Production of muons from heavy-flavour hadron decays in Pb-Pb collisions at the LHC

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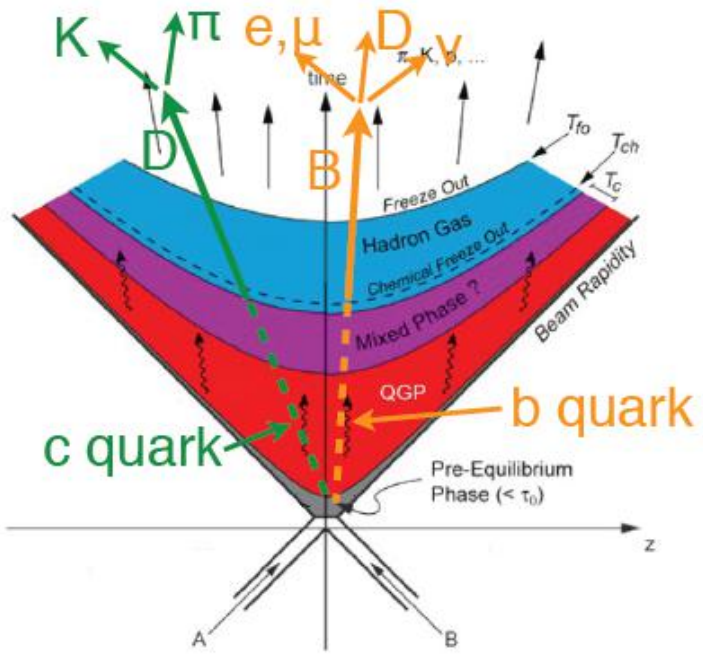
Outline

- Physics motivation
- Open heavy-flavour measurements with the ALICE muon spectrometer
- Analysis strategy
- Results
  - Nuclear modification factor of muons from heavy-flavour hadron decays as a function of p_T and centrality
  - Comparison to other measurements
  - Comparison with transport models
- Summary and outlook

Open heavy flavours in heavy-ion collisions at the LHC

- Charm and beauty quarks produced in initial hard scatterings with a short formation time $\tau_f \sim 1/m_{c/b}$ (~ 0.02-0.1 fm/c) << τ_{QGP} (~ 5-10 fm/c)
- Involved in the full evolution of the QCD medium
  - **Sensitive probes of the medium properties**



Open heavy flavours in A-A collisions:

Investigate the hot nuclear matter effects

- ✓ energy loss in the medium via gluon radiation and elastic collisions:
  - Color-charge and quark-mass dependence *Dokshitzer & Kharzeev, PLB 519 (2001) 199*
  - Expected: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

    $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$?
- ✓ participation in the collective expansion

Observations

- ✓ Nuclear modification factor $R_{AA}(p_T) = \frac{1}{< T_{AA} >} \times \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$
- ✓ Elliptic flow, v_2: $\frac{2\pi}{N}\frac{dN}{d\varphi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \psi_n)]$ with $v_2 = < \cos[2(\varphi - \psi_n)] >$

Open heavy flavours in pp and p-Pb collisions at the LHC

- **Heavy flavours in pp collisions:**
  Test of pQCD calculations and reference for p-Pb and Pb-Pb collisions

- **Heavy flavours in p-A collisions:**

✓ Control experiment for Pb-Pb collisions

✓ Cold nuclear matter effects :

- nuclear modification of parton distribution functions: shadowing/ gluon saturation[1]

[1]H.Fujii and K.Watanabe, Nucl.Phys.A915(2013) 1

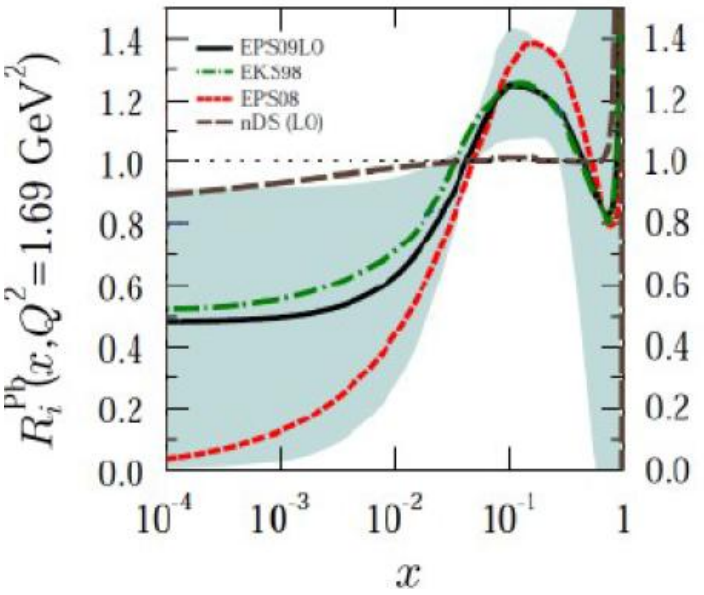
- energy loss[2]

[2]I. Vitev, Phys. Rev. C75(2007) 064906

- k_T broadening via multiple soft scatterings in the initial state[3]

