Global analyses of precision LHC data: from PDFs to the SMEFT

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Particle Physics Seminar

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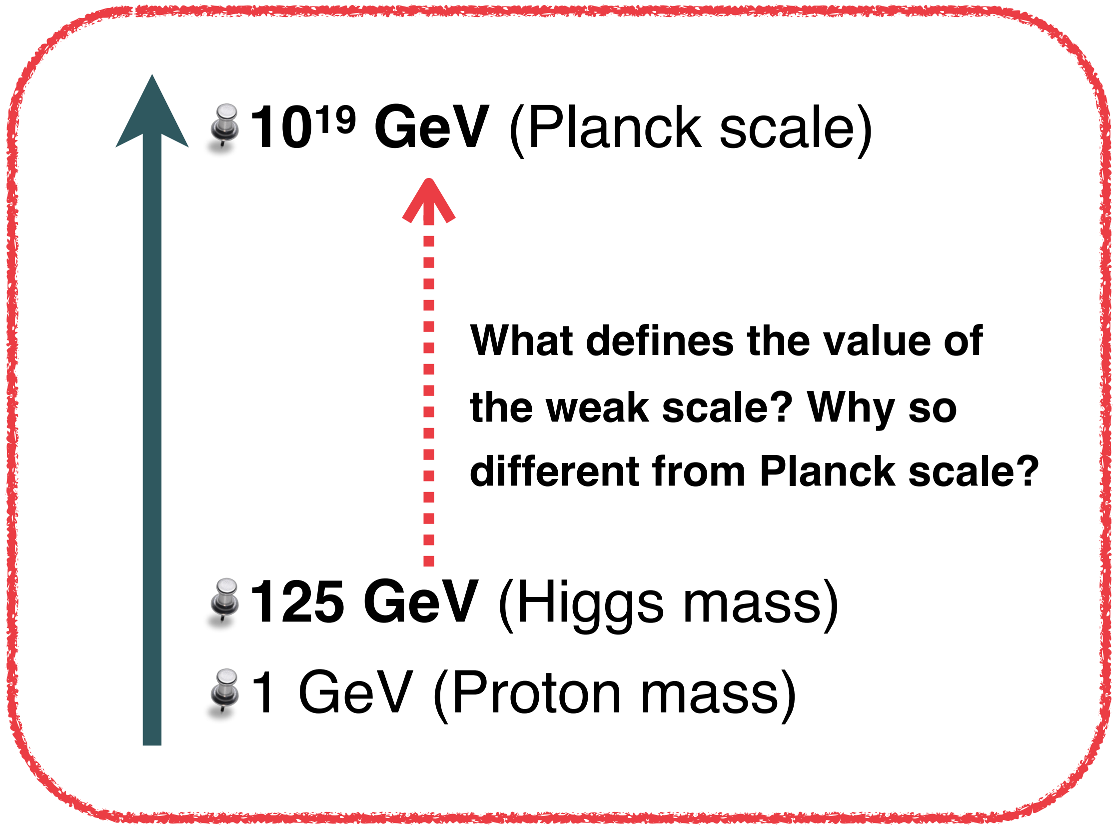
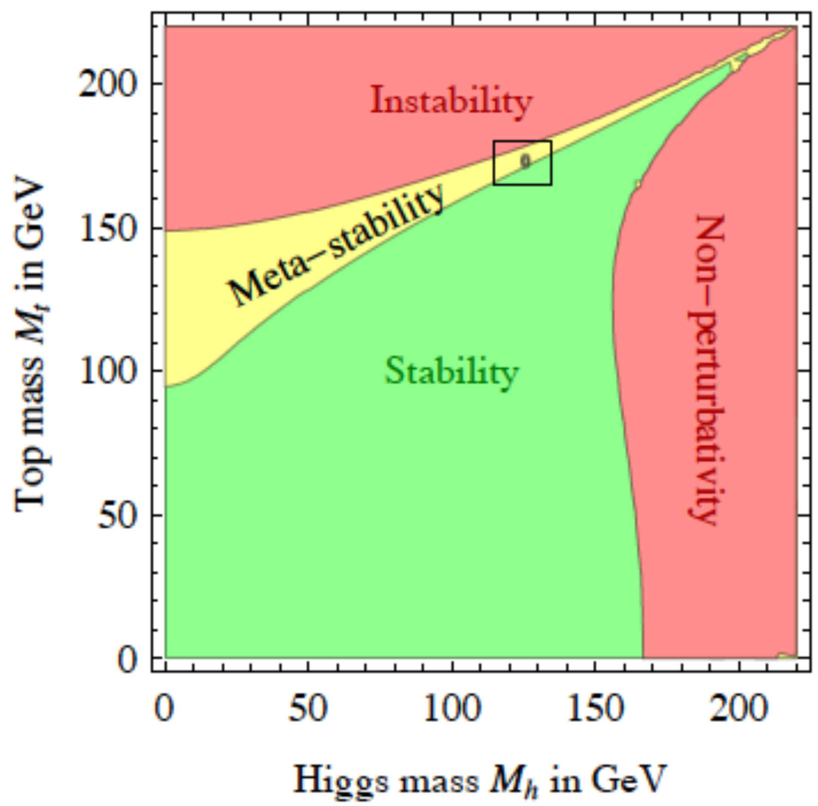
Particle Physics in the Higgs boson era

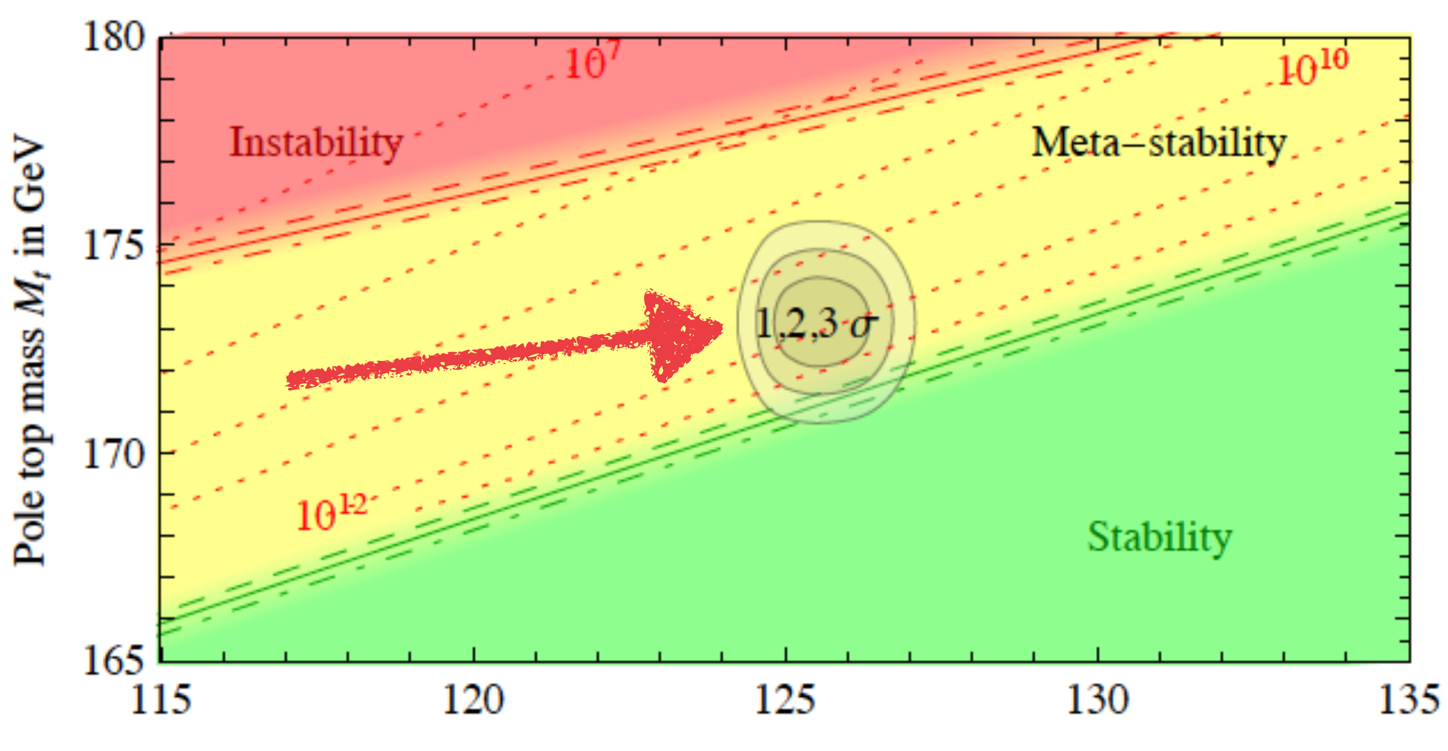
Open questions in particle physics

The Higgs boson

- Huge gap between **weak** and **Plank scales?**
- **Compositeness**? Non-minimal Higgs sector?
- Coupling to **Dark Matter**? Role in cosmological phase transitions?
- Is the **vacuum state of the Universe** stable?







