Heavy Flavour and Quarkonia Measurements from ALICE

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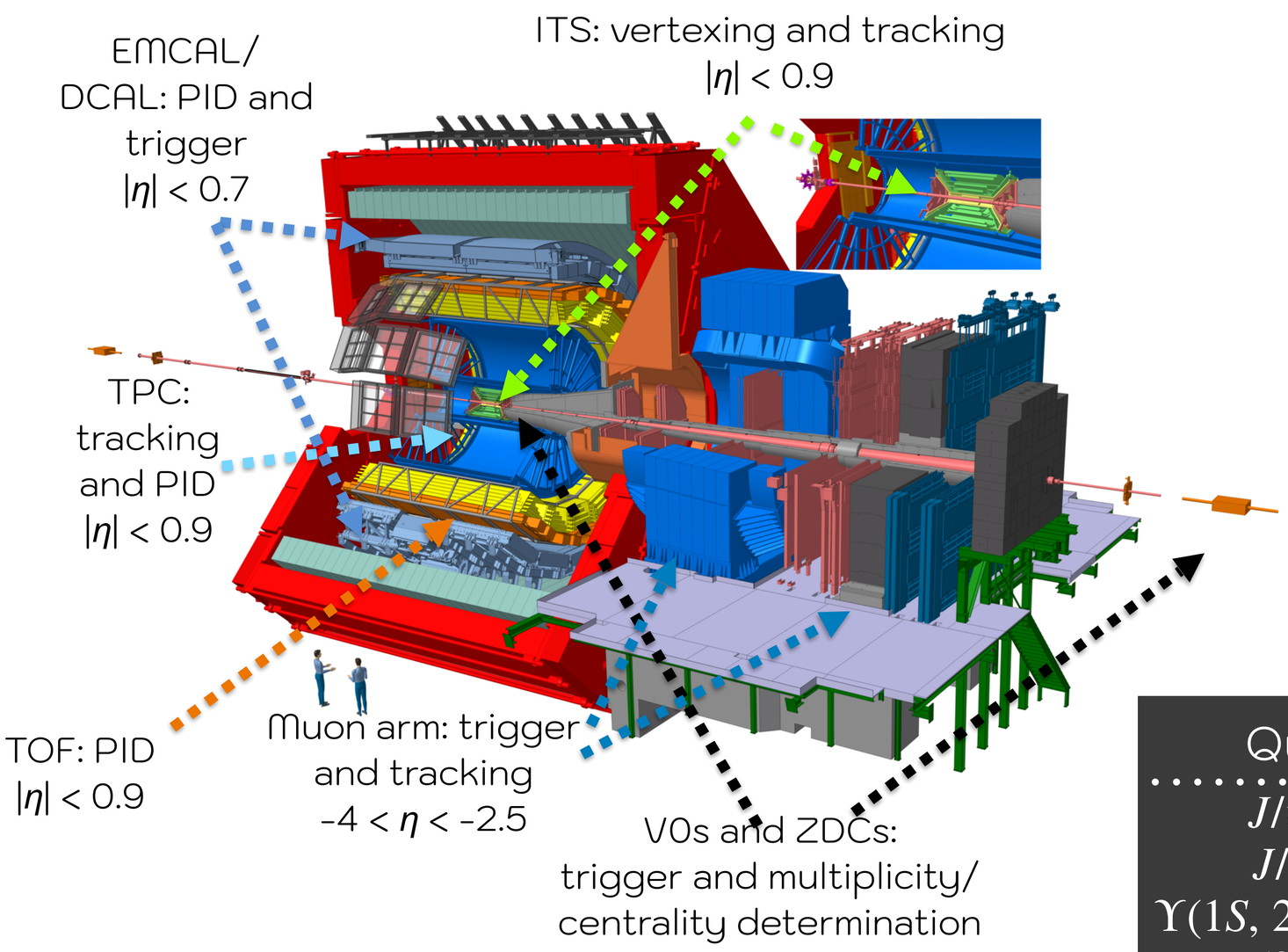
Utrecht University

ALICE

Experimental setup



Collision system	$\sqrt{s}$ or $\sqrt{s_{NN}}$ (TeV)
pp	2.76, 5.02, 7, 8, 13
p-Pb	5.02, 8.16
Pb-Pb	2.76, 5.02
Xe-Xe	5.44

Fully reconstructed D and Λ^+_c

$D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D^{*+} \to D^0\pi^+$
$D_s^+ \to \phi\pi^+ \to K^-K^+\pi^+$, $\Lambda_c^+ \to \pi^+K^-p^+$
$\Lambda_c^+ \to K_0^s p^+$

Quarkonia

$J/\psi \to \mu^+\mu^-$
$J/\psi \to e^+e^-$
$\Upsilon(1S, 2S, 3S) \to \mu^+\mu^-$
$\psi(2S) \to \mu^+\mu^-$

Semi-leptonic decays of open HF

$b, c \to e^{\pm}X$
$b, c \to \mu^{\pm}X$

Why charm and beauty?

Heavy Quarks

- High mass: produced in hard scatterings (short time scales)
- Propagate through the QGP interacting with its constituents

Open heavy flavour

- Hard fragmentation: carries large part of the c/b momentum
- Hadronization mechanisms

Quarkonia

- Sequential melting: can used as a thermometer
- Regeneration: Enhanced quarkonium production via (re)combination

- Reference for A-A collisions
- Test of pQCD-based calculations and production mechanisms

pp

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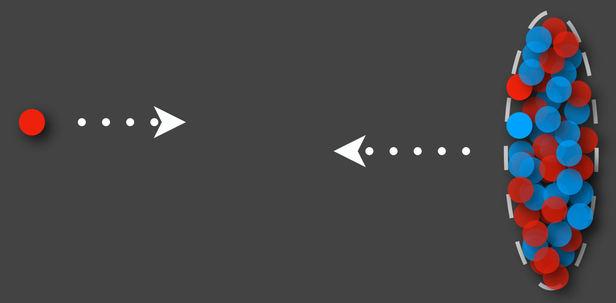
pp



- Reference for A-A collisions
- Address Cold Nuclear Matter (CNM) effects: Shadowing, k_T broadening, CNM energy loss, ...
- Collective effects?

p-Pb

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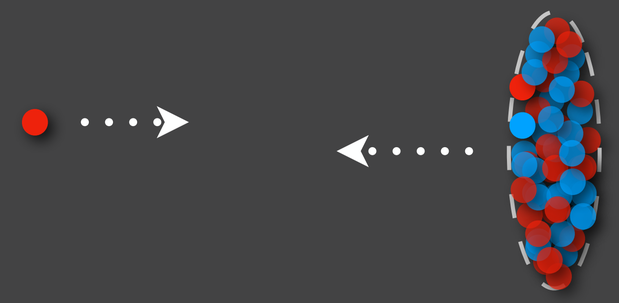
pp



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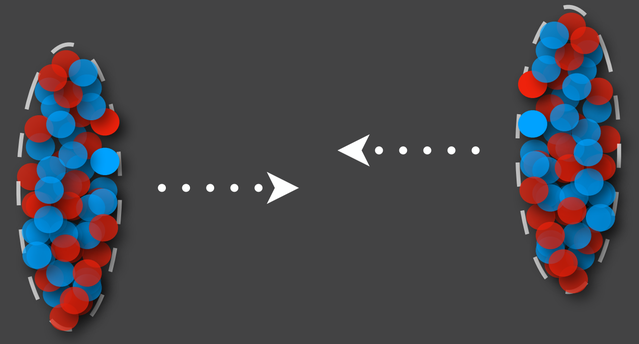
p-Pb



Study the Quark-Gluon Plasma

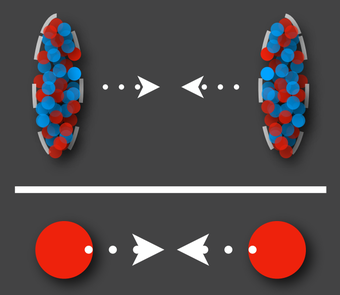
- Energy loss
- Collective effects
- Hadronisation
- Debye screening

Pb-Pb

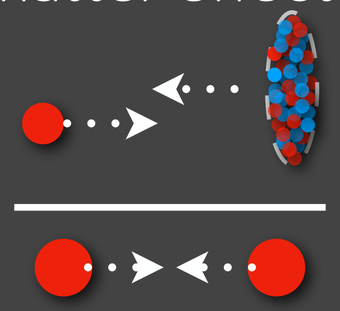
Study the production of HF particles across different systems

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

Energy loss in the QGP



Cold Nuclear Matter effects



Ratios of different particles:
understand fragmentation and hadronisation, constrain models, etc

Study production in jets

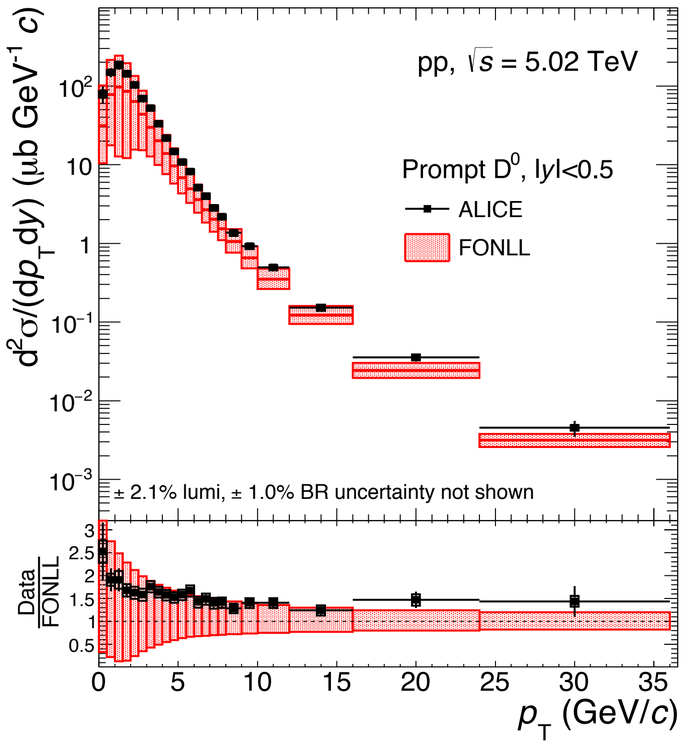
Open and hidden heavy-flavour production

D-meson and Λ^+_c production in pp

- Measurements for D^0, D^+ , D^{*+} and D^+_s (2.76 TeV, 5.02 TeV, 7 TeV and 13 TeV) and Λ^+_c (5.02 TeV and 7 TeV)

- D-meson $\frac{d^2\sigma}{dy dp_T}$ in agreement with different model predictions

D^0 @ 5.02 TeV



arXiv:1901.07979

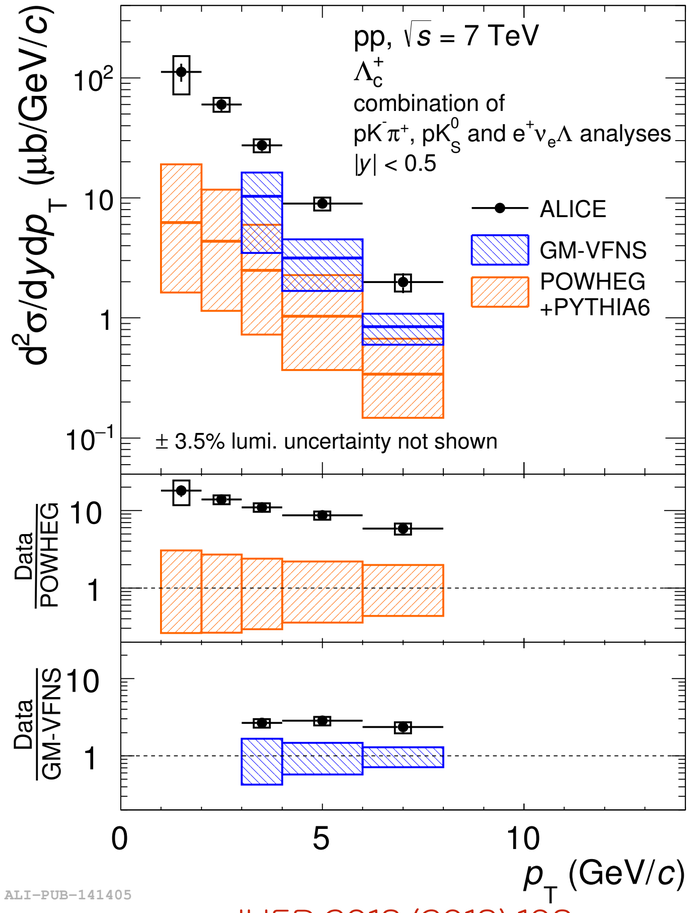
2.76 TeV: JHEP 1207 (2012) 191
7 TeV: EPJC 77 (2017) 550

FONLL: JHEP 1210 (2012) 137

D-meson and Λ^+_c production in pp

- Measurements for D^0, D^+, D^{*+} and D^+_s (2.76 TeV, 5.02 TeV, 7 TeV and 13 TeV) and Λ^+_c (5.02 TeV and 7 TeV)
- D-meson $\frac{d^2\sigma}{dydp_T}$ in agreement with different model predictions
- Λ^+_c $\frac{d^2\sigma}{dydp_T}$ underestimated by pQCD calculations which describe D-meson production

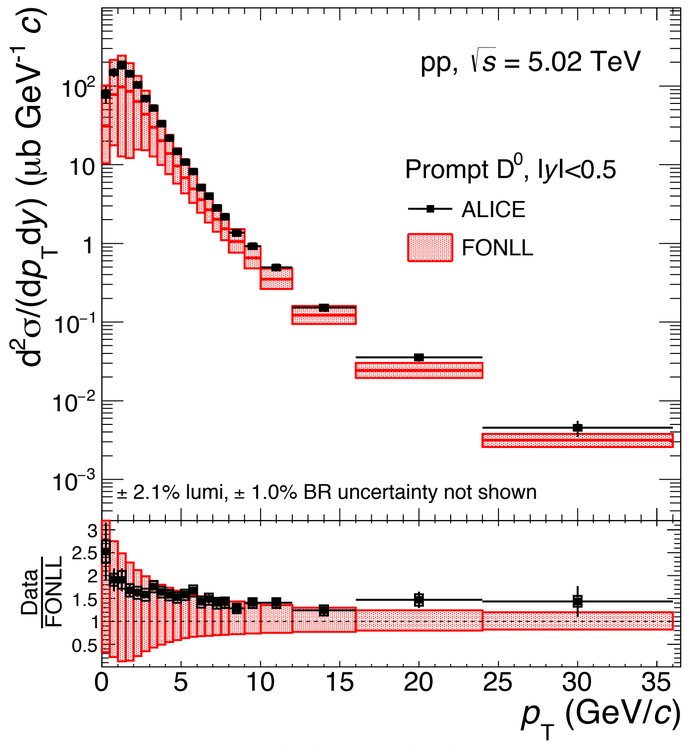
Λ^+_c @ 7 TeV



JHEP 2018 (2018) 108

GM-VFNS: EPJ C 41 (2005) 199
POWHEG: JHEP 0709 (2007) 126

D^0 @ 5.02 TeV



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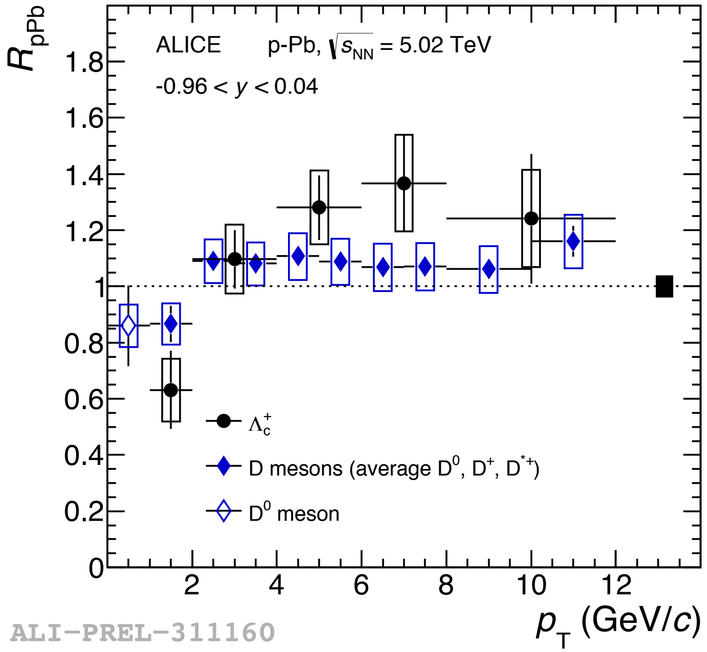
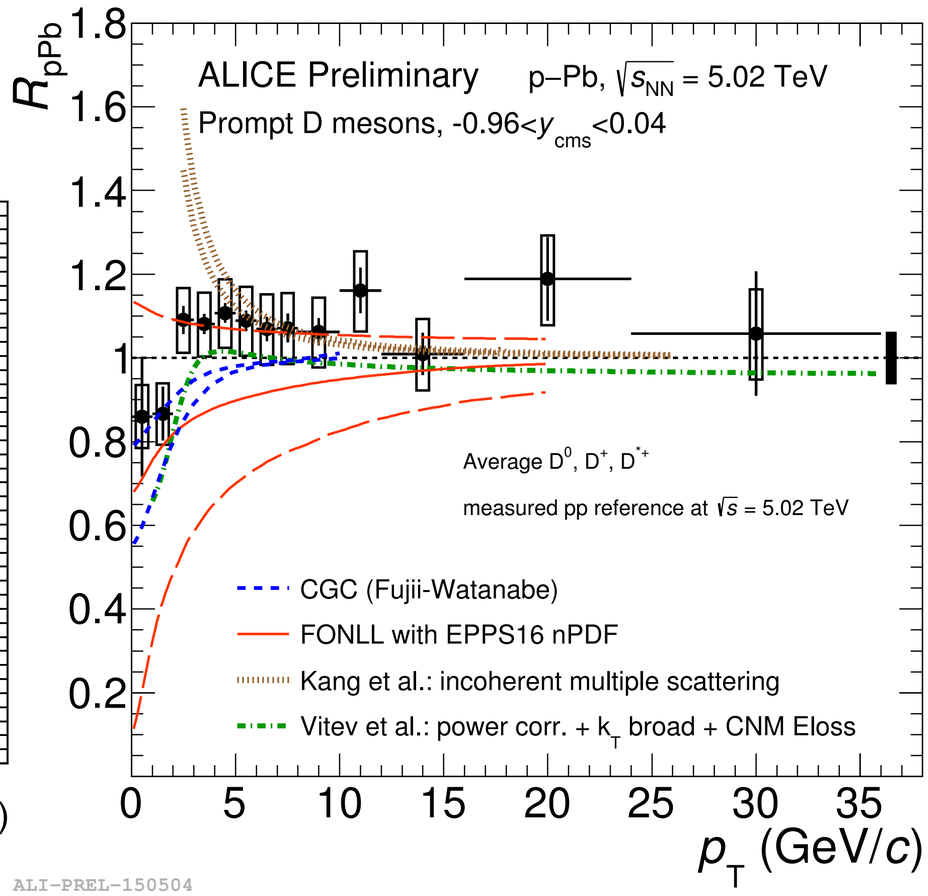
D-meson and Λ^+_c R_{pPb}

- R_{pPb} is compatible with unity for both D mesons and Λ^+_c
- Data does not favour a suppression larger than 10-20% for $5 < p_T < 12$ GeV/c
- Models qualitatively describe the results

Λ^+_c



D mesons



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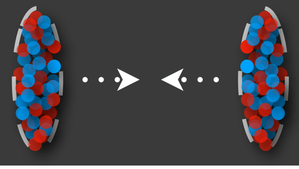
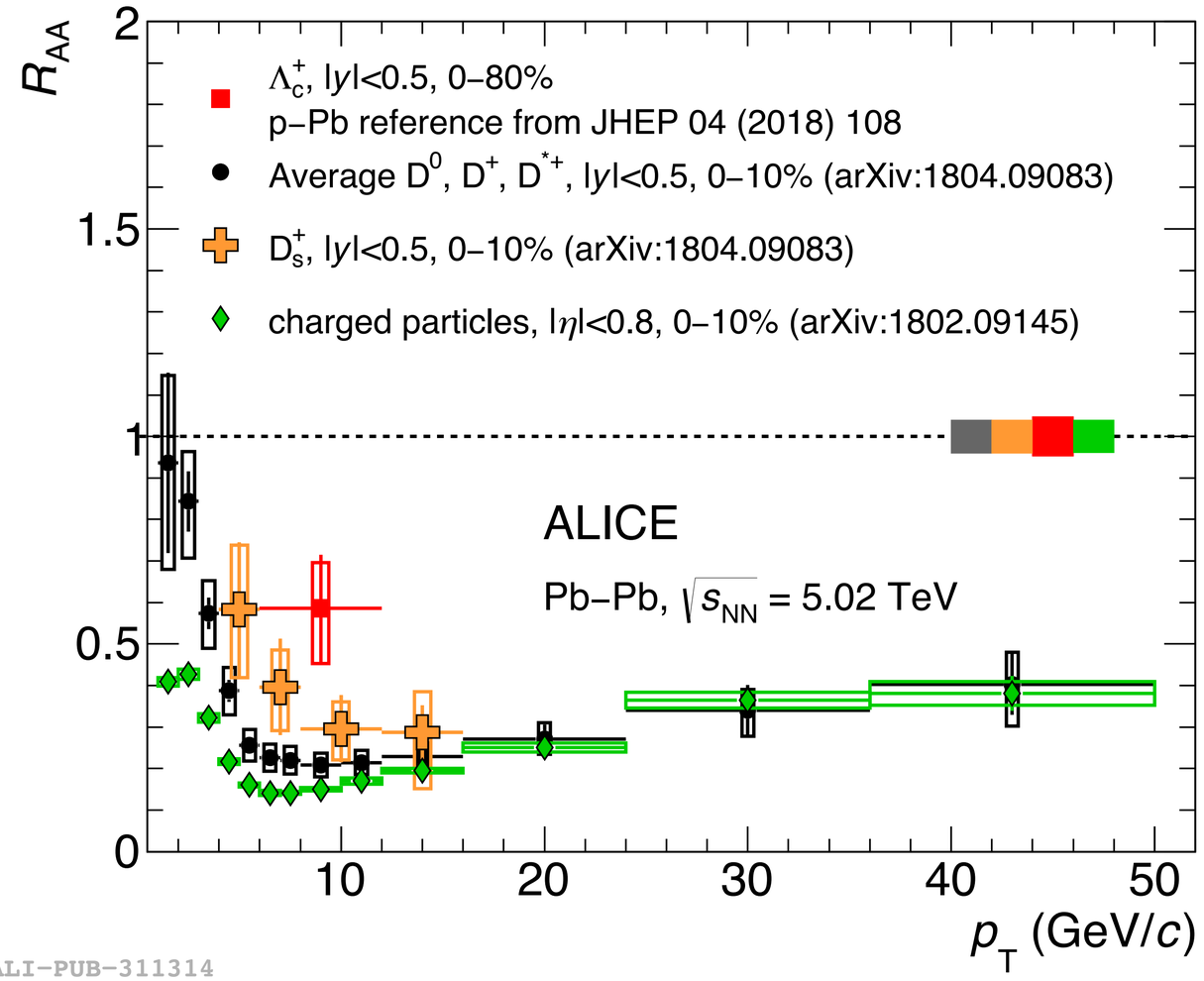
D-meson and Λ^+_c R_{AA}



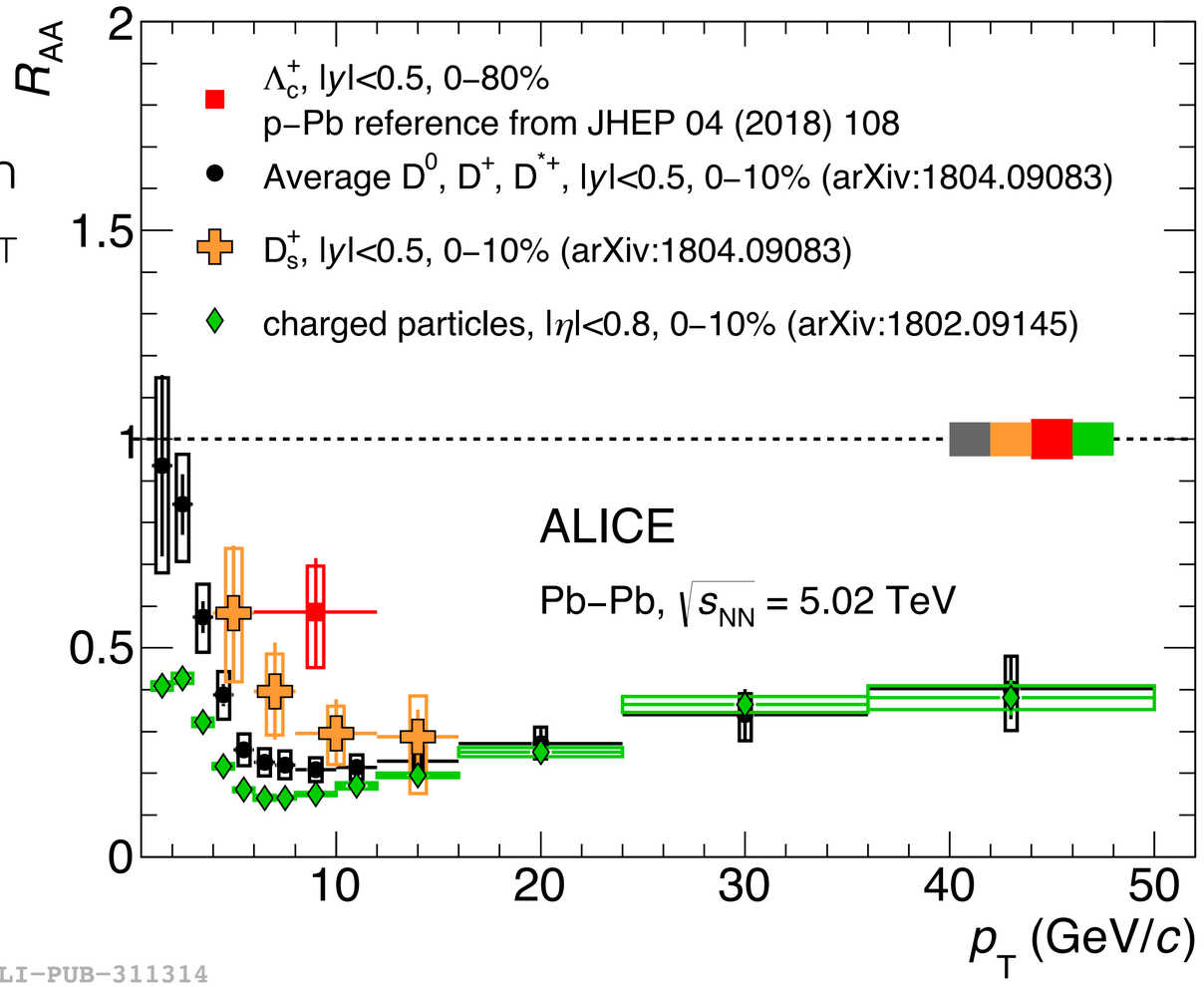


D mesons: JHEP 2018 (2018) 174 Λ^+_c: PLB 793 (2019) 212

D-meson and Λ^+_c R_{AA}

$[\Delta E(\pi) > \Delta E(D) \rightarrow]$ R_{AA}(light) < R_{AA}(D) ?