[3] X.N. Wang, Phys.Rev. C61(2000) 064910

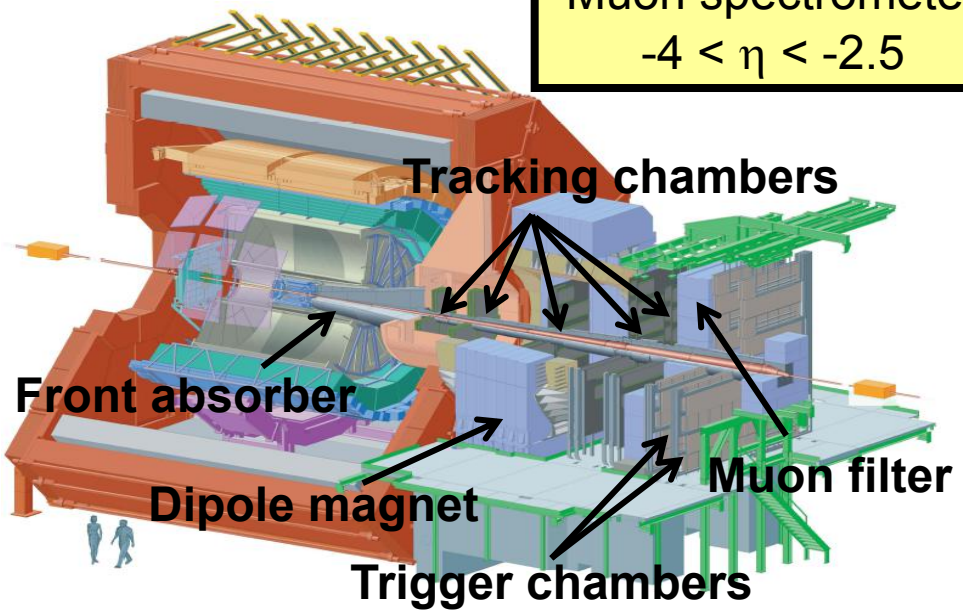
Ratio of PDF (gluons) in the nucleus and in the nucleon



K.J. Eskola et al., JHEP 0904(2009) 65
D.E. Kharzeev et al.,arXiv:1025.1554[hep-ph]
F.Dominguez et al., arXiv: 1109.1250[hep-ph]
R.Vogt, Phys.Rev C81 (2010) 044903
F. Arleo et al., arXiv: 1204.4609[hep-ph]
C. Lourenco et al., JHEP 0902 (2009) 014

Open heavy-flavours with the ALICE muon spectrometer

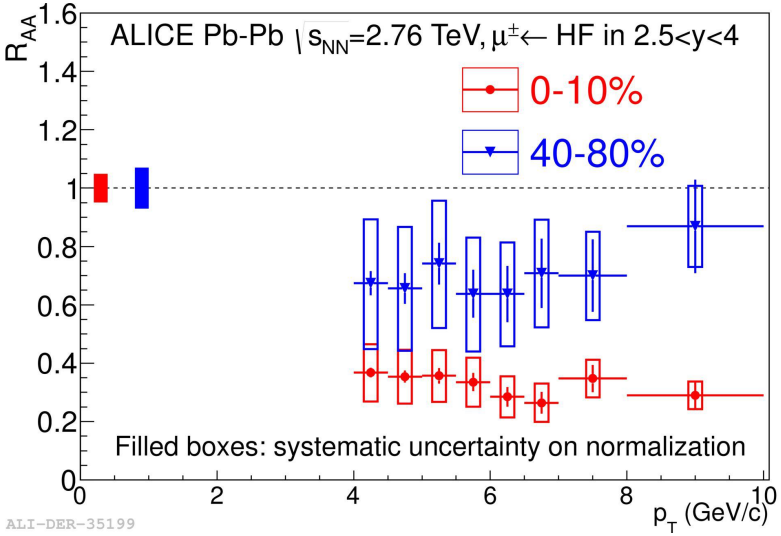
Muon spectrometer
$-4 < \eta < -2.5$



Semi-muonic decays:
D, B, Λ_c, … $\rightarrow \mu$ + anything

The aim of this analysis work is:
measure R_{AA} of muons from heavy-flavour hadron decays in a wider p_T internal

Pb-Pb: ALICE Collaboration, Phys. Rev. Lett: 109, 112301 (2012)



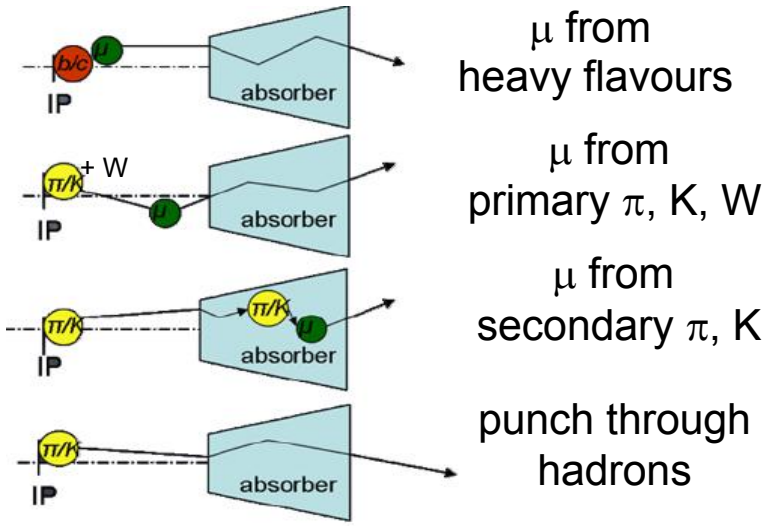
Data sample and Muon selection

Data sample: 2011 Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

- **Trigger condition: signal in the two V0 arrays (minimum bias trigger) with**
  - ✓ at least one muon with a low p_T trigger threshold of 1 GeV/c
    (MSL data sample, $L_{int} \approx 3.6\ \mu b^{-1}$, 0-90% centrality class)
  - ✓ at least one muon with a high p_T trigger threshold of 4.2 GeV/c
    (MSH data sample, $L_{int} \approx 63.8\ \mu b^{-1}$, 0-90% centrality class)

Muon track selection

- **Acceptance & geometrical cuts**
  select tracks in the spectrometer acceptance
- **p_T cut at 2 GeV/c**
  reject μ from secondary π, K
- **Tracks matched with trigger**
  reject hadrons crossing the absorber
- **p×DCA in 6 σ**
  reject beam-gas interactions & particles produced in the absorber



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

- **Remaining background:** μ ← primary π, K decays estimated via data-tuned MC cocktail (Pb-Pb and p-Pb collisions) or MC (pp collisions); μ ← W (high p_T) via POWHEG simulation

