Quarkonium measurements in small systems at the LHC

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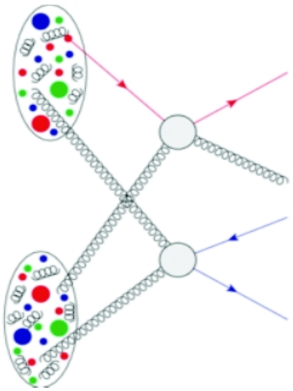
Quarkonium production vs multiplicity

- **pp collisions**: several models that are able to describe qualitatively observed features as a function of multiplicity are based on ***Multiple Parton Interactions (MPI)***



(1) Initial hard scattering process: ***relevant for HF quarks production***

(2) Underlying event (UE):

– semi-hard MPI interactions → **still relevant for *hard processes* at LHC energies !**

– soft hadronic processes → important for "bulk" particle production (including multiplicity)

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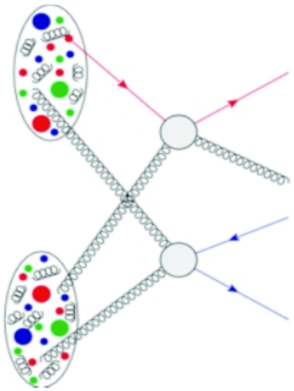

  – multiplicity dependent measurements of quarkonia in pp allow to

  → ***study interplay between hard scattering and underlying event***

  → ***shed light on MPI***

- **p-Pb collisions**: similar considerations as in pp hold, but additional complications
  → p-N geometry + Cold-Nuclear Matter effects

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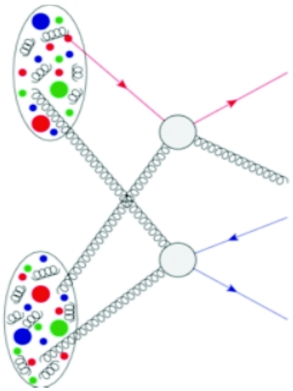

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- ***Intriguing observation***: multiplicity-dependent studies in **small systems** show remarkable similarities with AA collisions (e.g. strong hints for collectivity, strangeness enhancement,...)

  → ***phenomena considered signatures of deconfinement in heavy-ions observed in high-multiplicity pp !***

Where everything started... ALICE Run-1

- **J/ψ vs multiplicity**

  – approximately (faster than) linear increase of J/ψ yield at (mid-*y*) forward-*y*

  – measurements extended up to **4 times** the minimum-bias multiplicity

  – PYTHIA6 (Perugia 2011 tune) predicts opposite trend vs multiplicity

- Several questions triggered:

  – dependence on flavour content ?

  – dependence on $\sqrt{s}$?

  – dependence on the hardness of hard probe ?

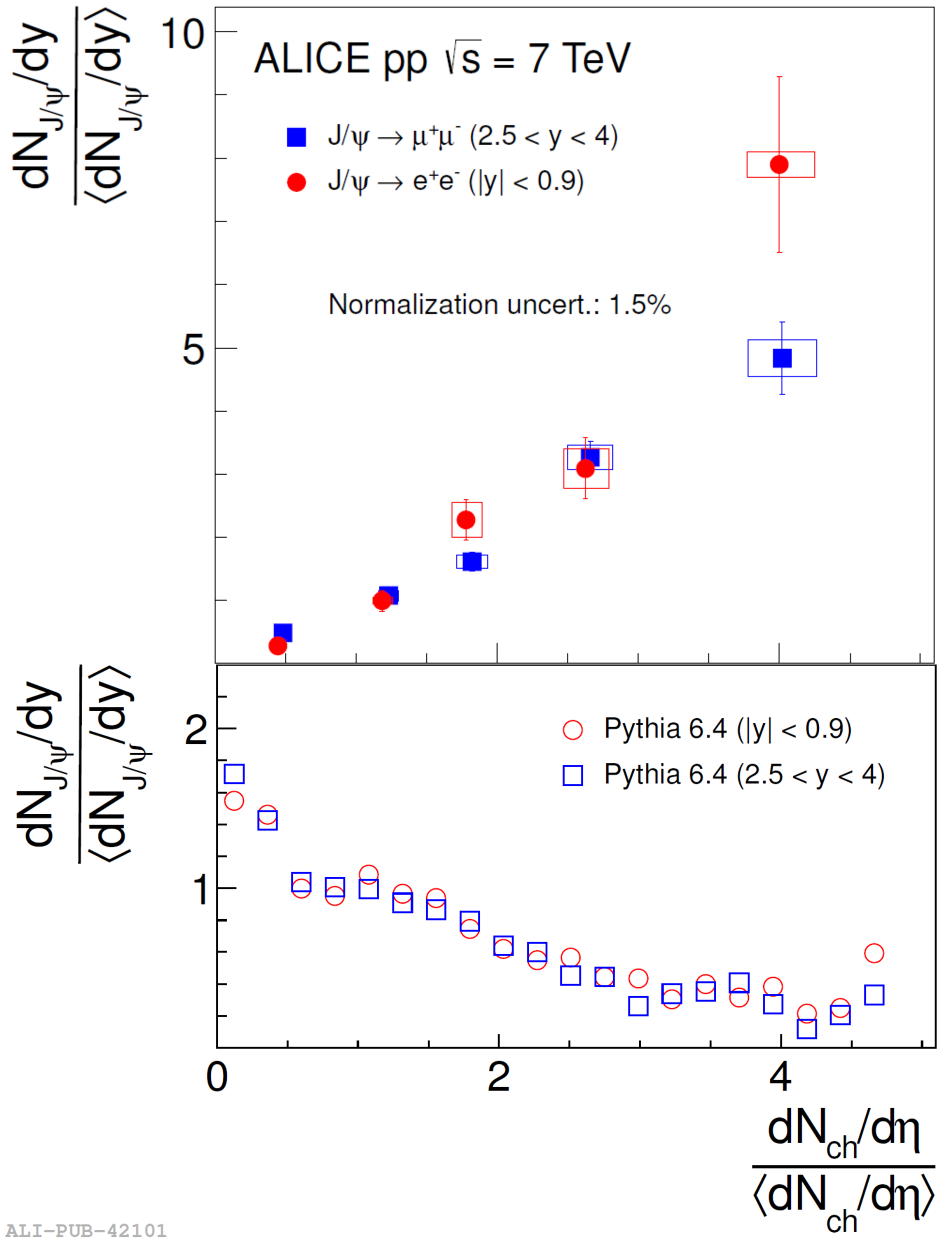
  – importance of η-gap ?

- Significant improvement in the last years:

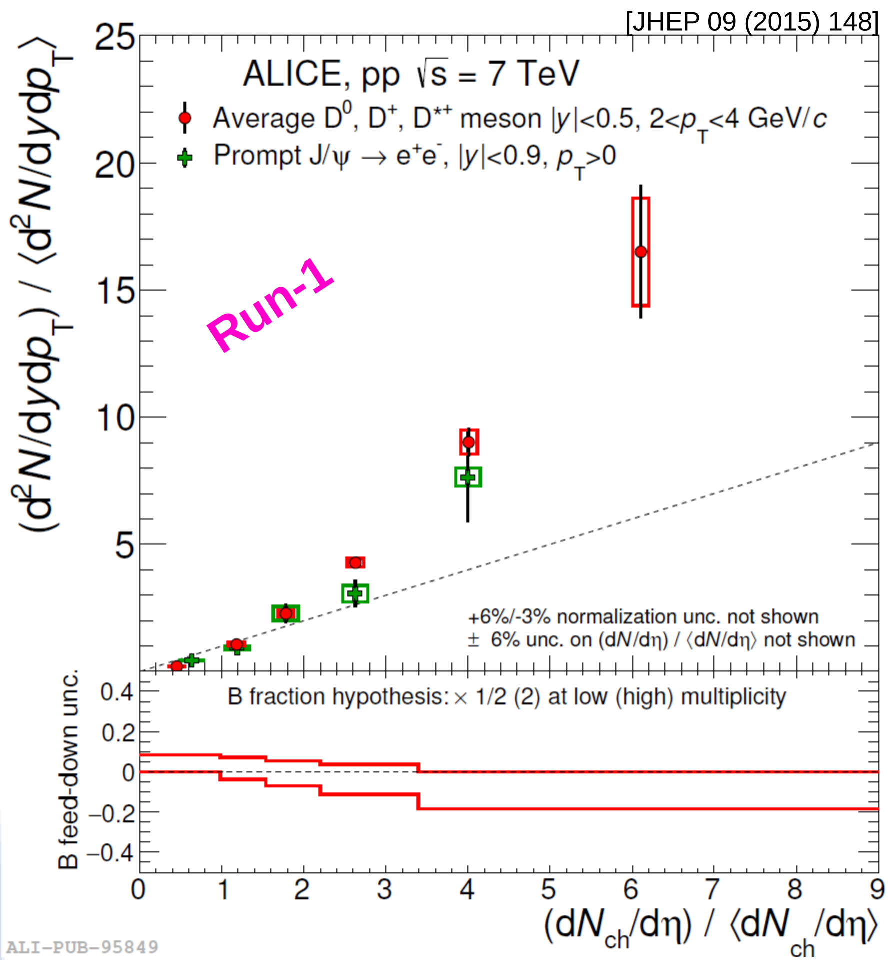
  – combination of Run-1 and Run-2 statistics

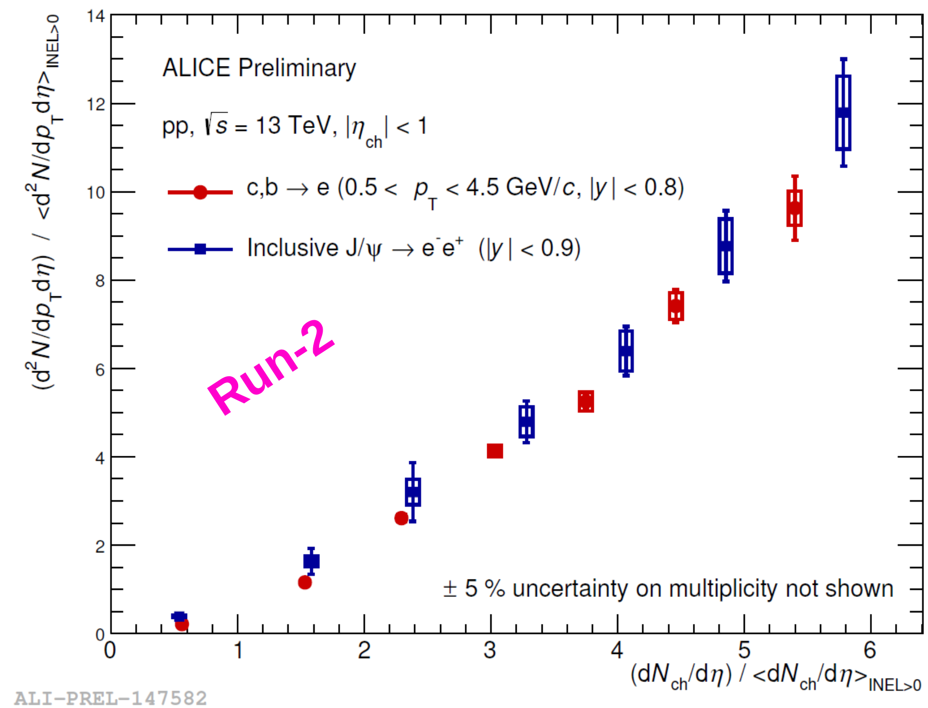
  – Improvement / development of models

[Phys. Lett. B 712, 165 (2012)]



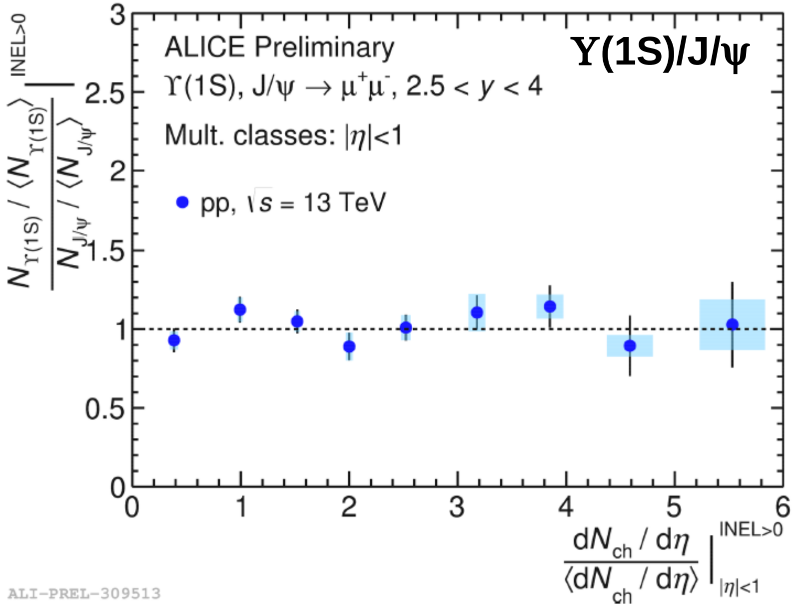
Dependence on flavour content

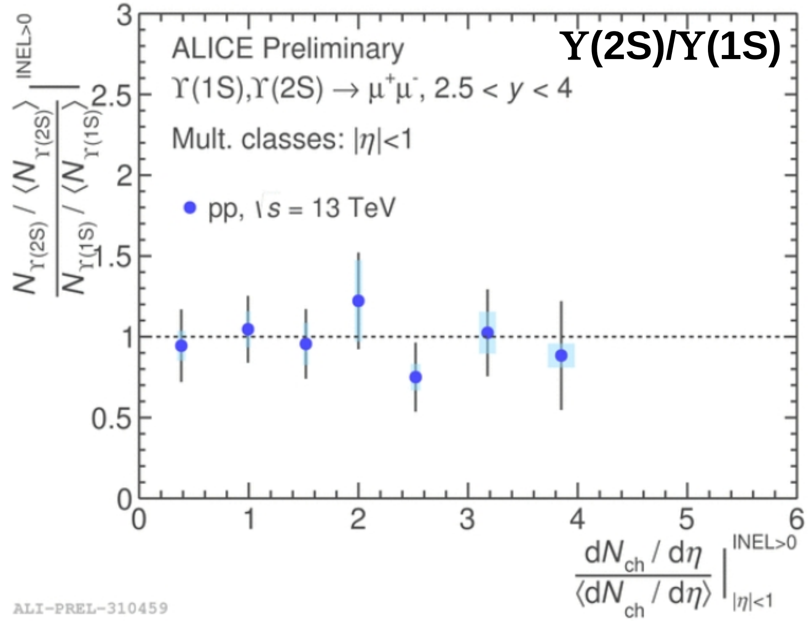




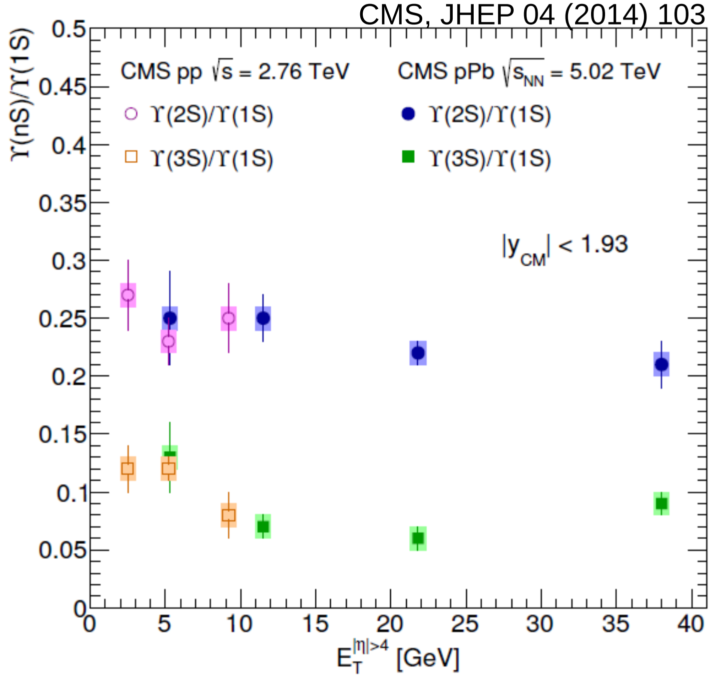
- ✔ Similar trend for prompt J/ψ and open charm in Run-1
- ✔ Very similar (faster than linear) trend observed for open and hidden HF measurements observed also in Run-2 (but significantly higher multiplicity reached for J/ψ compared to Run-1)

Dependence on flavour content





CMS, JHEP 04 (2014) 103

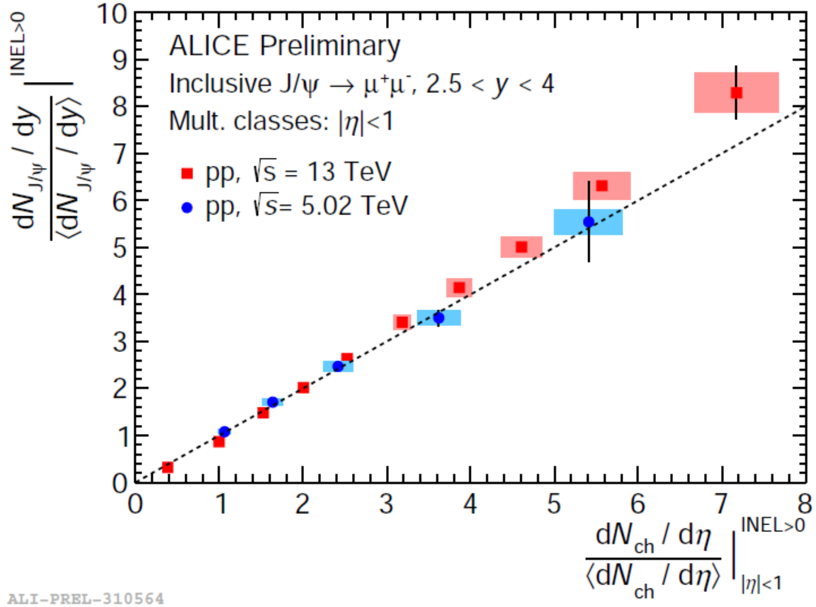


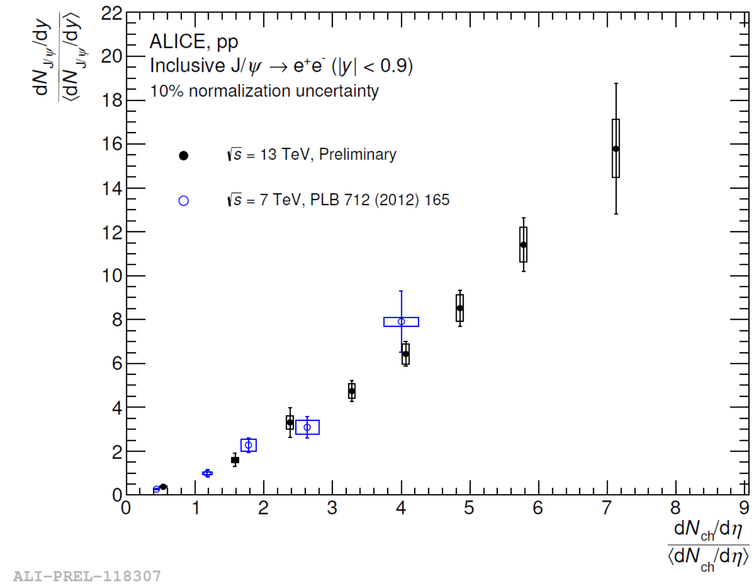
- ✔ Double ratios Υ(1S)/J/ψ and Υ(2S)/Υ(1S) independent on multiplicity
- ✔ Similar results found for Υ(2S)/Υ(1S) and Υ(3S)/Υ(1S) by CMS
- ✔ η-gap present for both ALICE and CMS measurements

→ suggests that the multiplicity trend does not depend significantly on heavy-quark content

Dependence on center-of-mass energy

5.02 TeV → 13 TeV





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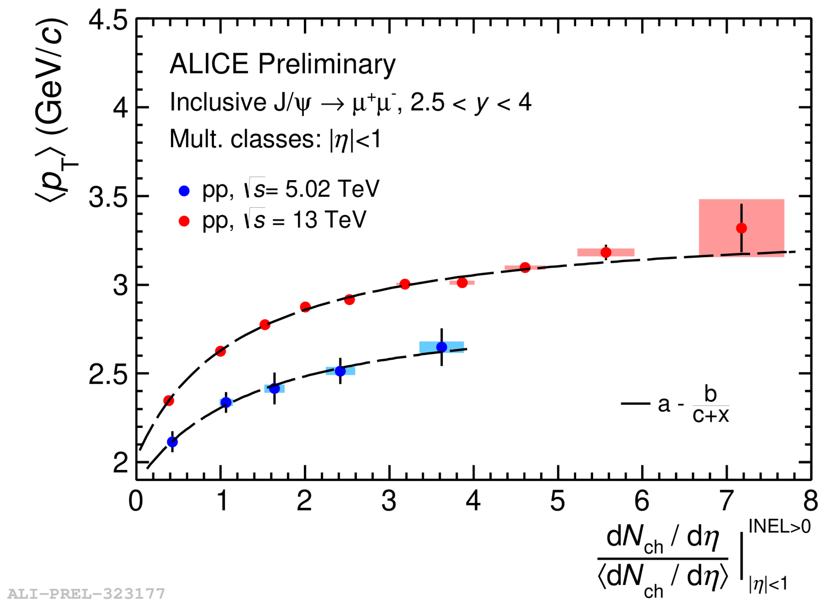

- ✔ J/ψ yields in a specific multiplicity event class not dependent on $\sqrt{s}$ at LHC energies
- ✔ J/ψ spectra systematically harder at higher $\sqrt{s}$

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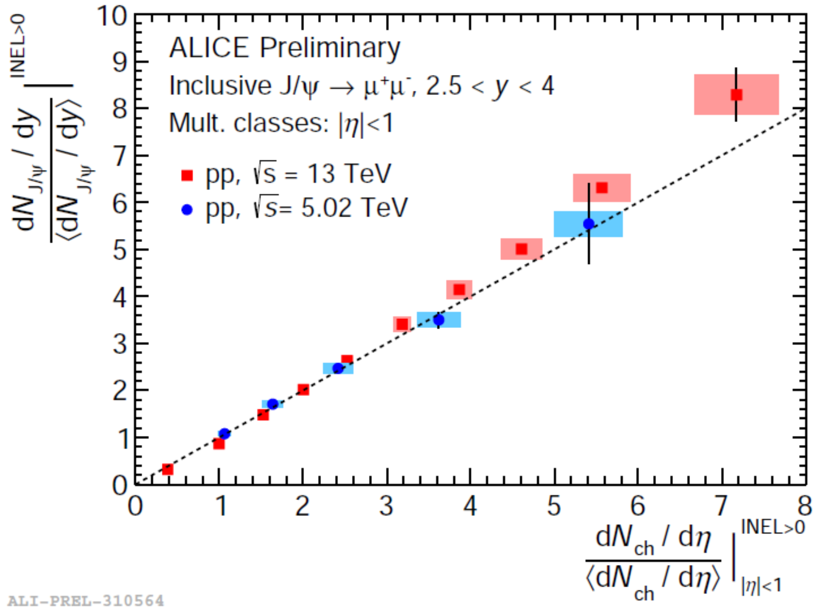

