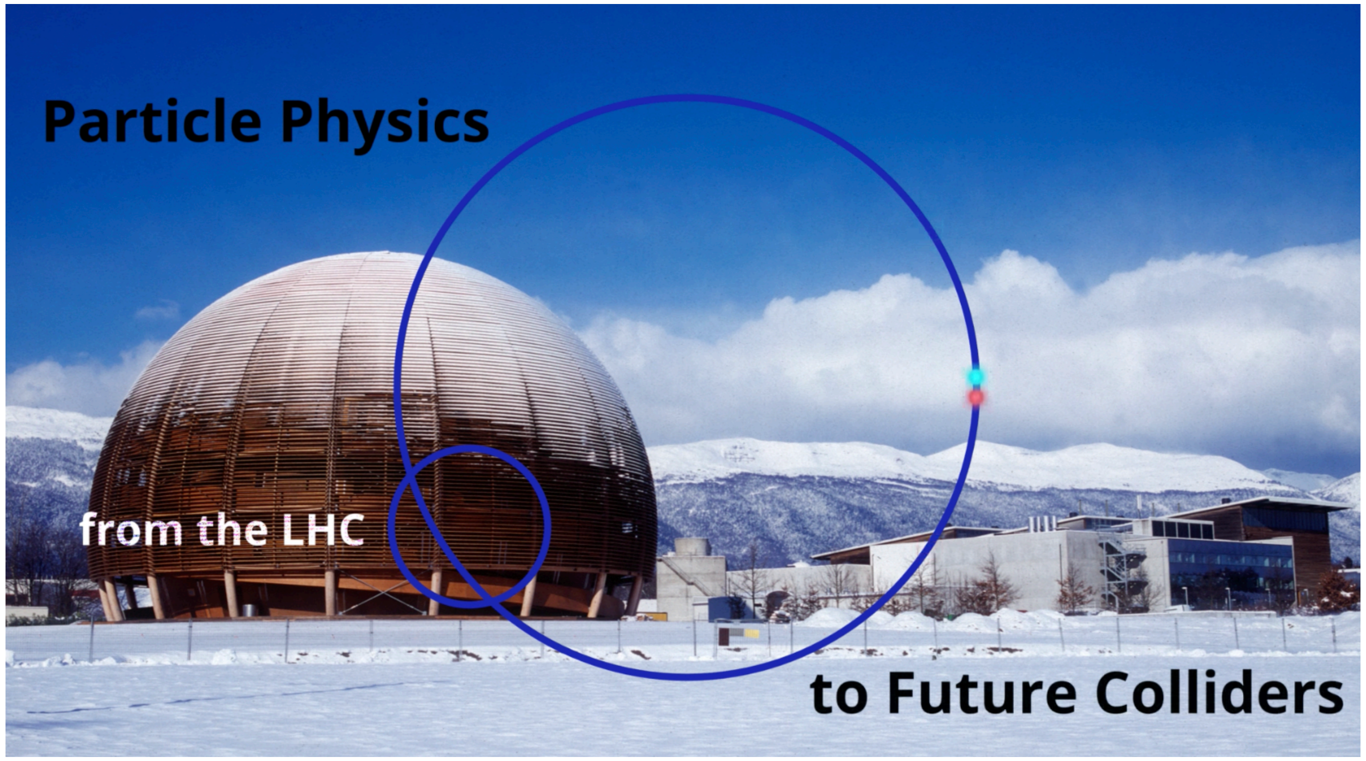
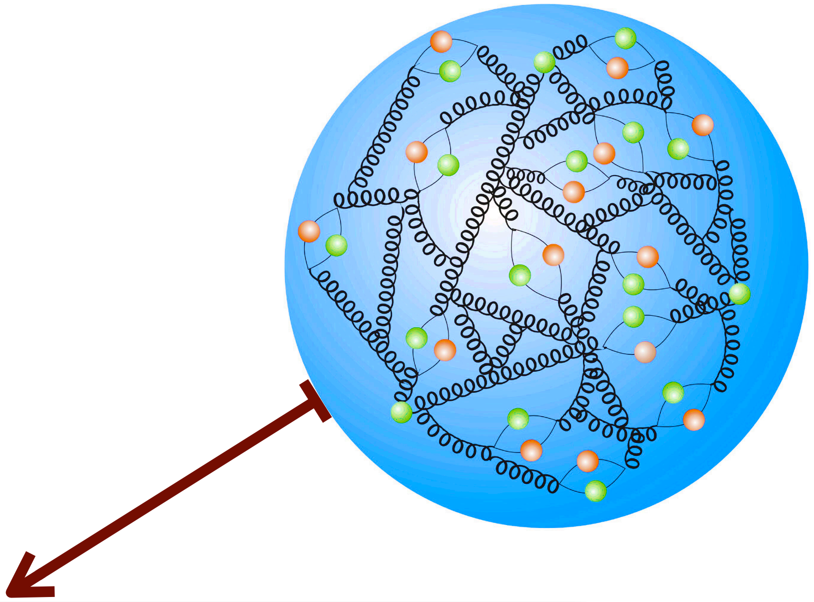
Proton Structure from the LHC to Future Colliders



Juan Rojo, VU Amsterdam & Nikhef

Zurich Phenomenology Workshop, 8th January 2023

Why proton structure?



Key component of predictions for particle, nuclear, and astro-particle experiments

- **pp**: ATLAS, CMS, LHCb, ALICE
- **pA & AA**: (HL-)LHC, RHIC
- **pp (future)**: HL-LHC, FCC-hh, SppS
- **ep**: fixed target DIS, HERA
- **ep (future)**: EIC, LHeC, FCC-ep
- **neutrinos (cosmic)**: IceCube, KM3NET,
- **neutrinos (collider)**: FASER, SND@LHC, FPF

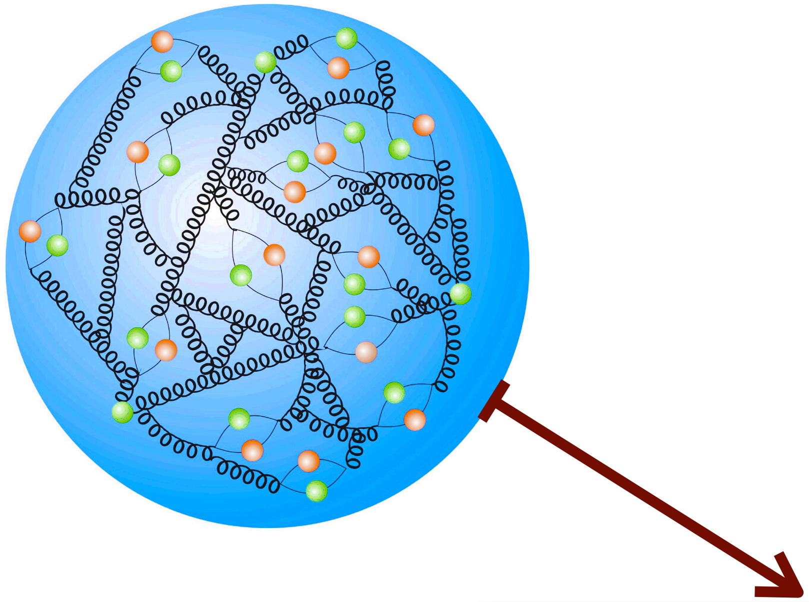
$$\sigma_{\rm pp} \propto \sum_{i,j} f_i^{(p)}(x,Q^2) \otimes f_j^{(p)}(x,Q^2) \otimes \widetilde{\sigma}_{ij}(\alpha_s,\alpha)$$

$$\sigma_{\rm pA} \propto \sum_{i,j} f_i^{(p)}(x,Q^2) \otimes f_j^{(A)}(x,Q^2) \otimes \widetilde{\sigma}_{ij}(\alpha_s,\alpha)$$

$$\sigma_{\rm ep} \propto \sum_{i,j} f_i^{(p)}(x,Q^2) \otimes \widetilde{\sigma}_i^{(\rm eq)}(\alpha_s,\alpha)$$

$$\sigma_{\nu {\rm A}} \propto \sum_{i,j} f_i^{(A)}(x,Q^2) \otimes \widetilde{\sigma}_i^{(\nu {\rm q})}(\alpha_s,\alpha)$$

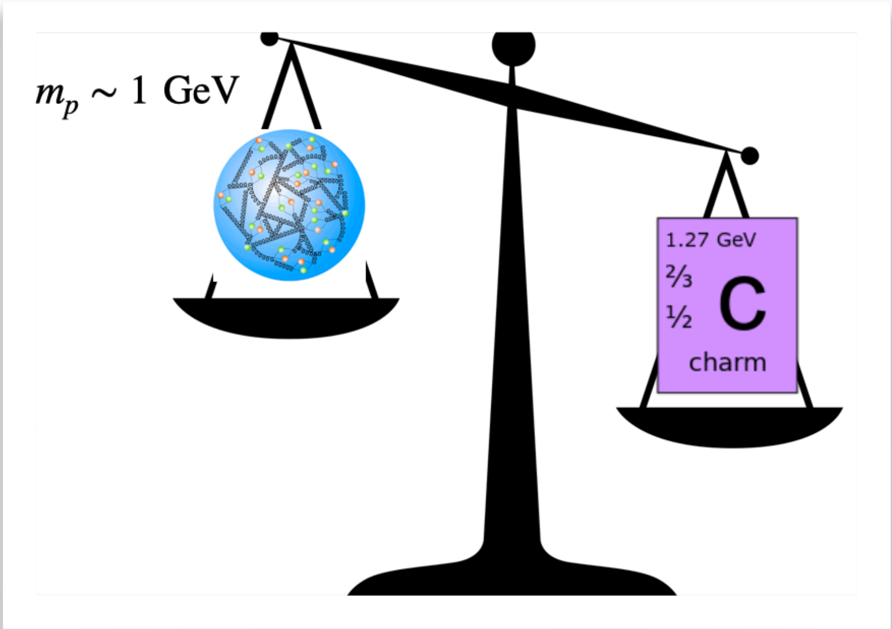
Why proton structure?



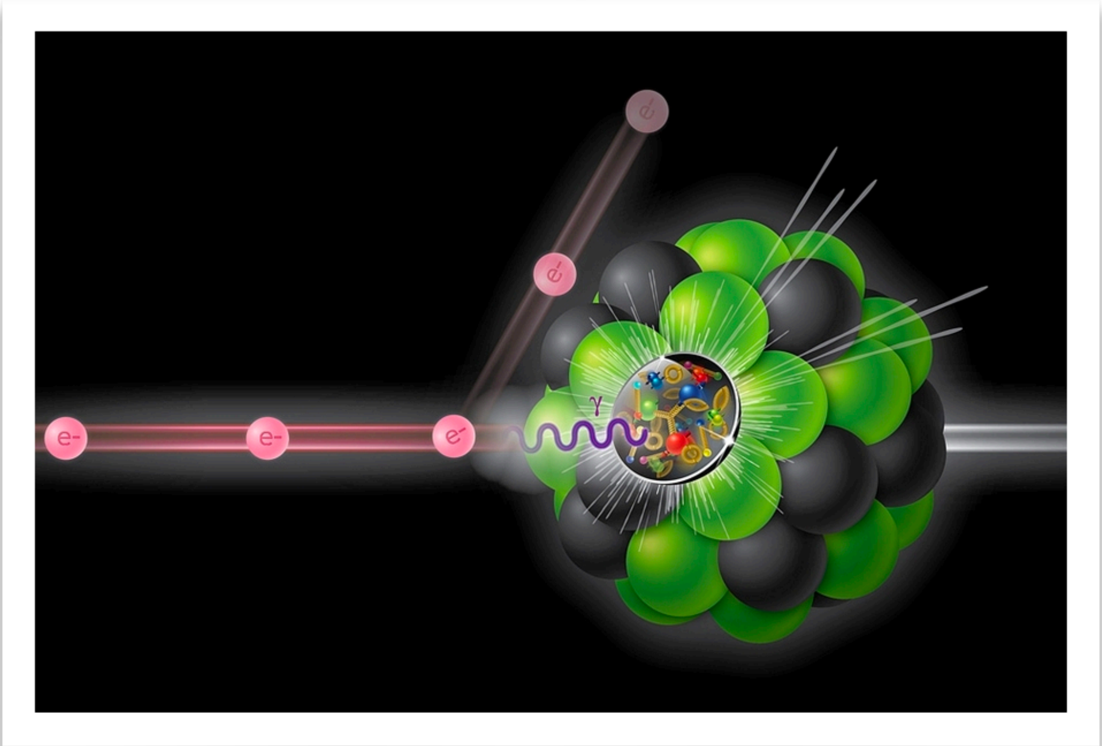
Address fundamental questions in Quantum Chromodynamics

- origin of mass & spin?
- **heavy quark** & antimatter content?
- three-dimensional structure?
- **gluon-dominated matter**?
- **nuclear modifications**?
- electroweak partons?
- beyond the SM physics sensitivity?

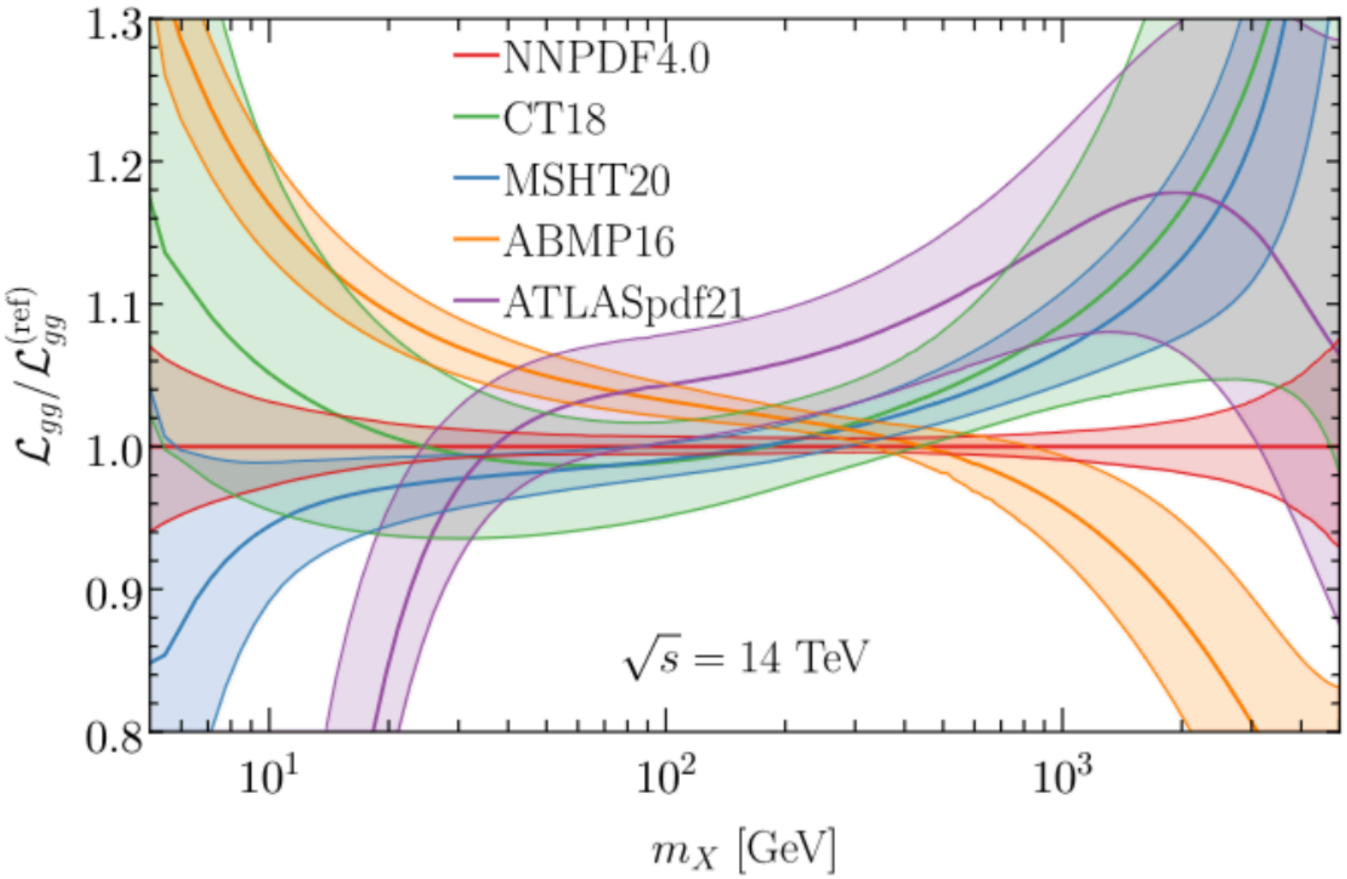
components heavier than itself?

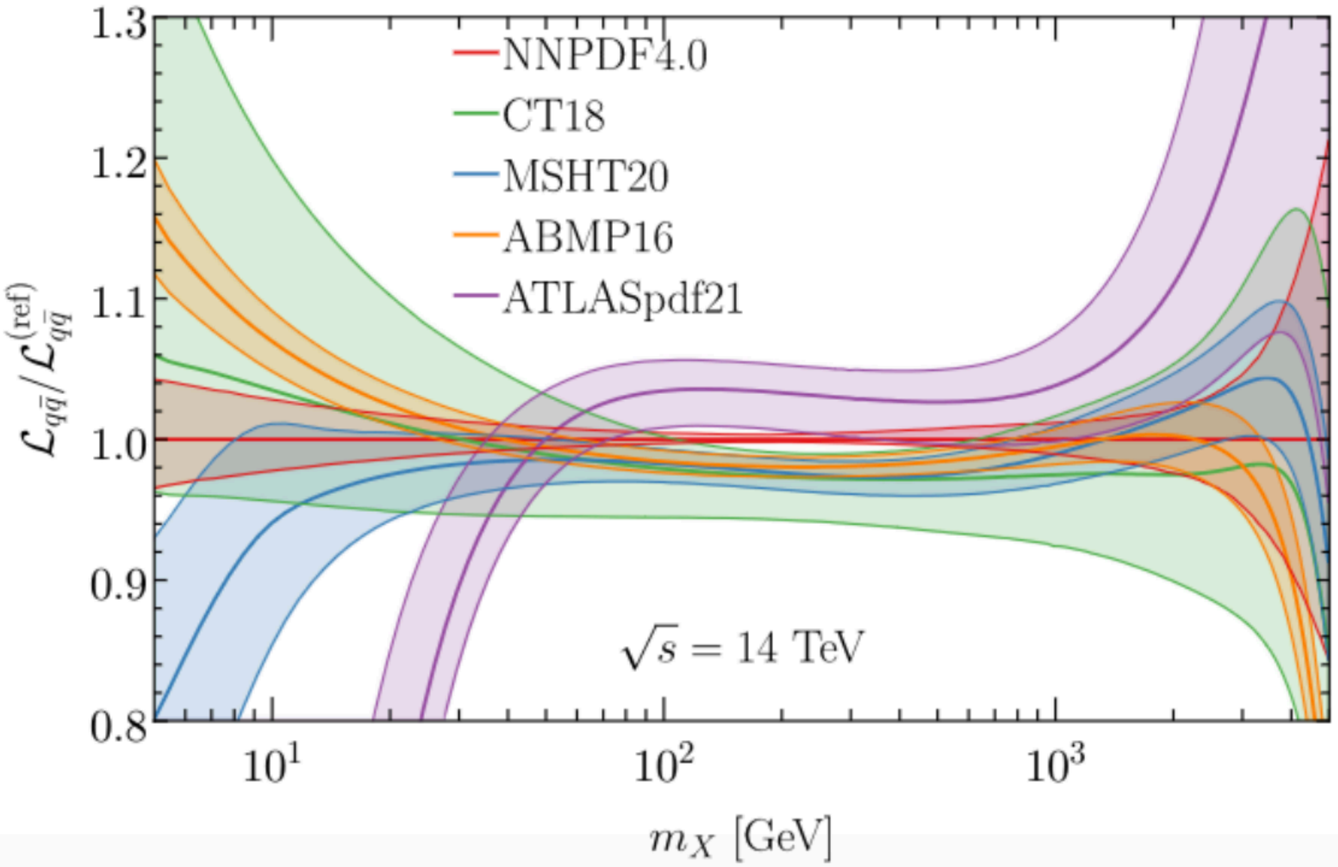


gluon shadowing & color-glass condensate?

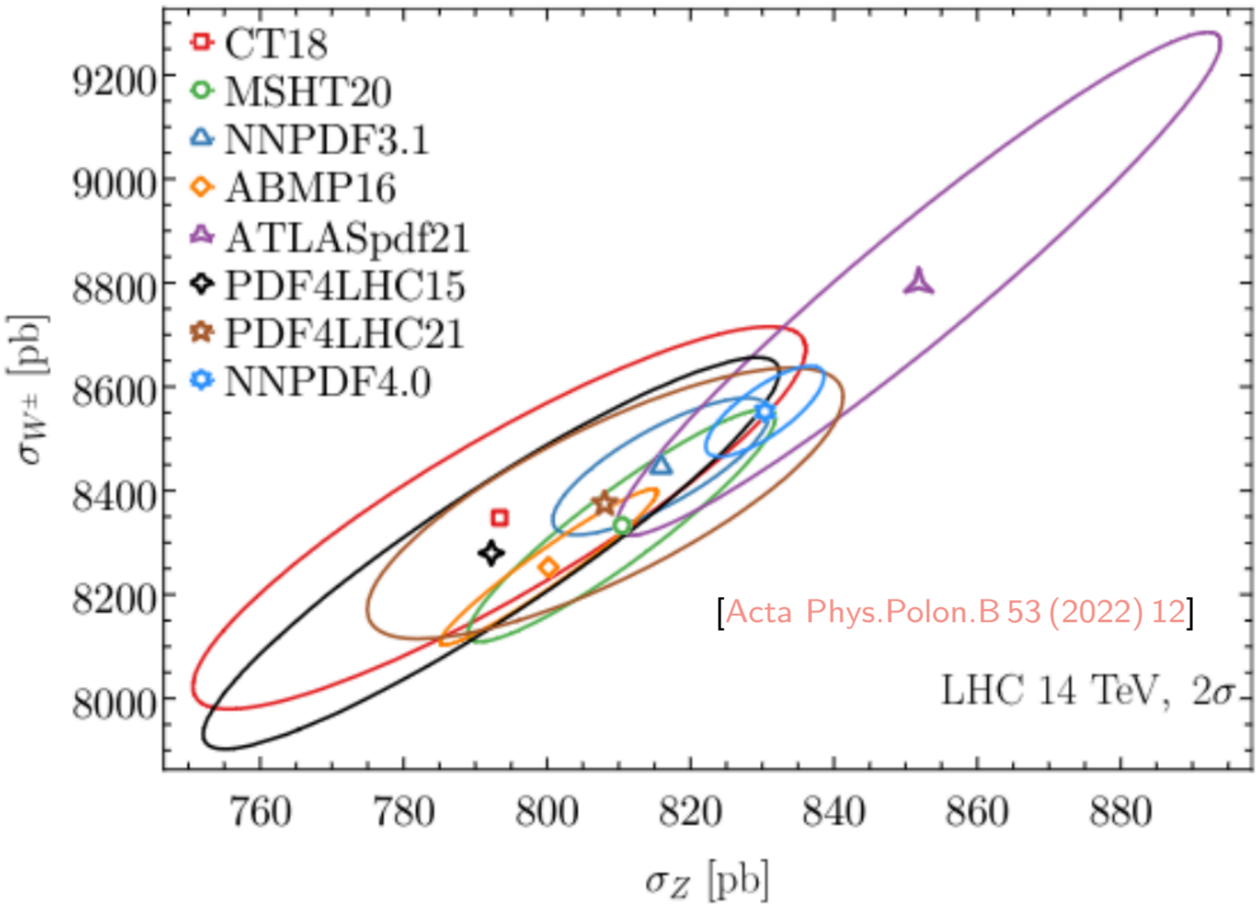


Proton structure at the LHC Run III



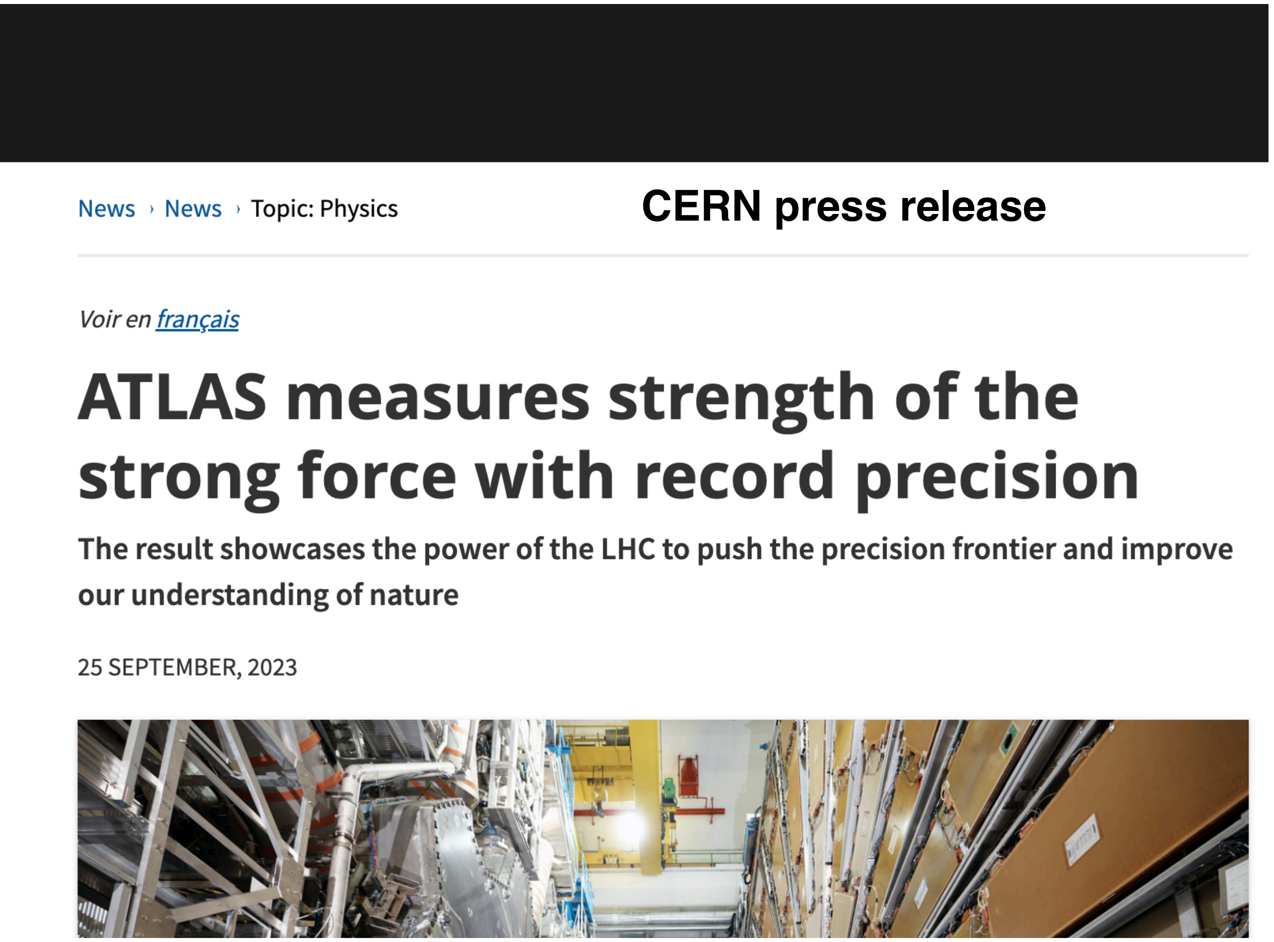


- Agreement for some flavour combinations and kinematic regions (e.g. gluon-gluon luminosity for Higgs production), less so for others (e.g. **large-mass relevant for BSM**)
- Differences both in **central values** and **PDF uncertainty estimates**
- Already **limiting factor** for precision physics at the LHC



[Acta Phys.Polon.B 53 (2022) 12]

Proton structure at the LHC Run III



News › News › Topic: Physics

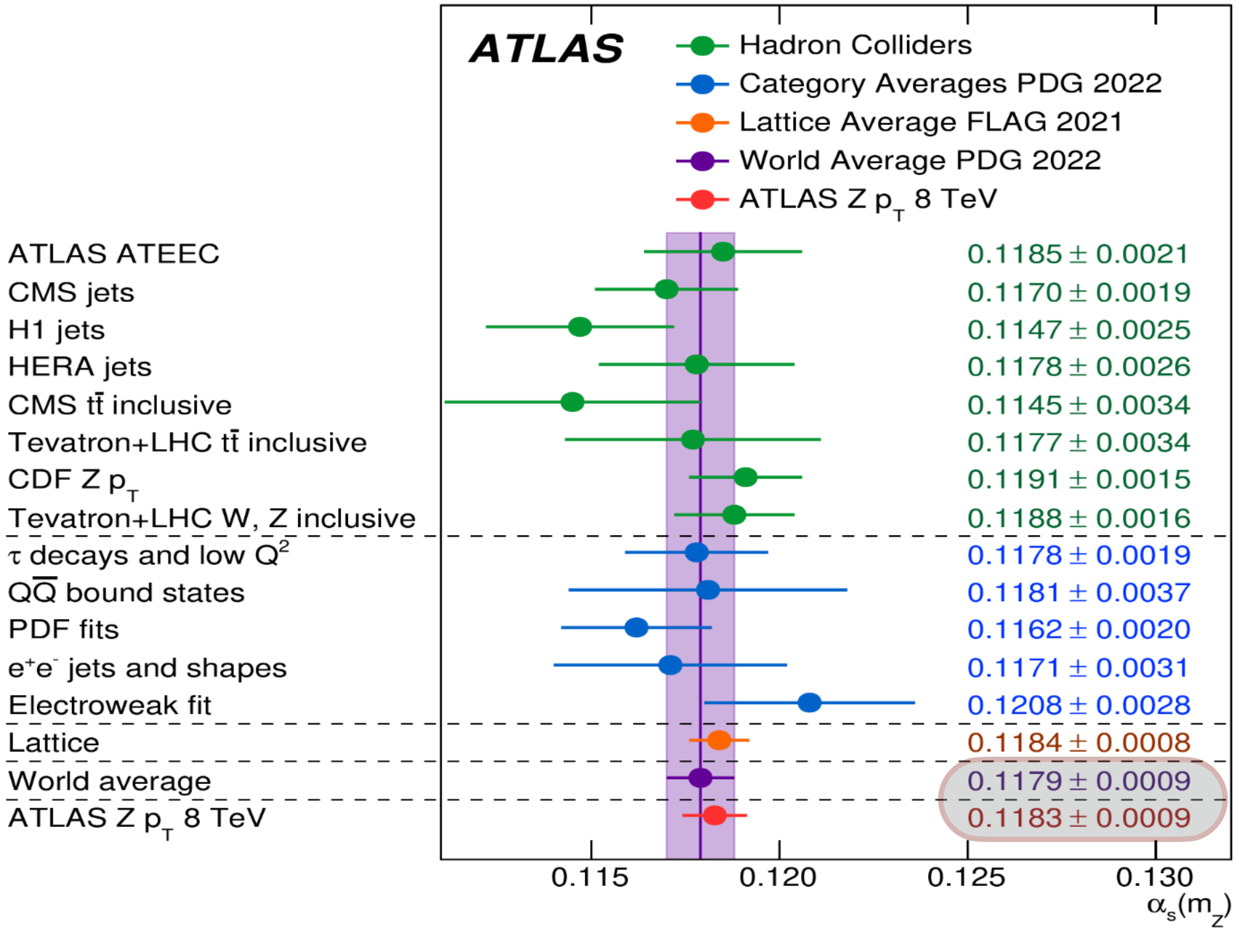
CERN press release

Voir en français

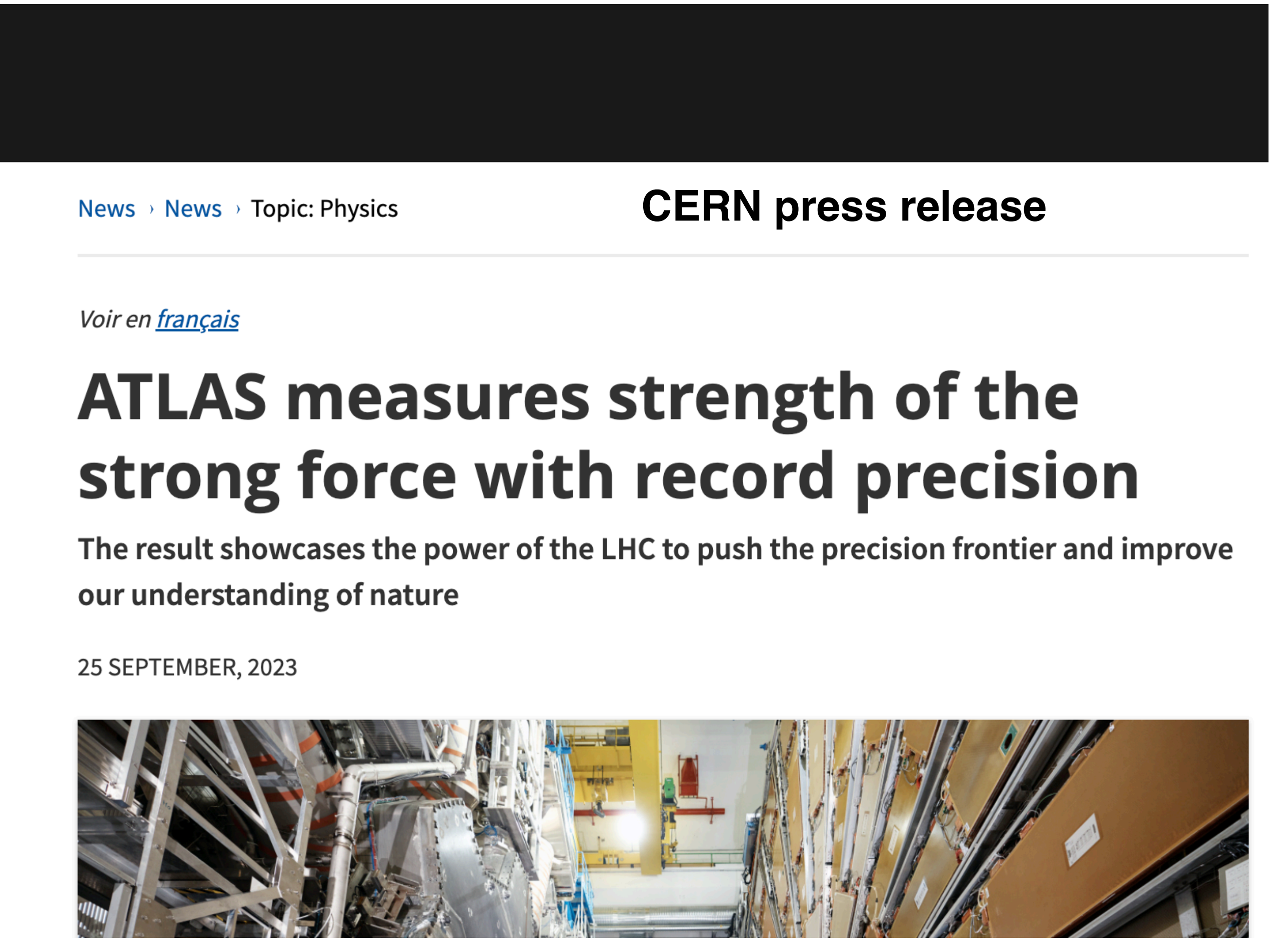
ATLAS measures strength of the strong force with record precision

The result showcases the power of the LHC to push the precision frontier and improve our understanding of nature

