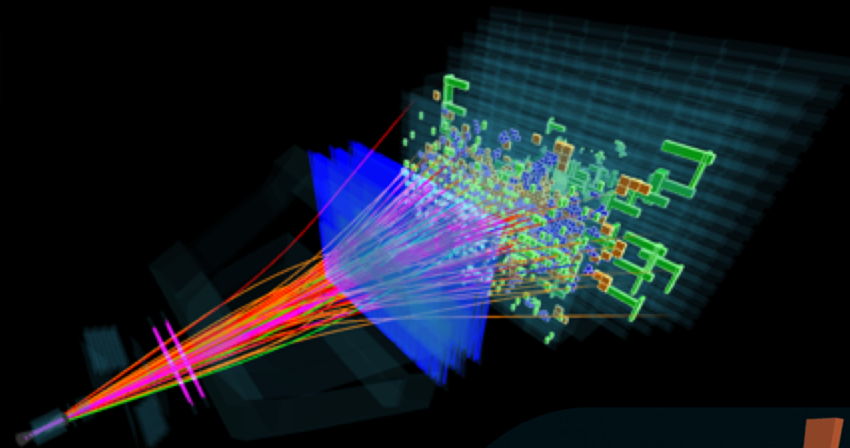

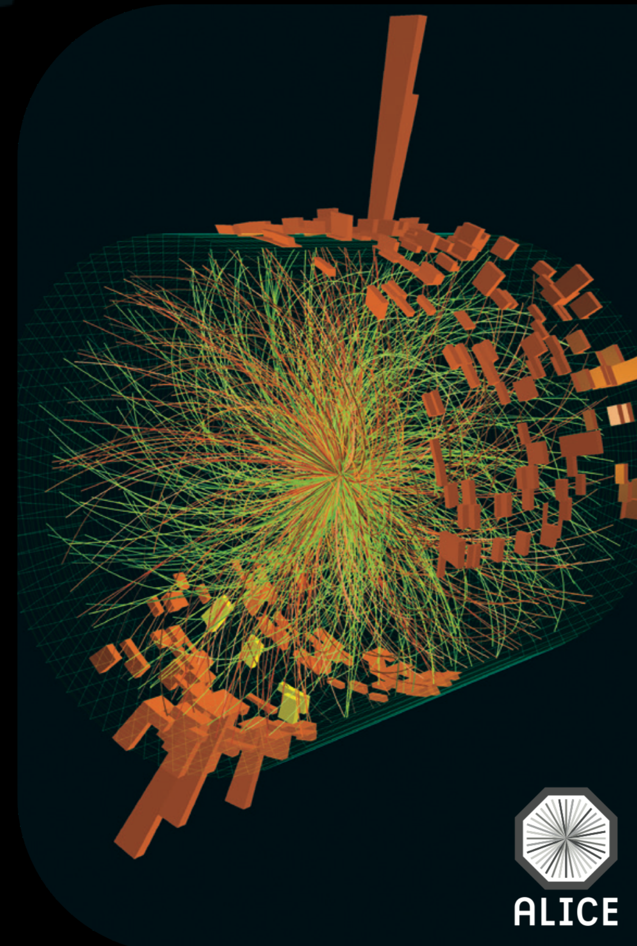

Recent results on hard probes in heavy-ion collisions from ALICE and LHCb

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Hard probes in heavy-ion collisions

Originate in initial Hard Scatterings (HS) of partons

- HS process is calculable perturbatively
  → Well calibrated probes
- Initial HS occurs at earlier stage than Quark-Gluon Plasma (QGP) formation (<< 1 fm/*c*)
  → Entire evolution of QGP can be probed

> In this presentation,
> - ✓ Jets
> - ✓ Heavy flavours (charm, bottom)

AA collisions

- Jet-medium interaction
  - Suppression/enhancement of production yields, Modification of the jet structure…
- Collectivity

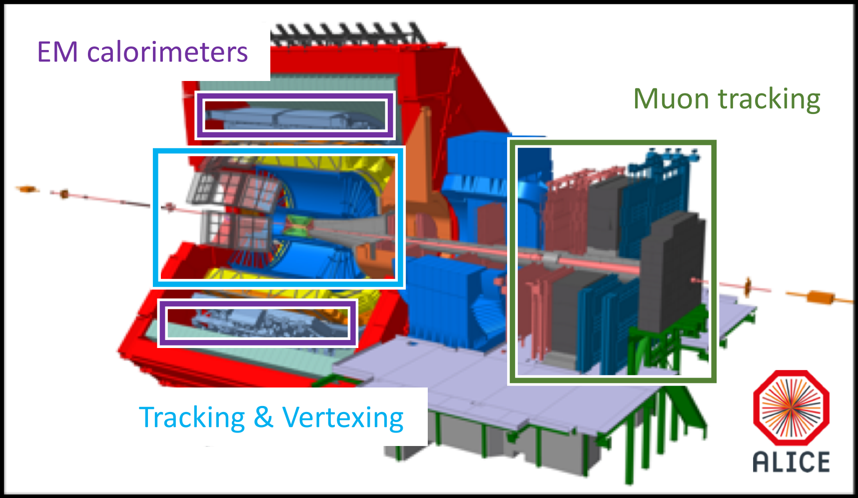
pA and pp collisions

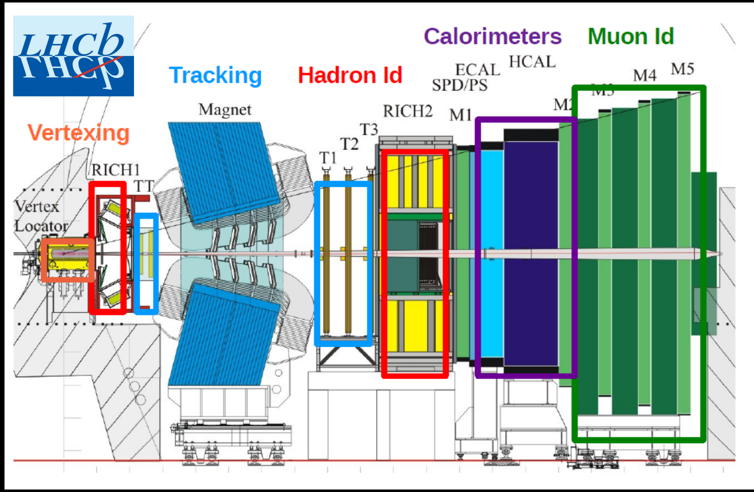
- Reference for AA collisions
- Study of Cold Nuclear Matter (CNM) effects (pA)
- Study of initial conditions ((n)PDF, CGC)
- Study of Multi-Parton Interaction (MPI)
- QGP formation in small systems?

The ALICE and LHCb detectors

ALICE

- Jet reconstruction, heavy flavour via hadronic decays
  - Central barrel trackers ($|\eta|<0.9$) and EM calorimeters ($|\eta|<0.7$)
- Heavy flavour via semi-leptonic decay modes
  - $e^{\pm}$: Central barrel trackers, EM calorimeters
  - $\mu^{\pm}$: Forward muon tracker
- Excellent tracking for wide momentum range
  - Momentum resolution, PID



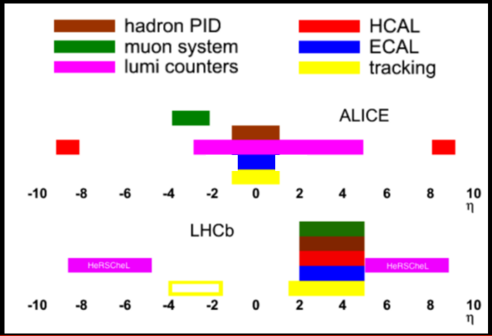


Presentation at Moriond QCD 2019 (D. Marangotto)

LHCb

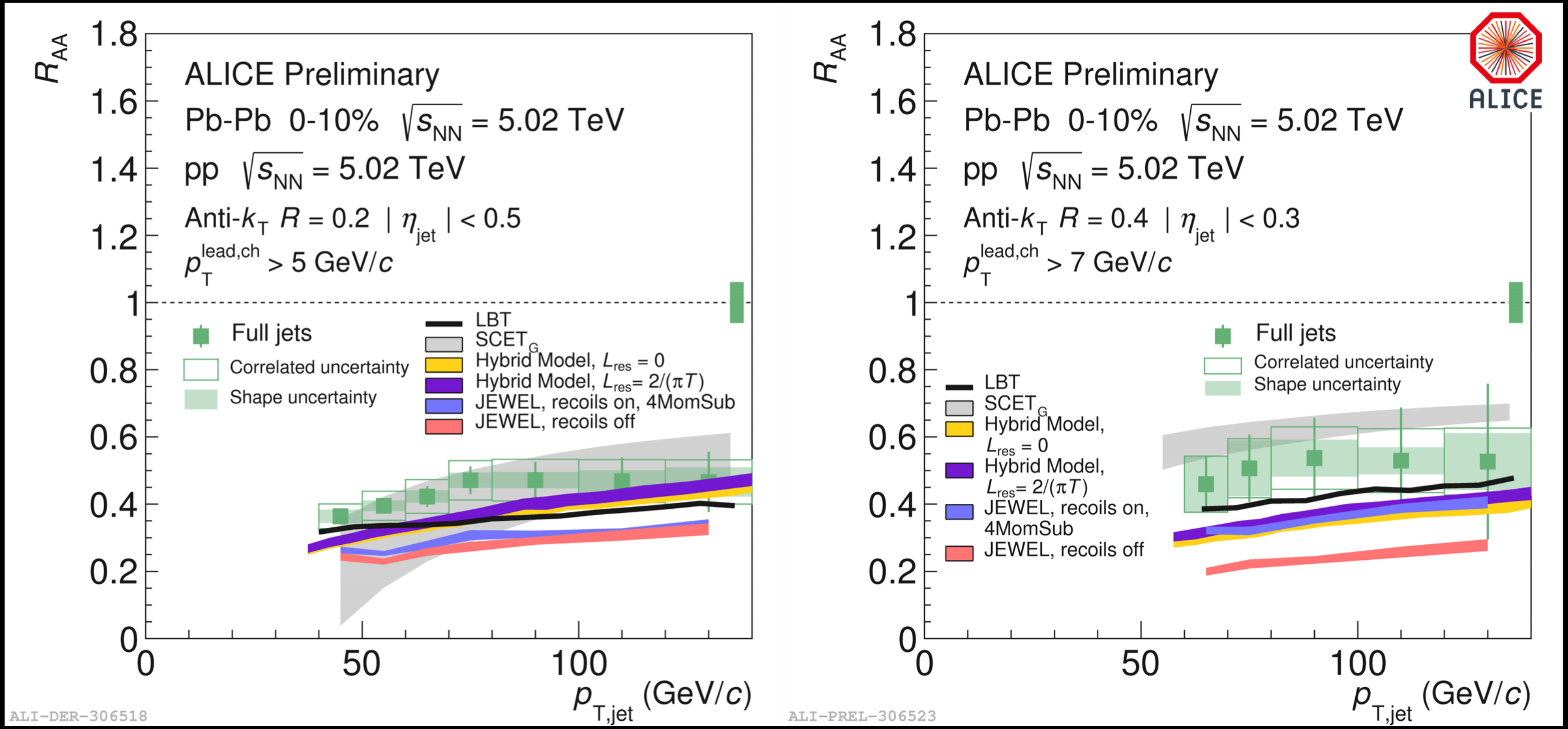
- Fully instrumented in $2 < \eta < 5$
- Tracking with excellent momentum resolution, PID
- Unique forward coverage at the LHC
- Unique fixed-target program at the LHC
  - System size study of heavy-ion collisions

