UNIVERSITÄT
HEIDELBERG
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SEIT 1386

ISOQUANT
SFB1225

Overview of experimental results of heavy-flavour and quarkonia v_n in small systems

Andrea Dubla

Outline

➪ **pp collisions:**
- Test pQCD calculations
- Study hadronization mechanism
- Set a reference for p-Pb and Pb-Pb

➪ **p-A collisions**
- Study cold nuclear matter (CNM) effects like nPDF, shadowing, gluon saturation, kT-broadening, energy loss in CNM in the initial and final state
- Address possible collective effects and effects related to the (possible) formation of a QGP in p-A collisions.

➪ **A-A collisions**
- Heavy-quarks effective probe for the properties of the hot and dense QCD matter
- Heavy-quark energy loss
- Quarkonium dissociation/regeneration

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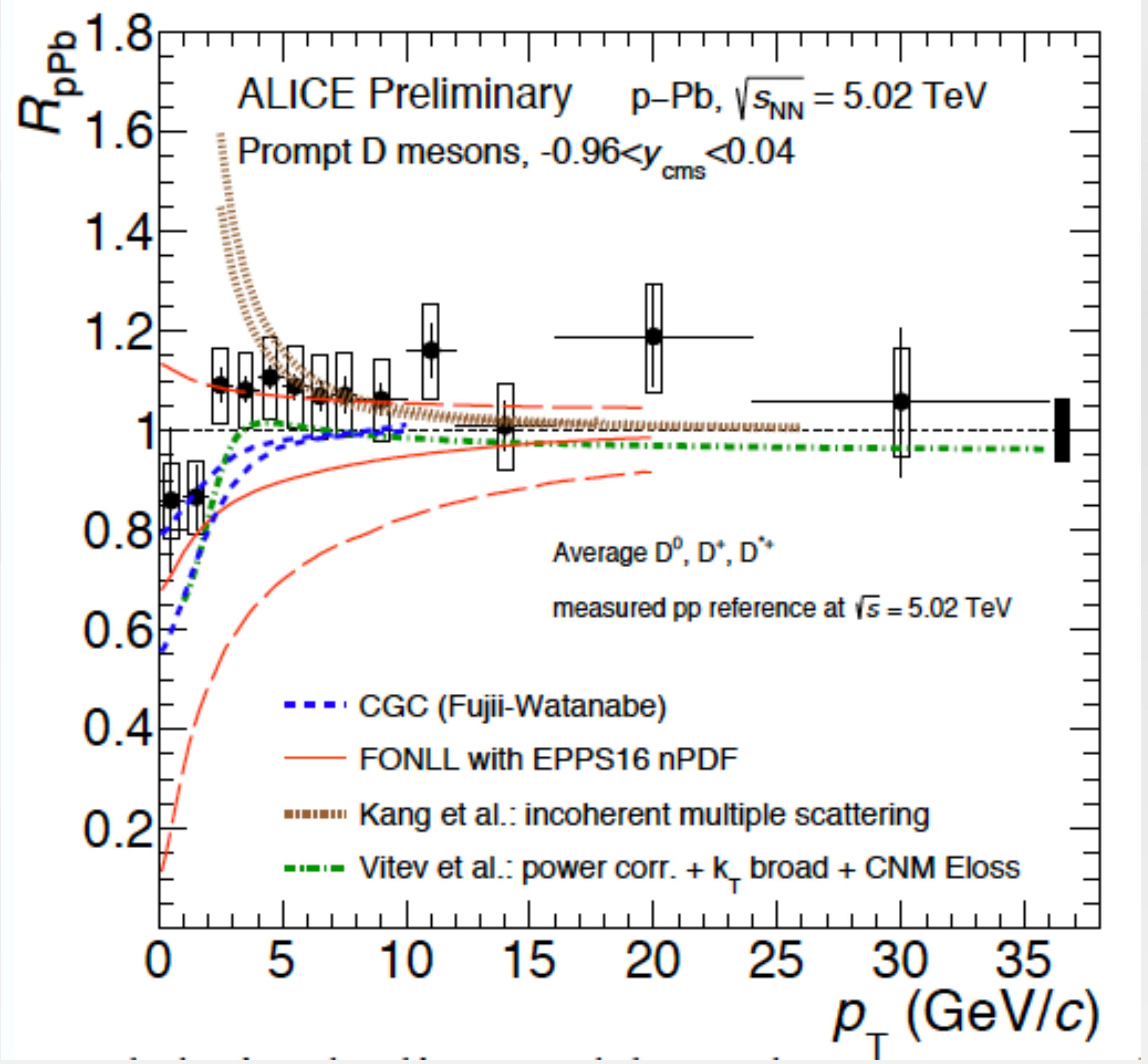
Heavy-flavour production in p-Pb collisions

D meson production in p-Pb collisions



⇨ Described by models including **cold nuclear-matter effects**

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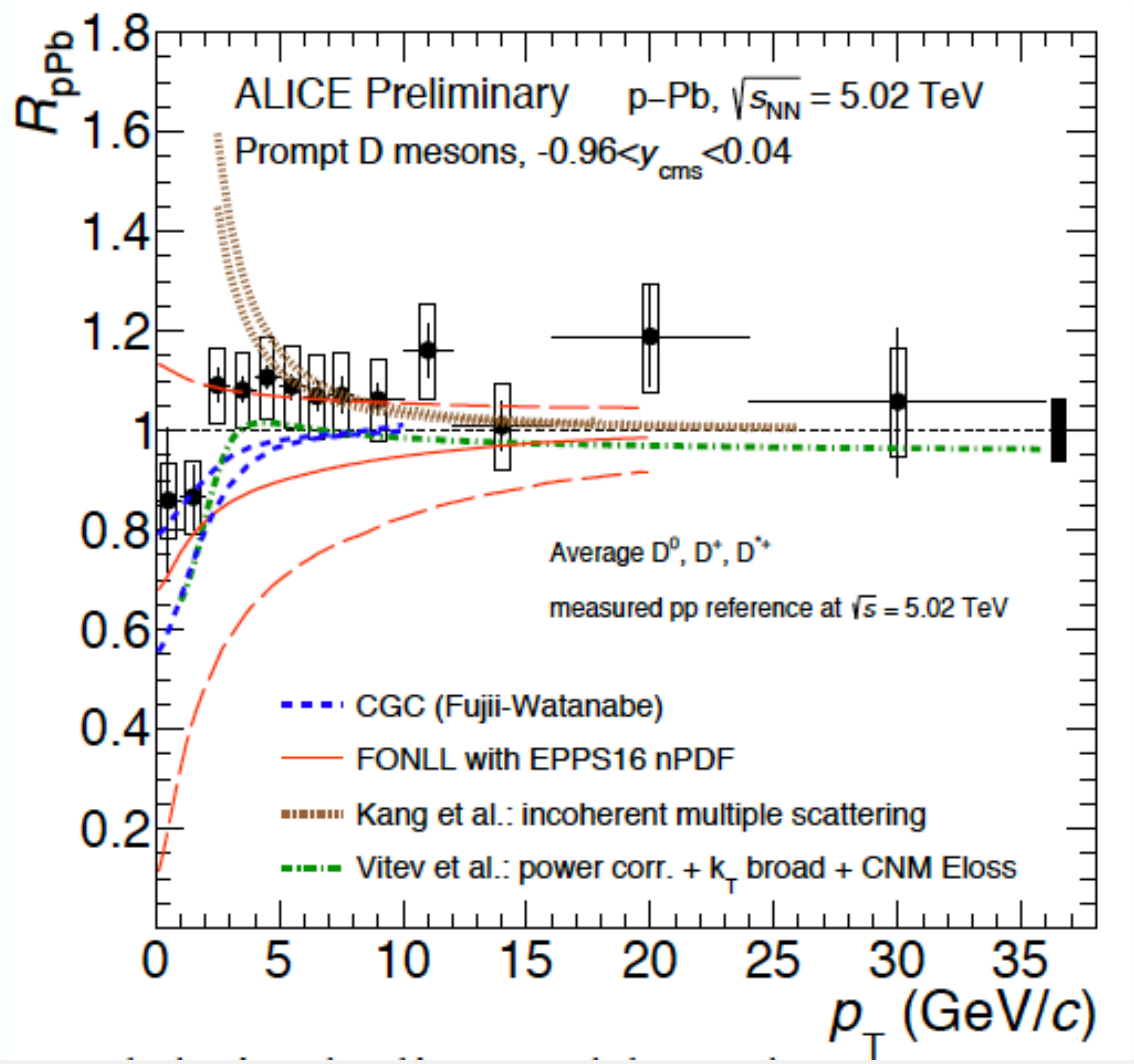

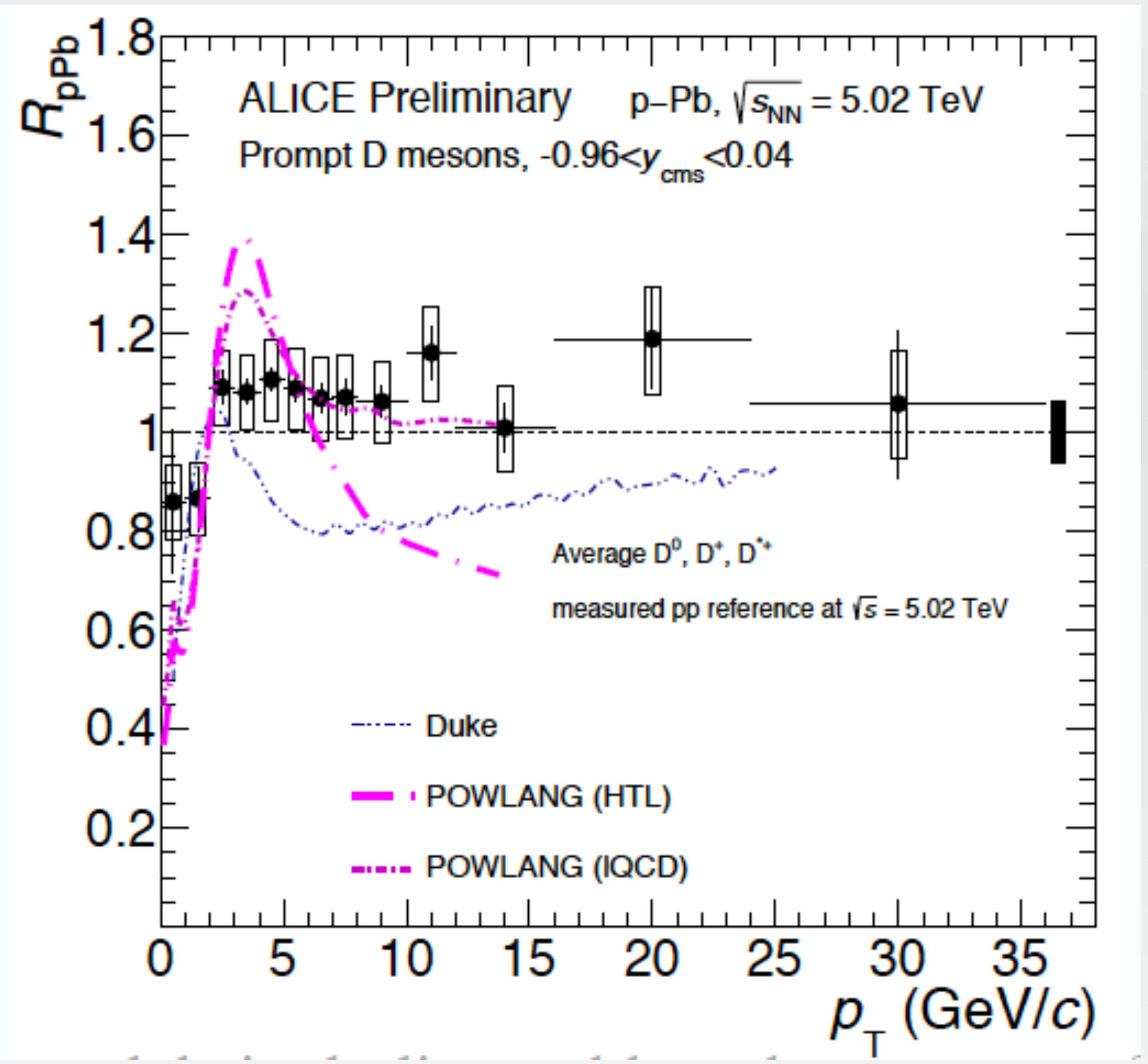

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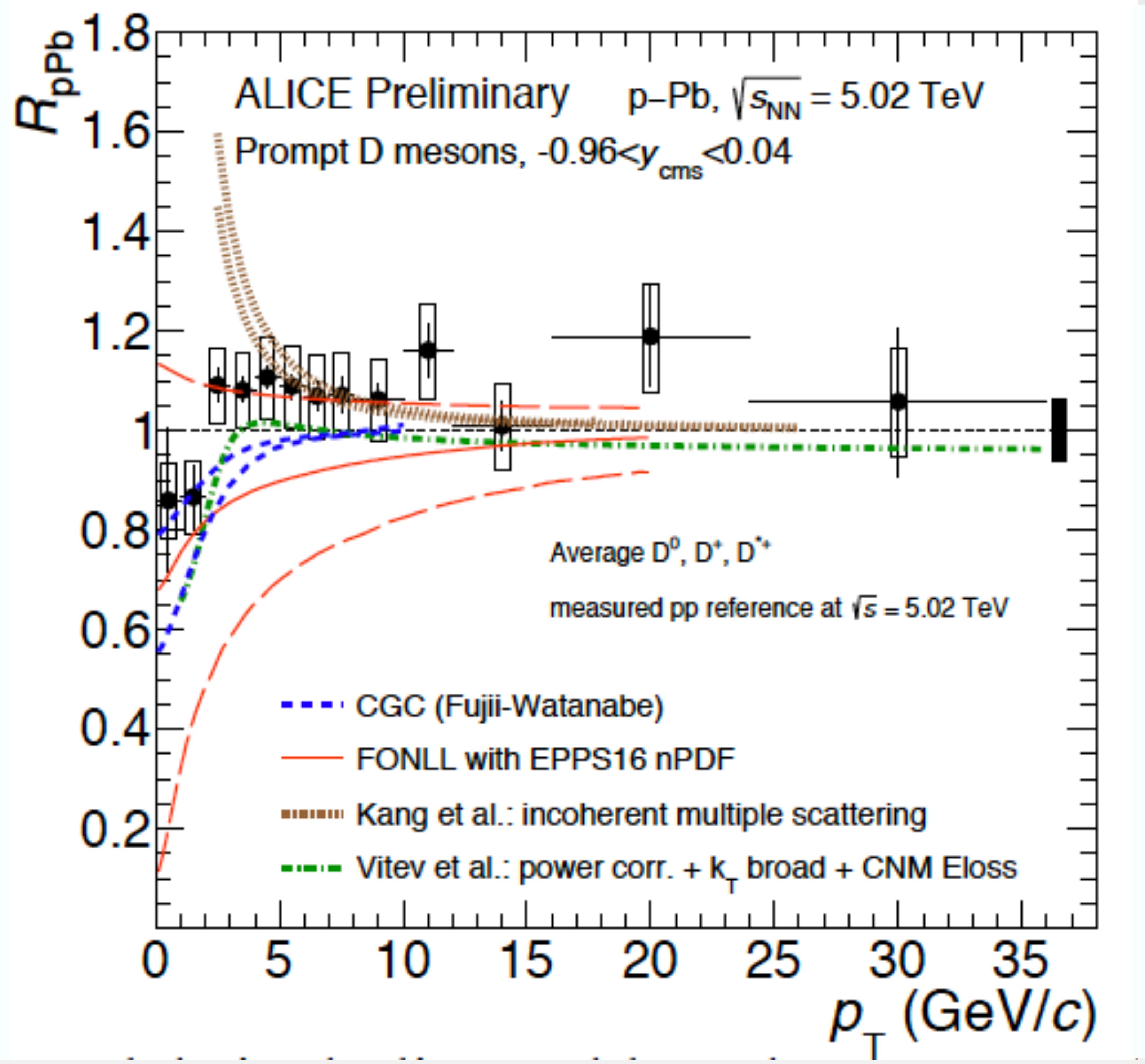
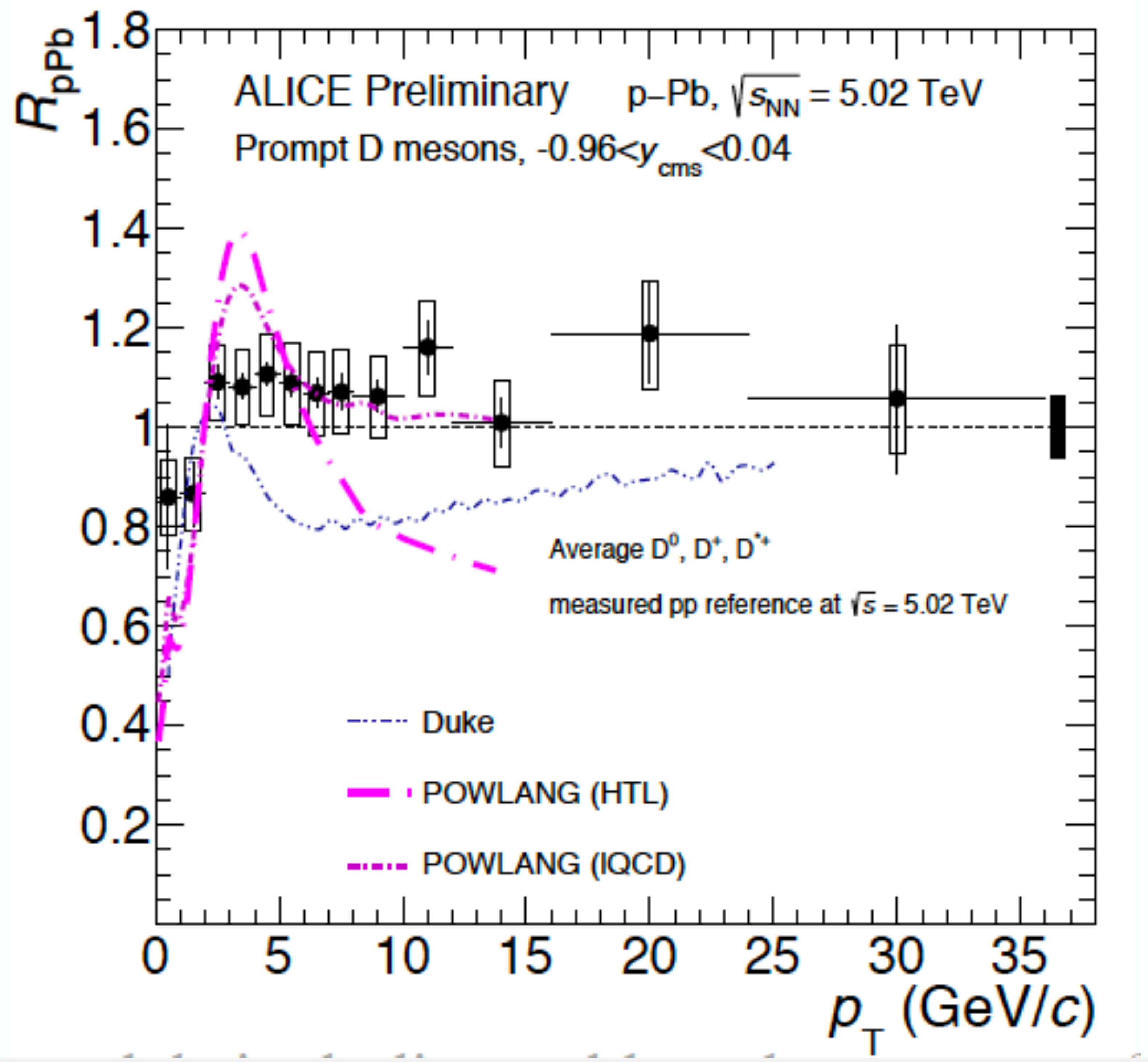
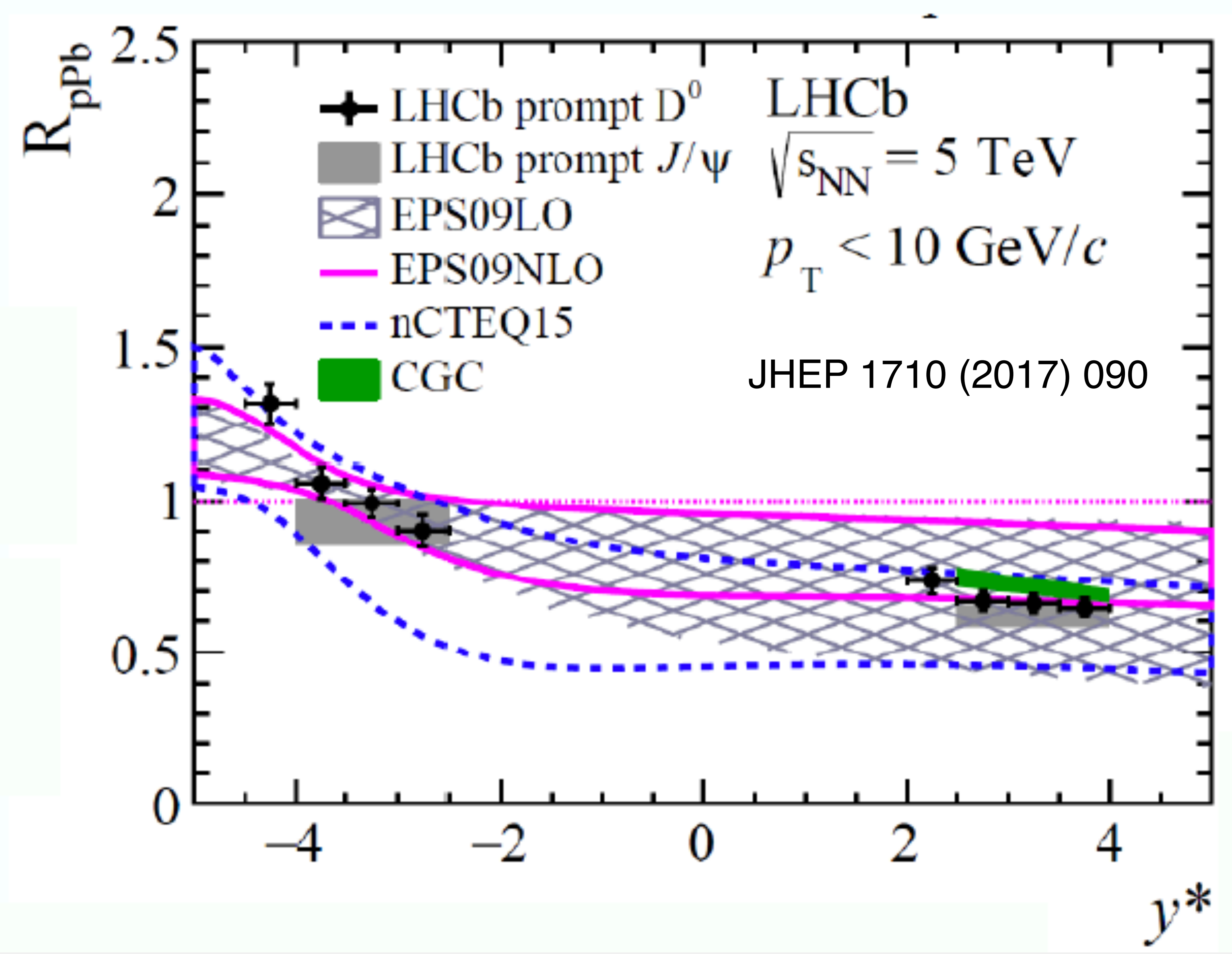
- data disfavour suppression >~15% at high p_T
- need to improve the precision of the measurement
- need to look at complementary observables

D meson production in p-Pb collisions







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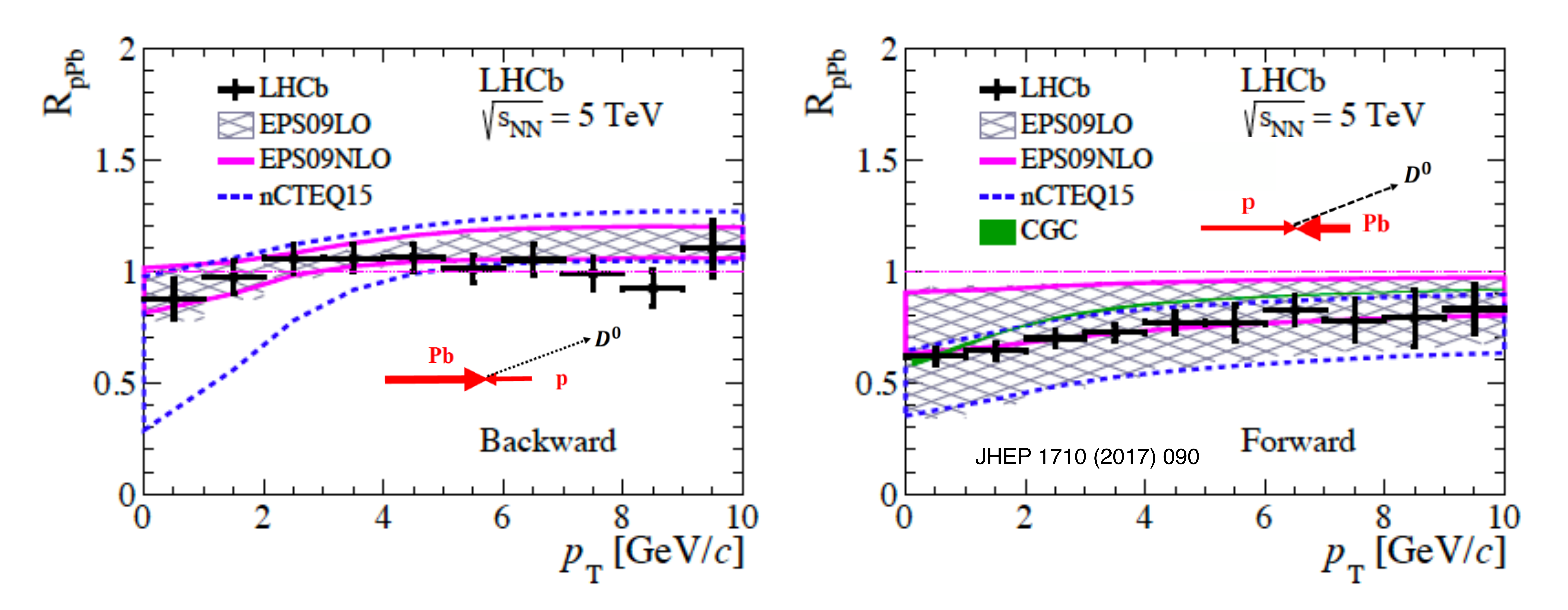
⇨ Data **agree with nPDF and CGC** - to notice that experimental precision starts to be better than theoretical one:
- Large data sample will be analyzed and will grant significantly larger precision

D meson production in p-Pb collisions



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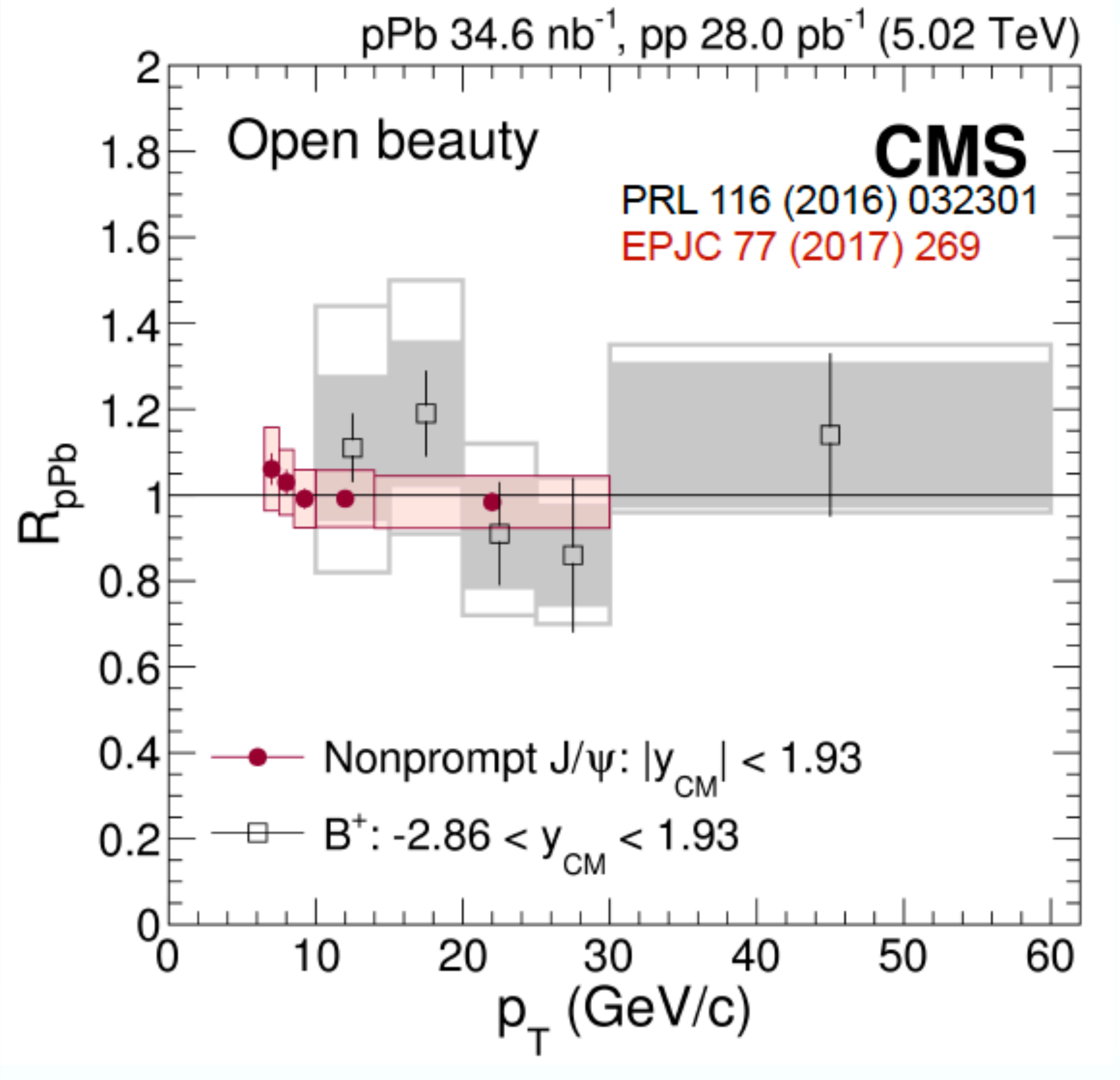
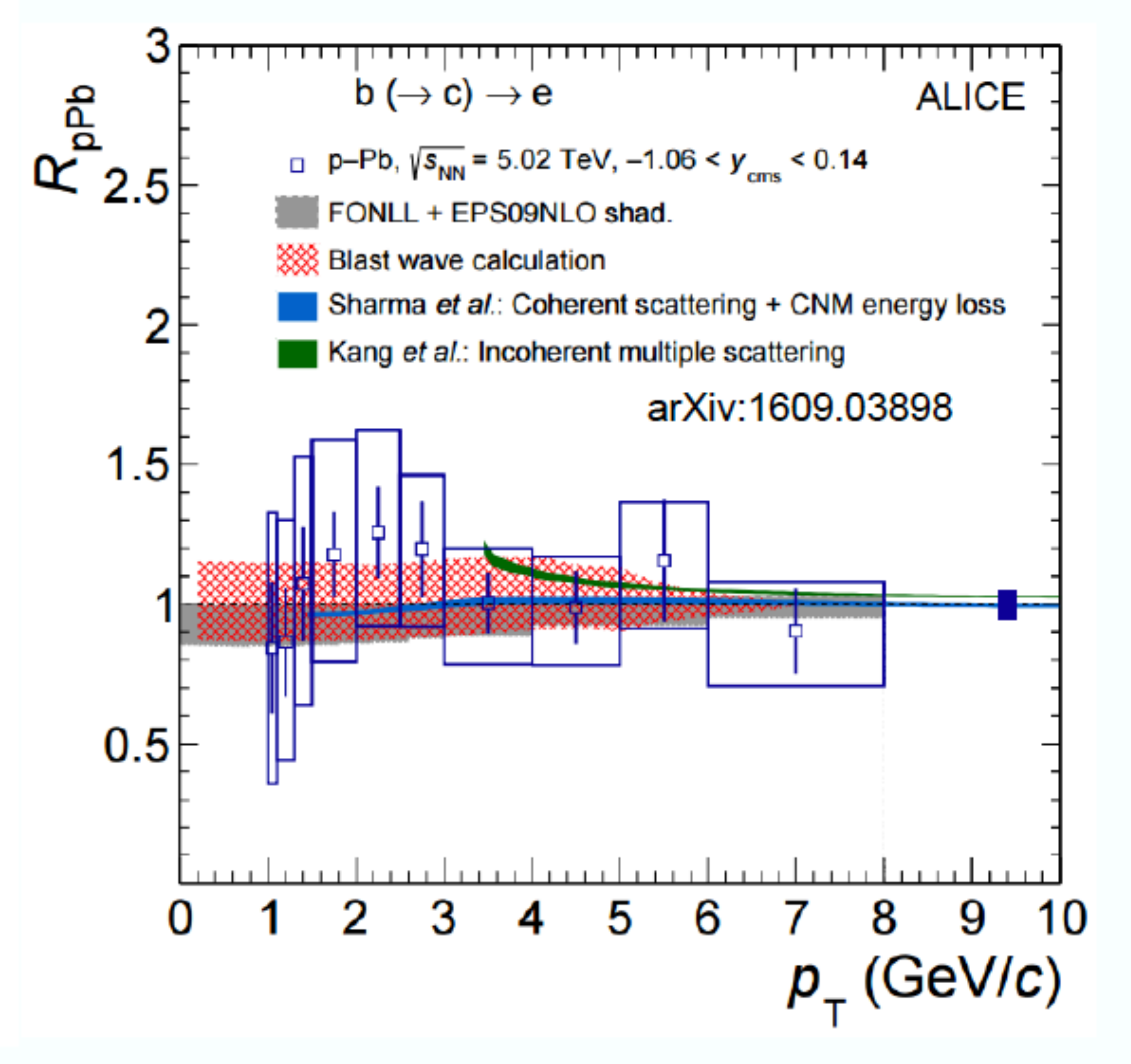
EPS09LO
Eur. Phys. J. C77 (2017) 1, arXiv:1610.05382
EPS09NLO
Comput. Phys. Commun. 184 (2013) 2562
nCTEQ15
Comput. Phys. Commun. 198 (2016) 238,
CGC
Phys. Rev. D91 (2015) 114005,

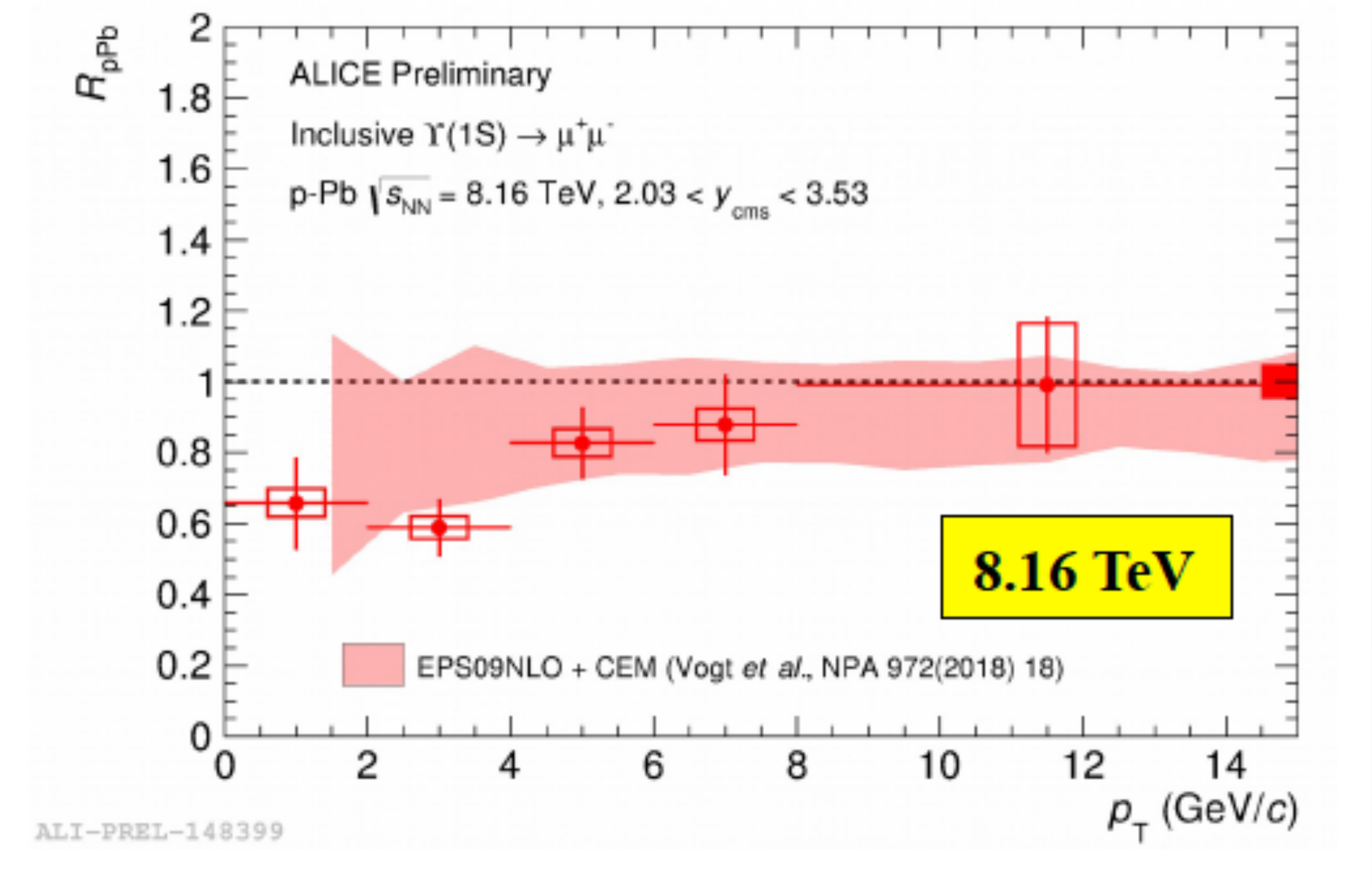
Beauty production in p-Pb collisions at LHC

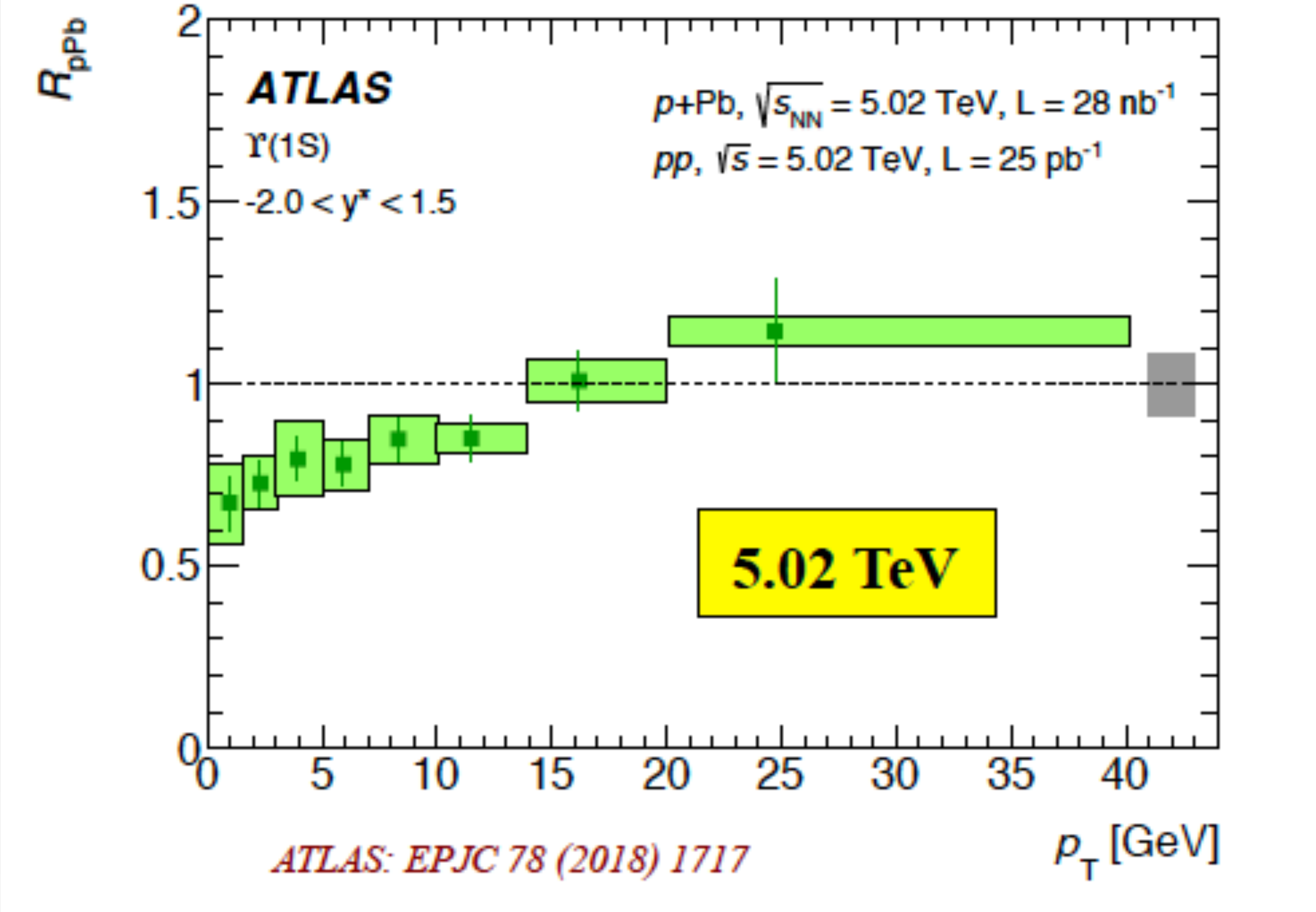




➪ Beauty production consistent with unity

Quarkonia production in p-Pb collisions at LHC





⇨ ϒ(1S): **30-40% suppression at low p_T**

- Need to be taken into account when interpreting results in Pb-Pb collisions

Nothing unexpected!!

⇨ Production of heavy-flavour in p-A collision follows the **expected pattern**:
- no suppression due to final state effects observed with present precision
- results consistent with calculations including modification of nPDF (shadowing)

⇨ **Data** start to show **higher precision** than **theory**!

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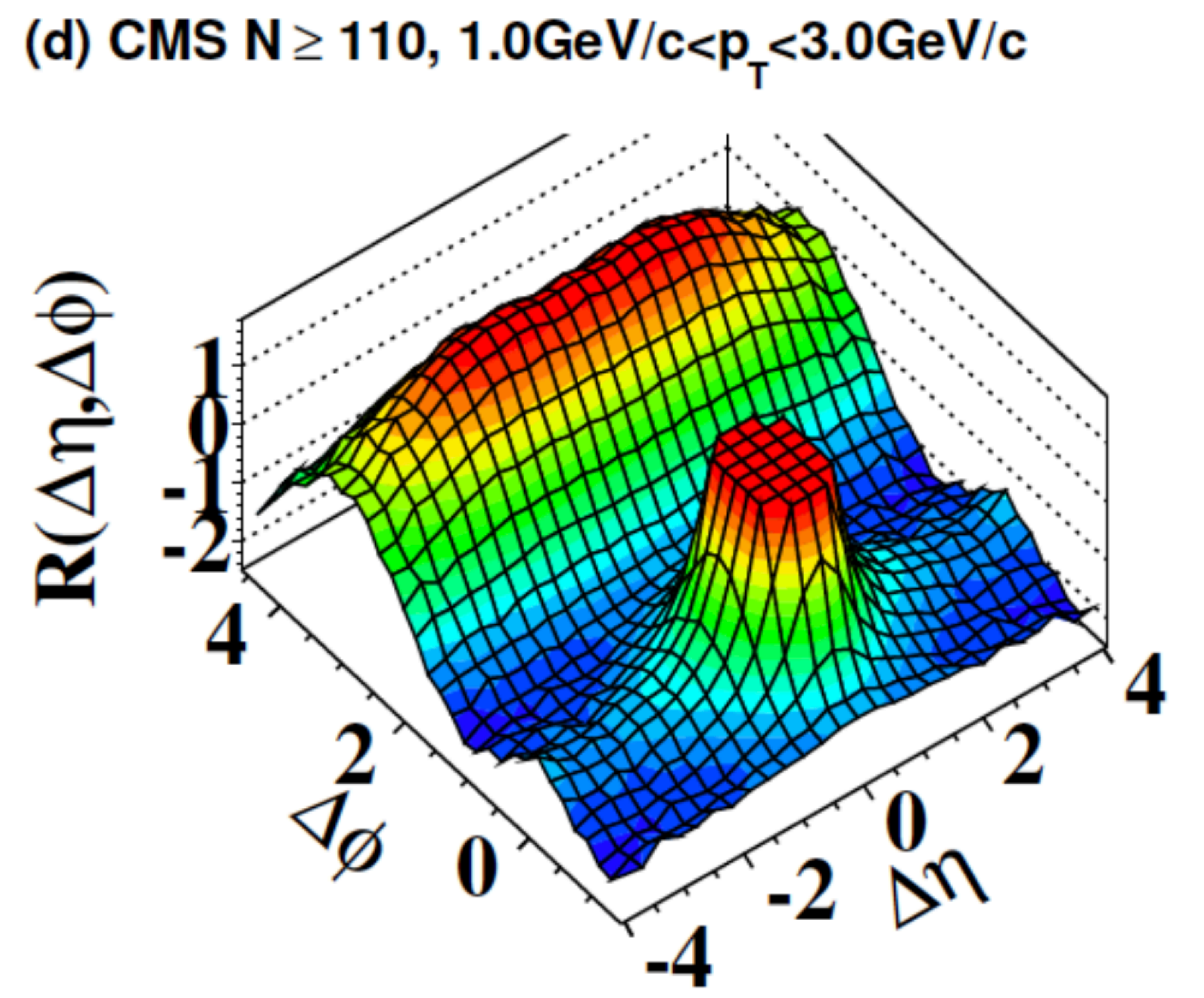
What about collectivity in p-Pb collisions

Collectivity in small system

pp collisions

(CMS Collaboration) JHEP 09, (2010) 091



- ➯ **LHC data opened a new hera**: detailed study of high-multiplicity events (both in pp and p-A) becomes possible
- ➯ In 2010 CMS Collaboration publish a paper presenting the observation of **a double-ridge structure (di-hadron correlation) in high-multiplicity pp events**

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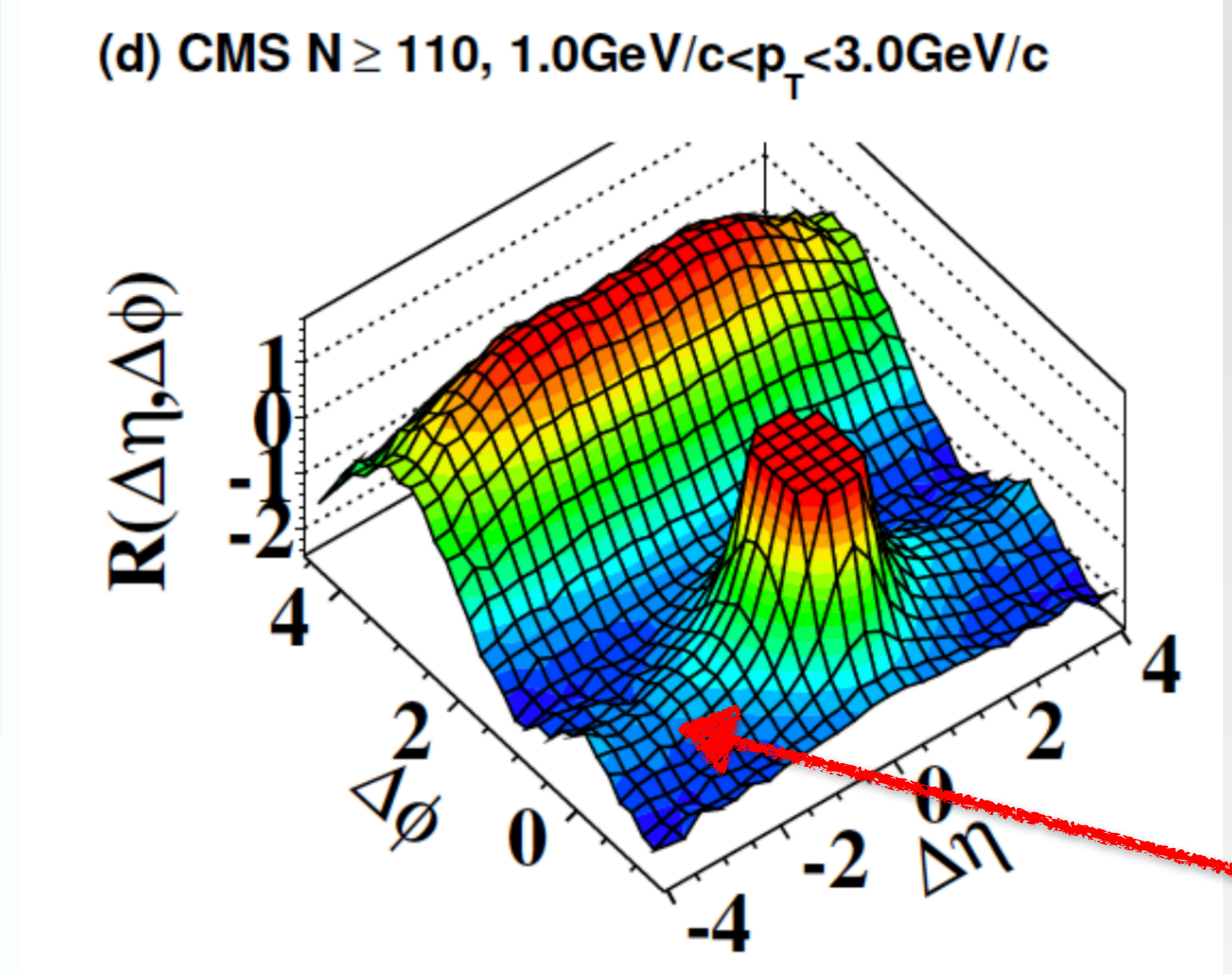

