Measurements of heavy-flavour decay leptons with ALICE

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3rd International Conference on New Frontiers in Physics
Kolympari-Crete-Chania Greece
2nd August 2014

Heavy-Flavour (HF) in pp, p-Pb & Pb-Pb

- Heavy-flavour (charm & beauty) in pp collisions
  - test for perturbative QCD (pQCD)
    - produced on a short timescale in hard partonic scatterings
  - reference for Pb-Pb collisions
- Heavy-flavour in heavy-ion collisions
  - created in initial parton-parton scattering
  - traverse and interact with the hot & dense QCD matter
    - a good probe to study the properties of the medium
    - nuclear modification factor
      - Sensitive to colour charge and mass dependence of in-medium parton energy loss
    - azimuthal anisotropy in non-central collisions
      - strong coupling, participation in the collective expansion of medium
      - energy loss at high p_T
- Heavy-flavour in p-A collisions
  - control measurement for heavy-ion collisions to disentangle initial from final state effects

Charm & Beauty Energy Loss

- In-medium parton energy loss
  - Radiative energy loss (Djordjevic et al. PLB 632, 81)
    - gluon bremsstrahlung
    - smaller energy loss for heavy than for light quarks due to "dead cone" effect (Dokshitzer & Kharzeev, PLB 519 (2001) 199.)
    - energy loss depends on the colour charge and is larger for gluons than for quarks
  - Collisional energy loss (Adil & Vitev PLB 649, 139)
    - energy loss via elastic scattering
- Experimental observable = nuclear modification factor:

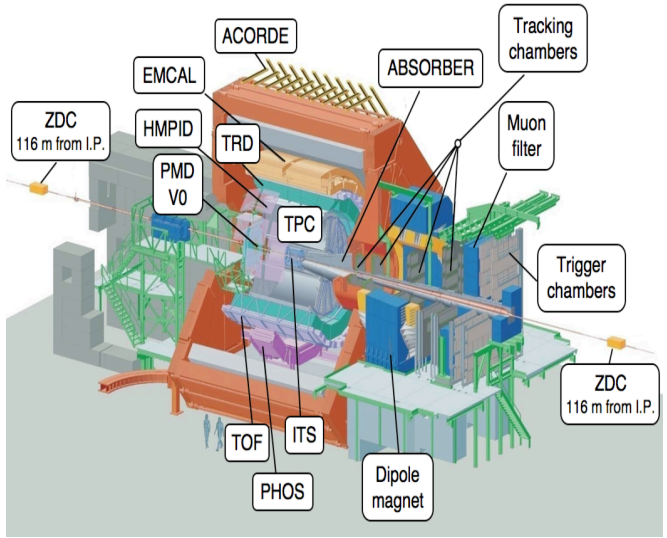
$$R_{AA}(p_T) = \frac{d\,N_{AA}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}/dp_T}$$

Hierarchy in g, light quarks, c, b quark energy loss reflected into

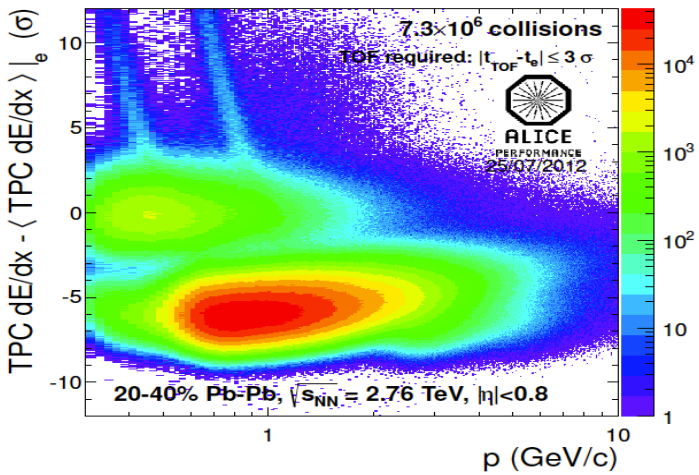
$E_{loss}(g) > E_{loss}(u,d,s) > E_{loss}(c) > E_{loss}(b) \longrightarrow \boxed{R^{\pi}_{AA} < R^{D}_{AA} < R^{B}_{AA}}$?

ALICE experiment

- Electron reconstruction & identification (mid-rapidity)
  - ITS: track & vertex reconstruction
  - TPC: tracking & PID via dE/dx
  - TOF: time of flight
  - TRD: transition radiation
  - EMCal: energy (E/p), trigger
  - background: conversion & Dalitz decay
    - estimated by two method: cocktail (MC) & invariant mass

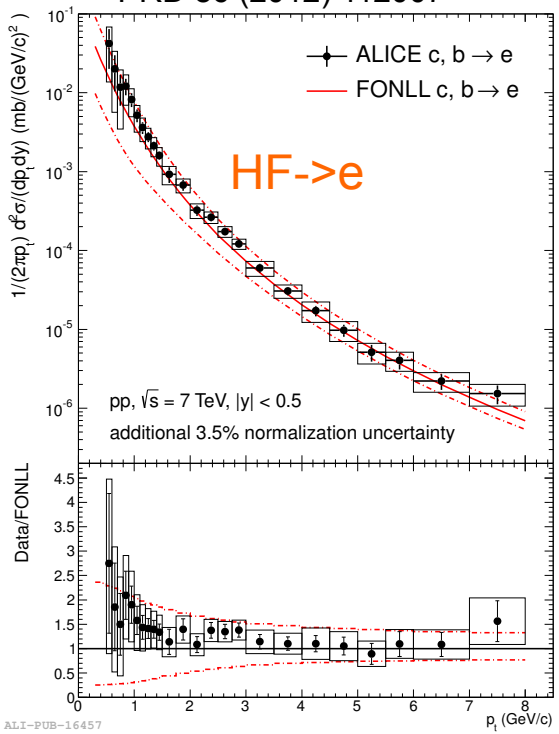


- Muon Spectrometer (-4 < η < -2.5)
  - tracking and trigger of muons
  - background: dominated by μ from π, K decaying upstream from the absorber
    - estimated via fast MC based on measured π & K spectra at mid-rapidity



HF -> e,μ production in pp collisions

PRD 86 (2012) 112007



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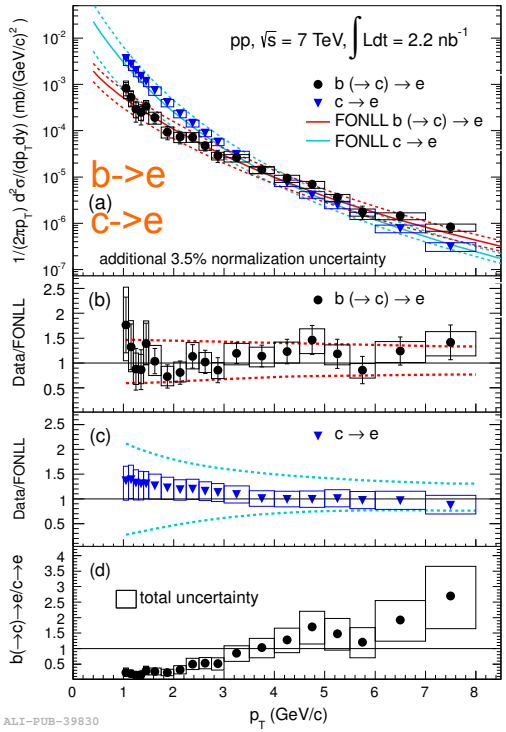

