Heavy flavour elliptic flow and azimuthal angular correlations with ALICE

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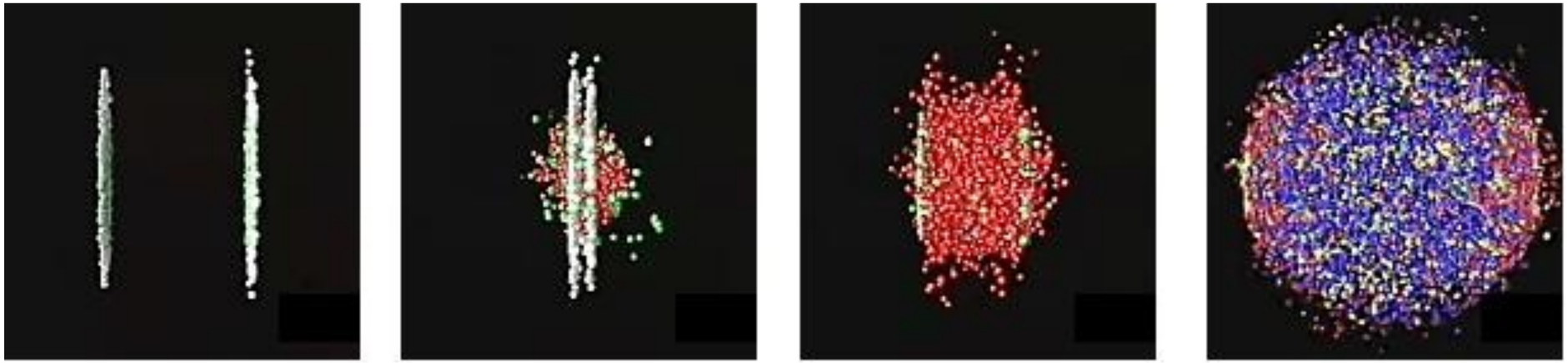
for the ALICE collaboration

Outline

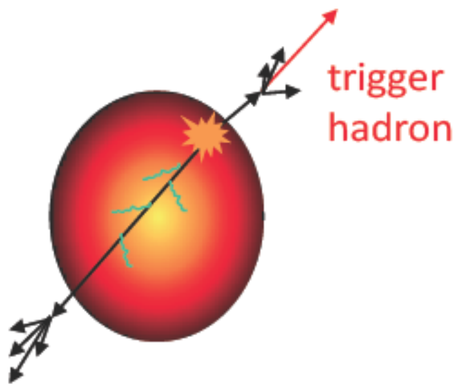
- *Motivations*
- *The ALICE detector*
- *Reconstruction of D mesons and identification of leptons from Heavy Flavour (HF) decays*
- *Elliptic flow results*
  - D mesons
  - Electrons from Heavy-Flavour decays
  - Muons from Heavy-Flavour decays
- *Correlation results*
  - D mesons in pp @ $\sqrt{s}$ = 7 TeV
  - Electrons from Heavy Flavour in pp @ $\sqrt{s}$ = 7 TeV, p-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV, Pb-Pb @ $\sqrt{s_{NN}}$ = 2.76 TeV
- *Summary and outlook*

Physics motivation (I)

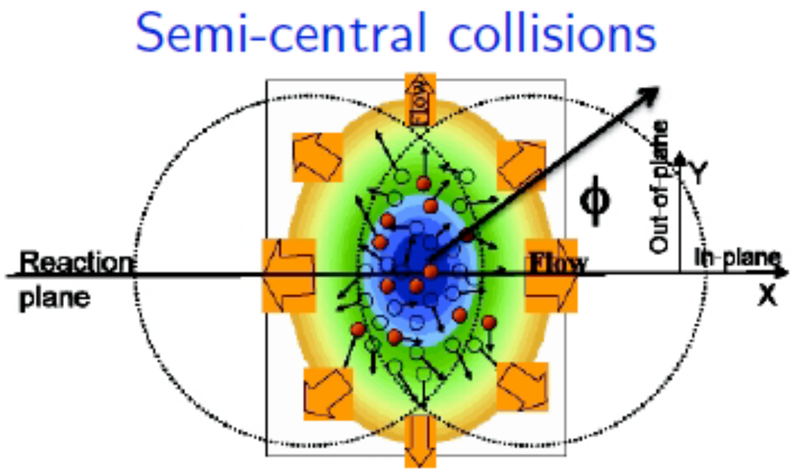
- In heavy-ion collisions, heavy quarks are produced in hard scattering processes, before the formation of the Quark-Gluon-Plasma: they experience the full collision history
- The measurement of charm production in p-p collisions is an excellent pQCD test tool
- In Pb-Pb collisions, we can study the interactions of charm quarks with the medium by measuring the nuclear modification factor and elliptic flow



- The azimuthal correlation function can be used to:
  - *Study medium modifications of charm hadronization*
  - *Explore the double ridge structure in p-Pb collisions*
  - *Give further insight in charm production mechanism in pp, Pb-Pb and p-Pb*



Physics motivation (II)



- **In the overlap region created in non-central nucleus-nucleus collision, anisotropic pressure gradients give rise to momentum anisotropies in the final state**

- **This anisotropy can be quantified via a Fourier expansion in azimuthal angle with respect to the reaction plane,**

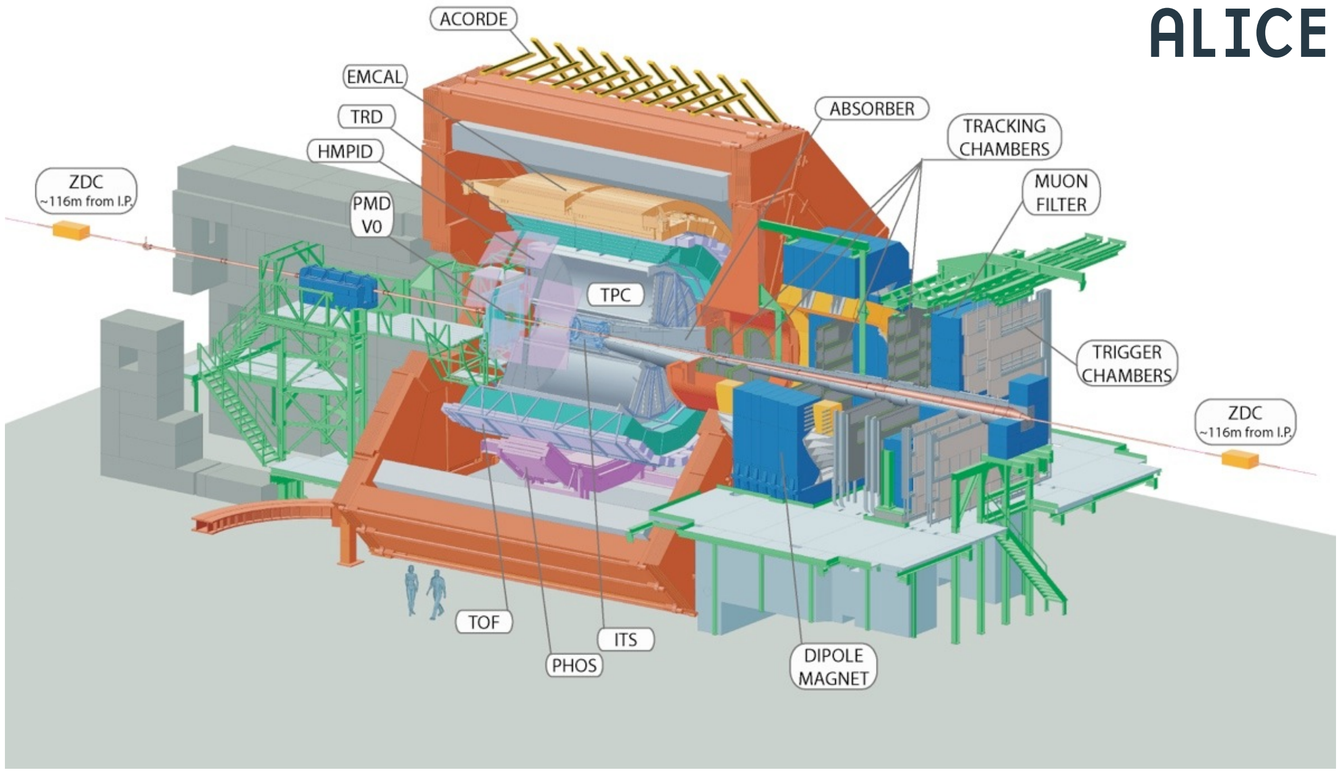
$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi} + \frac{N_0}{\pi}\sum_n^{\infty} v_n \cos\left(n\left(\varphi - \psi_{RP}\right)\right)$$

the second order coefficient, v_2, is called "elliptic flow"

- ***at low p_T*** **: charm hadron v_2 gives information on the interaction of the charm quark with the created medium: expected longer relaxation time for charm than for light quarks**
- ***at high p_T*** **: sensitive to the path length dependence of heavy quark energy loss**

The ALICE detector

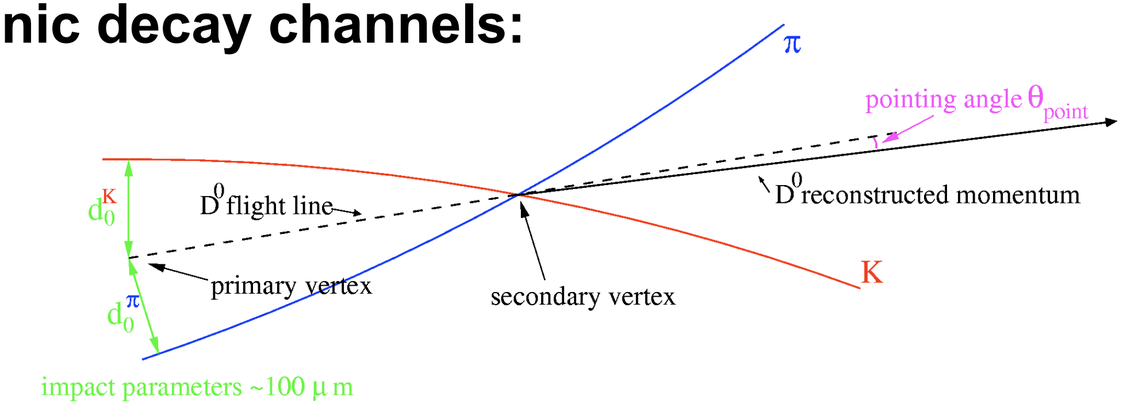
- **Triggers:**
  - **Silicon Pixel Detector (SPD)**
  - **VZERO scintillator at large η**
  - **Muon forward trigger**
- **Central barrel detectors:** *-0.9< η<0.9*
  - ***Inner Tracking System (ITS)* - used for tracking and vertexing**
  - ***Time Projection Chamber (TPC)* - used for tracking and particle identification**
  - ***Time of Flight (TOF)* - used for particle identification**
  - ***EMCal* - used for electron identification**
- **Forward detectors:** *2.5< η<4*
  - ***Forward muon spectrometer* - used for tracking of muons**
- **Centrality estimation:**
  - ***Based on VZERO amplitude***
  - ***Geometrical Model to extract the total cross section***



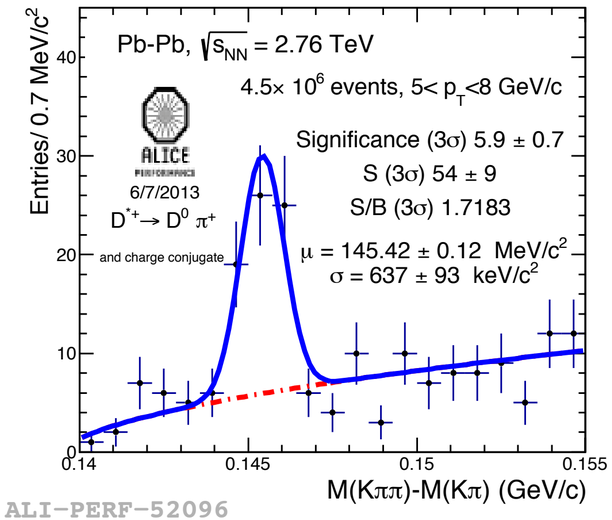
- **Data set:**
  - ***7 TeV pp minimum bias trigger: 3.1x10^8 events (2010)***
  - **2.76 *TeV Pb-Pb centrality trigger (2011)***
    - ***16x10^6 events in 0-7.5%***
    - ***7.1x10^6 events in 15-30%***
    - ***9.5x10^6 events in 30-50%***
  - **5.02 *TeV p-Pb minimum bias trigger: 10.2x10^7 events(2013)***

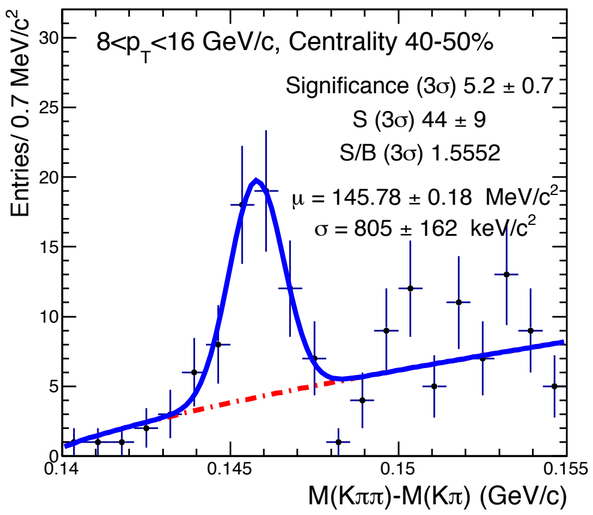
D meson reconstruction

- **D mesons are reconstructed via their hadronic decay channels:**
  - $D^0 \rightarrow K^-\pi^+$
  - $D^+ \rightarrow K^-\pi^+\pi^+$
  - $D^{*+} \rightarrow D^0\pi^+$ with $D^0 \rightarrow K^-\pi^+$



- **The reconstruction is based on the secondary vertex identification**
- **PID is used to further reduce the combinatorial background**
- **An invariant mass analysis is performed to select the candidates**





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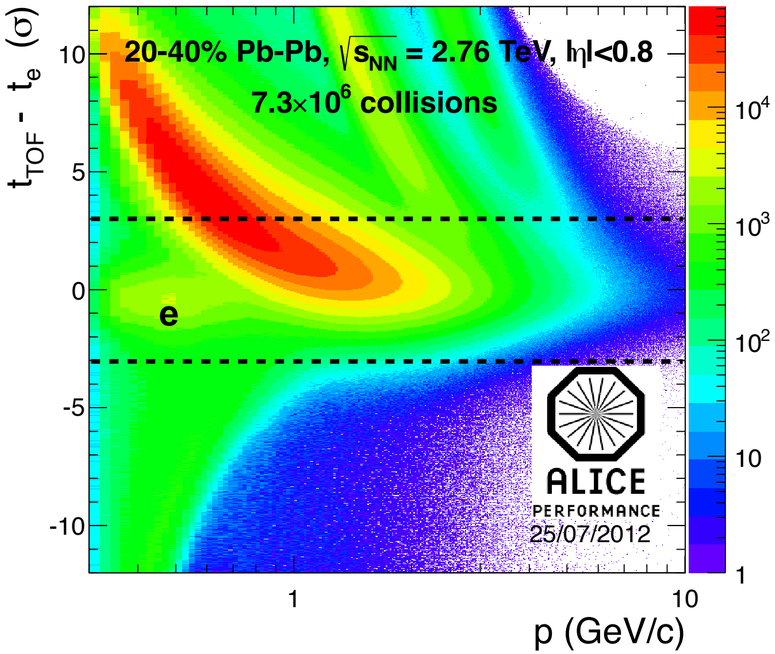
Leptons from heavy flavour decays

Electron selection:

TOF: 3σ band around electron hypothesis



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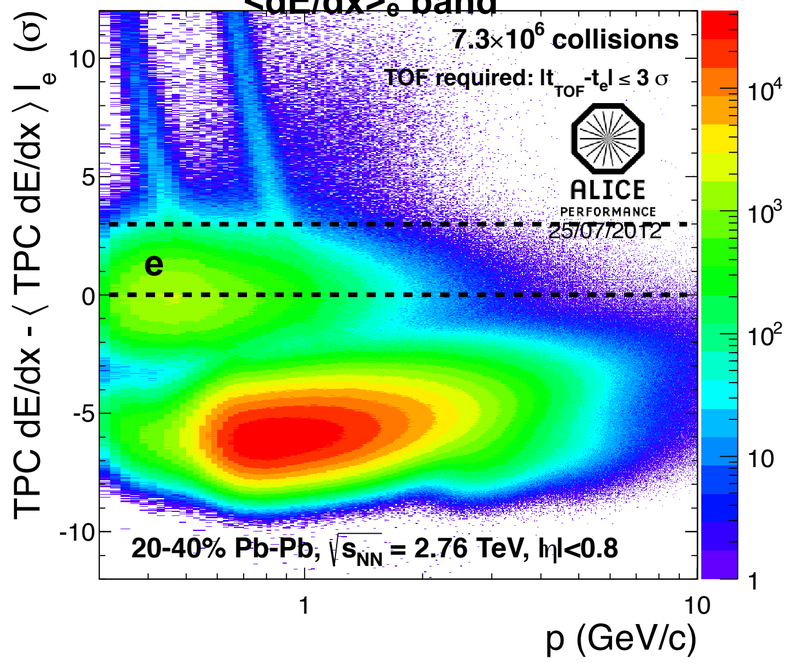
TPC: 0-3σ of $\langle dE/dx \rangle_e$ band



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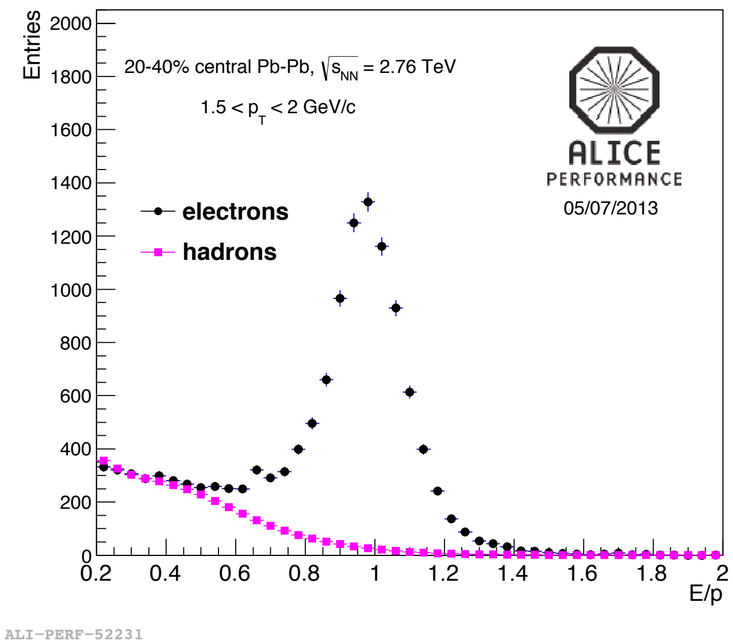
EMCAL: 0.8 < E/p < 1.2



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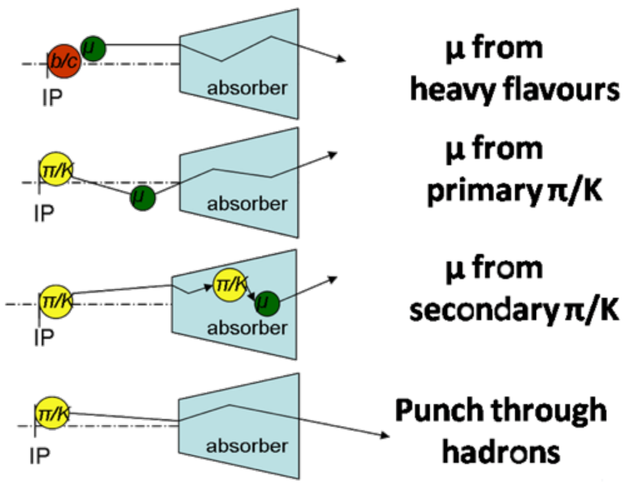
Muon identification:

Track selection:

- -4<η<-2.5: acceptance of ALICE MUON spectrometer;
- muon trigger matching: reject hadrons that cross the absorber;
- pointing angle to the vertex: remove beam-gas and particles produced in the absorber.