25 SEPTEMBER, 2023



Proton structure at the LHC Run III



News › News › Topic: Physics

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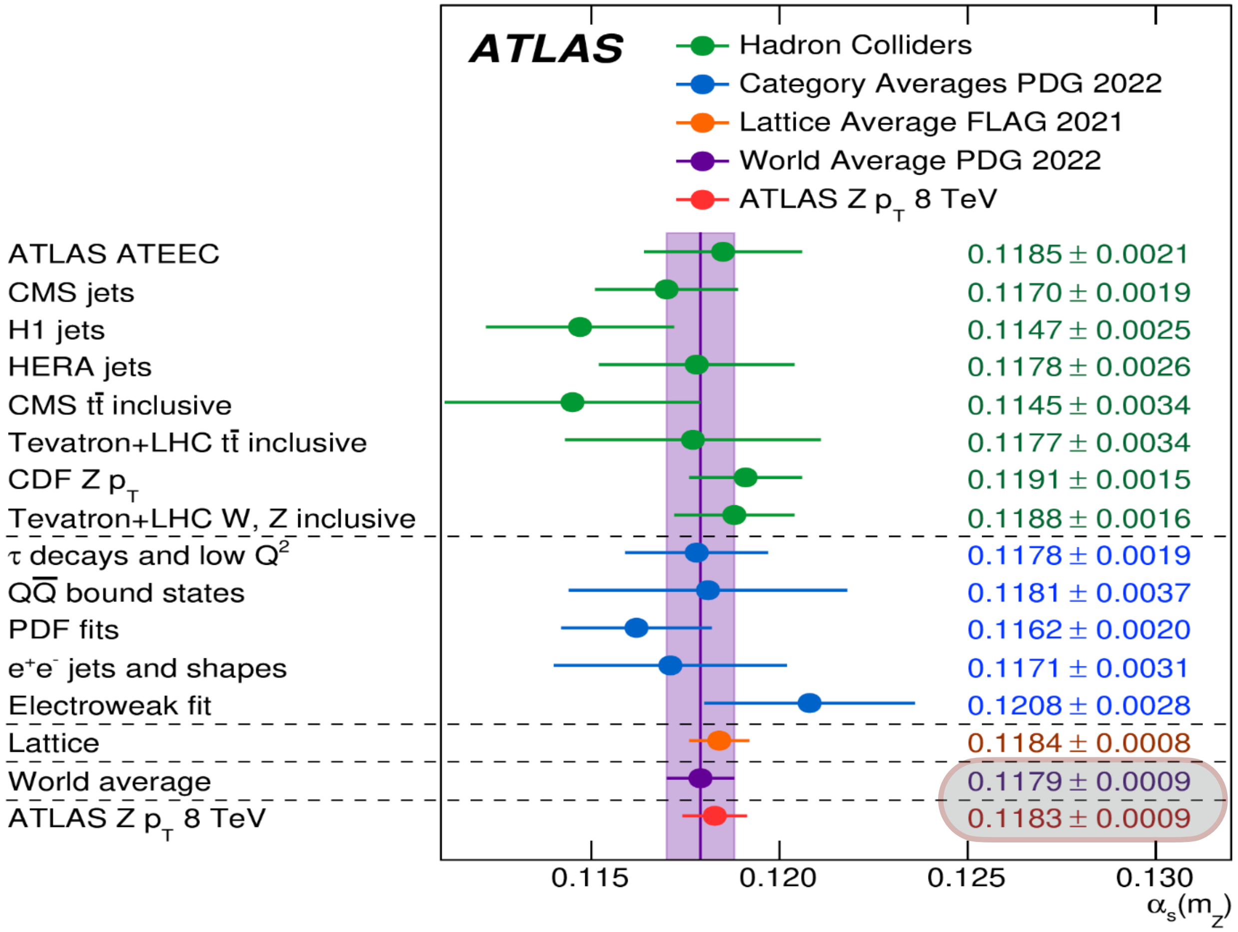


	PDF set	$\alpha_s(m_Z)$	PDF uncertainty	g [GeV^2]	q [GeV^4]
baseline	MSHT20 [37]	0.11839	0.00040	0.44	−0.07
	NNPDF4.0 [84]	0.11779	0.00024	0.50	−0.08
	CT18A [29]	0.11982	0.00050	0.36	−0.03
	HERAPDF2.0 [65]	0.11890	0.00027	0.40	−0.04

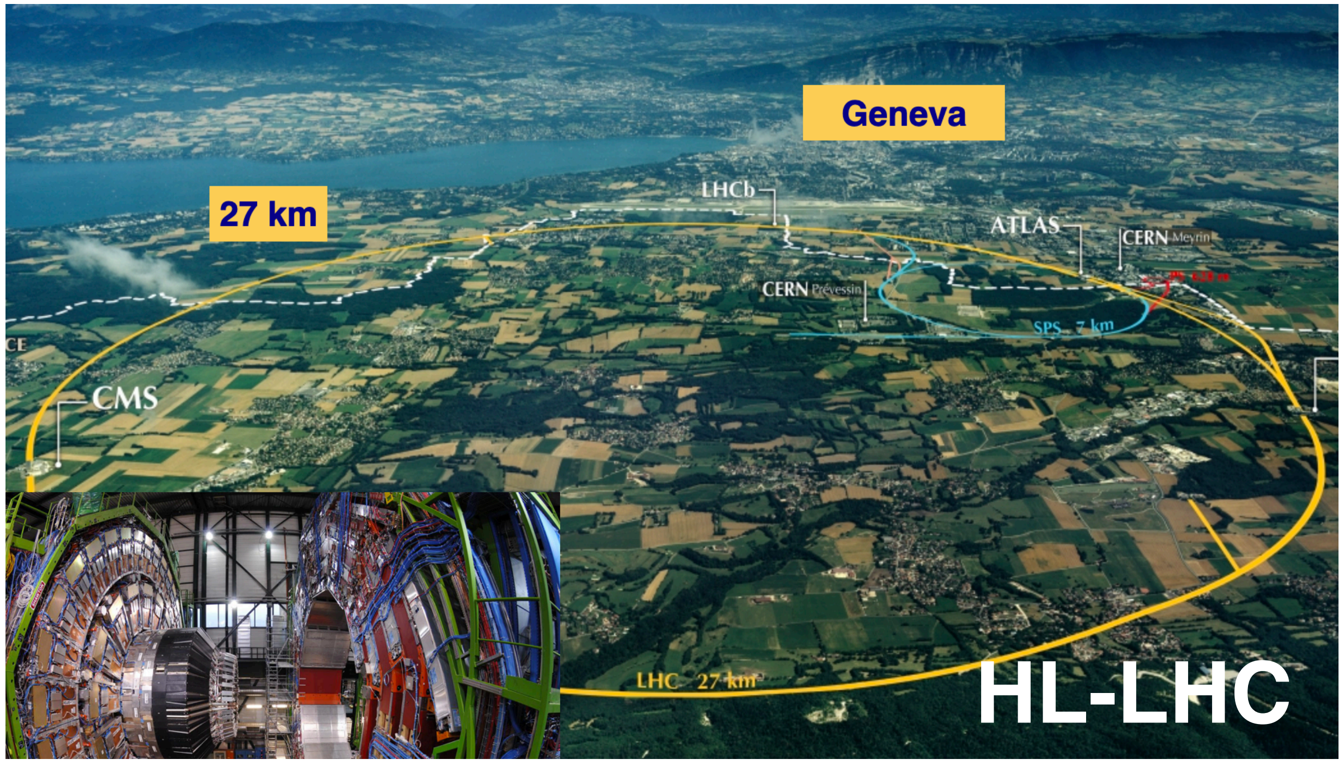
$$\Delta_{\mathrm{PDF}}\left(\mathrm{MSHT20\ only}\right) = 0.34\,\%$$

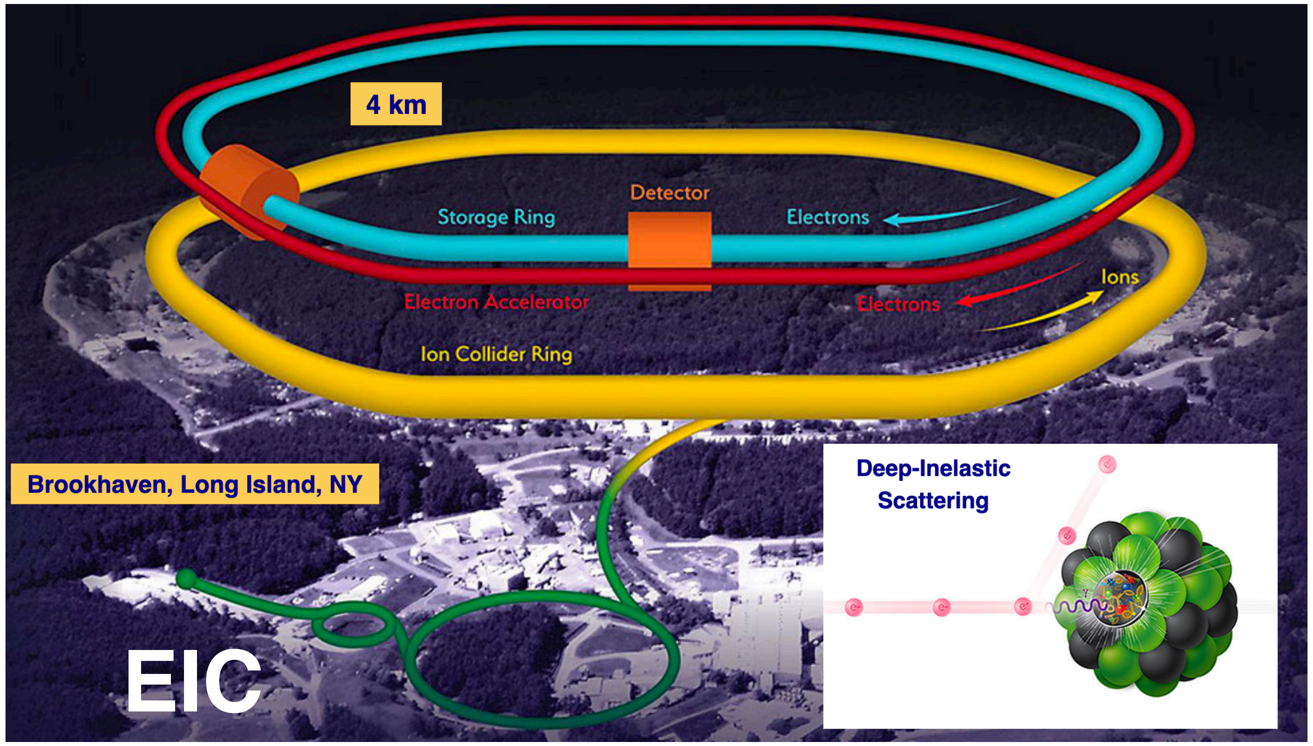
$$\Delta_{\mathrm{PDF}}\,(\mathrm{NNPDF4.0} - \mathrm{CT18A}) = 1.6\,\%$$

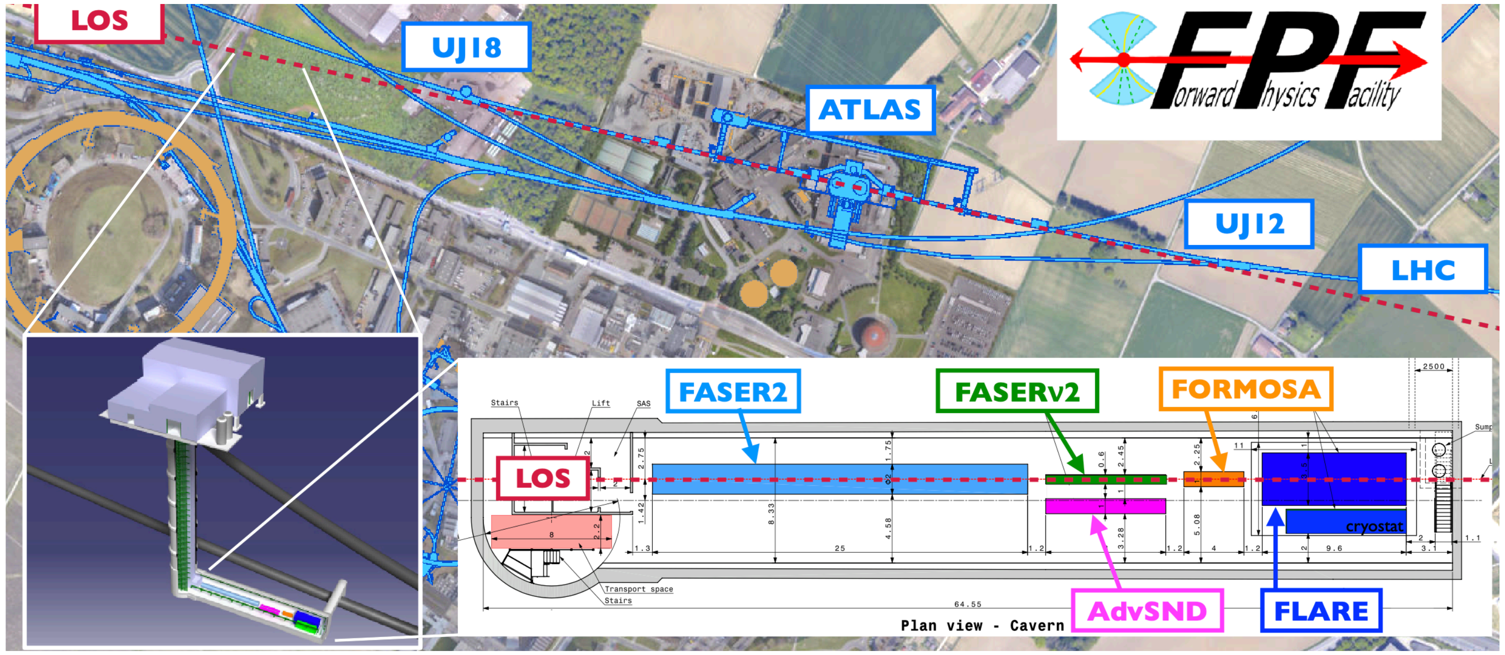
``true PDF uncertainty'' that should be associated to this measurement? **baseline PDF different** for each analysis i.e. ATLAS takes CT18 for *W*-mass …

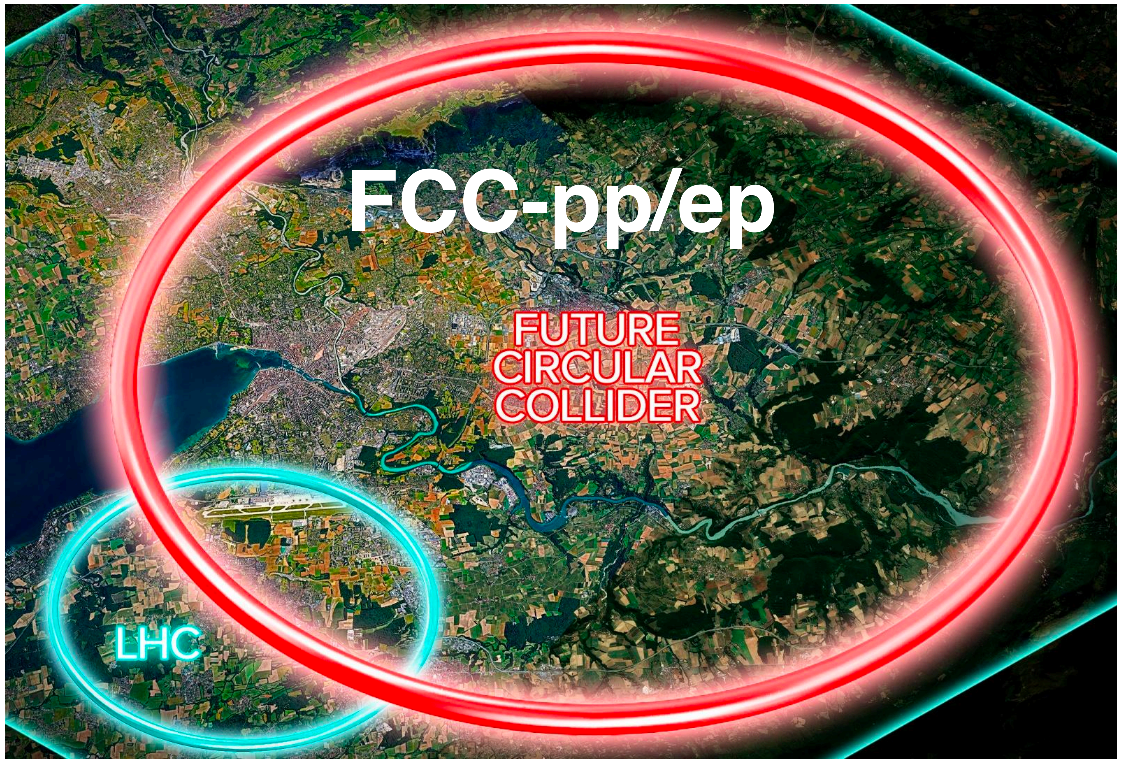
Proton structure and future colliders

at any experiment with **initial-state hadrons,** proton structure is both a **key input** and a **target for dedicated physics studies**









Proton structure @ ZPW24

Pushing the precision frontier

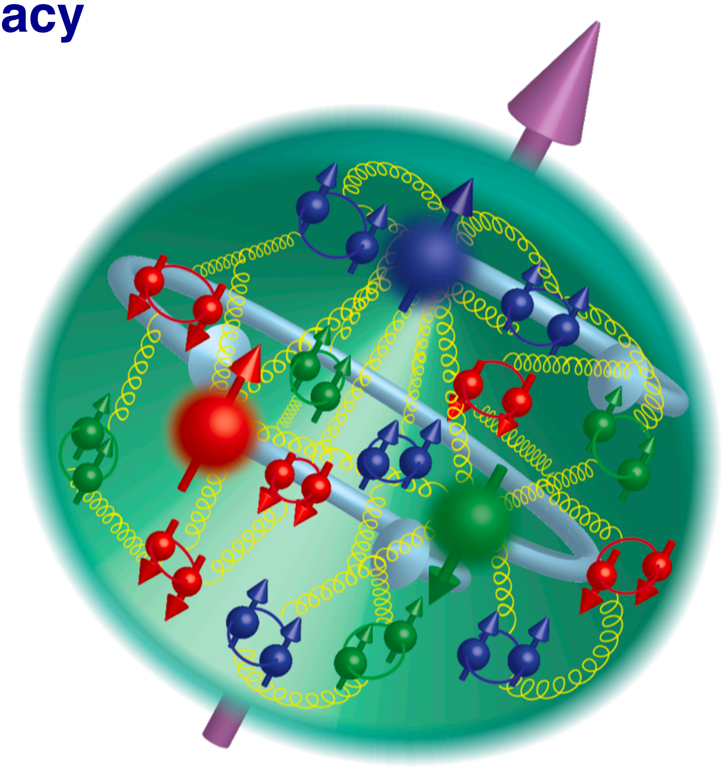
Proton structure at aN^{3}LO accuracy

[HL-LHC]

The LHC as a Neutrino Collider

Neutrino DIS from a ‘recycled’ beam

[Forward Physics Facility]



Hidden Charms

Proton structure and quest for new constituents

[HL-LHC, EIC, FPF]

New avenues & challenges for BSM

Proton structure and New Physics searches

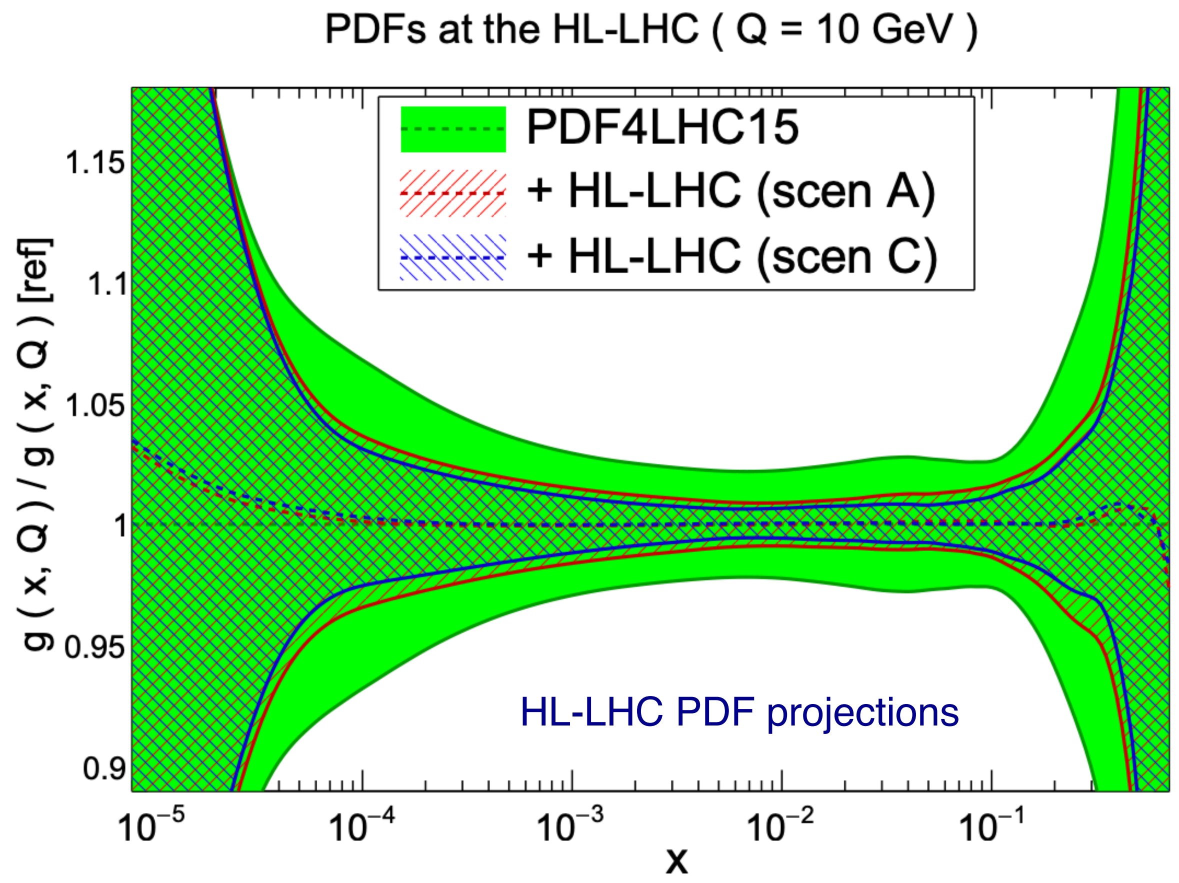
[HL-LHC, EIC]

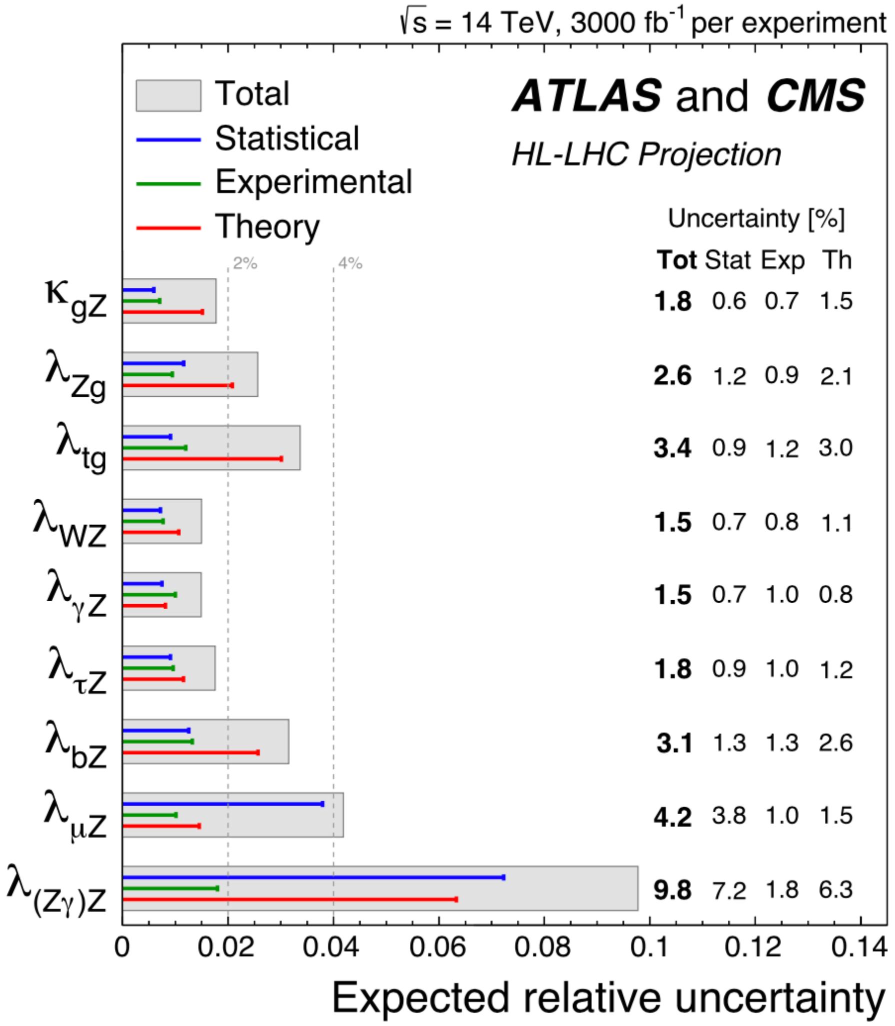
The Path to PDFs at N^3LO

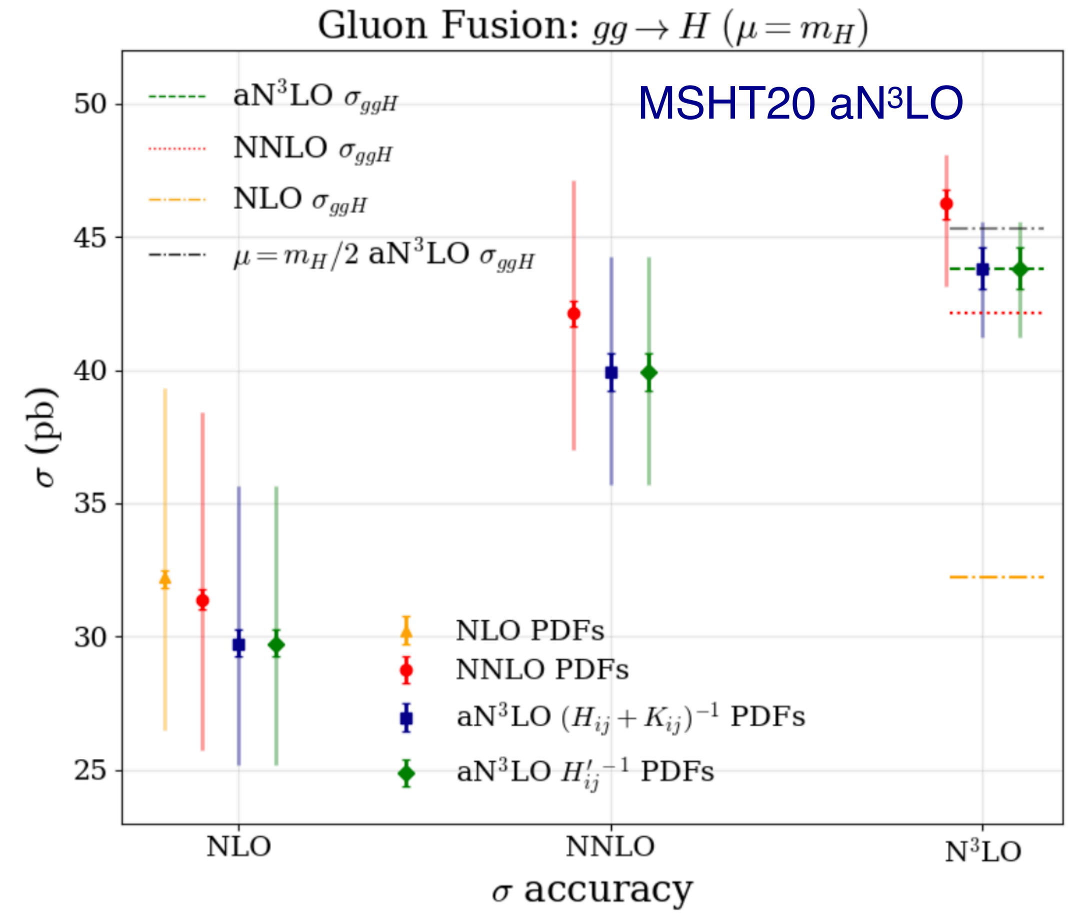
NNPDF Collaboration, **to appear soon**

Precision physics in the HL-LHC era

- Meeting the **precision targets of the HL-LHC** demands progress in PDF analyses
- Dedicated projections demonstrate the PDF **constraining power of HL-LHC data**
- What about theory uncertainties? Most Higgs cross-sections known at **N³LO accuracy**
- A first aN3LO PDF fit (MSHT20) leads to a **5% reduction of the Higgs xsec** in gluon-fusion …

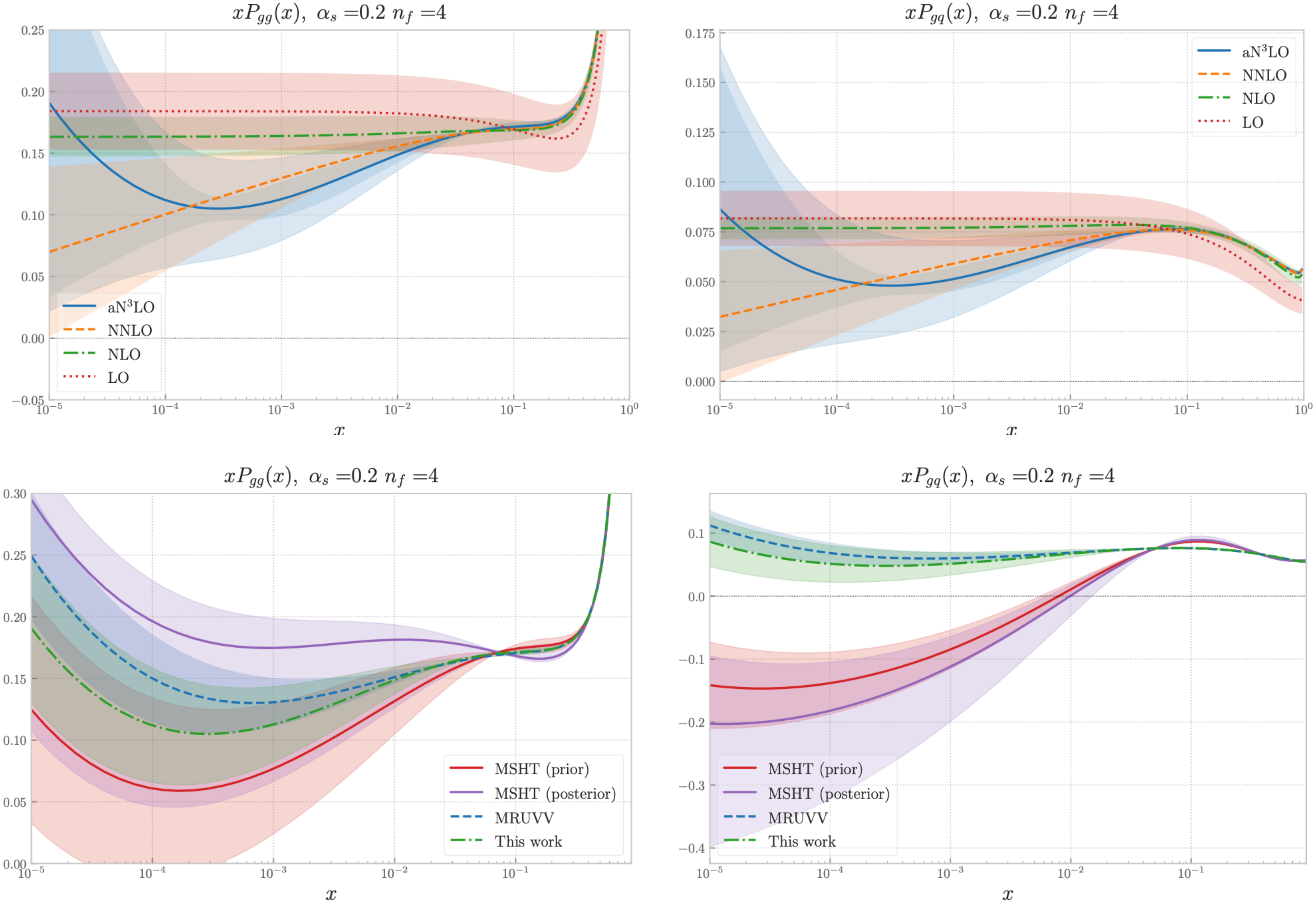






NNPDF4.0 at aN^{3}LO

- Approximate parametrisation for the N^{3}LO splitting functions satisfying known **exact results and limits**



LO, NLO, NNLO: **MHOU (μ_F)**

N^{3}LO: **MHOU (μ_F) + IHOUs**

MRUVV: Moch et al, arXiv:2310:05744

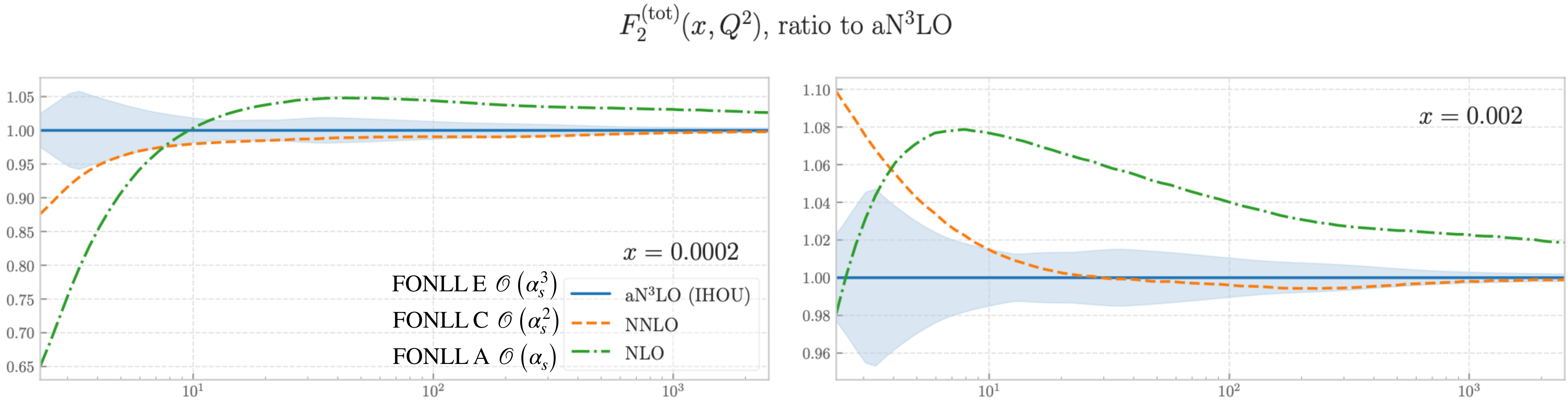
MSHT20: **IHOUs (prior & posterior)**

[IHOUs constrained from data via **nuisance parameters]**

Differences with MSHT20 related to *i)* reduced set of **theory inputs** and *ii)* **constraining IHOUs from data**

NNPDF4.0 at aN^{3}LO

- Approximate parametrisation for the N^{3}LO splitting functions satisfying known **exact results and limits**
- (Approximate) deep-inelastic coefficient functions at N^{3}LO accuracy
- Massless coefficients known, parametrisation of the massive coefficients reproducing known results, extension of the **FONLL general -mass scheme at N^{3}LO**



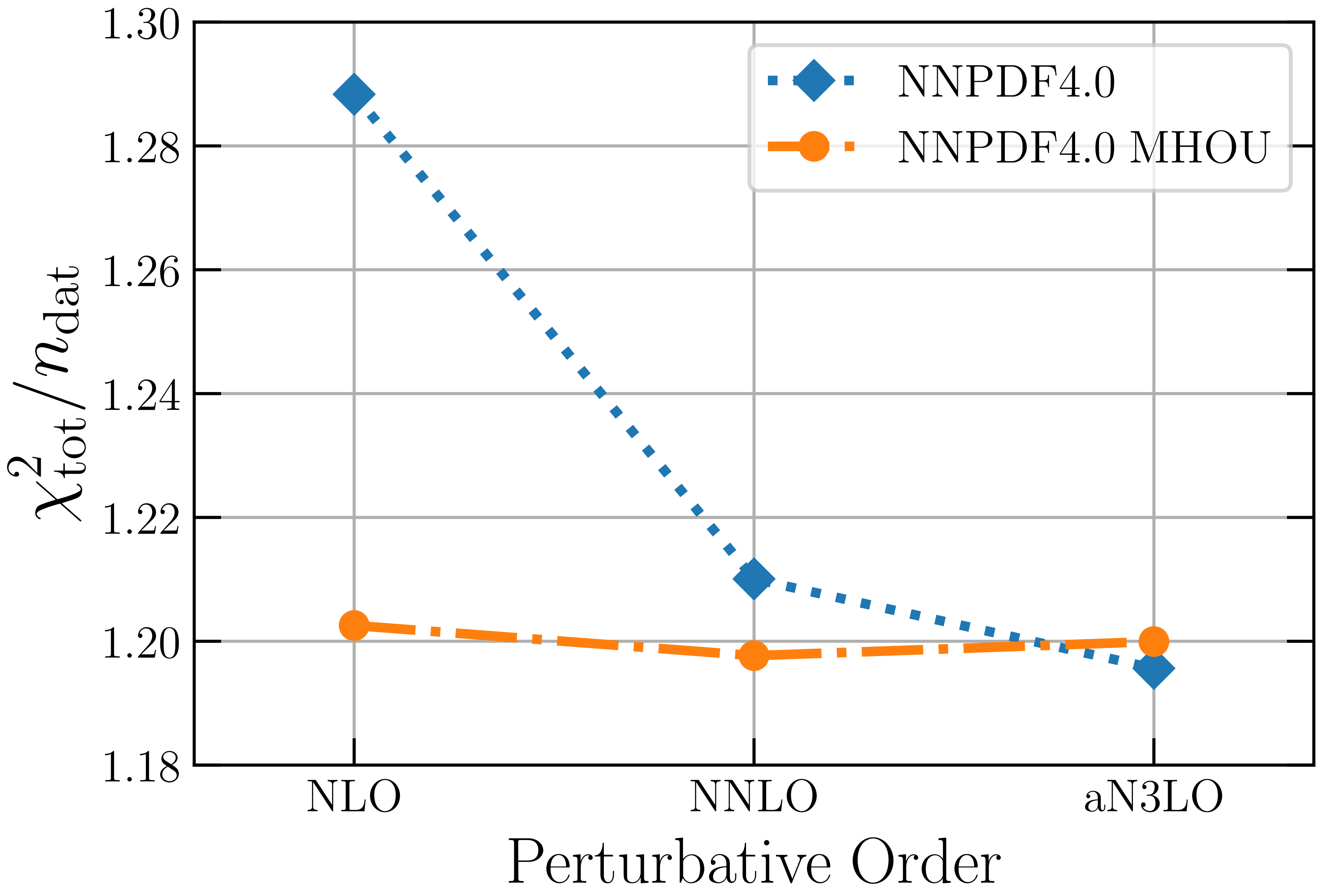
Large corrections close to **charm threshold**