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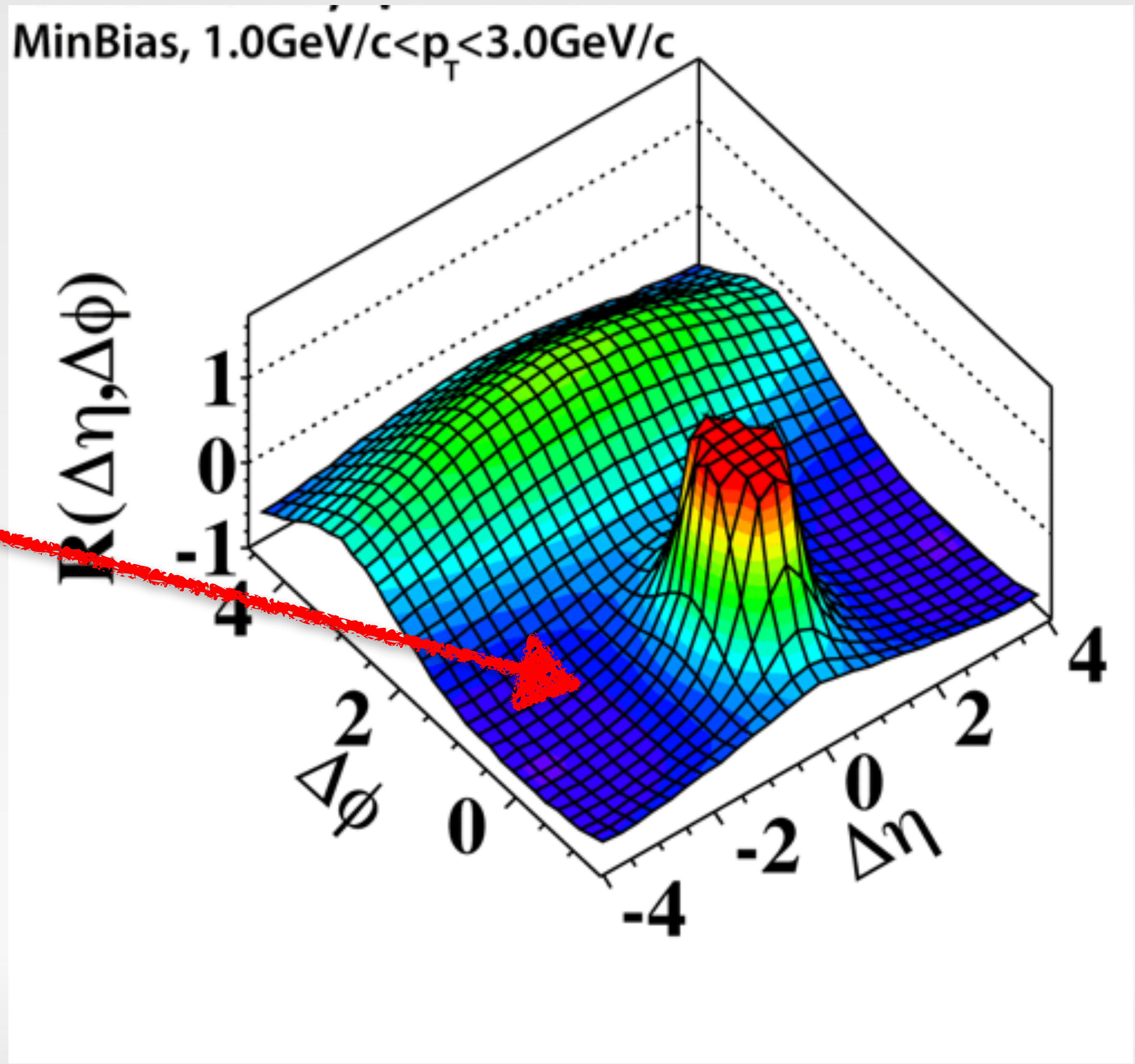

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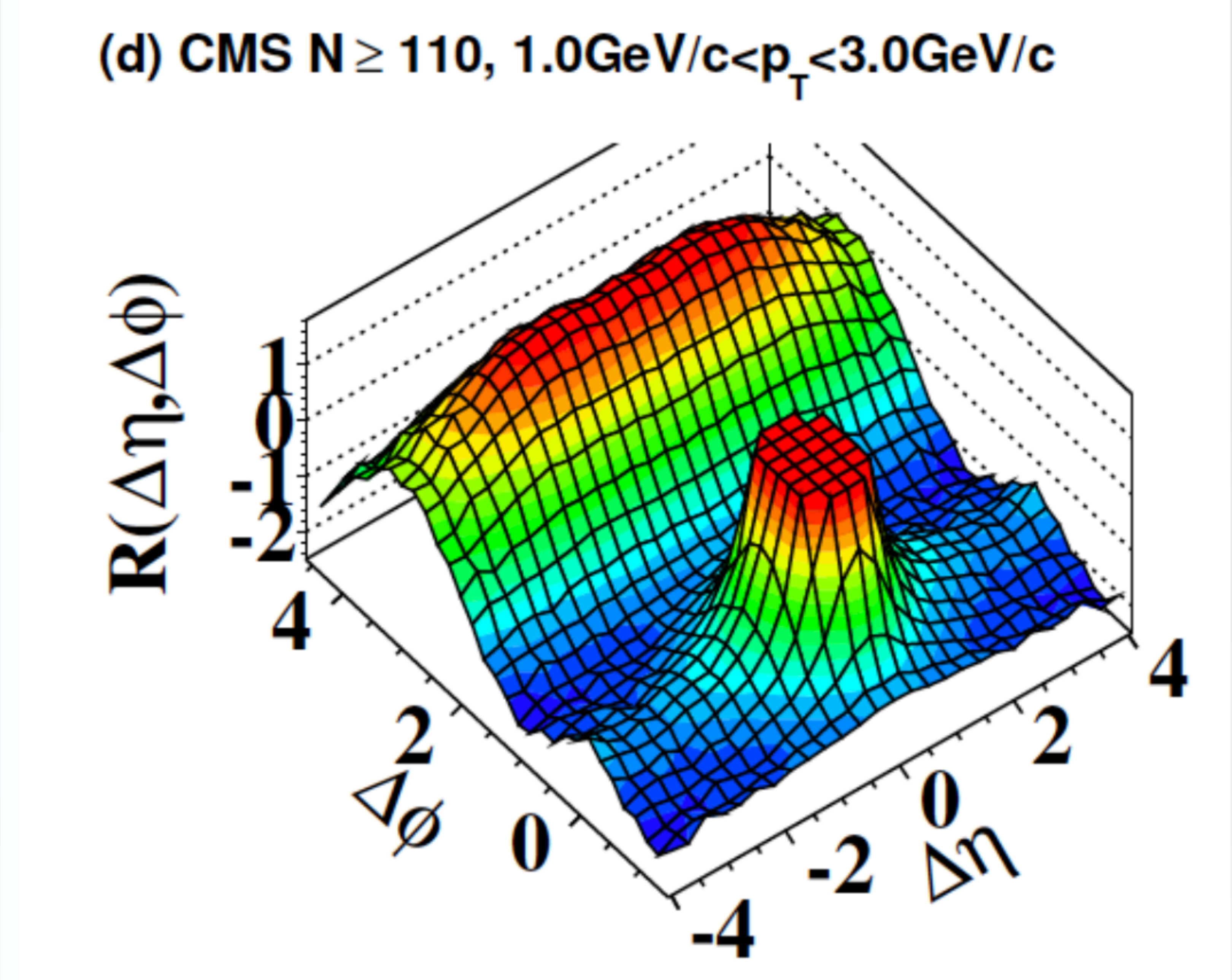

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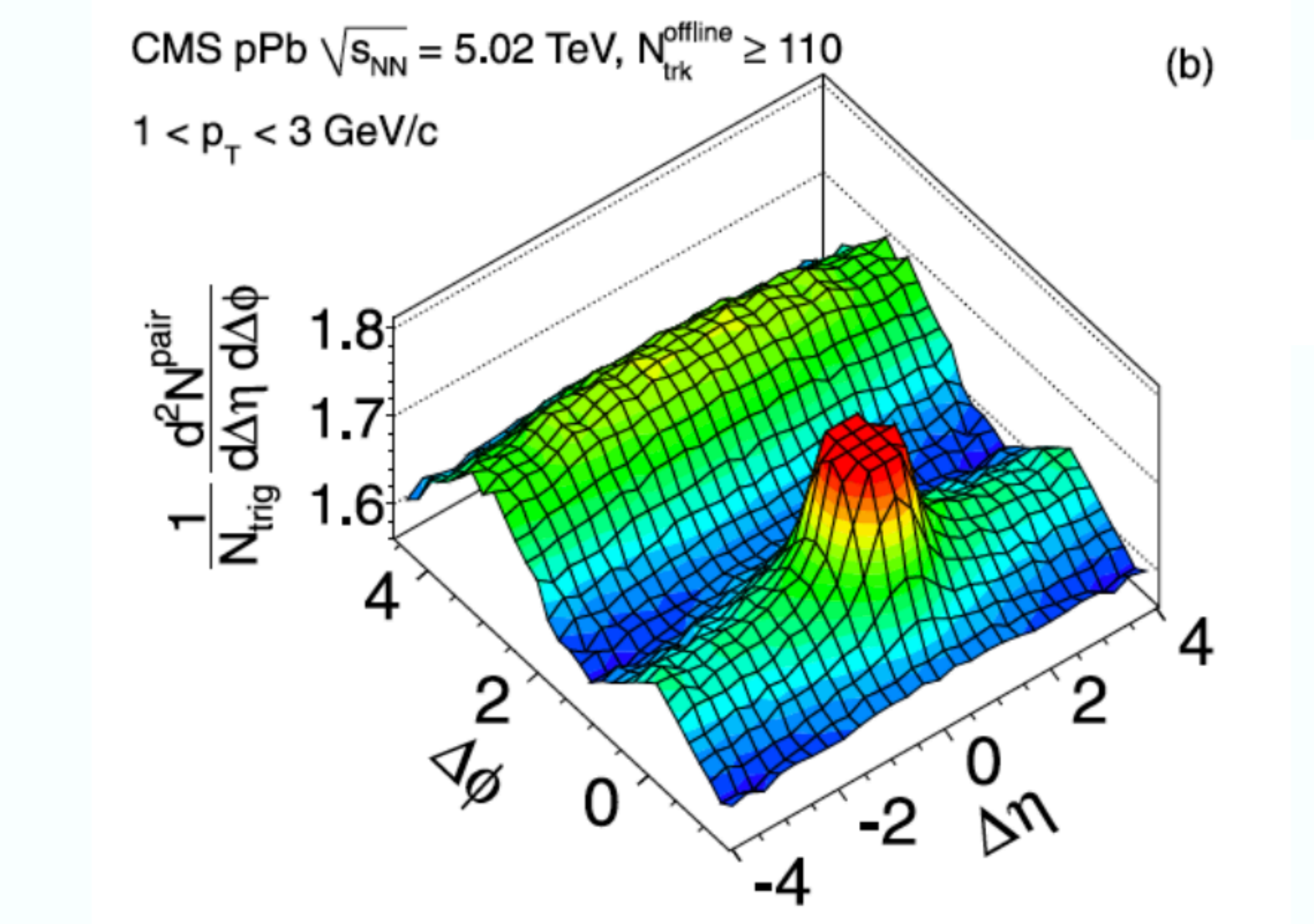
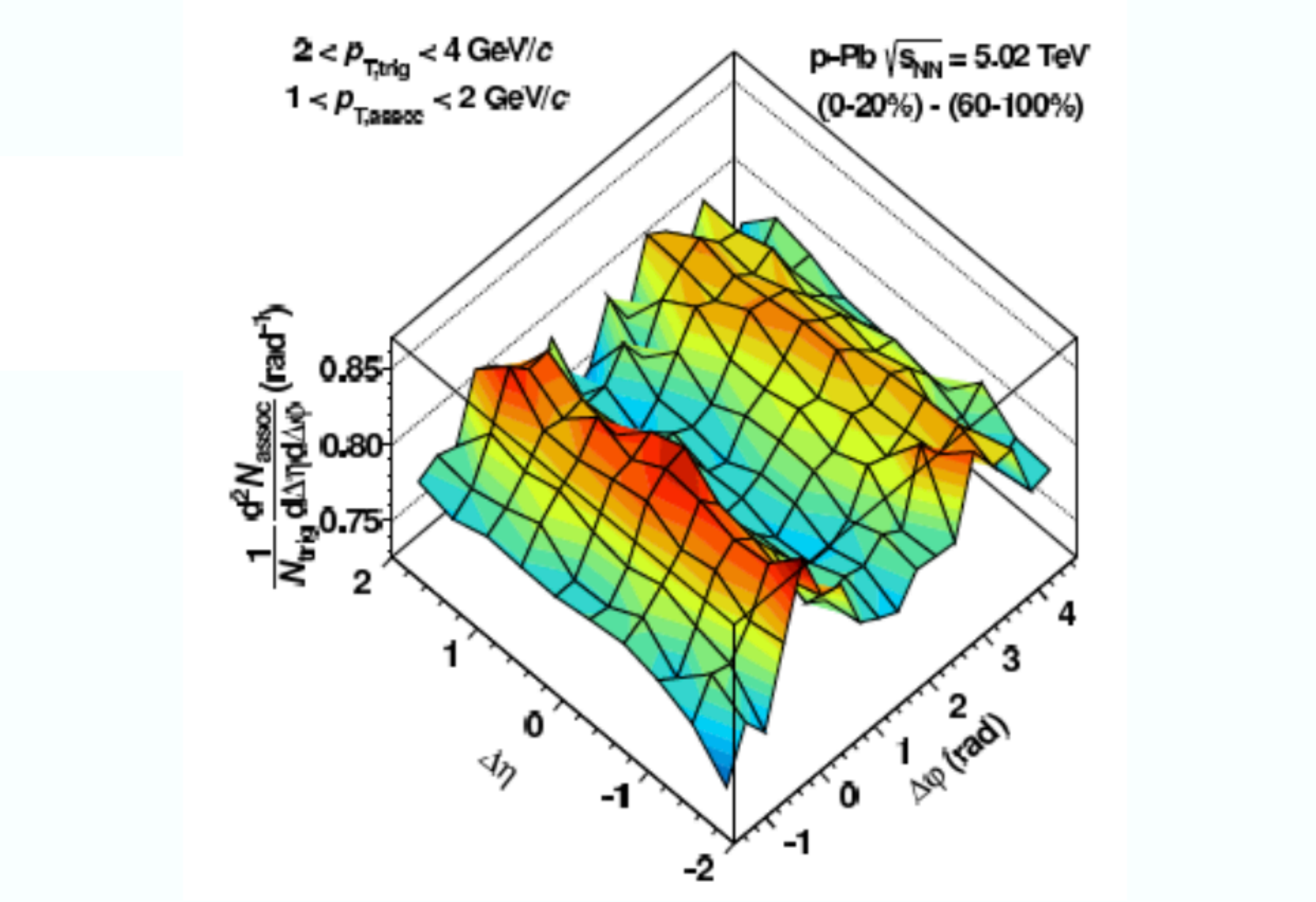
(CMS Collaboration) Phys. Lett. B718, (2013) 795



(ALICE Collaboration): Phys. Lett. B719, (2013) 29

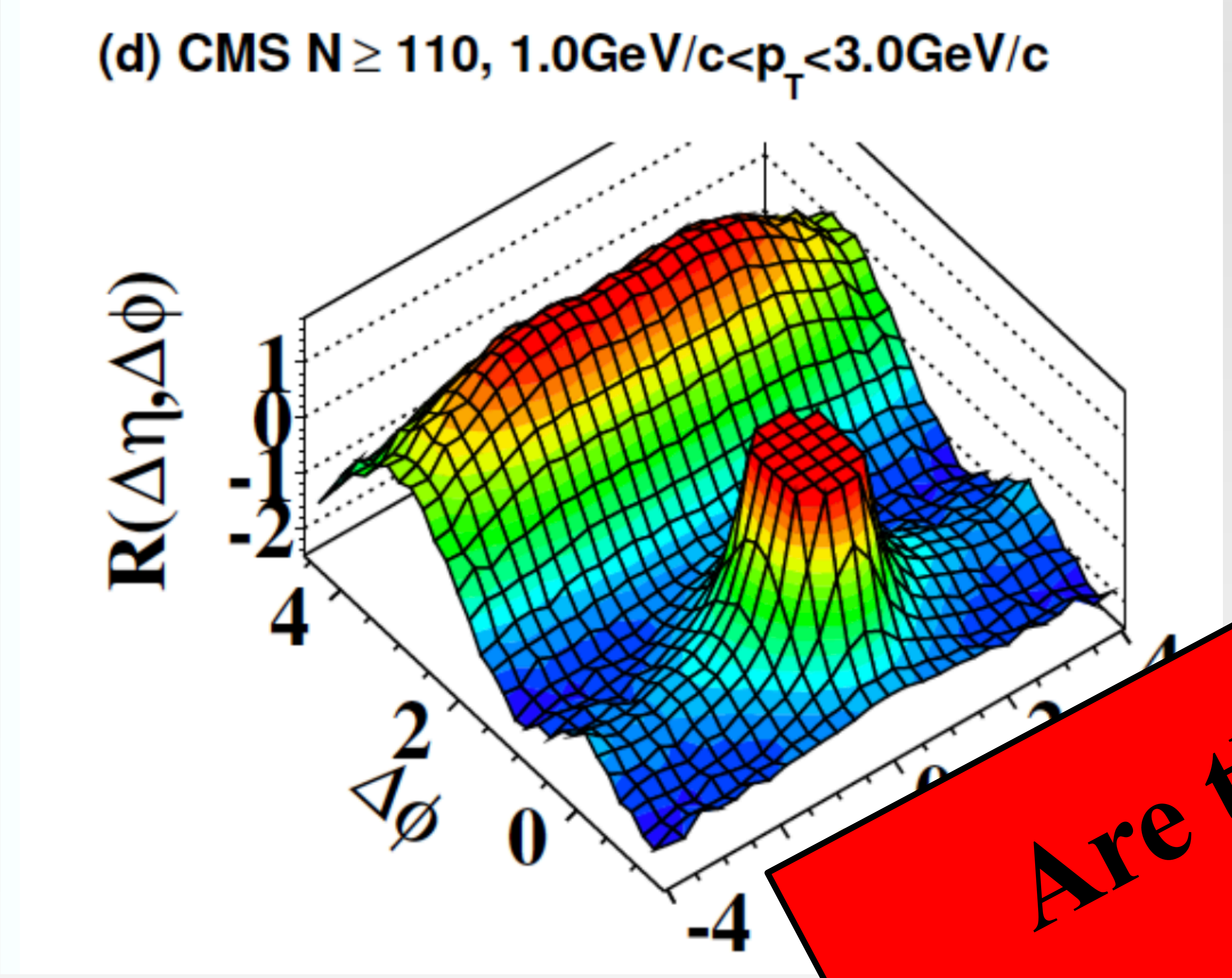


p-Pb collisions

Collectivity in small system

pp collisions

(CMS Collaboration) JHEP 09, (2010) 091



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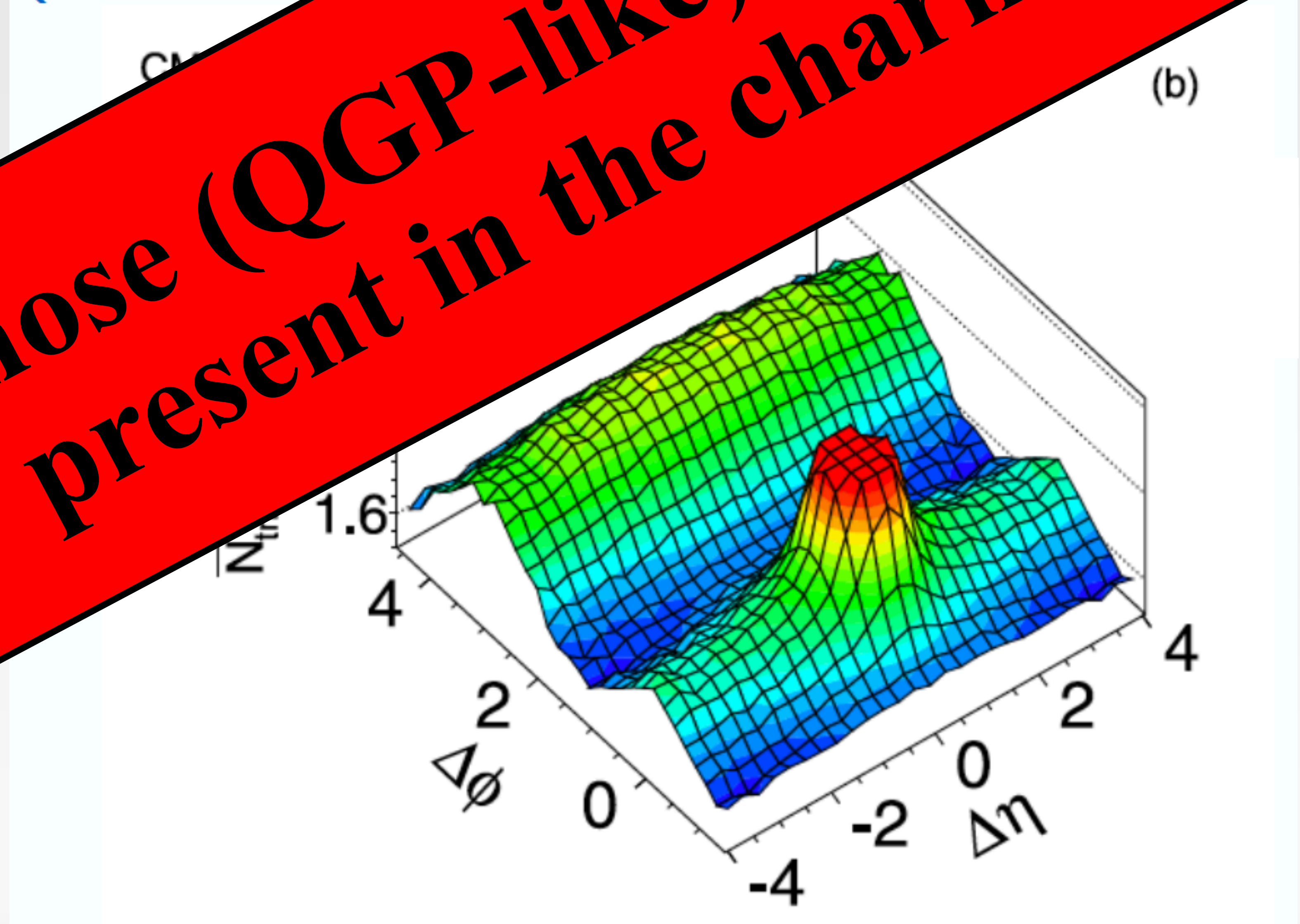
- In 2010 CMS Collabo... ...esenting the observation of a... ...(di-hadron correlation) in high-mul...

Are those (QGP-like) collective effects present in the charm sector

(CMS Collabo...



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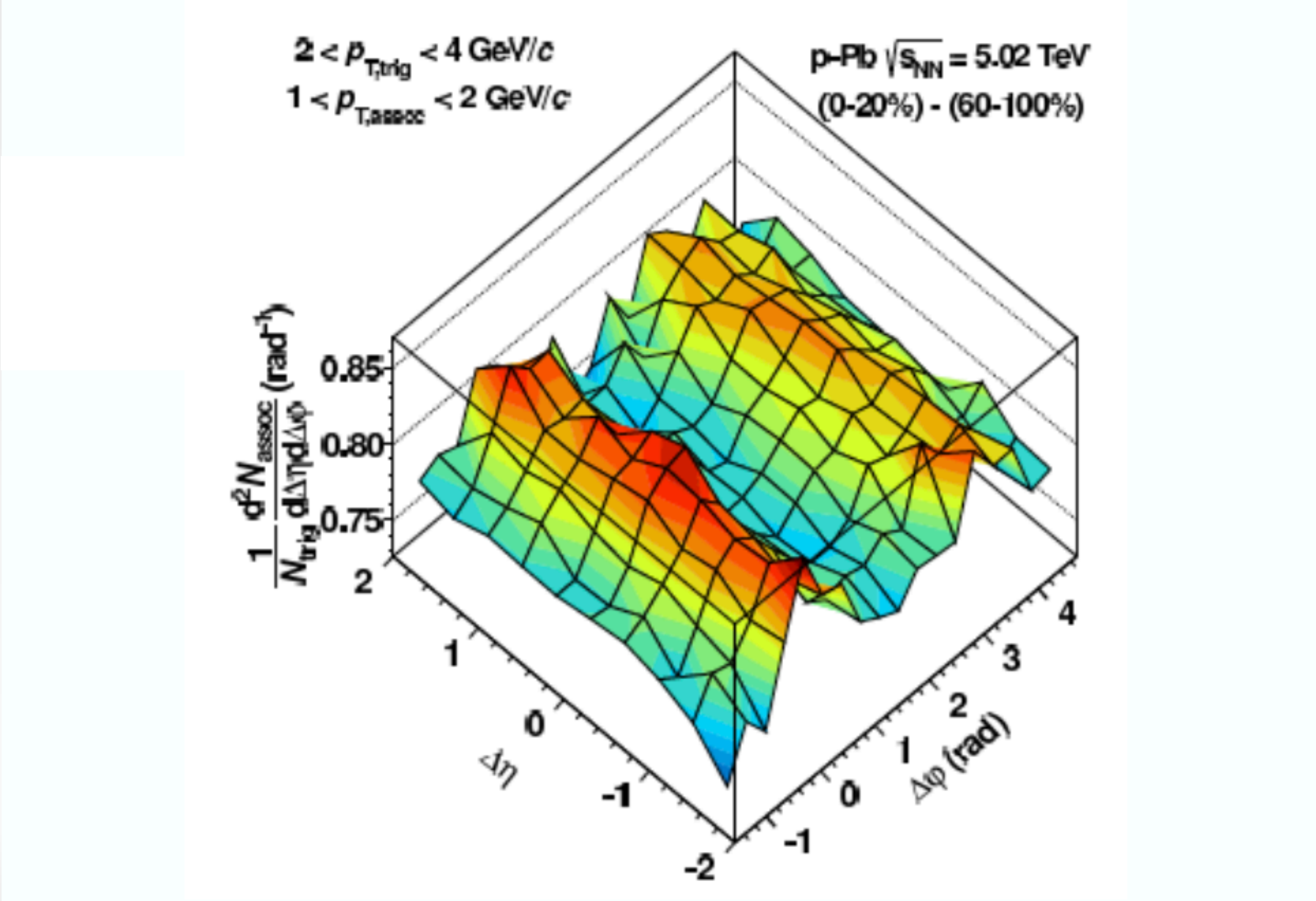
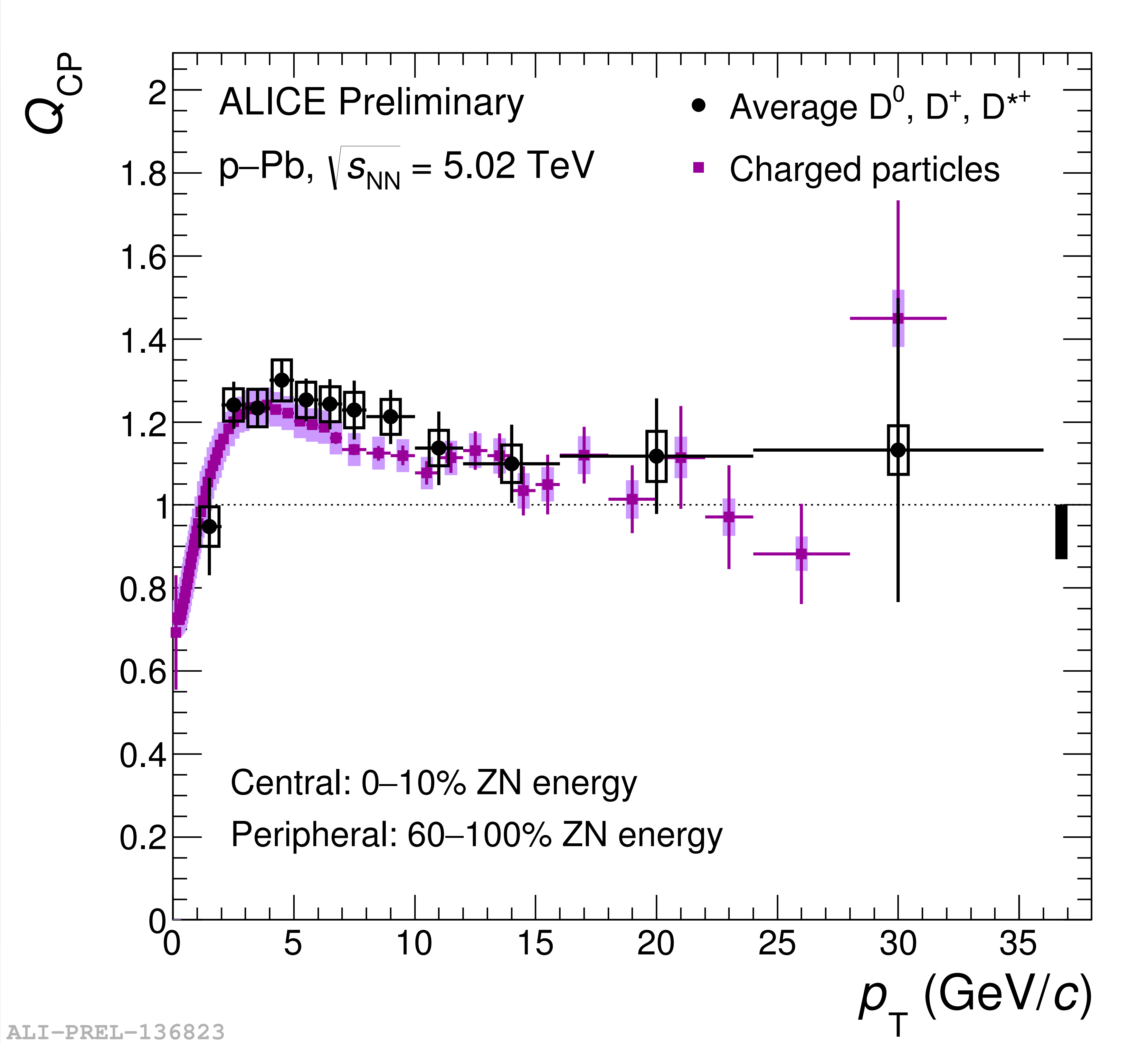


p-Pb collisions

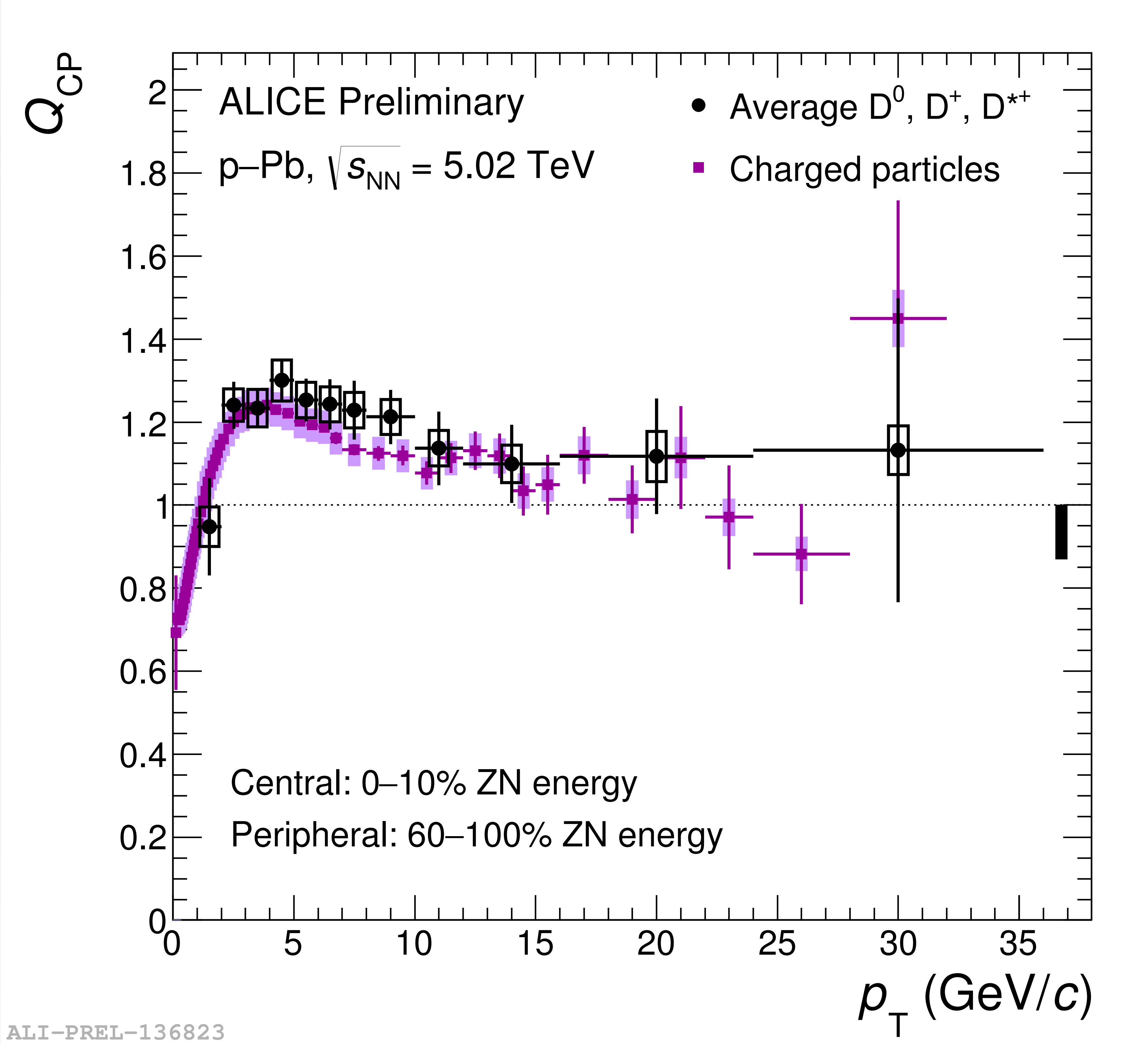
D meson production vs centrality

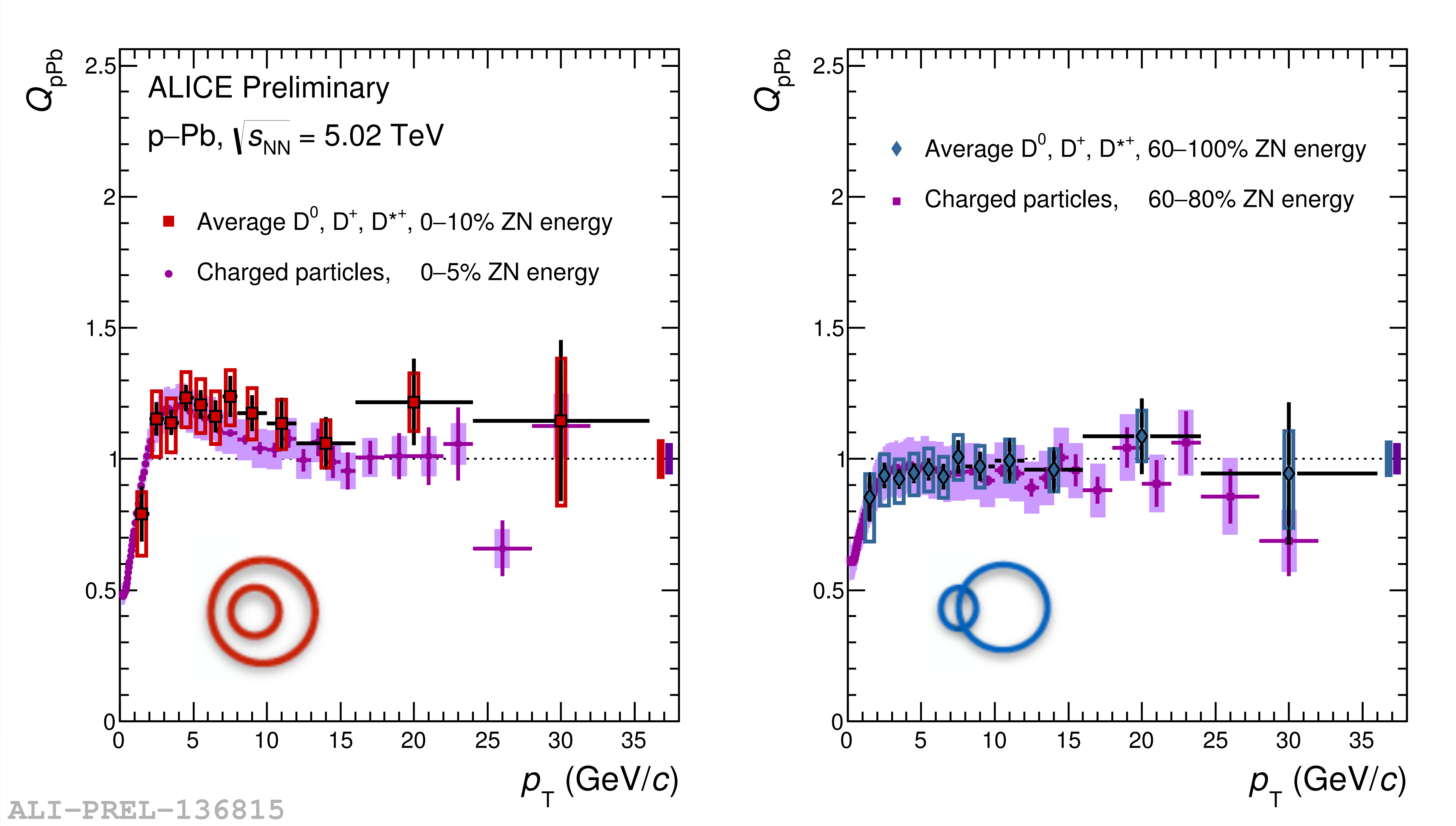


$$Q_{\mathrm{pPb}}^{0\text{–}10\%}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{pPb}}^{0\text{–}10\%} / \mathrm{d}p_{\mathrm{T}}}{\langle T_{\mathrm{AA}} \rangle_{0\text{–}10\%} \times \mathrm{d}\sigma_{\mathrm{pp}} / \mathrm{d}p_{\mathrm{T}}}$$

- Hint for D-meson “Central-to-peripheral” ratio (QCP) larger than unity
  - 1.5σ in 3 < p_T < 8 GeV/c

D meson production vs centrality





$$Q_{pPb}^{0-10\%}(p_T) = \frac{dN_{pPb}^{0-10\%} / dp_T}{\langle T_{AA} \rangle_{0-10\%} \times d\sigma_{pp} / dp_T}$$

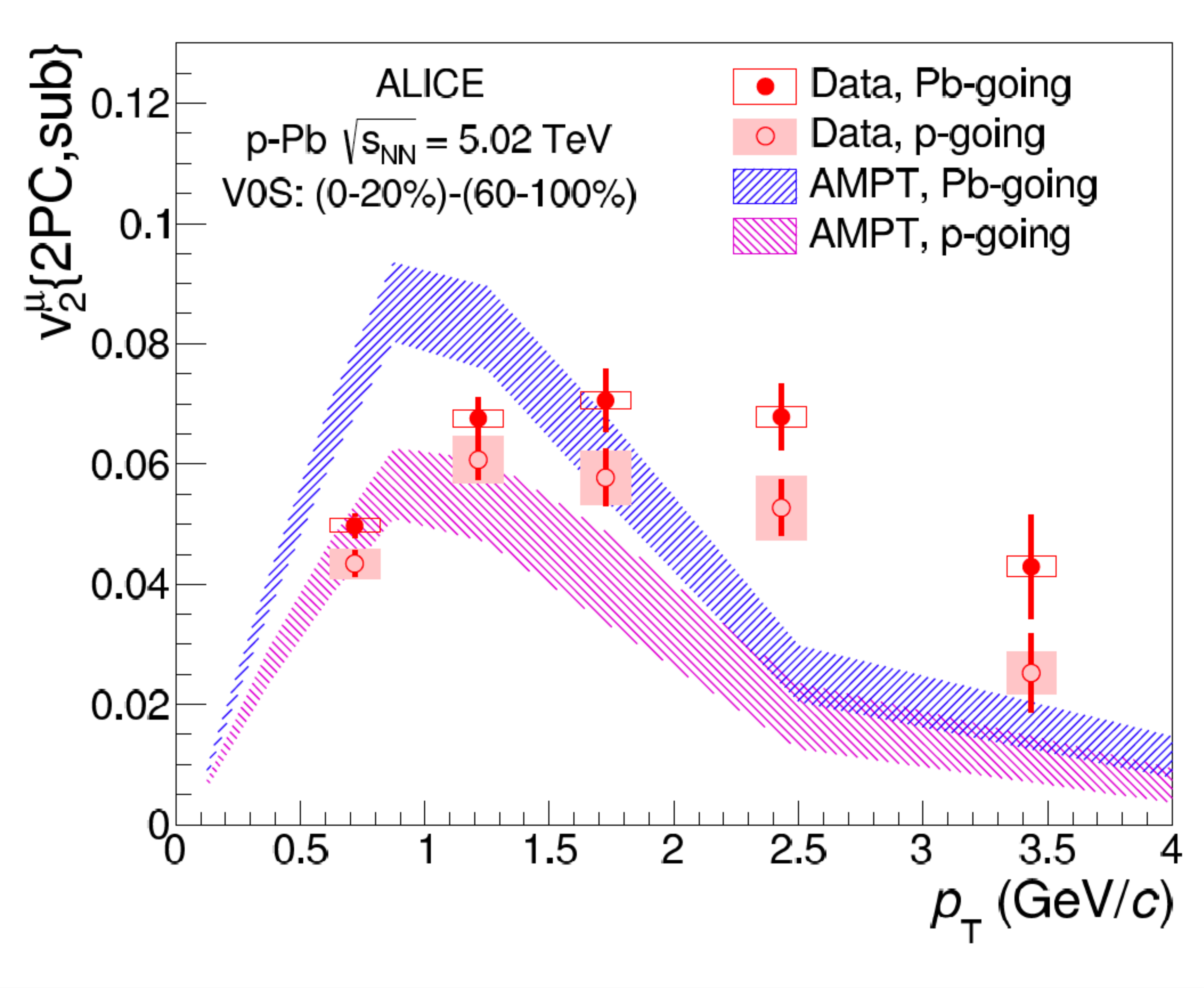
- Hint for D-meson "Central-to-peripheral" ratio (Q_{CP}) larger than unity
  - 1.5σ in 3 < p_T < 8 GeV/c

- Very similar to charged particle (pion dominated)
  - Initial-state effect? Mass effect? Radial flow?

… need comparison with theoretical calculations

Heavy-flavour collectivity in p-Pb collisions??

➪ **Non-zero elliptic flow (v_2) as a measure of collectivity**



ALICE, PLB 753 (2016) 126

➪ **Indirect hint** of non-zero heavy-flavour flow in p-Pb from inclusive muons at forward rapidity (p_T > 2 GeV/c)
- High-p_T inclusive muons are HF dominated.

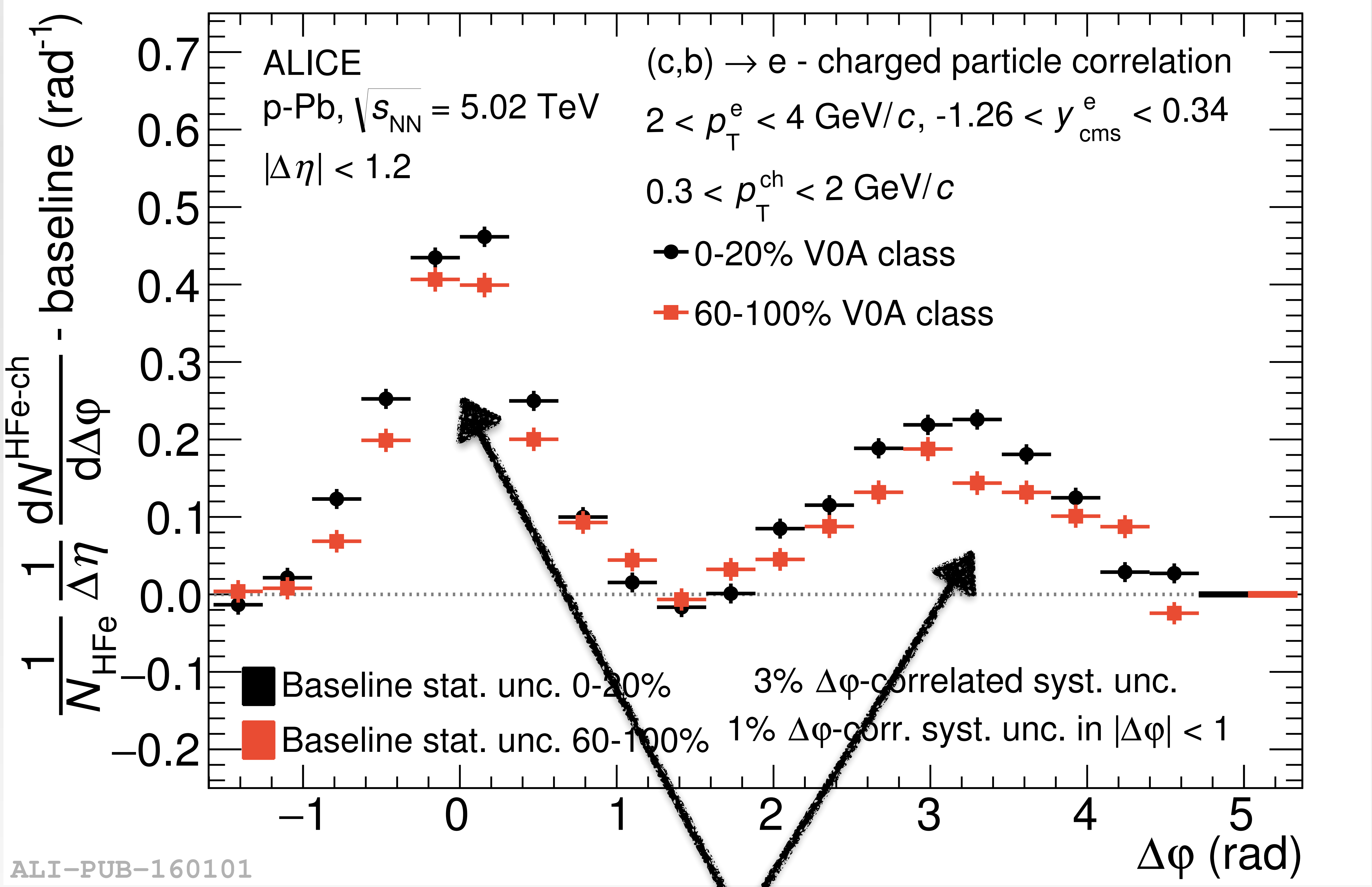
➪ **Need direct proof (Prompt D mesons, heavy-flavour hadron decay leptons)**

Heavy-flavour electrons v_2 in p-Pb collisions

- **Two-particle correlations** of HFe with charged particles in **high multiplicity** and **low multiplicity** events

- Near and away side **modification** from low multiplicity to high multiplicity

PhysRevLett.122.072301



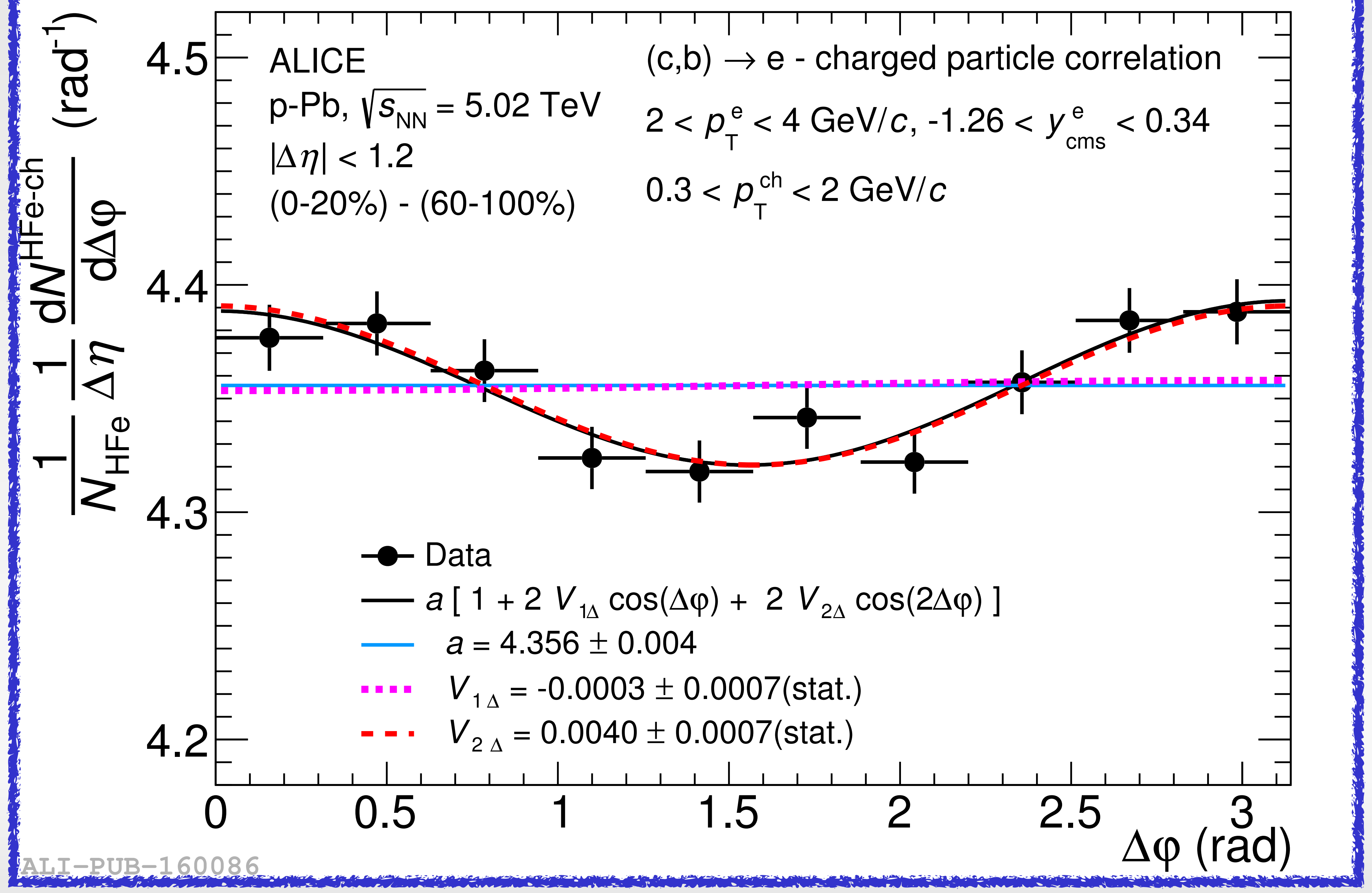
Modification

Heavy-flavour electrons v_2 in p-Pb collisions

➪ **Jet subtraction**: high mult. - low mult.