- $R_{AA}(D^{0,+,*+}) > R_{AA}$(ch. part.) for intervals with $3 < p_T < 8$ GeV/c (2σ) but similar at high p_T



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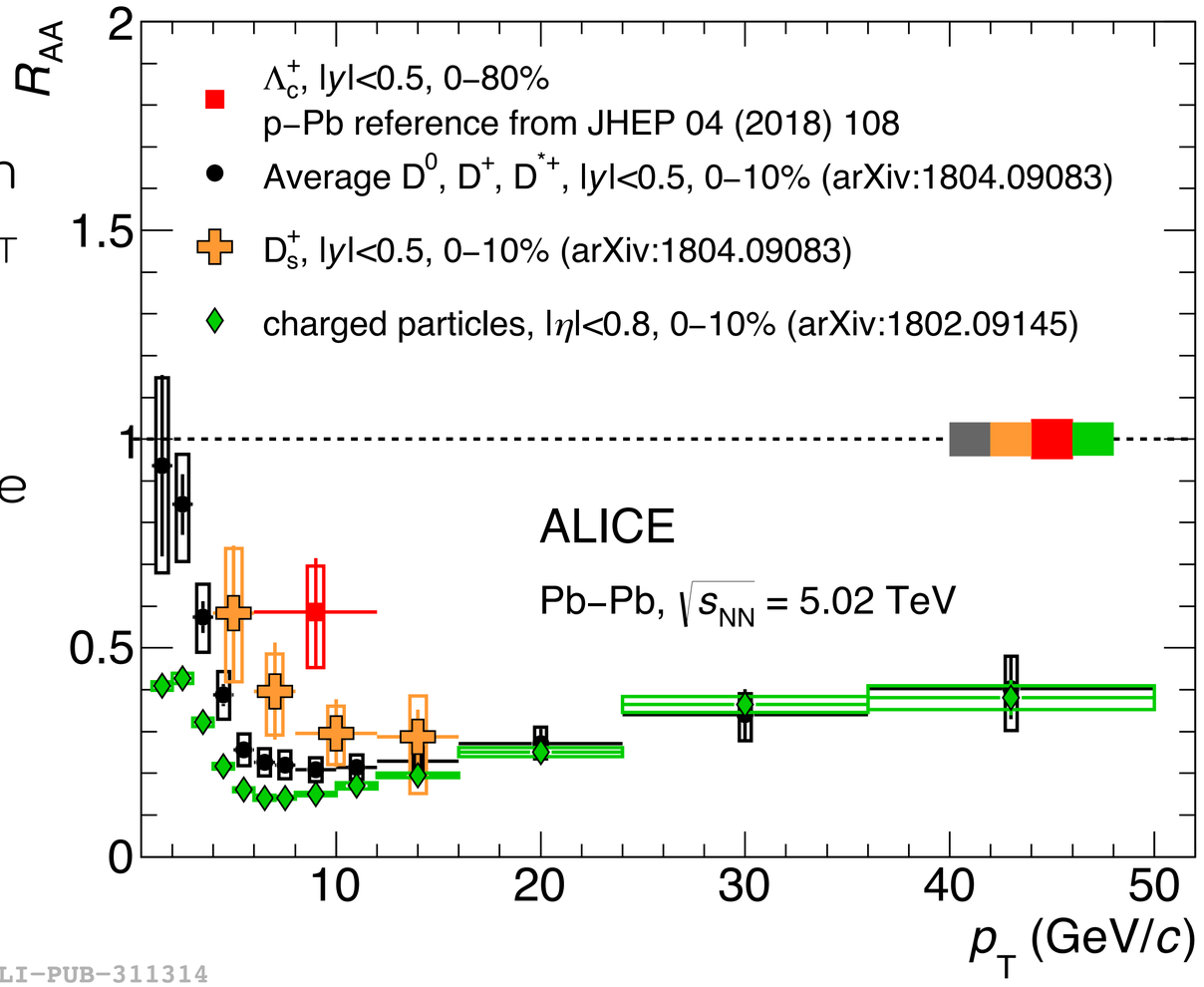
- $R_{AA}(D^+_s) > R_{AA}(D^{0,+,*+})$, but only 1σ difference



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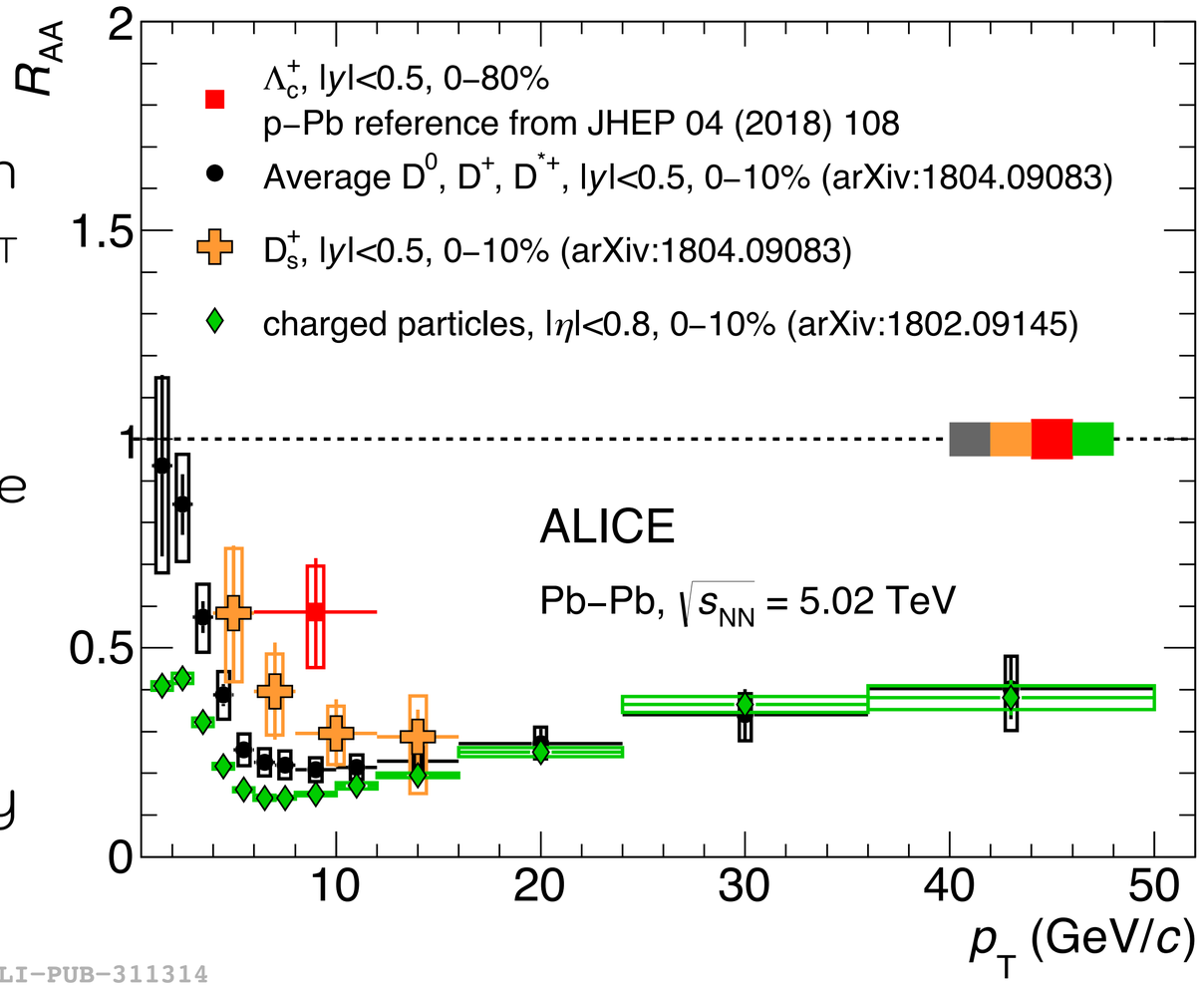
Baryons vs mesons ?

- $R_{AA}(\Lambda^+_c) > R_{AA}(D^{0,+,*+})$ in 1.7σ (0-80%)
  Charmed-baryon production increased by hadronisation via coalescence?



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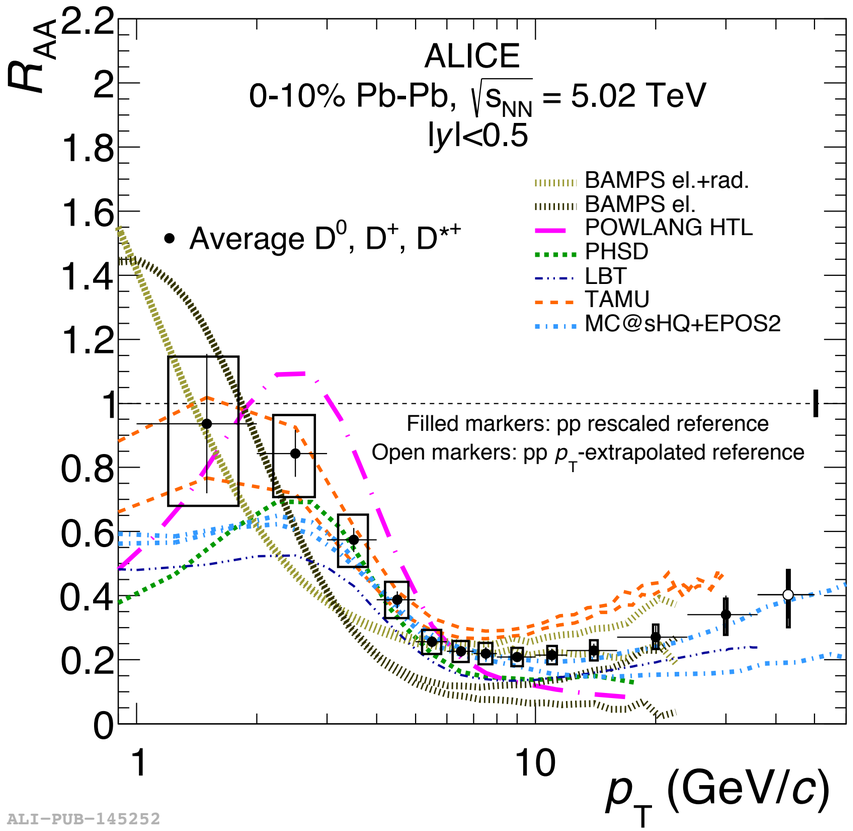


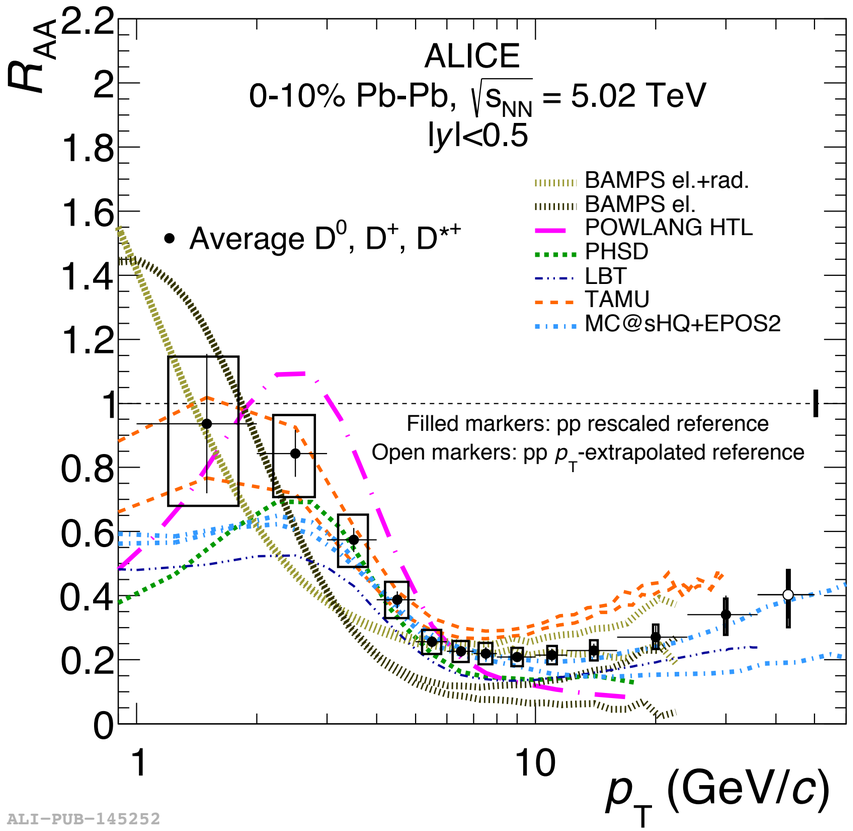
Heavy-quark transport

- Qualitative agreement between different models and data.

JHEP 2018 (2018) 174

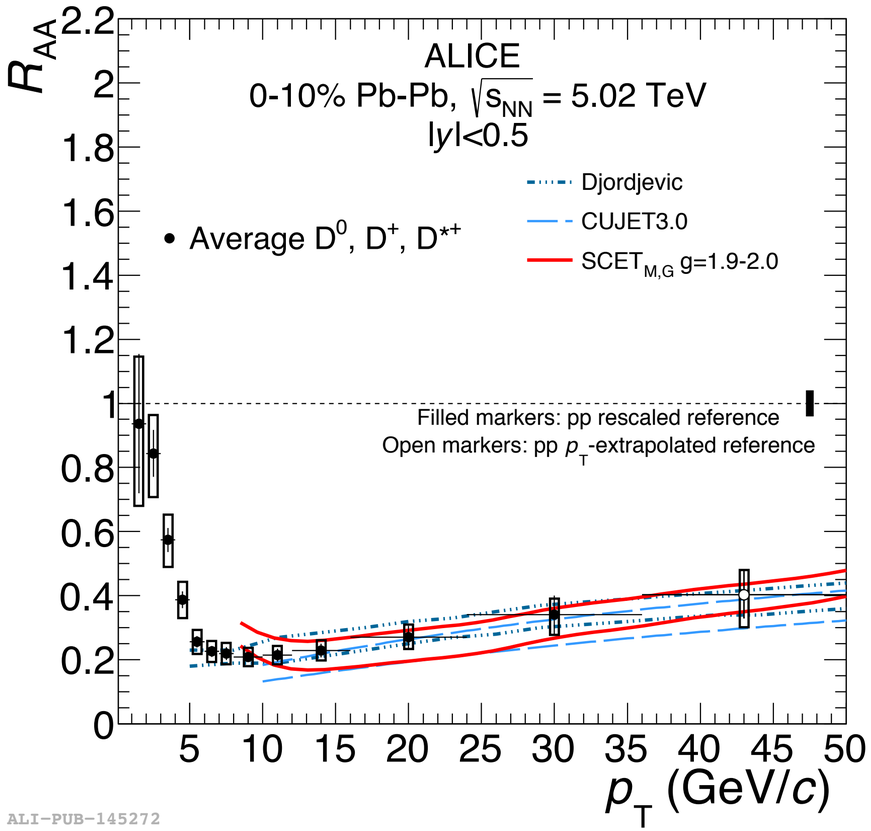
- Precise measurement provides constrains to models

Models: D-meson R_{AA}



pQCD energy loss

Heavy-quark transport



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JHEP 2018 (2018) 174

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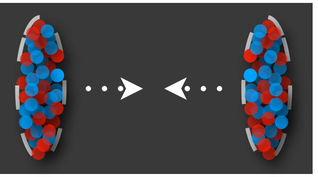
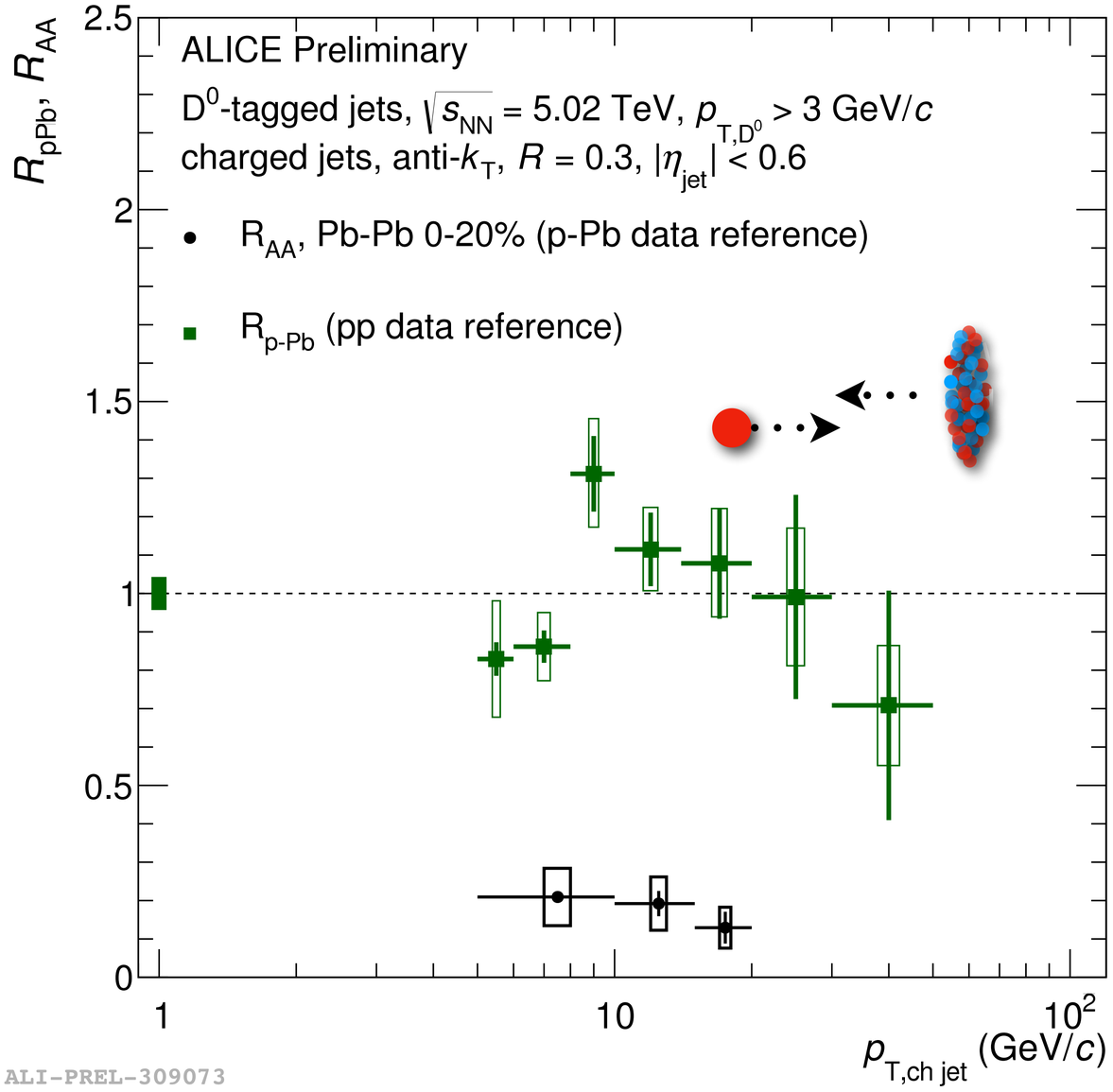


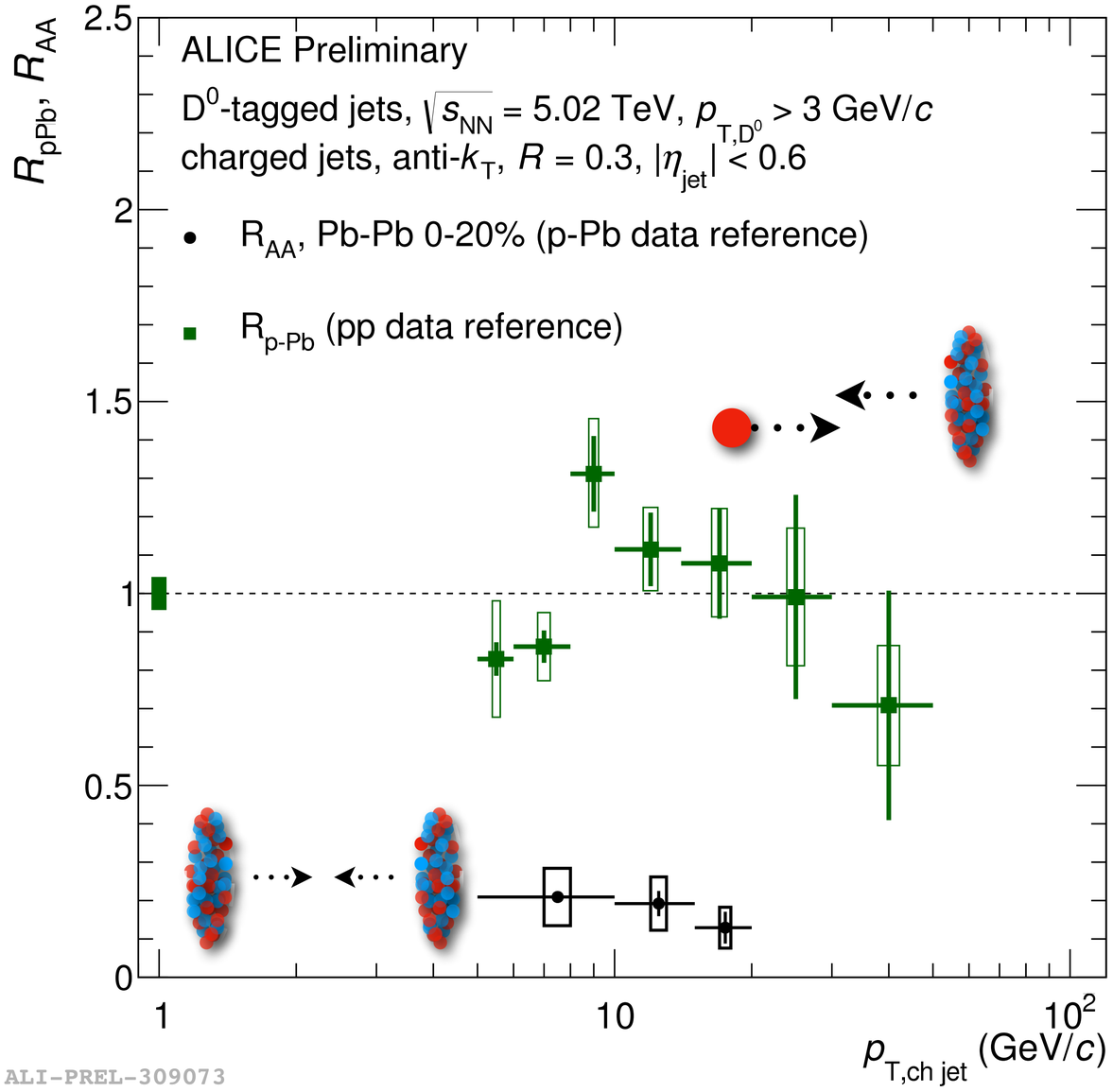
D^0-tagged jets R_{AA} and R_{pPb}

- R_{pPb}:
  - Compatible with unity within uncertainties



D^0-tagged jets R_{AA} and R_{pPb}

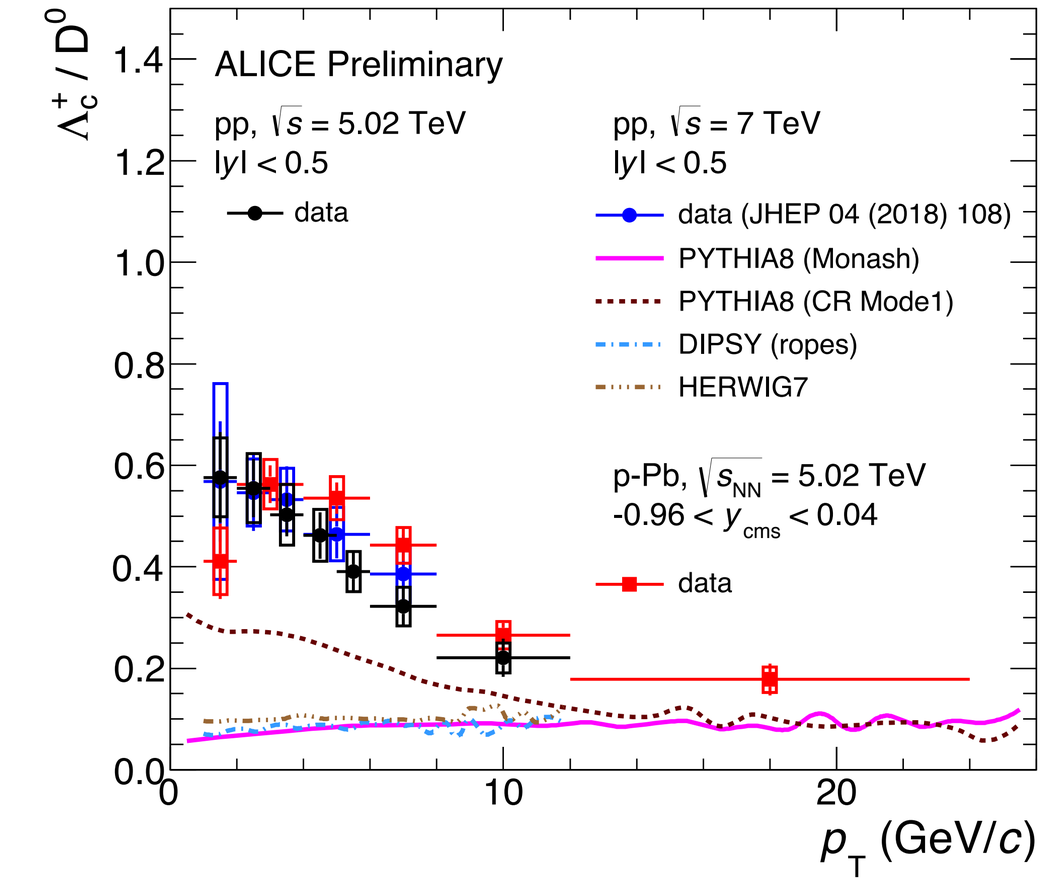
- R_{pPb}:
  - Compatible with unity within uncertainties
- R_{AA}:
  - Strong suppression of D^0-tagged jets for $p_T > 5$ GeV/c
  - Similar suppression for D^0-tagged jets and D^0 mesons



Λ^+_c/D^0 ratios

- Sensitive to hadronisation mechanisms
- Λ^+_c/D^0 higher than measured e^+e^- and ep collisions at lower $\sqrt{s_{NN}}$ (Λ^+_c/D^0 ~ 0.1-0.22)
- Λ^+_c/D^0 similar in pp and p-Pb collisions
- Ratios in Pb-Pb collisions higher than in p-Pb collisions
- Ratios underestimated by models: PYTHIA8 calculations with enhanced colour reconnection mode is the closest to the measurement

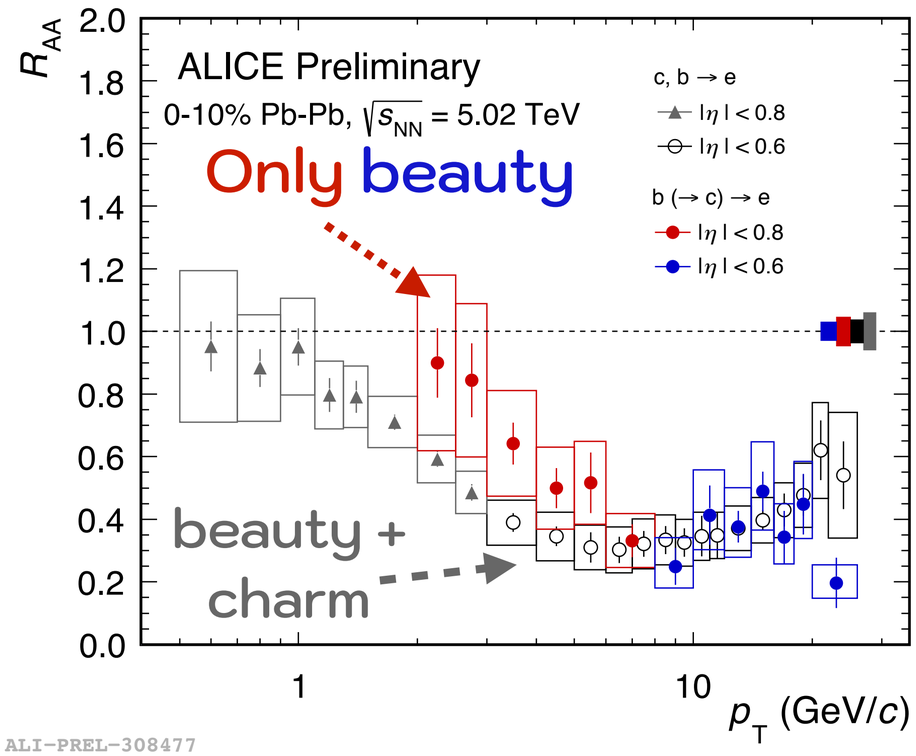
PYTHIA8 Monash	EPJC 74 (2014) 3024
PYTHIA8 CR Mode1	JHEP 08 (2015) 003
DIPSY	JHEP 08 (2011) 103
HERWIG7	EPJC 58 (2008)



$$\left(\frac{\Lambda_c^+}{D^0}\right)_{Pb-Pb} = 1.07 \pm 0.20(\text{stat})^{+0.15}_{-0.14}(\text{syst})$$

Pb-Pb: PLB 793 (2019) 212

HF decay leptons: R_{AA}



[ΔE(D) > ΔE(B) →] R_{AA}(D) < R_{AA}(B) ?