Degrassi et al 12

Open questions in particle physics

The Higgs boson

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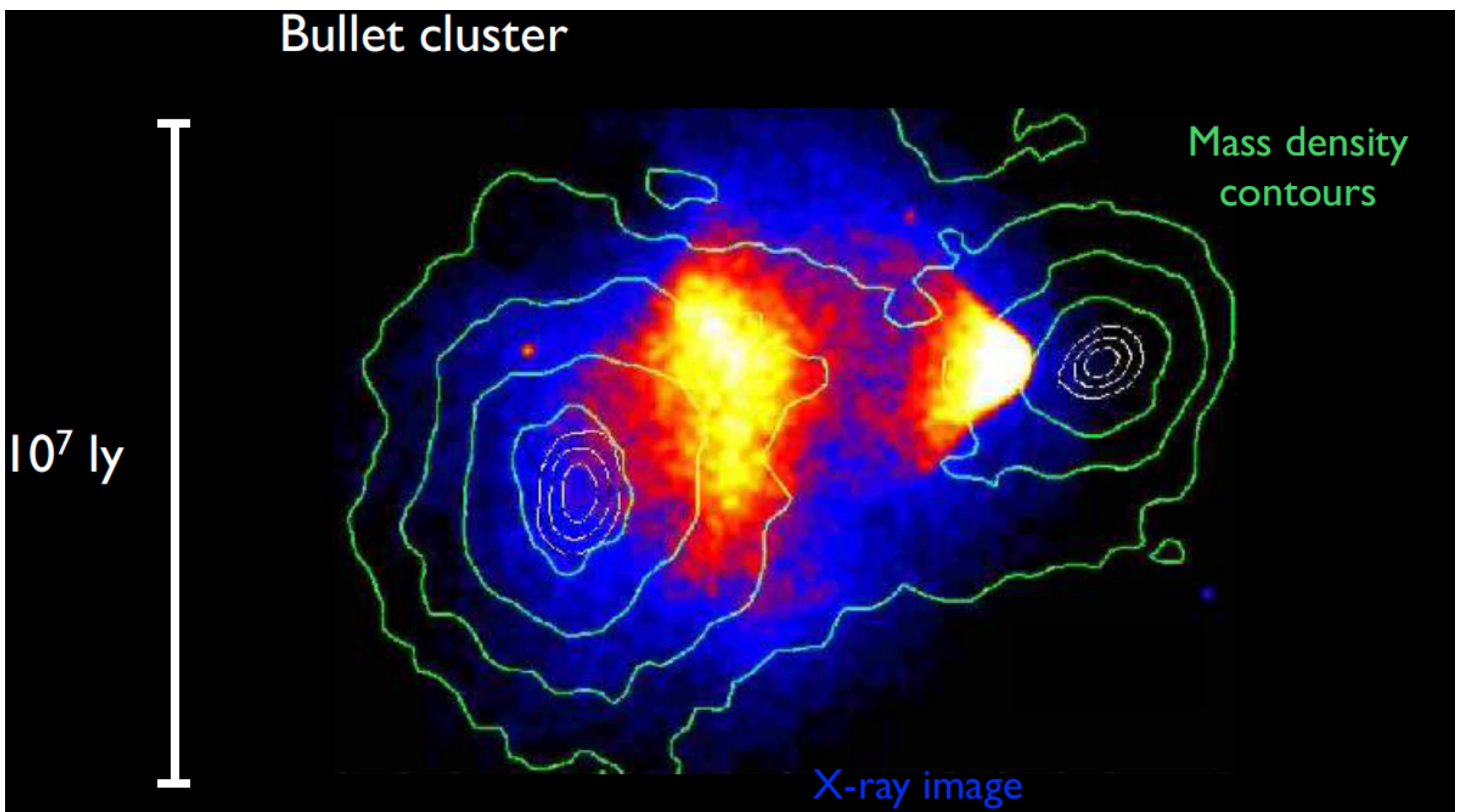
Dark matter

- **Weakly interacting massive particles**? Neutrinos? Ultralight particles (axions)?
- **Interactions** with SM particles? Self-interactions?
- **Structure** of the Dark Sector?



Open questions in particle physics

The Higgs boson

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Quarks and leptons

- Why **3 families?** Origin of **masses, mixings**?
- Origin of **Matter-Antimatter asymmetry?**
- Are **neutrinos Majorana or Dirac**? CP violation in the lepton sector?

Dark matter

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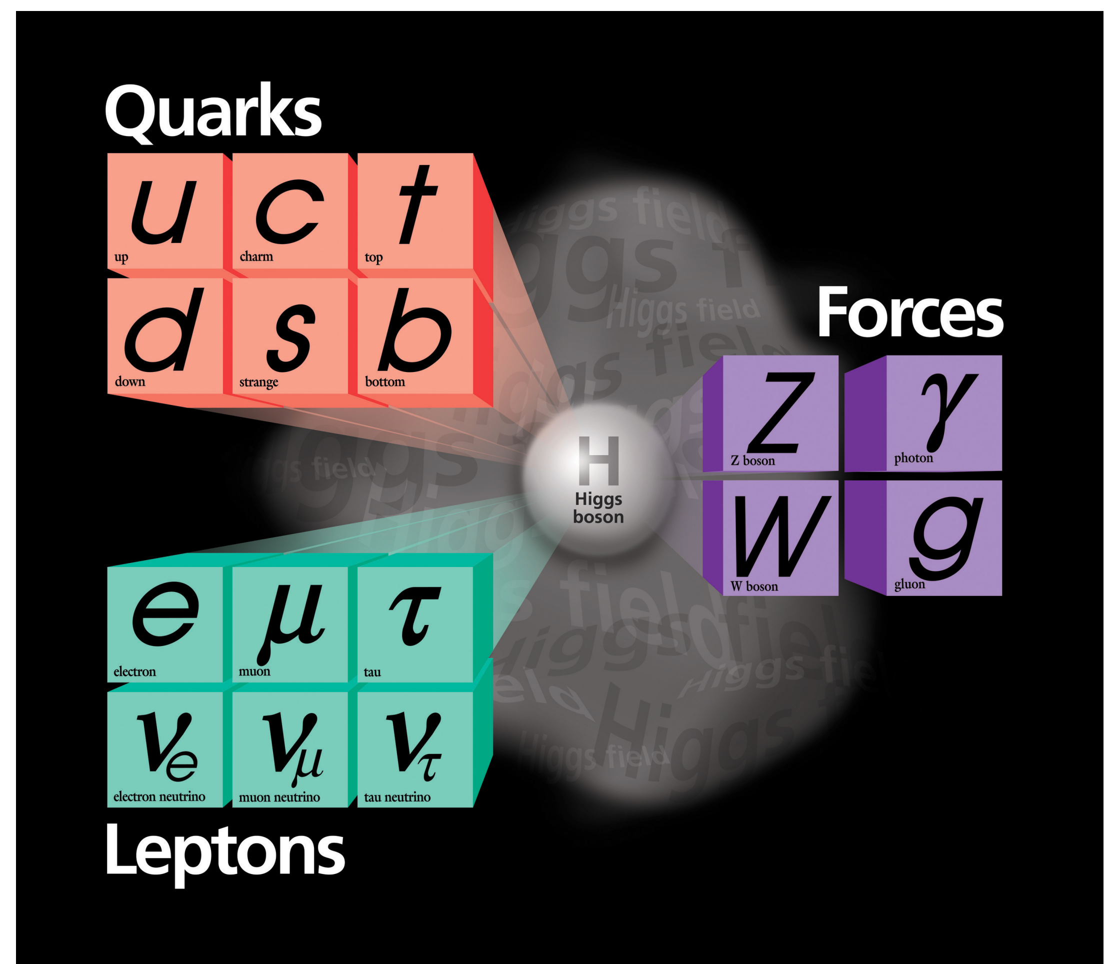
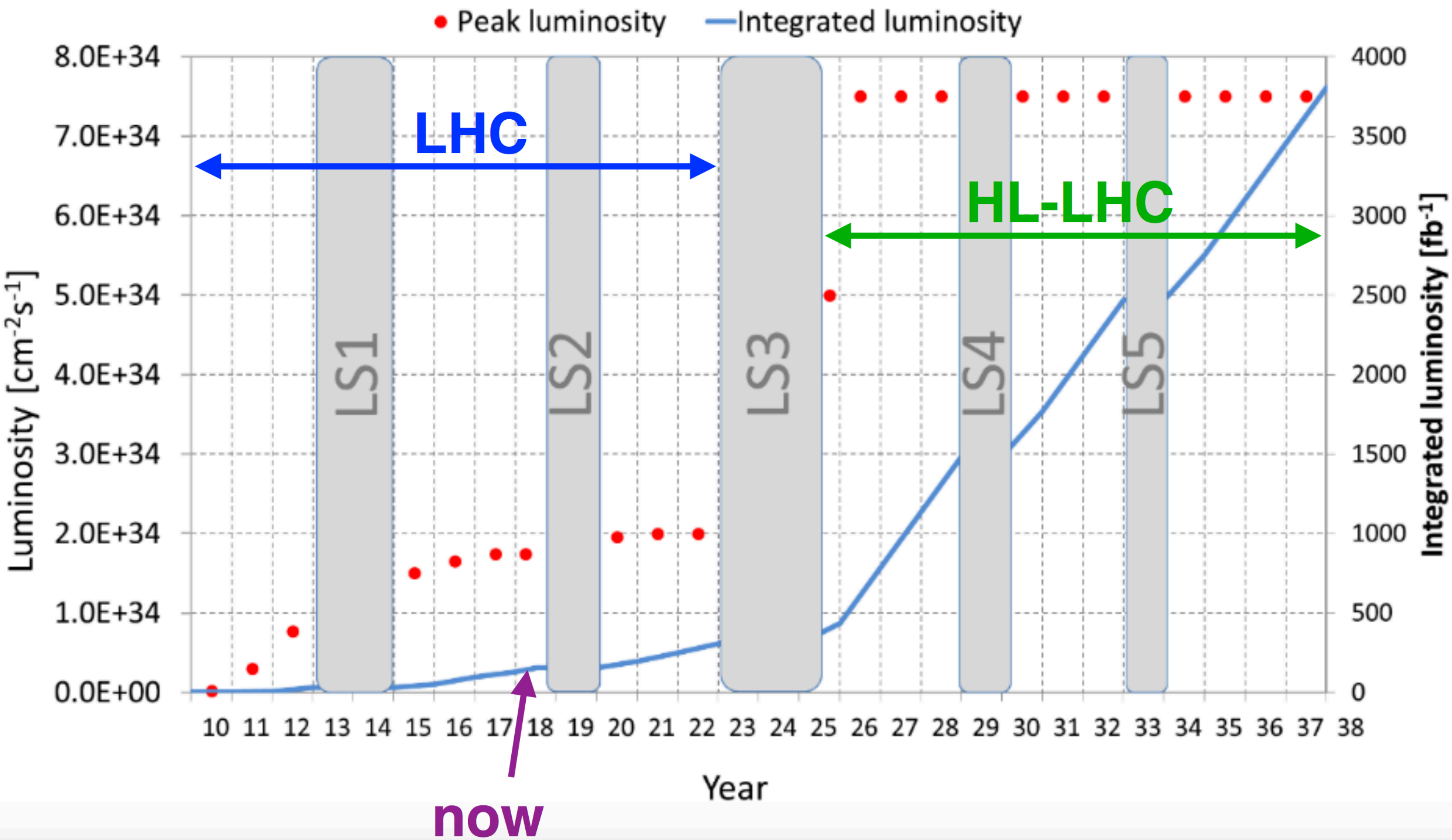


Open questions in particle physics



Crucial information on these fundamental questions will be provided by the LHC: the **exploration of the high-energy frontier** has just started!