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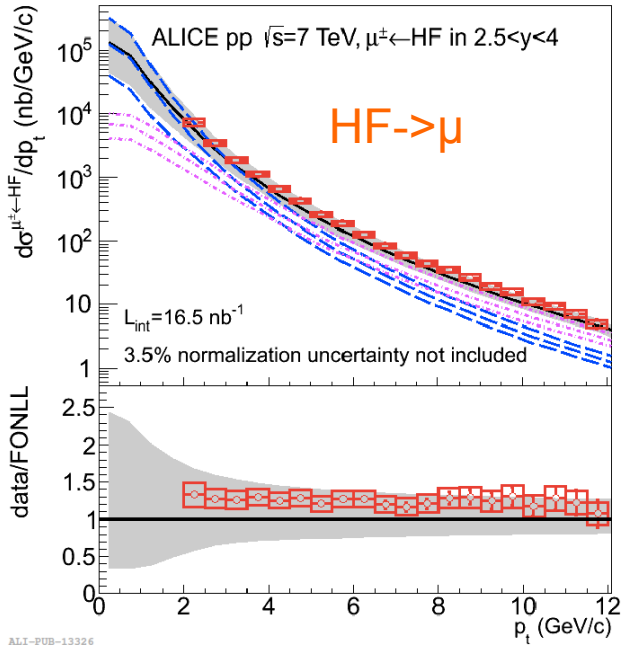
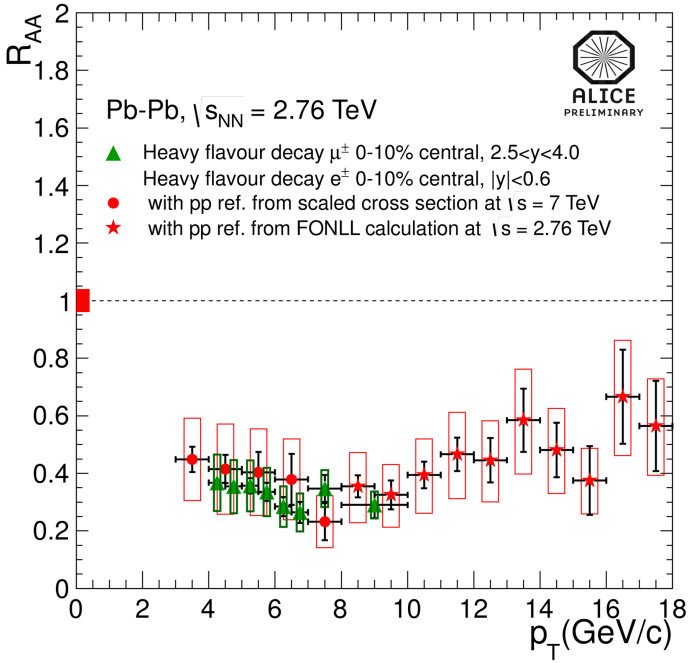
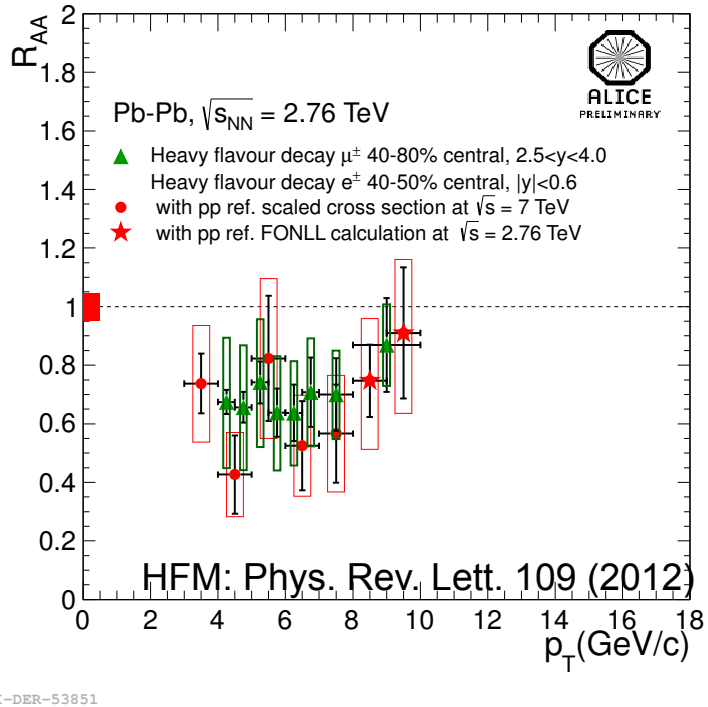


- Heavy-flavour production (c+b, b) at mid-rapidity and forward rapidity (c+b) well described by pQCD calculations
- Reference for Pb-Pb collisions
  - due to limited statistics of pp collisions at 2.76 TeV, a pQCD-based √s-extrapolation of the cross section measured at 7 TeV is performed for HF->e & b (arXiv 1107.3243)
  - for HF->μ the pp reference is taken from the measurement at 2.76 TeV