- *Hint* of a smaller suppression for beauty-decay electrons for p_T < 6 GeV/c

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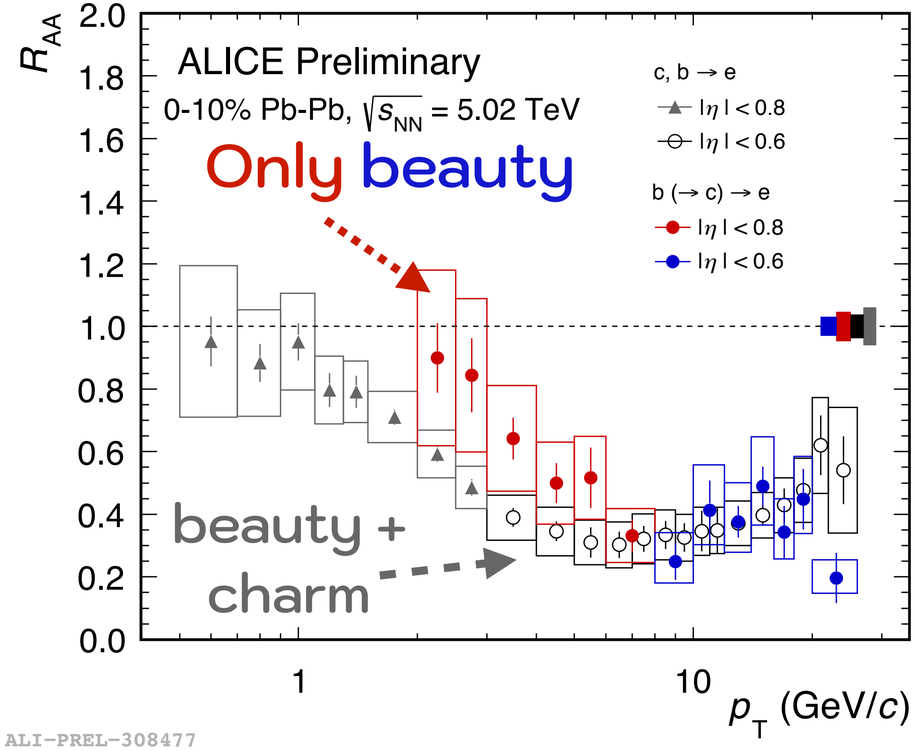

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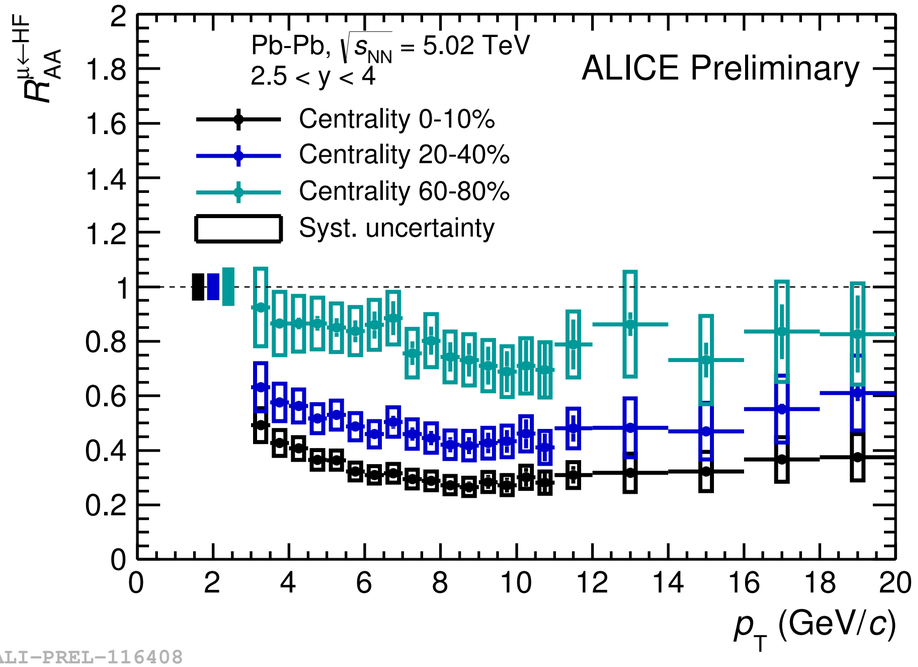
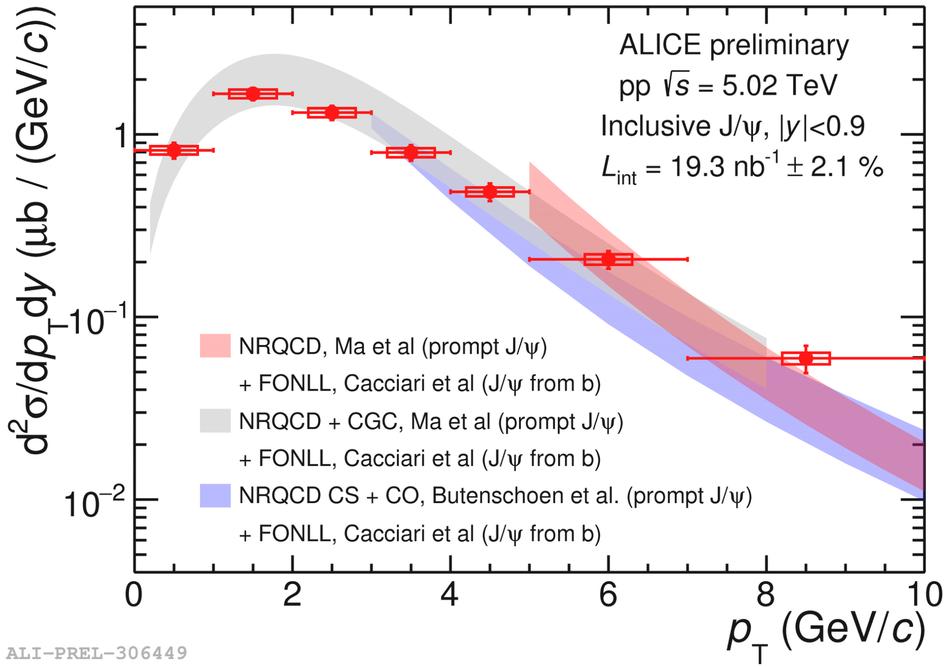


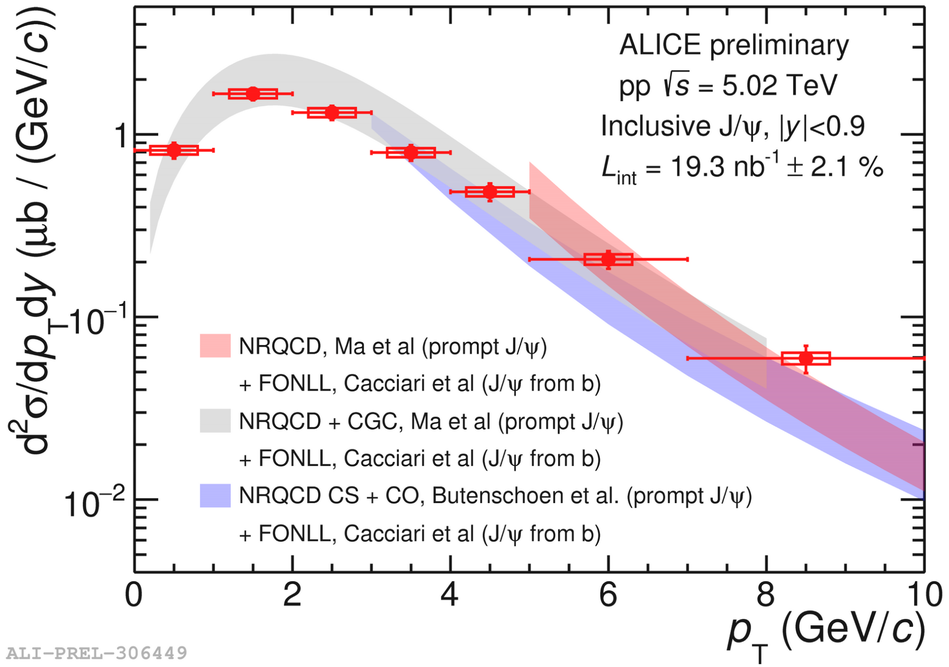
- HF muons are heavily suppressed in central Pb-Pb collisions
- R_{AA} grows from central to peripheral collisions

Charmonium production in pp



- Measurements of the J/ψ cross section at different energies and rapidities

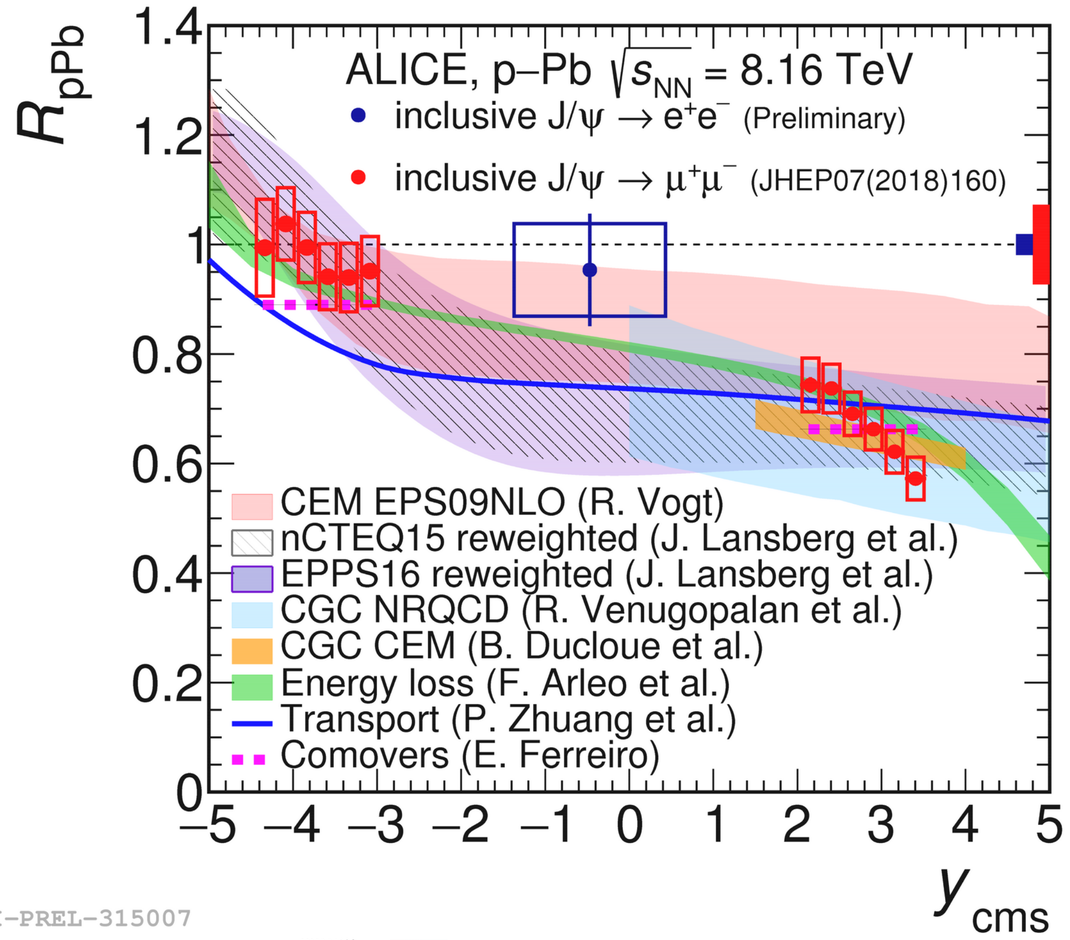
Charmonium production in pp



- Measurements of the J/ψ cross section at different energies and rapidities
- Good agreement with calculations from NRQCD calculations (prompt) + FONLL (non-prompt)

J/ψ R_{pPb}

- Backward rapidity and mid rapidity: no significant suppression is observed
- Models in qualitative agreement



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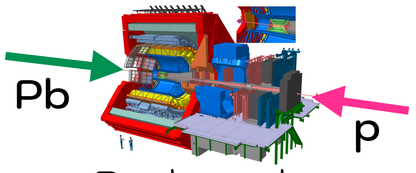
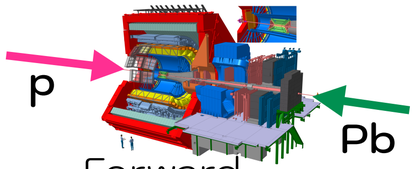


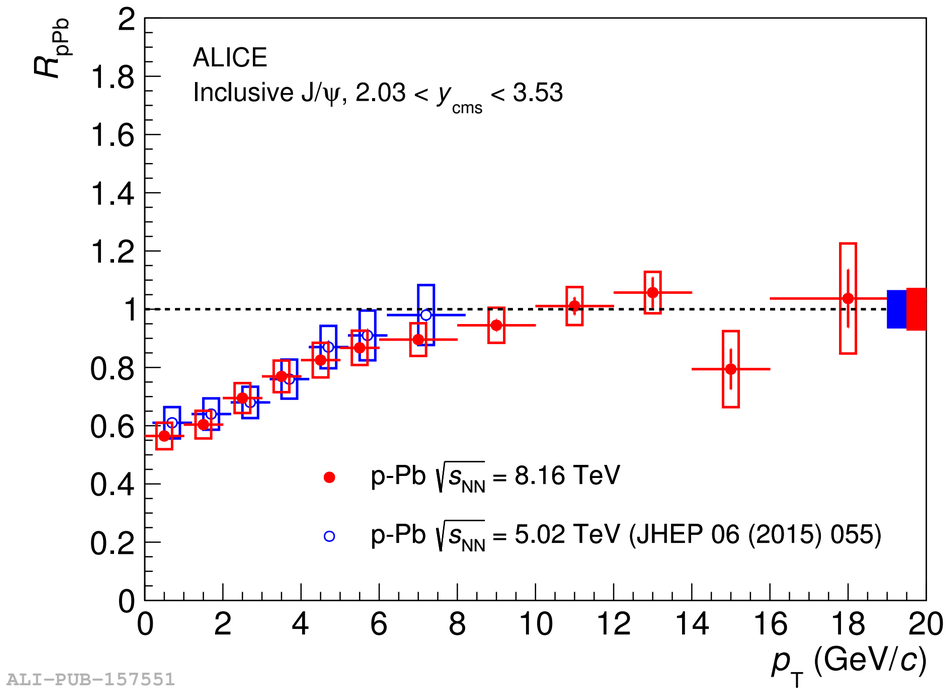
Backward

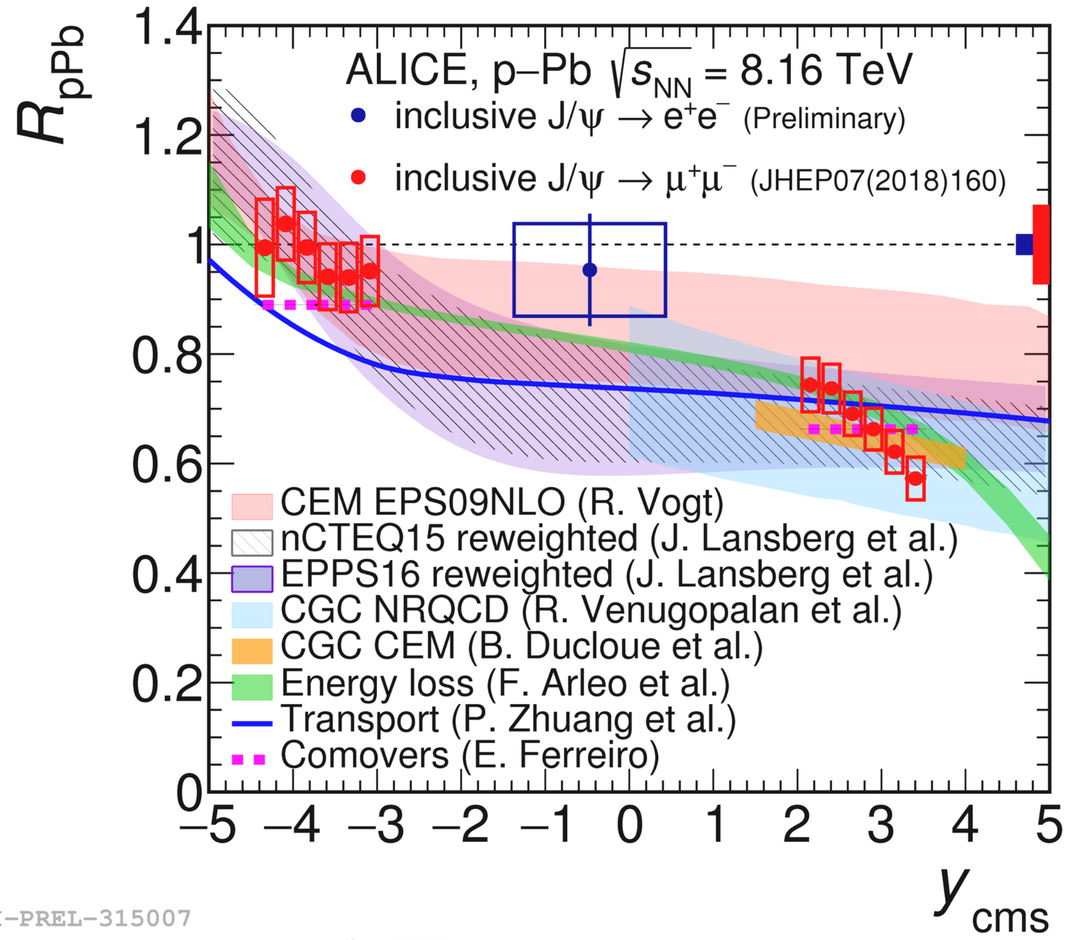


Forward

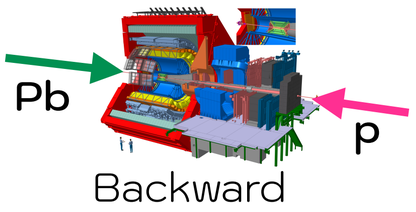
J/ψ R_{pPb}

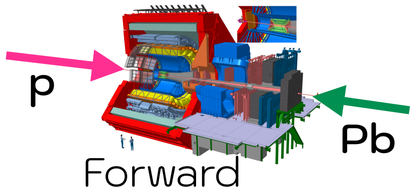
- Backward rapidity and mid rapidity: no significant suppression is observed
- Models in qualitative agreement
- Forward rapidity: suppression of the J/ψ yield for p_T < 5 GeV/c



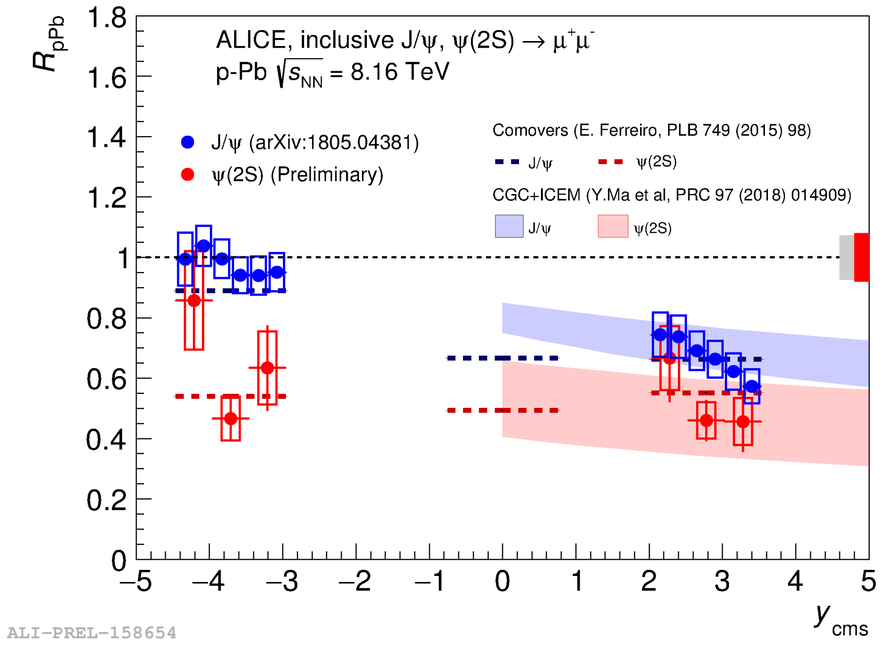


JHEP 07 (2018) 160

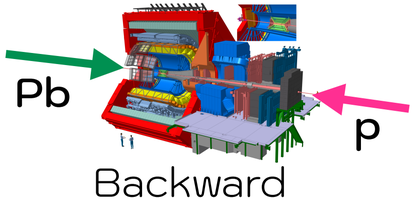


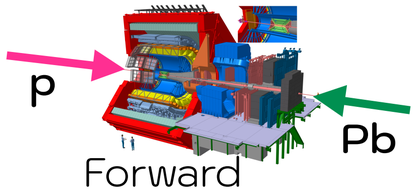


ψ(2S) and Υ(1S, 2S) R_{pPb}



- $R_{pPb}^{\Psi(2S)} < R_{pPb}^{J/\Psi}$ at backward rapidity
- Models with final-state effects reproduce the ψ(2S) R_{pPb} at backward rapidity





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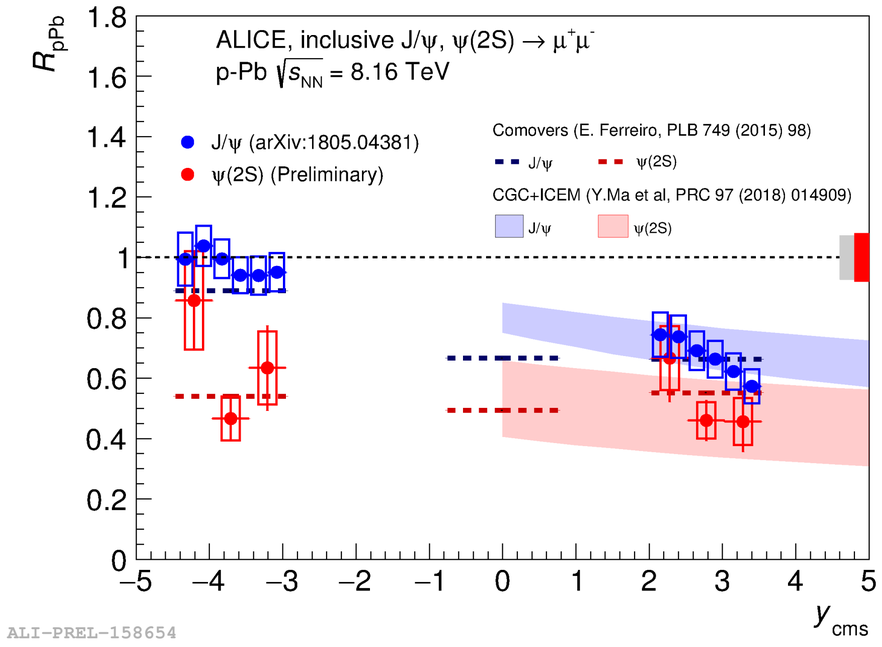

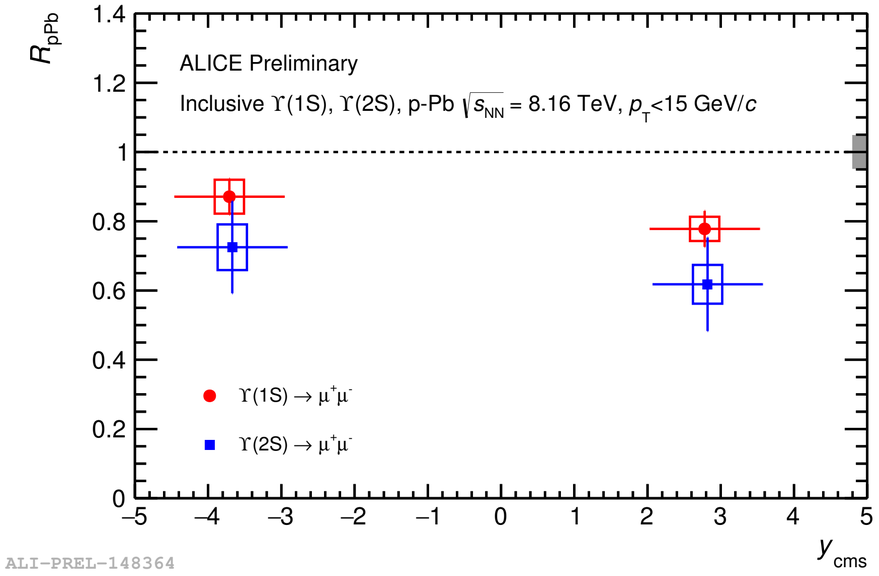

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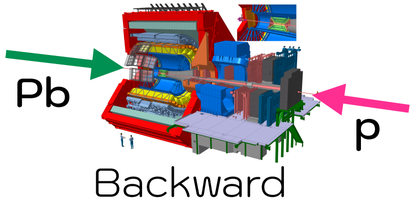
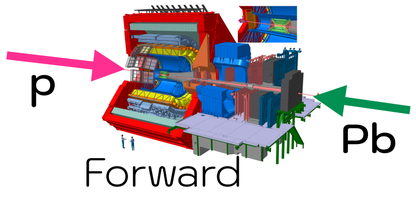
- Models with final-state effects reproduce the ψ(2S) R_{pPb} at backward rapidity