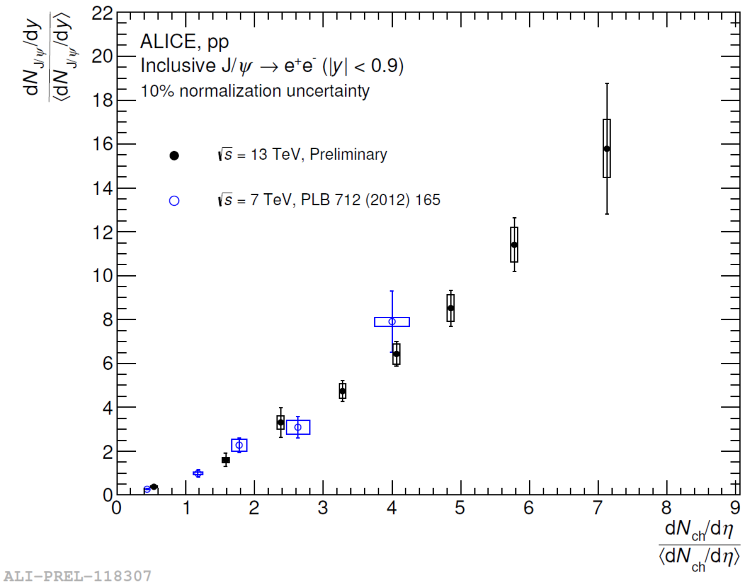

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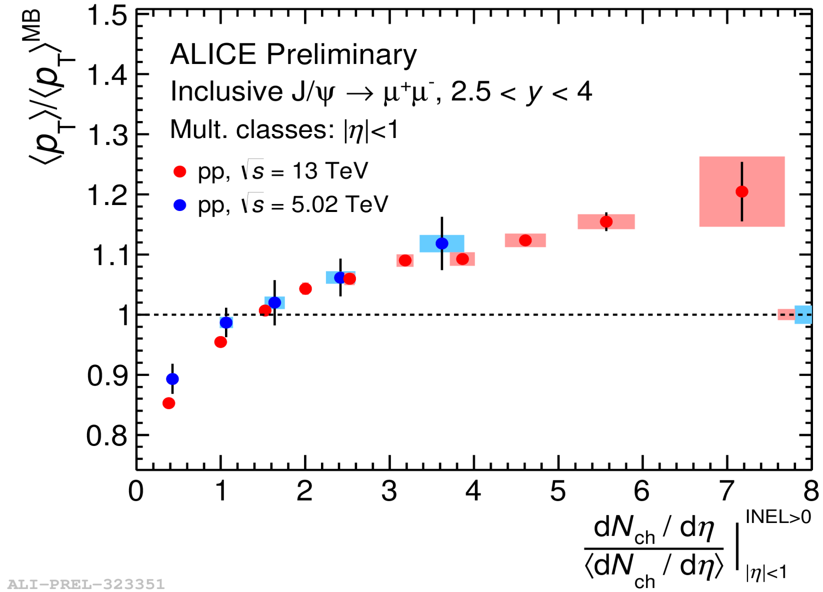

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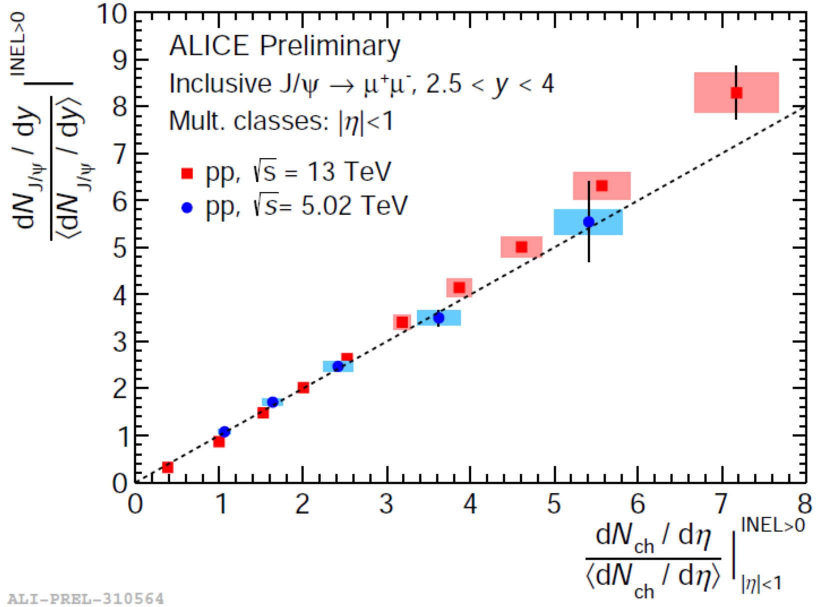

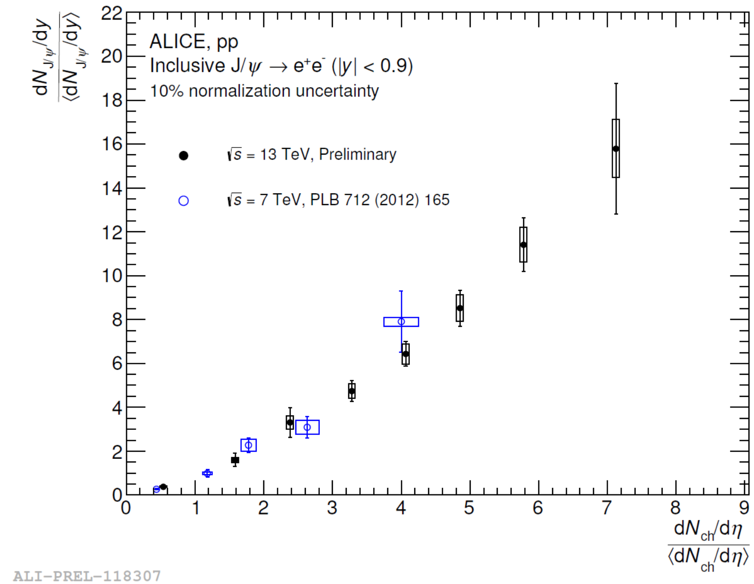

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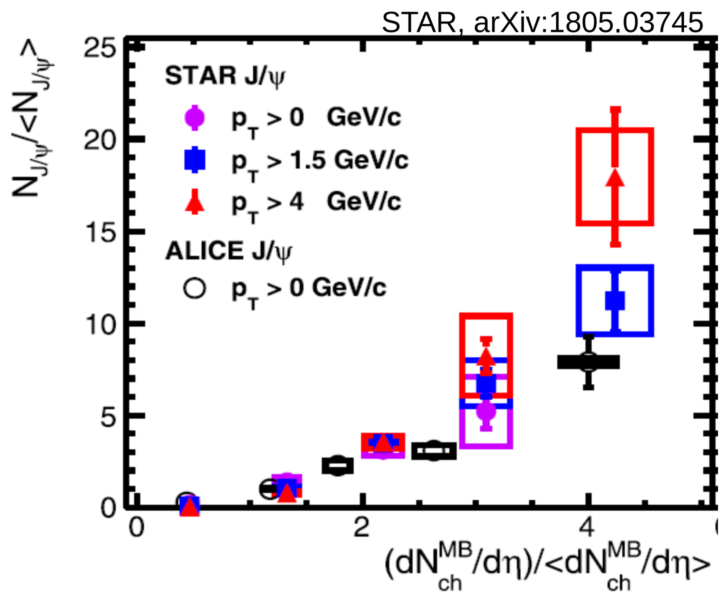

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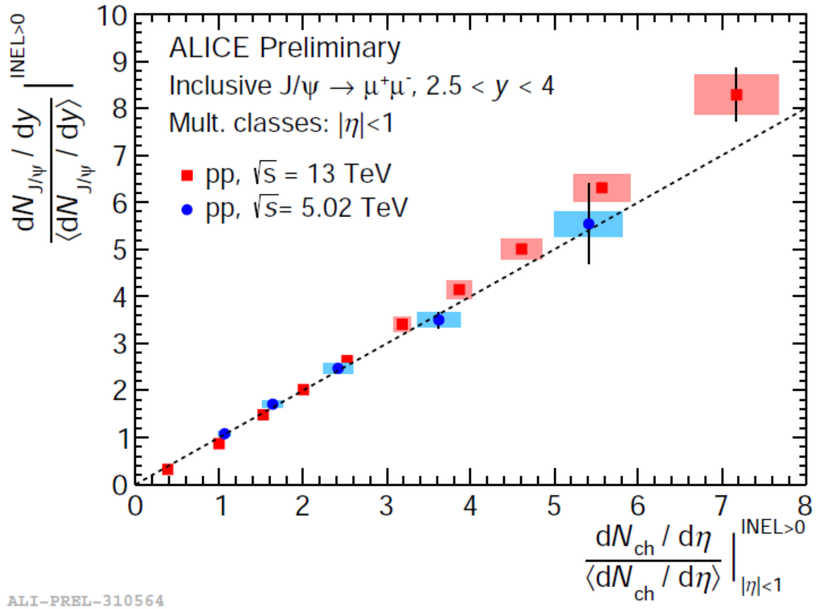

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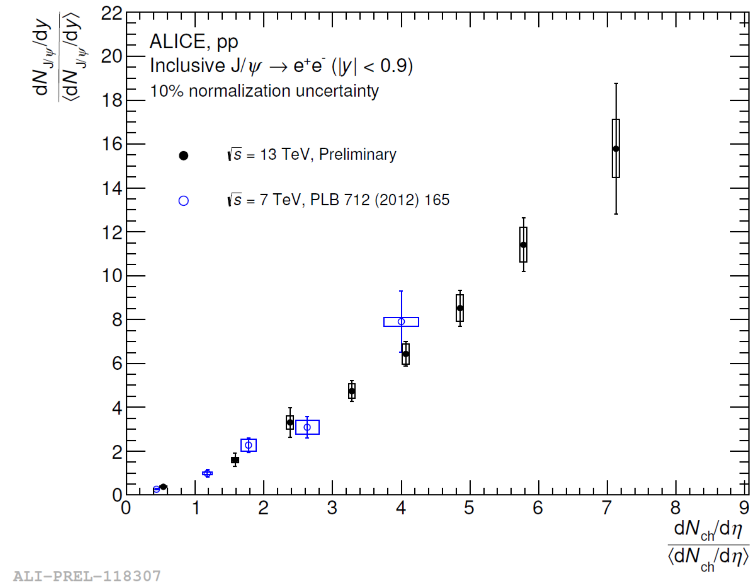

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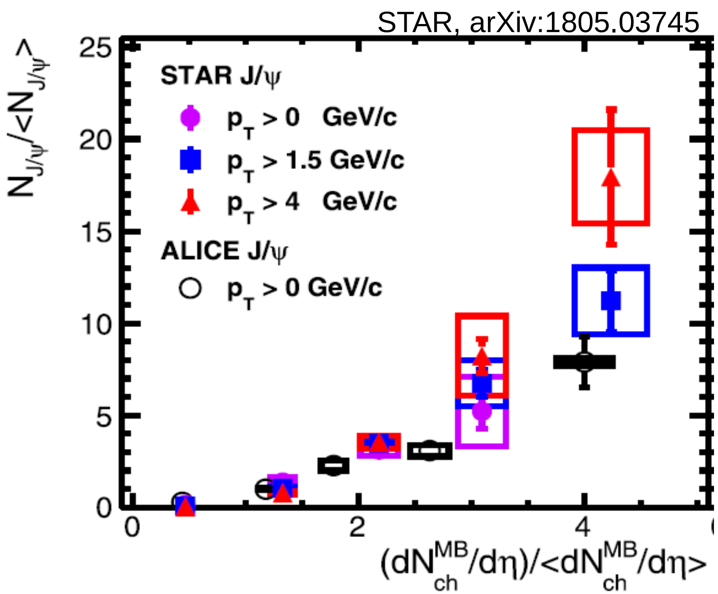

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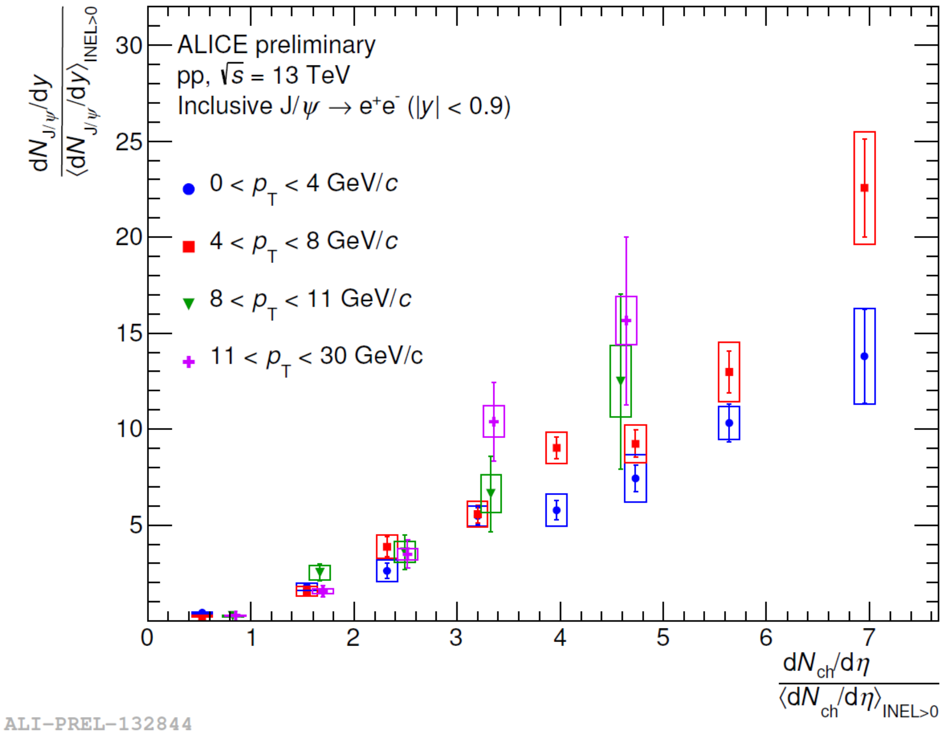
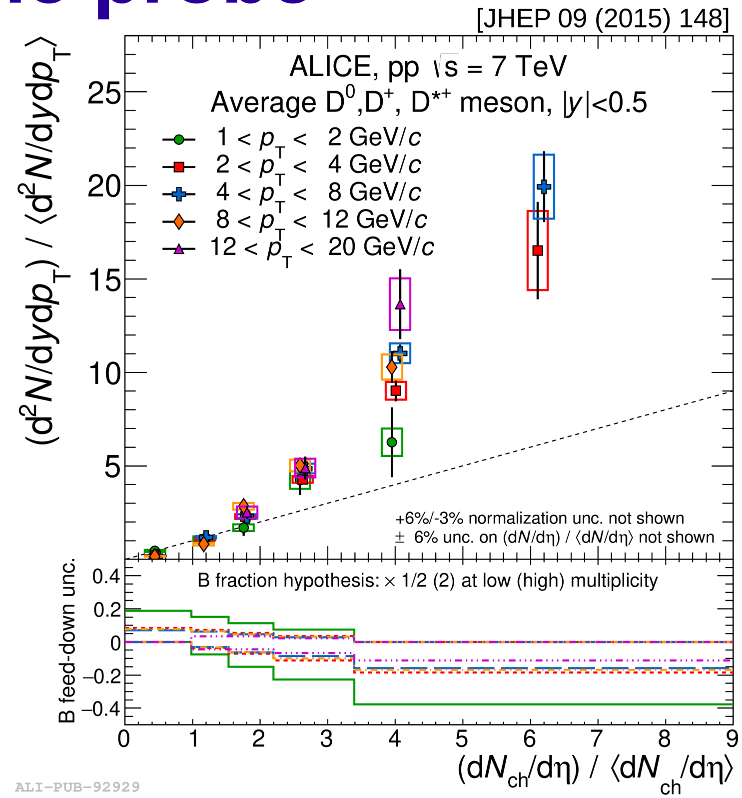
→ suggests that the multiplicity dependence is not significantly affected by √s

Hardness of the probe





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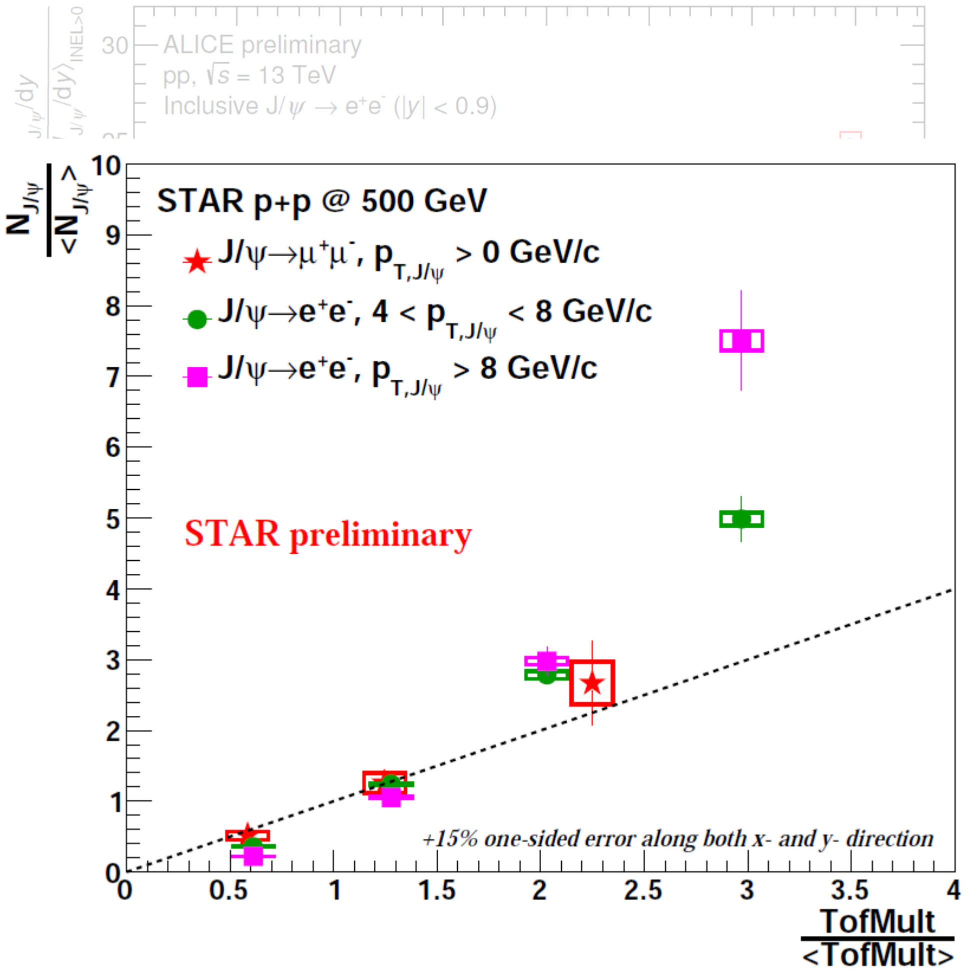

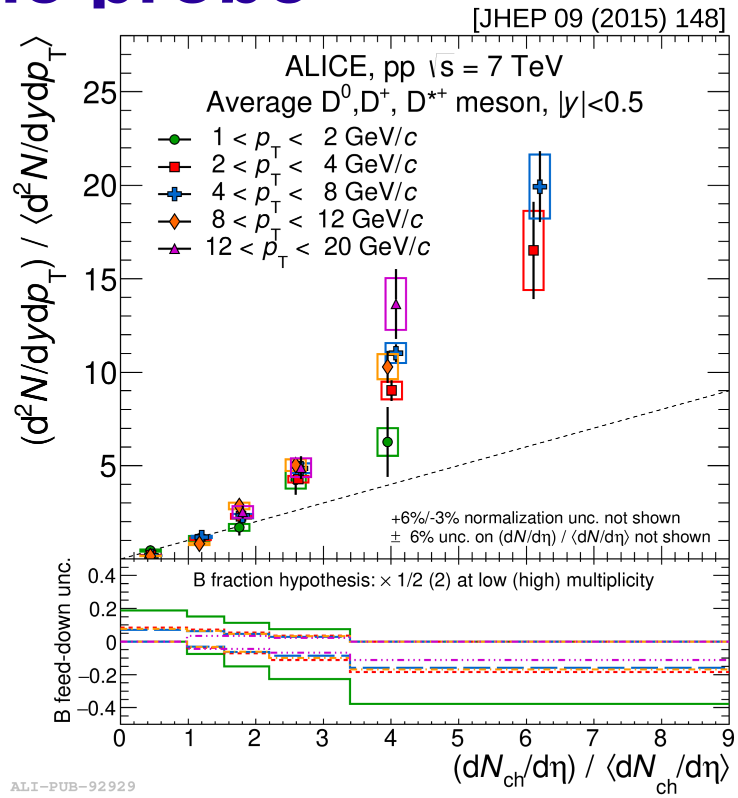

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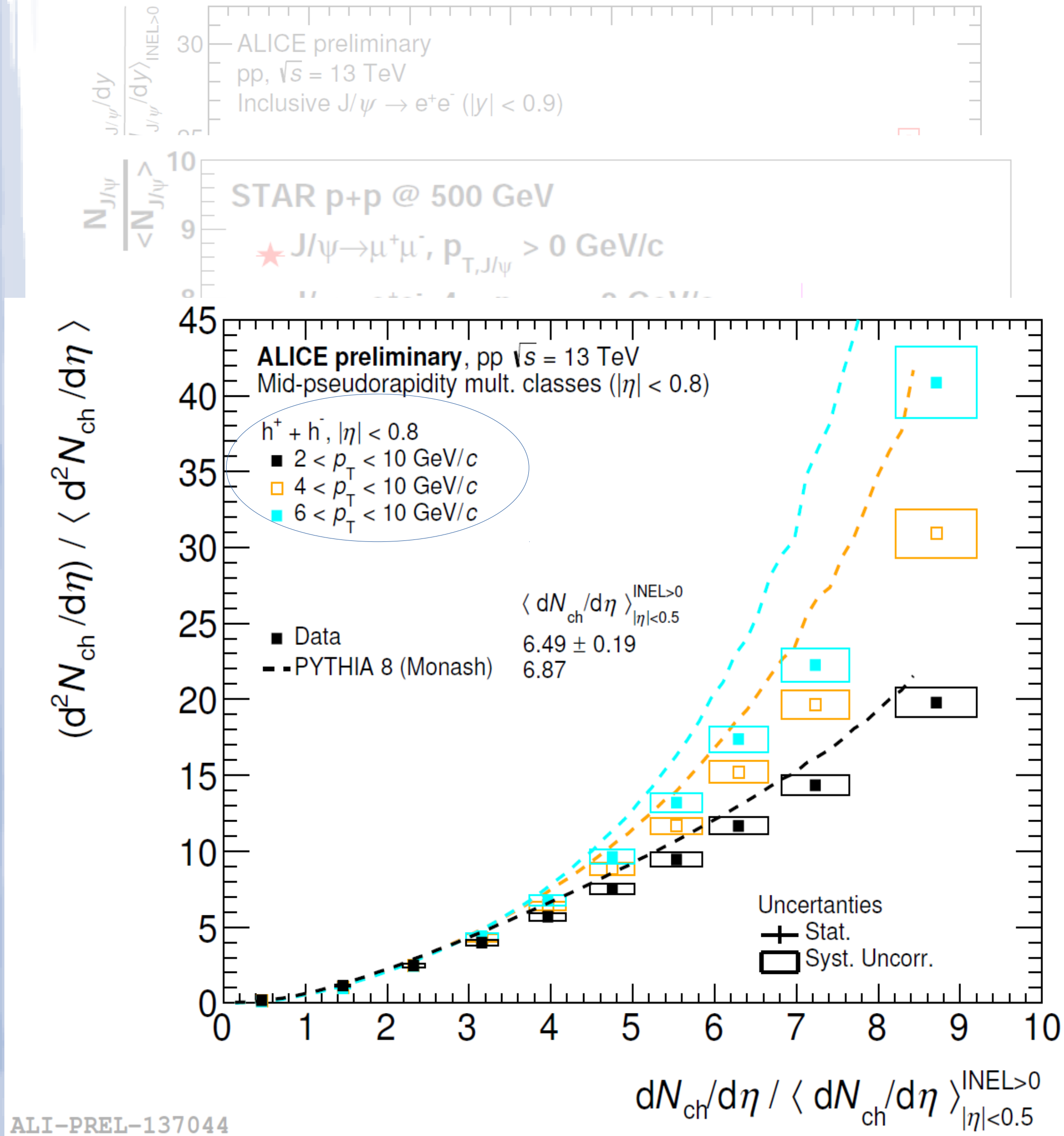

