Experimental Overview of Heavy Flavor Dynamics and Jet quenching in Small Systems

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22 June 2023

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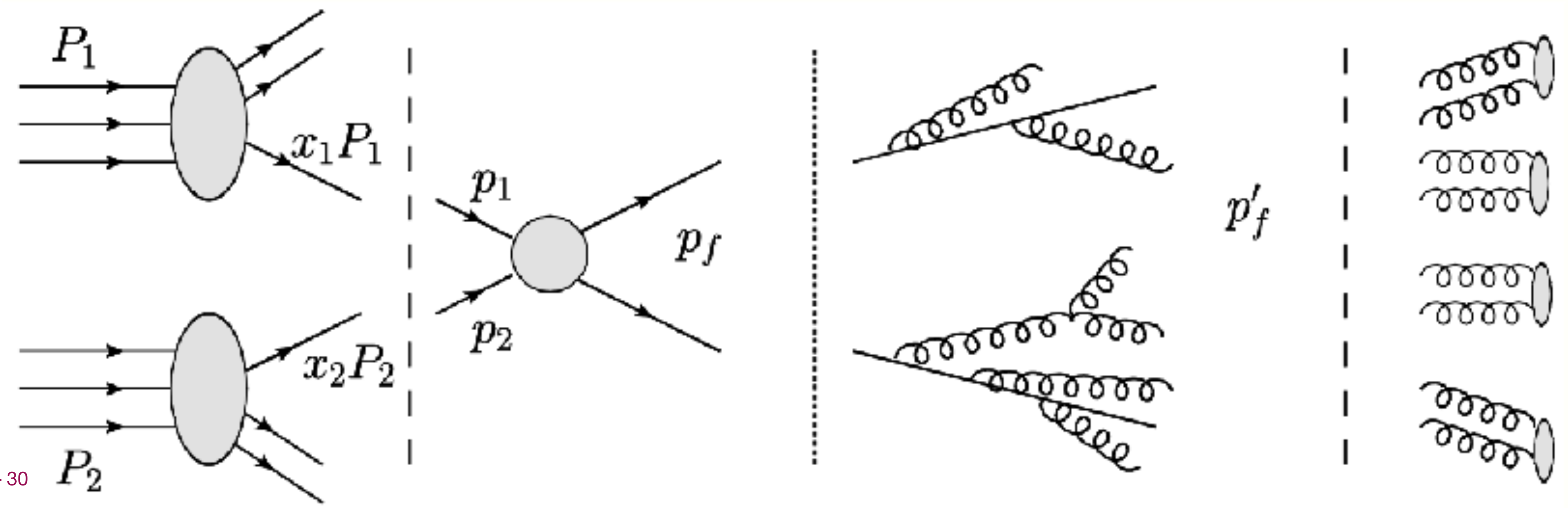
Introduction

- Heavy quarks (charm and beauty) are primary produced in hard scattering processes with large momentum transfer
- Production cross-sections is calculated in pQCD utilizing a factorization approach.



Physics Procedia 51 (2014) 25 – 30

Fractorization theorem

$f_i(x_i, \mu_F)$ pdf — non-perturbative — Initial condition from data

$d\sigma$ hard x-section — perturbative

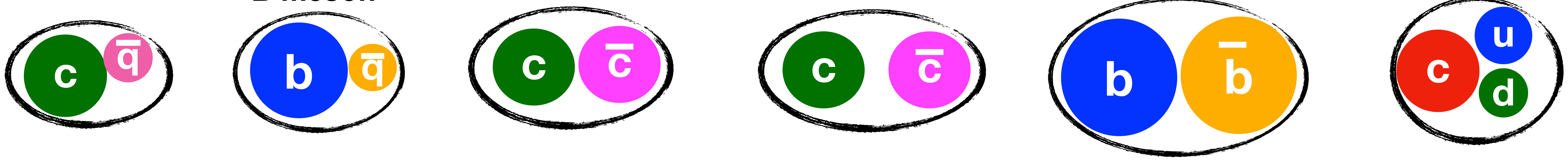
Parton shower — perturbative

Hadronization — non-perturbative — phenomenology + fit to data (e+e-, e-p)

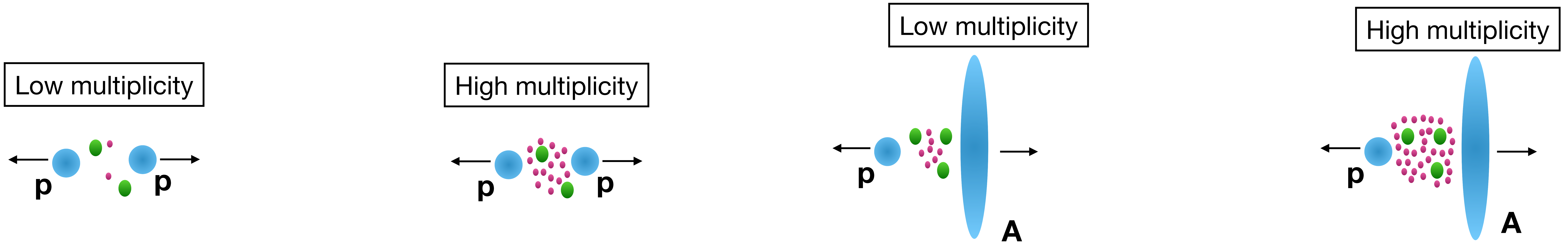
$$\frac{d\sigma^D}{dp_T^D}(\mu_F, \mu_R) = PDF(x_1)\ PDF(x_2)\ \times\ \frac{d\sigma^c}{dp_T^c}\ \times\ D_{c\to D}(z = p_D/p_c)$$

Measurements of heavy flavor particles (open HF hadrons, Quarkonia) —> test the pQCD calculations and provide input for the data driven npQCD quantities.

D meson **B meson** **J/Ψ** **Ψ(2S)** **Υ(nS)** **Λc baryon**



System size dependence



pp

- Test and constraint pQCD calculations and phenomenological models.
- Multi parton interactions (MPI)
- Study correlation between hard processes and soft underlying event

p-A

- study effects of cold nuclear matter
  - nPDFs
  - Initial and final state radiation
  - Gluon saturation at low x
  - k_T broadening

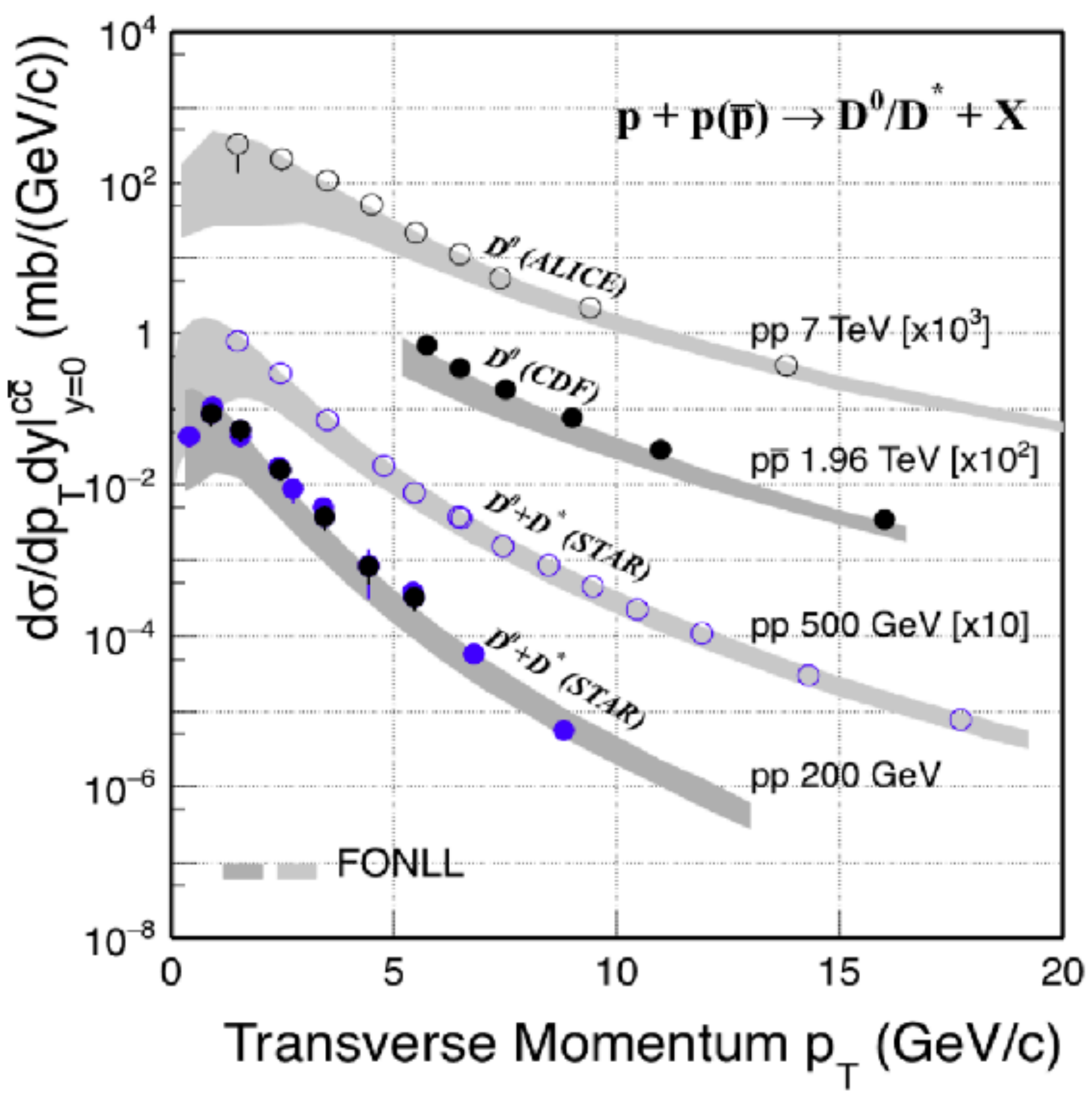
Study collective effects —> small QGP droplet?
Other signatures of QGP in small systems such as HF suppression, sequential suppression of Quarkonia?

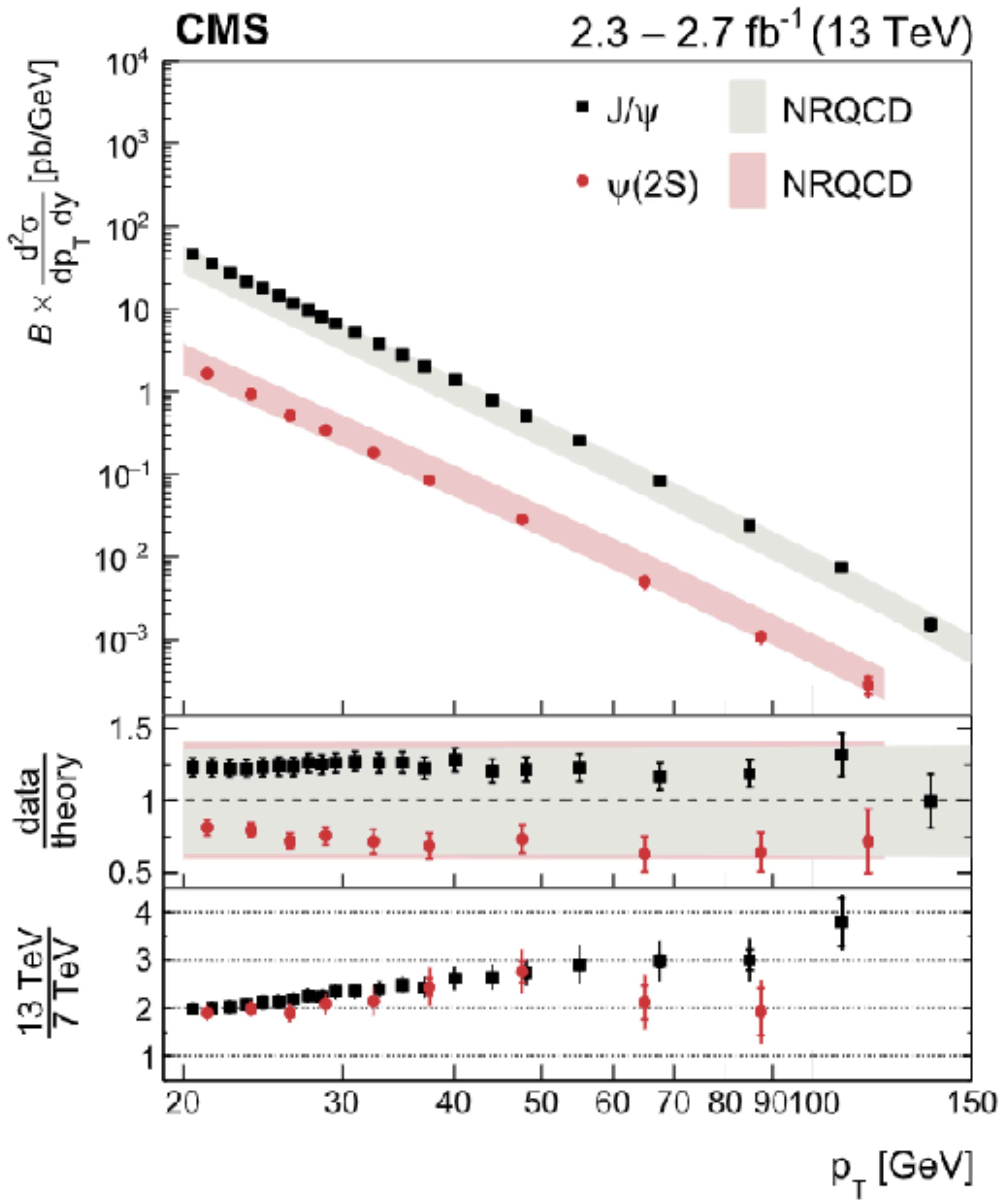
This talk:
- Heavy flavor production in pp and p-A collisions in MB and vs. multiplicity
  - open charm and beauty, charmonium and bottomonium
- Measurements studying heavy-flavor fragmentation and hadronization
- Search for jet quenching effects in small systems

*Only a selection of results

Charm hadron cross-section

Test pQCD calculations with charm hadron and charmonium cross-sections



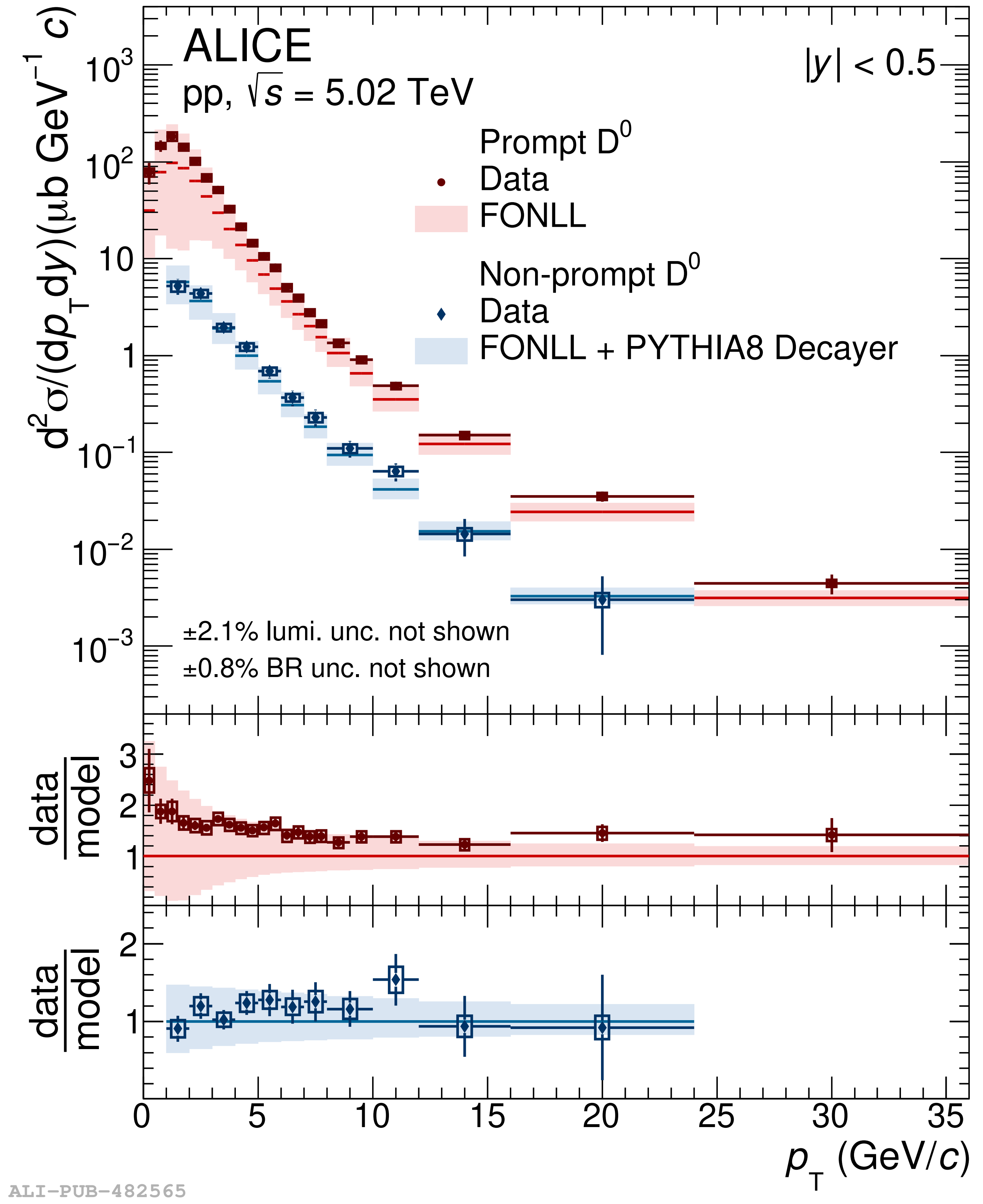


PLB 780 (2018) 251

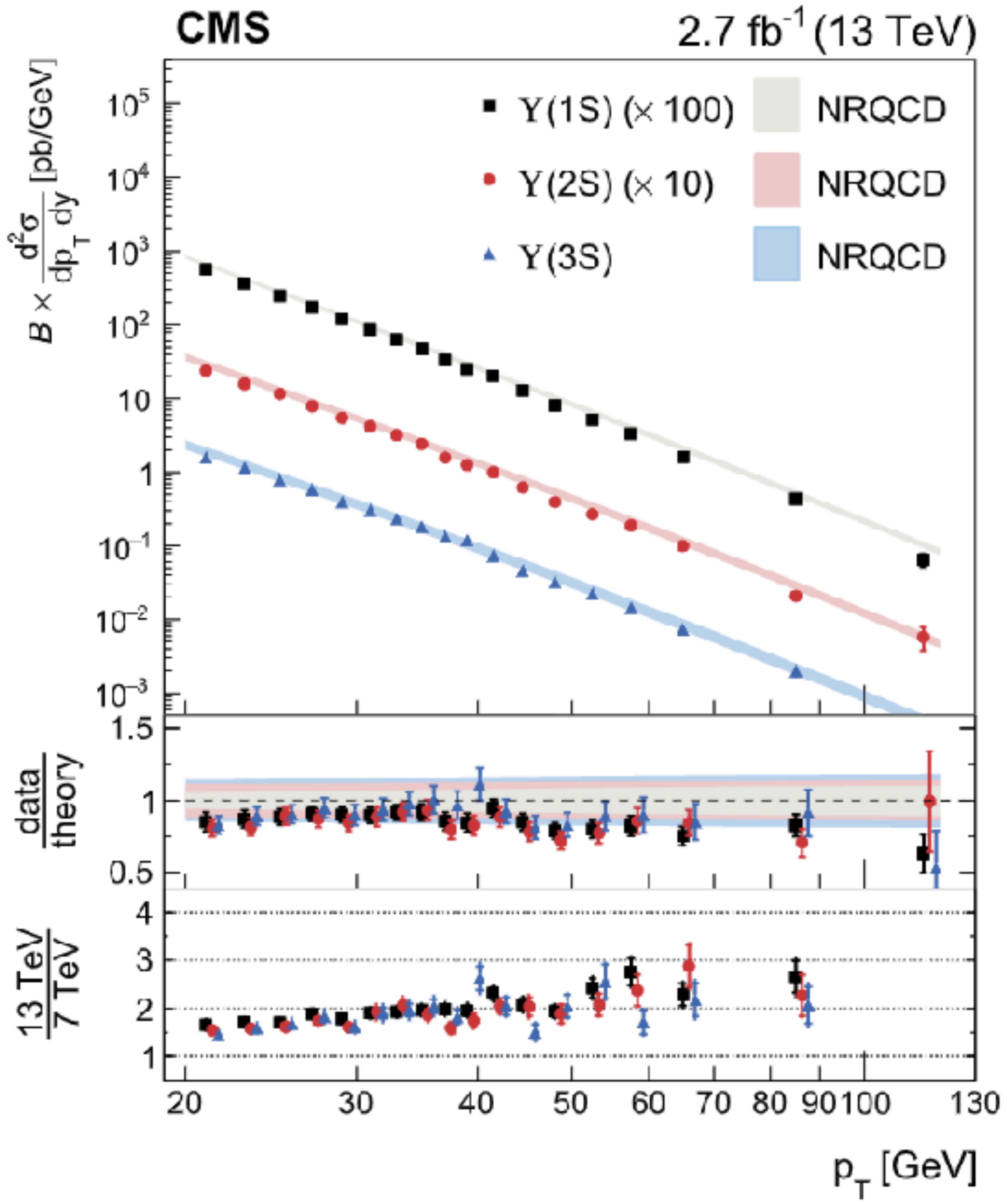
- p_T and η differential cross-section measurements performed for open charm, J/Ψ, Ψ(2S) at different energies.
- pQCD based calculations describe the open charm cross-sections within large uncertainties.
- Charmonium production, both J/Ψ and Ψ(2S), described by NLO NRQCD calculations.

Beauty hadron cross-section

Test pQCD calculations with beauty hadron and bottomonium cross-sections



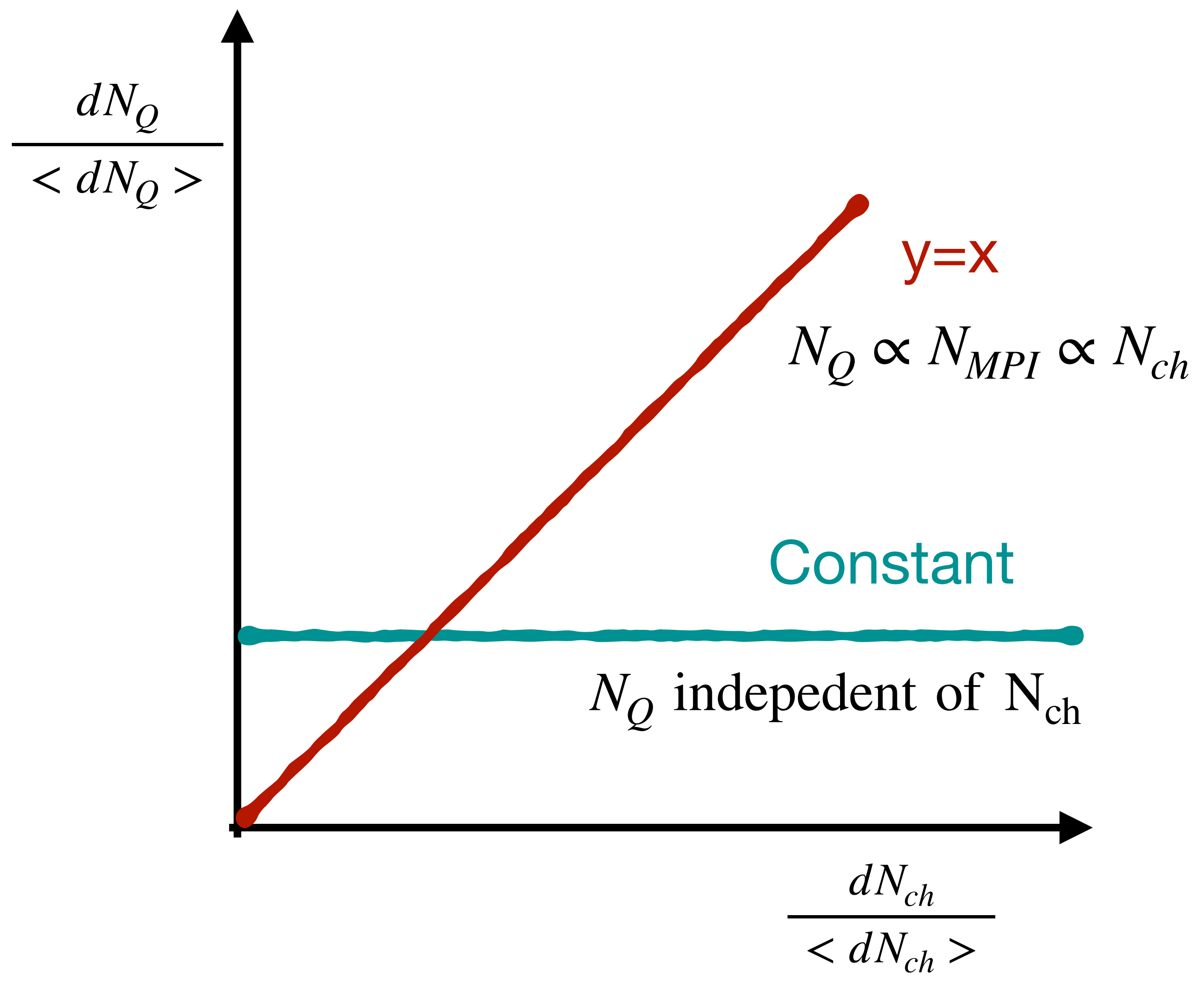
JHEP 05 (2021) 220
PLB 780 (2018) 251



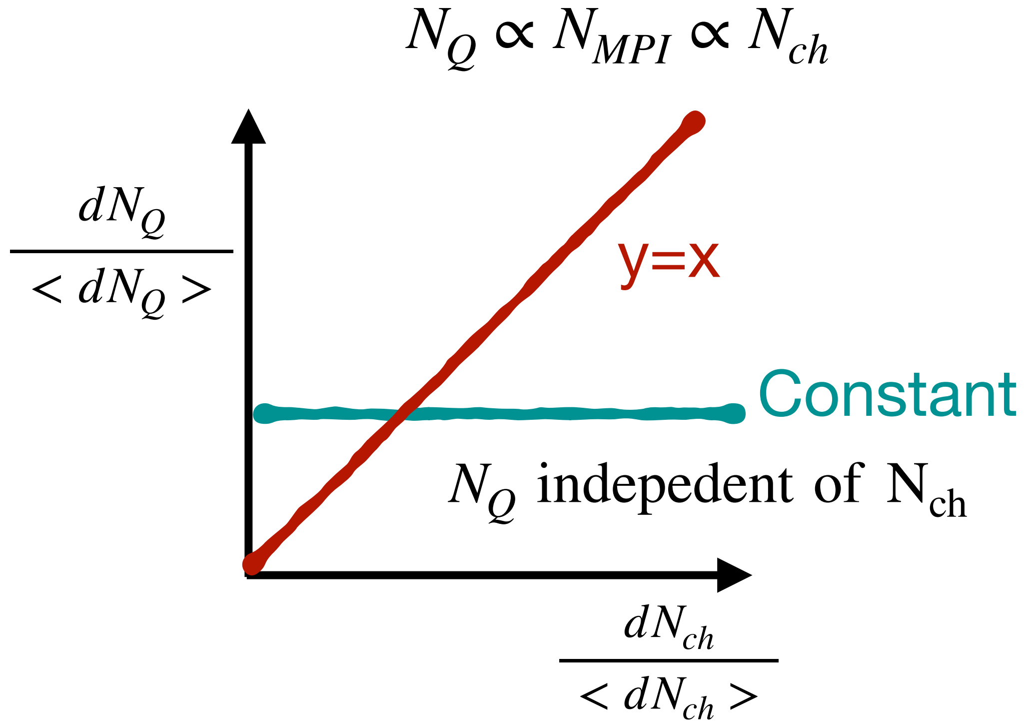
- p_T and η differential cross-section measurements performed for b->D^0, B mesons, Υ(1S), Υ(2S), Υ(3S) at different energies.
- pQCD calculations describe the cross-sections within large uncertainties.
- Bottomonium production well described by NLO NRQCD calculations.