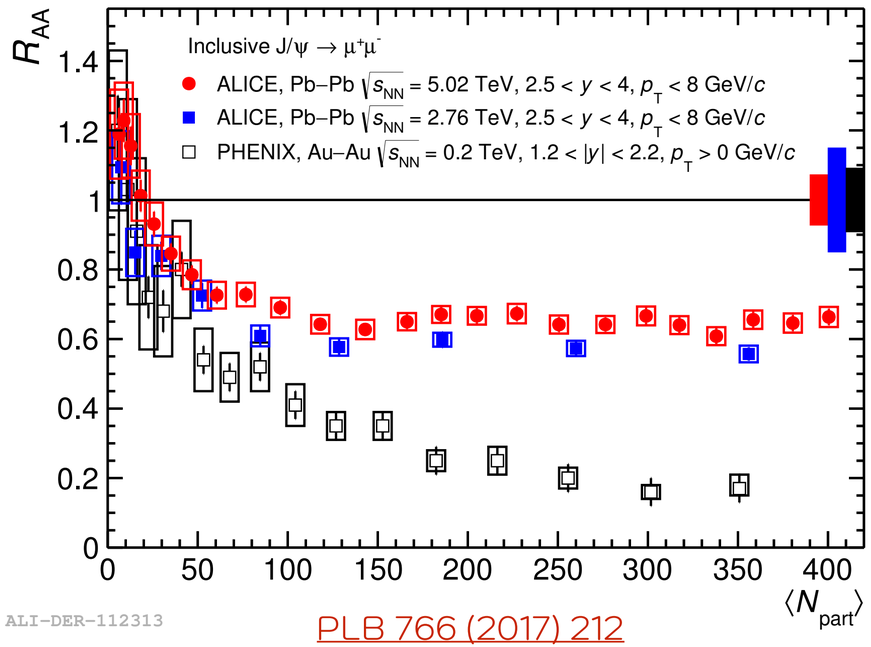
- $R_{pPb}^{\Upsilon(2S)}$ compatible with $R_{pPb}^{\Upsilon(1S)}$, but smaller for both backward and forward rapidities





J/ψ R_{AA}

Centrality grows



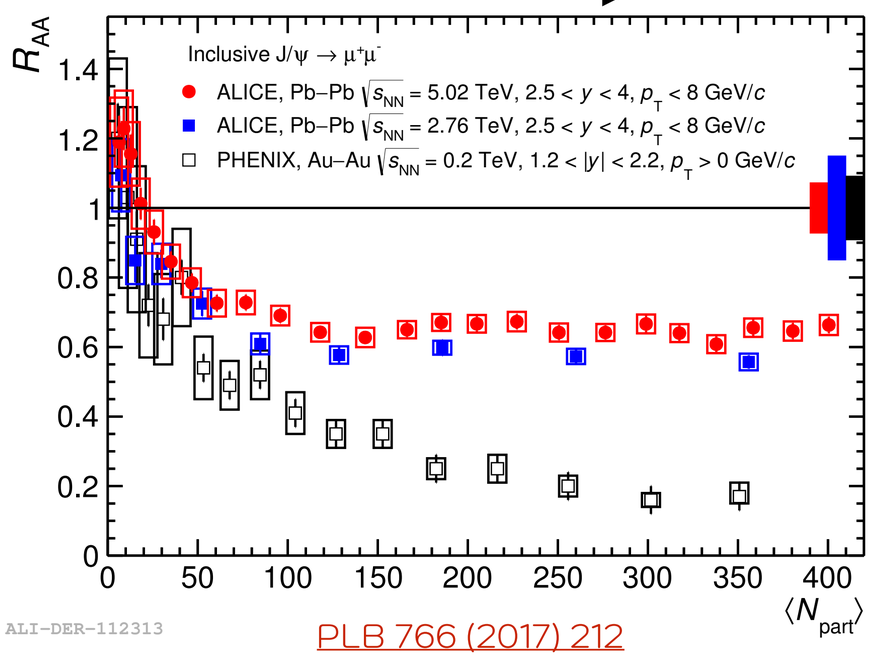
PLB 766 (2017) 212

- R_{AA} decreases with <N_{part}> up to ~100. Change of ~10% w.r.t. 2.76 TeV.

- R_{AA}(LHC) > R_{AA}(RHIC) for forward results.

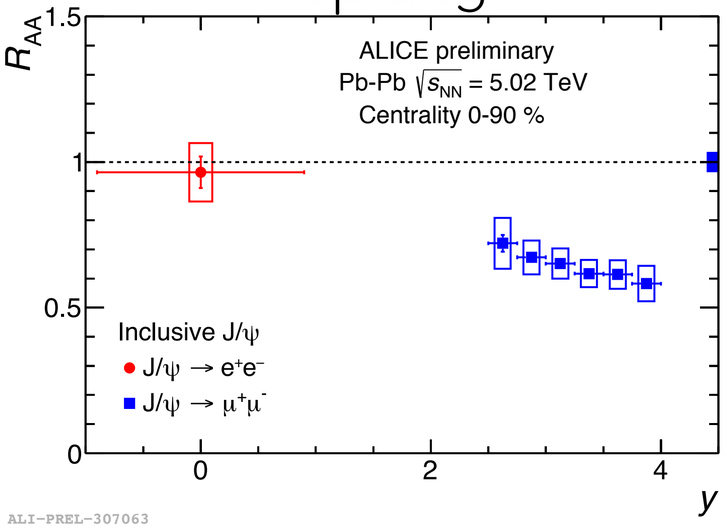
J/ψ R_{AA}

Centrality grows

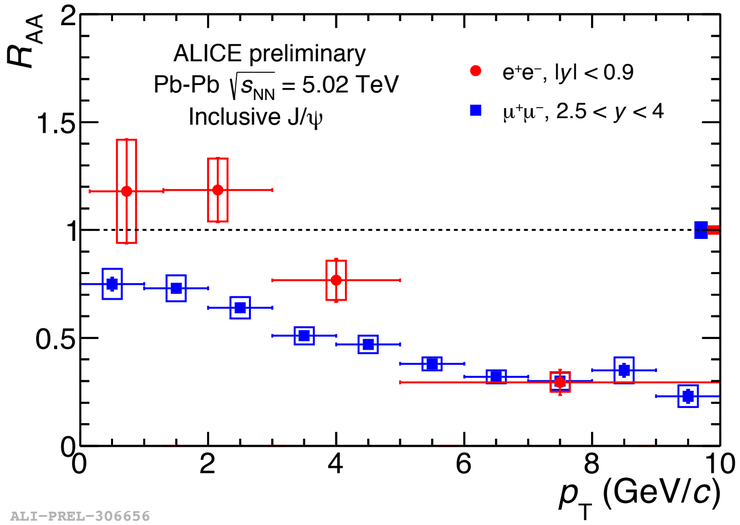


PLB 766 (2017) 212

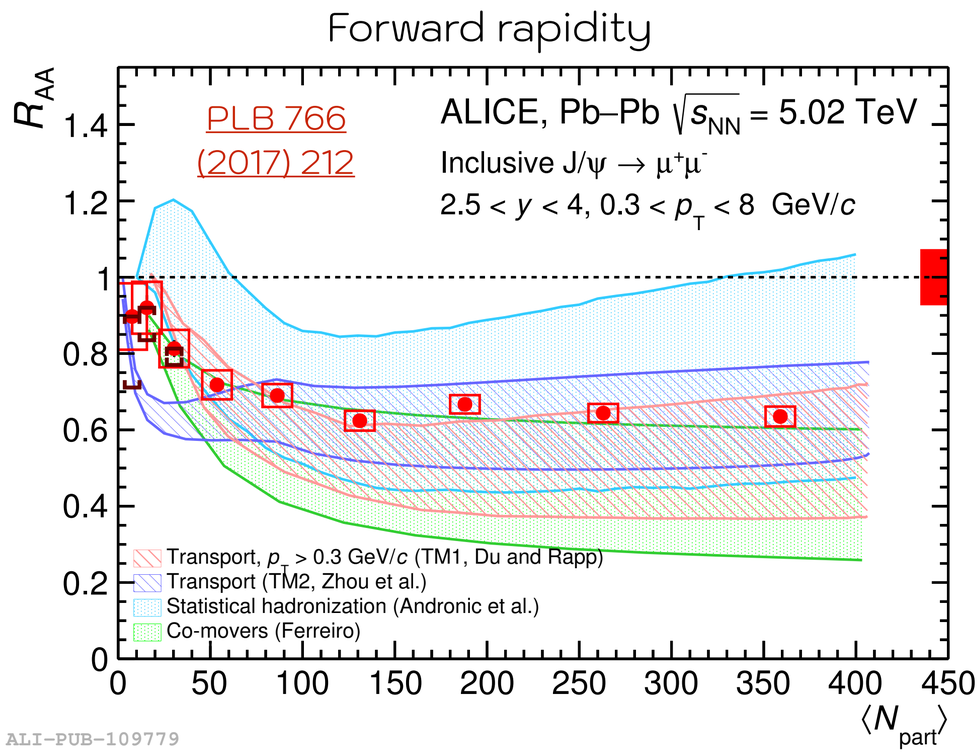
Rapidity



Transverse momentum

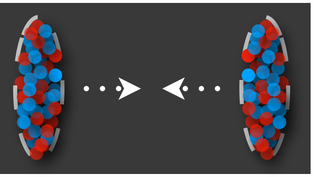


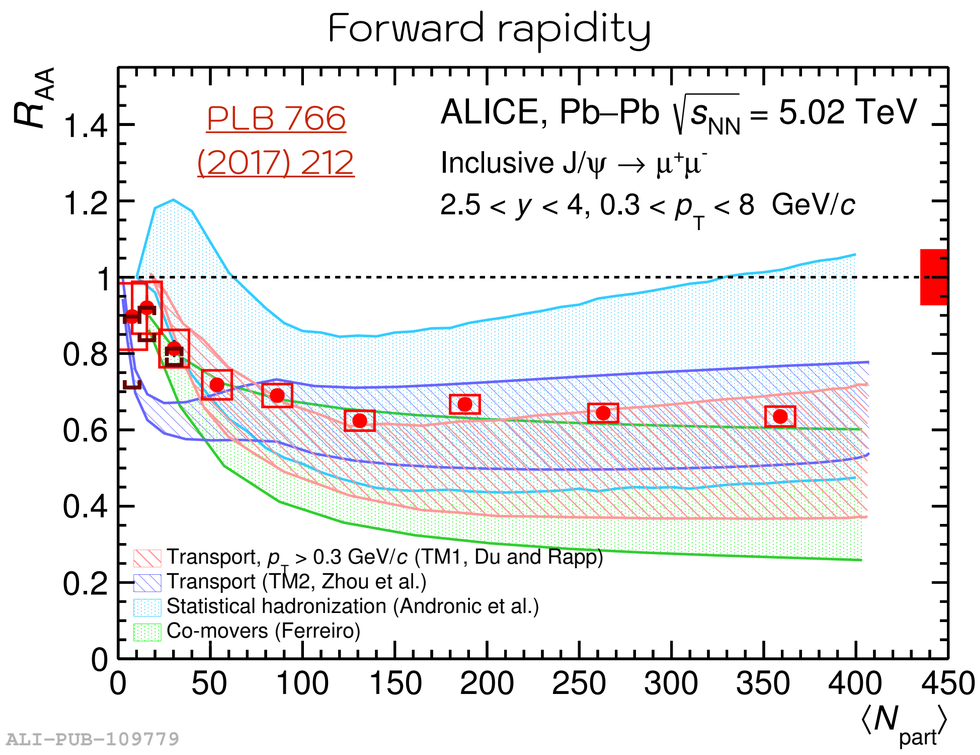
- R_{AA} decreases with <N_{part}> up to ~100. Change of ~10% w.r.t. 2.76 TeV.
- R_{AA}(LHC) > R_{AA}(RHIC) for forward results.
- R_{AA} increases towards low p_T.
- R_{AA} decreases with increasing y. R_{AA}(forward) < R_{AA}(mid)

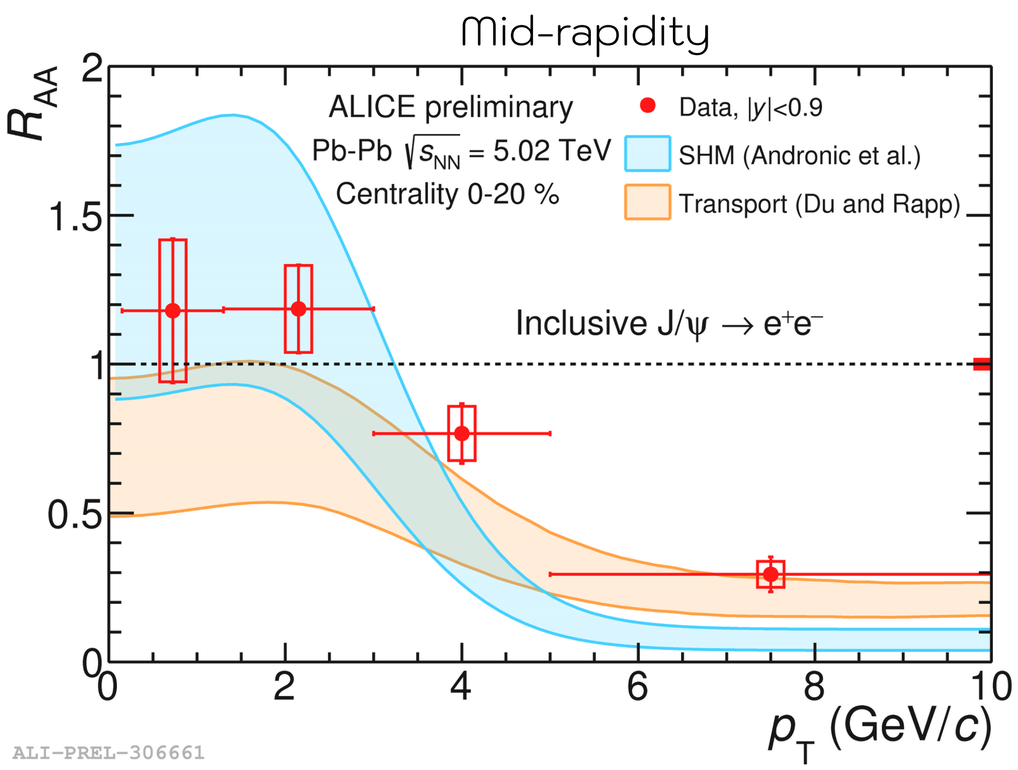


- Qualitative agreement between different models and data.

Models: J/ψ R_{AA}

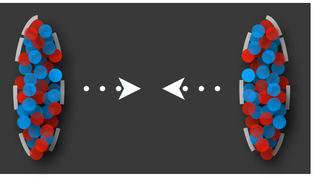




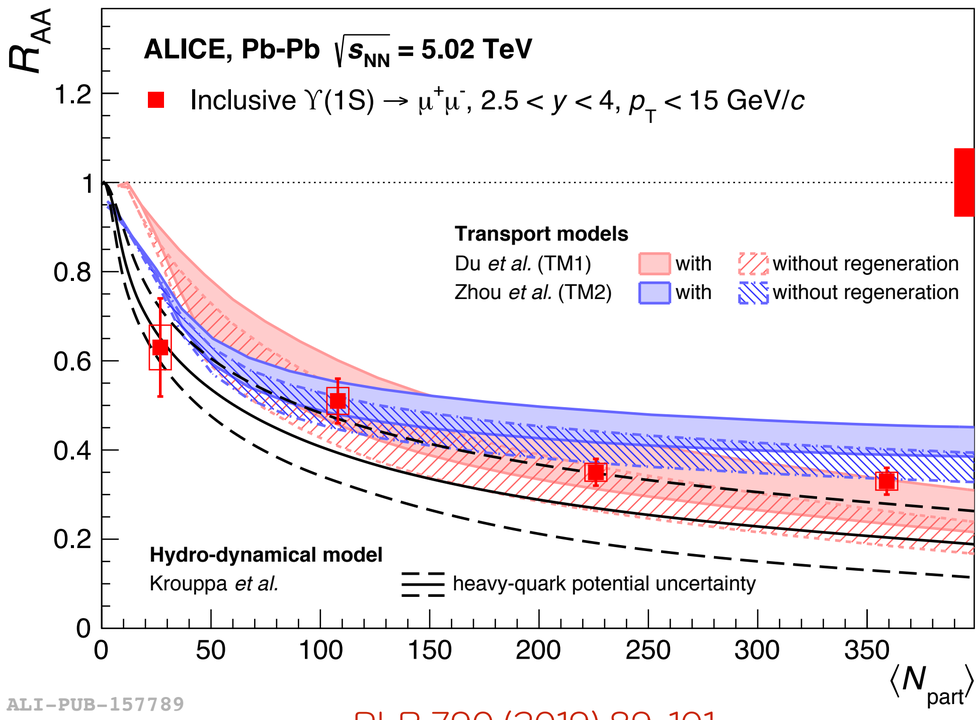


- Qualitative agreement between different models and data.
- R_{AA} increases towards low p_T: compatible with the regenerated J/ψ scenario.
- Calculations need a more precise $d\sigma_{cc}/dy$ measurement to reduce uncertainties.

Models: J/ψ R_{AA}



Υ(1S) and Υ(2S) R_{AA}



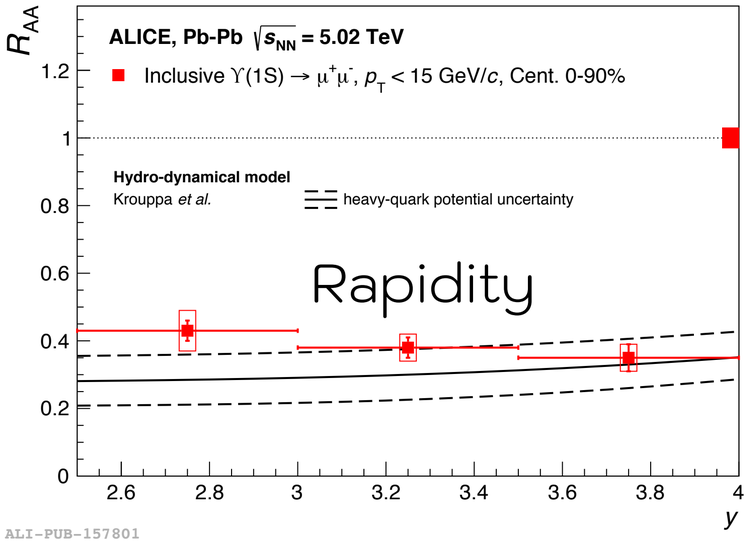
PLB 790 (2019) 89-101

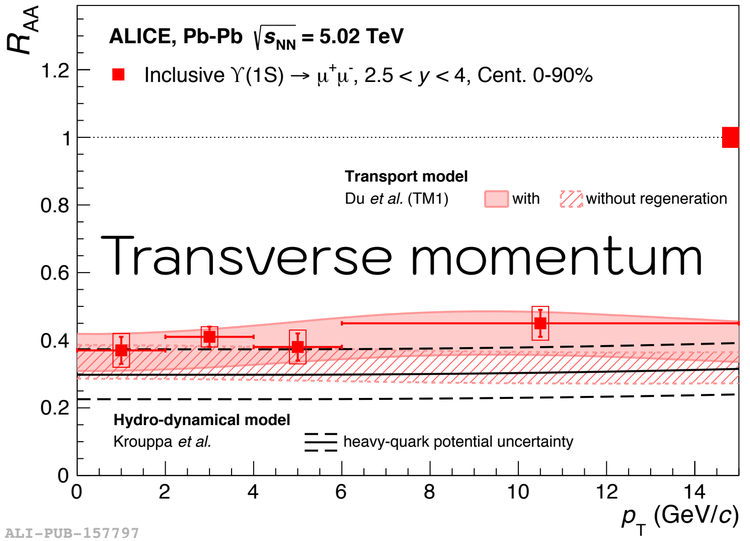
- Strong suppression of Υ(1S, 2S) in central Pb-Pb.

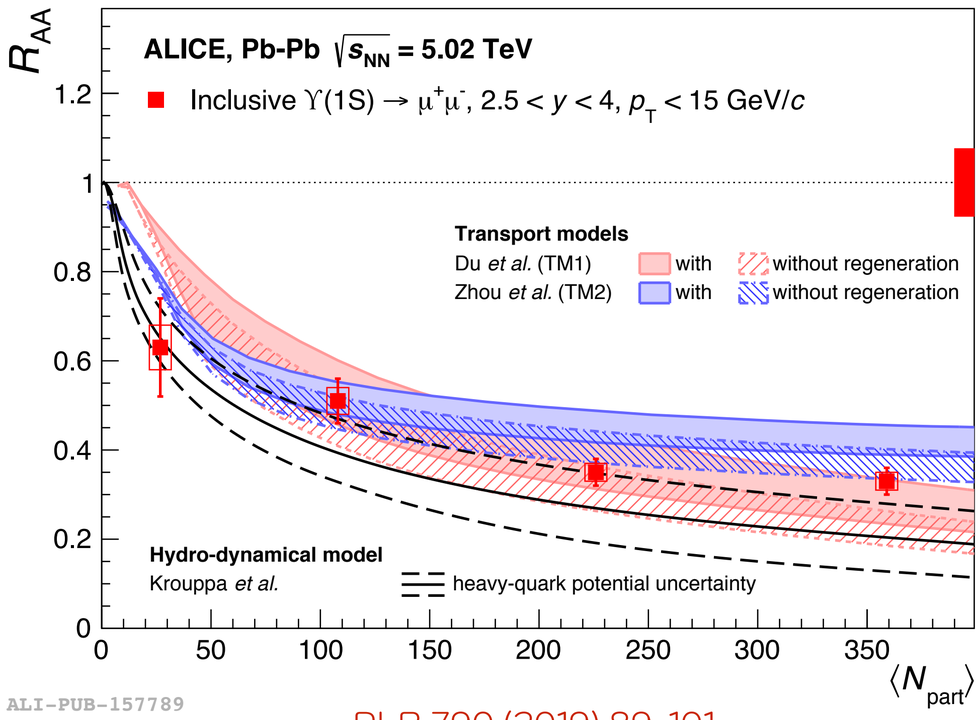
$$\frac{R_{AA}^{\Upsilon(2S)}}{R_{AA}^{\Upsilon(1S)}} = 0.28 \pm 0.12(\text{stat.}) \pm 0.06(\text{syst.})$$

- Υ(2S) suppression w.r.t. Υ(1S)

Υ(1S) and Υ(2S) R_{AA}







PLB 790 (2019) 89-101

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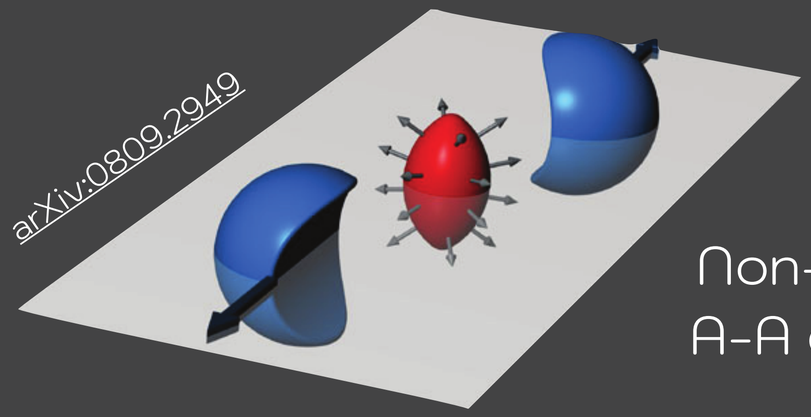
- Υ(2S) suppression w.r.t. Υ(1S)

- Strong suppression of Υ(1S, 2S) in central Pb-Pb.
- No multiplicity/ transverse momentum dependence
- Models qualitatively describe the results

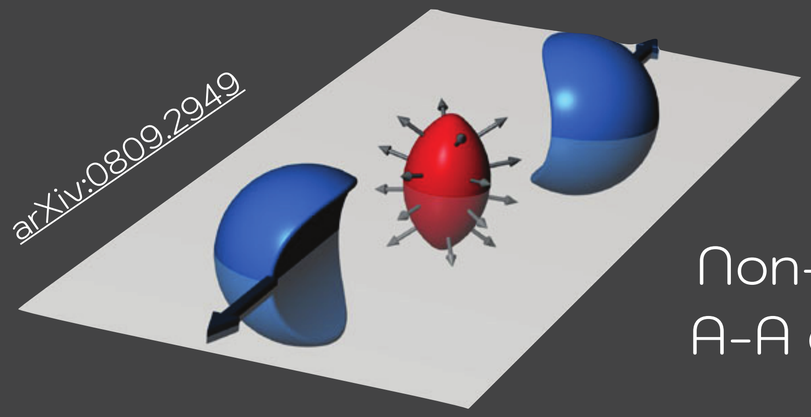


Non-central
A-A collision

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{+\infty} v_n \cos[n(\varphi - \psi_n)]$$

Dominant term in non-central A-A collisions: v_2 (elliptic flow)

Azimuthal Anisotropy (v_n)



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Dominant term in non-central A-A collisions: v_2 (elliptic flow)

In Pb-Pb calculated using the angular differences w.r.t the event plane

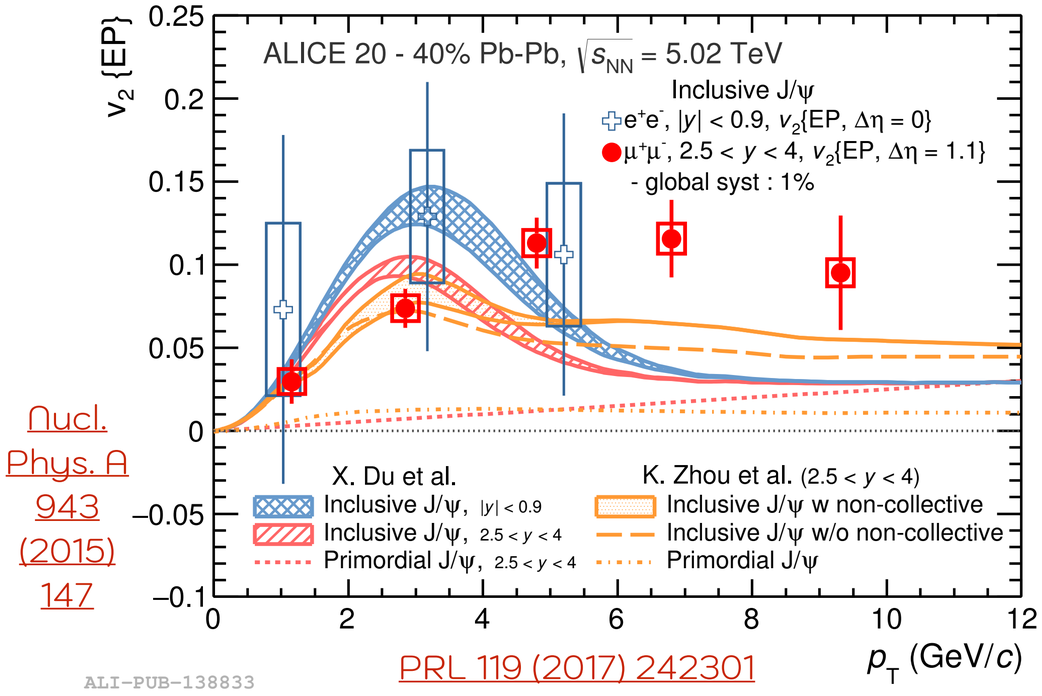
$$v_2 = \langle \cos(\varphi_{part} - \Psi_{EP}) \rangle$$

In p-Pb calculated using two-particle correlations (with low multiplicity subtraction):

$$HM - LM = a_0[1 + 2v_1 \cos(\Delta\varphi) + 2v_2 \cos(\Delta\varphi)]$$

Azimuthal Anisotropy (v_n)

Inclusive J/ψ: v_2 and v_3 in Pb-Pb



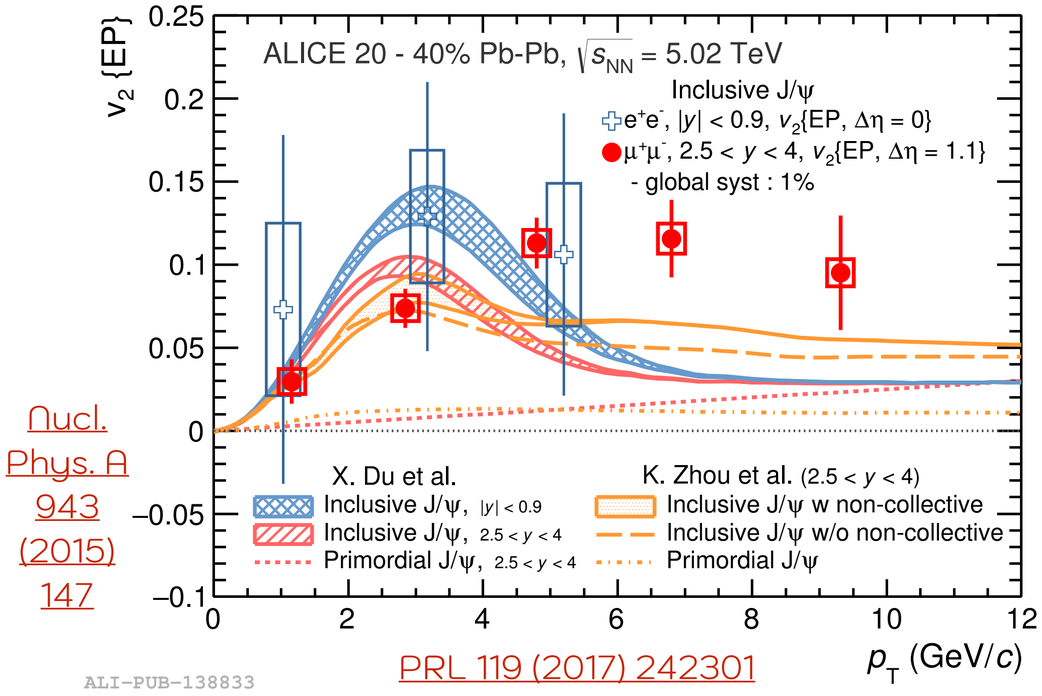
Nucl. Phys. A 943 (2015) 147

PRL 119 (2017) 242301

PRC 89 (2014) 054911.

