SQM

DUBNA 2015

Measurement of D-meson production in Pb-Pb collisions at the LHC with ALICE

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INFN Istituto Nazionale di Fisica Nucleare

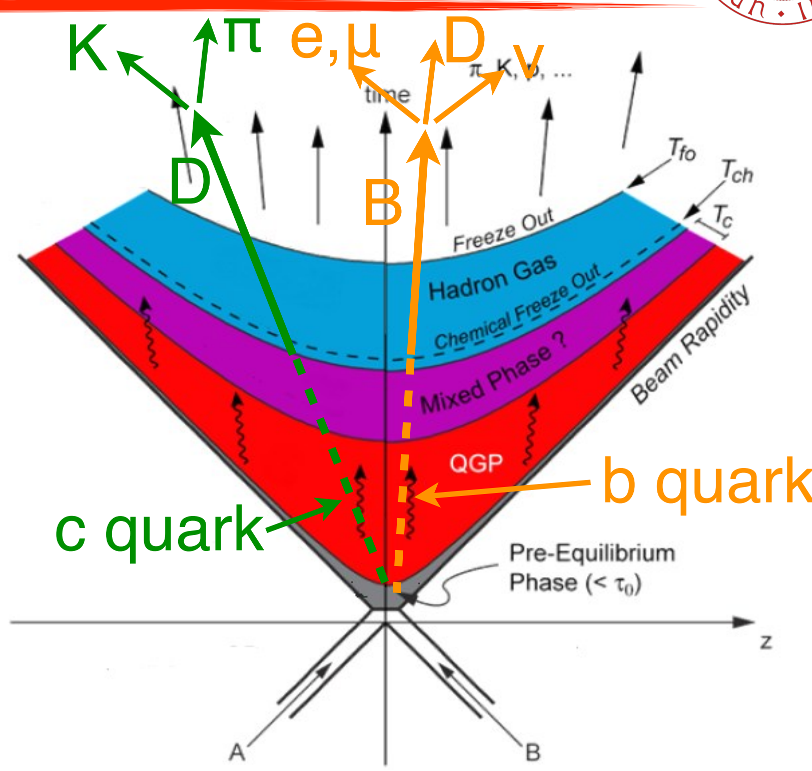
ALICE

Outline

- Motivation and experimental observables
- ALICE experiment
- D-meson reconstruction
- Results
  - Nuclear modification factor vs. p_T and centrality
  - Azimuthal anisotropy
- Conclusions

Motivation

- Charm and beauty quarks produced in hard-scattering processes before the QGP formation
- Initially-produced heavy quarks in Pb-Pb collisions propagate through the medium interacting with its constituents → sensitive probes of the properties of the QGP



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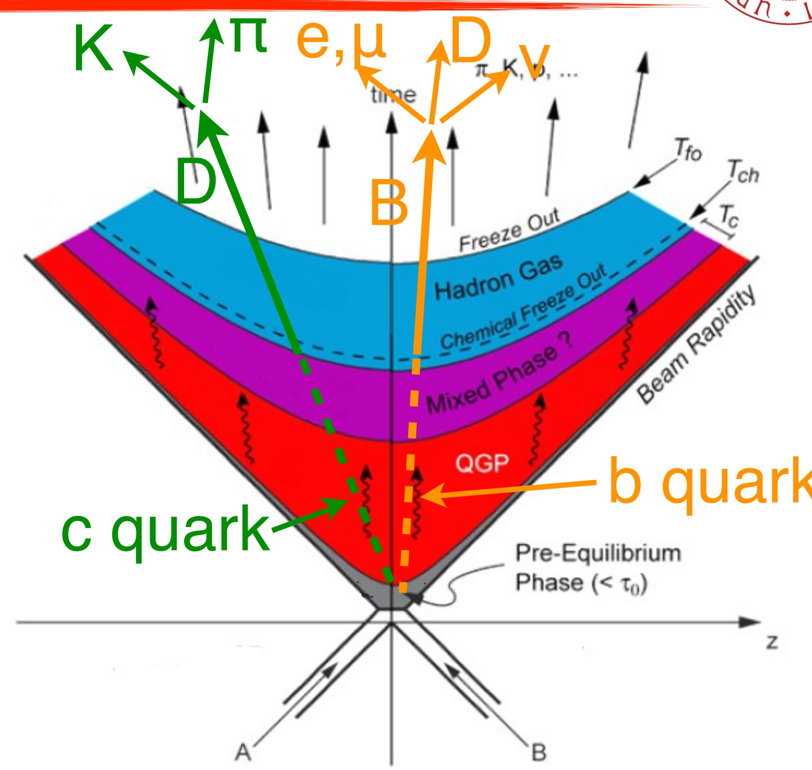

INTERACTION WITH THE MEDIUM

- **Parton energy loss** via radiative (gluon emission) and collisional processes
  - colour charge
  - quark mass
  - path length and medium density

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

Compare $R_{AA}{}^{\pi}$, $R_{AA}{}^{D}$, $R_{AA}{}^{B}$

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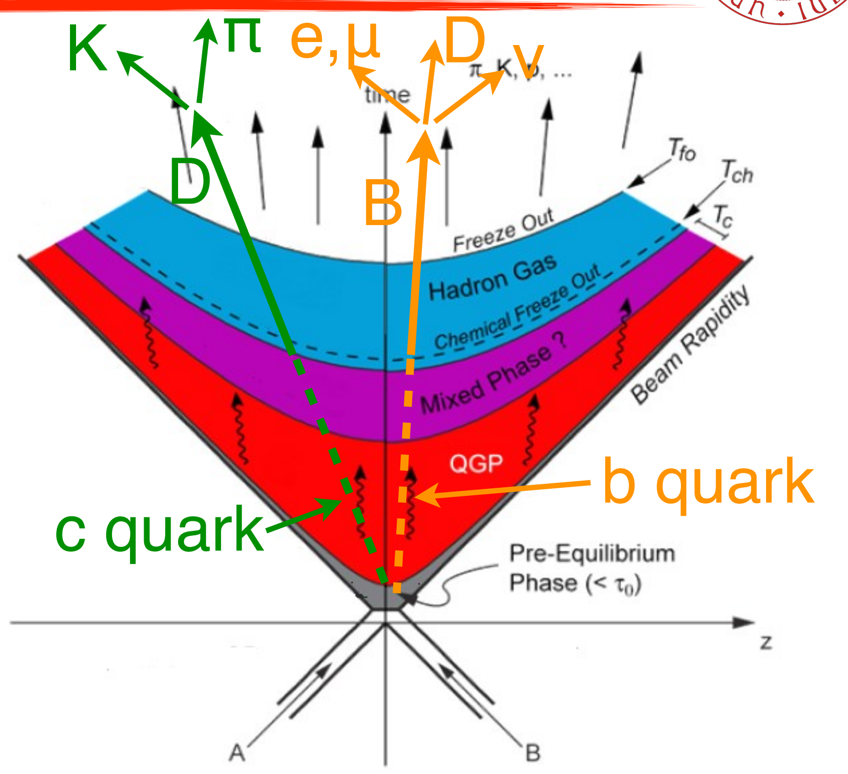

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Compare R_{AA}^{π}, R_{AA}^{D}, R_{AA}^{B}

- Medium modification of the **hadronisation** process
  - quark coalescence mechanism ?
- Participation in the **collective expansion**
  - radial and elliptic flow

⇨ D-meson azimuthal anisotropy

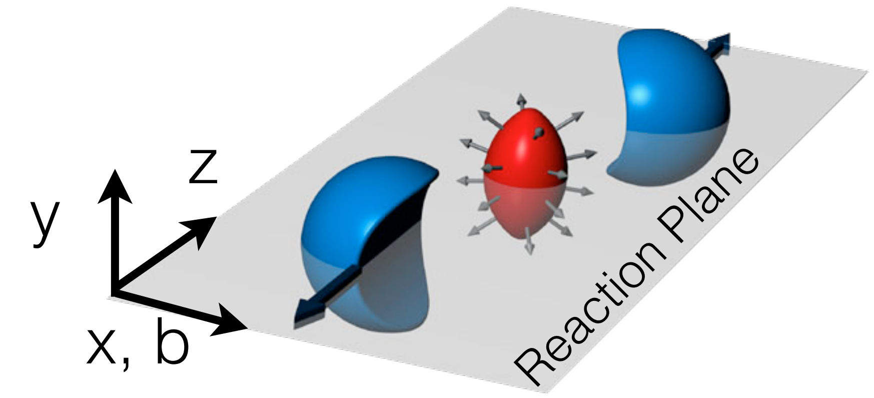
Observables

- Nuclear modification factor R_{AA}:

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

- *Sensitive to parton energy loss*
- *Compares production yields in Pb-Pb collisions to a binary-scaled pp reference*

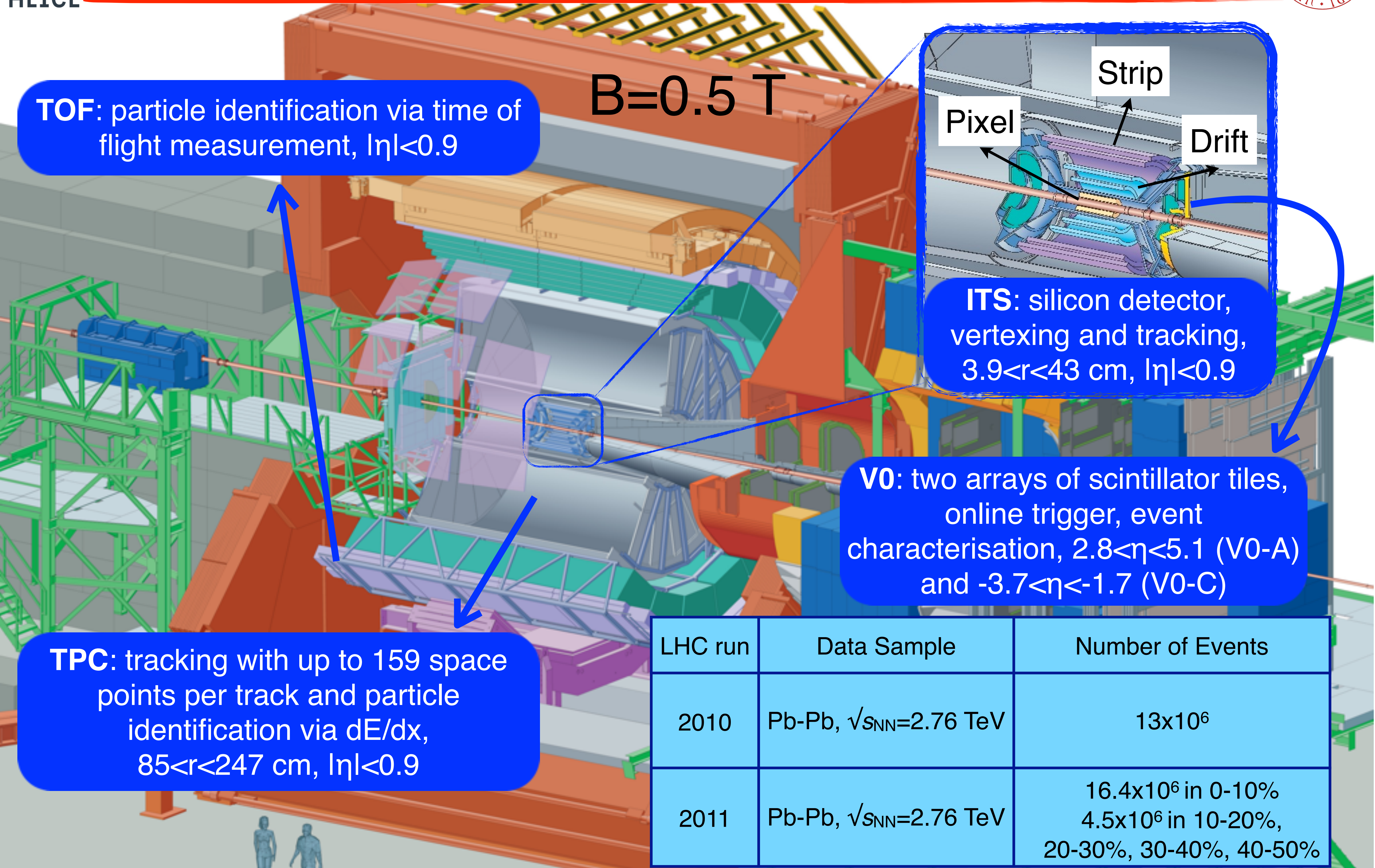
- Non-central Pb-Pb collisions → asymmetric spatial distribution of partons
- Collective expansion: initial spatial anisotropy → momentum anisotropy of the final-state particles
- Heavy-quarks in-medium interactions + energy loss →? participation in the collective expansion
- Azimuthal anisotropy quantified in terms of



- elliptic flow v_2 $$v_2 = \langle \cos[2(\varphi - \Psi_{RP})] \rangle$$

- azimuthal dependence of R_{AA} with respect to the reaction plane

ALICE Experiment

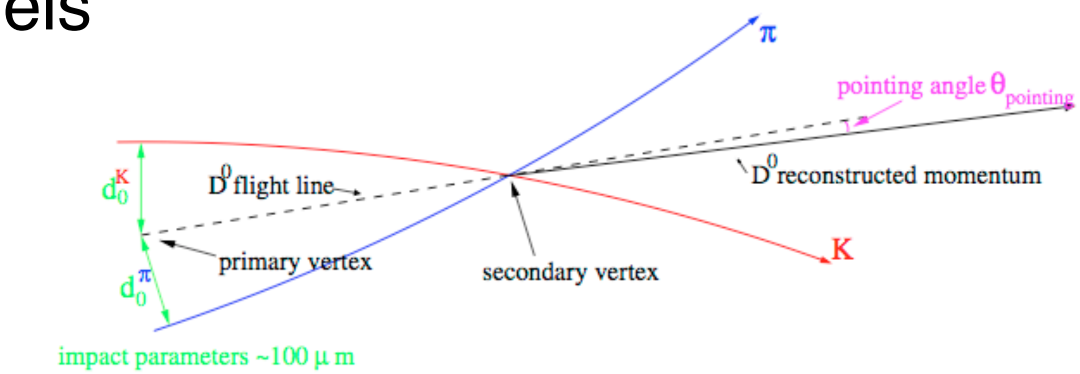


LHC run	Data Sample	Number of Events
2010	Pb-Pb, $\sqrt{s_{NN}}$=2.76 TeV	13×10^6
2011	Pb-Pb, $\sqrt{s_{NN}}$=2.76 TeV	16.4×10^6 in 0-10% 4.5×10^6 in 10-20%, 20-30%, 30-40%, 40-50%