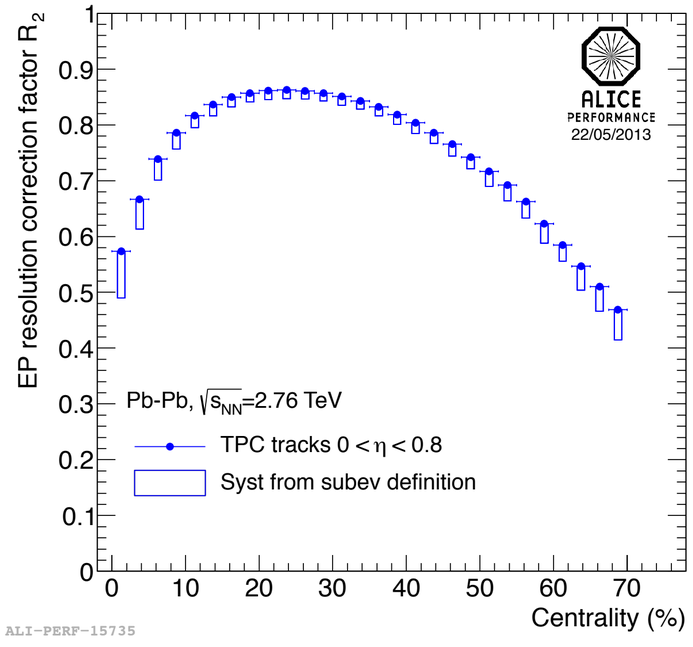
Results from flow analyses

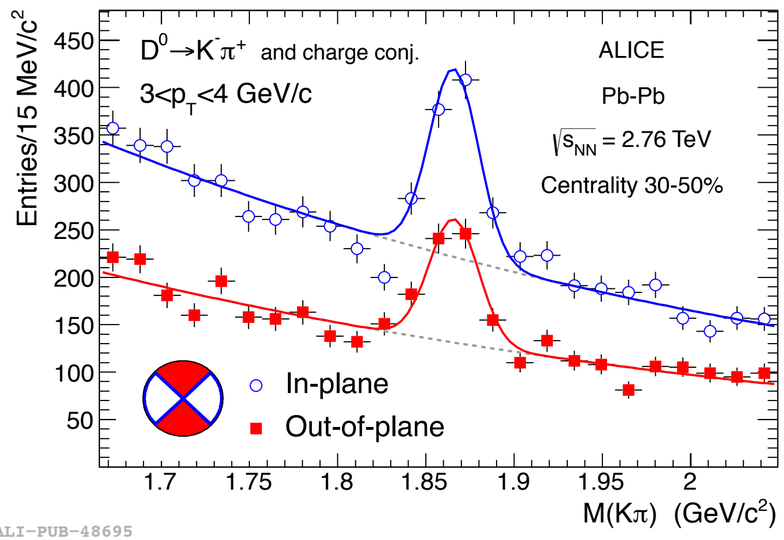
Flow via Event Plane method

Event plane: determined with TPC tracks with $0<\eta<0.8$ from the Q_n vector

$$Q_n = \begin{pmatrix} \sum_{i=0}^{N} w_i \cos n\phi_i \\ \sum_{i=0}^{N} w_i \sin n\phi_i \end{pmatrix} \qquad \Psi_n = \frac{1}{n}\tan^{-1}\left(\frac{Q_{n,y}}{Q_{n,x}}\right)$$

$$v_n = \frac{v_n^{obs}}{\langle \cos n(\Psi_n - \Psi_{RP}) \rangle}$$





- **With the event plane methods:**
  - **Extraction of the D meson yield in and out of plane**
    - **In plane:** $0<|\Delta\phi| < \pi/4$
    - **Out-of-plane:** $\pi/4 <|\Delta\phi| < 3\pi/4$

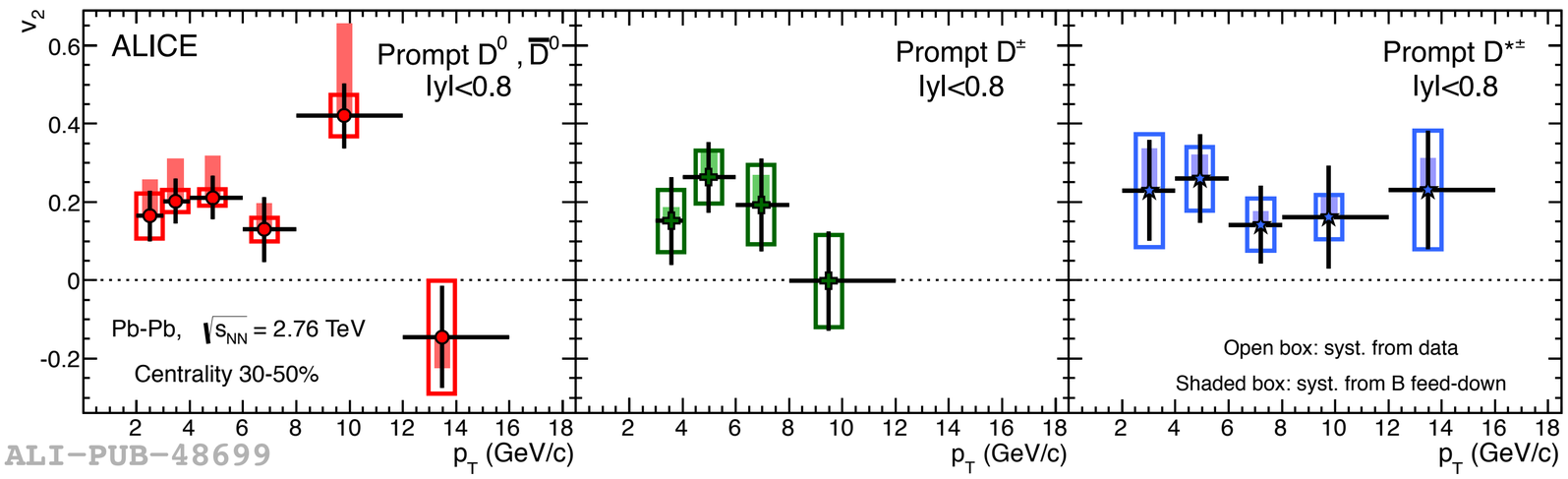
$\Delta\phi = \phi - \psi_2$

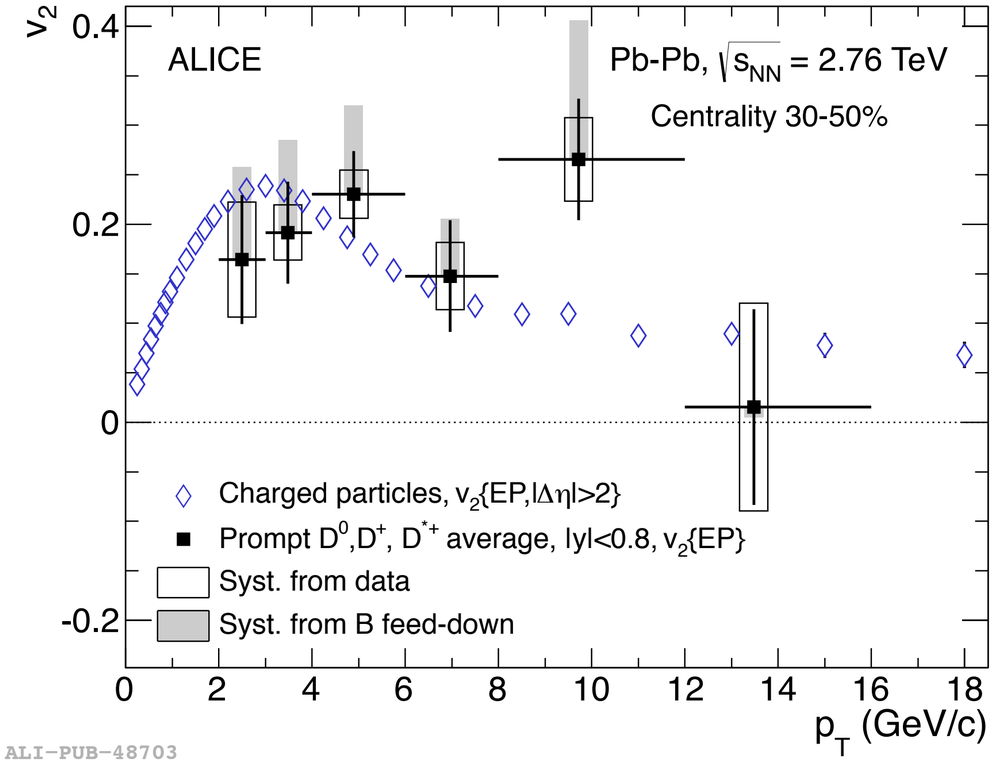
$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{IN} - N_{OUT}}{N_{IN} + N_{OUT}}$$

D meson flow

Phys. Rev. Lett. 111, 102301 (2013)

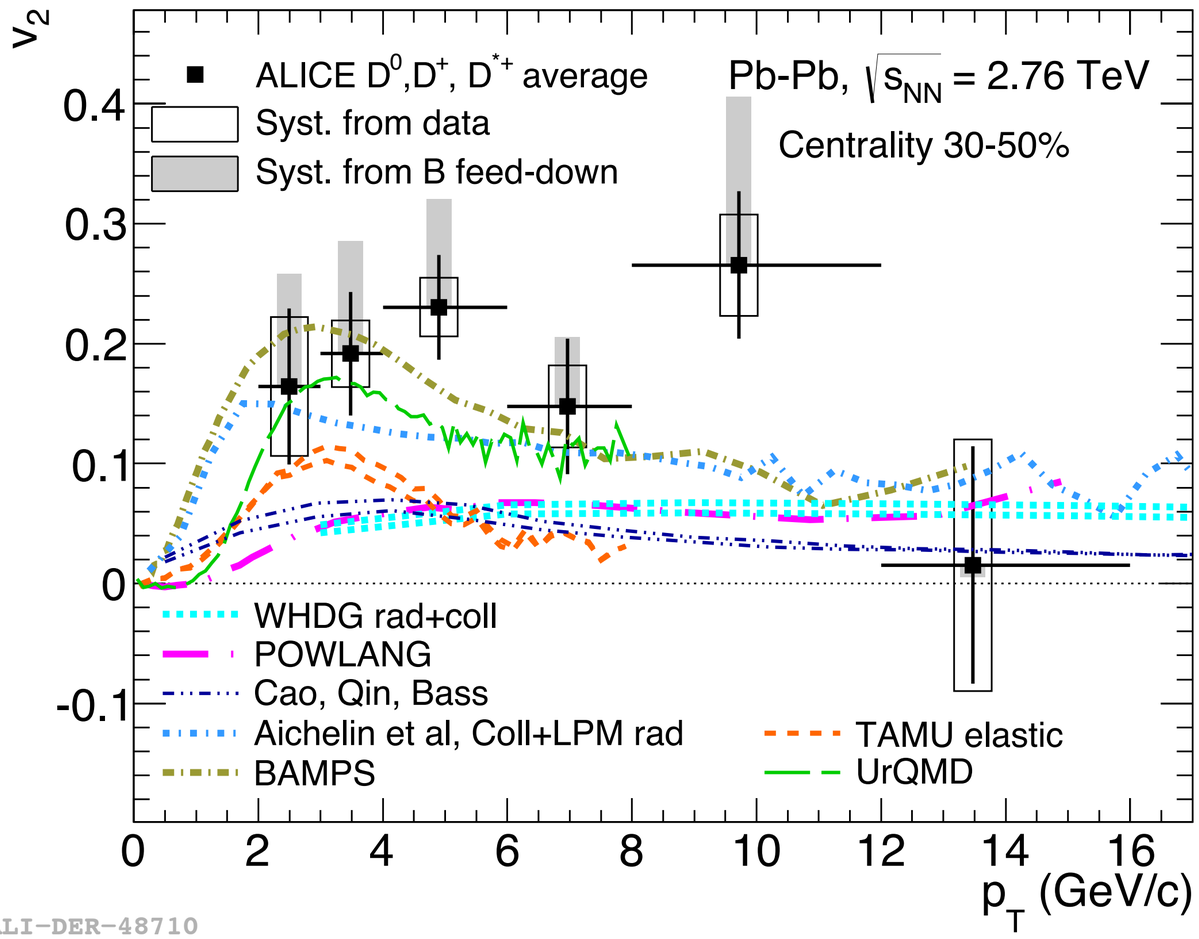
Consistency between the three D meson species

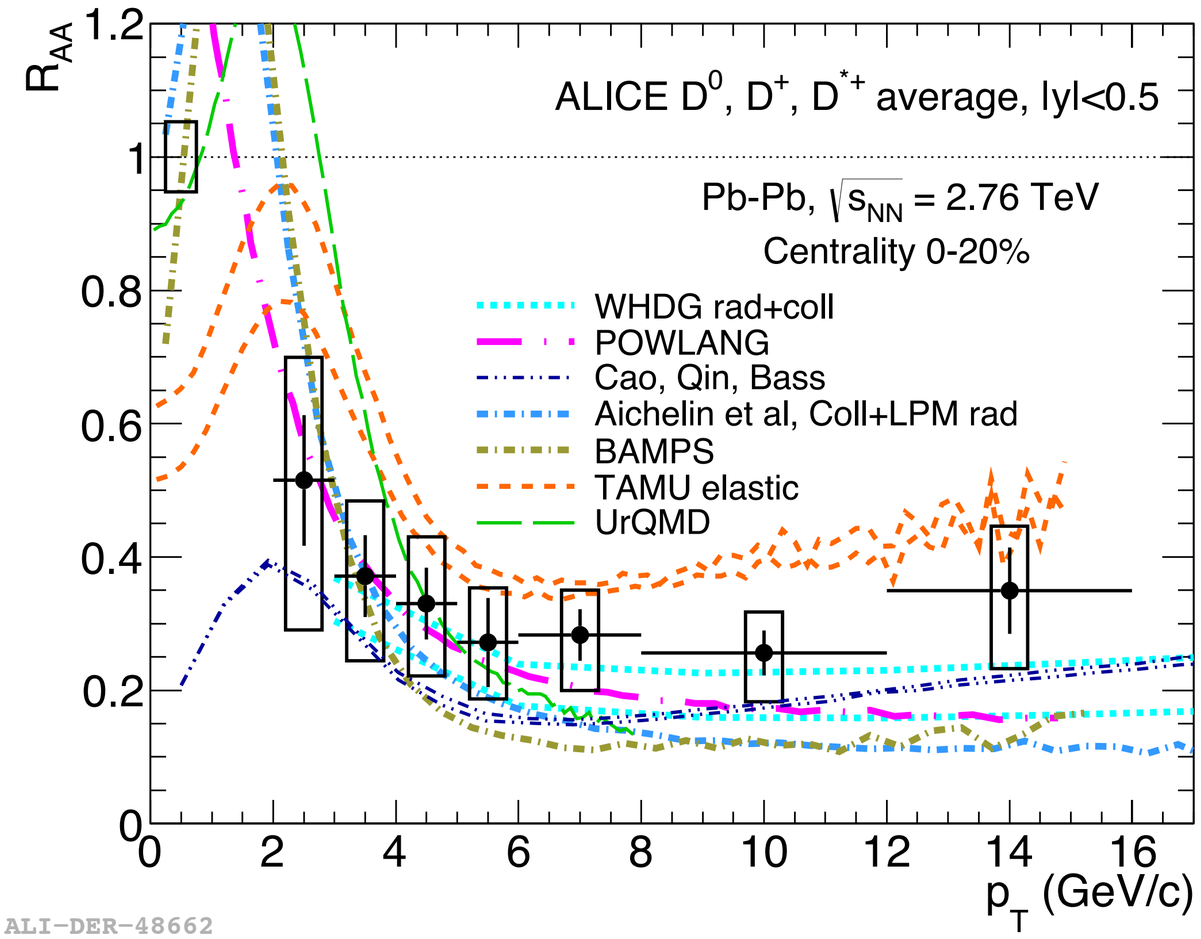




- **Positive D meson v_2 for $2<p_T<6$ GeV/c (5 σ effect)**
- **D meson v_2 similar to charged hadron v_2 measured by ALICE in the same centrality class (30-50%)**