Global analyses of LHC data

Many important open issues in particle physics require **global analyses** combining a large number of LHC measurements

The quark and gluon substructure of protons

- PDF constraints from LHC measurements
- Parton distributions with theoretical uncertainties
- Projections for future colliders: HL-LHC and LHeC

Model-independent bSM searches from precision measurements

- Towards a global fit of the Standard Model Effective Field Theory
- The SMEFiT analysis of the top quark sector

The inner life of protons

See also ``The structure of the proton in the LHC precision era''

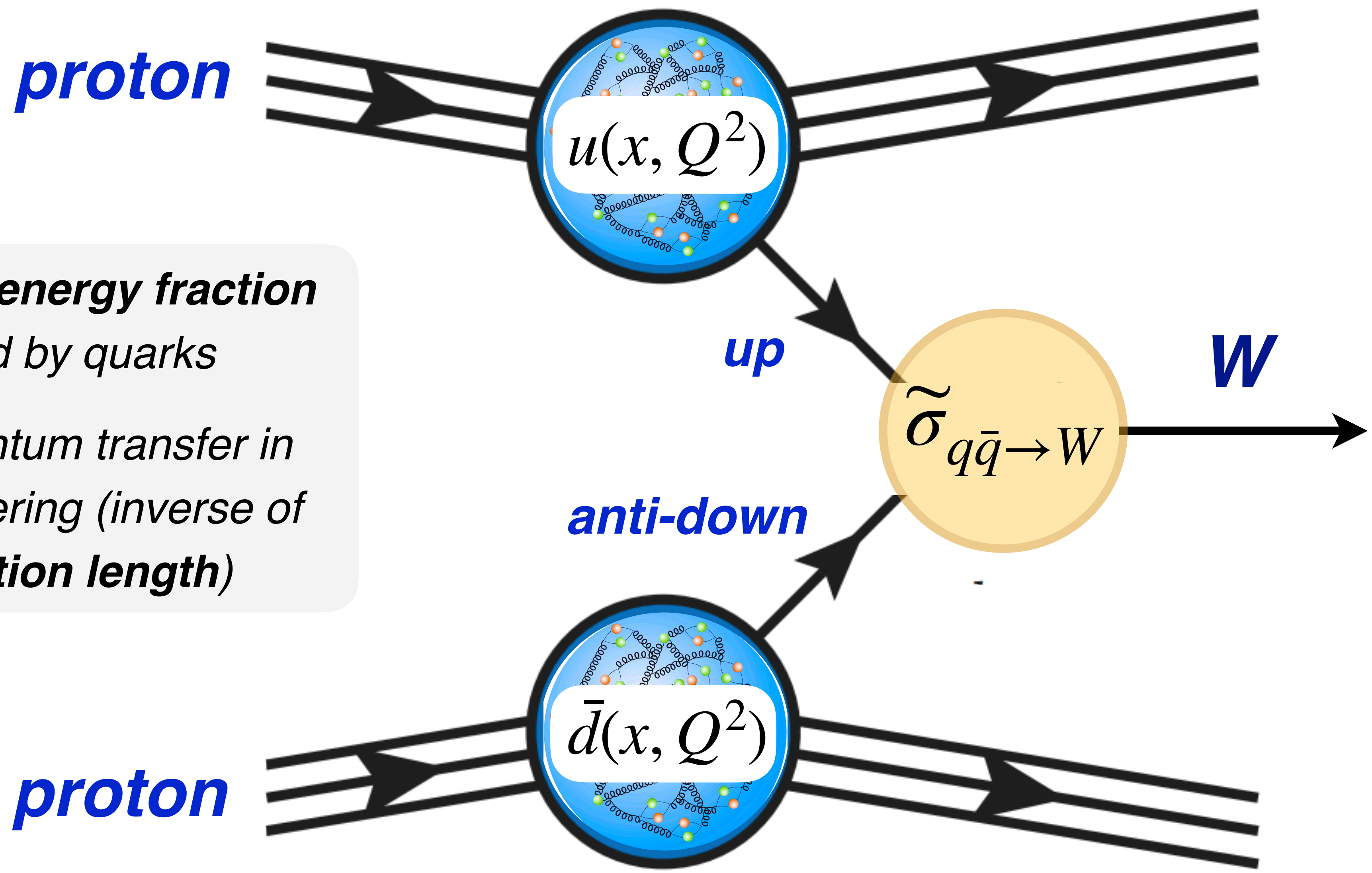
J. Gao, L. Harland-Lang, JR (Physics Reports 17)

Parton distributions @ LHC

QCD Factorisation theorem:

Event rates = **parton distributions** + hard-scattering partonic cross-sections

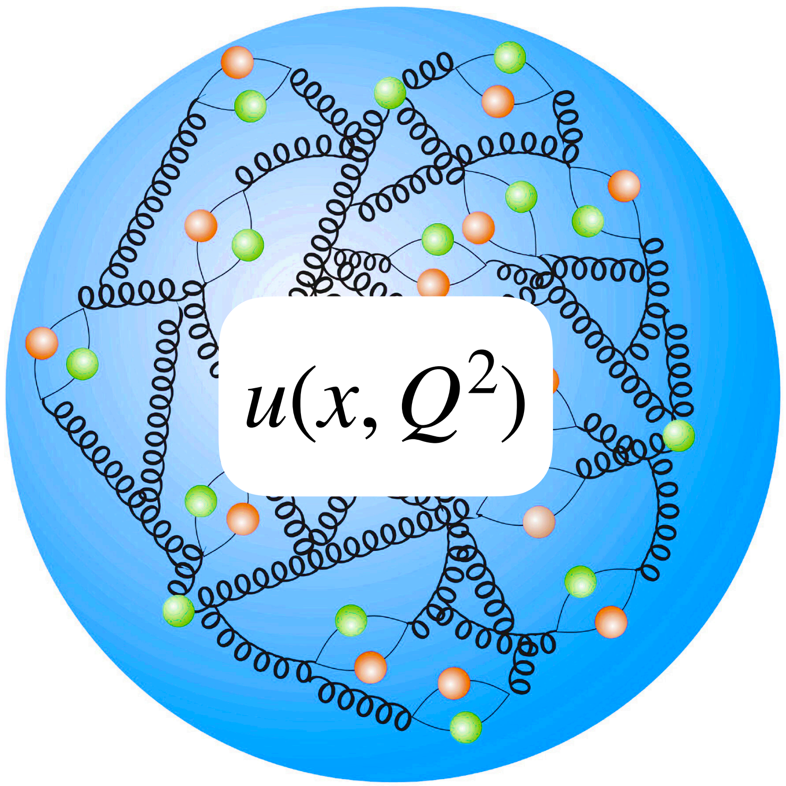
$$N_{\rm LHC}(W) \sim q \otimes \bar{q} \otimes \widetilde{\sigma}_{q\bar{q}\to W} + \mathcal{O}(\alpha_s)$$



x: *proton's* ***energy fraction*** *carried by quarks*

Q: *momentum transfer in hard scattering (inverse of* ***resolution length****)*

Parton distributions @ LHC



Challenging to compute **from first principles**

Determine from data:

Global QCD analysis

Mass? Spin?
Heavy quarks?

Event rates LHC,
RHIC, IceCube?

DGLAP evolution
(*upwards in Q*)

$$\frac{\partial}{\partial \ln Q^2} q_i(x, Q^2) = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(Q^2)\right) q_j(z, Q^2)$$

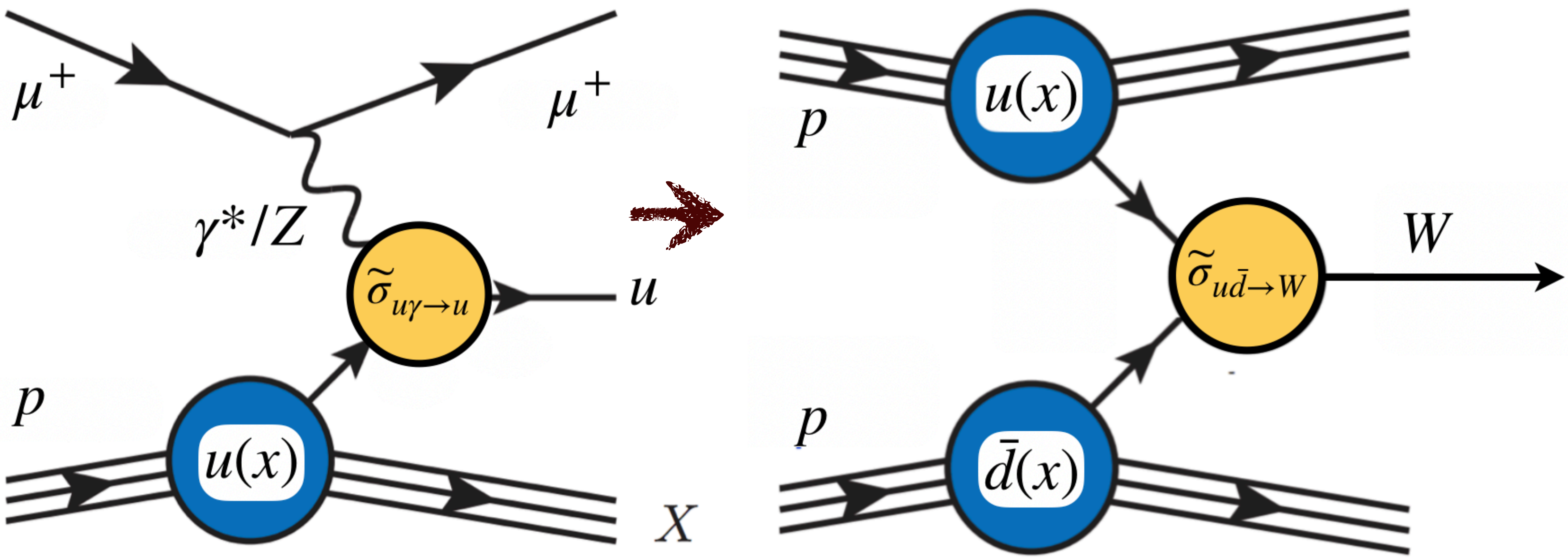
Momentum sum rule
(*energy conservation*)

$$\int_0^1 dx\, x \left(\sum_{i=1}^{n_f} \left[q_i((x, Q^2) + \bar{q}_i(x, Q^2)\right] + g(x, Q^2) \right) = 1$$