Multiplicity dependent production in pp

Study correlations between heavy-flavor production and soft underlying event



Multiplicity dependent production in pp



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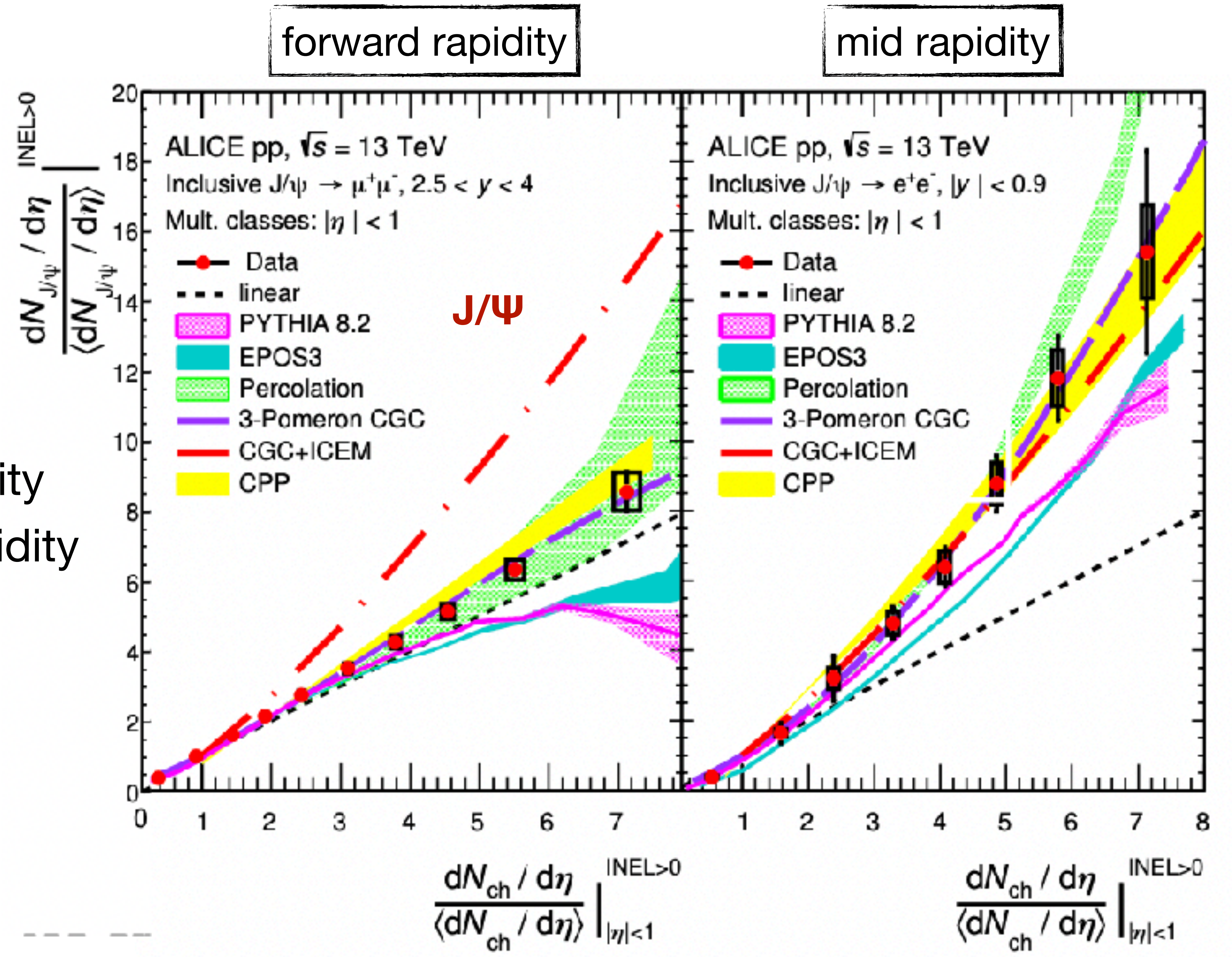
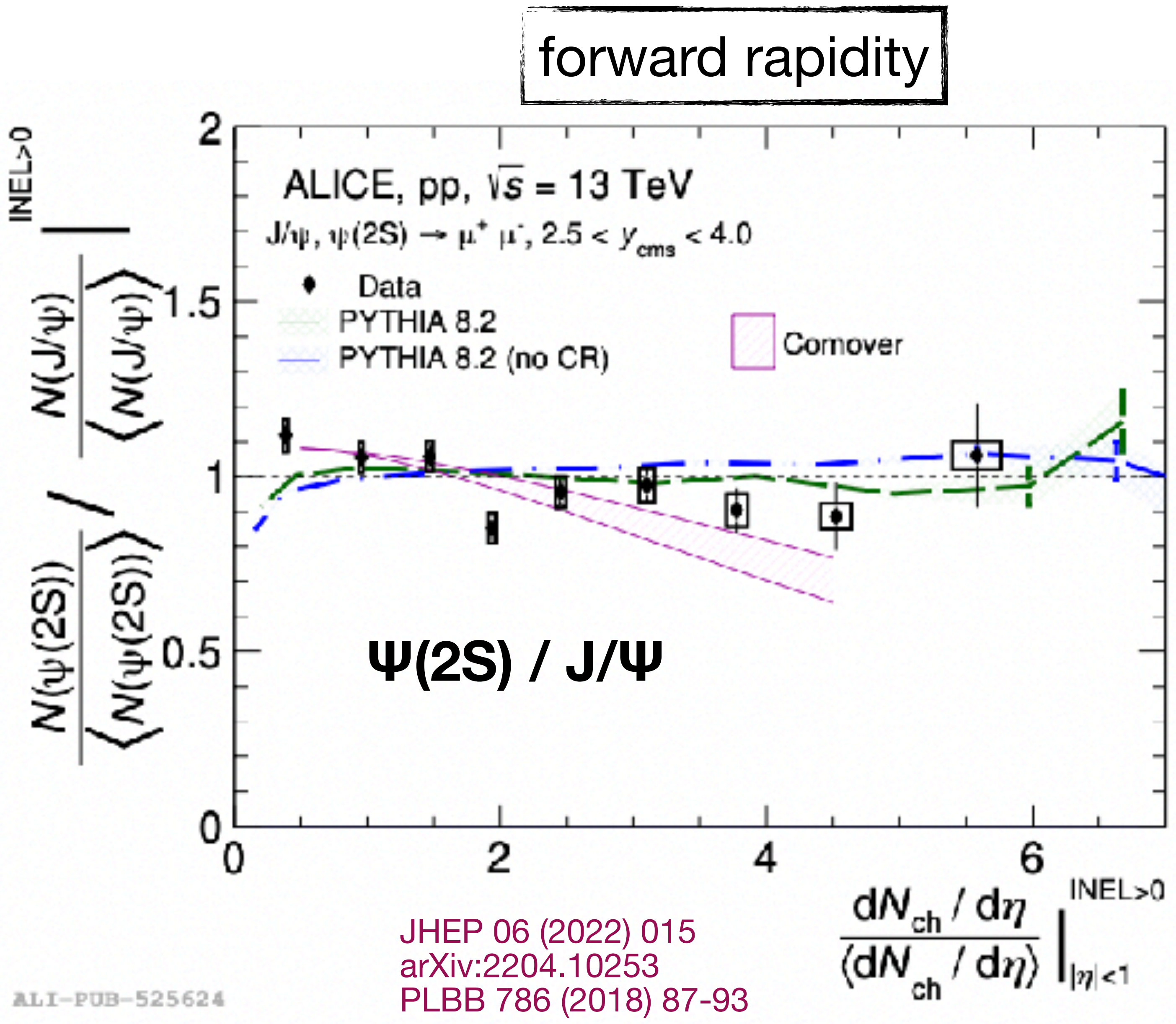




JHEP 06 (2022) 015
arXiv:2204.10253
PLBB 786 (2018) 87-93

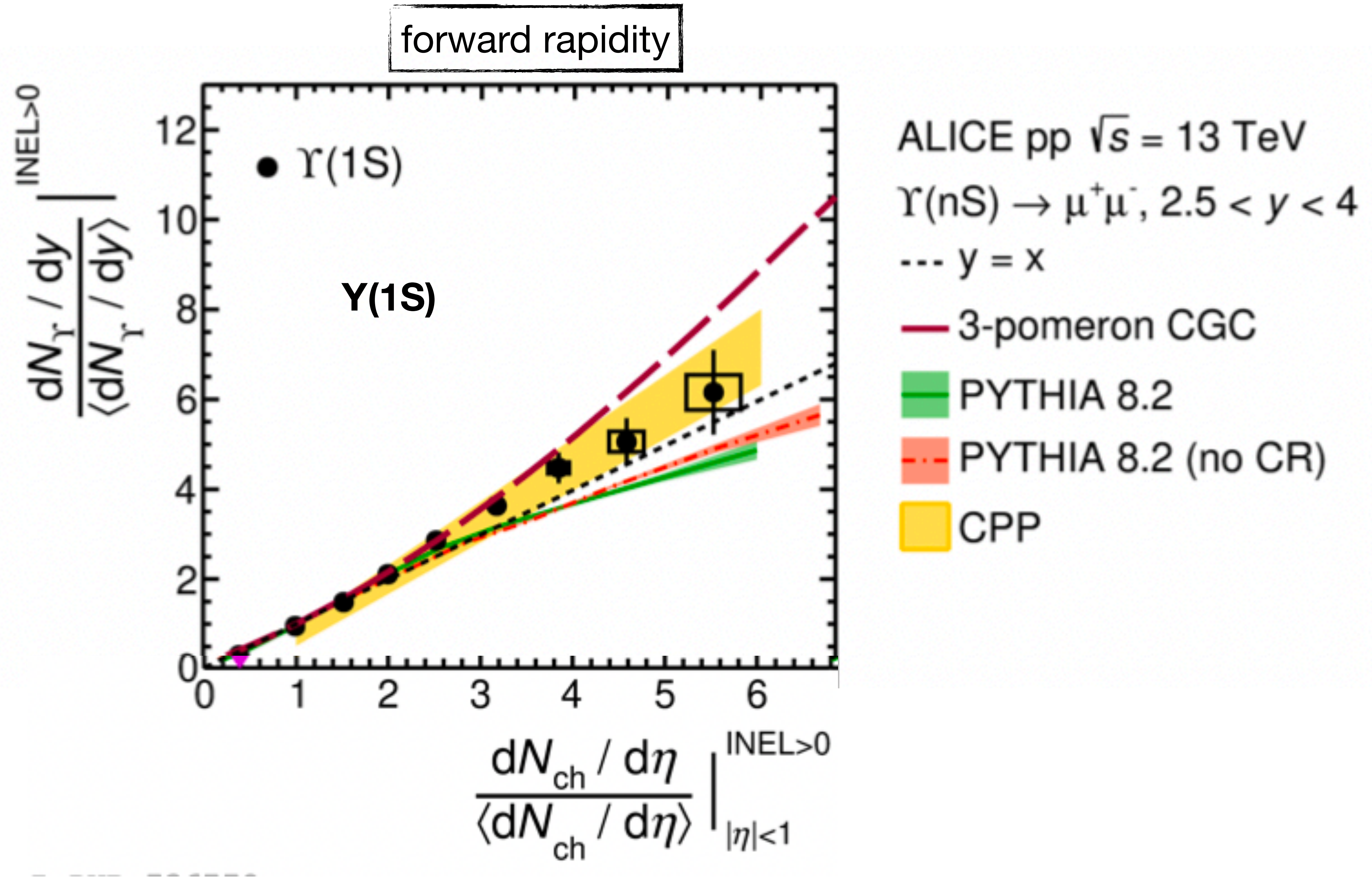
- Linear dependence in forward rapidity
- Faster than linear growth in mid rapidity
  - effects of autocorrelations
- No $\sqrt{s}$ dependence
  - same trend at RHIC and at LHC
- Similar behavior for open charm mesons

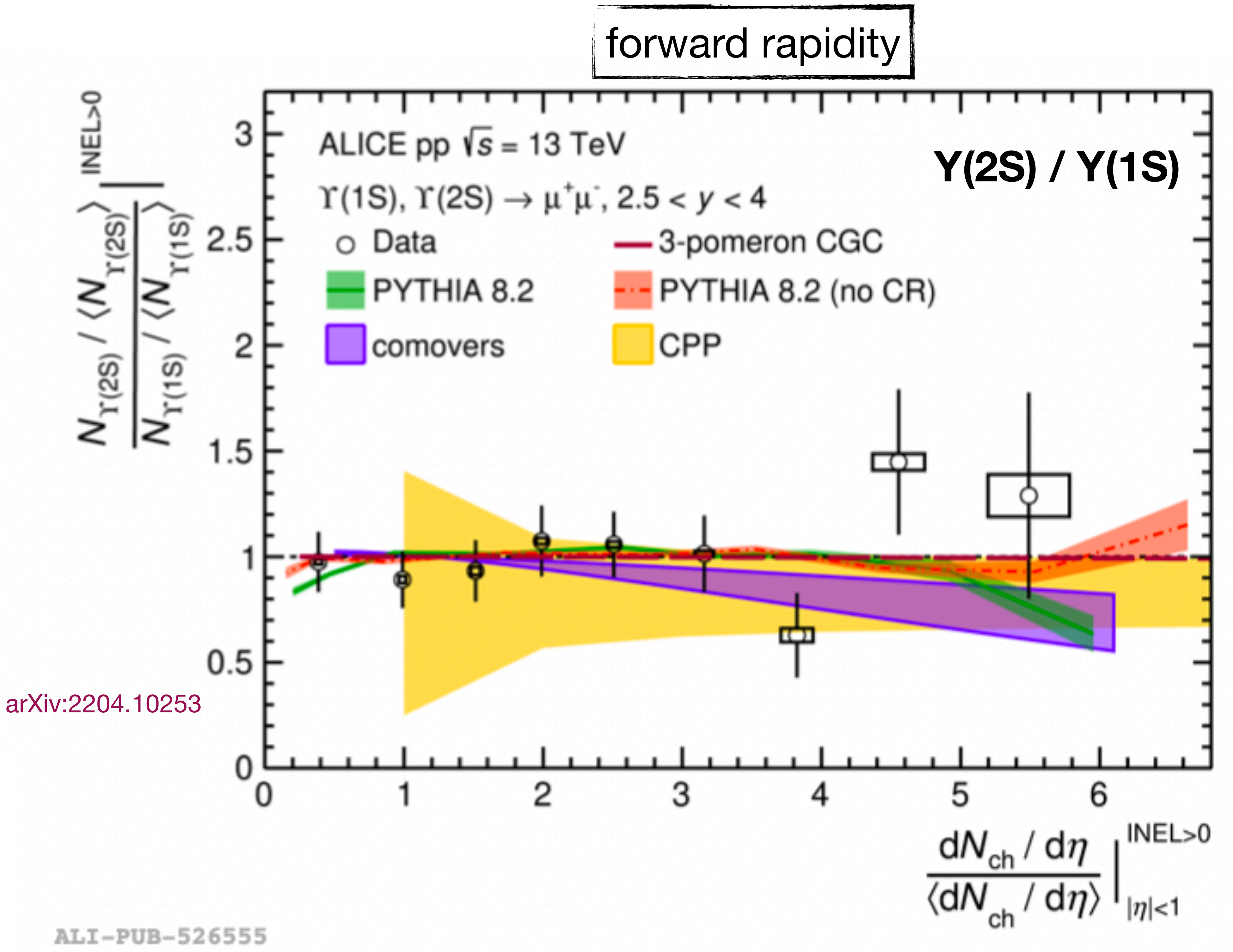
- Similar multiplicity dependence for Ψ(2S) / J/Ψ
- PYTHIA describes the data

- Percolation, Coherent Particle Production (CPP) and the 3-Pomeron Color Glass Condensate models agree with data in both rapidity intervals.

Multiplicity dependent production in pp

Study correlations between heavy-flavor production and soft underlying event



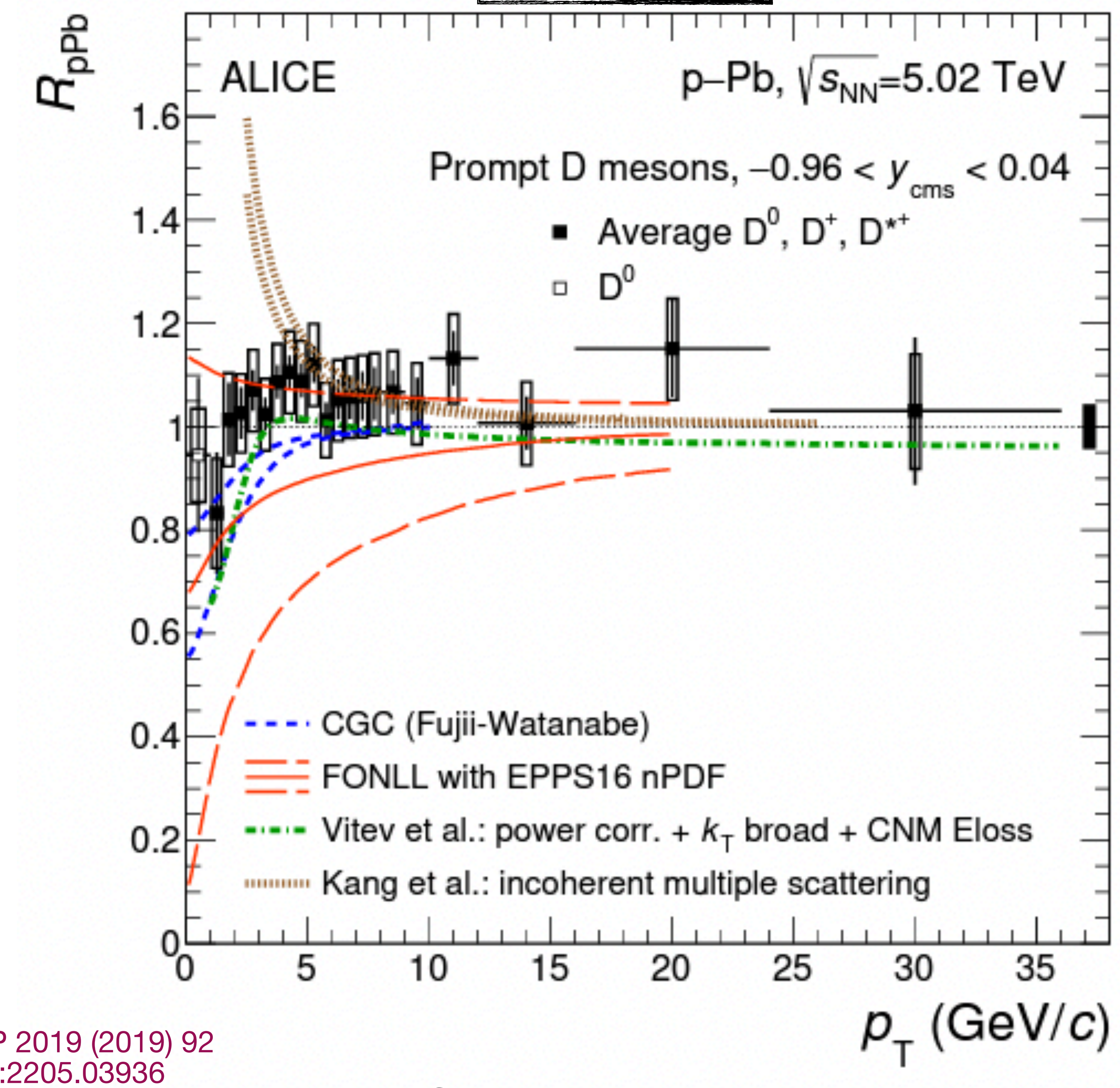


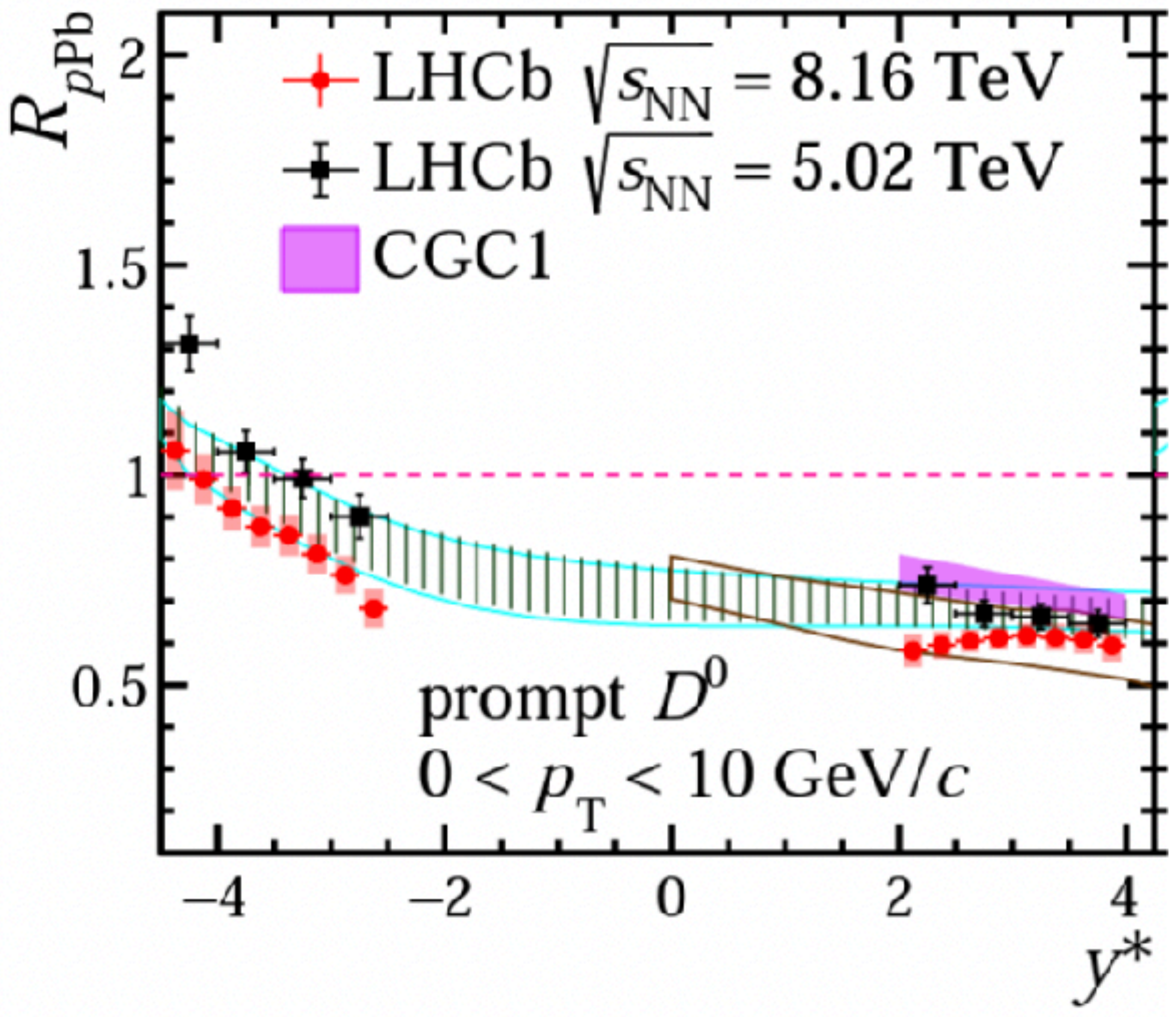
- Linear dependence for Y(nS) vs multiplicity at forward rapidity
- Coherent Particle Production (CPP) model best describes the data
- Understanding of these measurements not straight forward due to several components
  - UE modeling, auto correlation effects, p_T spectra vs multiplicity
  - Benchmark models on many of these aspects to better constraint

Charm production in p-A

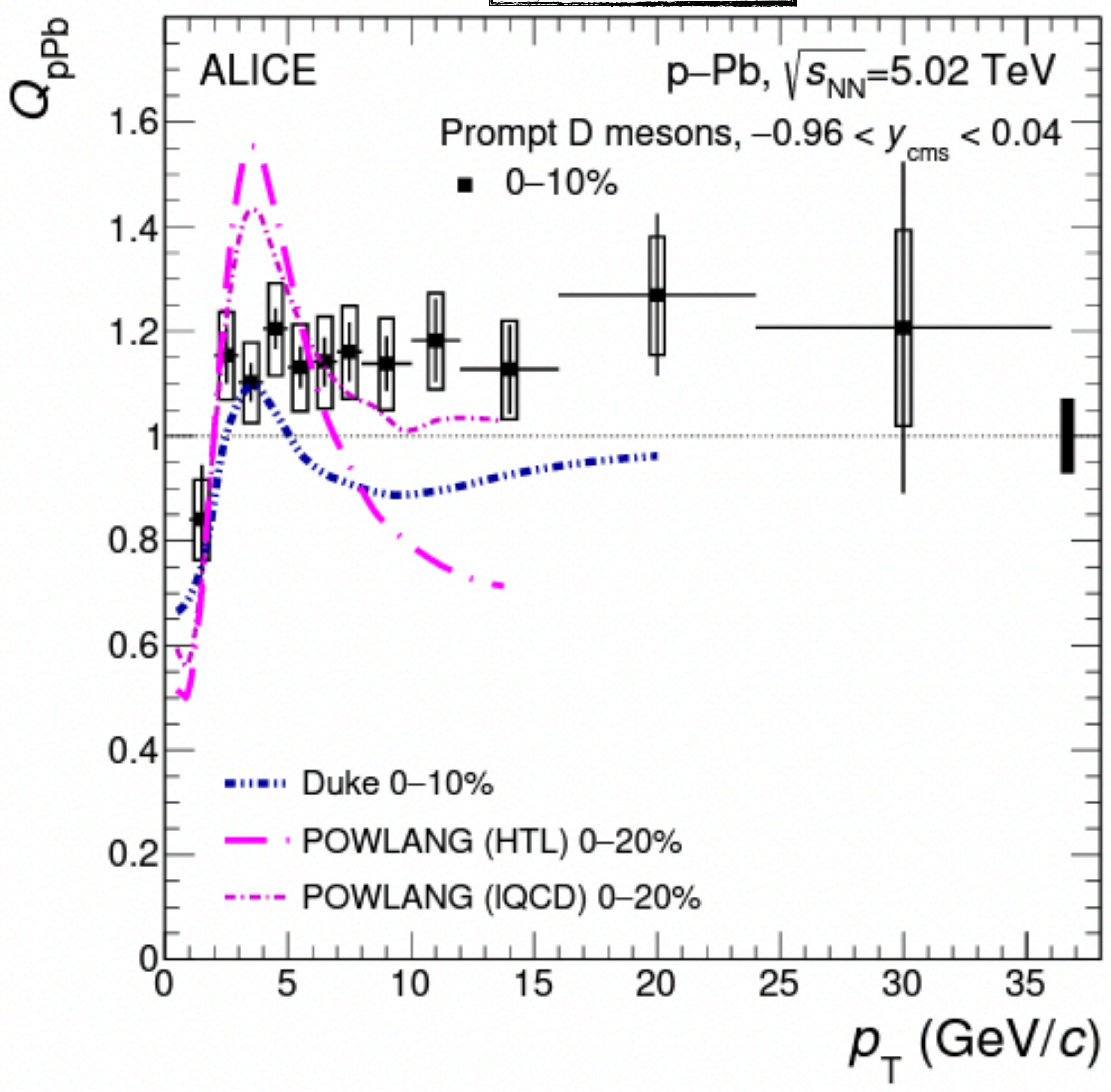
Study cold nuclear matter effects and multiplicity dependence with D mesons

mid rapidity





mid rapidity

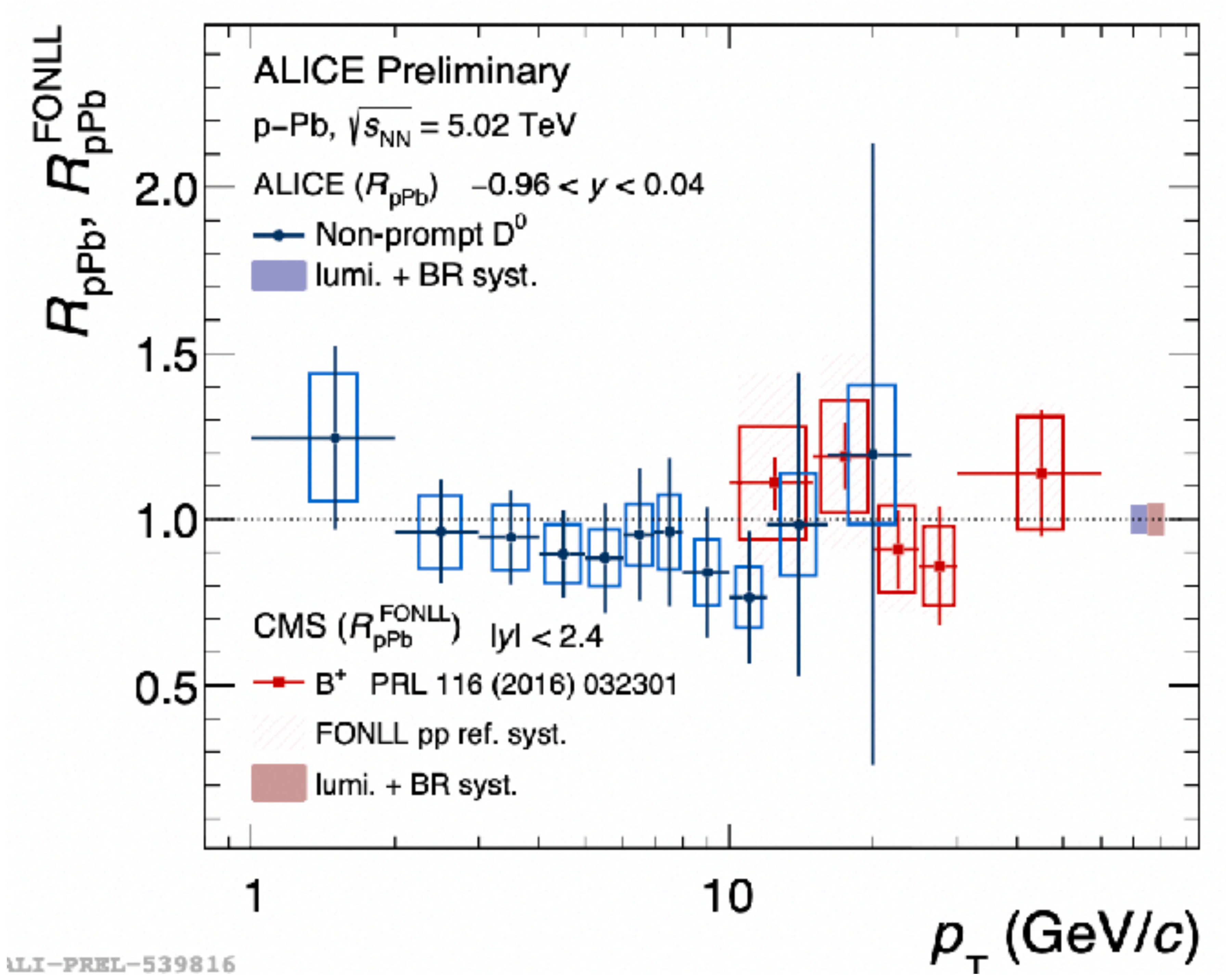


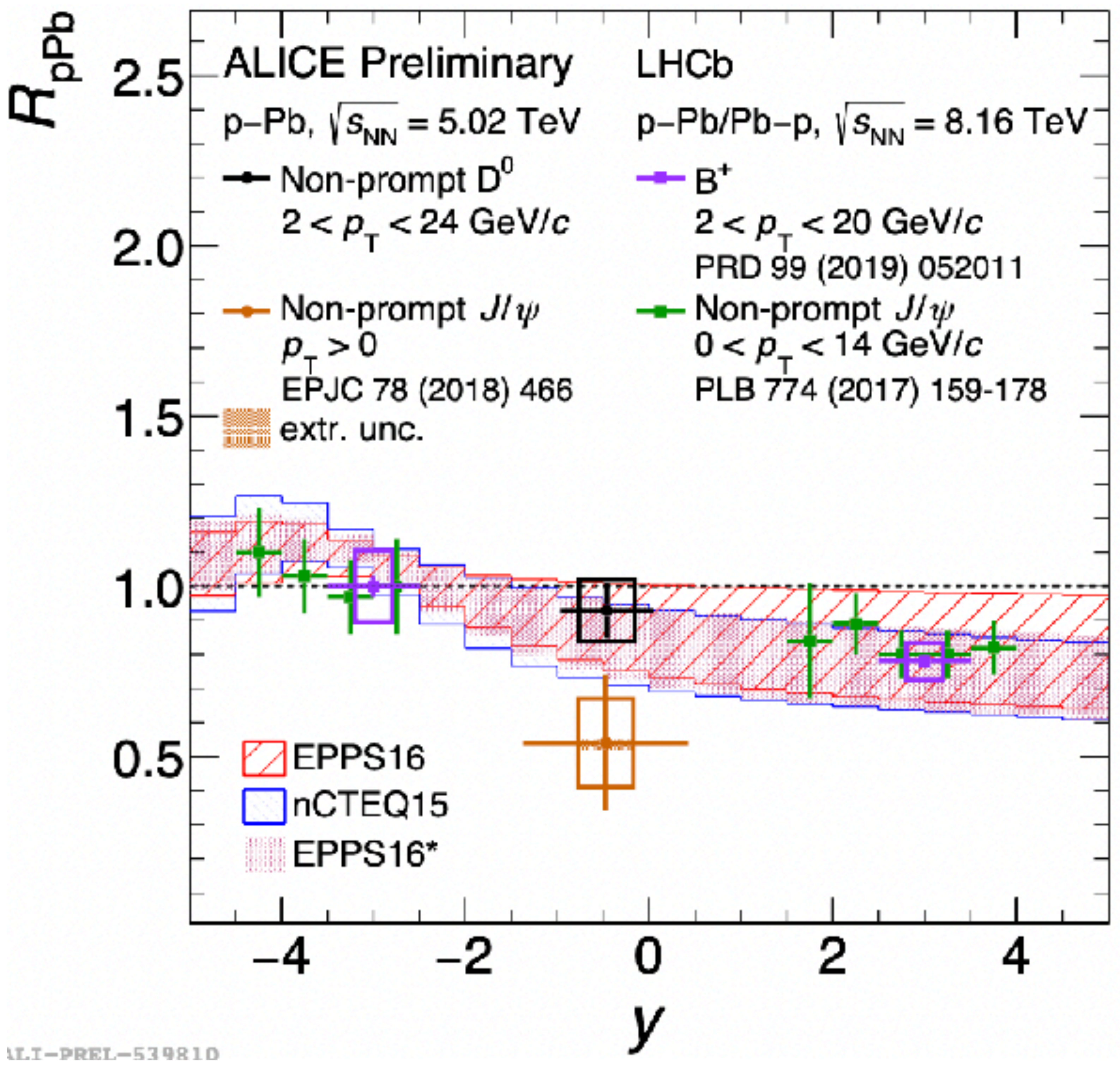
JHEP 2019 (2019) 92
arXiv:2205.03936

- R_{pPb} of D mesons consistent with unity in mid-rapidity
- Significant suppression at forward rapidity.
- Models with CNM effects describes the data.
- Q_{pPb} in 0-20% centrality class compared to Transport models with QGP droplet does not describe the data.