➪ **Modulation present!** Collective effects
Initial- or final-state effect

PhysRevLett.122.072301



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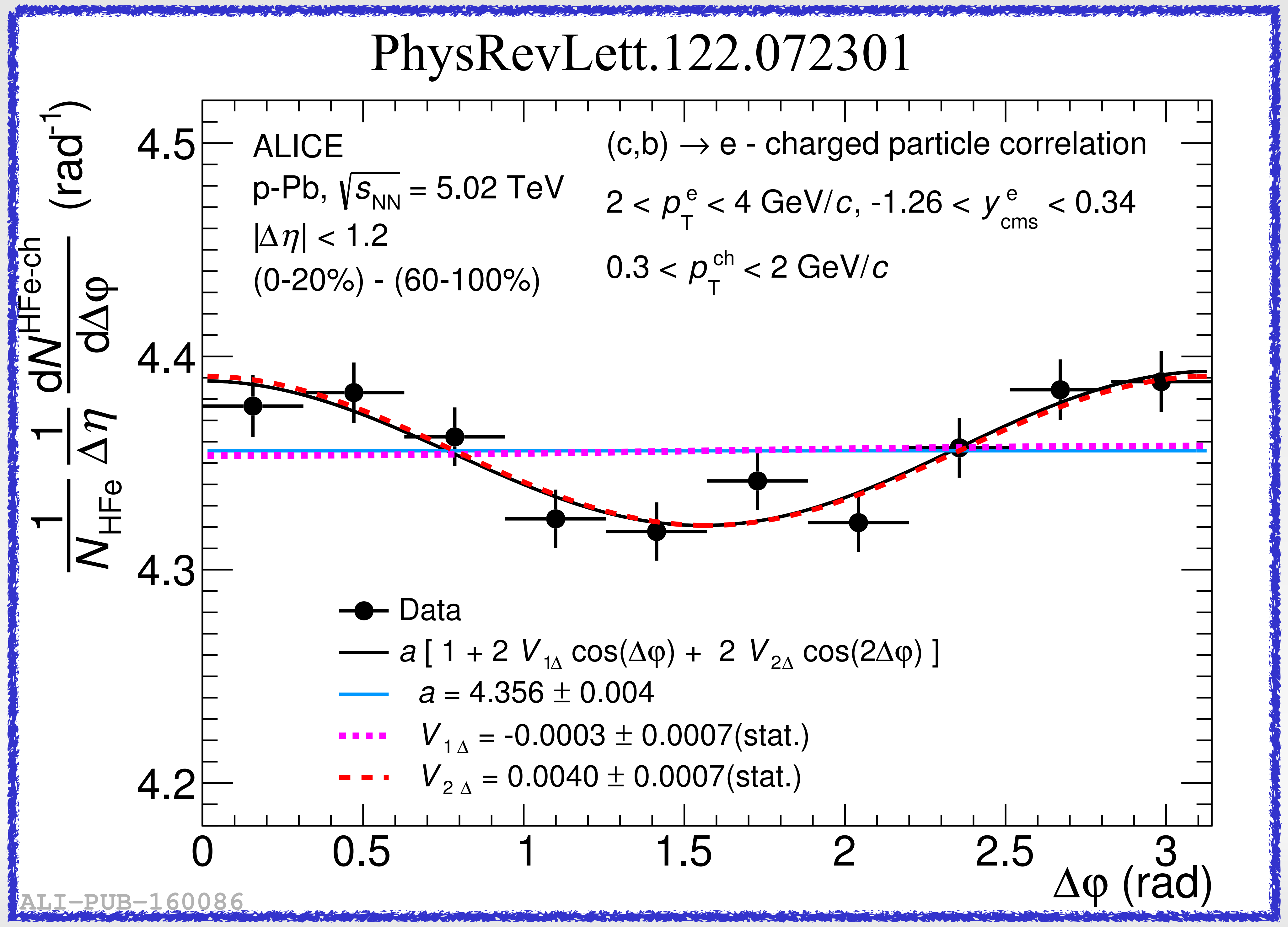
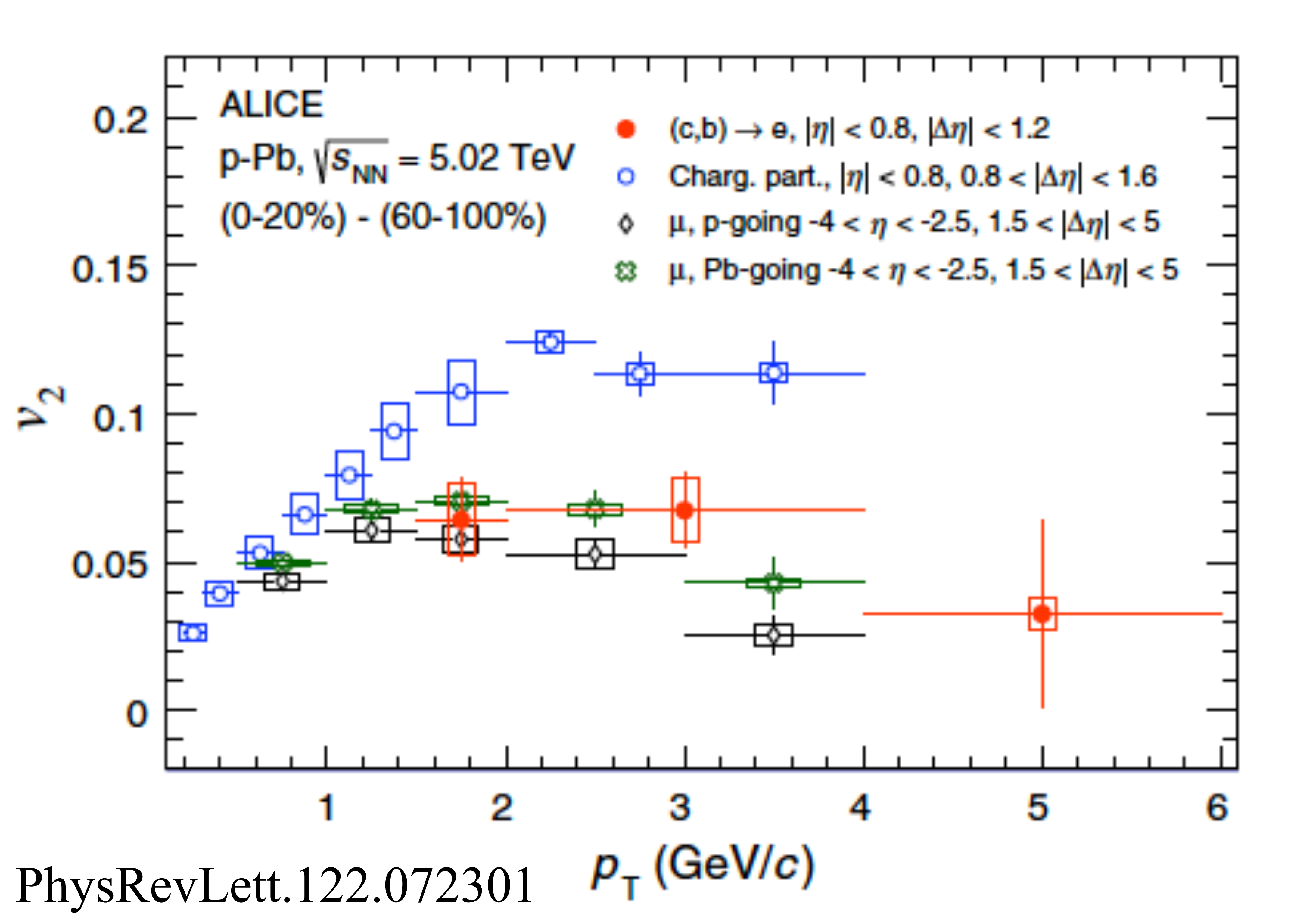
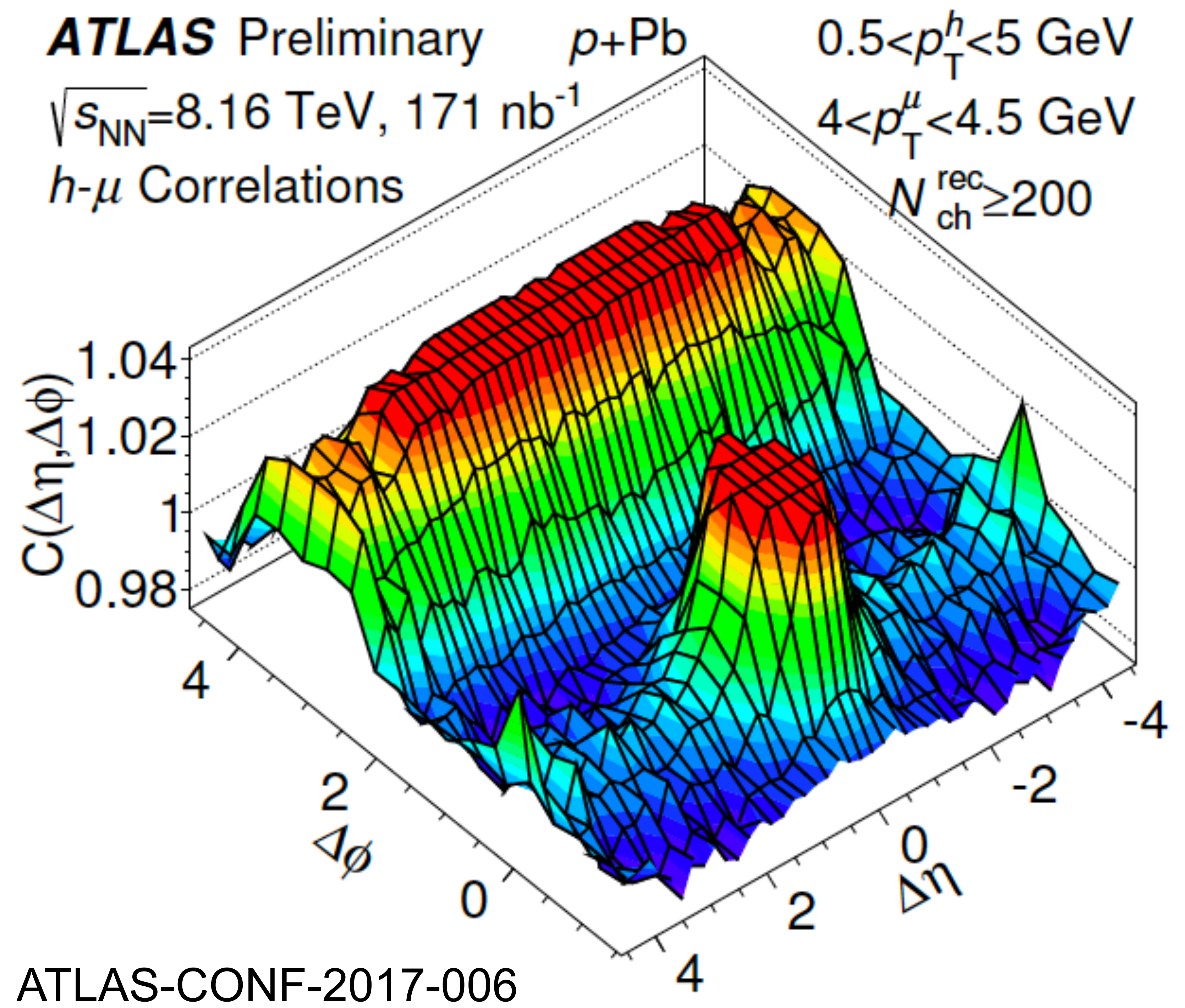




➪ Significance: **5.1σ for 1.5< p_{Te}< 4 GeV/*c***

➪ **Effect is similar to the one observed for inclusive muons**

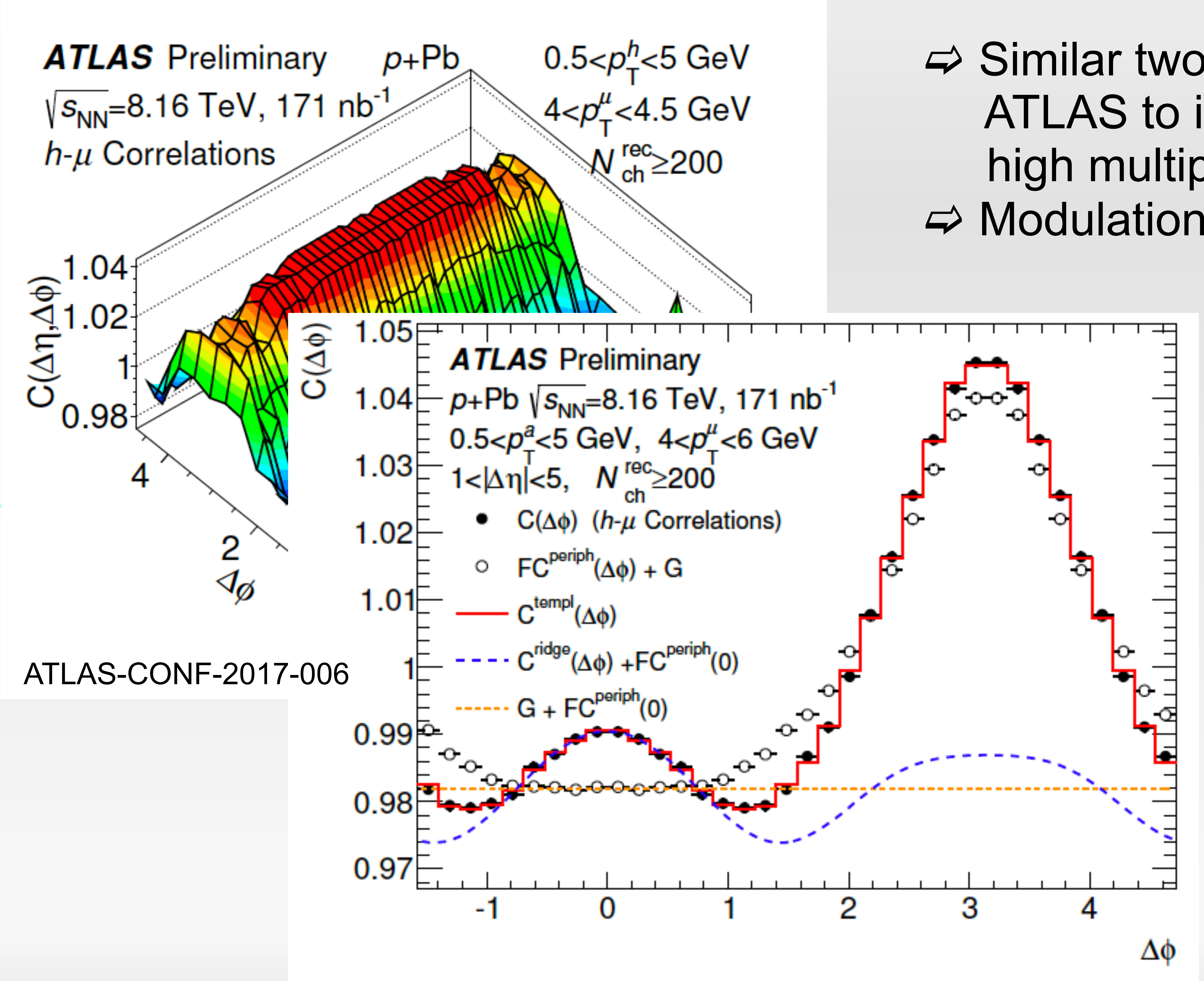
μ-hadron correlation in p-Pb collisions



ATLAS-CONF-2017-006

- Similar two particle correlation technique (μ-h) used in ATLAS to investigate flow-like effect for high pt muons in high multiplicity p-Pb at 8.16 TeV

μ-hadron correlation in p-Pb collisions



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- ➯ Modulation observed in the correlation function

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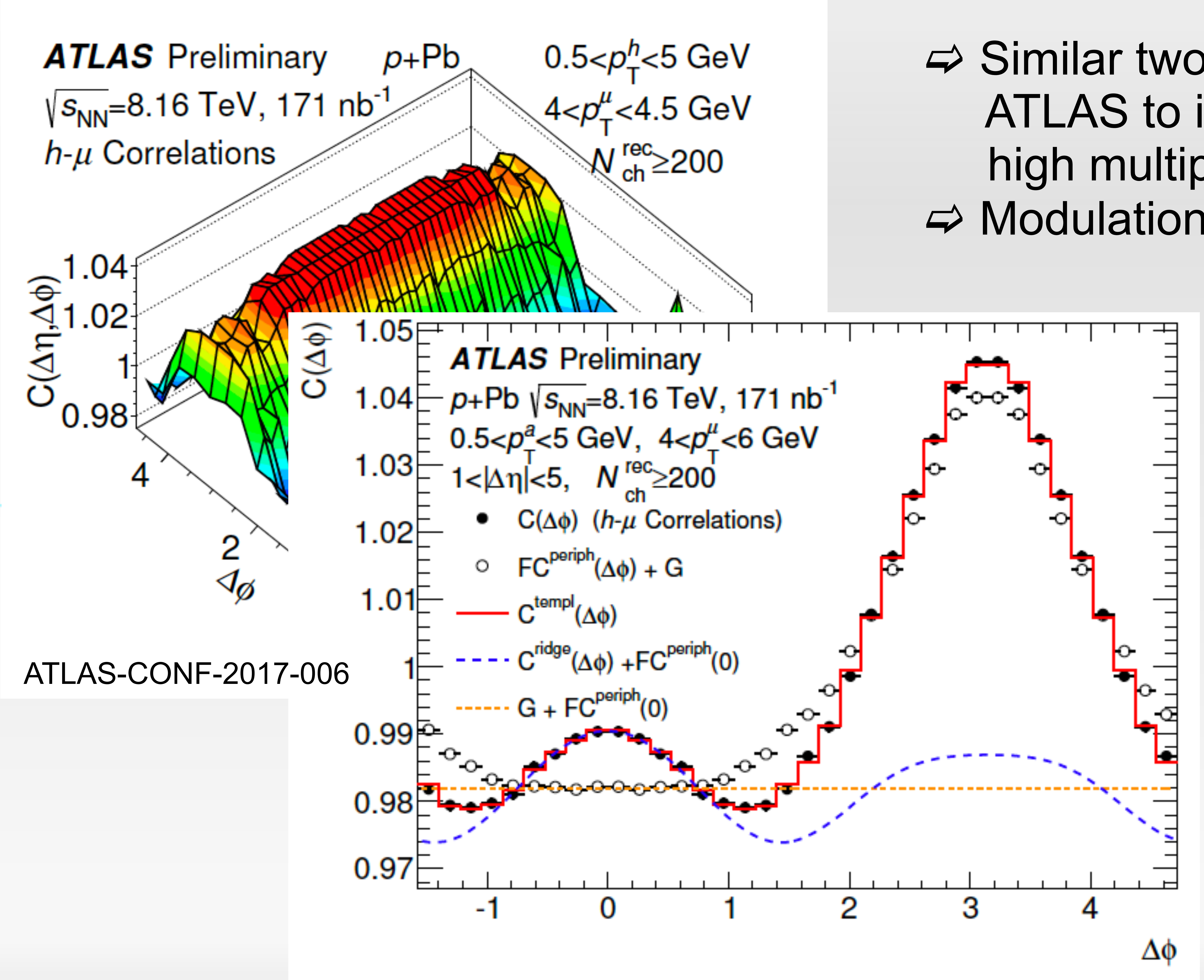
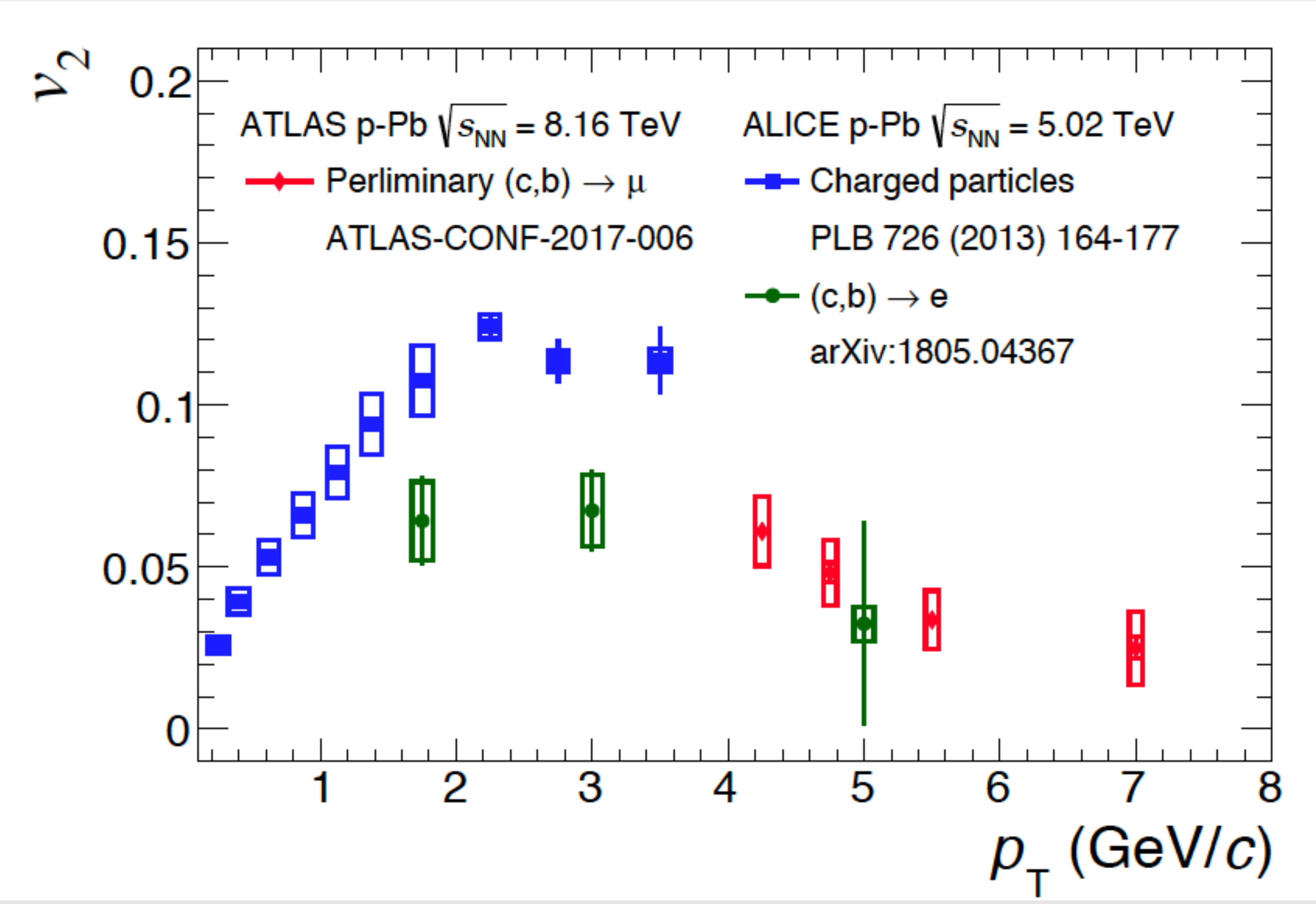


- ⇨ Similar two particle correlation technique (μ-h) used in ATLAS to investigate flow-like effect for high pt muons in high multiplicity p-Pb at 8.16 TeV
- ⇨ Modulation observed in the correlation function

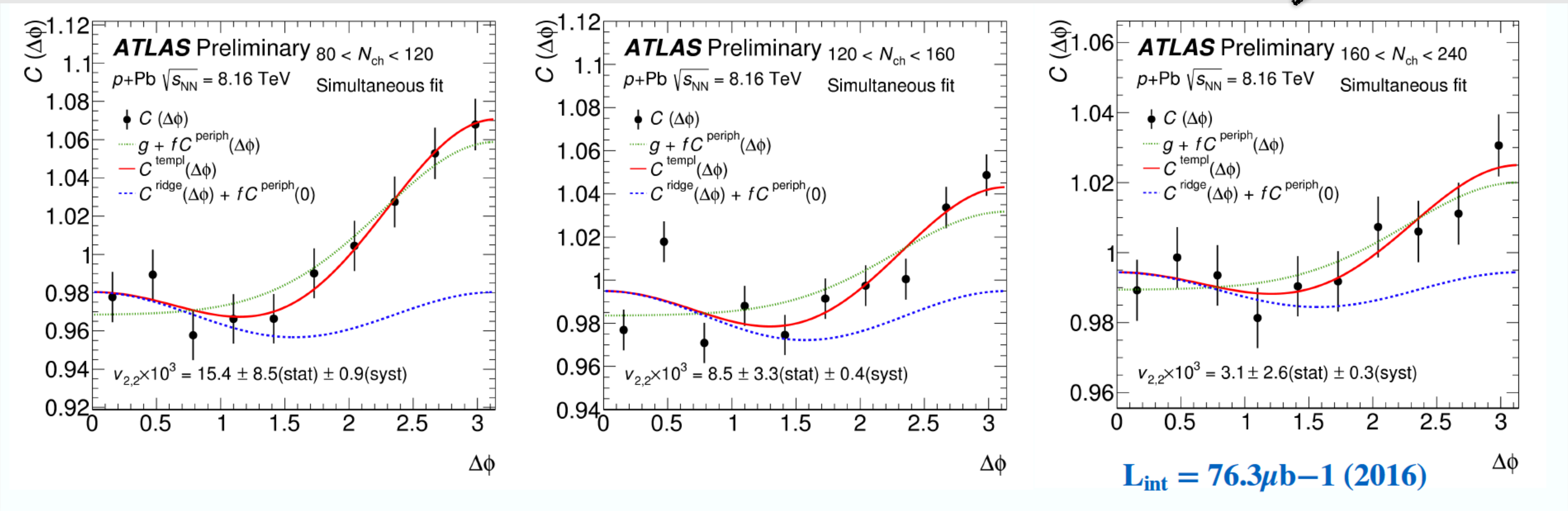
⇨ Compatible and complementary results obtained by different experiment



D-hadron correlation in p-Pb collisions

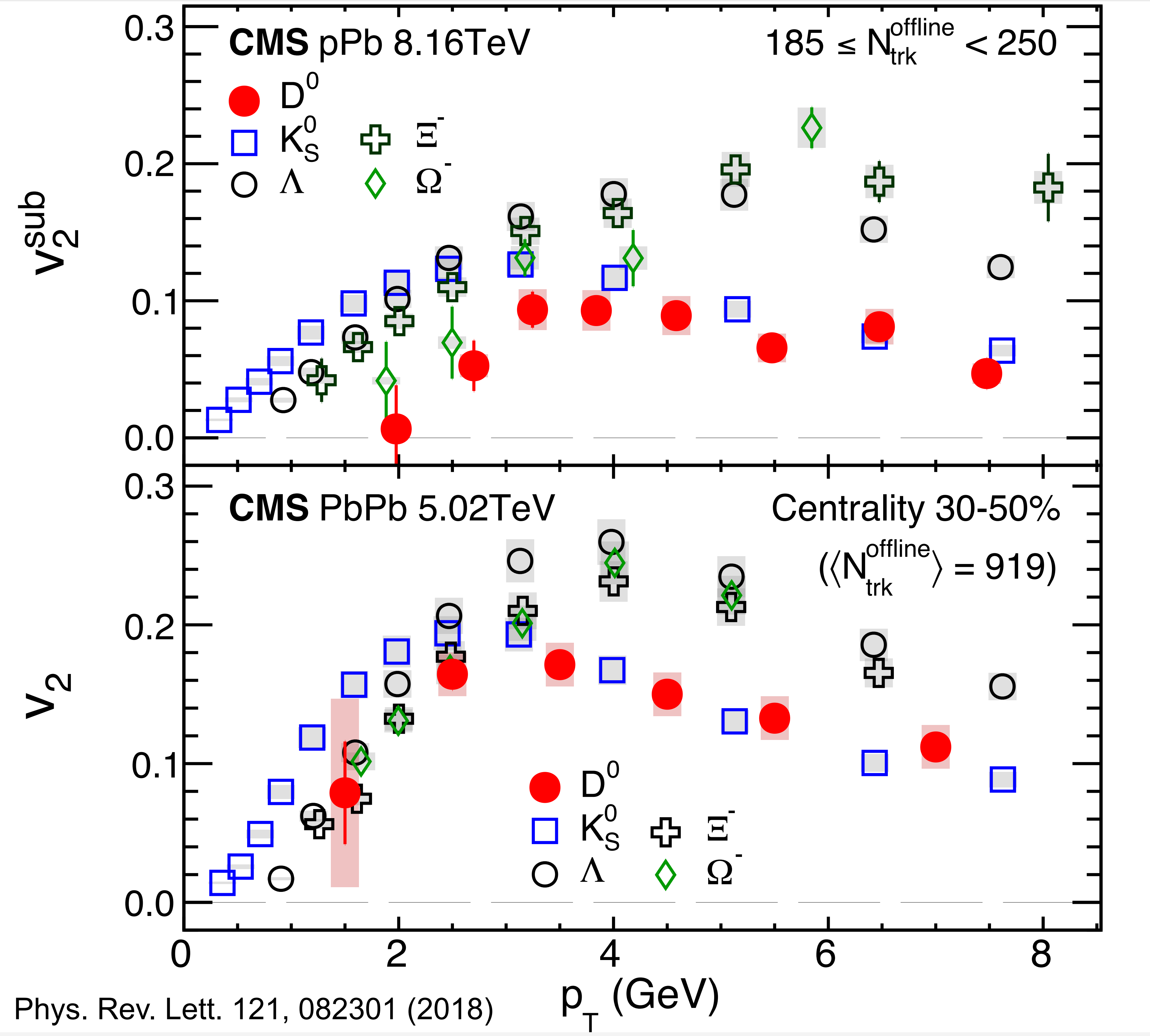
ATLAS-CONF-2017-073

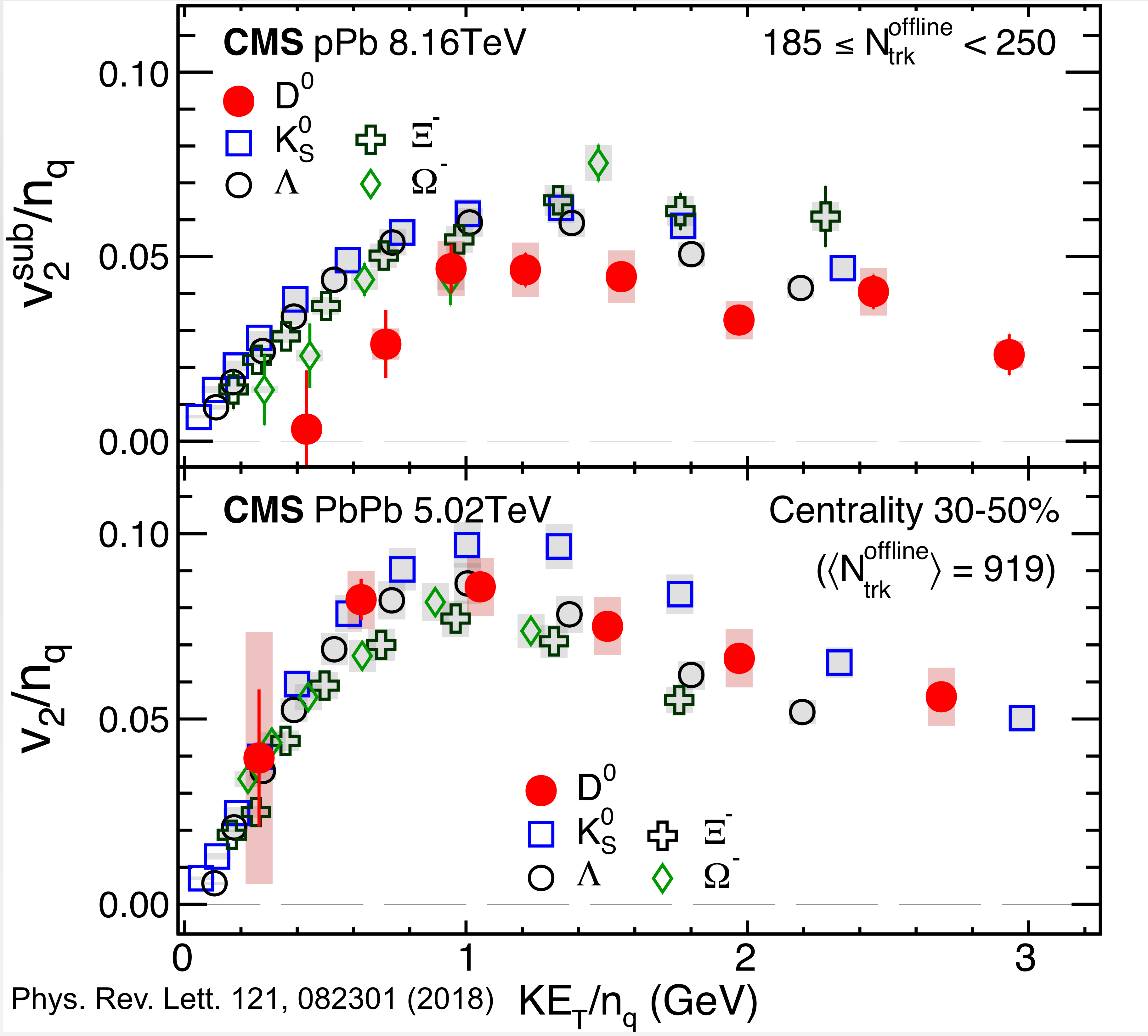
$\mathbf{N_{ch}}$



$$v_{2,2}(80 < N_{ch} < 120) = (15.4 \pm 8.5(\text{stat}) \pm 0.9(\text{syst})) \times 10^{-3},$$
$$v_{2,2}(120 < N_{ch} < 160) = (8.5 \pm 3.3(\text{stat}) \pm 0.4(\text{syst})) \times 10^{-3},$$
$$v_{2,2}(160 < N_{ch} < 240) = (3.1 \pm 2.6(\text{stat}) \pm 0.3(\text{syst})) \times 10^{-3}.$$

D^0 elliptic flow in p-Pb collisions





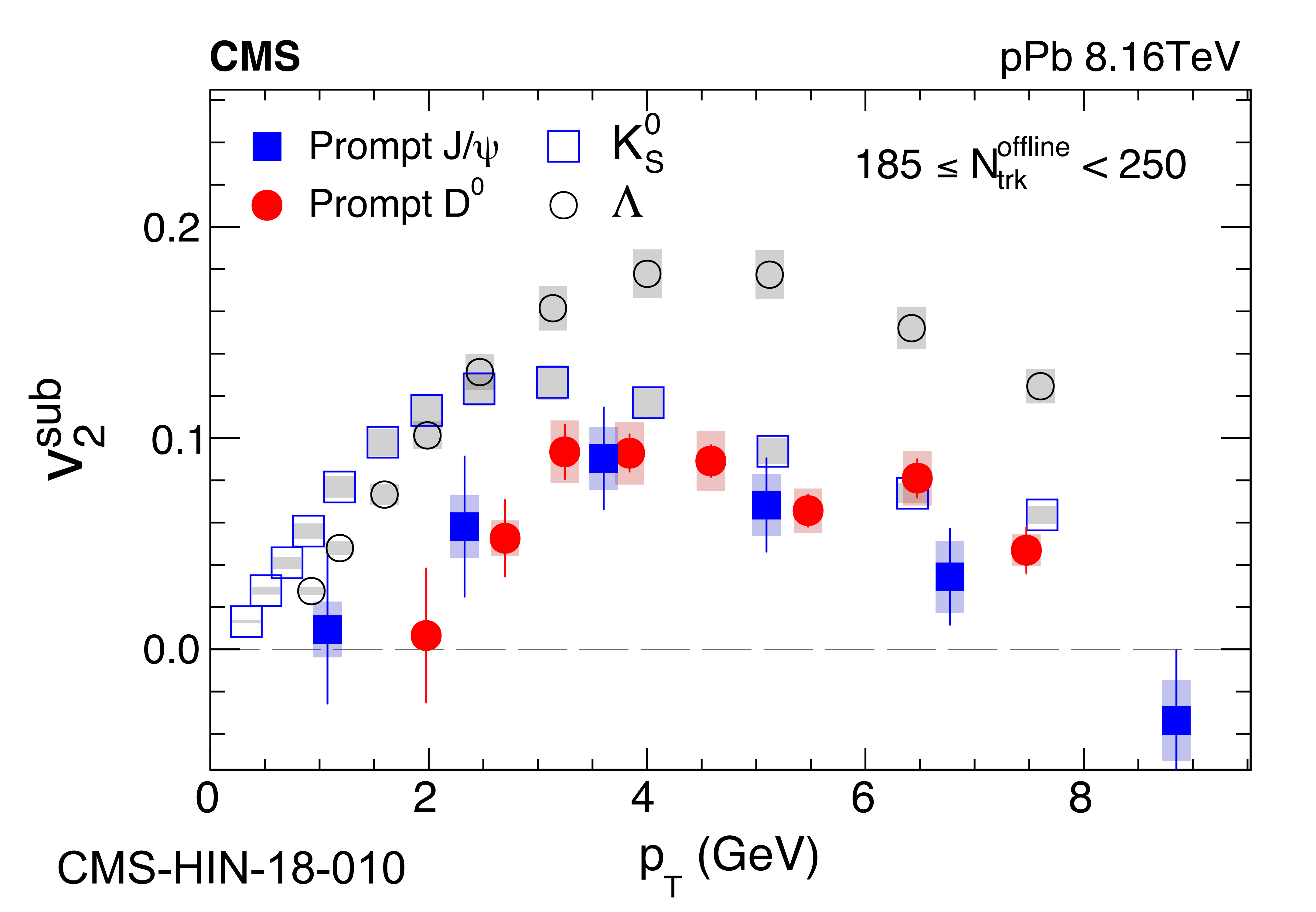
➪ Comparing to strange-hadron results, the **D^0 v_2 values are positive but smaller** at a given p_T, or at similar transverse kinetic energy per constituent quark, after normalizing v_2 by the number of constituent quarks.

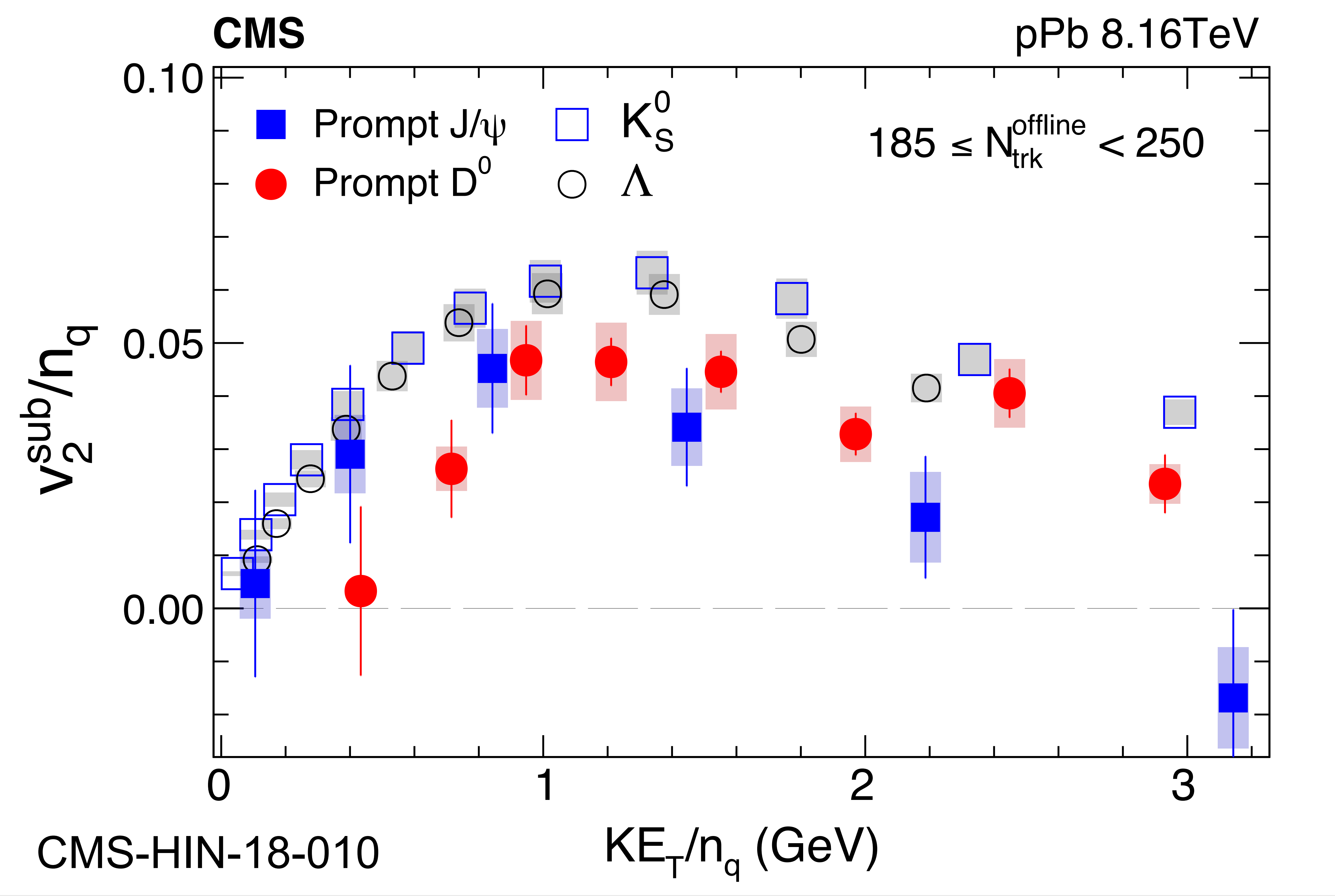
➪ This indicates that in high-multiplicity p-Pb collisions, the **collective behaviour of charm quarks is weaker than that of the light-flavor quarks**. This effect is not seen in Pb-Pb collisions.

J/ψ v_2 in p-Pb collisions

- **Significant J/ψ v_2 observed**
- Consistent with the previous conclusion that **charm quarks develop a weaker collective dynamics** than light quarks in small systems

- **Caveat**: different rapidity ranges for different particle species could bias the comparison





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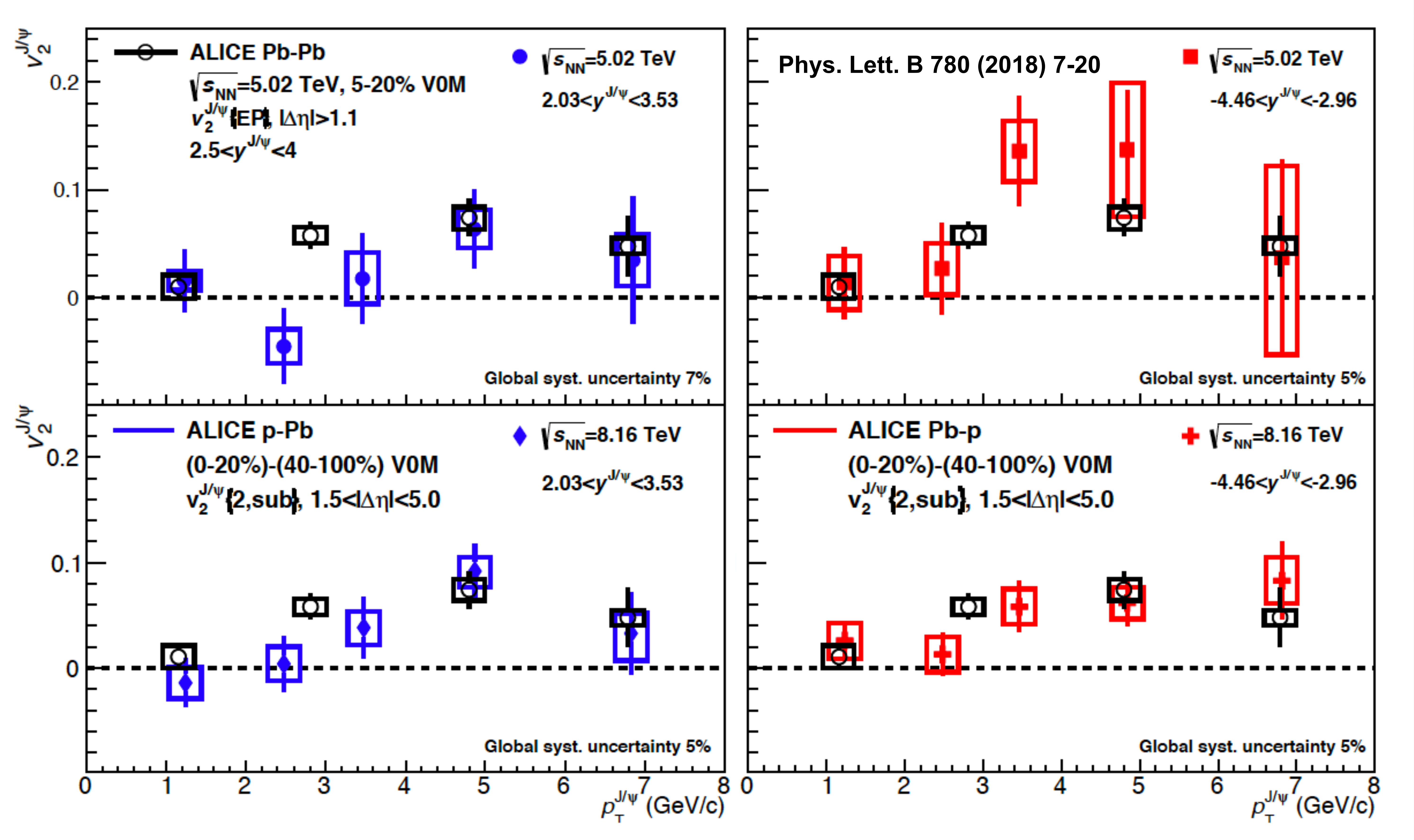


- ➪ **Significant J/ψ v_2 observed for p_T > 3 GeV/c**

- ➪ The measured values, albeit with large uncertainties, are comparable with those measured in Pb-Pb collisions at 5.02 TeV in forward rapidity

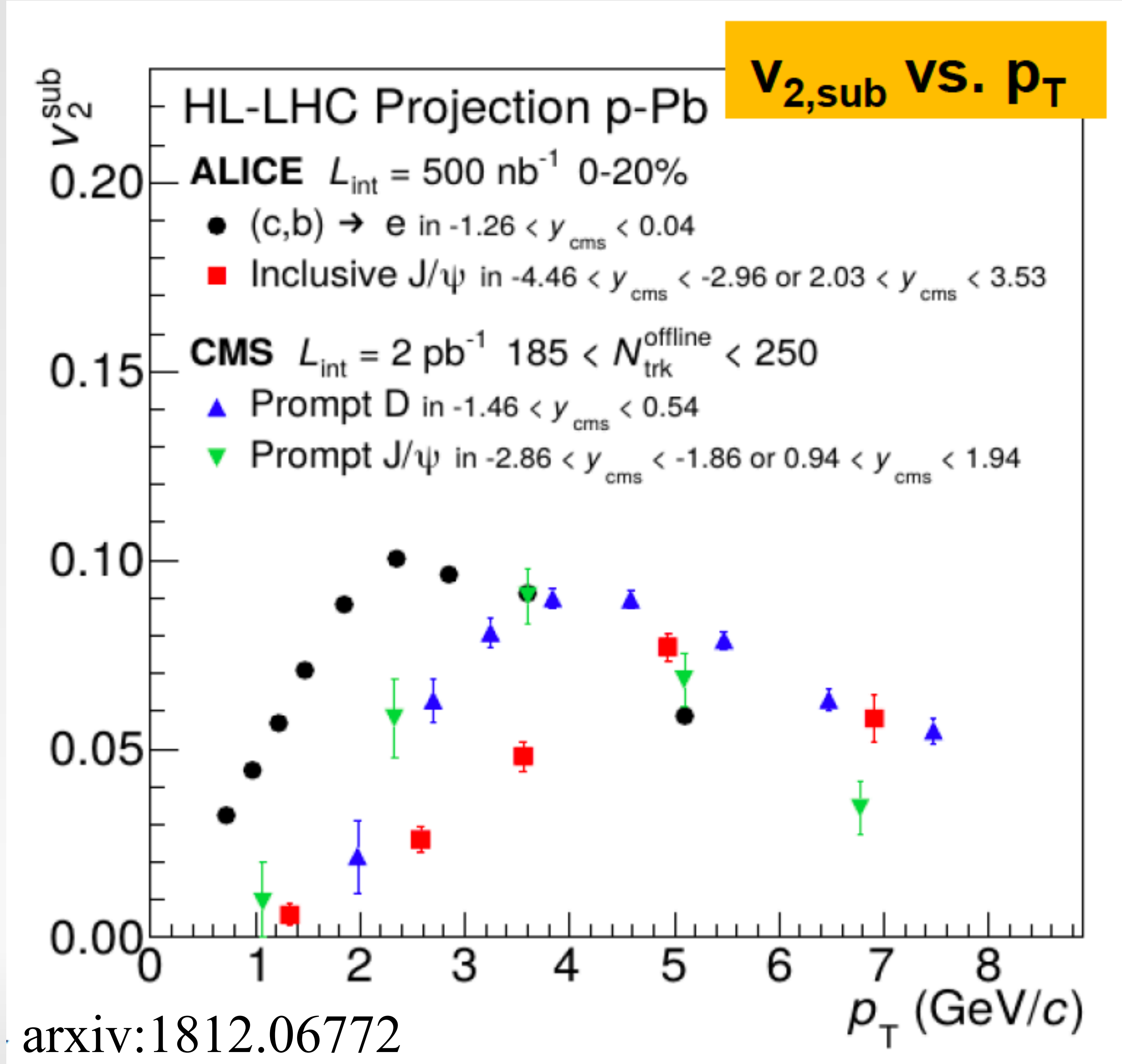
- ➪ The underlying mechanism is not understood - comparable magnitude of the J/ψ v_2 in p-Pb and Pb-Pb indicates that the same mechanism could be at play

What about the future?