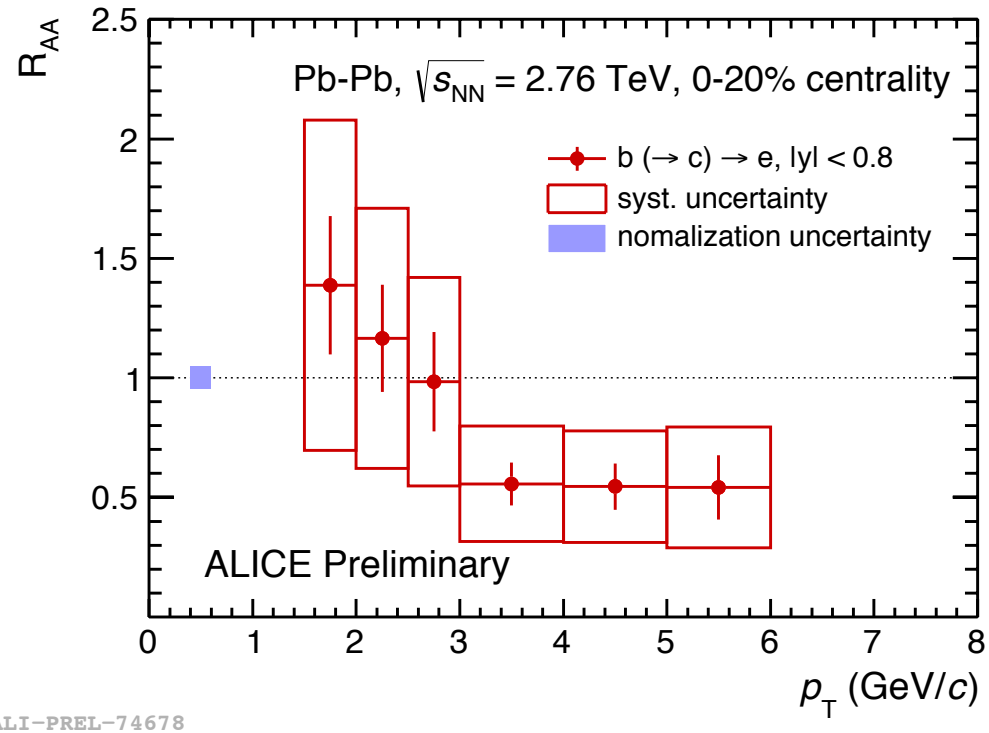
HF production in Pb-Pb collisions

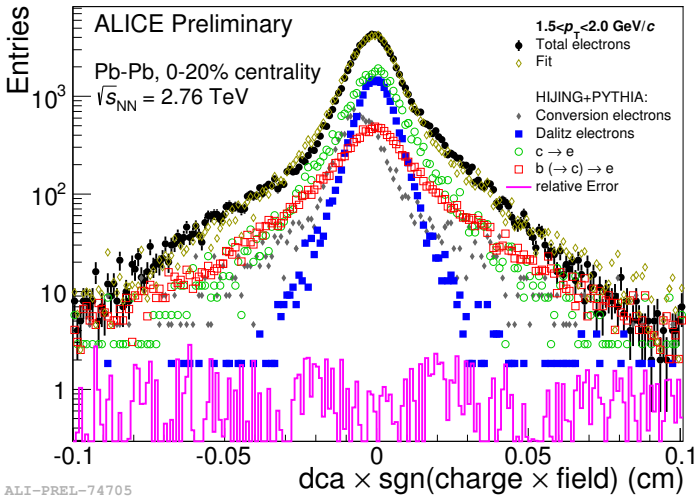




- R_{AA} of HF->e (mid-rapidity: |y|<0.6) & HF->μ (forward-rapidity: 2.5<y<4.0) in most-central & mid-central collisions
  - strong suppression (p_T>3 GeV/c) of HFE & HFM in central collisions
  - similar suppression of HFE & HFM in different rapidity regions
- Suggest significant energy loss of c and b quarks in the medium

R_{AA} of beauty decay electrons

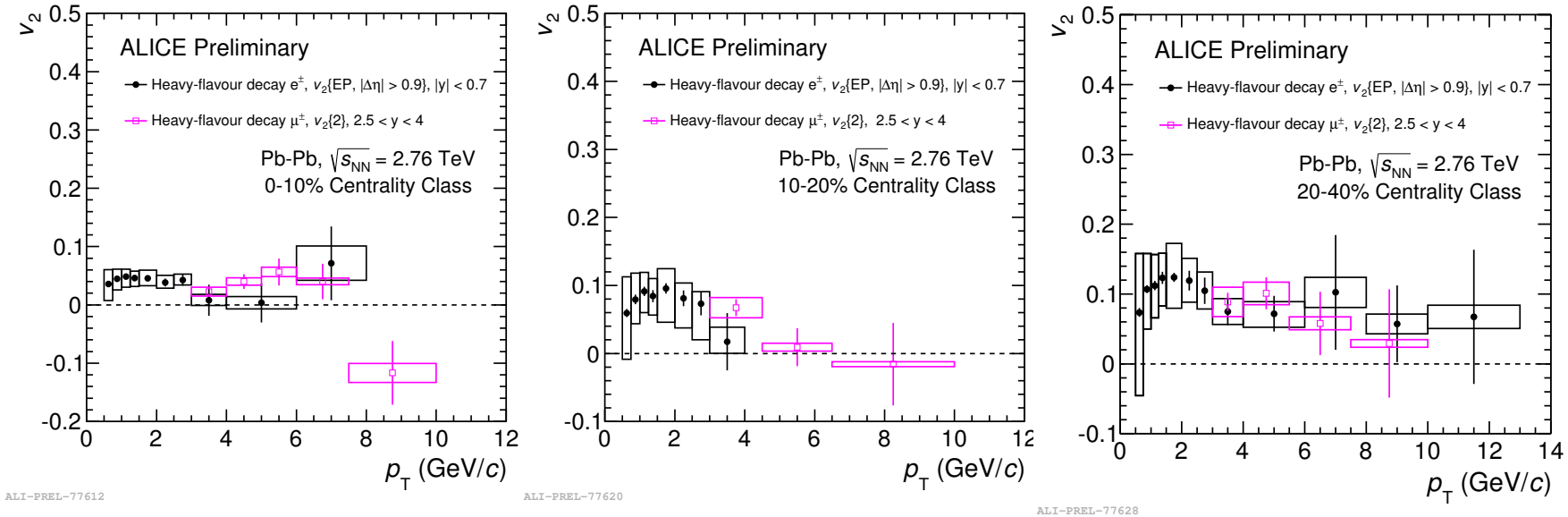




- Charm & beauty separation is crucial to understand HF energy loss in the hot & dense QCD matter
- Beauty-decay electrons in Pb-Pb via impact parameter measurement
  - $c\tau$~ 500μm for B hadron
- A hint of beauty suppression in central collisions (0-20%)

