Heavy-flavour elliptic flow in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV with ALICE

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on behalf of the ALICE collaboration

XXIV QUARK MATTER
DARMSTADT 2014

GOETHE
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FRANKFURT AM MAIN

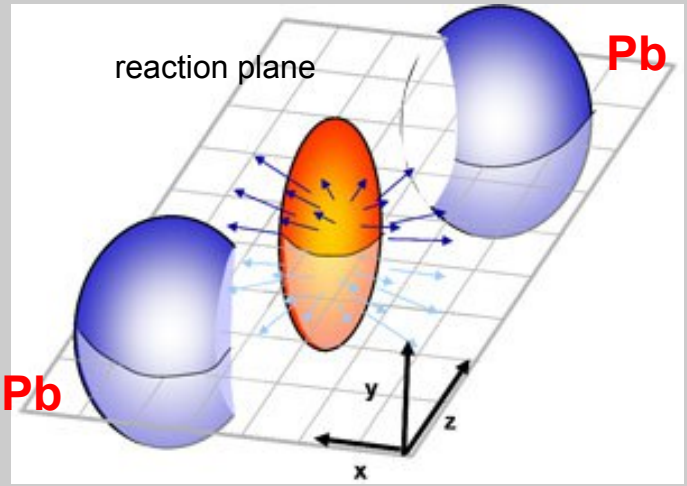
Outline

- **Motivation**
- **ALICE**
- **Elliptic flow**
  - **Mid-rapidity: D mesons, heavy-flavour decay e**
  - **Forward rapidity: heavy-flavour decay μ**
- **Summary and Outlook**

Motivation

Heavy quarks, i.e. charm and beauty, produced in initial hard scattering experience the full evolution of the system
→ Heavy-flavour hadrons sensitive to medium properties

Initial spatial anisotropy →



Momentum anisotropy of heavy-flavour (HF) hadrons if enough scattering of heavy quarks in the medium

Study azimuthal distribution of heavy-flavour hadrons w.r.t. the reaction plane

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + \dots\right)$$

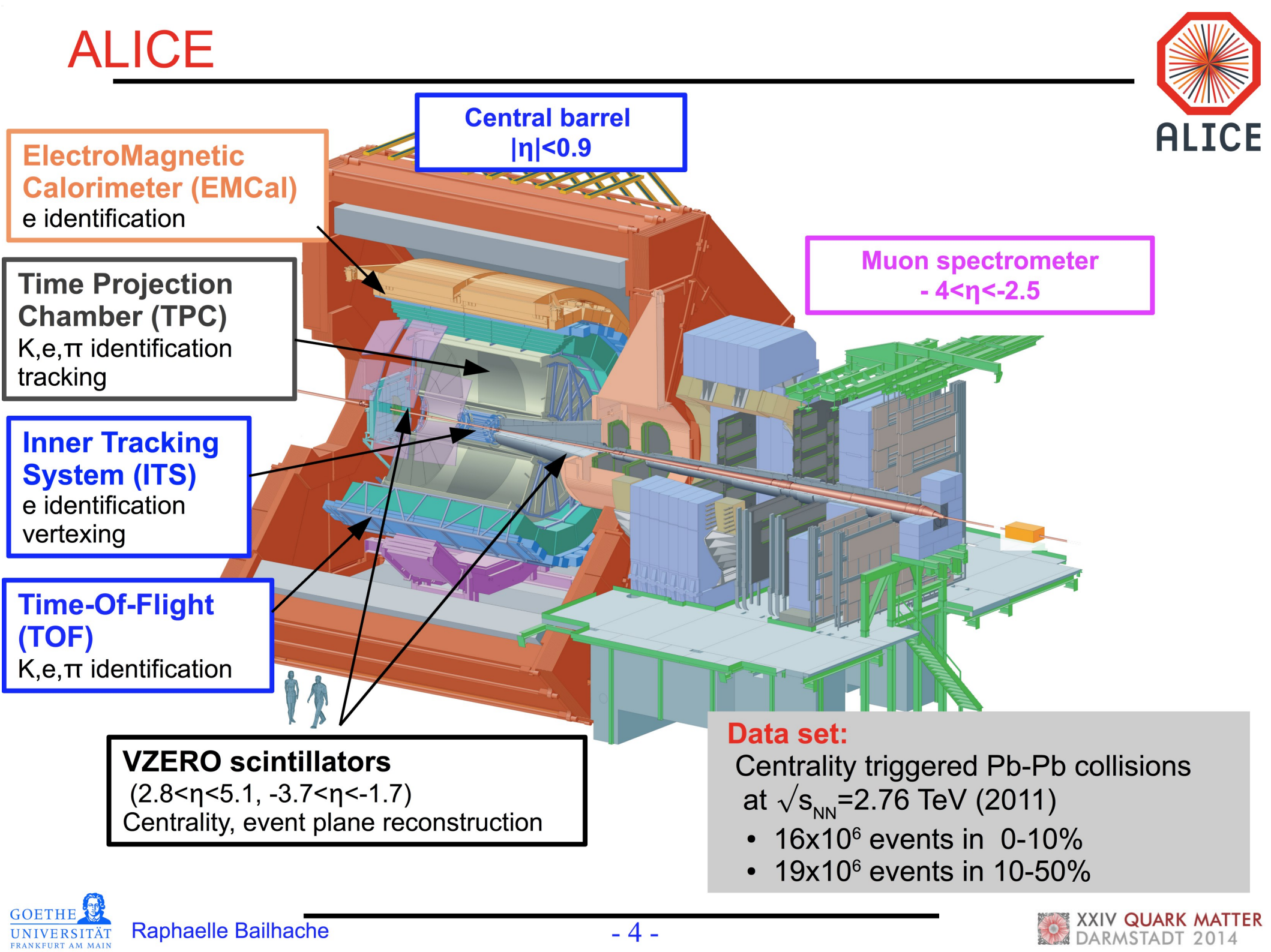
Heavy-flavour v_2 measurements probe:

- **Low/intermediate p_T: Collective motion, thermalization of heavy quarks**
  Hadronization mechanism (recombination)
  Important for the understanding of recent J/Ψ results

- **High p_T: Path-length dependence of heavy-quark energy loss**
  - Linear for collisional energy loss (elastic)
  - Close to quadratic for radiative processes (inelastic)

Talk Julian Book
Tue 20.04 09:20

ALICE



Data set:

Centrality triggered Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV (2011)

- 16x10^6 events in 0-10%
- 19x10^6 events in 10-50%

D mesons

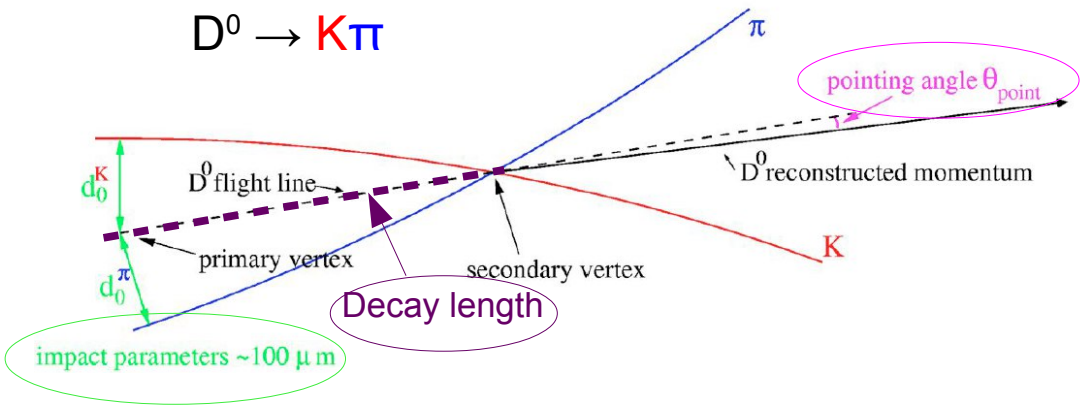
Reconstruction of D mesons

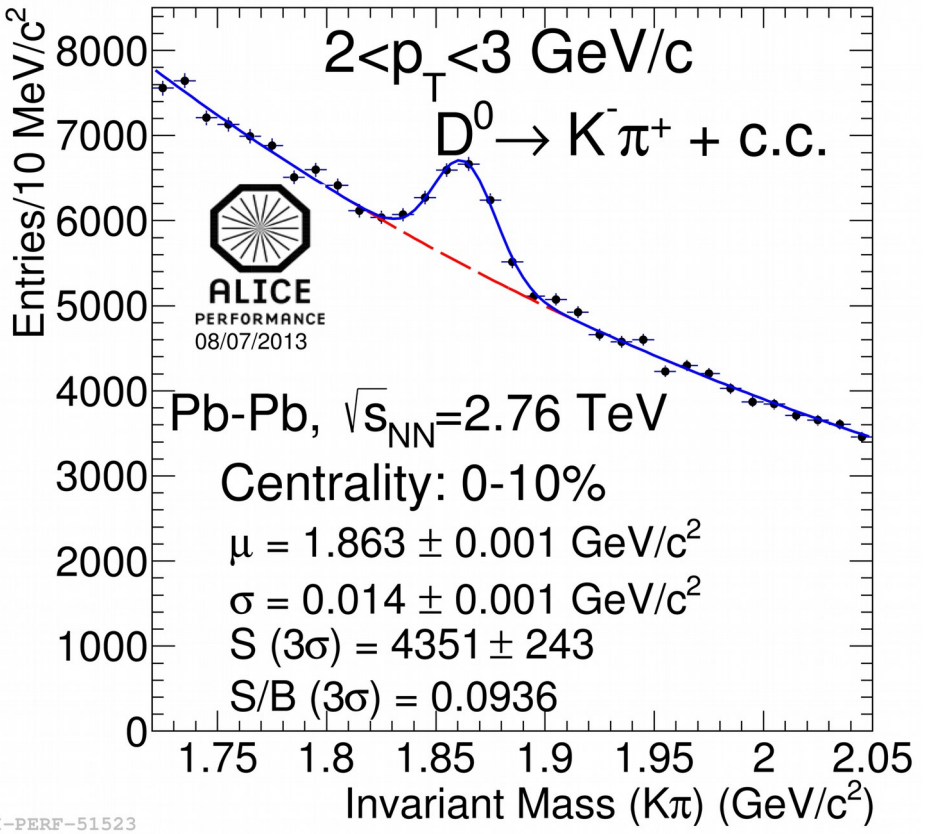
- D mesons reconstructed via hadronic decay channels

$D^0 \rightarrow K^-\pi^+$	$c\tau = 123\,\mu m$	BR=3.88%
$D^+ \rightarrow K^-\pi^+\pi^+$	$c\tau = 312\,\mu m$	BR=9.13%
$D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^-$		BR=2.63%

Central barrel
$|\eta| < 0.8$

- Reconstructed secondary vertices





- TPC and TOF used to identify π and K to reduce combinatorial background

- An invariant mass analysis performed to extract the signal yield

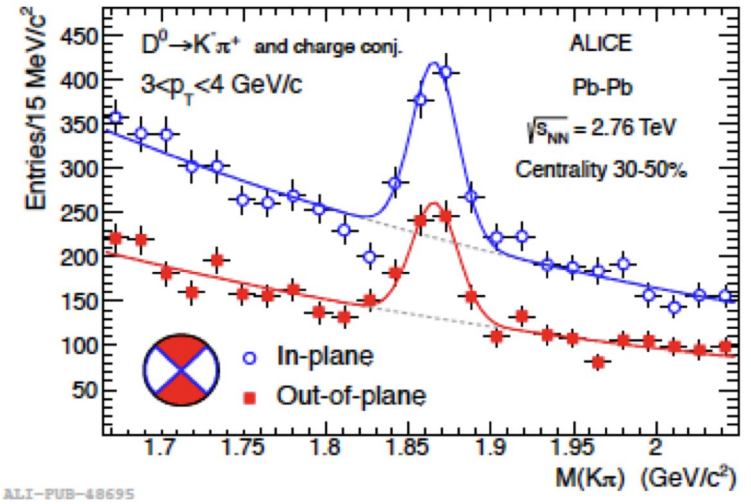
D-meson flow: methods

ALICE collaboration, PRL 111, 102301 (2013)
ALICE collaboration, arXiv:1405.2001 [nucl-ex]

- **Event plane method (TPC 0<η<0.8 or VZERO event plane)**
  - Extraction of the D-meson yield in- and out-of-plane

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

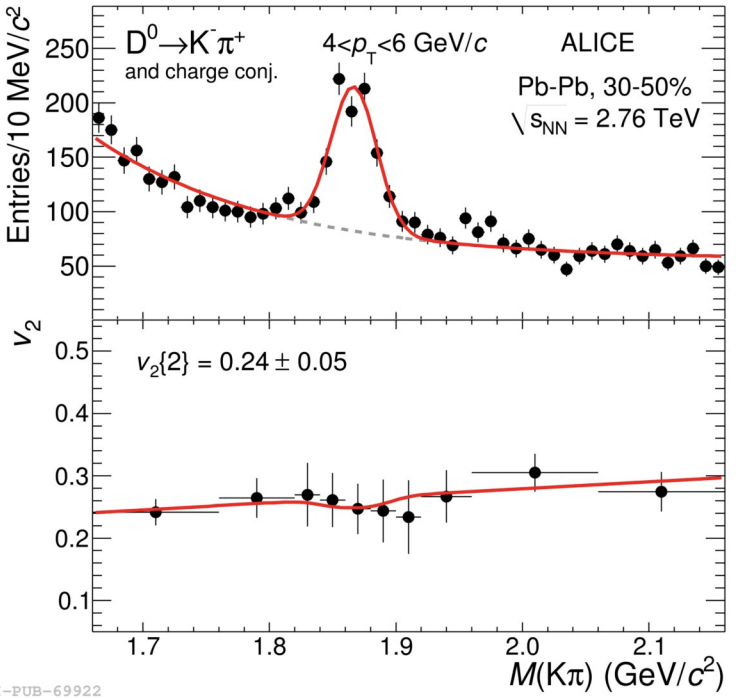
Event plane resolution correction factor R_2



