Recent highlights on study of the QGP matter at the LHC

With personal bias

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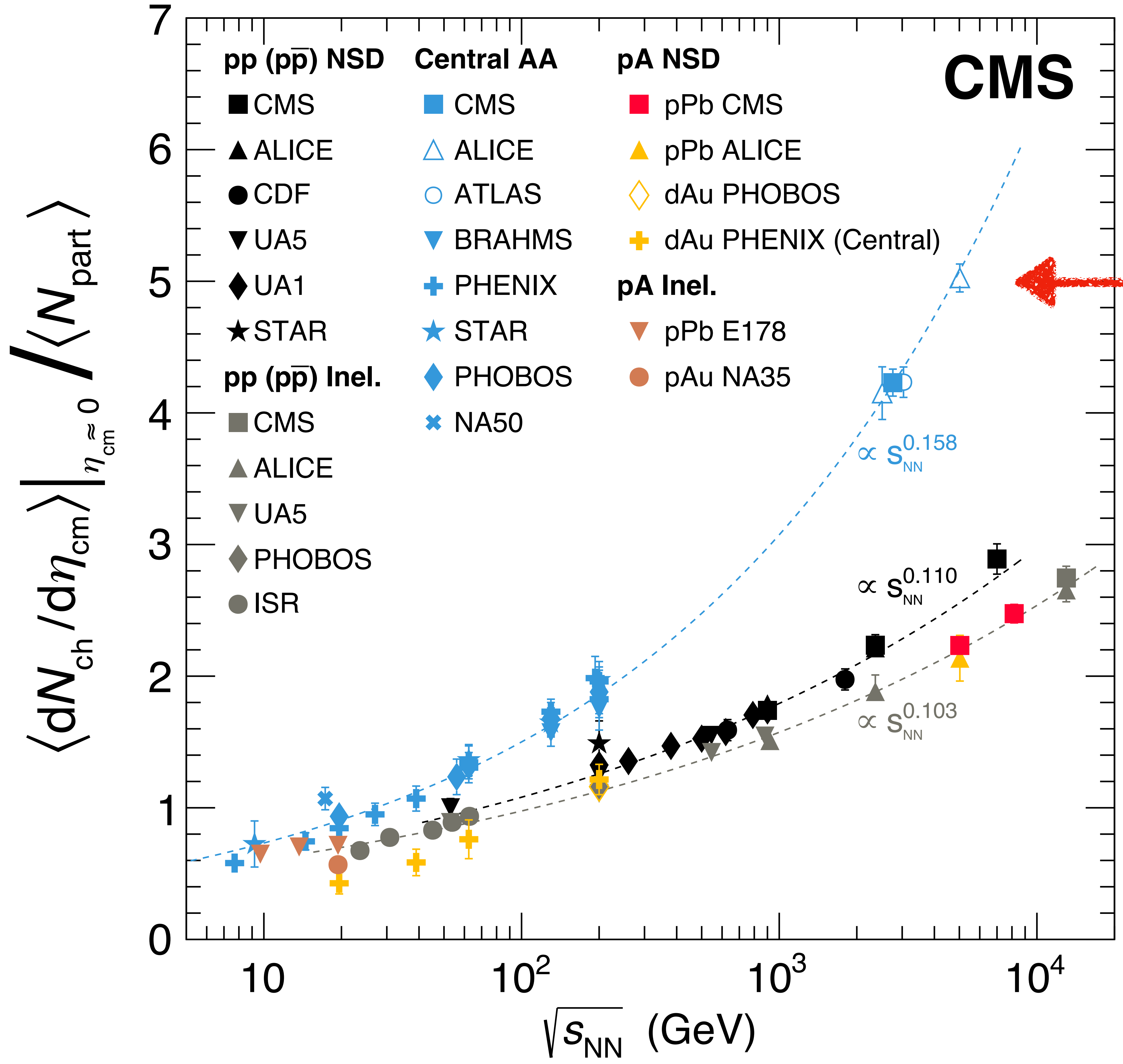
The 100th e-Forum on High Energy Nuclear Physics in China

16 April 2020

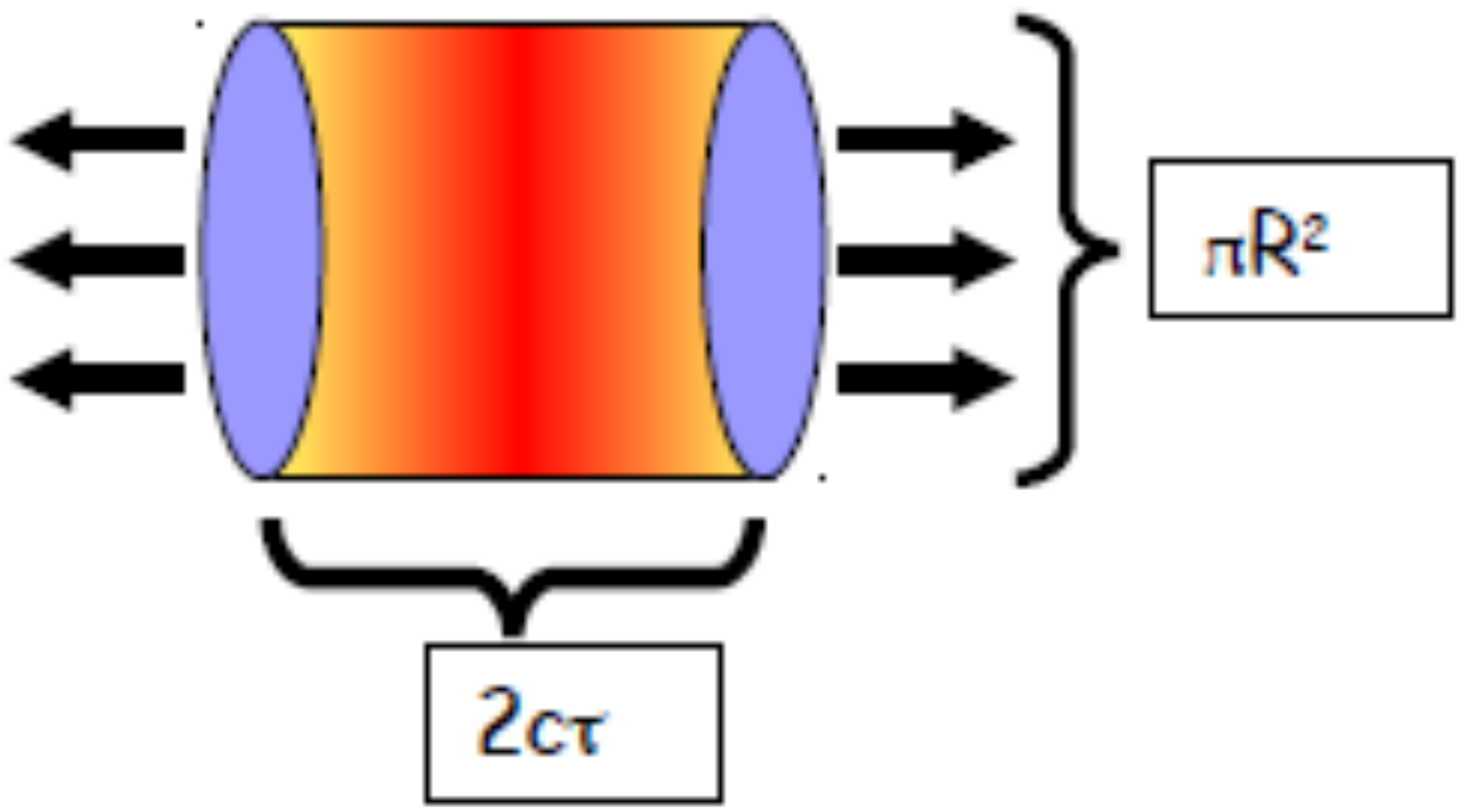
Charged particle multiplicity

CMS *JHEP* 1801 (2018) 045



5% most Pb–Pb
$\sqrt{s_{NN}}$ = 5.02 TeV

Bjorken estimate:



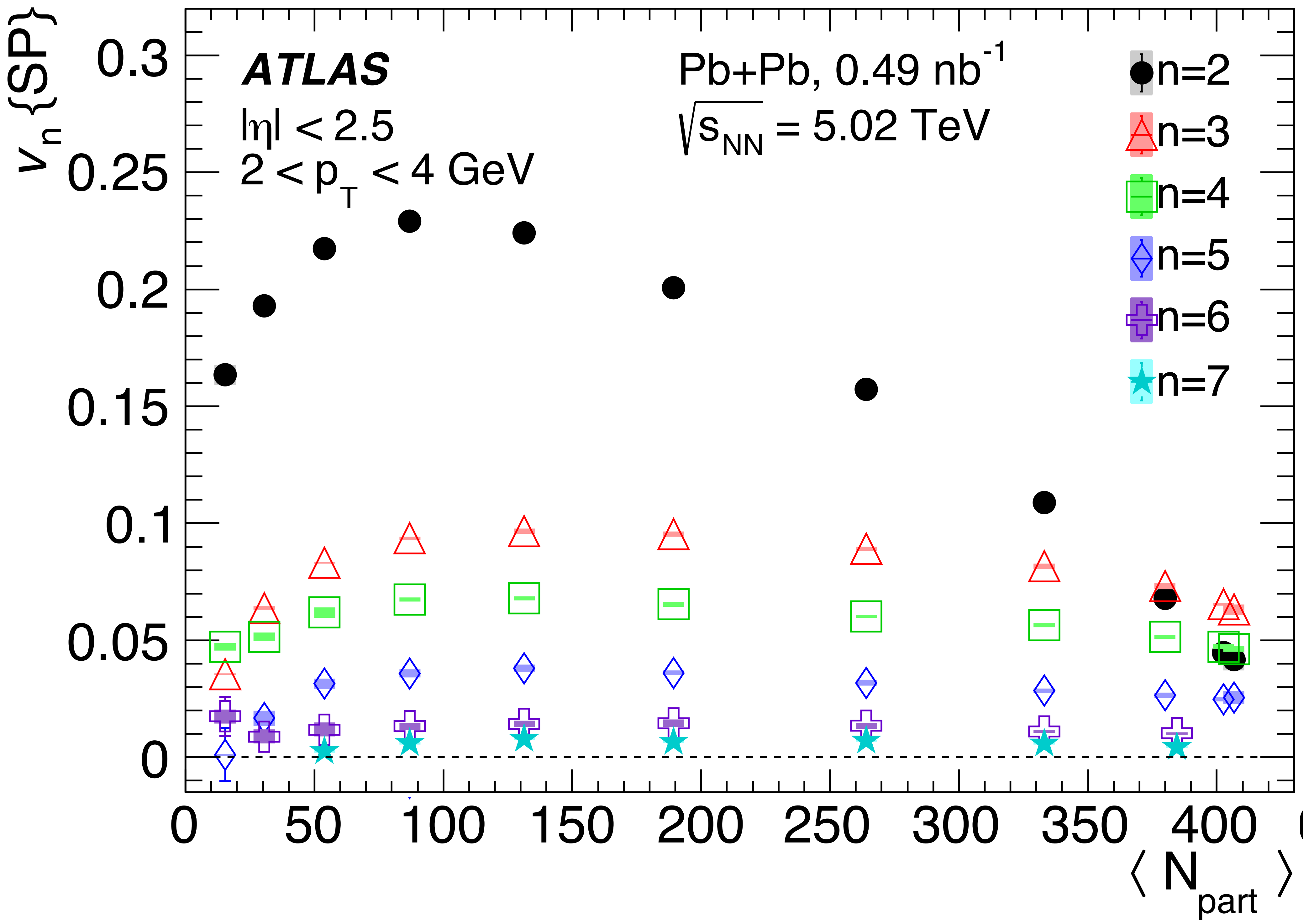
$$\langle \varepsilon \rangle (\tau) = \frac{1}{\tau \pi R^2} \frac{dE_T}{dy} \longleftrightarrow dN/d\eta$$

5% most Pb–Pb at 5.02 TeV: dN/dη ~ 2000

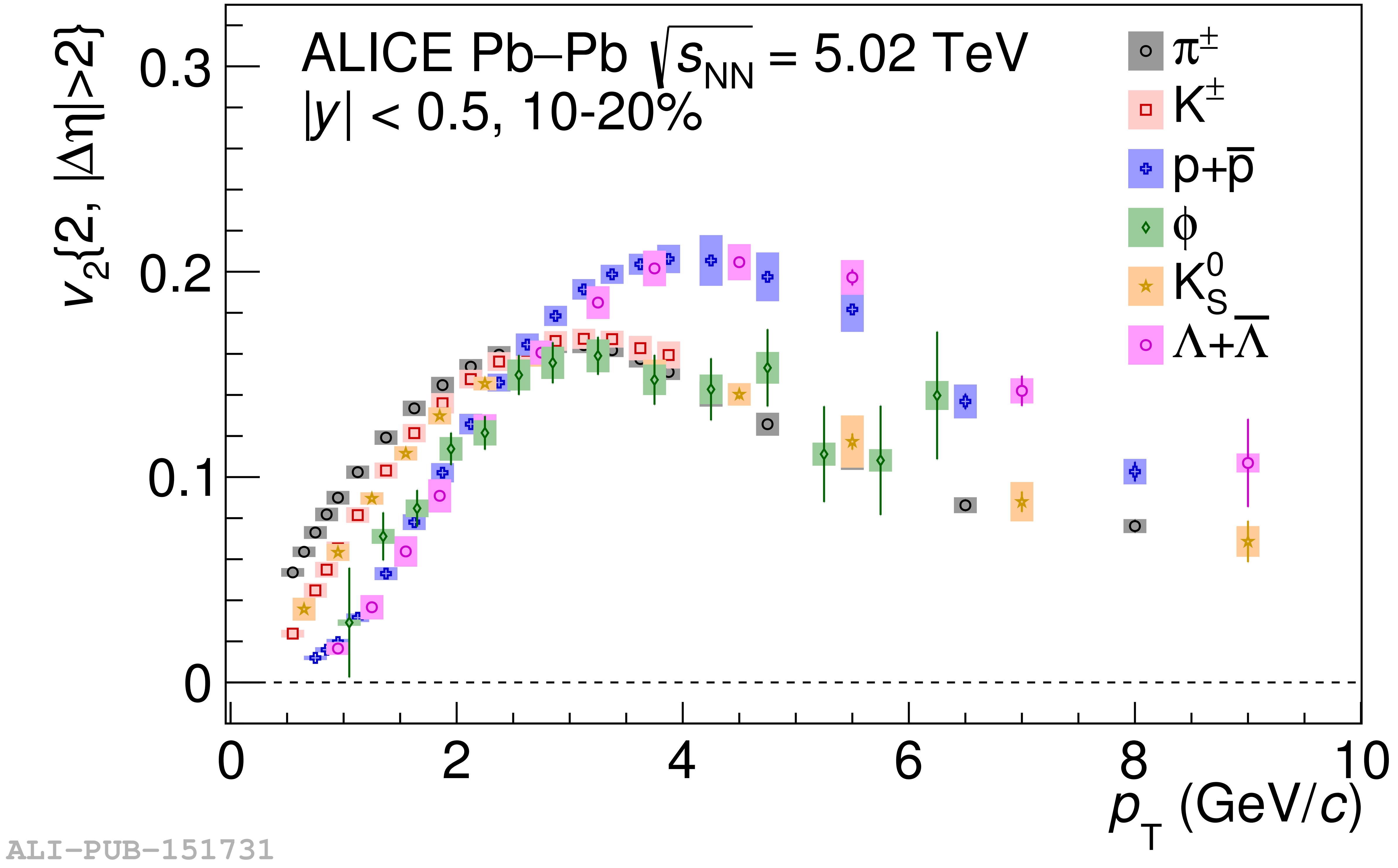
- Energy density ε ~ 18 GeV/fm^3
- Above deconfinement transition (~1 GeV/fm^3)

Anisotropic flow

ATLAS *Eur. Phys. J.* **C78** (2018) 997



ALICE *JHEP* **1809** (2018) 006



Flow harmonics

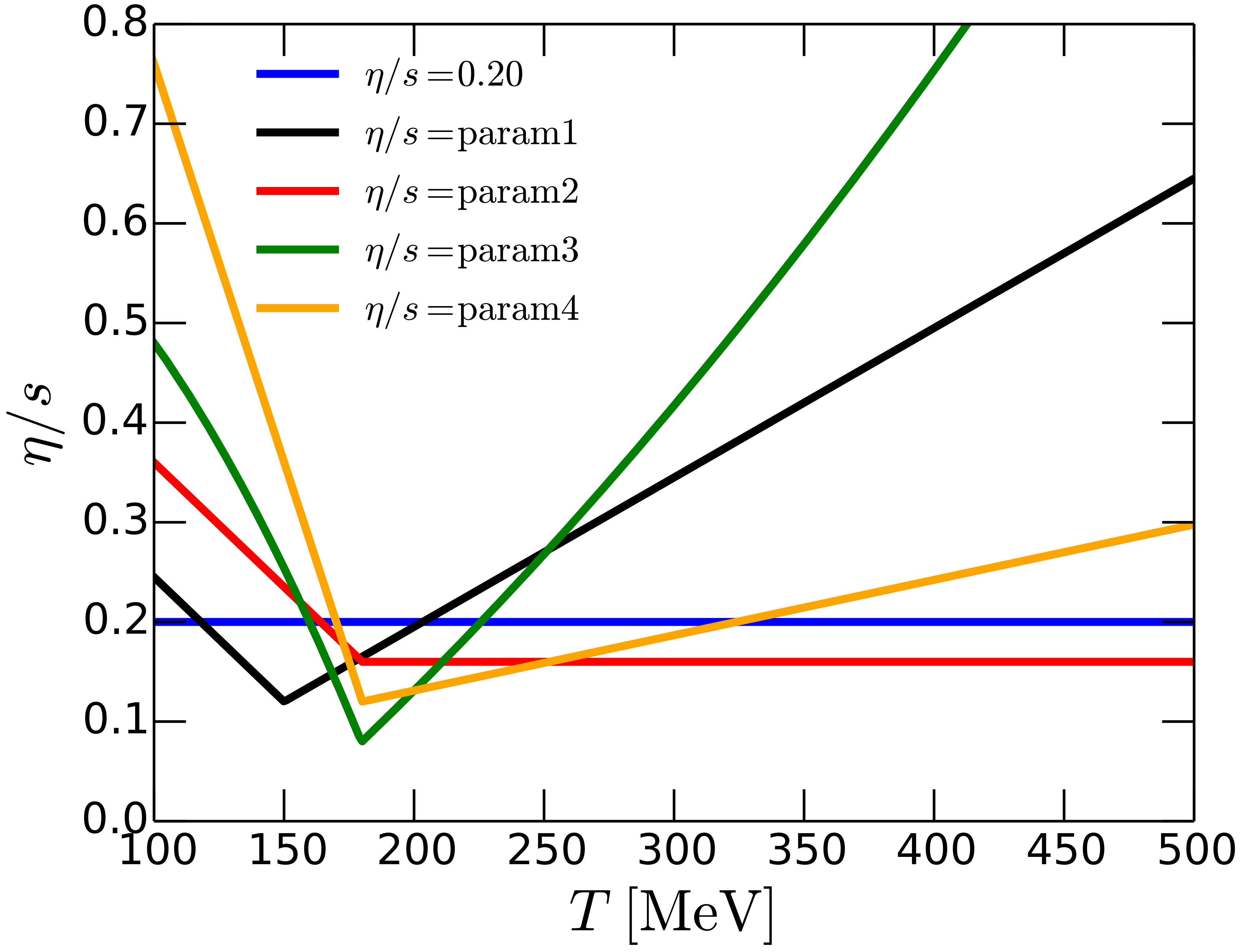
- Max v_2 observed in semi-central collisions
- $v_{n+1} < v_n$, except for central collisions