D-meson Reconstruction

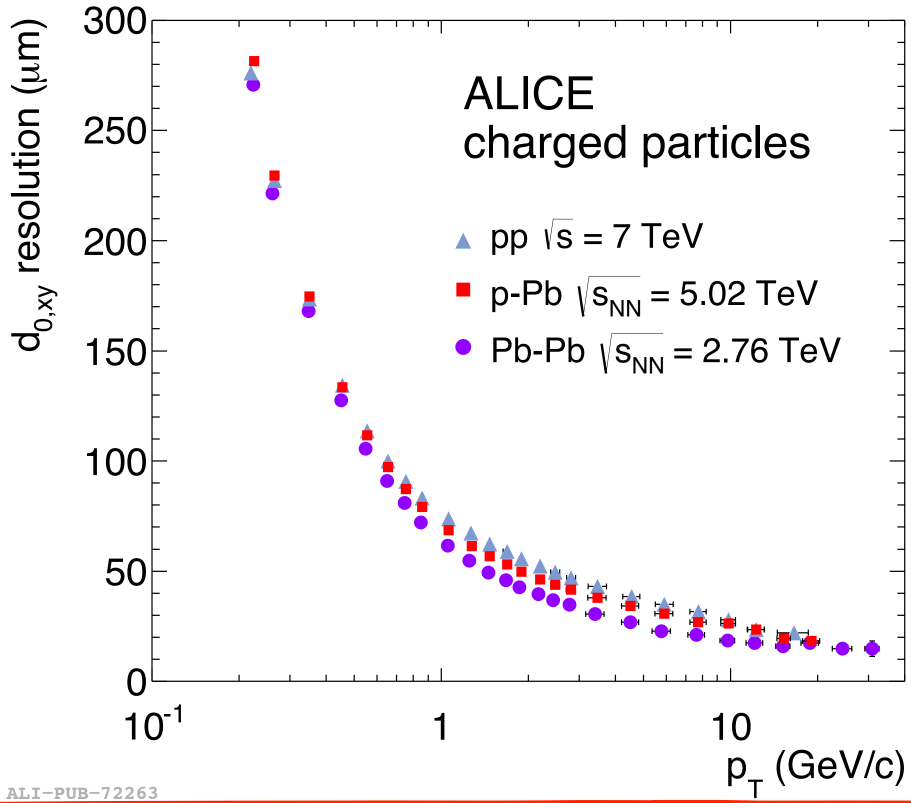
- D^0, D^+ and D^{*+} and their antiparticles were reconstructed in the central rapidity region from their charged hadronic decay channels

$D^0 \rightarrow K^- \pi^+$	[BR 3.88±0.05%, cτ≈123 μm]
$D^+ \rightarrow K^- \pi^+ \pi^+$	[BR 9.13±0.19%, cτ≈312 μm]
$D^{*+} \rightarrow D^0 \pi^+$	[strong decay, BR 67.7±0.5%]

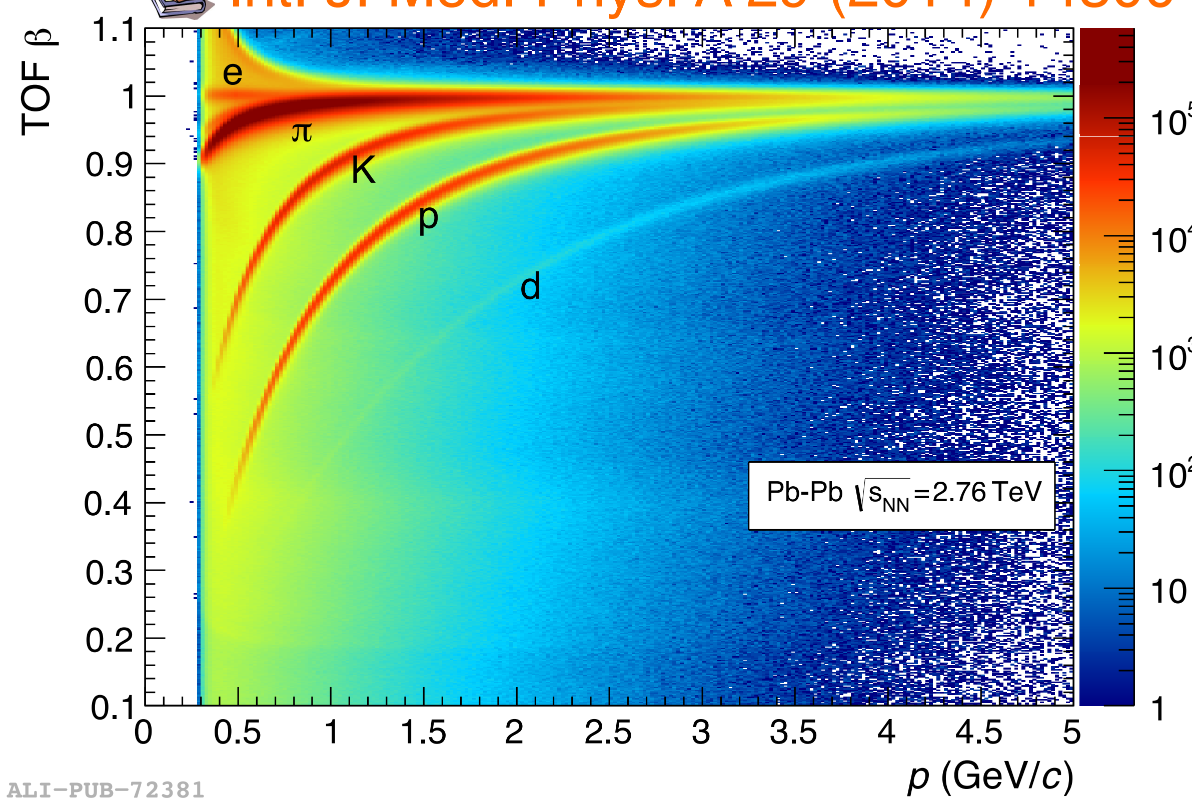


- Selection based on the reconstruction of secondary-vertex topologies displaced by a few hundred μm from the interaction vertex

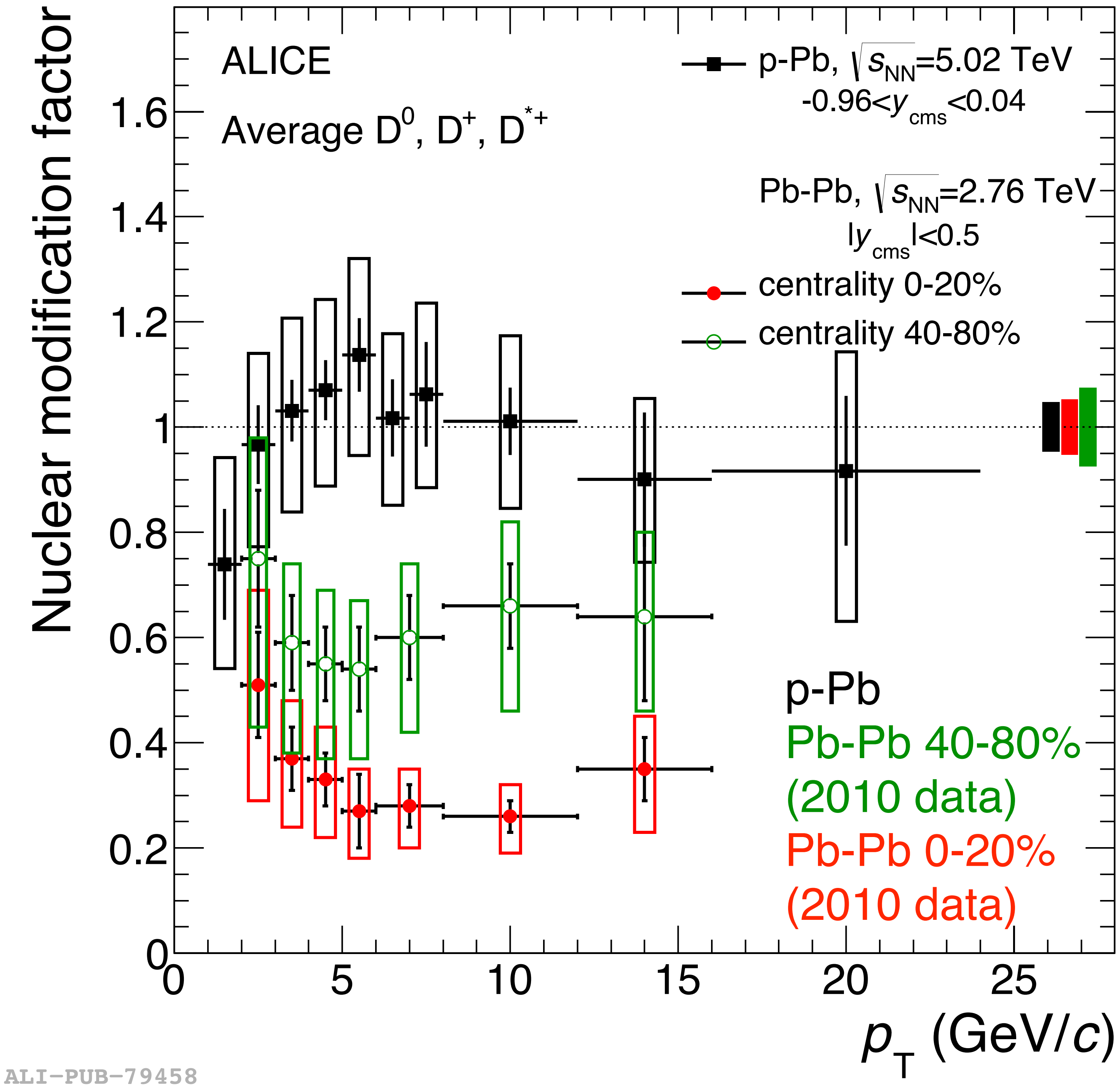
- Topological cuts and particle identification of pions and kaons to reduce combinatorial background



Int. J. Mod. Phys. A 29 (2014) 1430044



D-meson R_{AA} and R_{pA} vs. p_T

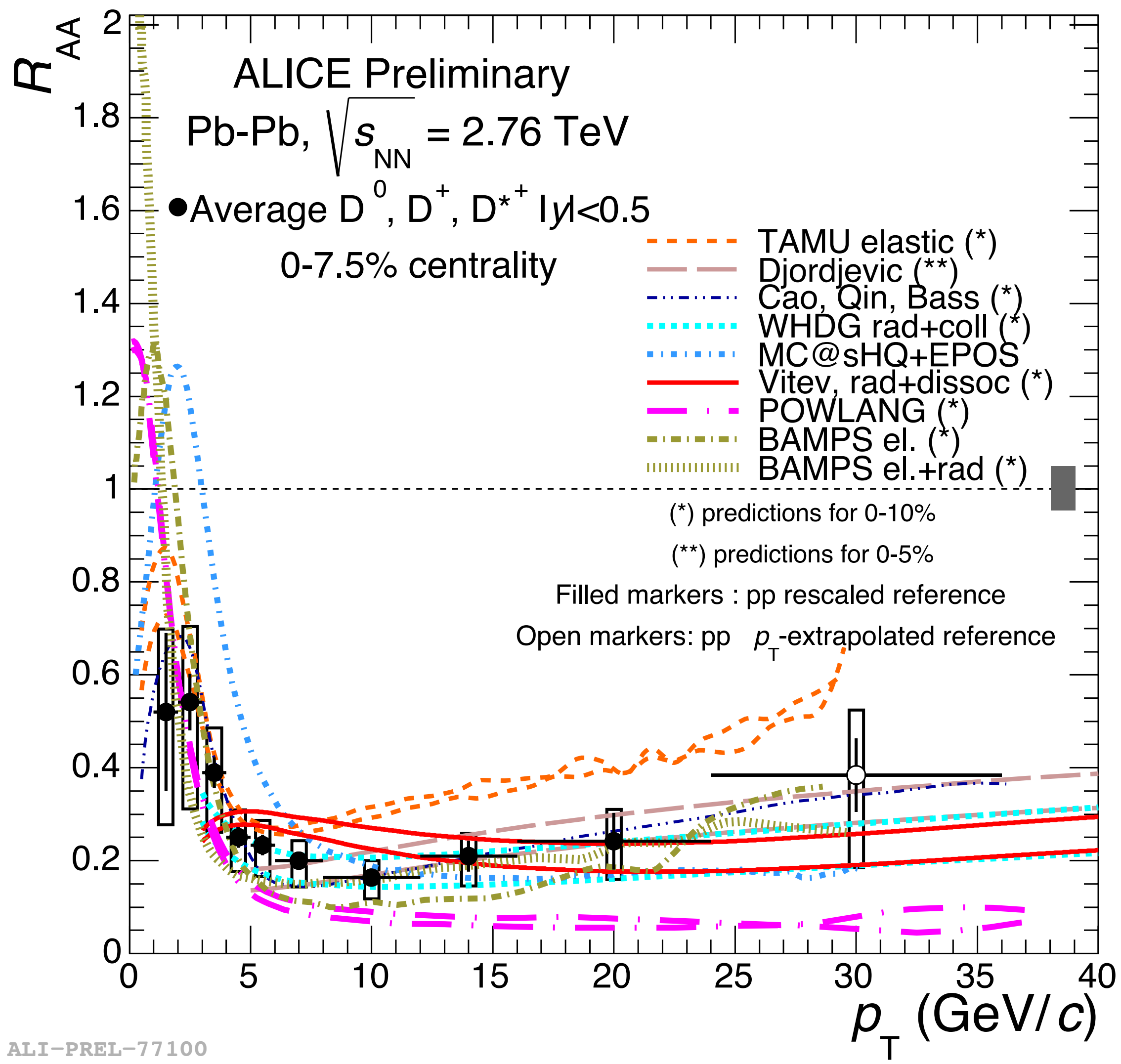


JHEP 9 (2012) 112
Phys. Rev. Lett. 113 (2014) 232301

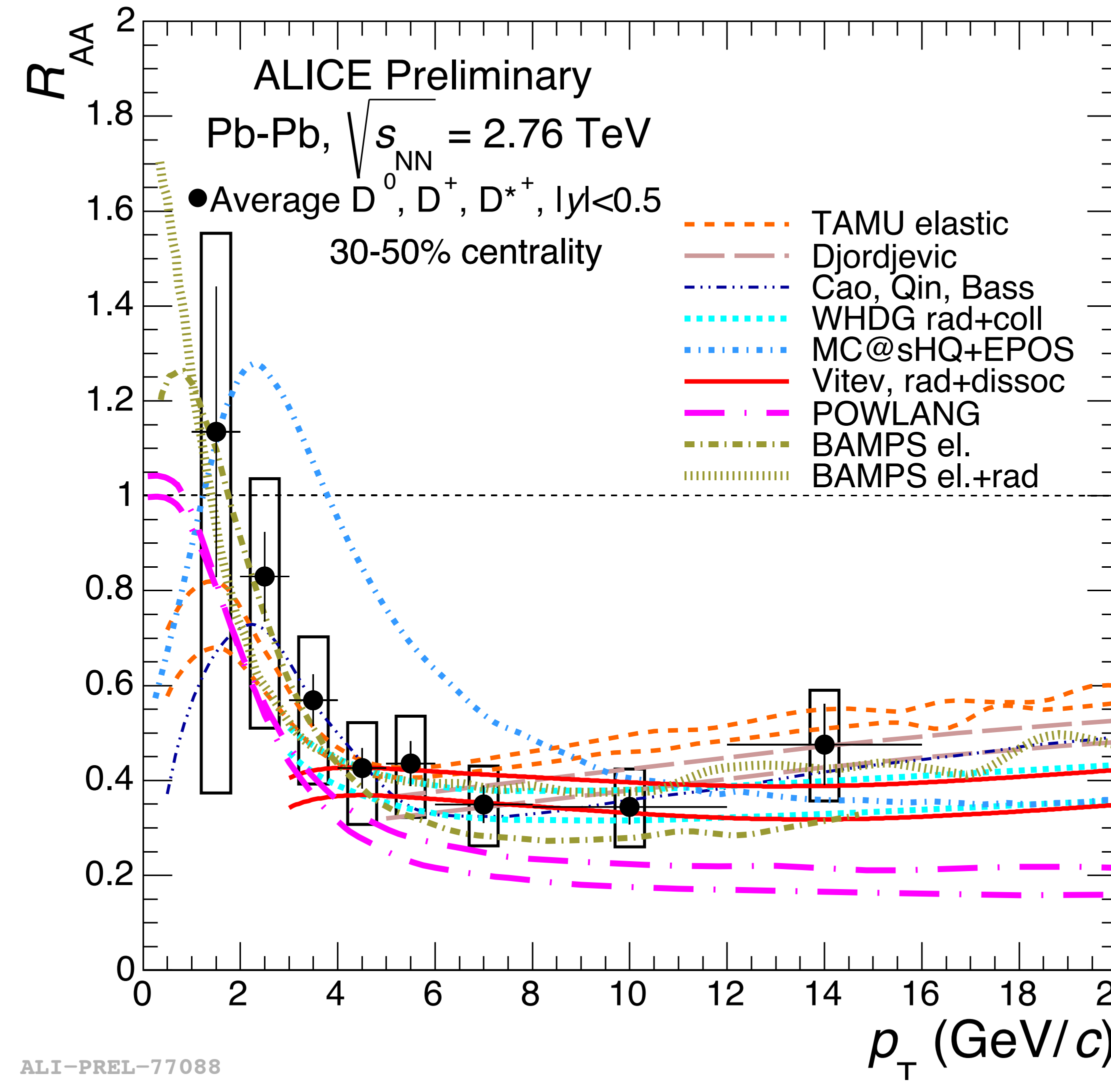
- **Observed suppression (factor 3-5) for p_T > 5 GeV/c in central (0-20%) Pb-Pb collisions is due to strong final-state effects induced by hot and dense partonic matter**