- MHOUs associated to (unknown) N^{3}LO **partonic cross-sections** for hadronic data via theory covariance matrix

Some hadronic calculations relevant for N^{3}LO PDF fits (e.g. **Drell-Yan**) not publicly available

- Data and methodology same as in NNPDF4.0, except for theory errors (scale variations) now included via the **theory covariance matrix formalism**

Results: Fit quality

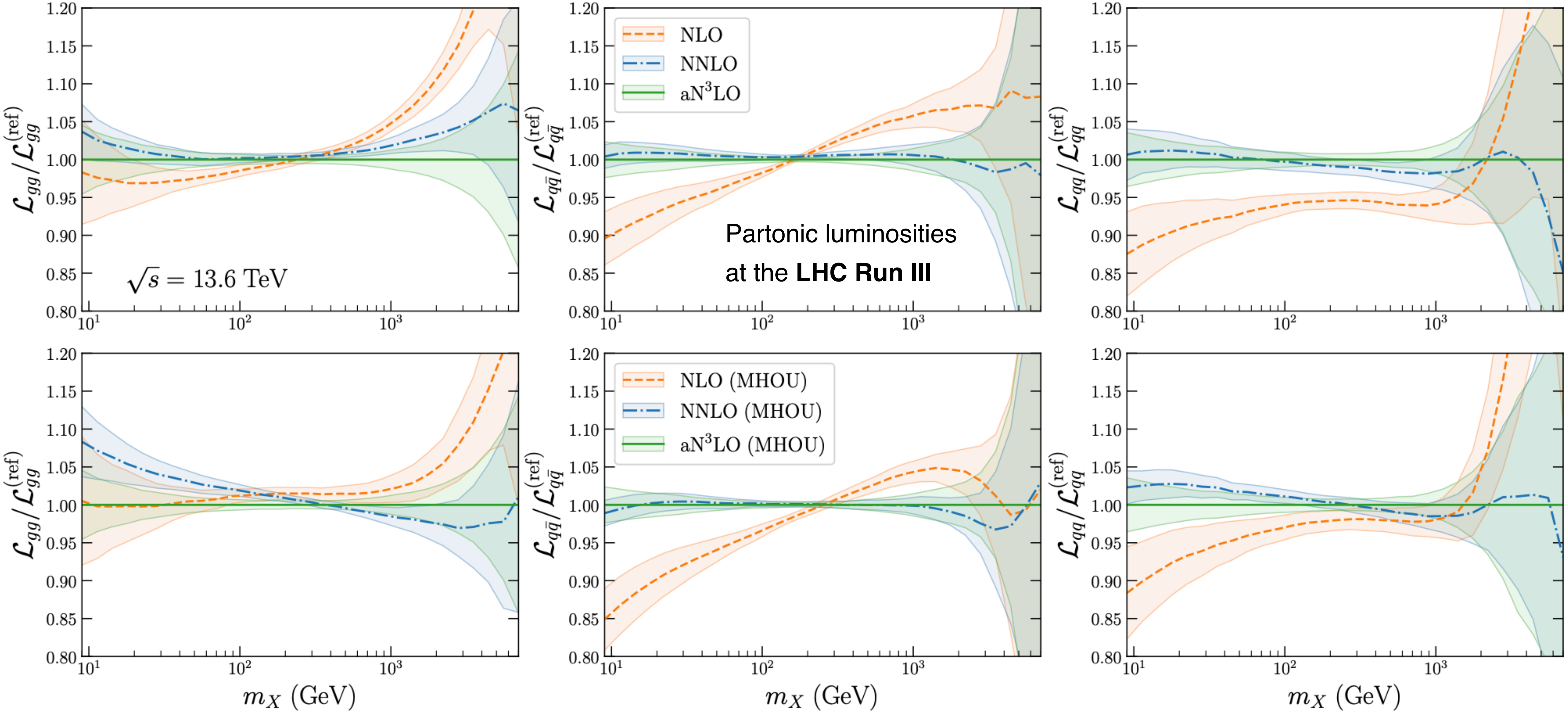


Results shown ***still preliminary****, final version to be released soon*

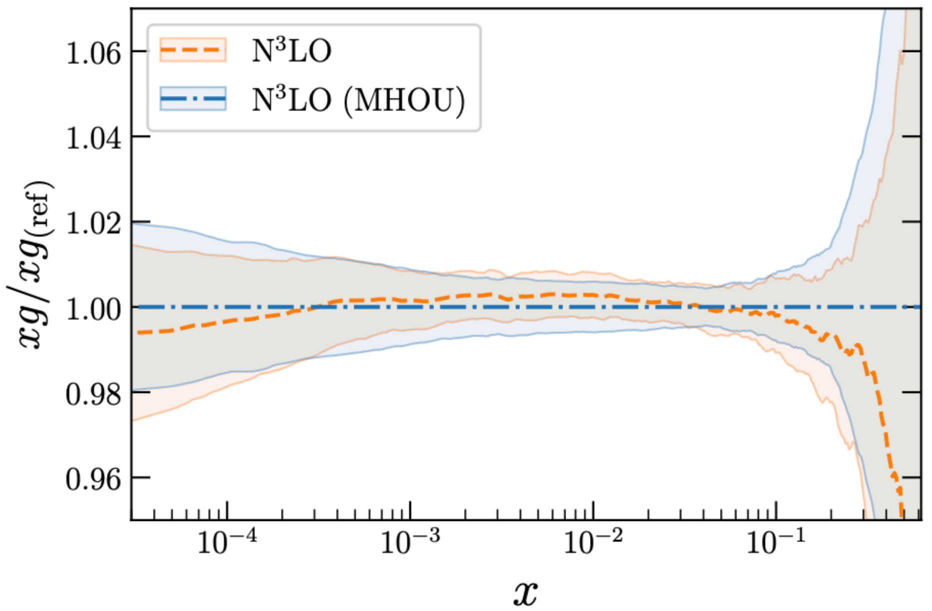
- Without MHOUs, the **χ^2 improves with the perturbative accuracy** of the PDF fit
- With MHOUs, the **χ^2** becomes **independent of perturbative accuracy**
- At aN3LO impact of MHOUs is small (also at PDF level)

N^3LO corrections required for perturbative convergence at the PDF fit level

Results: perturbative stability

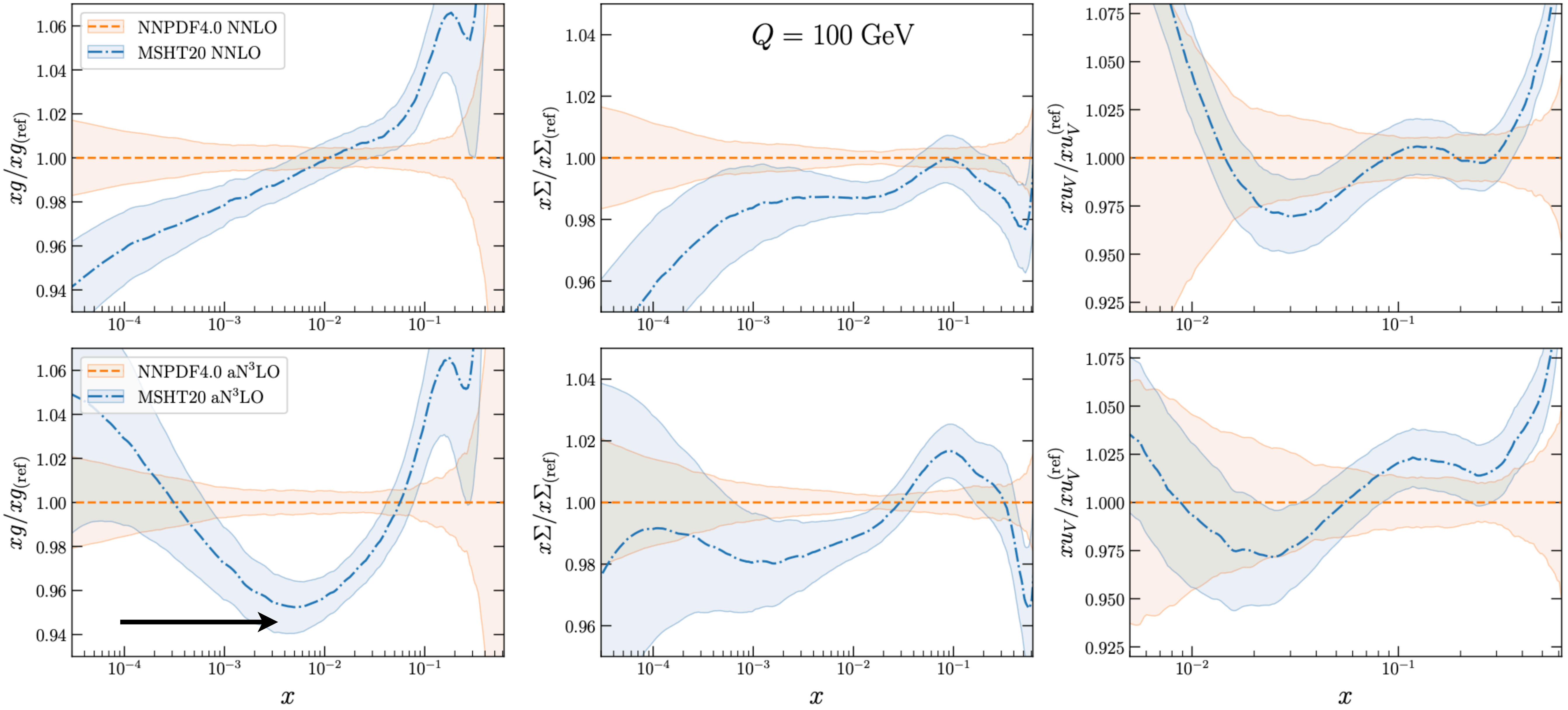


Partonic luminosities at the **LHC Run III**



- N³LO corrections **moderate**, specially for quark luminosities
- Impact of **MHOUs negligible** at **N³LO**
- MHOUs at NNLO most relevant for the gluon, presumably due to the **deweighting of jet data**

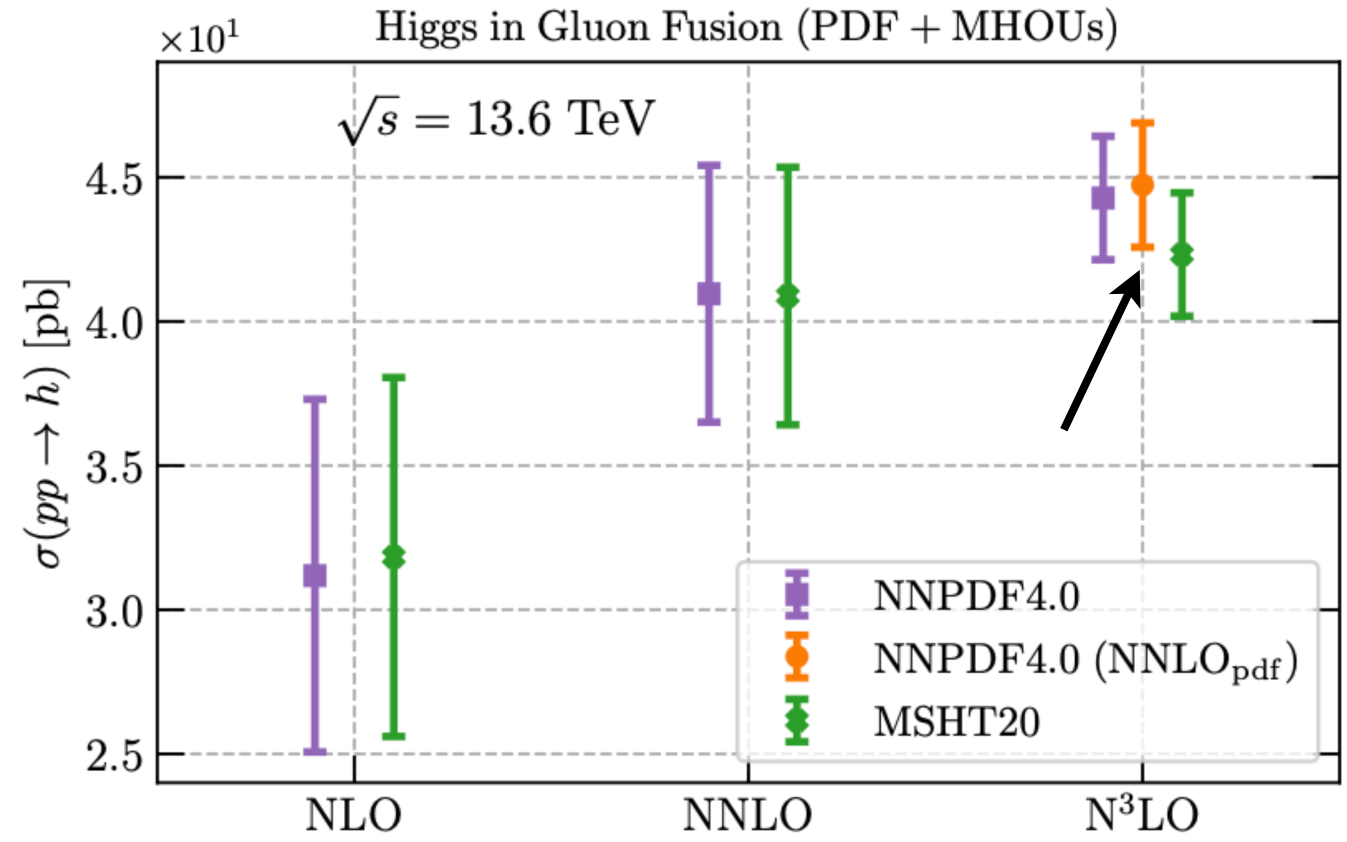
Results: comparison with MSHT20

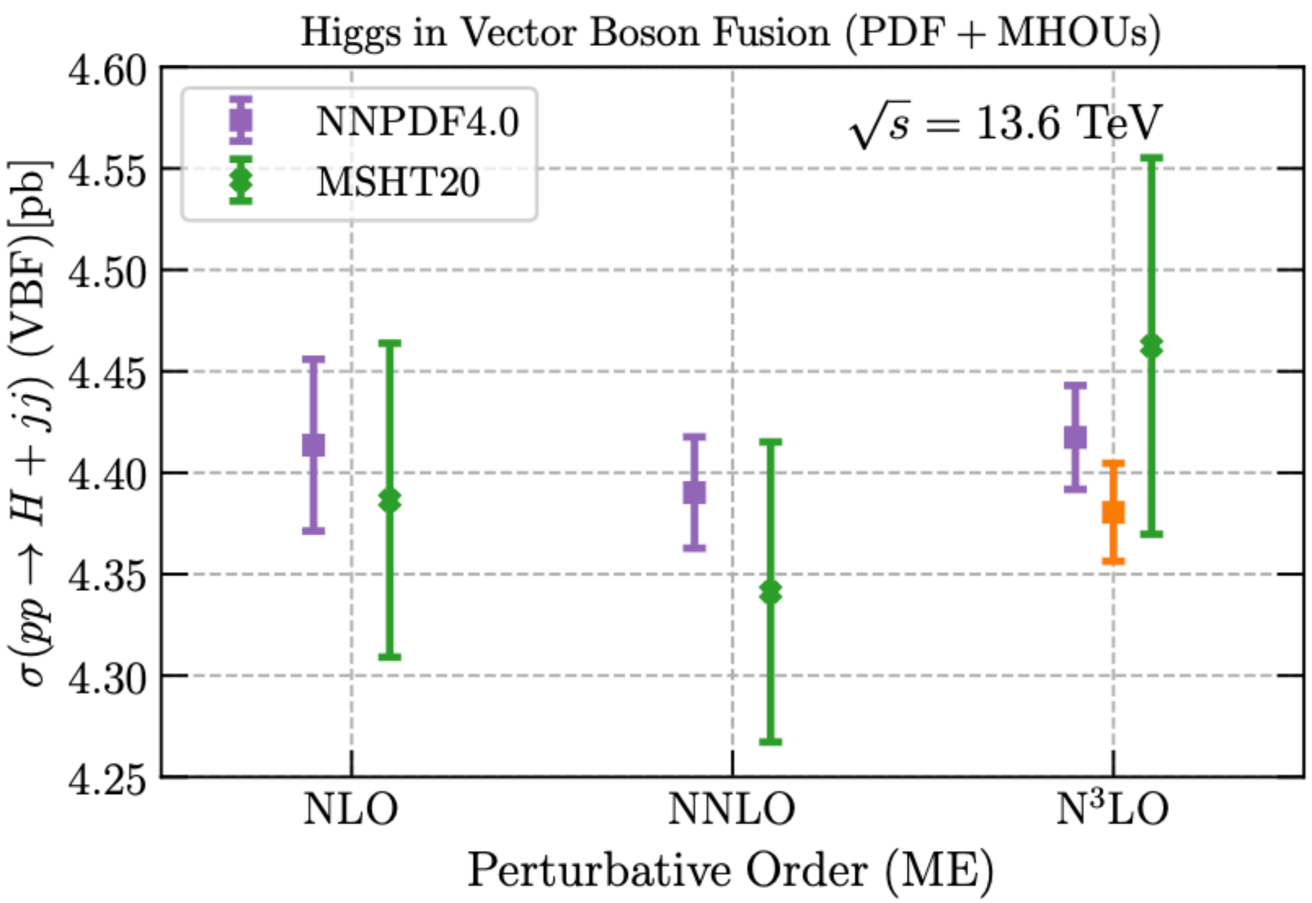


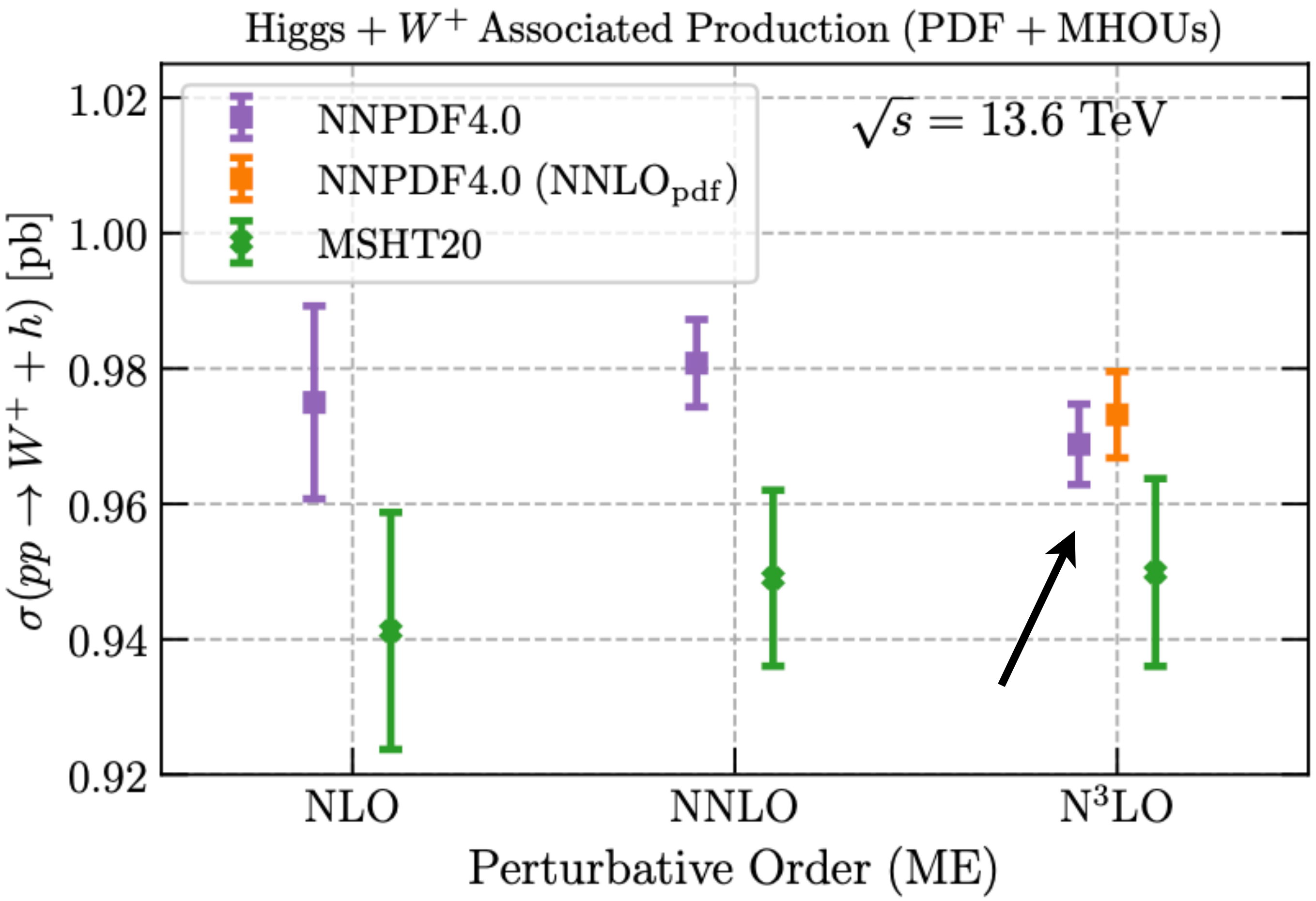
- As compared to existing results at NNLO, once the comparison is upgraded to N^{3}LO, main qualitative differences for the **gluon PDF**, quarks stable

- MSHT20 gluon PDF **suppressed by 5% at *x*=0.005** in comparison with NNPDF4.0, at small-x the agreement is improved with N^{3}LO corrections

LHC phenomenology: Higgs production





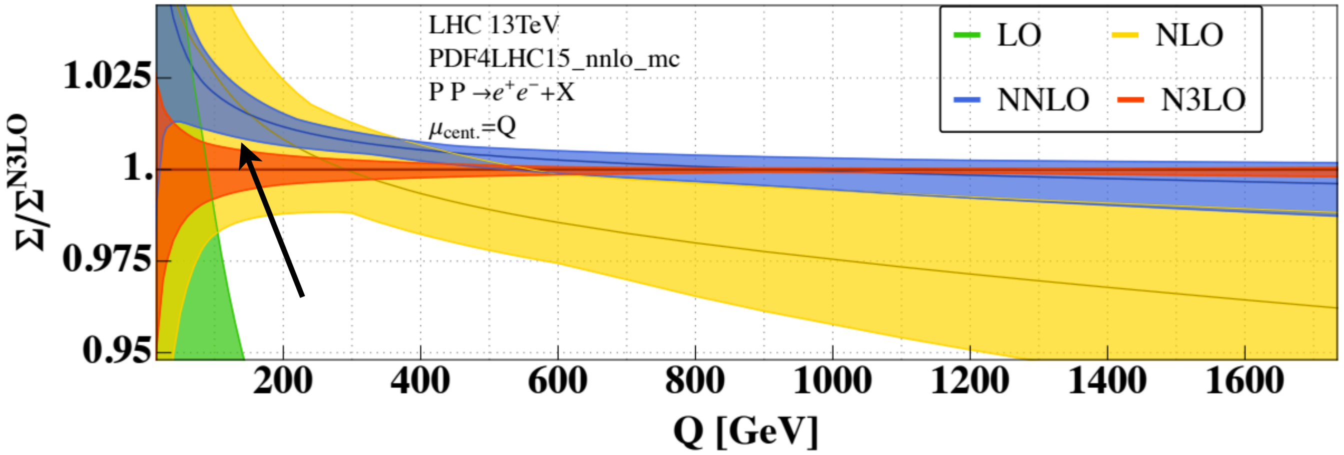


- N^{3}LO PDF corrections to **Higgs in gluon fusion small**, unlike MSHT20 prediction
- N^{3}LO corrections improve agreement between NNPDF4.0 and MSHT20 for ***hW***
- **Higgs VBF** perturbatively stable

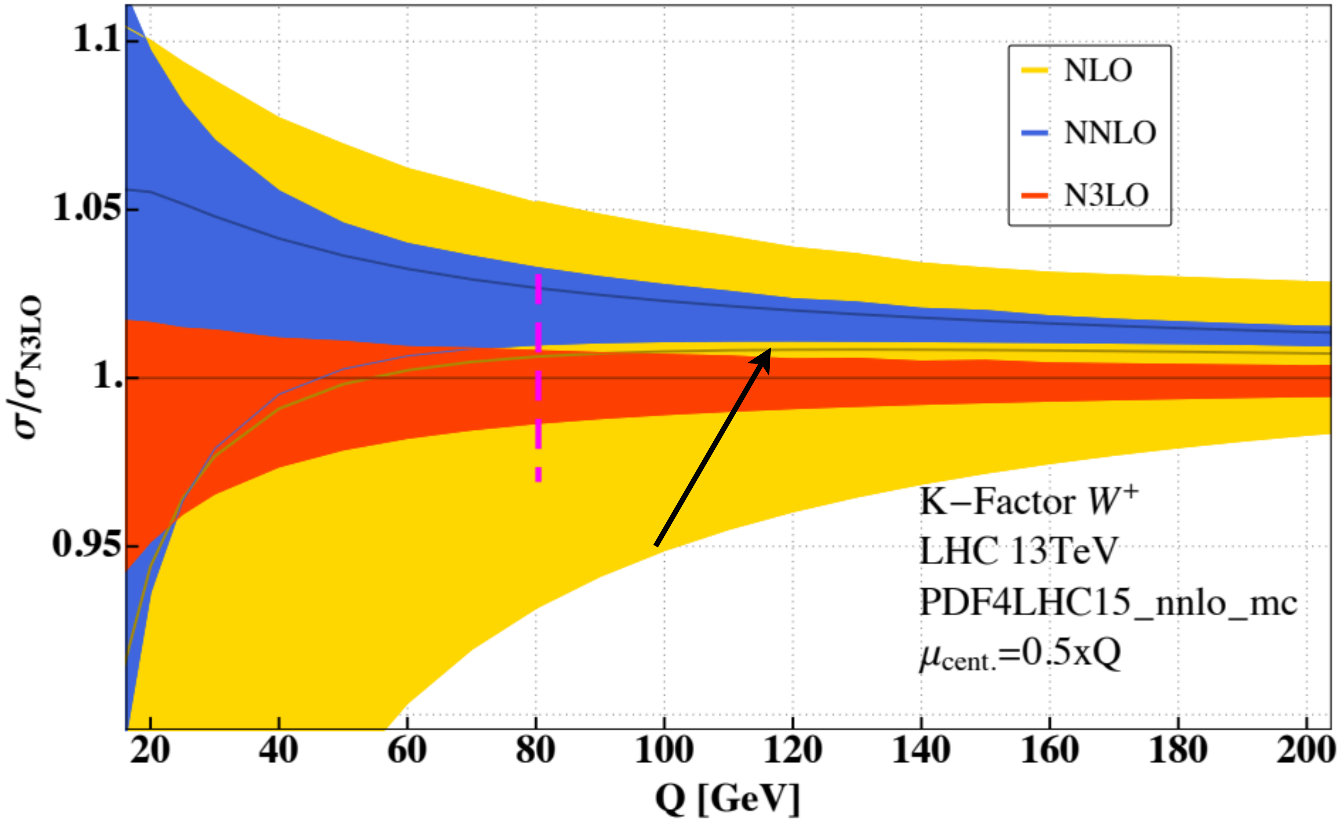
LHC phenomenology: Drell-Yan

Often predictions for N³LO cross-sections are evaluated with NNLO PDFs. What happens when **aN³LO PDFs are used**?

Neutral-current Drell-Yan



Charged-current Drell-Yan

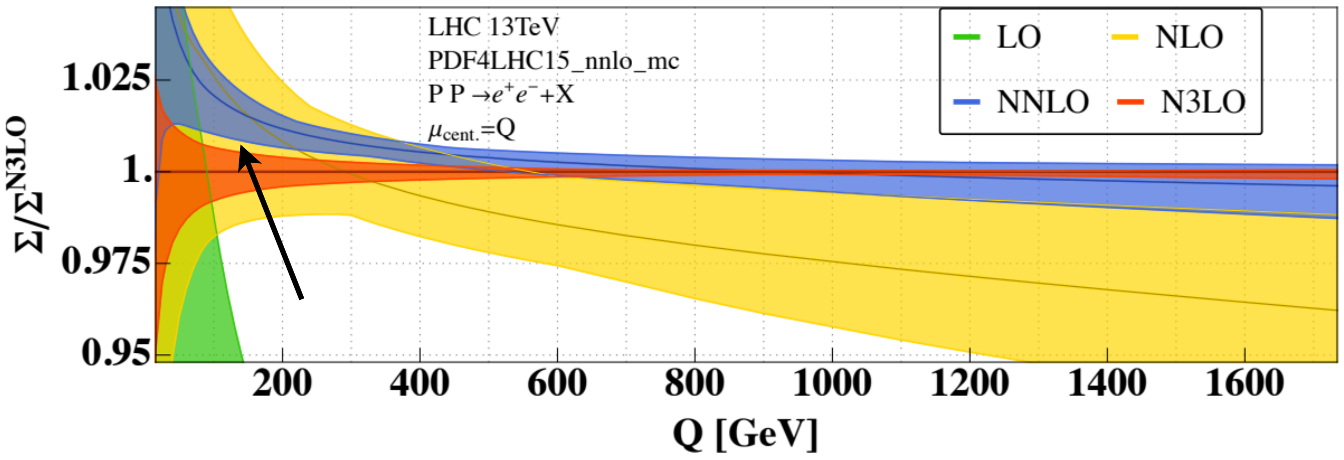


LHC phenomenology: Drell-Yan

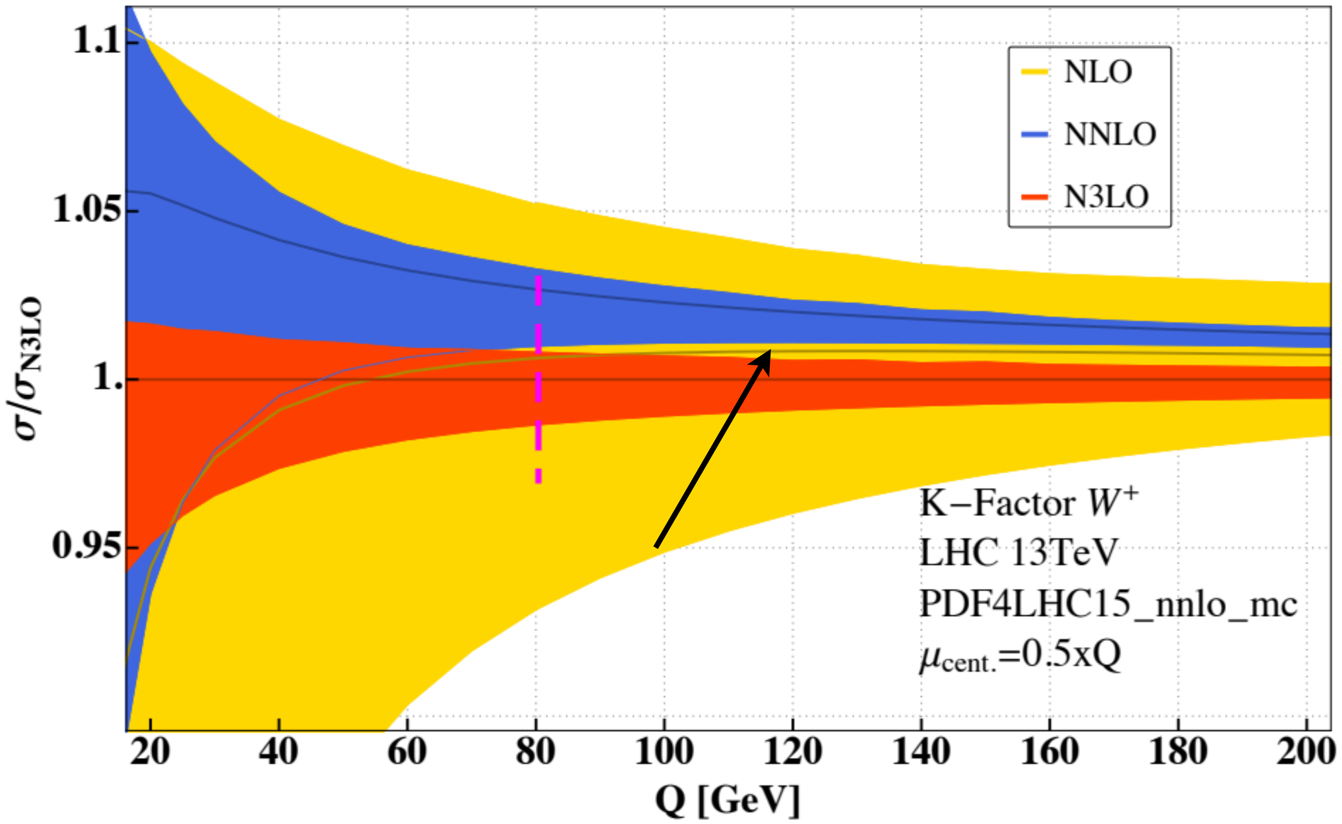
Often predictions for N³LO cross-sections are evaluated with NNLO PDFs. What happens when **aN³LO PDFs are used**?