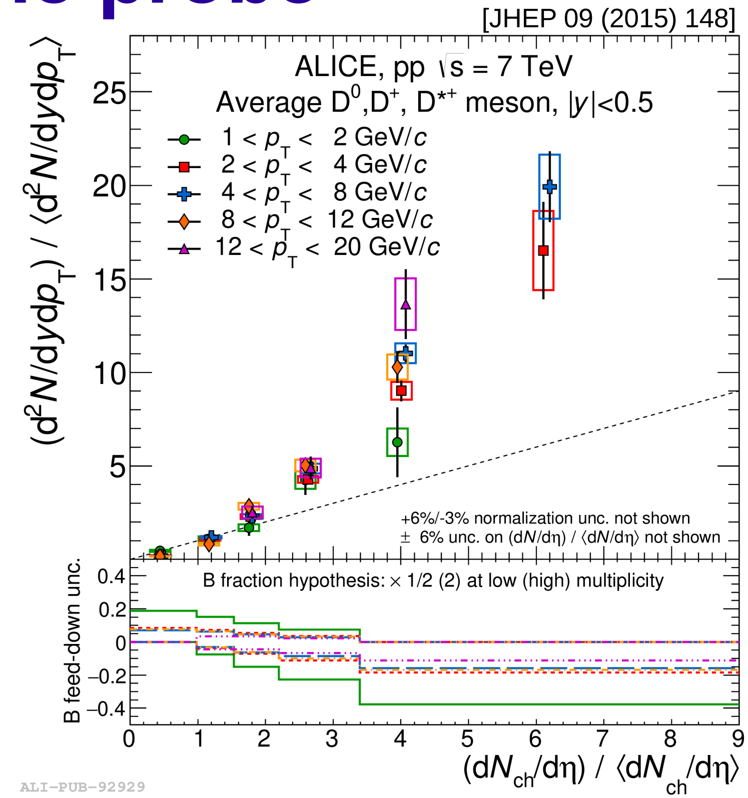

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- Similar trend for other hard-processes regardless the flavour content

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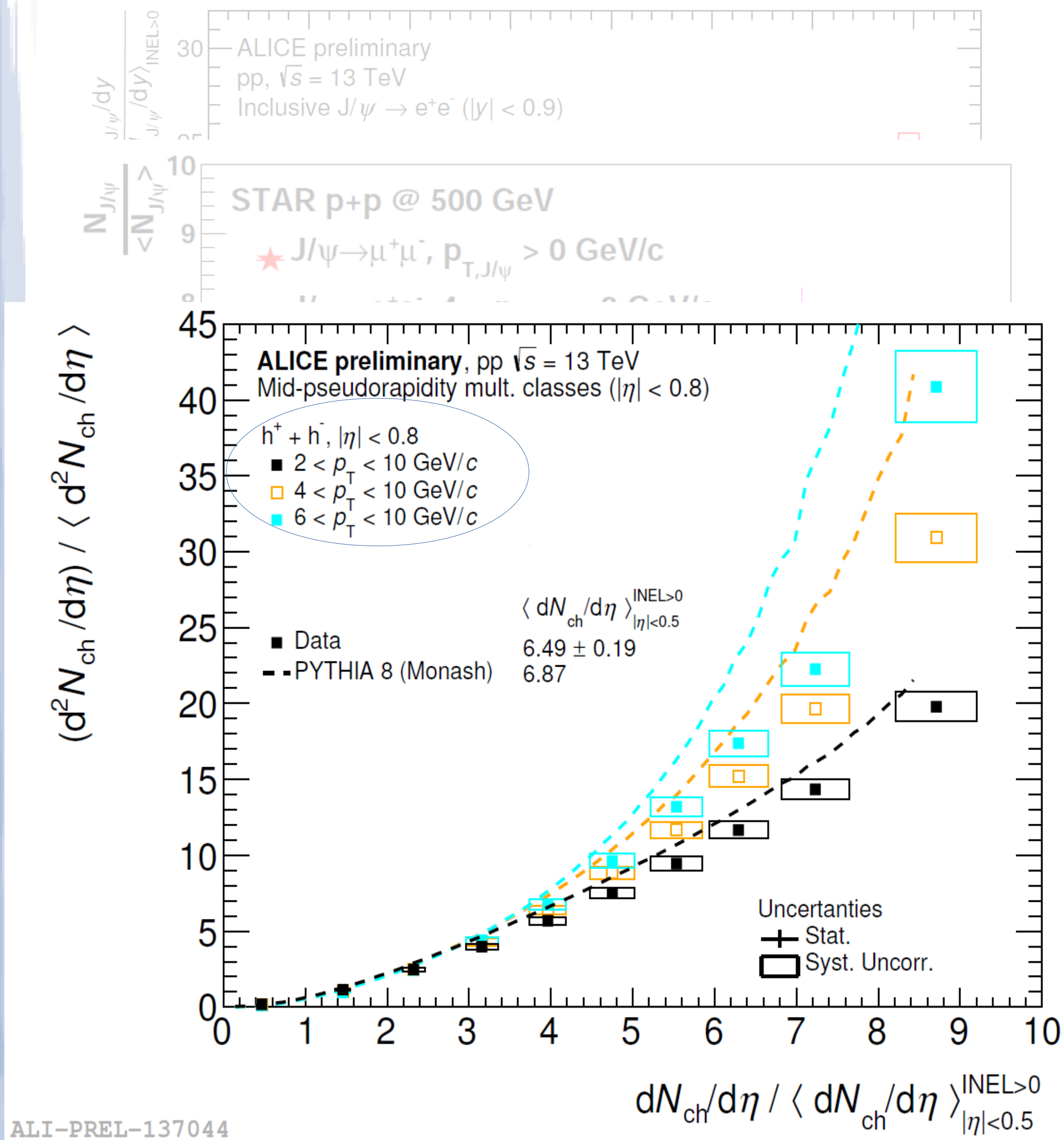

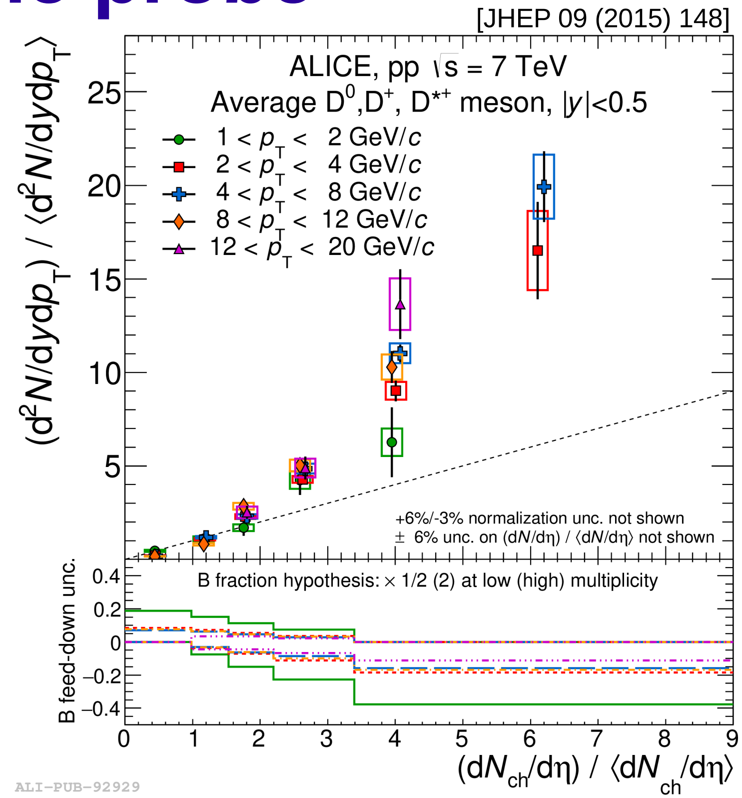

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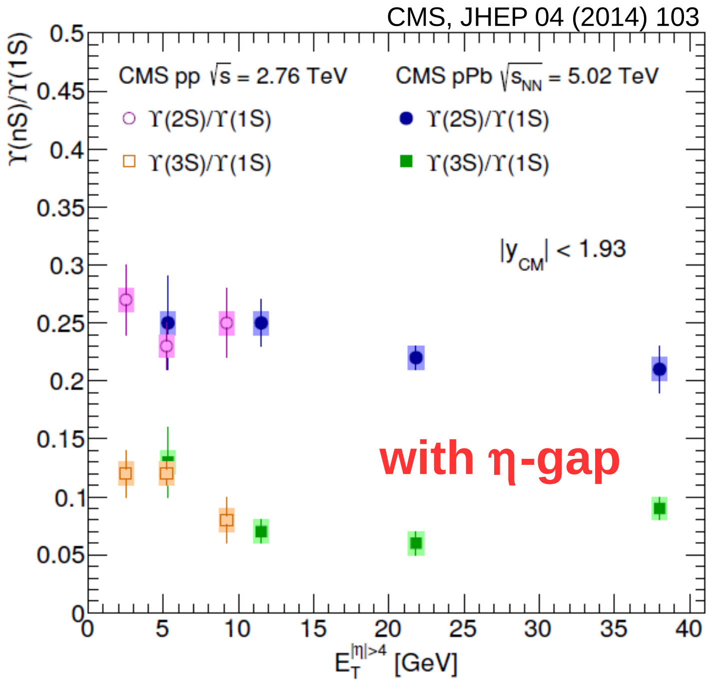
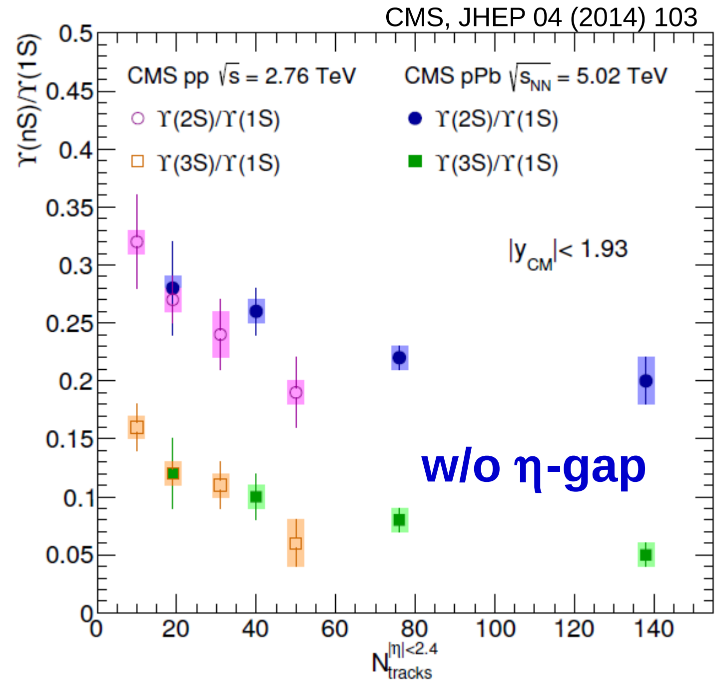
→ steepness of the multiplicity dependent trends increases with the hardness of the probe

Impact of η-gap





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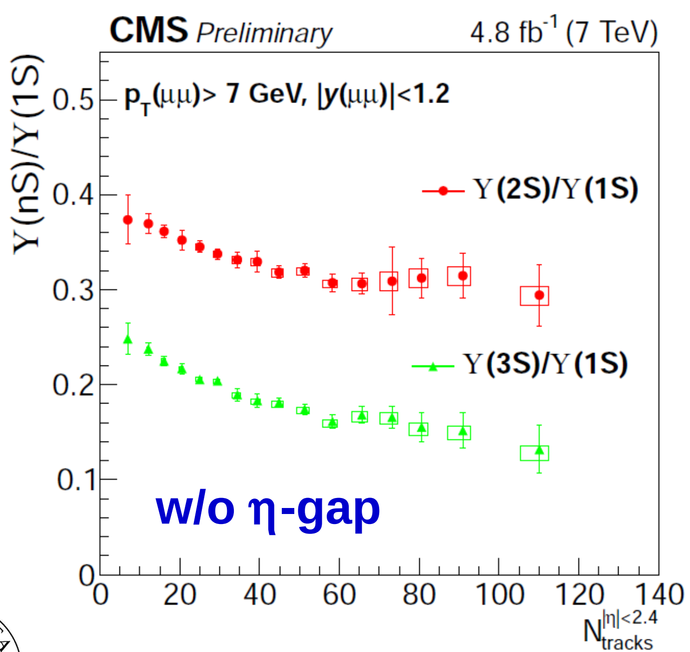

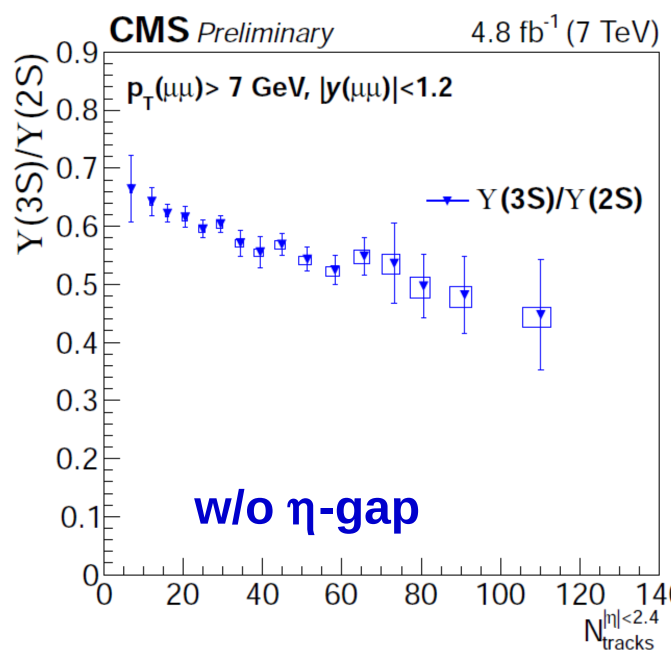

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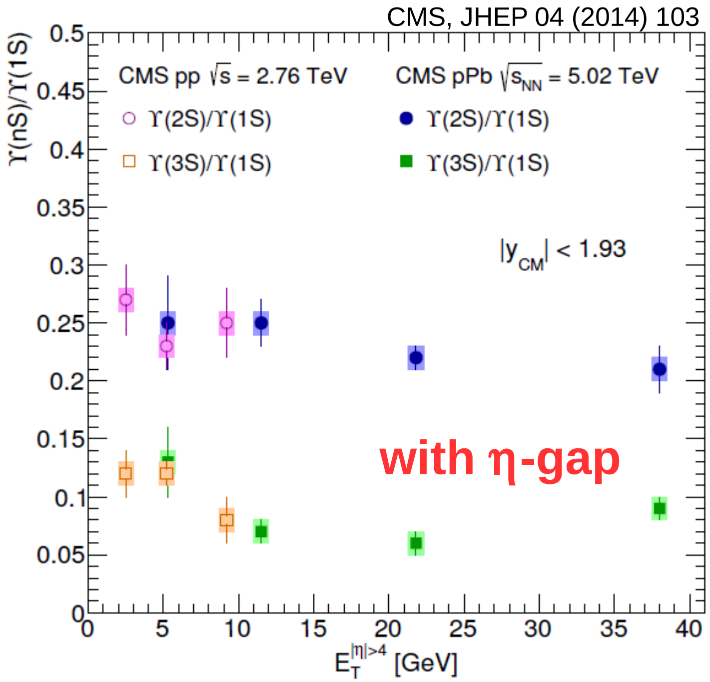

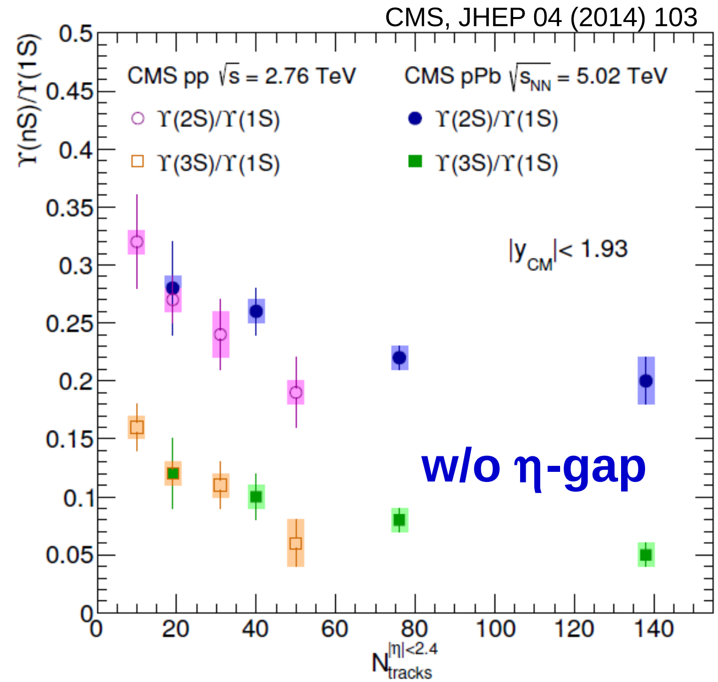

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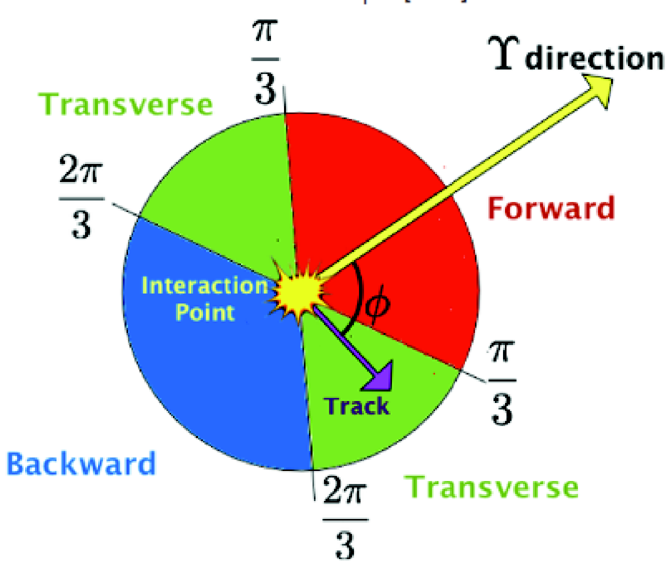

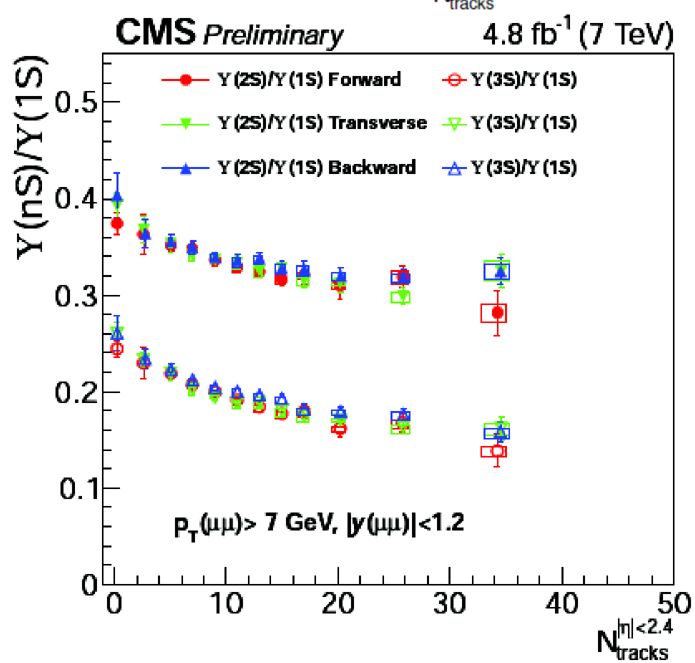

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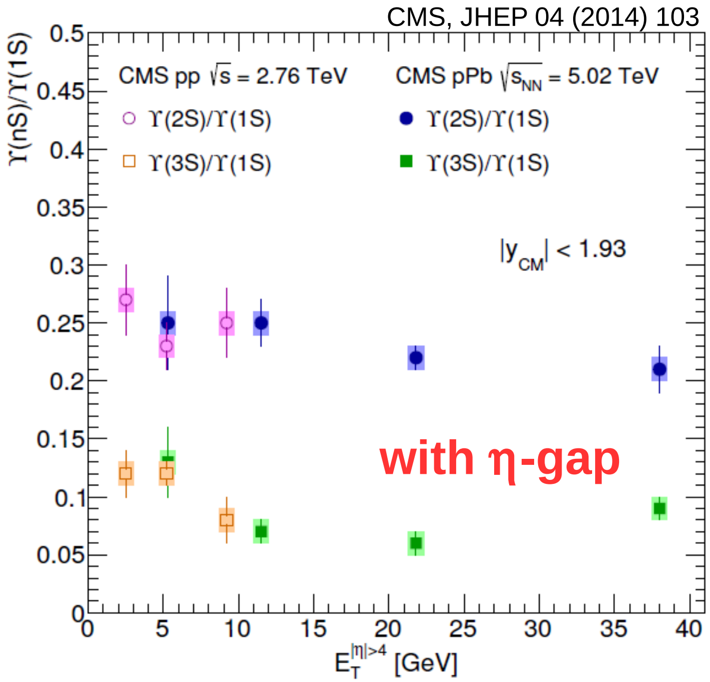