D-meson R_{AA} vs. p_T (2011 data)

Average R_{AA} (0-7.5%)



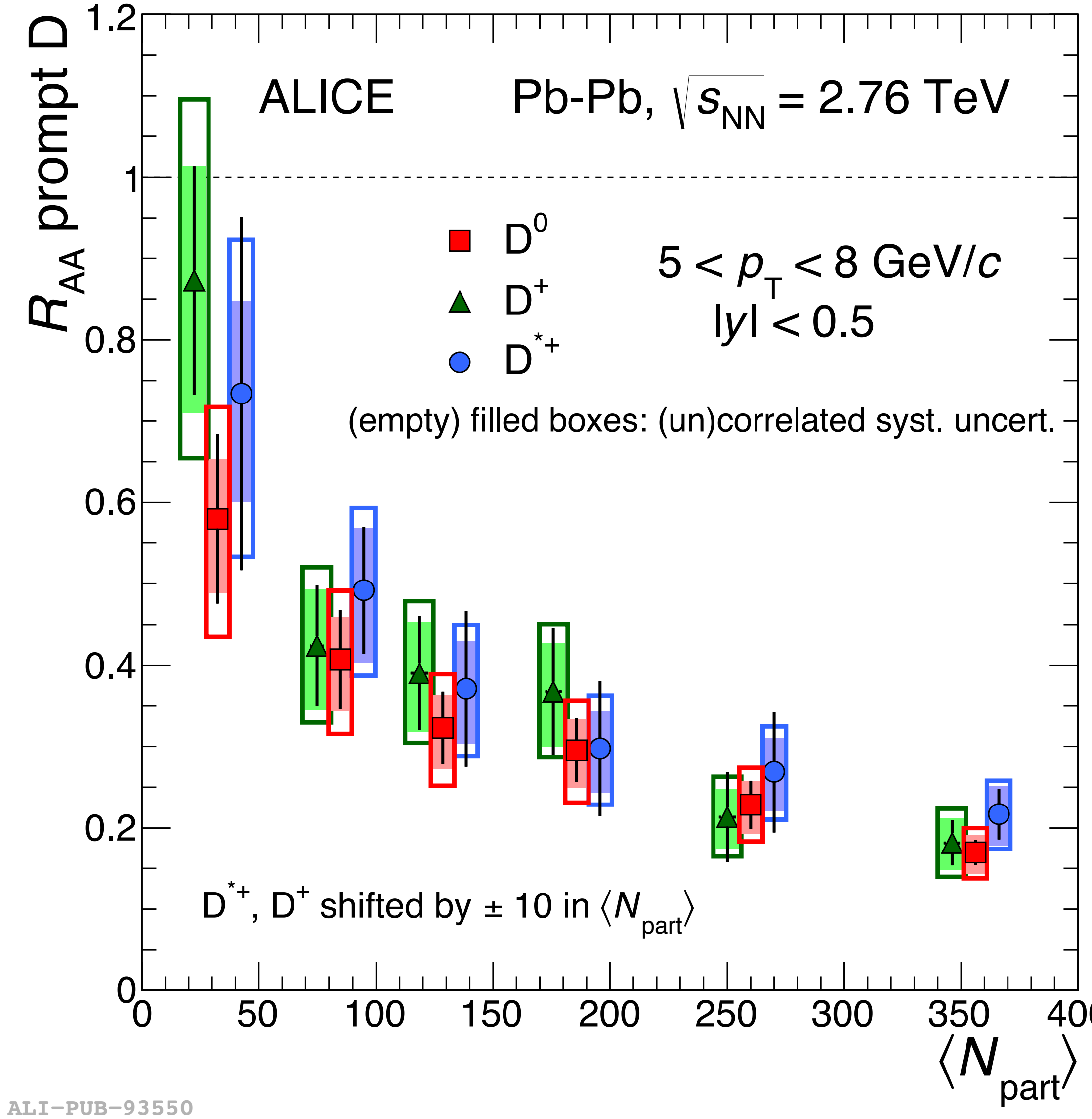
Average R_{AA} (30-50%)

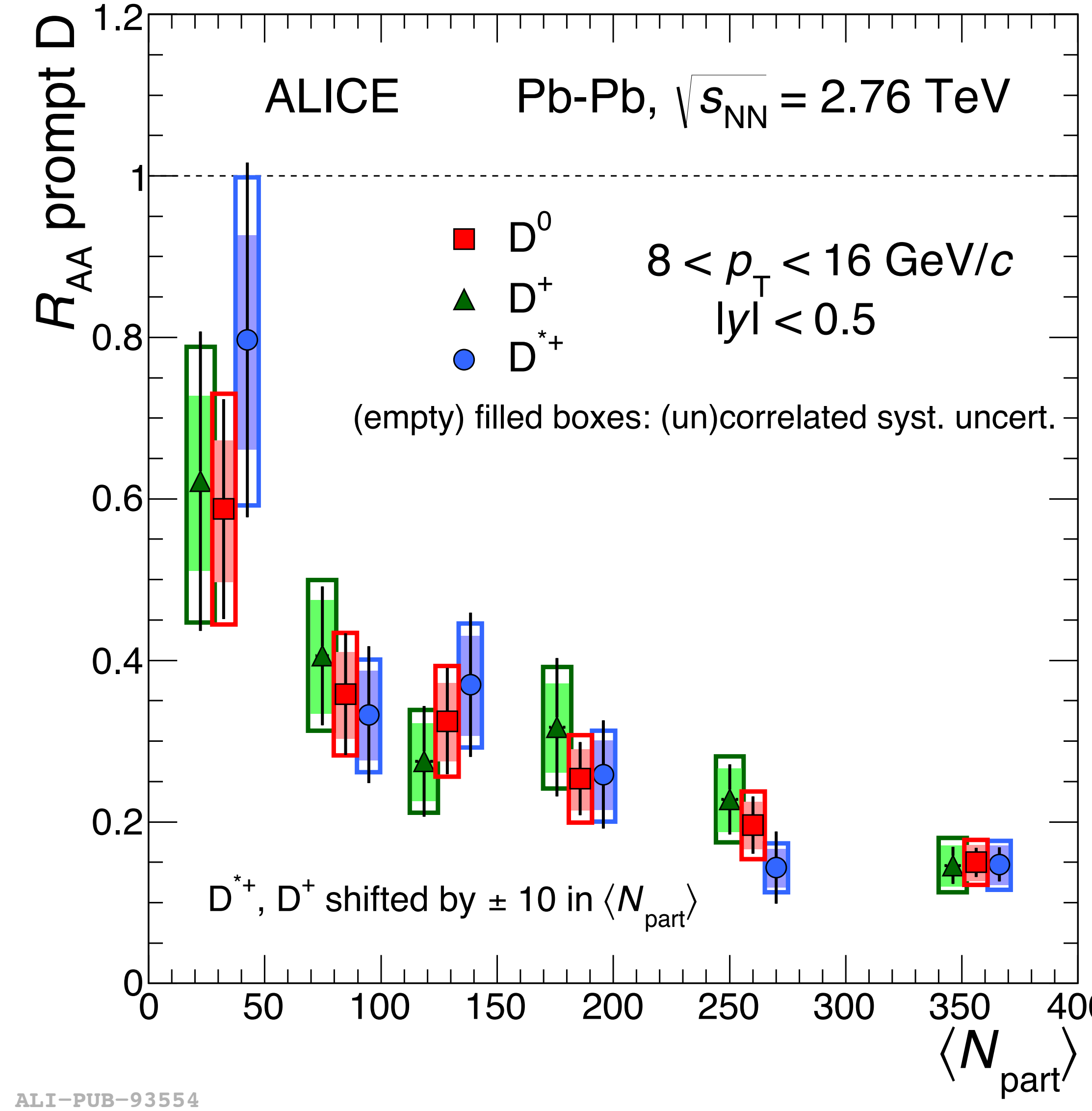


- Large suppression (factor 6) at p_T=10 GeV/c in the 0-7.5% centrality class
- Suppression for p_T> 4 GeV/c observed in the 30-50% centrality class
- Models including charm interactions with medium constituents can describe both measurements

TAMU elastic: arXiv:1401.3817
Djordjevic: arXiv:1307.4098
Cao, Qin, Bass: PRC 88 (2013) 044907
WHDG rad+coll: Nucl. Phys. A 872 (2011) 265
MC@sHQ+EPOS: PRC 89 (2014) 014905
Vitev, rad+dissoc: PRC 80 (2009) 054902
POWLANG: JPG 38 (2011) 124144
BAMPS: PLB 717 (2012) 430

