Open and hidden heavy flavor measurements in ALICE

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on behalf of the ALICE Collaboration

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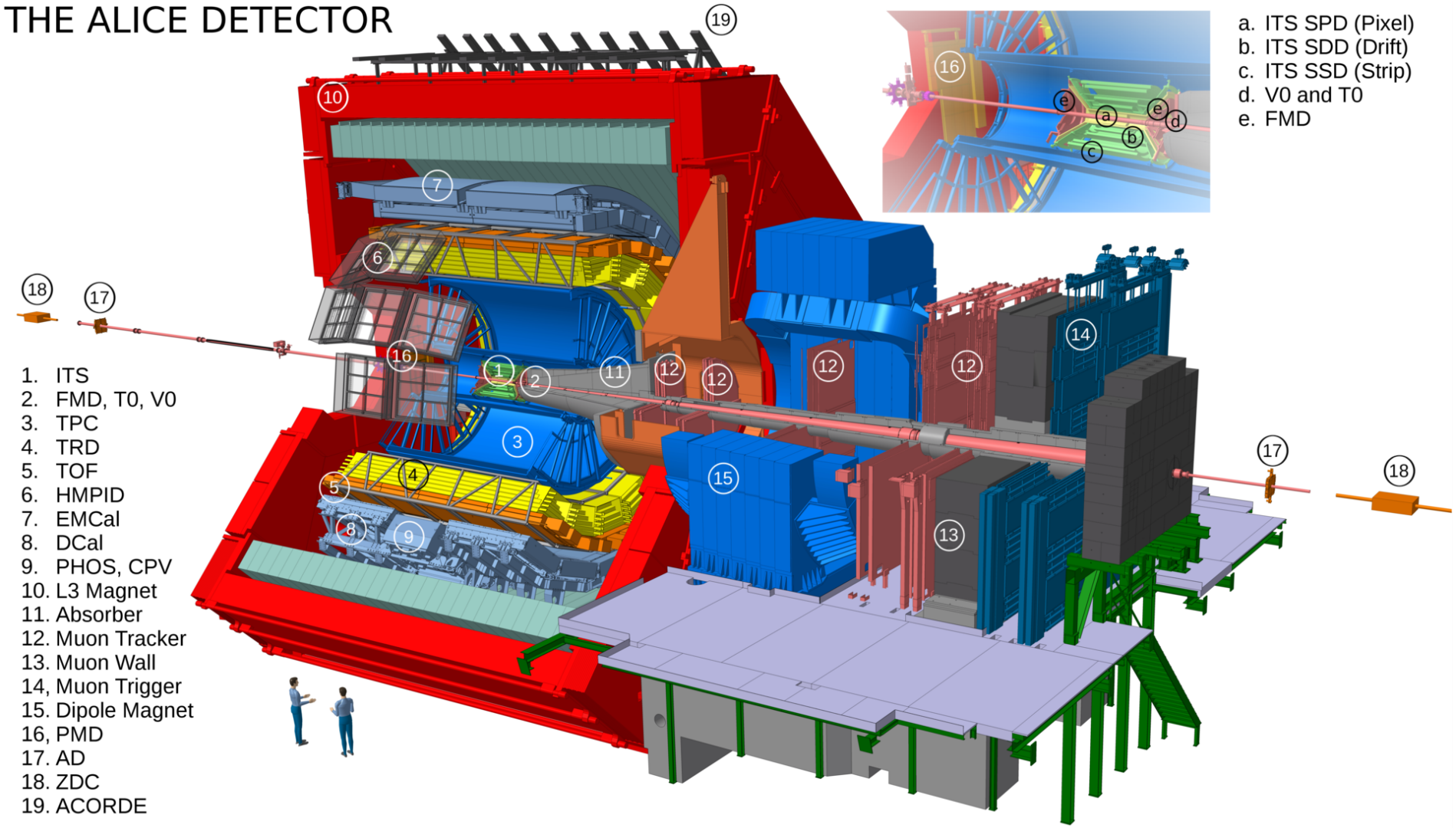
Contents:

- R_{AA} of open and hidden HF
- Anisotropic flow and ESE in Pb-Pb collisions
- HF-tagged jets in pp, p-Pb and Pb-Pb collisions
- ψ(2S) suppression in p-Pb collisions
- Anisotropic flow in p-Pb collisions
- Open-HF and quarkonia in high-multiplicity pp collisions

ALICE setup



Quarkonia (down to $p_T = 0$)

$|y|<0.9$: J/ψ

$2.5<y<4$: J/ψ, ψ(2S), Υ(1S), Υ(2S), Υ(3S)

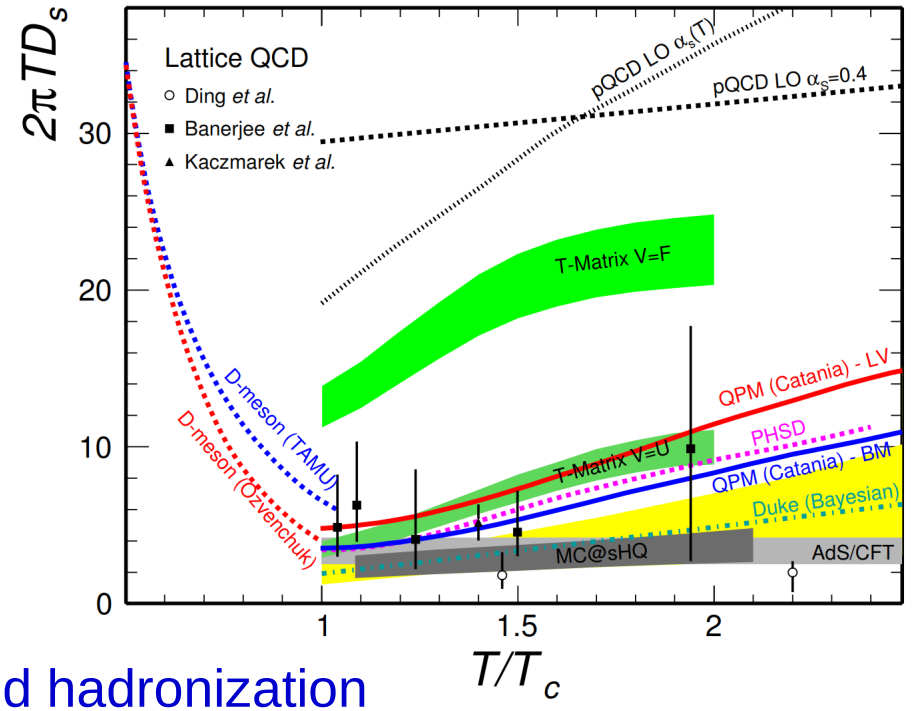
Open HF

$|y|<0.9$: HF-e, D^0, D^+, D^{*+}, D^+_s, Λ_c

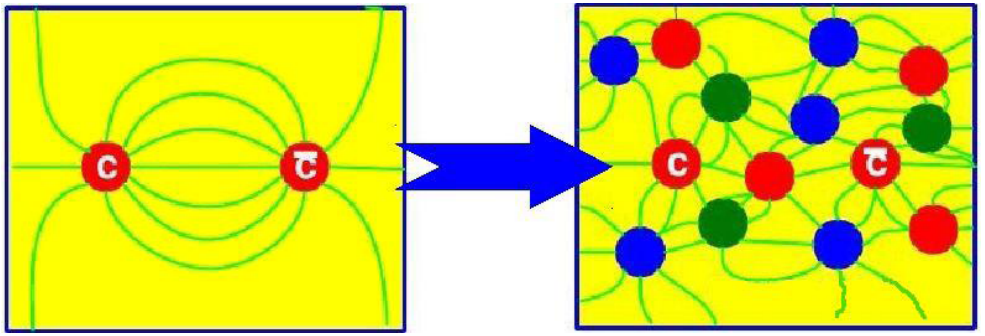
$2.5<y<4$: HF-μ

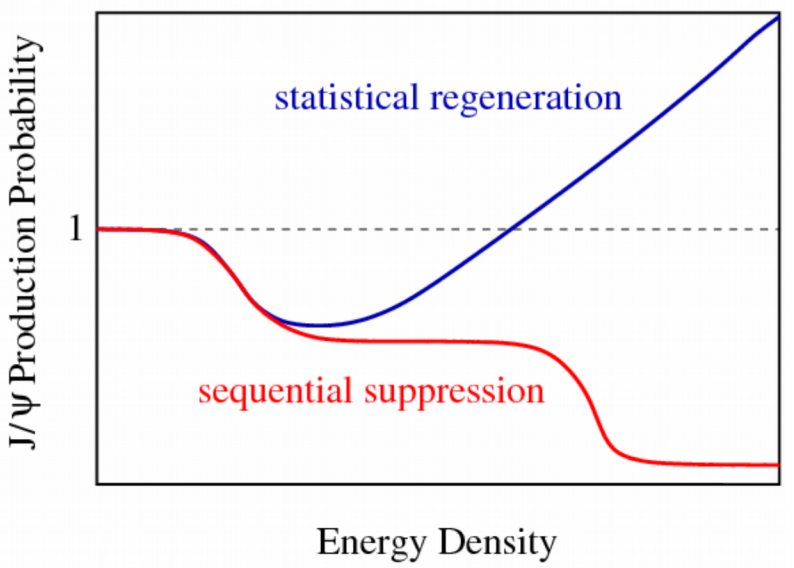
Heavy-quark production

- Early heavy-quark production (negligible thermal production)
  - Perturbative QCD methods applicable
  - Initial yields affected by CNM effects
- Multiple elastic (collisional) and inelastic (radiative) scatterings in the QGP
  - Sensitive to transport properties (e.g. diffusion coefficient D_s)
- Affected by the collective bulk evolution and hadronization
  - Major theoretical challenge



Quarkonium production



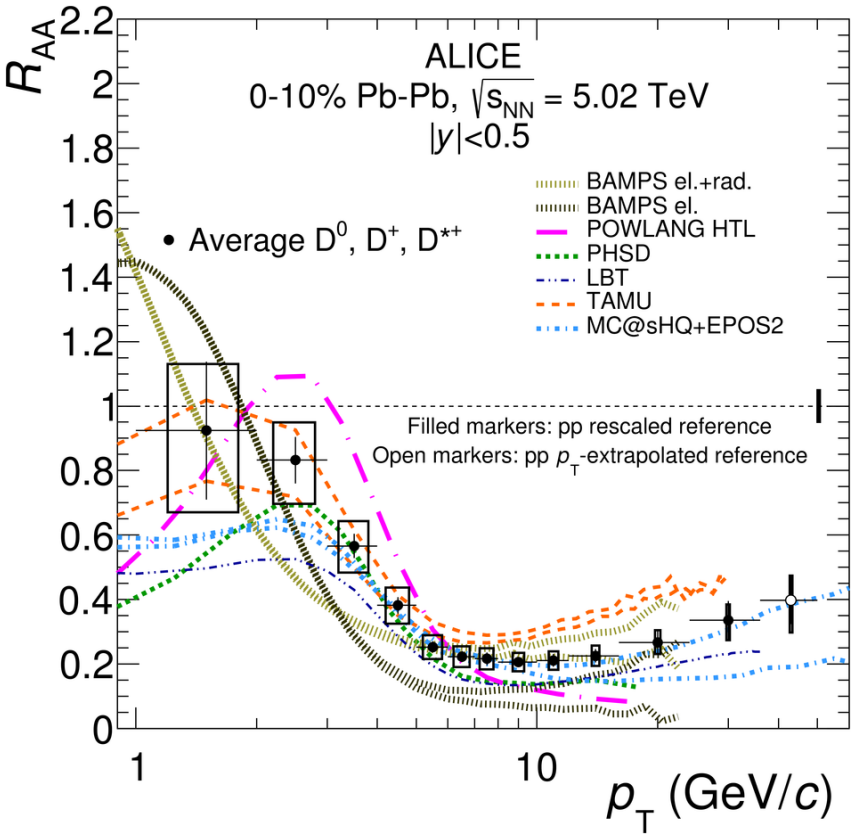


- Early proposed probe of nuclear matter deconfinement (*Matsui and Satz, PLB178 (1986) 416*)
- Temperature dependence of quarkonia binding energies and dissociation rates sensitive to
  - medium transport properties
  - spectral and correlation functions → tests for lattice QCD
- At the LHC: strong recombination effects, sensitive to HQ equilibration time

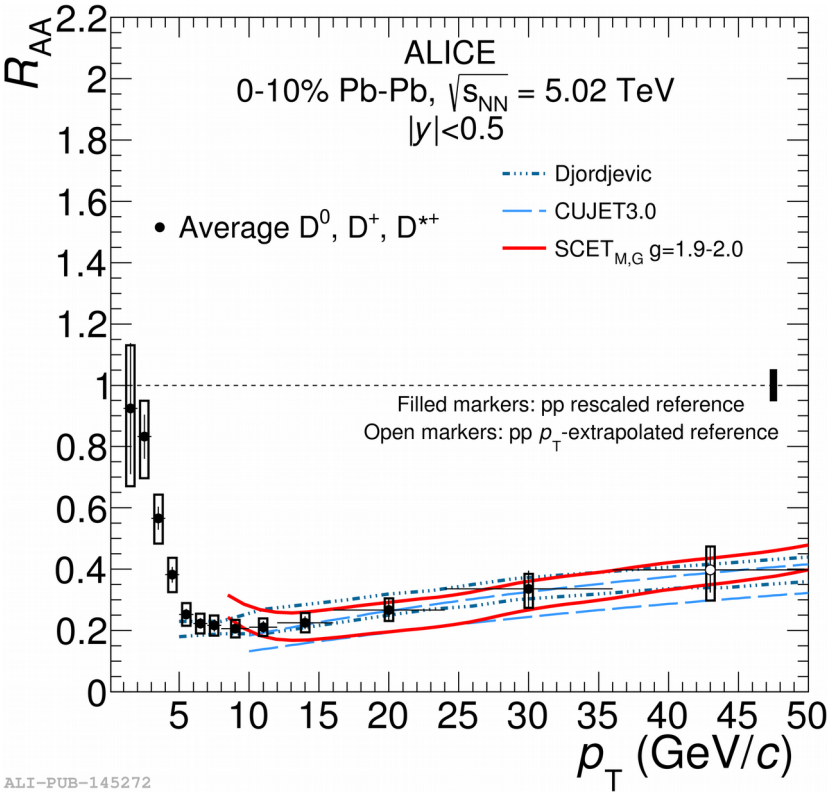
R_{AA} of non-strange D mesons

ALICE, JHEP 1810 (2018) 174

transport models



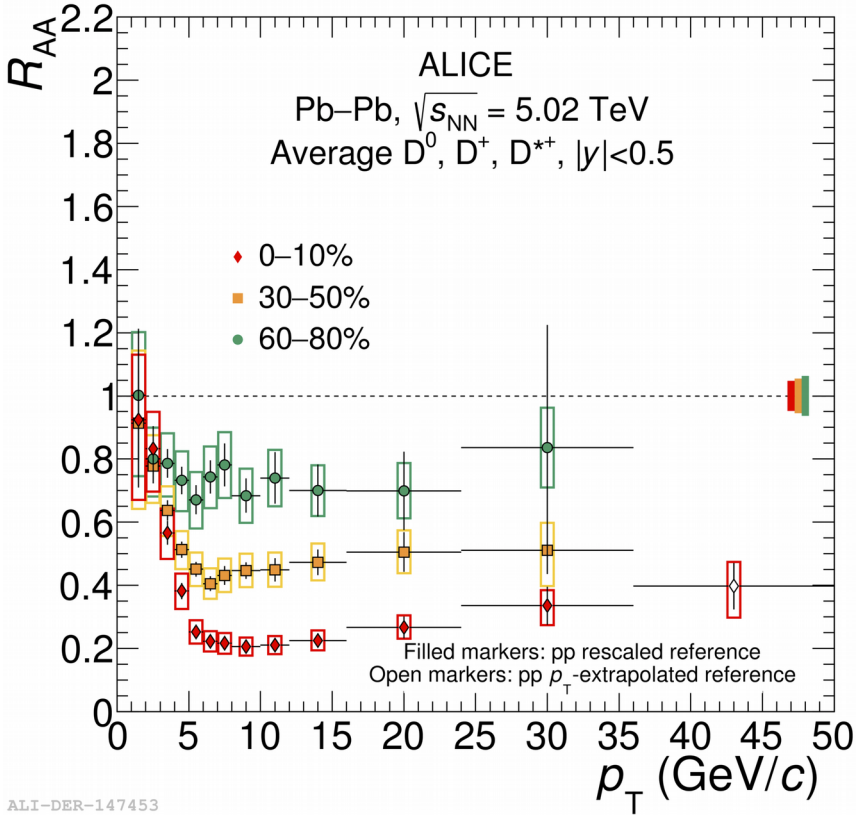
pQCD calculations



- Low p_T: qualitative description of the data for models implementing medium evolution and hadronization effects (quark recombination)
- High p_T: pQCD based calculations in good agreement with data