Background estimation in Pb-Pb collisions

- **μ←K/π (main background contribution at low and intermediate p_T)**
  - ✓ Input: K/π spectra in pp and Pb–Pb collisions at central rapidity measured with ALICE extrapolated in p_T
  - ✓ extrapolate K/π spectra in Pb-Pb collisions to forward rapidity

$$\frac{1}{N_{ev}}\frac{d^2N_{AA}^{K/\pi}}{dp_T dy} = n_y \times \frac{1}{N_{ev}}\frac{dN_{AA}^{K/\pi}}{dp_T}\Big|_{|y|<0.8} \times \exp\left(\frac{-y^2}{2\sigma_y^2}\right)$$

varying n_y between 0 and 200% to estimate the systematic uncertainty on unknown quenching effect at forward rapidity, the central value obtained with $n_y = 1$; $\sigma_y = 3.18$ estimated from PYTHIA and PHOJET (systematic uncertainty ≈ 14%)

  - ✓ produce the K/π decay muon background in Monte-Carlo with fast detector simulation

- **μ←W（dominant backgroud contribution at high p_T）**
  - ✓ Pb-Pb templates obtained by combining pp, pn, np and nn with POWHEG simulation

$$\frac{d\sigma_{Pb-Pb}}{dp_t} \approx \frac{Z^2}{A^2}\times\frac{d\sigma_{pp}}{dp_t} + \frac{(A-Z)^2}{A^2}\times\frac{d\sigma_{nn}}{dp_t} + \frac{Z\cdot(A-Z)}{A^2}\left\{\frac{d\sigma_{pn}}{dp_t} + \frac{d\sigma_{np}}{dp_t}\right\}$$

(A = 208, Z = 82)

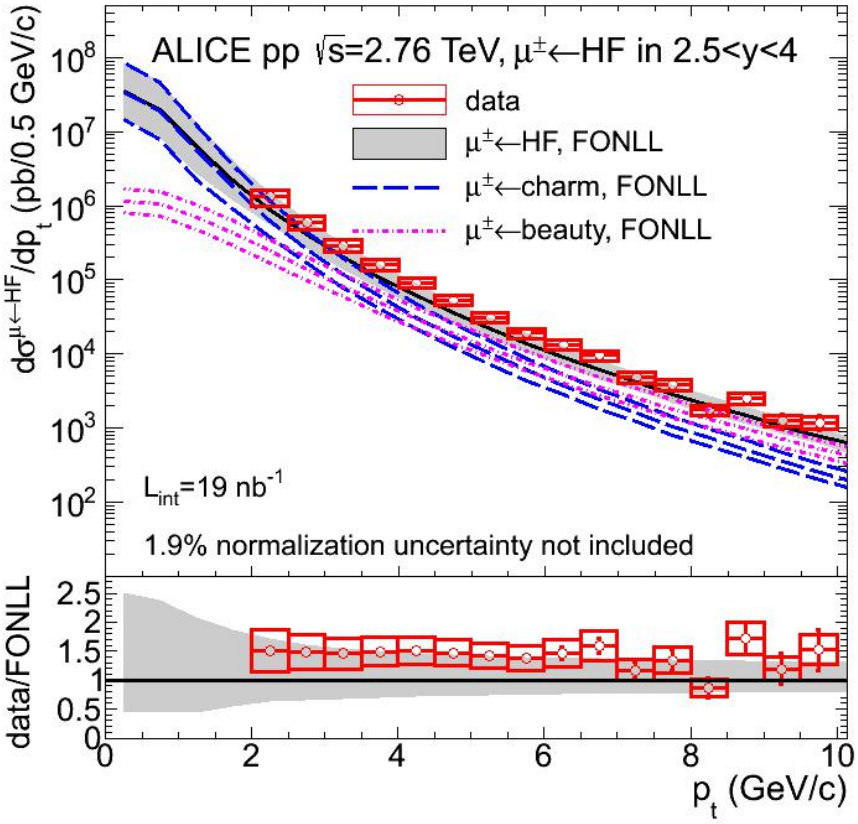
pp reference

$$R_{AA}(p_T) = \frac{1}{< T_{AA} >} \cdot \frac{dN_{AA}^{\text{inclusive }\mu}/dp_T - dN_{AA}^{\text{bkg}}/dp_T}{d\sigma_{pp}^{\mu<-HF}/dp_T}$$

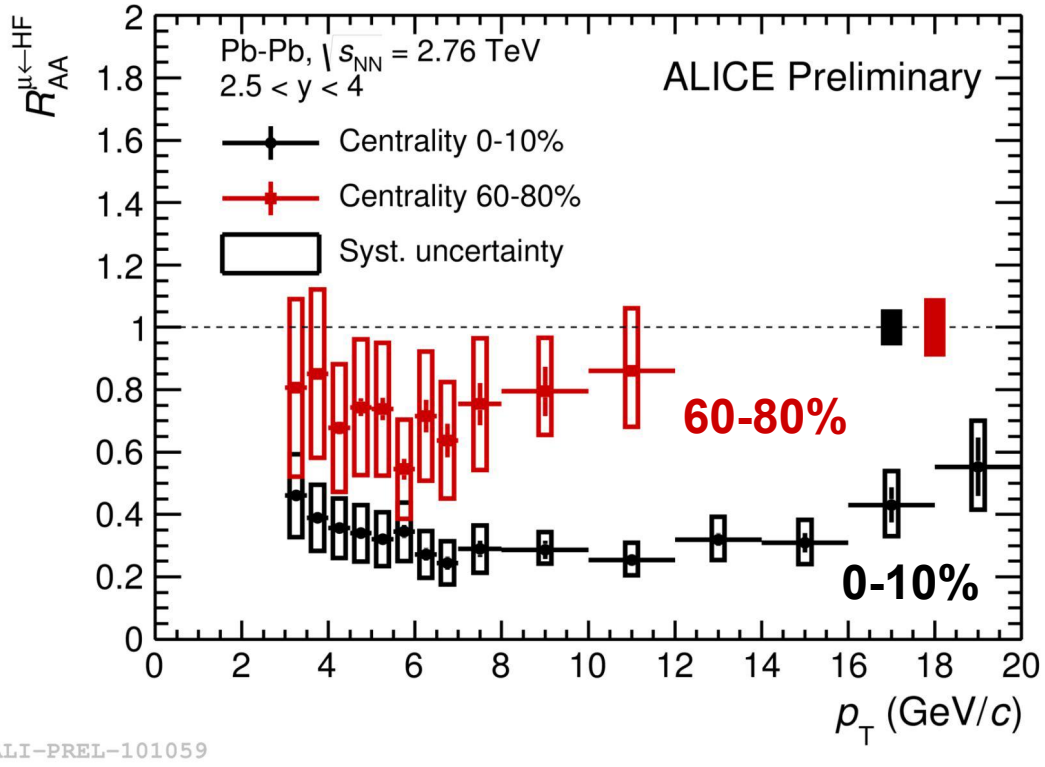
- p_T-differential cross section of heavy-flavour decay muons in $2 < p_T < 10$ GeV/c is published systematic uncertainty: 14-20% (Phys. Rev. Lett. 109 (2012) 112301)