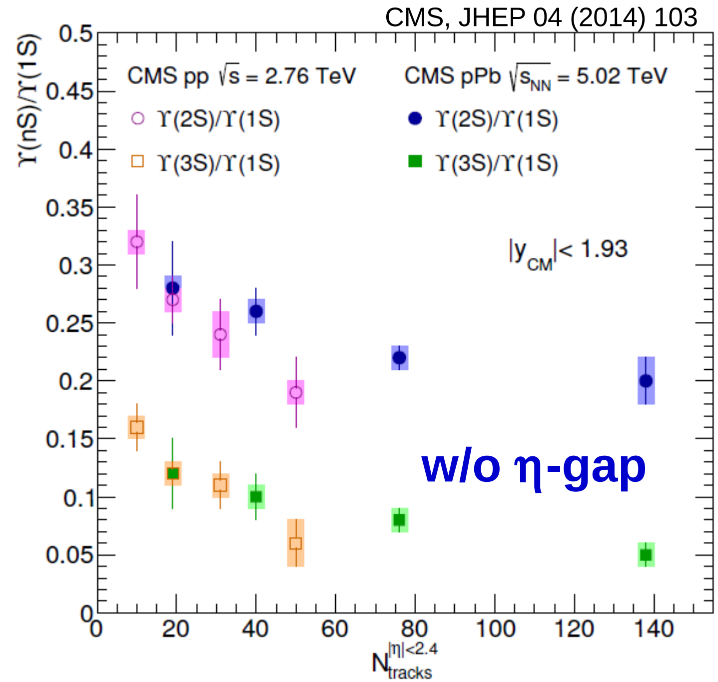

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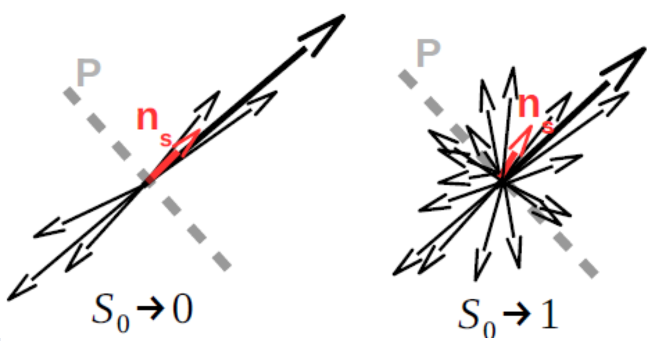
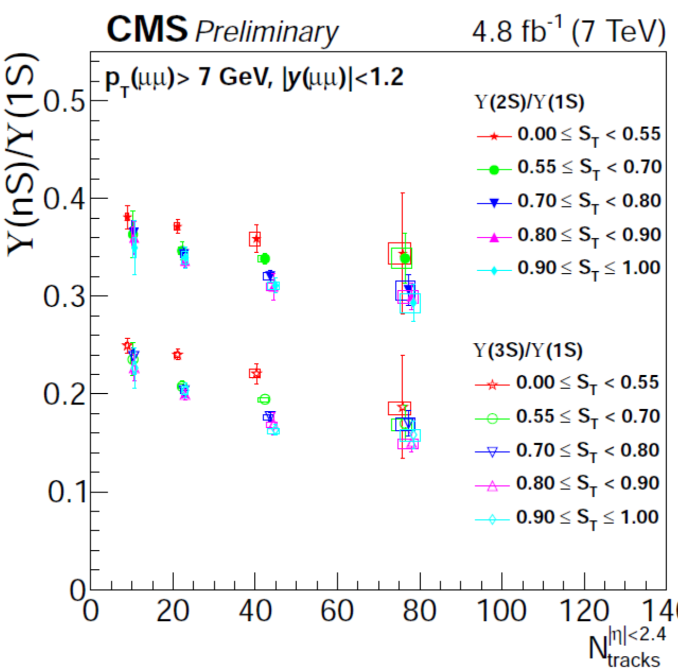


$S_0 =$ { **0 → "jet-like" events**; **1 → "isotropic" events** }



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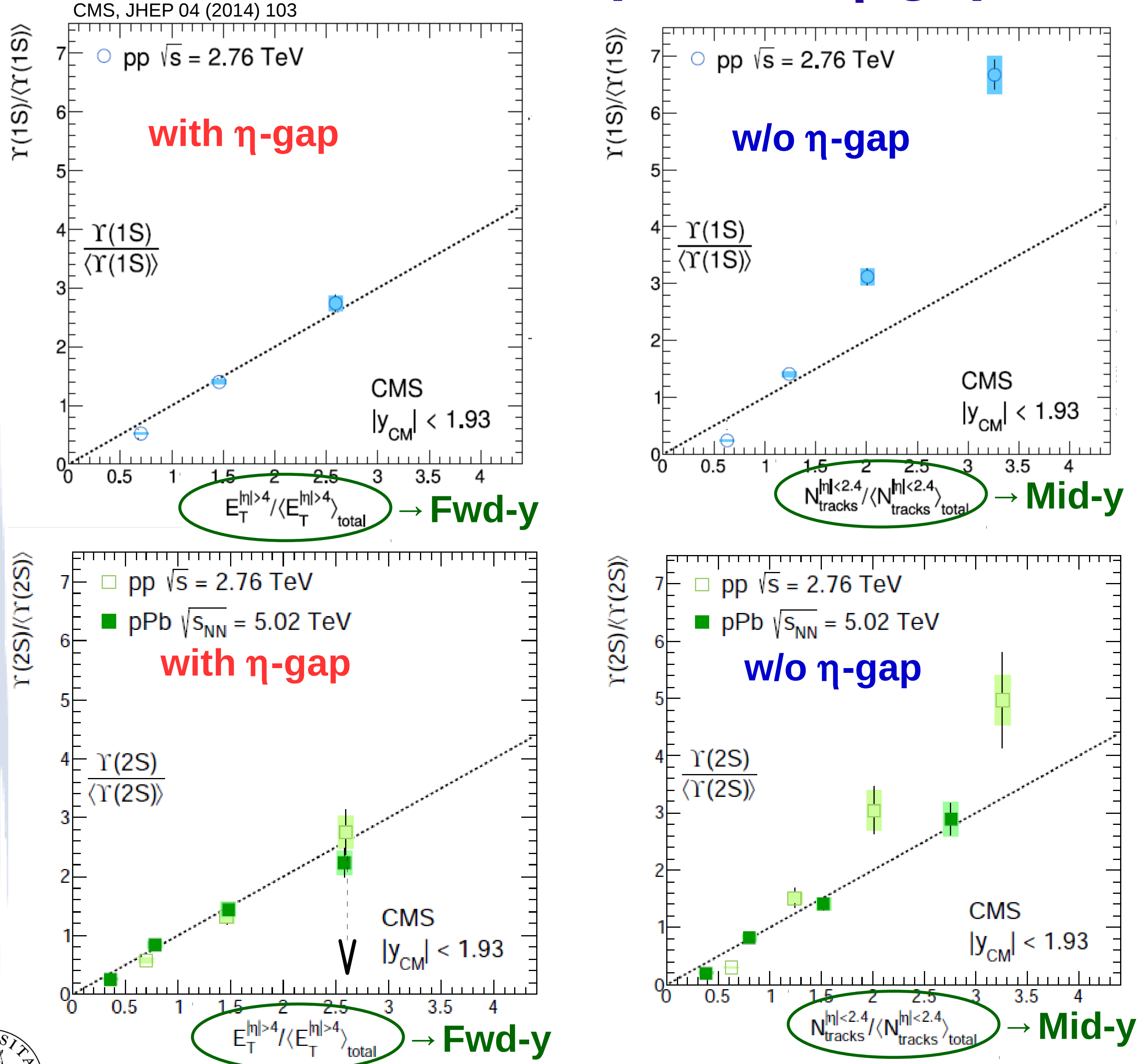
- ✔ No significant change of ratios observed after adding a ϕ-gap
- ✔ Similar evolution also as a function of the "sphericity"

Impact of η-gap



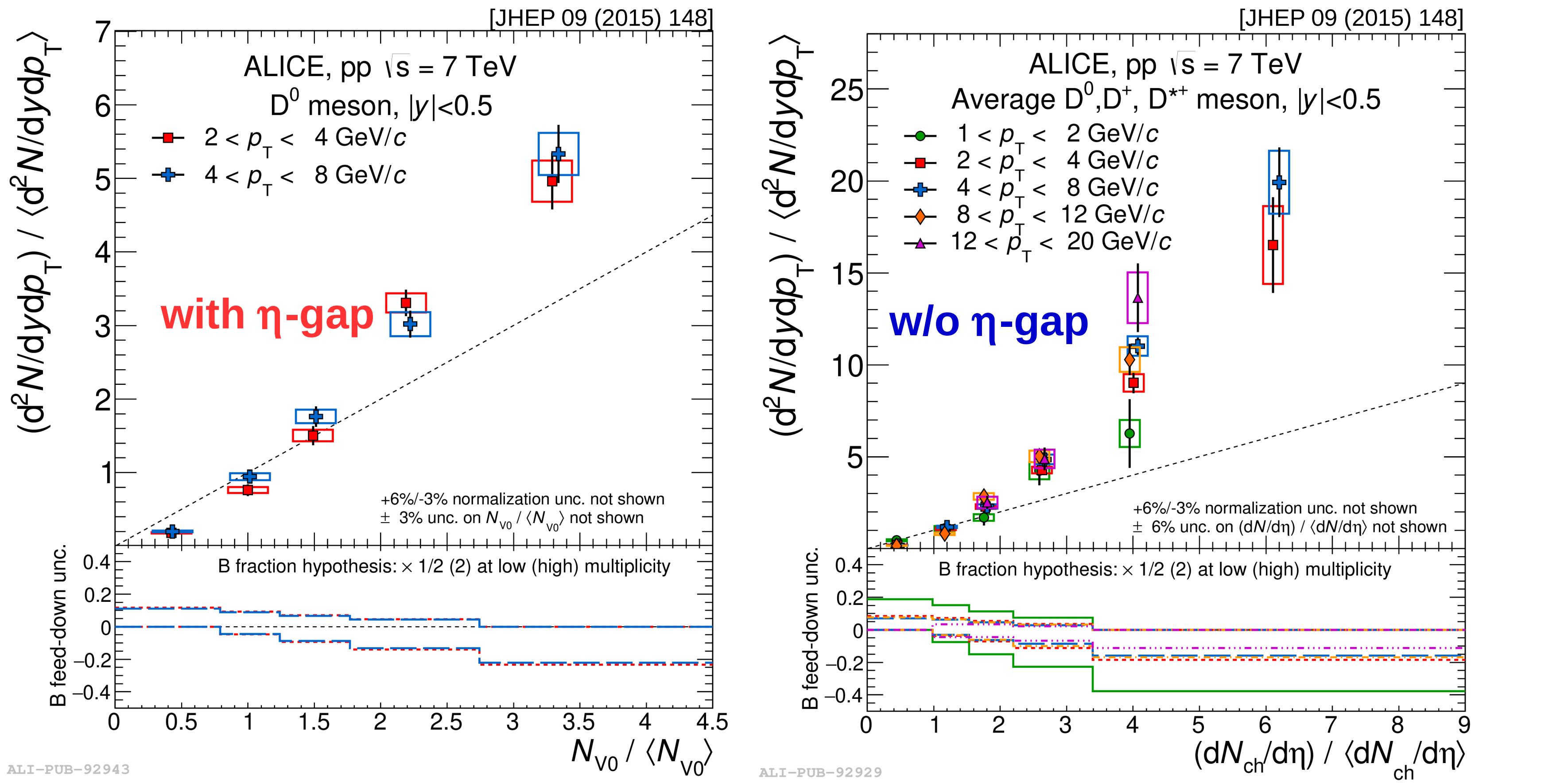
- Self-normalized bottomonium yields measured by CMS (mid-*y*)

  – **linear** increase with η-gap

  – faster than linear increase w/o η-gap

  – lower multiplicity reach when fwd-*y* estimator is used

Impact of η-gap – other hard processes



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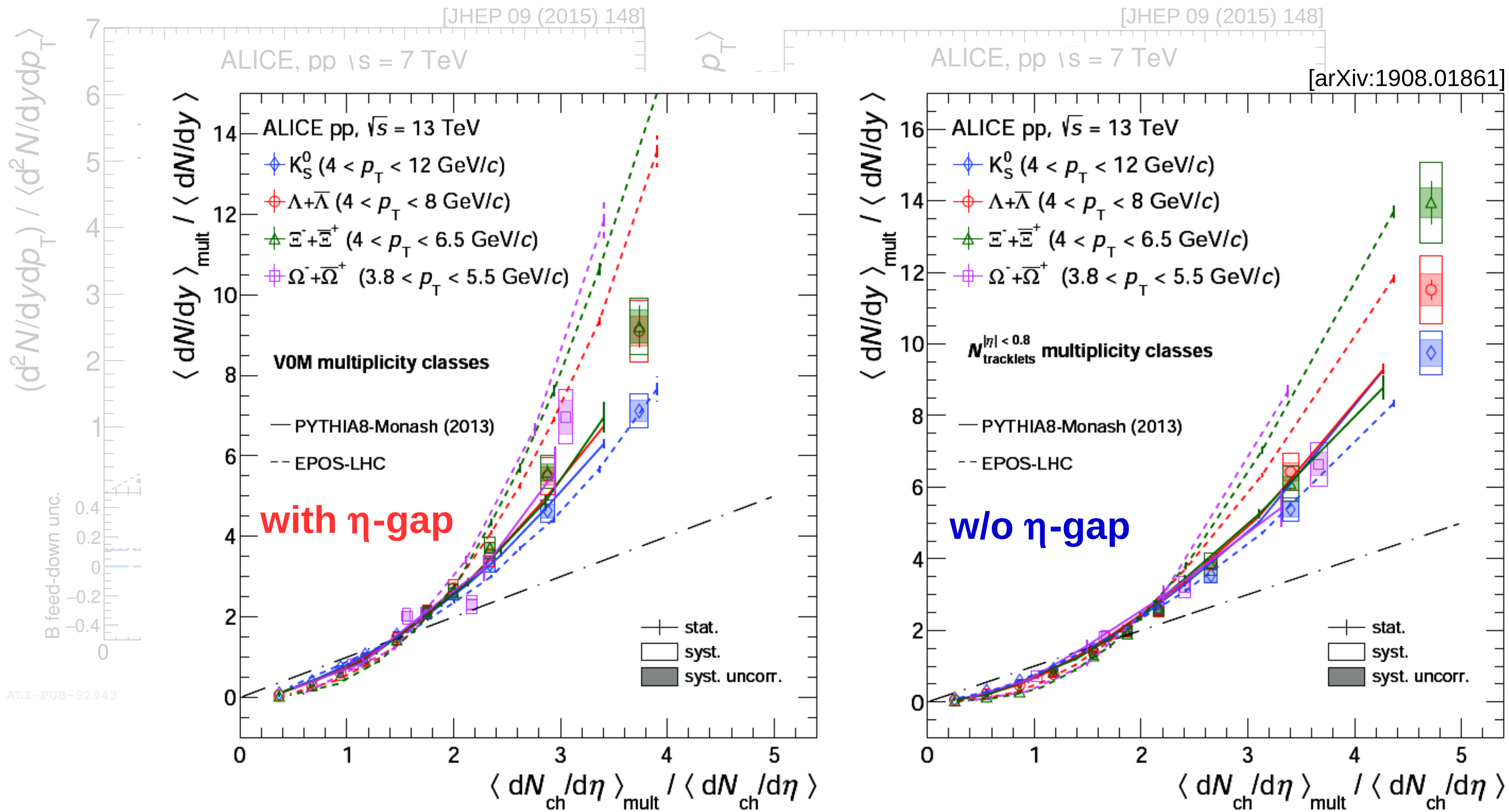

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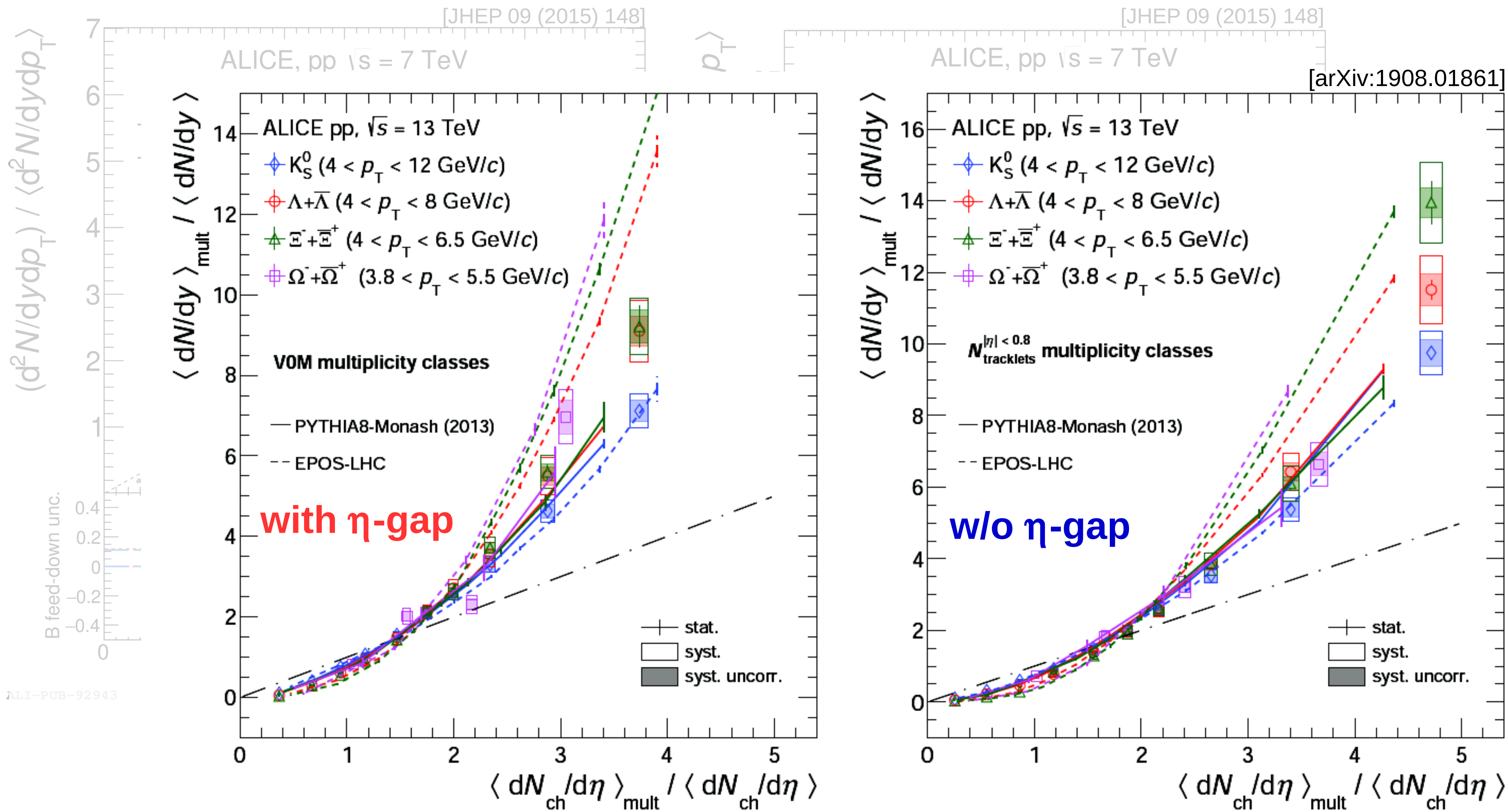

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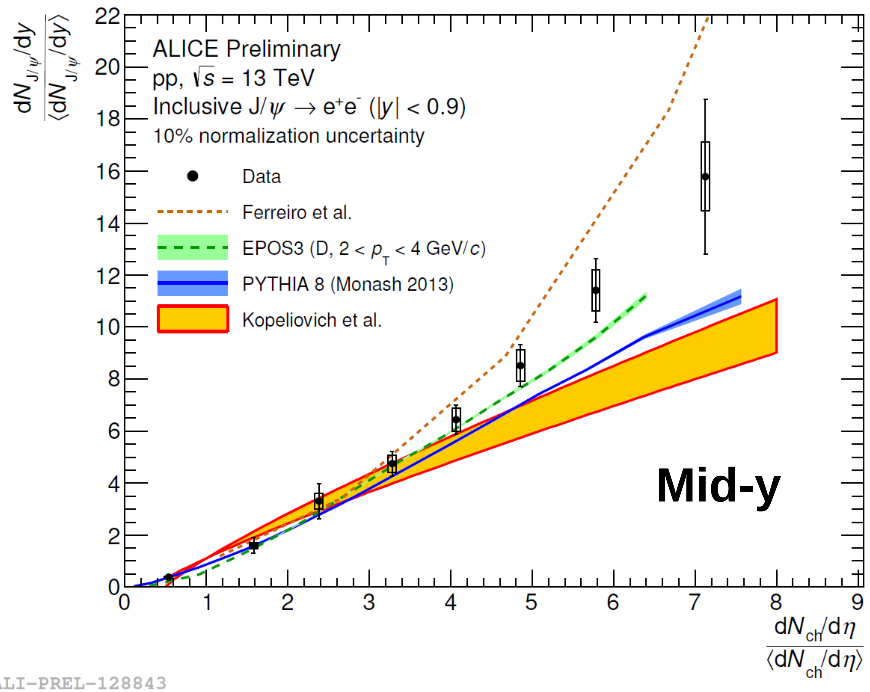
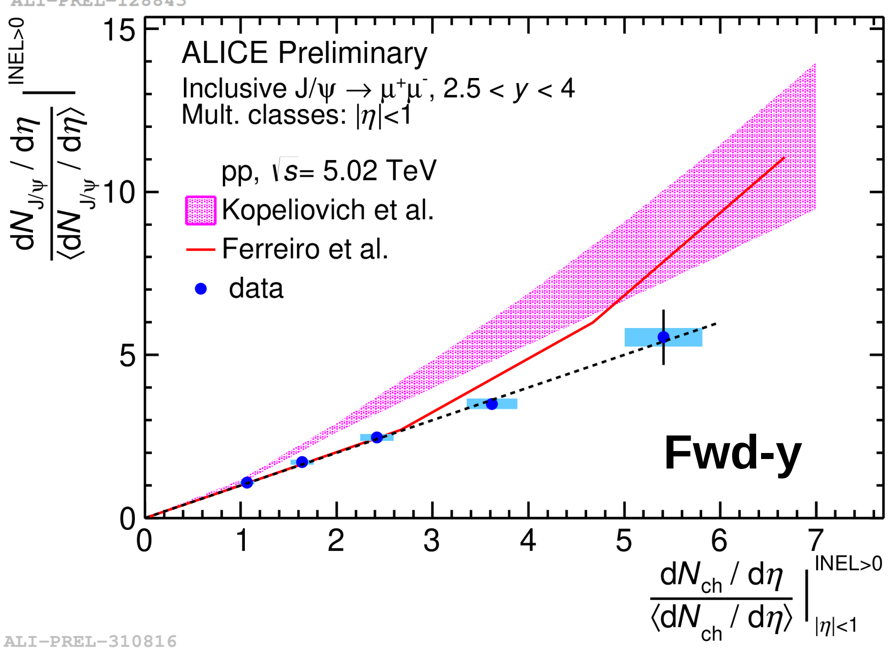
→ not possible to conclude so far about implications of η-gap, more measurements are needed

Comparison with models





- **PYTHIA8 (Monash 2013)**
  - Initial hard processes
  - Hard processes in MPI
  - ISR / FSR
- **Percolation model**
  - Soft sources stronger affected than hard sources with increasing density (multiplicity)
- **EPOS3**
  - Gribov-Regge formalism (MPI included)
  - Hydro evolution of the system
  - version 3.2 include also parton saturation (smaller impact than collectivity)
- **Kopeliovich et al.**
  - contributions of higher Fock states (increased number of gluons) which increase probability to produce a J/ψ