R_{AA} of non-strange D mesons vs centrality

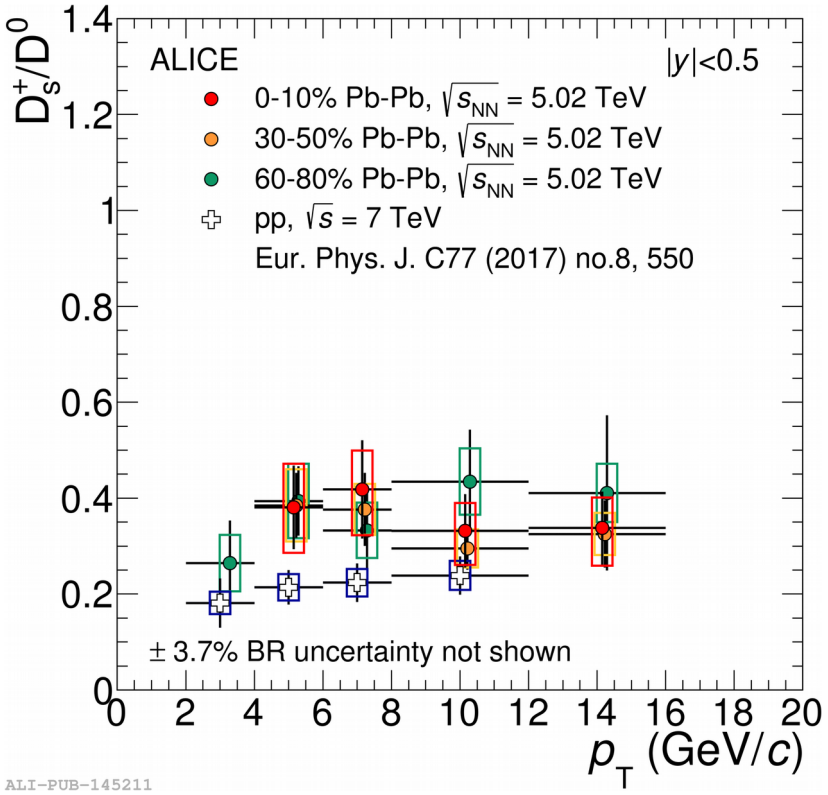
ALICE, JHEP 1810 (2018) 174



- High p_T: strong centrality dependence
- Low p_T: many competing effects
  - Hadronization effects, radial flow, charm conservation

Strange D-meson production in Pb-Pb collisions

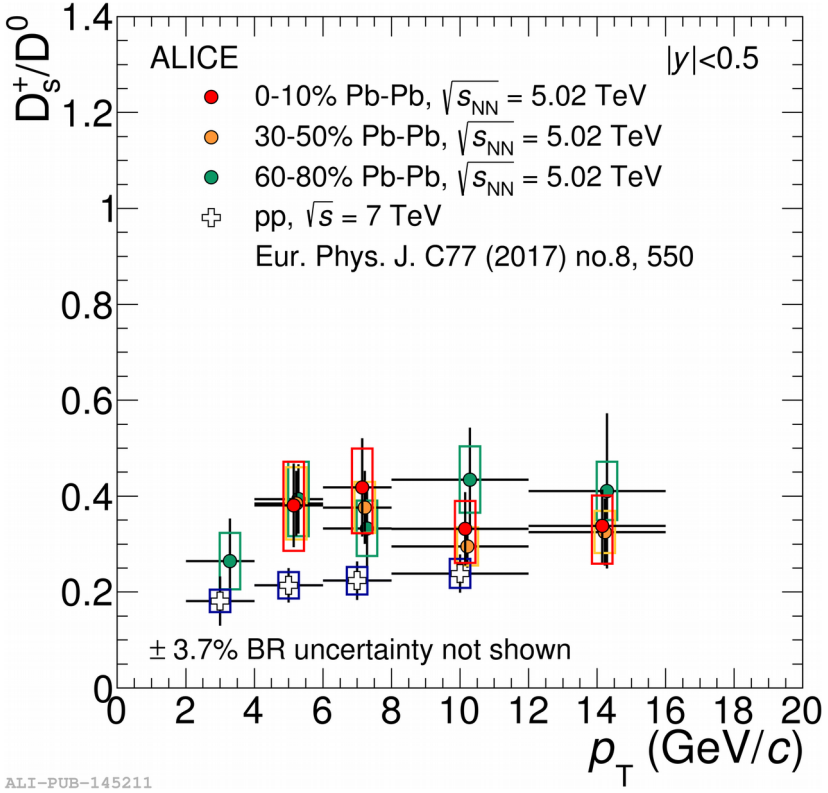
ALICE, JHEP 1810 (2018) 174



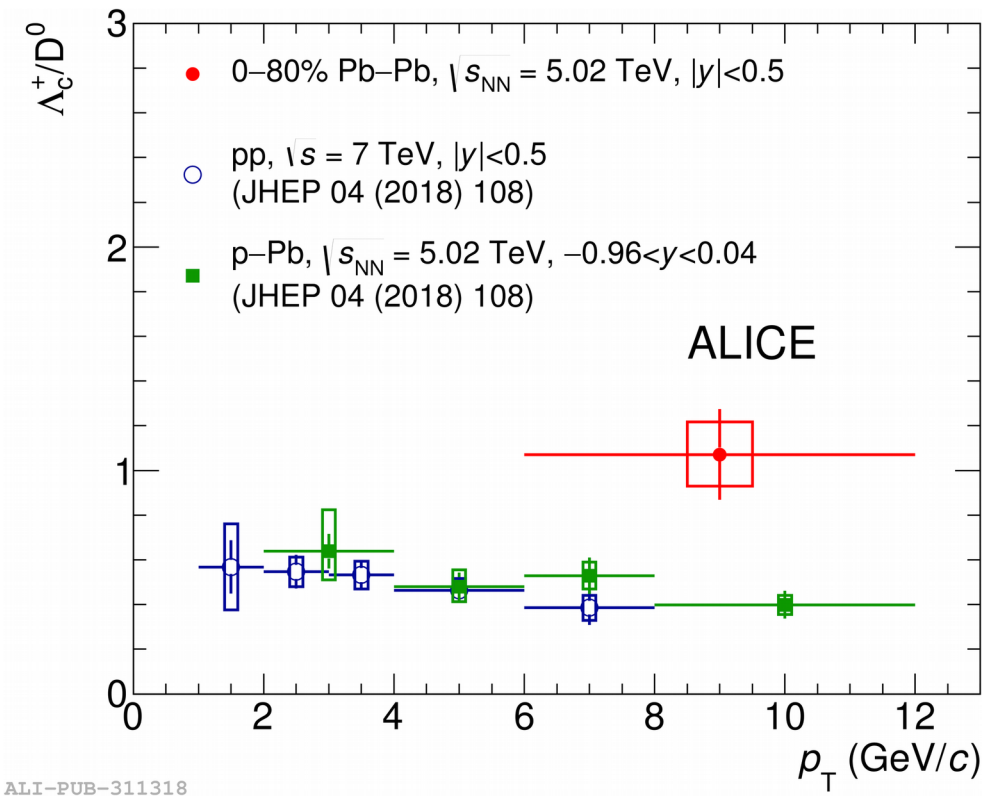
- Hint of a strong enhancement of D^+_s in Pb-Pb collisions, expected from quark recombination models

Λ_c^+ production in Pb-Pb collisions

ALICE, JHEP 1810 (2018) 174



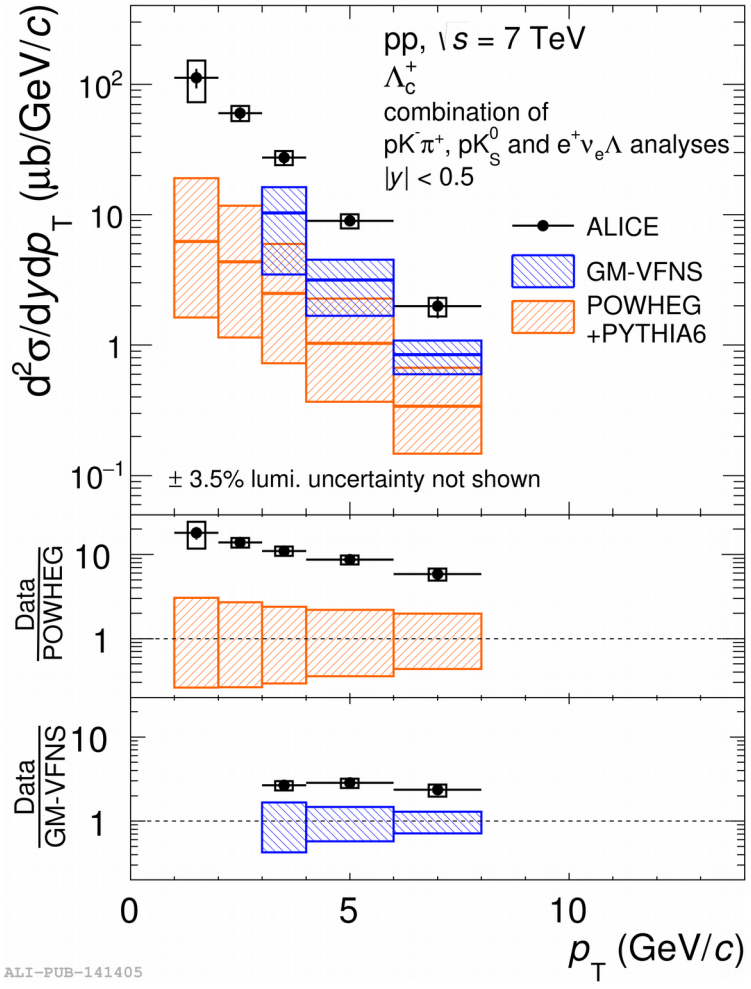
ALICE, arxiv:1809.10922

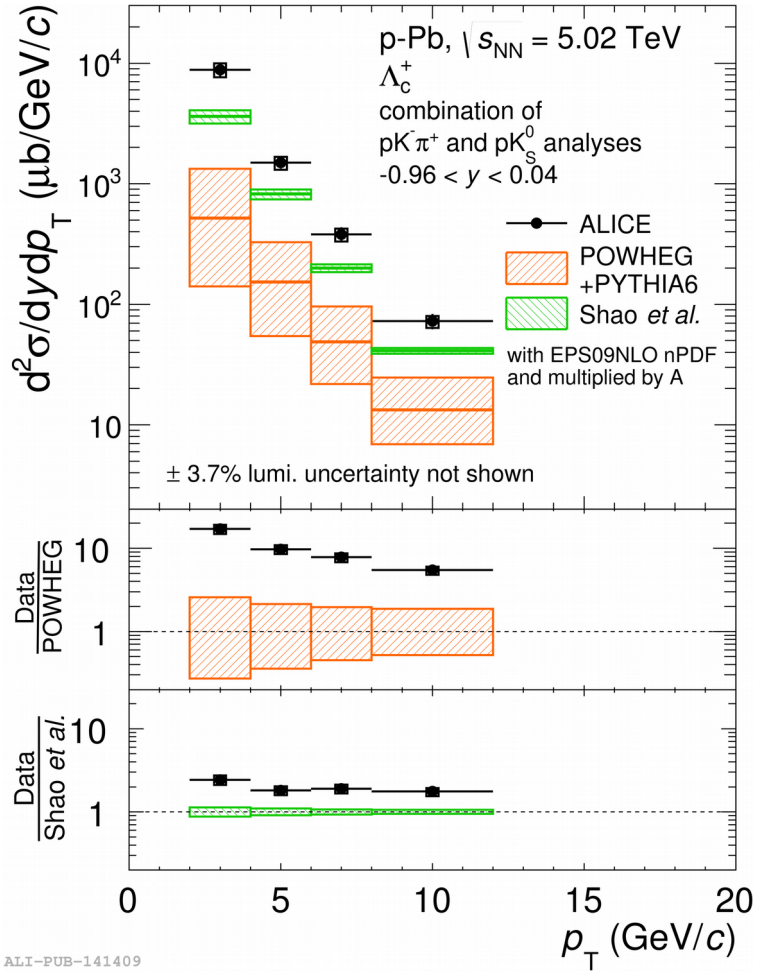


- Hint of a strong enhancement of D^+_s in Pb-Pb collisions, expected from quark recombination models
- First Λ_c results in Pb-Pb collisions at the LHC: large enhancement at moderate p_T
  - Large radial flow effects ?
  - Charmed baryons get an unexpected large fraction of the whole $c\bar{c}$ budget
  - Moreover ...