✓ ALICE and LHCb have complementary acceptance



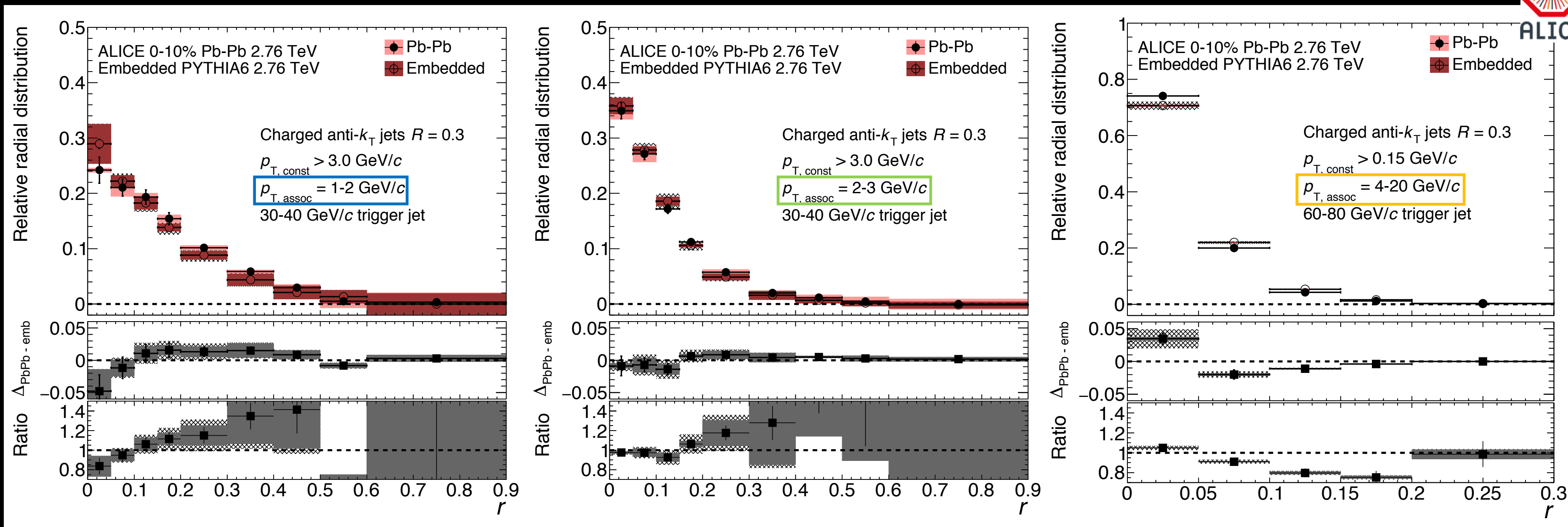
Jets

Inclusive jets production in Pb—Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV



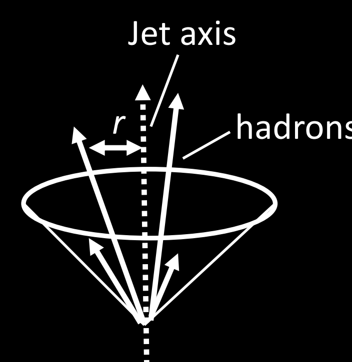
- Nuclear modification factor $R_{\mathrm{AA(pA)}} = \frac{\mathrm{d}N^{\mathrm{AA(pA)}}\mathrm{d}p_{\mathrm{T}}}{N_{\mathrm{coll}} \cdot \mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$
- Deviation from unity
  - Jet R_{AA} = 0.4 – 0.5, slight p_{T} dependence
    - Qualitatively described by model predictions
    - Most of the models are in slight tension with the data

Charged jets radial profile in Pb—Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV



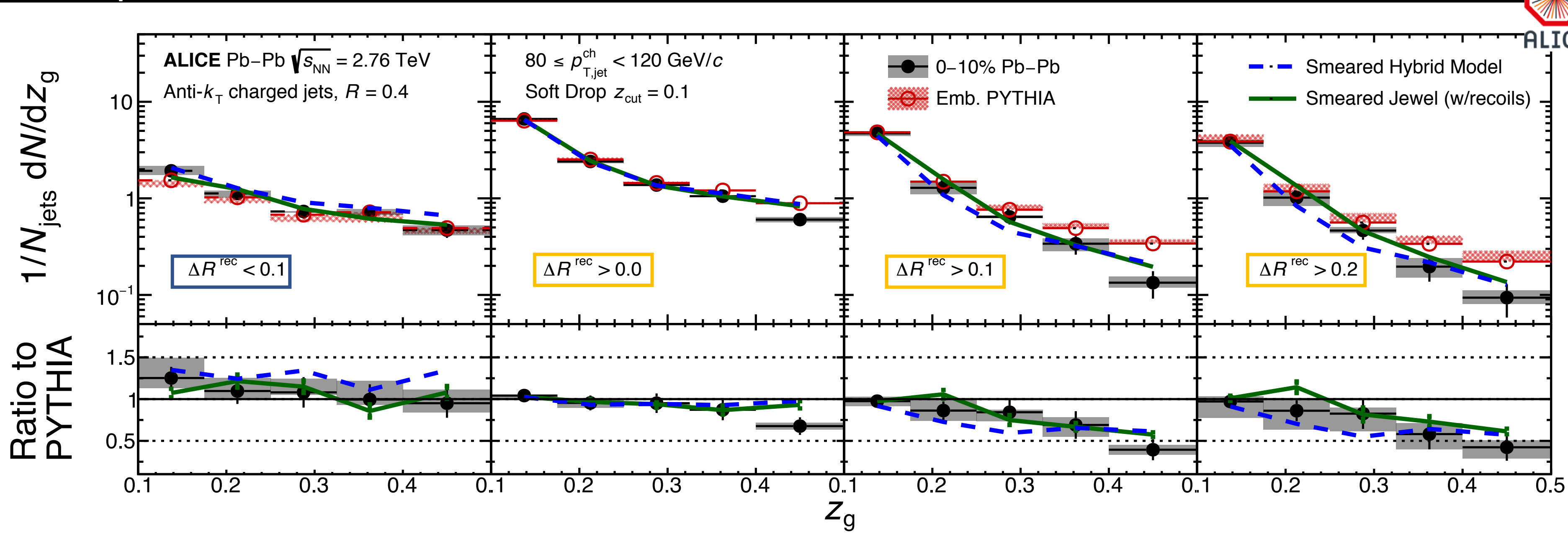
arXiv:1904.13118 [nucl-ex]

- Charged hadron distribution w.r.t. R = 0.3 jet axis
- Distribution of hadrons with given p_T is compared to embedded PYTHIA pp reference
  - 1– 2 GeV/c associated hadrons distribution : Suppression at small r , Enhancement at large r
    - Hint of a broadening of the jet radial shape
  - 2– 3 GeV/c associated hadrons distribution : No significant modification
  - 4– 20 GeV/c associated hadrons distribution : Enhancement at small r , Suppression at large r
    - Hint of a jet core collimation



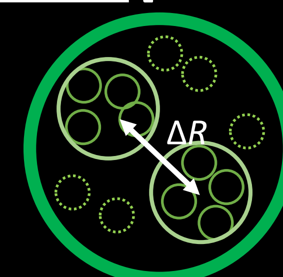
*Charged jets: Reconstructed with charged tracks only

Charged jets substructure in Pb—Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

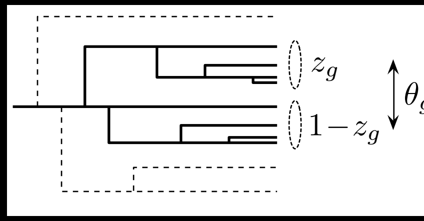


- Mapping the jet substructure within jet cone — **arXiv:1905.02512 [nucl-ex]**
  - Jet constituents are re-clustered with Cambridge/Aachen (CA) algorithm
  - De-clustered based on Soft Drop algorithm
    - Hard 2-prong substructure is focused