Ferreiro, Pajares, PRC86 (2012) 034903
EPOS3, Werner et al., Phys.Rept.350 (2001) 93
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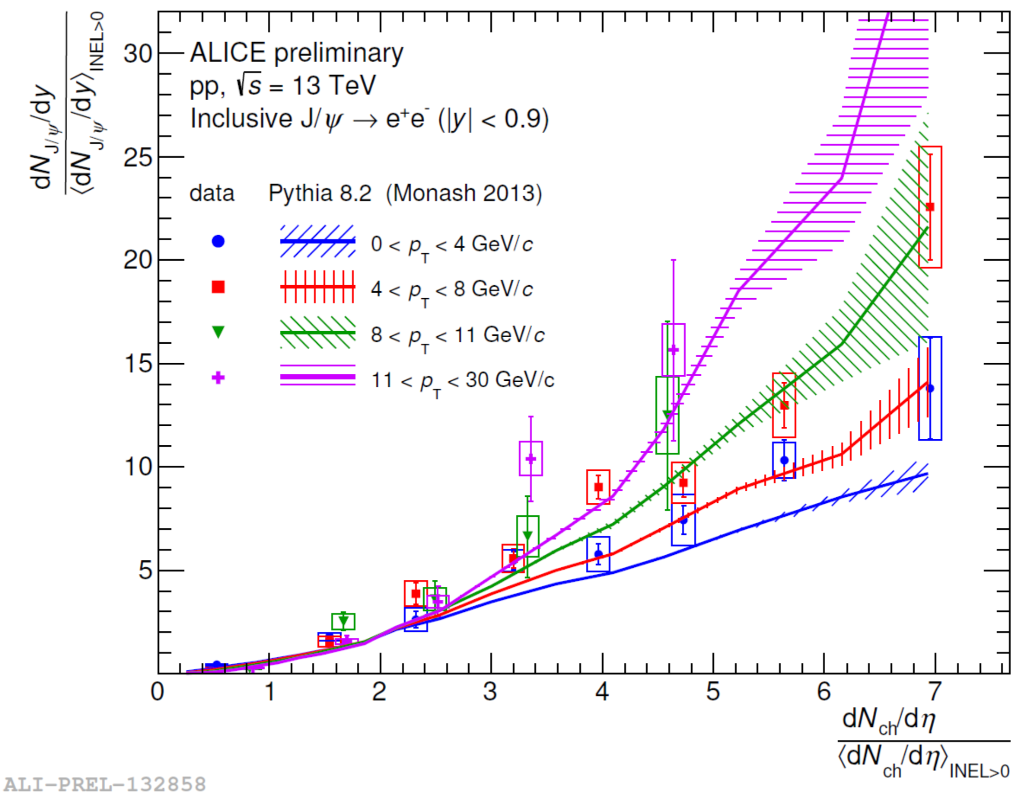
Comparison with models



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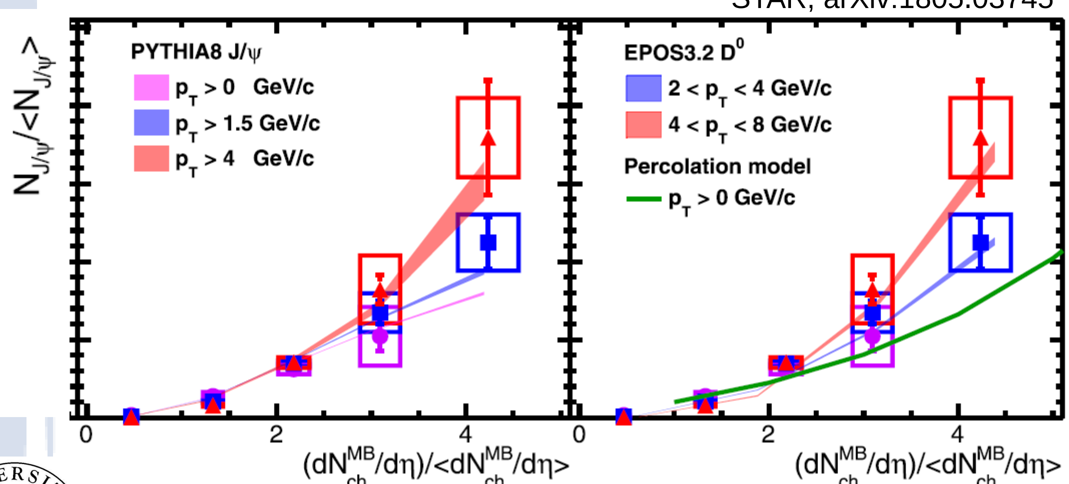
STAR, arXiv:1805.03745



- PYTHIA8 calculations qualitatively describe the p_T dependent trends of ALICE data
- PYTHIA8 and EPOS 3 show a fair agreement with low energy measurements from STAR

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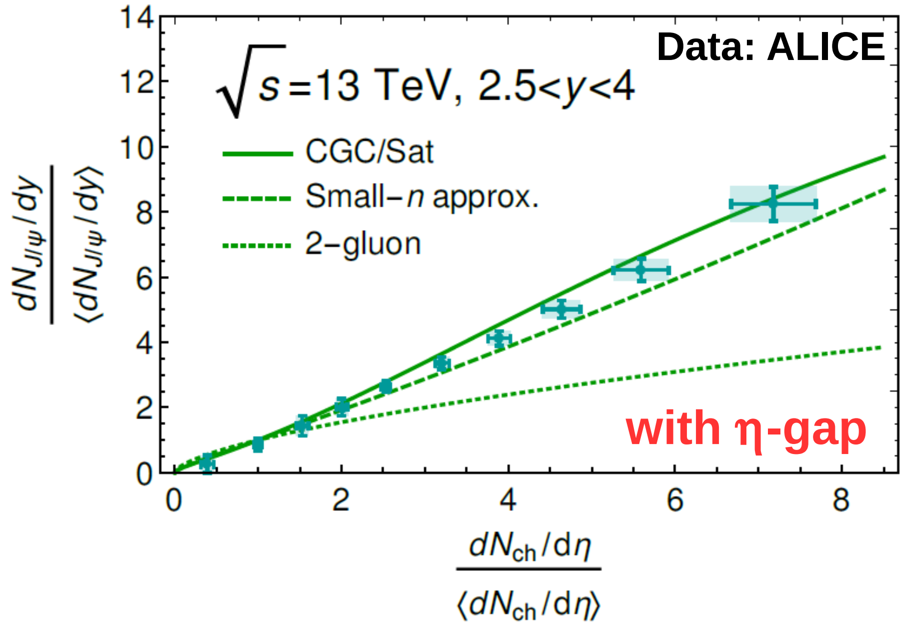

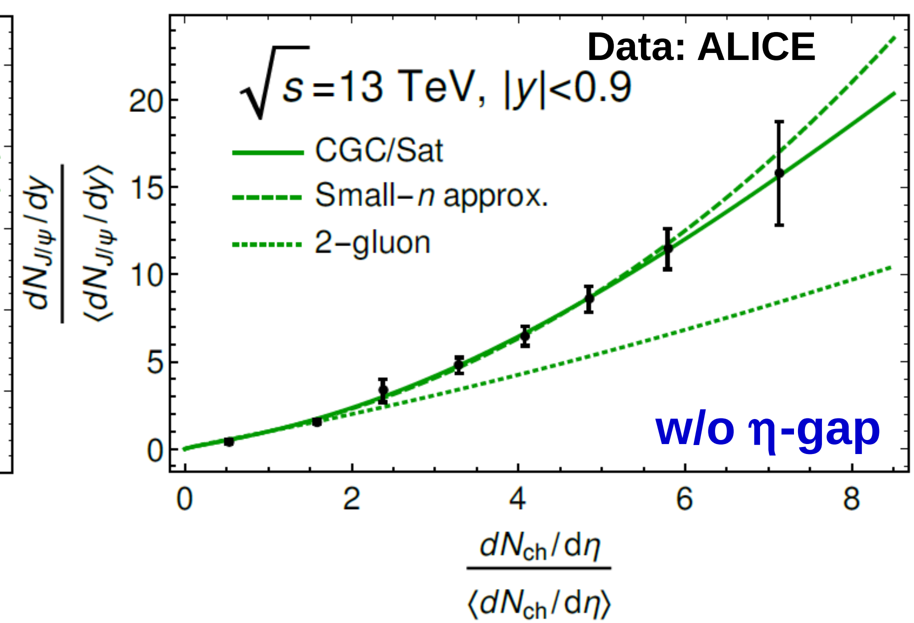

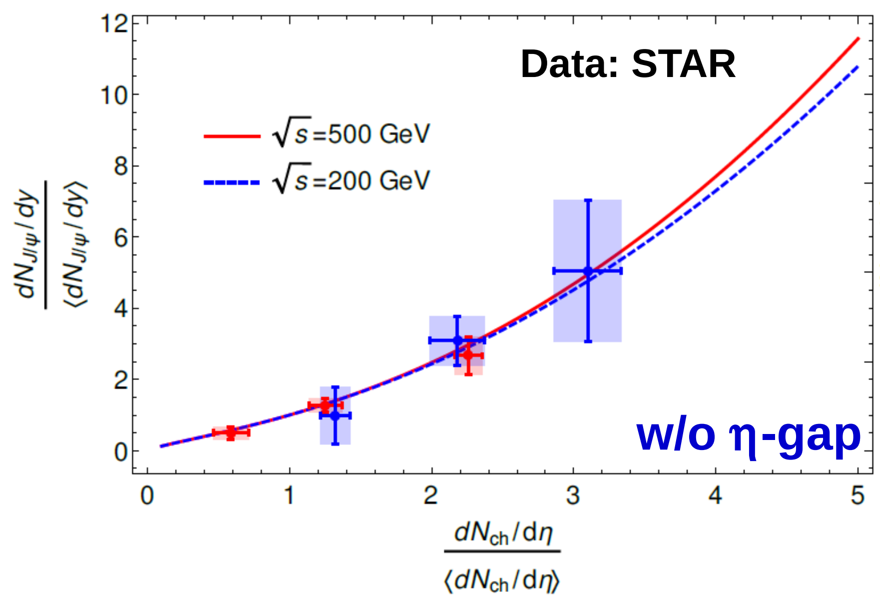

- ✔ Multiplicity dependence of J/ψ described in terms of two-gluon and three-gluon fusion mechanisms

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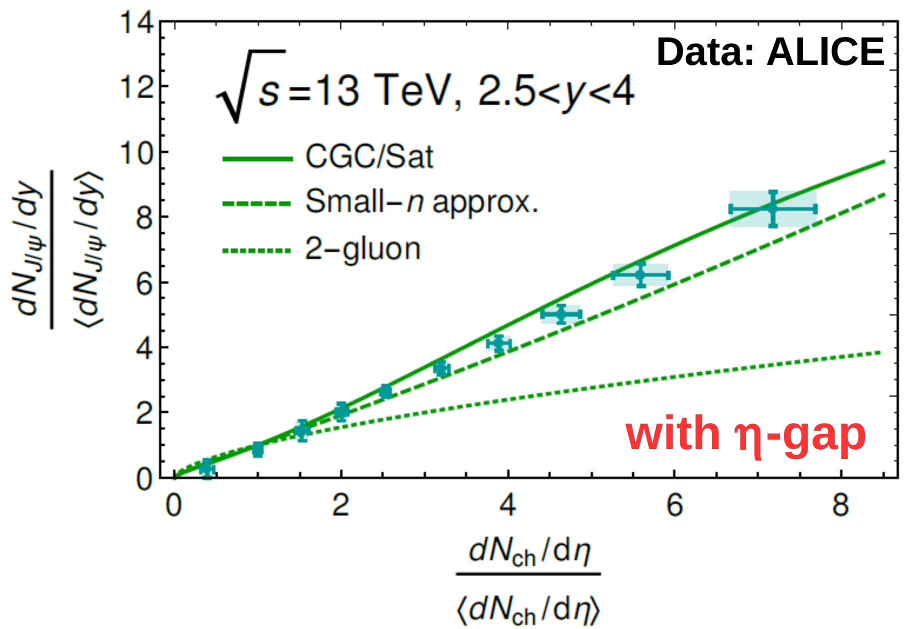
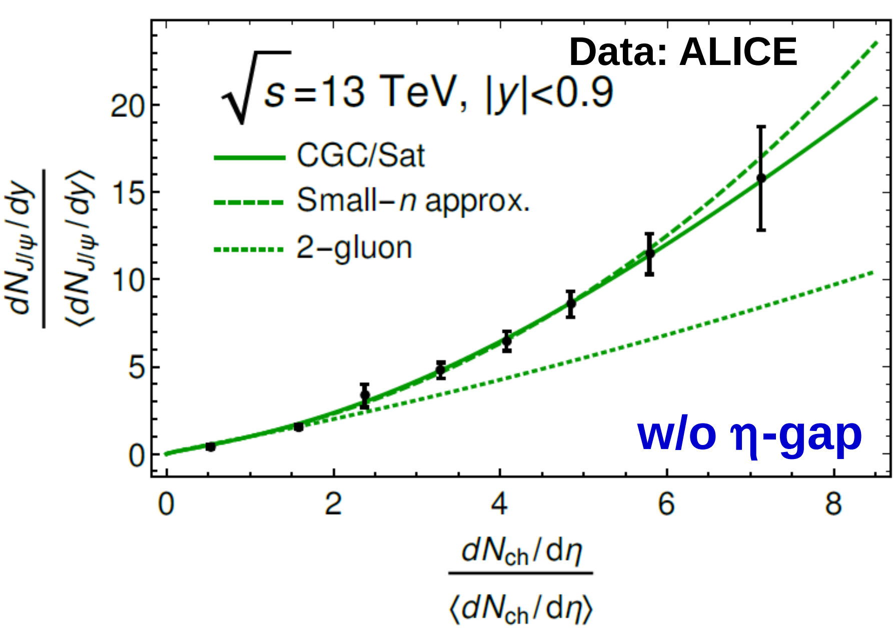
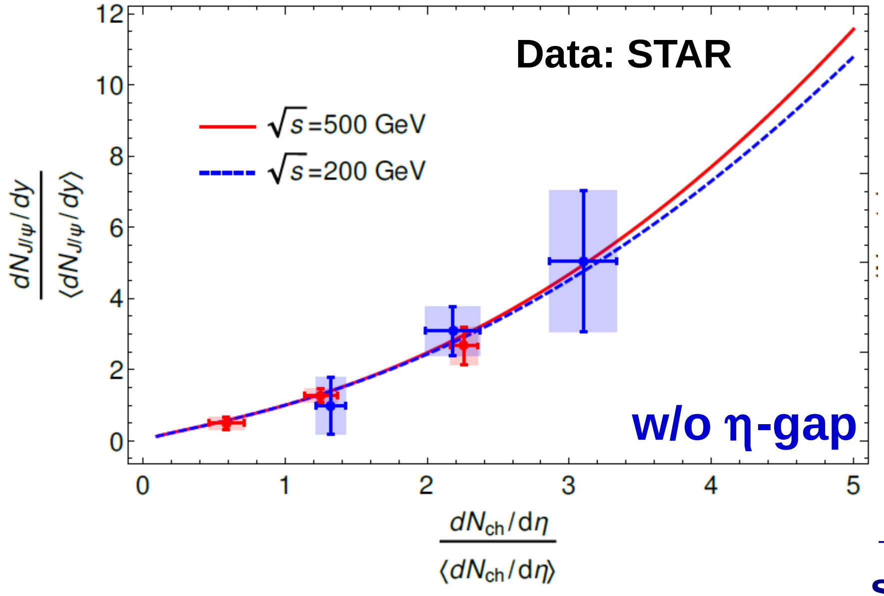
- ✔ Good agreement with lower energy results (RHIC)

Siddikov, Levin, Schmidt, arXiv:1910.13579v1 (2019)

Comparison with models







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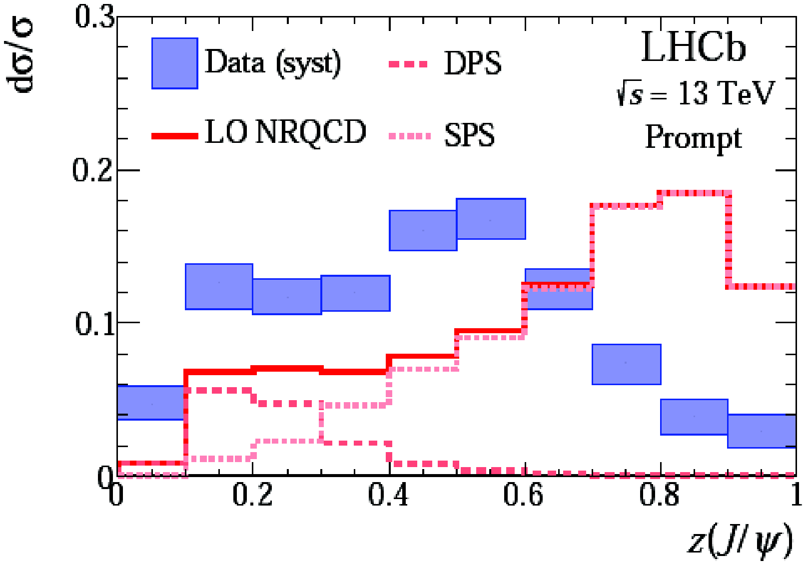
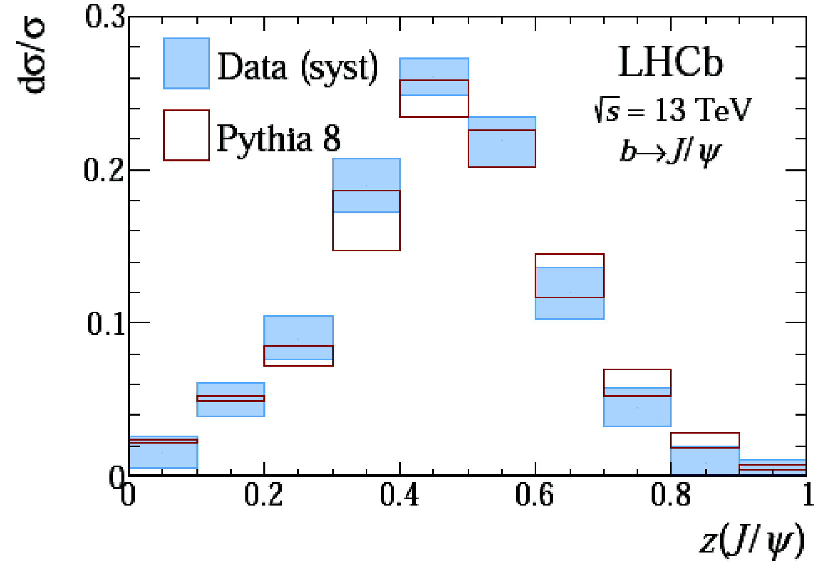
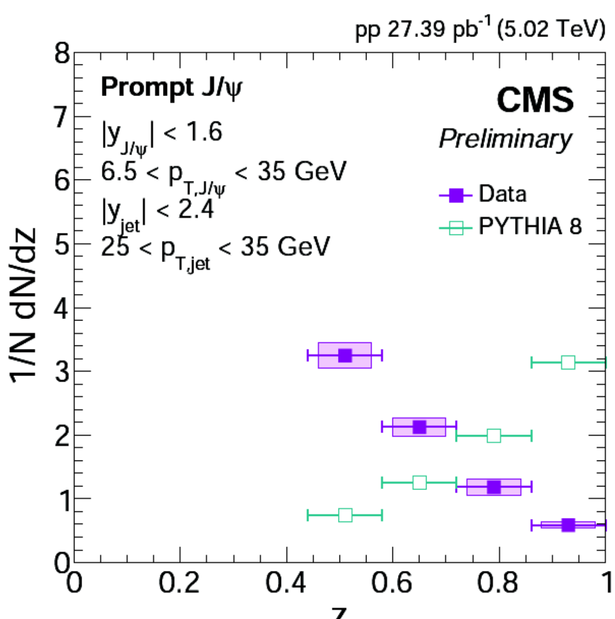
→ models including HF production in MPI, parton saturation / gluon fusion mechanisms describe qualitatively the observed trends vs multiplicity

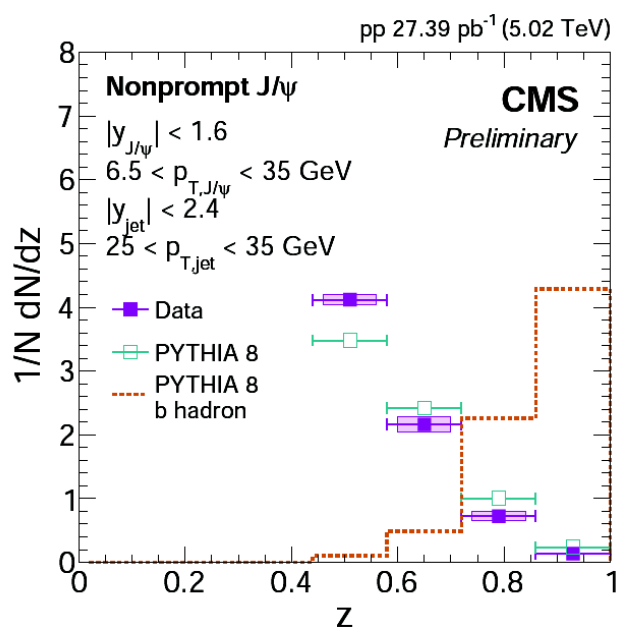
Comparison with models

- Quarkonia production in association with jets could provide further constraints for tuning models









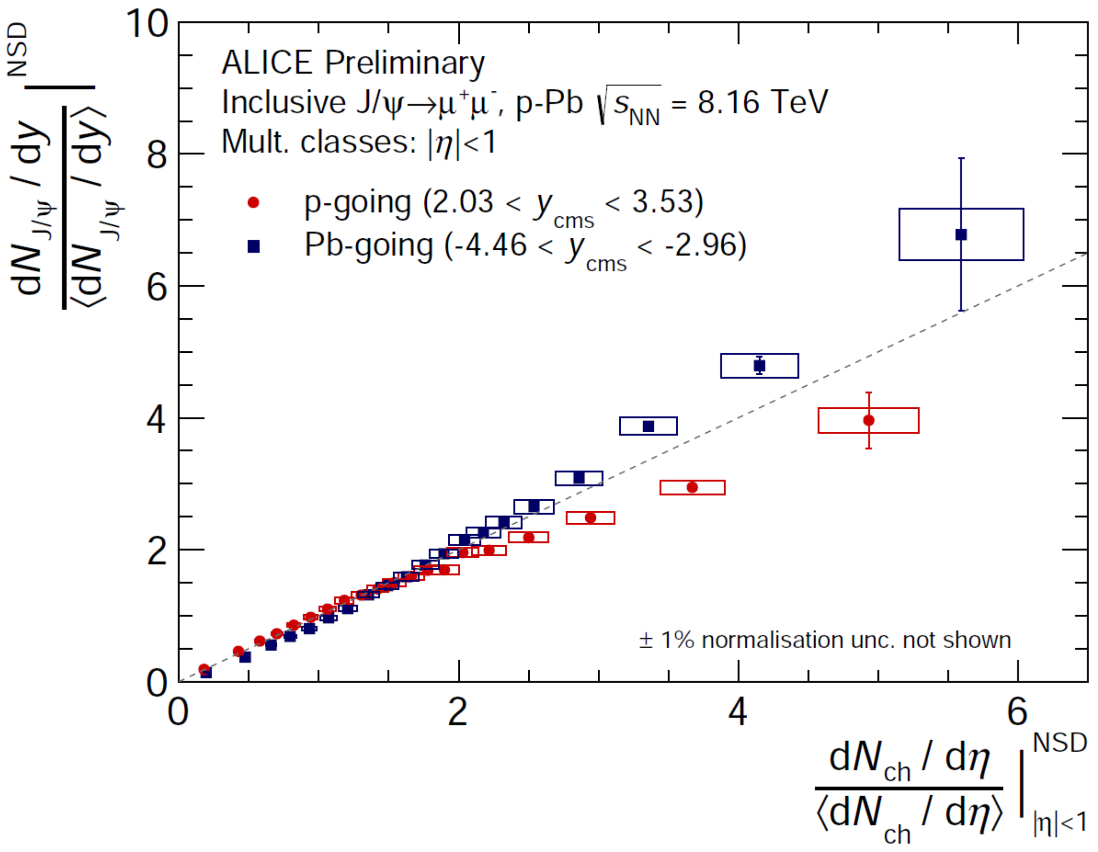
$$z(J/\psi) \equiv p_{\mathrm{T}}(J/\psi)/p_{\mathrm{T}}(\mathrm{jet})$$