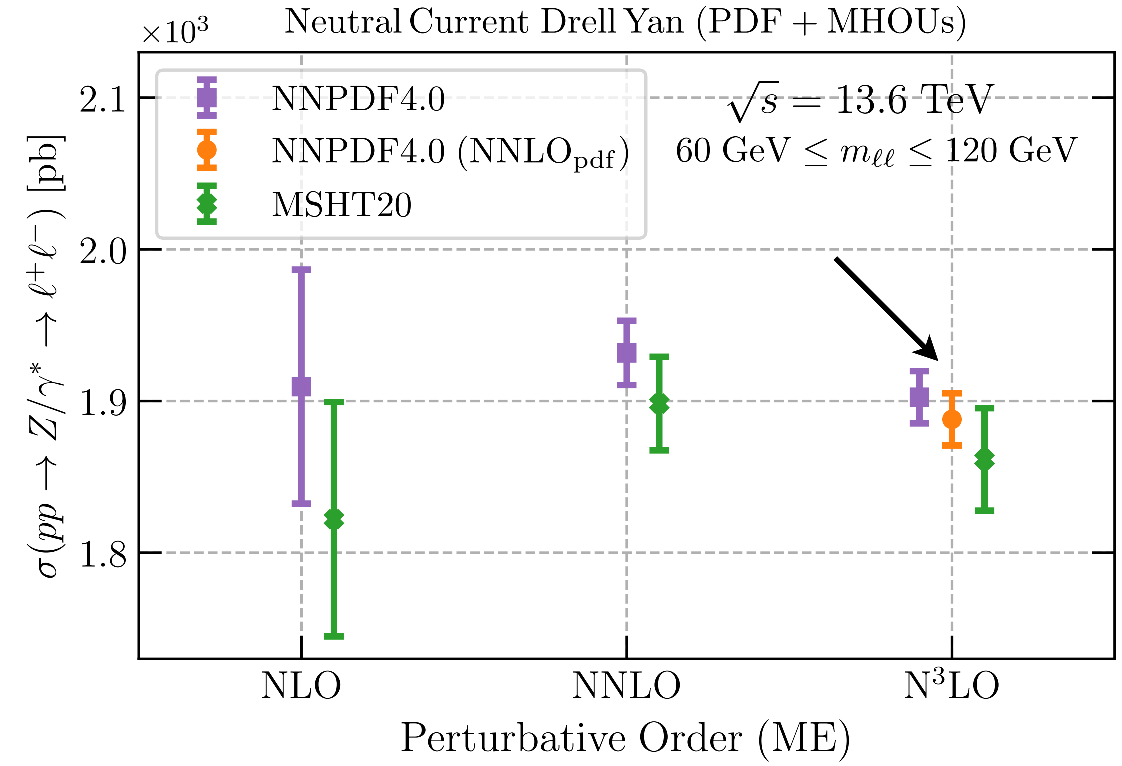
Consistent use of **aN³LO PDFs** with N³LO MEs improves **perturbative convergence**

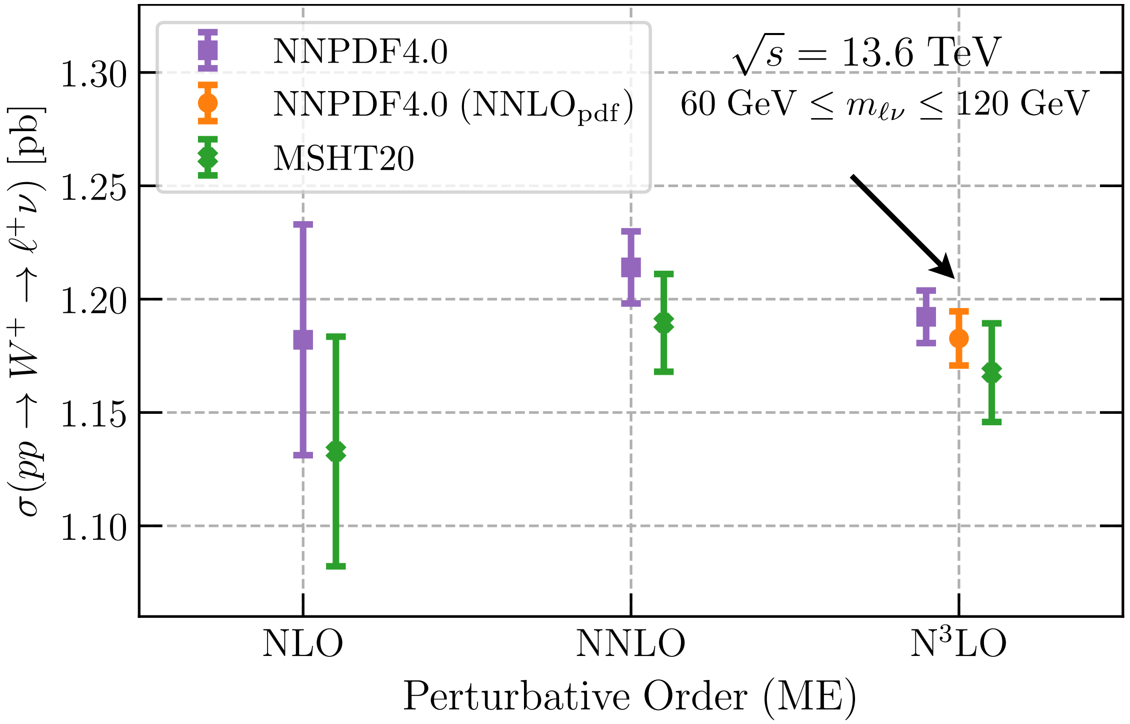
Neutral-current Drell-Yan



Charged-current Drell-Yan





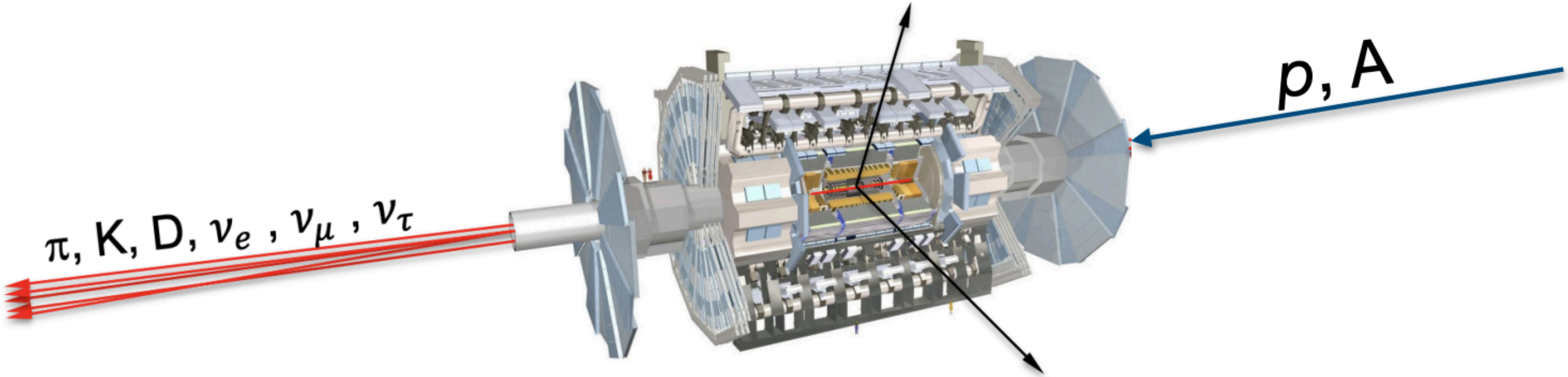


The LHC as a Neutrino Collider

J. M. Cruz-Martinez, M. Fieg, T. Giani, P. Krack, T. Makela,
T. Rabemananjara, and J. Rojo, ***arXiv:2309.09581***

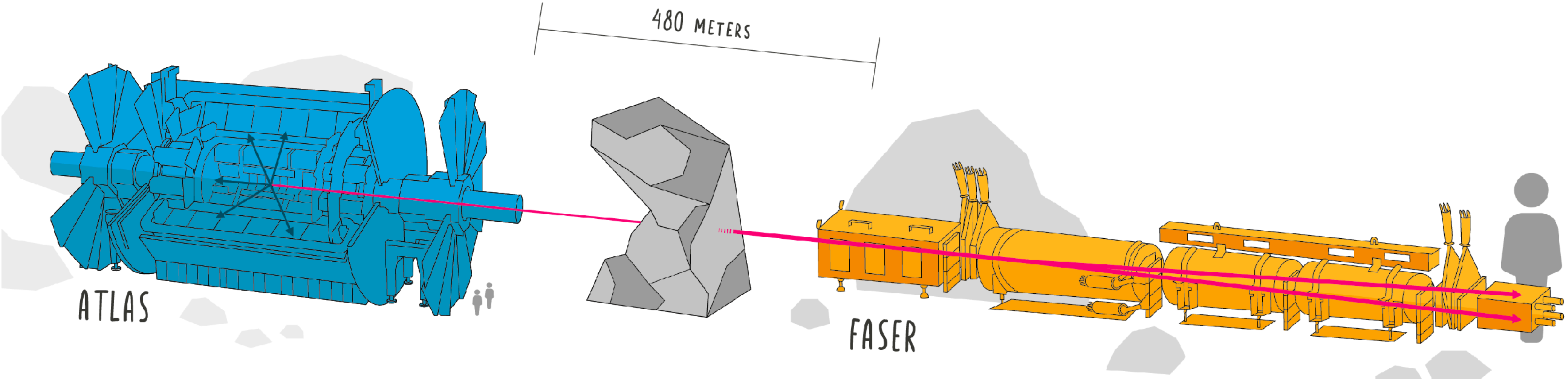
Neutrinos at the LHC

- LHC collisions result into a **large flux of energetic neutrinos** which escape the detectors unobserved: **major blind spot of the LHC**



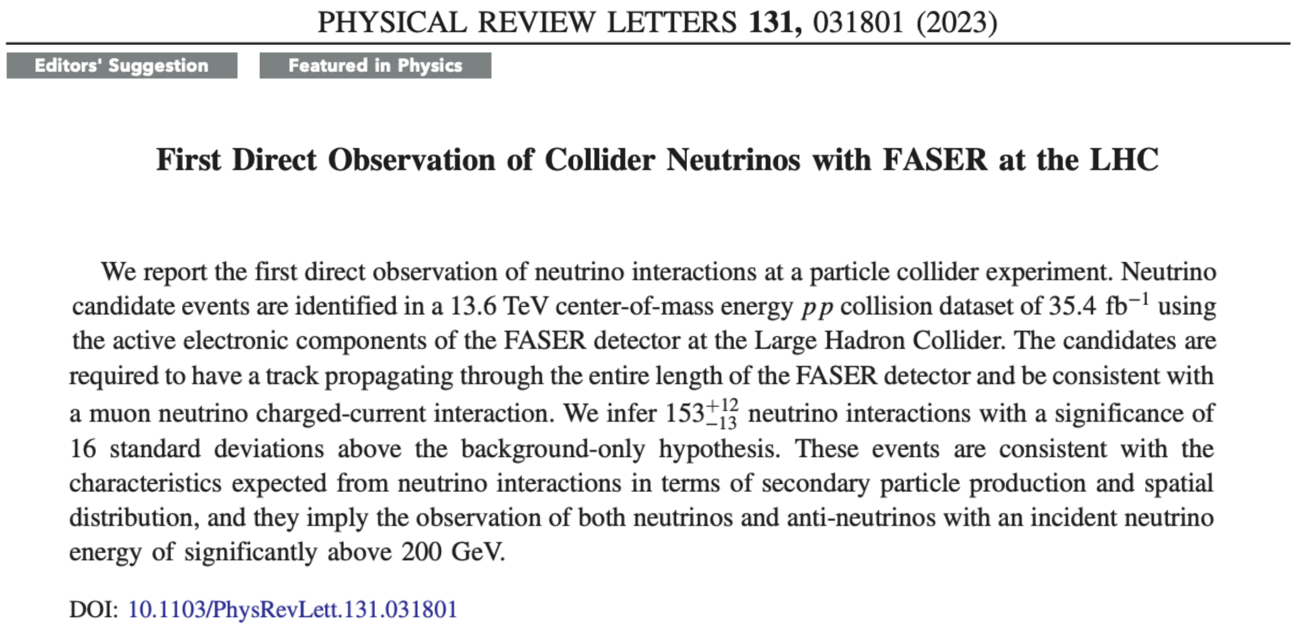
- Being able to detect and utilise the **most energetic human-made neutrinos ever produced** would open many exciting avenues in QCD, neutrino, and astroparticle physics

solution: install **far-forward detectors** instrumenting an hitherto uncharted region



The dawn of the LHC neutrino era

- Two far-forward experiments, **FASER** and **SND@LHC**, have been instrumenting the LHC far-forward region since the begin of Run III and reported **evidence for LHC neutrinos** (March 2023)



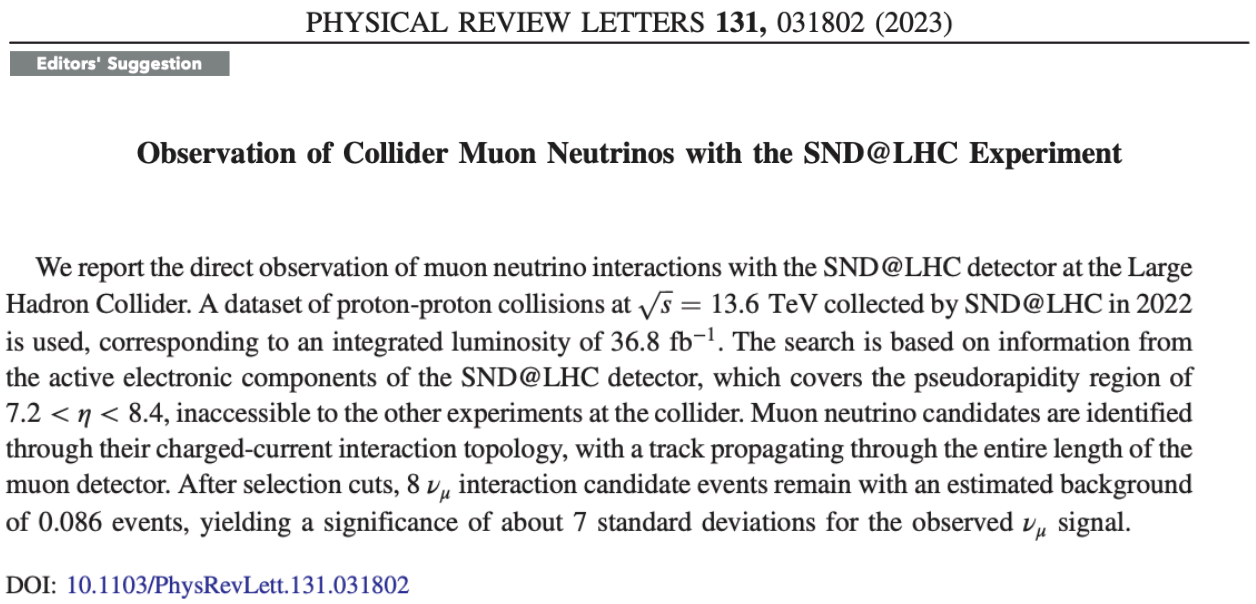
PHYSICAL REVIEW LETTERS **131,** 031801 (2023)

Editors' Suggestion **Featured in Physics**

First Direct Observation of Collider Neutrinos with FASER at the LHC

We report the first direct observation of neutrino interactions at a particle collider experiment. Neutrino candidate events are identified in a 13.6 TeV center-of-mass energy pp collision dataset of 35.4 fb^{-1} using the active electronic components of the FASER detector at the Large Hadron Collider. The candidates are required to have a track propagating through the entire length of the FASER detector and be consistent with a muon neutrino charged-current interaction. We infer 153^{+12}_{-13} neutrino interactions with a significance of 16 standard deviations above the background-only hypothesis. These events are consistent with the characteristics expected from neutrino interactions in terms of secondary particle production and spatial distribution, and they imply the observation of both neutrinos and anti-neutrinos with an incident neutrino energy of significantly above 200 GeV.

DOI: 10.1103/PhysRevLett.131.031801



PHYSICAL REVIEW LETTERS **131,** 031802 (2023)

Editors' Suggestion

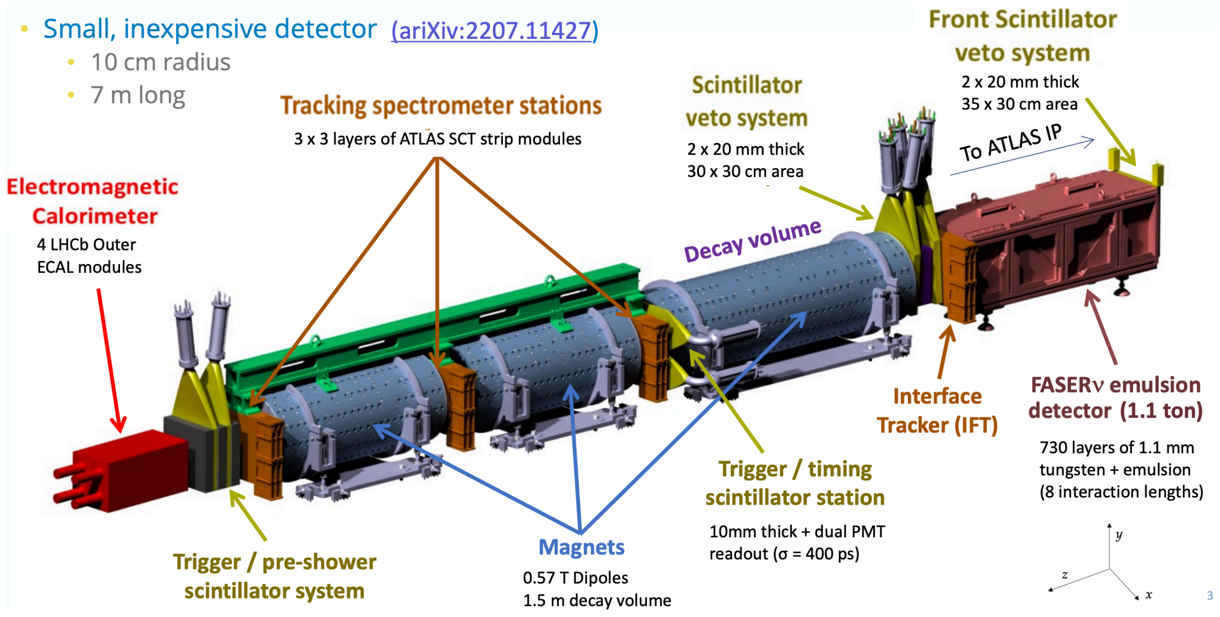
Observation of Collider Muon Neutrinos with the SND@LHC Experiment

We report the direct observation of muon neutrino interactions with the SND@LHC detector at the Large Hadron Collider. A dataset of proton-proton collisions at $\sqrt{s} = 13.6$ TeV collected by SND@LHC in 2022 is used, corresponding to an integrated luminosity of 36.8 fb^{-1}. The search is based on information from the active electronic components of the SND@LHC detector, which covers the pseudorapidity region of $7.2 < \eta < 8.4$, inaccessible to the other experiments at the collider. Muon neutrino candidates are identified through their charged-current interaction topology, with a track propagating through the entire length of the muon detector. After selection cuts, 8 ν_μ interaction candidate events remain with an estimated background of 0.086 events, yielding a significance of about 7 standard deviations for the observed ν_μ signal.

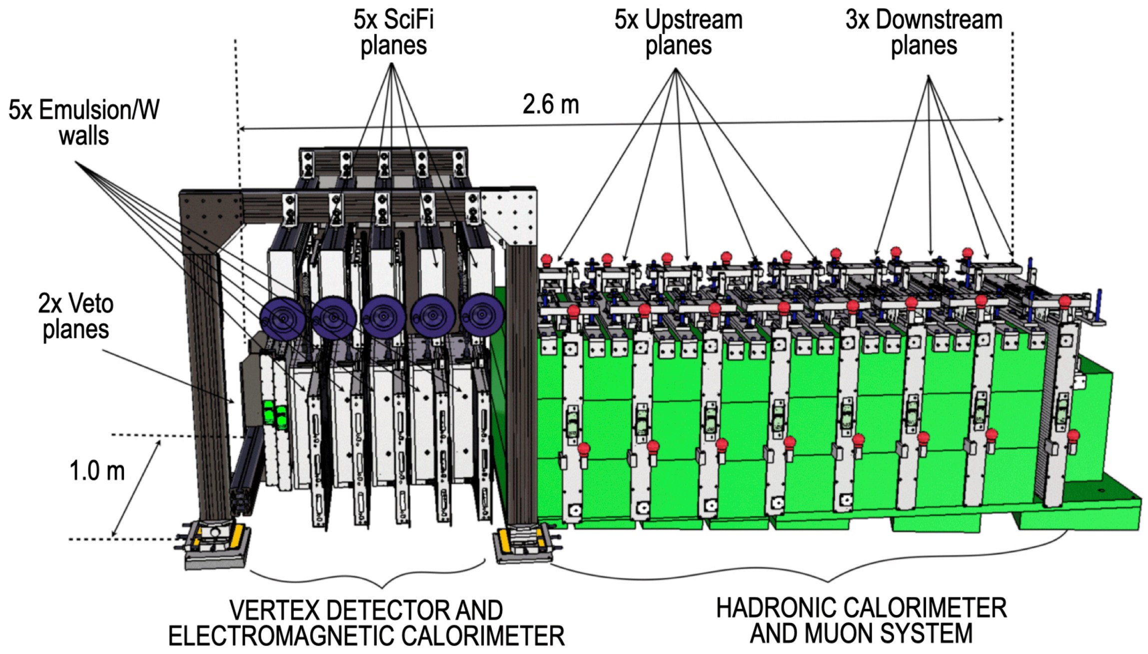
DOI: 10.1103/PhysRevLett.131.031802

153 neutrinos detected, 151± 41 expected

8 neutrinos detected, 4 expected

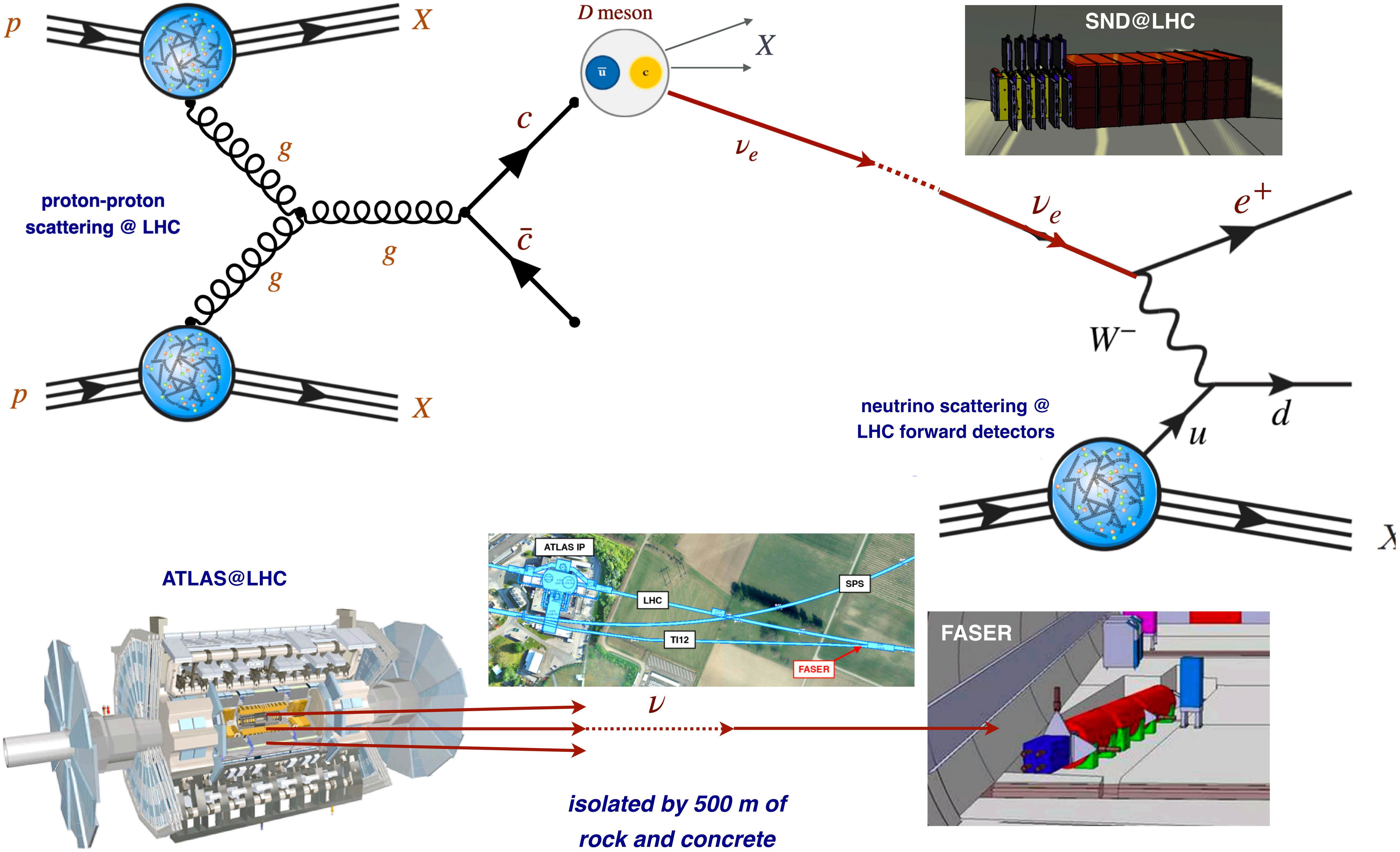


- Small, inexpensive detector (ariXiv:2207.11427)
  - 10 cm radius
  - 7 m long



Now is the time to start exploiting their physics potential

Neutrinos at the LHC



SND@LHC

proton-proton scattering @ LHC

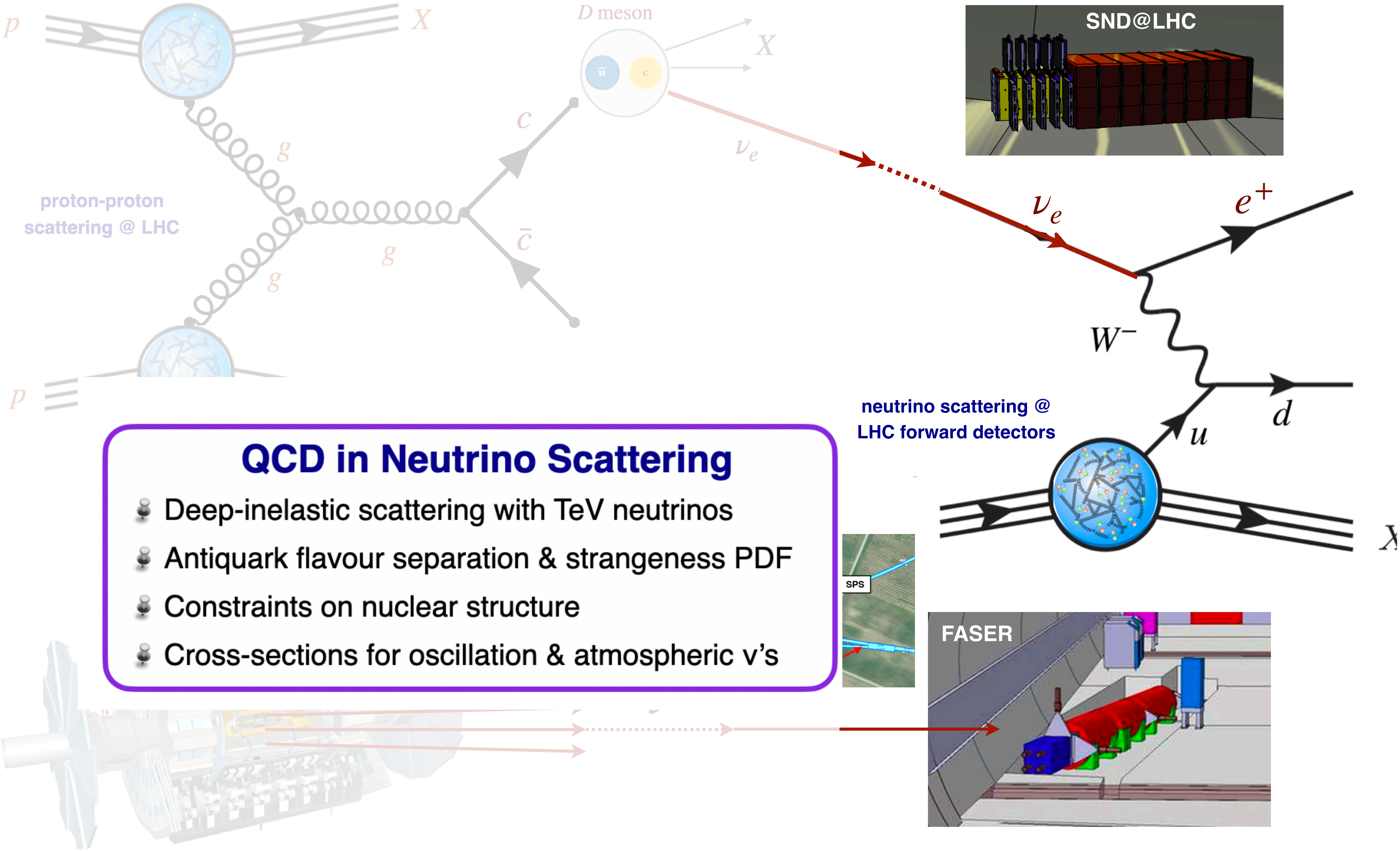
neutrino scattering @ LHC forward detectors

ATLAS@LHC

FASER

isolated by 500 m of rock and concrete

Neutrinos at the LHC



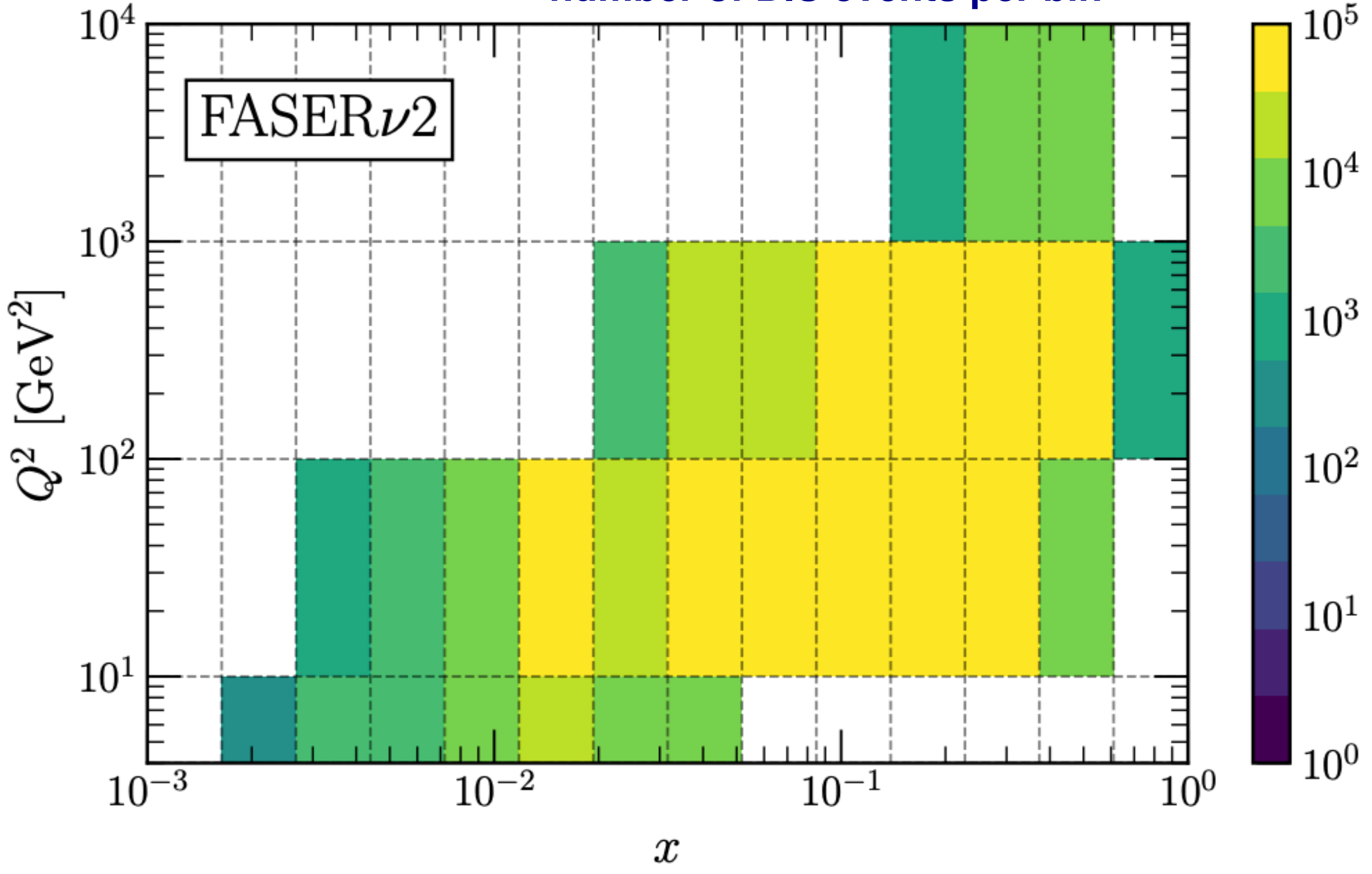
QCD in Neutrino Scattering

- Deep-inelastic scattering with TeV neutrinos
- Antiquark flavour separation & strangeness PDF
- Constraints on nuclear structure
- Cross-sections for oscillation & atmospheric ν's

Neutrinos at the LHC

- Generate **DIS pseudo-data** at current and proposed LHC neutrino experiments
- Fully differential calculation based on **state-of-the-art QCD** calculations
- Model **systematic errors** based on the expected performance of the experiments
- Consider both inclusive and **charm-production DIS**

number of DIS events per bin



Events per bin

$$N_{\rm ev}^{(i)} = n_T L_T \int_{Q^{2(i)}_{\rm min}}^{Q^{2(i)}_{\rm max}} \int_{x^{(i)}_{\rm min}}^{x^{(i)}_{\rm max}} \int_{E^{(i)}_{\rm min}}^{E^{(i)}_{\rm max}} \frac{dN_\nu(E_\nu)}{dE_\nu} \left(\frac{d^2\sigma(x,Q^2,E_\nu)}{dx dQ^2} \right) \mathcal{A}(x,Q^2,E_\nu) dQ^2 dx dE_\nu$$

Geometry

Binning

neutrino fluxes (include rapidity acceptance)

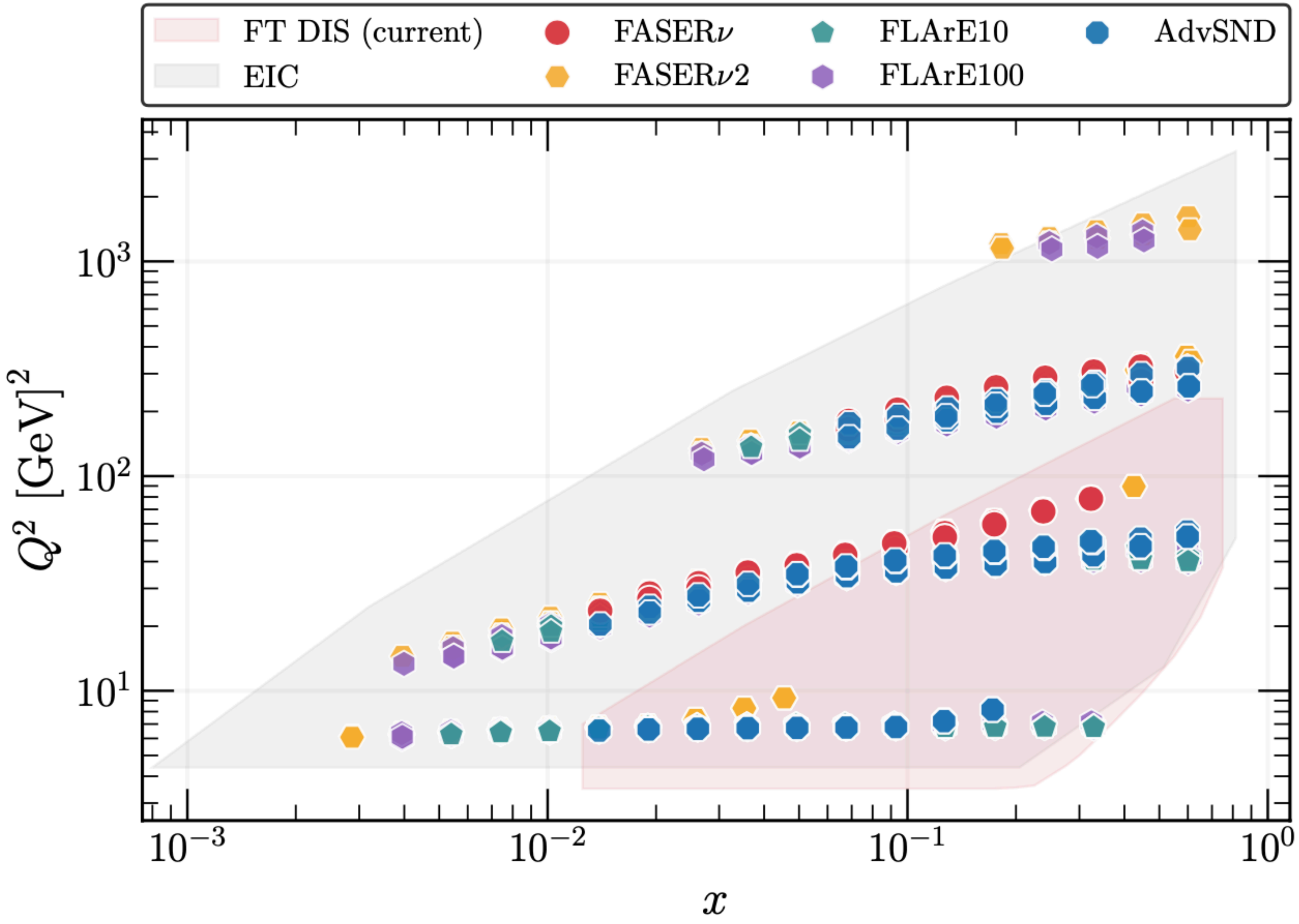
DIS differential cross-section

Acceptance

Based on **current designs**, may be different in final experiments

$$\begin{aligned} E_\nu &= E_h + E_\ell \,, \\ Q^2 &= 4(E_h + E_\ell) E_\ell \sin^2(\theta_\ell/2) \\ x &= \frac{4(E_h + E_\ell) E_\ell \sin^2(\theta_\ell/2)}{2 m_N E_h} \end{aligned}$$

Neutrinos at the LHC

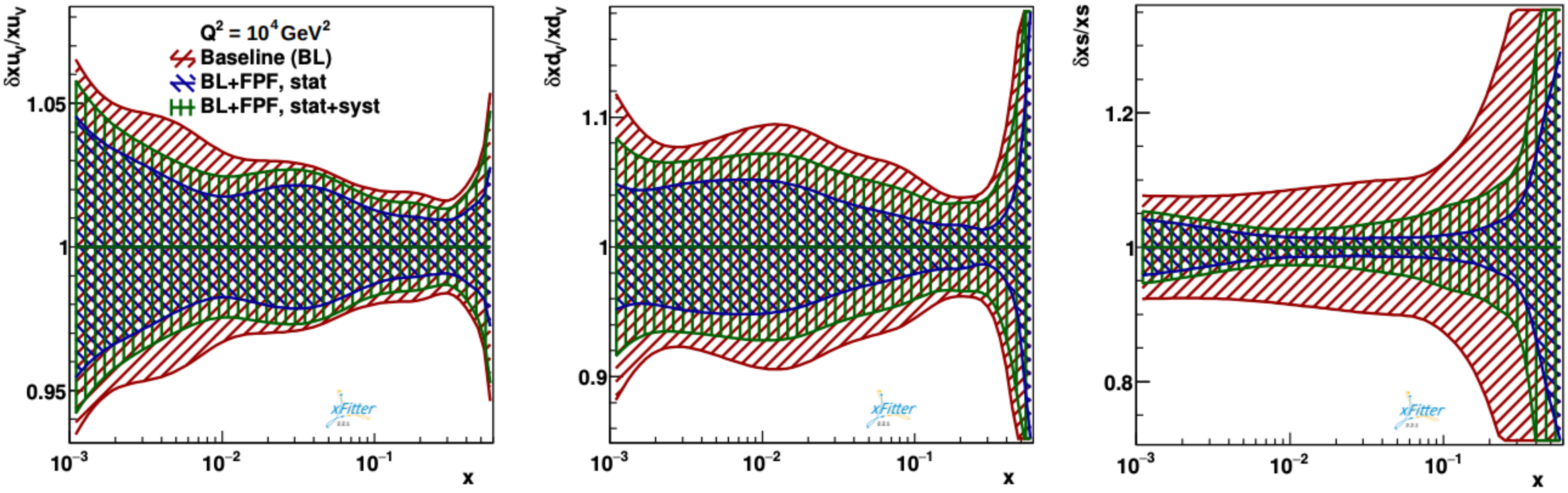


x: momentum fraction of quarks/gluons in the proton

Q^2: momentum transfer from incoming lepton

- Continue highly succesful program of neutrino **DIS experiments @ CERN,**
- **Expand kinematic coverage** of available experiments by an order of magnitude in x and Q^2
- Charged-current counterpart of the **Electron-Ion Collider** in a comparable region of phase space

