Measurements of heavy-flavor decay leptons in pp, p-Pb, and Pb-Pb collisions with ALICE

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for the ALICE collaboration

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Overview

- Introduction
- Measuring heavy-flavors (HF) with ALICE
- HF decay leptons in pp, p-Pb, and Pb-Pb collisions
    - Production cross sections
    - Nuclear modification factor in p-Pb and Pb-Pb collisions
    - Elliptic flow in Pb-Pb collisions
    - HF electron-hadron correlations in pp and p-Pb collisions
- Summary

Why study open heavy-flavour?

- At the LHC - abundant production of heavy quarks (charm and beauty)

  RHIC to the LHC:
  ~ 10* σ_{cc}
  ~ 50* σ_{bb}

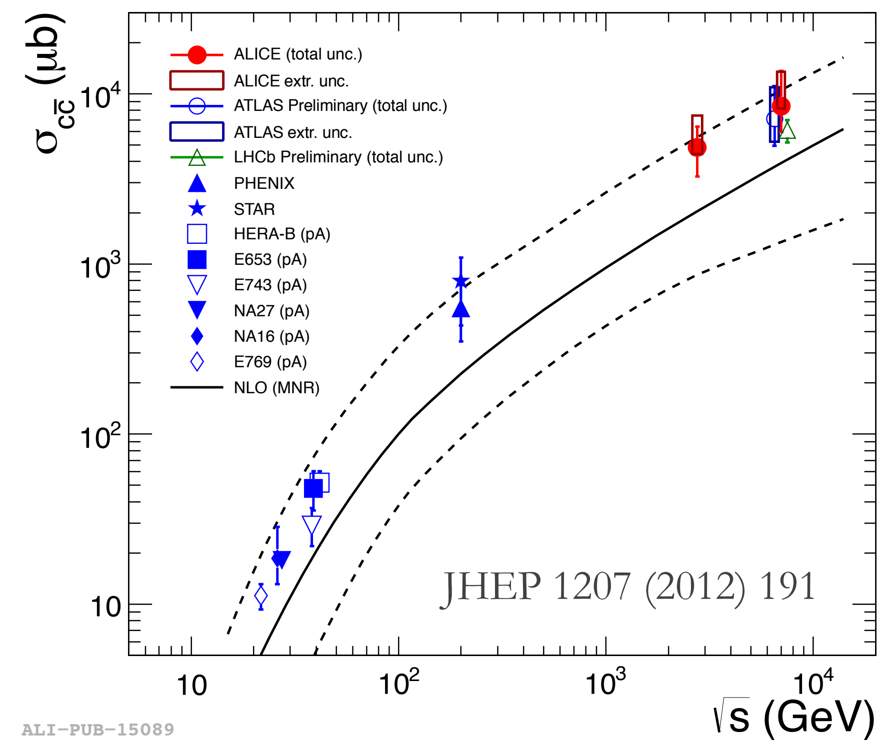
- **Heavy quarks are produced via hard parton scatterings in the initial phase of the collision**
  - large mass → short formation time

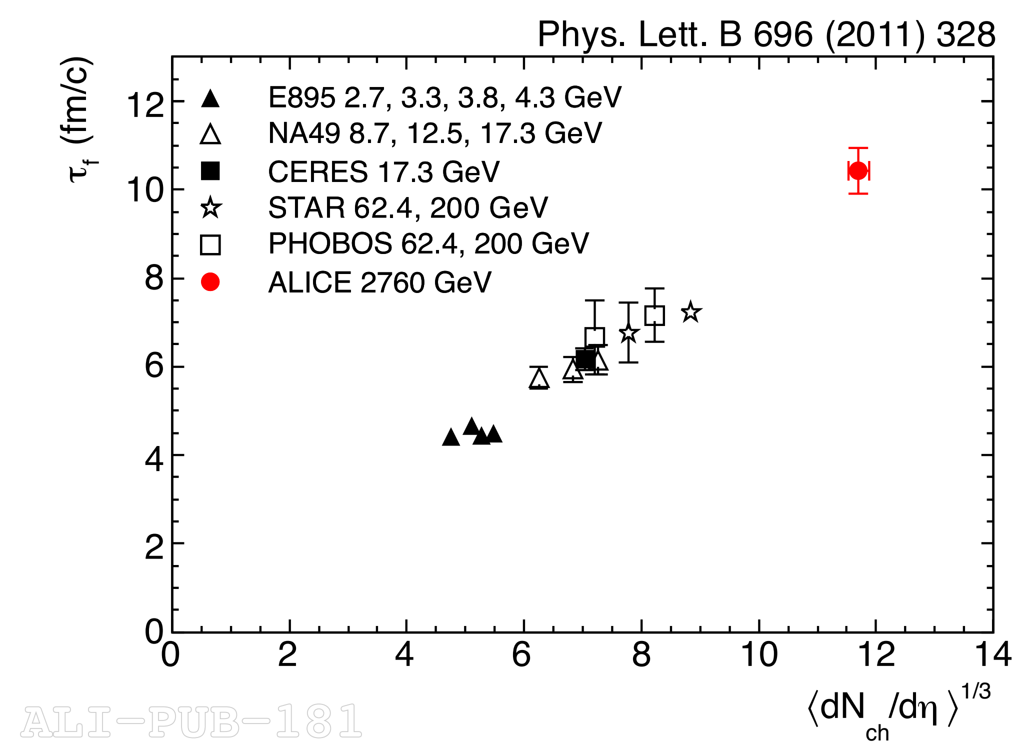
  τ_{charm} ~ $1/2m_c$ ~ 0.1 fm

- Formation time (τ_{form}) of the Quark Gluon Plasma (QGP) is < 1 fm/c

- At LHC energies, in central (0-5%) collisions, the QGP fireball lifetime (τ_f) is estimated to be ~ 10 fm/c (PLB 696 (2011) 328)

$\tau_{charm} < \tau_{form} << \tau_f$





Why study open heavy-flavour?

Pb-Pb collisions: Probing the QGP matter

- Heavy quarks experience the full evolution of the system, making them excellent probes
- In-medium partonic energy loss - Both mass (dead cone) and color charge dependent

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

L. Dokshitzer, D.E. Kharzeev Phys. Lett. B 519 (2001) 199,
N. Armesto, C., A. Salgado and U. A. Wiedemann. PRD 69 (2004) 114003

- Medium transport properties (collectivity). Do heavy quarks participate in the collective expansion of the system? Do they thermalize with the medium?

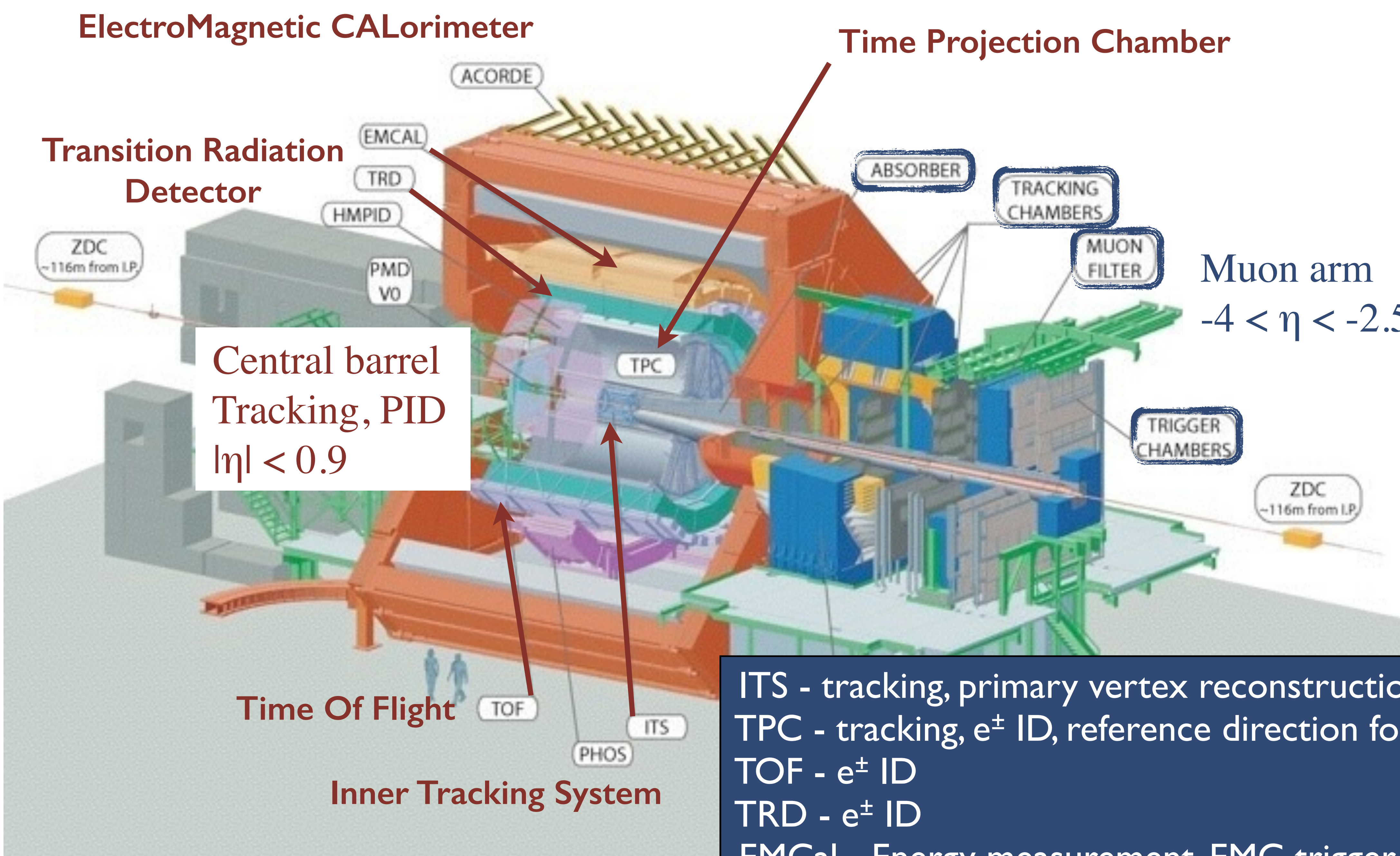
pp collisions

- Important test of perturbative QCD predictions
- Baseline for effects found in p-Pb and Pb-Pb collisions

p-Pb collisions

- Control experiment for Pb-Pb
- Study cold nuclear matter effects
  - Modification of parton distributions in nuclei (shadowing/parton saturation)
  - k_T-broadening, energy loss in cold nuclear matter

A Large Ion Collider Experiment



ITS - tracking, primary vertex reconstruction
TPC - tracking, $e^{\pm}$ ID, reference direction for $\mu^{\pm}$ flow
TOF - $e^{\pm}$ ID
TRD - $e^{\pm}$ ID
EMCal - Energy measurement, EMC trigger
V0 - Minimum bias trigger, centrality and event selection
Muon Spectrometer - $\mu^{\pm}$ tracking, $\mu^{\pm}$ trigger

Open heavy-flavour program

Mid rapidity ($|\eta| < 0.9$)

D mesons (D^0, D^+, D^*, D_s) via hadronic decays
- Select on displaced vertices using TPC and ITS
- Particle ID using TPC and TOF
- Invariant mass (M_{inv}) analysis

See talk by C. Jena

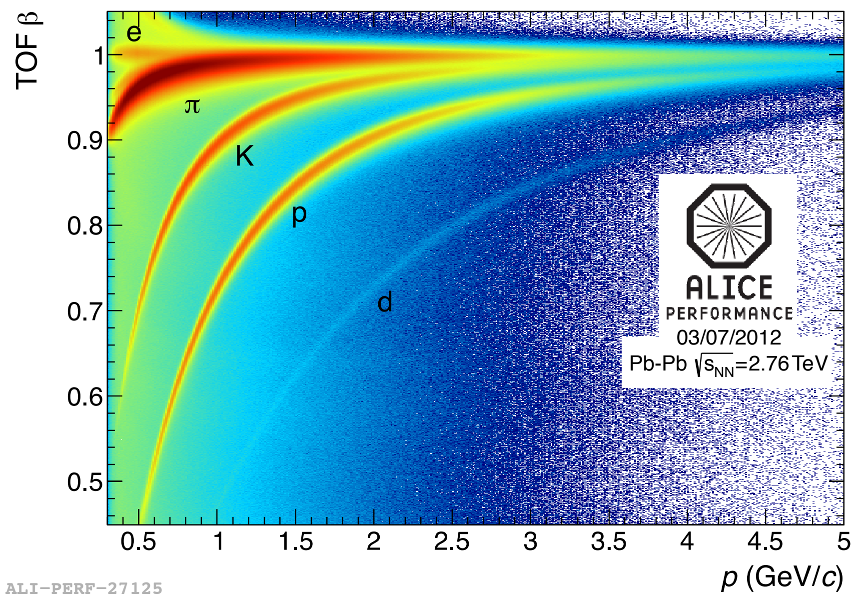
Single electrons from semi-leptonic heavy-flavour hadron decays
- $e^{\pm}$ ID using TPC, TOF, EMCal and TRD

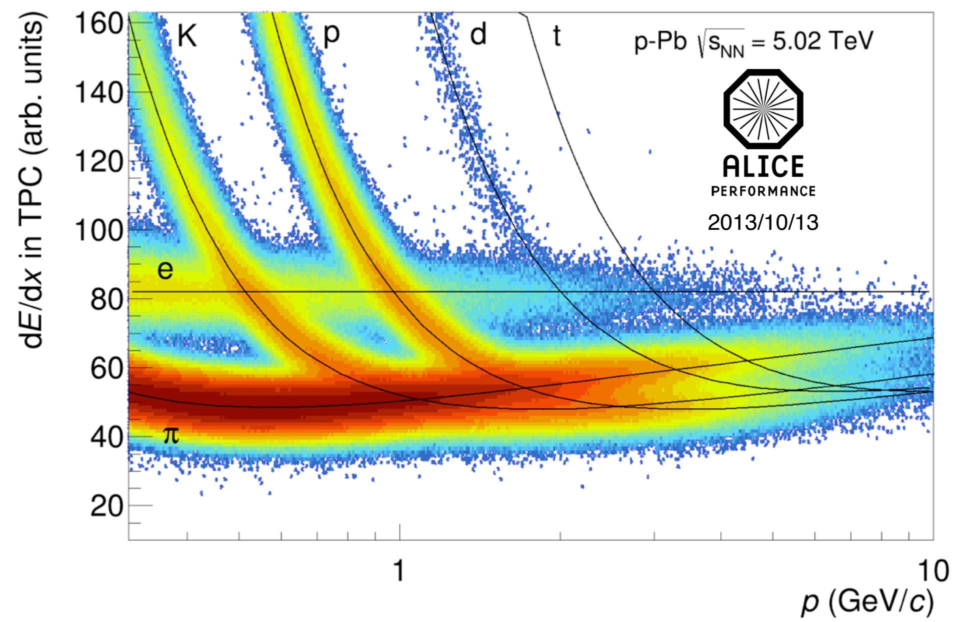
Forward rapidity ($-2.5 < \eta < -4$)

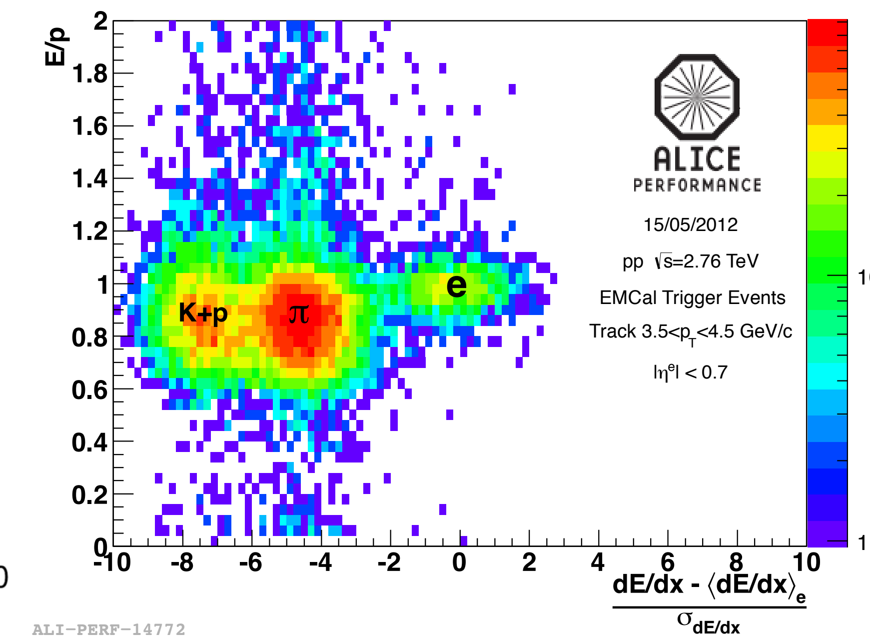
Single muons from semi-leptonic heavy-flavour hadron decays
- Muon spectrometer

