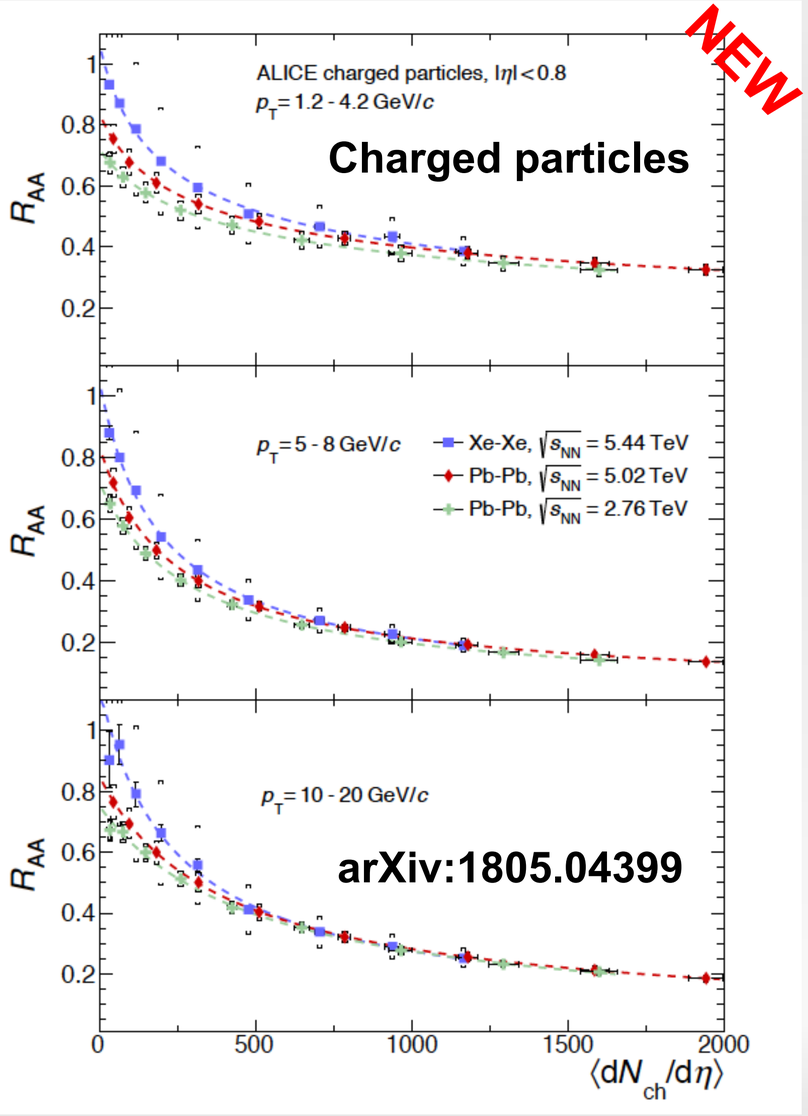
– Similar R_{AA} is measured between the two collision energies.
  ⇨ interplay between **harder p_T spectra** and **larger energy loss** at 5.02 TeV w.r.t 2.76 TeV
    - modulo different charm/beauty fraction
– Suppression compatible with the one observed for **muons** from heavy-flavour hadron decay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