Λ_c production in pp and p-Pb collisions

ALICE, JHEP 1804 (2018) 108

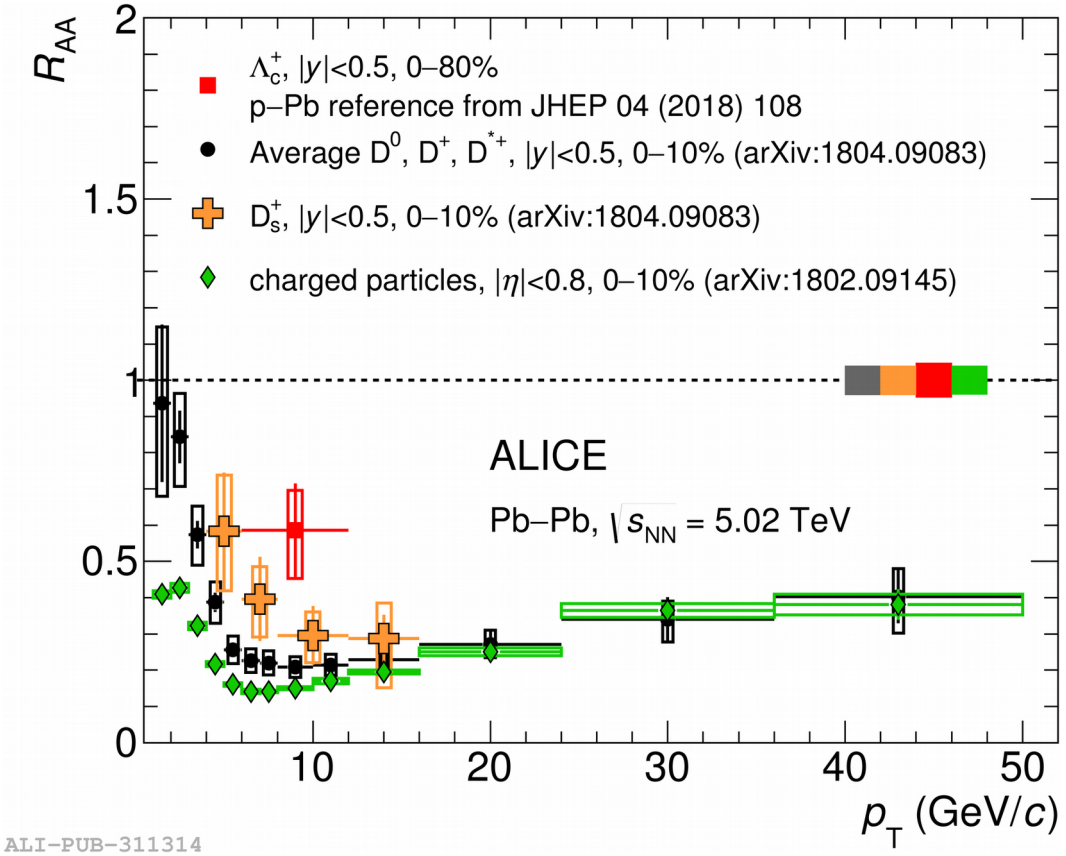




- Λ_c production for pp and p-Pb collisions is heavily underestimated in model calculations
  - R_{AA} measurements of final-state particles affected by large hadronization effects

R_{AA} of charmed mesons and baryons

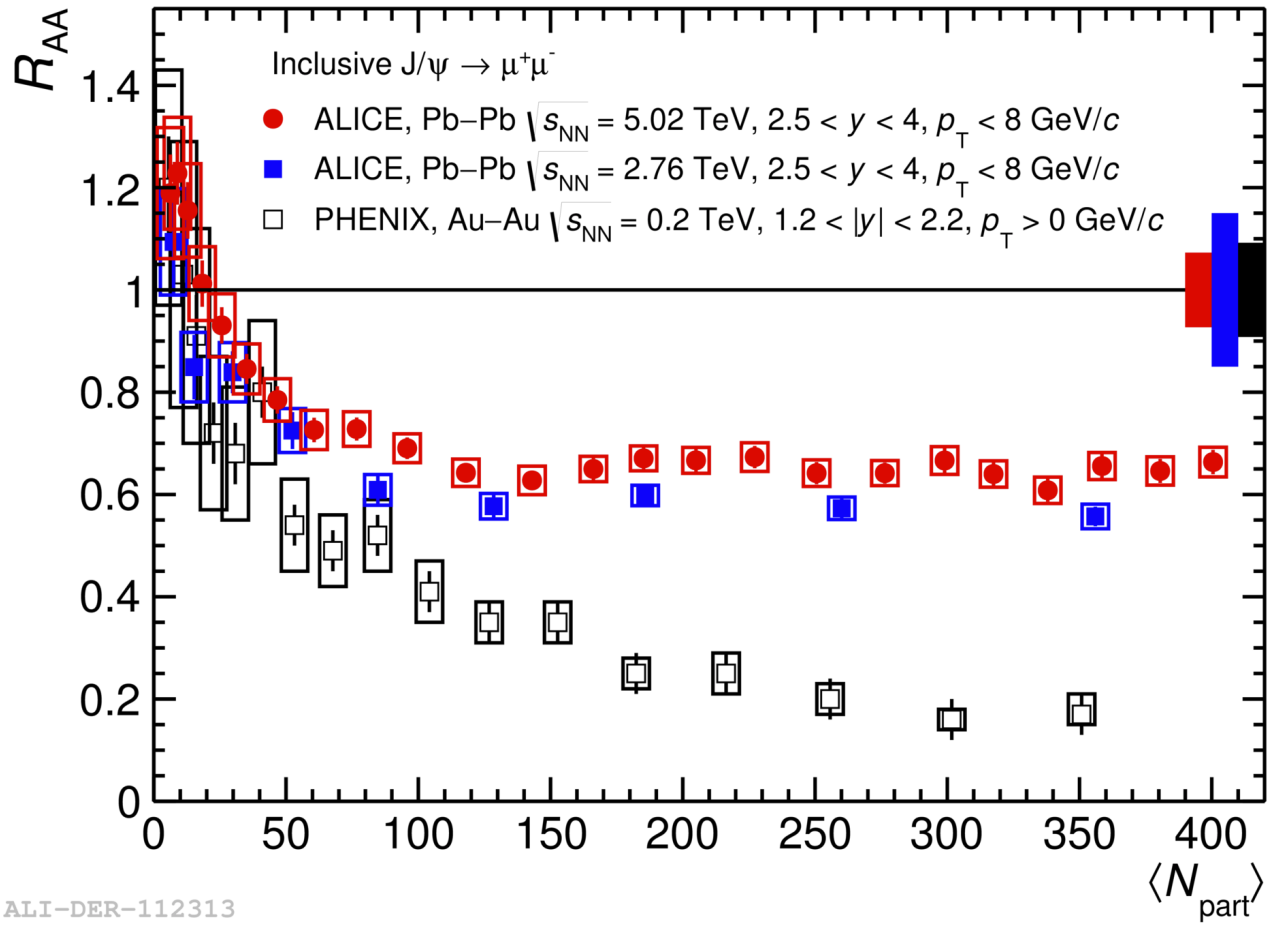
ALICE, JHEP 1804 (2018) 108



- Low and intermediate p_T:
  - Still large experimental uncertainties, but a suppression hierarchy emerging:
    - $R_{AA}(\pi) < R_{AA}(\text{non-strange D}) < R_{AA}(D_s) < R_{AA}(\Lambda_c)$
- High p_T: similar suppression for pions and non-strange D mesons

R_{AA} of J/ψ vs centrality

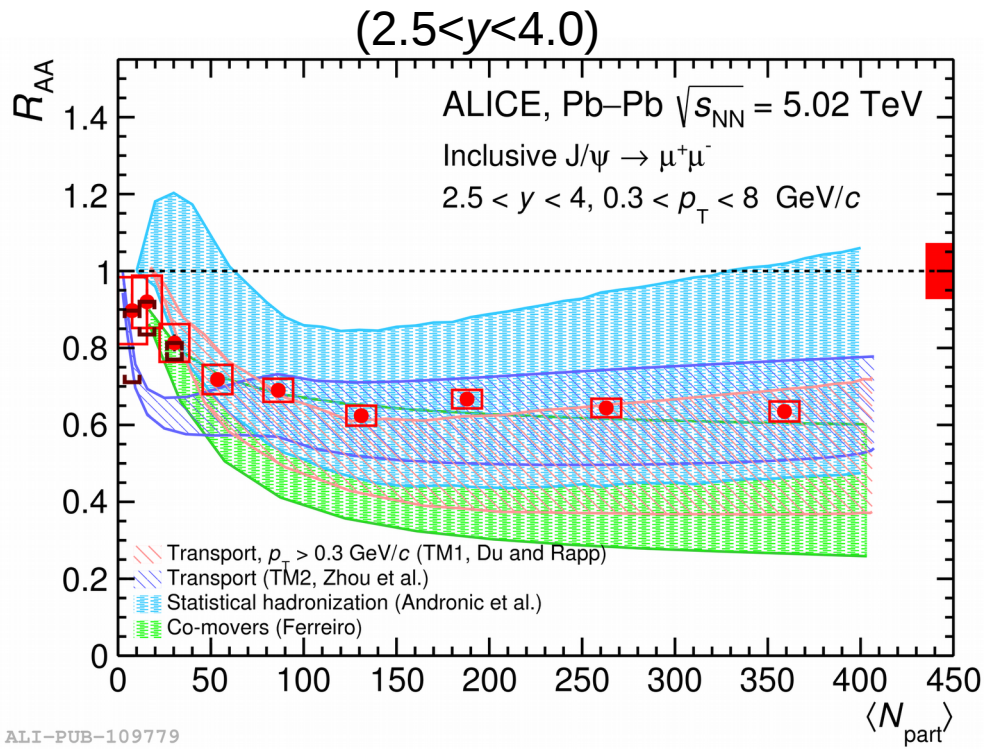
ALICE, PLB 734 (2014) 314
ALICE, PLB 766 (2017) 212

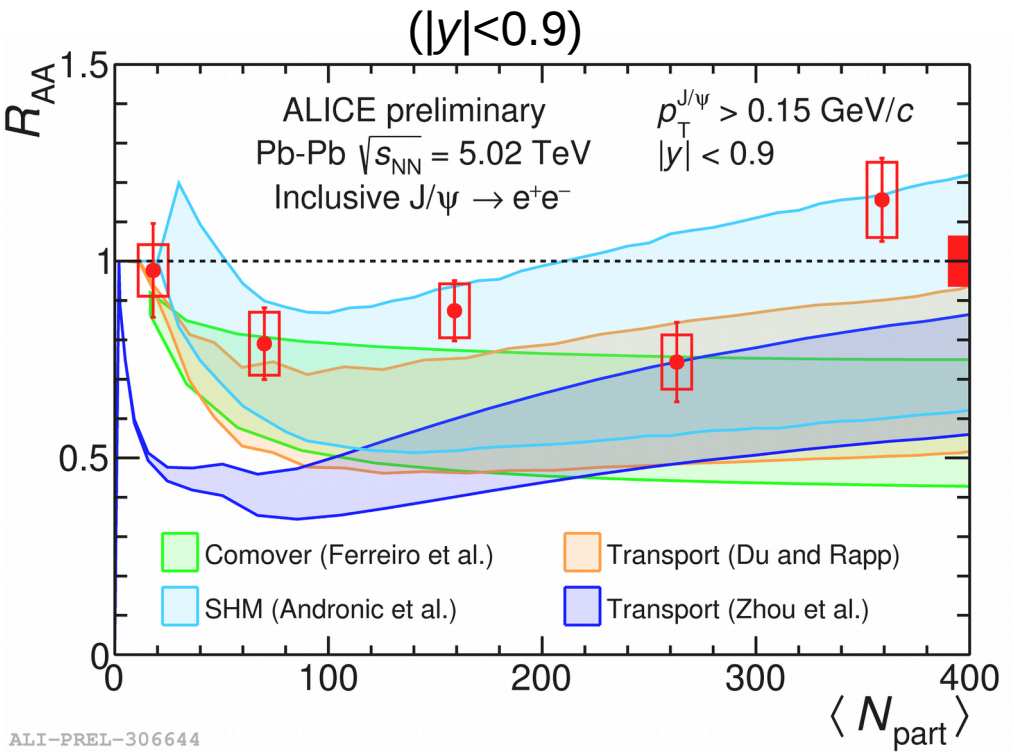


- Very little centrality dependence of J/ψ suppression at the LHC for N_{part} > 50
  - In strong contrast to RHIC measurements

R_{AA} of J/ψ vs centrality

ALICE, PLB 766 (2017) 212

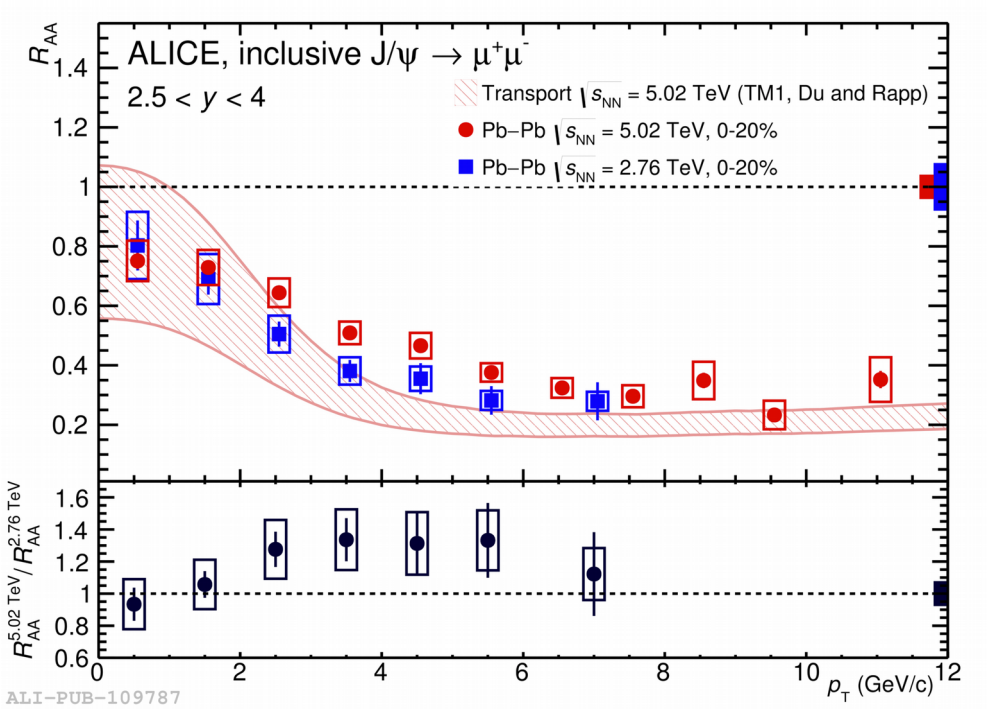


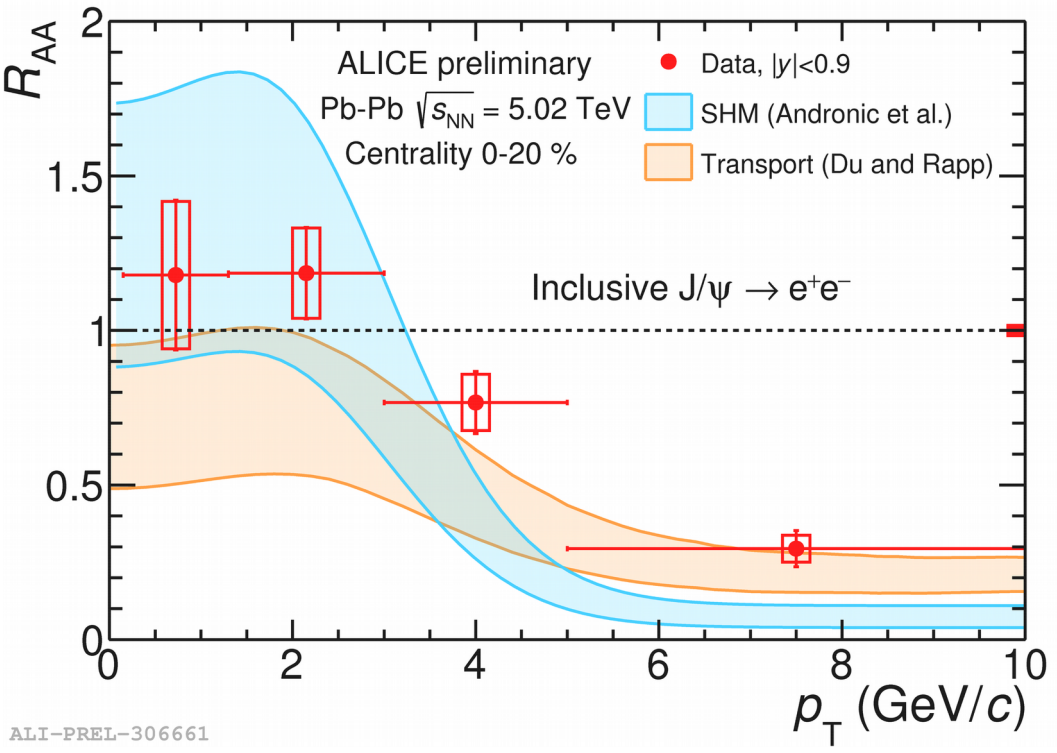


- Suppression level in qualitative agreement with models which include charm-quark recombination:
  - Full charm-quark thermalization in QGP → yields generated at the bulk chemical freeze-out (SHM)
  - Finite HQ relaxation time, continuous dissociation and regeneration of charmonia → Texas and Tsingua models
  - Comover interaction → Ferreiro et al.
- Very large model uncertainties due to the primordial $c\bar{c}$ cross section

