PDF constraints from new data and from future experiments

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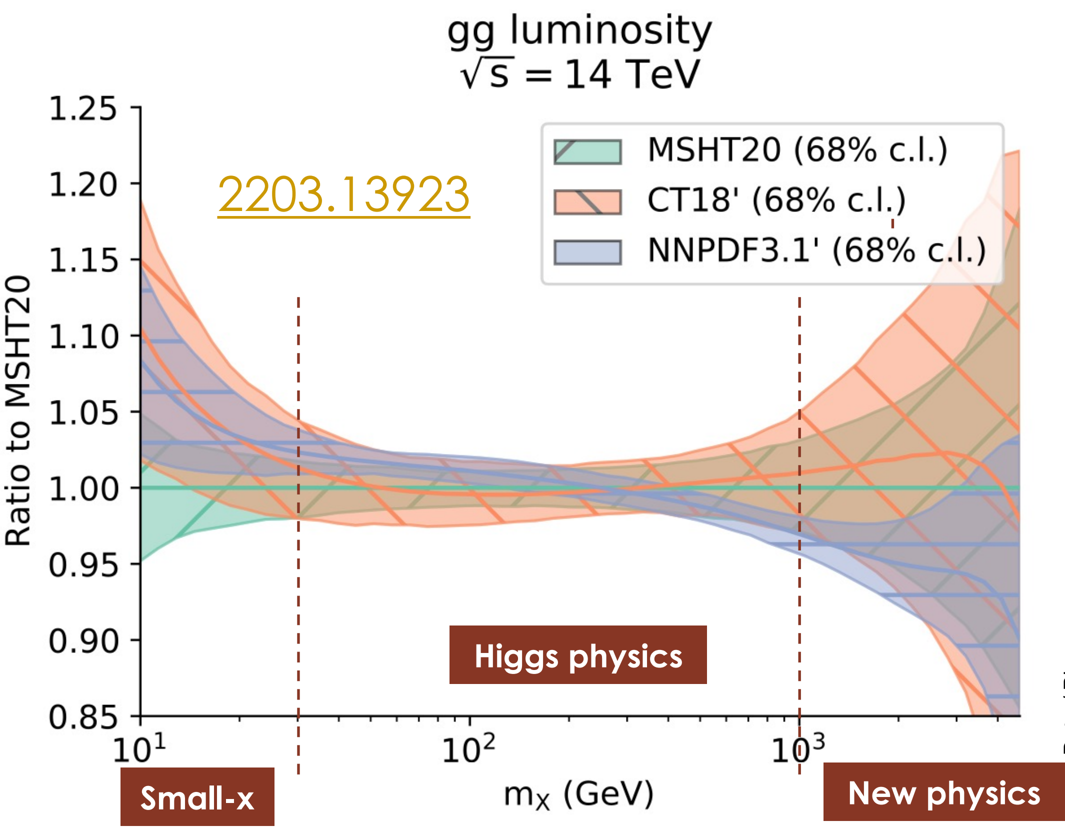
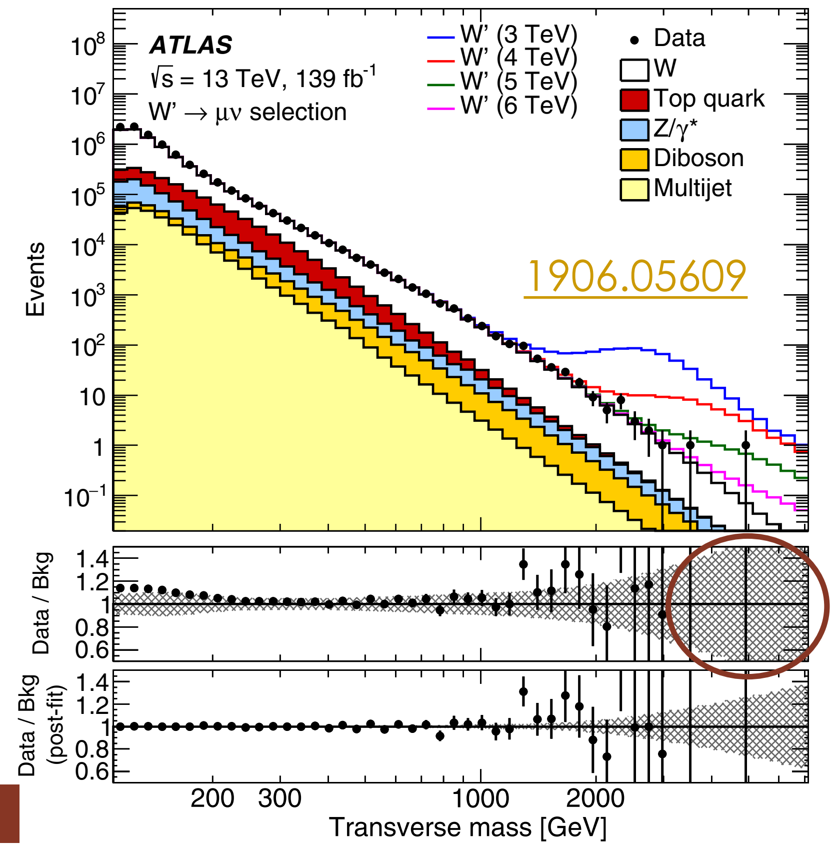
Why proton PDFs matter

- Precise knowledge of Parton Distribution Functions (PDFs) is essential
- PDFs have large uncertainties in the LHC kinematics regions
  - Significant source of uncertainty for Higgs and top production
  - Limits precision on fundamental parameters (m_W, α_S, etc.)
  - Limits searches for new massive particles

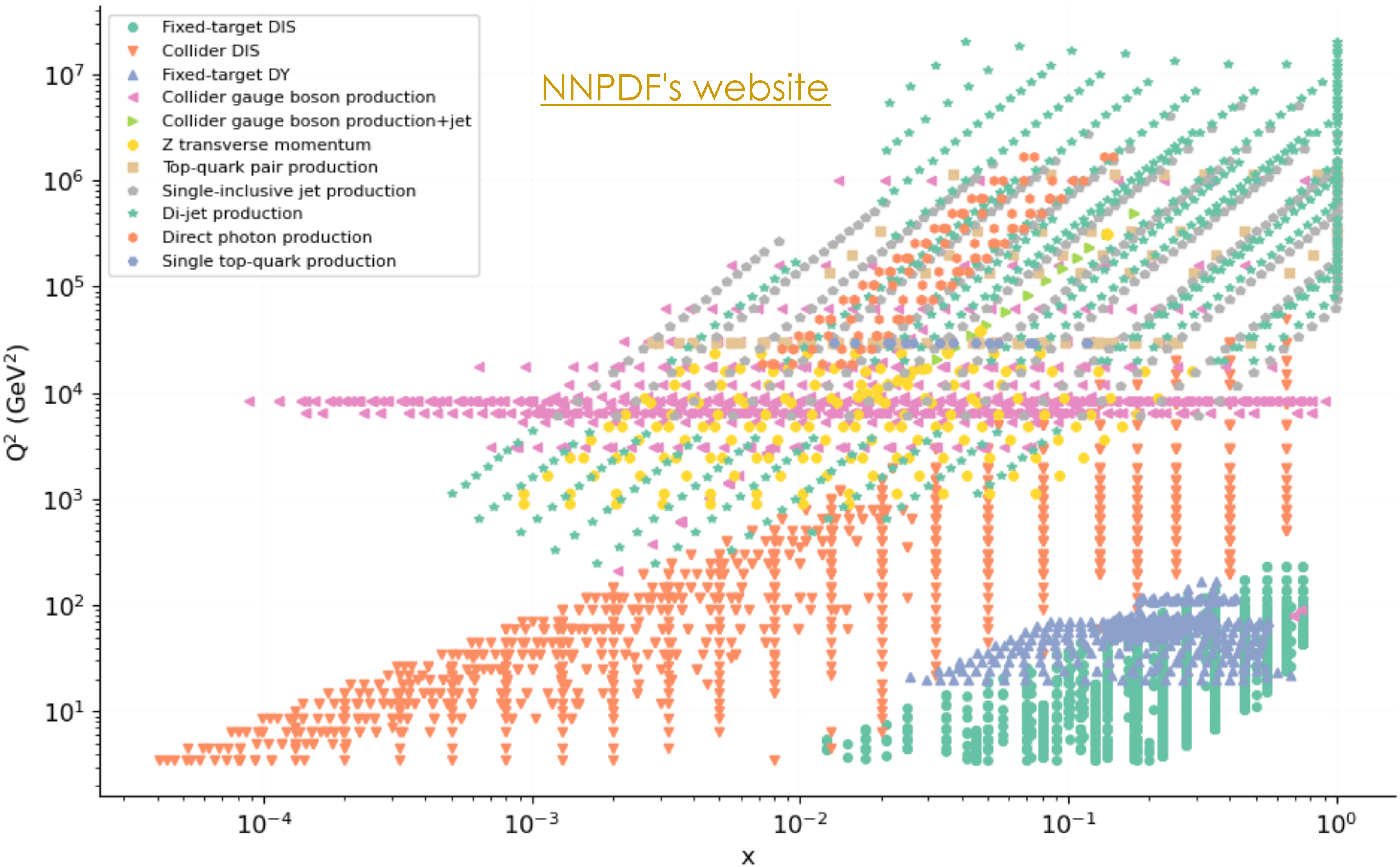




Data useful for PDF fits

- **DY W,Z:** quark flavour separation
  - Cross sections and asymmetries: $u_V, d_V, \bar{d}$ and $\bar{s}$
  - W,Z + jets: gluon, resolves ambiguities in high-x shapes i.e. $\bar{s}$ suppression at high-x
- **DY γ^*:** $\bar{u}$, photon PDF
- **DY W,Z + heavy flavour:** discrimination between 4FS and 5FS, $\bar{s}$ (W + c), intrinsic charm (Z + c in the forward region)
  - NNLO predictions and discussion on how to include fragmentation in a theoretically consistent manner
- **$t\bar{t}$:** gluon at medium- and high-x
- **Inclusive, di- and tri-jets:** gluon on a wide range of x
- **Single top:** down-type quarks at low-x
- **Direct photon:** gluon at medium- and high-x
- **Photon + heavy flavour:** discrimination between 4FS and 5FS
  - γ + c does not offer very discrimination for intrinsic charm

Kinematic coverage



Outline of the talk

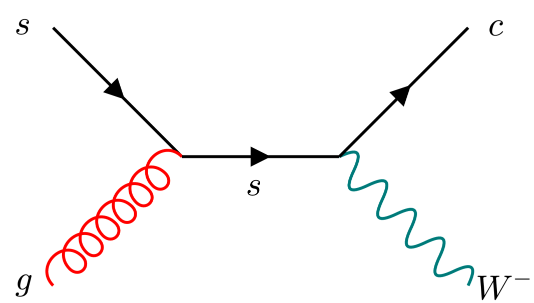
- This talk will focus on the following QCD related measurements from LHC :
  - Measurement of **W + charmed hadron** - 2302.00336 (accepted by PRD)
  - **Z + c** in the forward region - PRL 128 (2022) 082001
  - **Inclusive jet** production at $\sqrt{s}$ = 13 TeV - JHEP 02 (2022) 142
  - **Dijets** production at $\sqrt{s}$ = 13 TeV - CMS-PAS-SMP-21-008
  - **Inclusive-photon** production and its dependence on photon isolation at $\sqrt{s}$ = 13 TeV using 139 fb^{-1} of ATLAS data - JHEP 07 (2023) 086

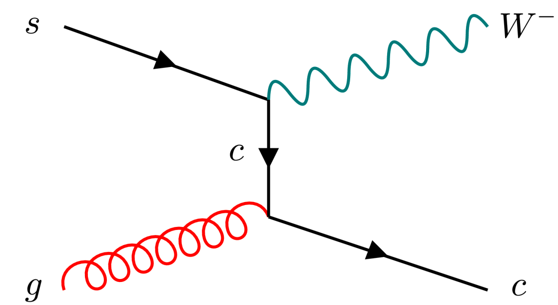
- PDF sensitivities studies from future colliders:
  - HL-LHC
  - LHeC
  - EIC

- Disclaimer: **only *unpolarised proton PDFs* covered in this talk**

Measurement of W + charmed hadron

- W boson decaying leptonically ($e\nu/\mu\nu$)
- Lepton p_T > 30 GeV and $|\eta_l|$ < 2.5
- $p_T(D)$ > 8 GeV and $|\eta(D)|$ < 2.2
- E_T^{miss} > 30 GeV
- $m_T(W)$ > 60 GeV

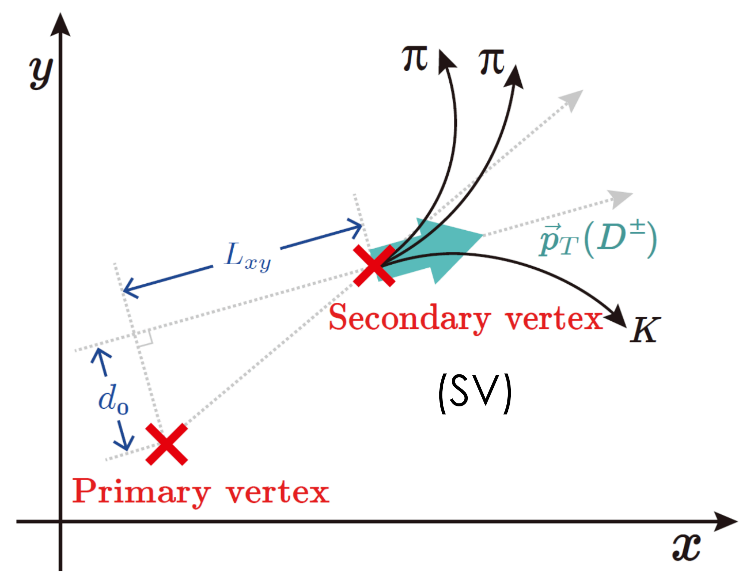




PRD 108 (2023) 032012

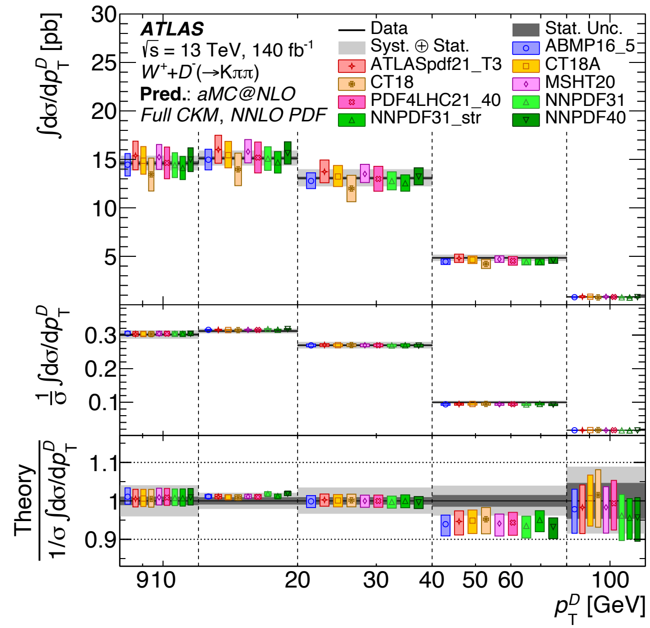
- Strategy: identify c-jet via charmed hadron reconstruction
  - $D^{\pm} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}$
  - $D^{*\pm} \rightarrow D^{0}\pi^{\pm} \rightarrow (K^{\mp}\pi^{\pm})\pi^{\pm}$
- D^* mesons decay prompt
- Combine with prompt tracks ($\pi^{\pm}$)
- Check candidates against selection criteria

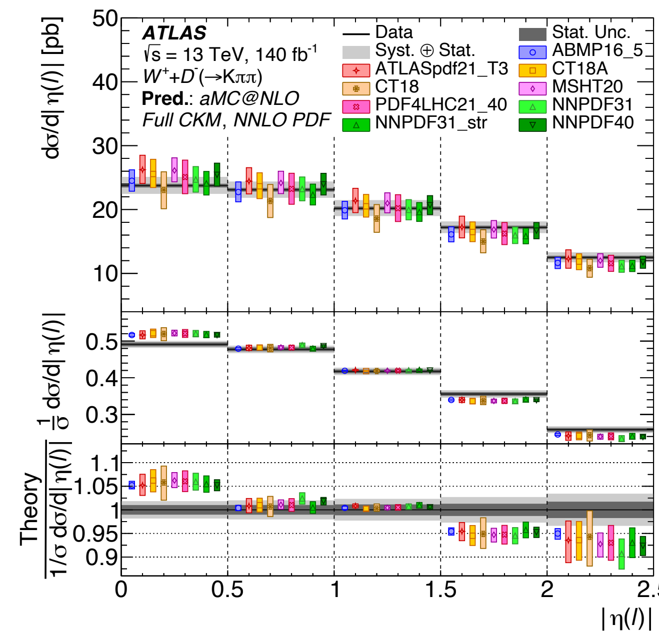
D⁺ meson



Measurement of W + charmed hadron

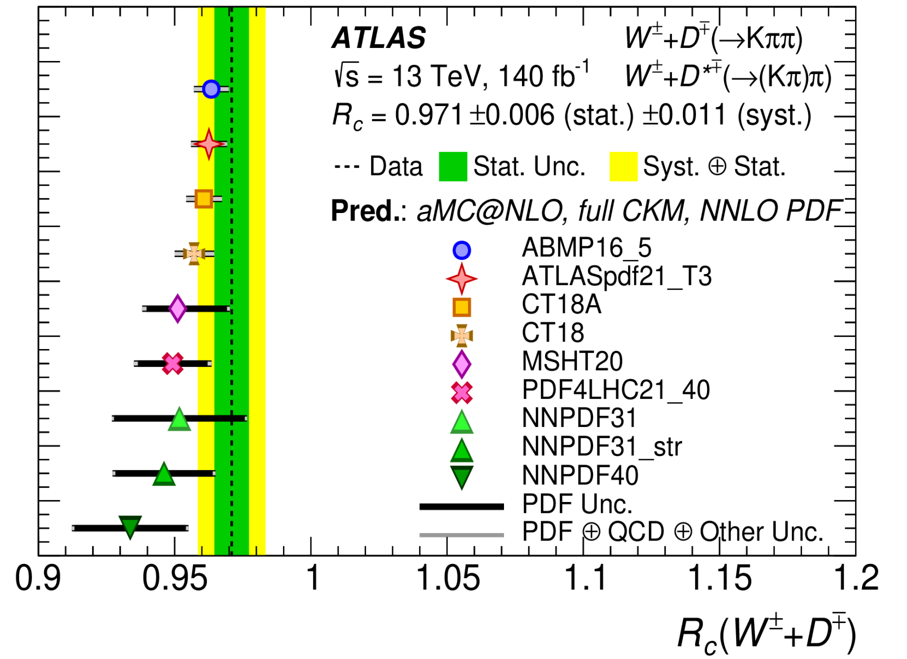
- Background normalisation and systematic constraints via likelihood fit of 5 $p_T(D^{(*)})$ or $|\eta_l|$ bins
- **Systematics** in the "+" and "-" channels **mostly cancel out in $R_c^{\pm}$**
- MC and data **statistics dominate** (from 0.7% to 1.3%)
- Smaller systematics in $|\eta_l|$ than $p_T(D^{(*)})$
  - SV reconstruction independent of $|\eta_l|$
- Similar trend observed for various PDF sets and different predictions (different MC generators, but same 'merged'accuracy)





Measurement of W + charmed hadron

- PDFs which assume $(s-\bar{s})$ asymmetry in worse agreement with our data
- This suggests $(s-\bar{s})$ **asymmetry** is **small** in the region probed by this analysis
- Ratio of σ in 2 decay channels in agreement within uncertainties
- **Similar results found in a recent CMS paper** - 2308.02285
- What next? Include these data in a PDF fit
- New IRC safe definition of jet flavour at NNLO/all orders available on the market ☺
- Current lack of NNLO predictions ☹

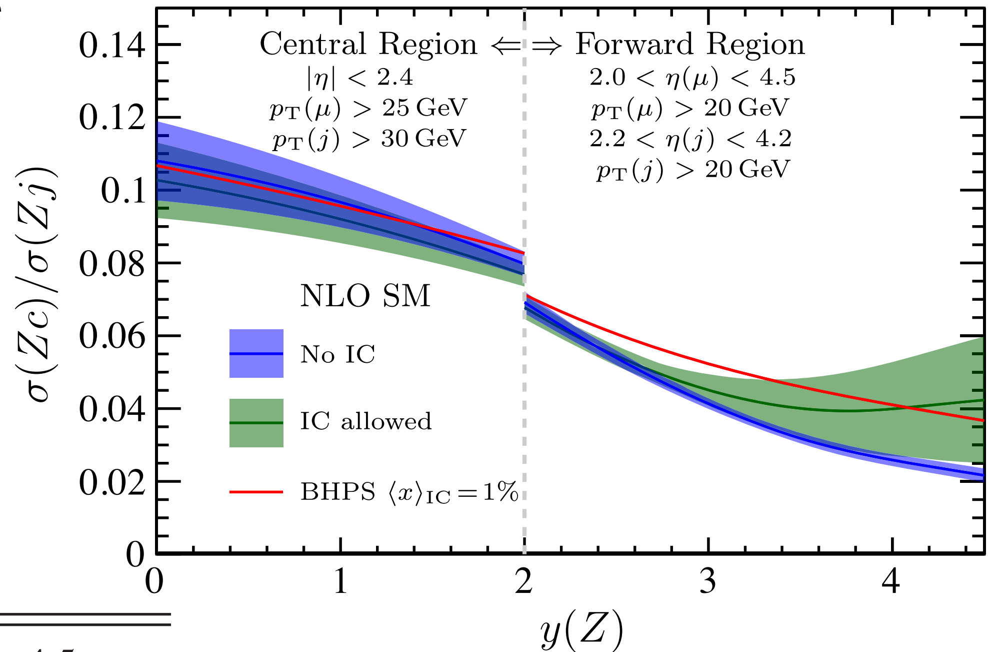


Channel	$\sigma_{\text{fid}}^{\text{OS-SS}}(W+D^{(*)}) \times B(W\to\ell\nu)$ [pb]
W^-+D^+	50.2 ± 0.2 (stat.) $^{+2.4}_{-2.3}$ (syst.)
W^++D^-	48.5 ± 0.2 (stat.) $^{+2.3}_{-2.2}$ (syst.)
W^-+D^{*+}	51.1 ± 0.4 (stat.) $^{+1.9}_{-1.8}$ (syst.)
W^++D^{*-}	50.0 ± 0.4 (stat.) $^{+1.9}_{-1.8}$ (syst.)
	$R_c^{\pm} = \sigma_{\text{fid}}^{\text{OS-SS}}(W^++D^{(*)})/\sigma_{\text{fid}}^{\text{OS-SS}}(W^-+D^{(*)})$
$R_c^{\pm}(D^+)$	0.965 ± 0.007 (stat.) ± 0.012 (syst.)
$R_c^{\pm}(D^{*+})$	0.980 ± 0.010 (stat.) ± 0.013 (syst.)
$R_c^{\pm}(D^{(*)})$	0.971 ± 0.006 (stat.) ± 0.011 (syst.)