QCD factorisation

The **QCD factorization theorems** guarantee **PDF universality**

$$\sigma_{l\,p\to\mu\,X} = \widetilde{\sigma}_{u\gamma\to u} \otimes u(x) \;\rightarrow\; \sigma_{p\,p\to W} = \widetilde{\sigma}_{u\bar{d}\to W} \otimes u(x) \otimes \bar{d}(x)$$



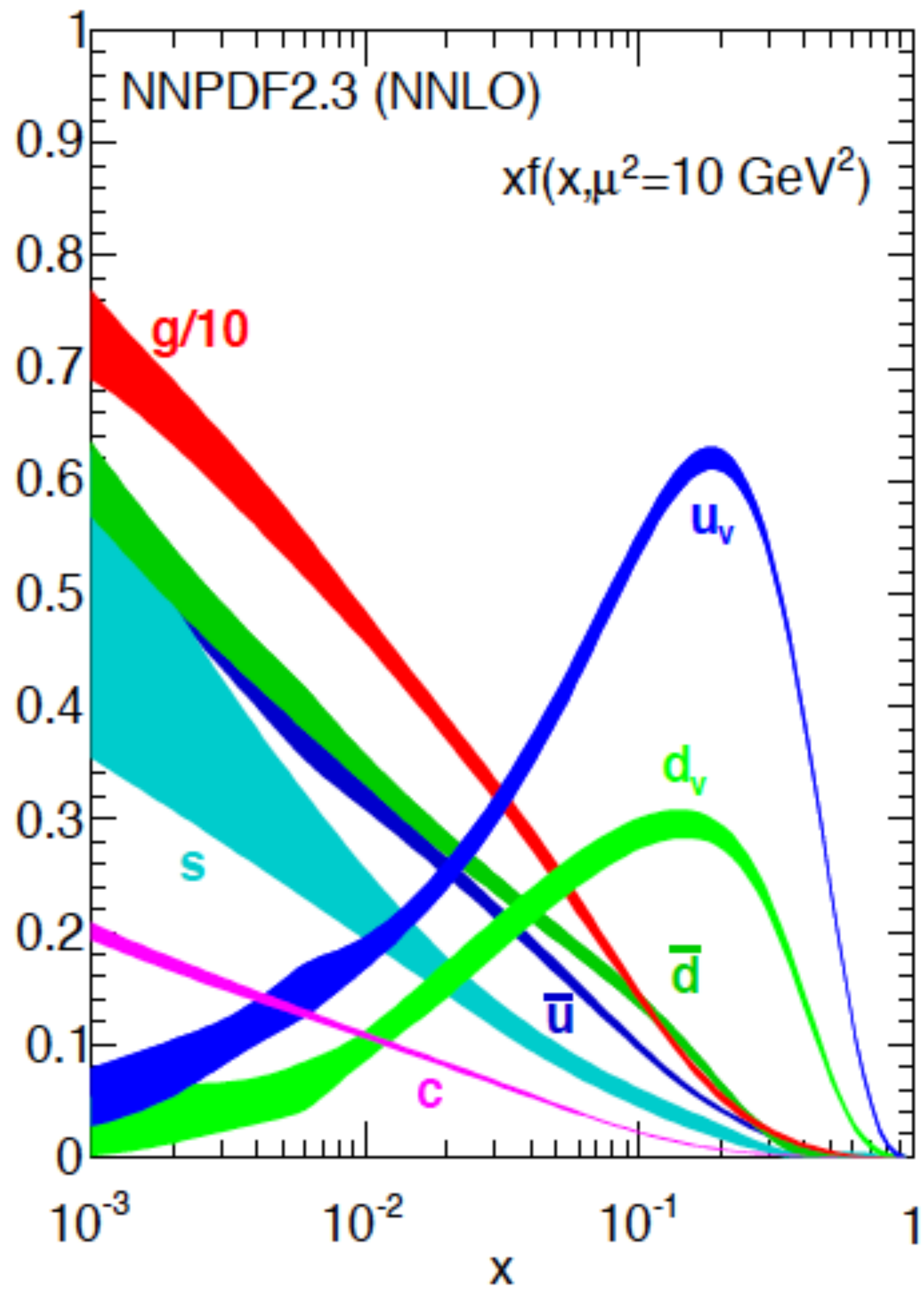
*Determine PDFs in **lepton-proton collisions** (deep-inelastic scattering) …*

*… and use them to compute predictions for **proton-proton collisions***

From the proton mass to the LHC

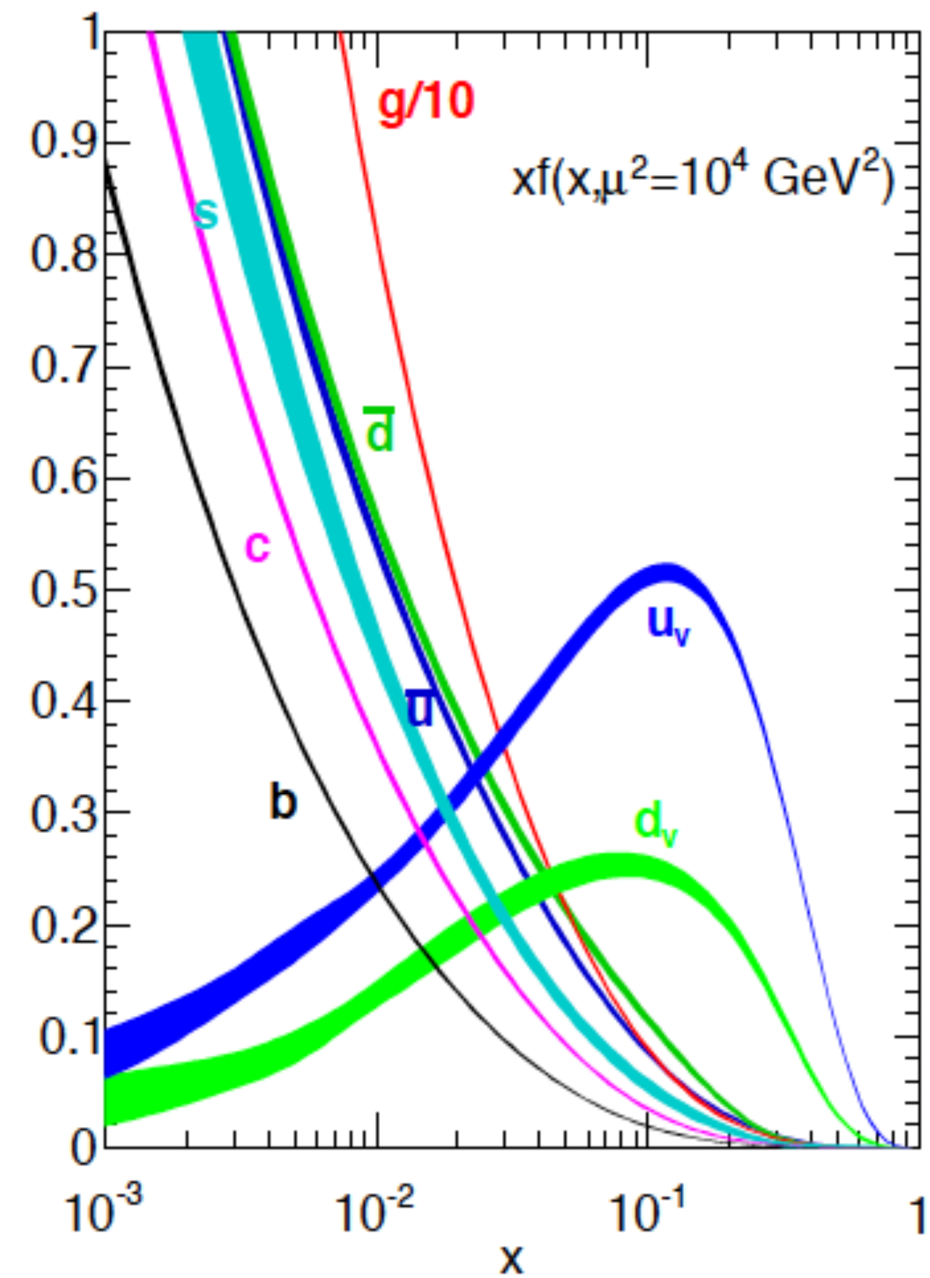
- **Extract PDFs** at hadronic scales (few GeV**),** where **non-perturbative QCD** sets in
- Use **perturbative evolution** to compute PDFs at high scales as **input to LHC predictions**