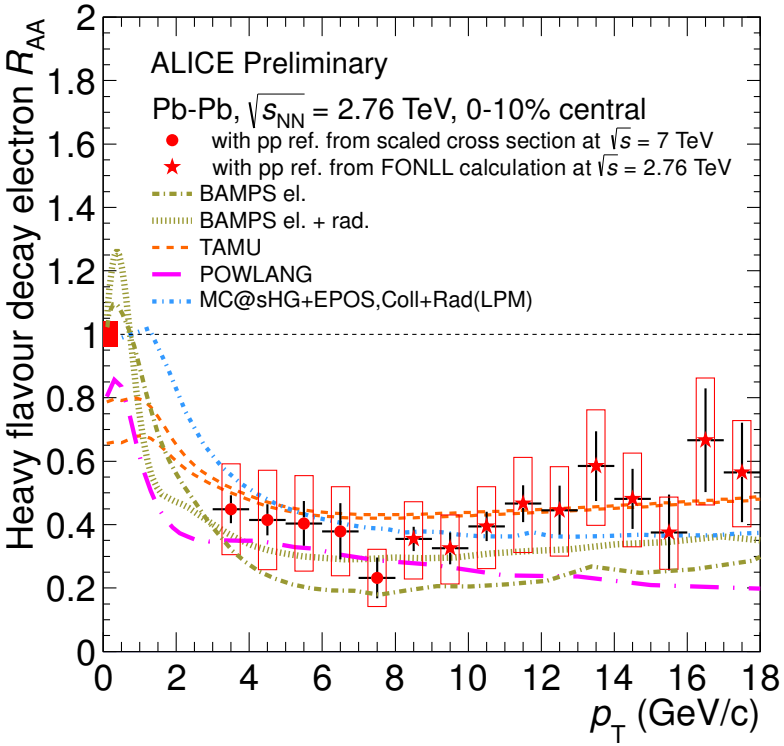
v_2 of HF->e and HF->μ

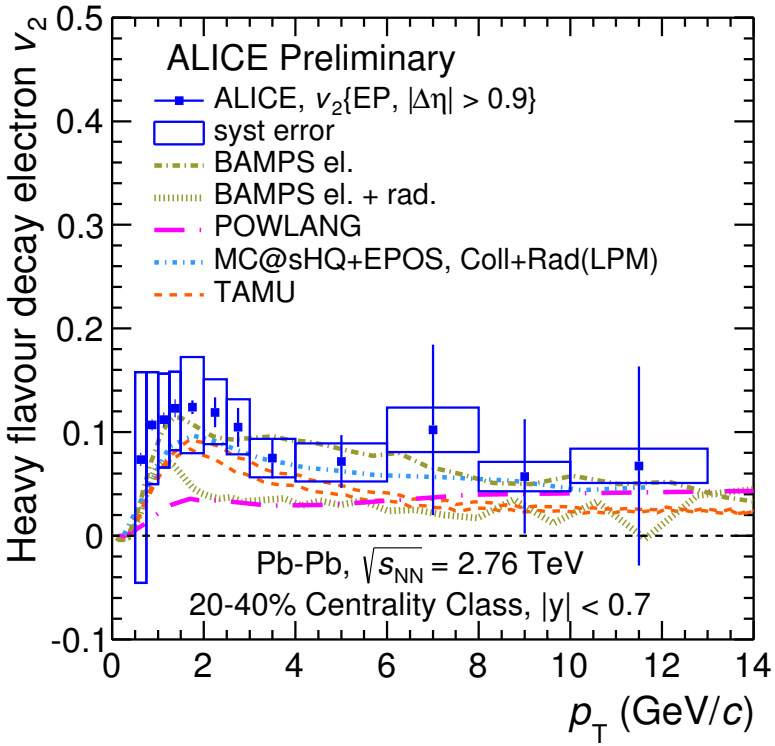
$$dN/d(\varphi-\psi_{RP}) = N_0 \{1+\ldots+ 2v_2\cos(2(\varphi-\psi_{RP})) +\ldots\}$$



- Positive v_2 measured
  - 3σ effect in $2<p_T<3$ GeV/c in 20-40% centrality class
- Measurement indicates centrality dependence of strength of v_2
  - increase of v_2 from central (0-10%) to mid-central (20-40%) collisions
- v_2 of HF->e at mid-rapidity and HF->μ at forward-rapidity compatible within uncertainties
  - no significant rapidity dependence
- Suggests that charm quarks take part in the collective expansion in medium

Comparison with models





- Theoretical calculations predict strong suppression of HF->e yield at high p_T in Pb-Pb collisions
- Significantly different strength of HF->e v_2 in models especially at low p_T
- Simultaneous description of R_{AA} and v_2 constraints models

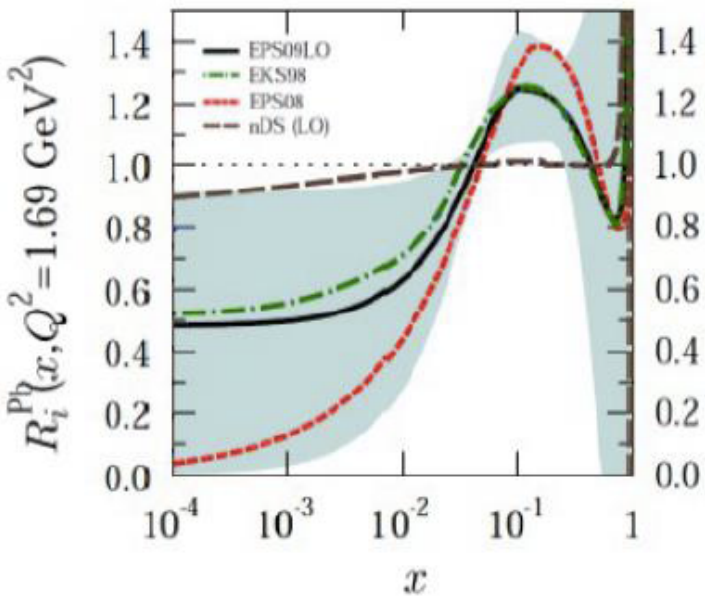
p-A collisions

- Heavy-flavour in p-A collisions
  - control measurement for heavy-ion collisions to disentangle initial (cold nuclear matter effects) from final state effects
- Cold nuclear matter effects
  - nuclear modification of Parton distribution Functions (PDF): shadowing or gluon saturation

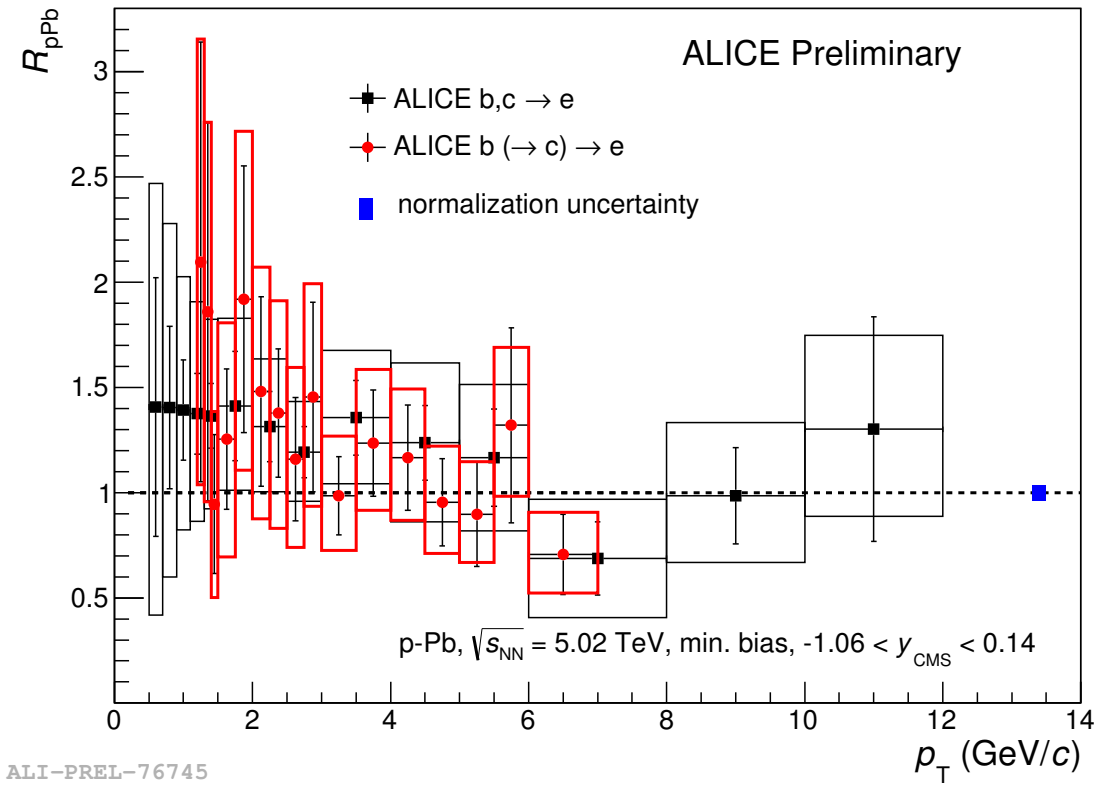
    K.J. Eskola et al., JHEP 0904(2009)65