- p_T-differential cross section of heavy-flavour decay muons at $p_T > 10$ GeV/c: scale FONLL predictions according ratio between data & FONLL at $2 < p_T < 10$ GeV/c

- Total systematic uncertainty: from FONLL (16-24%); from fit ratio between data & FONLL (6%)

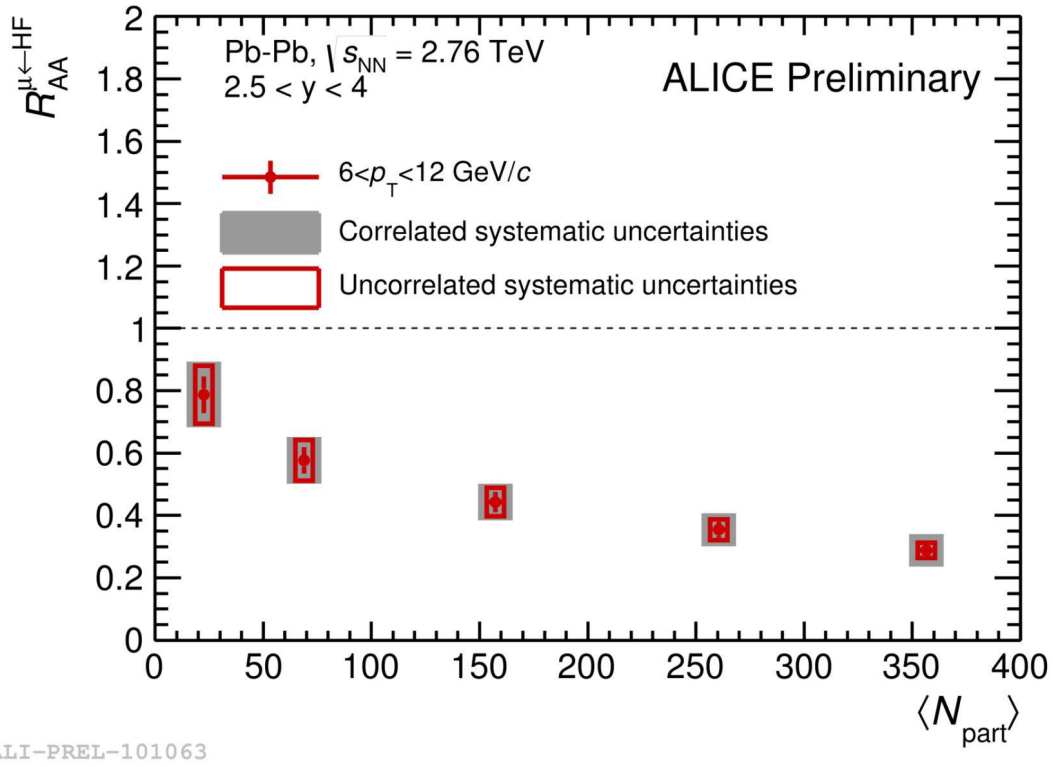


p_T-differential R_{AA} of heavy-flavour decay muons in different centrality classes



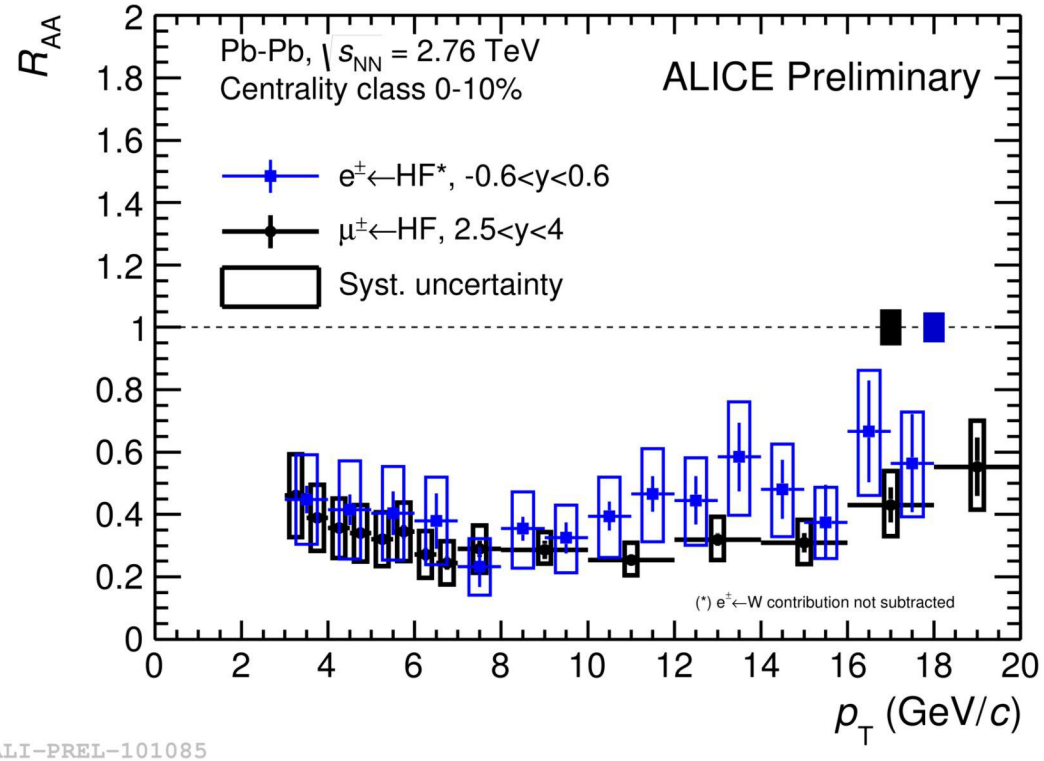
- Suppression of heavy-flavour decay muon yields in the 10% most central collisions compared to binary-scaled pp yields
- Stronger suppression in central collisions than in peripheral collisions reaching a factor of 3-4 in the 10% most central collisions and in $6 < p_T < 12$ GeV/c