- **Two-particle correlation methods (Q cumulant, scalar product)**
  - Simultaneous fit of the distributions of the measured candidate yield and v_2 as function of the invariant mass M

$$v_2(M) = [S(M).v_2^S + B(M).v_2^B(M)] / [S(M) + B(M)]$$

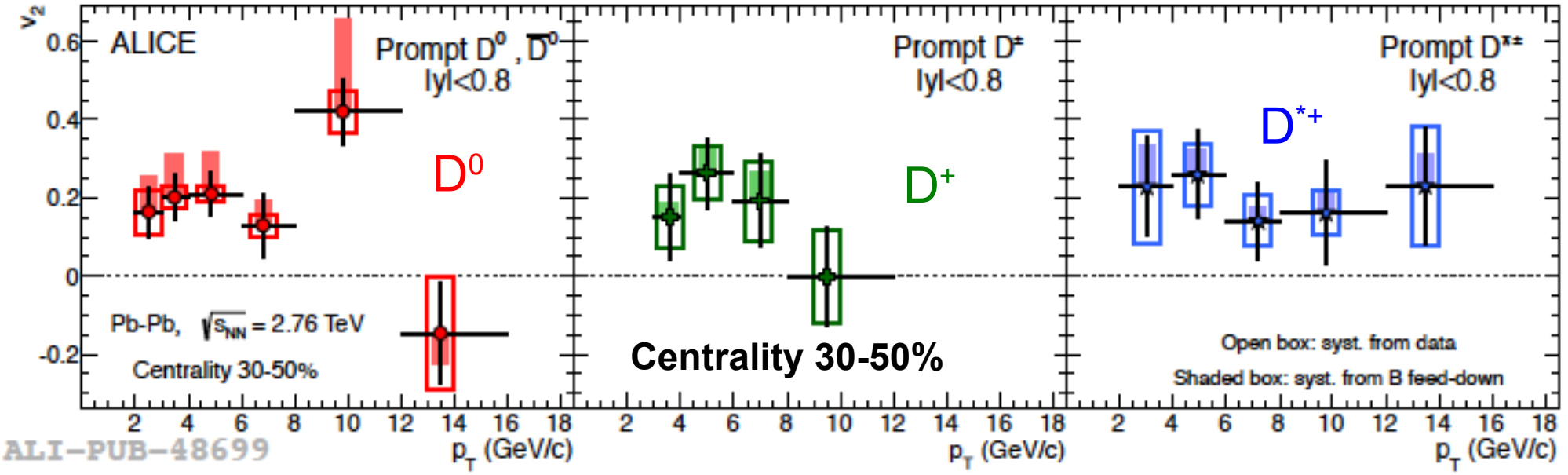
S, B: signal and background yields
v_2^B: background elliptic flow parametrized by a linear function of M
v_2^S: elliptic flow of D mesons



D-meson flow: results

ALICE collaboration, PRL 111, 102301 (2013)
ALICE collaboration, arXiv:1405.2001 [nucl-ex]

Syst. from B feed-down contribution estimated based on FONLL pQCD calculations
and hypothesis on secondary D-meson R_{AA} and v_2



Consistent between the three D-meson species

Positive D-meson v_2 (v_2^D) observed

5.7σ effect for D^0, D^+, D^{*+} averaged for $2 < p_T < 6$ GeV/c in 30-50% centrality

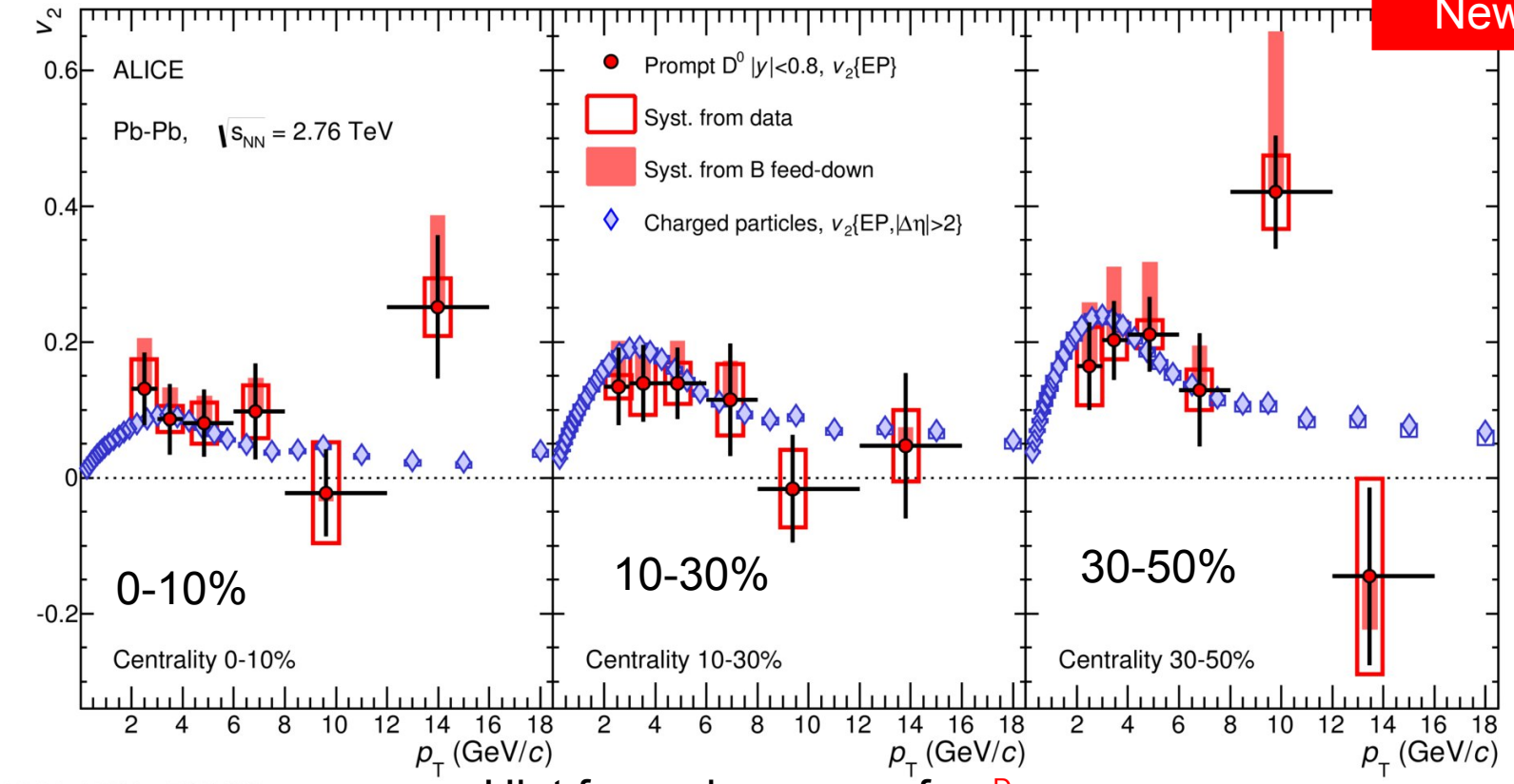
Poster Davide Caffarri
Tue 20.04 16:30-18:30

D-meson flow

Poster Davide Caffarri
Tue 20.04 16:30-18:30

ALICE collaboration, PRL 111, 102301 (2013)
ALICE collaboration, arXiv:1405.2001 [nucl-ex]

New



Hint for an increase of v_2^D

central → semi-central

D-meson v_2 similar to charged particle v_2

- Confirm significant **interaction of charm quarks with the medium**
- Suggest **collective motion of low-p_T charm quarks** in the expanding fireball

D-meson flow and R_{AA}

Poster Davide Caffarri
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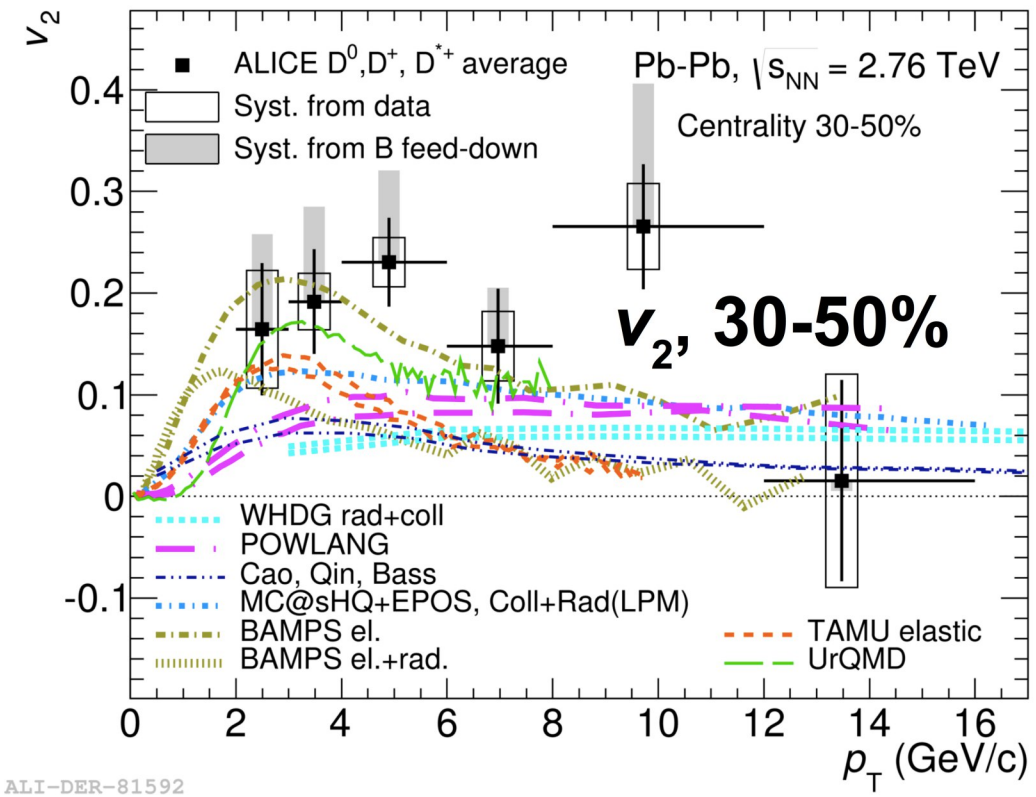
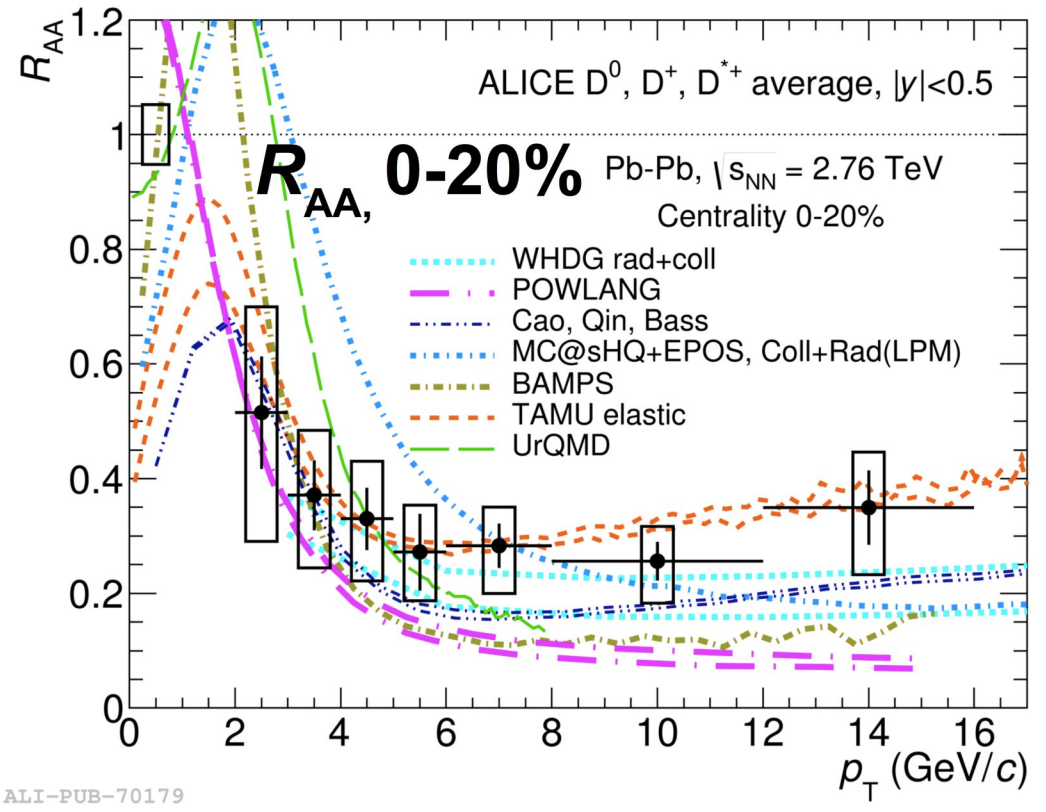
ALICE collaboration, PRL 111, 102301 (2013)
ALICE collaboration, arXiv:1405.2001 [nucl-ex]





v_2^D and R_{AA}^D measurements together start to **provide contraints for the models**

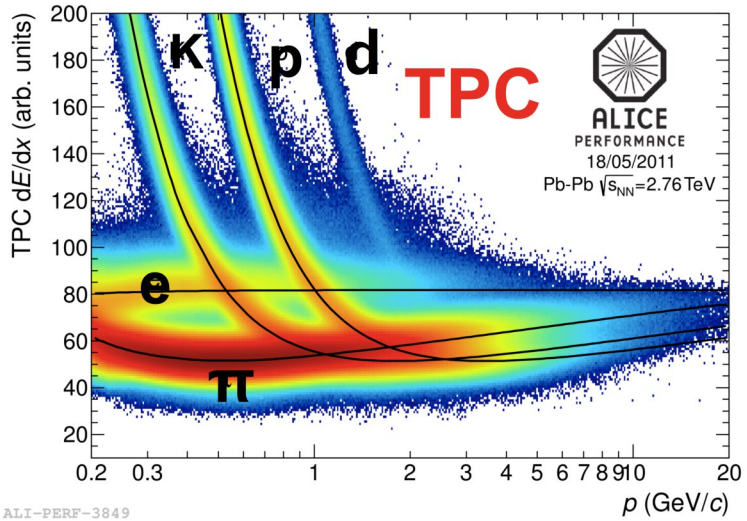
WHDG: Nucl. Phys. A 872 (2011) 265; MC@sHQ+EPOS, Coll+Rad(LPM): Phys. Rec. C89 (2004) 014905; TAMU elastic: arXiv:1401.3817 [nucl-th]; POWLANG: Eur. Phys. J. C71 (201) 1666, J.Phys. G 38 (2011) 124144; BAMPS: Phys. Rev. C 84 (2011) 024908; J. Phys. G38 (2011) 124152 Phys. Lett. B 717 (2012) 430;arXiv:1310.3597v1[hep-ph] ; UrQMD: arXiv:1211.6912[hep-ph]; J. Phys.Conf. Ser. 426 (2013) 012032; Cao, Qin, Bass: Phys. Rev. C 88 (2013) 044907

Electrons
from heavy-flavour hadron decays

Identification of electrons

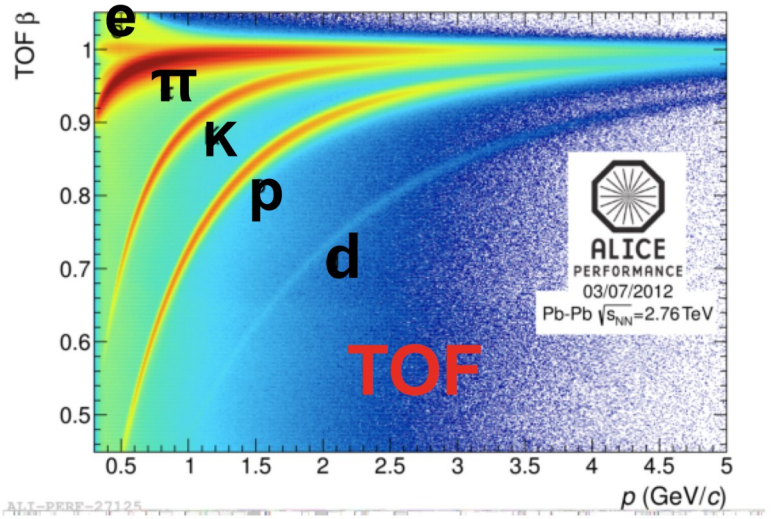
- Low-p_T electrons (p_T<3 GeV/c): identified with ITS, TPC and TOF