D-meson R_{AA} vs. centrality

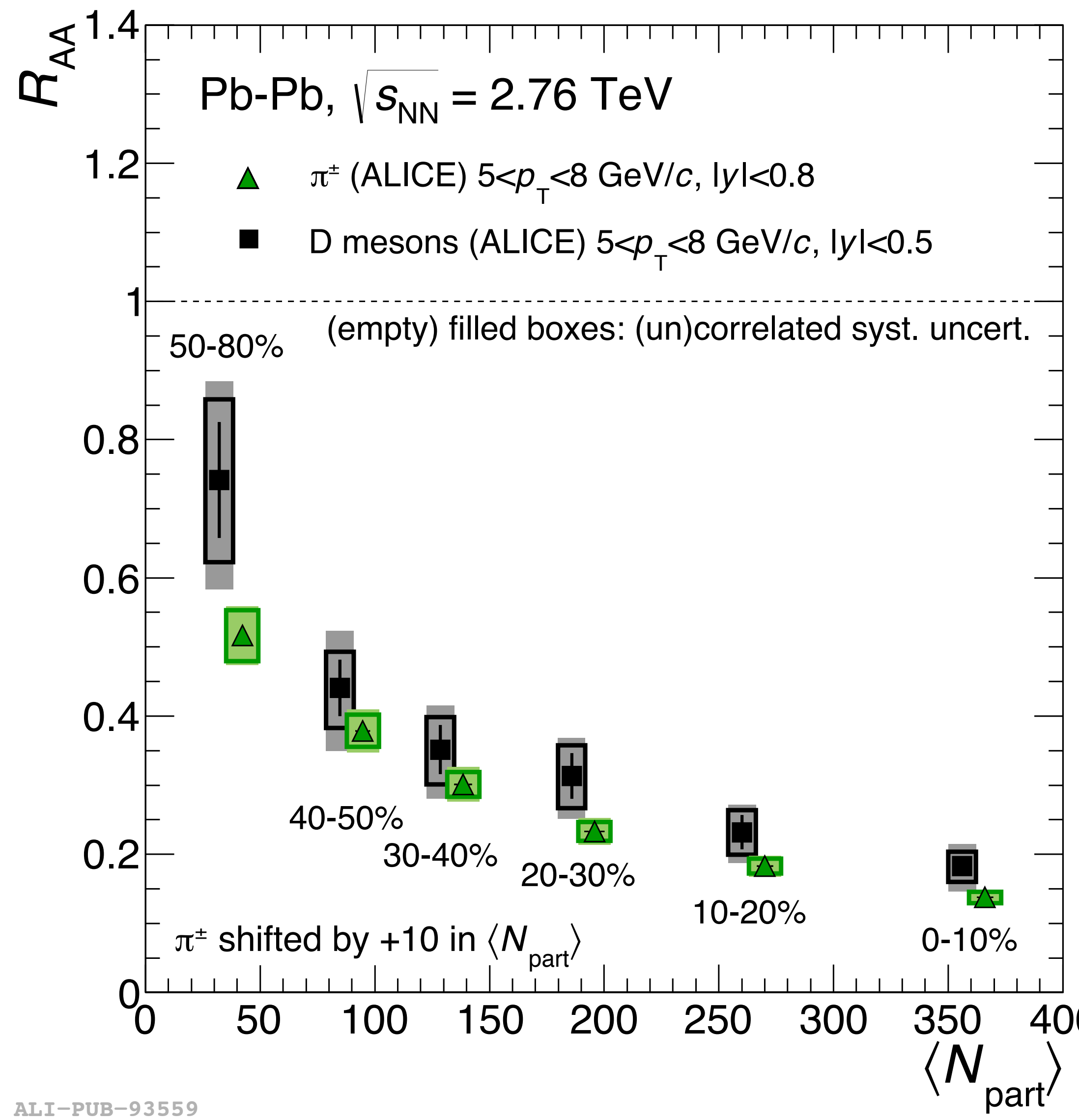


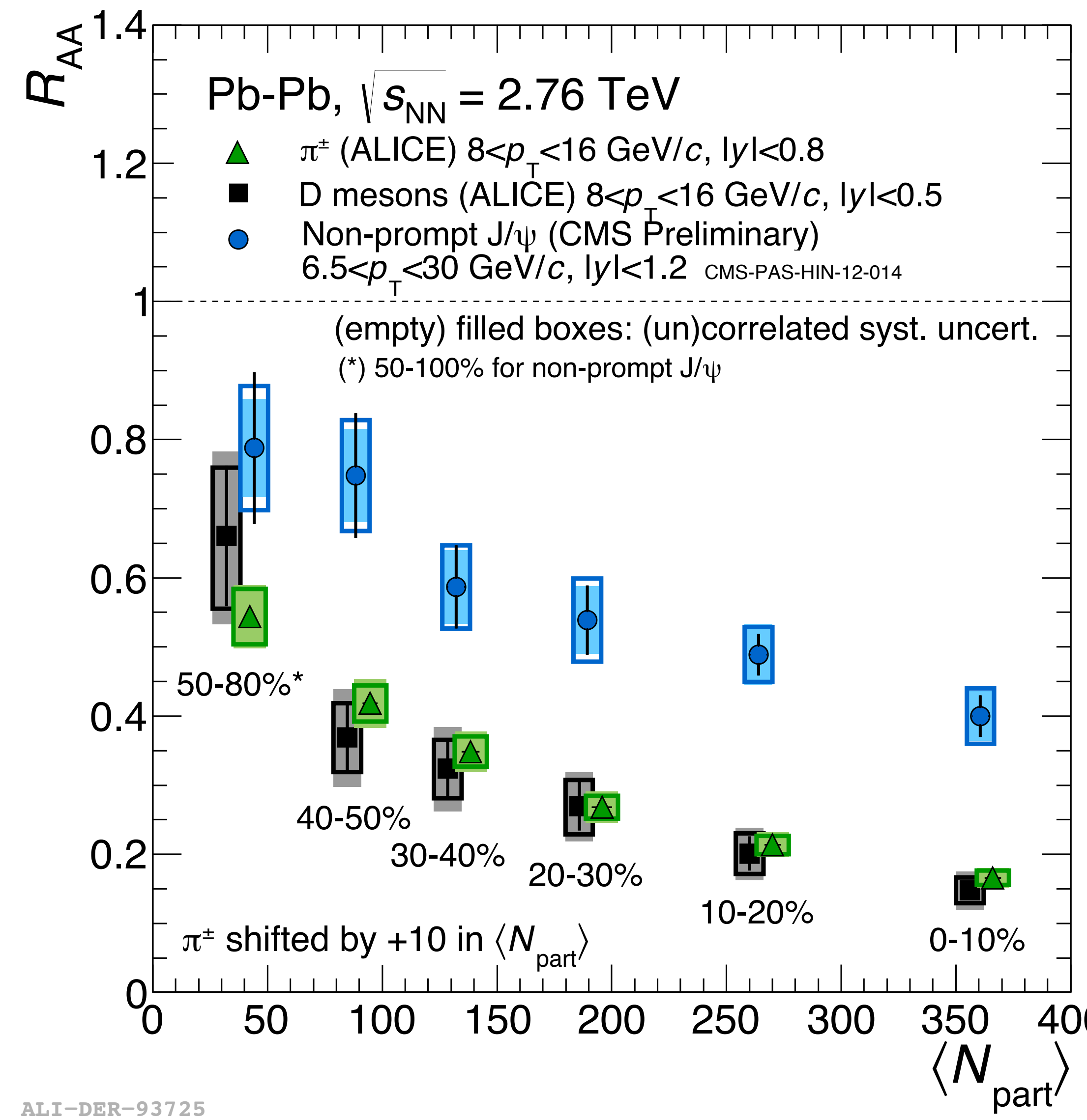


- Centrality quantified in terms of <N_{part}> (average number of nucleons participating in the collision)
- Consistent results among the three D-meson species in both p_T intervals
- **Suppression increases with centrality —> factor 5-6 in the most central collisions**

arXiv:1506.06604

D-meson R_{AA}: comparison with pions and beauty



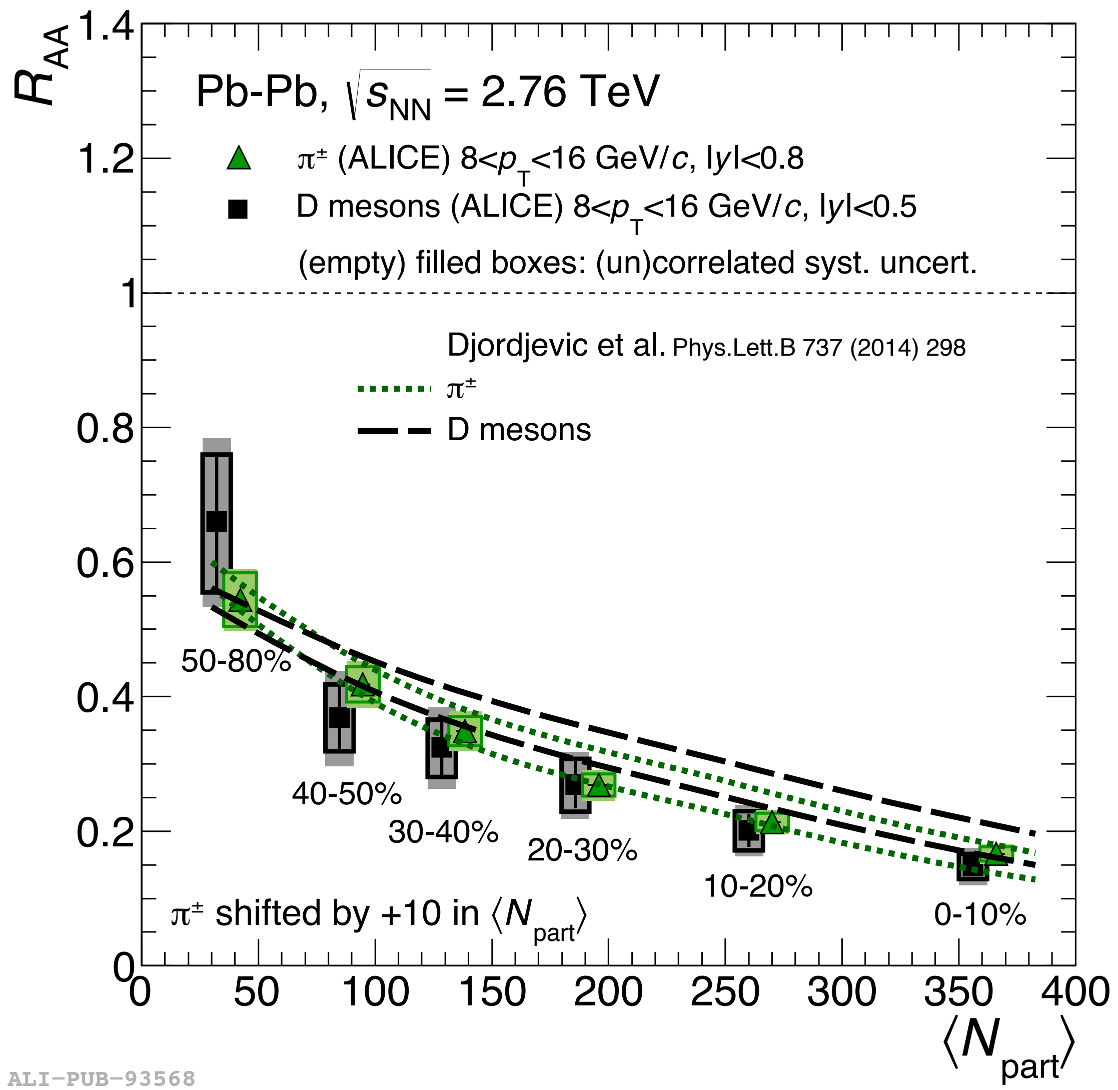


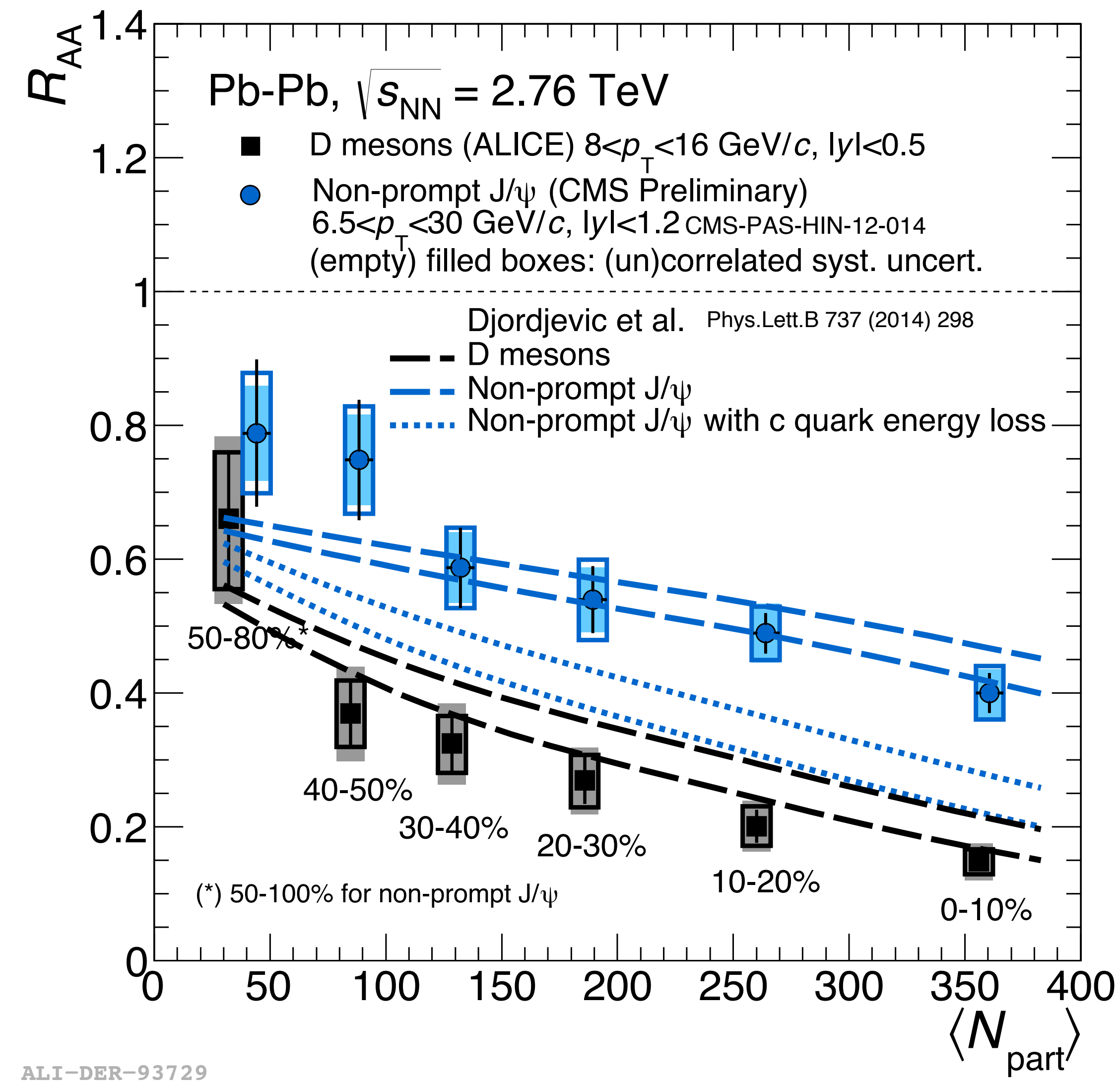
- Comparison of charged-pion and D-meson R_{AA} in 5<p_T<8 GeV/c
- **Compatible results within uncertainties**

arXiv:1506.06604

- Comparison of charged-pion, D-meson and non-prompt J/ψ R_{AA}
- Similar <p_T> (~10 GeV/c) for D and B mesons (B → J/ψ)
- **Indication of R_{AA}(D) < R_{AA}(B) in central Pb-Pb collisions**