Identified particle flow

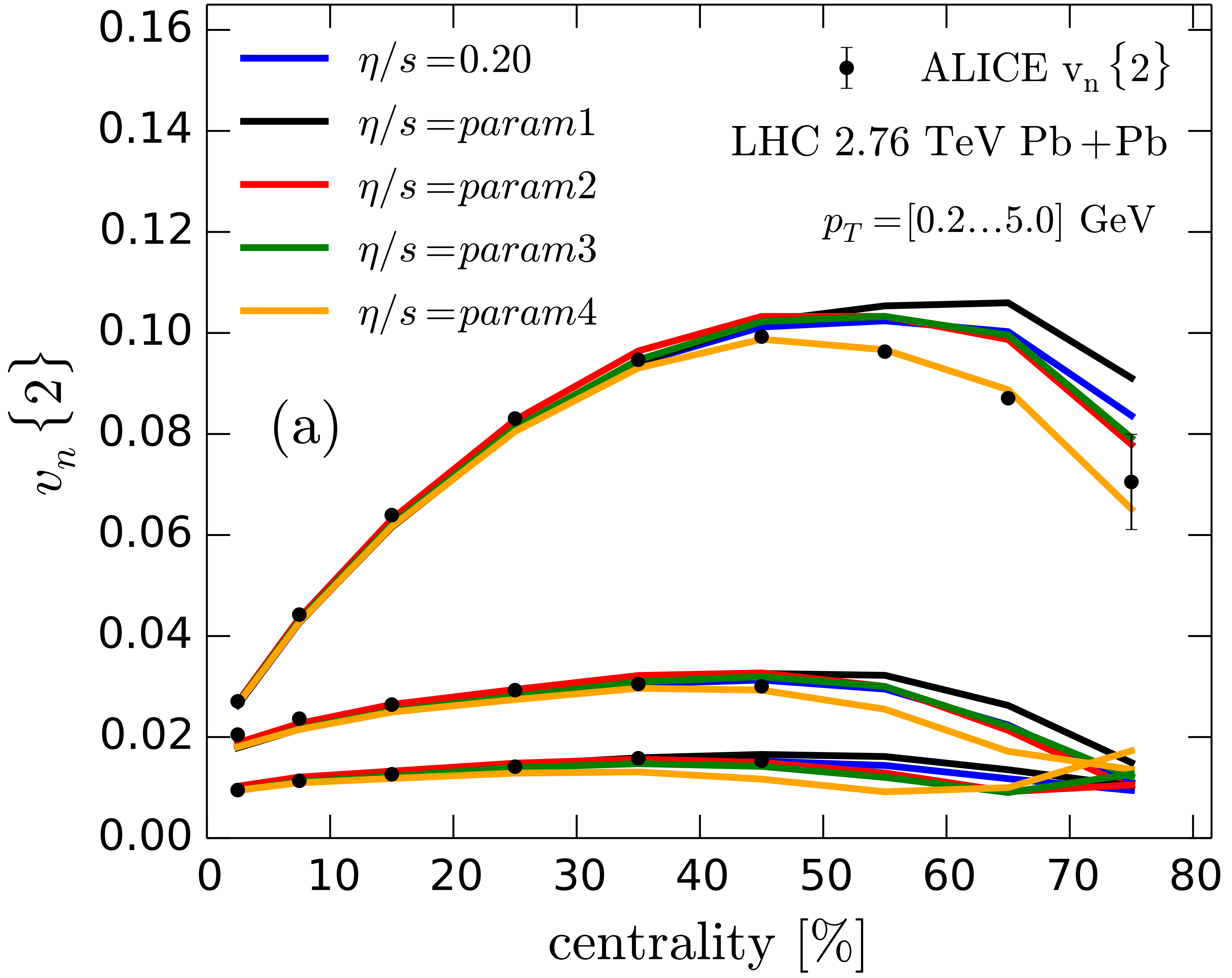
- Low p_T, mass ordering
- High p_T, quark content grouping

Anisotropic flow

Phys. Rev. C93 (2016) 024907



ALICE *Phys. Rev. Lett.* 107 (2011) 032301

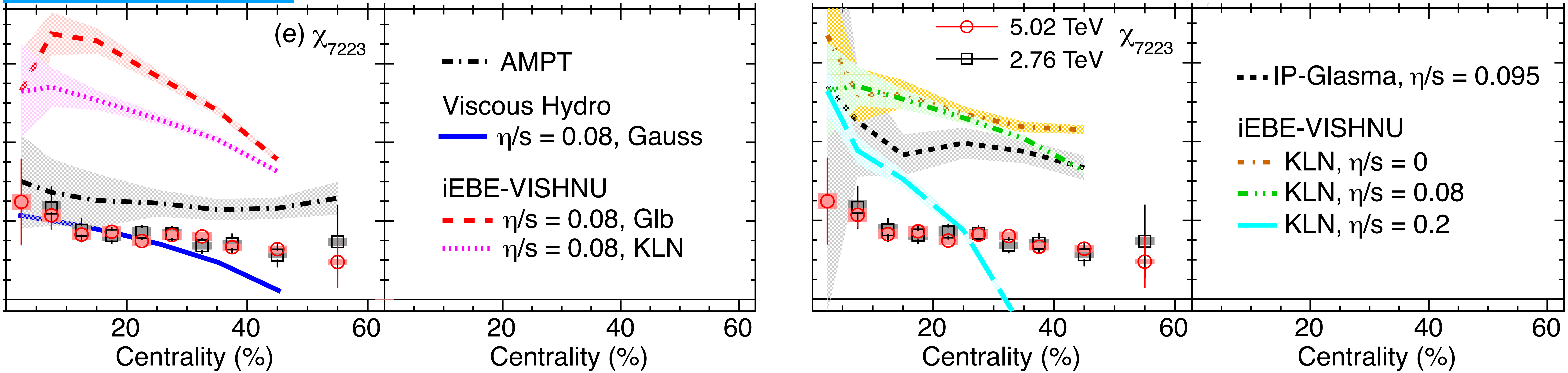


- Flow — initial fluctuations + hydrodynamic evolution (+ hadronic scatterings)
- Differential measurements are required

Non-Linear response of harmonics

- $v_5 = v_{5L} + \chi_{523} v_2 v_3$
- $v_7 = v_{7L} + \chi_{725} v_2 v_{5L} + \chi_{734} v_3 v_{4L} + \chi_{7223} (v_2)^2 v_3$

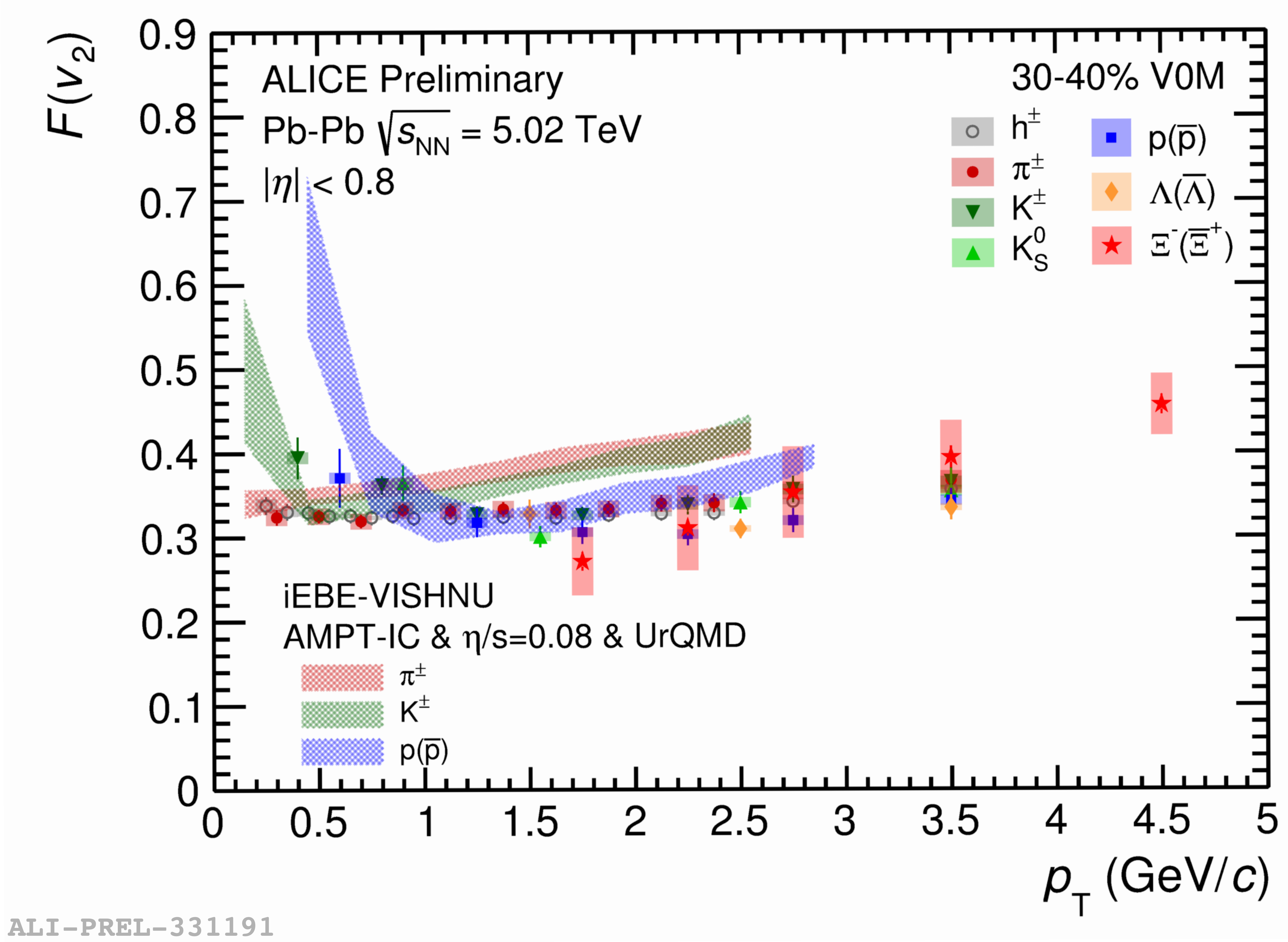
CMS arXiv:1910.08789



- Higher order v_n (n>3), arise from some order anisotropy or that of lower orders
- Nonlinear response coefficient measured up to n =7, sensitive to both initial conditions and medium transport coefficient

Flow fluctuations

$v_n\{4\} = v_n\{6\} = v_n\{8\}$ only if $P(v_n)$ follows Bessel-Gaussian



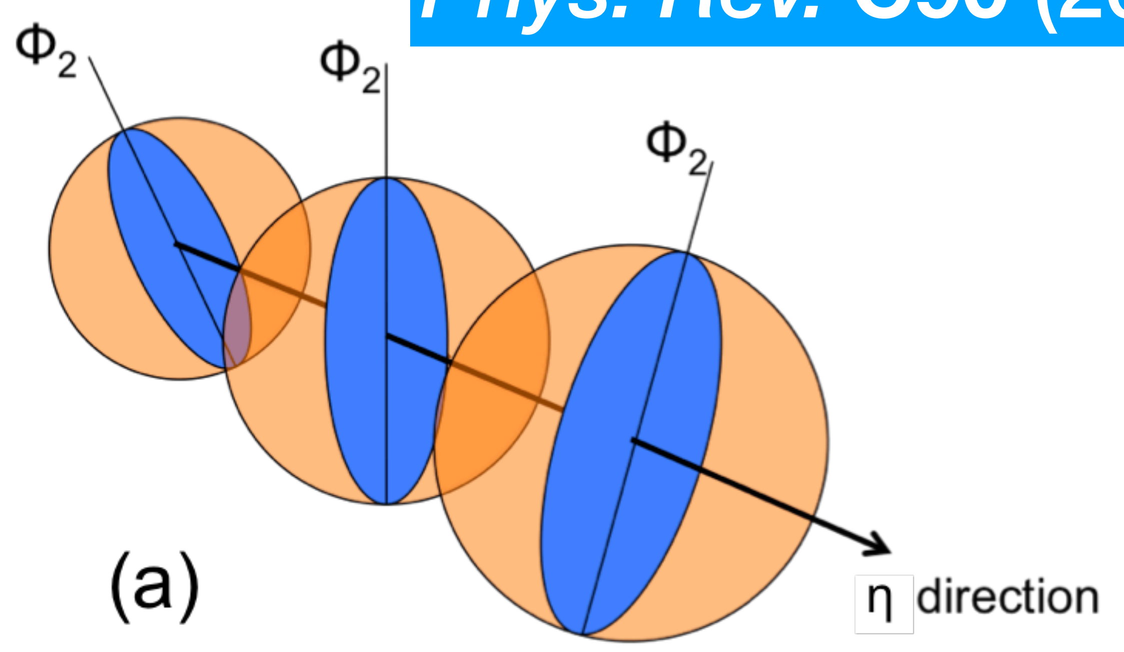
$F(v_n) = \sigma(v_n) / \langle v_n \rangle$

- $\sigma(v_n) \approx \sqrt{(v_n\{2\}^2 - v_n\{4\}^2)/2}$
- $\langle v_n \rangle \approx \sqrt{(v_n\{2\}^2 + v_n\{4\}^2)/2}$

- p_T dependence — inference from the final state (?)
- Particle species dependence in models is not observed in data

Longitudinal flow decorrelations

Phys. Rev. C90 (2014) 034905

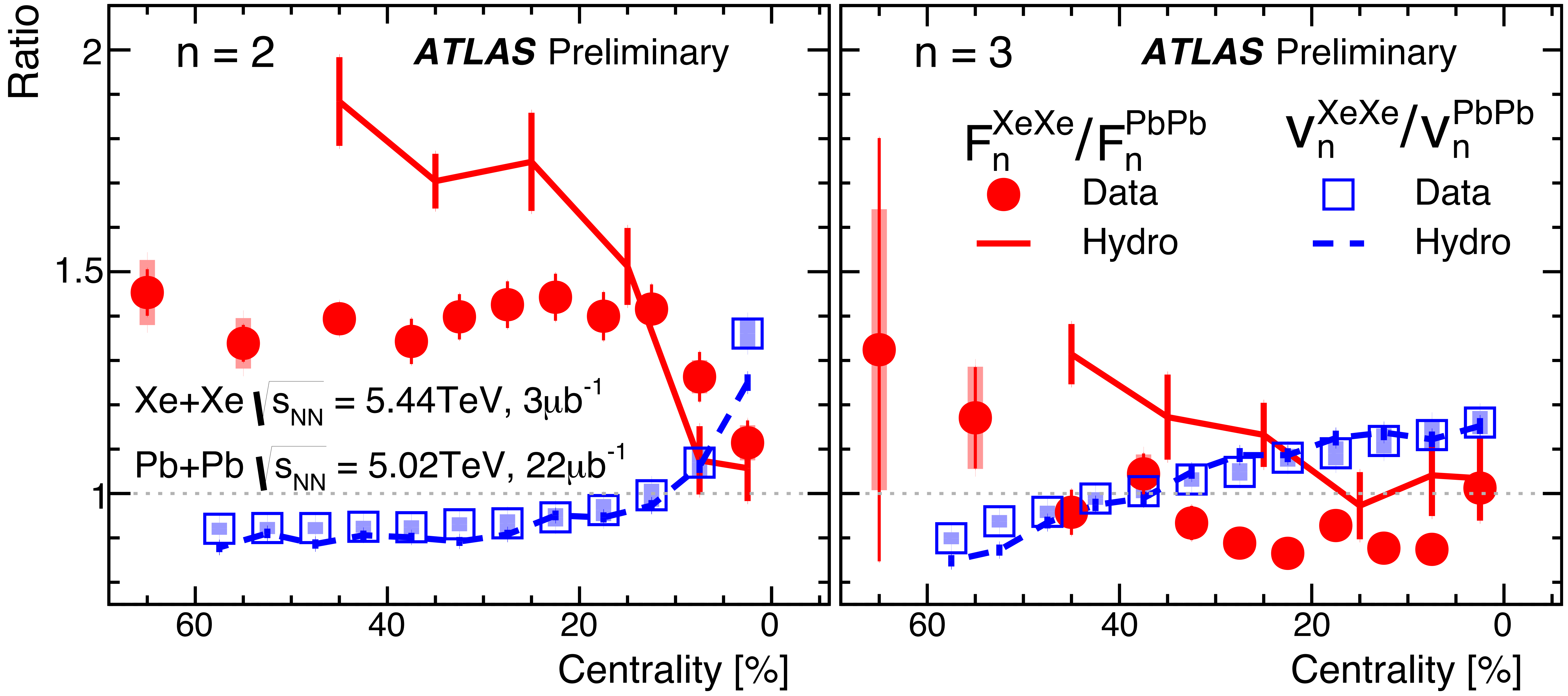


Characterized by $r_n(\eta)$

- $r_n(\eta) = 1$ — no de-correlation
- $r_n(\eta) < 1$ — decorrelations

- F_n — slop parameter of $r_n(\eta)$
- $F_n^{XeXe} / F_n^{PbPb} \propto r_n^{XeXe} / r_n^{PbPb}$

ATLAS-CONF-2019-055

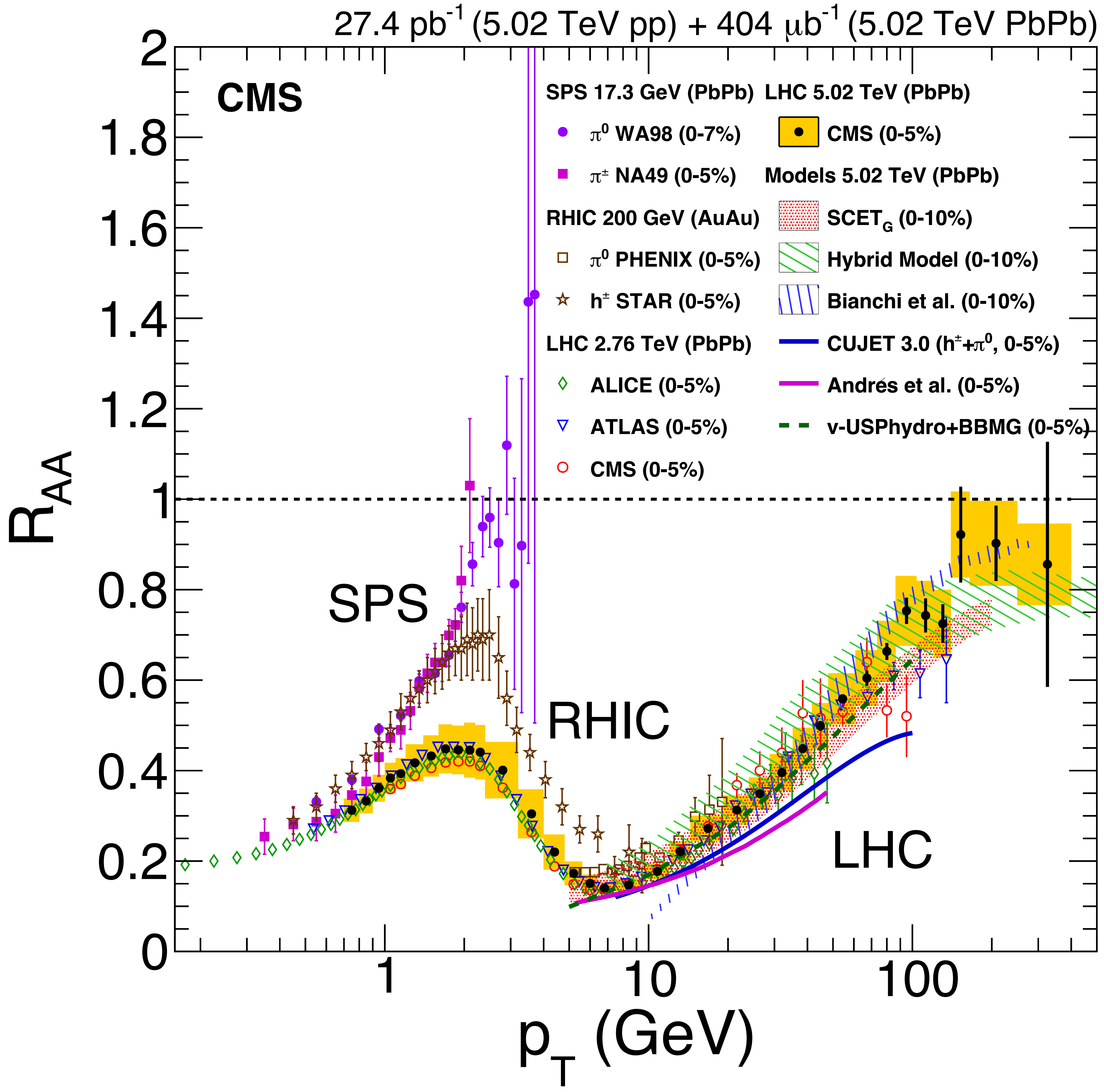


Important constraints on

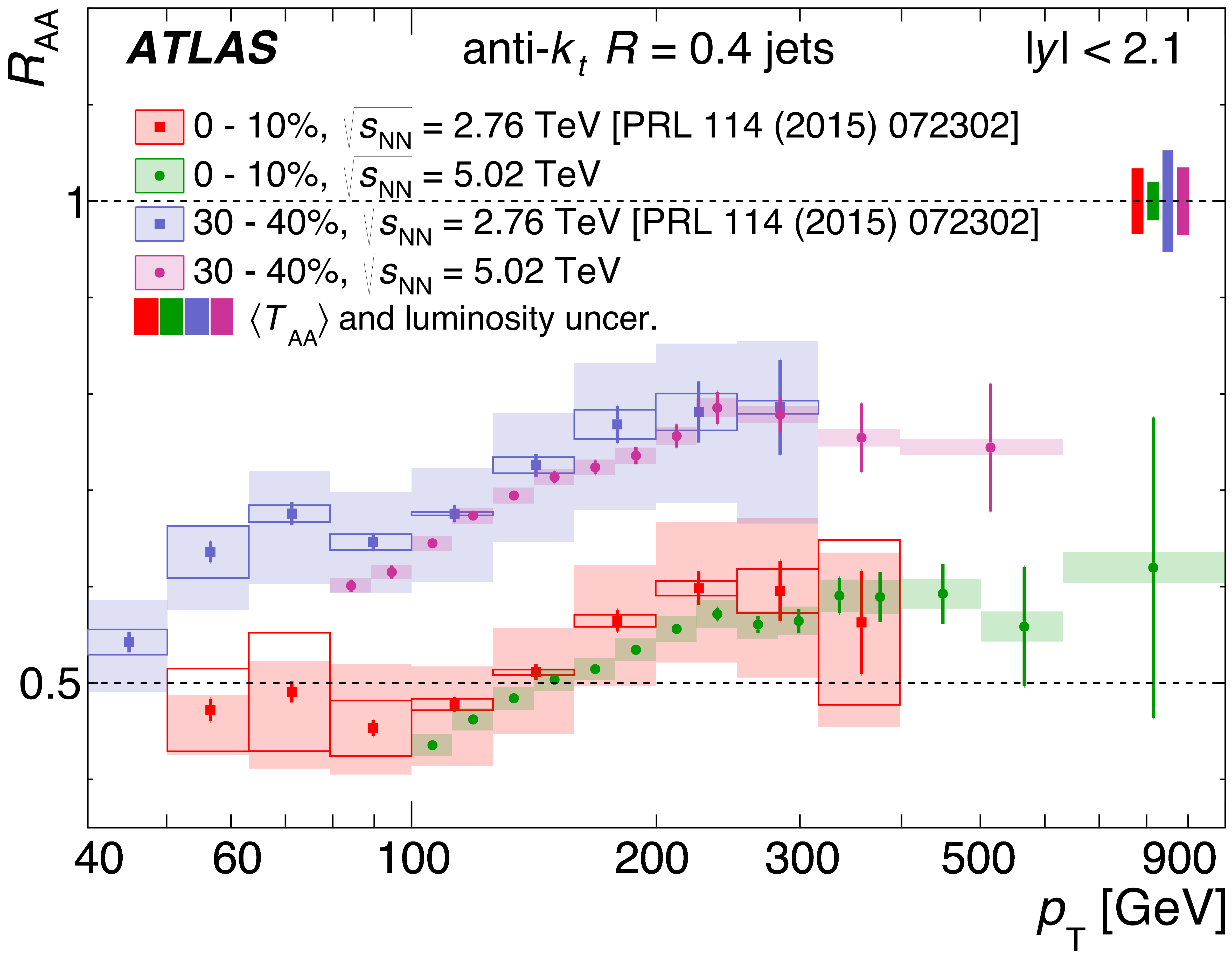
- Longitudinal structure of the initial-state geometry
- Dynamics of v_n in the longitudinal direction