D meson flow: comparison with models





Challenging for models to reproduce both R_{AA} and v_2 simultaneously

Flow of heavy flavour decay electrons

Flow of electrons from Heavy Flavour decays

$$v_2^{HFE} = \frac{(1+R_{SB})v_2^{incl} - v_2^{back}}{R_{SB}}$$

v_2^{incl} -v_2 of inclusive electrons

v_2^{HFE} -v_2 of HF electrons

v_2^{back} -v_2 of background electrons

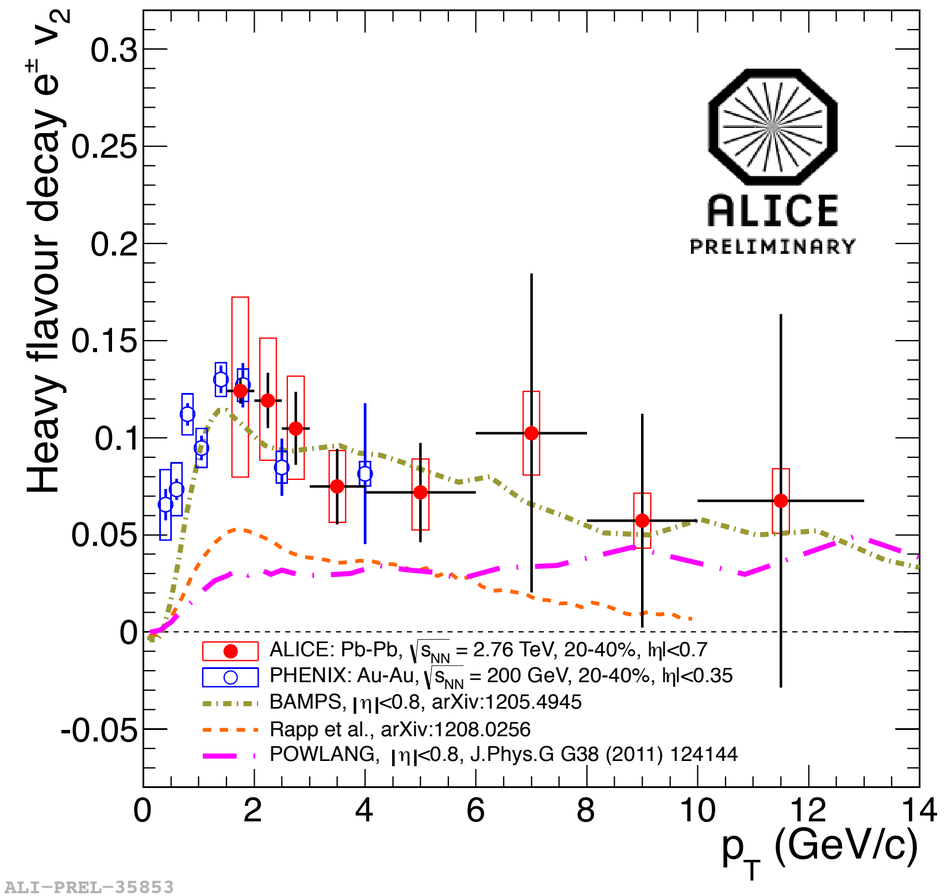
$$v_2^{back} = \sum_i R_i v_2^i$$

v_2^i - electron v_2 of source *i*

R_{SB} -Signal to background ratio

R_i -contribution of source *i*

computed used a cocktail method with experimental inputs (v_2 of background sources of electrons)



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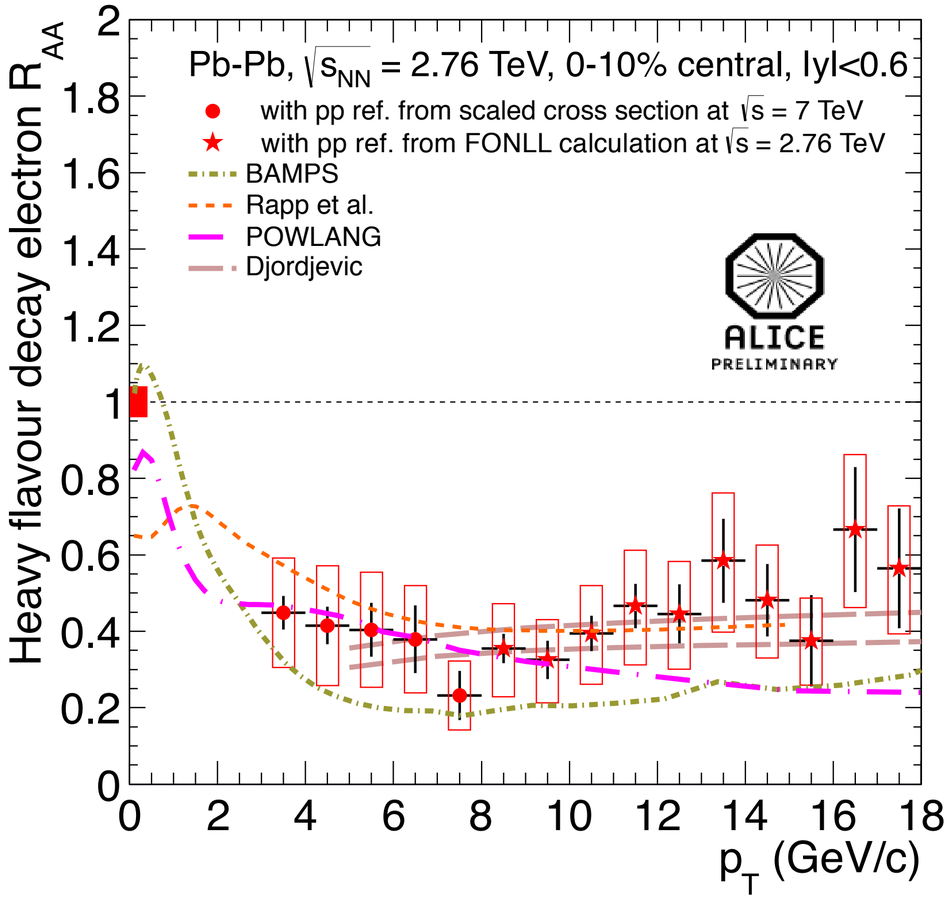

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Flow of heavy flavour decay muons

Flow of electrons from Heavy Flavour decays

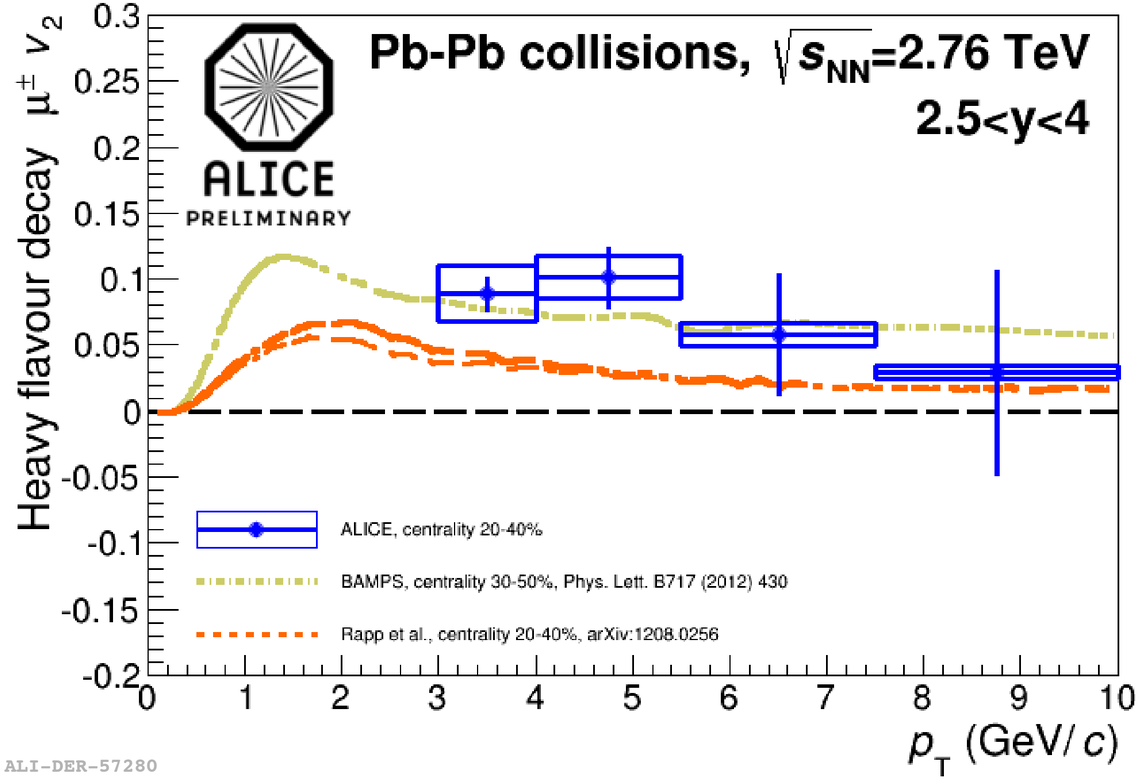
$$v_2^{\mu \leftarrow HF} = \frac{v_2^{incl.\mu} - f_{decay\mu} \cdot v_2^{decay\mu}}{1 - f_{decay\mu}}$$

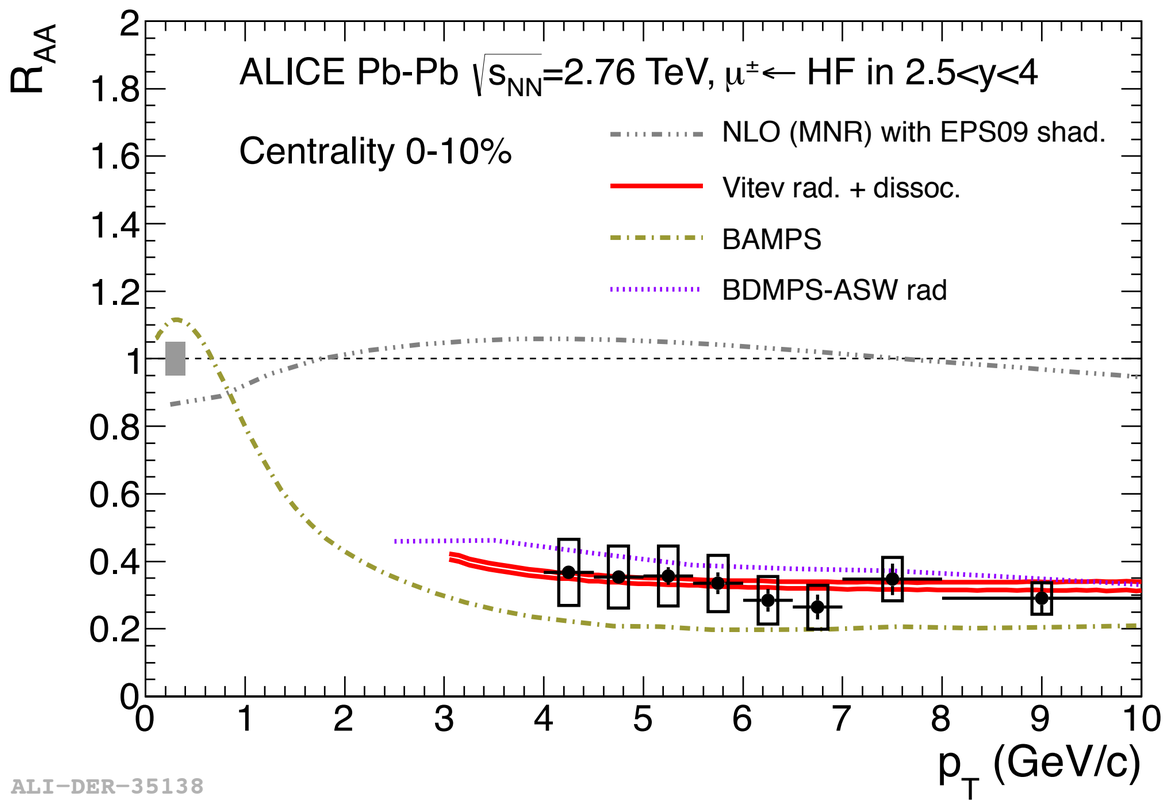
v_2^{incl} -v_2 of inclusive muons

f_{decay} -fraction of muons from decay

v_2^{decay} -v_2 of muons from decay

computed used a cocktail method with experimental inputs (v_2 of background sources of muons at forward rapidity)





Results from correlation analyses

D meson -charged hadron correlations

pp @ $\sqrt{s}$ = 7 TeV

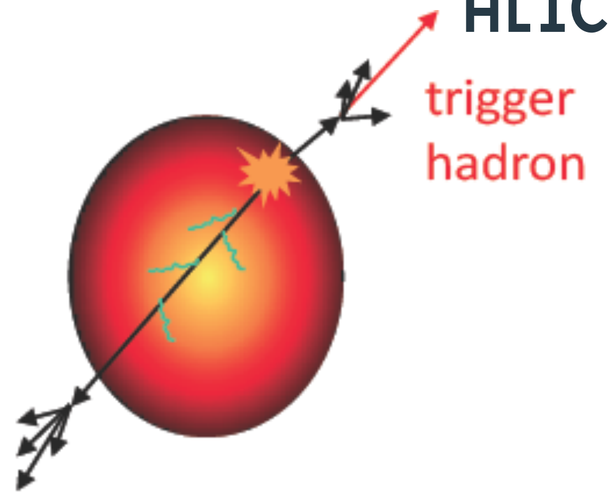
ALICE

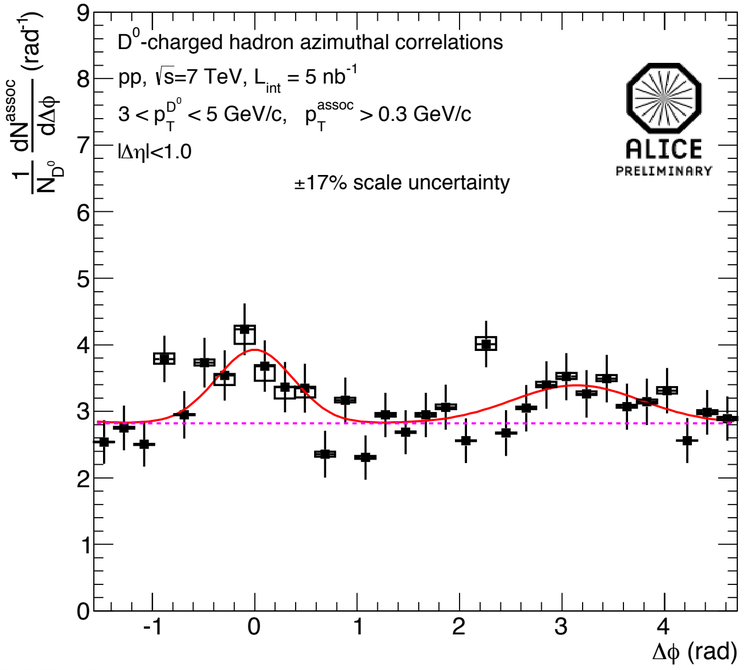
Correlation function obtained from pairing a D meson candidate with the charged hadrons in the event

Raw correlation from same event analysis

$$C(\Delta\phi,\Delta\eta) = \frac{S(\Delta\phi,\Delta\eta)}{B(\Delta\phi,\Delta\eta)}$$

Correlation from mixed event analysis corrects for the limited detector acceptance and inhomogeneity





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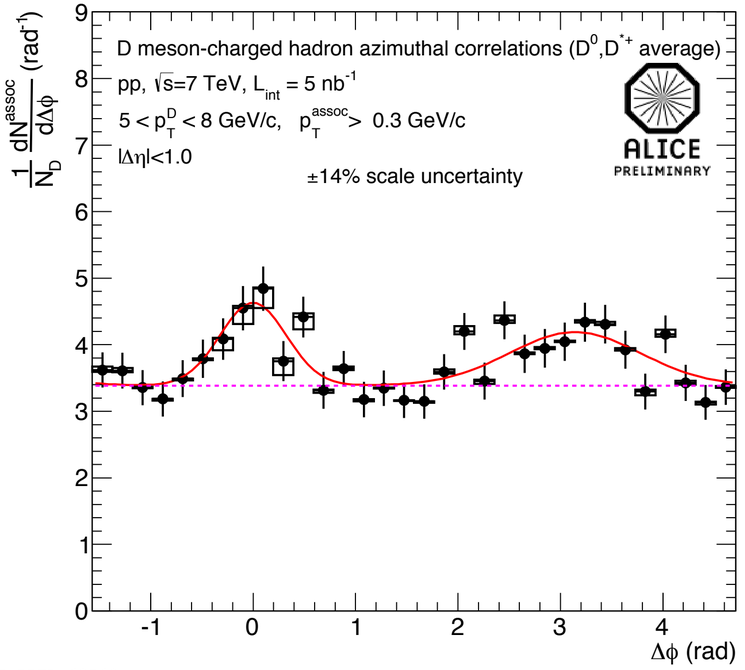