- $v_2 > 0$ for $2 < p_T < 8$ GeV/c
- Low p_T: v_2 consistent with thermalisation of charm quarks and J/ψ (re)generation
- High p_T: higher than predictions including path-length dependent energy loss

Inclusive J/ψ: v_2 and v_3 in Pb-Pb



Nucl. Phys. A 943 (2015) 147

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PRL 119 (2017) 242301

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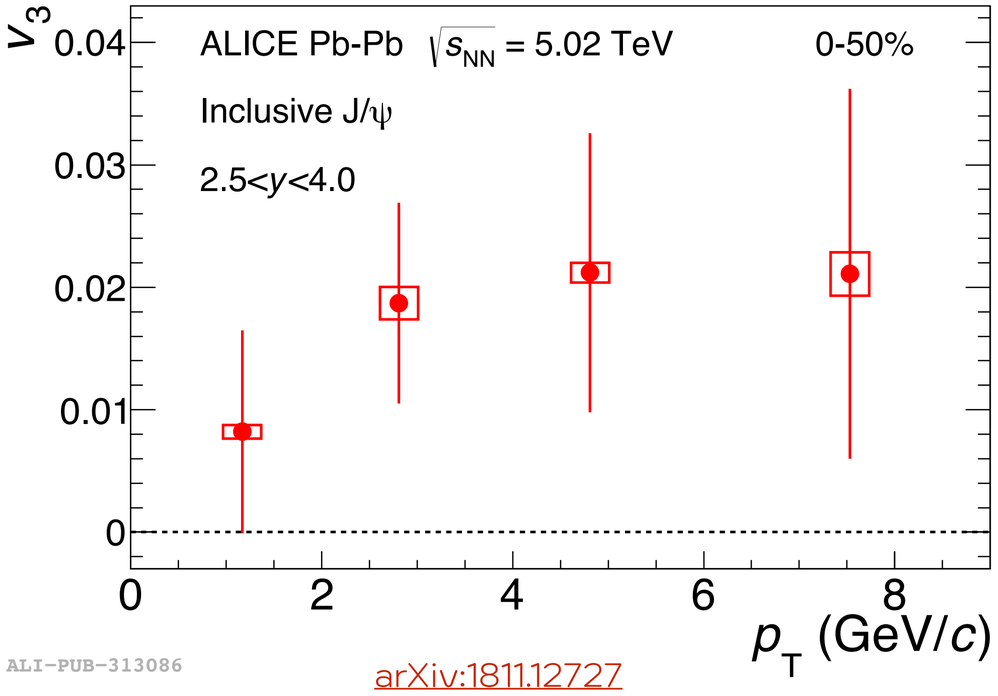
- Low p_T: v_2 consistent with thermalisation of charm quarks and J/ψ (re)generation
- High p_T: higher than predictions including path-length dependent energy loss

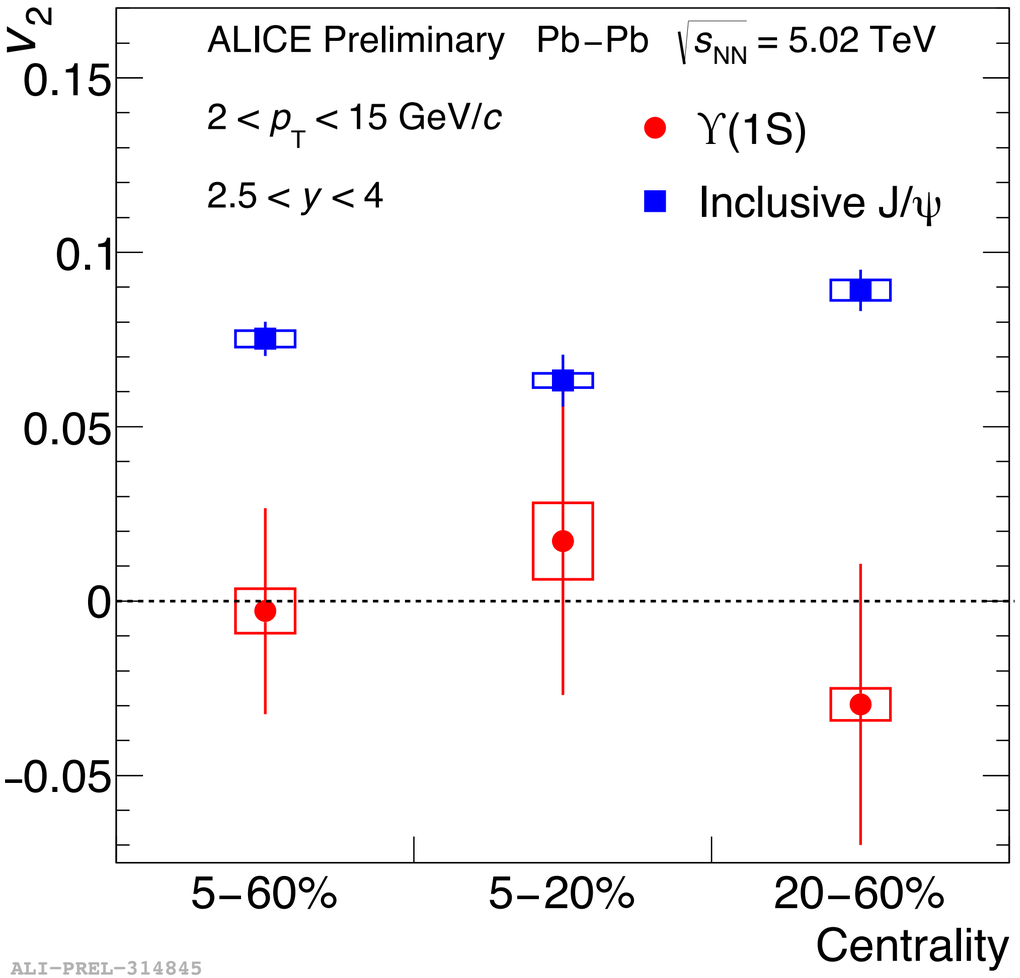
- First observation of J/ψ $v_3 > 0$ in Pb-Pb collisions (significance 3.7σ)
- Important to undestand initial conditions



arXiv:1811.12727

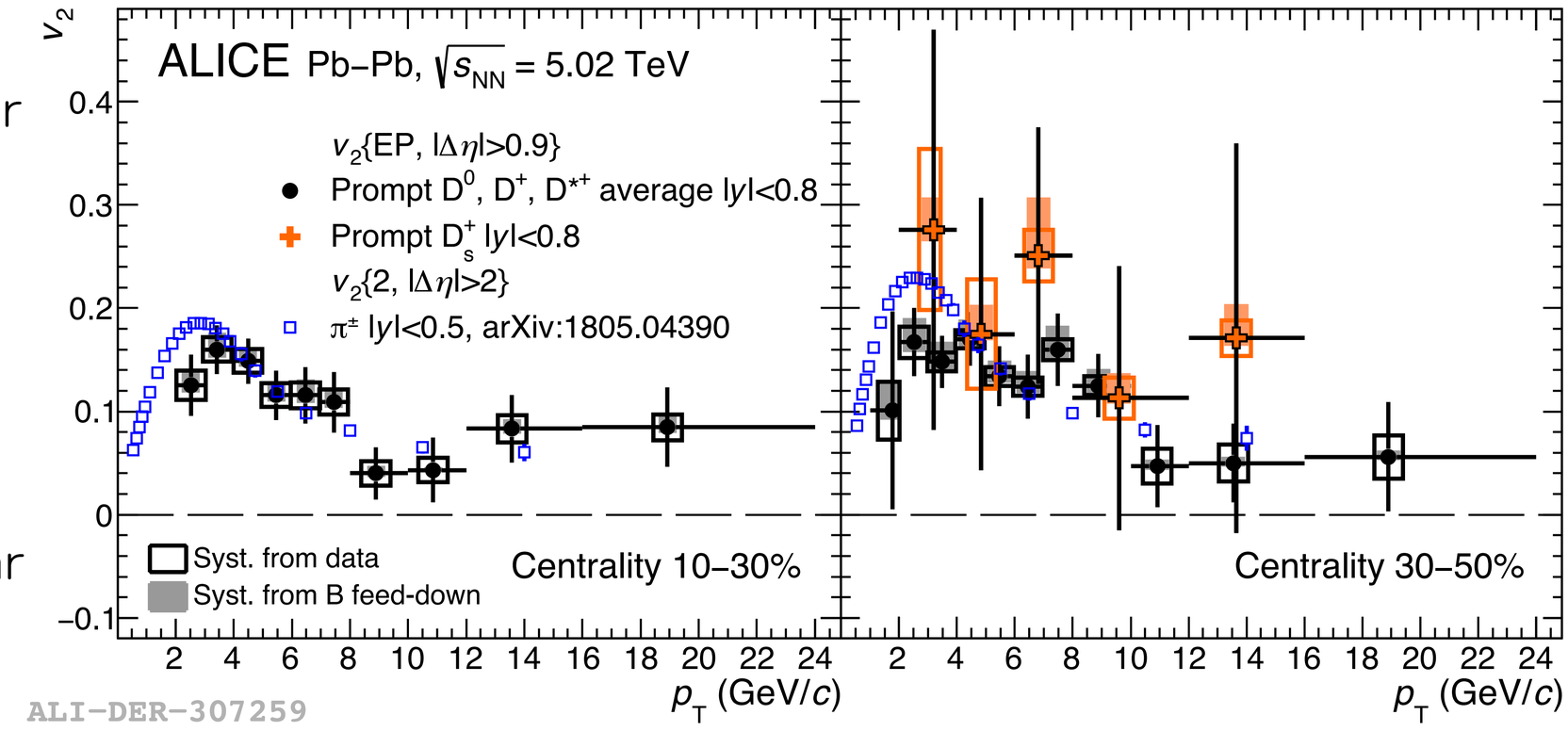
Υ(1S) v_2 in Pb-Pb

- First look at the Υ(1S) v_2



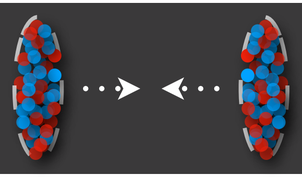
- Values are compatible with zero, but the uncertainties are large.

- D^0, D^+ and D^{*+} $v_2 > 0$ for p_T bin 2-10 GeV/c
- D_s^+ $v_2 > 0$ with 2.6σ significance for p_T bin 2-8 GeV/c
- v_2^D and v_2^π have similar values.
  - Difference of 2σ for 2-4 GeV/c

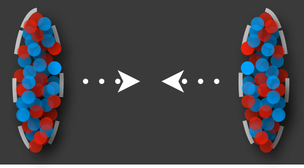


PRL 120 (2018) 102301

D-meson v_2 in Pb-Pb



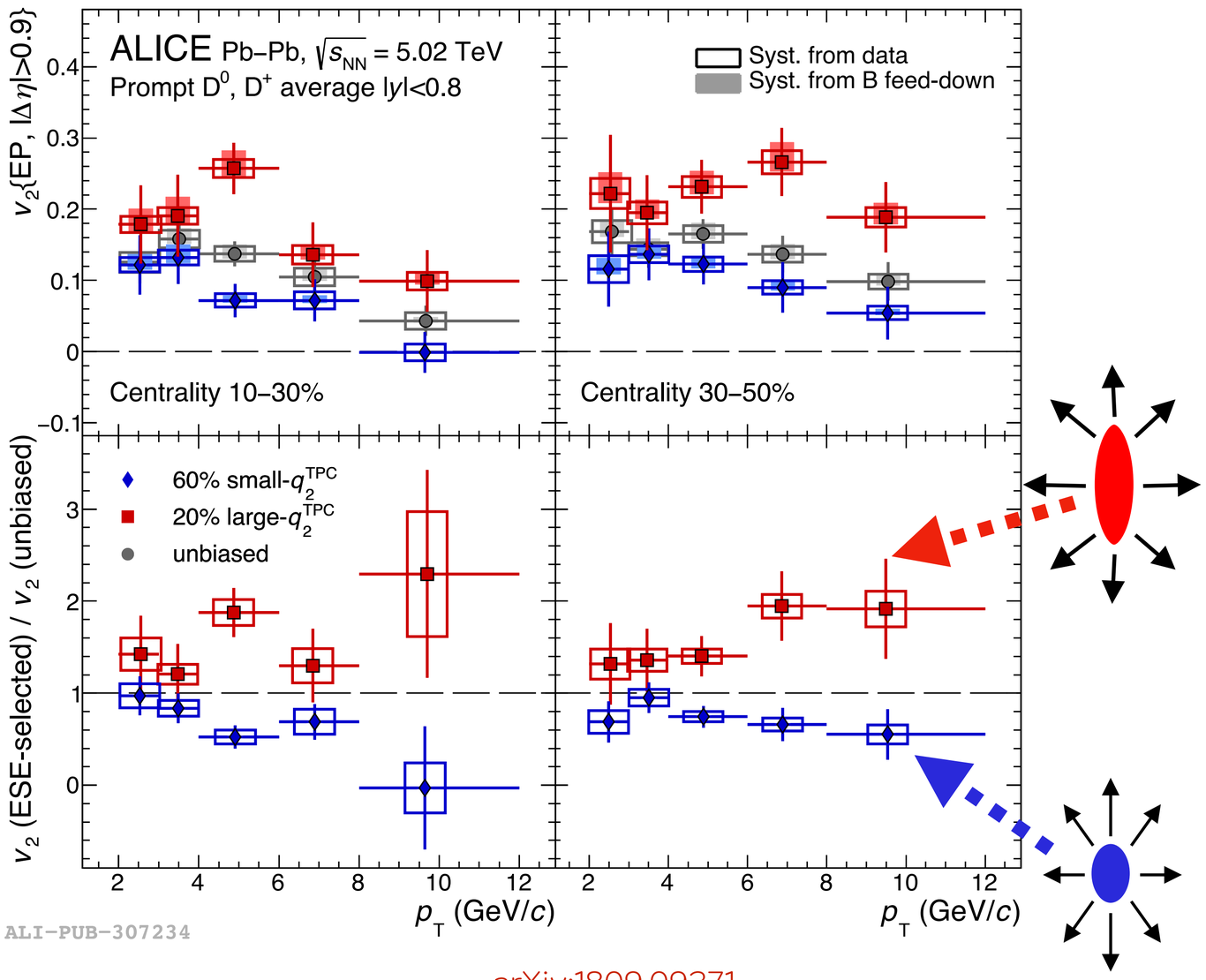
D-meson v_2 with ESE



Bulk v_2

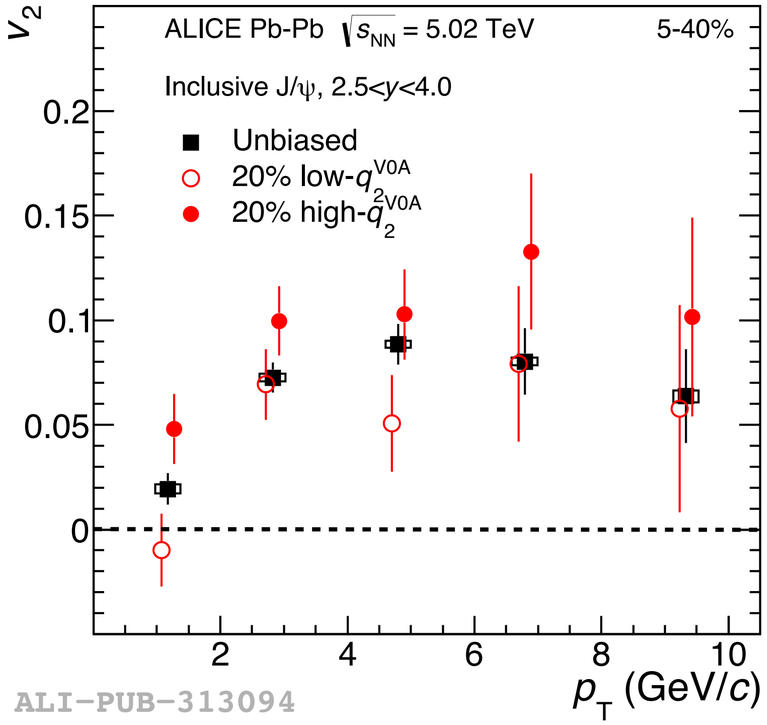
$$\langle q_2^2 \rangle \approx 1 + \langle\langle M-1 \rangle\rangle \left\langle \langle v_2^2 + \delta_2 \rangle \right\rangle$$

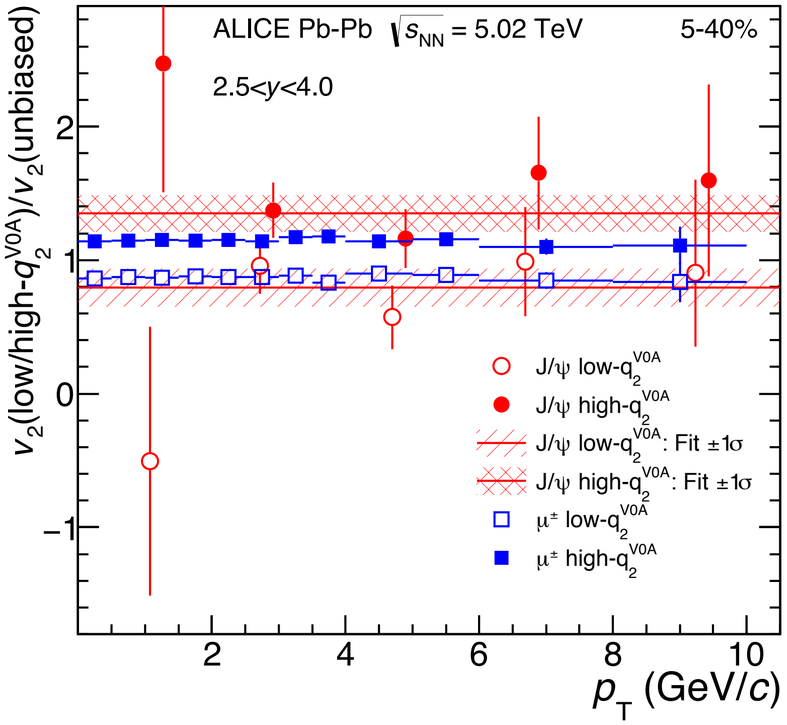
- Slice events based on its shape.
- 20% large-q_2^{TPC} -> ~40% more v_2
- 60% small-q_2^{TPC} -> ~25% less v_2
- D mesons are sensitive to the light-quark collectivity and event-by-event fluctuations in initial conditions

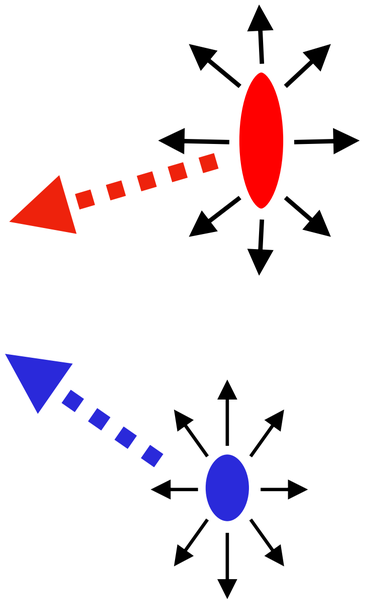


arXiv:1809.09371

J/ψ v_2 with ESE

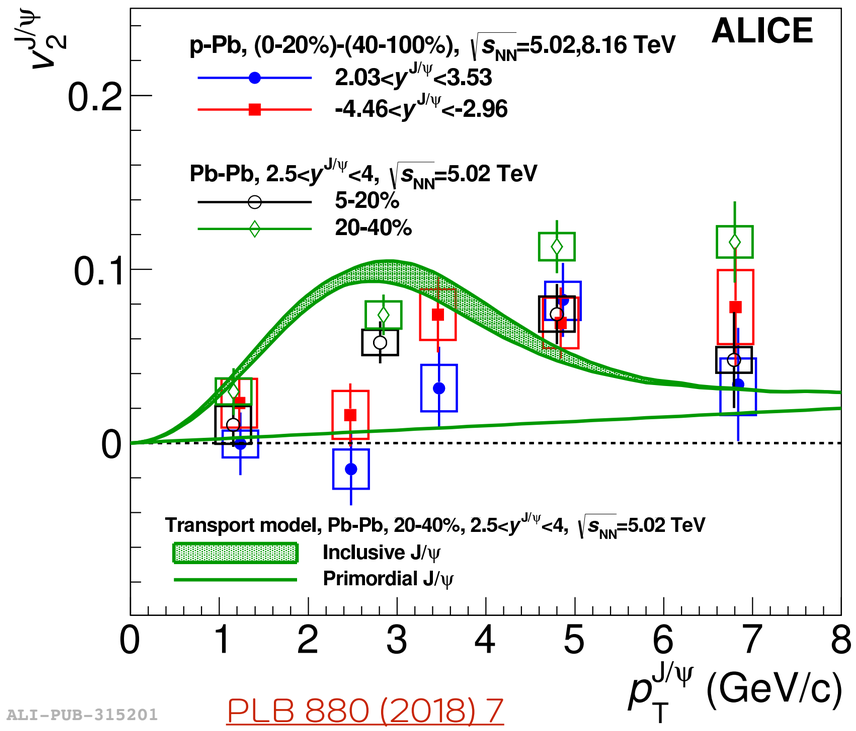






arXiv:1811.12727

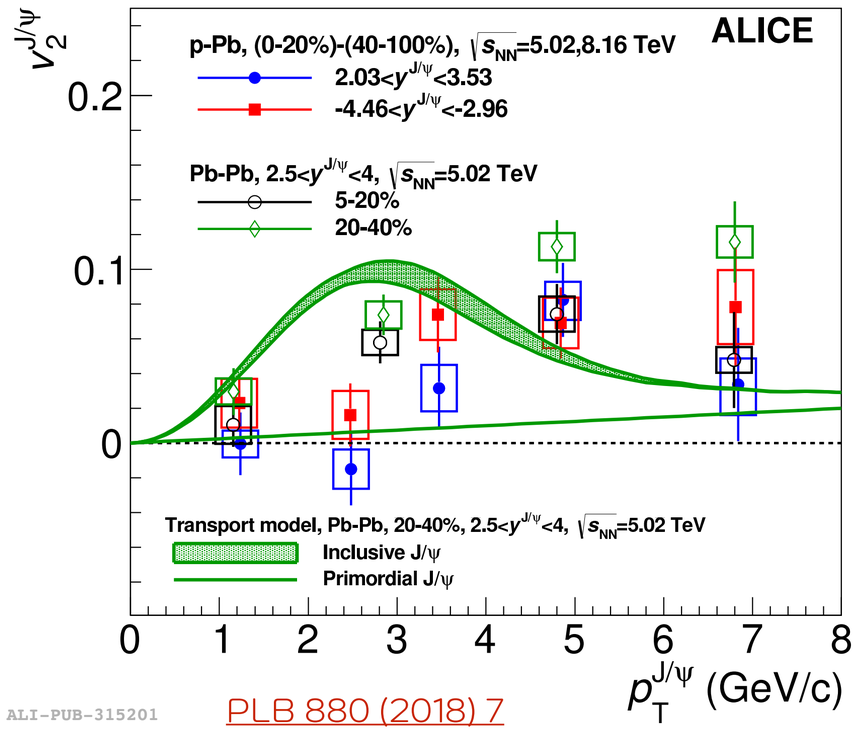
- J/ψ v_2 increases 35% in the high q_2 class (ratio: 1.35±0.14) and decreases in the low q_2 class (ratio: 0.79±0.14).
- Compatible with the expected variations of the eccentricity of the initial-state geometry within the uncertainties.