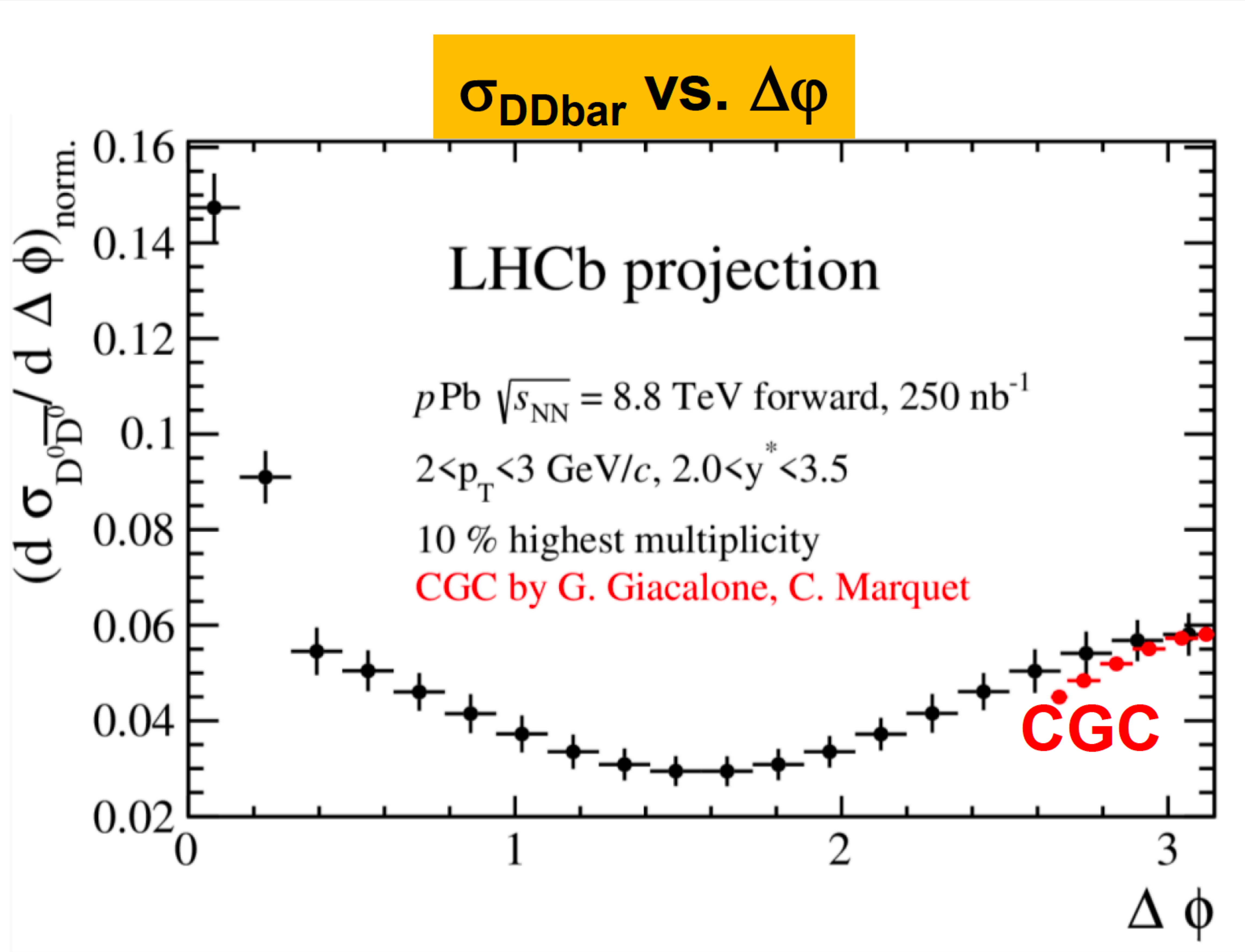
HL-LHC projections for p-Pb collisions

➪ The projected precision with p-Pb integrated luminosities Lint ~2 pb^{-1} (ATLAS and CMS) and ~1 pb^{-1} (ALICE) has the potential to **shed light on the different mechanisms behind the observed anisotropy**

➪ **D-Dbar correlation** -> a window to the CGC



arxiv:1812.06772



Conclusion

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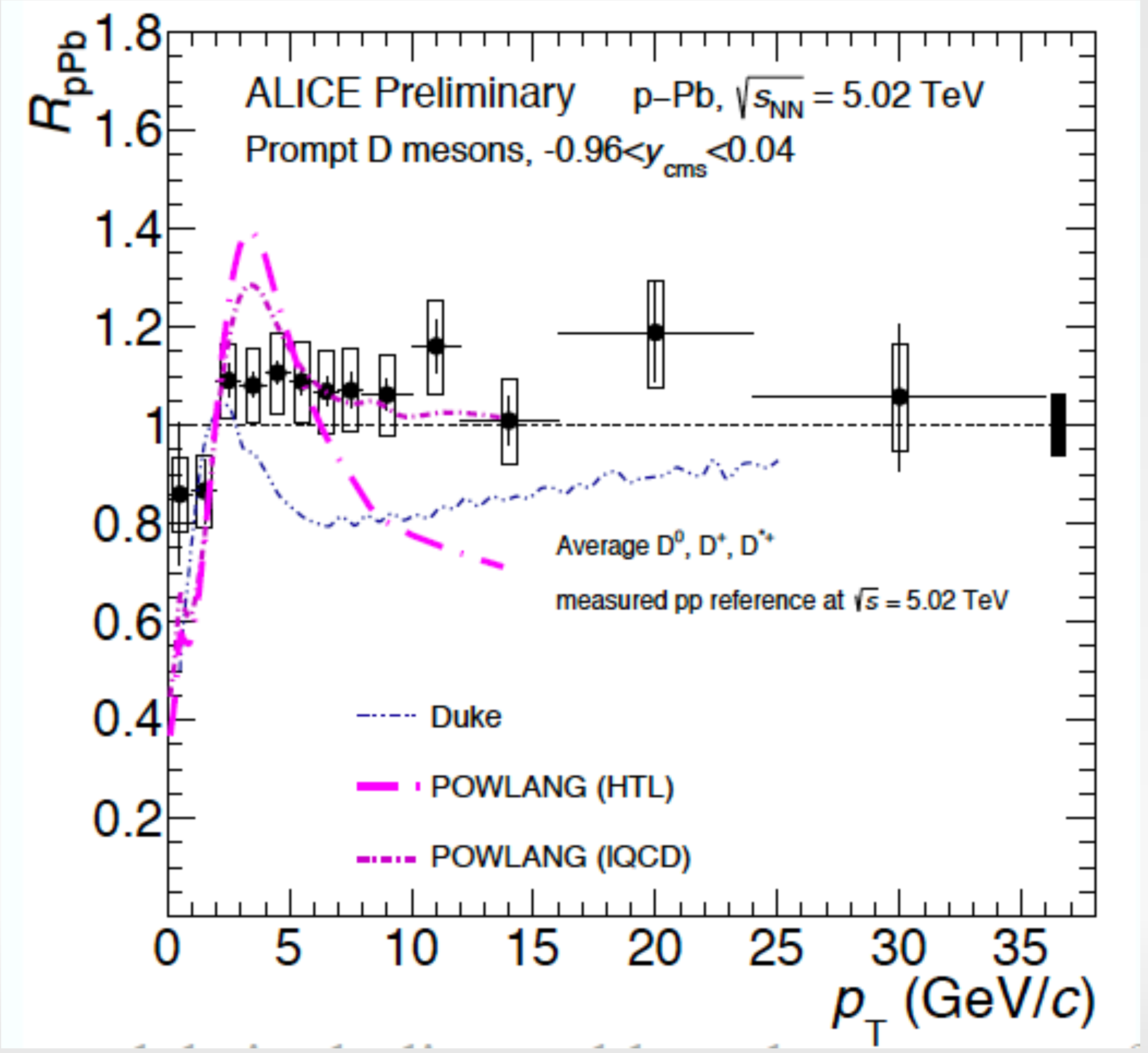
- no suppression observed at the RpPb level -> **no final state effect?**



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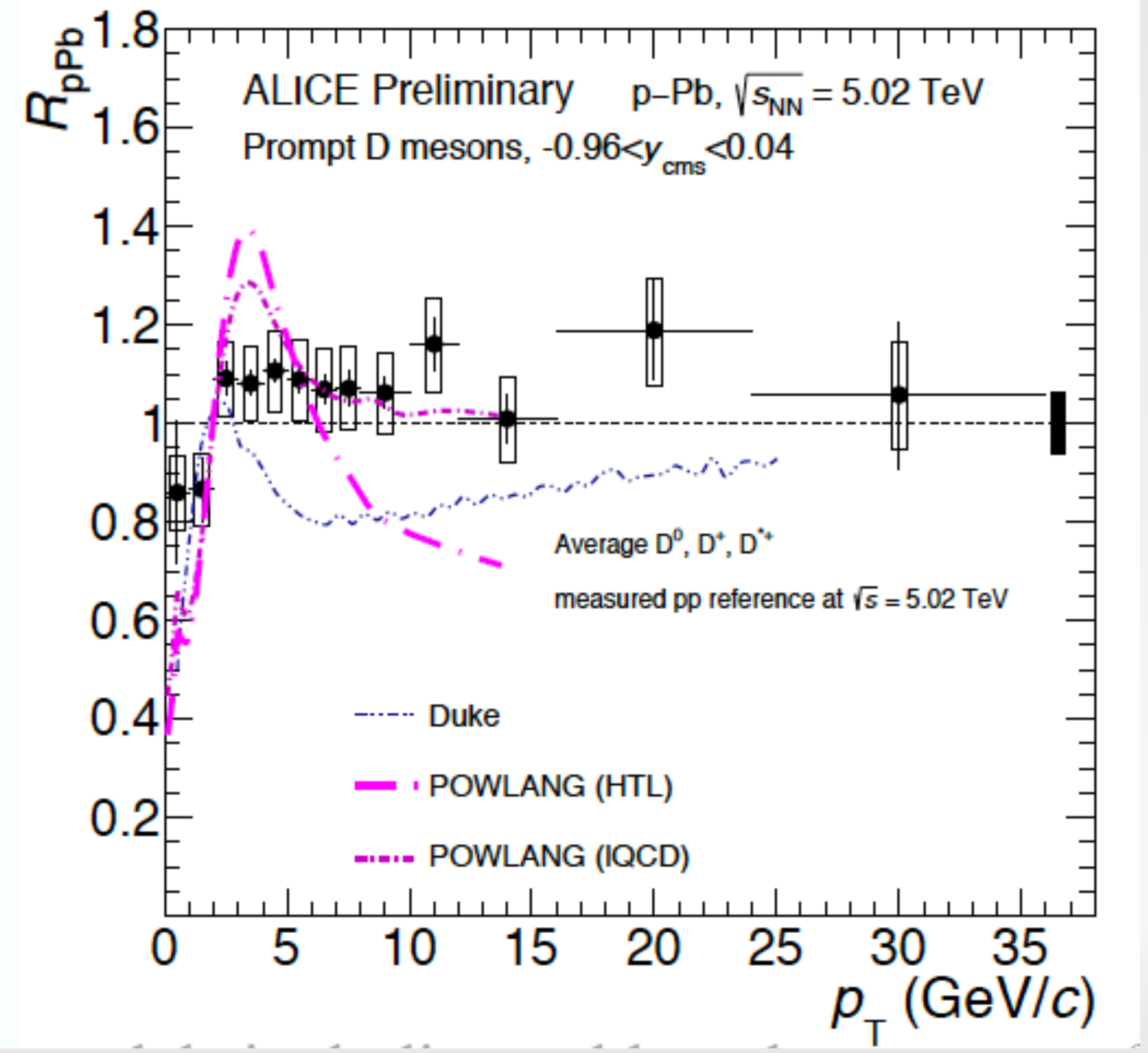
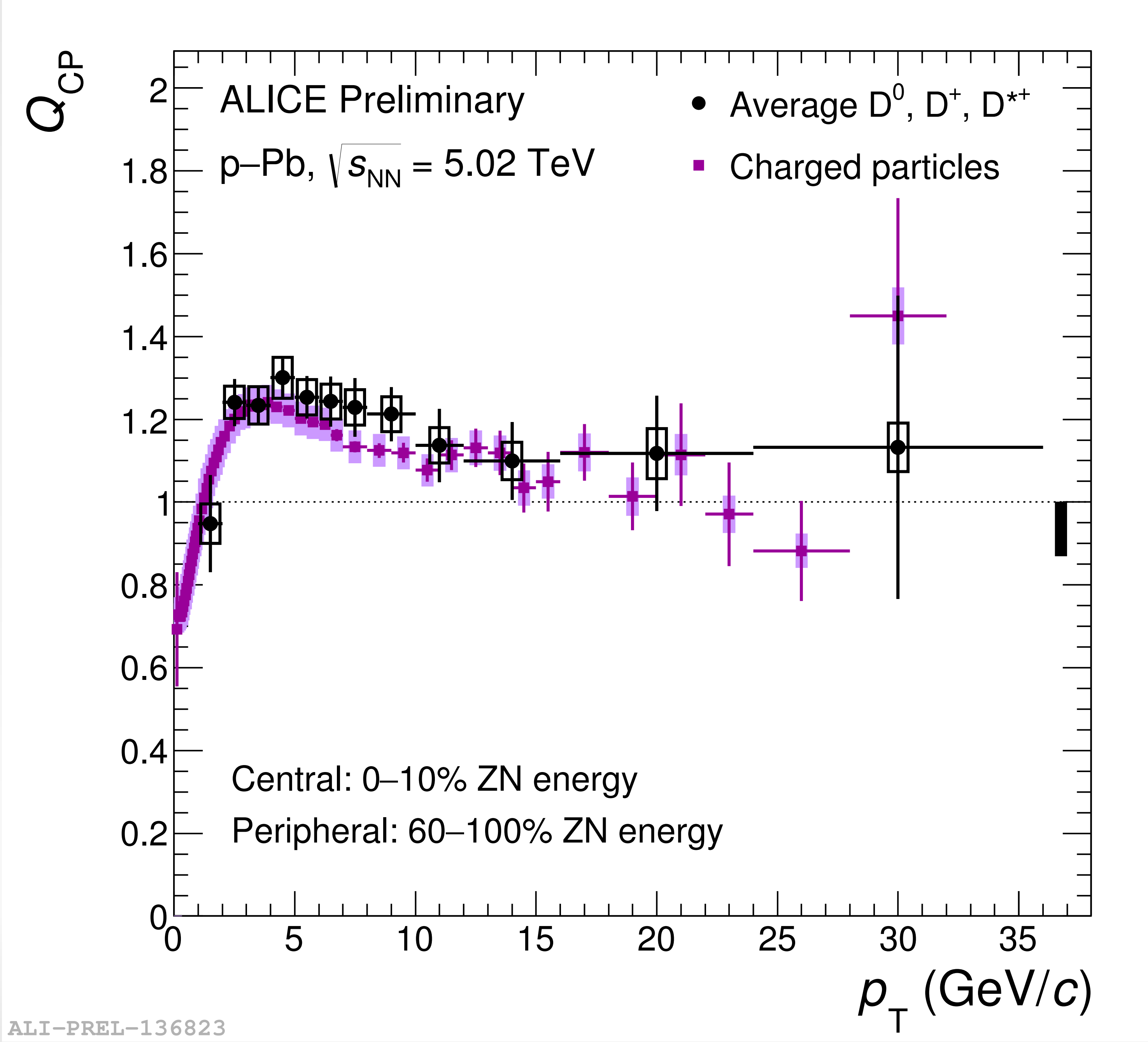
- no suppression observed at the QpPb/QCP level in most central pPb collision -> **no final state effect?**





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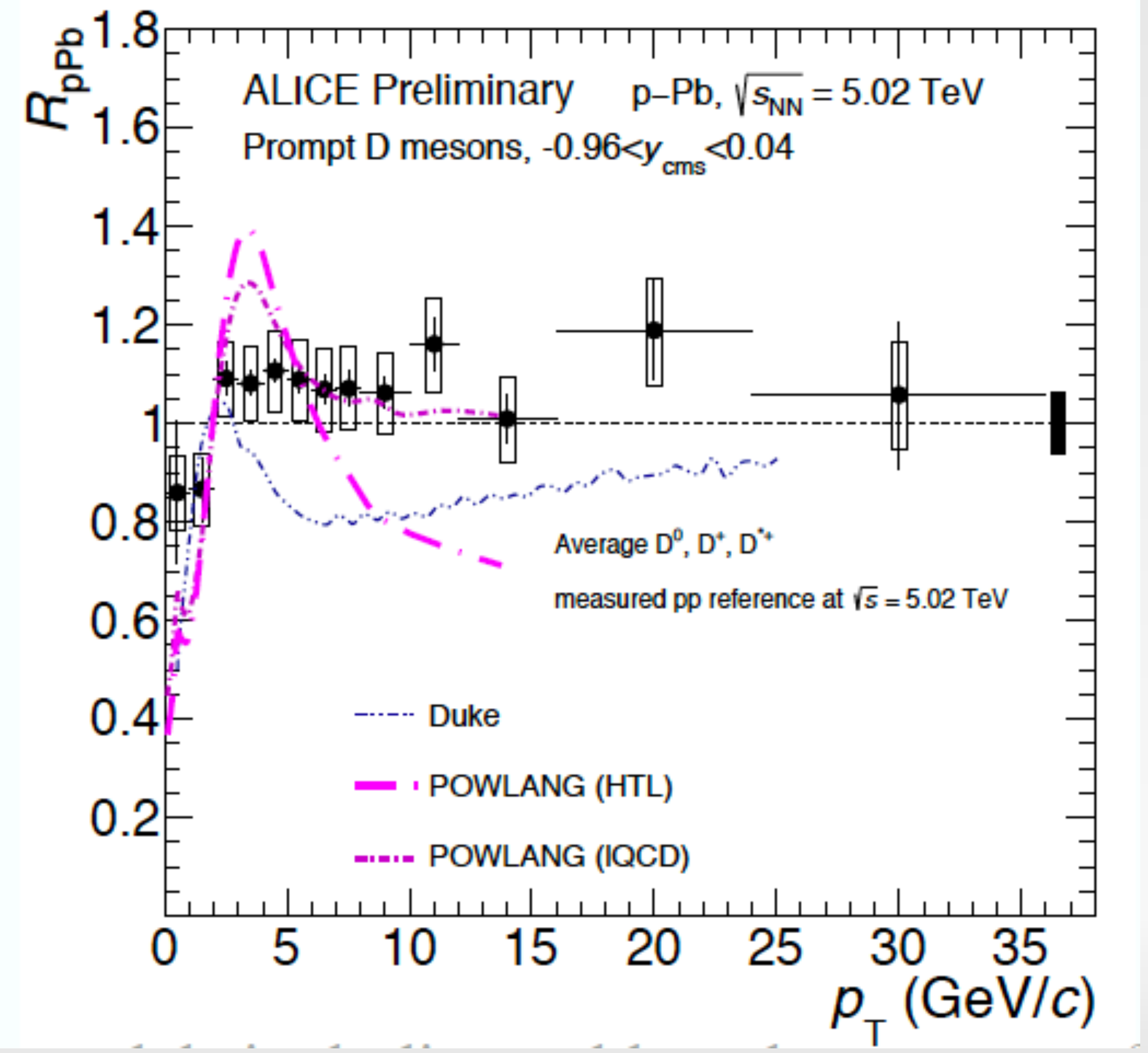
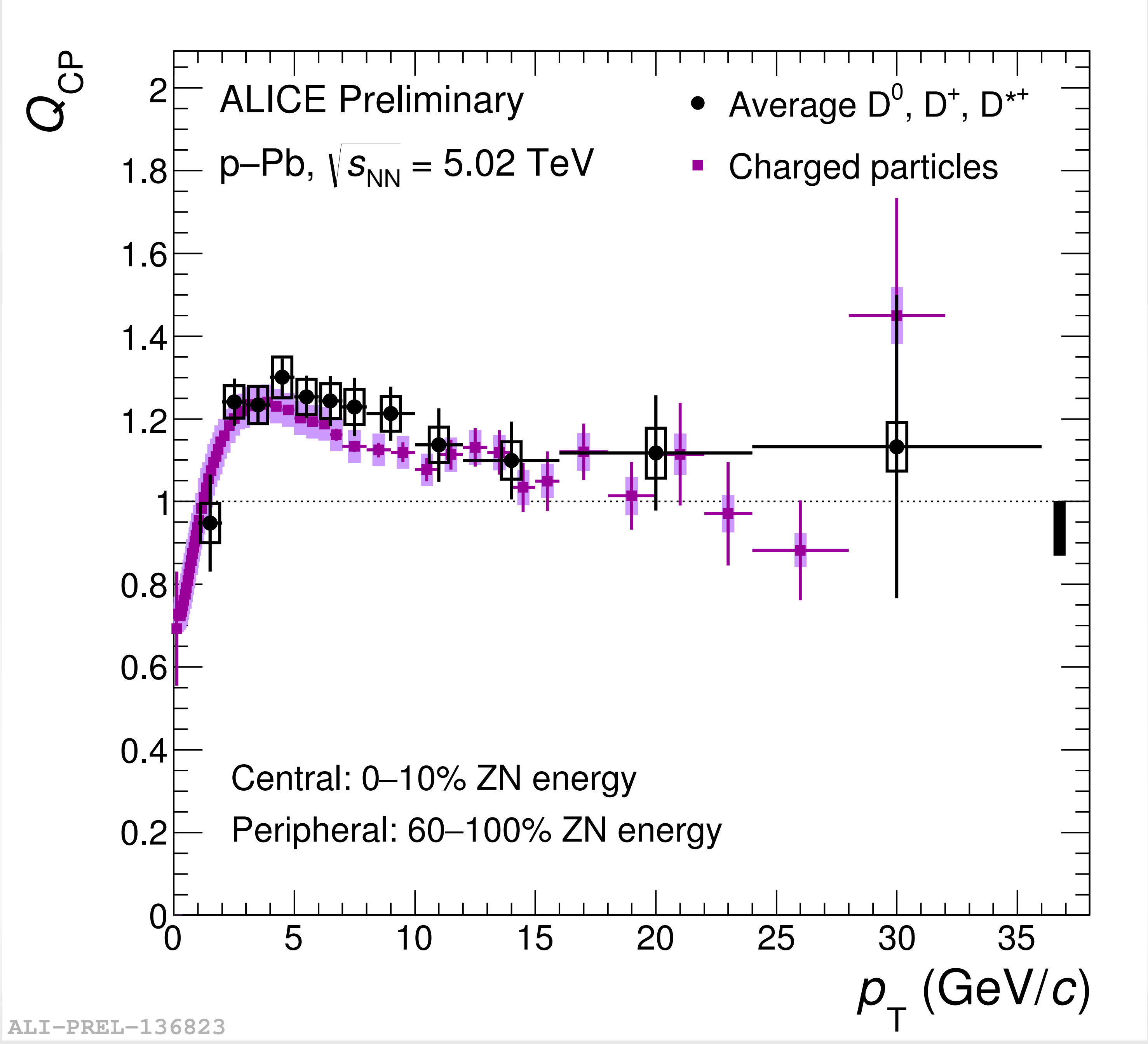
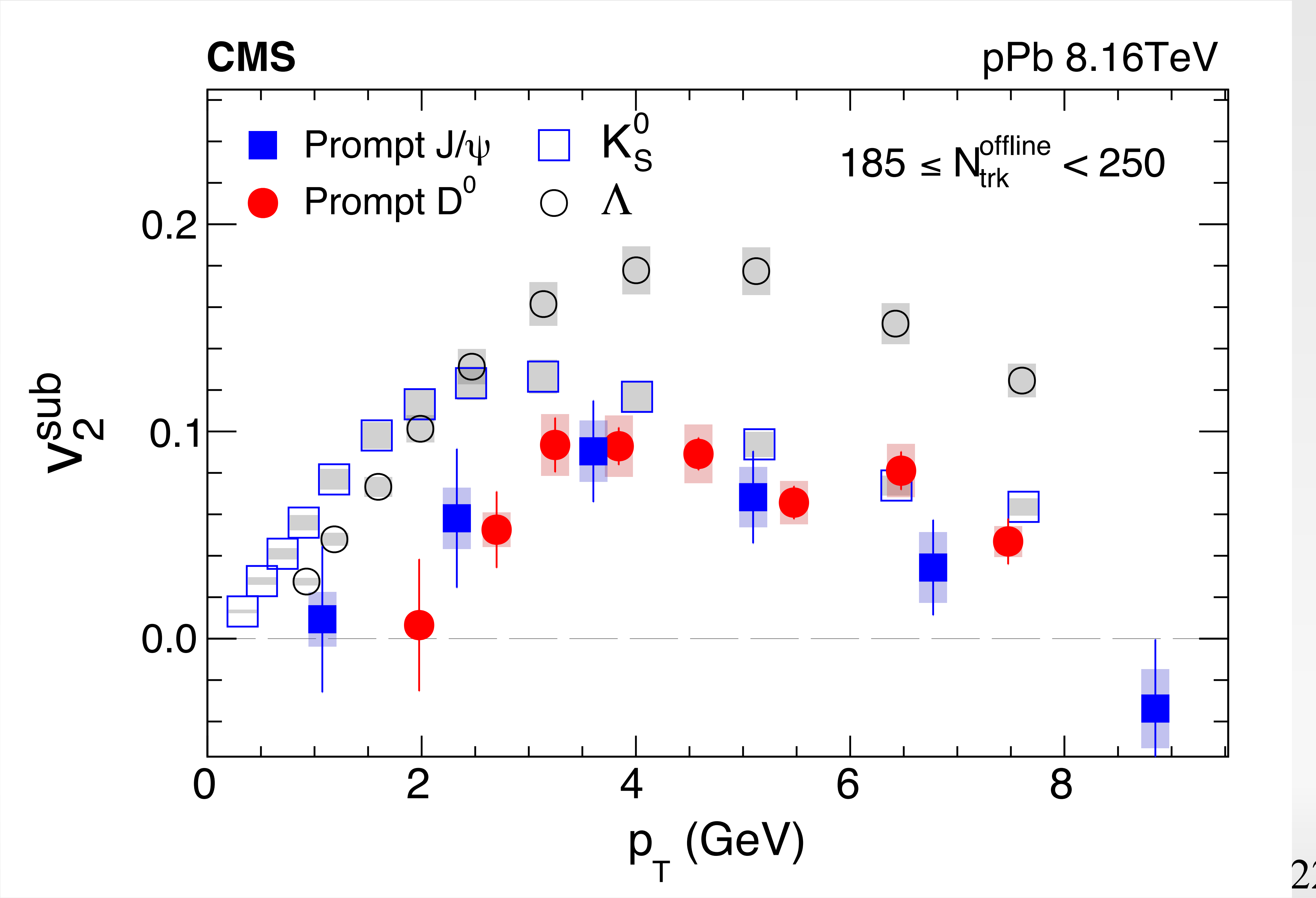
- no suppression observed at the RpPb level -> **no final state effect?**
- no suppression observed at the QpPb/QCP level in most central pPb collision -> **no final state effect?**
- significant elliptic flow measured in the HF sector up to intermediate/high pT -> **final state or initial state effect?**





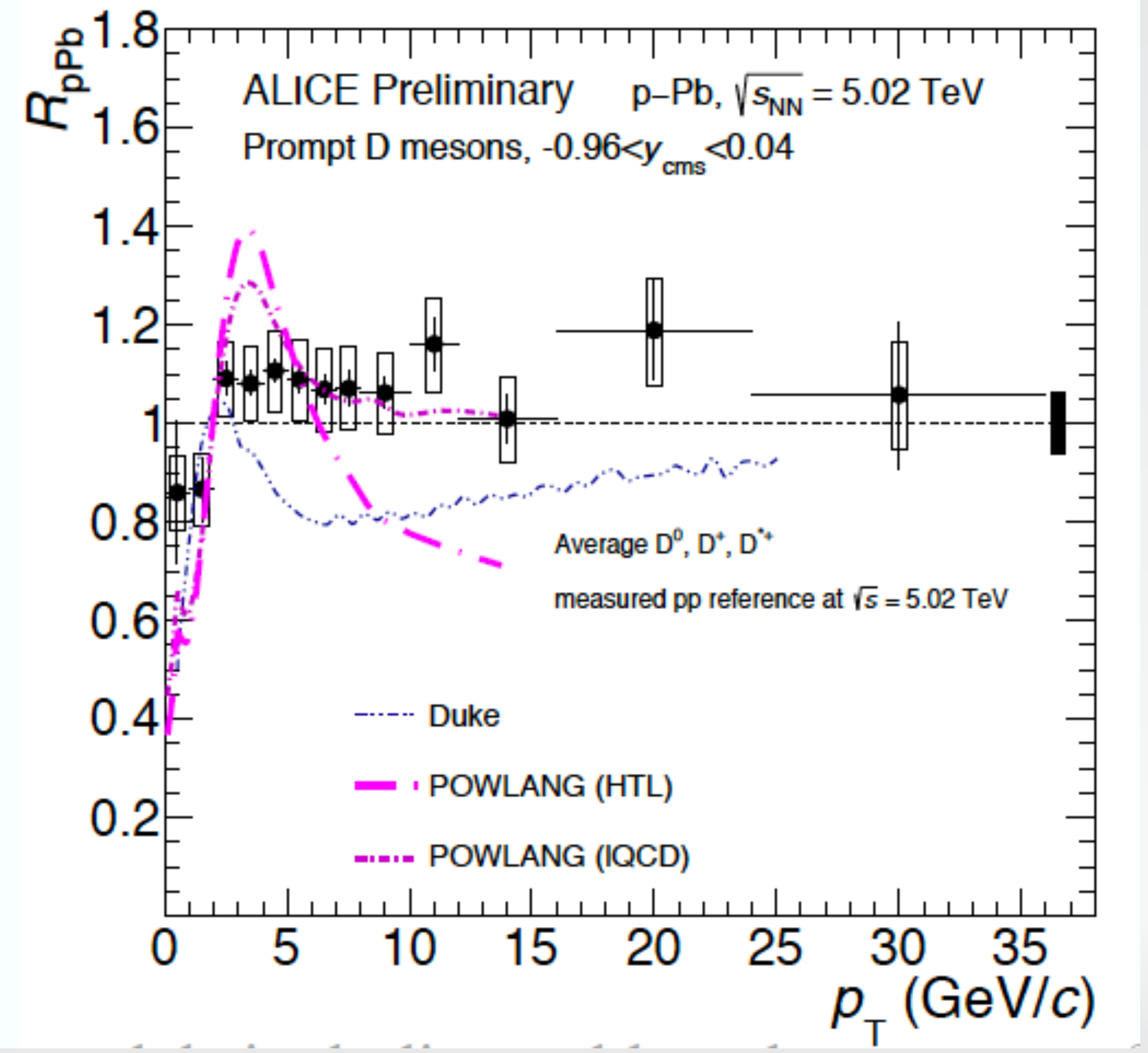


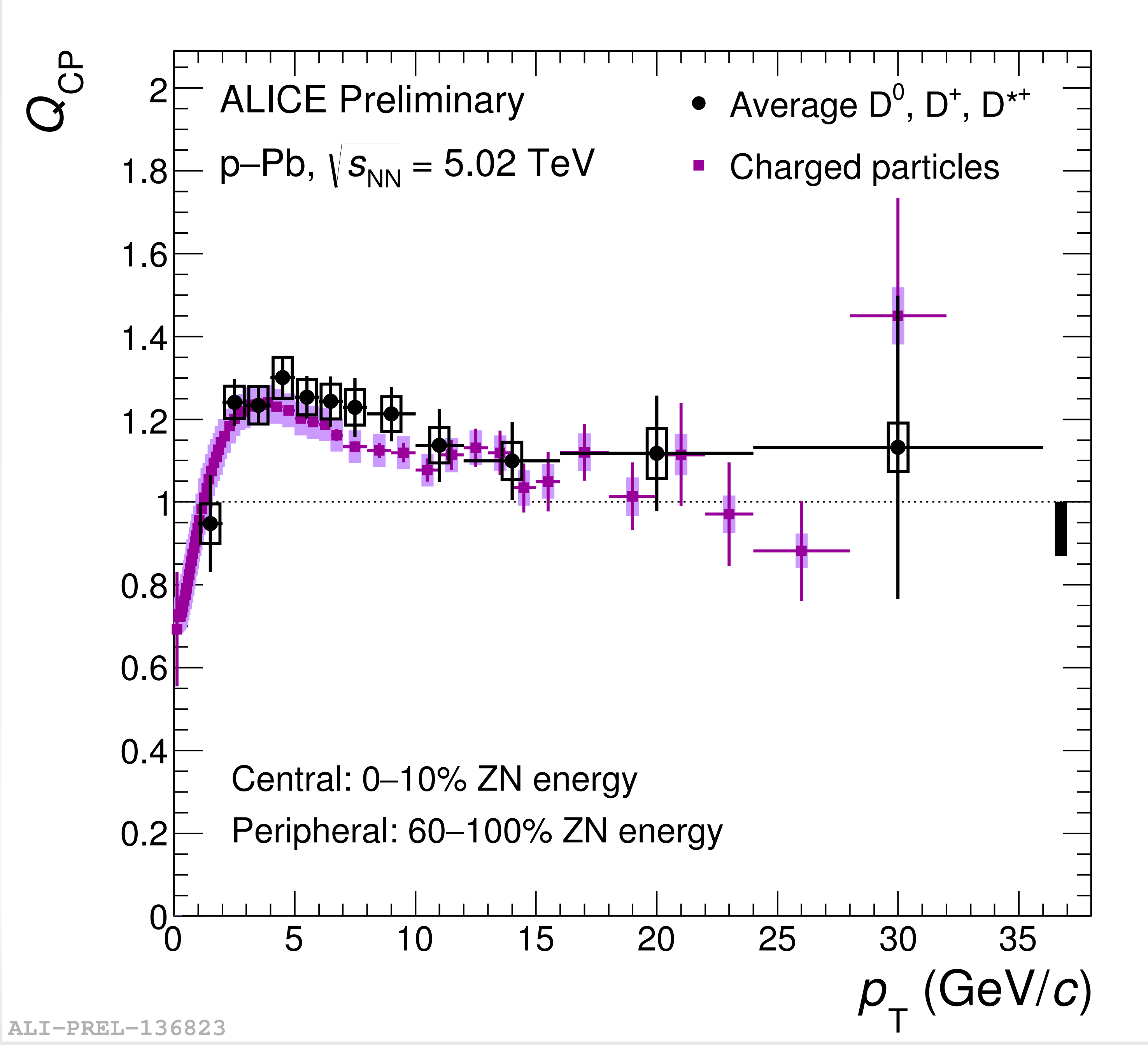
Conclusion

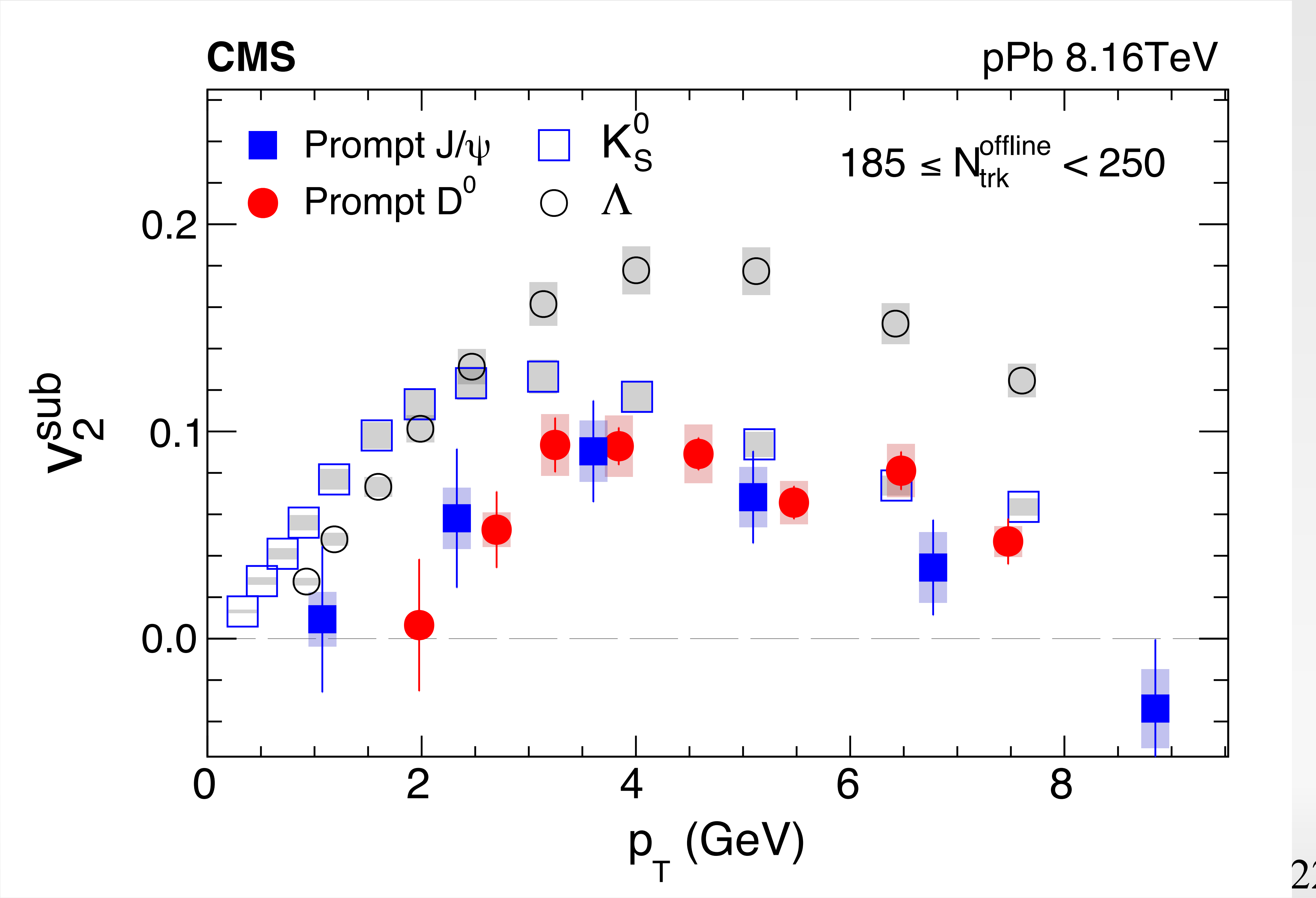
⇨ **Current understanding is still puzzling:**

- no suppression observed at the RpPb level -> **no final state effect?**
- no suppression observed at the QpPb/QCP level in most central pPb collision -> **no final state effect?**
- significant elliptic flow measured in the HF sector up to intermediate/high pT -> **final state or initial state effect?**

⇨ Need more comparison with theory calculation and higher precision in experimental measurements (achievable with Run3/4)



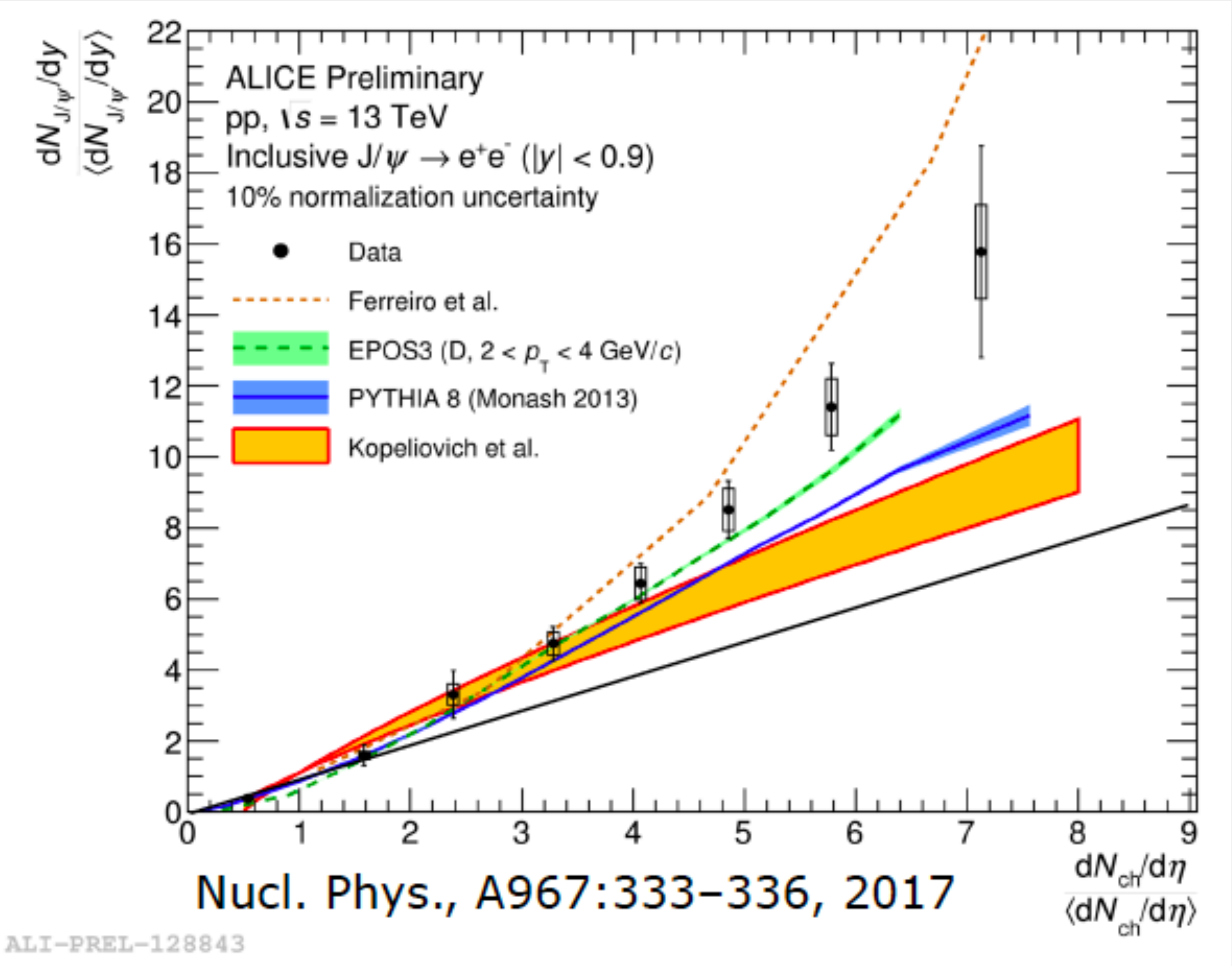




….and in pp collisions?

One observable as example….

S. Weber, A. Dubla, A. Andronic, A. Morsch
Eur. Phys. J. C (2019) 79 no.1, 36.



⇨ **J/ψ** production increases **faster-than linear with the charged multiplicity (*N*ch)**. This could tie in with **hints of a QGP-like** behaviour in high-multiplicity pp events

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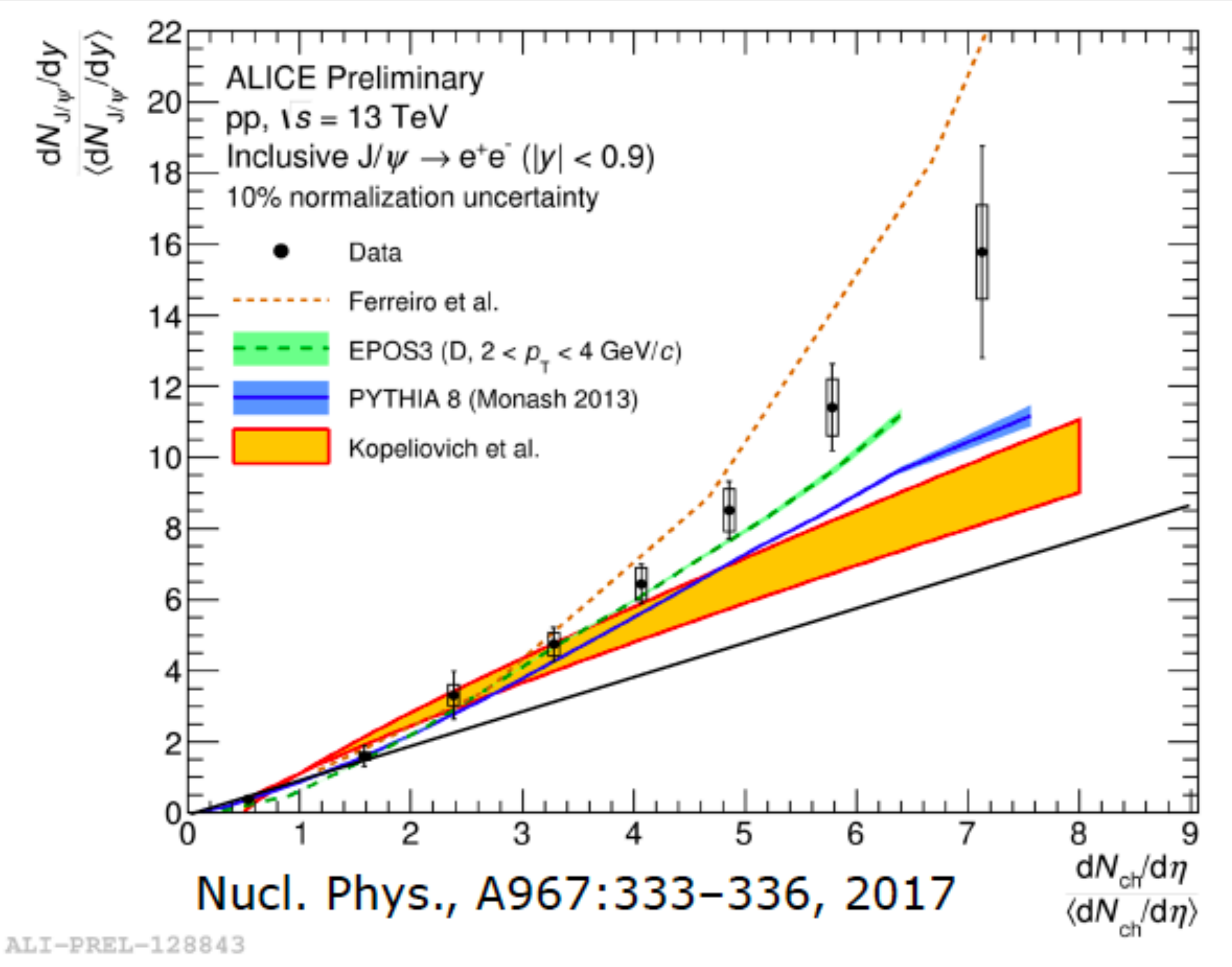

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  Phys.Rev. C86 (2012) 034903

- **Kopeliovich**: Draw analogy between high multiplicity pp an pA collisions
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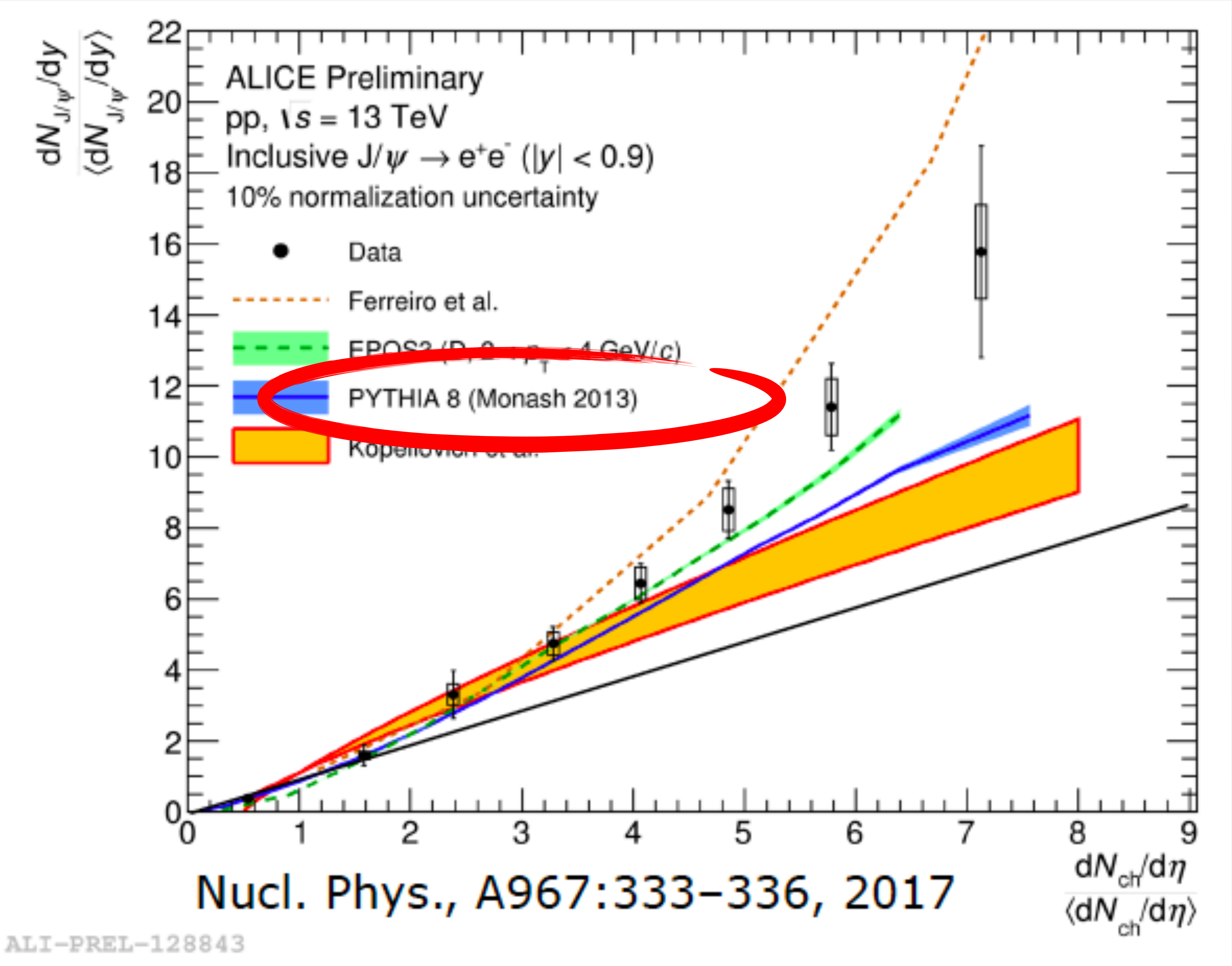

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Auto-correlation effects

⇨ **The charged-particle multiplicity and the J/ψ yield are not independent quantities**

1) **J/ψ decay daughters**. Two additional charged particles are produced in events containing a J/ψ

2) In **NRQCD** processes the J/ψ is typically produced together with a gluon, e.g. via $\mathbf{g\,g \to [Q\bar{Q}]\,g}$ which will hadronize and increase the multiplicity. Additionally, if the pre-resonant state is a **colour-octet, an additional gluon** is emitted in the transition to the physical J/ψ state

3) In the case of J/ψ from **cluster collapse**, the charm quark and antiquark are both produced together with another charm antiquark and charm quark, which in turn will produce additional particles

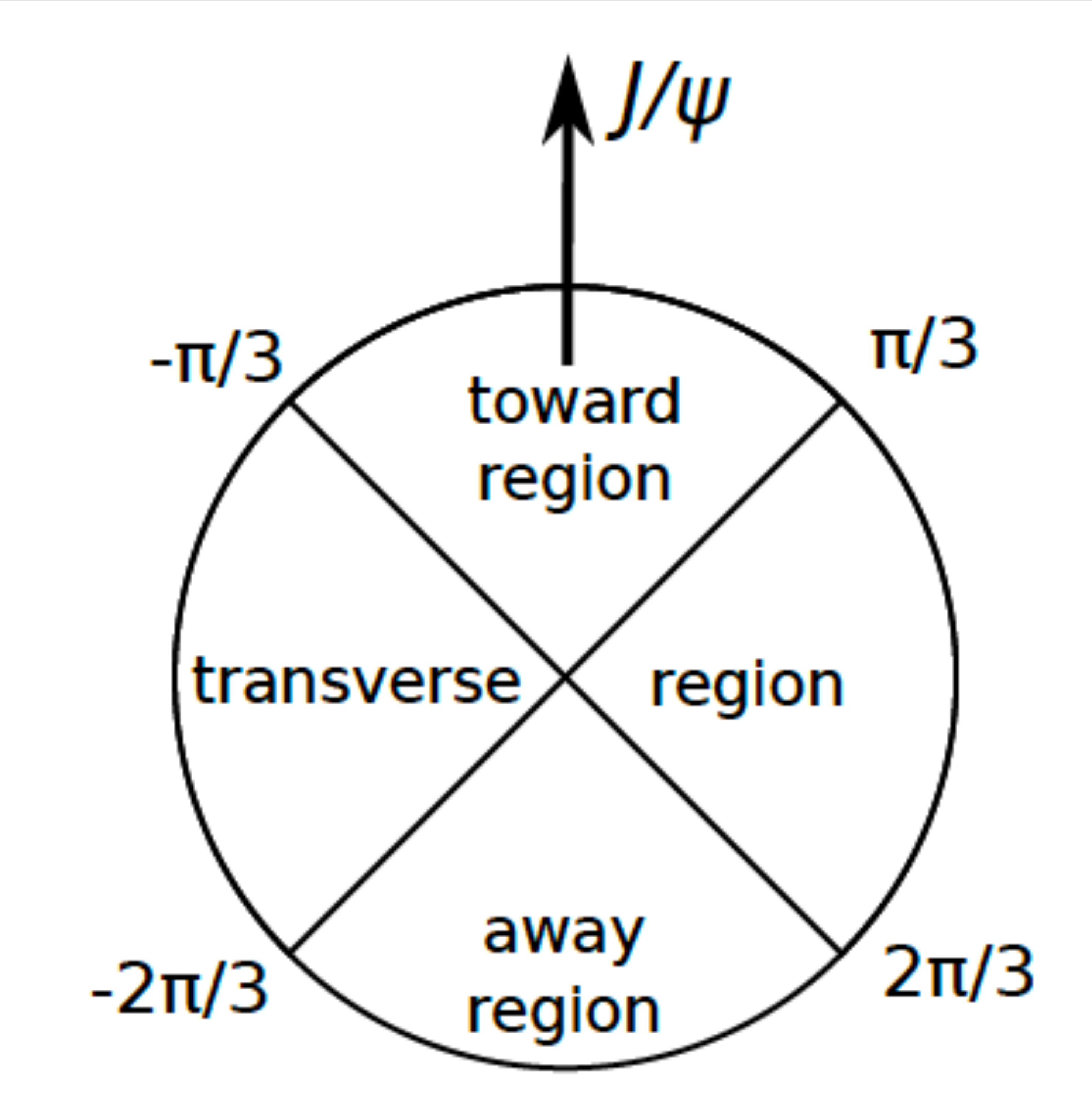
4) **non-prompt J/ψ (same for other open heavy-flavours)**:

- **b → B → J/ψ + X**: decay daughters X located close to J/ψ flight direction in rapidity and azimuthal angle

- beauty quark accompanied by **final state radiation**: enhancing the multiplicity in the region around it

- gg → bb: The **recoil jet** is at an **azimuthal angle of 180 degrees** with respect to the initial b quark, but can be at a **different rapidity**

Auto-correlation effects



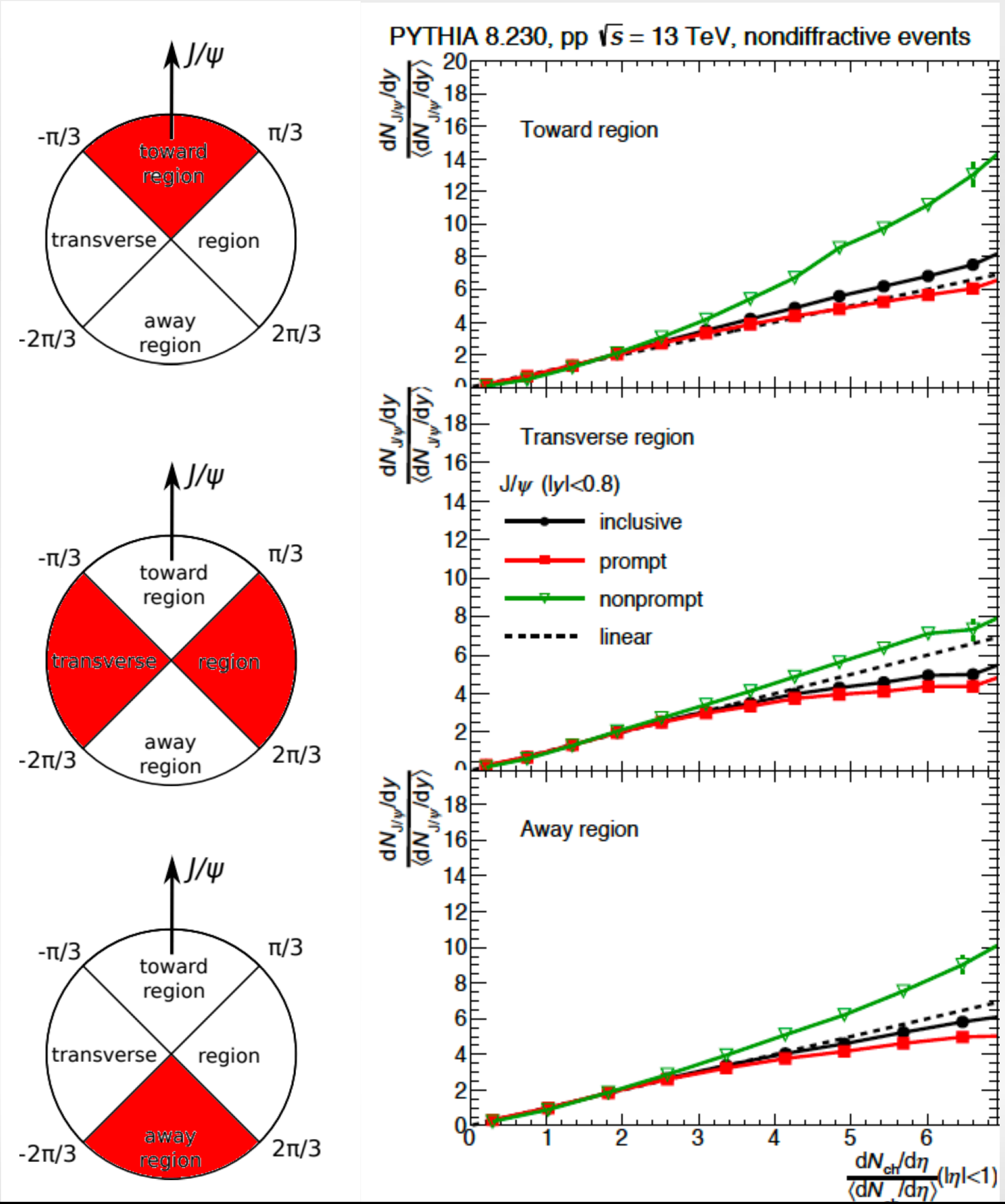
➪ Investigate J/ψ production as function of multiplicity in different azimuthal regions w.r.t. J/ψ flight direction, with or without rapidity gap between J/ψ production ψ and multiplicity

➪ **toward region**, same rapidity: additional decay daughters

➪ **away region:** backward jet

➪ **transverse region**: sensitive to underlying event

Expectations for experiments



- ⇨ Weaker-than-linear increase of direct J/ψ in the Transverse and Away region, while a linear increase in the Towards region

- ⇨ Non-prompt J/ψ exhibit a stronger-than-linear increase due to recoils jet in Towards and Away region and an almost linear in the Transverse one (gluon emission)

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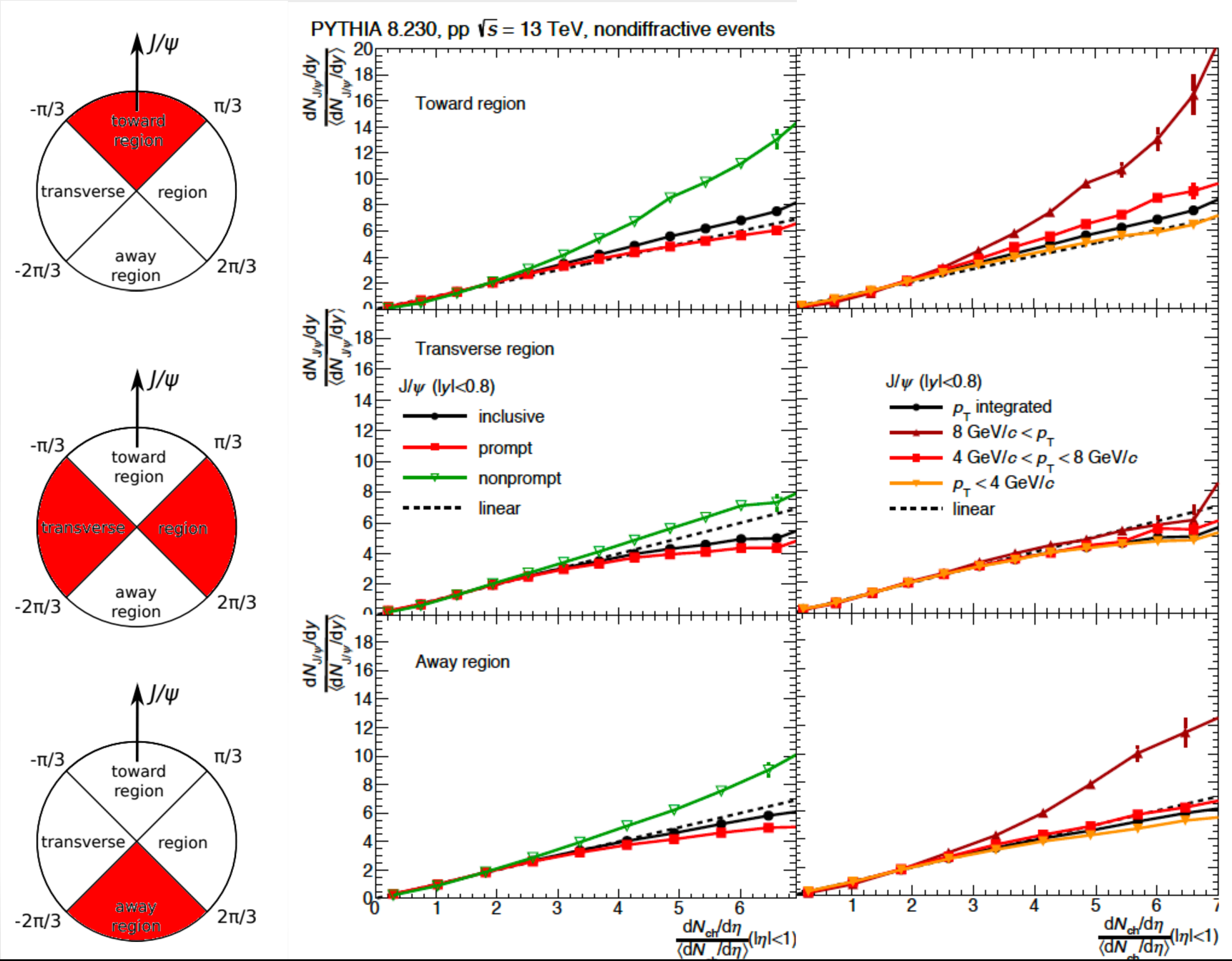

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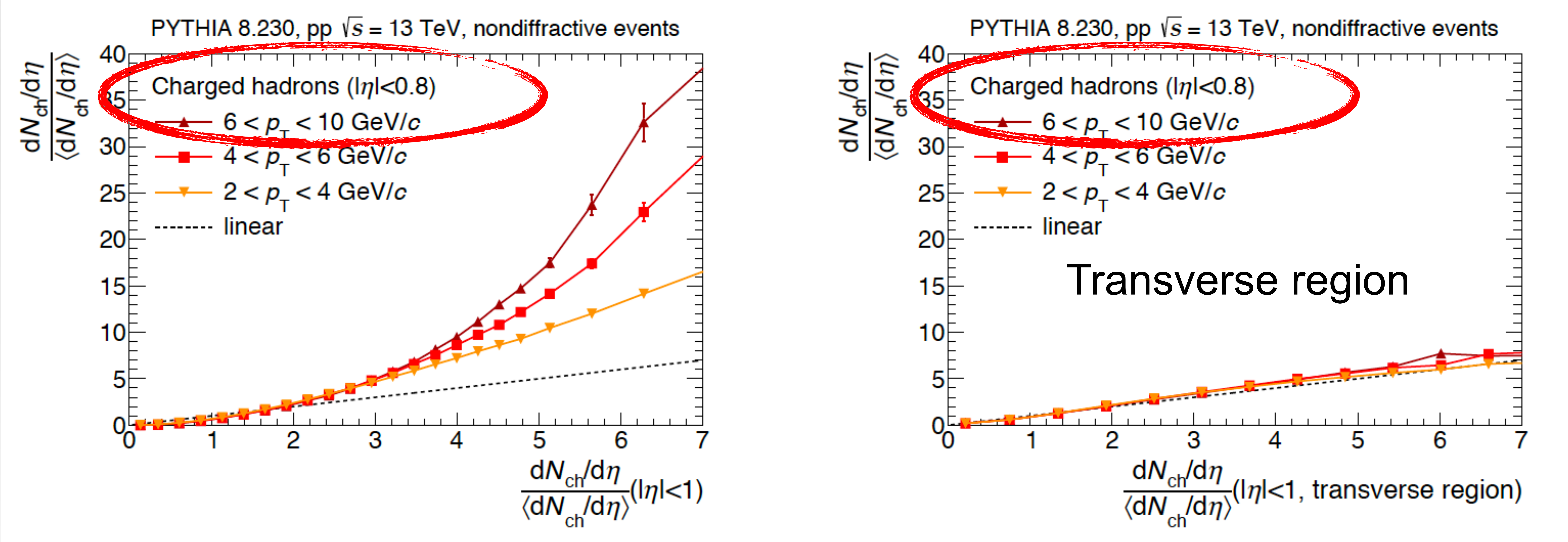
- ➩ Non-prompt J/ψ exhibit a stronger-than-linear increase due to recoils jet in Towards and Away region and an almost linear in the Transverse one (gluon emission)
- ➩ Transverse momentum dependence only present as function of N_{ch} in toward and away region, absent for N_{ch} in UE region

Expectations for experiments

➪ **Testing effects for intermediate/high p_T charged hadrons**



➪ non-linearity rises with the p_T of the hadron for the multiplicity integrated case

➪ Transverse region: closer to linear and the p_T dependence is fully removed

Conclusion

➪ **Stronger-than-linear increase** of J/ψ production probability with charged-particle multiplicity and p_T dependence qualitatively **reproduced with PYTHIA8**

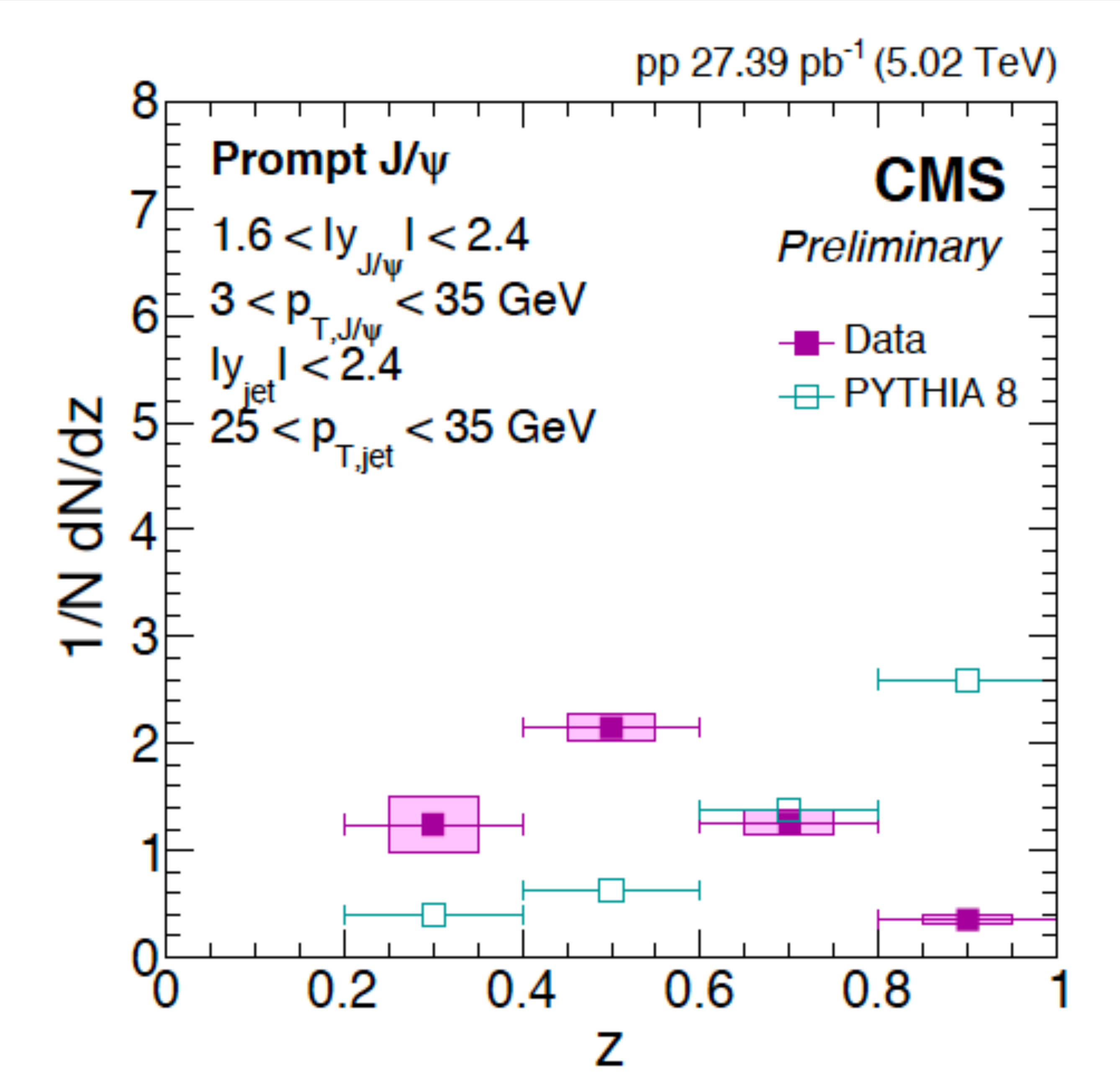
➪ **Investigation of in different azimuthal regions** (with, without rapidity gap) allows to disentangle effects from underlying event or jet fragmentation/auto-correlation

➪ **Suggestion** to experiments to perform the self-nomalized yield in different azimuthal regions

➪ Caveat: No quantitative agreement with data!

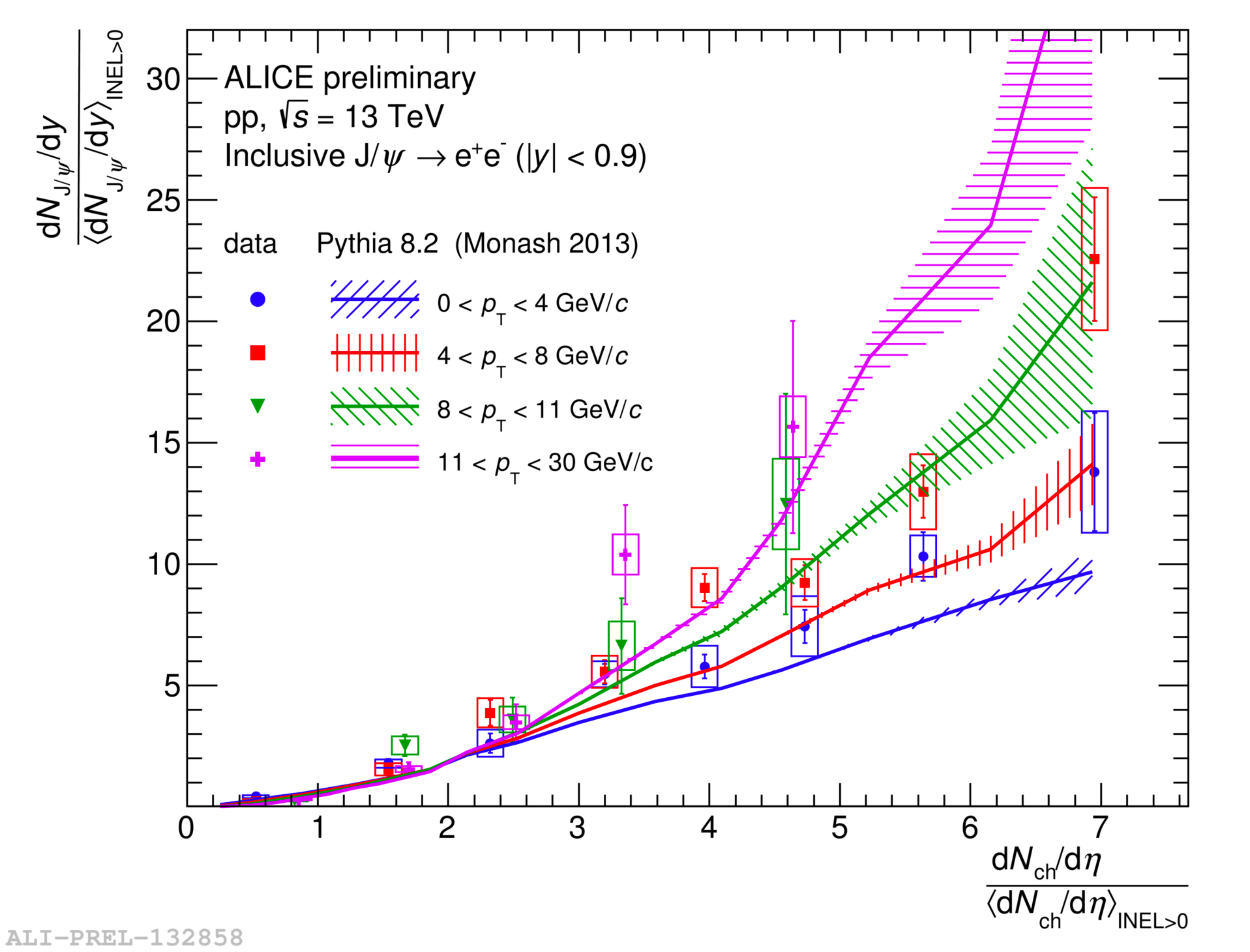
➪ Direct J/ψ production not perfectly described by leading order NRQCD in PYTHIA
- CMS/LHCb measurement of J/ψ production in jets: J/ψ less isolated than expected

- https://cds.cern.ch/record/2318344/files/HIN-18-012-pas.pdf
- Phys. Rev. Lett.118, 192001 (2017)



BACKUP

Simply checking in PYTHIA…



➪ Technicalities:
- PYTHIA8.230, Monash 2013 tune
- non-diffractive events
- J/ψ production forced to decay in dielectron channel

➪ Stronger-than-linear increase reproduced qualitatively by PYTHIA8

- Effect more pronounced for higher p_T reproduced

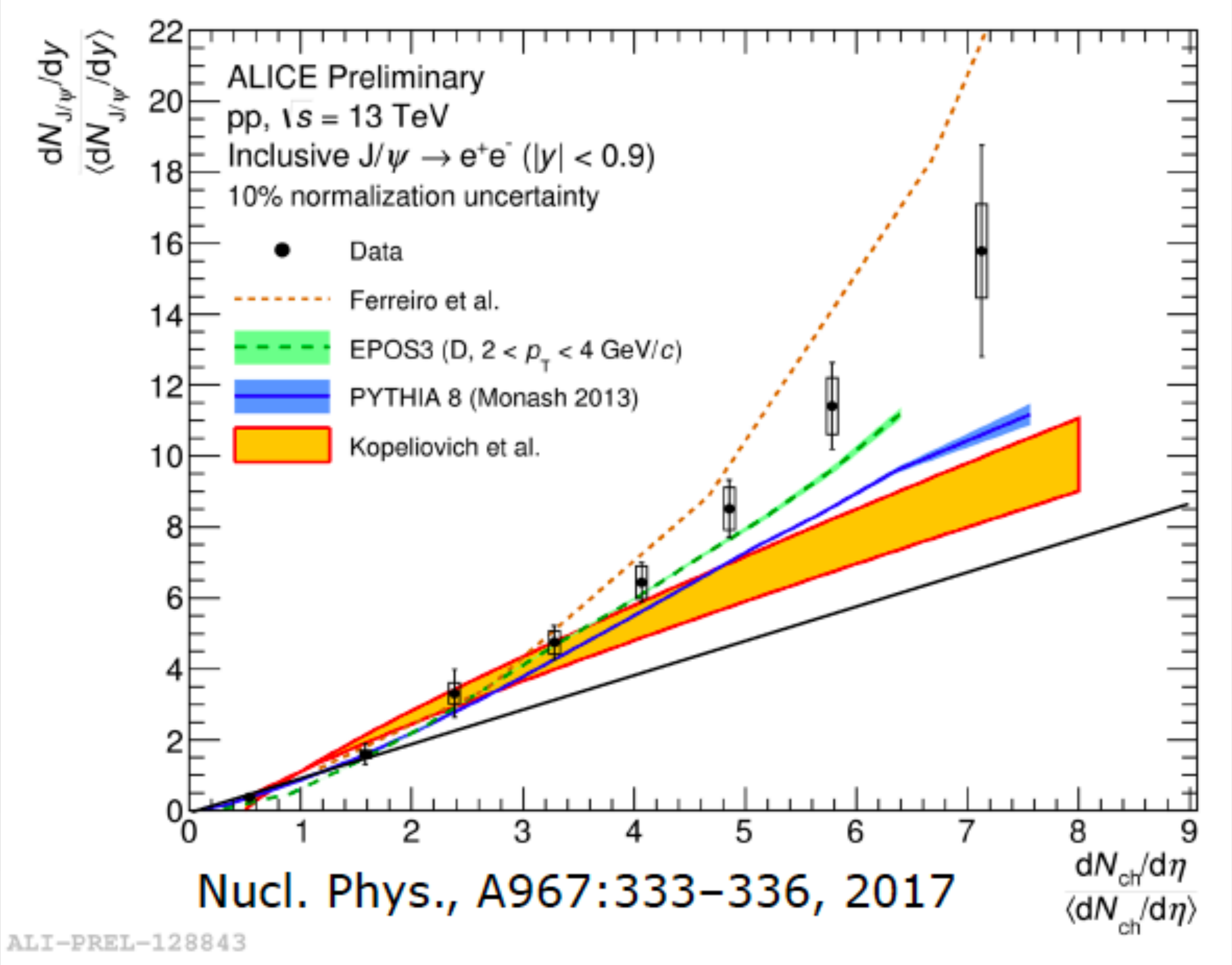
➪ Will investigate in the following the influence of:

- Multi-parton interactions (**MPI**)

- Colour reconnection (**CR**)

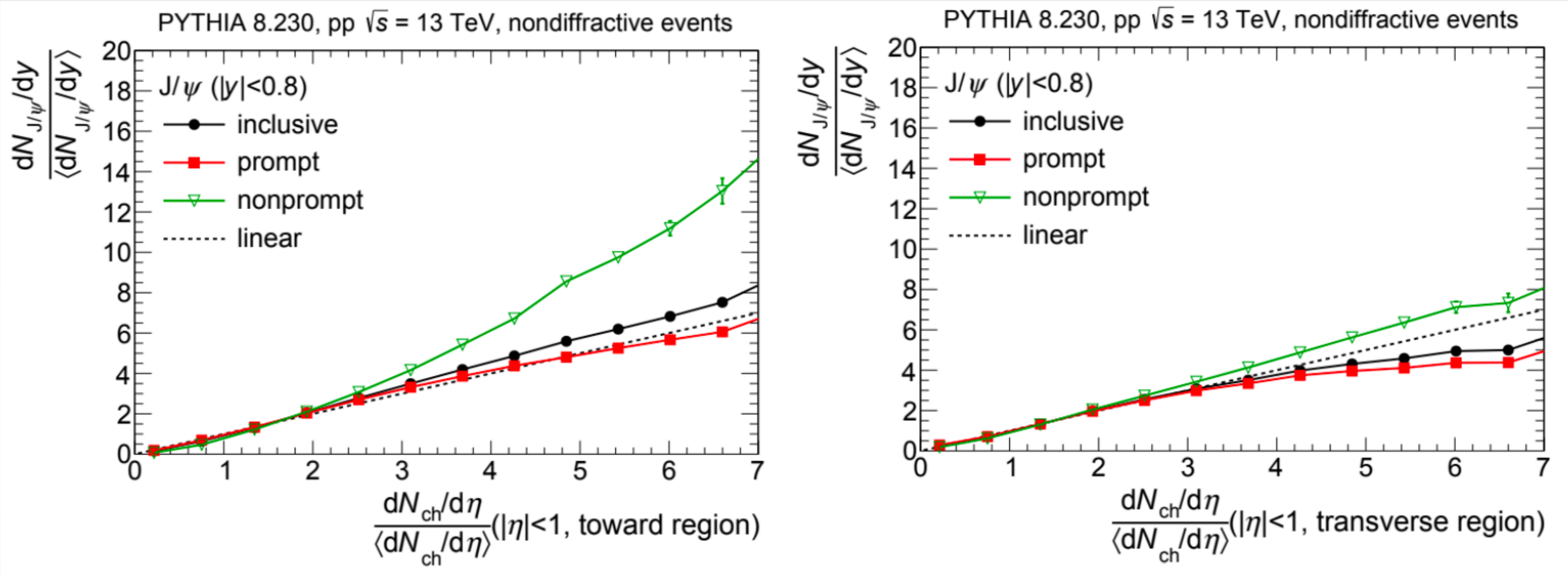
- **Auto-correlation** effects

QGP in small system?



S. Weber, A. Dubla, A. Andronic, A. Morsch
arXiv:1811.07744 [nucl-th], accepted EPJC

➪ J/ψ production increases faster-than-linear with the charged multiplicity (N_{ch}). This could tie in with hints of a QGP-like behaviour in high-multiplicity pp events

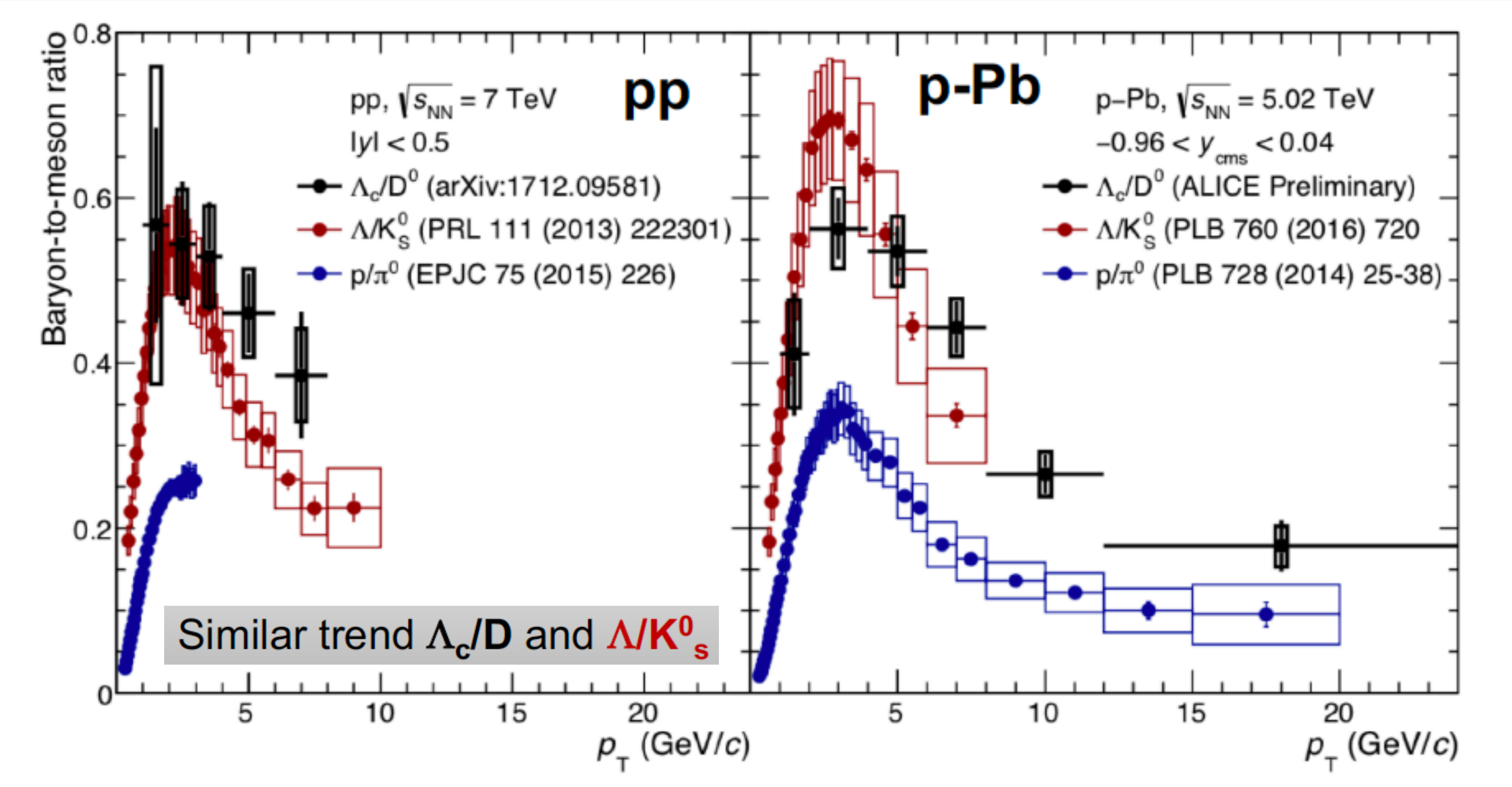


➪ Studied how J/ψ production rates are associated with the N_{ch} in PYTHIA

- Stronger-than-linear increases due to **autocorrelation effects**
- **Weaker-than-linear increase** of J/ψ production with N_{ch} in the Underlying Event region

Λ_c production at LHC

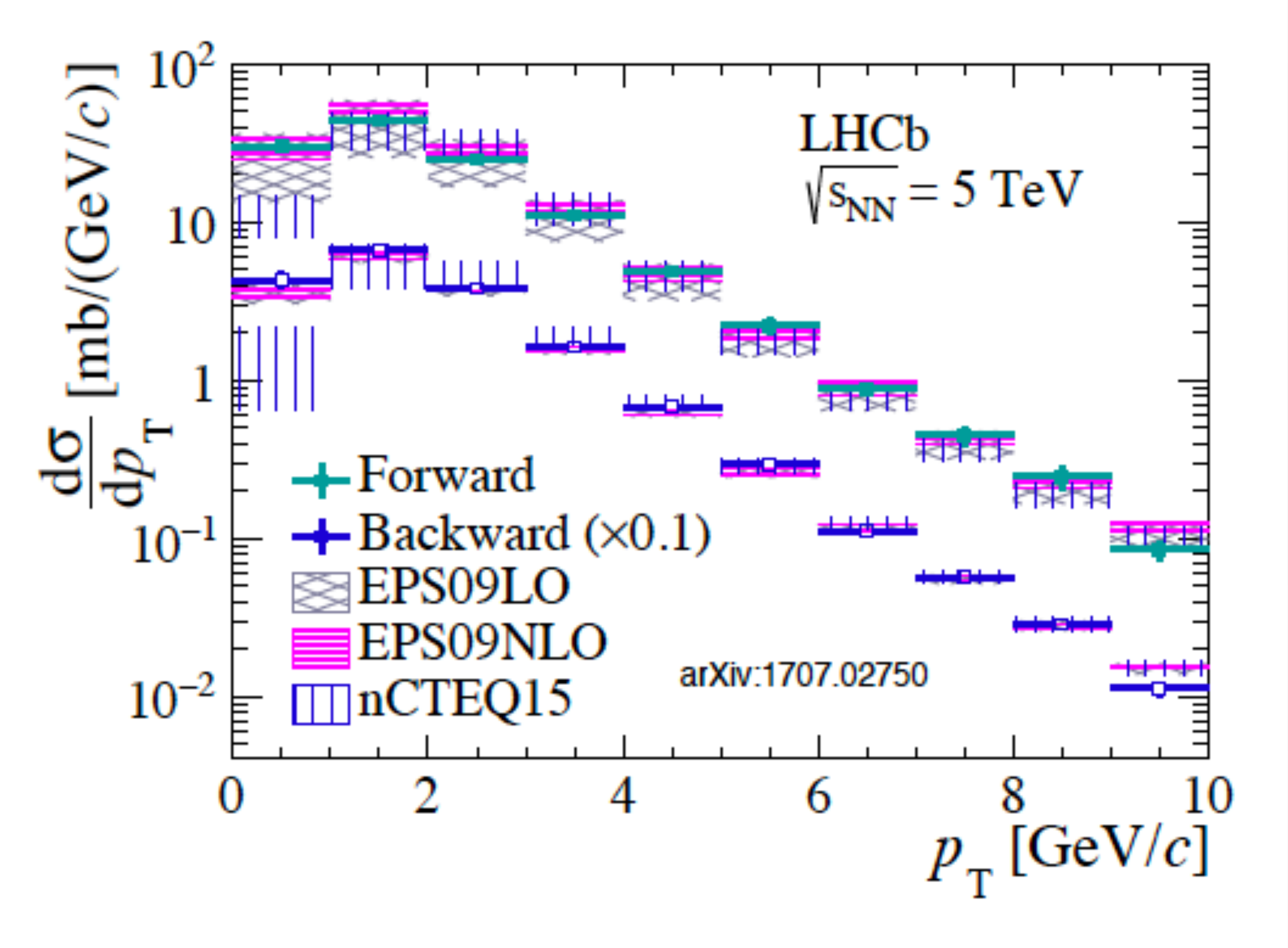
$\Lambda c/D^0$ ratio similar to the baryon-to-meson ratio observed in the **light sector**.
Significantly larger than expectation from MC PYTHIA8.
— Something not understood in charm fragmentation?

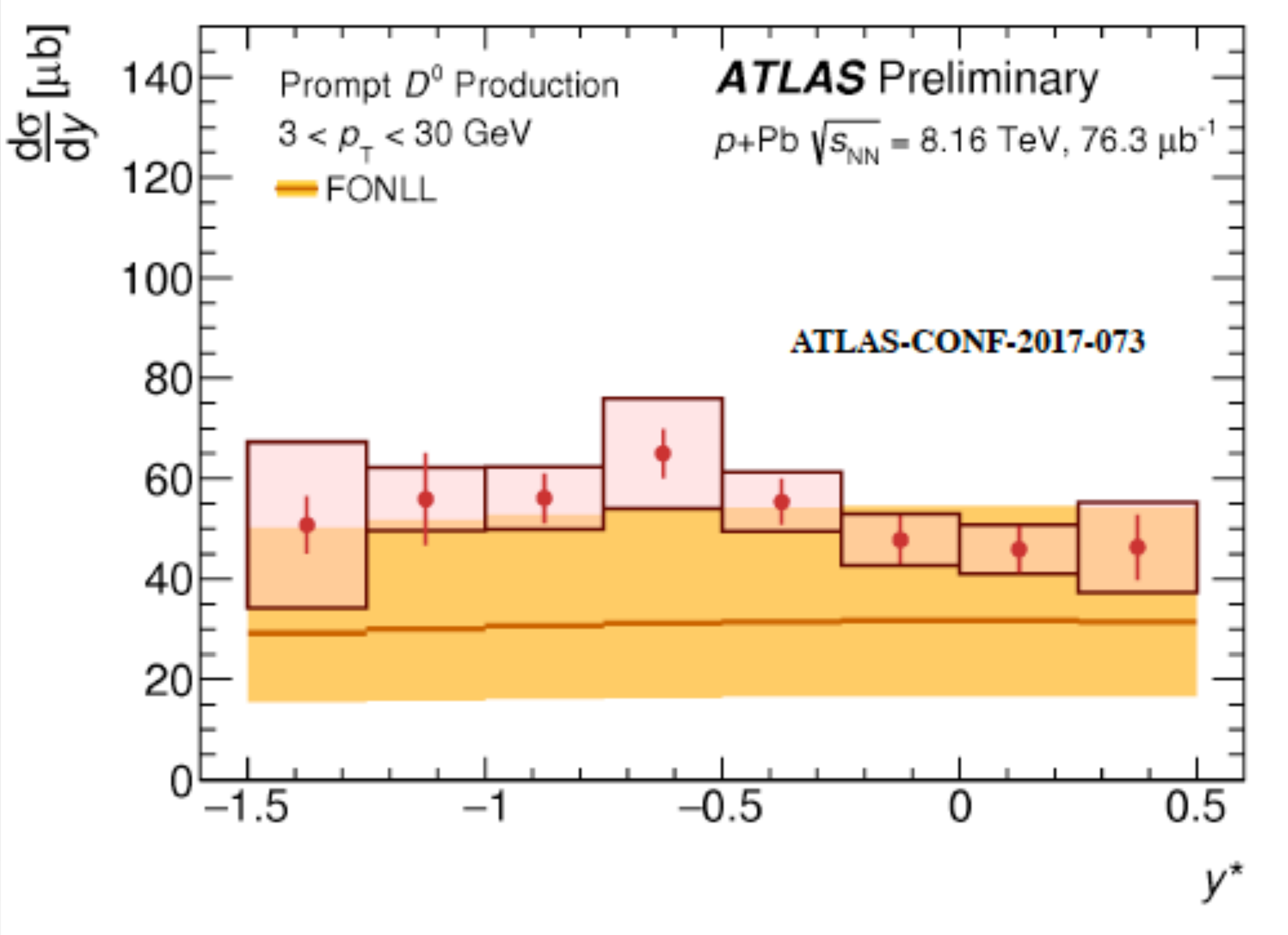


Quarkonia production in p-A collisions at RHIC

- ➪ **p/³He-going:** about 10-20% suppression with Au nuclei. Consistent with shadowing expectation
- ➪ **Au/Al-going:** indication of suppression in p-Au collisions?

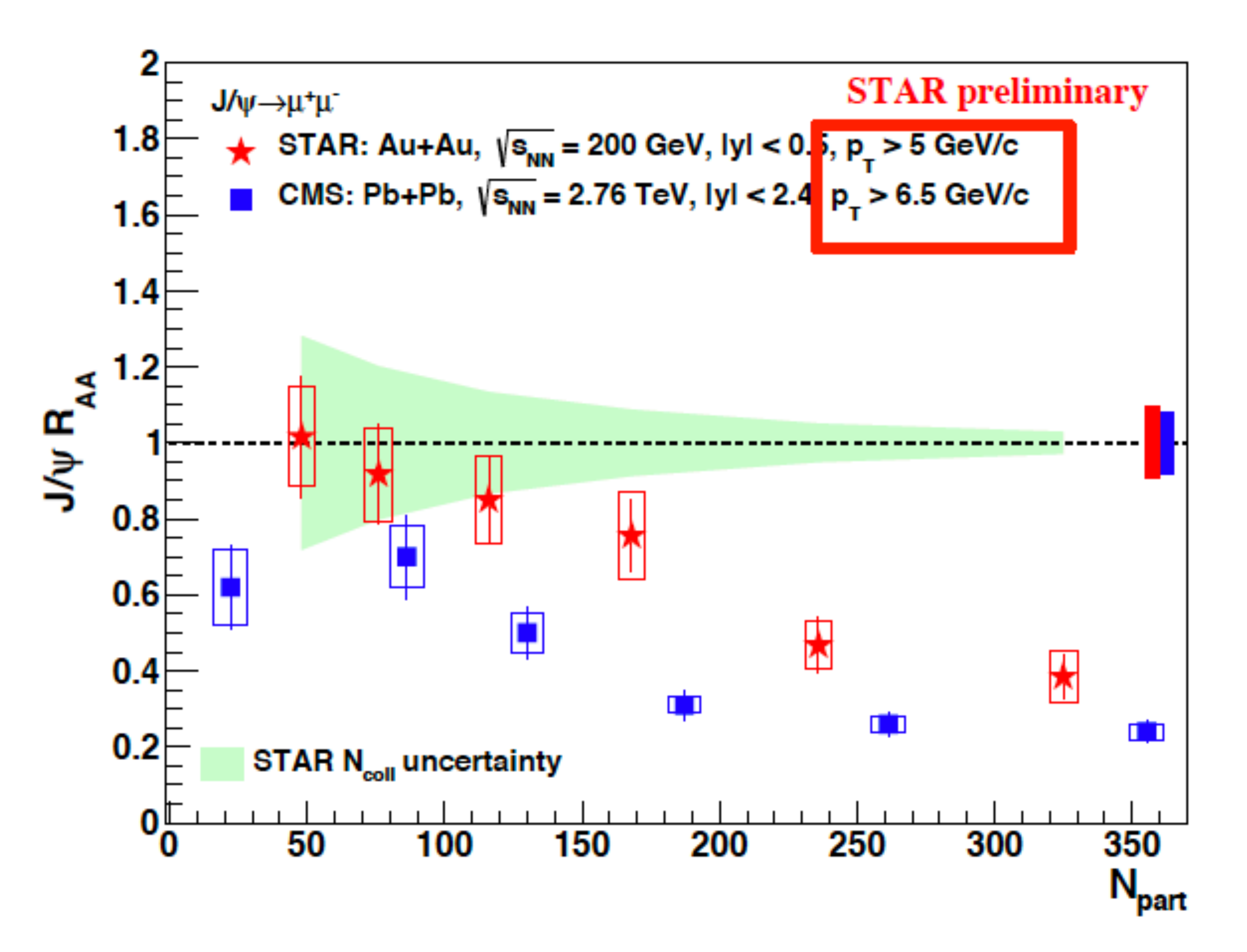
D meson production in p-Pb collisions

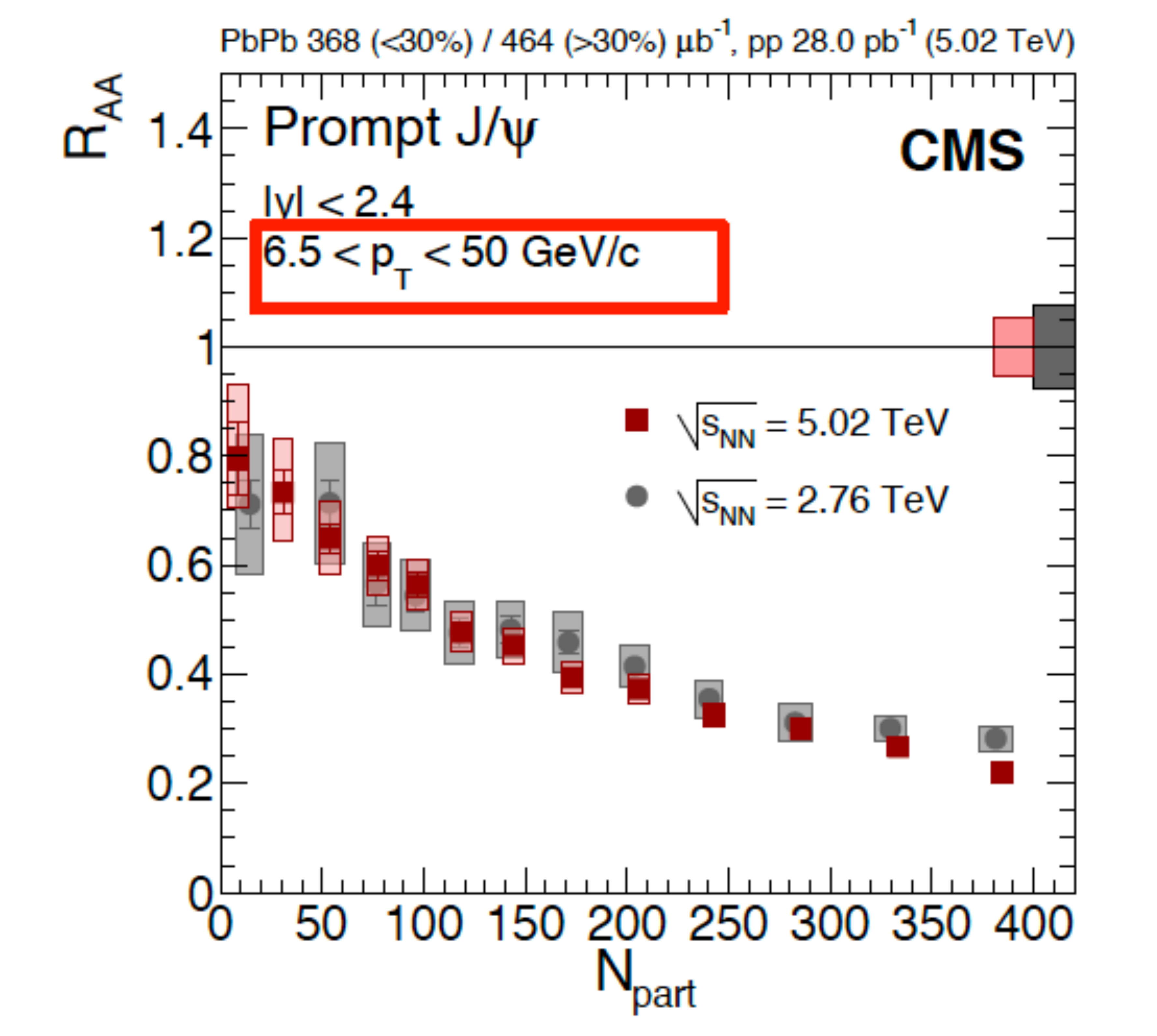




- ➪ Production cross-sections measured in a **large rapidity interval and down to ~0 pT**
- ➪ General **agreement with pQCD** calculations including nuclear modifications of PDF
- ➪ Possibility to **investigate 5.02 and 8.16 TeV** energy regimes at LHC.
- ➪ Data agree with nPDF and CGC but experimental precision starts to be better than theoretical one