Nuclear modification factor in Xe-Xe collisions at 5.44 TeV

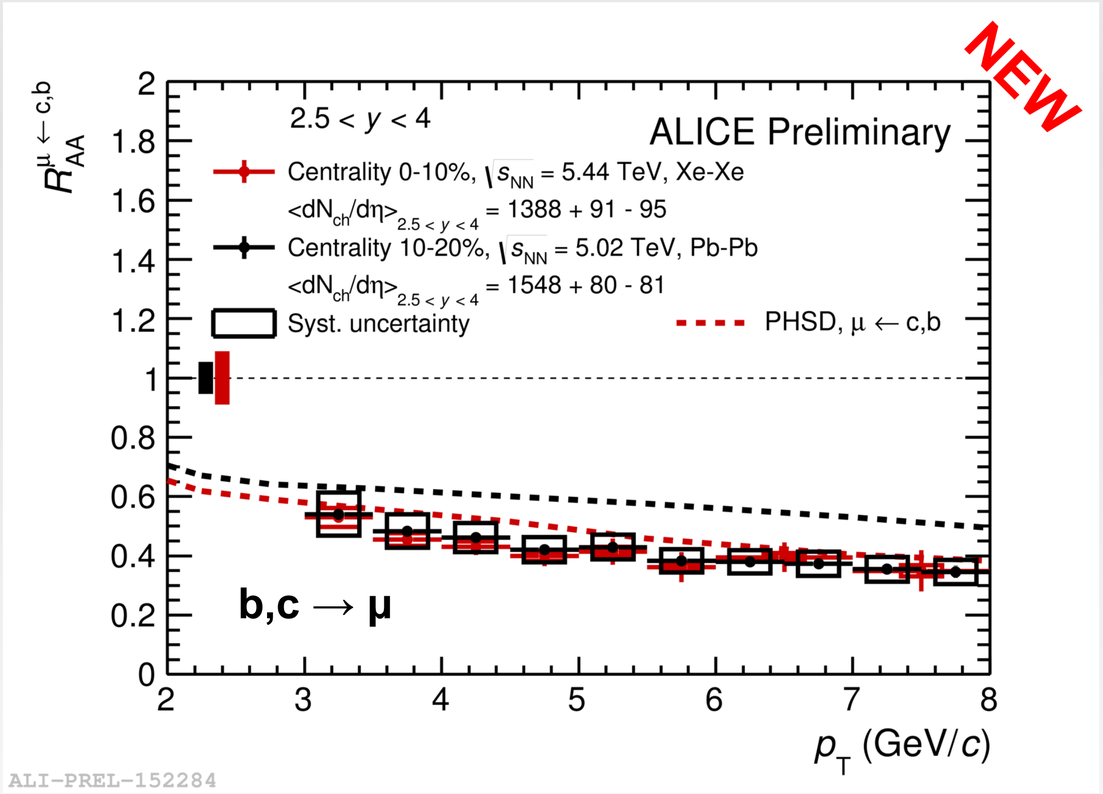


Similar R_{AA} is observed in Xe-Xe and Pb-Pb when compared at similar <dN/dη>

Nuclear modification factor in Xe-Xe collisions at 5.44 TeV



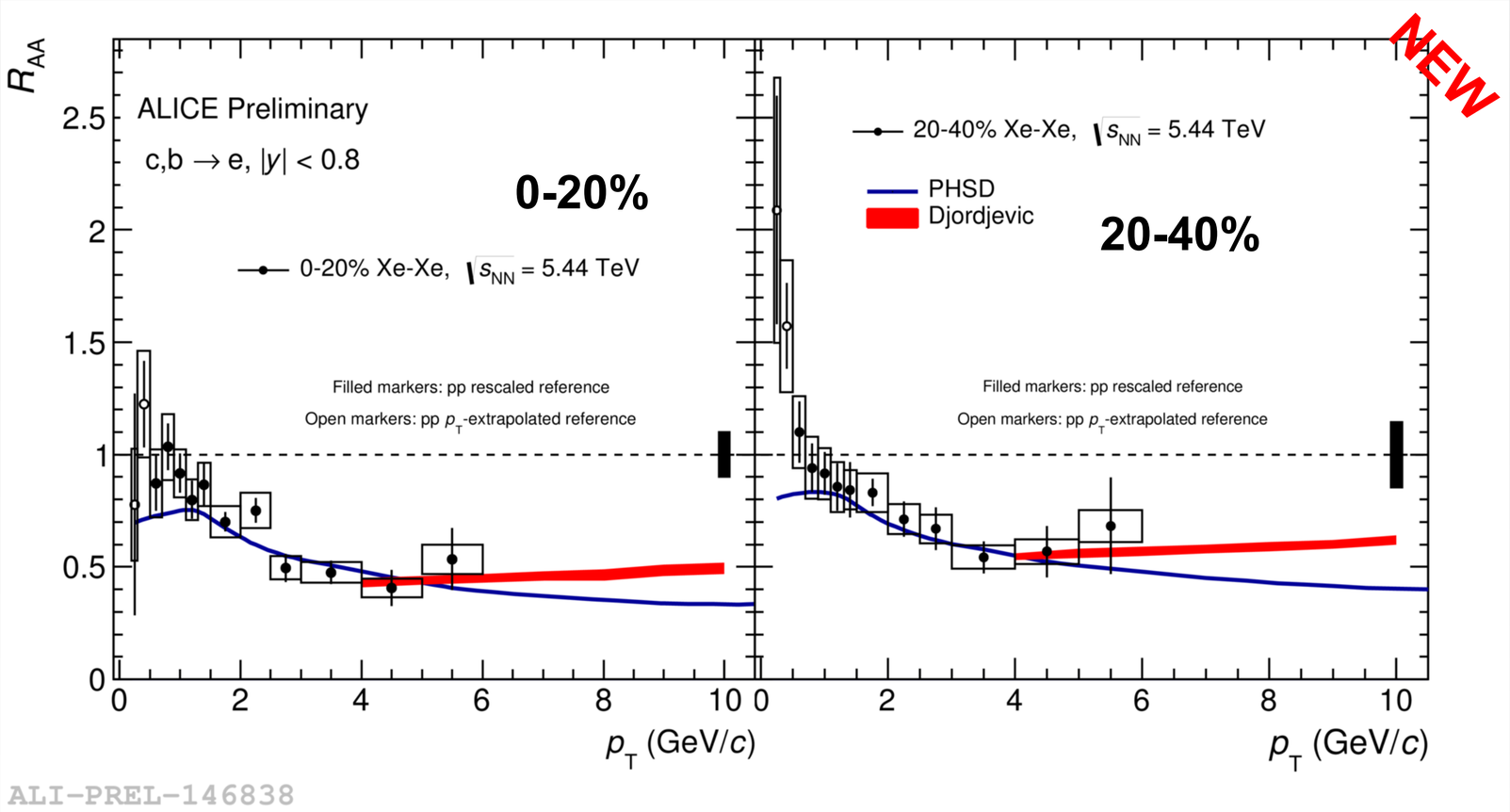
Similar R_{AA} is observed in Xe-Xe and Pb-Pb when compared at similar $\langle dN/d\eta \rangle$



– 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

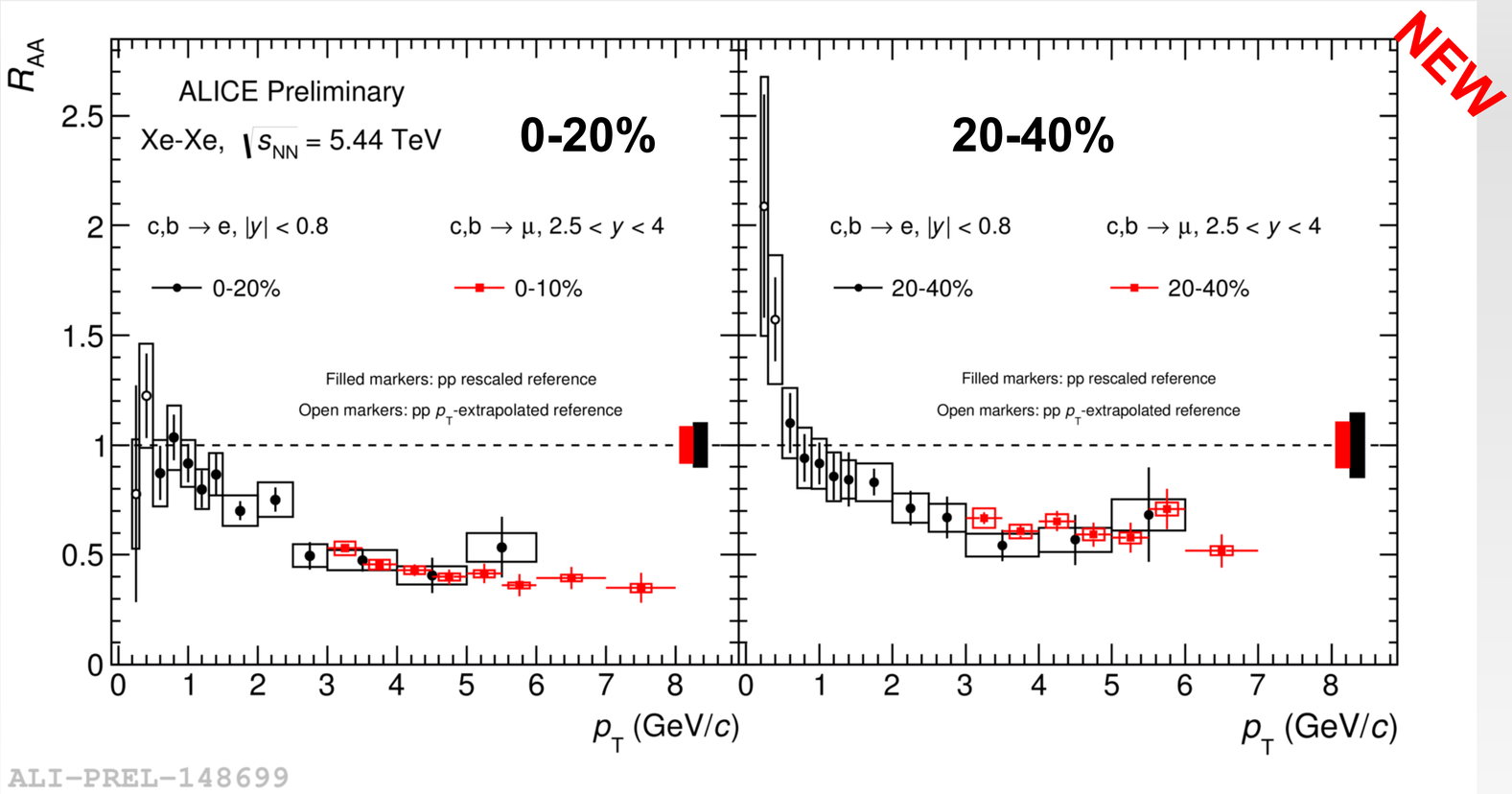
– **New R_{AA}** measured down to **p_T = 0.2 GeV/c** thanks to the low B field used in ALICE during the Xe-Xe data taking!



– 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}

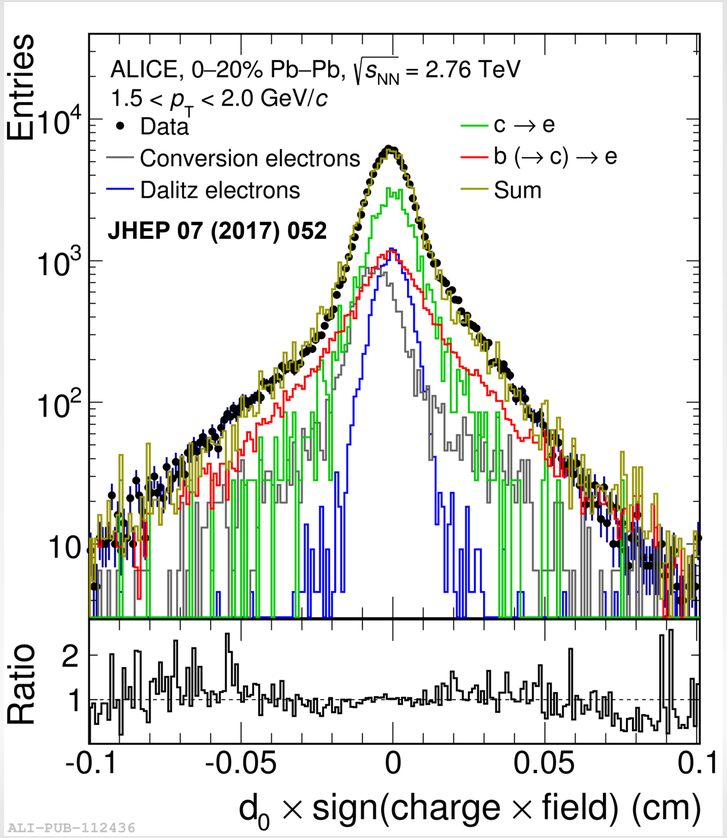
– Analysis based on the electron impact parameter distribution