Hadronic scale: Global PDF fit results

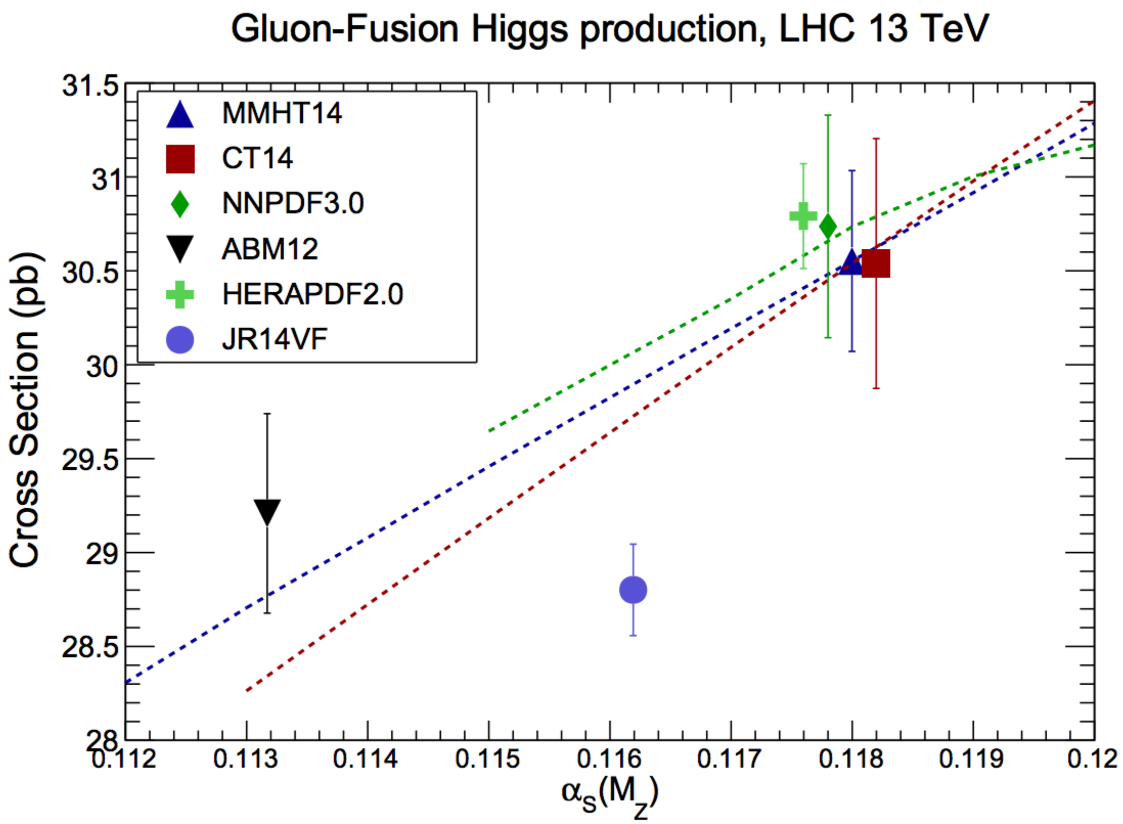


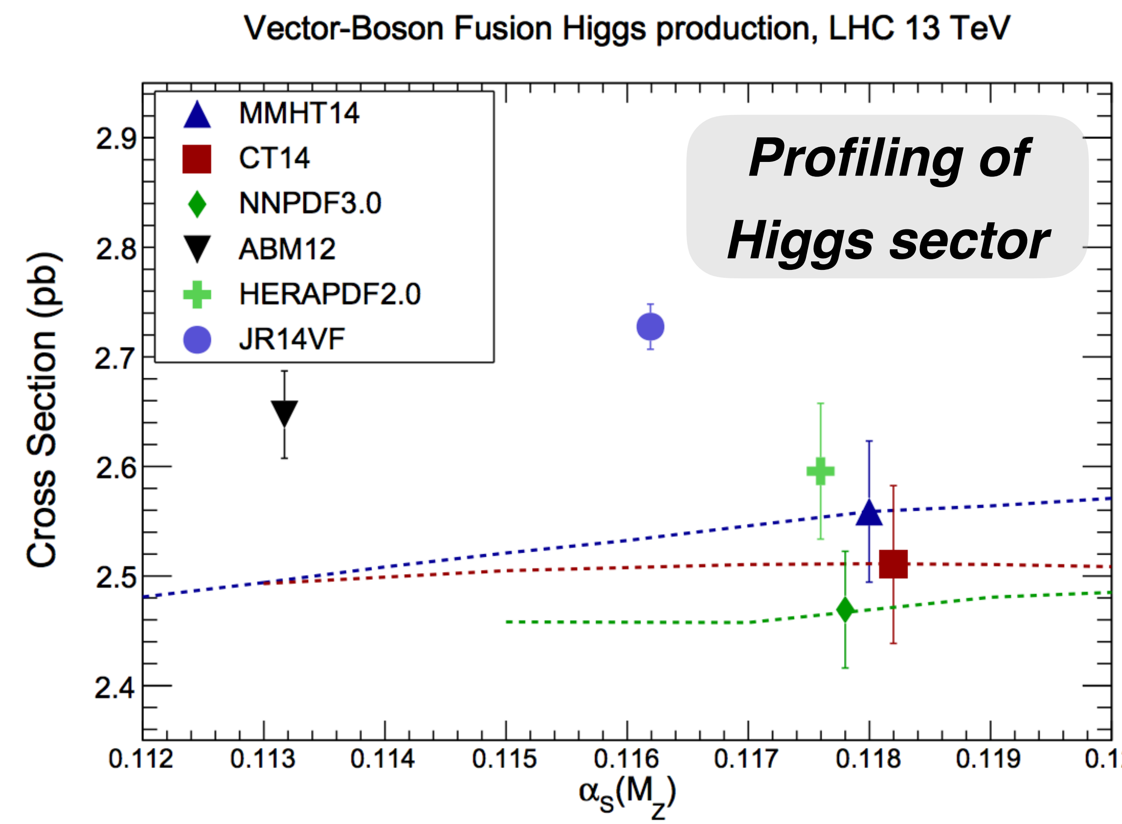
DGLAP Evolution

High scales: input to LHC

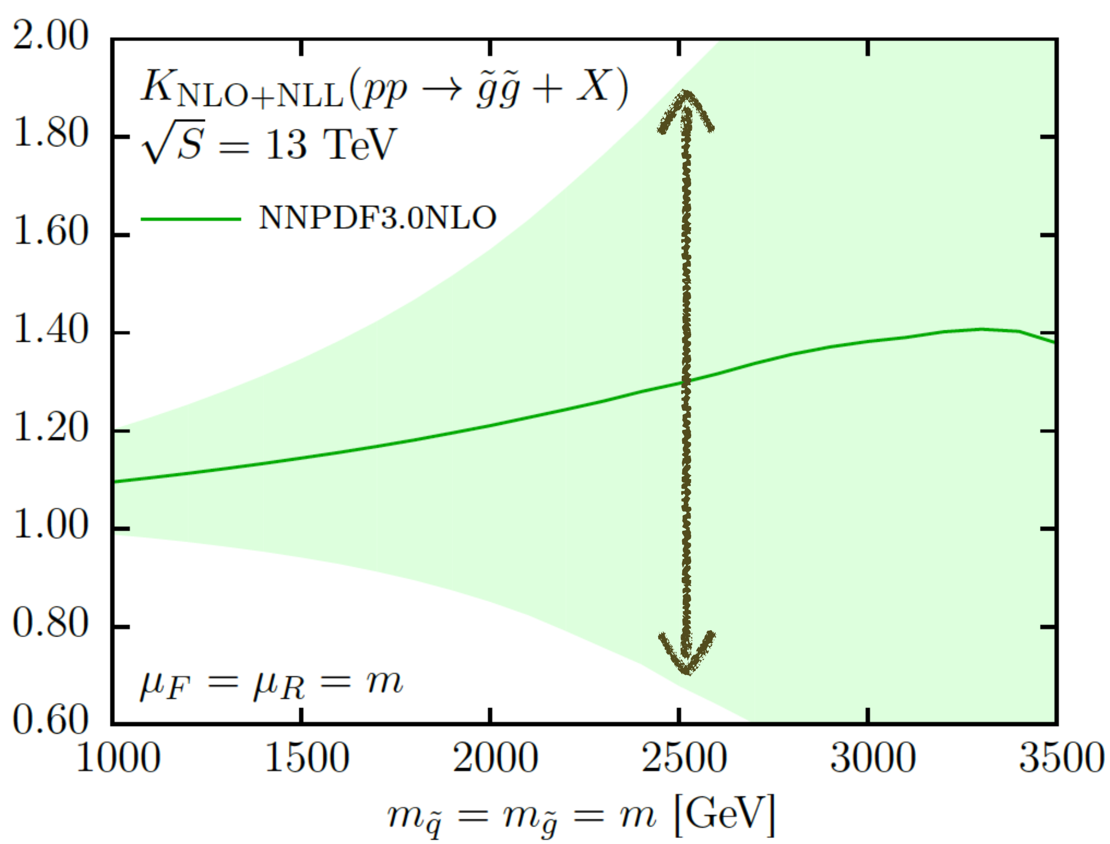


Why better PDFs?