R_{AA} of J/ψ vs p_T

ALICE, PLB 766 (2017) 212

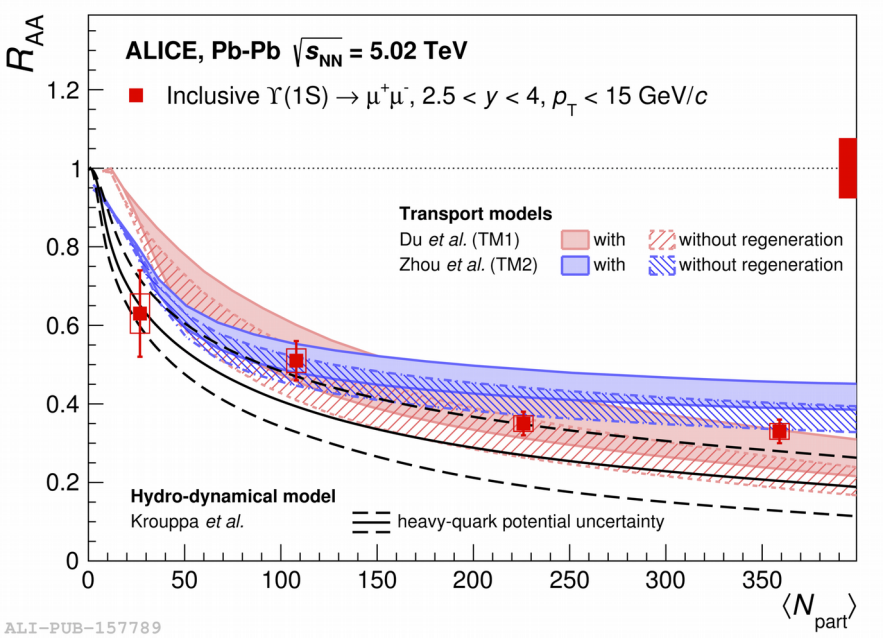


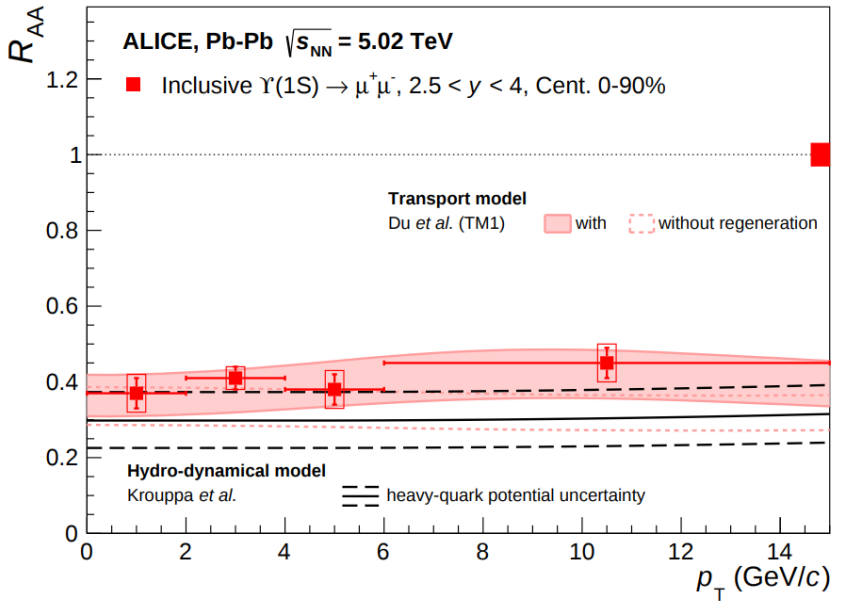


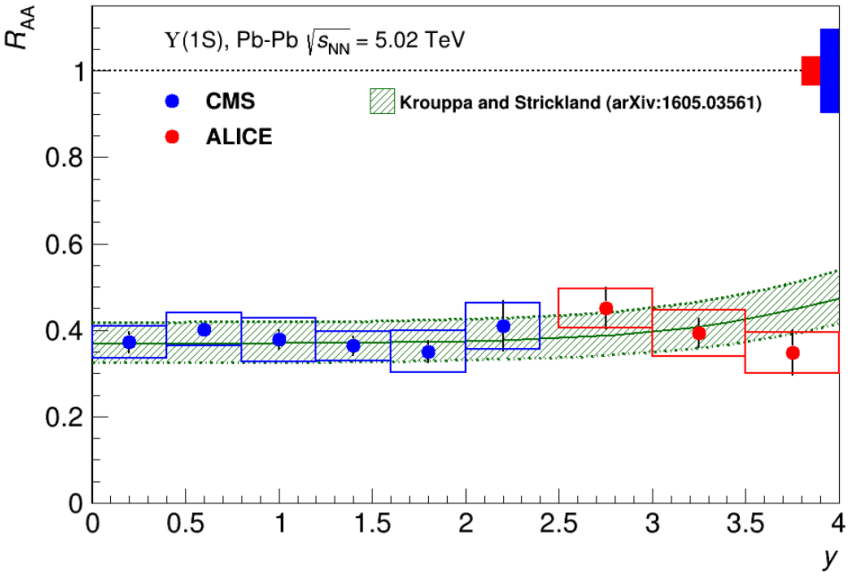
- Low p_T: little suppression at fwd-*y* and even enhancement at mid-*y*
  - Production predominantly via recombination
- High p_T: strong suppression, similar to D mesons and open beauty measurements

Υ suppression in Pb-Pb collisions

ALICE, arXiv: 1805.04387

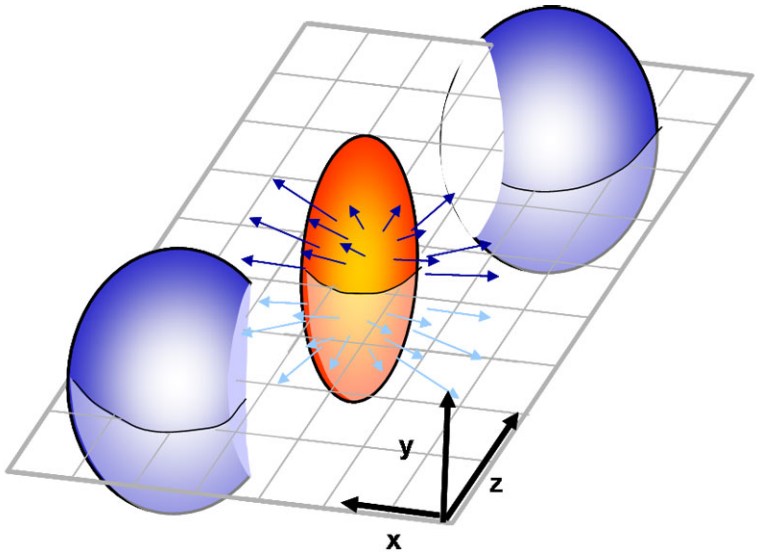






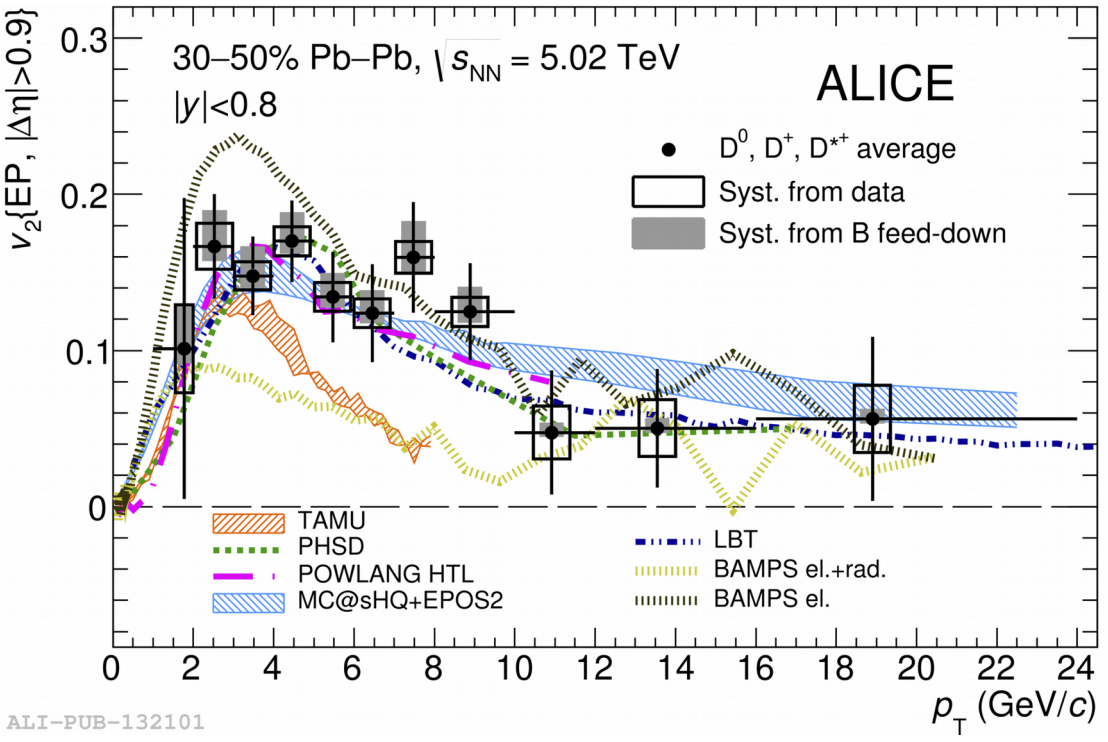
- Moderate centrality dependence
- None or very weak p_T and rapidity dependence
- In agreement with model calculations
  - Possible regeneration effects cannot be established with the current uncertainties

D-meson elliptic flow



$$\frac{dN}{d\phi} \simeq 1 + 2\sum_n v_n \cos\left[n(\phi - \Psi_n)\right]$$

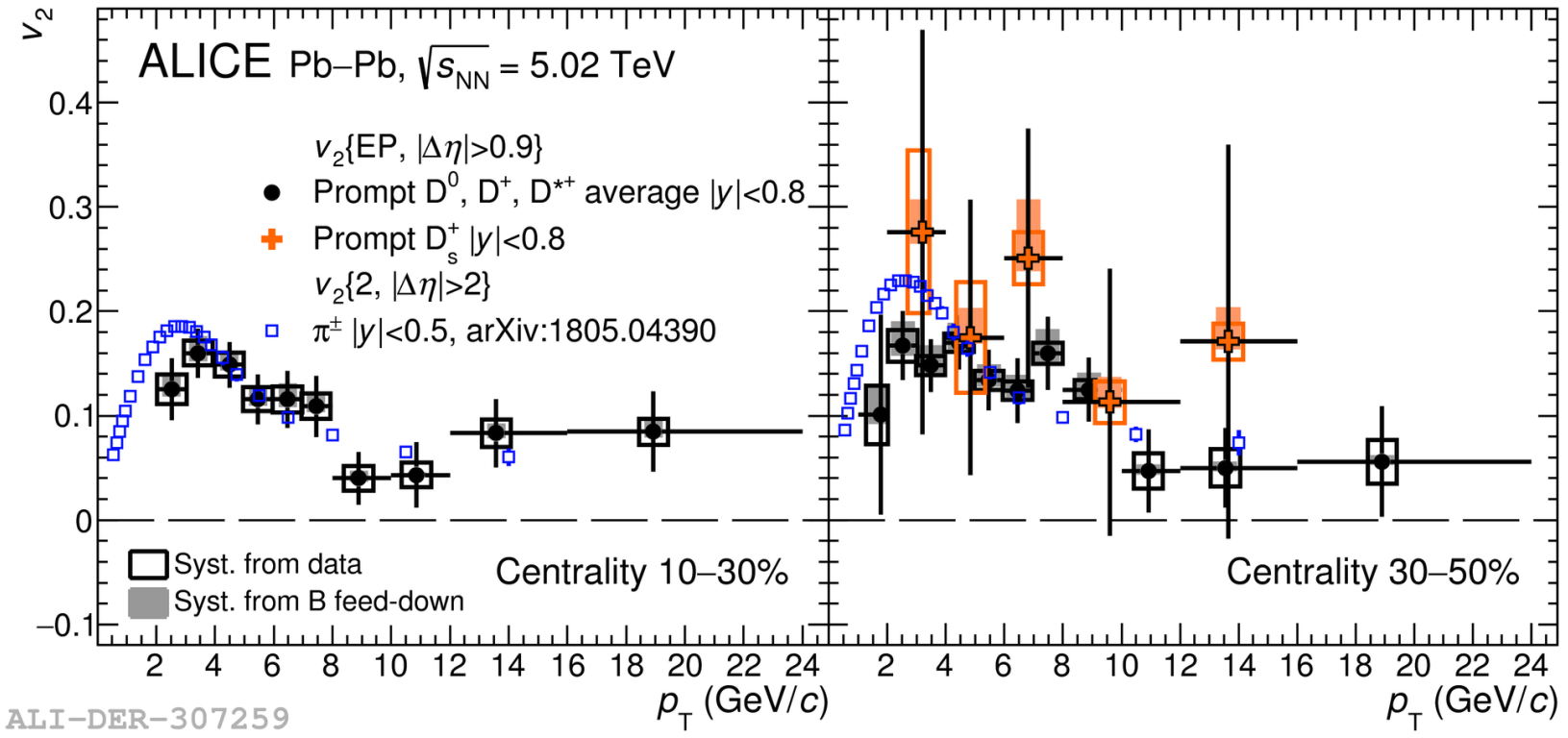
ALICE PRL 120 (2018) 102301



- Significant elliptic flow observed in semi-central collisions
  - In agreement with most transport models which implement a detailed fireball evolution
  - Challenging to describe both R_{AA} and elliptic flow
    - PHSD and MC@sHQ+EPOS2 give reasonable description of both

D-meson elliptic flow

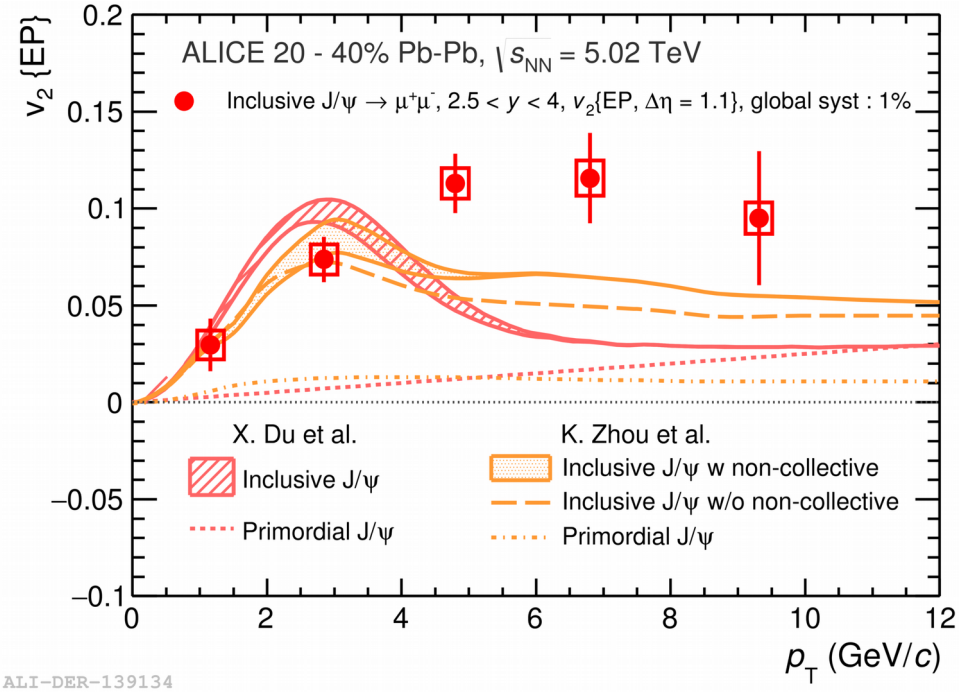
ALICE PRL 120 (2018) 102301

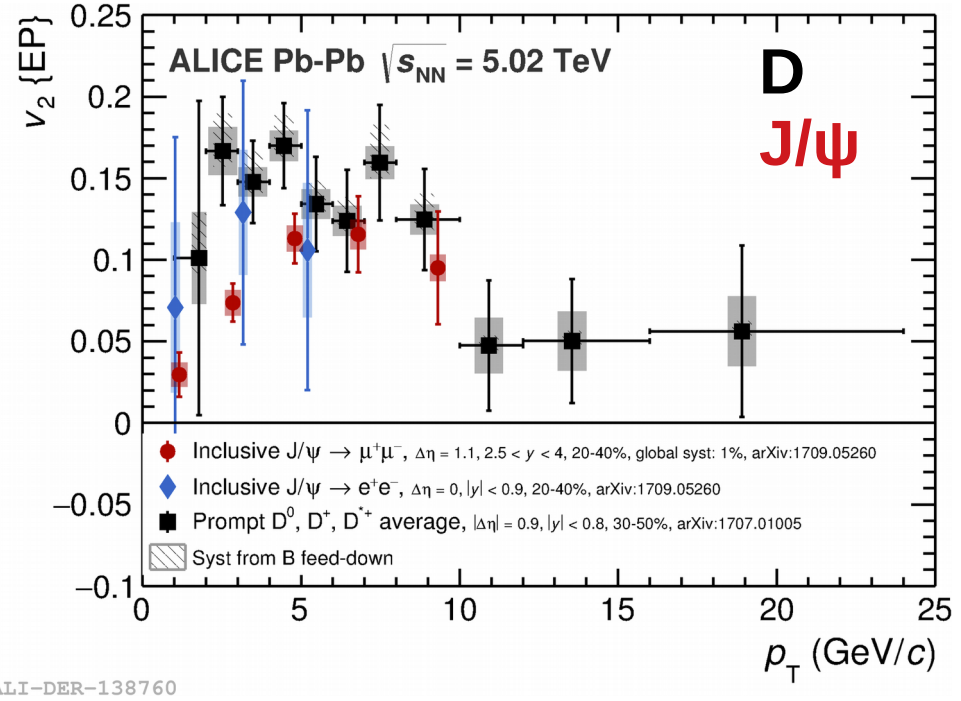


- Similar elliptic flow to charged pions at intermediate and high p_T
- Within current uncertainties, similar elliptic flow for strange and non-strange D mesons