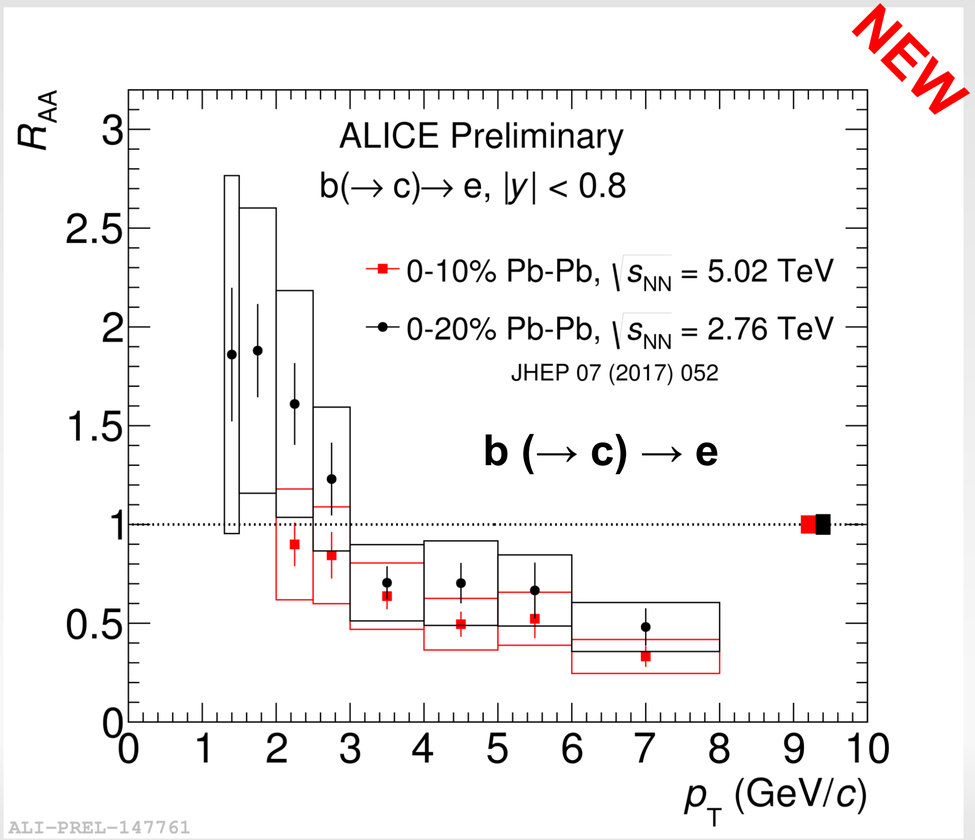
JHEP 07 (2017) 052

– **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**

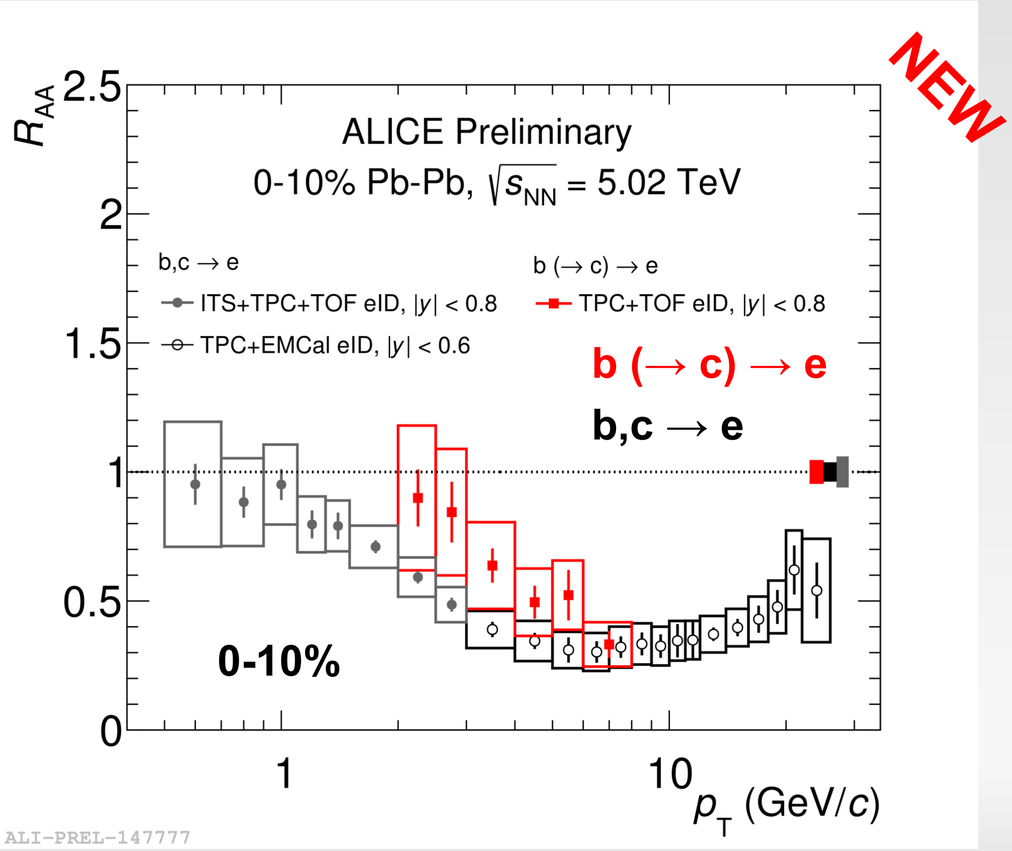
⇨ $R_{AA} < 1$ for $p_T > 3$ GeV/c and compatible with the R_{AA} measured at 2.76 TeV