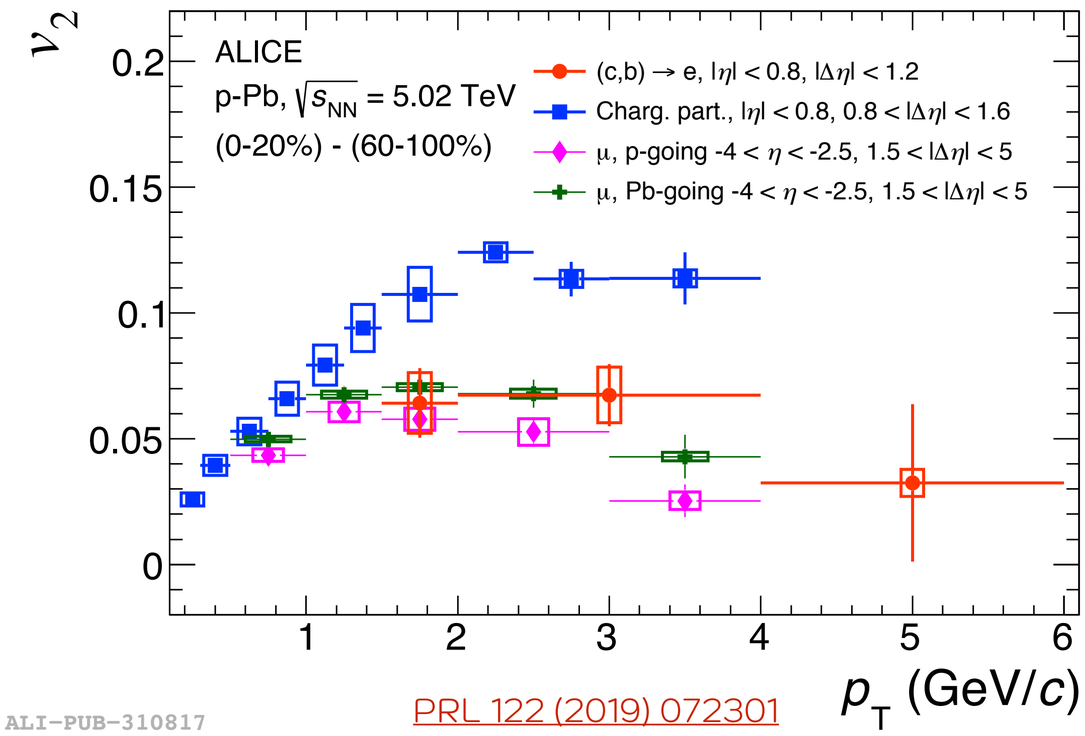
PLB 880 (2018) 7

- $v_2 > 0$ for $3 < p_T < 6$ GeV/c with a significance >5σ (backward+forward 5.02 and 8.16 TeV)

J/ψ and HF electron v_2 in p-Pb



PLB 880 (2018) 7



PRL 122 (2019) 072301

- $v_2 > 0$ for $3 < p_T < 6$ GeV/c with a significance >5σ (backward+forward 5.02 and 8.16 TeV)

- $v_2 > 0$ with a significance of more than 5σ for $1.5 < p_T < 4$ GeV/c.
- $v_2^{HFe} \cong v_2^{\mu}$ and $v_2^{HFe} < v_2^{ch.\ part.}$.

J/ψ and HF electron v_2 in p-Pb

Summary

- Production: open and hidden HF production in pp, p-Pb and Pb-Pb.
  - Suppression of open and hidden heavy flavour in Pb-Pb. **Mass ordering?** Mid-rapidity R_{pPb} compatible with unity.
  - Λ^{+}_{c}/D^{0} in Pb-Pb higher than in p-Pb (2σ) and $R_{AA}(\Lambda^{+}_{c}) > R_{AA}(D^{0,+,*+})$ in 1.7σ. **Coalescence production?**
  - Suppression of quarkonium states. **Consistent with a (re)generation scenario.**

Summary

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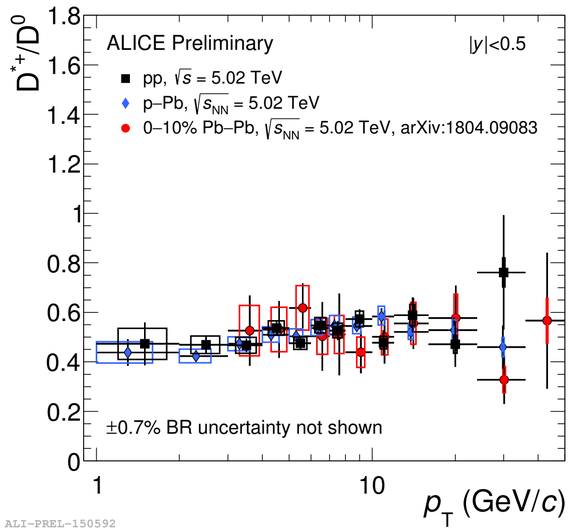
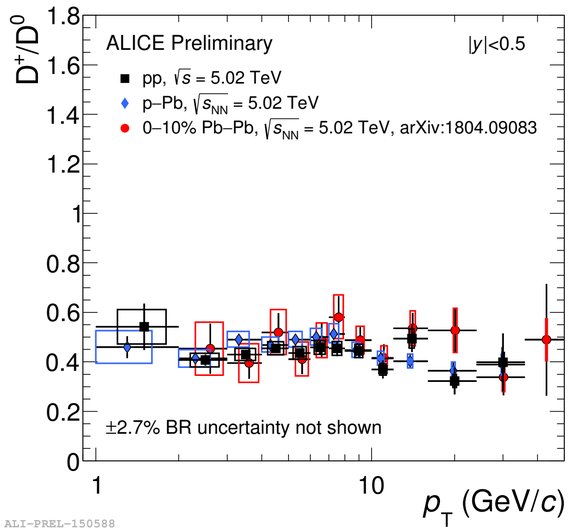
  - Suppression of quarkonium states. **Consistent with a (re)generation scenario.**
- Azimuthal anisotropy: detailed study of open and hidden HF flow in Pb-Pb and p-Pb
  - Positive v_2 for open and hidden HF in Pb-Pb collisions. **Charm quarks participate in the medium collective motion.**
  - First measurement of the J/ψ v_3. **Information about the initial state.**
  - Event Shape Engineering studies for D mesons and J/ψ. **HF v_2 sensitive to bulk v_2.**
  - Positive v_2 for open and hidden HF in p-Pb collisions. **Collective effects in p-Pb?**

Backup

D-meson Ratios

- Sensitive to the fragmentation functions: universality of D-meson fragmentation functions



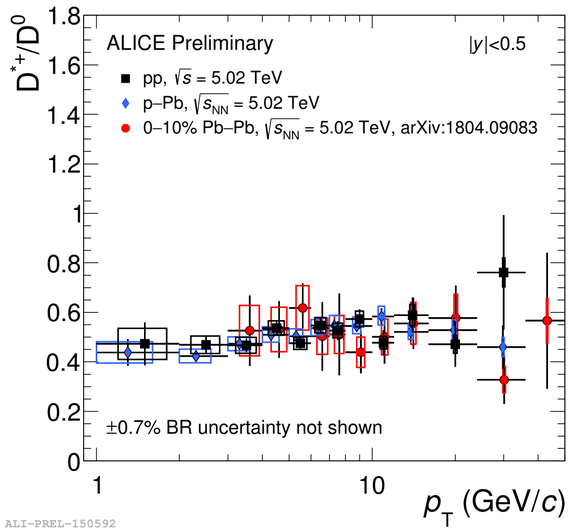


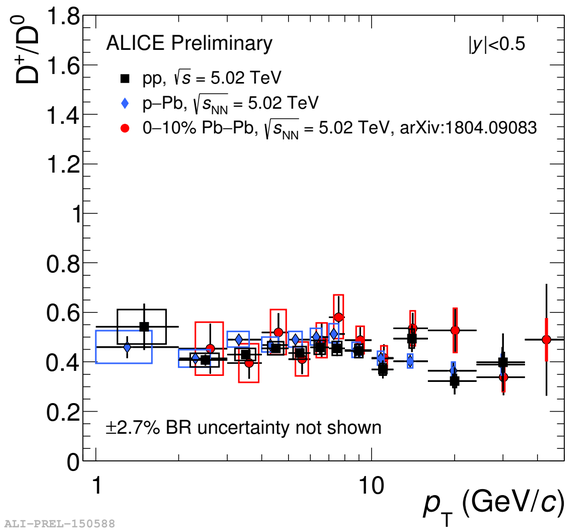
No significant p_T dependence found

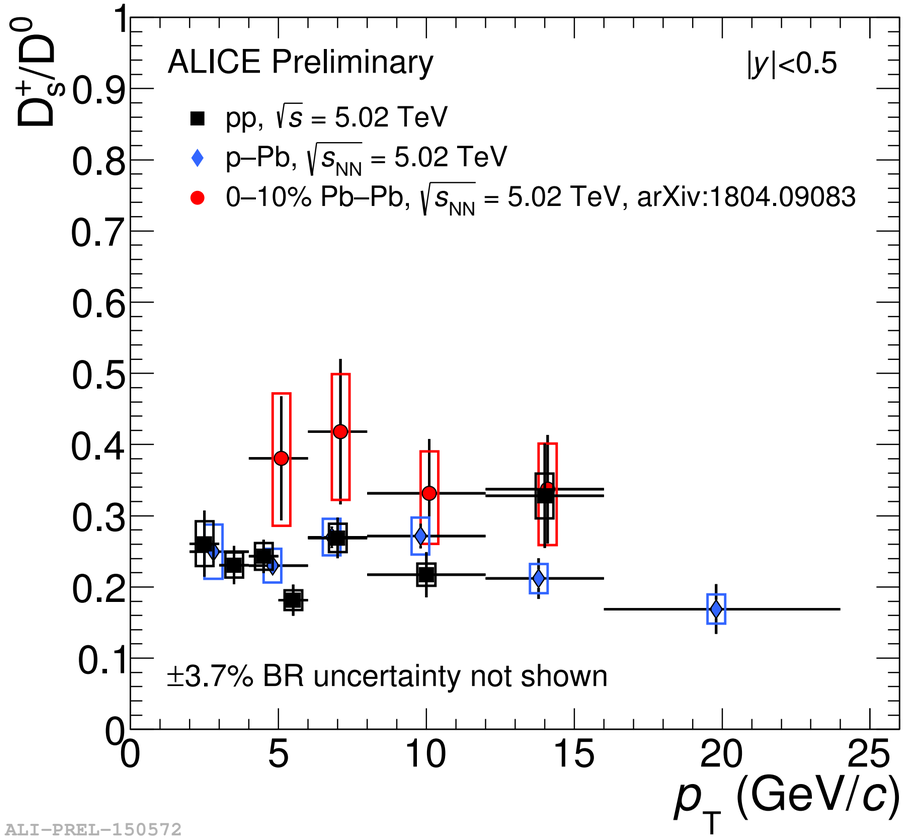
pp arXiv:1901.07979

D-meson Ratios

- Sensitive to the fragmentation functions: universality of D-meson fragmentation functions
- No difference between the pseudoscalar (D^0, D^+, D^+_s) and vector (D^{*+}) in pp and p-Pb
- No difference between D^+_s/D^0 ratios in pp and p-Pb. D^+_s/D^0 higher in Pb-Pb, but compatible within uncertainties.



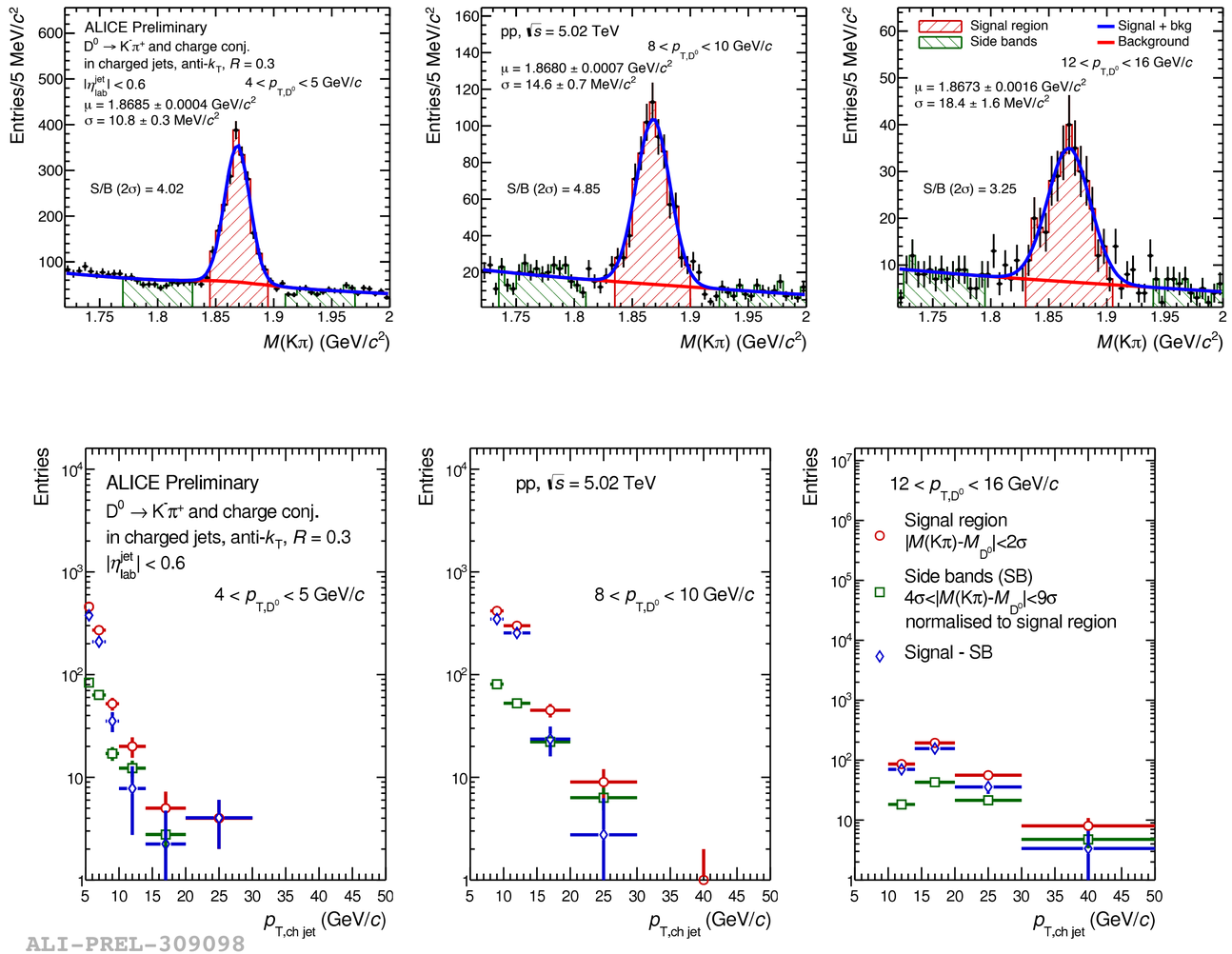


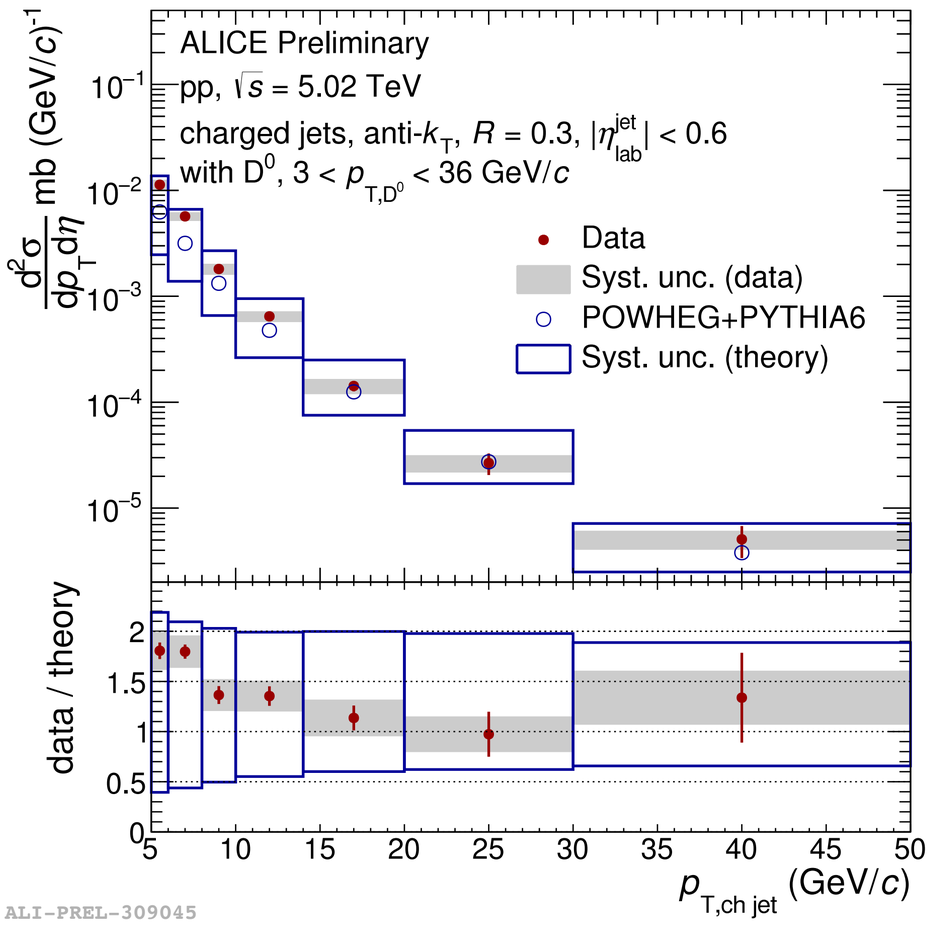


No significant p_T dependence found

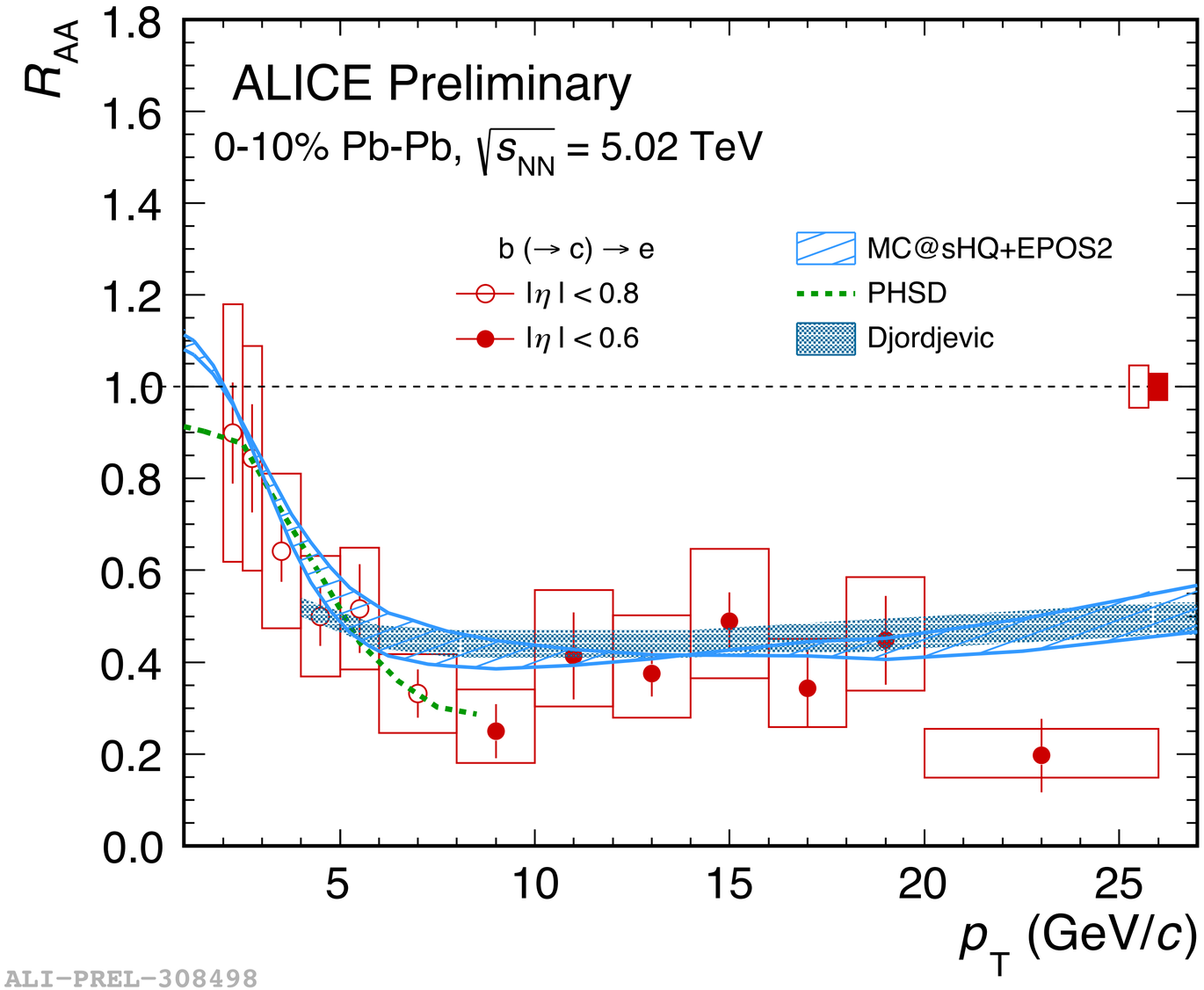
pp arXiv:1901.07979

D^0 jets


ALICE Preliminary
D0 → K-π+ and charge conj.
in charged jets, anti-kT, R = 0.3
|ηjet lab| < 0.6
4 < pT,D0 < 5 GeV/c
μ = 1.8685 ± 0.0004 GeV/c2
σ = 10.8 ± 0.3 MeV/c2
S/B (2σ) = 4.02
pp, √s = 5.02 TeV
8 < pT,D0 < 10 GeV/c
μ = 1.8680 ± 0.0007 GeV/c2
σ = 14.6 ± 0.7 MeV/c2
S/B (2σ) = 4.85
Signal region
Side bands
Signal + bkg
Background
12 < pT,D0 < 16 GeV/c
μ = 1.8673 ± 0.0016 GeV/c2
σ = 18.4 ± 1.6 MeV/c2
S/B (2σ) = 3.25
Entries/5 MeV/c2
M(Kπ) (GeV/c2)
Entries
pT,ch jet (GeV/c)
Signal region
|M(Kπ)-MD0|<2σ
Side bands (SB)
4σ<|M(Kπ)-MD0|<9σ
normalised to signal region
Signal - SB
ALI-PREL-309098

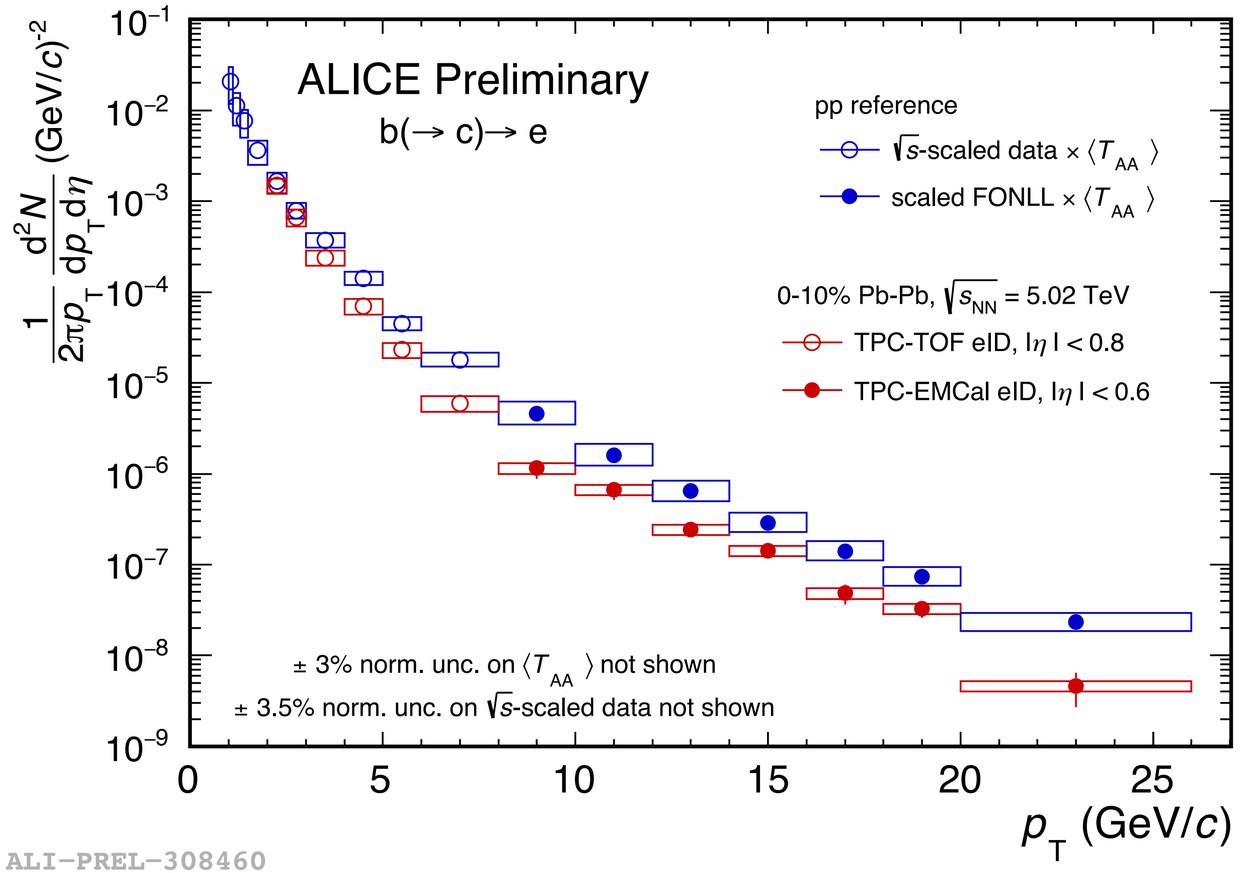

ALICE Preliminary
pp, √s = 5.02 TeV
charged jets, anti-kT, R = 0.3, |ηjet lab| < 0.6
with D0, 3 < pT,D0 < 36 GeV/c
Data
Syst. unc. (data)
POWHEG+PYTHIA6
Syst. unc. (theory)
d2σ/dpTdη mb (GeV/c)-1
data / theory
pT,ch jet (GeV/c)
ALI-PREL-309045