    H. Fuji & K. Watanabe, NPA 915 (2013) 1
  - energy loss I. Vitev et al., PRC 75(2007) 064906
  - k_T broadening
  - multiple collisions

    A.M. Glenn et al., PLB 644(2007)119

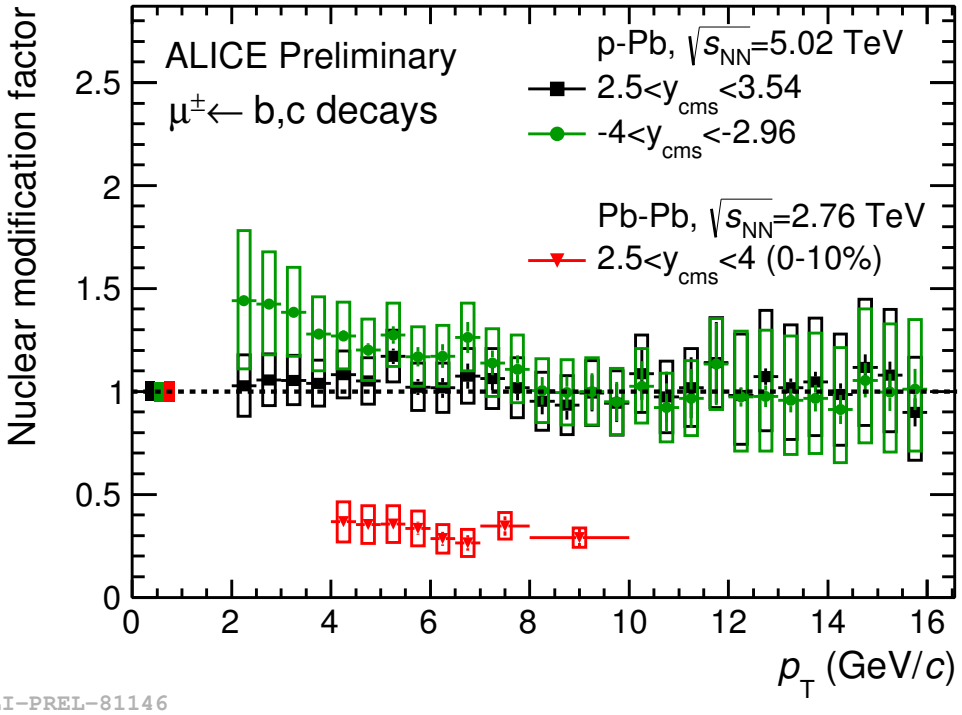


HF production in p-Pb collisions at mid-rapidity



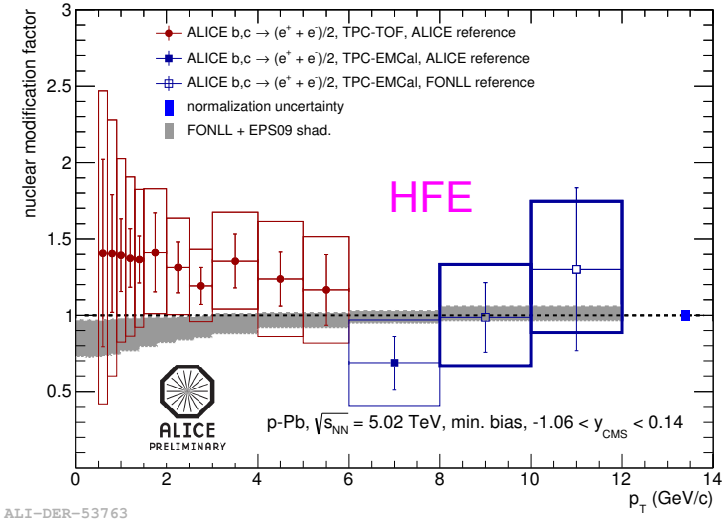
- R_{pPb} of HF->e and b->e are consistent with unity within uncertainties
- Suppression of HF->e & b->e (R_{AA}<1) in Pb-Pb collisions is due to interaction with the hot and dense medium

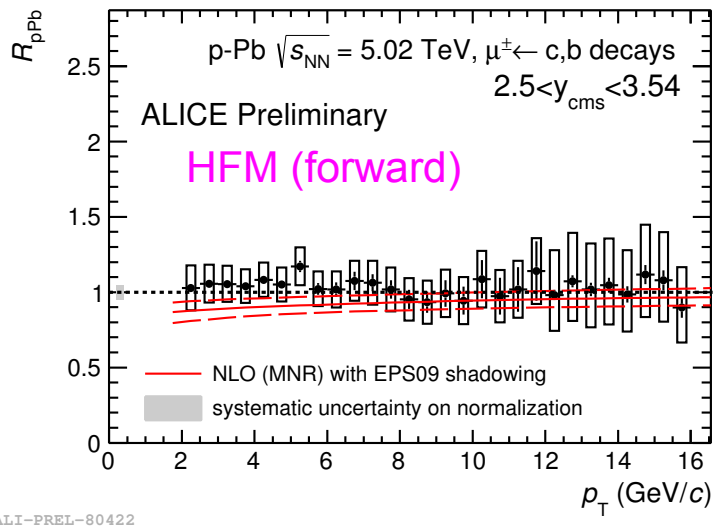
HF production in p-Pb collisions at forward rapidity



- R_{pPb} of HF->μ at forward ($2.5<y_{CMS}<3.54$) and backward ($-4<y_{CMS}<-2.96$) rapidity
  - forward (proton going): consistent with unity
  - backward (Pb going): consistent with unity, however, slightly larger 1 for $p_T<4$ GeV/c
- Strong suppression of HF->μ in Pb-Pb collisions is due to interaction with the hot and dense medium