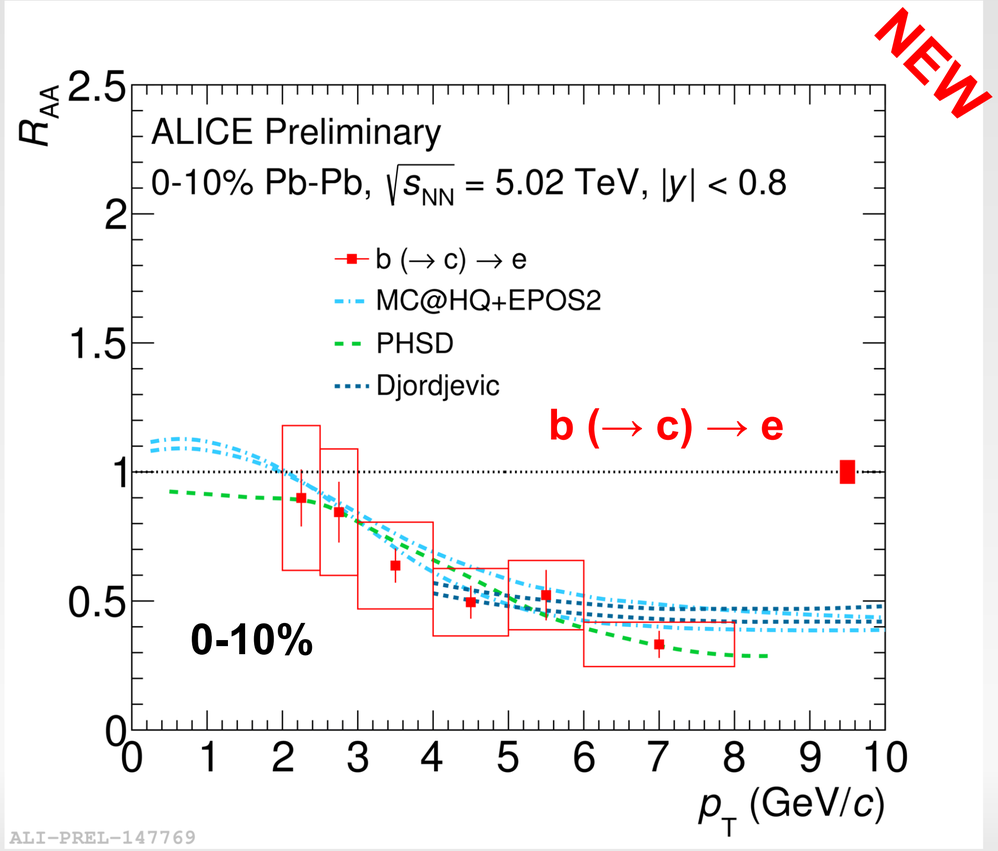




Beauty-decay electron R_{AA}

– **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





Where we are….

pp collisions

- ⇨ Production cross section described by pQCD calculations
  - ✓ HF are a calibrated probe of the medium created in heavy-ion collisions
  - ✓ new di-electron measurements allow to study heavy-flavour production

Pb-Pb and Xe-Xe collisions

- ⇨ Substantial **modification of D and B meson p_T spectra**
  - ✓ Potential to constrain energy loss mechanisms and medium transport coefficients
- ⇨ Indication for $R_{AA}^{beauty} > R_{AA}^{charm}$
  - ✓ Consistent with the predicted quark-mass dependent energy loss
- ⇨ Positive heavy-flavour particle **elliptic flow**
  - ✓ Suggests that charm quarks take part in the collective expansion of the medium

p-Pb collisions

- ⇨ Original motivation: a control experiment
  - ✓ Confirm that D and B meson suppression in Pb-Pb at high p_T is a final-state effect
  - ✓ Small cold nuclear matter effects at mid-rapidity
- ⇨ But also unexpected results qualitatively resembling the collective behaviour observed in Pb-Pb collisions

… and what next

Pb-Pb: larger samples at higher energy

- ⇨ Improved precision + extended p_T coverage
  - ✓ Quantitatively constrain energy loss models
  - ✓ Study whether charm and beauty quarks thermalize in the medium
  - ✓ Total charm cross-section measurement

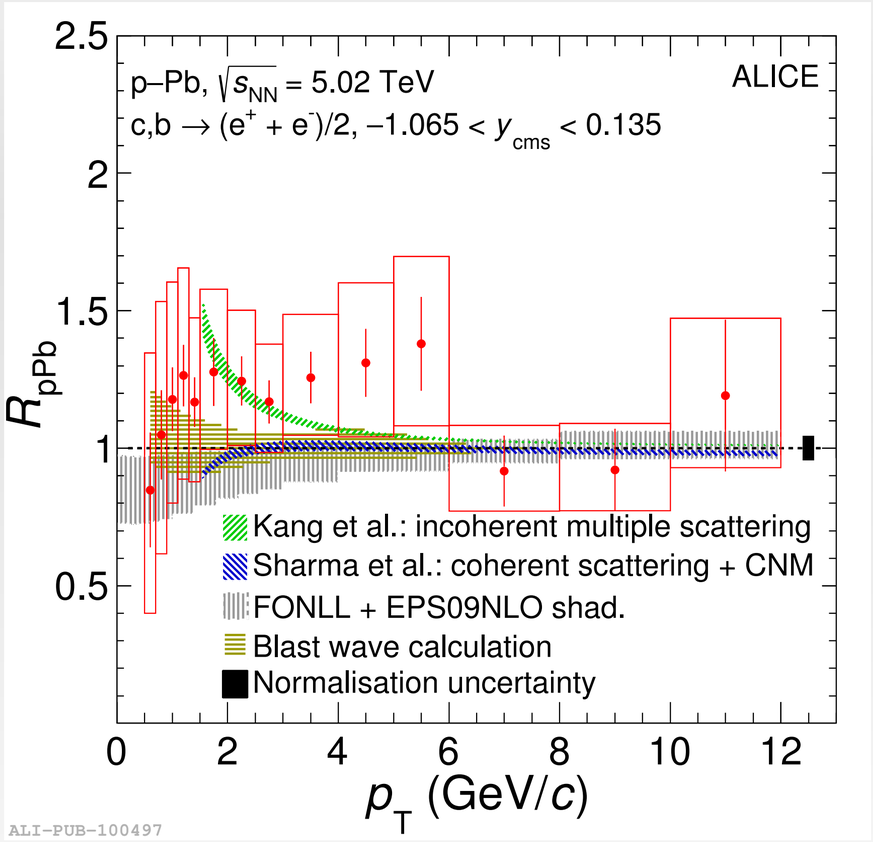
p-Pb and pp collisions

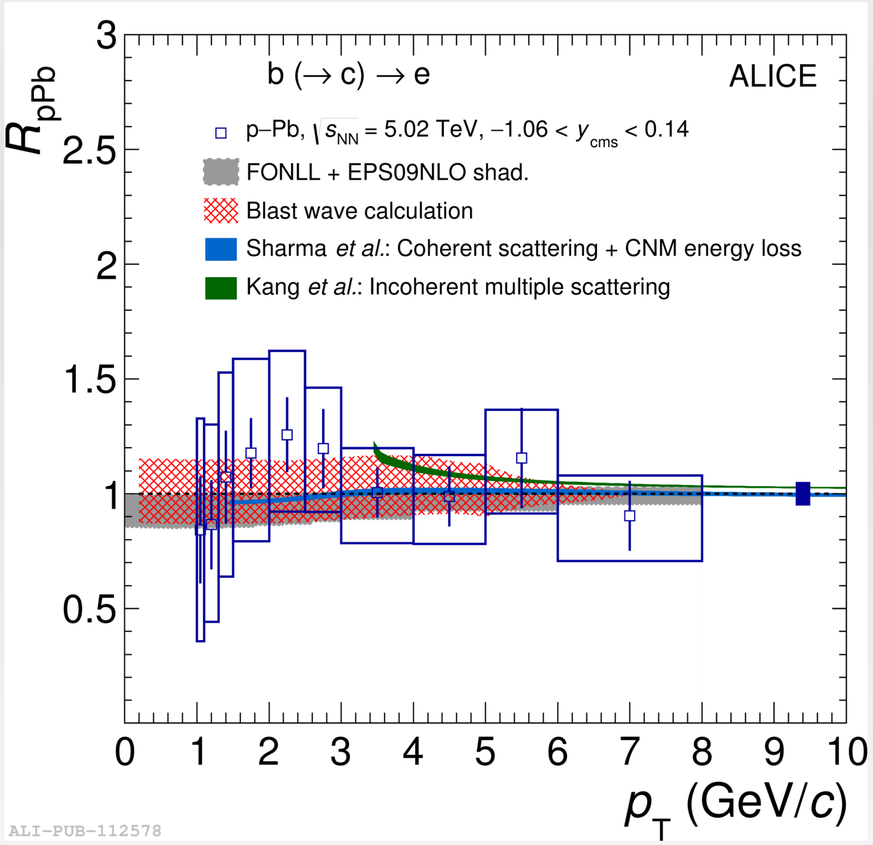
- ⇨ Improved precision on pp reference and assessment of CNM effects
  - ✓ Crucial role in the interpretation of Pb-Pb results
- ⇨ Production vs. multiplicity/centrality
- ⇨ Additional studies on collectivity in high multiplicity pp and p-Pb collisions in the HF sector

