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Measurement of non-strange D-meson production and azimuthal anisotropy in Pb-Pb collisions with ALICE at the LHC

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On behalf of the ALICE Collaboration

NWO
Netherlands Organisation for Scientific Research

Nikhef

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Heavy flavours in heavy-ion collisions

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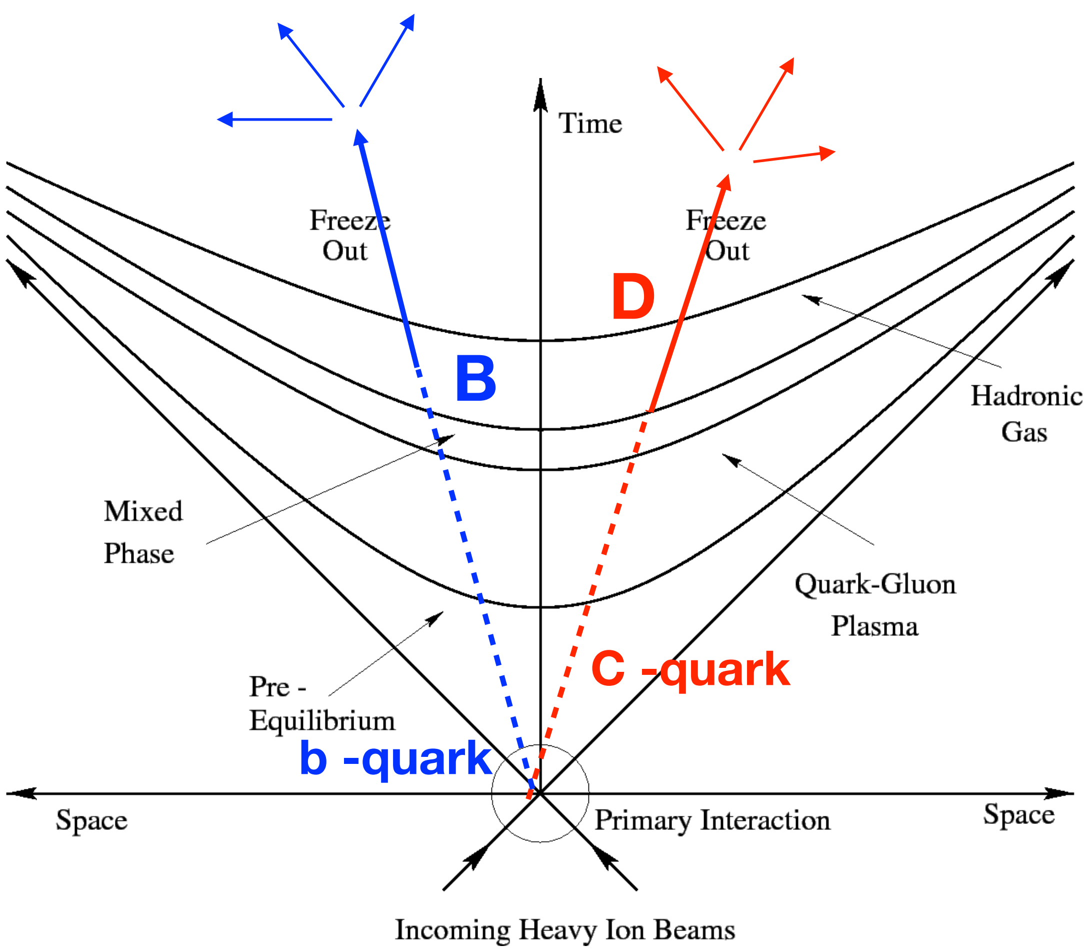
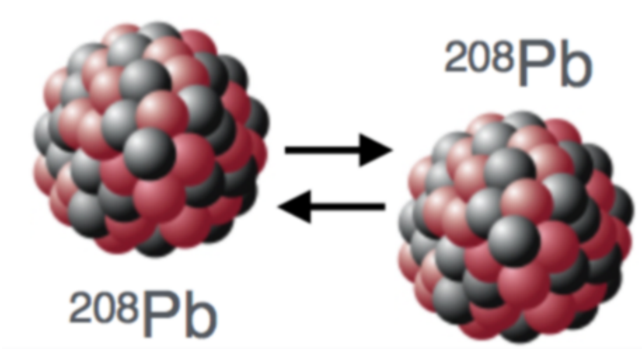
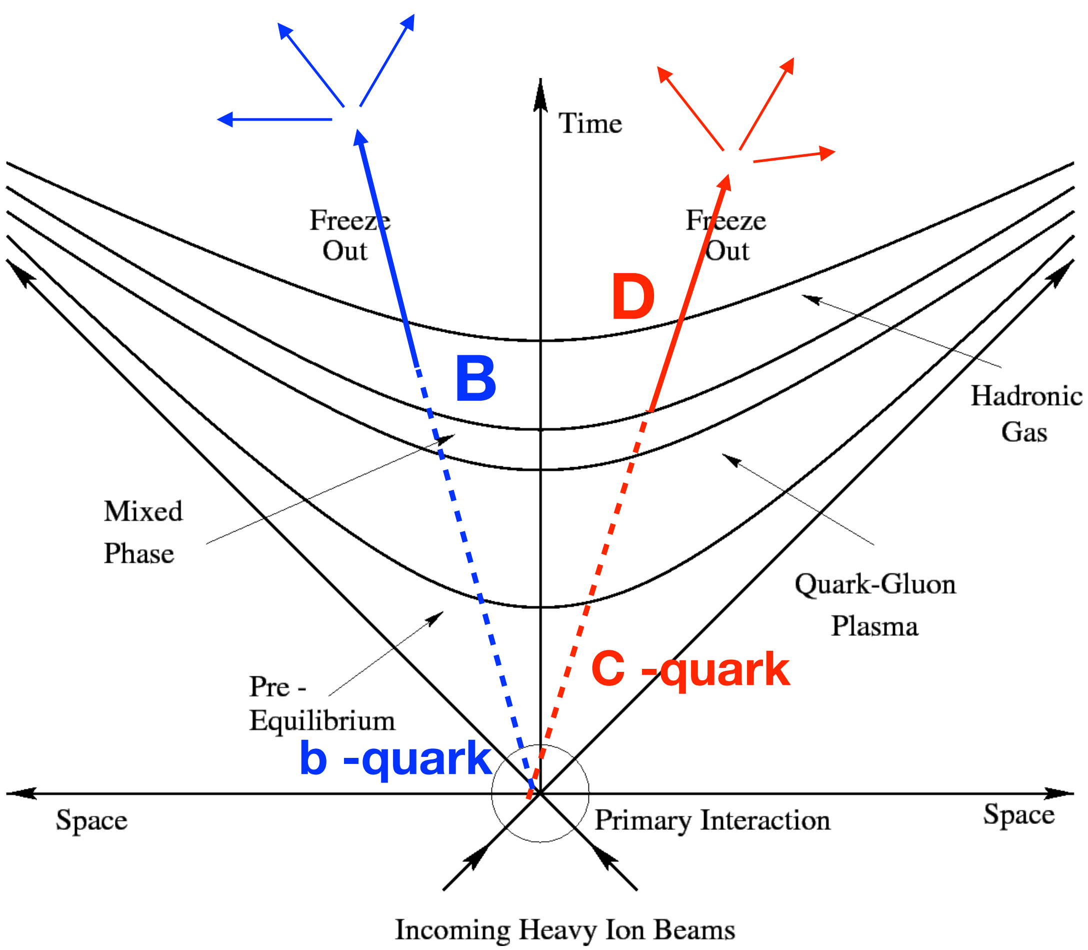
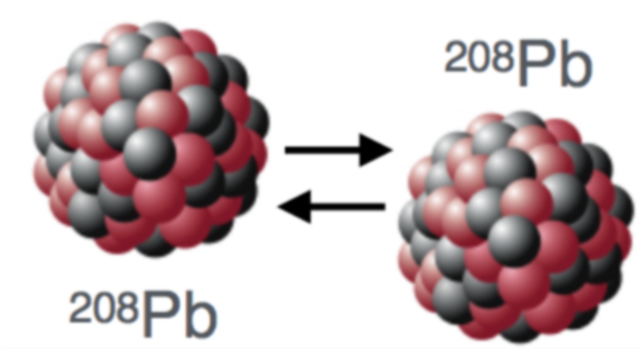




- Heavy quarks (charm & beauty) produced in hard parton scattering processes (in the early stage of collision)
- HF production time: ~ 0.1(0.02) fm/*c* for charm (beauty)
  Quark-Gluon Plasma formation time: ~ 0.3 fm/*c* at the LHC

Heavy flavours in heavy-ion collisions





- Heavy quarks (charm & beauty) produced in hard parton scattering processes (in the early stage of collision)
- HF production time: ~ 0.1(0.02) fm/*c* for charm (beauty)
  Quark-Gluon Plasma formation time: ~ 0.3 fm/*c* at the LHC
- HF experience the whole system evolution
- HF interact strongly with the constituents of the medium and lose part of their energy

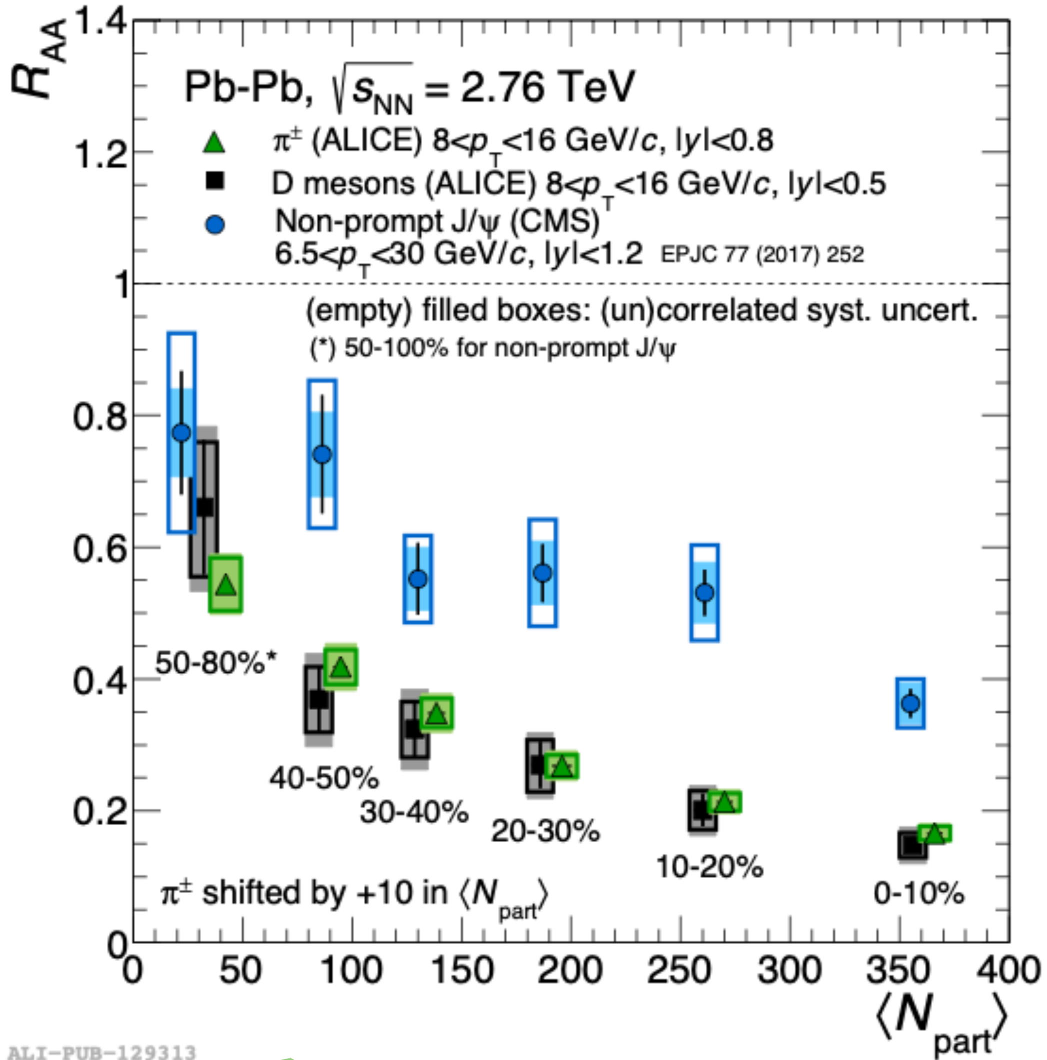
→ **Powerful probe for the characterisation of the Quark-Gluon Plasma**

Heavy-flavour observables in heavy-ion collisions

1) Nuclear modification factor

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \cdot \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

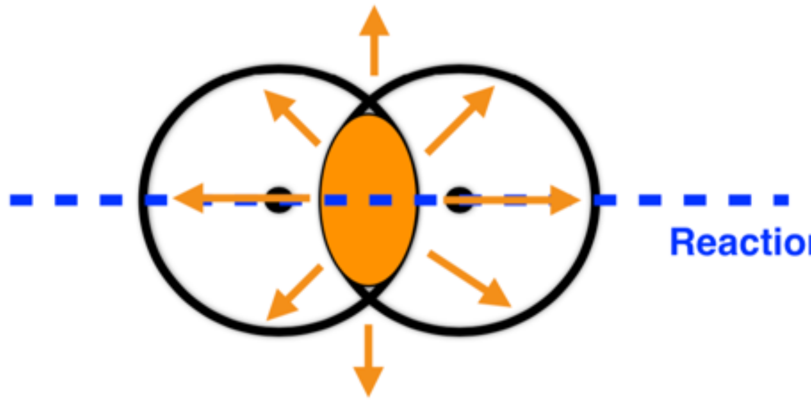
- Study the parton energy loss in the medium via:
  - inelastic processes (gluon radiation) [1]
  - elastic scatterings (collisional processes) [2]
- Medium density and path-length dependence [3]
- Colour-charge and quark-mass dependence of energy loss [4]



10.1007/JHEP11(2015)205

[1] Baier et al. Nucl. Phys. B 483 (1997) 291-320
[2] E. Braaten, M. H. Thoma, Phys. Rev. D 44, no. 9, R2625 (1991)
[3] B. W. Zhang, E. Wang, X. N. Wang, Phys. Rev. Lett. 93, 072301 (2004)
[4] Y. L. Dokshitzer and D. E. Kharzeev, Phys. Lett. B 519, 199 (2001)

2) Azimuthal anisotropy



$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3p} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_{\mathrm{T}}\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\left\{1+\sum_{n=1}^{\infty}v_n\cos[n(\varphi-\Psi_{\mathrm{RP}})]\right\}$$

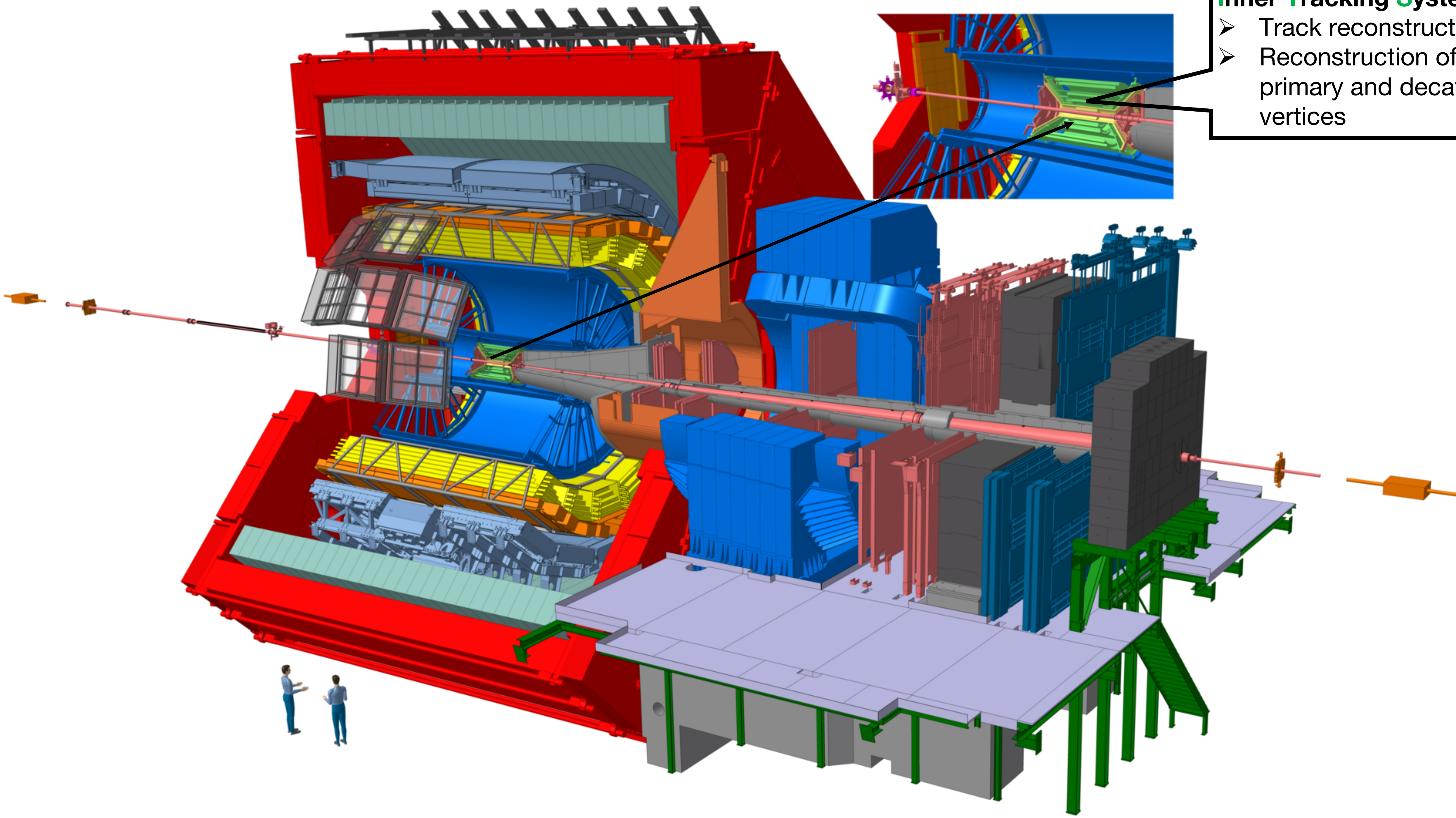
$$v_2 = \langle\cos[2(\varphi-\Psi_{\mathrm{RP}})]\rangle$$

2nd harmonic coefficient, Elliptic Flow

- v_2 carries information on medium transport properties:
  - thermalisation of heavy quarks in QGP at low p_{T} [1]
  - path-length dependence of energy loss at high p_{T} [2]