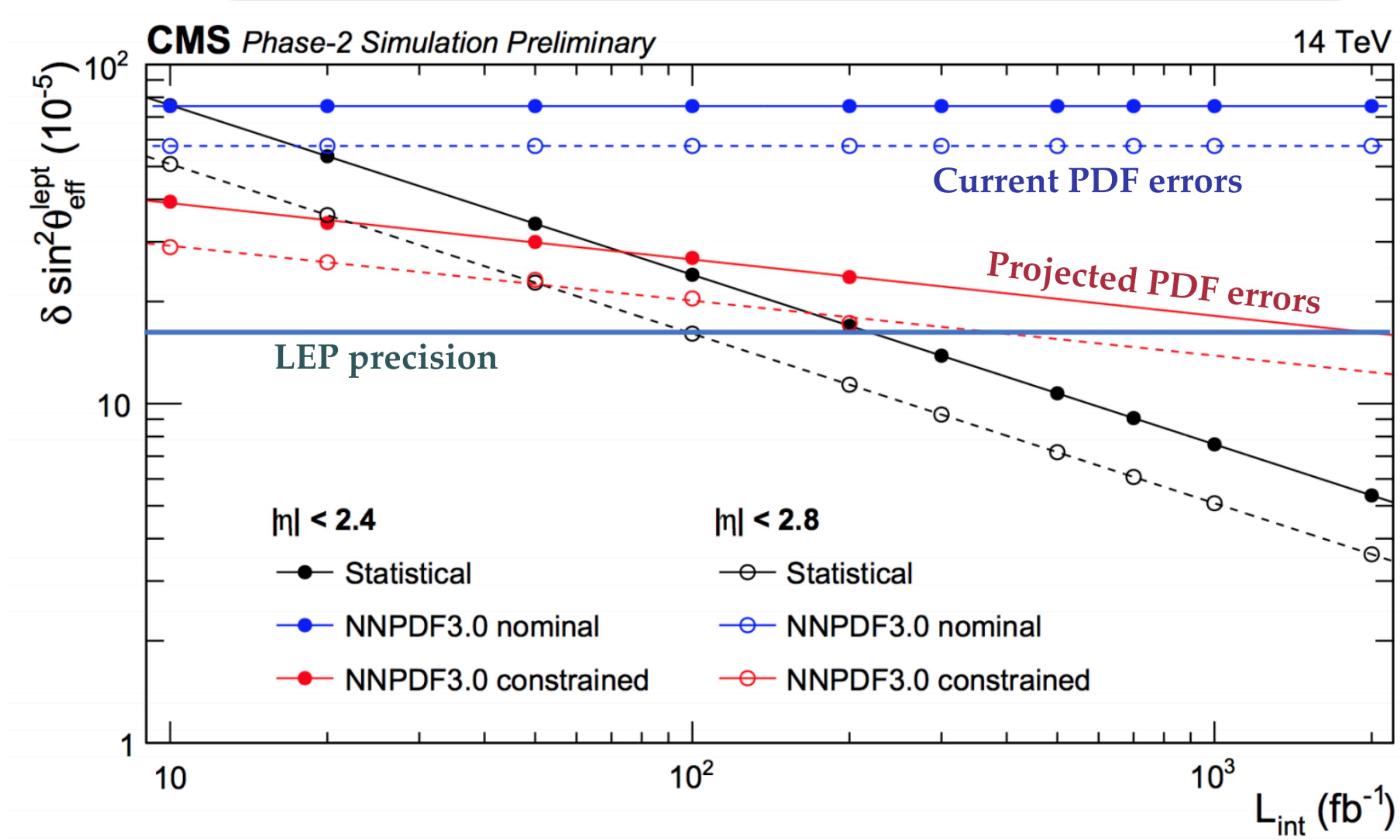




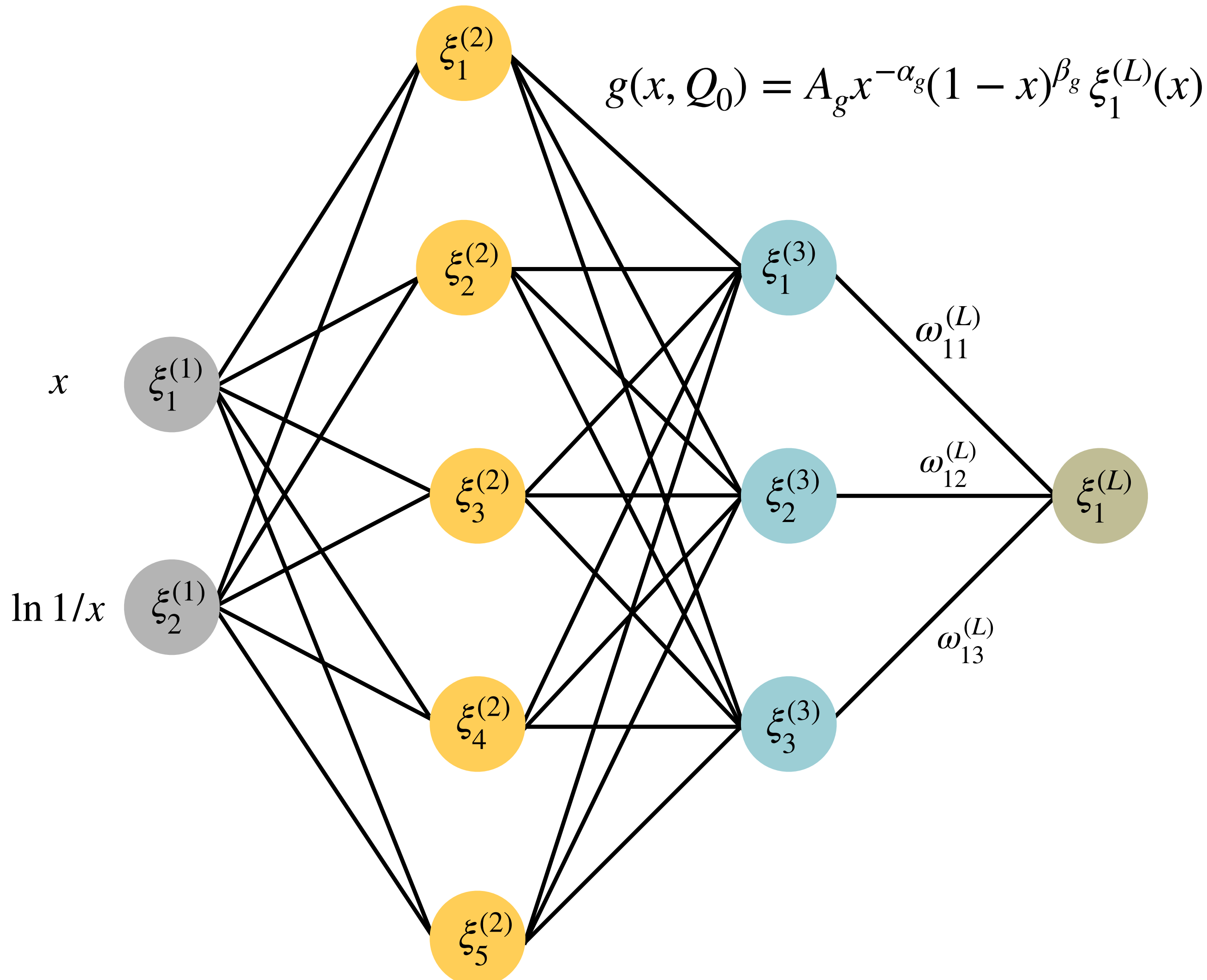
High-mass bSM searches



Precision electroweak measurements



The NNPDF approach to PDF fits



- **Neural Networks** as universal unbiased interpolants to **parametrise PDFs:** eliminate model assumptions
- **Monte Carlo replicas** to propagate uncertainties wo Gaussian assumptions
- **Genetic algorithms** and **Machine Learning** to explore parameter space

	Proton PDFs	***Nuclear PDFs***
Traditional	$g(x) \simeq x^{-b}(1-x)^c$	$R_g(x,A) \simeq (1+bx+cx^2)\times A^d$
Neural Nets	$g(x) \simeq \mathrm{NN}(x)$	$R_g(x,A) \simeq \mathrm{NN}(x,A)$

The NNPDF approach to PDF fits

Experimental data

Fixed-target & collider DIS
Tevatron and LHC measurements
Jets, DY, top, Z pT, ...

Statistical framework

PDF parametrisation,
PDF uncertainties and propagation
Model and theory uncertainties

Theory calculations

The global QCD fit

Minimise figure of merit (*) and determine PDF parameters

fit validation, statistical estimators, diagnosis tools

APFEL WEB

http://apfel.mi.infn.it/
on-line plotting toolbox

LHAPDF

lhapdf.hepforge.org

standard interface for public PDF delivery

(*) $$\chi^2\left(\{a_i\}\right) = \sum_{m,n=1}^{N_{\rm dat}} \left(\sigma_m^{(\rm exp)} - \sigma_m^{(\rm th)}\left(\{a_i\}\right)\right) \left({\rm cov}_{\rm exp} + {\rm cov}_{\rm th}\right)^{-1}_{mn} \left(\sigma_n^{(\rm exp)} - \sigma_n^{(\rm th)}\left(\{a_i\}\right)\right)$$

APPLgrid, FastNLO, aMCfast....

NNLO DGLAP evolution
DIS structure functions

APFEL, HOPPET, QCDNUM, ...

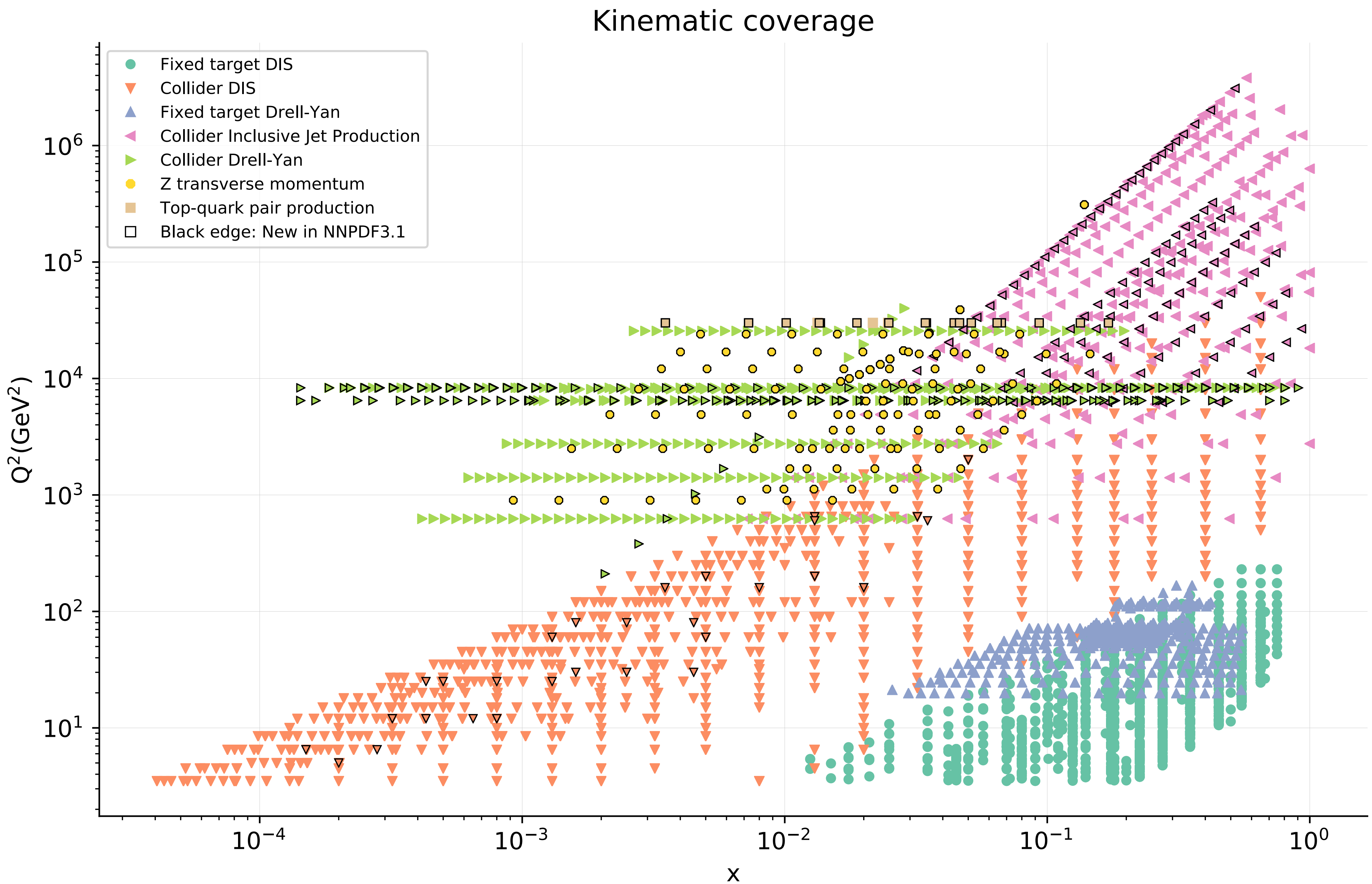
Fast NLO grids
NNLO QCD &
NLO EW K-factors

External (N)NLO codes

MCFM, NLOjet++, FEWZ,
DYNNLO, private codes...

*Combine **precision measurements** and **state-of-the-art theory** within robust statistical framework*

The NNPDF approach to PDF fits



Highly non-trivial validation of the **QCD factorisation framework**:

Including **O(5000) data** points, from **O(40) experiments**, some of them with ≲**1% errors**,

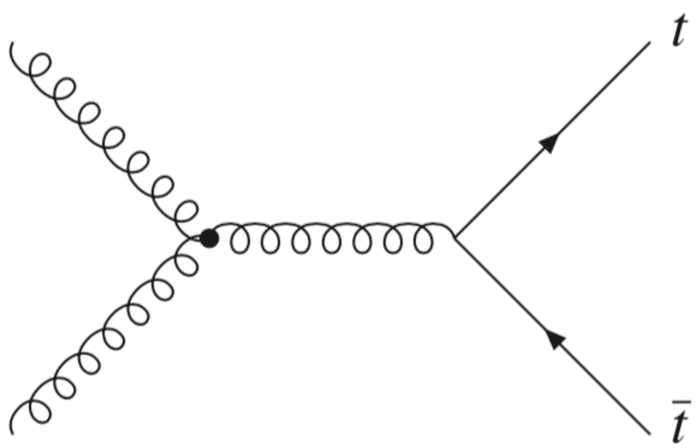
yet the global PDF fit achieves $\boldsymbol{\chi^2/N_{dat}} \approx \mathbf{1}$!