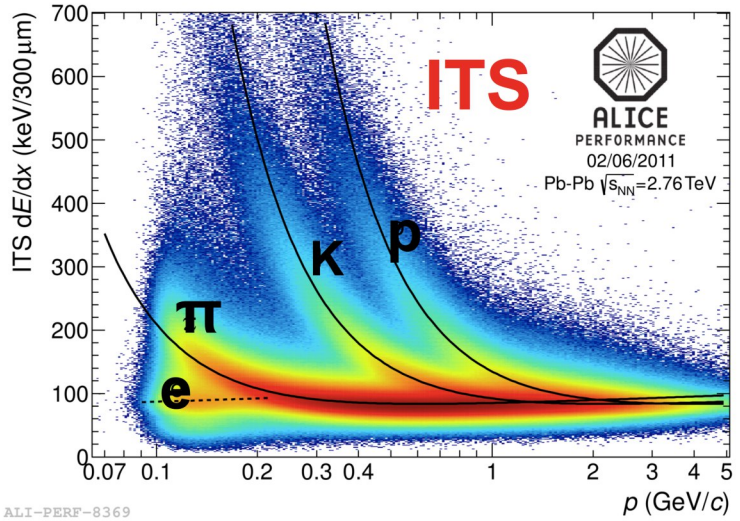
Central barrel
|y| < 0.7



Energy loss in TPC:
- Excellent separation of e from π
- Crossing of e with K and p

→ Solved by using ITS and TOF





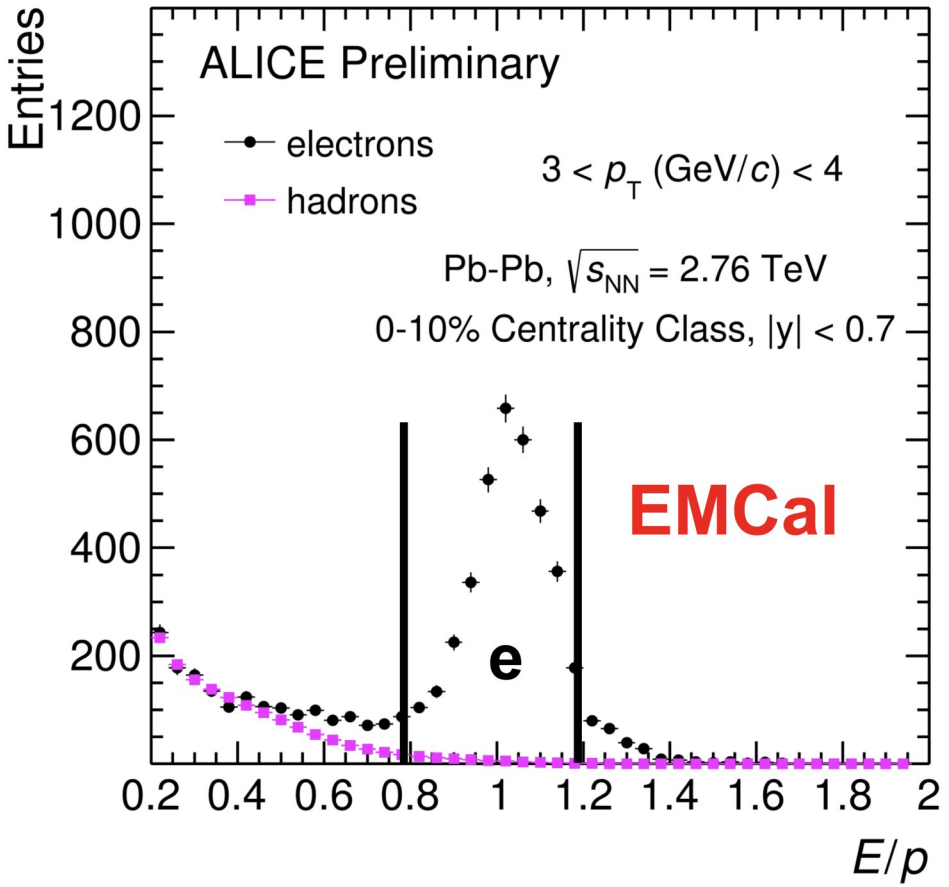
- High-p_T electrons (p_T>3 GeV/c): identified with TPC and EMCal

Identification of electrons

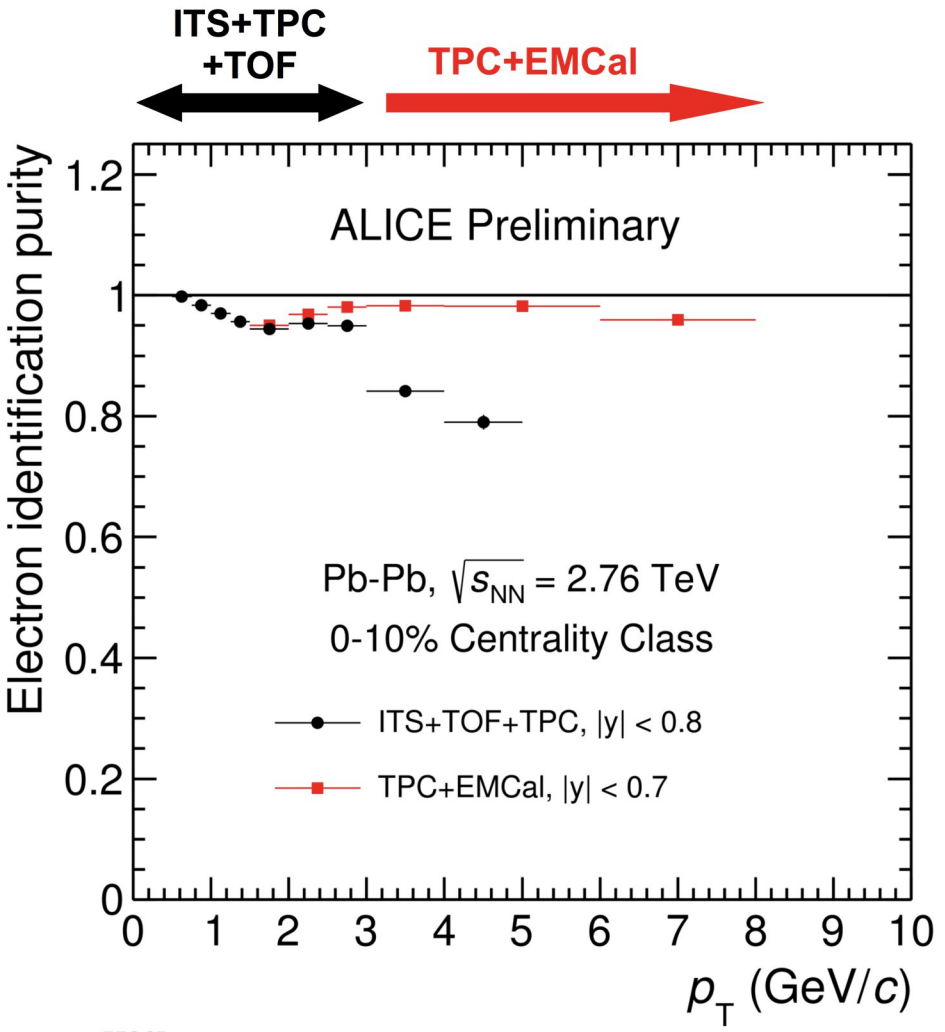
- p_T>3 GeV/c: e identified with TPC and EMCal

Central barrel
|y| < 0.7

Electrons selected in the TPC with:
$-1\sigma < (dE/dx-(dE/dx)_e)_{TPC} < 3\sigma$
Hadrons selected in the TPC with:
$dE/dx-(dE/dx)_e < -4\sigma$



Electron purity



ALI-PREL-77265

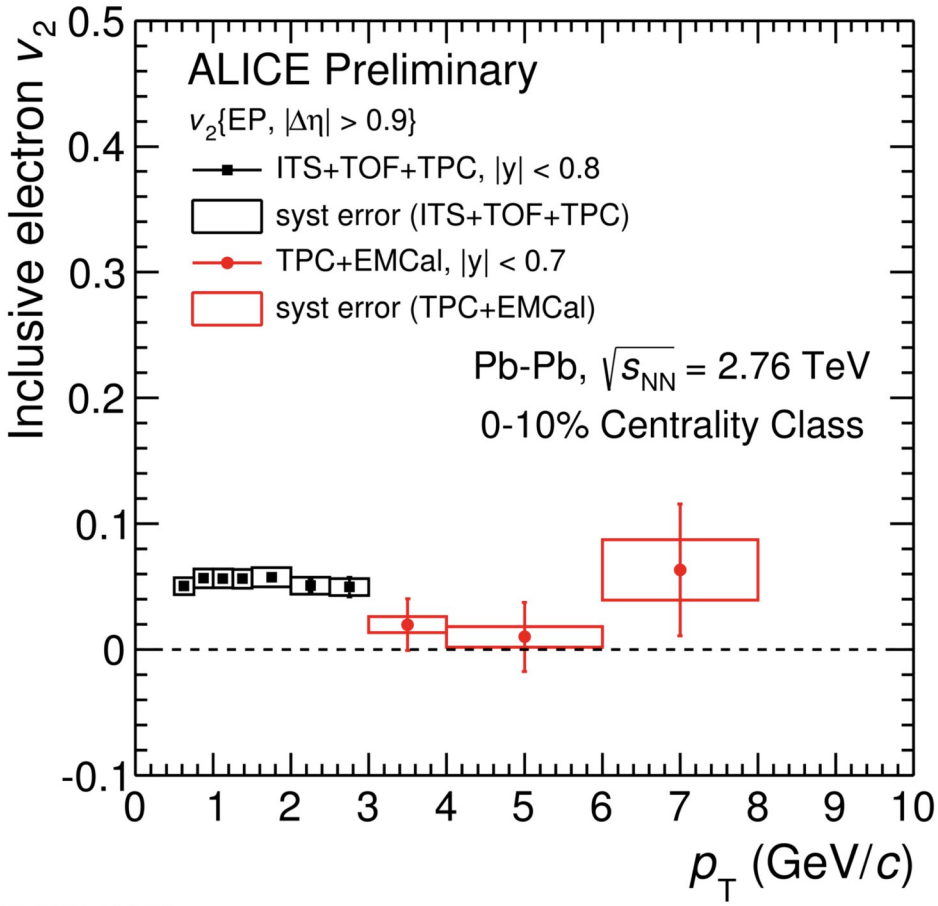
Heavy-flavour decay electrons: method

$$v_2^{e \leftarrow HF} = \frac{(1 + R_{SB})\, v_2^{incl\ e} - v_2^{back\ e}}{R_{SB}}$$

Poster Andrea Dubla
Tue 20.04 16:30-18:30

Inclusive electron $v_2^{incl\ e}$

- $v_2^{incl\ e}$ of inclusive electrons : **measured** with the event plane method using VZERO



Event plane method with VZERO

Heavy-flavour decay electrons: method

$$v_2^{e \leftarrow HF} = \frac{(1 + R_{SB})\, v_2^{\text{incl e}} - v_2^{\text{back e}}}{R_{SB}}$$

Poster Andrea Dubla
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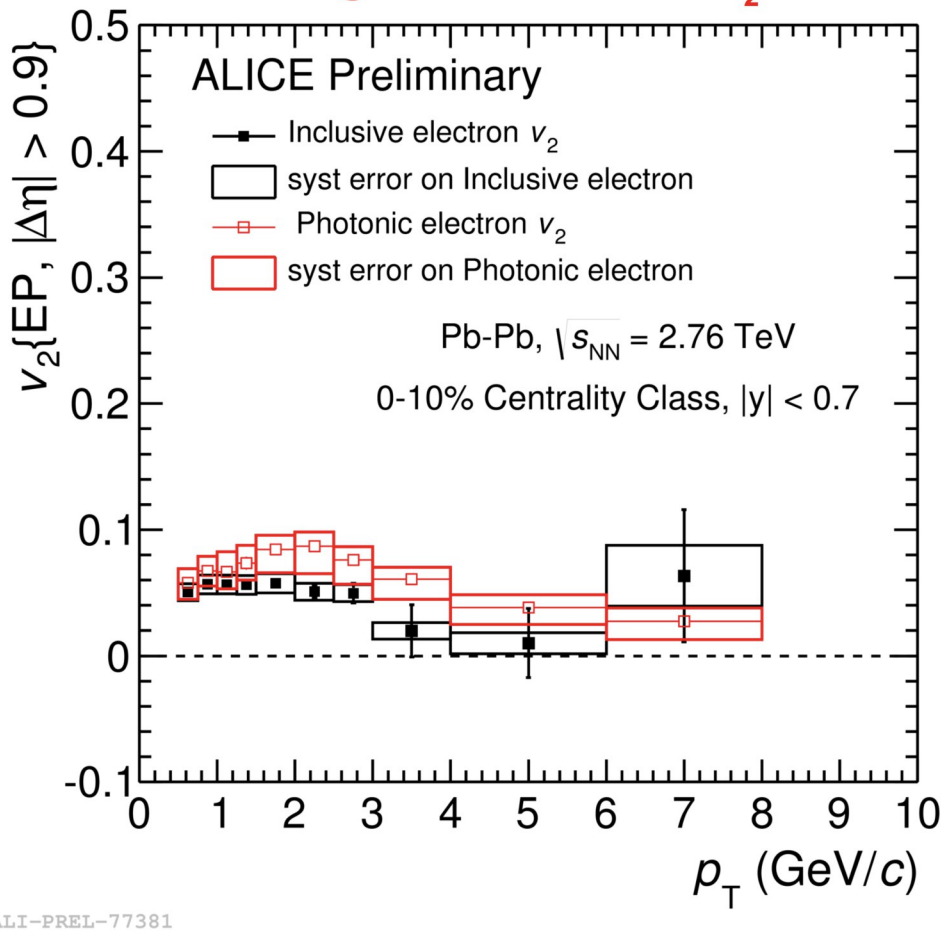
- $v_2^{\text{incl e}}$ of inclusive electrons
- $v_2^{\text{back e}}$ of background electrons
  - Electrons from γ conversion
  - Electrons from π^0 Dalitz decay
- **p_T<1.5 GeV/*c*: measured** New
  Invariant mass method (e^+e^- pairs)
- **p_T>1.5 GeV/*c*: estimated**
  Cocktail method based on data
  (π^0,$\pi^\pm$, direct γ)

Inclusive electron $v_2^{\text{incl e}}$
Background electron $v_2^{\text{Back e}}$



Event plane method with VZERO

Heavy-flavour decay electrons: method

$$v_2^{e\leftarrow HF} = \frac{(1 + R_{SB})\, v_2^{incl\ e} - v_2^{back\ e}}{R_{SB}}$$