- Similar results obtained by CMS and LHCb at different $\sqrt{s}$

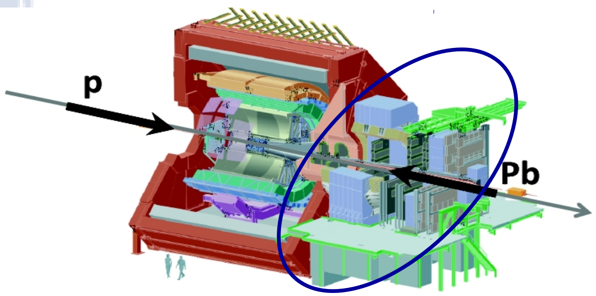
- **J/ψ are less isolated in data compared to PYTHIA8**

From pp to pPb

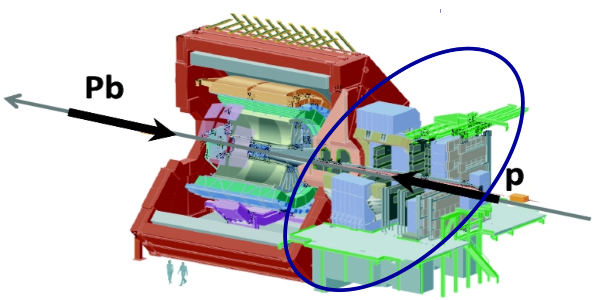
J/ψ vs multiplicity in p-Pb



- ✔ J/ψ vs multiplicity in p-Pb at $\sqrt{s_{NN}}$ = 8.16 TeV measured by ALICE
  - – hint of faster than linear trend at backward rapidity
  - – suppression observed at forward rapidity
  - → **compatible with expected CNM effects**

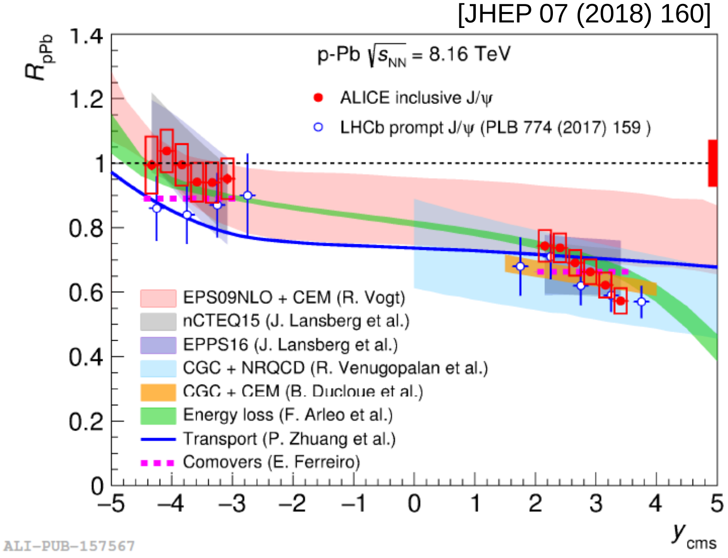


Forward rapidity

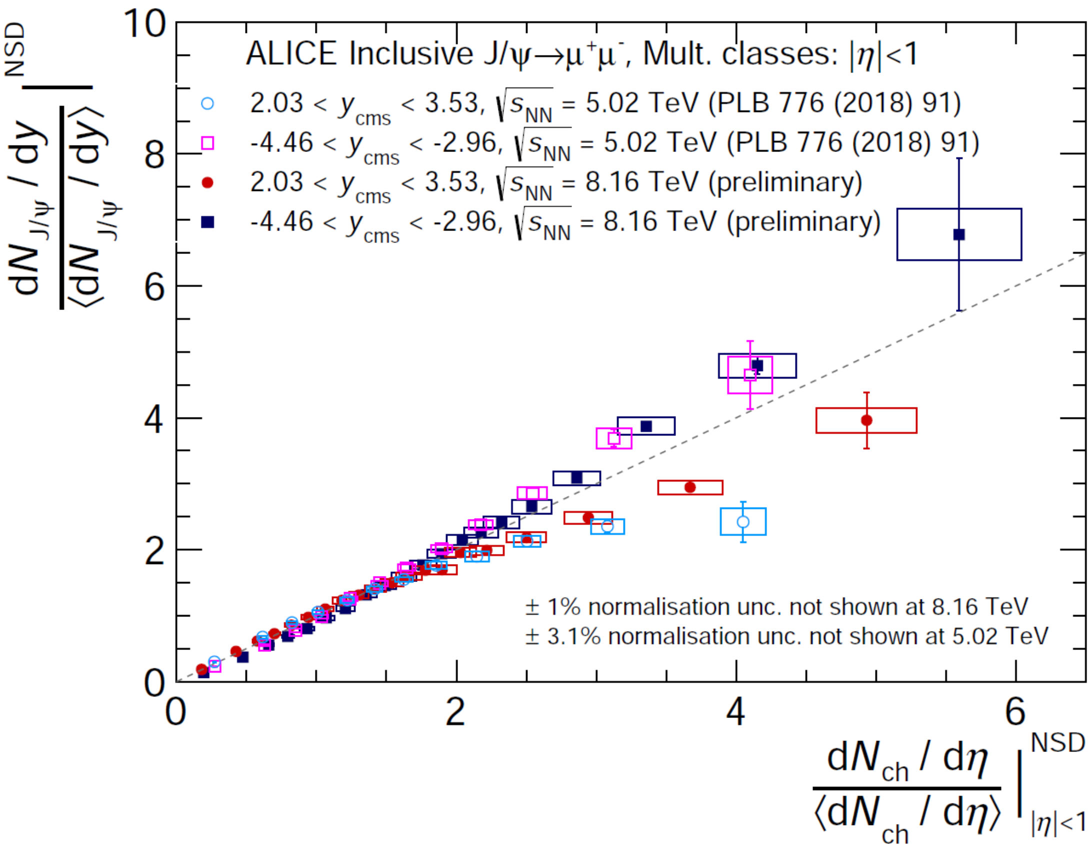


Backward rapidity

[JHEP 07 (2018) 160]



J/ψ vs multiplicity in p-Pb



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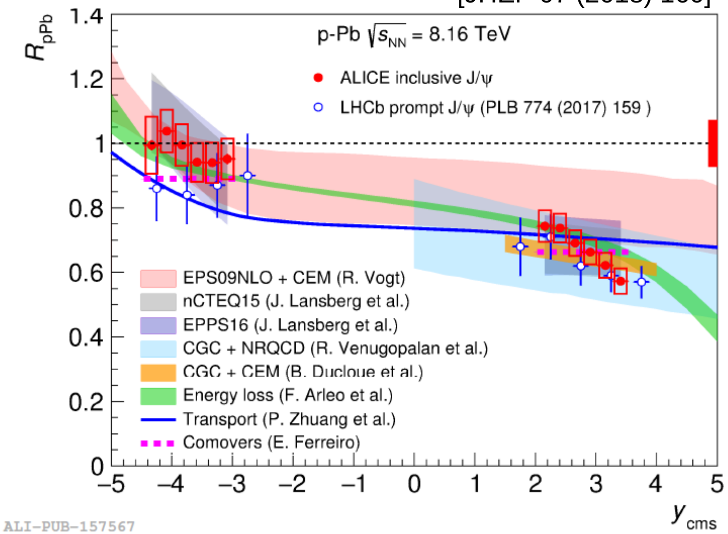
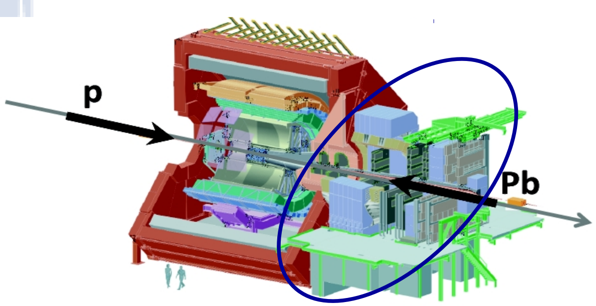
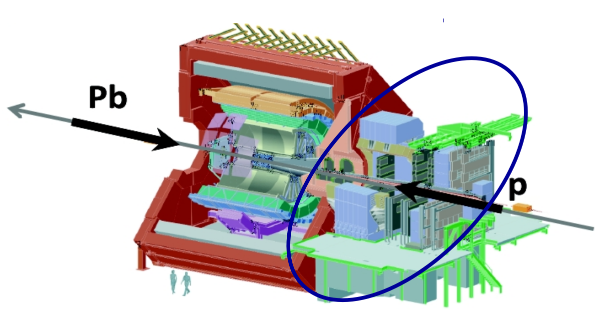
  - → **compatible with expected CNM effects**
- Comparison with $\sqrt{s_{NN}}$ = 5.02 TeV results show no dependence on center-of-mass energy (as observed in pp)

[JHEP 07 (2018) 160]





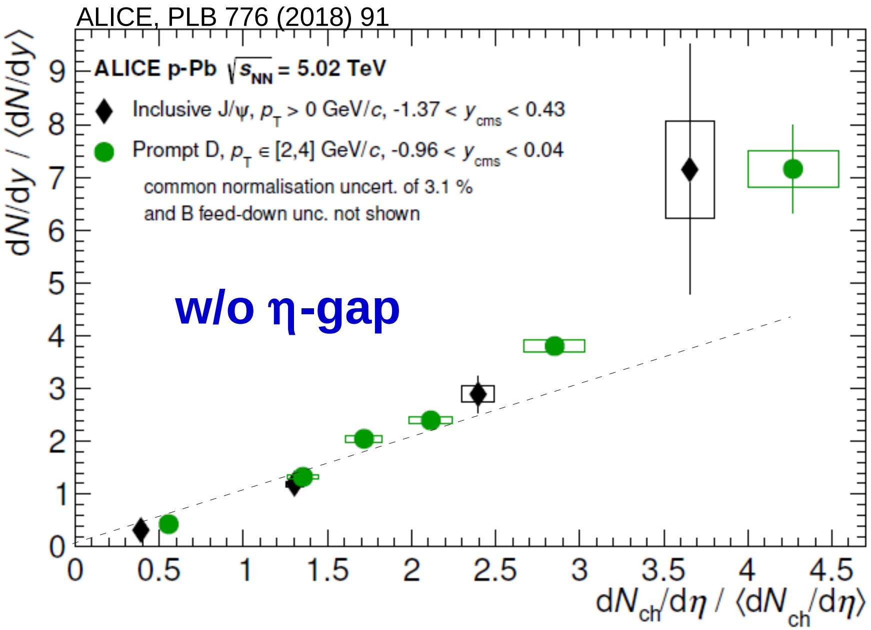
Forward rapidity

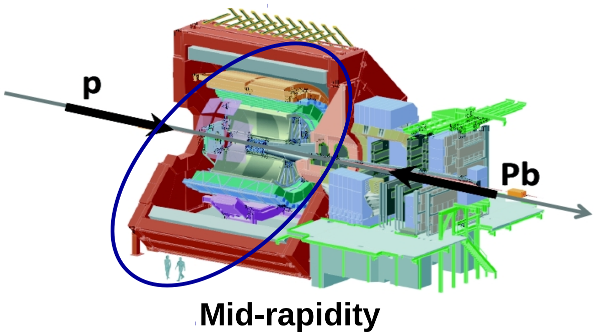


Backward rapidity

Quarkonia vs multiplicity in p-Pb

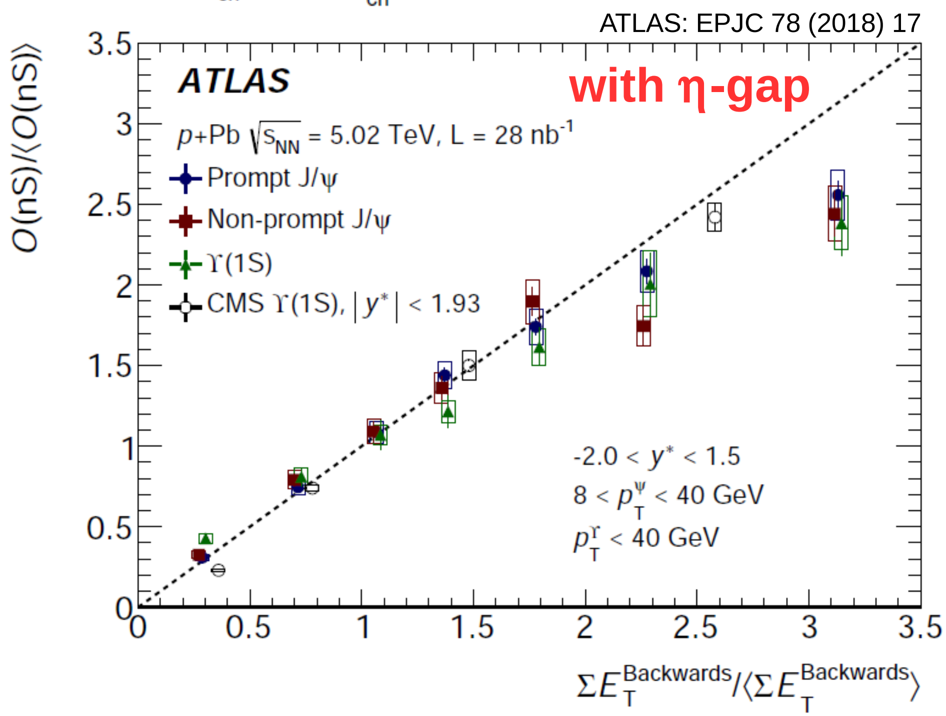
ALICE, PLB 776 (2018) 91





- At mid-rapidity quarkonia and open-heavy flavour vs multiplicity show similar trend vs multiplicity:
  - – ALICE: faster than linear trend w/o η-gap
  - – ATLAS (+CMS): suppression towards higher multiplicities with η-gap

ATLAS: EPJC 78 (2018) 17



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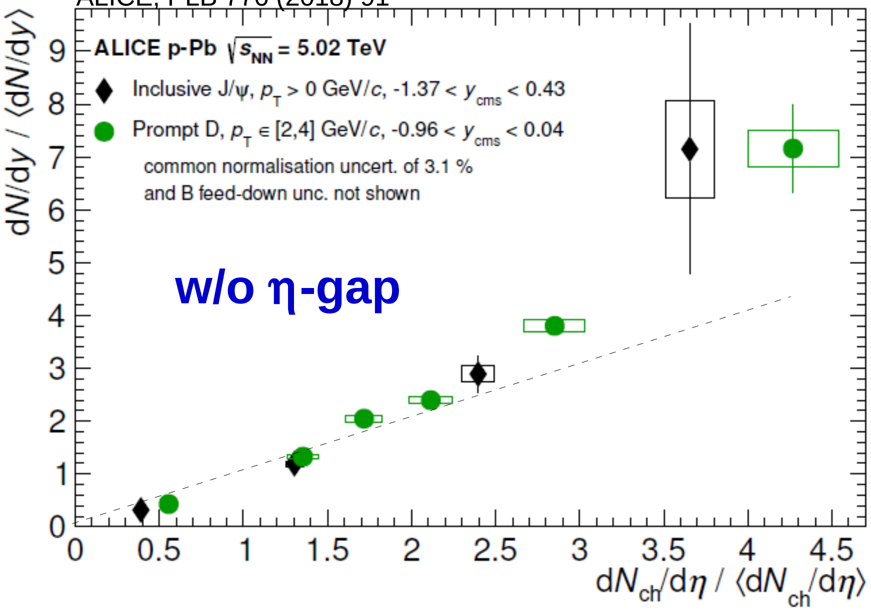
ALICE, PLB 776 (2018) 91



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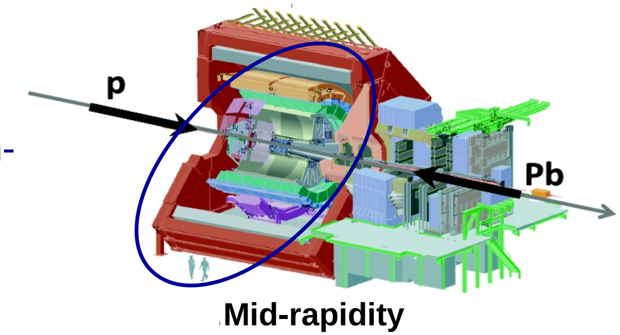
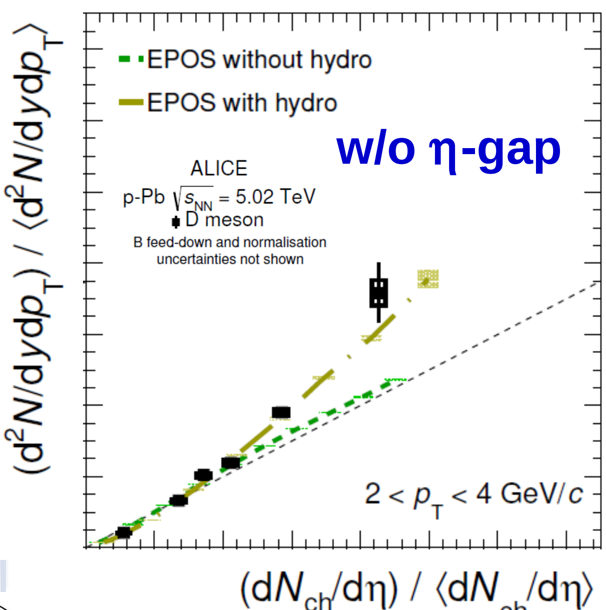
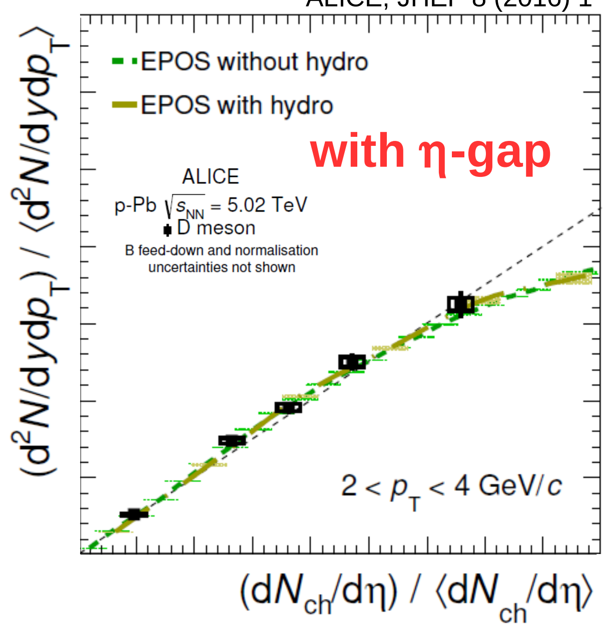


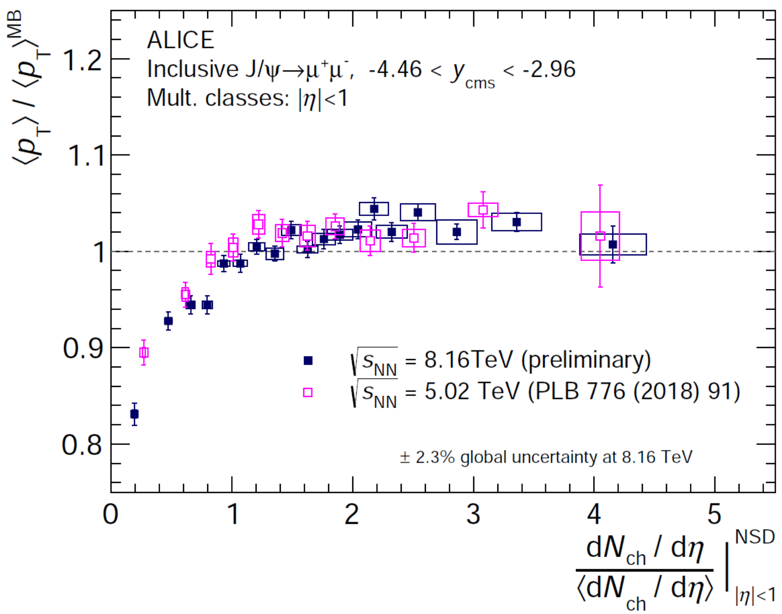


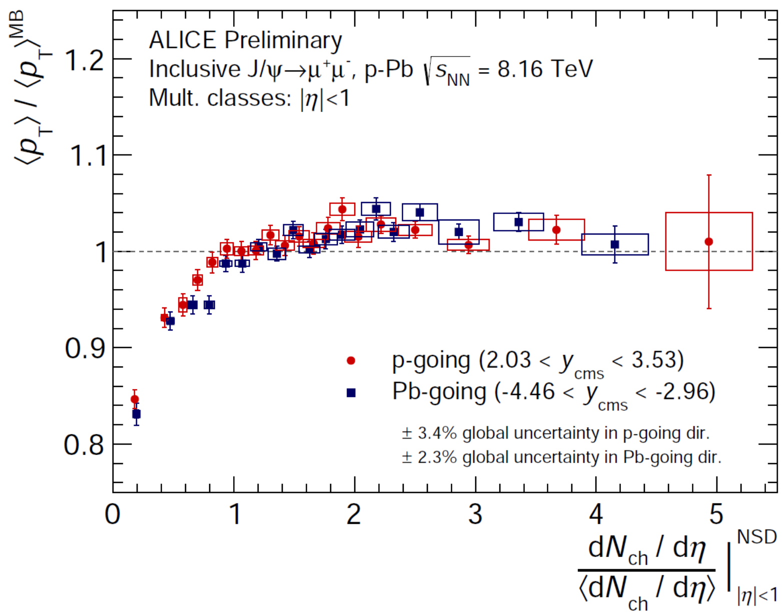
ALICE, JHEP 8 (2016) 1



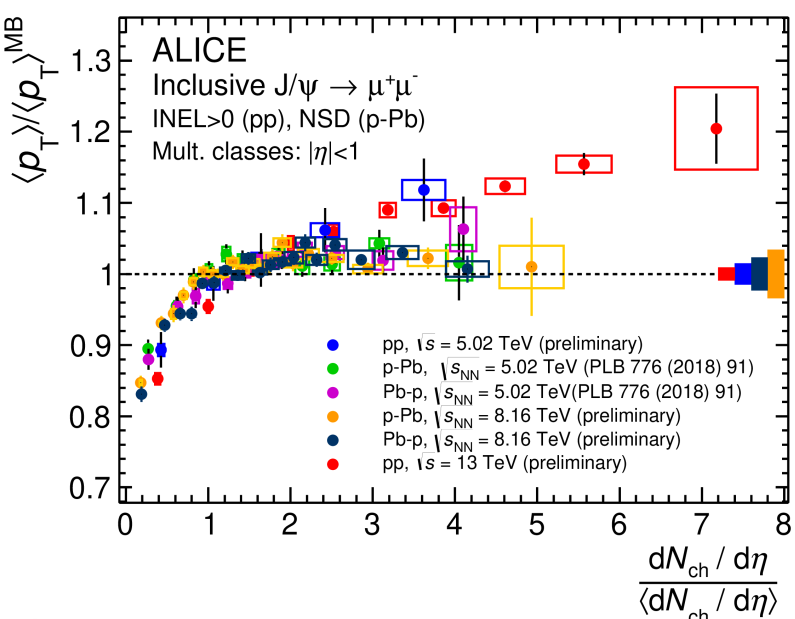
- ✔ Similar behaviour observed for D-mesons when multiplicity with and w/o η-gap
- ✔ Comparison with models suggest that a hydro could provide a possible explanation → collectivity ?