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}$$



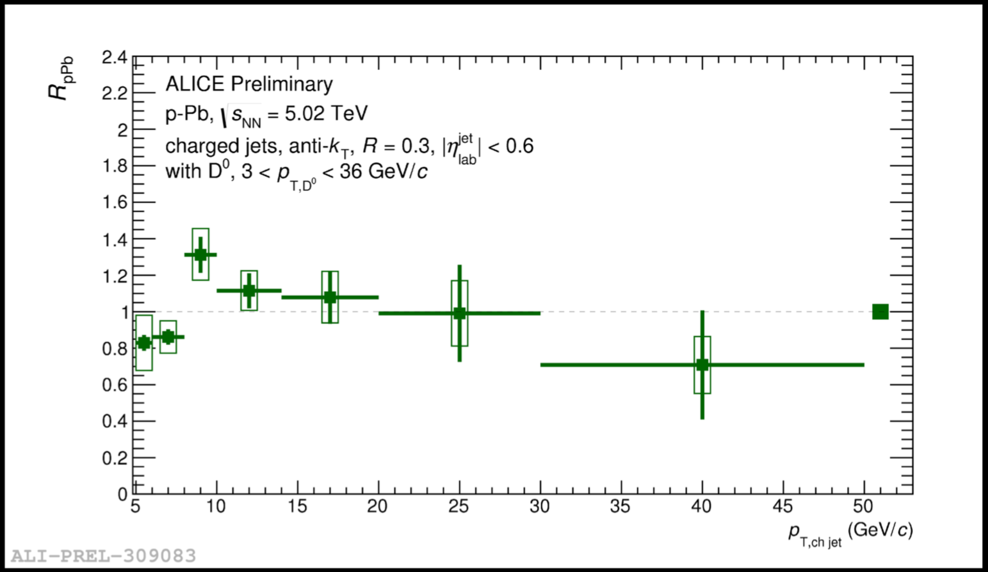
- Compared to embedded PYTHIA reference
  - Suppression of symmetric splitting rate ($z_g \approx 0.5$) for larger angle splitting ($\Delta R > 0.1$)
  - A hint of enhancement of small angle splitting ($\Delta R < 0.1$)
- Described by model predictions qualitatively

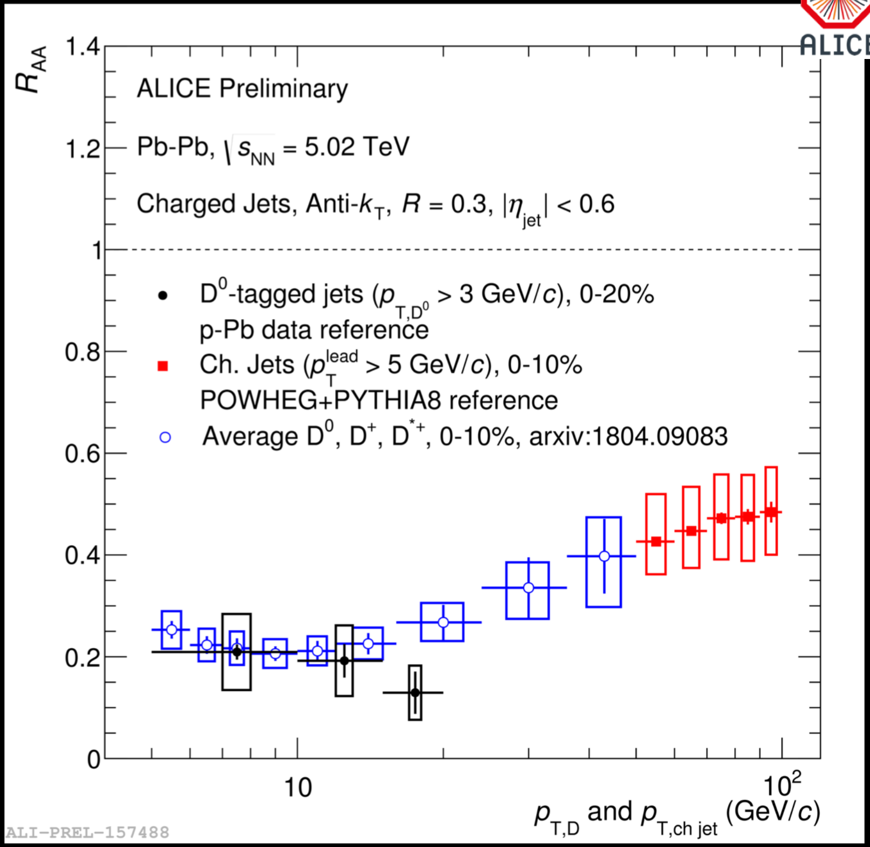


$$\theta = \frac{\Delta R}{R}$$

Open heavy flavour

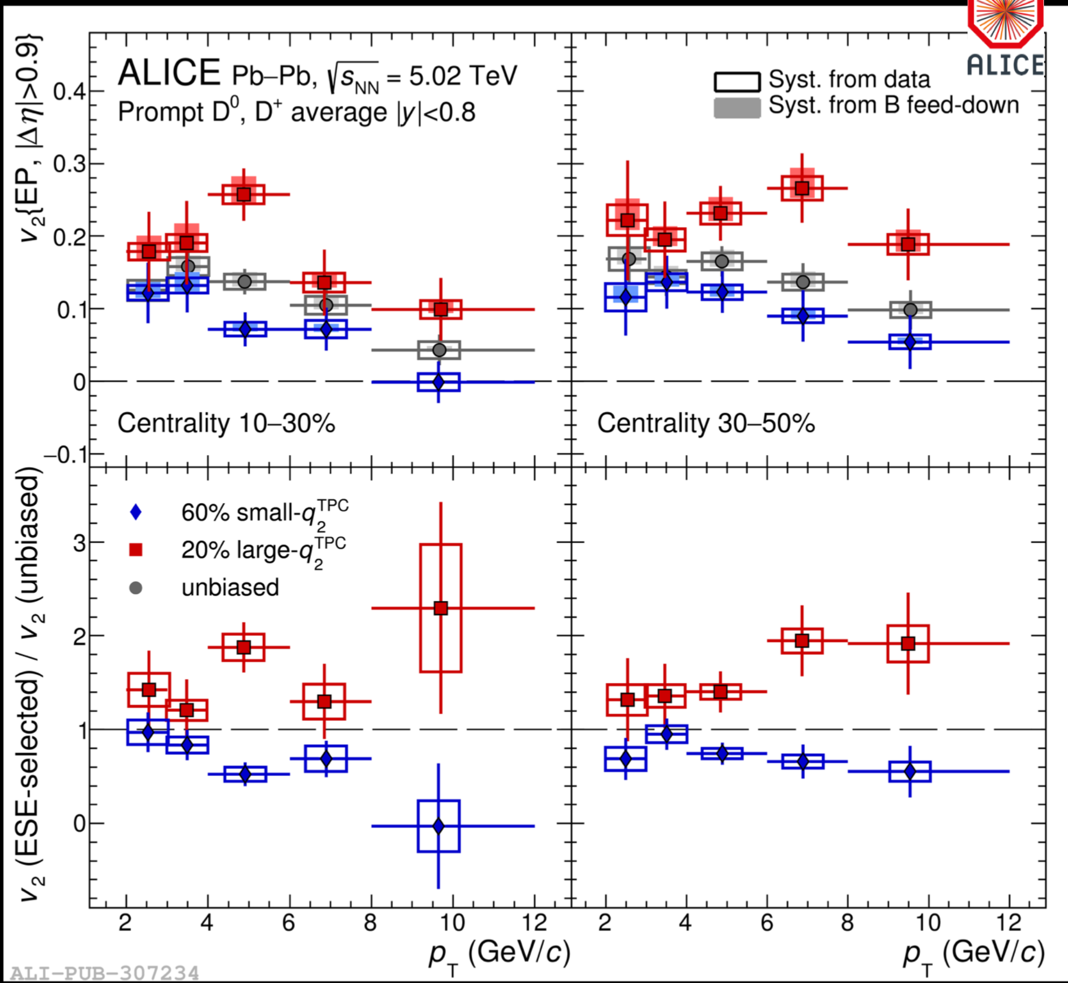
Heavy flavour tagged charged jets in p—Pb and Pb—Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV





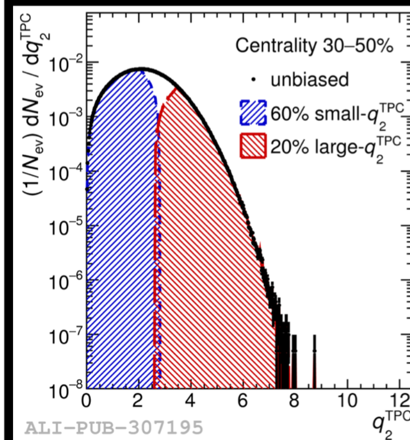
- D^0 meson tagged jets nuclear modification factor
  - p—Pb : Consistent with unity
    - No modifications on jets production
  - Pb—Pb : R_{AA} ≈ 0.2, similar to prompt D-meson suppression

D meson elliptic flow with event shape engineering in Pb—Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV



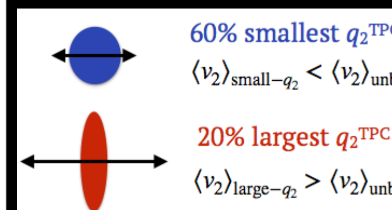
JHEP02(2019)150

- Event Shape Engineering (ESE)
  - Controls Initial collision geometry



$$q_2 = |\overrightarrow{Q_2}|/\sqrt{M}$$

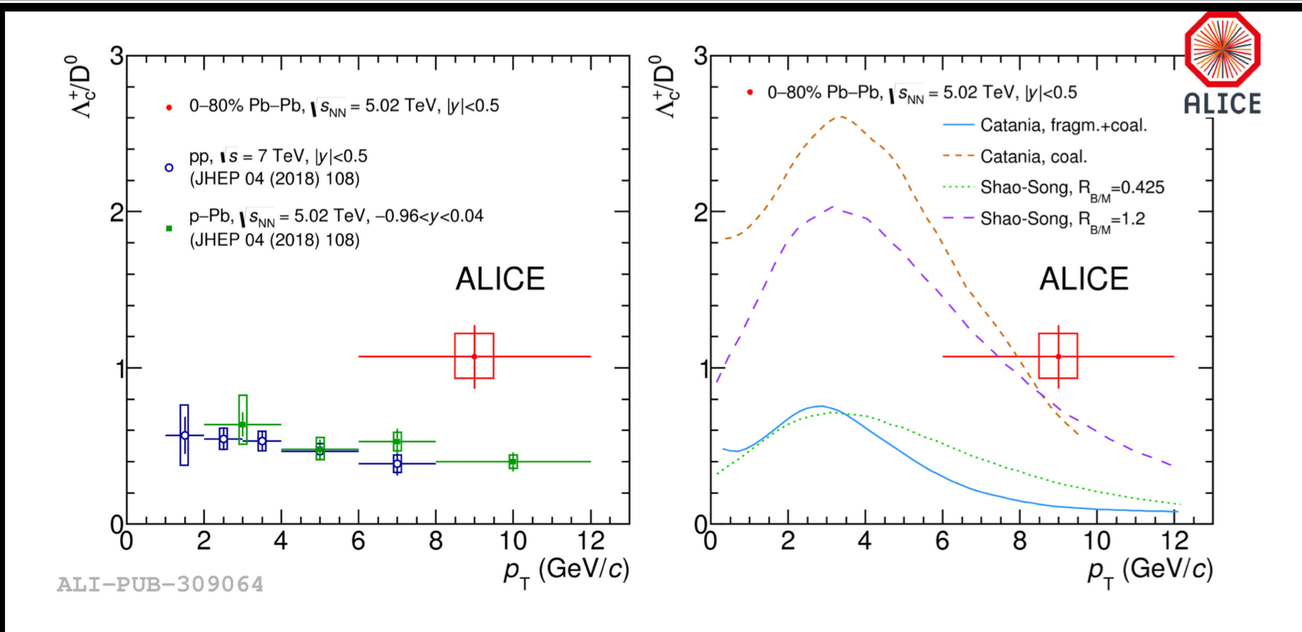
$$\overrightarrow{Q_2} = \sum_{j=1}^{M} e^{i2\varphi_j}$$