Poster Andrea Dubla
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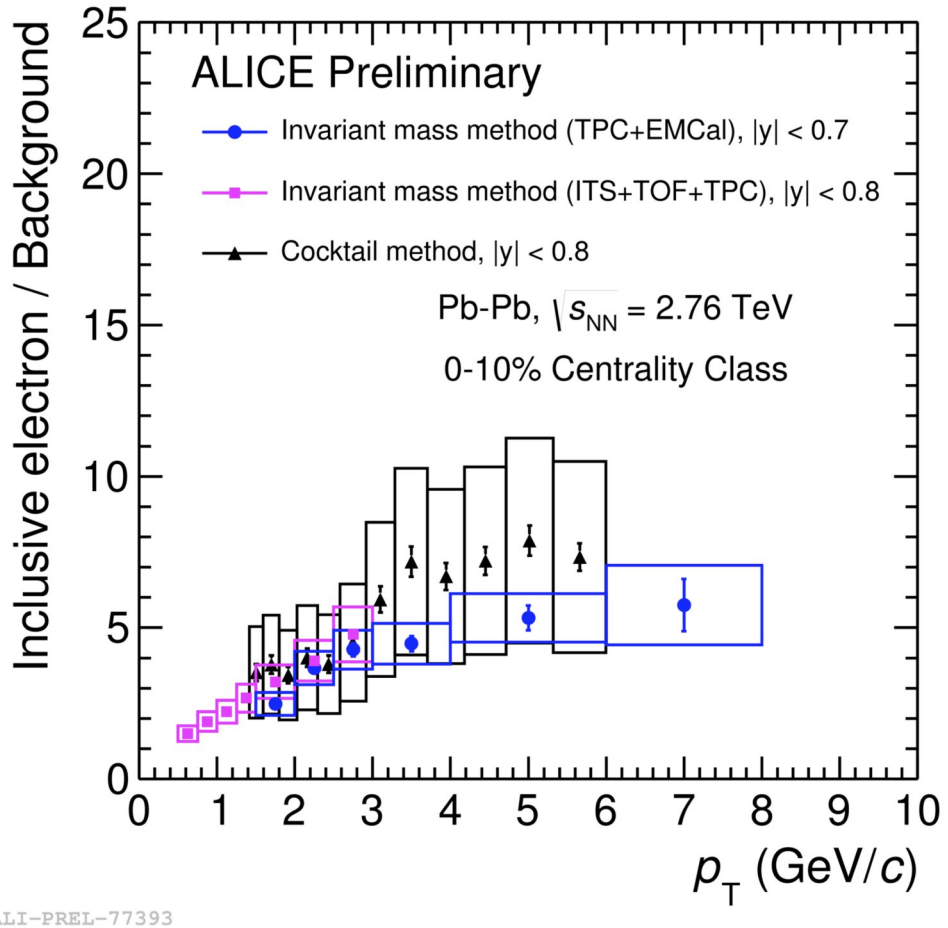
- $v_2^{incl\ e}$ of inclusive electrons
- $v_2^{back\ e}$ of background electrons
  - Electrons from γ conversion
  - Electrons from π^0 Dalitz decay
- Signal to background ratio R_{SB}:

New

  - New results (ITS-TPC-TOF/TPC-EMCal): **Measured** via the invariant mass method
  - Previous results (TPC-TOF analysis): **Estimated** via the cocktail method

$(1+R_{SB})$

R_{SB}, signal to background ratio



Event plane method with VZERO

Heavy-flavour decay electrons: results

New

New

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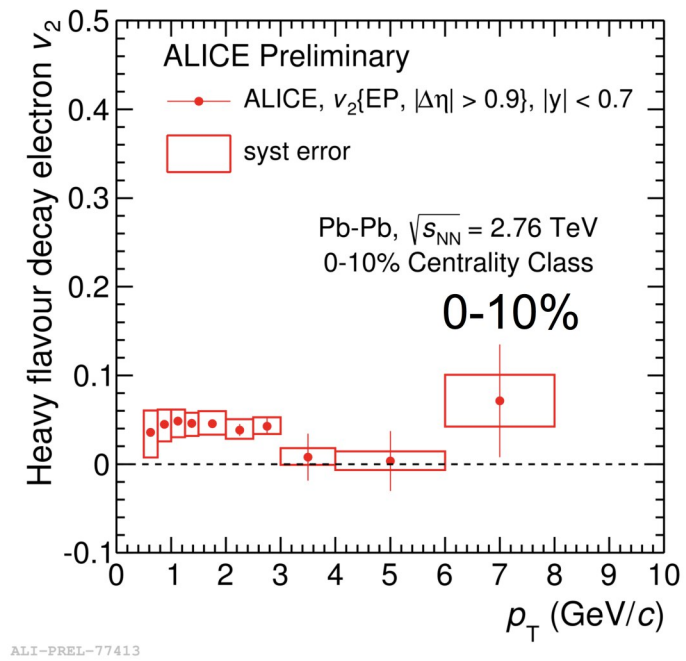
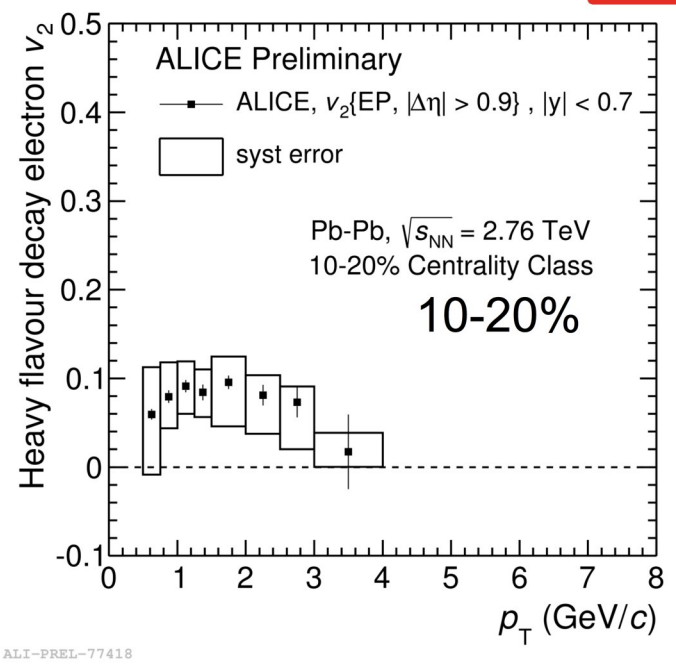
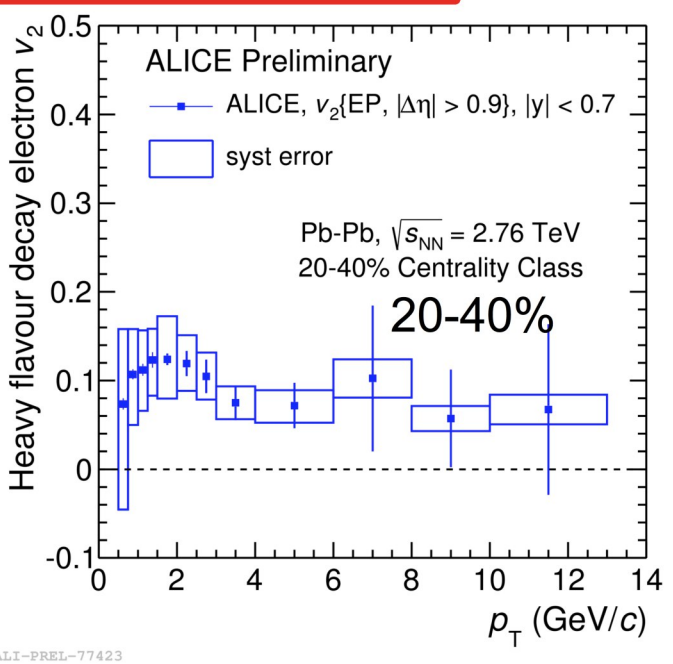






Hint for an increase of $v_2^{e \leftarrow HF}$

central → semi-central

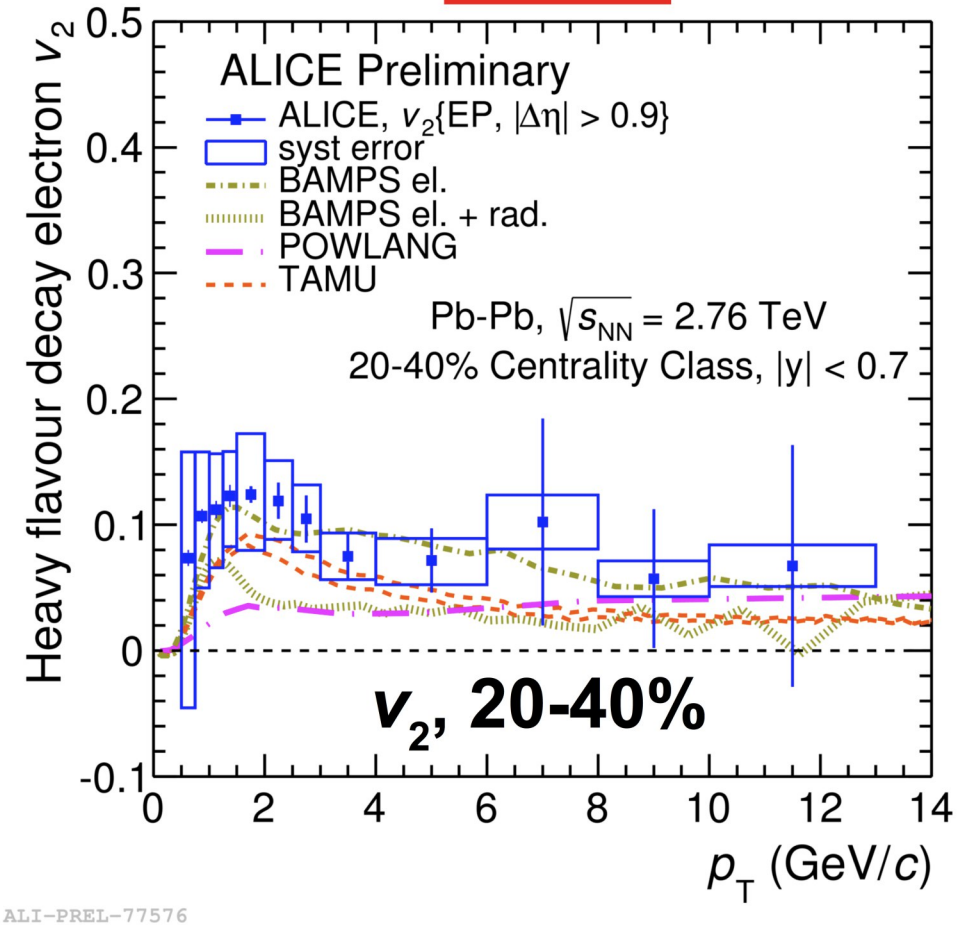
Positive $v_2^{e \leftarrow HF}$ observed

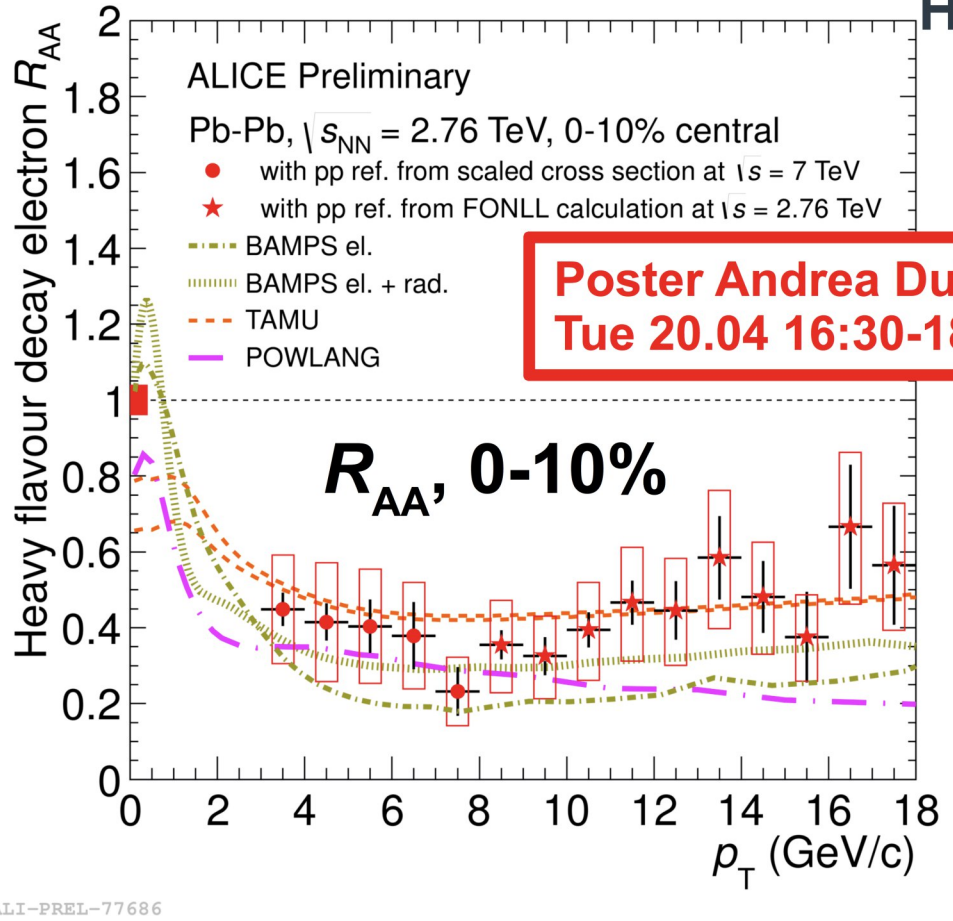
(3σ effect for $2<p_T<3$ GeV/c in 20-40% centrality)

- Confirm significant **interaction of heavy quarks with the medium**
- Suggest **collective motion of low-p_T heavy-quarks (mainly charm)** in the expanding fireball

Heavy-flavour decay electrons: v_2 and R_{AA}

New





Poster Andrea Dubla
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Similar picture from the comparison of R_{AA} and v_2 to models as for D mesons

Consistent results with D mesons

$v_2^{e\leftarrow HF}$ and $R_{AA}^{e\leftarrow HF}$ measurements start to **provide constraints for the models**

TAMU elastic:: arXiv:1401.3817[nucl-th] (2014); **POWLANG**: Eur. Phys. J. C71 (201) 1666, J.Phys. G 38 (2011) 124144; **BAMPS**:Phys. Lett. B 717 (2012) 430; arXiv:1310.3597v1 [hep-ph]