Centrality dependence of R_{AA} of heavy-flavour decay muons



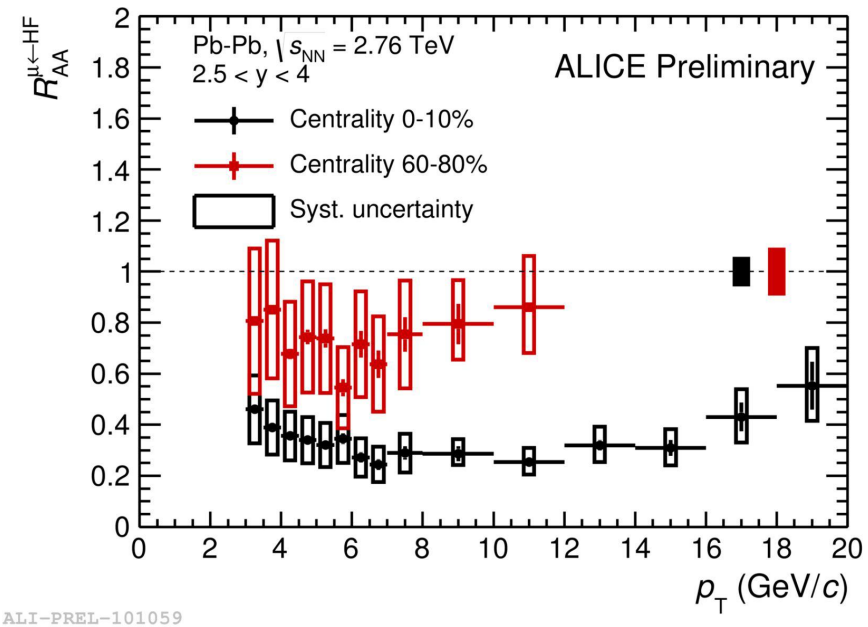
- Investigated in the region 6 < p_T < 12 GeV/c where the contribution of muons from B decays becomes dominant in pp collisions
- Suppression increases with increasing centrality, reaches a factor of about 4 in the 10% most central collisions

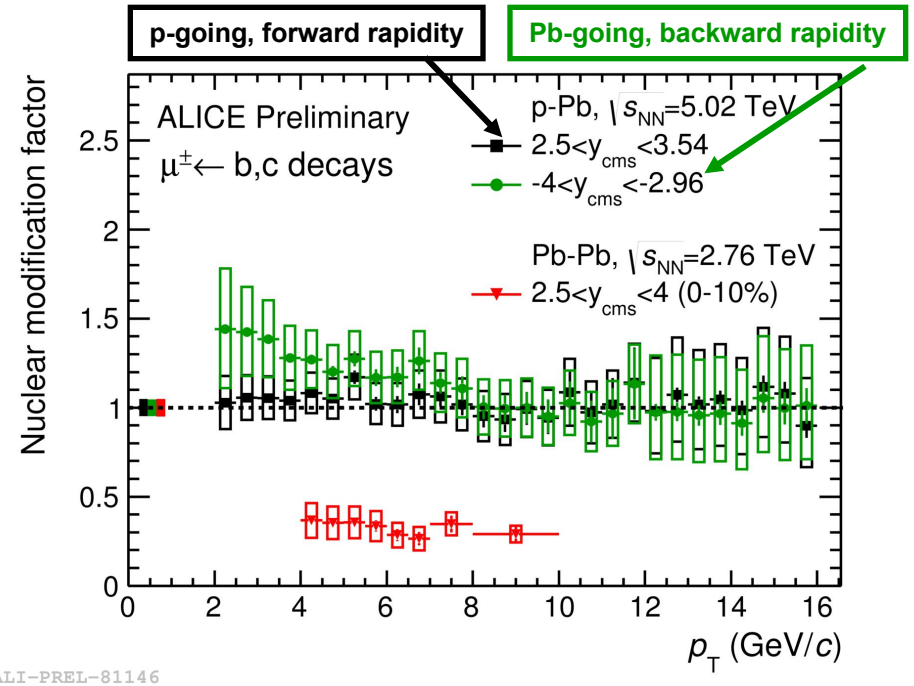
Comparison with the p_T-differential R_{AA} of heavy-flavour decay electrons



- Compatible results within uncertainties for heavy-flavour decay electrons (|y| < 0.6) and HF decay muons (2.5 < y < 4) R_{AA} in 0-10% centrality class
- Indicate that heavy quarks suffer a strong interaction in a wide rapidity internal

Comparison with p-Pb measurements



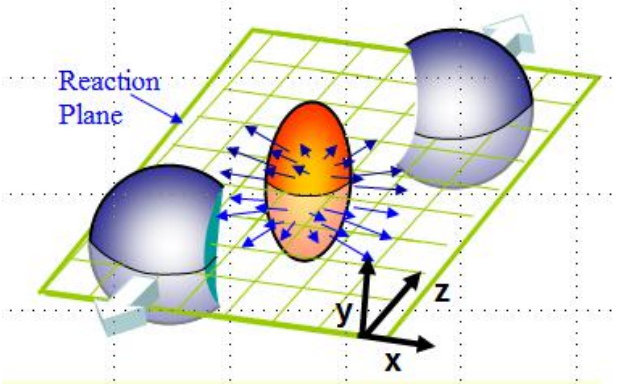


Pb-Pb: ALICE Collaboration, Phys. Rev. Lett: 109, 112301 (2012)