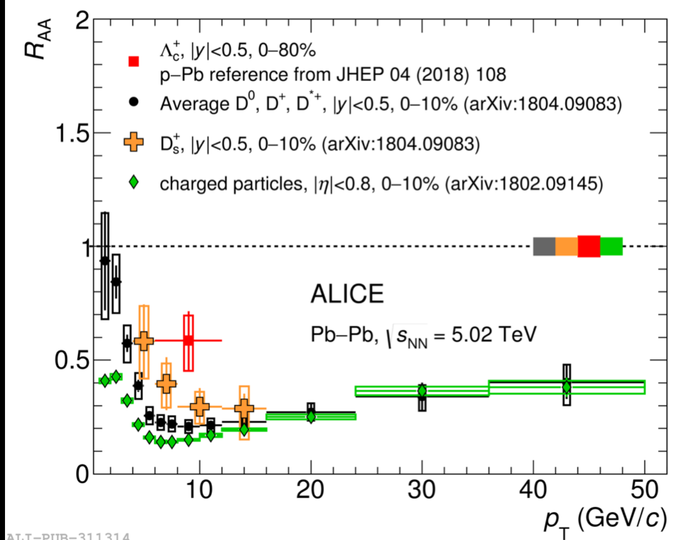
- v_2 (large-q_2) > v_2 (unbiased)
  - About 40 % effect
- v_2 (small-q_2) < v_2 (unbiased)
  - About 25 % effect

- Correlation to collective expansion of the bulk of light hadrons

Λ_c production in Pb—Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

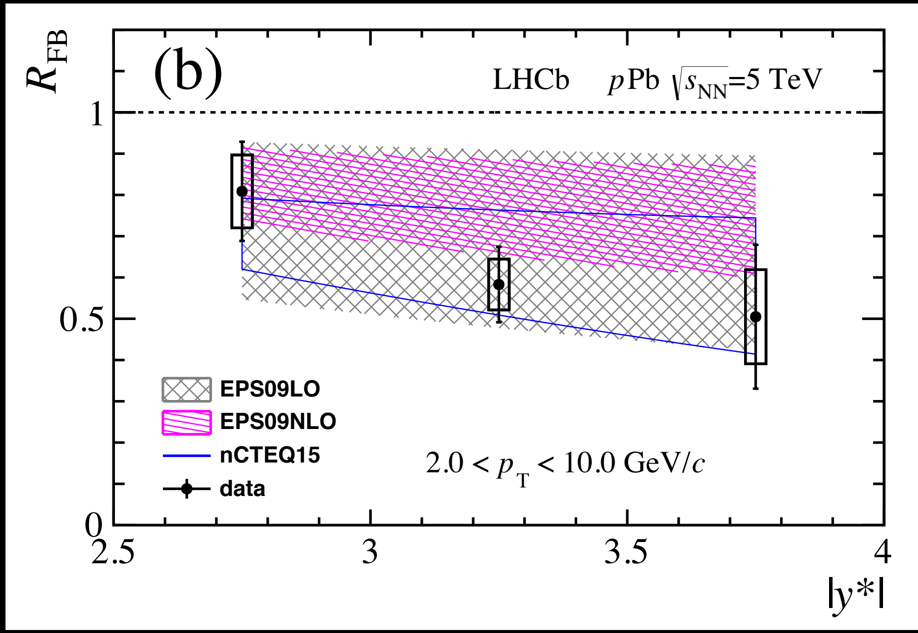


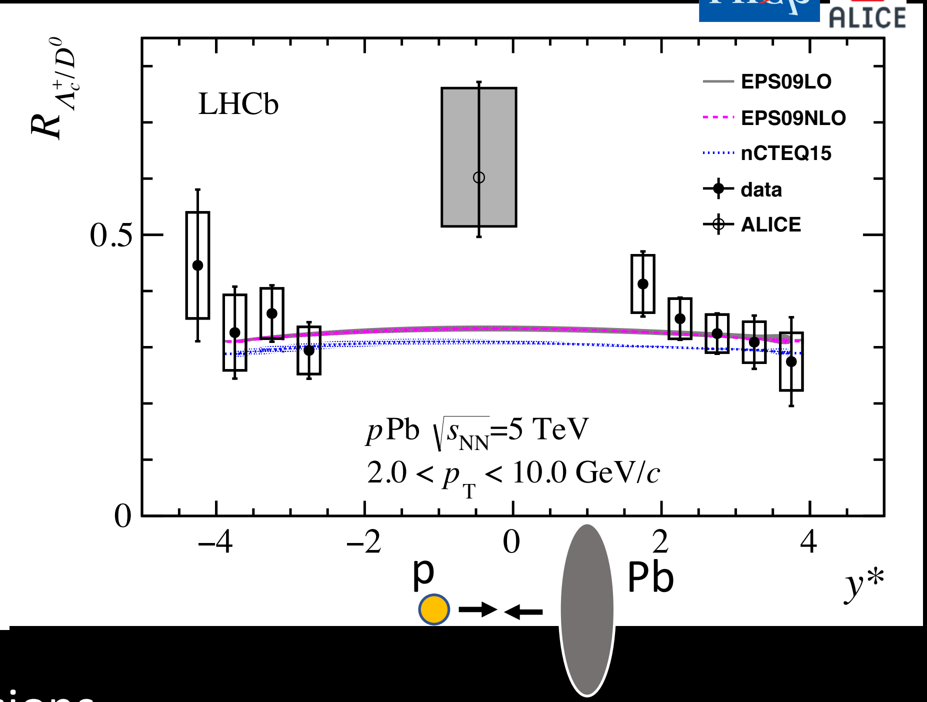
Phys. Lett. B 793 (2019) 212



- Ratio to D^0 meson
  - Larger than that of pp and p—Pb collisions
  - Described by a model
    - With charm quark hadronization via quark coalescence without vacuum fragmentation
- Nuclear modification factor
  - Suggest less suppression than inclusive charged hadrons and D mesons

Λ_c production in p—Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV





- Forward/Backward ratio in p—Pb collisions
  - Consistent with theoretical predictions including nPDF

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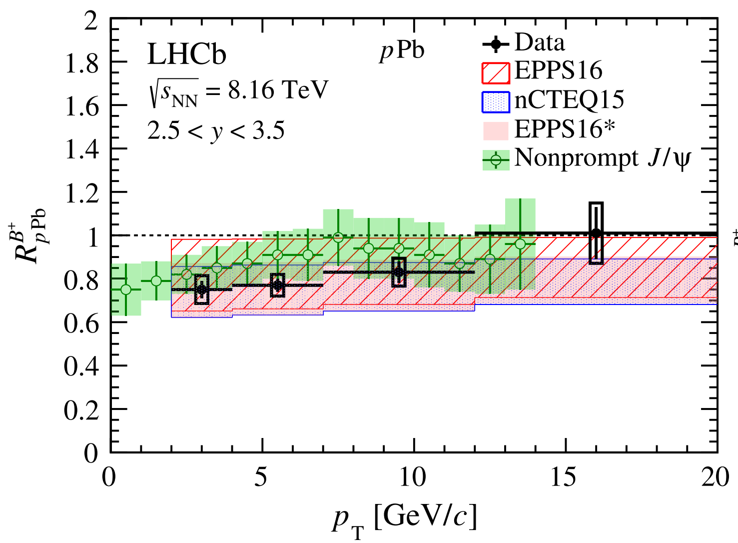
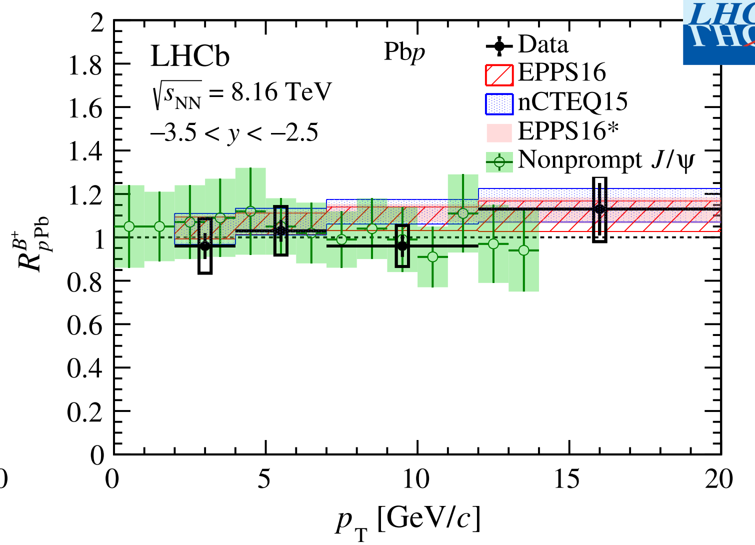
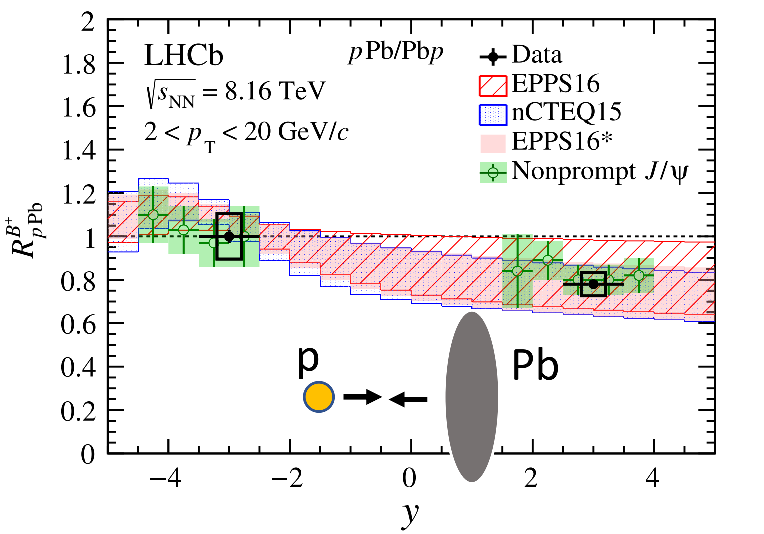
- Ratio to D^0 meson
  - Forward/Backward rapidity: Consistent with theoretical predictions
  - Mid rapidity: Significant excess from theoretical predictions
    - Rising trend at forward rapidity is compatible with mid rapidity results?