Electron identification

Mid rapidity (|η| < 0.9)



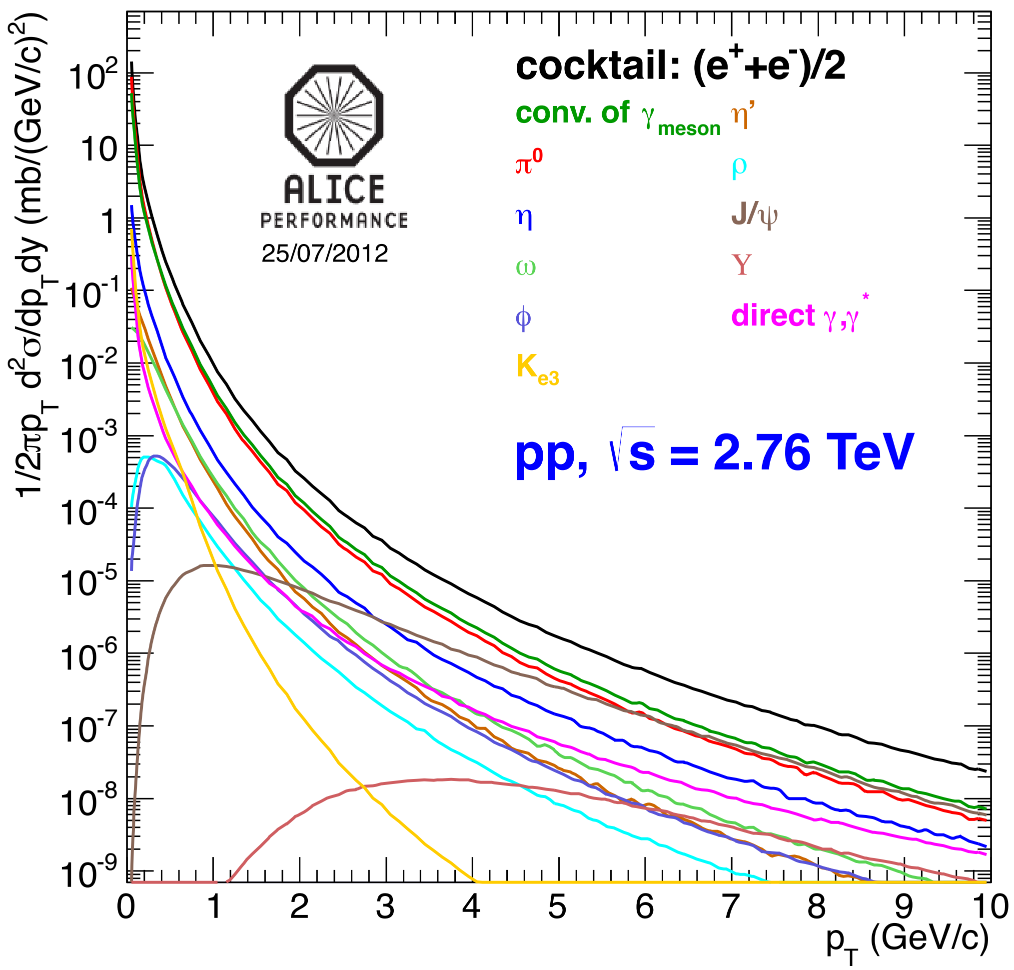




electrons at low momentum {
- **TOF** - Velocity measurement
- **TPC** - Specific energy loss, dE/dx

high momentum ⟶ **EMCal** - Deposited energy, where E/p ~ 1 for electrons

Heavy-flavour decay electron selection



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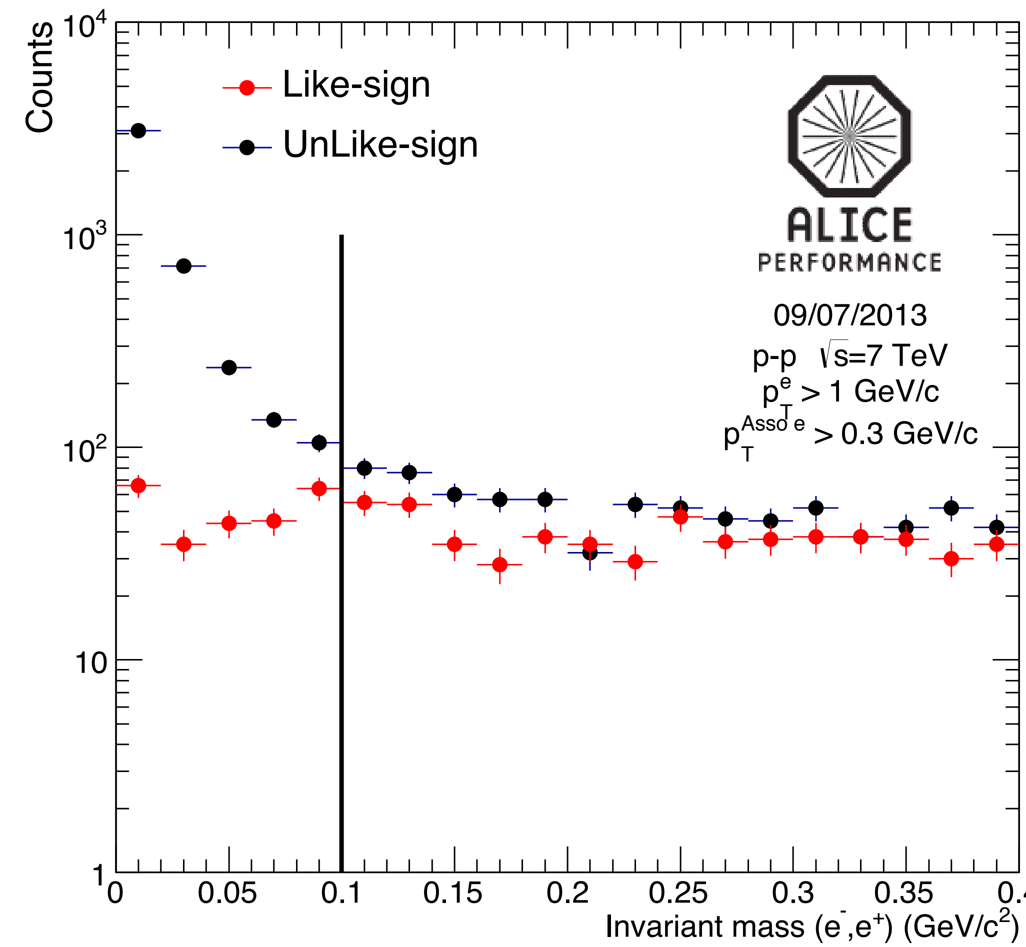

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Single electrons from semi-leptonic heavy-flavour hadron decays

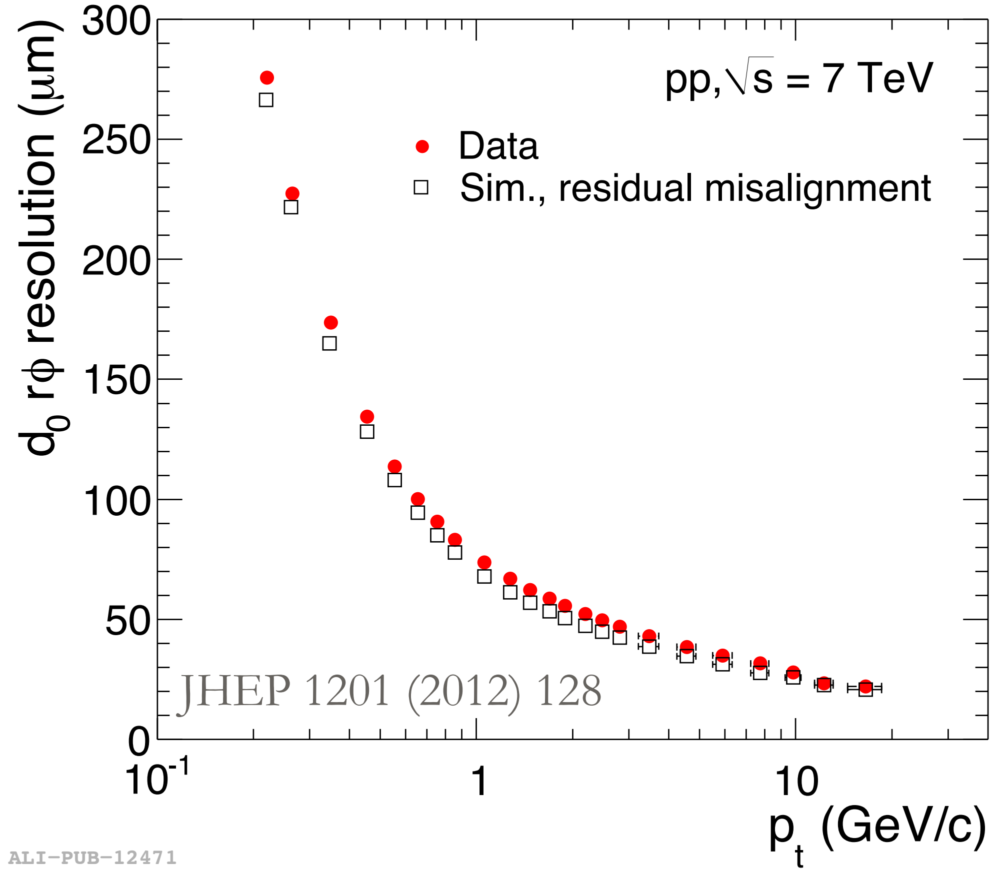
- Background estimated from MC cocktail or e^+e^- invariant mass method
  - The cocktail is based on measured cross sections of background sources
  - Di-electron pairs from photon conversions and Dalitz decays, mainly π^0, are primary contributors to low M_{inv} (e^+e^-) peak

Beauty hadron decay electrons

The approach:

- Separate electrons from B decays
- Exploit relatively long lifetime of B mesons
- Excellent resolution given by the ALICE Inner Tracking System

σ_{d0} < 75 μm for p_T > 1 GeV/c



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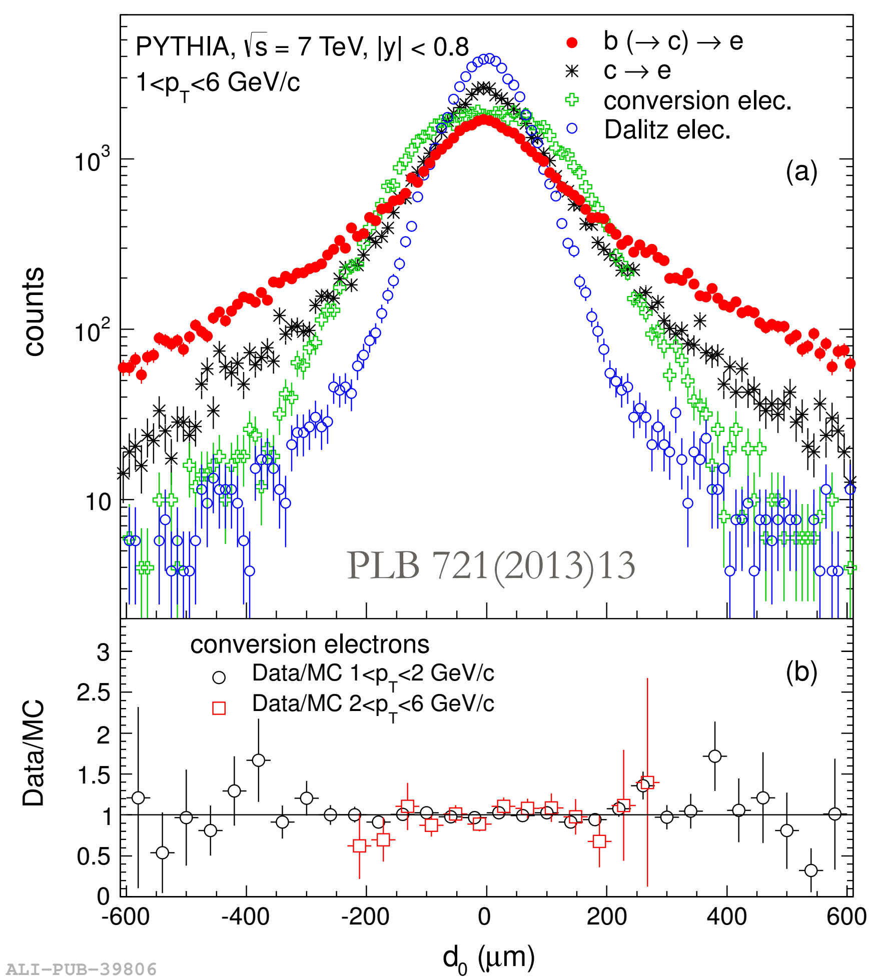

Impact parameter (IP) analysis (Main method used by ALICE)

- Beauty decay electrons have broader IP (d_0) distribution compared to backgrounds
- Electrons must satisfy p_T dependent minimum condition on d_0
- Background subtraction using MC cocktail, with measured cross sections as input

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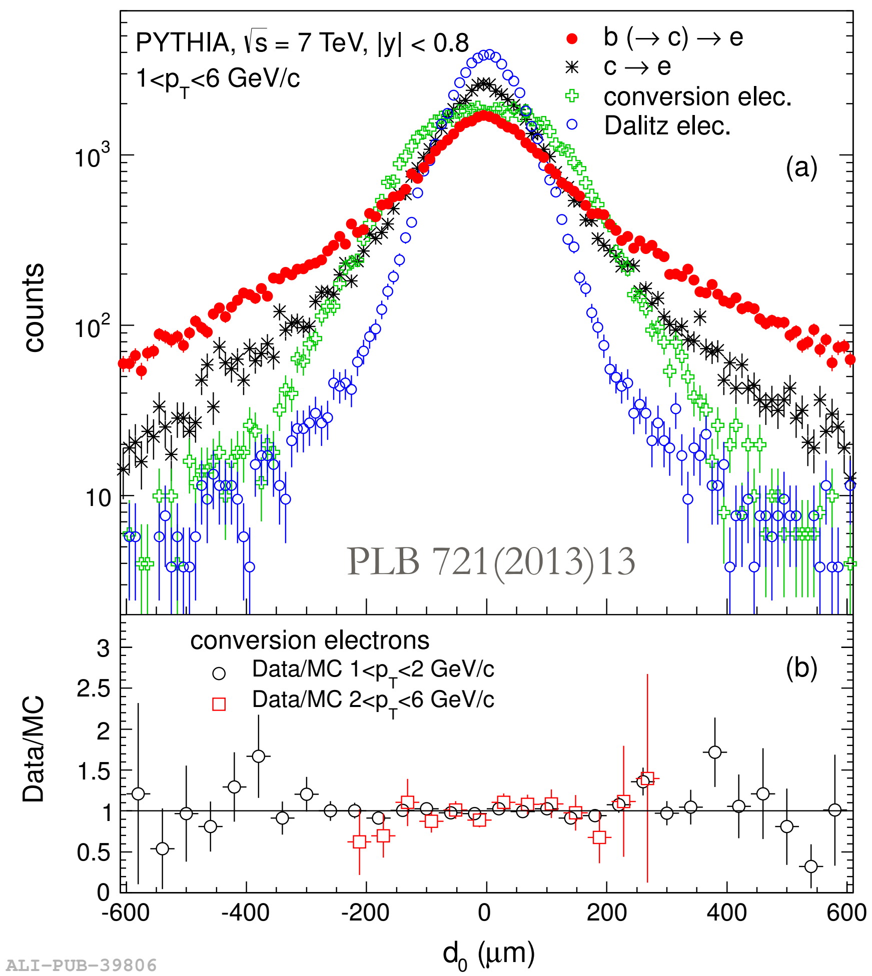

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Alternative methods using EMCal triggered events:

Displaced electron-hadron (e-h) vertices

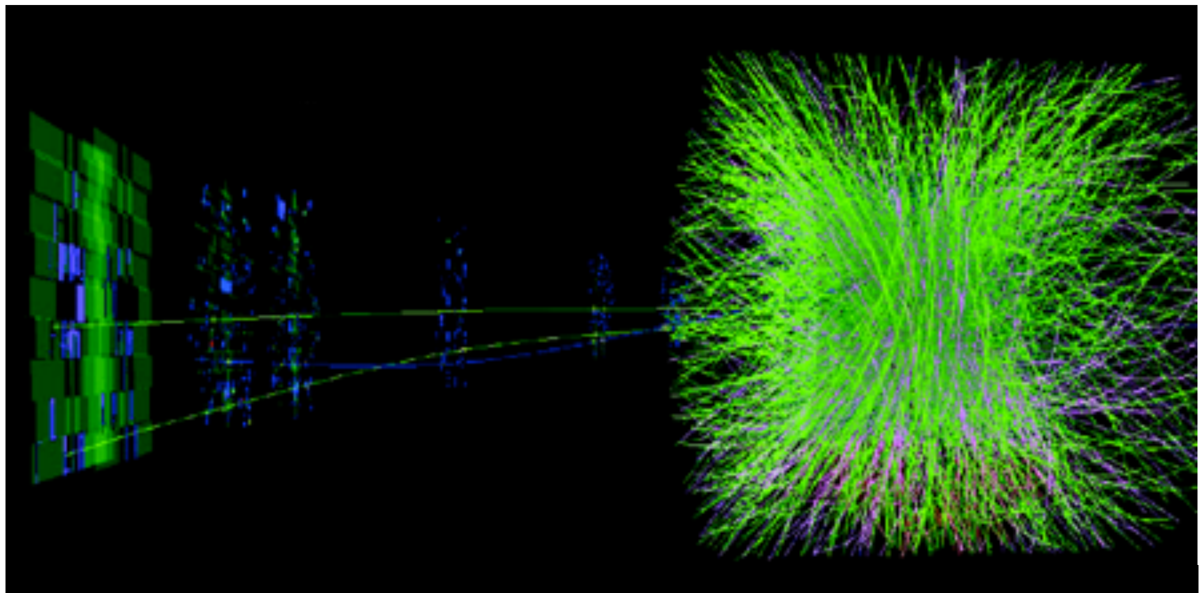
- Reconstruct e-h displaced vertices
- Selection: e-h M_{inv}, distance to primary vertex, and p_T of hadron

e-h azimuthal correlations ($\Delta\varphi_{e\text{-}h}$)

- Near-side peak wider for beauty compared to charm hadron decays
- Pythia templates used to estimate relative contribution

Muon track selection

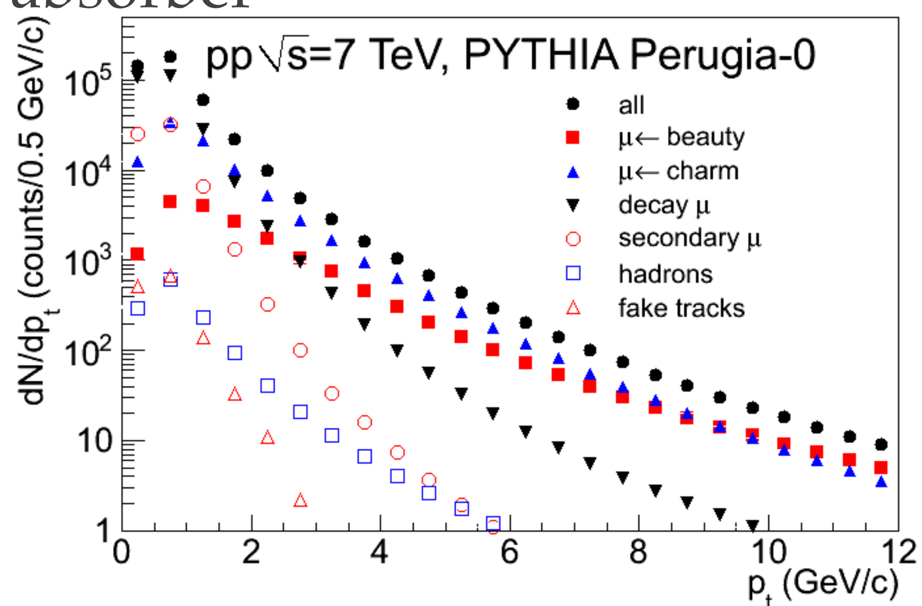
Forward rapidity (-2.5 < η < -4)



ALICE Event display showing muon tracks in 2010 Pb-Pb collisions at $\sqrt{s_{NN}}$= 2.76 TeV.

Track selection

1. muon trigger matching: reject hadrons that cross the front absorber
2. correlation between track momentum and distance of closest approach: remove beam gas and particles produced in the absorber



PLB 708 (2012) 265

Single muons from semi-leptonic heavy-flavour hadron decays

- After track selection, HF decay muons dominate the total yield above 4 GeV/c
- Dominant background sources are from the decays of π and K
  - In pp, estimated using a MC simulation
  - In Pb-Pb, extrapolated from the measured π, K yields at mid rapidity

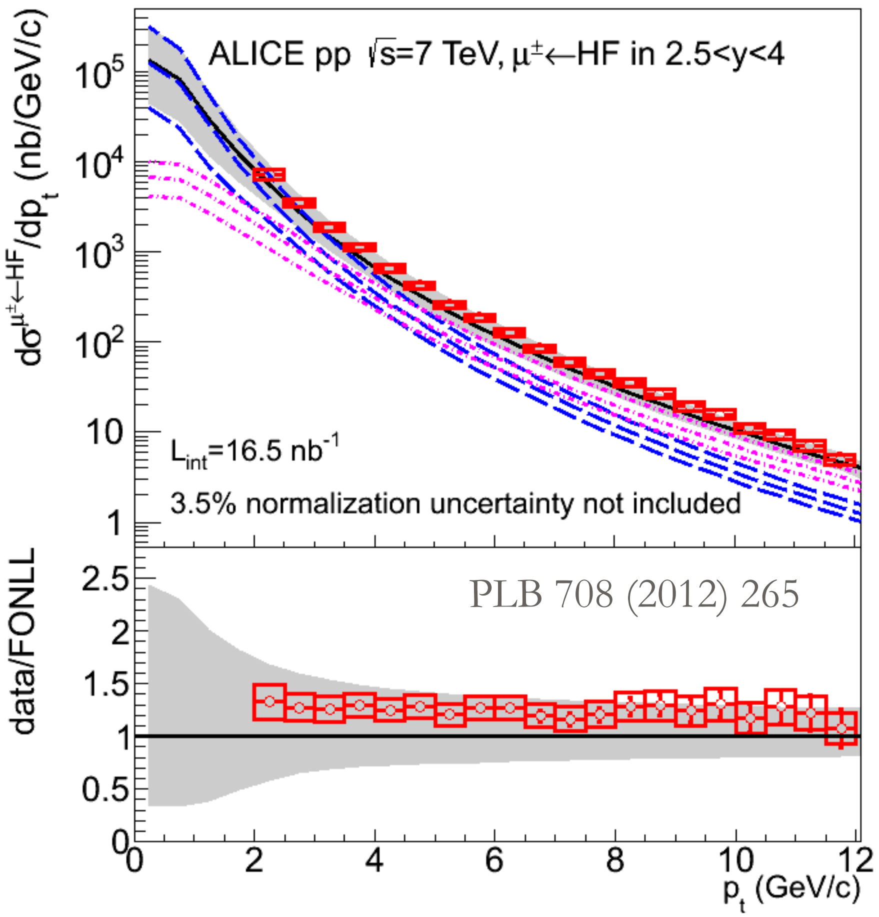
pp collisions

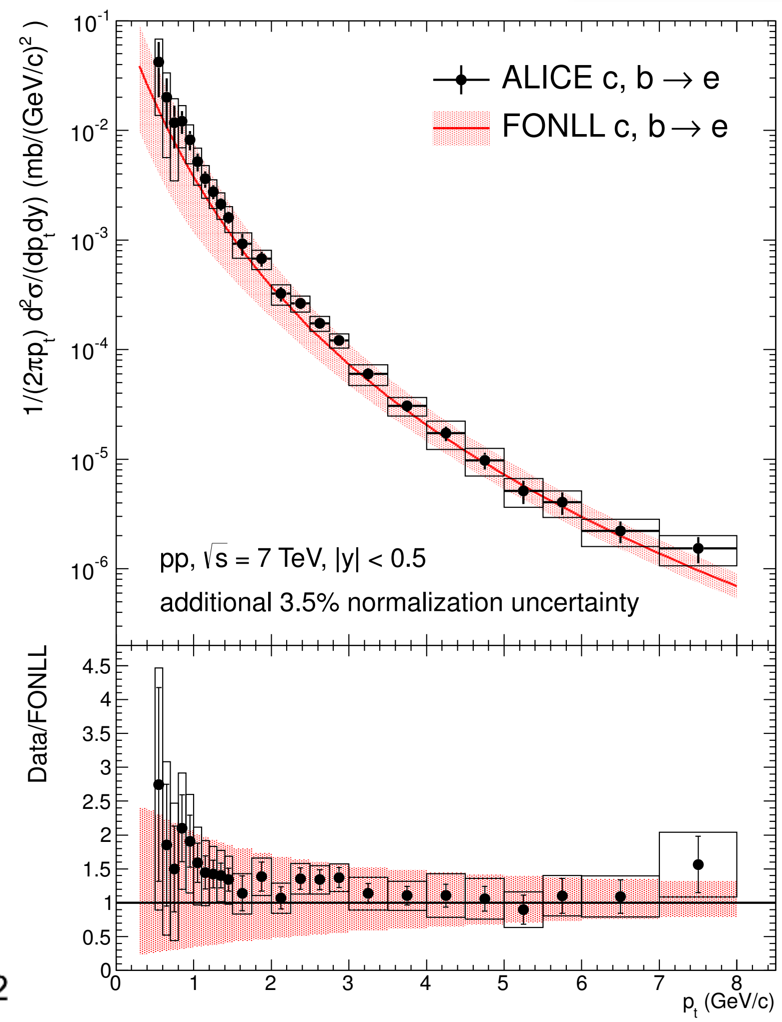
	7 TeV	2.76 TeV
Muons	2010 run, $\mathcal{L}_{int}$ = 16.5 nb^{-1}, MB and muon trigger	2011 run, $\mathcal{L}_{int}$ = 19 nb^{-1} muon trigger
Electrons	2010 run, $\mathcal{L}_{int}$ = 2.6 nb^{-1} from MB trigger, $\mathcal{L}_{int}$ = 2.1 nb^{-1} from EMCal trigger	2011 run, $\mathcal{L}_{int}$ = 1.1 nb^{-1} from MB trigger, $\mathcal{L}_{int}$ = 14.8 nb^{-1} from EMCal trigger

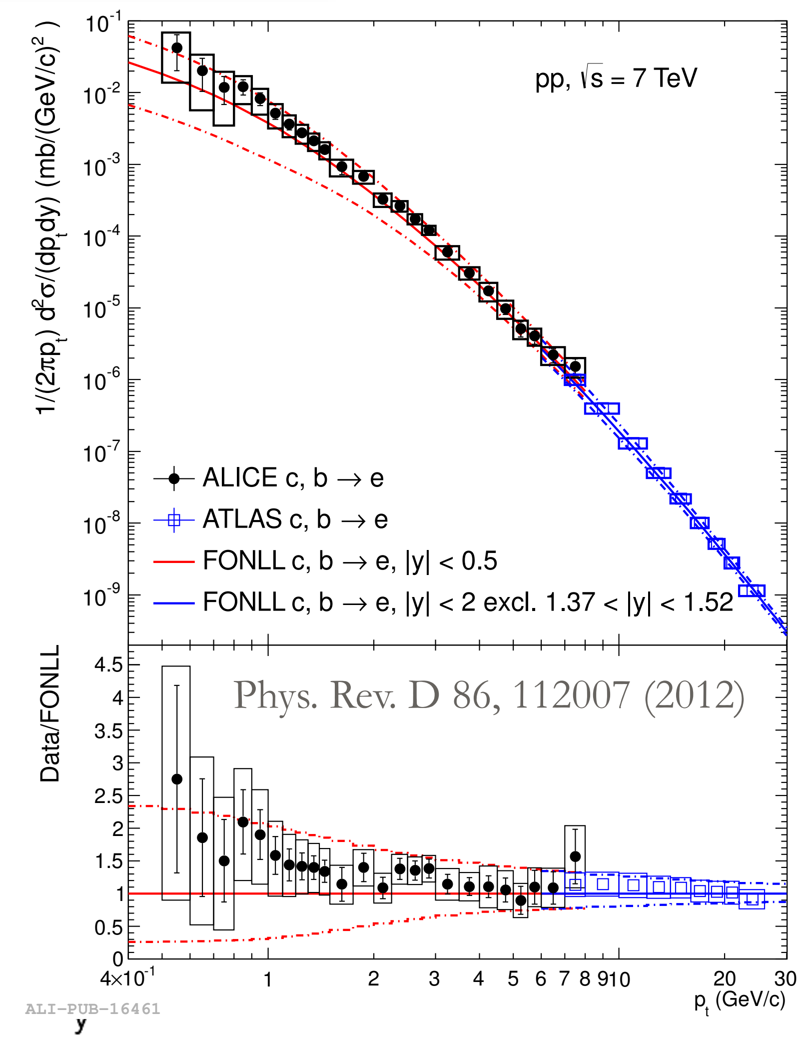
Single HF decay leptons in pp collisions at 7 TeV

HF decay electrons

HF decay muons







- Measured production cross section of HF decay muons and electrons
- Measurements of HF decay electrons in p_T region complementary to ATLAS results
- pQCD predictions (FONLL shown) describe the data within uncertainties

FONLL: Cacciari et al., JHEP 9805 (1998) 007, JHEP 0103 (2001) 006, GM-VFNS: EPJ C72(2012)2082, k_T factorization: arXiv:1301.3033

Beauty decay electrons in pp collisions at 7 TeV

Impact parameter (IP) analysis

p_T differential production cross section of electrons from **beauty** hadron decays

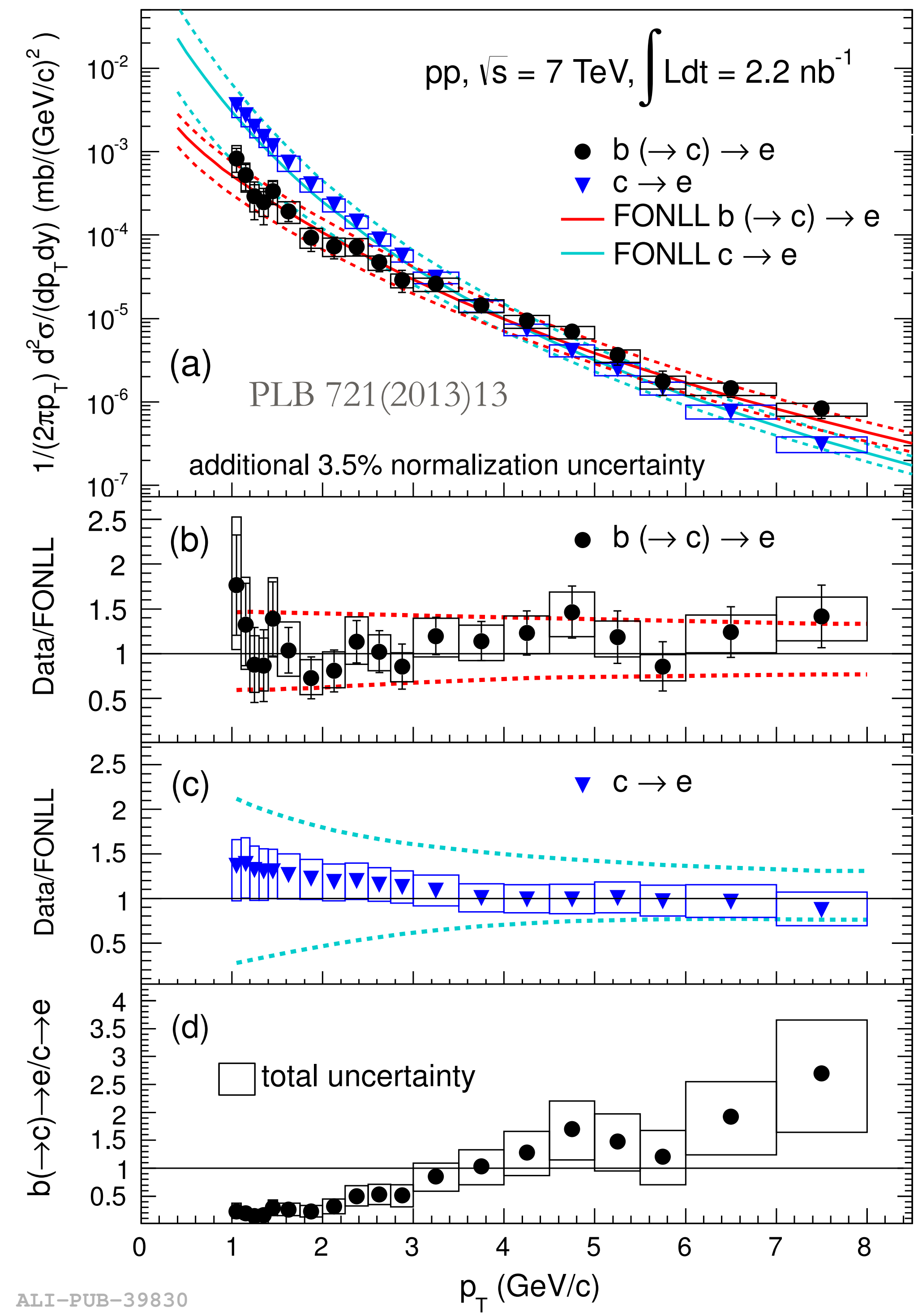
- Estimate electrons from **charm** hadron decays using D mesons measured by ALICE
- Beauty decay electrons start to dominate, relative to charm at p_T of ~ 4 GeV/c