$\langle p_T \rangle$ of J/ψ vs multiplicity in p-Pb



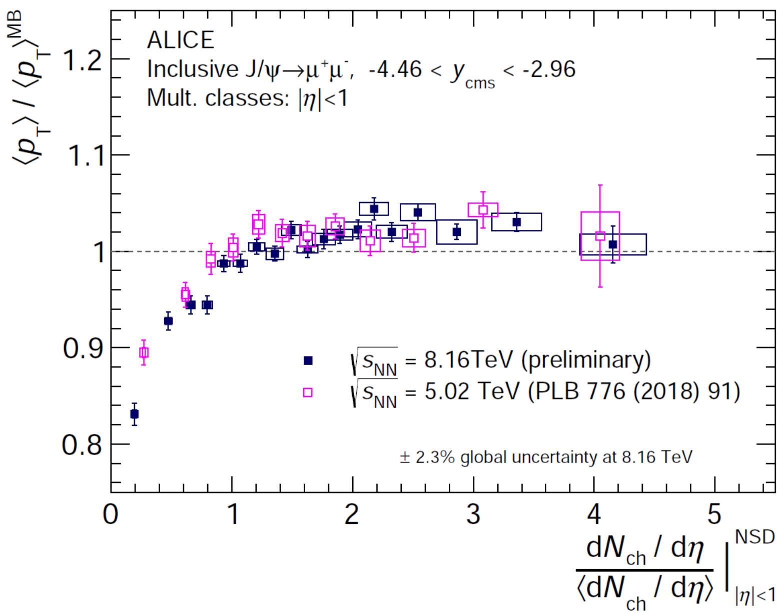


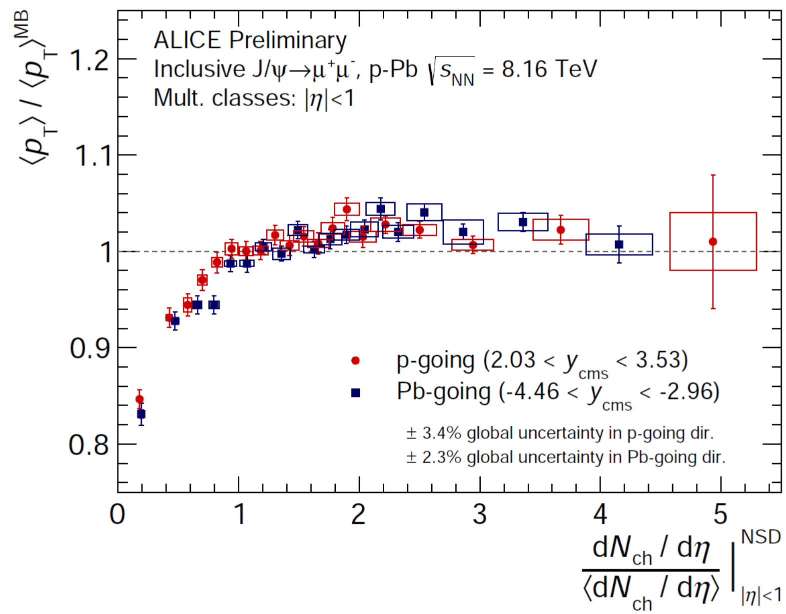
- Self-normalized $\langle p_T \rangle$ vs multiplicity increases similarly for different $\sqrt{s_{NN}}$ and rapidities



- saturation towards high-multiplicity for pPb
- continuous increase for pp

$\langle p_T \rangle$ of J/ψ vs multiplicity in p-Pb





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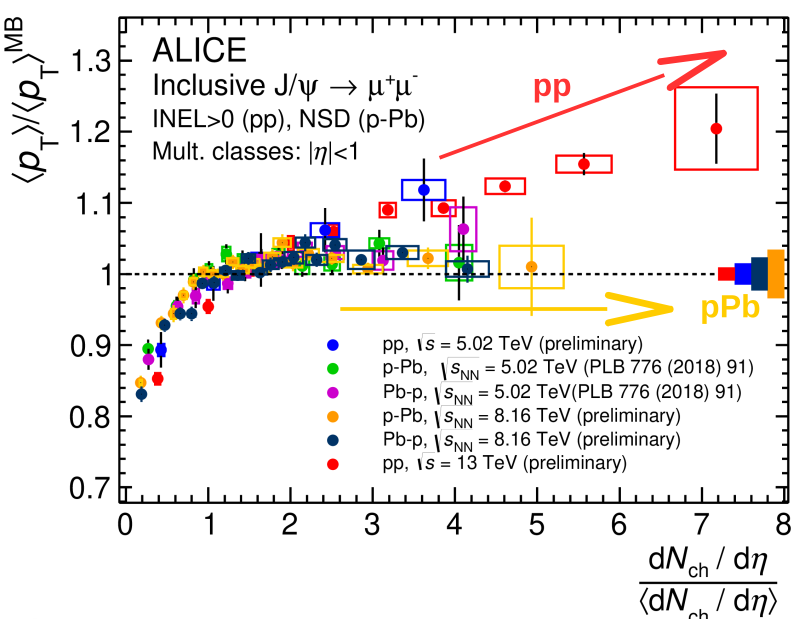

- ✔ saturation towards high-multiplicity for pPb
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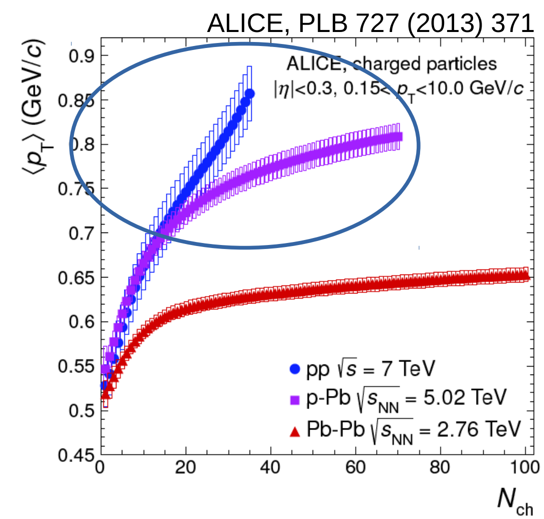
→ similar behaviour observed for charged particles (saturation in Pb-Pb is interpreted in terms of collectivity)

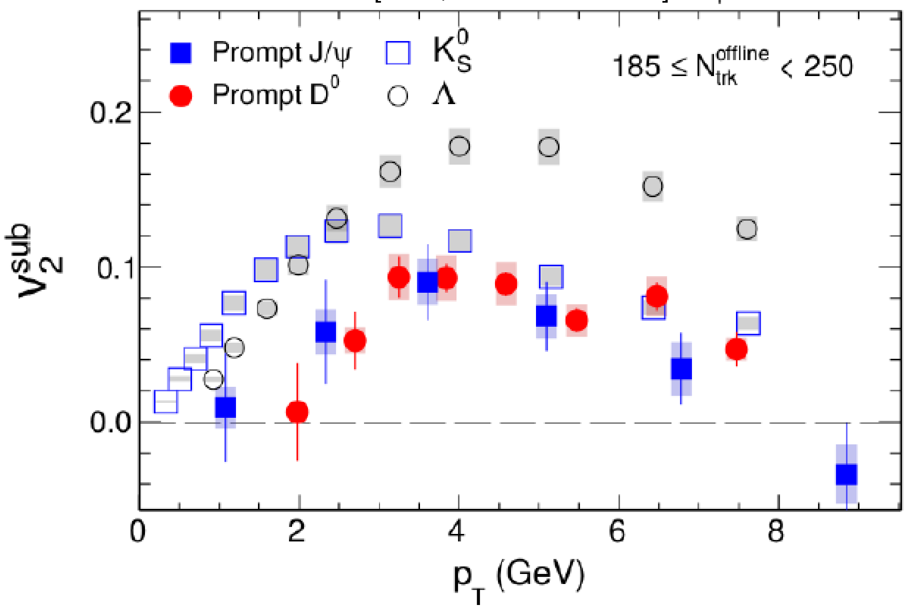


J/ψ elliptic flow in p-Pb

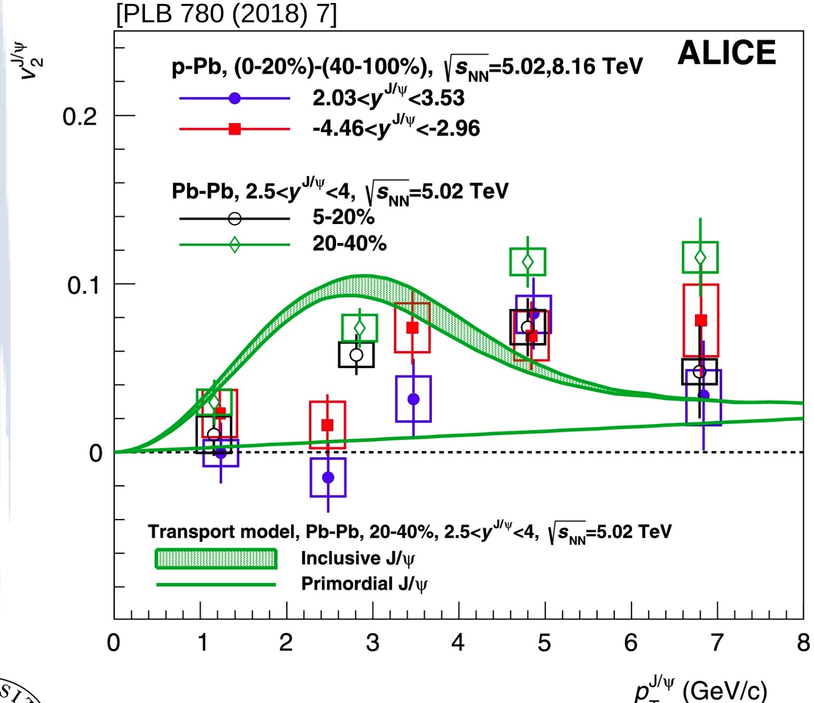
- Prompt J/ψ v_2 measured by CMS at high-multiplicity (estimated in $|\eta|<2.4$)

  – compatible with D-meson and K0s at high-pT

[CMS, arXiv:1810.01473]



[PLB 780 (2018) 7]



- Inclusive J/ψ v_2 measured looking at **long-range angular correlations** between backward / forward rapidity J/ψ and charged hadrons produced at mid-rapidity (rapidity gap ~ 1.5)

- Non-zero v_2 observed for p_T > 3 GeV/*c* (~5σ significance)

  - Similar v_2 compared to Pb-Pb measurements → very intriguing result: **common underlying mechanism** (besides what's included in current calculations) at the origin of J/ψ v_2?

  - **Initial conditions** ?

Conclusions

- pp collisions:
  - not significantly affected by $\sqrt{s}$ and quarkonium specie
  - impact of η-gap still not clear, more measurements needed
  - steepness of the multiplicity dependence increases with the p_{T} of the particles
  - several models **can describe qualitatively the observed trends**

- p-Pb collisions:
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- Outlook:
  - "new" observables (e.g. quarkonia-h correlations, quarkonia production in jets, spherocity dependence) could help to disantangle / further constrain models
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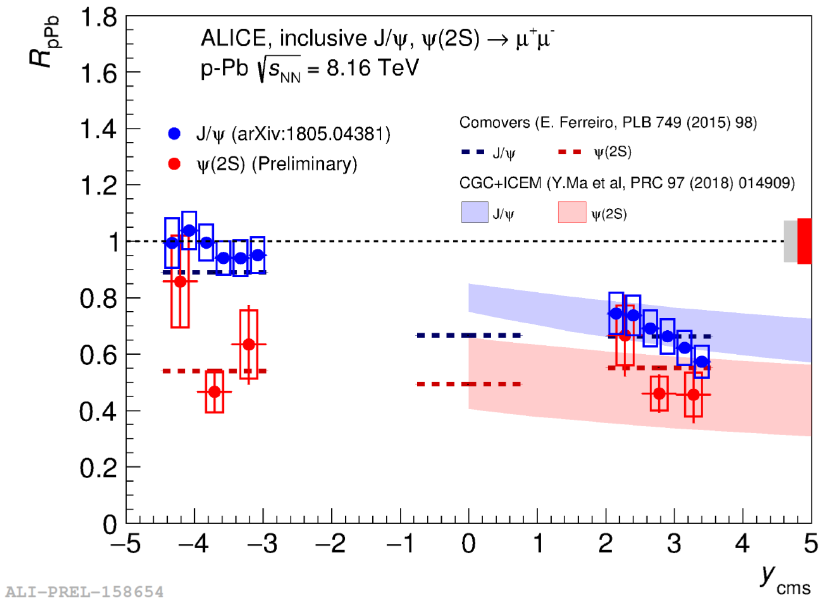
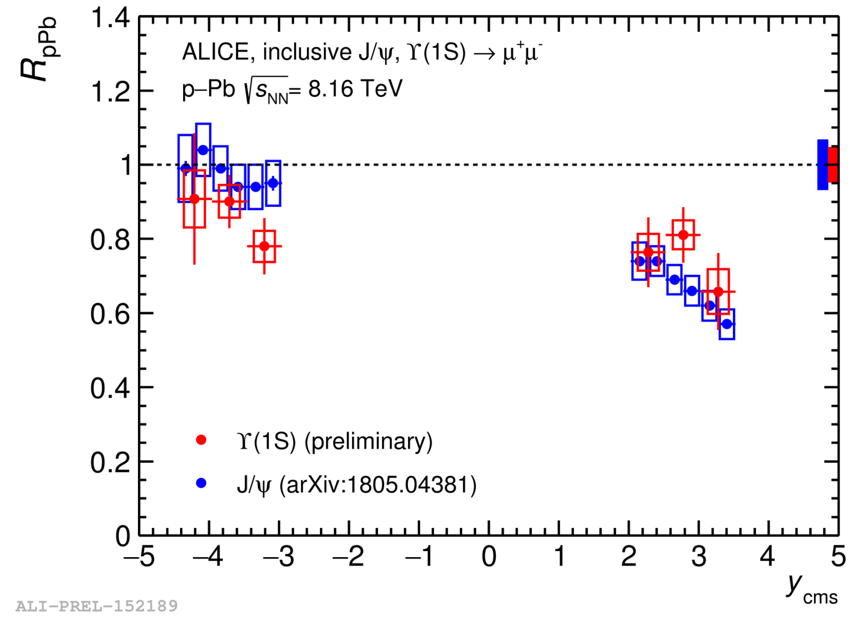
Thank you for your attention !

BACK-UP

Nuclear modification factor R_{pPb}





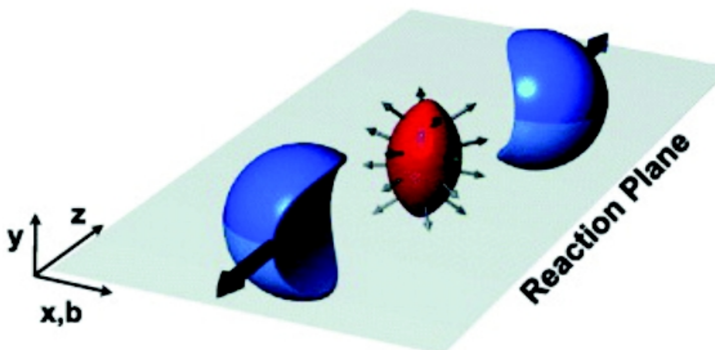
- ✔ Similar suppression observed for J/ψ and ψ(2S) at forward rapidity
- ✔ ψ(2S) suppressed significantly more than J/ψ at backward rapidity
  - ✔ Final state effects needed to explain ψ(2S) modification

- ✔ Similar suppression observed for J/ψ and Υ(1S) at both backward and forward rapidity

Azimuthal anisotropy (v_2)

- In a strongly interacting medium, pressure gradients convert any initial geometrical anisotropy into an anisotropy in the momentum space

[Figure: Raimond Snellings New J. Phys. 13 (2011)]



  - anisotropy is quantified by the 2nd order coefficient v_2 of the Fourier expansion of the particle azimuthal angle distribution

$$\frac{dN}{d\varphi} = \frac{N}{2\pi}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n\left(\varphi - \Psi_R\right)\right)\right]$$

$$v_2 = < cos2(\varphi_{part} - \Psi_{EP}) >$$

- In heavy-ion collisions **non-zero v_2** indicates the **participation in the collective expansion** of the system

- J/ψ v_2 measured looking at l**ong-range angular correlations** between backward / forward rapidity J/ψ and charged hadrons produced at mid-rapidity (rapidity gap ~ 1.5)

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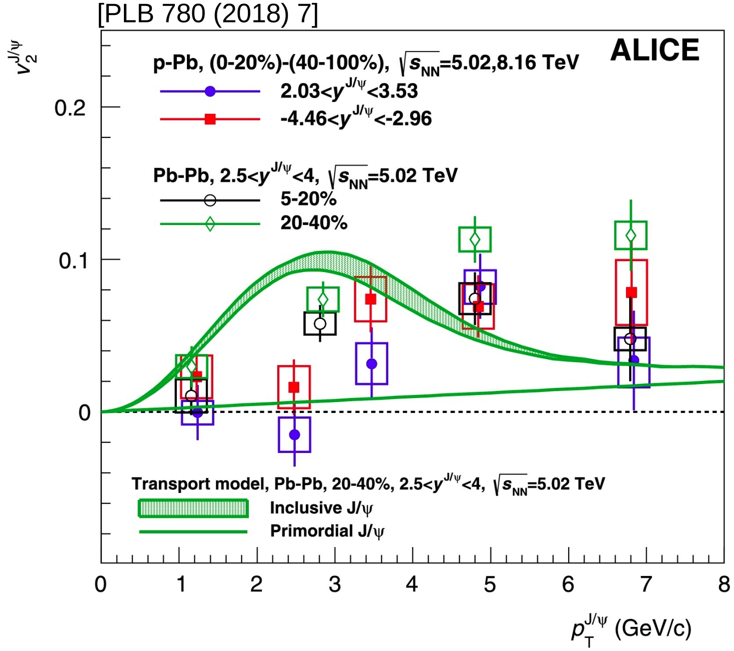
[PLB 780 (2018) 7]



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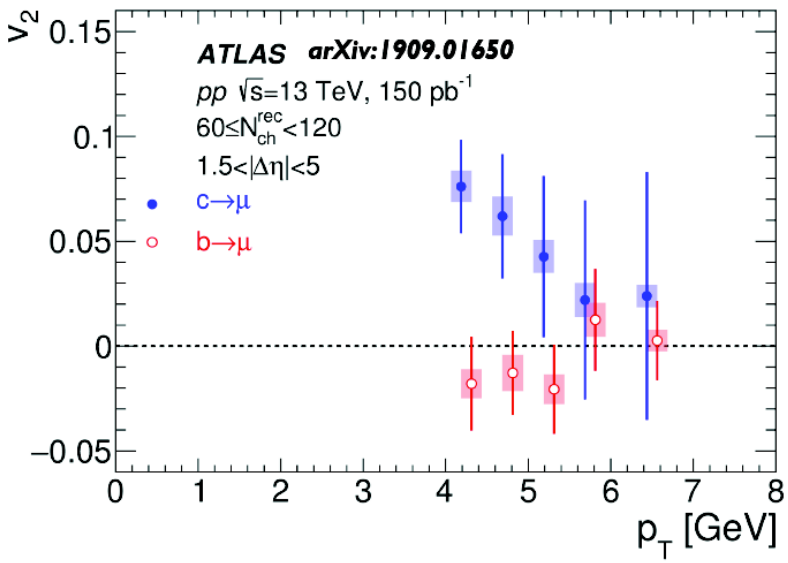
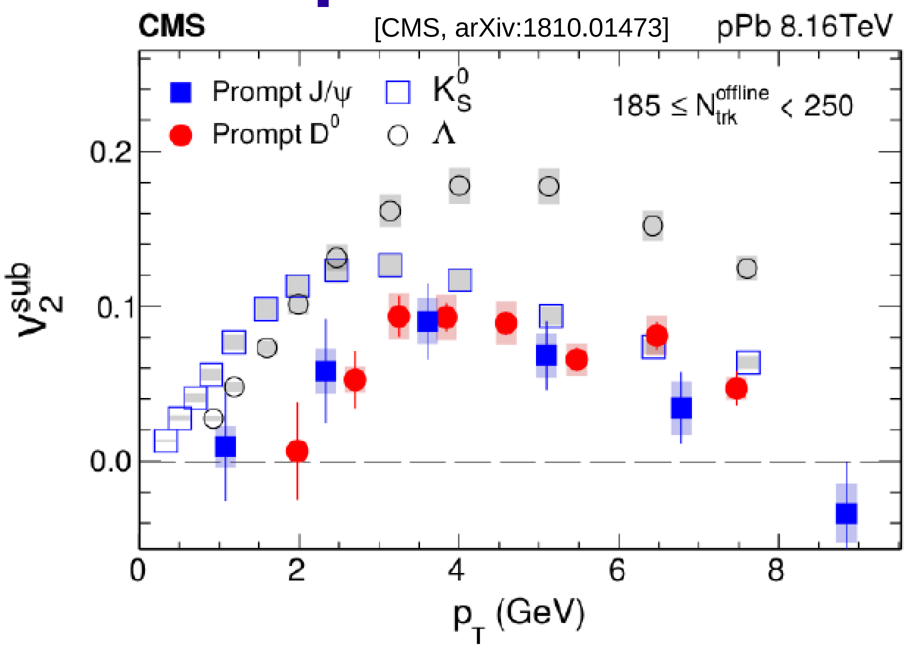
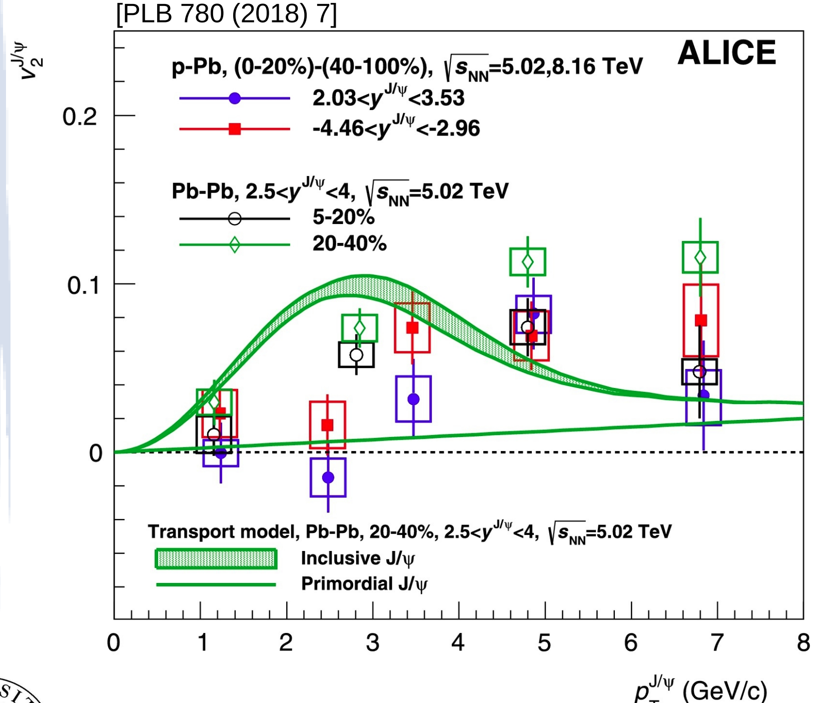