Beauty production in p-Pb

Study cold nuclear matter effects with B hadrons





- R_{pPb} of b->D^0 and B hadrons consistent with unity in mid-rapidity and suppression at forward rapidity.
- Models with CNM effects describes the data.

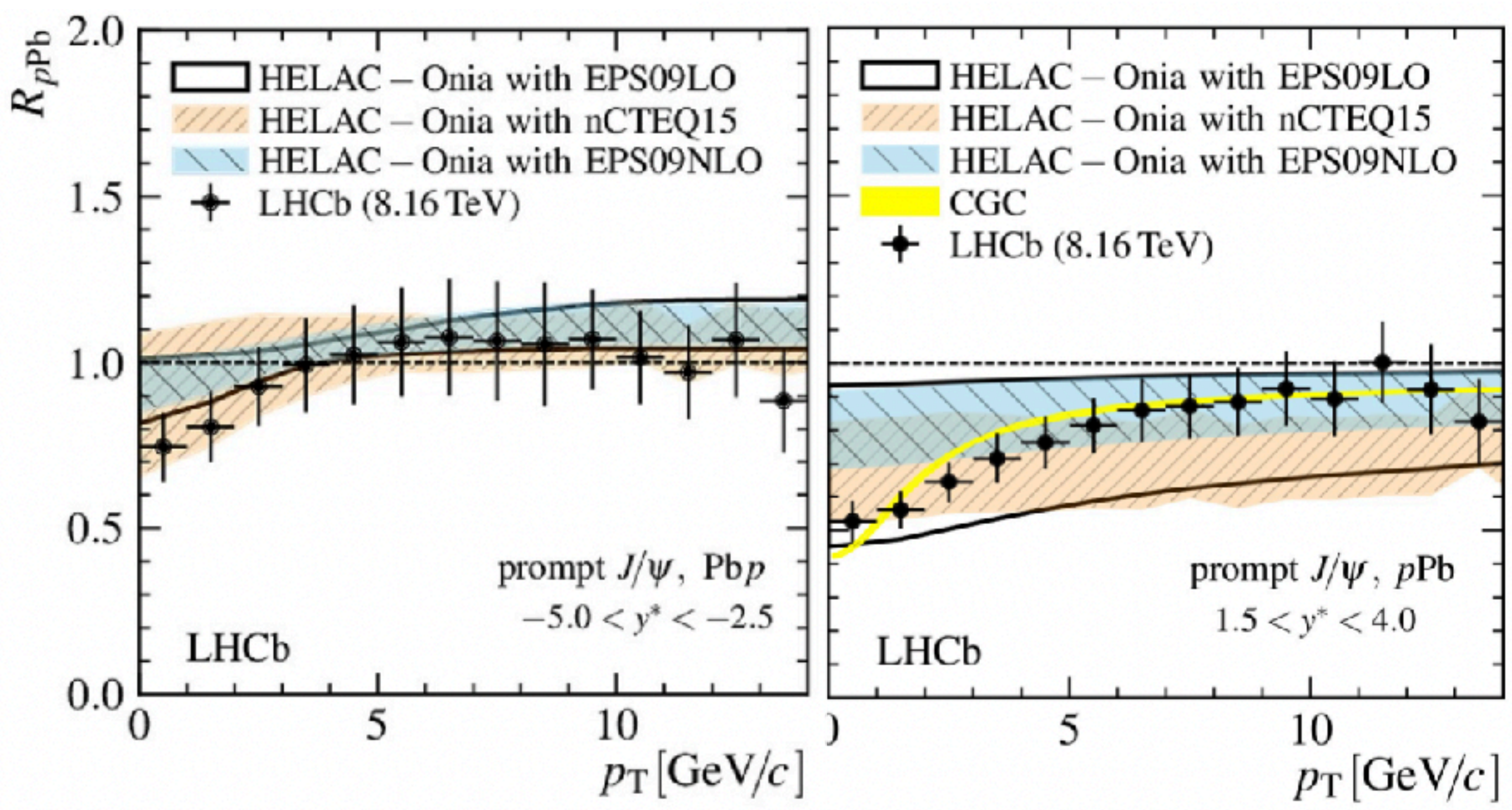
Charmonium production in p-A

Study cold nuclear matter effects and final state effects with J/Ψ and Ψ(2S)

- nPDF, CGC, energy loss in nucleus, final state interactions with co-moving medium or a QGP

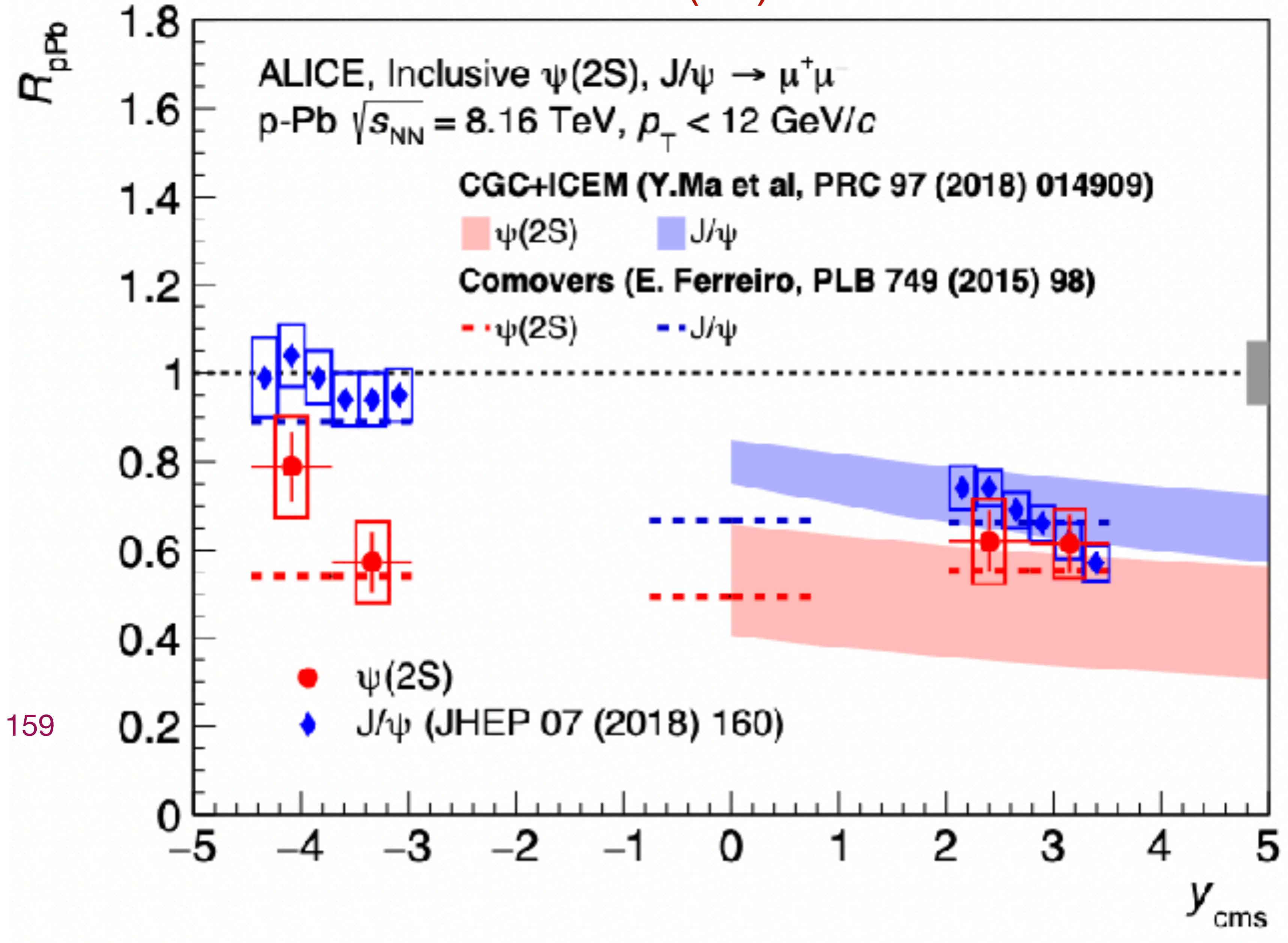
backward rapidity (large x in Pb)

forward rapidity (low x in Pb)



Phys. Lett. B774 (2017) 159
JHEP 03 (2016) 133
JHEP07 (2020) 237

J/Ψ
Ψ(2S)



- Strong suppression at low p_T and at forward rapidity for J/Ψ
- R_{pA} ~ 1 at high p_T
- No energy dependence
- Models with different nPDFs, CGC describe data.

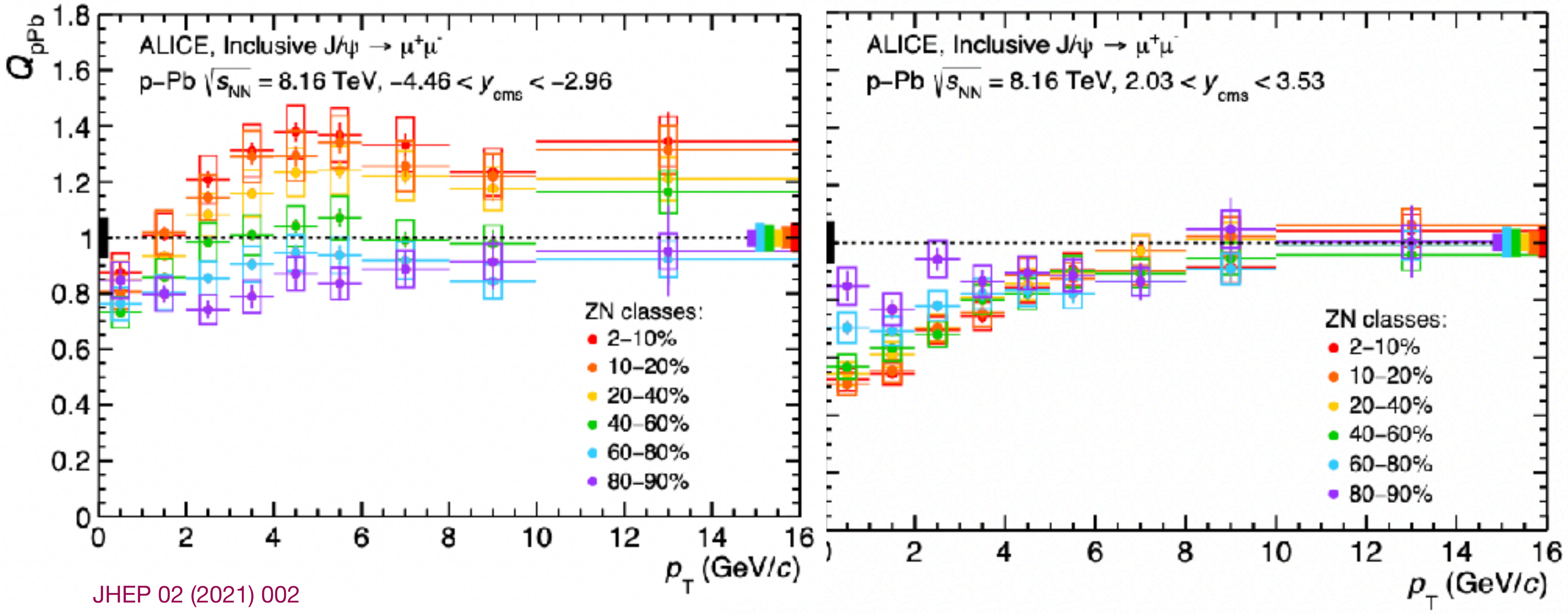
- Ψ(2S) is more suppressed than J/Ψ at backward rapidity.
- Models that include final state interactions leading to charmonium breakup (comover interaction model) describe the data.

Charmonium production in p-A

Multiplicity dependent nuclear medication factor for J/Ψ

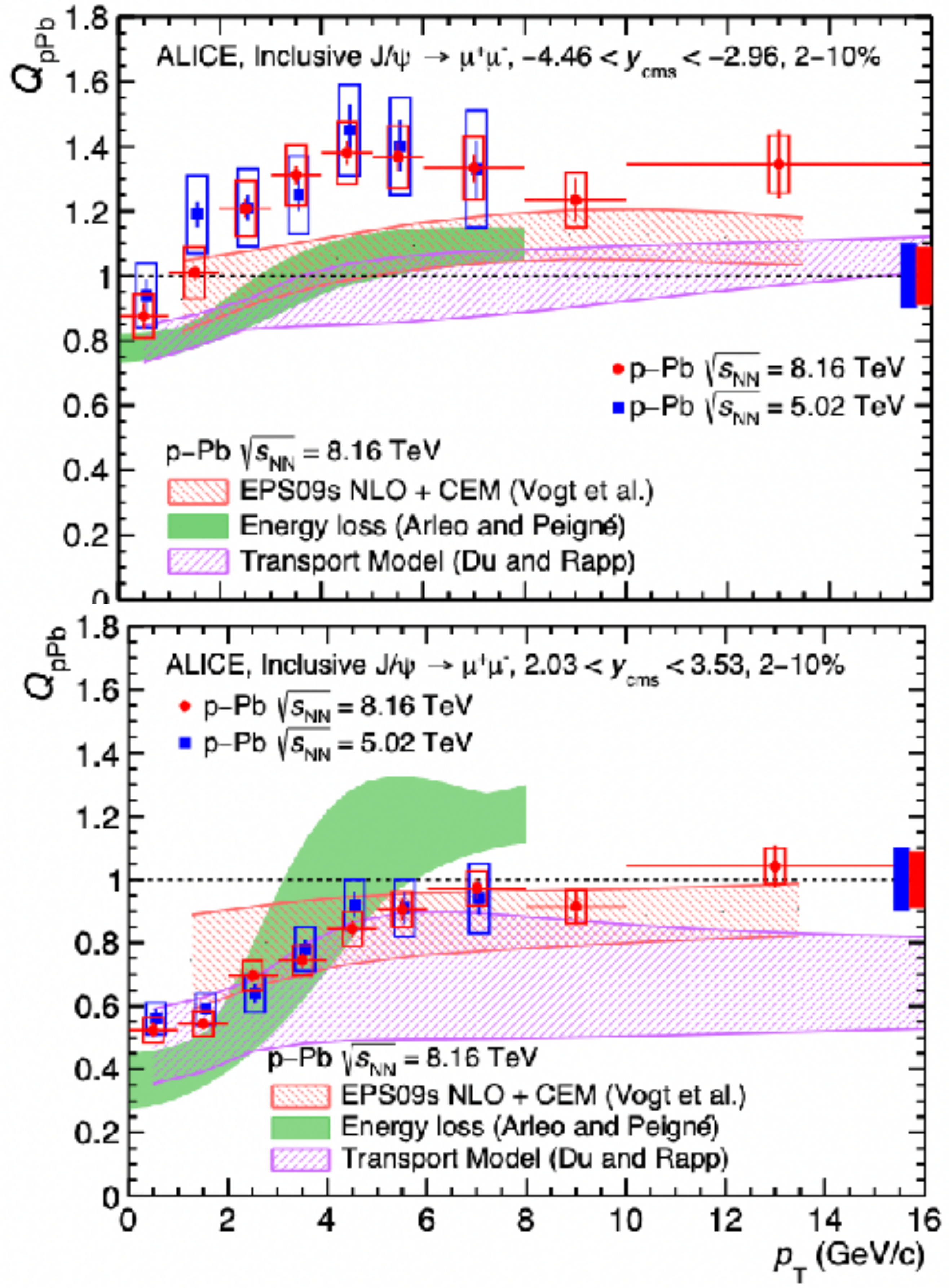
backward rapidity (large x in Pb)

forward rapidity (low x in Pb)



JHEP 02 (2021) 002

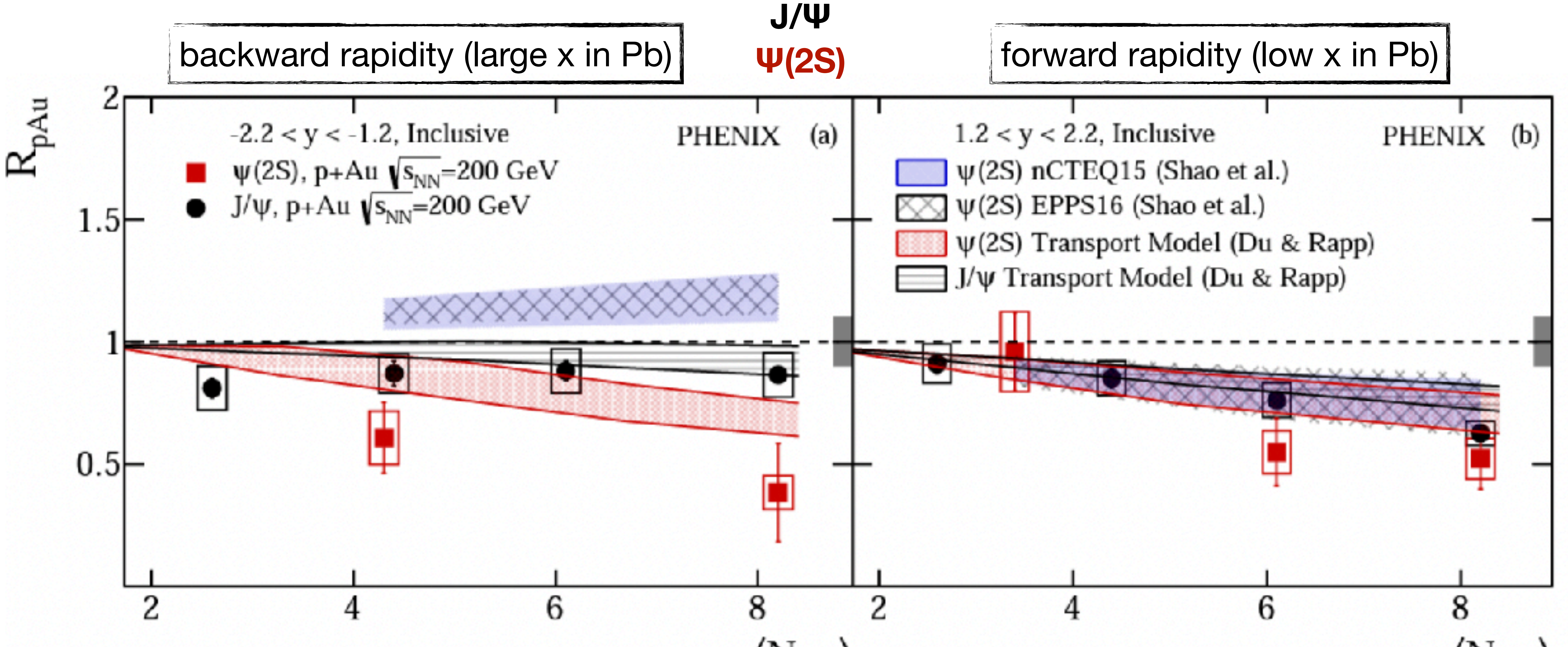
- Backward: Q_{pPb} increases with p_T reaching a plateau for p_T > 5 GeV/c
  - value of plateau highest for most central collisions.
- Forward: Q_{pPb} is < 1 at low p_T; values increasing to 1 with p_T
  - Strong centrality dependence observed —> stronger suppression in central collisions



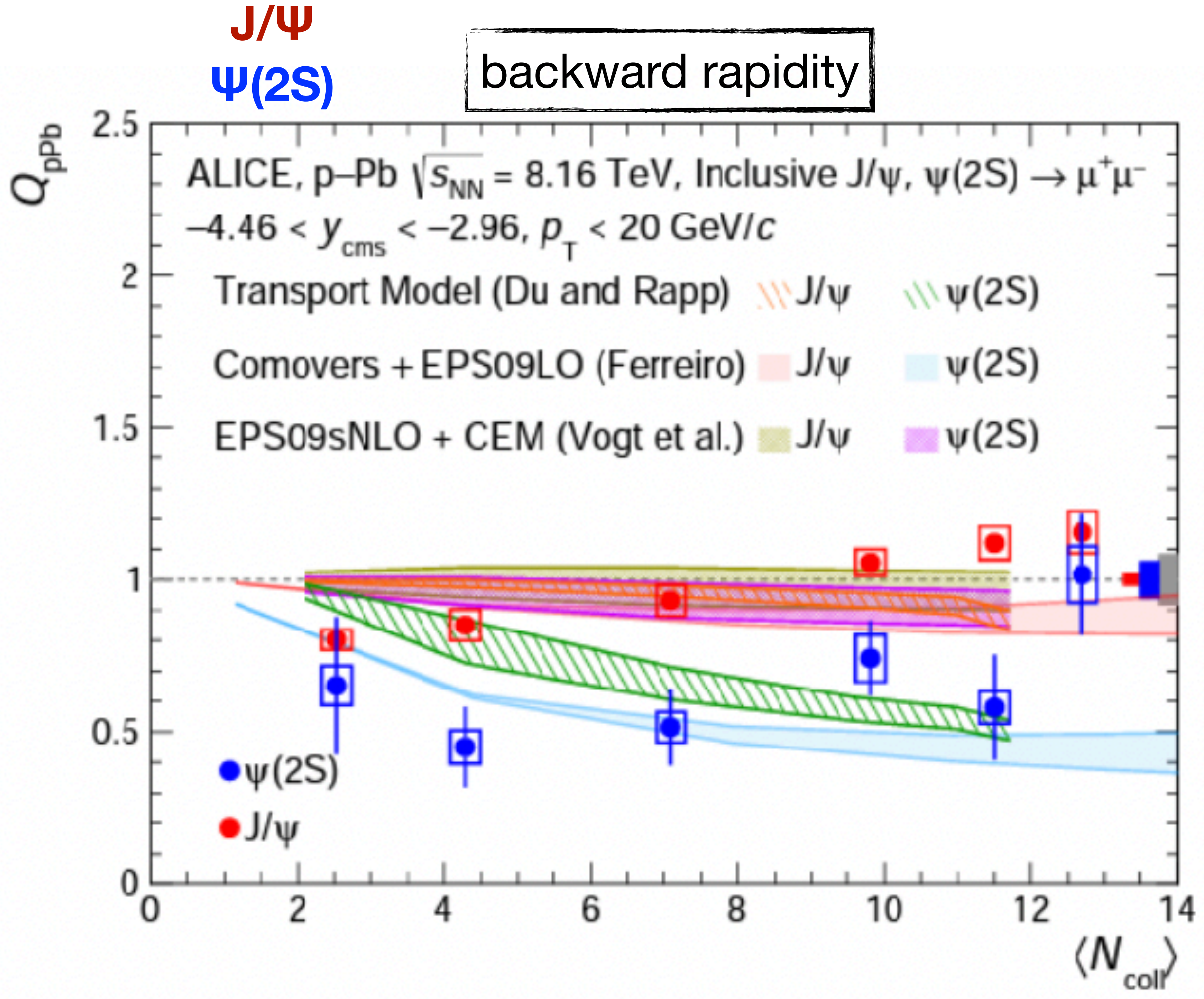
- Models with CNM effect, coherent energy loss and thermal model with QGP describe data in forward rapidity within large uncertainties.
- All models fails to describe the p_T dependence in backward rapidity.

Charmonium production in p-A vs multiplicity

Multiplicity dependent nuclear medication factor for Ψ(2S)



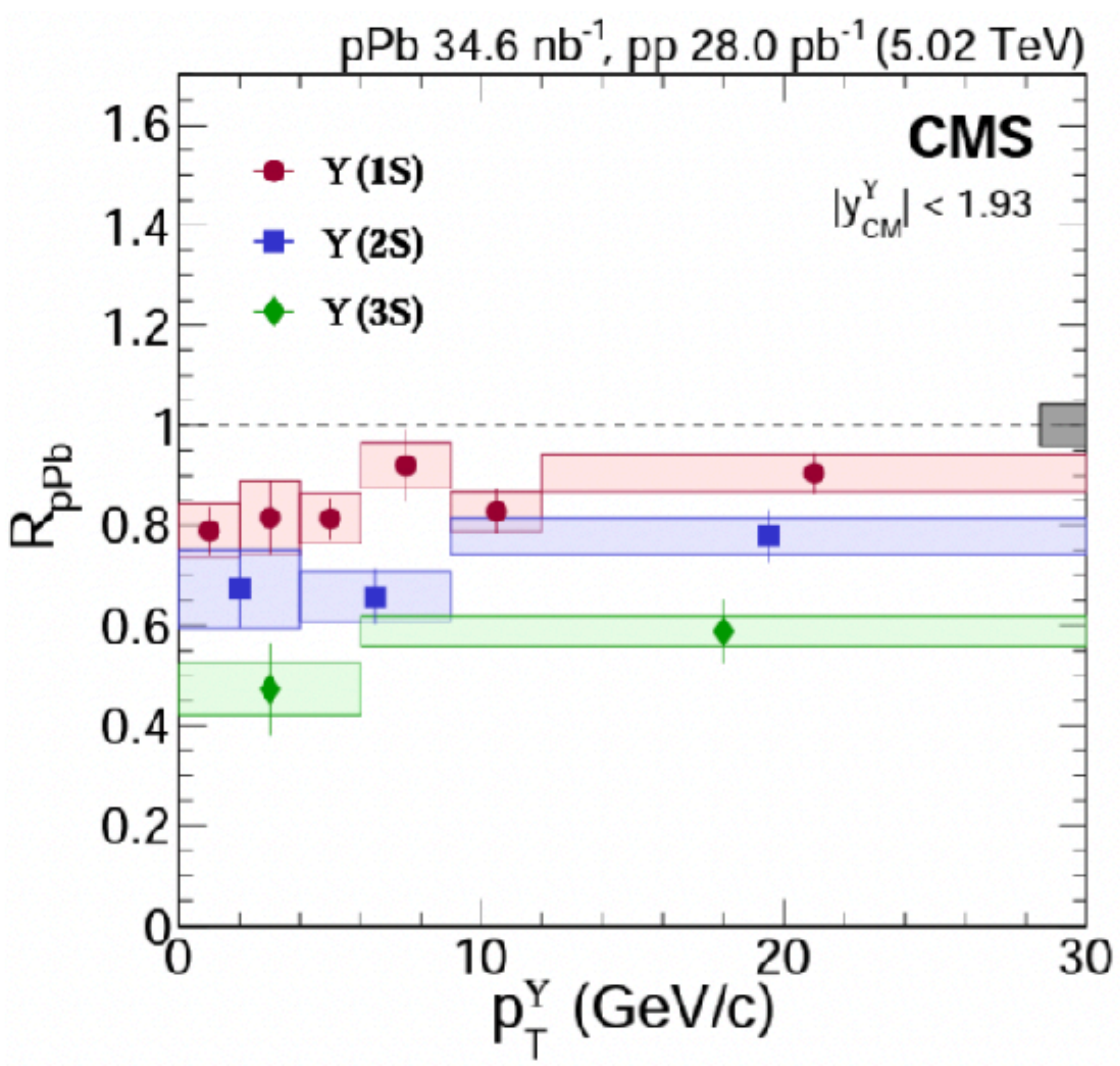
Phys. Rev. C 105, 064912 (2022)
JHEP 02 (2021) 002

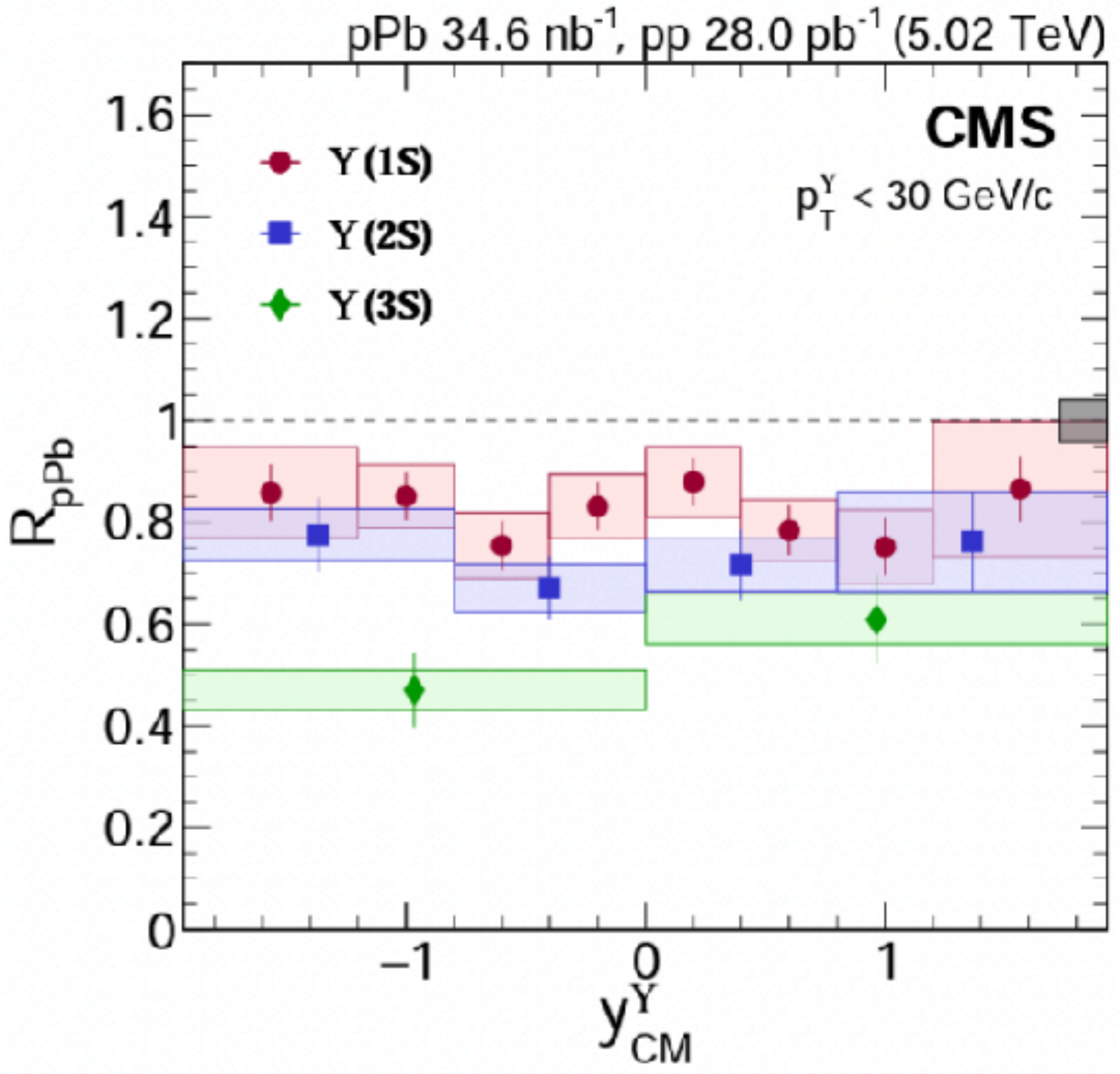


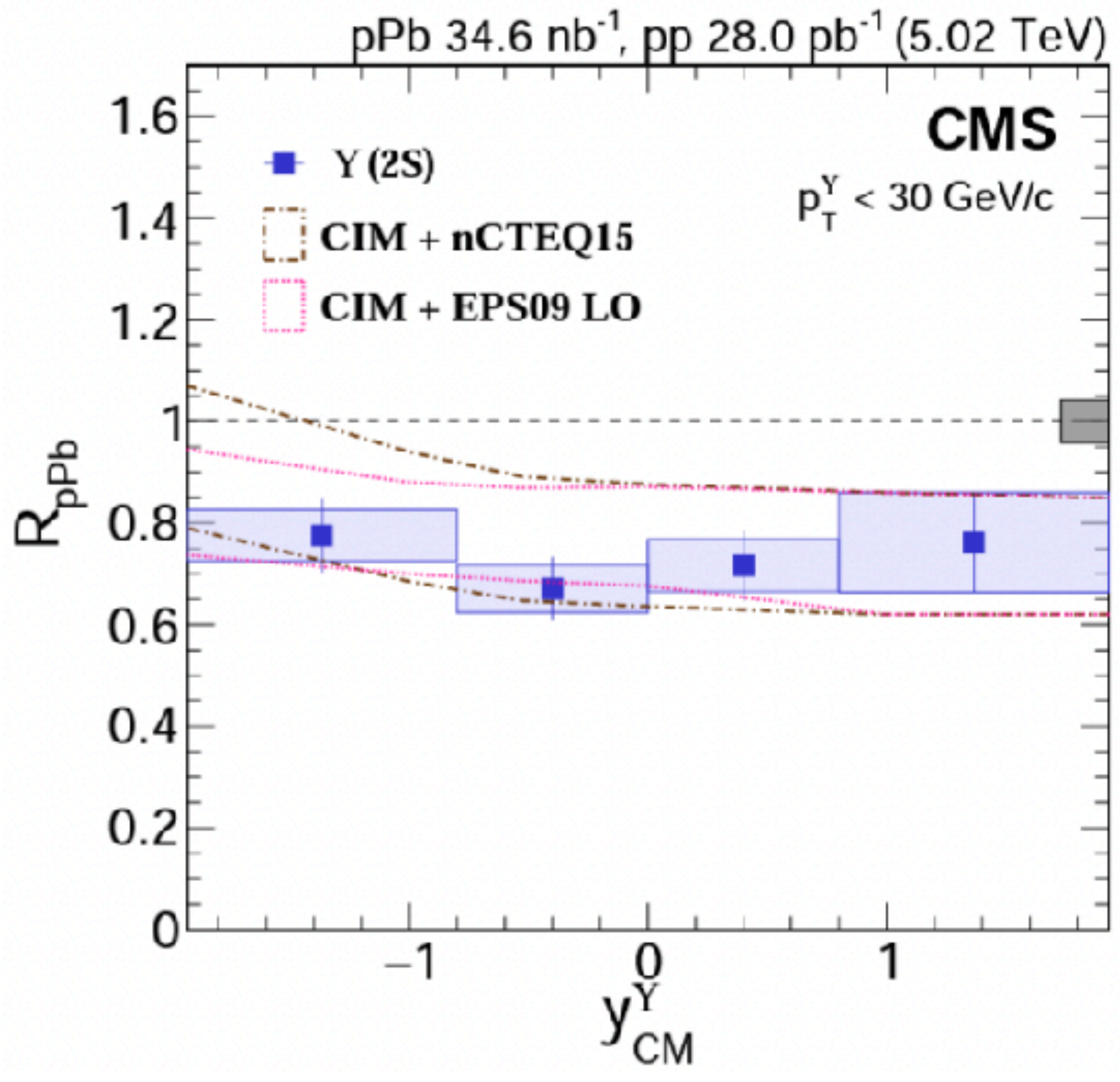
- Backward rapidity: difference in R_{pA} for J/Ψ and Ψ(2S)
- Forward rapidity: similar R_{pA} trend for J/Ψ and Ψ(2S)
- Transport model with QGP and comover interaction model predicts similar suppression pattern for Ψ(2S)