D-meson R_{AA}: comparison with model predictions



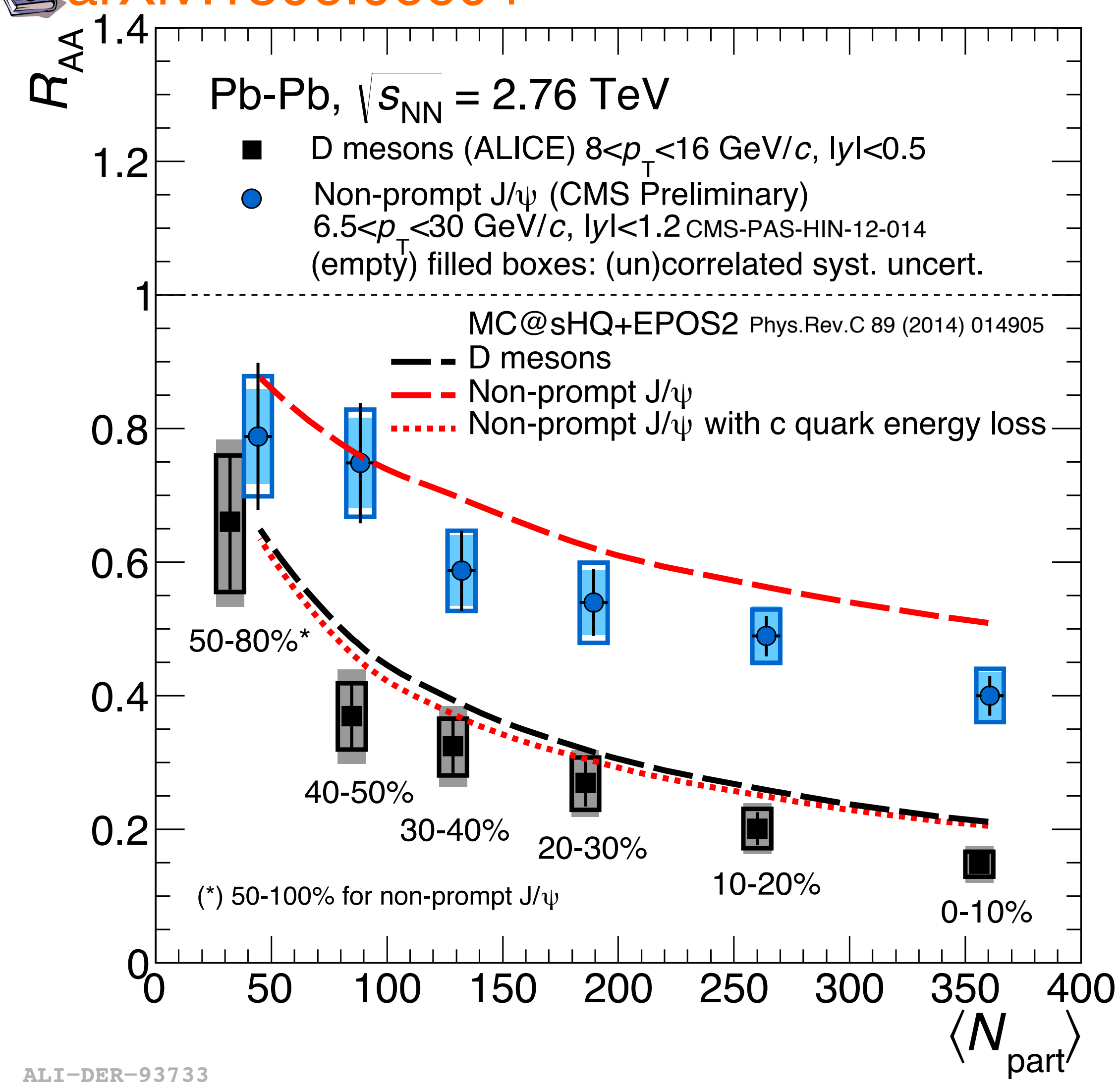


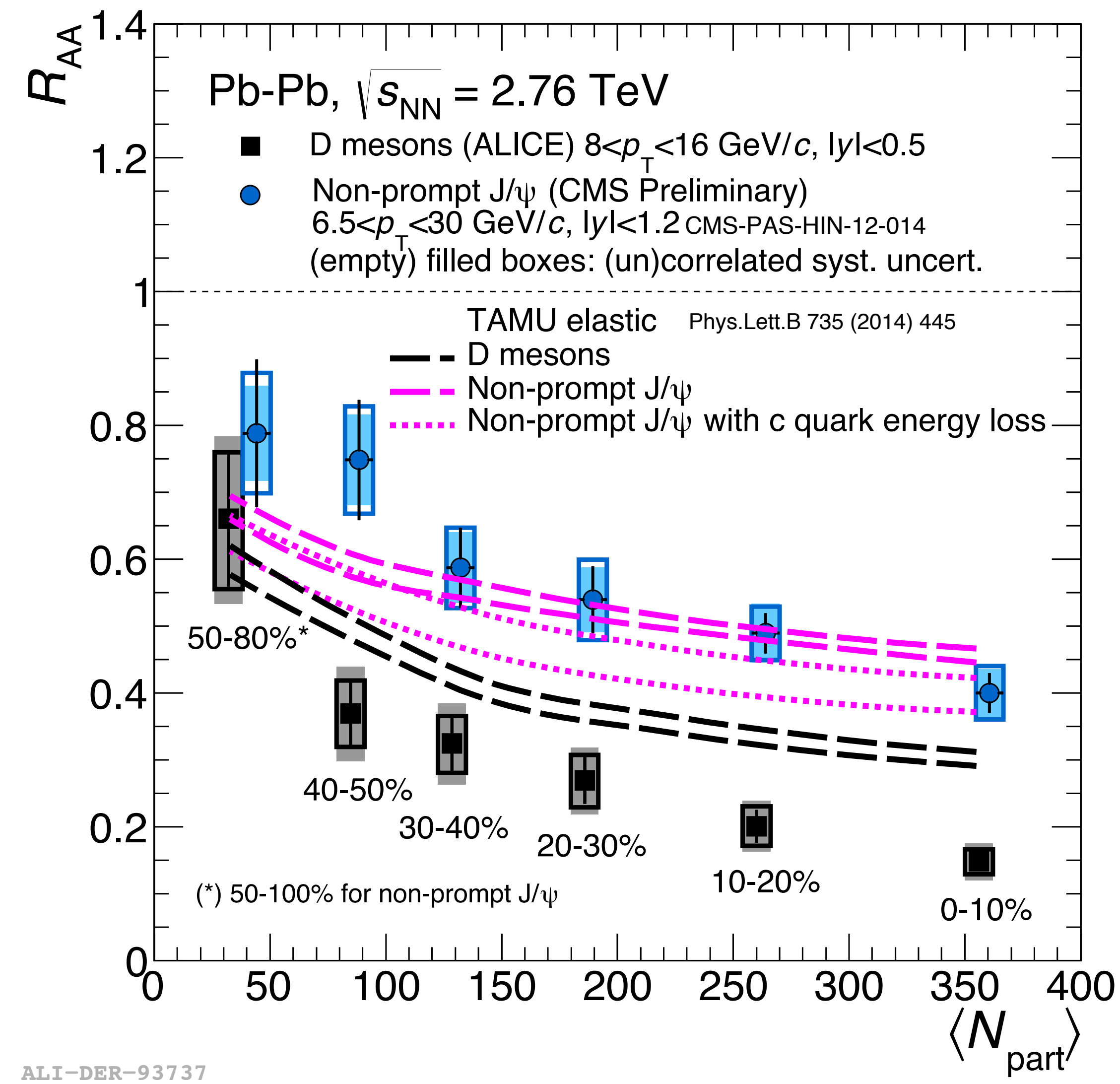
Comparison with a pQCD model including mass-dependent radiative and collisional energy loss:

- Agreement between D-meson and pion R_{AA}
- Colour-charge effect compensated by softer fragmentation and p_T spectrum of gluons with respect to c quarks
  - arXiv:1506.06604
  - Phys. Lett. B 737 (2014) 298
- Larger suppression of D mesons than of non-prompt J/ψ for the most central collisions
- Difference driven predominantly by the quark-mass dependence of energy loss

D-meson R_{AA}: comparison with model predictions

arXiv:1506.06604





- Model including *collisional processes* + *radiative corrections* + hydrodynamical expanding medium + quark recombination
- Large difference between D mesons and non-prompt J/ψ —> mass dependence of energy loss

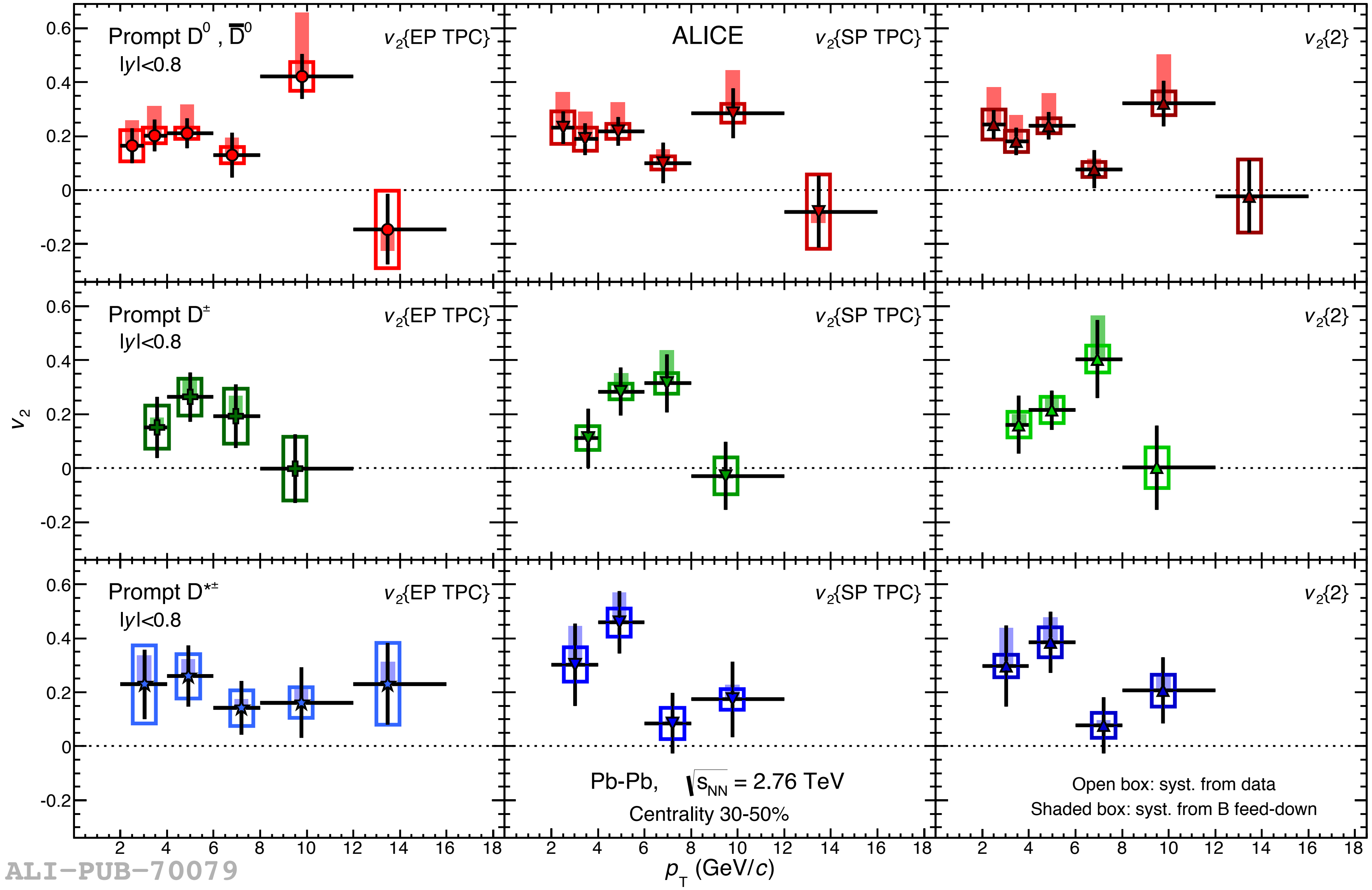
Phys. Rev. C 89 (2014) 014905

- Model including *only collisional processes* (*T*-matrix approach) + hydrodynamic medium evolution + quark recombination
- No radiative ΔE —> smaller mass effect

Nucl. Phys. A 910-911 (2013) 409; Phys. Lett. B 735 (2014) 445

D-meson v_2

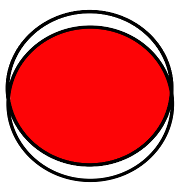
- D-meson v_2 measured with
  - event-plane method (experimental estimate of the reaction plane)
  - correlation methods: scalar product and 2-particle cumulants

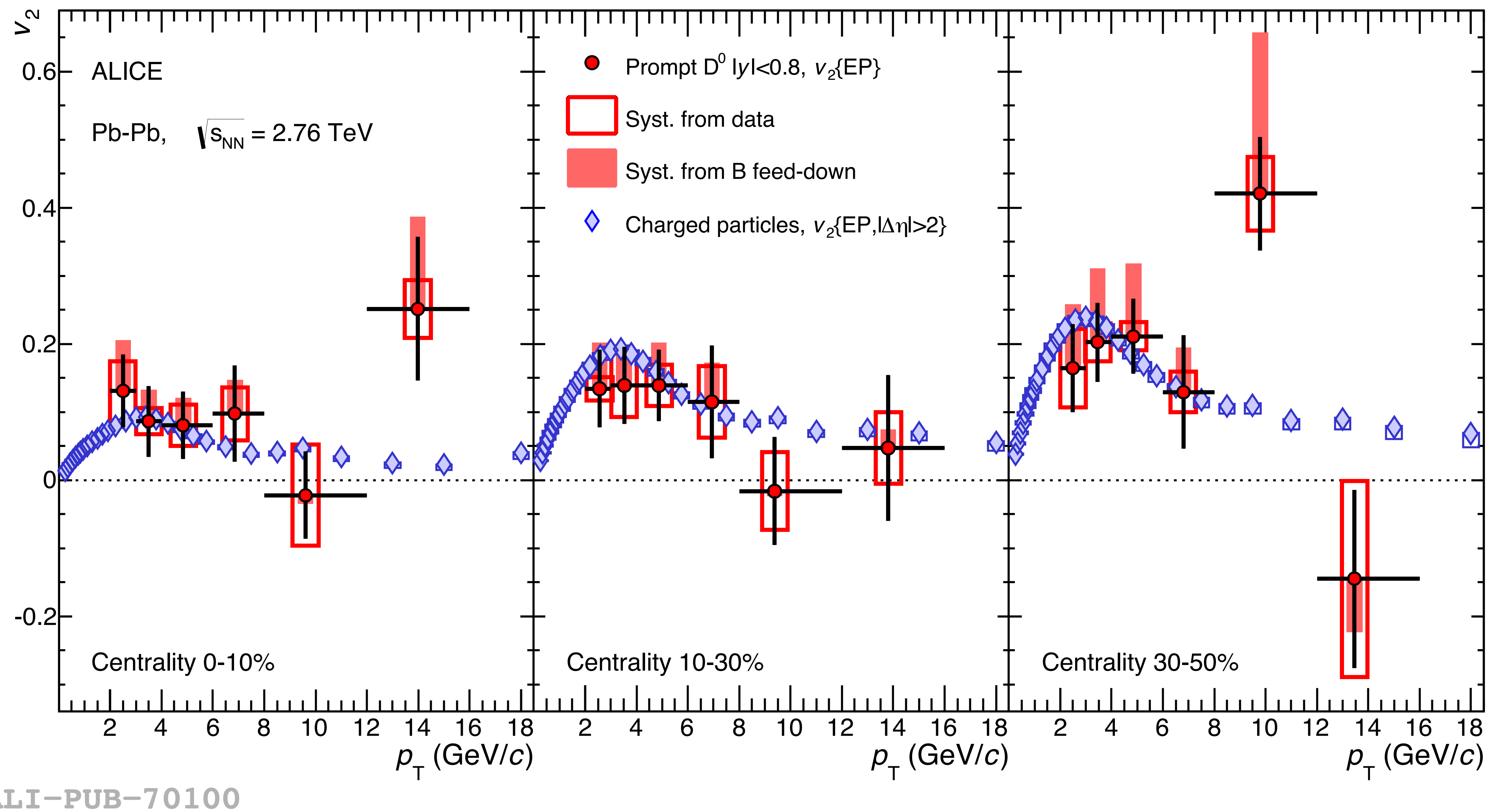


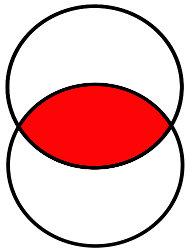
- v_2 of the three species consistent within uncertainties
- v_2 larger than 0 in $2<p_T<6$ GeV/c, consistent results from the three methods