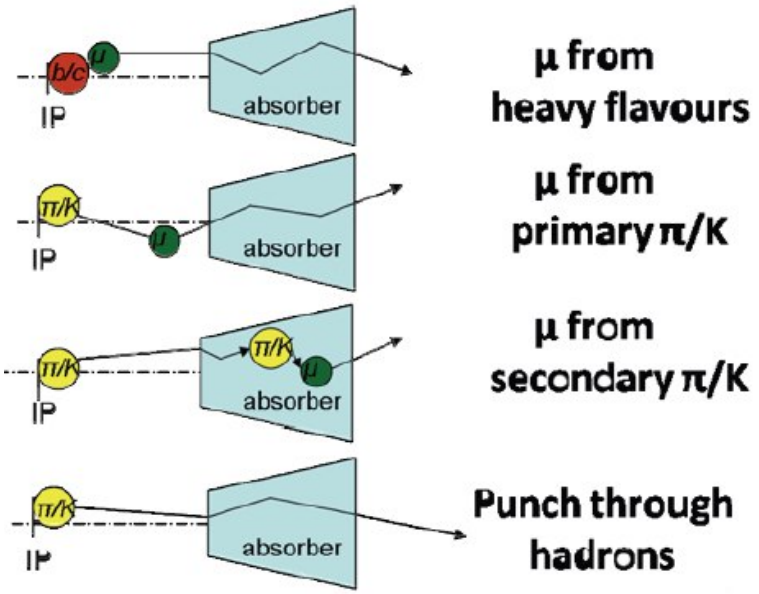
Muons
from heavy-flavour hadron decays

Identification of muons

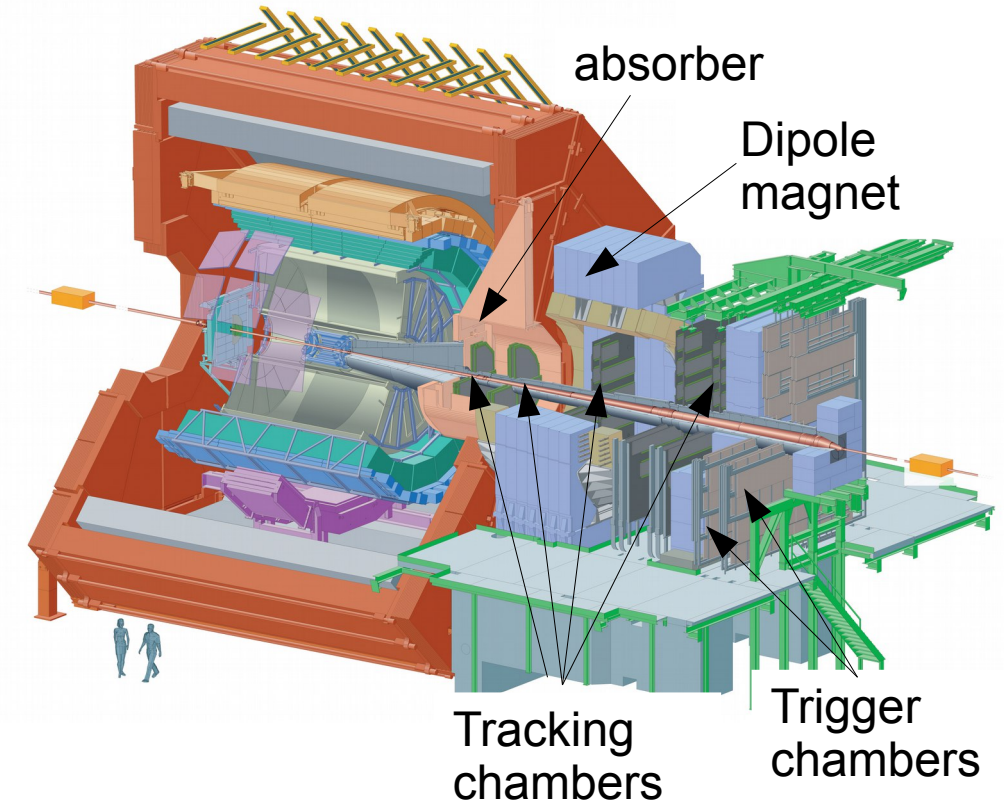
Track selection:

- Acceptance and geometrical cuts:
  select tracks in the acceptance of the spectrometer
- Muon trigger matching:
  reject hadrons that cross the absorber
- Pointing angle to the vertex:
  remove beam-gas and particles produced in the absorber

→ Remaining main background:
μ from primary π/K decays



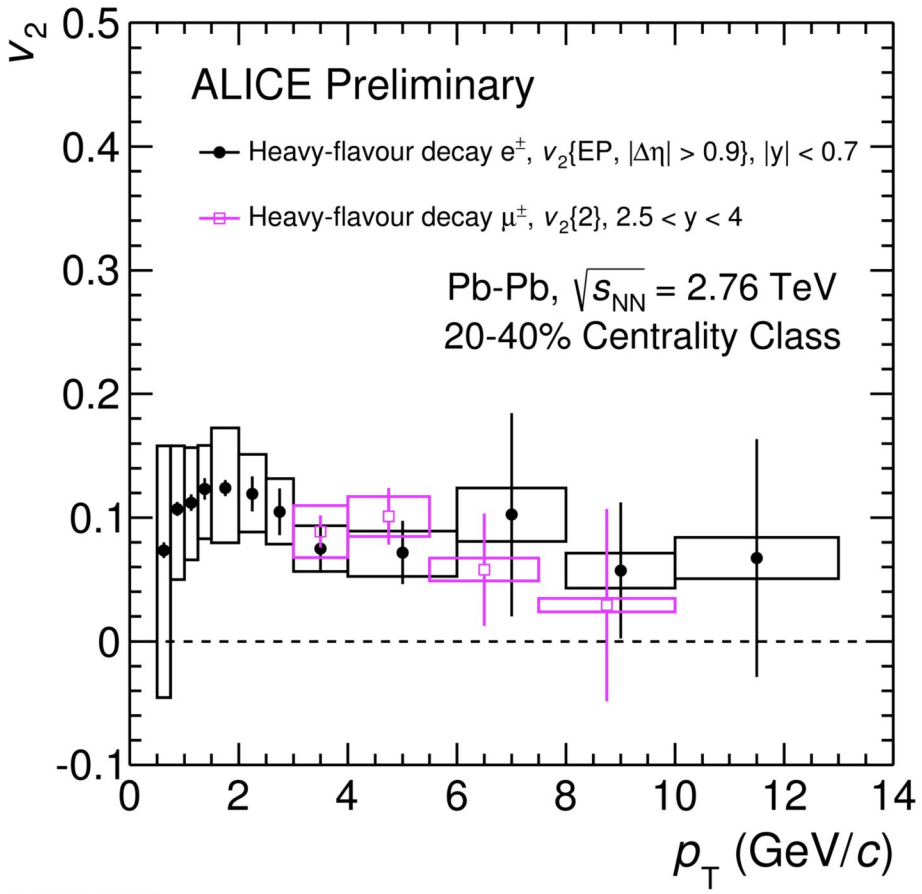
Muon spectrometer
- 4 < η < -2.5



Heavy-flavour decay muons

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

- Measure $v_2^{\text{incl }\mu}$ of inclusive muons
- Estimate $f_{\text{decay }\mu}$ and $v_2^{\text{decay }\mu}$:
  - $f_{\text{decay }\mu}$ ~ 15%(5%) at p_T = 3 (10) GeV/c based on extrapolation of π/K spectra measured at mid-rapidity
  - $v_2^{\text{decay }\mu}$ cocktail method based on data



Q{2} cumulant method for $v_2^{\mu \leftarrow HF}$
Event plane method with VZERO for $v_2^{e \leftarrow HF}$

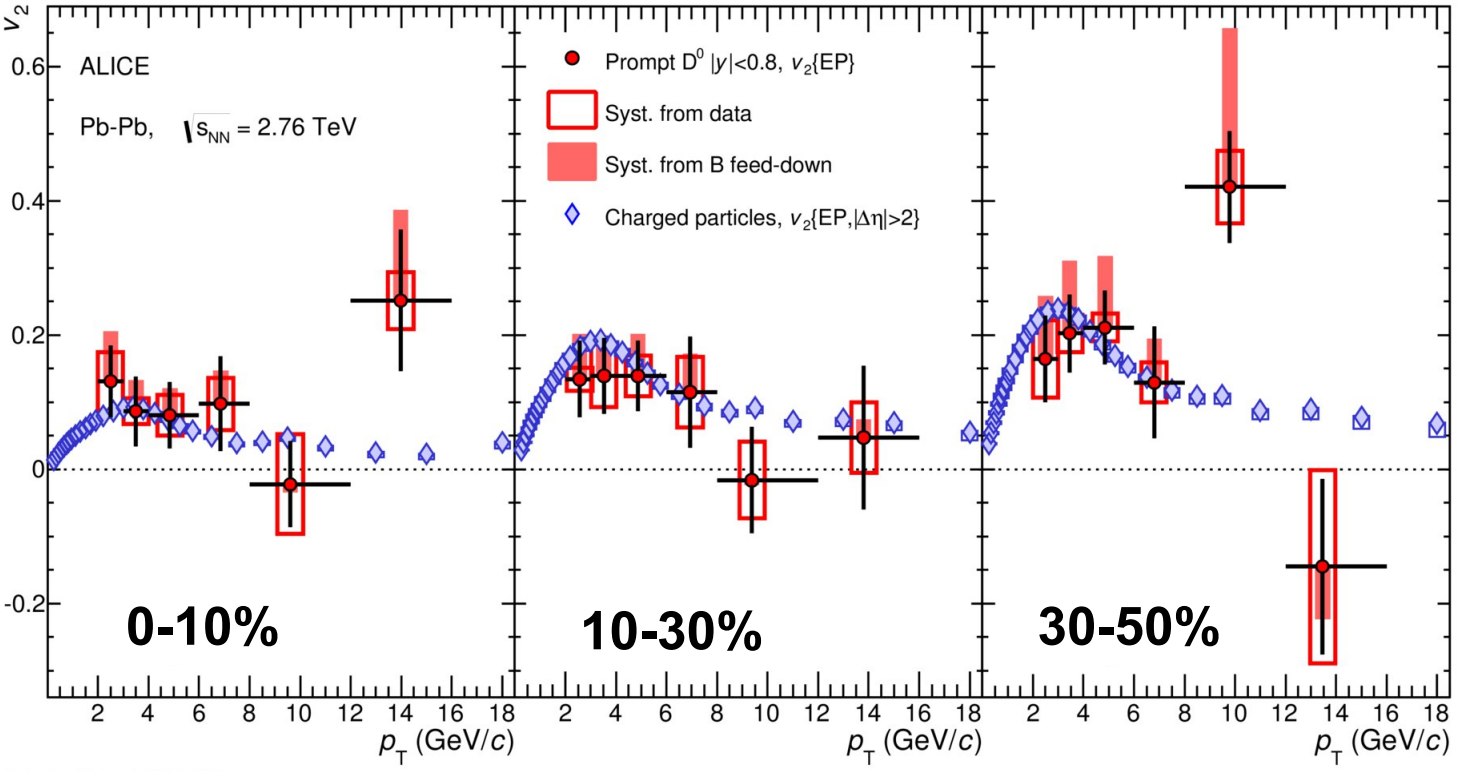
- **Positive $v_2^{\mu \leftarrow HF}$ observed**
  (3σ effect for $3<p_T<5$ GeV/c)
- $(v_2^{\mu \leftarrow HF})_{\text{foward rapidity}} \sim (v_2^{e \leftarrow HF})_{\text{mid-rapidity}}$

Consistent results

ALI-PREL-77628

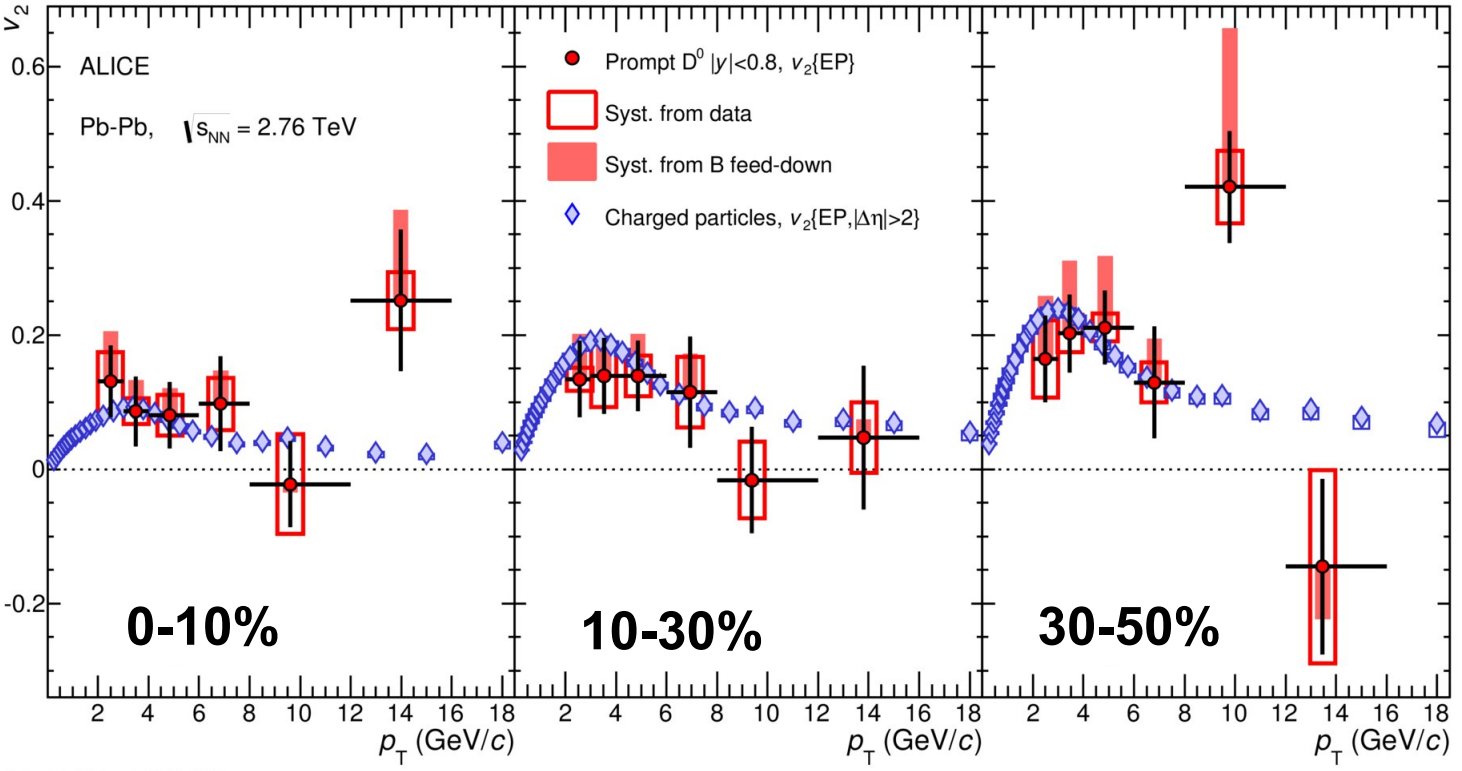
Summary

Non-zero v_2^{D}, $v_2^{e\leftarrow HF}$ and $v_2^{\mu\leftarrow HF}$ observed in semi-central Pb-Pb collisions