- R_{pPb} at forward rapidity: consistent with unity within uncertainties over whole p_T range
- R_{pPb} at backward rapidity: slightly larger than unity in $2 < p_T < 4$ GeV/c and compatible with unity at higher p_T
- R_{pPb} being consistent with unity, the suppression observed at high p_T in central Pb-Pb collisions results from final-state effects related to parton energy loss

p_T-differential v_2 of heavy-flavour decay muons

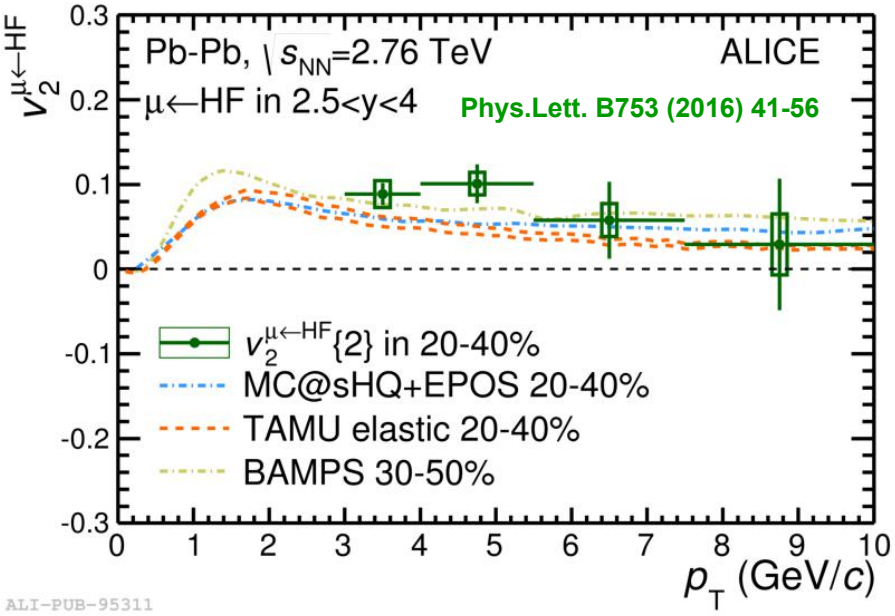
(complementary measurement to R_{AA} is v_2)



- v_2 sensitive to:
  - Low p_T: collective motion
  - High p_T: path-length dependence of parton energy loss

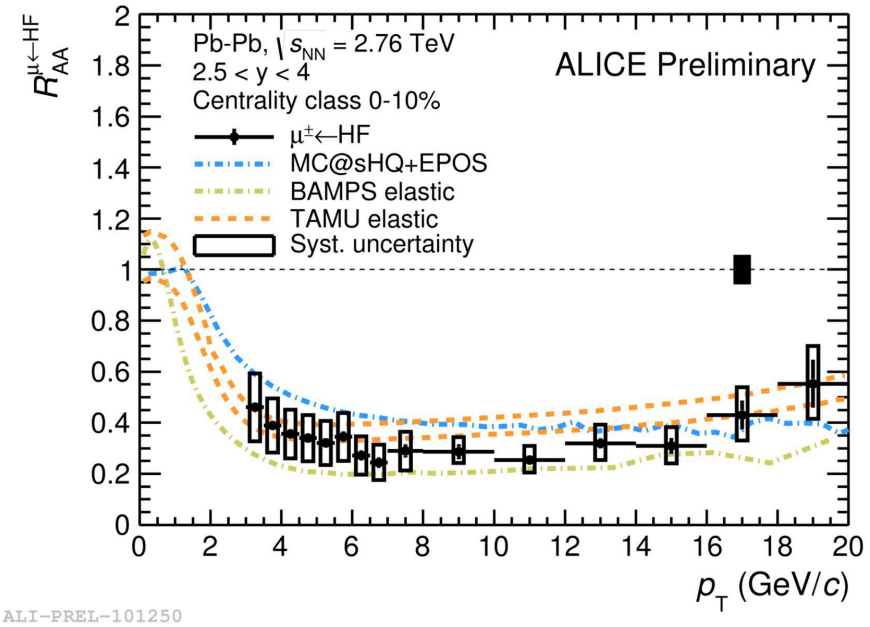
$$\frac{2\pi}{N}\frac{dN}{d\varphi} = 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \psi_n)]$$

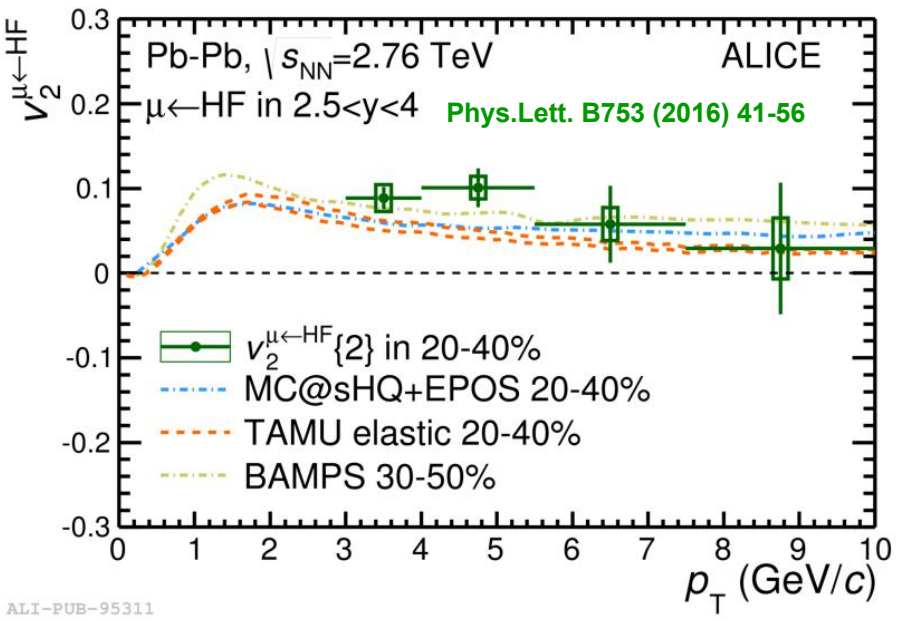
v_2, 2nd order Fourier coefficient is the elliptic flow



