HUGS2023

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# GLOBAL PDF FITS: CONNECTING LOW TO HIGH ENERGY PHYSICS

## LECTURE V

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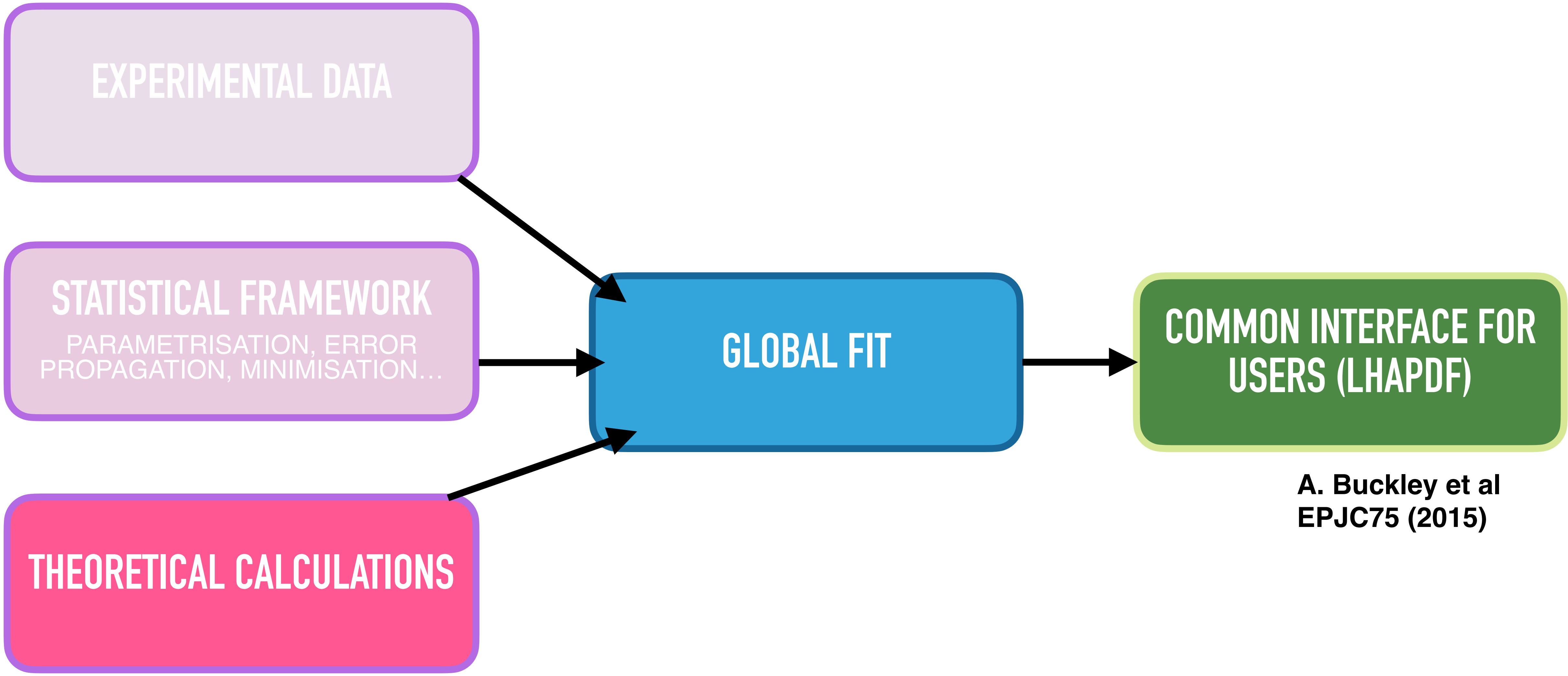
University of Cambridge

# Outline

- First two lectures (Tuesday)
  - Motivation:
    the high energy big picture
  - Parton Model and QCD
  - Collinear Factorisation
- Third and fourth lecture (yesterday)
  - Ingredients of a PDF global fits
  - Experimental input
  - Methodological aspects
- Fourth lecture (today)
  - New frontiers and challenges
    - Theoretical aspects and theory frontiers
    - State-of-the-art PDFs
    - PDF and new physics interplay
    - Intrinsic charm

# A complex machinery




**A. Buckley et al EPJC75 (2015)**

# Theoretical aspects & theory frontiers

# Theory predictions in PDF fits

$$\chi^2 = \sum_{i,j=1}^{N_{\rm dat}} (T_i - D_i)\,({\rm cov}_{\rm exp})^{-1}_{ij}\,(T_j - D_j)$$

PDF parameters determined by minimising figure of merit

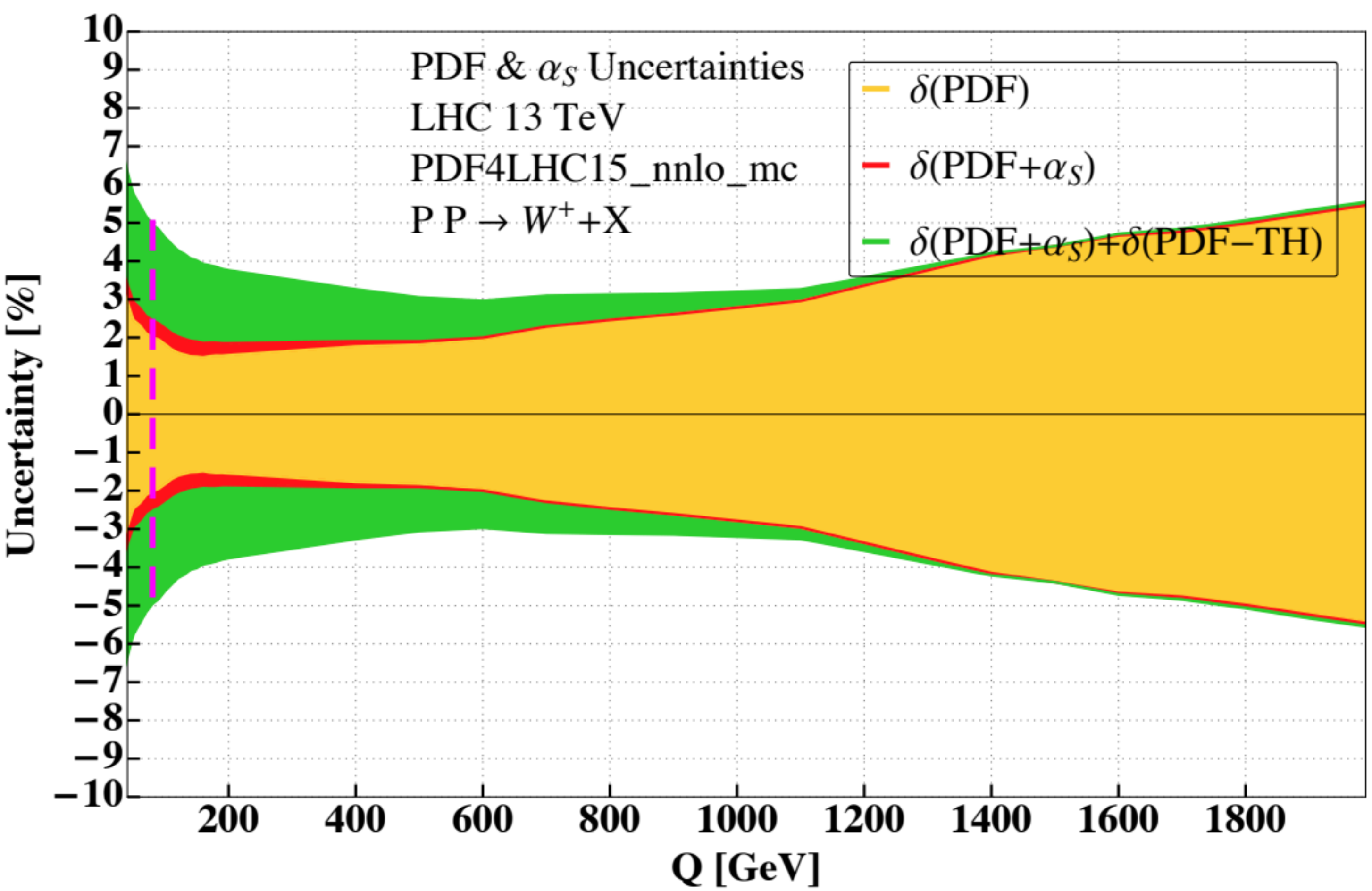
$$\boxed{T = f_1\,(\otimes f_2)\,\otimes\,\hat{\sigma}}$$

$$\hat{\sigma} = \alpha_s^p \sigma_0 + \alpha_s^{p+1}\sigma_1 + \alpha_s^{p+2}\sigma_2 + \mathcal{O}(\alpha_s^{p+3})$$

- Standard global PDF fits based on fixed-order NNLO QCD calculations
- Standard global PDF fits set specific values for
  - $\alpha_s(M_z)$
  - $M_w$, $M_z$, $\alpha_e(M_z)$
  - CKM matrix elements
  - Heavy quark mass thresholds
  - Branching ratios…
- MHOUs in perturbative expansion, the uncertainty on the value of the parameters that enter a PDF fit are <u>NOT</u> included in PDF error bars

# Mismatch between pert. orders

- PDF fits performed at given perturbative order - NNLO
- PDF uncertainties only reflect lack of information from data
- Theoretical uncertainties (dominated by MHOU) ignored so far
- New frontier for partonic cross sections is N3LO
- Mismatch between perturbative order of partonic cross section and PDFs becoming significant source of uncertainty




$$\delta(PDF-TH) = \frac{1}{2}\left|\frac{\sigma^{(2)}_{\mathrm{NNLO-PDFs}} - \sigma^{(2)}_{\mathrm{NLO-PDFs}}}{\sigma^{(2)}_{\mathrm{NNLO-PDFs}}}\right|$$

C. Duhr et al, *JHEP* 11 (2020) 143

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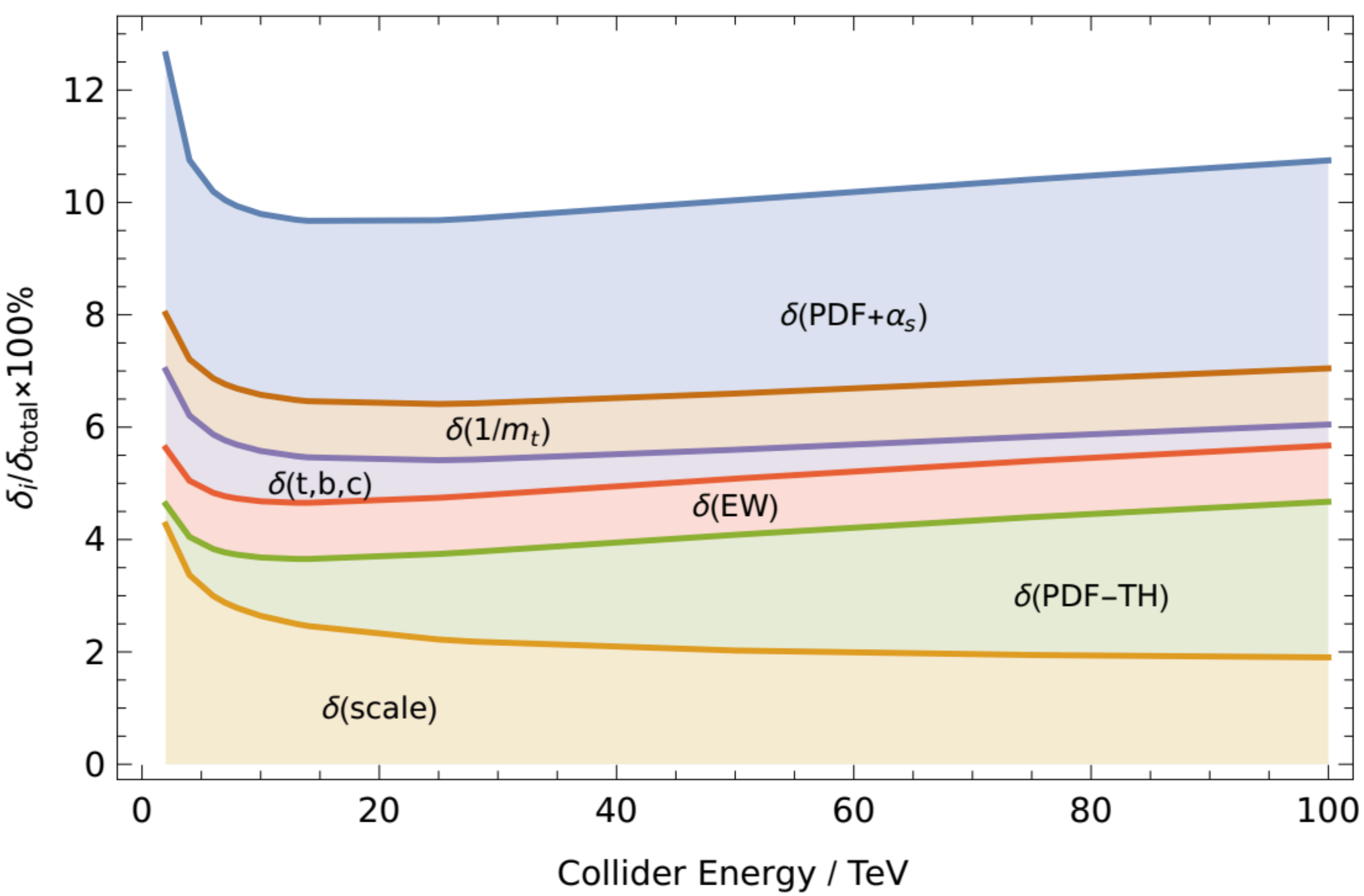
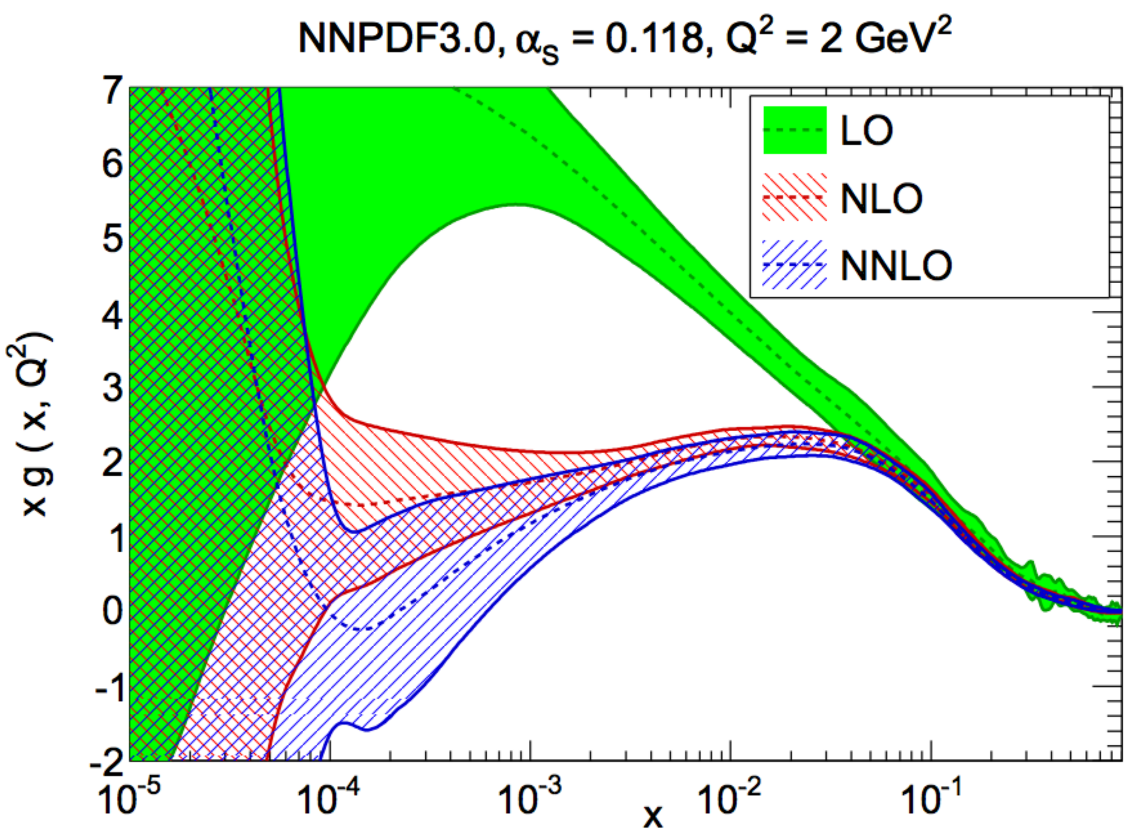


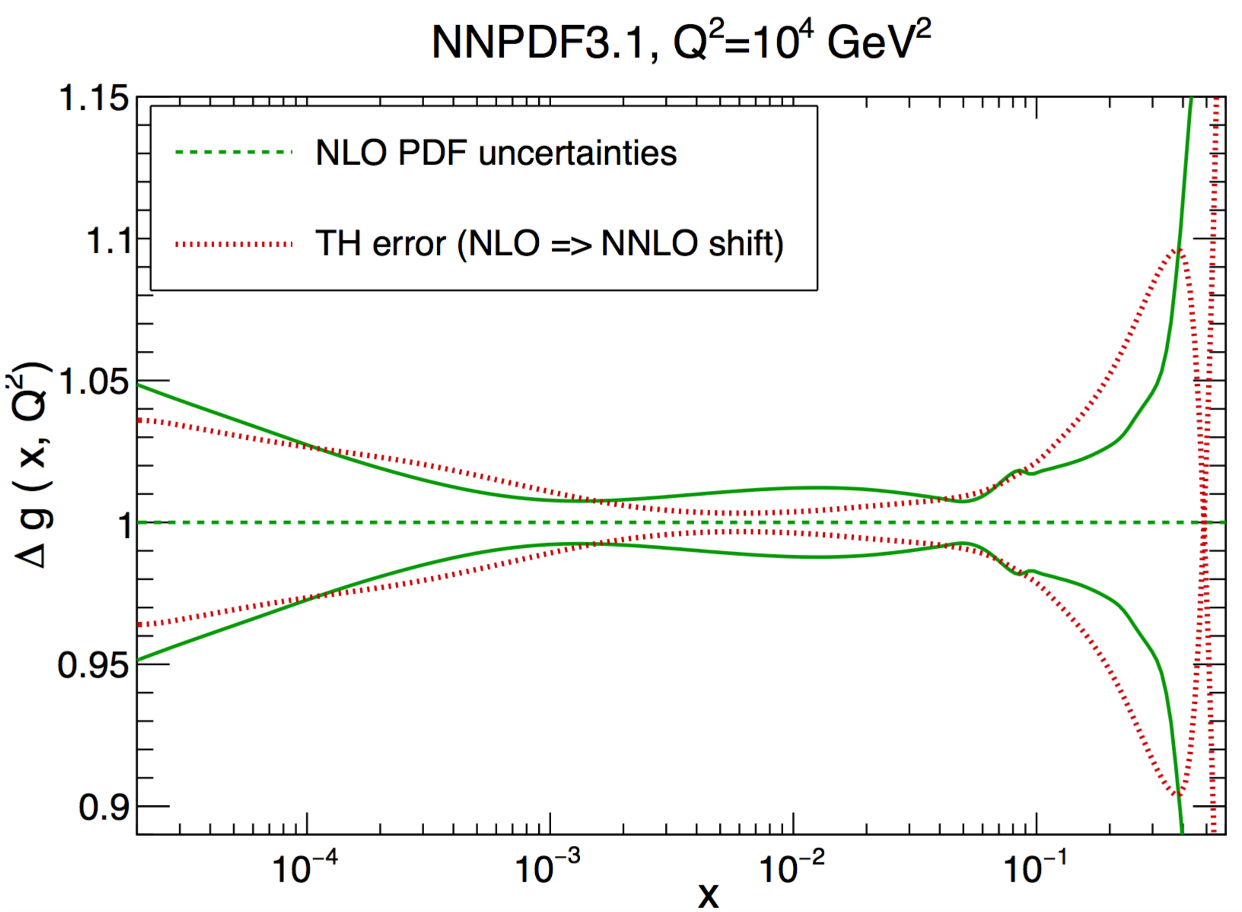

$$\delta(PDF-TH) = \frac{1}{2}\left|\frac{\sigma^{(2)}_{\rm NNLO-PDFs} - \sigma^{(2)}_{\rm NLO-PDFs}}{\sigma^{(2)}_{\rm NNLO-PDFs}}\right|$$

M. Cepeda et al. [HL/HE WG2 group], arXiv:1902.00134

# MHOU in PDF fits

- In a fit based on NLO theoretical predictions the theory error is already comparable to experimental error. What about a NNLO fit?
- How to include MHOUs in PDF error bands at NNLO?




Ball et al, EPJC 77 (2017)

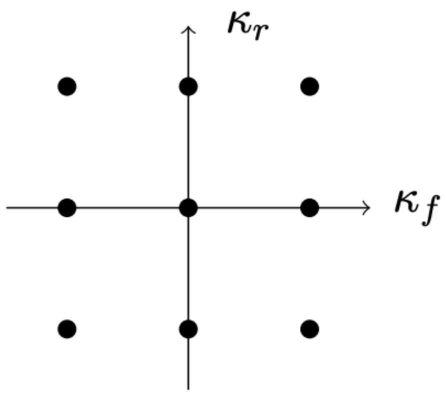
# MHOU in PDF fits

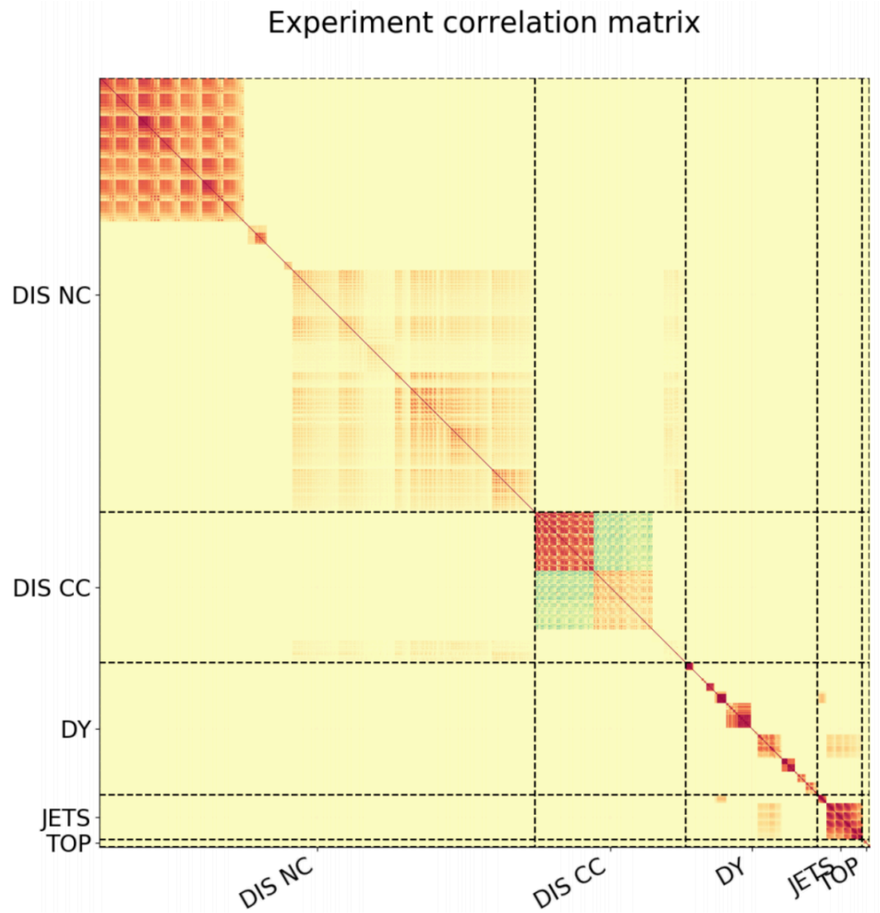
Option 1 - theory covmat [NNPDF: 1906.10698]

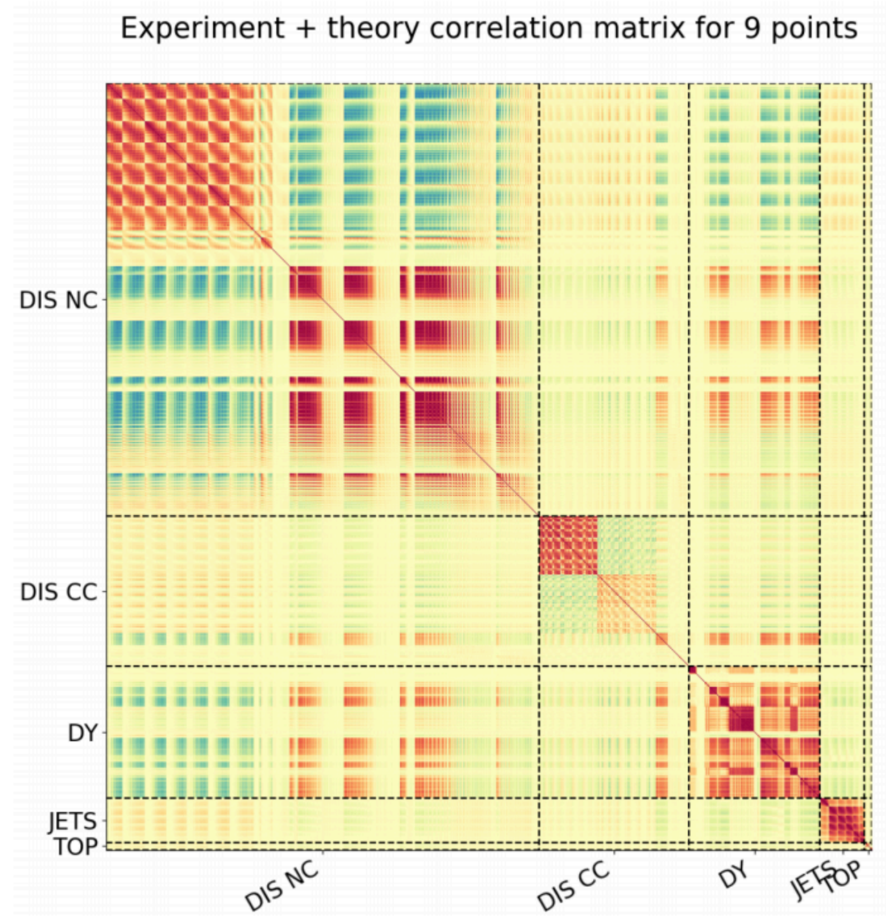
Construct a theory covariance matrix from scale-varied cross sections and combine it with the experimental covariance matrix

$$\chi^2 = \sum_{i,j=1}^{N_{\mathrm{dat}}} (T_i - D_i)\,(\mathrm{cov}_{\mathrm{exp}} + \mathrm{cov}_{\mathrm{th}})^{-1}_{ij}\,(T_j - D_j)$$

- Assumptions: experimental and theoretical errors independent and Gaussian
- Assumptions on correlation of scales and scale ratio will determine the specific form of the covariance matrix



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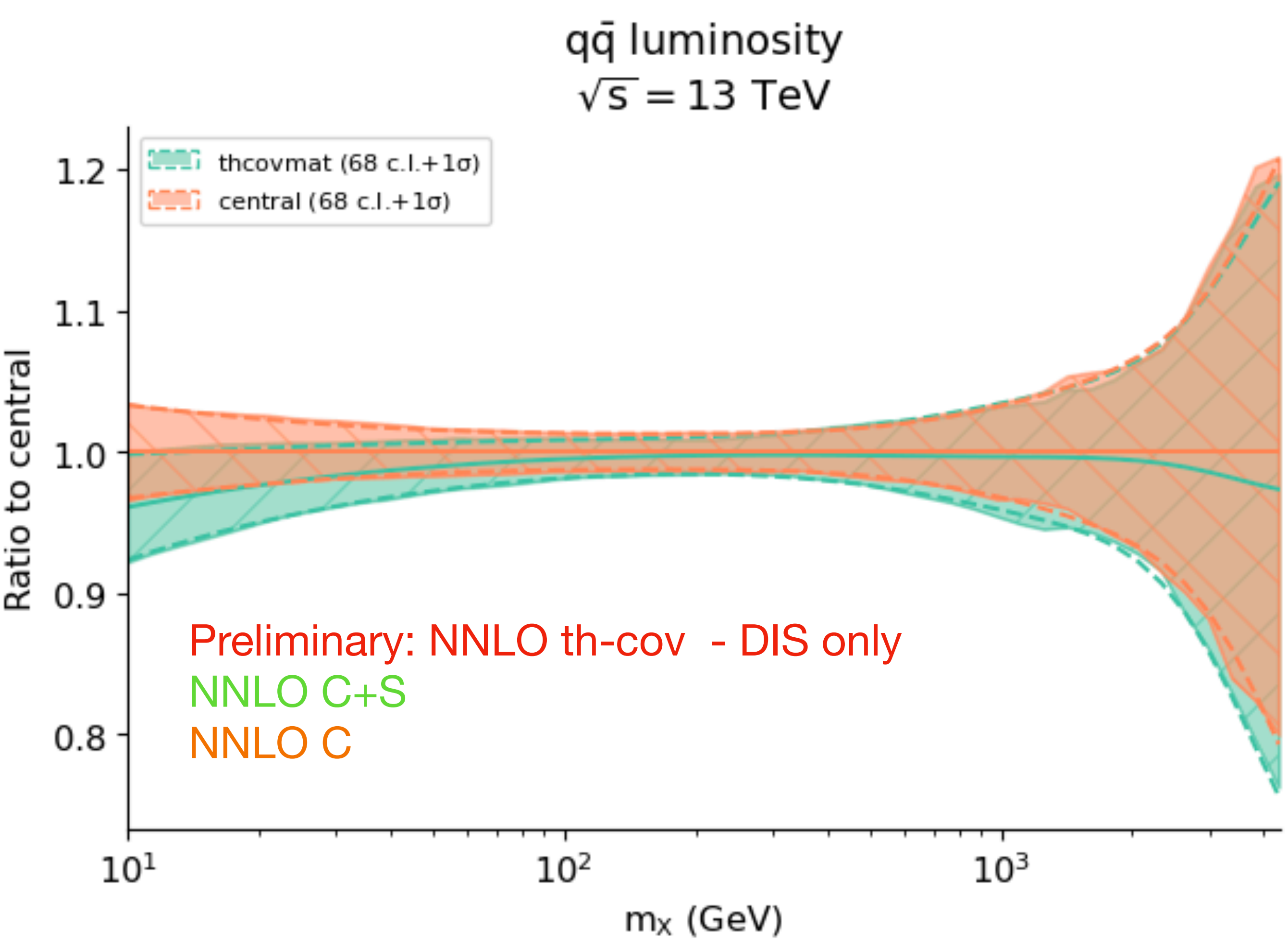
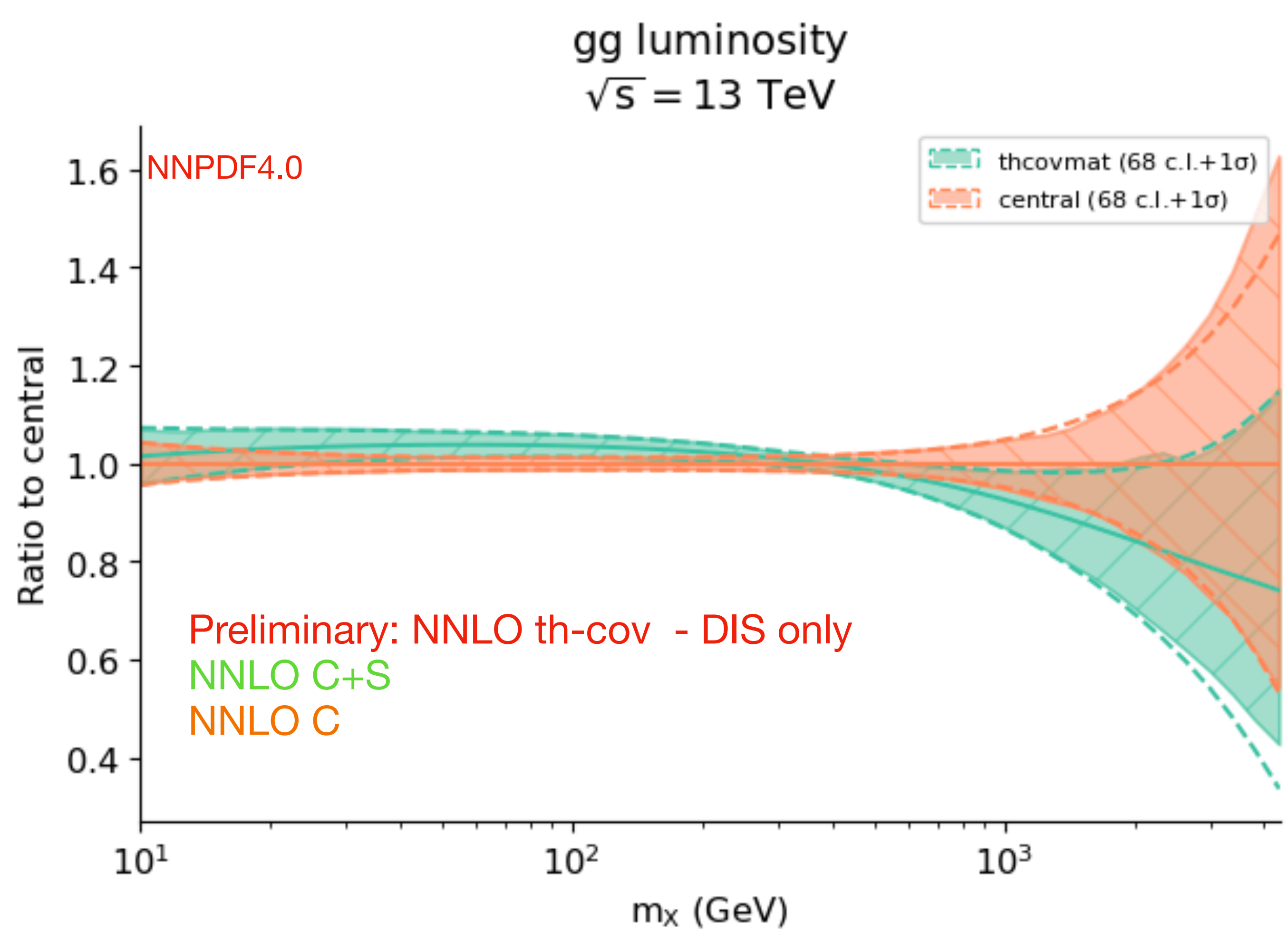


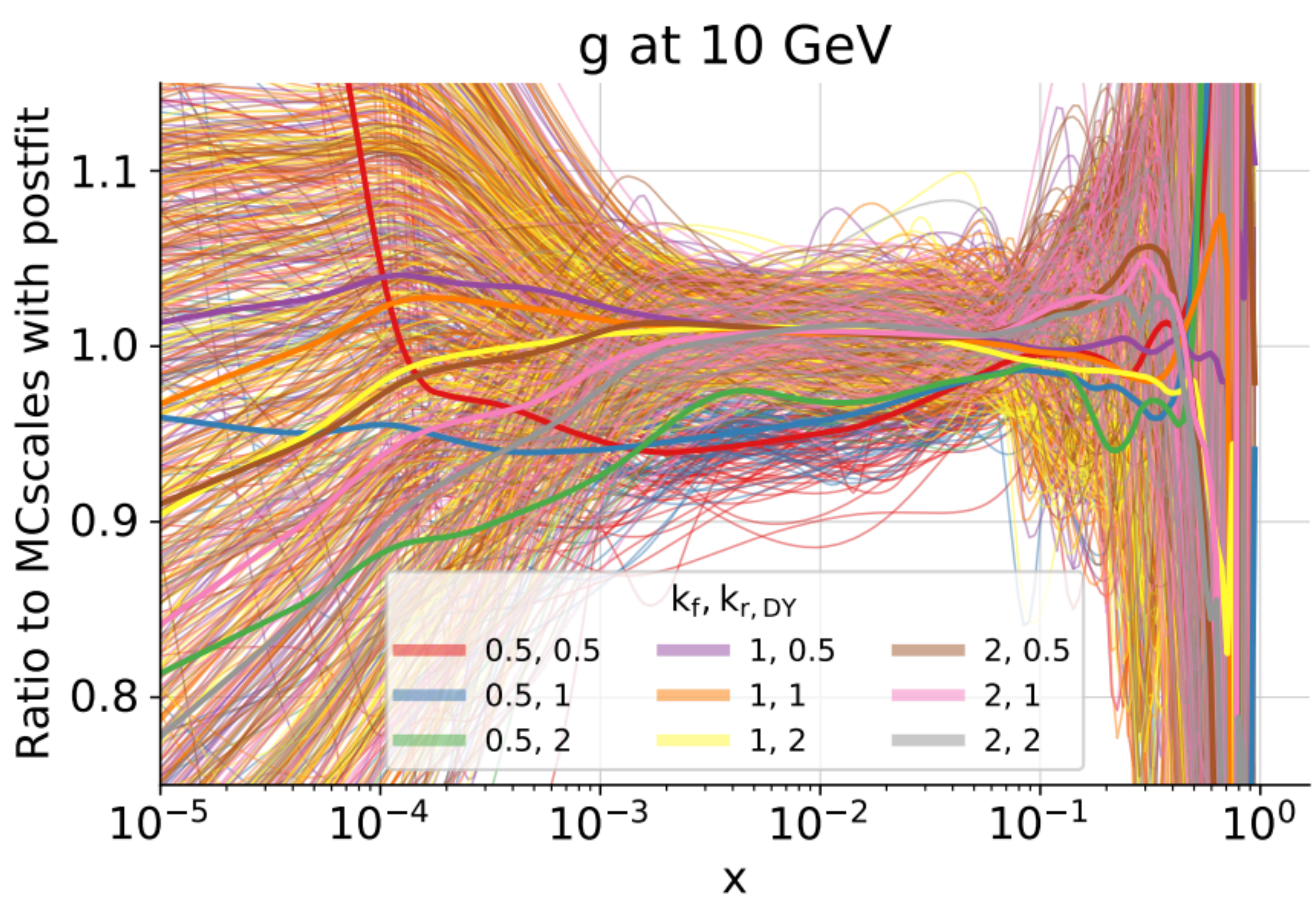



# MHOU in PDF fits

Option 2 - MCscales [Kassabov et al: 2207.07616]

Main idea: renorm. and fact. scales are free parameters of the fixed-order theory, that induce an uncertainty on theory predictions included in a PDF fit & need to be propagated

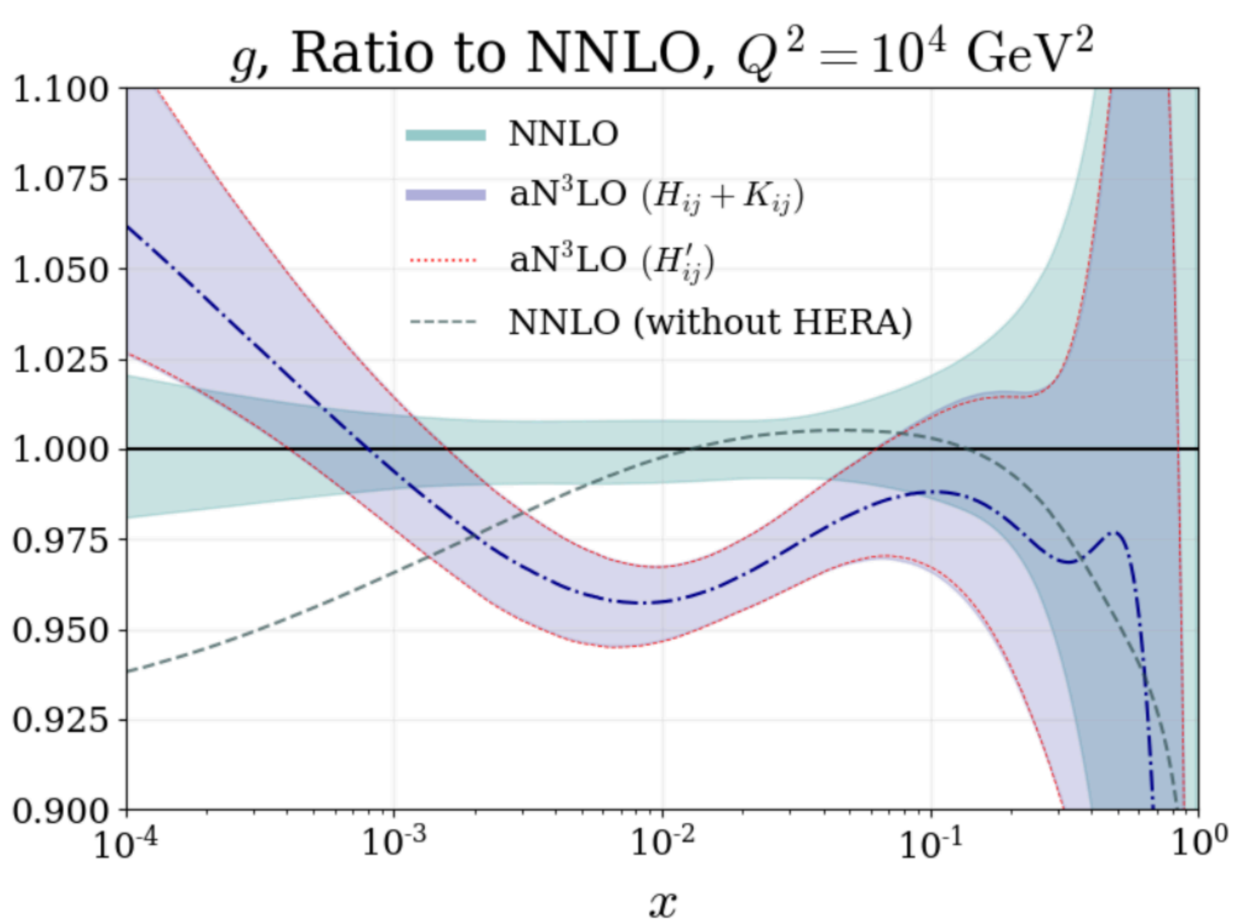
- Joint sampling of experimental uncertainty (propagated to PDF uncertainty by Monte Carlo) by specifying a suitable prior probability distribution of all possible scale choices and an a-posteriori criterion based on agreement with the data.

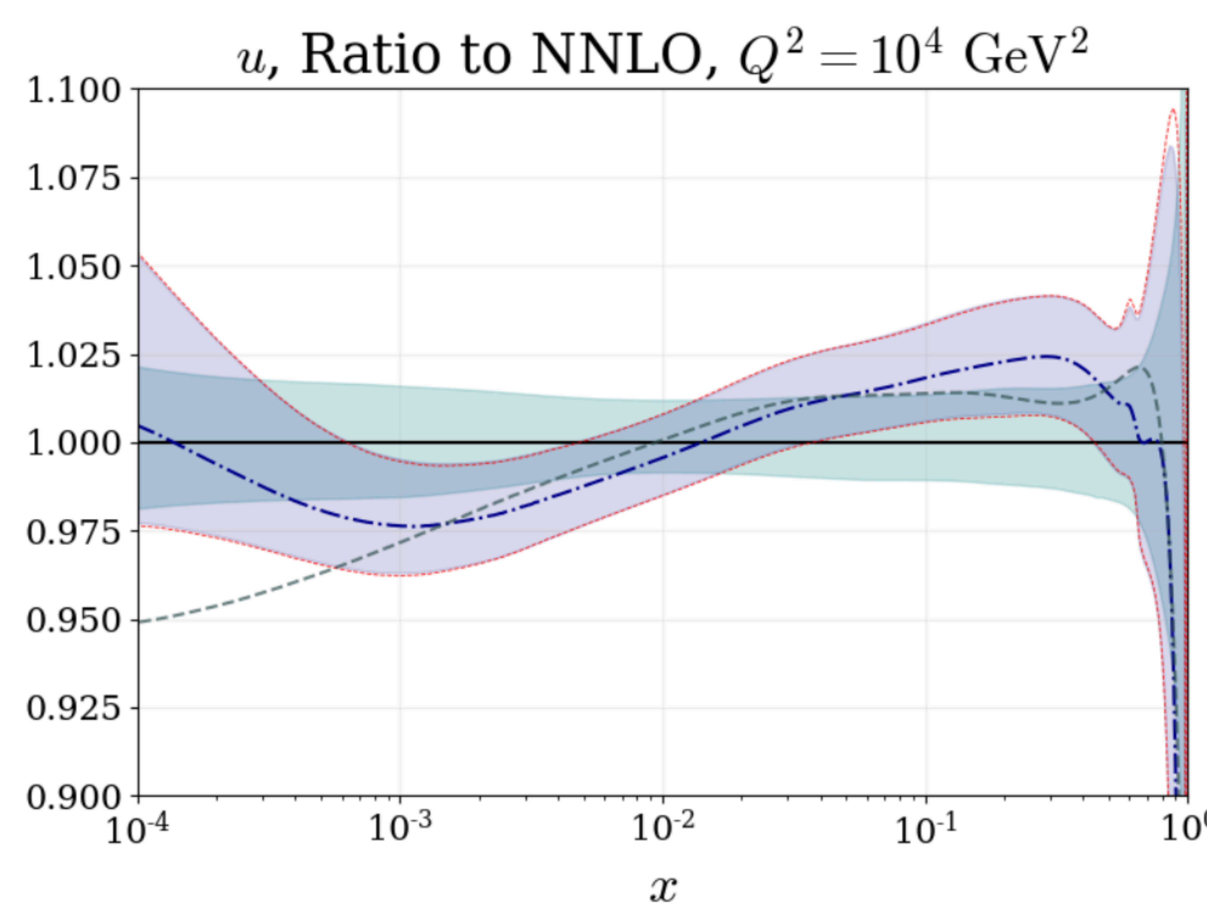


# MHOU in PDF fits

Option 3 - theory nuisance parameters [MMHT: 2207.04739]

Main idea: add MHOU as nuisance parameters and fit nuisance parameters from data. Unknown terms in N3LO theory added via a Gaussian prior and parameters fitted from the data give rise to approximated N3LO MSHT PDFs



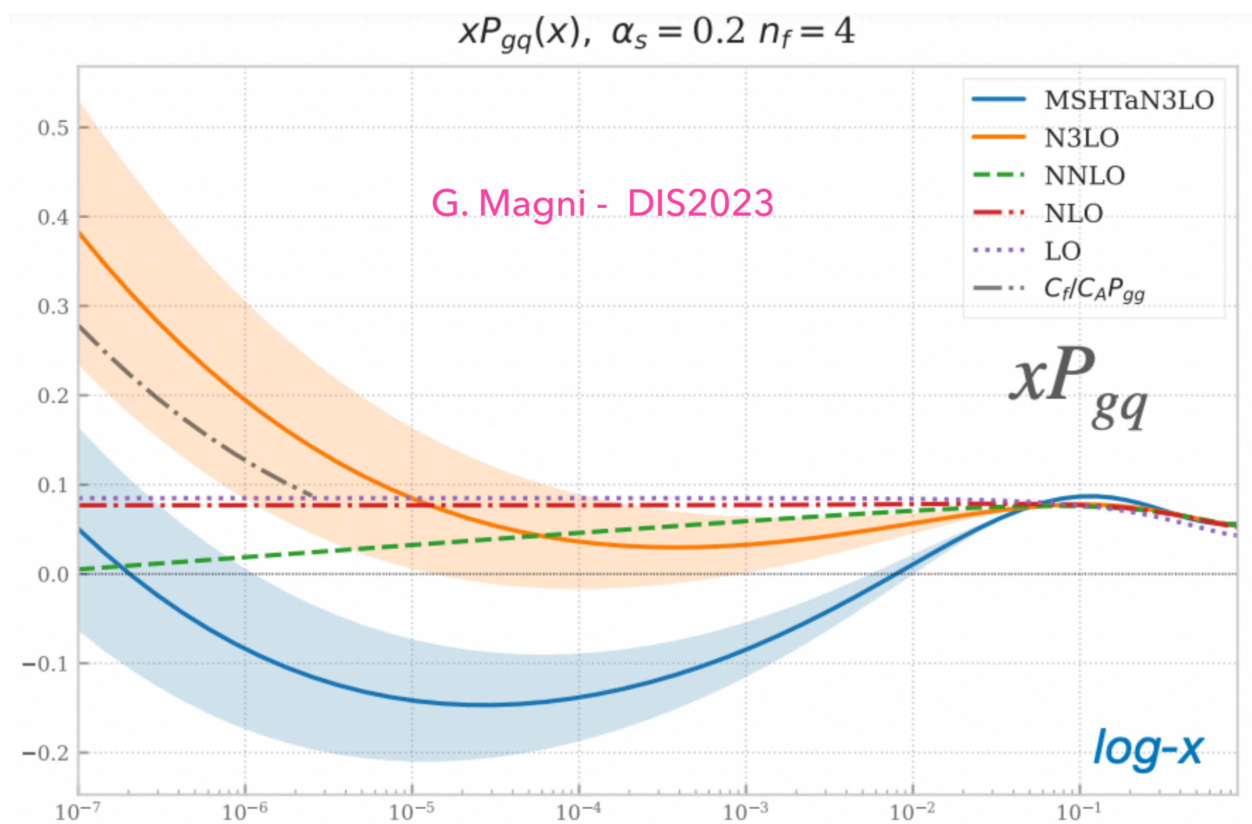



# The N3LO frontier

- MSHT & NNPDF: inclusion of available theoretical ingredients at N3LO (non-singlet splitting functions, singlet splitting function in the large nf limit, small-x limit, large-x limit, Mellin moments + DIS structure functions in the massless limit and approximate heavy flavour structure functions between known limits + hadronic N3LO K-factors)

- MSHT: MHOU and IHOU (incomplete higher order uncertainty) both added as nuisance parameters and fitted from the data

- NNPDF: MHOU added via theory covariance matrix, IHOU added as extra additional theory uncertainties computed by varying each of the possible parametrisation that interpolate the known ingredients



# Beyond fixed order

- Multi-scale processes: log(Qi/Qj) = L arise, which may spoil perturbative expansion
- If ($\alpha_S$ * L) ~ O(1) fixed order perturbative QCD is no longer justified
- Resummation effectively rearranges perturbative series

fixed order

$$\frac{\sigma}{\sigma_0} = 1 \quad \text{LO}$$
$$+ c_1\alpha \quad \text{NLO}$$
$$+ c_2\alpha^2 \quad \text{NNLO}$$
$$+ \ldots$$

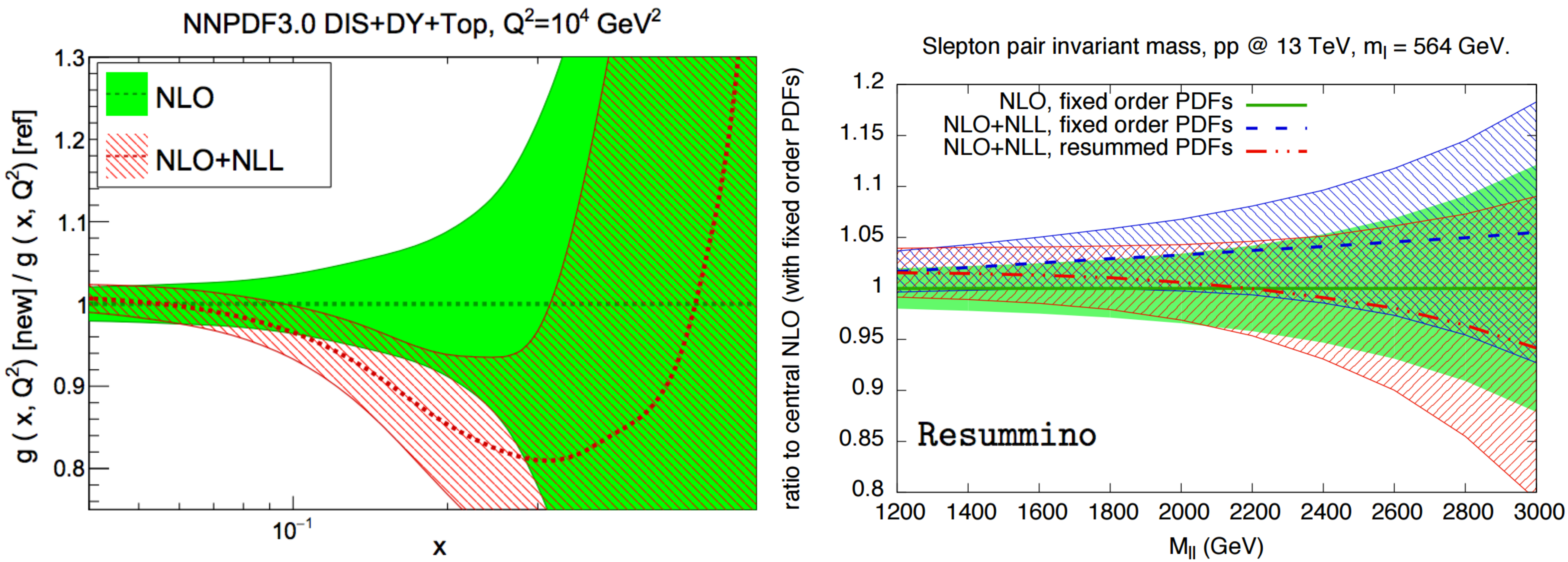
all order (L = some large logarithm)

$$\ln\frac{\sigma}{\sigma_0} = \alpha^n L^{n+1} \quad \text{LL}$$
$$+ \alpha^n L^n \quad \text{NLL}$$
$$+ \alpha^n L^{n-1} \quad \text{NNLL}$$
$$+ \ldots$$

- Various kinds of logs:

L = log (1-x) threshold (soft-gluon) resummation
L = log (1/x) high-energy (small-x) resummation
L = log (pT/M) transverse momentum resummation

# Threshold resummation

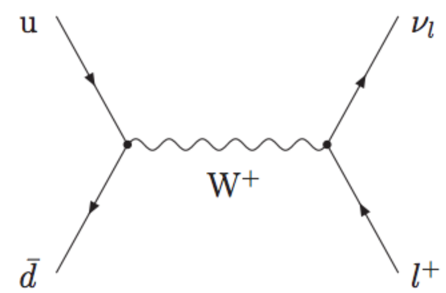


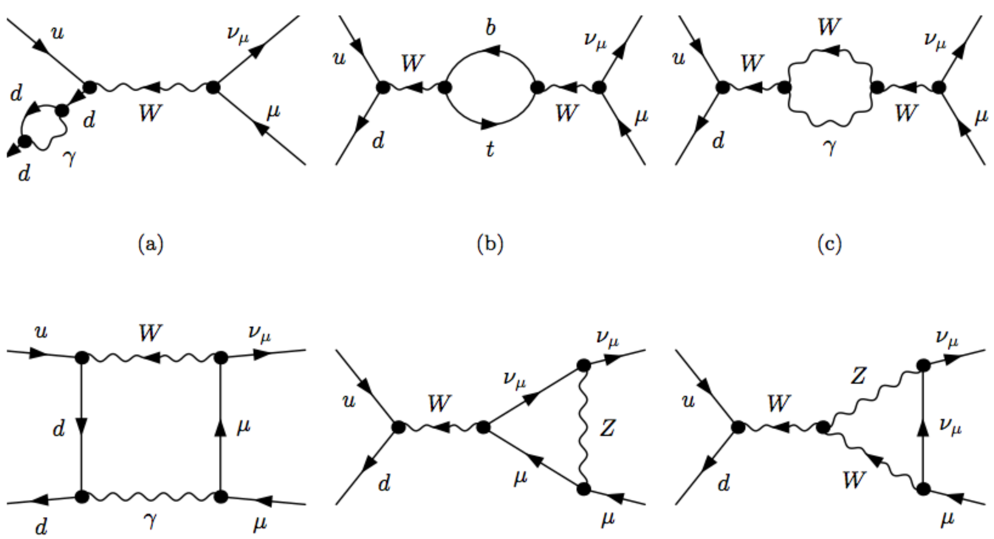

Bonvini et al, JHEP 1509 (2015) 191

- In the MSbar scheme PDF evolution does not contain large-x logs and the effect of resummation can be included in resummed partonic cross sections
- Threshold-resummed PDFs will be suppressed as compared to fixed-order PDFs
- Mostly due to enhancement of NLO+NLL partonic xsecs used in the fit of DIS structure functions and DY distributions
- Phenomenologically relevant for new physics processes [Beenakker et al. EPJC76 (2016)2, 53]

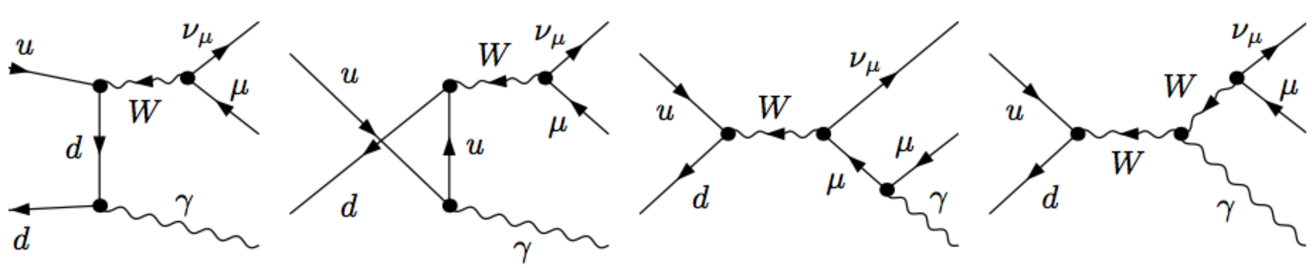
# Electroweak corrections

- Given that $\alpha(M_Z) \sim \alpha_S(M_Z)/10 \Longrightarrow$ NLO EW corrections ~ NNLO QCD corrections

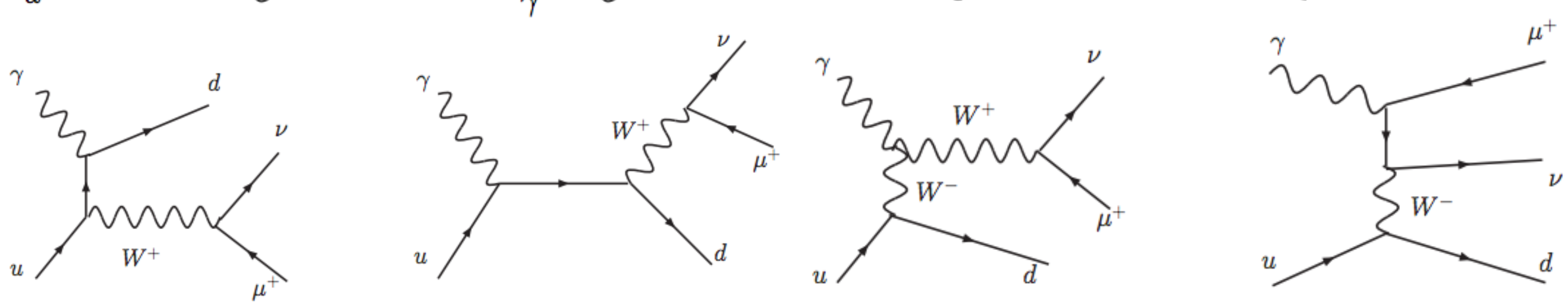



**Virtual EW corrections**



**Real EW corrections - quark initiated**



**Real EW corrections - photon initiated**

# Electroweak corrections

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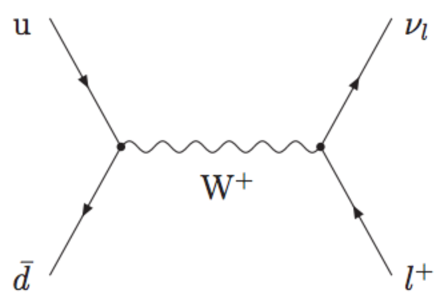
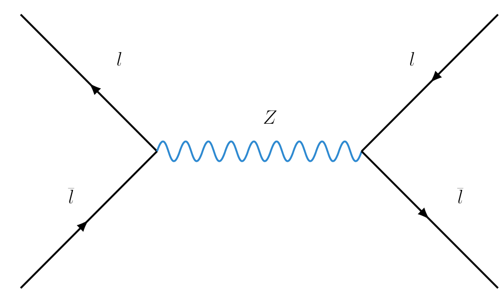
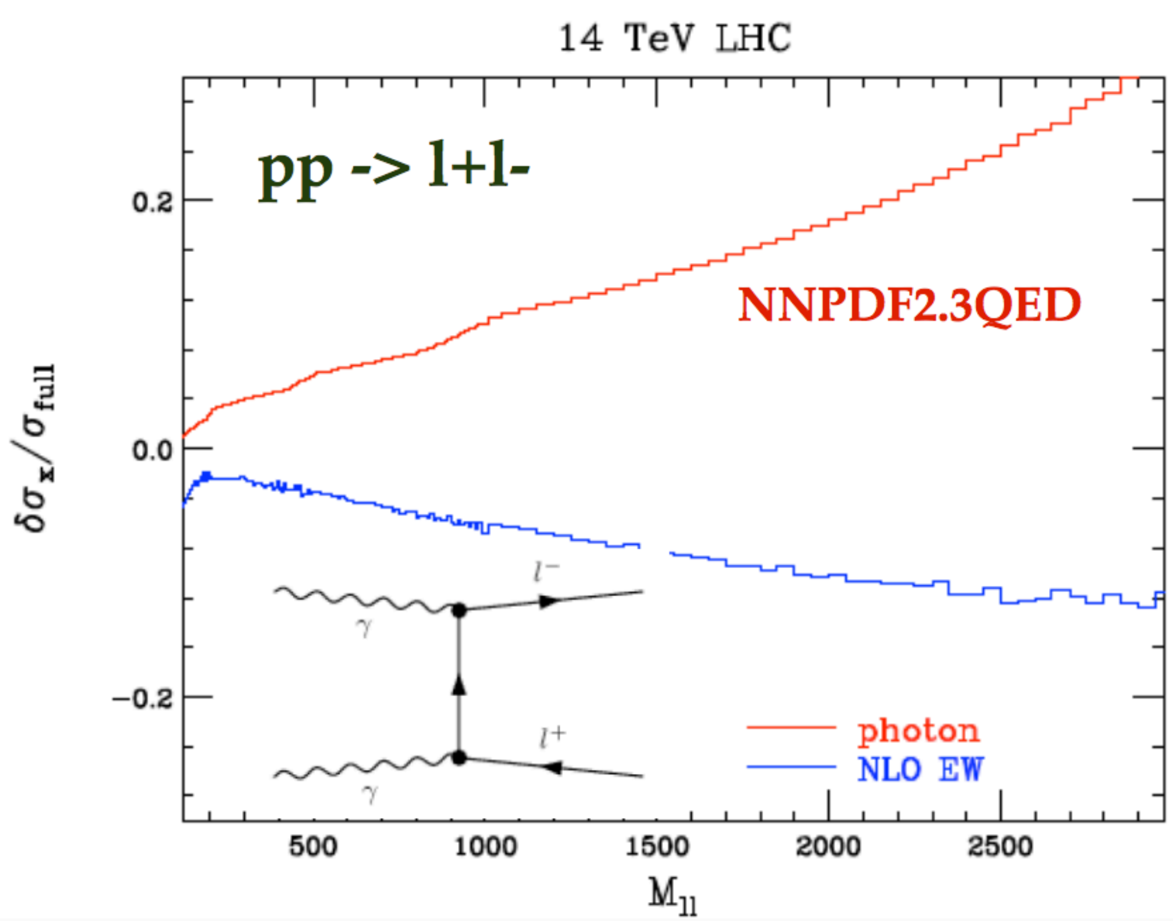



- NLO virtual EW corrections become large in the large $p_T$ region of lepton but partially compensated by photon-initiated real corrections




Boughezal et al Phys.Rev. D89 (2014)3, 034030

# Photon-modified DGLAP

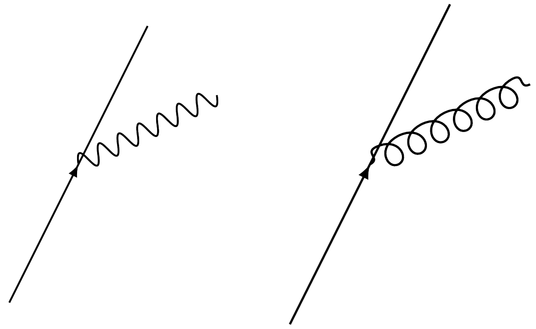
- How are PDFs modified by inclusion of initial photon PDF?

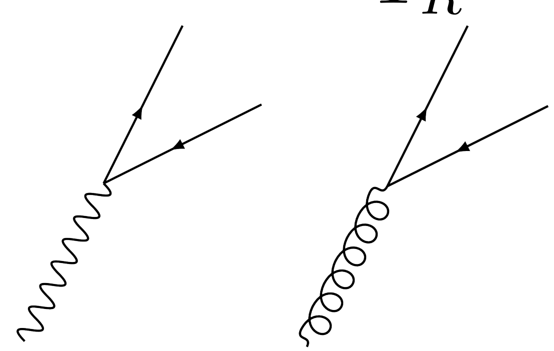
$$\boxed{\begin{aligned}
Q^2\frac{\partial}{\partial Q^2}g(x,Q^2) &= \sum_{q,\bar{q},g} P_{ga}(x,\alpha_s(Q^2))\otimes f_a(x,Q^2) + P_{g\gamma}(x,\alpha_s(Q^2))\otimes\gamma(x,Q^2),\\
Q^2\frac{\partial}{\partial Q^2}q(x,Q^2) &= \sum_{q,\bar{q},g} P_{qa}(x,\alpha_s(Q^2))\otimes f_a(x,Q^2) + P_{q\gamma}(x,\alpha_s(Q^2))\otimes\gamma(x,Q^2),\\
Q^2\frac{\partial}{\partial Q^2}\gamma(x,Q^2) &= P_{\gamma\gamma}\otimes\gamma(x,Q^2) + \sum_{q,\bar{q},g} P_{\gamma a}(x,\alpha_s(Q^2))\otimes f_a(x,Q^2).
\end{aligned}}$$

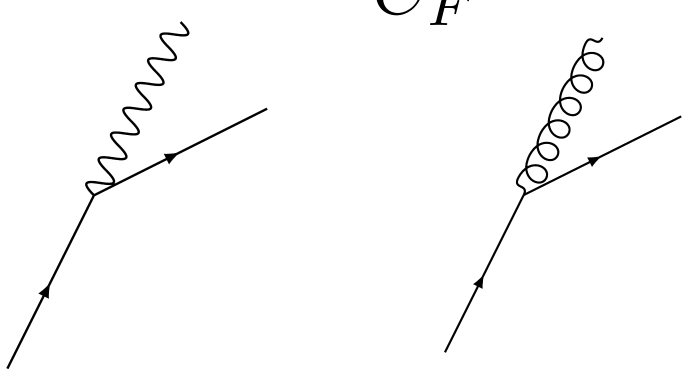
- DGLAP splitting functions expanded in powers of $\alpha_s$ and $\boldsymbol{\alpha}$

$$P_{ij} = \sum_{m,n}\left(\frac{\alpha_S}{2\pi}\right)^m\left(\frac{\alpha}{2\pi}\right)^n P_{ij}^{(m,n)}$$

$$P_{qq}^{(0,1)} = \frac{e_q^2}{C_F}P_{qq}^{(1,0)} \qquad P_{q\gamma}^{(0,1)} = \frac{e_q^2}{T_R}P_{qg}^{(1,0)} \qquad P_{\gamma q}^{(0,1)} = \frac{e_q^2}{C_F}P_{gq}^{(1,0)}$$

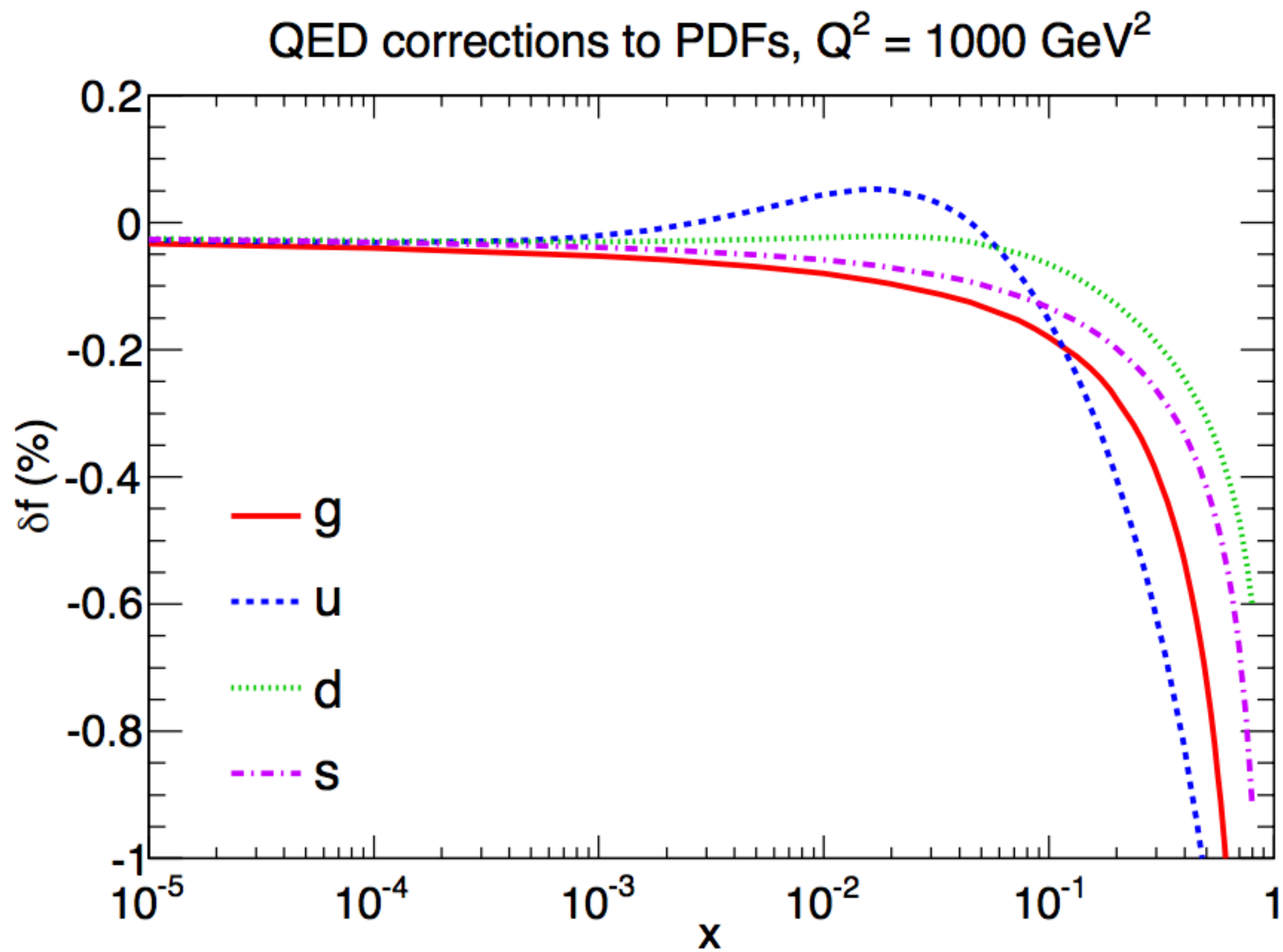






# Photon-modified DGLAP

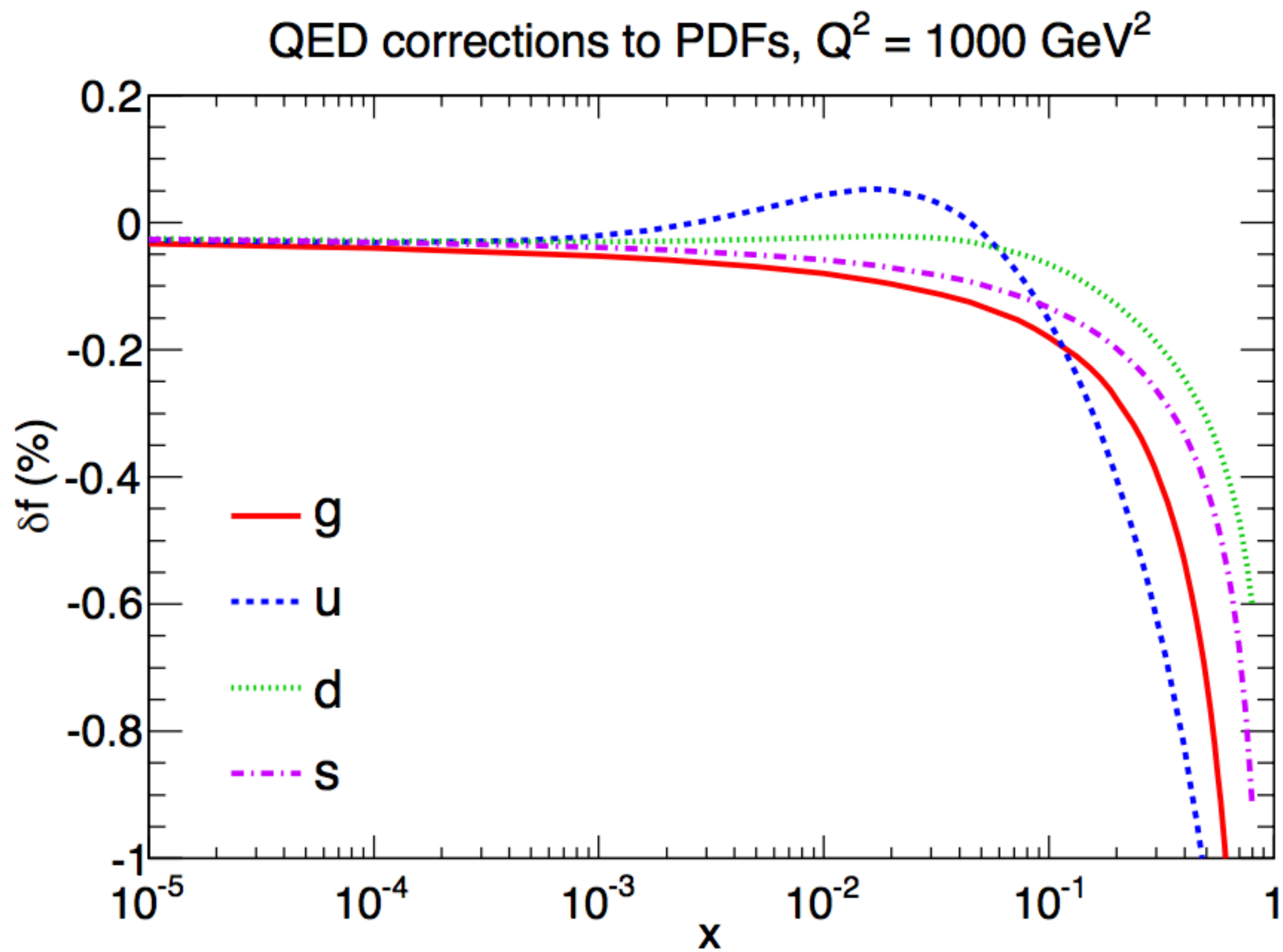
- Quark and gluon PDFs change up to 1% at large x




Ball et al, Nucl.Phys. B877 (2013) 290-320

# Photon-modified DGLAP

- Quark and gluon PDFs change up to 1% at large x
- How do we determine the photon PDF?
- Two ways in the next slides: from data or from theory
- In the best possible world: theory input and data input together

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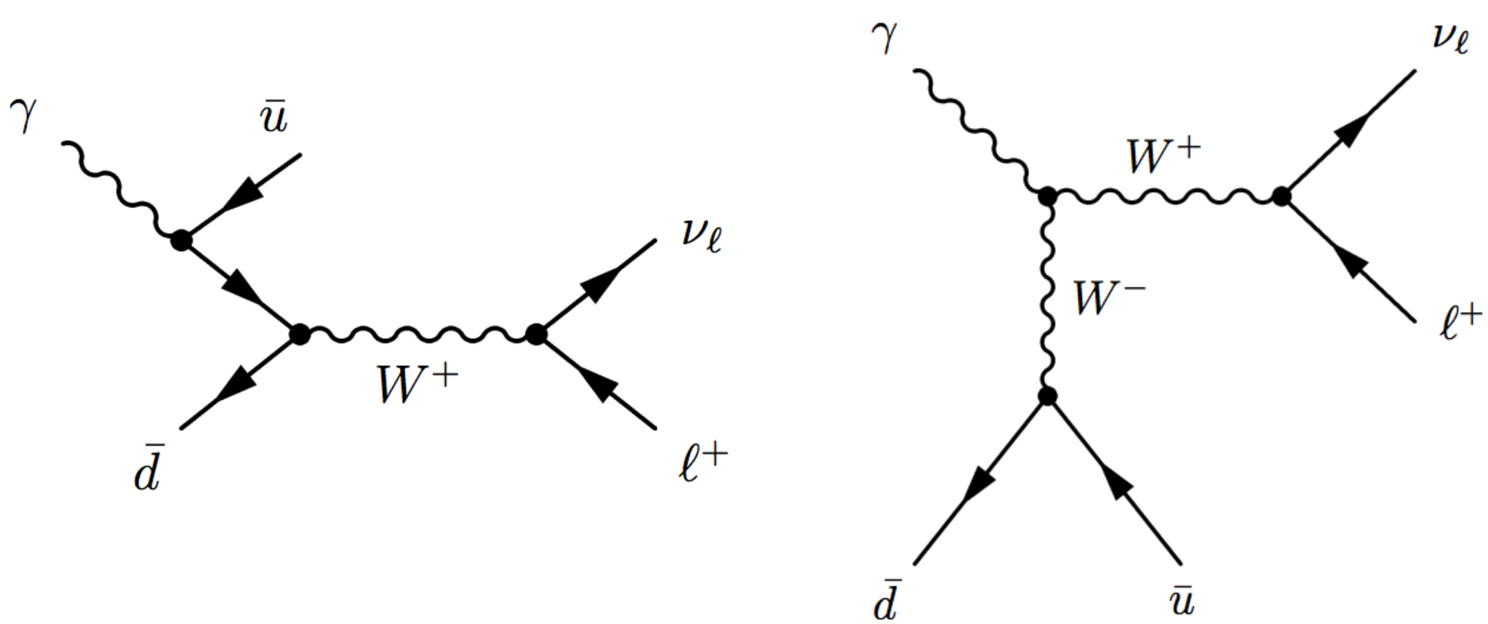
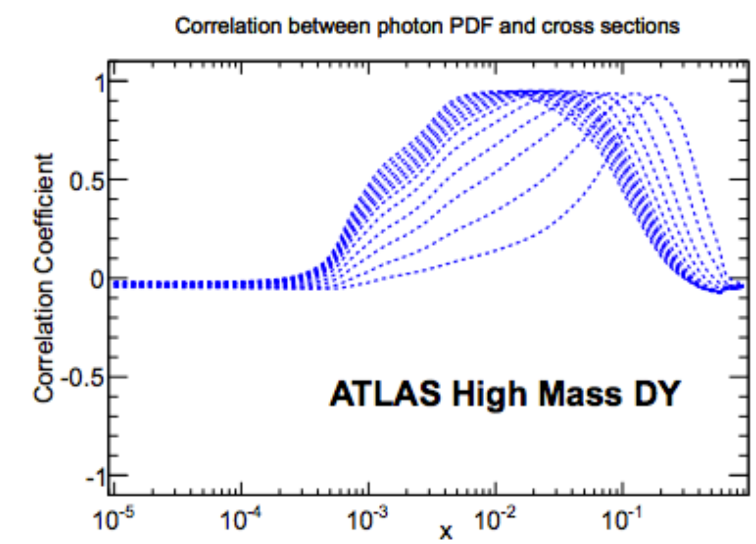
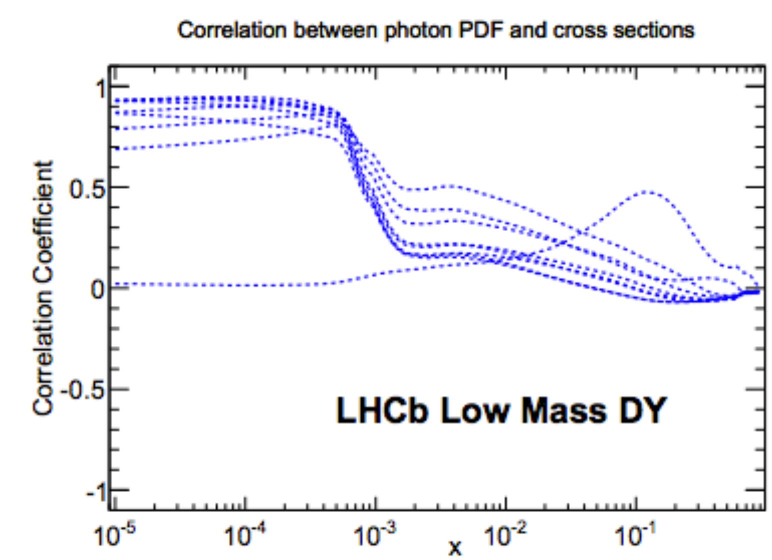
# Photon PDFs

- Largest correlations between photon PDFs and pp cross sections are for Drell-Yan processes, but also for top pair production and VV production

$$Q = 100\,\mathrm{GeV}$$



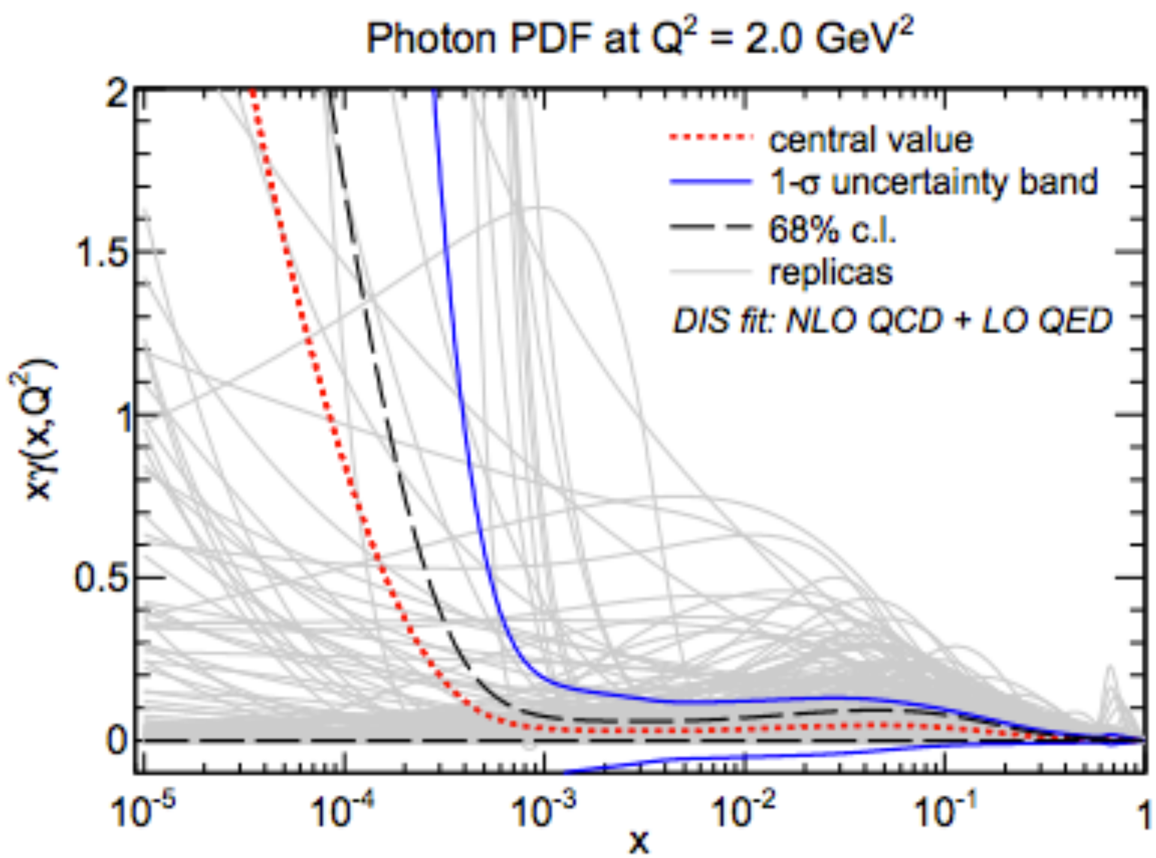



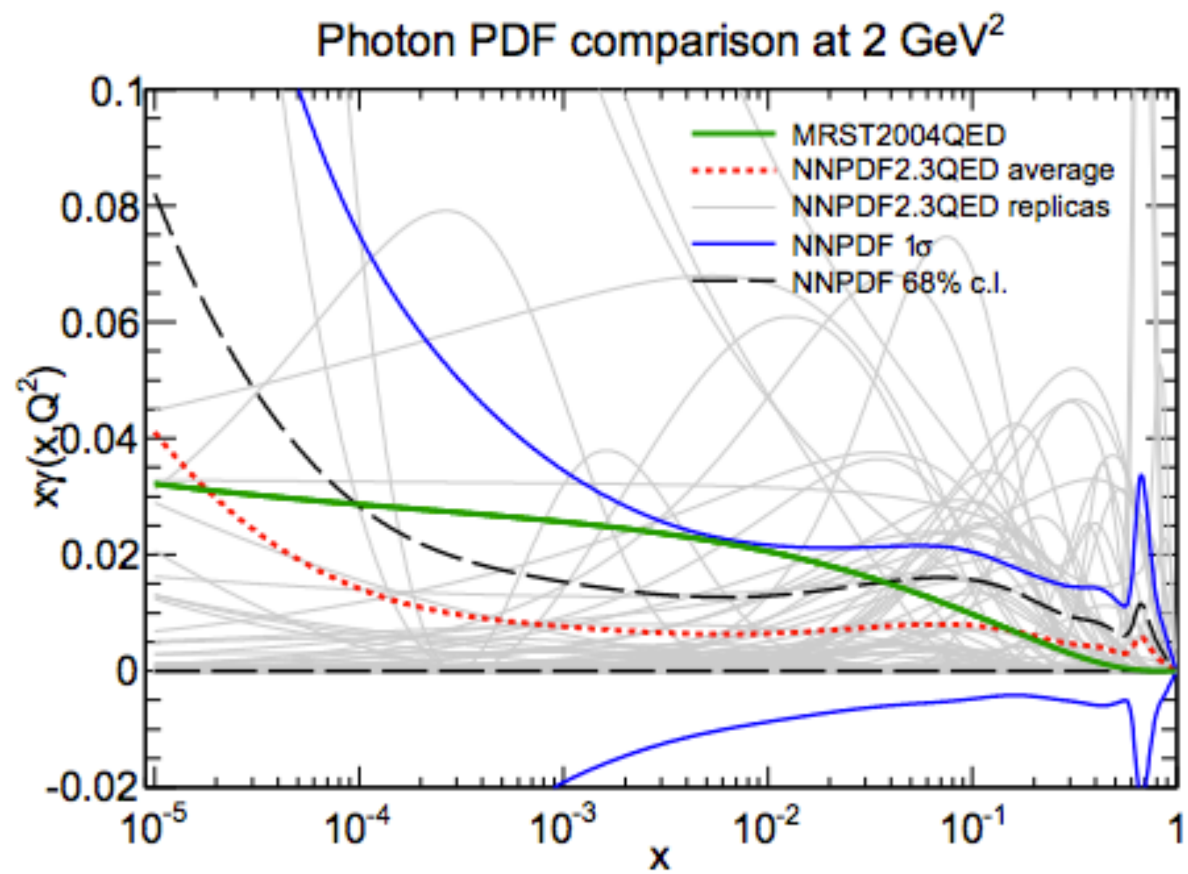

Photon-induced Drell-Yan

Ball et al, Nucl.Phys. B877 (2013) 290-320

# Photon PDFs

Data-driven knowledge

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- Data-driven approach associated with a large uncertainty on photon PDF
- Theory breakthrough: LUX PDF [Manohar, Nason, Salam, Zanderighi,1607.04266]

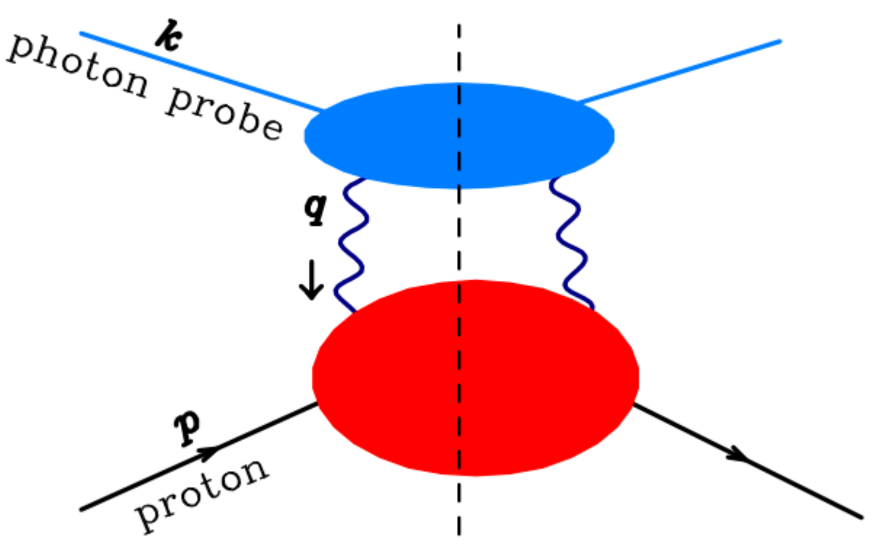
# Photon PDFs

- QED is perturbative down to low scales $\Longrightarrow$ The photon must be computable if the input substructure is known
- Manohar et al: write the cross section for a chosen BSM process, e.g. production of heavy supersymmetric lepton L in ep collision (Drees, Zeppenfeld 1989)

$$\sigma = \frac{1}{4p\cdot k}\int \frac{d^4q}{(2\pi)^4 q^4} e^2_{\rm ph}(q^2)\left[4\pi W_{\mu\nu}(p,q)\, L^{\mu\nu}(k,q)\right]\ 2\pi\delta((k-q)^2 - M^2)$$

$$\sigma = c_0 \sum_a \int_x^1 \frac{dz}{z}\,\hat\sigma_a(z,\mu^2)\,\frac{M^2}{zs} f_{a/p}\left(\frac{M^2}{zs},\mu^2\right)$$

$$l(k) + p(p) \to L(k') + X$$




$$\begin{aligned}\sigma = \frac{c_0}{2\pi}\int_x^{1-\frac{2xm_p}{M}} \frac{dz}{z}\int_{Q^2_{\rm min}}^{Q^2_{\rm max}} \frac{dQ^2}{Q^2}\alpha^2_{\rm ph}(-Q^2)\Bigg[\Bigg(2-2z+z^2 \\ + \frac{2x^2m_p^2}{Q^2} + \frac{z^2Q^2}{M^2} - \frac{2zQ^2}{M^2} - \frac{2x^2Q^2m_p^2}{M^4}\Bigg) F_2(x/z,Q^2) \\ + \left(-z^2 - \frac{z^2Q^2}{2M^2} + \frac{z^2Q^4}{2M^4}\right) F_L(x/z,Q^2)\Bigg], \quad (3)\end{aligned}$$

Manohar et al 1607.04266

<u>Theory-driven knowledge</u>

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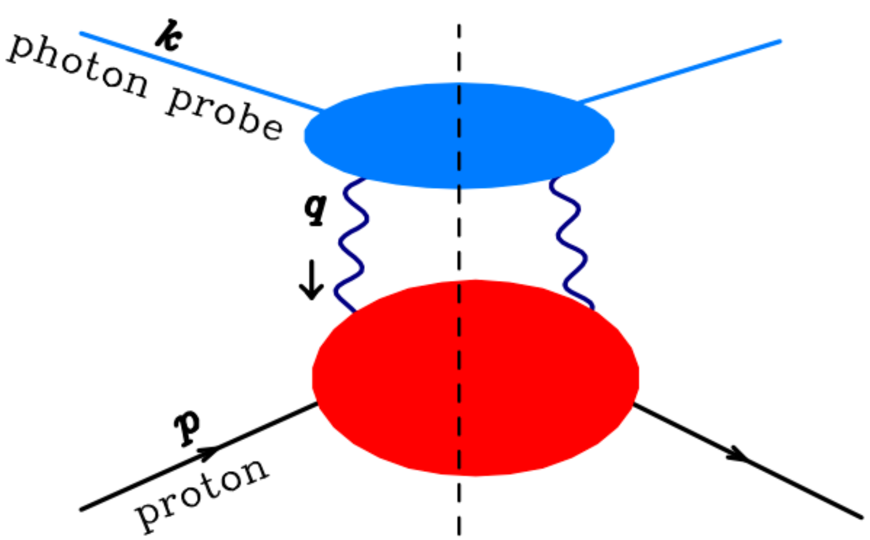
- Manohar et al: write the cross section for a chosen BSM process, e.g. production of heavy supersymmetric lepton L in ep collision (Drees, Zeppenfeld 1989)
- Equate the two expressions and find analytically the PDF of the photon

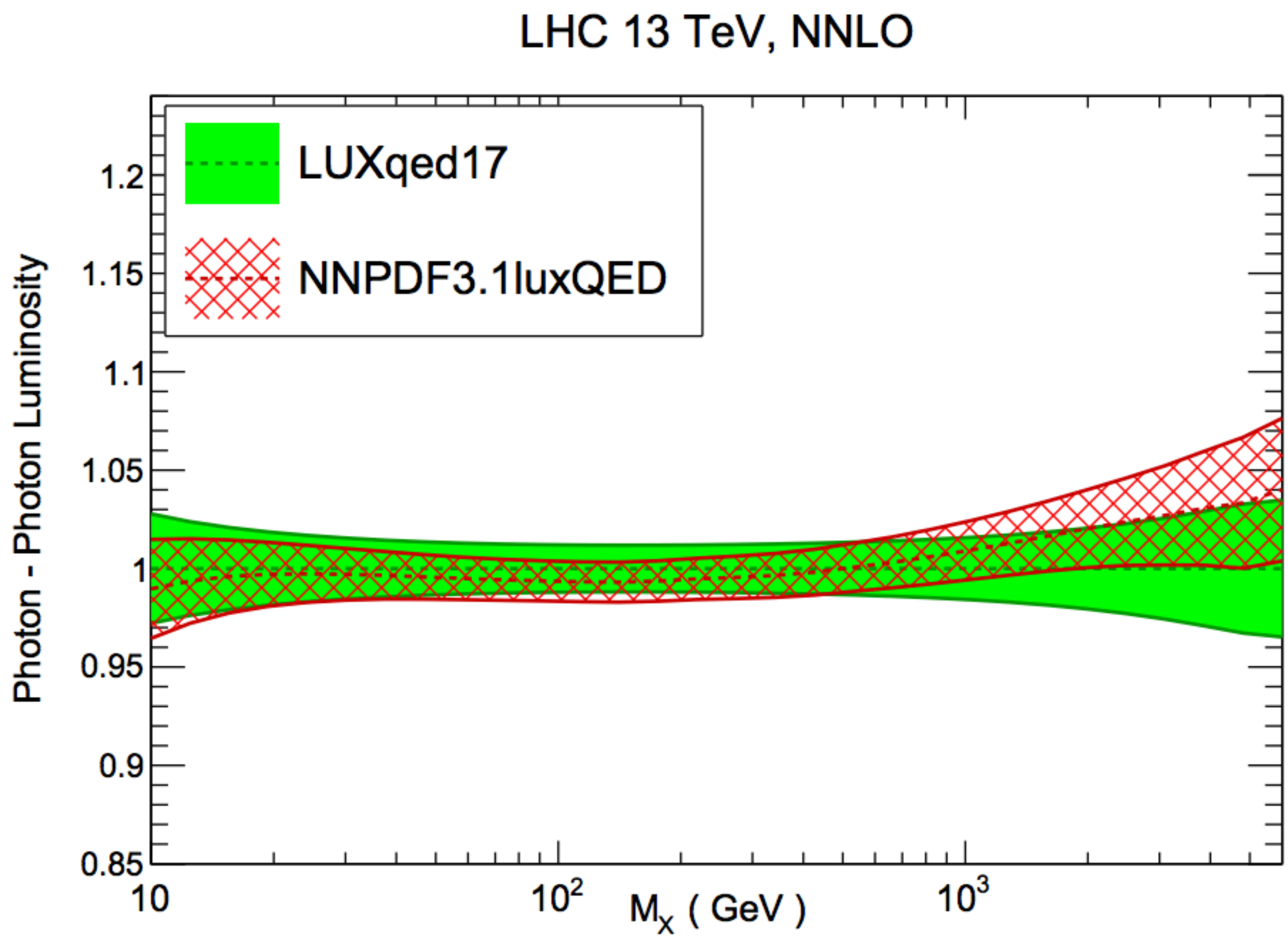
⇒ PDFs expressed in terms of the structure functions integrated over all scales, including elastic form factors (in the x →1 region)




$$x f_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)}\int_x^1 \frac{dz}{z}\left\{\int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2}\alpha^2(Q^2)\left[\left(z p_{\gamma q}(z) + \frac{2x^2 m_p^2}{Q^2}\right)F_2(x/z,Q^2) - z^2 F_L\left(\frac{x}{z},Q^2\right)\right] - \alpha^2(\mu^2)\, z^2 F_2\left(\frac{x}{z},\mu^2\right)\right\},$$

<u>Theory-driven knowledge</u>

# Photon PDFs




Bertone et al, 1712.07053

<u>(Data+Theory)-driven knowledge</u>

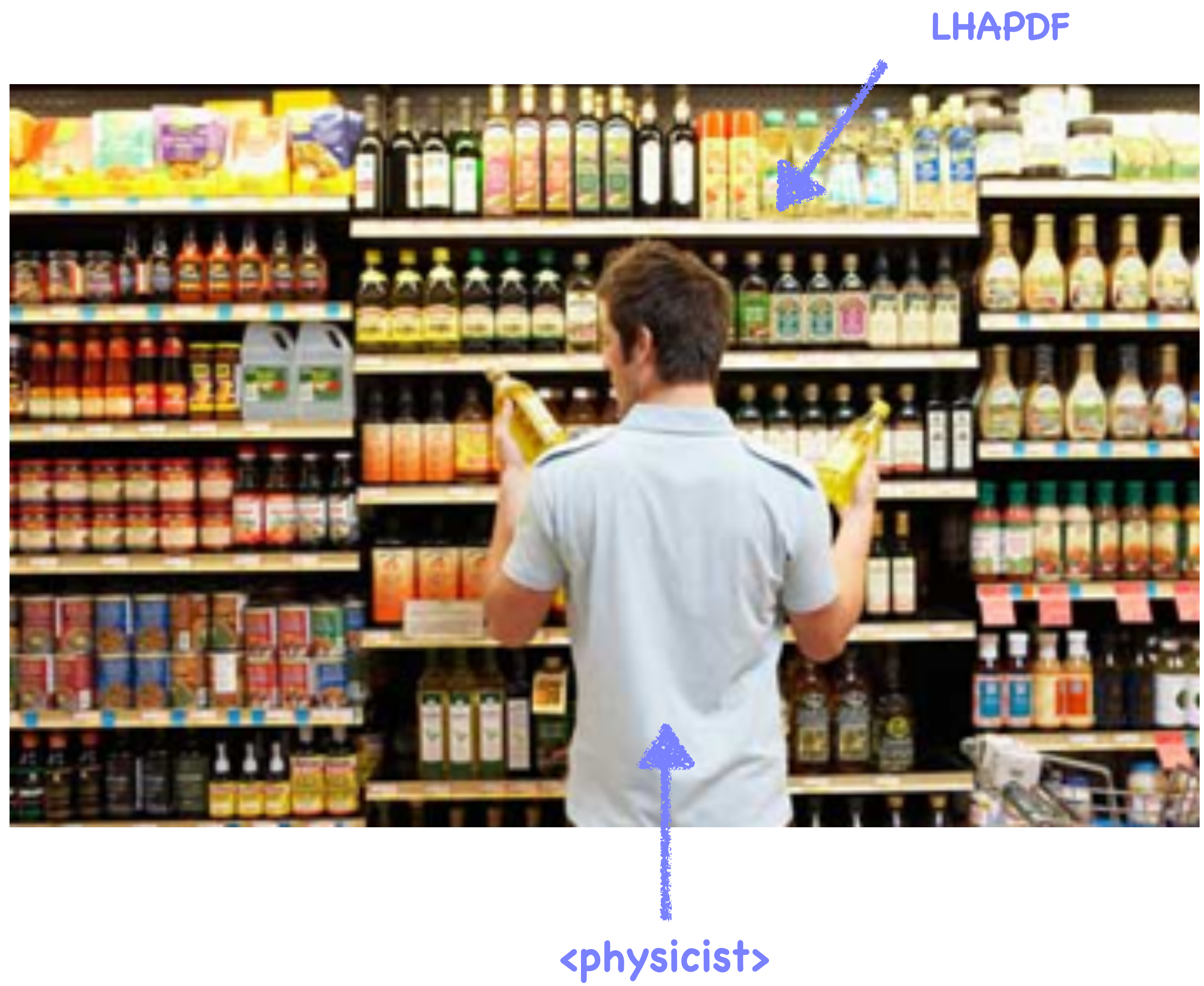
# State-of-the-art PDFs

# The choice of PDFs matters

- What does PDF uncertainty include? How reliable it is?

- How do we interpret the difference predictions using different PDF sets?

- Shall we just pick a set out of the PDFs “supermarket” shelf or take the envelope of ALL predictions?



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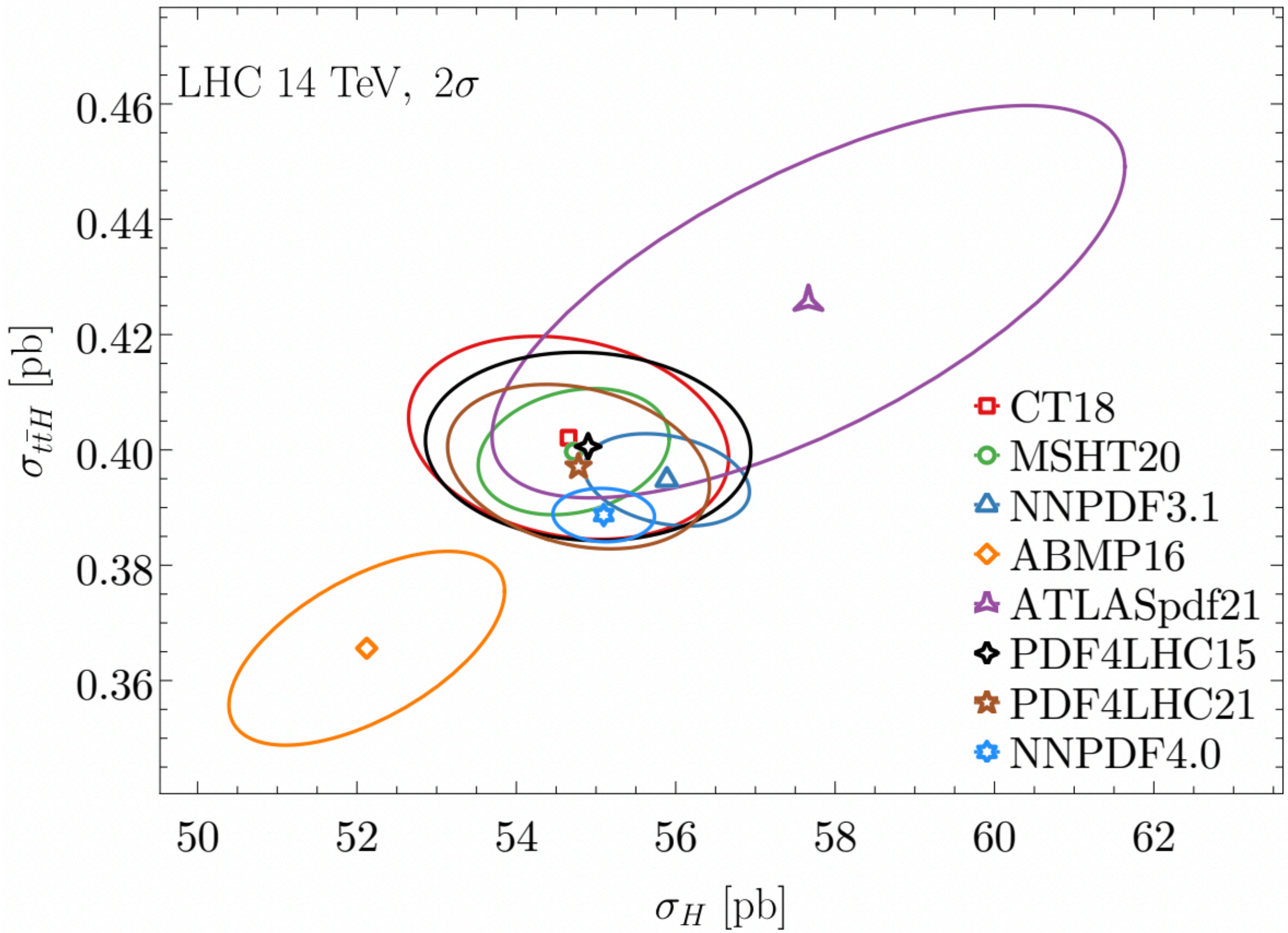


Snowmass 2022 white paper, arXiv: 2203.13923

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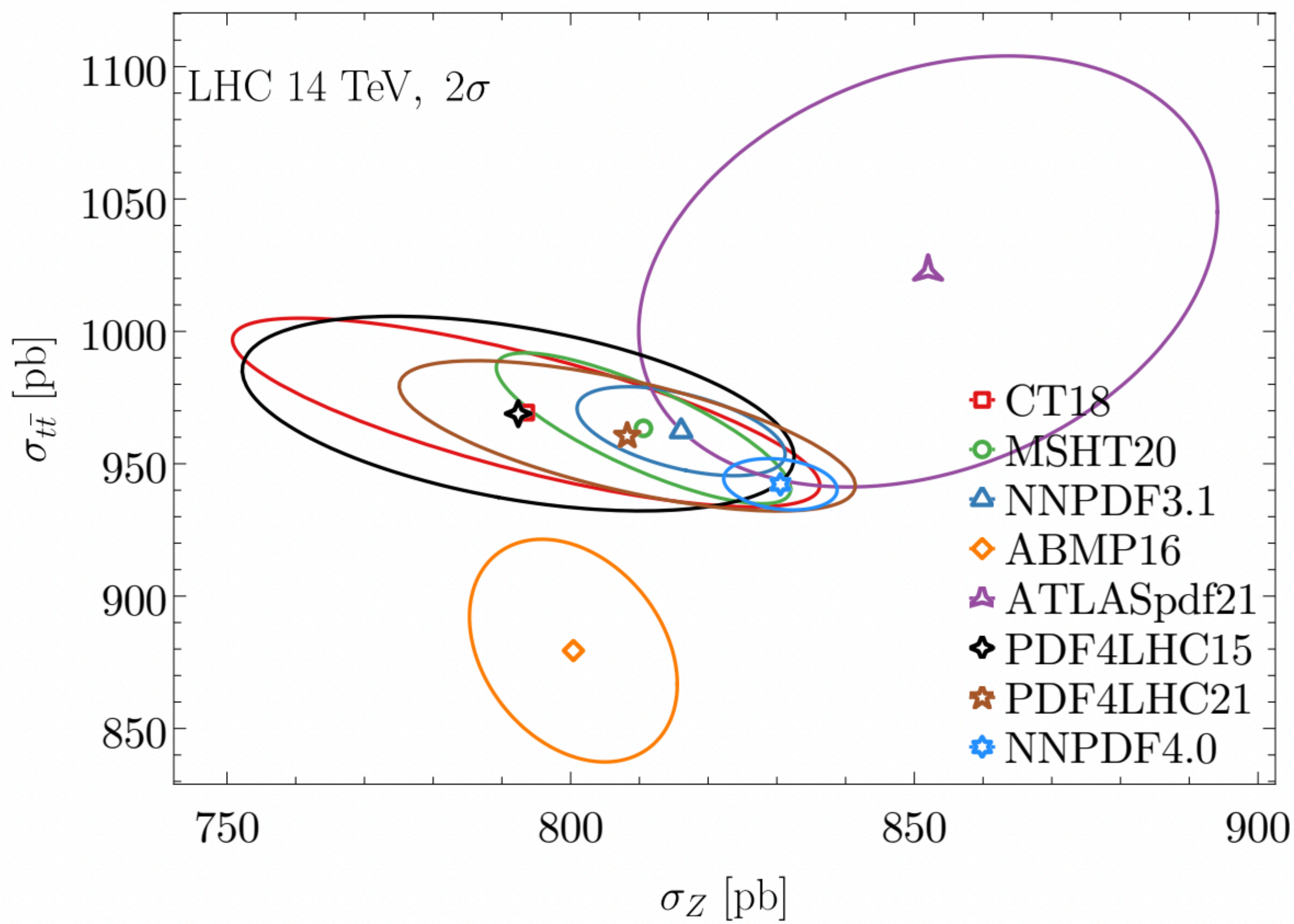


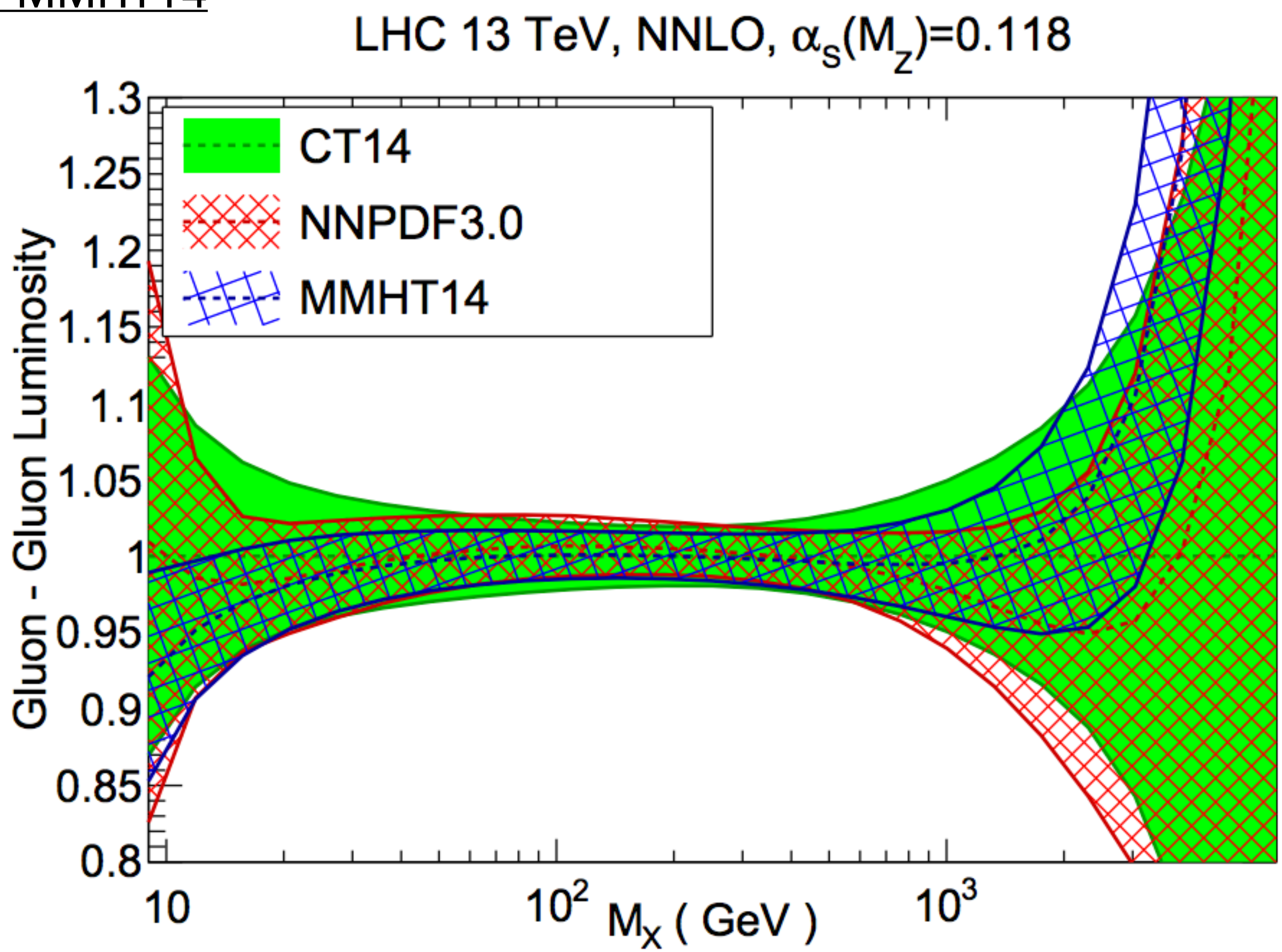

Snowmass 2022 white paper, arXiv: 2203.13923

# The players

| June 2022 | NNPDF4.0 | MSHT20 | CT18 | ABMP16 | CJ15 | JAM |
|---|---|---|---|---|---|---|
| Fixed Target DIS | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ |
| HERA I+II | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ |
| HERA jets | ✔ | ✔ | ✘ | ✘ | ✘ | ✘ |
| Fixed Target DY | ✔ | ✔ | ✔ | ✔ | ✔ | ✔ |
| Compass SIDIS | ✘ | ✘ | ✘ | ✘ | ✔ | ✔ |
| Tevatron W,Z | ✔ | ✔ | ✔ | ✔ | ✔ | ✘ |
| Tevatron jets | ✔ | ✔ | ✔ | ✘ | ✘ | ✘ |
| LHC jets | ✔ | ✔ | ✔ | ✘ | ✘ | ✘ |
| LHC vector boson | ✔ | ✔ | ✔ | ✔ | ✘ | ✘ |
| LHC top | ✔ | ✔ | ✔ | ✔ | ✘ | ✘ |
| Stat. treatment | Monte Carlo | Hessian $\Delta\chi^2$ dynamical | Hessian $\Delta\chi^2$ dynamical | Hessian $\Delta\chi^2=1$ | Hessian $\Delta\chi^2=1,10$ | Monte Carlo Baysian |
| Parametrization | Neural Networks | Polynomial (Chebyshev ) | Polynomial (Bernstein) | Polynomial | Polynomial | Polynomial (50 pars) |
| HQ scheme | FONLL | TR' | ACOT-$\chi$ | FFN (+BMST) | ACOT | ACOT |
| Order | NNLO | NNLO | NNLO | NNLO | NLO | NLO |

# Gluon luminosity

NNPDF3.0 / CT14 / MMHT14

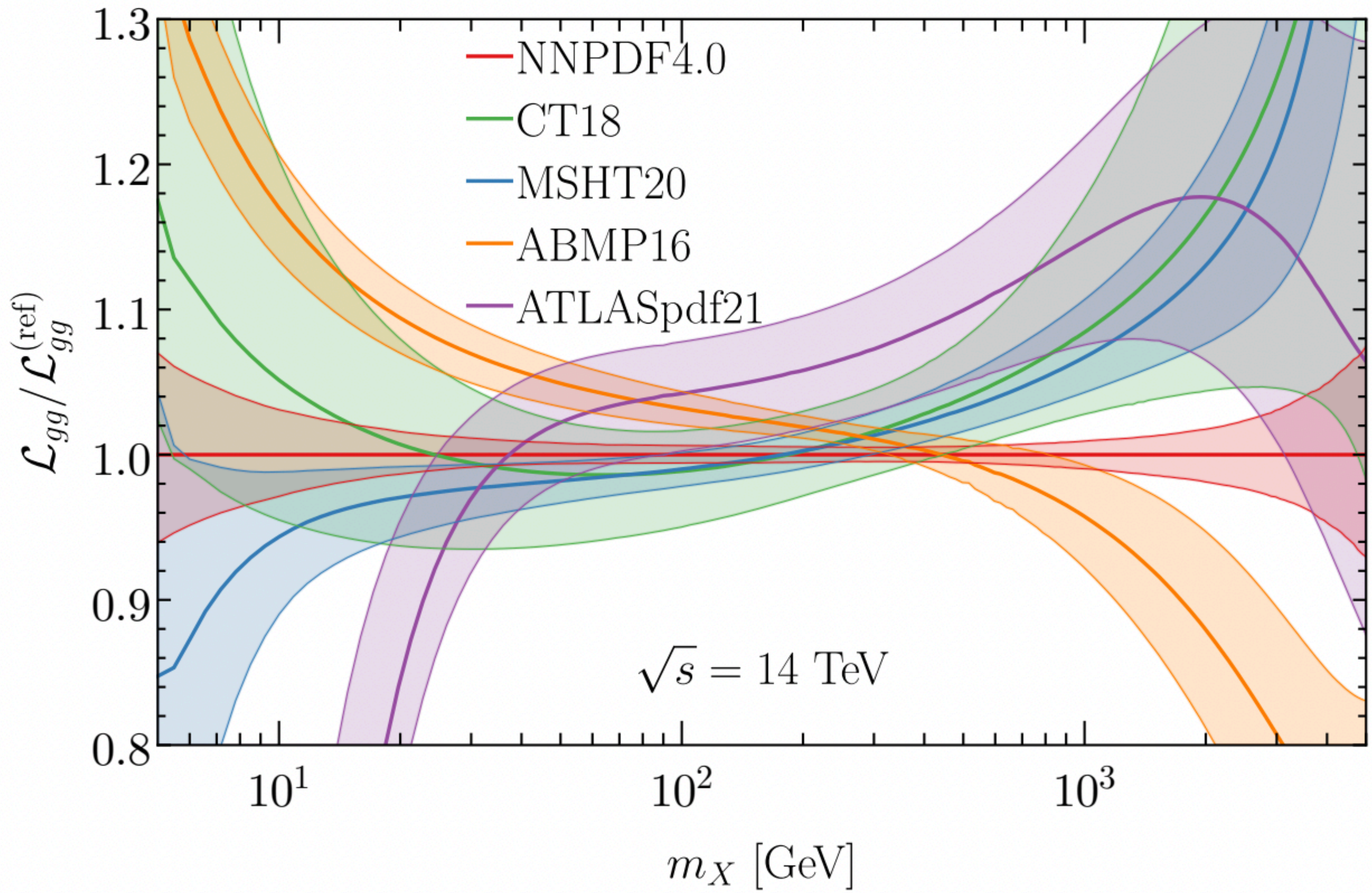



(2016)

J. Butterworth et al, J.Phys. G43 (2016) 023001

# Gluon luminosity

NNPDF4.0/ CT18/MSHT20/ABMP16/ATLASpdf21

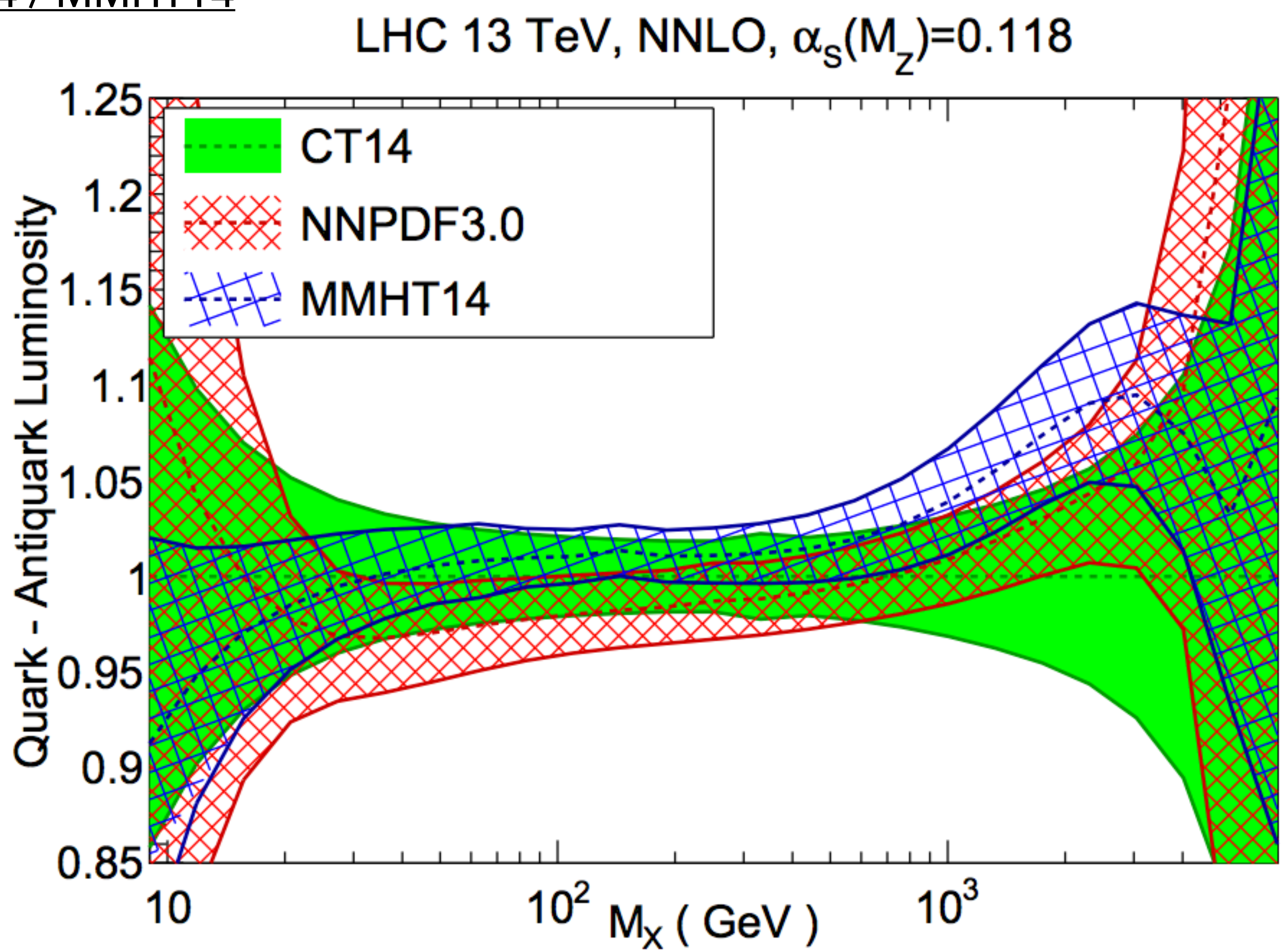



(2022)

Snowmass 2022 white paper, arXiv: 2203.13923

# Quark-Antiquark luminosity

NNPDF3.0 / CT14 / MMHT14

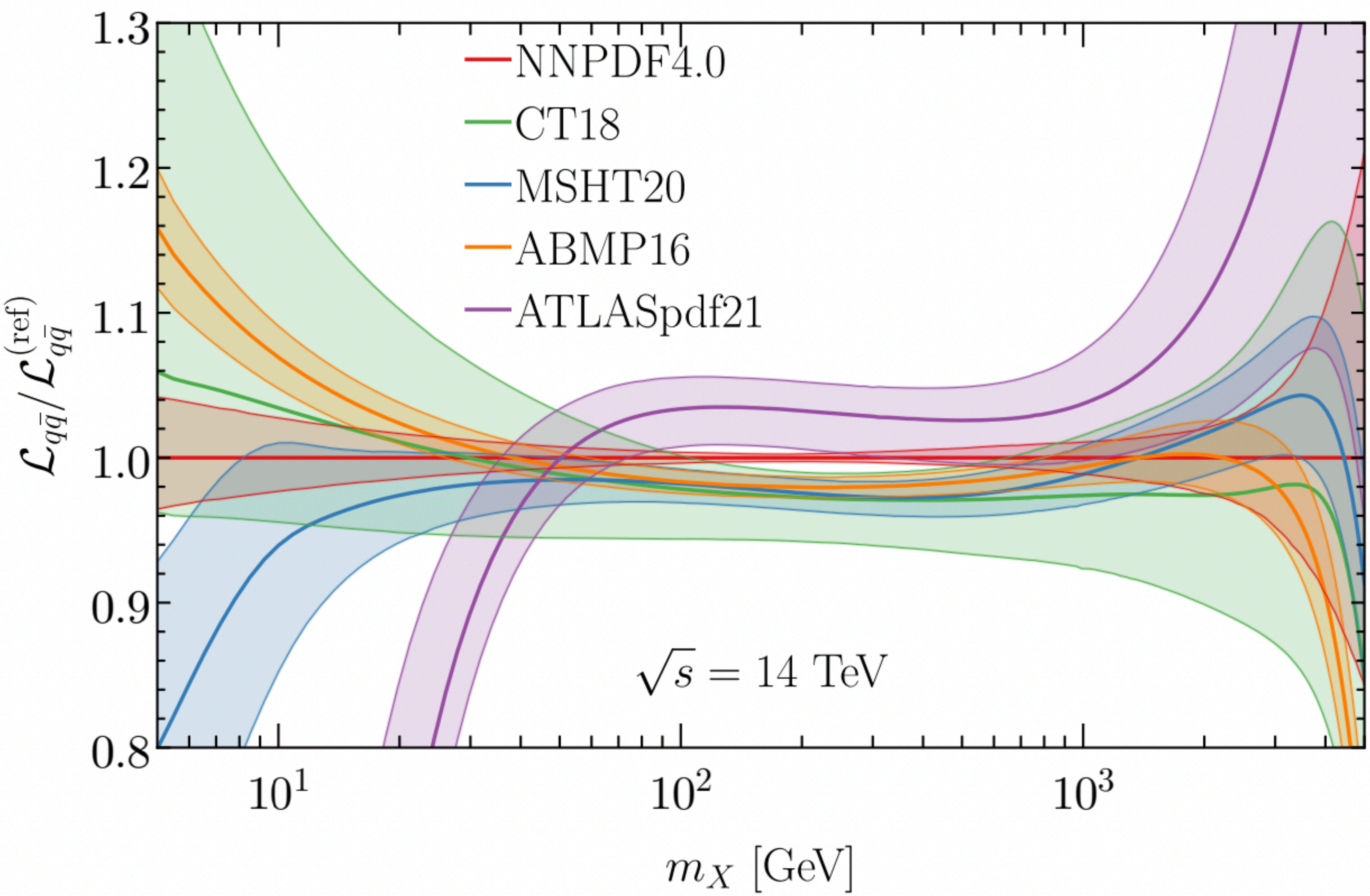



(2016)

J. Butterworth et al, J.Phys. G43 (2016) 023001

# Quark-Antiquark luminosity

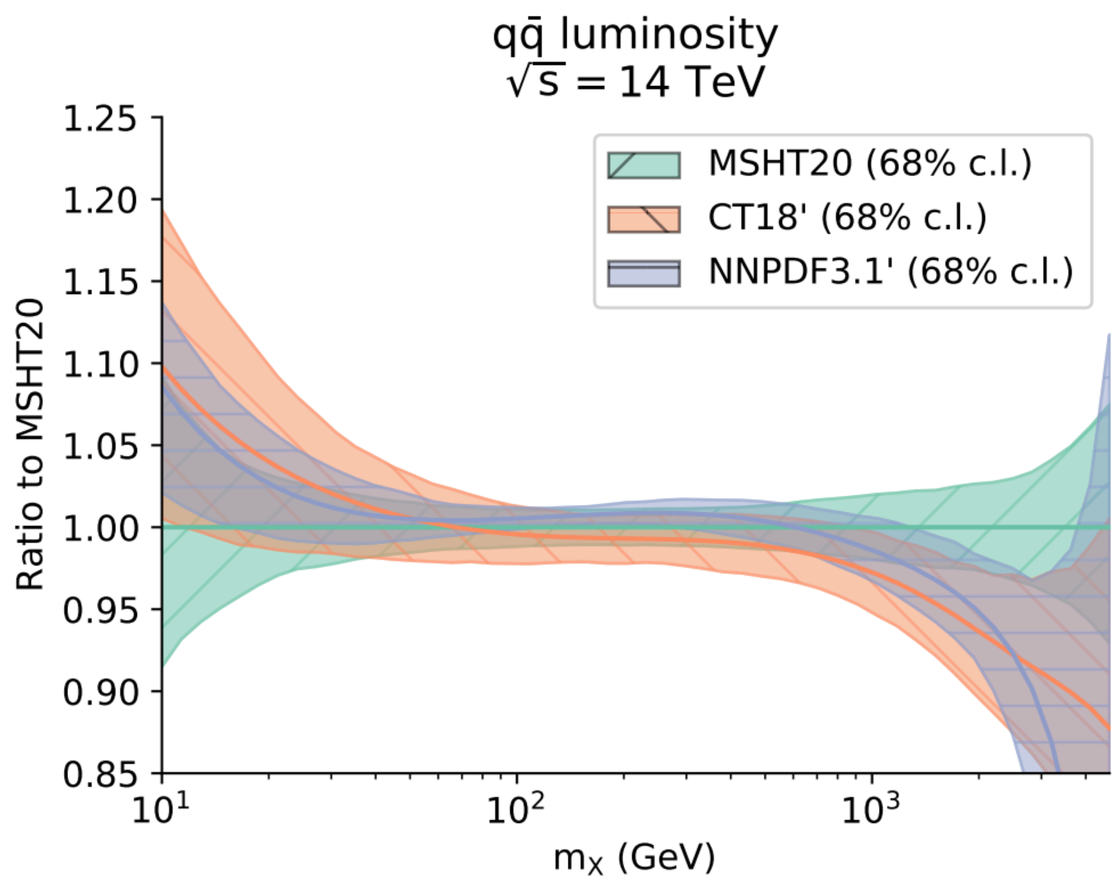
NNPDF4.0/ CT18/MSHT20/ABMP16/ATLASpdf21



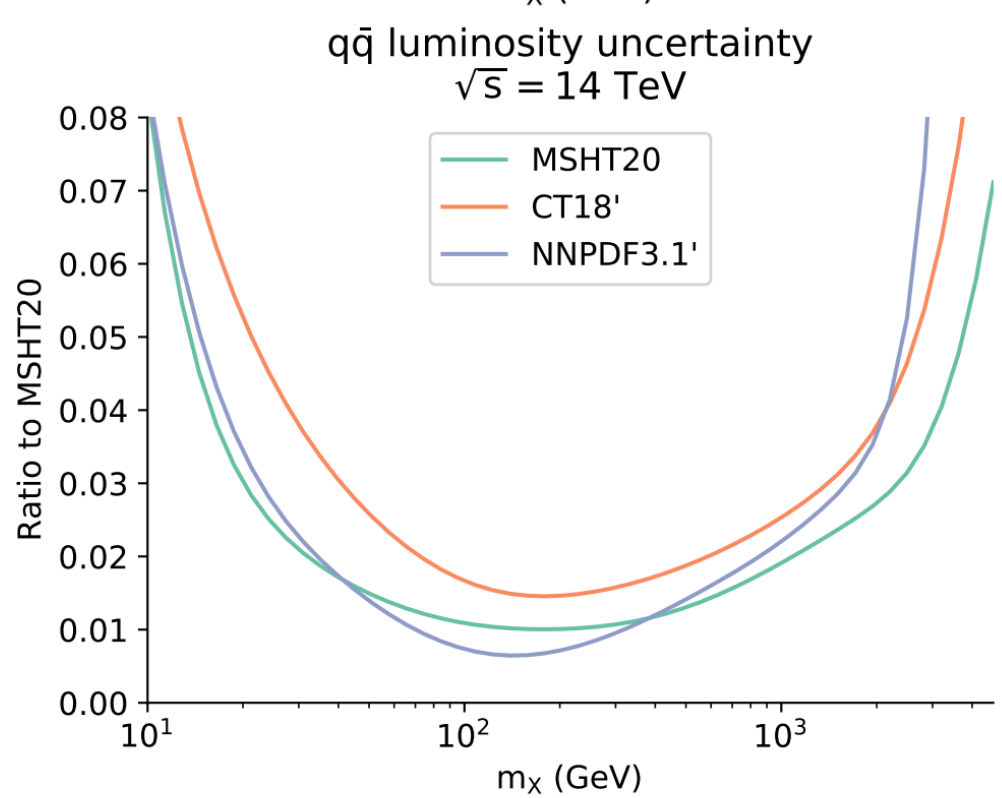

(2022)

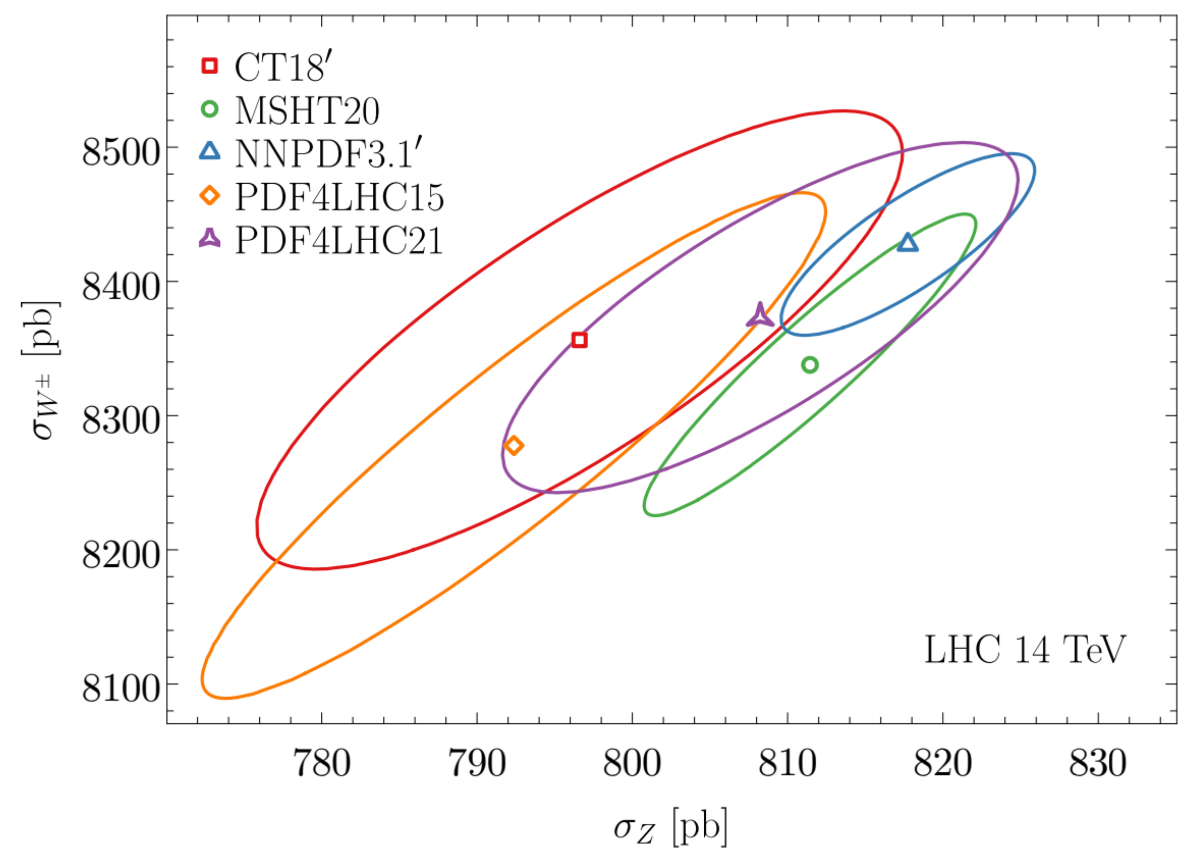
Snowmass 2022 white paper, arXiv: 2203.13923

# Ongoing benchmarks

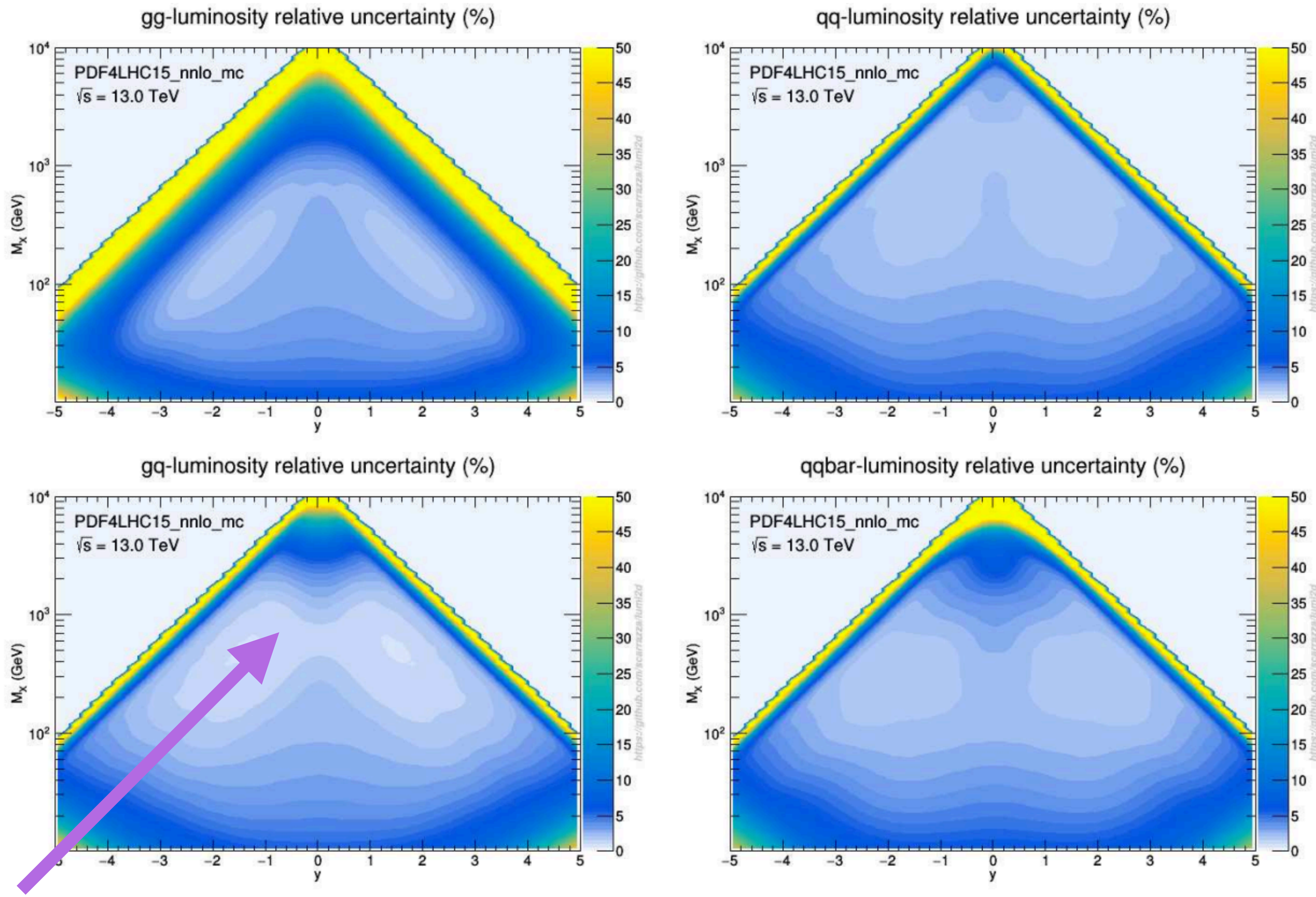



- Benchmark exercise among NNPDF3.1, MSHT20 and CT18 at the basis of PDF4LHC combination
- Overall agreement, which improves once common dataset is used, differences in uncertainties with ΔCT ≳ ΔMHST ≳ ΔNN due to methodology



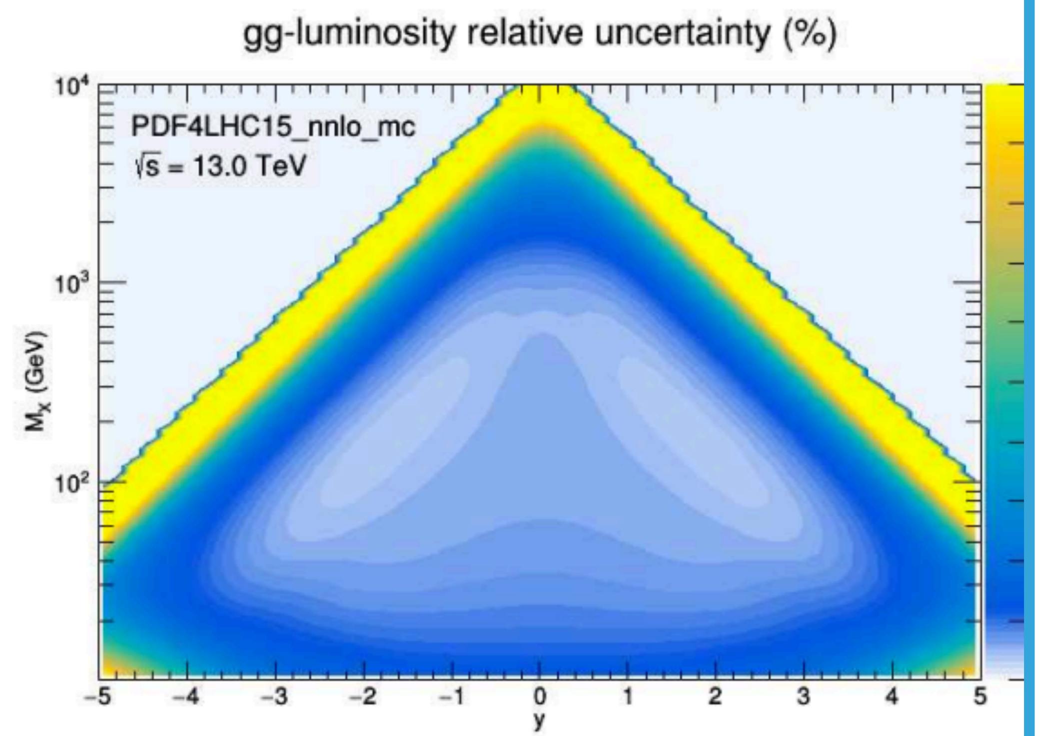



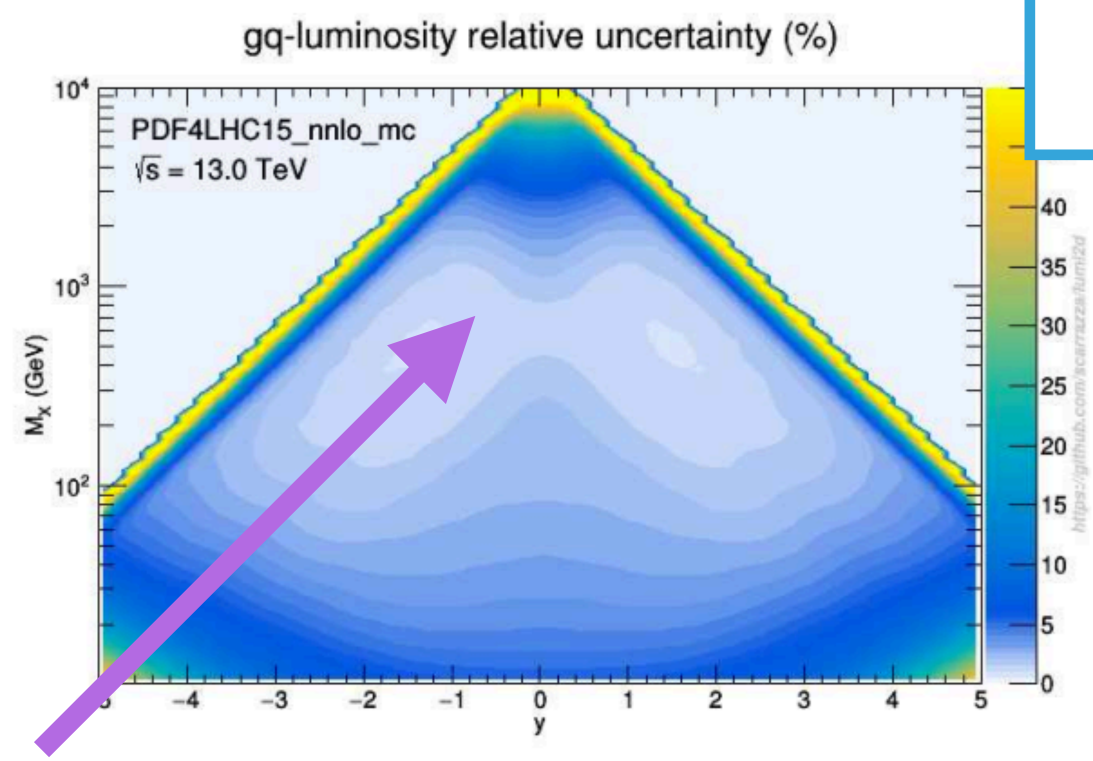
# The precision frontier

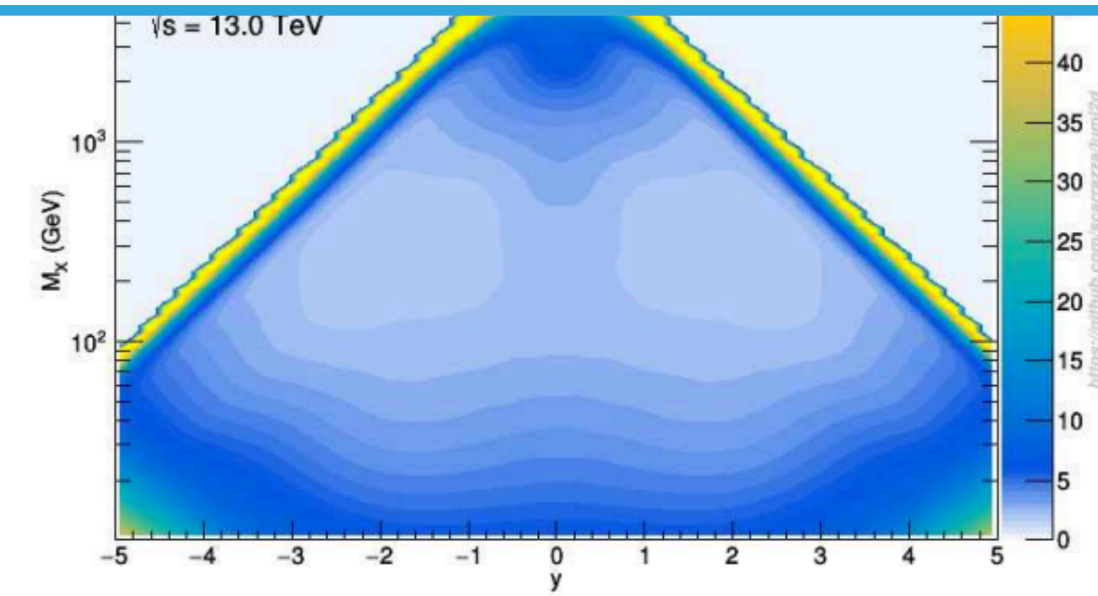


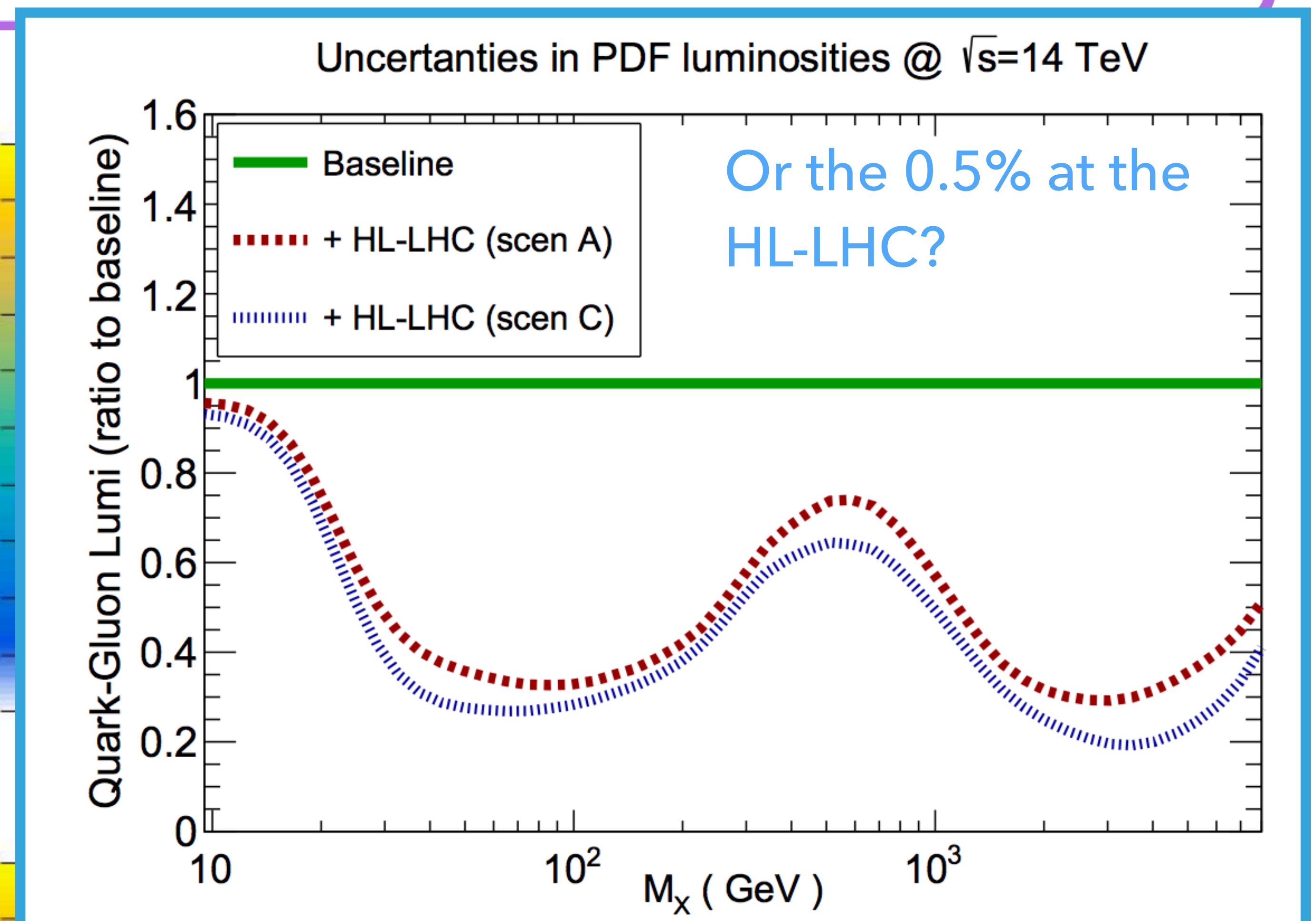

Can we trust 1% accuracy?

# The precision frontier



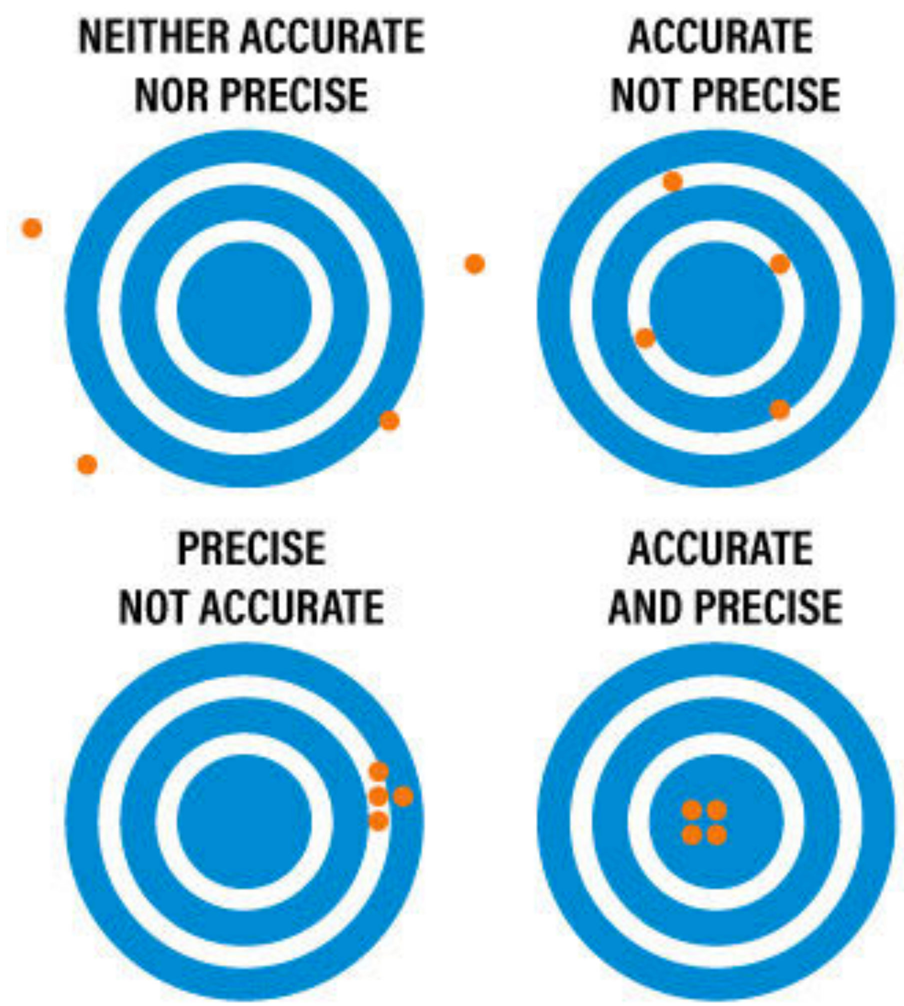



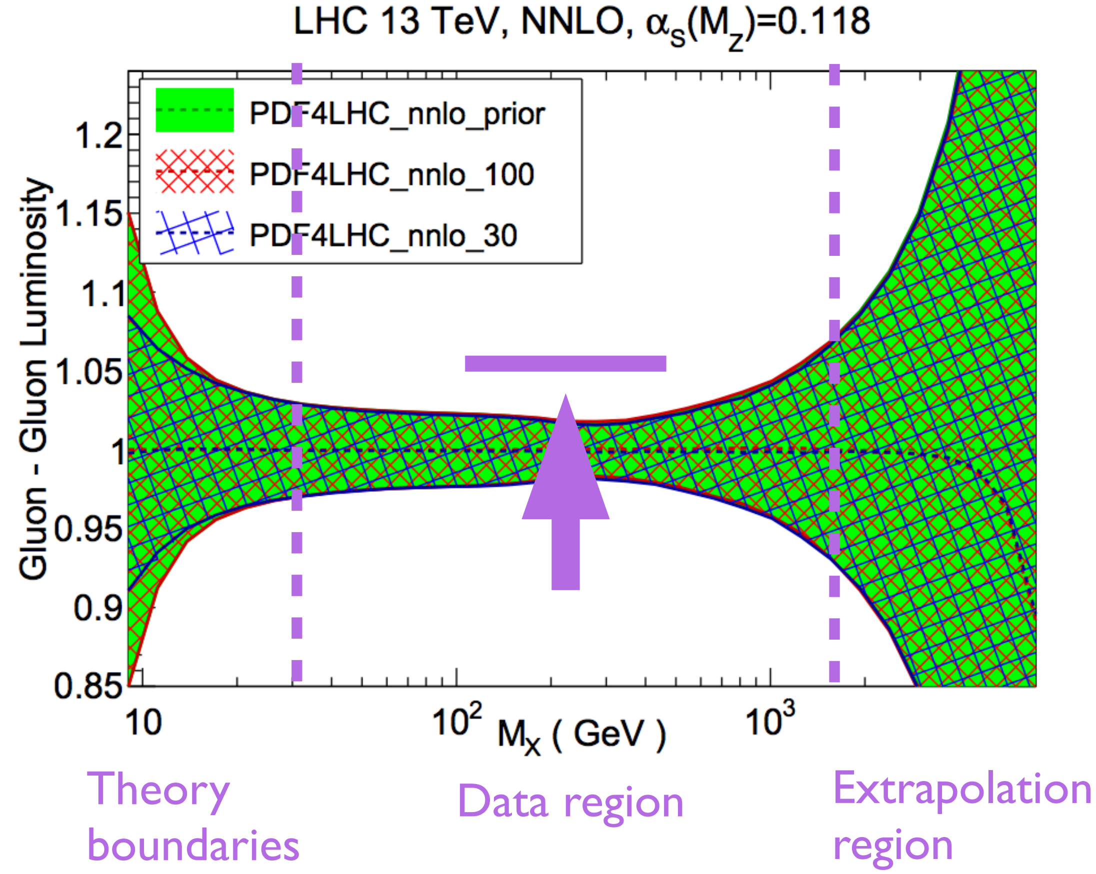

Or the 0.5% at the HL-LHC?

Can we trust 1% accuracy?

# Theory uncertainties

On top of benchmarking different PDF sets, each set must deal with inconsistencies in updated determinations.

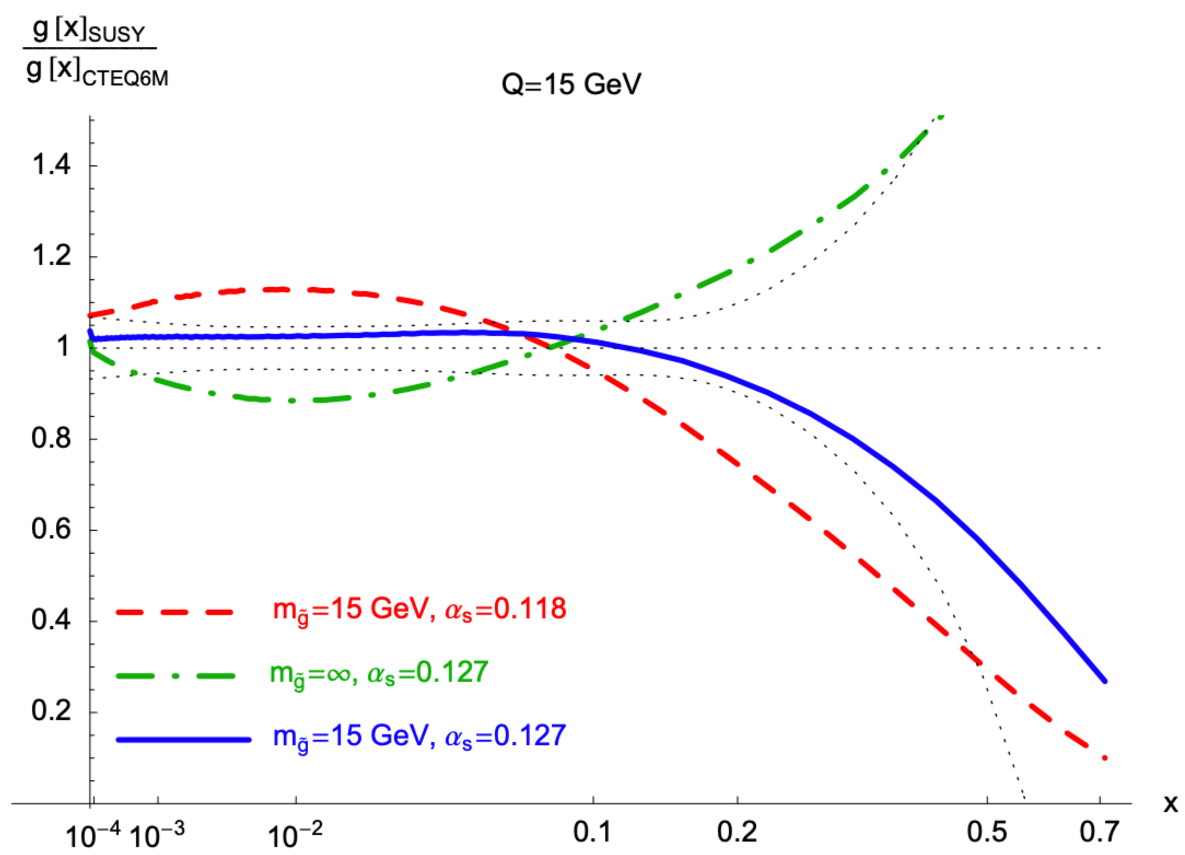


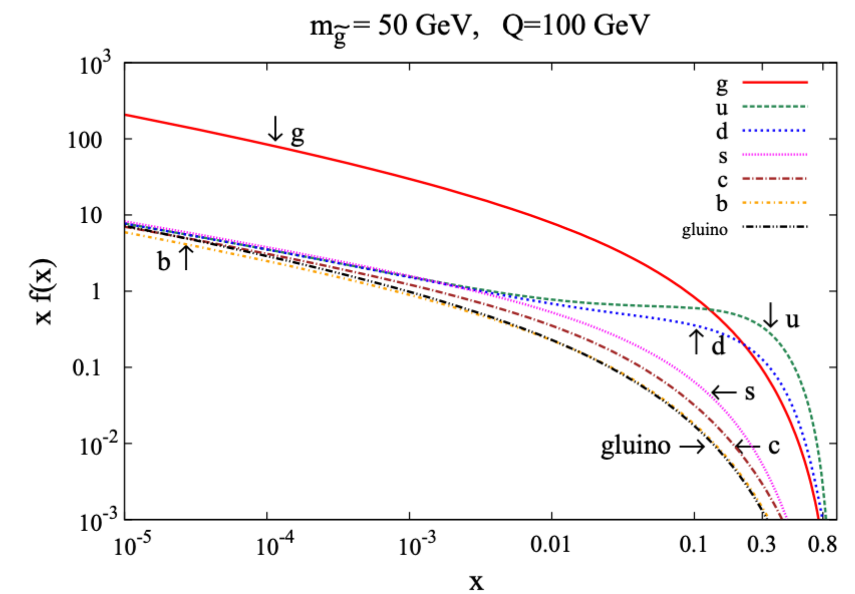

- Inconsistent data → Tolerance/ Statistical estimators
- Updated parametrization
- Differences in fitting methodology/minimisation? → Closure Test
- Changes in theory? → MHOU/New Physics

# PDF fits and New Physics interplay

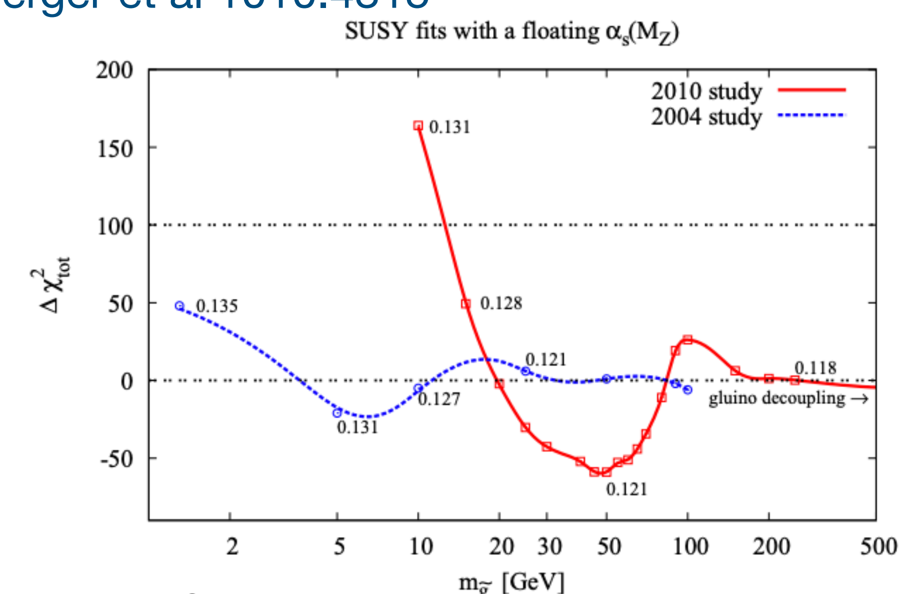
# 1. New partons




Berger et al hep-ph/0406143




Berger et al 1010.4315




- Pre-LHC studies: what is there was a light SUSY coloured partner?
- A light SUSY Parton would modify DGLAP equation and running of $\alpha_s$
- Comparison to data excludes any light coloured parton on increasing mass range as more (and more precise) data are included in the global PDF fit

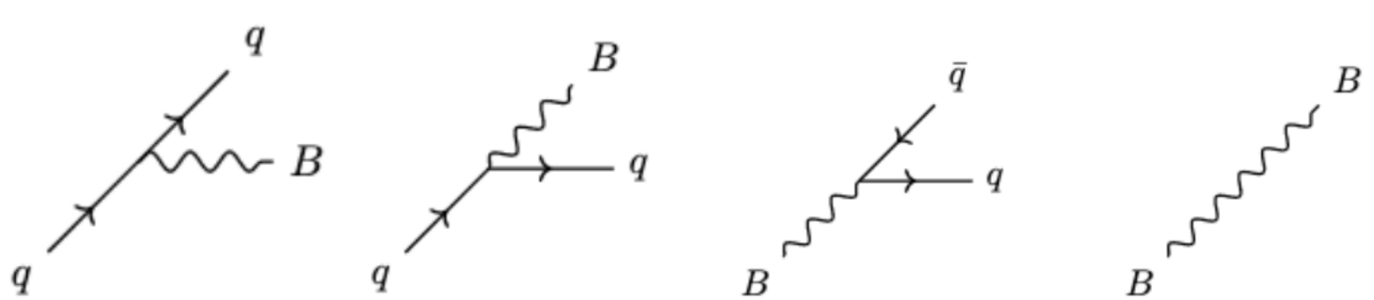
# 1. New partons

M. McCullough, J. Moore, MU, arXiv:2203.12628

- Idea: now PDFs are known very precisely, and their uncertainties will continue to reduce in the near future with the HL-LHC, could we do the same for a colourless particle too?
- If there was a lepto-phobic dark photon weakly coupled to quarks via effective Lagrangian

$$\mathcal{L}_{\text{int}} = \frac{1}{3} g_B \bar{q} \not{B} q \qquad\qquad m_B \in [2,80]\ \text{GeV}$$

  it would appear among the partons of the proton.
- To include the dark photon as a constituent of the proton: compute the dark photon splitting functions, and add them to DGLAP evolution. Starting from an appropriate initial-scale ansatz (dark photon generated dynamically off quarks and antiquarks at threshold) and a reference PDF set, evolve using the modified DGLAP equations

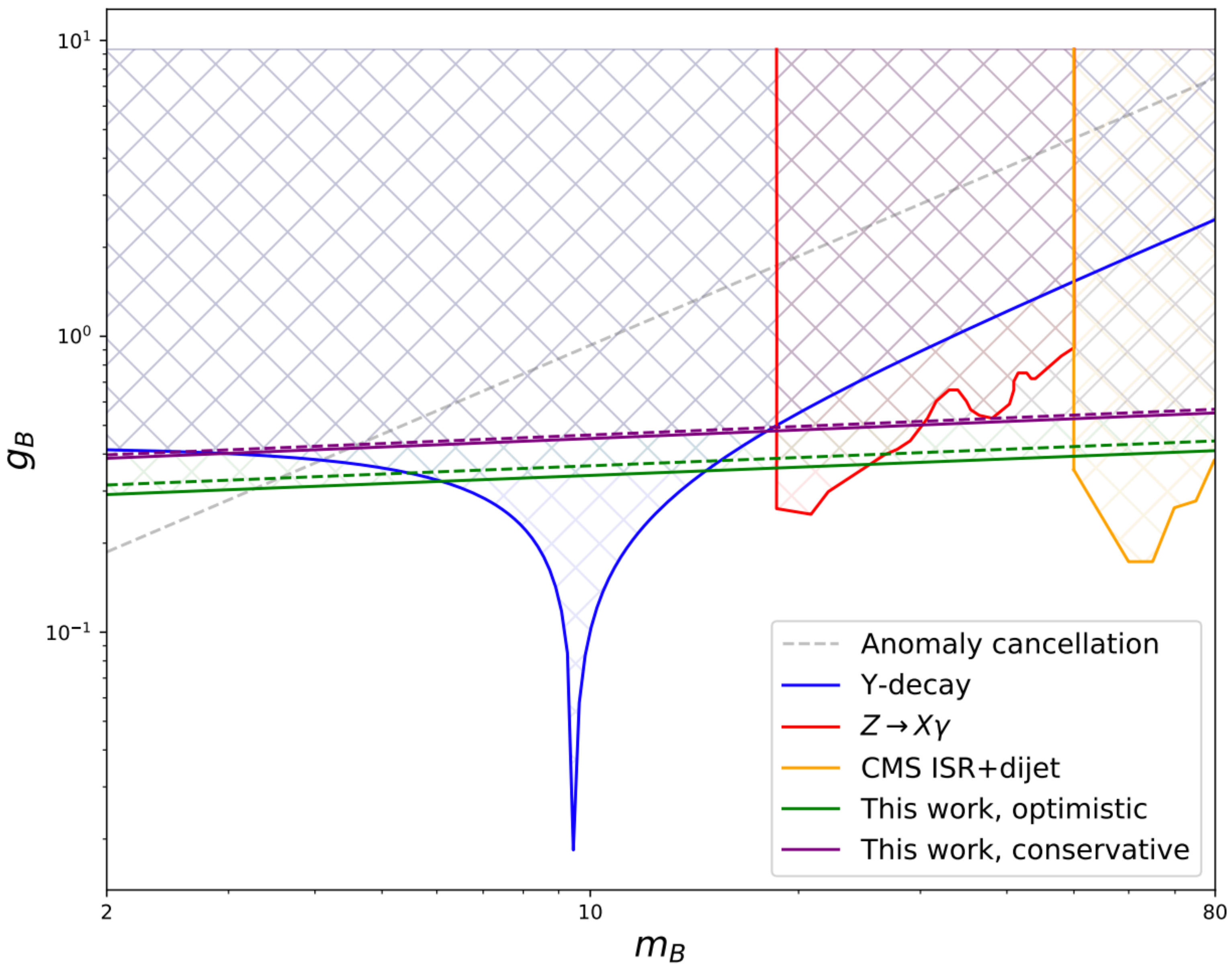



$$P_{ij} = \boxed{\left(\frac{\alpha_s}{2\pi}\right) P_{ij}^{(1,0,0)} + \left(\frac{\alpha_s}{2\pi}\right)^2 P_{ij}^{(2,0,0)} + \left(\frac{\alpha_s}{2\pi}\right)^3 P_{ij}^{(3,0,0)}} \boxed{+ \left(\frac{\alpha}{2\pi}\right) P_{ij}^{(0,1,0)} + \left(\frac{\alpha_s}{2\pi}\right)\left(\frac{\alpha}{2\pi}\right) P_{ij}^{(1,1,0)}} + \left(\frac{\alpha}{2\pi}\right)^2 P_{ij}^{(0,2,0)} \boxed{+ \left(\frac{\alpha_B}{2\pi}\right) P_{ij}^{(0,0,1)}} + \cdots,$$

$$\boxed{\alpha_B \sim 0.001}$$

# 1. New partons

M. McCullough, J. Moore, MU, arXiv:2203.12628



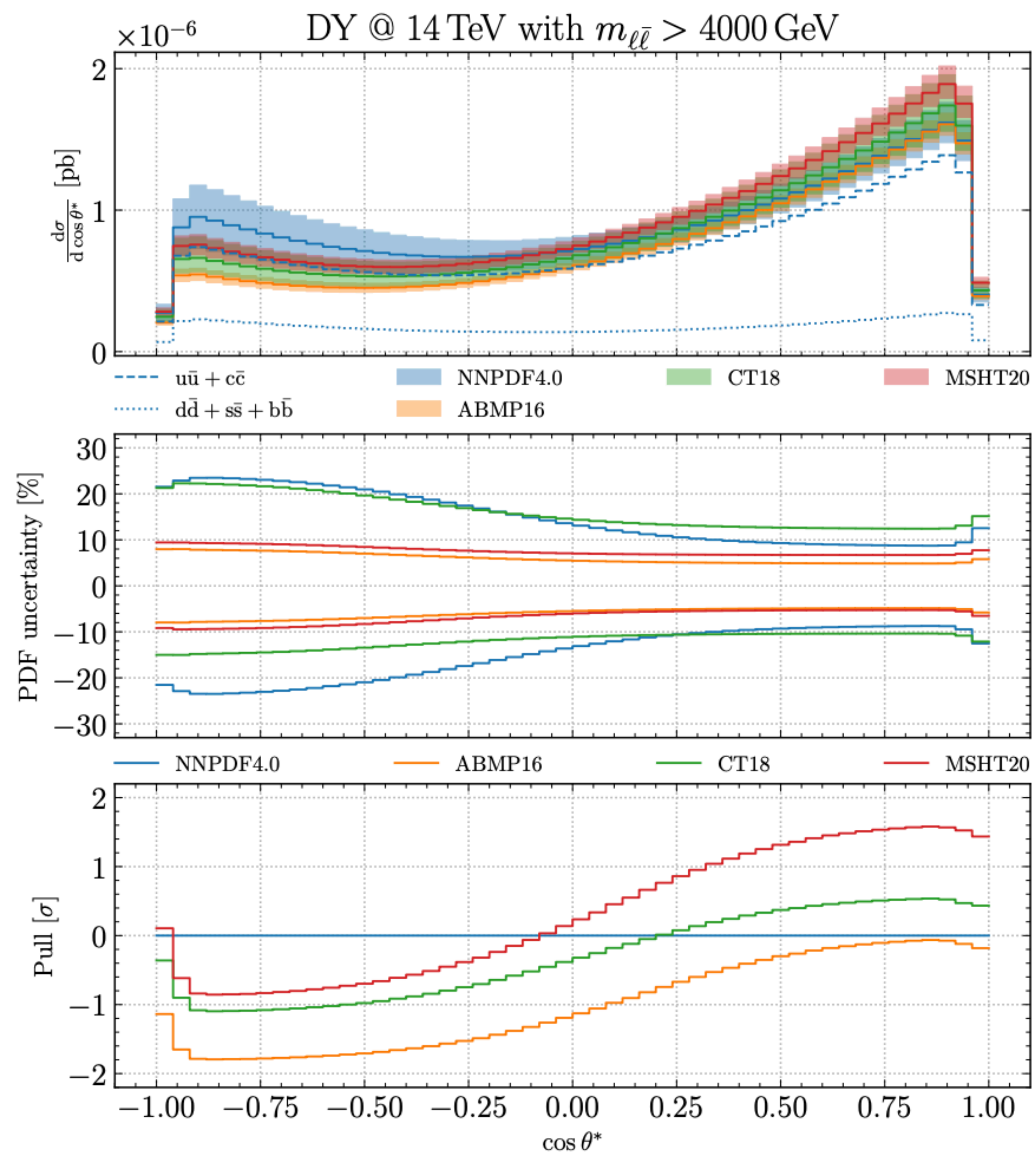

- The presence of the dark Parton would modify the evolution of standard quarks and gluon.
- Interesting to combine with dark photon effects in DIS structure functions [N. T. Hunt-Smith et al arXiv:2302.11126]

Precise LHC data can indirectly constrain parameter space of the dark photon in a competitive way compared to direct searches

# 2. Large-x PDFs and new physics

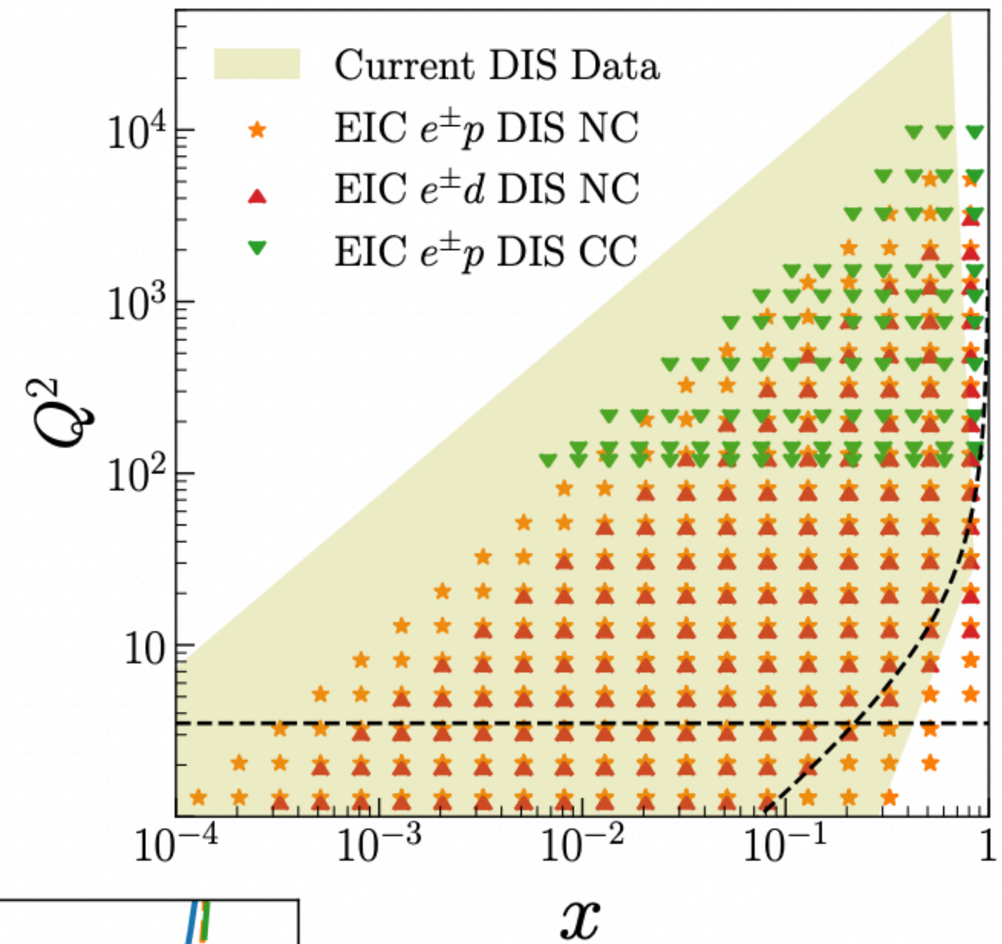
- ✓ High mass Drell-Yan tails affected by large PDF uncertainties
- ✓ This affects searches for new physics, for example in forward-backward asymmetry
- ✓ Need data constraining large-x to see and characterise new physics (at the LHC high energy - high-x)

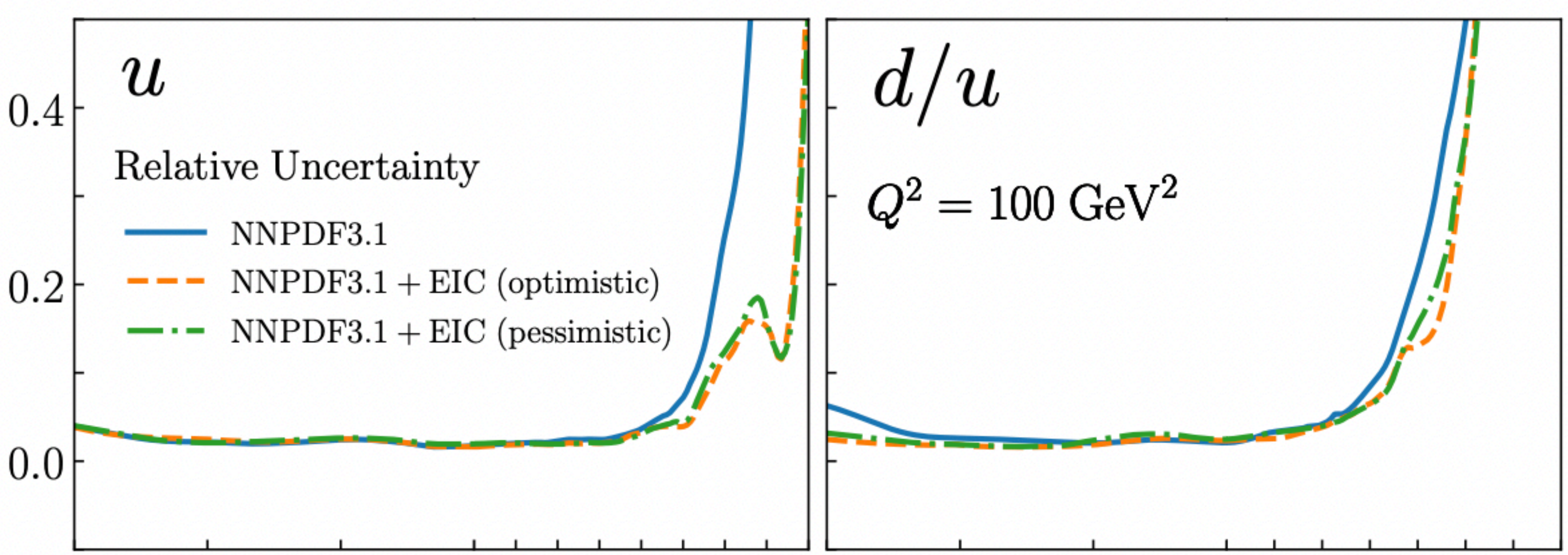
$$\frac{d\sigma}{d\cos\theta^*} = \int_{m_{\ell\bar{\ell}}^{\min}}^{\sqrt{s}} dm_{\ell\bar{\ell}} \int_{\ln(m_{\ell\bar{\ell}}/\sqrt{s})}^{\ln(\sqrt{s}/m_{\ell\bar{\ell}})} dy_{\ell\bar{\ell}} \frac{d^3\sigma}{dm_{\ell\bar{\ell}}\, dy_{\ell\bar{\ell}}\, d\cos\theta^*}$$



# 2. Large-x PDFs and new physics

- ✓ High mass Drell-Yan tails affected by large PDF uncertainties
- ✓ This affects searches for new physics, for example in forward-backward asymmetry
- ✓ Need data constraining large-x to see and characterise new physics (at the LHC high energy - high-x)
- ✓ EIC crucial to give complementary constraints



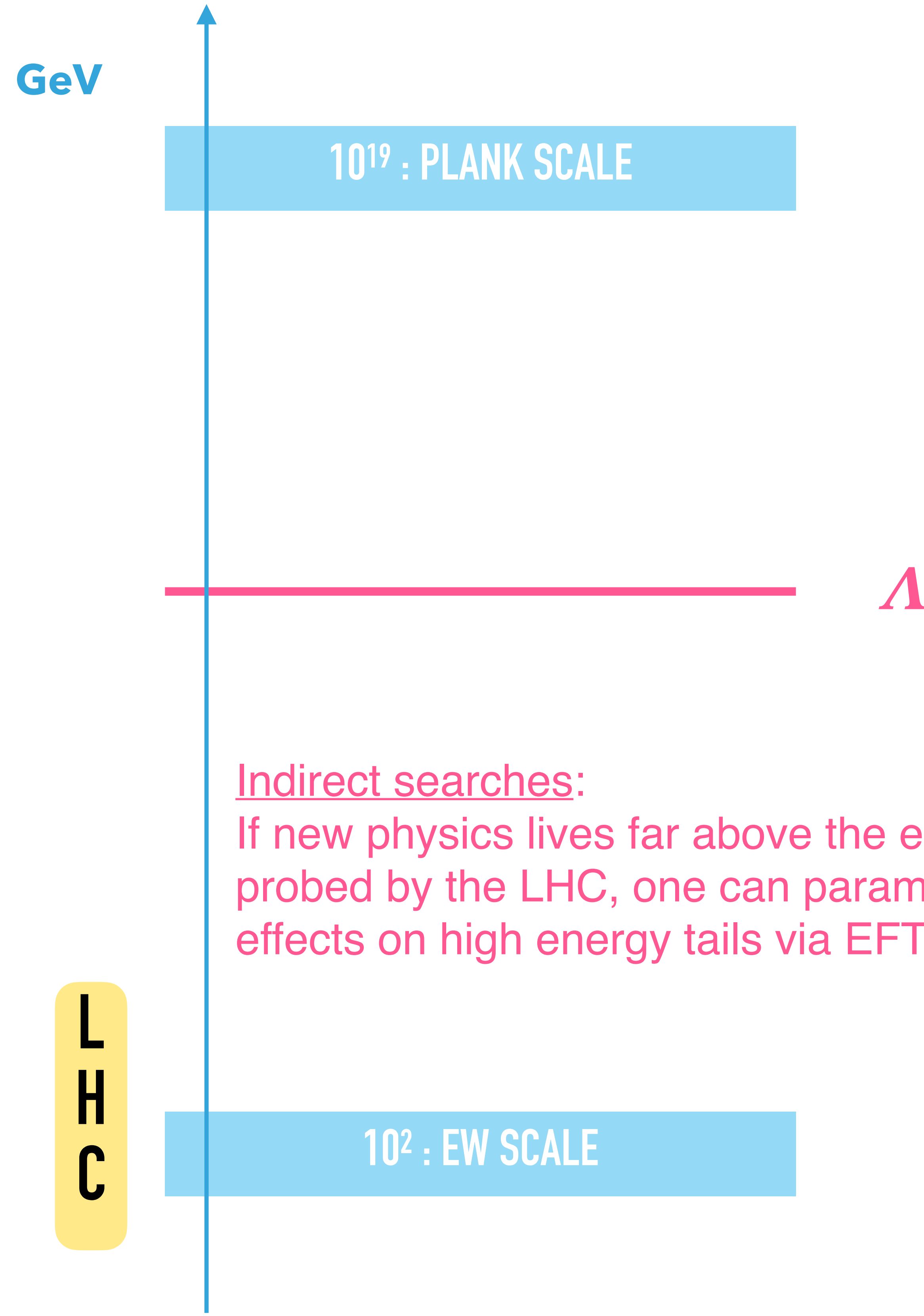

Rabah Abdul Khalek et al, arXiv:2102.00018

# 3. Indirect searches for New Physics

- EFT is a well-defined theoretical approach for indirect searches
- Assumption: new physics states are heavy
- Write the Lagrangian with only light SM particles
- BSM effects can be incorporated as a momentum expansion
- SMEFT: assume SM field content and gauge symmetries (apart from accidental)

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4}\mathcal{O}_j^{(8)} + \dots$$

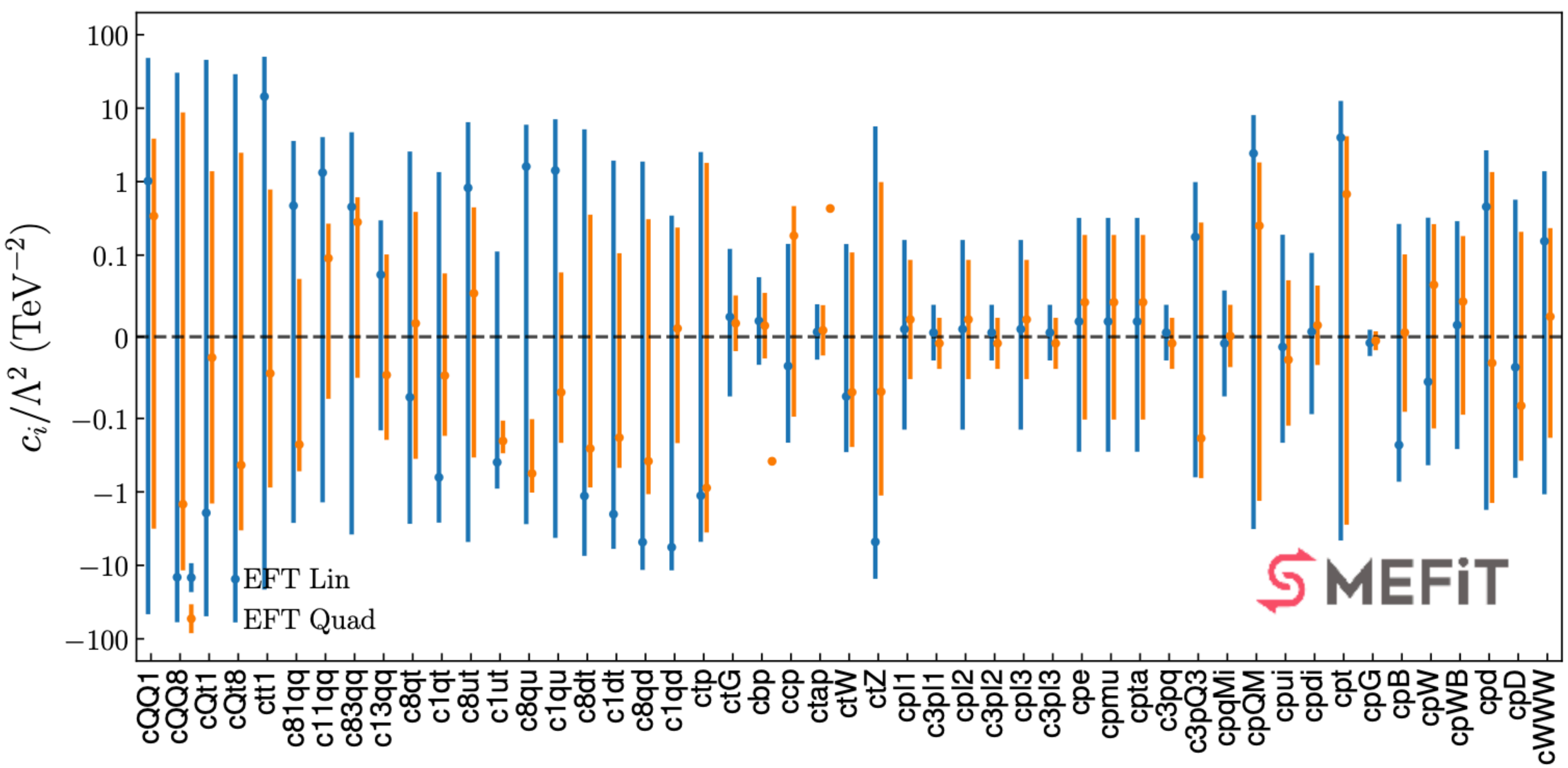
- Full dim-6 basis of operators under SMEFT assumptions includes **2499** operators **[Grzadkowski et al, arXiv:1008.4884]**




Indirect searches:
If new physics lives far above the energy probed by the LHC, one can parametric effects on high energy tails via EFT

# 3. Indirect searches for New Physics

- Current SMEFT fits make flavour assumptions and restricted to a few observables/sectors & reduce the number of operators.
- **SMEFiT**: SMEFT fit based on Monte Carlo technique for propagation of experimental uncertainty **[Hartland et al, arXiv:1901.05965]**
- Global dim-6 SMEFT fit of Higgs, diboson, and top quark production and decay measurements (36 independent Wilson coefficients, including linear and quadratic contributions and NLO QCD corrections to SMEFT) **[Either et al, arXiv:2105.00006]**




**Either et al, arXiv:2105.00006**

# 3. Indirect searches for New Physics

$$\chi^2 = \frac{1}{N_{\rm dat}} \sum_{i=1}^{N_{\rm dat}} (T_i(\{\theta\},\{c\}) - D_i)\, {\rm cov}^{-1}_{ij}\, (T_j(\{\theta\},\{c\}) - D_j)$$

$$T_i(\boxed{\{\theta\}},\boxed{\{c\}}) = {\rm PDFs}(\{\theta\},\{c\}) \otimes \hat{\sigma}_i(\{c\})$$

(B)SM parameters: $\alpha_s(M_Z)$, $M_W$, $\theta_W$ ,**SMEFT WCs**……

Parameters determining PDFs at initial scale

✓ In a PDF fit typically

$$T_i(\{\theta\}) = {\rm PDFs}(\boxed{\{\theta\}},\{c=0\}) \otimes \hat{\sigma}_i(\{c=0\})$$

✓ In a fit of SMEFT Wilson Coefficients

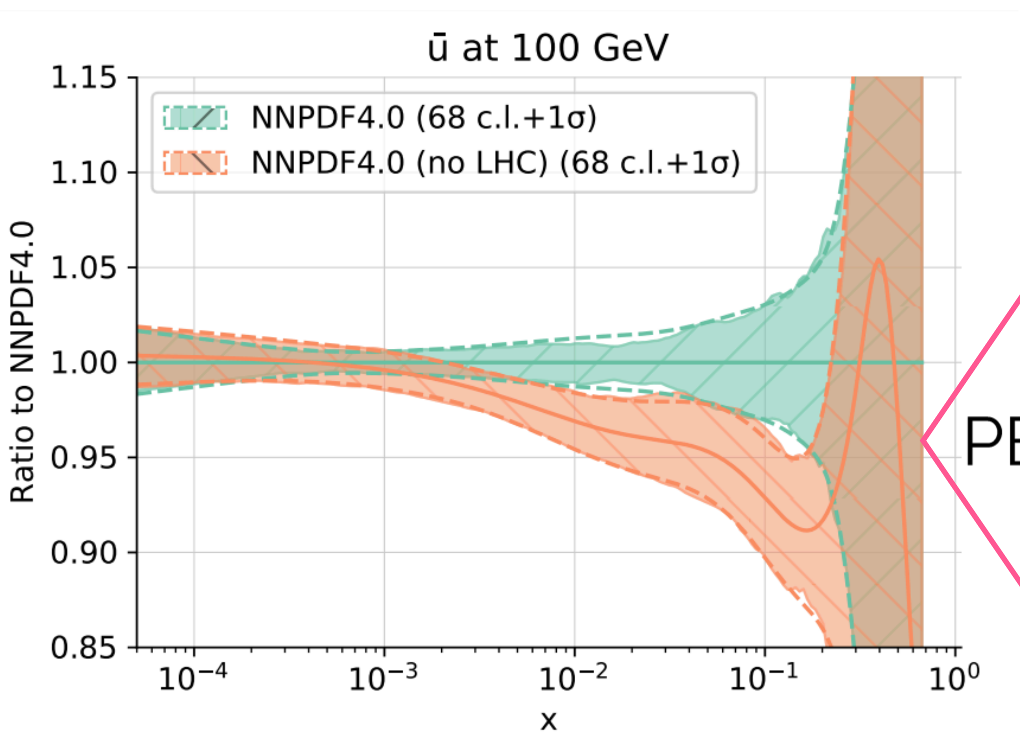
$$T_i(\{c\}) = {\rm PDFs}(\{\theta=\bar{\theta}\},\{c=0\}) \otimes \hat{\sigma}_i(\boxed{\{c\}})$$

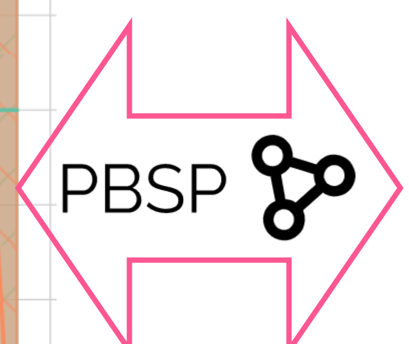
# 3. Indirect searches for New Physics

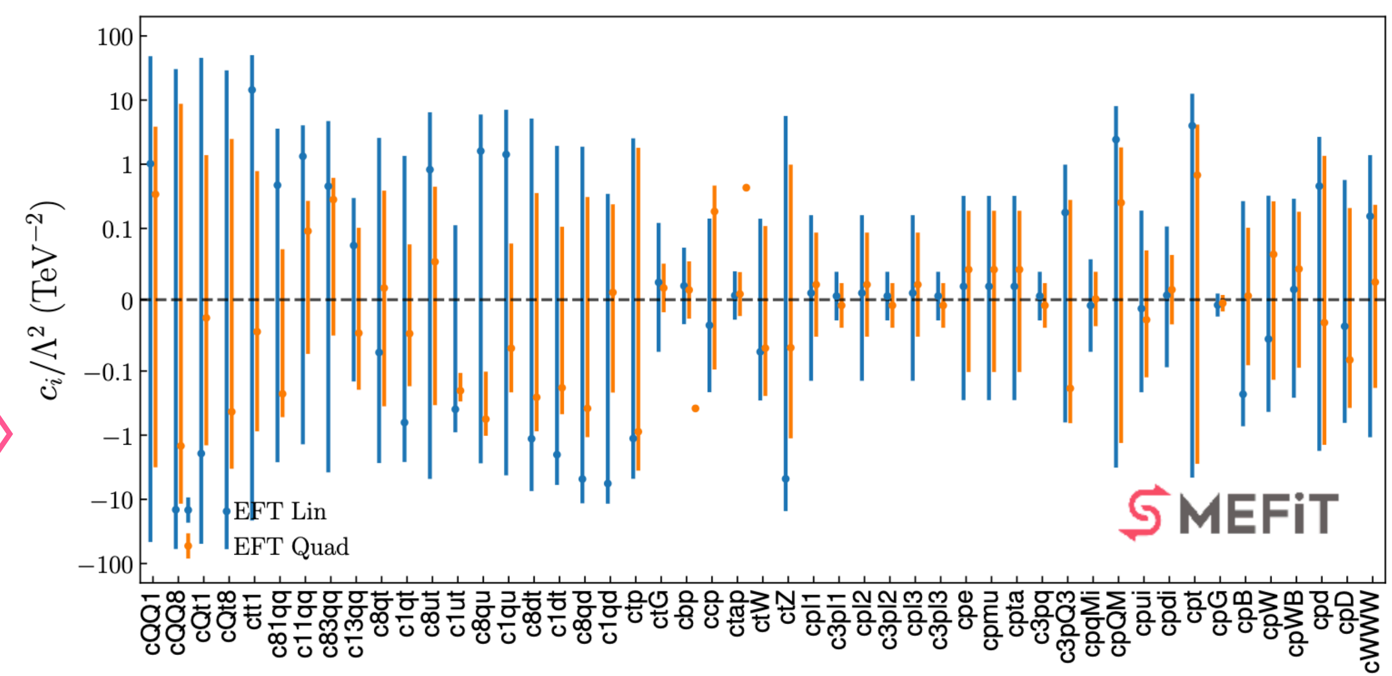
- In principle low-scale physics is separable from high-scale physics, BUT the complexity of the LHC environment might well intertwine them.

- PDFs are low-scale quantities extracted from experimental data at all scales, without considering any potential high-scale contamination due to new physics.

- (SM)EFT fits are performed by assuming a priori that PDFs are SM-like.



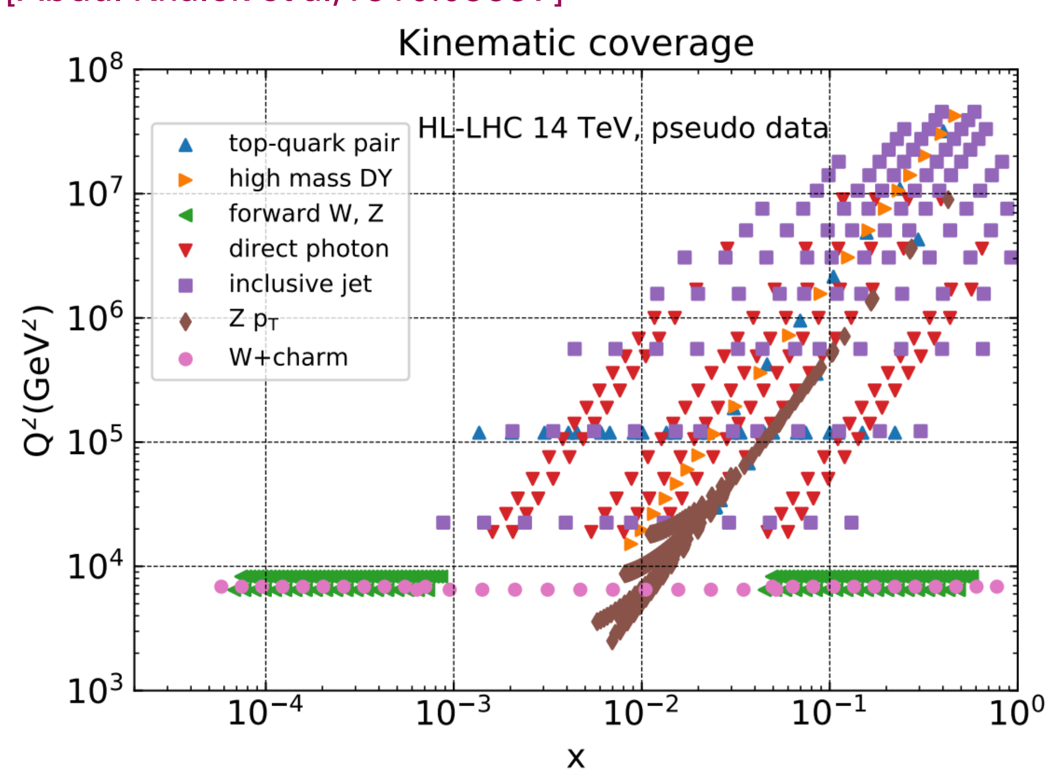



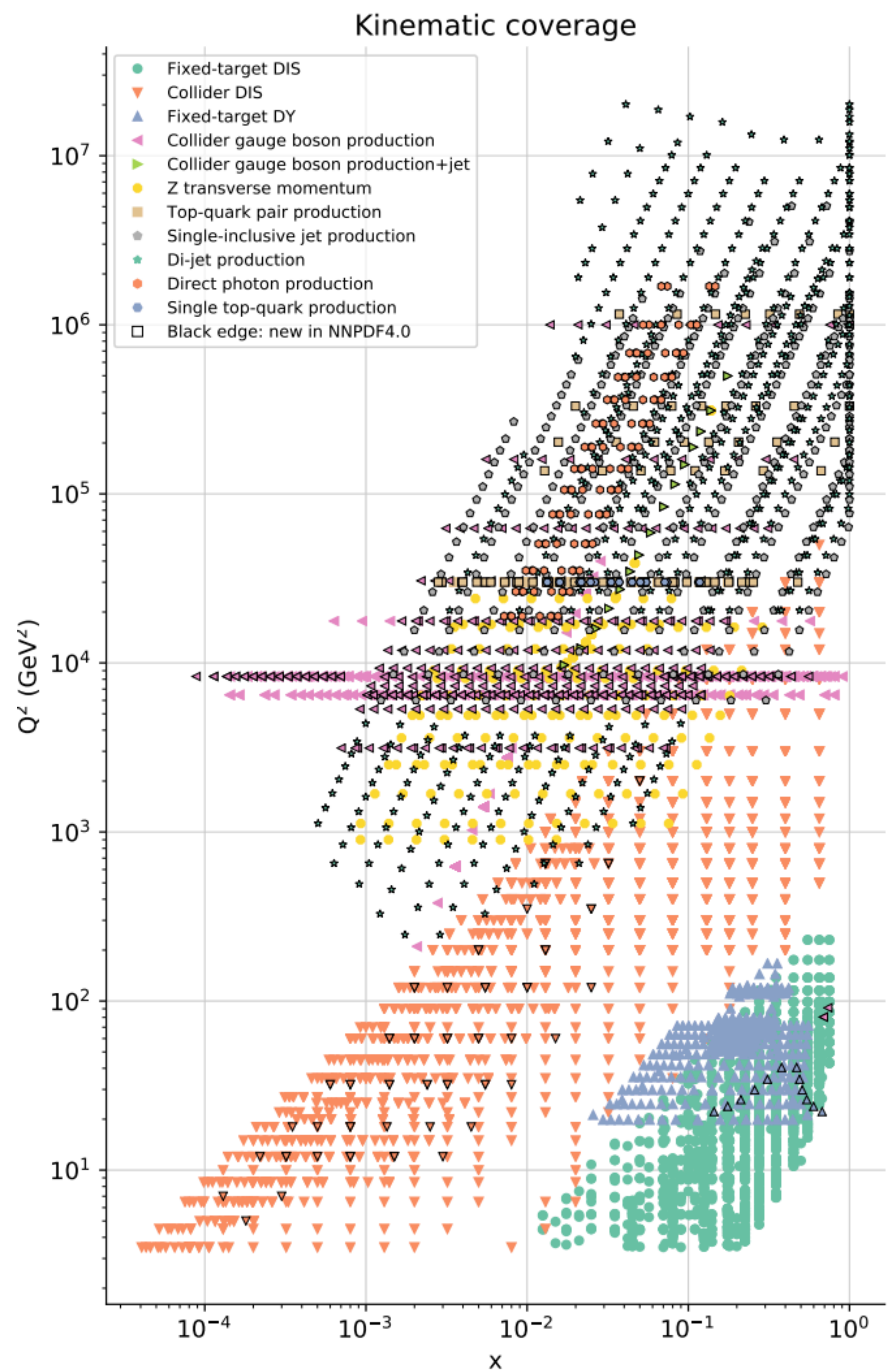

Ethier et al, arXiv: 2105.00006

Ball et al, arXiv:2109.02653

# Data overlap

- ➡ Top pair production and single top data included in SMEFT analysis [Hartland et al 1901.05965] [Ellis et al 2012.02779]
- ➡ Dijets data [Bordone et al 2103.10332] [Alioli et al 1706.03068]
- ➡ Drell-Yan data in [Farina et al 1609.08157] [Torre et al 2008.12978]
- ➡ Inclusive jets in [Alte et al 1711.07484]
- ➡ Overlap enhanced in HL-LHC projections [Abdul Khalek et al,1810.03639]



# 3. Indirect searches for New Physics

- From the point of view of PDF fits:
  - ➡ How to make sure that new physics effects are not inadvertently fitted away in a PDF fit?

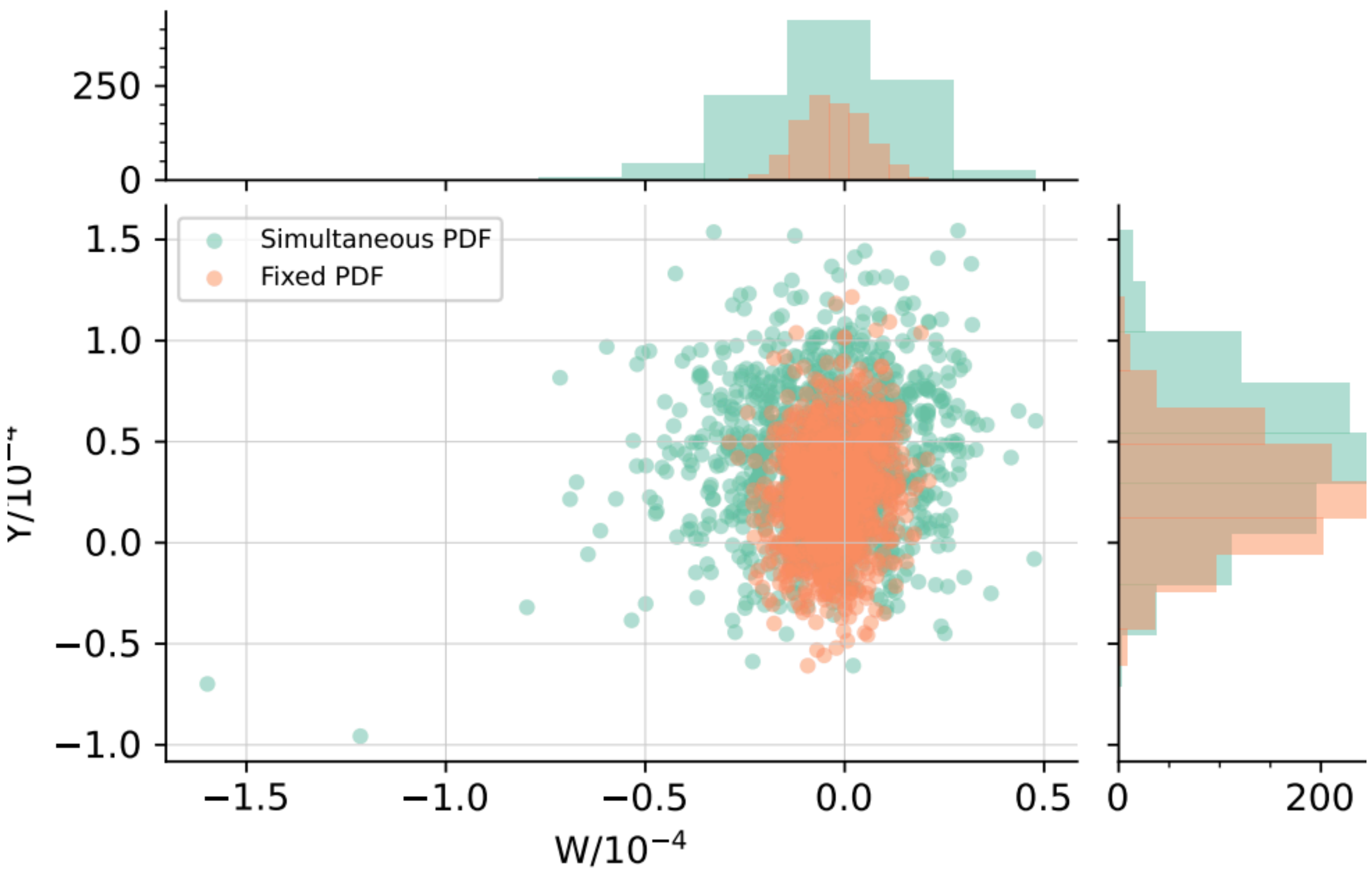
- From the point of view of SMEFT fits:
  - ➡ Should I make sure I am using a clean set of PDFs in a SMEFT analysis? How to define it? Is it enough?
  - ➡ How would the bounds change if I was consistently using PDFs that include in the fit theory predictions computed adding the same operators that I am fitting?

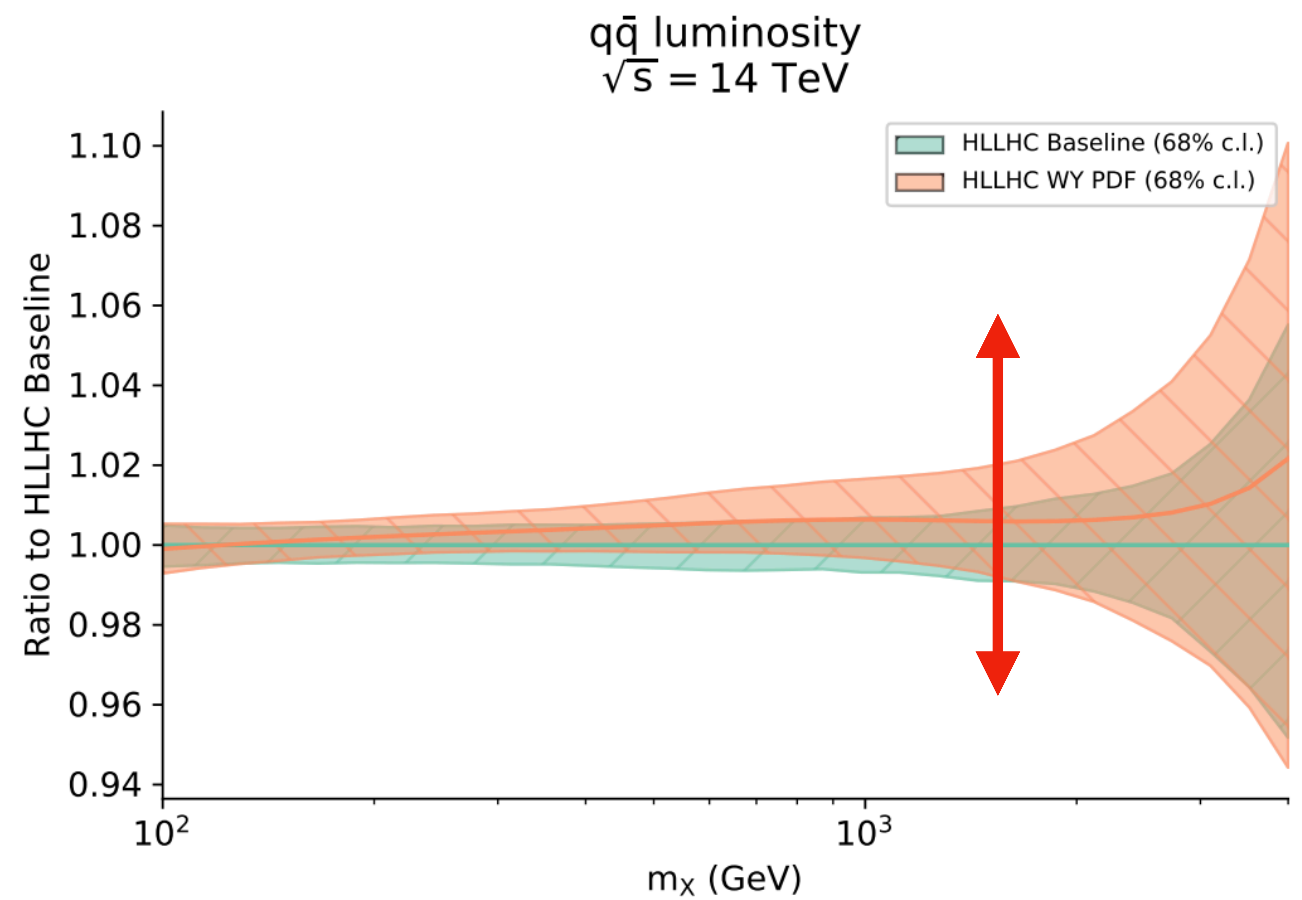
$$T_i(\{\theta\},\{c\}) = \mathrm{PDFs}(\{\theta\},\{c\}) \otimes \hat{\sigma}_i(\{c\})$$

Simultaneous fits can shed light on their interplay

# 3. Test-ground: DY data at HL-LHC

x 2.3 broadening of bounds for W
x 1.3 broadening of bounds for Y



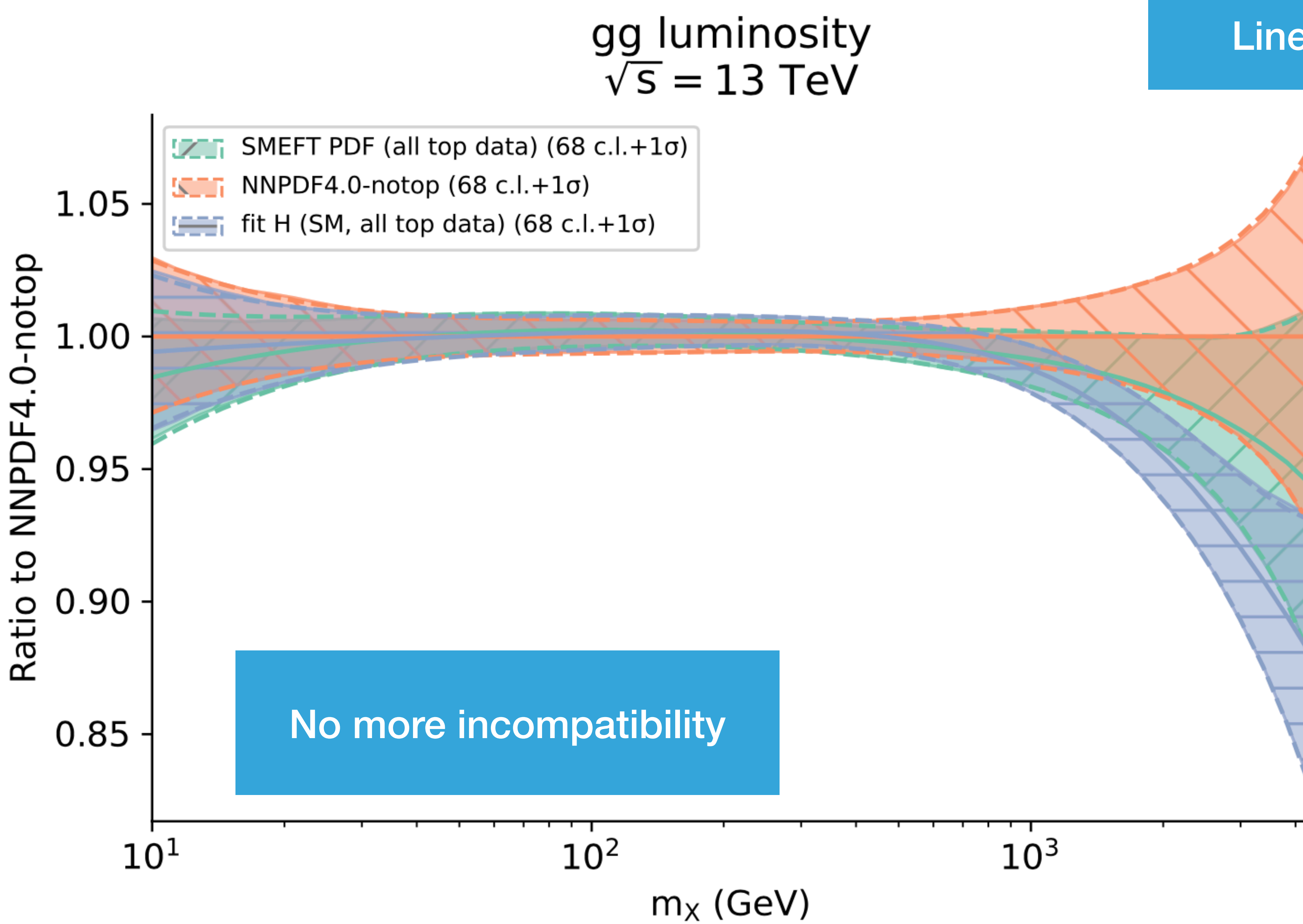

✓ Simultaneous fit shows that at HL-LHC the effect of interplay between SMEFT fits and PDF fits becomes important as bounds on Wilson Coefficients that affect high-mass invariant tails broaden

✓ Also PDF uncertainties broaden significantly once SMEFT effects allowed in theory predictions entering PDF fit

S. Iranipour, MU - arXiv: 2201.07240

# 3. Test-ground: top data at LHC

Linear SMEFT



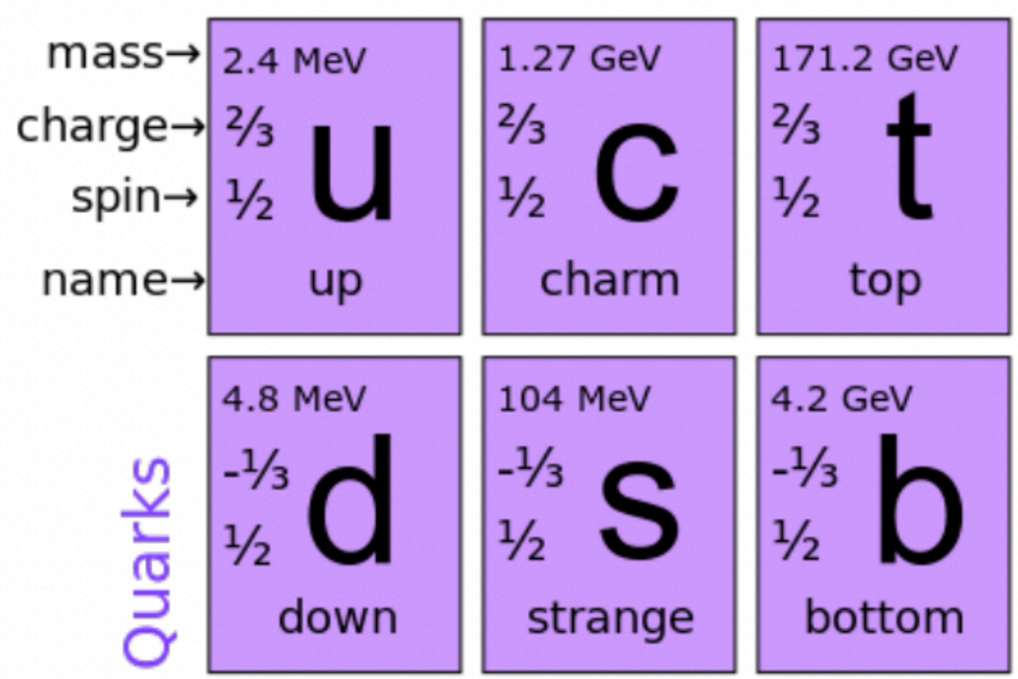

No more incompatibility

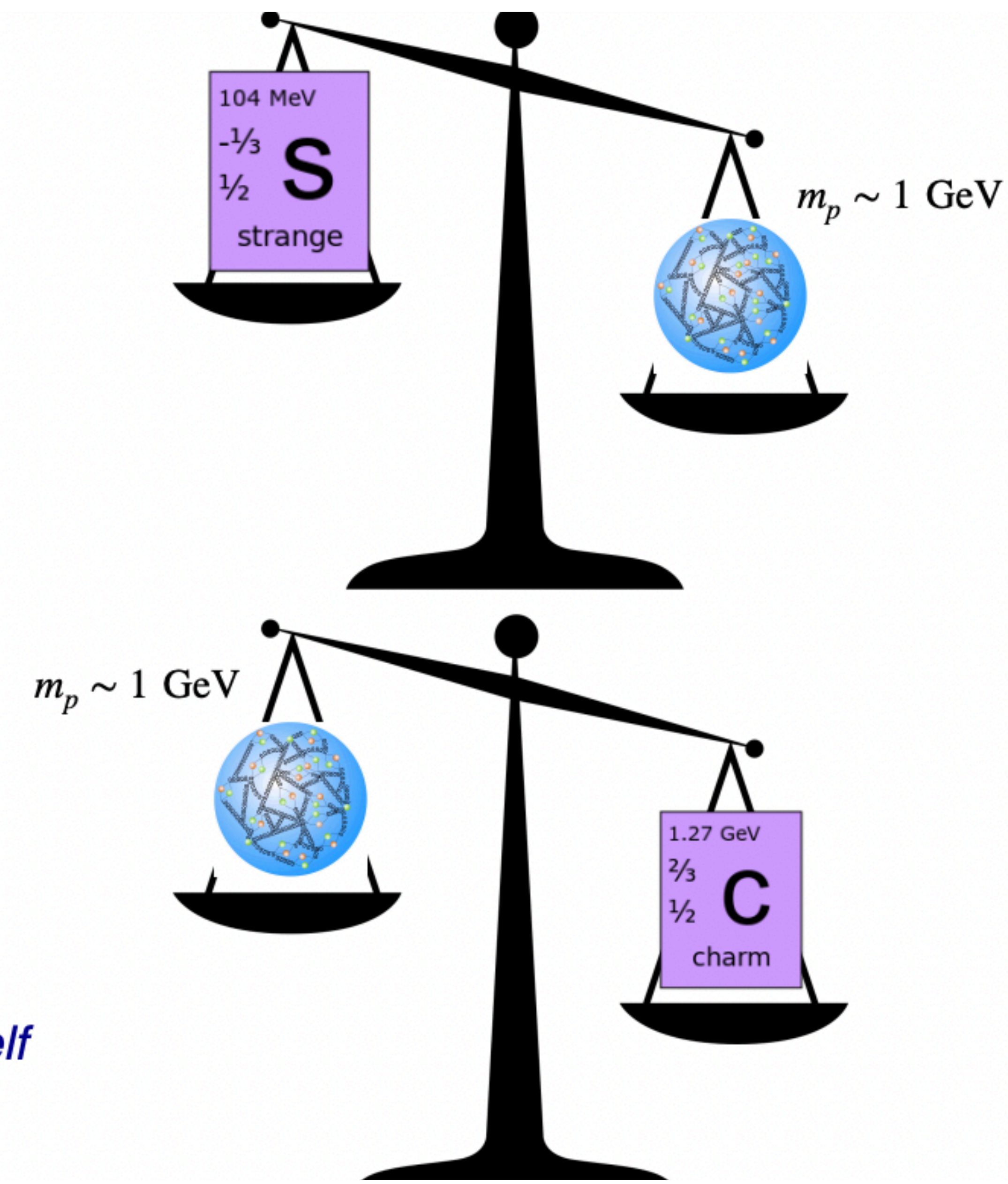
Z. Kassabov, M. Madigan, L. Mantani, J. Moore, M. Morales, J. Rojo, MU - arXiv: 2303.06159

# Intrinsic charm

# The charm of the proton

✓ Common assumption in PDF fits: the static proton wavefunction does not contain charm quarks: the proton contains intrinsic up, down, strange quarks and anti quarks but no intrinsic charm quarks




*charm quarks heavier than the proton itself*

From J. Rojo's talk at KIT

# The charm of the proton

✓ Common assumption in PDF fits: the static proton wavefunction does not contain charm quarks: the proton contains intrinsic up, down, strange quarks and anti quarks but no intrinsic charm quarks

✓The charm PDF is generated perturbatively (DGLAP evolution from radiation off gluons and quarks)

$$\underbrace{f_c^{(n_f)} = 0}_{\text{3FNS charm}} \quad \rightarrow \quad \underbrace{f_c^{(n_f+1)}}_{\text{4FNS charm}} \propto \alpha_s \ln \frac{Q^2}{m_c^2} \left( P_{qg} \otimes \underbrace{f_g^{(n_f+1)}}_{\text{4FNS gluon}} \right) + \mathcal{O}\left(\alpha_s^2\right)$$

***NLO matching***

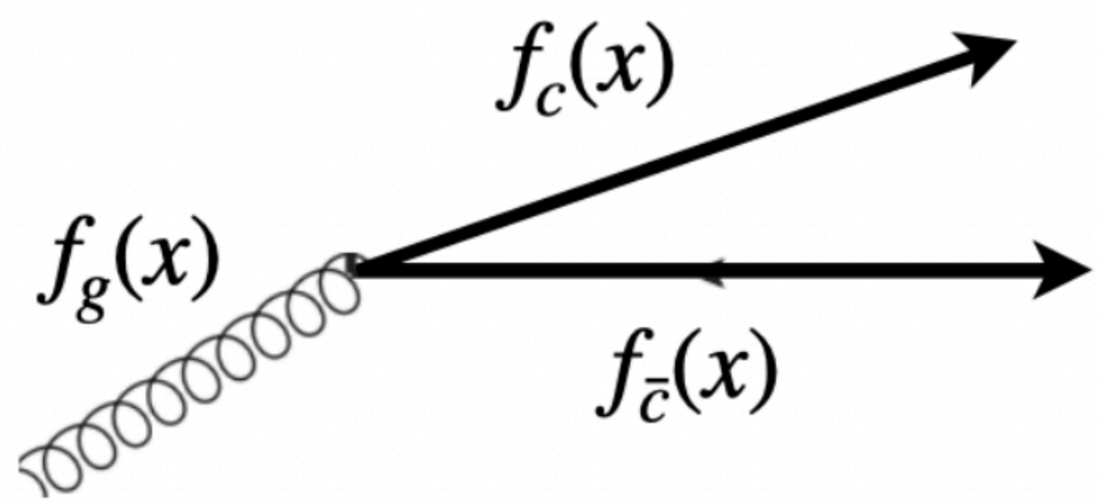
4 flavour scheme, $Q > m_c$

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

$\updownarrow \quad \updownarrow$

3 flavour scheme, $Q < m_c$

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




If charm is **perturbatively generated**, the charm PDF is **trivial**

From J. Rojo's talk at KIT

# The charm of the proton

- ✓ Common assumption in PDF fits: the static proton wavefunction does not contain charm quarks: the proton contains intrinsic up, down, strange quarks and anti quarks but no intrinsic charm quarks
- ✓ It does not need to be so, as an intrinsic charm component is predicted in many models.

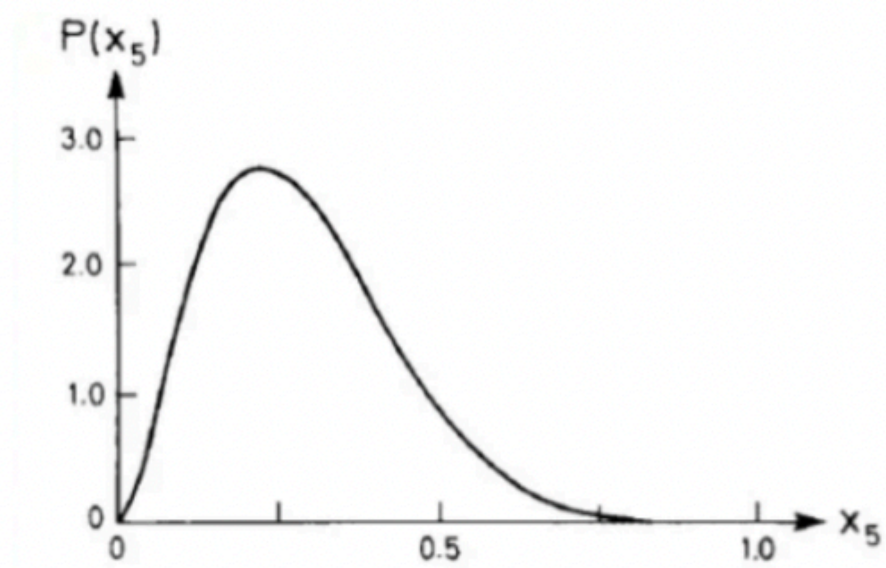
**THE INTRINSIC CHARM OF THE PROTON**

S.J. BRODSKY [1]
*Stanford Linear Accelerator Center, Stanford, California 94305, USA*

and

P. HOYER, C. PETERSON and N. SAKAI [2]
*NORDITA, Copenhagen, Denmark*

Received 22 April 1980




$$|p\rangle = \mathscr{P}_{3q}|uud\rangle + \mathscr{P}_{5q}|uudc\bar{c}\rangle + \ldots$$

Recent data give unexpectedly large cross-sections for charmed particle production at high $x_F$ in hadron collisions. This may imply that the proton has a non-negligible uudc$\bar{c}$ Fock component. The interesting consequences of such a hypothesis are explored.

# The charm of the proton

- ✓ Common assumption in PDF fits: the static proton wavefunction does not contain charm quarks: the proton contains intrinsic up, down, strange quarks and anti quarks but no intrinsic charm quarks
- ✓ It does not need to be so, as an intrinsic charm component is predicted in many models.

in this scenario, the charm PDF extracted from data in the global fit is the combination of the **perturbative** (DGLAP) and the **intrinsic** components

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

***Extracted phenomenologically from data***

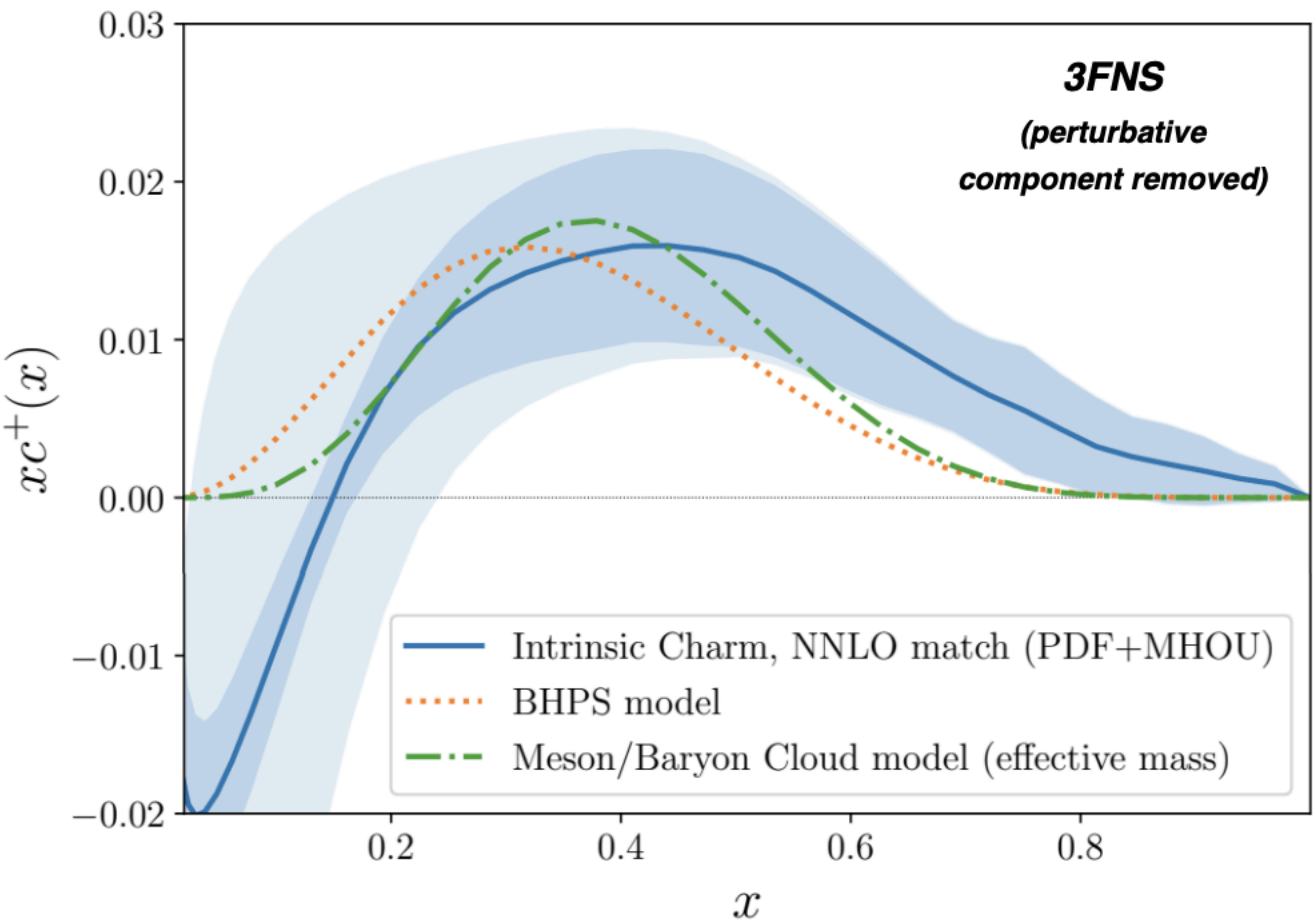
***from QCD evolution and matching***

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

How to **disentangle perturbative** from **intrinsic components?**

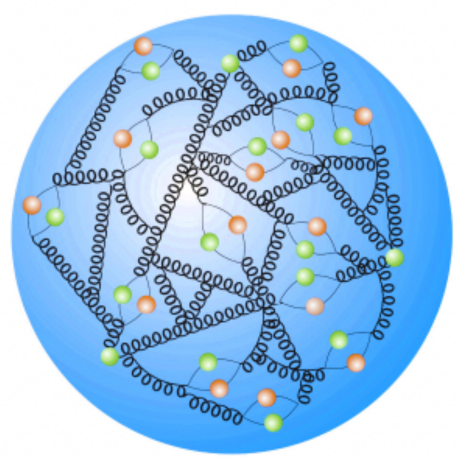
*nb we **define IC** as the charm PDF once know perturbative component is removed*

# The charm 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)

# Conclusions



✓ The fits of the subnuclear structure of the proton involve wealth of ingredients from low to high energy: non-perturbative effects, perturbative QCD, experimental measurements, statistical and mathematical problems, higher order predictions, phenomenology tools, machine learning

✓ We reached a precision that was unthinkable and the very same precision opens deeper problems

✓ After nearly 20 years spent looking into the proton …

*"The same thrill, the same awe and mystery, come again and again when we look at any problem deeply enough. With more knowledge comes deeper, more wonderful mystery, luring one on to penetrate deeper still.*
*Never concerned that the answer may prove disappointing, but with pleasure and confidence we turn over each new stone to find unimagined strangeness leading on to more wonderful questions and mysteries -- certainly a grand adventure! "*

R. P. *Feynman*

Thank you for listening and for your questions!

# What happens at very high energy?

- What happens at scales much above the EWK scale (100 GeV)? SU(3) x SU(2) x U(1) unbroken!

$$f_i(x,\mu) = x \int \frac{dy}{2\pi}\, e^{-i\,2x\bar{n}\cdot p\,y} \langle p|\, \bar{\psi}^{(i)}(y)\, \bar{n}\!\!\!/\, \psi^{(i)}(-y) |p\rangle\,,$$
$$f_{\bar{i}}(x,\mu) = x \int \frac{dy}{2\pi}\, e^{-i\,2x\bar{n}\cdot p\,y} \langle p|\, \psi^{(i)}(y)\, \bar{n}\!\!\!/\, \bar{\psi}^{(i)}(-y) |p\rangle\,,$$

- 42: 8 quark PDFs and 4 lepton PDFs for each generation
- 1 gluon PDF

$$\begin{pmatrix} f_\gamma \\ f_Z \\ f_{\gamma Z} \end{pmatrix} = \begin{pmatrix} c_W^2 & s_W^2 & c_W s_W \\ s_W^2 & c_W^2 & -c_W s_W \\ -2c_W s_W & 2c_W s_W & c_W^2 - s_W^2 \end{pmatrix} \begin{pmatrix} f_B \\ f_{W_3} \\ f_{BW} \end{pmatrix}$$

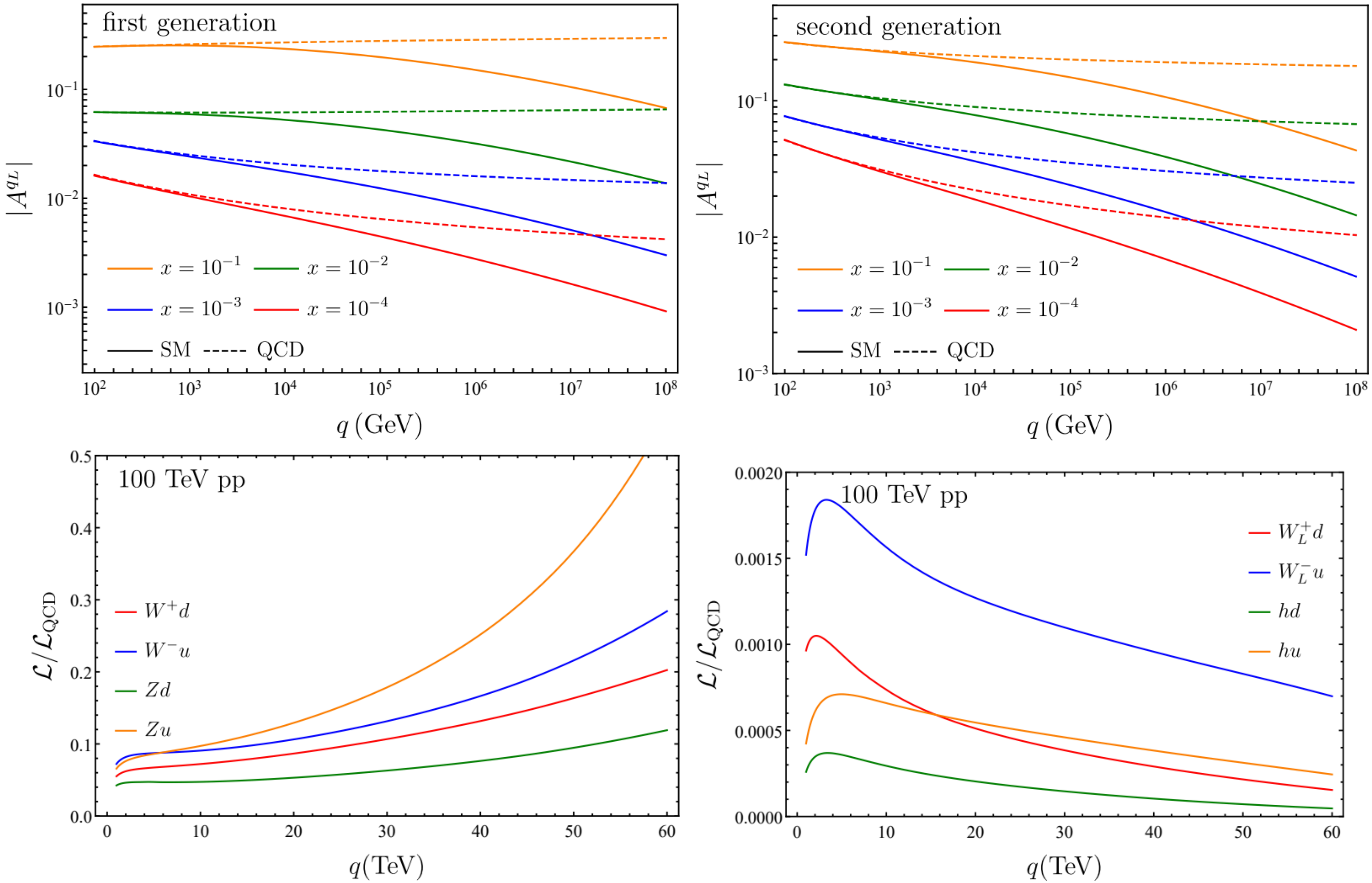
3 V PDFs (mixed BW)

$$f_H(x) = x \int \frac{dy}{2\pi}\, e^{-i\,2x\bar{n}\cdot p\,y} \langle p|\, \Phi(y)\Phi(-y) |p\rangle$$

4 PDFs for the Higgs

Bauer et al,1703.08562

# What happens at very high energy?




Bauer et al,1703.08562