Summary

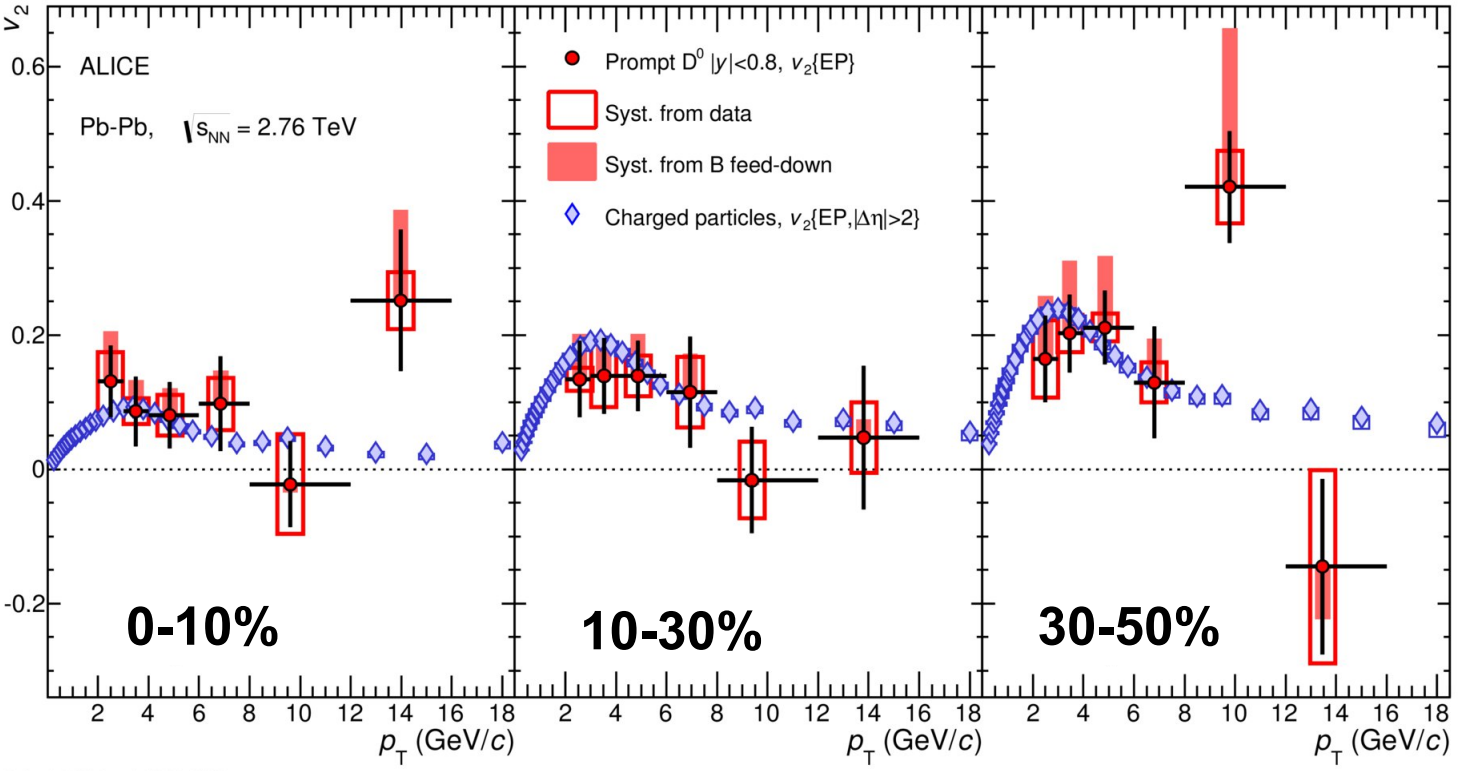
Hint for an **increase of** v_2^{D}, $v_2^{e\leftarrow HF}$, $v_2^{\mu\leftarrow HF}$
from central to semi-central collisions



central → semi-central

Summary

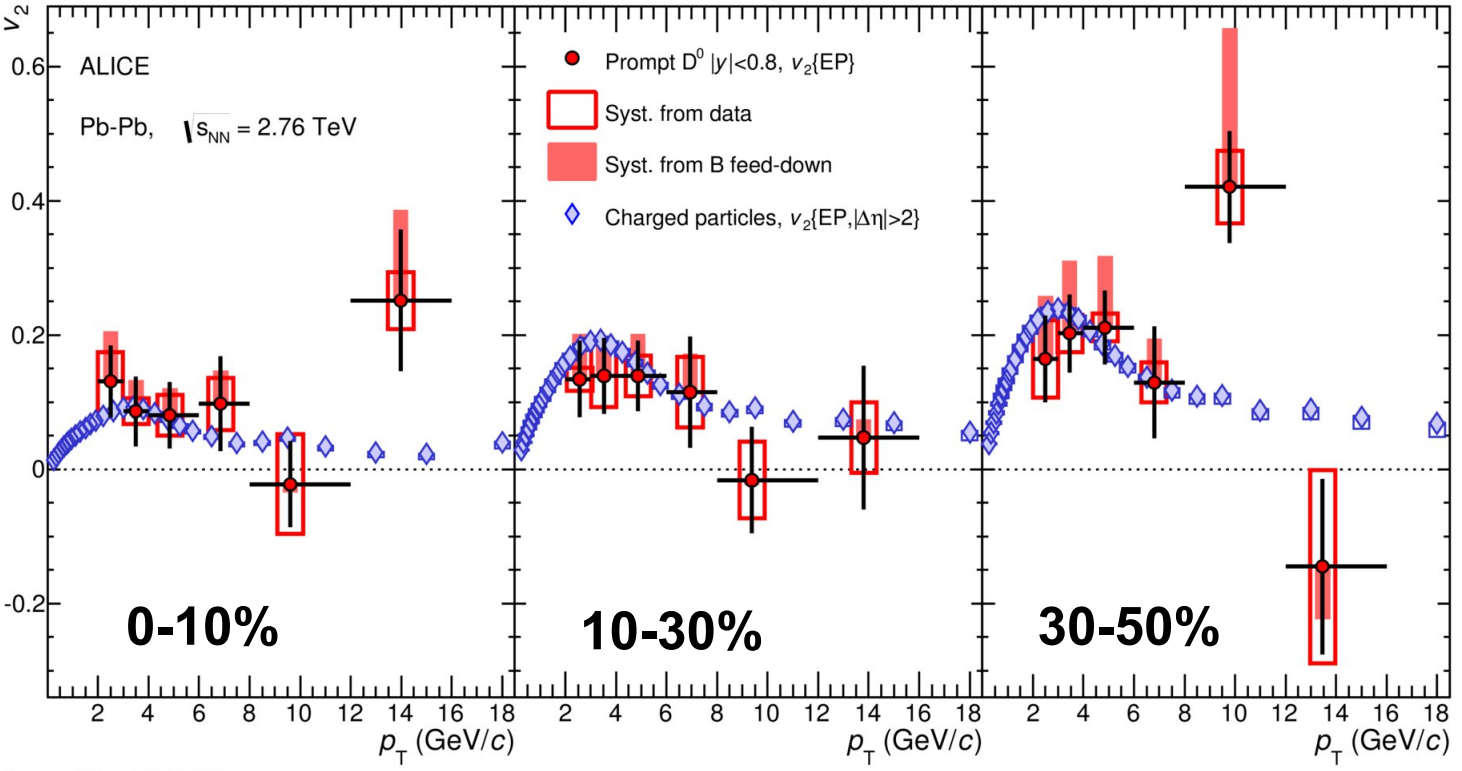
v_2^D ~ charged particle v_2



ALI-PUB-70100

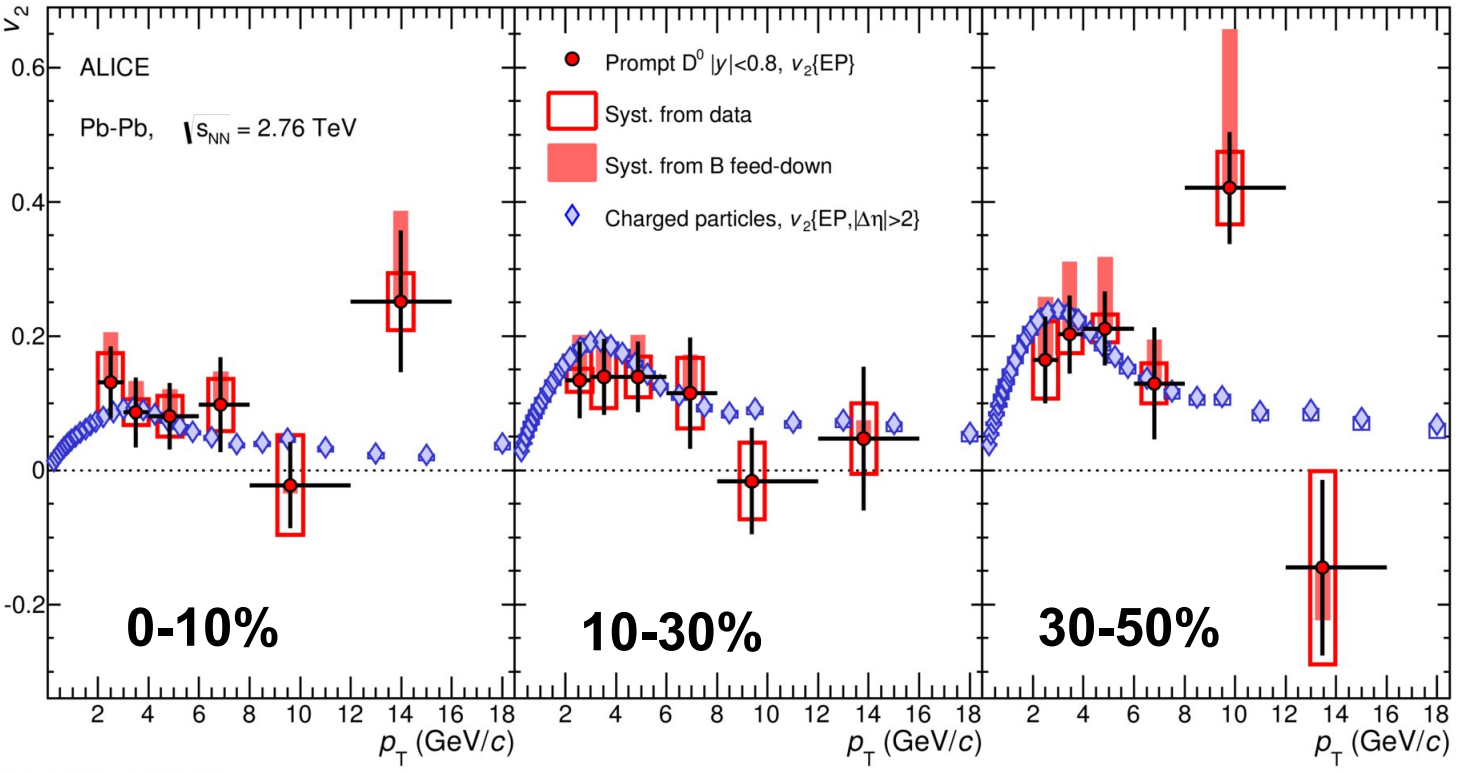
Summary

Suggest **collective motion of low-p_T heavy-quarks**
(mainly charm)



Outlook

Analyses will profit strongly from **more statistics** and the **ALICE upgrades**



(See poster: v_2 of electrons from beauty-hadron decays)

Poster Denise Godoy
Tue 20.04 16:30-18:30

Prompt D mesons

ALICE collaboration, PRL 111, 102301 (2013)
ALICE collaboration, arXiv:1405.2001 [nucl-ex]

$$v_2^{\text{prompt}} = \frac{1}{f_{\text{prompt}}} v_2^{\text{all}} - \frac{1 - f_{\text{prompt}}}{f_{\text{prompt}}} v_2^{\text{feed-down}}$$

- **R_{AA} assumptions:**

  Comparison R_{AA} of prompt D mesons measured by the ALICE collaboration and $J/\Psi \leftarrow B$ measured by CMS collaboration suggests D more suppressed than B

  - $1 < R_{AA}^{\text{feed-down}} / R_{AA}^{\text{prompt}} < 3$ for sys
  - $R_{AA}^{\text{feed-down}} / R_{AA}^{\text{prompt}} = 2$ for the point value

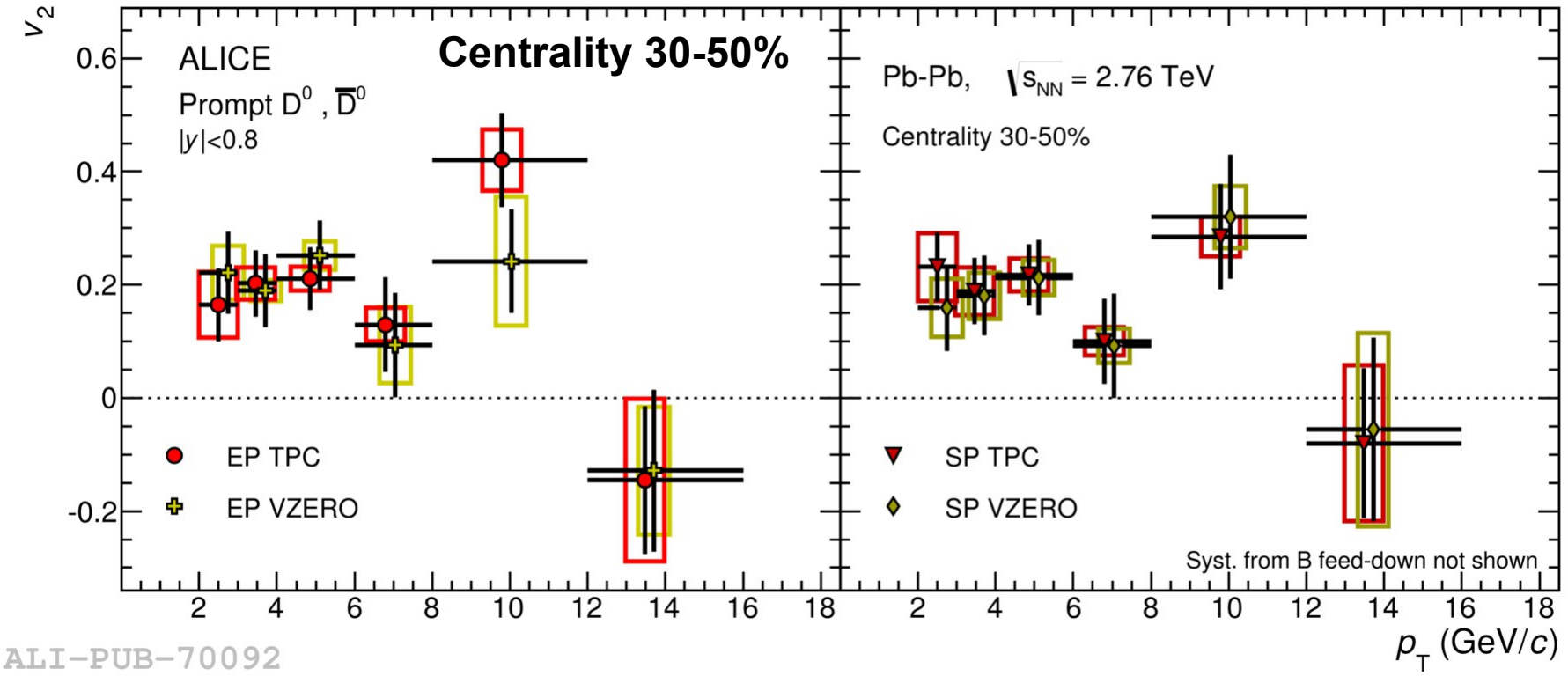
- **v_2 assumptions:**

  - $0 < v_2^{\text{feed-down}} < v_2^{\text{prompt}}$ for sys
  - $v_2^{\text{feed-down}} = v_2^{\text{prompt}}$ for the point value

D-meson flow: results

ALICE collaboration, PRL 111, 102301 (2013)
ALICE collaboration, arXiv:1405.2001 [nucl-ex]

New



Consistent between the different methods

Bias due to non-flow correlations within the statistical precision of the measurement

Poster Davide Caffarri
Tue 20.04 16:30-18:30

D meson models

New

ALICE collaboration, PRL 111, 102301 (2013)
ALICE collaboration, arXiv:1405.2001 [nucl-ex]

- **WHDG:** S. Wicks, W. A. Horowitz, M. Djordjevic, and M.Gyulassy, Nucl. Phys. A 784 (2007) 426
  W.A. Horowitz and M.Gyulassy, Nucl. Phys. A 872 (2011) 265

  pQCD parton energy loss with radiative and collisional processes
  Use Glauber model for the collision geometry without hydrodynamical expansion
  Hadronization with vacuum fragmentation functions
  Tuned to RHIC data and scaled to LHC energies with charged particle multiplicity results