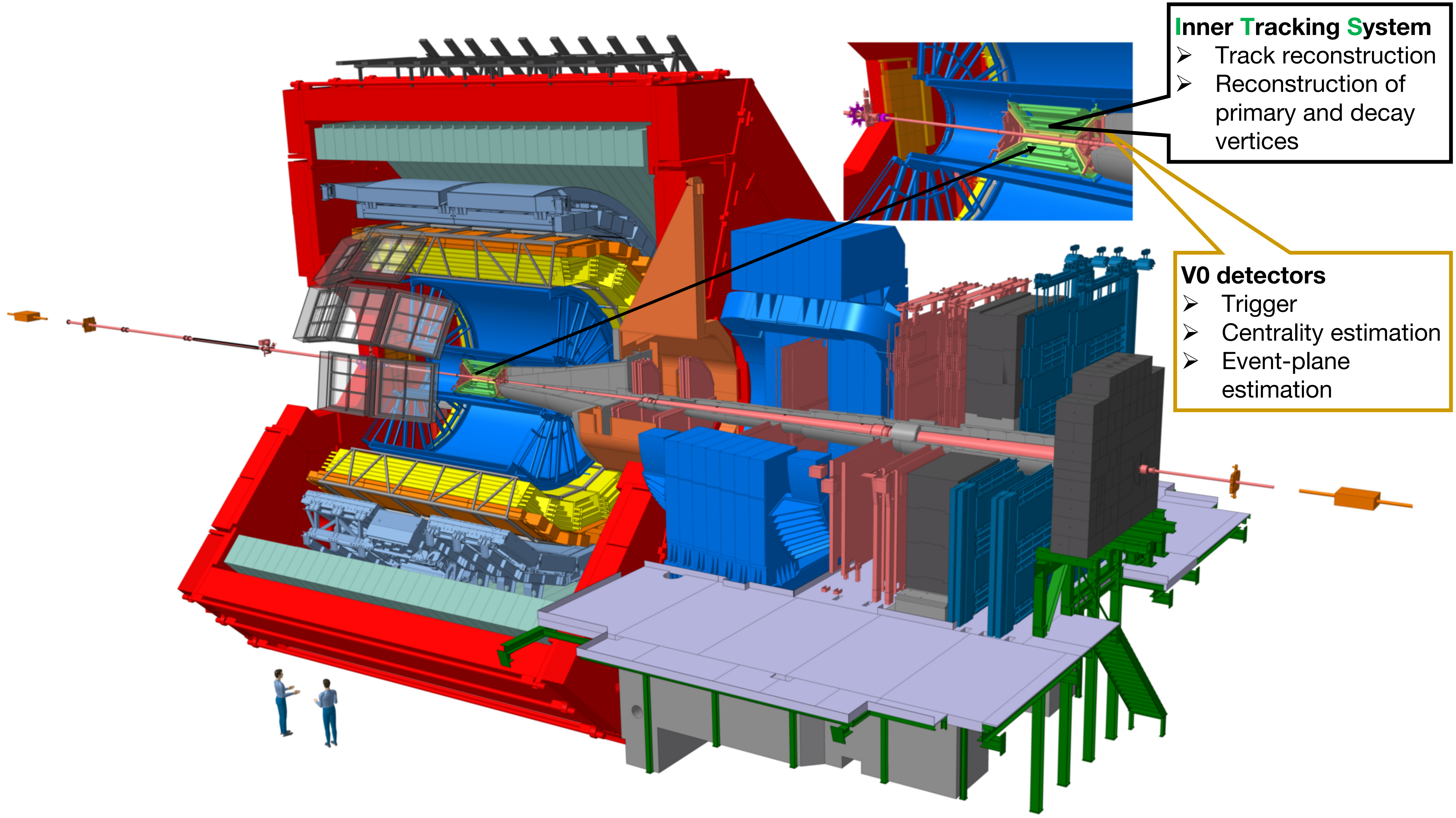
[1] S. Batsouli, S. Kelly, M. Gyulassy, J. L. Nagle, Phys. Lett. B 557, 26 (2003)
[2] M. Gyulassy, I. Vitev, X. N. Wang, Phys. Rev. Lett. 86, 2537 (2001)

The ALICE detector

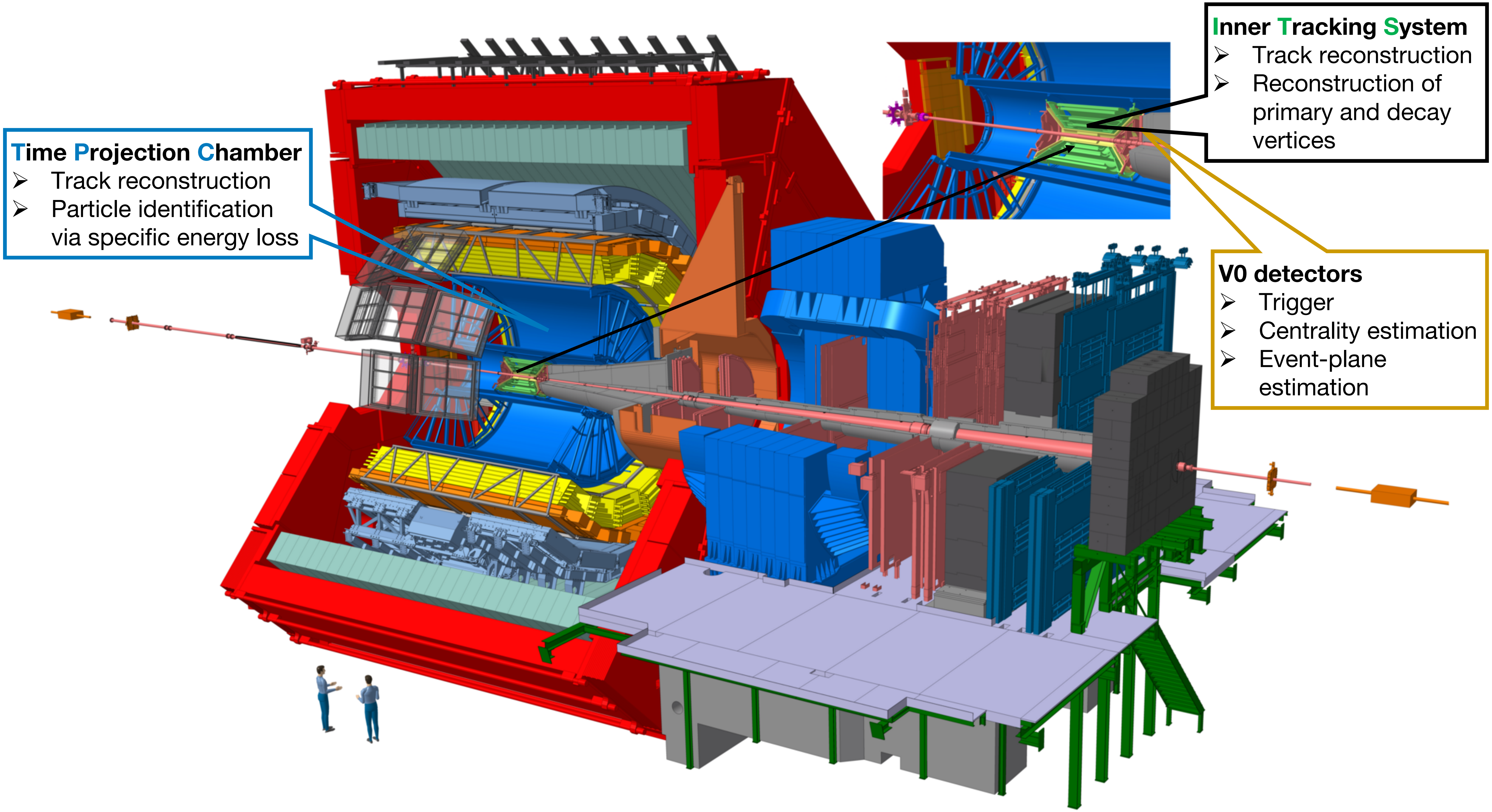


Inner Tracking System
- Track reconstruction
- Reconstruction of primary and decay vertices

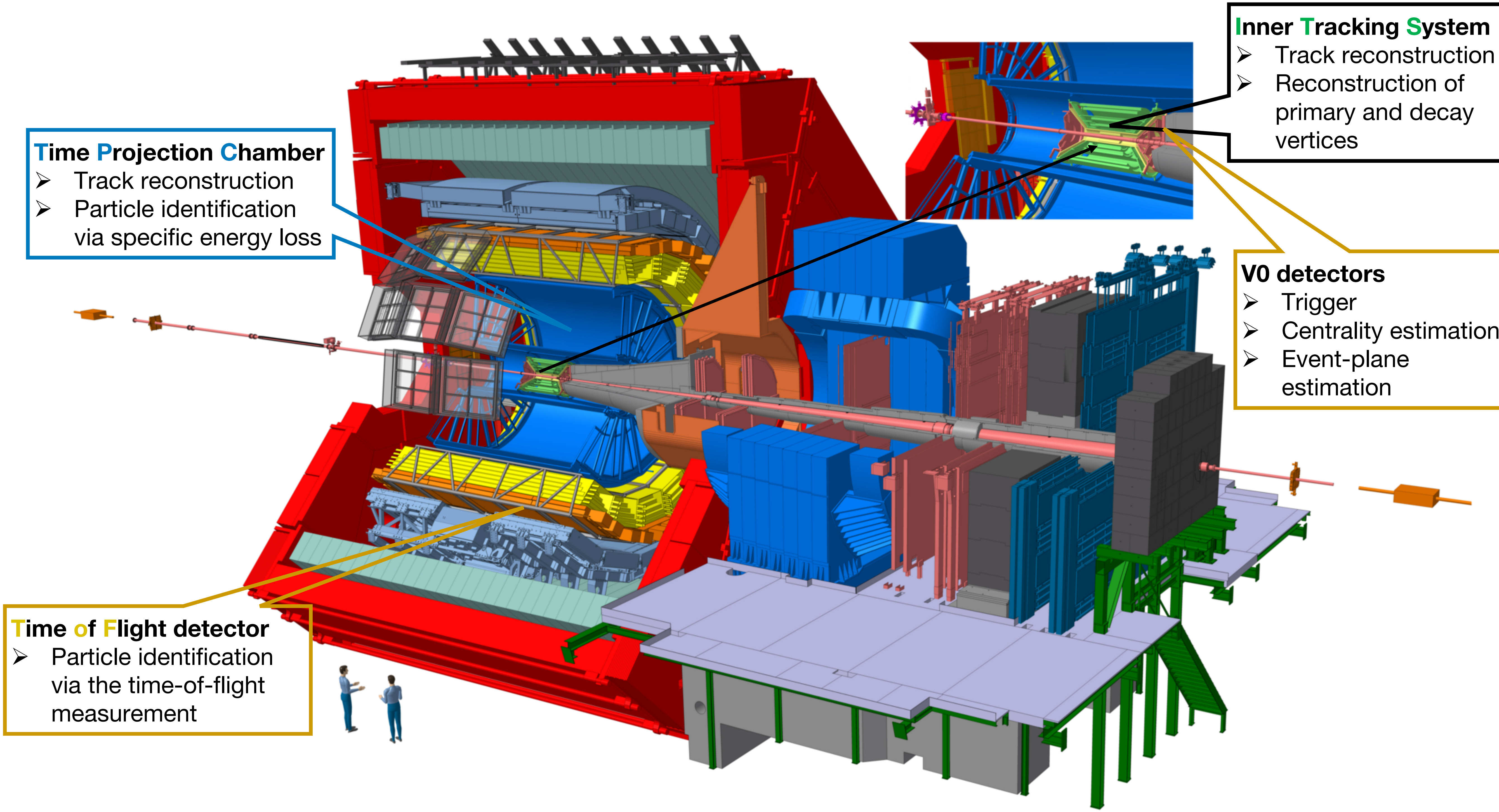
The ALICE detector



The ALICE detector



The ALICE detector



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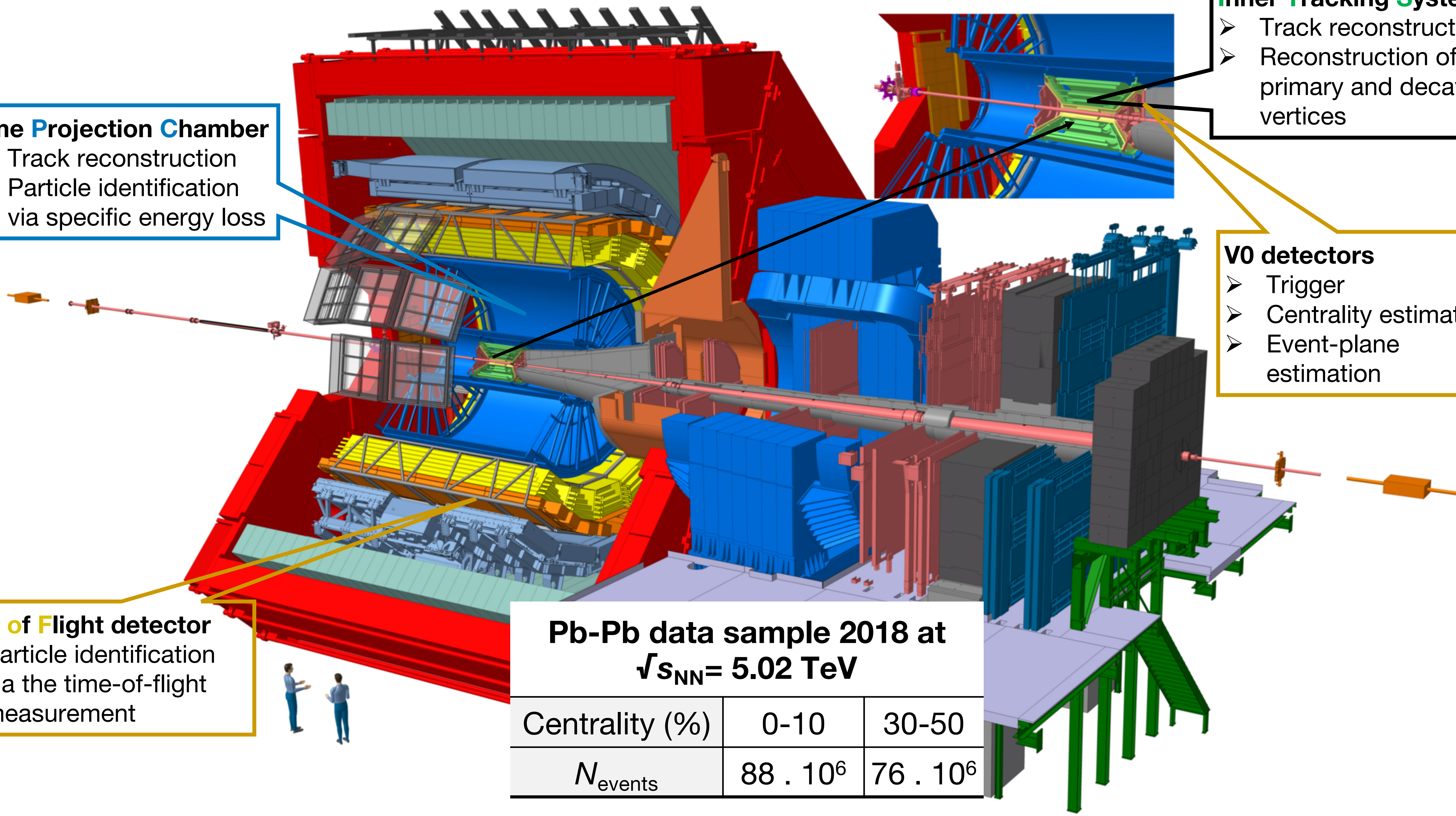
The ALICE detector



Time Projection Chamber
- Track reconstruction
- Particle identification via specific energy loss

Inner Tracking System
- Track reconstruction
- Reconstruction of primary and decay vertices

V0 detectors
- Trigger
- Centrality estimation
- Event-plane estimation

Time of Flight detector
- Particle identification via the time-of-flight measurement

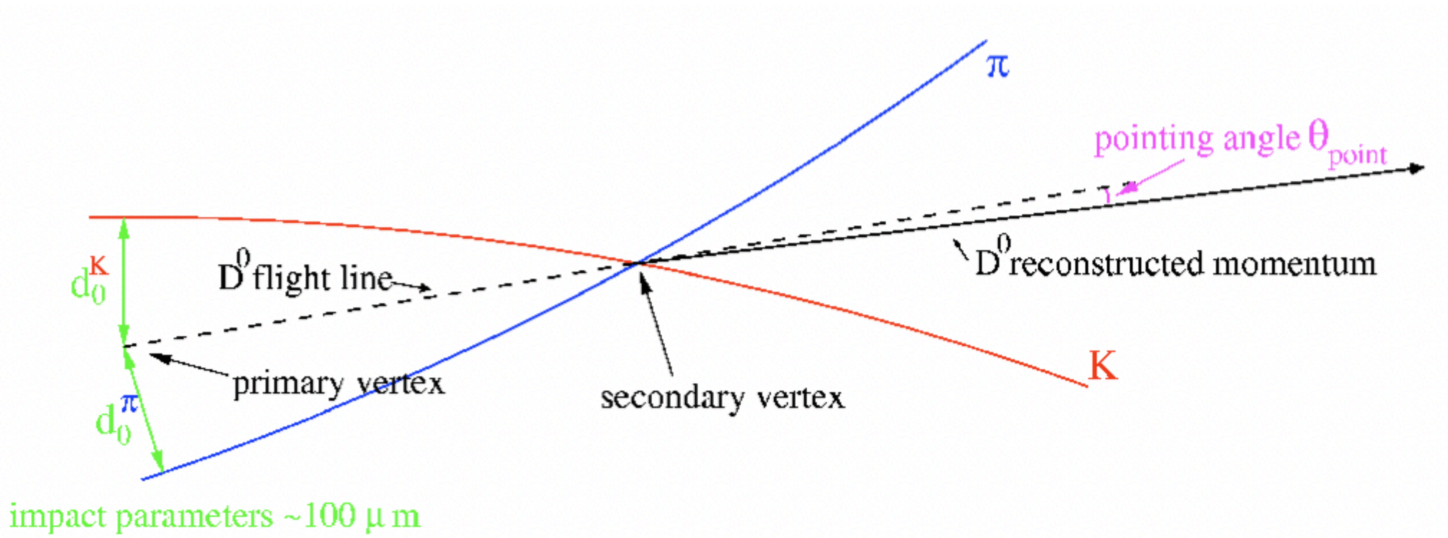
Pb-Pb data sample 2018 at $\sqrt{s_{NN}}$= 5.02 TeV

Centrality (%)	0-10	30-50
N_{events}	$88 \cdot 10^6$	$76 \cdot 10^6$

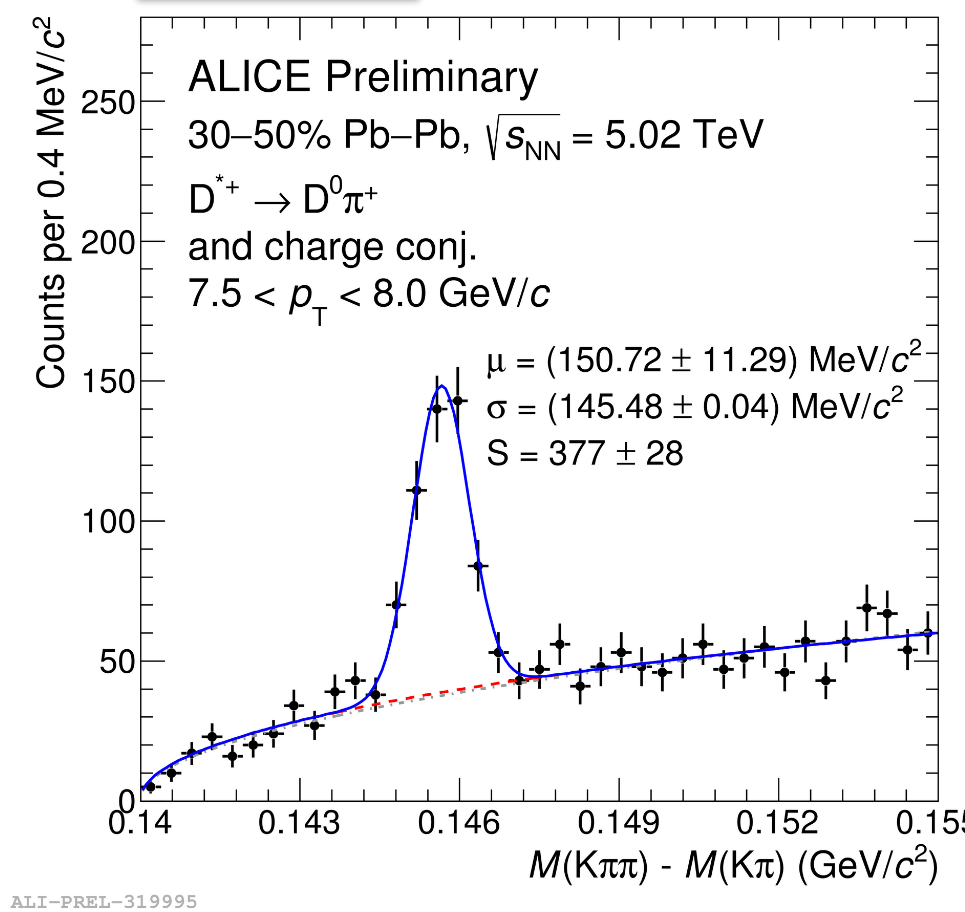
D-meson reconstruction in ALICE

Meson	Mass (GeV/c^2)	$c\tau$ (μm)	decay	BR (%)
D^0	1.865	123	$K^- \pi^+$	~ 3.93
D^+	1.870	312	$K^- \pi^+ \pi^+$	~ 9.46
D^{*+}	2.010	-	$D^0 (K^- \pi^+) \pi^+$	~ 67.7 x 3.93
D_s^+	1.969	150	$\phi (K^- K^+) \pi^+$	~ 2.27%