Bottomonium production in p-A

Study cold nuclear matter effects and final state effects with Υ(nS)







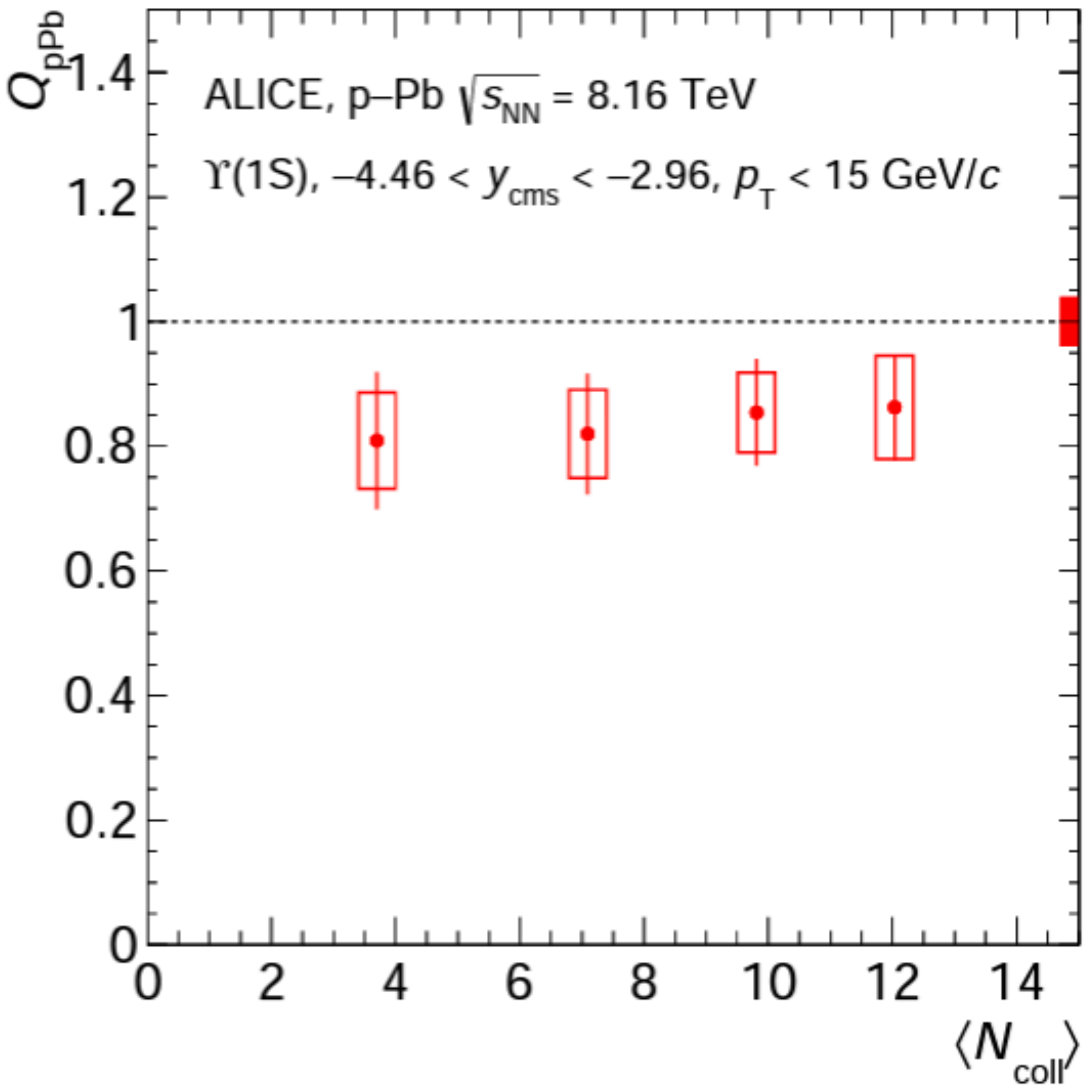
Eur. Phys. J. C 78 (2018) 171
PLB 835 (2022) 137397

- All Υ(ns) states shows suppression in p-A collisions; R_{pPb}(Υ(1S)) > R_{pPb}(Υ(2S)) > R_{pPb}(Υ(3S))
- No y dependence for all states; slightly higher suppression at low p_T for all states.
- Predictions using the CNM effects + comover interaction model (CIM) shows similar ordered suppression.

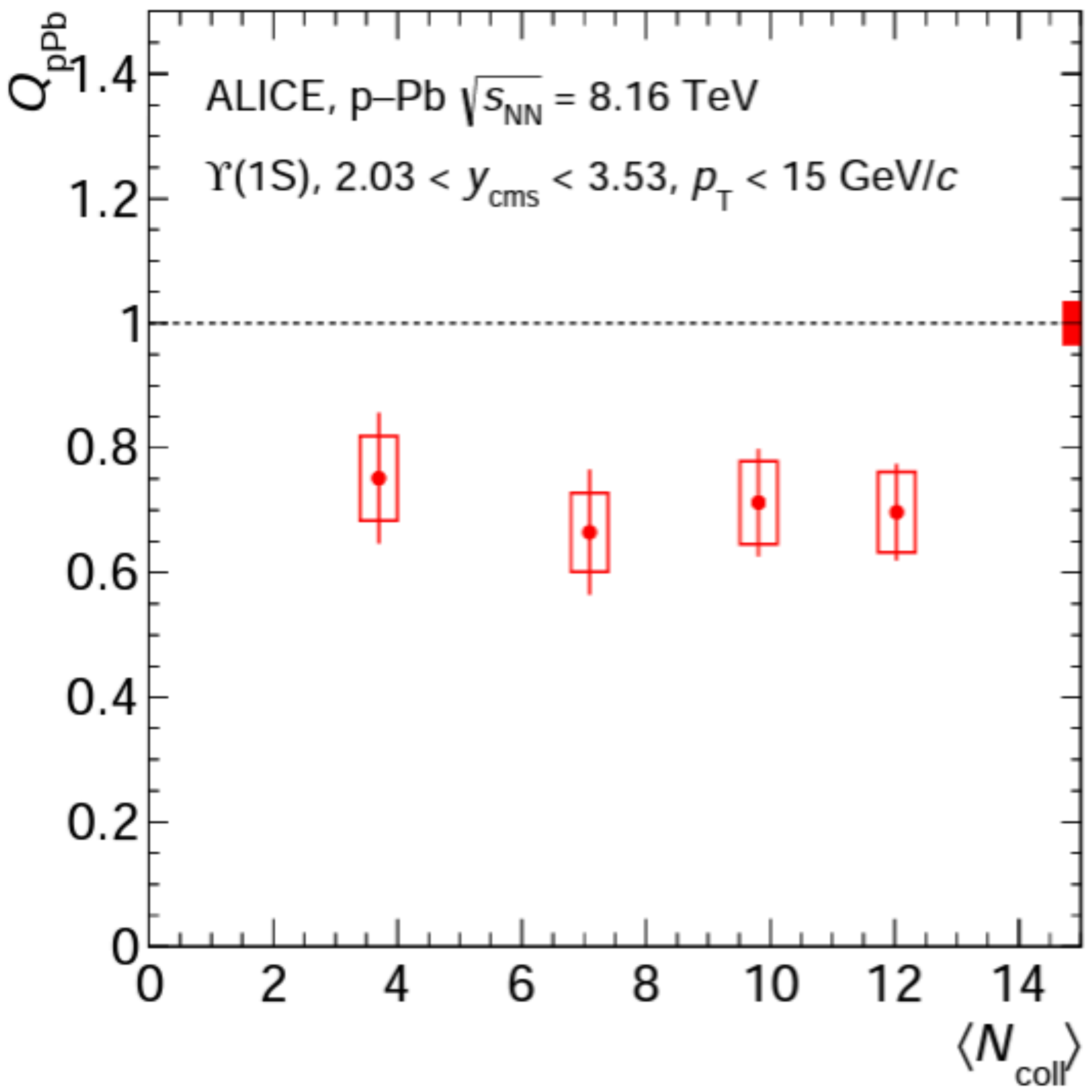
Bottomonium production in p-A vs multiplicity

Multiplicity dependent nuclear medication factor for Υ(1S)

backward rapidity (large x in Pb)



forward rapidity (low x in Pb)

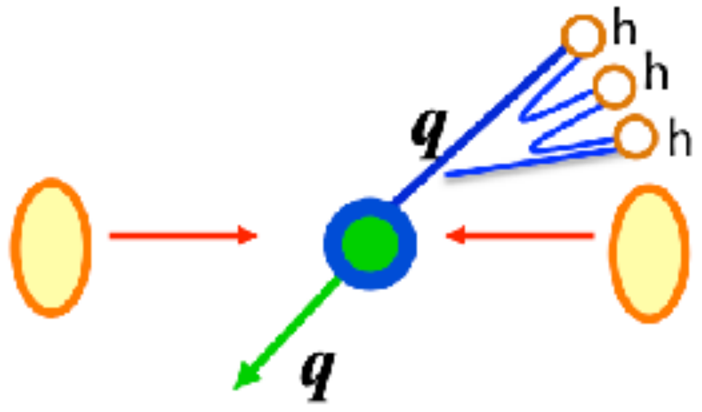


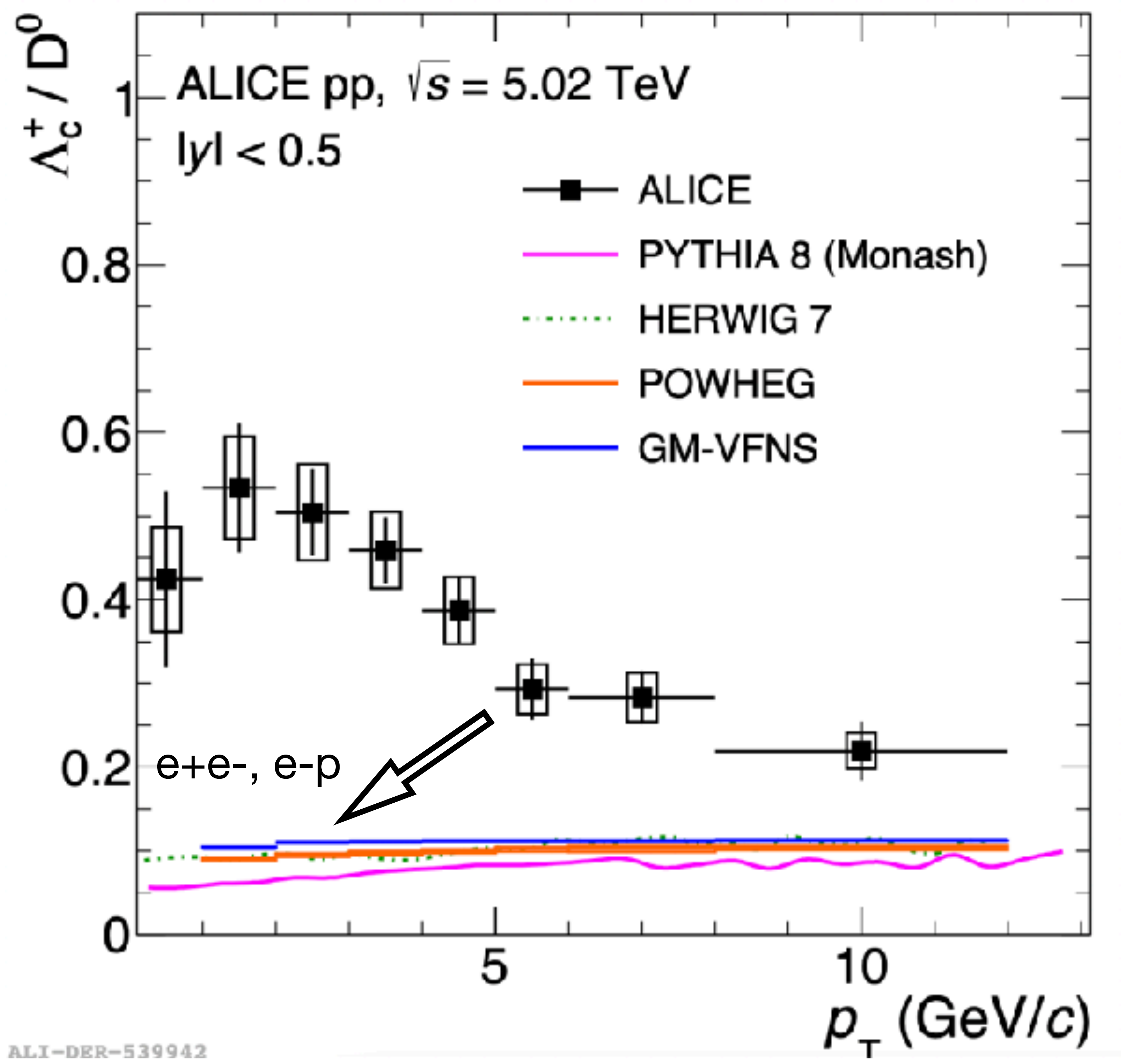
PLB 806 (2020) 135486

- Q_{pPb} of Υ(1S) independent of <N_{coll}> at backward and forward rapidity.

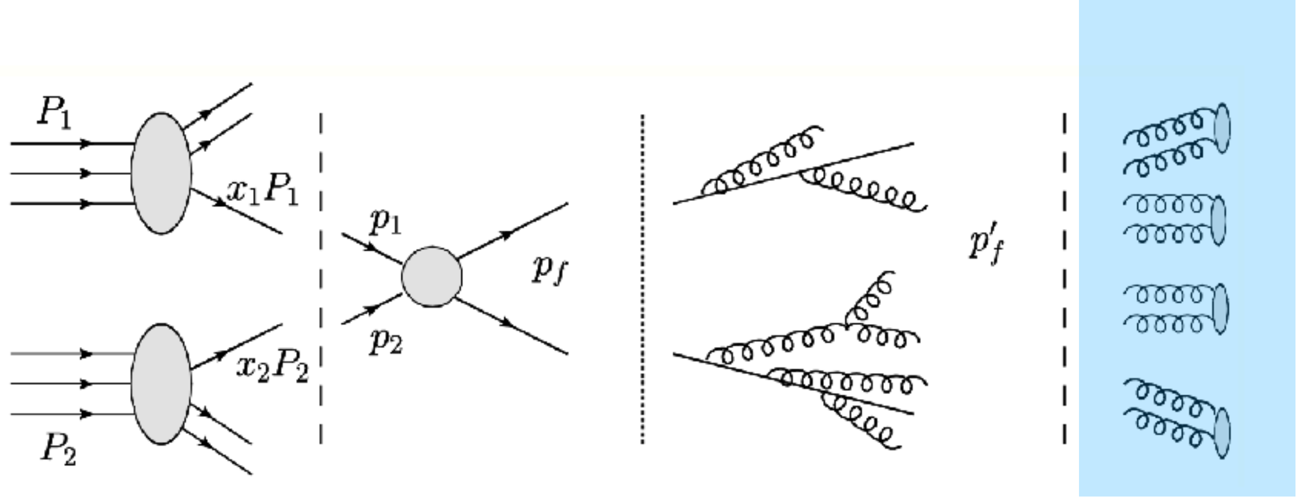
Hadronization

Study heavy-flavor hadronization using baryons

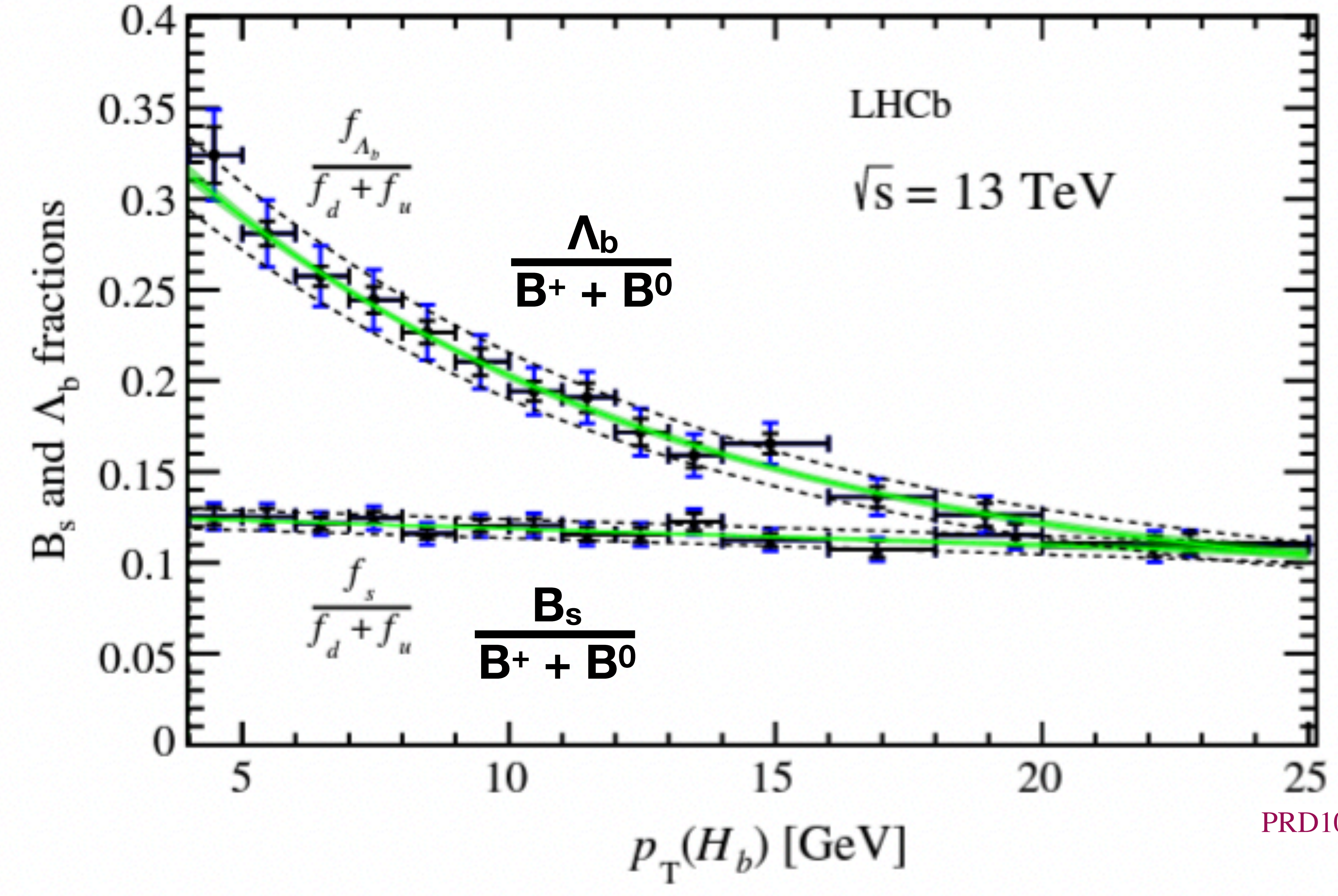




arxiv 2211.14032



Hadronization



PRD100 (2019) no.3, 031102

Λ_c/D^0 ratio higher (x4-5) values at low p_T than e^+e^-; approaches e+e- at high p_T

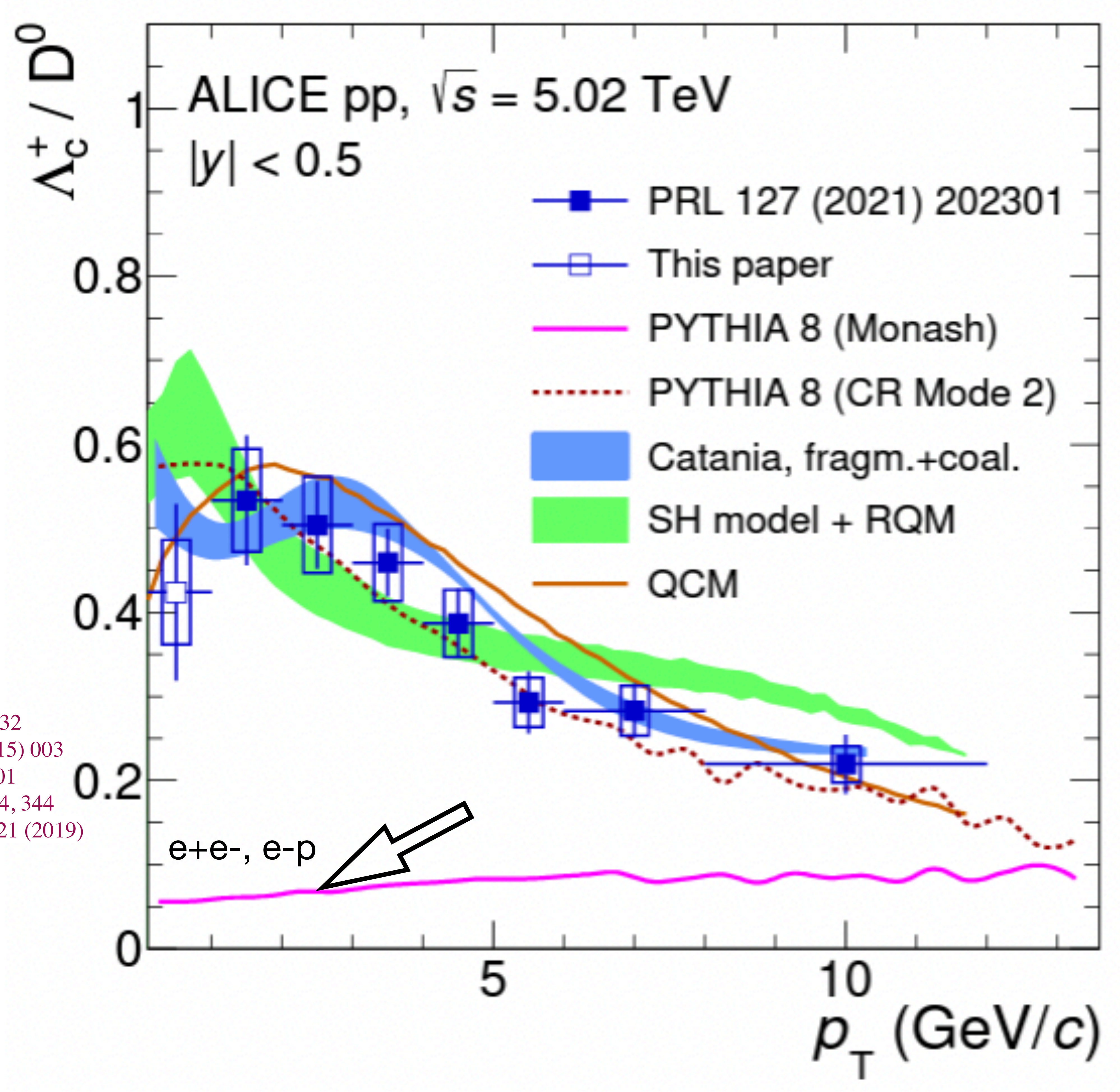
pQCD based calculations constrained to e+e- data:

- works for mesons but **not baryons**

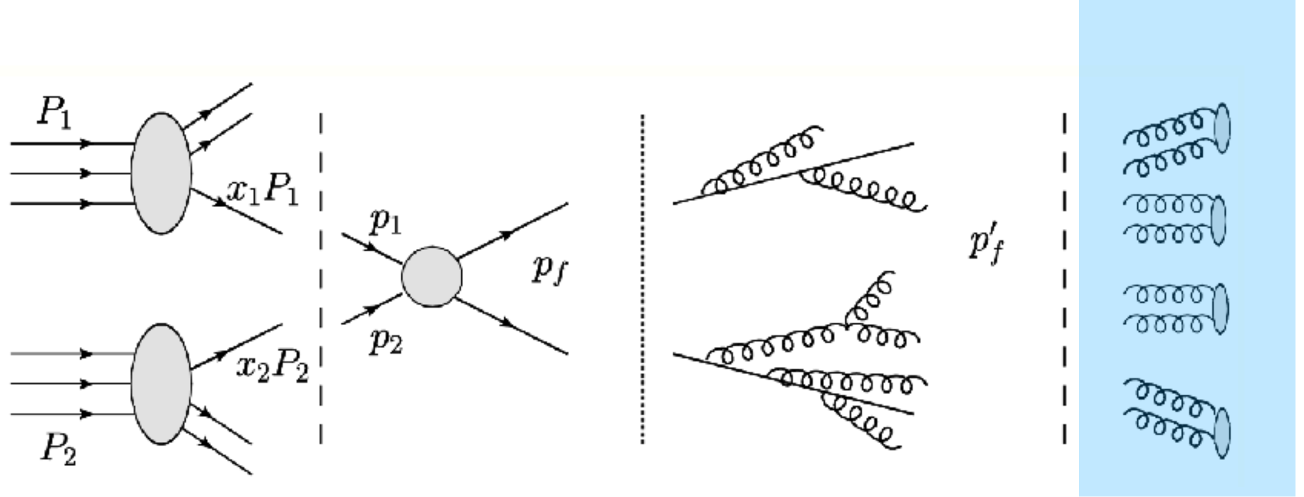
Same trend for both charm and beauty hadrons

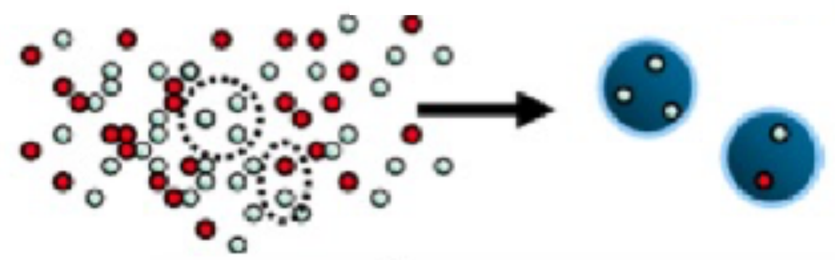
Hadronization

Study heavy-flavor hadronization using baryons



arxiv 2211.14032
JHEP 1508 (2015) 003
arxiv 2012.12001
EPJC 78, 2018 4, 344
PLB 795 117-121 (2019)





Hadronization

PYTHIA8 (CR mode2): String Formation beyond Leading Colour

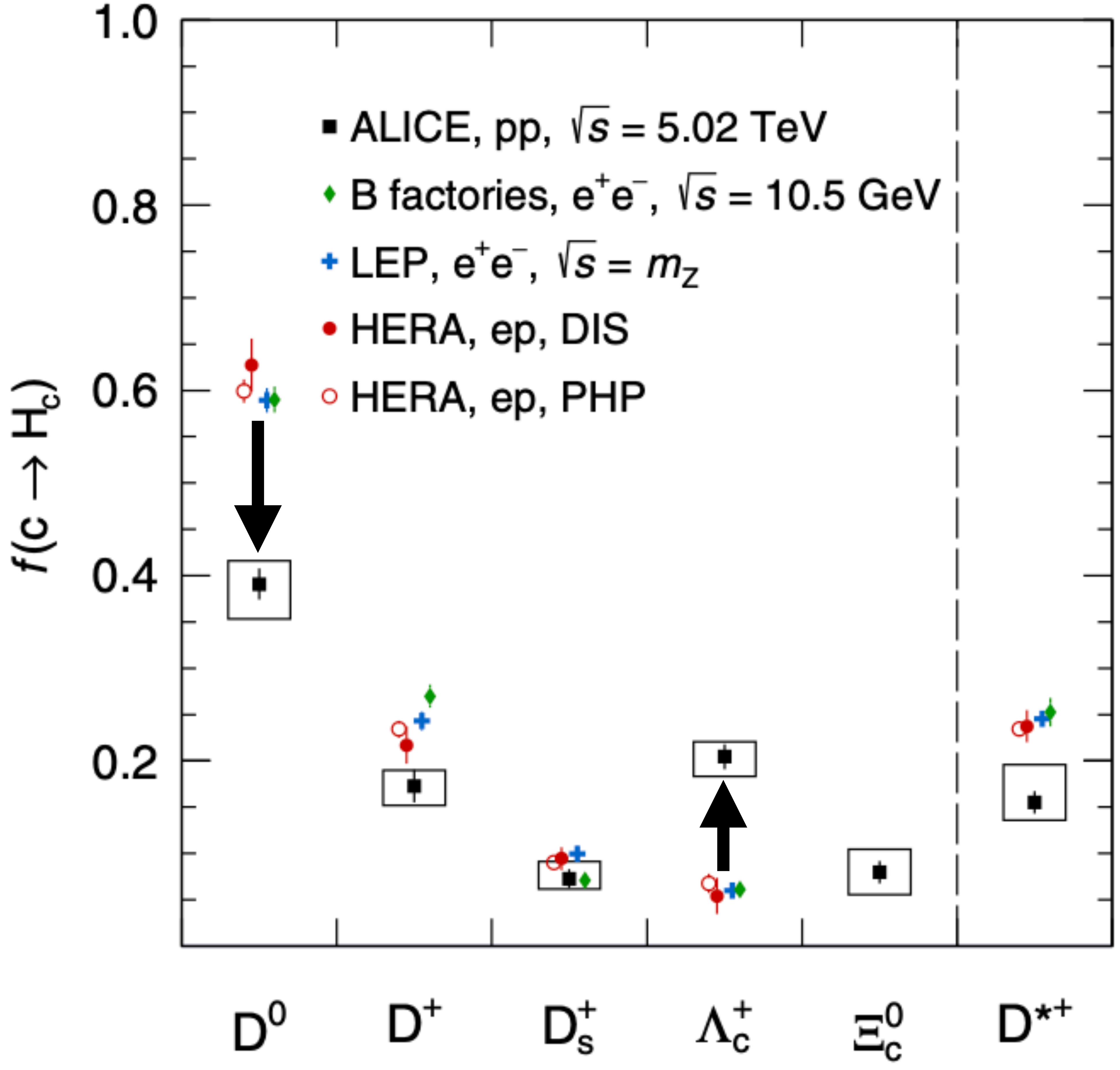
Catania model: coalescence + "vacuum" fragmentation

QCM: recombination model based on statistical weights + "equal quark-velocity"

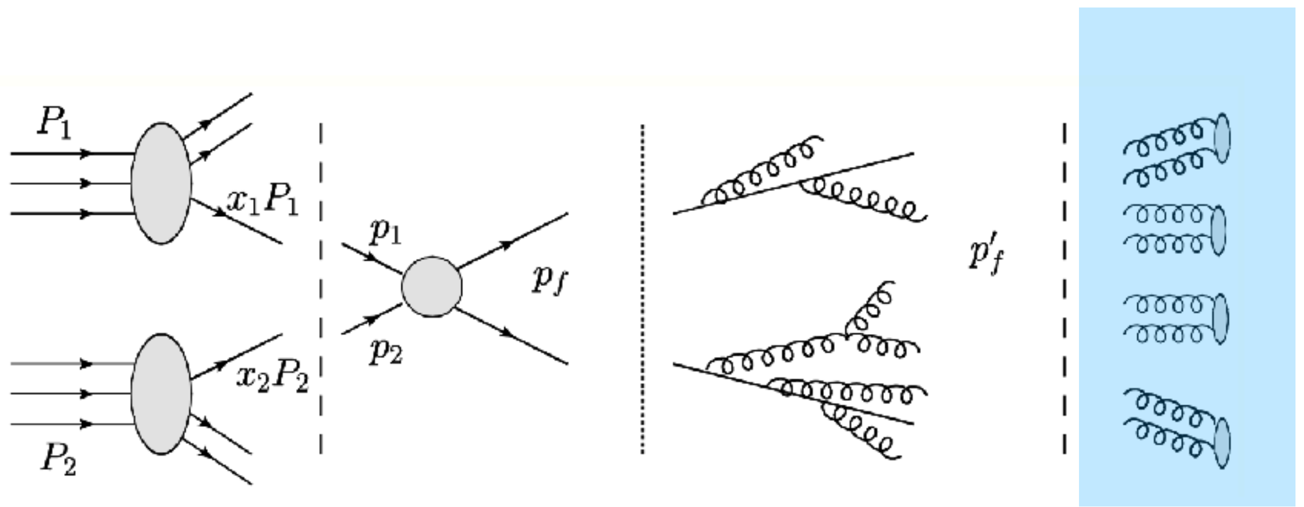
SH+PDG/RQM: Hadron abundances based on statistical hadronisation model + feed-down from excited states of charm-baryon states

Further constraints on these models possible with higher state charm and beauty baryons.