- Compatibility with FONLL calculations

Cacciari et al., JHEP 9805 (1998) 007, JHEP 0103 (2001) 006

- The calculations GM-VFNS and k_T-factorization are also in agreement

Nucl. Phys. B 872 (2013) 253-264, arXiv:1306.6808



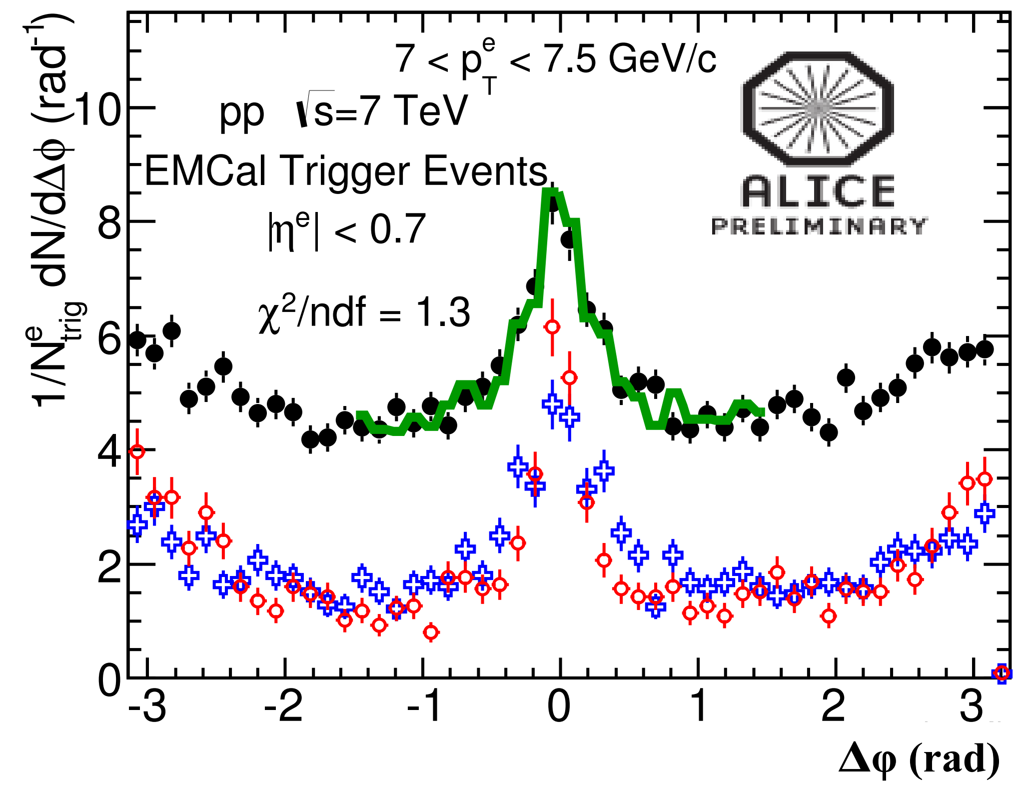
More beauty in pp collisions at 7 TeV

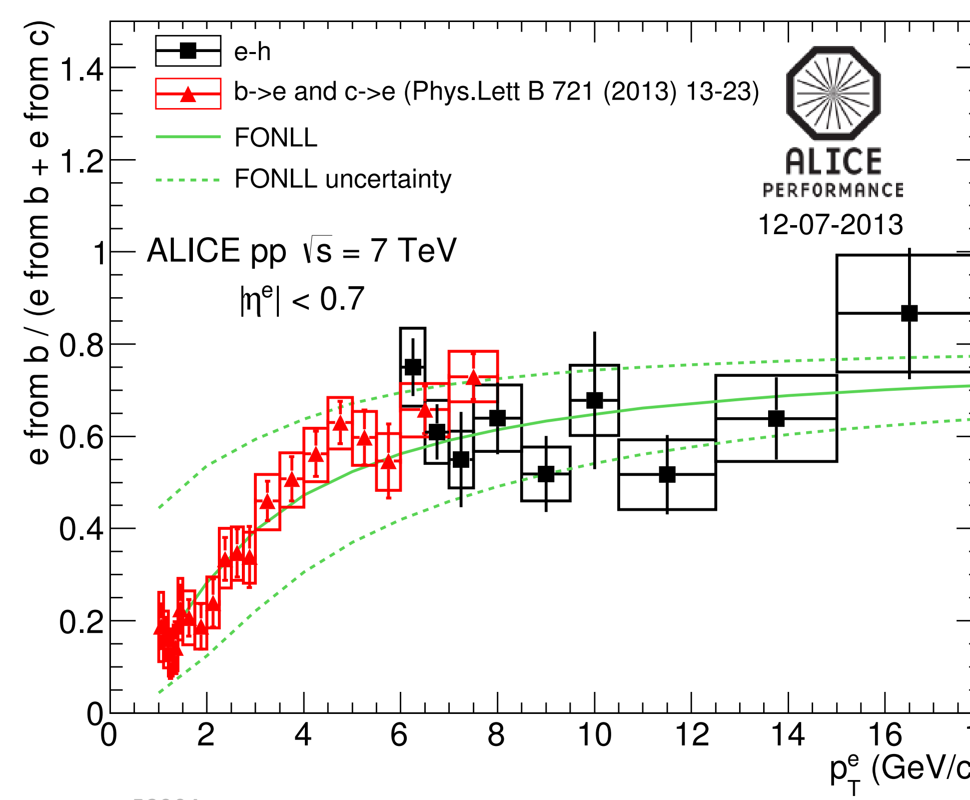
e-h correlations in $\Delta\varphi$

- Pythia **template** for charm and beauty used to estimate the relative fraction of beauty decay electrons

- Extends to a p_T of 18 GeV/c

- Possible, using total cross section of electrons from HF hadron decays, to calculate production cross section of electrons from beauty hadron decays



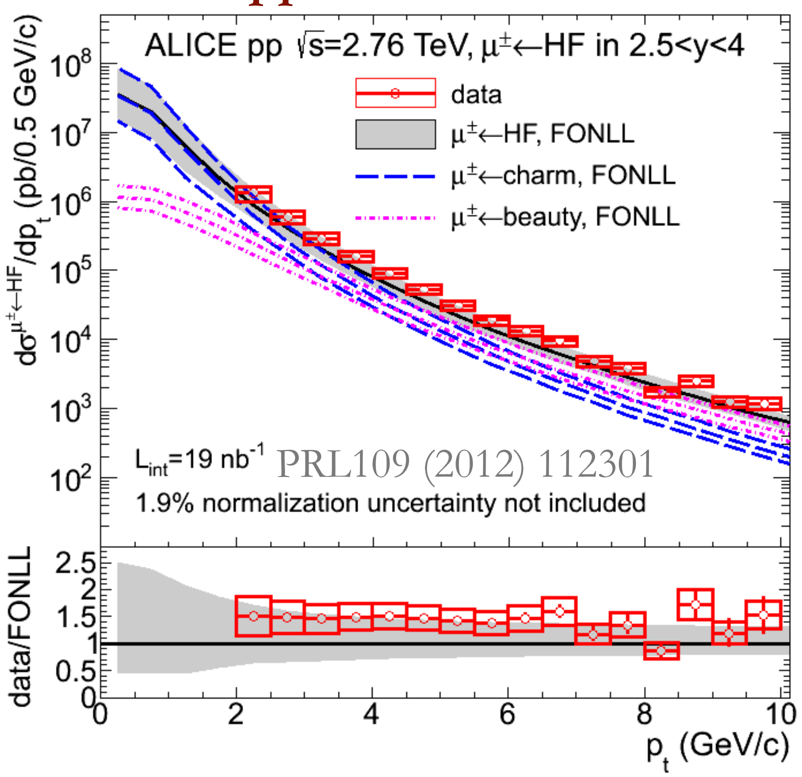


Various HF results in pp collisions at 2.76 TeV*

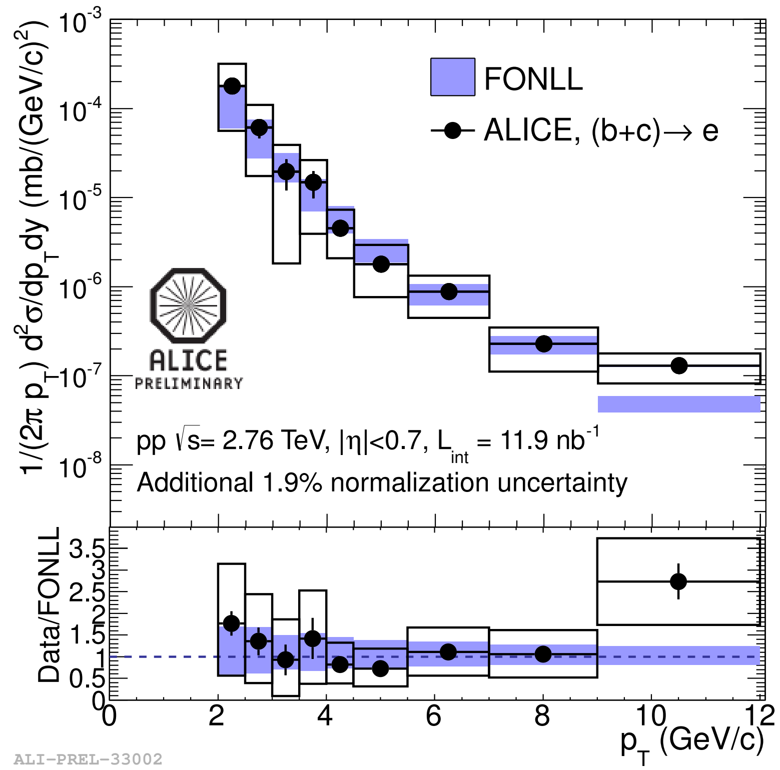
*reference energy for Pb-Pb

HF decay muons

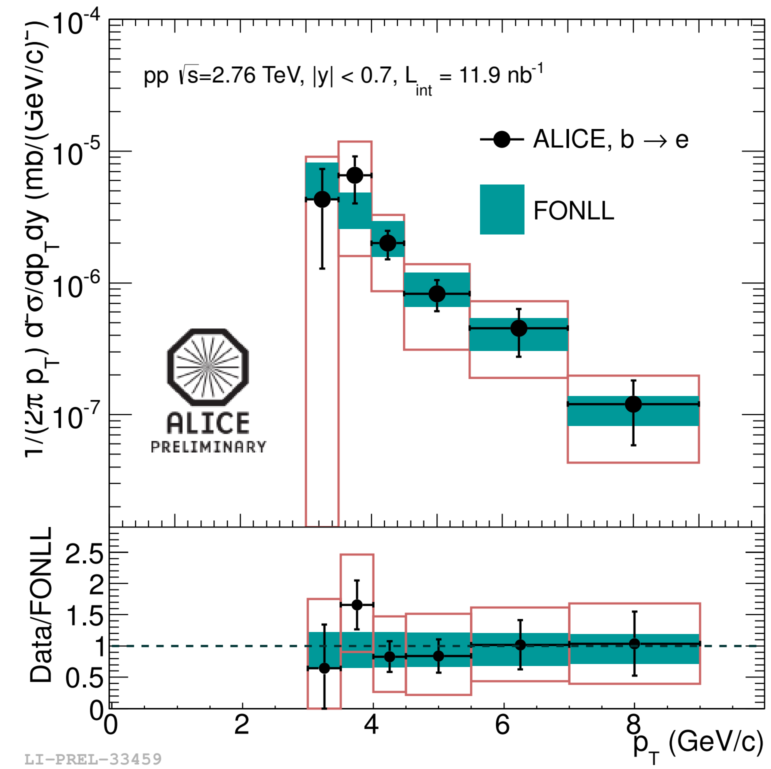
Used as pp reference for Pb-Pb



HF decay electrons



Beauty decay electrons



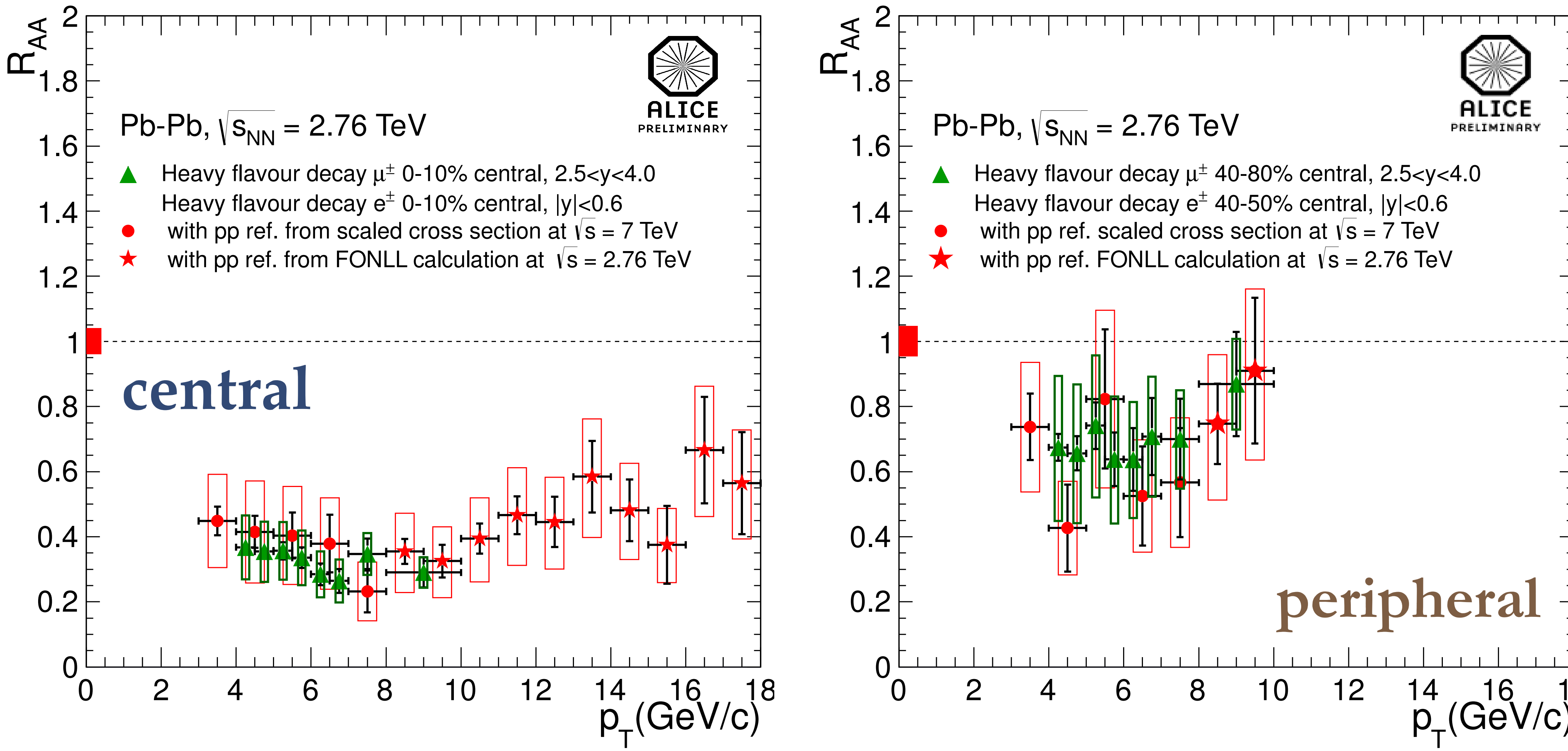
HF decay electrons - pp reference

- Smaller uncertainties in 7 TeV sample
- pp reference for Pb-Pb and p-Pb (R. Averbeck et al., arXiv:1107:3243)
  - p_T < 8 GeV/c: computed using FONLL to scale the cross section measured at 7 TeV to 2.76 and 5.02 TeV
  - p_T > 8 GeV/c: use FONLL cross section
- FONLL scaled 7 TeV cross section is consistent with the 2.76 TeV result

Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

Muons	R_{AA}: 2010 run, $\mathcal{L}_{int}$ = 2.7 μb^{-1}, MB trigger
	v_2: 2011 run, 8 M semi-central trigger and 8. 7 M central trigger events
Electrons	R_{AA}: 2011 run, 16.7 M central trigger and 0.67 M EMCal trigger in 0-10%
	v_2: 2011 run, 7.3 M semi-central trigger and 1.3 M EMCal trigger in 20-40%

R_{AA} of HF decay leptons in Pb-Pb collsions

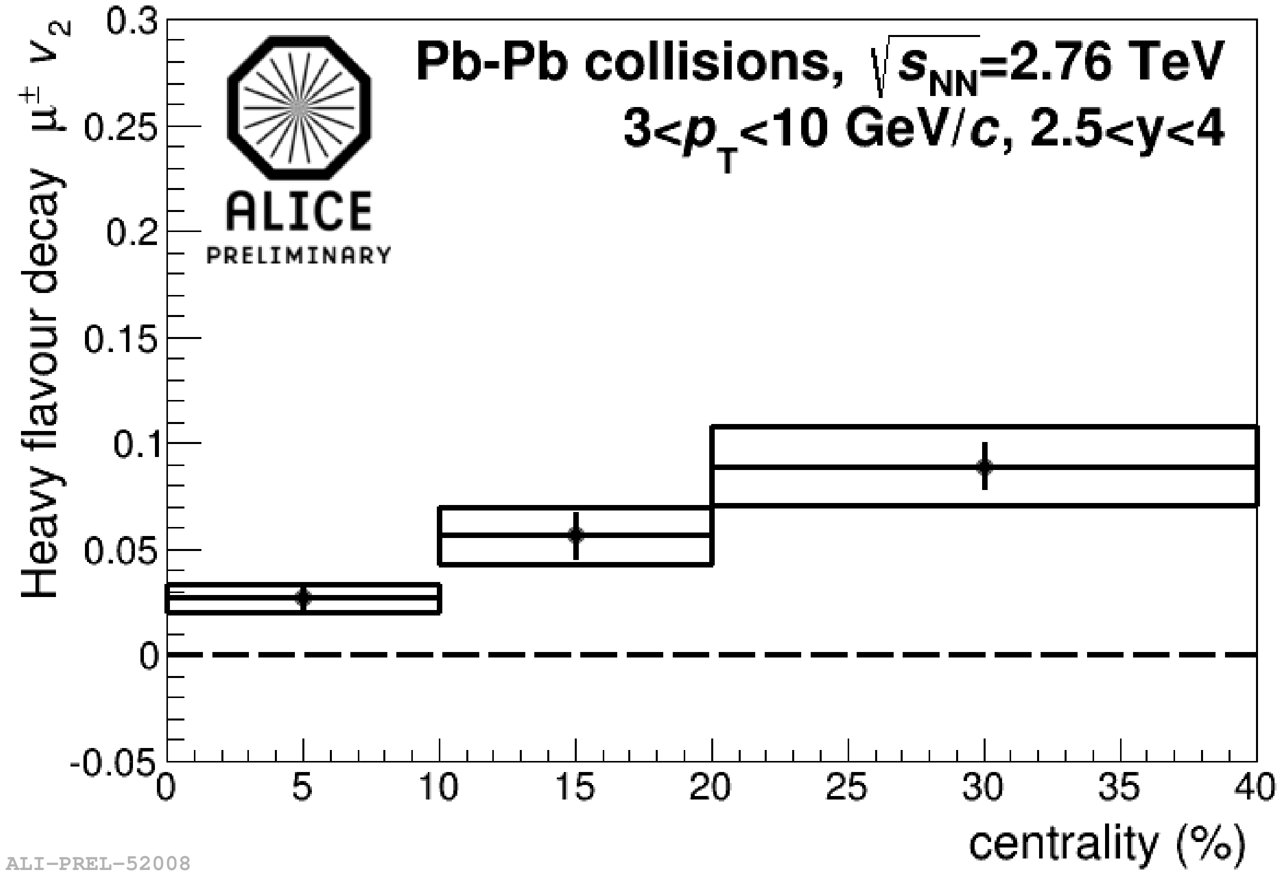


R_{AA} of HF decay **muons** and **electrons** measured in central (0–10%) and peripheral (40–50% for electrons and 40-80% for muons) collisions.

- For p_T ~ 7 GeV/c suppression factor 3-5 for most central collisions
- Suppression of HF decay electrons and HF decay muons comparable
- HF decay electrons suggest rise for higher p_T

Elliptic flow of HF decay leptons in Pb-Pb collisions

p_T integrated (3-10 GeV/c) elliptic flow (v_2) of muons from HF decays measured in 2.5 < y < 4

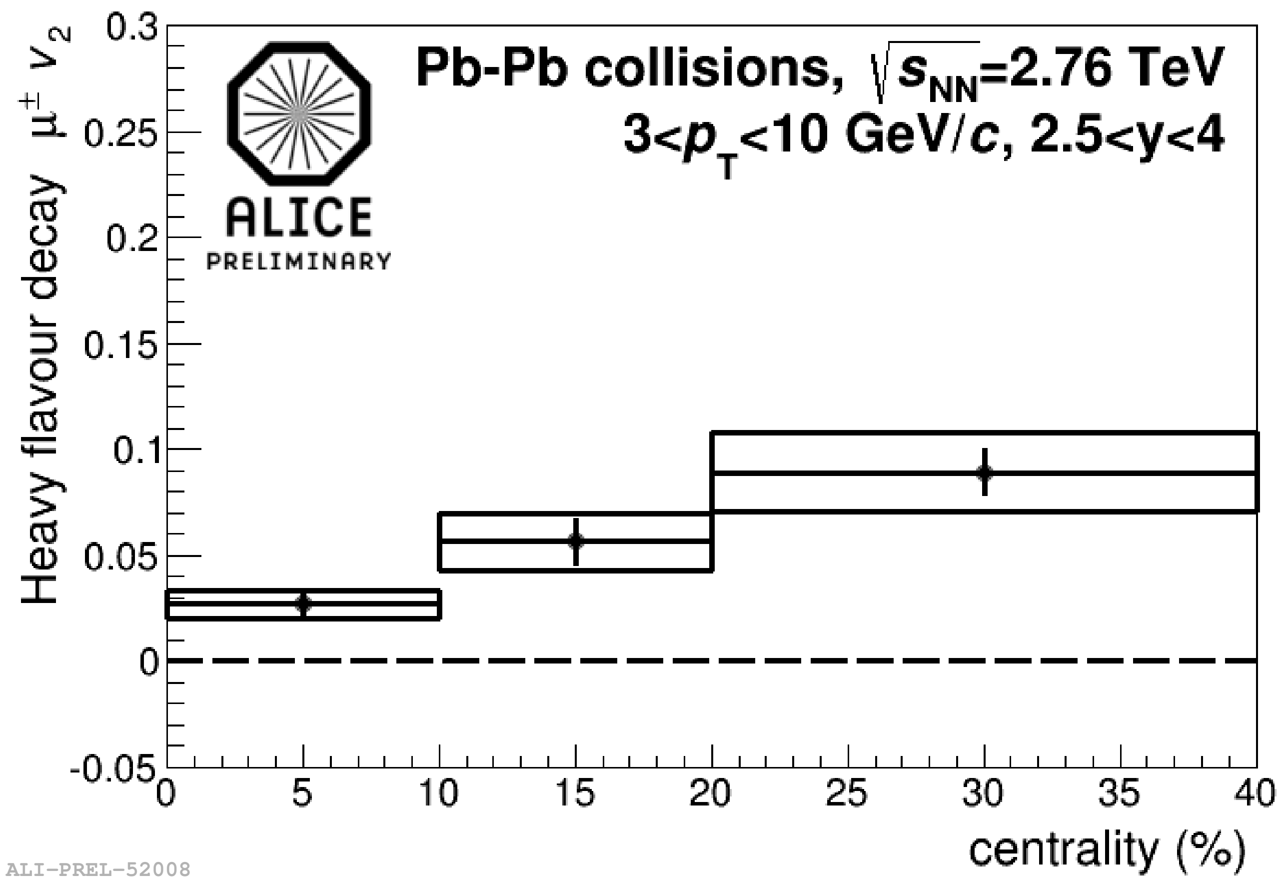


- v_2 increases from central to peripheral collisions (0-40% range)
- Positive v_2 (3σ effect) in semi-central (20-40%) collisions

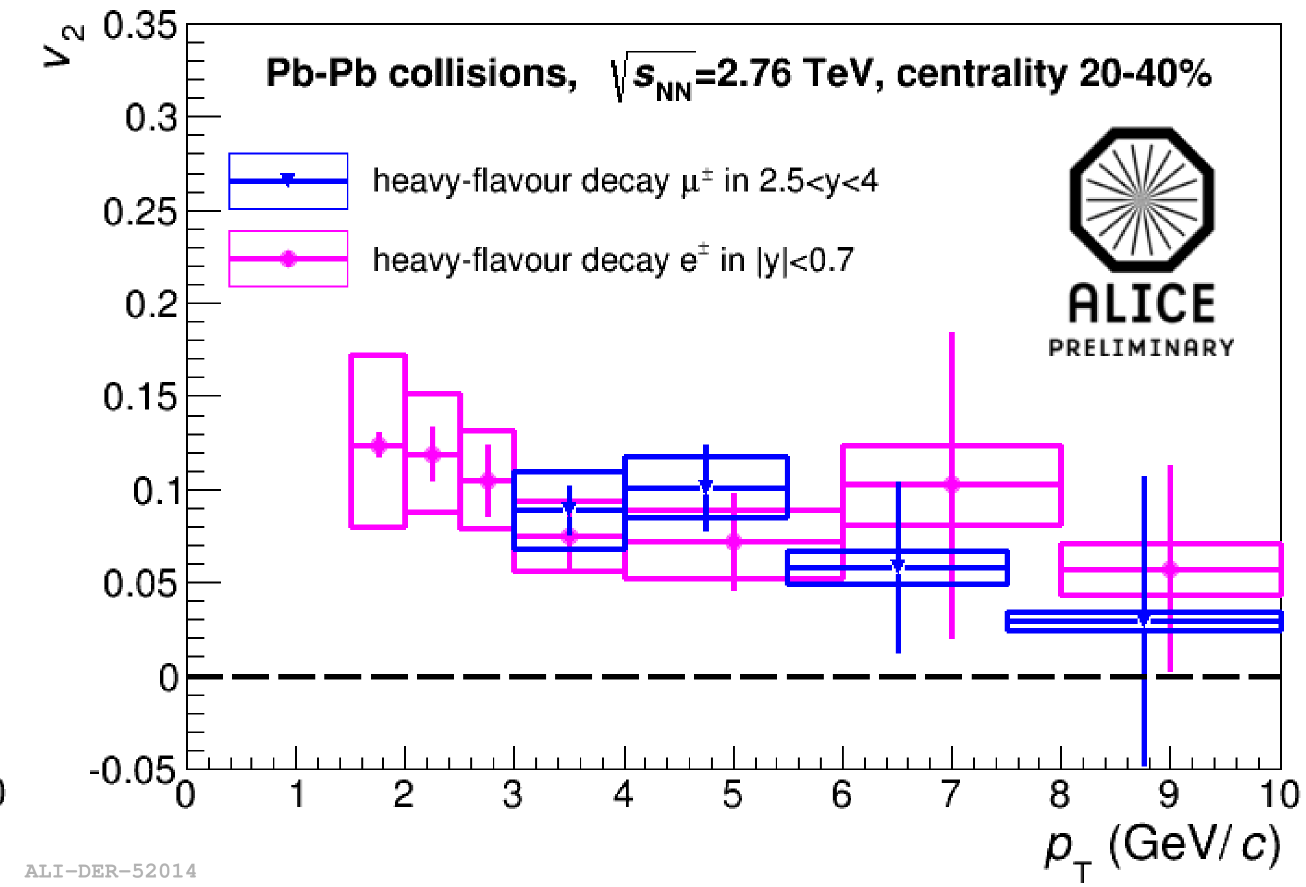
Elliptic flow of HF decay leptons in Pb-Pb collisions

ALICE

p_T integrated (3-10 GeV/c) elliptic flow (v_2) of muons from HF decays measured in 2.5 < y < 4

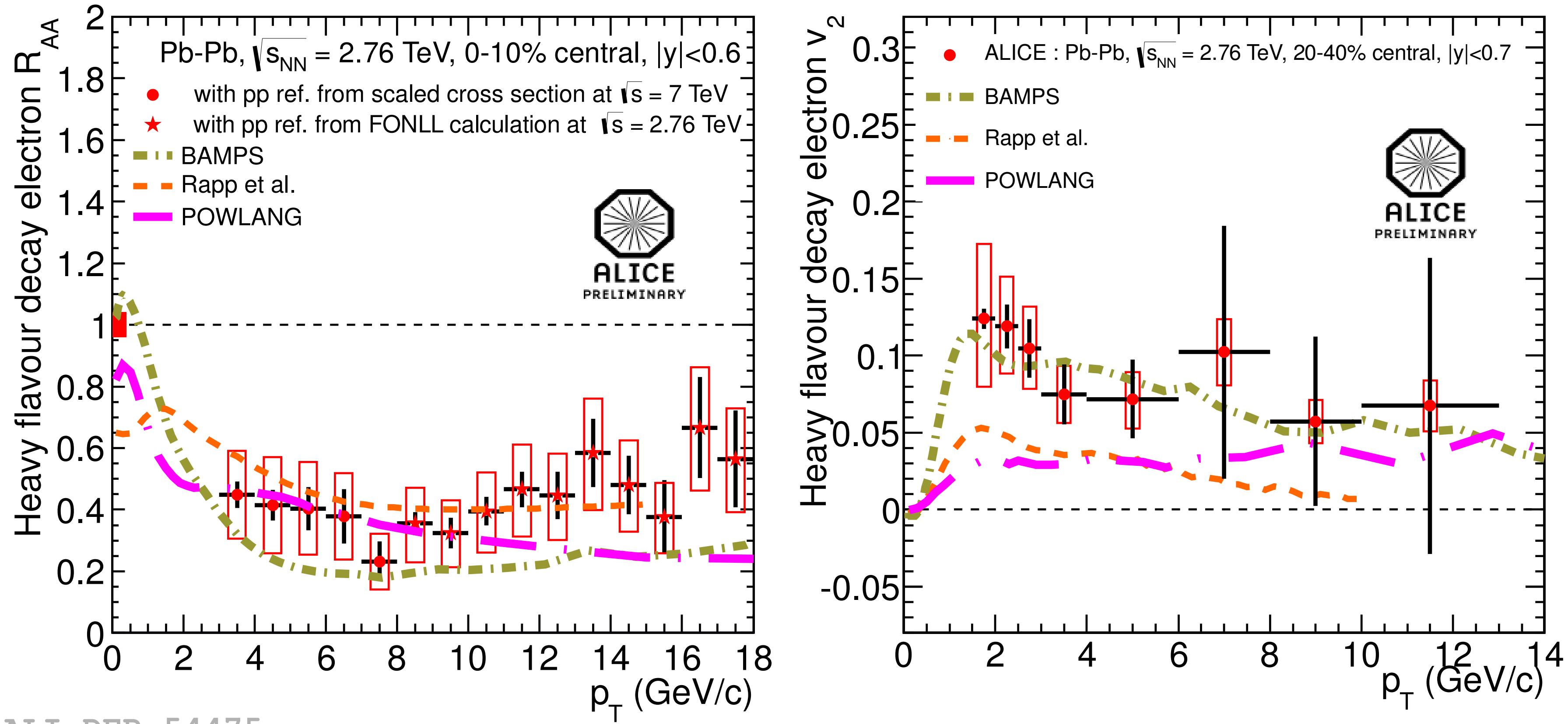


p_T dependent (20-40% central) v_2 of muons from HF decays measured in 2.5 < y < 4