Forward Z + c

PRL 128 (2022) 082001

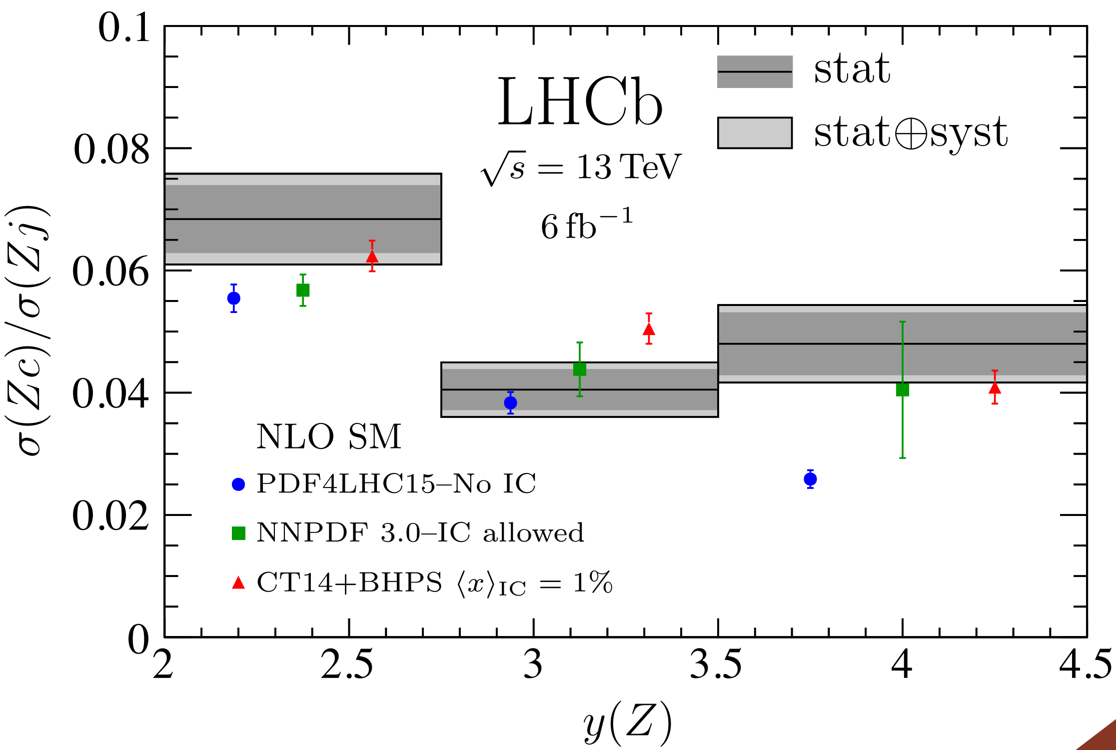
- **First study** of Z boson produced with a c-quark in the **forward region**, using full Run 2 data – optimized charm jet identification JINST 17 (2022) P02028
- **Measure $\sigma(Z_c)/\sigma(Z_j)$**
  - At NLO a percent-level valence-like IC contribution would produce significant enhancement in the ratio at high y(Z) region
  - IC-allowed model at **high y(Z)** is largely unconstrained
  - Many jet-related systematics cancel in the ratio



Fiducial phase-space

Z bosons	$p_T(\mu) > 20$ GeV, $2.0 < \eta(\mu) < 4.5$, $60 < m(\mu^+\mu^-) < 120$ GeV
Jets	$20 < p_T(j) < 100$ GeV, $2.2 < \eta(j) < 4.2$
Charm jets	$p_T(c\,\text{hadron}) > 5$ GeV, $\Delta R(j, c\,\text{hadron}) < 0.5$
Events	$\Delta R(\mu, j) > 0.5$

Forward Z + c



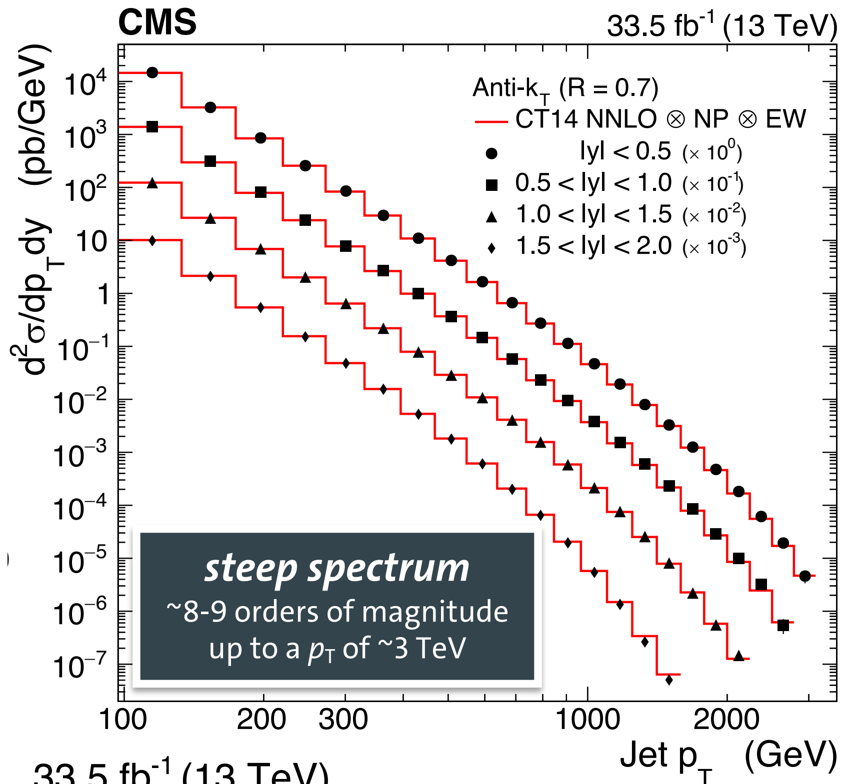
- **Clear enhancement in the highest y bin**
- More consistent with expected effect from $|uudc\bar{c}>$ component predicted by LFQCD
- Incorporating forward results into a global analysis should strongly constrain the large-x charm PDF
- Current results are statistically limited → Run 3 dataset will allow for finer binning
- Need **more NNLO**, **better showering calculations** and further **progress in quantifying PDF uncertainties**

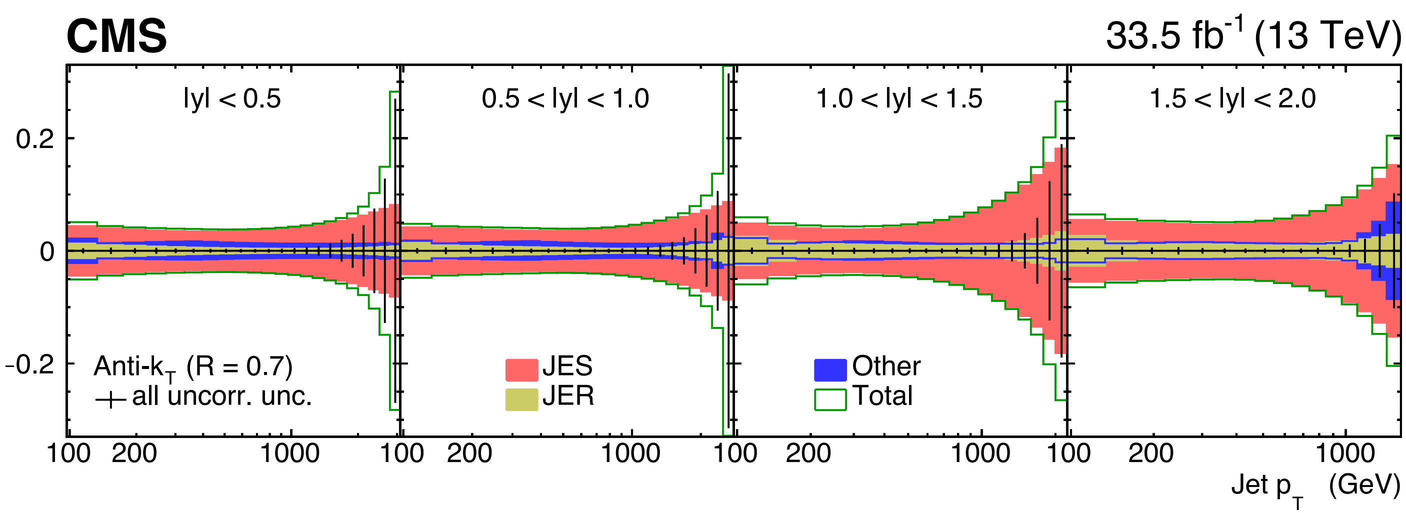
NNPDF analysis finds LHCb Z + c and EMC $F_2^{c\bar{c}}$ data both favour IC at about 3σ

CTEQ analysis expects no significant evidence for NNPDF4.0 IC

Inclusive jet production

- **Double-differential** cross section measured as a function of **jet p_T** and **rapidity** for anti-k_T jets with R = 0.4, 0.7
- Good experimental precision
- **< 5%** uncertainty in main measurement region
- Dominant uncertainty contribution from Jet Energy Scale (**JES**)





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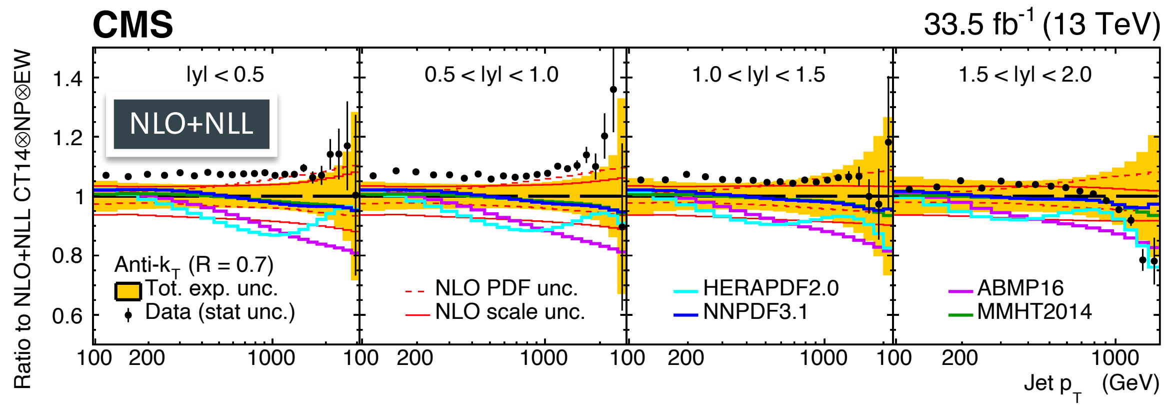
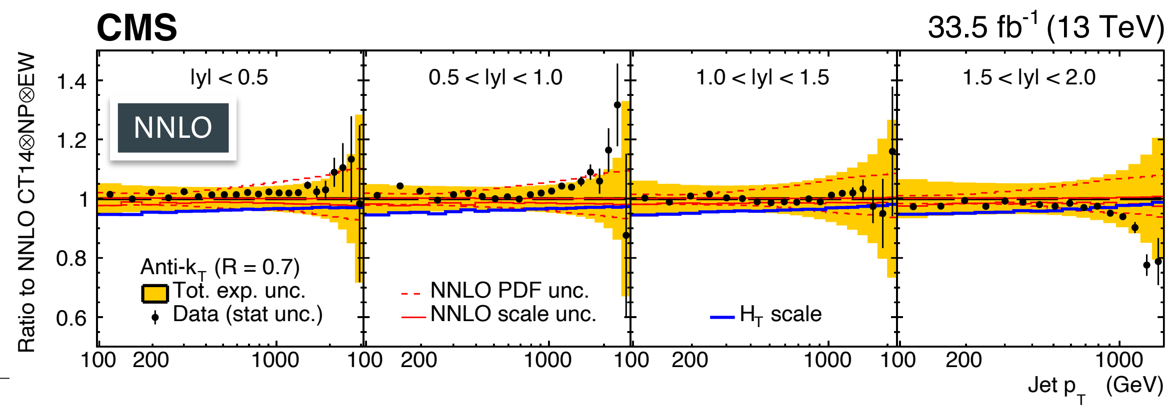
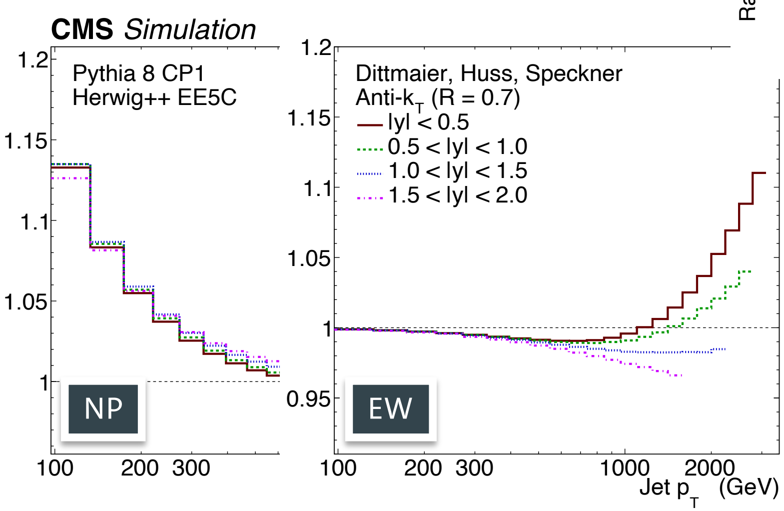
Inclusive jet production

- Comparison to **FO pQCD** theory at **NNLO** and **NLO+NLL**
- Corrections for NP and EW contributions added as well
- Improved description of data at NNLO and **reduced scale uncertainty**







- NNPDF3.1 and MMHT14 provide a better data description wrt ABMP16 and HERAPDF2.0
- **Some disagreement** between global PDF sets, especially in the **high-p_T region**

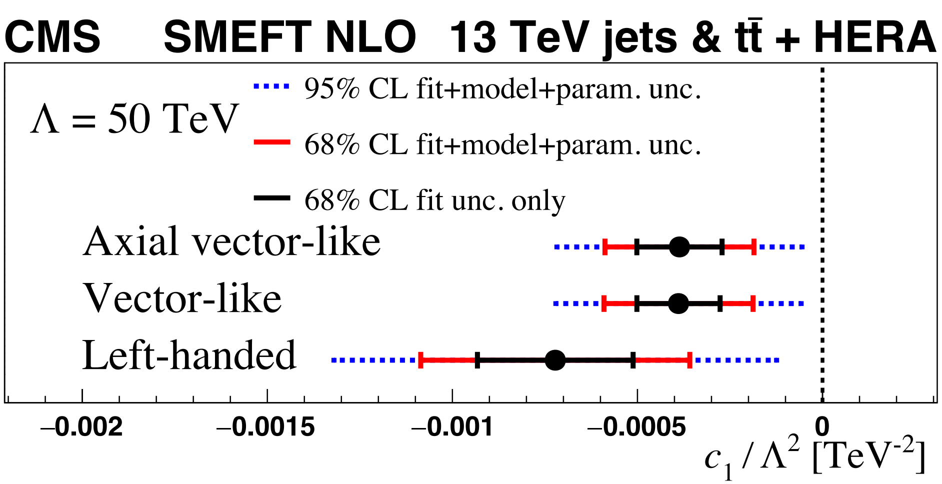
Inclusive jet production

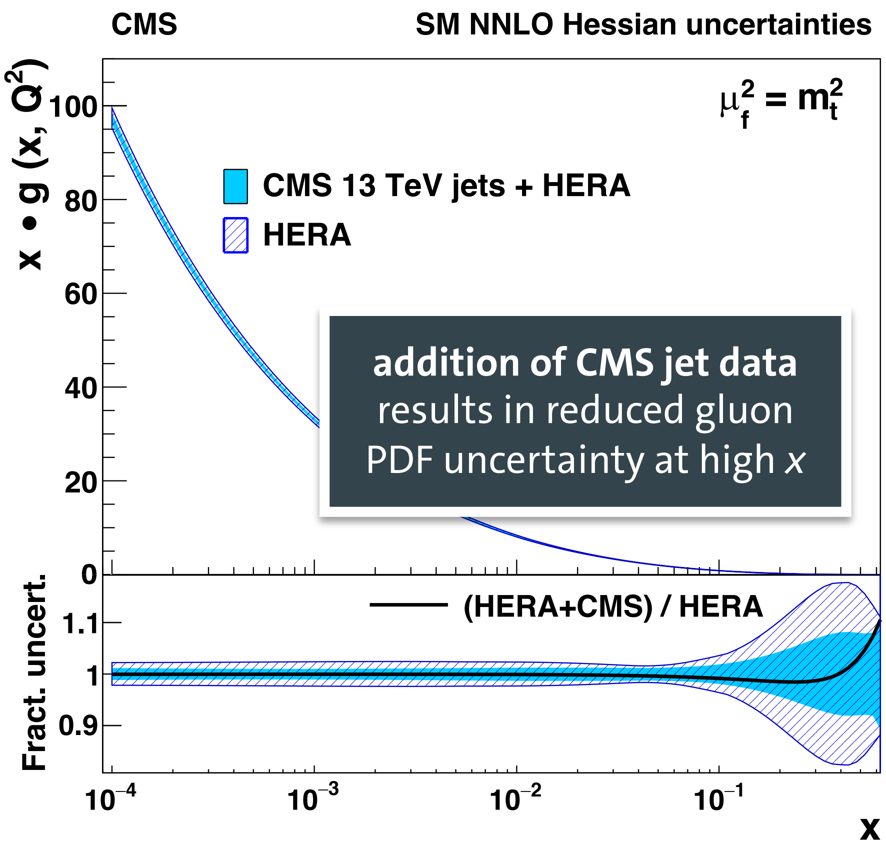
- Determination of **PDFs and α_s at NNLO**