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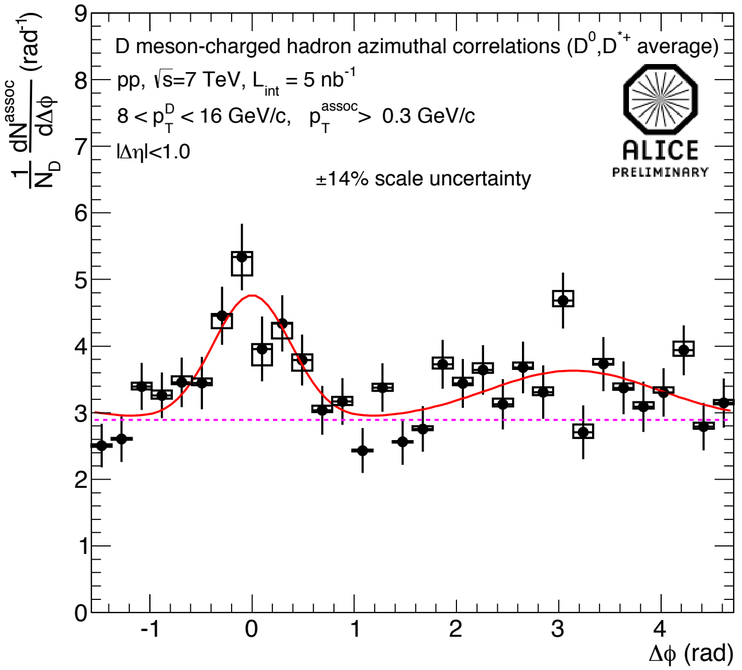

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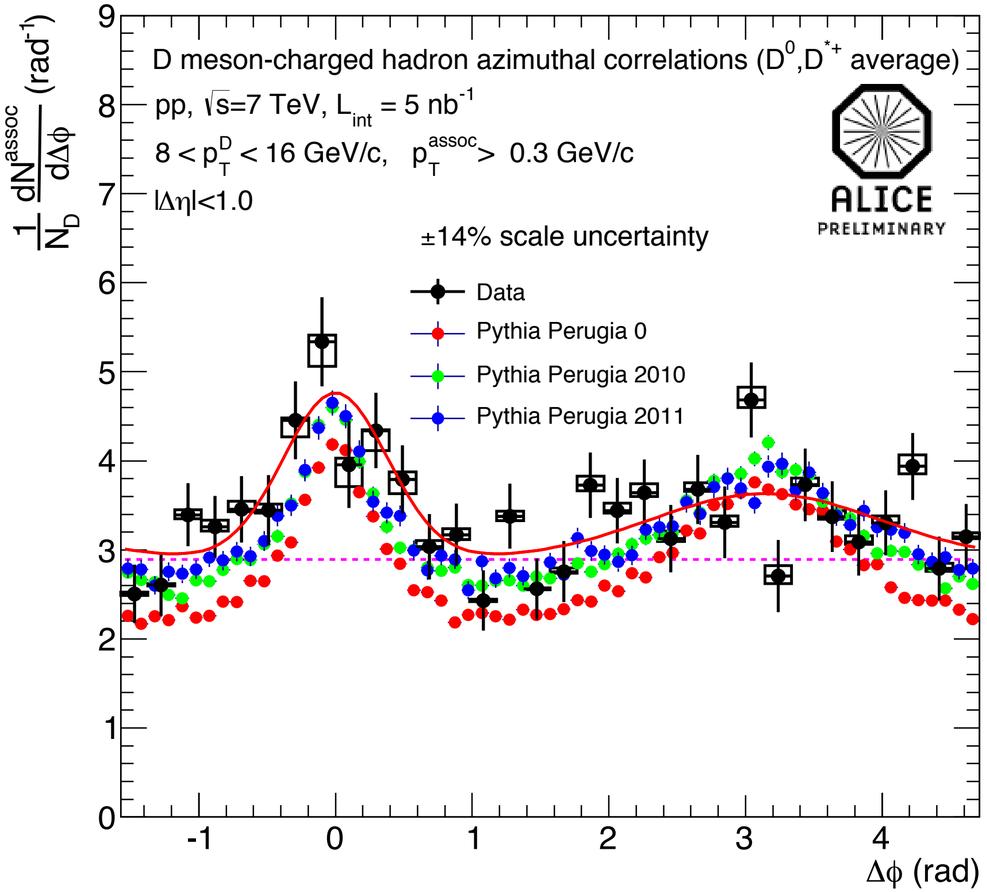
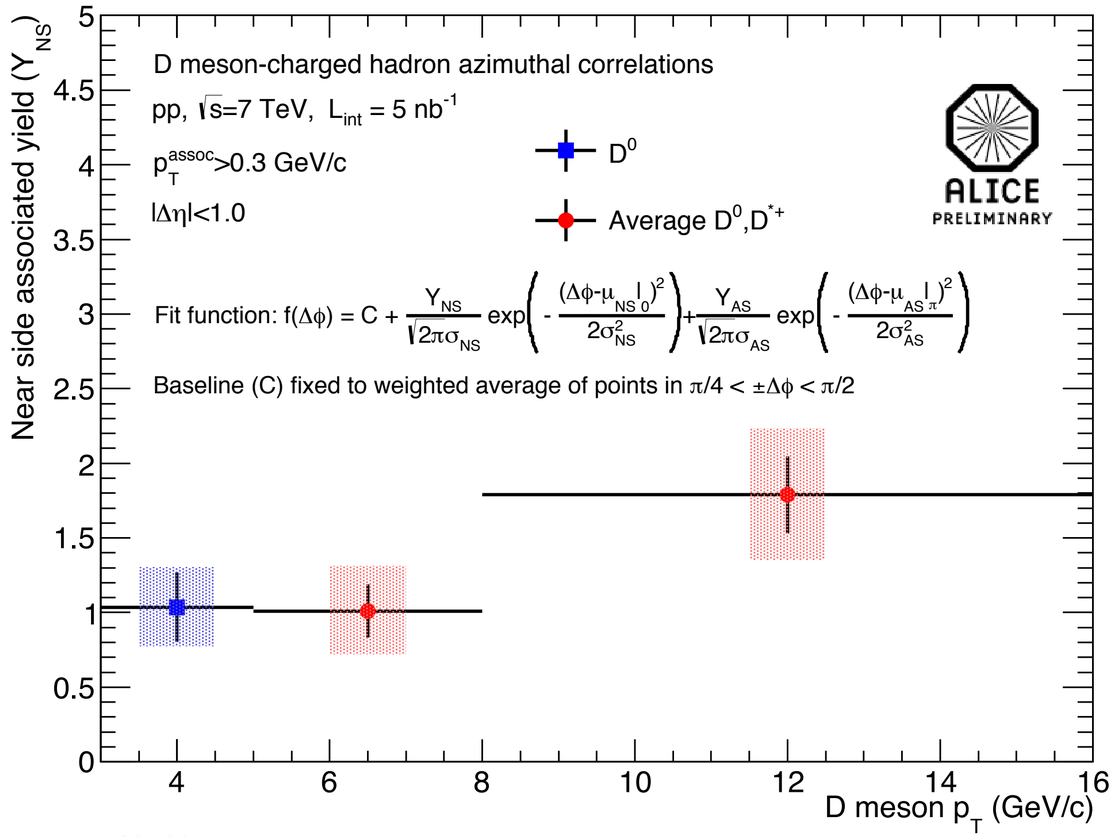
D meson -charged hadron correlations

pp @ $\sqrt{s}$ = 7 TeV

Comparison with different Pythia tunes shows a good agreement within large uncertainties



ALI-DER-63803



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Hard to make conclusions due to large uncertainties

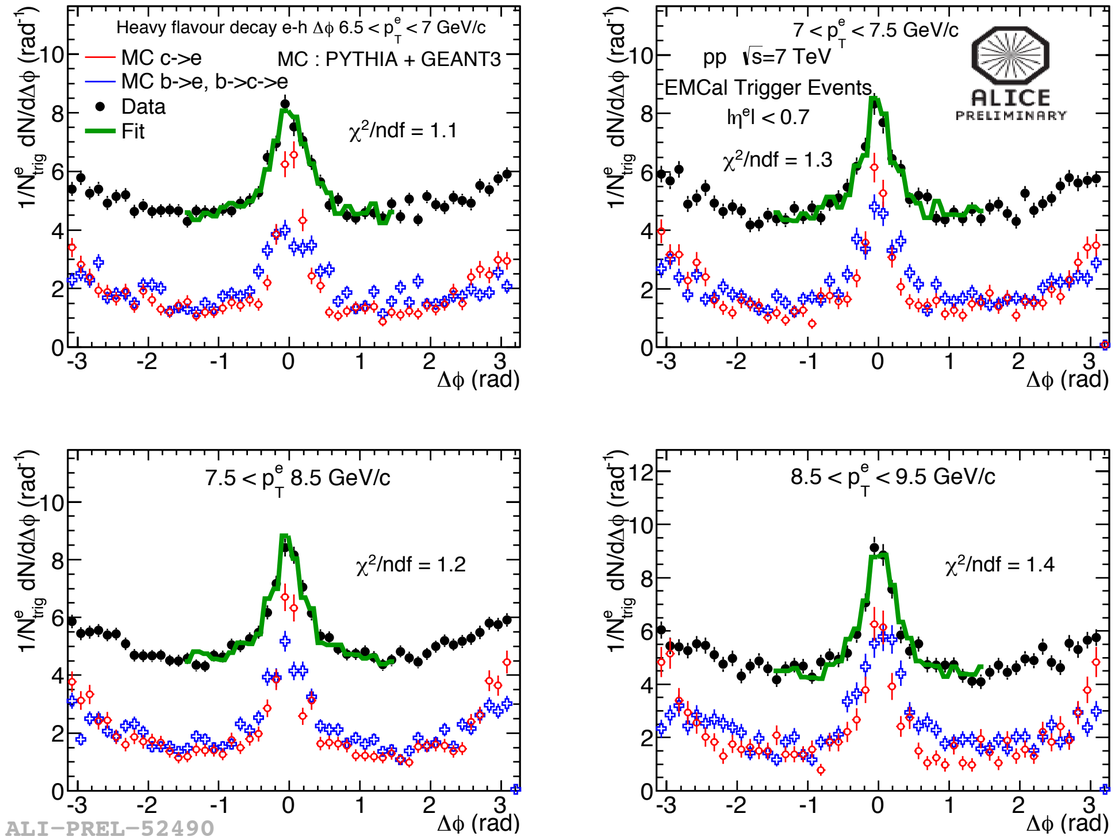
More precise measurement expected from Run II

HF electron - charged hadron correlations

pp @ $\sqrt{s}$ = 7 TeV

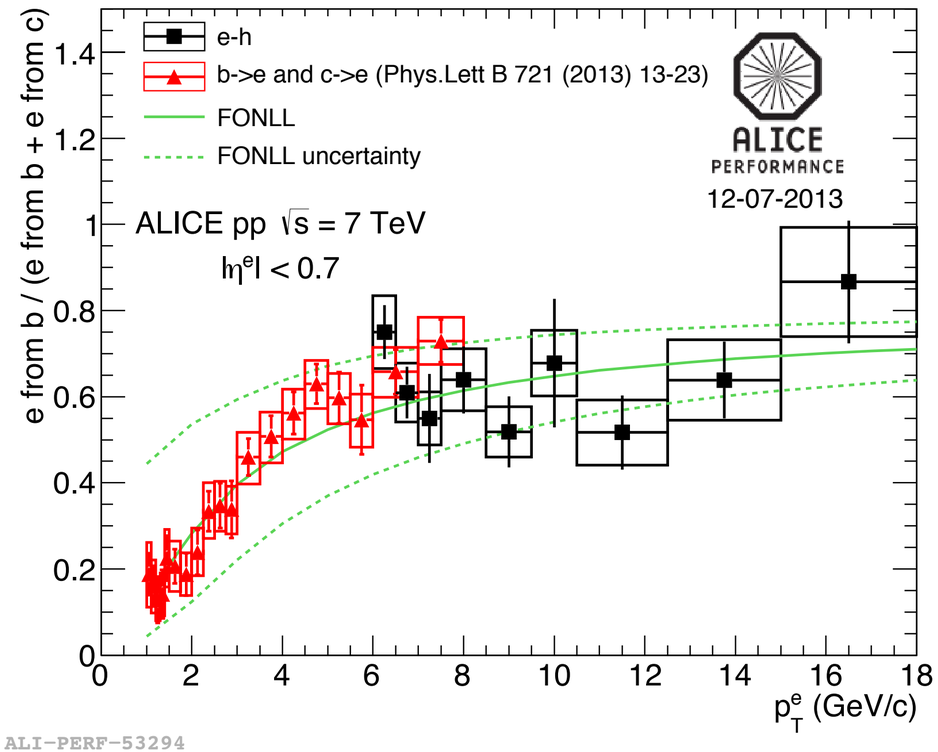
Strategy to build the correlation function similar to the D meson

Main goal in pp - separate the beauty and charm contributions for Heavy Flavour Electrons (HFE)
Beauty quarks are heavier than charm → wider correlation distribution for electrons from beauty



The correlation distribution is fitted with MC templates to extract the beauty to charm ratio

$$\Delta\phi = const + r_B \Delta\phi^B_{templ} + (1 - r_B)\Delta\phi^C_{templ} \quad , \quad r_B = \frac{N^e_B}{N^e_B + N^e_C}$$



r_B ratio compatible with results obtained by selection on the electron impact parameter

r_B ratio compatible with FONLL prediction

HF electron - charged hadron correlations

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

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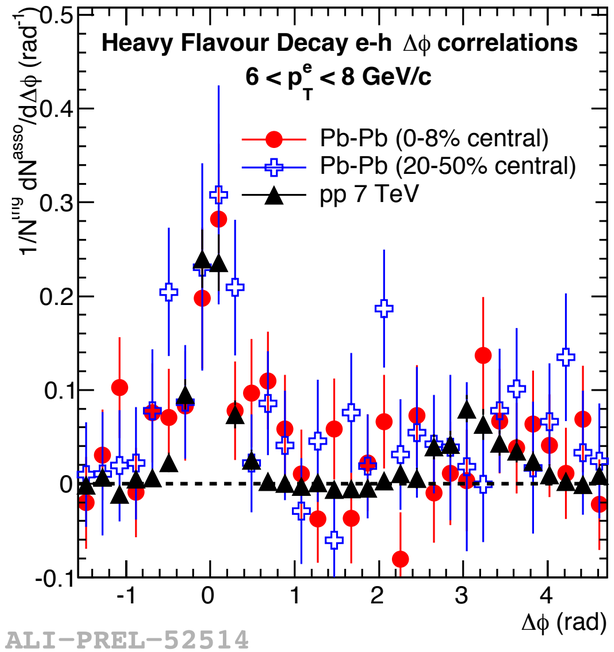
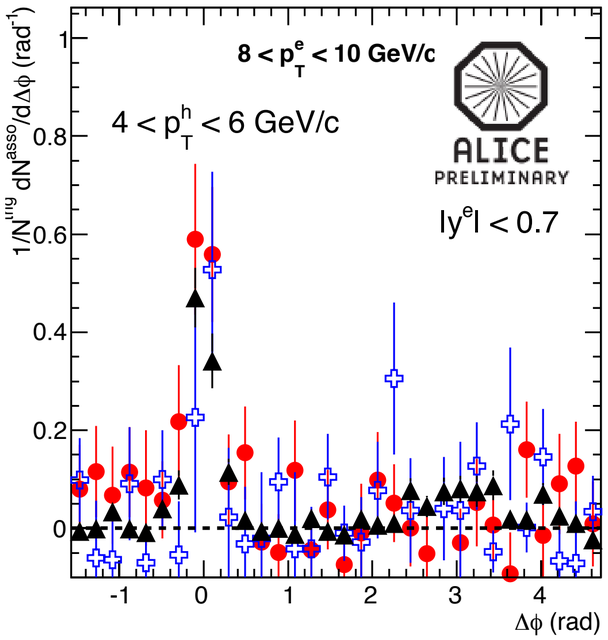
Goal: look for possible modification of the fragmentation function in Pb-Pb collisions

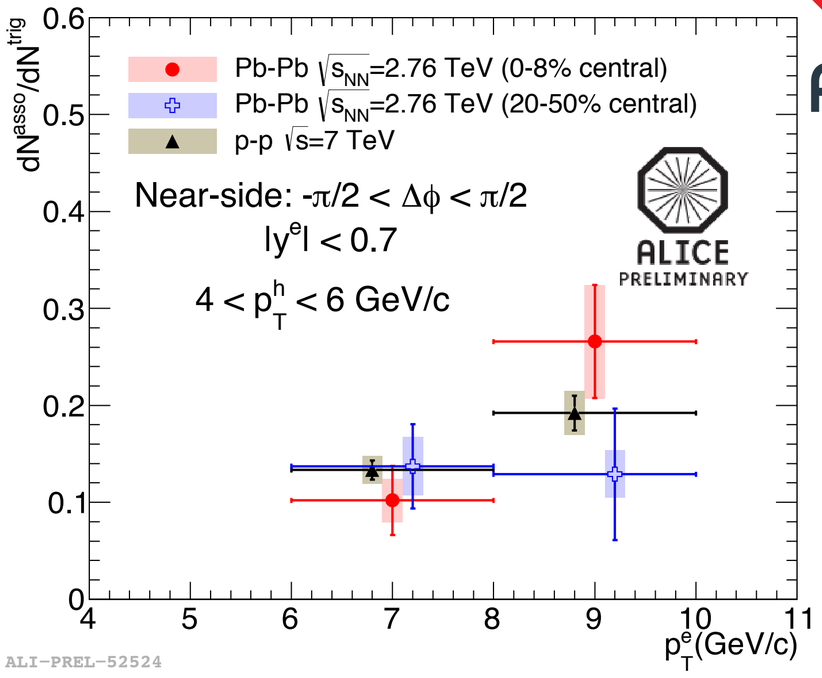


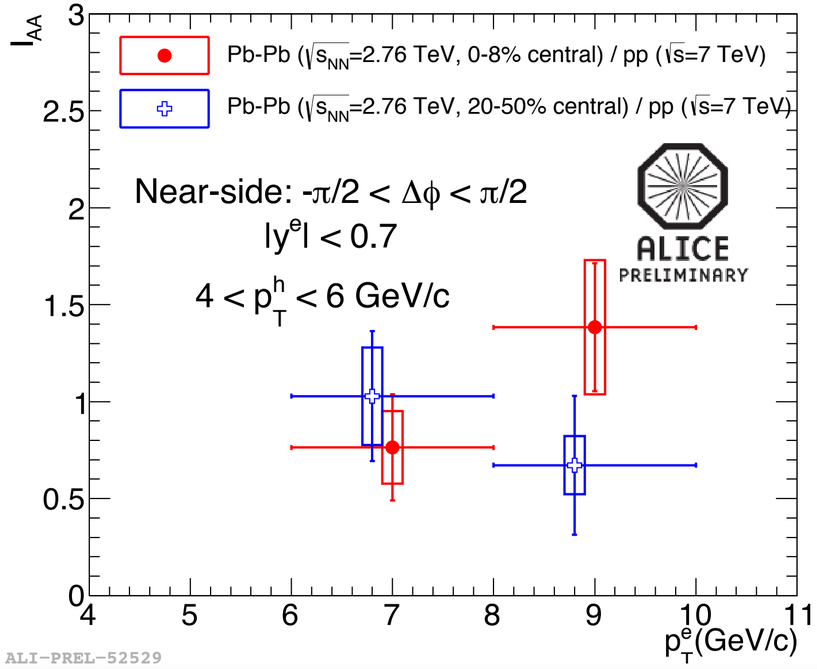


$$I_{AA} = \frac{N^{Asso}_{Pb-Pb} / \ N^{Trig}}{N^{Asso}_{p-p} / \ N^{Trig}}$$

I_{AA} ~ 1

difficult to conclude on eventual modification of the fragmentation function because of the limited statistics