- v_2 increases from central to peripheral collisions (0-40% range)
- Positive v_2 (3σ effect) in semi-central (20-40%) collisions
- v_2 of HF decay electrons at **mid-rapidity** is compatible with v_2 of HF decay muons at **forward rapidity** within the experimental uncertainties
- heavy quarks seem to experience the anisotropic expansion of the medium

Model comparison to HF decay electron results



ALI-DER-54475

Partonic transport models

BAMPS - Collisional energy loss in a deconfined medium with a mimicking of radiative energy loss via an increase in the elastic cross section

J. Uphoff et al. arXiv 1205.4945

Rapp et al. - Collisional (elastic) processes via a non-perturbative T-matrix approach

R. Rapp et al. arXiv 1208.0256

POWLANG - Based on Langevin equation with collisional energy loss in a deconfined medium

A.Beraudo et al J.Phys.G G38 124144

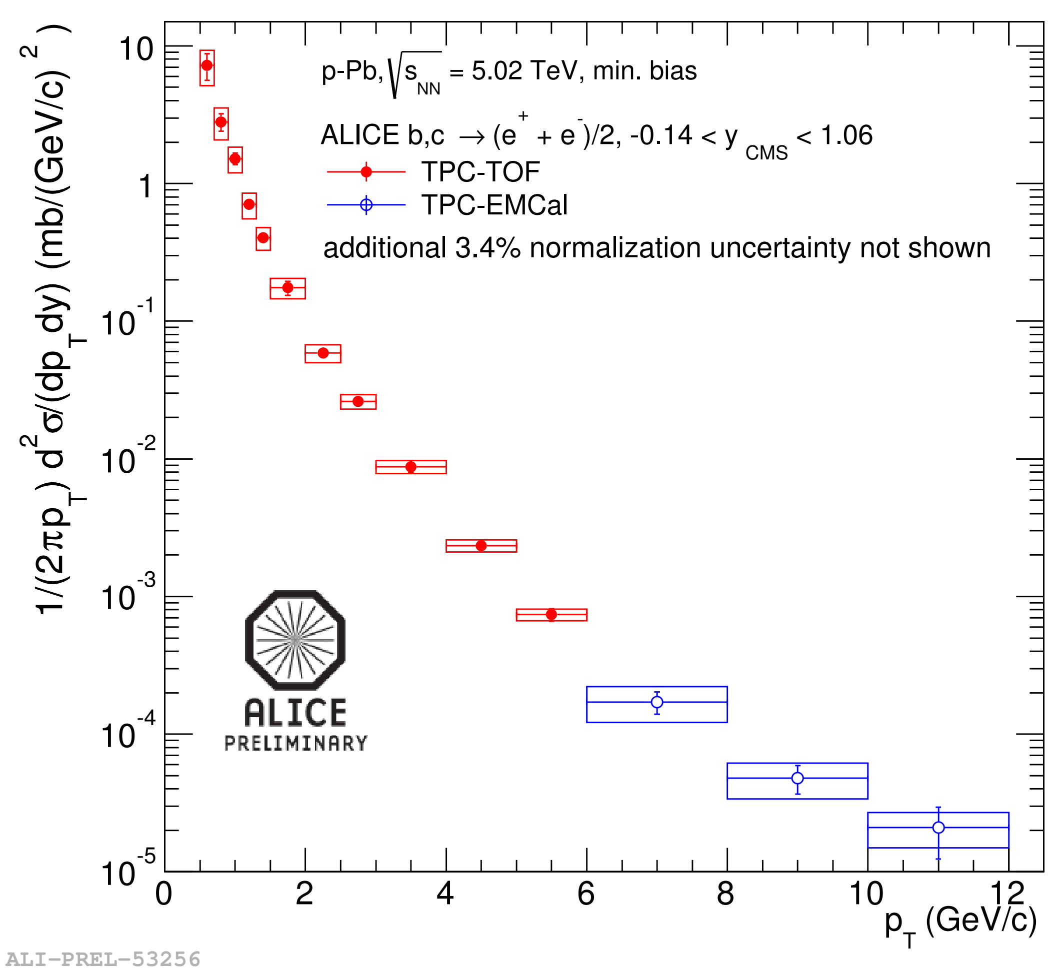
Simultaneous description of both observables not easily achieved

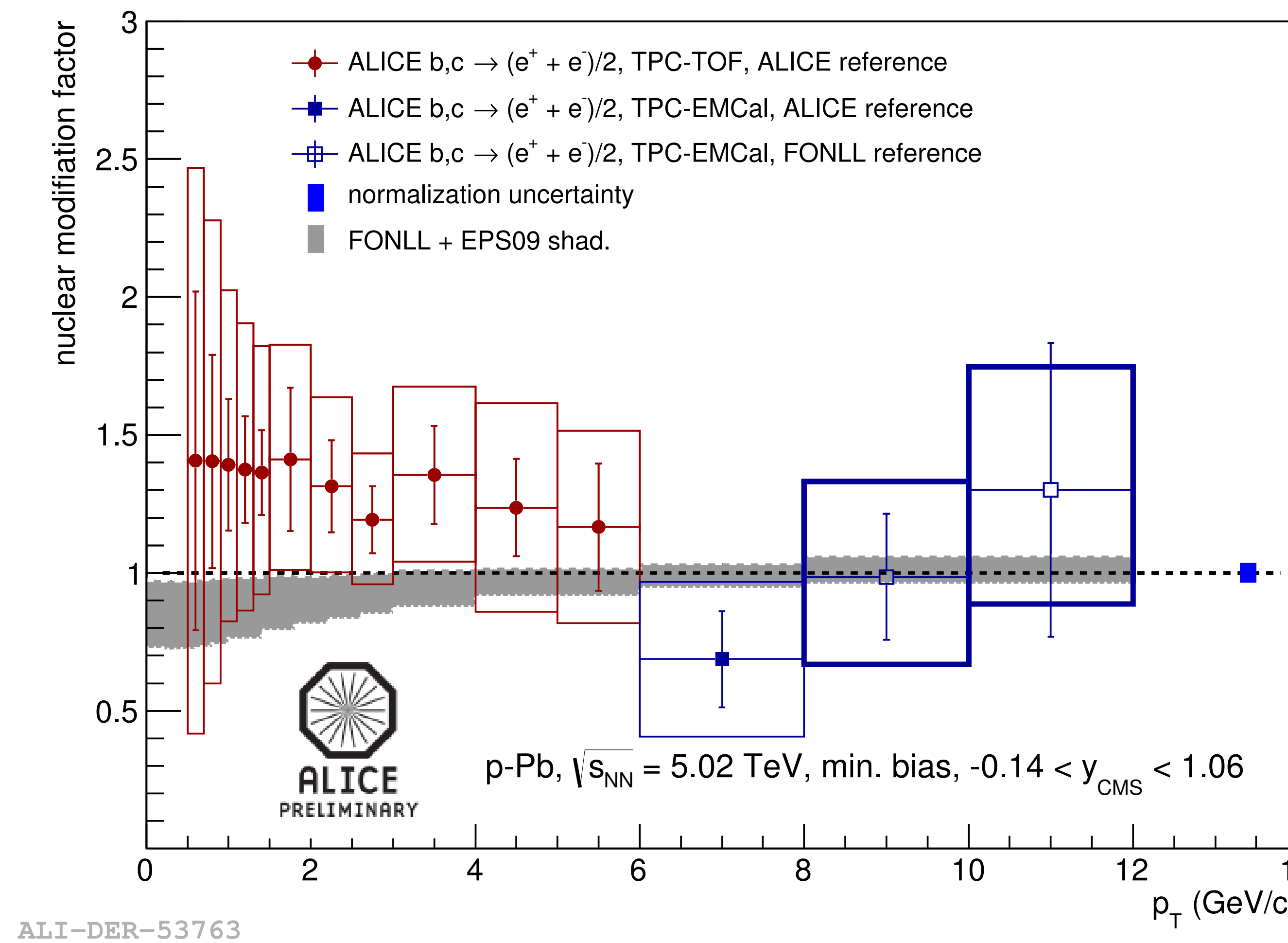
Prompting refinement of the models e.g. R.Rapp et al. arXiv:1401.3817, updated with radiative processes and a softer expansion

p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

Electrons	**R_{pPb}: 2013 run, 105 M MB trigger events**
	e-h: 2013 run, 91 M MB trigger events

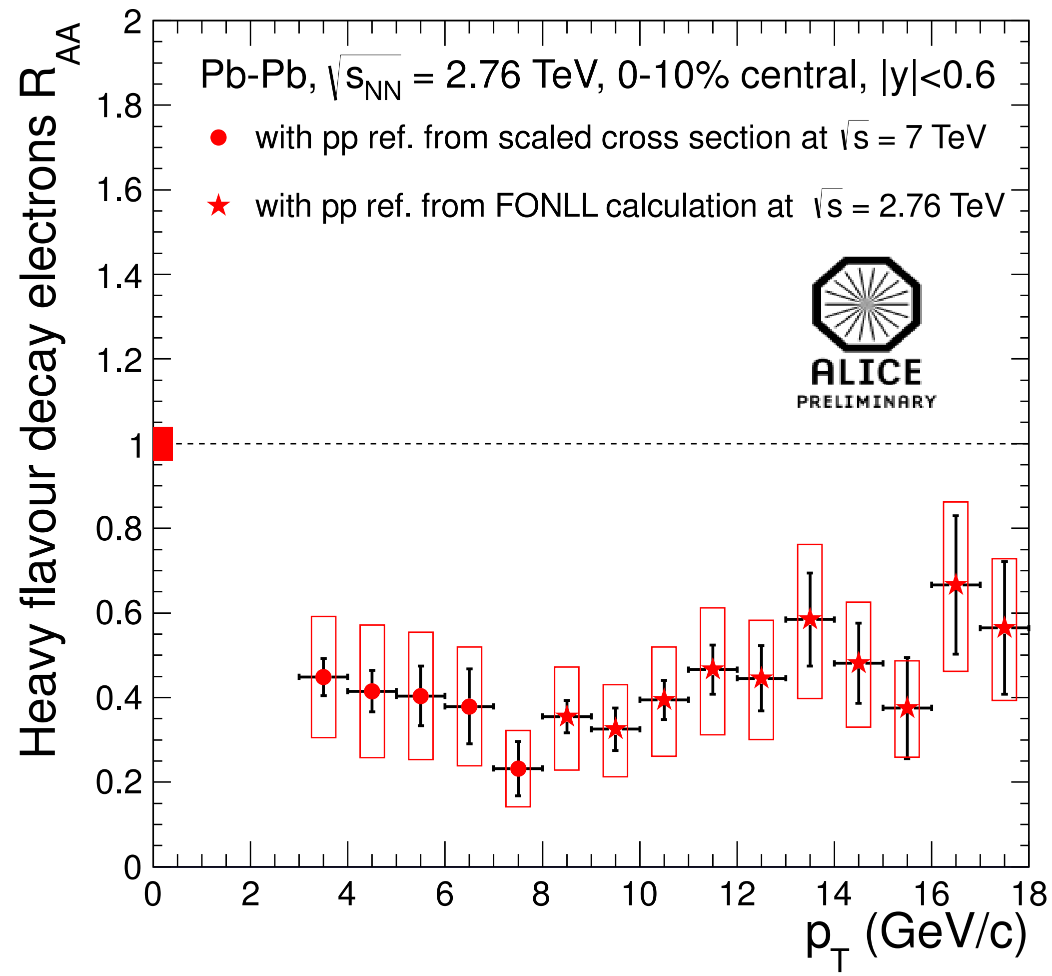
R_{pPb} of electrons in p-Pb collisions at 5.02 TeV





- Results using two different electron ID strategies are consistent
- Data described by FONLL+EPS09 parametrization of shadowing, within the uncertainties K. J. Eskola, H. Paukkunen and C.A. Salgado JHEP 0904 (2009) 065

Comparison of HF decay electron R_{AA} and R_{pPb}



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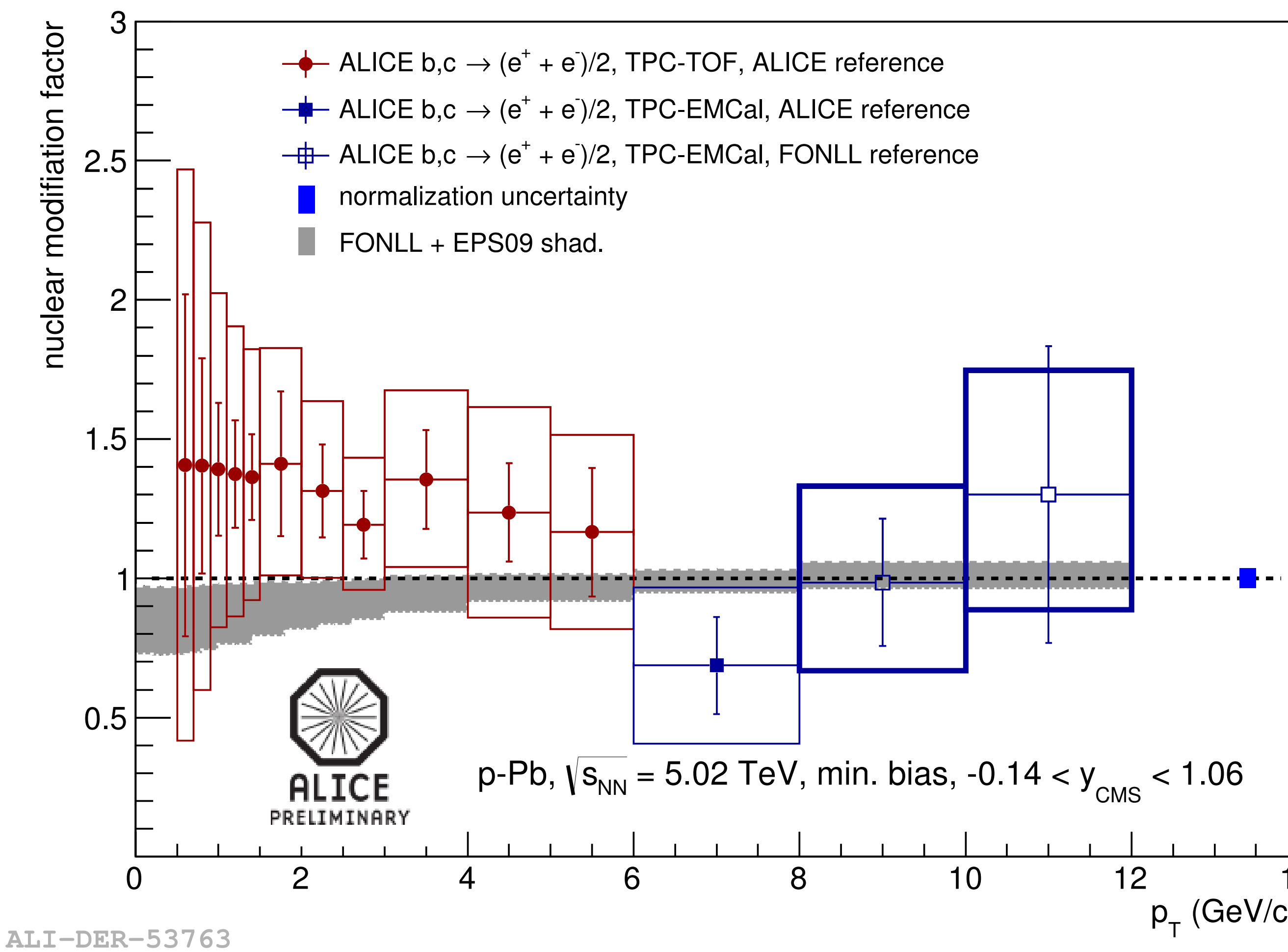
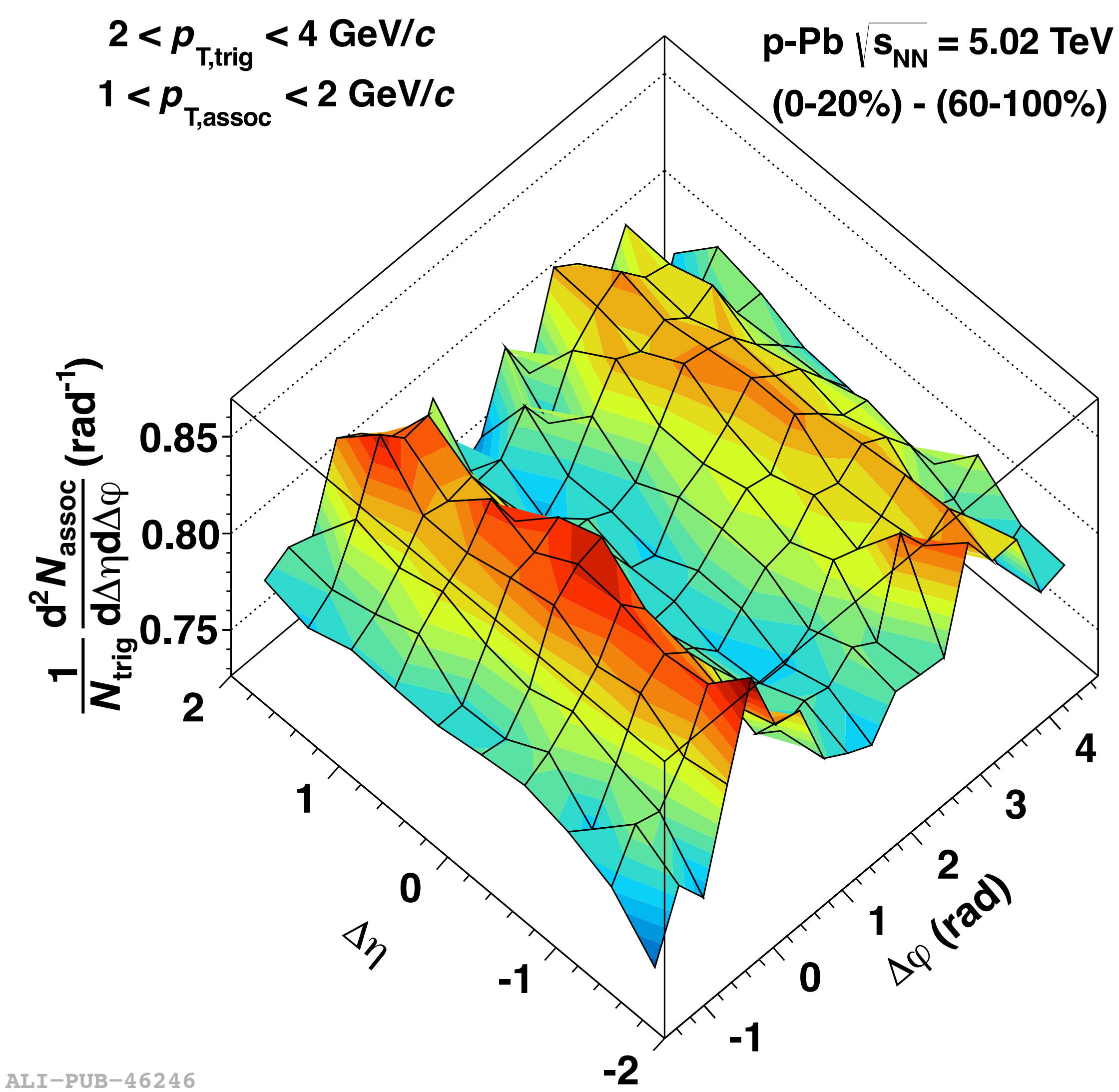