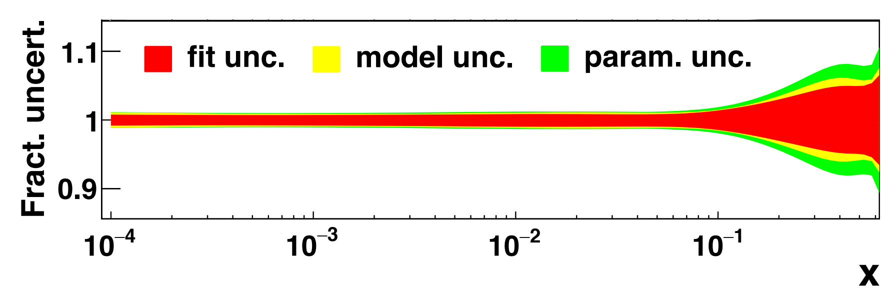
$$\alpha_s(m_Z)_{\mathrm{NNLO}} = 0.1166\ (14)_{\mathrm{fit}}\ (7)_{\mathrm{model}}\ (4)_{\mathrm{scale}}\ (1)_{\mathrm{param.}}$$

↳ $\chi^2 / n_{\mathrm{dof}} = 1302 / 1118$

- **With $t\bar{t}$ data**: limits on Wilson coefficients for four-quark contact interactions
  - Multiple coupling structures probed
  - No significant deviations found



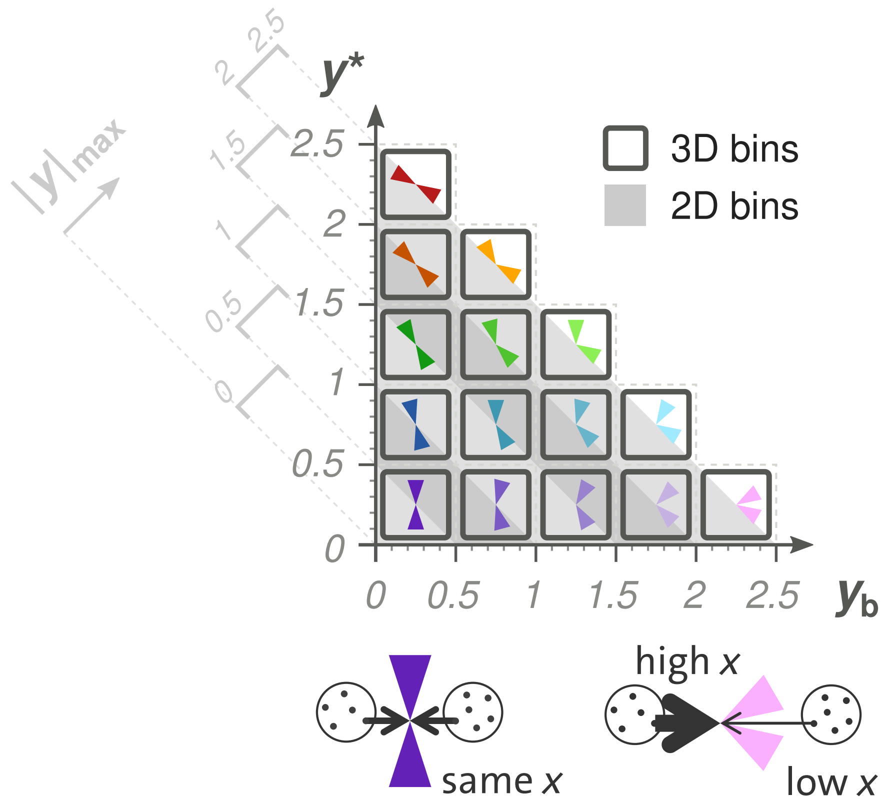


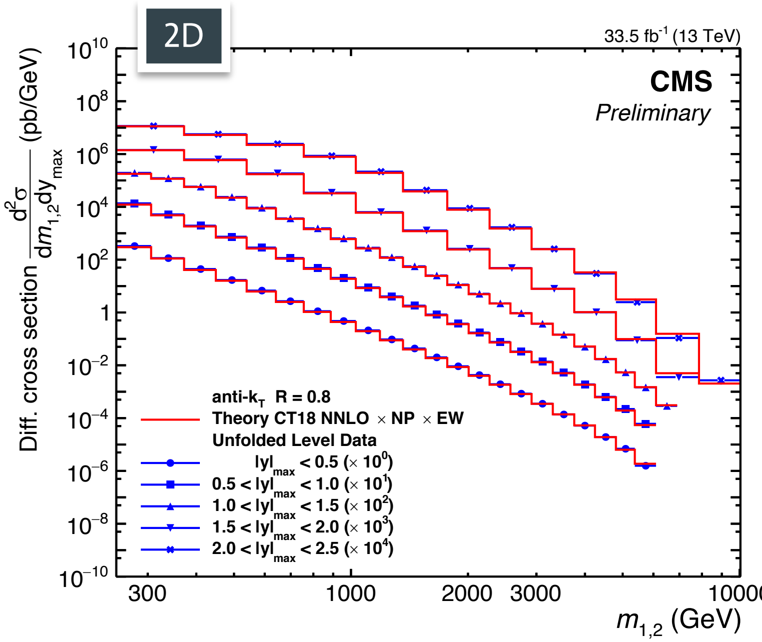


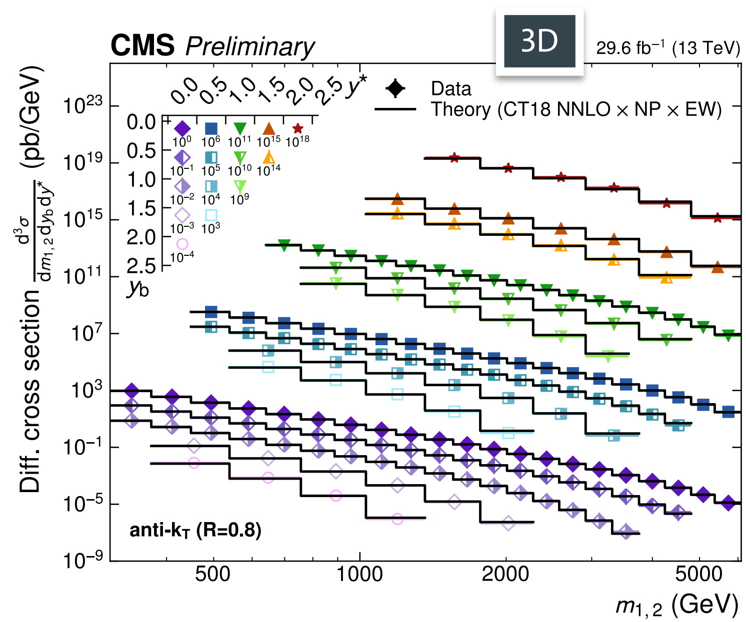
Dijets production

CMS-PAS-SMP-21-008

- **Double- and triple-**differential cross section measured as a function of **dijet invariant mass $m_{1,2}$** and **rapidity** of anti-k_T jets with **R = 0.4, 0.8**
- Disentangle regions of different Bjorken x carried by partons → **PDF fits**

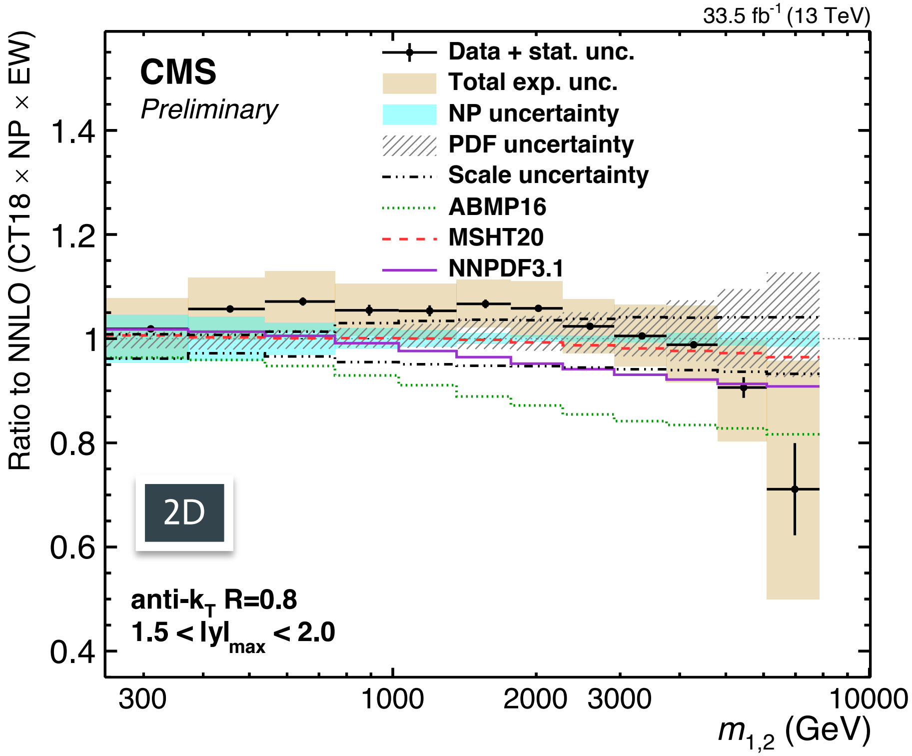


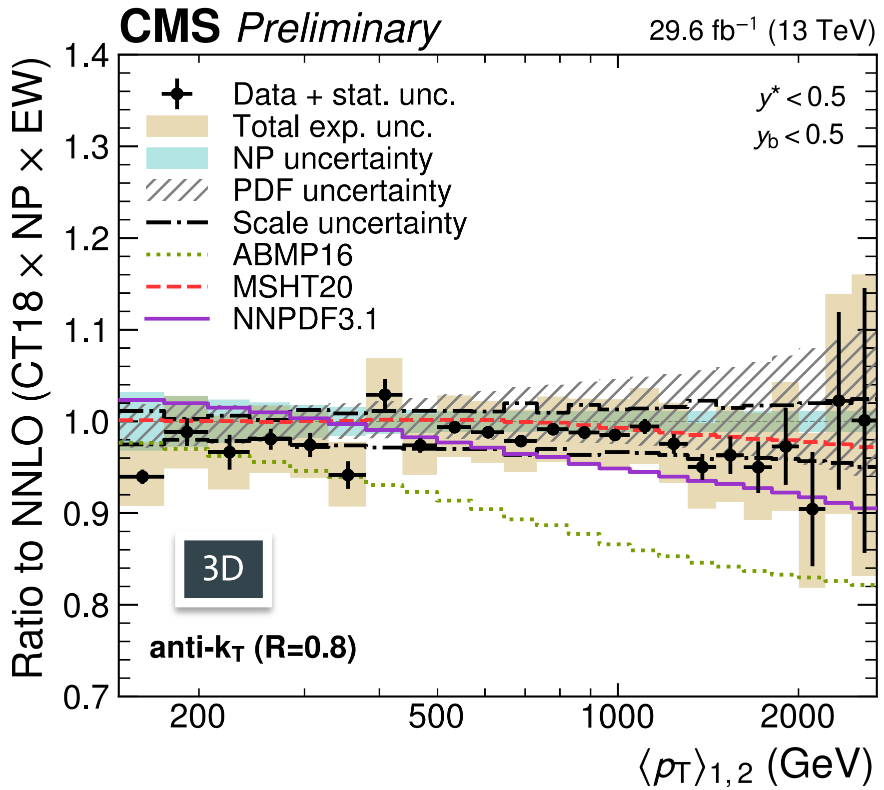




Dijets production

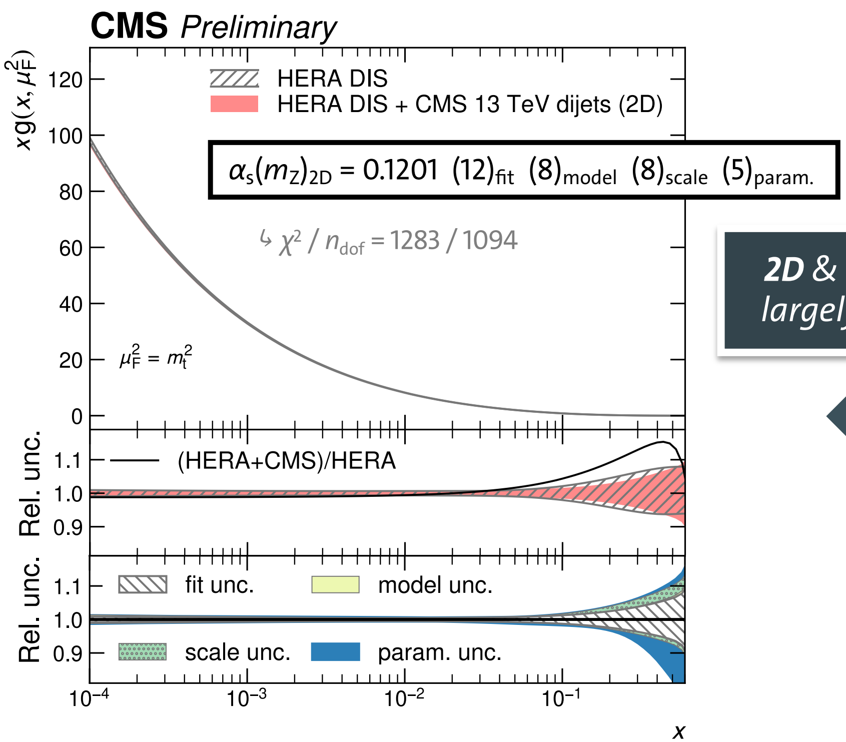
- Comparison to **FO theory** predictions at **NNLO + EW + NP**
- Data generally well described by the theory
- Here **R = 0.8** (similar agreement found for R = 0.4)
- MSHT20 (ABMP16) provides the best (worst) description of the data



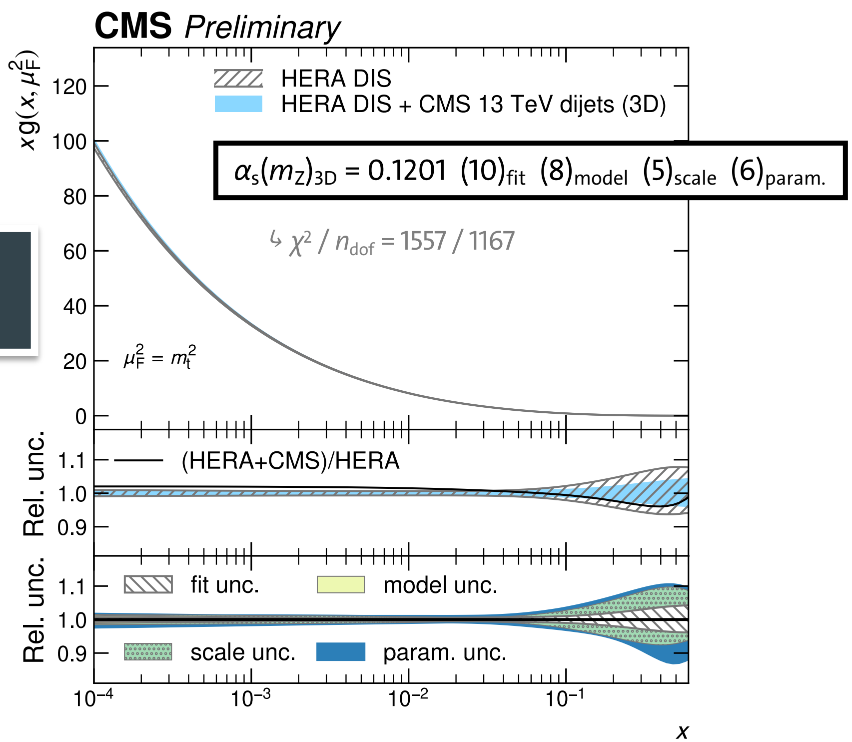


Dijets production

- Determination of **PDFs and α_s at NNLO**
- Larger α_s value wrt the one obtained when fitting the inclusive jet distributions
- Impact on the gluon PDF (and its uncertainty) mostly for Bjorken x > 0.1
- Pulls in different directions

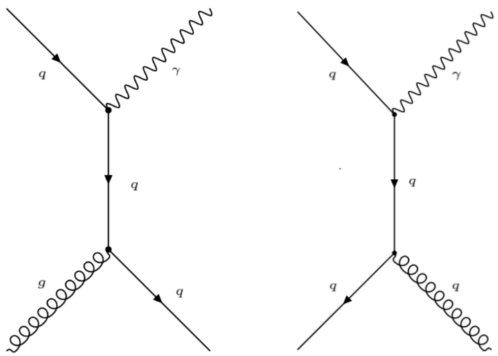


2D & 3D fit results largely compatible



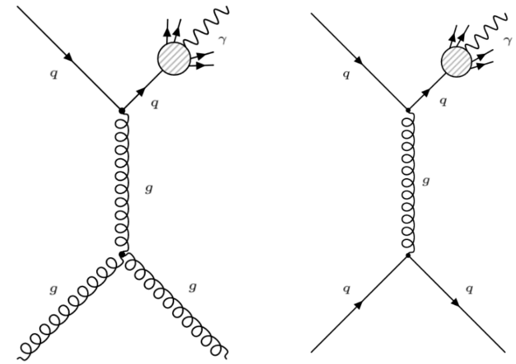
Inclusive photon production

- The production of high-p_T prompt photons (not coming from hadron decays) proceeds via 2 mechanisms:



Direct processes

JHEP 07 (2023) 086

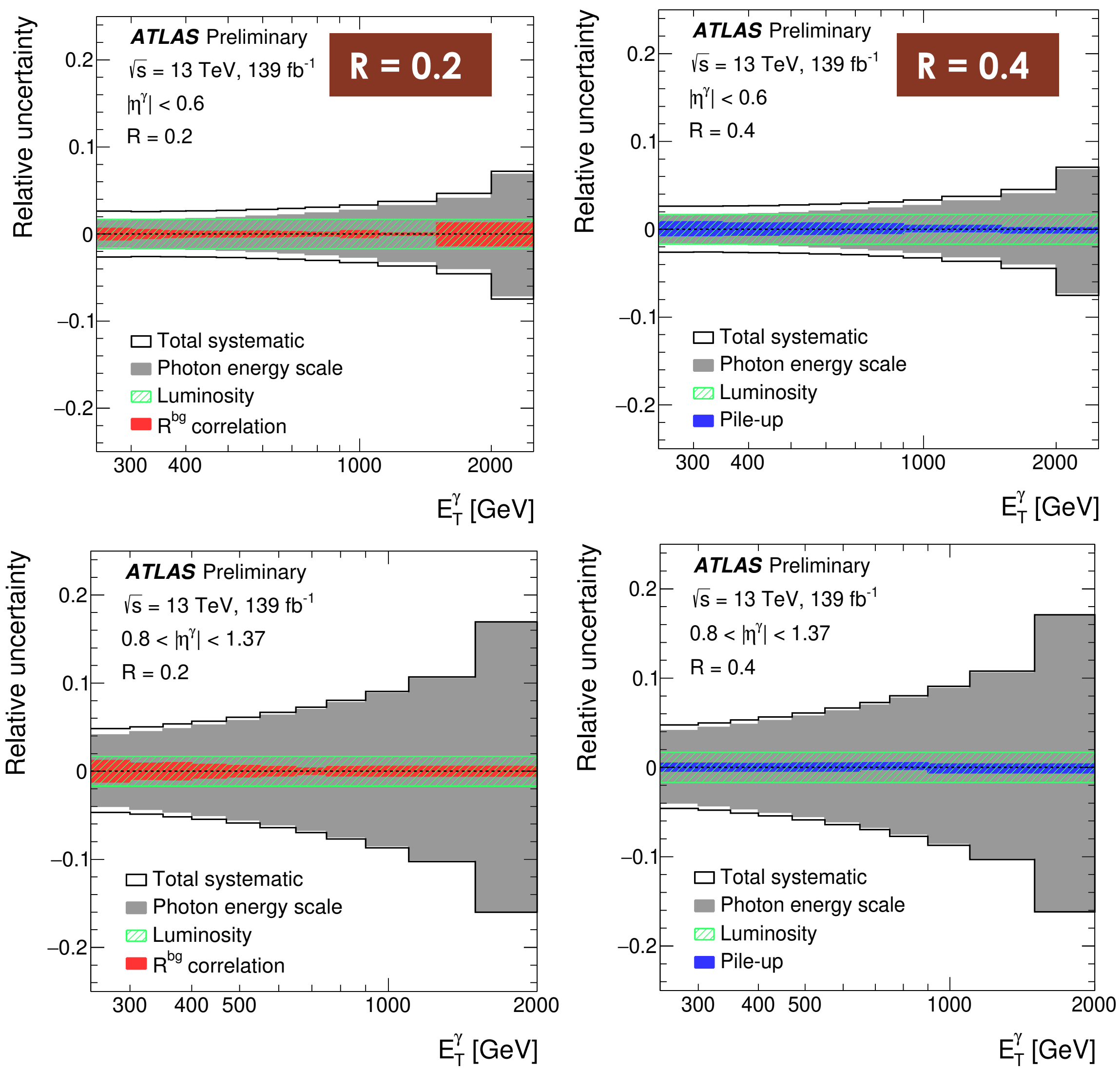


Fragmentation processes

- Measurements of inclusive isolated-photon cross sections
  - Provide a testing ground for pQCD with a hard colourless probe
  - Are sensitive to the gluon PDF (via $qg \rightarrow q\gamma$) → input for global QCD fits