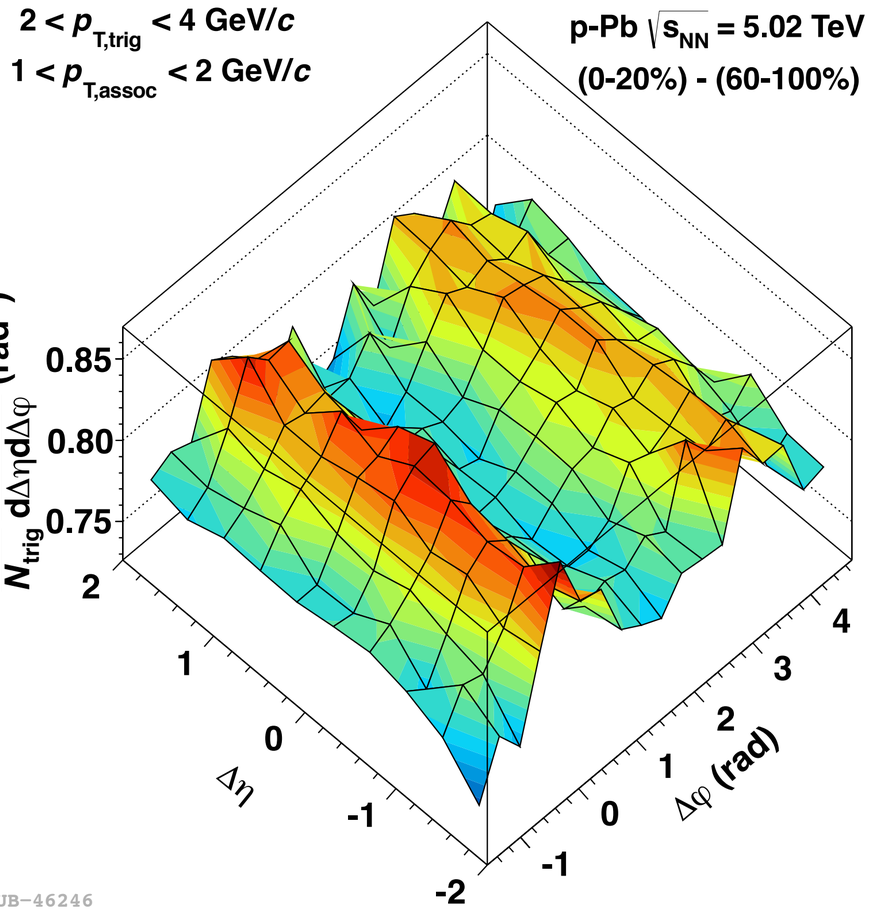


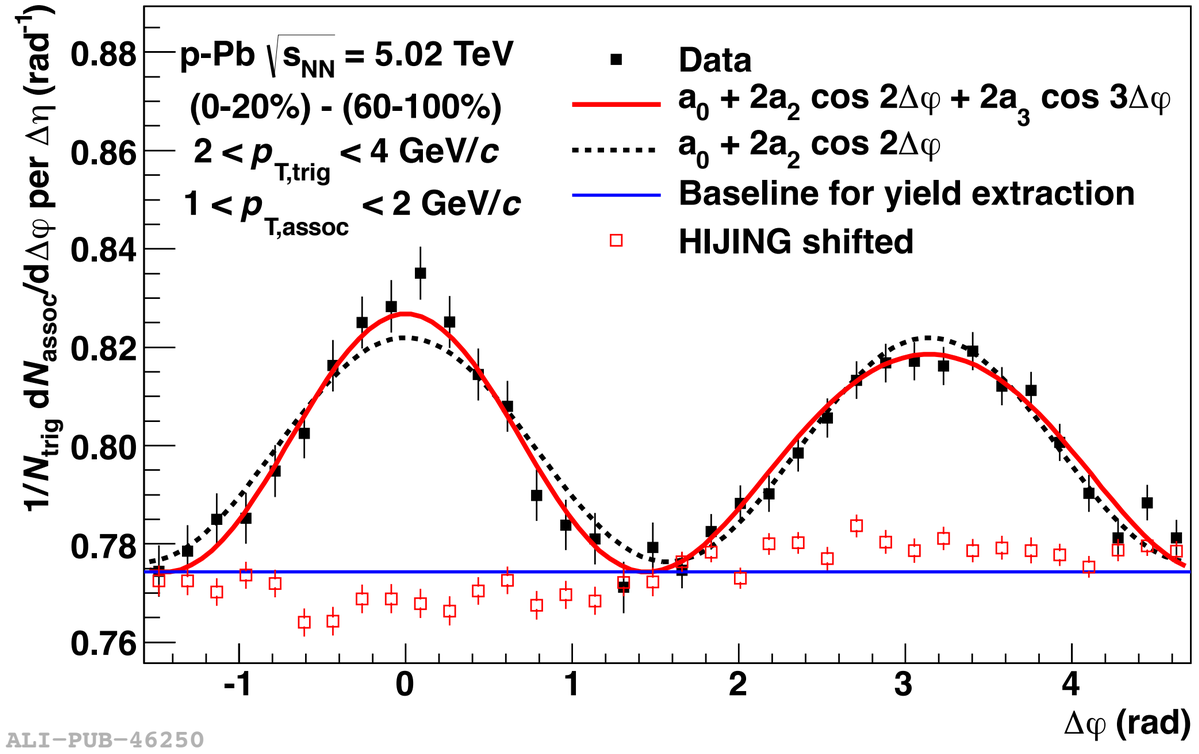
Hadron - hadron correlations

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

ALICE

In p-Pb collisions, a double ridge structure was seen in hadron hadron correlation analyses, after subtracting the most "peripheral" from the most "central"





"Double Ridge"structure

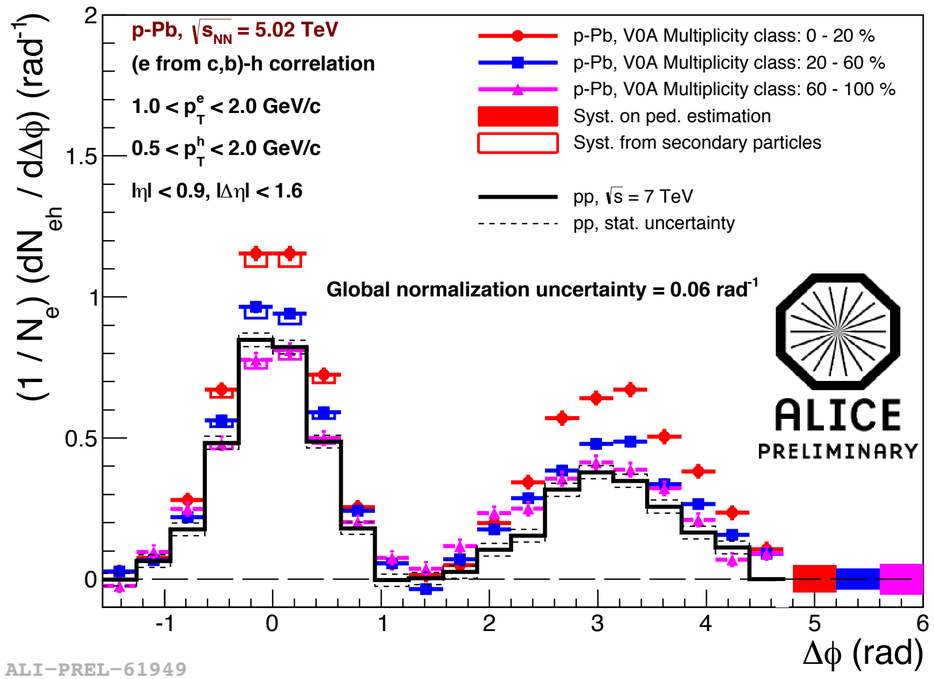
The double ridge observed in hadron-hadron correlations explained by Hydrodynamics and Color Glass Condensate models

HF electron - charged hadron correlations

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

ALICE

In p-Pb collisions, study of HF electron-hadron correlations to address the "ridge" structure in the HF sector



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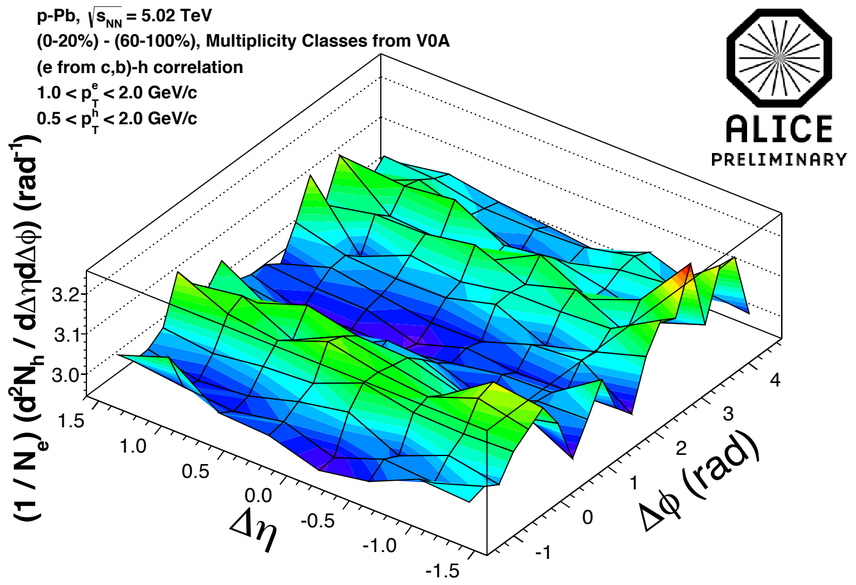
Multiplicity dependence clearly visible in the correlation distribution



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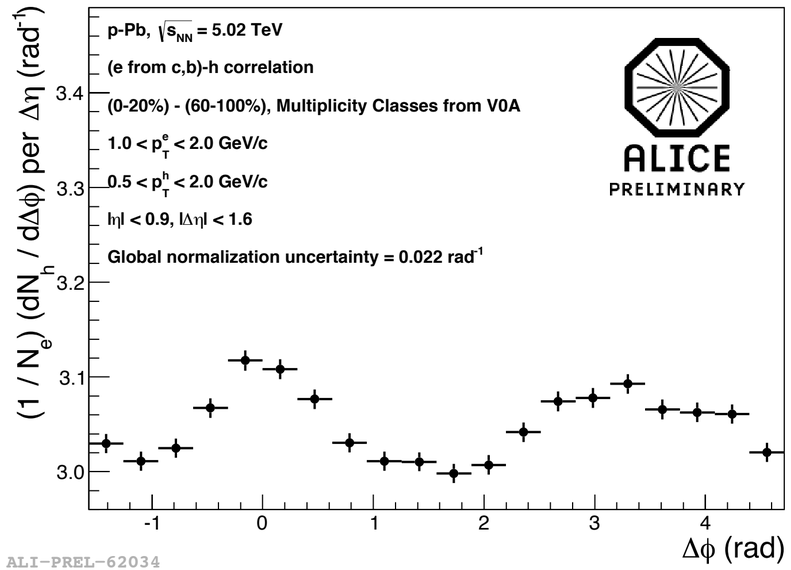
From the subtraction of the most peripheral correlations from the most central



ALI-PREL-62034

"Double Ridge" structure

The double ridge also observed in heavy flavour sector which might point to the same origin of the effect

Summary and outlook

- ALICE has measured a positive elliptic flow of D mesons in the p_T region $2<p_T<6$ GeV/c, similar to that of charged hadrons

- The elliptic flow of heavy flavour decay electrons (at mid rapidity) and muons (at forward rapidity) has a similar magnitude

- The simultaneous description of the HF elliptic flow and the R_{AA} presents a challenge for the models

- First measurement of correlations between D mesons and charged hadrons in pp @ 7 TeV was shown - compatibility with various Pythia tunes - to be used as baseline for p-Pb and Pb-Pb measurements

- In Pb-Pb collisions, from the I_{AA} measurement, it is hard to conclude on the modification of the fragmentation due to limited statistics

- Correlations of heavy flavour electrons and charged hadrons show double ridge structure in p-Pb collisions.

- Most of the heavy flavour measurements will profit strongly of the ALICE upgrades

BACKUP

BACKUP - B feed down for flow analysis

- The selection of D mesons selects both D mesons from c and from b
- Since v_2 is additive, it is possible to write

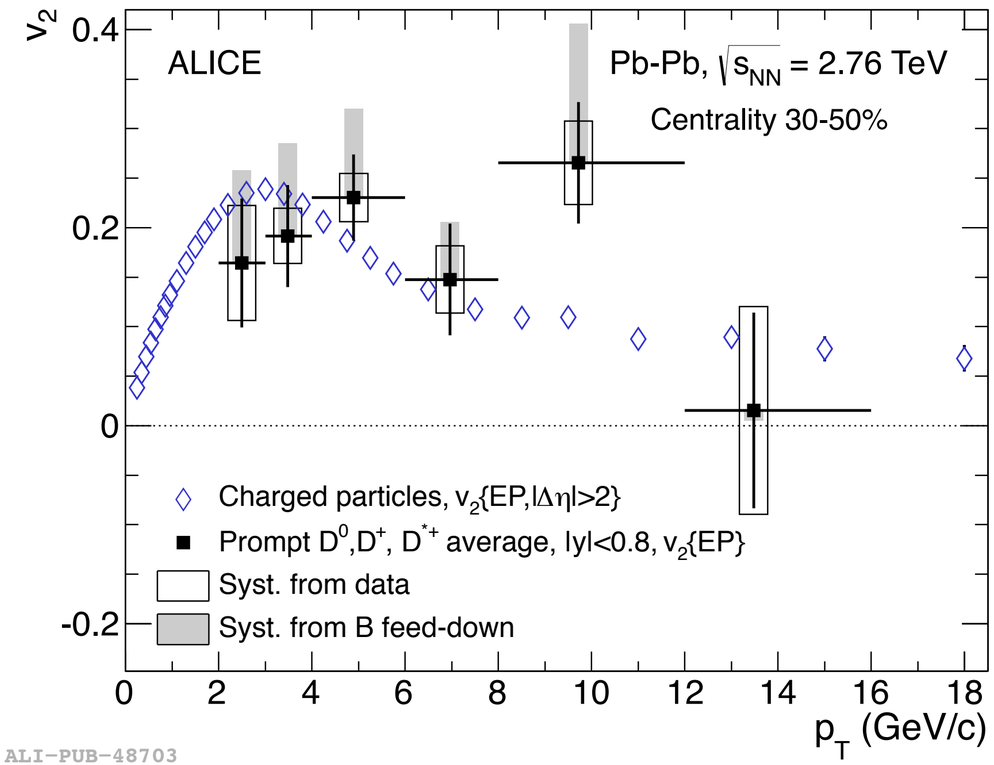
$$v_2^{prompt} = \frac{1}{f_{prompt}} v_2^{incl.} - \frac{1 - f_{prompt}}{f_{prompt}} v_2^{FD}$$