ALI-DER-53763

Observed suppression in Pb-Pb is mainly a final state effect, due to in-medium energy loss

Two particle correlations in p-Pb collisions

Motivation for the study of HFe-h correlation studies in p-Pb



(0-20%)-(60-100%) Multiplicity classes*

* Multiplicity classes defined by V0A detector with multiplicity in the region of $2.8 < \eta < 5.1$ in the Pb hemisphere

Hadron-hadron correlations: long range structure observed on near and away side. Also observed for h-π, h-K, and h-p.

ALICE Collaboration PLB 719 (2013) 29
ALICE Collaboration PLB 726 (2013) 164

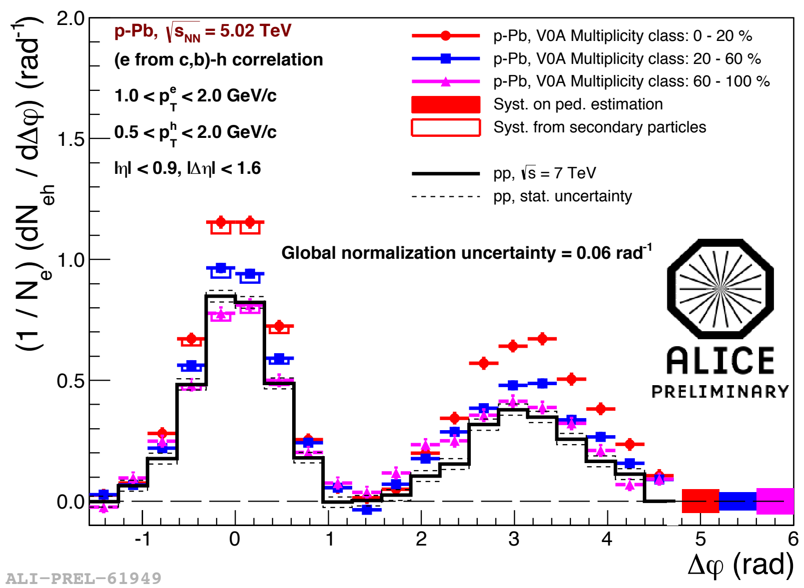
Origin of 'double ridge' structure?

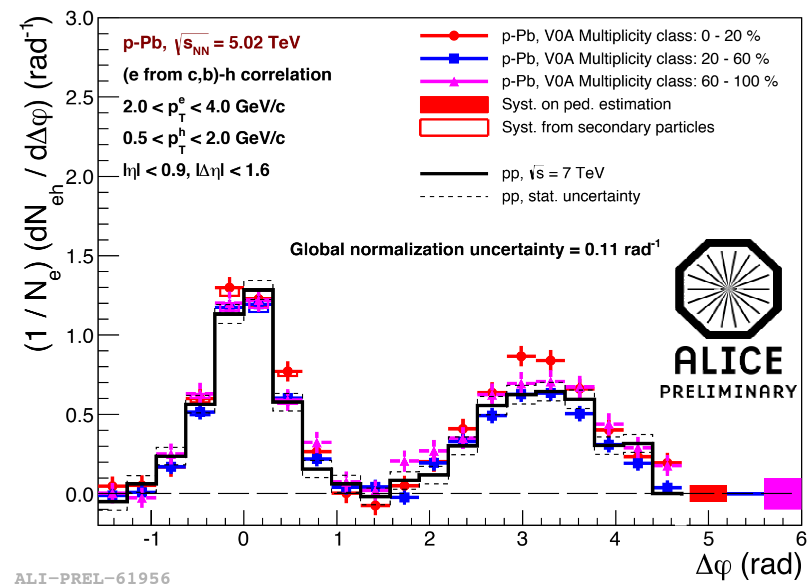
1. **Initial state effects**
   Parton saturation in the nucleus - Color Glass Condensate (CGC)
   K. Dusling and R.Venugopalan, arXiv:1302.7018

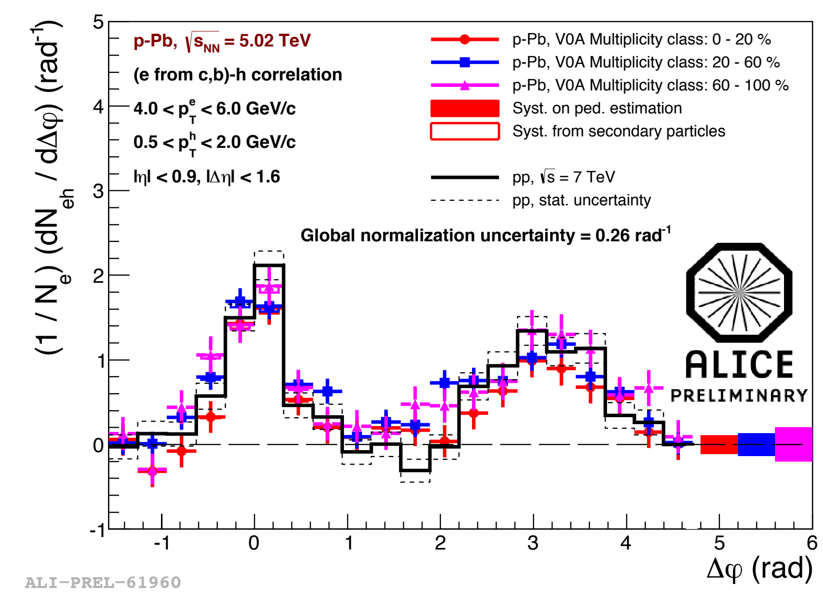
2. **Final state effects**
   Multi-parton interactions in high multiplicity pp collisions
   S.Alderweireldt and P.Van Mechelen, arXiv:1203.2048
   Hydrodynamic expansion
   - **pp collisions**
   K.Werner, I. Karpenko, and T. Pierog, PRL 106 (2011) 122004
   - **p-Pb collisions**
   Bozek et al., PLB 718 (2013) 1557

HFe-h correlations in p-Pb collisions

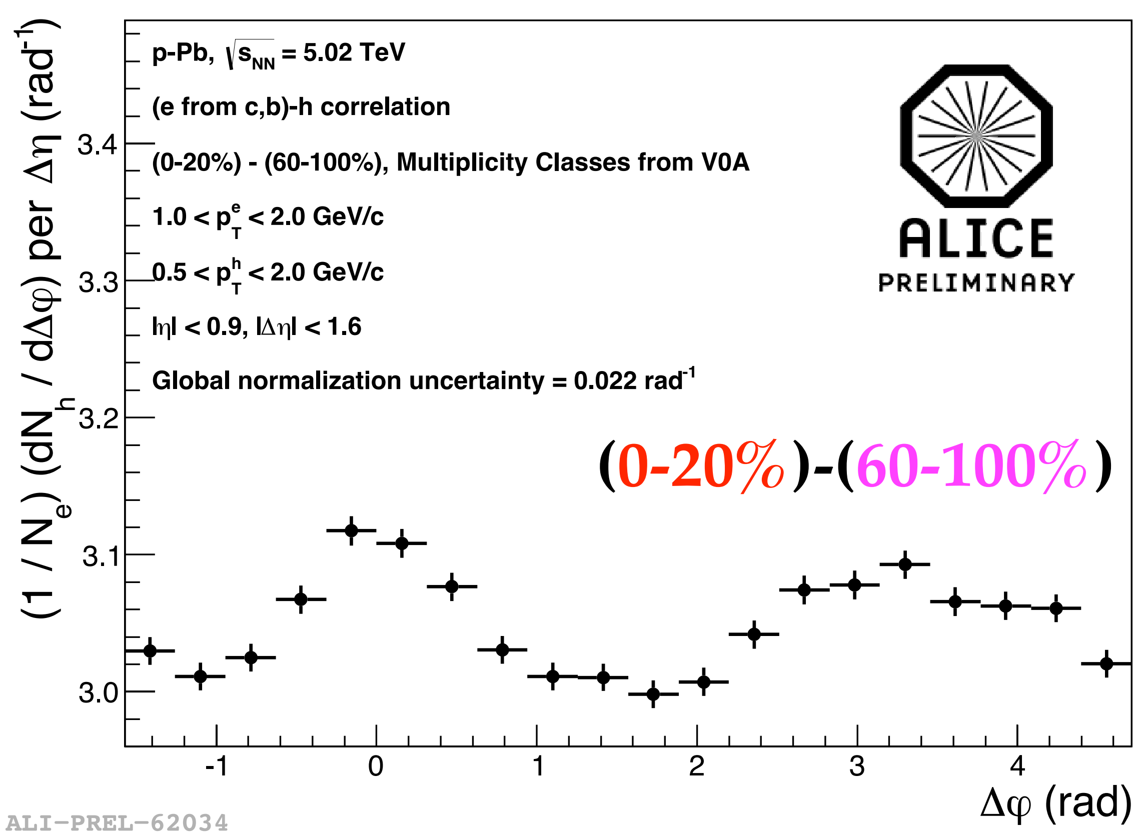
$1 < p_T^{trigger} < 2$ GeV/c | $2 < p_T^{trigger} < 4$ GeV/c | $4 < p_T^{trigger} < 6$ GeV/c







*For all $0.5 < p_T^{assoc.} < 2$ GeV/c



Multiplicity classes

0-20%

20-60%

60-100%

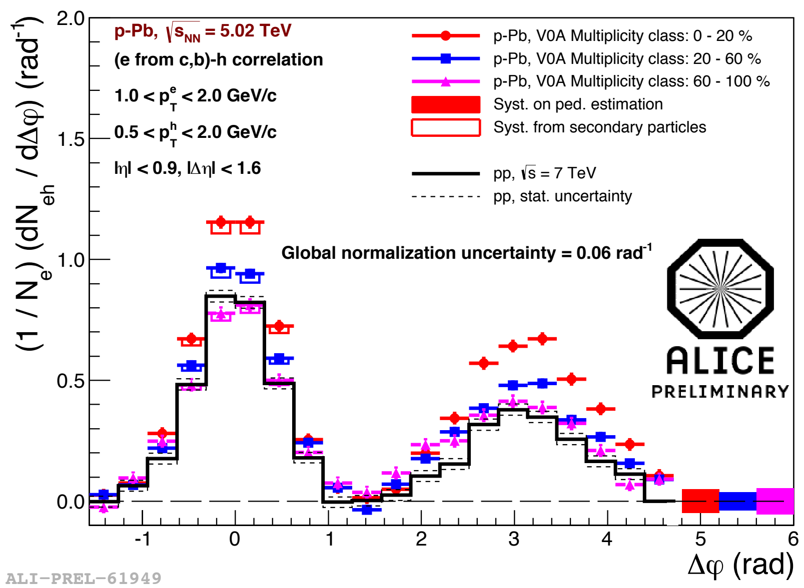
<u>In high multiplicity events:</u>

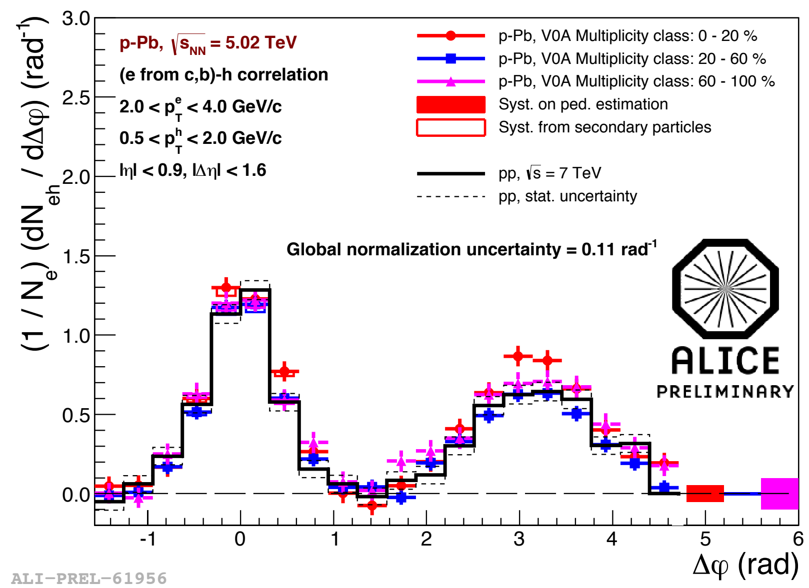
At low electron p_T a hint of near and away side enhancement