High p_T suppression

CMS *JHEP* 1704 (2017) 039

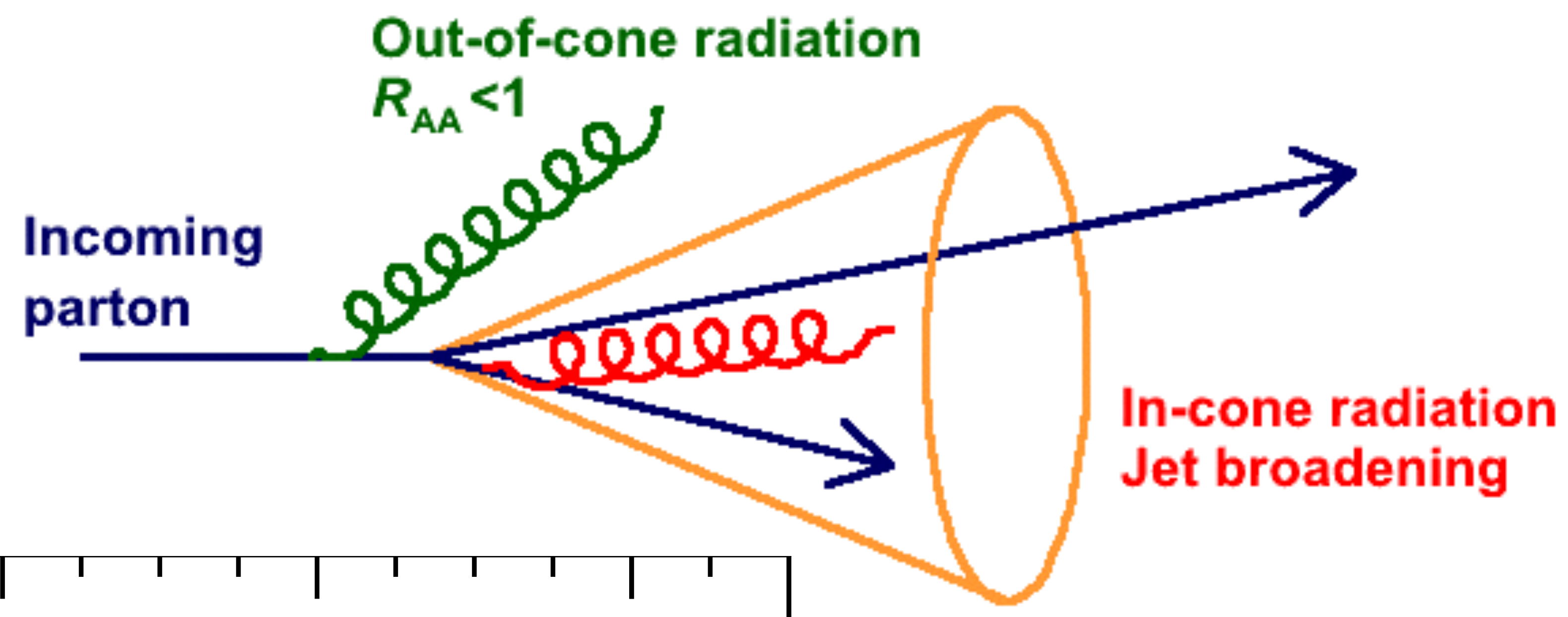


ATLAS *Phys. Lett.* B790 (2019) 108

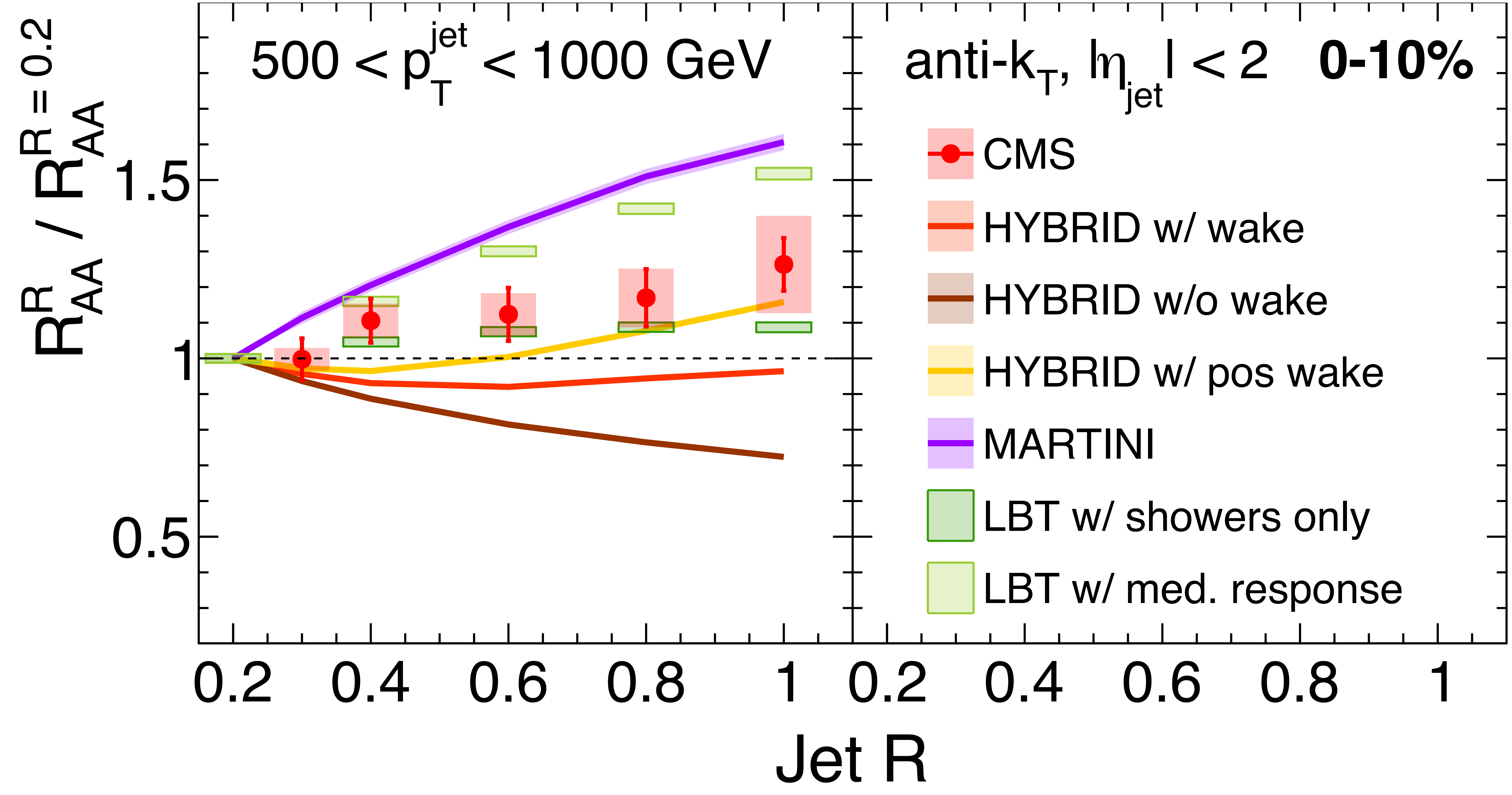


- R_{AA} of high-p_T hadrons reaches to unity
- Strong suppression on jet production up to TeV

Large radius jets



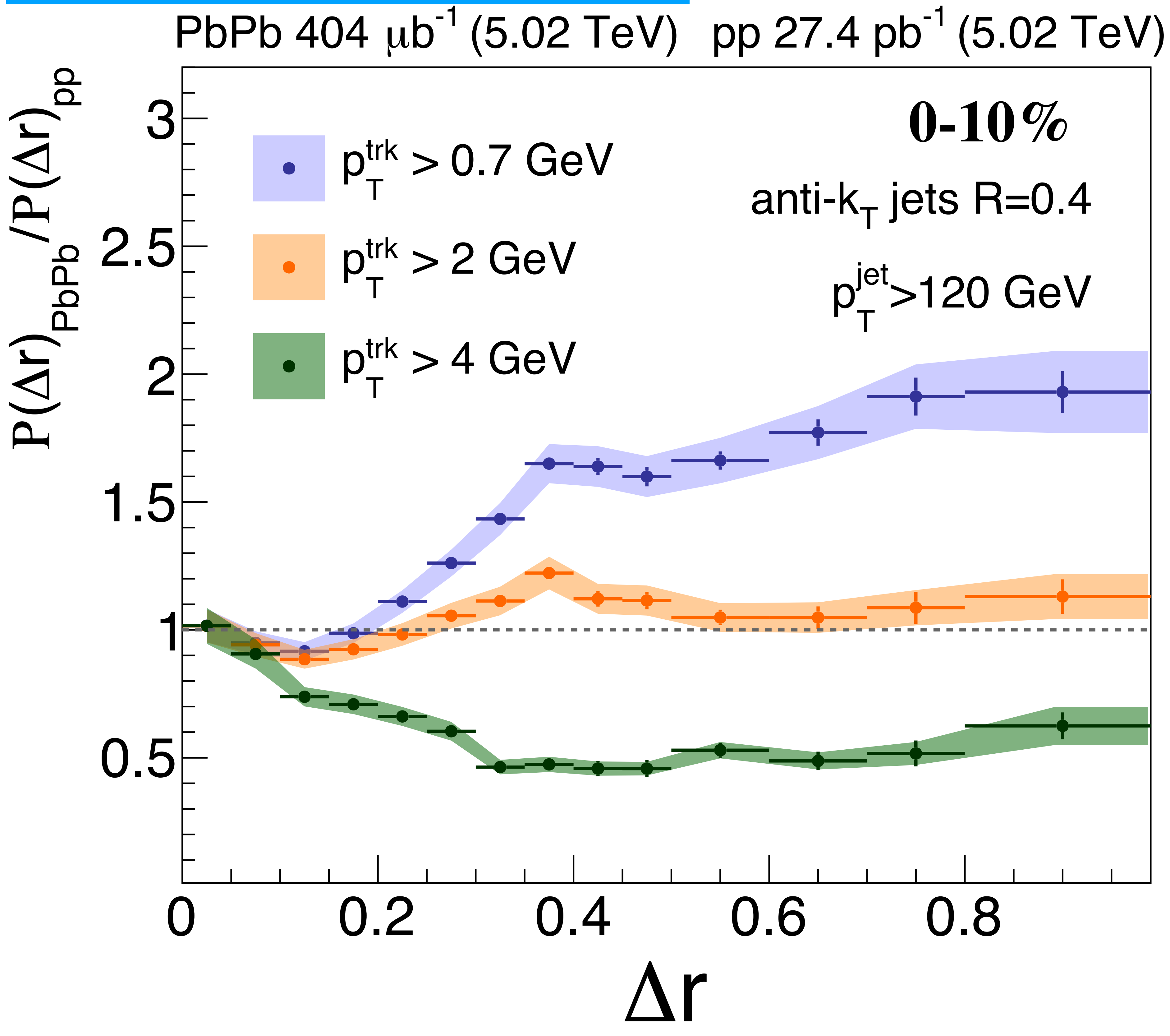
CMS-PAS-HIN-18-014



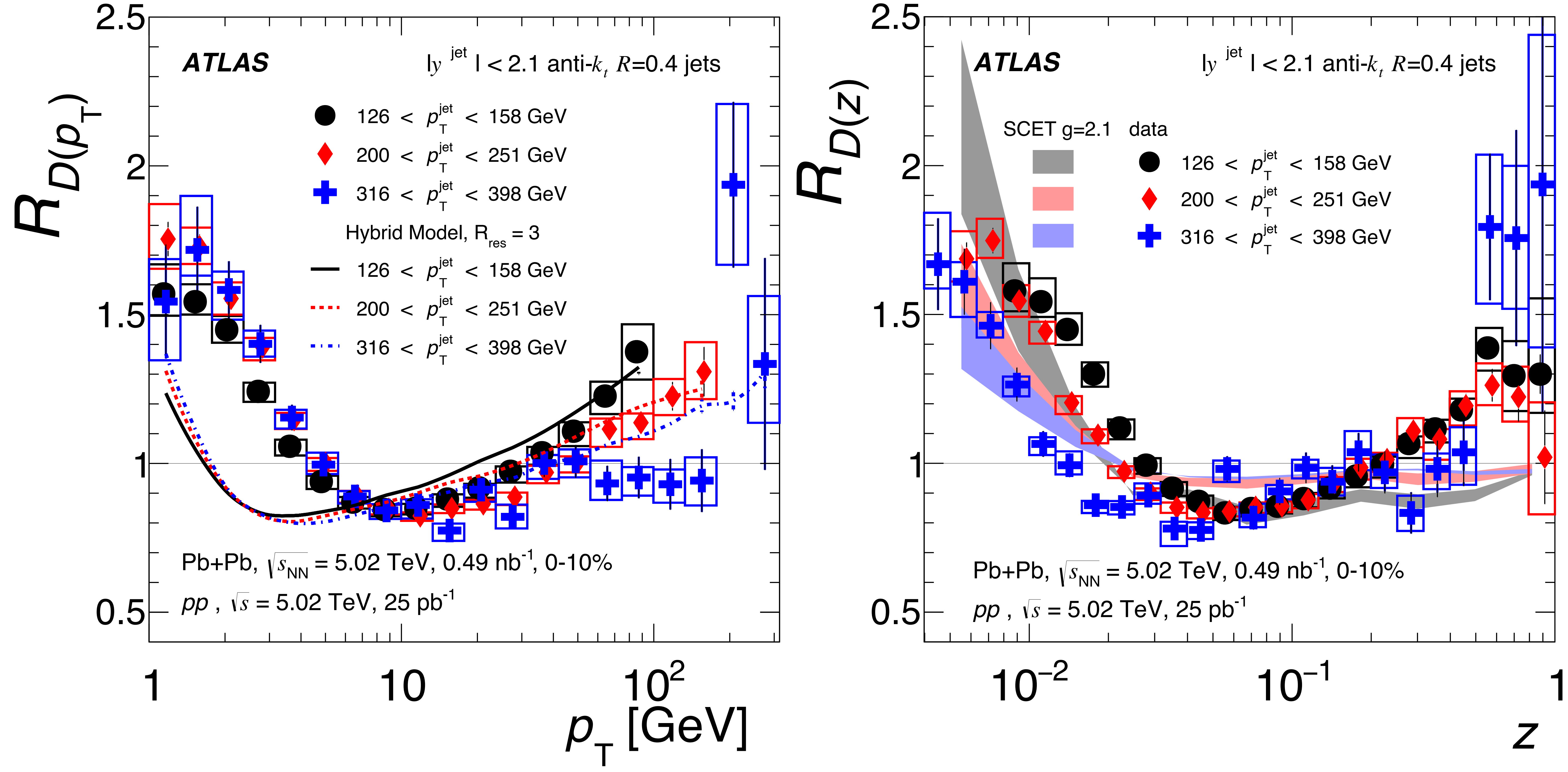
- Hint of energy recovery in central collisions, important constraint on predictions

Jet profiles

CMS *JHEP* 1805 (2018) 006



ATLAS *Phys. Rev.* C98 (2018) 024908

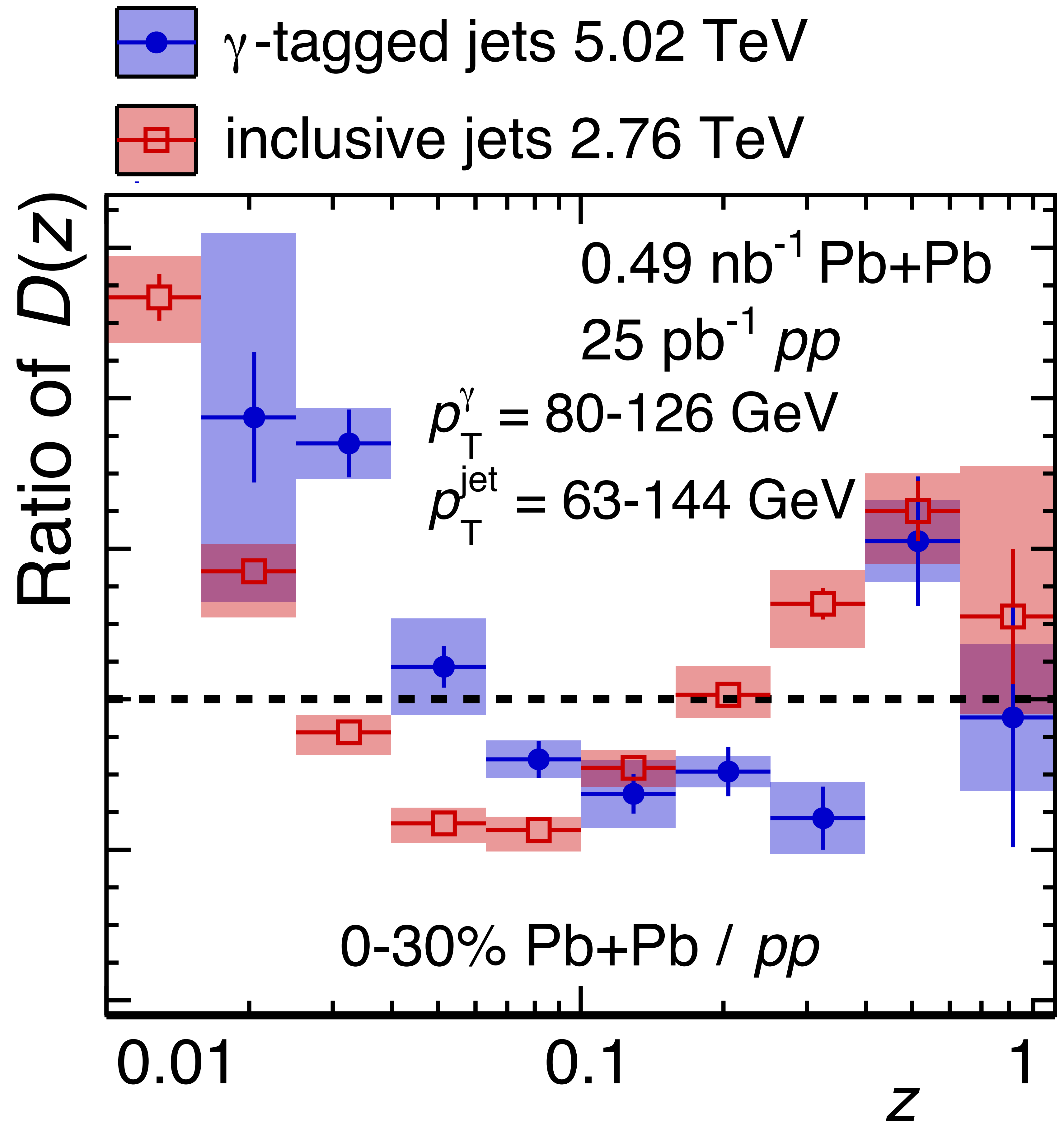


- Consistent with radial profile results
- Tensions on model predictions

- Low-p_T (z) enhancement at large Δr
- More collimated at high-p_T (z) (?)