[CMS, arXiv:1810.01473]



[PLB 780 (2018) 7]



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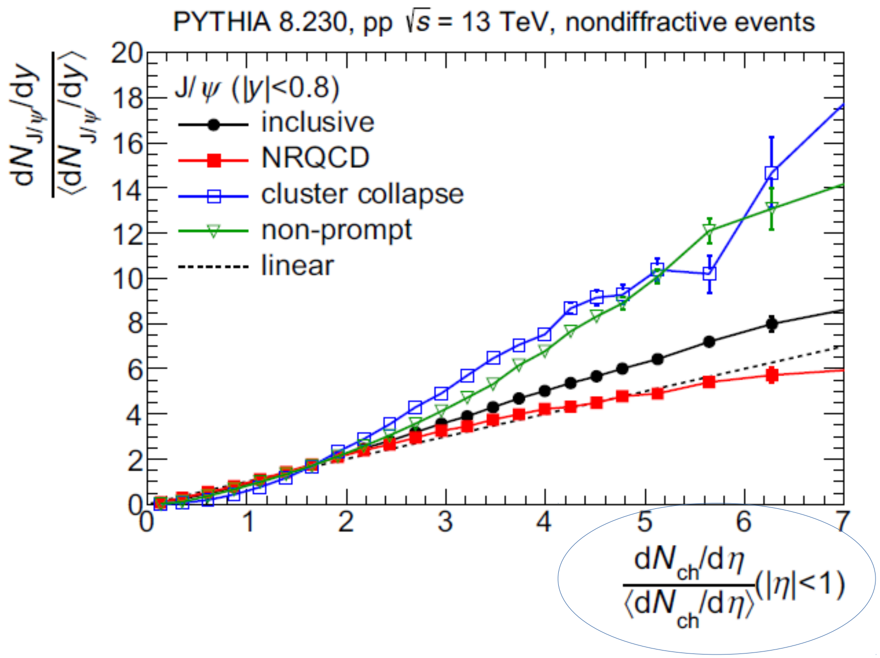
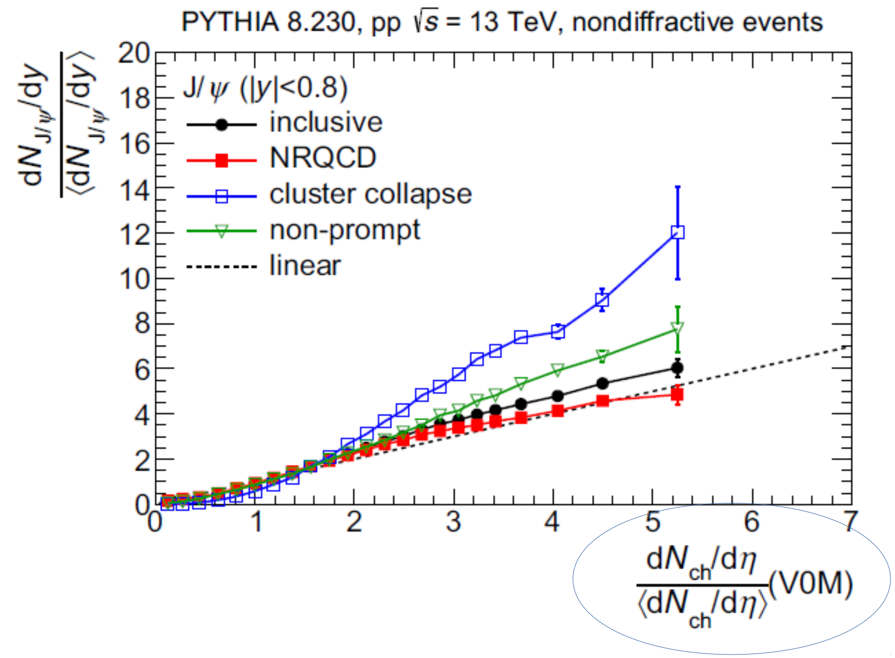
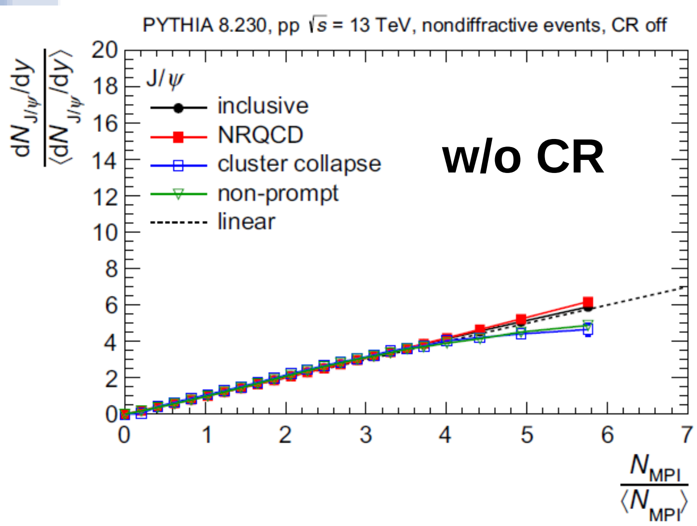
J/ψ production vs multiplicity in PYTHIA8

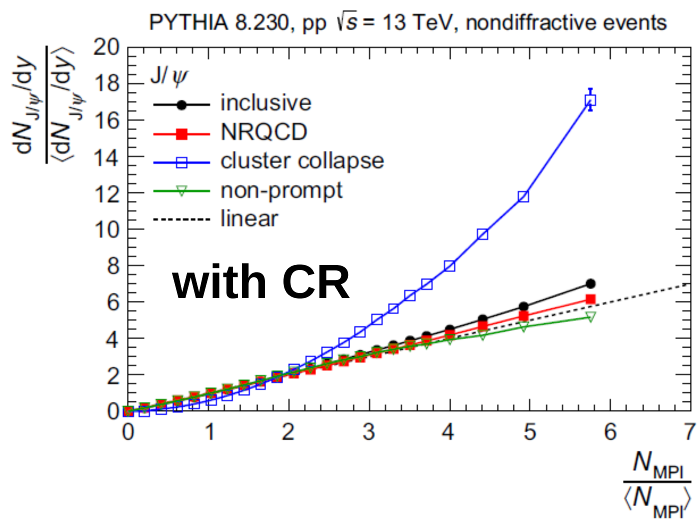
Eur. Phys. J. C (2019) 79

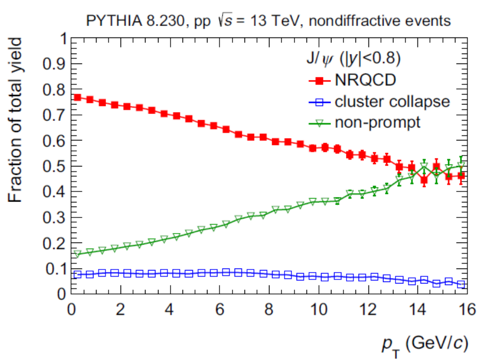
- J/ψ yields result from different contributions











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Eur. Phys. J. C (2019) 79

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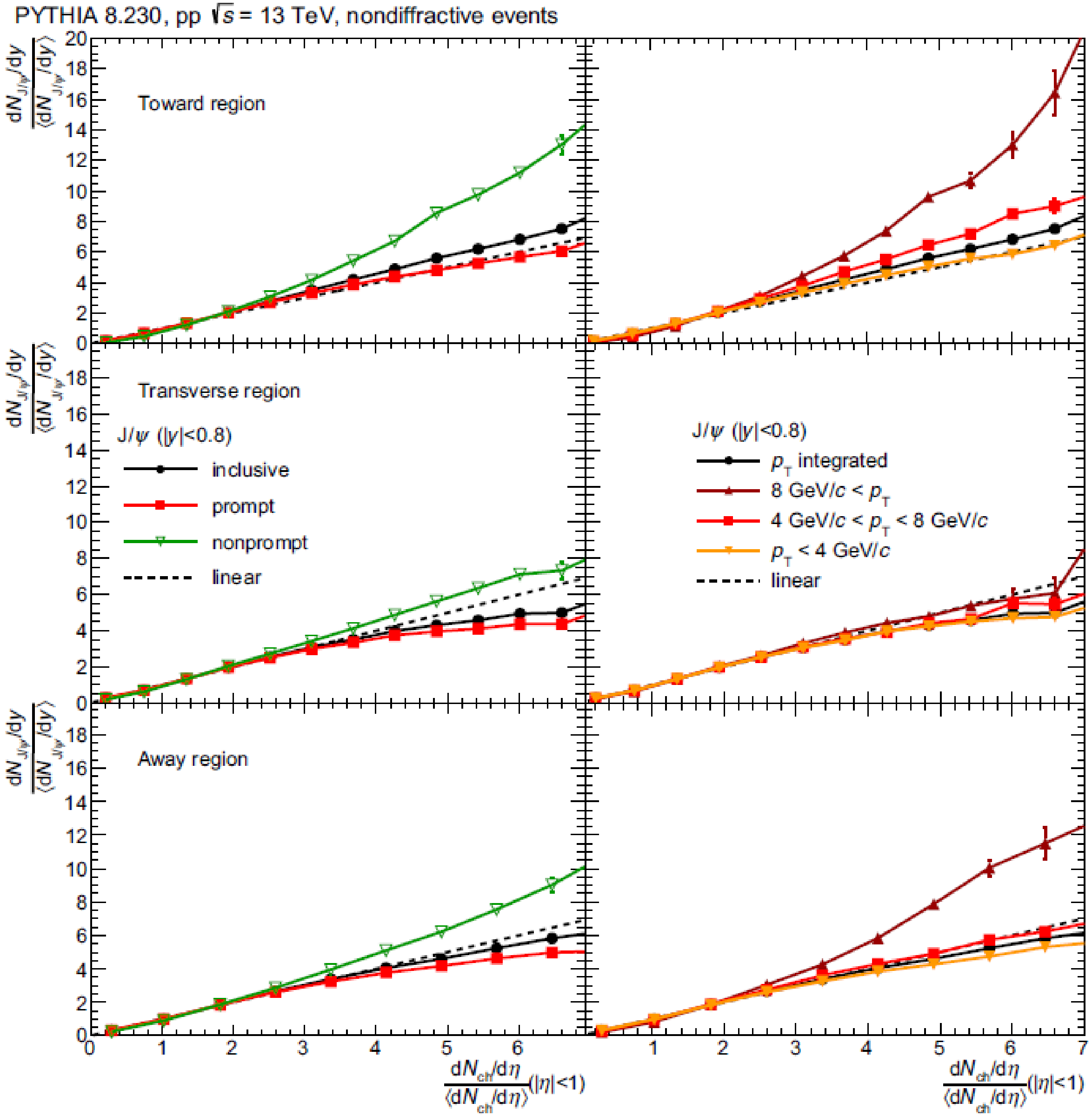
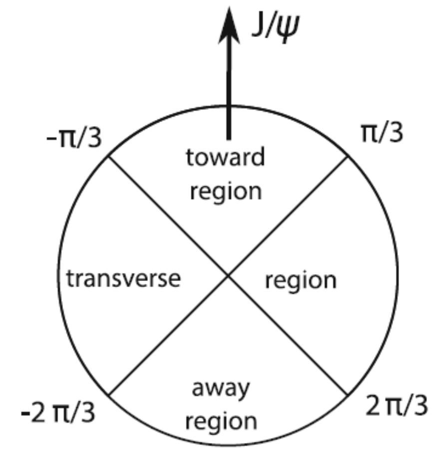
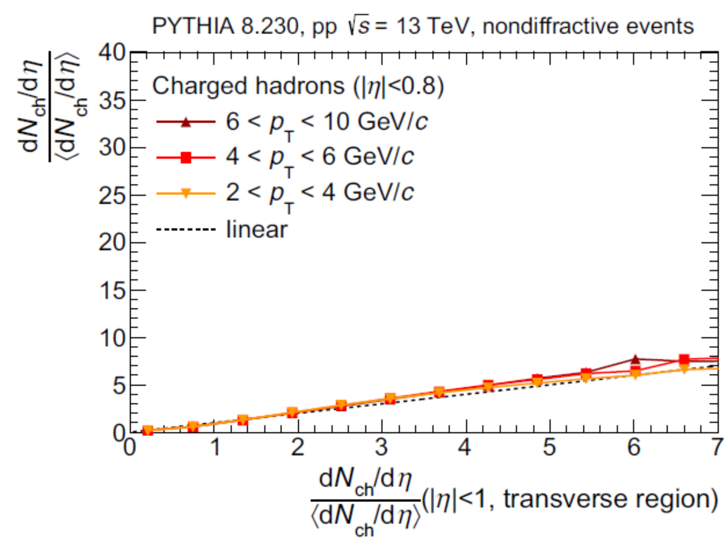
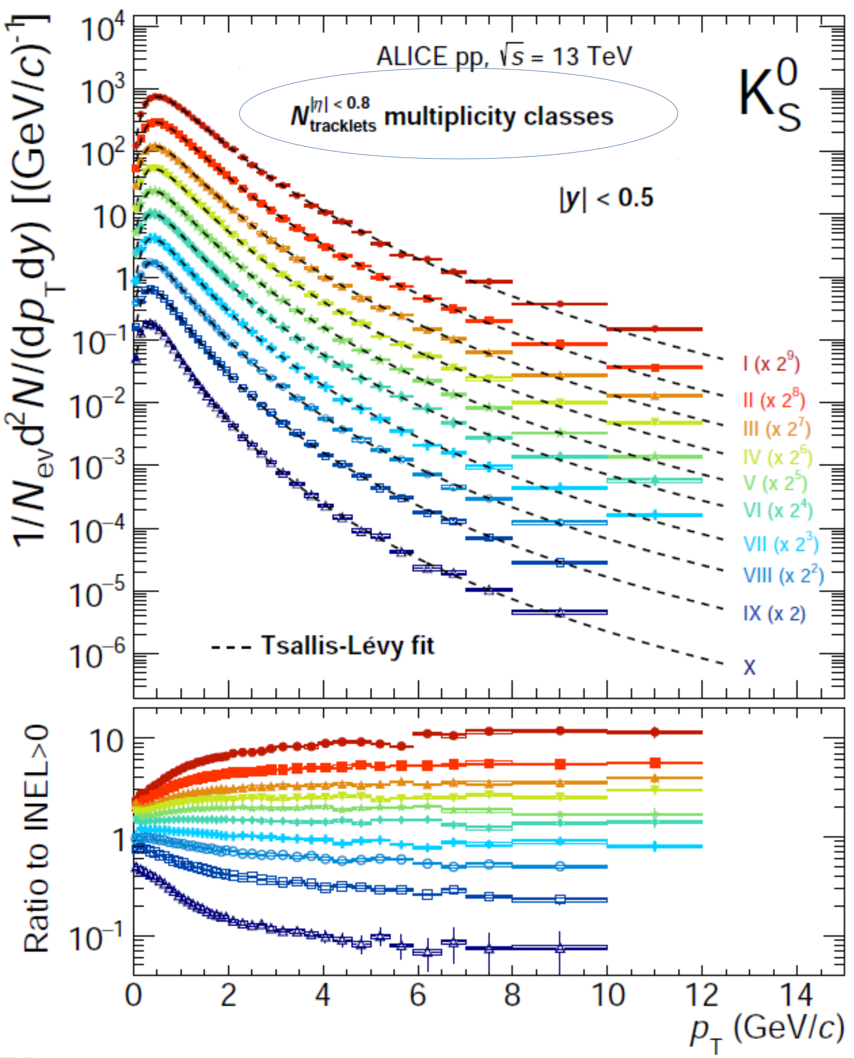
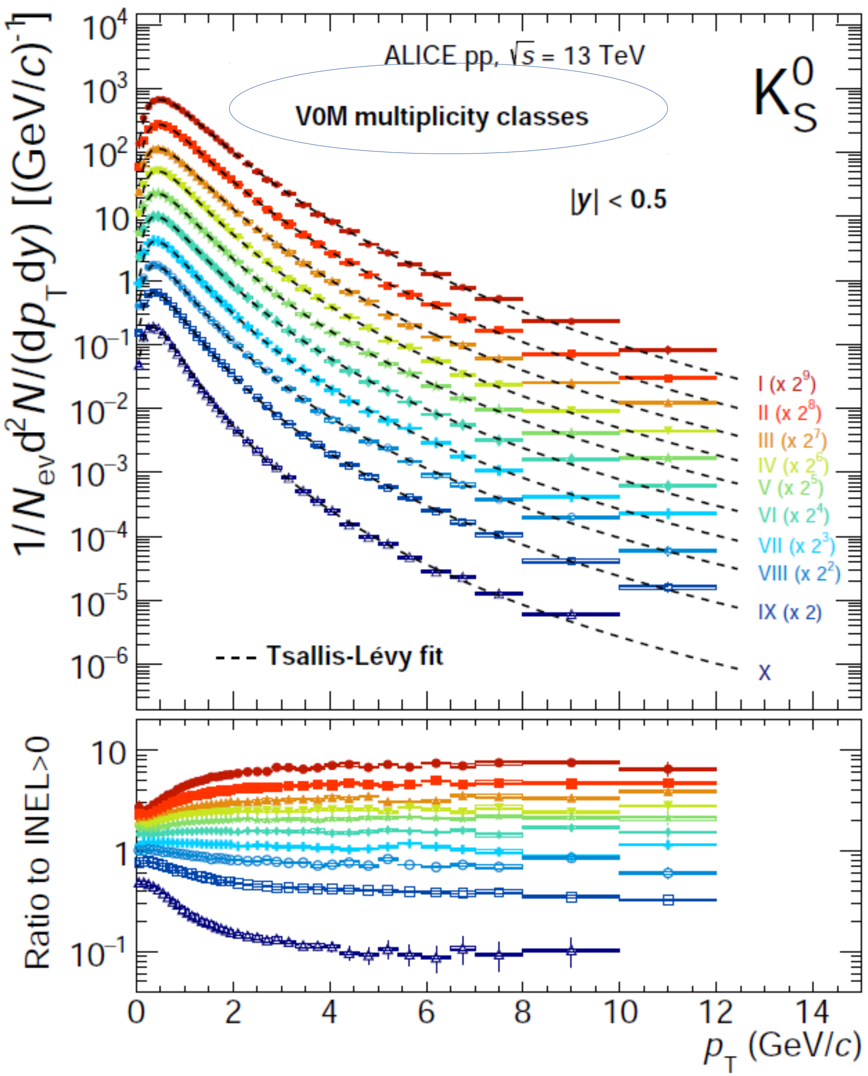






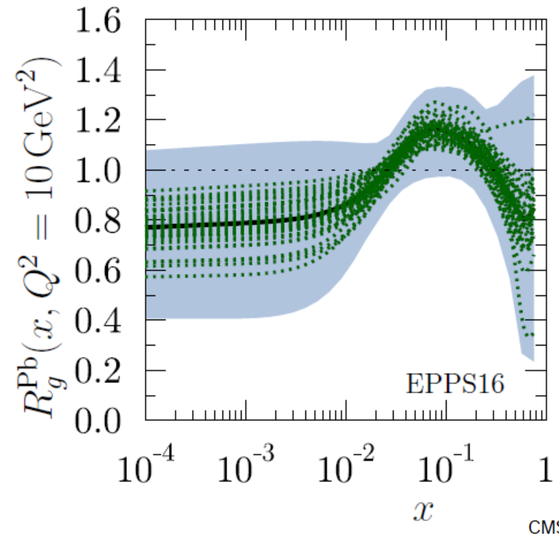
Ratio-to-INEL>0



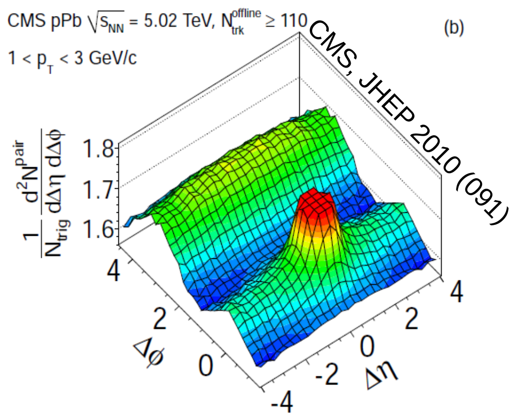


Production in p-Pb collisions

- Cold Nuclear Matter (CNM) effects:
  - (anti-)shadowing modifications for nuclear PDFs
  - gluon saturation, Colour Glass Condensate
  - parton energy loss
  - final state dissociation (absorption, comovers)



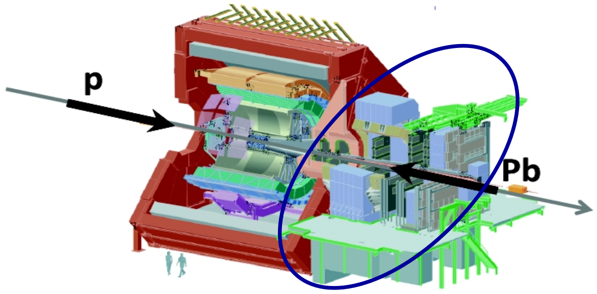
[EPJ C77 (2017) 163]



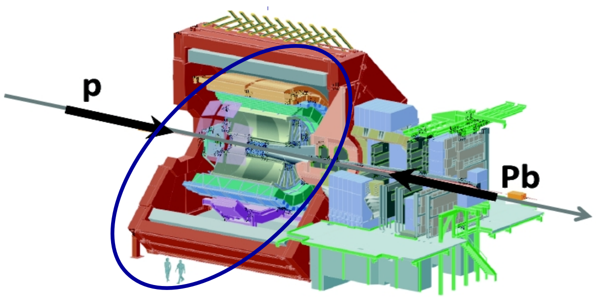
CMS, JHEP 2010 (091)

- Open questions: QGP formation in small systems ? Collectivity ?

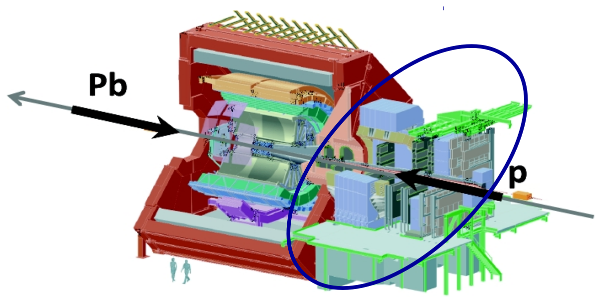
- Two beam configurations: p-Pb / Pb-p (two energies: $\sqrt{s_{NN}}$ = 5.02, 8.16 TeV)



Forward rapidity



Mid-rapidity



Backward rapidity