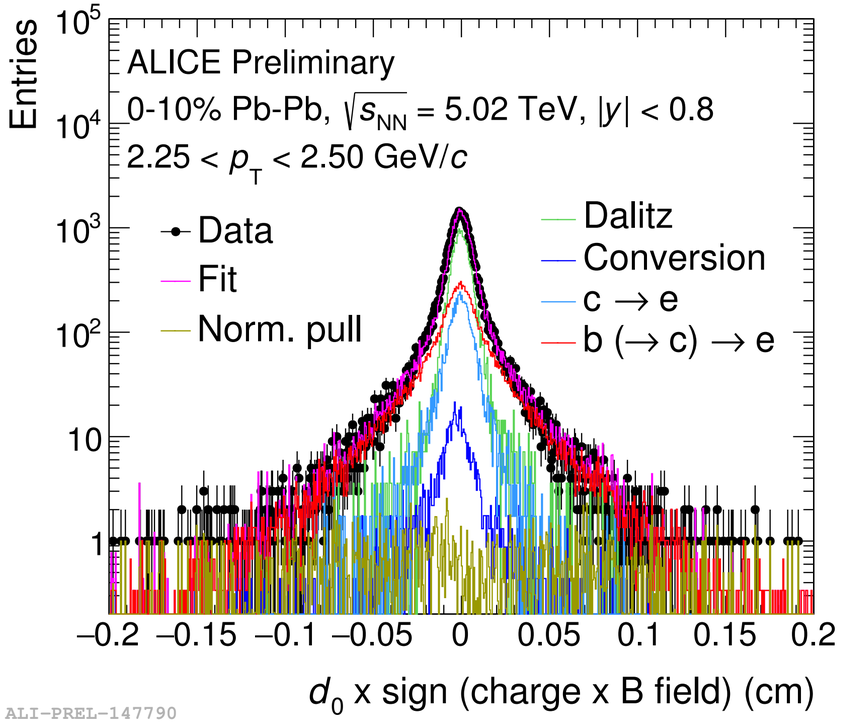
HF decay leptons: R_{AA}



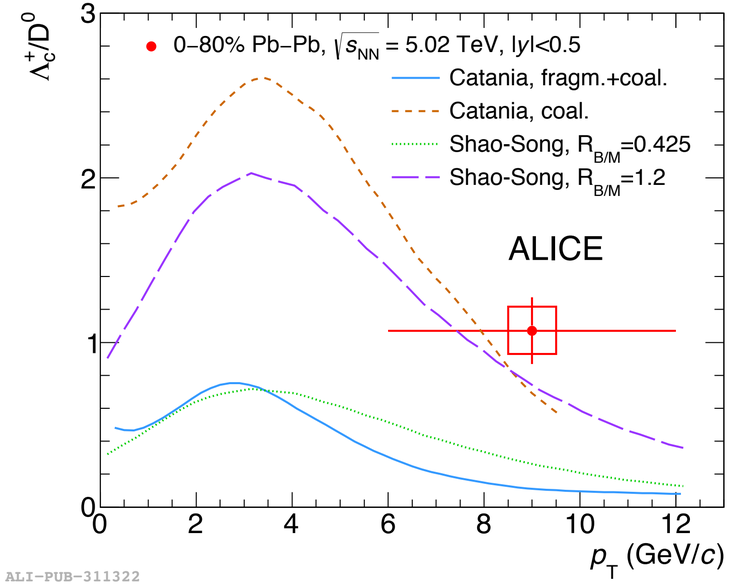
- Models with mass dependent energy loss provide a good description

Beauty electron R_{AA}



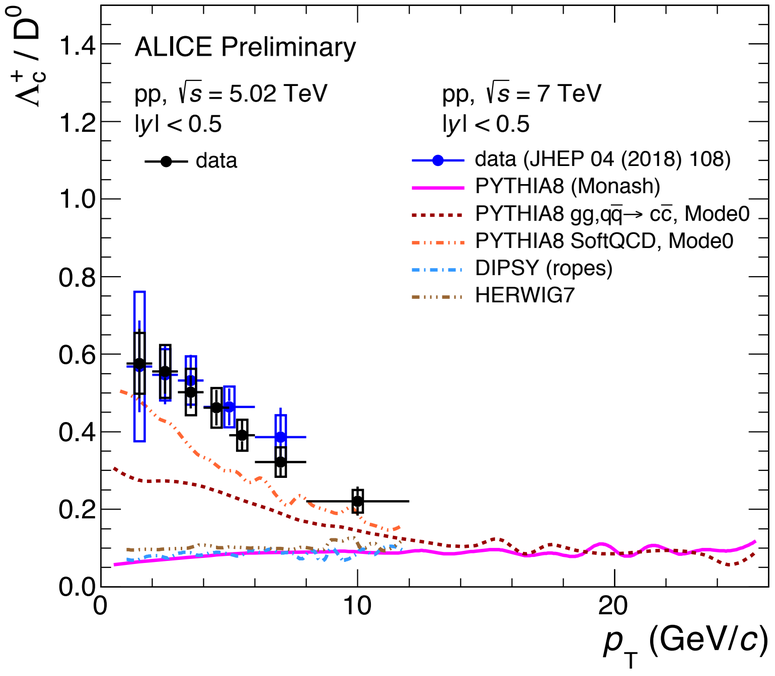


Baryon/Meson ratios vs models



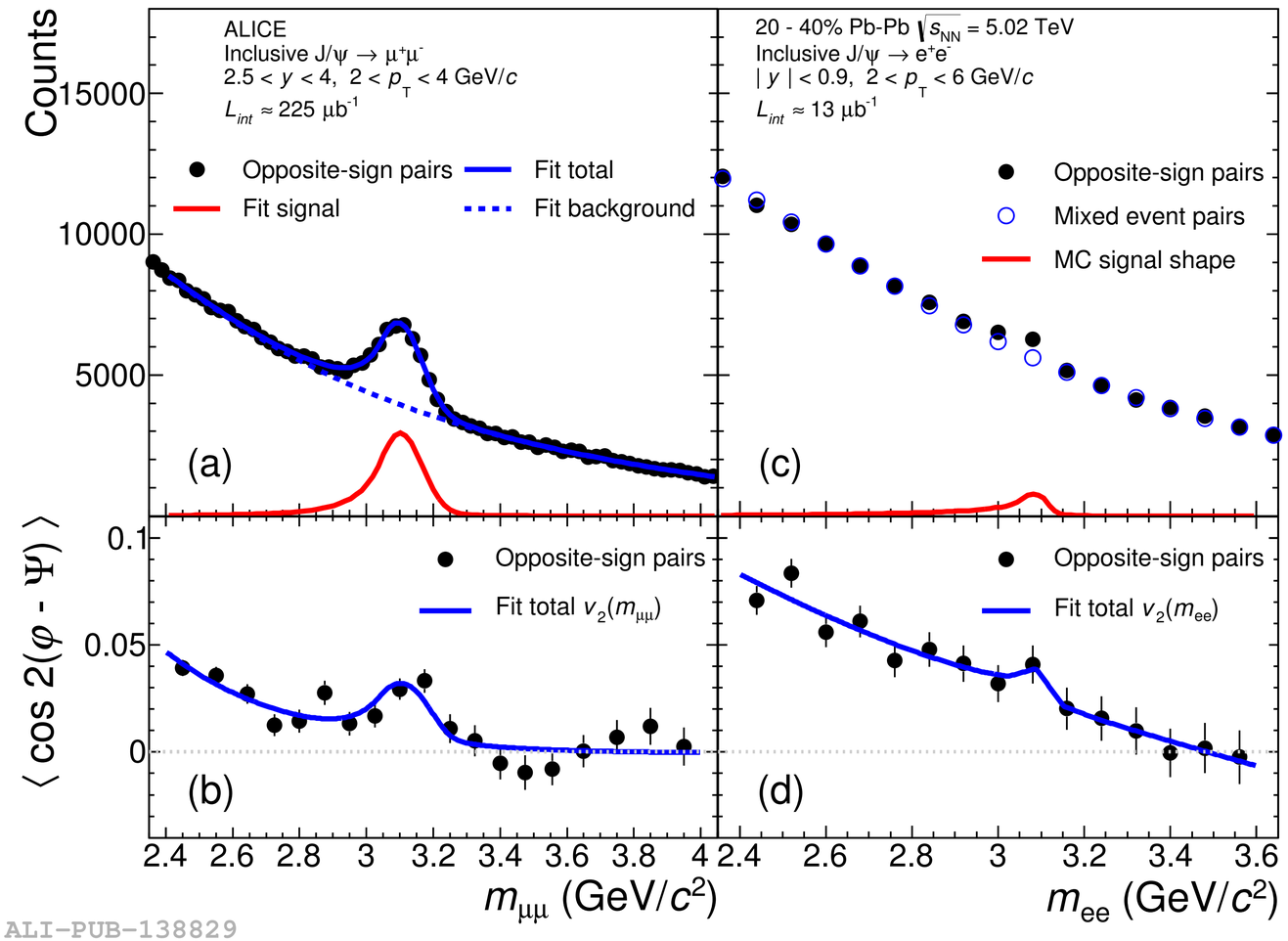
Catalina: EPJC 78 (4) (2018) 348
Shao-Song:
PRC 97 (6) (2018) 064915

Results described by model calculations including only coalescence



PYTHIA8 Monash	EPJC 74 (2014)
PYTHIA8 Mode0	JHEP 08 (2015) 003
DIPSY	JHEP 08 (2011) 103
HERWIG7	EPJ C58 (2008)

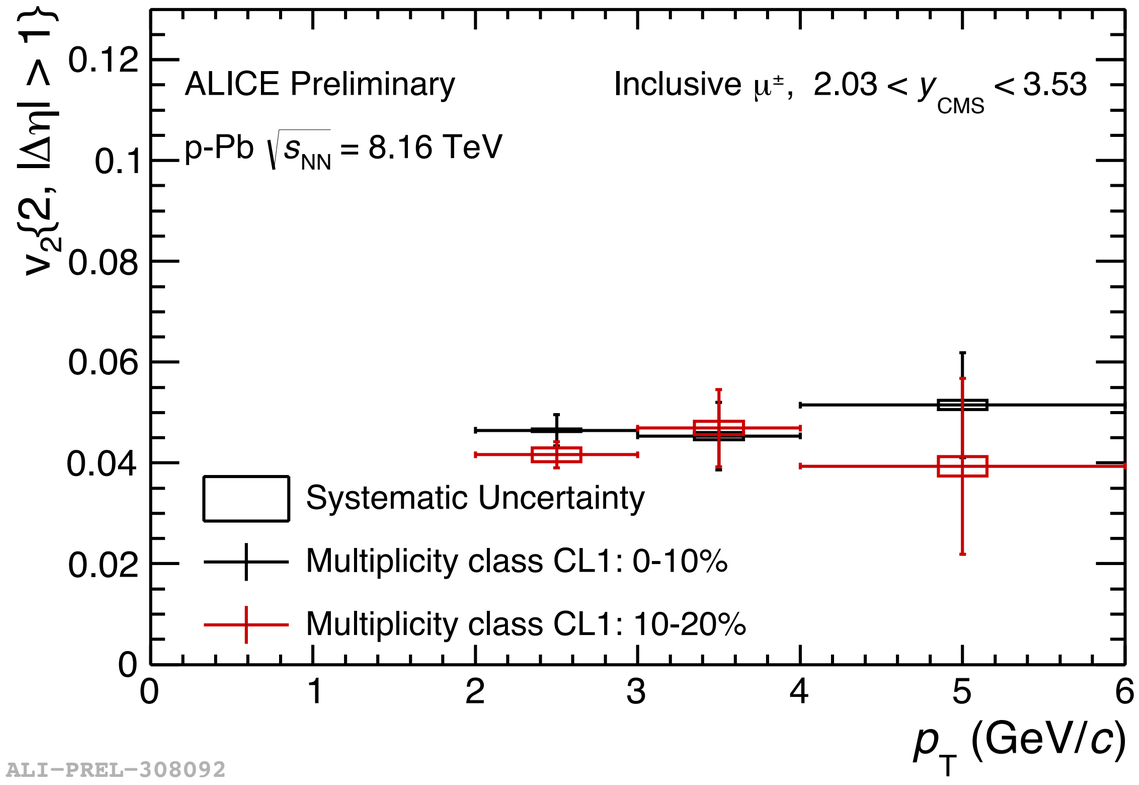
Inclusive J/ψ: v_2 calculation (Pb-Pb)



ALI-PUB-138829

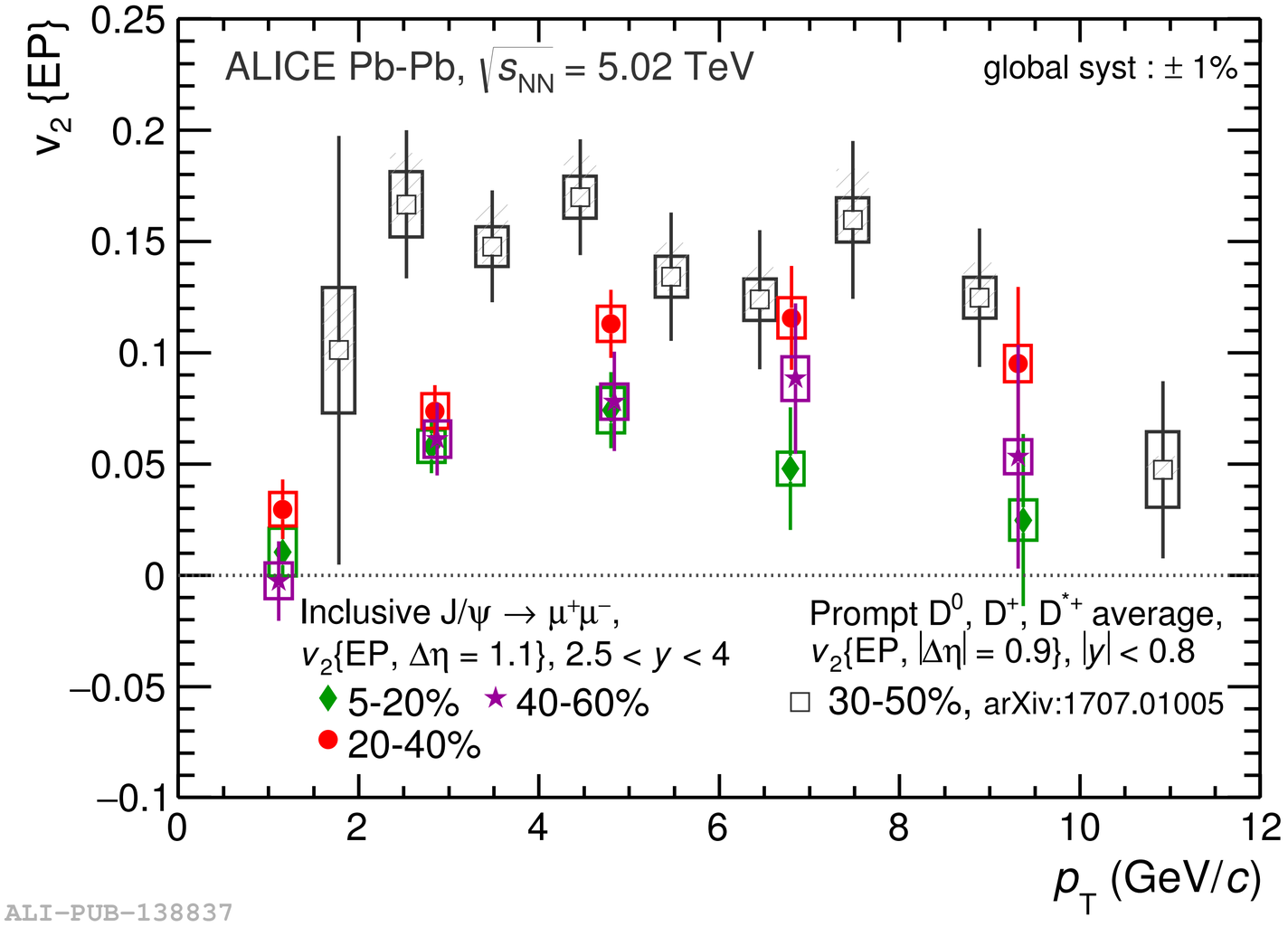
Inclusive muon v_2 in p-Pb

- Dominated by muons from open heavy in the ranged studied
- Calculated using cumulants
- Non-flow contributions subtracted using pp collisions
- Positive v_2 measured.

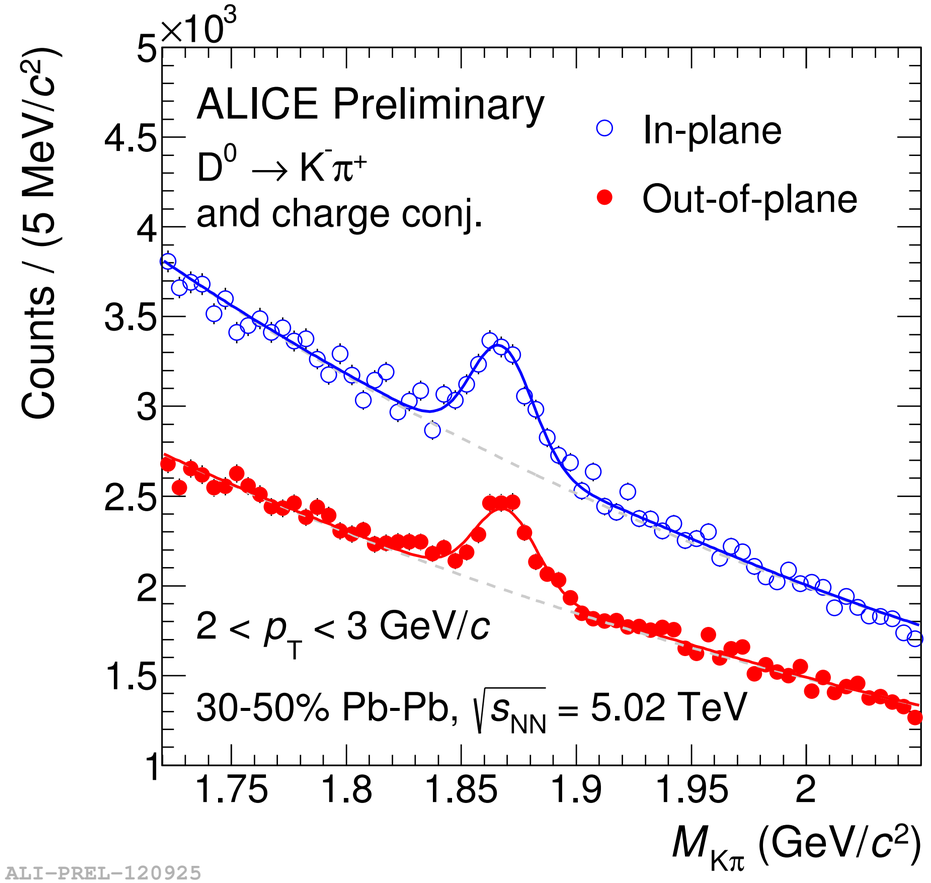


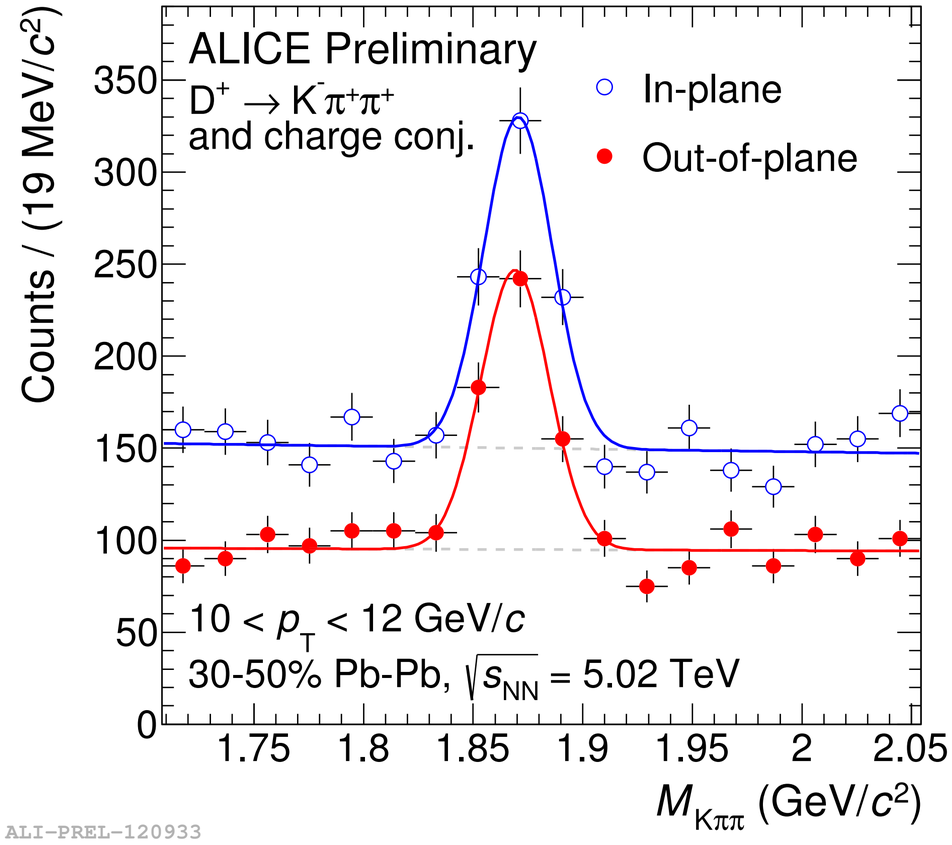
Inclusive J/ψ: v_2 and v_3

- $v_2 > 0$ for $2 < p_T < 8$ GeV/c for 3 centrality classes studied
- Comparison to D mesons is not straightforward, but values are of the same magnitude



D-meson v_2

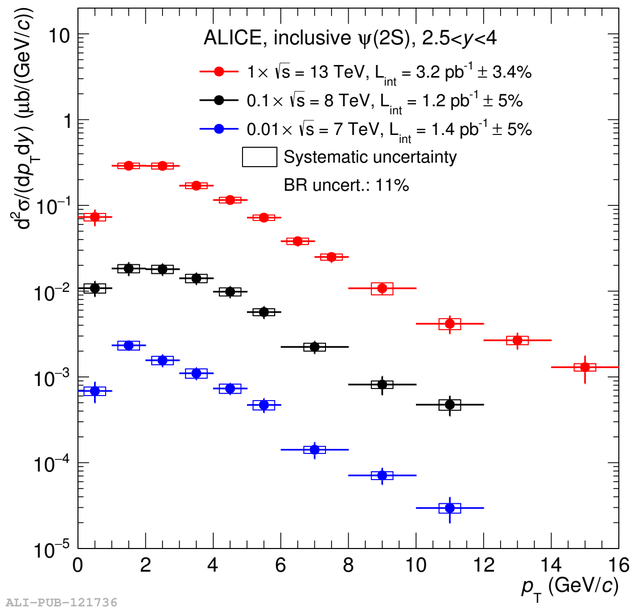

ALICE Preliminary
$D^0 \rightarrow K^-\pi^+$
and charge conj.
In-plane
Out-of-plane
$2 < p_T < 3$ GeV/c
30-50% Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
Counts / (5 MeV/c^2)
$\times 10^3$
$M_{K\pi}$ (GeV/c^2)
ALI-PREL-120925


ALICE Preliminary
$D^+ \rightarrow K^-\pi^+\pi^+$
and charge conj.
In-plane
Out-of-plane
$10 < p_T < 12$ GeV/c
30-50% Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
Counts / (19 MeV/c^2)
$M_{K\pi\pi}$ (GeV/c^2)
ALI-PREL-120933

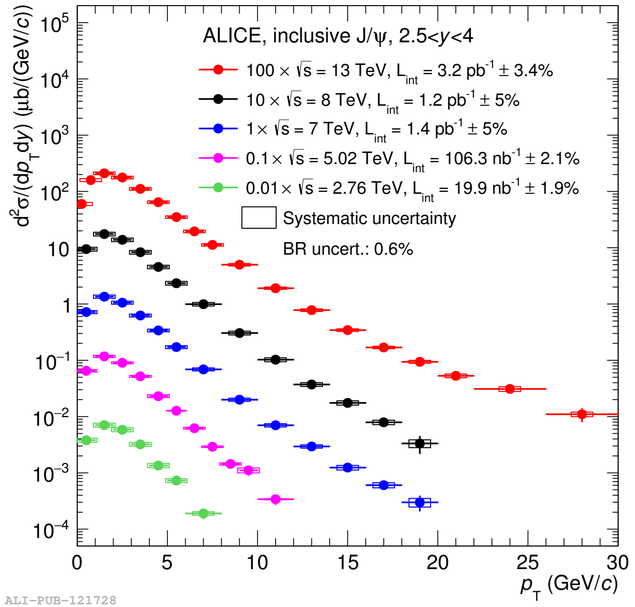
Charmonium production in pp

- 13 TeV significantly extend the p_T range
- Spectra is harder for increasing energy

ψ(2S)



J/ψ



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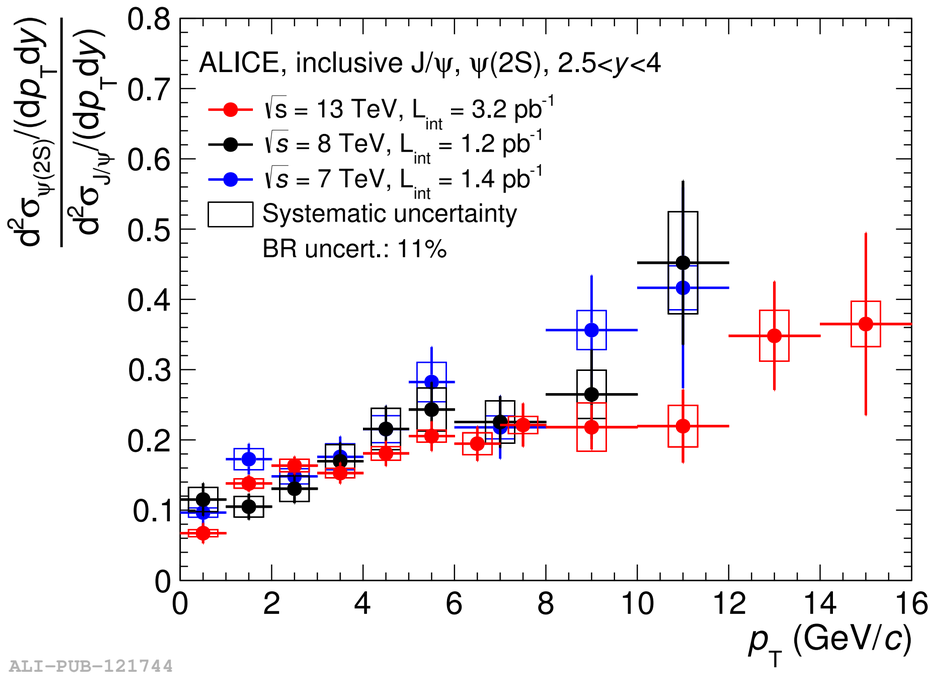
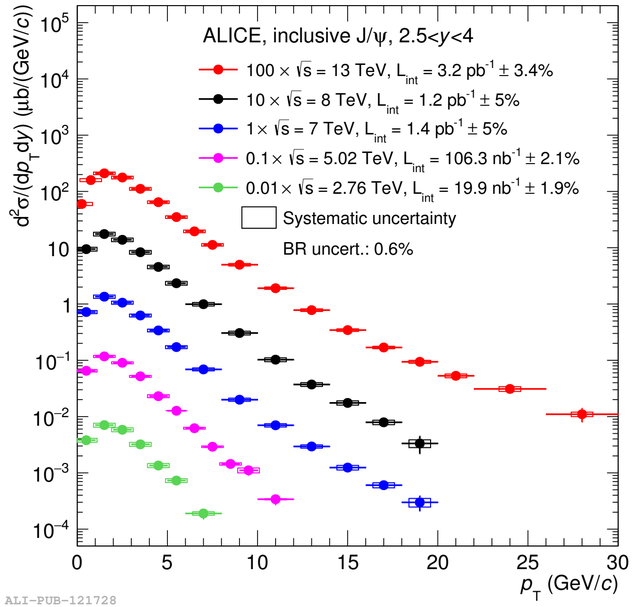
Charmonium production in pp