- Previous studies performed using 36 fb^{-1} from 2015+2016 data taking
  - Including the full Run-2 data provides higher E_T^{γ} values with smaller statistical uncertainties
  - The new measurements benefit from reduced systematics thanks to the work of the ATLAS Combined Performance groups

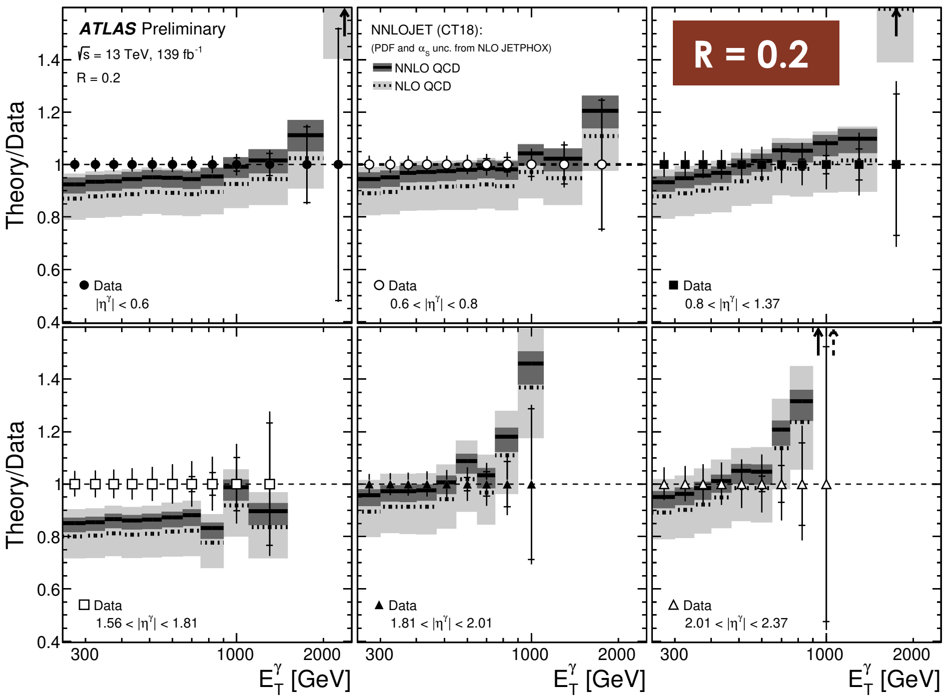
Inclusive photon production

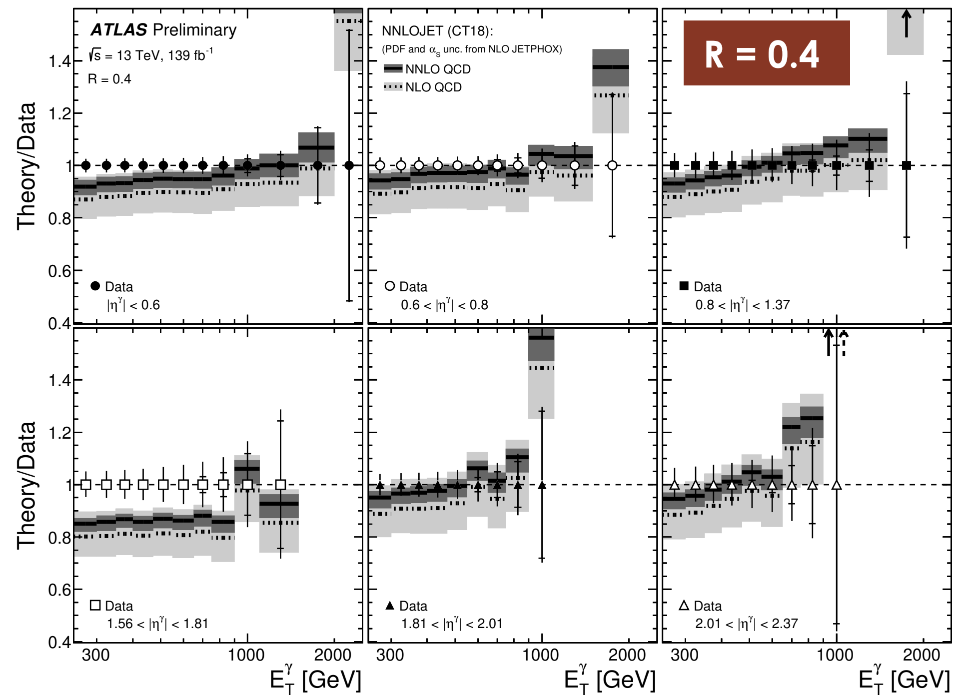


- Total systematic uncertainty and dominant contributions
- Dominant sources:
  - Photon energy scale
  - Luminosity measurement
  - R^{bg} correlation (Pile up) for R = 0.2 (R = 0.4)
- Photon ID efficiency uncertainty significantly reduced wrt the previous analysis (1-3% → ~0.6%)

Inclusive photon production

- The NNLO pQCD predictions of NNLOJET compared to the measured differential cross sections as functions of E_T^{γ} in different $|y^{\gamma}|$ regions



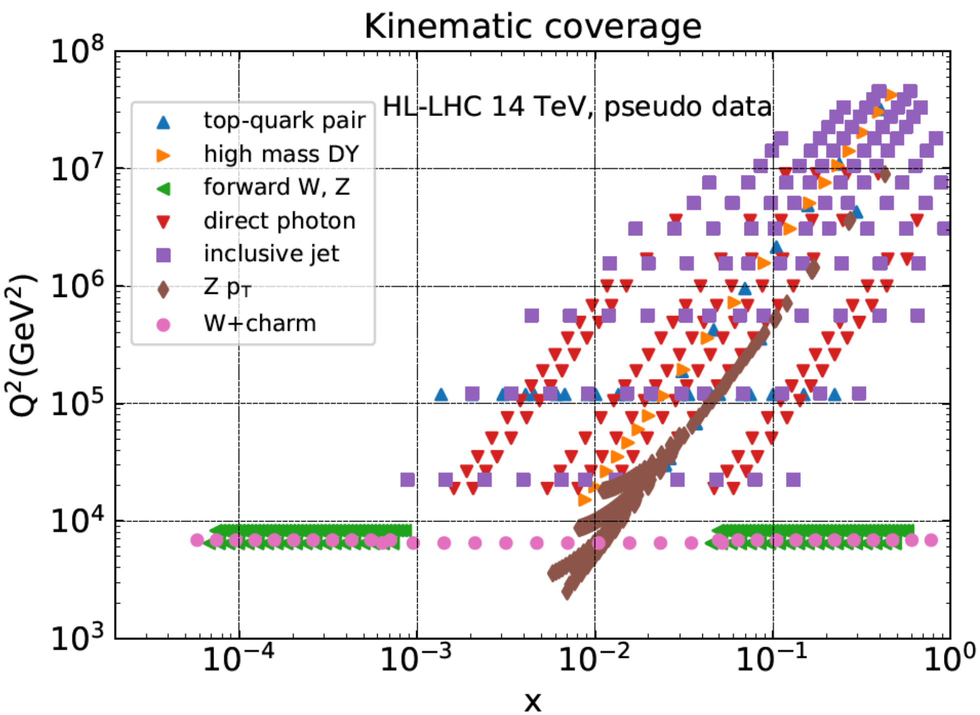


- Predictions are consistent with the measurements within uncertainties, except in the region $1.56 < |y^{\gamma}| < 1.81$, where the NNLO predictions underestimate the data

- Visible reduction of scale uncertainties in NLO → NNLO

- **Different isolation radii for the first time** as requested by theorists - 1904.01044

HL-LHC PDFs

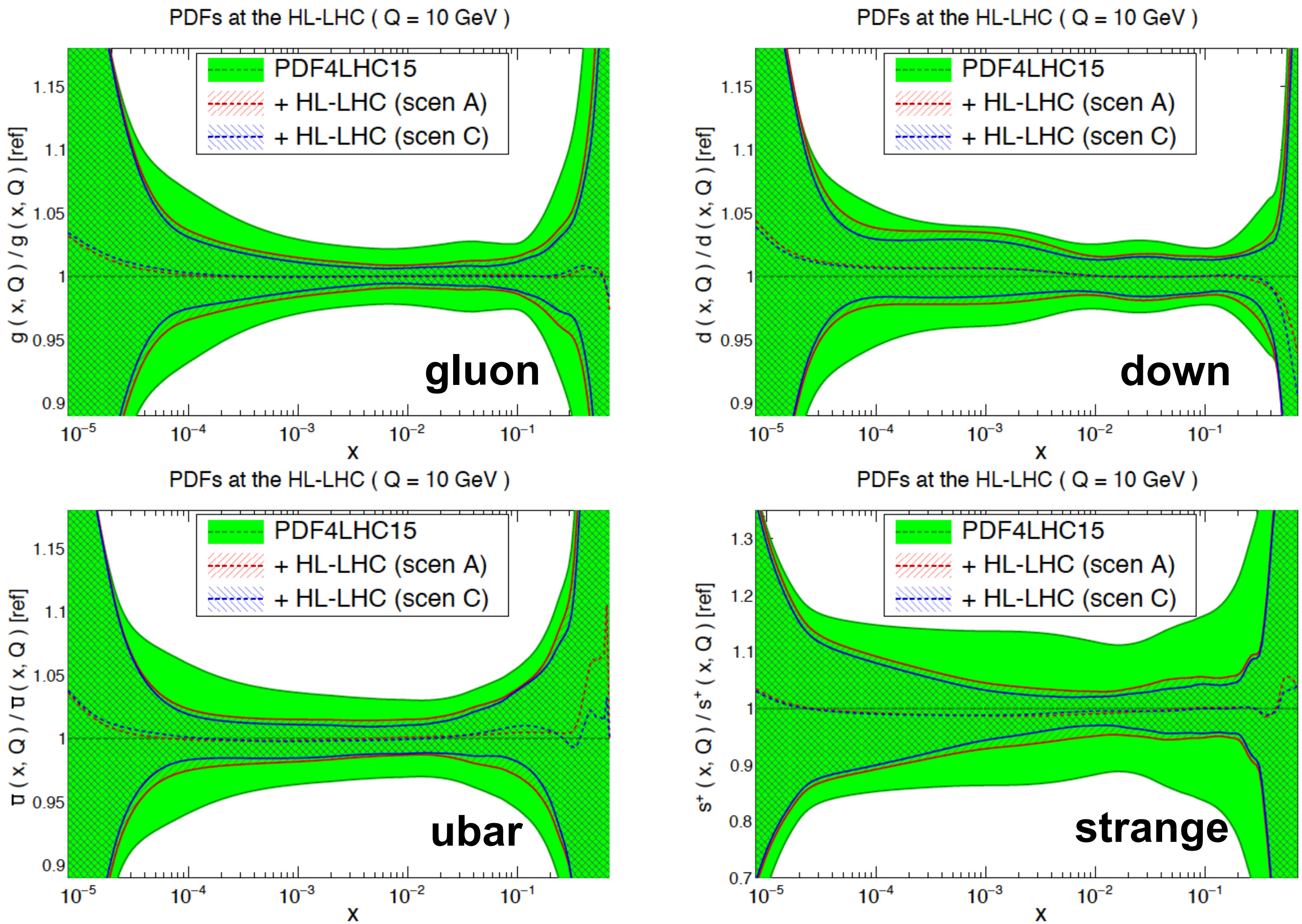


sys(14 TeV) ~ f_{corr} × f_{red} × sys(8/13 TeV)

Hessian profiling of PDF4LHC15 (with tolerance T = $\sqrt{\Delta\chi^2}$ = 9)

- **Study PDF constraints** expected from LHC measurements by end of HL-LHC phase (2027 to end-2030s)
- ATLAS+CMS 3 ab^{-1}, LHCb 0.3 ab^{-1}
- CERN YR: 1902.04070
- Focus on datasets sensitive to mid-to-large-x and not already systematics limited
- Systematics taken from existing data
- Treated as uncorrelated (f_{corr} = 0.5), chosen to approximately reduce effect of systematic correlations
- f_{red} to estimate improvement to systematics

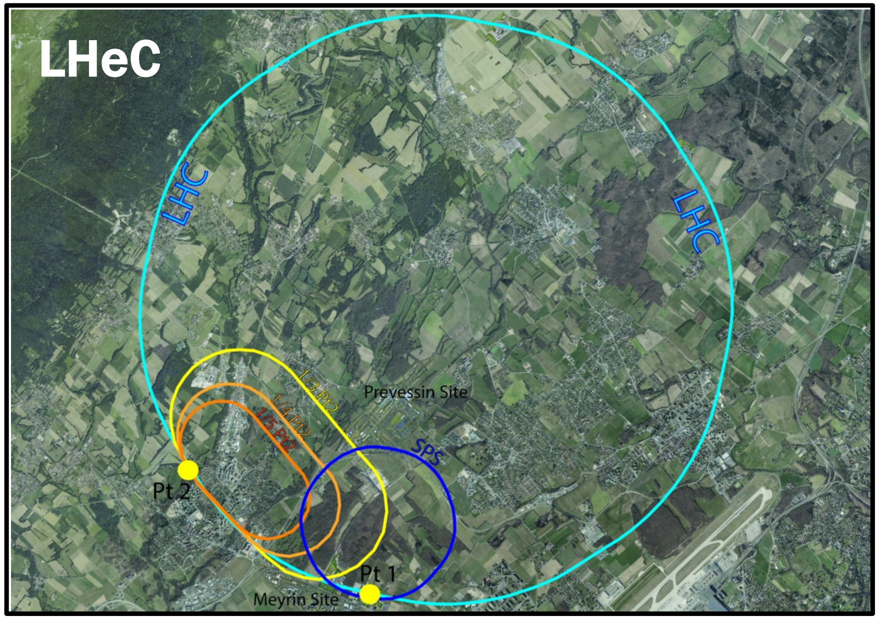
HL-LHC PDFs

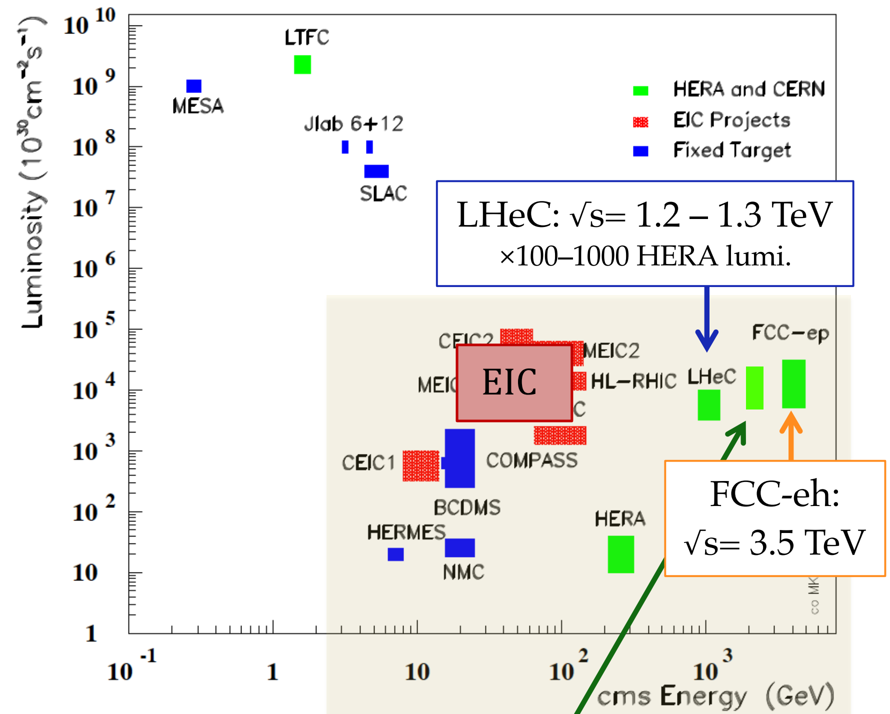


f_{red} { 1/0.5 (8/13) TeV → scenario A: conservative
0.4/0.2 (8/13 TeV) → scenario C: optimistic

Together with intermidiate scenario B, all are available in LHAPDF format

LHeC, FCC-eh and PERLE

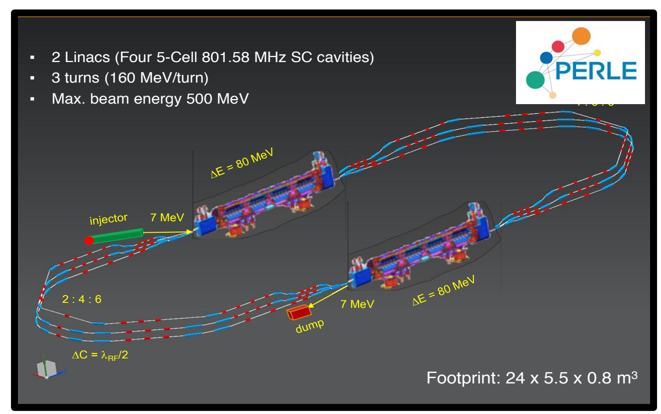




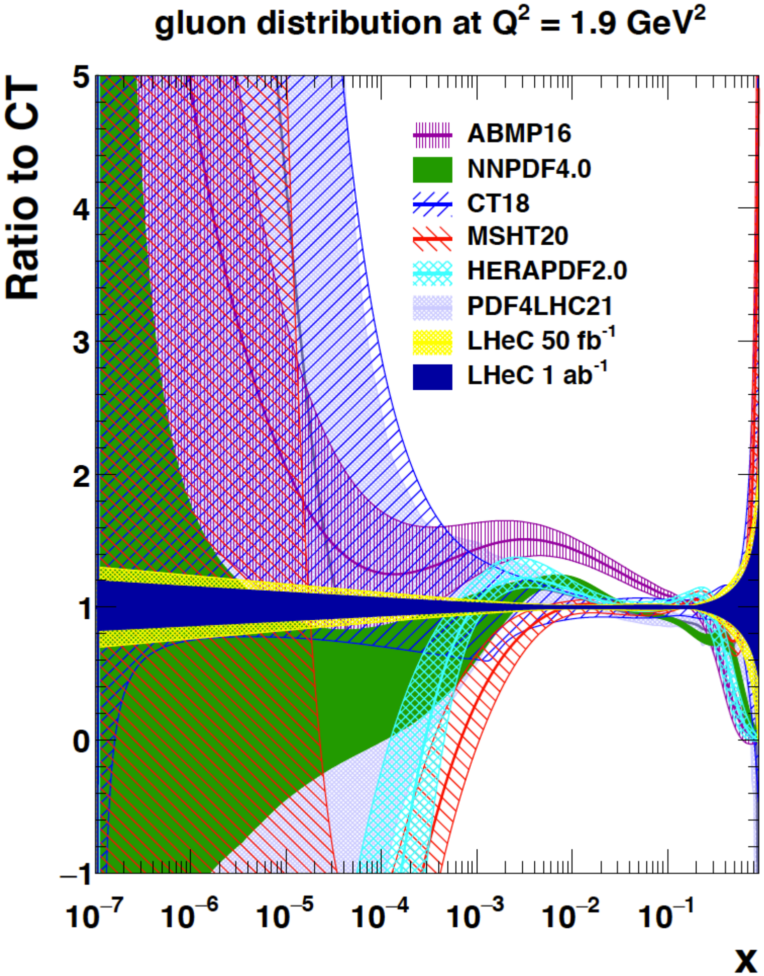
"LE-FCC-eh": √s= 2.1 TeV
(earlier operation with current magnet technology, Ep=19 TeV)

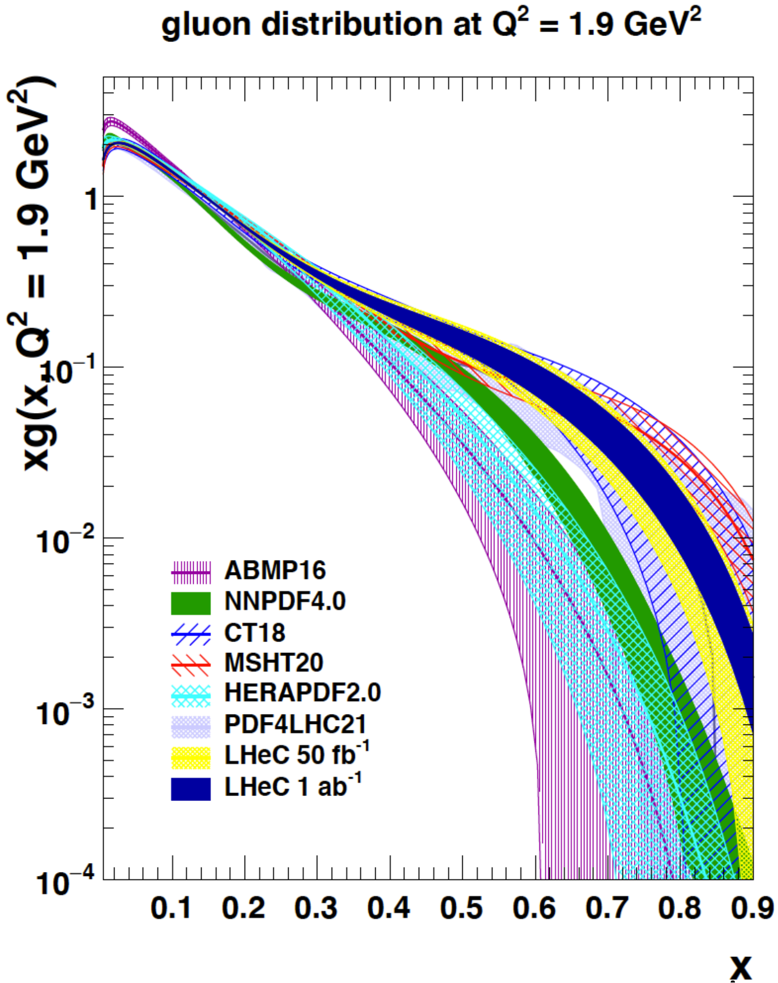
- **Energy Recovery LINAC** (ERL) <u>attached to HL-LHC (or FCC)</u>
  - e beam → 50/60 GeV
  - e polarisation → ± 0.8
  - $\int \mathcal{L}$ = 1-2 ab^{-1} (x100-1000 HERA!)