Fragmentation Fractions



PRD 105, L011103 (2022)



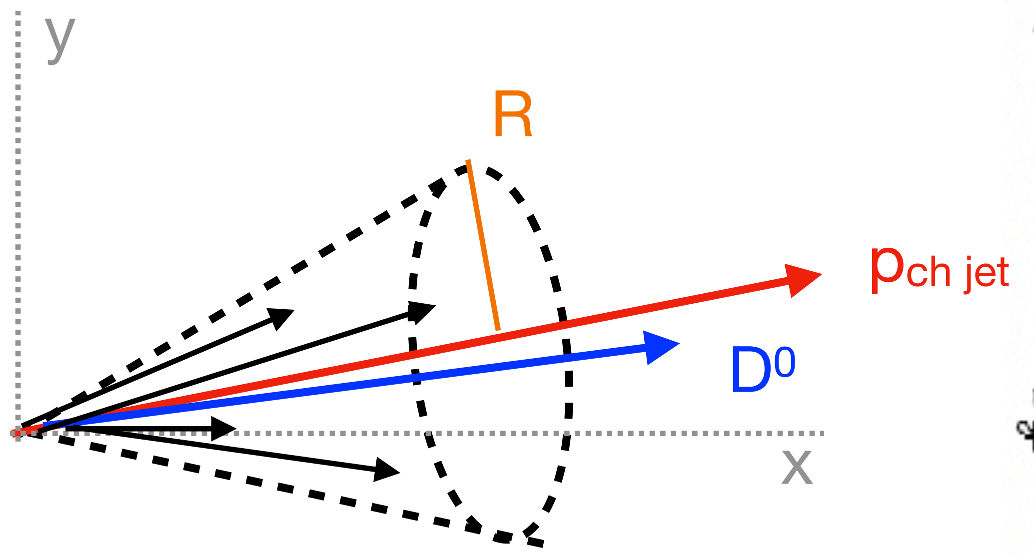
Hadronization

- Fragmentation fractions from all ground state charm hadrons.
- Large increase in c —> Λ_c and c —> Ξ_c w.r.t e+ e-
- More than 1/3rd of charm quarks hadronizes to baryons.
- **Fragmentation functions not universal among different collision systems.**

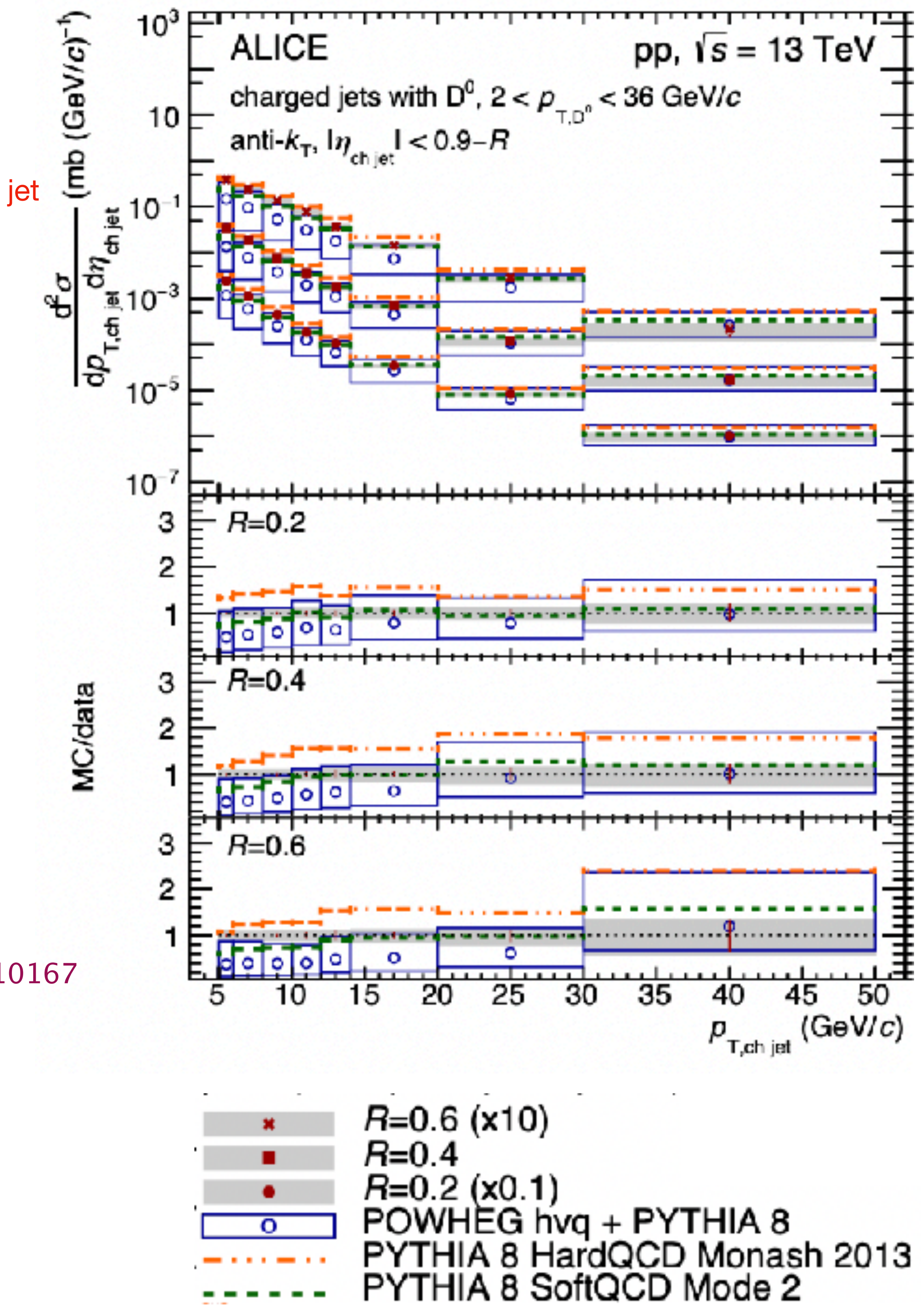
Fragmentation Function, D mesons

Study charm jets and fraction of jet momentum carried by D mesons

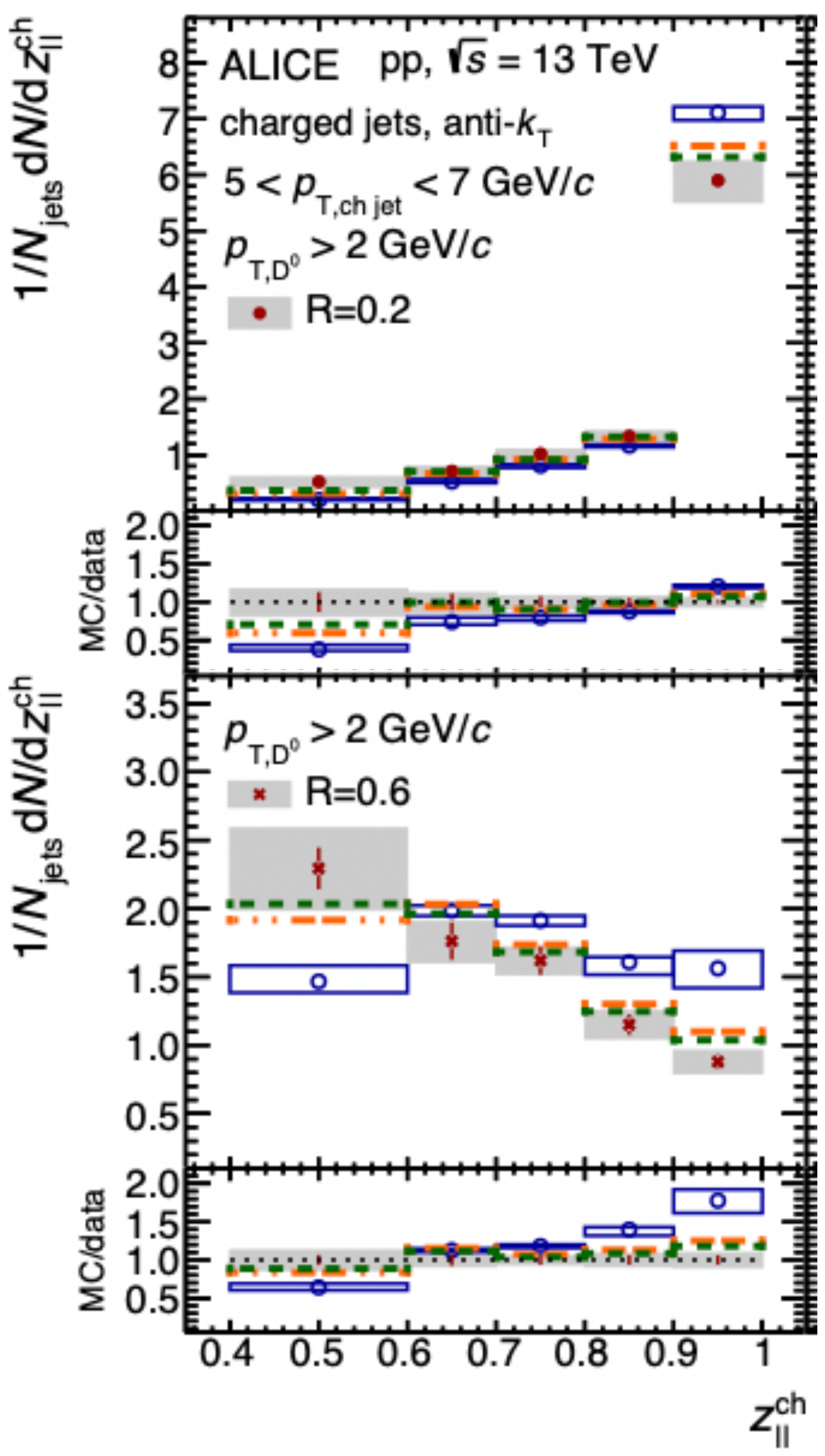
- provide insight into charm fragmentation

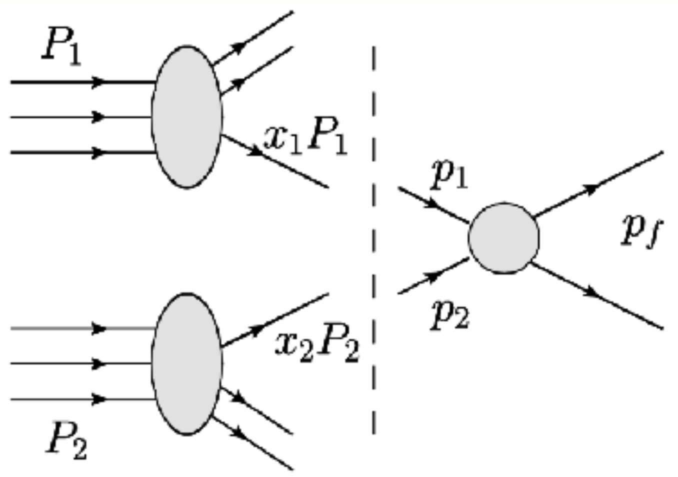


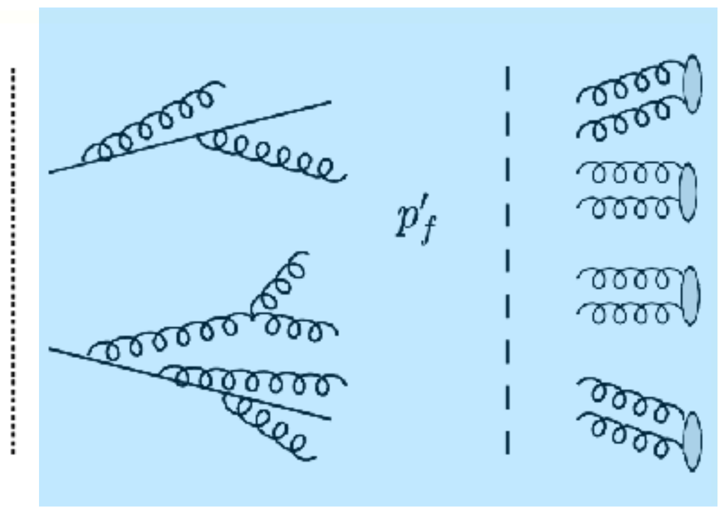
$$z_{||}^{ch} = \frac{p_{jet} \cdot p_{HF}}{p_{jet} \cdot p_{jet}}$$



arXiv:2204.10167





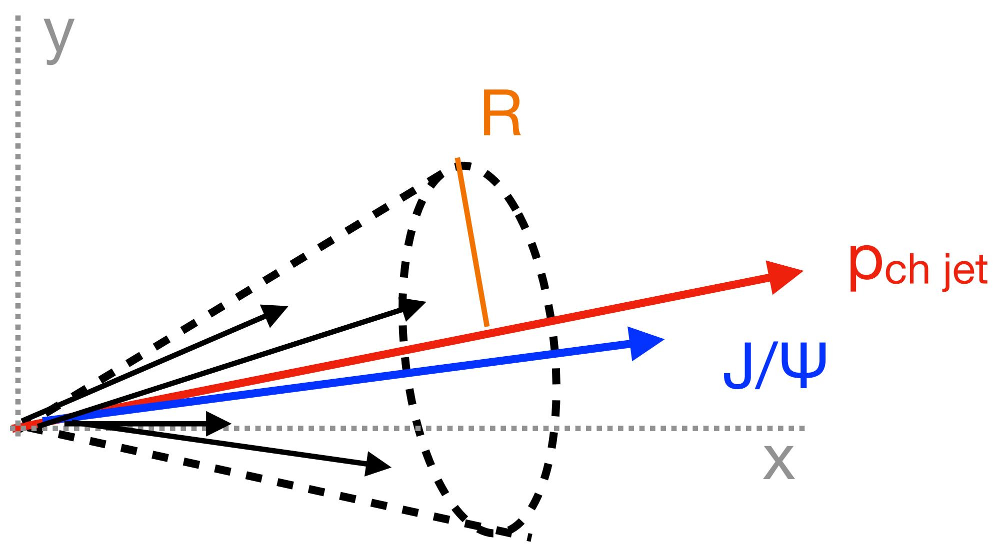


Parton shower and hadronization

- D^0-jets measured for different R
  - described by PYTHIA and POWHEG MC simulations.
- $z^{ch} \sim 1$ for low p_T^{Jet} and R =0.2
  - D^0 is the only constituent
- z^{ch} distribution much softer for larger R
  - more activity inside the jet.
- z^{ch} well described by PYTHIA and POWHEG at high p_T^{Jet}
  - small deviations observed at low p_T^{Jet} especially for POWHEG

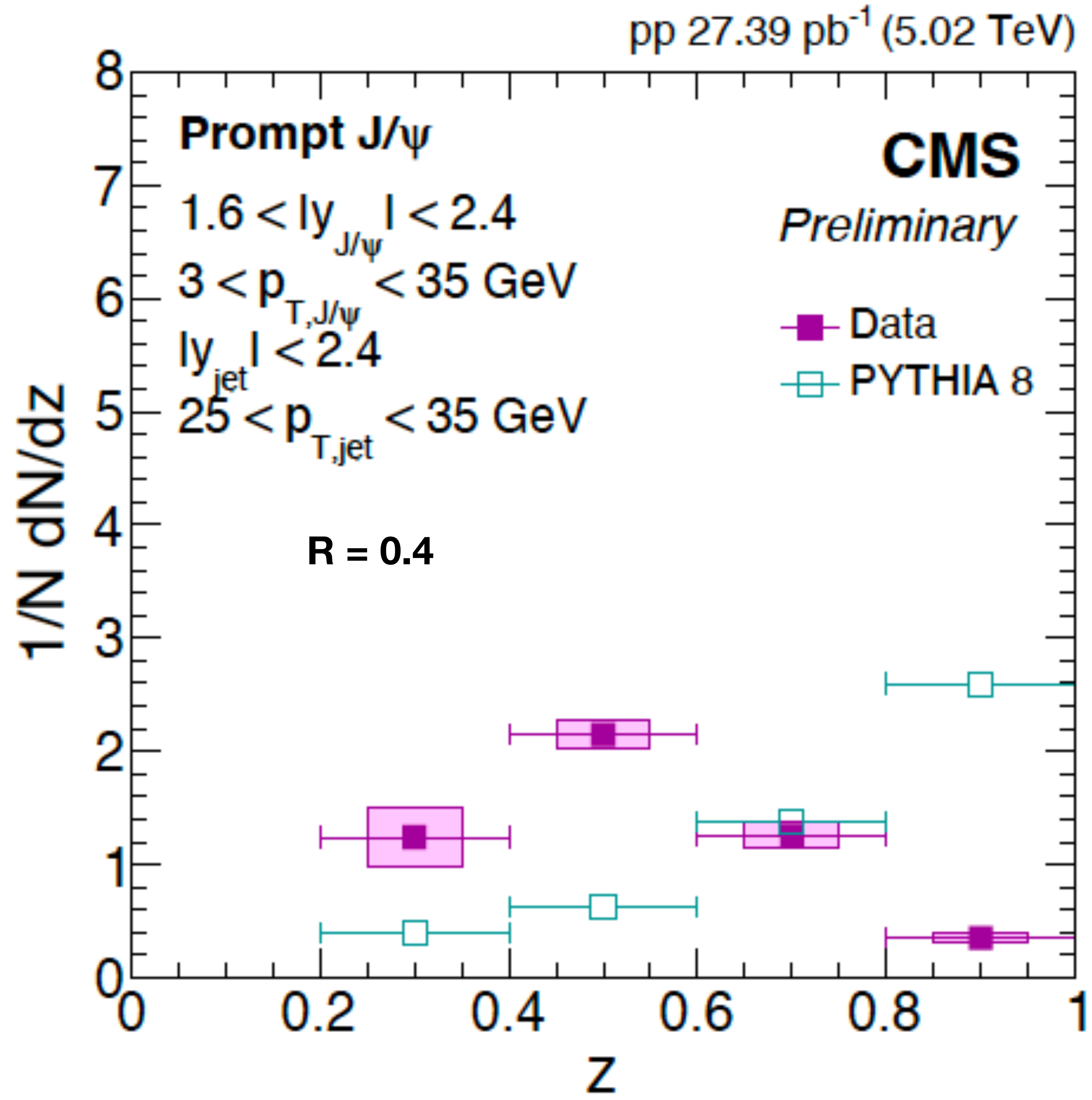
Fragmentation Function, J/ψ

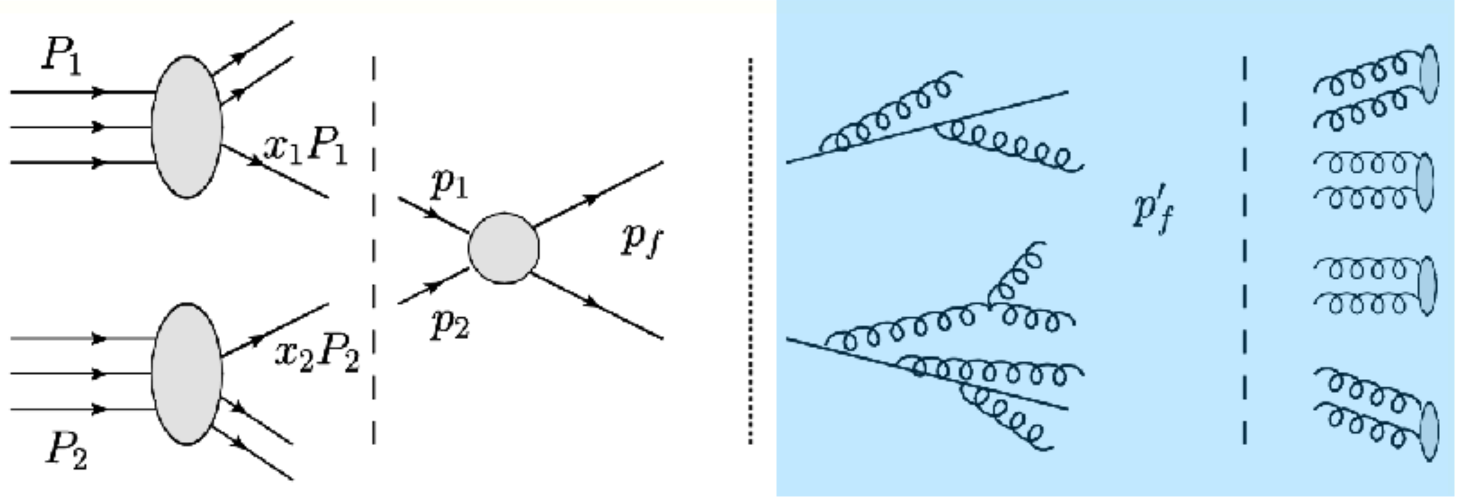
Study jet fragmentation function for prompt J/ψ



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

CMS-PAS-HIN-18-012
Phys. Rev. Lett. **118**, 192001





Parton shower and hadronization

Soft fragmentation of jets to J/ψ

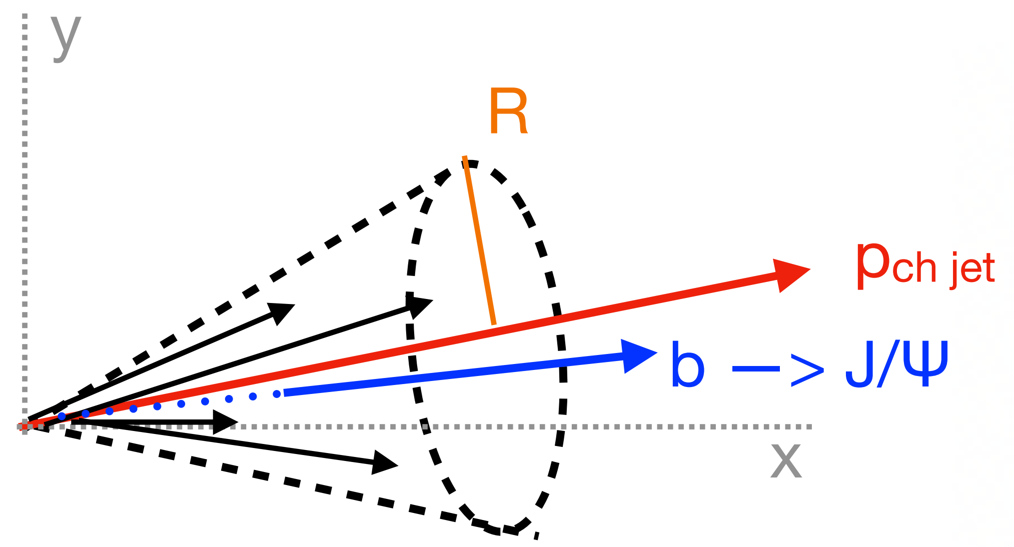
- J/ψ carry smaller fraction of jet momentum
- More jet activity accompanying J/ψ

PYTHIA 8 predicts harder fragmentation.

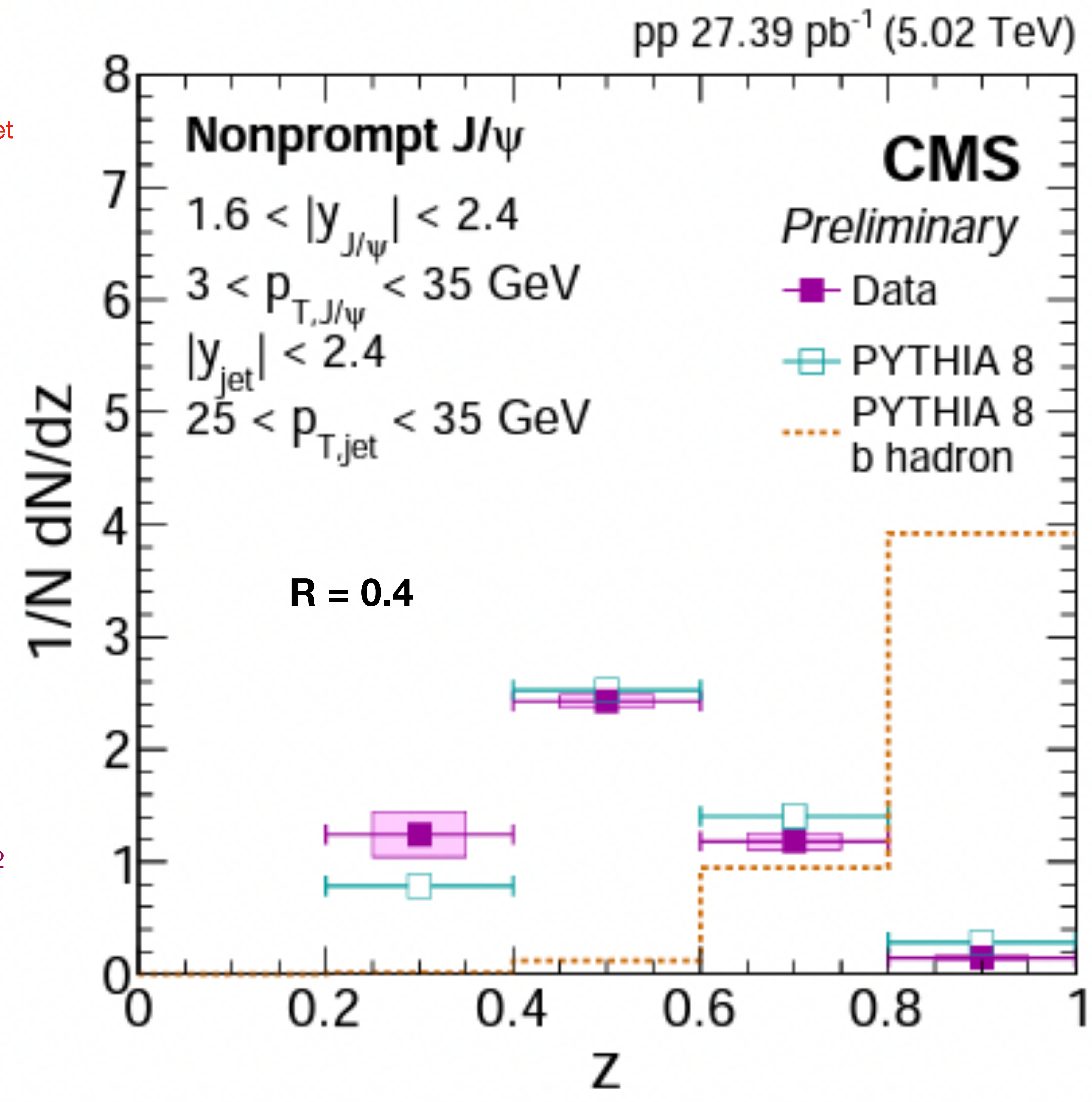
- fraction of J/ψ produced in jets also under predicted.