Comparison with models in p-Pb collisions

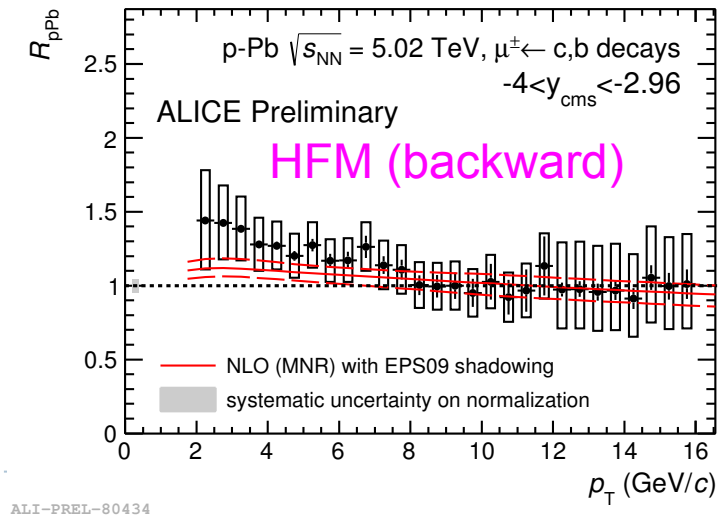




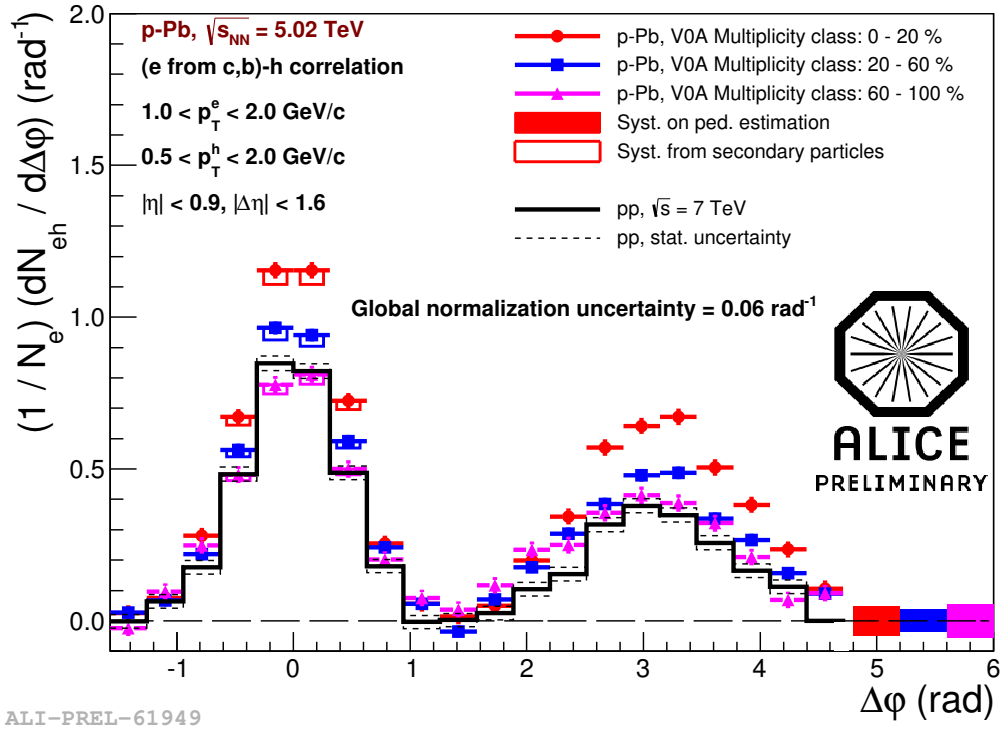
- Comparison with MNR pQCD calculations for heavy-flavour production with EPS09 parametrization of shadowing

  MNR: Nucl. Phys. B 373 (1992) 295
  EPS09: JHEP 0904 (2009) 065

  - calculations in agreement with data (HF->e & HF->μ) within uncertainties in different rapidity regions
  - seems to under-predict R_{pPb} of HF->μ at low p_T

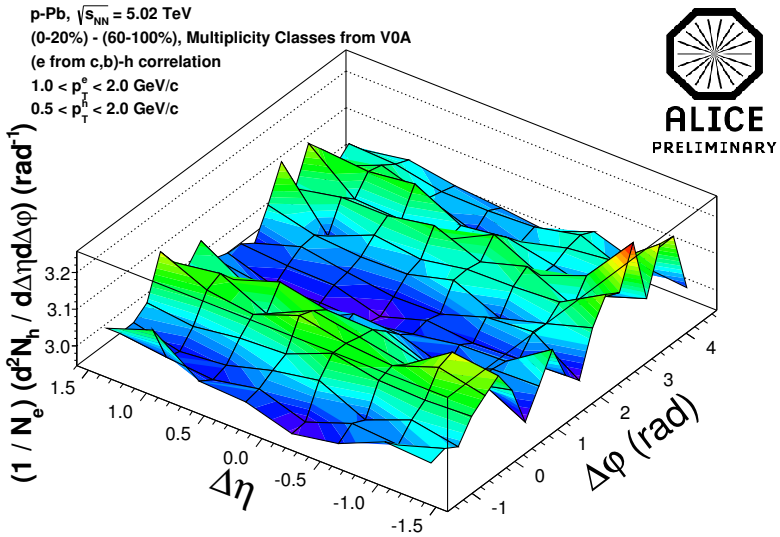


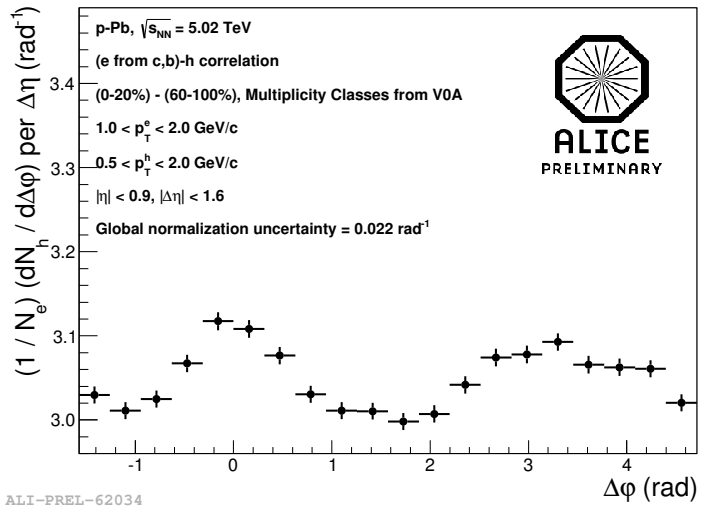
Azimuthal correlations of HF->e - hadron in p-Pb collisions (1)



- Azimuthal correlation between HF->e and hadrons
  - trigger particle: heavy flavour decay electrons
  - clear correlation on near & away side: jet like structure
- Enhancement in high (0-20%) w.r.t. low-multiplicity (60-100%) collisions

Azimuthal correlations of HF->e - hadron in p-Pb collisions (2)





- Subtract low mult. correlations from high mult. to remove jet contributions
- Observed long-range ridge structures on the near-side and away-side in heavy-flavour production in p-Pb collisions
  - similar structure observed hadron-hadron correlations: PLB 719(2013)29-41 [ALICE]
- Possible origins:
  - Color Glass Condensate (CGC) in the initial state
  - collective (hydrodynamic) expansion in the final state

Summary

- Heavy-flavour production in pp collisions
  - pQCD calculations describe data within uncertainties
- Heavy-flavour production in Pb-Pb collisions
  - Strong suppression of heavy-flavour yield at high p_T
    - clear indication for substantial energy loss of heavy-flavour in the hot and dense medium
  - Non-zero v_2 in low p_T
    - suggests that charm quarks take part in the collective expansion of the medium
- Heavy-flavour production in p-Pb collisions
  - R_{pPb} is consistent with unity
    - confirms that the suppression observed in Pb-Pb is due to interactions with the hot and dense medium
  - Long-range ridge structures
    - the mechanisms (CGC or hydro) proposed for light-hadron correlations affect also HF
- Heavy flavours observed to be significantly affected by hot and dense QCD medium (energy loss and v_2)
- Constraining the models with our data and learn mechanism of HF productions