- Decay topology via secondary vertex reconstruction and PID used to reduce combinatorial background
- Invariant mass analysis
- Feed-down from b-hadron decays subtracted using FONLL-based method [1,2]



New

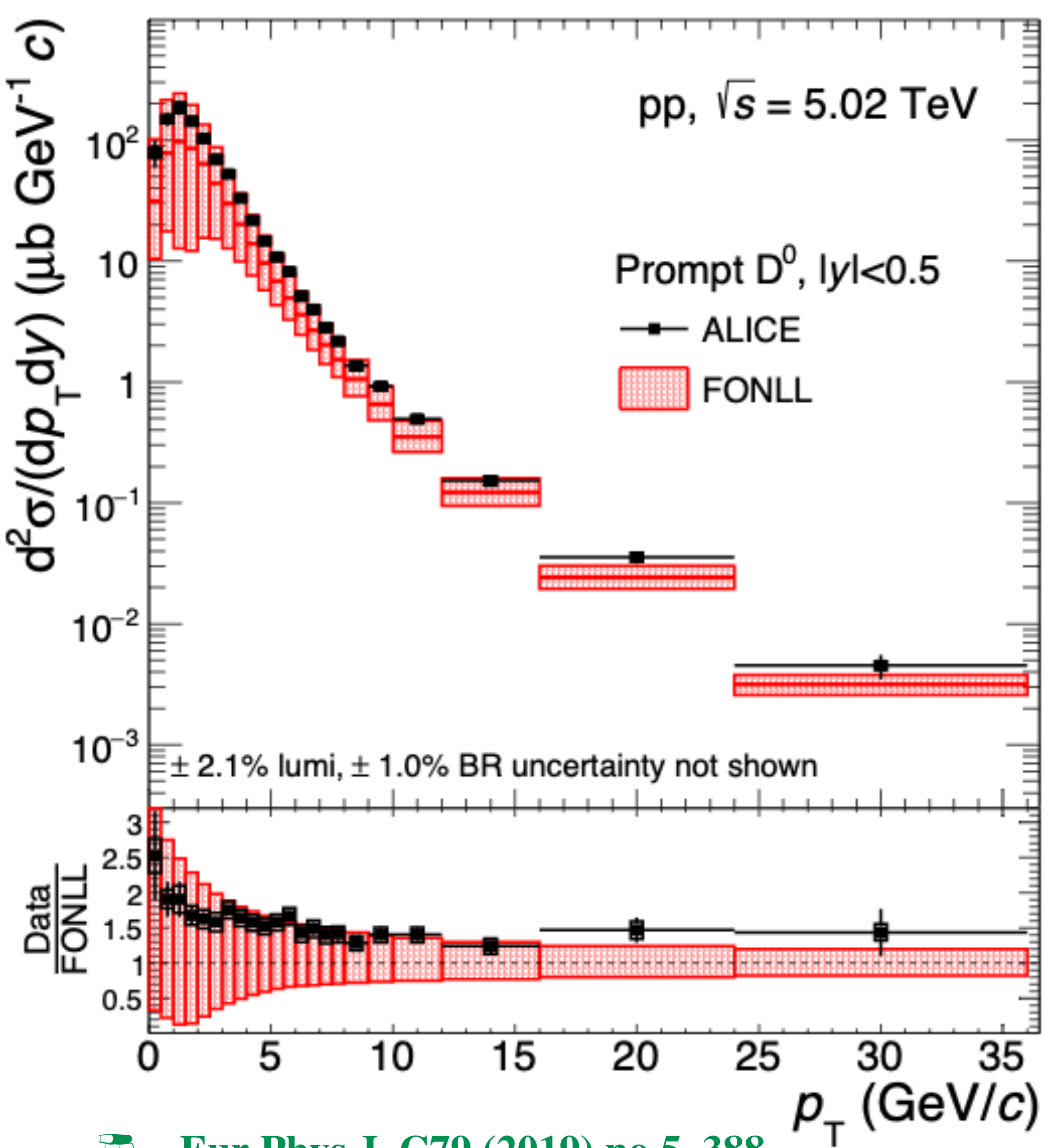


[1] M. Cacciari, M. Greco, P. Nason, JHEP 9805, 007 (1998)
[2] ALICE Collaboration 10.1007/JHEP11(2015)205

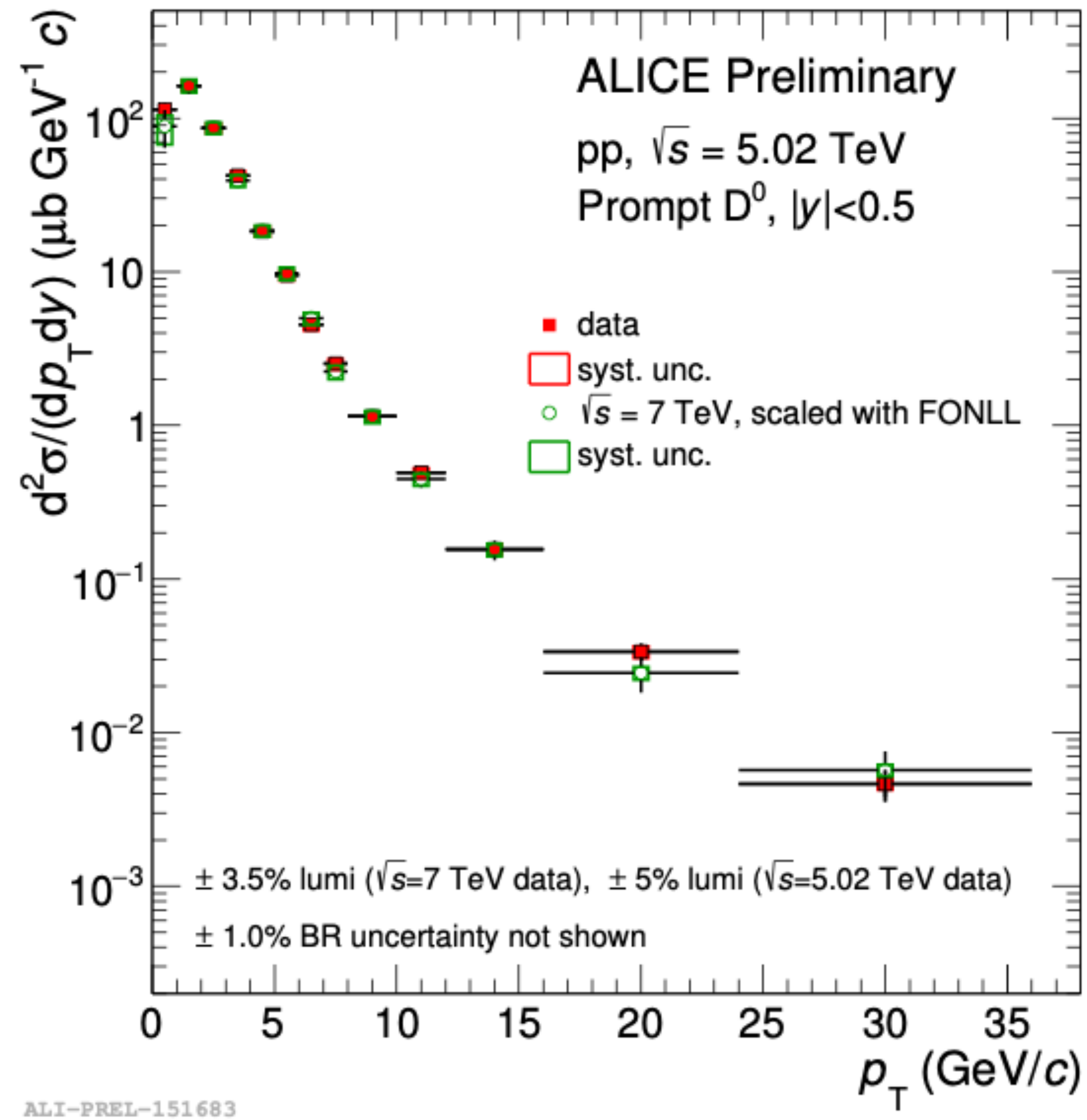
Towards R_{AA}: pp reference

e.g.: D^0

New reference for D mesons in pp collisions at $\sqrt{s}$ = 5.02 TeV



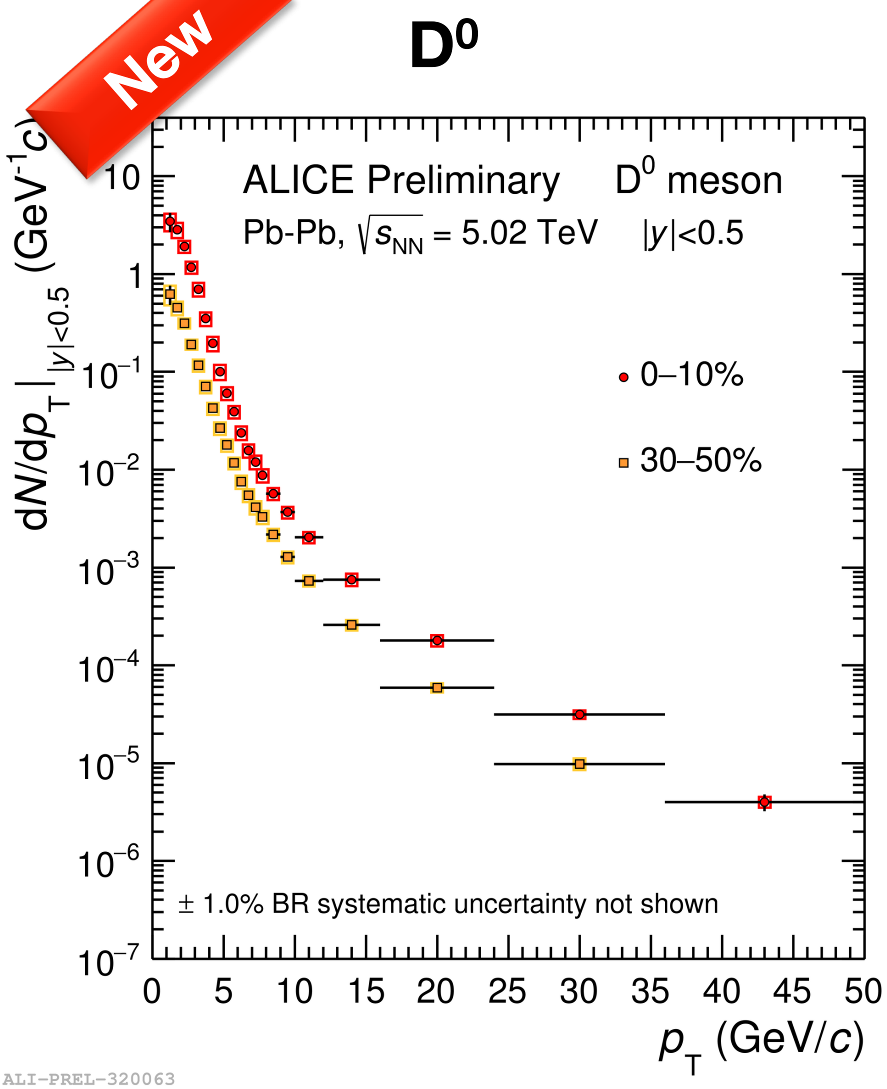
Eur.Phys.J. C79 (2019) no.5, 388

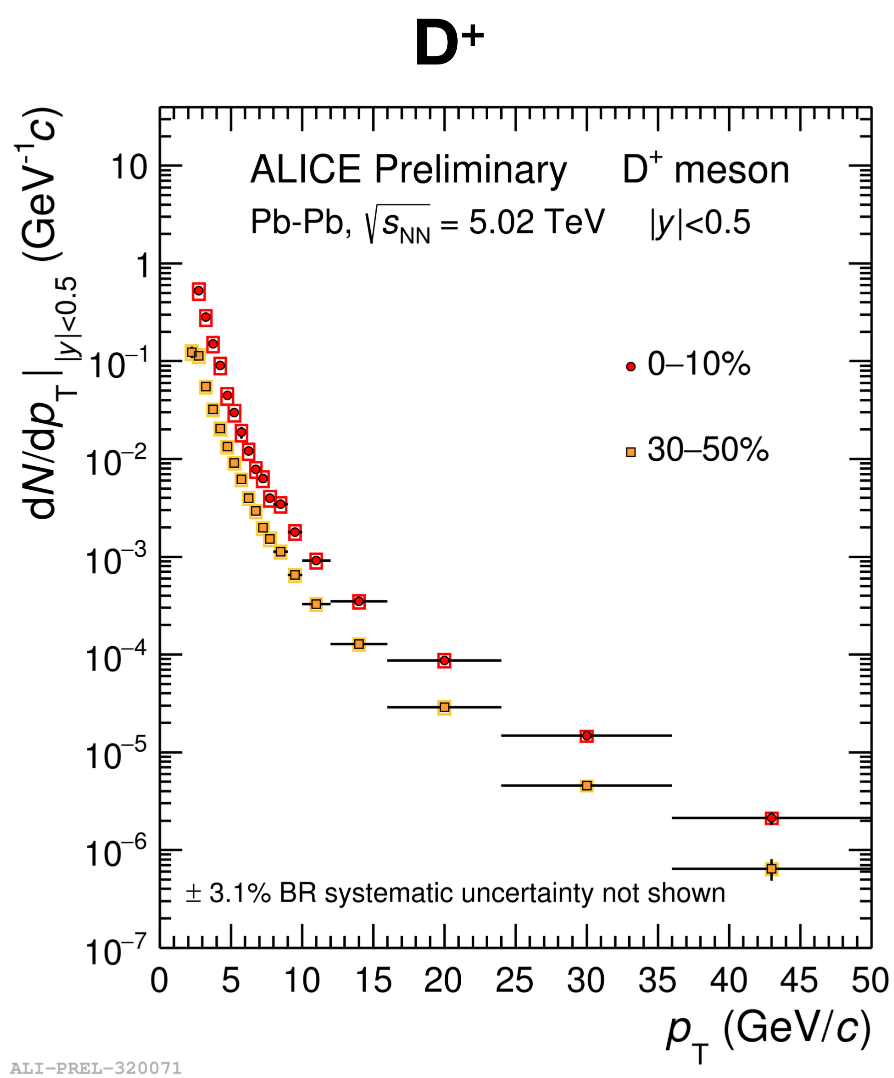


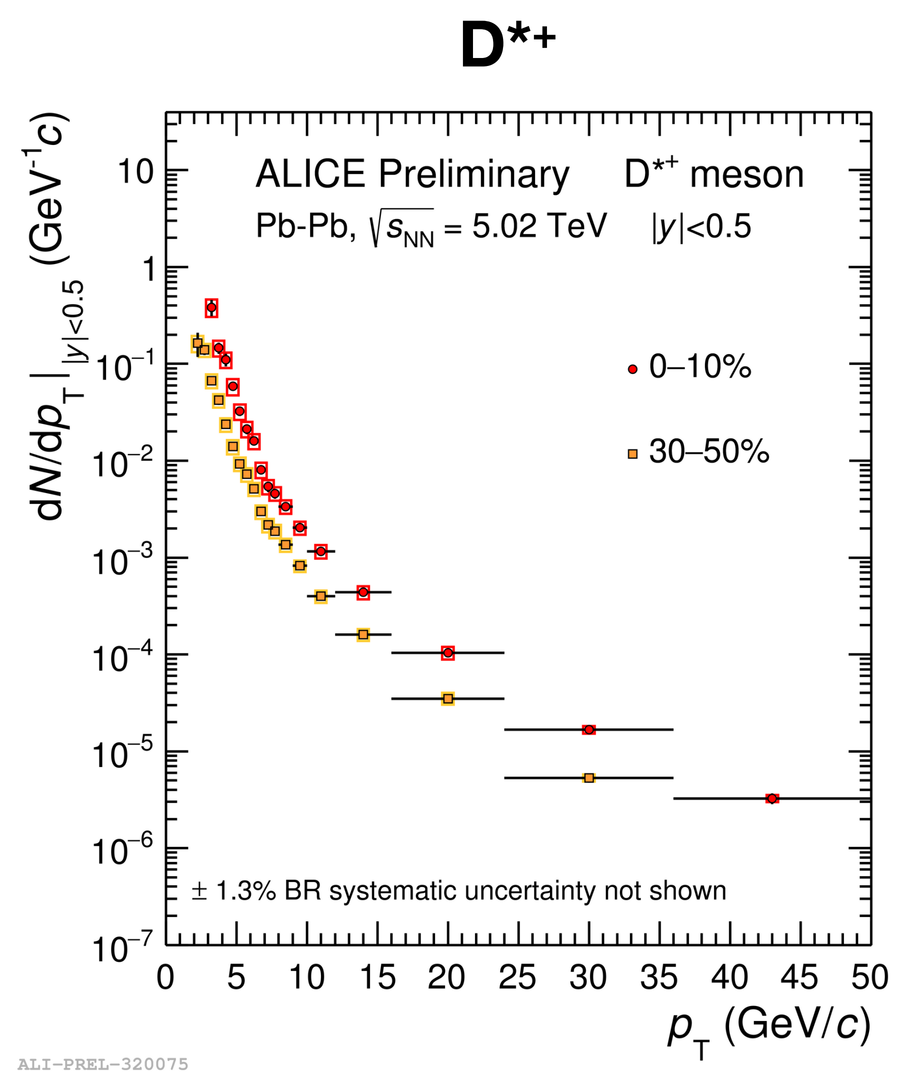
- Improved measurement in terms of uncertainties reduction using minimum-bias data sample collected 2017
- New results compatible with scaled reference at 7 TeV

