Experimental evidence for saturation — a mini-review

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The VIth International Conference on the
INITIAL STAGES
OF HIGH-ENERGY NUCLEAR
COLLISIONS

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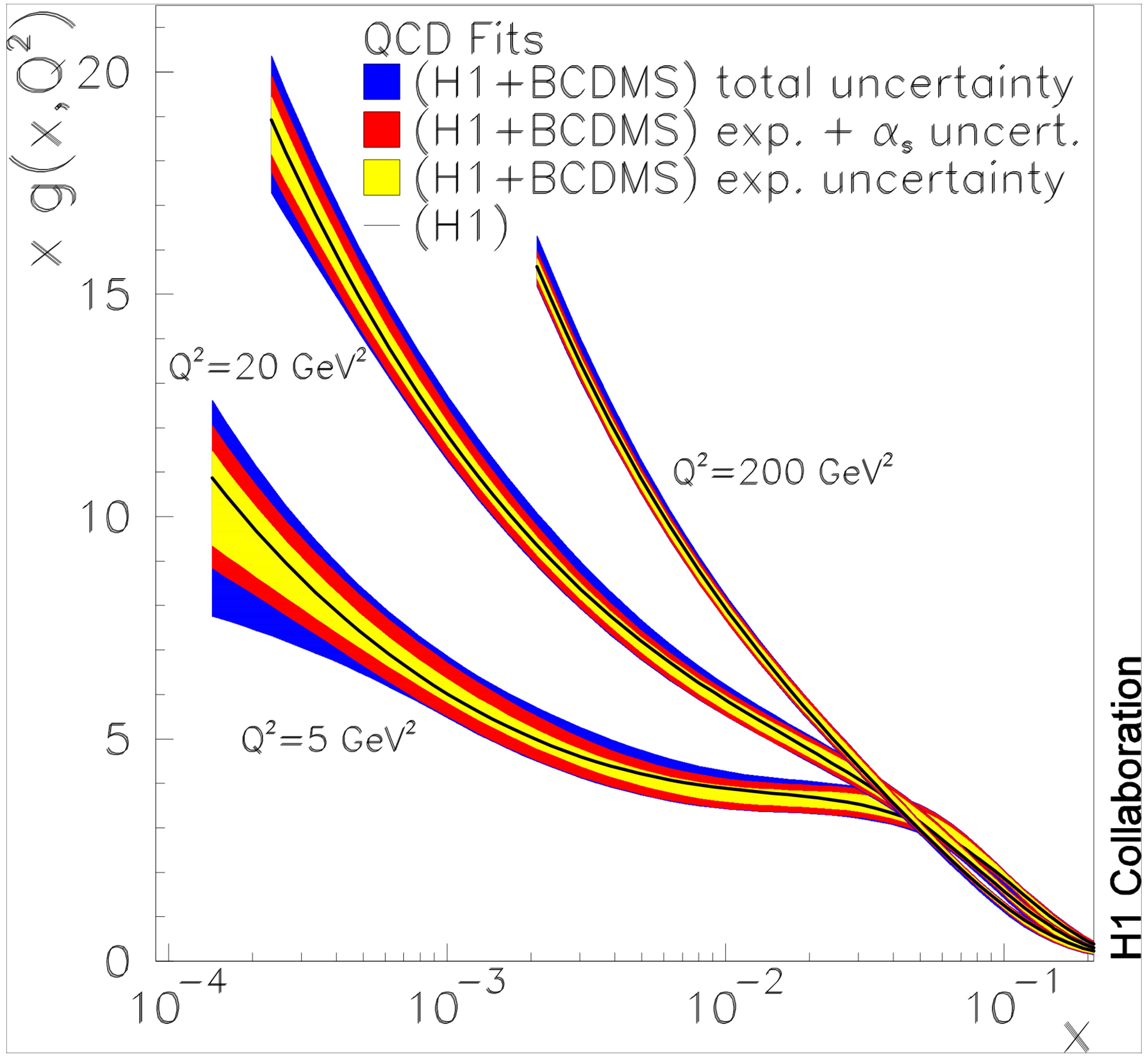
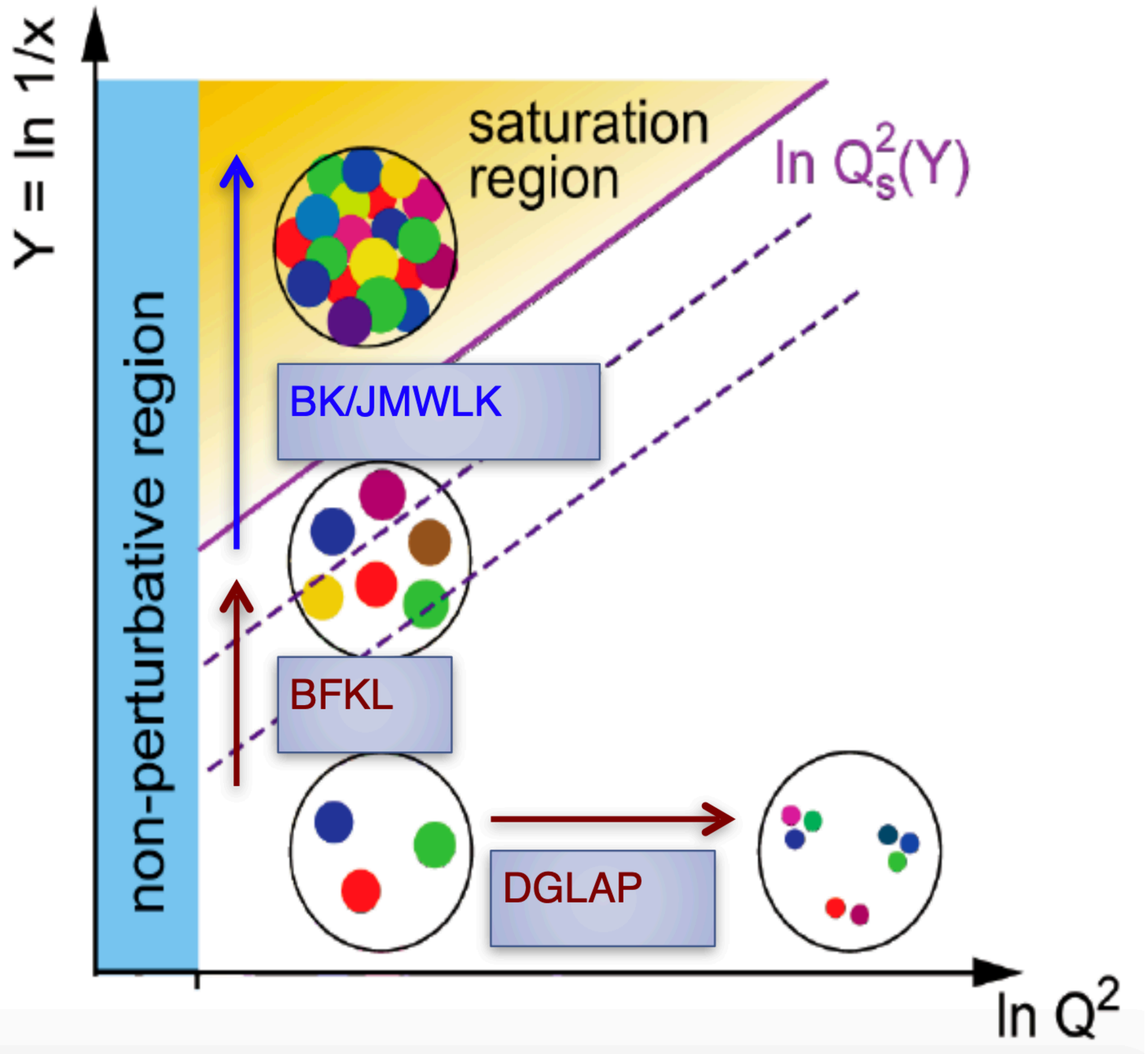
Physics Utrecht
EMMEΦ

Experimental evidence of saturation?

Q^2 evolution: gluon density



Gluon content of proton rises quickly with Q^2



Something must 'tame' the gluons at low *x*
non-linear evolution, gluon fusion?

Where do we expect saturation?

- Non-linear processes, gluon fusion expected to become important
  - At small $Q^2 < Q^2_s$
  - At small *x*, i.e. where Q_s is large enough
  - Effect sets in earlier in nuclei than in protons
- Most studies to date: compare nuclei to protons/neutrons

$$Q_s^2 \approx \frac{xG_A(x, Q^2)}{\pi R_A^2} \propto A^{1/3} x^{-\lambda}$$

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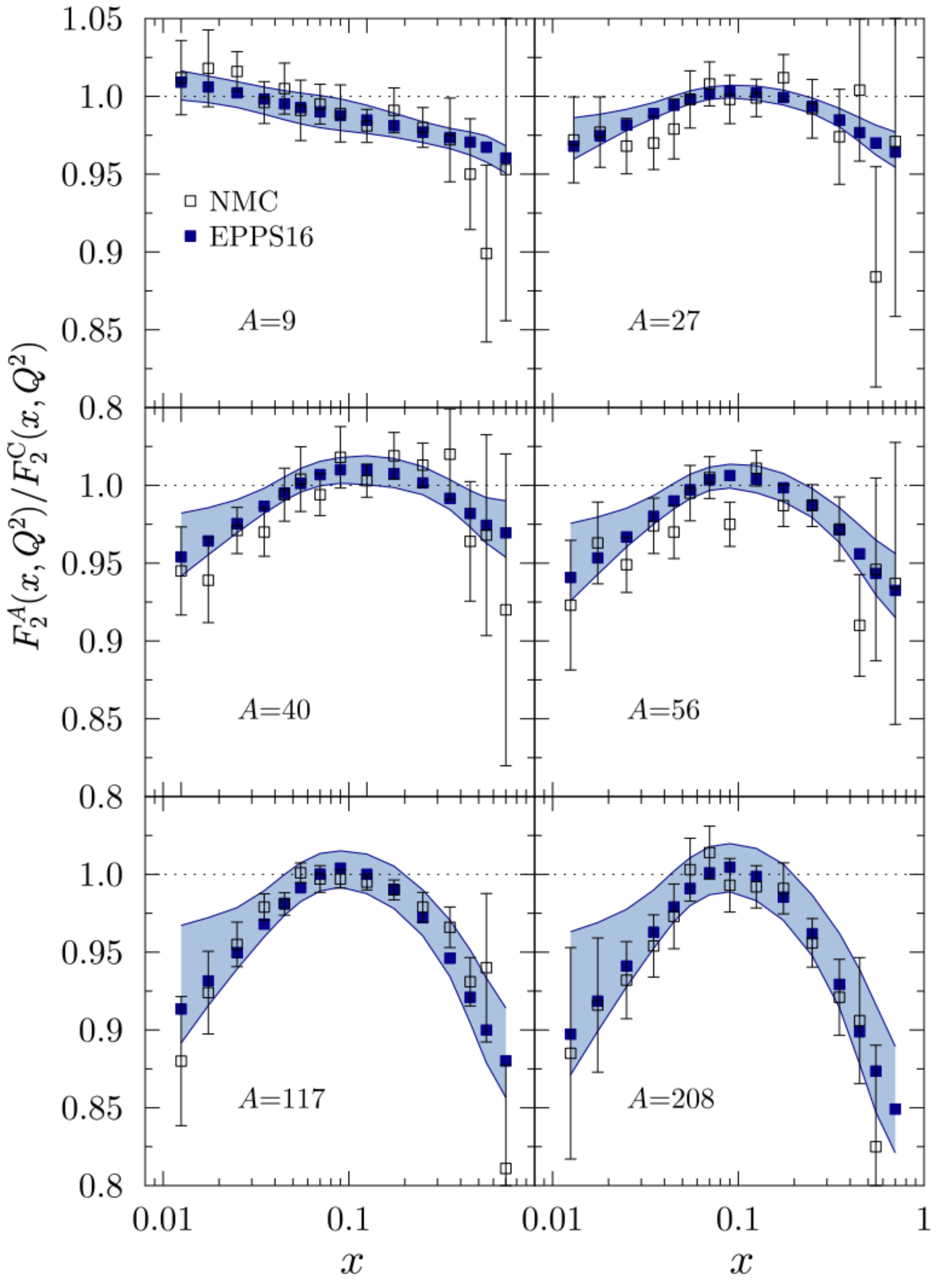
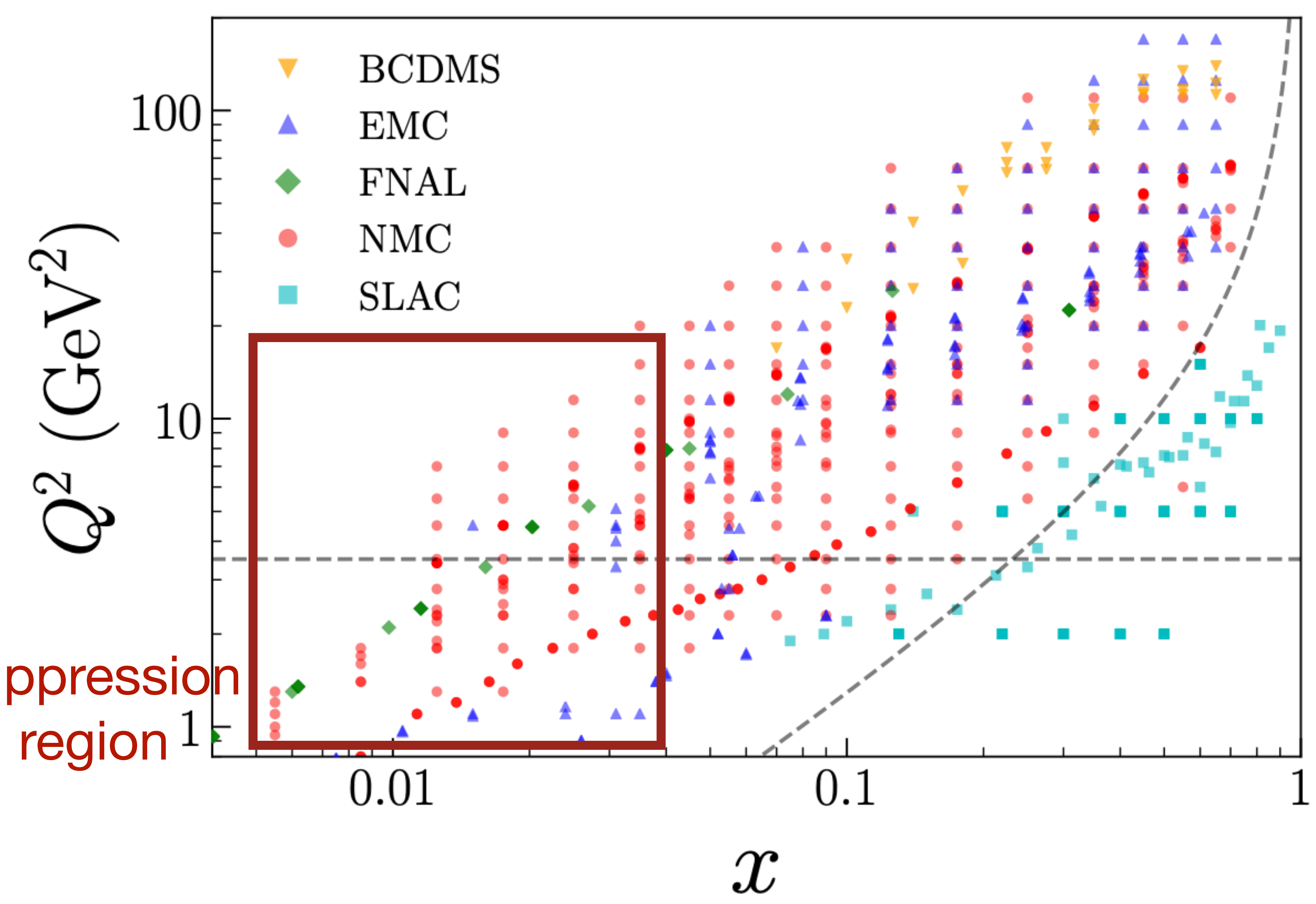
- Observables/measurements:
  - Inclusive production: forward, moderate to low p_T probes small x
    - Forward open charm: reach to smallest x in current LHC results
    - Direct photons: clean probe, but mostly measured at mid-rapidity, fairly high p_T
    - Electroweak bosons: both forward and mid-rapidity, large Q^2 —> Not discussed here
  - UPC J/ψ production: very small x, small Q^2
  - Two-particle correlations: look for mono-jet topology, multi-gluon recoil

Evidence for saturation/shadowing from DIS: NMC data

EPPS16 PDF fit



EPPS16, *EPJC* 77 3, 163



DIS kinematics: small x is also small Q^2

Small x reach depends on Q^2 cut-off

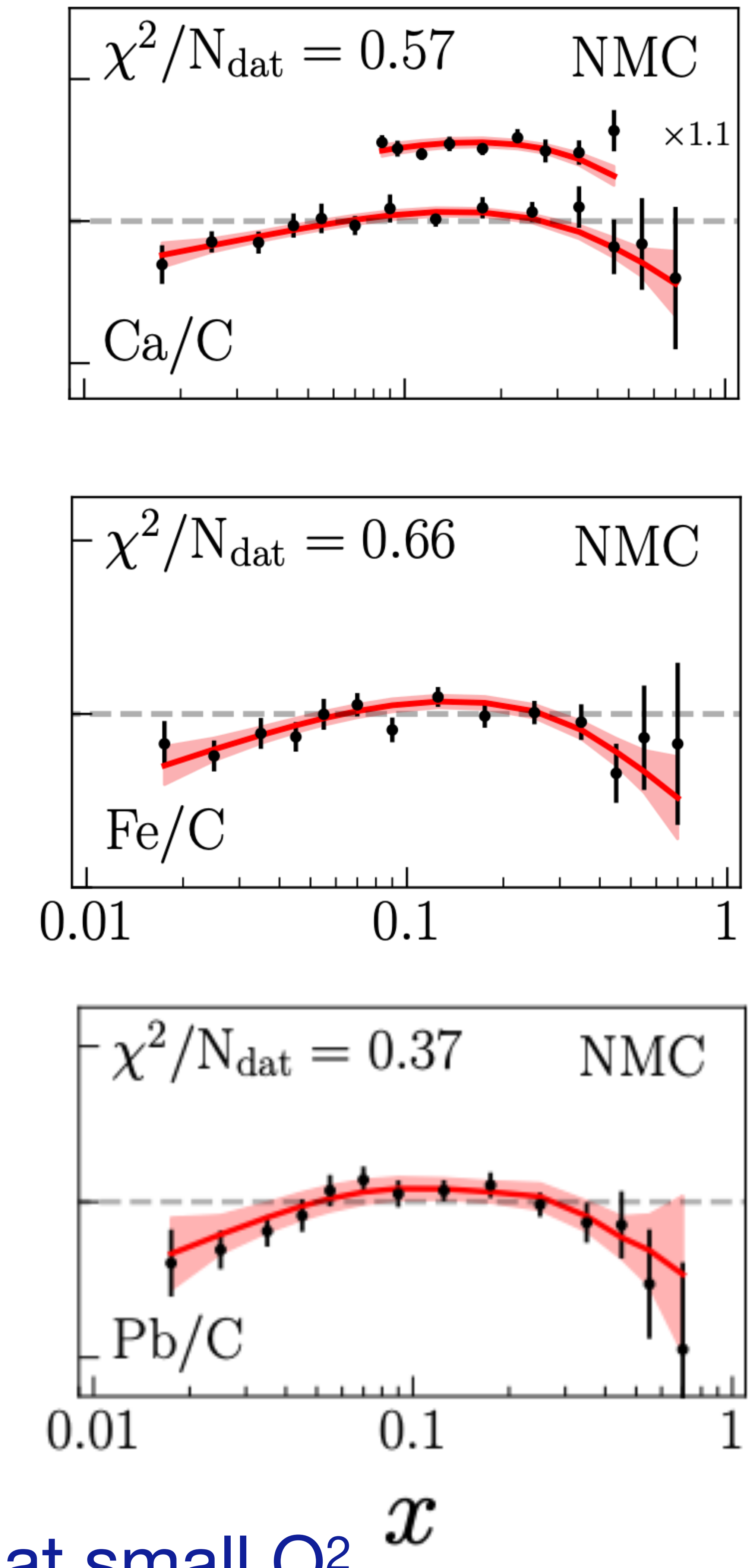
EPPS16

Q^2_{min} = 1.69 GeV^2

nNNPDF

Q^2_{min} = 3.5 GeV^2

nNNPDF fit



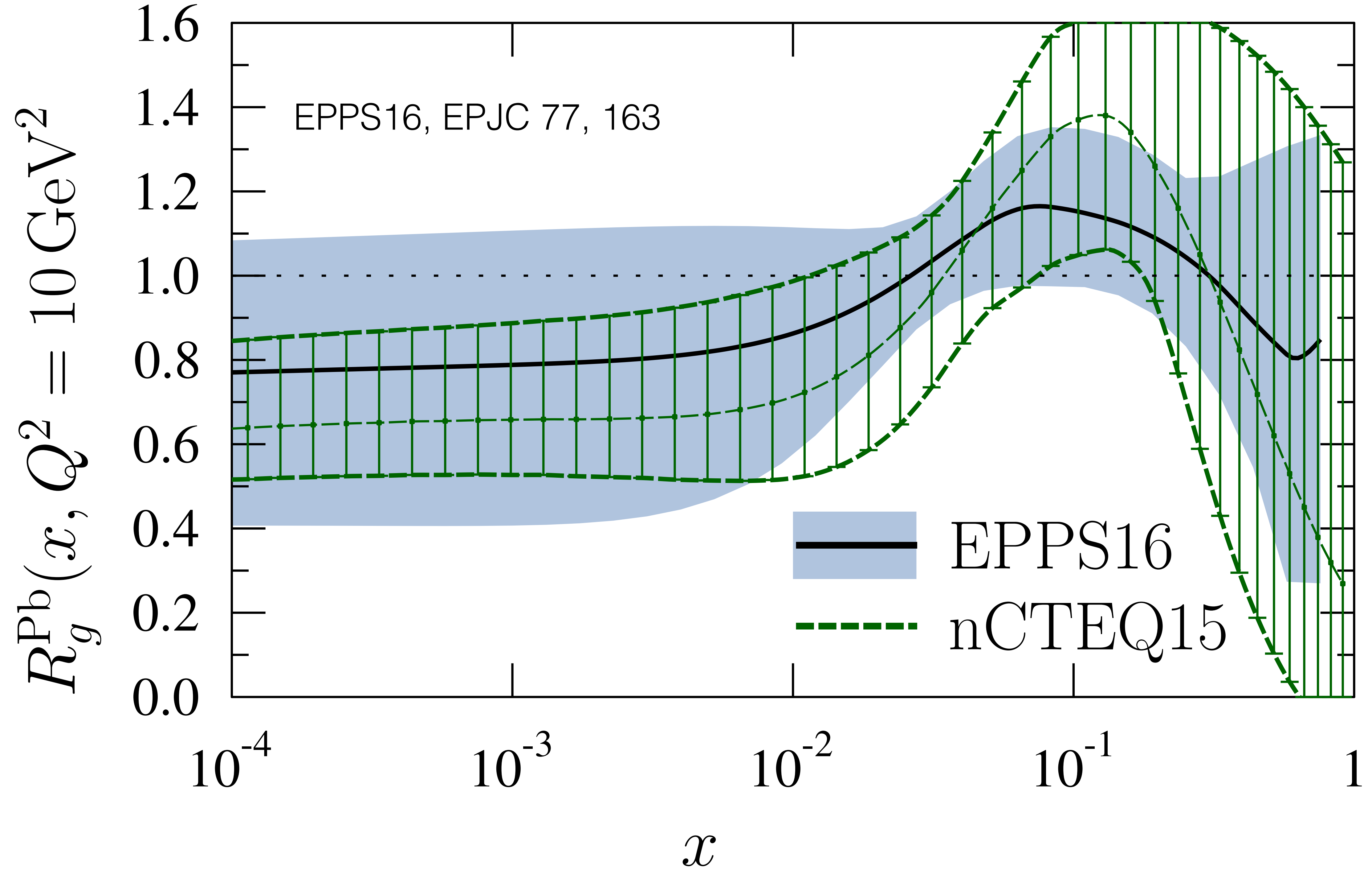
nNNPDF: R. A. Khalek et al, EPJC 79 6, 471, JHEP 09 (2020) 183

Main evidence for shadowing/saturation from DIS concentrated at small Q^2

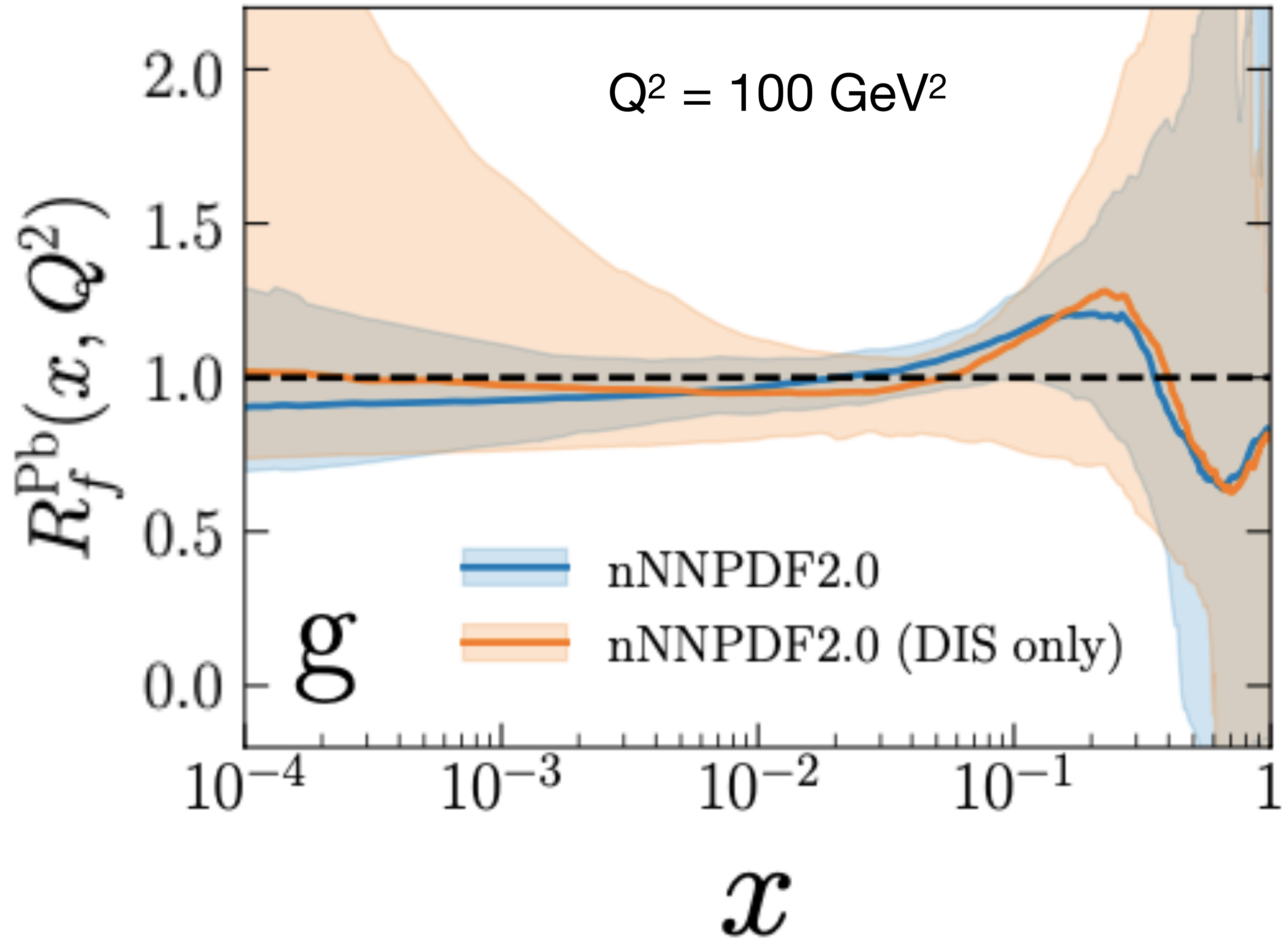
NMC, Nucl.Phys. B441, 3

nPDF gluon densities at small x

EPPS16 gluon density in Pb nucleus



nNNPDF 2.0 gluon density



JHEP 09 (2020) 183

Suppression of gluon density 'shadowing' from global fit; small-x driven by NMC data

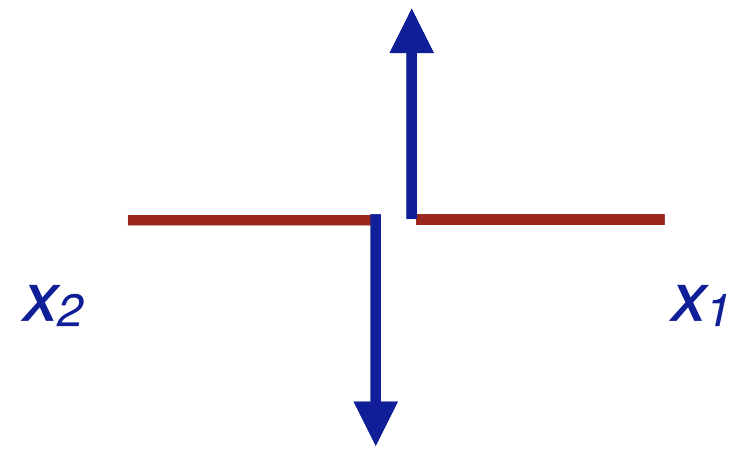
Amount of suppression varies between fits

Large uncertainties over broad range $x < 10^{-2}$

Probing gluons with inclusive particle production

2-parton kinematics

Both outgoing partons at mid-rapidity

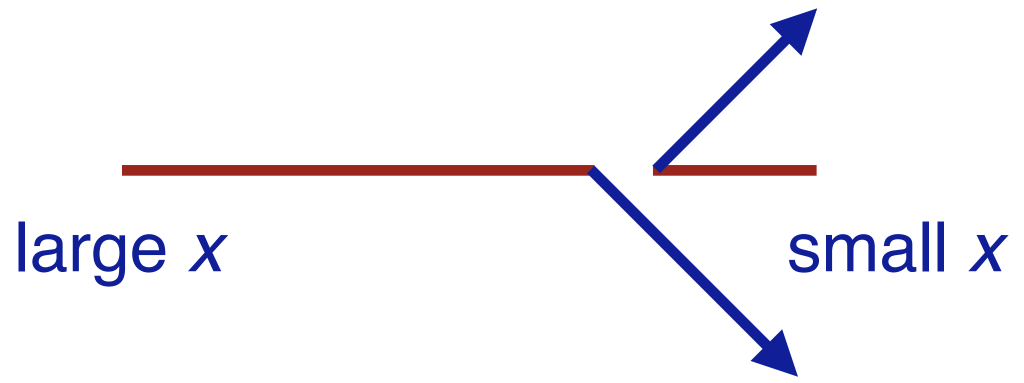


Both incoming partons at moderate x

$$\hat{s} = x_1 x_2 s \approx (2\, p_T)^2$$

$$x_1 \approx x_2 \approx \frac{2\, p_T}{\sqrt{s}}$$

Both outgoing partons at forward rapidity

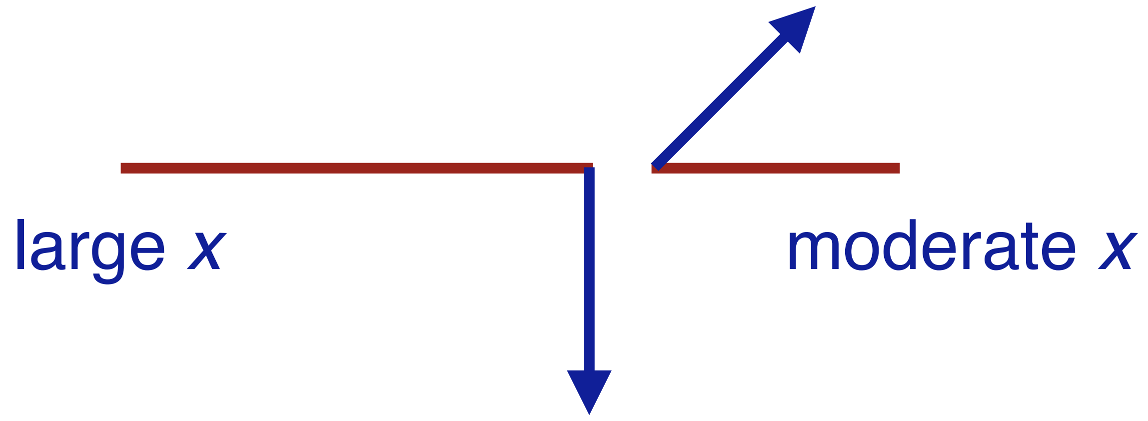


Boosted configuration: One small-x, one large-x parton

$$\hat{s} = x_1 x_2 s \approx (2\, p_T)^2$$

$$x_1 \approx \frac{p_T}{\sqrt{s}}\, e^{-y}$$

One parton forward, one closer to mid-rap



Large mass final state

$$Q^2 = \hat{s} > (2\, p_T)^2$$

small probability

Note: 2 to 2 scattering is LO kinematics; NLO processes add additional freedom/smearing