- PERLE: international collaboration built to realise 500 MeV facility at Orsay, for development of ERL with LHeC conditions



Gluon PDF





- **Uncertainties on the high-x gluon PDF reduced drastically!**
- LHeC data have even a better effect when jets are involved (not here) – more results in backup

Combining HL-LHC and LHeC

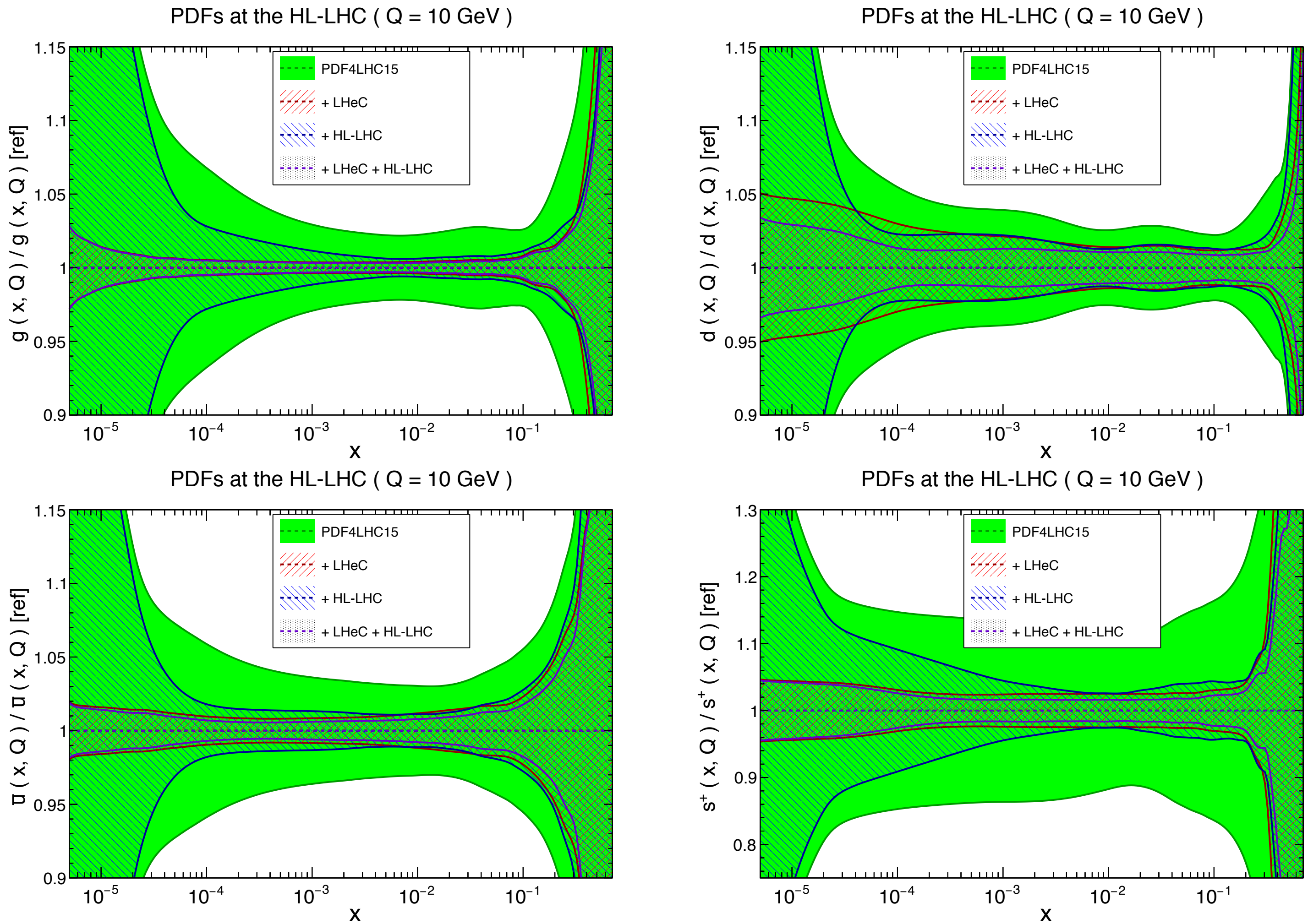
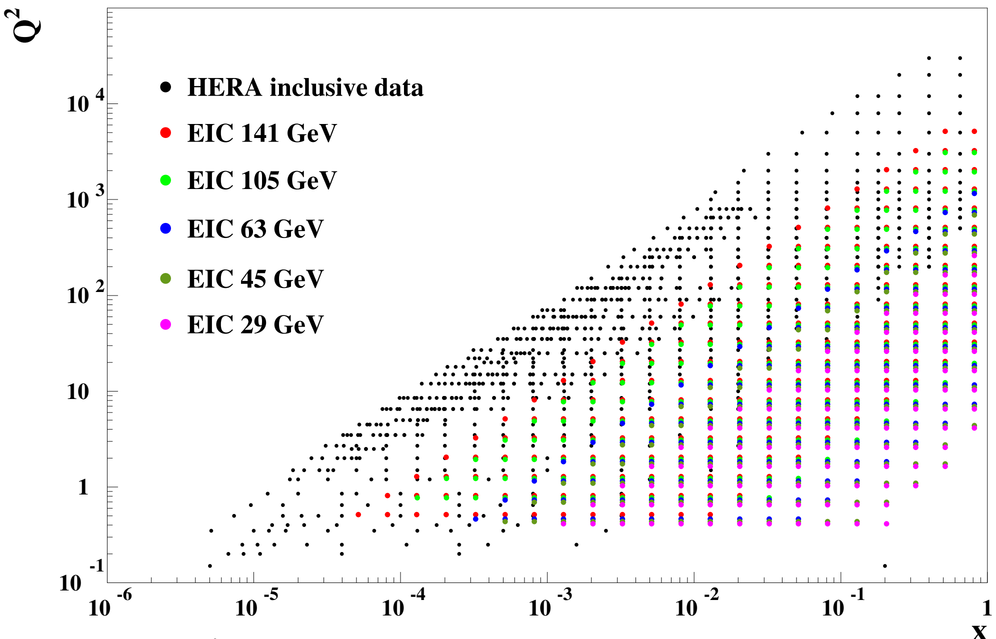


Figure 9.9: Impact of LHeC on the 1-σ relative PDF uncertainties of the gluon, down quark, anti–up quark and strangeness distributions, with respect to the PDF4LHC15 baseline set (green band). Results for the LHeC (red), the HL-LHC (blue) and their combination (violet) are shown. EPJC 78 (2018) 11, 962

PDFs at the EIC

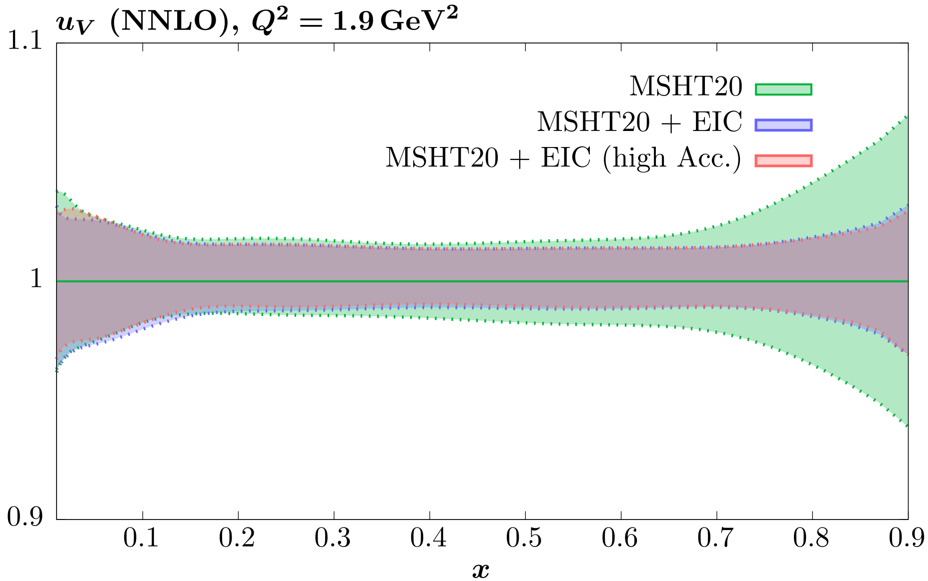
- **EIC** will be the first
  - **eA collider**
  - **High lumi ep collider**
  - **Polarised target collider**
- Detailed simulation work to optimise resolution throughout phase space → 5 bins per decade in x and Q^2
- Kinematic coverage: $Q^2 > 1$ GeV^2, $0.01 < y < 0.95$, $W > 3$ GeV
- Lower y accessible in principle, but easier to rely on overlaps between data at different $\sqrt{s}$

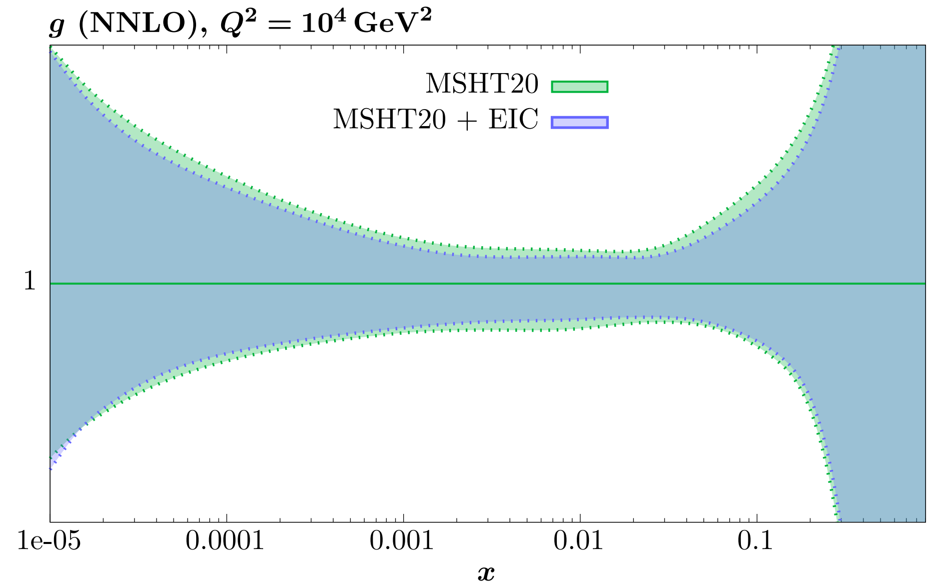
e-beam E	p-beam E	$\sqrt{s}$ (GeV)	inte. Lumi. (fb^{-1})
18	275	140	15.4
10	275	105	100.0
10	100	63	79.0
5	100	45	61.0
5	41	29	4.4



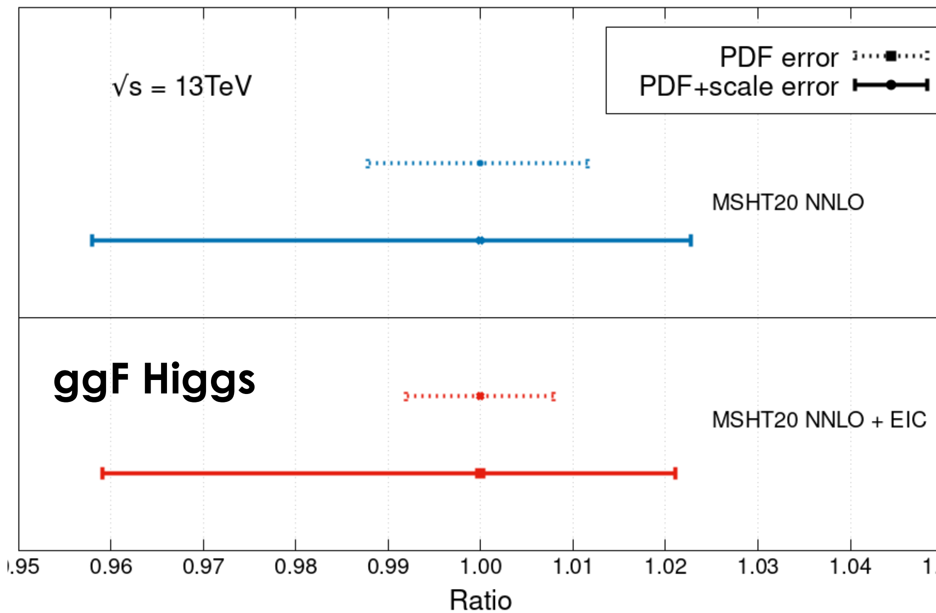
- Dominant sources at HERA were:
  - Electron energy scale (intermidiate y)
  - Photoproduction background (high y)
  - Hadronic energy scale/noise (low y)
- **EIC will improve in all areas** – systematics assumptions in YR:
  - 1.5-2.5% point-to-point uncorrelated
  - 2.5% normalisation (uncorrelated between different $\sqrt{s}$)

Impact of EIC on MSHT20





Small but valuable improvements in all parton species at all (x, Q²)



More in Paul's talk on Wednesday

Summary

- We are now in the middle of LHC Run 3… More and more data to be analysed soon!

- They will allow to:
  - Test precisely perturbative QCD
  - Measure fundamental parameters of the SM
  - Improve our understanding of PDFs
  - Provide important inputs to simulations

- Energy frontier ep/eA colliders essential for full exploitation of current and future hadron colliders - **all critical PDF information can be obtained!**

- Few aspects to work on:
  - Compute higher order corrections
  - Include correlations between different data sets might have few % effect (EPJC 82 (2022) 5, 438) – crucial if O(1%) is sought on PDF determination
  - More 'realistic' predictions for future colliders - real data always has tensions and non-Gaussian systematics

- Incredibly interesting time ahead… Stay tuned! ☺

Backup Slides

Factorisation theorem

$$\sigma(x, Q^2) = \int_x^1 \frac{dz}{z} C_i(z, \alpha_S(Q^2)) f_i\left(\frac{x}{z}, Q^2\right) = C_i \otimes f_i$$

Partonic cross sections:
- Process dependent
- High-scale (short-distance) objects
- Computable in perturbation theory (LO, NLO, NNLO, N^{3}LO)

PDFs:
- Universal (process independent)
- Low-scale (long-distance) objects
- Non computable in perturbation theory
- Scale dependence perturbative (DGLAP)

➢ Once PDFs have been **determined at a given scale**, the **DGLAP** evolution equations can be used to **evolve them to any other scale**

$$\mu^2 \frac{\partial}{\partial \mu^2} f_i(\mu) = P_{ij} \otimes f_j(\mu)$$

$$P_{ij}(y) = \frac{\alpha_S(\mu)}{2\pi} P_{ij}^{(0)}(y) + \left(\frac{\alpha_S(\mu)}{2\pi}\right)^2 P_{ij}^{(1)}(y) + \ldots$$

Splitting functions

How do we determine PDFs?

- Presently, the most accurate and reliable way is through **fits to data**

$f_i(x, Q_0^2)$

$x = p_i/p_p$
$0 < x < 1$
$Q_0 \sim 1$ GeV
(initial scale)

DGLAP

$f_i(x, Q^2)$

Q = scale of the fitted data

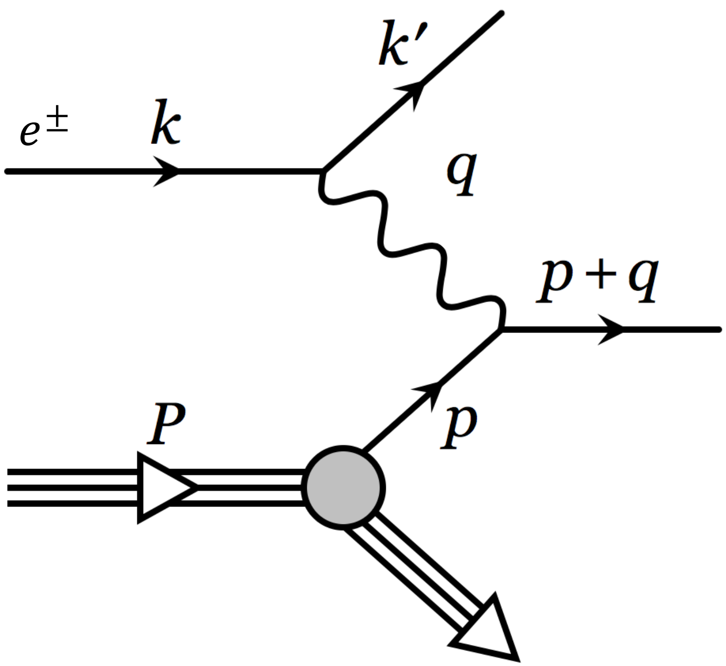
Factorisation theorem

$\sigma = C_i \otimes f_i$

Fitting

Predictions vs data

Deep Inelastic Scattering (DIS)



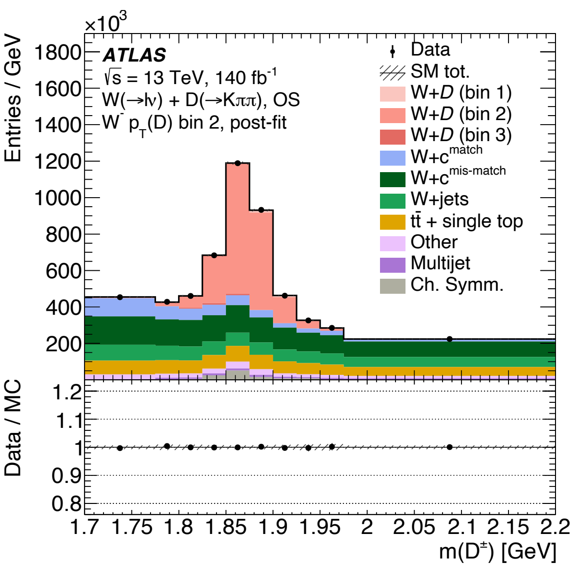
Measurement of W + charmed hadron

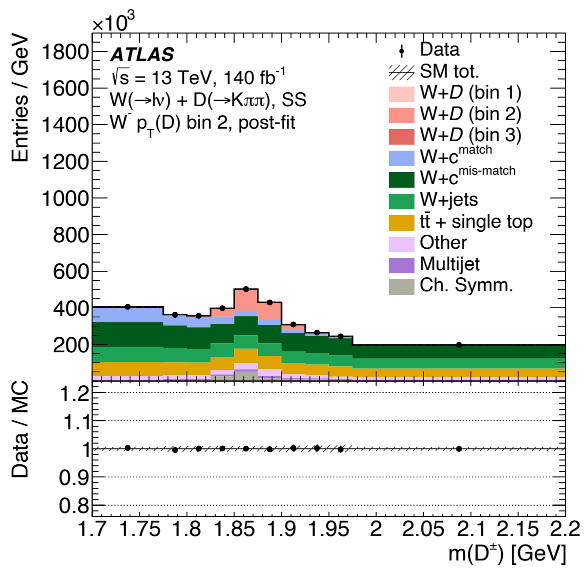
- Main backgrounds:
  - W + c^{match}: tracks in SV belong to different c-hadron or decay mode
  - W + c$^{mis\text{-}match}$: not all tracks belong to $D^{\pm(*)}$ candidate
  - W + jets: no track belong to $D^{\pm(*)}$ candidate
  - Top constrained in data region with ≥ 1 b-jet
  - Multijet from fake-enriched region in data