Phys. Rev. C 90 (2014) 034904

D^0 and Charged-particle v_2



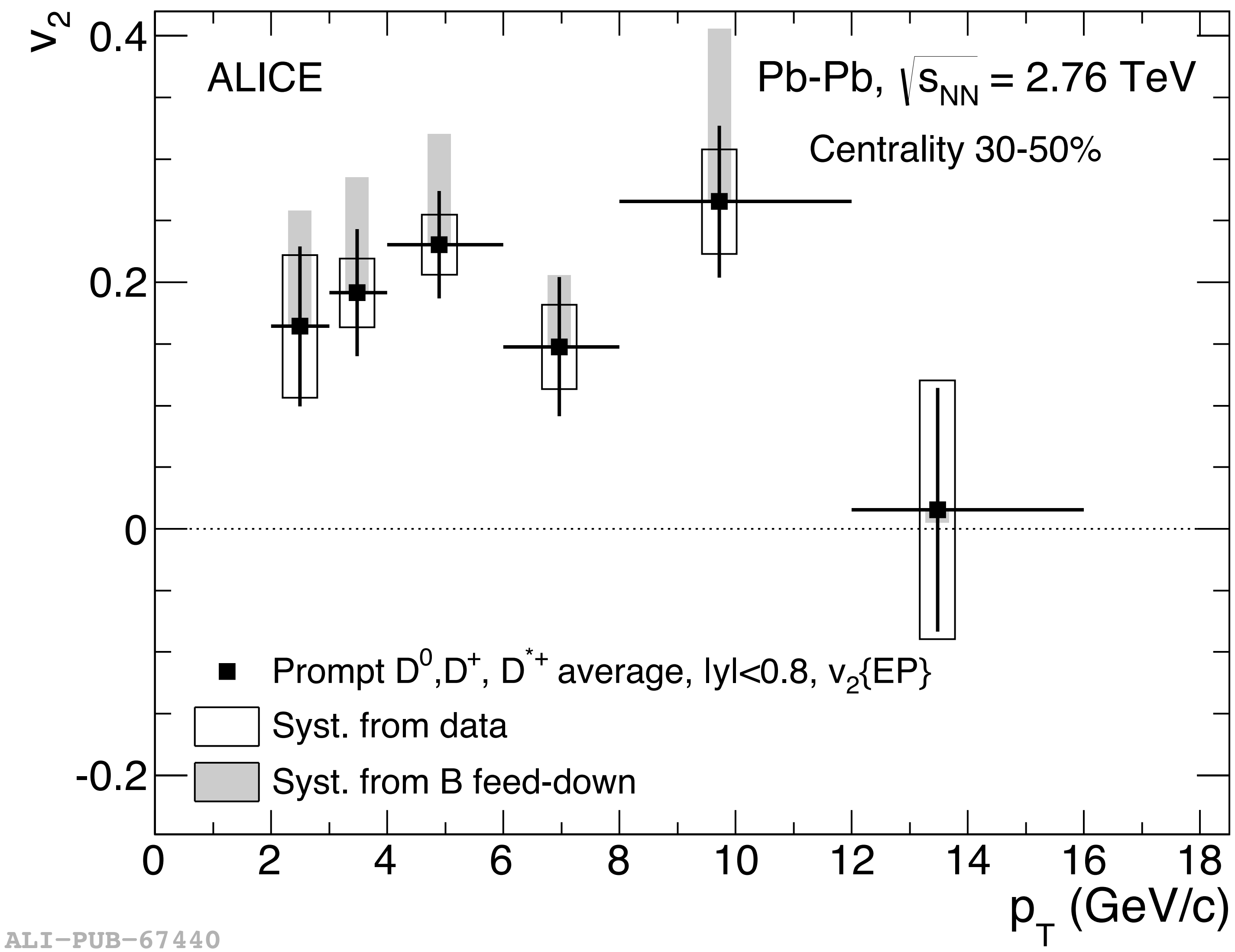


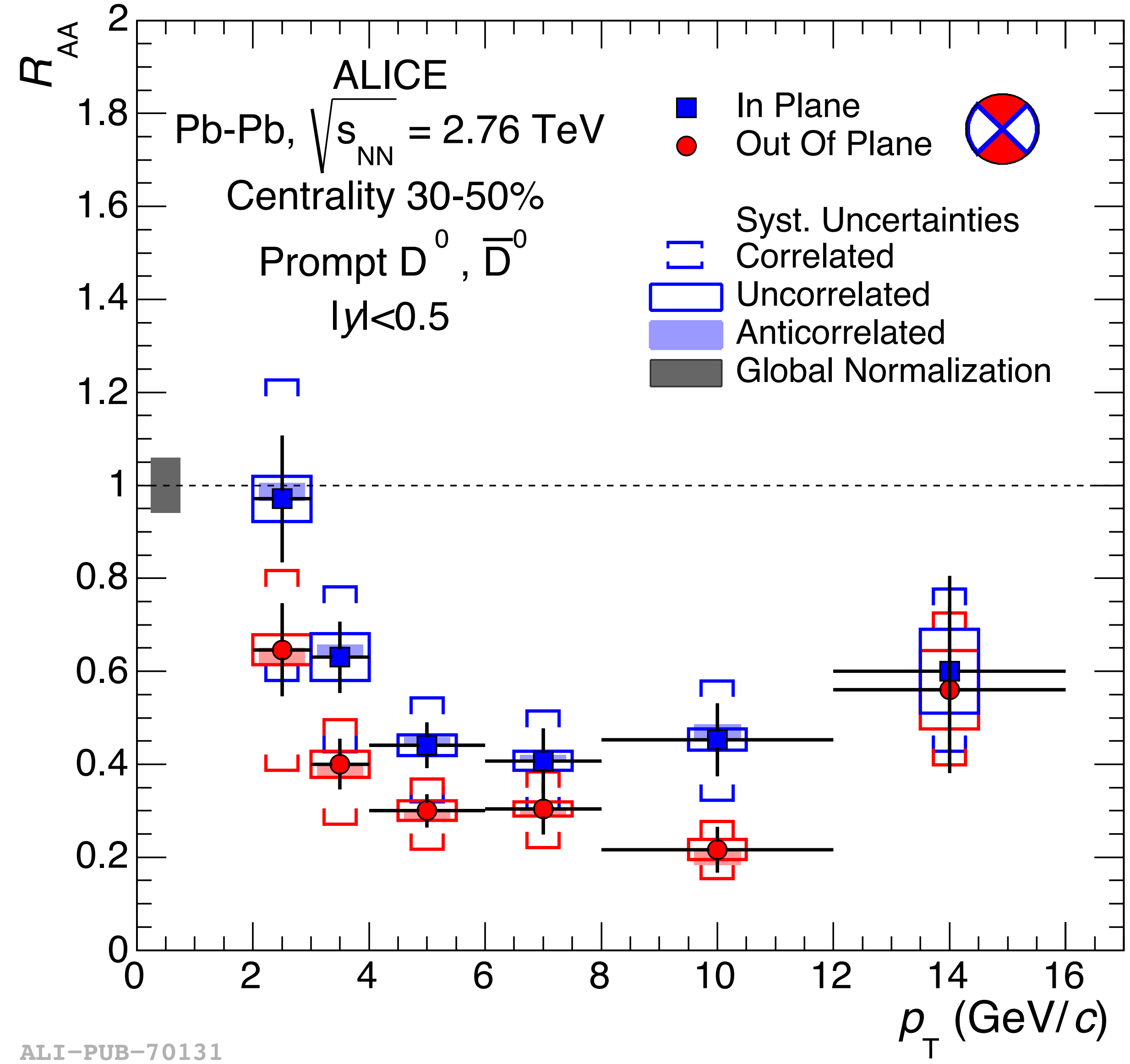


- v_2 of similar magnitude for charmed hadrons and light-flavour hadrons
- Indication of decreasing trend of v_2 towards more central collisions (consistent with decreasing initial-state geometrical asymmetry)

Phys. Rev. C 90 (2014) 034904

D-meson Azimuthal Anisotropy





- D-meson v_2 and, in-plane and out-of-plane D^0 R_{AA} in Pb-Pb collisions in the 30-50% centrality class
- v_2 larger than 0 in $2<p_T<6$ GeV/c with a significance of about 5σ
- Less suppression in the in-plane direction

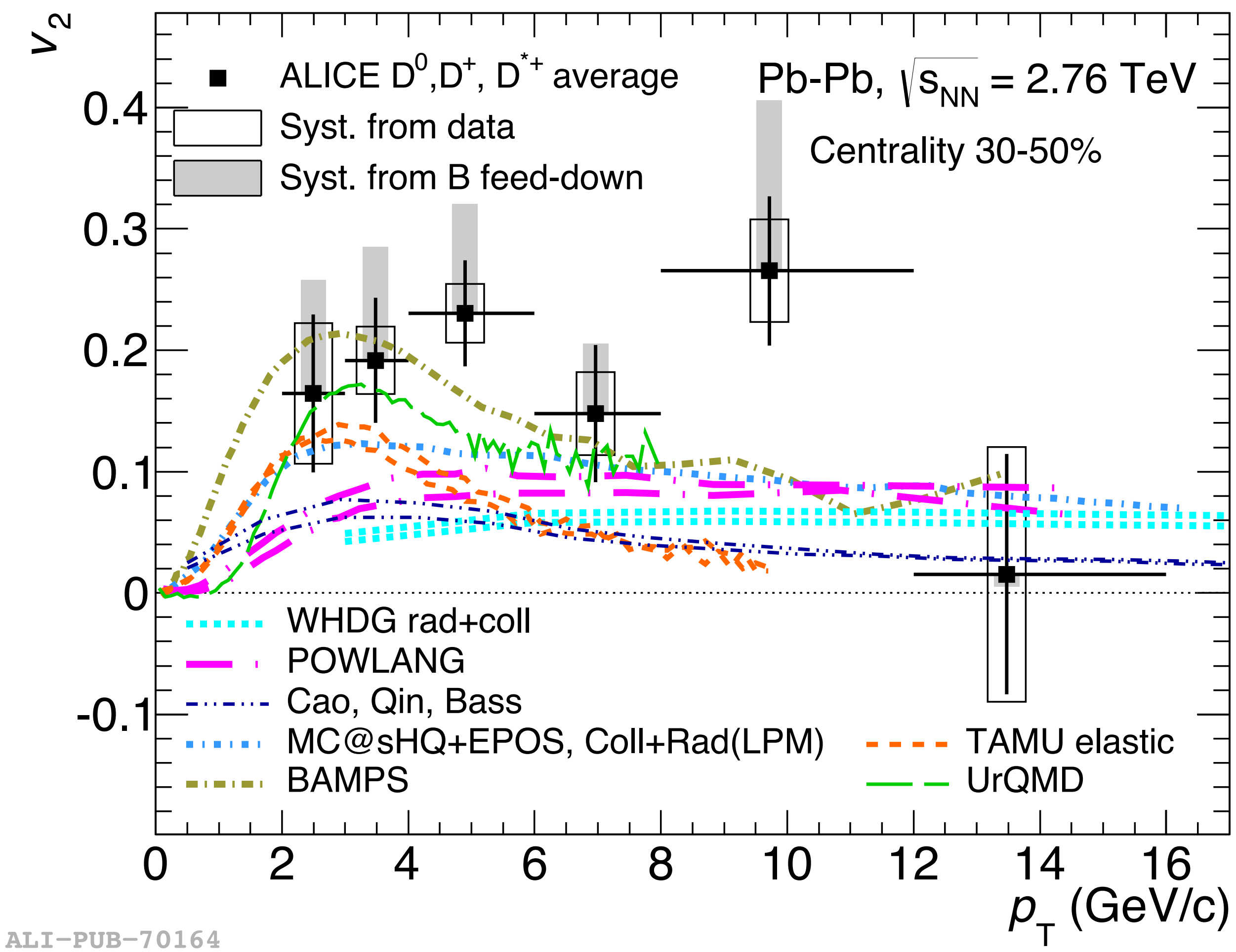
→ Consistent with expectations from collective flow

Phys. Rev. Lett. 111 (2013) 102301 Phys. Rev. C 90 (2014) 034904

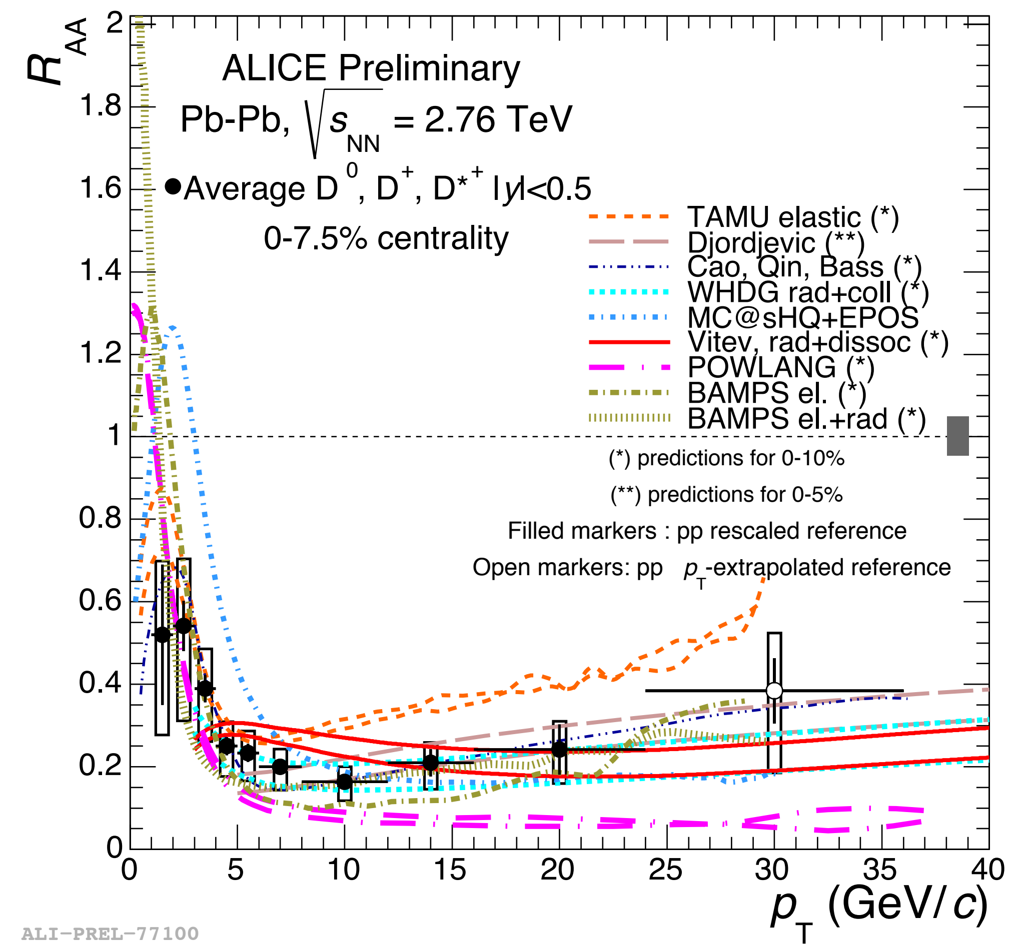
D-meson v_2 and R_{AA}

Comparison of theoretical model predictions to different observables simultaneously —> constraints on the description of the energy-loss mechanisms.

v_2 (30-50%)



R_{AA} (0-7.5%)



- Anisotropy best described by models including mechanisms that transfer to the charm quark the elliptic flow of the medium during the system expansion (collisional processes, hadronisation by recombination with light quarks)
- Models that best describe R_{AA} tend to underestimate the measured v_2

Phys. Rev. Lett. 111 (2013) 102301   Phys. Rev. C 90 (2014) 034904

Conclusions

- Strong **suppression** of **D mesons** observed in **central Pb-Pb** collisions for $p_T > 5$ GeV/c

- p-Pb results demonstrate that the suppression at high p_T in Pb-Pb collisions is due to the interaction with the **hot and dense partonic medium**

- Similar **D-meson** and **charged-pion** R_{AA} over the entire centrality range

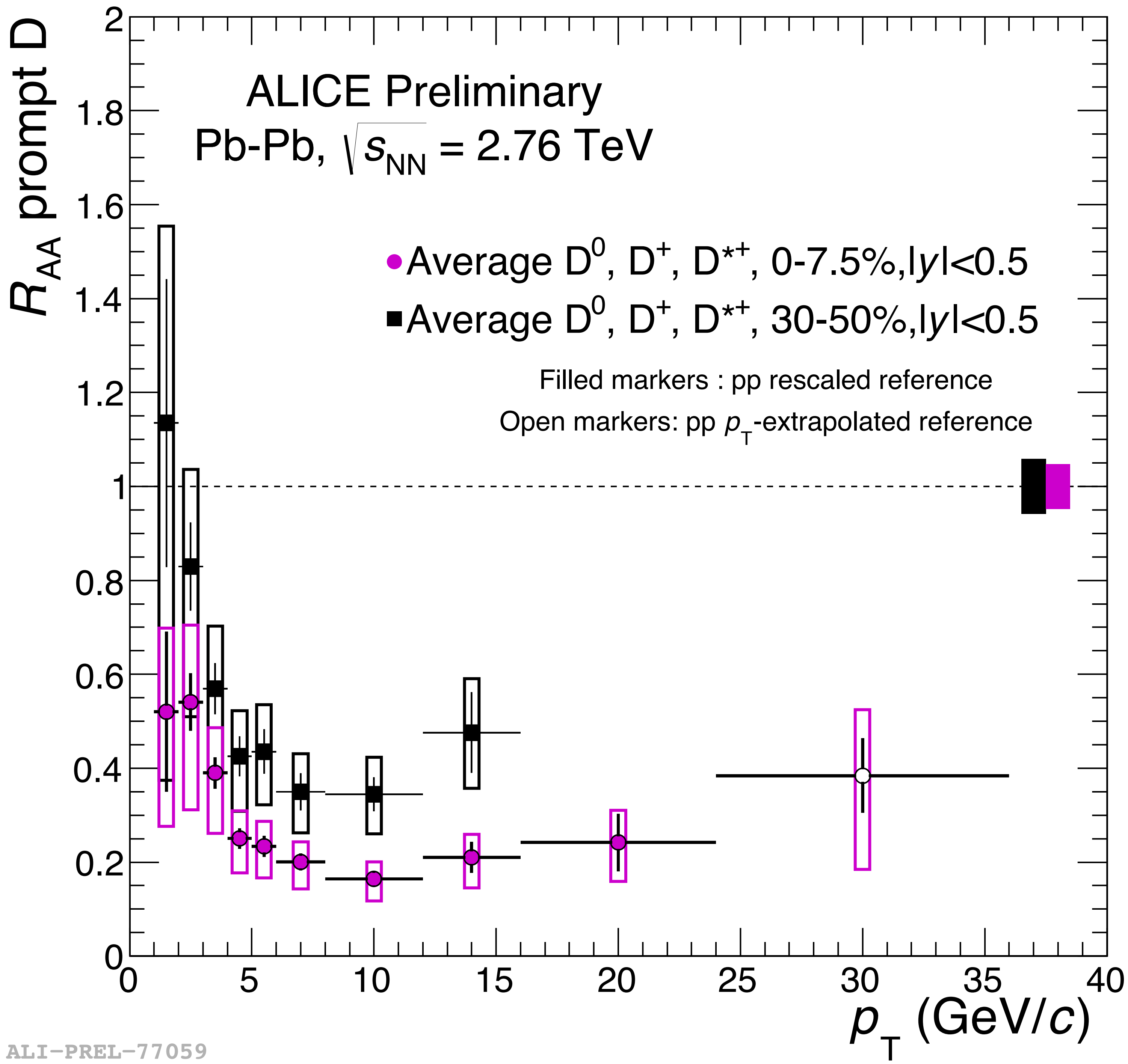
- Larger suppression of **D mesons** with respect to **B mesons** (non-prompt J/ψ by CMS) at $p_T \sim 10$ GeV/c