Fragmentation Function, b-> J/ψ

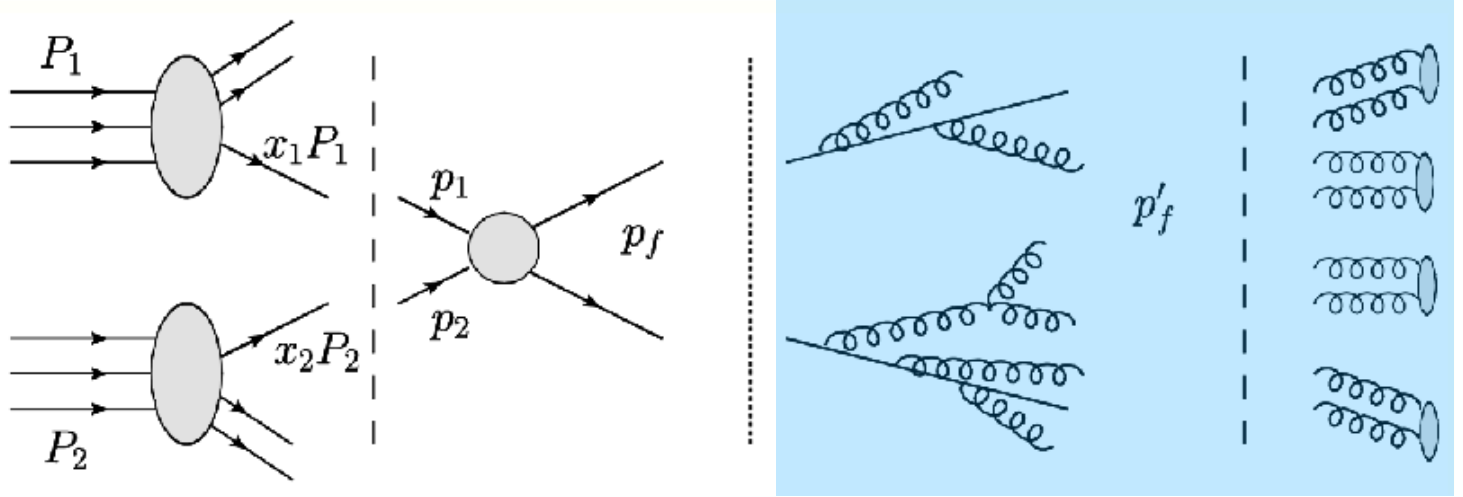
Study jet fragmentation function for non-prompt J/ψ



$$z \equiv \frac{p_{T,J/\Psi}}{p_{T,jet}}$$



CMS-PAS-HIN-18-012



Parton shower and hadronization

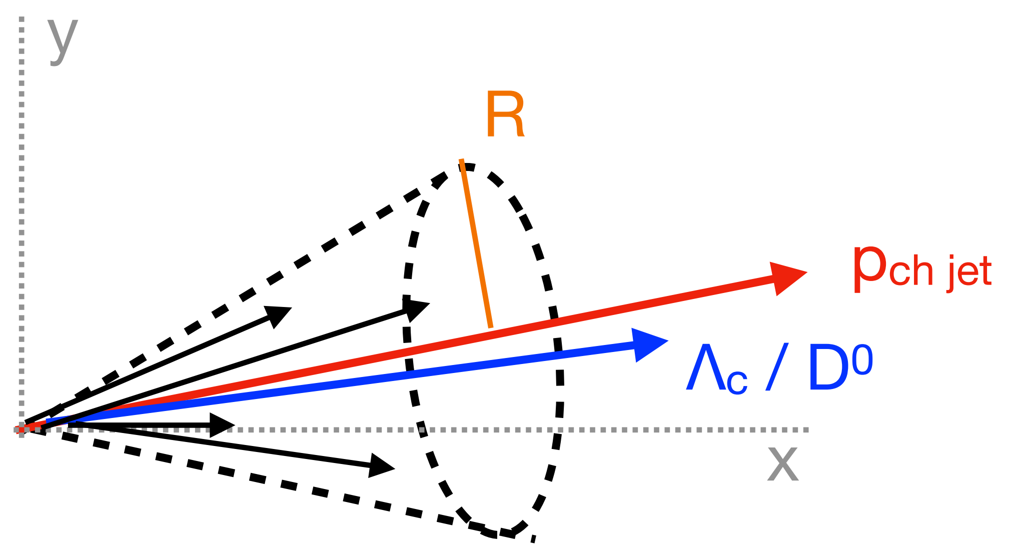
Soft fragmentation of jets to b —> J/ψ.

Well described by PYTHIA 8.

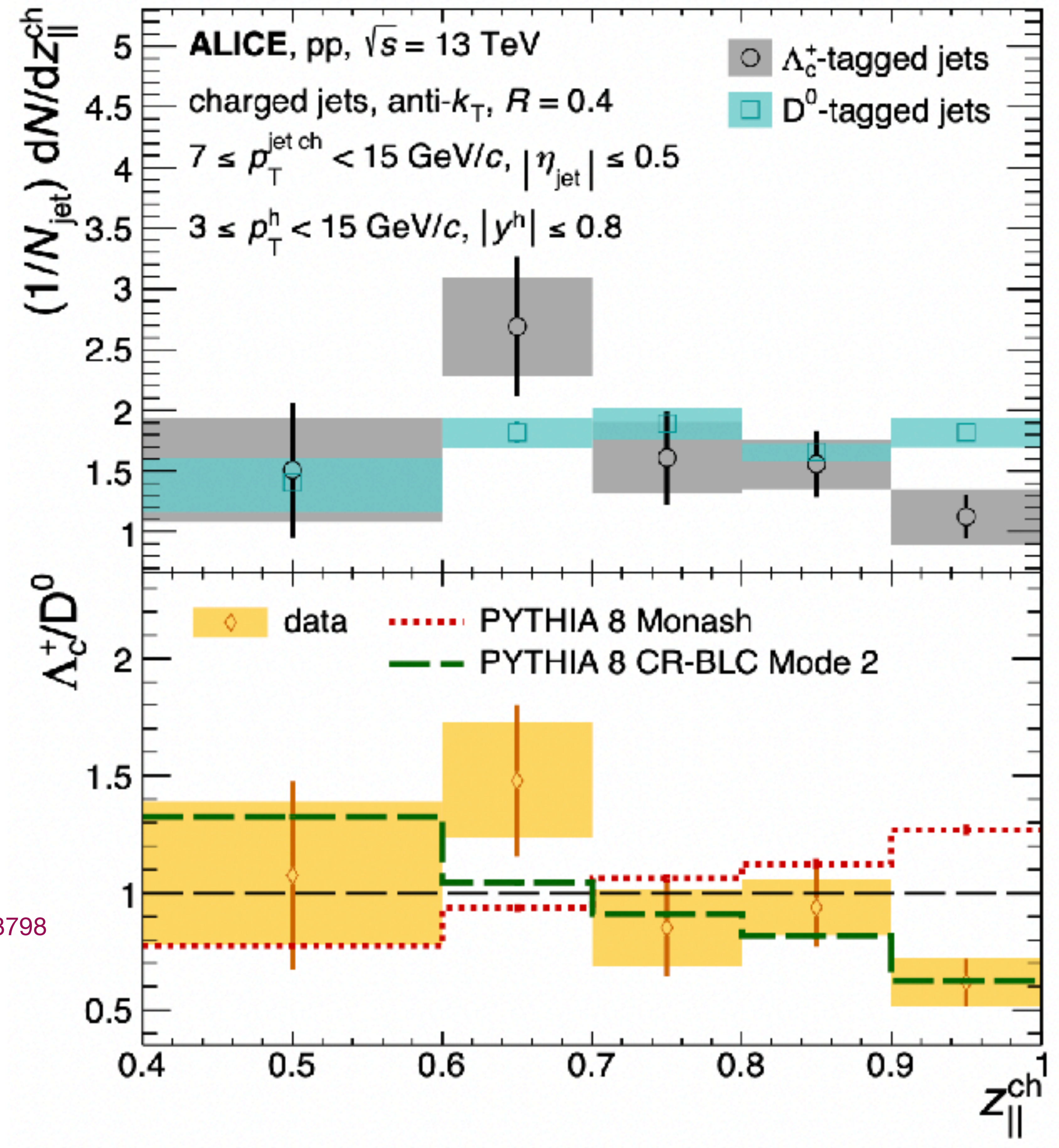
- z distribution of parent B hadron peaked at higher values.

Fragmentation Function, charm baryon

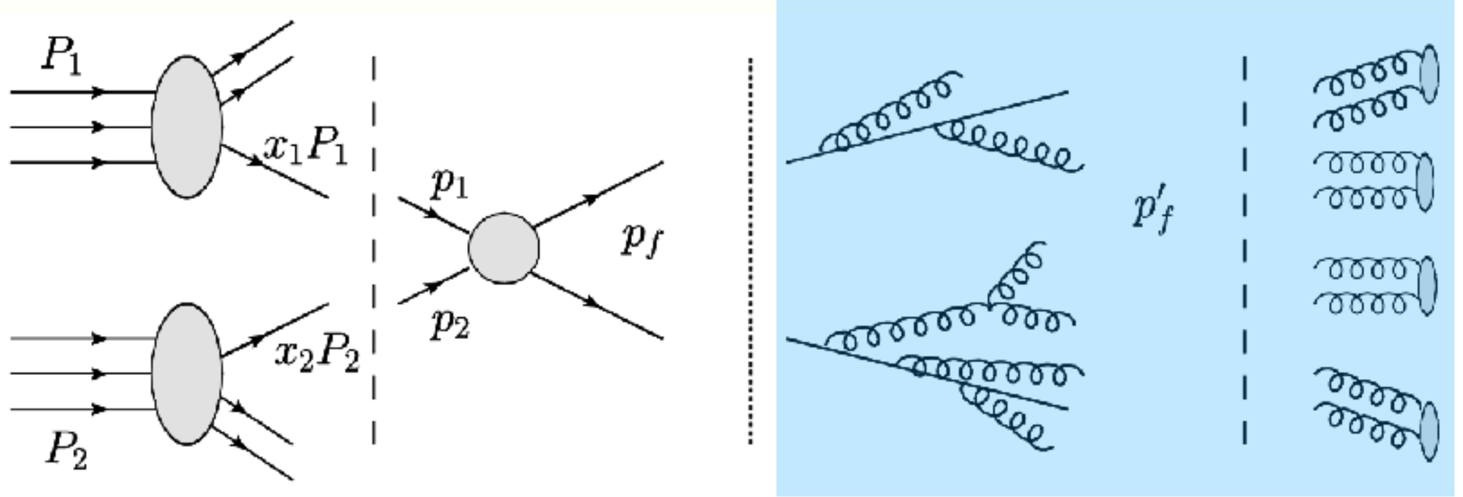
Study charm jet fragmentation function to baryons



$$z_{||}^{ch} = \frac{p_{jet} \cdot p_{HF}}{p_{jet} \cdot p_{jet}}$$



arXiv:2301.13798



Parton shower and hadronization

Softer fragmentation of charm quarks to Λ_c compared to D^0 mesons.

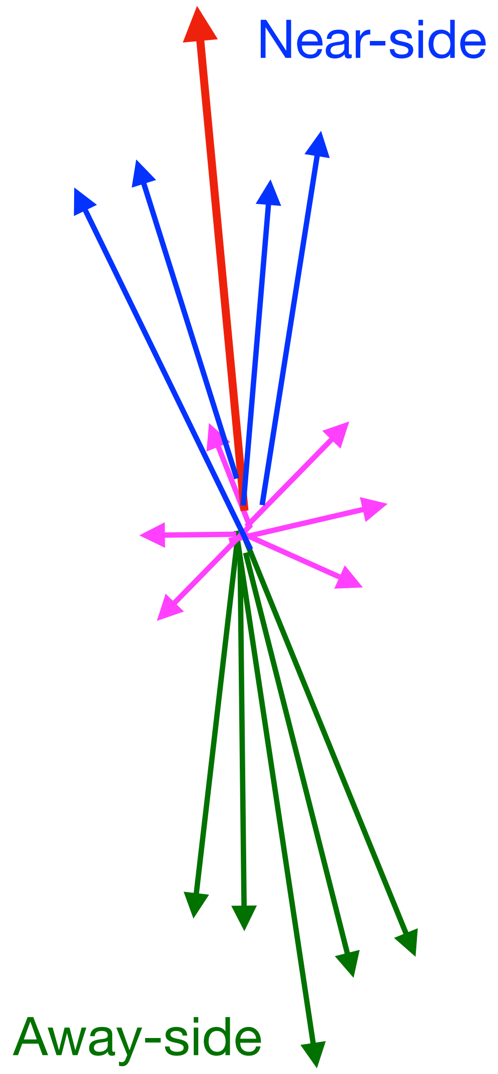
—> charm-baryon production is favored in the presence of higher particle multiplicity originating from jet fragmentation and underlying event

MC models:

- PYTHIA 8 Monash employs lund string fragmentation, tuned on e+e- data, predicts harder fragmentation than data
- PYTHIA 8 with CR mechanism gives a better description

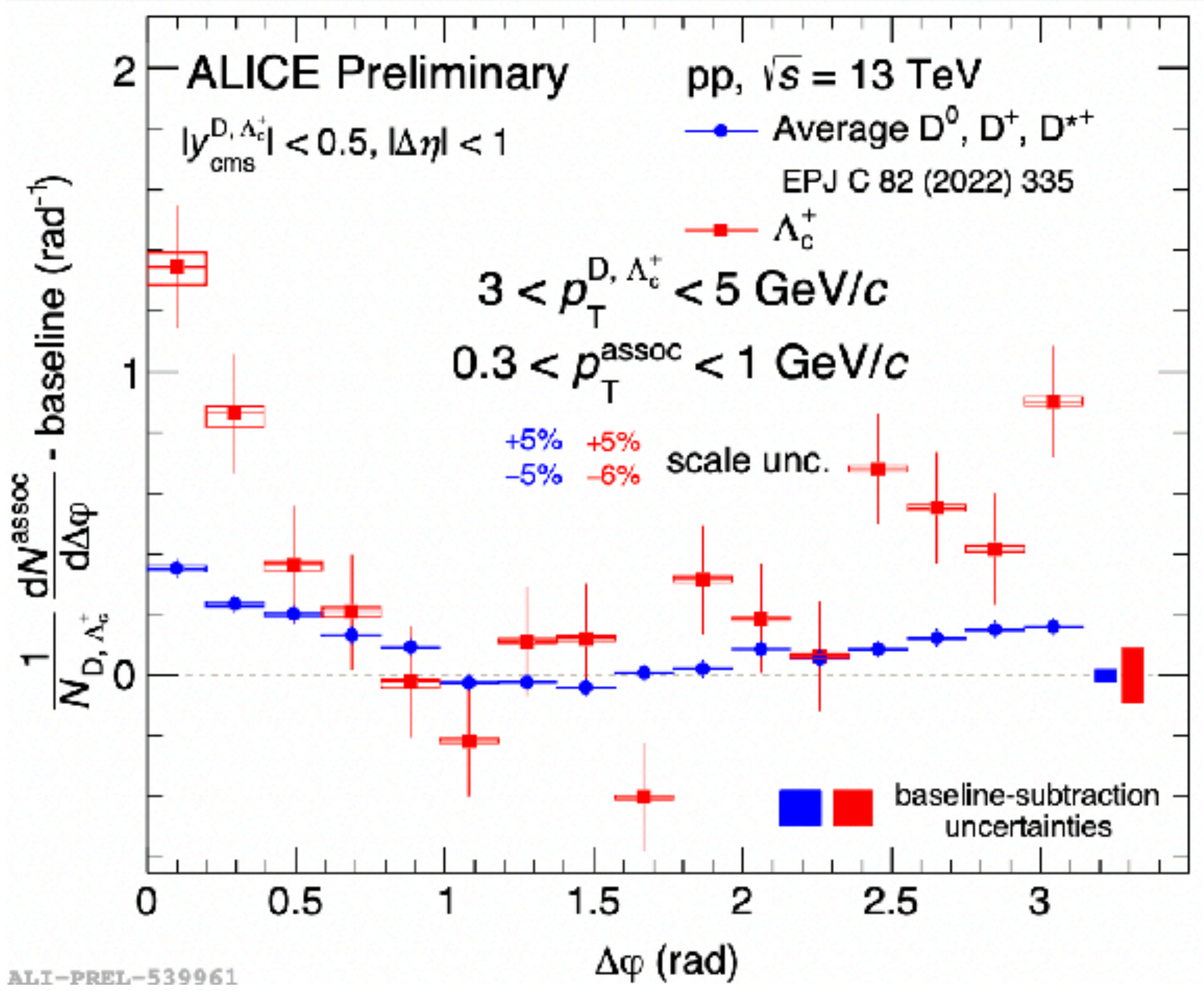
Jet shape and composition

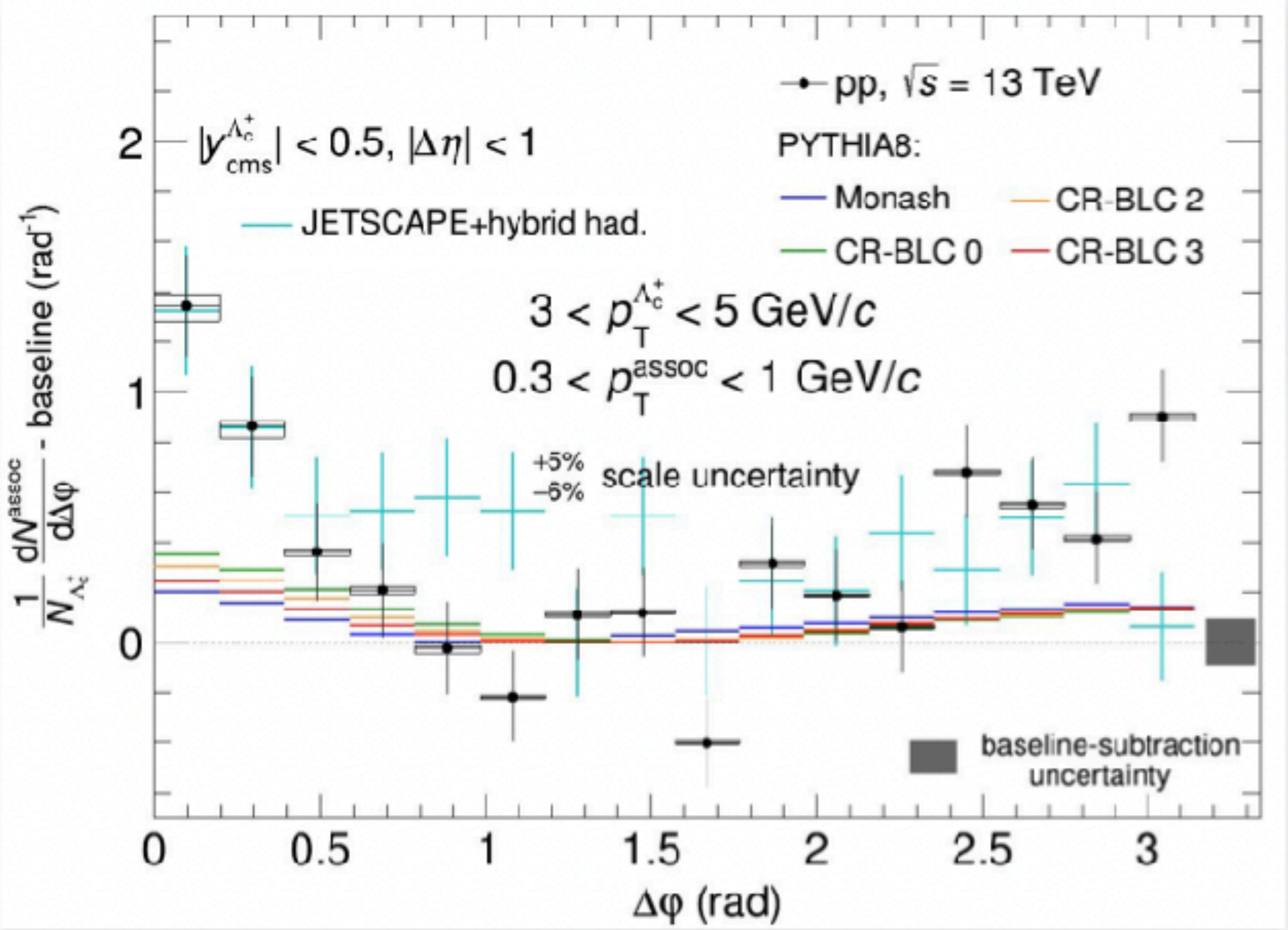
Study HF jet radial profile and composition using HF-charged particle azimuthal distribution



HF-h Δφ distribution at LO:

- Near Side (NS): fragmentation of the tagged HF quark
- Away Side (AS): fragmentation of the other quark
- Transverse Region : Underlying event



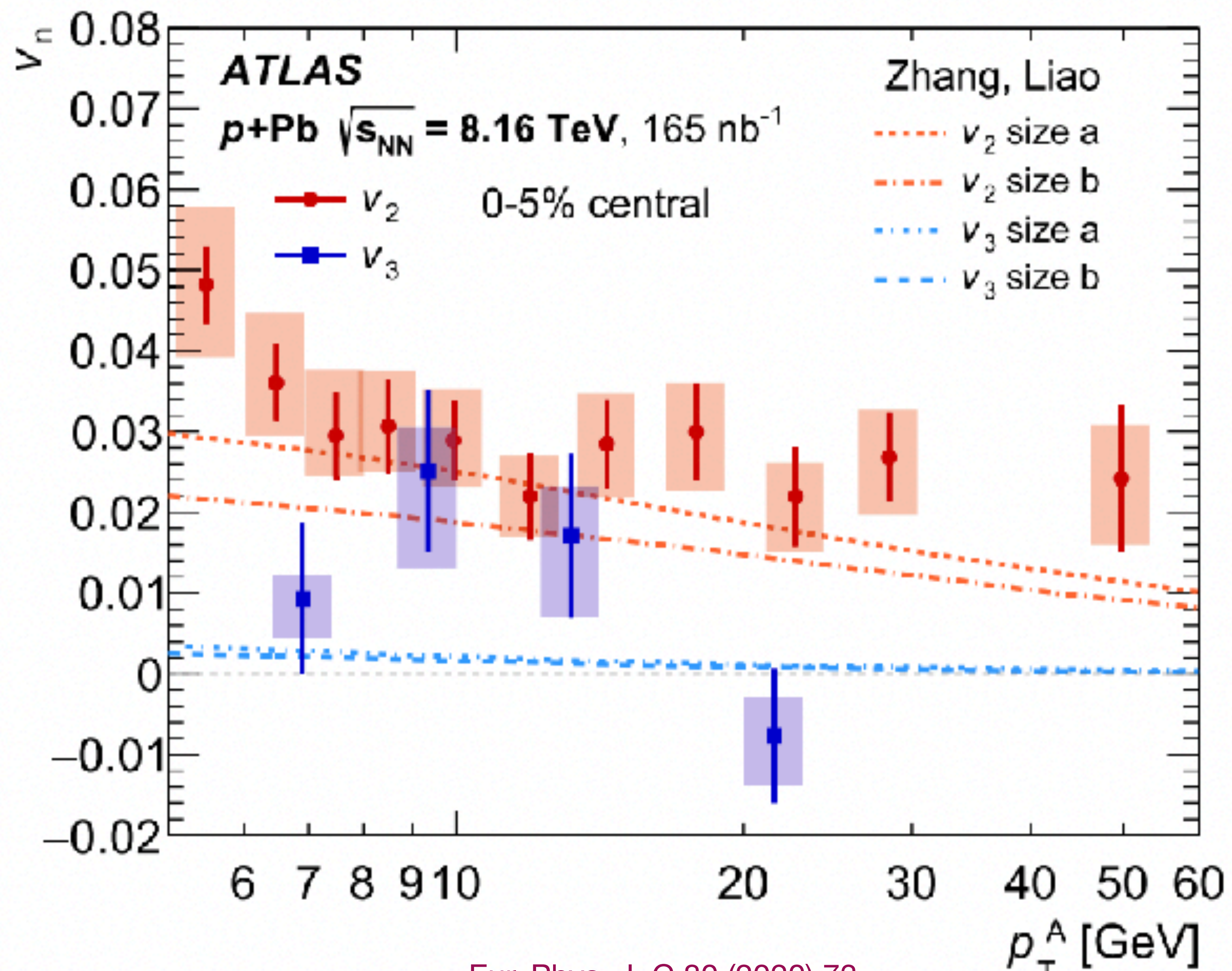


Significant deviation between Λ_c-h and D-h low p_T

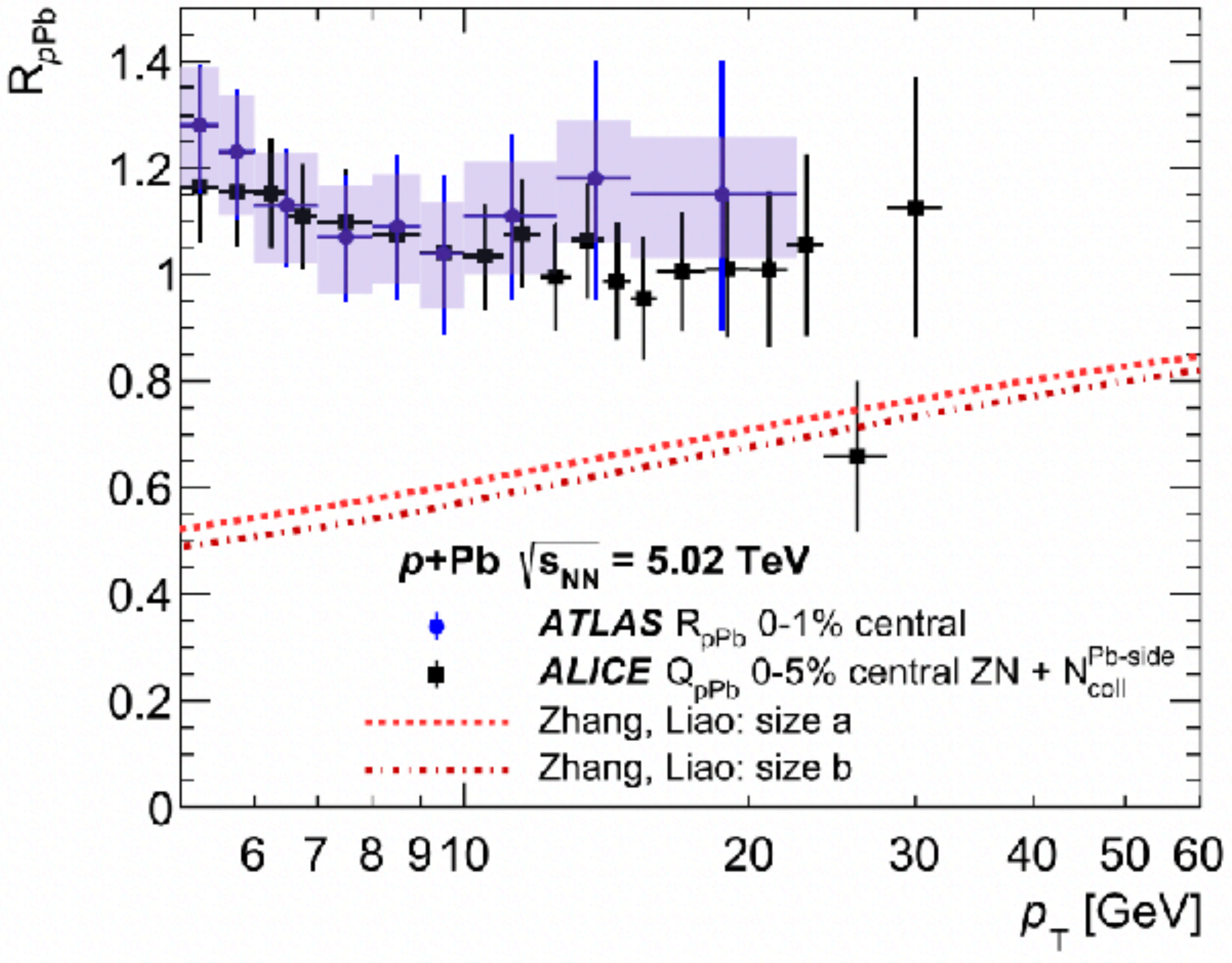
- probably as a consequence of softer fragmentation to Λ_c giving larger particle multiplicity inside the jet.

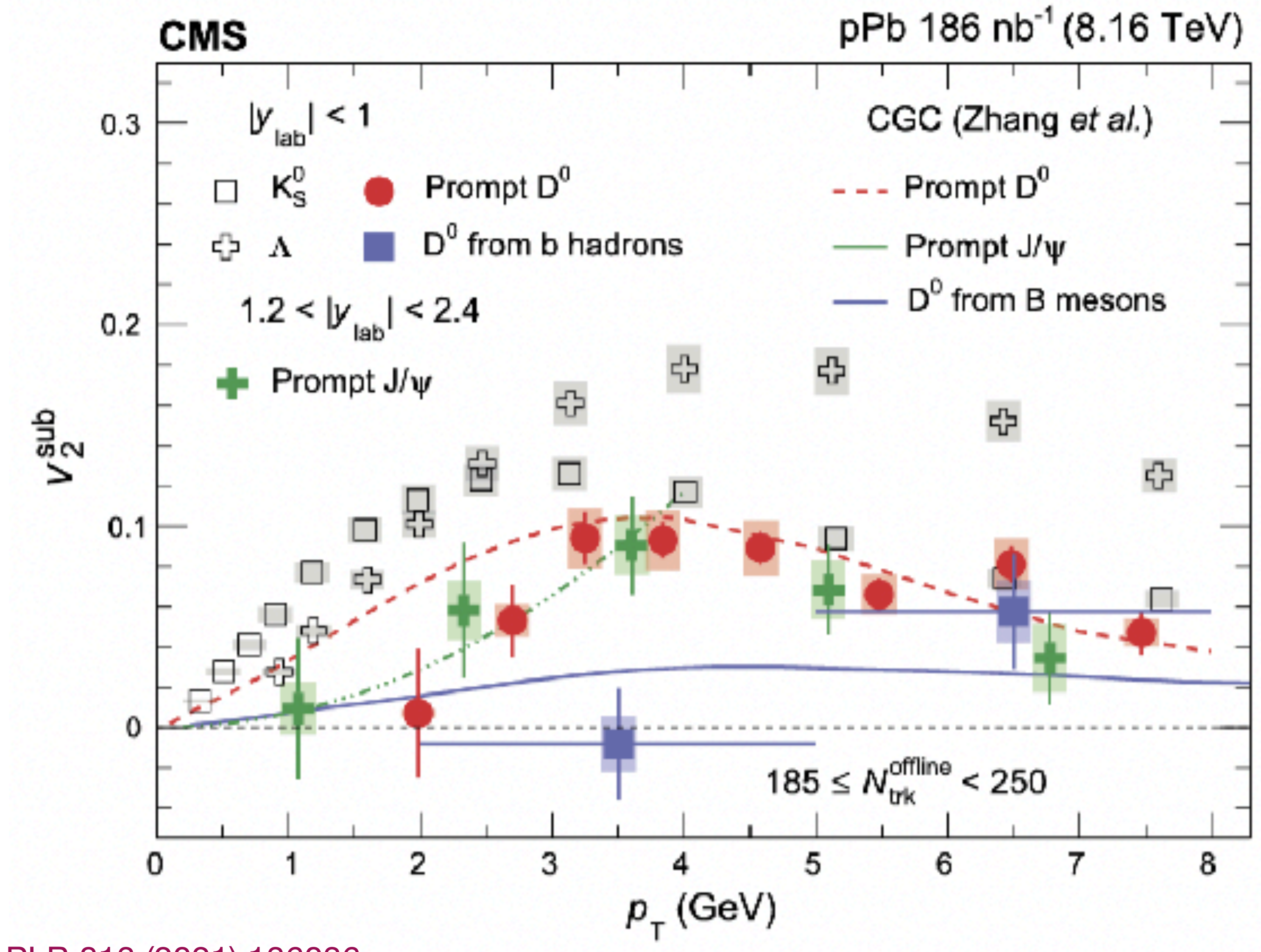
- PYTHIA 8 tunes underestimates NS and AS peaks
- JETSCAPE with hybrid hadronization better describes the data (need better precision)

Search for jet quenching in small systems



Eur. Phys. J. C 80 (2020) 73





PLB 813 (2021) 136036

Several QGP like signatures in high multiplicity pp and p-A collisions; but several questions remain.