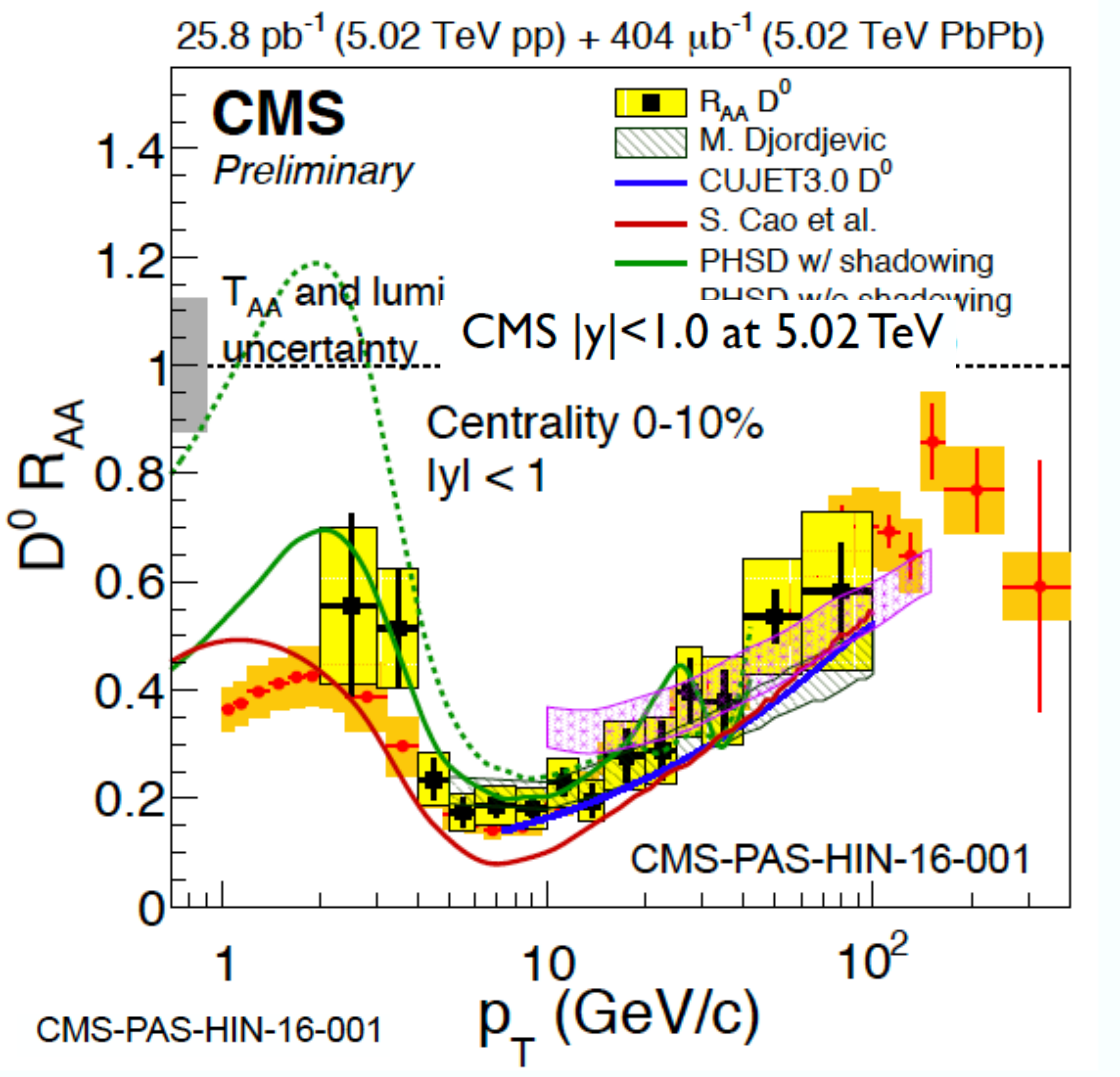
High p_T J/ψ: RHIC vs LHC

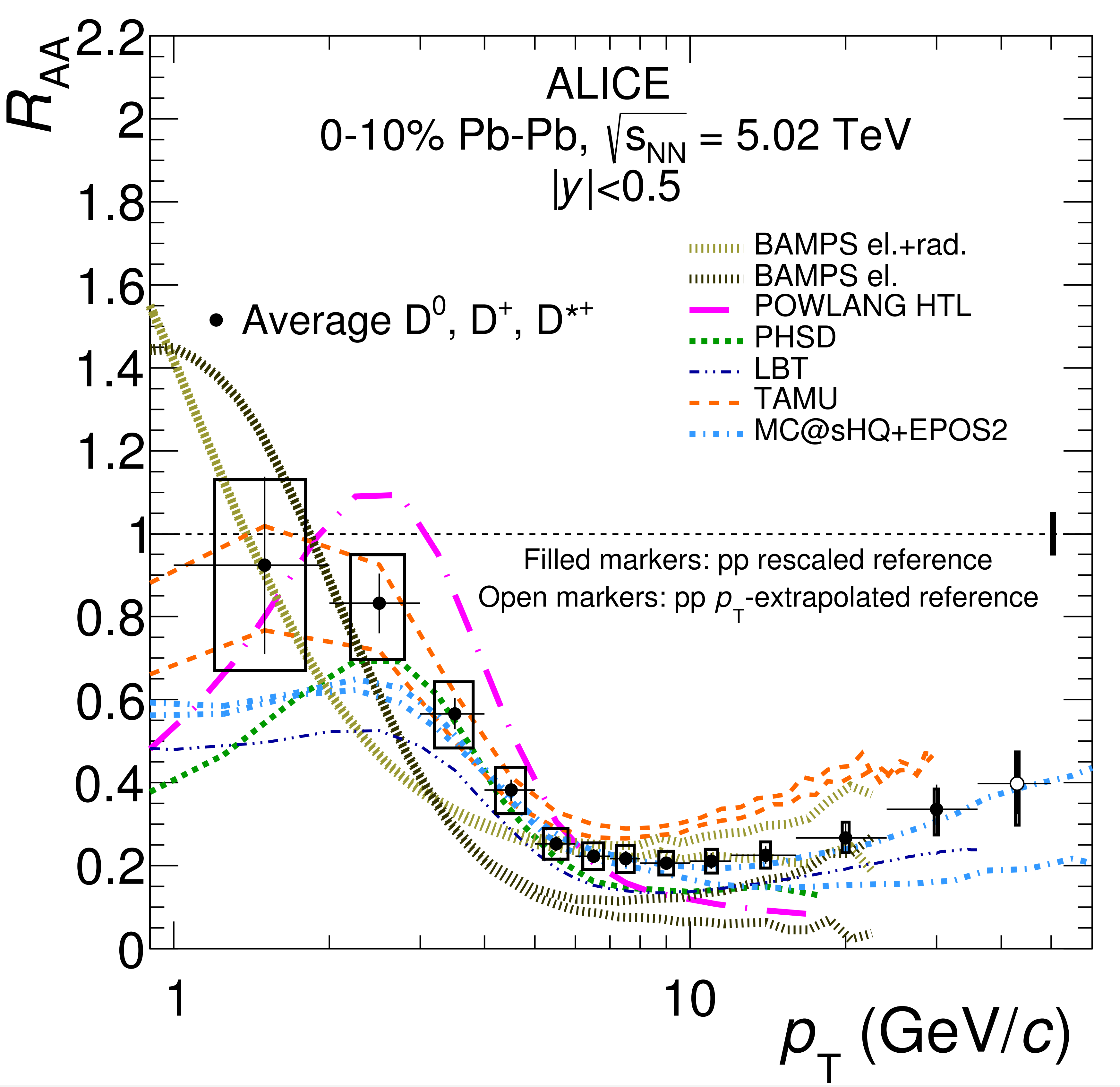




➪ At high p_T, R_{AA} decreases towards central collisions
- CNM & regeneration effects small → energy loss picture?
- R_{AA} RHIC >~ R_{AA} LHC/2.76TeV >~ R_{AA} LHC/5.02TeV

Comparison with theoretical model

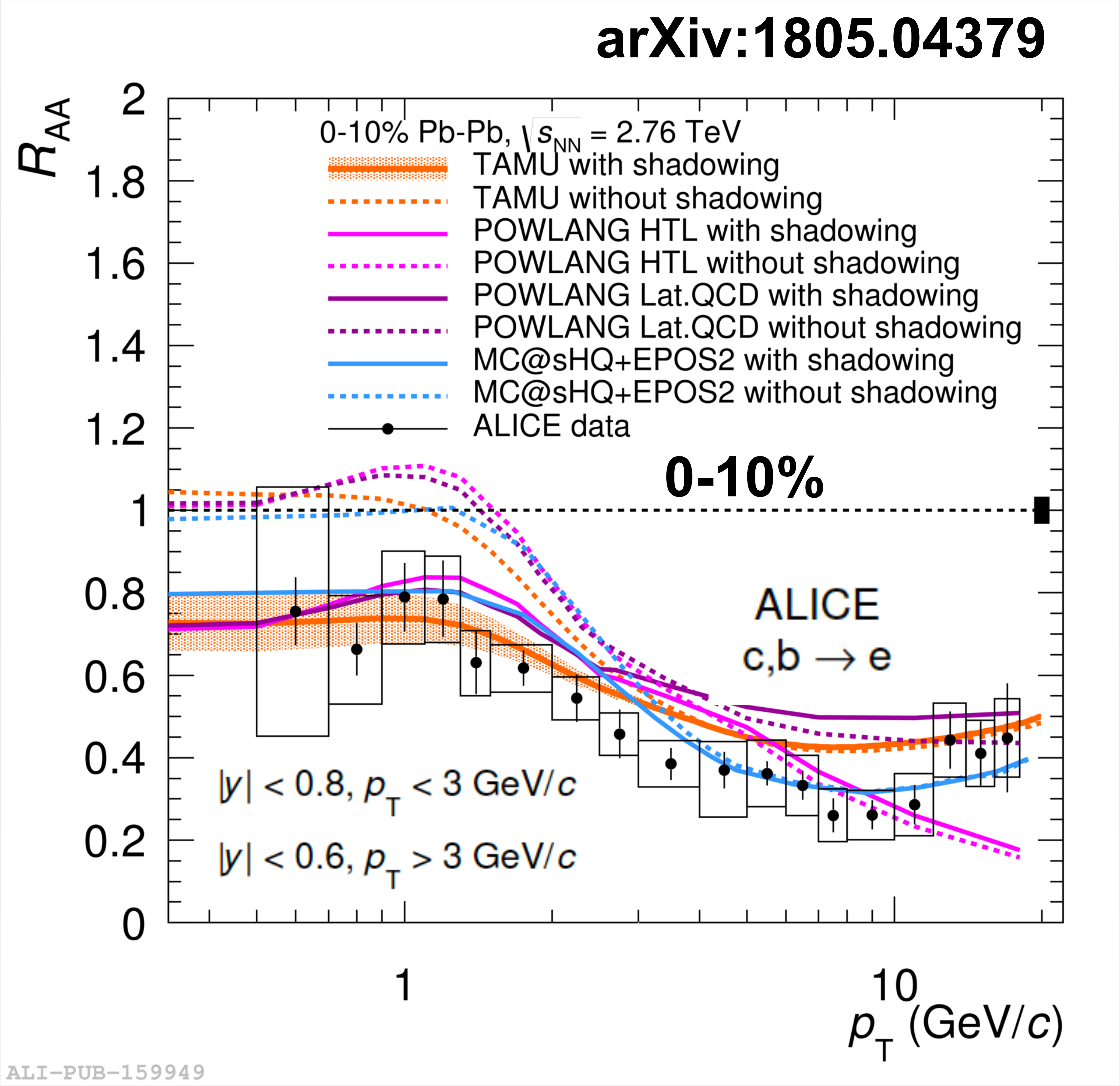


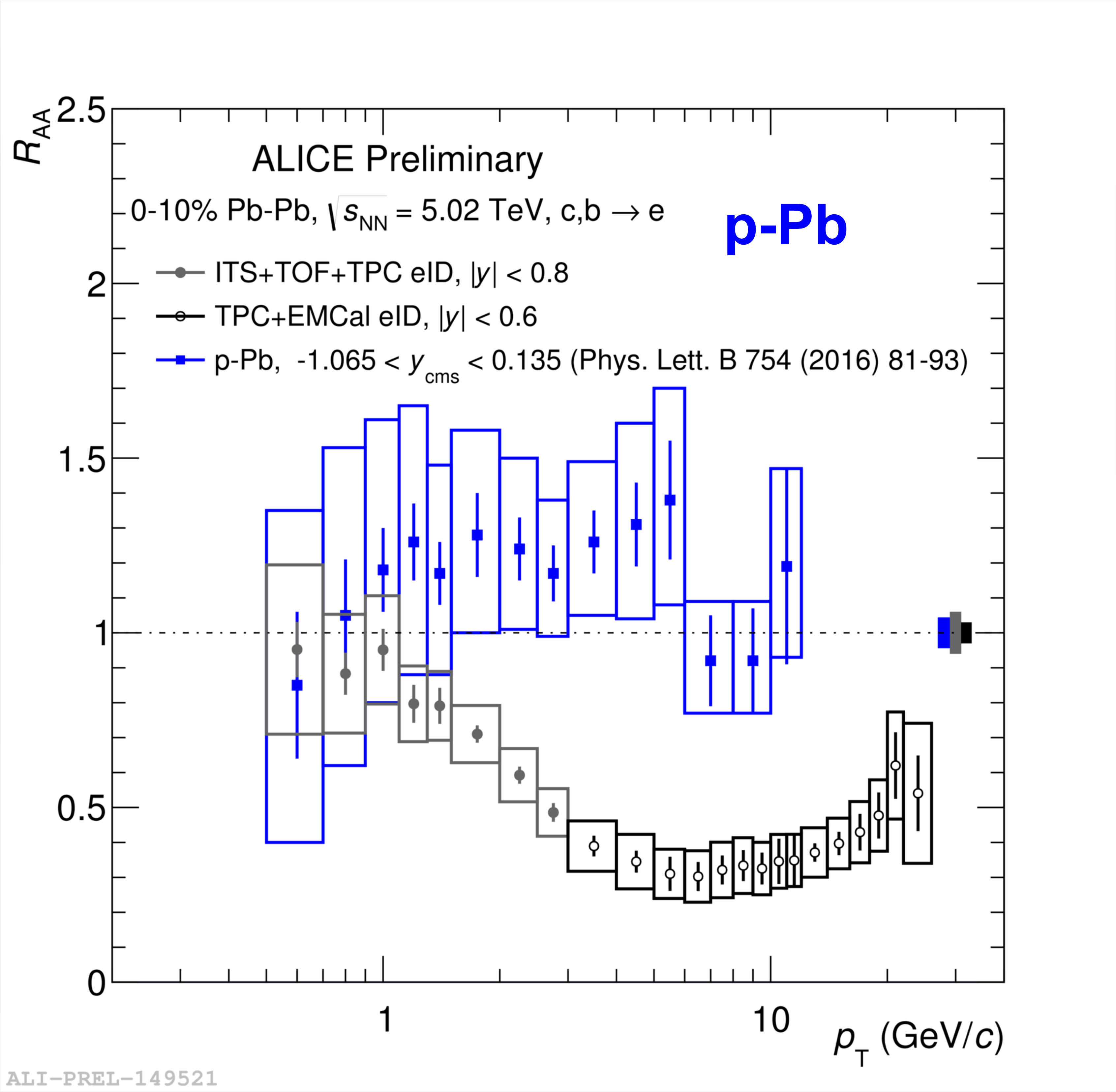


Experiment start putting strong constraints on theoretical calculations!

- need of **radiative** energy loss to describe the **high p_T** region (most of the case)
- Hints at **low p_T** that **collisional** energy loss is non negligible
- **Shadowing** improve description of the data at **low p_T**

Heavy-flavour hadron decay electron nuclear modification factor

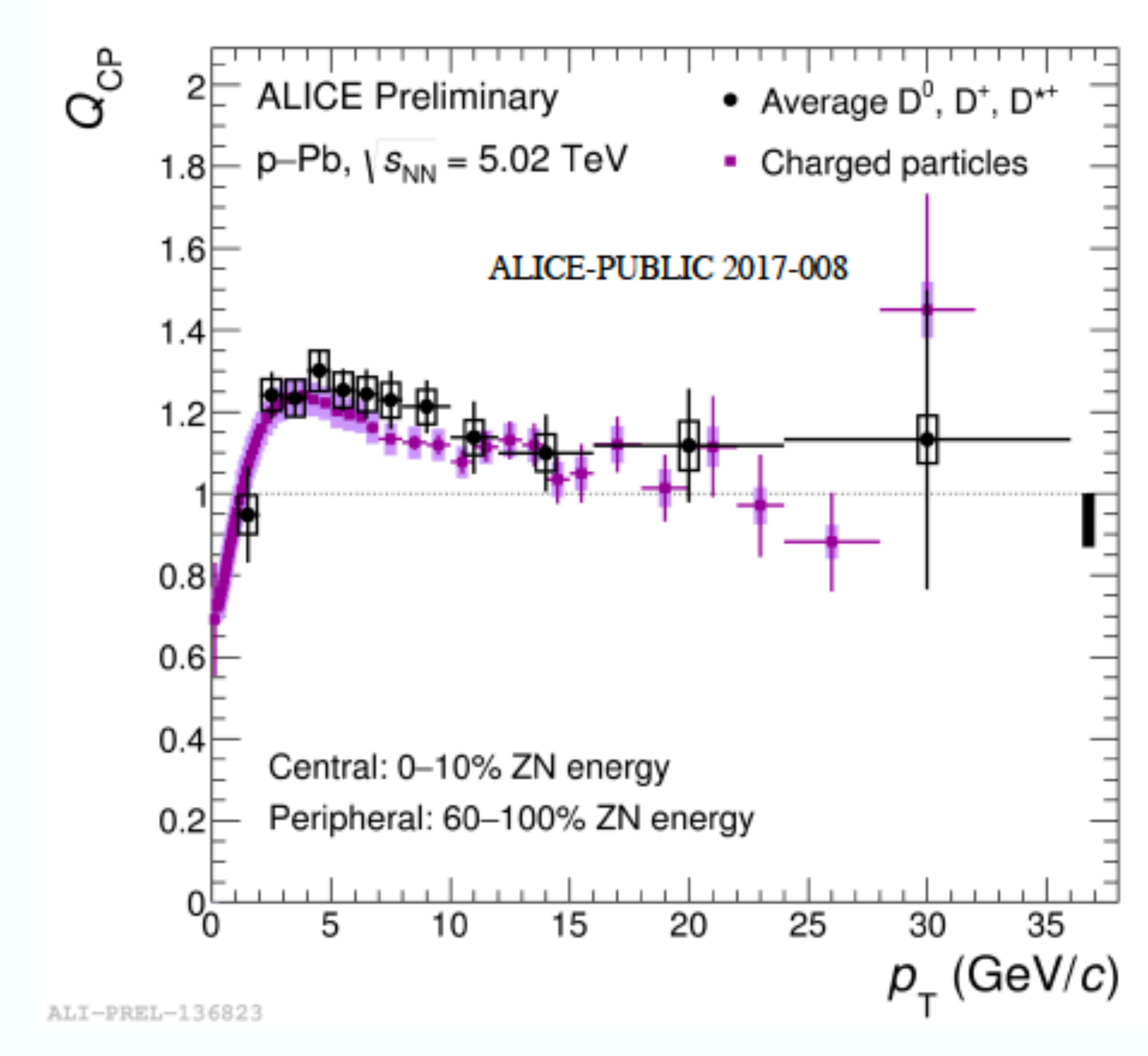


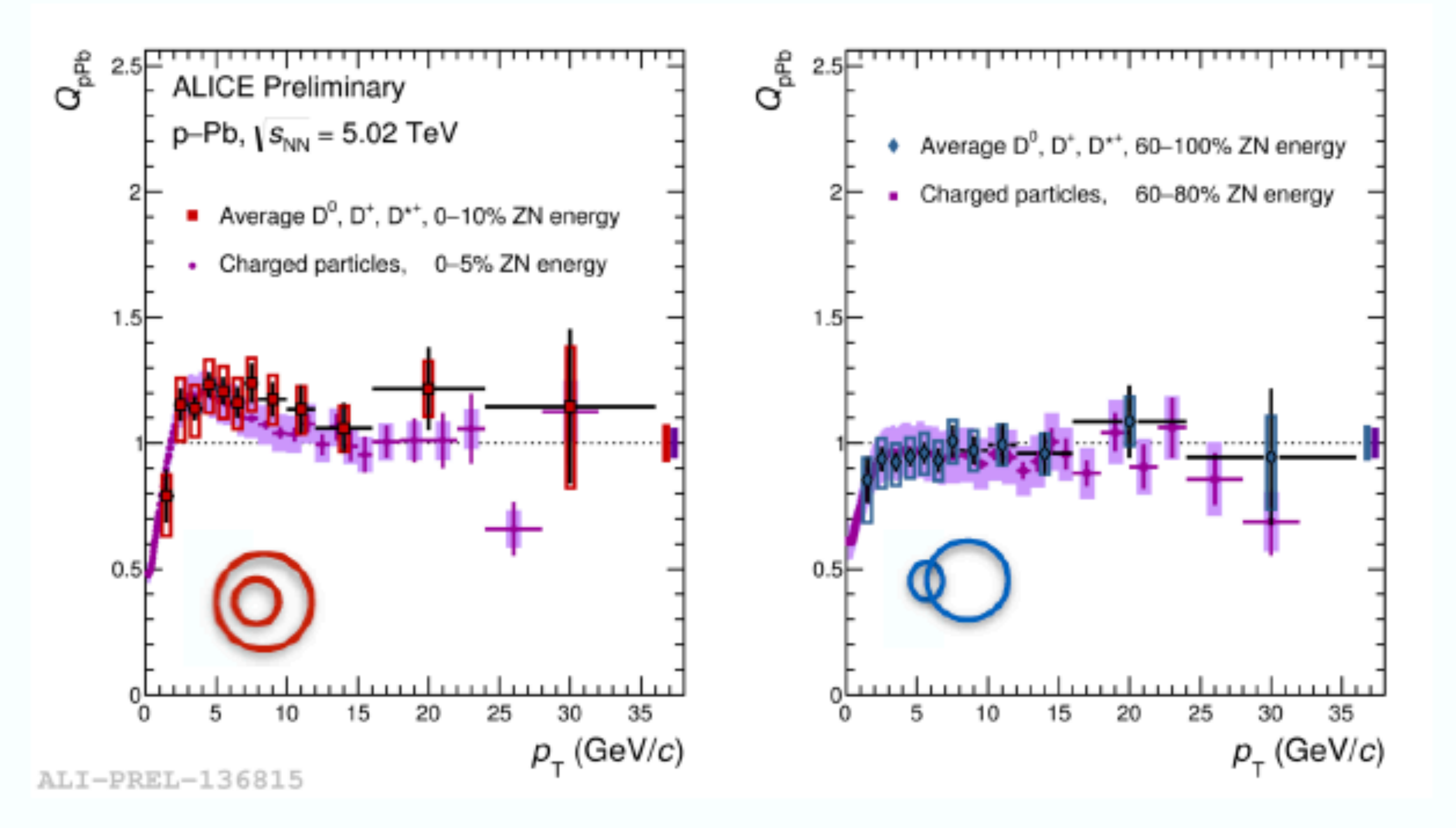


- ⇨ Data are better described when the nuclear **PDFs (EPS09)** are **included** in the model calculation
- ⇨ Suppression at intermediate/high p_T is better described by models that include both **radiative** and **collisional energy loss** processes
- ⇨ ***R_{pPb}* consistent with unity** → **Large suppression** at high p_T in **Pb-Pb** collisions is due to **final-state effect** due to heavy-quark **in-medium energy loss**

– POWLANG: Eur.Phys.J. C73 (2013) 2481;
– TAMU: Phys.Lett. B735 (2014) 445–450;
– MC@HQ+EPOS: PRC 89 (2014) 014905;

D meson production vs centrality



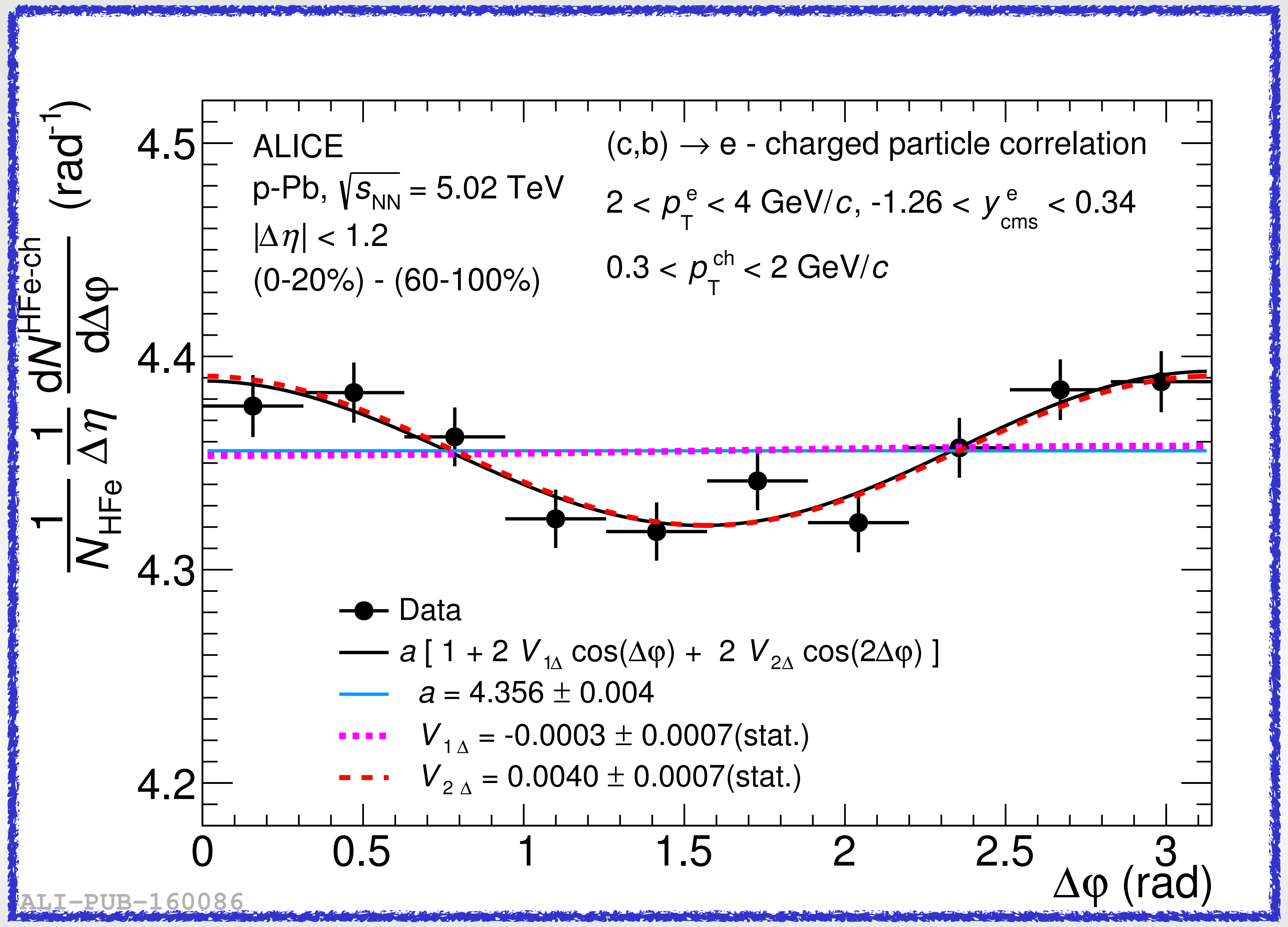


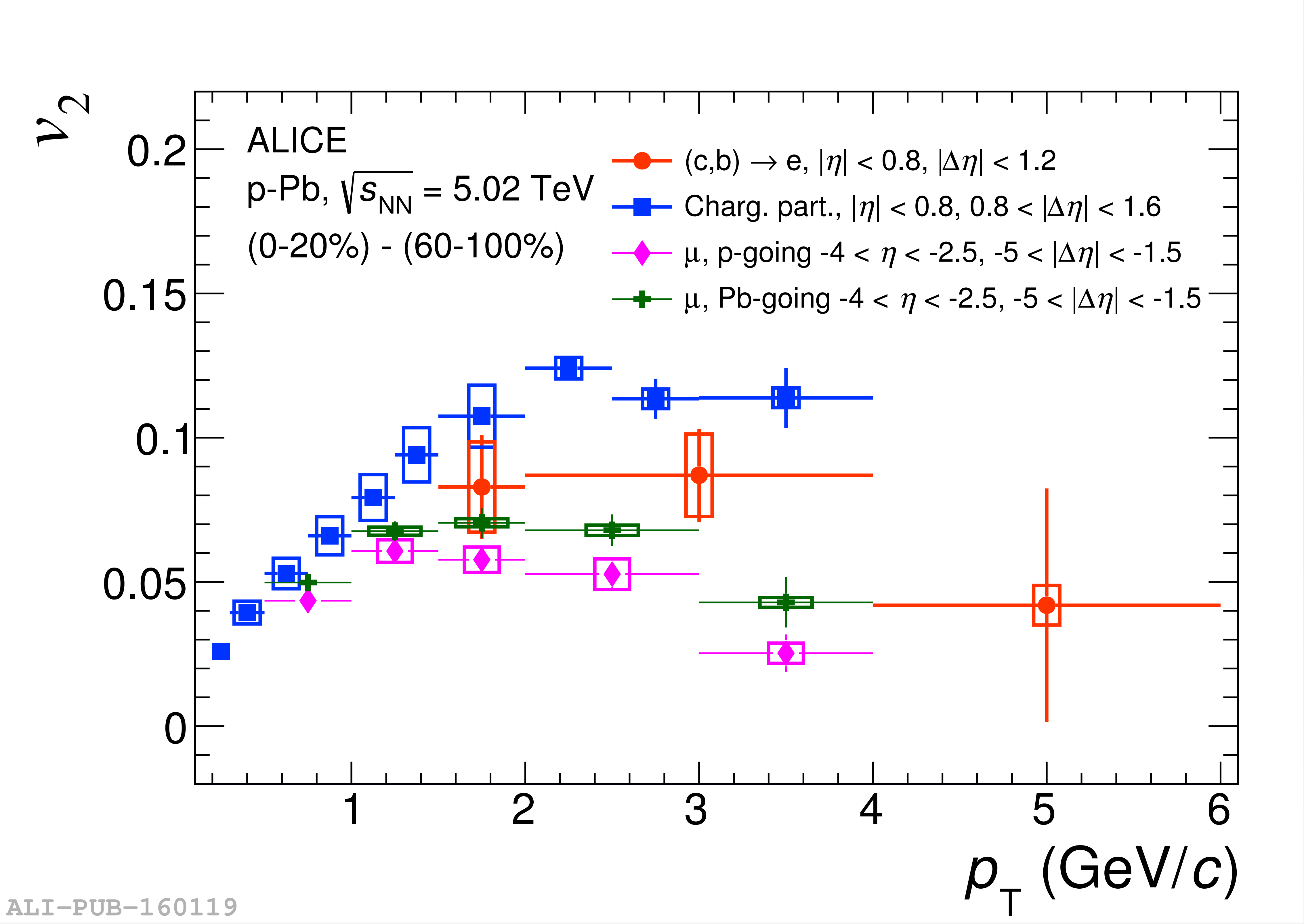
$$Q_{pPb}^{0-10\%}(p_T) = \frac{dN_{pPb}^{0-10\%} / dp_T}{\langle T_{AA} \rangle_{0-10\%} \times d\sigma_{pp} / dp_T}$$

- Hint for D-meson "Central-to-peripheral" ratio (Q_{CP}) larger than unity
  ✓ 1.5σ in 3<p_T<8 GeV/c
- Very similar to charged pion Q_{CP}
  Initial-state effect? Mass effect? Radial flow?
  … need comparison with theoretical calculations

Heavy-flavour elliptic flow in p-Pb collisions

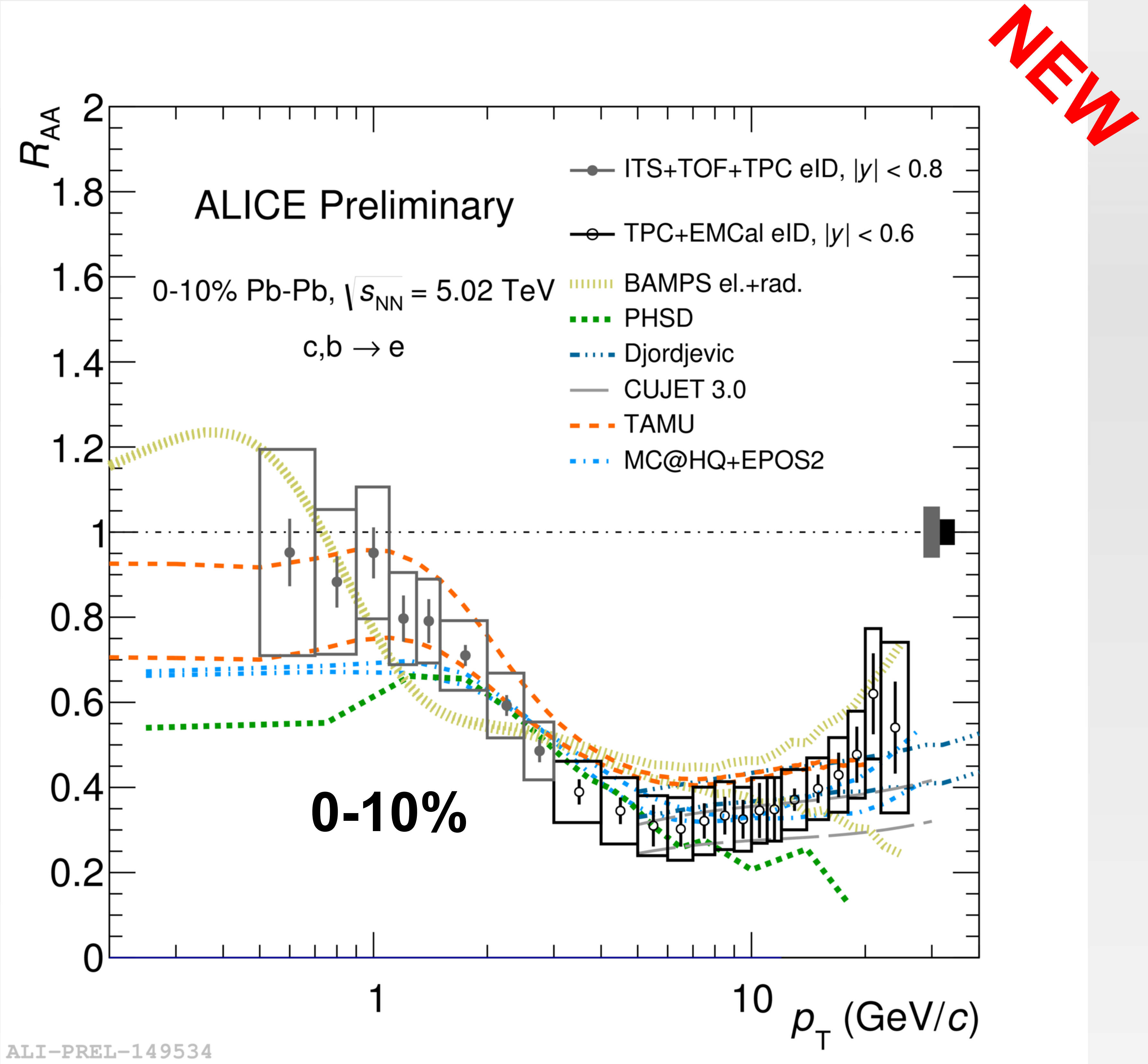
- Jet subtraction: high mult. - low mult.
- **Modulation present!** Collective effects
  Initial- or final-state effect

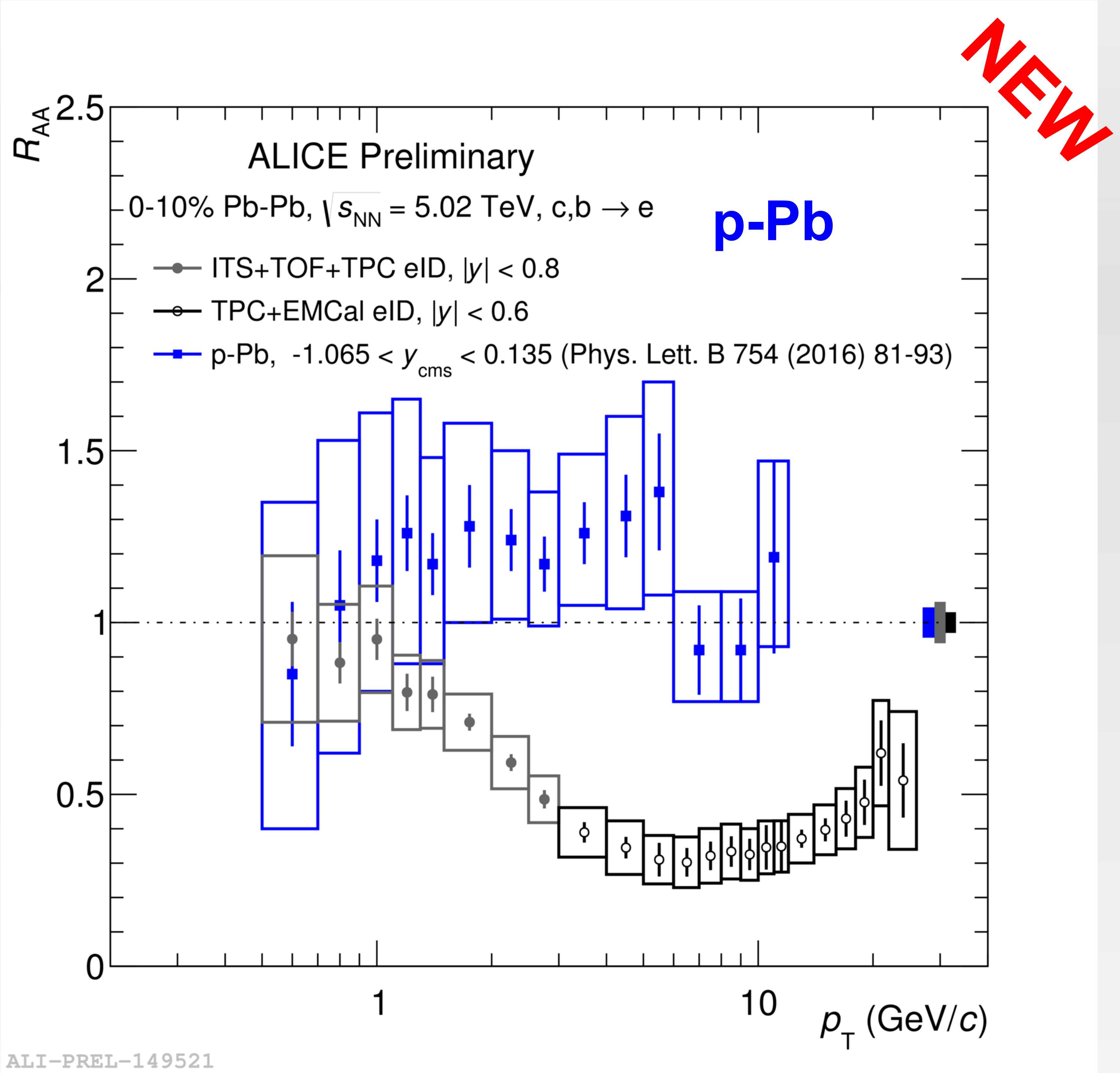




- Significance: **5.1σ for 1.5< p_{Te}< 4 GeV/*c***
- Effect is qualitatively similar to the one observed for light flavours and inclusive muons

Heavy-flavour hadron decay electron nuclear modification factor

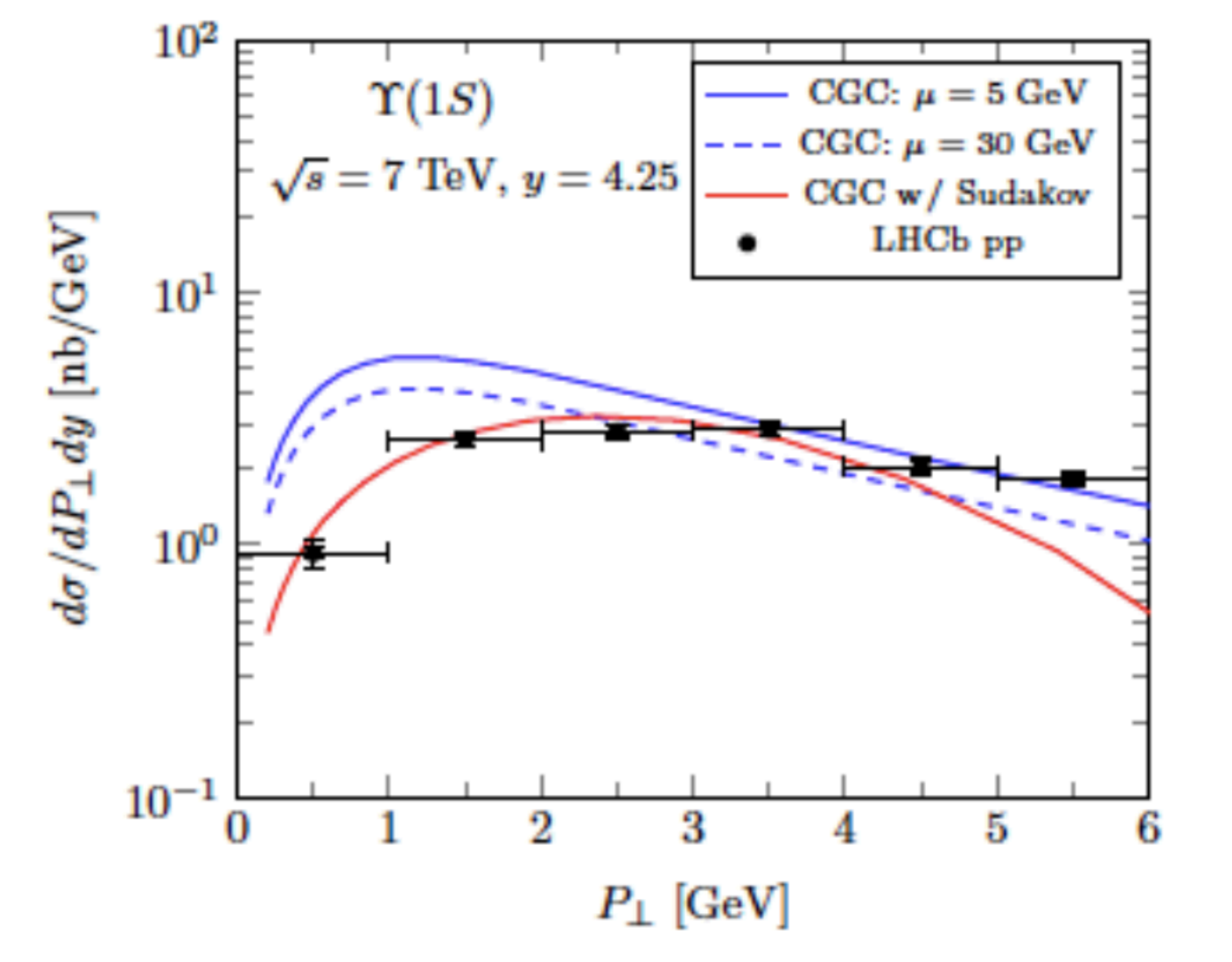


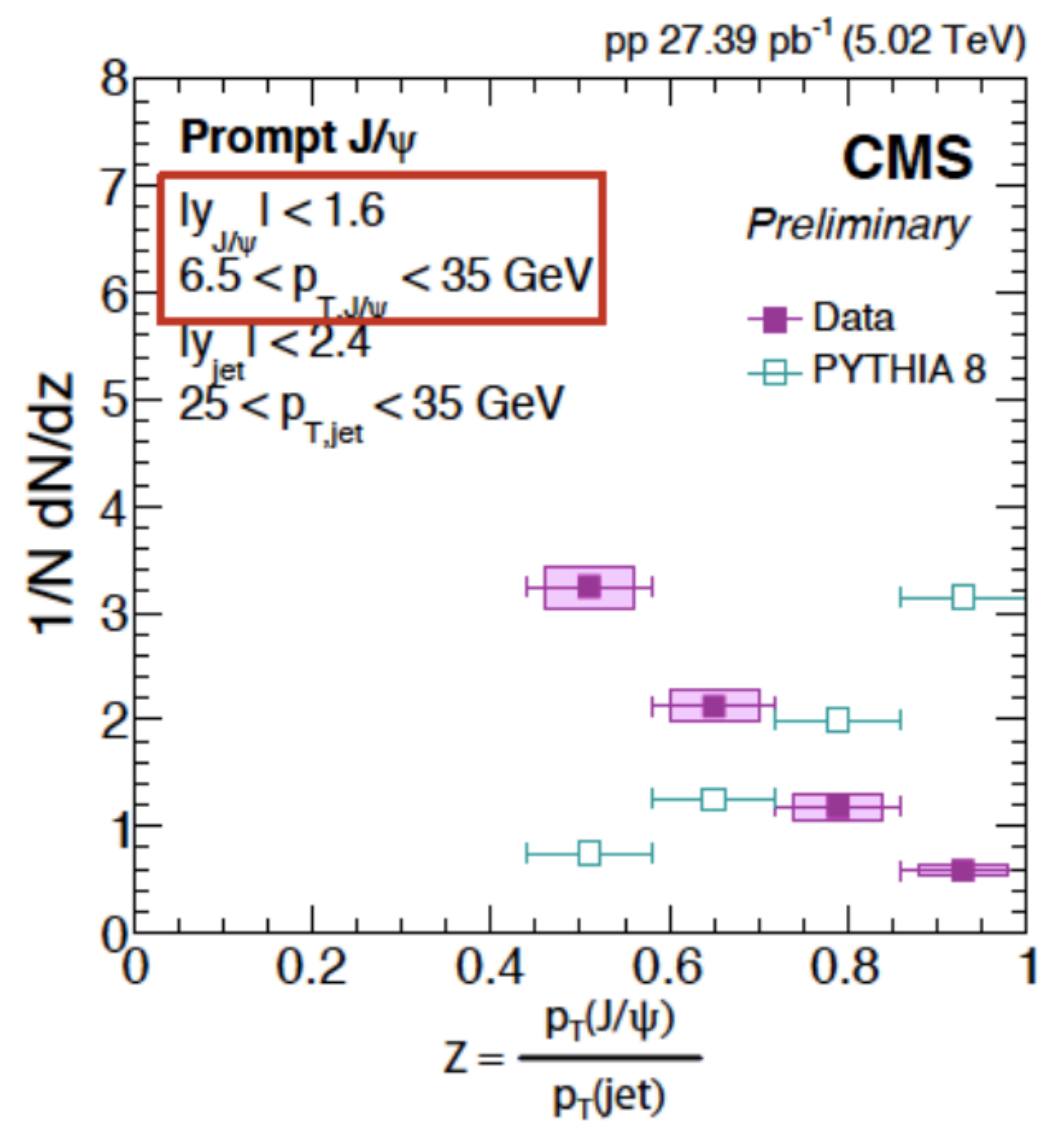


- **New R_{AA}** measurements in Pb-Pb collisions at **5.02 TeV** down to p_T = 0.5 GeV/c
- **R_{pPb} consistent with unity (PLB 754 (2016) 81)** → no strong modification of heavy-flavour decay electron spectra in p-Pb collisions relative to pp collisions
- **Large suppression** at high p_T in **Pb-Pb** collisions
  - ⇨ **final-state effect** due to heavy-quark in-medium energy loss

- Mattia Faggin (HD/Padova)
- A.D. (HD/GSI)

Quarkonia production in pp collisions



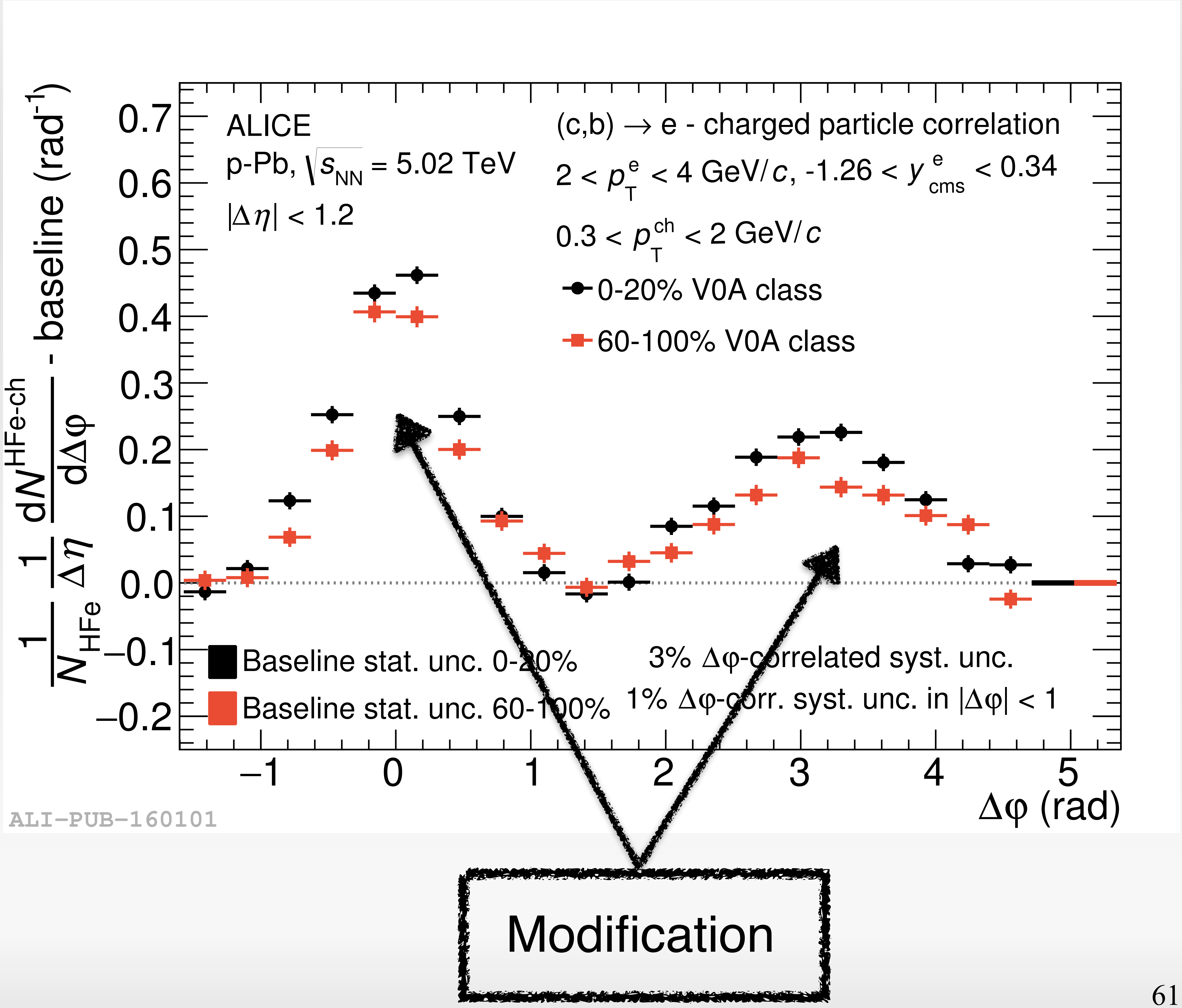


- CGC: addition of Sudakov summation can describe the Υ(1S) production at low p_T
- J/ψ production is accompanied by other hadrons
  - PYTHIA disagrees with data

Heavy-flavour elliptic flow in p-Pb collisions

– **Two-particle correlations** of HFe with charged particles in **high multiplicity** and **low multiplicity** events

– Near and away side **modification** from low multiplicity to high multiplicity



Beauty-decay electrons R_{AA}

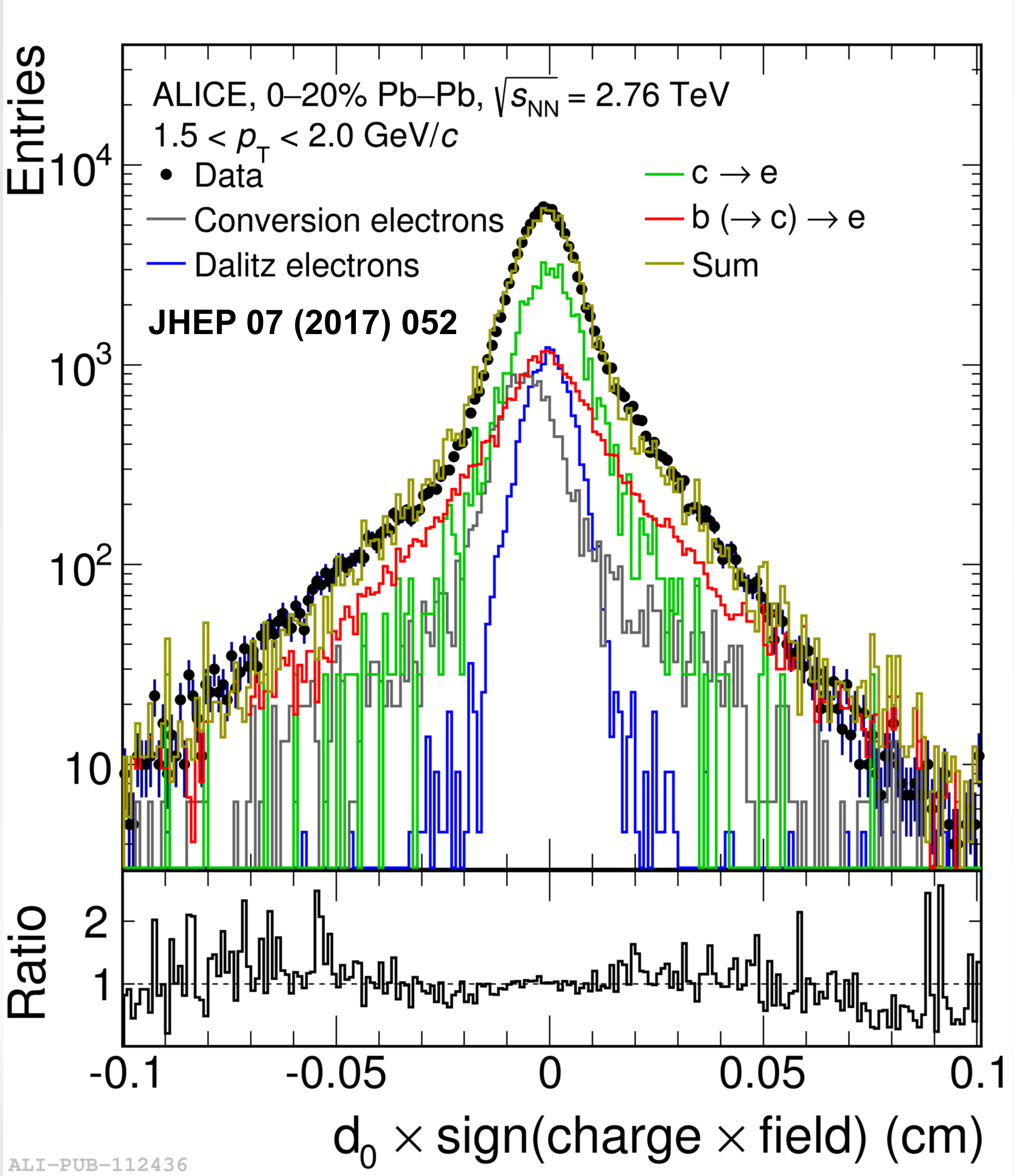
– Analysis based on the electron impact parameter distribution