Bottom production in p—Pb collisions at $\sqrt{s_{\rm NN}}$ = 8.16 TeV



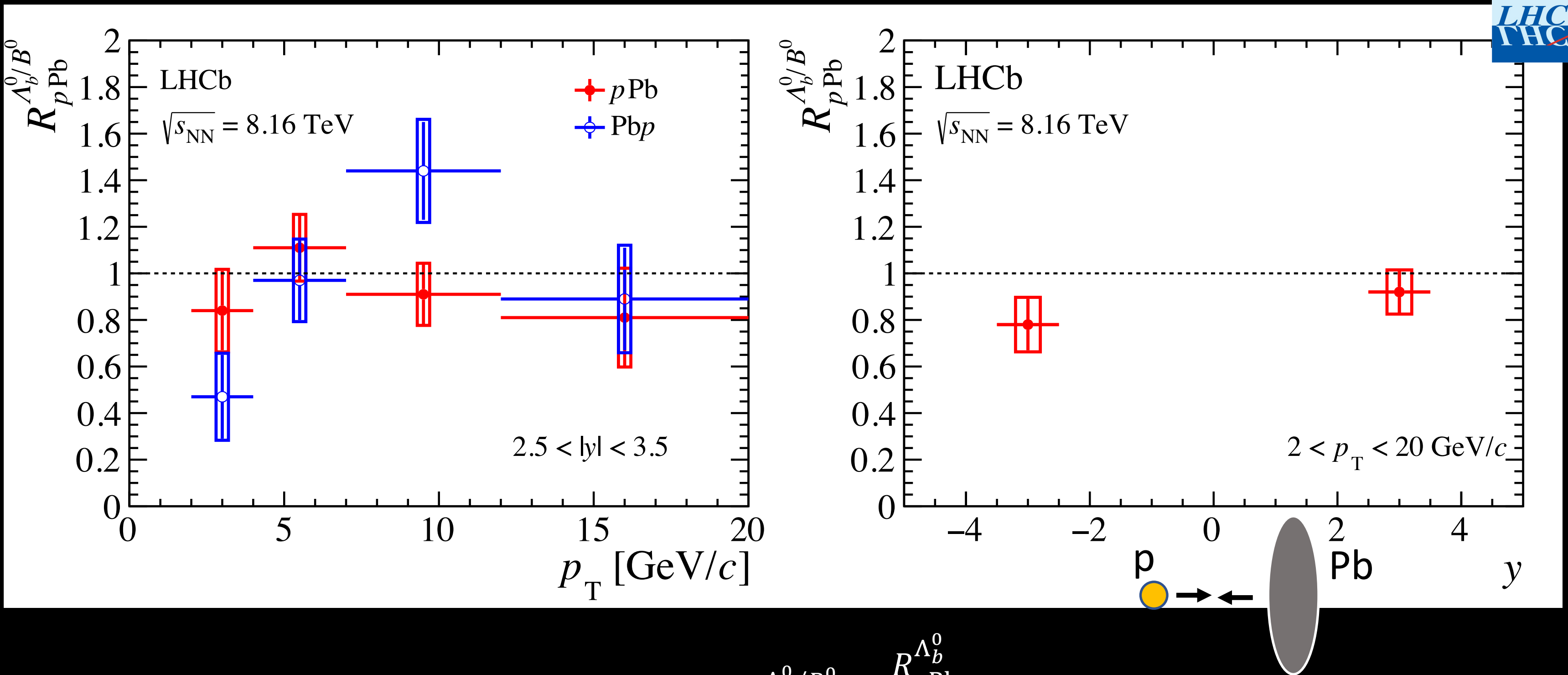




Phys. Rev. D99 052011 (2019)

- B^+ meson nuclear modification factors
  - Significant suppression by more than 20% at forward (p—Pb) rapidity
    (low p_T bins (top left), p_T integrated (bottom))
  - Consistent with the results of non-prompt J/ψ
  - Well described by theoretical calculations with three different nPDFs

Bottom production in p—Pb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV



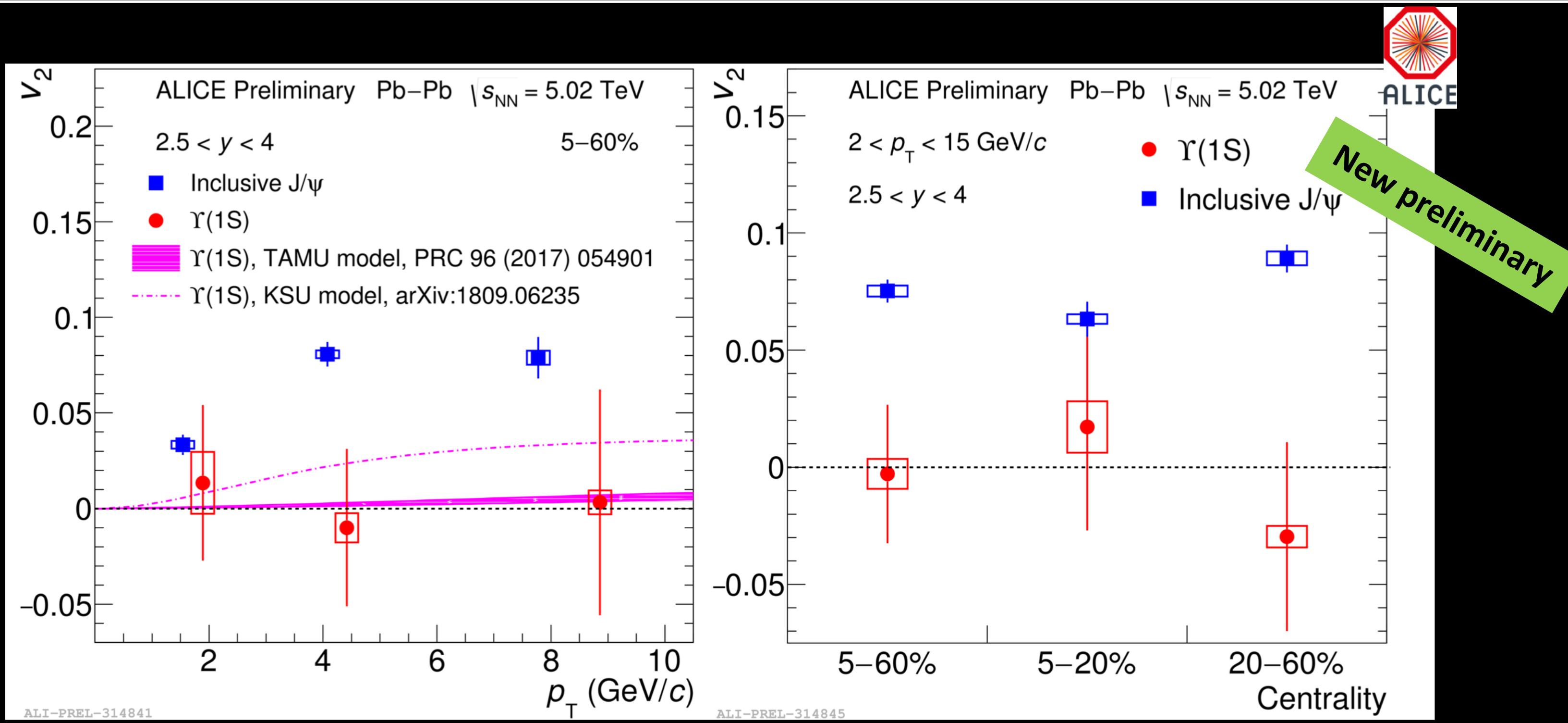
- Ratio of nuclear modification factors $R_{pPb}^{\Lambda_b^0/B^0} \equiv \frac{R_{pPb}^{\Lambda_b^0}}{R_{pPb}^{B^0}}$

Phys. Rev. D99 052011 (2019)

- Consistent with unity in all kinematic bins at forward (p—Pb) rapidity
- Deviations from unity at backward (Pb—p) rapidity by about two standard deviation (1st and 3rd p_T bin (left), p_T integrated bin(right))
  - May be a hint of non-identical nuclear effects for bottom meson (B^0) and bottom baryon (Λ_b^0) ?