γ-jets and jet charges

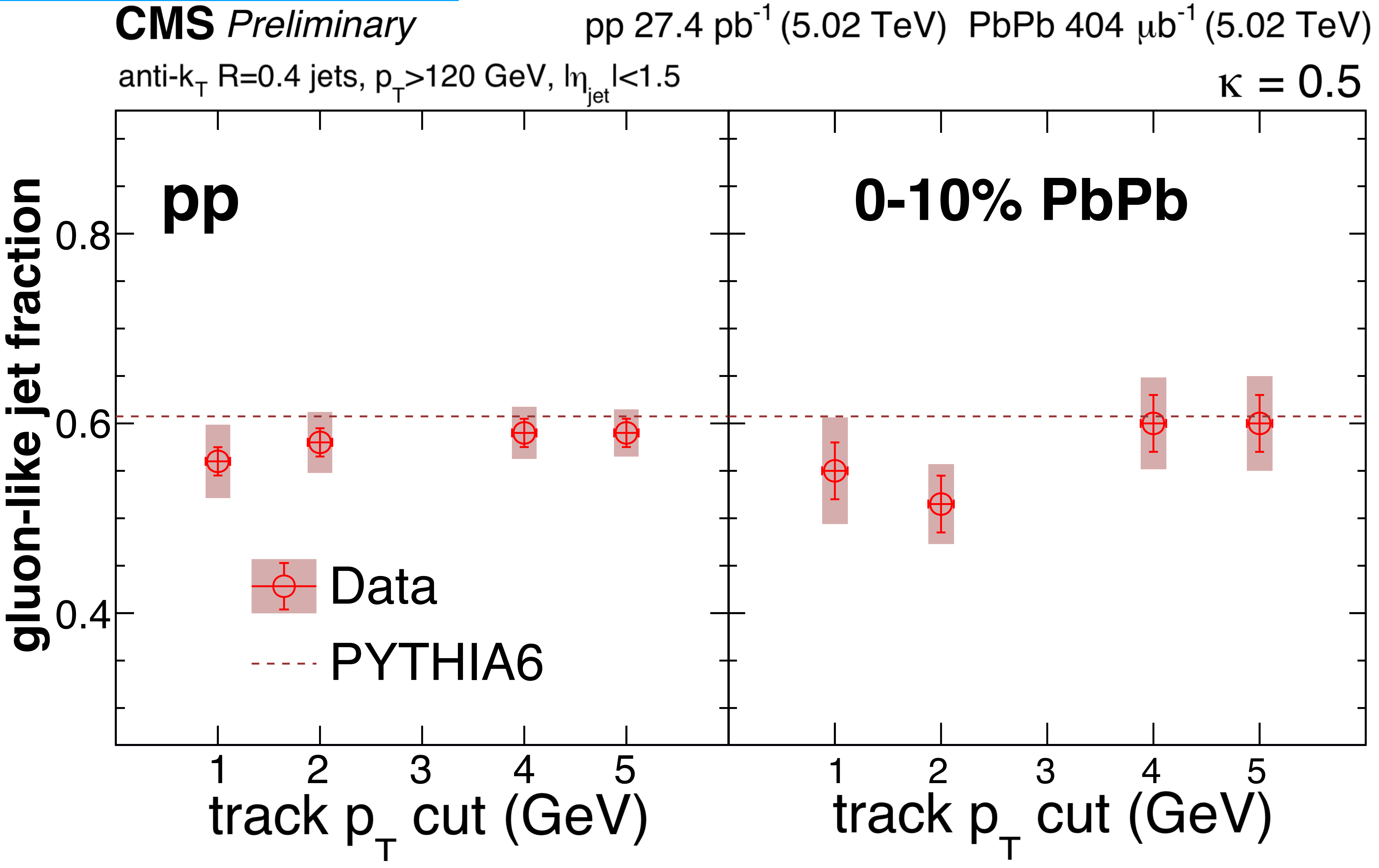
ATLAS *Phys. Rev. Lett.* **123** (2019) 042001



- γ-jets vs inclusive jets

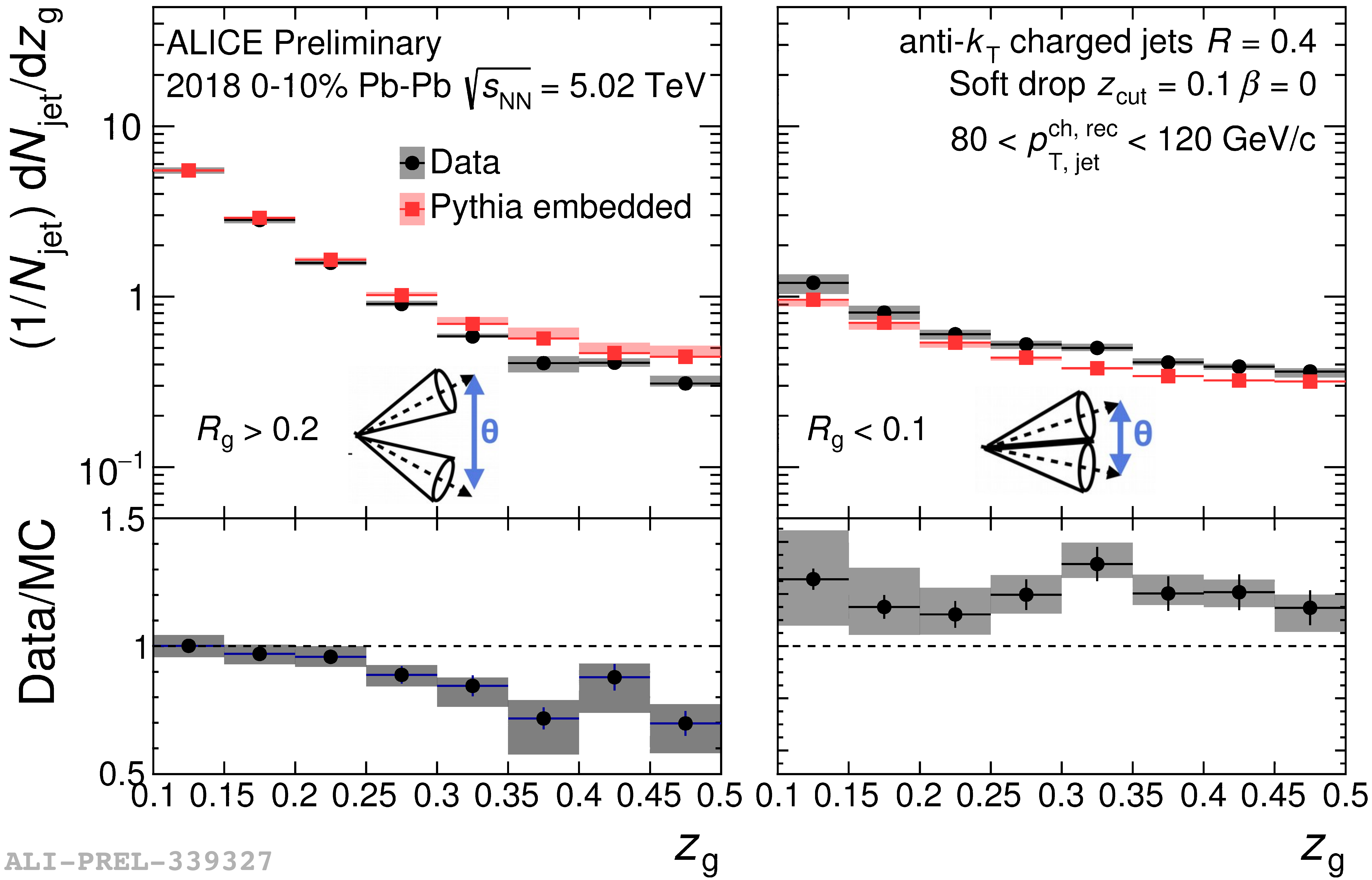
➡ Quark / gluon jets

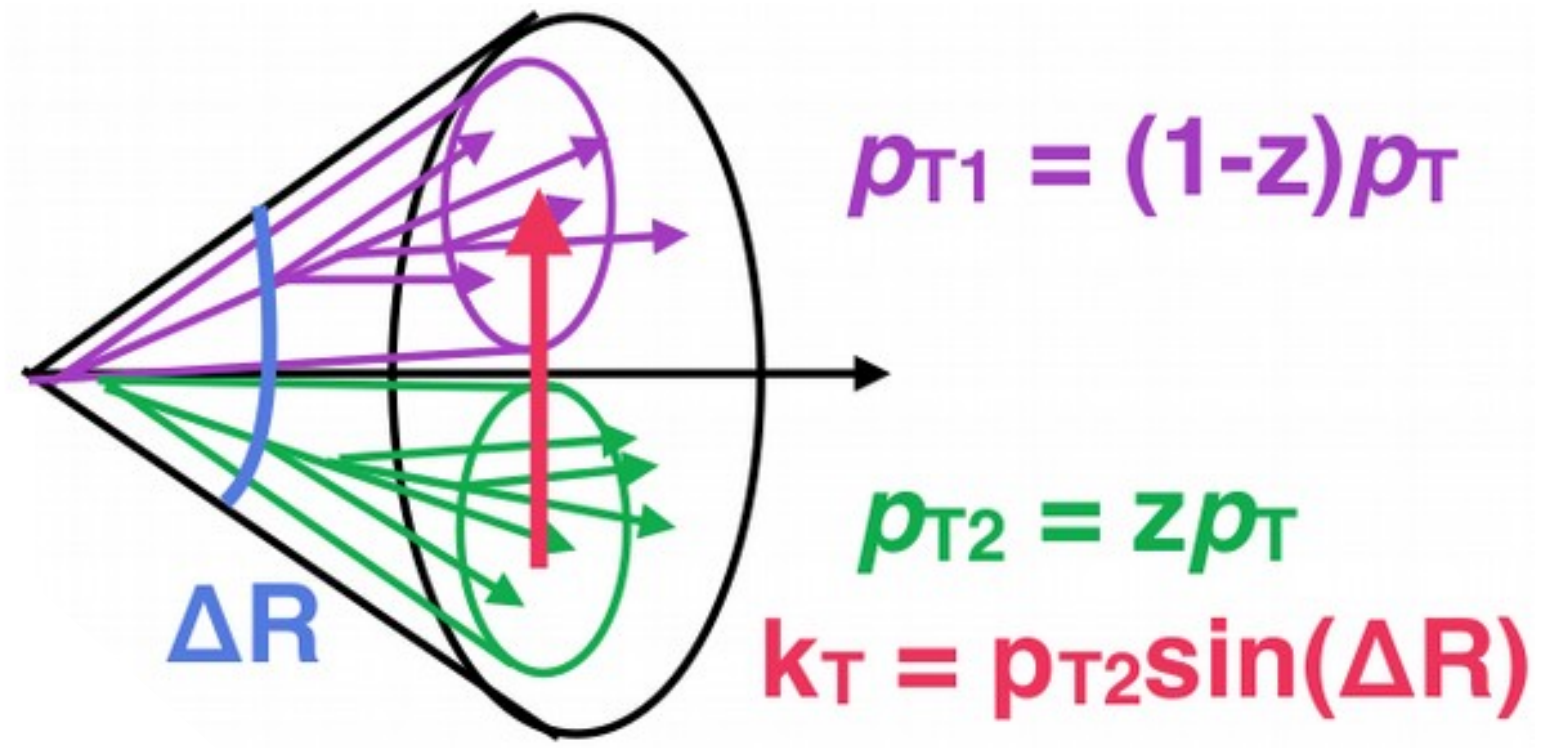
CMS-PAS-HIN-18-018



- No significant modification observed in Pb–Pb

Jet grooming



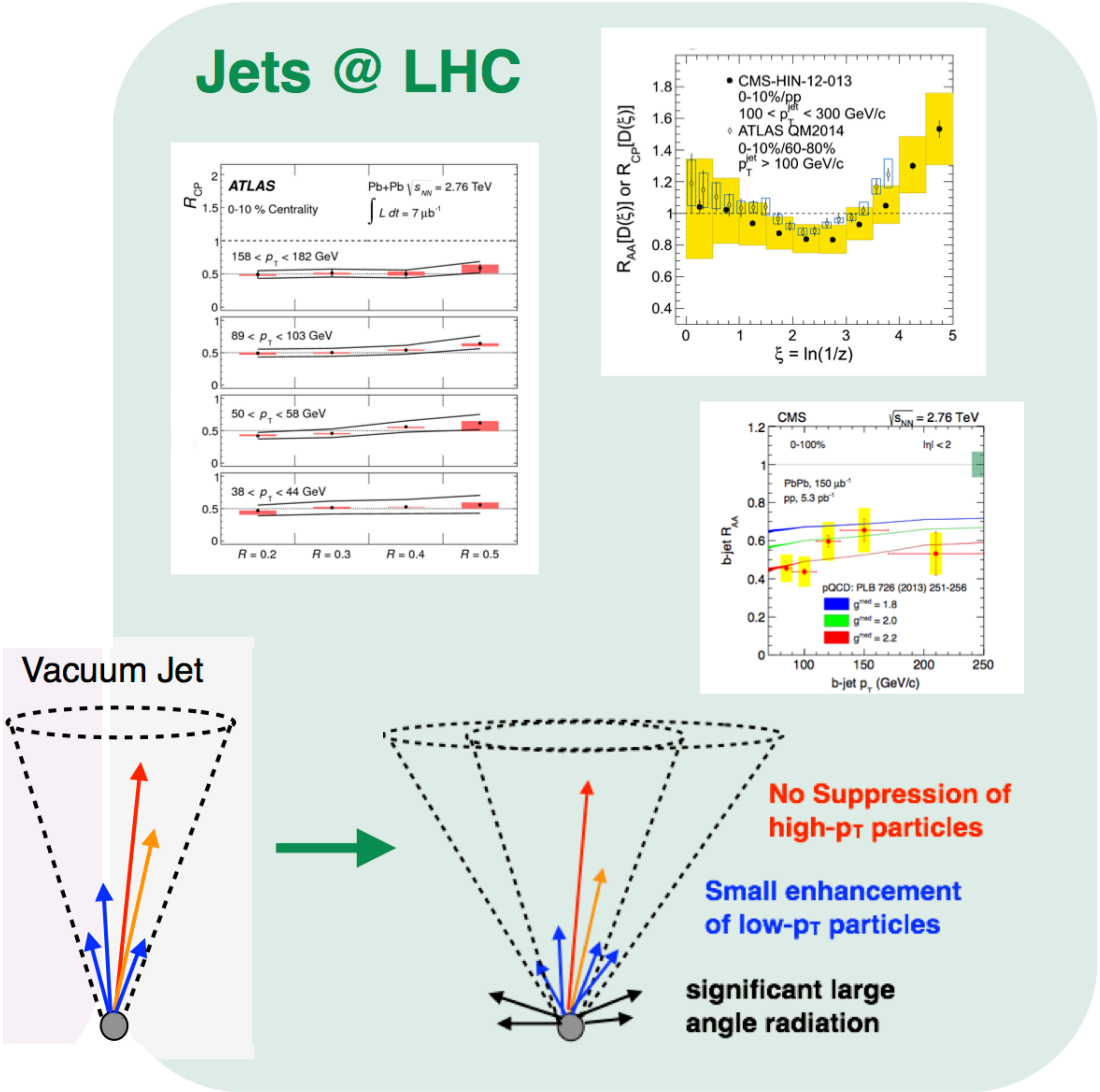


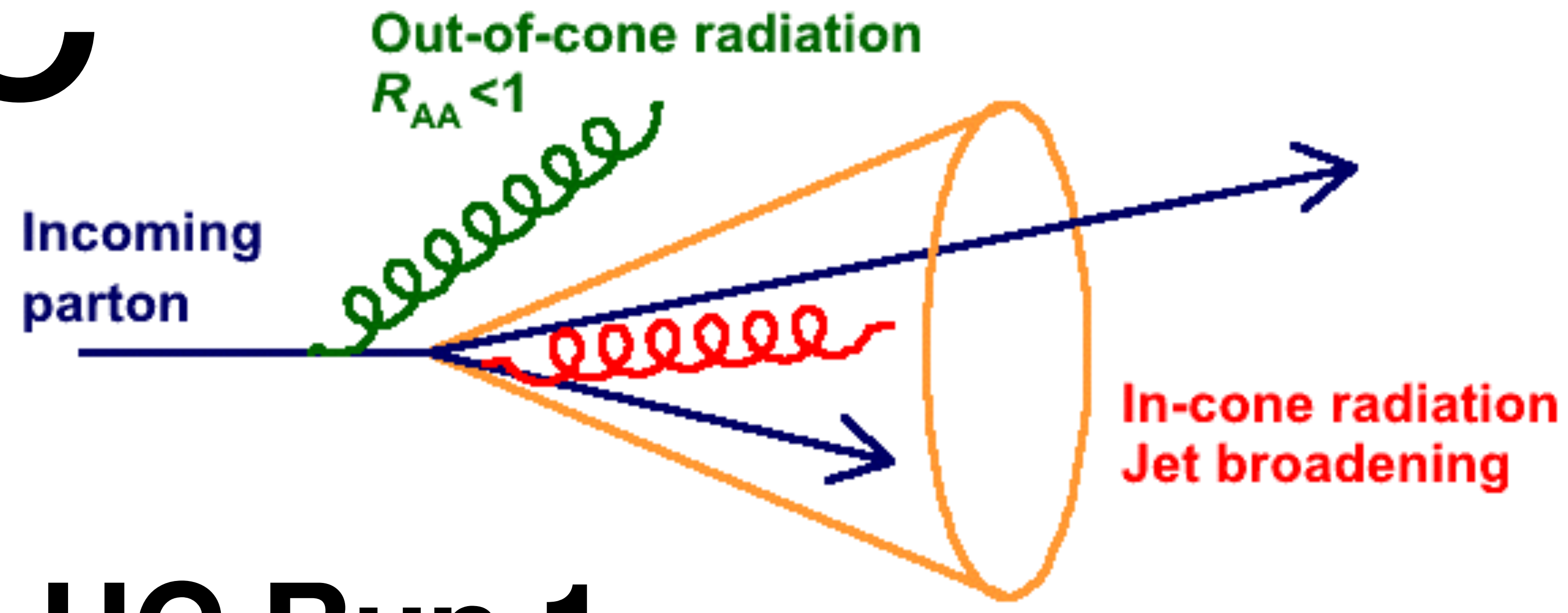
$$z_g = \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}}$$