Inclusive J/ψ v_2

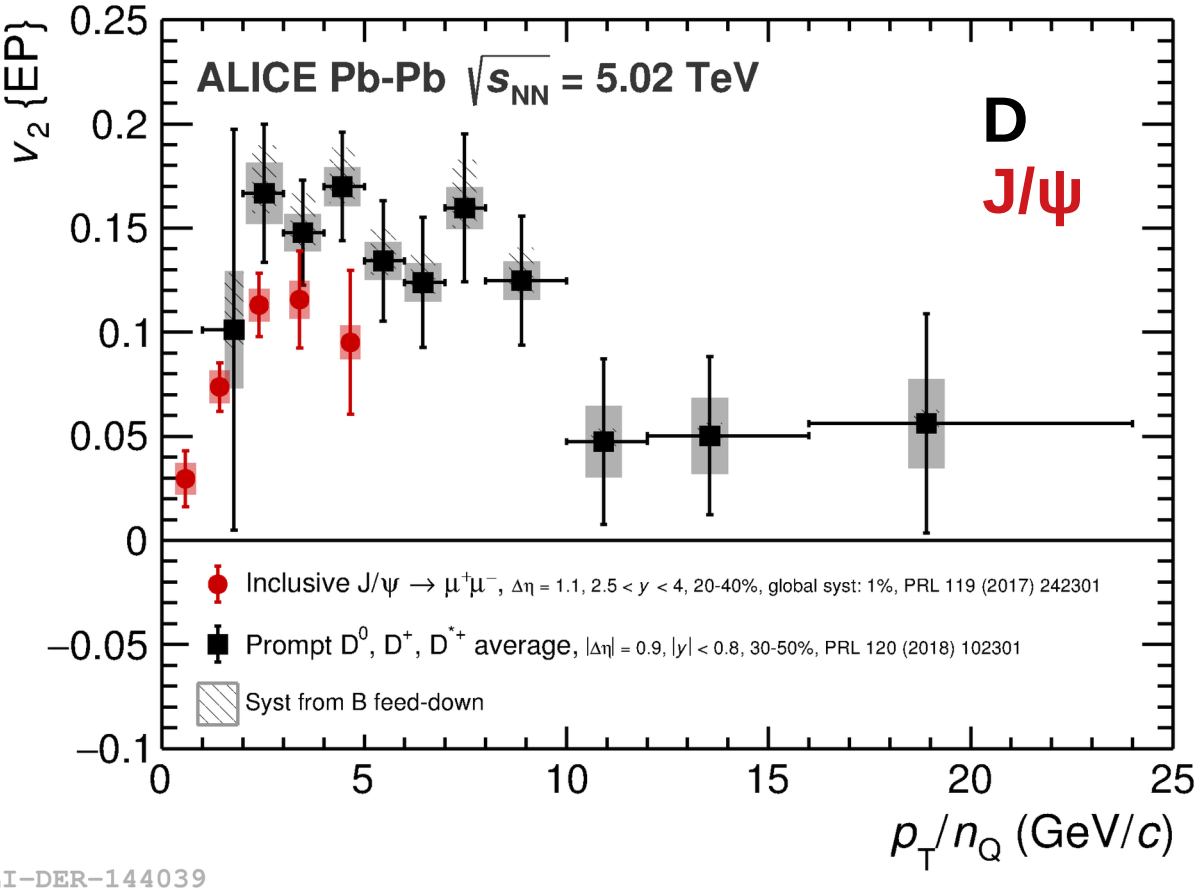
ALICE, PRL119 (2017) 242301
ALICE PRL 120 (2018) 102301





- Positive J/ψ v_2 observed at low and intermediate p_T
  - Expected from charm recombination
  - Transport models do not reproduce the v_2 at larger p_T
    - Path-length dependent effects stronger than expected?
    - Contribution from higher mass states feed-down ?
- Is there any relation between the D-meson and J/ψ v_2?

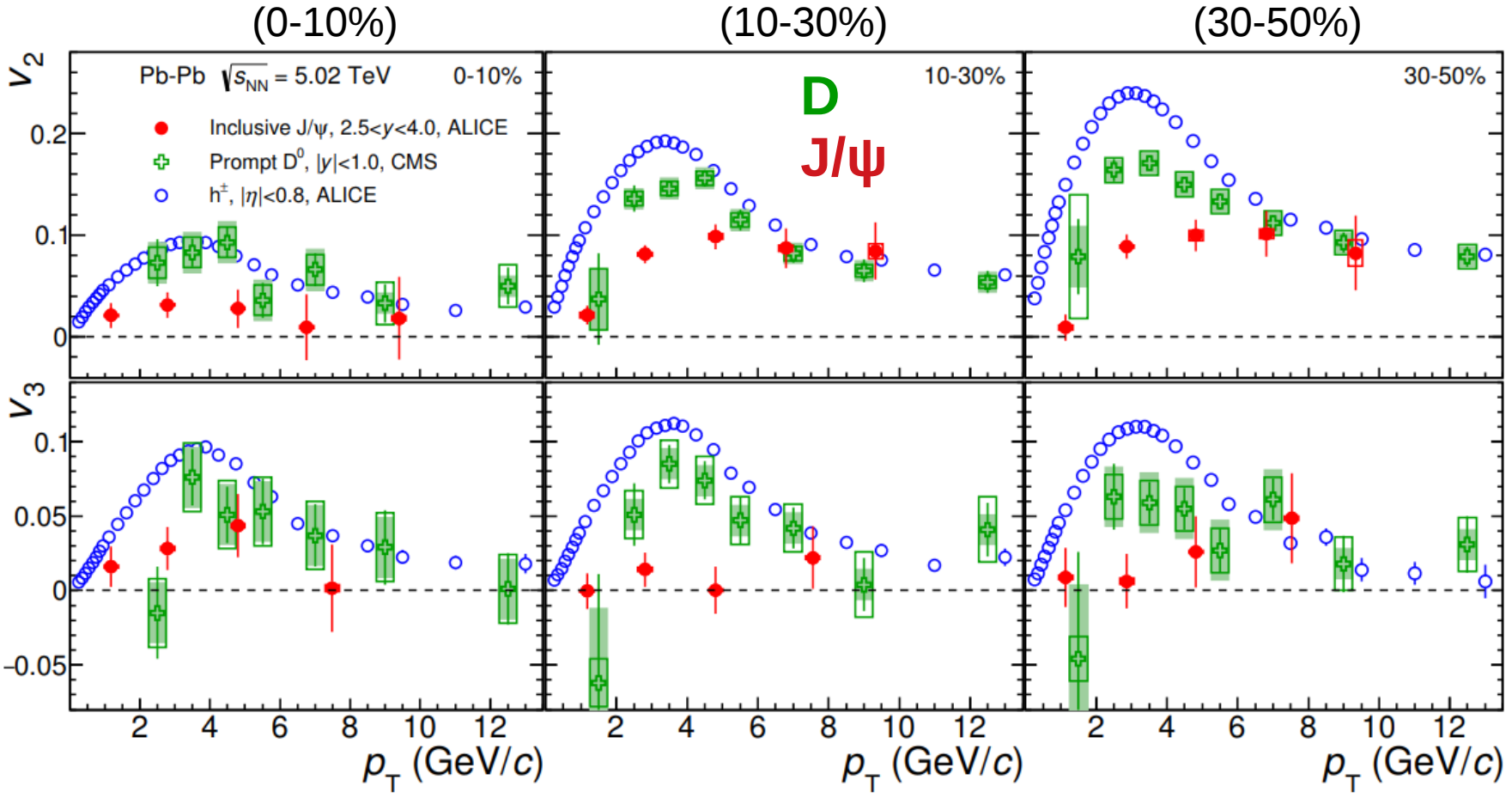
J/ψ and D-meson v_2



- Approximate scaling of v_2 with the number of constituent charm-quarks?
  - Expected at low charm-quark p_T from recombination models
- Caveats:
  - J/ψ measured at fwd-y, D mesons at mid-y
  - Different centrality intervals

J/ψ v_2 and v_3

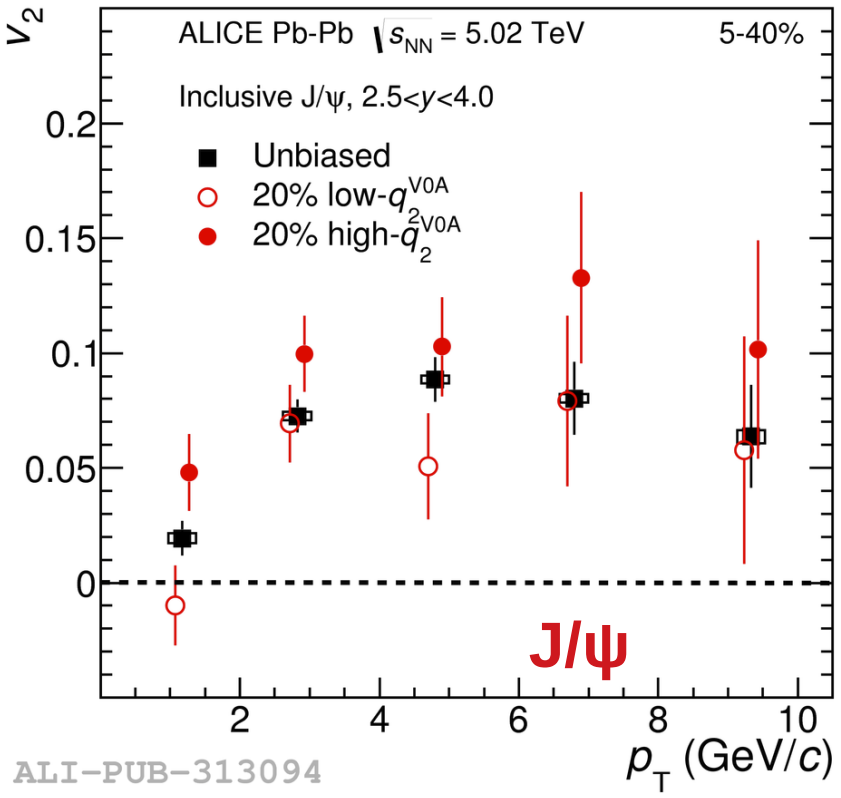
ALICE, arXiv: 1811.12727, JHEP

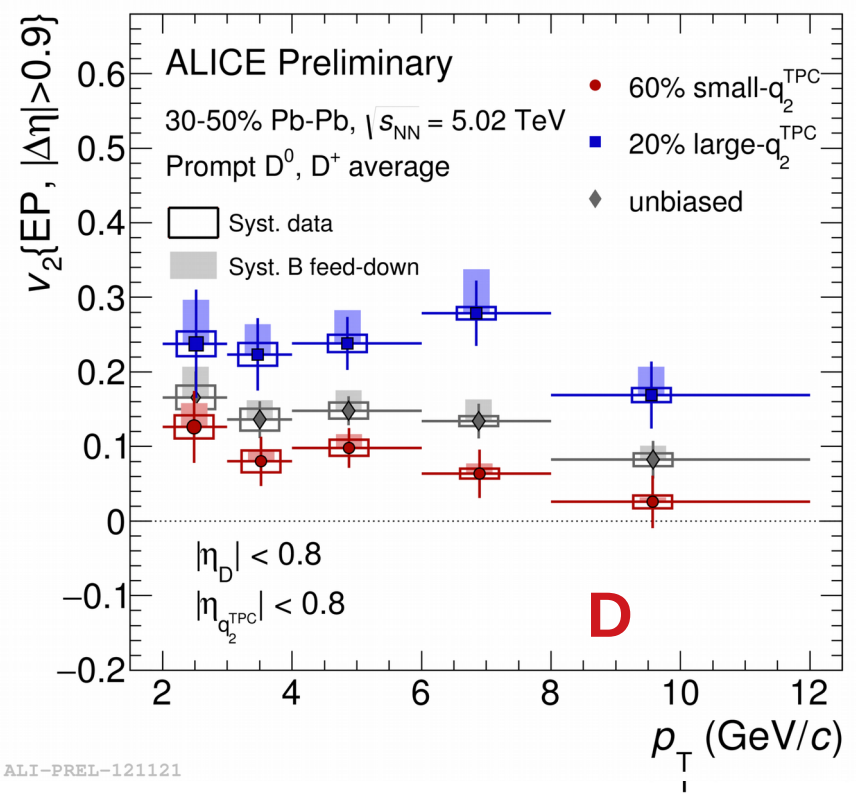


- v_2 of charged hadrons, D mesons and J/ψ converge at high p_T in semi-central collisions
- Significant v_3 observed for D mesons at all centralities
- Hint of smaller v_3 for J/ψ (except for the 0-10% central collisions)

Event shape engineering

ALICE, arXiv: 1811.12727, JHEP





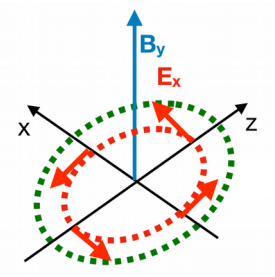
$$q_2 = \frac{|\boldsymbol{Q}_2|}{\sqrt{M}}$$

large q_2

small q_2

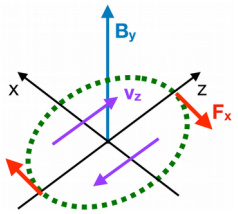
- Both D-meson and J/ψ elliptic flow sensitive to event shape engineering (ESE)
  - Charm flows with the bulk