- $v_2 > 0$ at high p_T but $R_{pA} \sim 1$.
- $v_2(D) \sim v_2(J/\psi)$; $v_2(B) \sim 0$
  - CGC calculations qualitatively agree with the data.

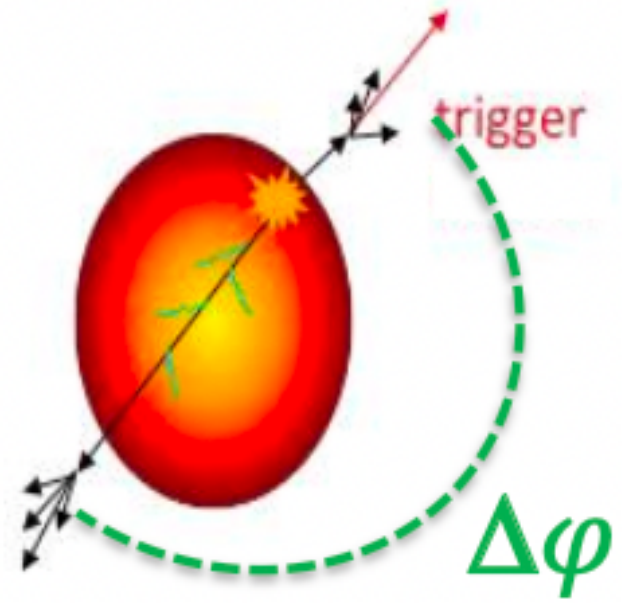
QGP in small system? —> jet quenching is a necessary consequence but expected to be small.

- R_{pA} affected by biases in T_{pA} calculations —> limits sensitivity to jet quenching.
- **Several alternate searches proposed**

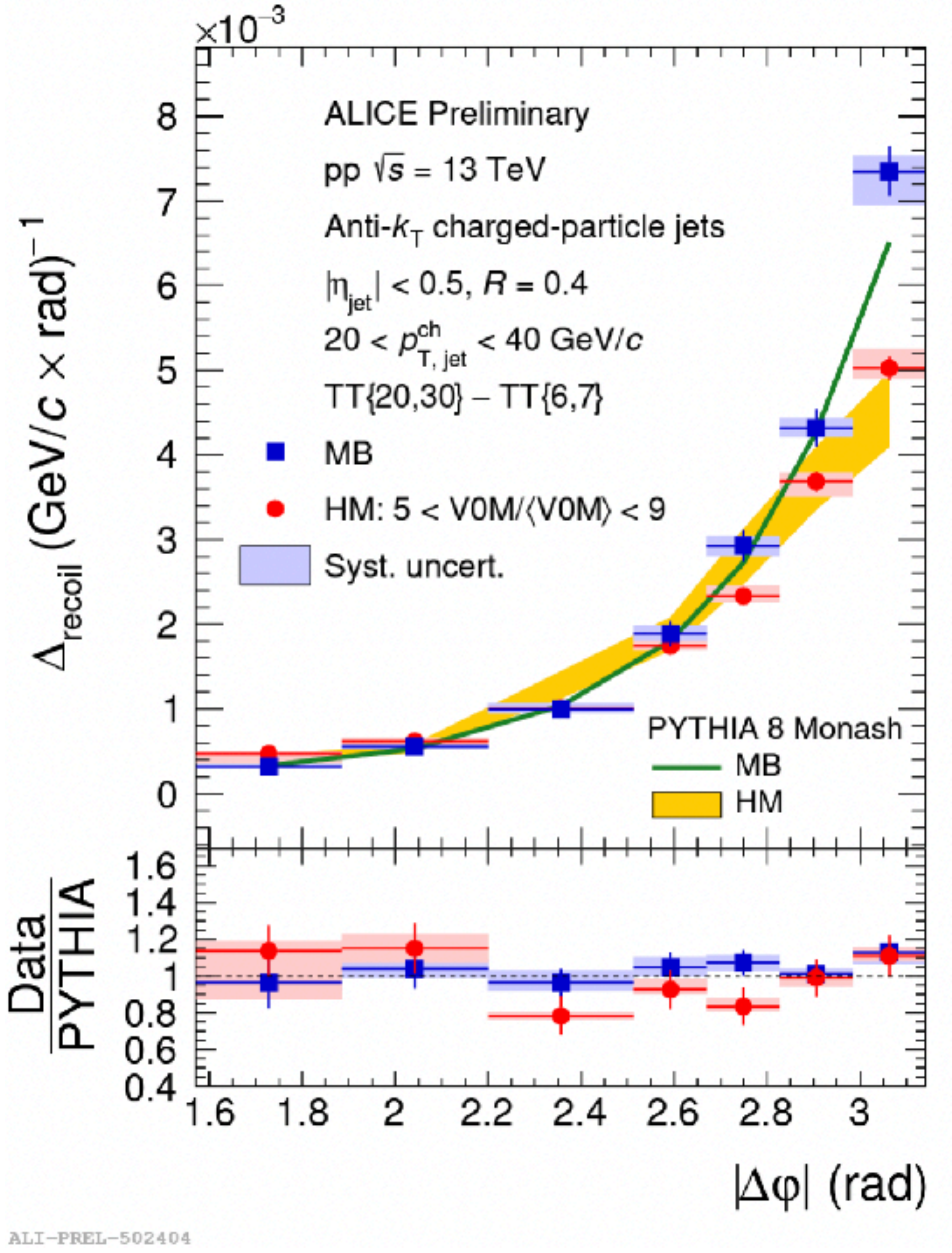
Dennis Perepelitsa
Mon@11am

Jet quenching in small systems

Search for jet quenching in high multiplicity pp collisions using hadron-jet acoplanarity



Comparing distributions of Δϕ between high p_T hadron trigger and correlated recoil jets in MB and HM events



$$\Delta_{\mathrm{recoil}}(\Delta\varphi) = \frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}N_{\mathrm{jet}}}{\mathrm{d}\Delta\varphi}\bigg|_{\mathrm{TT}\{20,30\}\,\&\,p^{\mathrm{ch}}_{\mathrm{T,jet}}} - c_{\mathrm{ref}} \cdot \frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}N_{\mathrm{jet}}}{\mathrm{d}\Delta\varphi}\bigg|_{\mathrm{TT}\{6,7\}\,\&\,p^{\mathrm{ch}}_{\mathrm{T,jet}}}$$

Jet quenching in the QGP expected to broaden Δϕ distribution due to in-medium multiple scattering.

- Significant broadening and suppressed of back-to-back correlation observed in HM events.
- PYTHIA 8 shows similar suppression pattern —> **effect not due to jet quenching**
  - bias on the HM event selection

More discussion on jet quenching in small systems

Isobel Kolbe and Carlota Andres
Thur@11.30am, 12pn

Summary and outlook

- **Heavy quarks are excellent tools to study small systems**
- What we have learnt:
  - Cross-sections in pp collisions are described by pQCD based calculation.
  - R_{pPb} described by models that include CNM effects and final state interactions.
  - No strong evidence of heavy-flavor suppression in high multiplicity events.
  - Fragmentation functions not universal across systems.
- Questions:
  - Origin of collectivity in small systems.
  - Further test/constraint models with more differential study of HF production and fragmentation.
    - Jet substructure, higher state and exotic hadron production, …
- **Future:**
  - New data at LHC and RHIC will allow more differential measurements.
  - More studies on collectivity possible with p-O collisions *Aleksas Mazeliauskas Thur@2pn*

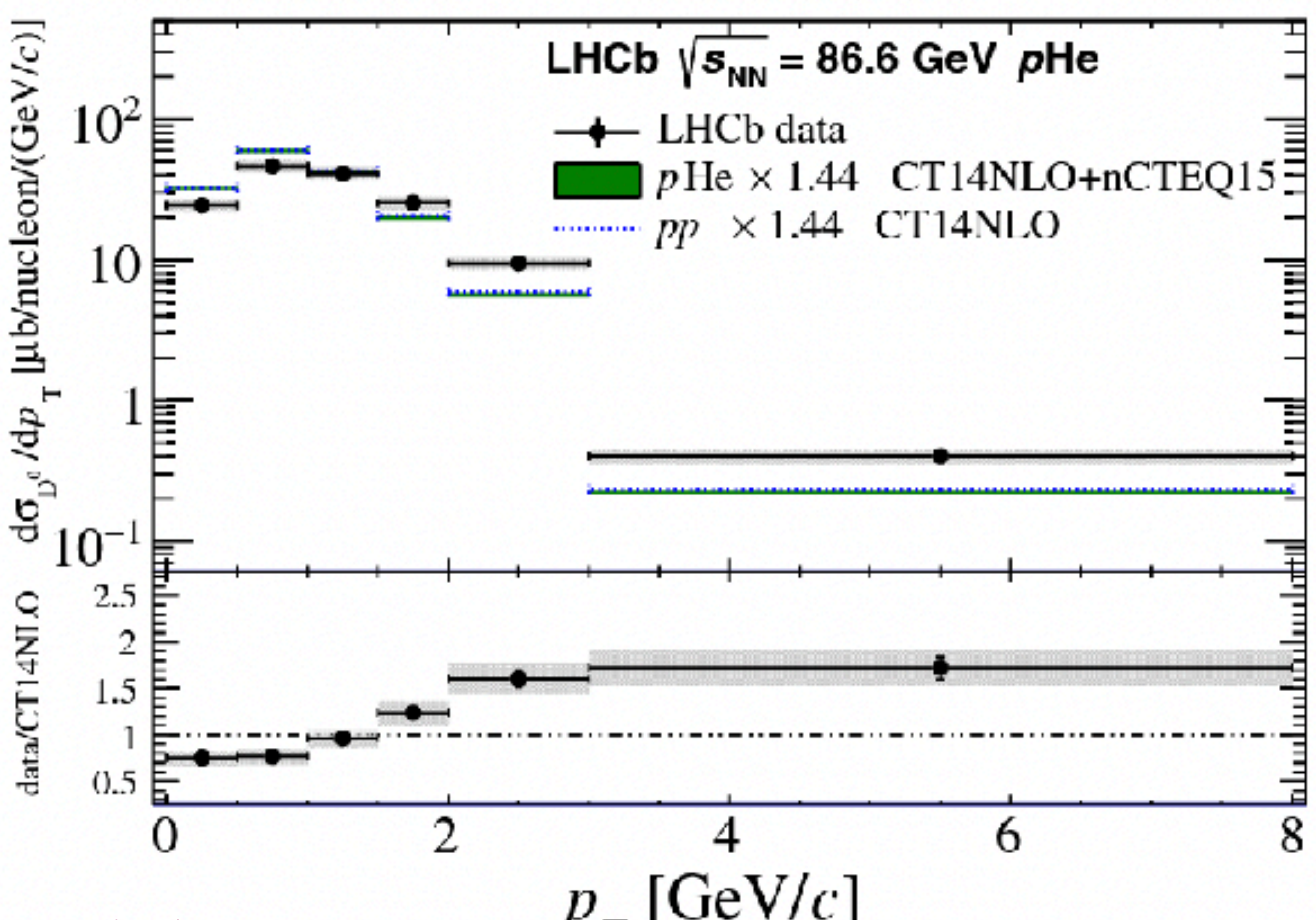
Thanks to Barbara Trzeciak, Debojit Sarkar, Isobel Kolbe, Jasmine Brewer, Laura Havener, Nima Zardoshti, Raghav Elayavalli, Rongrong Ma for input and discussions

Backup

Fixed target measurements

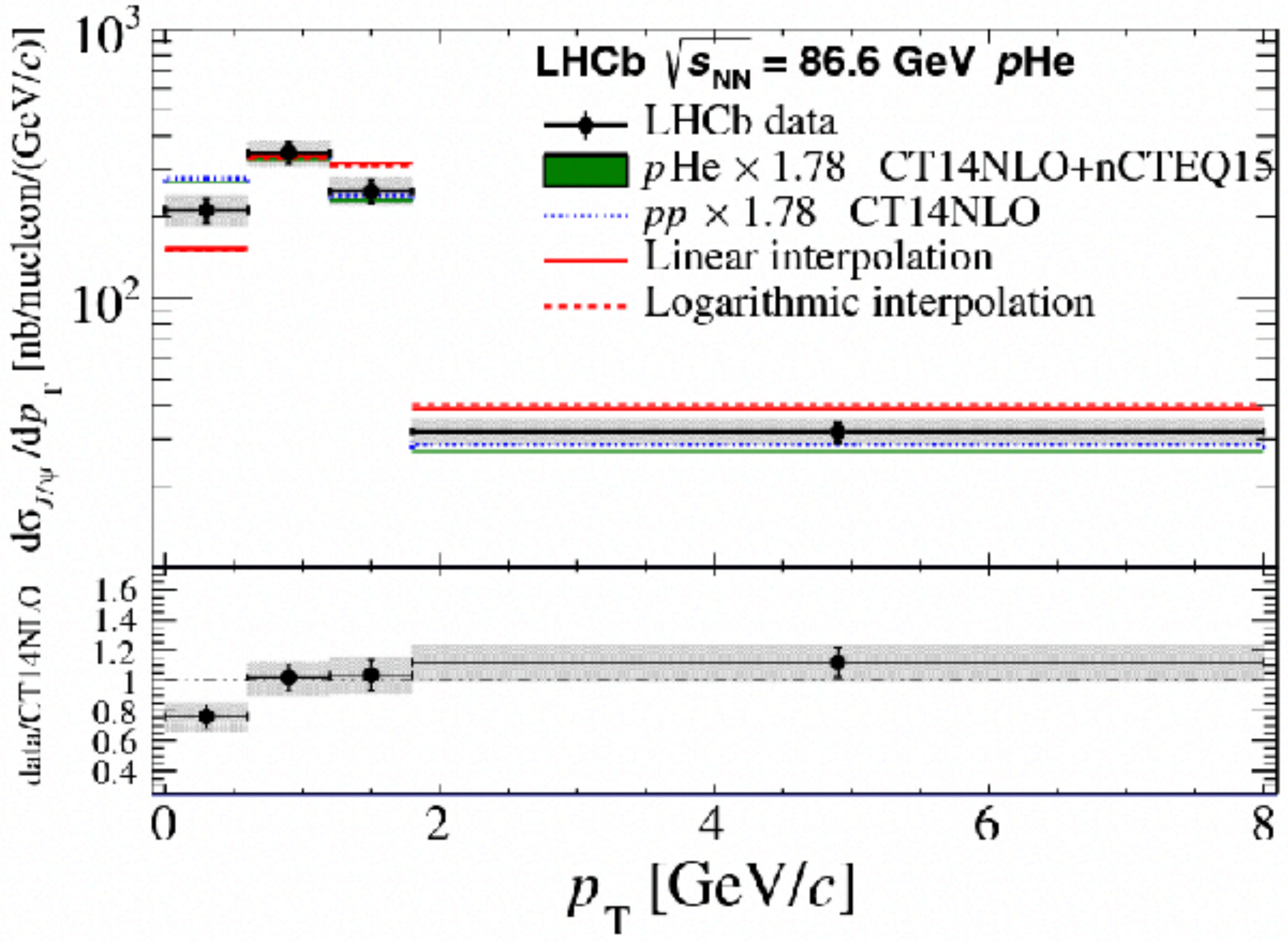
Study heavy flavor production at lower √s in a fixed-target mode

D^0 meson

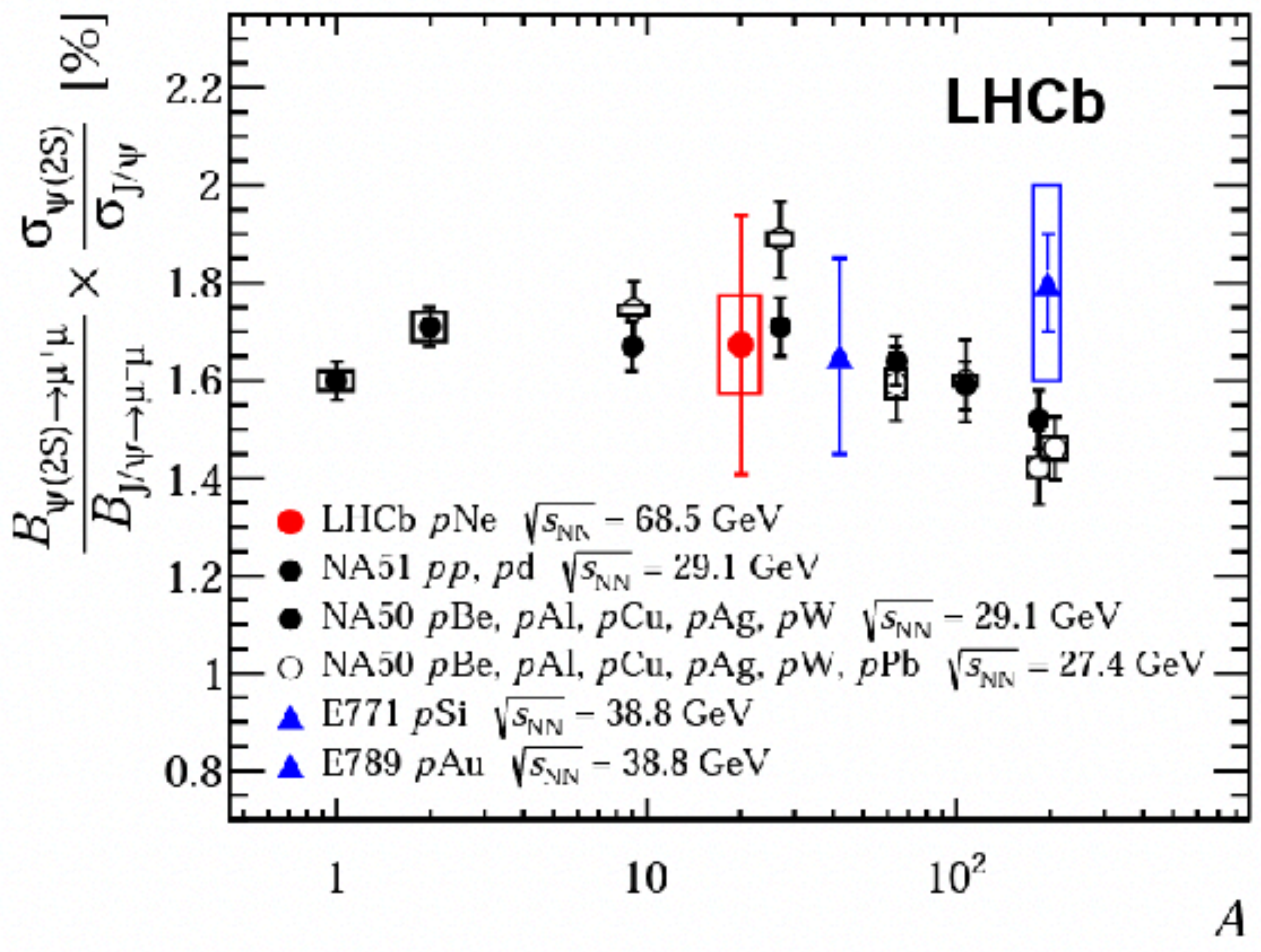


PRL 122 (2019) 132002
arXiv:2211.11645

J/Ψ

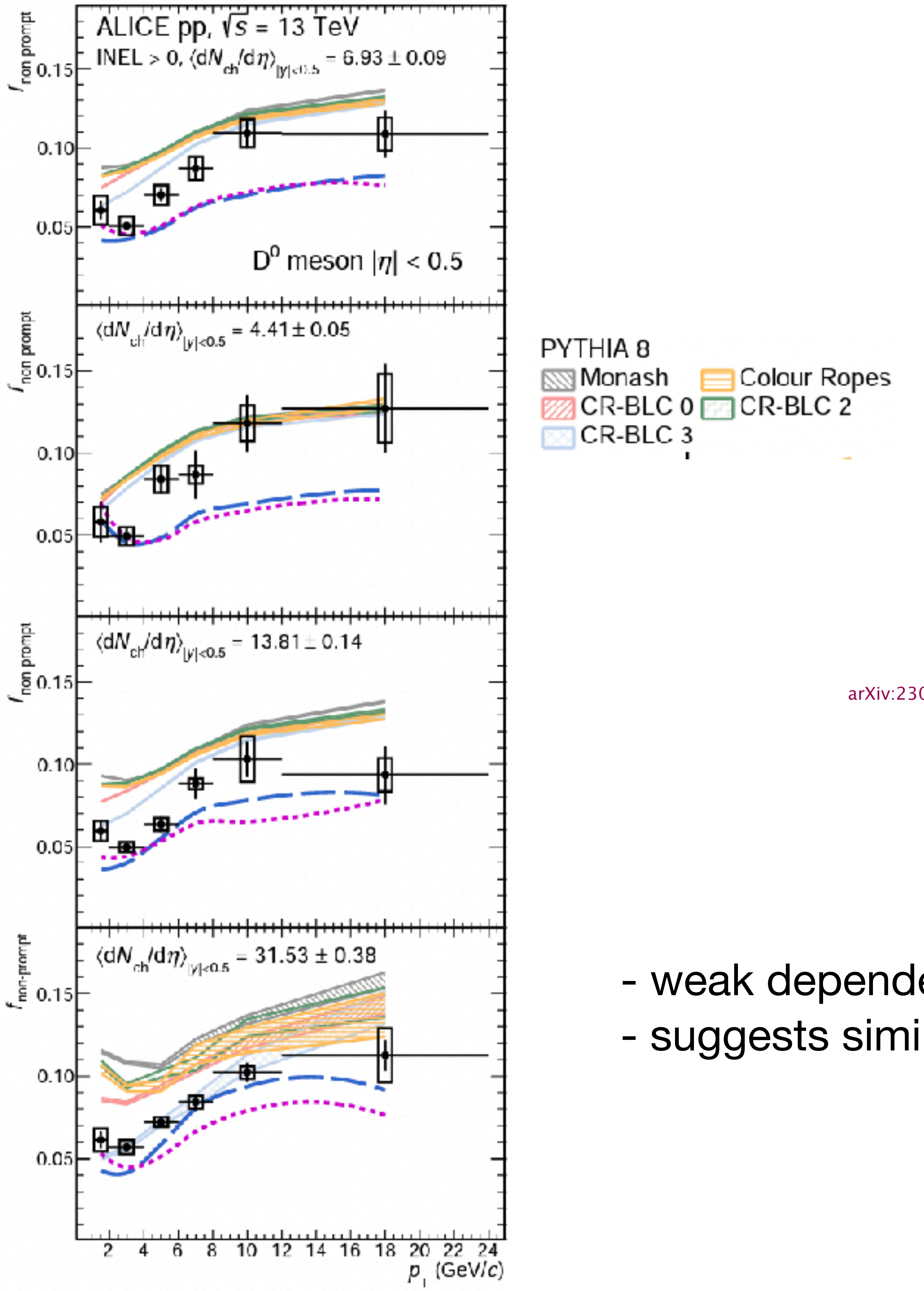


Ψ(2S) / J/Ψ

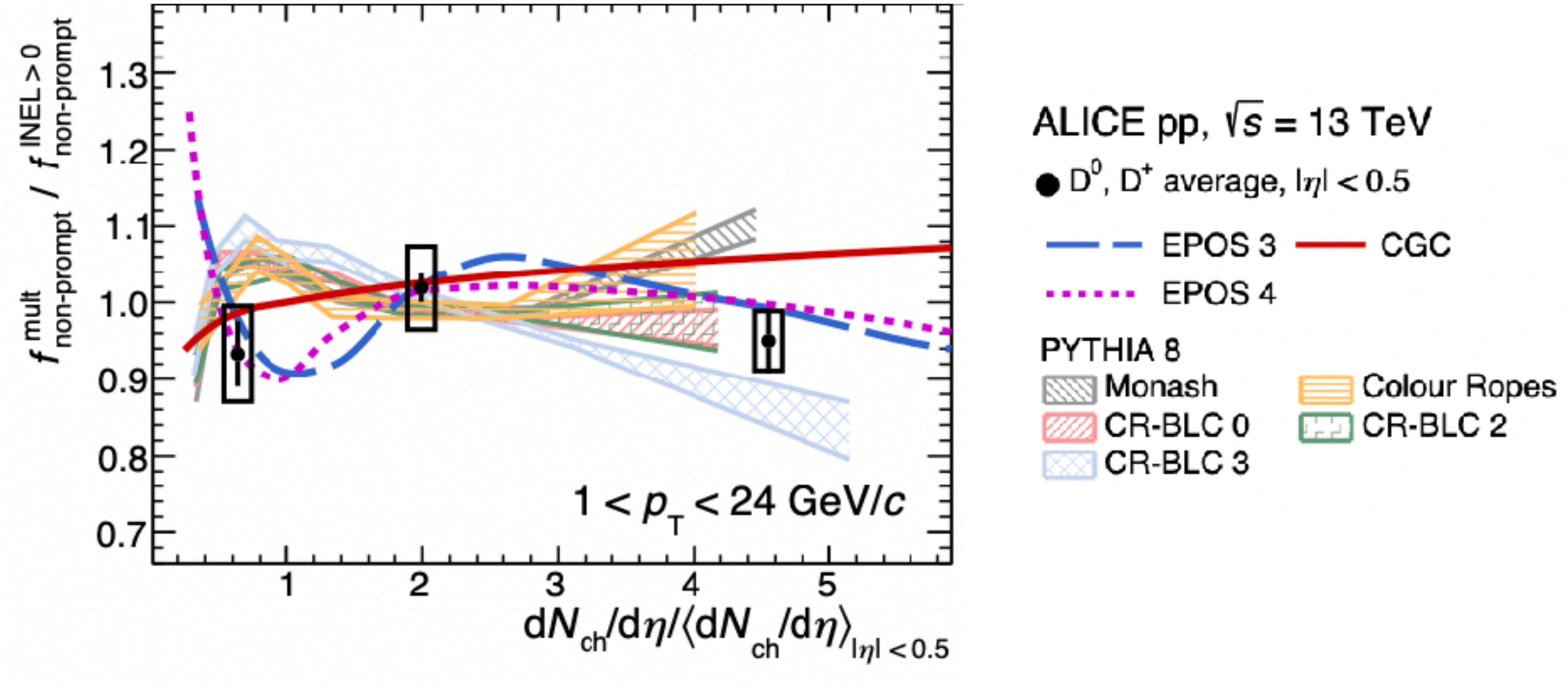


- D meson, J/Ψ cross-section measured in p-Ne √s =68.5 GeV, p-He at √s =86.6 GeV, and in p-Ar at √s =110.4 GeV.
- NRQCD based model calculations needs recalling to compare the shape of the distribution.
- Ψ(2S) / J/Ψ ratio measured and is compatible with other p-A measurements for small values of A.