- All models predict $v_2^{prompt} \geq v_2^{feed\text{-}down}$
- Central point computed by the assumption

$$v_2^{prompt} = v_2^{feed\text{-}down}$$

- Systematic error computed by varying $v_2^{feed\text{-}down}$

$$0 \leq v_2^{feed\text{-}down} \leq v_2^{prompt}$$



BACKUP - Scalar product method for D mesons

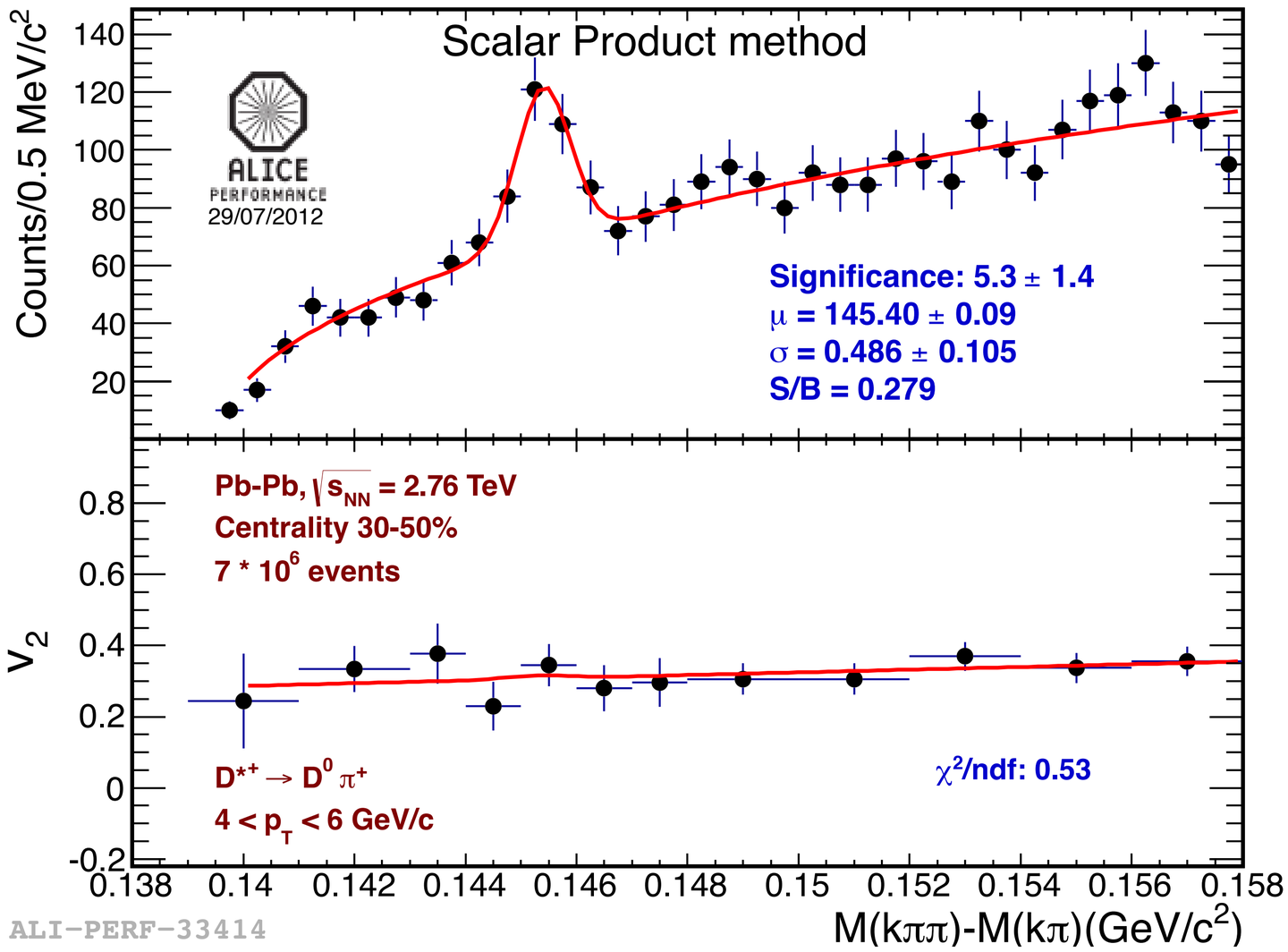
Scalar Product method

$$v_{2,SP} = \frac{\langle \mathrm{u} \cdot \frac{\mathrm{Q}}{\mathrm{M}} \rangle}{\sqrt{\langle \frac{Q_a}{M_a} \cdot \frac{Q_b}{M_b} \rangle}} \qquad \mathrm{u} = e^{i2\phi} \qquad Q = \sum_{j=1}^{M_{RP}} \exp^{i2\phi_j}$$

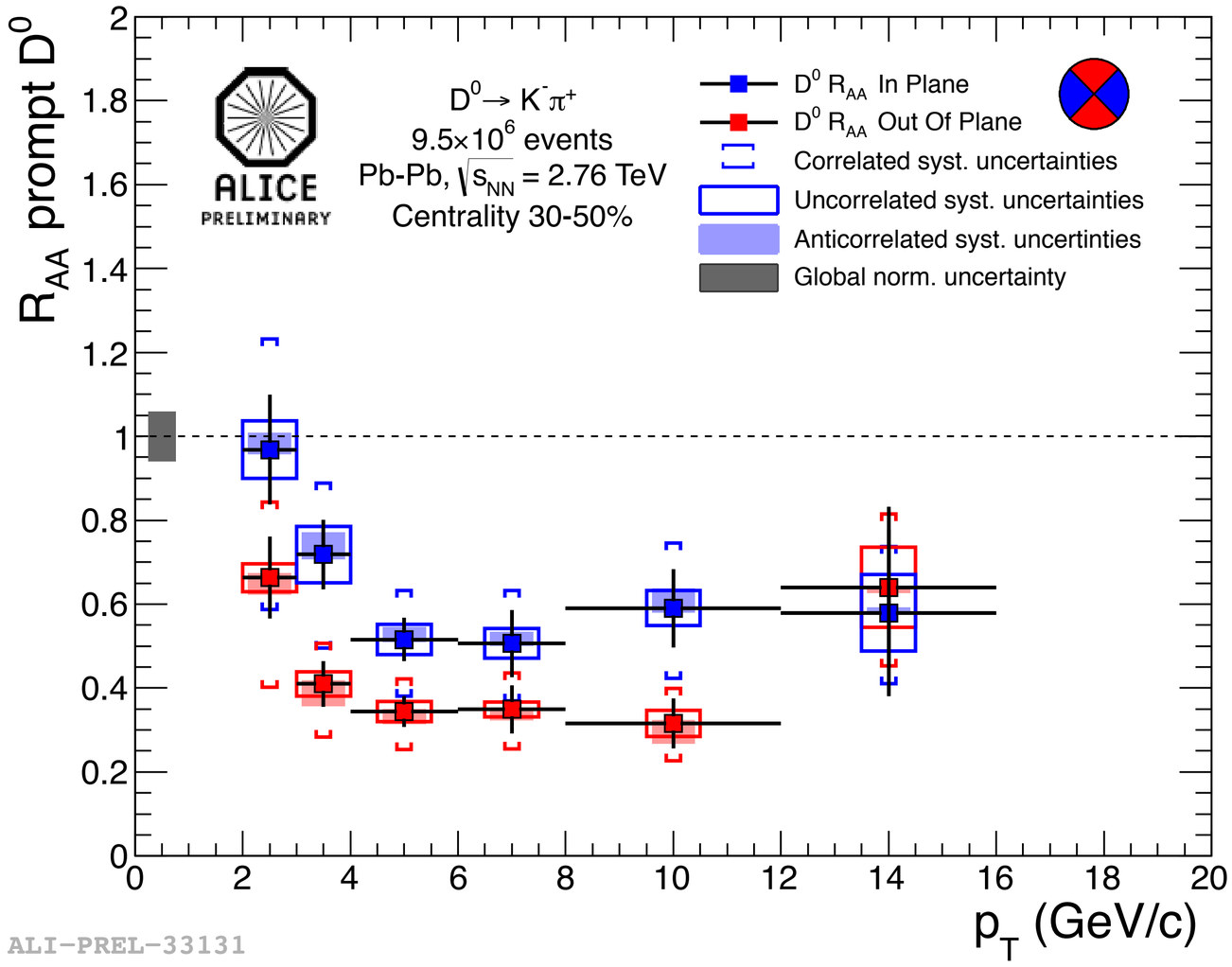
ϕ=Azimuthal angle of the D meson

ϕ_j=Azimuthal angle of the reference particles

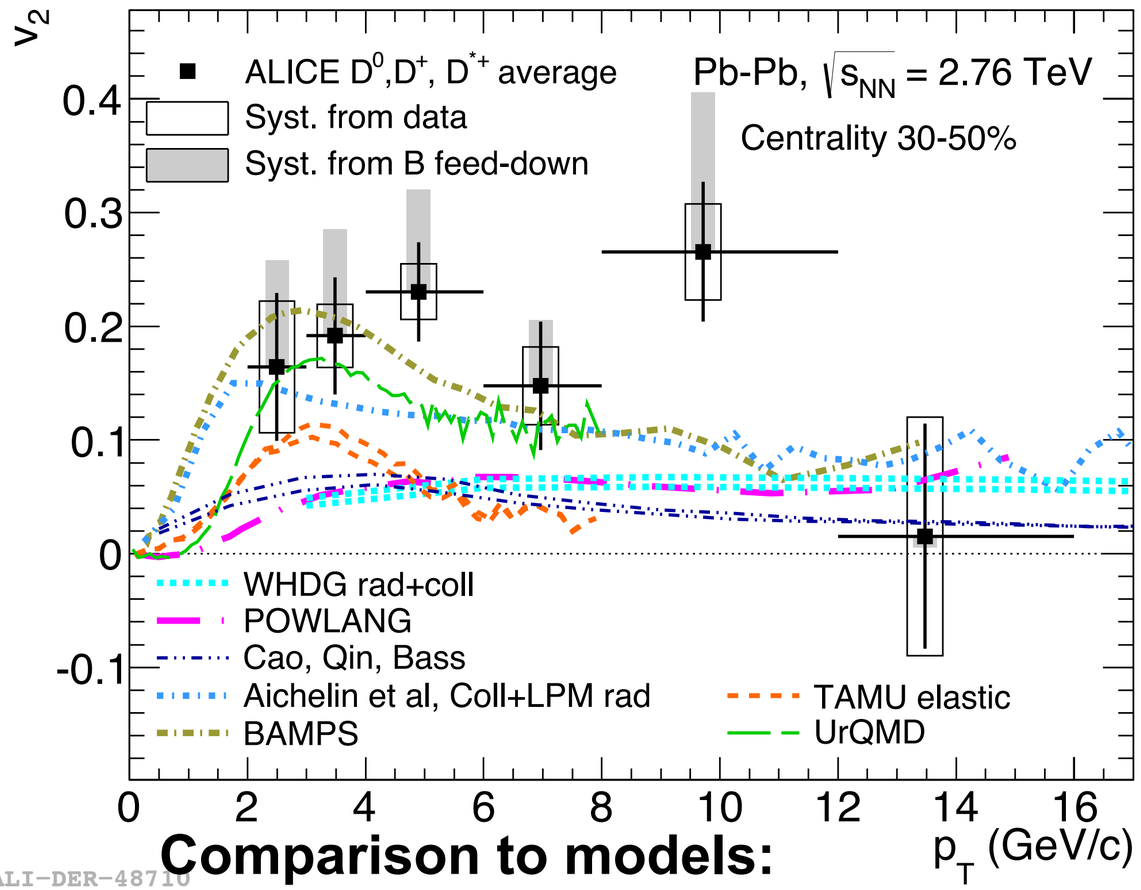
M_{RP}=Multiplicity of reference particles

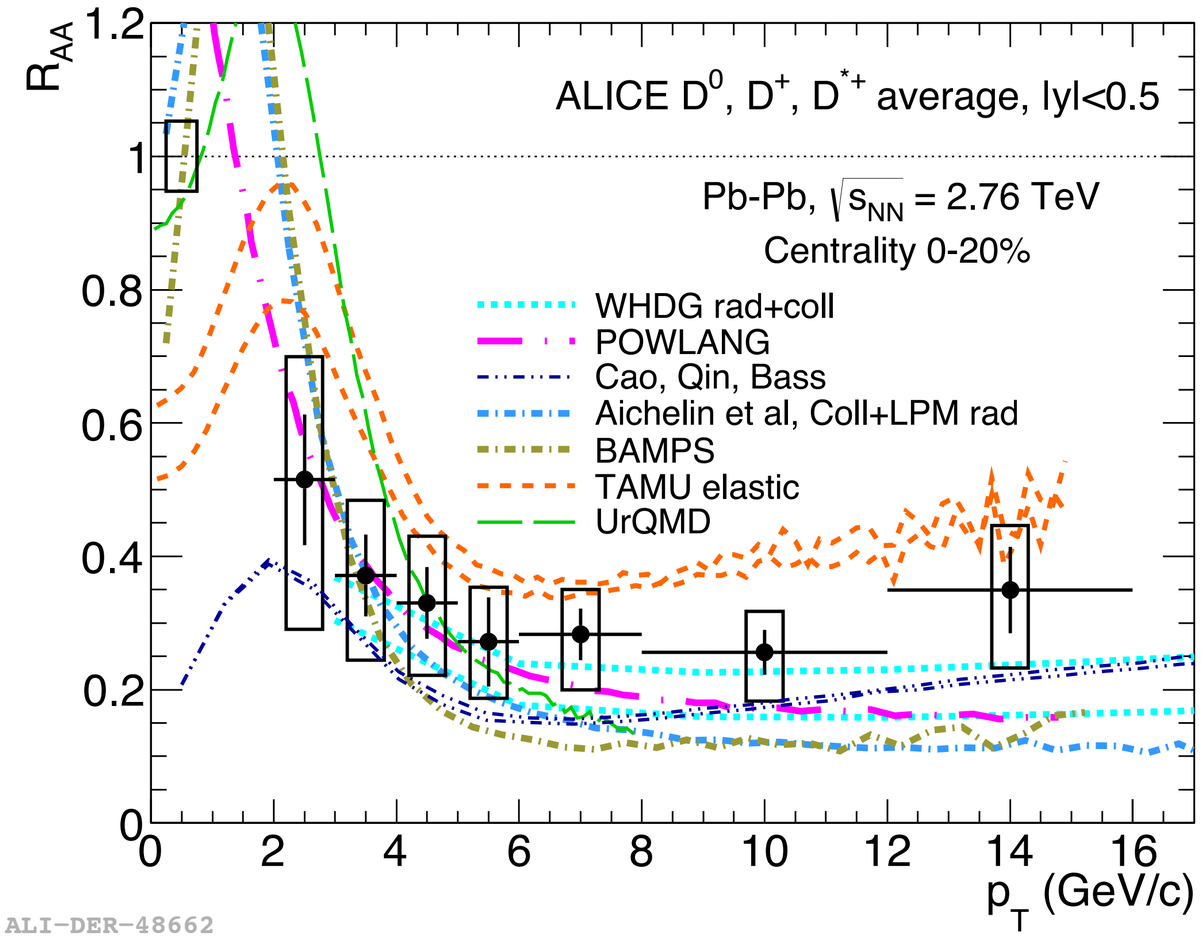


BACKUP - R_{AA} of D^0 in- and out- of plane



BACKUP - D meson flow with models





Comparison to models:

BAMPS: *heavy quark transport with collisional and radiation energy loss in expanding QGP* **consistent with v_2 and Raa**

TAMU elastic: *heavy quark transport with in-medium resonance scattering and coalescence* **underestimates v_2 and overestimates Raa**

POWLANG: *heavy quark transport (Langevin eq.) with collisional energy loss* **underestimates v_2 consistent with Raa**