D-meson v_1



Faraday effect

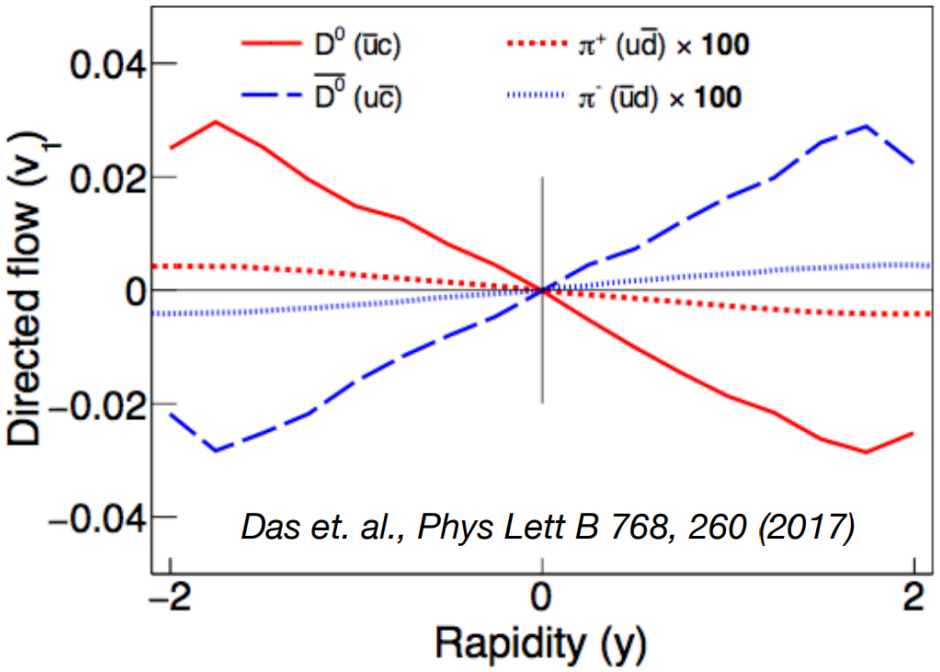
$\Delta \mathbf{x} \mathbf{E} = -\partial \mathbf{B}/\partial t$



Hall effect

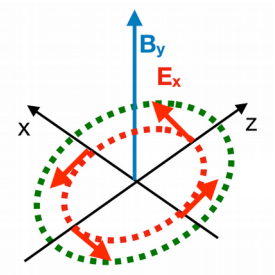
$\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$

PRC 89(2014) 054905



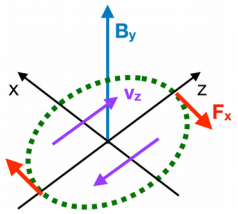
- Strong time dependent magnetic field produced by the spectators in non-central AA collisions
- Charm quarks, created early, affected by the magnetic field dynamics
- Charge dependent directed flow expected due to the Faraday and Hall effects

D-meson v_1



Faraday effect

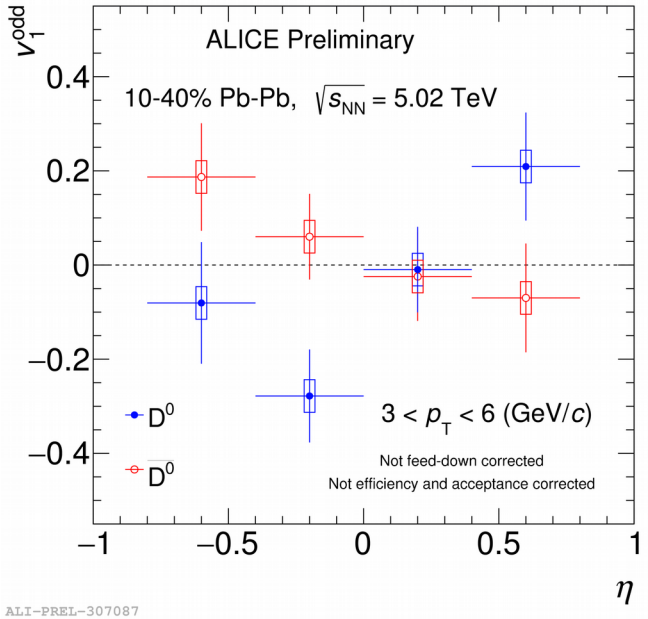
$\Delta x \mathbf{E} = -\partial \mathbf{B}/\partial t$

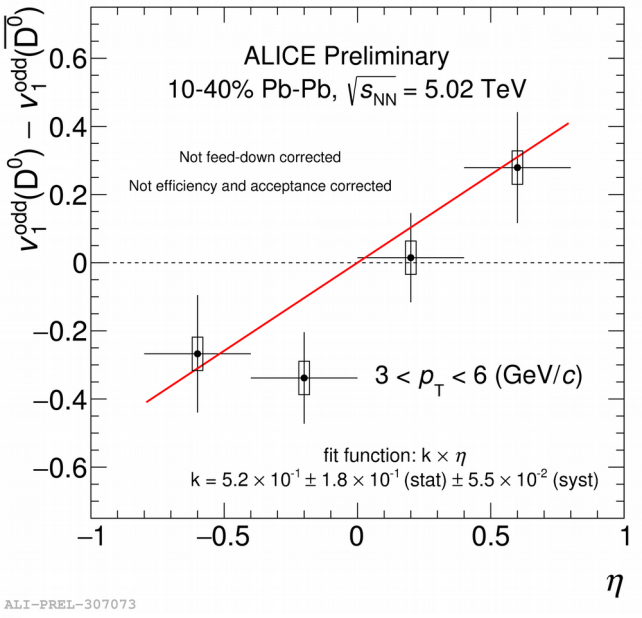


Hall effect

$\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$

PRC 89(2014) 054905



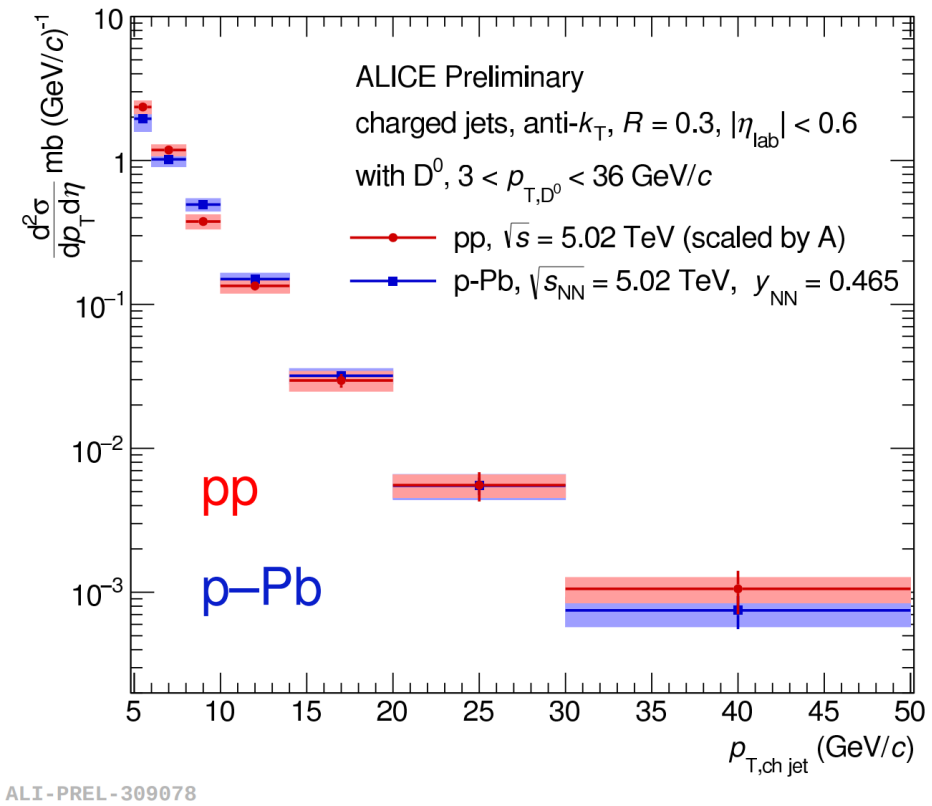


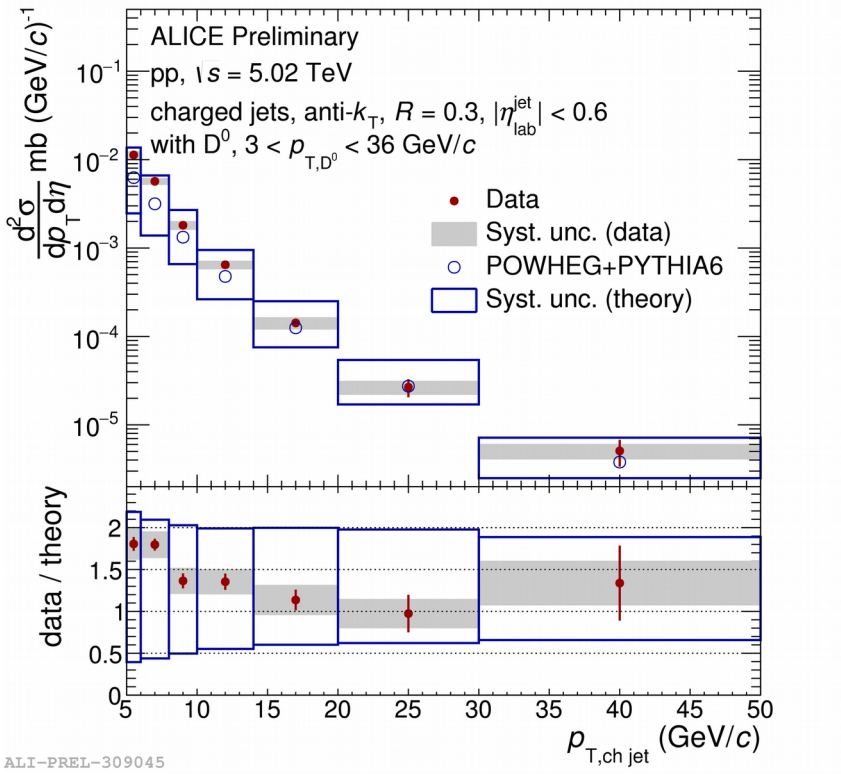
- D^0 and $\overline{D}^0$ v_1 have opposite slopes as a function of η in 10-40% collisions
  - Significance of the effect is 2.7σ for 3<p_T<6 GeV/c *(opposite wrt theory expectation)*
  - Magnitude of the effect: x 1000 wrt charged hadrons !!
  - Hint of charge dependent v_1 also seen in STAR data (*see next talk*)

Heavy Flavor jets

- Direct access to heavy-quark kinematics
- Smaller effects from hadronization
- In vacuum: study HF fragmentation
- In medium:
  - color and parton mass dependence of energy loss
  - modification of internal jet substructure

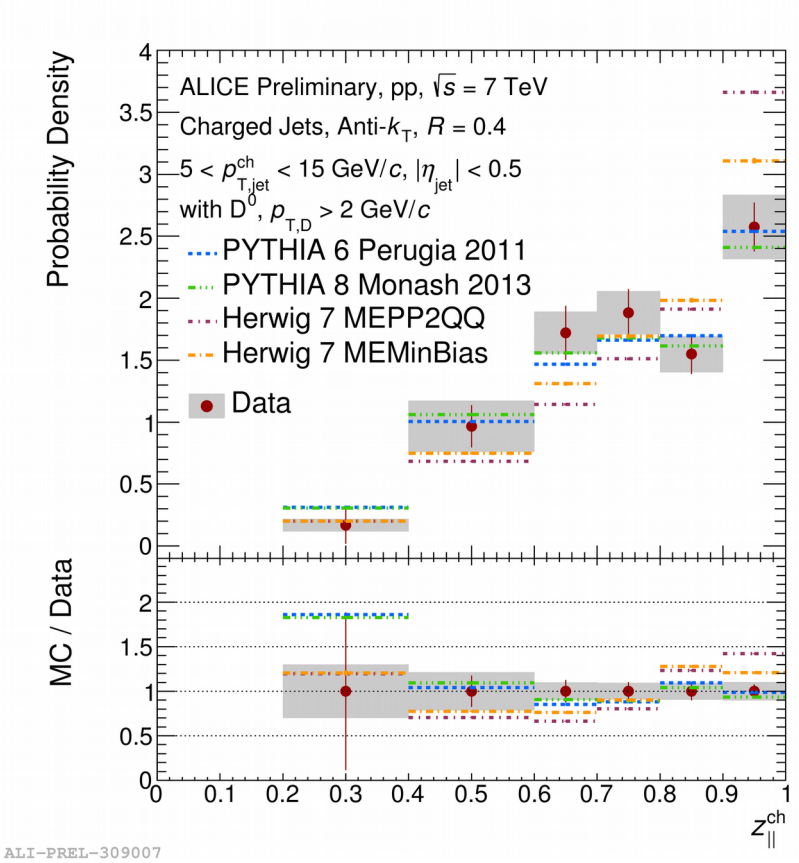
D-meson tagged jets

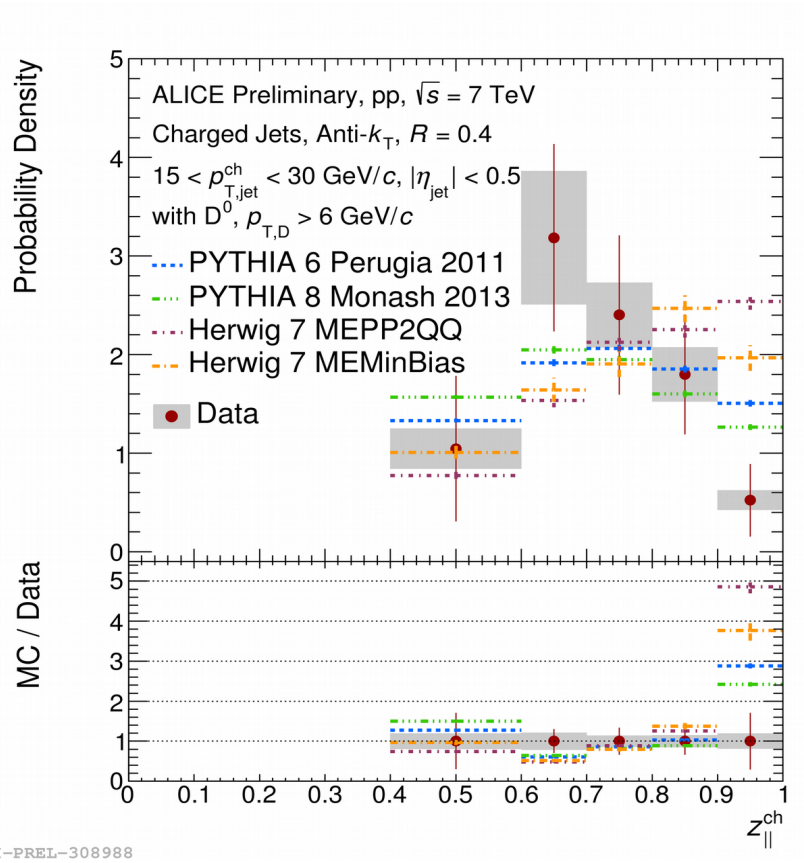




- Jets containing a D^0 meson in the p_T range 3 < p_T < 36 GeV/c
- Cross-section measurement in pp in agreement with POWHEG+PYTHIA6 calculations