- Suggest more collimated and harder core jets in Pb–Pb w. r. t. pp

Jet quenching at the LHC

arXiv:1502.02730





Since LHC Run 1

- In-cone: more collimated hard core
- Out-of-cone: large energy redistribution

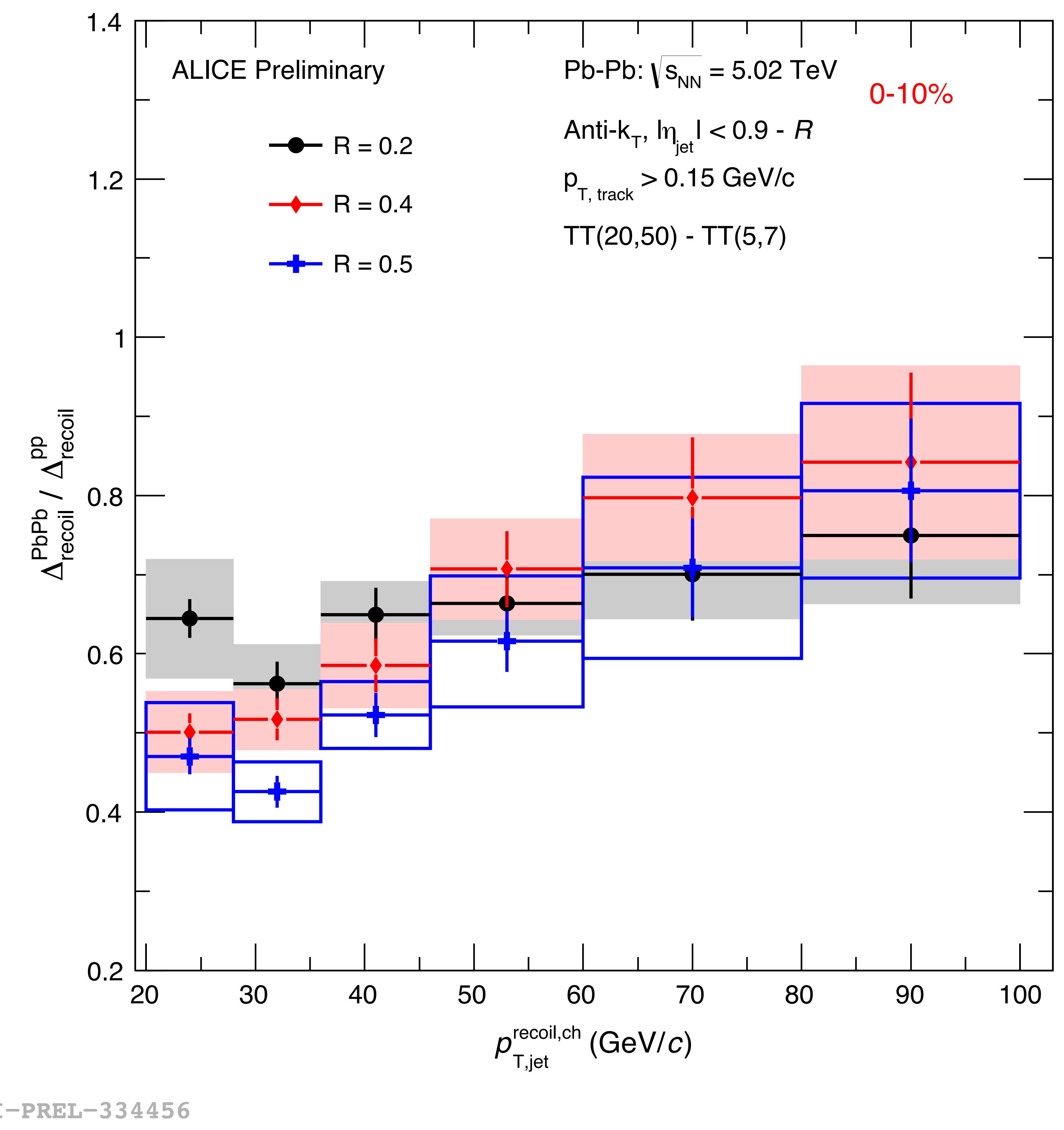
LHC Run 2

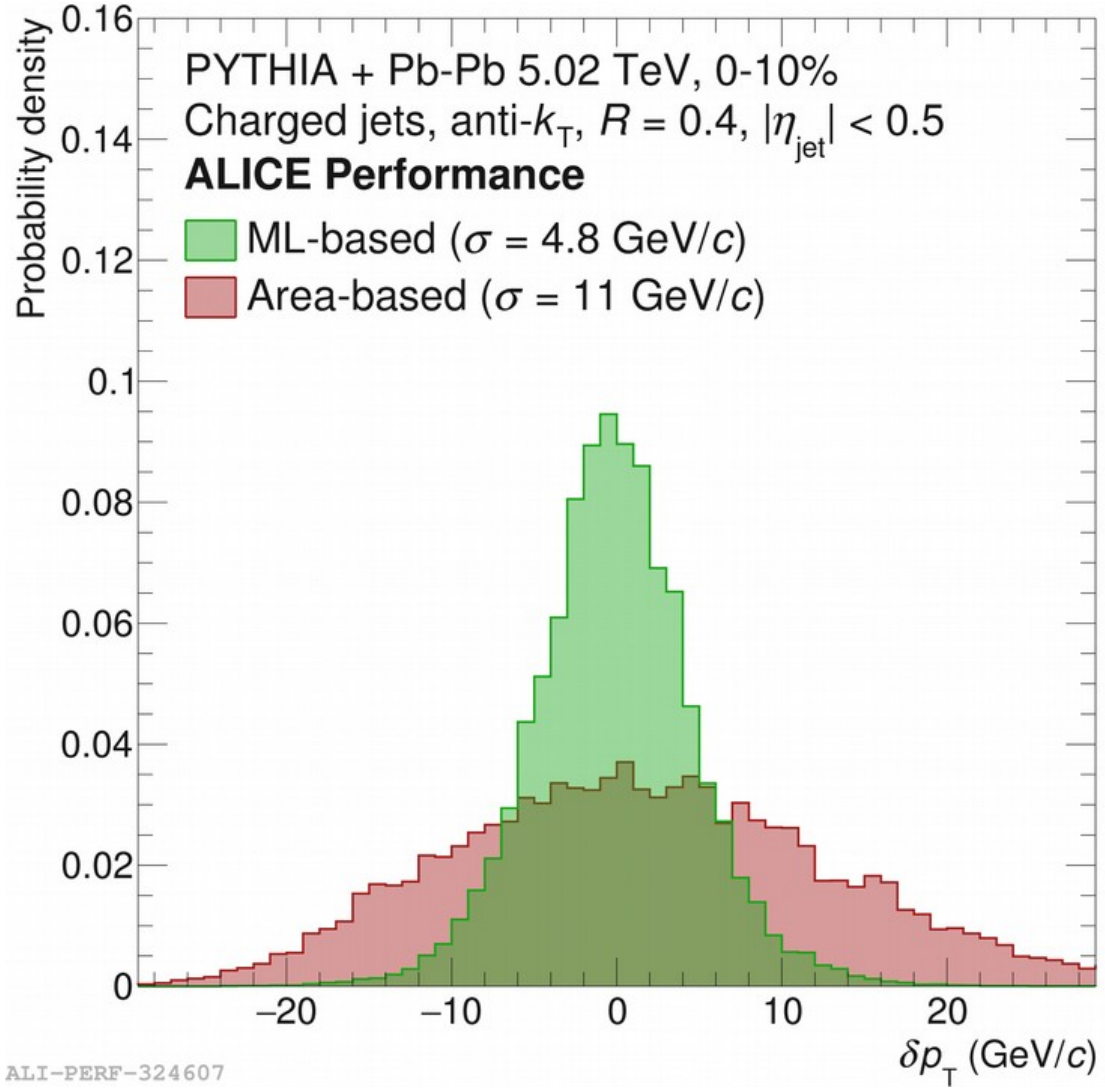
- More precise, more differential studies

Challenge

- Mapping energy (re)distribution
- Low-p_T large and radius jets

Toward low-p_T and large radius jets





Semi-inclusive measurements

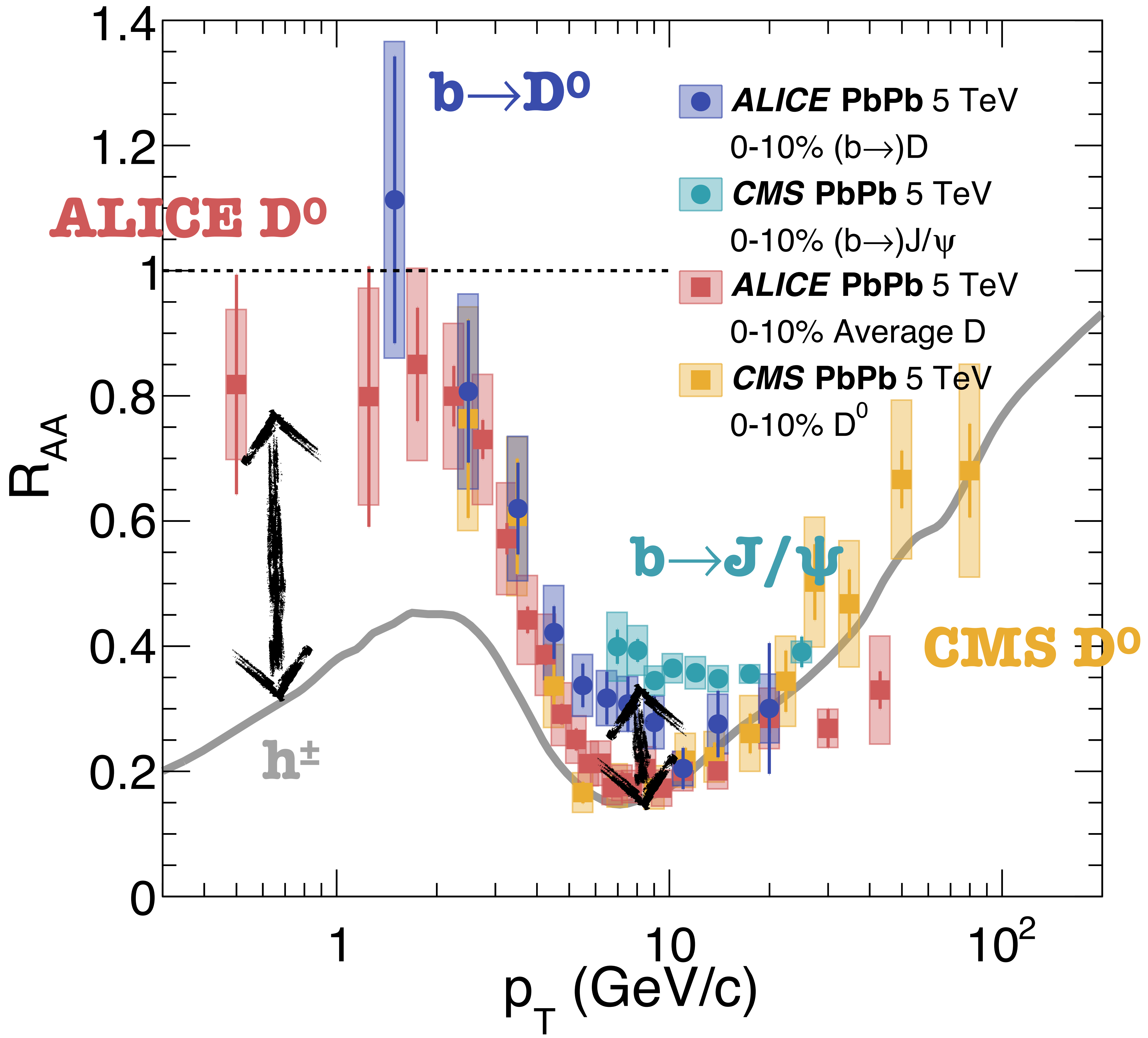
- Dependent on knowing of FF

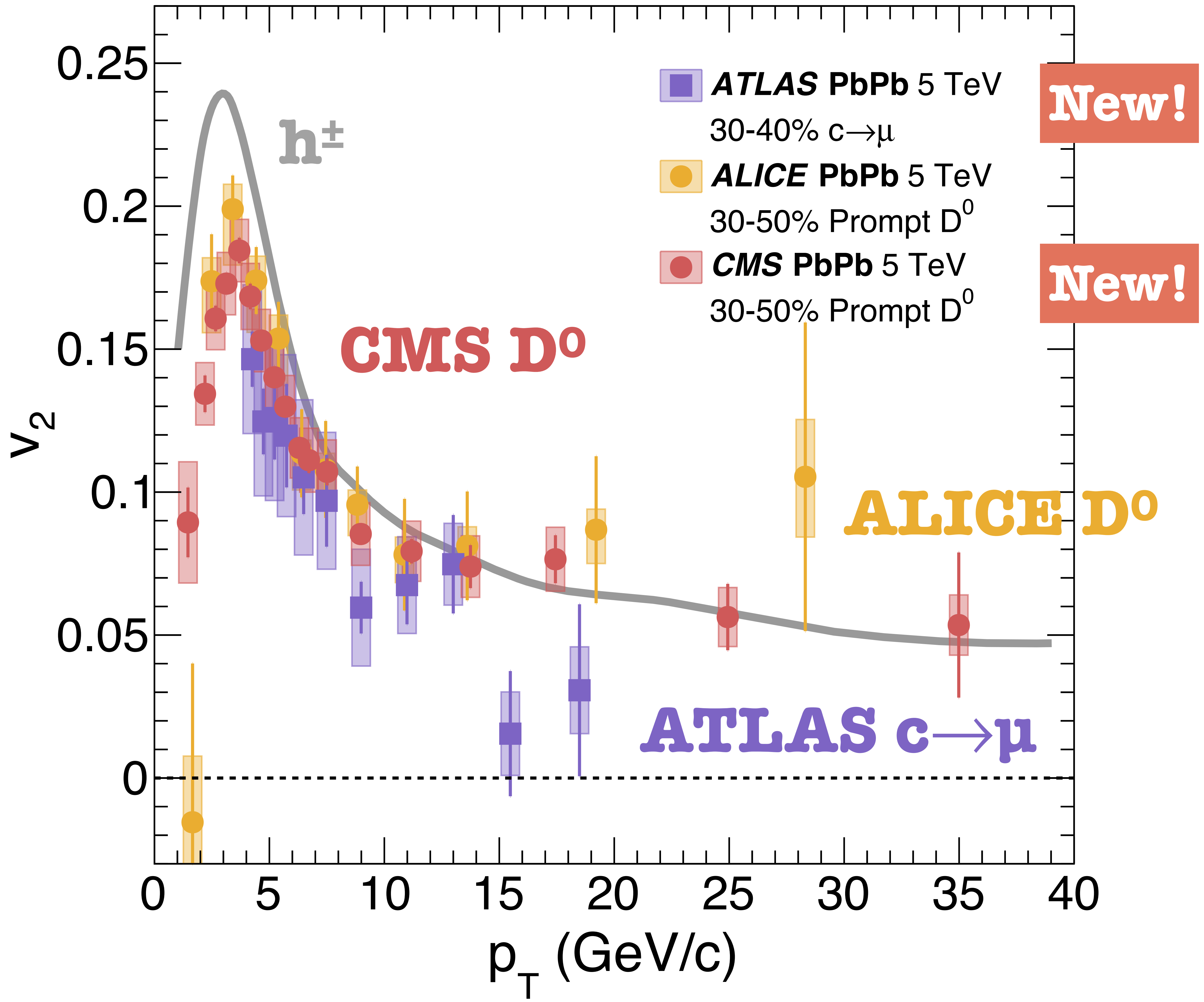
ML-based studies

- Sensitive to models

Heavy quark transport

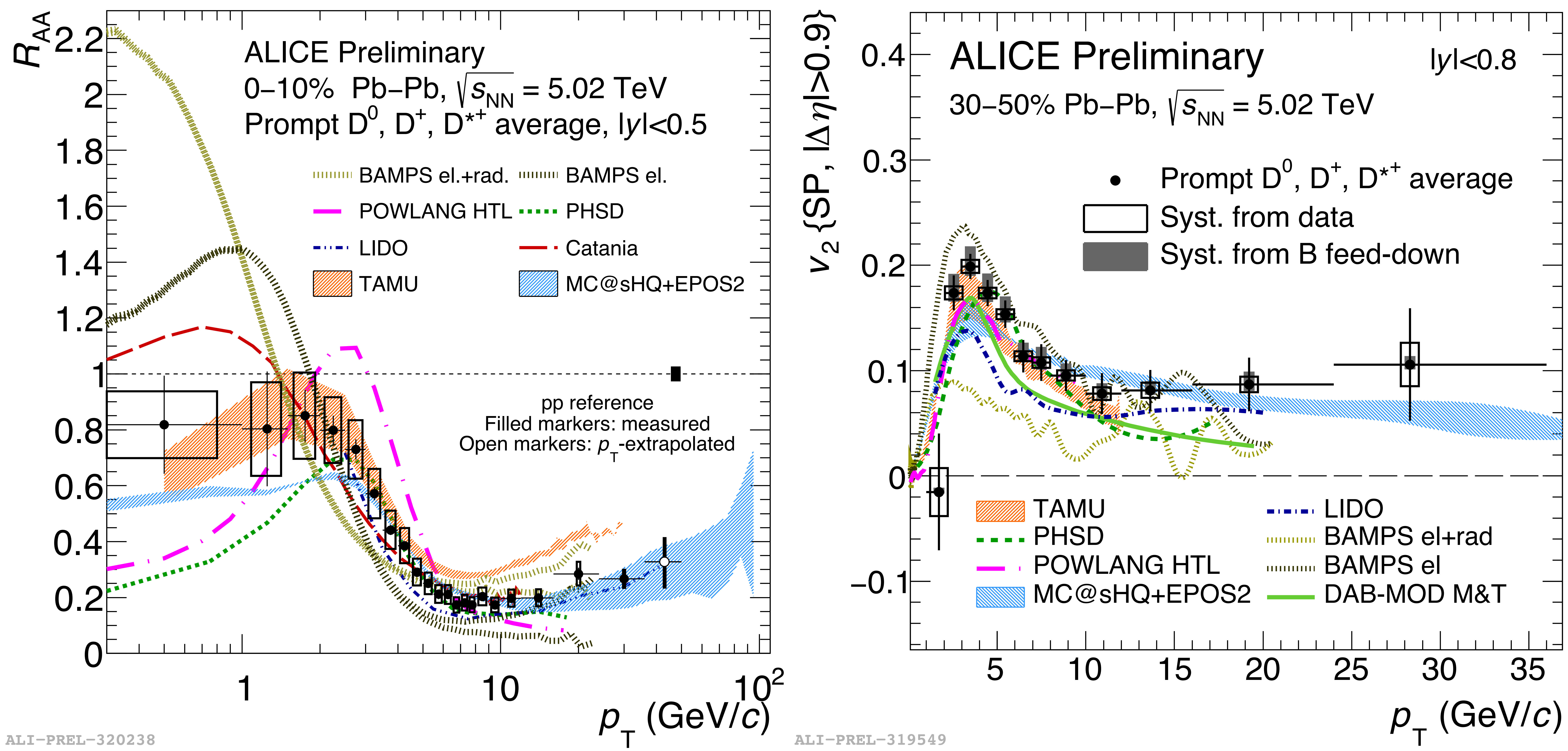
J. Wang QM'19





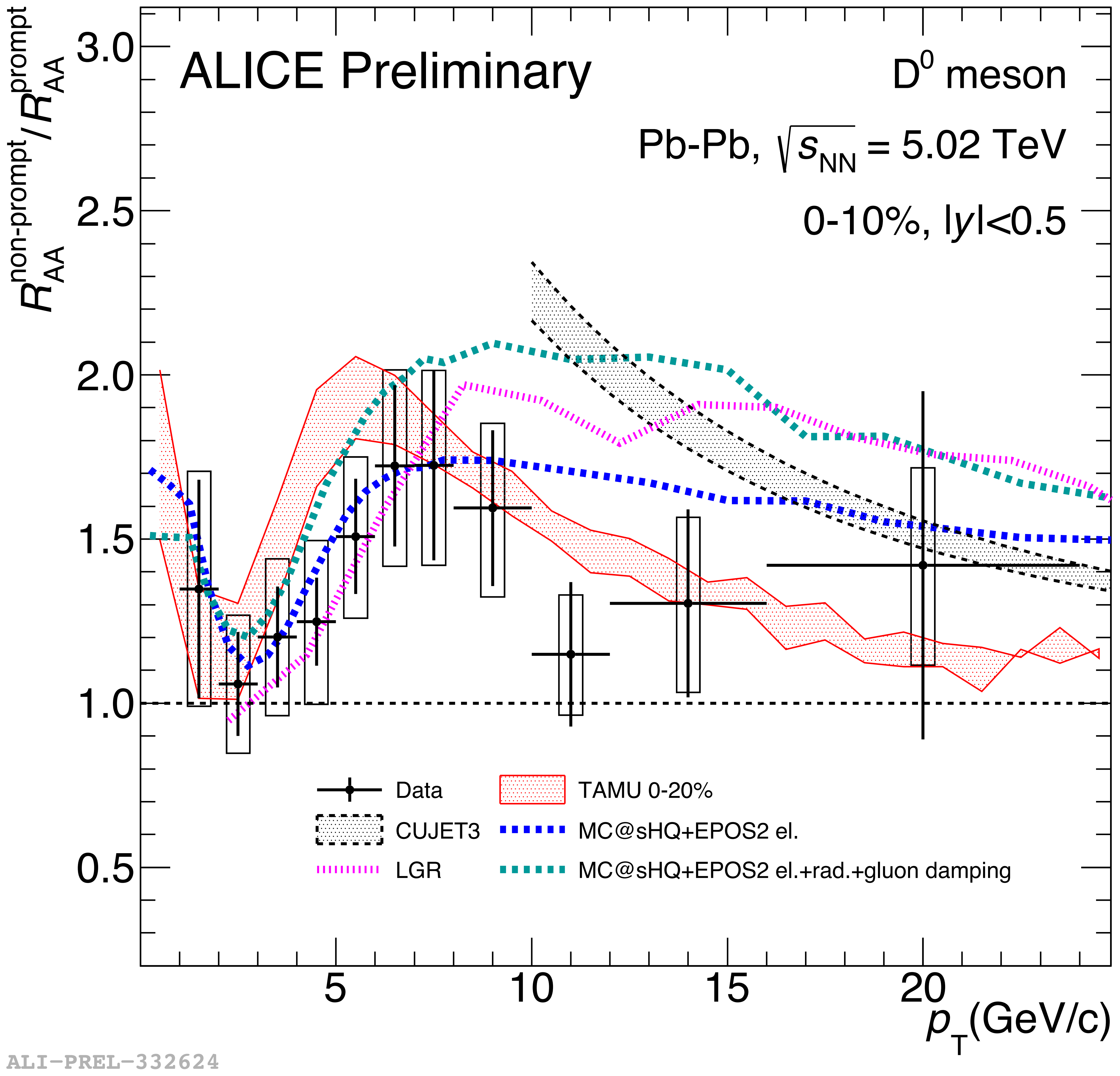
- **LHC Run 1** hint of R_{AA} hierarchy, R_{AA} and v_2 puzzle
- **LHC Run 2** more players on the table, higher precision, more complemented