RHIC forward particle suppression

- Nuclear modification factor R_{dAu}

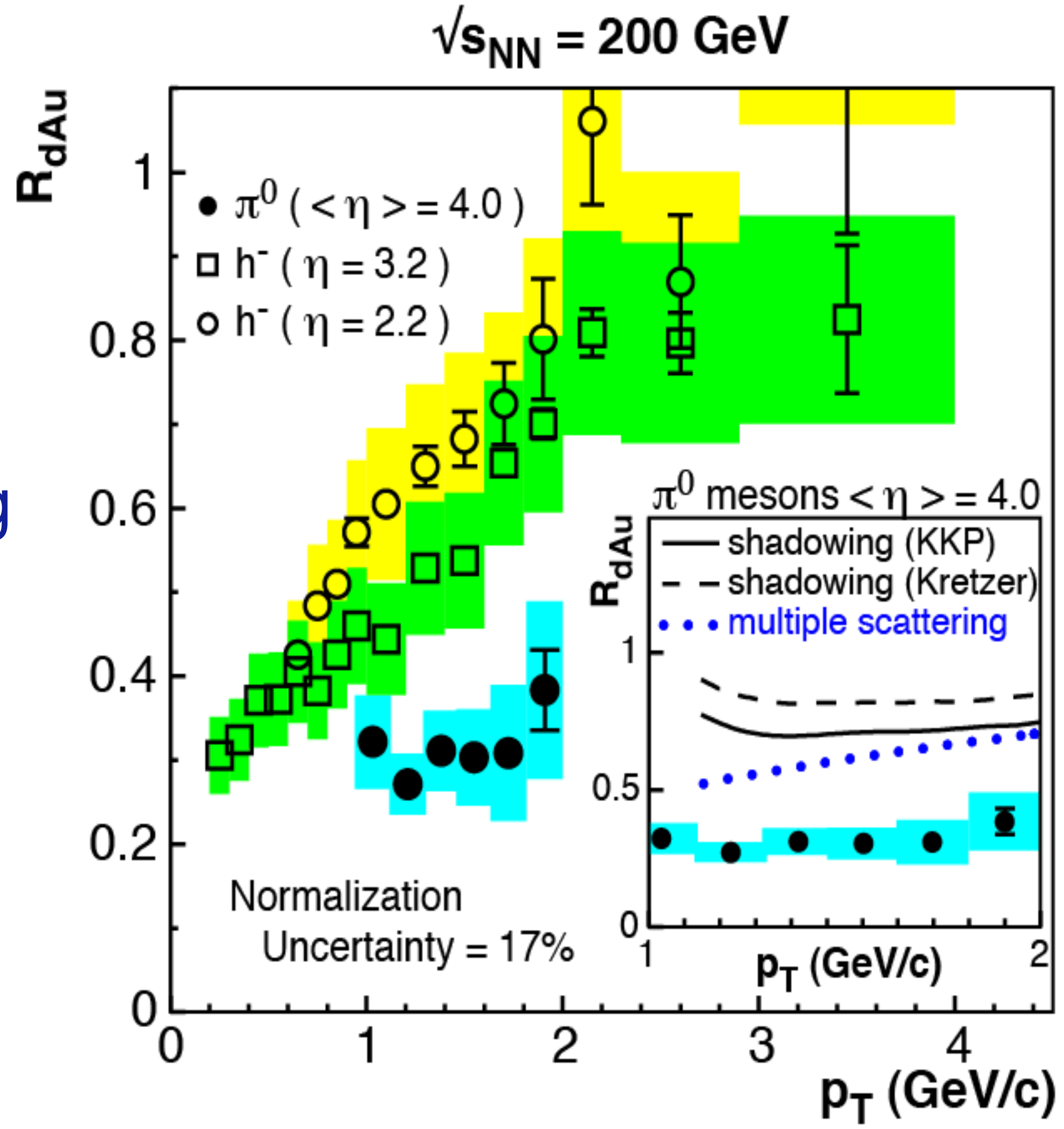
$$R_{dAu} = \frac{dN/dp_T|_{dAu}}{A d\sigma/dp_T|_{pp}}$$

- Yield suppression $R_{dAu} < 1$ seen at RHIC
  - Low p_T: expect also N_{part} vs N_{coll} scaling
  - $p_T > 2$ GeV, $R_{dAu} \sim 0.8$

Probes x ~ 10^{-3}

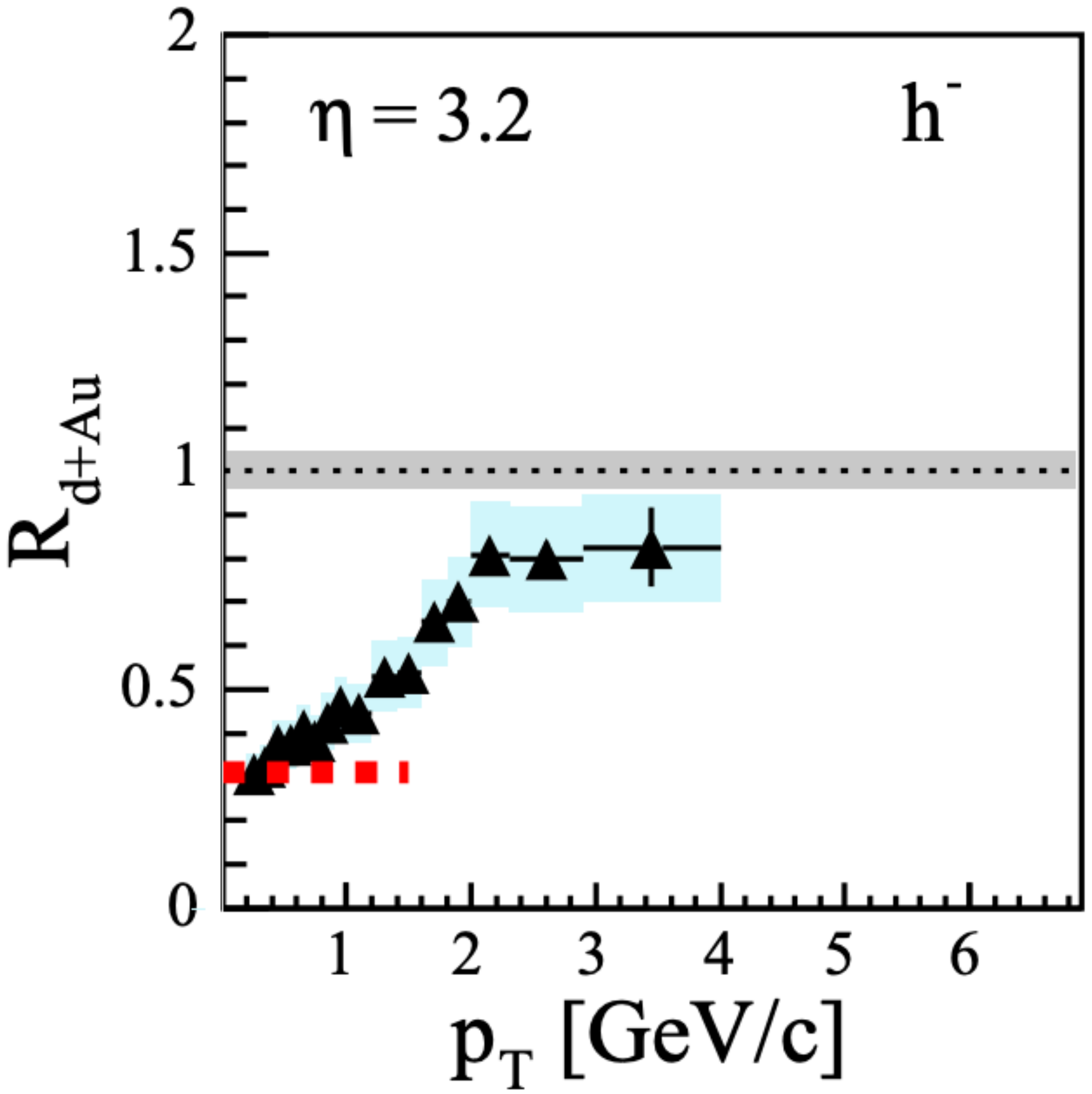
First hint of saturation?
⇒ Can we confirm this at LHC?

STAR: charged hadrons, π^0



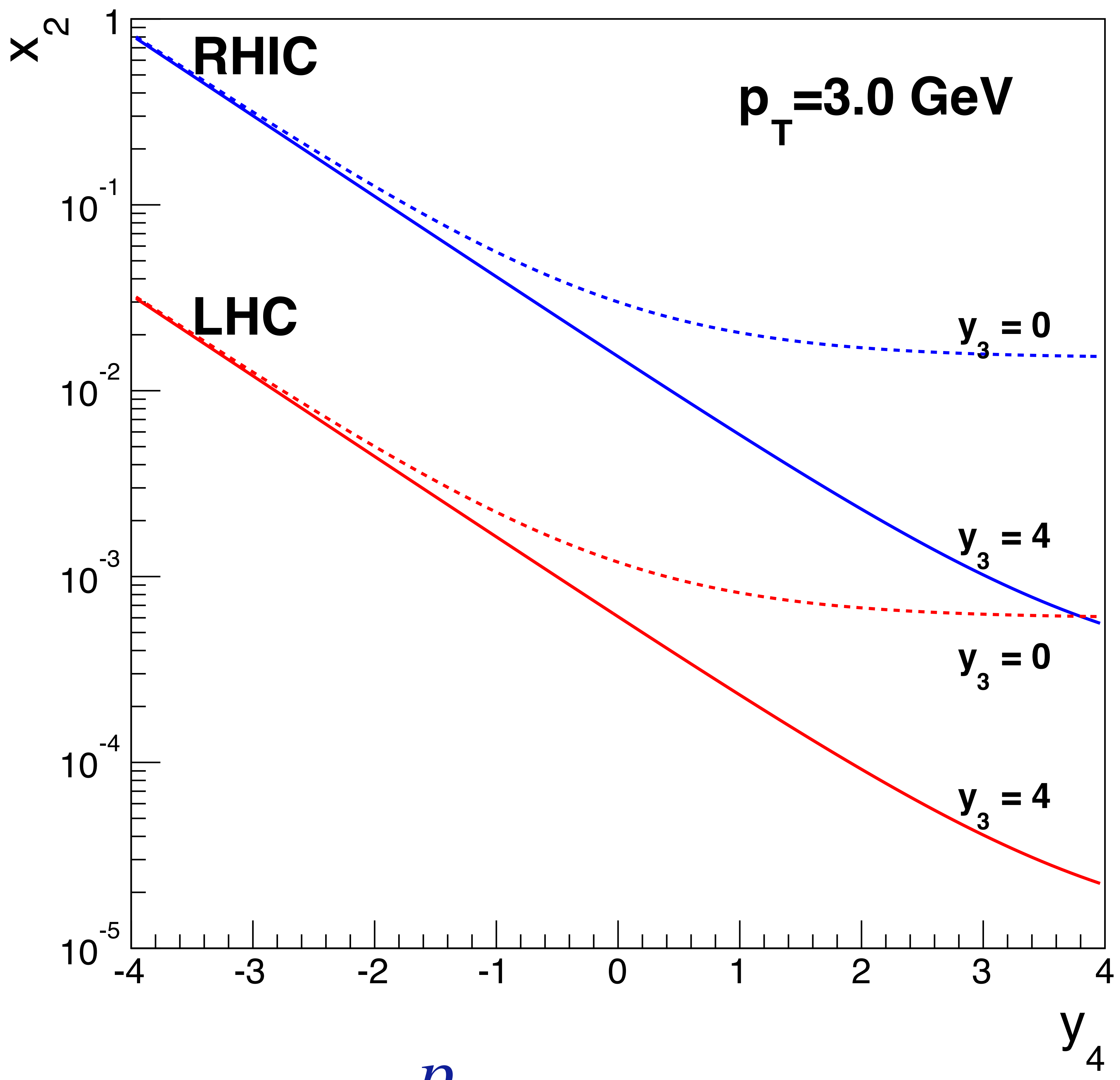
STAR, PRL 97 152302

BRAHMS: charged hadrons



BRAHMS, Phys. Rev. Lett. 93, 242303

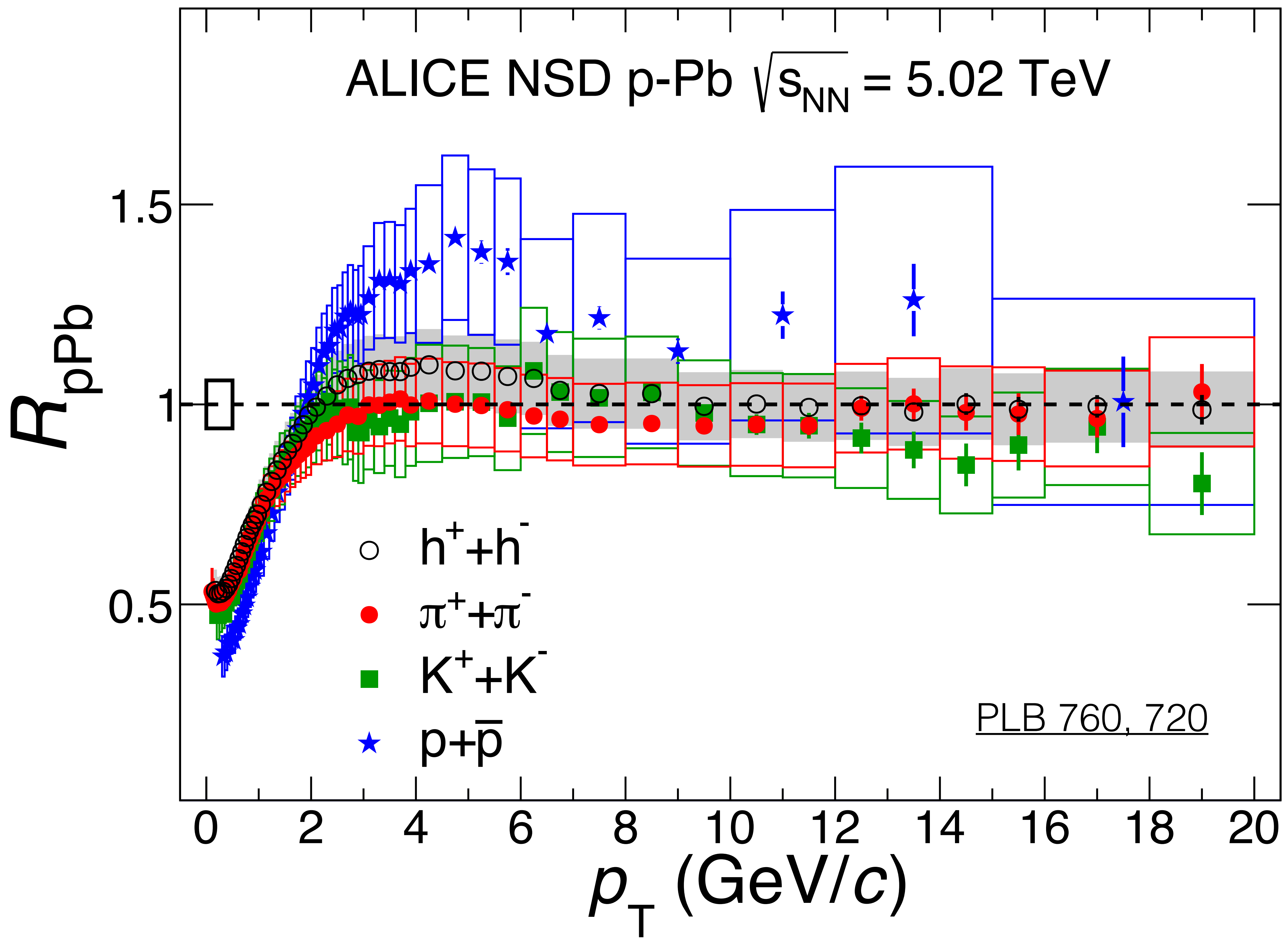
RHIC and LHC for x ~ 10^{-4}



$$x_2 \approx \frac{p_T}{\sqrt{s}} \left(e^{-y_3} + e^{-y_4}\right)$$

Mid-rapidity at LHC ≈ forward rapidity at RHIC

Light-flavour R_{pPb}



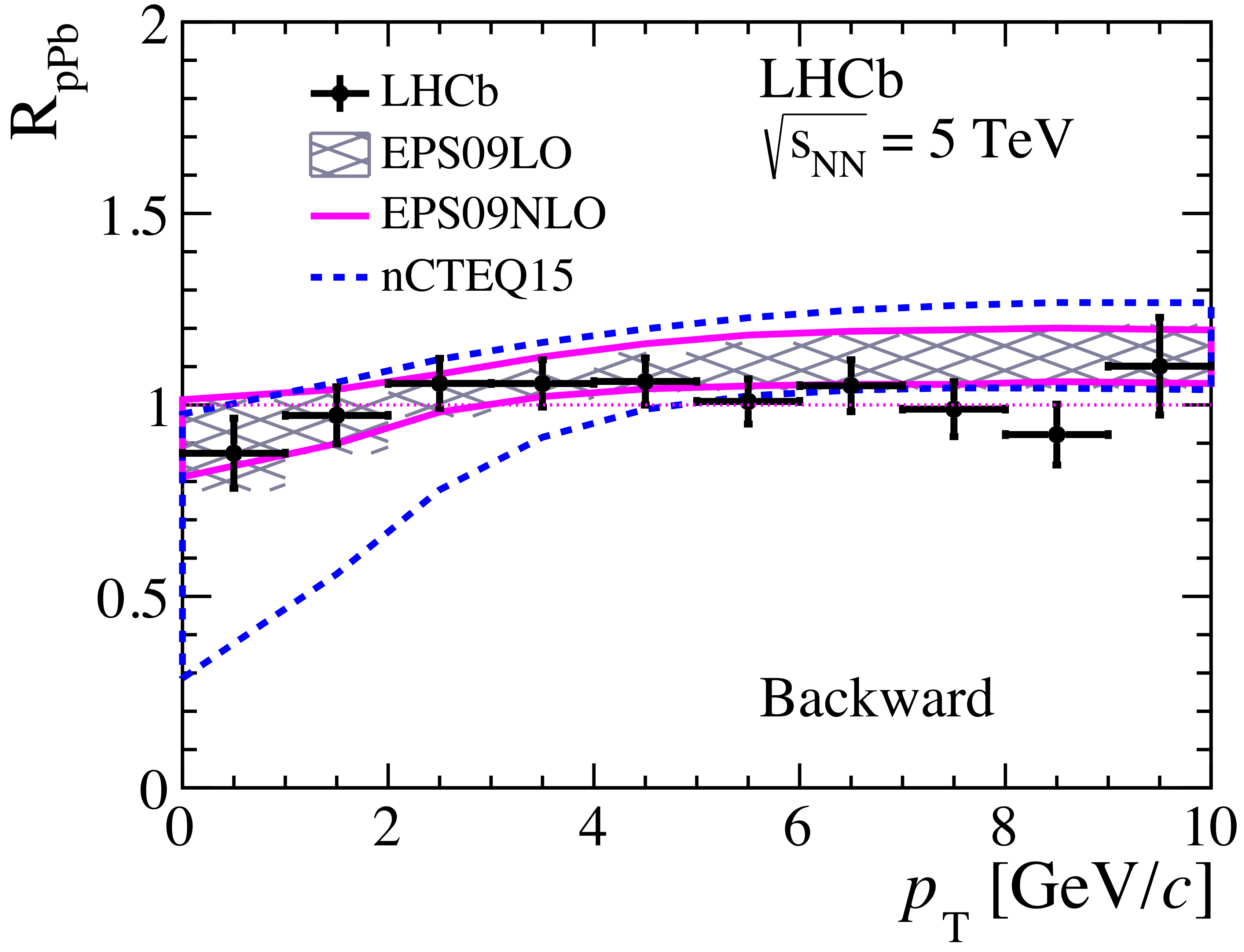
No sign of suppression at high $p_T > 2$ GeV

$p_T < 2$ GeV expect soft effects; N_{part} scaling

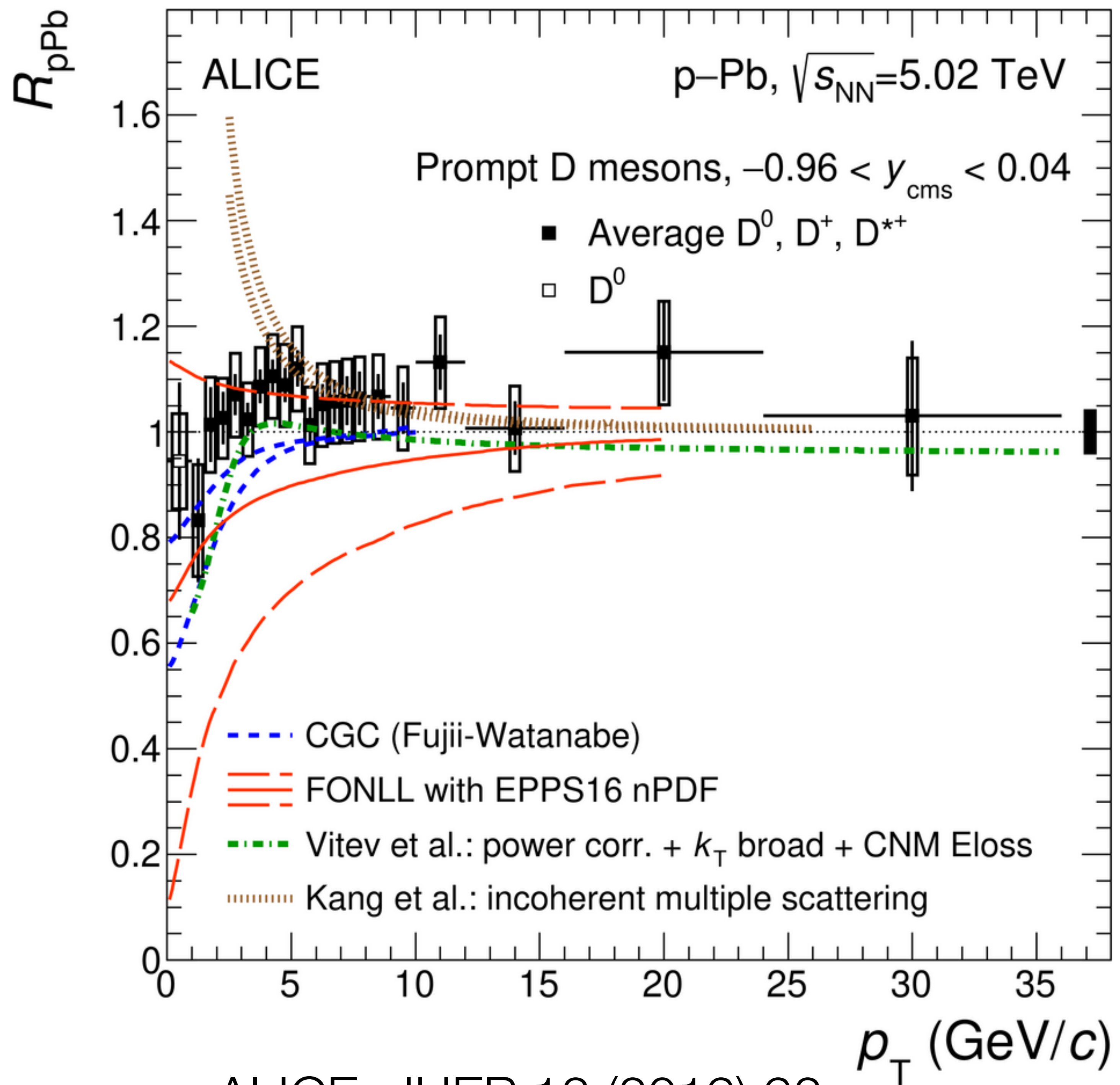
Enhancement for protons?

Open charm production vs rapidity at LHC

Backward rapidity: large x

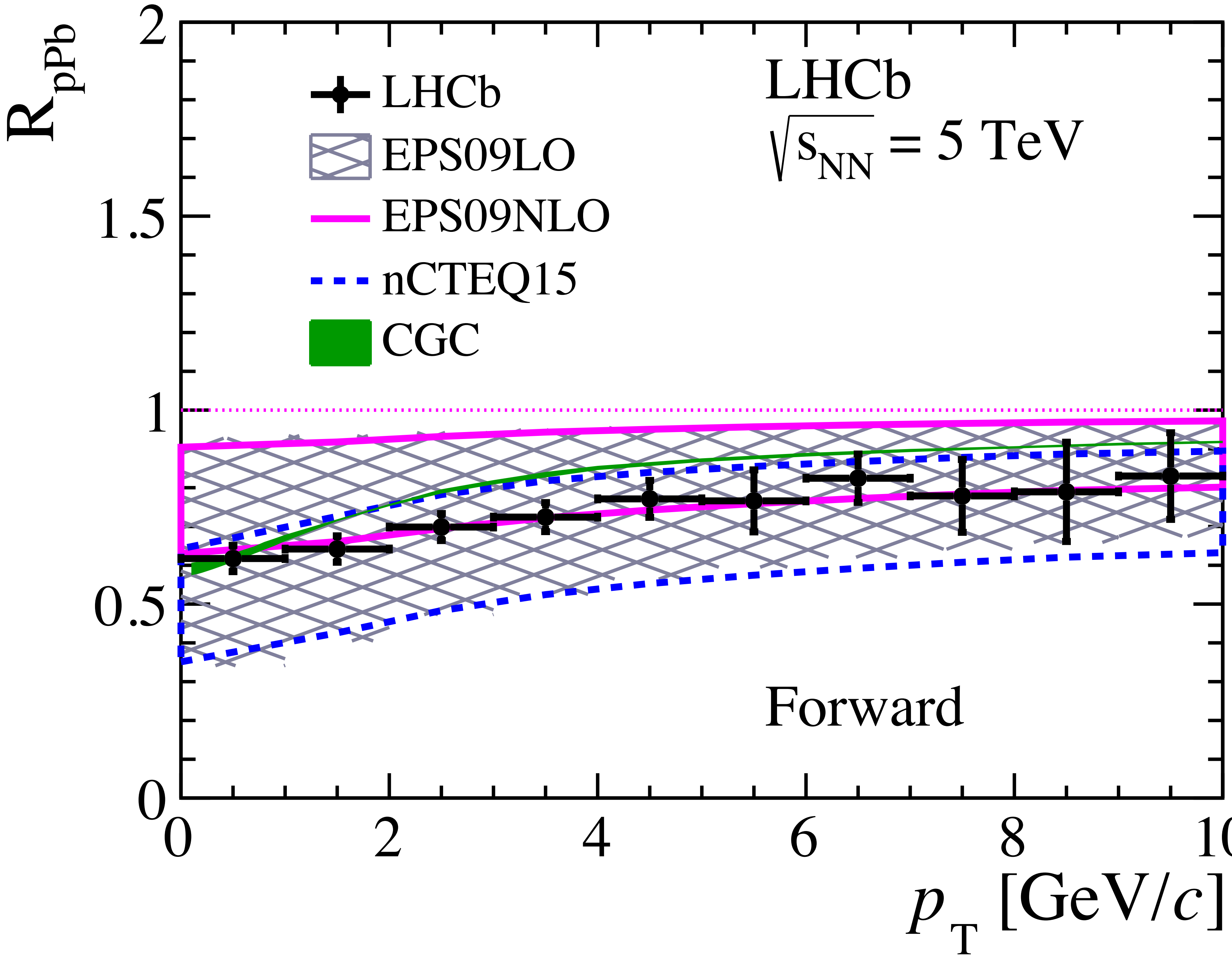


Mid-rapidity



ALICE, JHEP 12 (2019) 92

Forward rapidity: small x



LHCb, arXiv:1707.02750

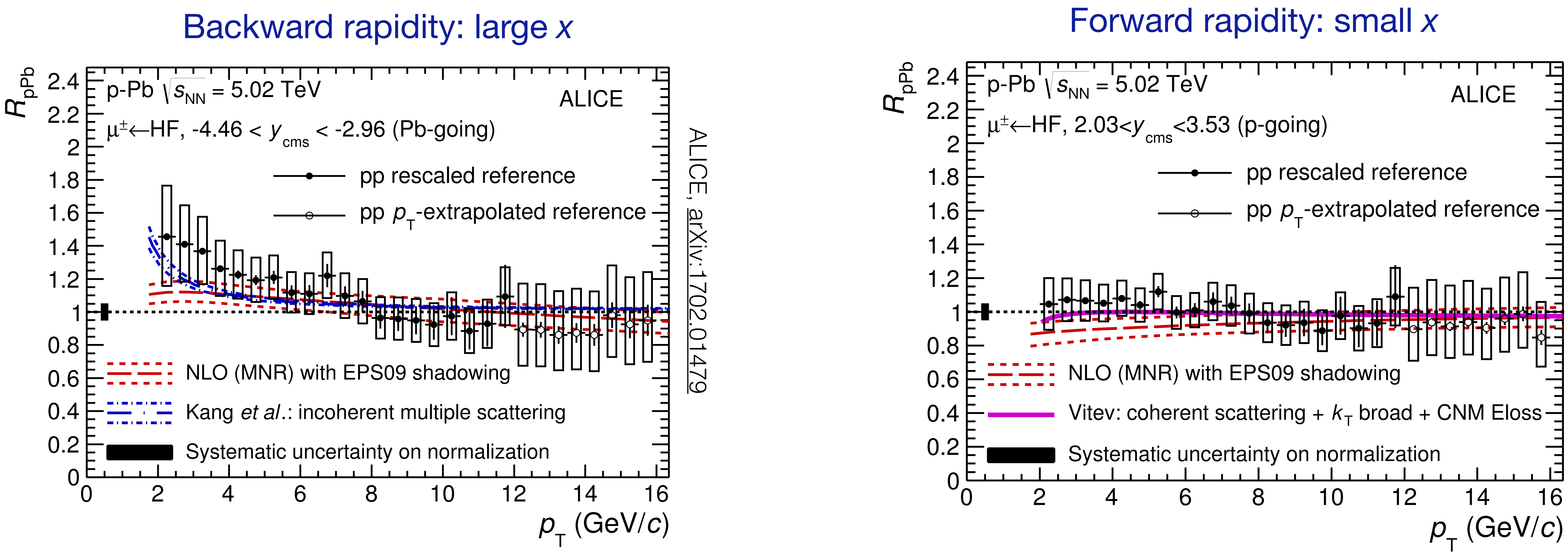
R_{pPb} ~ 1 at backward and mid-rapidity; below 1 at forward rapidity

Suppression mainly at small-x compatible with nuclear PDFs (shadowing) and CGC calculations

CGC: Decloue et al, PRD 91, 114005

Open charm production at backward and forward rapidity

ALICE: Heavy flavour decay muons



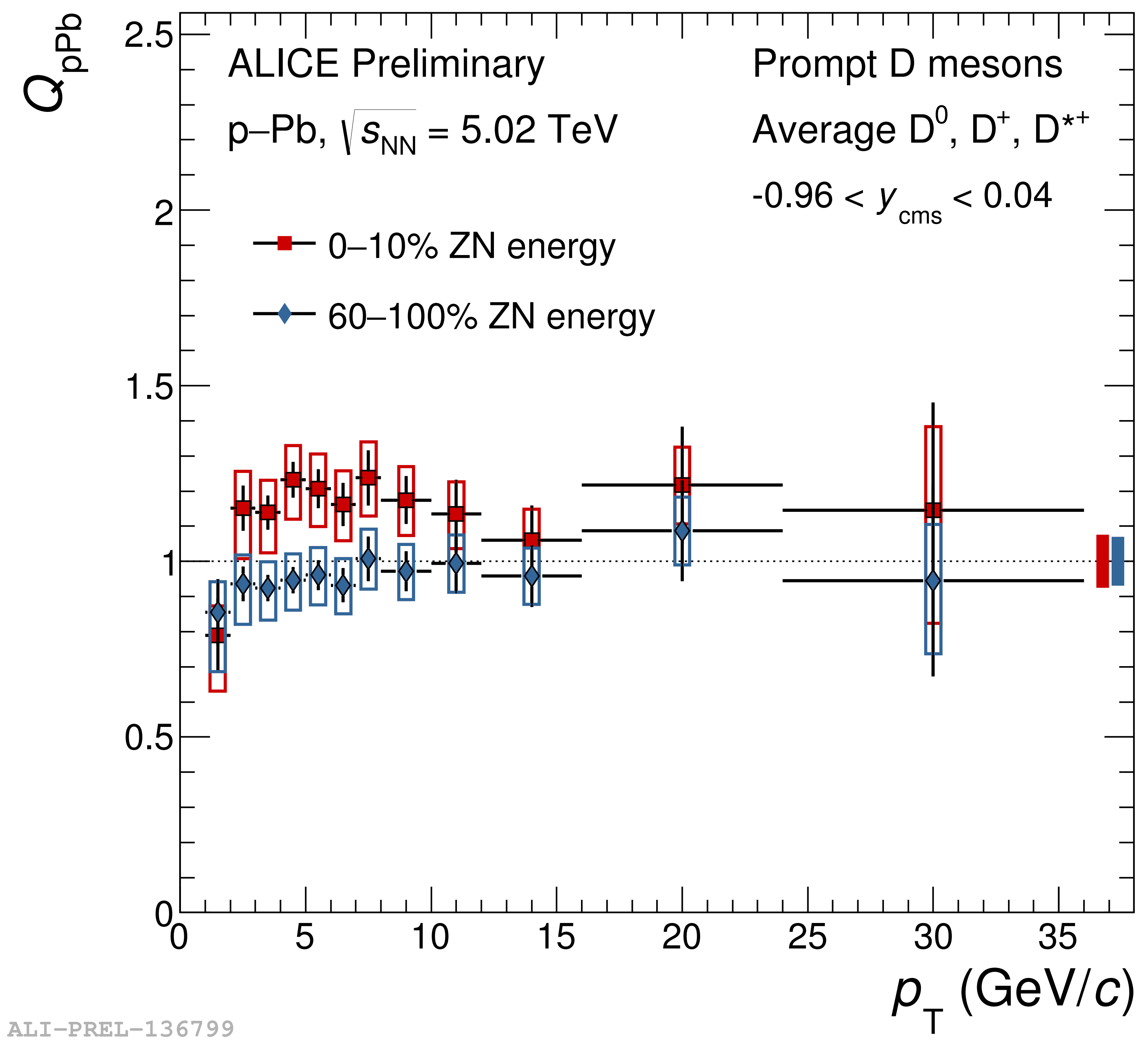
Forward muons (ALICE) show similar trend, different normalisation:
R_{pPb} ≈ 1 at forward (small-x), but enhancement in backward direction

(Note: measured p_T is from decay muon)

Final state effects in p-Pb collisions: 'radial and elliptic flow'?