Non-strange D-meson corrected p_T-spectra

New

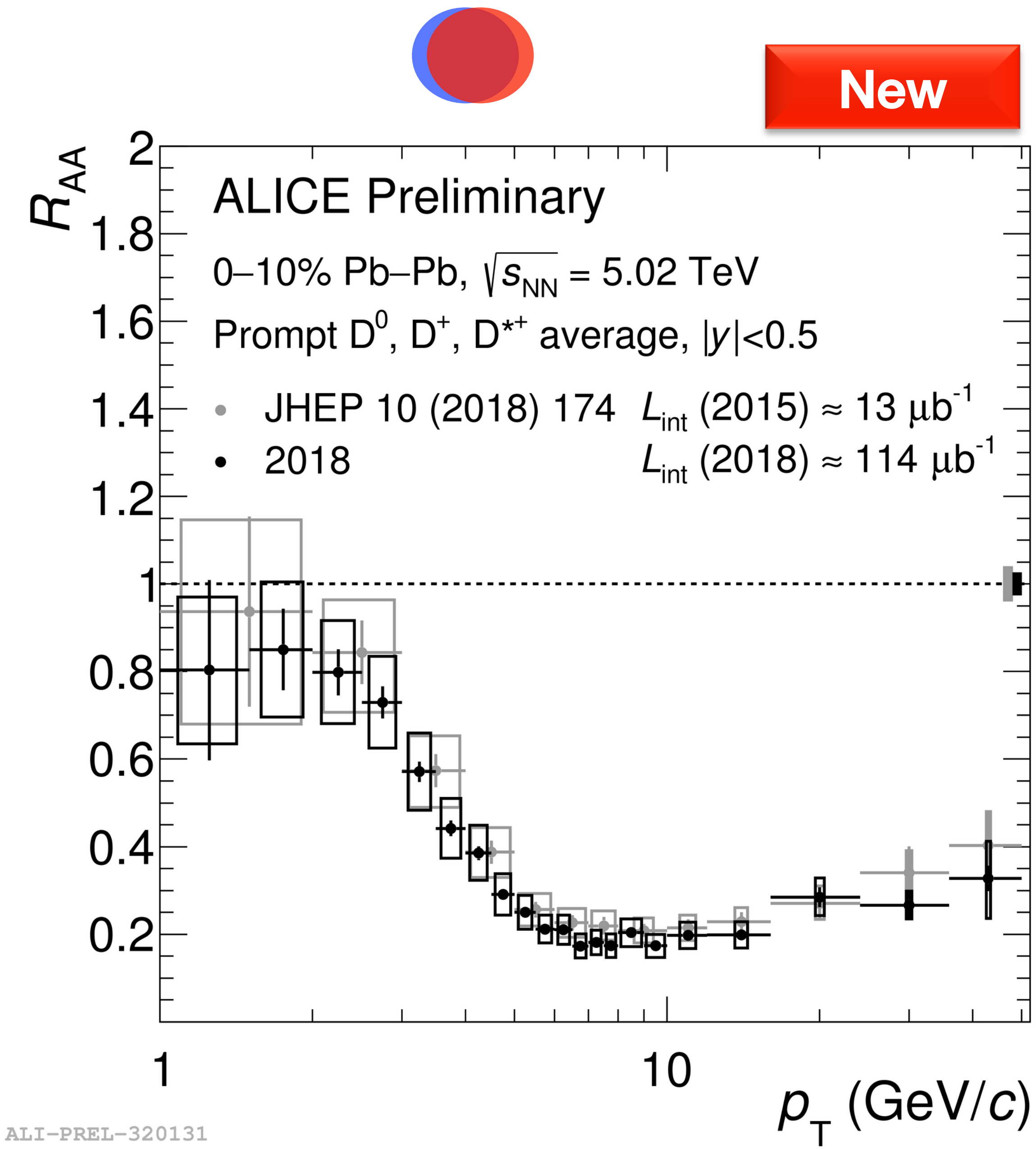


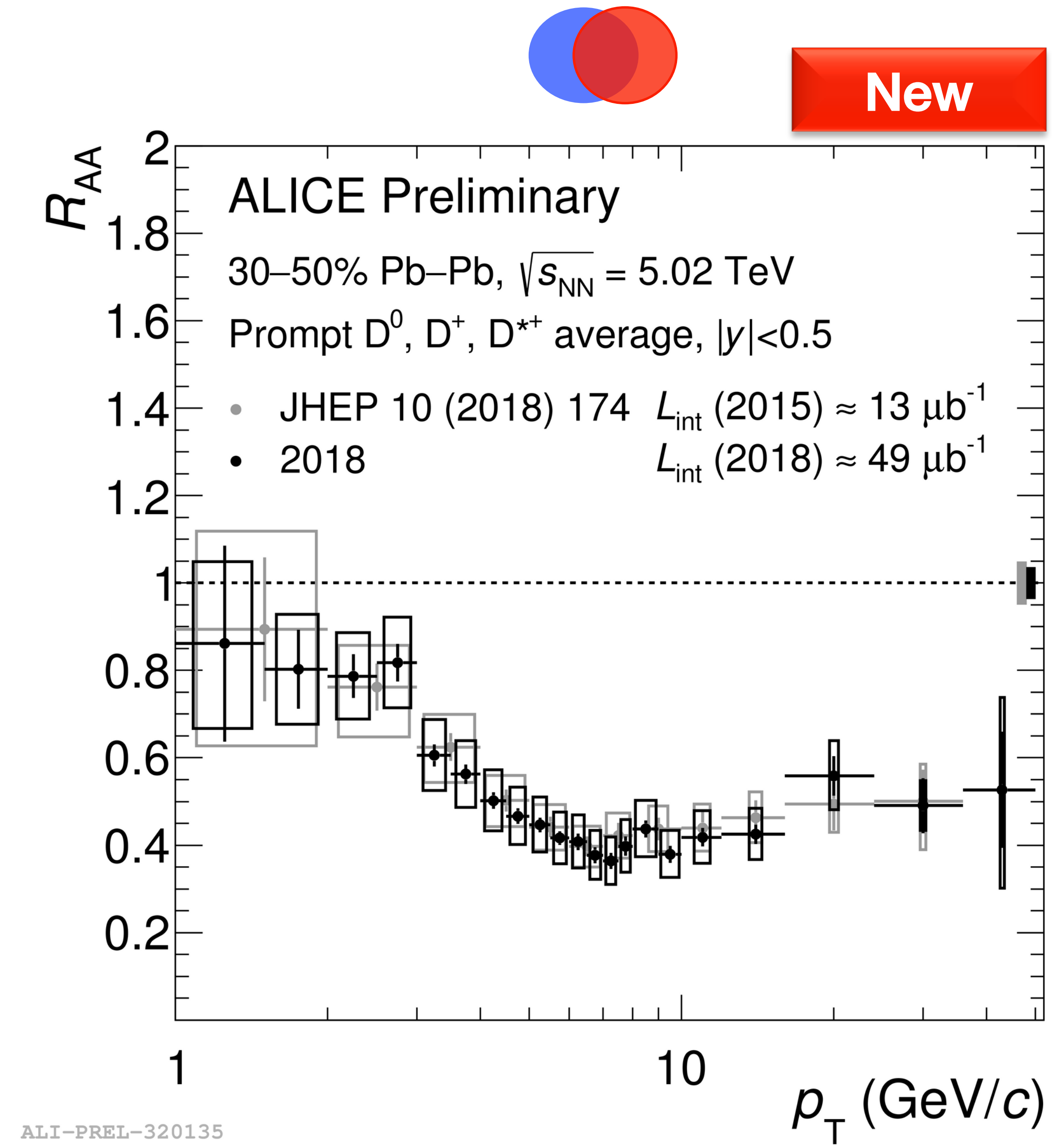




- D mesons $\mathrm{d}N/\mathrm{d}p_T$ in finer p_T bins w.r.t. 2015 data → thanks to large data sample in Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV collected in 2018

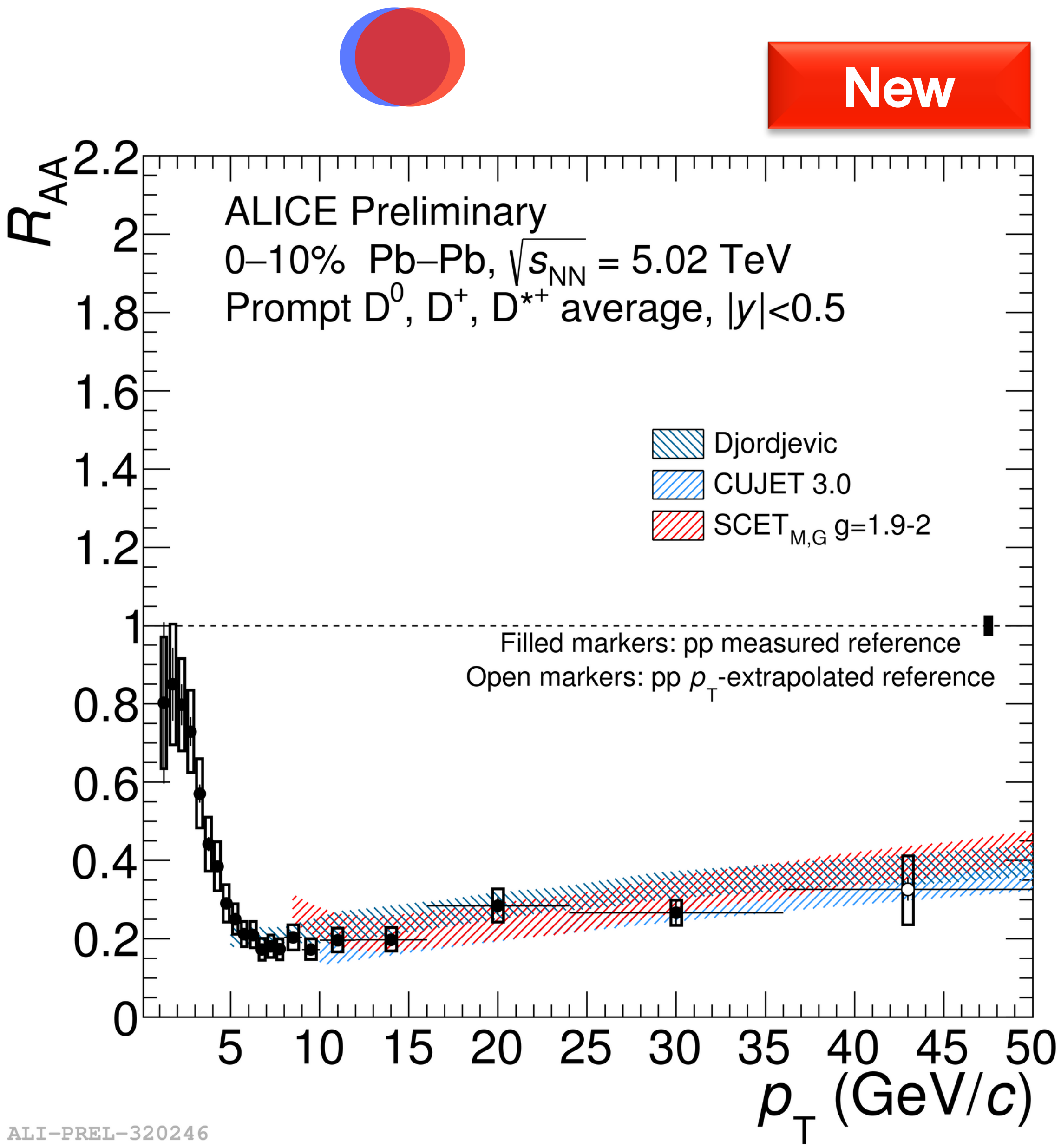
Non-strange D-meson R_{AA}

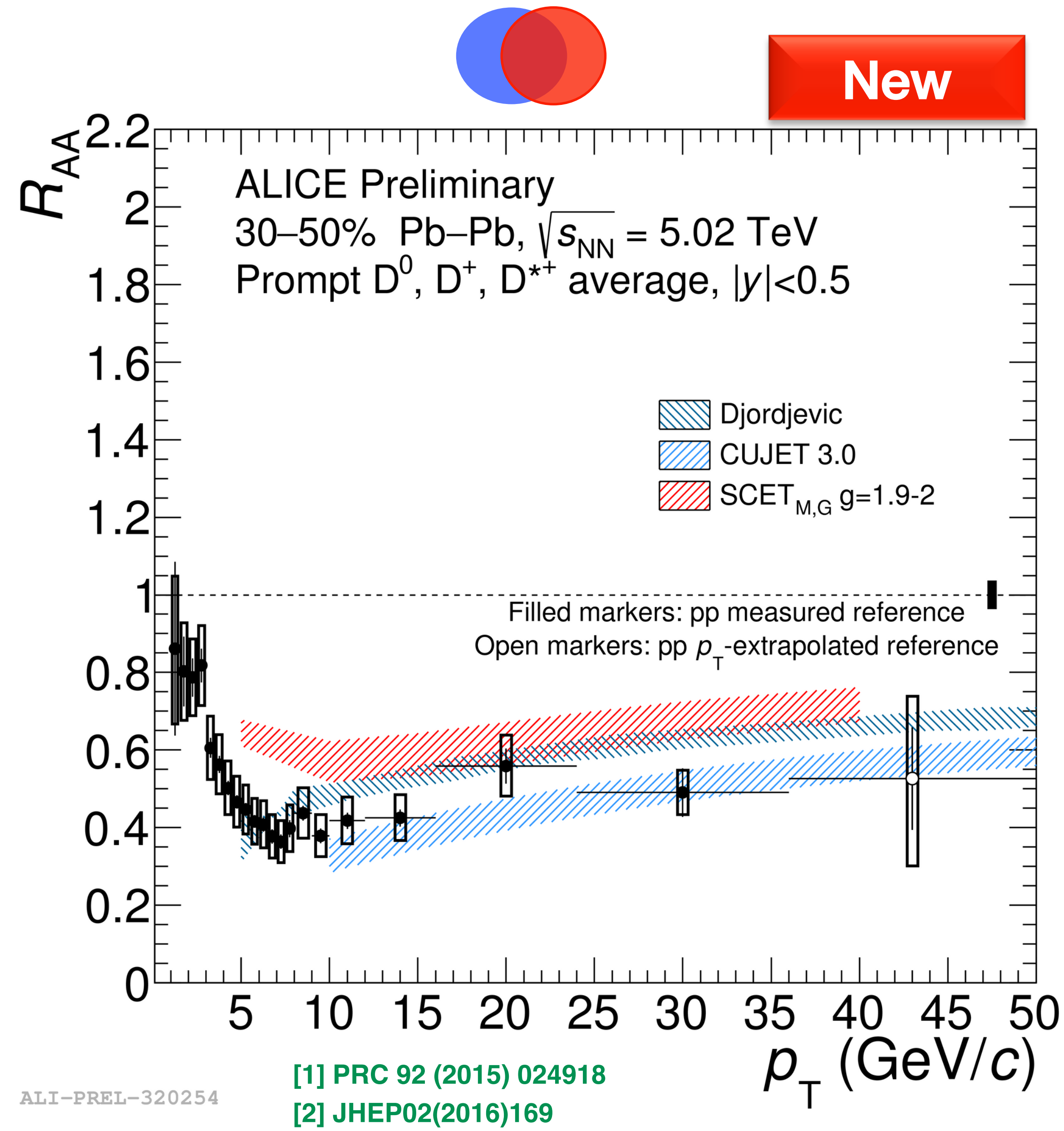




- Improved measurement (in terms of precision) of D-meson R_{AA} using 2018 data with respect to 2015 data
- More p_T-differential R_{AA} with 2018 data w.r.t. 2015 data below 10 GeV/c → important to constraint models at low p_T