Charm quark transport

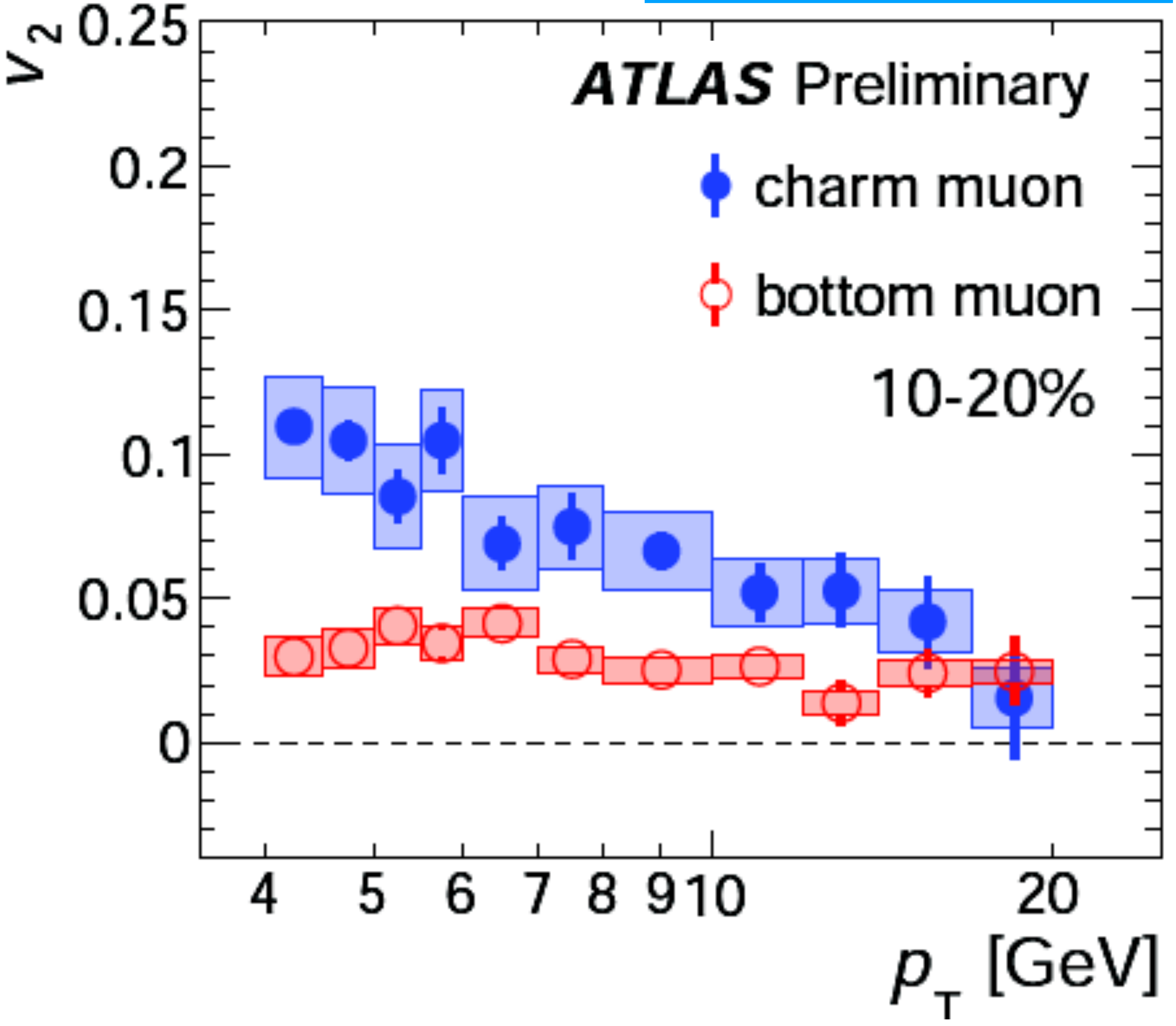


- Improved discrimination power for models
- Recombination and elastic energy loss are important to describe data at low p_T

Beauty quark transport



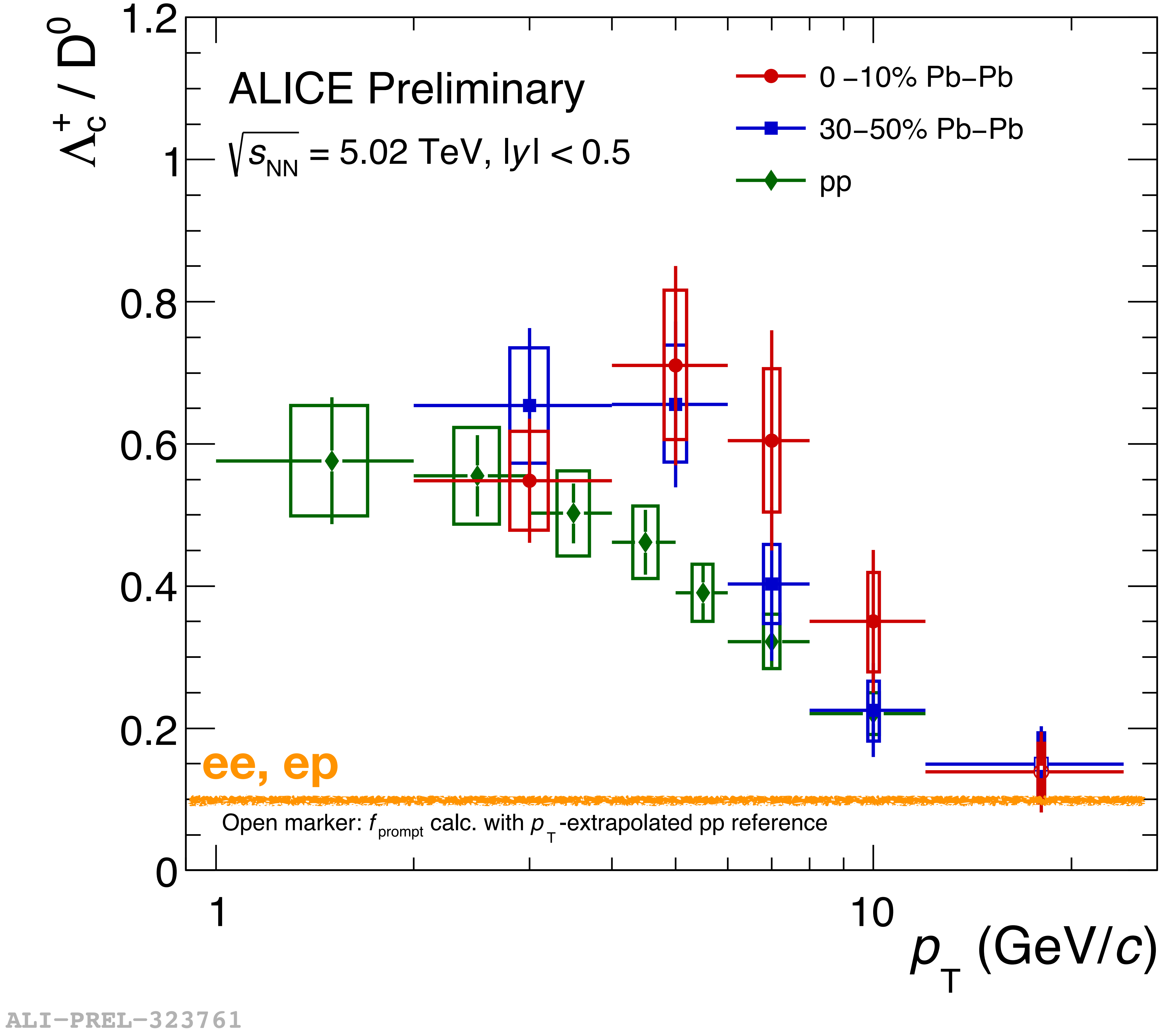
ATLAS-CONF-2019-053



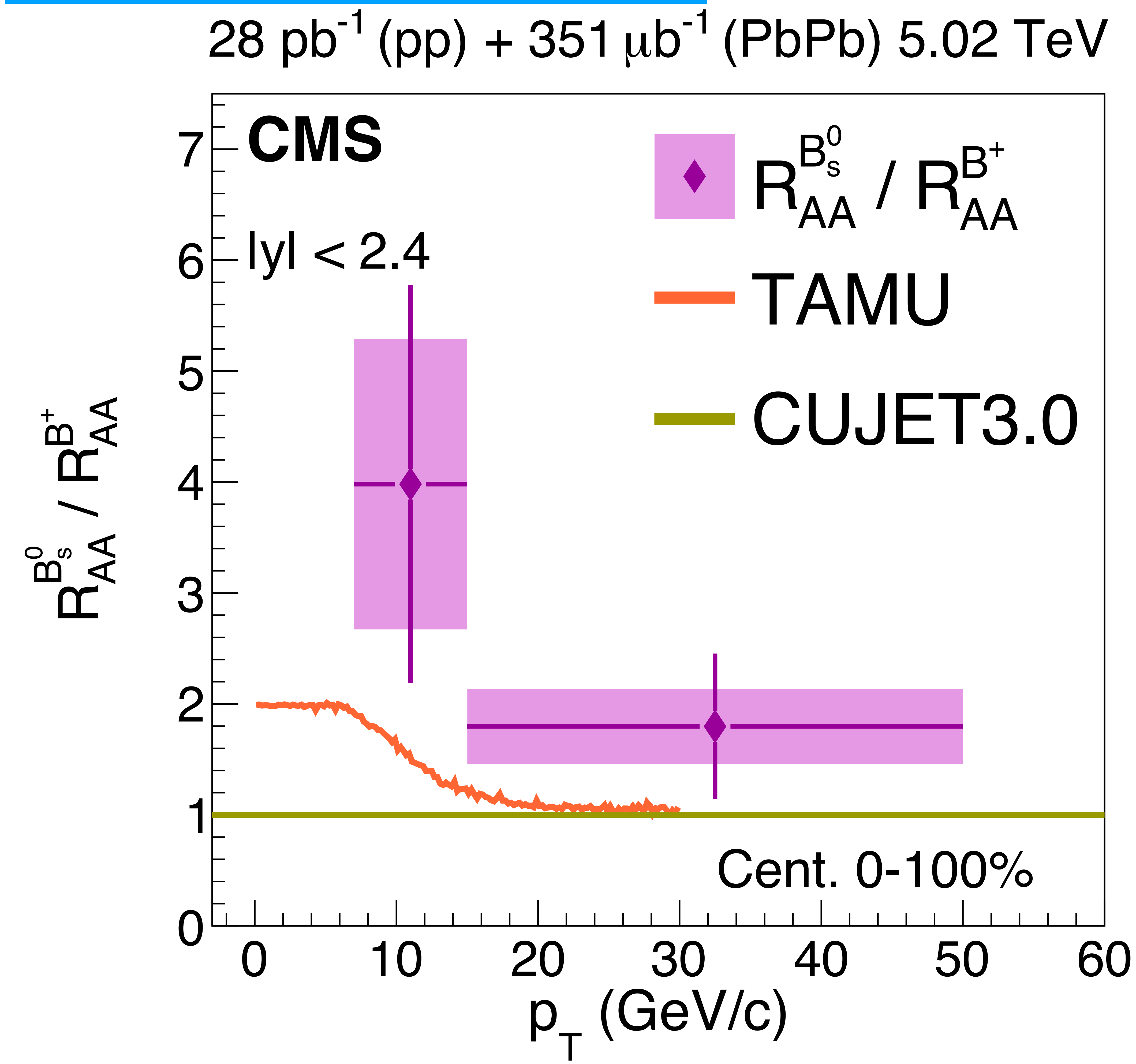
- Double ratio of R_{AA}(D←B) / R_{AA}(D)
- Further constraint on beauty transport

- Beauty quarks are flowing
- Effect less pronounced than charm

Heavy quark hadronization in bulk



CMS *Phys. Lett.* B796 (2019) 168

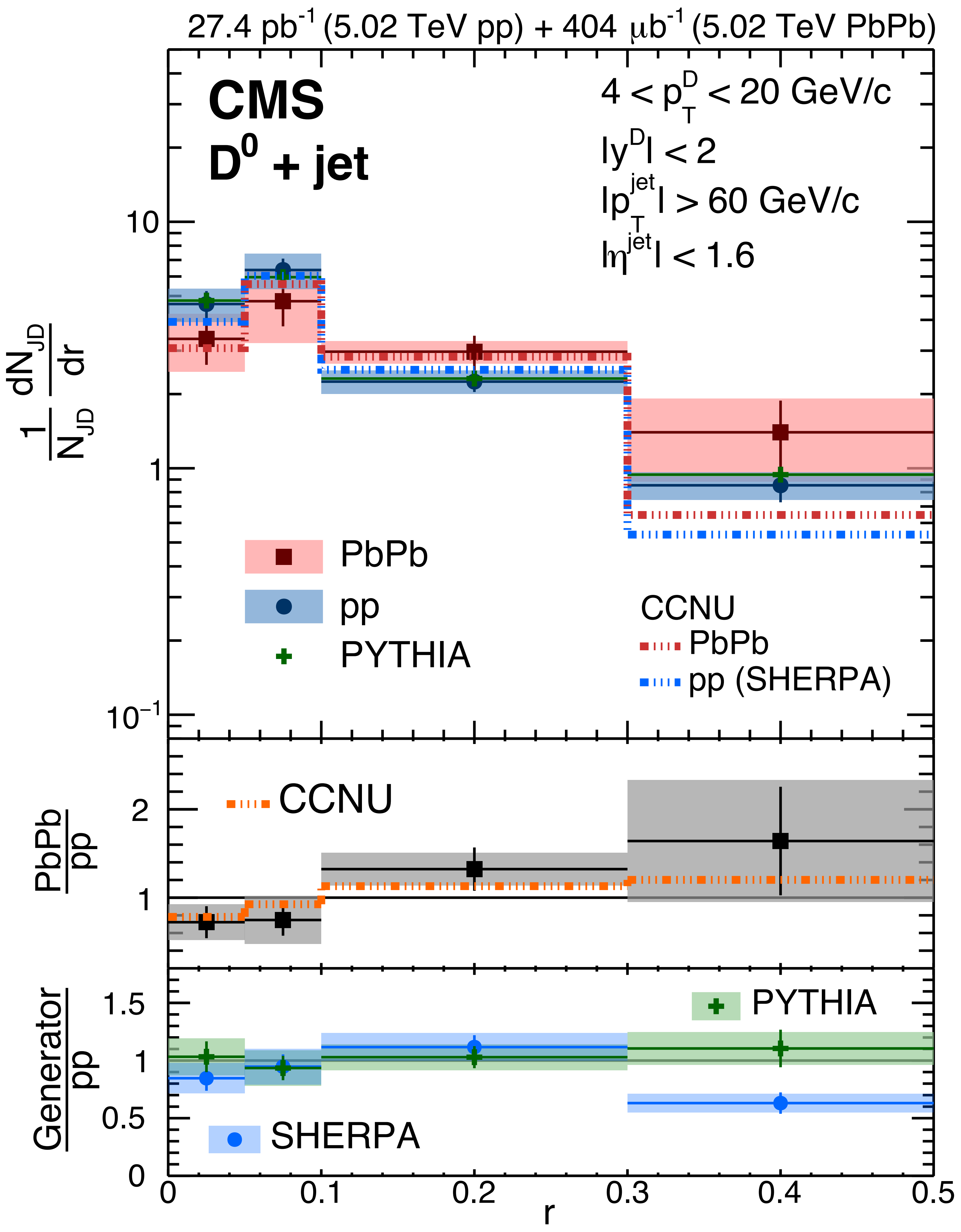


- Hint of Λ_c enhancement in Pb–Pb
- Tensions on fragmentation

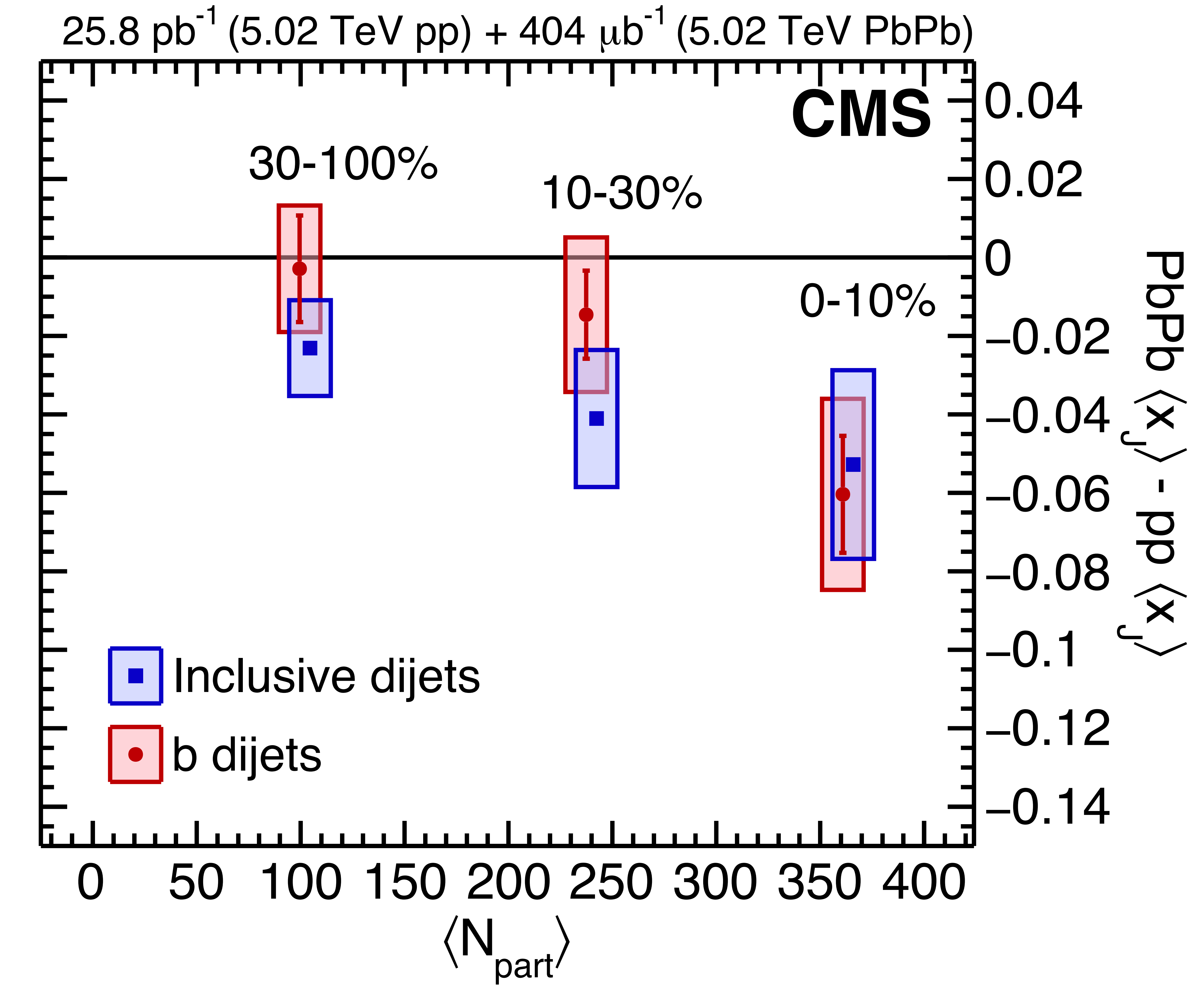
- Hint of enhanced B_s R_{AA}
- Challenge on predictions