PDF constraints from LHC neutrinos



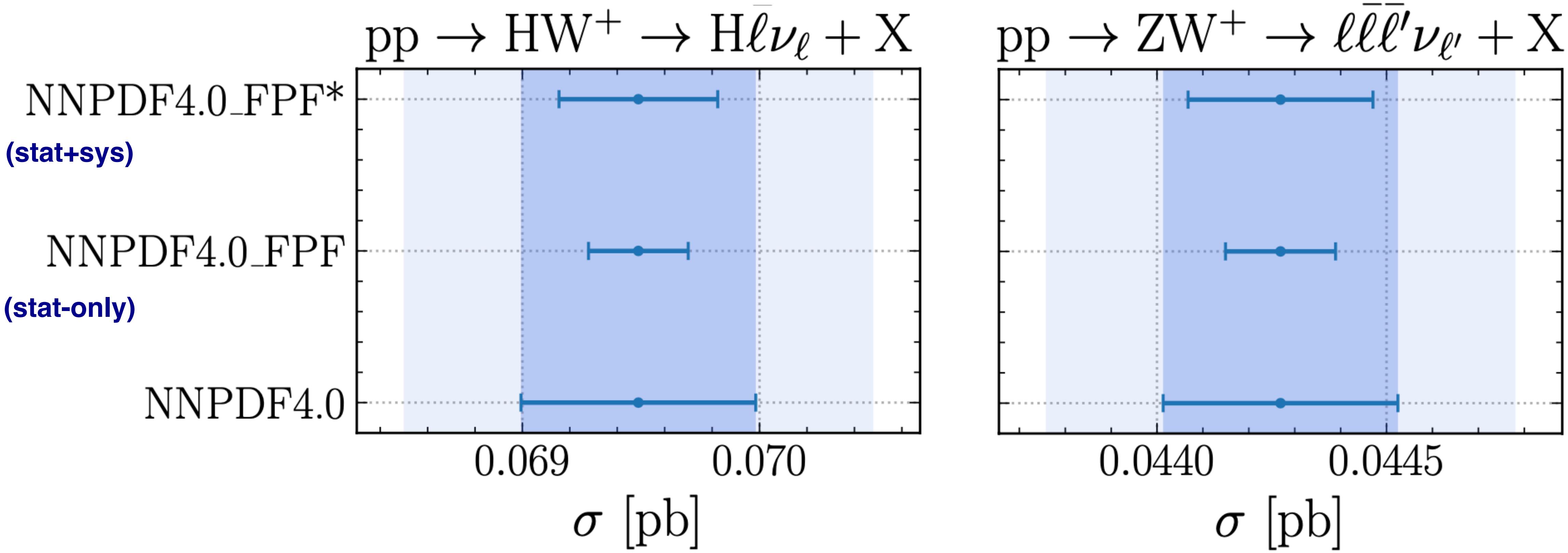
- Impact on proton PDFs quantified by both the **Hessian profiling of PDF4LHC21** (xFitter) and by direct inclusion in the global **NNPDF4.0 fit**

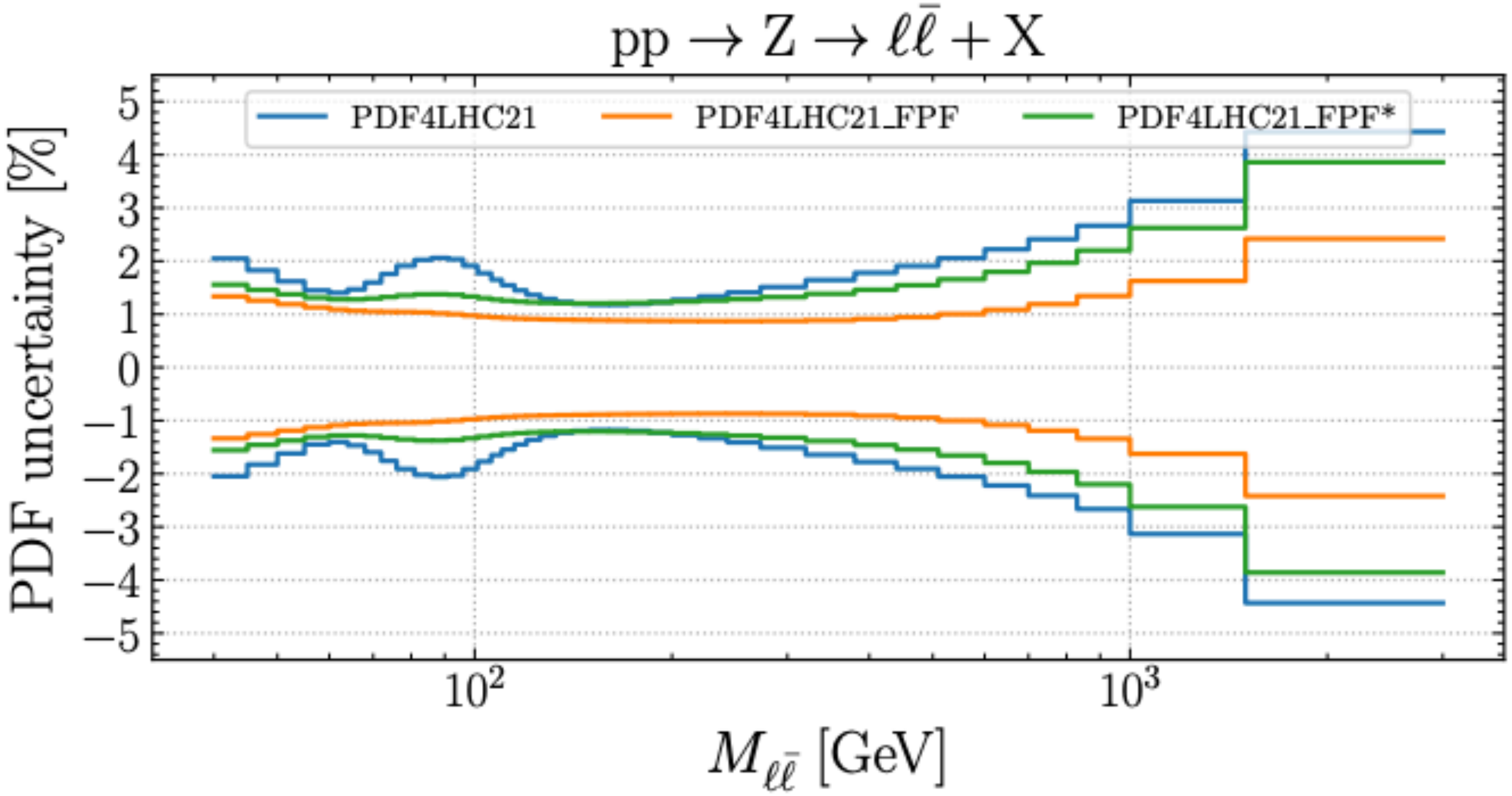
new: PineAPPL interface to xFitter
enables use of YADISM, MATRIX, aMC@NLO calculations

- Impact on **up/down valence quarks** as well as in **strangeness,** ultimately limited by systematics

Far-forward neutrino detectors effectively extend CERN with a **Neutrino-Ion Collider** by ``recycling'' an otherwise discarded beam (with the highest energies ever achieved in a lab)

PDF constraints from LHC neutrinos





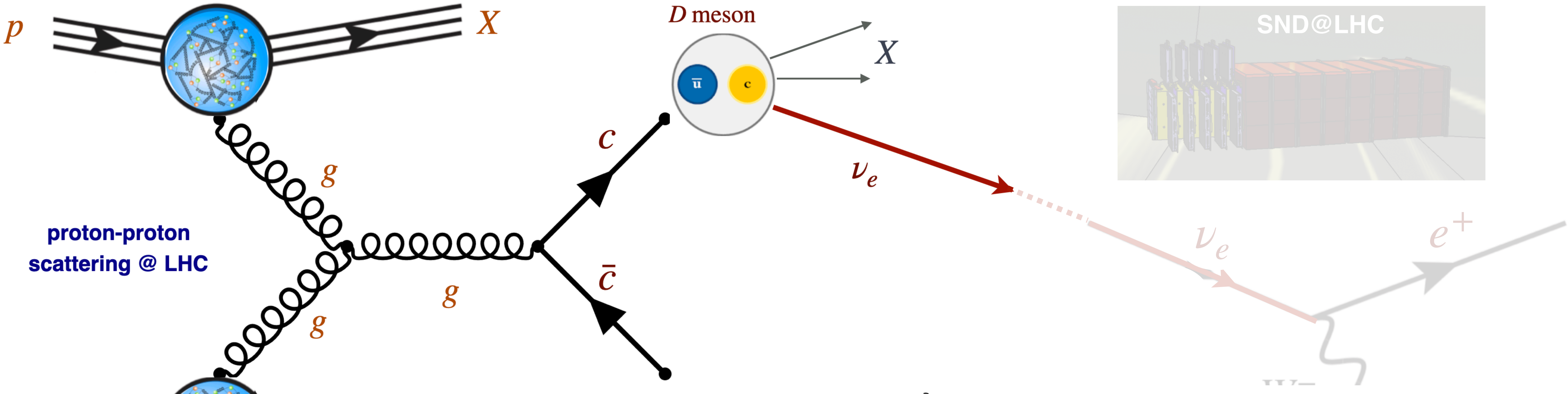
- Impact on **core HL-LHC processes** i.e. single and double weak boson production and Higgs production (VH, VBF)

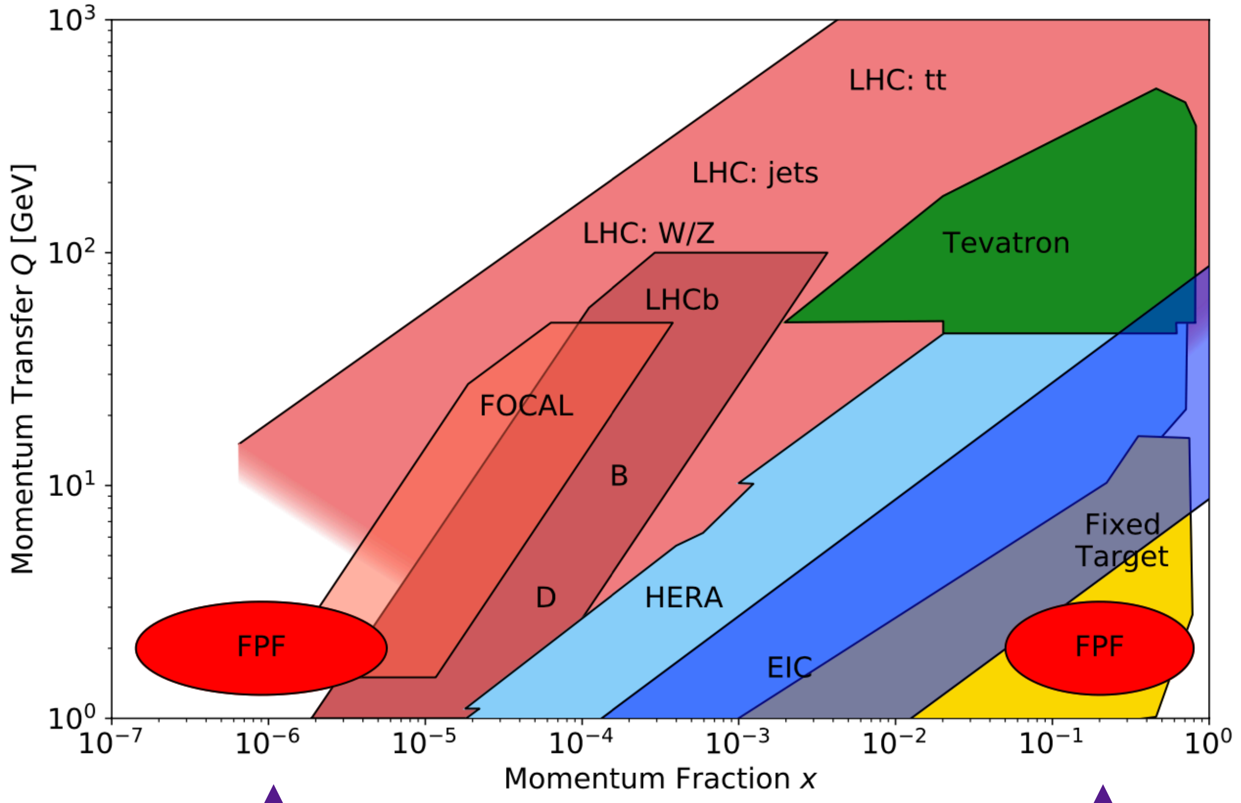
- Also relevant for **BSM searches at large-mass** (via large-*x* PDFs)

e.g. high-mass dilepton resonances

Independent extraction of large-x PDFs without risk of absorbing BSM

LHC neutrinos and small-x QCD





small-x gluon

large-x

QCD in Neutrino Production

- Small-x gluon & large-x charm PDFs
- BFKL, non-linear QCD, cross-sections for UHE neutrinos
- *D*-meson fragmentation
- Forward light hadron production & cosmic ray modelling

Relevant for **FCC-pp, UHE neutrinos, cosmic rays**

LHC neutrinos and small-x QCD

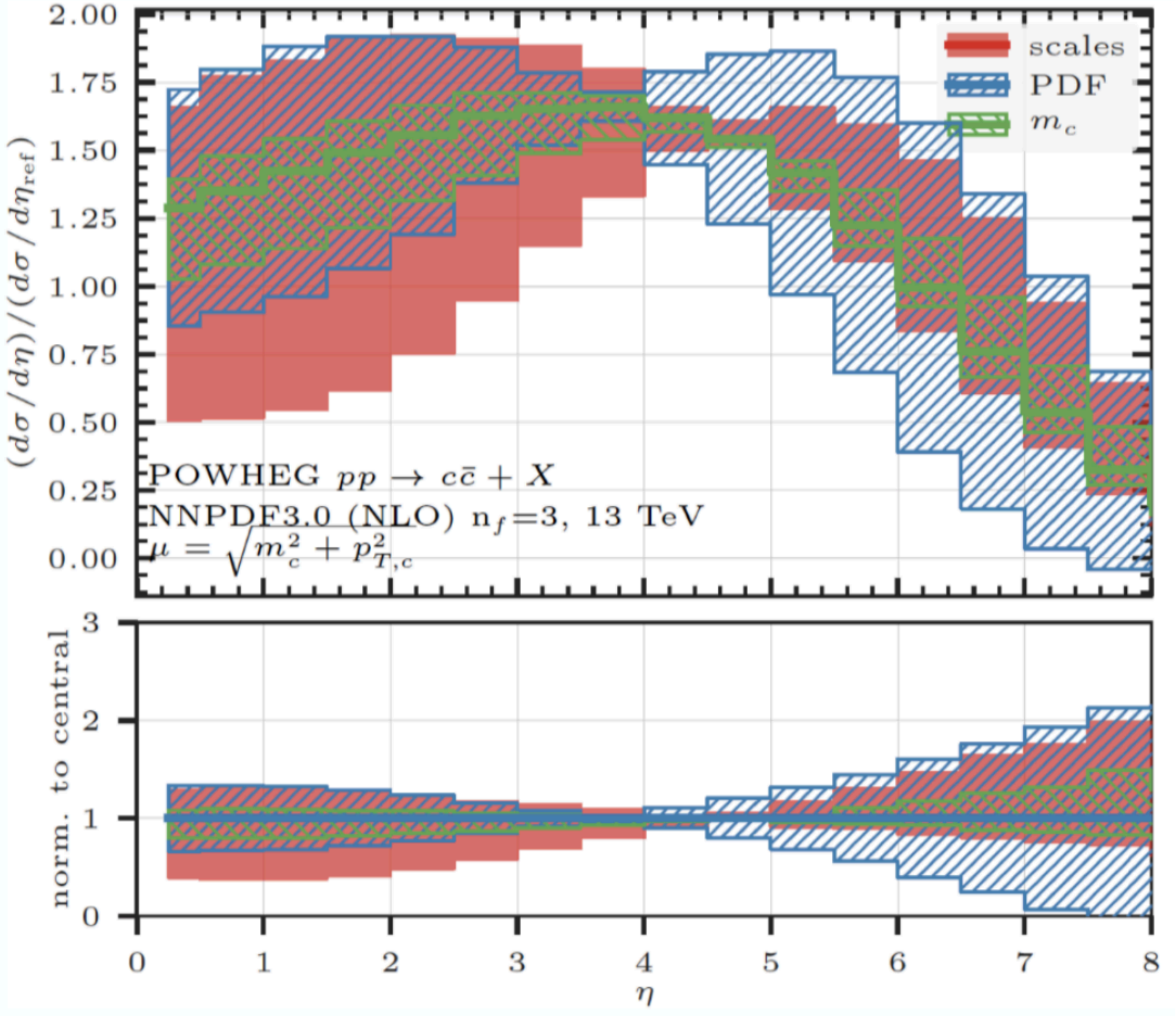
$$\frac{d^2\sigma(\mathrm{pp}\to D(\to\nu)+X)}{p_T^\nu y_\nu} \propto f_g(x_1,Q^2)\otimes f_g(x_2,Q^2)\otimes \frac{d^2\hat{\sigma}(gg\to c\bar{c})}{p_T^c y_c}\otimes D_{c\to D}(z,Q^2)\otimes \mathrm{BR}(D\to\nu+X)$$

Extract from measured neutrino fluxes

Constrain from LHC neutrino data

QCD prediction: NLO + PS large theory uncertainties

QCD prediction/models + non-perturbative physics



- **Only laboratory experiment** which can inform both UHE neutrino interactions, cosmic ray collisions, and FCC-pp cross-sections

- Challenges in **modelling forward charm production**: QCD corrections, fragmentation, interaction with beam remnants ….

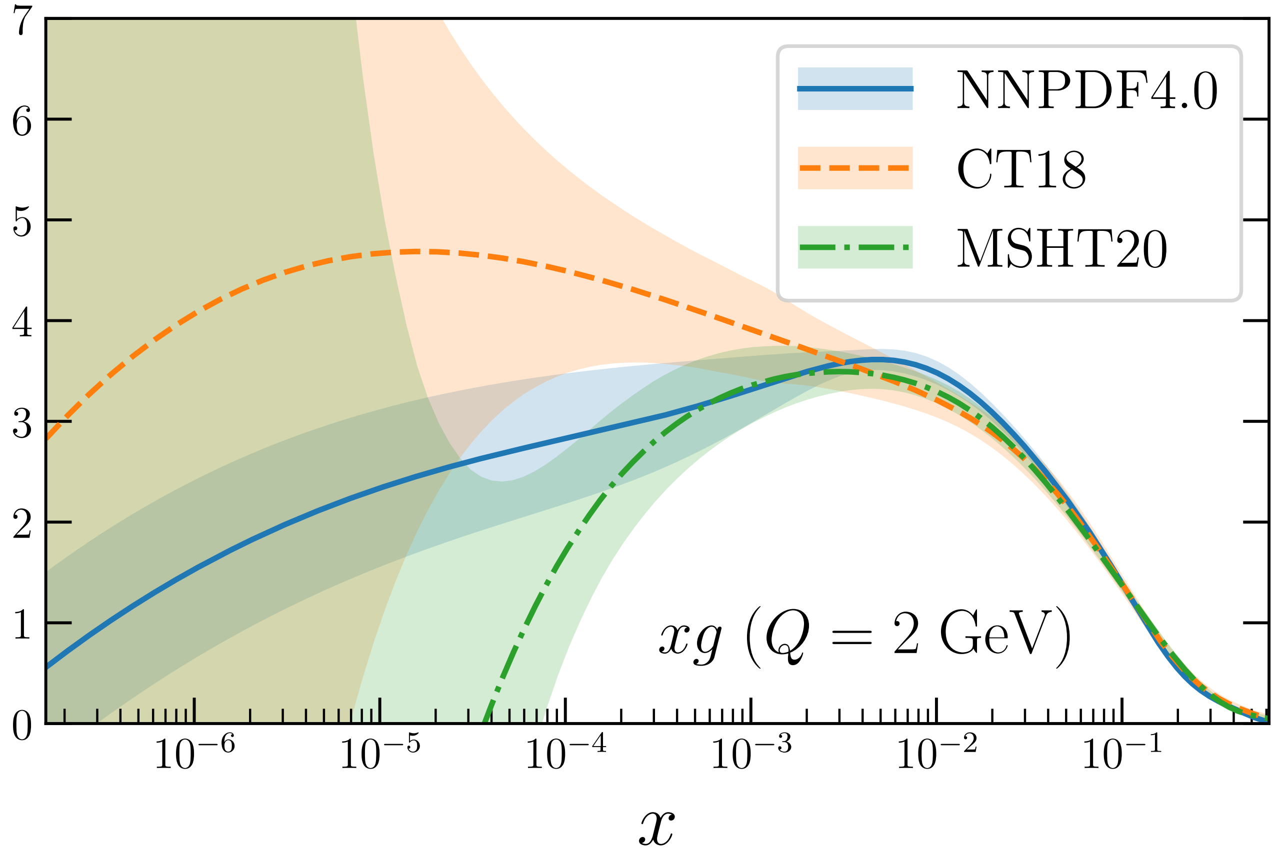
- Requires designing observables where **theory systematics cancel out**

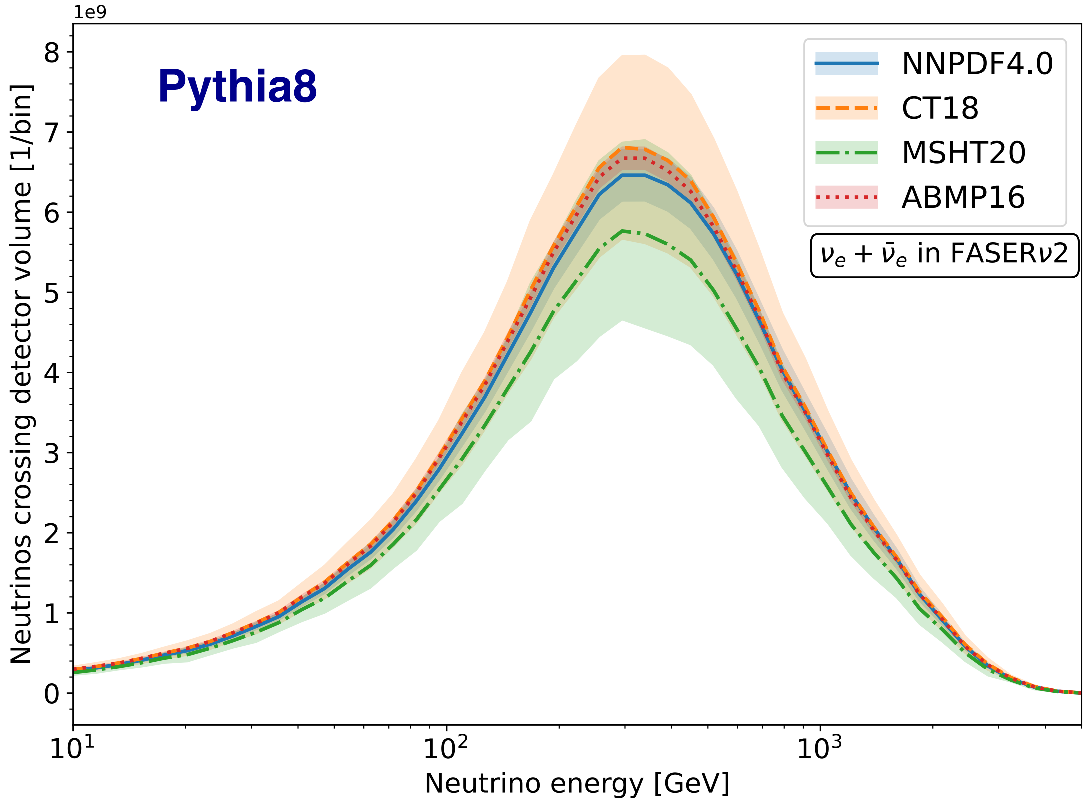
  ☑ Ratios to reference rapidity bin

  ☑ Ratios between CoM energy

  ☑ Ratios between correlated observables

LHC neutrinos and small-x QCD





- Spread of PDF predictions (e.g. small-x gluon) modifies **predicted fluxes up to factor 2**
- Focus on electron and tau neutrinos, with the largest **contribution from charm production** where QCD factorisation can be applied
- Construct **tailored observables** where QCD uncertainties (partially) cancel out

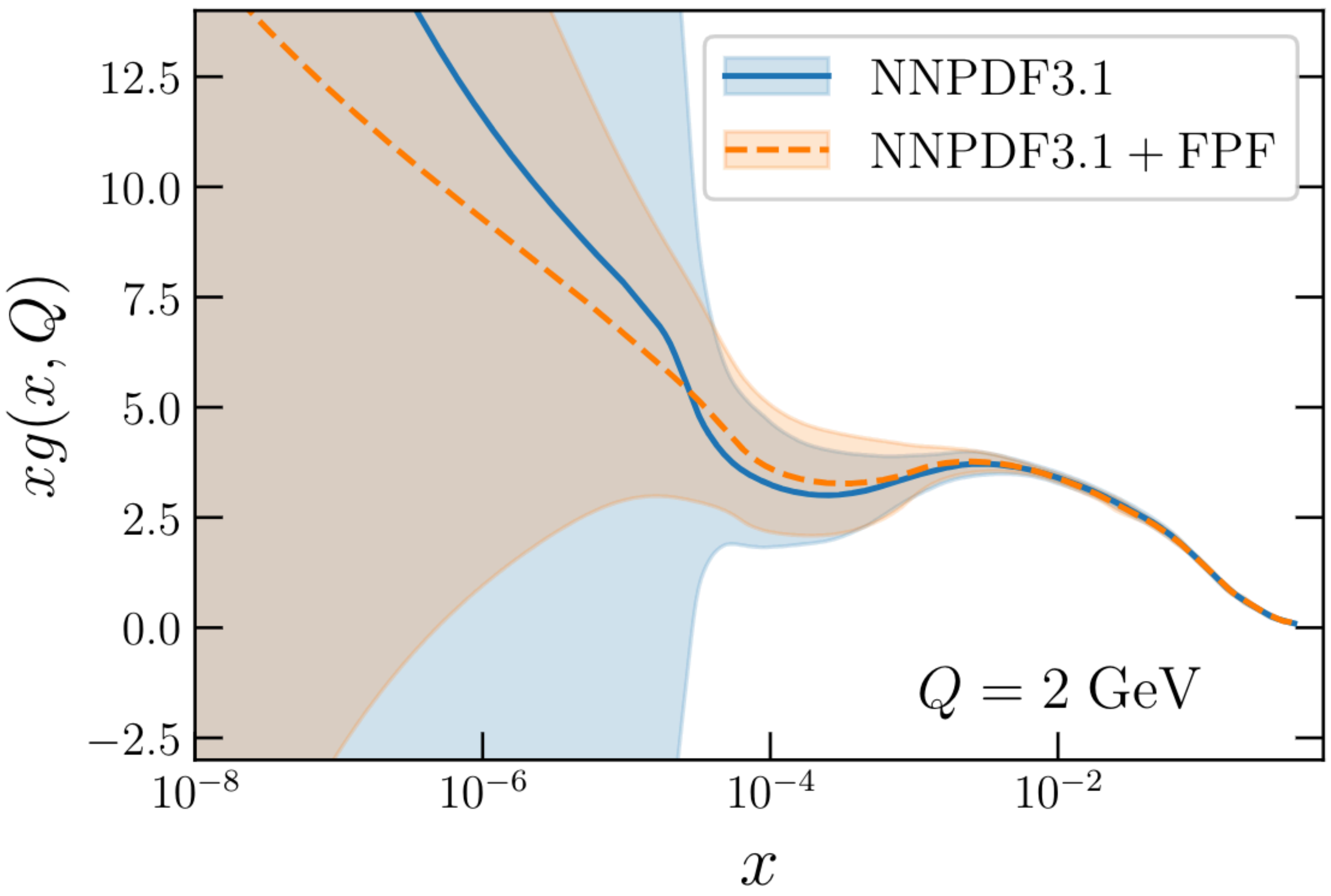
$$R_{\tau/e}(E_\nu) \equiv \frac{N(\nu_\tau + \bar{\nu}_\tau; E_\nu)}{N(\nu_e + \bar{\nu}_e; E_\nu)}\,, \qquad R^{\nu_e}_{\rm exp}(E_\nu) = \frac{N_{\rm FASER\nu}(\nu_e + \bar{\nu}_e E_\nu)}{N_{\rm SND@LHC}(\nu_e + \bar{\nu}_e; E_\nu)}$$

Retain PDF sensitivity while reducing the large QCD uncertainties in the theory prediction

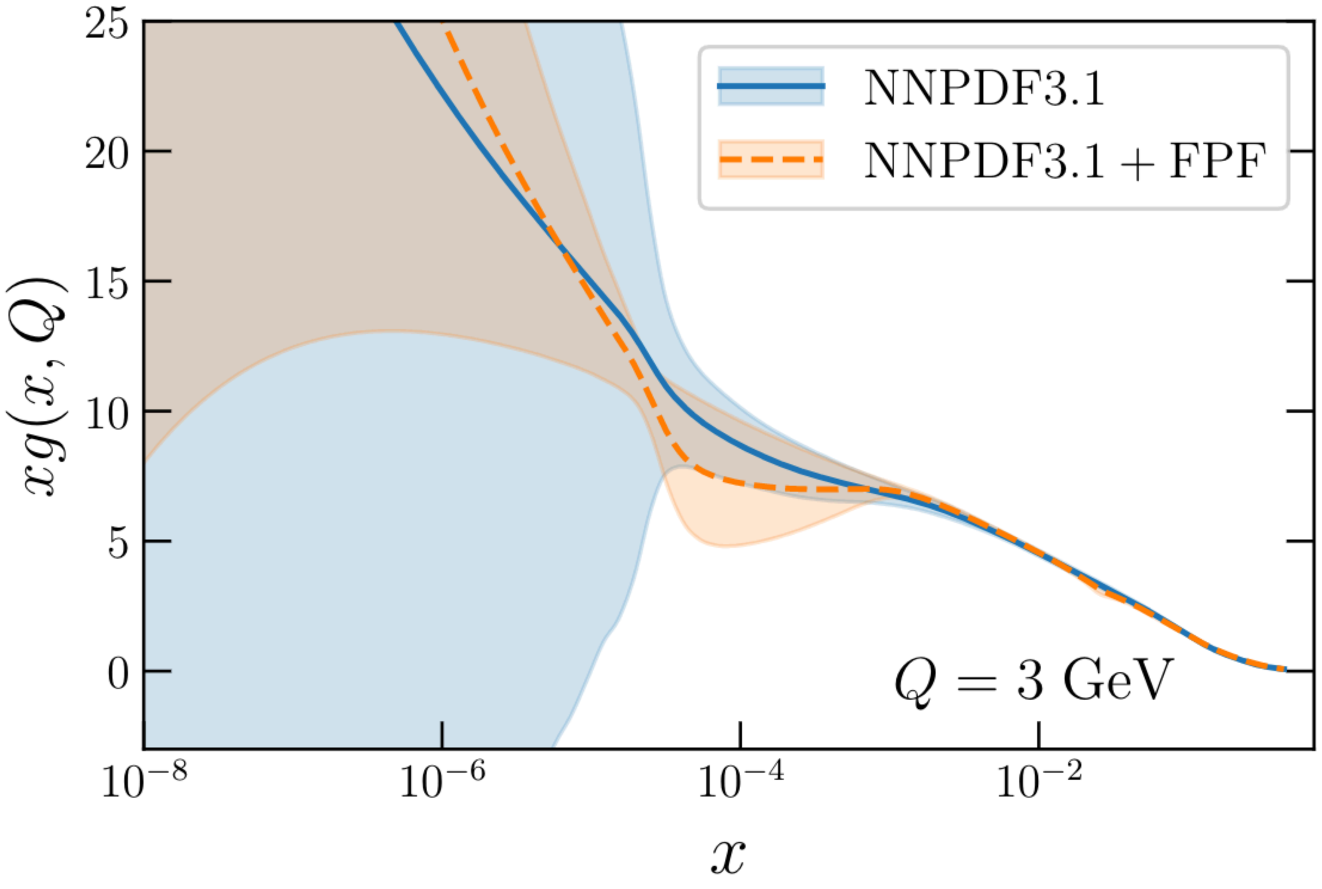
Proxy for 2D xsec differential in (energy, rapidity)

LHC neutrinos and small-x QCD

Electron neutrinos, 2% uncertainty in inclusive event rates



Tau neutrinos, 2% uncertainty in inclusive event rates

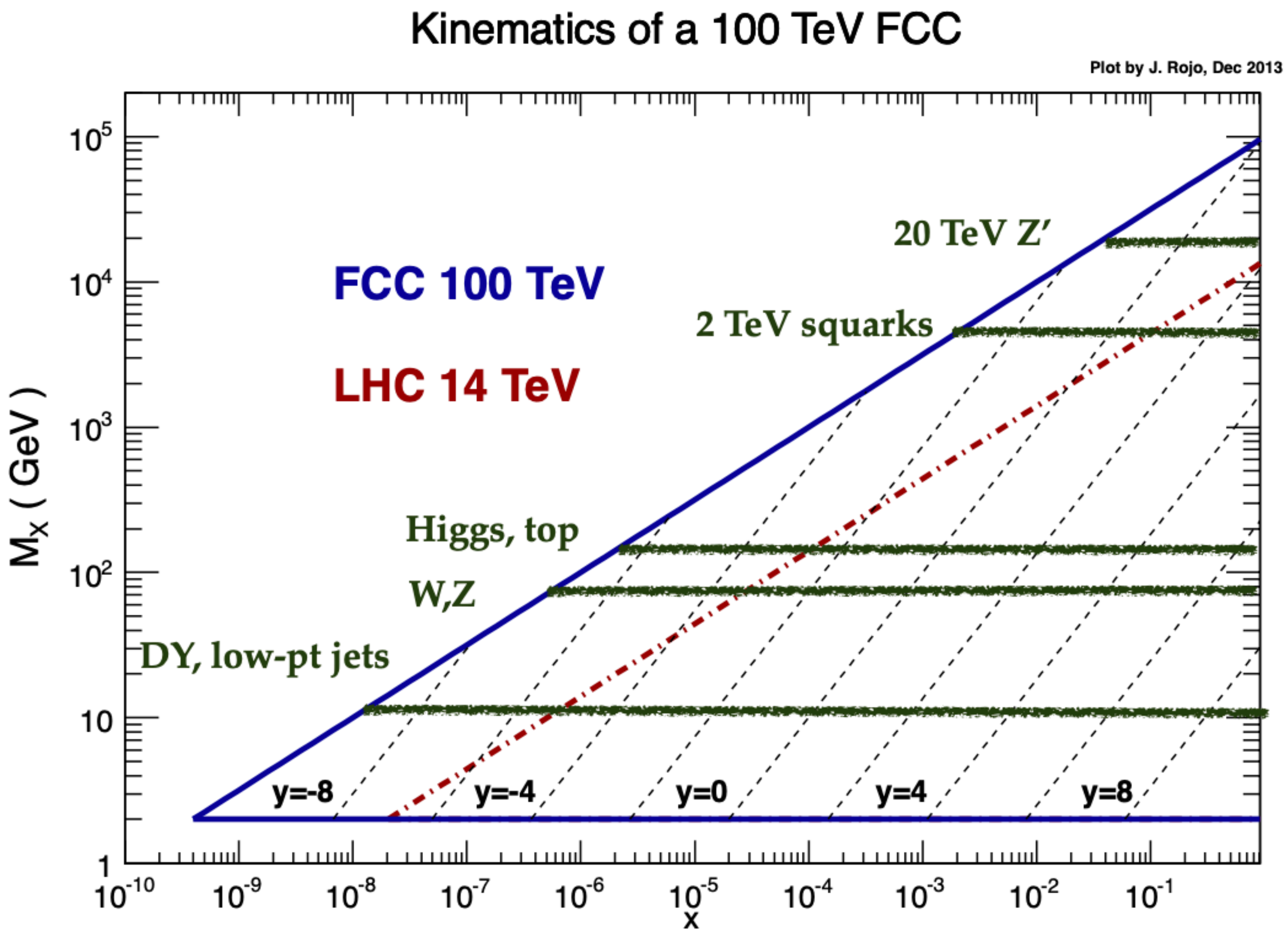


$$R_y^{(e)} \equiv \frac{N_{\nu_e}(E_\nu, 7.5 < y_\nu < 8.0)}{N_{\nu_e}(E_\nu, 8.5 < y_\nu < 9.0)}$$

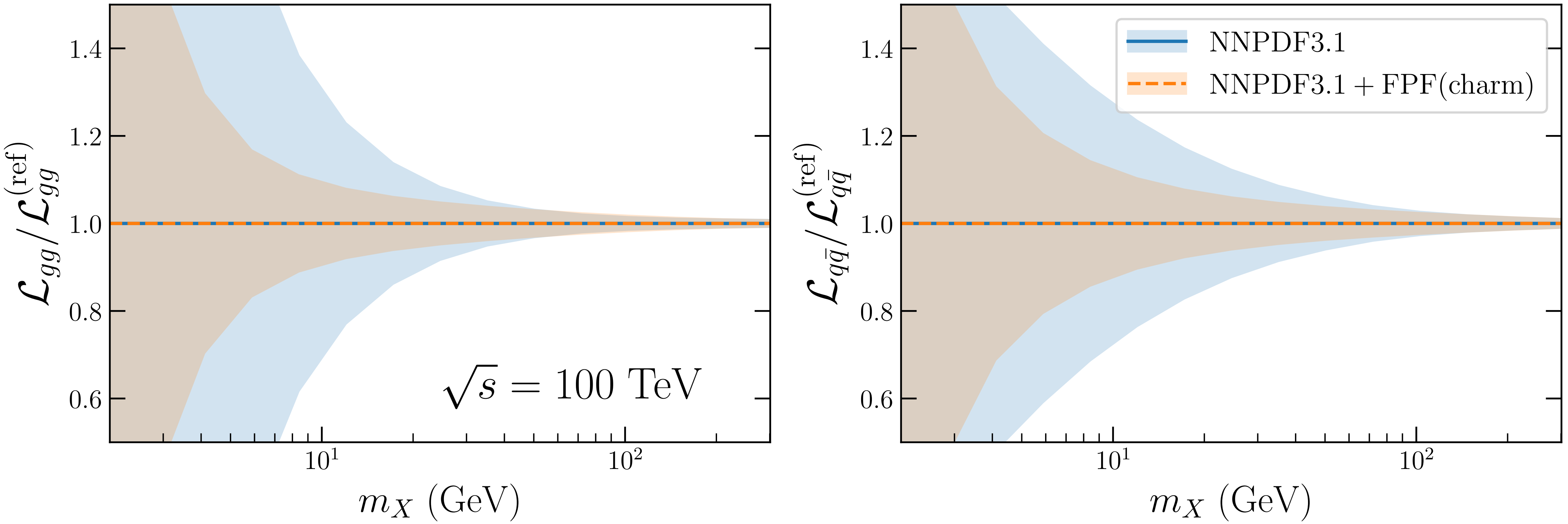
$$R_y^{(\tau)} \equiv \frac{N_{\nu_\tau}(E_\nu, 7.5 < y_\nu < 8.0)}{N_{\nu_\tau}(E_\nu, 8.5 < y_\nu < 9.0)}$$

- Sensitivity to **small-x gluon** outside coverage of any other (laboratory) experiment
- These initial projections are now being extended to full-fledged simulations with state-of-the-art QCD
- Quantify impact for **UHE neutrinos** and for cross-sections at a 100 TeV proton collider

Implications for the FCC-pp



- FCC-pp would be a **small-*x* machine,** even Higgs and EWK sensitive to small-*x* QCD
- LHC neutrinos: laboratory to test **small-x QCD** for dedicated FCC-pp physics and simulations
- Current projections show a marked PDF error reduction on **FCC-pp cross-sections** thanks to constraints from LHC neutrinos



The Intrinsic Charm Content of the Proton

R. D. Ball, A. Candido, J. Cruz-Martinez, S. Forte, T. Giani, F. Hekhorn, K. Kudashkin, G. Magni & J. Rojo, ***Nature*** **608 (2022) 7923, 483-487**

R. D. Ball, A. Candido, J. Cruz-Martinez, S. Forte, T. Giani, F. Hekhorn, E. R. Nocera, G. Magni, J. Rojo & R. Stegeman, ***arXiv:2311:00743***

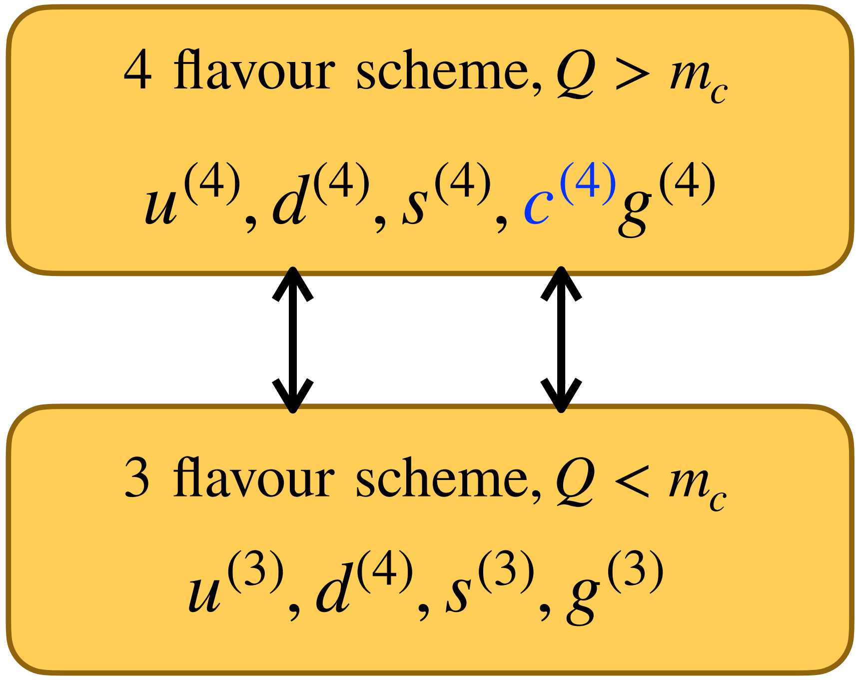
Disentangling intrinsic charm

common assumption in PDF fits: the static proton wave function does not contain charm quarks: the proton contains **intrinsic up, down, strange (anti-)quarks** but **no intrinsic charm quarks**

the charm PDF is **generated perturbatively** (DGLAP evolution) from radiation off gluons and quarks

$$f_c^{(n_f)} = 0 \quad \rightarrow \quad f_c^{(n_f+1)} \propto \alpha_s \ln \frac{Q^2}{m_c^2} \left(P_{qg} \otimes f_g^{(n_f+1)} \right) + \mathcal{O}\left(\alpha_s^2\right)$$

3FNS charm ***4FNS charm*** ***4FNS gluon*** ***NLO matching***

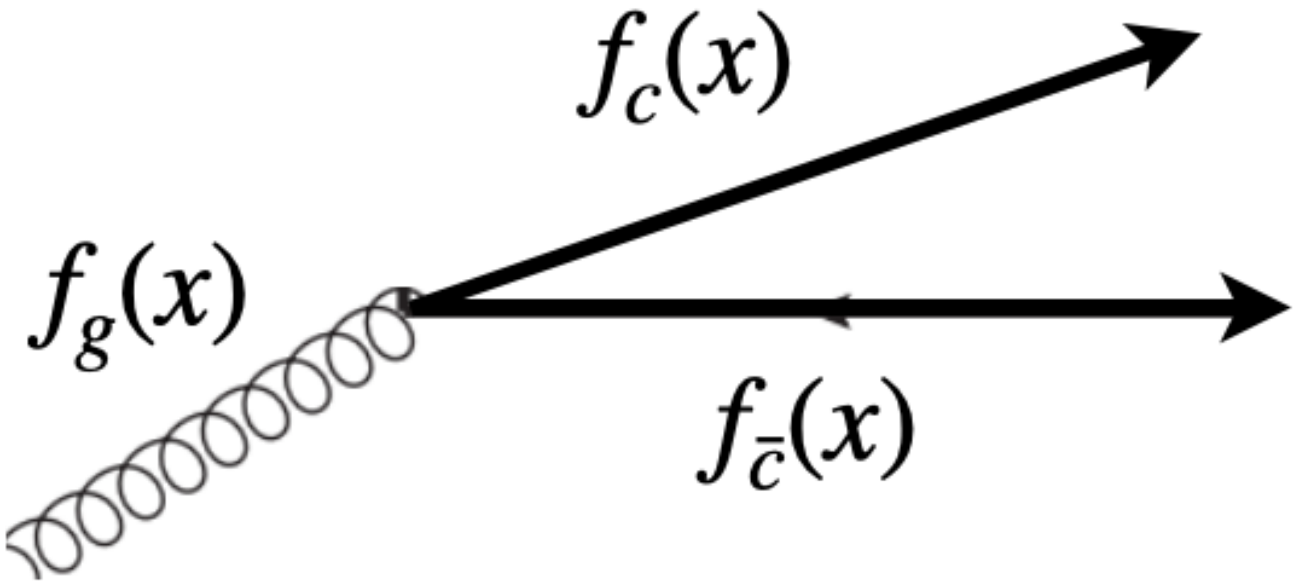


4 flavour scheme, $Q > m_c$

$u^{(4)}, d^{(4)}, s^{(4)}, c^{(4)} g^{(4)}$

3 flavour scheme, $Q < m_c$

$u^{(3)}, d^{(4)}, s^{(3)}, g^{(3)}$



If the **measured charm PDF** differs from the **perturbatively calculated PDF**, it would indicate non-perturbative or intrinsic charm in the proton

Evidence (or lack thereof) for intrinsic charm should be **empirical**

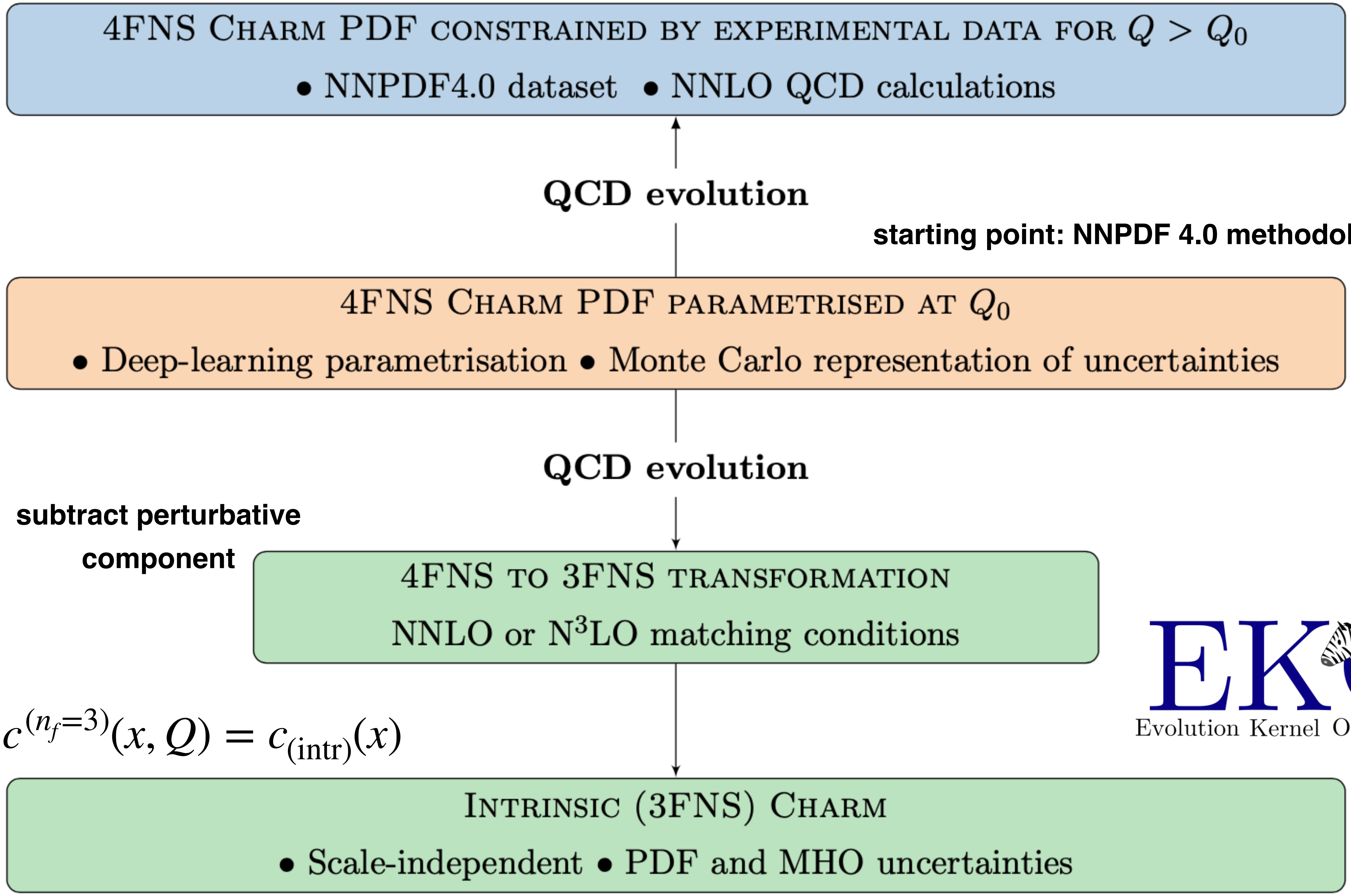
Disentangling intrinsic charm

$$c^{(n_f=4)}(x,Q) \simeq c^{(n_f=4)}_{\rm (pert)}(x,Q) + c^{(n_f=4)}_{\rm (intr)}(x,Q)$$

Extracted phenomenologically from data

from pQCD evolution and matching

from intrinsic component $c^{(n_f=3)}_{\rm (intr)}(x) \neq 0$



4FNS CHARM PDF CONSTRAINED BY EXPERIMENTAL DATA FOR $Q > Q_0$

- NNPDF4.0 dataset
- NNLO QCD calculations

QCD evolution

starting point: NNPDF 4.0 methodology

4FNS CHARM PDF PARAMETRISED AT Q_0

- Deep-learning parametrisation
- Monte Carlo representation of uncertainties

QCD evolution

subtract perturbative component

4FNS TO 3FNS TRANSFORMATION

NNLO or N^{3}LO matching conditions

$$c^{(n_f=3)}(x,Q) = c_{\rm (intr)}(x)$$

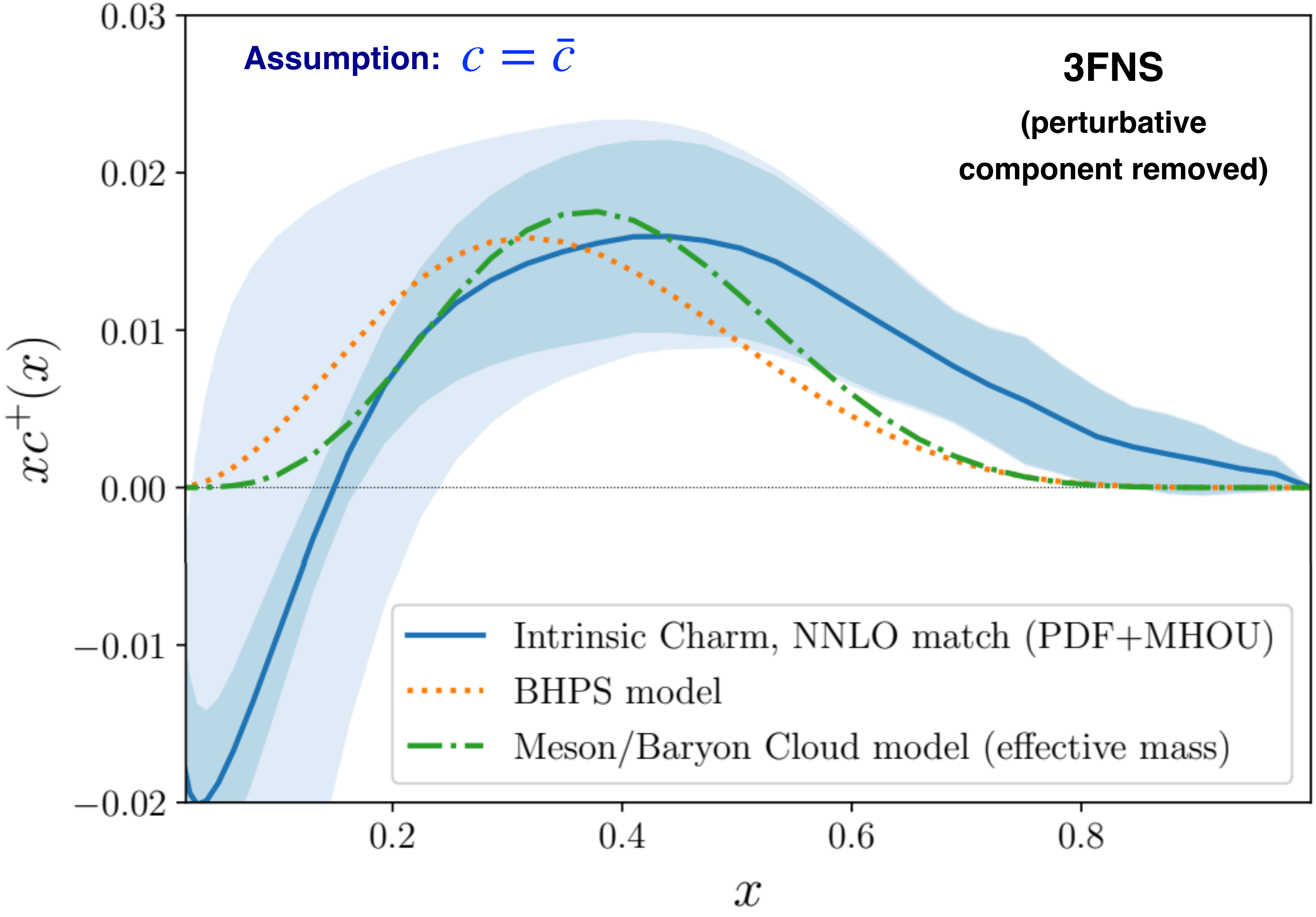
EKO

Evolution Kernel Operators

INTRINSIC (3FNS) CHARM

- Scale-independent
- PDF and MHO uncertainties

3FNS charm



The 3FNS charm PDF displays **non-zero component** peaked at large-*x* which can be identified with **intrinsic charm**

The valence charm PDF

- No reason why i**ntrinsic charm should be symmetric** (it is not in most models!)

  i.e. up, down, and strange quark PDFs are asymmetric

- Extend the NNPDF4.0 analysis with an **separate determination** of charm and anti-charm PDFs

- No perturbative mechanism generates a (sizeable) charm valence PDF: best **evidence for IC**

The valence charm PDF

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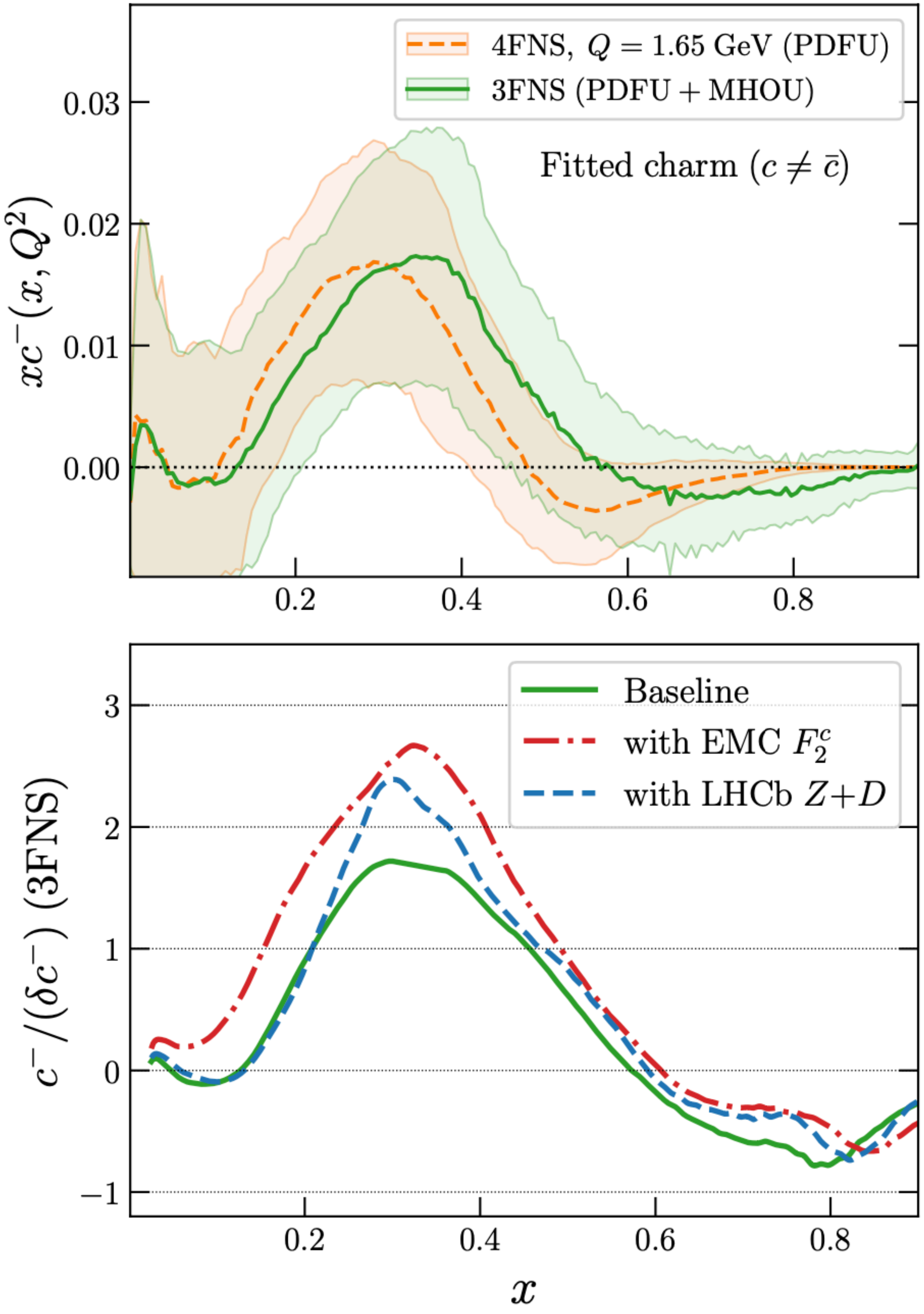
- Extend the NNPDF4.0 analysis with an **separate determination** of charm and anti-charm PDFs

- No perturbative mechanism generates a (sizeable) charm valence PDF: best **evidence for IC**

  - Preference for a **non-zero, positive IC asymmetry** around *x*=0.3
  - Consistent with the independent constraints from **EMC F_2^c** and **LHCb Z+D**

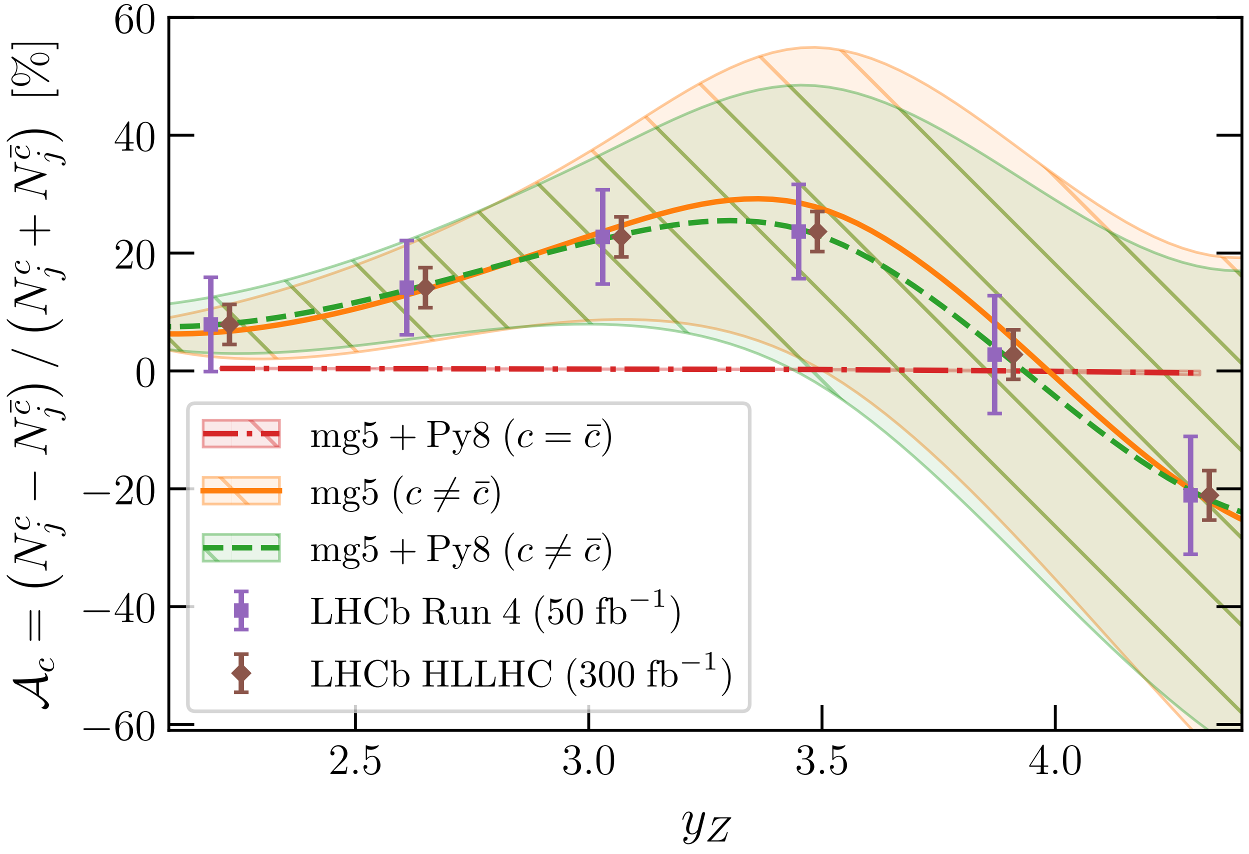
Total charm PDF (4FNS & 3FNS) essentially unaffected

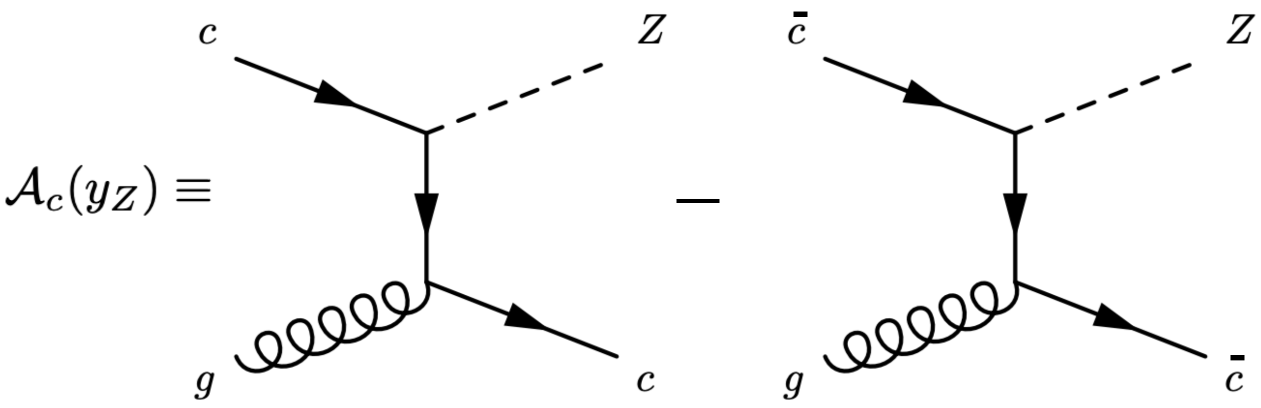


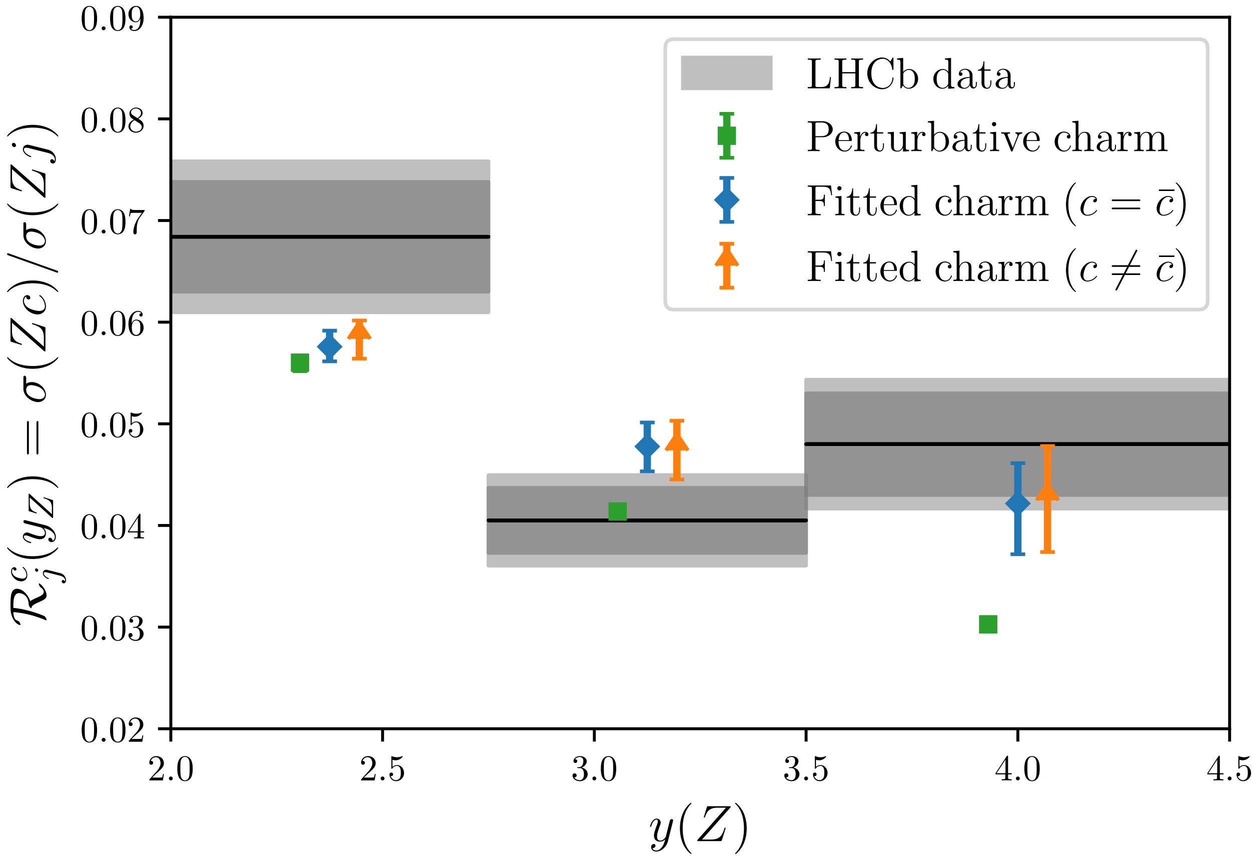
Charm asymmetries at LHCb

$$\mathcal{A}_c(y_Z) \equiv \frac{N_j^c(y_Z) - N_j^{\bar{c}}(y_Z)}{N_j^c(y_Z) + N_j^{\bar{c}}(y_Z)}$$

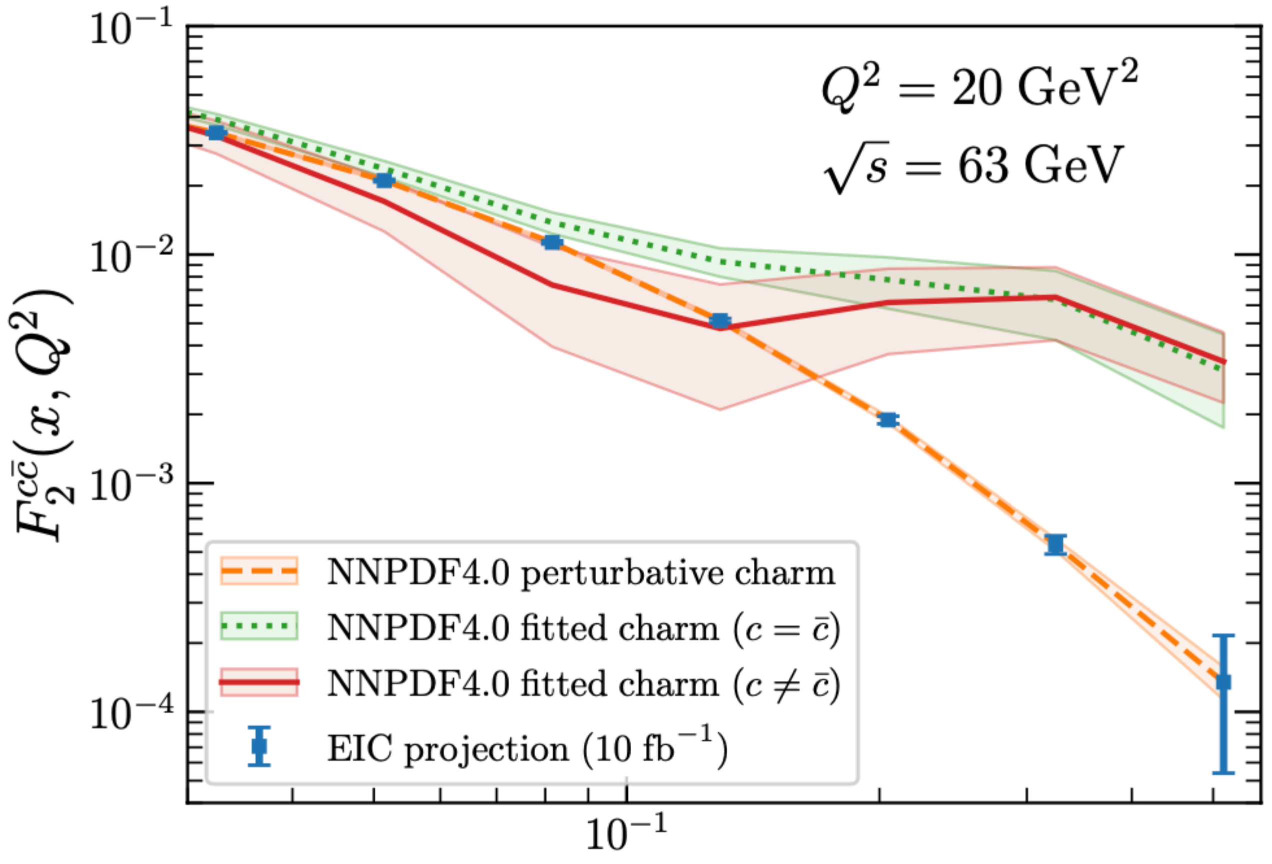
- Projections for LHCb *Z+D* measurements, constructing an **asymmetry between final states with D and Dbar mesons**
- Data from **upcoming LHC runs** will confirm or falsify a non-zero charm valence in the proton
- Ideally the measurement should be carry out in terms of **IRC-safe flavour jets,** to reduce sensitivity to charm fragmentation model

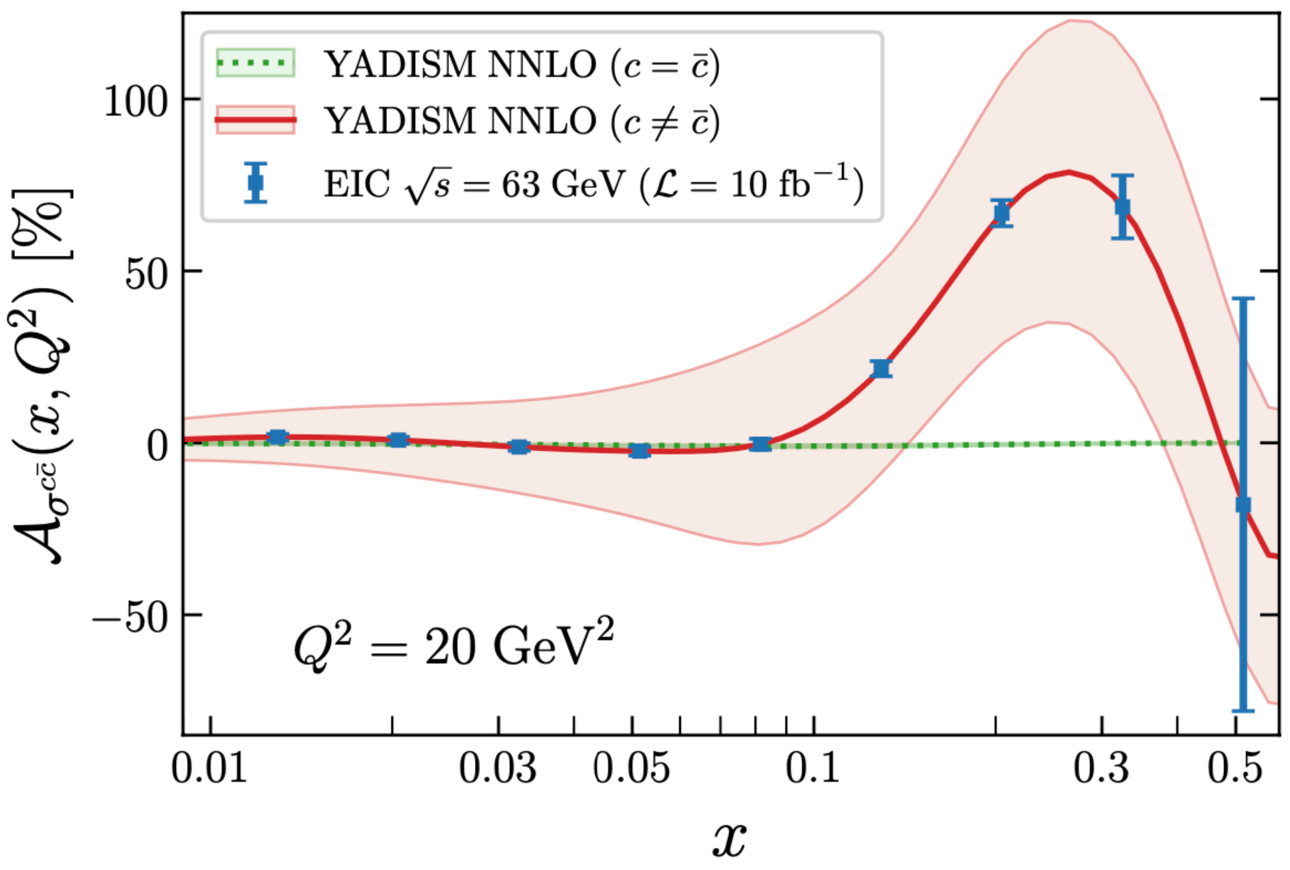






Charm asymmetries at the EIC





- Inclusive **F_2^c measurements at large-*x*** will clearly disentangle IC at the EIC (factor 100 effect!)

- Measurements of the **asymmetry between final states with D and Dbar mesons** will pin down a non-vanishing charm valence PDF

$$\mathcal{A}_{\sigma^{c\bar{c}}}(x, Q^2) \equiv \frac{\sigma^{c}_{\rm red}(x, Q^2) - \sigma^{\bar{c}}_{\rm red}(x, Q^2)}{\sigma^{c\bar{c}}_{\rm red}(x, Q^2)}$$

Charm-tagged EIC projections: arXiv:2107.05632

- Even at low luminosities, EIC will **cleanly identify the charm valence PDF** if non-zero

Proton Structure and BSM searches

Standard Model PDFs

Global PDF determinations are based on **Standard Model theoretical** calculations:

$$\sigma_{\rm th}(\boldsymbol{\theta}, M_X) \propto \sum_{ij=u,d,g,\ldots} \int_{M_X^2}^{s} d\hat{s}\ \mathscr{L}_{ij}^{(\rm sm)}(M, \sqrt{s}, \boldsymbol{\theta})\ \widetilde{\sigma}_{ij}^{(\rm sm)}(\hat{s}, \alpha_s(M)) \qquad \hat{s} = M^2/s$$

hadronic cross-section

Theory prediction to compare with experiment

SM PDF Luminosity

Constrain from data

PDF parameters

SM partonic cross-section

NNLO QCD & NLO EW

$$\mathscr{L}_{ij}^{(\rm sm)}(M, \sqrt{s}, \boldsymbol{\theta}) = \frac{1}{s} \int_{-\ln\sqrt{s}/M}^{\ln\sqrt{s}/M} {\rm d}y\, f_i^{(\rm sm)}\left(\frac{Me^{y}}{\sqrt{s}}, \boldsymbol{\theta}\right) f_j^{(\rm sm)}\left(\frac{Me^{-y}}{\sqrt{s}}, \boldsymbol{\theta}\right)$$

PDF parameters from likelihood maximisation: BSM effects potentially **``fitted away" into PDFs**

$$\chi^2\left(\boldsymbol{\theta}\right) = \frac{1}{n_{\rm dat}} \sum_{i,j=1}^{n_{\rm dat}} \left(\sigma_{\rm i,th}(\boldsymbol{\theta}) - \sigma_{\rm i,exp}\right) \left({\rm cov}^{-1}\right)_{ij} \left(\sigma_{\rm j,th}(\boldsymbol{\theta}) - \sigma_{\rm j,exp}\right)$$

SMEFT PDFs

What is the underlying short-distance theory is **not the SM** but instead the **SMEFT**?

$$\sigma_{\rm th}(\boldsymbol{\theta}, M_X) \propto \sum_{ij=u,d,g,\ldots} \int_{M_X^2}^{s} d\hat{s}\; \mathscr{L}_{ij}^{(\rm smeft)}(M, \sqrt{s}, \boldsymbol{\theta}, \boldsymbol{c}/\Lambda^2)\; \widetilde{\sigma}_{ij}^{(\rm smeft)}(\hat{s}, \alpha_s(M), \boldsymbol{c}/\Lambda^2)$$

hadronic cross-section

SMEFT PDF luminosity

PDF parameters

SMEFT partonic cross-section

EFT coefficients

In the case of new physics described within the **dimension-6 SMEFT framework:**

$$\widetilde{\sigma}_{ij}^{(\rm smeft)}(\hat{s}, \alpha_s, \boldsymbol{c}/\Lambda^2) = \widetilde{\sigma}_{ij}^{(\rm sm)}(\hat{s}, \alpha_s)\left(1 + \sum_{m=1}^{N_6} c_m \frac{\kappa_m^{ij}}{\Lambda^2} + \sum_{m,n=1}^{N_6} c_m c_n \frac{\kappa_{mn}^{ij}}{\Lambda^4}\right)$$

SMEFT PDFs** defined as PDFs extracted from the data when SMEFT used to model **partonic hard-scattering

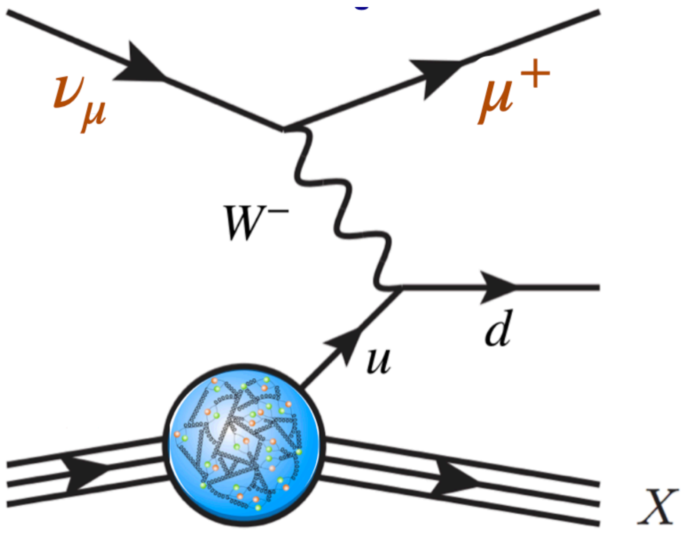
Given experimental constraints, how **different are SM and SMEFT PDFs**? Is there a risk to **fit away EFT effects into the PDFs?**

SMEFT PDFs

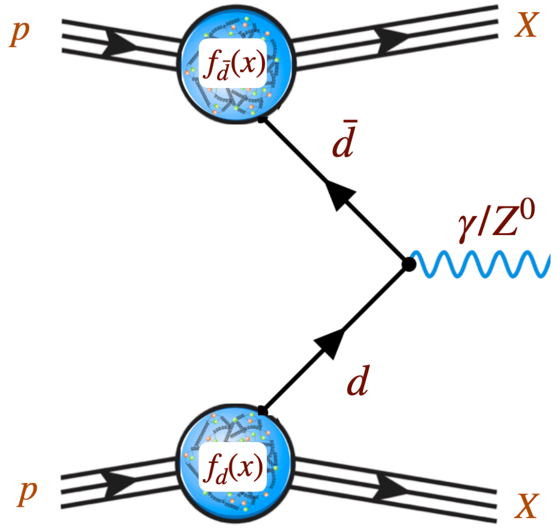
Differences between SM-PDFs and SMEFT-PDFs have two main consequences:

- Effects of higher-dimensional SMEFT operators **are partially reabsorbed into PDFs**, affecting indirectly prediction for other processes and **jeopardising validity of SM predictions**
- Bounds in **SMEFT operators will be modified** as compared to the assumption of SM-PDFs

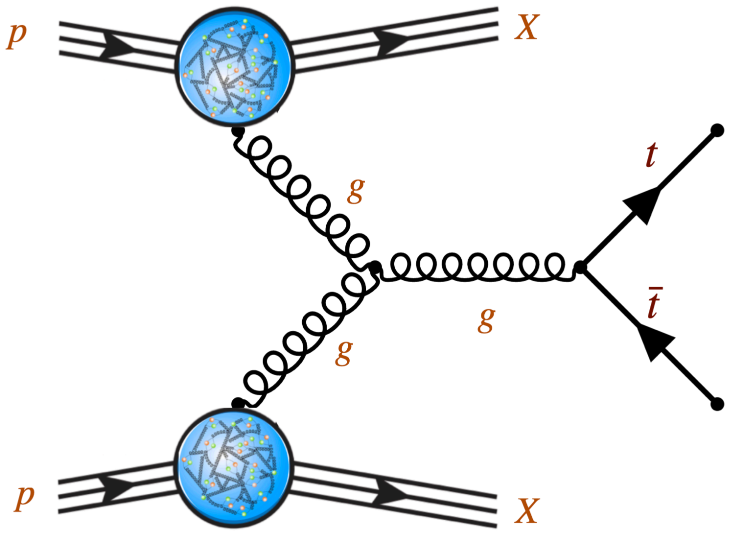
The answer depends on the **process** and on the **sensitivity** of available data. Needs to be studies on a case-by-case basis



Deep-Inelastic Scattering*: S. Carrazza, C. Degrande, S. Iranipour, JR, M. Ubiali, PRL 2019*

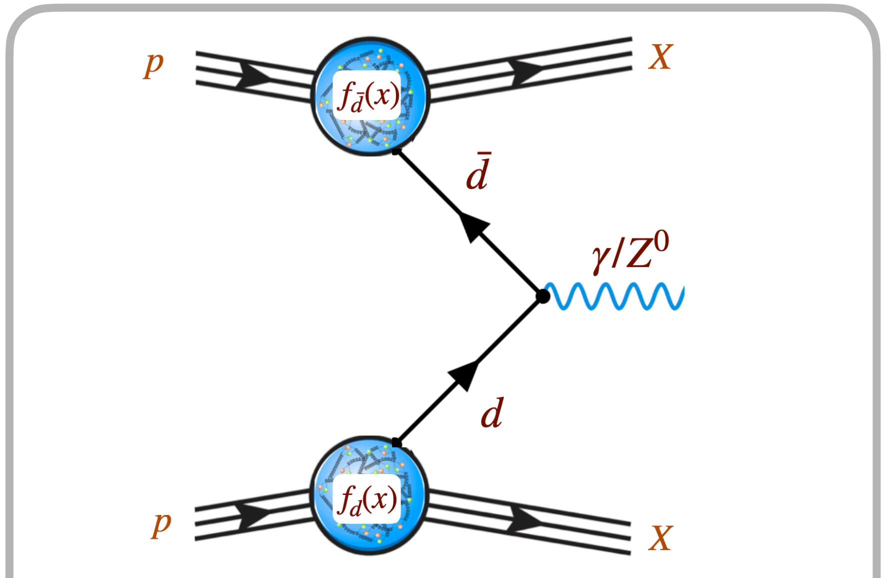


High-mass Drell-Yan: *A. Greljo, S. Iranipour, Z. Kassabov, M. Madigan, J. Moore, JR, M. Ubiali, C. Voisey, JHEP 2021*



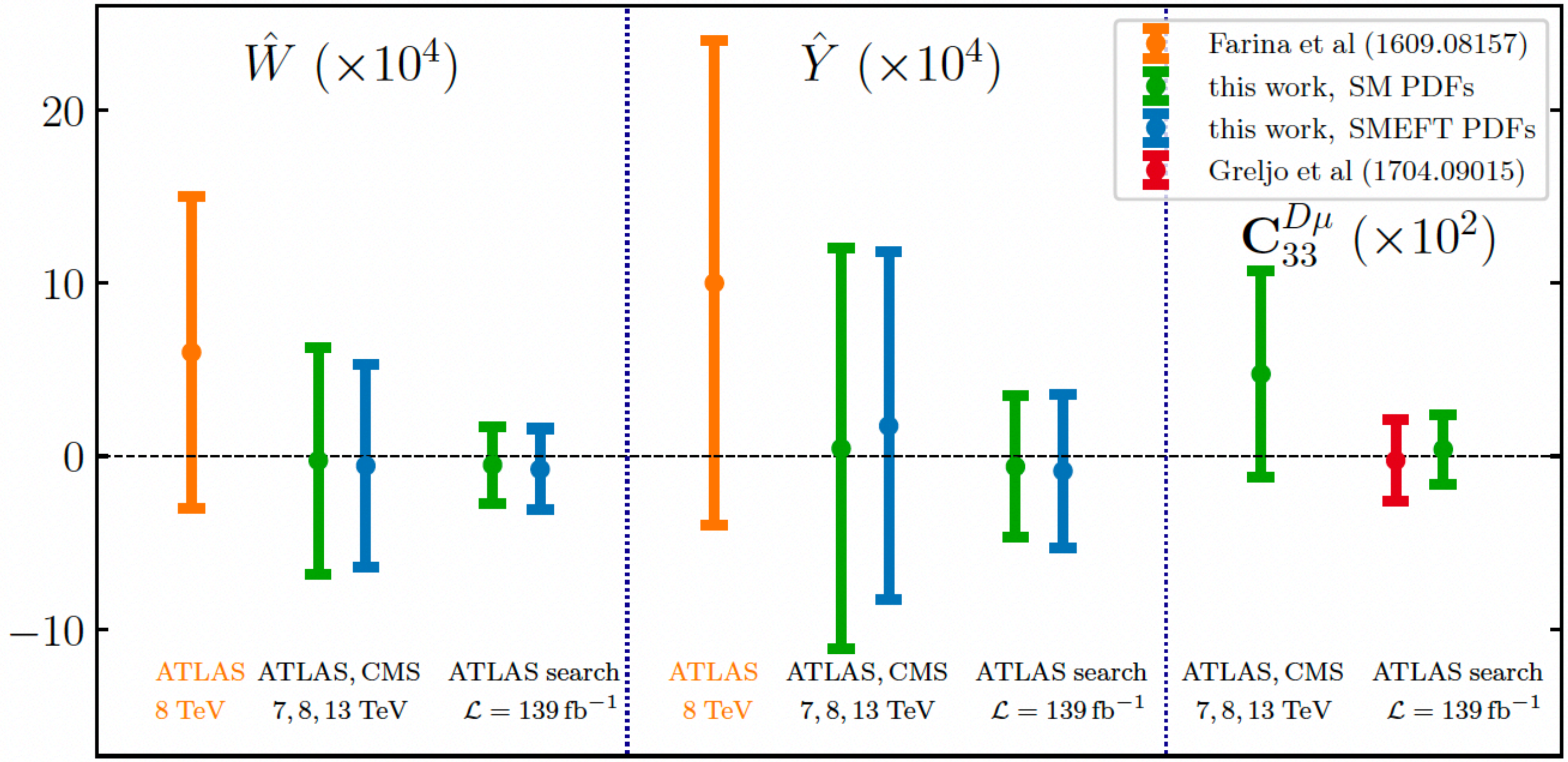
Top quark sector: *Z. Kassabov, M. Madigan, L. Mantani , J. Moore , M.Morales-Alvarado, JR , M. Ubiali, JHEP 2023*

SMEFT PDFs from high-mass Drell-Yan

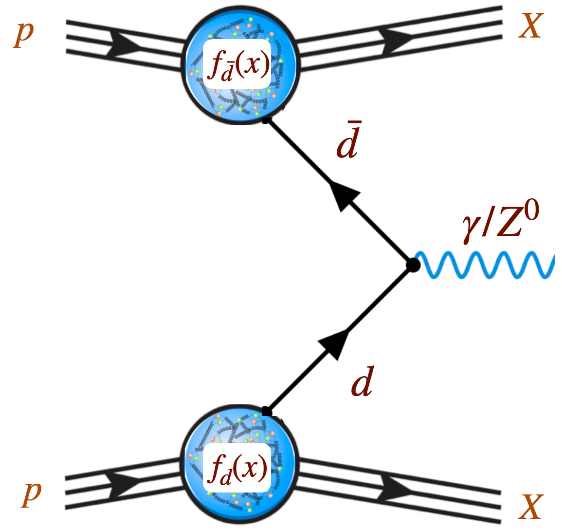


High-mass Drell-Yan: ***A. Greljo, S. Iranipour, Z. Kassabov, M. Madigan, J. Moore, JR, M. Ubiali, C. Voisey, JHEP 2021***

- Available data: **limited interplay** between PDF and EFT fits
- Best constraints from **searches,** but corresponding unfolded measurements not yet available
- SMEFT-PDFs modify bounds from SM-PDFs by around **10%**

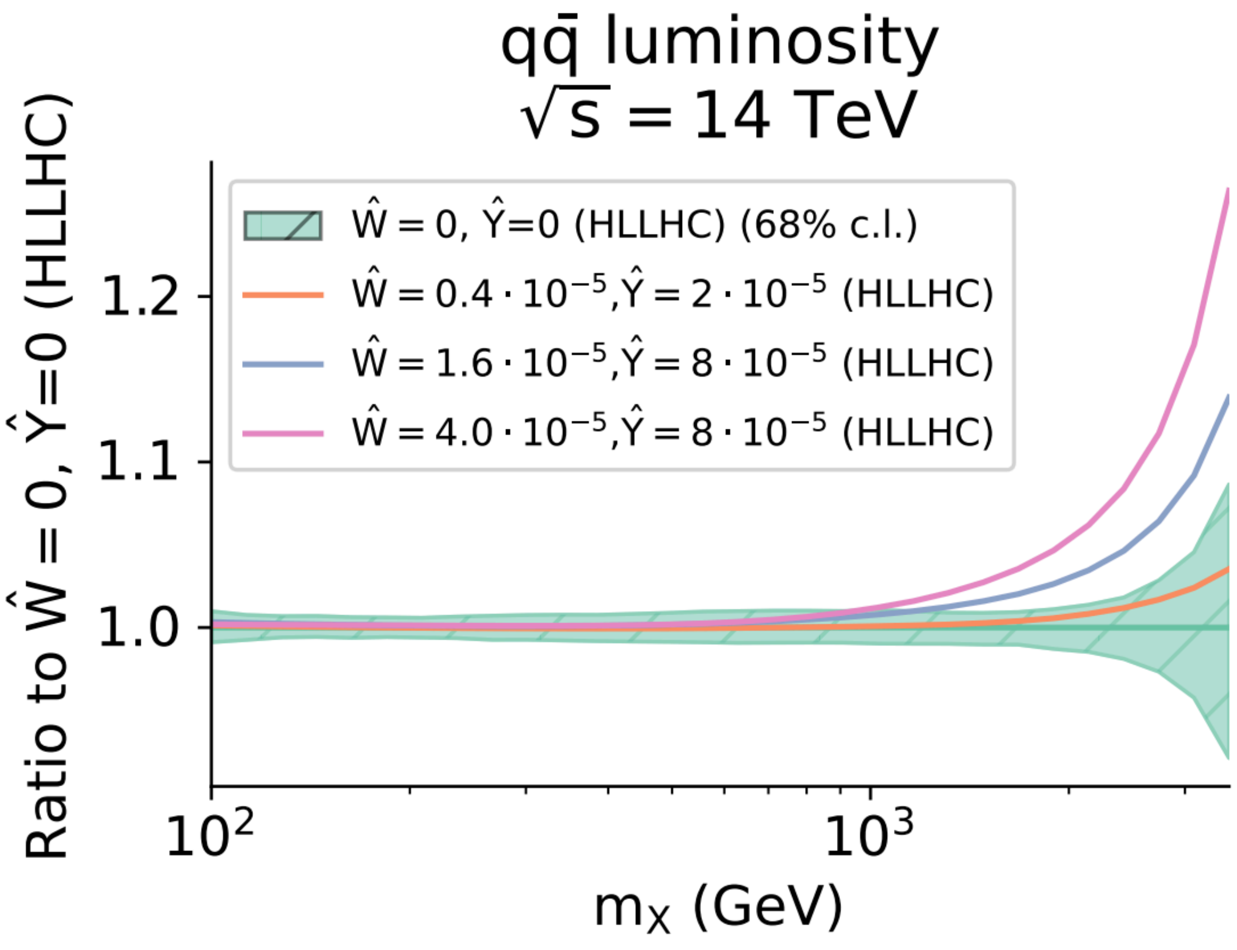


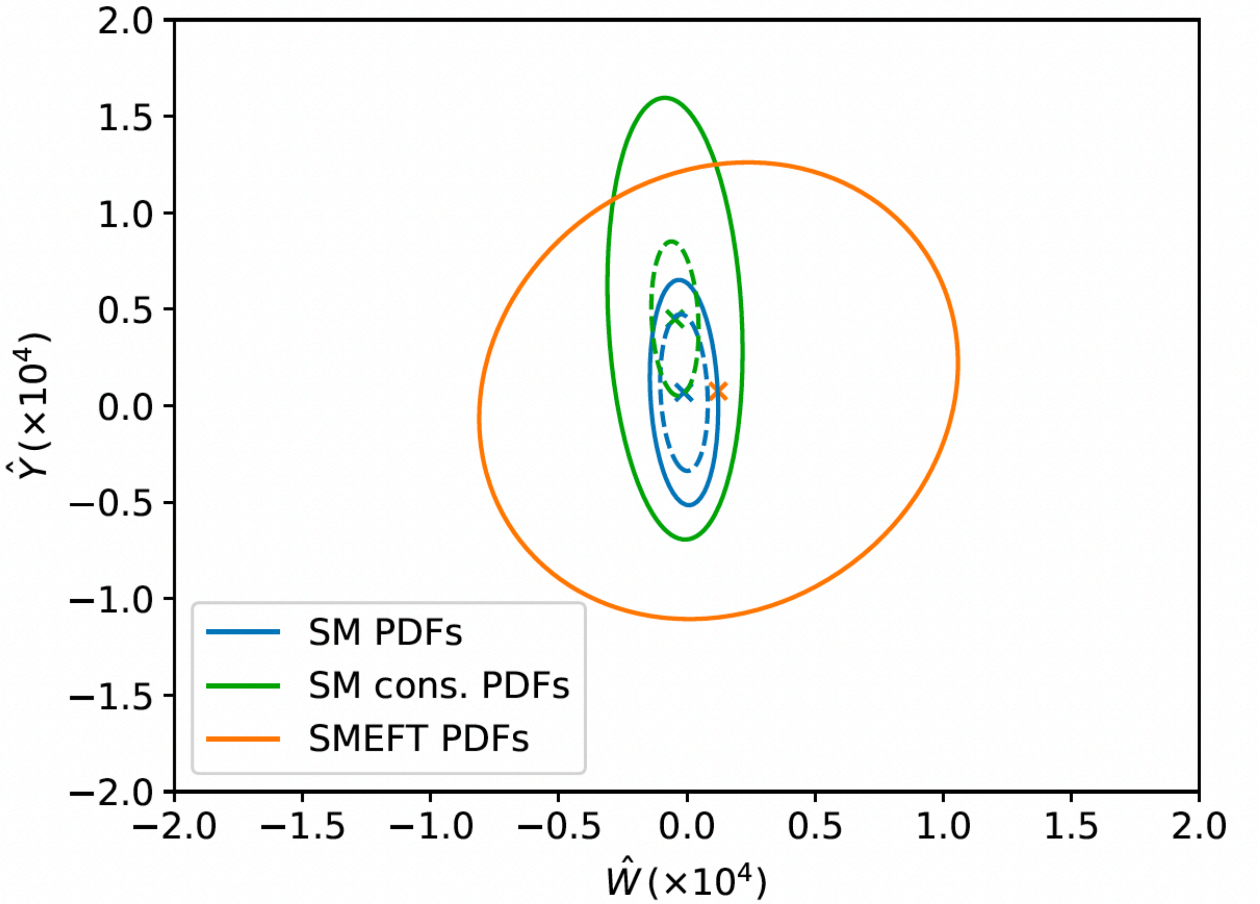
SMEFT PDFs from high-mass Drell-Yan



High-mass Drell-Yan: ***A. Greljo, S. Iranipour, Z. Kassabov, M. Madigan, J. Moore, JR, M. Ubiali, C. Voisey, JHEP 2021***

- HL-LHC projections: strong constraints on large-*x* antiquark PDFs, may be **reabsorbed into SMEFT PDFs**
- Bounds based on SM-PDFs **overly optimistic** as compared to those obtained from SMEFT-PDFs
- Emphasises importance of **SMEFT-PDF interplay** at the HL-LHC

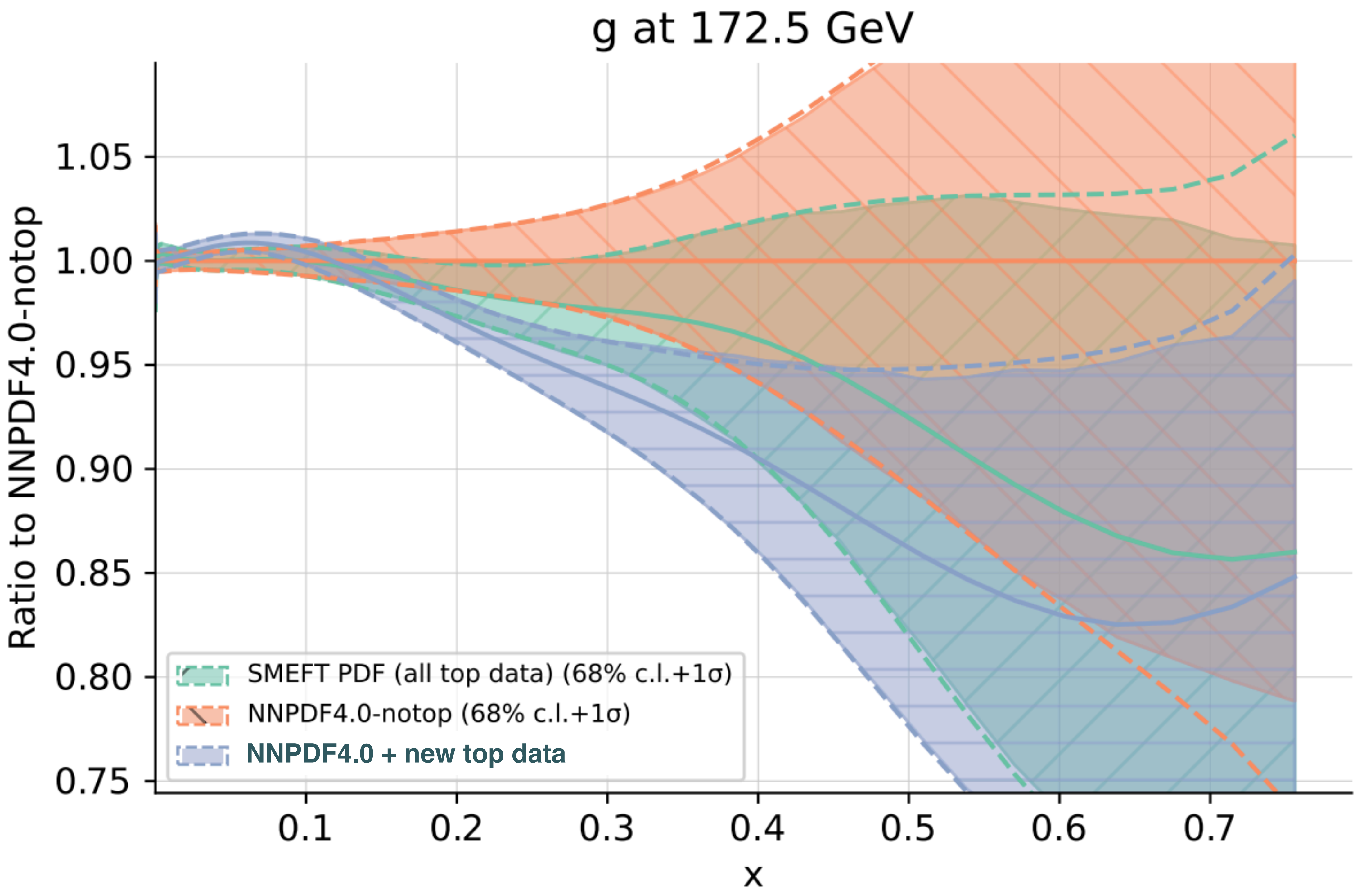




relevant also for legacy Run III measurements

SMEFT PDFs from top quark data

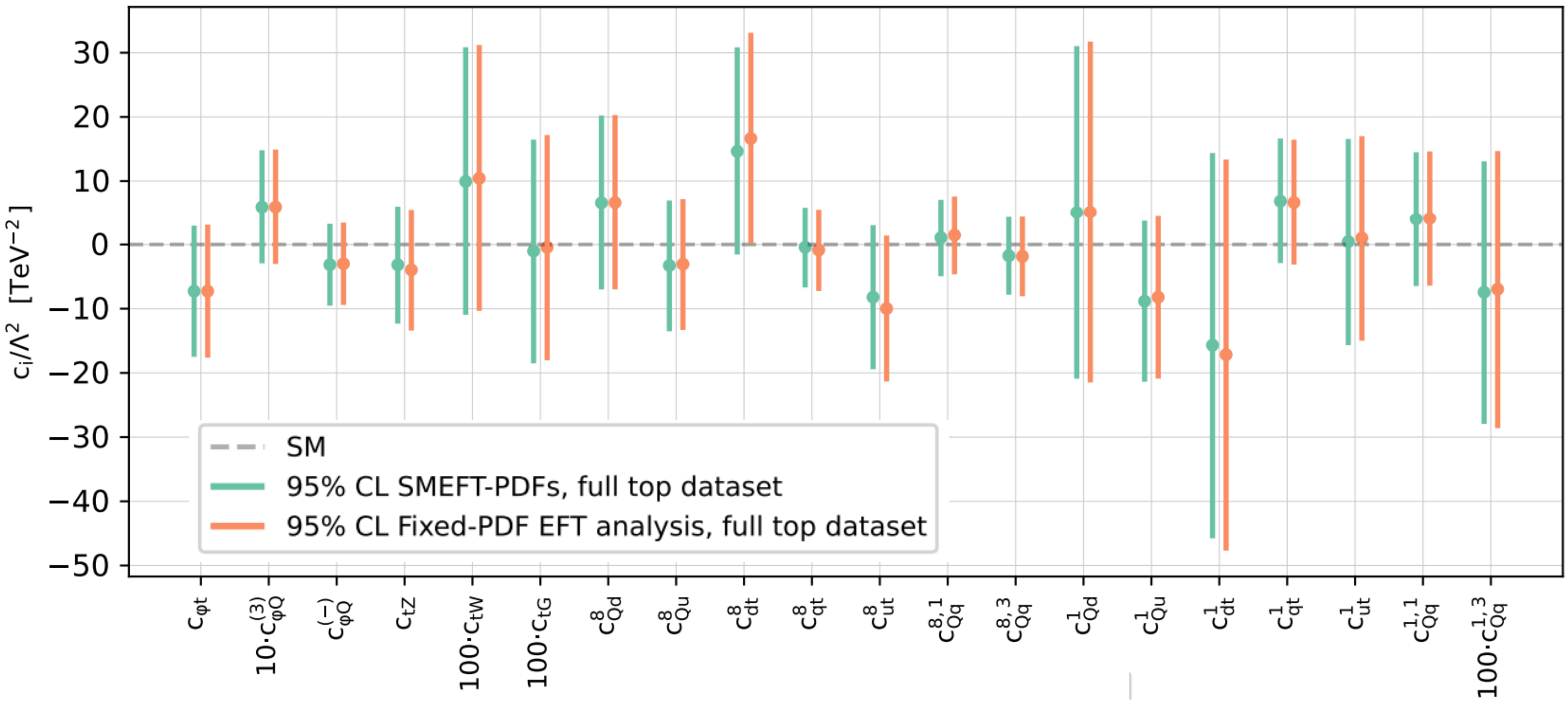
SMEFT-PDF results



Large-*x* gluon **distorted by EFT effects**, which partially absorb the data pulls

As a result, net effect of top quark data on PDFs **reduced** as compared to SM-PDFs

SMEFT PDFs from top quark data


SMEFT-PDF results

Despite differences between SMEFT-PDFs and SM-PDFs, **bounds on EFT coefficients stable**

PDF dependence **does not seem to affect** (for current data) EFT interpretations of top data

Summary and outlook

- ☑ Crucial ingredients for precision **HL-LHC phenomenology** are N^{3}LO PDFs which account for all sources of theory uncertainties

- ☑ The new aN^{3}LO NNPDF4.0 enable **consistent N^{3}LO calculations** of LHC cross-sections

- ☑ Preliminary assessment: **stability of the gluon-fusion Higgs** cross-section, improved perturbative convergence of **Drell-Yan production**

- ☑ The high-intensity, high-energy neutrino beam produced at the LHC enables unique opportunities for QCD studies, realising a **charged-current analog of the EIC**

- ☑ Extended NNPDF methodology to **constrain charm valence PDF from data**, finding preference for a non-zero, positive result peaking around x=0.3

- ☑ A non-zero valence charm PDF cannot be generated perturbatively: measurements of charm asymmetries at the EIC and the LHC **represent the ultimate smoking gun of IC**

- ☑ As the precision and kinematic reach of (HL-)LHC data increases, important to establish process-by-process the **interplay between PDF fits and BSM searchers**

Summary and outlook

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☑ The high-intensity, high-energy n LHC enables unique opportunities for QCD st **rrent analog of the EIC**

☑ Exte **onstrain charm valence PDF from data**, finding pr , positive result peaking around x=0.3

☑ A n ero valence charm PDF cannot be generated perturbatively: measurements of charm asymmetries at the EIC and the LHC **represent the ultimate smoking gun of IC**

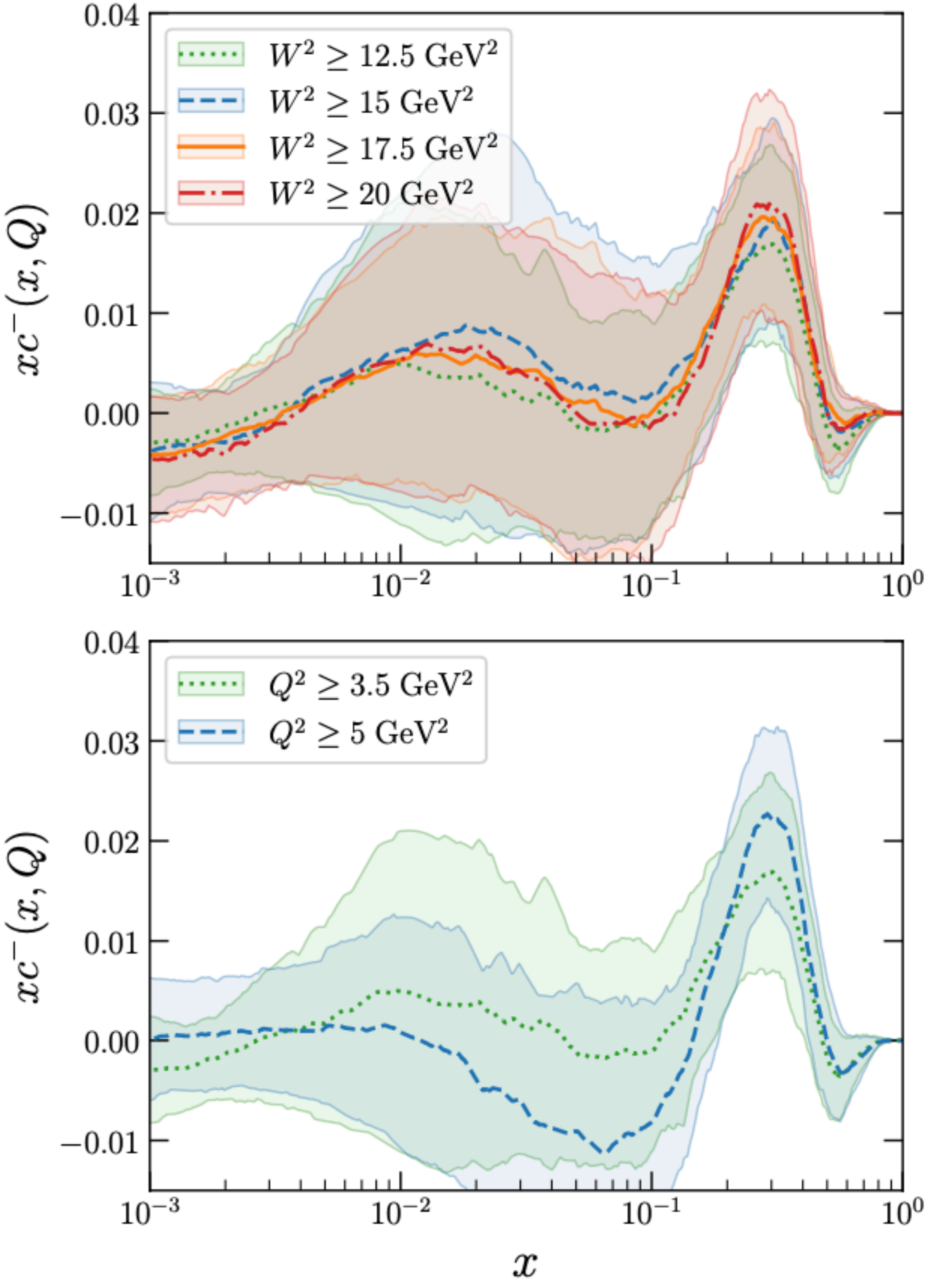
☑ As the precision and kinematic reach of (HL-)LHC data increases, important to establish process-by-process the **interplay between PDF fits and BSM searchers**