Heavy flavour study via electrons

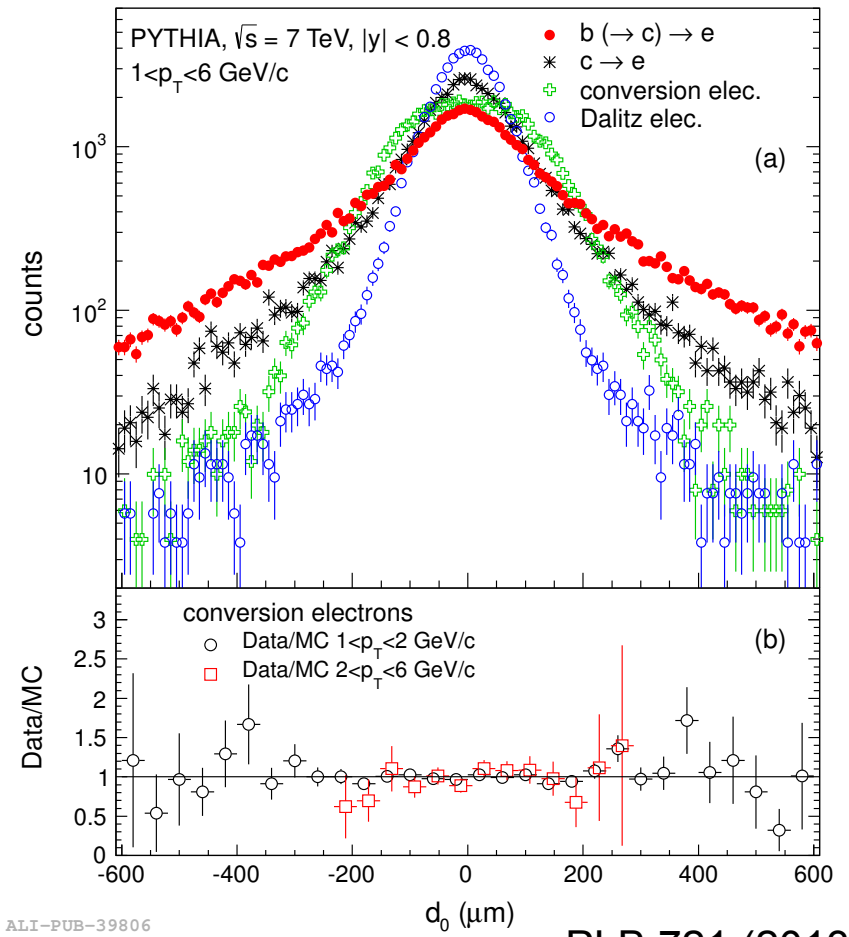
- Signal Electrons:
  - From semileptonic decay of charm & beauty hadrons
- Background Electrons:
  - From photon conversions
  - From Dalitz decays of neutral mesons
  - From quarkonia decays

Branching Ratios:

$c \rightarrow e + X$	$\mathcal{O}$ (9.6%)
$b \rightarrow e + X$	$\mathcal{O}$ (11%)
$b \rightarrow c \rightarrow e + X$	$\mathcal{O}$ (10%)

- Background subtraction
  - Cocktail method
    - Background calculated using measured hadron production cross section
  - Invariant mass method – electrons from 'photonic' sources
    - Reconstruction of electron pairs from the decays of neutral mesons & photon conversions
  - Heavy Flavour decay Electrons (HFE) dN/dp_T obtained via subtraction of the background from the inclusive electron spectrum

Beauty decay electron separation
- Impact parameter method



PLB 721 (2013) 13-23

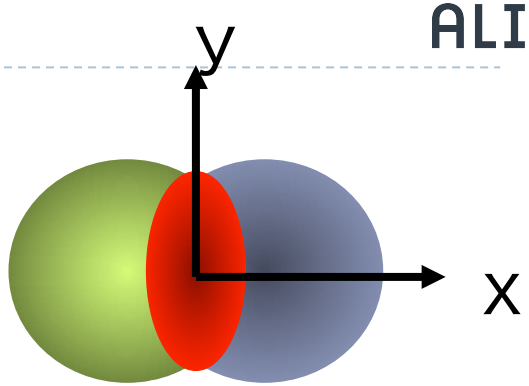
- Separation based on displacement from primary vertex
  - Preferential selection via their large impact parameter (d_0)
    - $c\tau$~ 500μm for B hadron
    - $|d_0|$>250μm (p_T ~ 2.5 GeV/c) (p_T dependent cut)
  - ITS ; impact parameter resolution < 75 μm for p_T>1 GeV/c
- Remaining backgrounds estimated based on measured π^0, η & D
- use in pp & p-Pb analysis

Azimuthal anisotropy

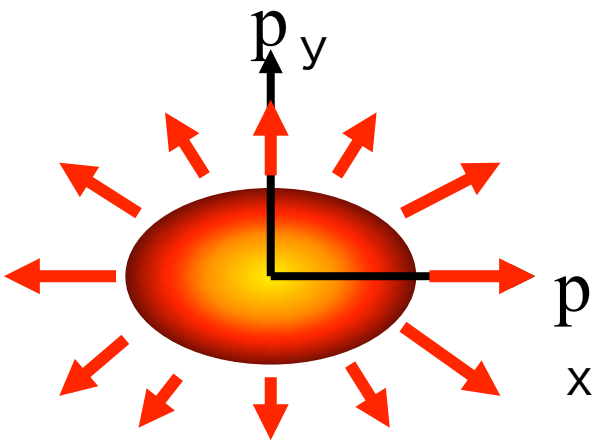
- Elliptic flow

$$dN/d(\varphi-\psi_{RP}) = N_0\{1+\ldots+2v_2\cos(2(\varphi-\psi_{RP})) +\ldots\}$$

- Transfer initial spatial anisotropy to momentum anisotropy
  - macroscopic: hydro model => pressure gradient
  - microscopic => scattering in the medium
- At low p_T, heavy flavour v_2 gives information about the coupling of heavy quarks with the medium and possibly their thermalization in the medium
- Path-length dependence of energy loss at high p_T