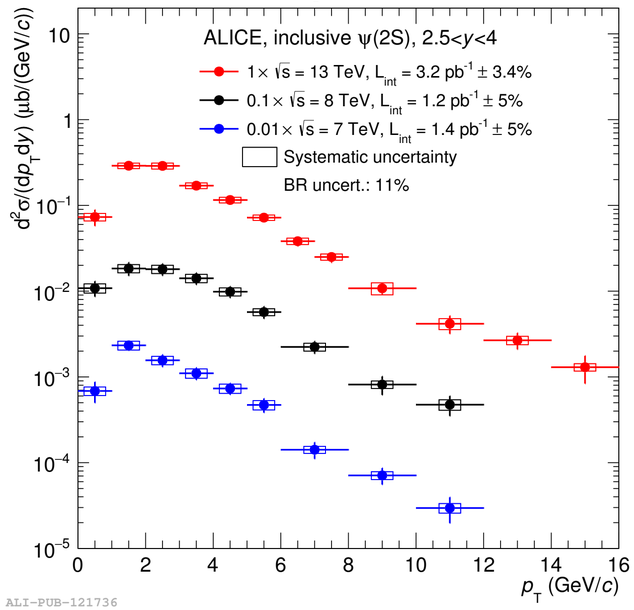
- 13 TeV significantly extend the p_T range
- Spectra is harder for increasing energy
- ψ(2S)/(J/ψ) ratios show no energy dependence



J/ψ



ψ(2S)



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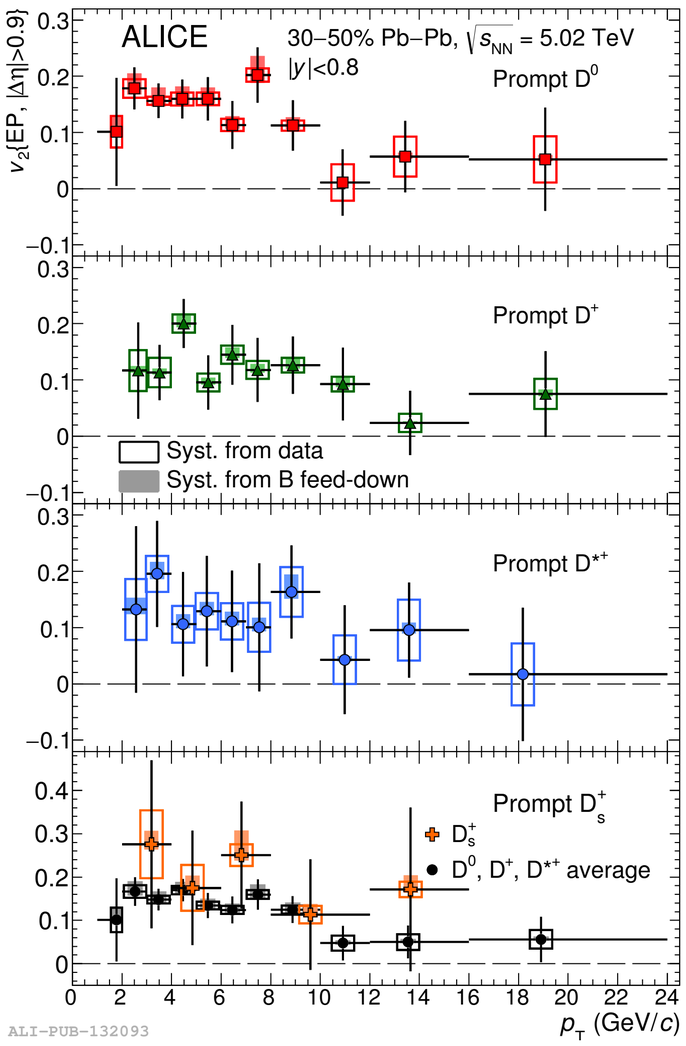
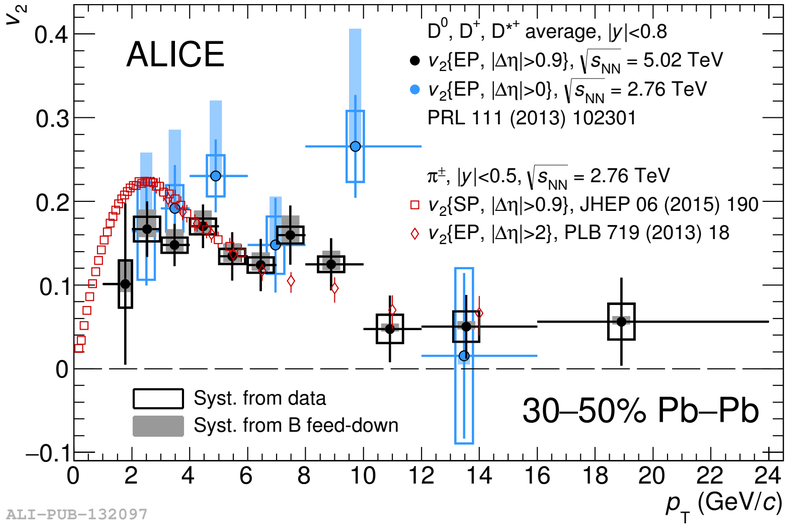
D-meson v_2

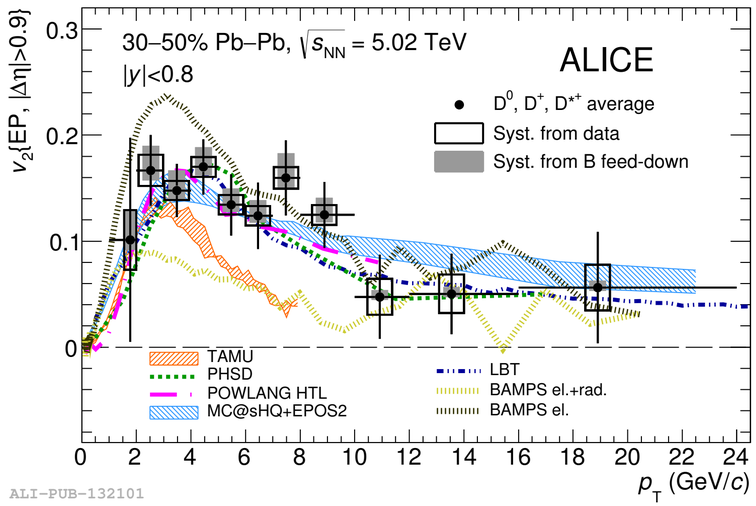
Per meson v_2

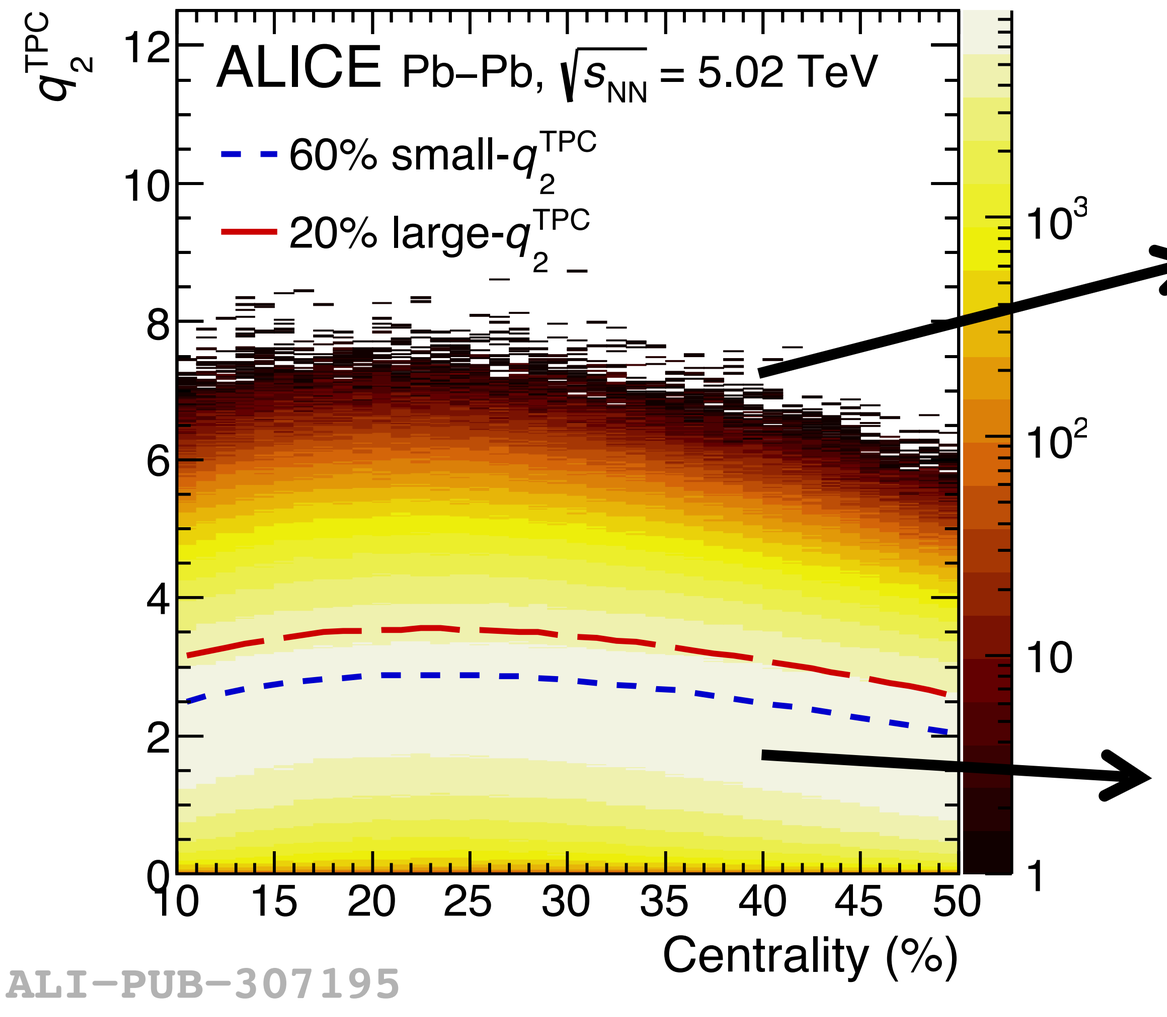


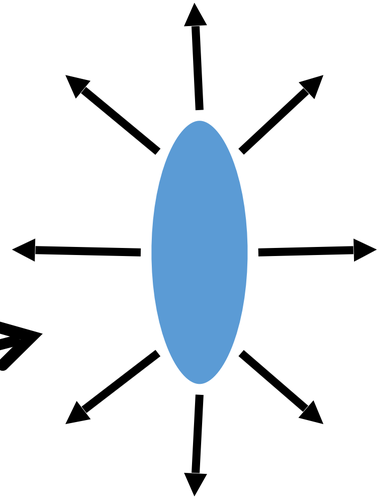
2.76 TeV vs 5.02

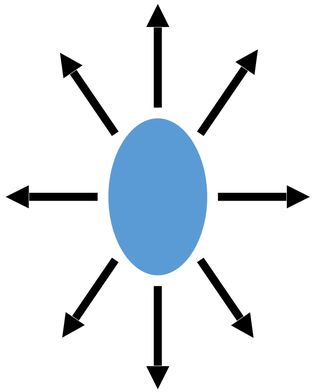


Model comparison









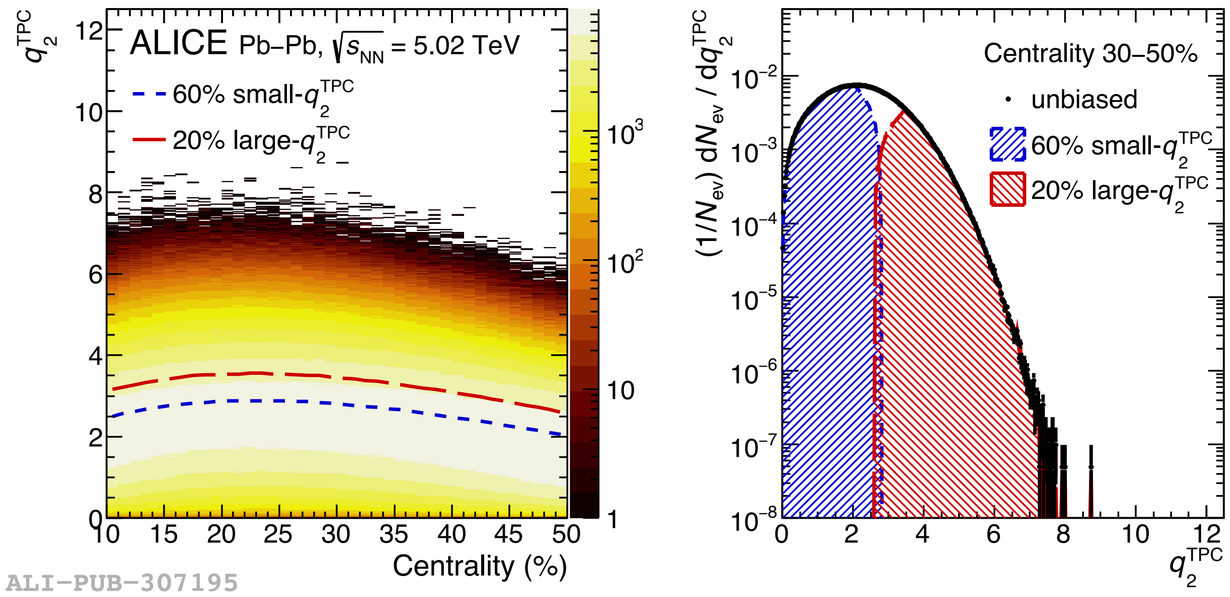
$$\langle q_2^2 \rangle \approx 1 + \langle \langle M - 1 \rangle \rangle \left\langle \langle v_2^2 + \delta_2 \rangle \right\rangle$$

How does the c quark couples with the bulk of light quarks?

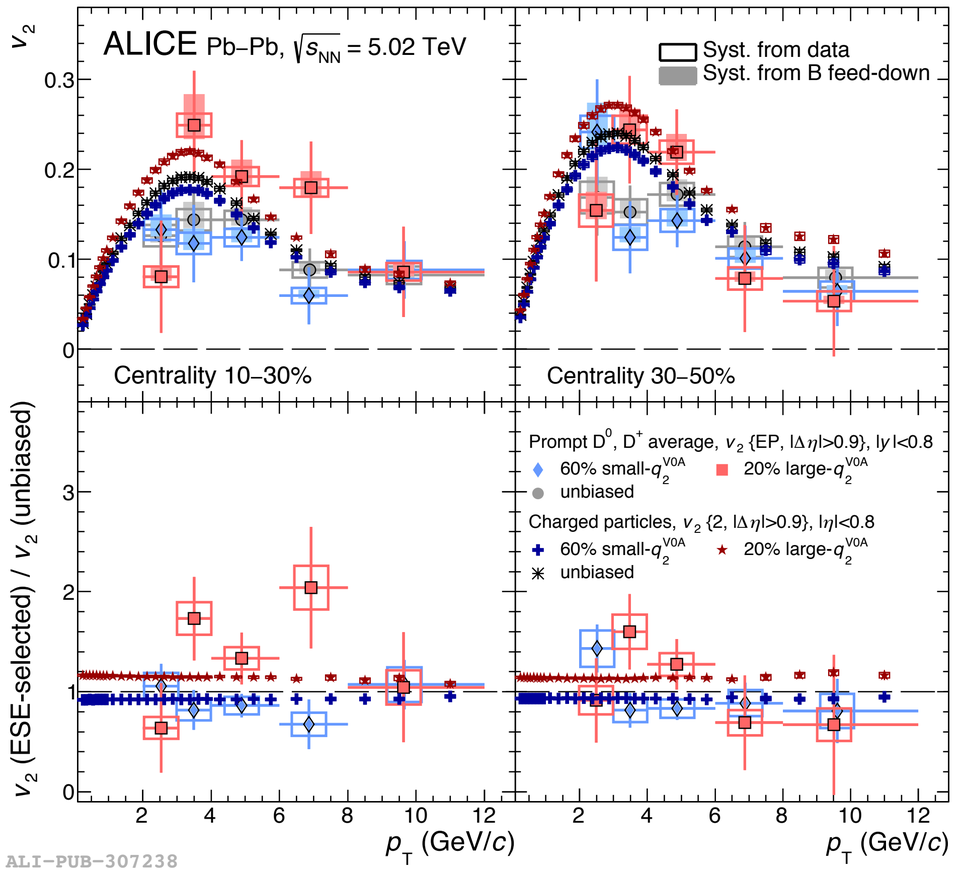
Selecting events with different eccentricity

D-meson v_2 with Event Shape Engineering

Selection in q_2 TPC



Results for V0A:
Reduced selectivity in q_2



Event-shape engineering (ESE) with the reduced flow vector:

$$q_2 = \left|Q_2\right| / \sqrt{M}$$

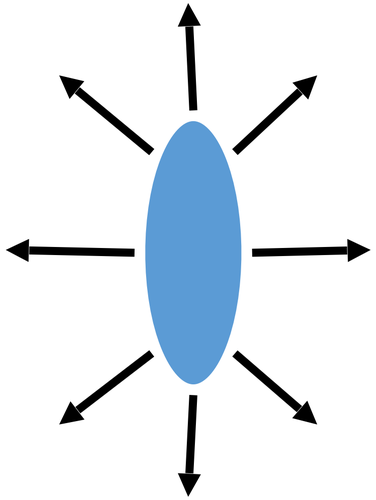
$$\left\langle q_2^2 \right\rangle \approx 1 + \left\langle \langle M - 1 \rangle \right\rangle \left\langle \left\langle v_2^2 + \delta_2 \right\rangle \right\rangle$$

Bulk-particle

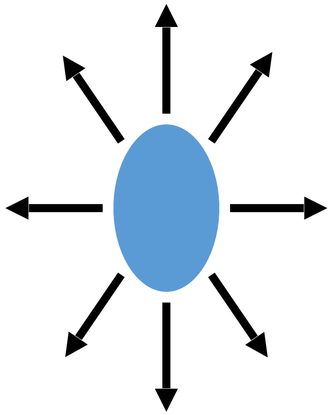
Study one observable in classes of events corresponding to the same centrality, but different eccentricity

High q_2

More Elliptical interaction area



How does the c quark couples with the bulk of light quarks?



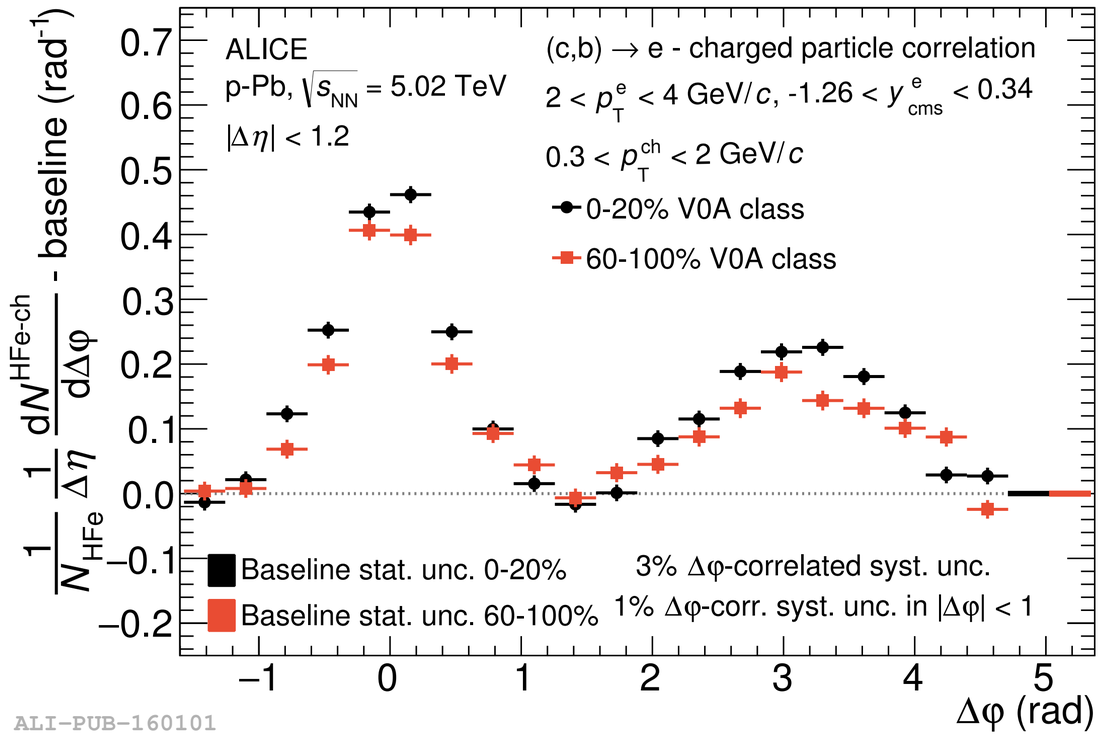
Low q_2

More circular interaction area

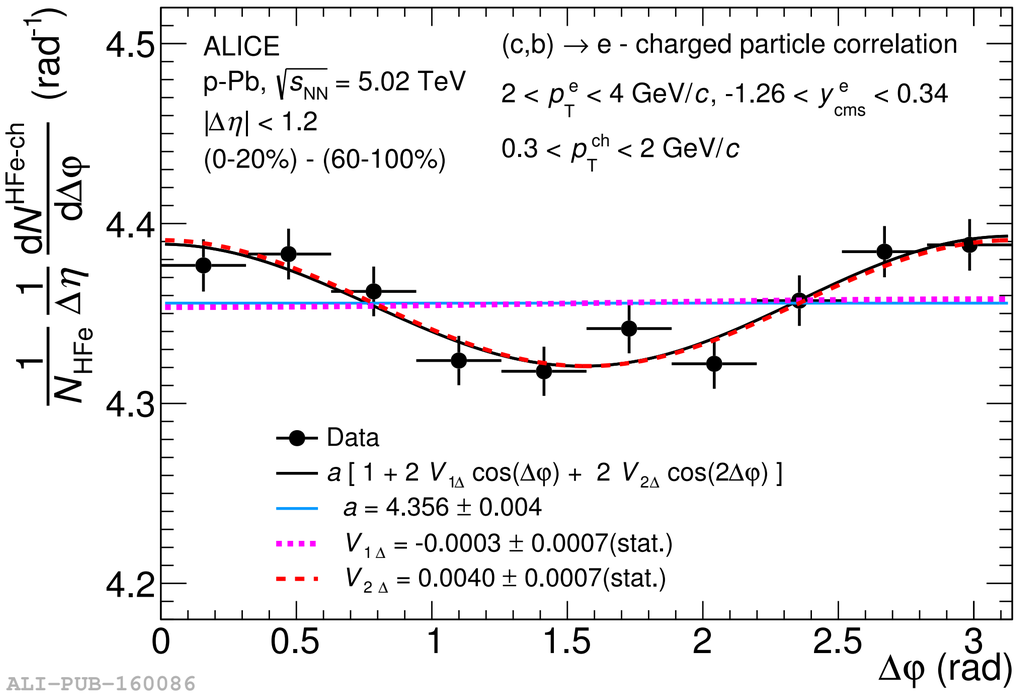
$$Q_n = \sum_{j=1}^{M} e^{i\varphi_j}$$

M: charged-particle multiplicity

HFe v_2 in p-Pb



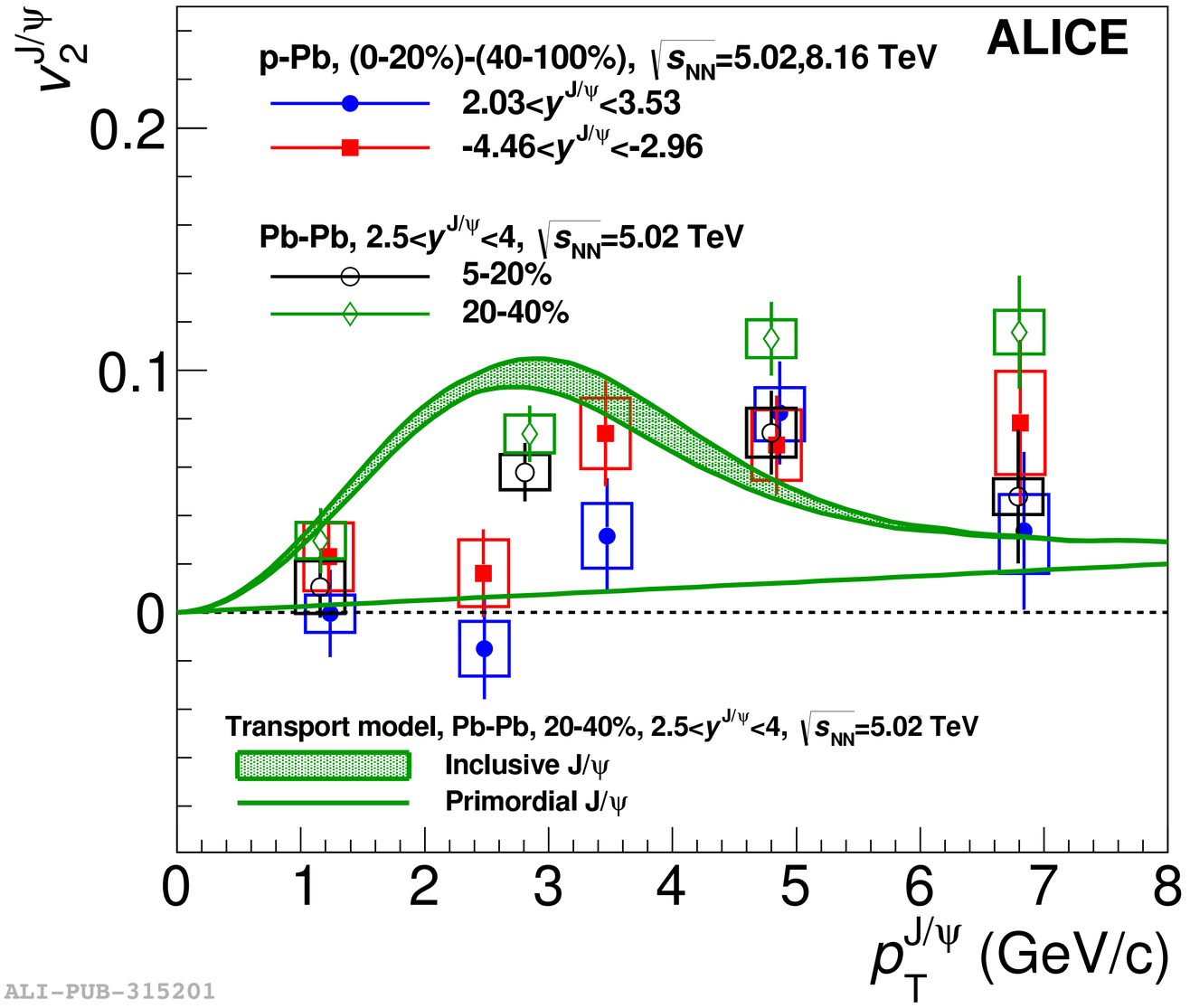
- Correlation obtained for high- and low-multiplicity events



- Jet subtraction: low multiplicity correlations used to remove most of short-range correlations

J/ψ v_2 in p-Pb

- v_2 compatible with zero for $p_T < 3$ GeV/c
- $v_2 > 0$ for $3 < p_T < 6$ GeV/c with a significance >5σ when combining backward and forward results at the two energies (5.02 and 8.16 TeV)
- Similar to the one obtained in Pb-Pb



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