Major step towards high-precision measurements in the HF sector with the detector upgrades after Run2

BACKUP

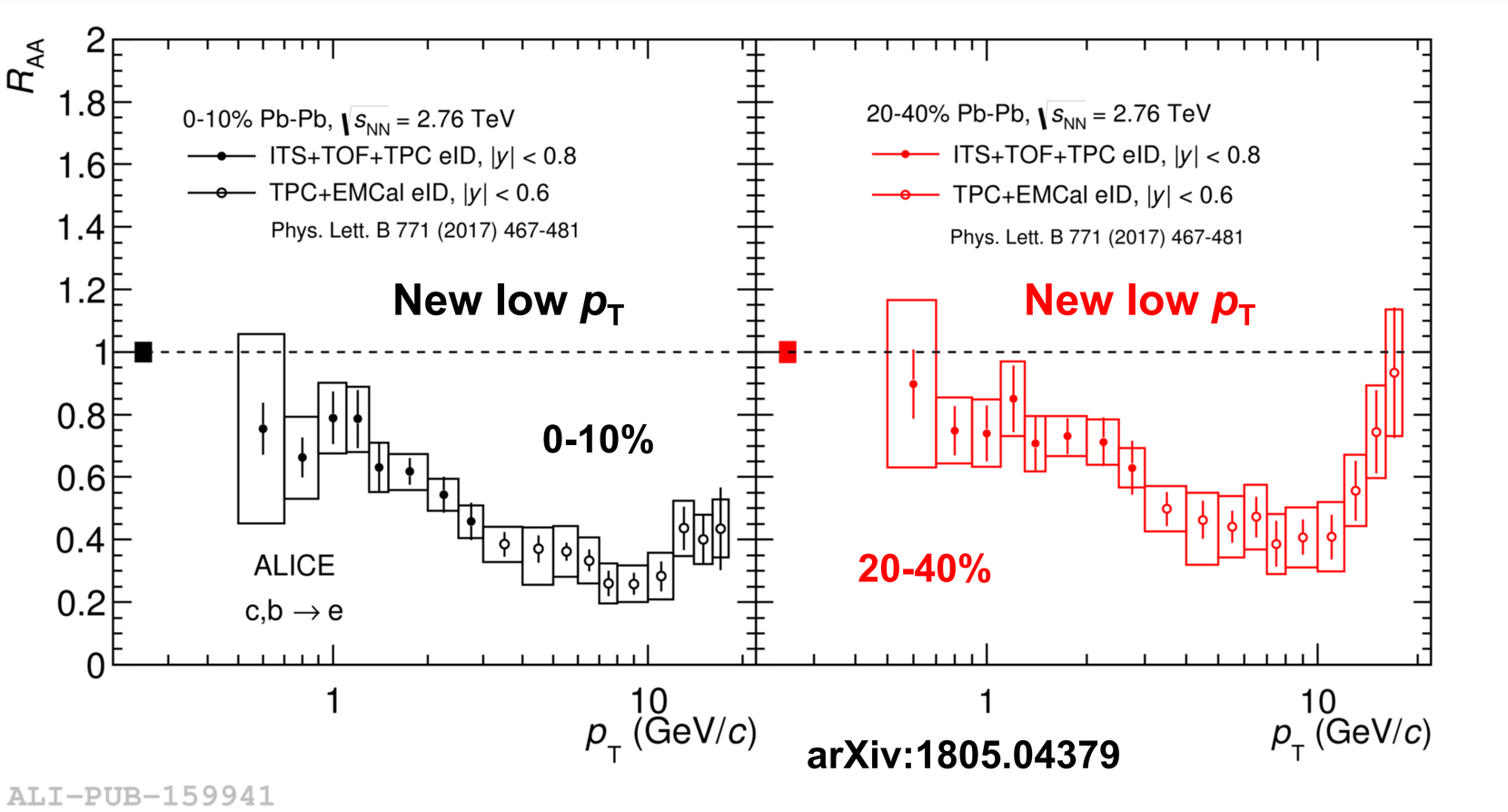
Production in p-Pb collisions





– For both inclusive HF and beauty decay electron an R_{pPb} = 1 has been measured within the uncertainties
  – No indication of significant cold nuclear matter effects on charm and beauty production
  – Large uncertainties do not allow to discriminate among models implementing different CNM effects

Heavy-flavour hadron decay electron nuclear modification factor



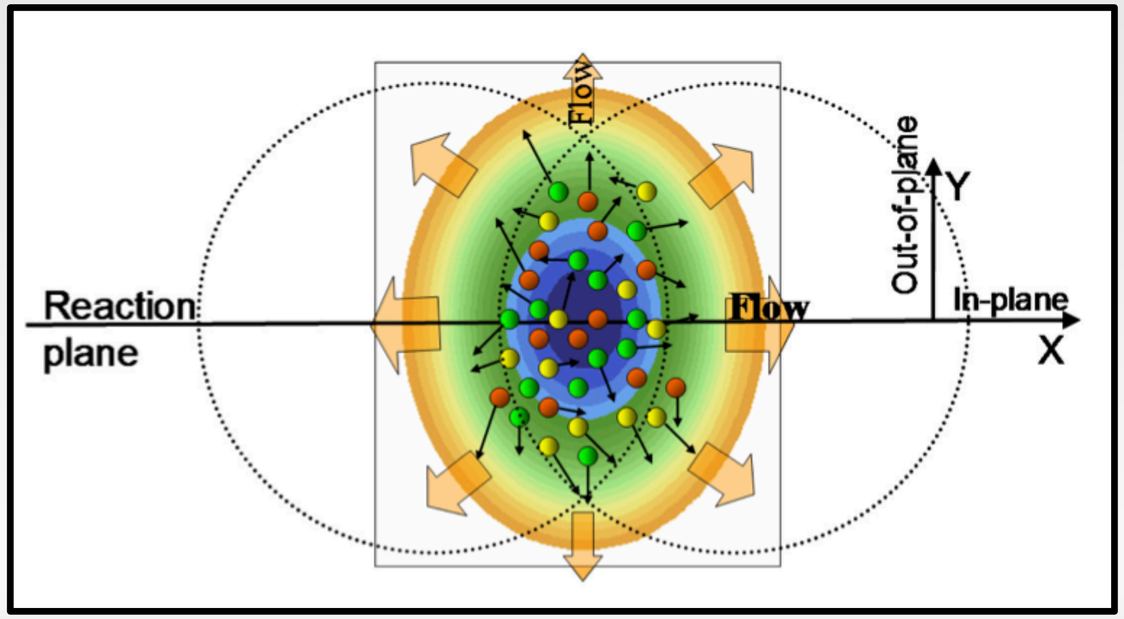
New R_{AA} measurements in Pb-Pb collisions at 2.76 TeV down to p_T = 0.5 GeV/c