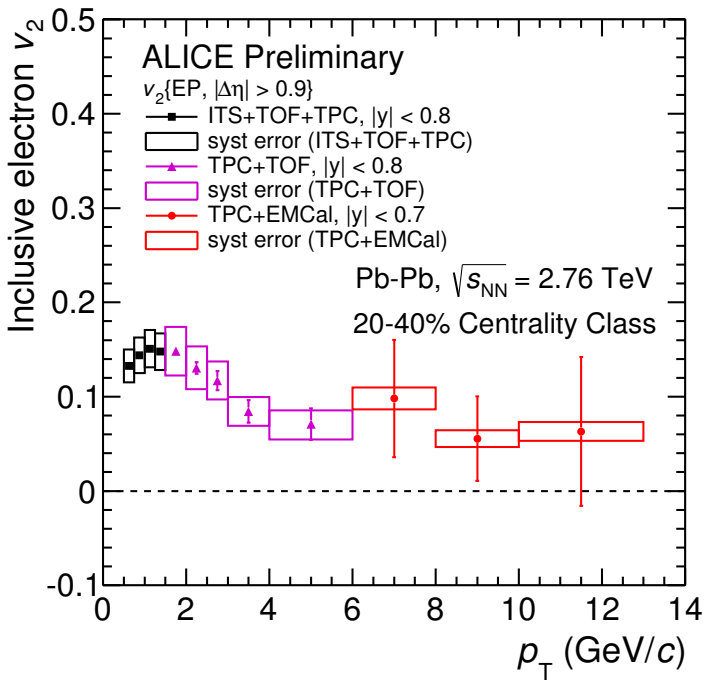


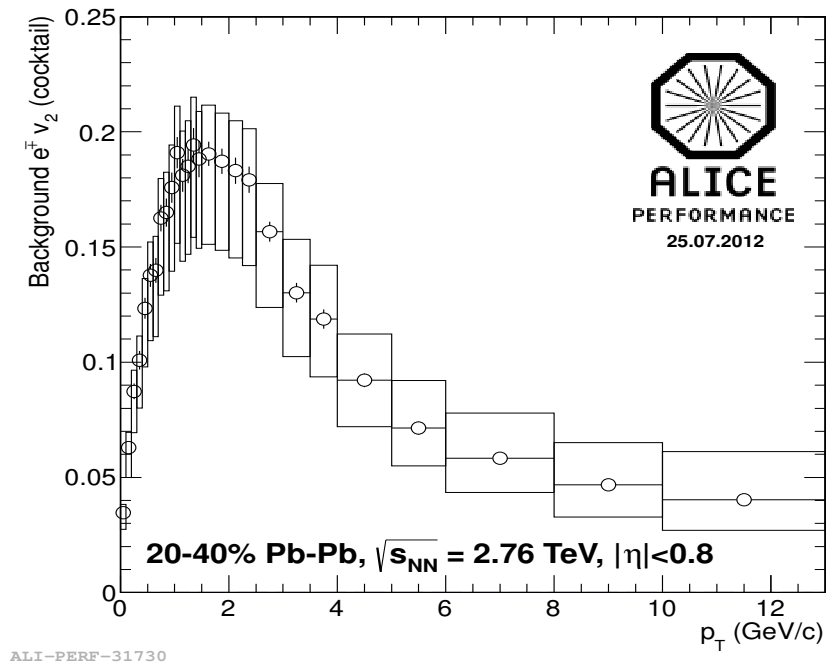
Initial spatial anisotropy



Momentum space anisotropy of particle emission

Azimuthal anisotropy of electrons

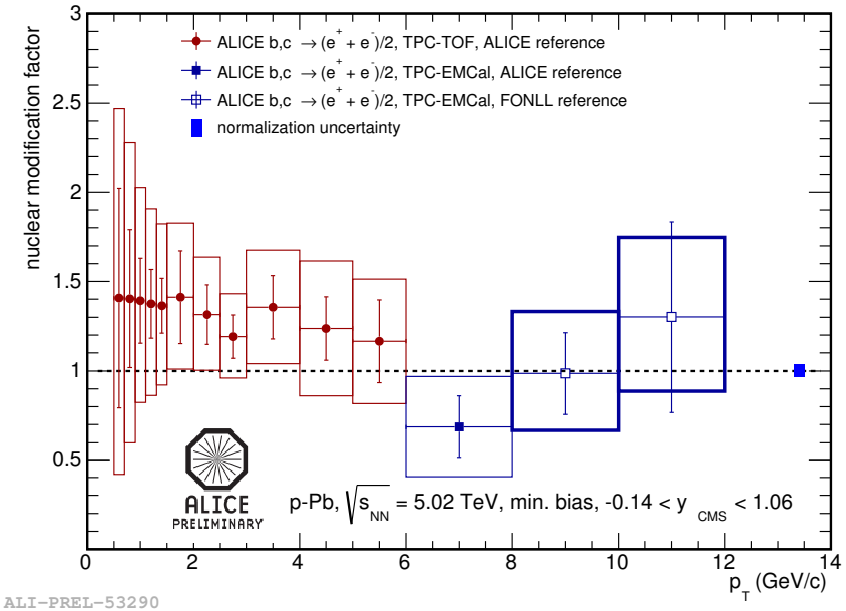


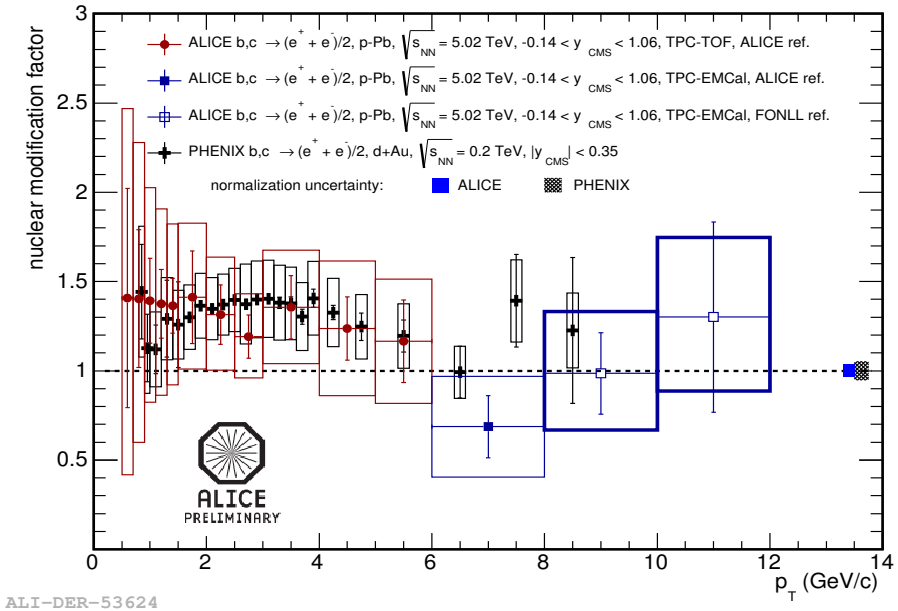


- Elliptic flow (v_2) ; $dN/d(\phi-\psi) = N\,(1 + 2v_2^{obs}\cos(2(\phi-\psi_{EP})))$
- Event plane determined with the VZERO detectors ($2.8<\eta<5.1$, $-3.7<\eta<-1.7$)
- HFE v_2 obtained by subtraction of the background electron v_2:

$$v_2^{HFE} = \frac{(1+R)v_2^{inclusive} - v_2^{background}}{R}, \quad R = \frac{N_{HFE}}{N_{background}}$$

R_{pPb} of HF->e





Phenix: Phys. Rev. Lett. 109 (2012) 242301

- R_{pPb} of HF->e
  - compatible with unity within uncertainties
  - similar behaviour observed at PHENIX for d-Au at $\sqrt{s_{NN}}$ = 0.2 TeV