- **D-meson v_2 larger than 0** in the interval $2 < p_T < 6$ GeV/c with a significance of 5σ

- LHC Run 2 objective: R_{AA} and v_2 measurements with better precision and in an extended p_T range

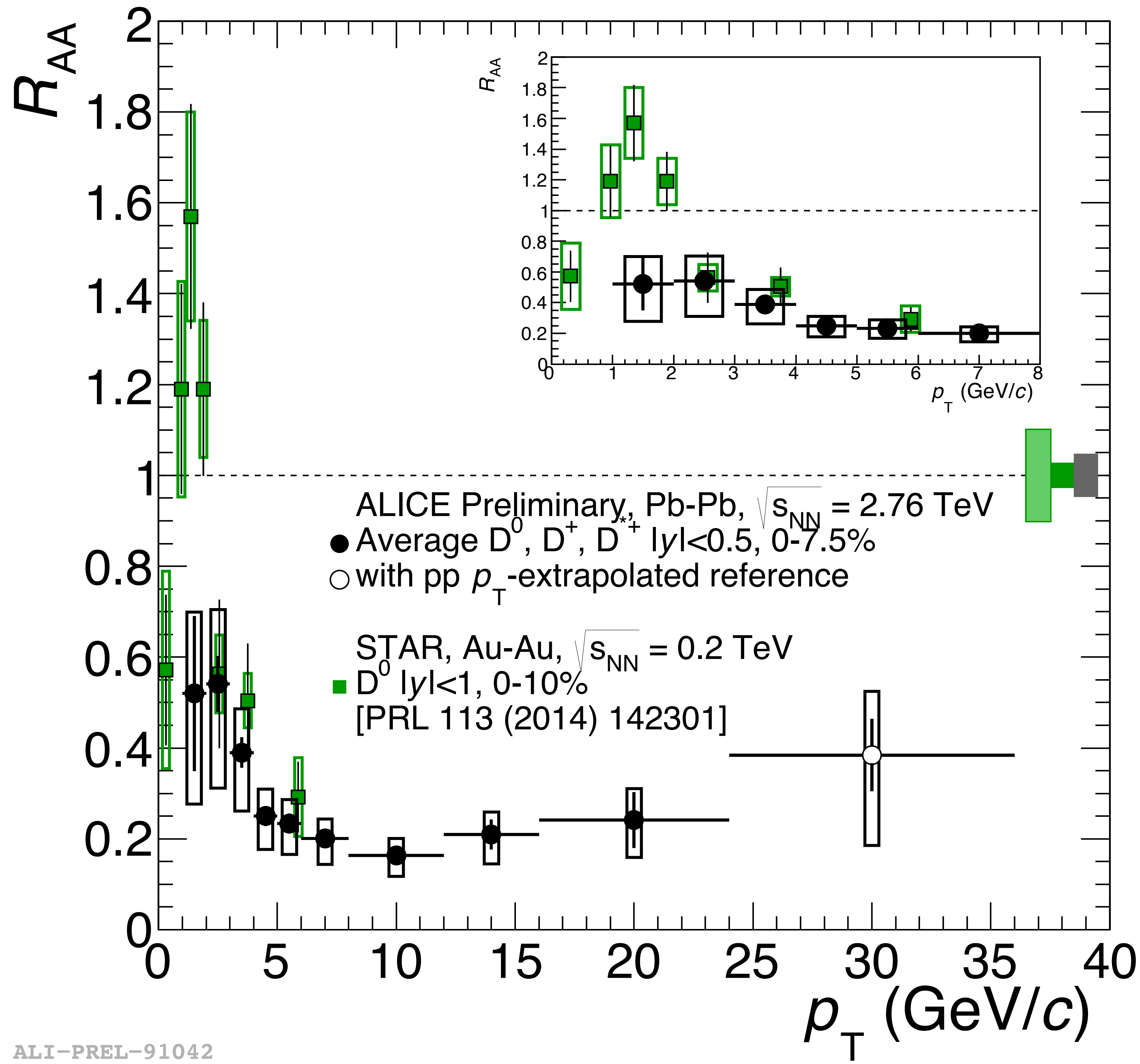
Backup

D-meson R_{AA} vs. p_T (2011 data)



- Large suppression (factor 6) at p_T=10 GeV/c in the 0-7.5% centrality class
- Suppression for p_T> 4 GeV/c observed in the 30-50% centrality class

D-meson R_{AA} vs. p_T (2011 data)



- D-meson R_{AA} at LHC and RHIC: different trend observed for p_T<2 GeV/c
  - stronger shadowing at LHC
  - momentum distribution less steep in pp collisions at LHC
  - different impact of coalescence

Feed-Down D-meson Subtraction

$$\left.\frac{d\sigma^{D^0}}{dp_T}\right|_{|y_{lab}|<0.5} = \frac{1}{\Delta y \Delta p_T} \frac{f_{prompt}(p_T) \cdot \frac{1}{2} \left. N_{raw}^{D^0+\overline{D^0}}(p_T)\right|_{|y_{lab}|<y_{fid}} \cdot c_{refl}(p_T)}{(Acc \times \epsilon)_{prompt}(p_T) \cdot BR \cdot L_{int}}$$

$$\begin{aligned} f_{prompt} &= 1 - \frac{N^{D^0 \text{ feed-down raw}}}{N^{D^0 \text{ raw}}} = \\ &= 1 - \langle T_{AA(pA)} \rangle \times \left(\frac{d^2\sigma}{dy\,dp_T}\right)^{FONLL}_{feed-down} \times R_{AA(pA)}^{feed-down} \times \\ &\times \frac{(Acc \times \epsilon)_{feed-down} \cdot \Delta y \Delta p_T \cdot BR \cdot N_{evt}}{N^{D^0 \text{ raw}}/2} . \end{aligned}$$

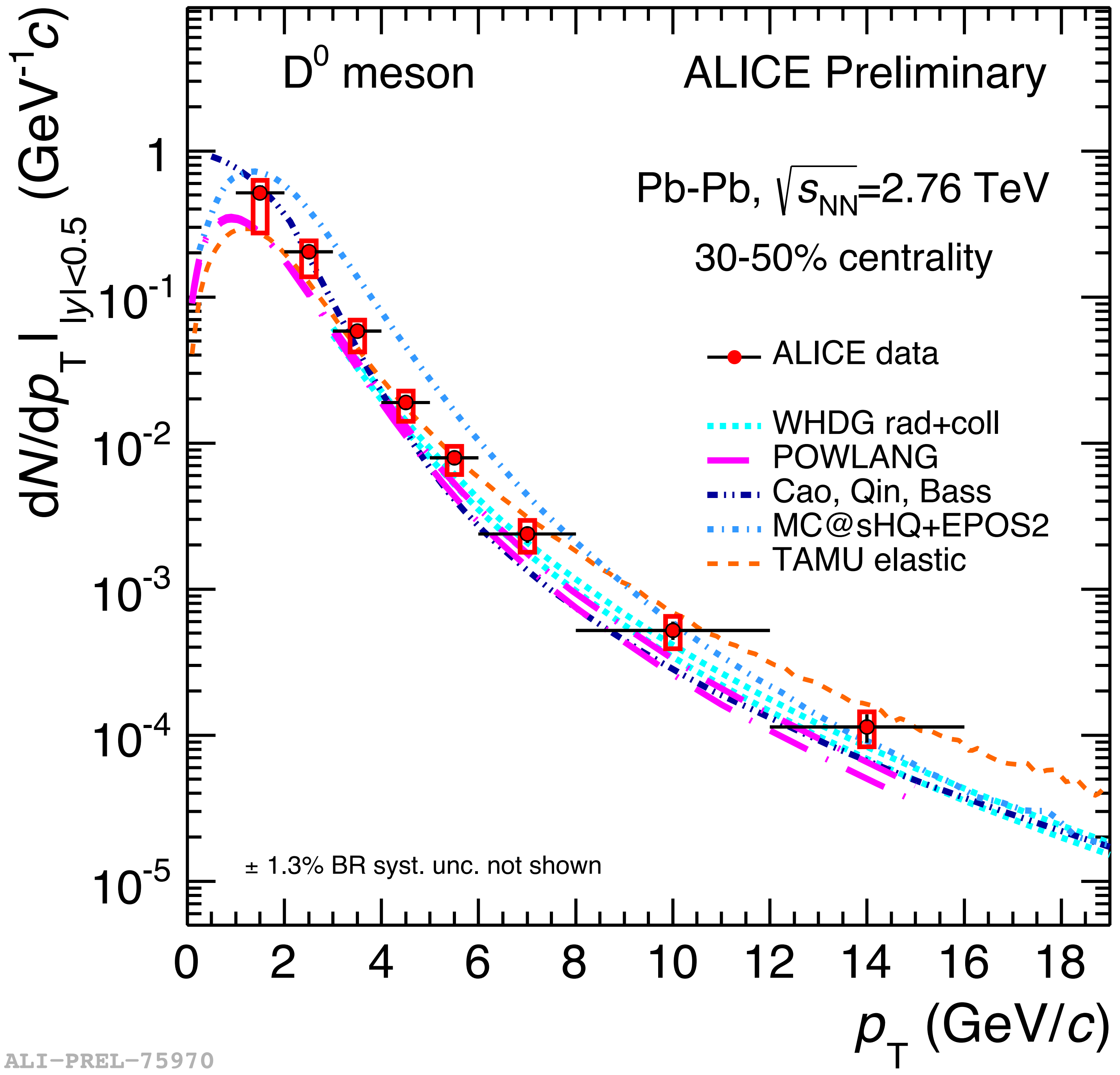
- pQCD calculation of the beauty production cross section —> D from B yield
- Assumption on the nuclear modification factor of D mesons from B decays.

$$R_{AA}^{feed-down} = 2 \cdot R_{AA}^{prompt}$$

$$1 < R_{AA}^{feed-down}/R_{AA}^{prompt} < 3$$

Variation considered to estimate the systematic uncertainty

D-meson Cross Section



WHDG rad+coll: Nucl. Phys. A 872 (2011) 265
POWLANG: JPG 38 (2011) 124144
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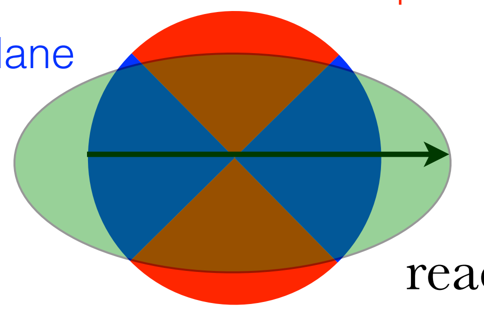
MC@sHQ+EPOS: PRC 89 (2014) 014905
TAMU elastic: arXiv:1401.3817

D-meson v_2 - Event-Plane Method

- D^0 meson azimuthal anisotropy quantified through:
  - elliptic flow v_2: the second coefficient of the expansion

$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{\mathrm{in-plane}} - N_{\mathrm{out-of-plane}}}{N_{\mathrm{in-plane}} + N_{\mathrm{out-of-plane}}}$$



  - nuclear modification factor R_{AA} azimuthal dependence with respect to the reaction plane

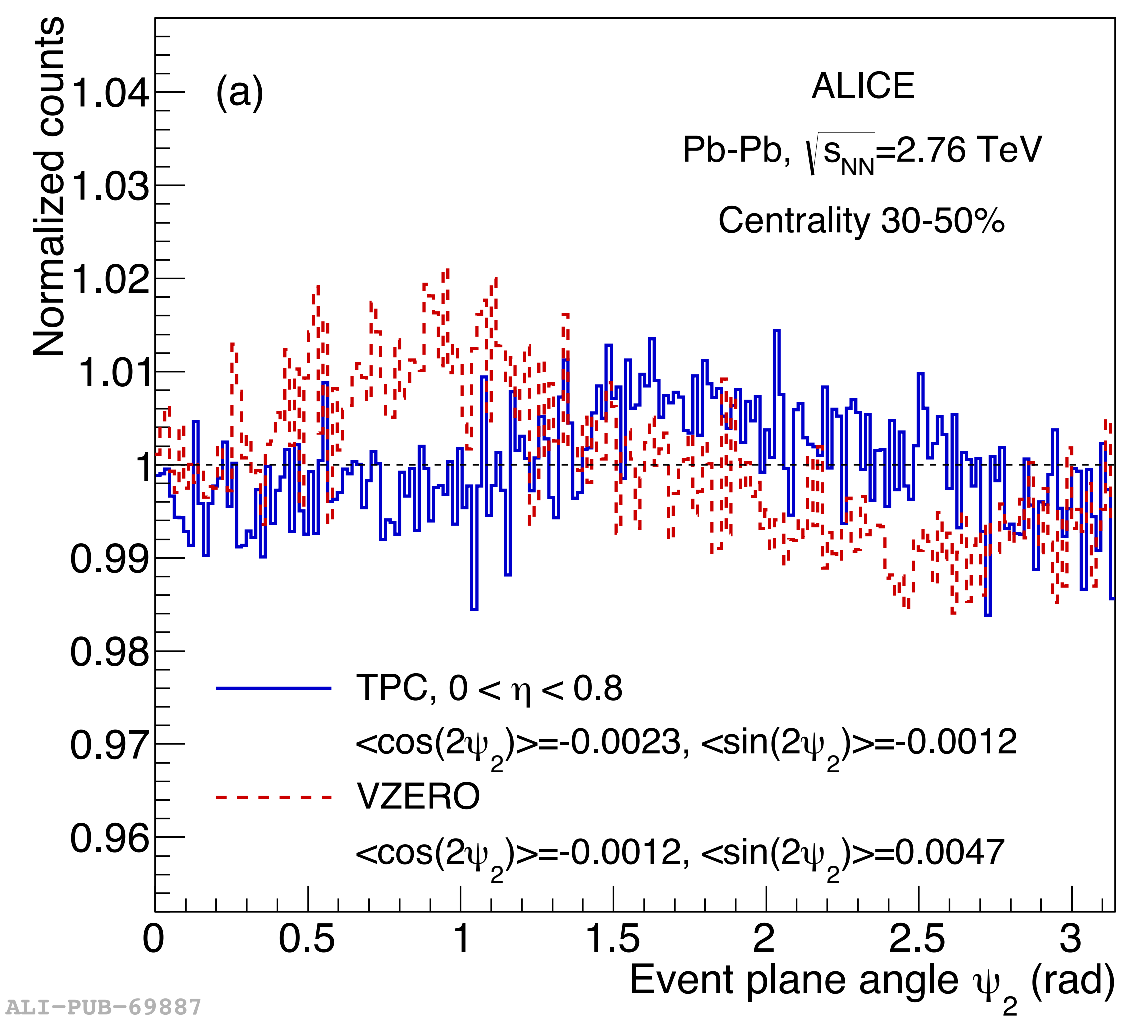
$$R_{\mathrm{AA}}^{\mathrm{in(out)}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{AA}}^{\mathrm{in(out)}}/\mathrm{d}p_{\mathrm{T}}}{\langle T_{\mathrm{AA}}\rangle \cdot (\mathrm{d}\sigma_{pp}/\mathrm{d}p_{\mathrm{T}})/2}$$