Thanks for your attention

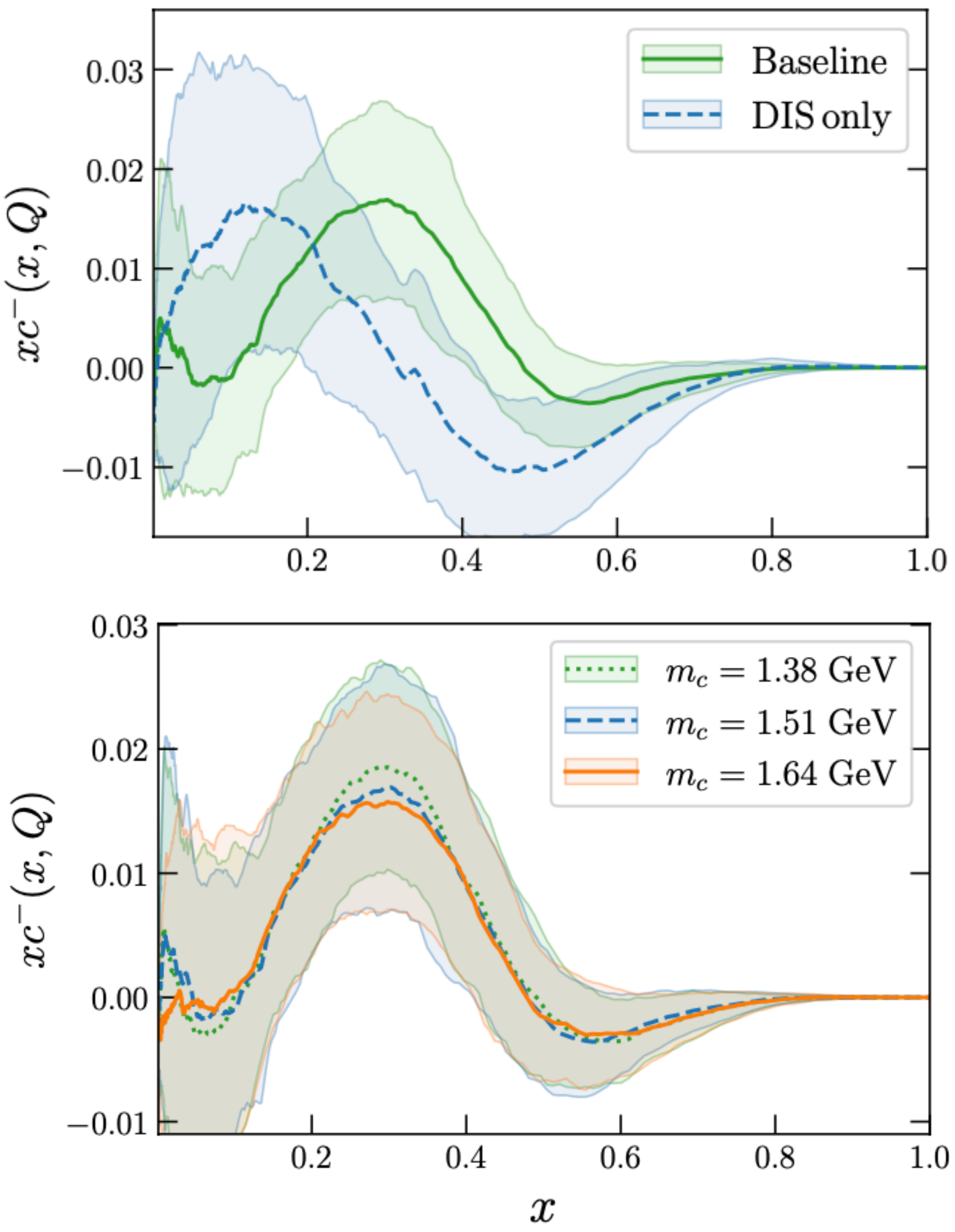
Extra Material

Charm valence stability

kinematic cuts & higher twists



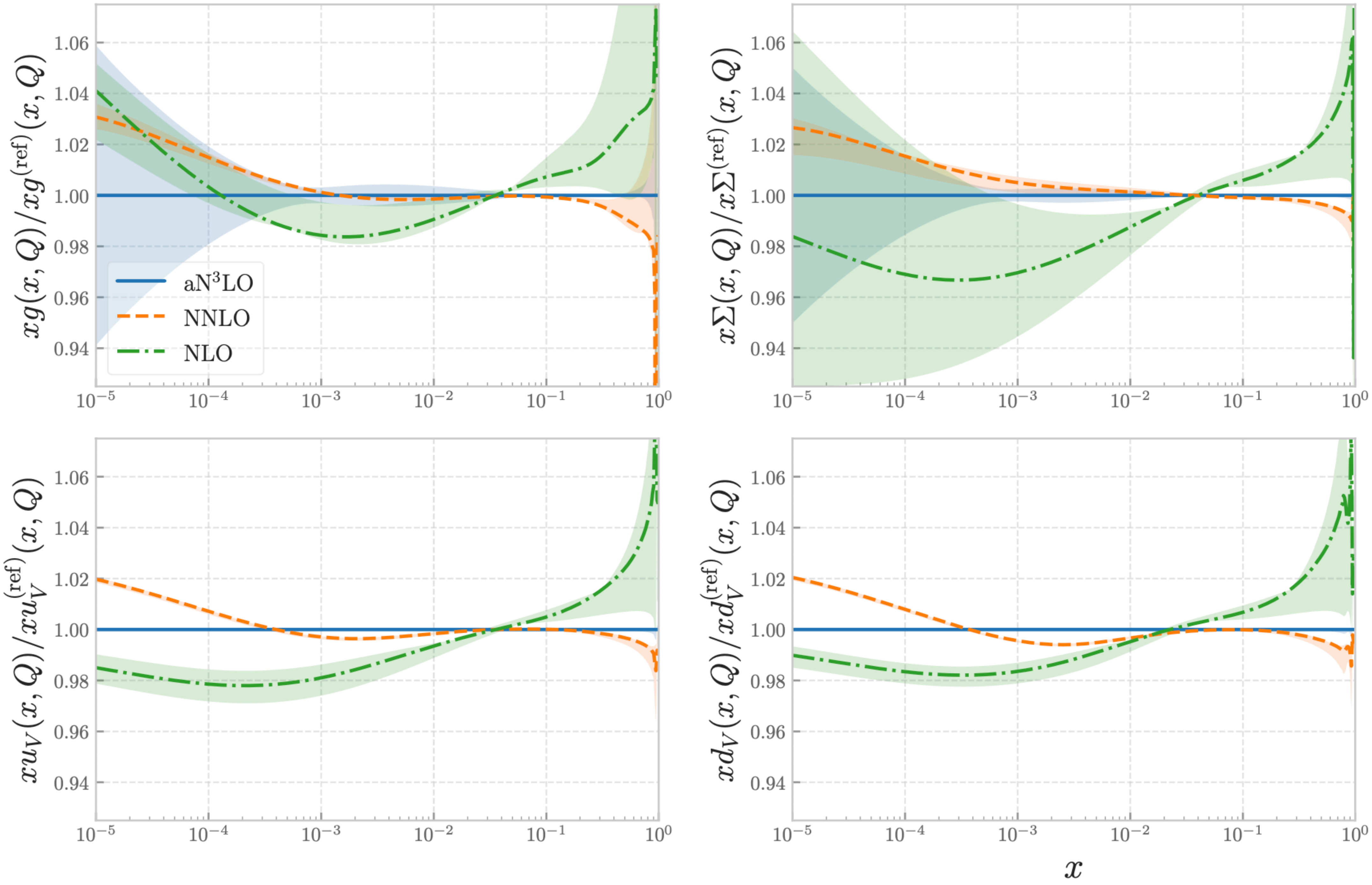
dataset & charm mass



NNPDF4.0 at aN³LO

- Approximate parametrisation for the N³LO splitting functions satisfying known **exact results and limits**

DGLAP evolution of NNPDF4.0 NNLO from $Q_0 = 1.65$ GeV to $Q = 100$ GeV



LO, NLO, NNLO:
MHOU (μ_F)

N³LO: **MHOU (μ_F) + IHOUs**

Effects of N³LO corrections to DGLAP evolution **< 1%** except at small-*x*

Theory uncertainties (MHOU + IHOU) at N³LO are **negligible** except in small-*x* region

PDFs and New Physics Searches with A_{FB}

BSM searches from high-mass DY

- DY @ LO: separated into **symmetric** and **antisymmetric** parton luminosities

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}m_{\ell\bar{\ell}}\,\mathrm{d}y_{\ell\bar{\ell}}\,\mathrm{d}\cos\theta^*} = \frac{\pi\alpha^2}{3m_{\ell\bar{\ell}}s}\left((1+\cos^2(\theta^*))\sum_q S_q\mathcal{L}_{S,q}(m_{\ell\bar{\ell}},y_{\ell\bar{\ell}}) + \cos\theta^*\sum_q A_q\mathcal{L}_{A,q}(m_{\ell\bar{\ell}},y_{\ell\bar{\ell}})\right)$$

dilepton invariant mass

dilepton rapidity

Collins-Soper angle

symmetric effective coupling

antisymmetric effective coupling

$$\mathcal{L}_{S,q}(m_{\ell\bar{\ell}},y_{\ell\bar{\ell}}) \equiv f_q(x_1,m^2_{\ell\bar{\ell}})f_{\bar{q}}(x_2,m^2_{\ell\bar{\ell}}) + f_q(x_2,m^2_{\ell\bar{\ell}})f_{\bar{q}}(x_1,m^2_{\ell\bar{\ell}})\,,$$

$$\mathcal{L}_{A,q}(m_{\ell\bar{\ell}},y_{\ell\bar{\ell}}) \equiv \mathrm{sign}(y_{\ell\bar{\ell}})\left[f_q(x_1,m^2_{\ell\bar{\ell}})f_{\bar{q}}(x_2,m^2_{\ell\bar{\ell}}) - f_q(x_2,m^2_{\ell\bar{\ell}})f_{\bar{q}}(x_1,m^2_{\ell\bar{\ell}})\right]$$

invariant under

$x_1 \leftrightarrow x_2$

- A **forward-backward (FB) asymmetry** arises when antisymmetric luminosity is non-zero

$$\left.\frac{d^3\sigma}{dm_{\ell\bar{\ell}}dy_{\ell\bar{\ell}}d\cos(\theta^*)}\right|_{\mathrm{FB}} = \left.\frac{d^3\sigma}{dm_{\ell\bar{\ell}}dy_{\ell\bar{\ell}}d\cos(\theta^*)}\right|_{\cos\theta^*} - \left.\frac{d^3\sigma}{dm_{\ell\bar{\ell}}dy_{\ell\bar{\ell}}d\cos(\theta^*)}\right|_{-\cos\theta^*}$$

$$\left.\frac{d^3\sigma}{dm_{\ell\bar{\ell}}dy_{\ell\bar{\ell}}d\cos(\theta^*)}\right|_{\mathrm{FB}} = \frac{2\pi\alpha^2\cos(\theta^*)}{3m_{\ell\bar{\ell}}s}\sum_q A_q\mathscr{L}_{A,q}$$

At LO, properties of forward-backward asymmetry dictated by antisymmetric parton luminosity

Positive or negative asymmetry?

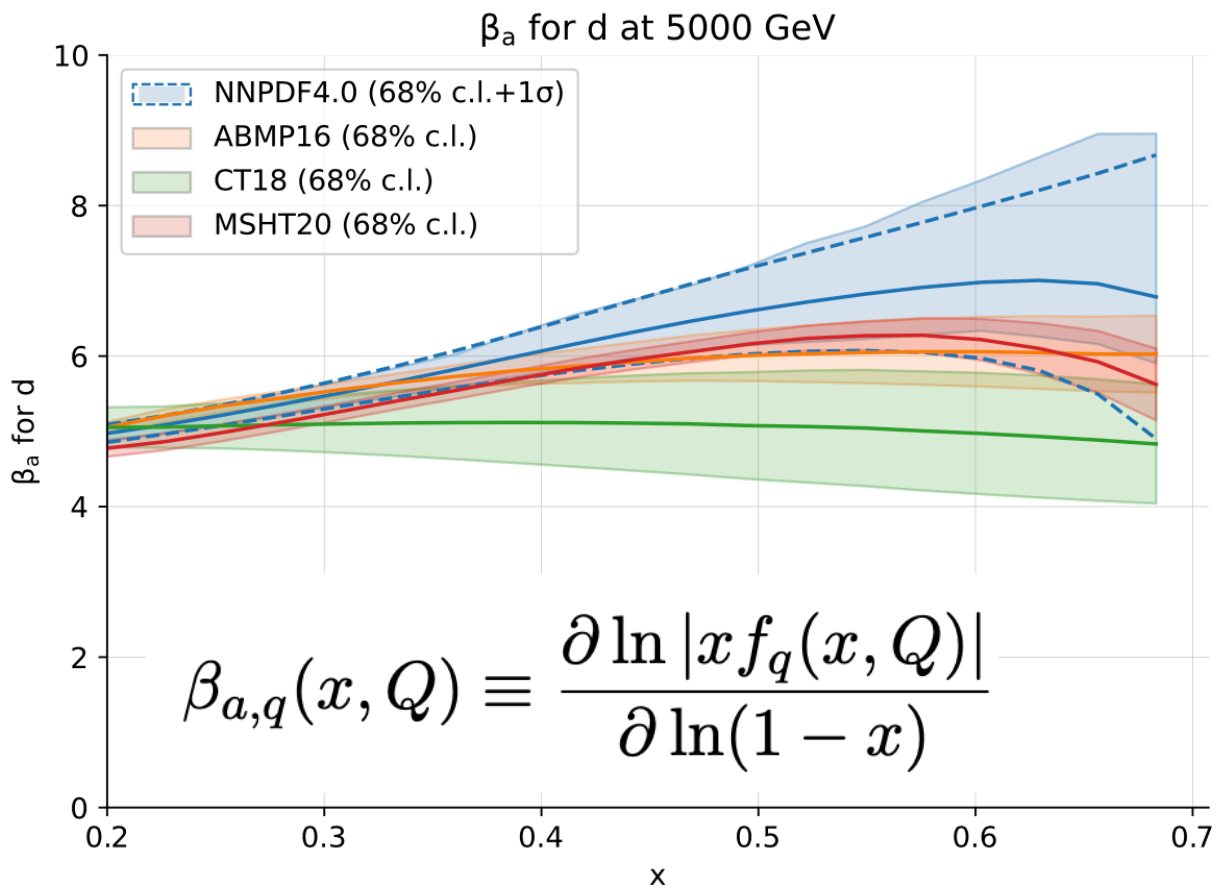
- Antisymmetric luminosity depends on **relative rate of decrease of the quark and antiquark PDFs**

$$\mathcal{L}_{A,q} = f_q(x_2) f_{\bar{q}}(x_2) \left[\underbrace{\frac{f_q(x_1)}{f_q(x_2)}}_{\text{fall-off rate quarks}} - \underbrace{\frac{f_{\bar{q}}(x_1)}{f_{\bar{q}}(x_2)}}_{\text{fall-off rate anti-quarks}} \right] , \quad x_1 > x_2$$

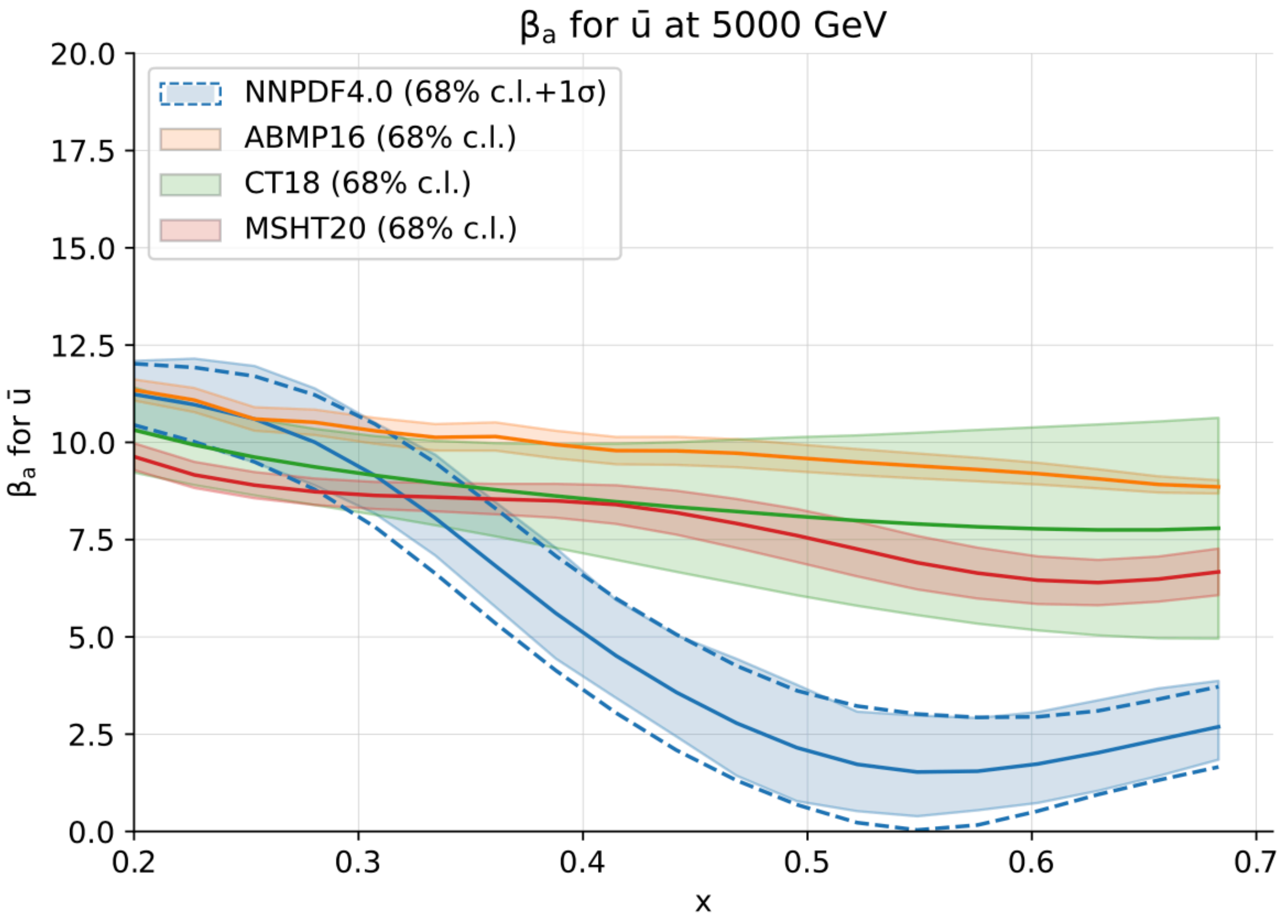
at high mass, no hierarchy between x_1 and x_2

- AFB sensitive to **subtle PDF property**: difference in decrease rates of large-*x* quarks vs antiquarks

- Quantified by the **effective asymptotic exponents**, which illustrate richer structure in NNPDF4.0

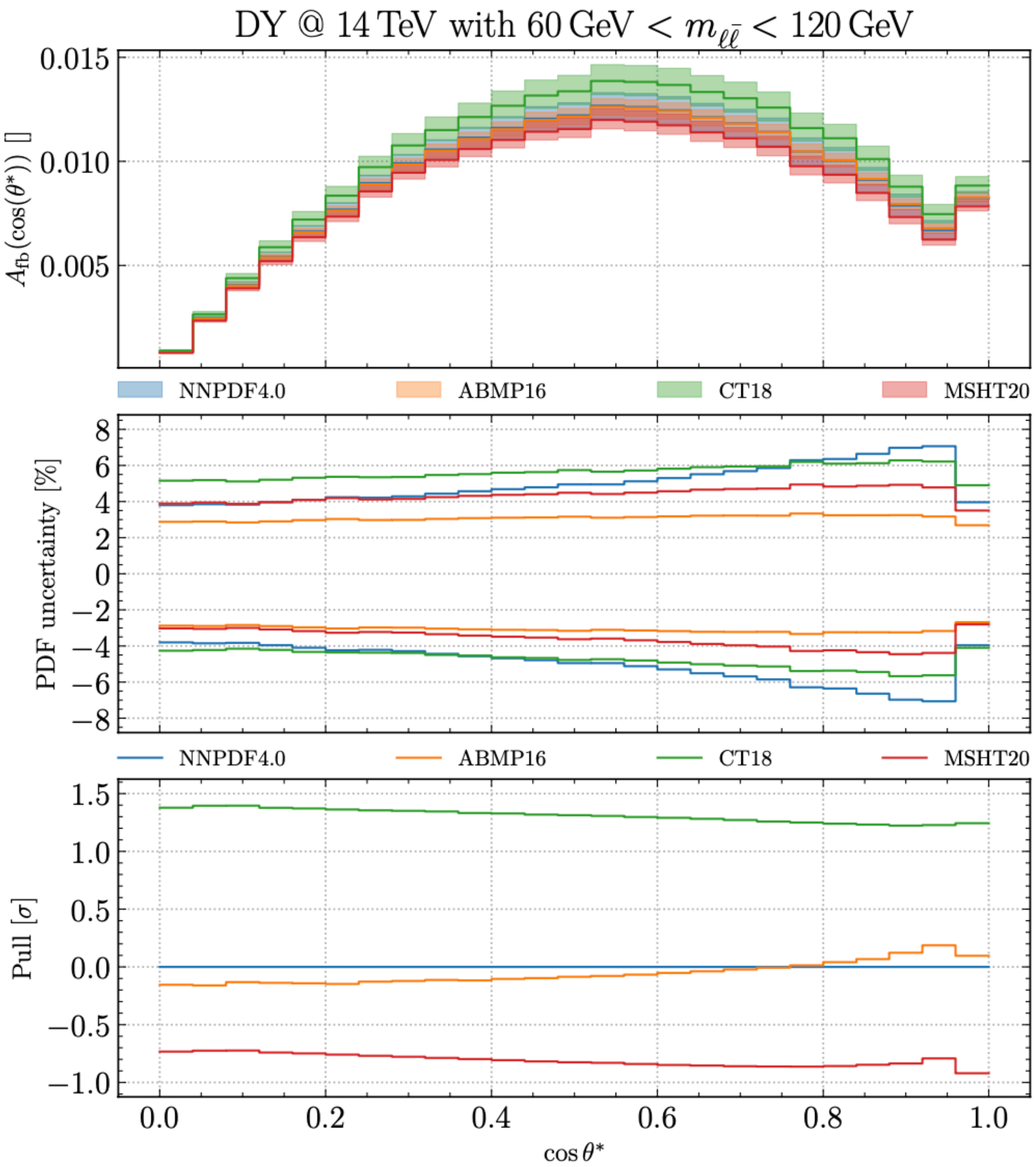


$$\beta_{a,q}(x,Q) \equiv \frac{\partial \ln |x f_q(x,Q)|}{\partial \ln(1-x)}$$



LHC phenomenology

- Validate our LO interpretation with realistic LHC simulations based on **mg5_aMC with NLO QCD and EW corrections** and with same fiducial selection cuts as in the ATLAS/CMS measurements

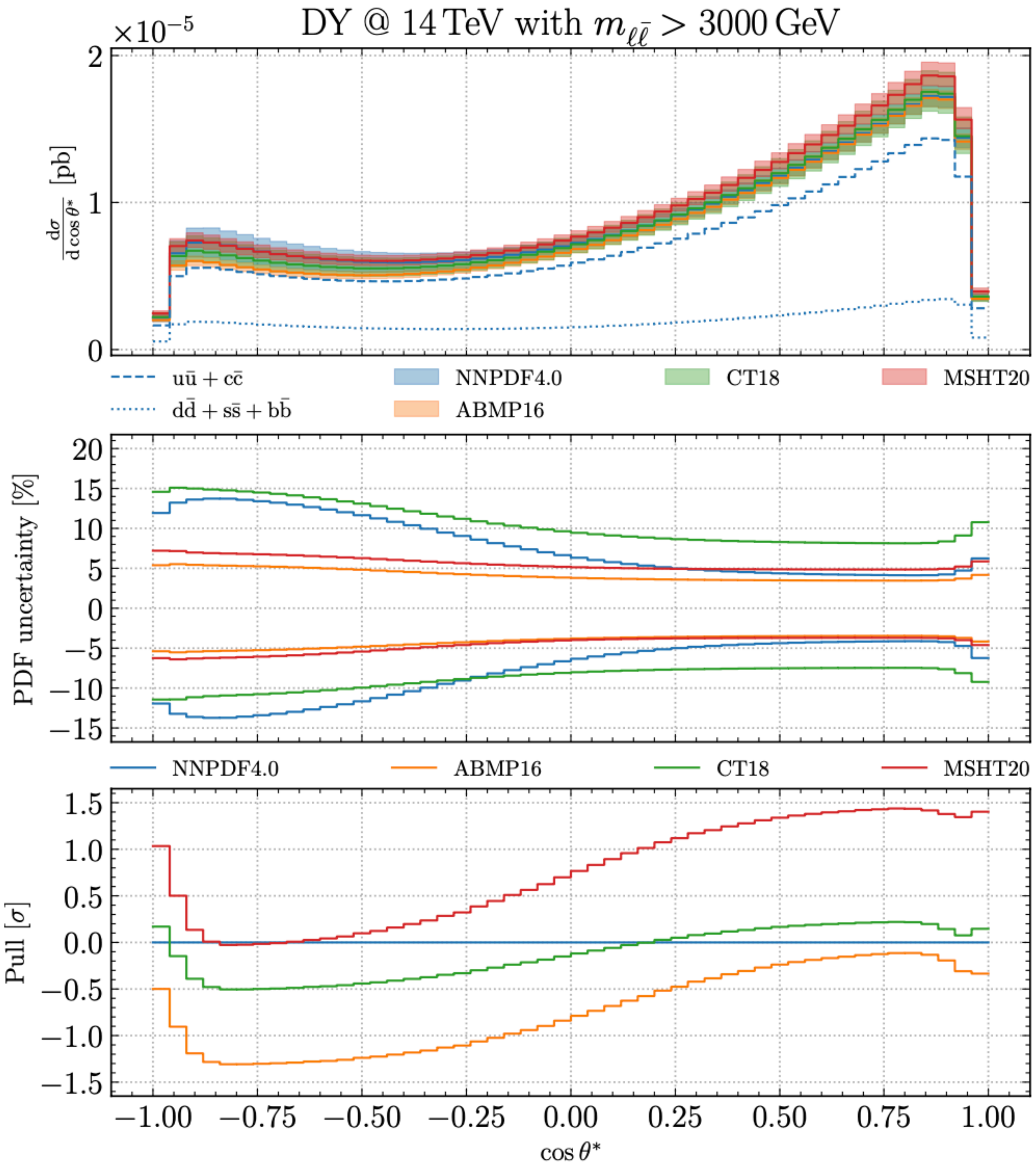


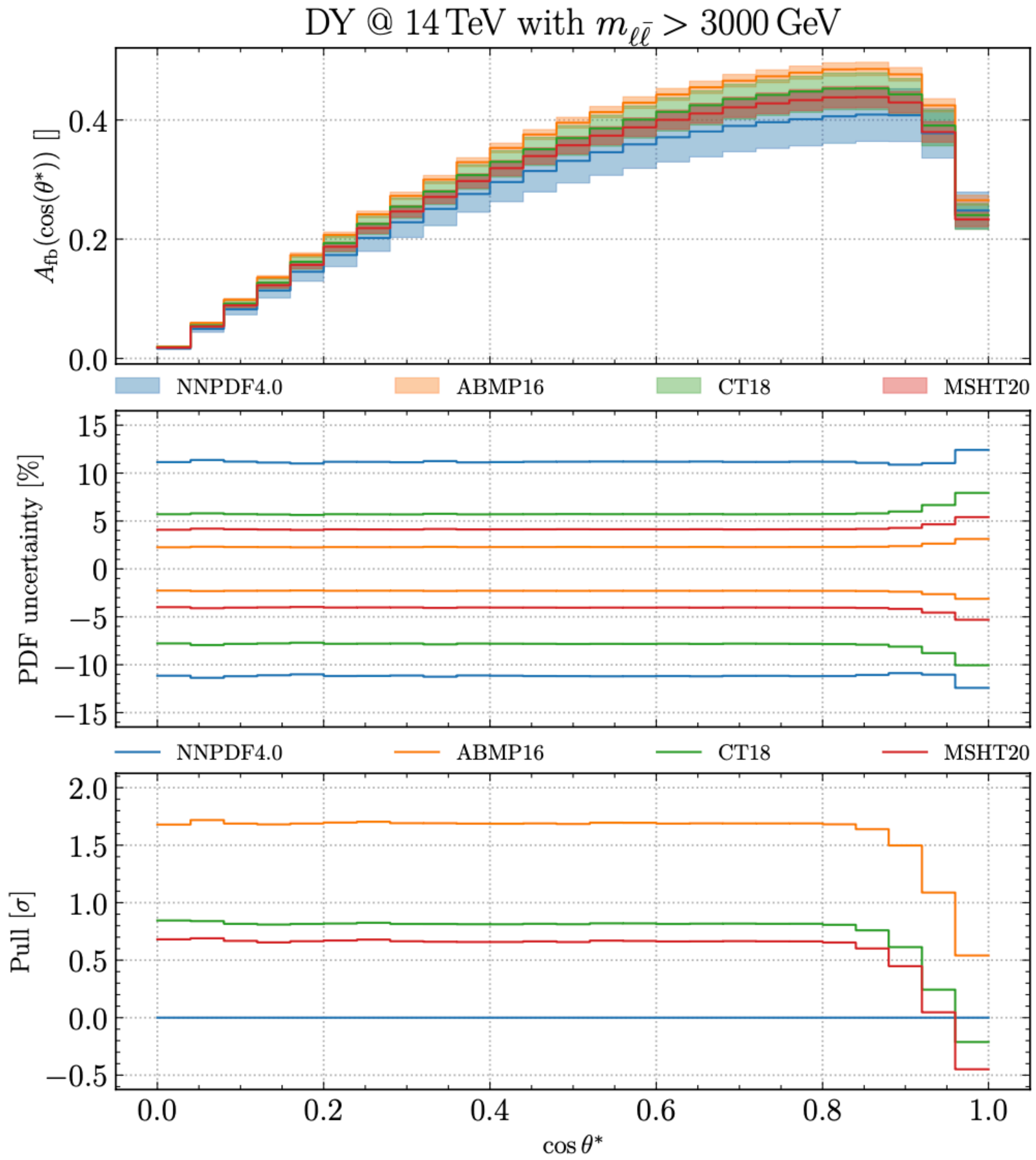
- As well known, **clearly positive FB asymmetry** with good agreement between PDF fits

- What happens at higher dilepton masses?

LHC phenomenology

- For **dilepton masses > 3 TeV**, same qualitative behaviour, with clearly positive ***A_{FB}***

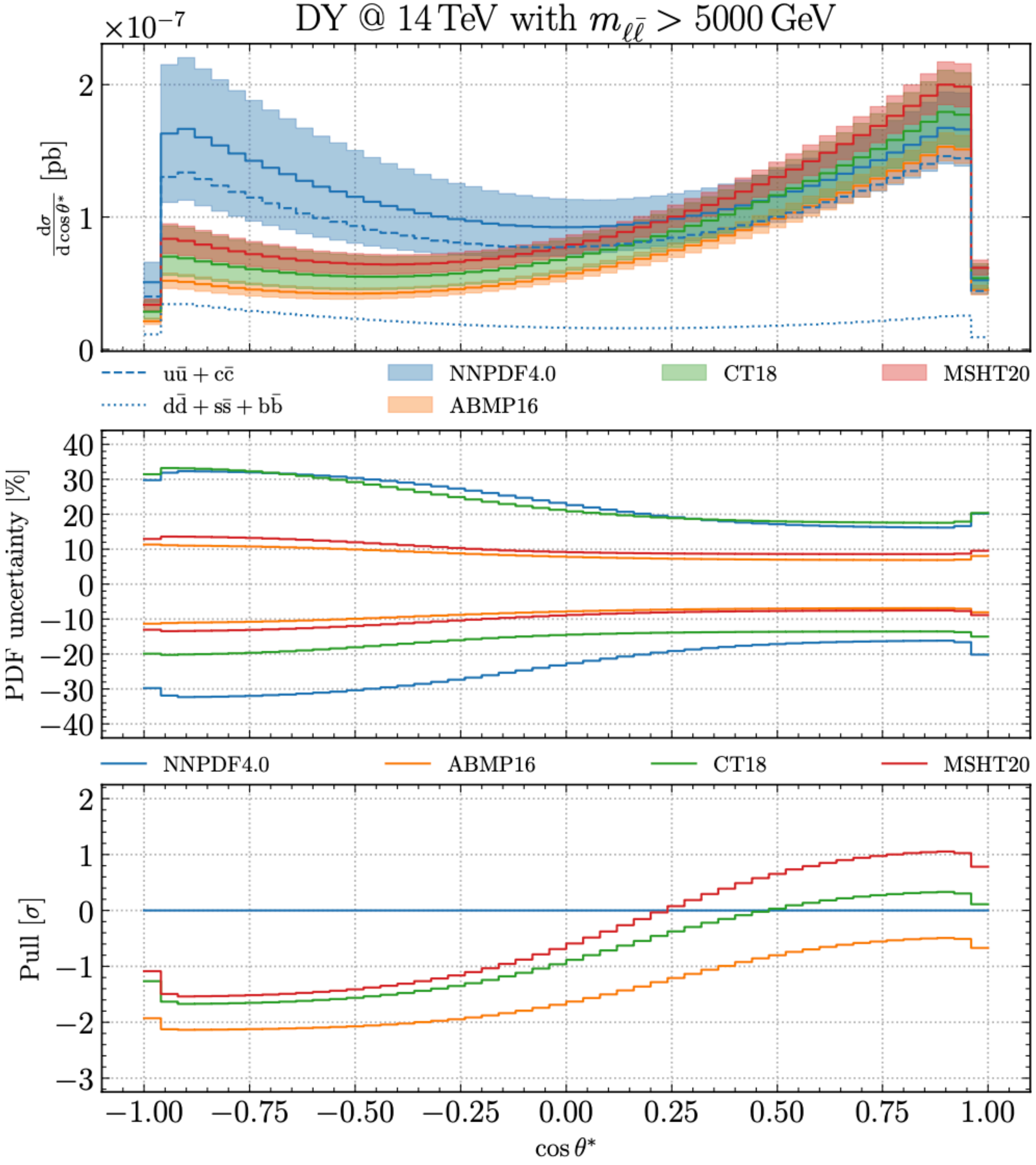


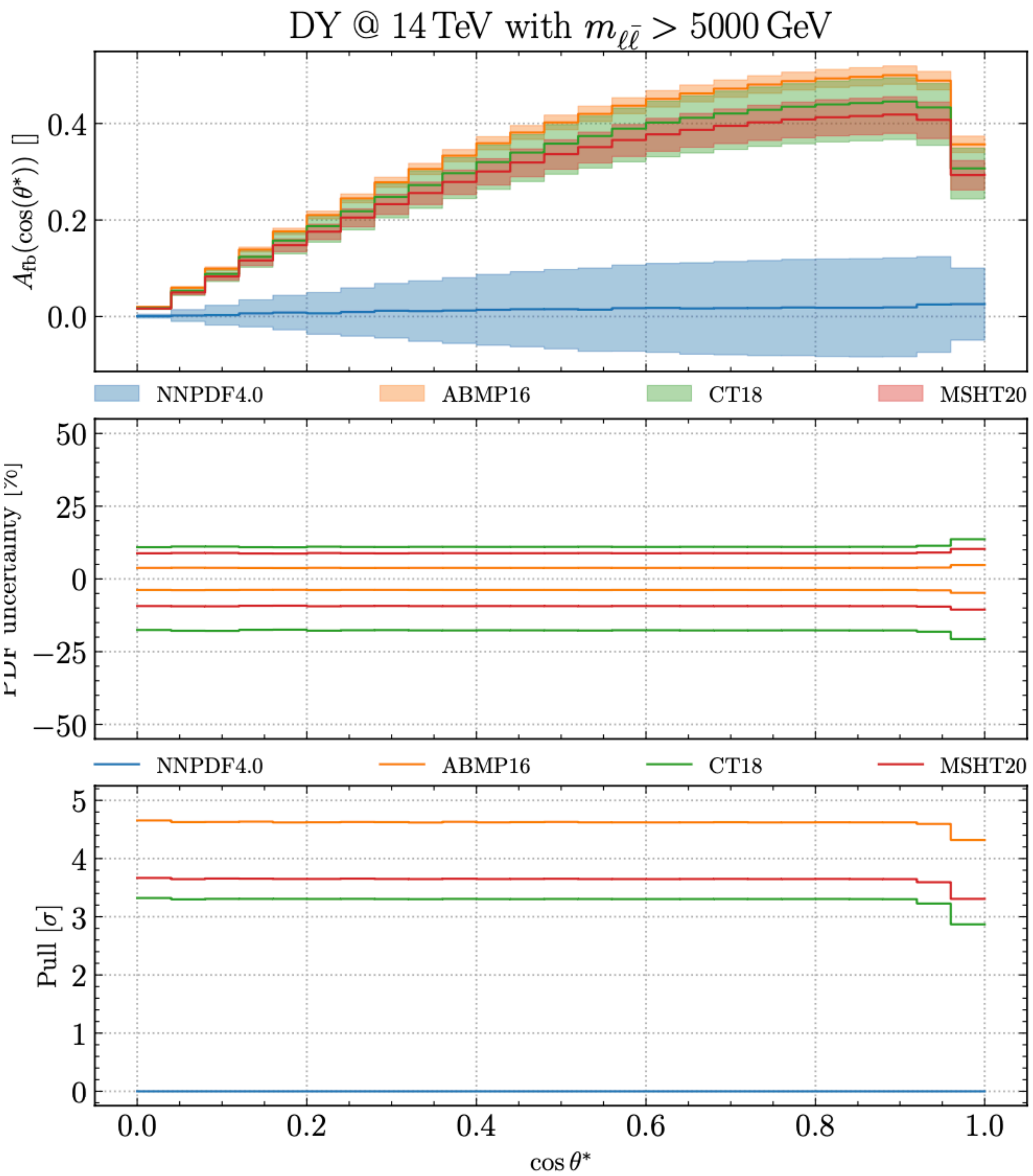


However, we know from the LO analysis that extrapolation to yet high masses may change the qualitative behaviour

LHC phenomenology

- For dilepton masses > 5 TeV, $\boldsymbol{A_{FB}}$ vanishes for NNPDF4.0, while other groups extrapolate





PDF uncertainties differ between PDF groups, with NNPDF4.0 displaying the largest ones