Non-strange D-meson R_{AA}

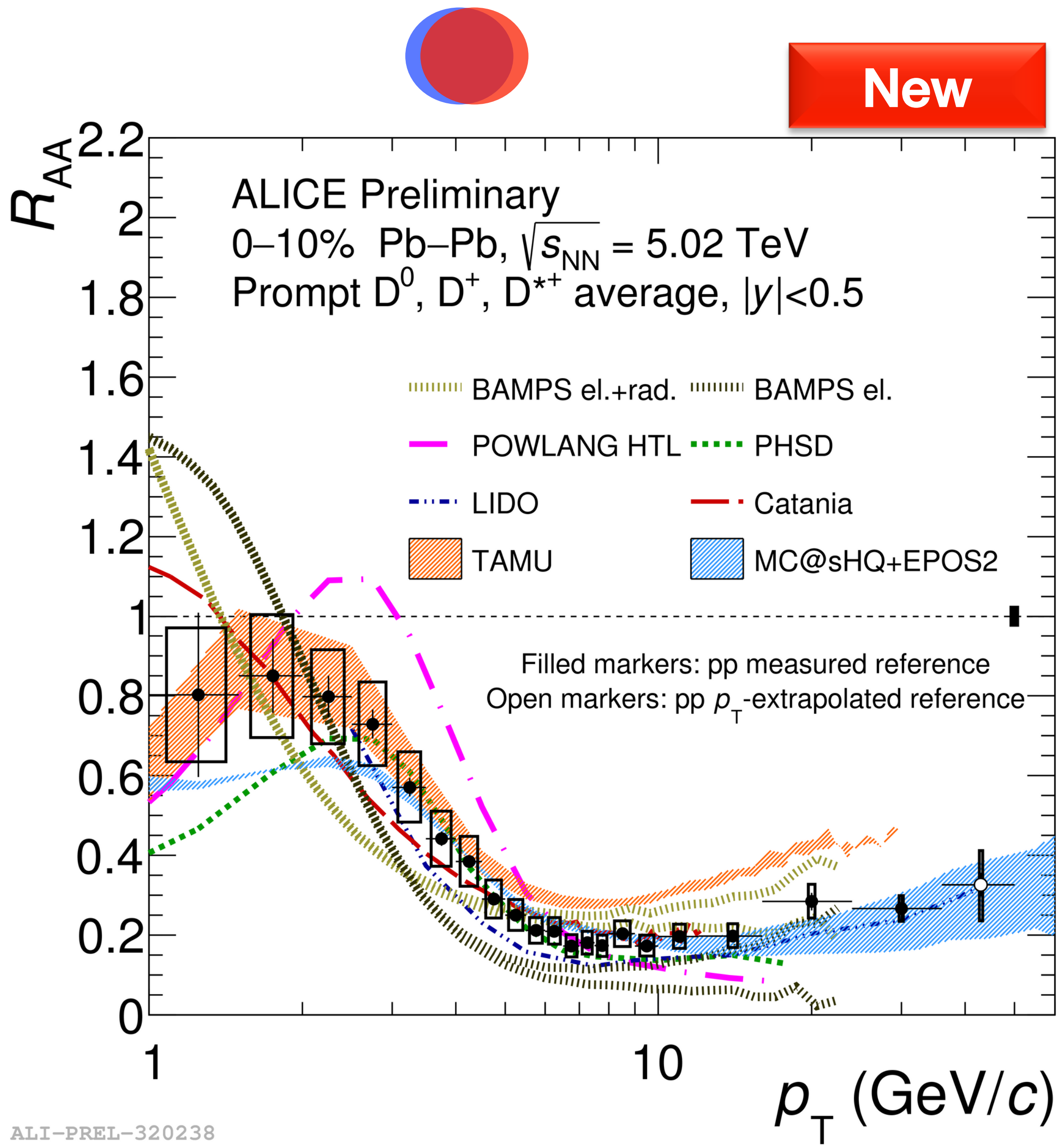


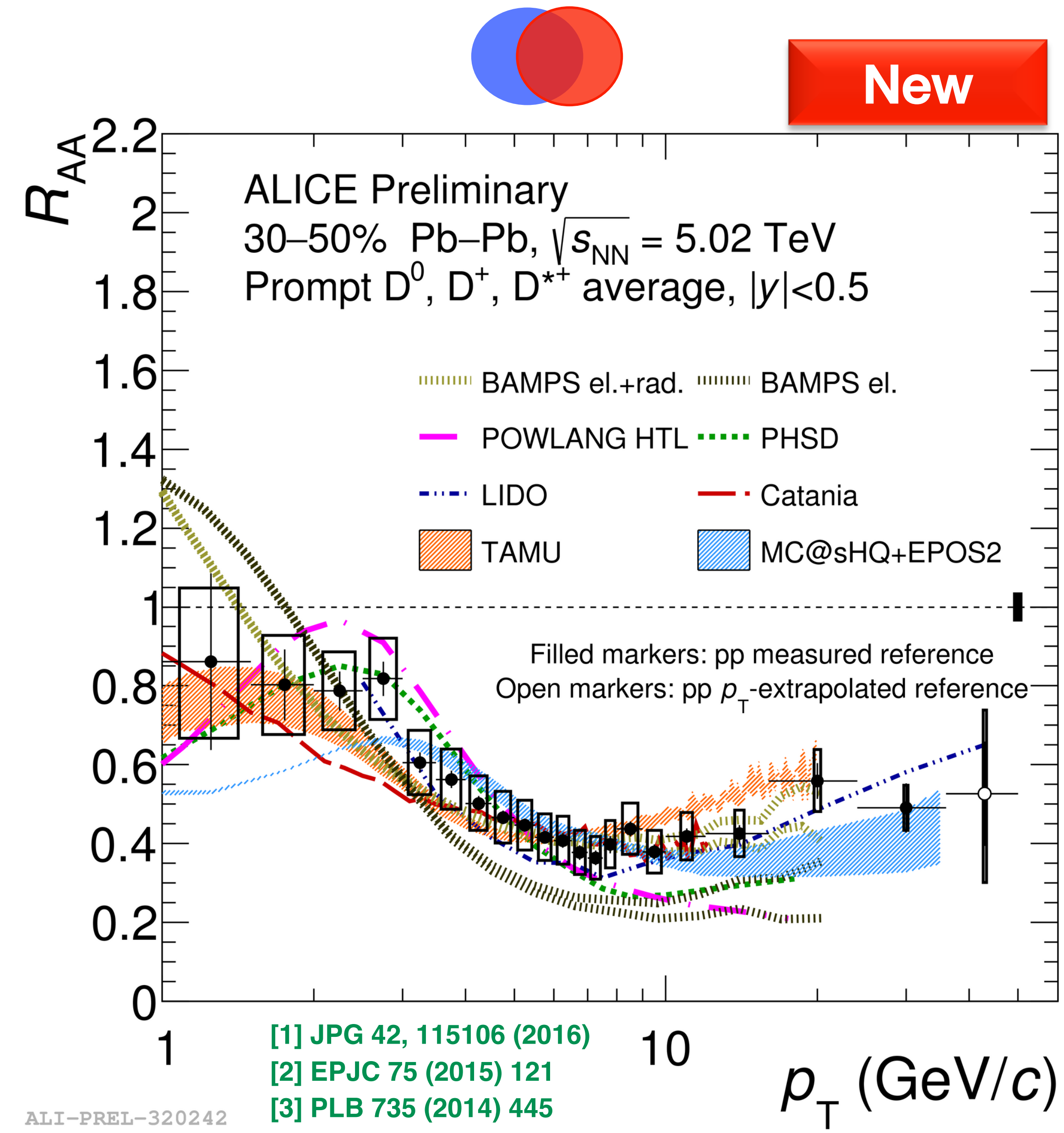


[1] PRC 92 (2015) 024918
[2] JHEP02(2016)169
[3] JHEP 03 (2017) 146

- Average non-strange D-meson R_{AA} compared to pQCD-based energy-loss models
- Djordjevic [1] and CUJET3.0 [2] include both radiative and collisional energy loss processes, while SCET [3] also includes medium-induced gluon radiation in the ingredients
- Djordjevic and CUJET3.0 describe well the R_{AA} for p_T > 10 GeV/c in both centralities, while SCET doesn't describe well the R_{AA} in semi central events

Non-strange D-meson R_{AA}

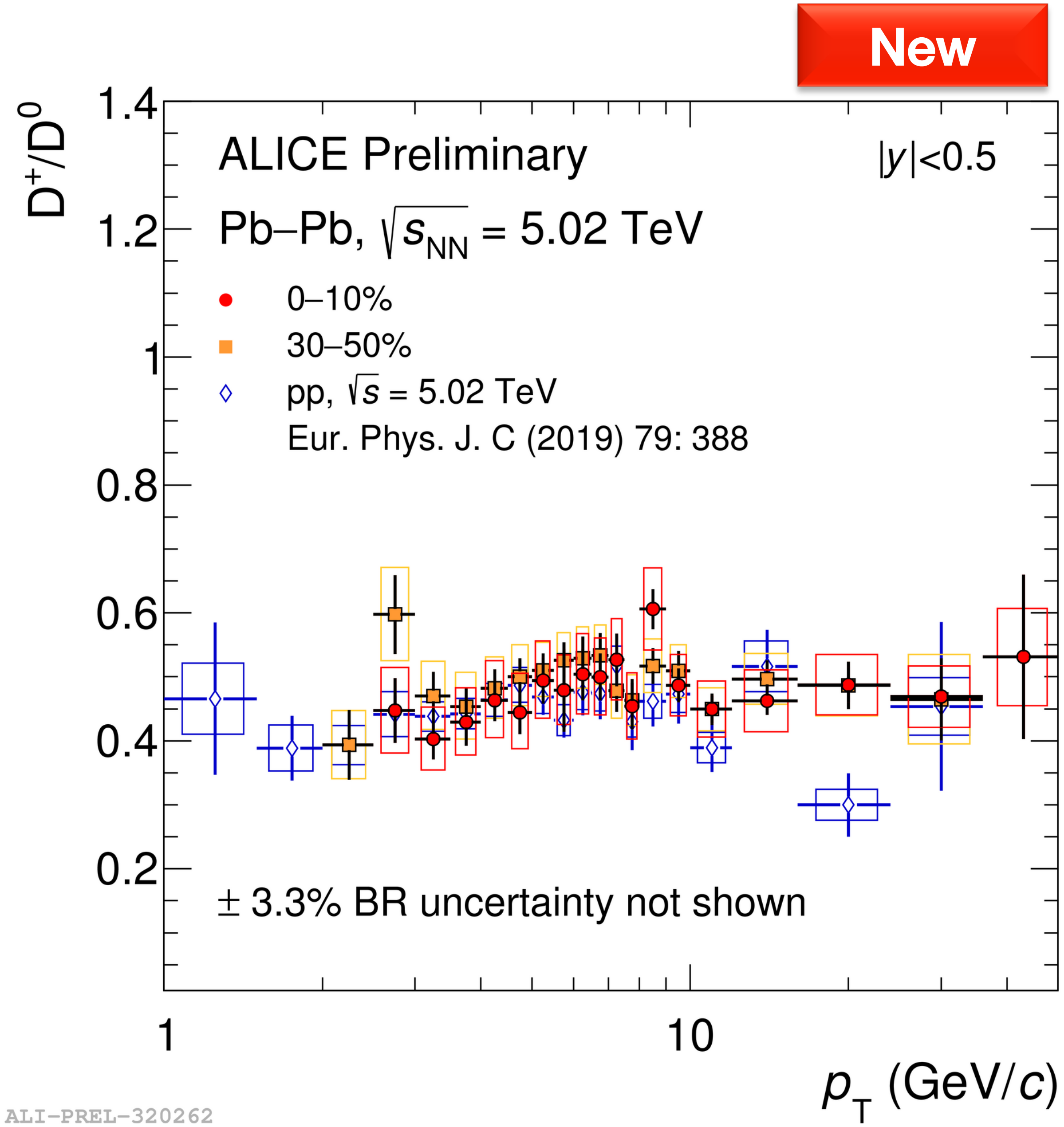


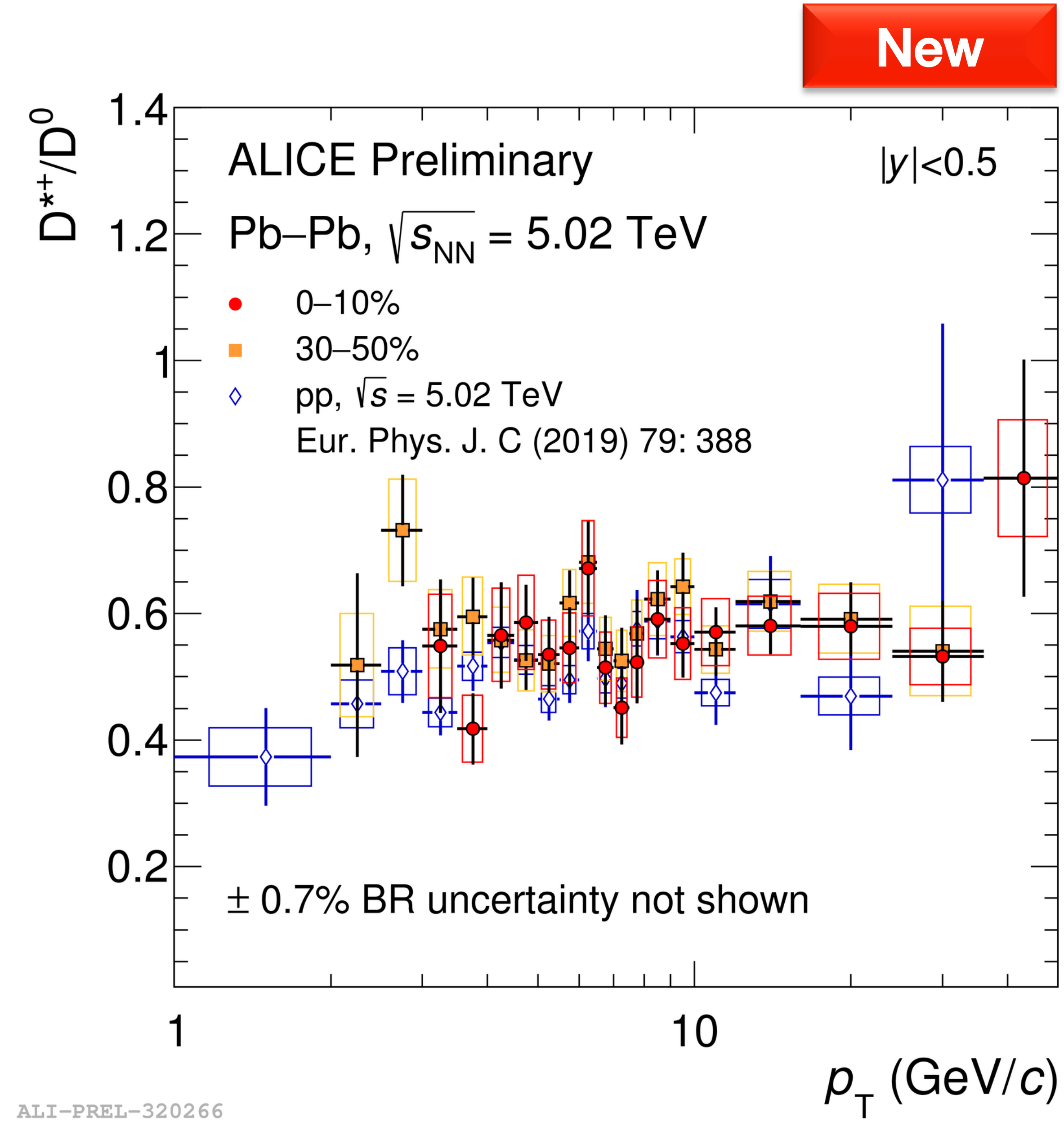


[1] JPG 42, 115106 (2016)
[2] EPJC 75 (2015) 121
[3] PLB 735 (2014) 445
[4] Phys. Rev. C 98, 064901 (2018)
[5] PRC 89 (2014) 014905
[6] PRC 93 (2016) 034906
[7] EPJC (2018) 78: 348

- Average non-strange D-meson R_{AA} compared to transport models
- $p_T < 10$ GeV/c → most of models provide a fair description of the data in central events (BAMPS el. [1] and POWLANG [2] show some tension) while in semi central events BAMPS el. tend to overshoot the data at low p_T
- $p_T > 10$ GeV/c → MC@sHQ+EPOS2 [5] and BAMPS el.+rad. [1] describe well the data in central events, while in semi central events MC@sHQ+EPOS2, BAMPS el.+rad., LIDO [4] and TAMU [3] describe well the data

Non-strange D-meson ratios - pp vs Pb-Pb collisions





- Similar D^+/D^0 and D^{*+}/D^0 in pp and Pb-Pb collisions for different centralities

D-meson elliptic flow Pb-Pb collisions

- The scalar product method is based on the measurement of the *Q-vectors*

$$Q_{2,x} = \sum_{i=1}^{N} w_i \cos(2\varphi_i) \quad Q_{2,y} = \sum_{i=1}^{N} w_i \sin(2\varphi_i)$$

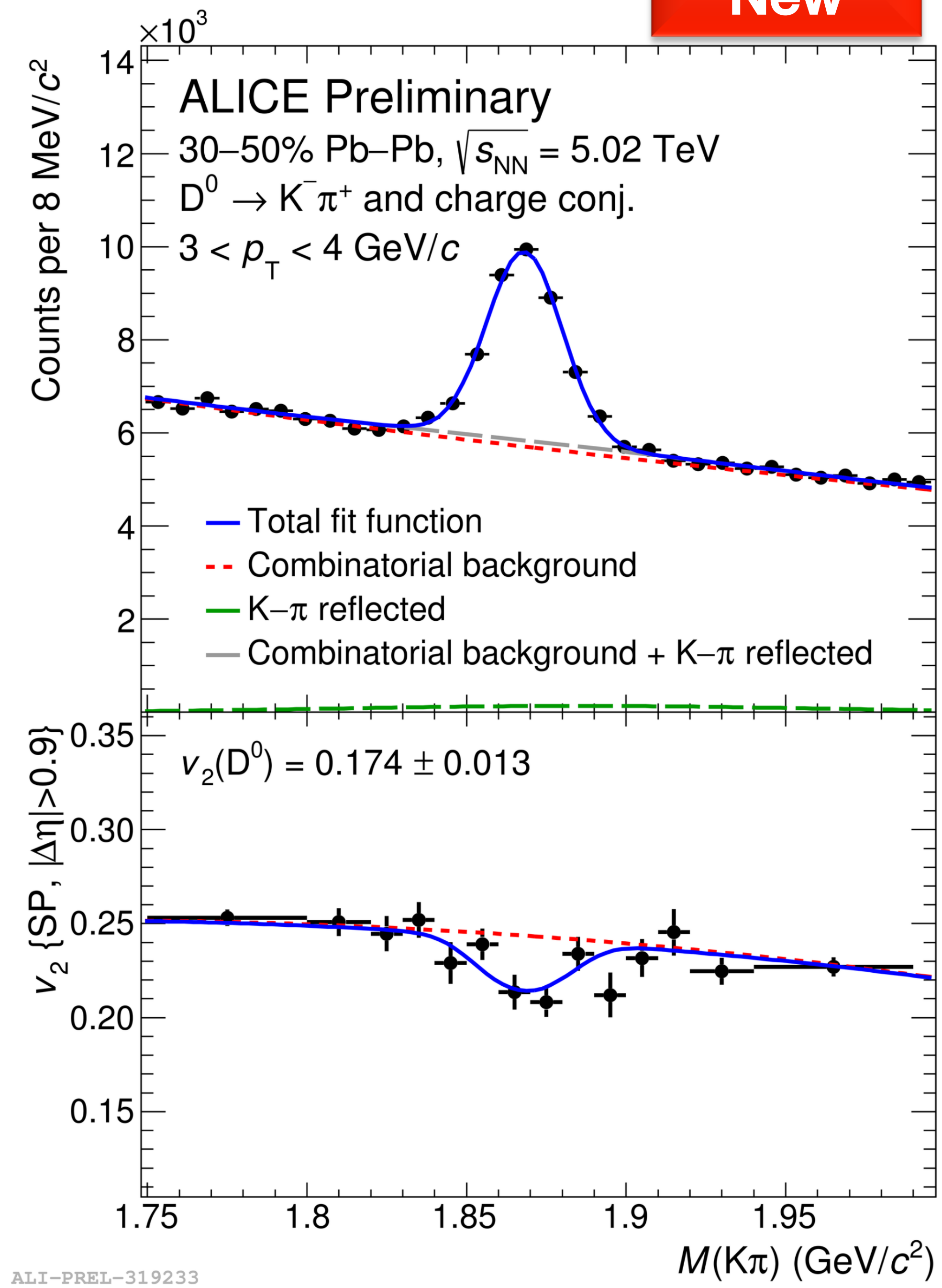
- v_2 is evaluated for all the candidates in bins of invariant mass (*M*)

$$v_2(M) = \frac{1}{R_2}\langle u_D \cdot Q_2^A / M^A \rangle(M)$$

- The v_2 of the signal is extracted via a simultaneous fit of $v_2(M)$ and *M*

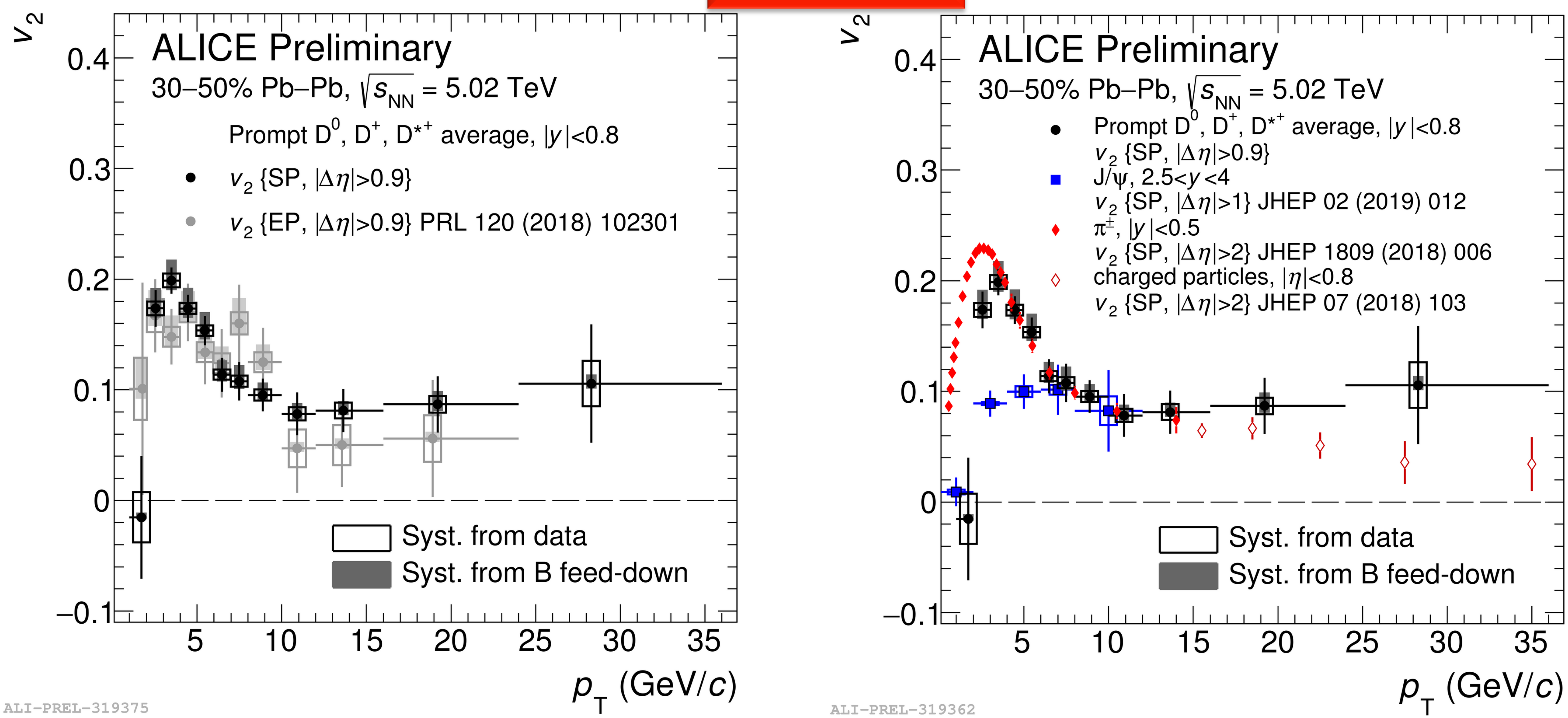
$$v_2(M) = v_2^S \frac{S(M)}{S(M)+B(M)} + v_2^B \frac{B(M)}{S(M)+B(M)}$$