Fragmentation function

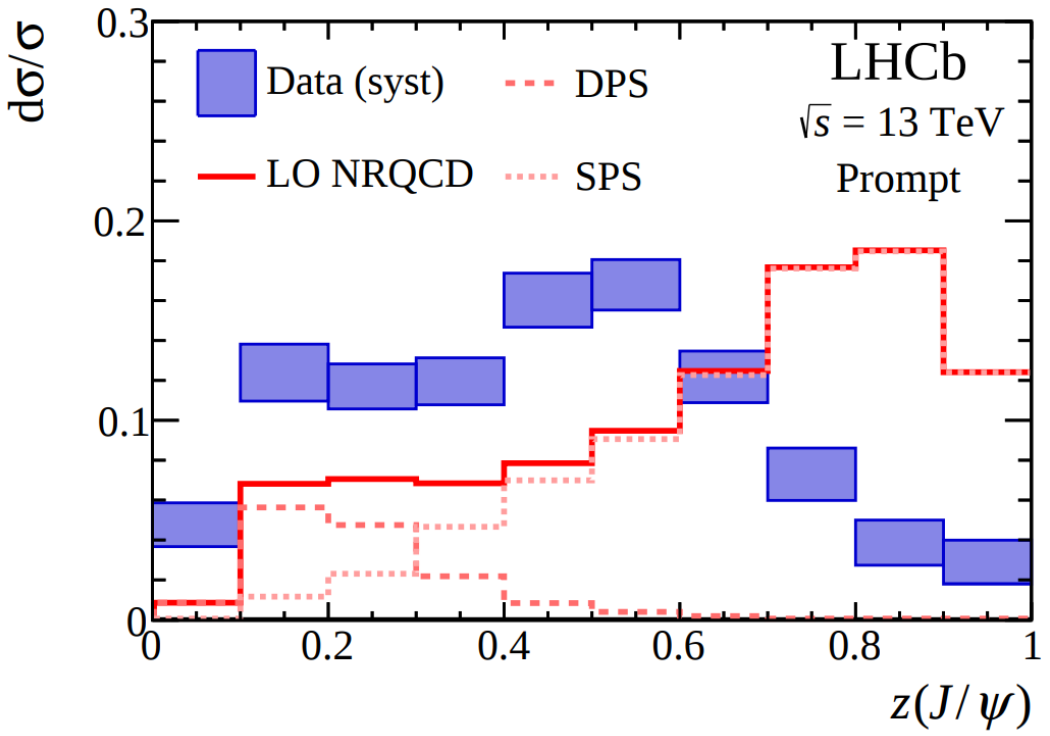


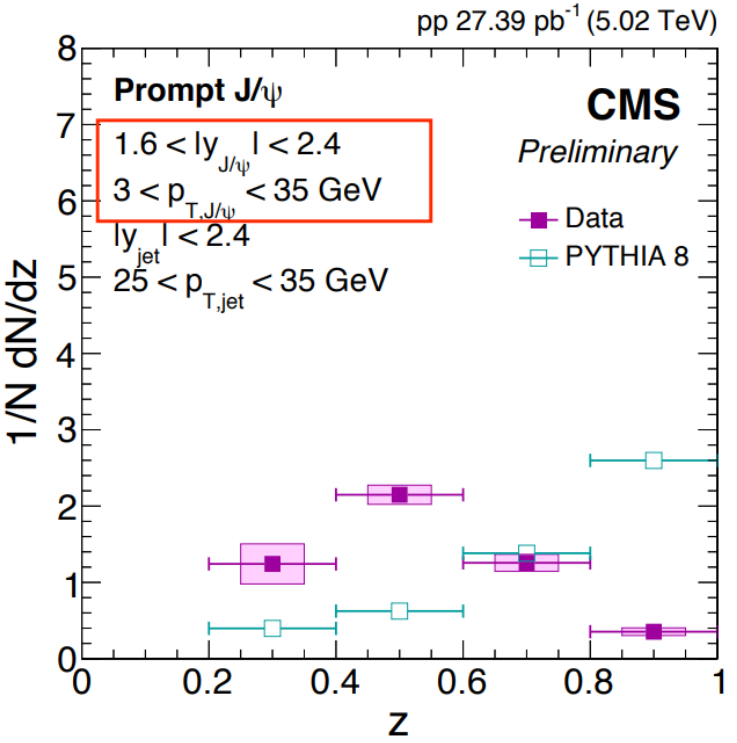


- $z_{||}^{ch}$: momentum fraction carried by the D meson
- Good agreement between data and models for jets < 15 GeV/c
- Hint of a softer fragmentation function in data wrt theory in particular for higher p_T jets

Fragmentation function

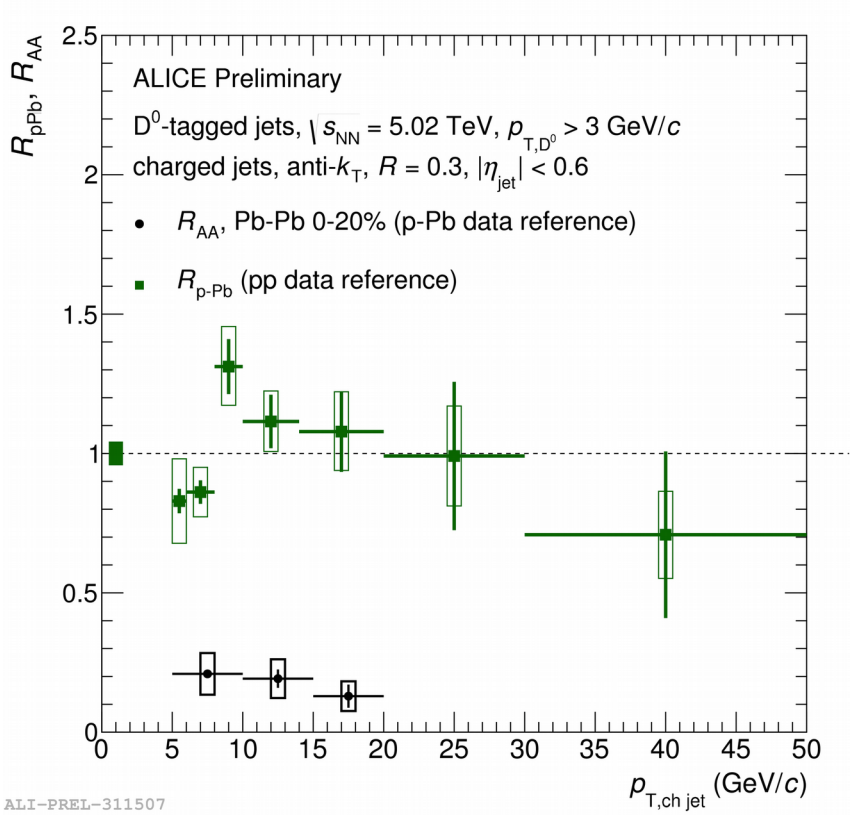
LHCb, PRL118 (2017) 192001

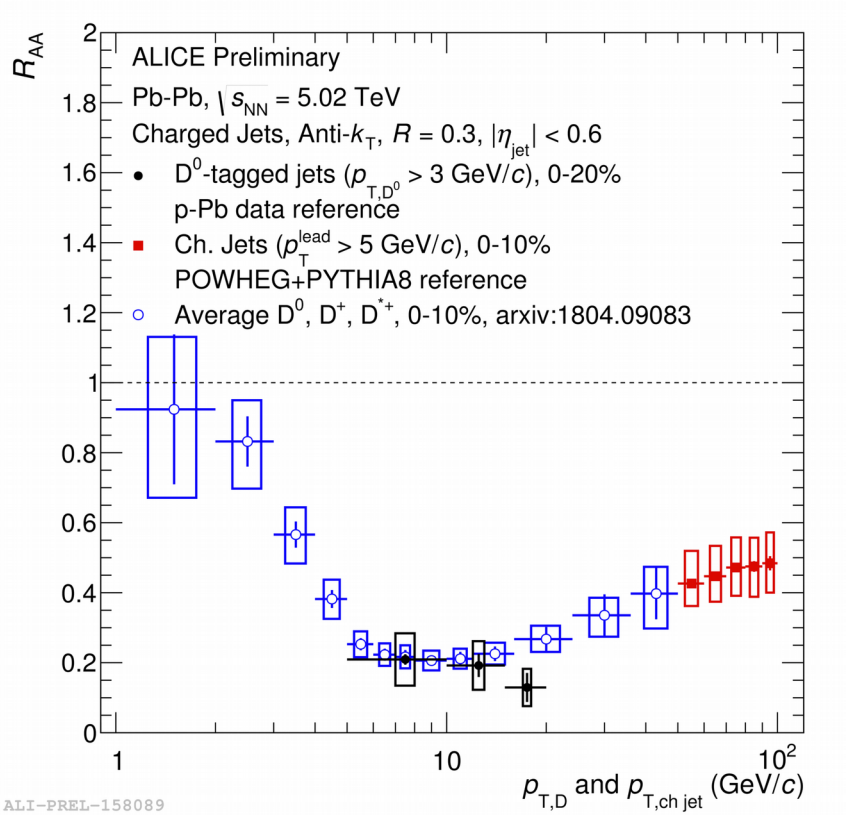




- Hint of a softer fragmentation function in data wrt theory
  - Similar observations for J/ψ by LHCb and CMS

Nuclear modification of HF-jets

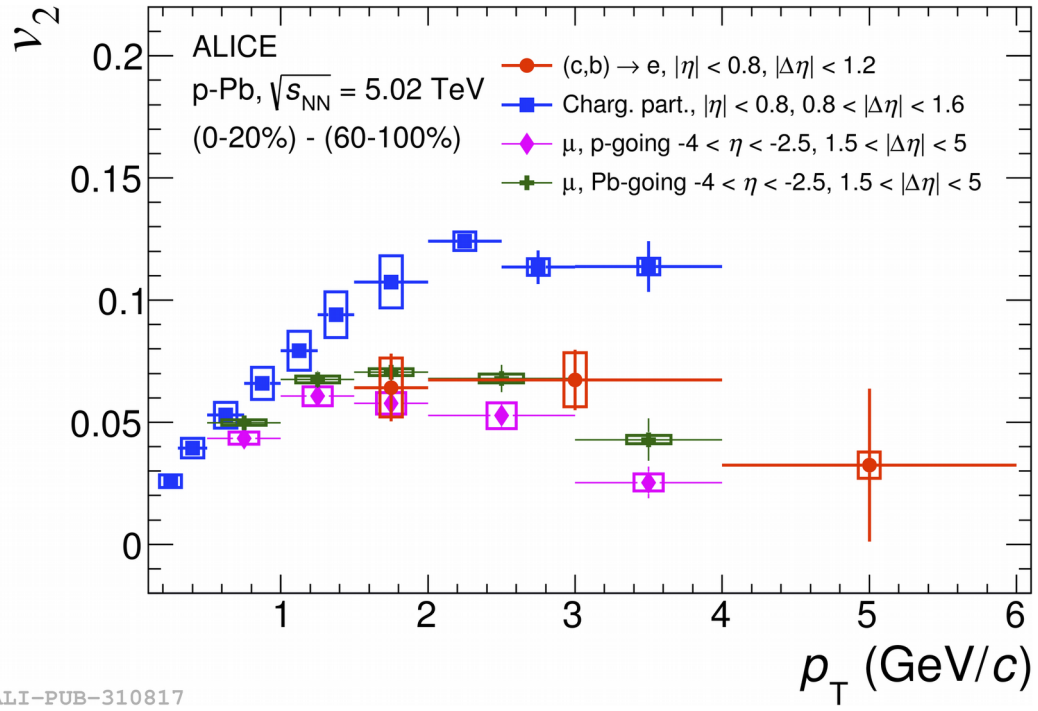




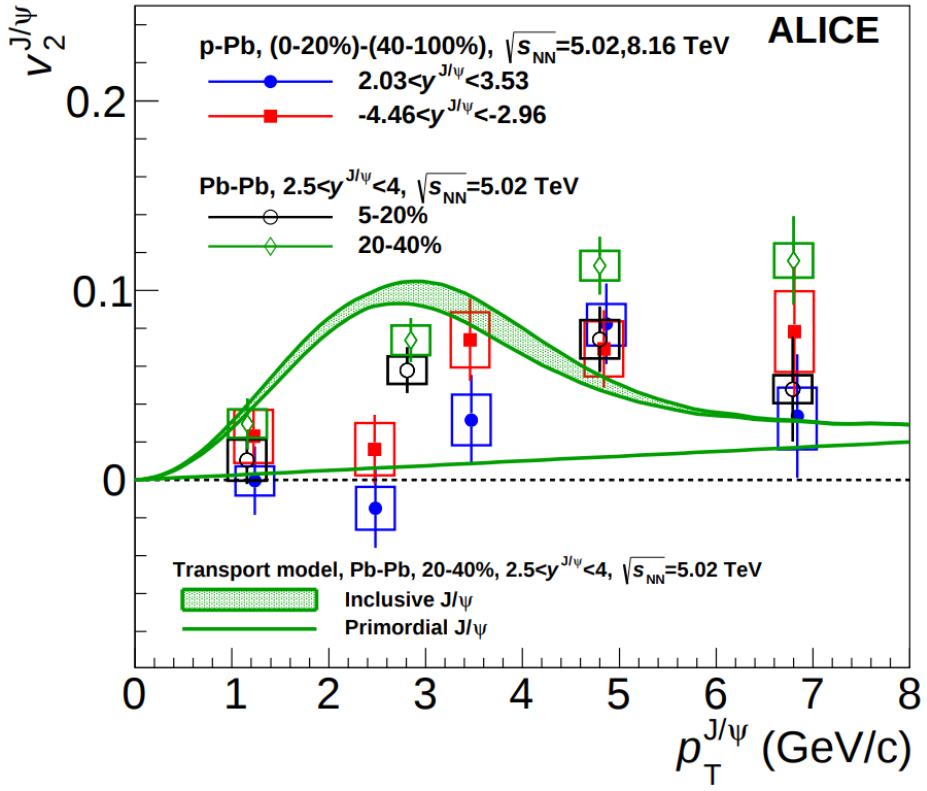
- In p-Pb: results are compatible with no nuclear modification
- In Pb-Pb: strong suppression, compatible to that observed for single D mesons

Anisotropic flow in p-Pb collisions

ALICE, arXiv: 1805.04367

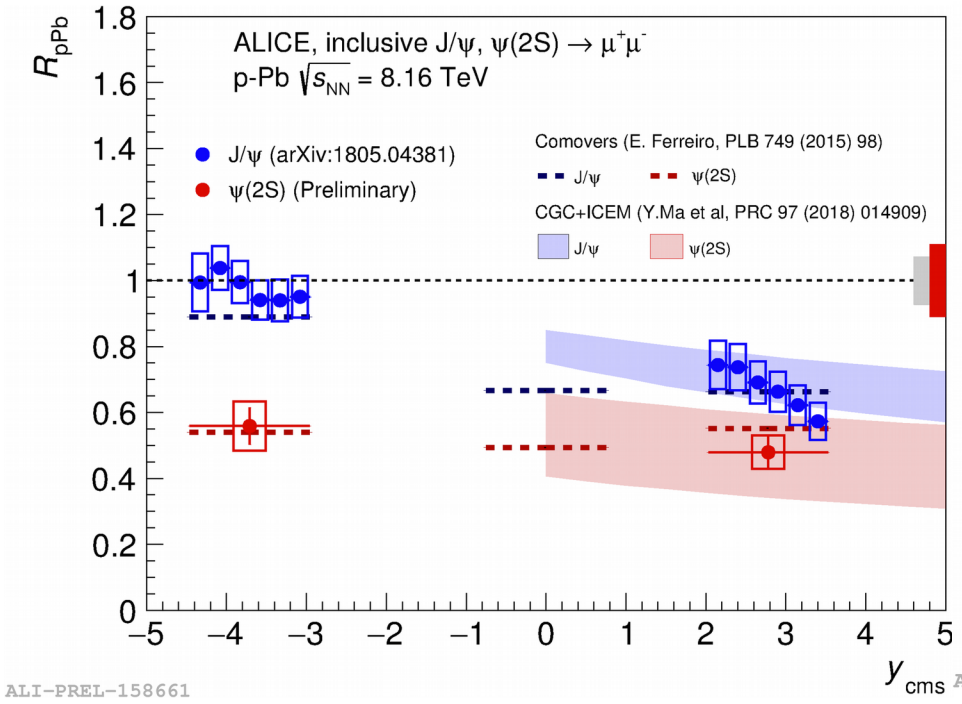


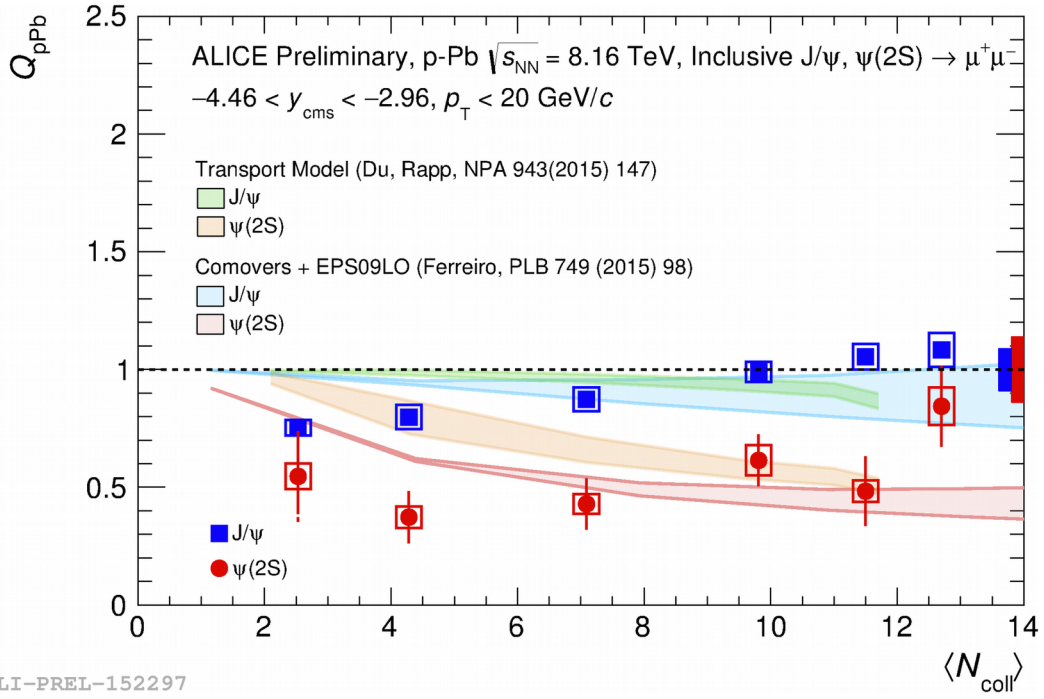
ALICE, PLB780 (2018) 7-20



- Elliptic flow measured in p-Pb collisions with large activity
  - Charged particles
  - HF electrons at mid-y
  - HF muons at fwd-y
  - J/ψ at fwd-y