BACKUP - HFE flow with models

Flow of electrons from Heavy Flavour decays

$$v_2^{HFE} = \frac{(1+R_{SB})v_2^{incl} - v_2^{back}}{R_{SB}}$$

v_2^{incl} -v_2 of inclusive electrons

v_2^{back} -v_2 of background electrons

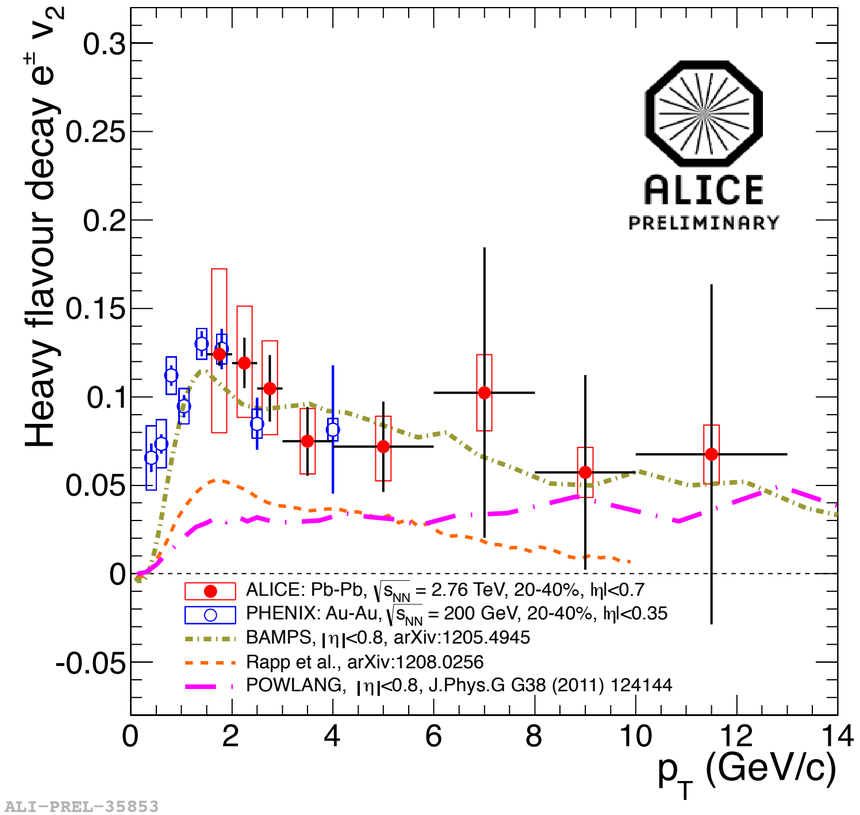
v_2^{HFE} -v_2 of HF electrons

$$v_2^{back} = \sum_i R_i v_2^i$$

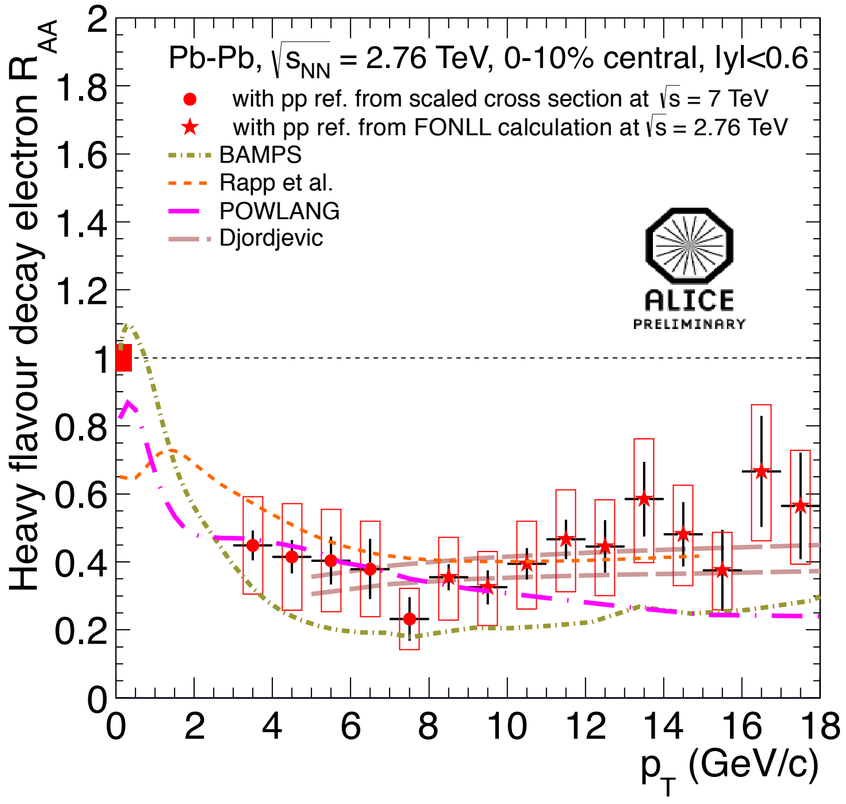
v_2^i - electron v_2 of source i

R_{SB} -Signal to background ratio

R_i -contribution of source i



ALI-PREL-35853



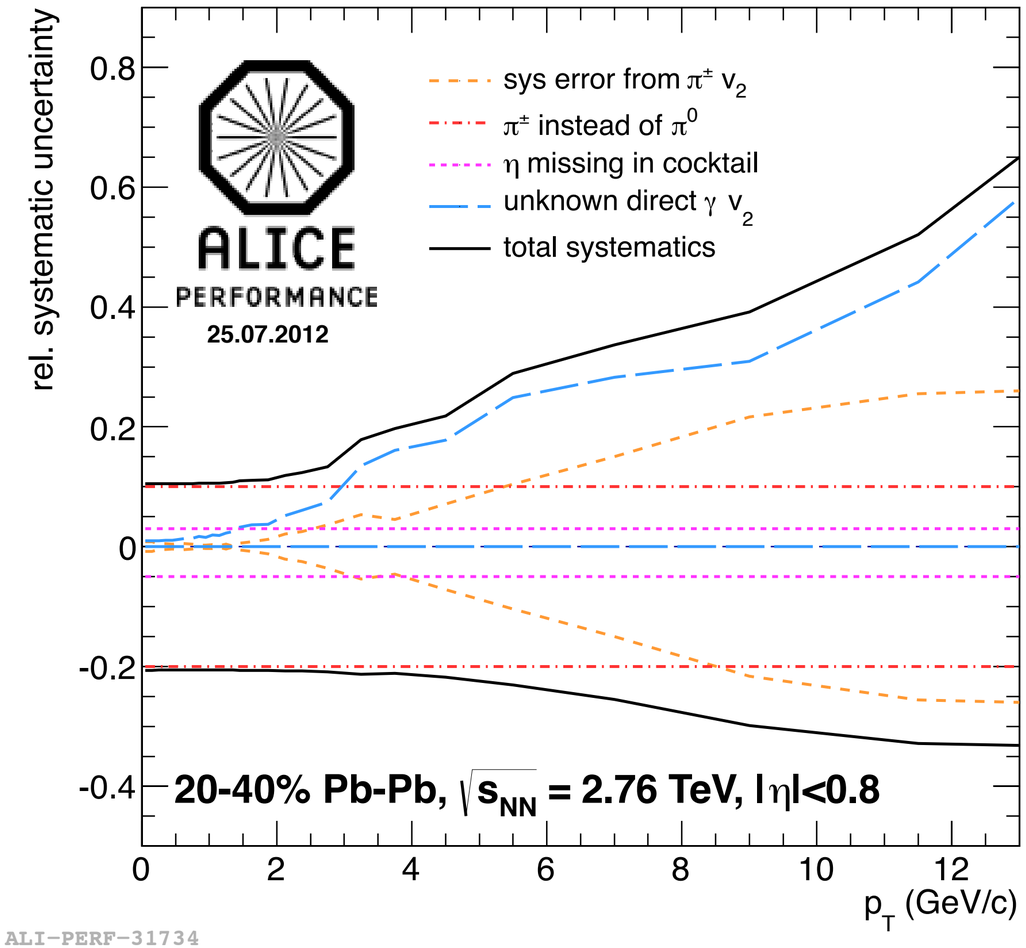
ALI-DER-57138

BAMPS: *heavy quark transport with collisional and radiation energy loss in expanding QGP* **- consistent with HFE v_2 overestimate HFE R_{AA}**

Rapp: *heavy quark transport with in-medium resonance scattering and coalescence* **- underestimates HFE v_2 consistent with HFE R_{AA}**

POWLANG: *heavy quark transport (Langevin eq.) with collisional energy loss* **- underestimates HFE v_2 consistent with HFE R_{AA} for p_T<12 GeV/c**

BACKUP - HFE cocktail



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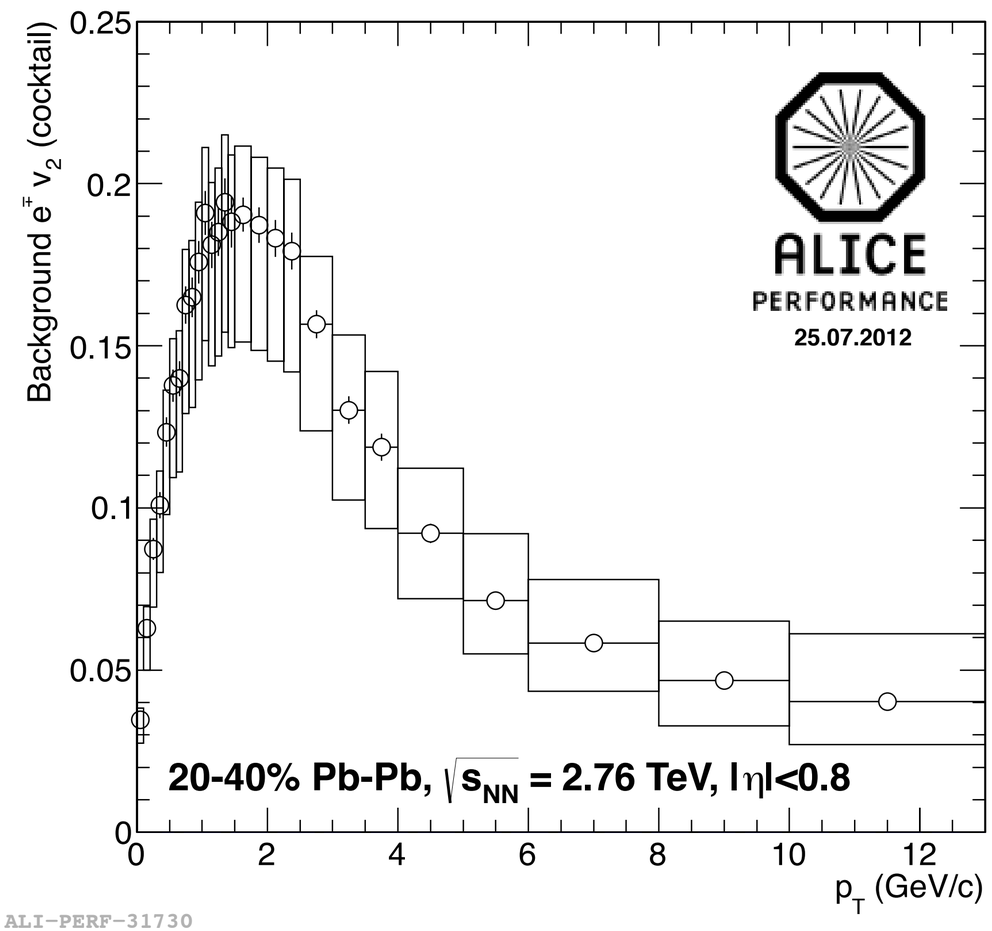

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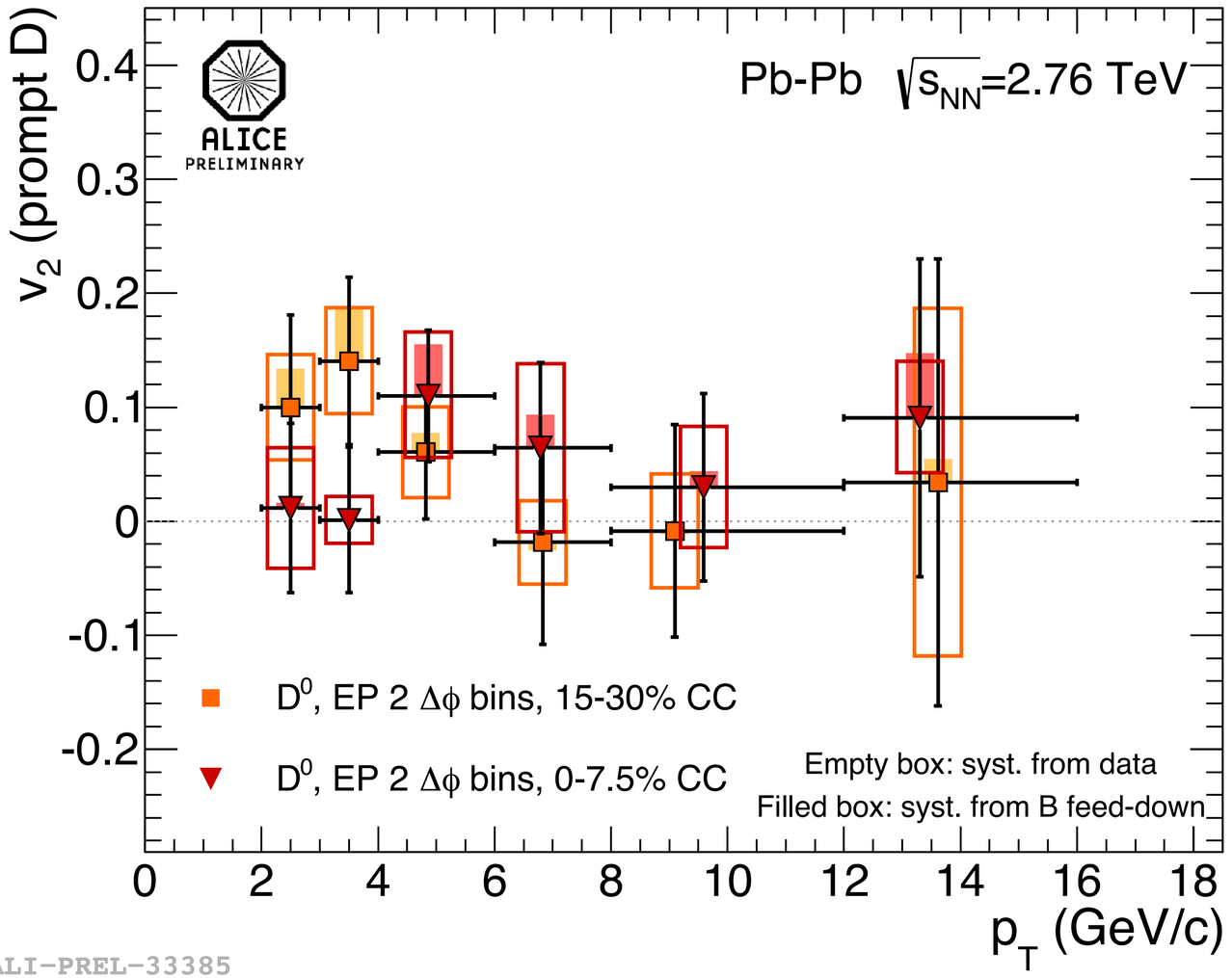
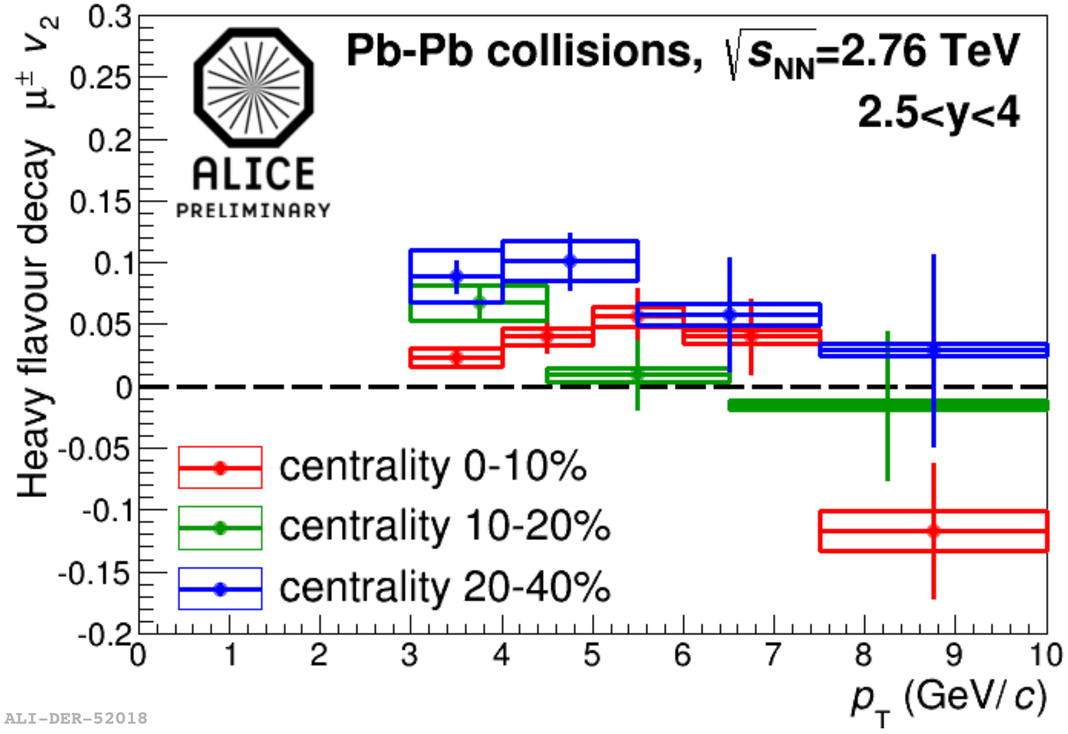
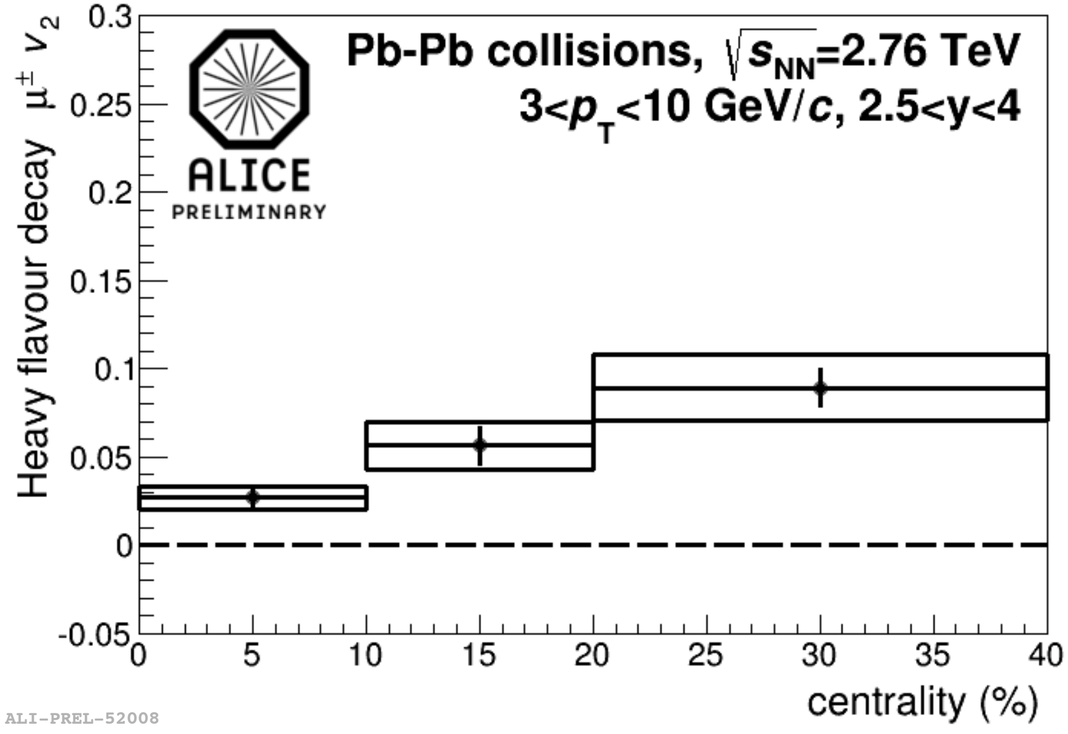
BACKUP - elliptic flow of D^0 0-7.5% and 15-30%