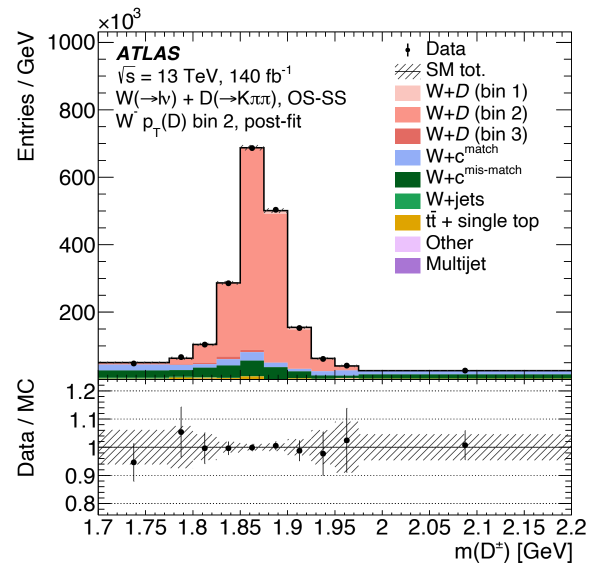
Backgrounds						
Z + jets	SHERPA 2.2.11	0–2j@NLO+3–5j@LO	NNPDF3.0NNLO	SHERPA	Default	SHERPA
$t\bar{t}$	POWHEG BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8	A14	EVTGEN
Single-t, Wt	POWHEG BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8	A14	EVTGEN
Single-t, t-channel	POWHEG BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8	A14	EVTGEN
Single-t, s-channel	POWHEG BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8	A14	EVTGEN
$t\bar{t}V$	aMC@NLO	NLO	NNPDF3.0NLO	PYTHIA 8	A14	EVTGEN
Diboson fully leptonic	SHERPA 2.2.2	0–1j@NLO+2–3j@LO	NNPDF3.0NNLO	SHERPA	Default	SHERPA
Diboson hadronic	SHERPA 2.2.1	0–1j@NLO+2–3j@LO	NNPDF3.0NNLO	SHERPA	Default	SHERPA

Measurement of W + charmed hadron

- Signal events have opposite-sign (OS) W boson and D meson
- Backgrounds mostly charge-symmetric, suppressed by subtracting same-sign (SS) events
- **Binned profile likelihood fit** of OS and SS $m(D^{(*)})$ template
- $m(D^{(*)})$ fit at particle level in bins of $p_T(D^{(*)})$ and $|\eta_l|$
- Simultaneous fit to **SS and OS templates**, extract signal cross sections in a background-subtracted OS-SS region



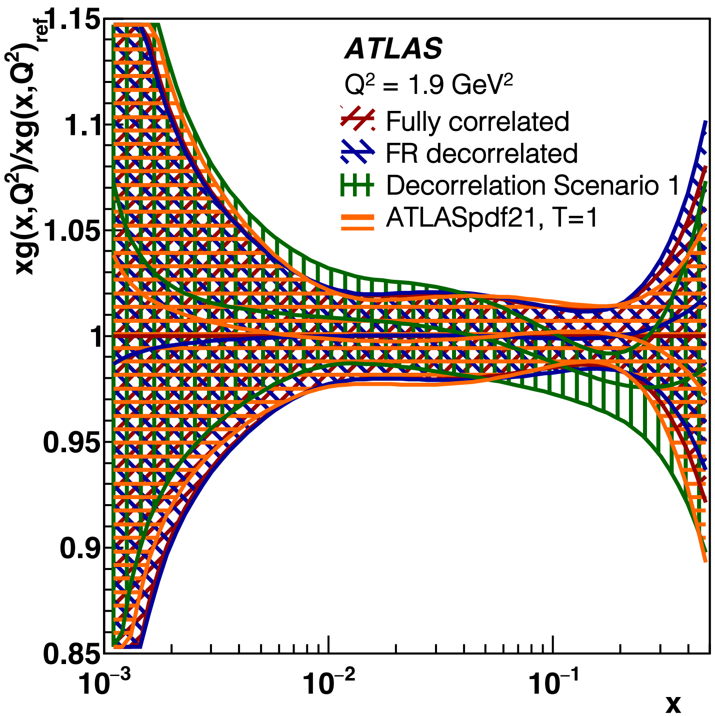


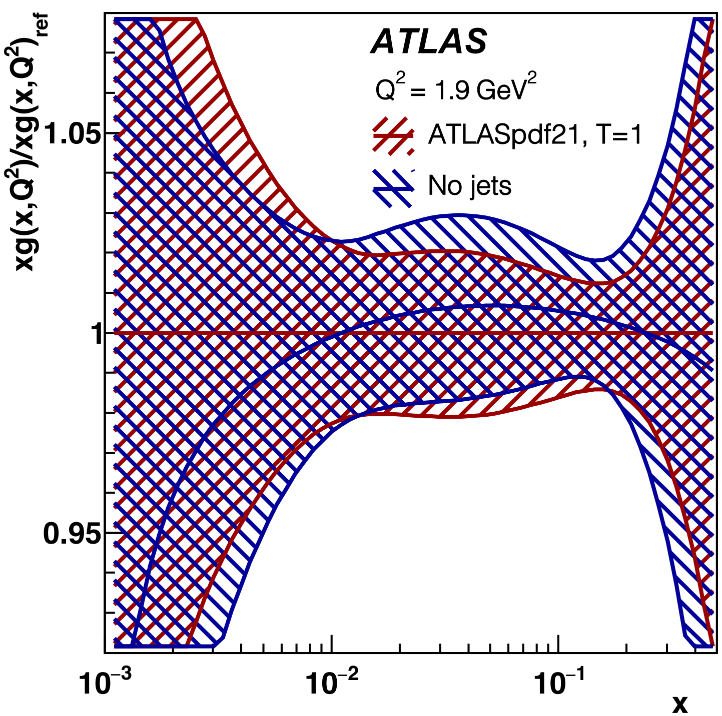


Talking about inclusive jets

- Different model to treat correlated systematics: EPJ C82 (2022) 5, 438
  - keeping them fully correlated
  - decorrelating the Jets Flavour Response (FR) between rapidity bins
  - Two decorrelation scenarios as recommended in the 8 TeV jet paper
- This affects the χ^2 but has little effect on the PDFs

jets 8 TeV R=0.6	Fully Correlated	FR Decorrelated	Decorrelation Scenario 1	Decorrelation Scenario 2
χ^2/NDP	289/171	227/171	250/171	248/171





Marginal shape change of the gluon PDF (blue to red) and **very substantial decrease in its high-x uncertainty**

Inclusive photon production

JETPHOX (fixed order)

- **Full fixed-order NLO pQCD calculations for direct and fragmentation processes**
- **Scales:** $\mu_R = \mu_F = \mu_f = E_T^\gamma/2\,(E_T^\gamma)$
- **Fragmentation functions:** BFG II
- **PDFs:** MMHT2014, CT18, NNPDF3.1, and HERAPDF2.0 at NLO; ATLASpdf21 at NNLO
- **Isolation:** fixed cone at parton level
- **Non-perturbative corrections:** estimated using PYTHIA samples. Consistent with unity within $\pm 1\,\%$ (no correction applied)

SHERPA NLO (multi-leg merged)

- **Parton-level calculations for** $\gamma + 1{,}2\,(3{,}4)$ **jets at NLO (LO) supplemented with PS**
- Only direct contribution (Frixione's isolation at ME level)
- **Scales:** dynamic scale setting (E_T^γ)
- **PDFs:** NNPDF3.0 NNLO
- **Fragmentation into hadrons and UE simulated as for SHERPA LO**
- **Isolation:** fixed cone at particle level

NNLOJET (fixed order)

- **Full fixed-order NNLO pQCD calculations for direct and fragmentation processes**
- **Scales:** $\mu_R = \mu_F = E_T^\gamma$

$$\mu_f = \sqrt{E_T^\gamma \cdot E_T^{\max}} \cdot R$$

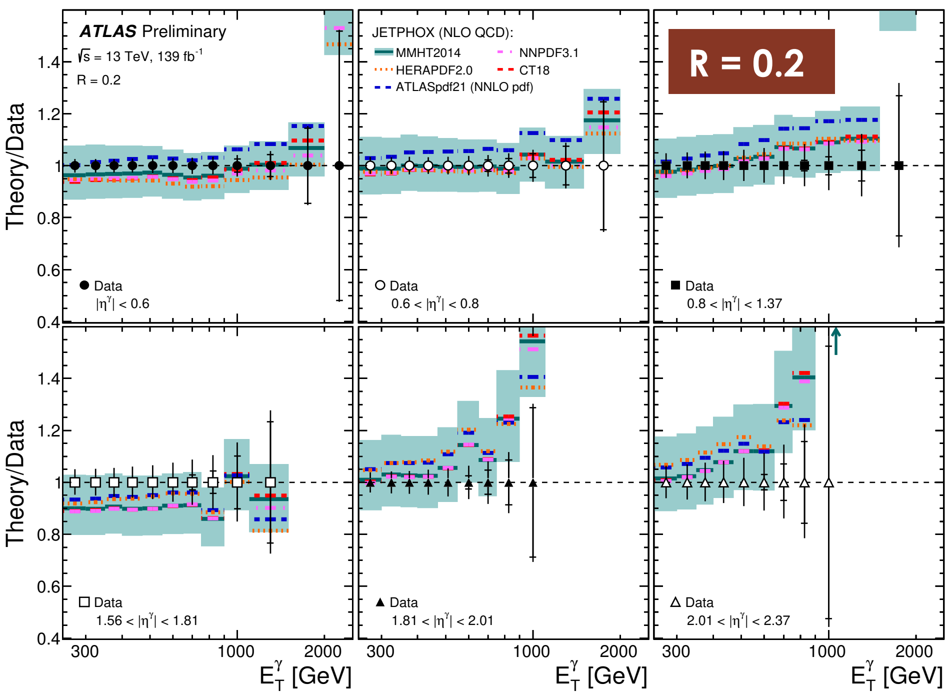
- **Fragmentation functions:** BFG II
- **PDFs:** CT18 NNLO
- **Isolation:** fixed cone at parton level
- **Non-perturbative corrections:** same estimation as for JETPHOX

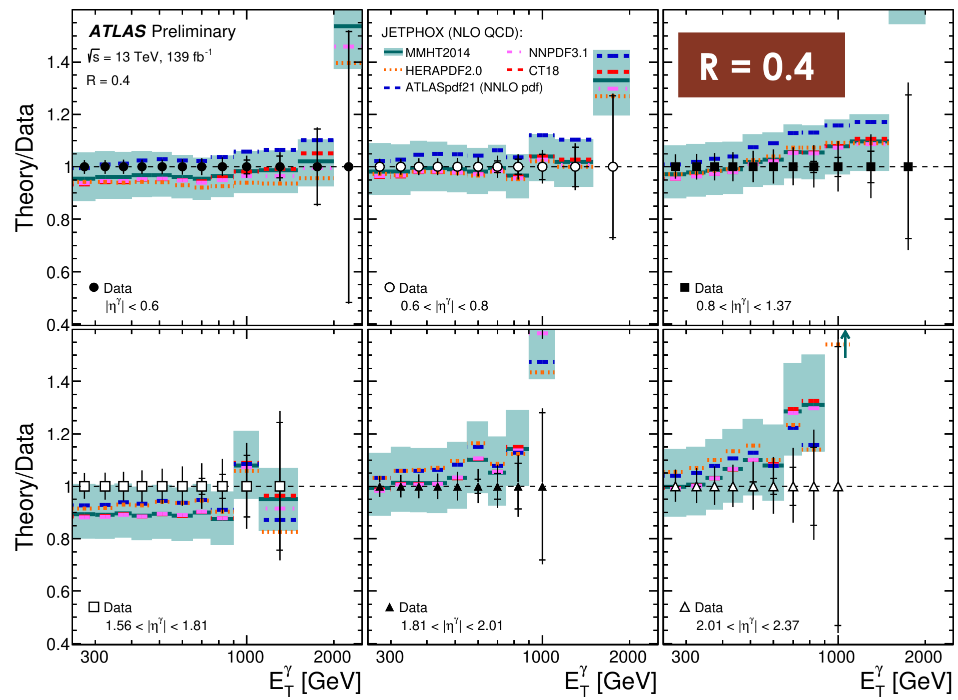
➢ Theoretical uncertainties: scale variations ($\mu_R, \mu_F \cdot$ 0.5, 2 varied singly or simultaneously), μ_f (fragmentation scale) PDFs, α_S, non-perturbative corrections (only JETPHOX and NNLOJET)

➢ NNLOJET scale uncertainties reduced by more than a factor of 2 wrt NLO calculations of JETPHOX and SHERPA

Inclusive photon production

- The NLO pQCD predictions of JETPHOX compared to the measured differential cross sections as functions of E_T^{γ} in different $|y^{\gamma}|$ regions
  - Several PDFs: MMHT14, CT18, NNPDF3.1, HERAPDF2.0 and ATLASpdf21

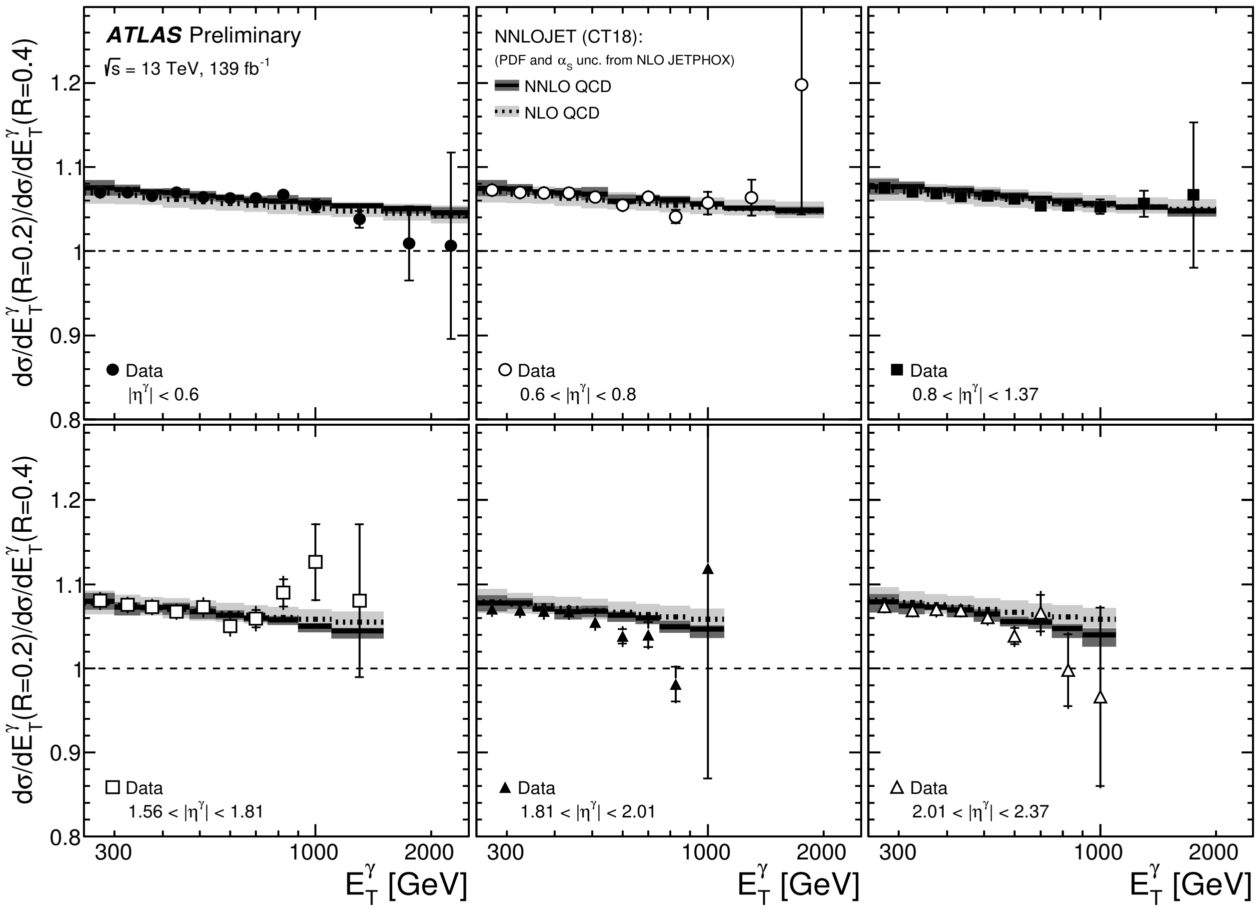




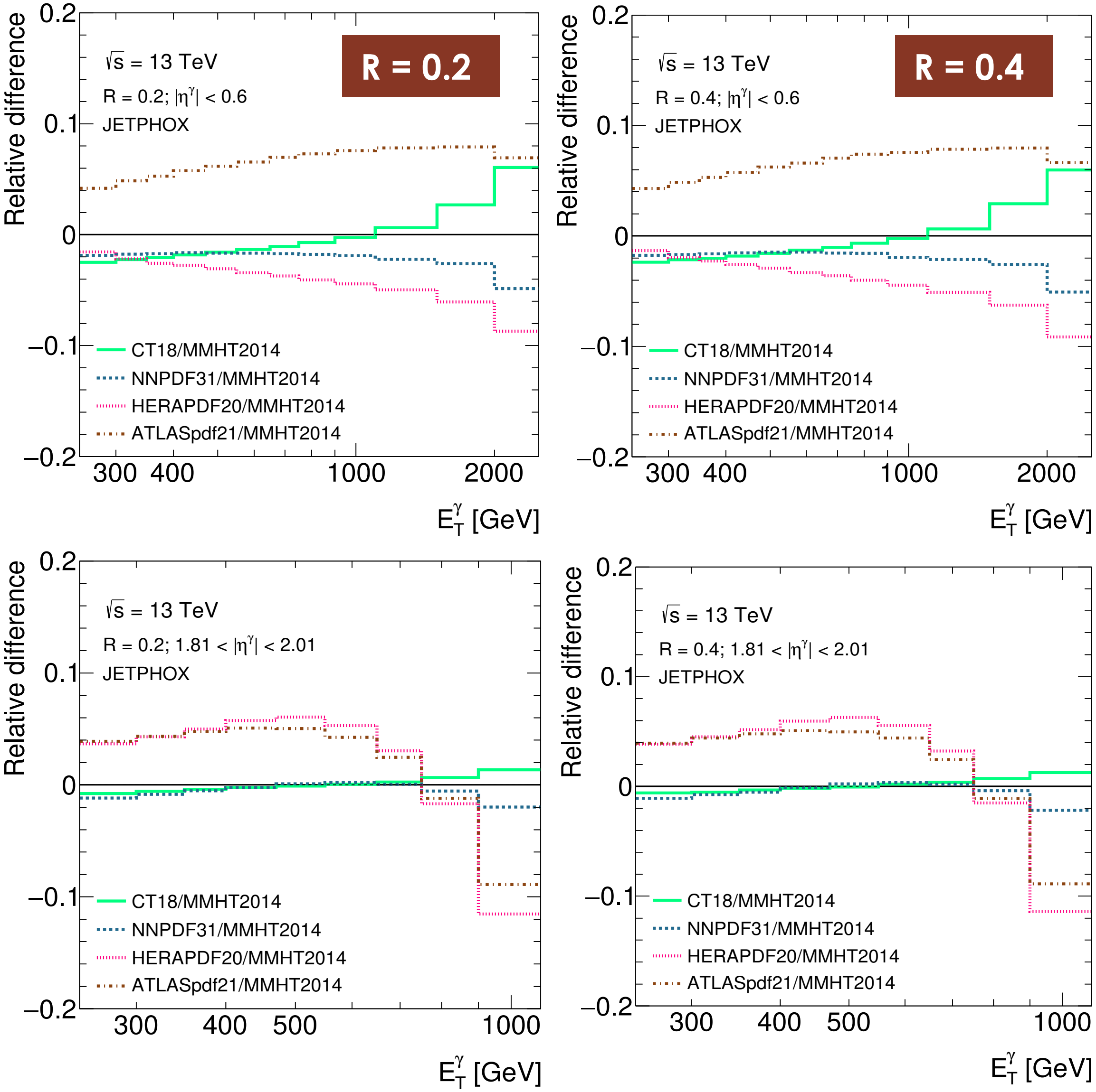
- Adequate description of the data within experimental and theoretical uncertainties

Inclusive photon production

- Ratios of differential cross sections for R = 0.2, 0.4 as functions of E_T^{γ} in the different $|\eta_{\gamma}|$ regions
- These measurements provide a stringent test of pQCD (systematics at ~1%-level)
- Nice overall data/MC agreement