⇨ **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

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



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

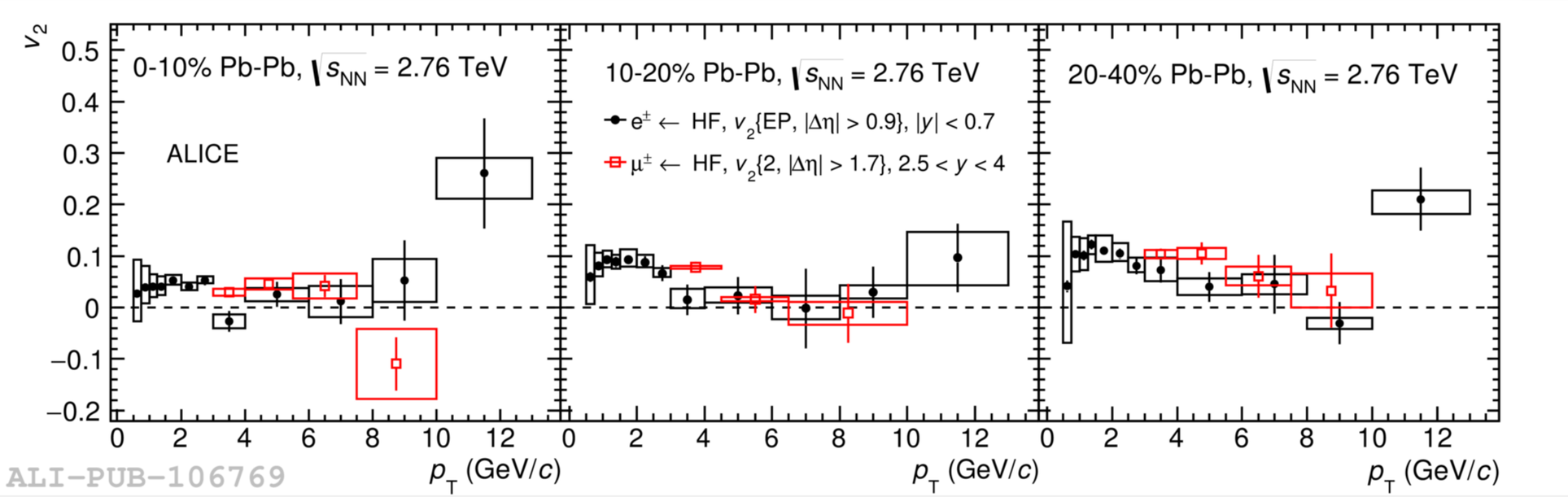
Heavy-flavour v_2 measurements probe:

- **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

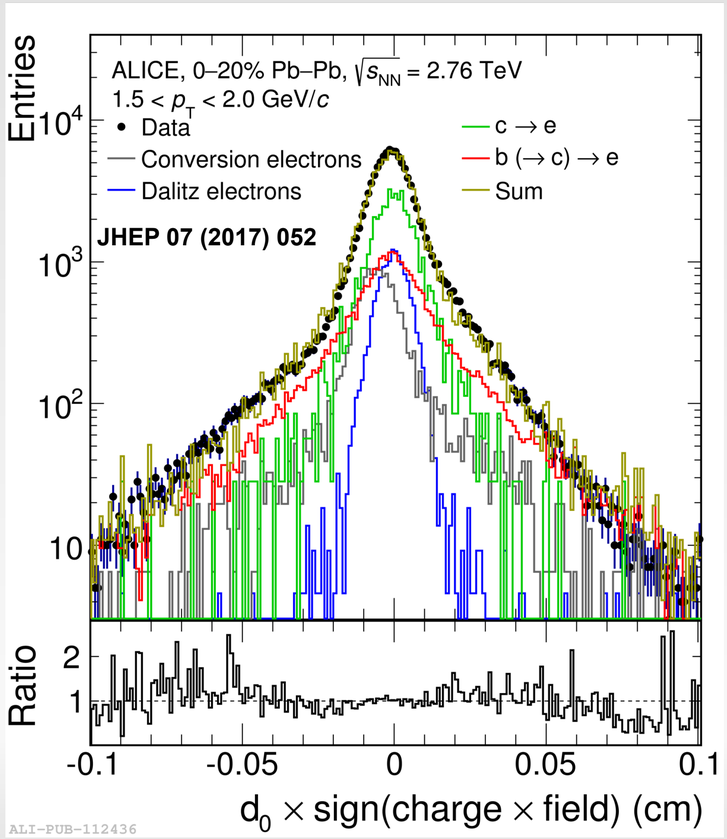


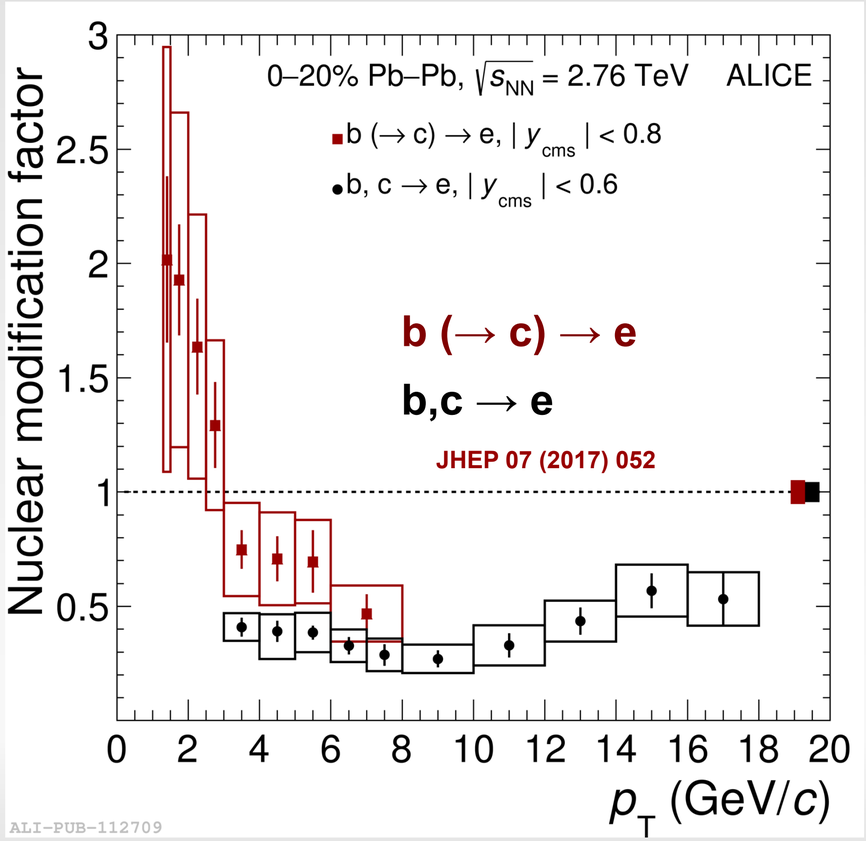
- Similar v_2 of heavy-flavour decay **electrons** at mid-rapidity and **muons** at forward rapidity classes.
- Positive v_2 observed → 5.9σ effect for $2 < p_T < 2.5$ GeV/*c* in 20-40% centrality class for the heavy-flavour decay electrons.
- Hint for an increase of v_2 from central to semi-central 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**