ALICE, PRL 122, 072301

Q_{pPb} for charm, central and peripheral



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ALICE, PRL 122, 072301

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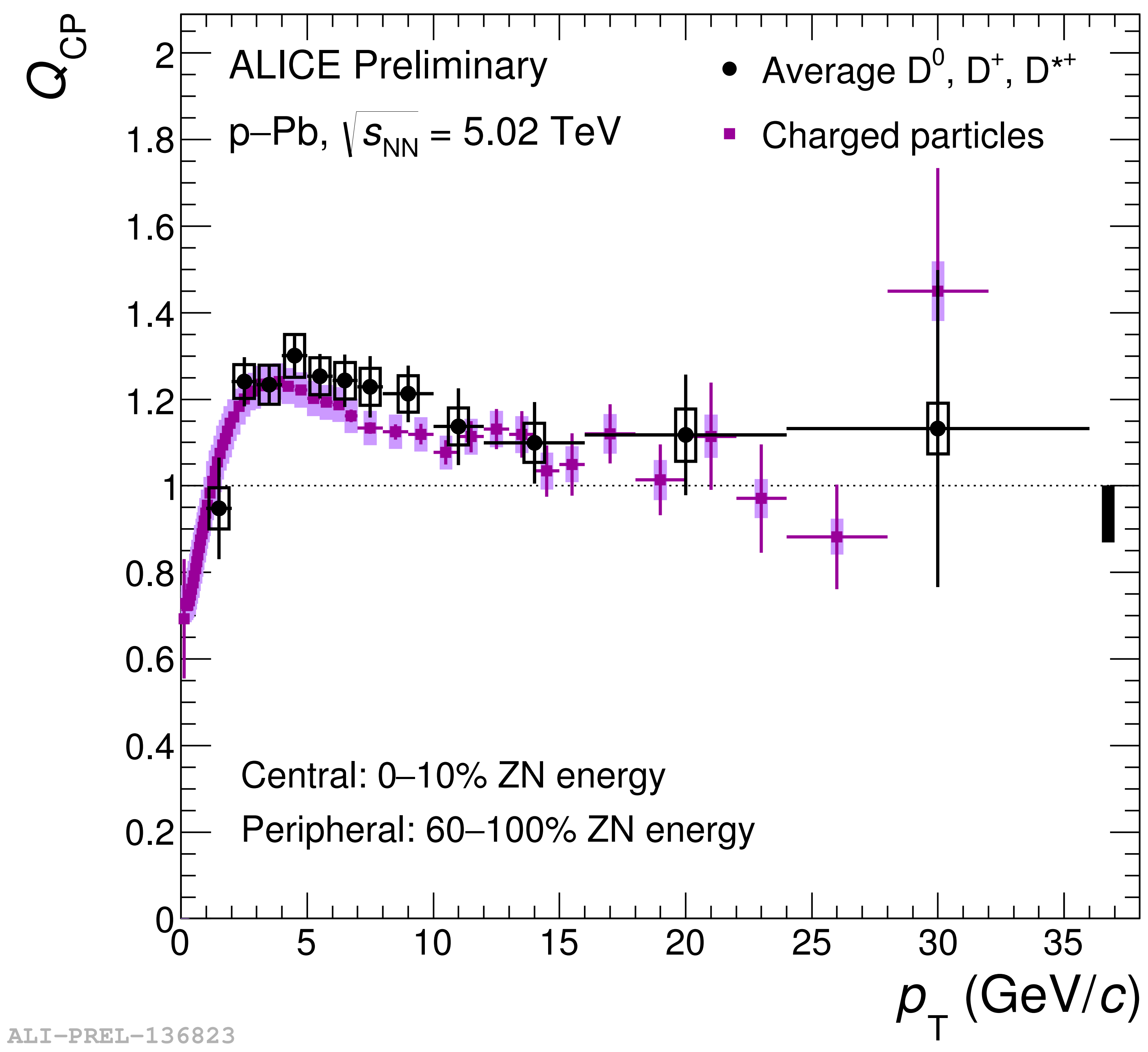

Ratio central/peripheral shows
hint of flow-like ‘bump’
($Q_{CP} > 1$ significance 1.5σ)

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ALICE, PRL 122, 072301

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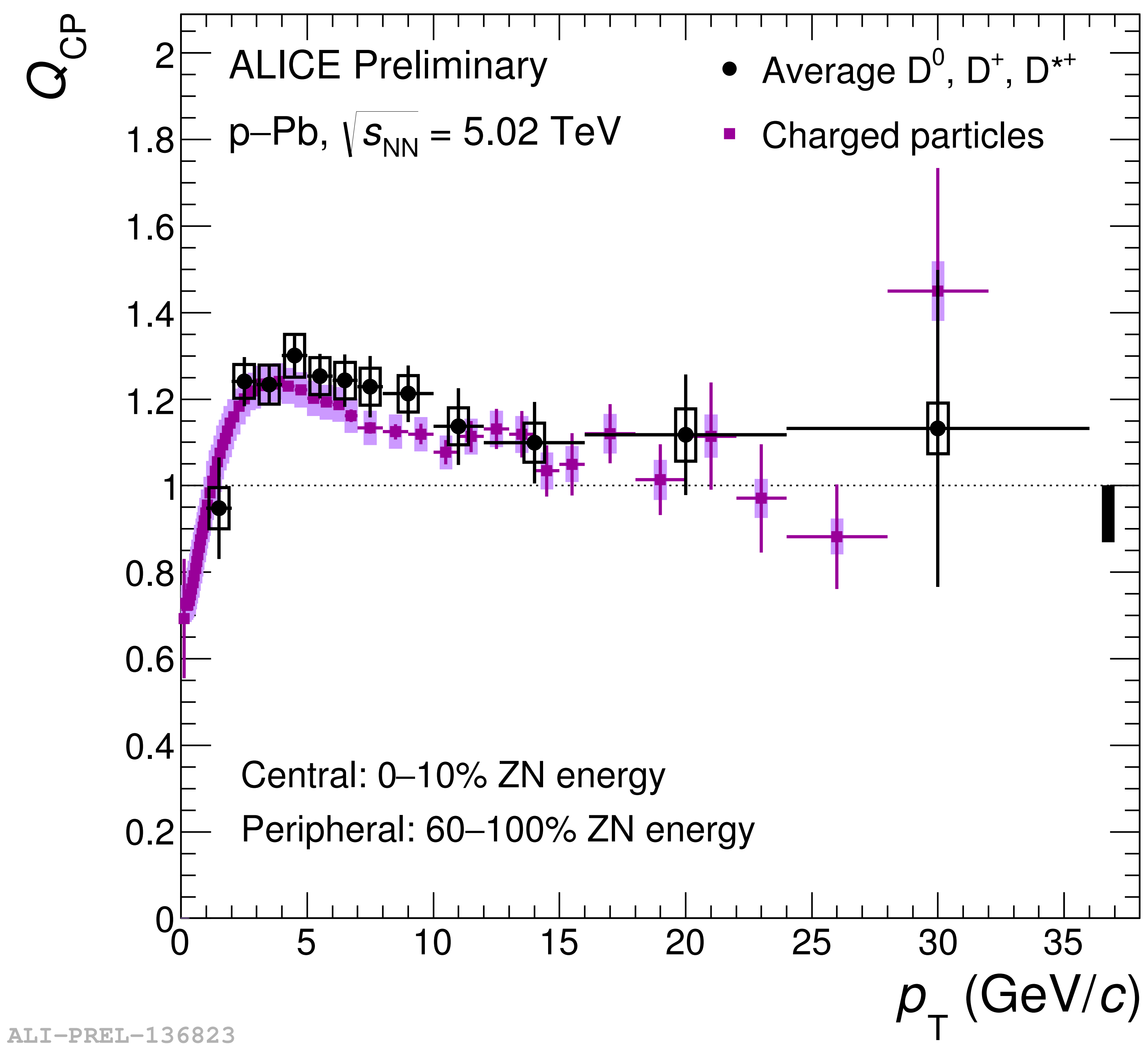

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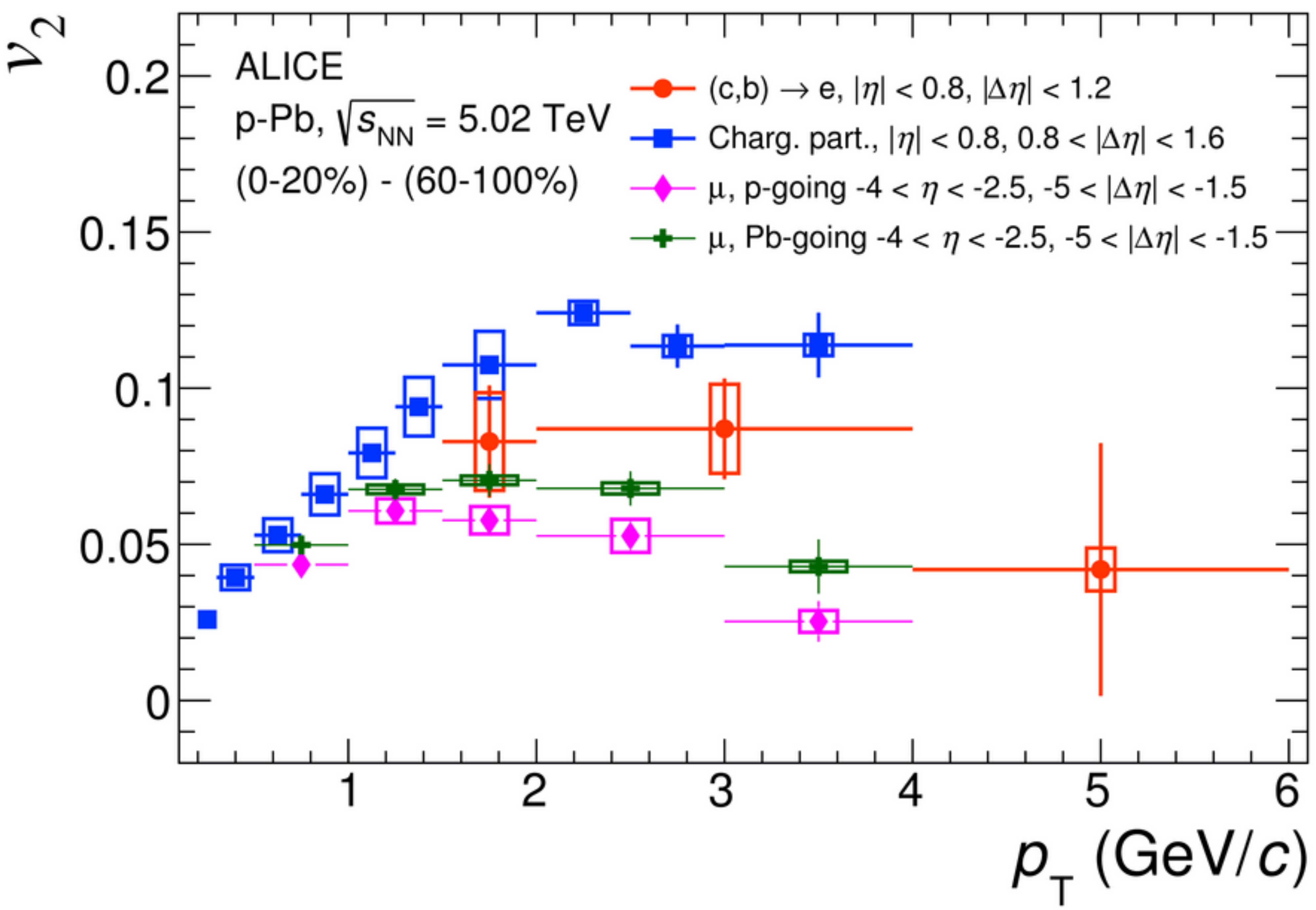
v_2 for heavy flavour electrons and muons



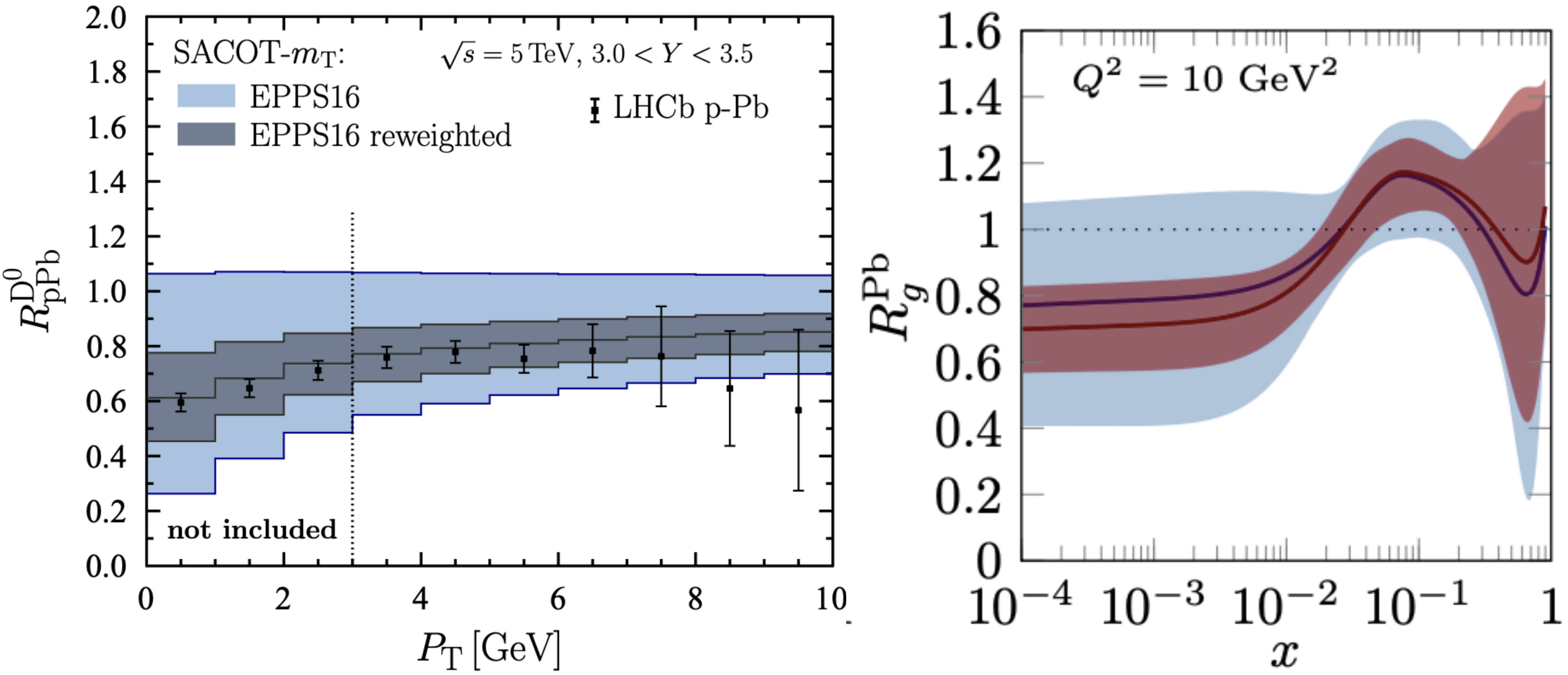
Clear v_2-like modulations for HF decay muons and electrons
strength of modulation smaller than for charged particles in p-Pb

Interesting physics, but a 'nuisance effect' for parton density studies…

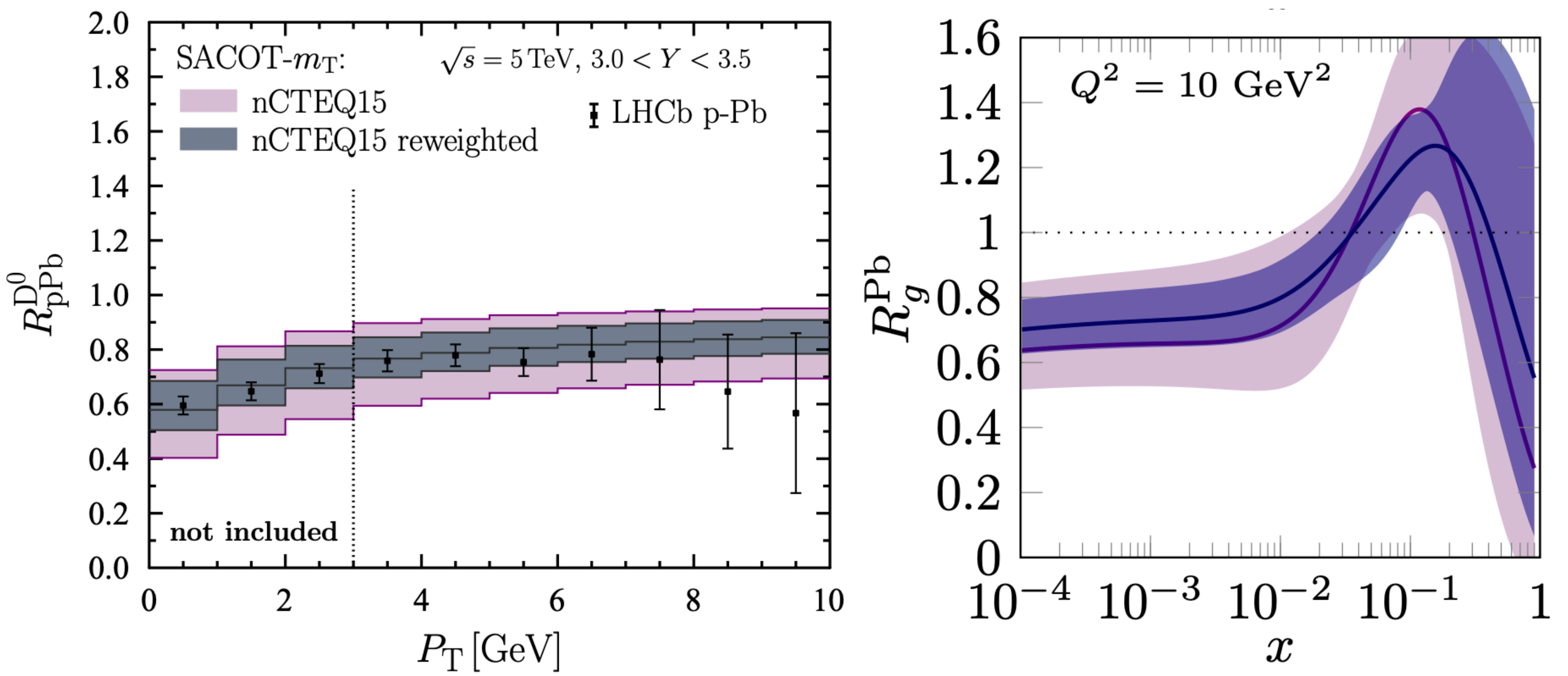
PDF reweighting with charm: full NLO charm calculation

Eskola, Helenius et al, *JHEP* 05 (2020) 037

EPPS16 reweighting



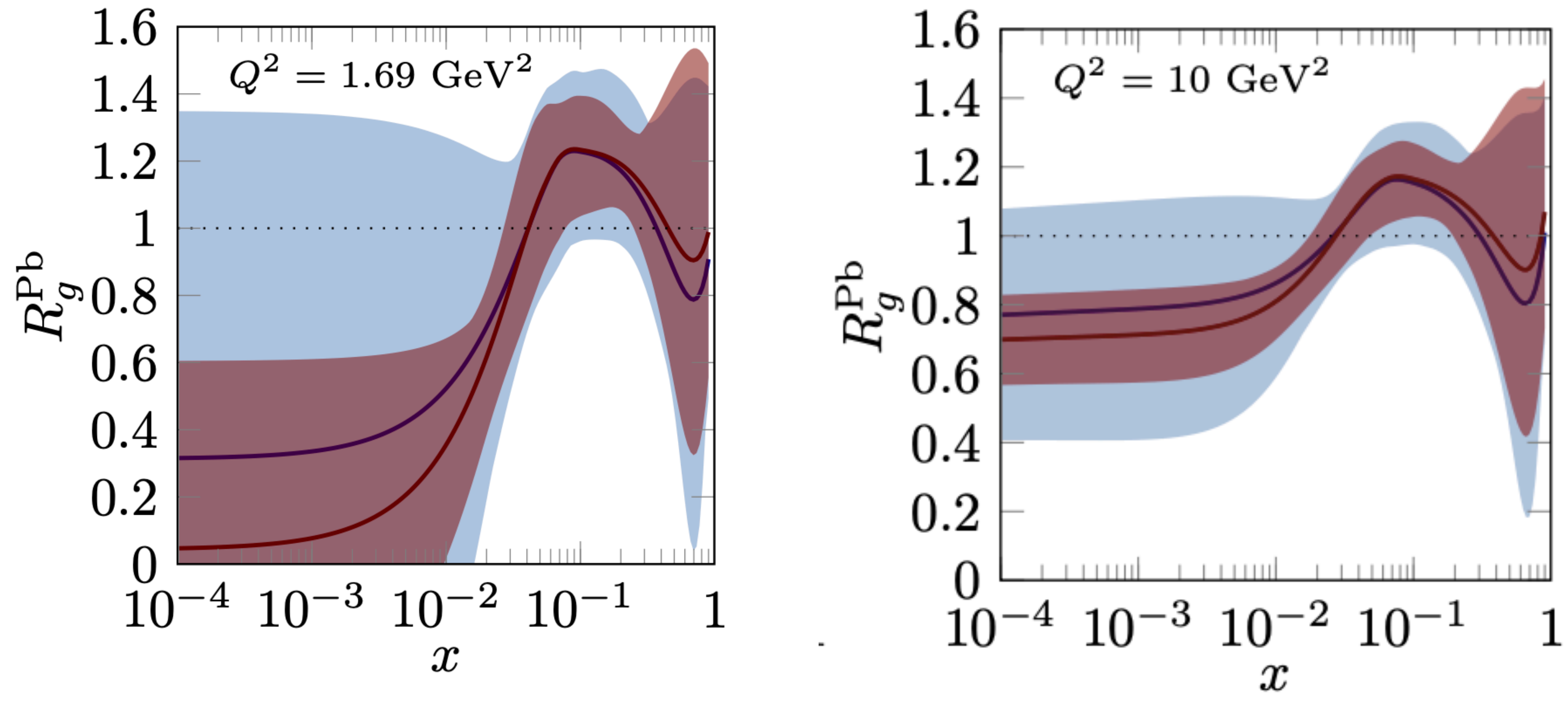
nCTEQ15 reweighting



Forward charm data brings significant constraints; prefer shadowing with $R_g \sim 0.7$ at $x < 5\ 10^{-3}$ ($Q^2 = 10$ GeV)

Q^2 dependence

EPPS16 reweighting



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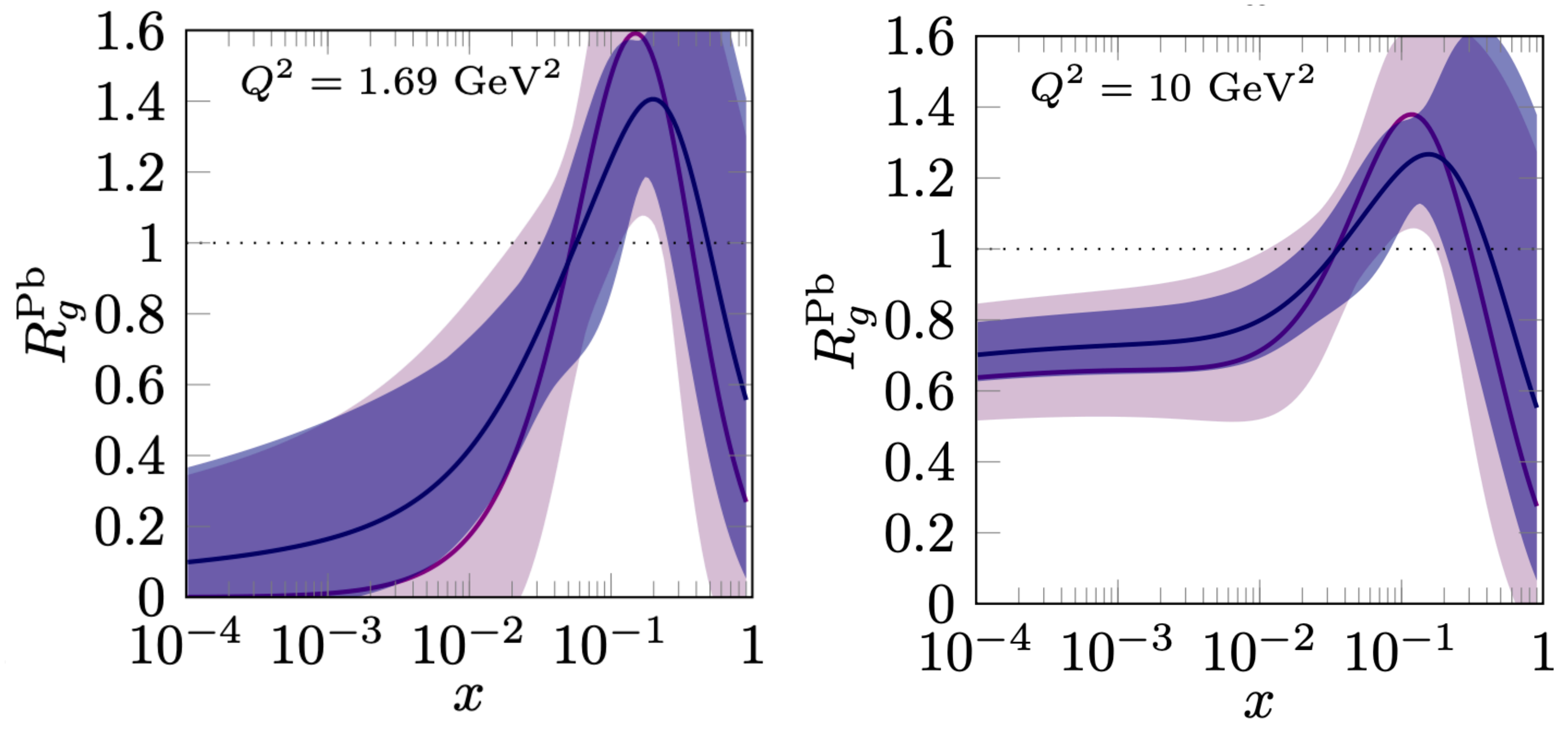


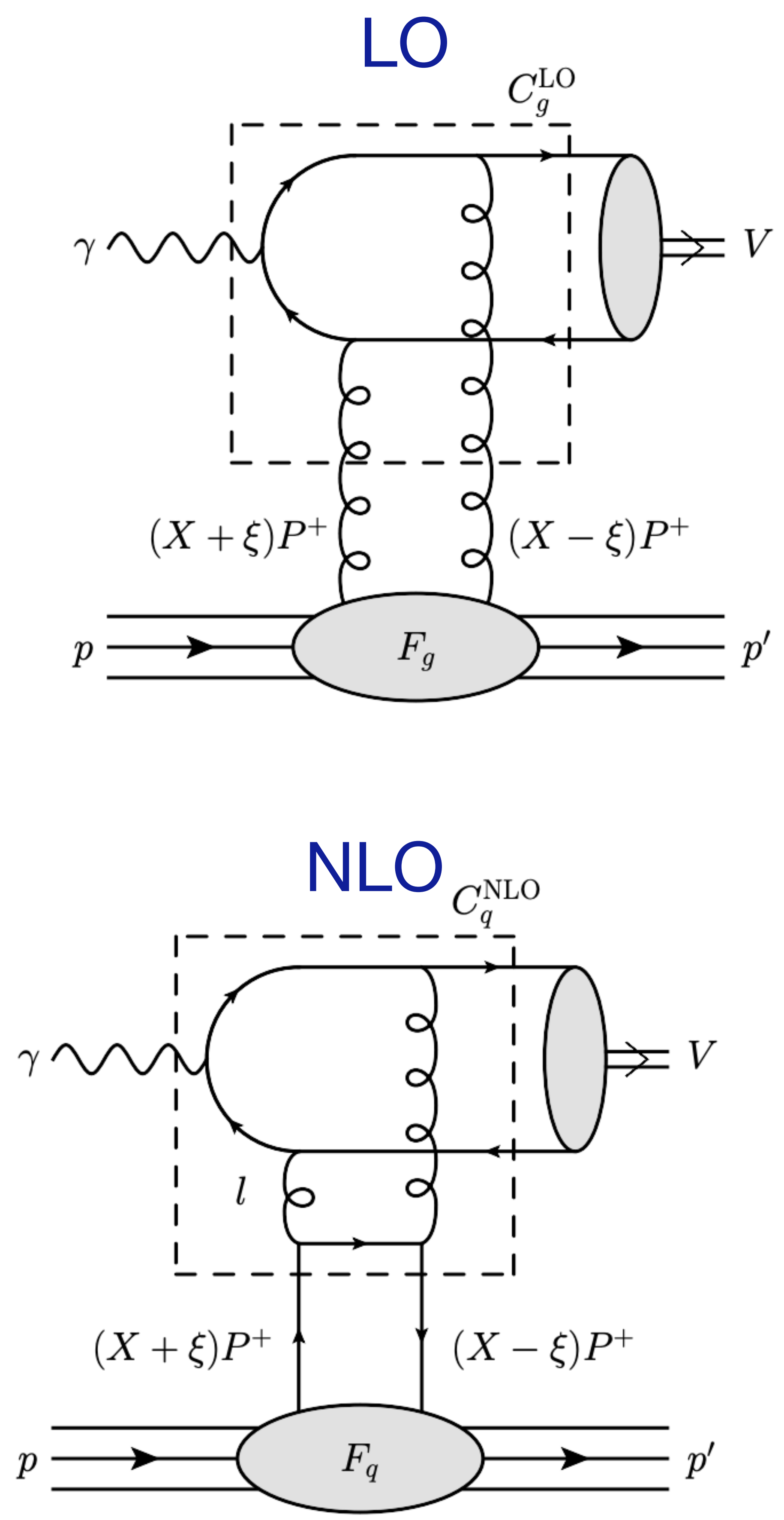
Charm reweighted PDFs show strong dependence on Q^2

Probably a robust feature: DGLAP evolution

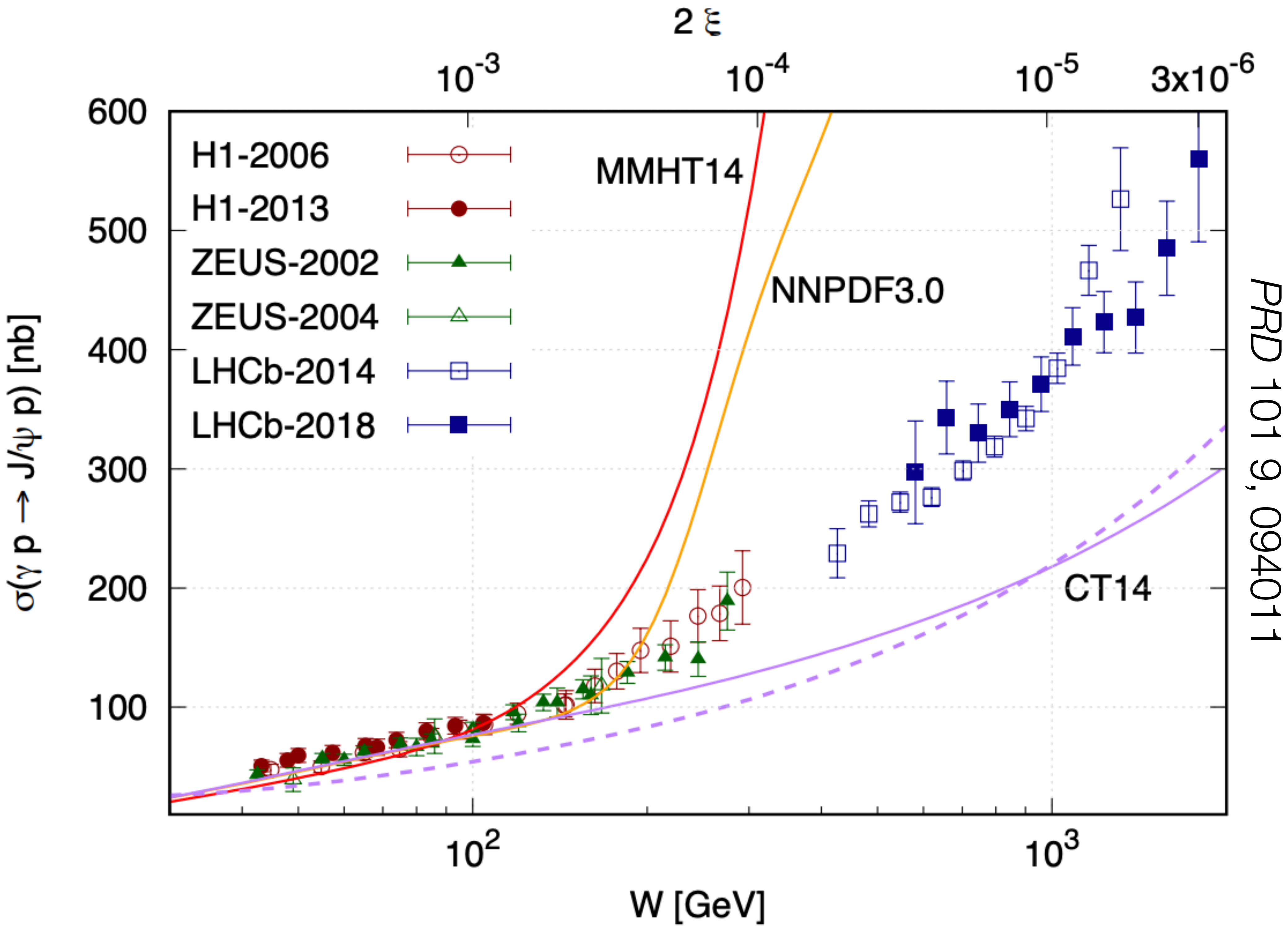
Can we test this experimentally? How low in Q^2 do we trust the formalism?