New



D-meson v_2 in mid-central Pb-Pb collisions

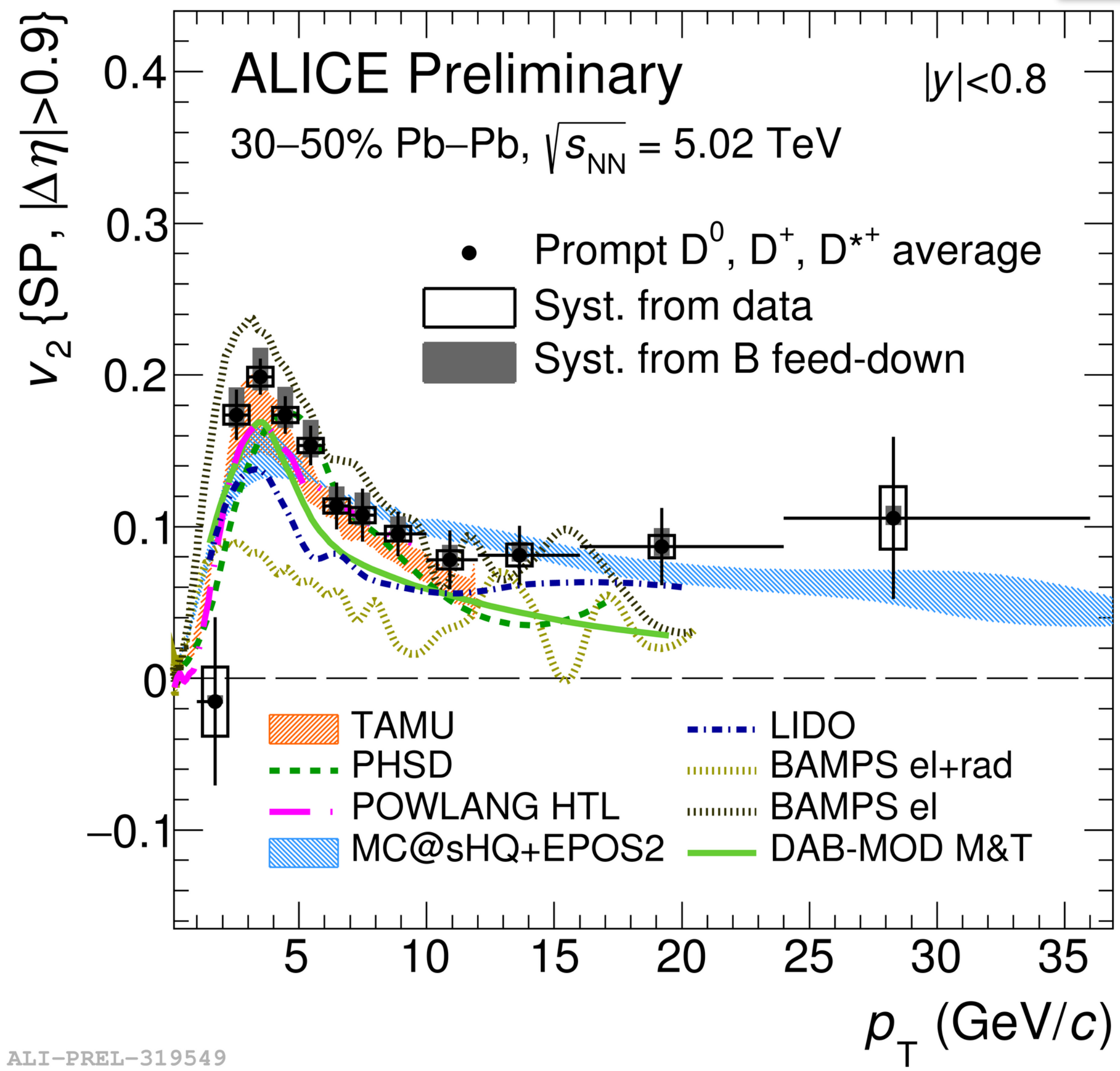
New

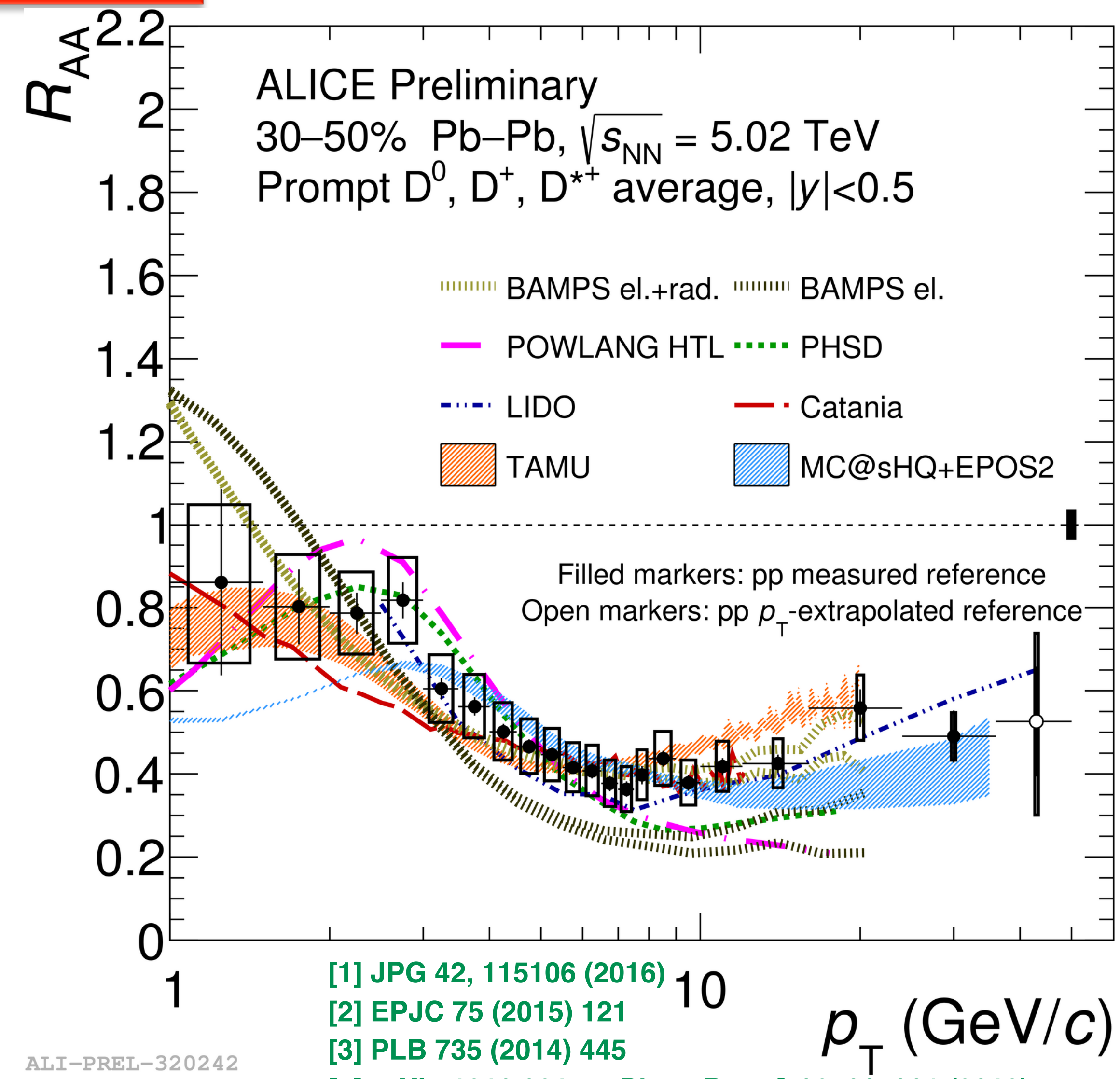


- Significant reduction of uncertainties and extended p_T coverage with 2018 data w.r.t. 2015 data
- Average non-strange D-meson v_2 :
  - indication lower than that of pions for p_T < 3 GeV/c
  - higher than that of J/psi for p_T < 6-8 GeV/c
  - compatible with the charged particles within uncertainty at high p_T

D-meson v_2 in mid-central Pb-Pb collisions

New





[1] JPG 42, 115106 (2016)
[2] EPJC 75 (2015) 121
[3] PLB 735 (2014) 445
[4] arXiv:1810.08177; Phys. Rev. C 98, 064901 (2018)
[5] PRC 89 (2014) 014905
[6] PRC 93 (2016) 034906
[7] Phys. Rev. C 96, 064903 (2017)
[8] EPJC (2018) 78: 348

- Non-zero D-meson v_2 above 2 GeV/c
- Improved precision with 2018 data: provide important constraints to the models to predict simultaneously R_{AA} and collectivity of heavy quarks in the QCD medium
- MC@sHQ+EPOS2 [5] model provides a fair description of v_2 (also PHSD [6] and TAMU [3] at p_T < 12 GeV/c) while BAMPS el. [1] model overestimates the maximum flow
- LIDO [4] and DAB-MOD M&T [7] describe the shape of v_2 but underestimate its magnitude

Event shape engineering for the D-meson v_2

- The second-harmonic reduced flow vector q_2 can be used to quantify the eccentricity (average v_2) of the events

$$q_2 = \frac{|Q_2|}{\sqrt{M}},$$

M : multiplicity

$$|Q_2| = \sqrt{Q_{2,x}^2 + Q_{2,y}^2}$$

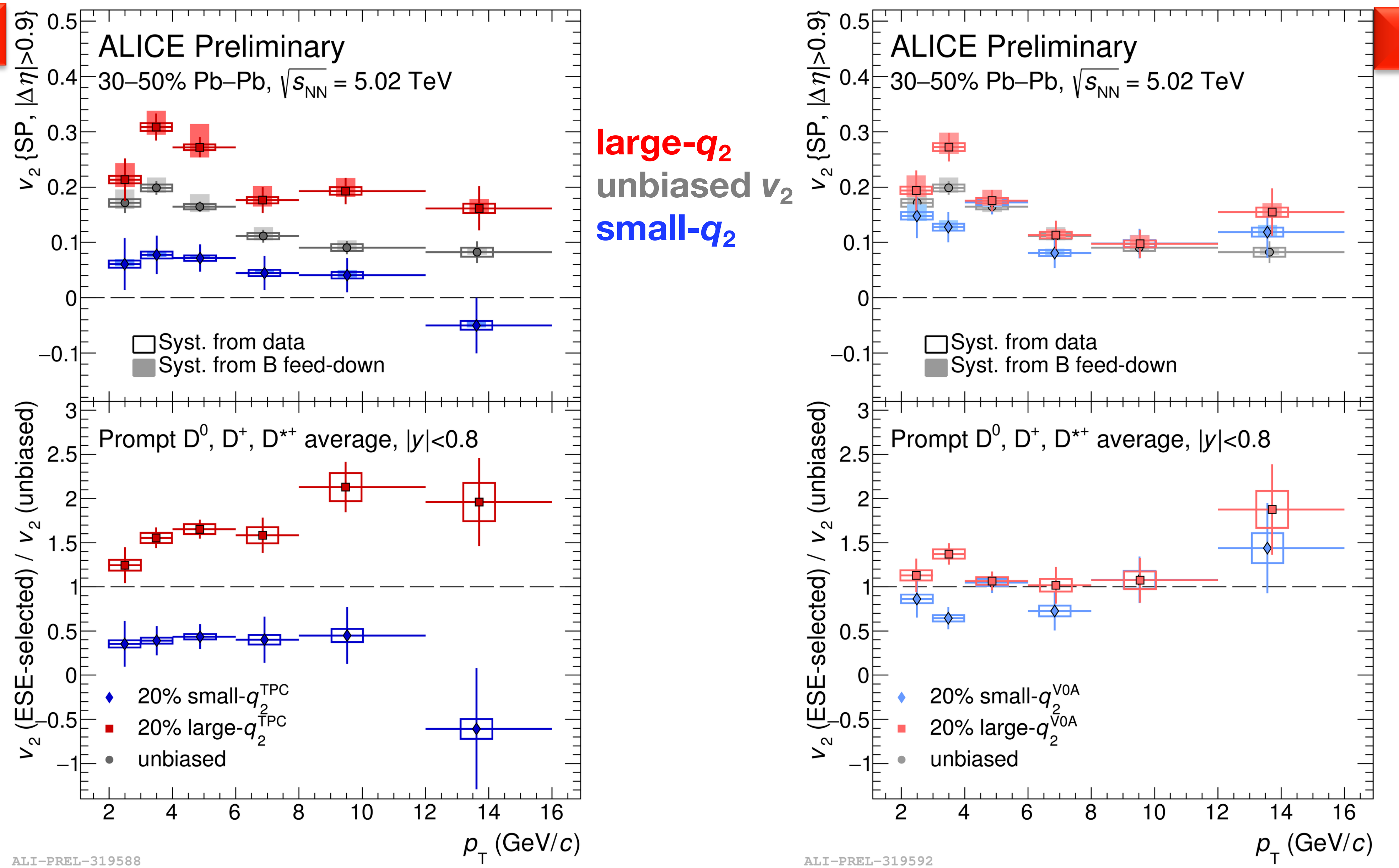
$$Q_{2,x}^2 = \sum_{i=1}^{M} \cos 2\varphi_i \;, Q_{2,y}^2 = \sum_{i=1}^{M} \sin 2\varphi_i$$

- Measuring the D-meson v_2 for different q_2 values gives the opportunity to study the coupling of c quark to the bulk of light quarks collectivity and event-by-event fluctuations in the initial state

$$\langle q_2^2 \rangle \simeq 1 + \langle (M-1) \rangle \langle (v_2^2 + \delta_2) \rangle$$ non-flow effect

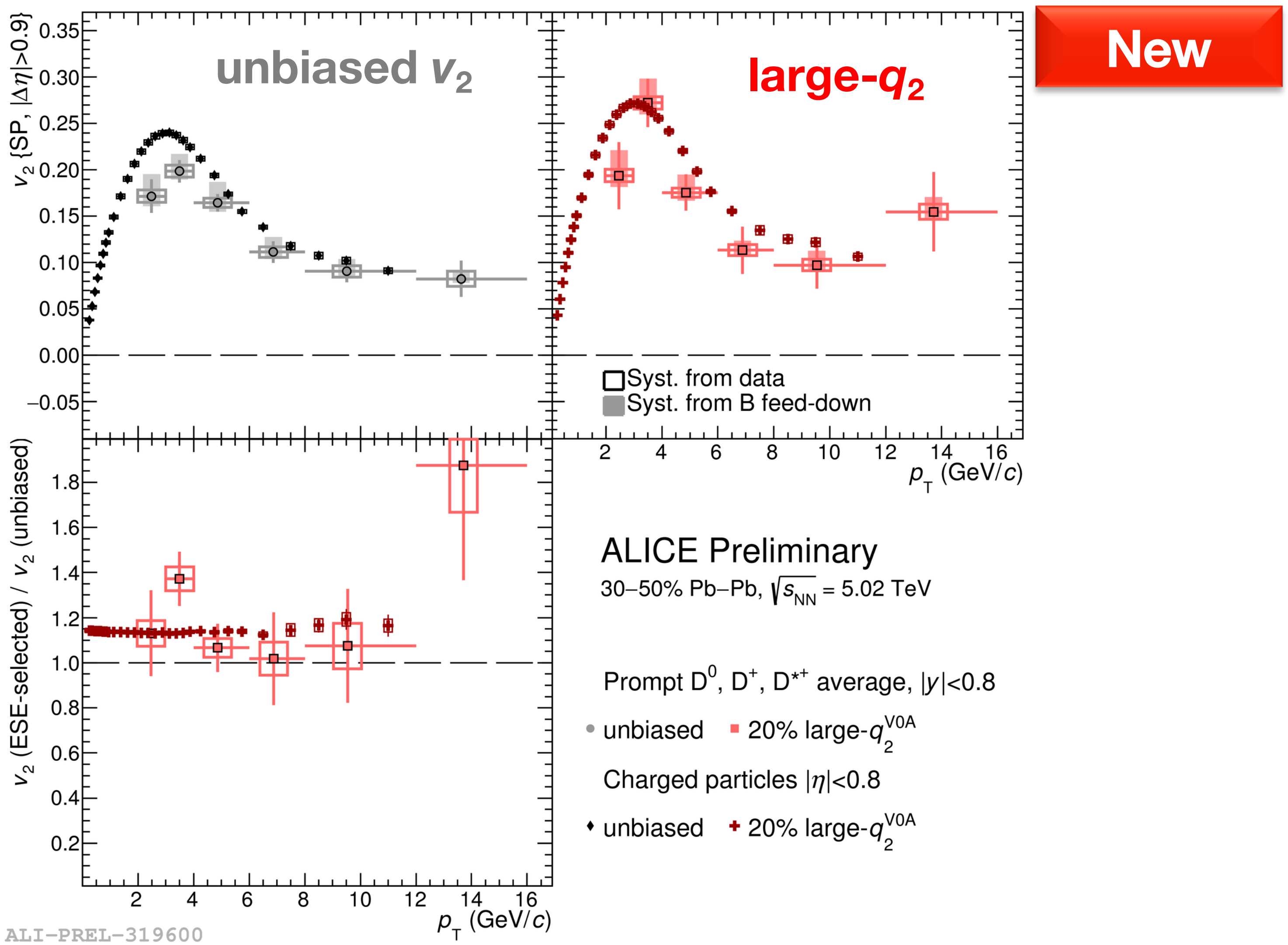
Phys. Rev. C 93 (2016) 034916
arXiv:1809.09371