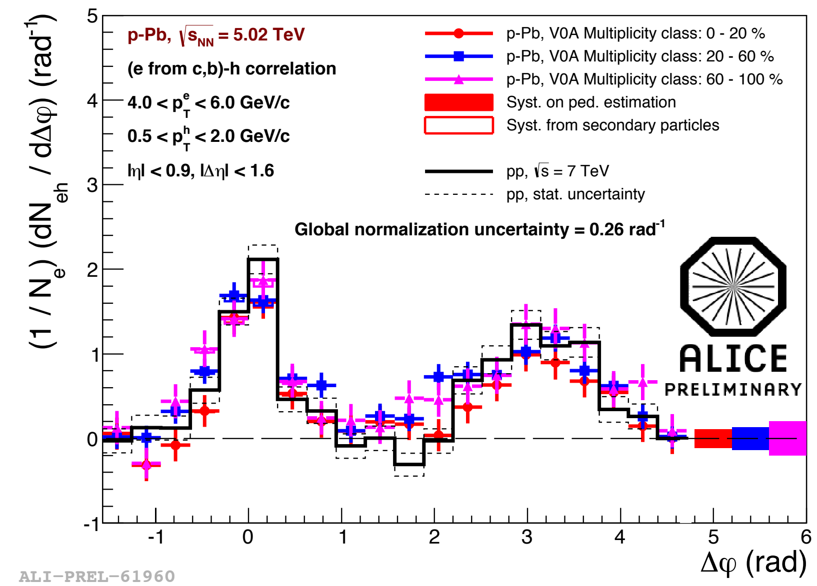
Indication for double ridge structure

HFe-h correlations in p-Pb collisions

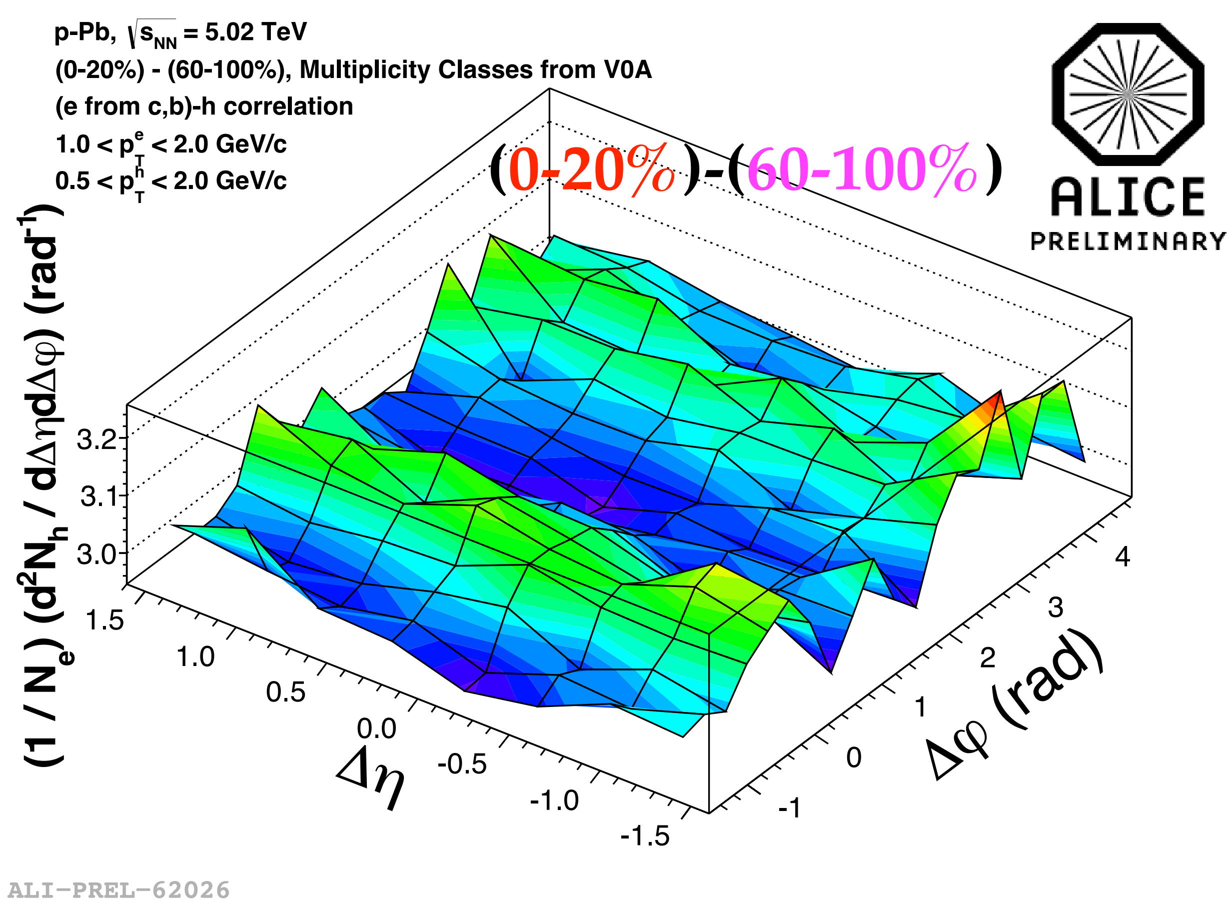
$1 < p_{T}^{trigger} < 2$ GeV/c $\quad$ $2 < p_{T}^{trigger} < 4$ GeV/c $\quad$ $4 < p_{T}^{trigger} < 6$ GeV/c







$*For\ all\ 0.5 < p_{T}^{assoc.} < 2$ GeV/c



In high multiplicity events:

At low electron p_T a hint of near and away side enhancement

Indication for double ridge structure

Heavy-flavour also affected by process responsible for long range correlations in $\Delta\eta$

Summary

Open heavy-flavour measured with ALICE via semi-leptonic decay channels

Nuclear modification factor:

- In Pb-Pb HF decay leptons show a strong suppression in central collisions for $p_T > 3$ GeV/c
- R_{AA} moves toward unity in peripheral collisions
- In p-Pb, compatible with unity within the experimental uncertainties

Suppression observed in Pb-Pb collisions mainly a final state effect

Elliptic flow:

- Indication of positive v_2 in semi-central collisions
- Comparable v_2 of muons in forward rapidity and electrons in the mid rapidity range

Heavy quarks experience anisotropic expansion of the medium

e-h azimuthal correlation:

- In high multiplicity p-Pb collisions a double ridge structure observed

CGC or collective effects?

Extras

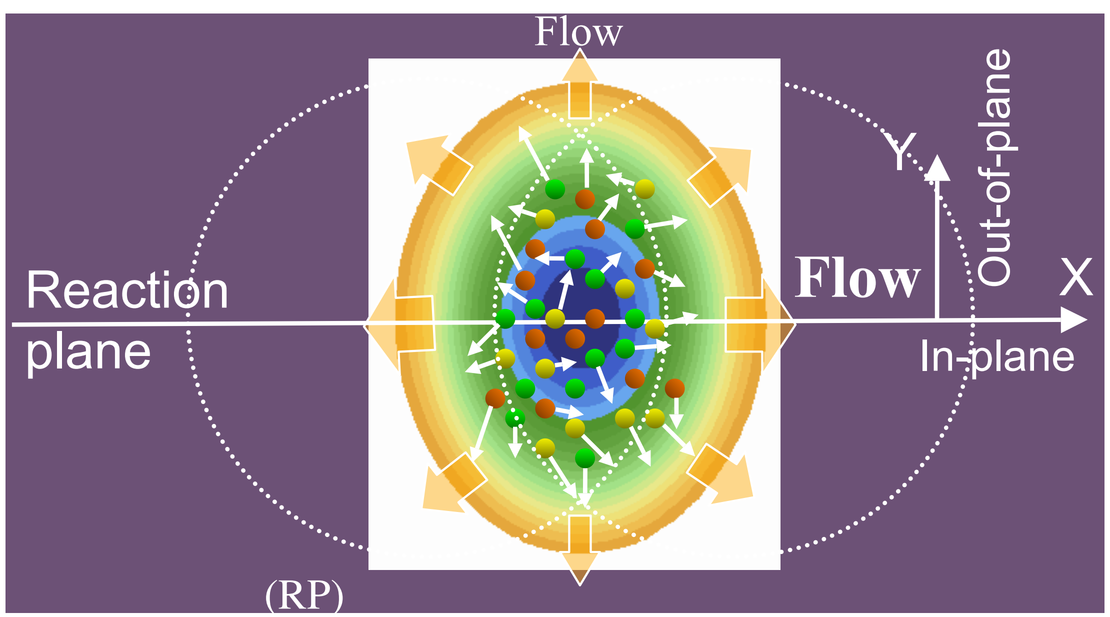
Pb-Pb and p-Pb collisions

- **Nuclear modification factor**

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{yield\ in\ AA}{yield\ in\ pp} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

* N_{coll} and T_{AA} depend on the centrality of the collision. Estimated using the Glauber model

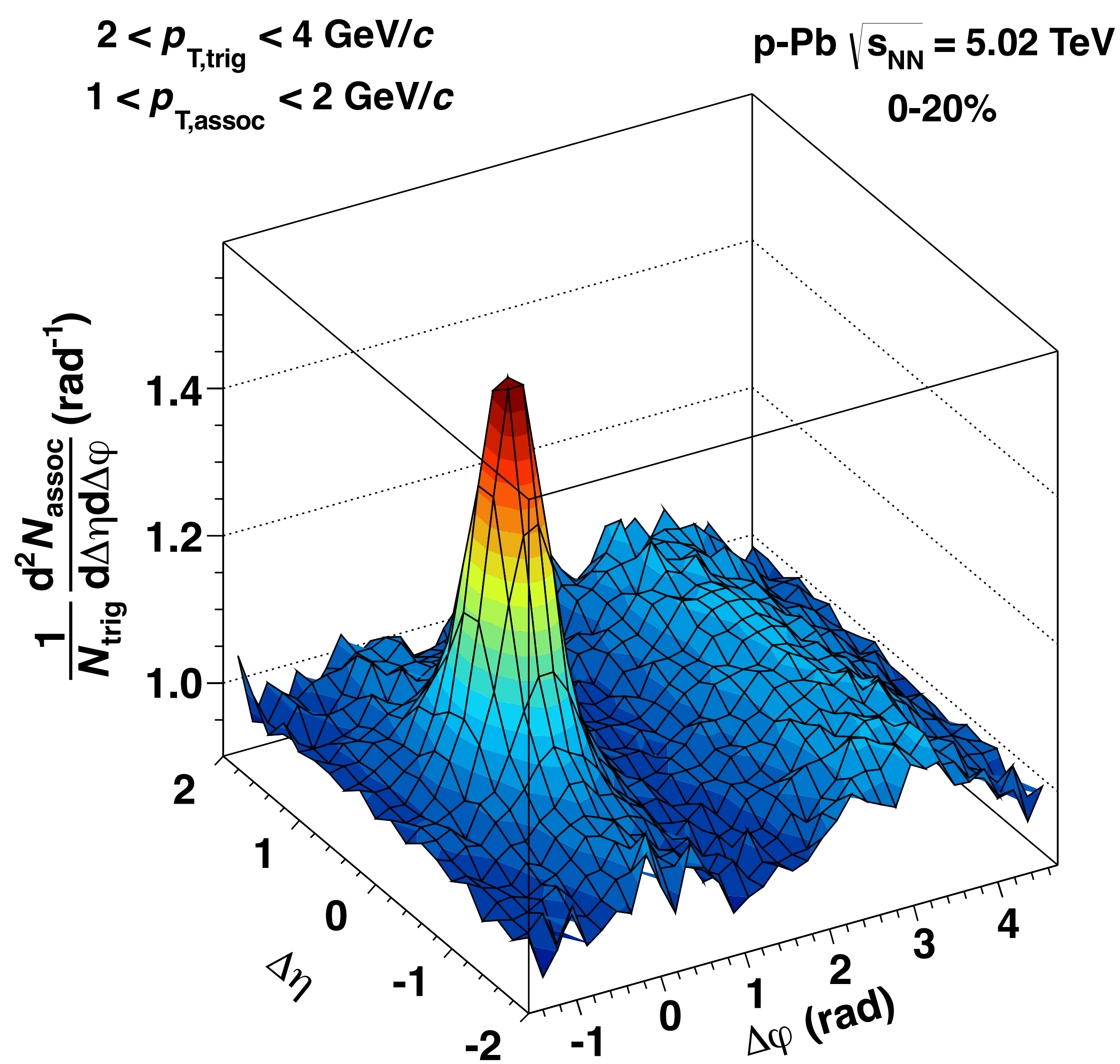
- **Elliptic flow**- Momentum space azimuthal anisotropy
  - sensitive to collectivity at low p_T and path length dependence of energy loss at high p_T



$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2n}{p_T dp_T dy}(1 + 2\sum_{n=1}^{\infty} \nu_n \cos[n(\phi - \Psi_{RP})])$$

$$\nu_2 =< \cos(2[\phi - \Psi_{RP}]) >$$

Two particle correlations in p-Pb



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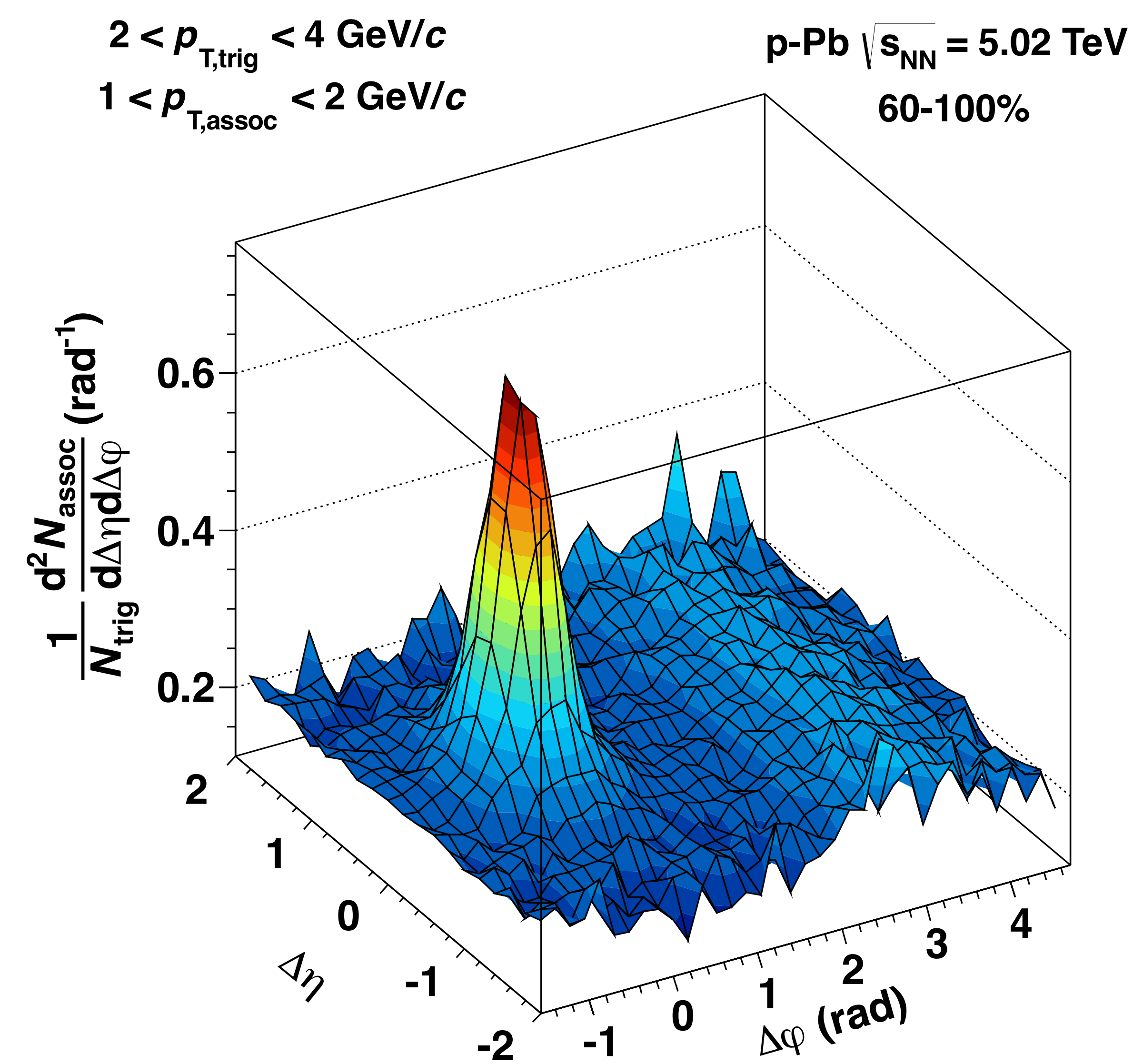

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