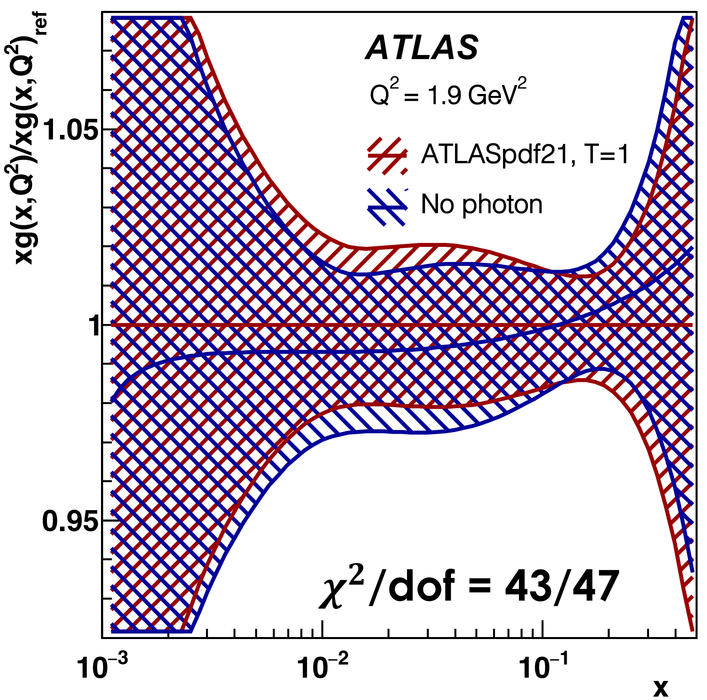
Inclusive photon production

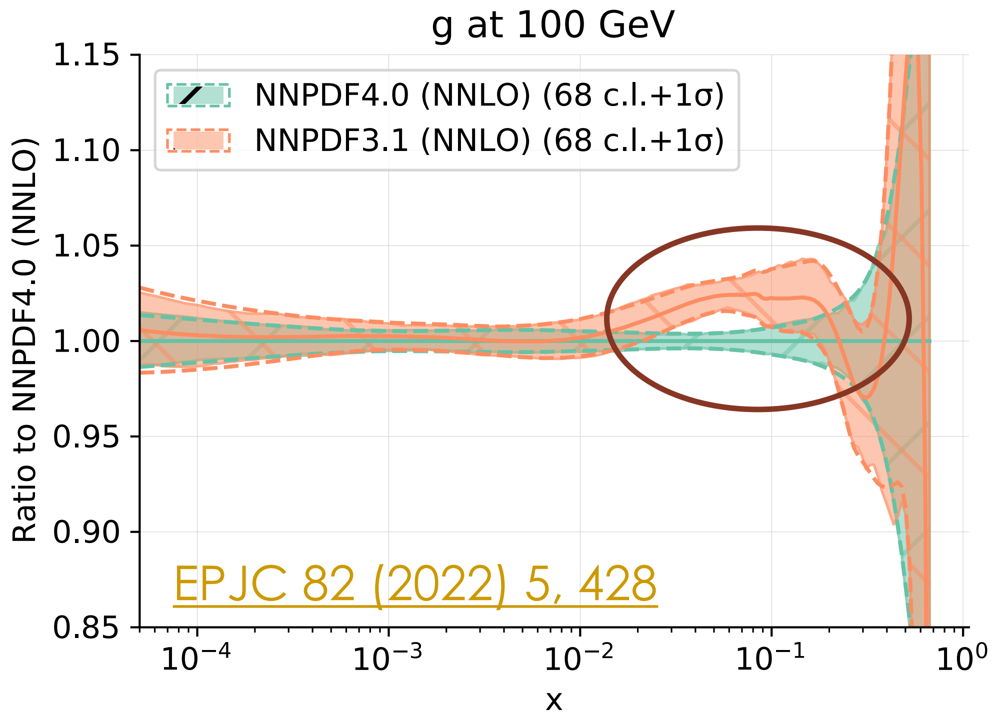


- The sensitivity to the PDFs investigated by comparing based on different PDFs
- MMHT14 as baseline
- Predictions based on the CT18/NNPDF3.1 are within 2%
- Predictions based on the HERAPDF2.0/ATLASpdf21 show differences of ~10%

Impact of the photon data sets on PDFs

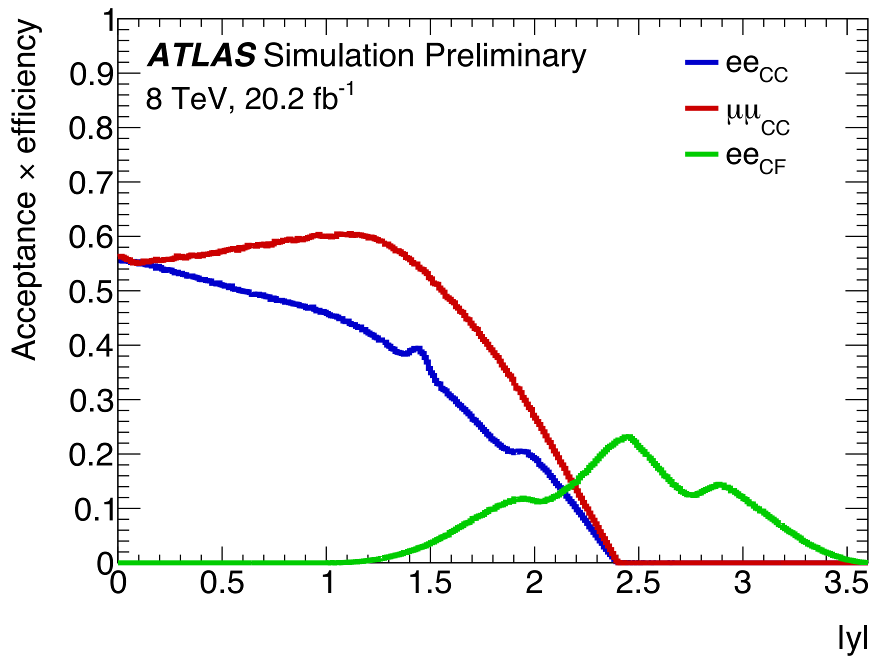
- **ATLASpdf21** is a PDF fit to **multiple ATLAS data sets** - EPJC 82 (2022) 5, 438
- We removed all the **13/8 TeV isolated photon ratio data** - JHEP 04 (2019) 093
- This results in a marginal softening of the high-x gluon (blue to red), no decreased uncertainty – confirmed in NNPDF4.0 studies (much more data in!)
- These data do not have a large impact on PDFs… but very good to know that NNLO predictions describe these data nicely!





Z p_T and rapidity at 8 TeV

- Stringent test of the state-of-art pQCD
- Probe large rapidity/small parton momentum fraction x using forward electrons
- Unique full lepton phase space rapidity cross section with per-mille total uncertainties to provide a gateway to a rich field of precise interpretations

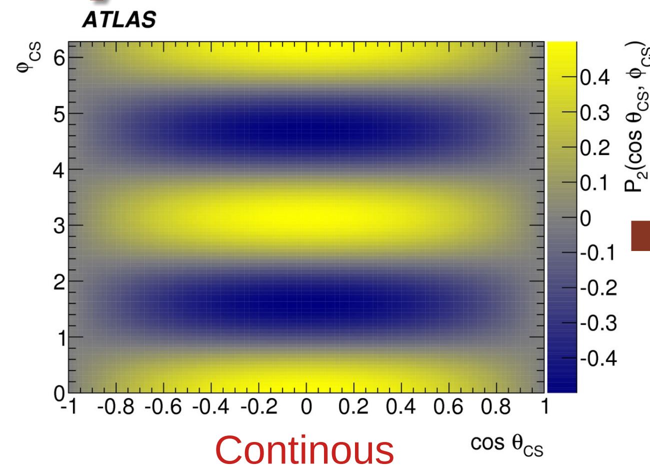


- ee_{CC}: two electrons with $p_T > 20$ GeV and $|\eta| < 2.4$
- $\mu\mu_{CC}$: two muons with $p_T > 20$ GeV and $|\eta| < 2.4$
- ee_{CF}: central electron with $p_T > 20$ GeV and $|\eta| < 2.4$ forward electron with $p_T > 20$ GeV and $2.5 < |\eta| < 4.9$

Z p_T and rapidity at 8 TeV

$$\frac{d\sigma}{dpdq} = \frac{d^3\sigma^{U+L}}{dp_T\,dy\,dm}\left(1+\cos^2\theta+\sum_{i=0}^{7}A_i(y,p_T,m)P_i(\cos\theta,\phi)\right)$$

- $d\sigma/dp_T$ → Transverse dynamics
- $d\sigma/dy$ → longitudinal dynamics (PDFs)
- Depends on 3 "boson production" variables (p_T, y, m) and 2 angular decay variables ($\cos\theta$, ϕ)
- Decomposition of ($\cos\theta$, ϕ) into 9 helicity cross sections → basis of spherical harmonics



Continous

$$\begin{pmatrix} H_0 \\ H_1 \\ H_2 \\ H_3 \\ H_4 \\ H_5 \\ H_6 \\ H_7 \\ H_8 \end{pmatrix}$$

Quantized

Expected Yield

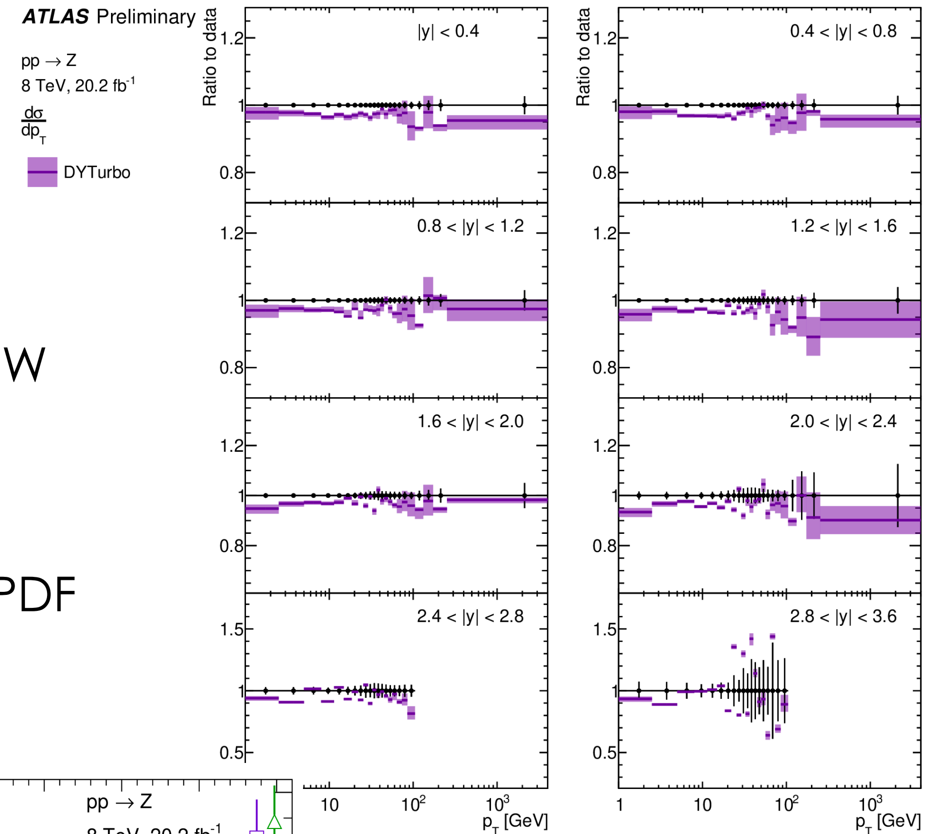
$$N^{n}_{\mathrm{exp}}(A,\sigma,\theta) = \left\{\sum_{j=1}^{N^{ana}_{bins}} \mathcal{L}\sigma_j\left[t^n_{8j}(\beta)+\sum_{i=0}^{7}A_{ij}t^n_{ij}(\beta)\right]\right\}\gamma^n+\sum_{B}^{bkgs}T^n_B(\beta)$$

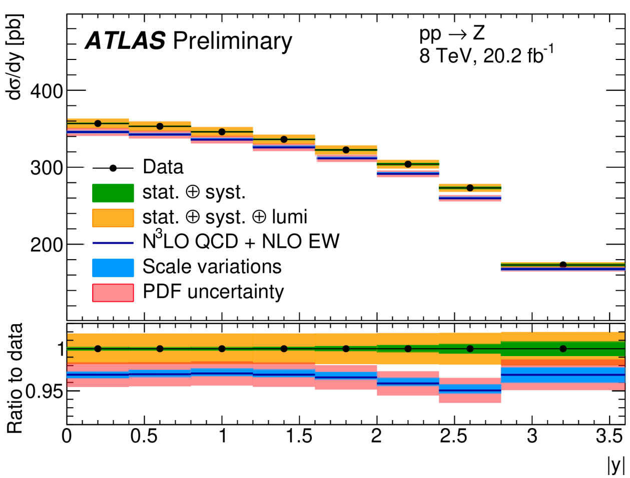
Reco (p_T^Z, y^Z, m^Z, cosθ, ϕ) bin; Cross section; Background template; Truth (p_T^Z, y^Z, m^Z) bin; Angular coefficient; Templated polynomial

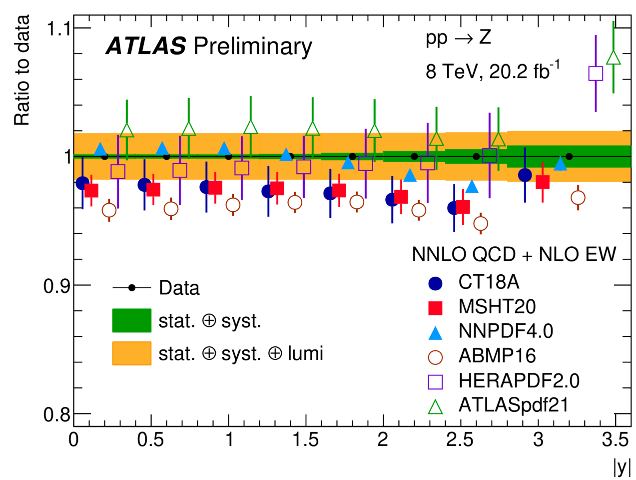
- Likelihood defined in 22528 ($\cos\theta$, ϕ, p_T) bins
- **<u>PoI</u>**: 8 A_i + 1 cross section in 176 (p_T, y) bins
- Measuring the A_i → a quantized representation of the ($\cos\theta$, ϕ) kinematic space
- **Very powerful**: trade systematics for statistics
- **Very useful**: provide analytic extrapolation of lepton cuts and enables a richer interpretation programme

Z p_T and rapidity at 8 TeV

- Per mille level precision in the central region
- Sub-percent precision up to |y| < 3.6
- First comparison to N³LO QCD + NLO EW predictions (DYTurbo + ReneSANCe)
- Allow precise PDF interpretations with QCD scale uncertainties smaller than PDF uncertainties







Good agreement with several high-order qT-resummed predictions

α_S extraction from Z p_T at 8 TeV

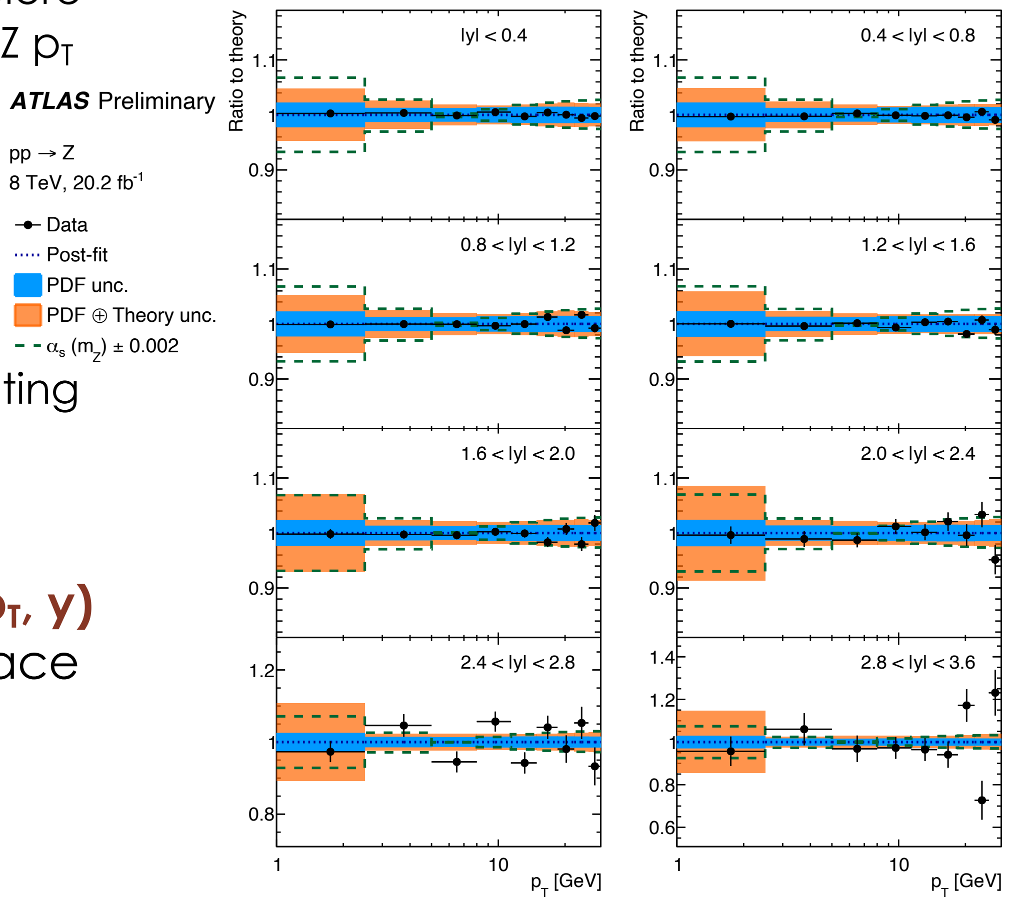
- Evaluate $\chi^2(\alpha_S)$ with α_S variations in LHAPDF
  - Include experimental ($\beta_{j,exp}$) and PDF uncertainties ($\beta_{k,th}$) in the $\chi^2(\alpha_S)$ definition
  - For each value of α_S, $\beta_{k,th}$ terms explore the PDF space to find the best fit to Z p_T data
  - aN^{3}LO MSHT20 PDF set is used for the α_S extraction

$$\chi^2(\beta_{\rm exp},\beta_{\rm th}) = \sum_{i=1}^{N_{\rm data}} \frac{\left(\sigma_i^{\rm exp} + \sum_j \Gamma_{ij}^{\rm exp}\beta_{j,\rm exp} - \sigma_i^{\rm th} - \sum_k \Gamma_{ik}^{\rm th}\beta_{k,\rm th}\right)^2}{\Delta_i^2} + \sum_j \beta_{j,\rm exp}^2 + \sum_k \beta_{k,\rm th}^2 \,.$$

correlated systematic uncertainties

uncorrelated systematic uncertainties

- Fit **Z p_T < 29 GeV region**
  - Non-perturbative form factor (affecting Z p_T < 5 GeV) is added with unconstrained nuisance parameter



- $\alpha_S(m_Z)$ extracted by fitting the **2D (p_T, y) cross section** in full lepton phase space