Event shape engineering for the D-meson v_2



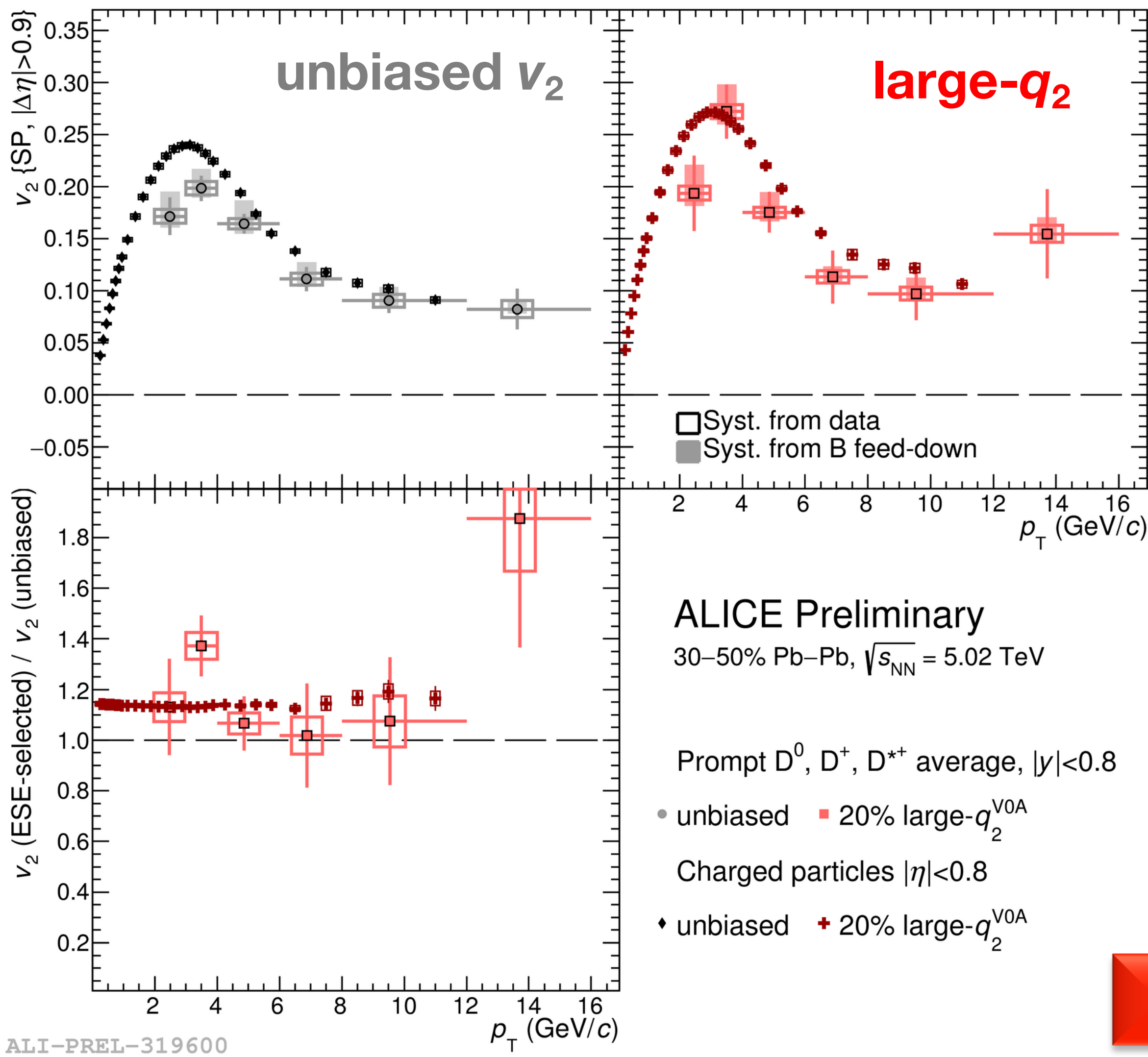
- D-meson v_2 with large q_2 > D-meson v_2 with small q_2
- Clear separation between v_2 measured in events with small/large q_2^{TPC}
- Hint of separation also with q_2^{V0A}

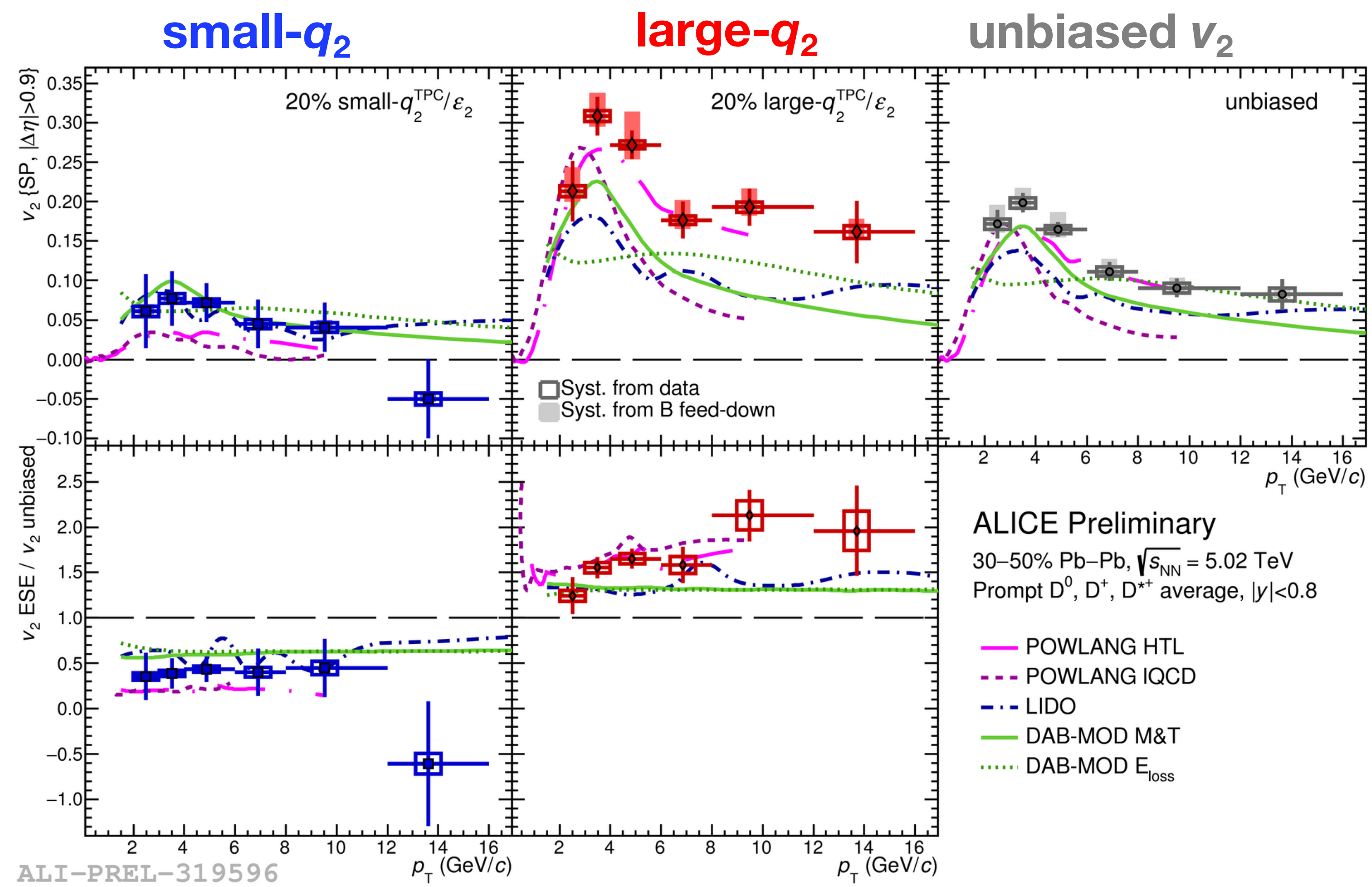
Event shape engineering for the D-meson v_2



- Both the average unbiased D-meson v_2 and D-meson v_2 related to q_2^{V0A} : compatible to that observed by charged particles
- Hint of separation also with q_2^{V0A}

Event shape engineering for the D-meson v_2



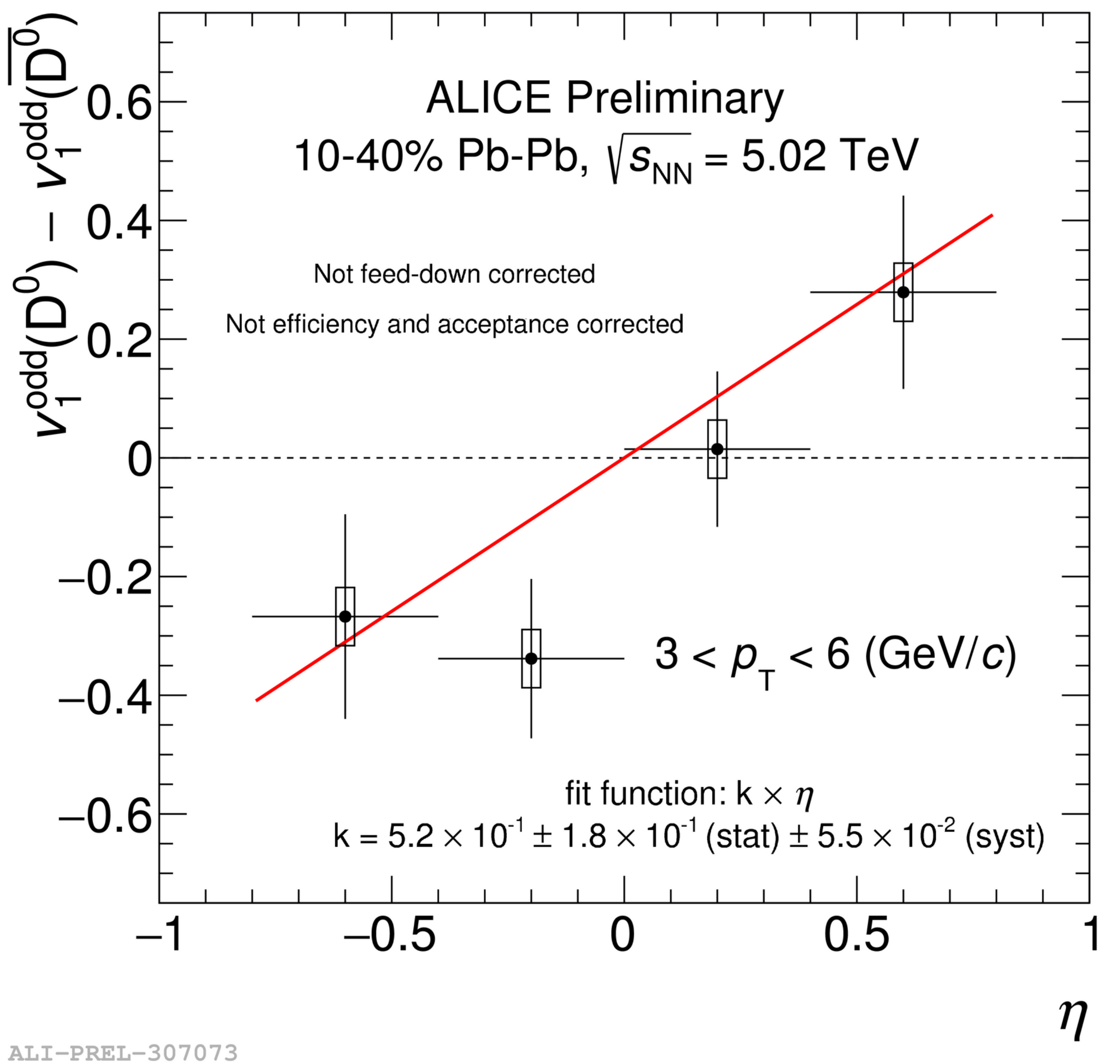


New

[1] EPJC 75 (2015) 121
[2] arXiv:1810.08177; Phys. Rev. C 98, 064901 (2018)
[3] Phys. Rev. C 96, 064903 (2017)

- Both the average unbiased D-meson v_2 and D-meson v_2 related to q_2^{V0A} : compatible to that observed by charged particles
- Hint of separation also with q_2^{V0A}
- Measurement with unbiased and large q_2^{TPC} compatible with prediction from POWLANG [1] model, while LIDO [2] and DAB-MOD M&T [3] models provide better description of the data for small q_2^{TPC}
- DAB-MOD E_{loss} [3] gives a fair description for unbiased v_2

Delta v_1 low p_T for D^0 meson



- The difference of the directed flow, Δv_1 → quantify the effect of the charge separation due to the presence of an electromagnetic field
- Rapidity dependence of the charge difference Δv_1 is fitted using a linear function with slope ***k***
- ***k* = 0.52 ± 0.18(stat) ± 0.05(syst)**
- The significance of the measurement **2.7σ**.

Conclusions

- Non-strange D-meson R_{AA} in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV for central (0-10%) and semi central (30-50%) events with 2018 data
  - constrains the model predictions with the finer bins with the new data sample for p_T < 10 GeV/c (improved measurement in terms of uncertainties reduction)
- Non-strange D-meson elliptic flow in mid-central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
  - charm quarks sensitive to collective expansion of the system
  - D-meson v_2 is higher that of J/psi for p_T < 6-8 GeV/c, while compatible with the charged particles within uncertainty at high p_T
- Event Shape Engineering for D-meson elliptic flow
  - sensitivity of c quark to the light-quark collectivity and event-by-event fluctuations in the initial state

Thank you !

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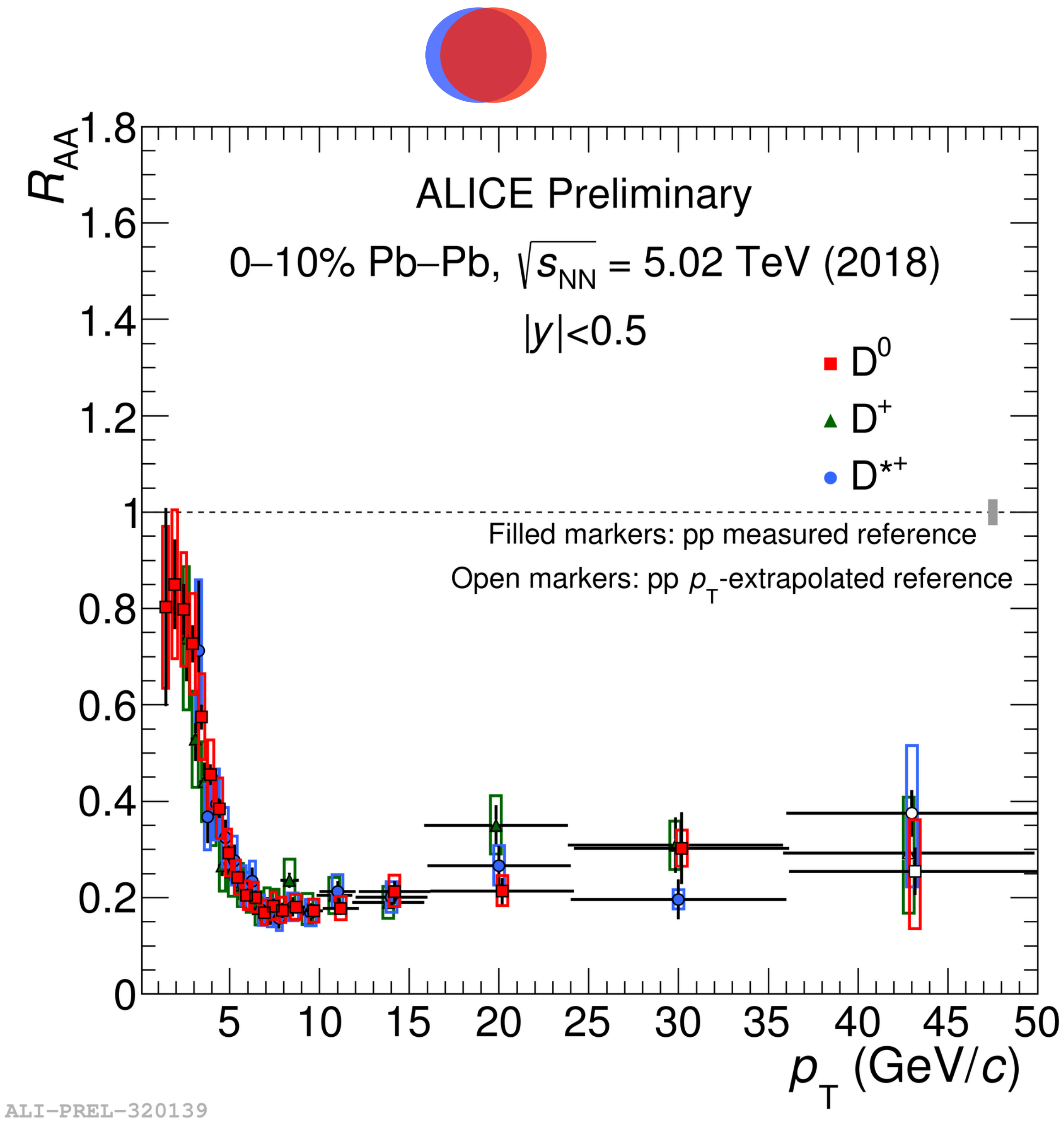
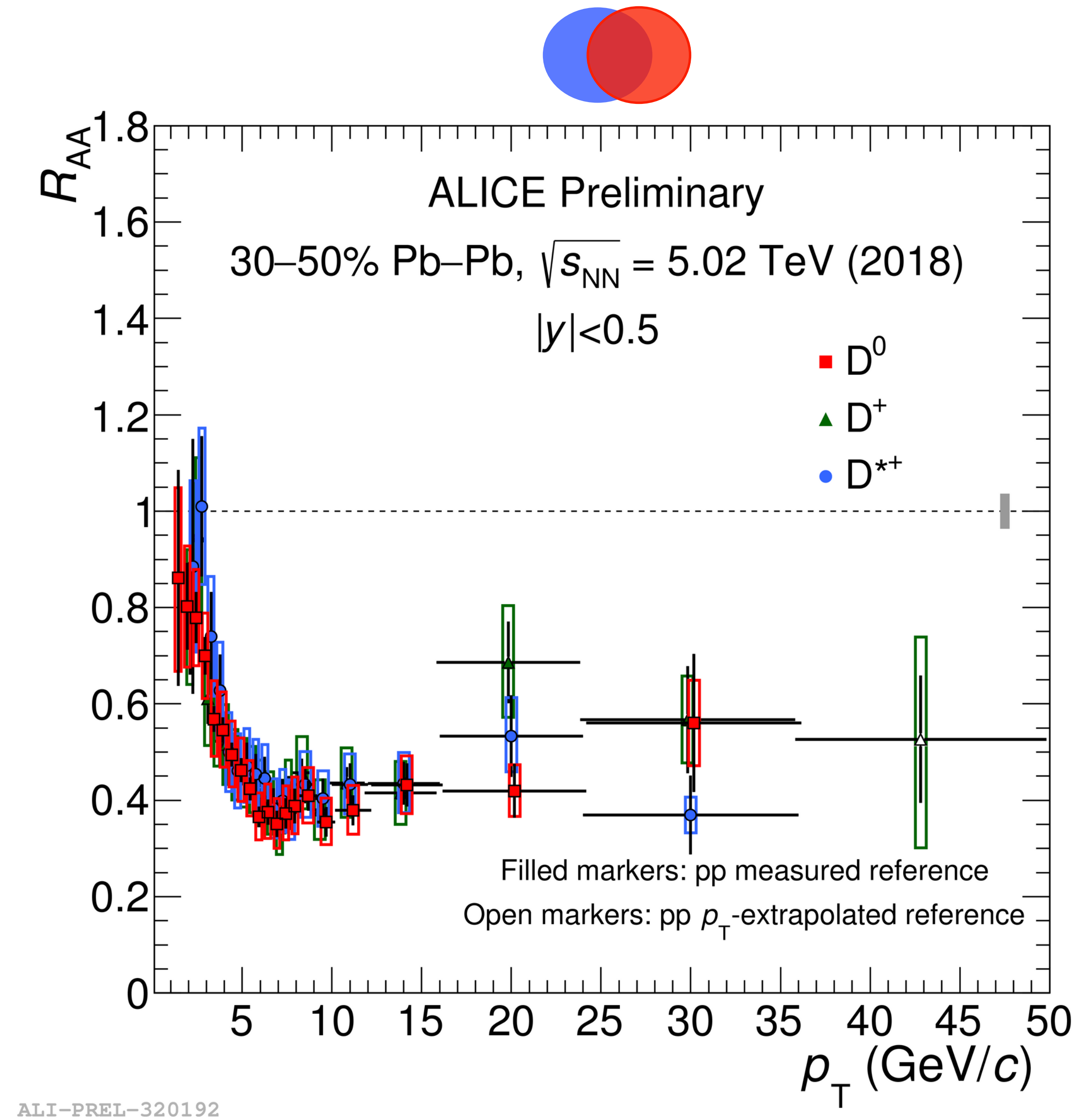
Backup slides