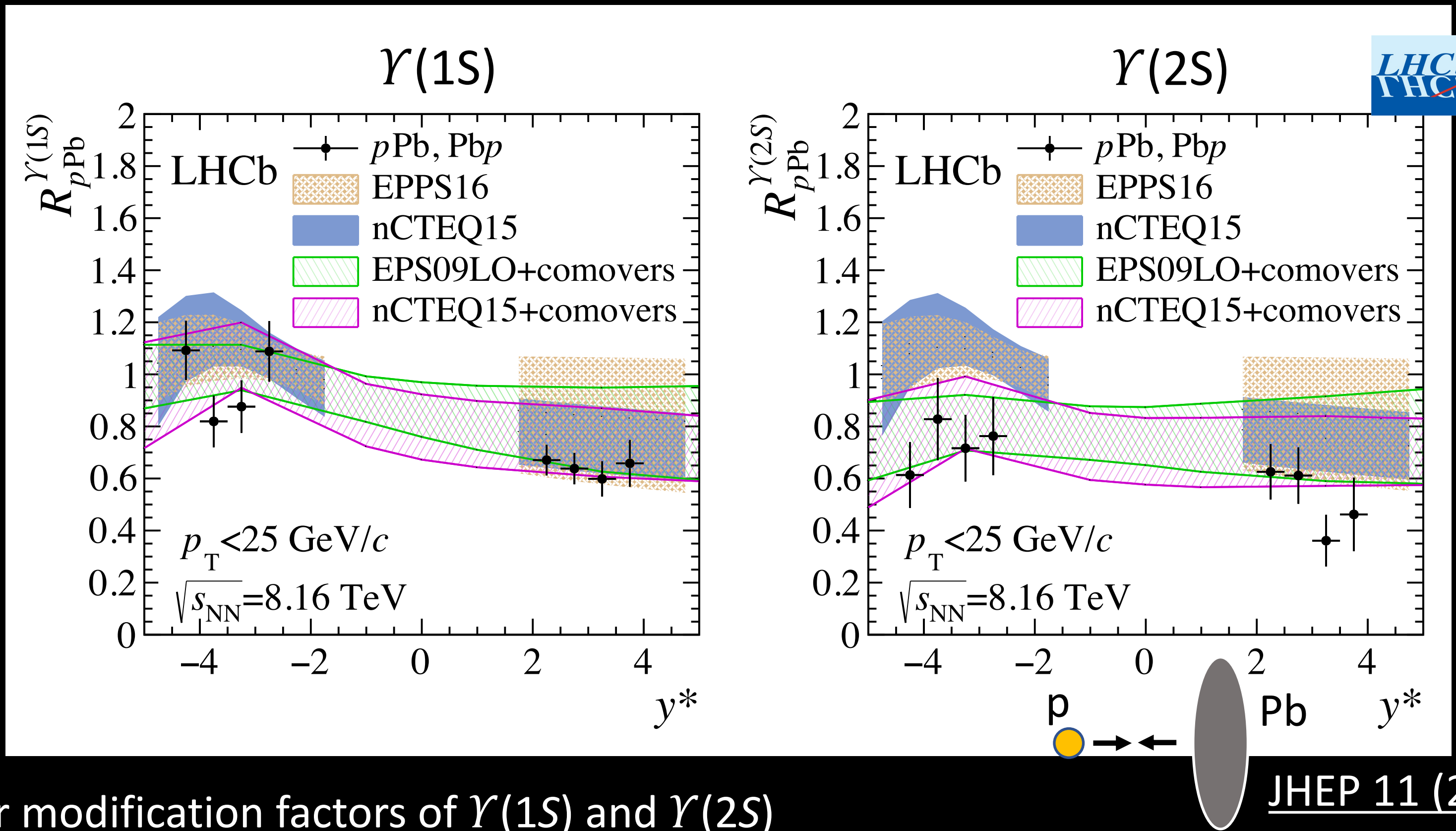
Quarkonia

Azimuthal anisotropy of Υ production in Pb—Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV



- Υ(1S) elliptic flow coefficient v_2
  - Consistent with zero within uncertainties
    - Smaller v_2 than that of inclusive J/ψ by about 2σ significance in 5-60% and 20-60% centrality intervals
  - No significant centrality dependence
- Compared to model predictions
  - Both predictions are consistent with the data within current uncertainties

Υ production in p−Pb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV



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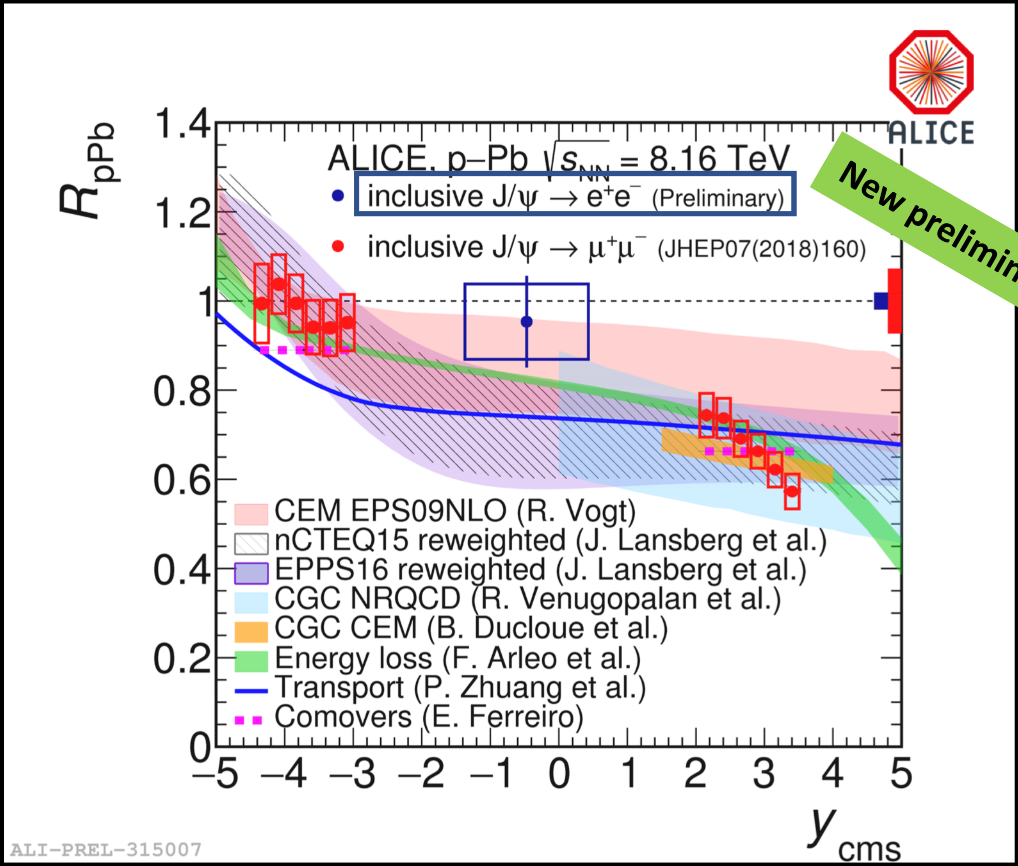
- Nuclear modification factors of $\Upsilon(1S)$ and $\Upsilon(2S)$
- R_{pPb} ($\Upsilon(2S)$) < R_{pPb} ($\Upsilon(1S)$)
- Agrees well with comover model predictions

(Phys. Rev. C88 (2013) 047901, JHEP 10 (2018) 094, Phys. Lett. B749 (2015) 98, Nucl. Phys. A943 (2015) 147, Phys. Rev. C97 (2018) 014909)

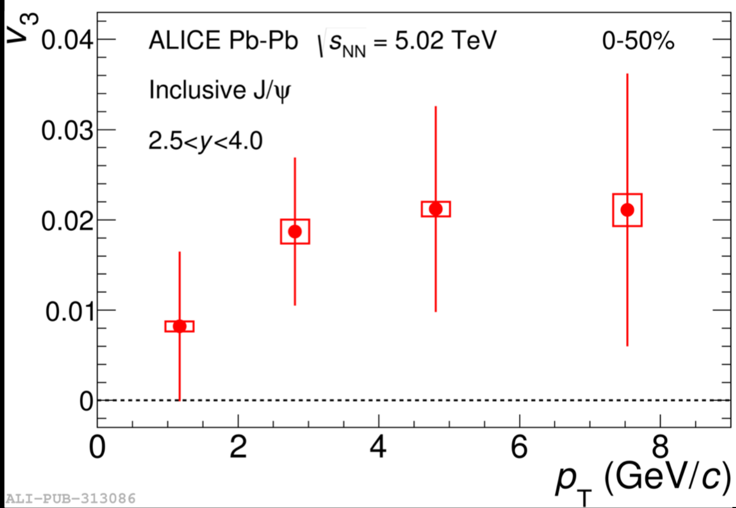
J/ψ production in p−Pb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV



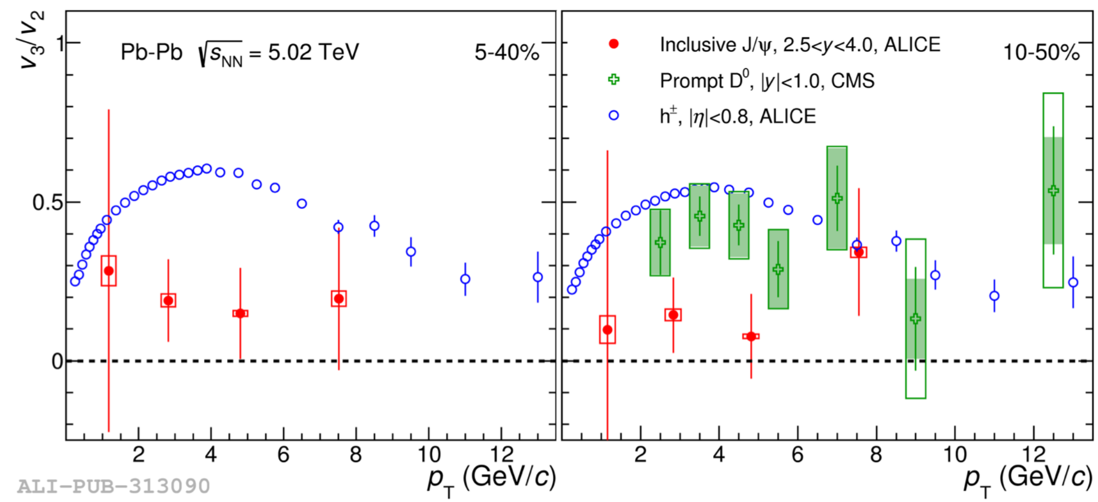
- Inclusive J/ψ nuclear modification factor at mid-rapidity has been newly measured
- Compatible with the trends at forward/backward rapidity
- Compared to several theoretical predictions
  - All models capture the trend qualitatively