Non-prompt D meson cross-section

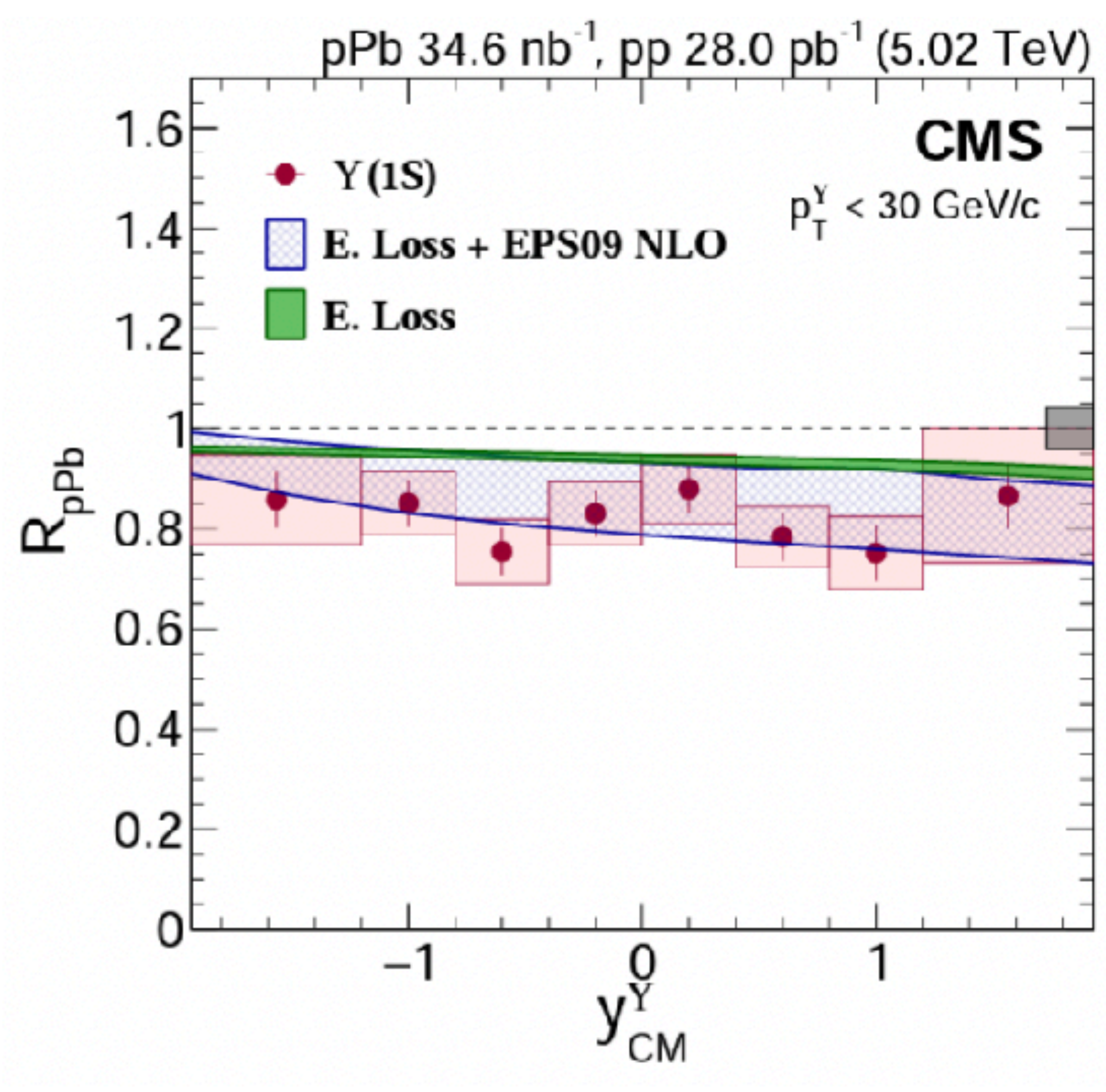


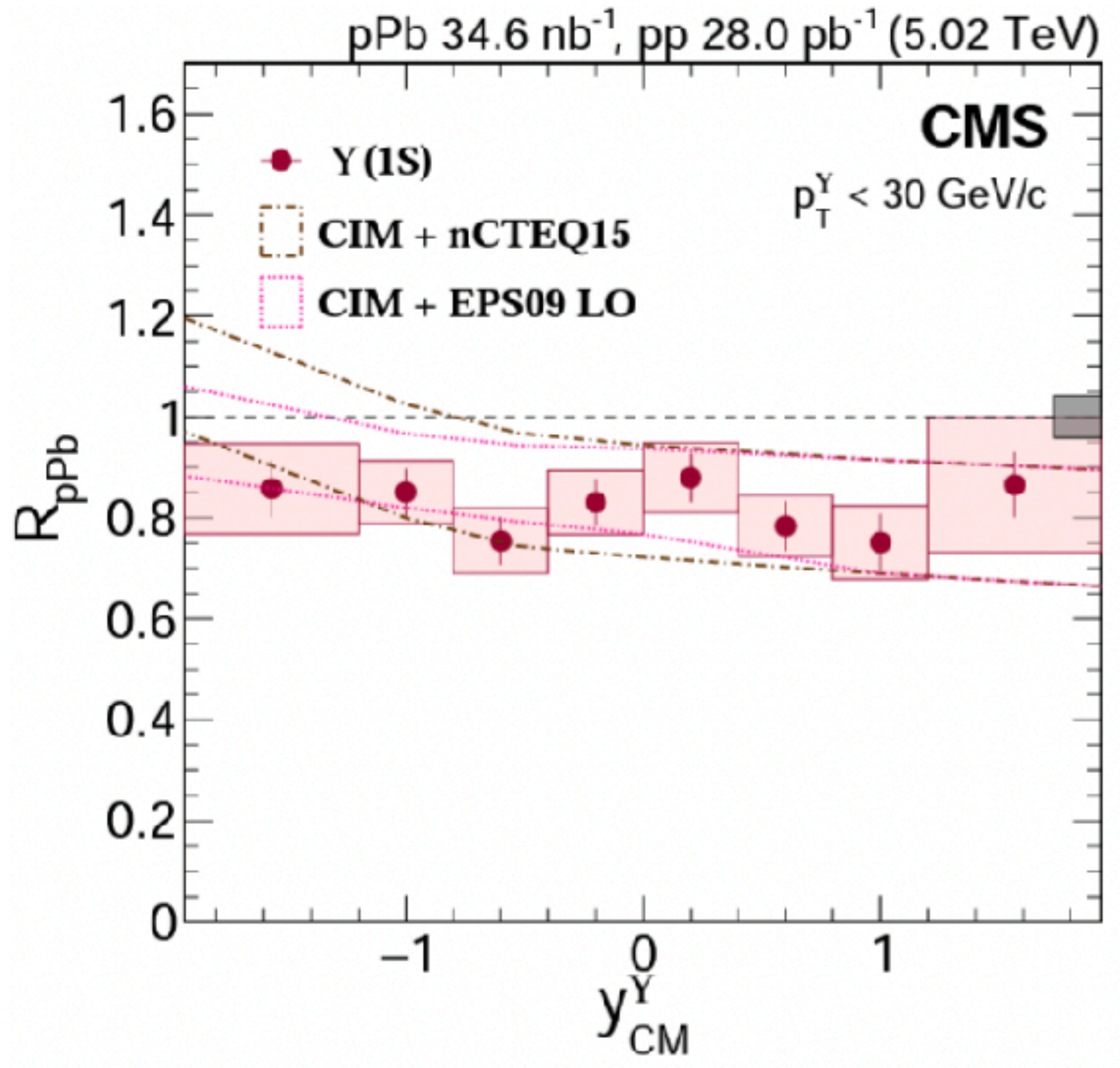
arXiv:2302.07783

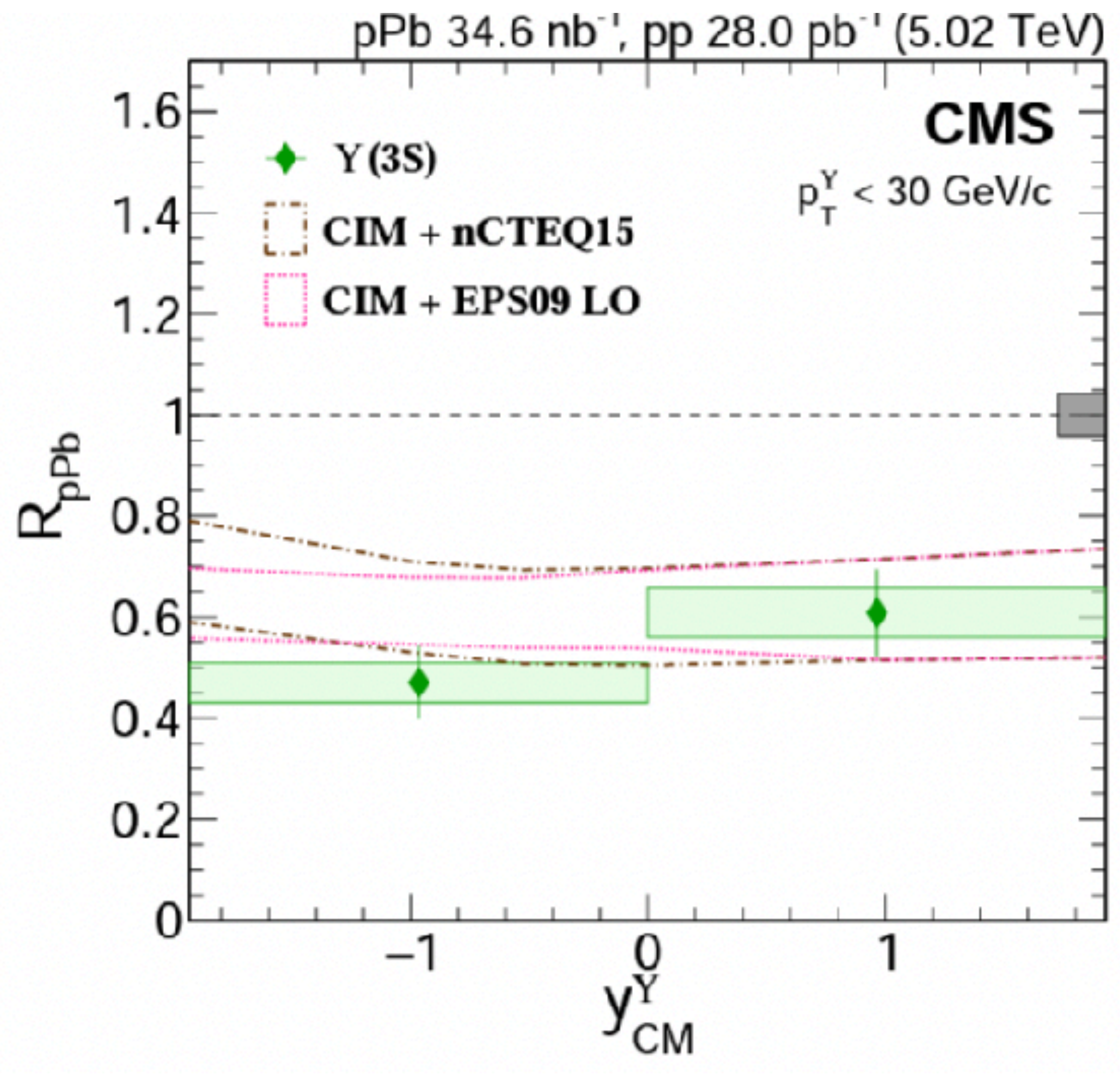


- weak dependence of $f_{\text{non-prompt}}$ with the charged-particle multiplicity.
- suggests similar production mechanisms of charm and beauty quarks as a function of multiplicity

Υ(ns) R_{pPb}


pPb 34.6 nb^{-1}, pp 28.0 pb^{-1} (5.02 TeV)
CMS
p_T^{Υ} < 30 GeV/c
Υ(1S)
E. Loss + EPS09 NLO
E. Loss
R_{pPb}
y_{CM}^{Υ}

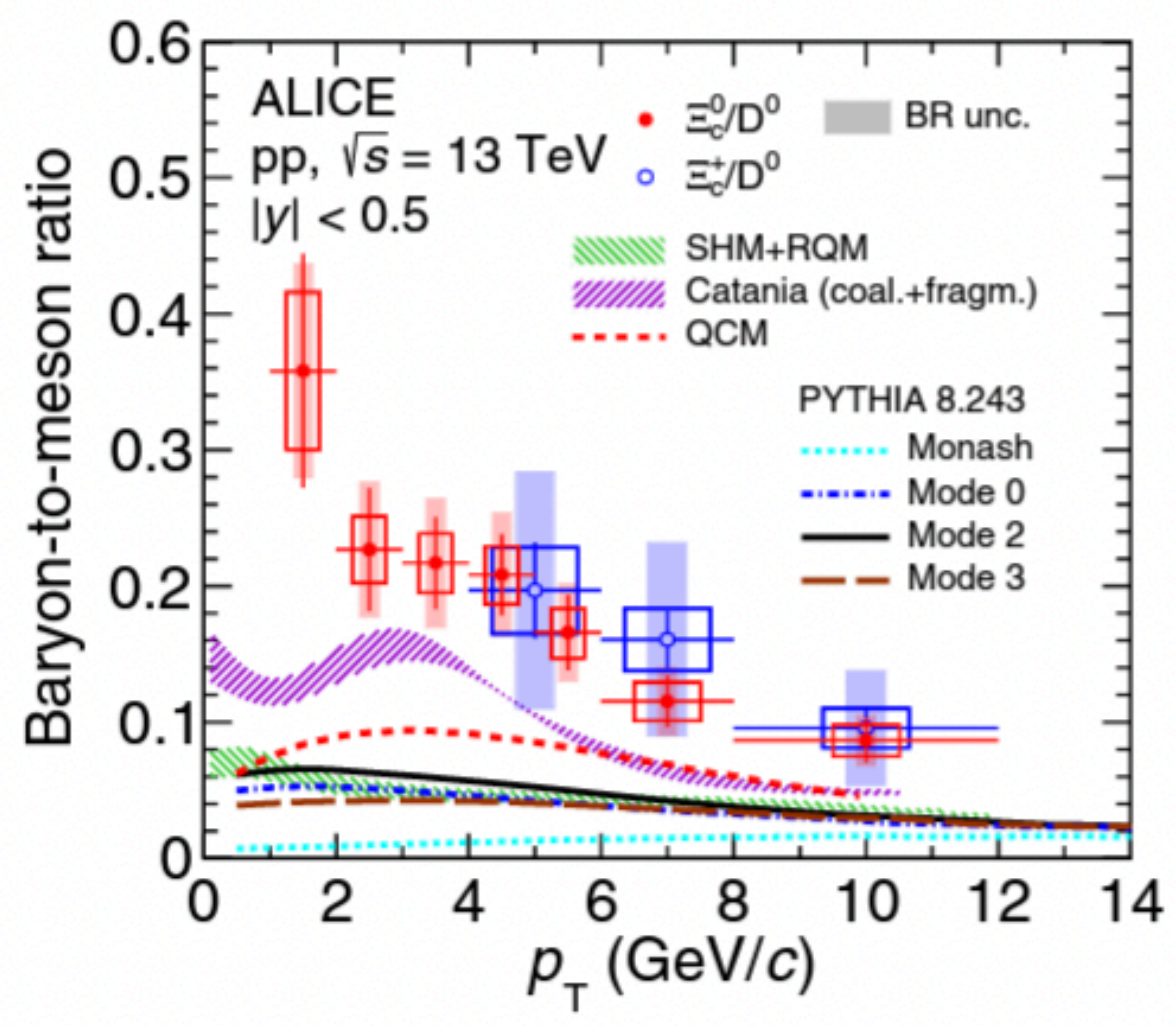

pPb 34.6 nb^{-1}, pp 28.0 pb^{-1} (5.02 TeV)
CMS
p_T^{Υ} < 30 GeV/c
Υ(1S)
CIM + nCTEQ15
CIM + EPS09 LO
R_{pPb}
y_{CM}^{Υ}

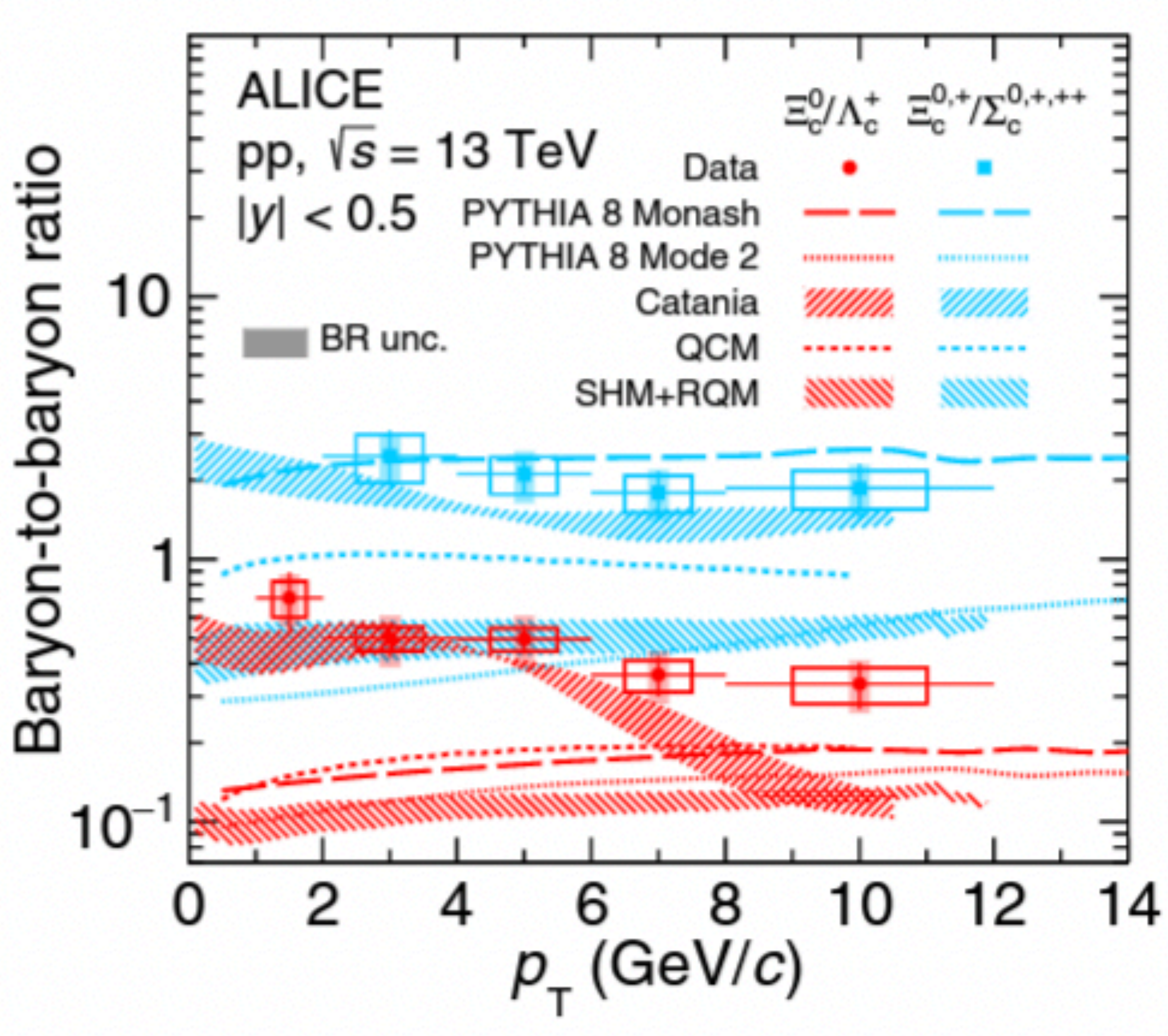

pPb 34.6 nb^{-1}, pp 28.0 pb^{-1} (5.02 TeV)
CMS
p_T^{Υ} < 30 GeV/c
Υ(3S)
CIM + nCTEQ15
CIM + EPS09 LO
R_{pPb}
y_{CM}^{Υ}

Hadronization, charm-strange baryons

Study heavy-flavor hadronization using baryons

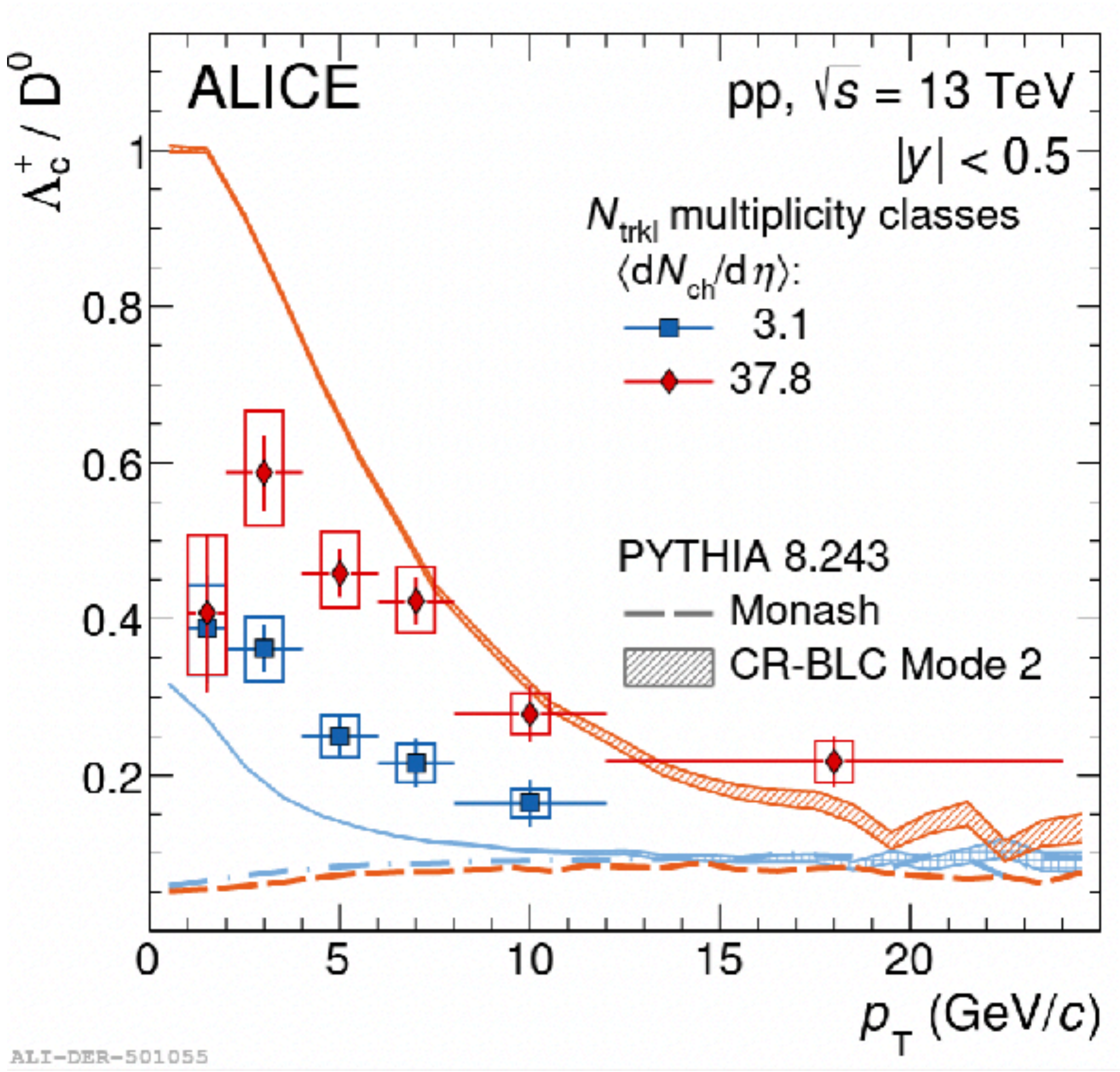
PRL. 127 (2021) 272001



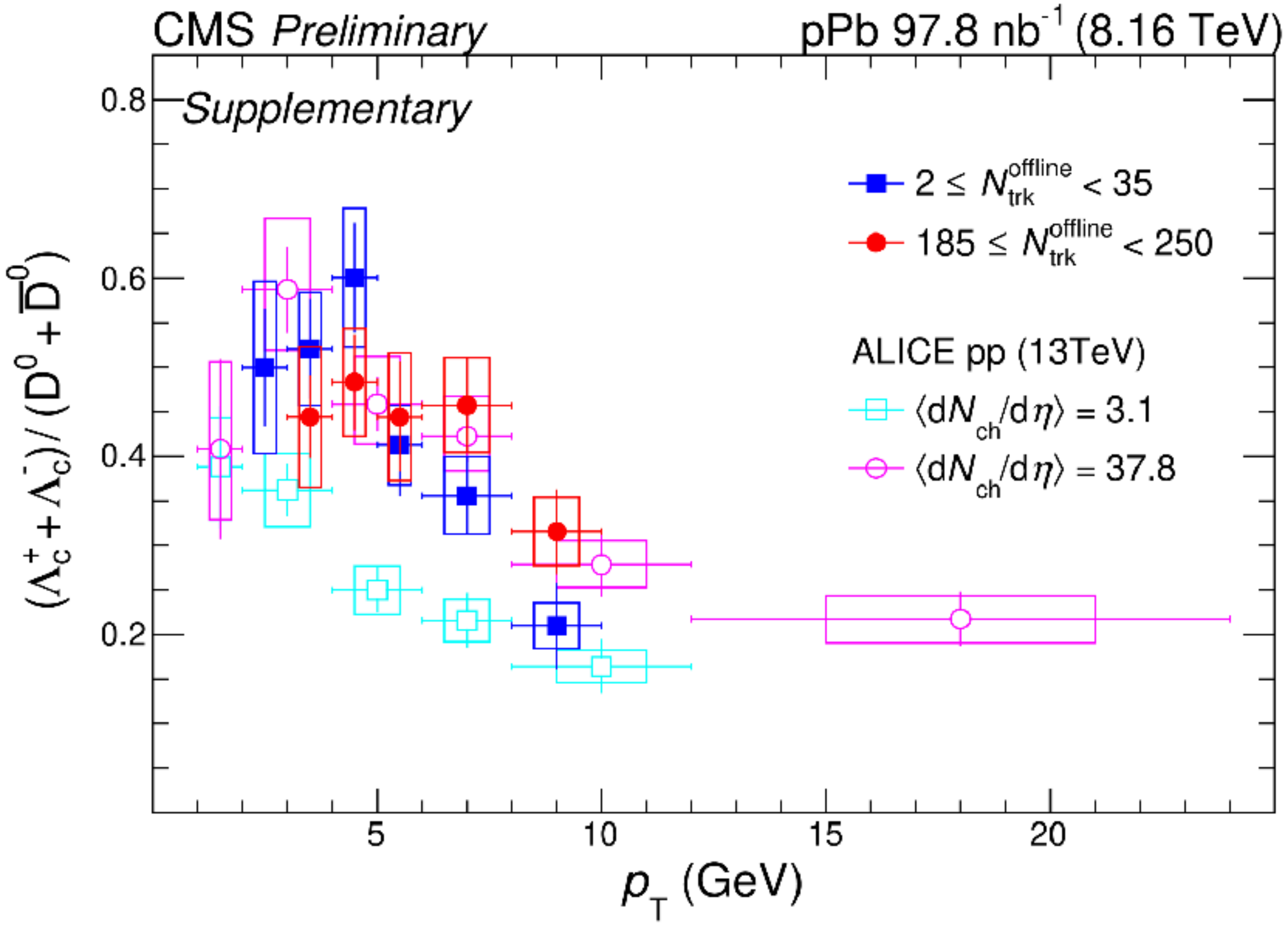


Additional challenges for models to describe charm baryons containing strange quarks

Hadronization studies vs multiplicity



PLB 829 (2022) 137065



CMS-PAS-HIN-21-016

Lc/D0 ratio increases with multiplicity in pp

Qualitatively reproduced by **PYTHIA8 with CR-BLC** → interplay of CR and MPI

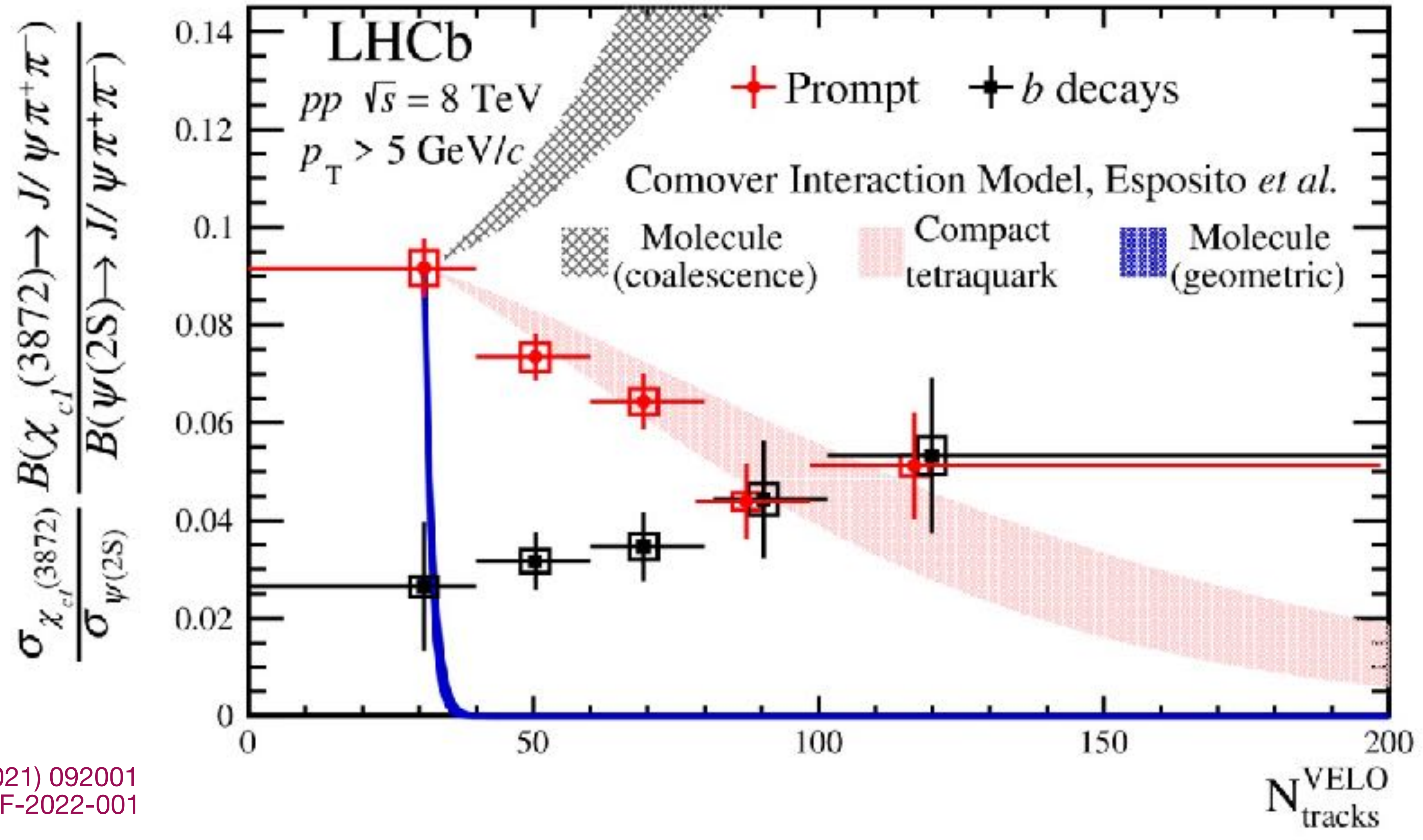
Coalescence process tends to saturate in p-Pb collisions

- p-Pb data close to high multiplicity pp

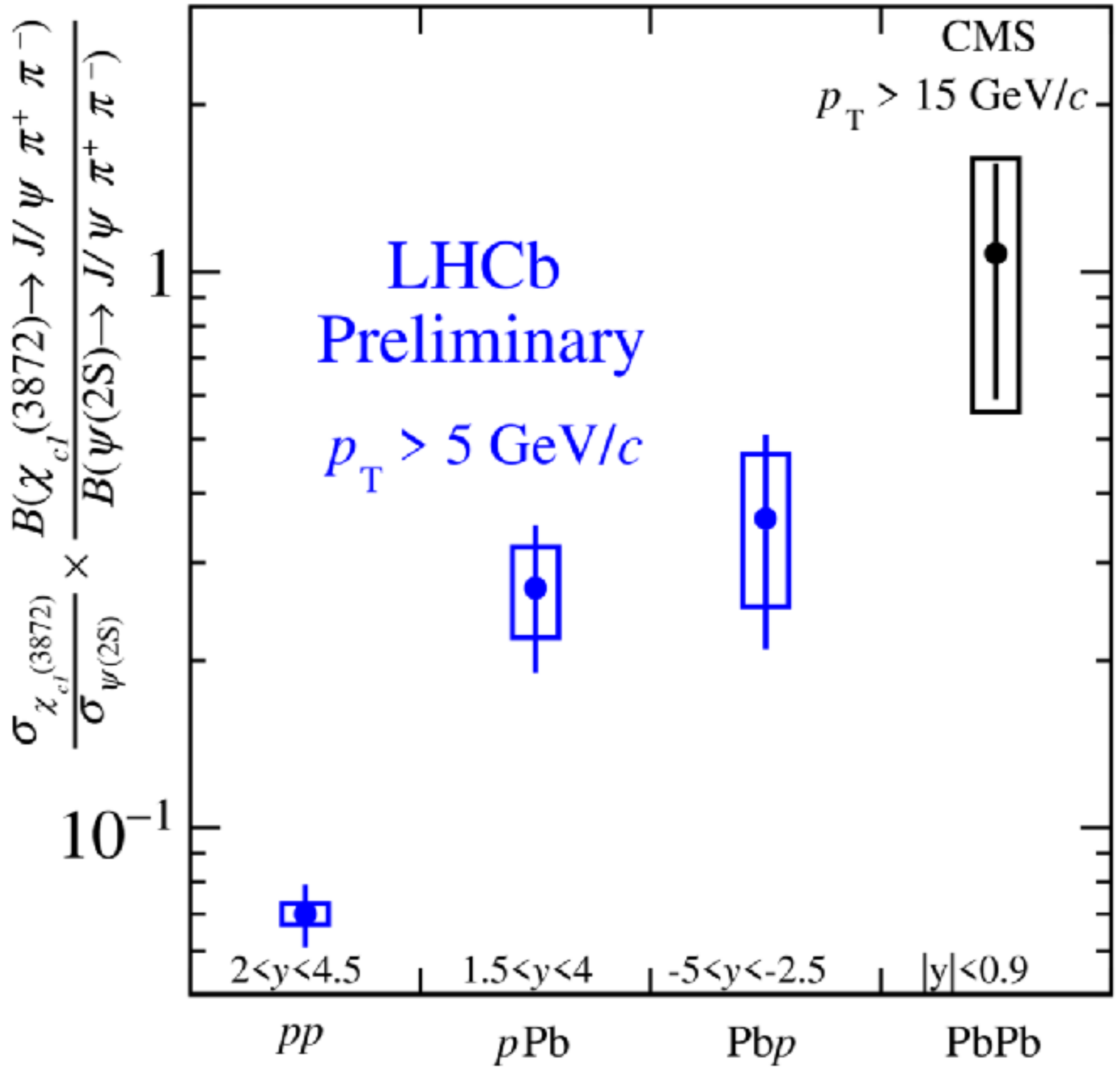
Exotic particle production

Study nature of exotic hadrons

- tetra quark composed of a diquark-anti diquark bound state or a hadrocharmonium state with two light quarks orbiting a charmonium core



PRL 126 (2021) 092001
LHCB-CONF-2022-001



Final state interactions with co-moving particles leads to breakup of X_{c1} at high multiplicity.

Large hadronic density in p-Pb and Pb-Pb allows quark coalescence affecting X_{c1} production.