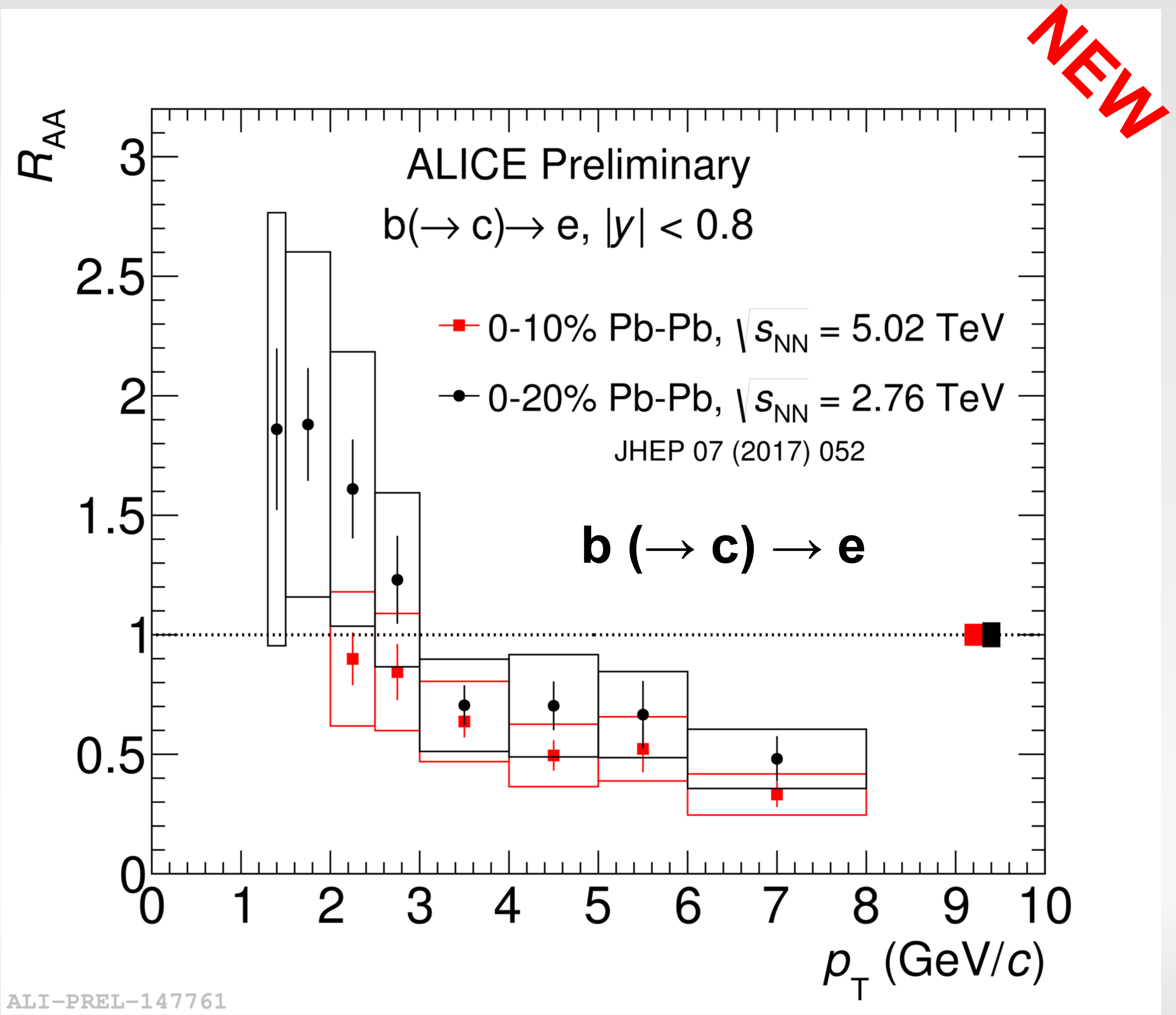
JHEP 07 (2017) 052

– **First R_{AA}** measurement of beauty-decay electrons in **0-20%** centrality at **2.76 TeV**

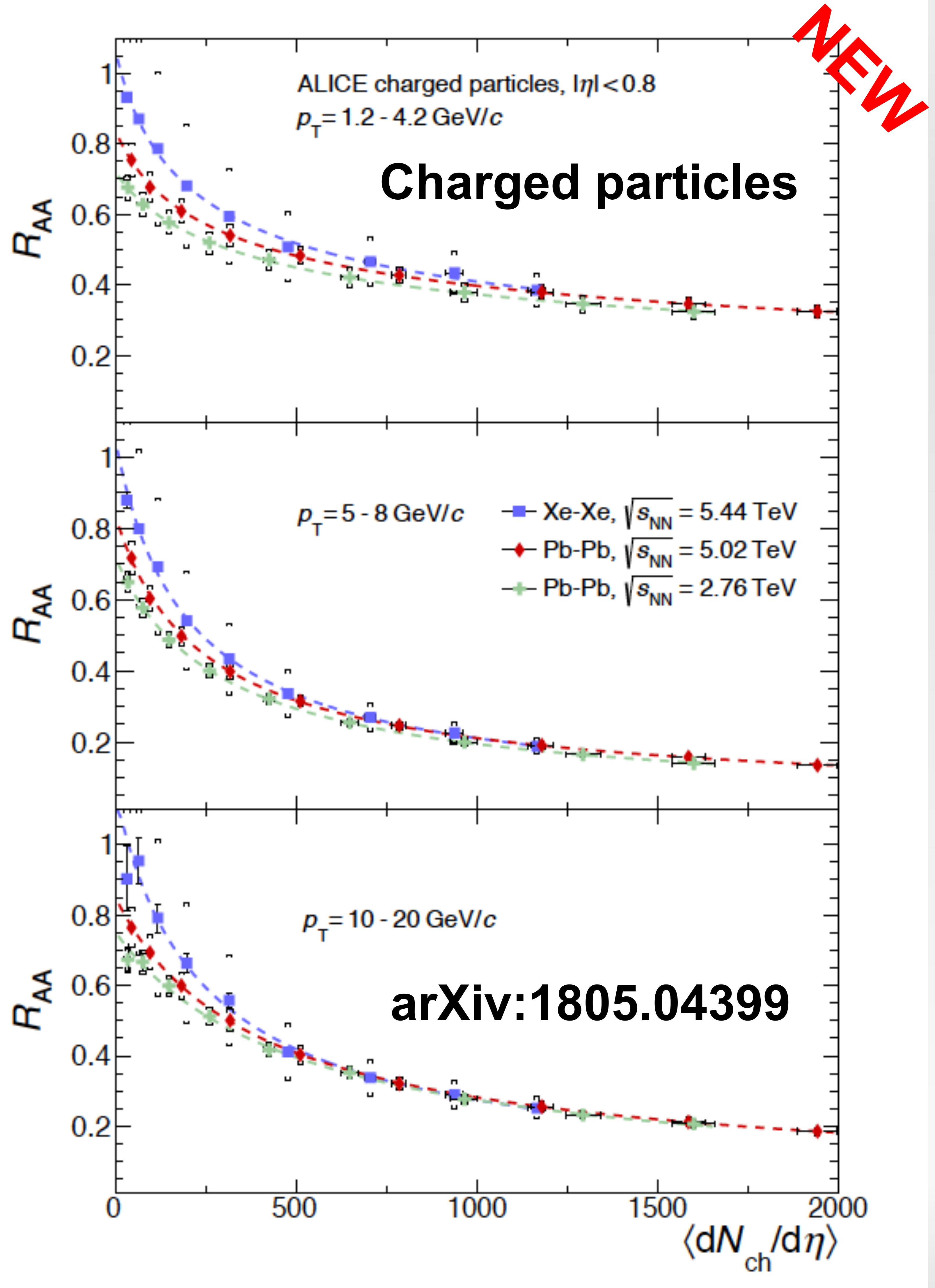
– **New R_{AA}** measurement of beauty-decay electrons in **0-10% centrality at 5.02 TeV**

⇨ $R_{AA} < 1$ for $p_T > 3$ GeV/c and compatible with the R_{AA} measured at 2.76 TeV

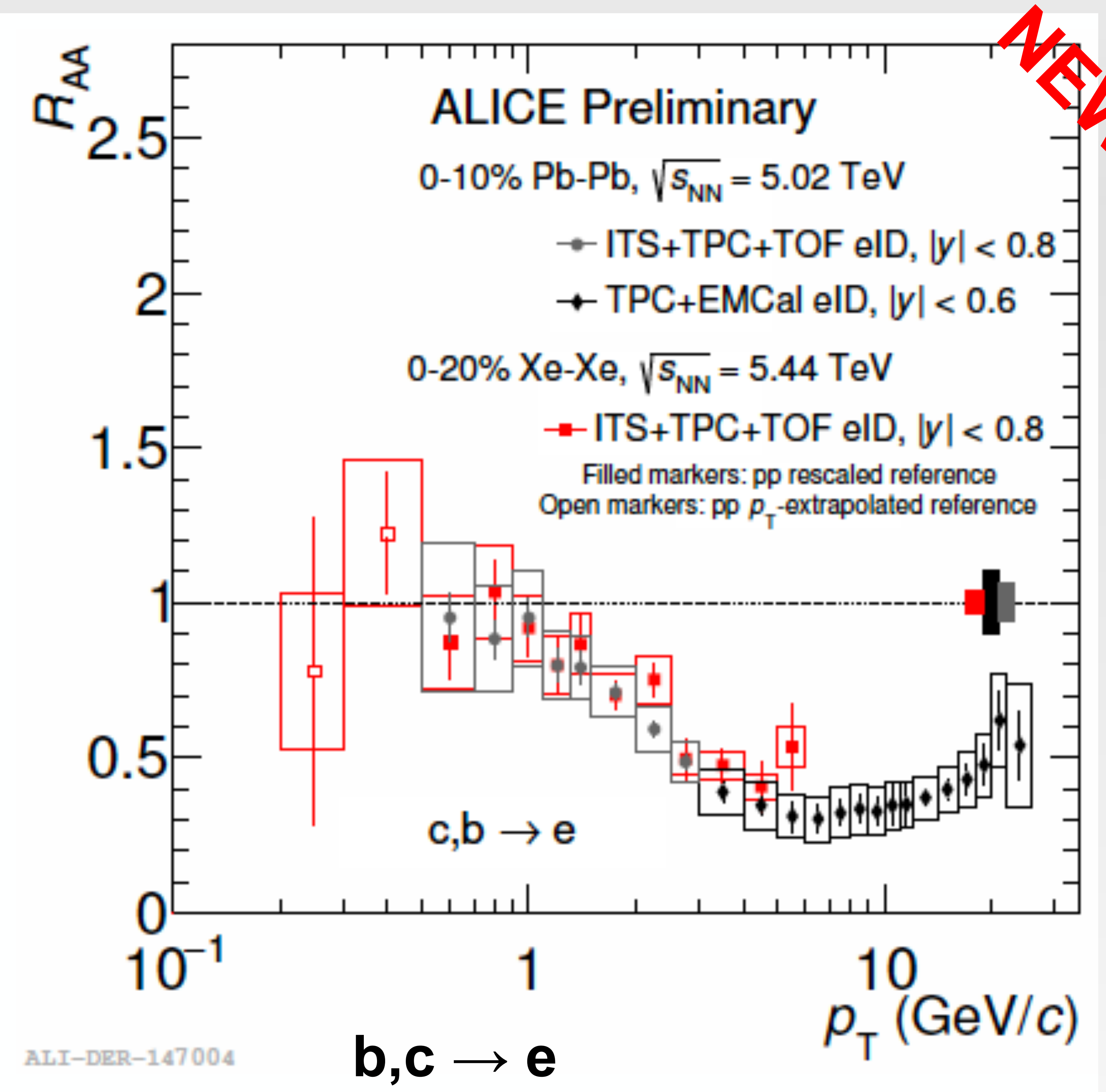




Nuclear modification factor in Xe-Xe collisions at 5.44 TeV

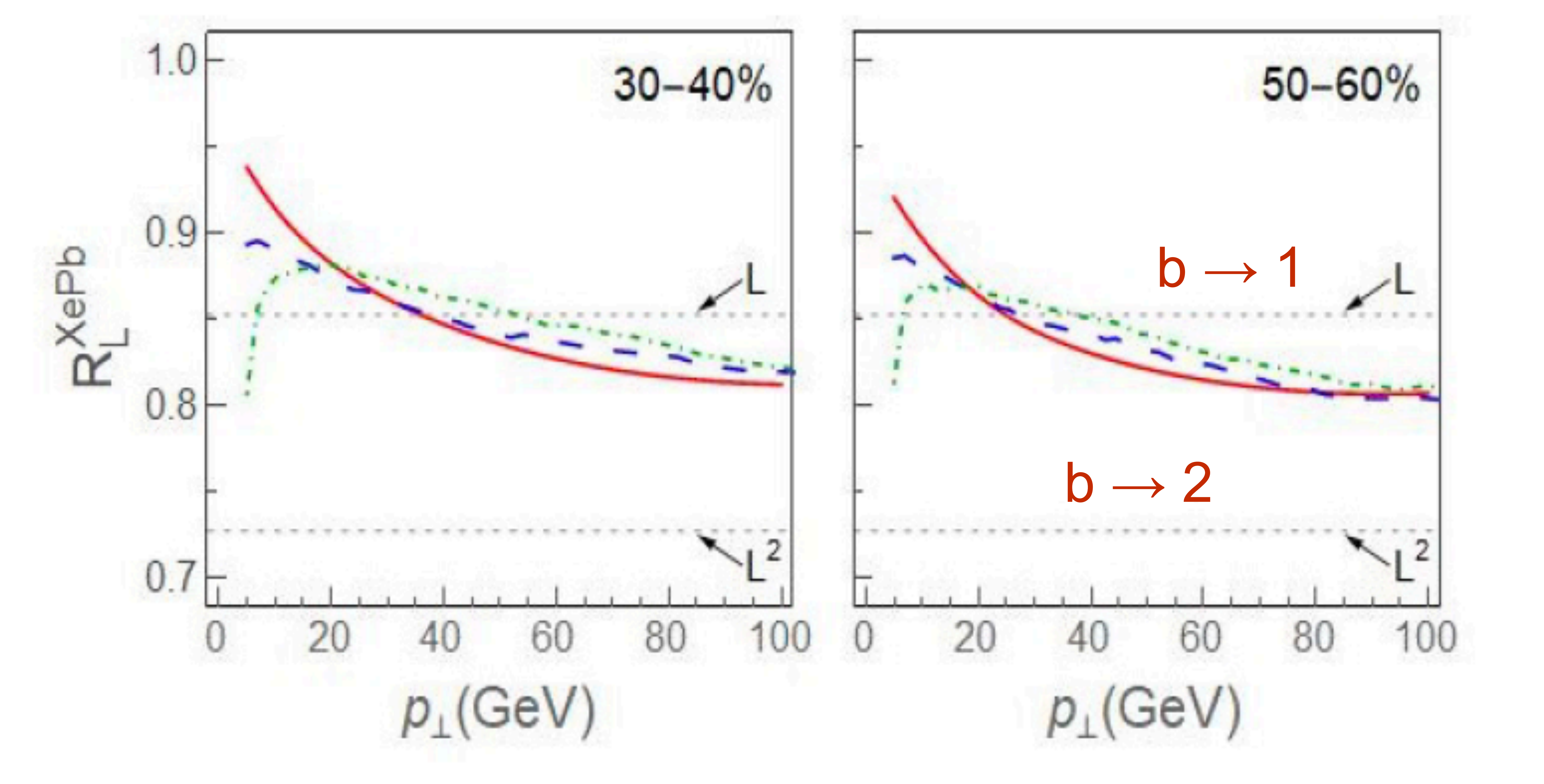


Similar R_{AA} is observed in Xe-Xe and Pb-Pb when compared at similar <dN/dη>



– Comparison of **Pb-Pb** and **Xe-Xe** collisions at different N_{part} or N_{ch} may add sensitivity to probe the path-length dependence of energy loss
⇨ both radiative and collisional processes relevant for heavy-flavour
⇨ constraints to model calculations

Test of path-length dependence



arXiv:1805.04030

$$R_L^{XePb} \equiv \frac{1 - R_{XeXe}}{1 - R_{PbPb}} \simeq \frac{T_{Xe}^a L_{Xe}^b}{T_{Pb}^a L_{Pb}^b} \simeq (\frac{A_{Xe}}{A_{Pb}})^{b/3}$$

- T: average medium temperature
- L: average path length
  - **- b → 1: linear dependence**
  - **- b → 2: quadratic dependence**

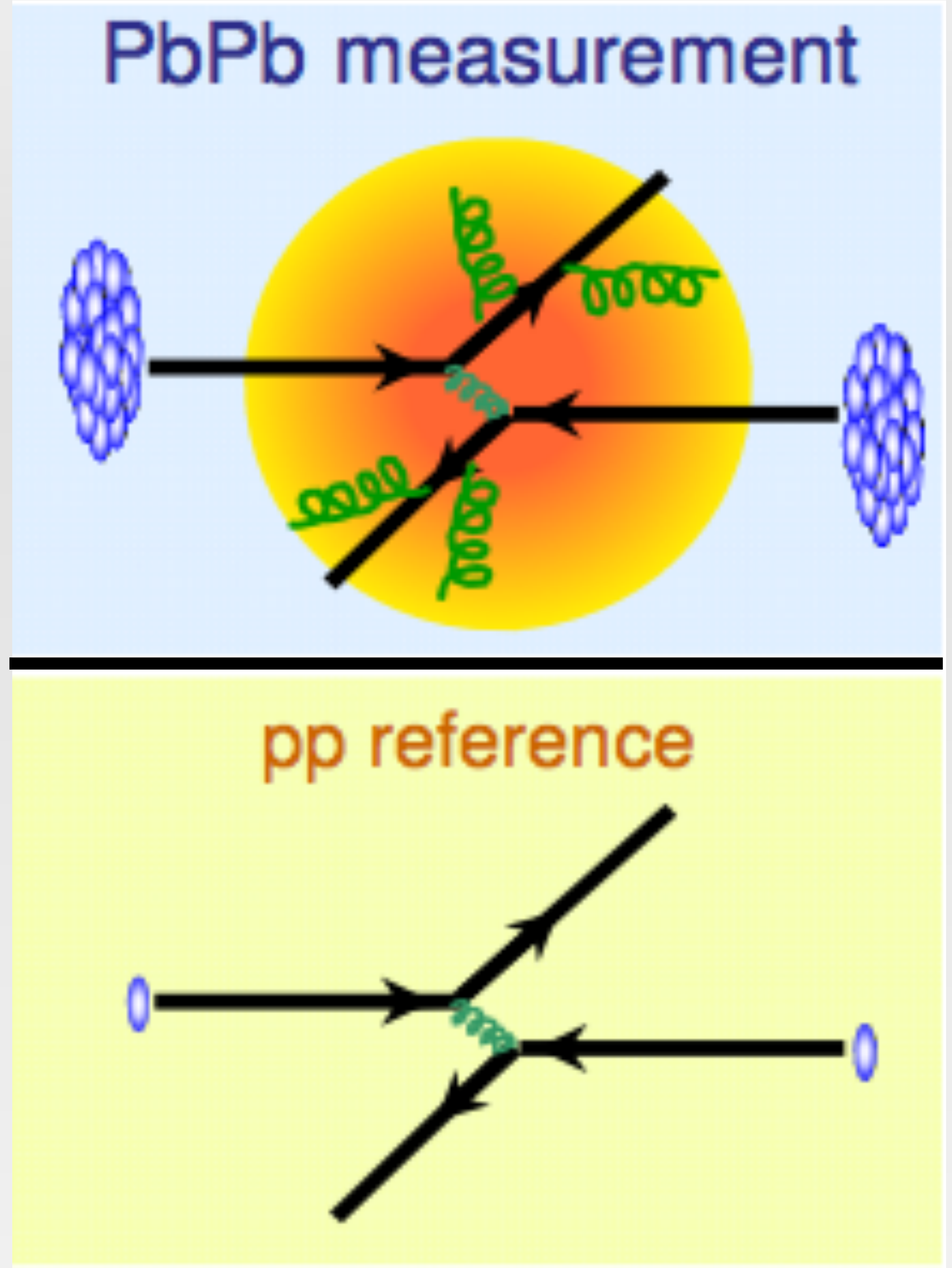
The scaling holds better for
- Similar average event multiplicity: $T_{Xe} \approx T_{Pb}$
- High initial parton p_T: $\Delta E/E$ is small
- Central collisions: $L_{Xe} / L_{Pb} \propto (A_{Xe} / A_{Pb})^{b/3}$

Nuclear modification factor

– Production of hard probes (heavy quarks, jets...) in AA collisions is expected to scale with the number of nucleon-nucleon collisions N_{coll} (**binary scaling**)

– **Observable**: nuclear modification factor

$$R_{\mathrm{AA}}(p_{\mathrm{T}},y) = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \cdot \frac{\mathrm{d}^2 N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\mathrm{d}^2 \sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} \sim \frac{QCD\ \mathrm{medium}}{QCD\ \mathrm{vacuum}}$$



– If no nuclear effects are present → $R_{\mathrm{AA}} = 1$

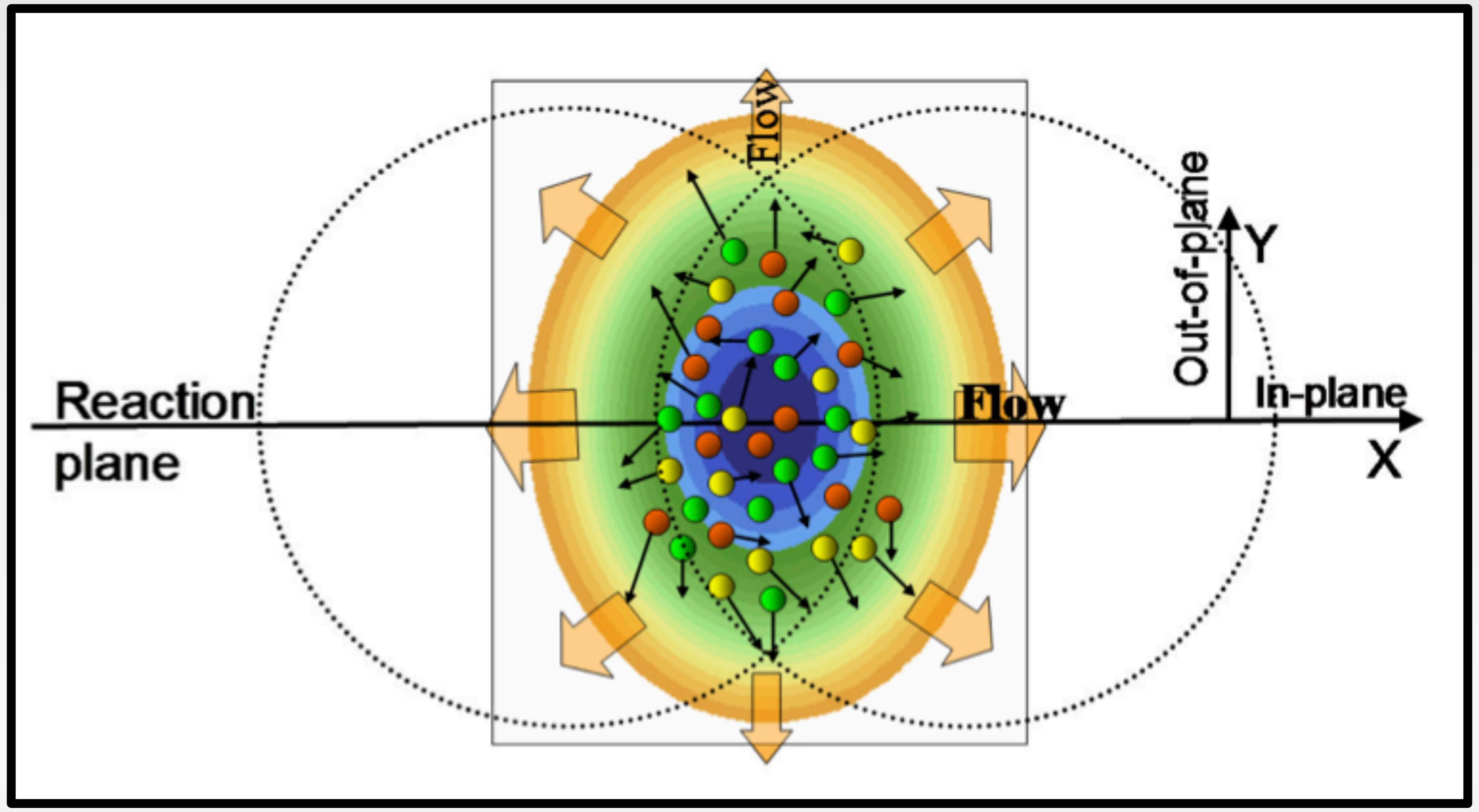
– **Cold Nuclear Matter** effects:
⇨ **shadowing** leads to a reduction of the heavy-flavour yield (important at **low p_{T}**)

– In-medium parton **energy loss** via **radiative** (gluon emission) and **collisional** processes depending on:
⇨ colour charge
⇨ quark mass (dead cone effect)
⇨ path length and medium density

Dokshitzer and Kharzeev, PLB 519 (2001) 199
Wicks, Gyulassy, J.Phys. G35 (2008) 054001

Collectivity: azimuthal anisotropy

- Re-scatterings among produced particles convert the initial **geometrical anisotropy** into an observable momentum anisotropy
- In addition, **path-length** dependent energy loss induces an asymmetry in momentum space
- **Observable**: **elliptic flow v_2 =** 2nd Fourier coefficient of the particle azimuthal distribution

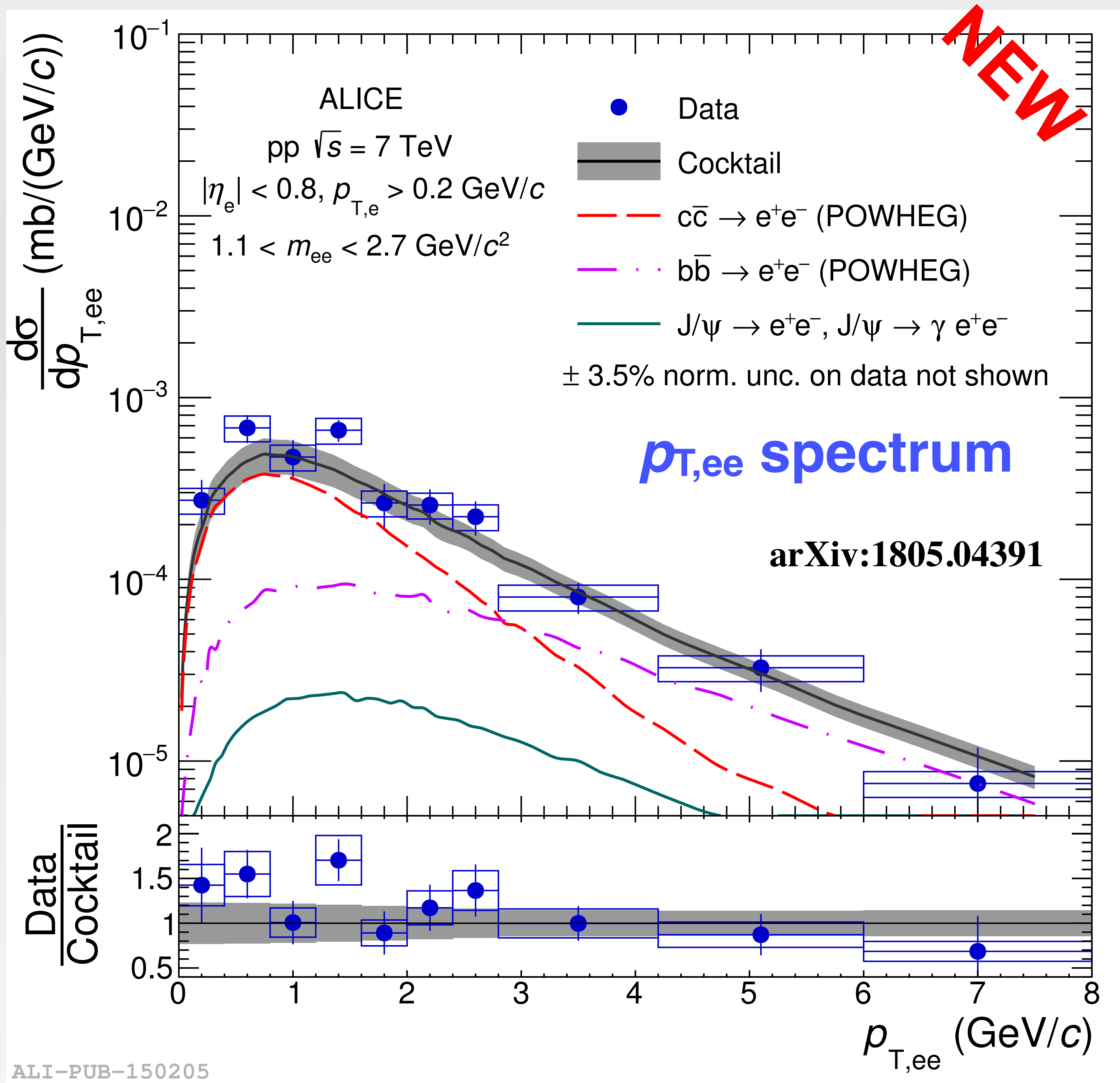


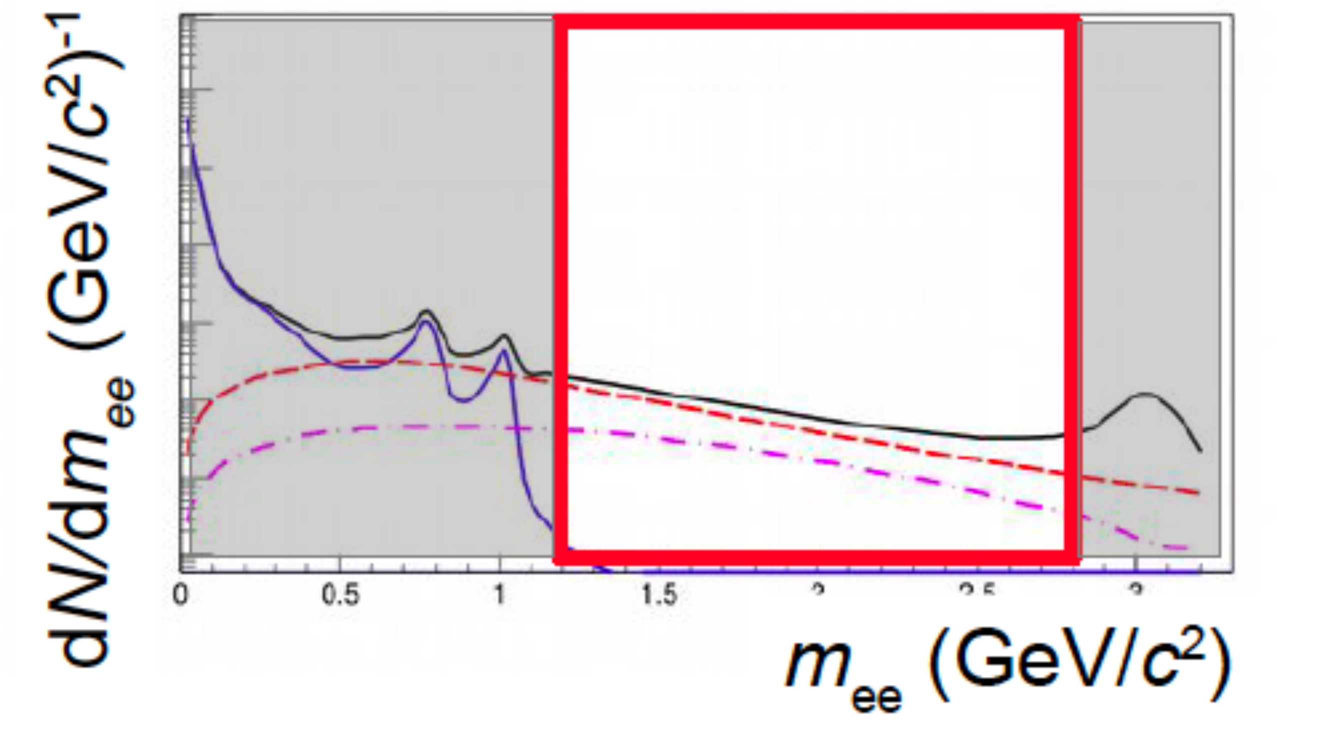
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_{RP})]\right)$$

Heavy-flavour v_2 measurements probe:

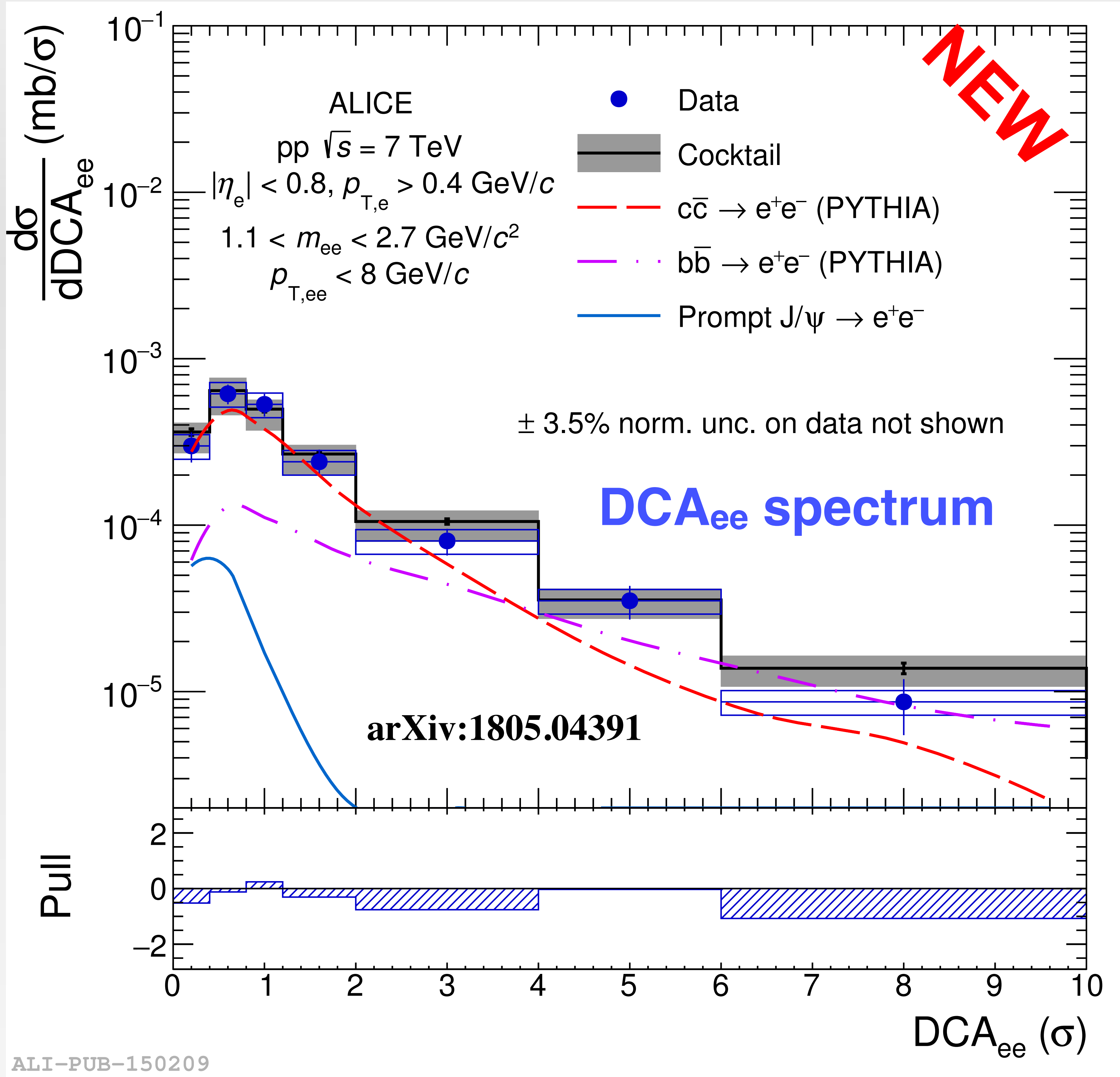
- **Low/intermediate p_T**: collective motion, degree of thermalization of heavy quarks and hadronization mechanism (recombination)
- **High p_T**: path-length dependence of heavy-quark energy loss

$p_{T,ee}$ and DCA$_{ee}$ analyses in pp at $\sqrt{s}$ = 7 TeV





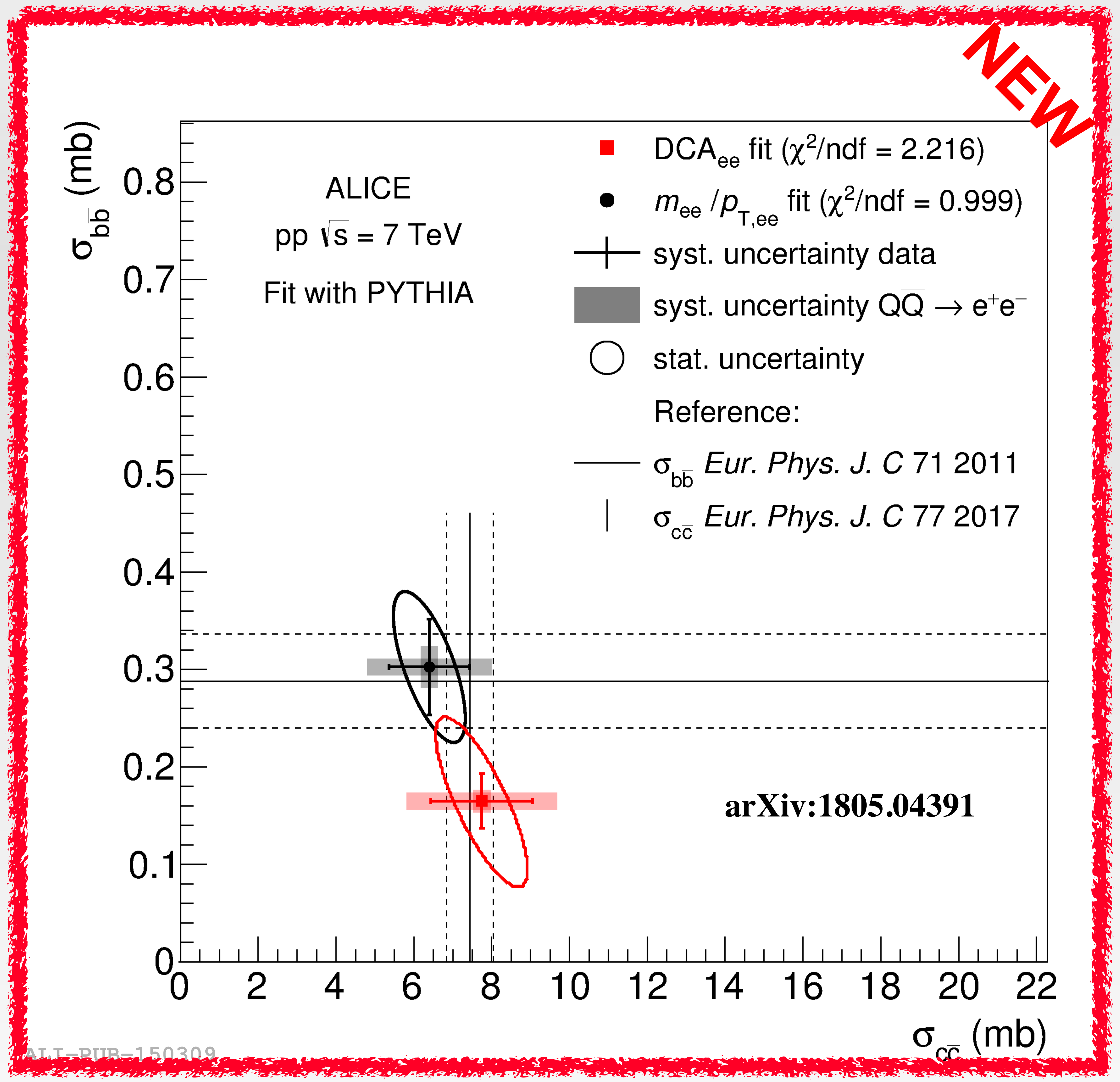
Intermediate-mass region



- ➯ **Charm** dominates at low $p_{T,ee}$ ($p_{T,ee} < 3$ GeV/c) and small DCA$_{ee}$
- ➯ **Beauty** dominates at large $p_{T,ee}$ ($p_{T,ee} > 4$ GeV/c) and large DCA$_{ee}$

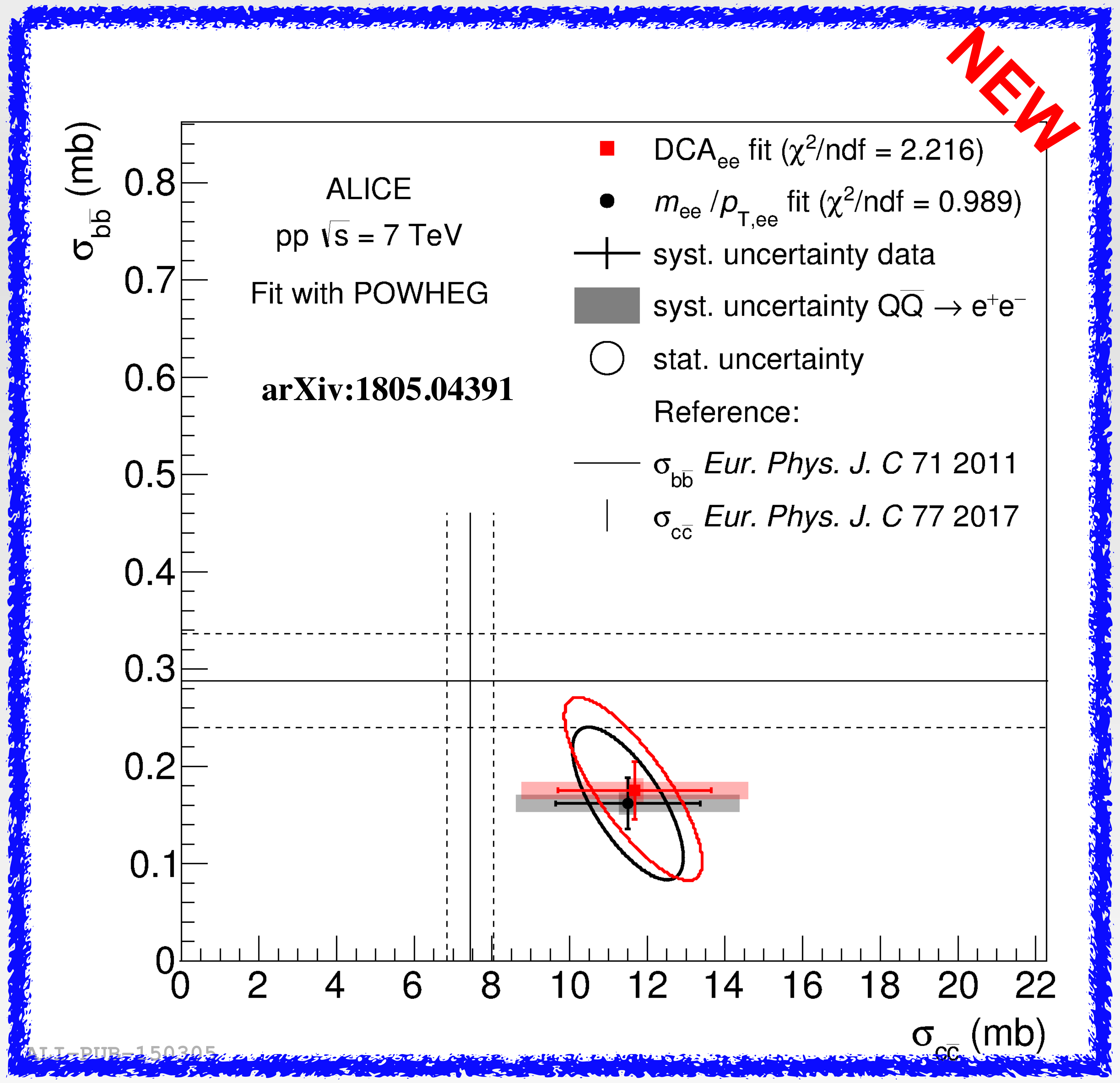
- ➯ Let the normalization of the charm and beauty contributions free in the cocktail
- ➯ Fit m_{ee}/$p_{T,ee}$ and DCA$_{ee}$ spectra independently to extract the total charm and beauty cross sections

Model dependence



PYTHIA 6 Perugia 2011 tune (LO with parton shower)

POWHEG (NLO) + PYTHIA 6 parton shower

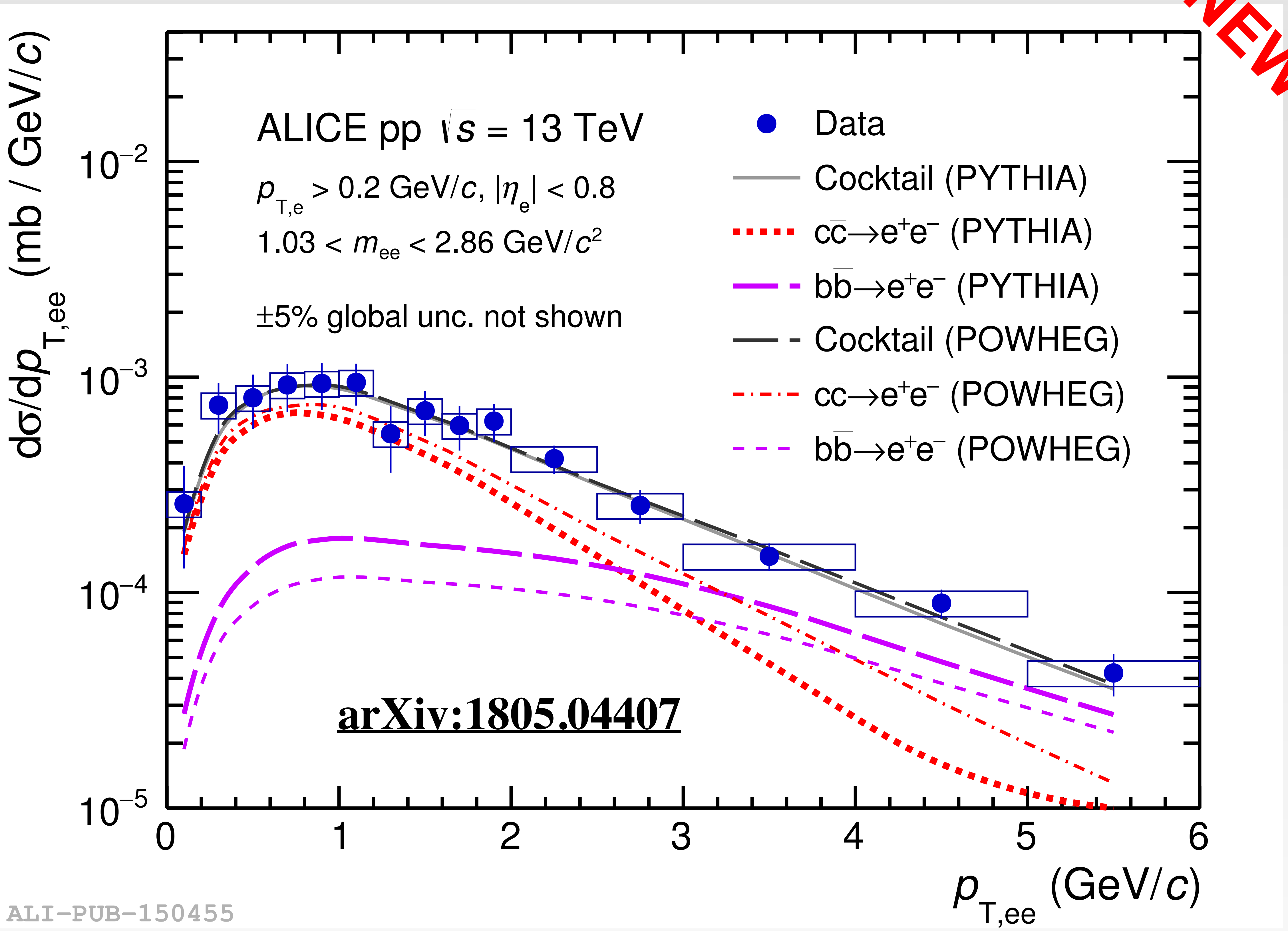


- ➪ Significant **model dependence** of the extracted total charm and beauty cross section
- ➪ **Sensitivity** to the different implementation of **heavy-quark production mechanisms**

Heavy-flavour production in pp at $\sqrt{s}$ = 13 TeV

$p_{T,ee}$ **spectrum**
in the intermediate-mass region

NEW



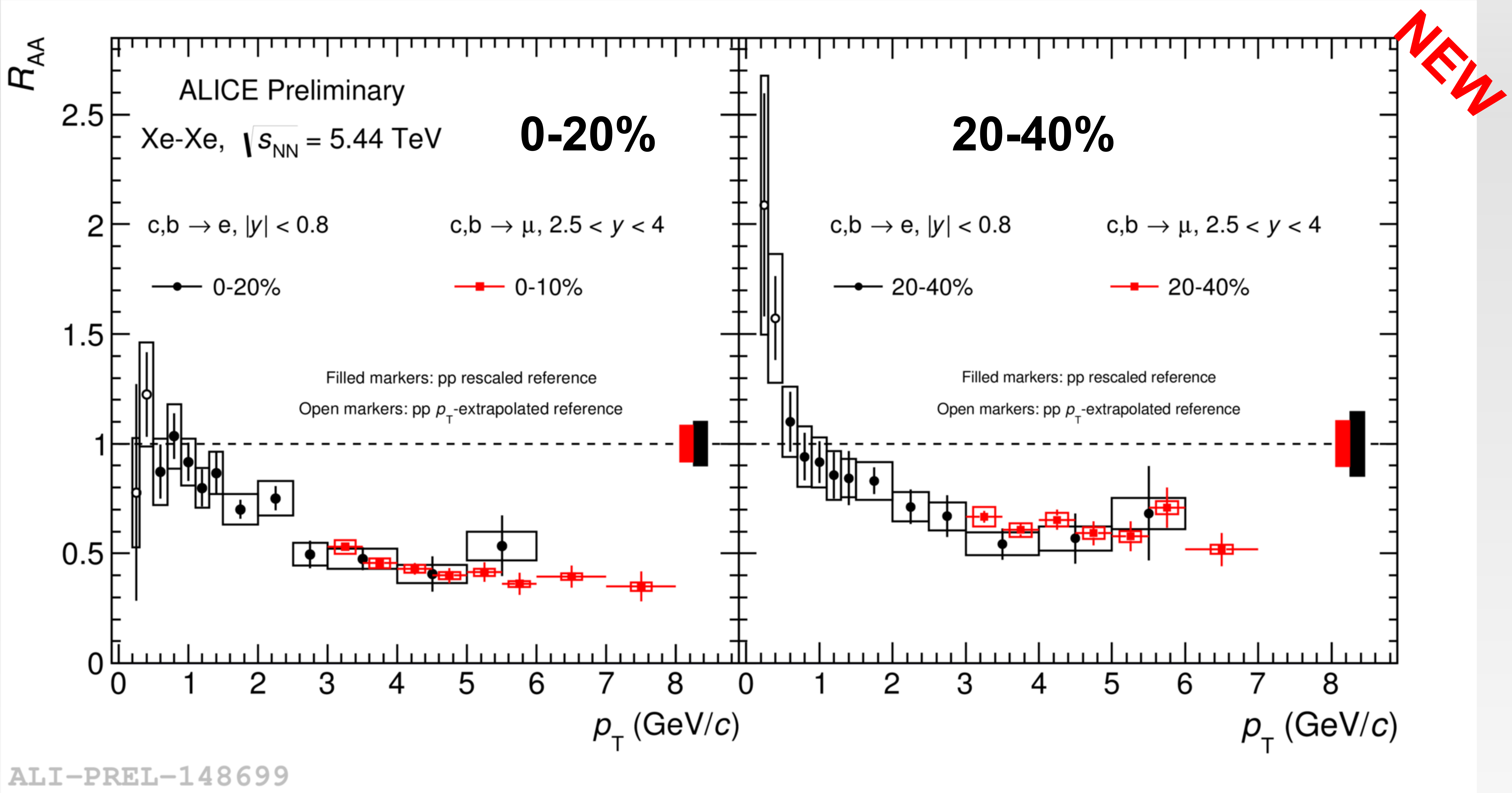
First measurement of $d\sigma_{c\bar{c}/b\bar{b}}/dy|_{y=0}$
in pp collisions at $\sqrt{s}$ = 13 TeV

	PYTHIA 6 Perugia 2011 tune (LO with parton shower)	POWHEG (NLO) + PYTHIA 6 parton shower
$d\sigma_{c\bar{c}}/dy|_{y=0}$	$974 \pm 138\,(\text{stat.}) \pm 140\,(\text{syst.})$ μb	$1417 \pm 184\,(\text{stat.}) \pm 204\,(\text{syst.})$ μb
$d\sigma_{b\bar{b}}/dy|_{y=0}$	$79 \pm 14\,(\text{stat.}) \pm 11\,(\text{syst.})$ μb	$48 \pm 14\,(\text{stat.}) \pm 7\,(\text{syst.})$ μb

- ⇨ **Fit 2D** $p_{T,ee}$ and m_{ee} spectra to extract $d\sigma_{cc/bb}/dy|_{y=0}$
- ⇨ Similar **model dependence** observed as at $\sqrt{s}$ = 7 TeV
- ⇨ Further studies of charm production mechanisms

Nuclear modification factor in Xe-Xe: rapidity dependence

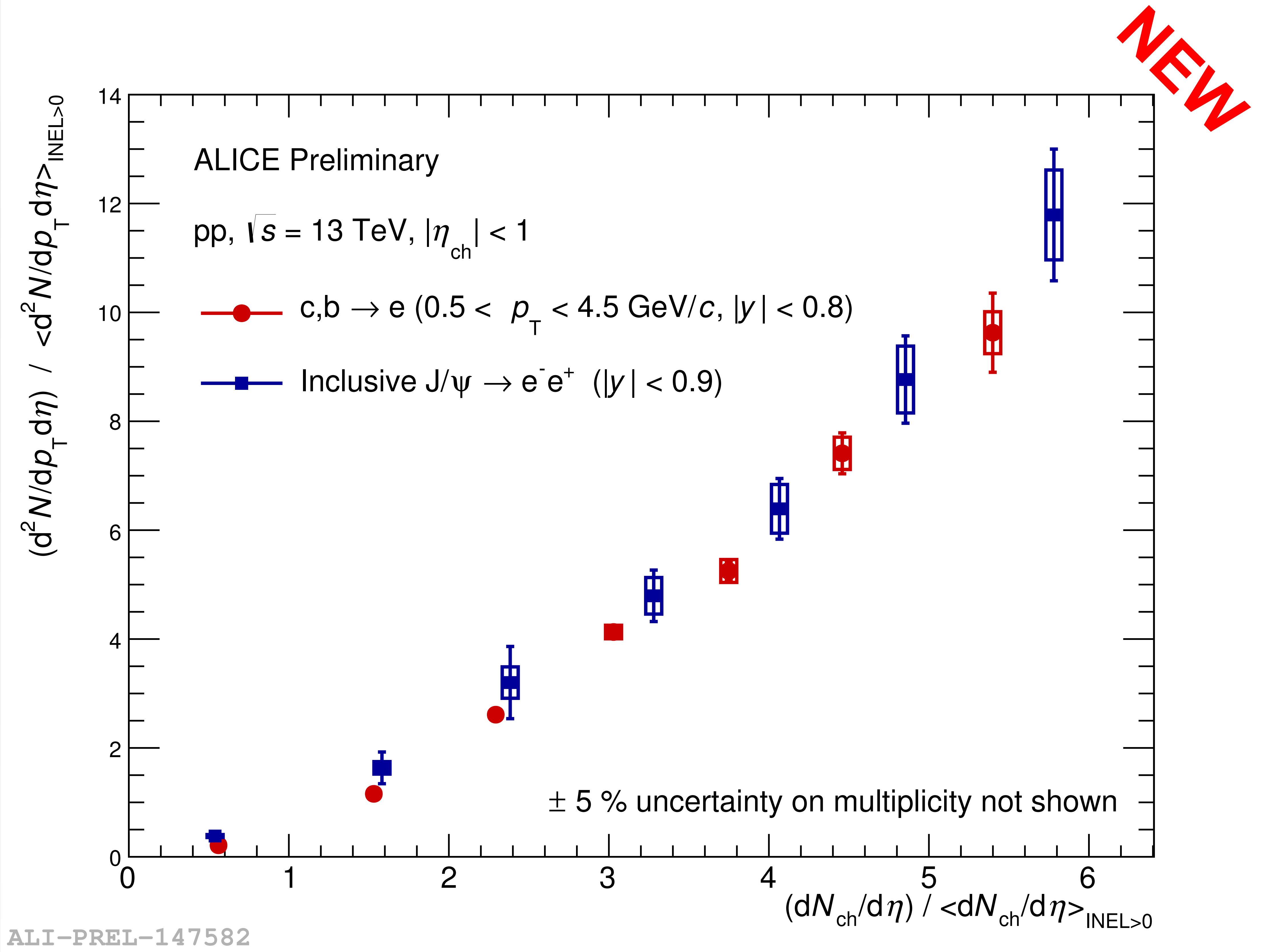
– **New R_{AA}** measured down to p_T **= 0.2 GeV/*c*** thanks to the low B field used in ALICE during the Xe-Xe data taking!