Heavy-flavour jets

CMS-HIN-18-007



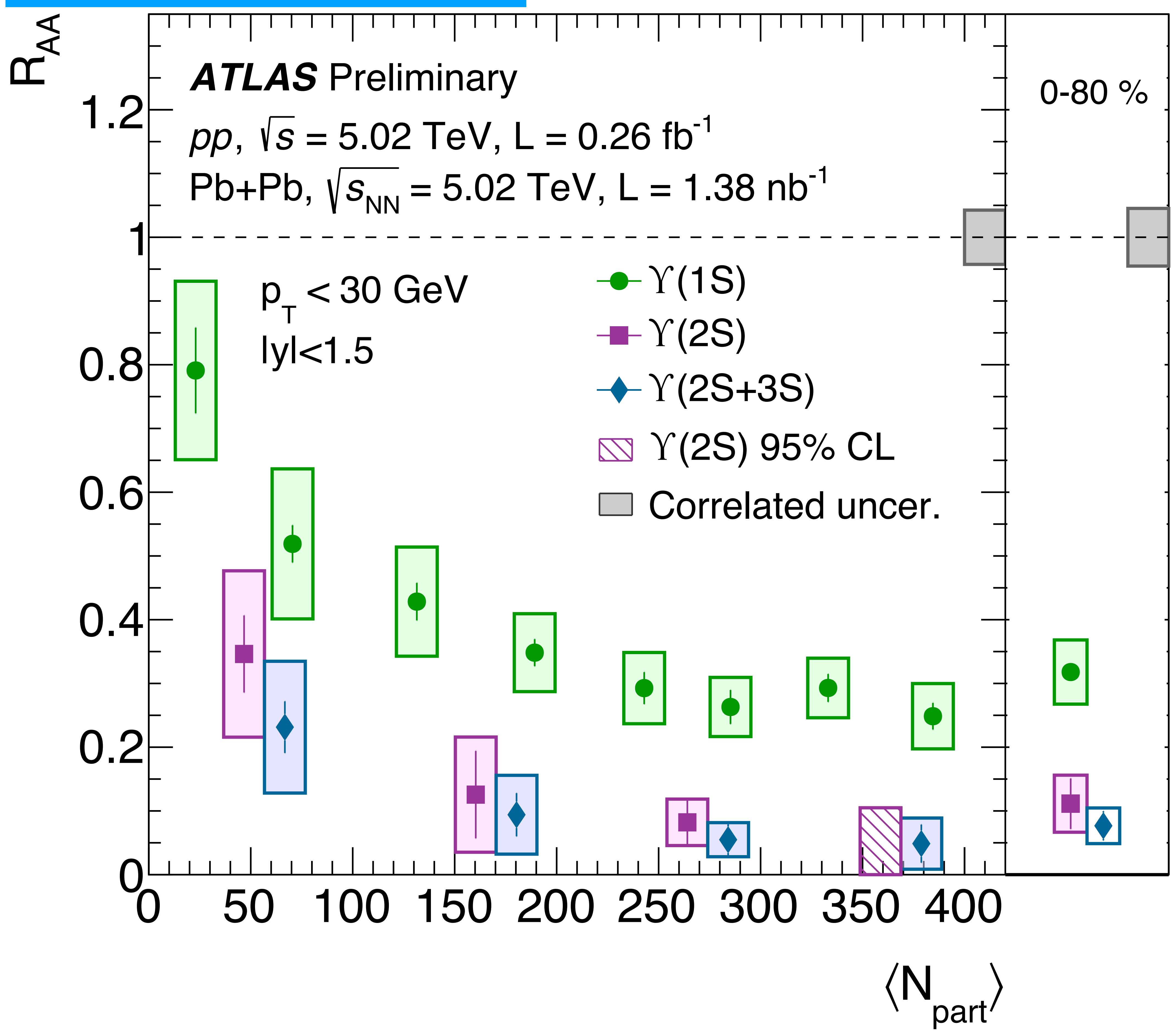
CMS *JHEP* 1803 (2018) 181



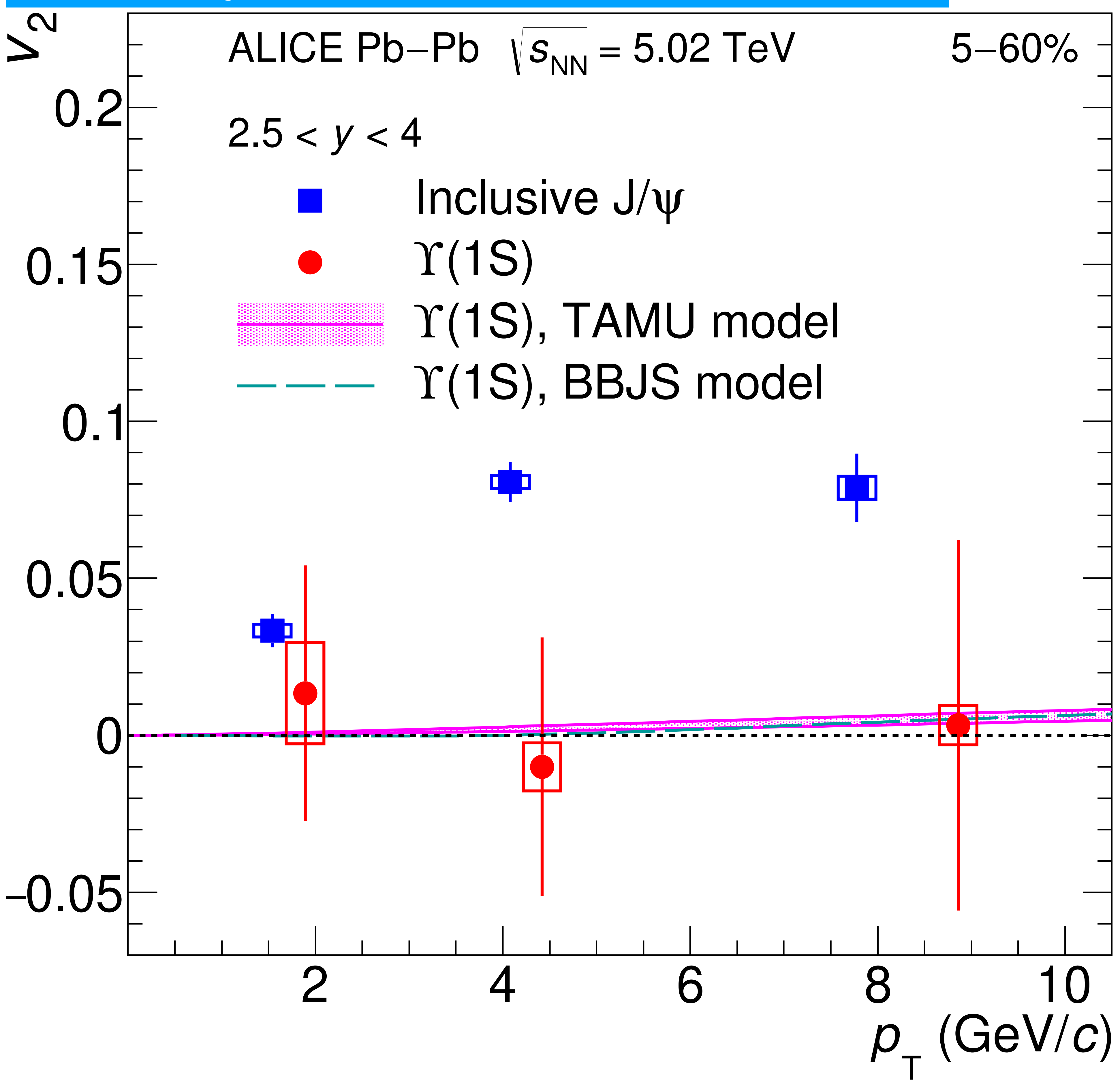
- Hint of wider D meson profile in Pb–Pb than pp
- Imbalance / suppression of b-jets is consistent with inclusive jets for the most central collisions

Bottomonium

ALTAS-CONF-2019-054



ALICE *Phys. Rev. Lett.* **123** (2019) 192301



- Data suggests the sequential suppression
- Υ(1S) v_2 is consistent with zero — insensitive to regeneration (?)

Conclusion

Charged particle multiplicity

- Energy density reaches ε ~18 GeV/fm^3, collision geometry is important

Anisotropy flow

- More differential studies, new constraints on initial state, η/s, EOS…

Jet production

- Energy redistribution, quark- / gluon-jets, toward low-p_T large radius jets

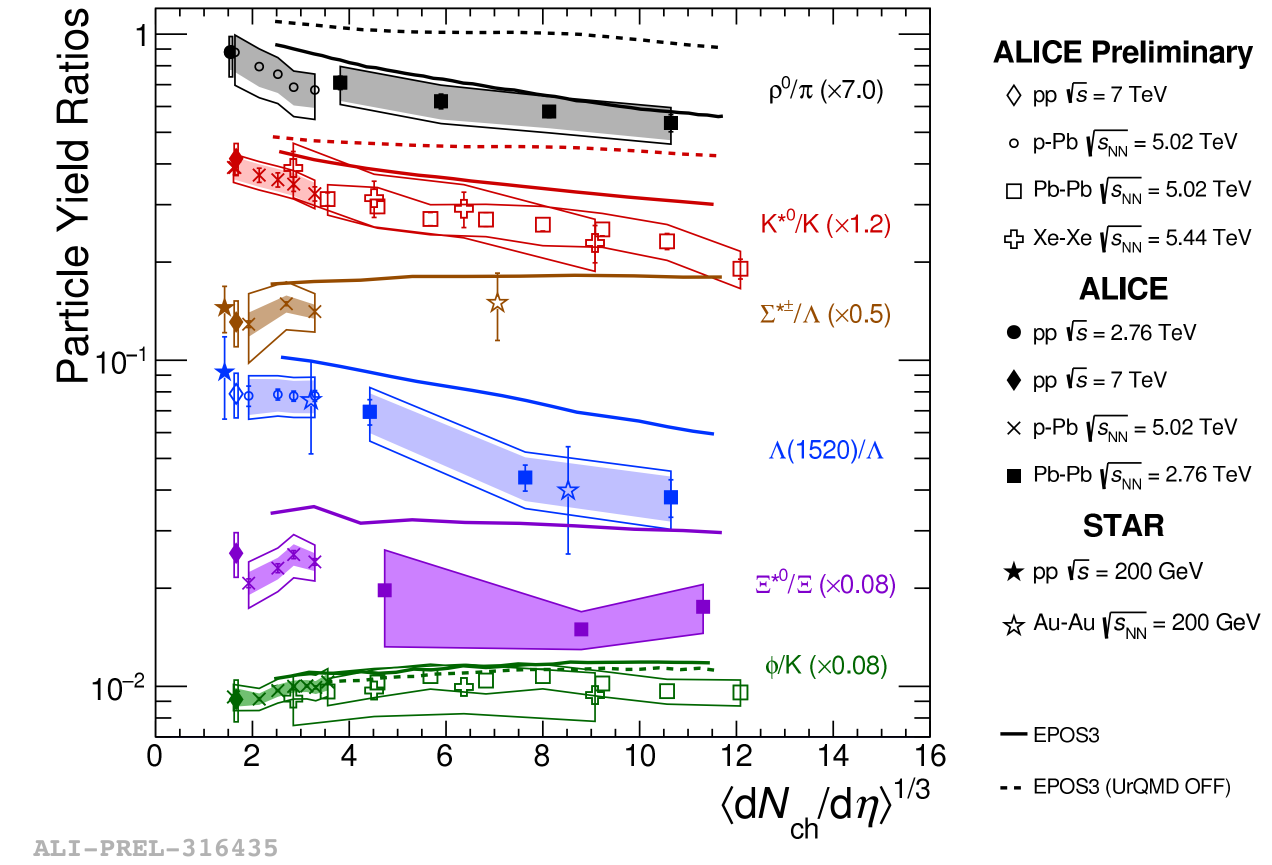
Heavy flavors

- **Open HF** Collisional vs. radiative energy loss, recombination, hadronization
- **Bottomonium** Dissociation vs. regeneration

More topics

Identified particle production Bulk properties, thermodynamics

System size dependence Collision geometry, path-length dependence



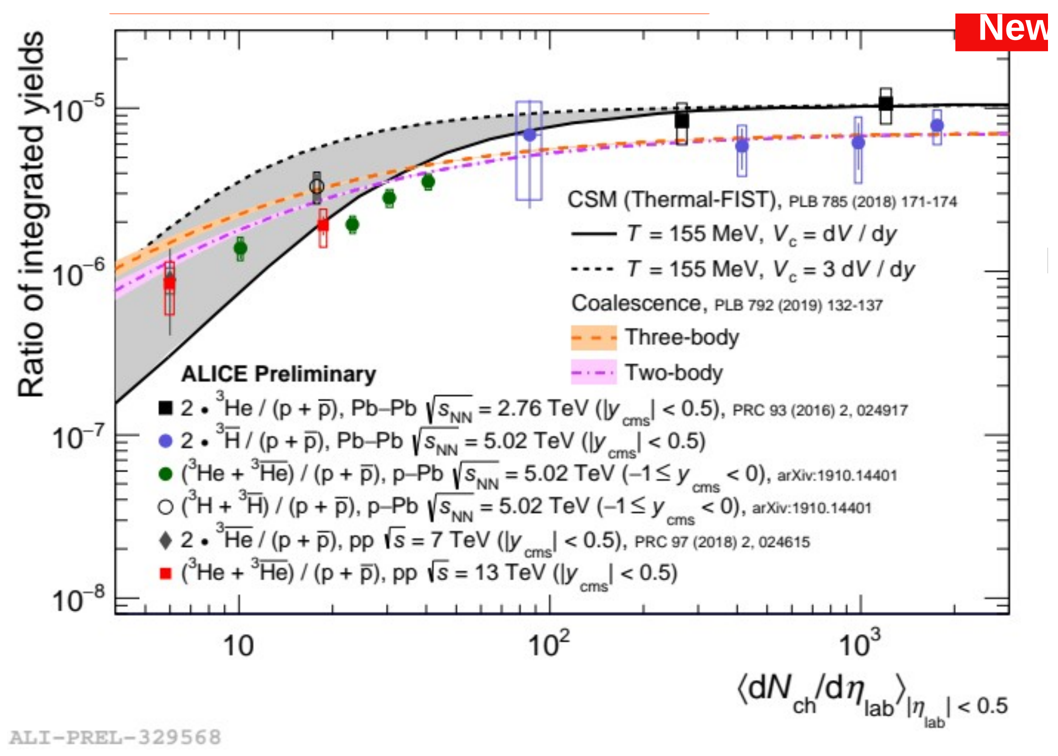
Magnetic effects Fundamental symmetry restoration

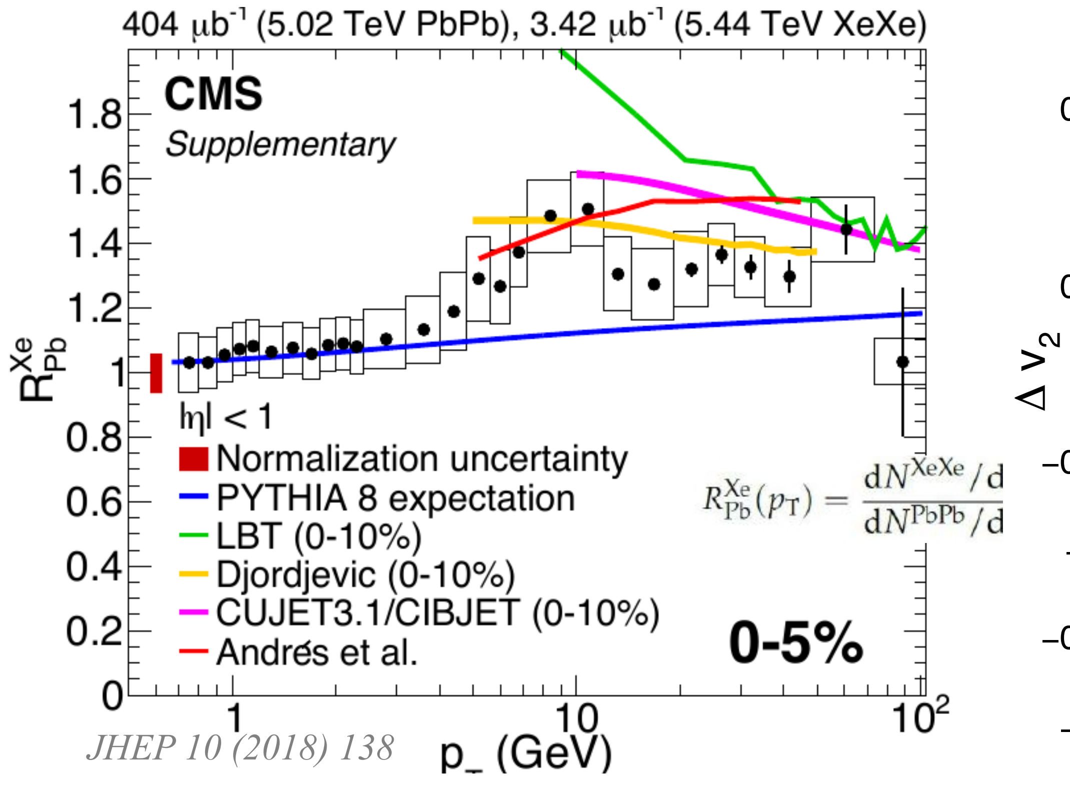
UPC and photoproduction nPDF down to low Bjorken-*x*

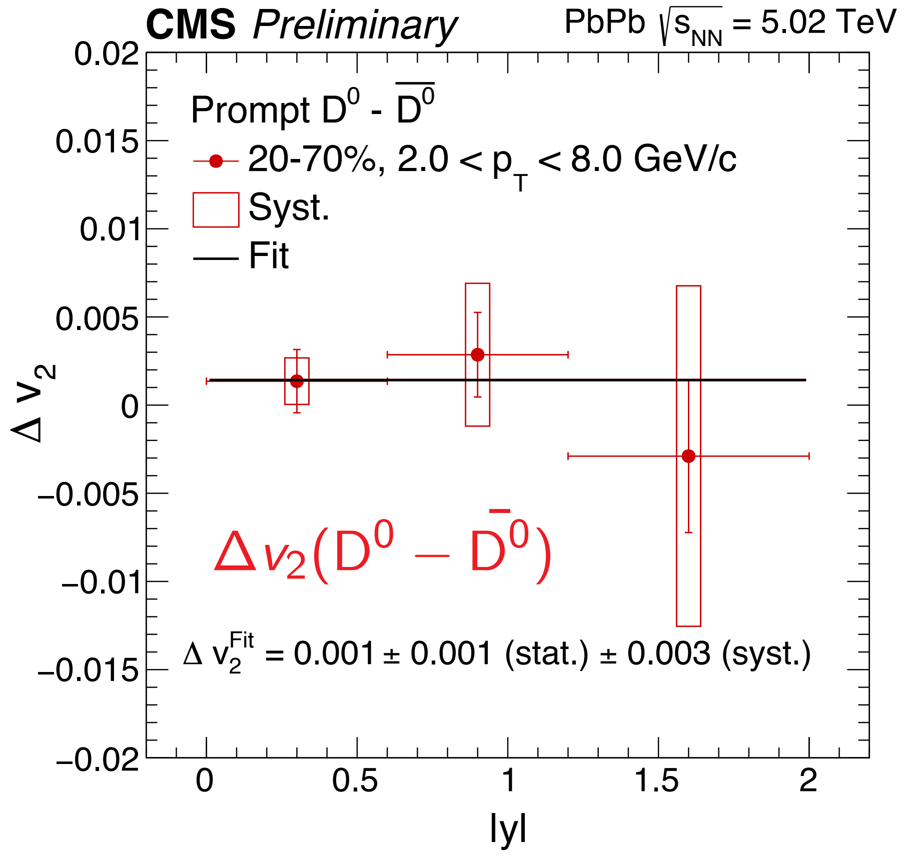
Hadron interactions and light nuclei

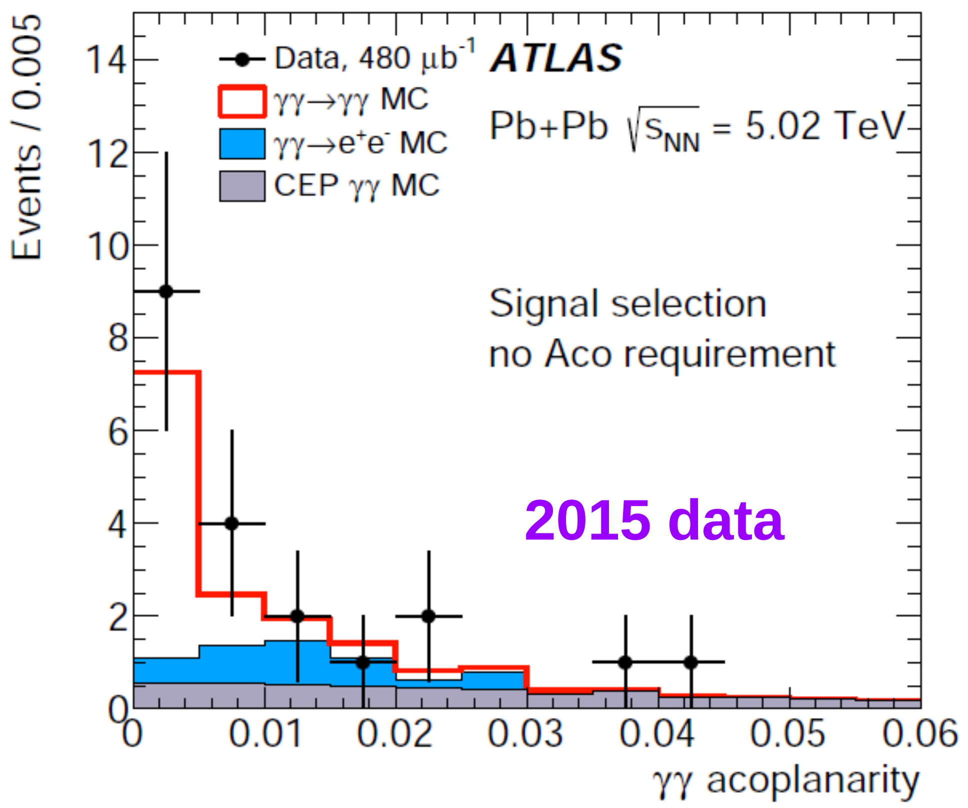
Small systems

...