- **MC@sHQ+EPOS, Coll+Rad(LPM):**
  M.Nahrgang, J.Aichelin, P.B. Gossiaux and K. Werner, Phys. Rec. C89 (2004) 014905

  pQCD parton energy loss with radiative and collisional processes
  Tuned to RHIC data
  Fluid dynamical expansion based on EPOS model
  Hadronization with a component from recombination of heavy quarks with light quarks

- **TAMU elastic**:M. He, R.J. Fries and R. Rapp, arXiv:1401.3817[nucl-th] (2014)

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- **POWLANG:** W.M. Alberico et al., Eur. Phys. J. C71 (201) 1666, J.Phys. G 38 (2011) 124144

  Transport model based on collisional processes within an expanding decondined medium
  Use Langevin equation matched to pQCD calculation for hard scatterings
  Hadronization with vacuum fragmentation functions

D meson models

ALICE collaboration, PRL 111, 102301 (2013)
ALICE collaboration, arXiv:1405.2001 [nucl-ex]

New

- **BAMPS:** O. Fochler, J. Uphoff, Z. Xu and C. Greiner, Phys. Rev. C 84 (2011) 024908; J. Phys. G38 (2011) 124152 Phys. Lett. B 717 (2012) 430;arXiv:1310.3597v1[hep-ph]
  Transport model based on collisional processes and for the latest version radiative processes
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  Scaling factor for the binary cross section to reproduce RHIC data

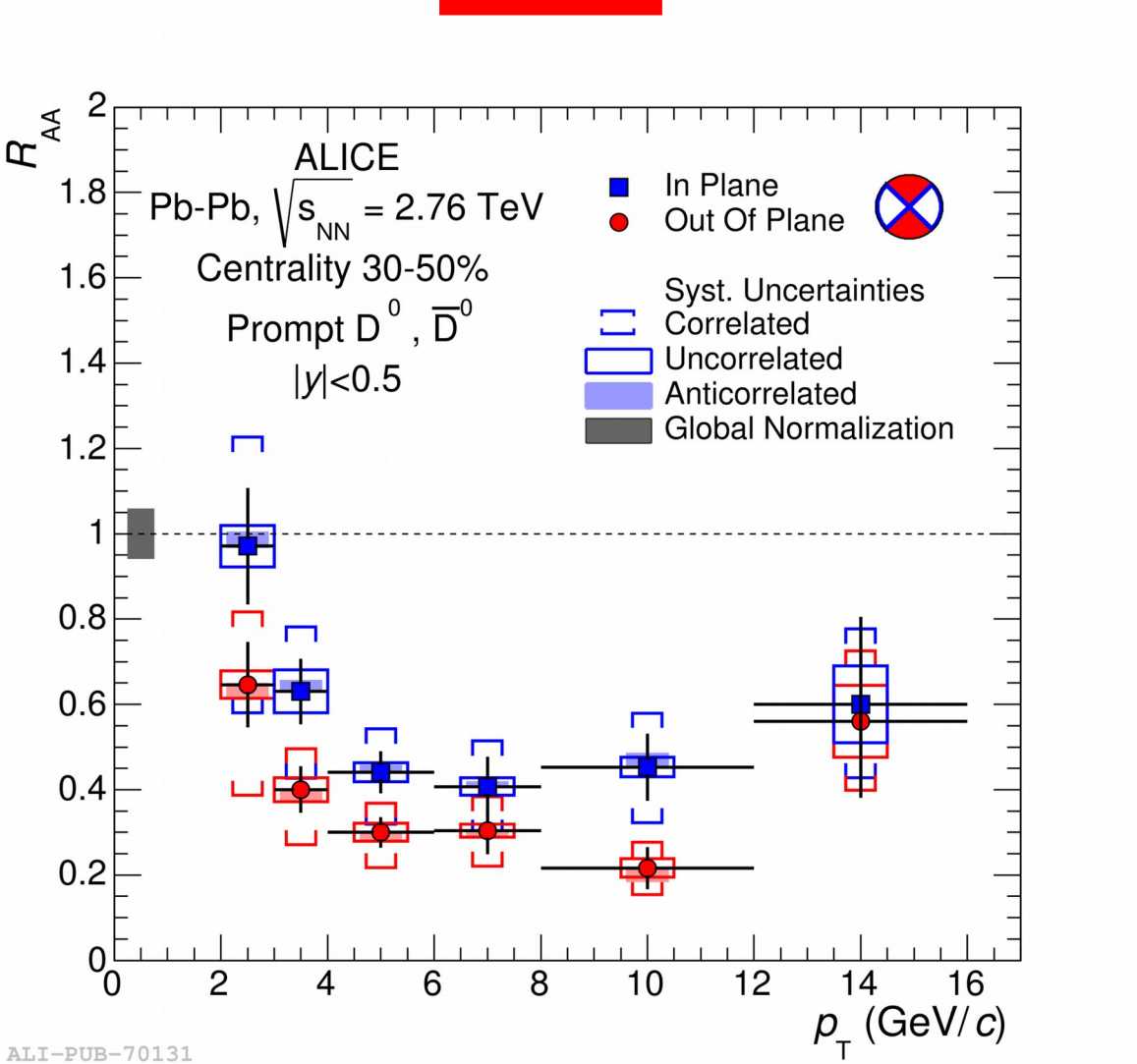
- **UrQMD:** T. Lang, H. Van Hees, J. Steinheimer and M.Bleicher, arXiv:1211.6912[hep-ph]; T. Lang, H. Van Hees, J. Steinheimer, Y.-P. Yan and M. Bleicher, J. Phys. Conf. Ser. 426 (2013) 012032
  Langevin approach for the transport of heavy quarks implemented within the UrQMD model
  Combination of hadronic transport and ideal hydrodynamics
  Transport of heavy quarks calculated with resonance model (decoupling T=130 MeV)
  Hadronization via quark coalescence included
  Tuned to reproduce heavy-flavour measurements at RHIC

- **Cao, Qin, Bass:** S. Cao, G.-Y. Qin and S. A. Bass, Phys. Rev. C 88 (2013) 044907
  Based on Langevin approach
  Quasi elastic scatterings and radiative energy loss included
  Space-time evolution of the medium modelled by viscous hydrodynamic simulation
  Hadronization including a recombination component

D meson: R_{AA} in and out-of-plane

ALICE collaboration, PRL 111, 102301 (2013)
ALICE collaboration, arXiv:1405.2001 [nucl-ex]

New



Nuclear Modification Factor:

$$R_{\mathrm{AA}}^{\text{in (out)}}(p_{\mathrm{T}}) = \frac{2 \cdot \mathrm{d}N_{\mathrm{AA}}^{\text{in (out)}}/\mathrm{d}p_{\mathrm{T}}}{\langle T_{\mathrm{AA}} \rangle \cdot \mathrm{d}\sigma_{pp}/\mathrm{d}p_{\mathrm{T}}}$$

Contains similar information as R_{AA} and v_2 measurements simultaneously:

$$v_2 = \frac{\pi}{4} \frac{R_{\mathrm{AA}}^{\text{in-plane}} - R_{\mathrm{AA}}^{\text{out-of-plane}}}{R_{\mathrm{AA}}^{\text{in-plane}} + R_{\mathrm{AA}}^{\text{out-of-plane}}}.$$

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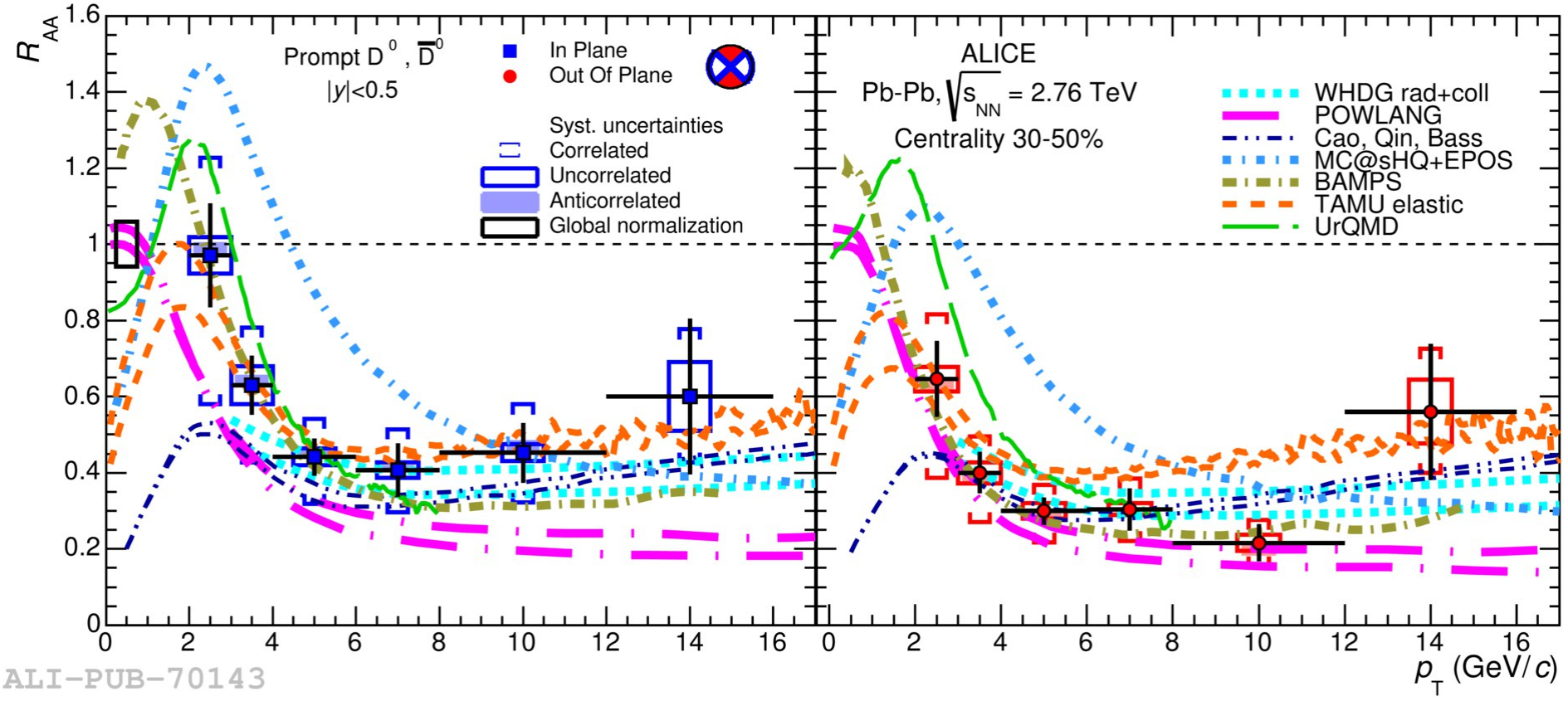
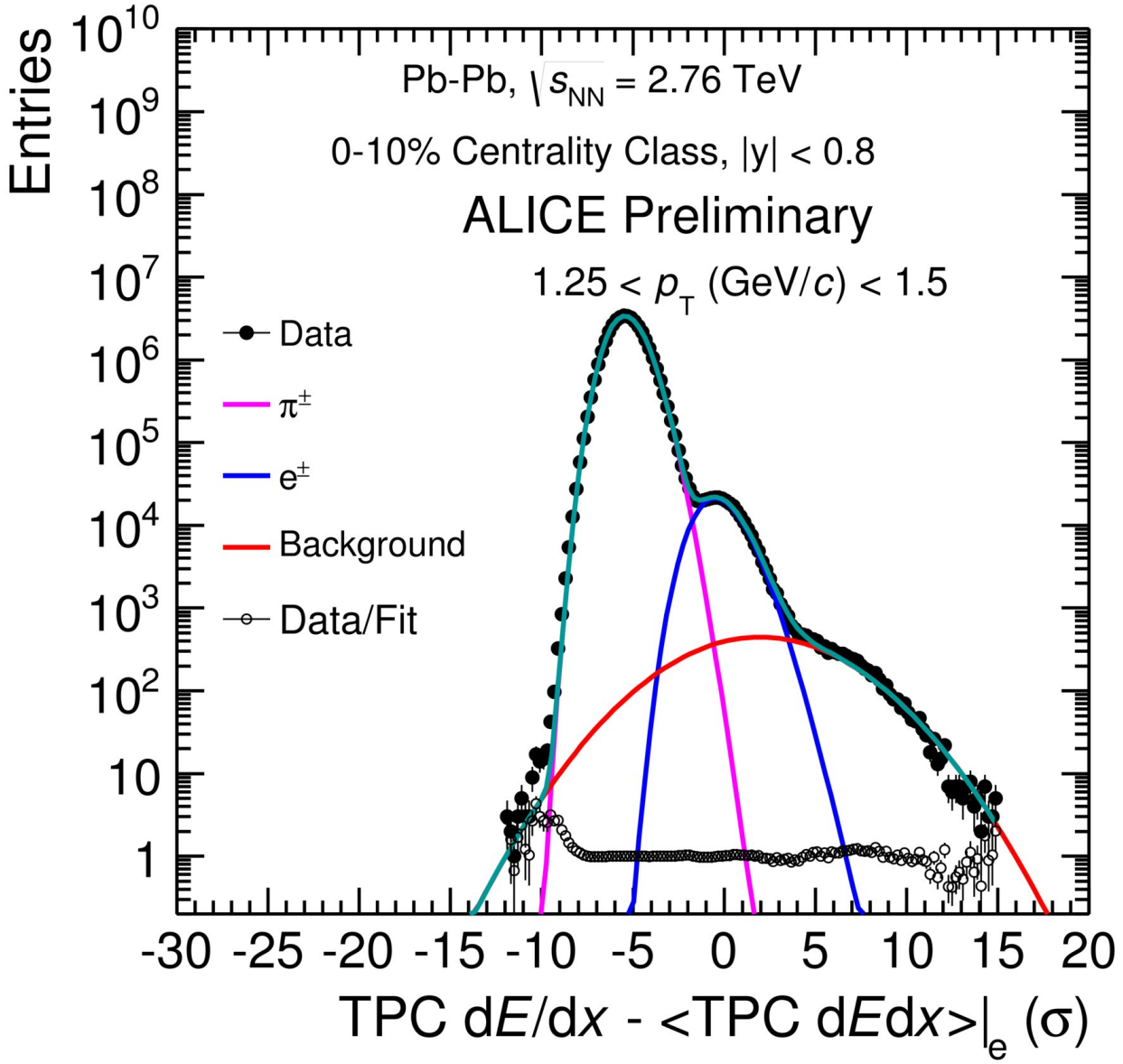
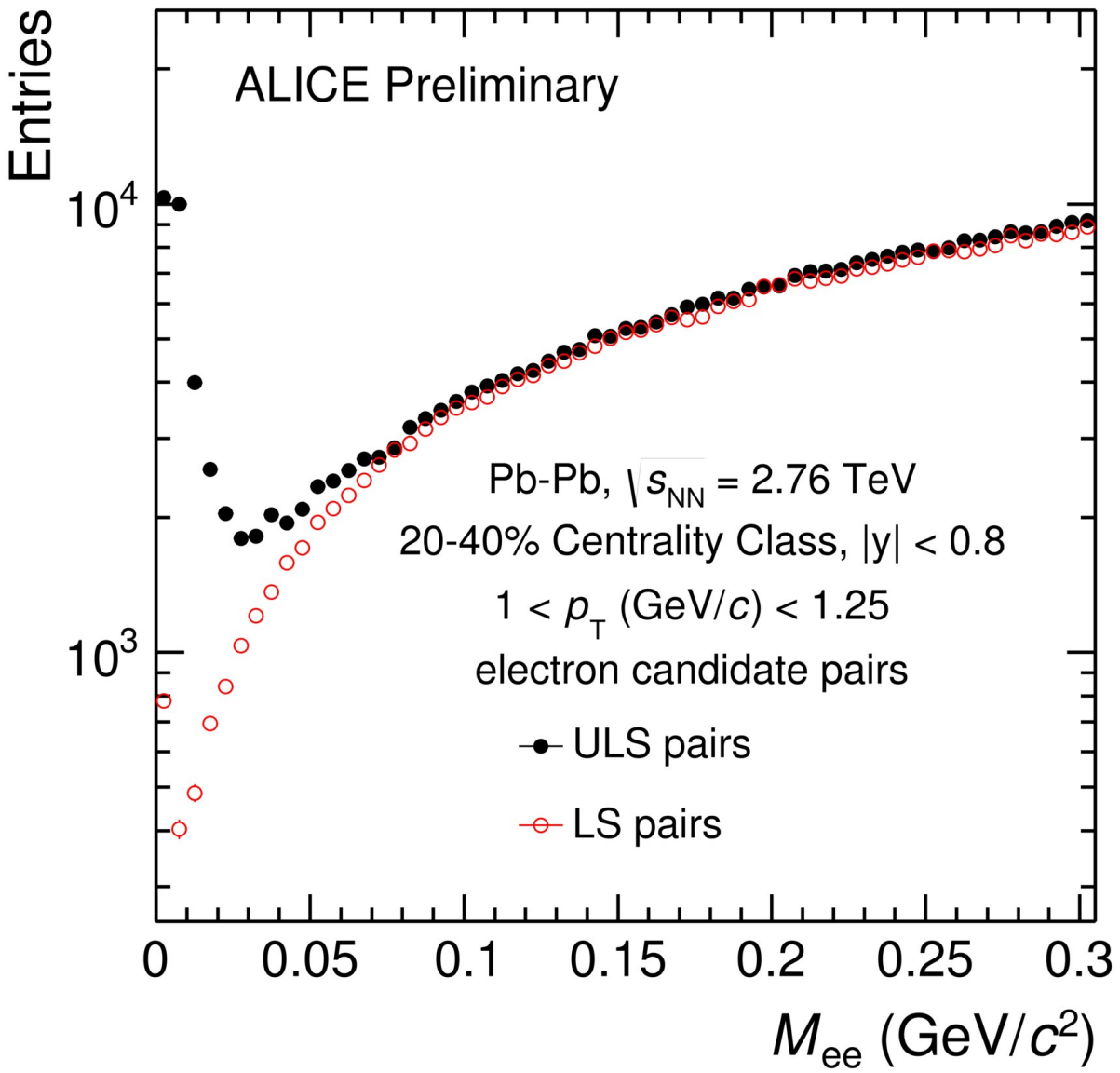
New