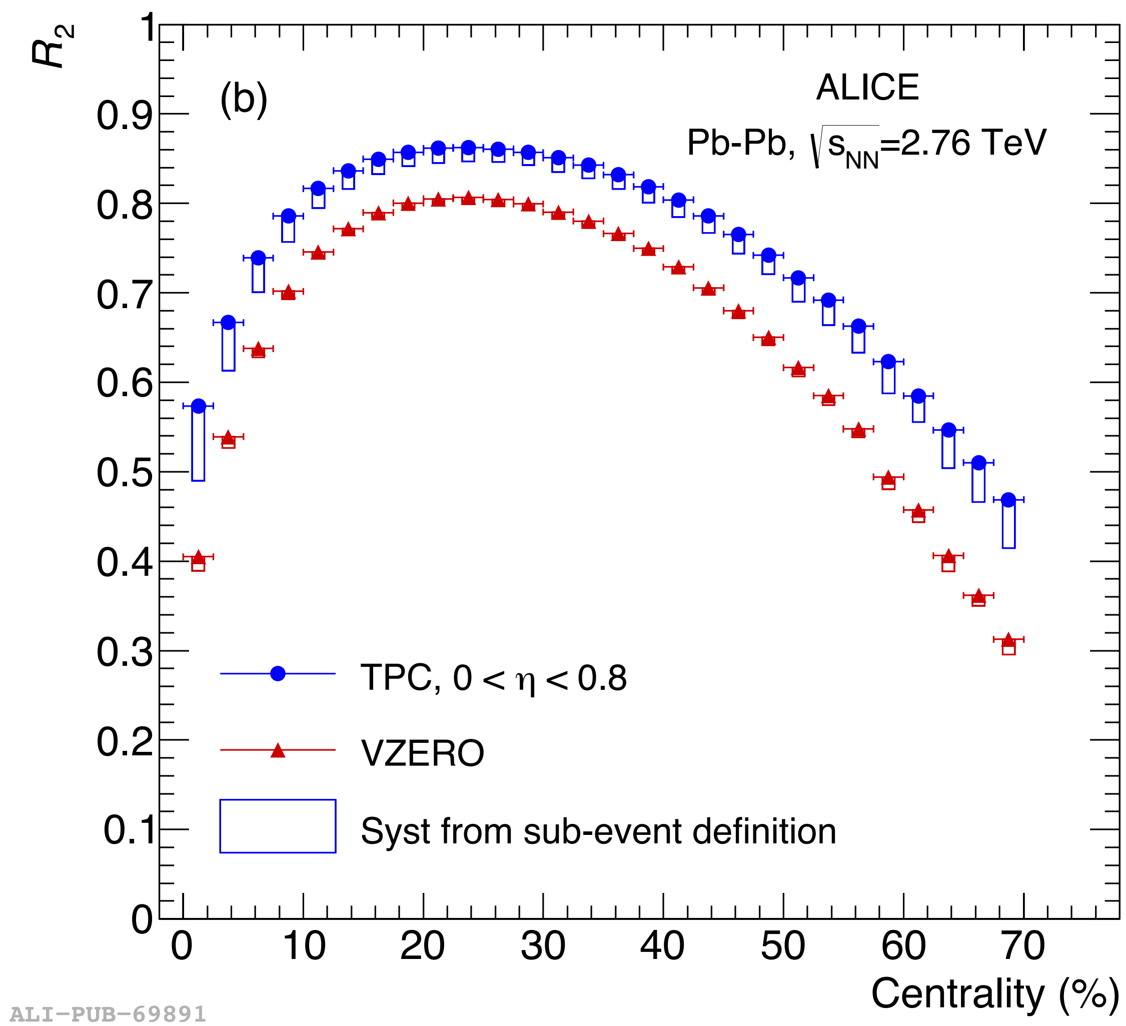
Event-Plane Angle

$$\vec{Q} = \begin{pmatrix} \sum_{i=1}^{N} w_i \cos 2\varphi_i \\ \sum_{i=1}^{N} w_i \sin 2\varphi_i \end{pmatrix}$$

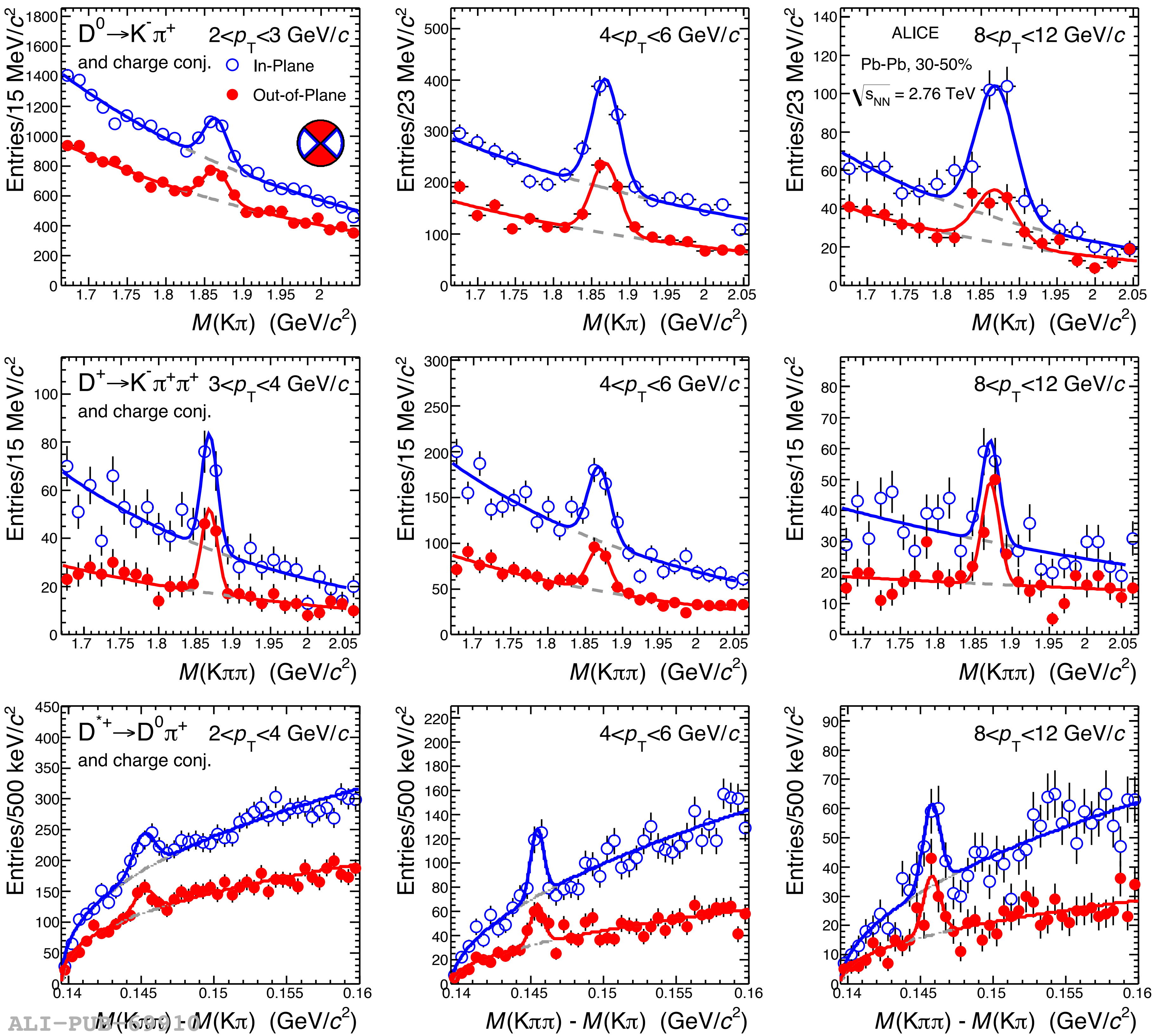
$$\psi_2 = \frac{1}{2}\tan^{-1}\left(\frac{Q_y}{Q_x}\right)$$

$$R_2^{\mathrm{sub}} = \sqrt{\langle \cos[2(\psi_2^A - \psi_2^B)] \rangle}$$



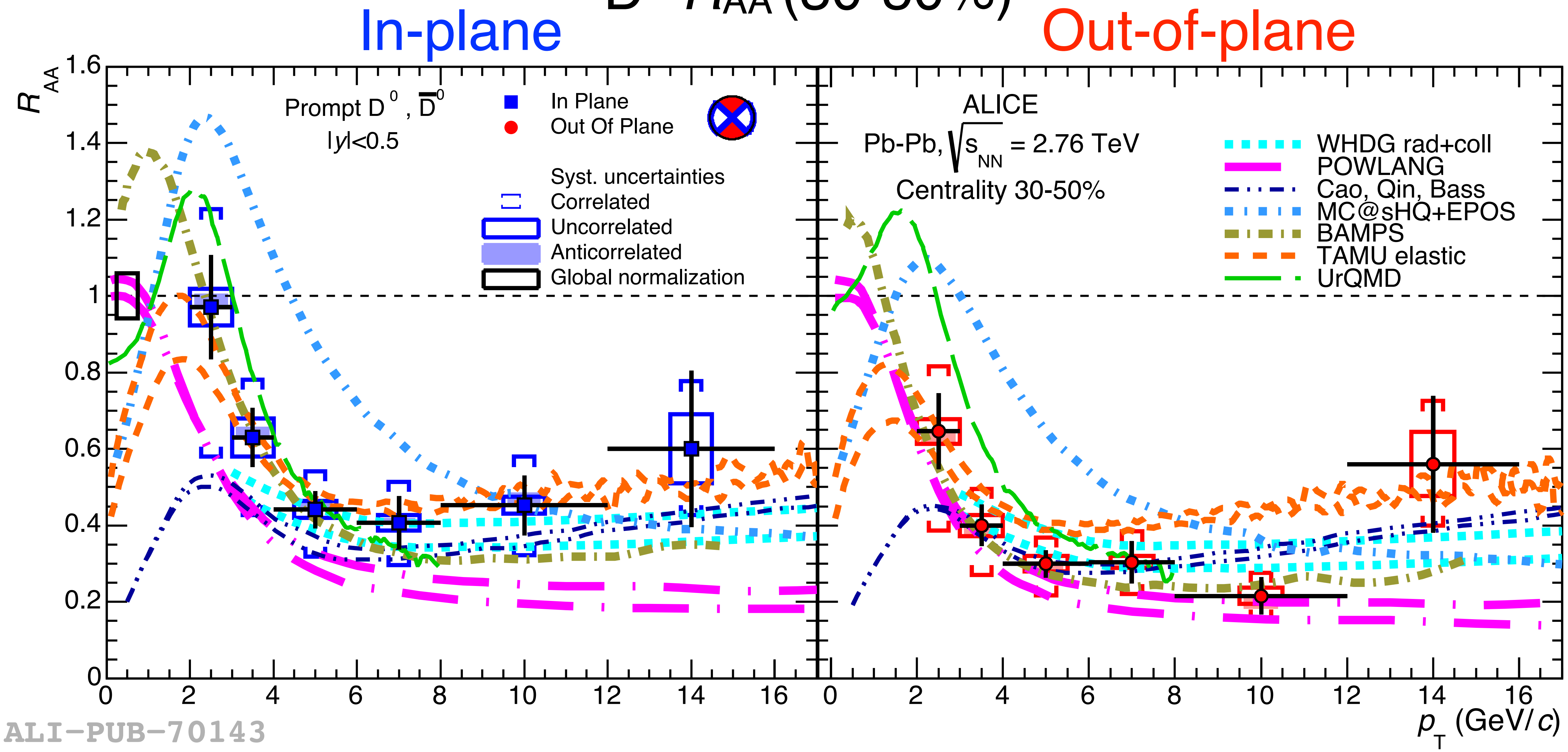


D-meson v_2 - Event-Plane Method



D-meson Azimuthal Anisotropy

D0 R_{AA} (30-50%)



- R_{AA} measured in-plane and out-of-plane, sensitive to
  - path length dependence of parton energy loss at high p_T
  - collectivity at low p_T

WHDG rad+coll: Nucl. Phys. A 872 (2011) 265
POWLANG: JPG 38 (2011) 124144
Cao, Qin, Bass: PRC 88 (2013) 044907
MC@sHQ+EPOS: PRC 89 (2014) 014905
BAMPS: PLB 717 (2012) 430
TAMU elastic: arXiv:1401.3817
UrQMD: J. Phys. Conf. Ser. 426 (2013) 012032
Phys. Rev. C 90 (2014) 034904

Feed-Down D-Meson v_2

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

Assumption

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

Variation considered to estimate the systematic uncertainty

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

Scalar Product

$$v_2\{\mathrm{SP}\} = \frac{1}{2}\left(\frac{\left\langle \vec{u}_a \cdot \frac{\vec{Q}_b}{N_b} \right\rangle}{\sqrt{\left\langle \frac{\vec{Q}_a}{N_a} \cdot \frac{\vec{Q}_b}{N_b} \right\rangle}} + \frac{\left\langle \vec{u}_b \cdot \frac{\vec{Q}_a}{N_a} \right\rangle}{\sqrt{\left\langle \frac{\vec{Q}_a}{N_a} \cdot \frac{\vec{Q}_b}{N_b} \right\rangle}} \right)$$

$$\vec{u} = (\cos 2\varphi_{\mathrm{D}}, \sin 2\varphi_{\mathrm{D}})$$

Elliptic flow computed by correlating D mesons from the positive eta-region and charged particles in the negative eta-region (and vice-versa)

Two-Particle Cumulant

$$v_2\{2\} = \frac{\left\langle \vec{u} \cdot \frac{\vec{Q}}{N} \right\rangle}{\sqrt{\left\langle \frac{\vec{Q}_a}{N_a} \cdot \frac{\vec{Q}_b}{N_b} \right\rangle}}$$

No pesudo-rapidity gap between the D mesons and reference particles