- $\mu \leftarrow$ c, b measured at forward rapidity in $2.5 < y < 4$ exhibit a positive v_2: a 3σ effect for $3 < p_T < 5$ GeV/c in 20-40% centrality class
- Confirmation of significant interaction of heavy quarks with the medium

Comparison with models





- Simultaneous description of R_{AA} in central collisions and v_2 in semi-central collsiions is challenging
- R_{AA} and v_2 measurements starts to provide constraints on energy loss models

MC@ sHQ+EPOS, Coll + Rad (LPM): Phys. Rev. C 89 (2014) 014905;
BAMPS: Phys. Lett. B 717 (2012) 430;
TAMU elastic: arXiv: 1401.3817

Summary

Summary

- **R_{AA} of muons from heavy-flavour decays measured in a wide p_T range ($3 < p_T < 20$ GeV/c)**
  - A strong suppression of high p_T muons from heavy flavour decays is observed: a factor of about 4 in the 10% most central collisions
  - R_{AA} similar to that of electrons from heavy flavour decays at central rapidity
  - The measured suppression is due to final-state effects ($R_{pPb} \sim 1$)

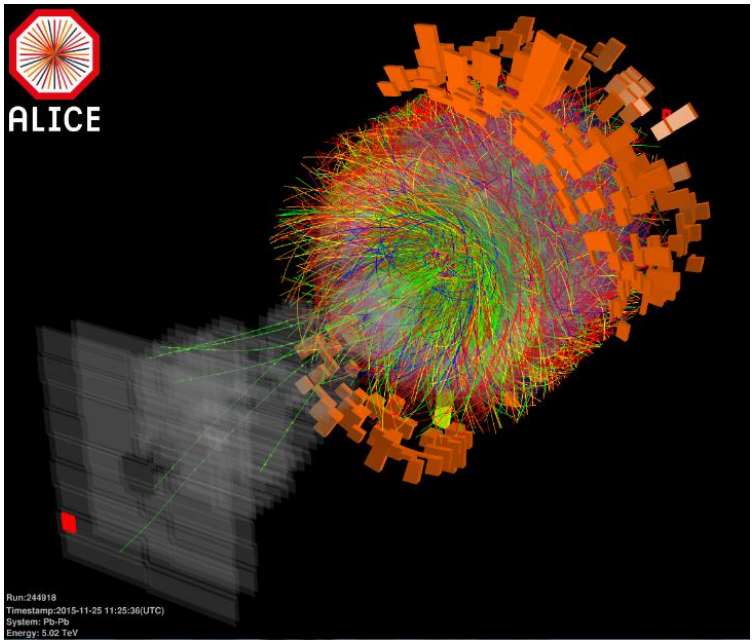
- **positive v_2: confirmation of significant interaction of heavy quarks with the medium**

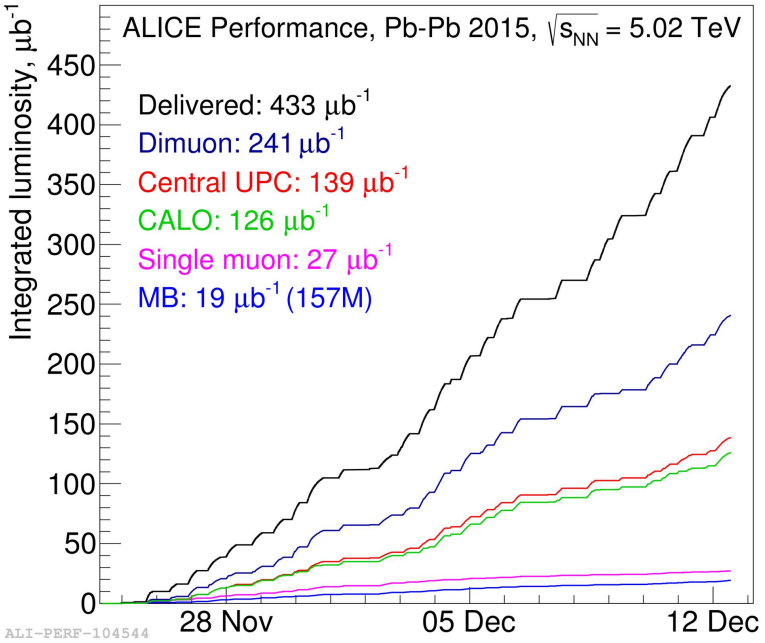
- **simultaneous description of R_{AA} and v_2 is a challenge for models**

Outlook

Outlook

- **Run 2: 2015-2018**
  - ✓ Measure muons from heavy-flavour hadron decays in pp and Pb-Pb collisions at 5.02 TeV with an improved precision in a new kinematic region