More topics

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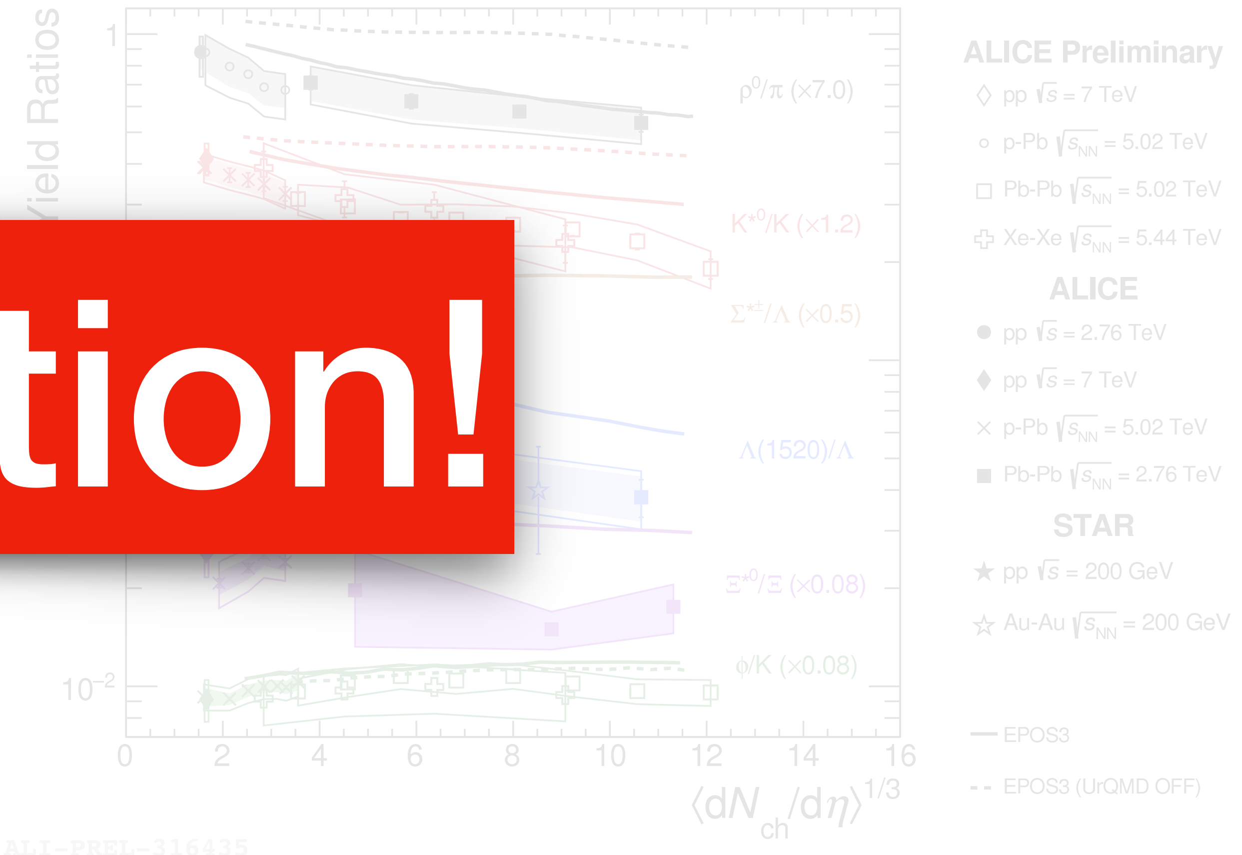
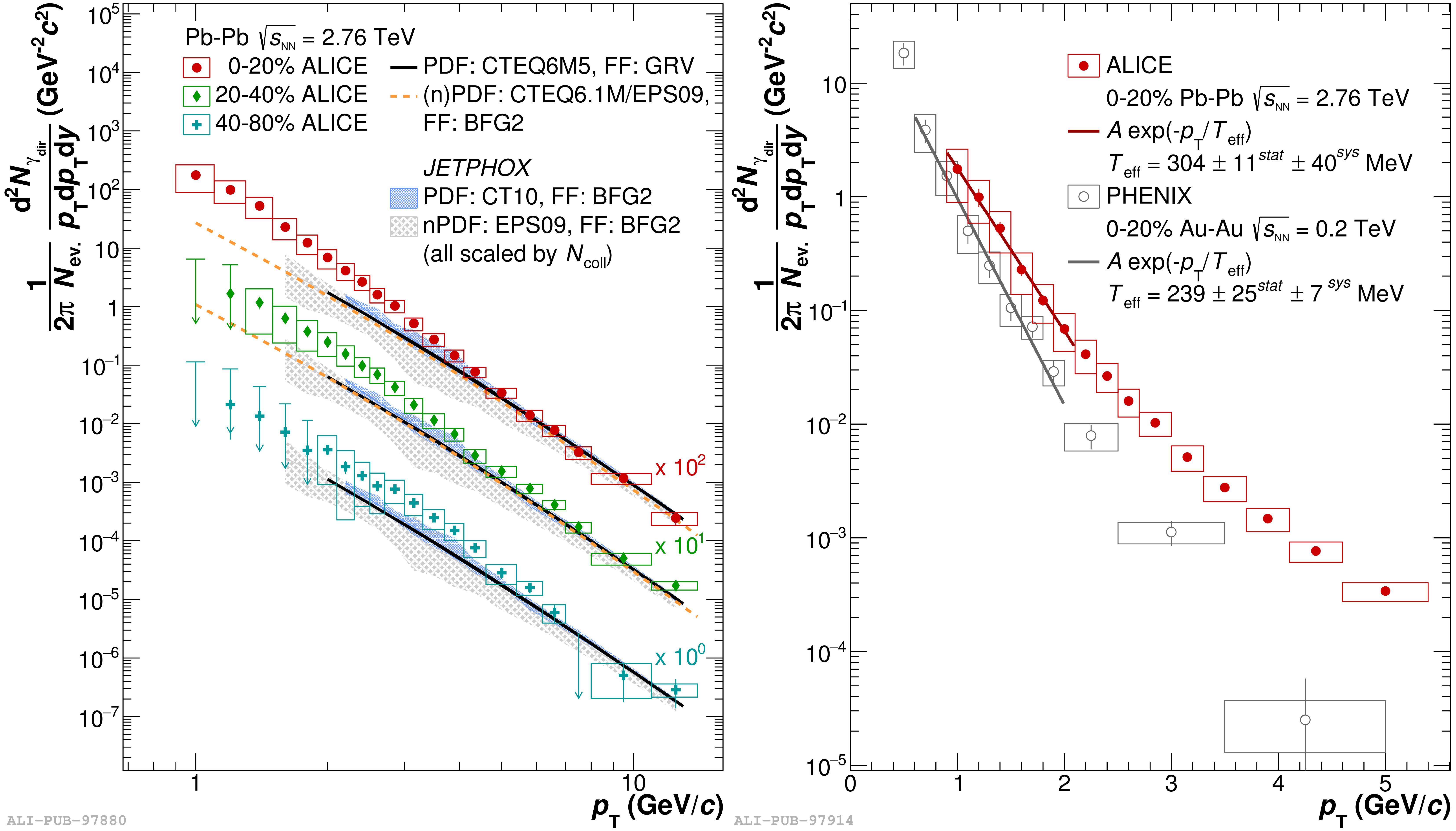


Thanks for your attention!

Backup

Exceeded photon production

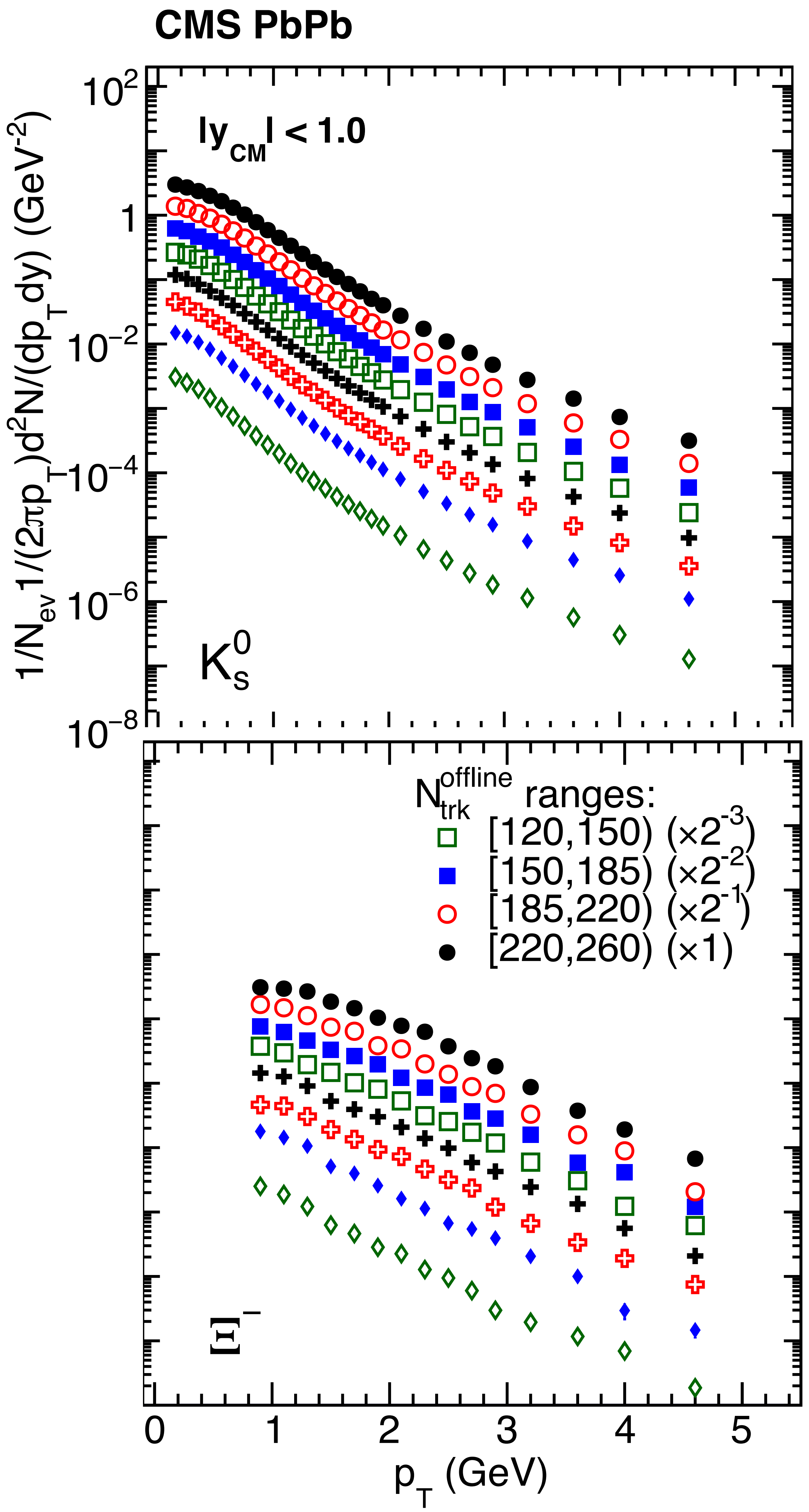
ALICE *Phys. Lett.* B754 (2016) 235

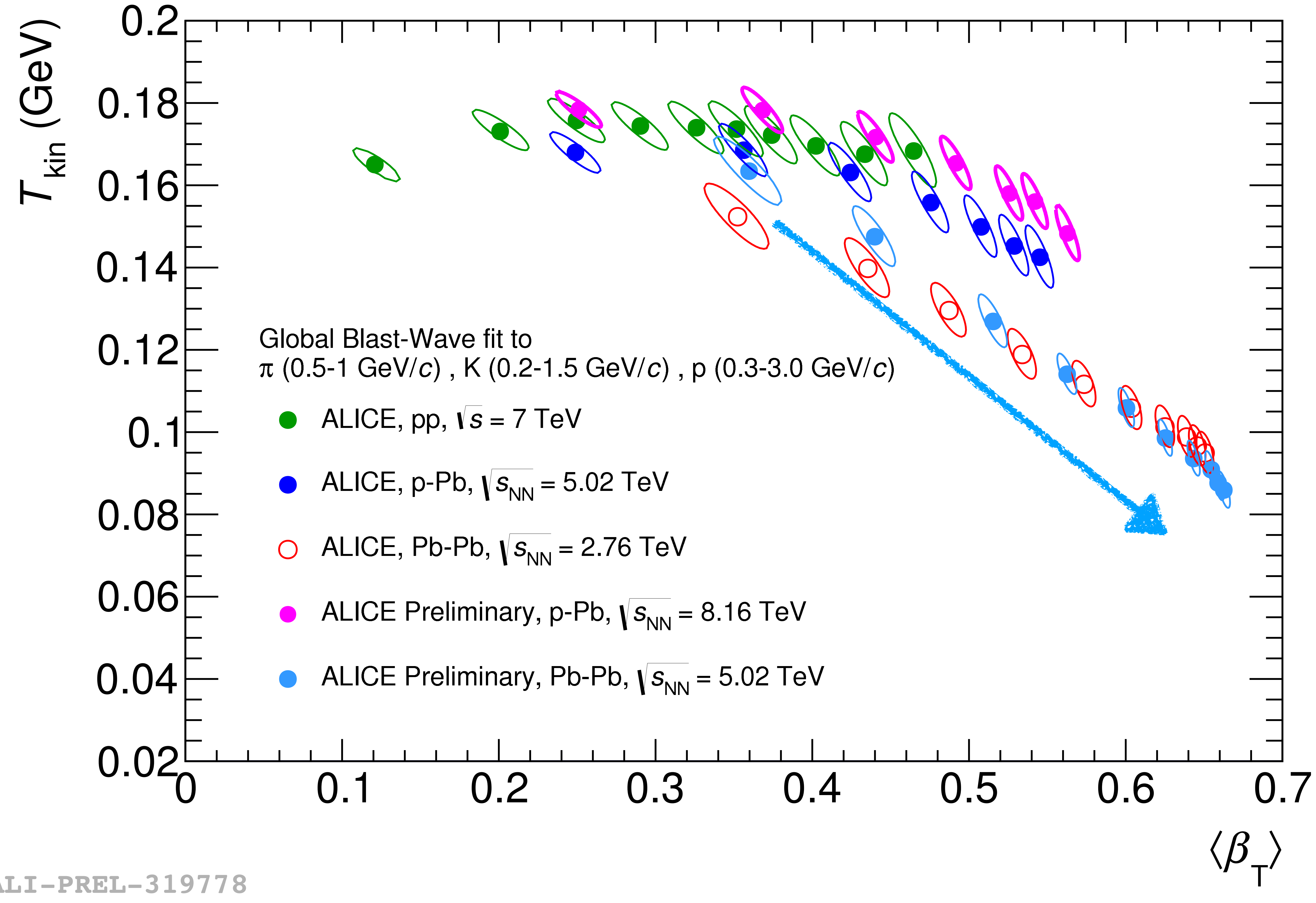


- Low-p_T: 2.6σ excess w. r. t. models in 0–20% central — thermal contribution
- T_{eff} = 304 ± 11(stat.) ± 40 (syst.) MeV in central collisions — way above T_c ~ 170 MeV

Identified particle production

CMS *Phys. Lett.* B768 (2017) 103

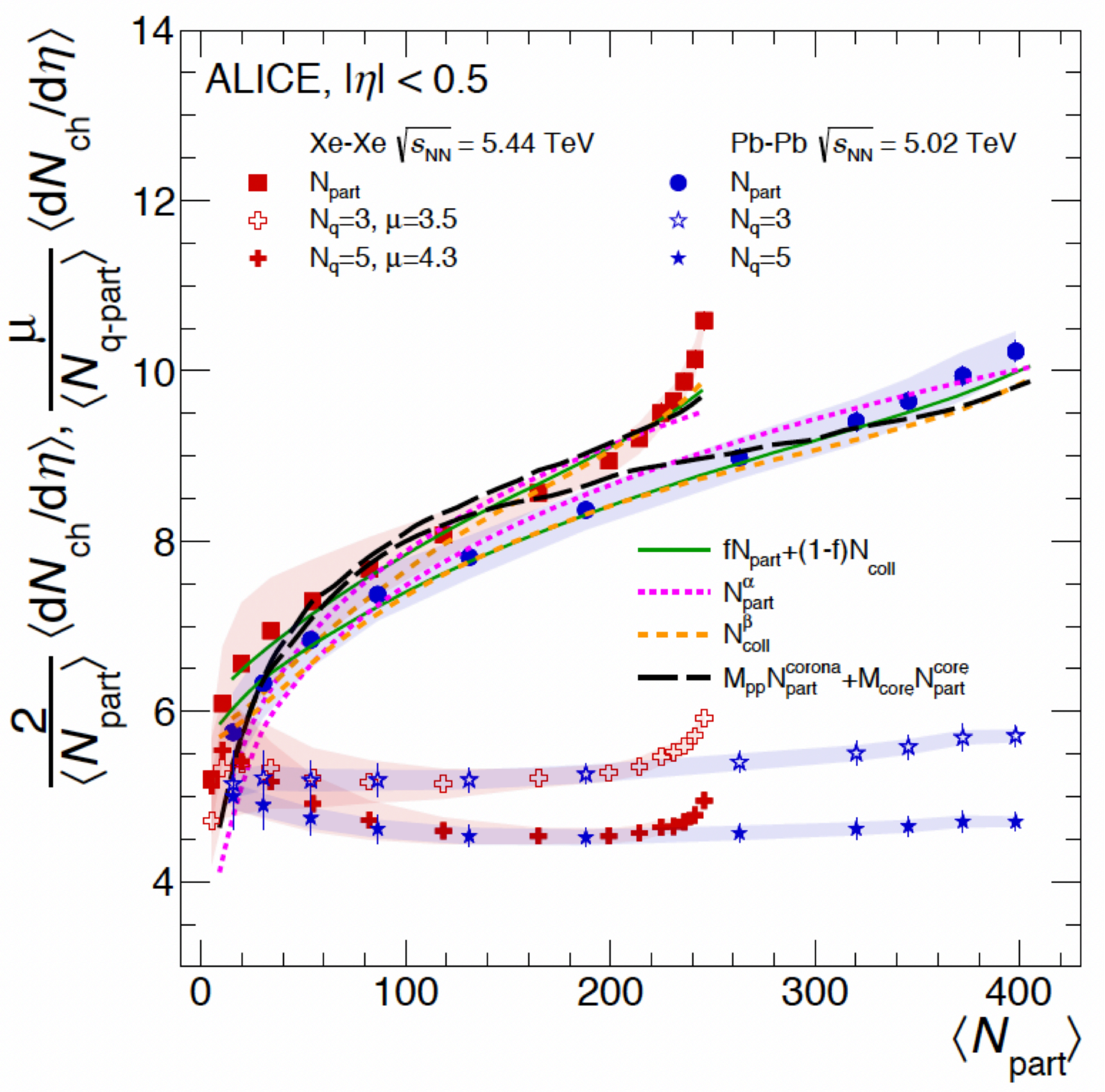




- T_{kin} decreases with increasing $\langle\beta_T\rangle$ from peripheral to central Pb–Pb collisions

Charged particle multiplicity

ALICE *Phys. Lett.* B790 (2019) 35



- N_{part} scaling violation: known since long time ago
- Confirmed by new Xe–Xe data
- Neither explained by participant quark scaling nor fully reproduced by models
- Collision geometry plays an important role on particle production