Probing the proton PDFs with UPC

$\gamma + p \to J/\psi + p$

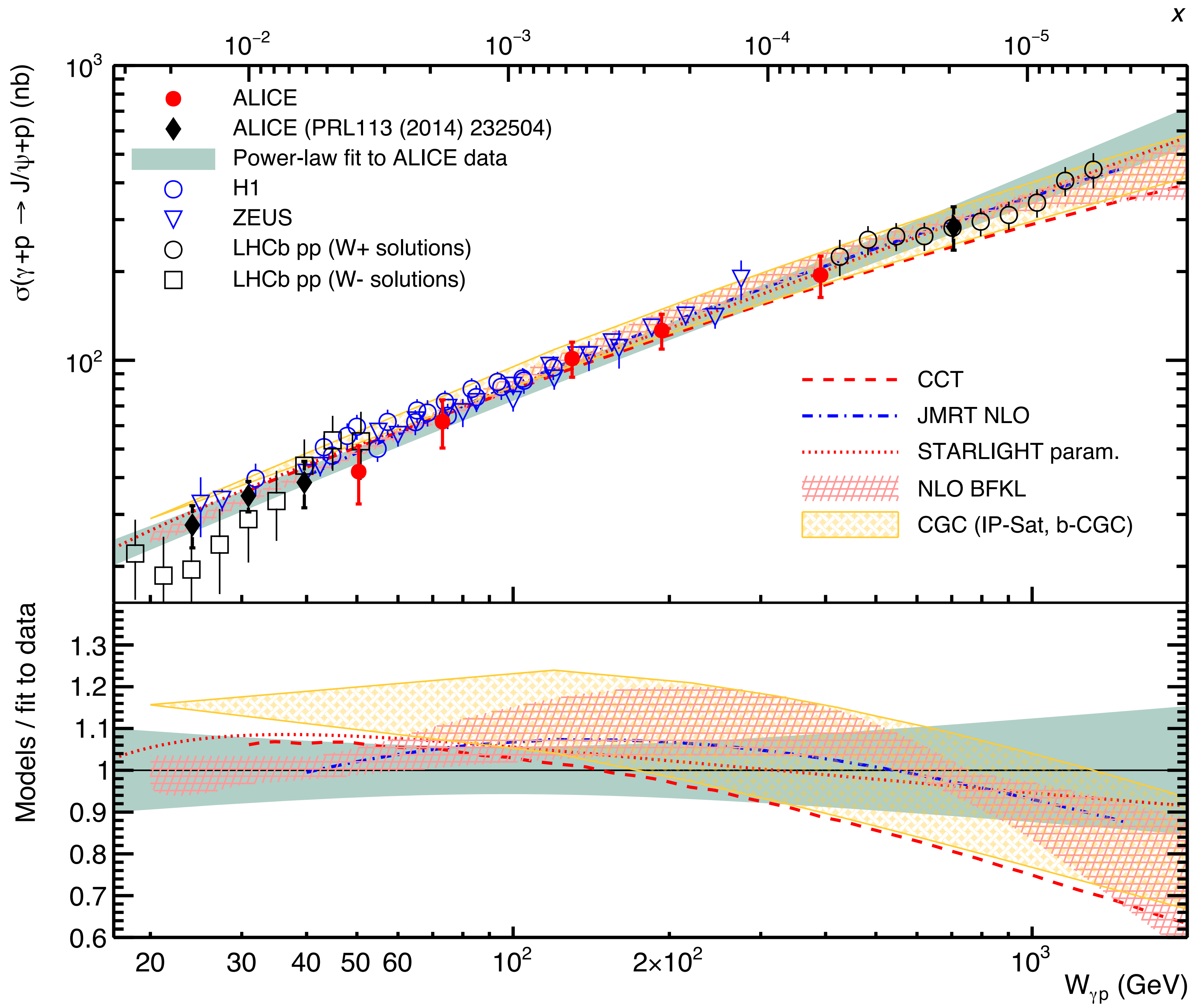


DIS and UPC pp



Flett, Jones, Martin, Ryskin, Teubner, *PRD* 101 9, 094011

DIS and UPC pp, Pb-p



ALICE, EPJ C 79, 402

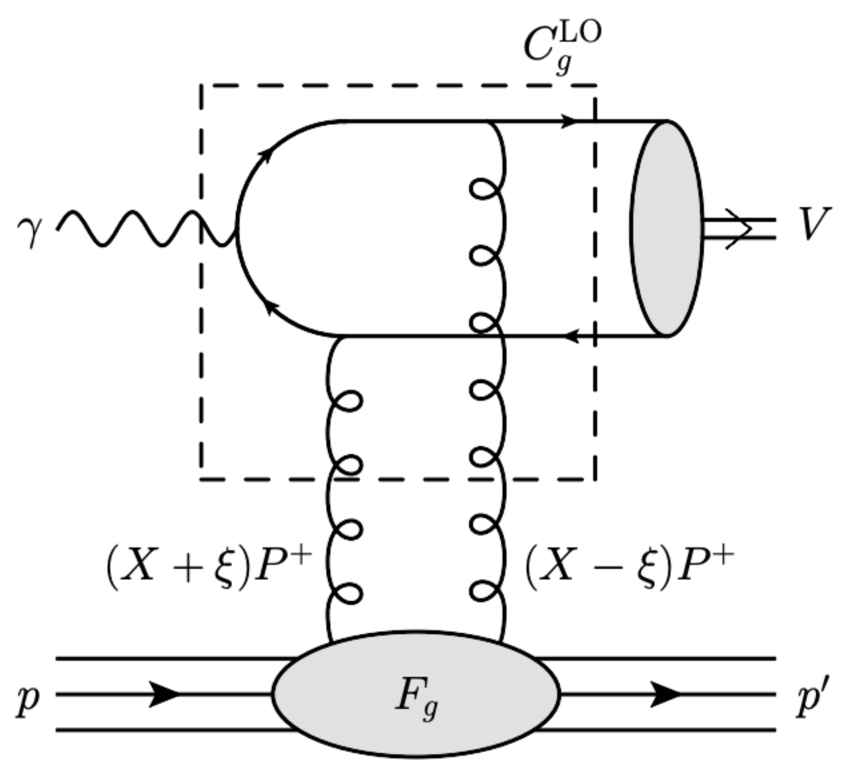
Pb-p: Photon emitted by Pb nucleus

parton level: $\gamma g \to c\bar{c}$

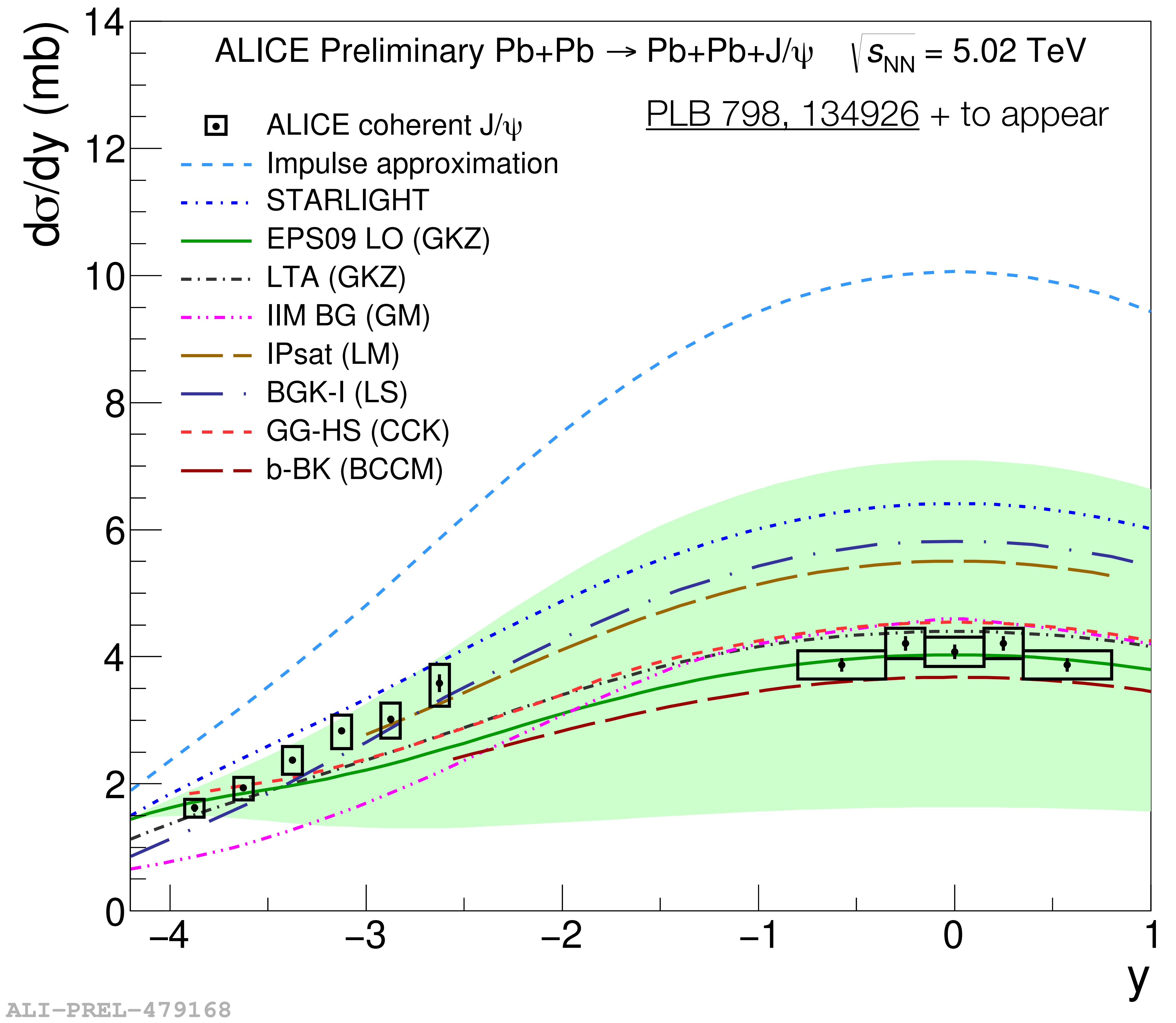
Probes proton structure at x < 10^{-4}; potential to constrain PDFs at small-x

UPC J/ψ production: Pb-Pb

UPC Pb-Pb probes
gluon density in nucleus



$$\left.\frac{d\sigma_{\gamma A \to J/\psi A}}{dt}\right|_{t=0} = \frac{M^3_{J/\psi}\Gamma_{ee}\pi^3\alpha_s^2(Q^2)}{48\alpha_{em}Q^8}\left[xg_A(x,Q^2)\right]^2$$



Measured cross section below
free-nucleon 'impulse approximation'

Indicates shadowing/saturation at Q ≈ 1/2 $m_{J/\psi}$

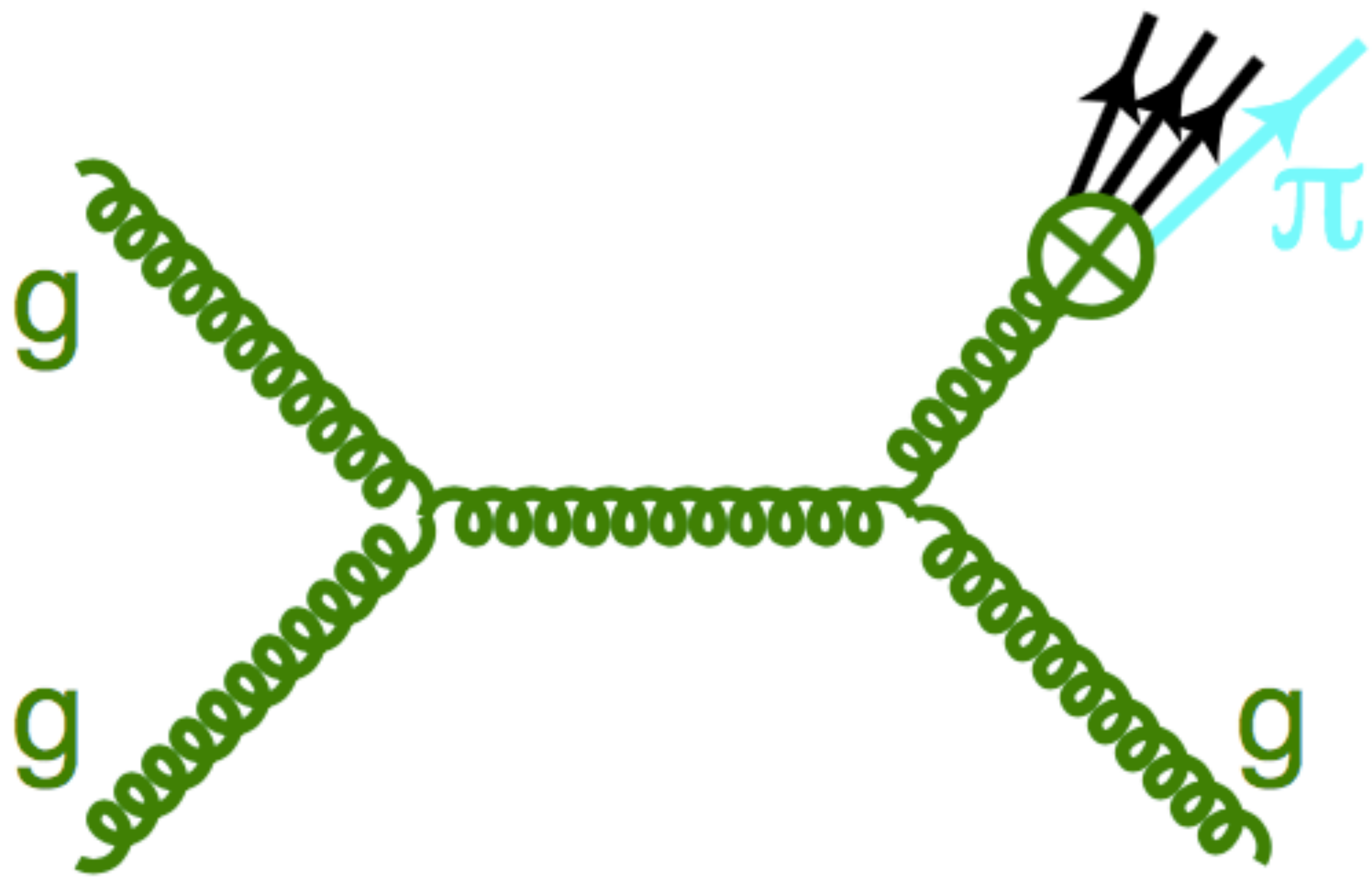
Summary so far

- Signs of suppression of inclusive particle production in small-x regime
  - RHIC: charged particle/light hadron suppression
  - LHC: *D* meson suppression at forward rapidity
- nPDF fits with forward *D* meson input: smaller gluon density in nuclei
- UPC results also indicate smaller gluon density in nuclei
- However, some open questions:
  - RHIC and LHC see effects at different *x*
    - Multiple interactions near kinematic limits?
  - Tension between ALICE forward muons and LHCb *D* mesons
  - Impact of flow-like effects? Final state scattering?

New/cleaner measurements (photons; maybe UPC?) and/or confirmation by multiple experiments very welcome!

Two-particle correlations: concept

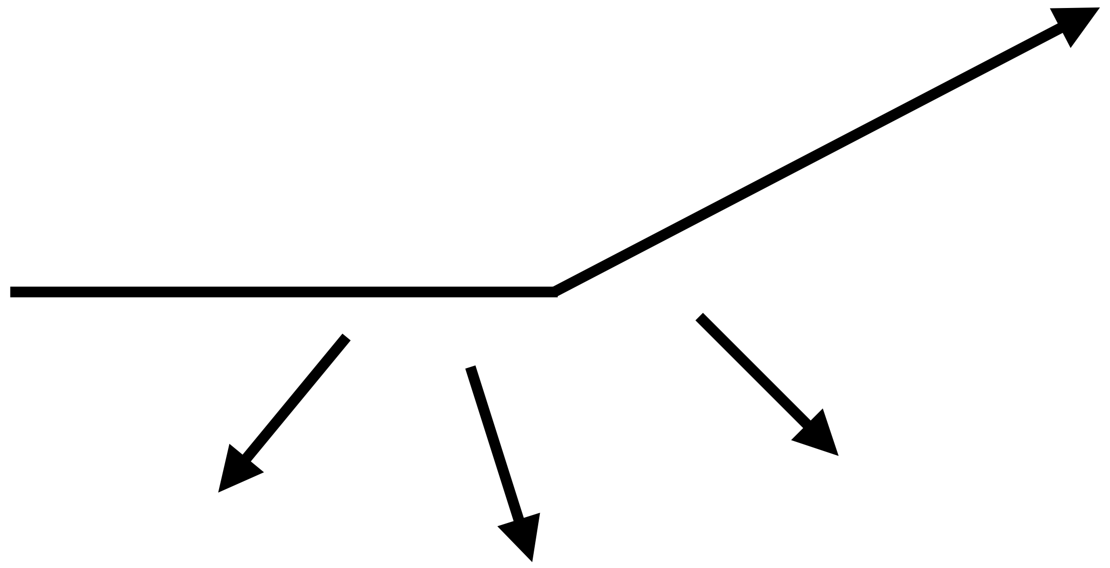
QCD 2 → 2 scattering



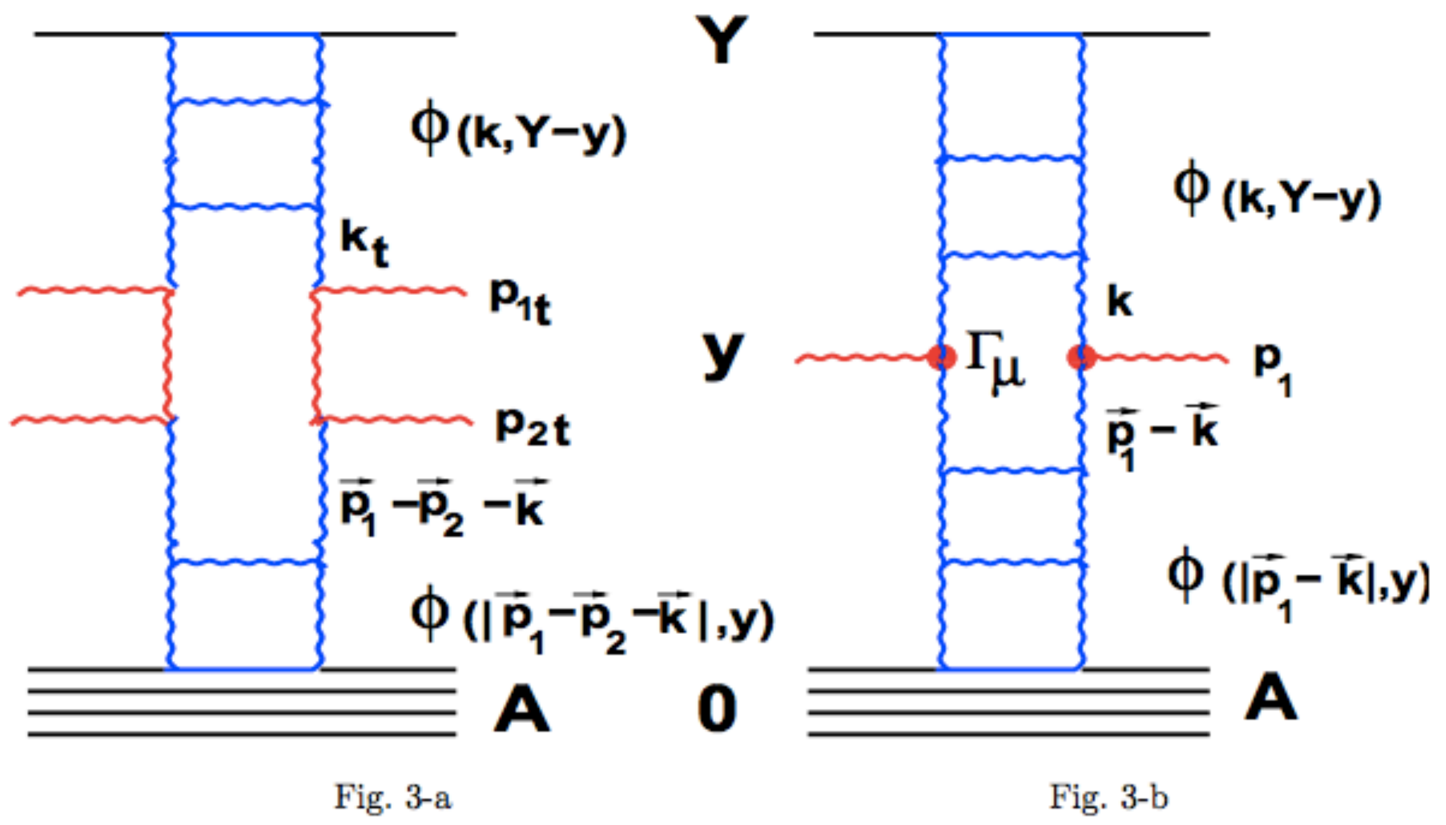
Produces a back-to-back jet

Attractive observable:
- Conceptually simple interpretation
- Probes multiple gluon interactions (CGC/saturation)
- Scan *x* (and Q^2) by varying rapidity of both jets

CGC: recoil taken by multiple gluons



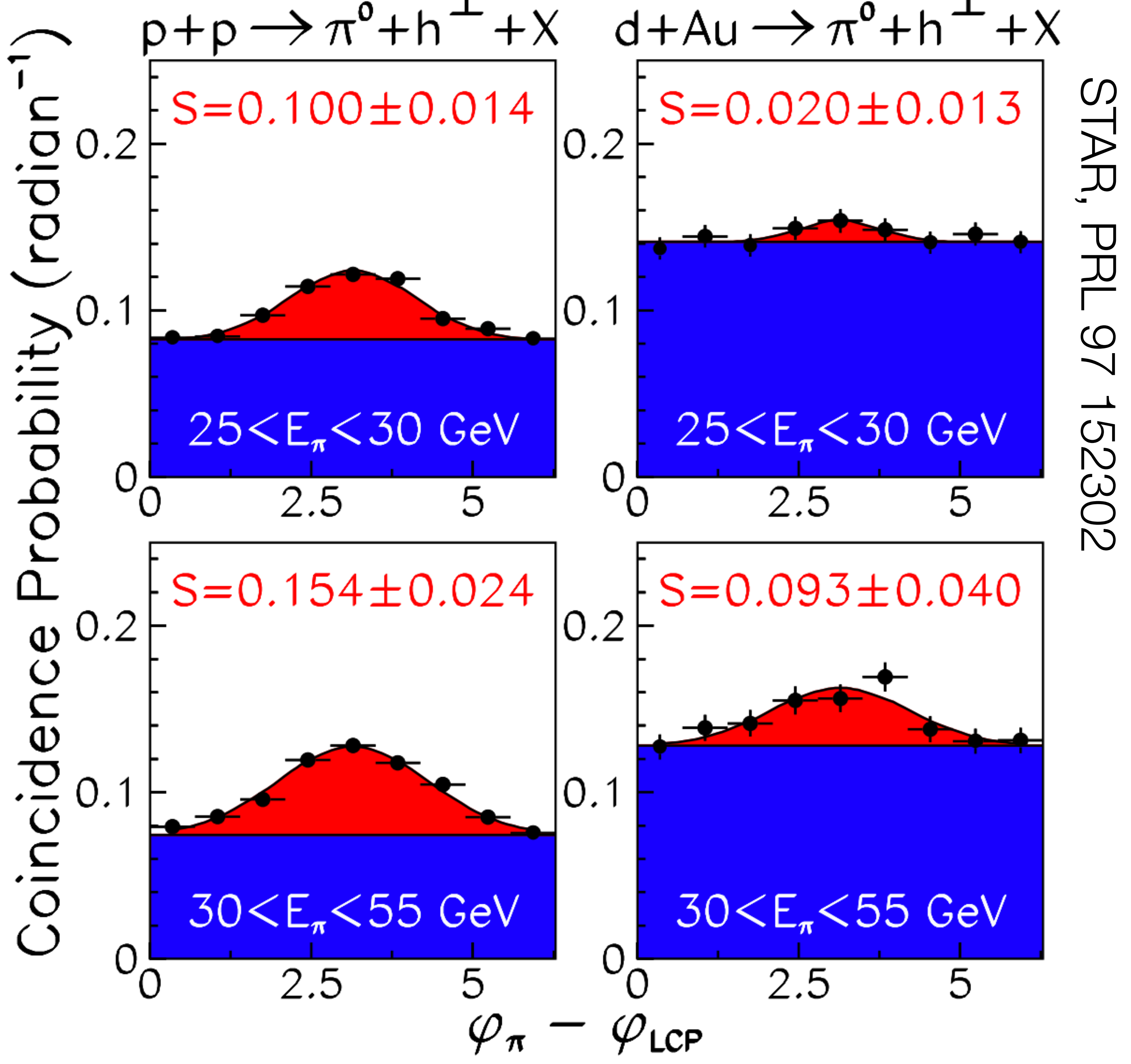
Recoil jet broadened/disappears

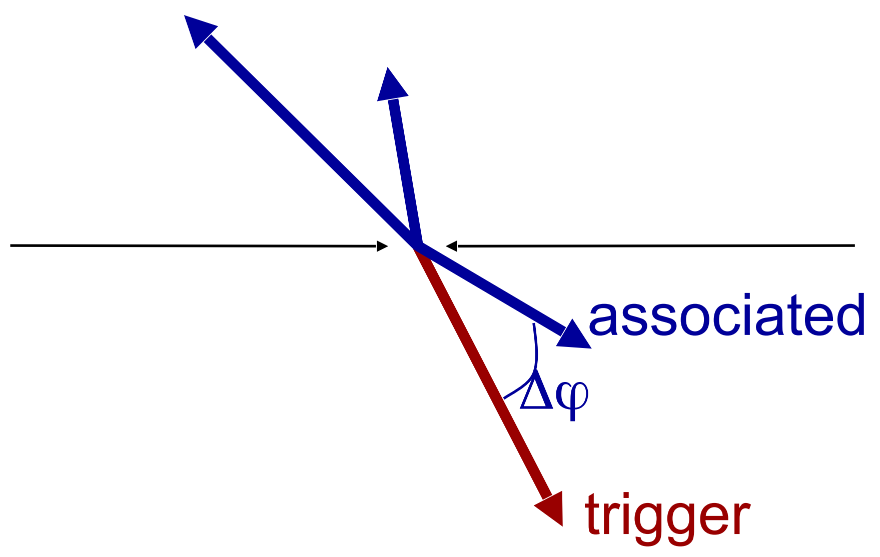


Kharzeev et al, hep-ph/0403271

Forward di-hadrons at RHIC: STAR

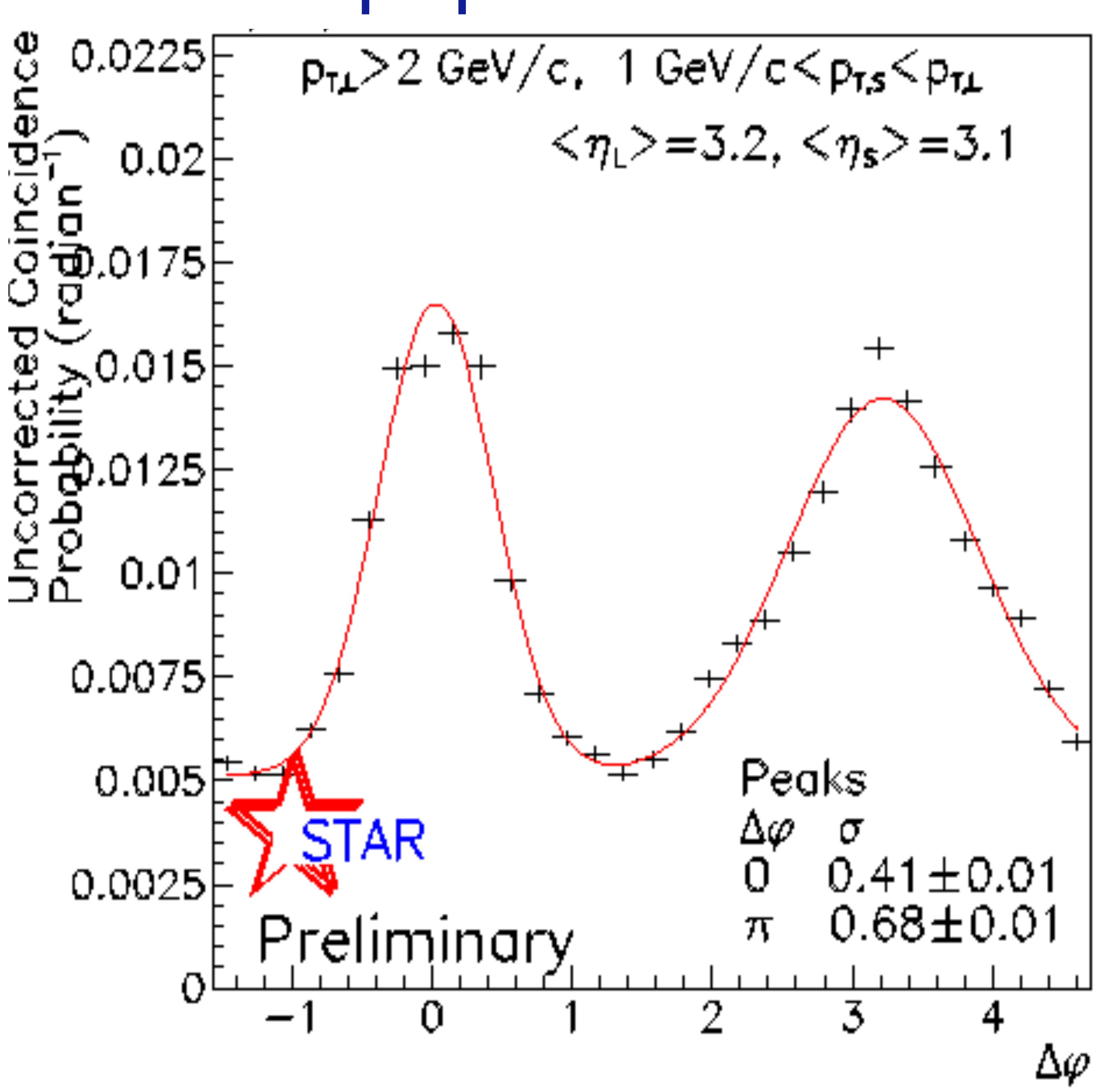
Mid-fwd correlations

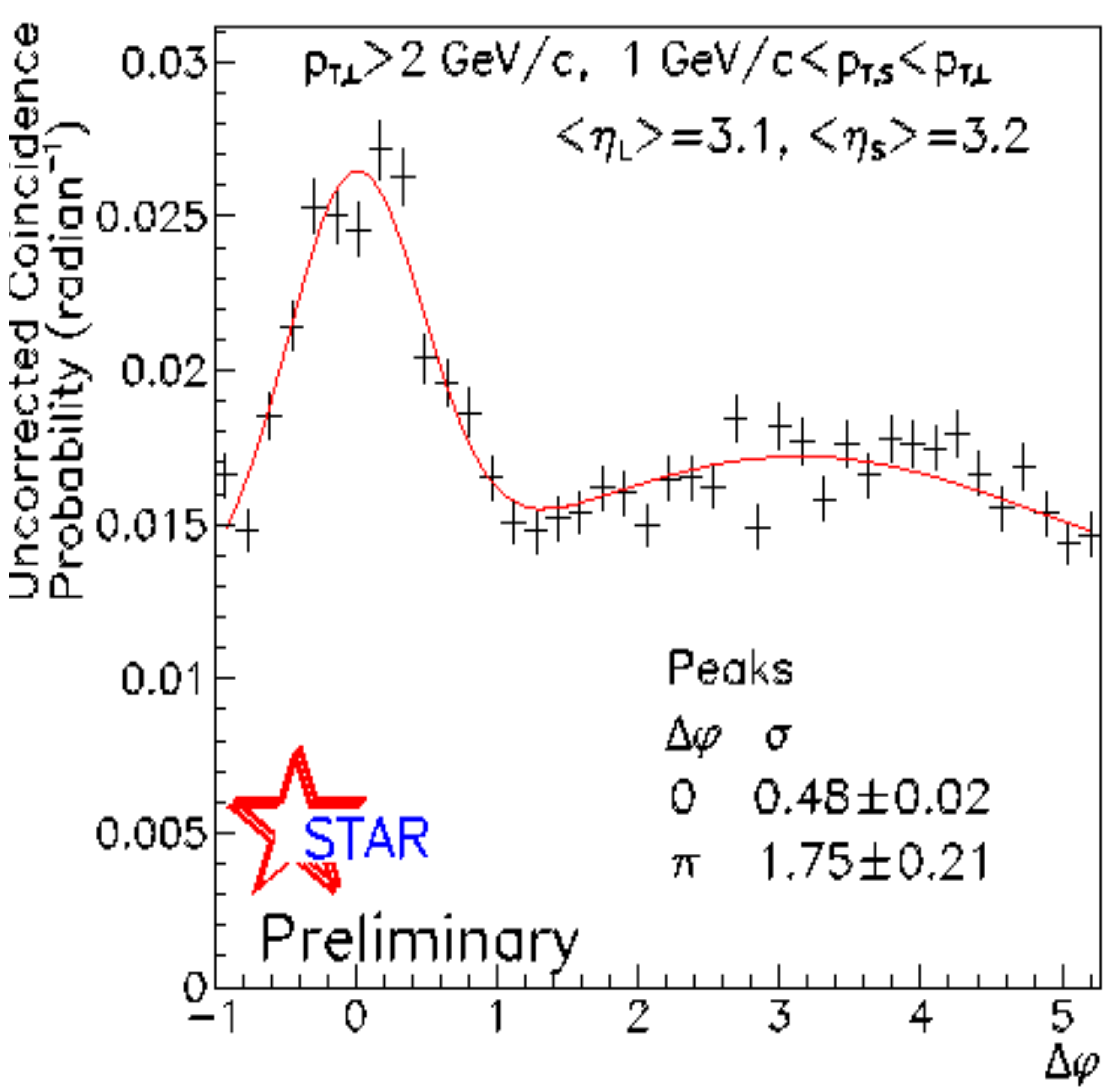




p+p collisions

Central d+Au collisions





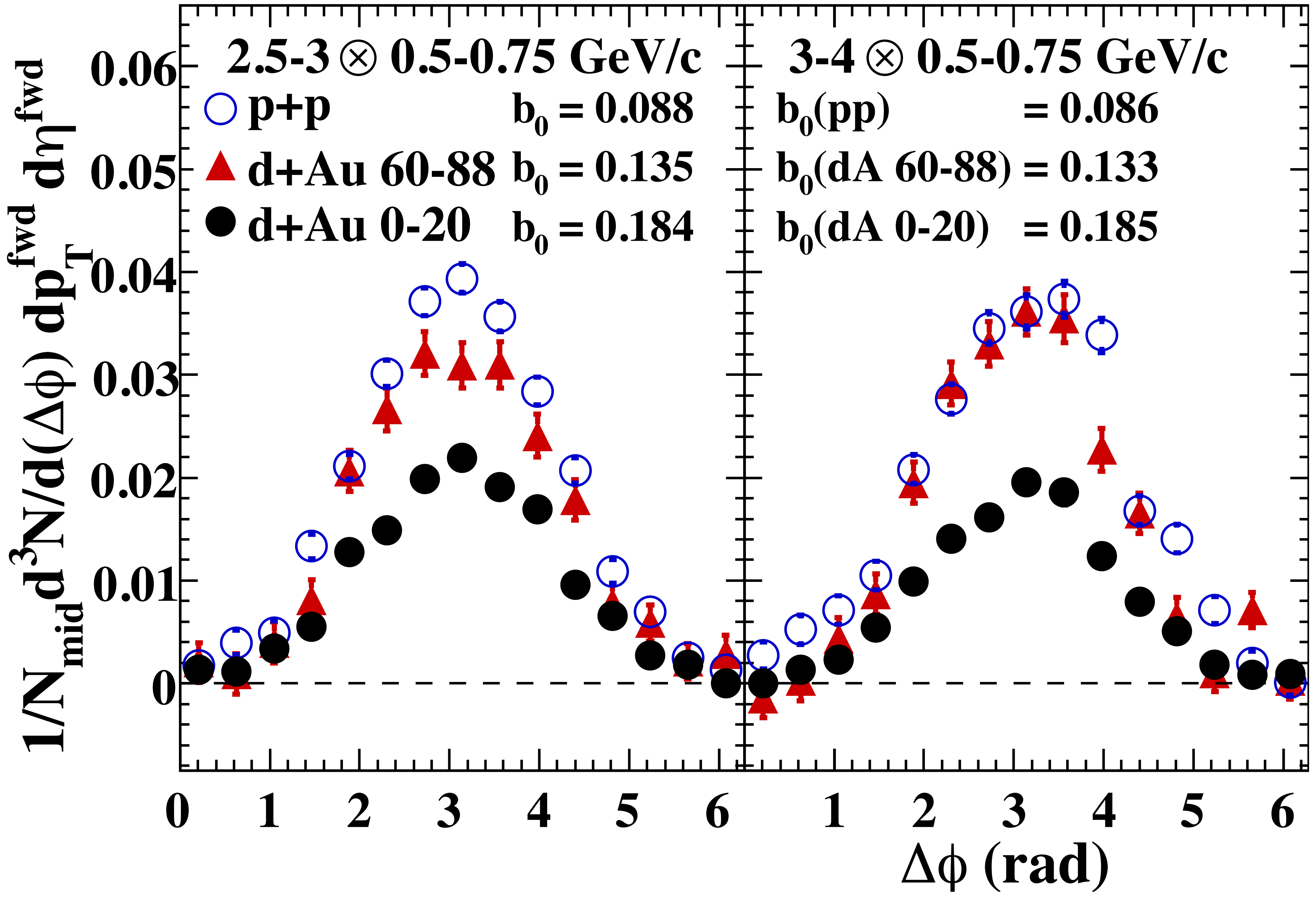
STAR, arXiv: 1005.2378

De-correlation of recoil yield for fwd-fwd correlations

- Consistent with CGC: coherent gluon field
- Very low p_T; other effects, e.g. multiple parton interactions might play a role

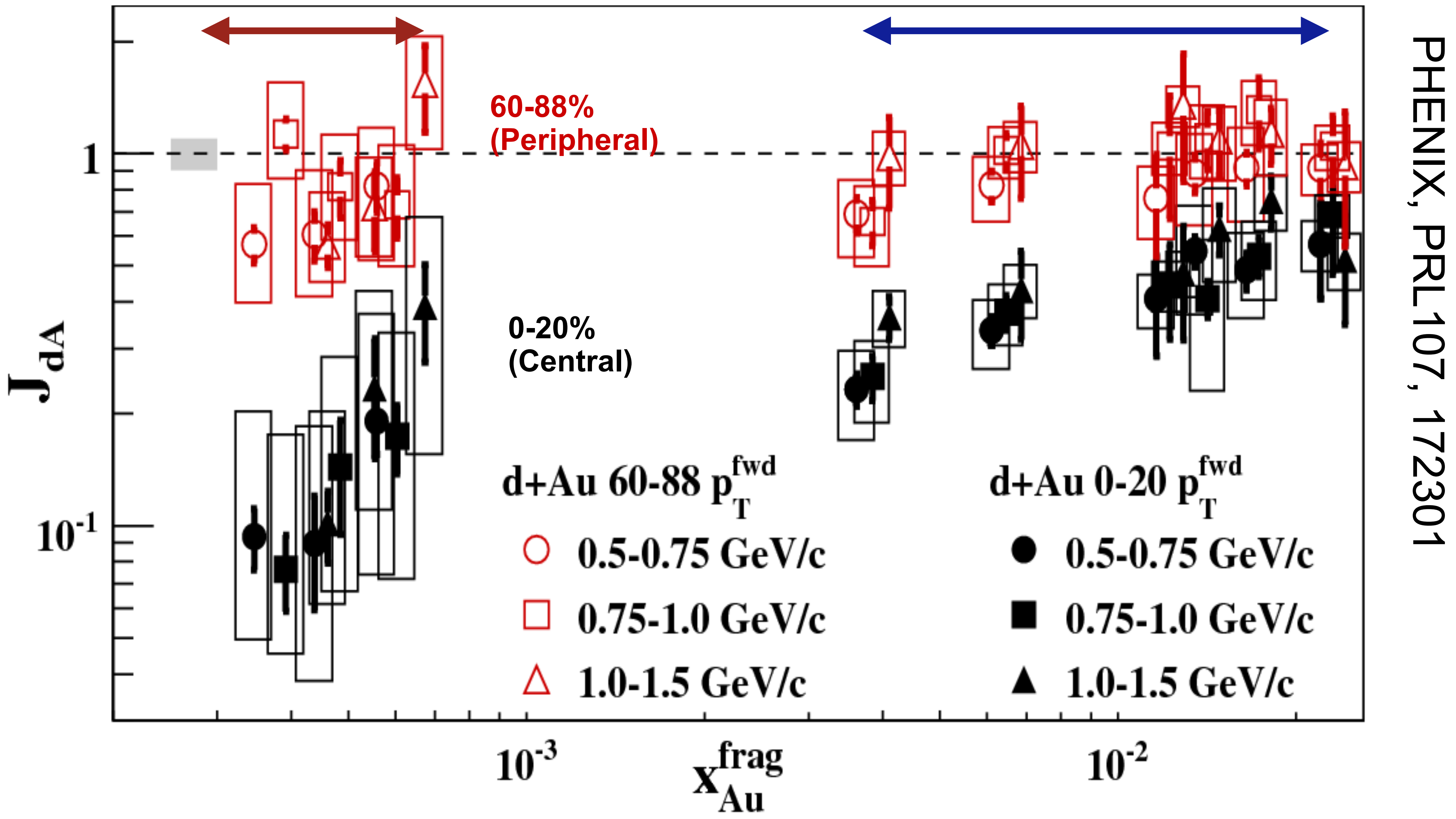
Di-hadron correlations at RHIC: PHENIX

π^0-π^0 mid - forward



$|\eta| < 0.35$ and $3.0 < \eta < 3.8$

Recoil yield ratio



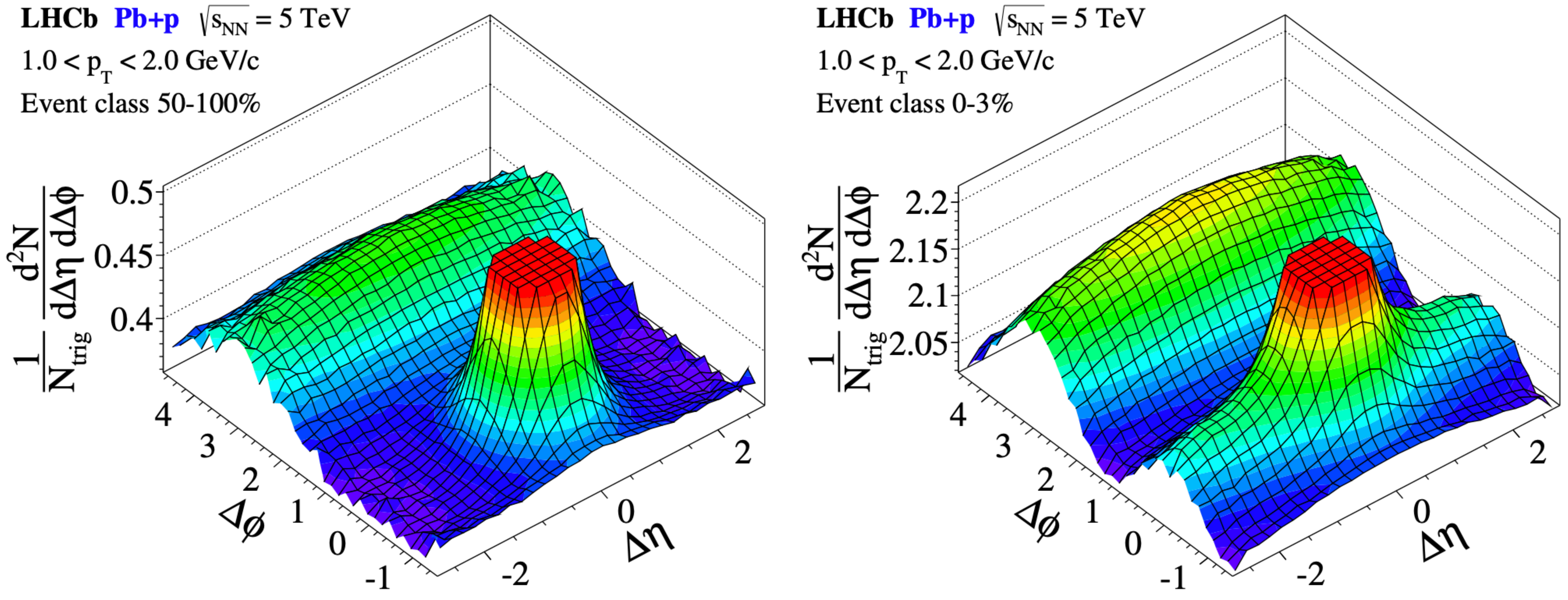
Scan '*x*' with p_{T1} and forward, mid rapidity

Similar effects, trends as a function of *x*

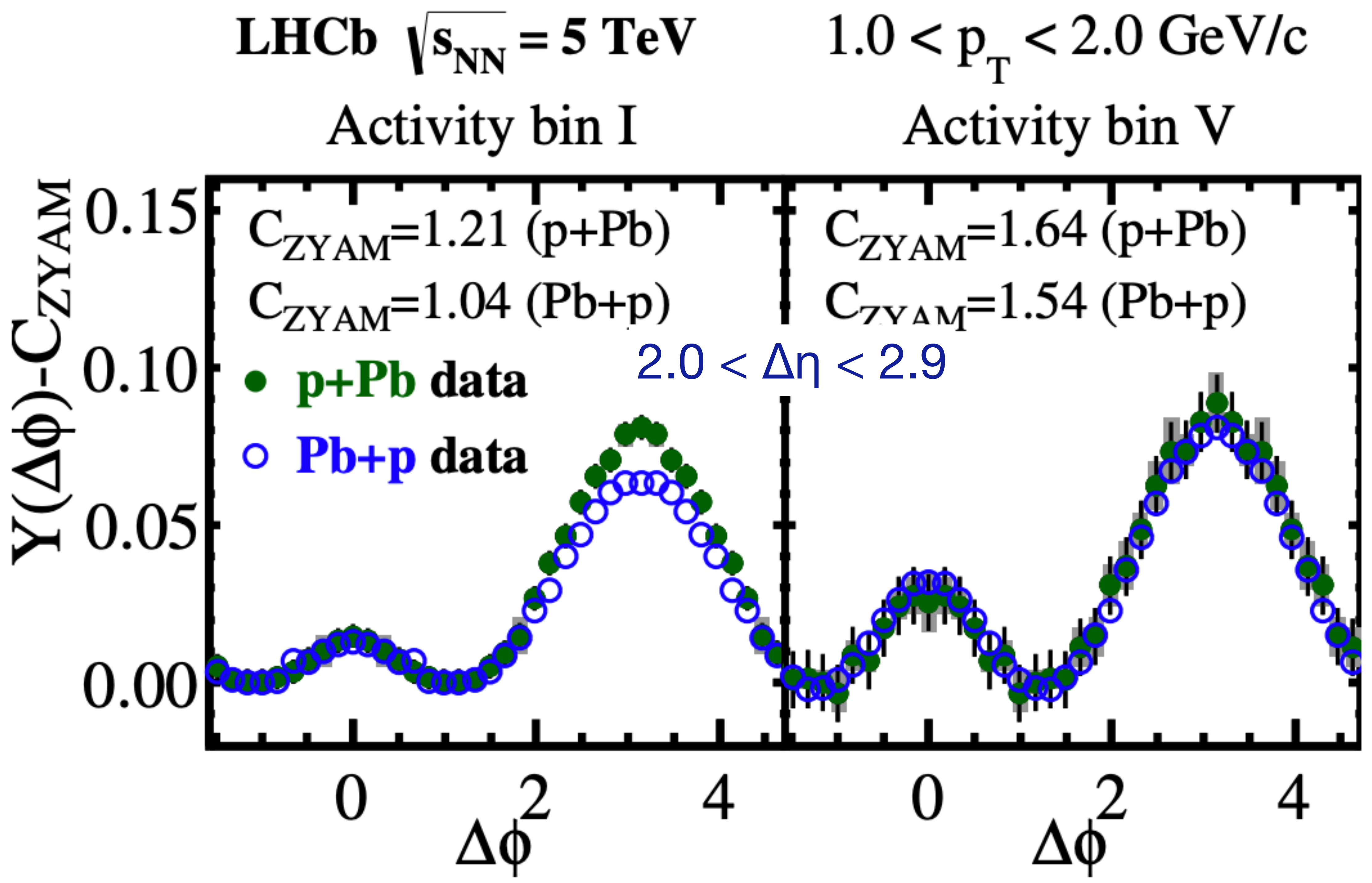
Large suppression at '*x*' < 10^{-3} in central events

Di-hadron correlations at LHC

LHCb, PLB762, 473



2.0 < η < 4.9



Multiplicity dependence of di-hadron correlations

Analysis geared towards flow-like effects:
Long range correlations

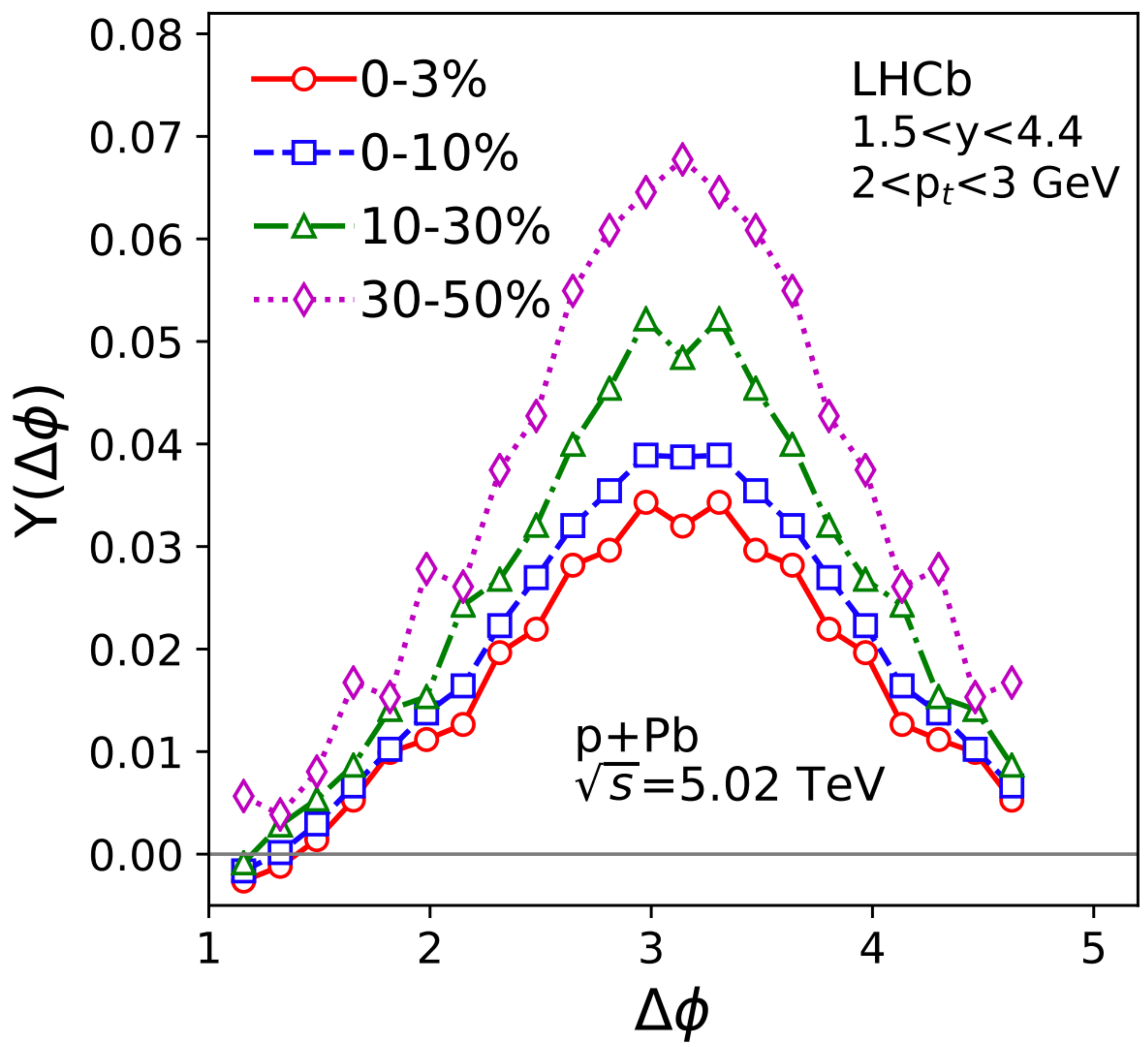
Try to separate jet-like and flow-like correlations?

Near side long range amplitude 20-50 per cent of away side!

Di-hadron correlations at LHC

G Giacalone, C Marquet, NPA 982, 291 (QM2018)

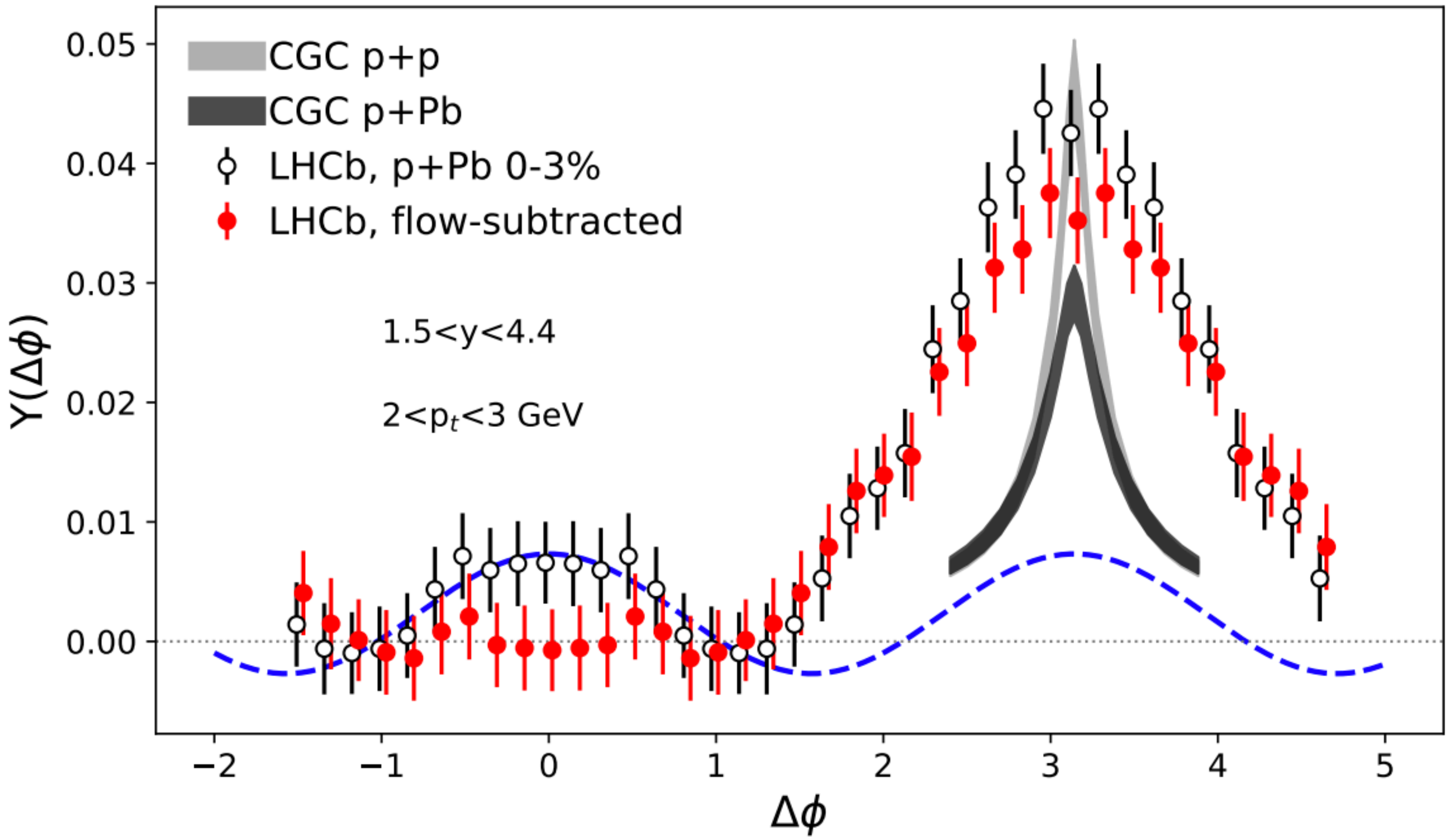
Away-side peak after flow subtraction



Assumes pure v_2; near-away symmetry for long-range component

Yield suppression and mild broadening?

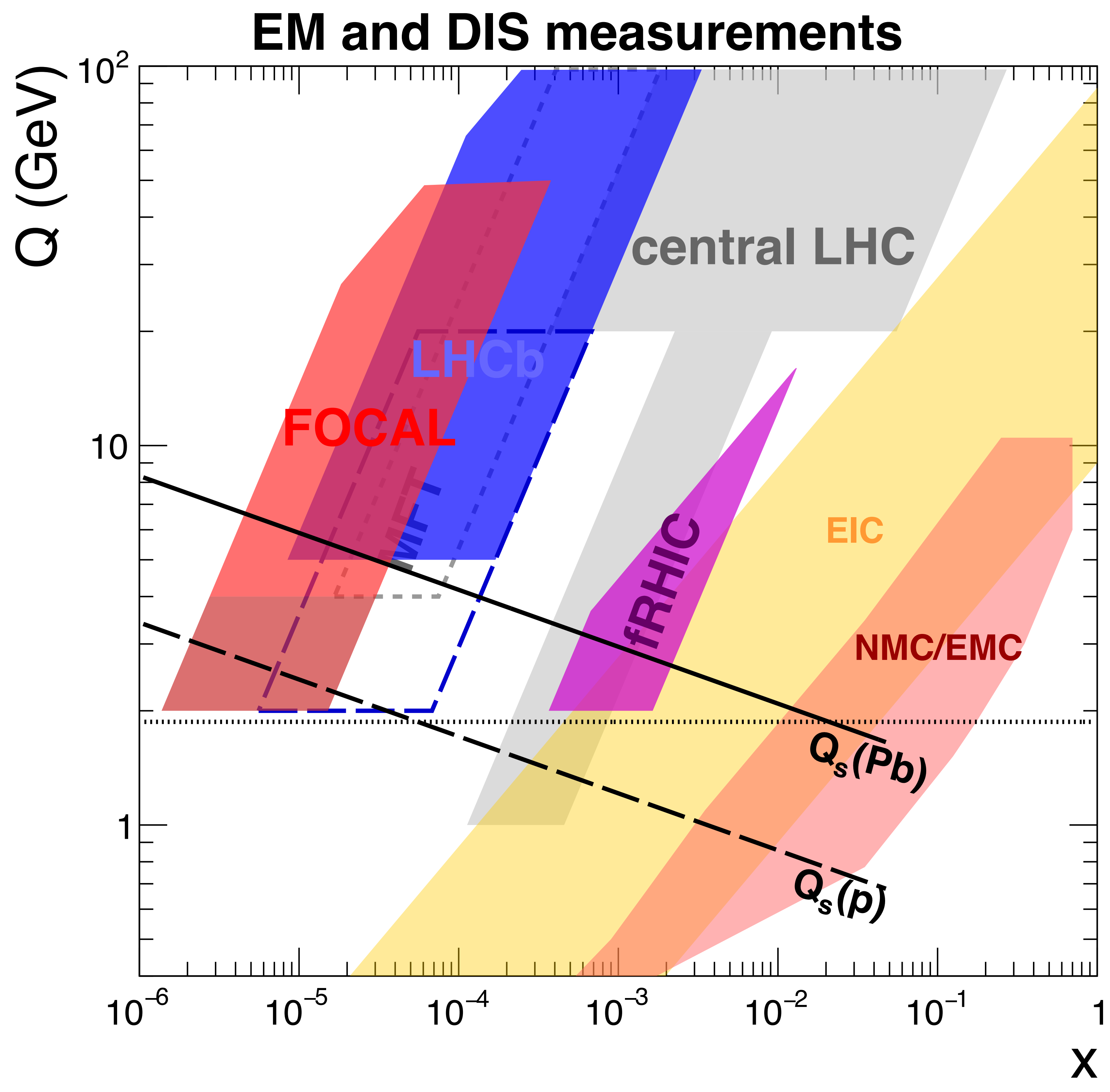
Comparison to CGC calculation



Theory calculations show narrow peak; add final state radiation/shower effects?

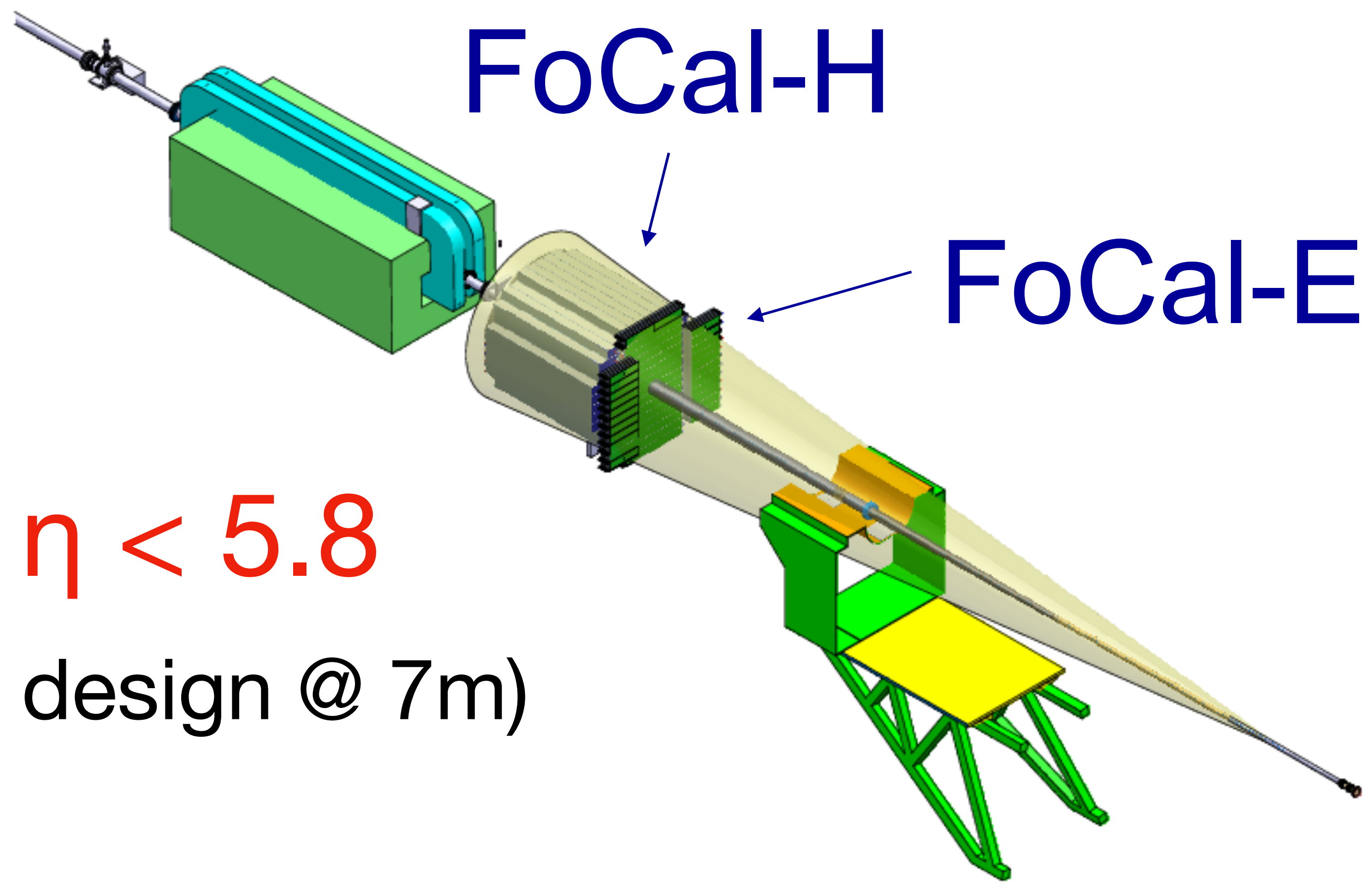
Summary

- Multiple indications of saturation/reduced gluon density at small *x* in the data:
  - DIS on nuclei
  - Forward particle production at RHIC and LHC
  - UPC
  - Di-hadron correlations — so far not conclusive?
- However, not a ‘closed case’
  - Are RHIC and LHC consistent?
  - (Most) observed are at small p_T: theory uncertainties?
  - Di-hadron correlations not systematically explored
- Possible future directions
  - Other forward hadron production at LHC, e.g. charged (identified) particles in LHCb
  - Photons at fwd rapidity: ALICE FoCal, LHCb
  - Systematically explore forward correlations at LHC
  - EIC



Thank you for your attention!

ALICE FoCal upgrade



3.4 < η < 5.8

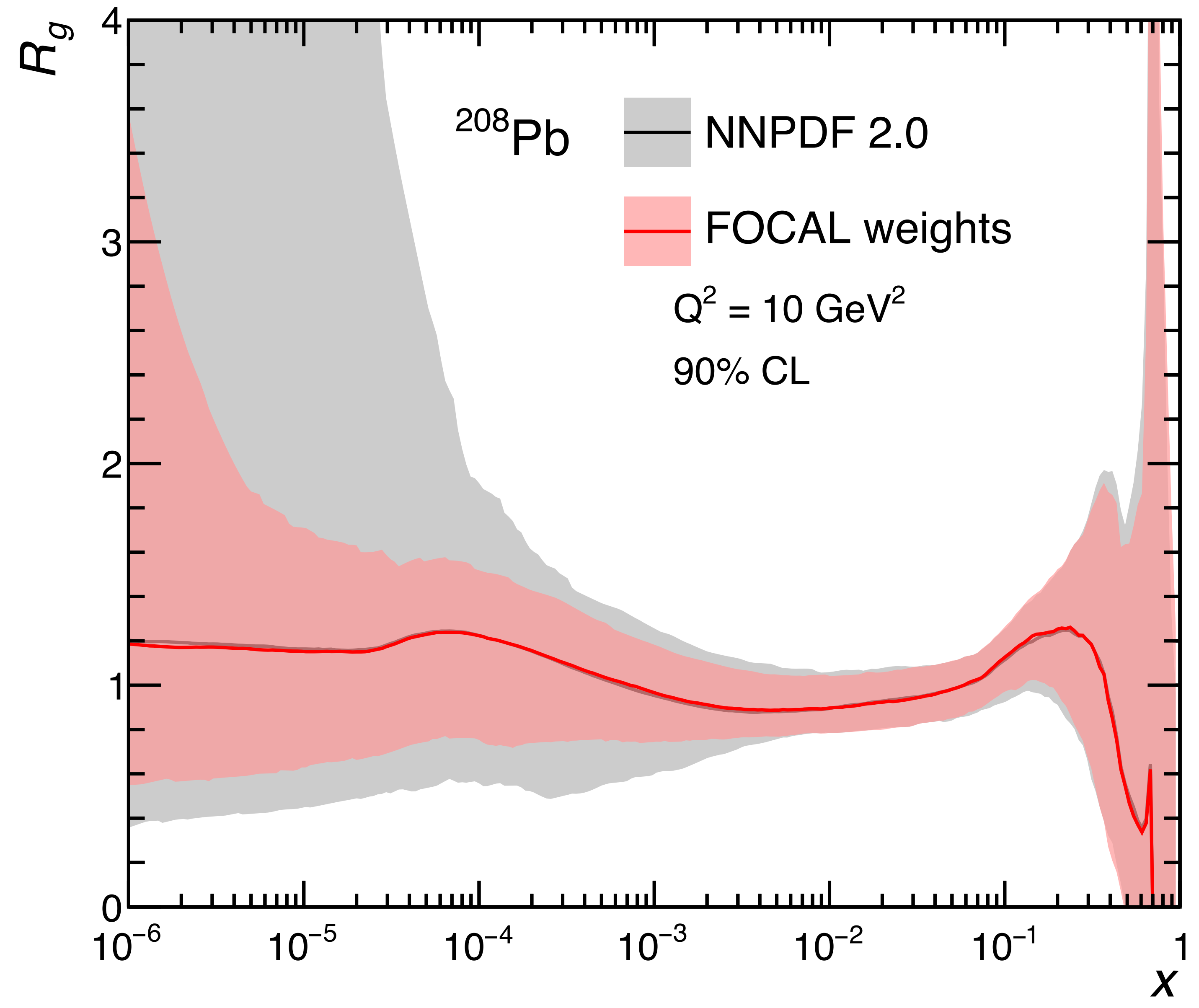
(baseline design @ 7m)

FoCal-E: high-granularity Si-W sampling calorimeter for photons and π^0
FoCal-H: conventional metal-scintillator sampling calorimeter for photon isolation and jets

Observables:

- π^0 (and other neutral mesons)
- **Isolated (direct) photons**
- Jets (and di-jets)
- J/ψ (Υ) in UPC
- W, Z
- Event plane and centrality

Reweighted gluon PDFs



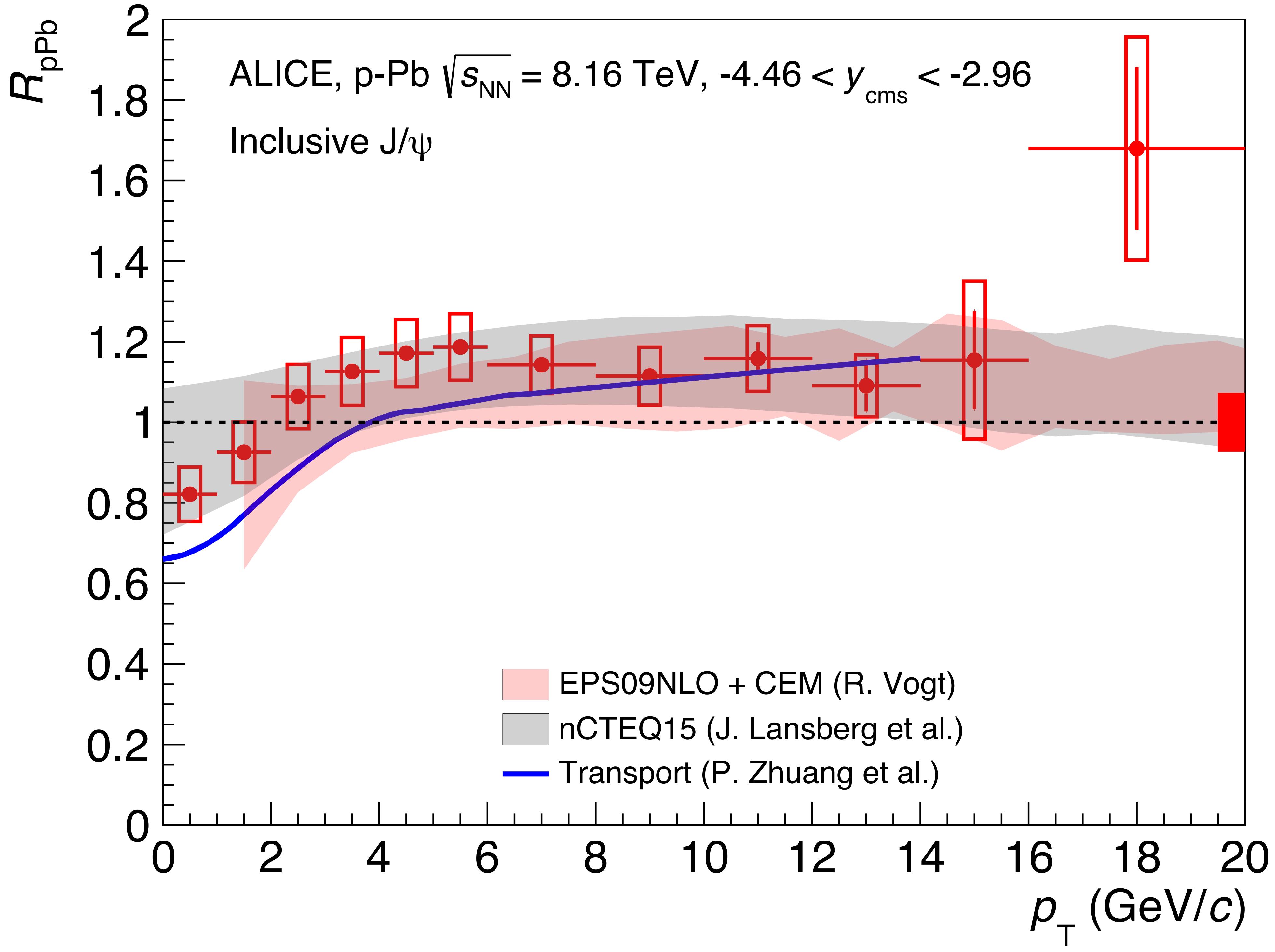
R. A. Khalek et al, JHEP 09 (2020) 183

Letter of Intent: LHCC-2020-009

Hidden charm: forward/backward J/Ψ production

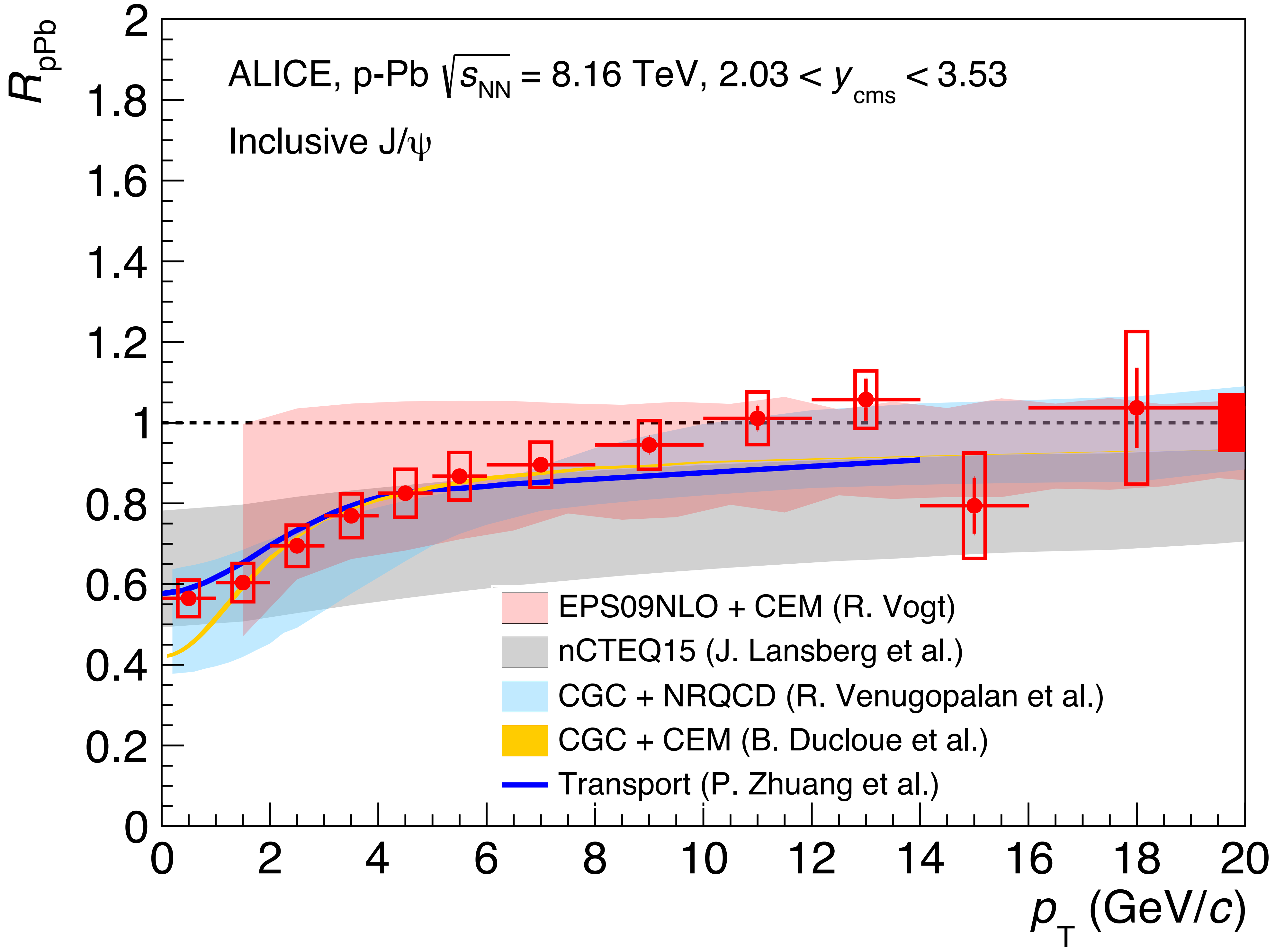
ALICE, JHEP 07 (2018) 160

Backward rapidity



High x: hint of anti-shadowing effect?

Forward rapidity



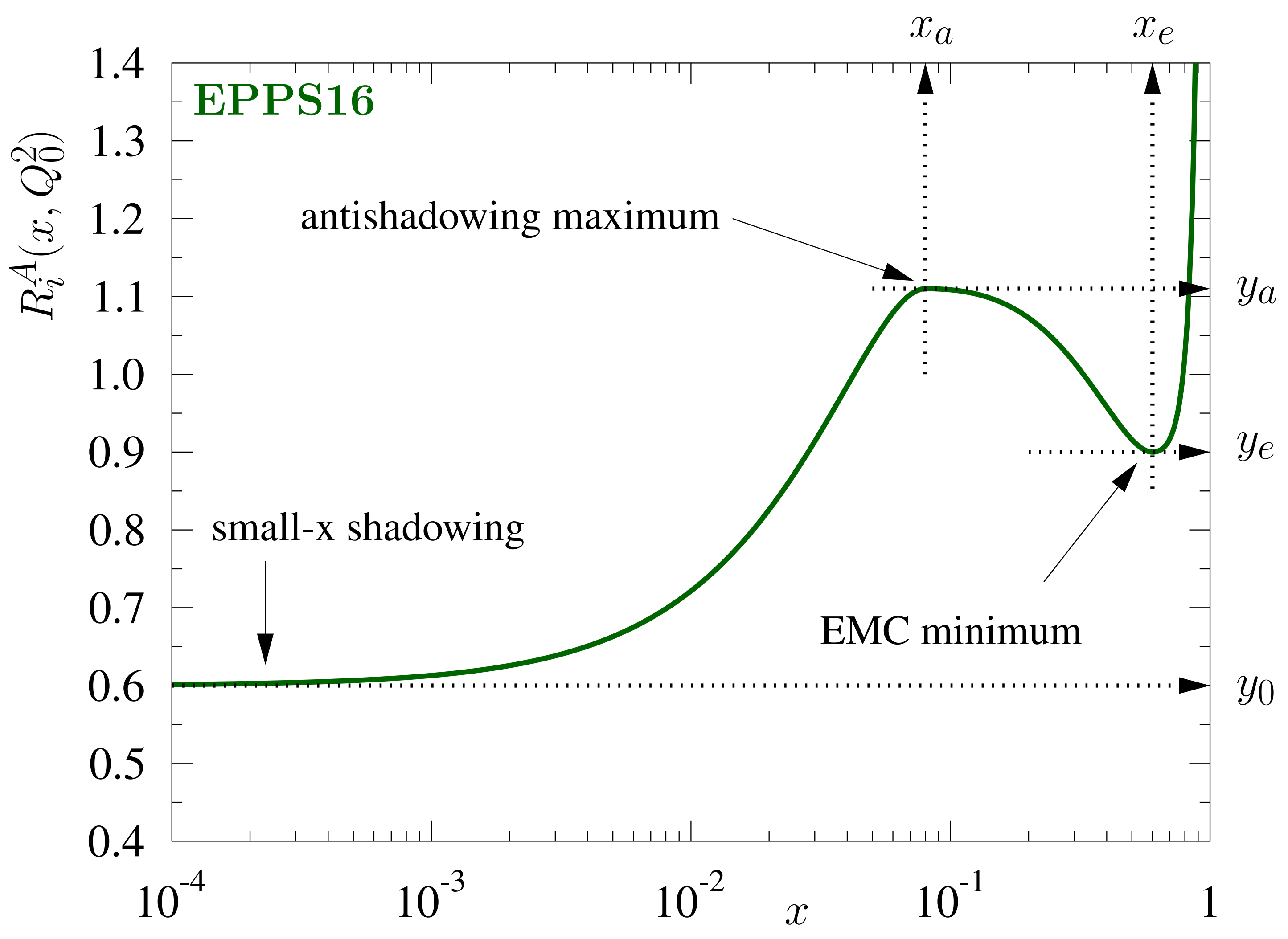
Suppression at low p_T < 6 GeV
qualitatively consistent with CGC expectations
nPDFs show less p_T dependence

Caveat: J/Ψ hadronisation and possible final state effects (e.g. co-movers) introduce sizeable uncertainties

x-Dependence of PDF modification

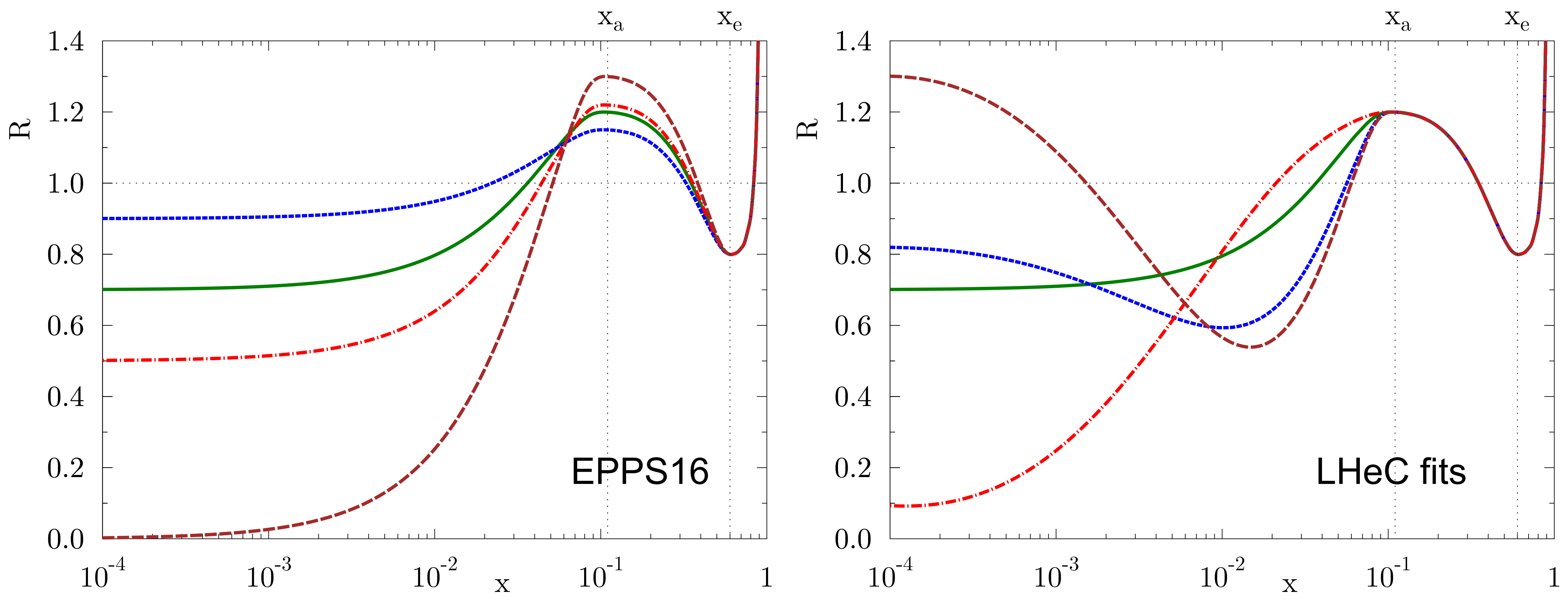
EPPS16, EPJC 77, 163

$$R_i^A(x,Q^2) = \begin{cases} a_0 + a_1(x-x_a)^2 & x \le x_a \\ b_0 + b_1 x^{\alpha} + b_2 x^{2\alpha} + b_3 x^{3\alpha} & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & x_e \le x \le 1 \end{cases}$$



- parameterisation of R_A
  - shape similar to EPS09
  - at low *x* leads to “plateau” in log(*x*)

- likely not sufficient
  - more flexible PDF used for LHeC estimates



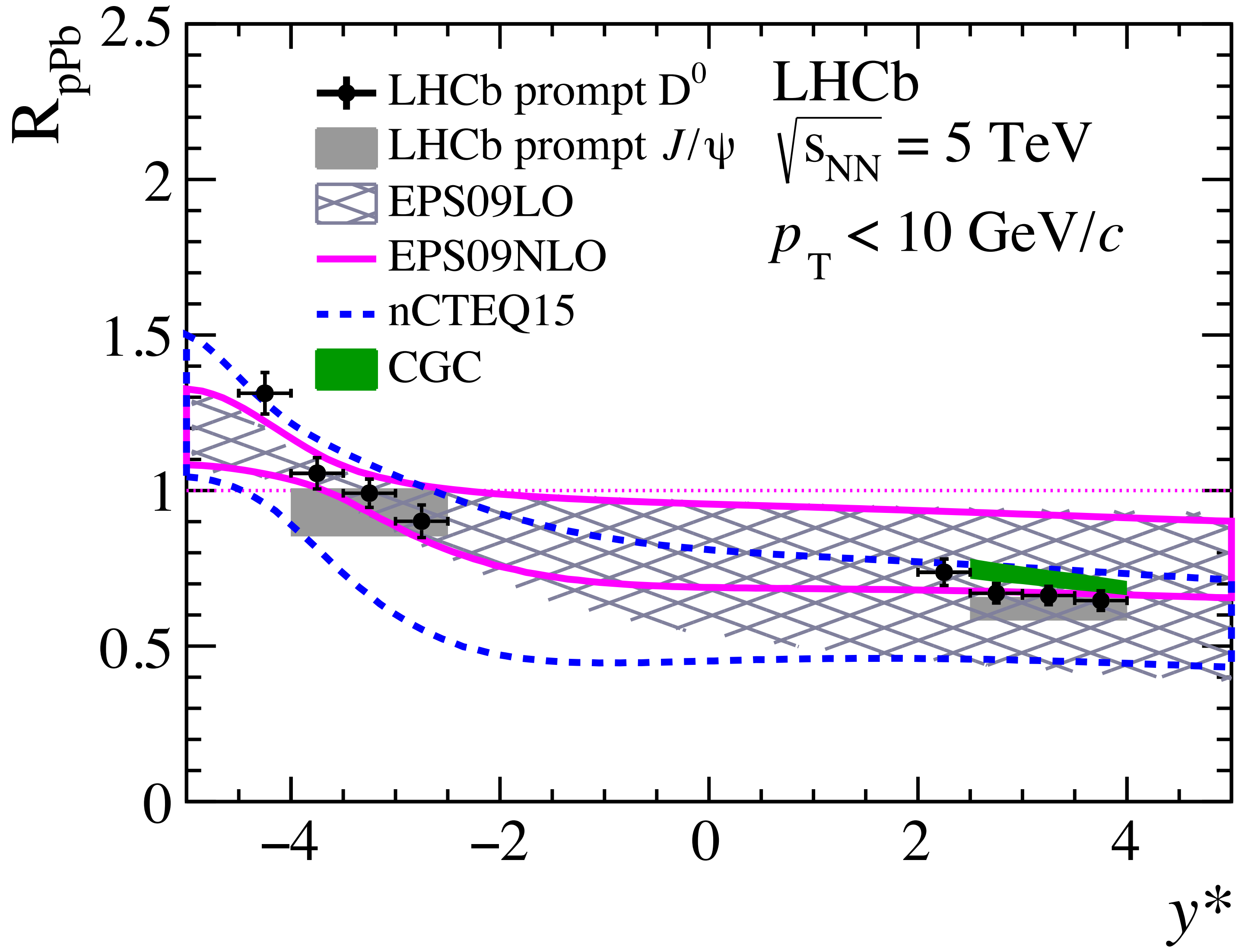
Helenius, Paukkunen, Armesto, arXiv:1606.09003

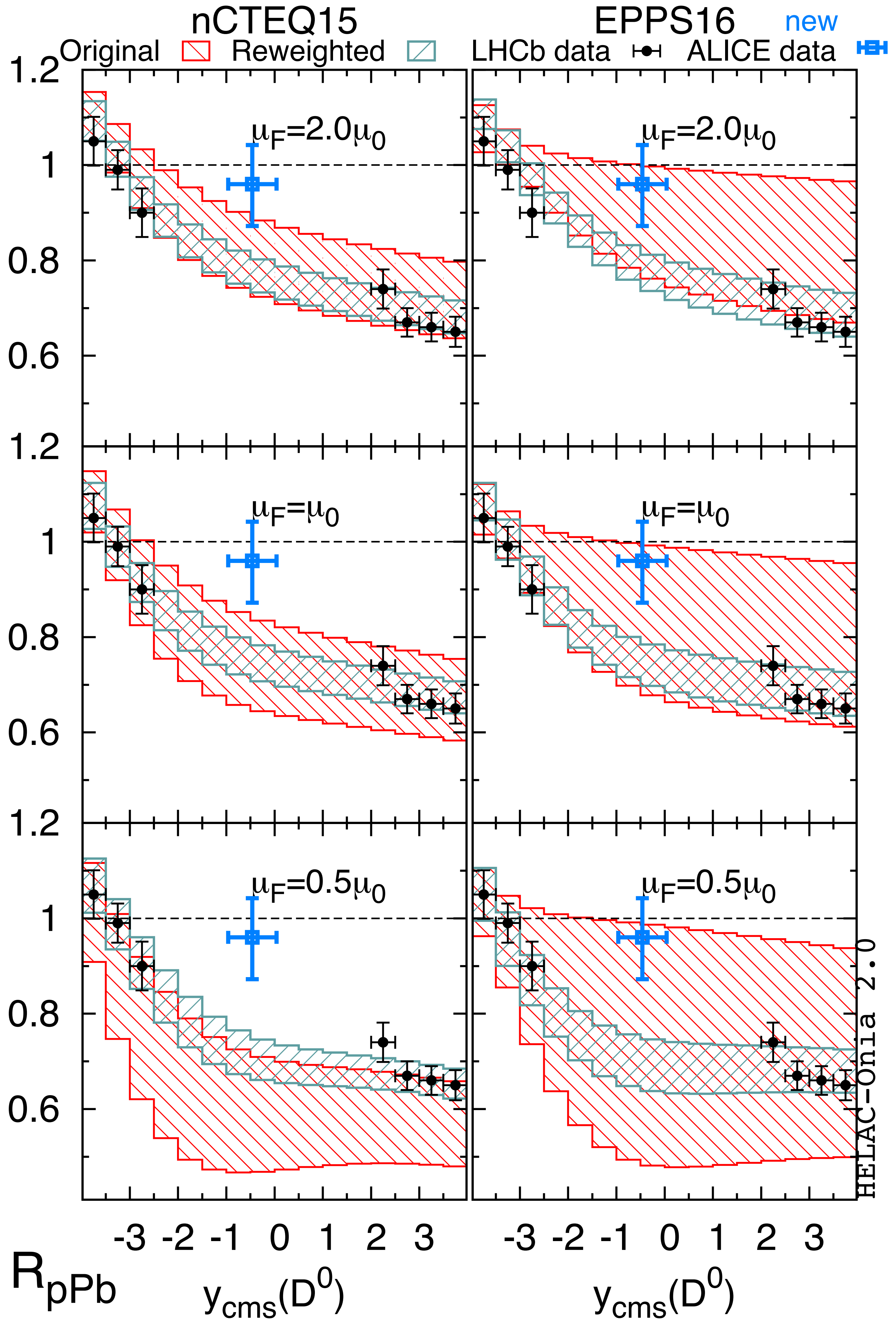
Constraining nPDFs with charm: reweighting

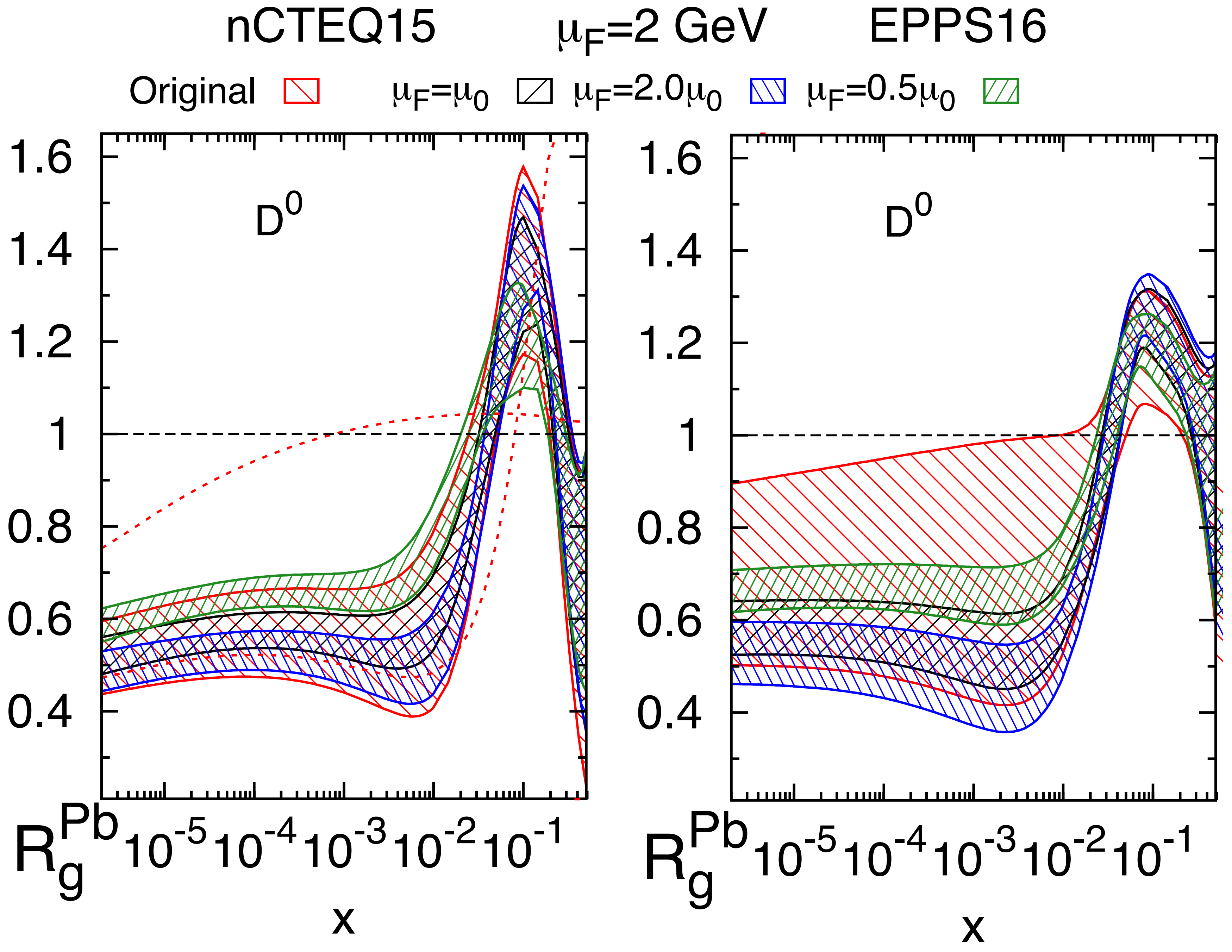
Kusina et al., PRL121 (2018) 052004

ALICE, arXiv:1906.03425

LHCb data



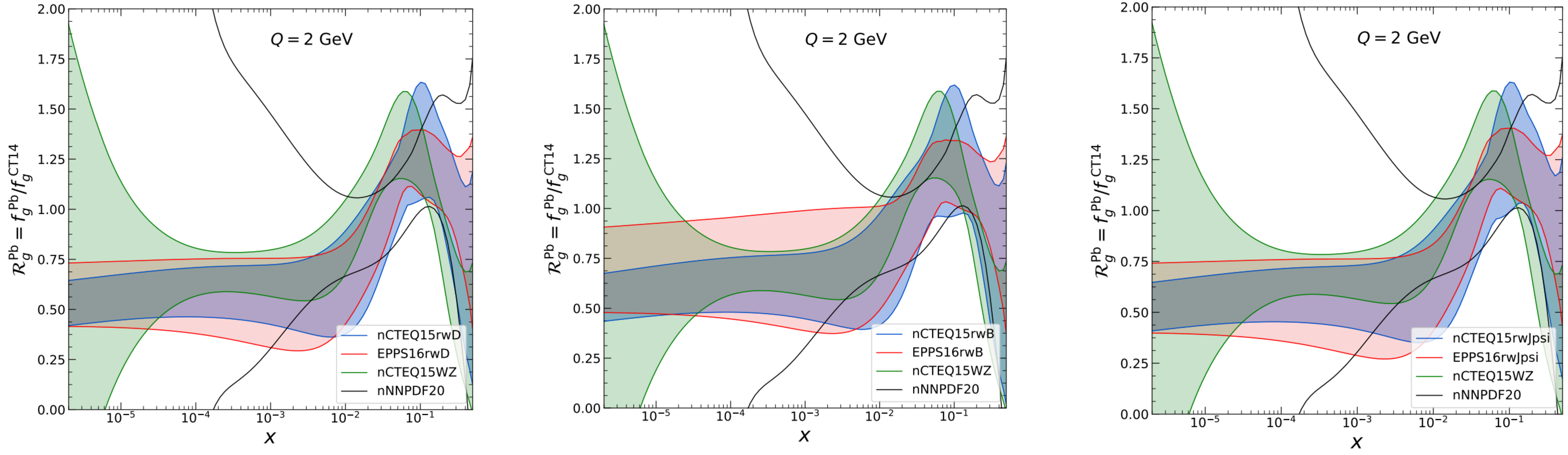




This reweighting procedure with a parametrised NLO calculation results in large shadowing; predict significant suppression at mid-rapidity; tension with data

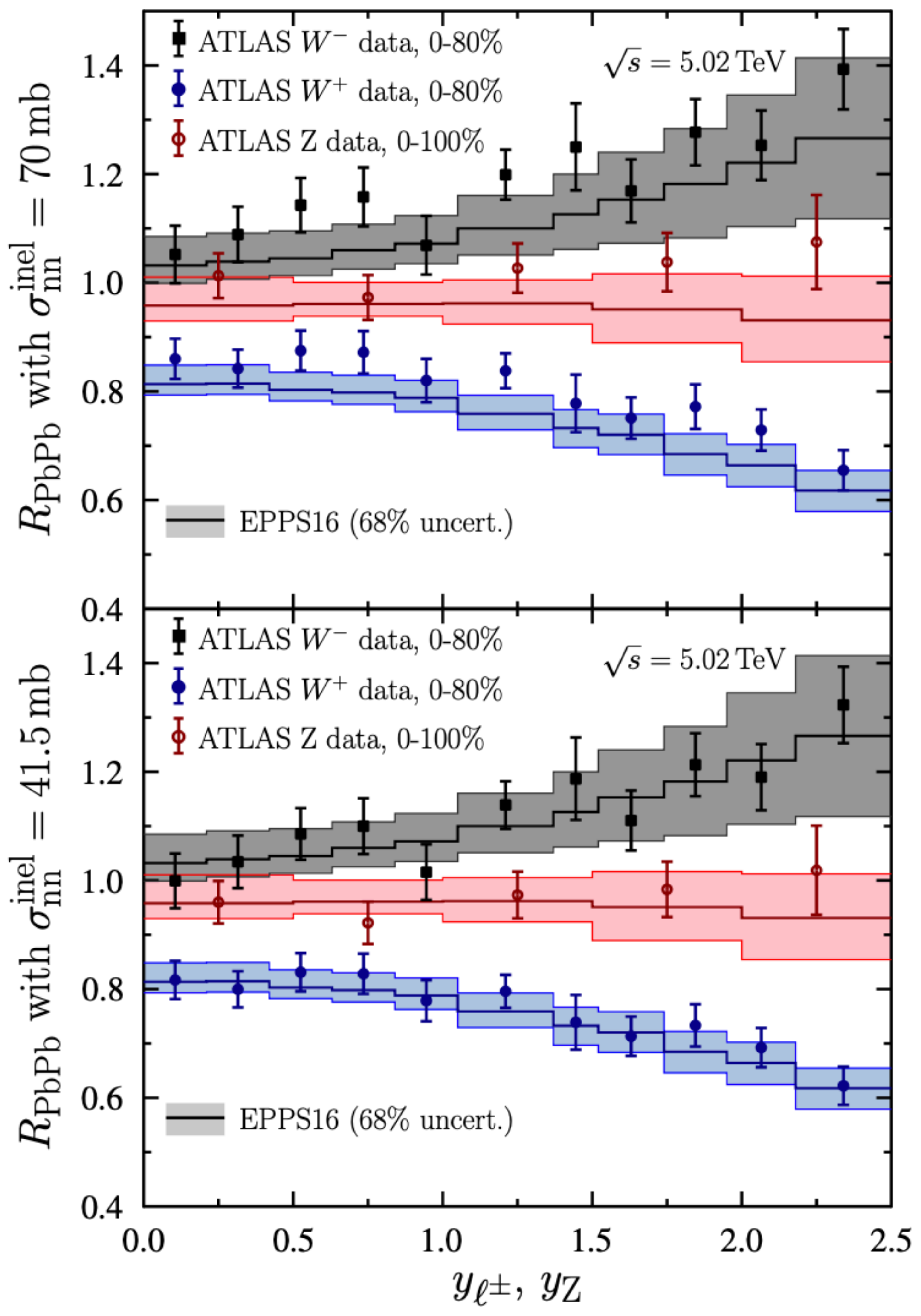
Reweighting with charm, beauty

Kusina, Lansberg, Schienbein, Shao, arXiv:2012.11462



(a) D RnPDFs (b) $B \to J/\psi$ RnPDFs (c) J/ψ RnPDFs

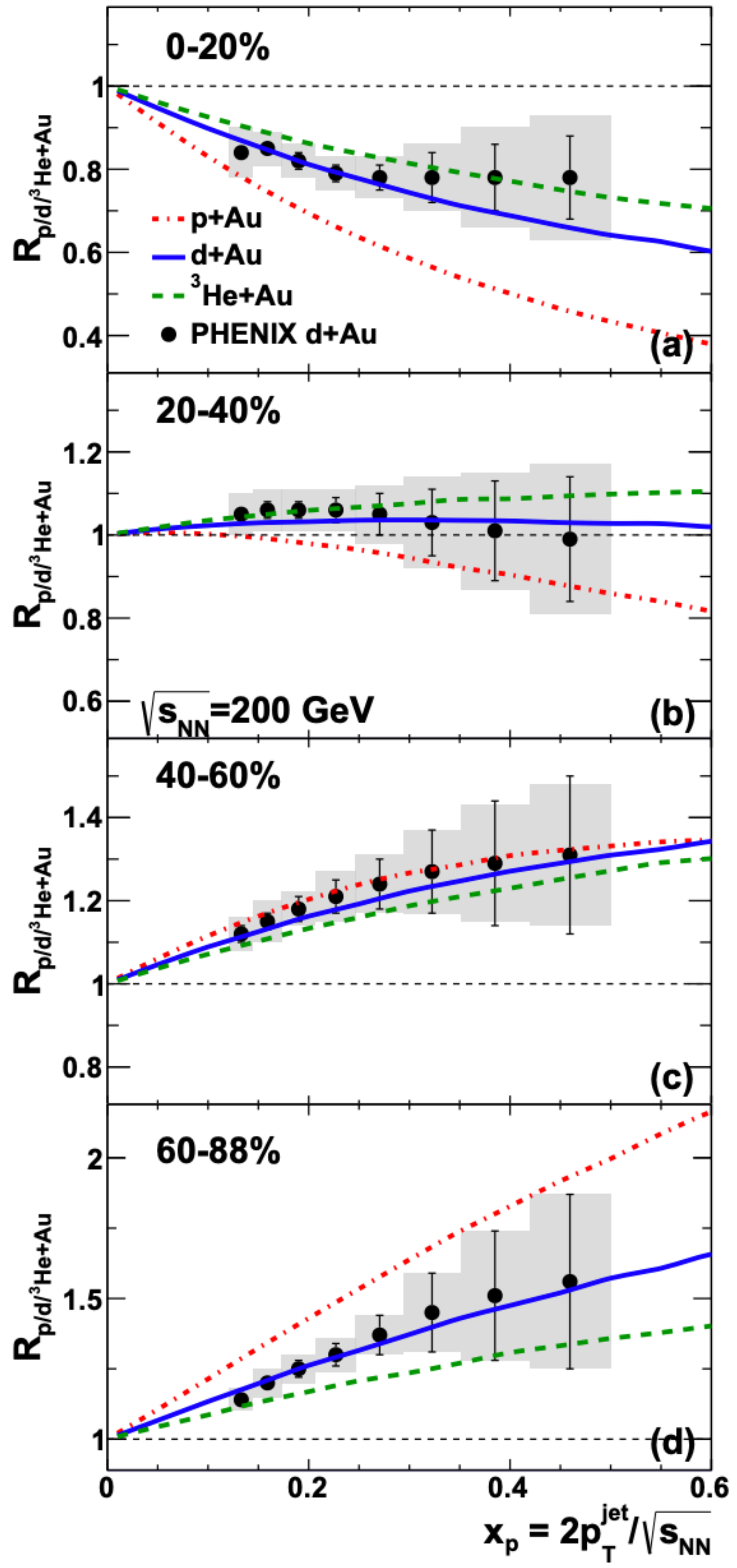
Changing the total cross section?



Eskola, Helenius, Puka, Paukkunen, *PRL* 125, 212301

Jyvaskyla group: ATLAS EW data suggest that effective total cross section is smaller in p-Pb than free nucleons

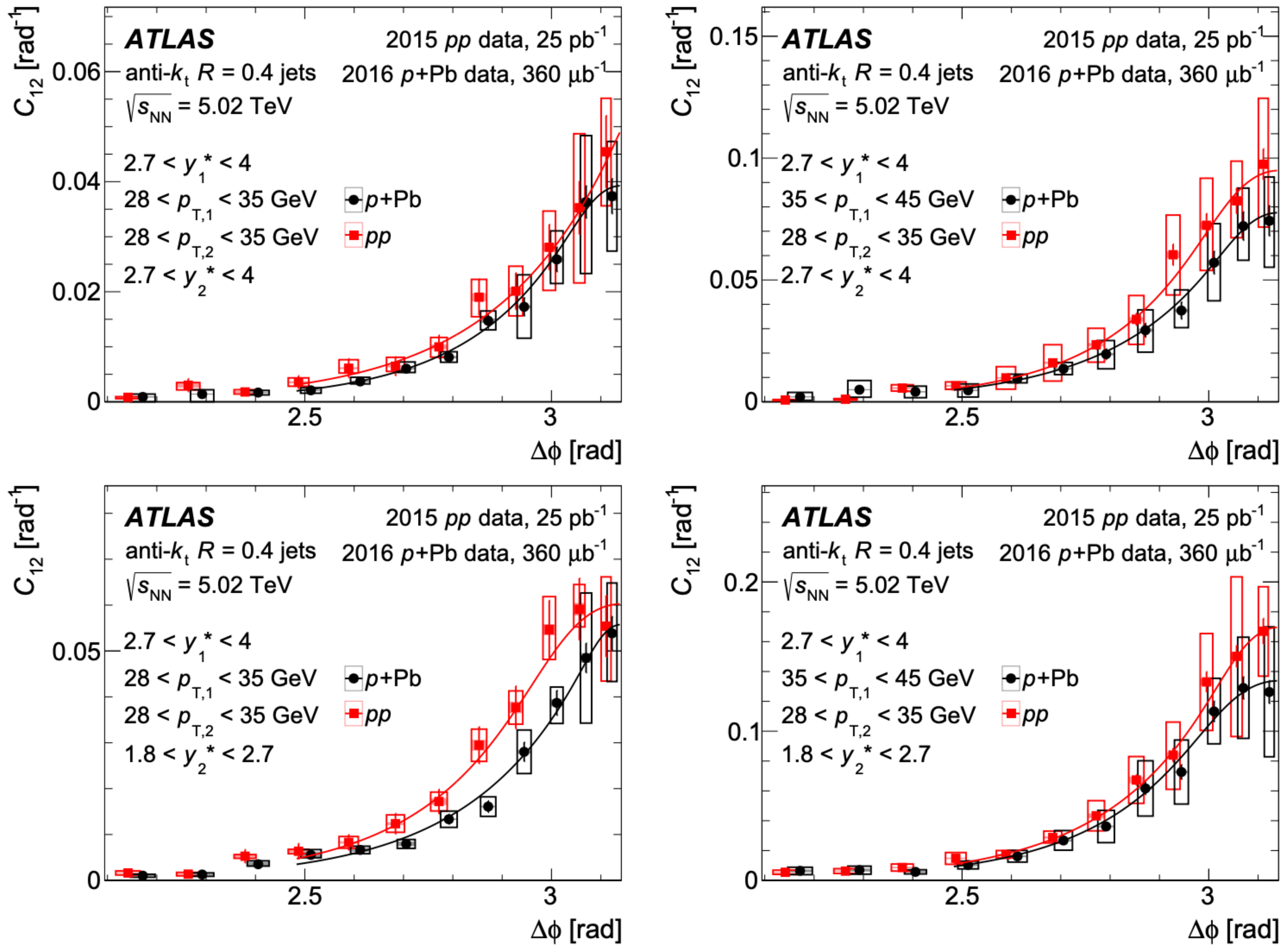
PHENIX R_{dAu}: unexpected centrality dependence
Suggested interpretation:
total cross section depends on x?



McClinchey, Nagle, Perepelitsa, *PRC* 94, 024915

Forward di-jet correlations at LHC

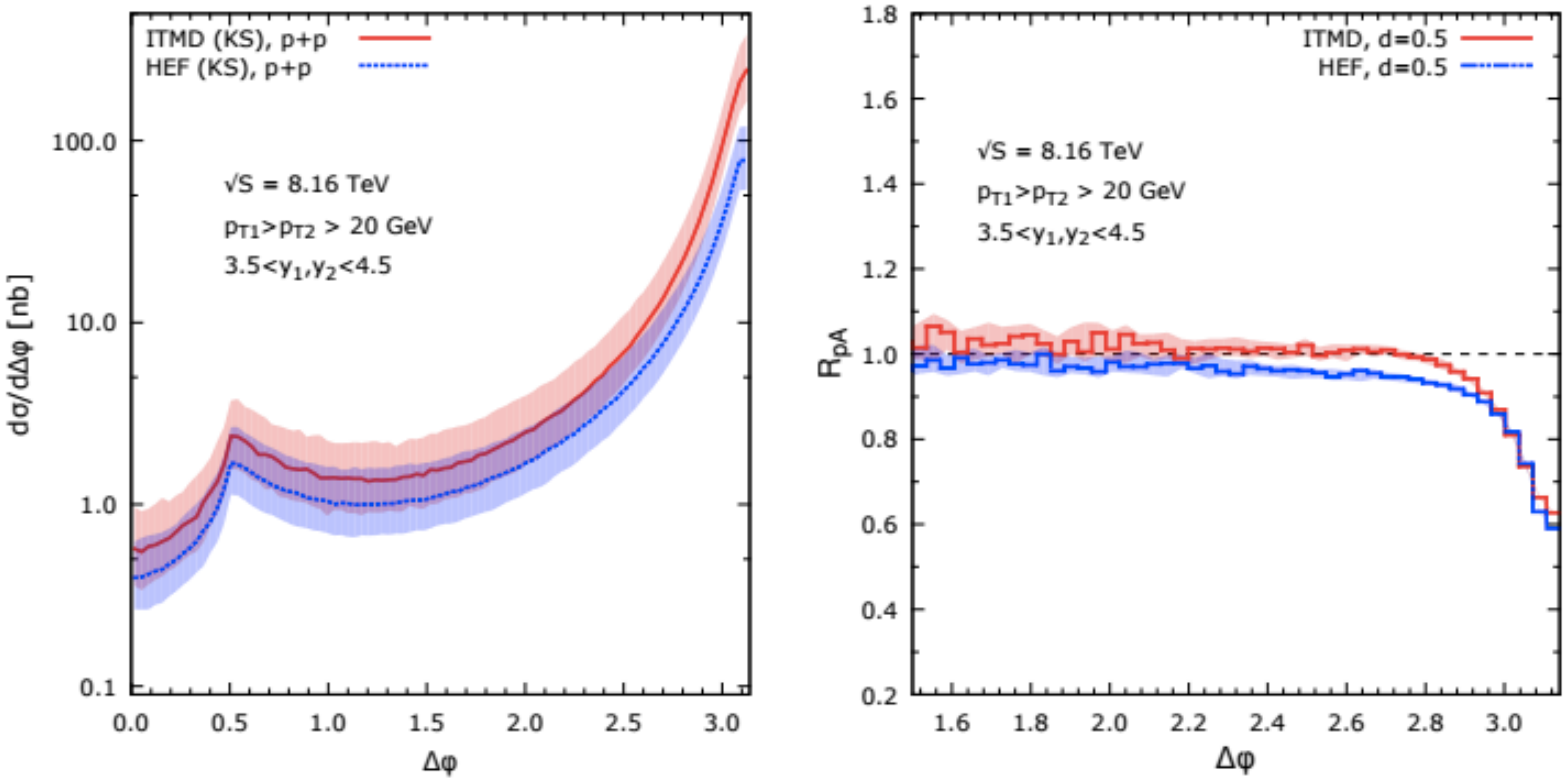
Di-jets with p_T 28-45 GeV



ATLAS, arXiv:1901.10440

Some bins show difference, but no clear trend…

TMD framework calculation



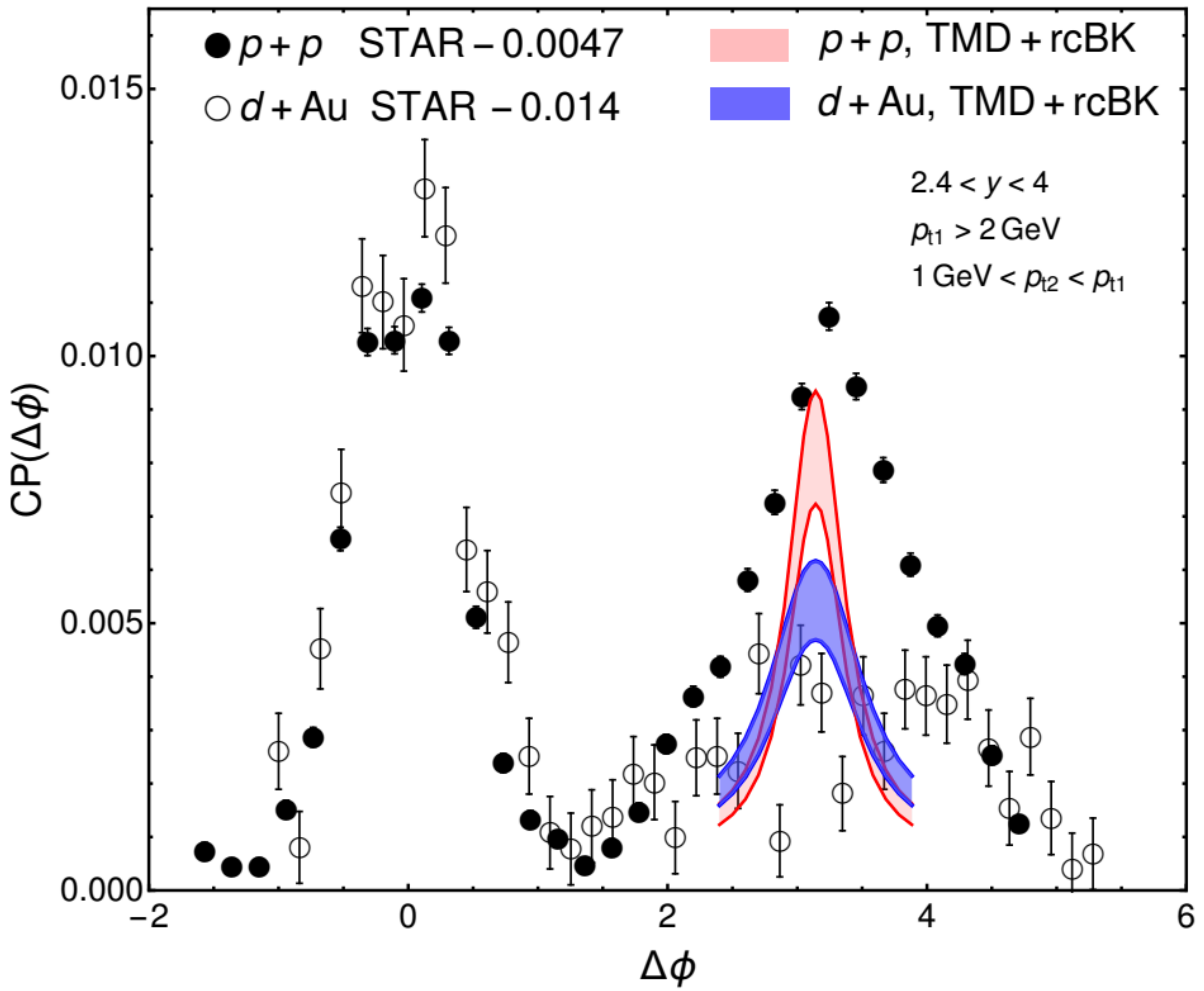
van Hameren et al, arXiv:1607.0312

TMD: expect 'dip' near $\Delta\varphi = \pi$ for balancing jets

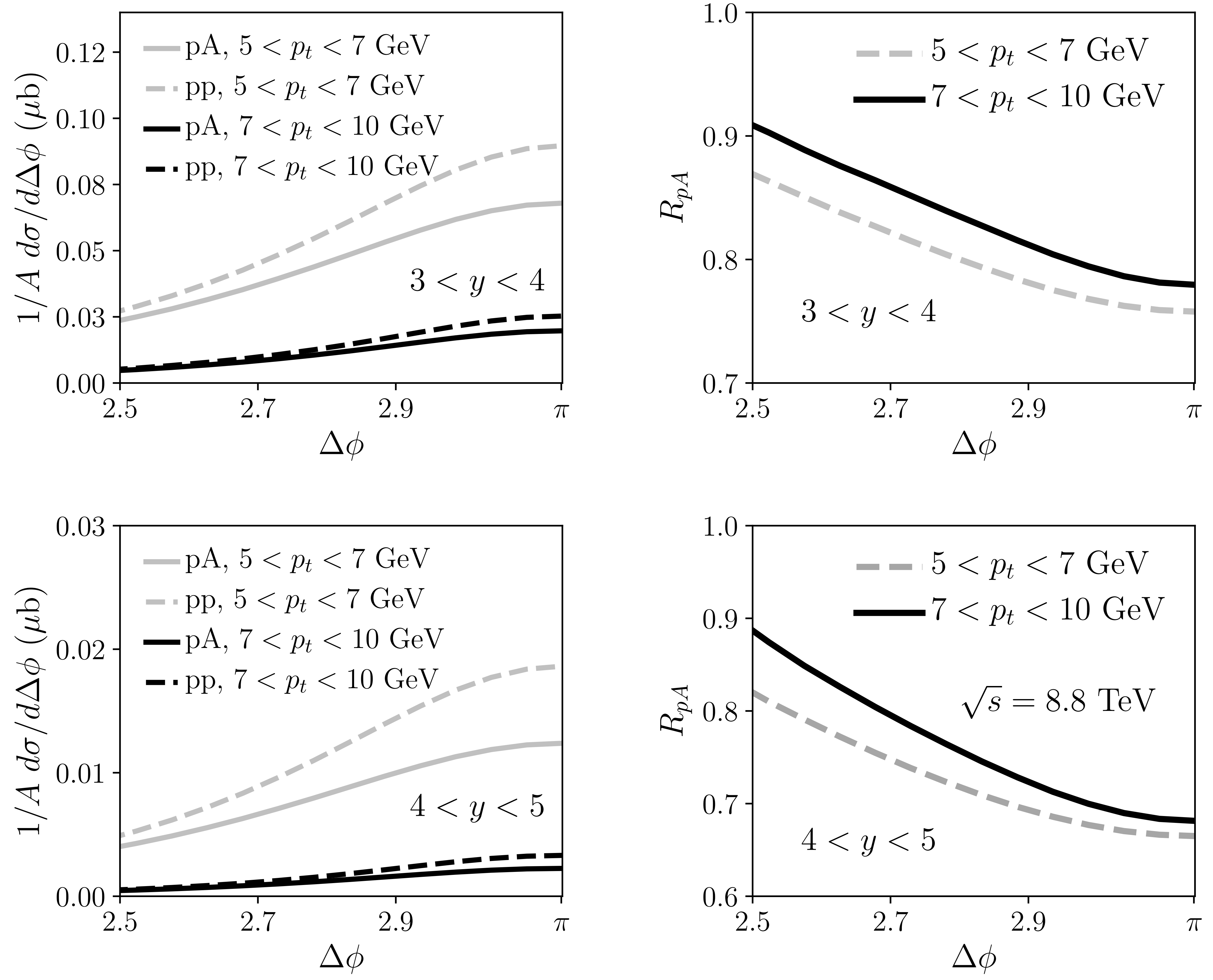
Physical origin?

Di-hadron correlations

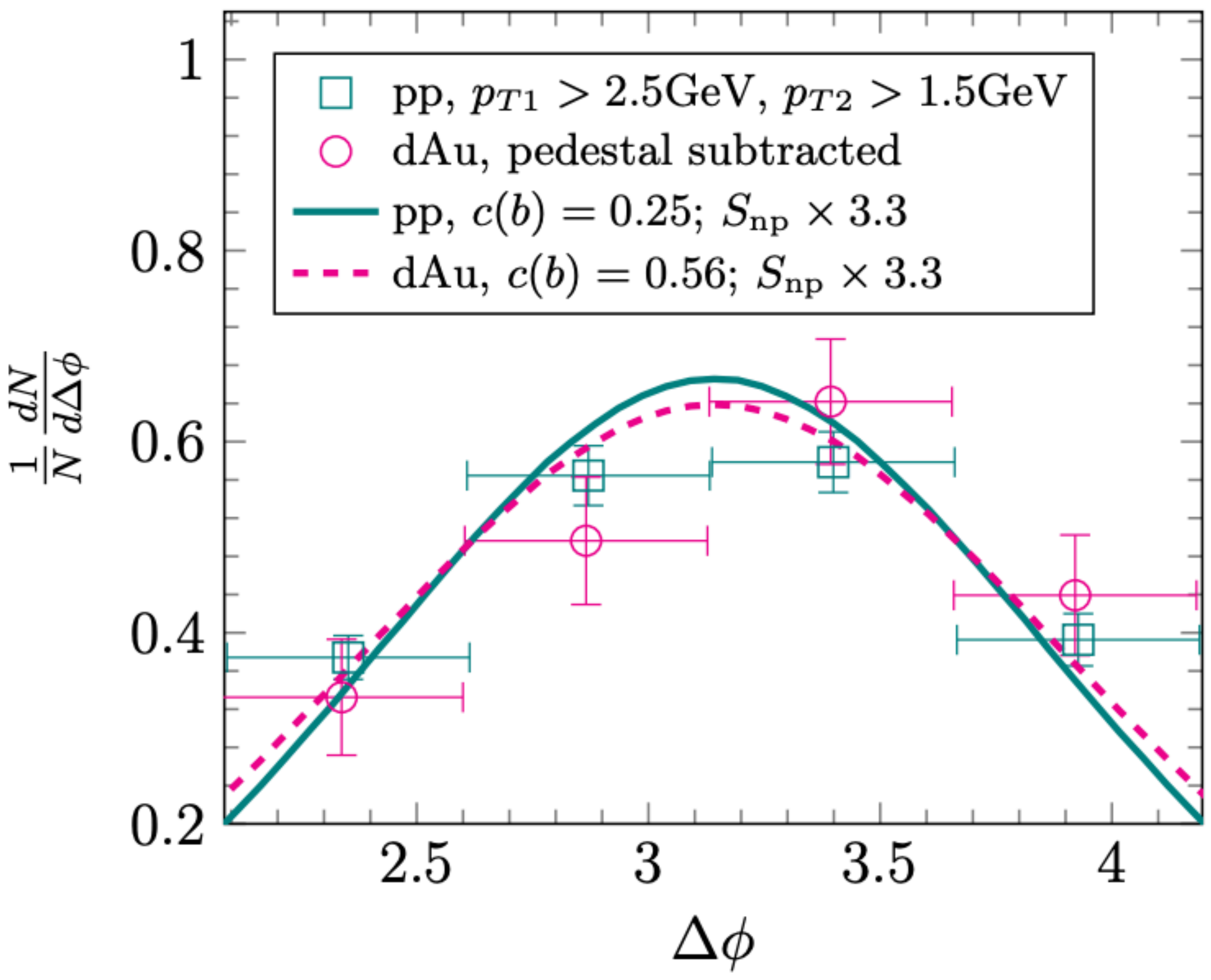
Albacete, Giacalone, Marquet, Matas, PRD 99, 014002



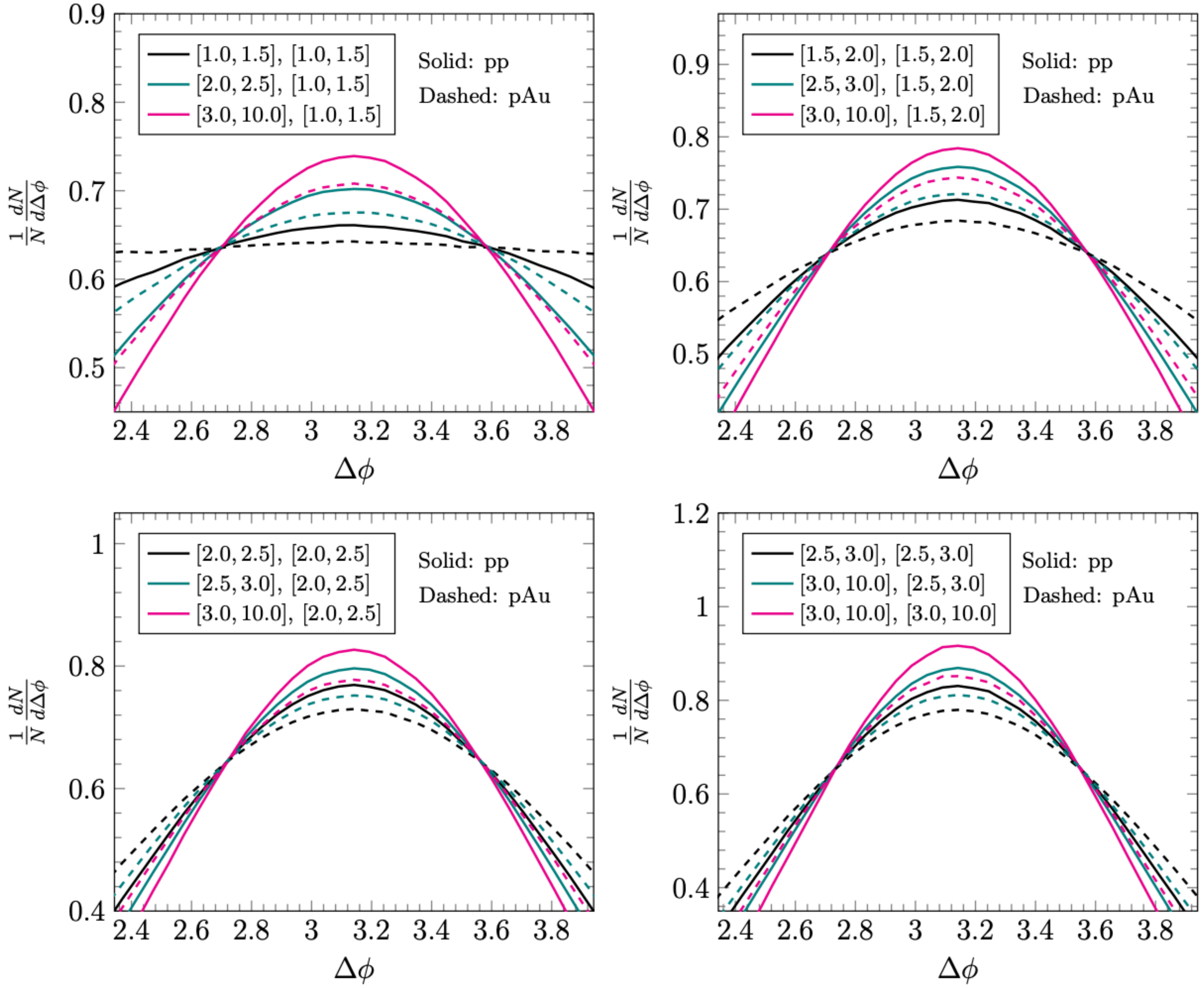
LHC prediction



Di-hadron correlation CGC theory: RHIC

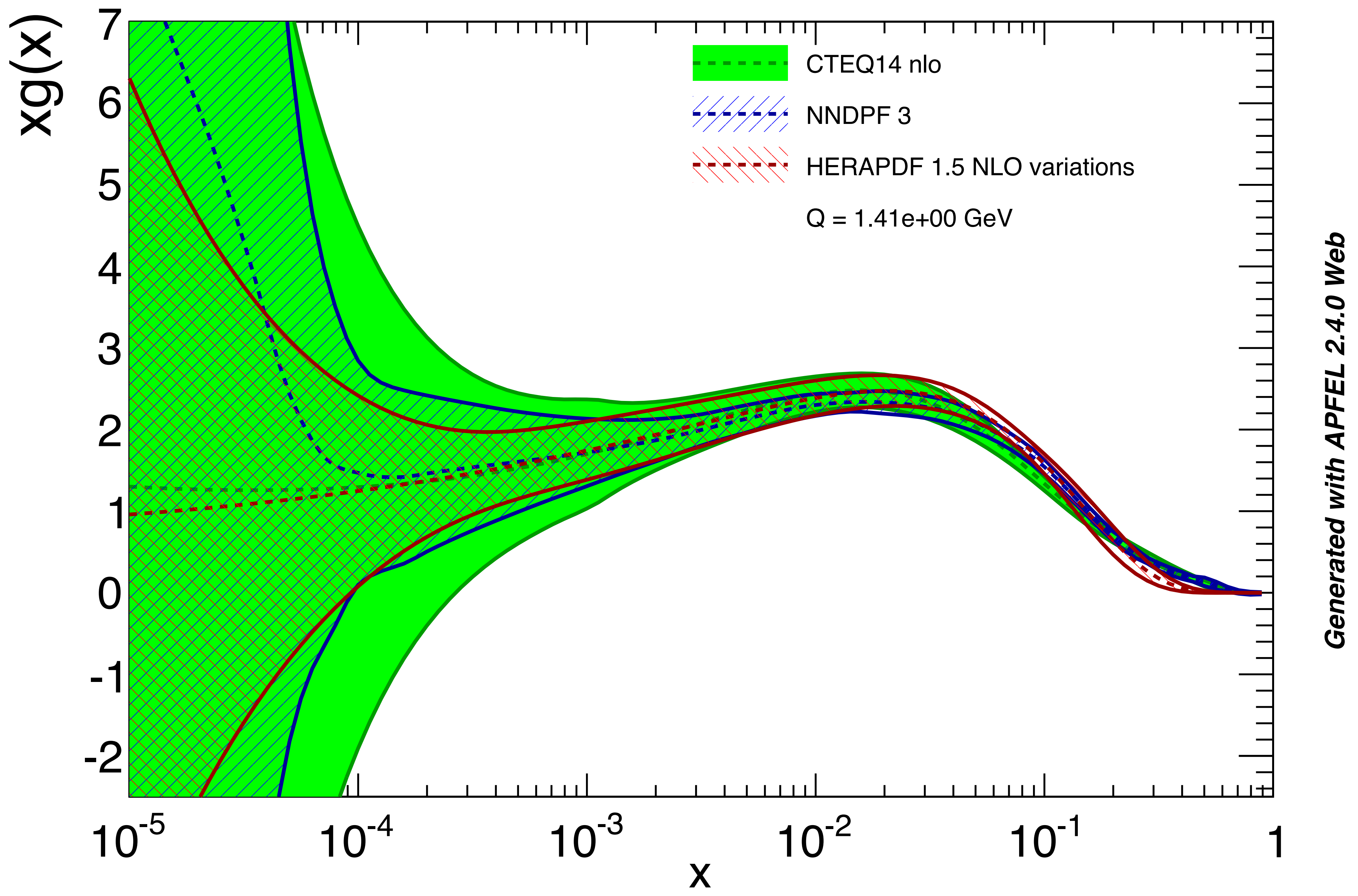


Stasto, Wei, Xiao, Yuan, *PLB* 784, 301



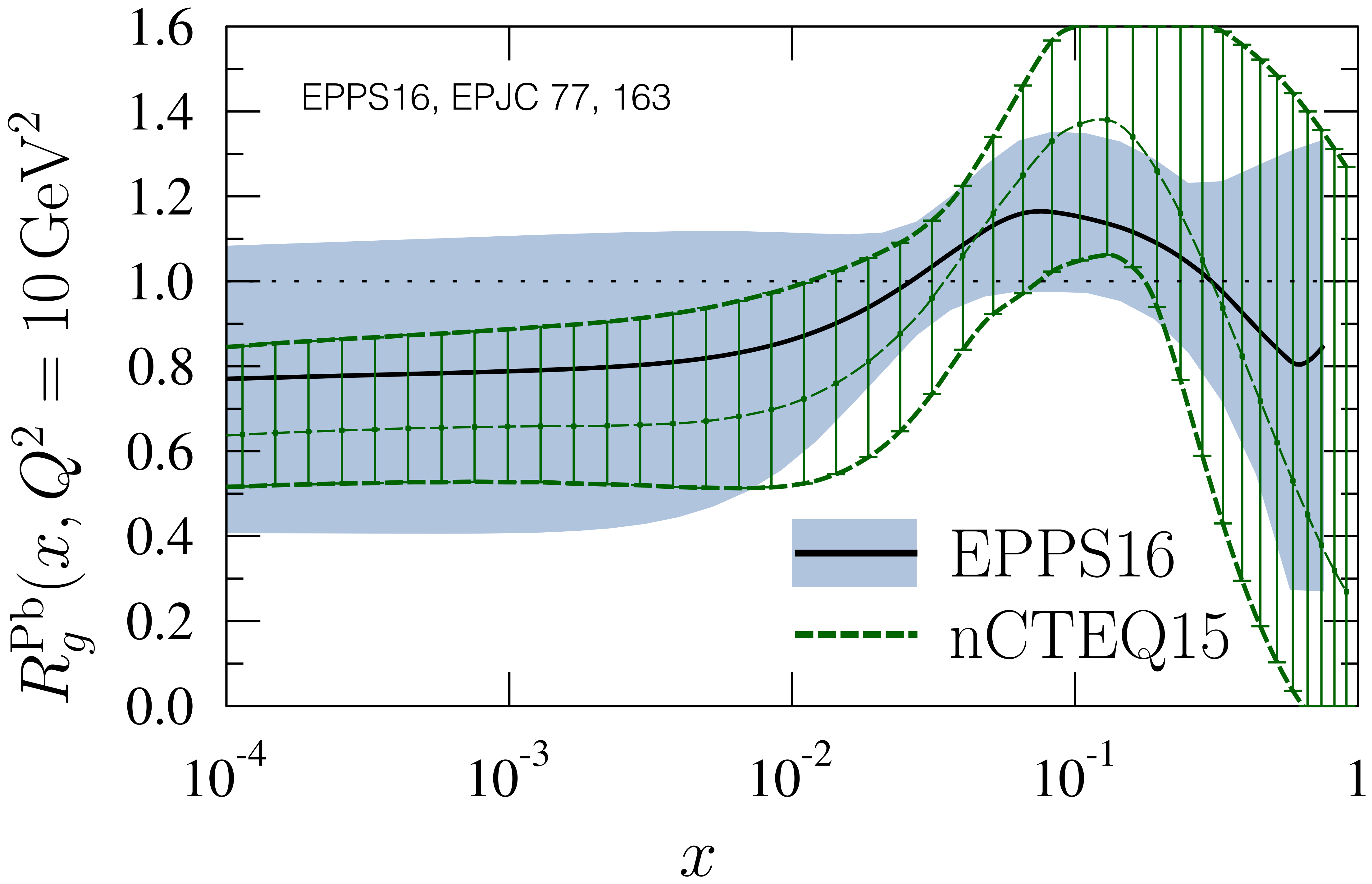
Gluon Densities at small x

Gluon density in proton



Even in the proton, limited information about gluons at $x < 10^{-4}$

Gluon density in Pb nucleus



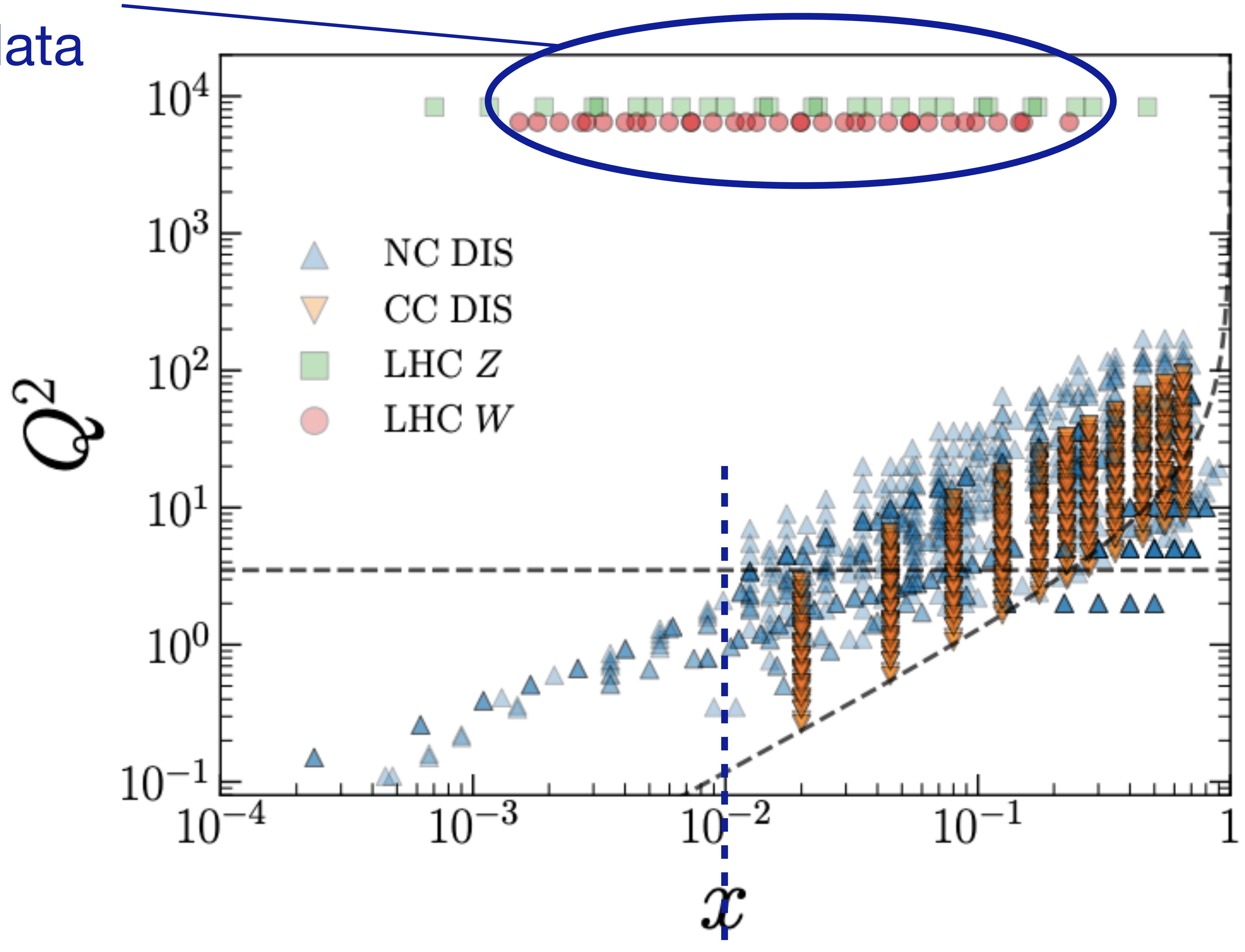
Ratio Pb/p has large uncertainties over broad range $x < 10^{-2}$

nPDFs with minimal constraints: nNNPDF

nNNPDF use a more
flexible parametrisation of PDFs at Q_0

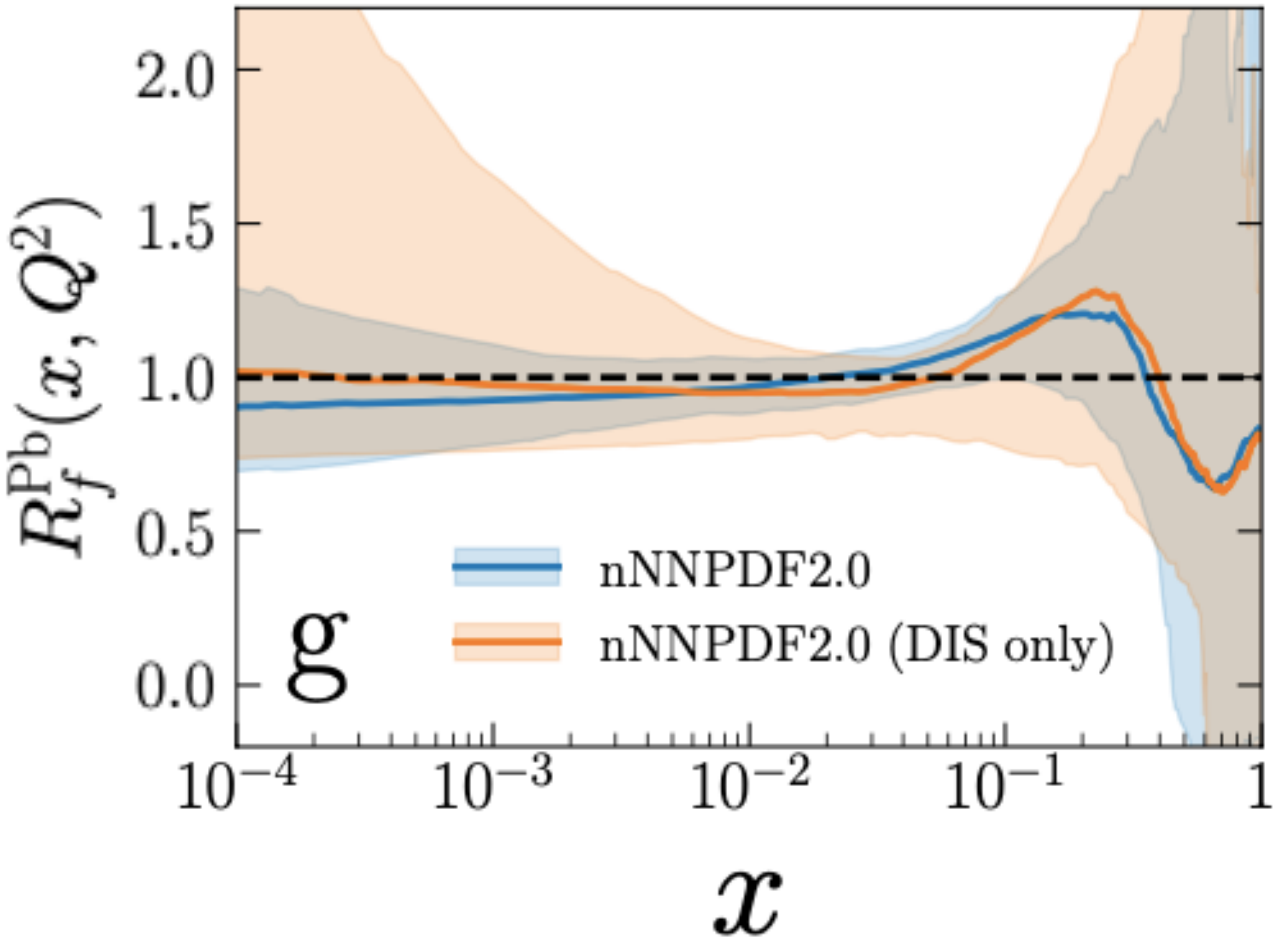
R.A. Khalek et al, EPJ C 79, 6
R.A. Khalek, J.J. Ethier et al, arXiv:2006.14629

nNNPDF 2.0: include
LHC electroweak data



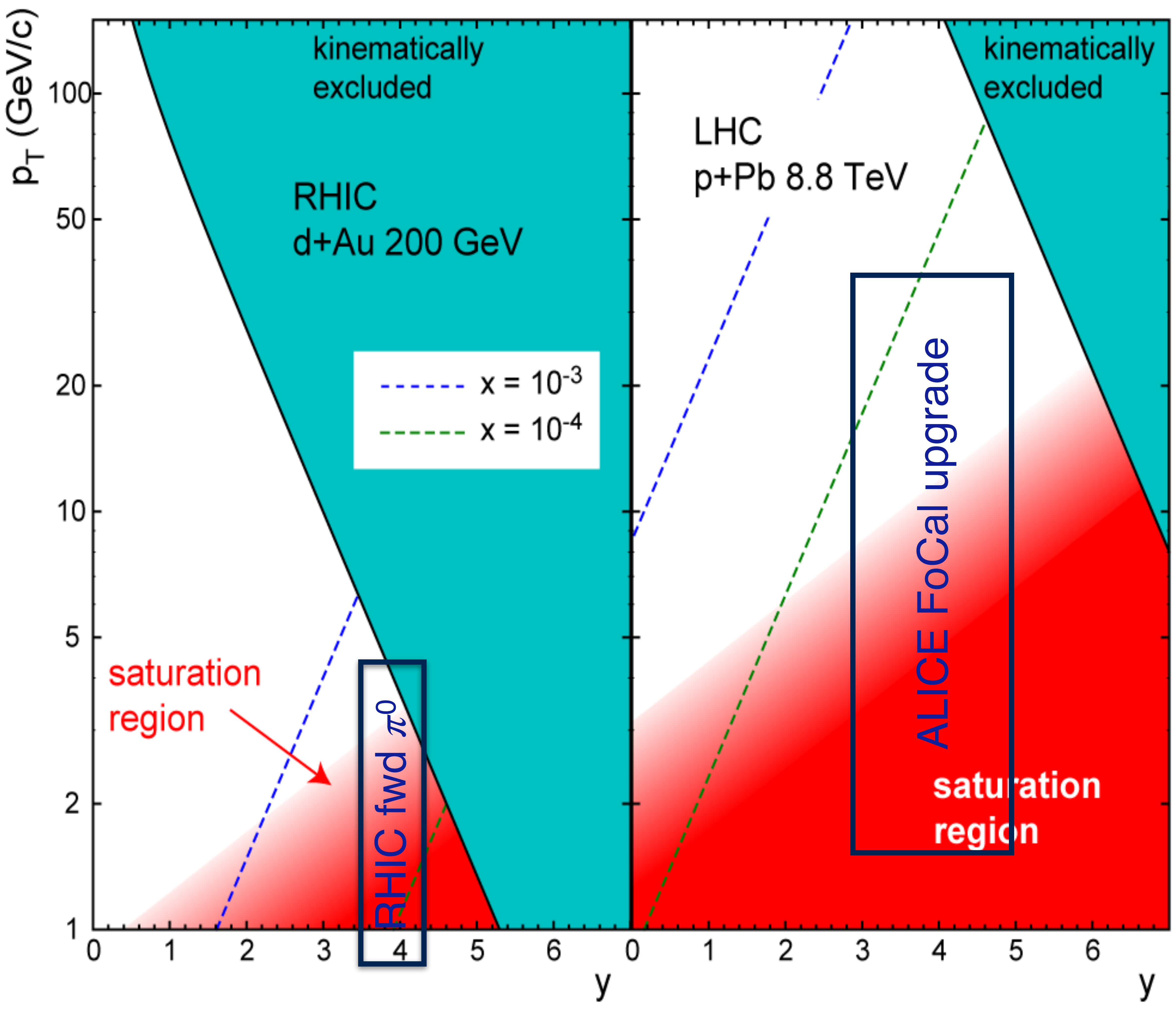
DIS input only
covers $x > 10^{-2}$

DIS only vs DIS + LHC



LHC EW data reduce uncertainty at small x
prefer no shadowing, $R_g \approx 1$

LHC vs RHIC

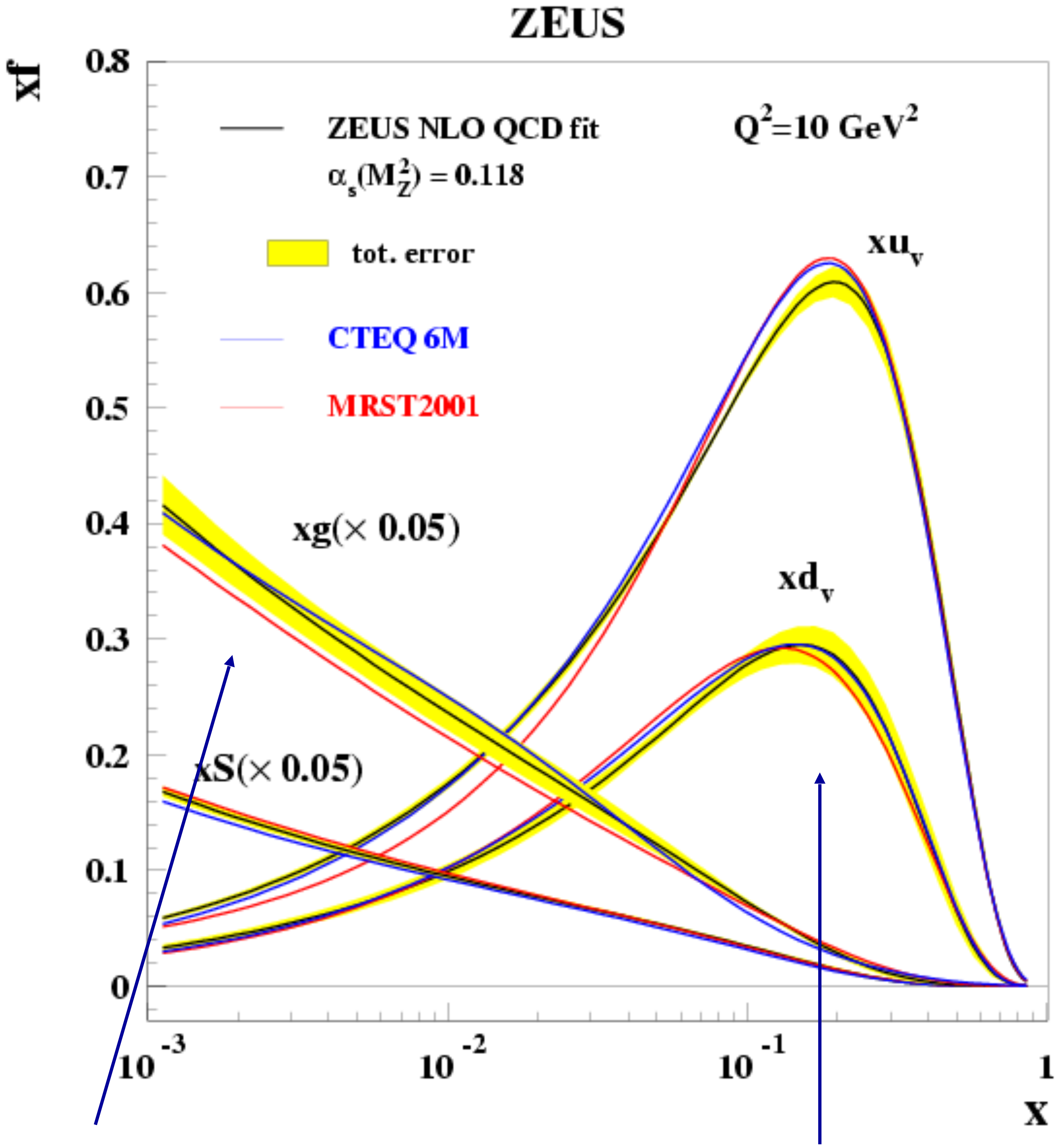


RHIC forward:
kinematic limit at p_T ~ 5 GeV

LHC: x~10^{-4} – 10^{-5} accessible,
with p_T~Q~3-4 GeV

Proton structure: parton density functions

Low Q^2: valence structure

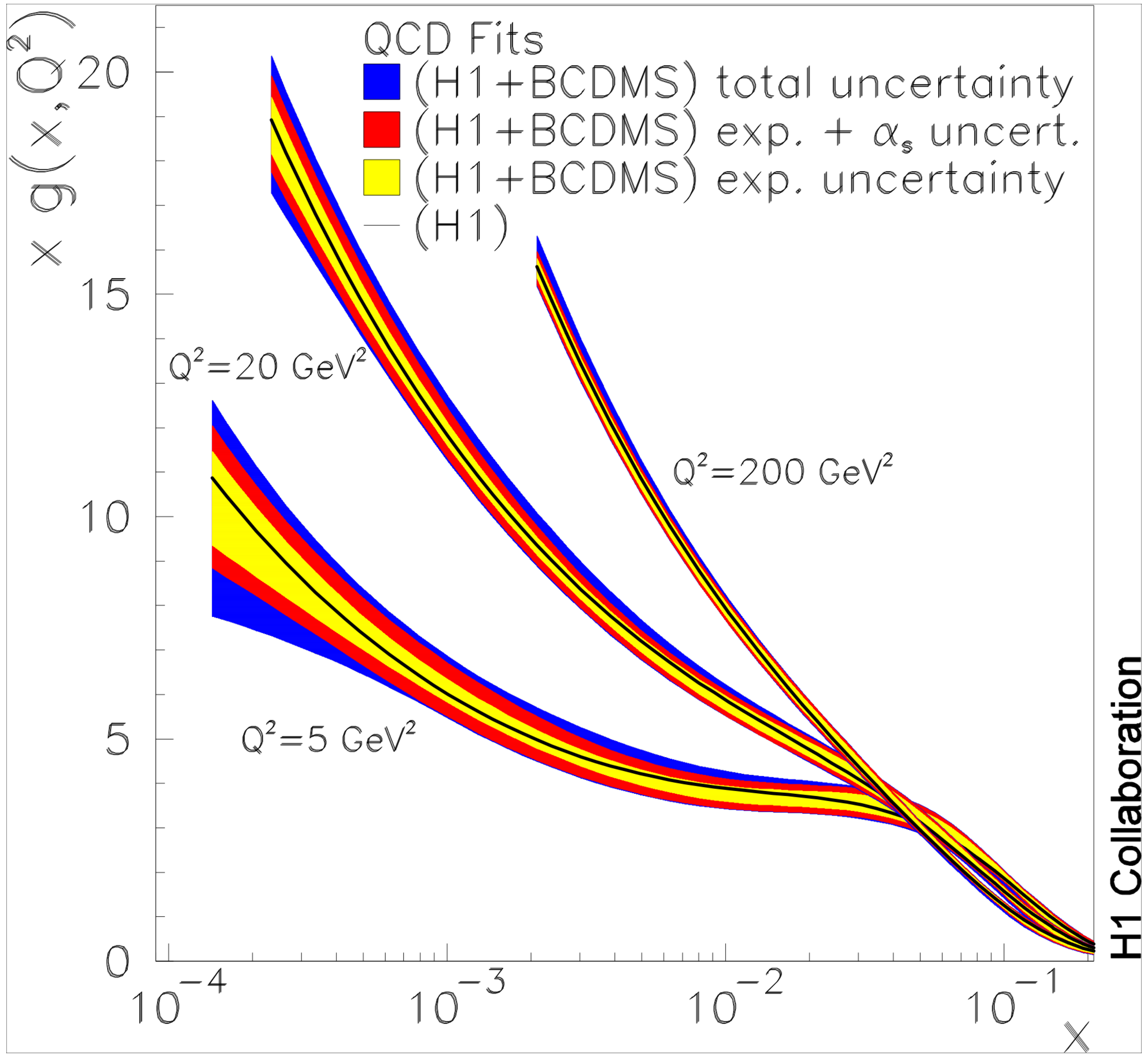


Soft gluons

Valence quarks (p = uud)
x ~ 1/3

x: momentum fraction
carried by parton

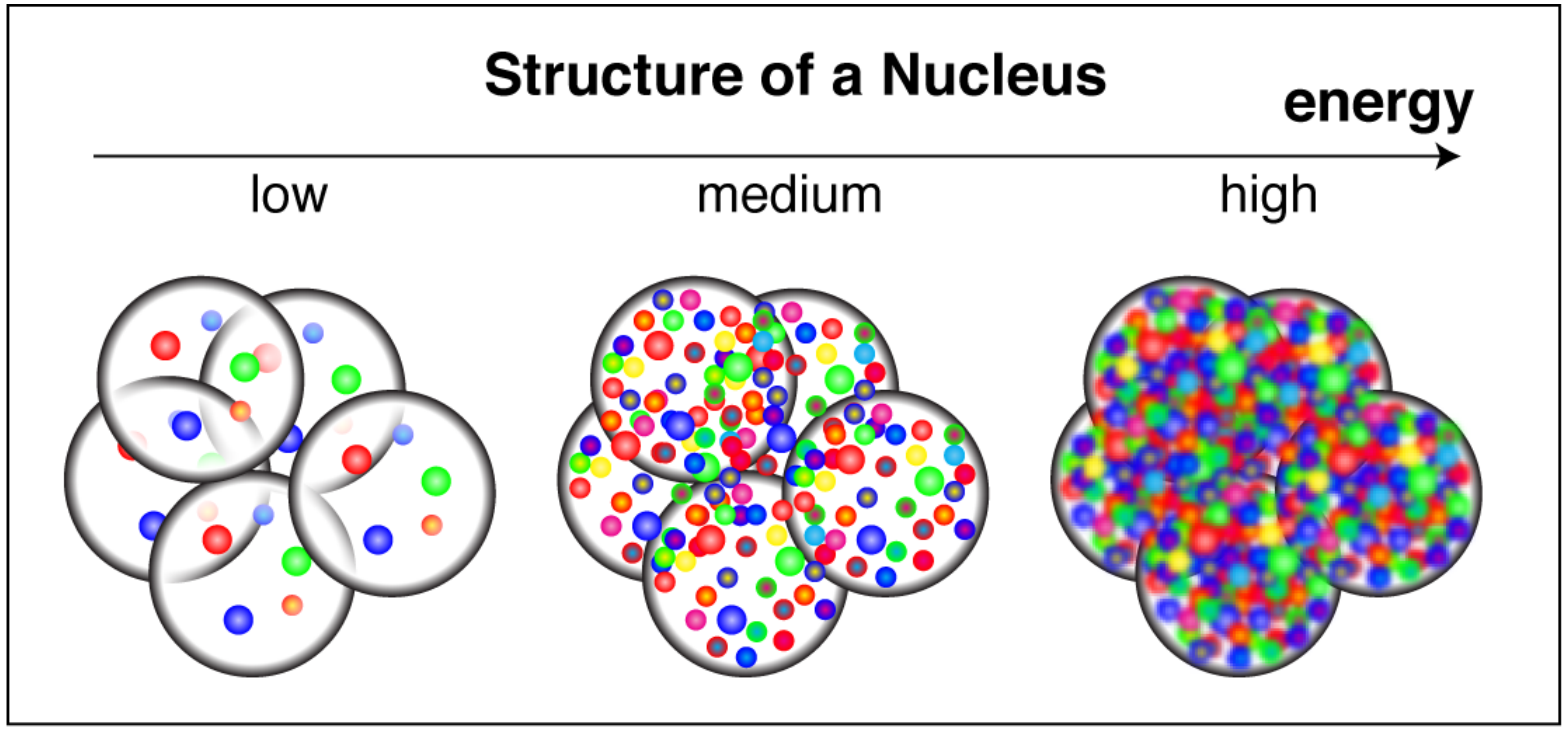
Q^2 evolution (gluons)



Gluon content of proton rises
quickly with Q^2

Something must 'tame' the gluons at low *x*
non-linear evolution, gluon fusion?

Saturation/Color Glass Condensate



Low x: large gluon density
Low Q^2: large effective size of gluons

} Strong fields, large occupation numbers

Large theoretical interest:

- Fundamentally new regime of QCD
- Theoretically calculable:
  Classical color fields; JIMWLK, etc

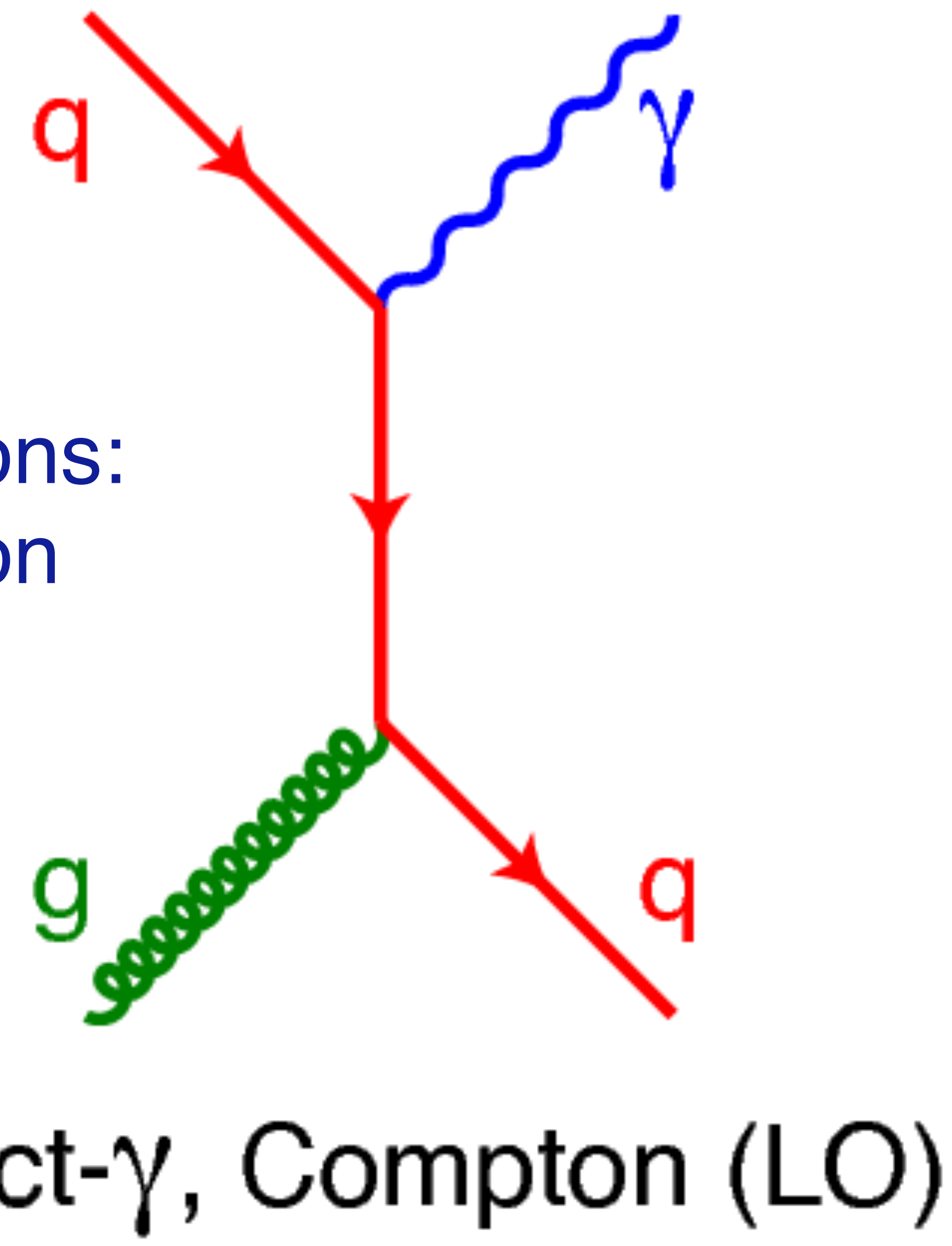
Experimental/phenomenological question:
Where/when is CGC dynamics relevant/dominant?

Non-linear evolution ⇔ Reduced gluon density ⇔ Suppression of yield
1 + many instead of 2 → 2 ⇔ Suppression of recoil jet (mono-jets?)
Multi-gluon emission and interference ⇔ Azimuthal anisotropy (flow-like effects)

Probing the gluon density in a hadron collider

Direct photon production

Incoming partons:
quark and gluon

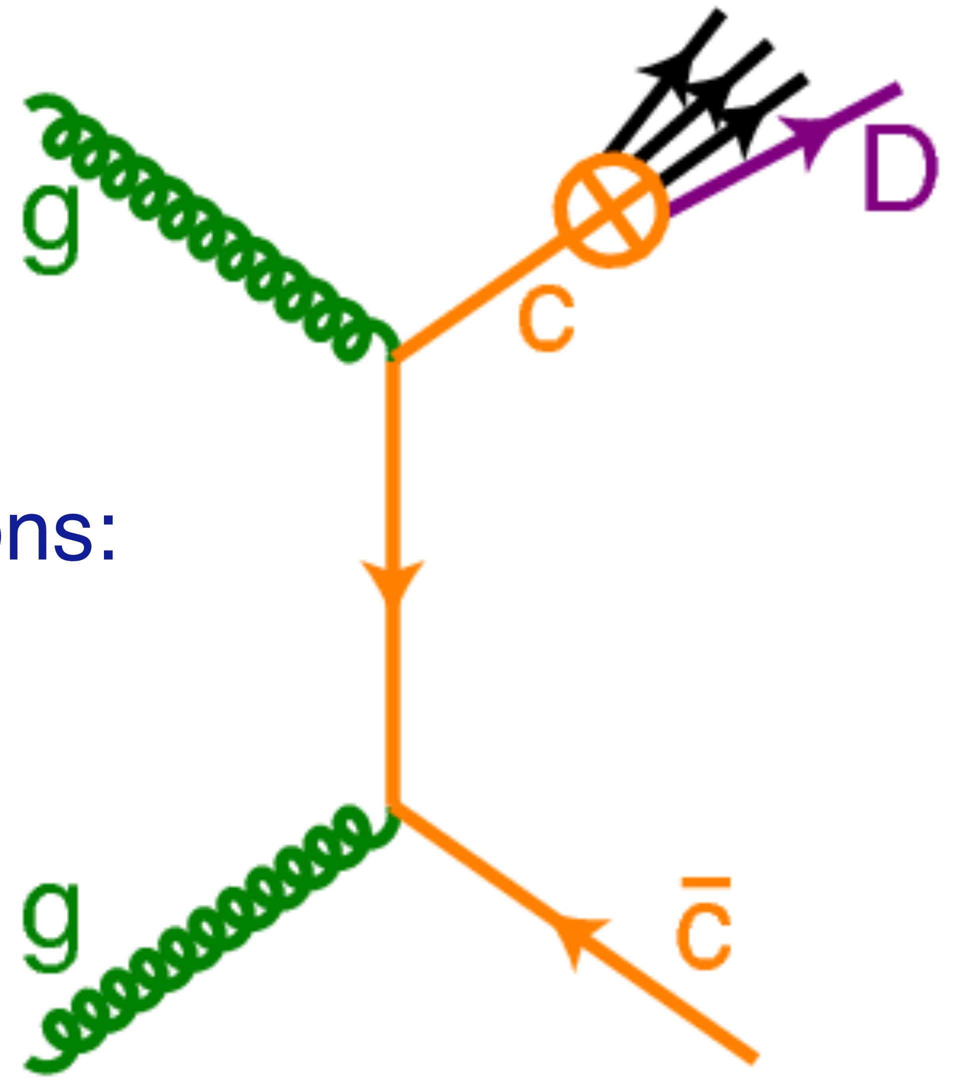


Sensitive to **gluons at LO**

Photon momentum directly related to incoming partons

Charm production

Incoming partons:
2 gluons



Heavy hadron:

also directly sensitive but fragmentation reduces kinematic constraint

More processes contribute, e.g. gluon splitting