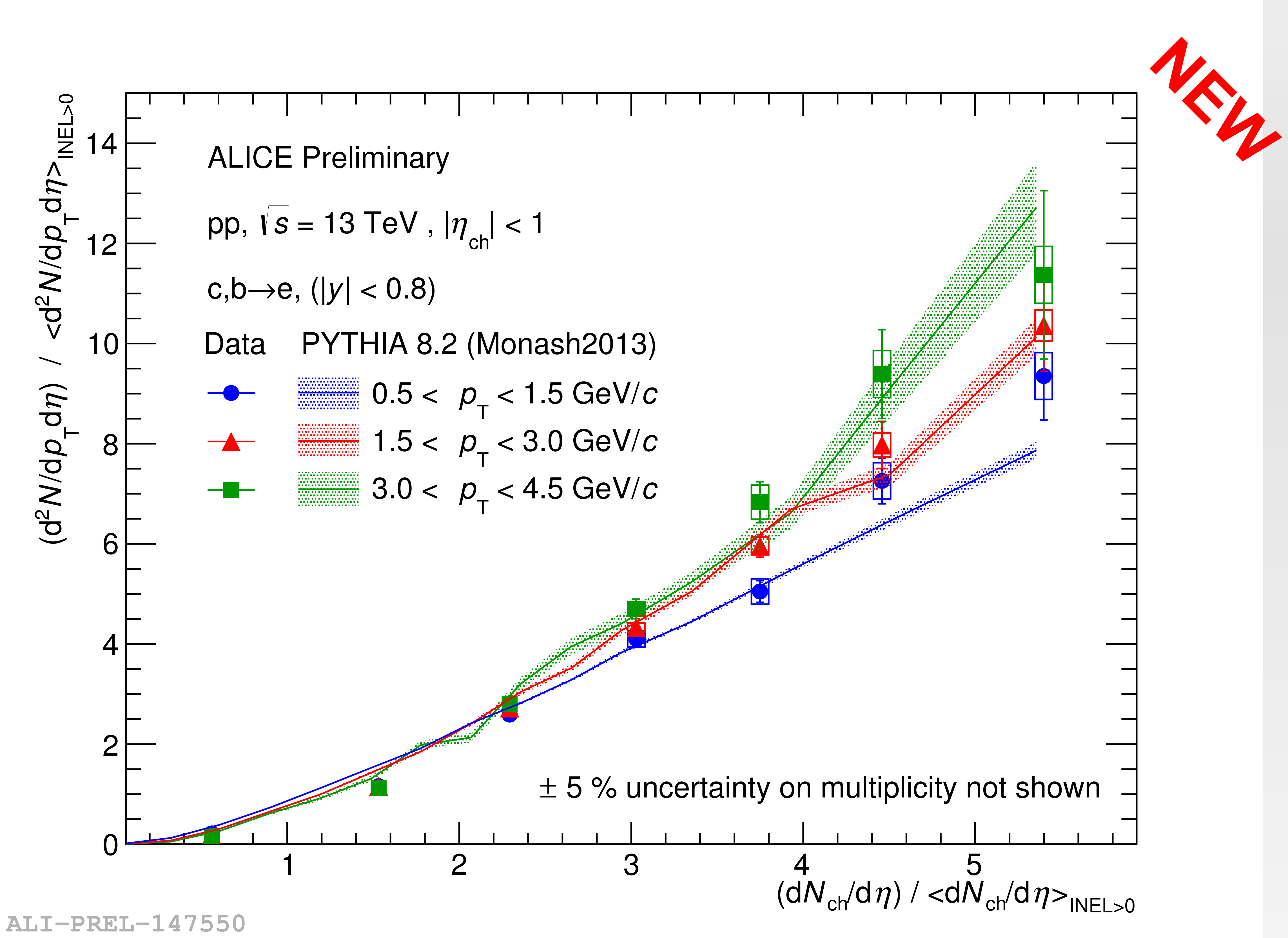


– Also in this collision system a similar suppression is observed with the **muons** from heavy-flavour hadron decay at forward rapidity

– Hint of a smaller suppression in 0-10% with respect to 20-40% centrality

Studies of heavy-flavour production as a function of multiplicity

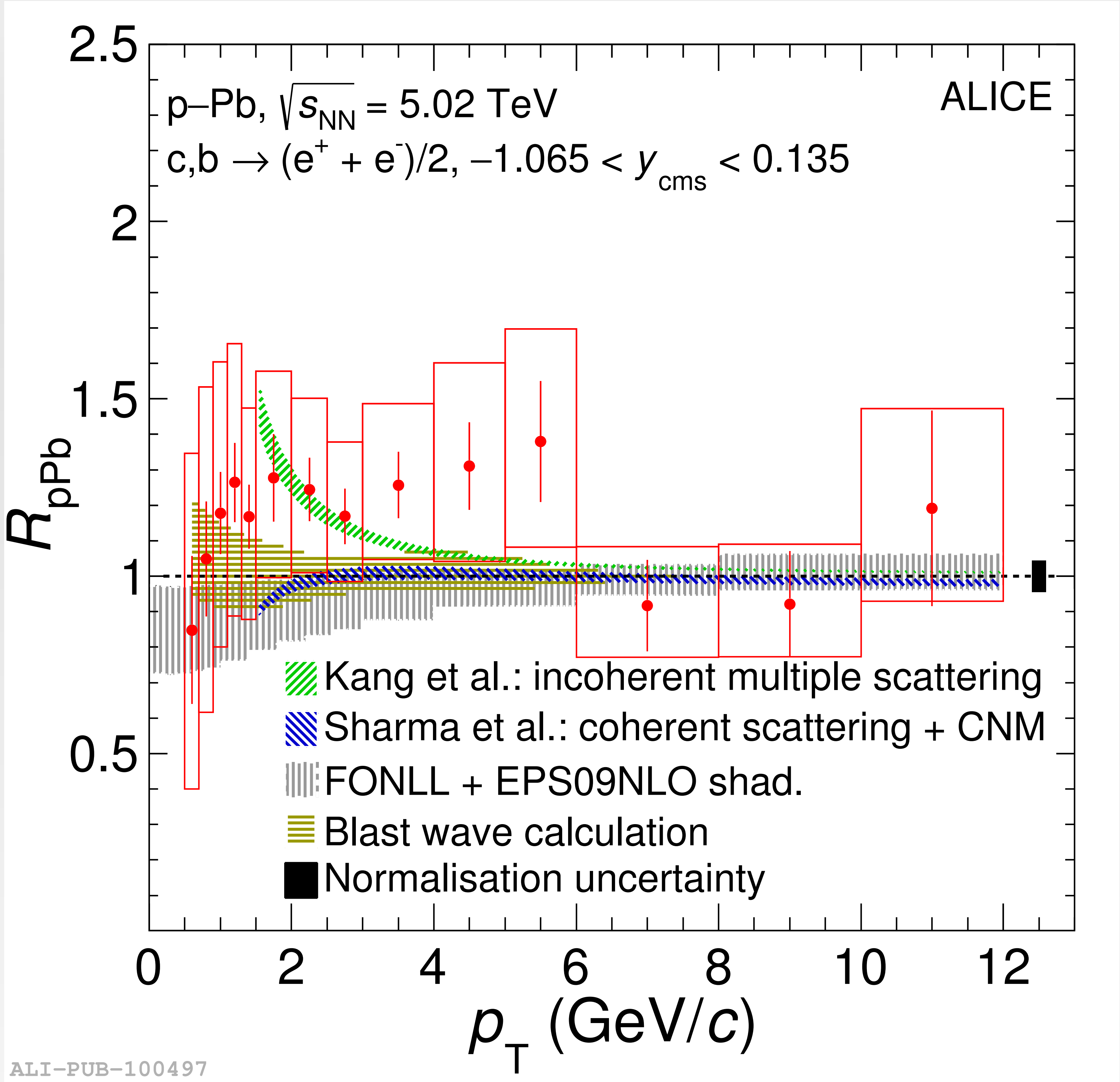


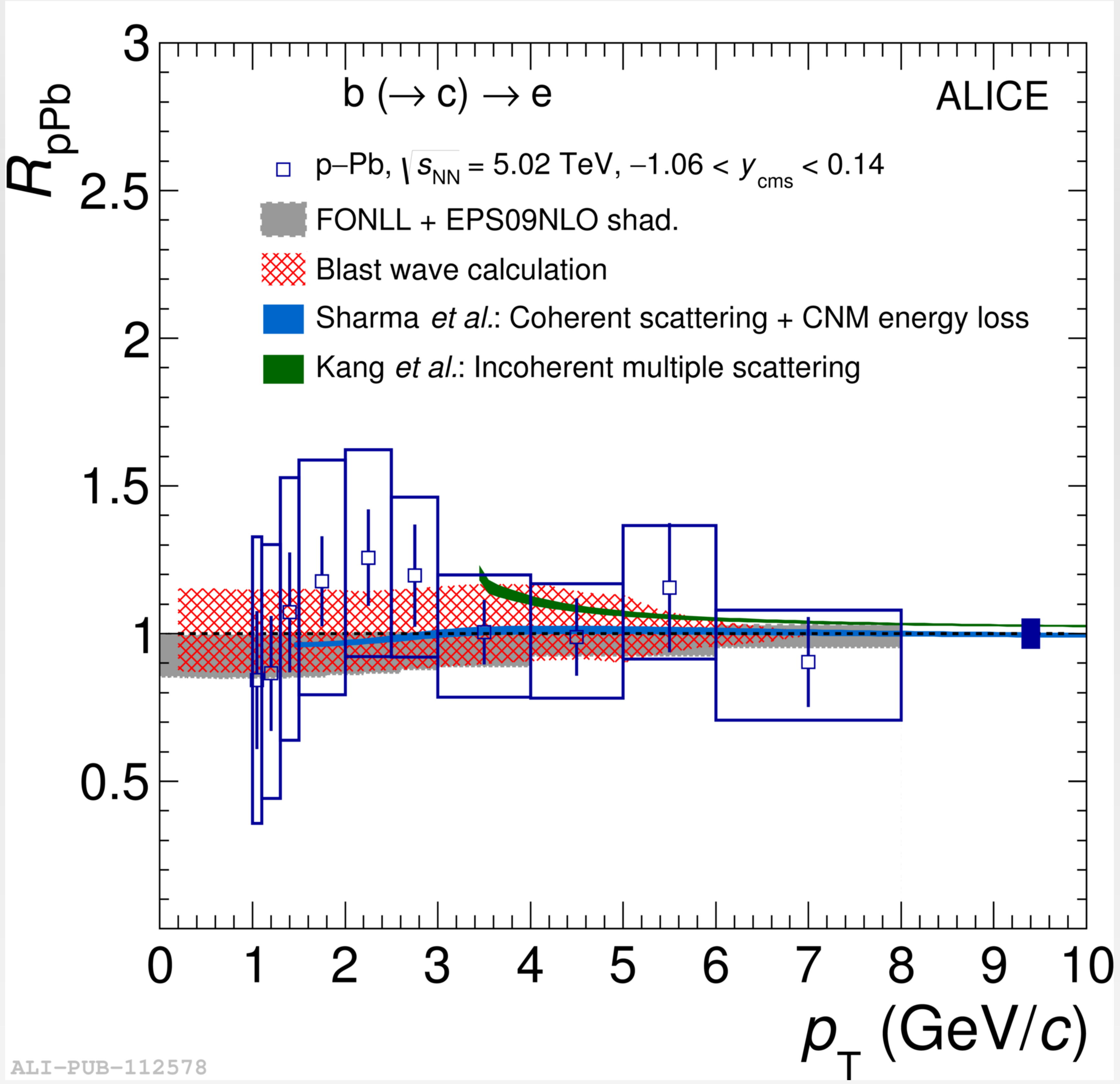


– Heavy-flavour production in pp collisions provides **insight into** their **production mechanisms** and into the interplay between **hard and soft processes** in particle production

– The self-normalized yield shows a **faster than linear increase** trend and are **comparable with J/ψ measurements and PYTHIA8.2 predictions**

Production in p-Pb collisions



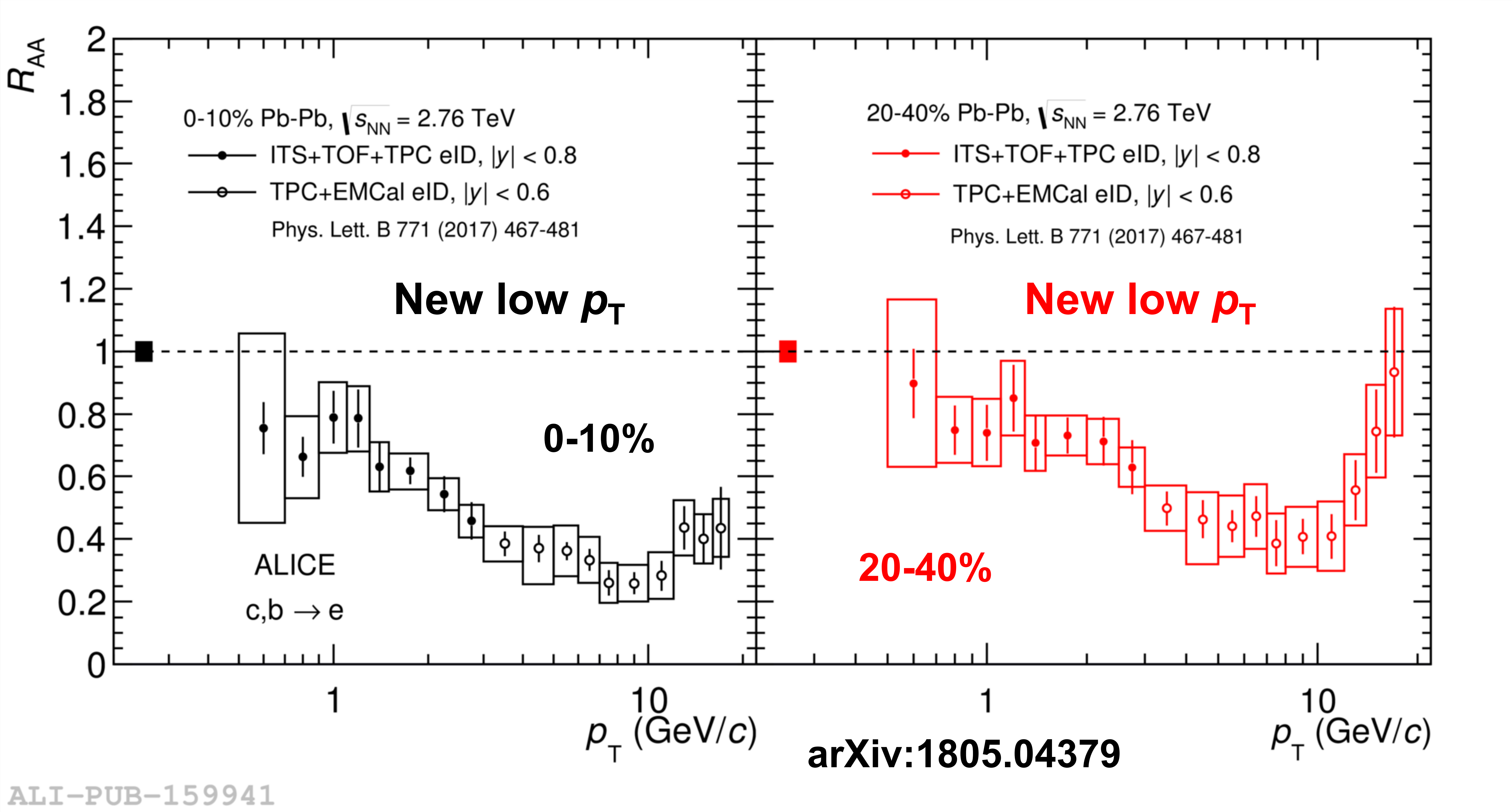


– For both inclusive HF and beauty decay electron an R_{pPb} = 1 has been measured within the uncertainties

– No indication of significant cold nuclear matter effects on charm and beauty production

– Large uncertainties do not allow to discriminate among models implementing different CNM effects

Heavy-flavour hadron decay electron nuclear modification factor



New R_{AA} measurements in Pb-Pb collisions at 2.76 TeV down to p_T = 0.5 GeV/c

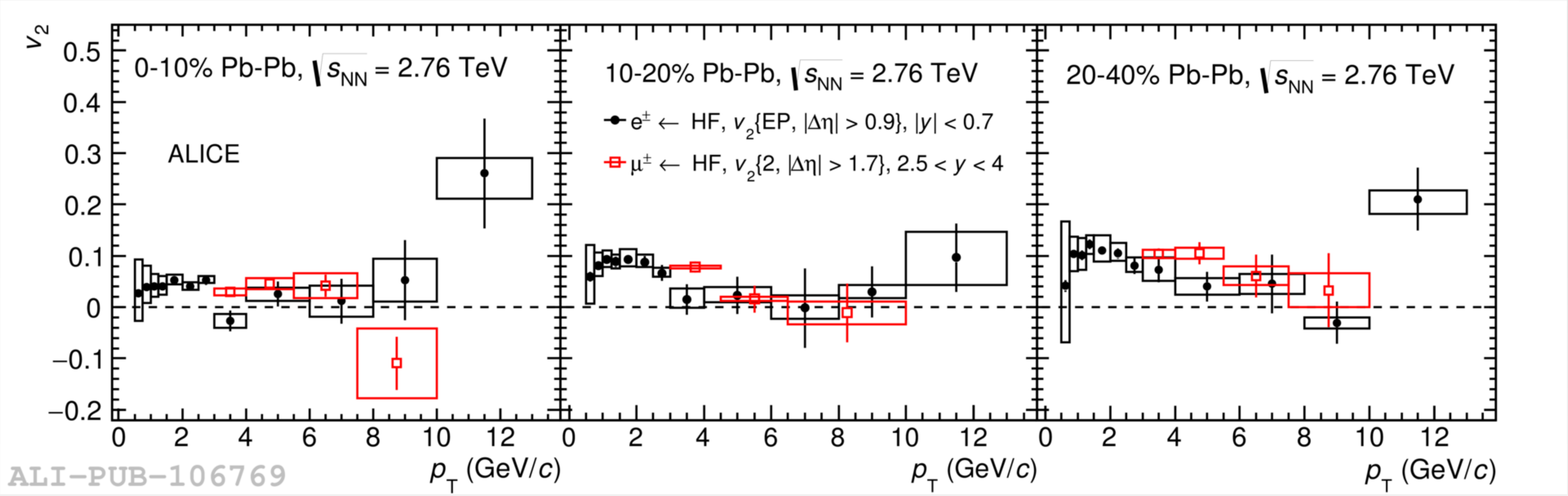
⇨ **low-p_T** measurements **crucial** in all systems to **test binary scaling** of total charm cross section and possible effect of initial-state effects like nuclear PDF (**shadowing**)

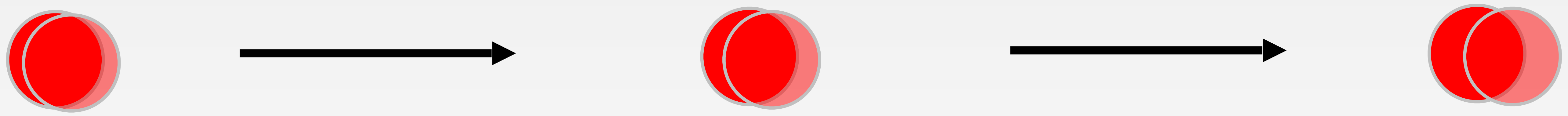
⇨ systematic uncertainty largely reduced thanks to the new pp reference at 2.76 TeV

Leptons from heavy-flavour hadron decays

HF-decay muons
2.5 < y < 4
PLB 753, (2016) 41

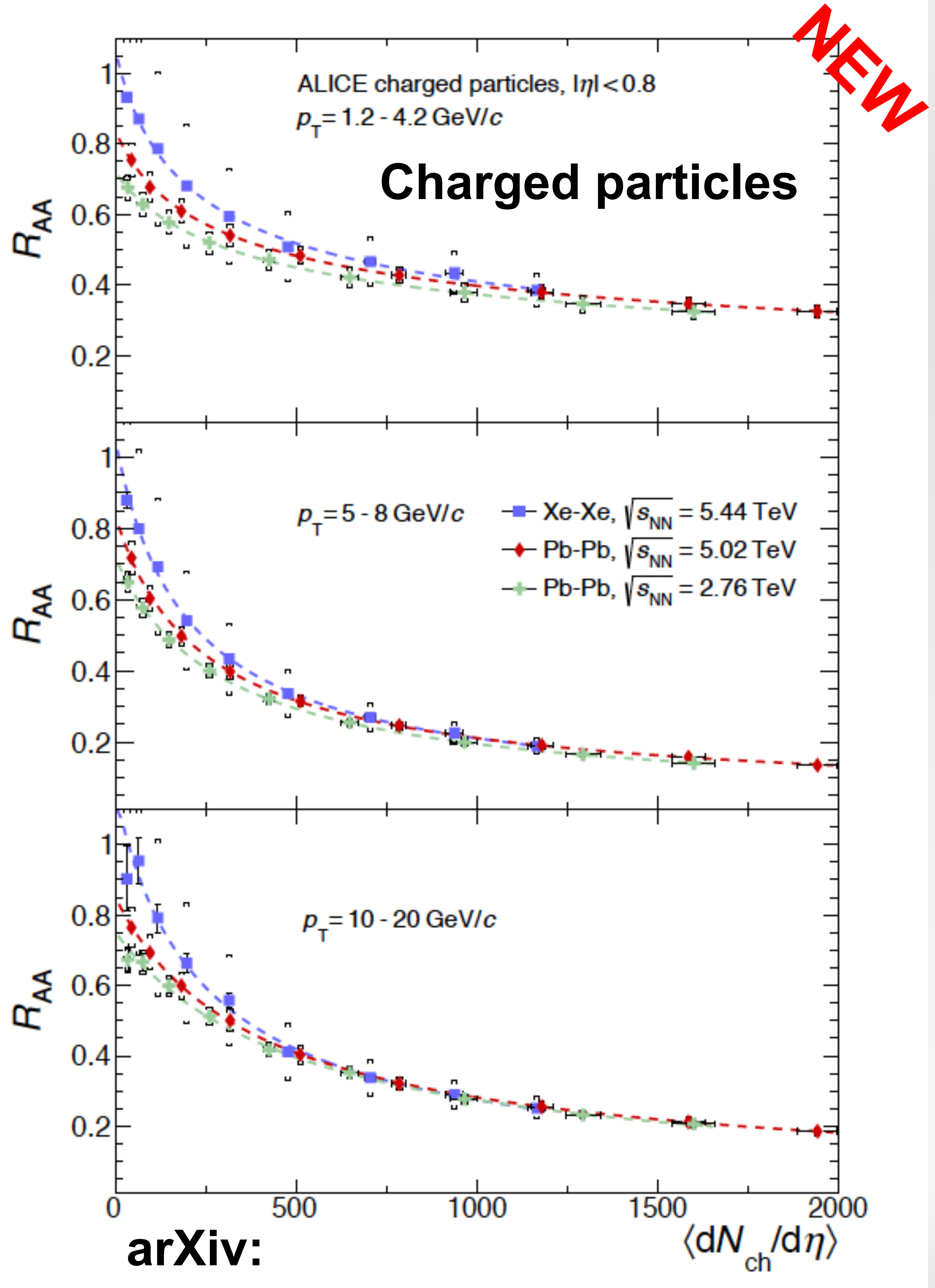
HF-decay electrons
$|y|$ < 0.7
JHEP 09 (2016) 028





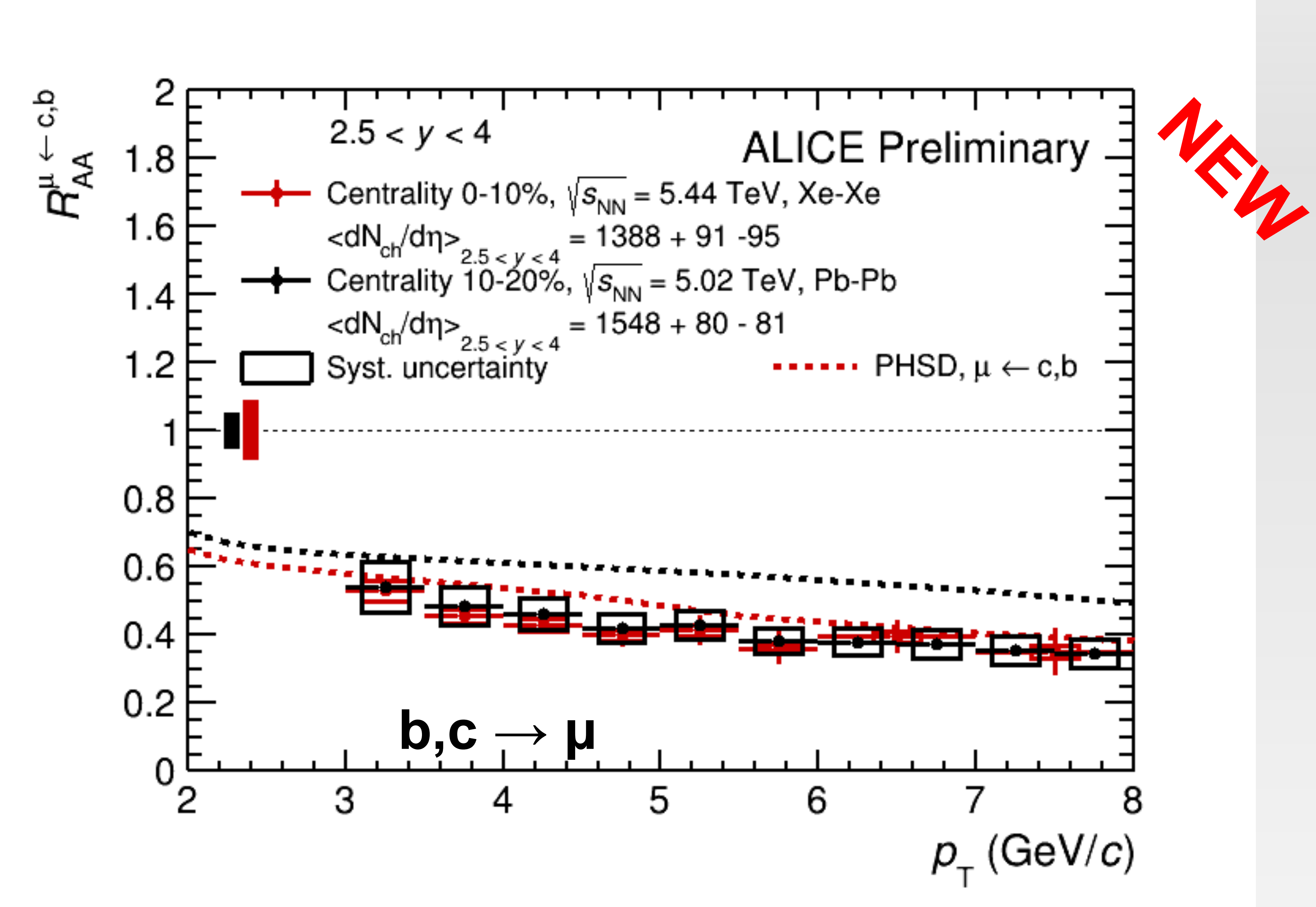
- Similar v_2 of heavy-flavour decay **electrons** at mid-rapidity and **muons** at forward rapidity classes.
- Positive v_2 observed → 5.9σ effect for 2 < p_T < 2.5 GeV/c in 20-40% centrality class for the heavy-flavour decay electrons.
- Hint for an increase of v_2 from central to semi-central collisions as observed for D mesons
- Suggests collective motion of low-p_T charm quarks in the expanding fireball

Nuclear modification factor in Xe-Xe collisions at 5.44 TeV



arXiv:

Similar R_{AA} is observed in Xe-Xe and Pb-Pb when compared at similar <dN/dη>

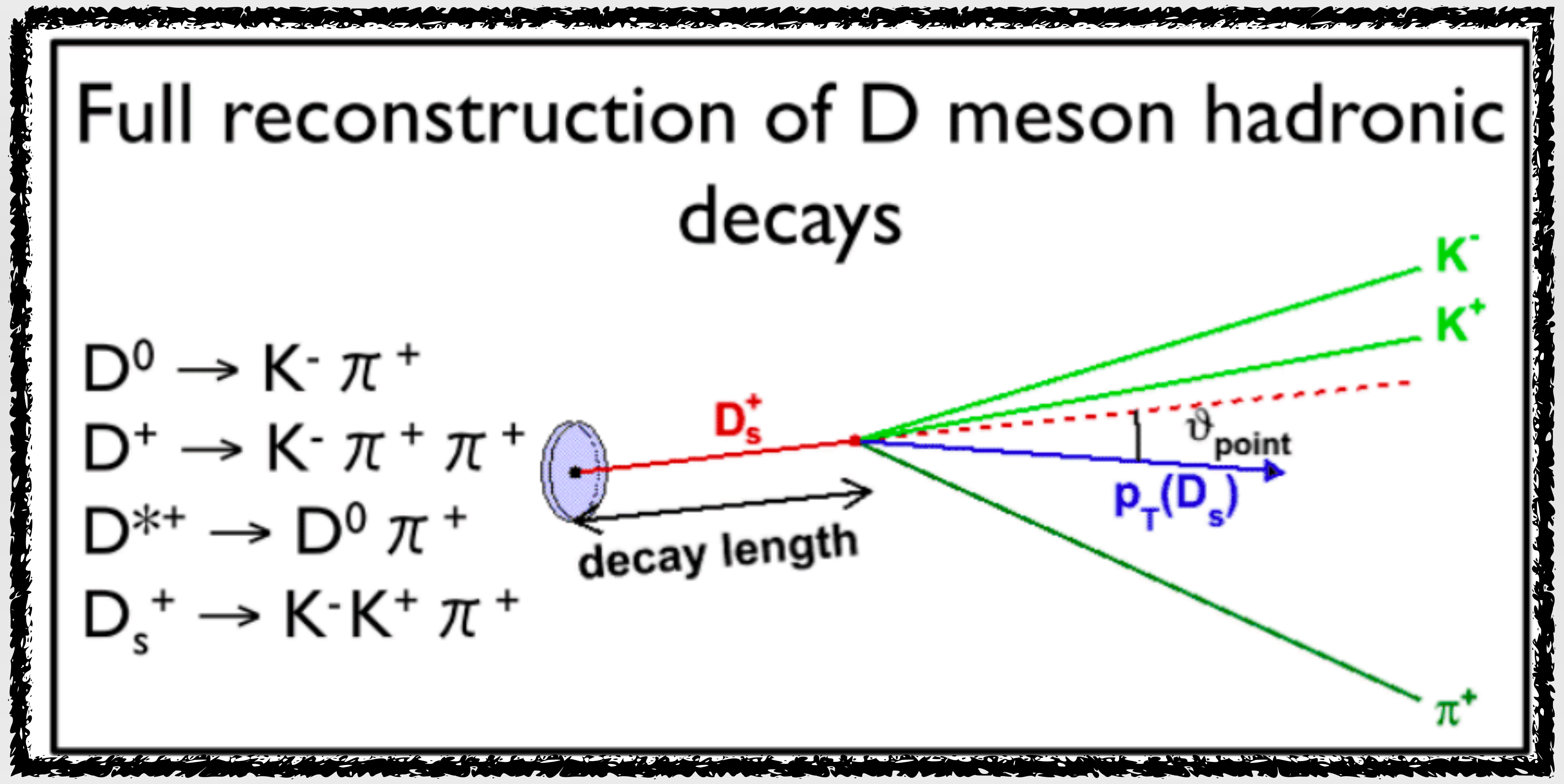


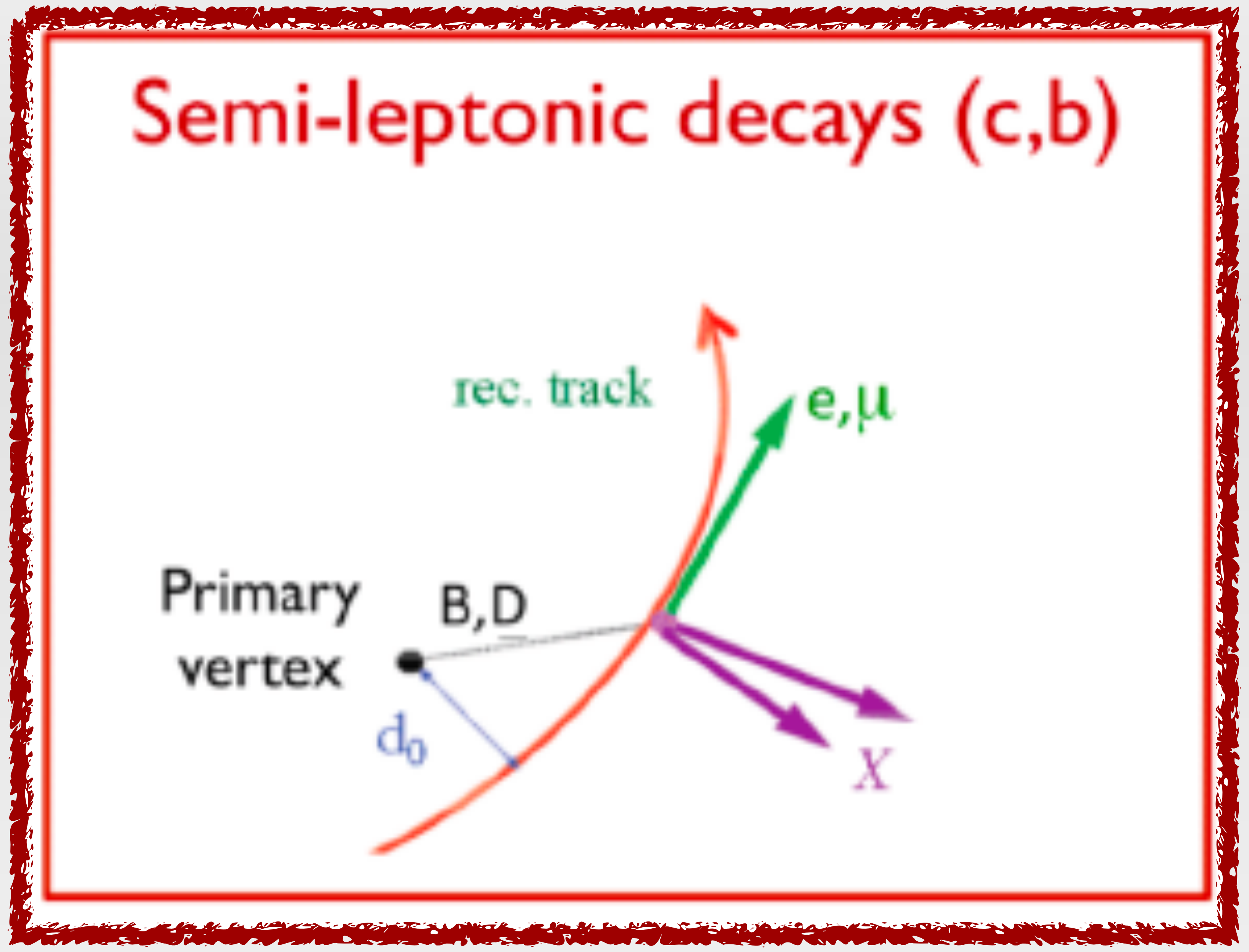
– Scenario consistent with the quadratic path length dependence of medium-induced **radiative energy loss**

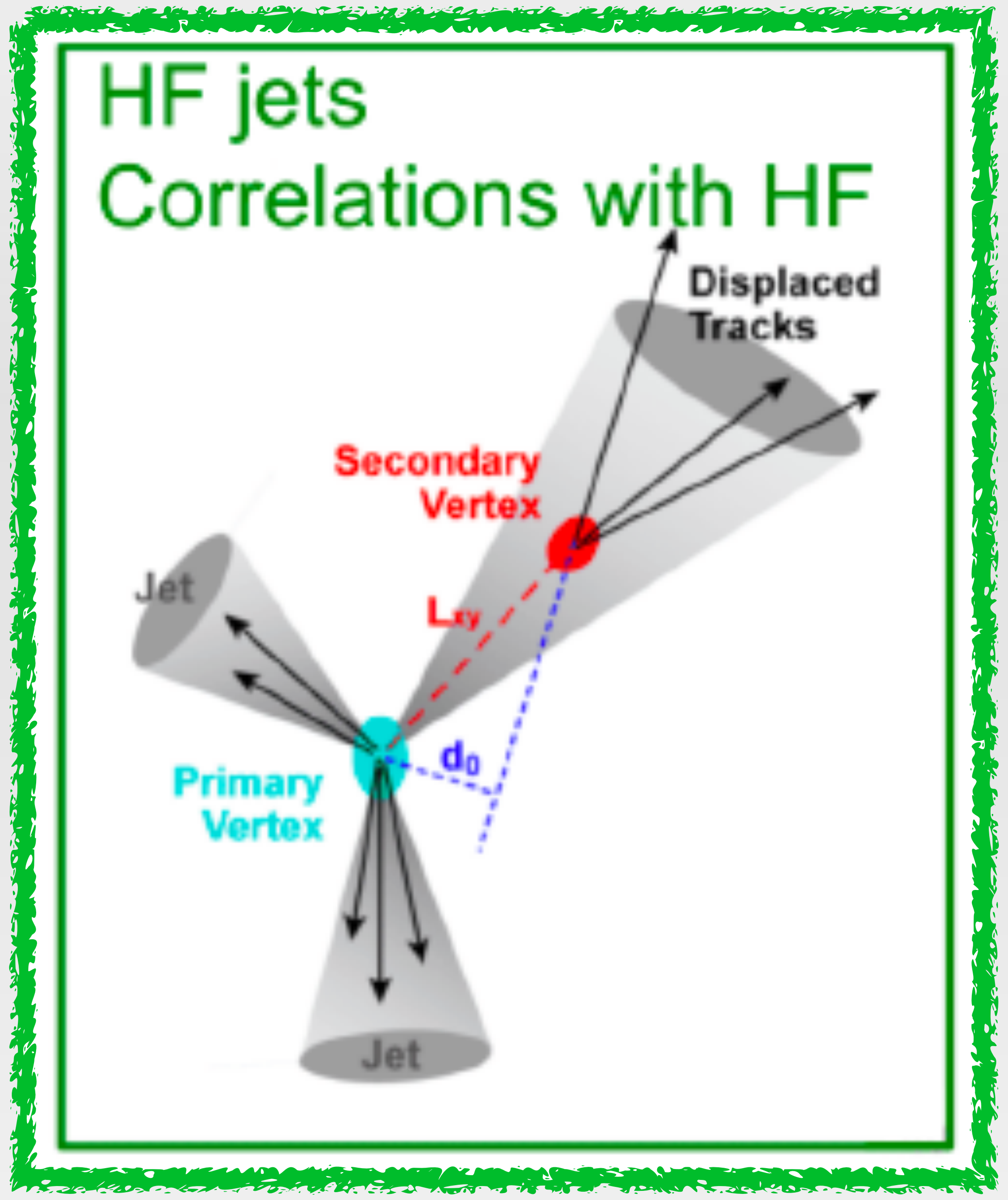
$$\langle \Delta E \rangle \propto \varepsilon \cdot L^2$$

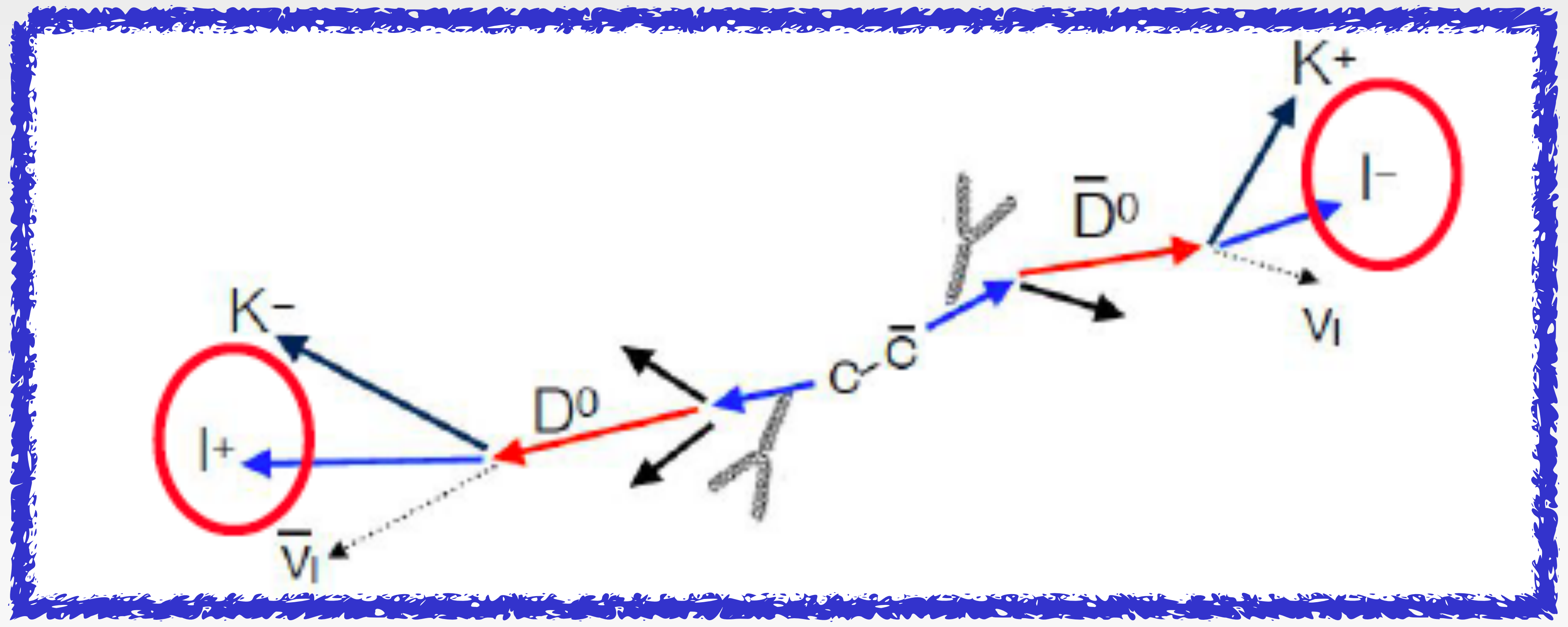
– Pb-Pb and Xe-Xe systems give excellent control over the path length → stringent constraints to all model calculations.

Heavy flavour









- ➪ **Full reconstruction of D mesons**
- ➪ **Electrons from semi-leptonic decays**
- ➪ **Heavy flavour jets and correlations**
- ➪ **Dielectrons via simultaneous semi-leptonic decays of D and B mesons**

Where we are….

pp collisions

- ⇨ Production cross section described by pQCD calculations
  - ✓ HF are a calibrated probe of the medium created in heavy-ion collisions

Pb-Pb and Xe-Xe collisions

- ⇨ Substantial **modification of D and B meson p_{T} spectra**
  - ✓ Potential to constrain energy loss mechanisms and medium transport coefficients
- ⇨ Indication for $R_{\mathrm{AA}}^{\mathrm{beauty}} > R_{\mathrm{AA}}^{\mathrm{charm}}$
  - ✓ Consistent with the predicted quark-mass dependent energy loss
- ⇨ Positive heavy-flavour particle **elliptic flow**
  - ✓ Suggests that charm quarks take part in the collective expansion of the medium
- ⇨ Very promising sensitivity to the effect of the early time magnetic field in heavy-ion collisions

p-Pb collisions

- ⇨ Original motivation: a control experiment
  - ✓ Confirm that D and B meson suppression in Pb-Pb at high p_{T} is a final-state effect
  - ✓ Small cold nuclear matter effects at mid-rapidity
- ⇨ But also unexpected results qualitatively resembling the collective behaviour observed in Pb-Pb collisions

… and what next

Pb-Pb: larger samples at higher energy

- ⇨ Improved precision + extended p_T coverage
  - ✓ Quantitatively constrain energy loss models
  - ✓ Total charm cross-section measurement
  - ✓ Study whether beauty quarks thermalize in the medium
  - ✓ Study of the magnetic field created in heavy-ion collisions

p-Pb and pp collisions

- ⇨ Improved precision on pp reference and assessment of CNM effects
  - ✓ Crucial role in the interpretation of Pb-Pb results
- ⇨ Production vs. multiplicity
- ⇨ Additional studies on collectivity in high multiplicity pp and p-Pb collisions

Major step towards high-precision measurements in the HF sector with the detector upgrades after Run2