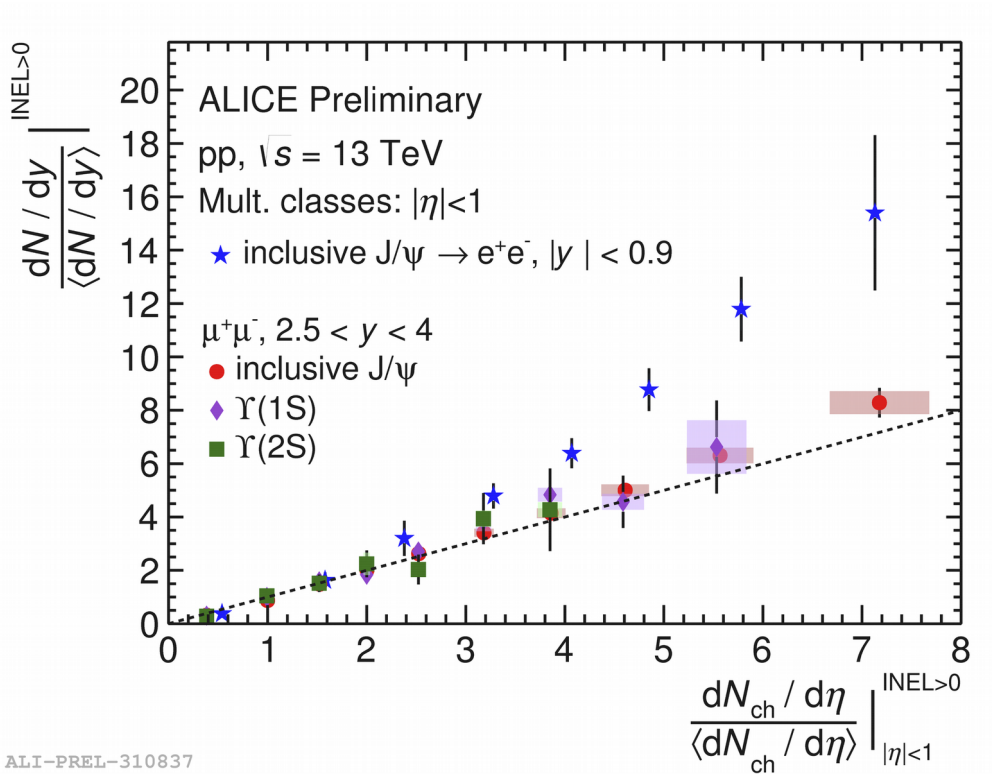
ψ(2S) in p-Pb collisions

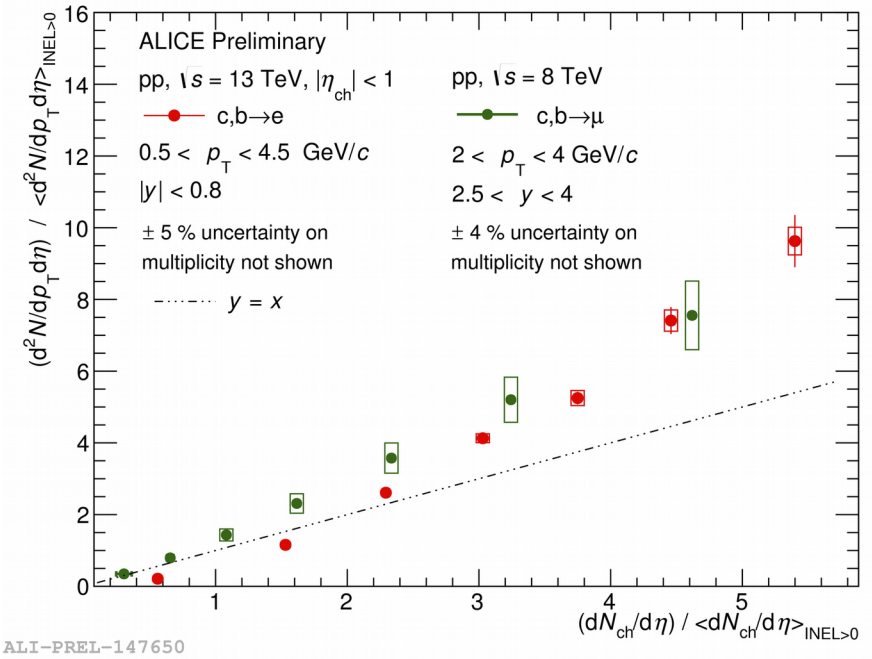




- ψ(2S) more suppressed than J/ψ, especially in the backward direction (Pb-going)
- Final-state effects needed

Open HF and quarkonia production in pp collisions





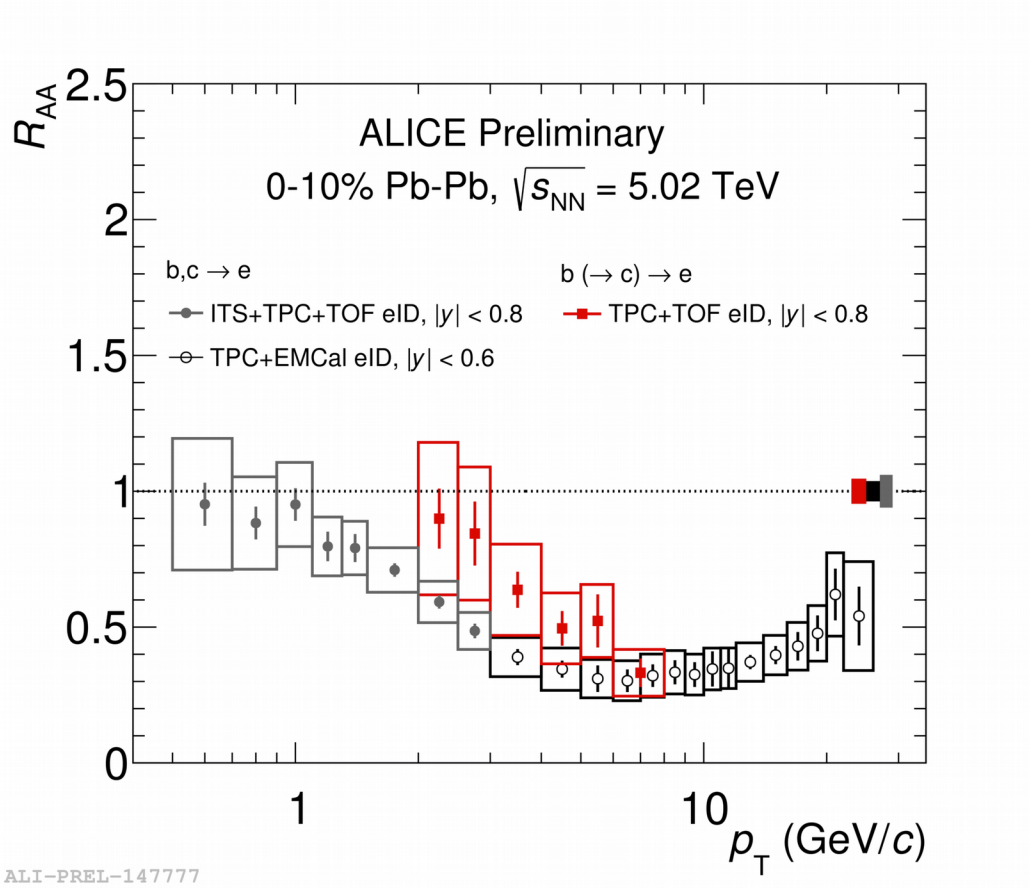
- Open HF and quarkonia measured as a function of the event activity at mid-*y*
- Multi Parton Interactions at the hard scale ?
- Sensitivity to collective effects in pp events with high activity ?
- Stronger than linear dependence of J/ψ at mid-*y:*
  - possible bias due to associated production with jets (e.g. *b*-jets)

Conclusions

- In medium transport properties and bulk properties studied using the R_{AA} and anisotropic flow measurements of open HF and quarkonia
  - Large hadronization (quark recombination) effects on R_{AA}: D_s, Λ_c, J/ψ
  - Significant v_2 and ESE dependence suggests charm thermalization
- Strong electro-magnetic field effects suggested by the D^0 and $\overline{D^0}$ v_1 measurements
- D-meson tagged jets
  - D^0 fragmentation function softer in data wrt calculations for high-p_T jets
  - None or small CNM effects
  - Similar suppression in Pb-Pb as for the D^0
- p-Pb puzzles
  - Elliptic flow of J/ψ and HF leptons
  - Larger ψ(2S) suppression than for J/ψ
- J/ψ and open HF production in pp collisions with high activity: study MPI effects at the hard scales, collectivity effects in small systems
- Outlook
  - Further hadronization effects studies (Λ_c)
  - HF-tagged jets in Pb-Pb: jet structure modification
  - Precision J/ψ measurements at mid-y: R_{AA} in central collisions, v_2
  - Low-p_T ψ(2S) suppression in Pb-Pb
  - Collectivity effects in small systems

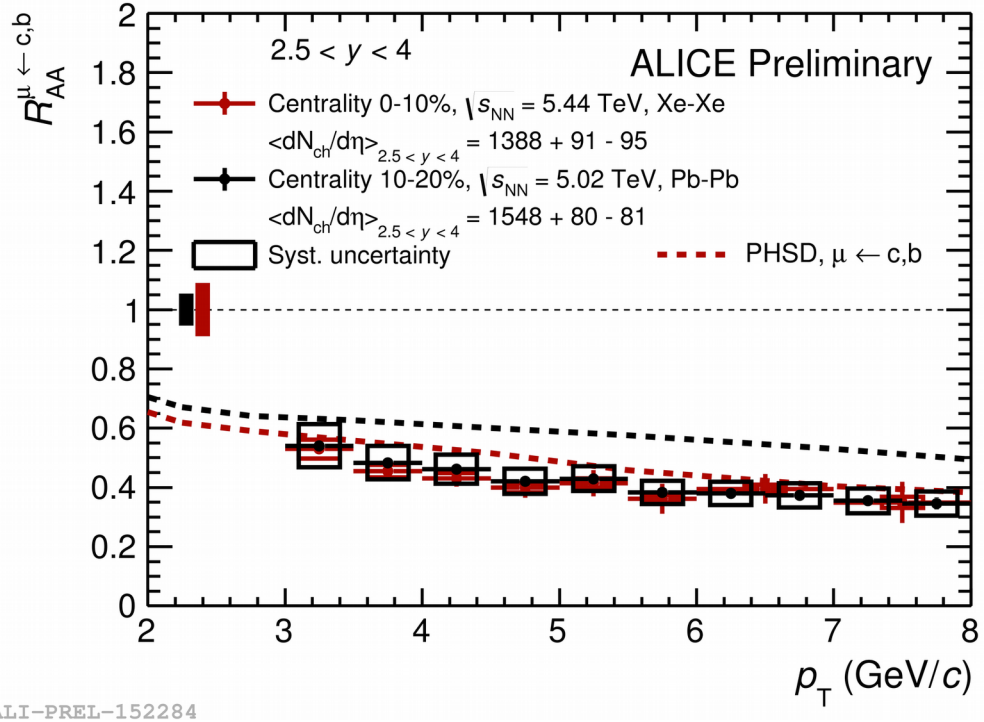
backup

Mass dependence of R_{AA} via HF electrons



- Hint of mass dependence of suppression: R_{AA}(b) > R_{AA}(c)

HF muons in Xe-Xe collisions



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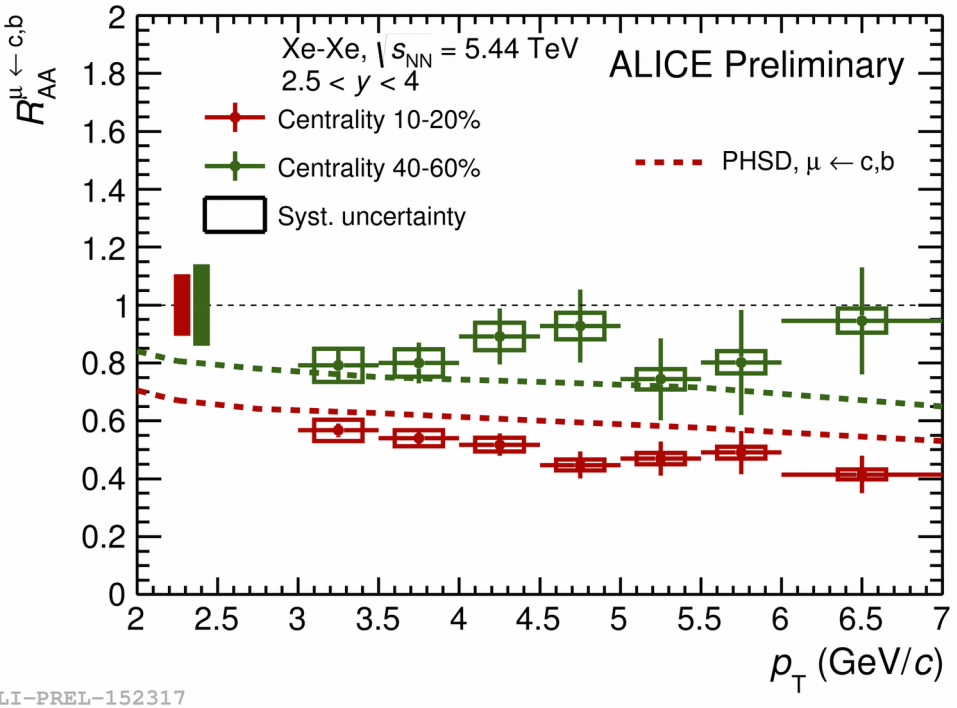

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