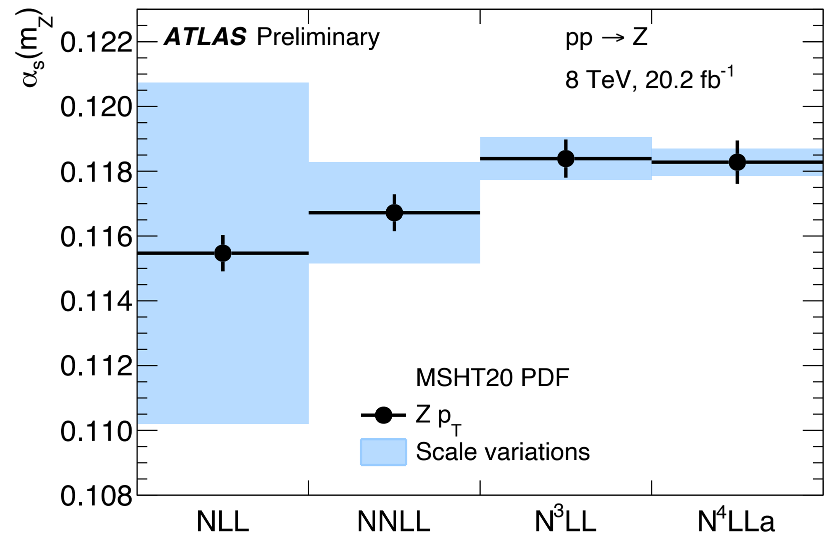
- χ^2**/ndf = 82/72**

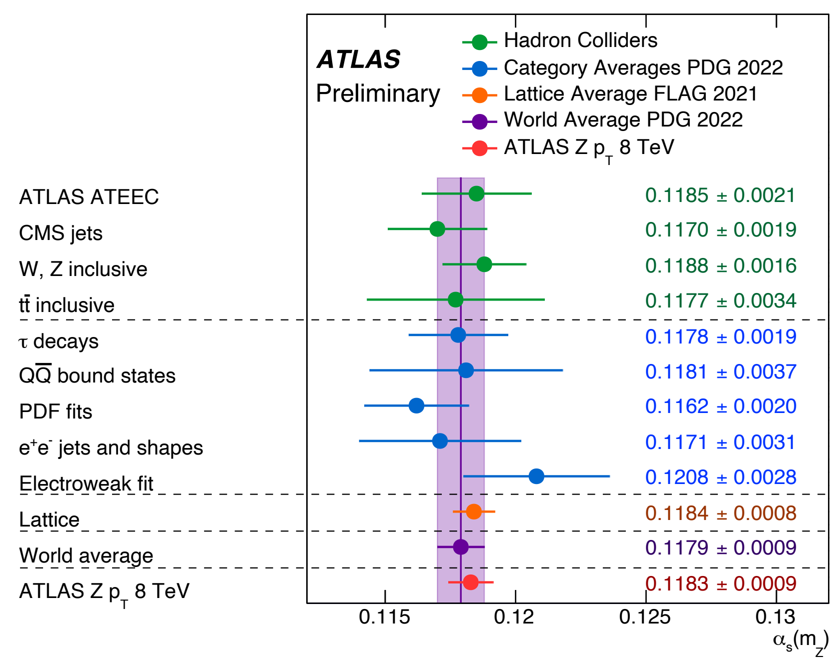
α_S extraction from Z p_T at 8 TeV

- **First $\alpha_S(m_Z)$ determination based on aN⁴LL+N³LO predictions**
- $\alpha_S(m_Z)$ determined at lower orders → good perturbative series convergence
- **Most precise experimental determination** of $\alpha_S(m_Z)$
- As precise as the PDG and Lattice WA

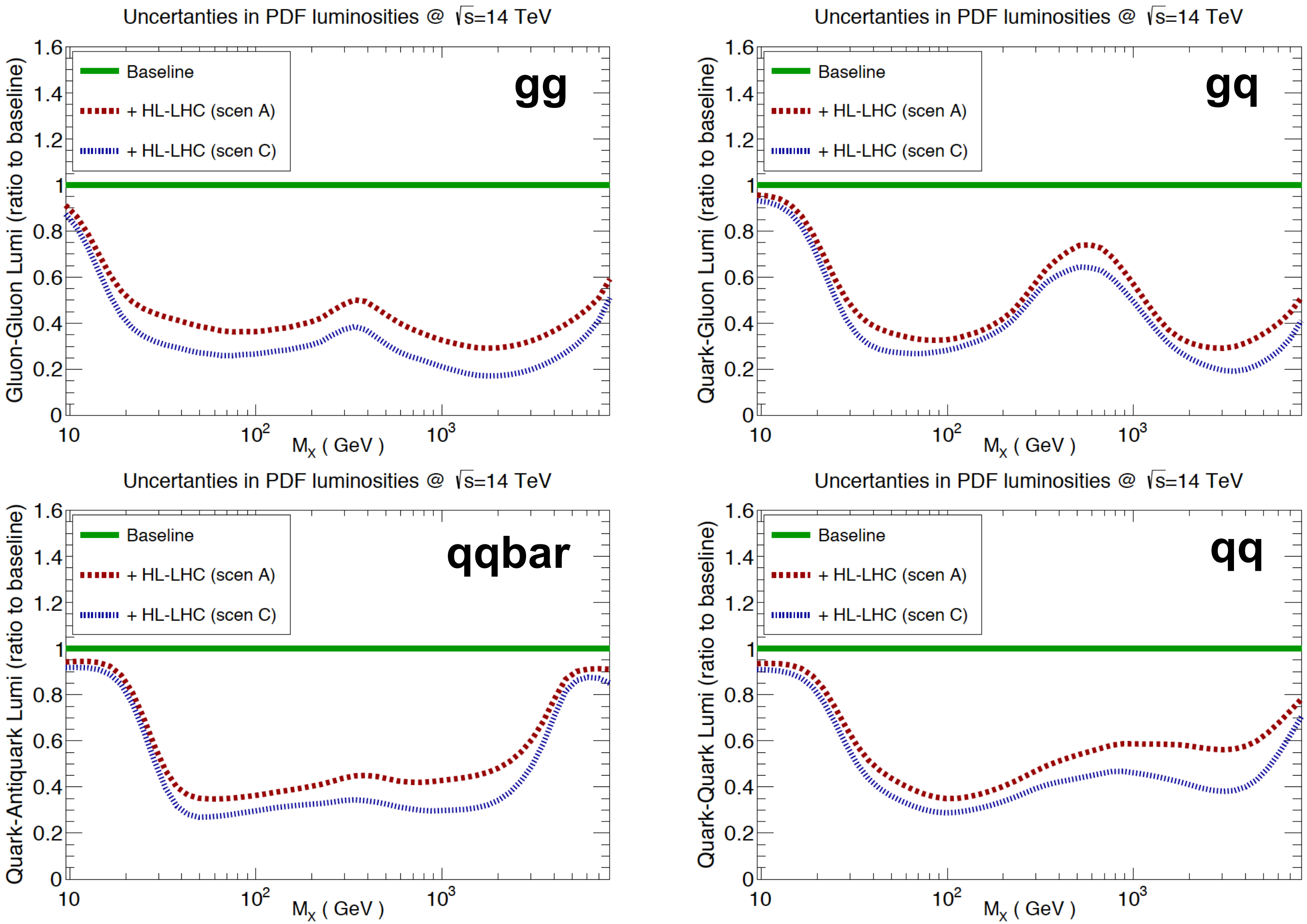
Experimental uncertainty	+0.00044	-0.00044
PDF uncertainty	+0.00051	-0.00051
Scale variations uncertainties	+0.00042	-0.00042
Matching to fixed order	0	-0.00008
Non-perturbative model	+0.00012	-0.00020
Flavour model	+0.00021	-0.00029
QED ISR	+0.00014	-0.00014
N4LL approximation	+0.00004	-0.00004
Total	+0.00084	-0.00088

$$\alpha_s(m_Z) = 0.11828^{+0.00084}_{-0.00088}$$





HL-LHC PDFs


Uncertanties in PDF luminosities @ √s=14 TeV
gg
Gluon-Gluon Lumi (ratio to baseline)
gq
Quark-Gluon Lumi (ratio to baseline)
qqbar
Quark-Antiquark Lumi (ratio to baseline)
qq
Quark-Quark Lumi (ratio to baseline)
Baseline
+ HL-LHC (scen A)
+ HL-LHC (scen C)
M_X (GeV)
10
10^2
10^3
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

Combining HL-LHC and LHeC

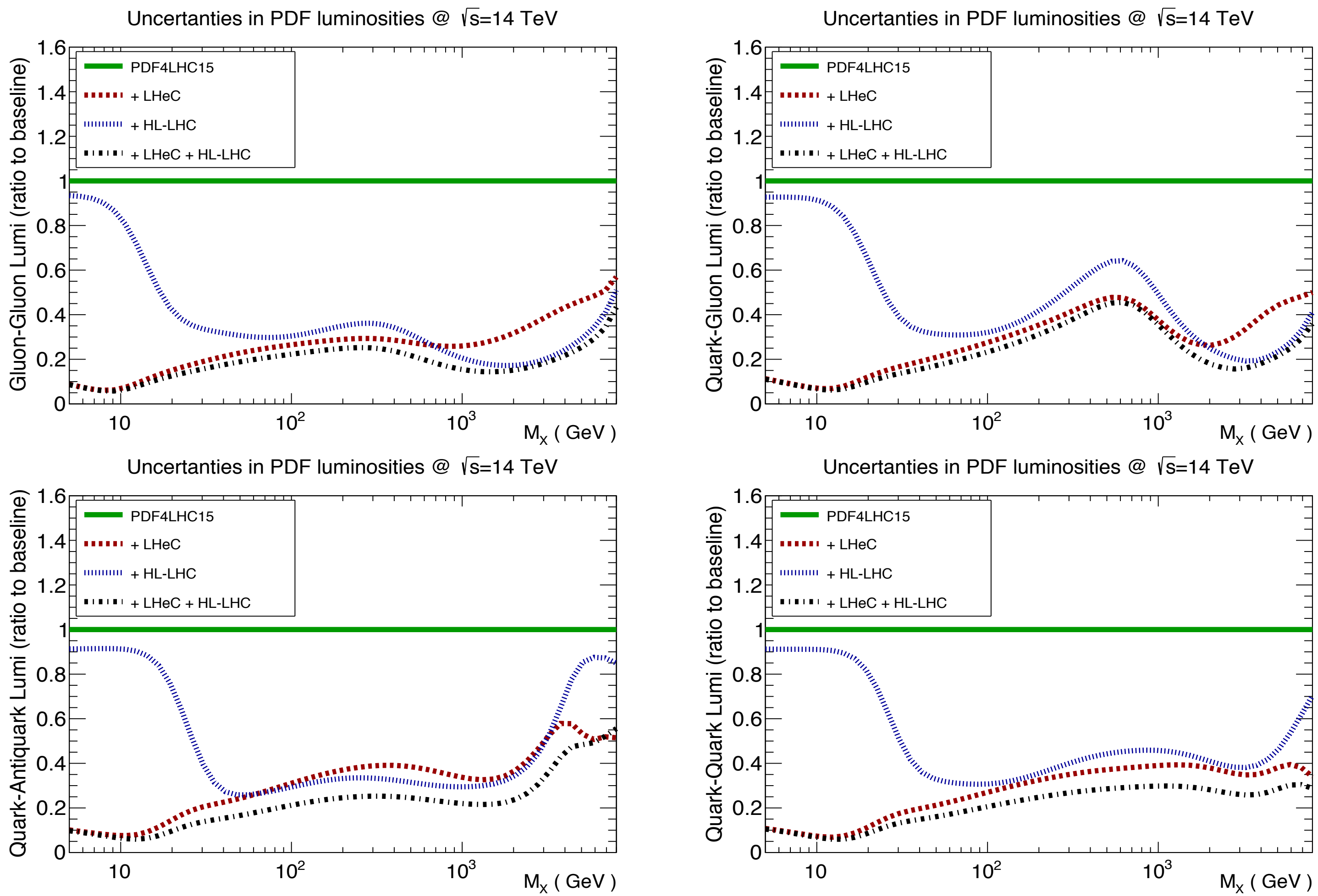


Figure 9.10: Impact of LHeC, HL-LHC and combined LHeC + HL-LHC pseudodata on the uncertainties of the gluon-gluon, quark-gluon, quark-antiquark and quark-quark luminosities, with respect to the PDF4LHC15 baseline set. In this comparison we display the relative reduction of the PDF uncertainty in the luminosities compared to the baseline.

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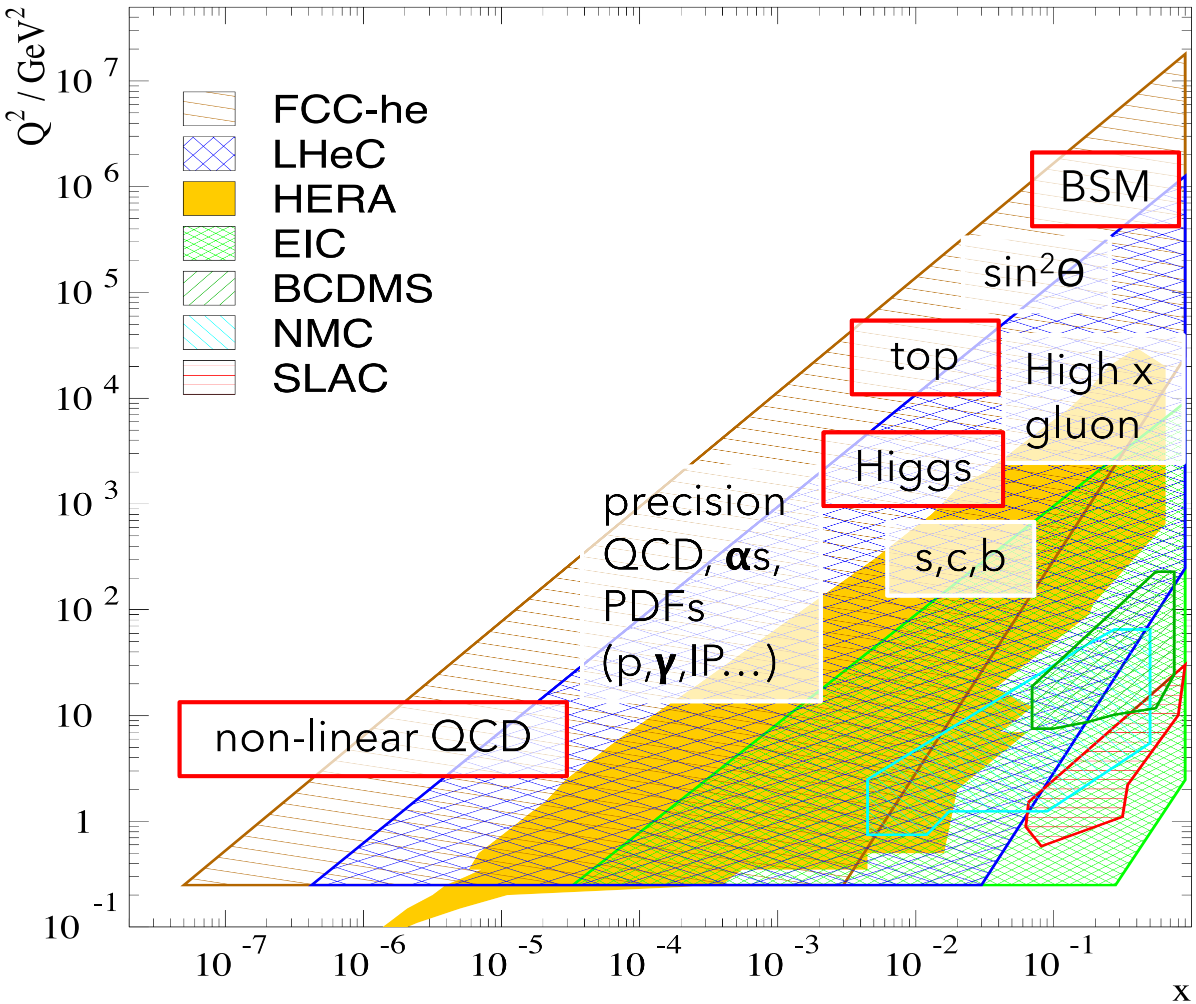
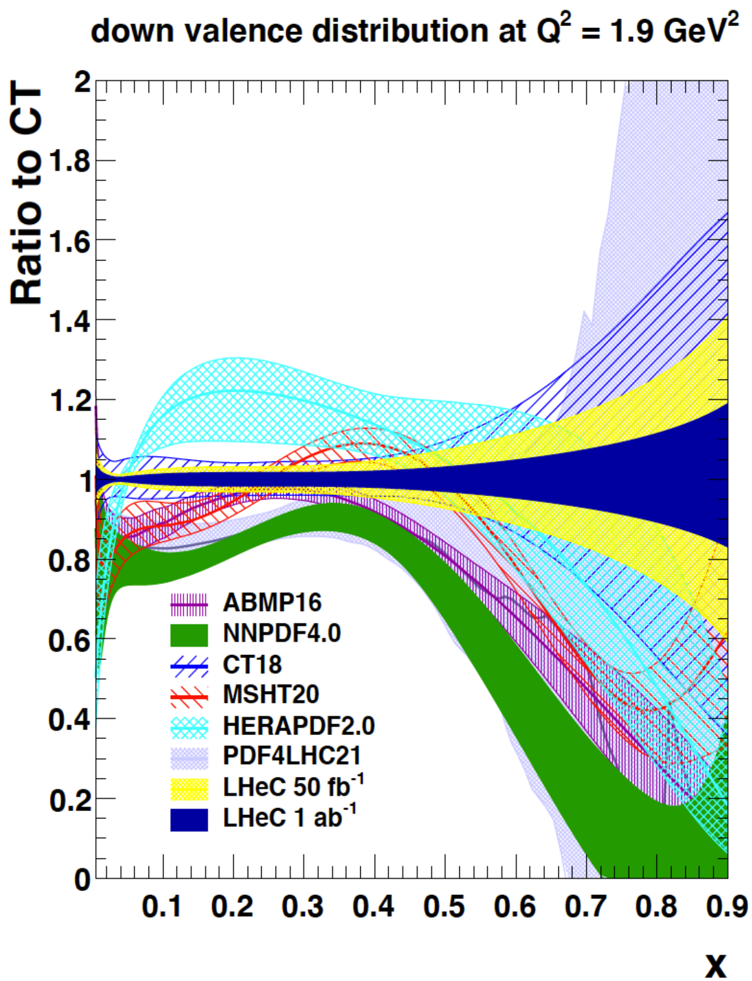
Physics with energy frontier DIS

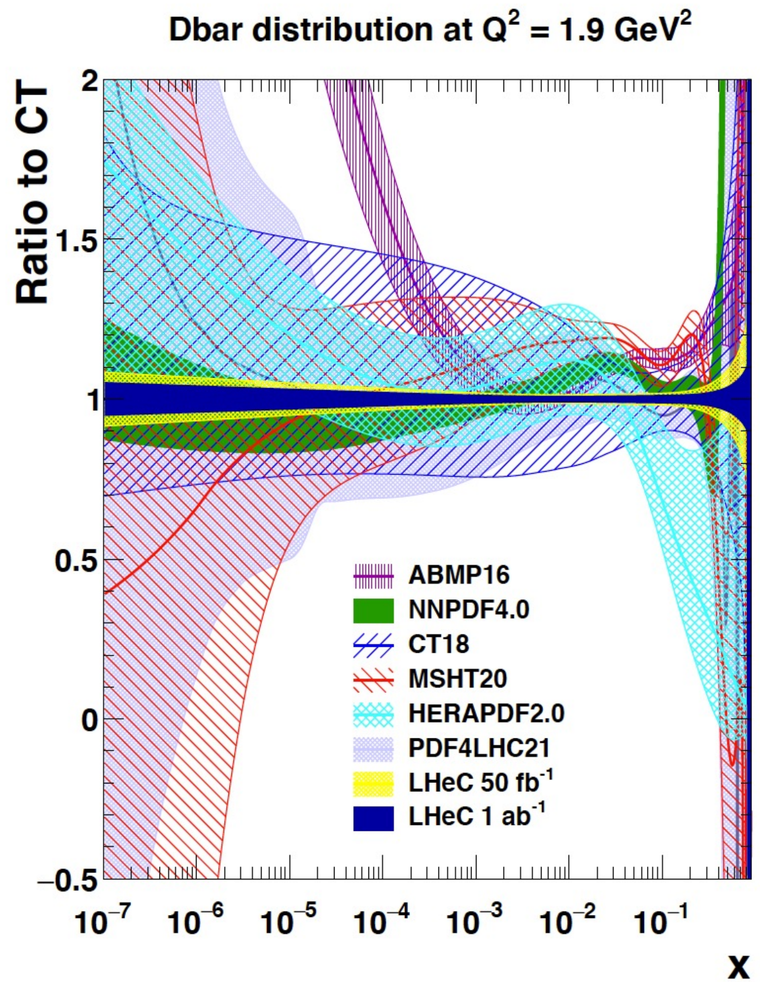


x15/120 extension in Q^2, 1/x reach wrt HERA

- DIS: cleanest high-resolution microscope
- **Opportunity for unprecedented increase in DIS kinematic reach**
- x10^3 luminosity increase wrt HERA
- QCD precision physics and discovery
- …+ Higgs, top EW, BSM
- Completely resolve all proton PDFs, sensitivity to x → 1, exploration of small-x regime, and α_S at per-mille level
- Empowering the HL-LHC and FCC-hh

Valence and sea quarks PDFs





- Uncertainty on the high-x d_V largely reduced
- **Reduction of the PDF error in the low-x region is visible** – particularly remarkable for sea quarks

Impact of EIC on HERAPDF

- ‘DIS-only’ fits
- Using xFitter framework
- HERA data have limited high-x sensitivity due to kinematic correlation between x,Q^2 and $1/Q^4$ factor in cross section
- Fractional total uncertainties w/wo EIC data along with HERA
- Linear x scale
- **EIC data** will bring **significant reduction in uncertainties for all parton species at large x**