Higher-order azimuthal anisotropy of J/ψ production in Pb—Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

Triangular flow coefficient (v_3)



Ratio of triangular and elliptic flow coefficients (v_3/v_2)

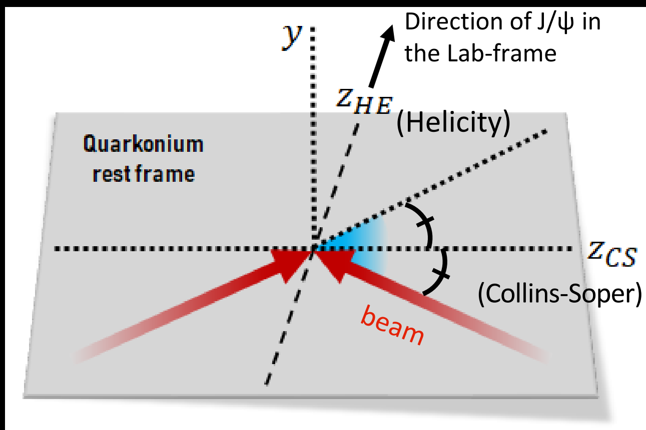


JHEP02(2019)012

- First measurement of the triangular flow coefficient v_3 for J/ψ production
  - Positive v_3 with 3.7 σ significance
  - Ordering v_3/v_2 (J/ψ) < v_3/v_2 (D^0) < v_3/v_2 ($h^{\pm}$)

J/ψ polarization in Pb—Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

Definition of the reference frame



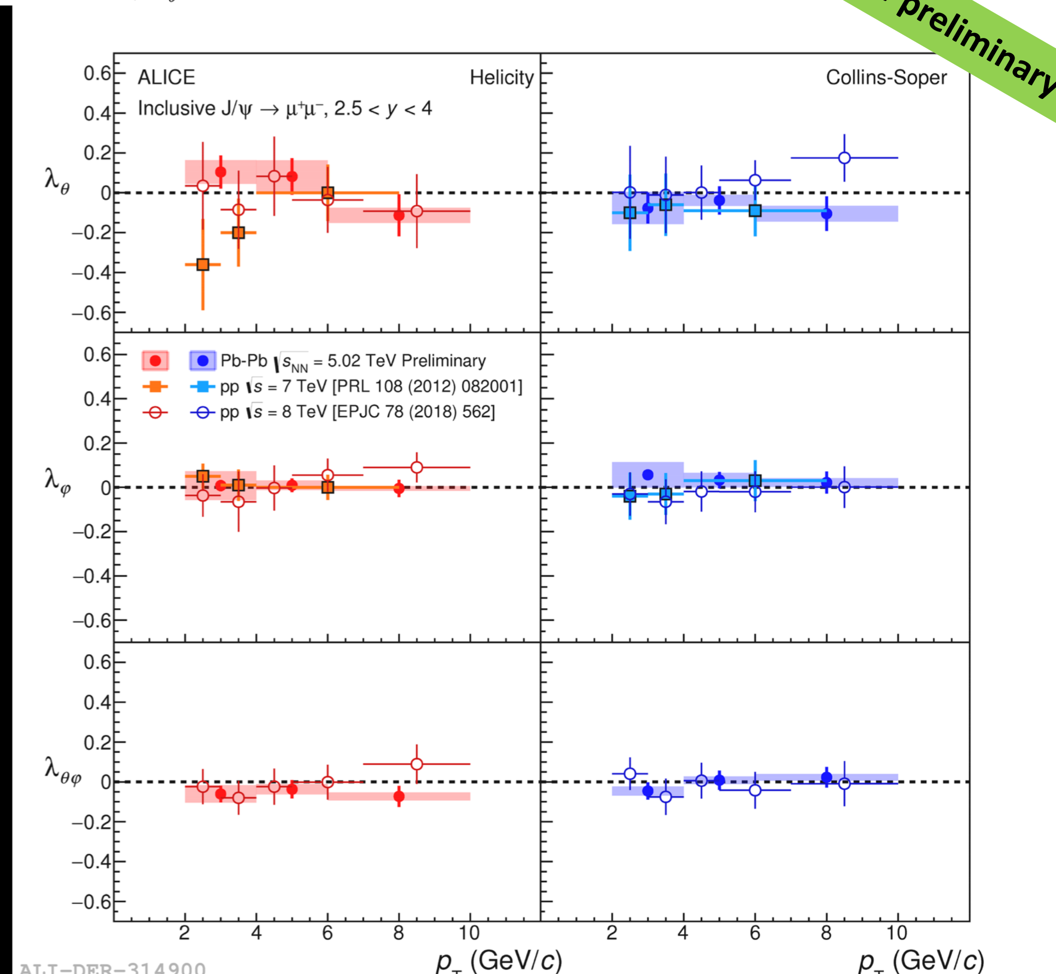
✓ X-axis is chosen so that the reference frame is right handed

- First measurement of J/ψ polarization in Pb-Pb collisions at LHC energy
  - The results suggests the polarization parameters are close to zero
  - No significant difference with the results in pp collisions

$$W(\cos\theta,\varphi) \propto \frac{1}{3+\lambda_\theta}\cdot(1+\lambda_\theta\cos^2\theta+\lambda_\varphi\sin^2\theta\cos2\varphi+\lambda_{\theta\varphi}\sin2\theta\cos\varphi)$$

New preliminary

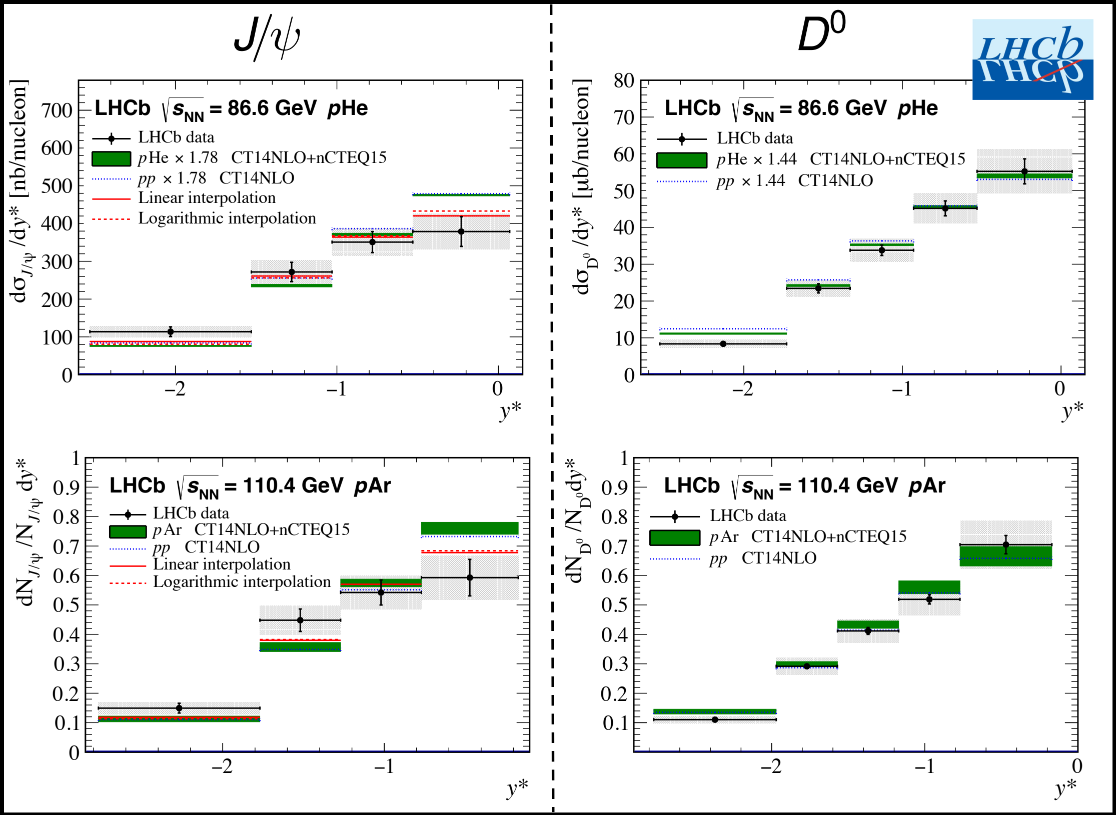
ALICE



Heavy flavour in fixed target configuration

First measurement of charm production in fixed target configuration at $\sqrt{s_{\mathrm{NN}}}$ = 86.6 (*p*He) and 110.4 (*p*Ar) GeV at the LHC

- *p*He: Cross sections are compared to predictions
  - Theoretical predictions underestimate the total cross section
- *p*Ar: Differential yields with arbitrary normalization are compared to predictions
- *J/ψ* results are compared to linear and log interpolation from the results at similar energy
  (Phys. Rev. D 52, 1307 (1995),
  Eur. Phys. J. C 60, 525 (2009),
  Phys. Rev. Lett. 98, 232002(2007))



Phys. Rev. Lett.122 (2019) 132002

- No strong difference between *p*He data and theoretical predictions which do not include intrinsic charm contribution at Bjorken-*x* range $x \in [0.17, 0.37]$ (at the most backward bin)
- No evidence of strong intrinsic charm content within current uncertainties

*Intrinsic charm: Charm quarks possibly exist in sea quarks

Summary and outlook

- ALICE and LHCb enable a complementary study of hard probes in heavy-ion collisions

- Various measurements of hard-probes have been carried out by ALICE and LHCb with LHC Run1/Run2 heavy-ion data
  - Differential jet measurements (ALICE)
  - Measurements of open and hidden heavy flavours over a wide rapidity range (ALICE, LHCb)
  - Heavy flavour measurements with fixed-target configuration (LHCb)