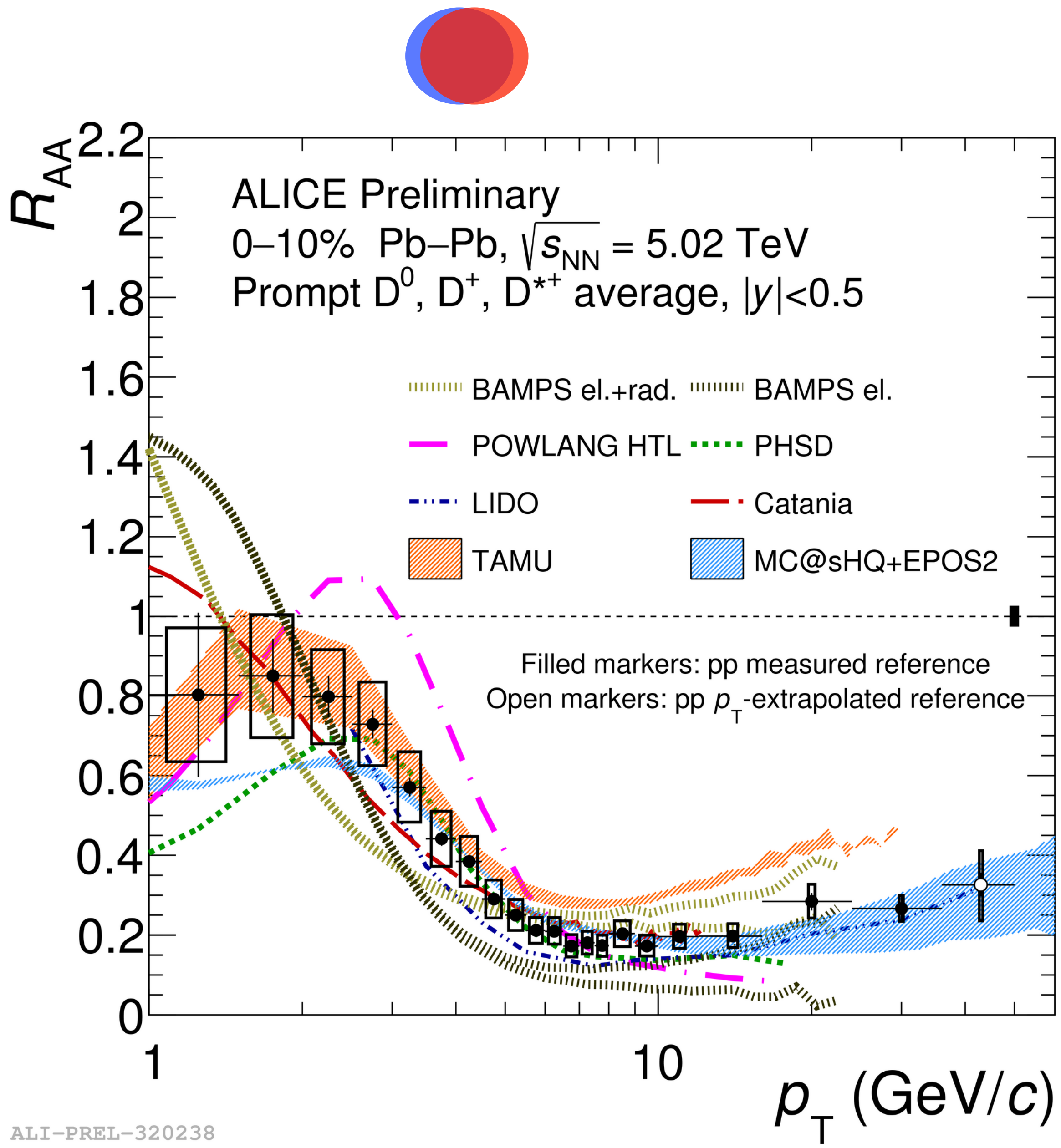
Non-strange D-meson R_{AA}

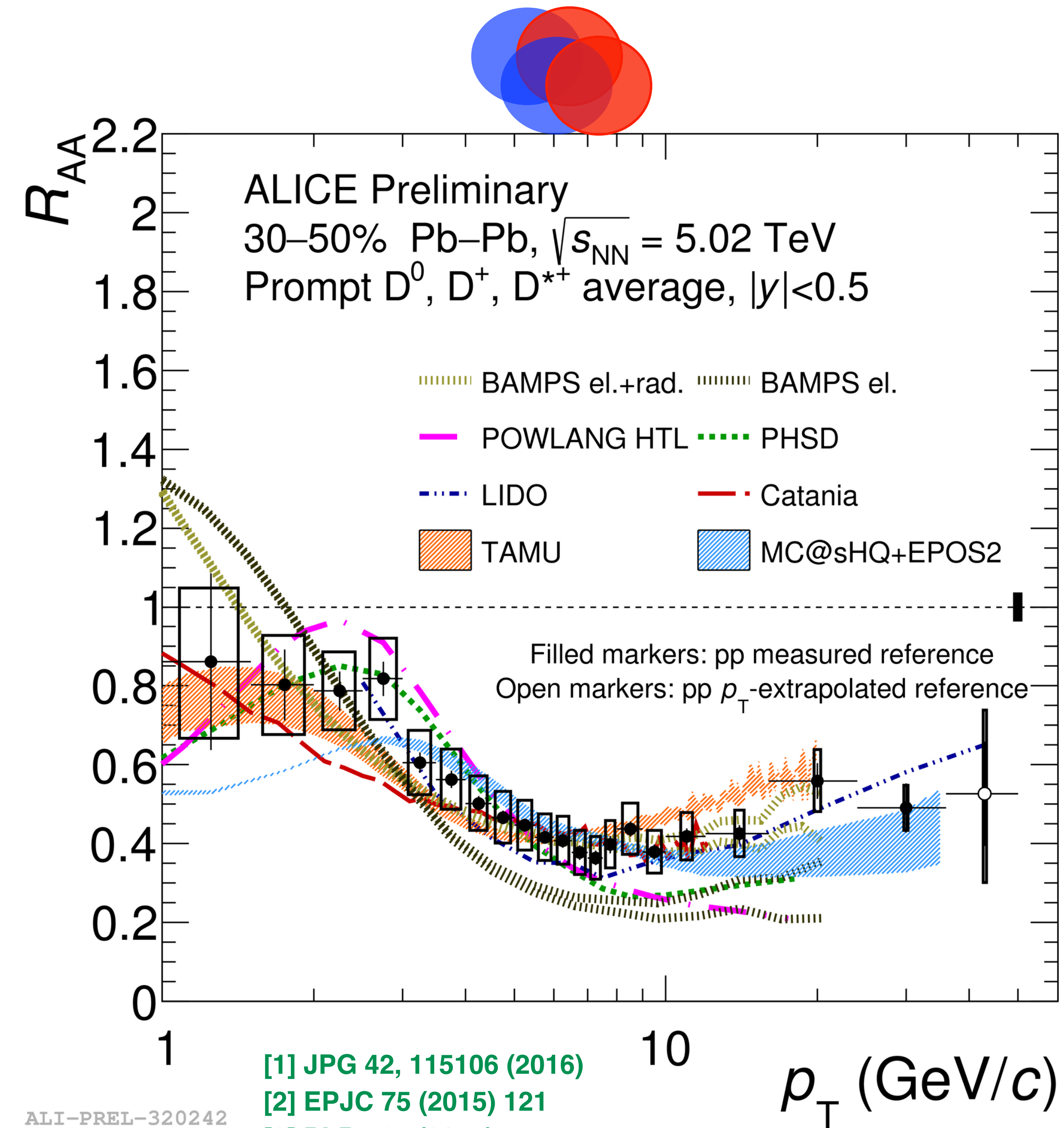




- Non-strange D-meson R_{AA} compatible within uncertainty
- R_{AA} semi central events (30-50%) > R_{AA} central events (0-10%) ➡ Increasing suppression from semi central to central collisions

Non-strange D-meson R_{AA}





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[5] PRC 89 (2014) 014905
[6] PRC 93 (2016) 034906
[7] Phys. Rev. C 89, 054914 (2014)

- Average non-strange D-meson R_{AA} compared to Transport models
- **BAMPS el.** [1], **POWLANG** [2] and **TAMU** [3] : the interactions described by collisional (i.e. elastic) processes
- **BAMPS el.+rad.** [1], **MC@sHQ+EPOS2** [5] and **PHSD** [6]: energy loss from medium-induced gluon radiation and collisional processes considered

D-meson elliptic flow Pb-Pb collisions

- The scalar product method is based one the measurement of the *Q-vectors*

$$Q_{2,x} = \sum_{i=1}^{N} w_i \cos(2\varphi_i) \quad Q_{2,y} = \sum_{i=1}^{N} w_i \sin(2\varphi_i)$$

- v_2 is evaluated for all the candidates in bins of invariant mass (M)

$$v_2(M) = \frac{1}{R_2}\langle u_D \cdot Q_2^{\mathrm{A}}/M^{\mathrm{A}}\rangle(M)$$

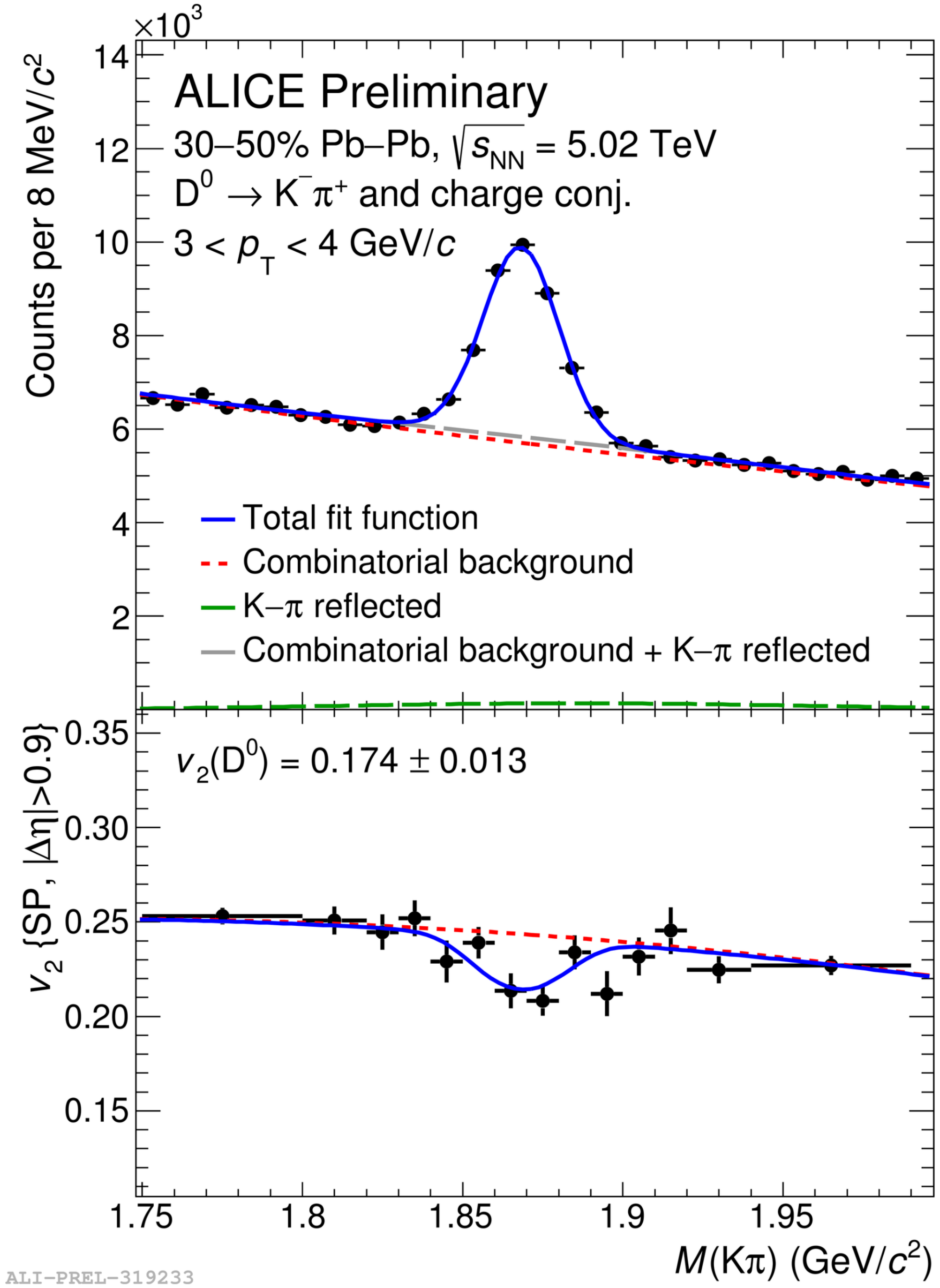
- The v_2 of the signal is extracted via a simultaneous fit of v_2 (M) and M

$$v_2(M) = v_2^S \frac{S(M)}{S(M)+B(M)} + v_2^B \frac{B(M)}{S(M)+B(M)}$$

- The v_2 of the background is parametrized with a linear function
- R_2 is the scalar-product resolution, which is computed with the 3 sub-event formula

$$R_2 = \sqrt{\frac{\langle Q_2^{\mathrm{A}} \cdot Q_2^{\mathrm{B}}/M^{\mathrm{A}}M^{\mathrm{B}}\rangle\langle Q_2^{\mathrm{A}} \cdot Q_2^{\mathrm{C}}/M^{\mathrm{A}}M^{\mathrm{C}}\rangle}{\langle Q_2^{\mathrm{B}} \cdot Q_2^{\mathrm{C}}/M^{\mathrm{B}}M^{\mathrm{C}}\rangle}}$$

A: signals in the V0C detector
B: signals in the V0A detector
C: reconstructed track in TPC with $|\eta| < 0.8$



Event shape engineering for the D-meson v_2

- Events are divided according to the magnitude of the second-harmonic reduced flow vector:

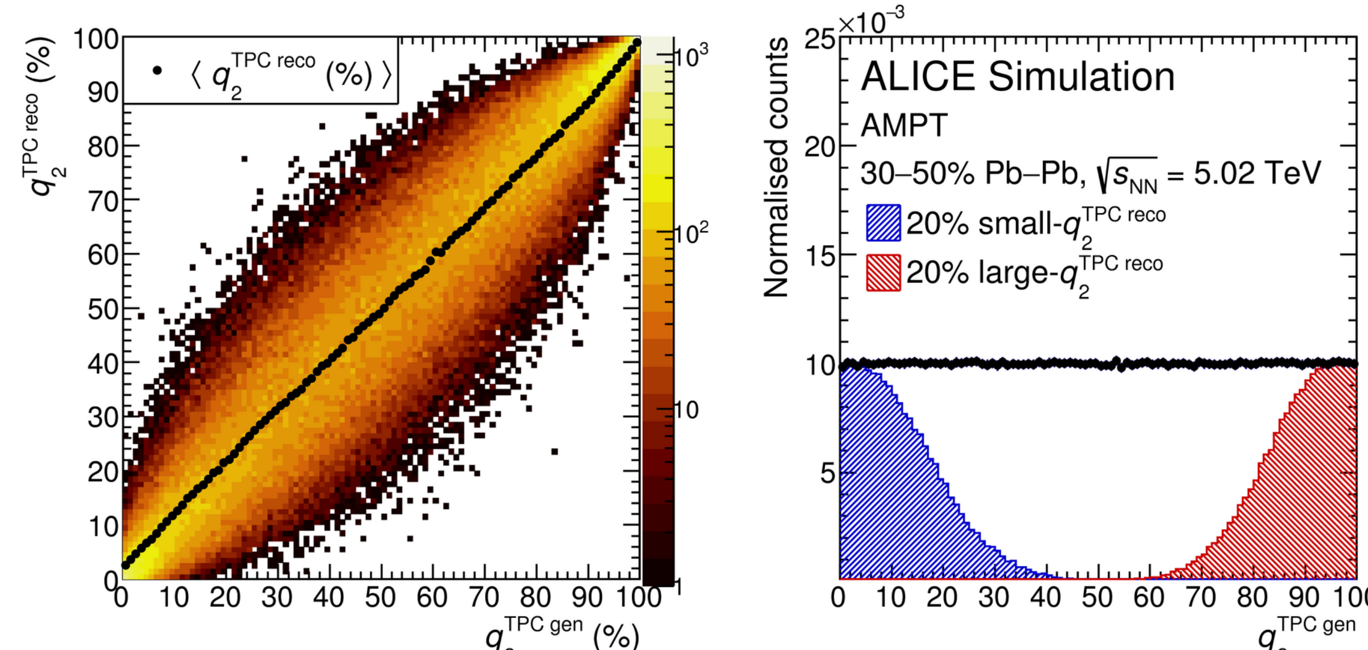
$$q_2 = \frac{|Q_2|}{\sqrt{M}}$$

- Two estimator used:
  (i) q_2^{TPC} to have better possible selectivity
  (ii) q_2^{V0A} to suppress non-flow contributions

- Two classes defined:
  (i) 20% events with larger q_2
  (ii) 20% events with smaller q_2

- q_2 percentiles defined in bins of 1% centrality to avoid centrality/multiplicity biases

- same centrality and multiplicity distributions in ESE-selected and unbiased samples



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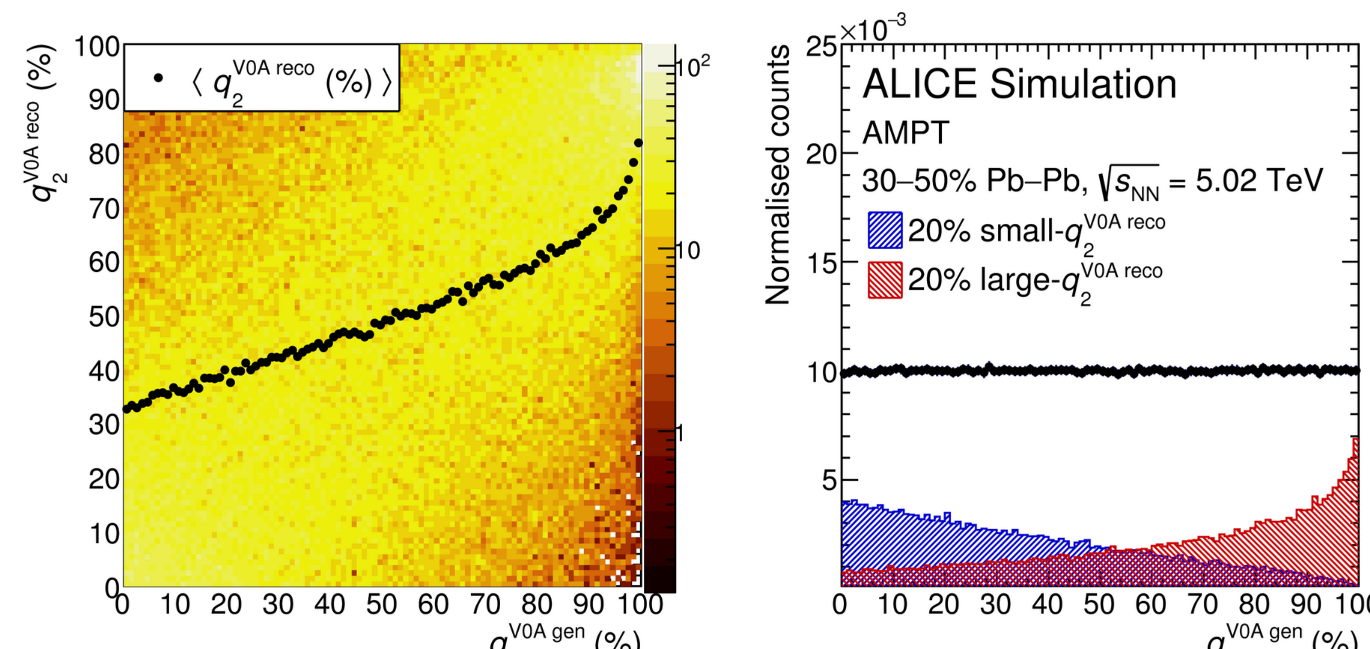

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