Data Samples

Xe-Xe@5.44 TeV

1 Million of MB events

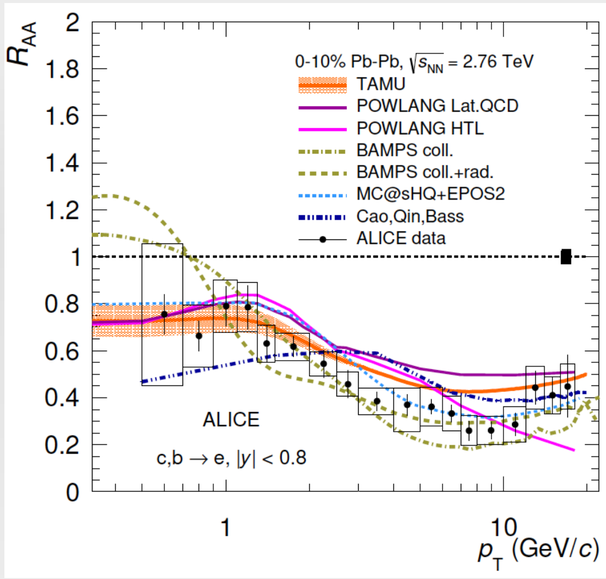
Pb-Pb@2.76 TeV

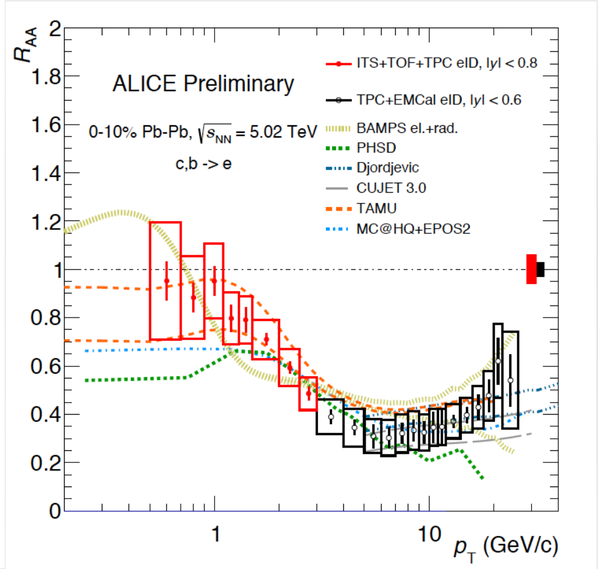
Centrality class	$\langle T_{AA} \rangle$ (mb^{-1})	N_{events}	L_{int} (μb^{-1})
0–10%	23.44 ± 0.76	16.4×10^6	21.3 ± 0.7
30–50%	3.87 ± 0.18	9.0×10^6	5.8 ± 0.2

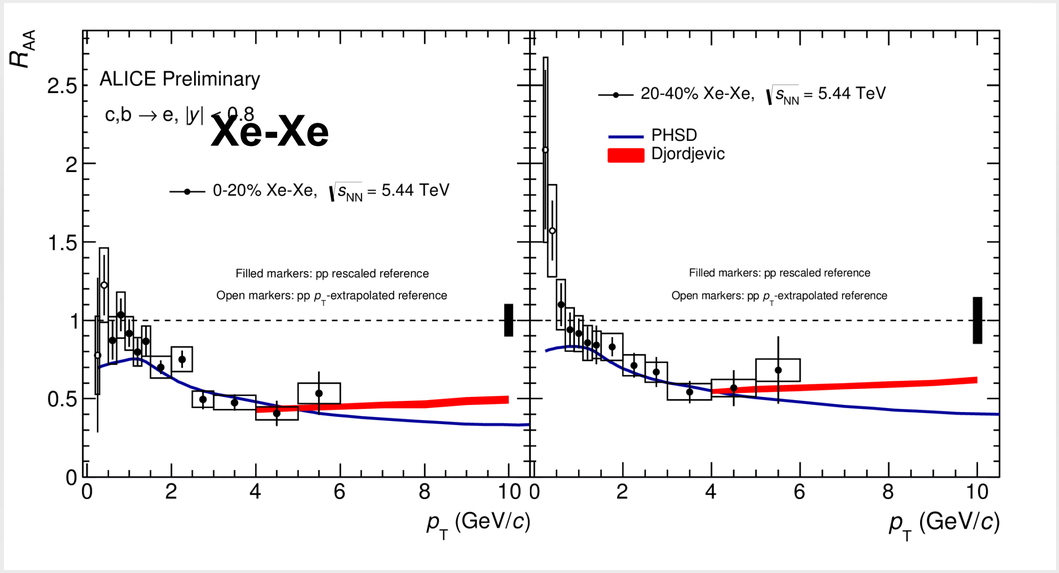
Pb-Pb@5.02 TeV

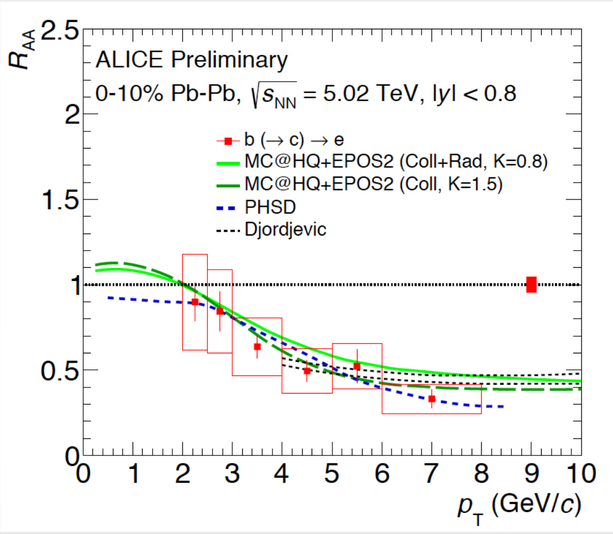
Centrality class	$\langle T_{AA} \rangle$ (mb^{-1})	N_{events}
0–10%	23.42 ± 0.75	10.4×10^6
30–50%	3.82 ± 0.14	20.8×10^6
60–80%	0.404 ± 0.017	20.8×10^6

Model predictions:





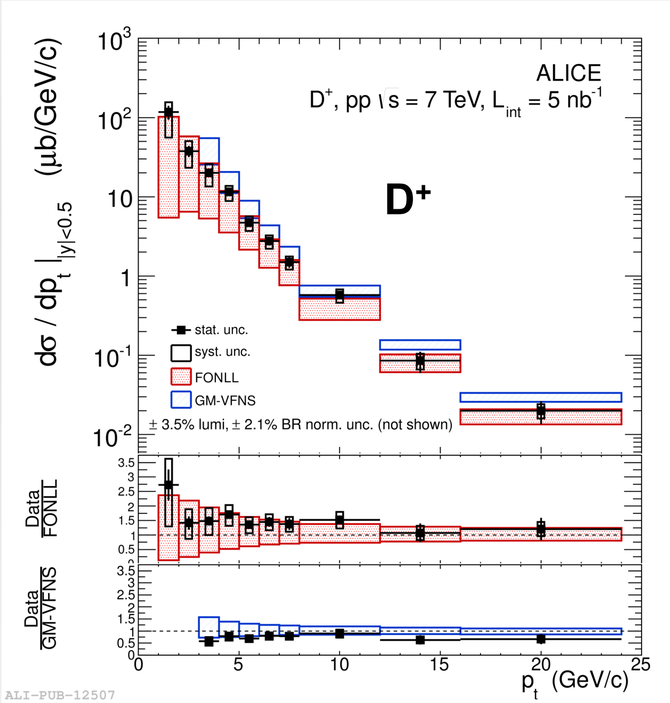




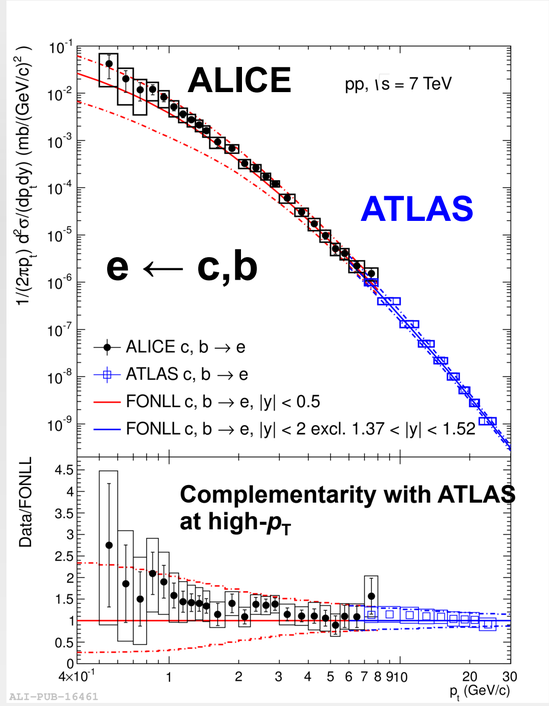
– **POWLANG: Eur.Phys.J. C73 (2013) 2481;**
– **TAMU: Phys.Lett. B735 (2014) 445–450;**
– **MC@HQ+EPOS: PRC 89 (2014) 014905;**
– **WHDG: Nucl. Phys. A 872 (2011) 256;**
– **BAMPS: PLB 717 (2012) 430; arXiv:1310.3597v1[hep-ph];**
– **UrQMD: arXiv:1211.6912[hep-ph]; J.Phys. Conf. Ser. 426 (2013) 012032;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