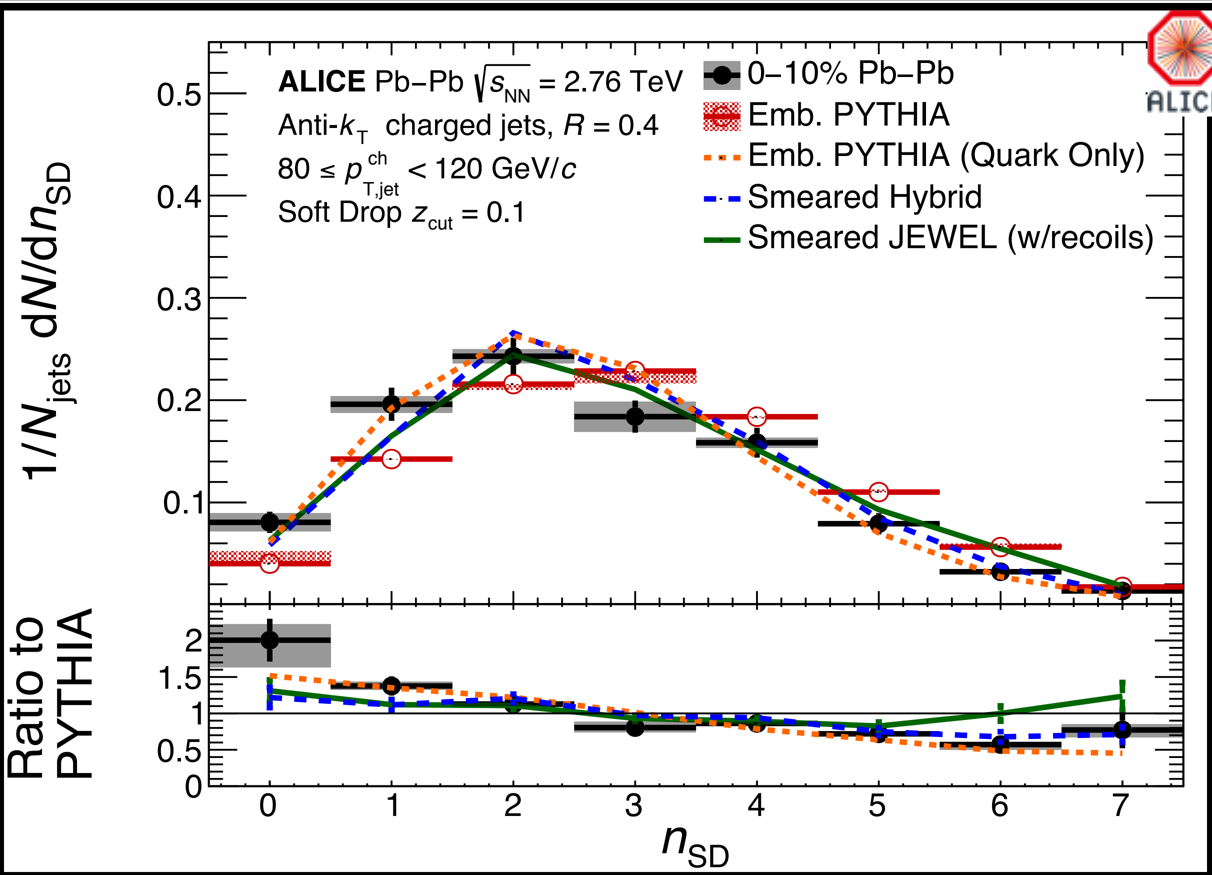
- Detector upgrades during LHC Long Shutdown 2 for Run3
  - ALICE: New Inner tracking system, New Muon forward tracker, High readout rate
  - LHCb: Detector upgrades for higher luminosity
    - Upgrade of Vertex Locator silicon detector
      - Saturates in central collisions with current configuration
        → centrality reach in Pb—Pb collisions will be improved with higher granularity
    - Upgrade of the fixed-gas target (SMOG2, public note: https://cds.cern.ch/record/2649878)
      - wider choice of usable gas species, better control over the target gas pressure, increase the integrated luminosities

Backup

Configurations of LHCb

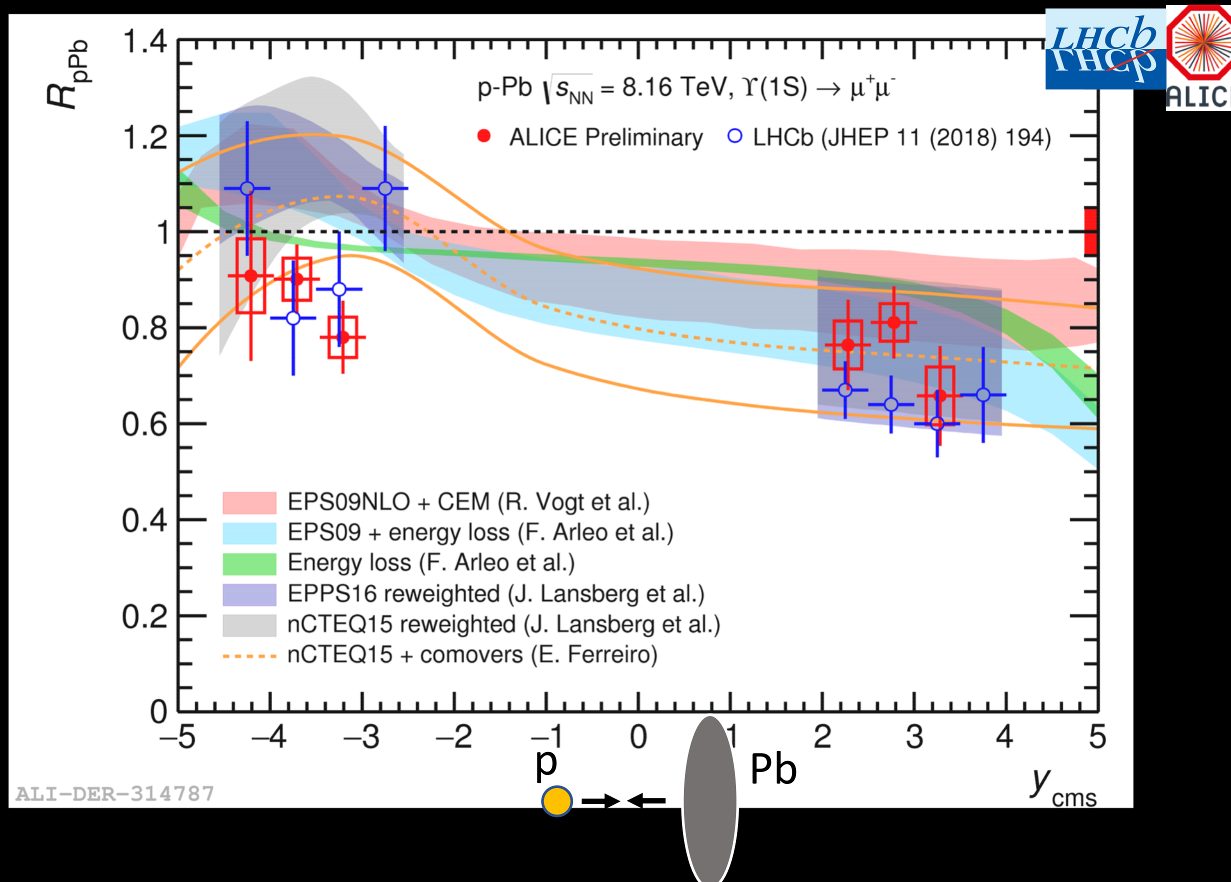
- *p*Pb collisions: proton beam towards detector
  - $1.5 < y < 4.0$
- Pb*p* collisions: lead beam towards detector
  - $-5.0 < y < -2.5$
- Fixed-target collisions (*p*Ar, *p*He)
  - $-2.5 < y < 0$

Jet substructure in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV



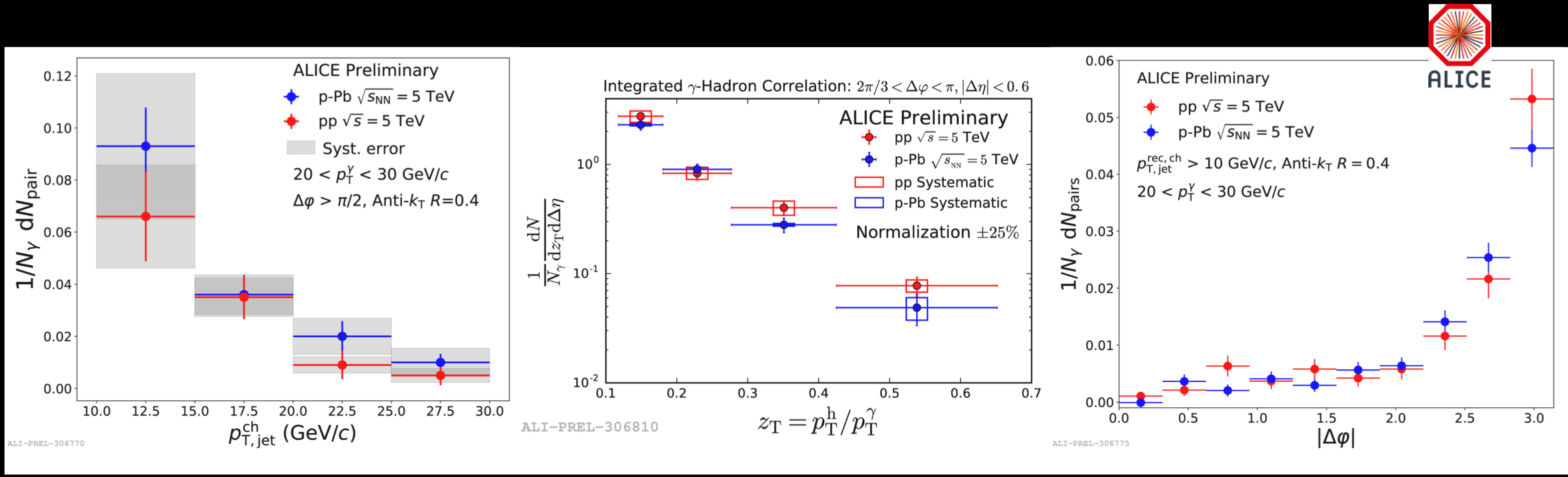
arXiv:1905.02512 [nucl-ex]

Υ production in pPb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 8.16 TeV



- Nuclear modification factors of $\Upsilon(1S)$ from two independent measurements from ALICE and LHCb
- The ALICE and LHCb results agree well

γ-jet correlations in pp and p-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV



Coherent J/ψ production in Pb—Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV