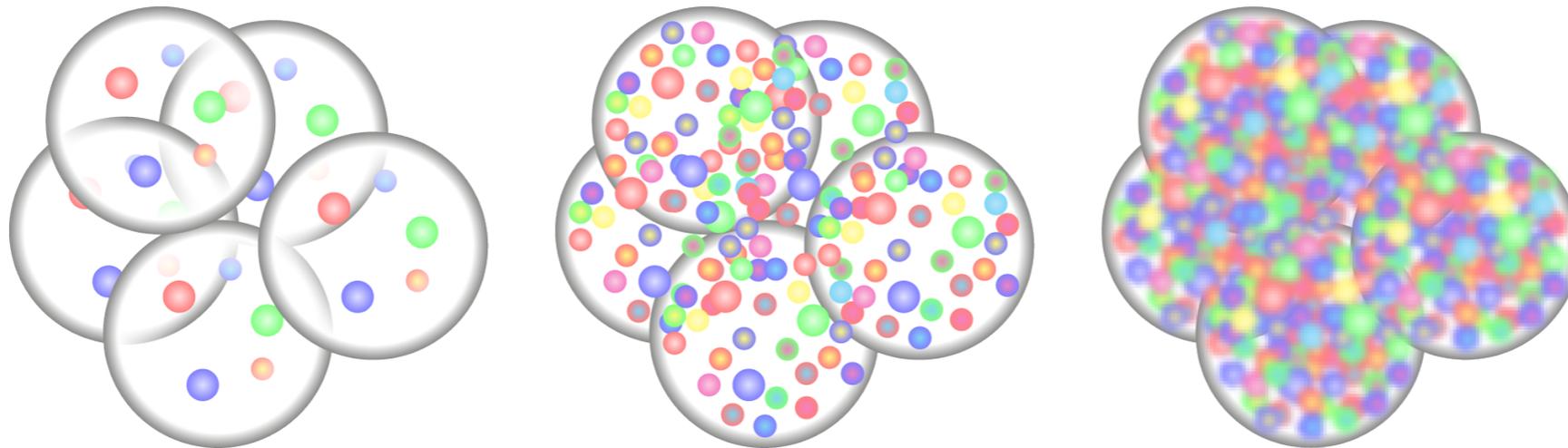


Topics in Forward Physics at the LHC

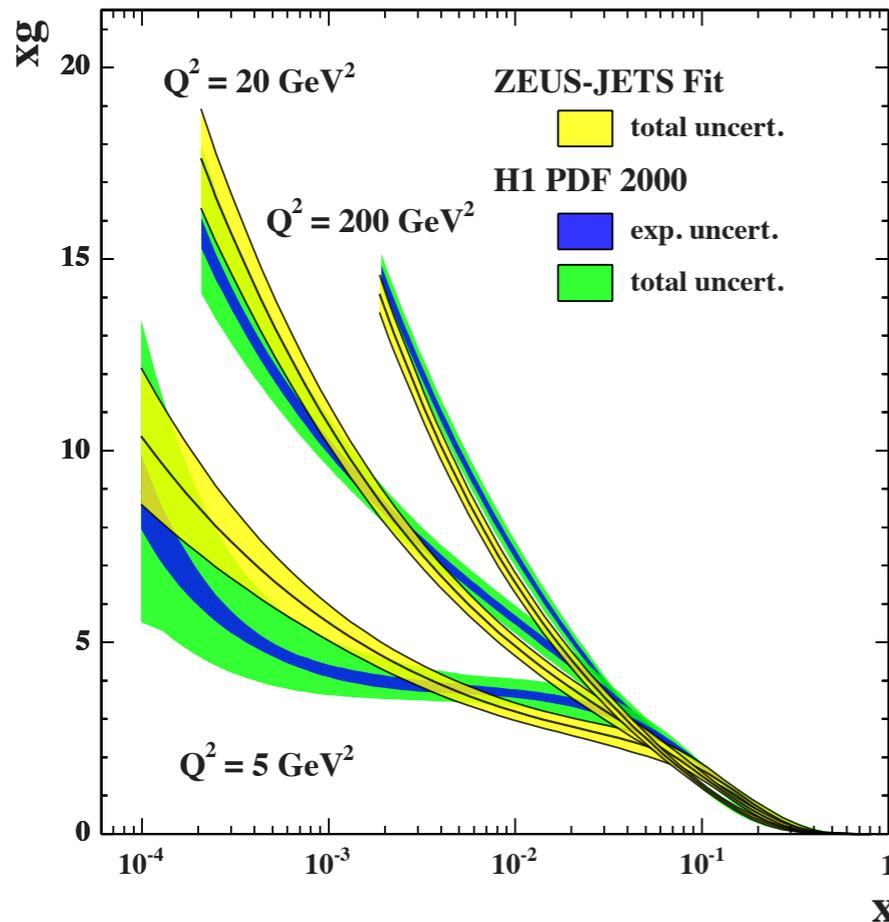


T. Peitzmann (Utrecht University/Nikhef)

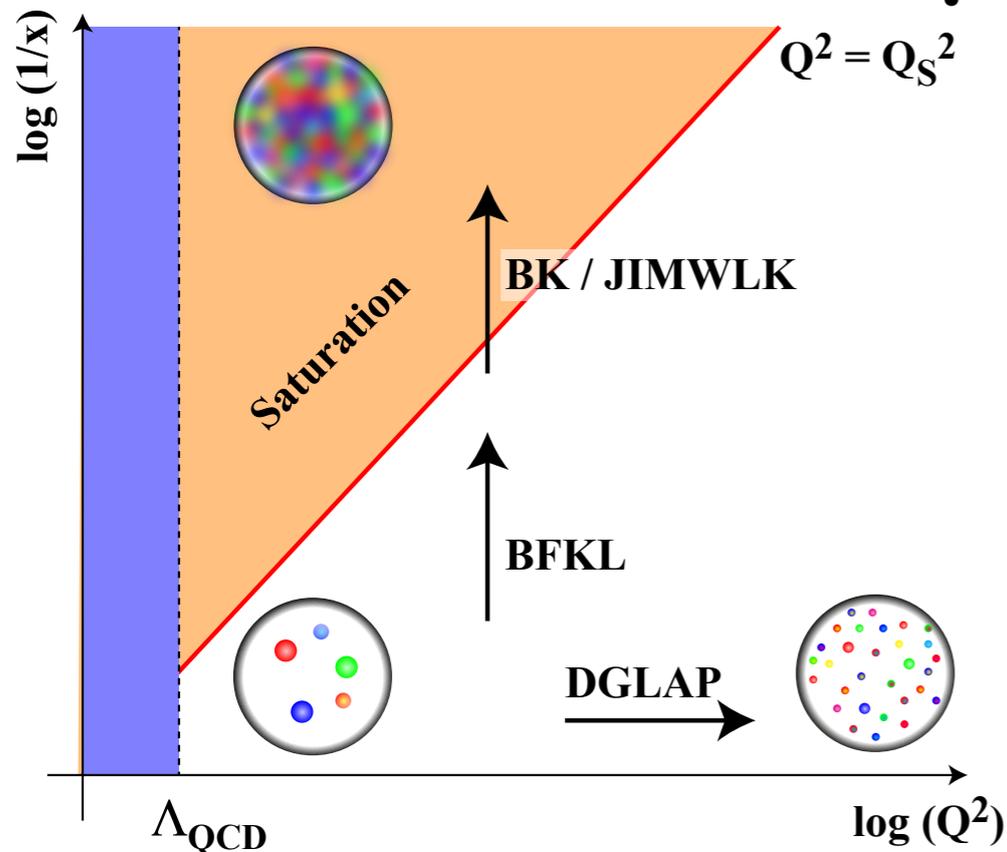
Outline

- Physics motivation: low- x PDFs and gluon saturation
- Observables at LHC
 - Forward charm production
 - Forward photons

H1+ZEUS PDFs and Gluon Saturation



- from evolution equations (DGLAP, BFKL):
 - gluon density increases with Q^2 and $1/x$
 - leads to very high gluon density
 - problems with unitarity
- for high density non-linear processes become important
- gluon saturation below saturation scale
 - enhanced in nuclei



$$Q_s^2(x) \approx \frac{\alpha_S}{\pi R^2} xG(x, Q^2) \propto A^{1/3} \cdot x^{-\lambda}$$

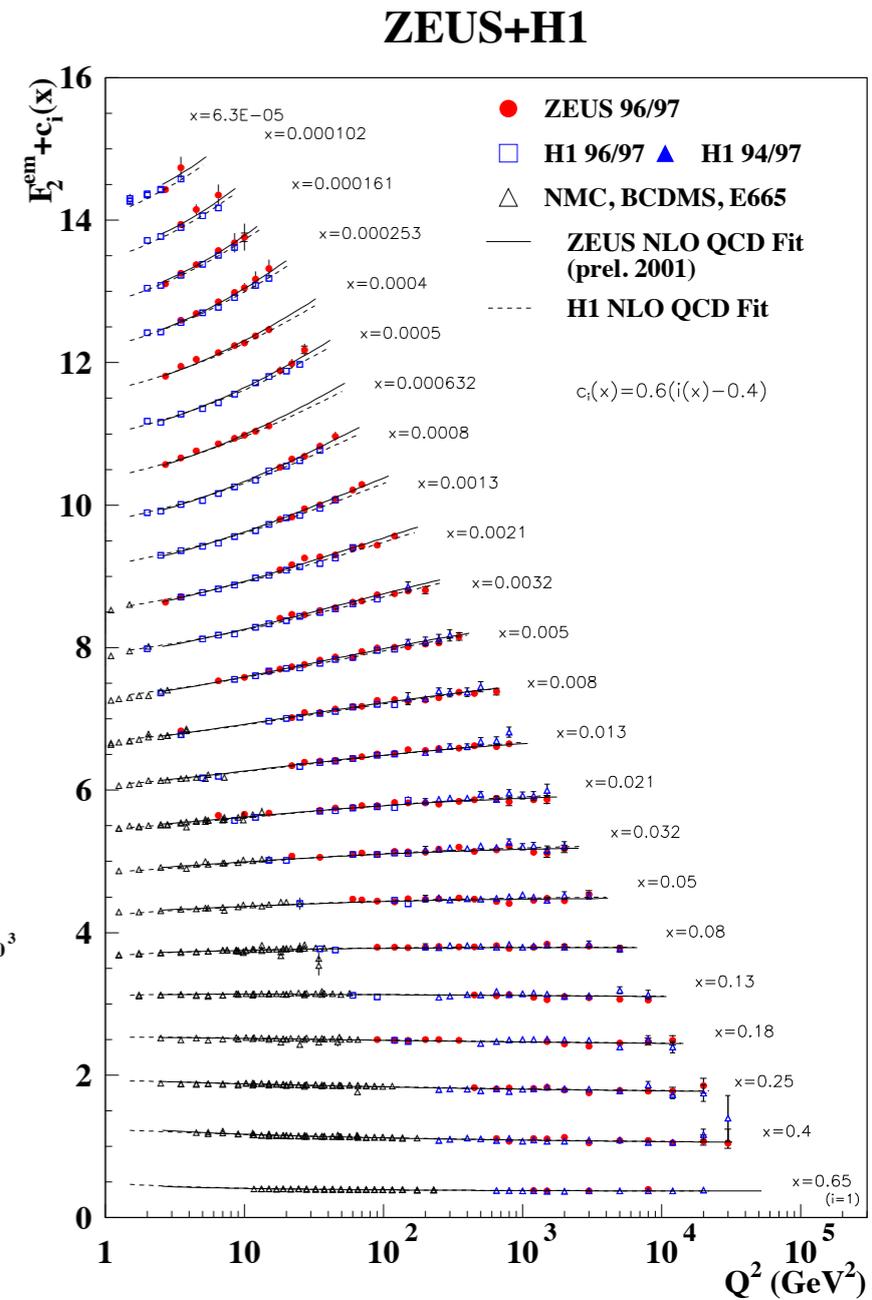
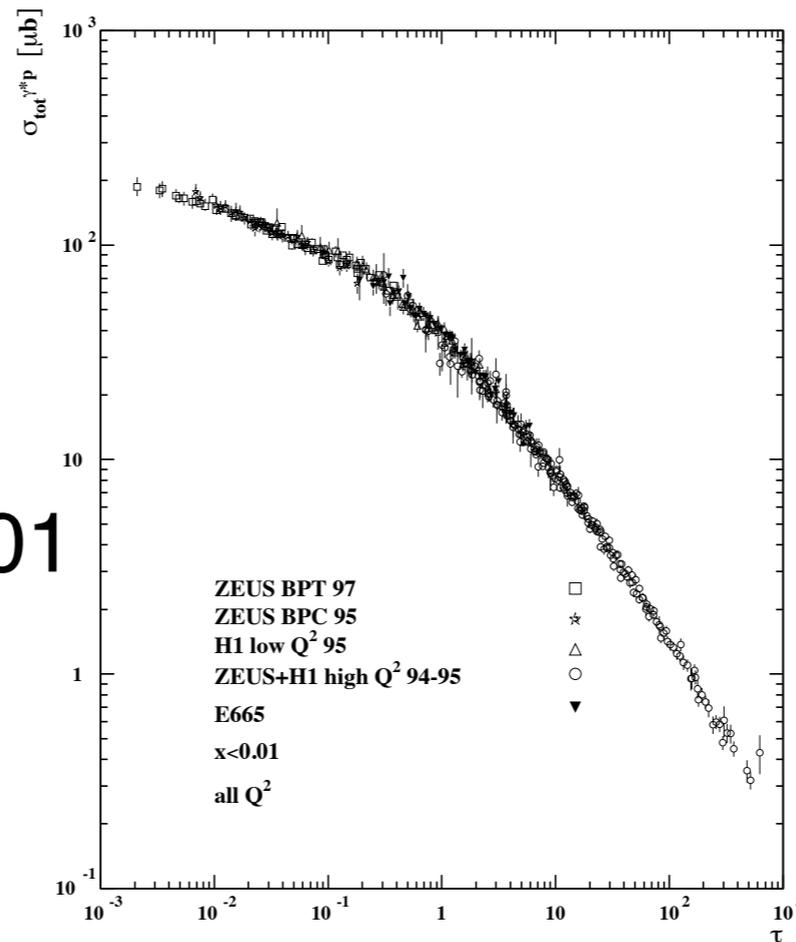
Geometric Scaling in DIS

- saturation models predict geometric scaling

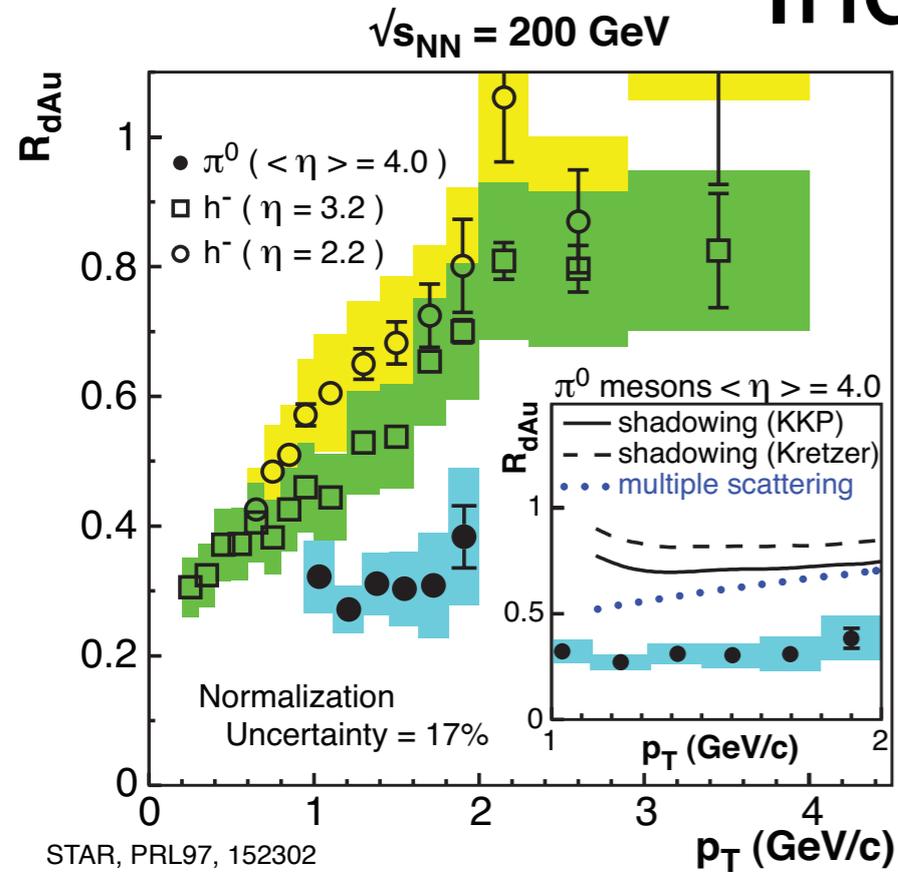
$$\sigma(x, Q^2) = \sigma(\tau), \quad \tau \equiv \frac{Q^2}{Q_S^2(x)}$$

- observed in DIS for $x < 0.01$
- same data well described by linear QCD

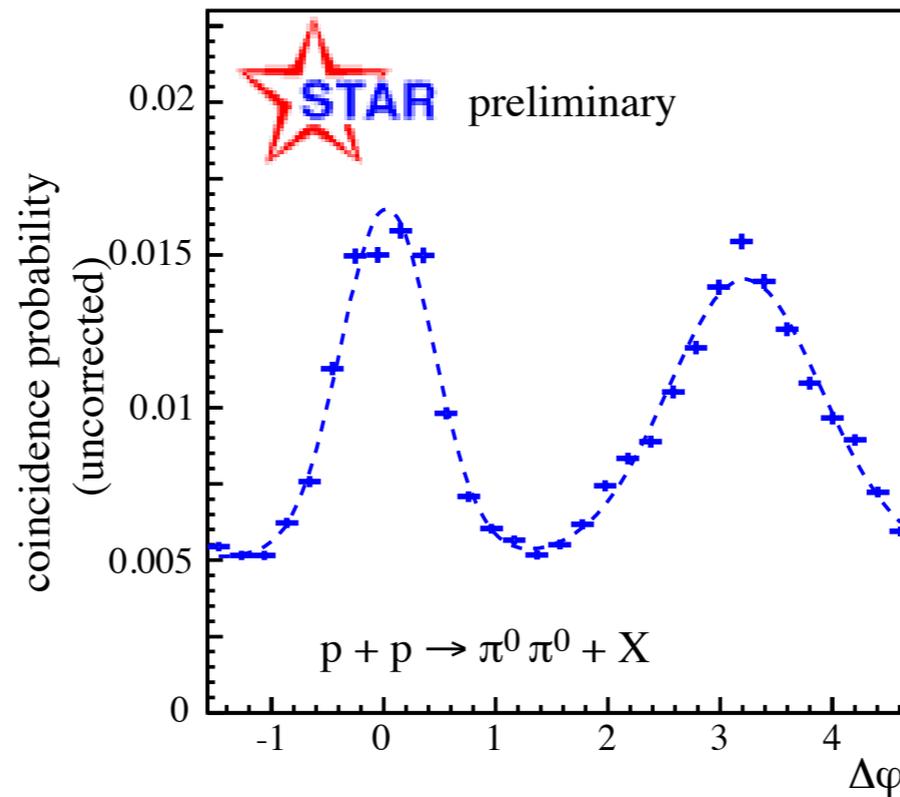
- proof of saturation needs to demonstrate deviation from linear evolution:
not yet shown



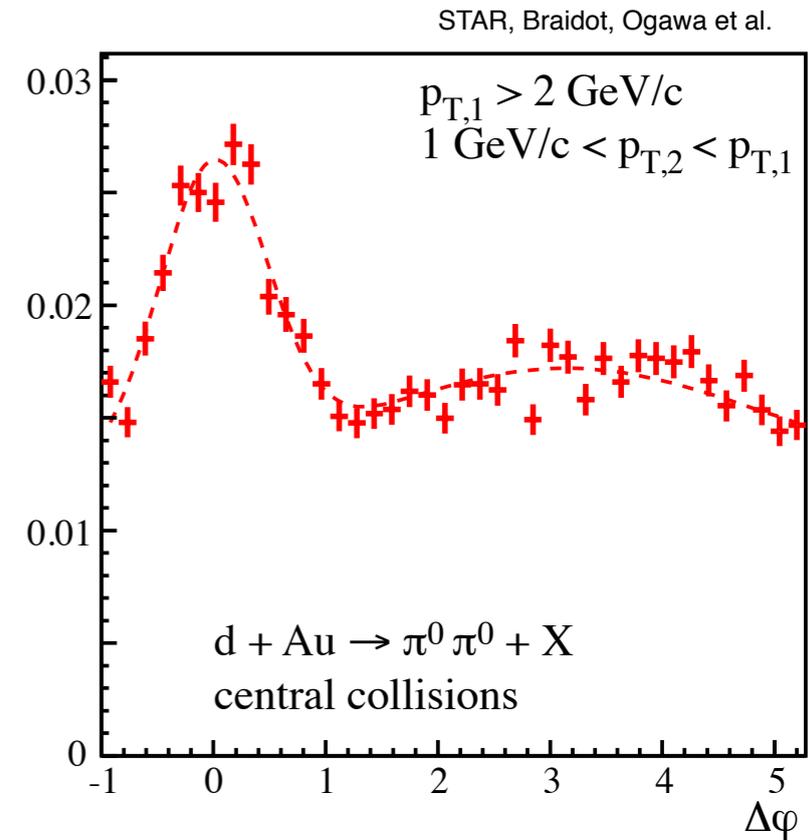
Indications from RHIC



R_{dA} : strong suppression of hadron yield at forward rapidity



di-hadron correlations: broadening/suppression of away-side peak in dAu

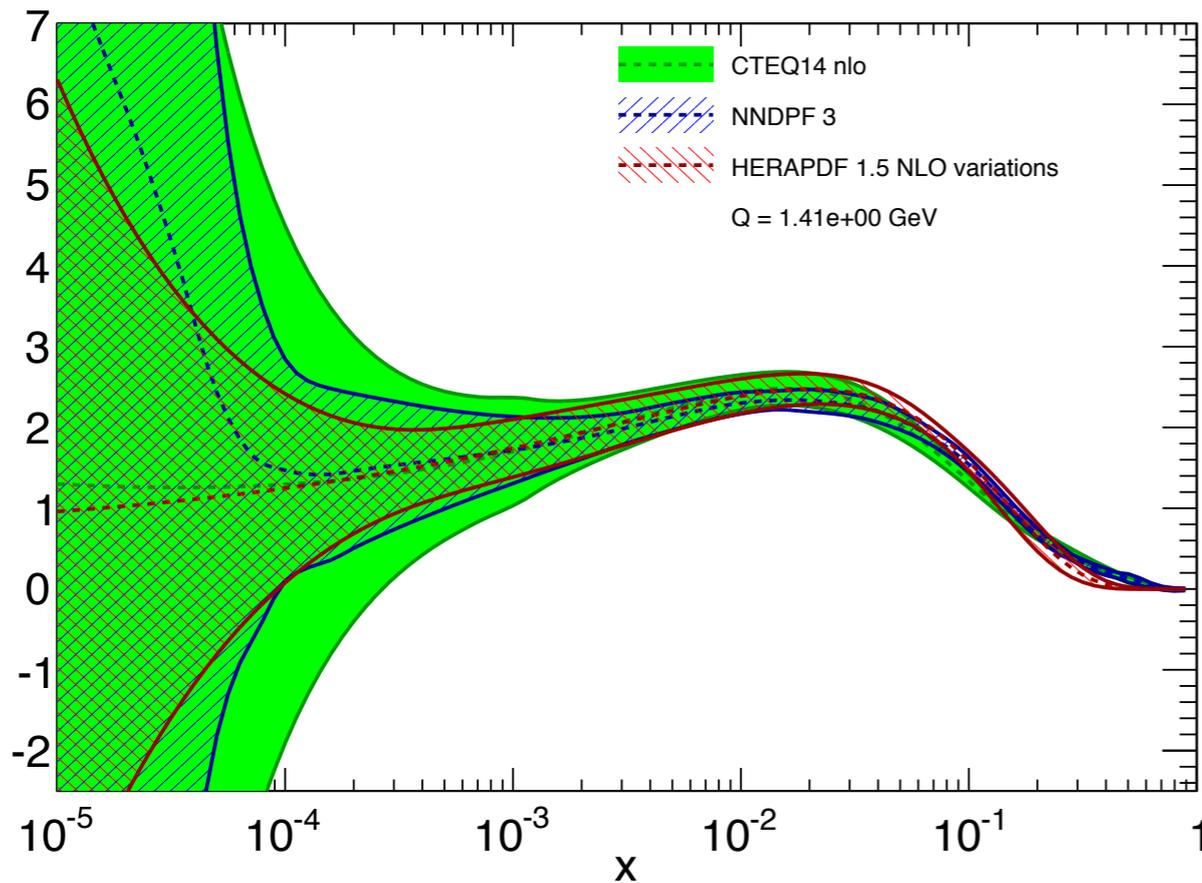


$$R_{dA} = \frac{dN/dp_T(dA)}{\langle N_{coll}(dA) \rangle dN/dp_T(pp)}$$

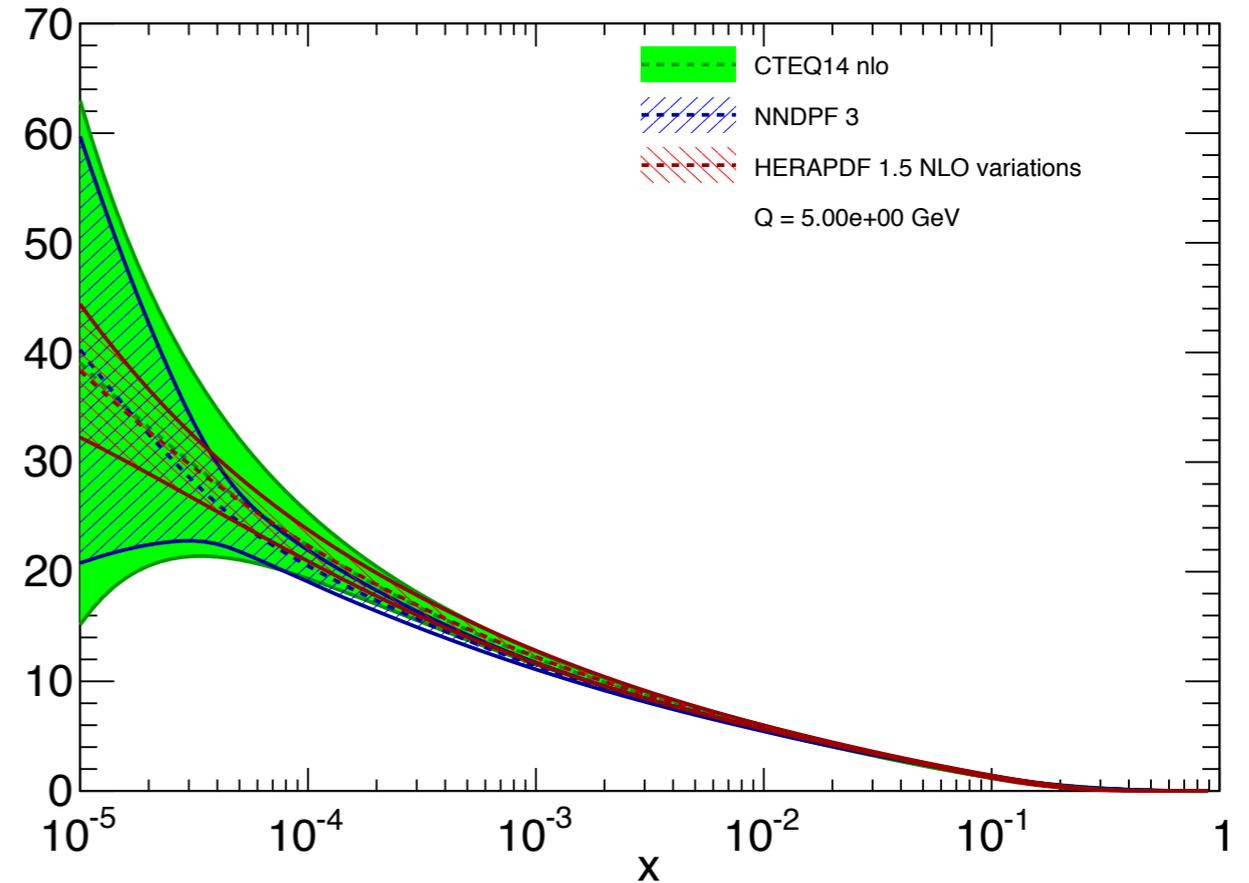
- qualitatively consistent with CGC, but ...
 - very low p_T , close to kinematic limit, hadron observable (final state interactions)!
- extend p_T and y range (not possible at RHIC)

Uncertainties in Proton PDFs

xg(x,Q), comparison



xg(x,Q), comparison

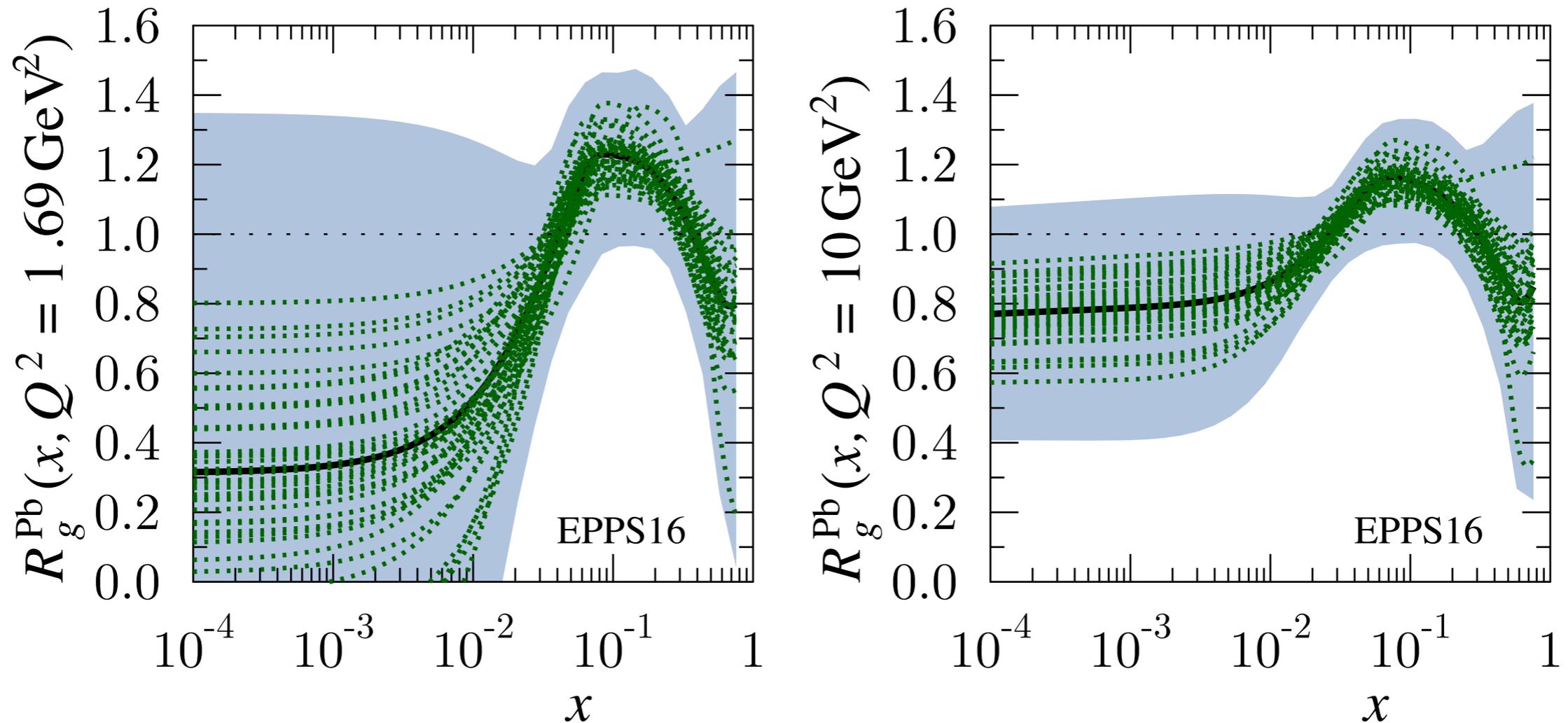


Generated with APFEL 2.4.0 Web

- large uncertainties of gluon PDFs for $x < 10^{-4}$
- relative uncertainty reduces for larger Q^2
 - contribution of “gluon radiation” off better constrained medium-x partons
 - relies on linear evolution (DGLAP)

Uncertainties in Nuclear PDFs

EPPS16, EPJC 77, 163

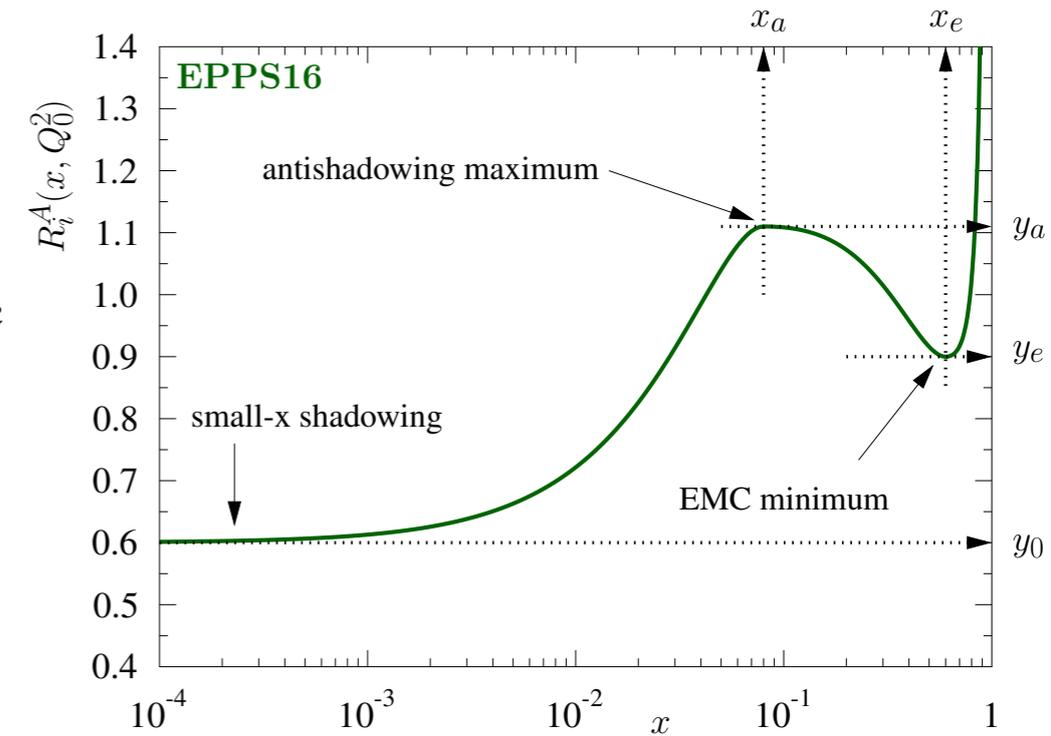


- large uncertainties of nPDFs
 - parameterised nuclear modification
 - recently updated to allow more freedom (e.g. flavour dependence)
- x-dependence?
 - very little dependence for $x < 10^{-2}$

x-Dependence of PDF modification

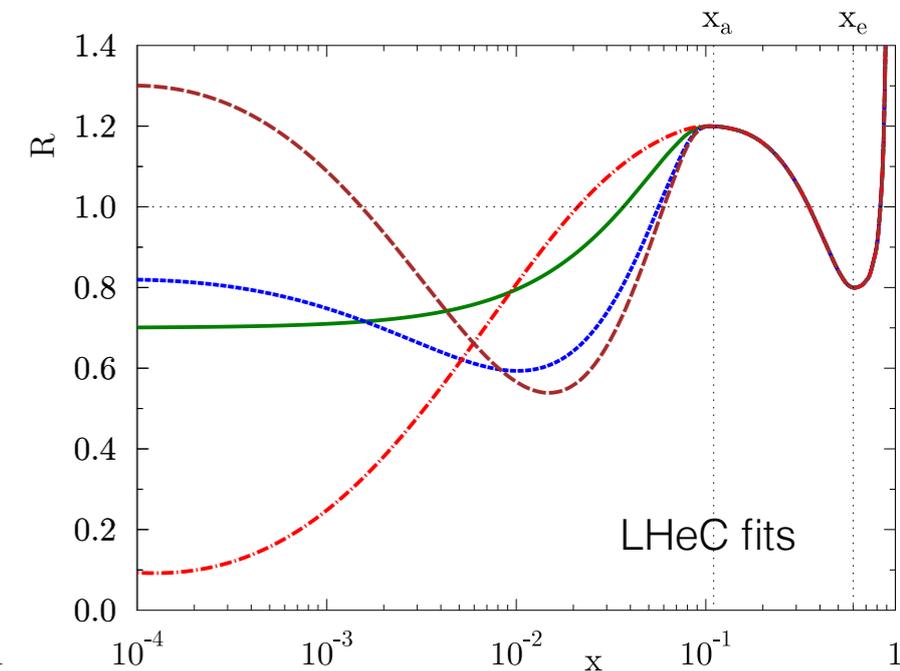
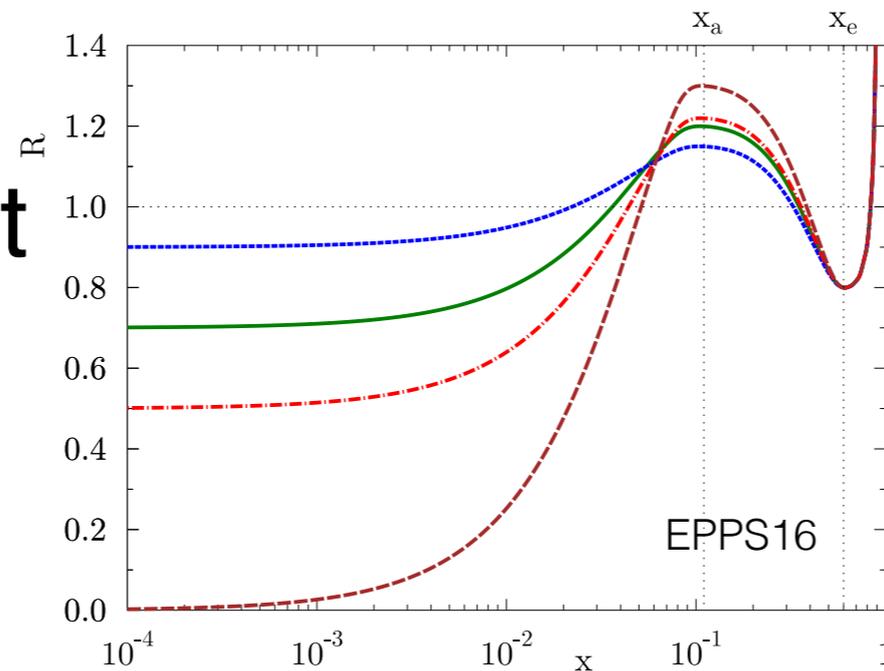
EPPS16, EPJC 77, 163

$$R_i^A(x, Q^2) = \begin{cases} a_0 + a_1(x - x_a)^2 & x \leq x_a \\ b_0 + b_1x^\alpha + b_2x^{2\alpha} + b_3x^{3\alpha} & x_a \leq x \leq x_e \\ c_0 + (c_1 - c_2x)(1 - x)^{-\beta} & x_e \leq x \leq 1 \end{cases}$$

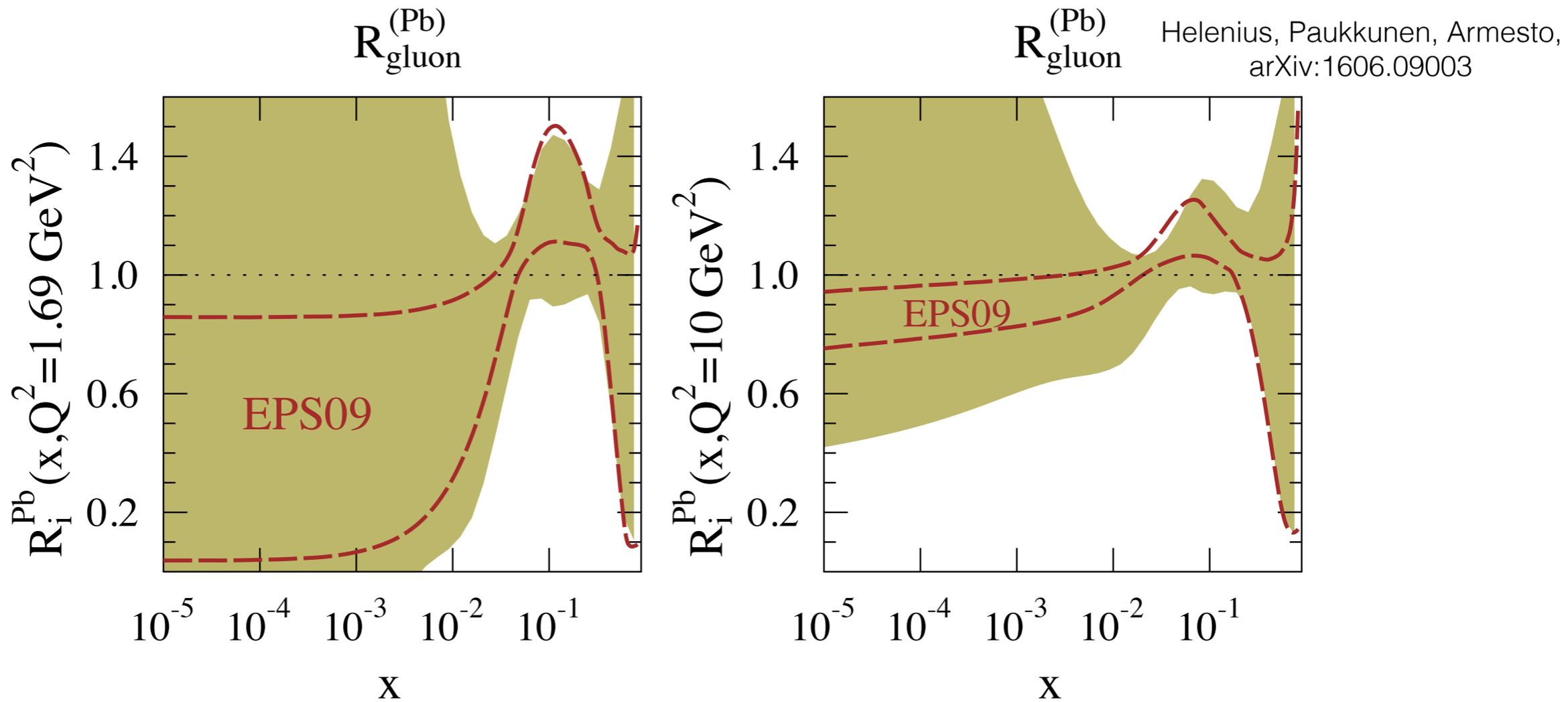


- parameterisation of R_A
 - shape similar to EPS09
 - at low x leads to “plateau” in $\log(x)$

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

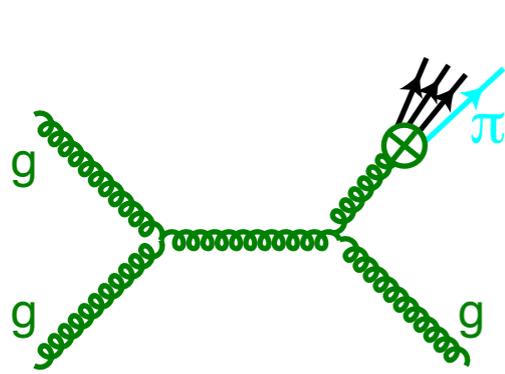


Uncertainties in Nuclear PDFs

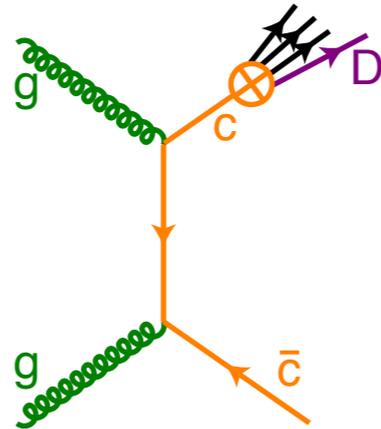


- still larger uncertainties (also compared to EPPS16)
 - due to larger shape flexibility of parameterisation
- likely a more reasonable assumption
 - last words?

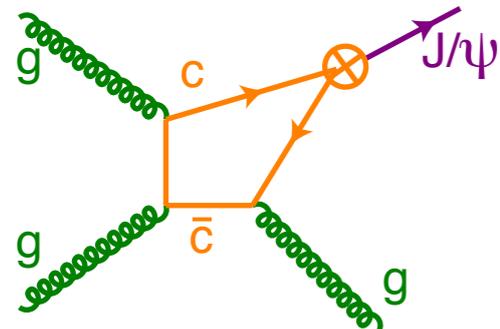
Hadronic Processes



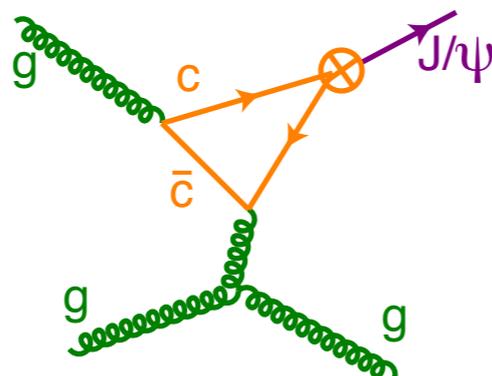
light hadron



heavy hadron



J/ψ

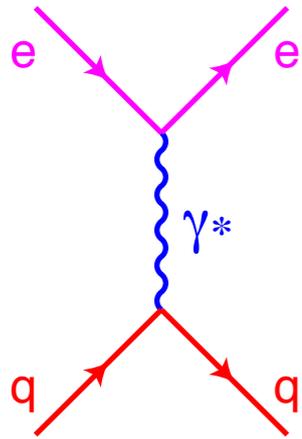


J/ψ (COM)

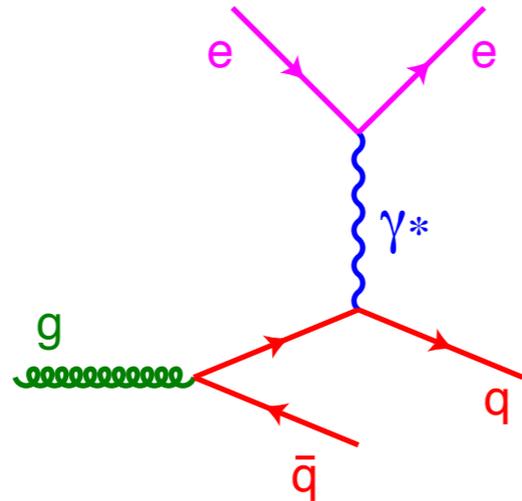
- hadron production needs fragmentation
 - other hadronisation mechanisms (coalescence)?
 - strong disadvantage for light hadrons
- heavy flavour
 - J/ψ not fully understood
 - open charm?

- possible other final-state modifications:
energy loss, collective flow

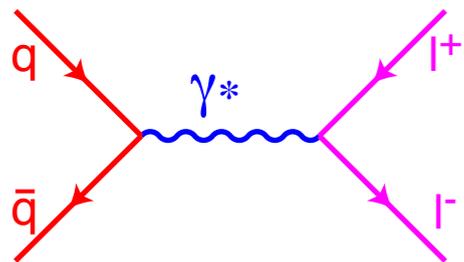
Electromagnetic Processes



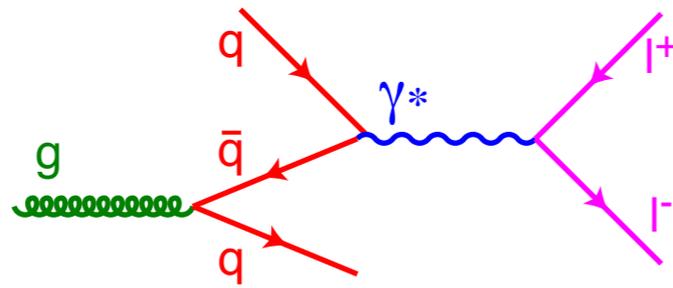
DIS (LO)



DIS (NLO)

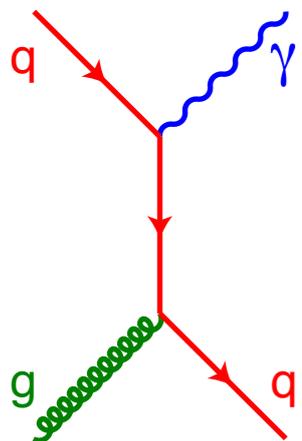


DY (LO)



DY, virtual Compton (NLO)

- DIS and Drell-Yan are equivalent processes
 - crossing symmetry
 - sensitivity to gluons only at NLO
 - e.g. virtual qg-Compton
- main disadvantage of DY: very low cross section
 - not accessible in pA



direct- γ , Compton (LO)

- real photons: sensitivity to gluons at LO, clear kinematic relation
 - higher order corrections?

Accessing small x – Kinematics

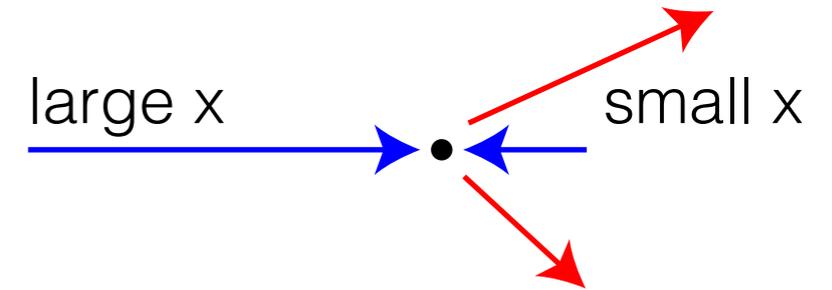
- for $2 \rightarrow 2$ process (LO on parton level):

$$x_{1,2} = \frac{M}{\sqrt{s}} \exp\left(\pm \frac{y_3 + y_4}{2}\right)$$

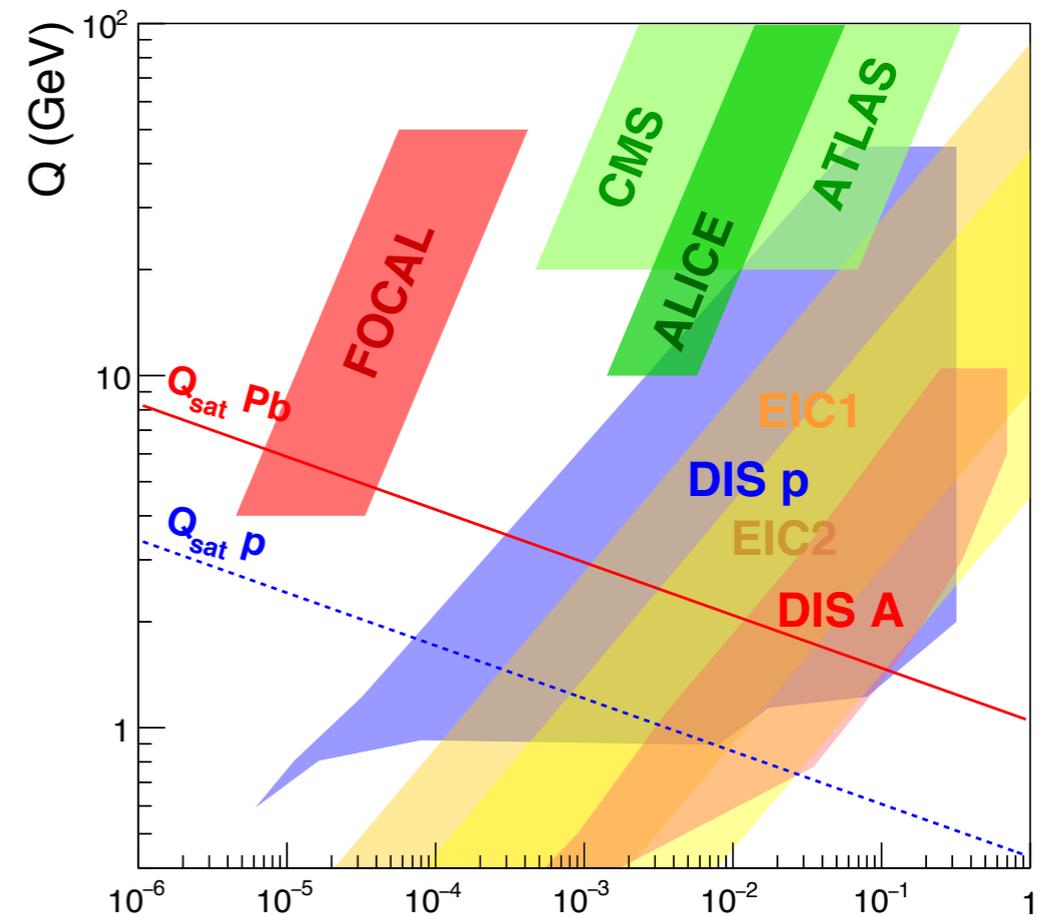
- forward rapidity selects small x
 - advantage for exclusive measurement
- for singles assume:

$$x_{1,2} \approx \frac{2m_T}{\sqrt{s}} \exp(\pm y)$$

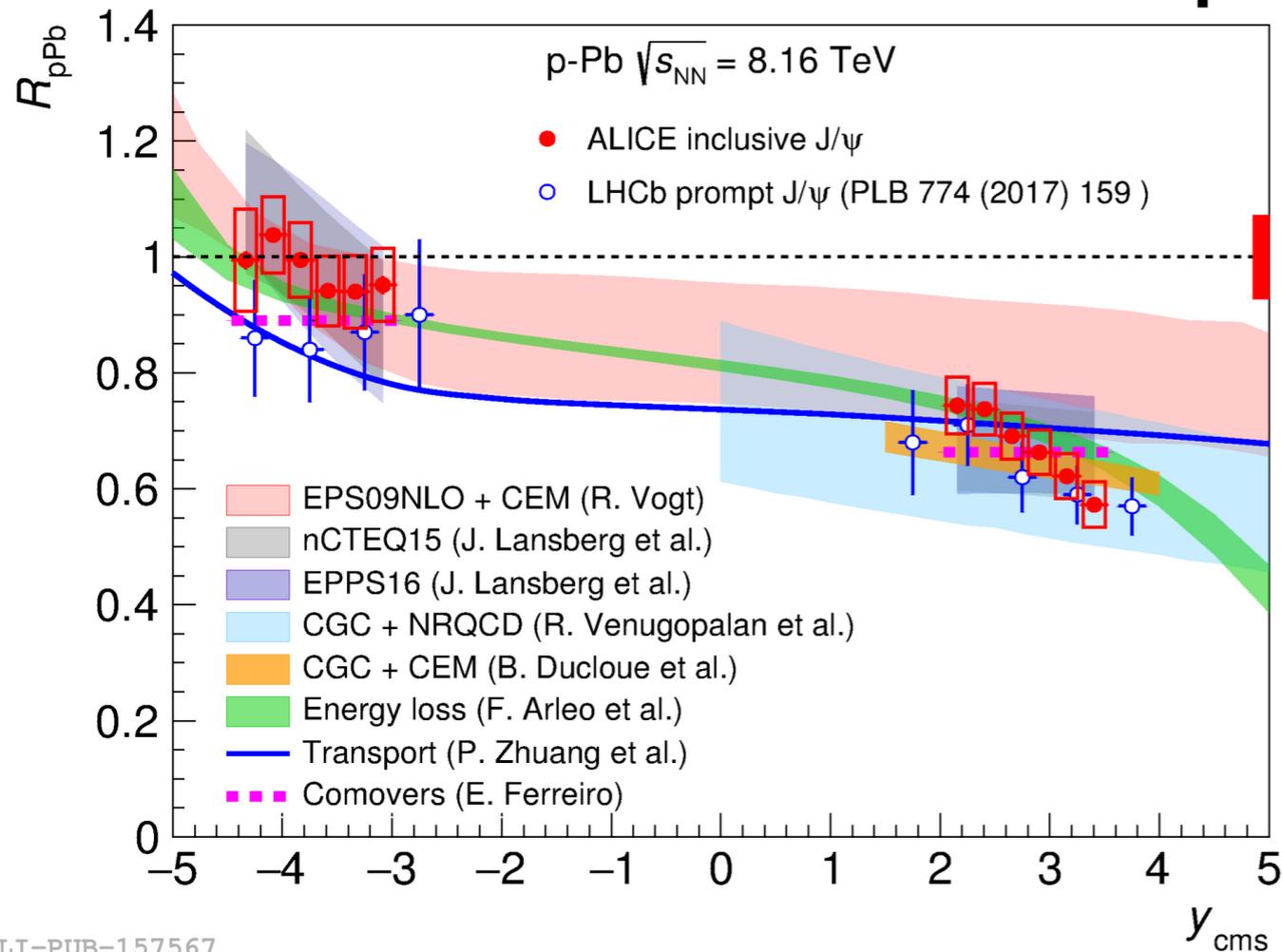
- valid for jets (large m_T) and photons
 - for hadrons take fragmentation into account!
- further modification via higher order contributions
 - significant at LHC
- limited data so far!



EM probes - kinematic coverage

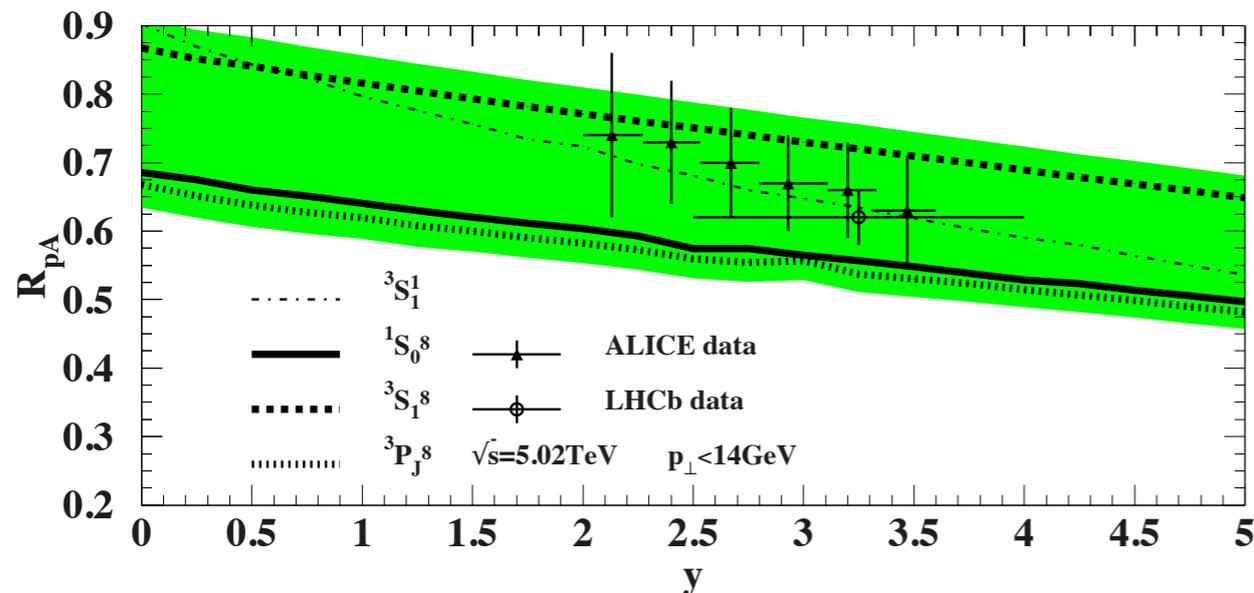


Results from p-Pb at LHC (1)

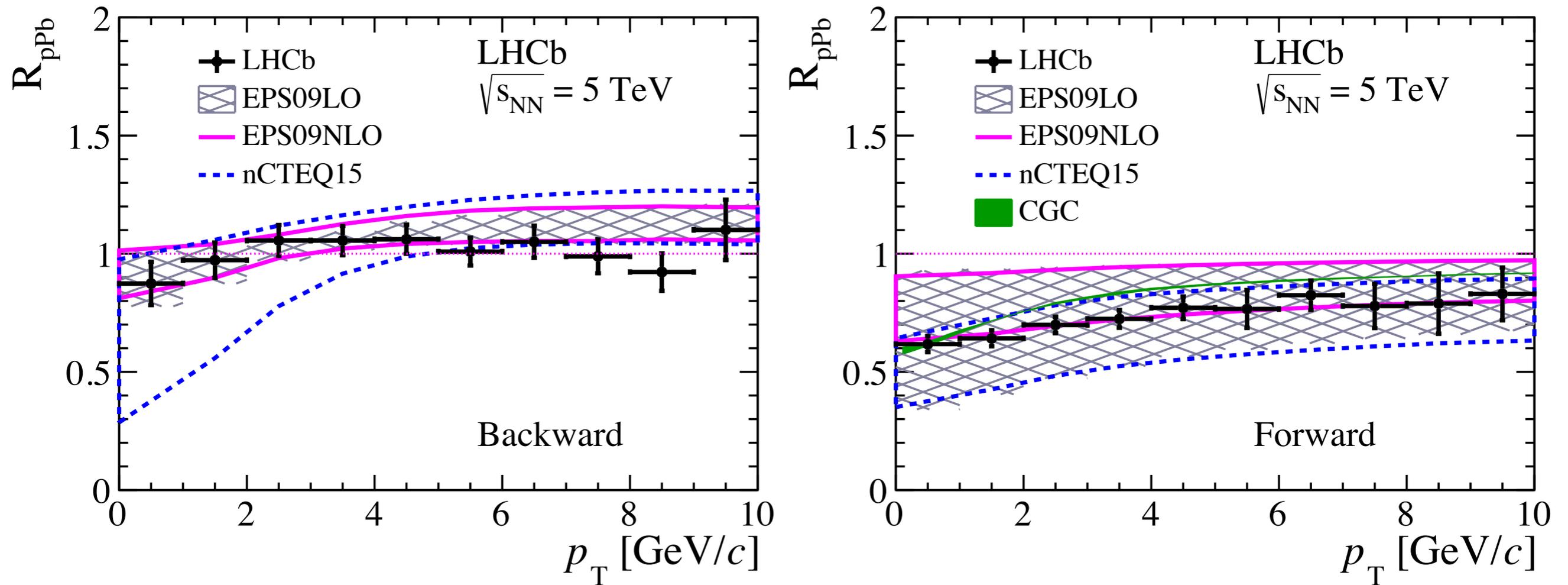


- nuclear modification factor R_{pPb} for charmonium
- J/ ψ suppressed at forward rapidity
 - can be described by very different theoretical calculations
- additional uncertainties from hadronisation?
 - e.g. uncertainties in CGC model due to population of different quantum states
- not conclusive

Ma, Venugopalan, Zhang, arXiv:1503.07772



Results from p-Pb at LHC (2)



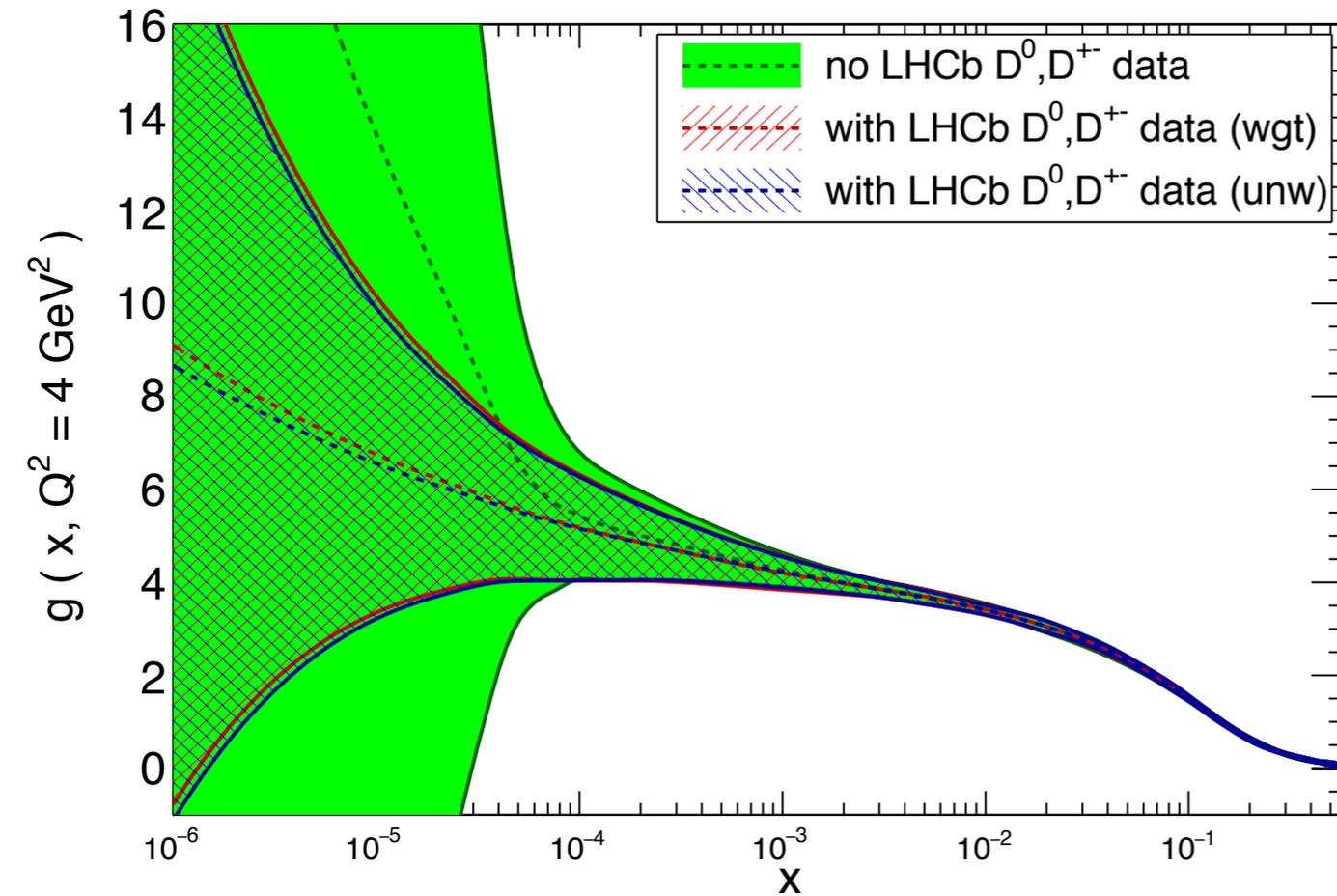
- prompt D^0 suppressed at forward rapidity
 - consistent with pQCD + shadowing (EPS09)
 - also consistent with CGC calculation

PDF constraints at low x

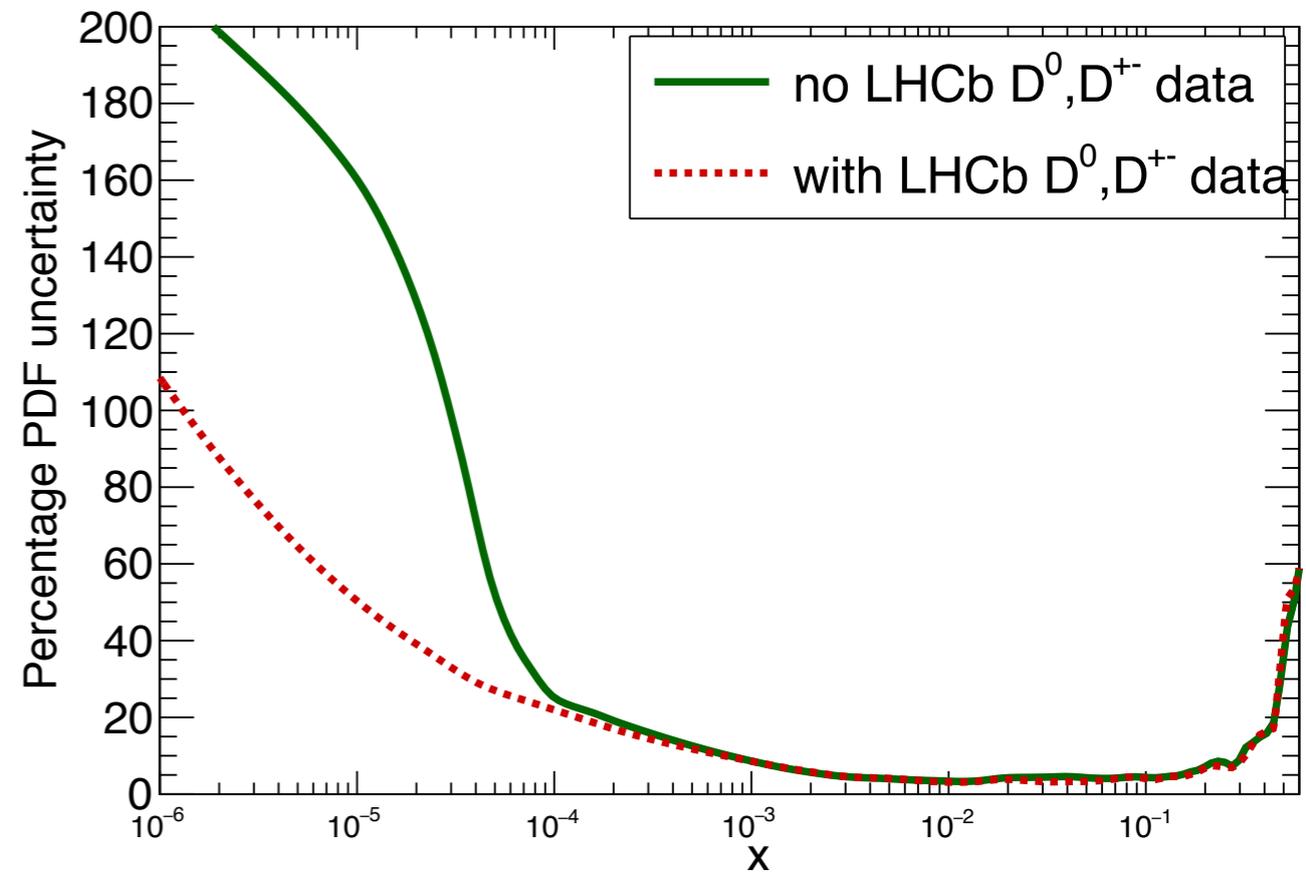
First results of constraining proton PDFs
with forward heavy flavour from LHCb

Gauld, Rojo et al, arXiv:1506.08025

NNPDF3.0 NLO $\alpha_s=0.118$



$\Delta(g(x, Q^2))$ for $Q^2=4 \text{ GeV}^2$, NNPDF3.0 NLO

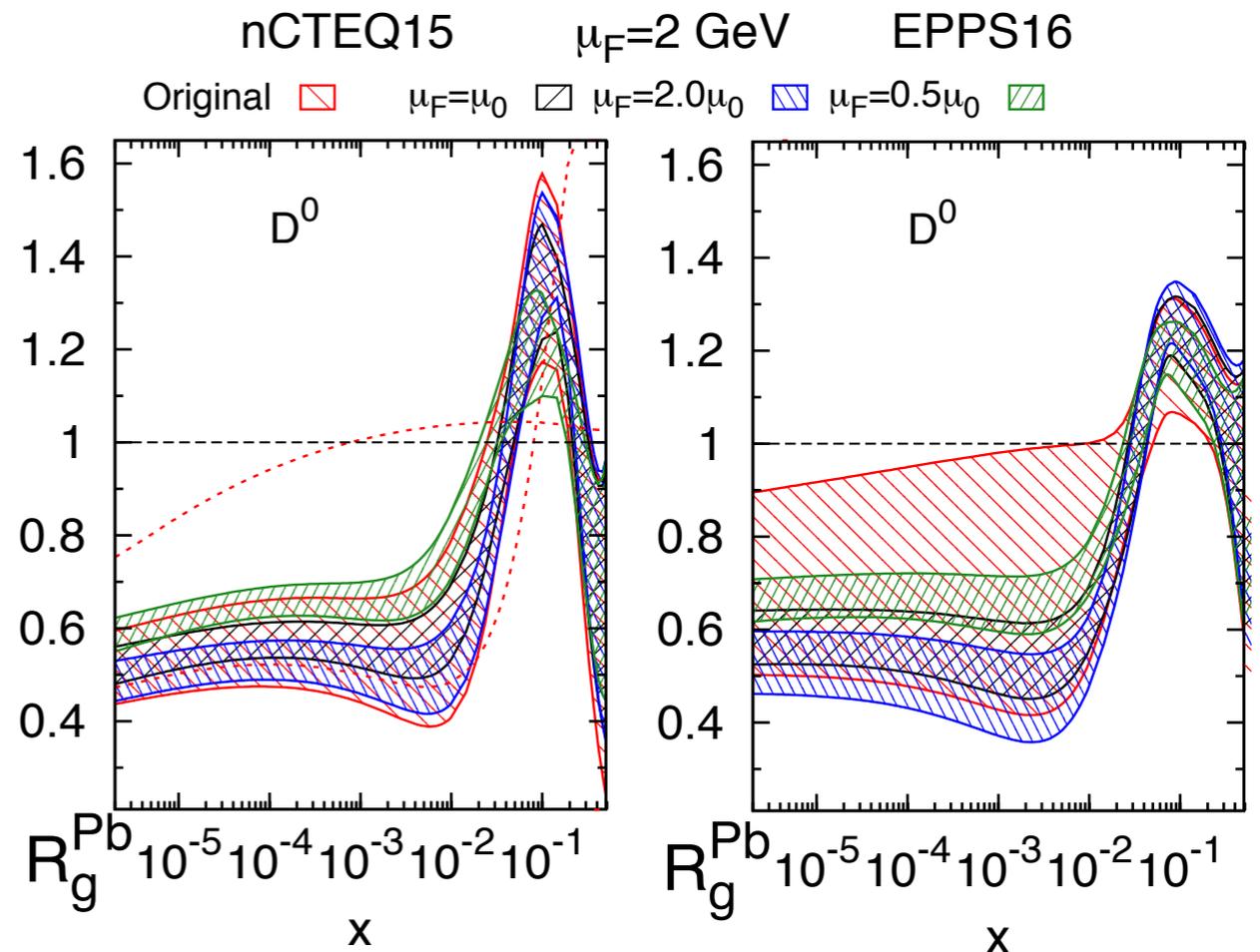
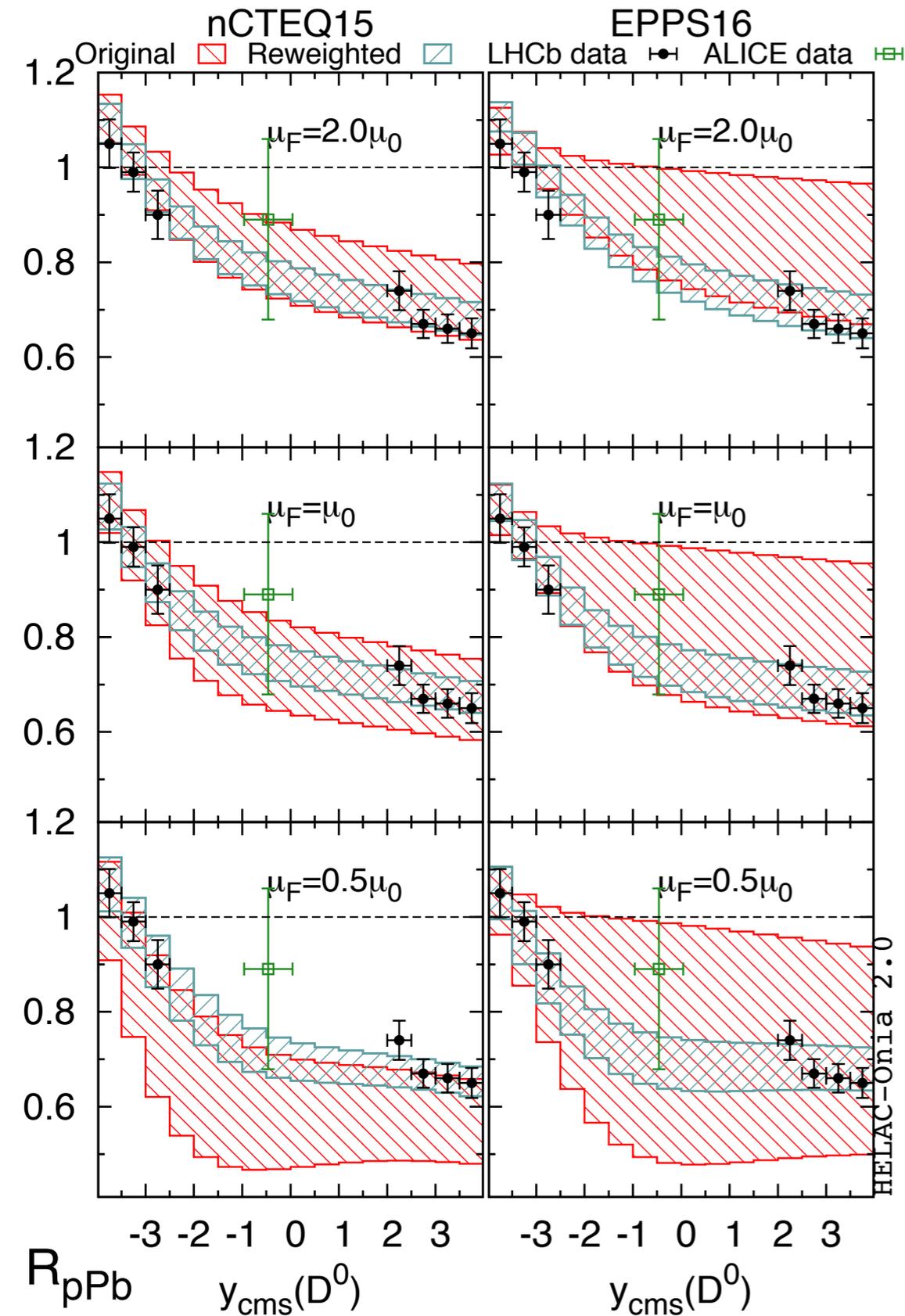


LHCb data adds constrains at $x \sim 10^{-4}$

See also: PROSA collab, Zenaiev et al

Recent: PDF Fits Using Charm

- open charm used in re-weighting
- significant reduction of uncertainties
- significant suppression – on the low side of current PDFs
- significant pQCD uncertainties (scale, fragmentation)
- **relies on shape of parameterisation:
very little x -dependence at low x !**



True x-Sensitivity?

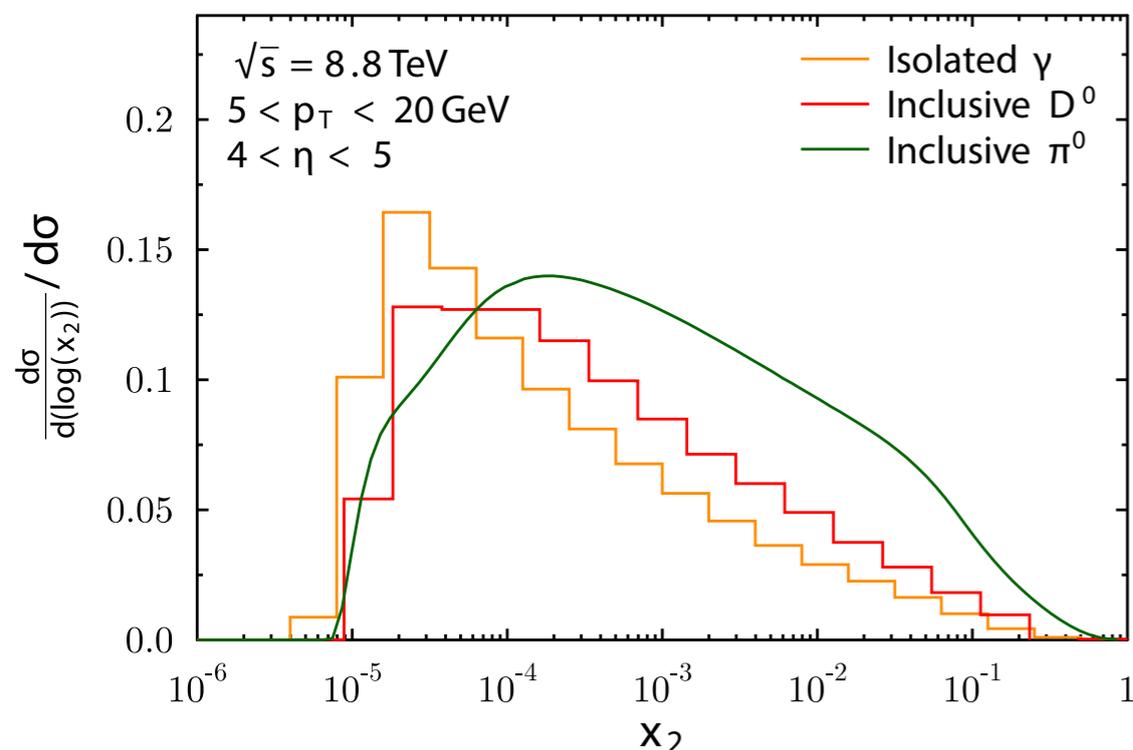
	\sqrt{s} (TeV)	y	p_T (GeV/c)	z	x_2
π	0.2	4	2	0.3	$1.2 \cdot 10^{-3}$
π	8.8	0	2	0.3	$1.5 \cdot 10^{-3}$
jet	8.8	4	20	1	$8.3 \cdot 10^{-5}$
π	8.8	4	2	0.3	$2.8 \cdot 10^{-5}$
D	8.8	4	0	0.5	$1.5 \cdot 10^{-5}$
γ	8.8	4	4	1	$1.7 \cdot 10^{-5}$
γ	8.8	4.5	4	1	$1.0 \cdot 10^{-5}$

$$x_{1,2} \approx \frac{2m_T}{\sqrt{s}} \exp(\pm y)$$

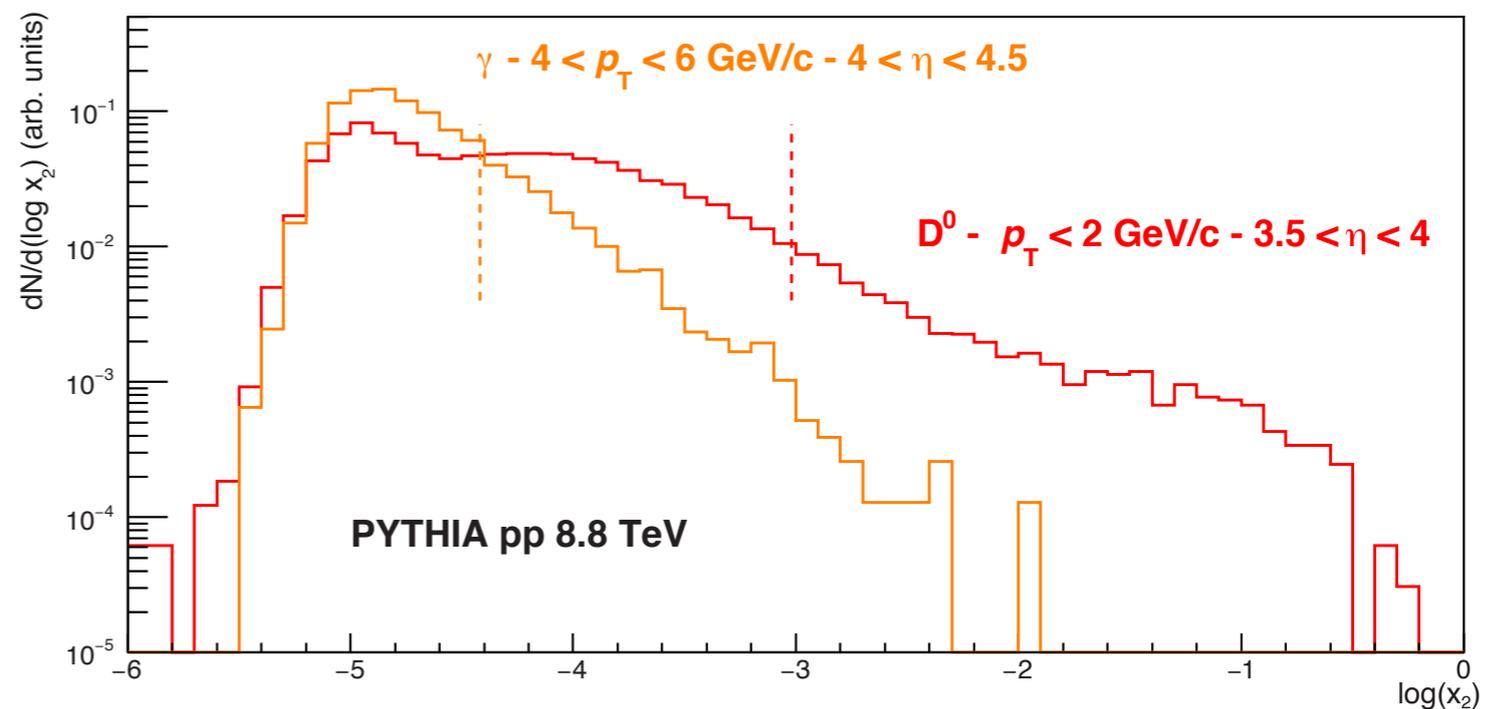
- LO kinematics estimates provide rather lower limit for x_2
- but: higher orders contribute significant tail towards large x_2

- compare D^0 (LHCb) and prompt γ (FoCal)
- expect better sensitivity for photons

- x-distributions from NLO pQCD



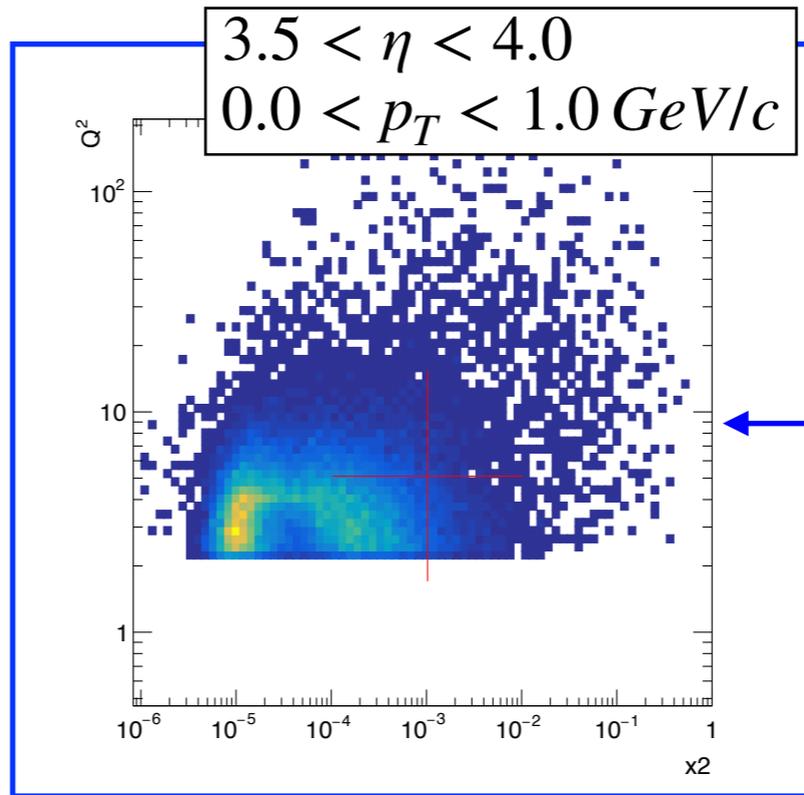
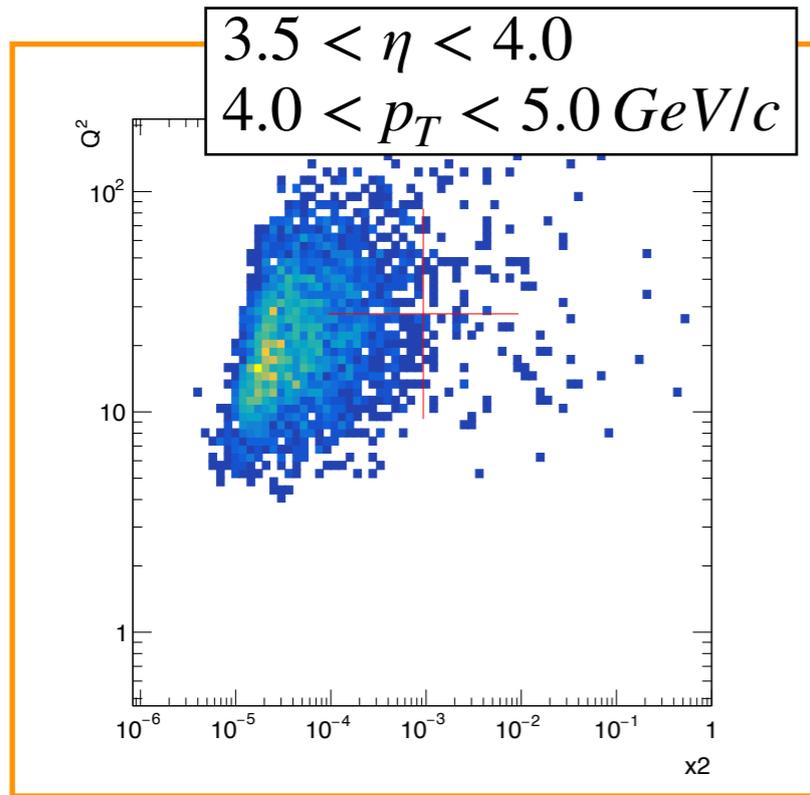
- x-distributions from PYTHIA



no analytical approximation, taking into account η of recoil parton

x - Q^2 -Sensitivity

D^0

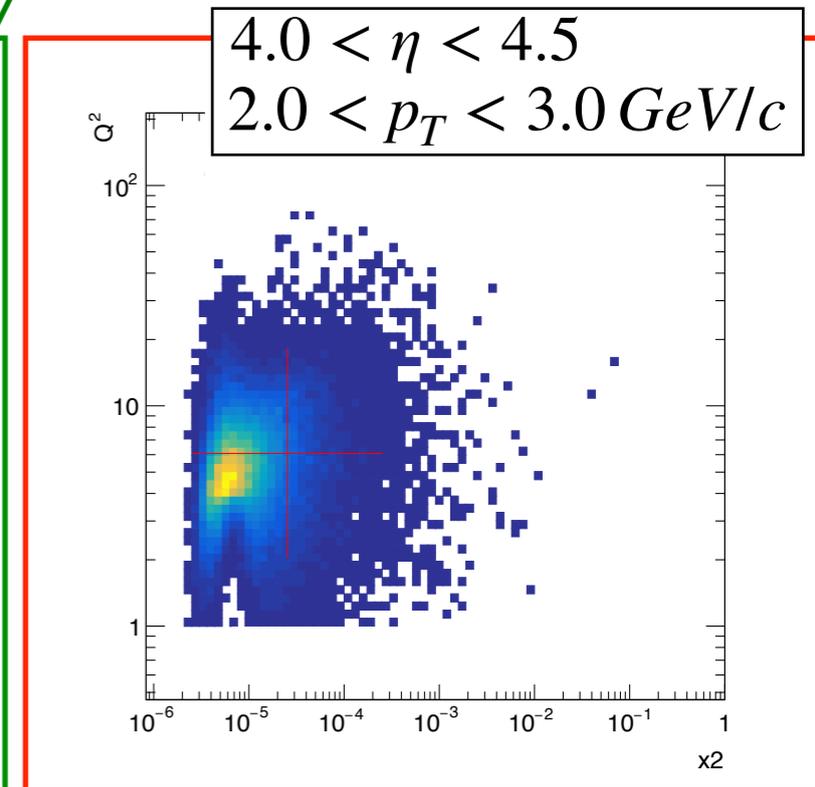
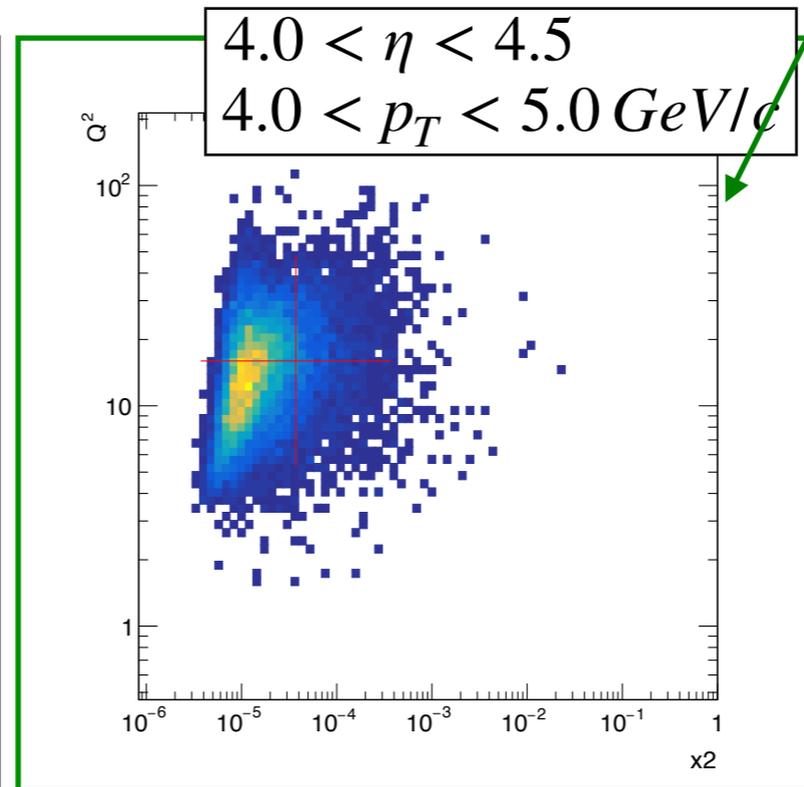
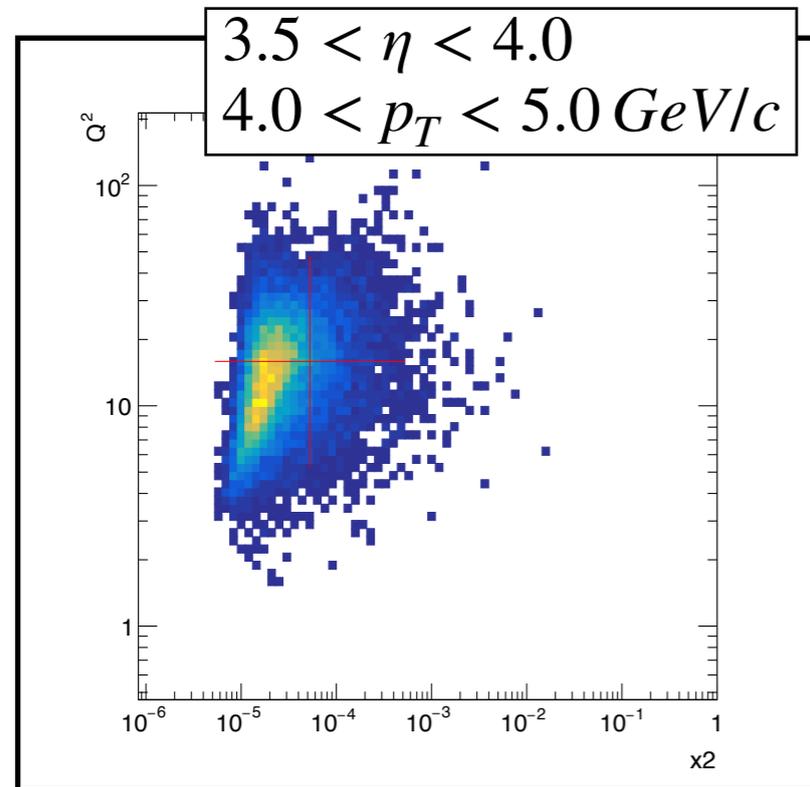


PYTHIA pp 8.8TeV
forward
measurements

$\langle x_2 \rangle = 1.0 \cdot 10^{-3}$
 $\langle Q^2 \rangle = 5.1 \text{ GeV}^2$

$\langle x_2 \rangle = 3.7 \cdot 10^{-5}$
 $\langle Q^2 \rangle = 16 \text{ GeV}^2$

γ

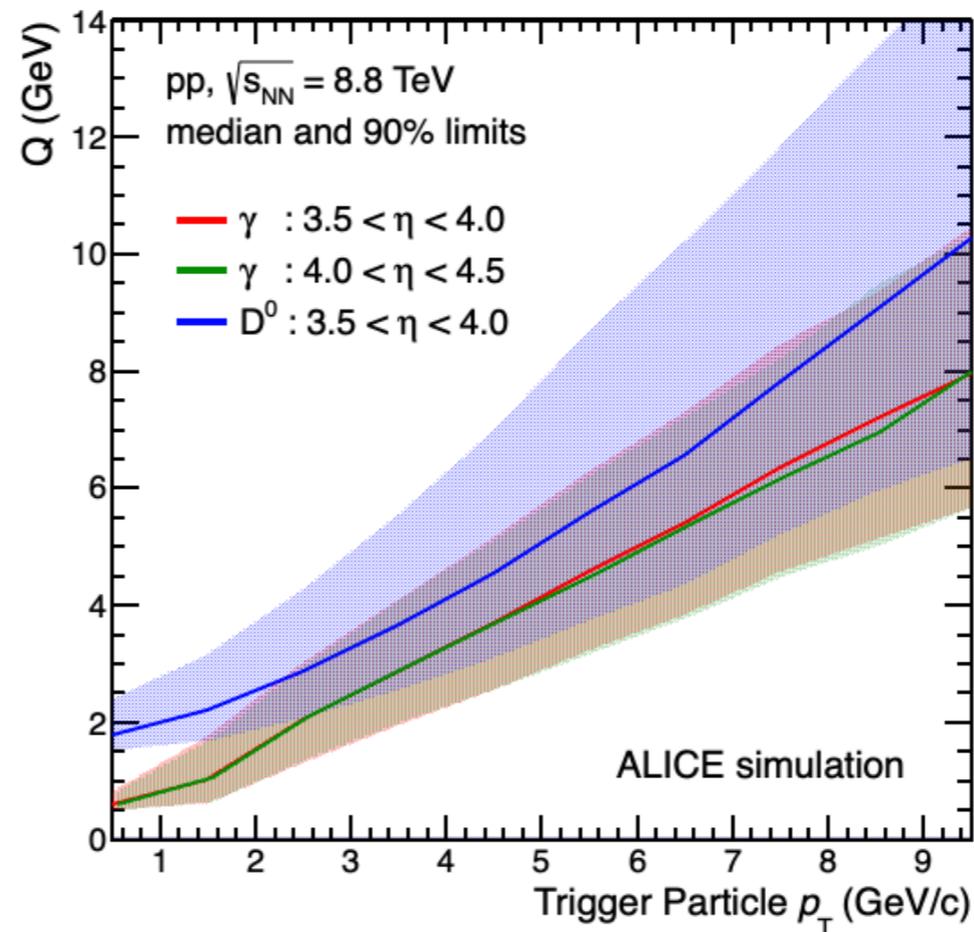
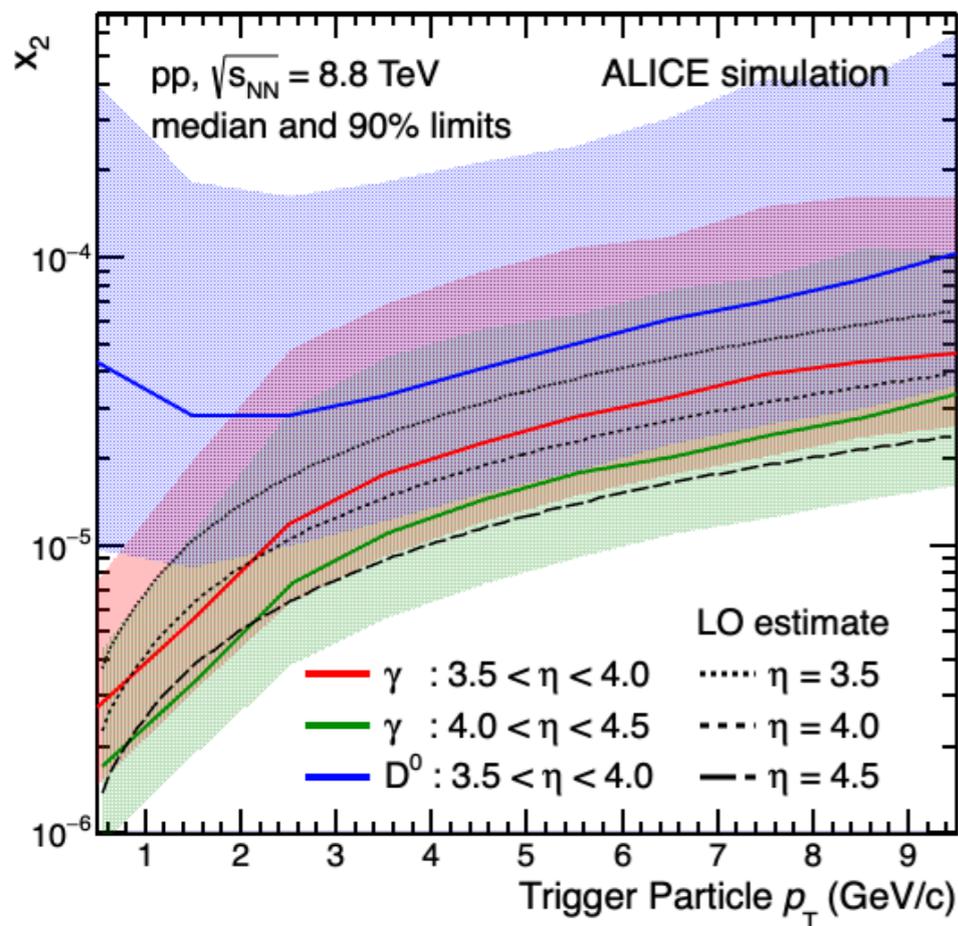
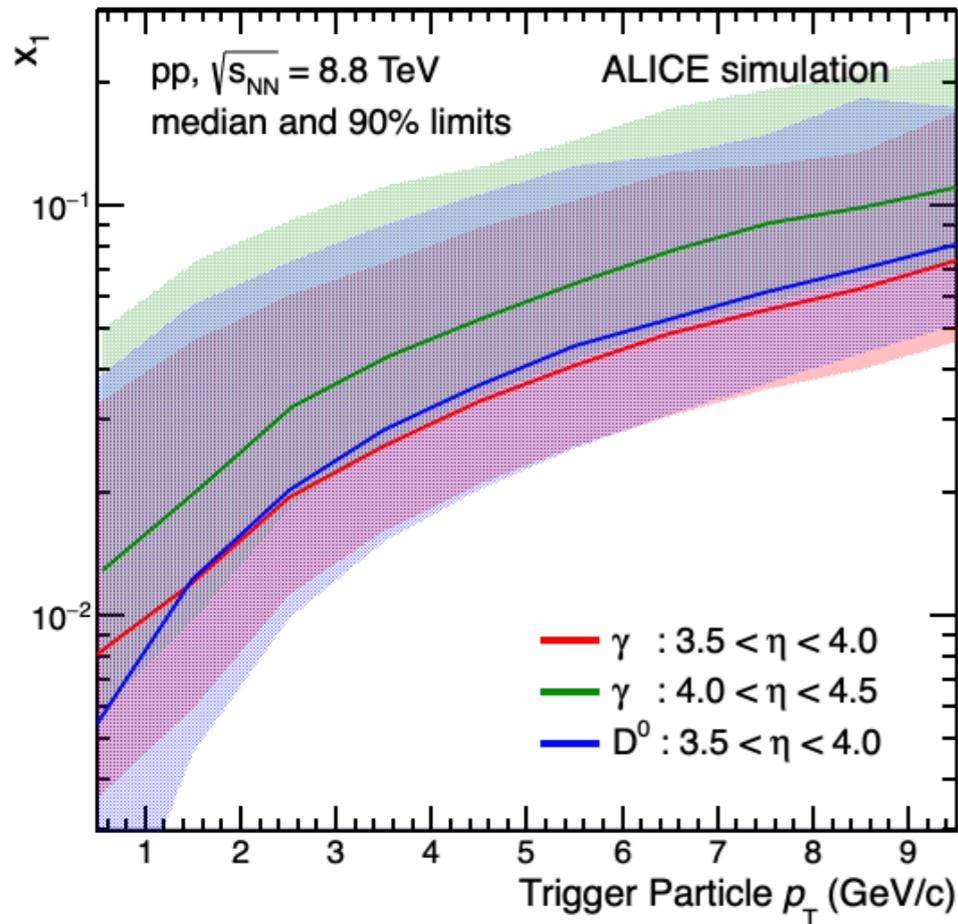


x - Q^2 -Sensitivity

PYTHIA pp 8.8TeV
forward measurements

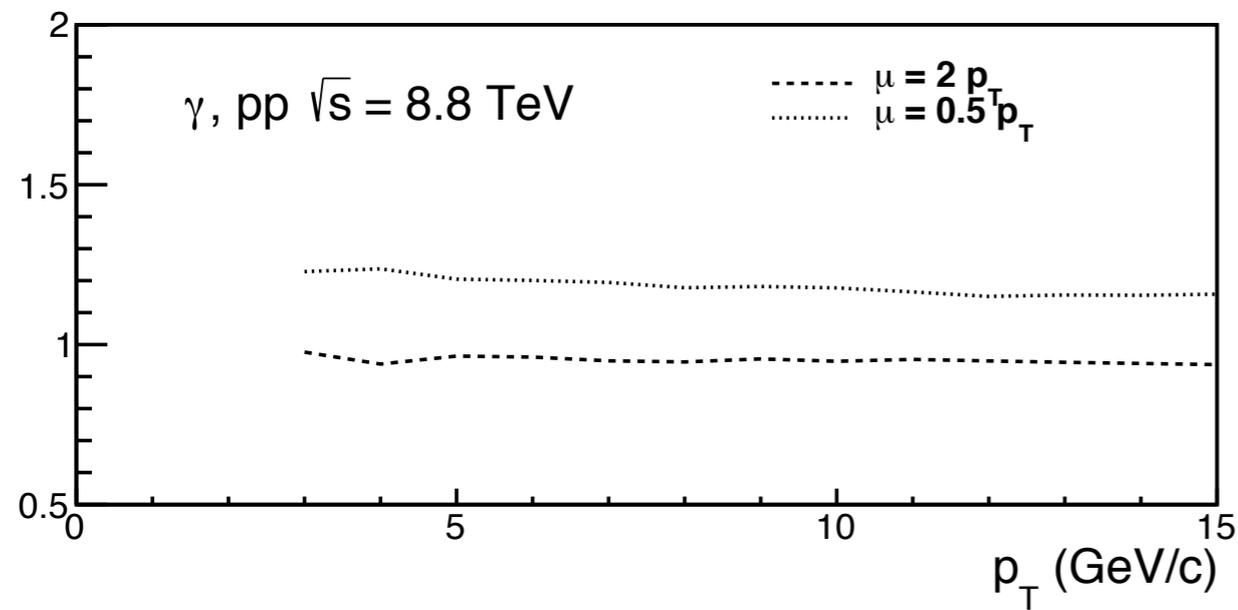
LHCb D0 vs FoCal photons

study median of distribution and
10% – 90% limits



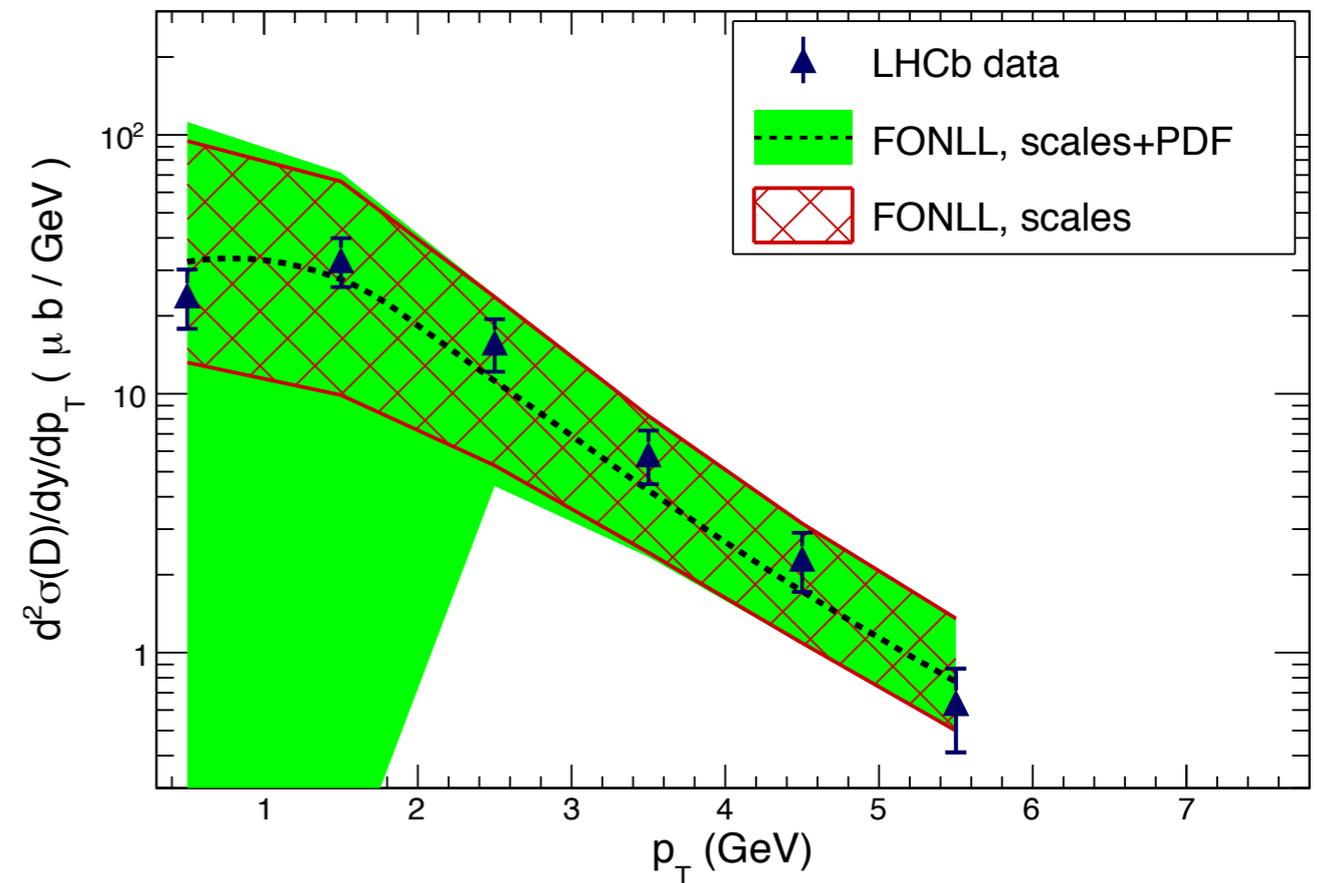
Theoretical uncertainties

Direct γ



Gamma: $\pm 5\text{-}20\%$

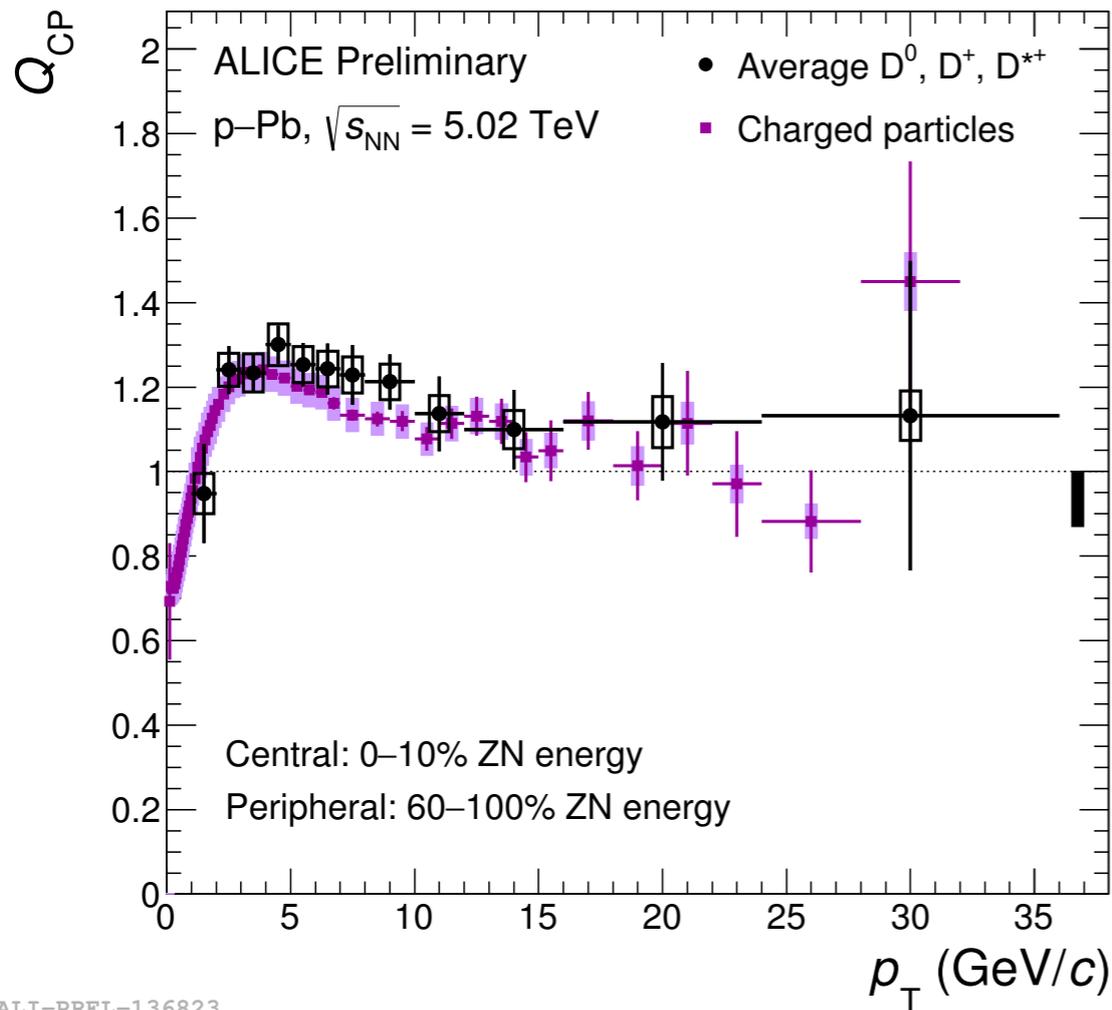
D^+ mesons, $4.0 < y < 4.5$



Scale uncertainty: factor 2

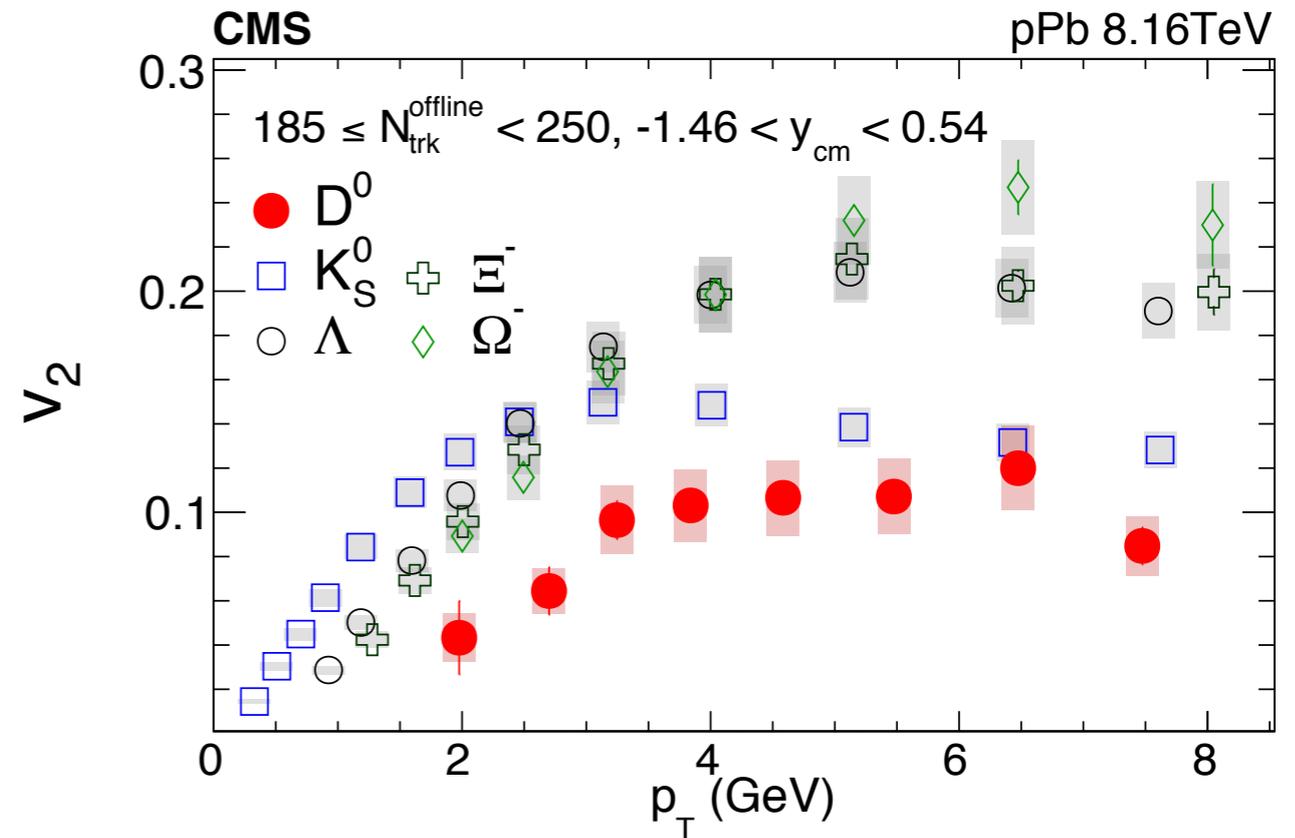
Current publications reduce this by looking at rapidity-dependence (taking ratios wrt to a specific point)

Final-State Modification of Open Charm in p–A?



nuclear modification for D mesons
 similar to charged hadrons,
 deviation from N_{coll} scaling at low p_T

CMS Collaboration, CERN-EP-2018-076



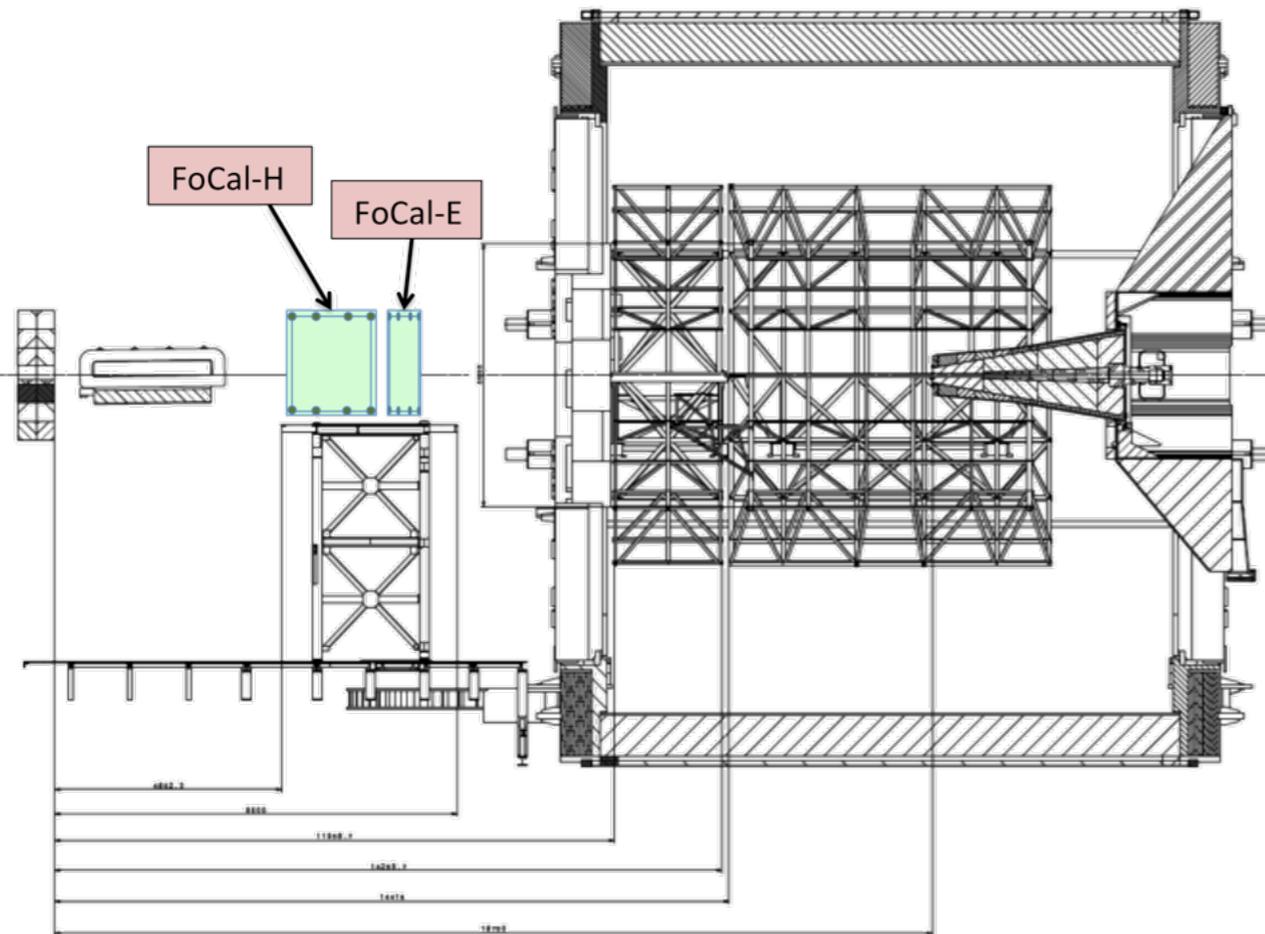
significant v_2 for D mesons,
 similar results for HF-decay leptons

- mechanism for modifications still unclear, possibly final-state interaction!
- relation between initial- and final-state kinematics may be obscured
- **introduces additional systematic uncertainty**

Low-x Probes

- Open charm and photons apparently most sensitive probes
- Some theoretical advantages for photons
- Charm measurements possible with existing LHCb apparatus
- Photons provide complementary measurement
- Not possible with existing experiments
 - need new detector

FoCal in ALICE



electromagnetic calorimeter (FoCal-E)
for γ and π^0 measurement

preferred scenario:

- at $z \approx 7\text{m}$ (outside solenoid magnet)
 $3.3 < \eta < 5.3$
- add hadronic calorimeter (FoCal-H)

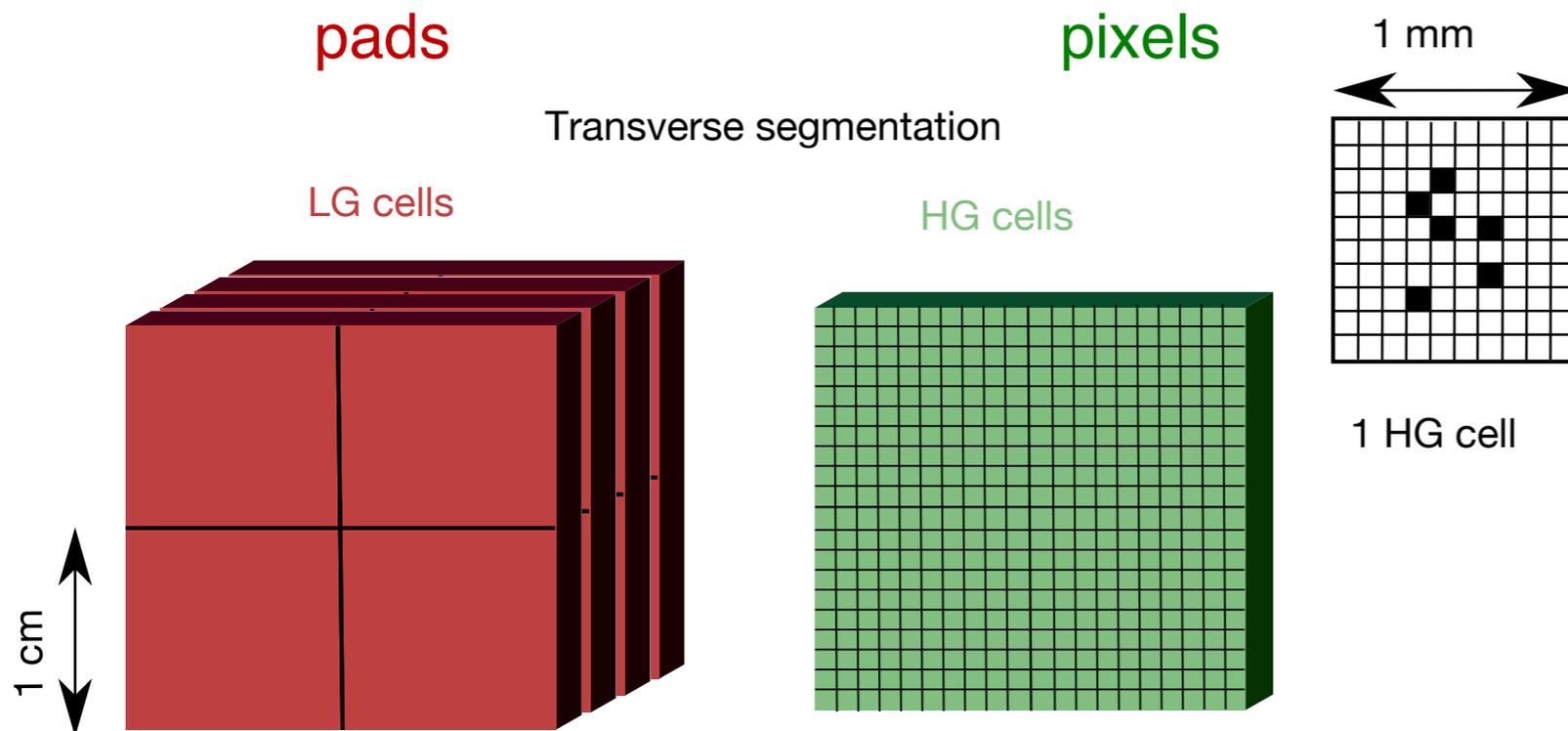
under internal discussion
possible installation in LS3

advantage in ALICE: forward region
not instrumented, “unobstructed view”

- main challenge: separate γ/π^0 at high energy
- need small Molière radius, high-granularity read-out
 - Si-W calorimeter, effective granularity $\approx 1\text{mm}^2$

note: two-photon separation from π^0 decay ($p_T = 10\text{ GeV}/c$, $y = 4.5$, $\alpha = 0.5$) is $d = 2\text{ mm}$!

The FoCal Detector – Strawman Design



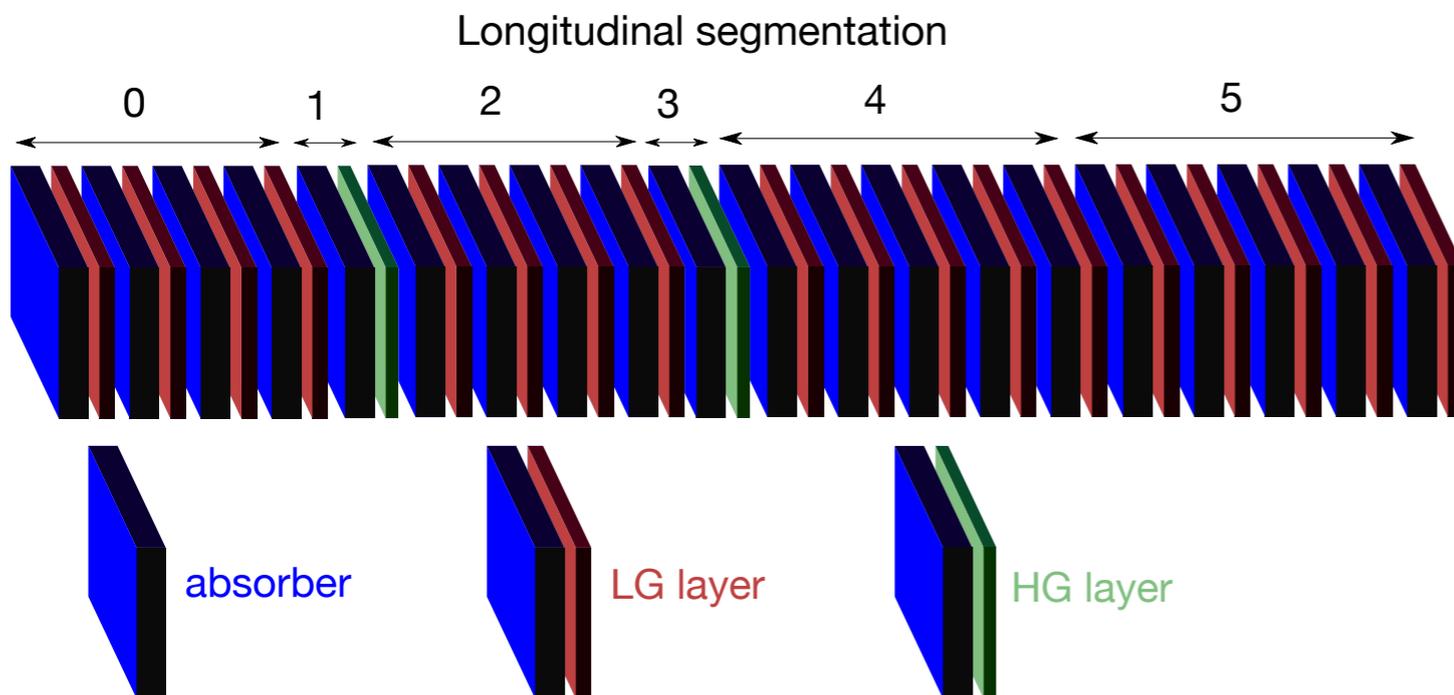
studied in performance simulations:

20 layers:

W (3.5mm $\approx 1 X_0$) + Si-sensors

hybrid design (2 types of sensors)

- **Si-pads** ($\approx 1 \text{ cm}^2$):
energy measurement, timing(?)
- **CMOS pixels** ($\approx 30 \times 30 \mu\text{m}^2$):
two-shower separation, position resolution



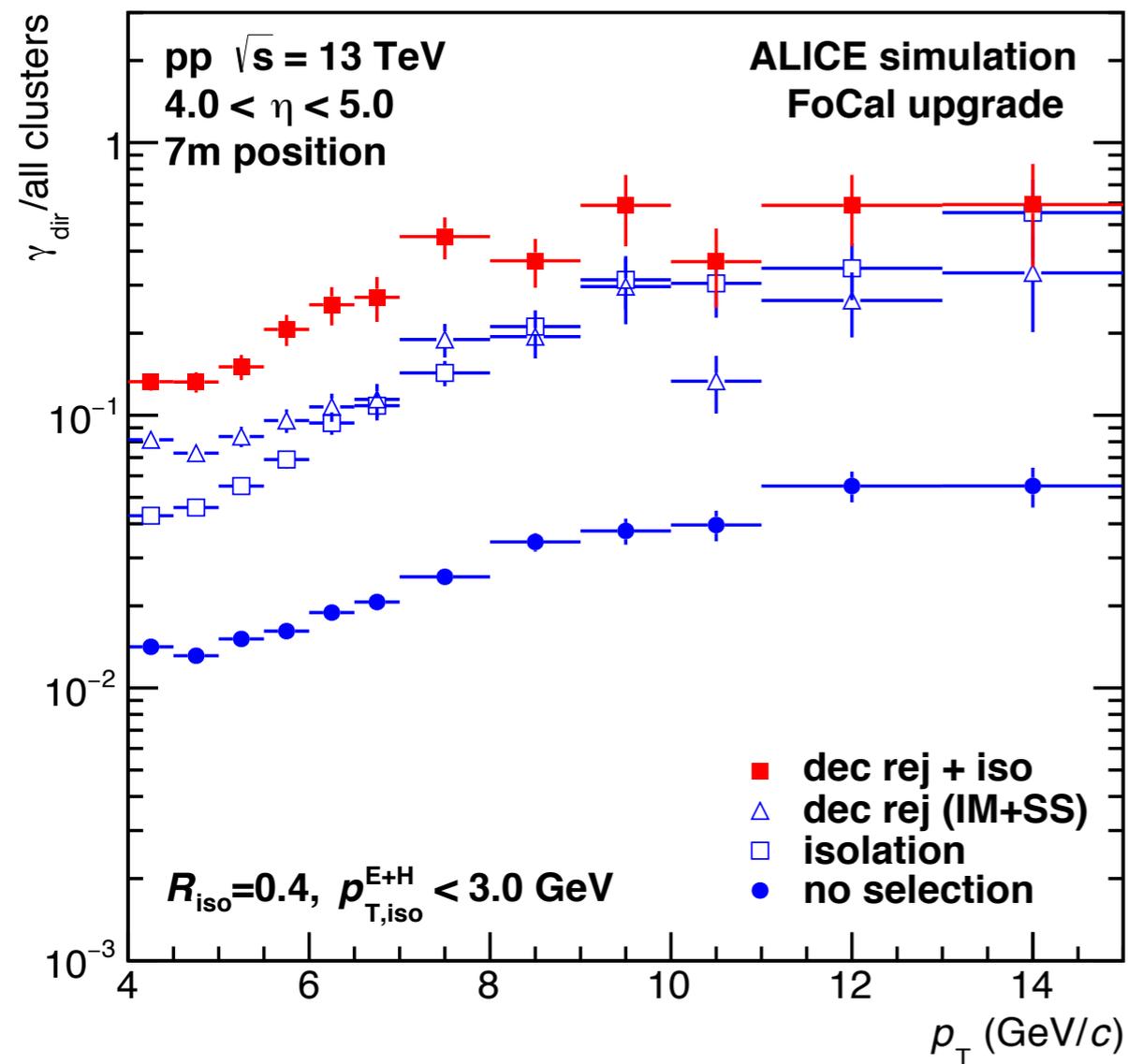
	Si-pads	Si-pixels
pixel/pad size	$\approx 1 \text{ cm}^2$	$\approx 30 \times 30 \mu\text{m}^2$
total # pixels/pads	$\approx 2.5 \times 10^5$	$\approx 2.5 \times 10^9$
readout channels	$\approx 5 \times 10^4$	$\approx 2 \times 10^6$

assuming $\approx 1 \text{ m}^2$ detector surface 24

Direct γ Performance in pp

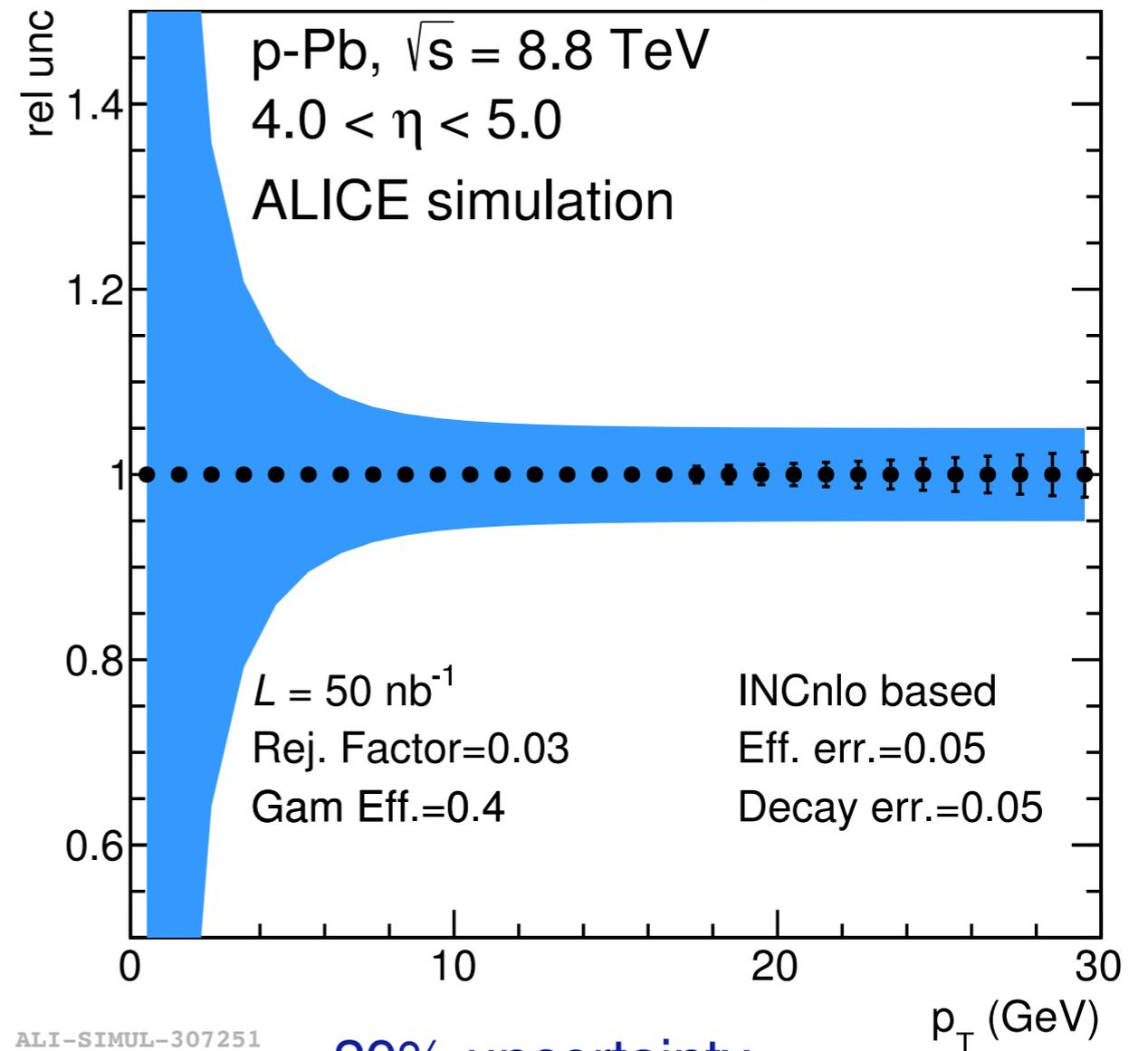
- combined rejection (invariant mass + shower shape, isolation)
- combined suppression of background relative to signal: factor ≈ 10
 - largely p_T -independent

Direct γ /all cluster ratio



direct photon/all > 0.1
 for $p_T > 4$ GeV/c

Direct γ uncertainty

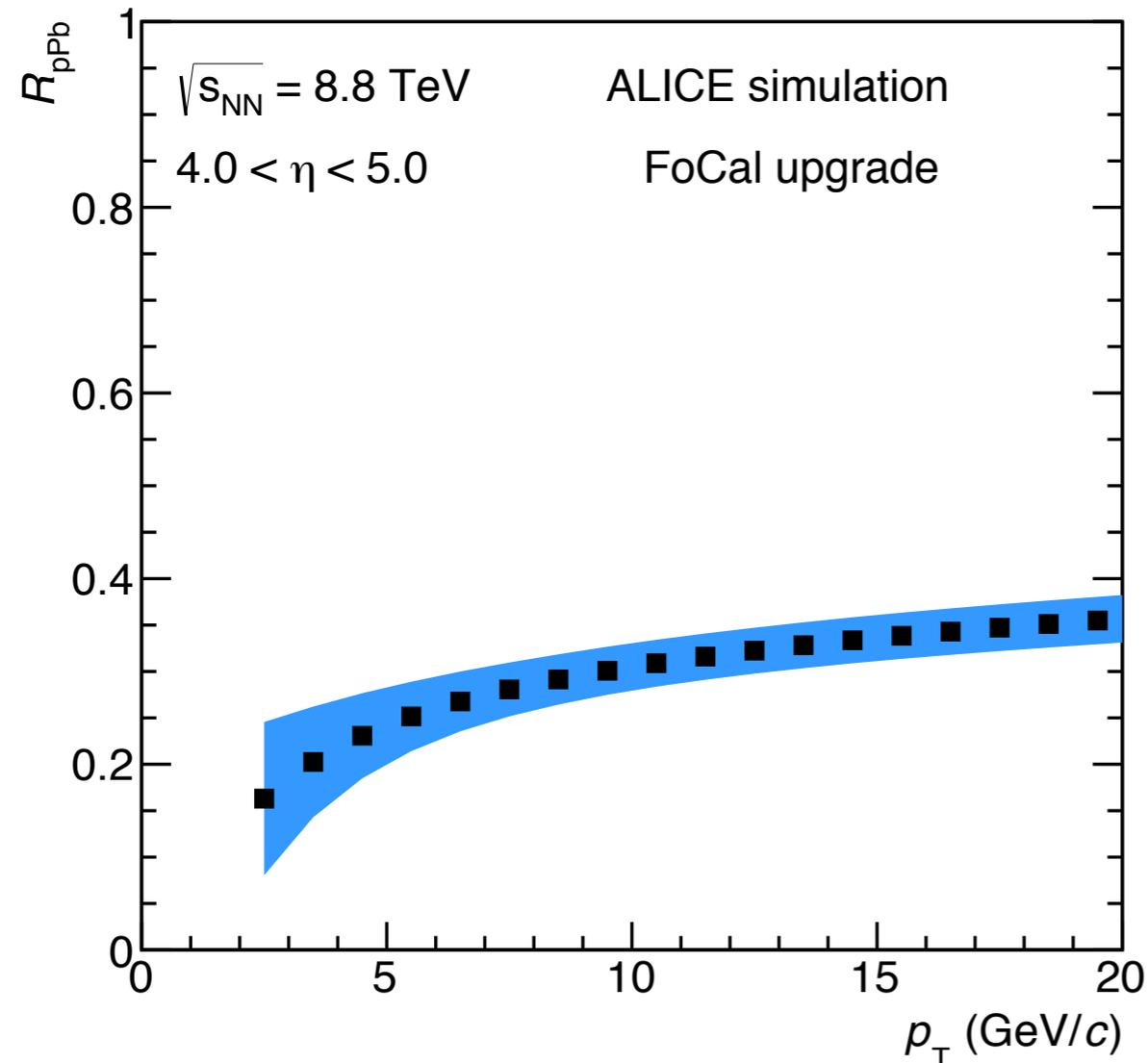


ALI-SIMUL-307251

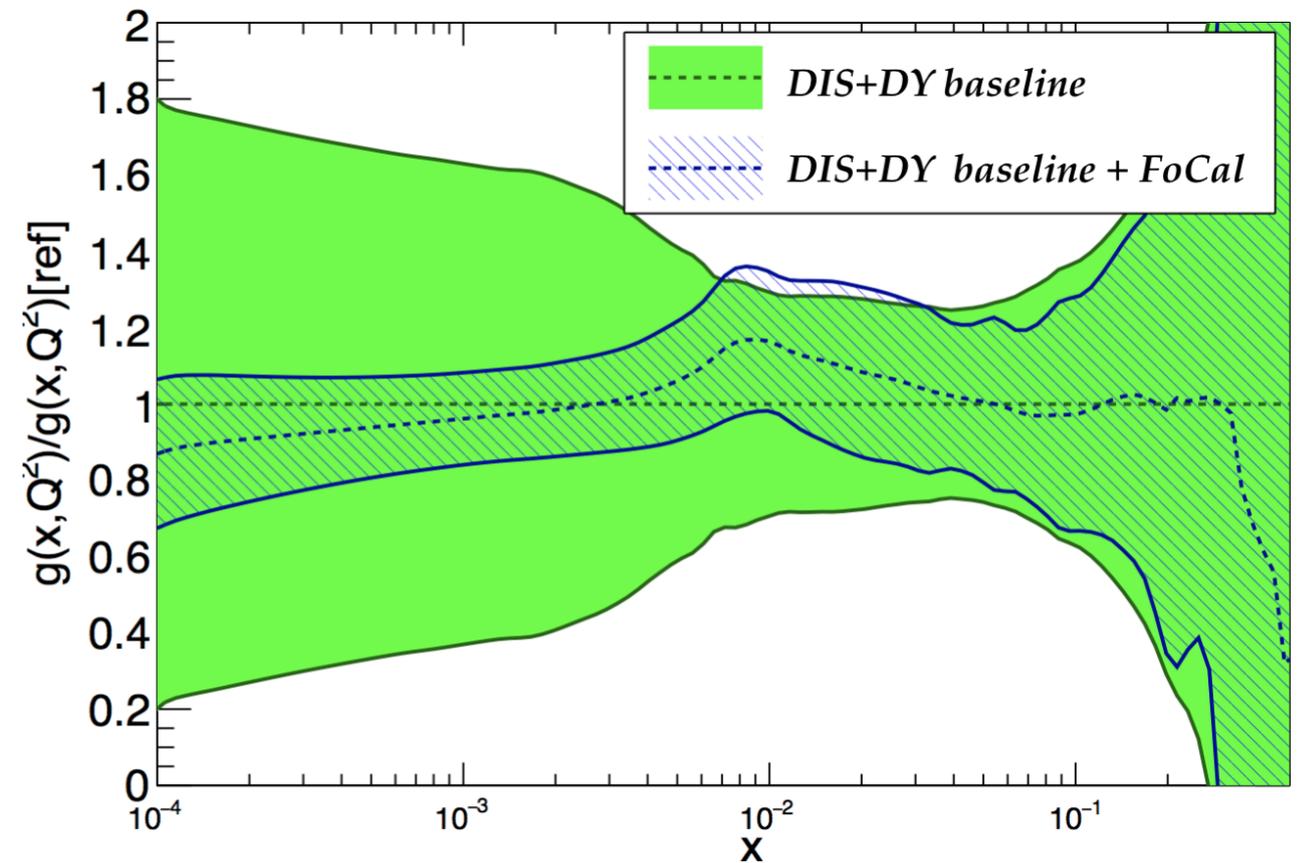
$\approx 20\%$ uncertainty
 at $p_T = 4$ GeV/c
 decreases with increasing p_T

Impact of Forward Photons on nPDFs

Performance estimate of FoCal measurement



uncertainty of nPDFs without/with FoCal
J. Rojo et al, priv. comm.,
arXiv 1610.09373, 1706.00428, 1802.03021
NNPDF3.1 NNLO, $Q^2 = 5 \text{ GeV}^2$



Uncertainties can be improved significantly

Still some discussion ongoing:

choice of $\Delta\chi^2$, effect of DGLAP evolution, shape of parameterisation

Work in progress!

Main Physics Motivation for FoCal (A Hierarchy)

1. prove or refute gluon saturation

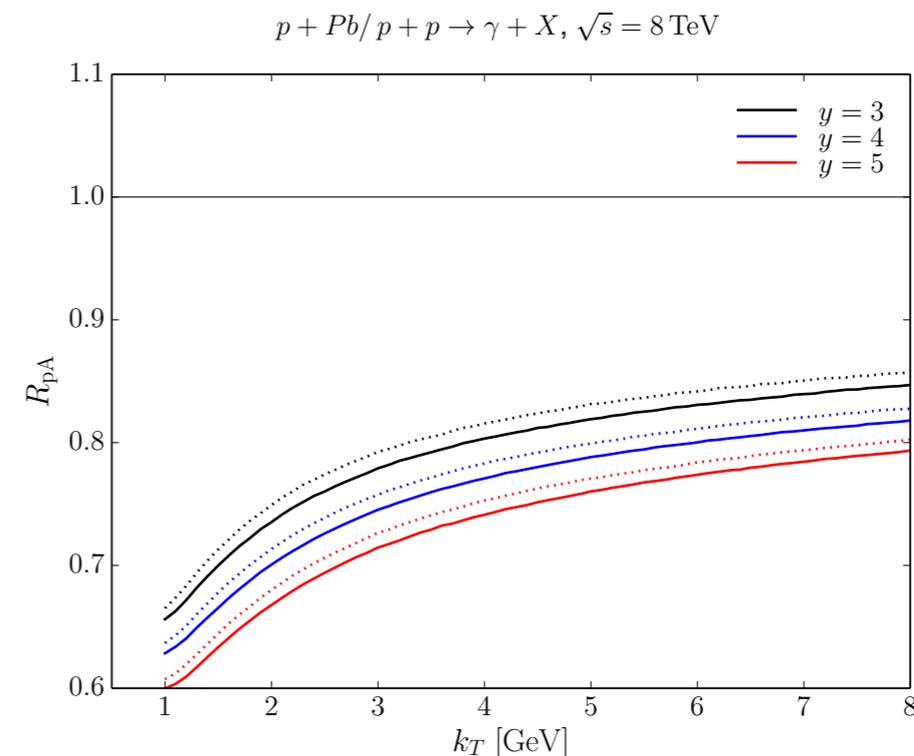
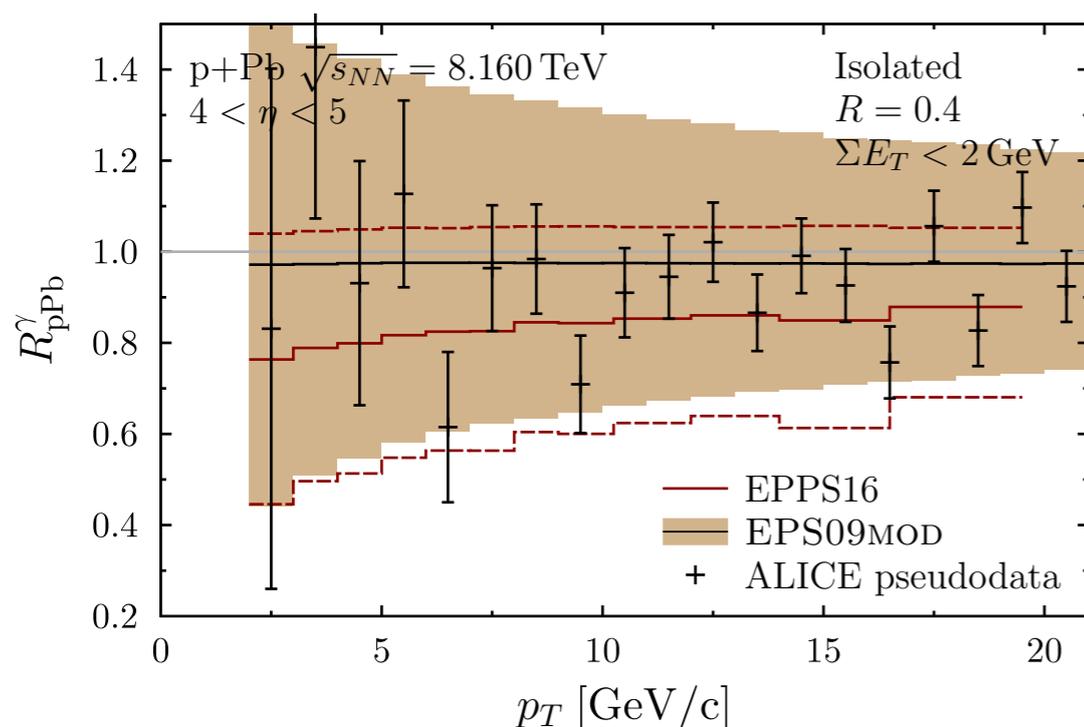
- compare saturation models with linear QCD
- depends on saturation model implementation and flexibility of PDF analytical shape

2. show invalidity of linear QCD at low x

- can all potential measurement outcomes be absorbed in a modified PDF?

3. constrain the PDFs at low x

- nuclei, also protons
- main observable: nuclear modification factor R_{pA} of direct photons
 - saturation stronger in nuclei
 - possibly non-existent in protons (calculation of reference in models?)



CGC Calculation:
Ducloué, Lappi,
Mäntysaari,
arXiv:1210.02206

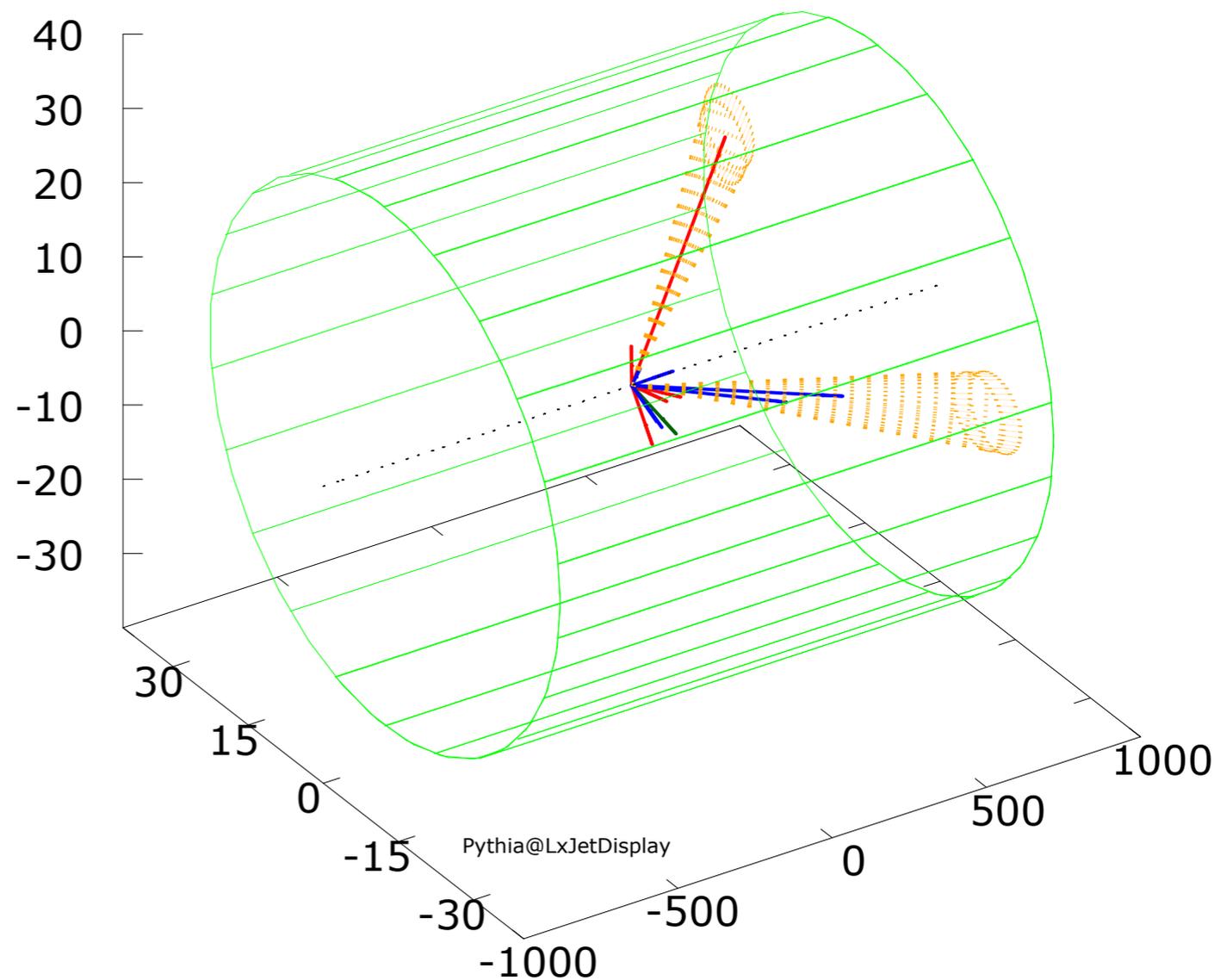
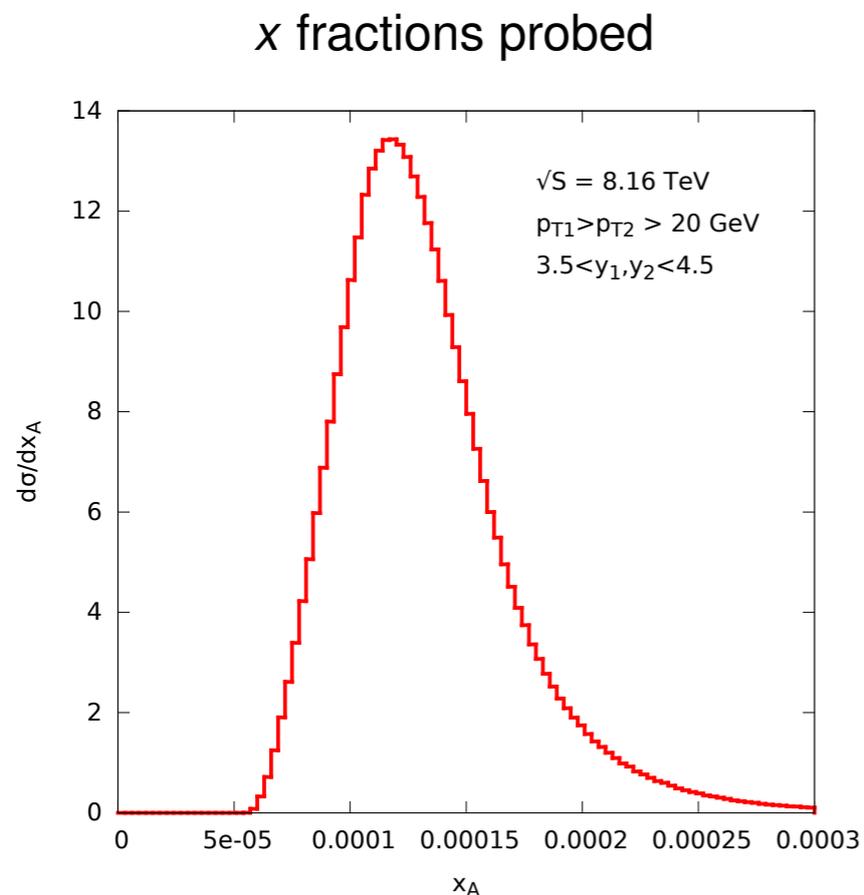
Other Probes of Saturation

- Suppression of singles visible in RpA tests gluon density
- Other probes: two-particle correlations
- Signal: Monojet production in place of dijets
 - sensitive to scattering off coherent gluon state

Results for dijet production in $p\text{Pb}$ at LHC

Kinematic cuts

- CM energy: $\sqrt{S} = 8.16 \text{ TeV}$
- require two jets with $(\Delta\phi)^2 + (\Delta\eta)^2 > R^2, R = 0.5$
- transverse momenta cuts: $p_{T1} > p_{T2} > 20 \text{ GeV}$
- rapidity cuts: $3.5 < y_1, y_2 < 4.5$



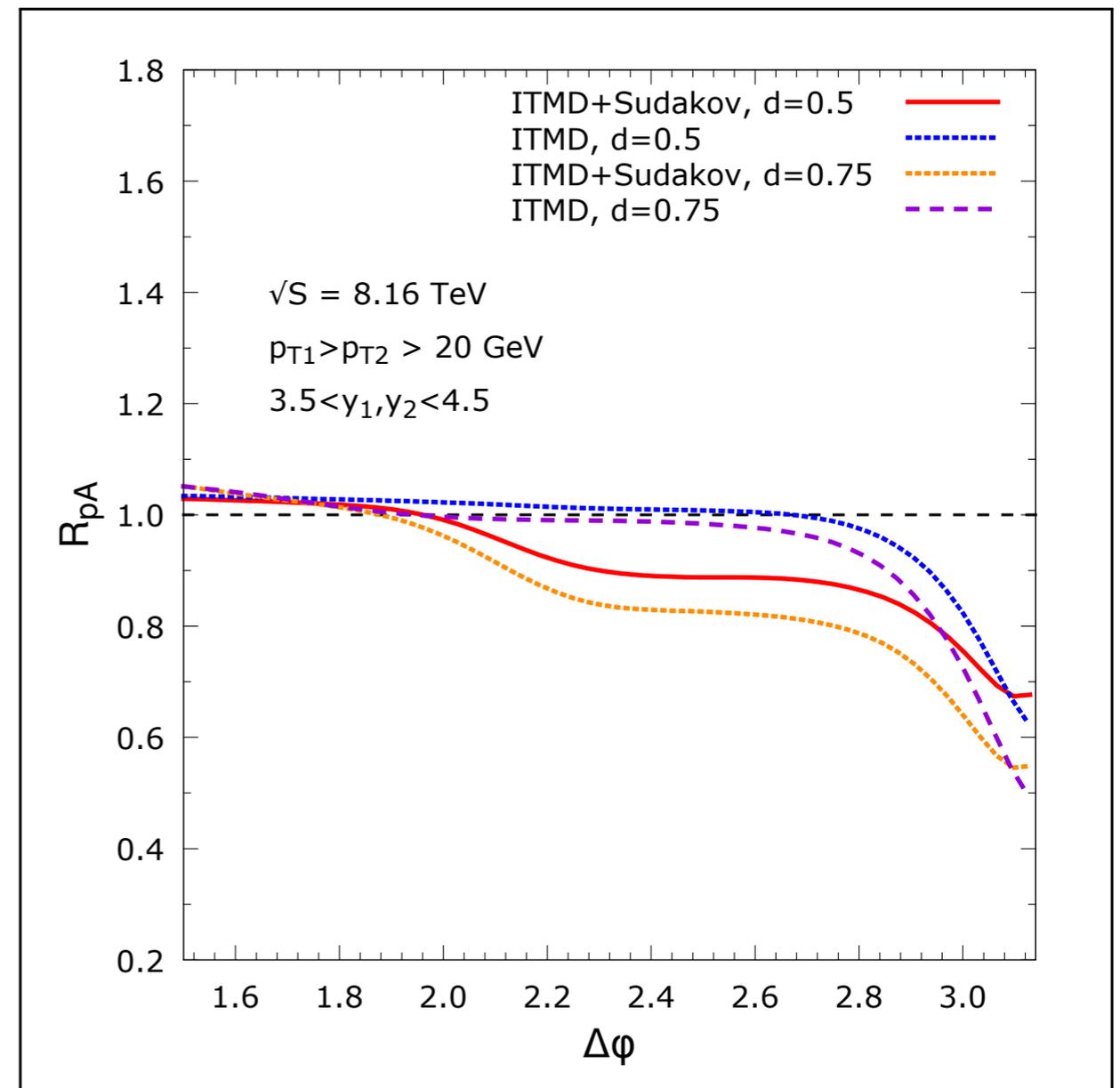
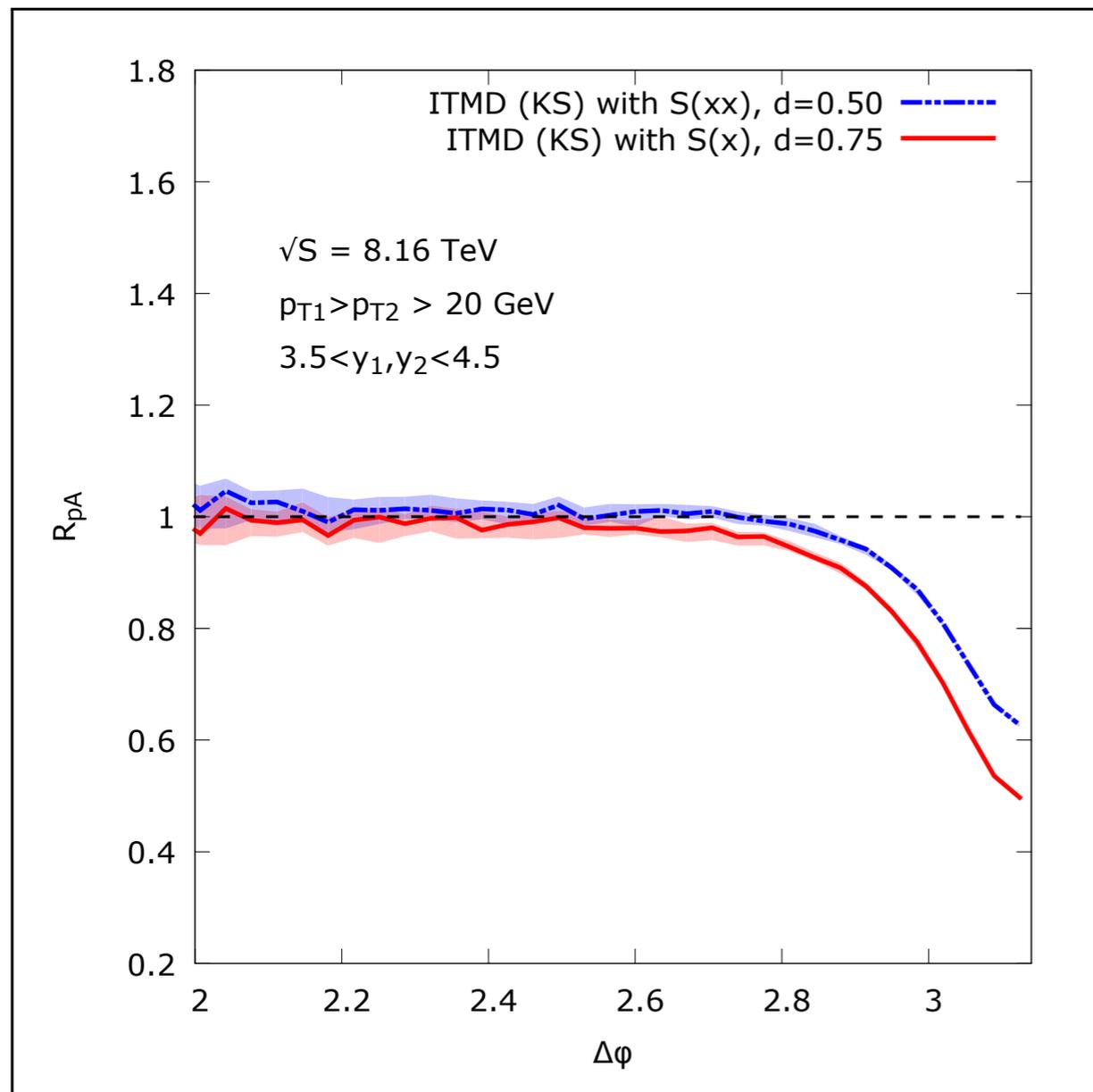
This particular PYTHIA event:

- jets with $p_{T1} \sim 27 \text{ GeV}, p_{T2} \sim 30 \text{ GeV}$
- $y > 3.5$
- 9 MPI events (not all visible; each in different color)
- jet imbalance $q_T \sim 10 \text{ GeV}$

Results for dijet production in $p\text{Pb}$ at LHC

Nuclear modification ratio for azimuthal decorrelations

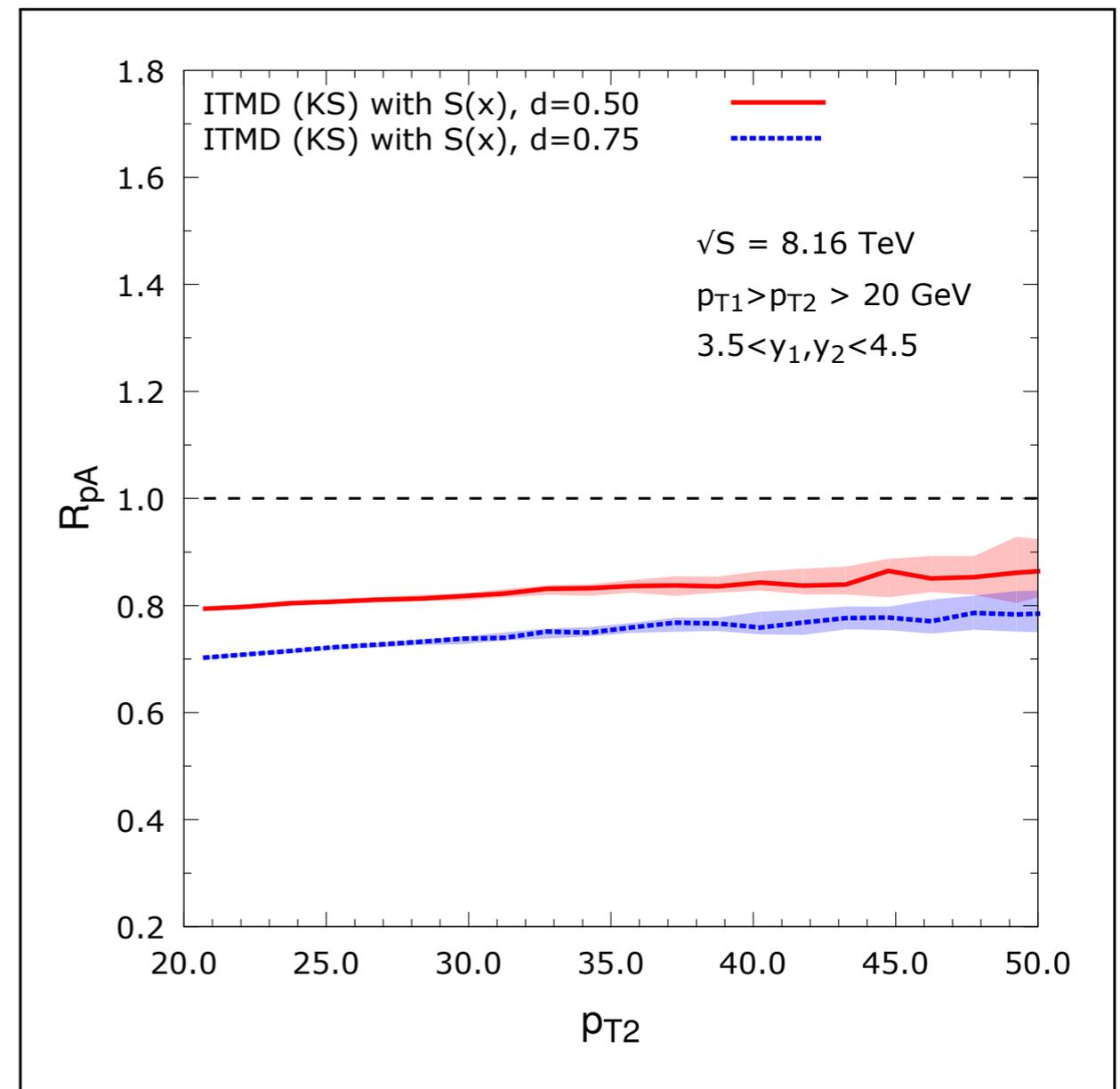
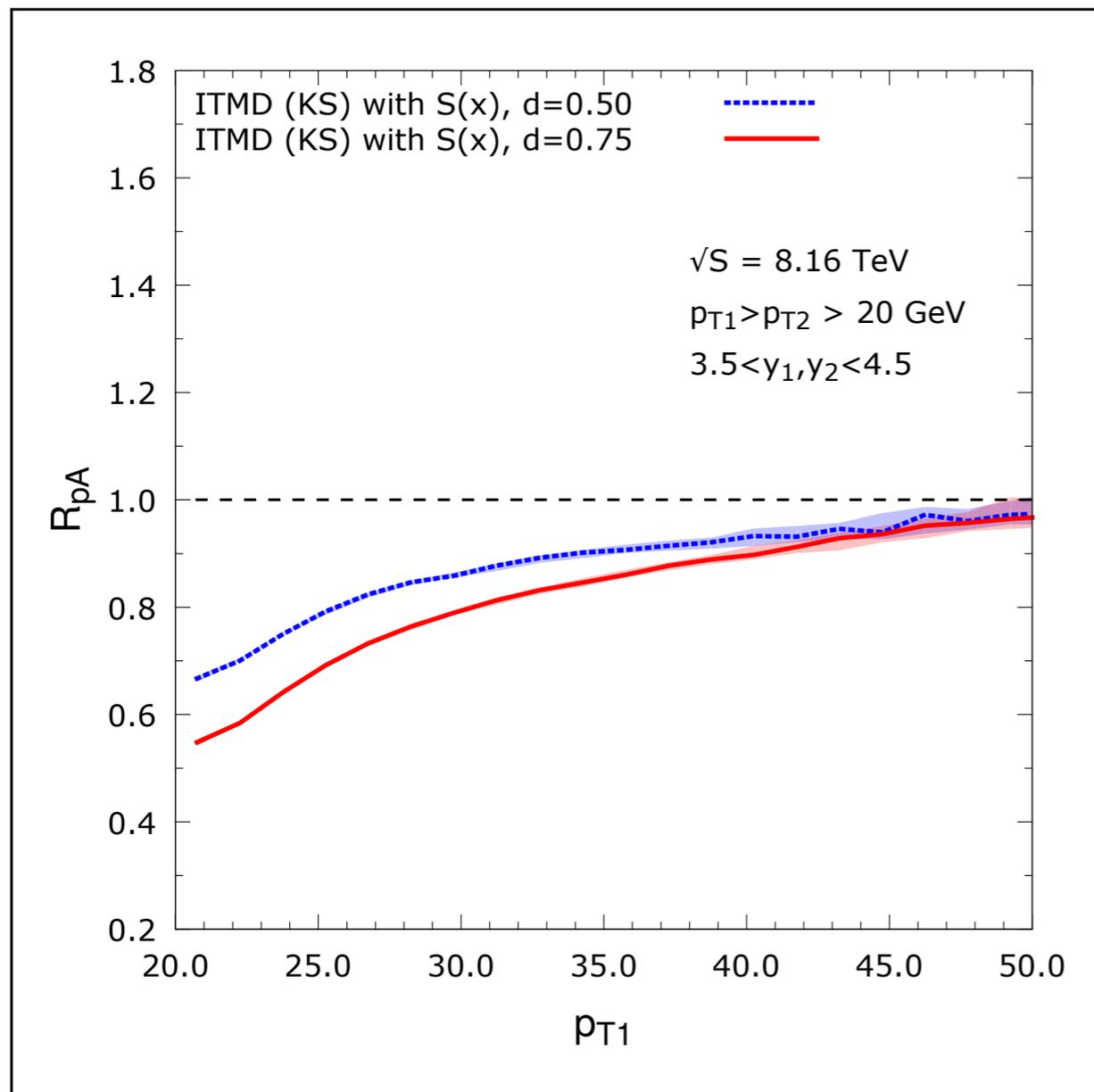
[A. van Hameren, P.K., K. Kutak, C. Marquet, E. Petreska, S. Sapeta, JHEP 1612 (2016) 034]



Results for dijet production in $p\text{Pb}$ at LHC

Nuclear modification ratio for jet p_T spectra

[A. van Hameren, P.K., K. Kutak, C. Marquet, E. Petreska, S. Sapeta, JHEP 1612 (2016) 034]



Summary

- Large uncertainties in low-x parton density, existence of gluon saturation
 - early experimental observations
- Forward measurements at LHC can access low-x physics
 - examples: J/ψ , D, photons
 - pros and cons
- Opportunity for photon measurement
 - complementary information to open charm measurement
 - requires significant R&D step beyond state of the art in calorimetry