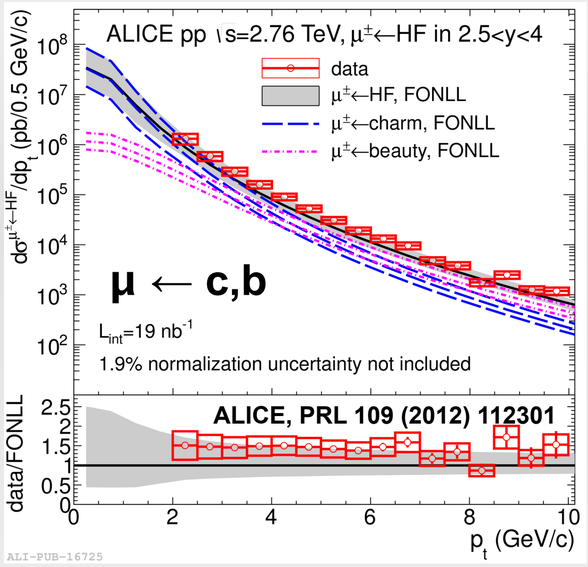
p_T-differential cross section

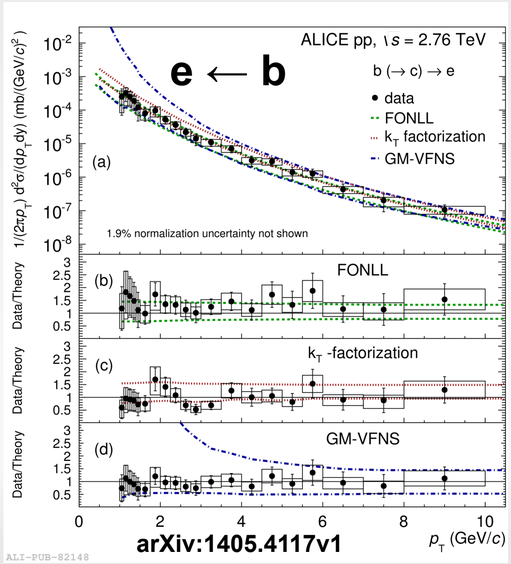


ALICE, JHEP 1201 (2012)



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

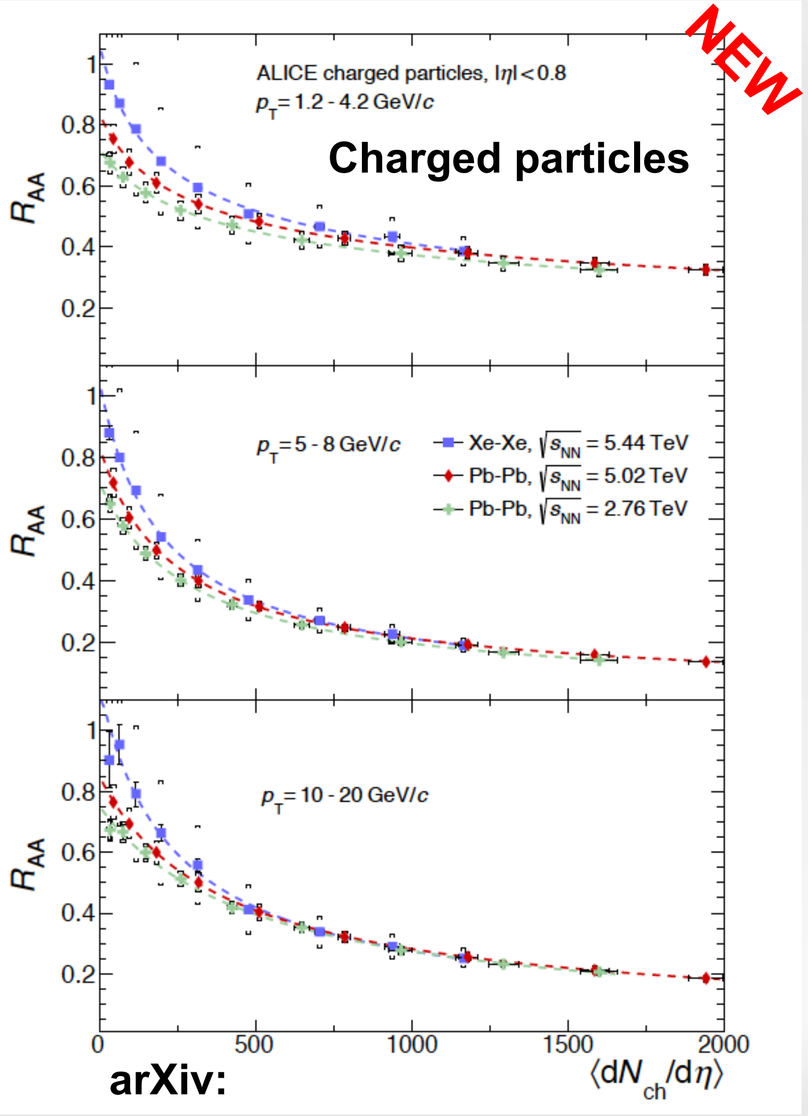




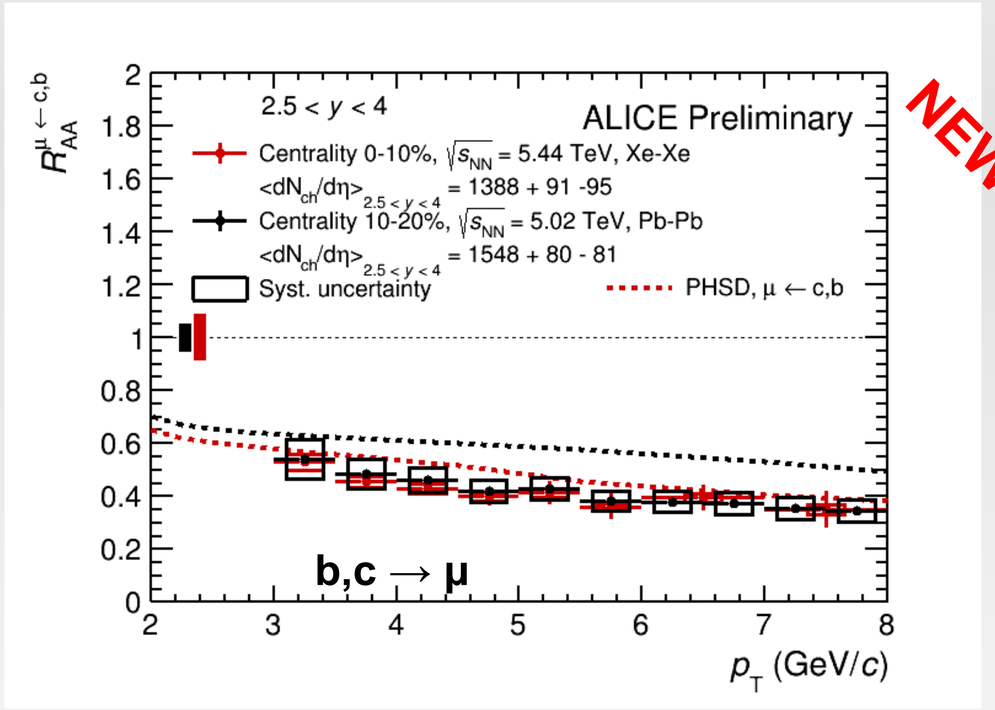
FONLL: JHEP 9805 (1998) 007
GM-VFNS: PRL 96 (2006) 012001
k_T Fact: PRD 62 (2000) 071502

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 <dN/dη>



– 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.