Identification of electrons



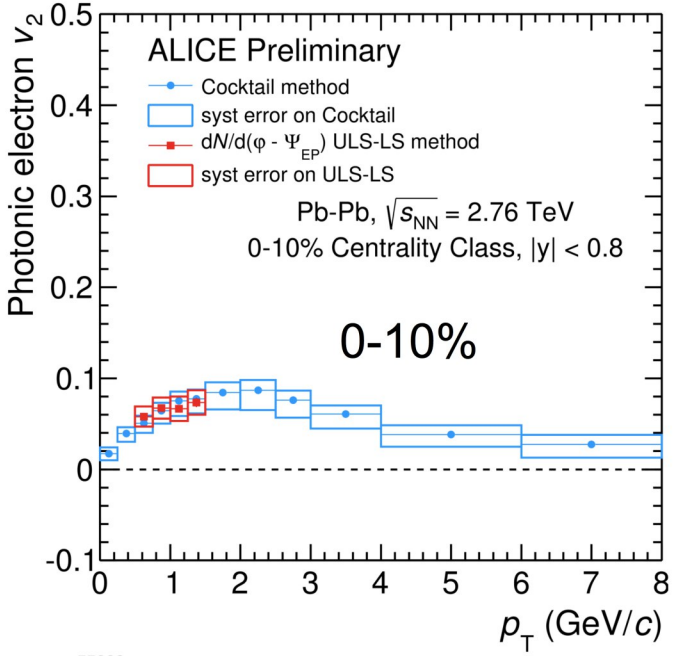
Heavy-flavour decay electrons



ALI-PREL-77219

Heavy-flavour decay electrons

New



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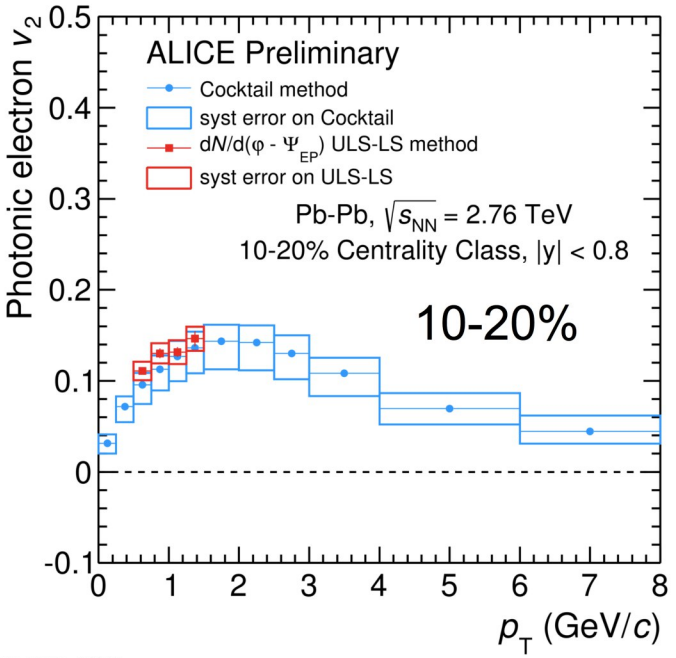

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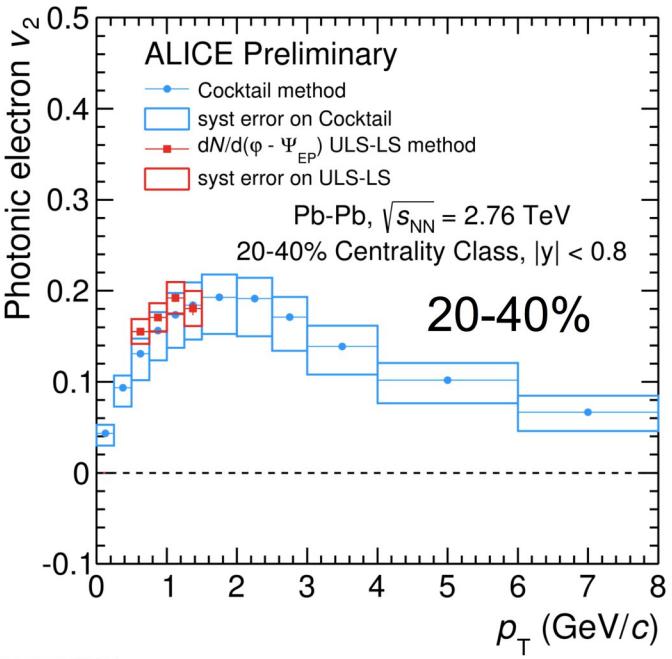

ALI-PREL-77351

Heavy-flavour decay electrons: models

- **BAMPS:** O. Fochler, J. Uphoff, Z. Xu and C. Greiner, Phys. Rev. C 84 (2011) 024908; J. Phys. G38 (2011) 124152 Phys. Lett. B 717 (2012) 430; arXiv:1310.3597v1[hep-ph]
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Heavy-flavour decay muons: $f_{\text{decay }\mu}$

- Input: K/π spectra in pp collisions and R_{AA} in Pb-Pb collisions at central rapidity measured with ALICE

  J. Phys. G: Nucl. Part. Phys 38 (2011) 124014 & 124080

- Extrapolate K/π spectra in pp collisions to forward rapidity by means of Monte-Carlo simulations (PYTHIA, sys with Phojet 15%)

  Phys. Rev. D76, (2007) 092002

- Get K/π spectra in Pb-Pb collisions at forward rapidity by scaling the extrapolated charged K/π spectra with their R_{AA} at central rapidity (vary R_{AA} within 100% for sys)

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

Heavy-flavour decay muons: $v_2^{\text{decay }\mu}$

- Parametrize the p_T and η dependence of charged hadron v_2 measured by the ATLAS collaboration and extrapolate to forward rapidity

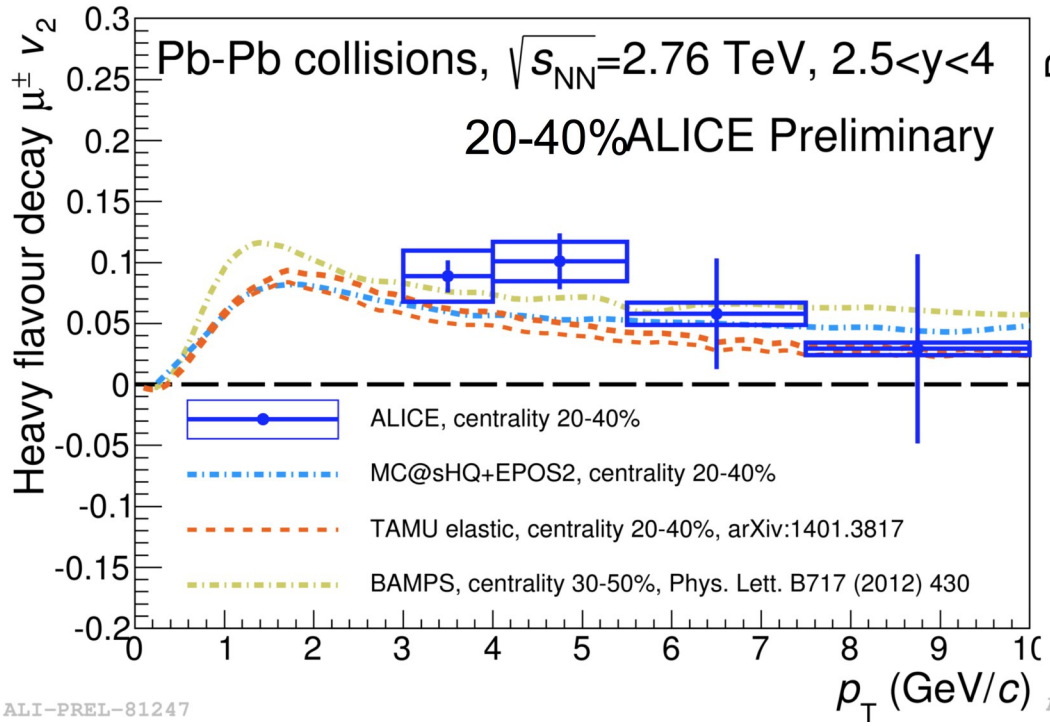
ATLAS collaboration, Phys. Lett. B707 (2012) 3301

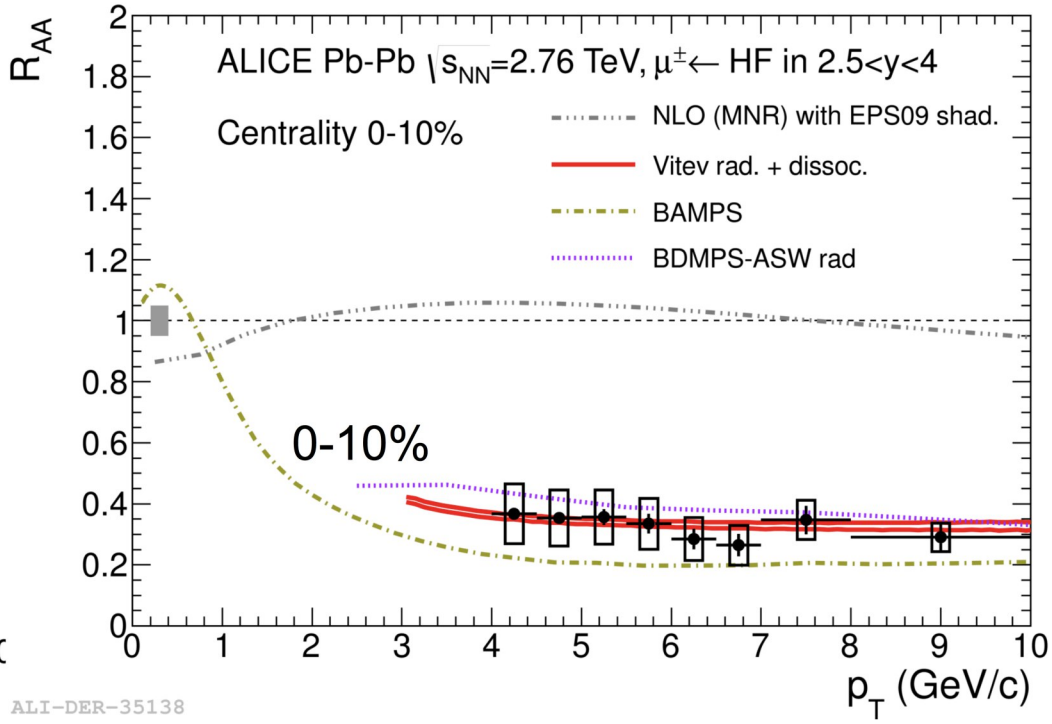
- Charged $v_2(p_T)$ extrapolated to forward rapidity used as input v_2 of pions and kaons, separately, to produce the v_2 of decay muons in the acceptance of the muon spectrometer

systematic uncertainty on decay muons v_2	
input v_2 bias	~ 9%
extrapolation	9%-12%
input data fluctuations	13%-15% (at high p_T)
K/π weights	<1%

Heavy-flavour decay muons

Q{2} cumulant method





- $v_2^{\mu\leftarrow HF}$ positive (3σ effect) in 20-40% central Pb-Pb
- Challenging to reproduce simultaneously $v_2^{\mu\leftarrow HF}$ and $R_{AA}^{\mu\leftarrow HF}$ measurements

Heavy-flavour decay muons: models

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- **MC@sHQ+EPOS, Coll+Rad(LPM):**
  M.Nahrgang, J.Aichelin, P.B. Gossiaux and K. Werner, Phys. Rec. C89 (2004) 014905
  pQCD parton energy loss with radiative and collisional processes
  Tuned to RHIC data
  Fluid dynamical expansion based on EPOS model
  Hadronization with a component from recombination of heavy quarks with light quarks

Heavy-flavour decay muons: models

R_{AA} only

- **NLO (MNR) with EPS09 shad.: JHEP, 0904:065 (2009)**
  Fixed-order next-to-leading order QCD calculations for heavy quarks
  NLO order global DGLAP analysis of nuclear parton distribution function for the shadowing

- **Vitev rad.+dissoc: Phys. Lett. B 713 (2012) 224**
  Model including radiative energy loss and dissociation

- **BDMPS+ASW rad.: Phys. Rev. D71 (2005) 054027**
  Model including radiative energy loss model