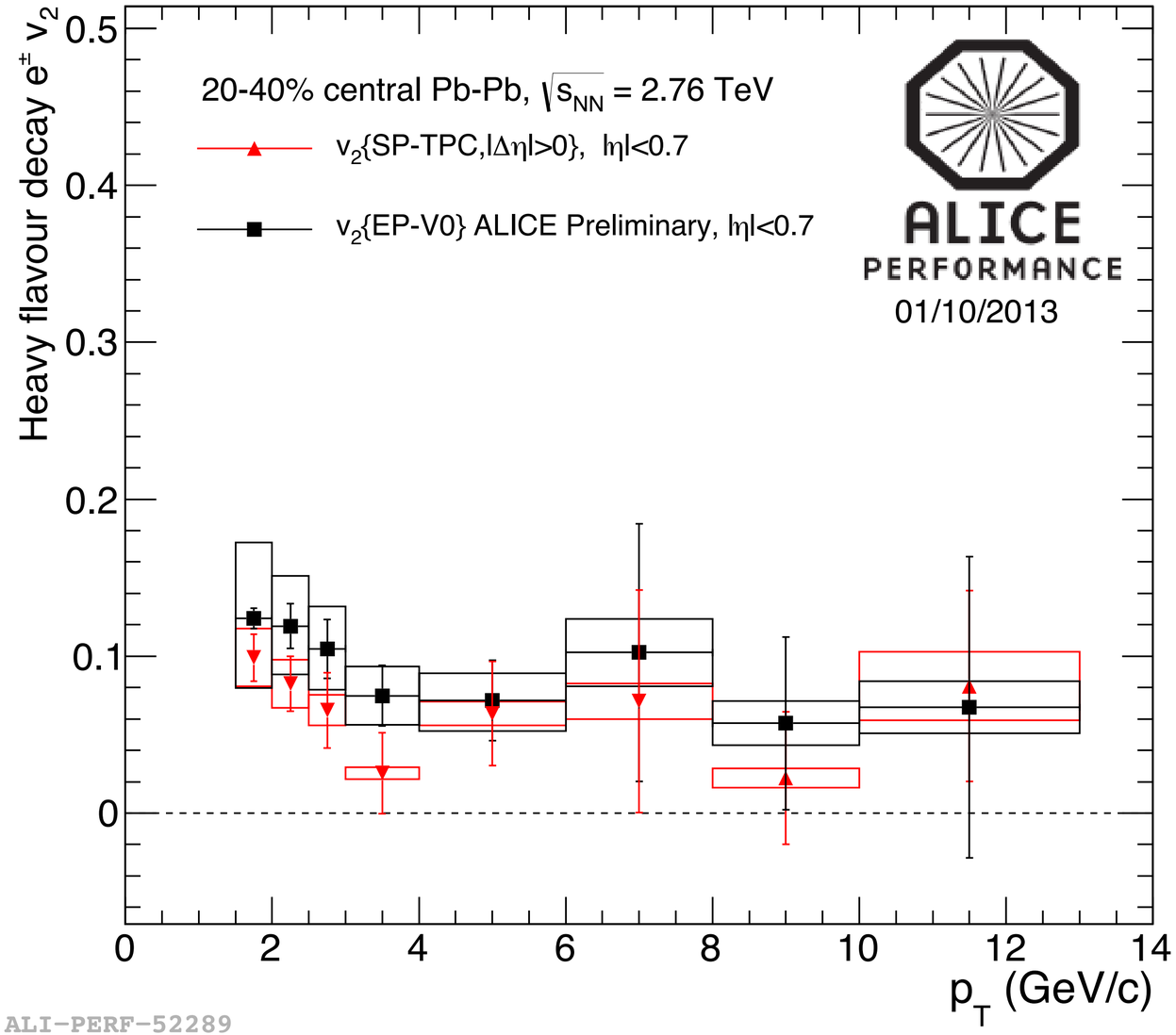
ALI-PREL-33385

BACKUP - elliptic flow of HF muons vs centrality

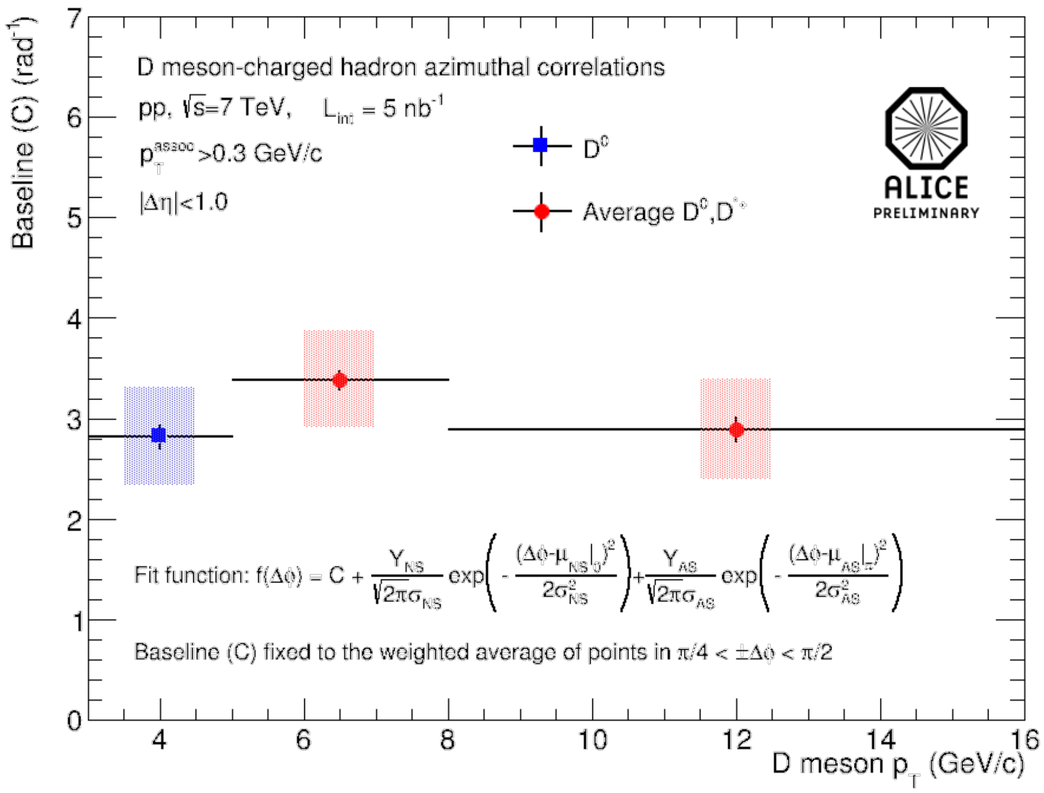


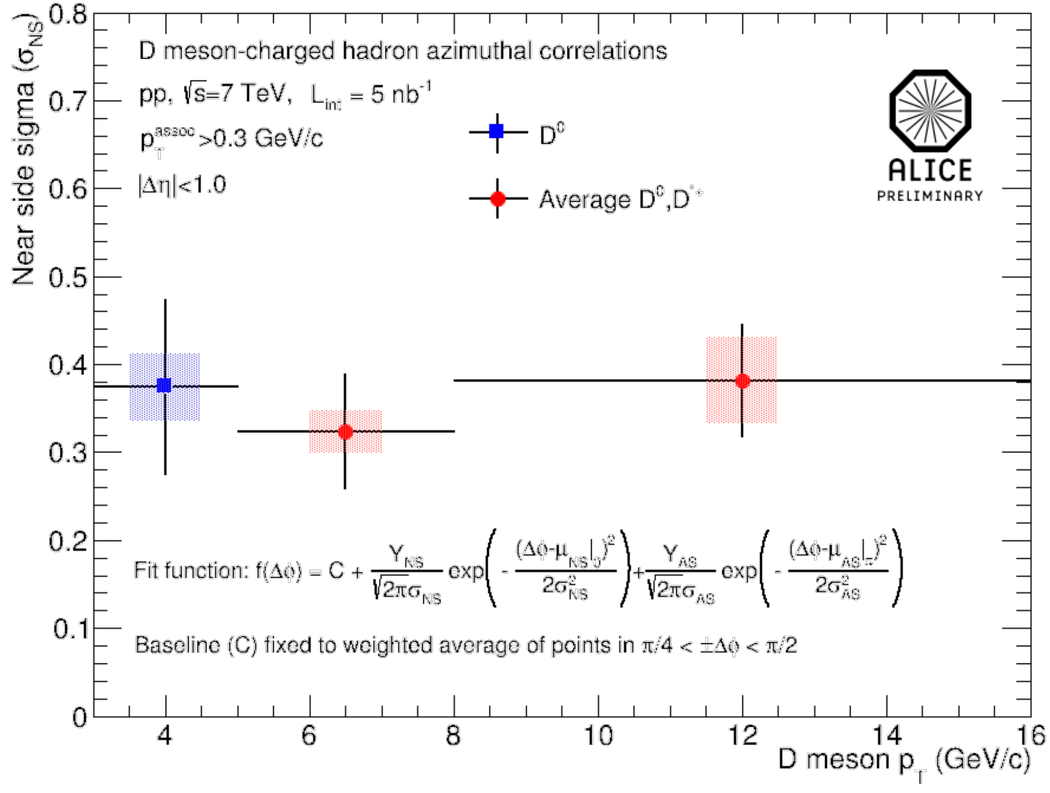


BACKUP - elliptic flow of HF electrons (SP vs EP)

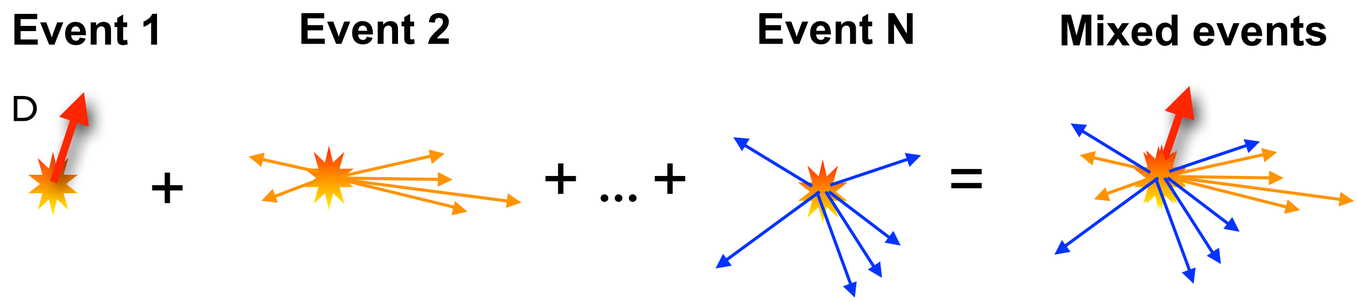


BACKUP - D meson correlations - widths and pedestal

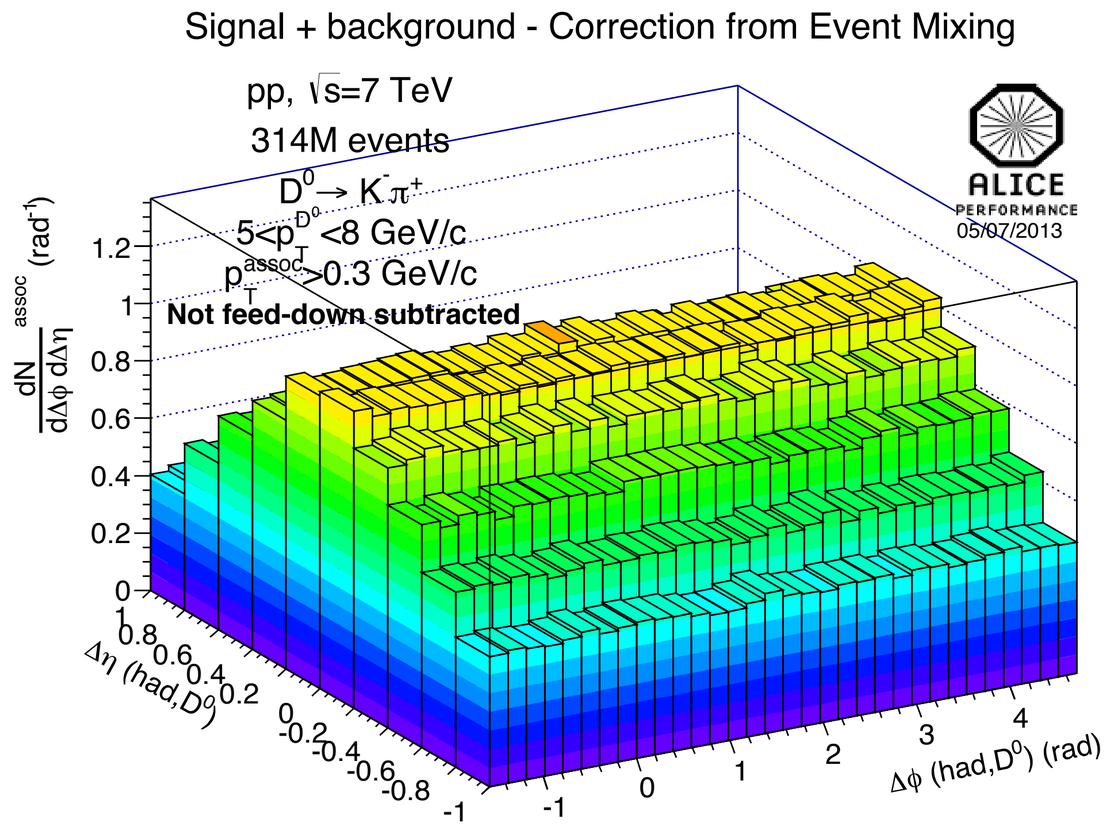
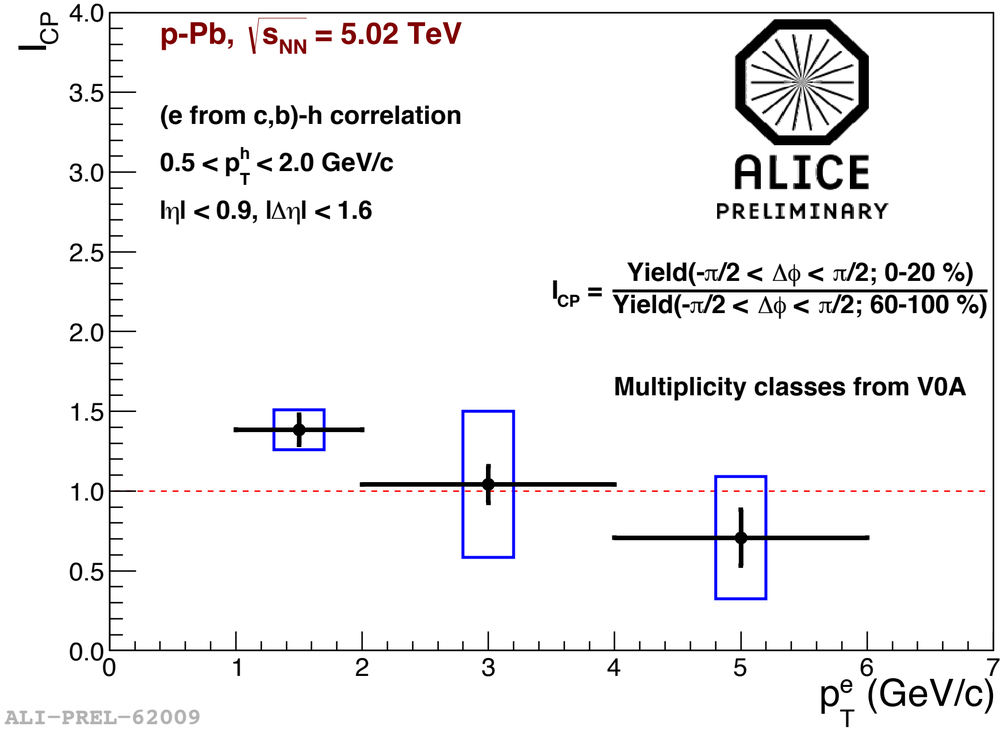
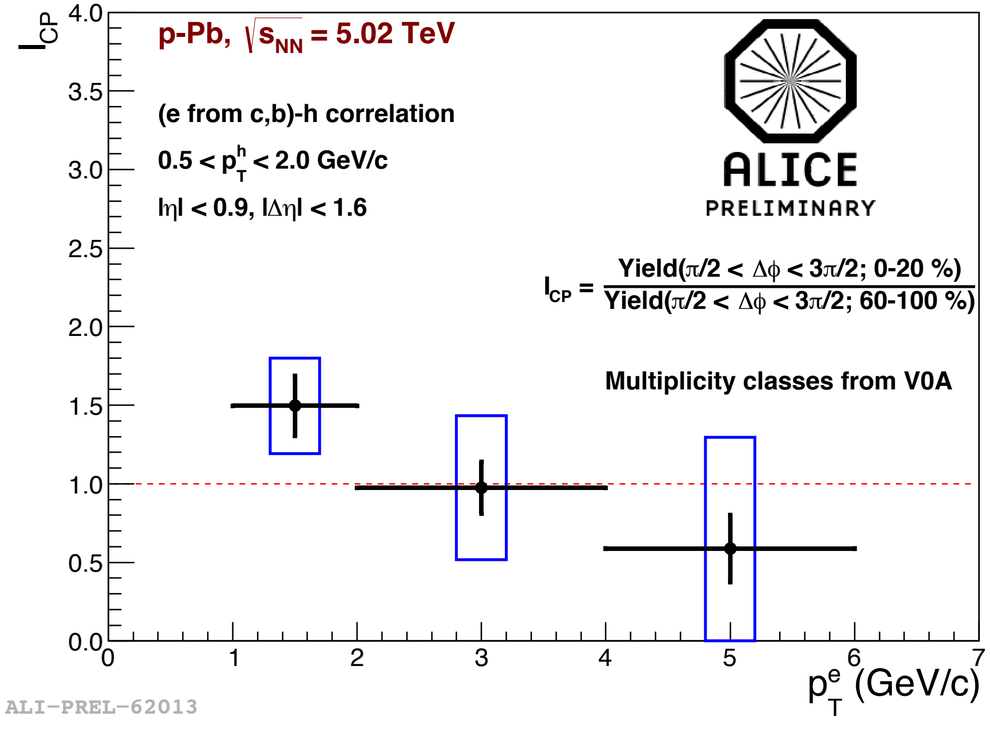




BACKUP - D meson correlations - EM corrections



$$\frac{d^2N^{Corrected}(\Delta\phi,\Delta\eta)}{d\Delta\phi d\Delta\eta} = \frac{\frac{d^2N^{SE}(\Delta\phi,\Delta\eta)}{d\Delta\phi d\Delta\eta}}{\frac{d^2N^{ME}(\Delta\phi,\Delta\eta)}{d\Delta\phi d\Delta\eta}} \frac{d^2N^{ME}(0,0)}{d\Delta\phi d\Delta\eta}$$



BACKUP - Icp of HF electrons in pPb