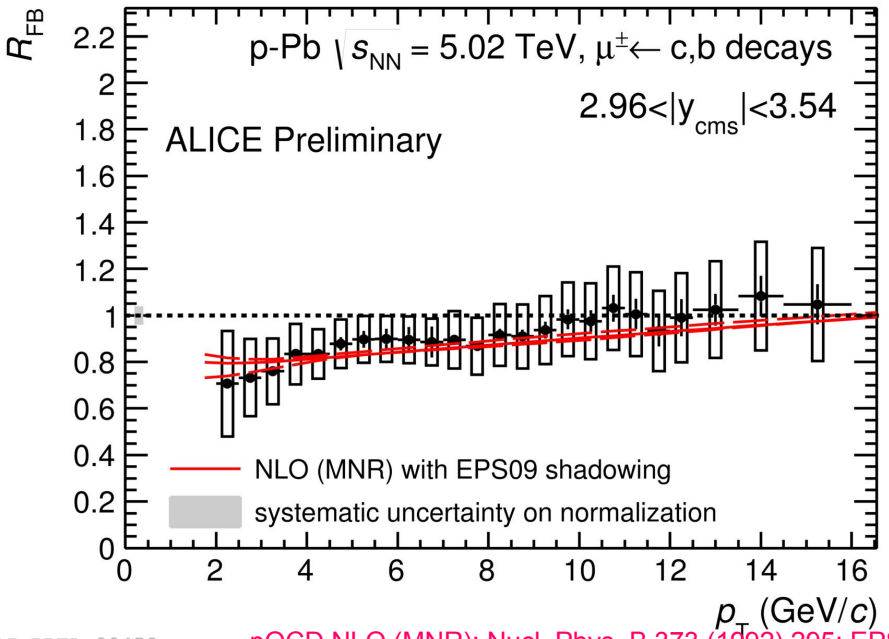
Thank you for your attention

Backup

Heavy-flavour decay muons: p_T-differential R_{FB}

Forward-to-backward ratio

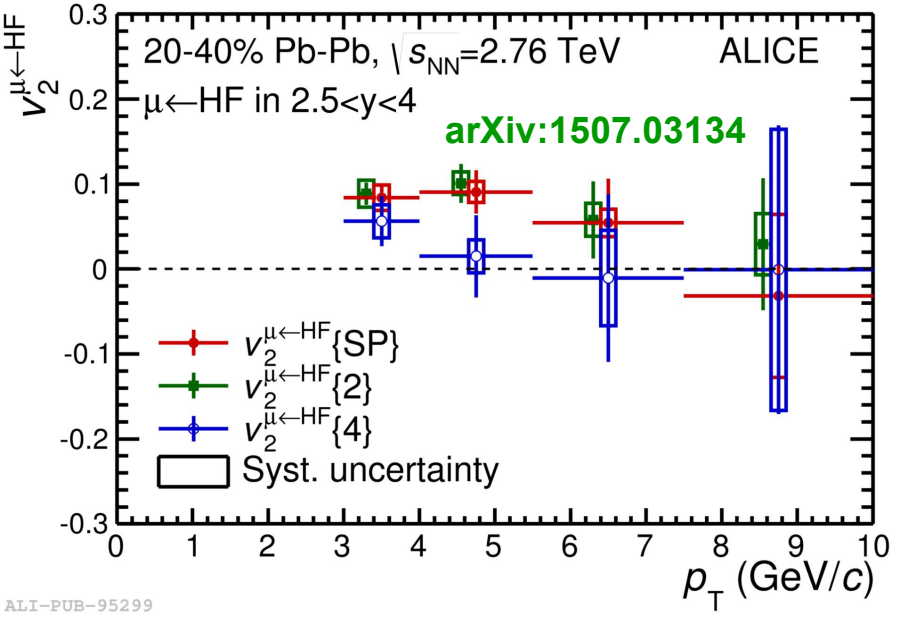
$$R_{FB}(2.96 < |y_{CMS}| < 3.54) = \frac{d\sigma/dp_T[\text{Forward}(2.96 < y_{CMS} < 3.54)]}{d\sigma/dp_T[\text{Backward}(-3.54 < y_{CMS} < -2.96)]}$$

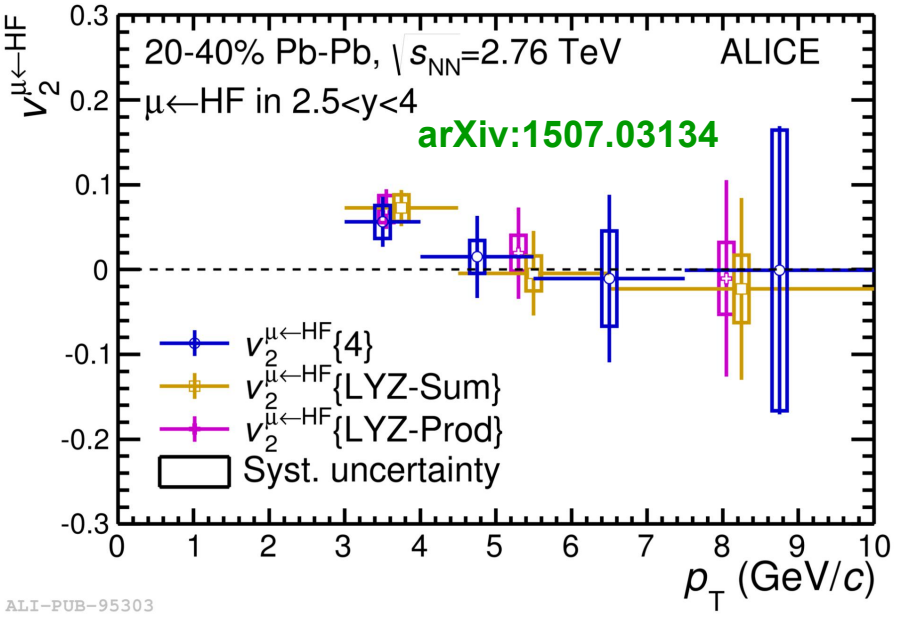


pQCD NLO (MNR): Nucl. Phys. B 373 (1992) 295; EPS09: K. J. Eskola et al., JHEP 04 (2009) 065

- R_{FB}: systematically smaller than unity in 2<p_T<4 GeV/c and close to unity at higher p_T
- Within uncertainties, data can be described by perturbative QCD calculations with EPS09

p_T-differential v_2 of heavy-flavour decay muons





- A positive v_2 from two-particle correlation methods (SP and QC2) in for 3< p_T <5 GeV/c in 20-40% with a 3σ significance when combining statistical and systematic uncertainties
- Results from QC4 are systematically lower than those from SP and QC2
  → due to different contributions of non-flow correlations and flow fluctuations
- 4-particle Q-cumulants give same v_2 as Lee-Yang zeroes within uncertainties
  → indication that non-flow effects are suppressed with 4-particle Q-cumulants
- Smaller v_2 values with multi-particle flow methods than with two-particle methods
  → an indication of flow fluctuation effects