PDF constraints from LHC data

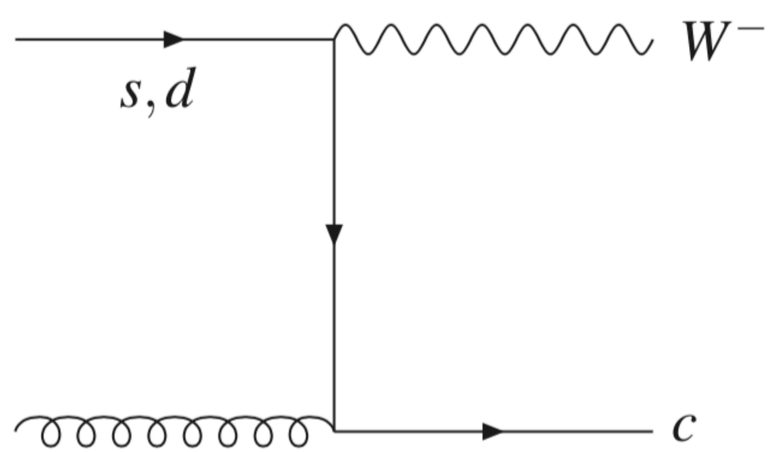
PDF information from p+p collisions

large-x gluon | *strangeness* | *antiquarks*

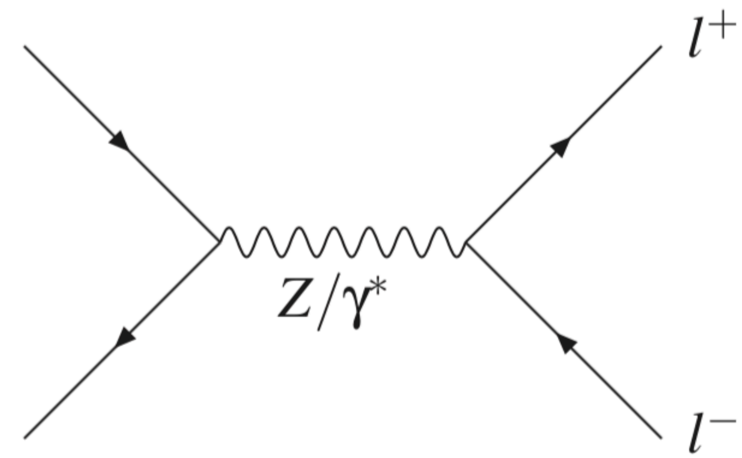
Top quark pair production



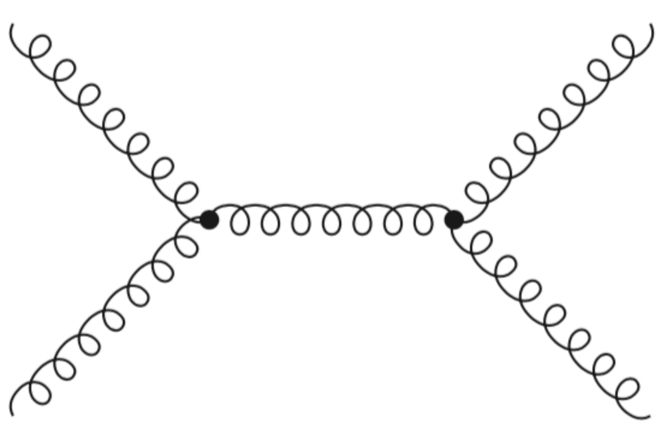
$W+c$ production



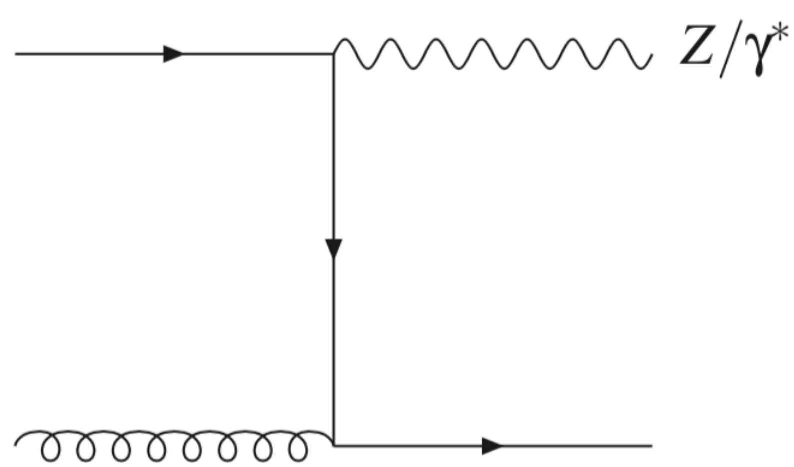
Drell–Yan production



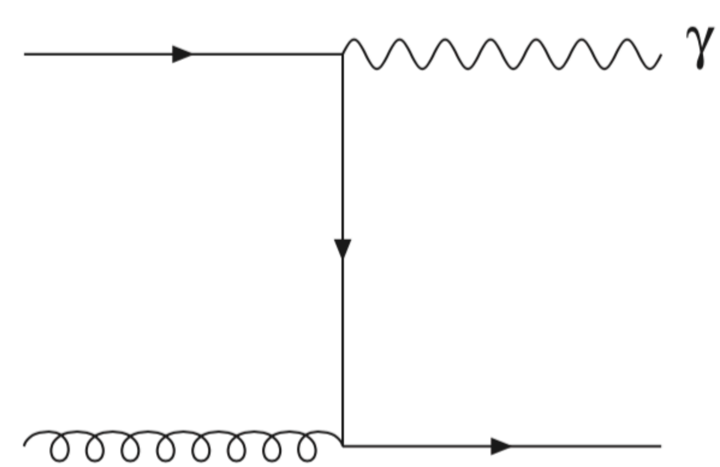
Jet production



$Z\ p_T$



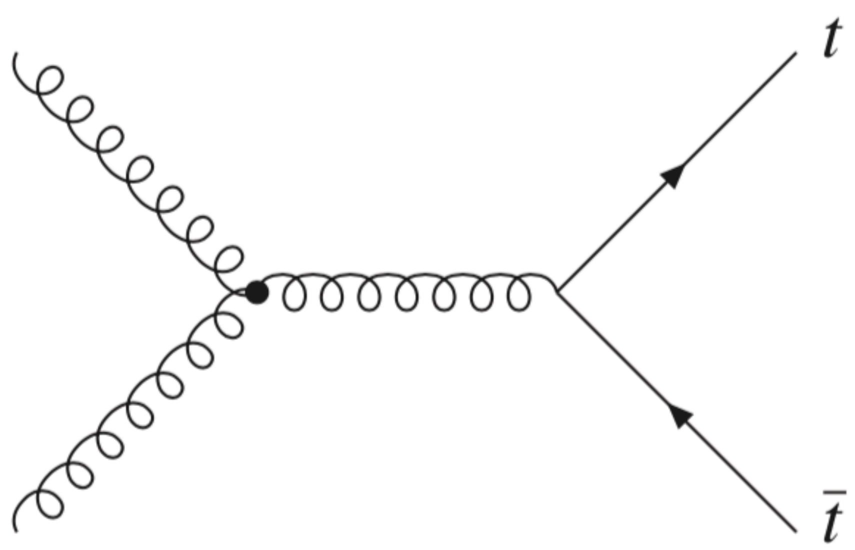
Direct photon production

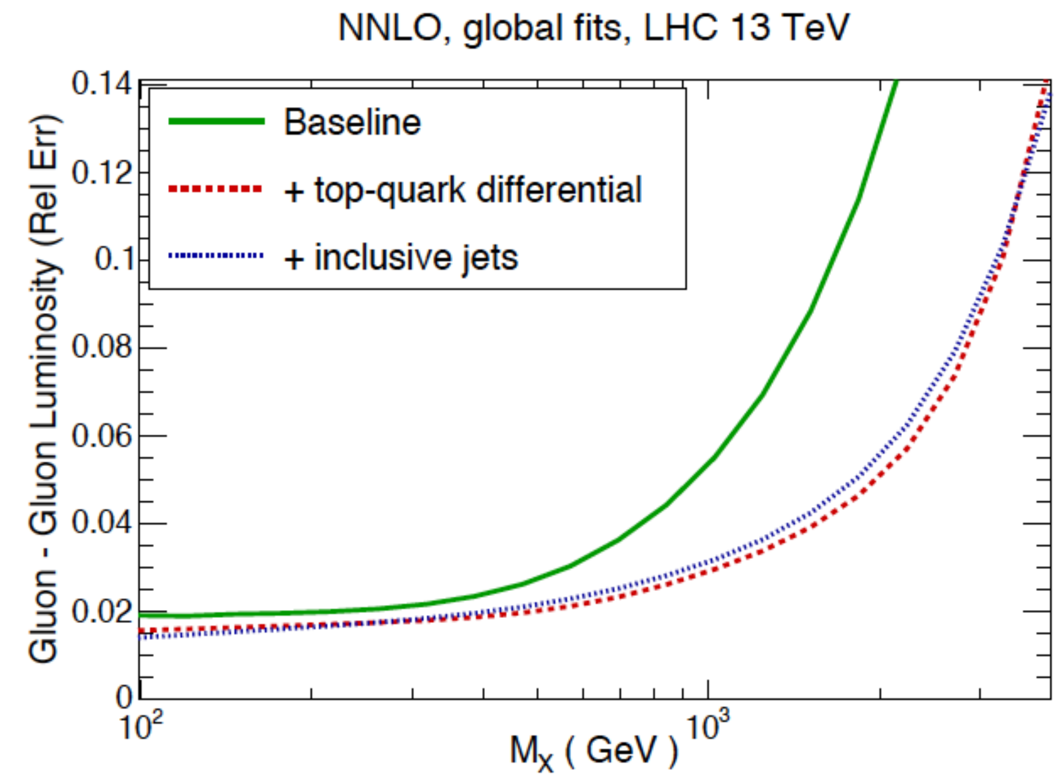


large-x gluon | *medium-x gluon* | *medium-x gluon*

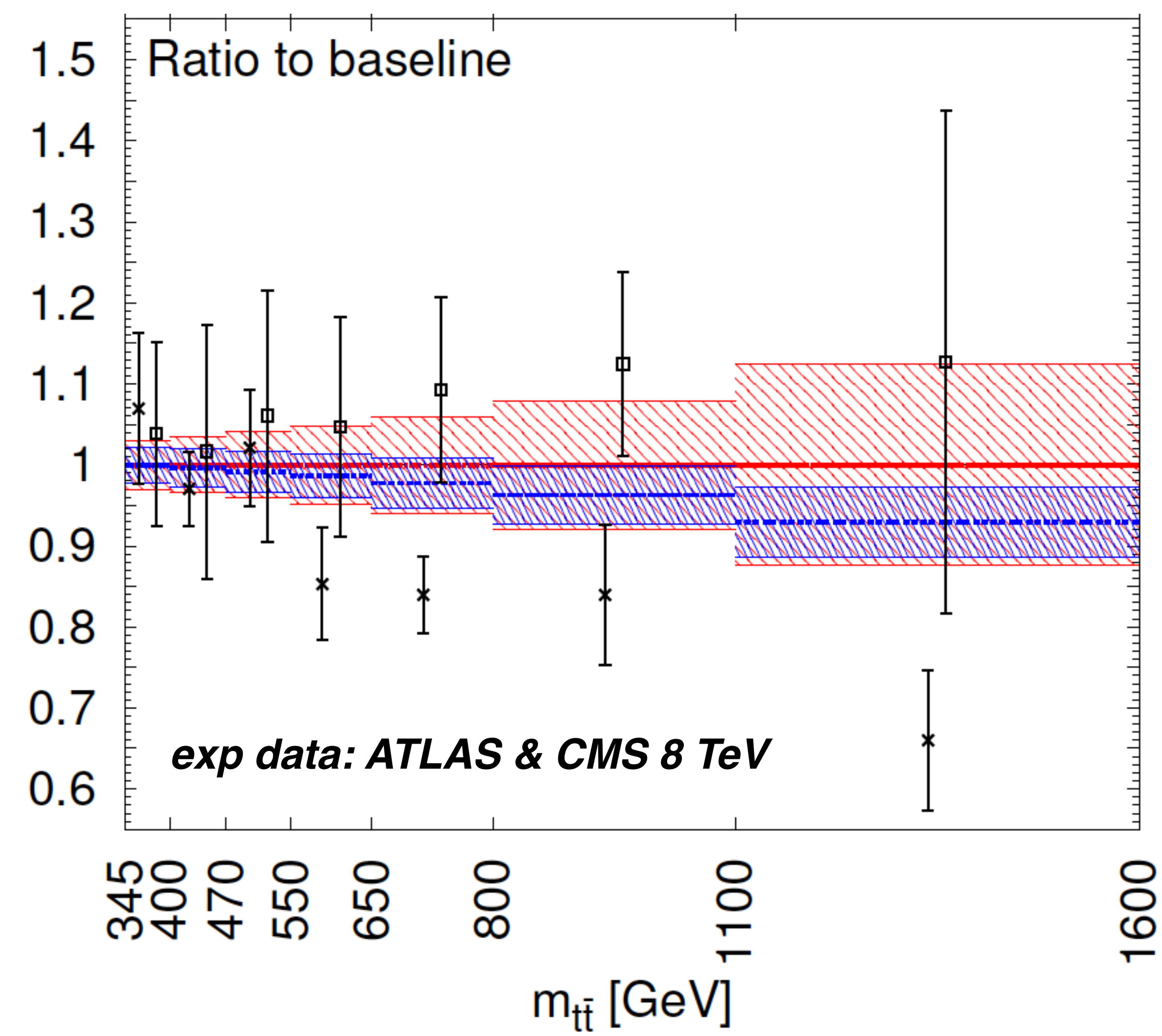
Gluon PDF from top quarks

Top quark pair production





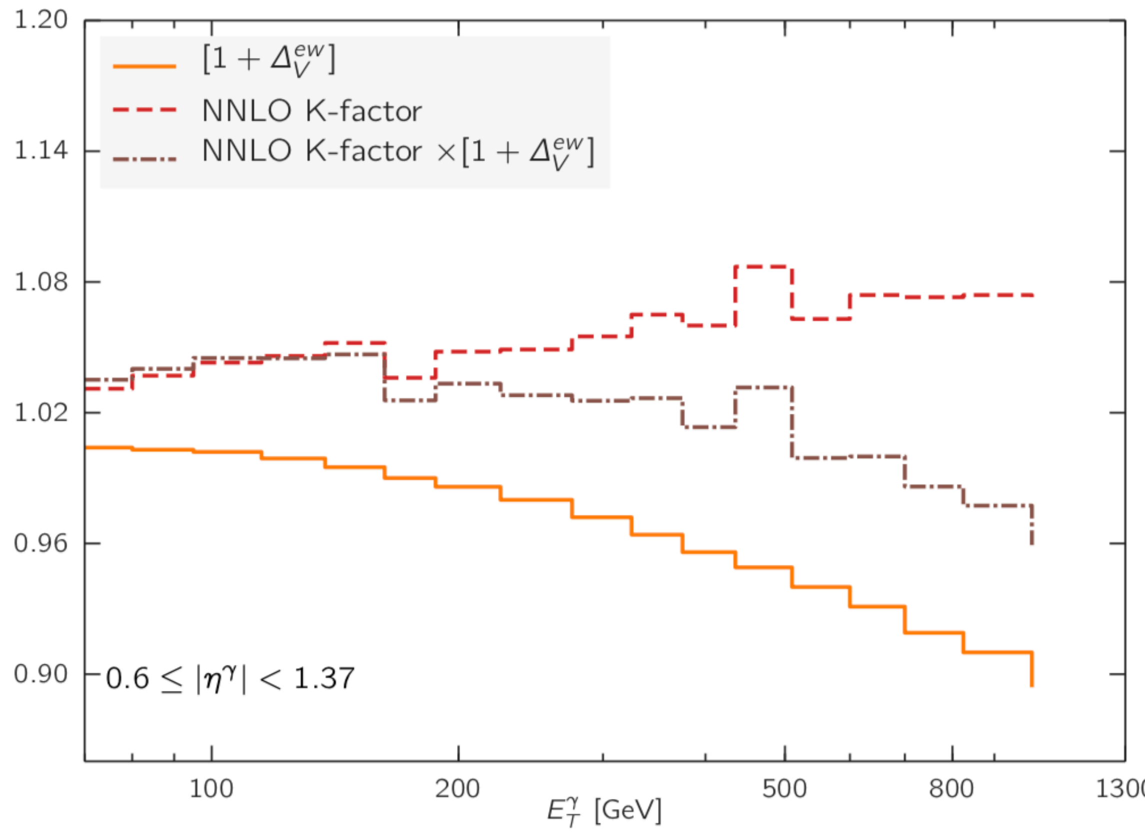
- Complementary probe of the **large-x gluon**
- Included **differential top distributions in NNPDF3.0 NNLO**: constraints on **large-*x* gluon** comparable to inclusive jet production
- Stability wrt choice of distribution (*i.e.* m_{tt} vs y_{tt})
- Reduced theory uncertainties in regions crucial for **searches**, *i.e.*, $\mathbf{m_{tt} > 1}$ **TeV** (fitting $\mathbf{y_t}$ and $\mathbf{y_{tt}}$)



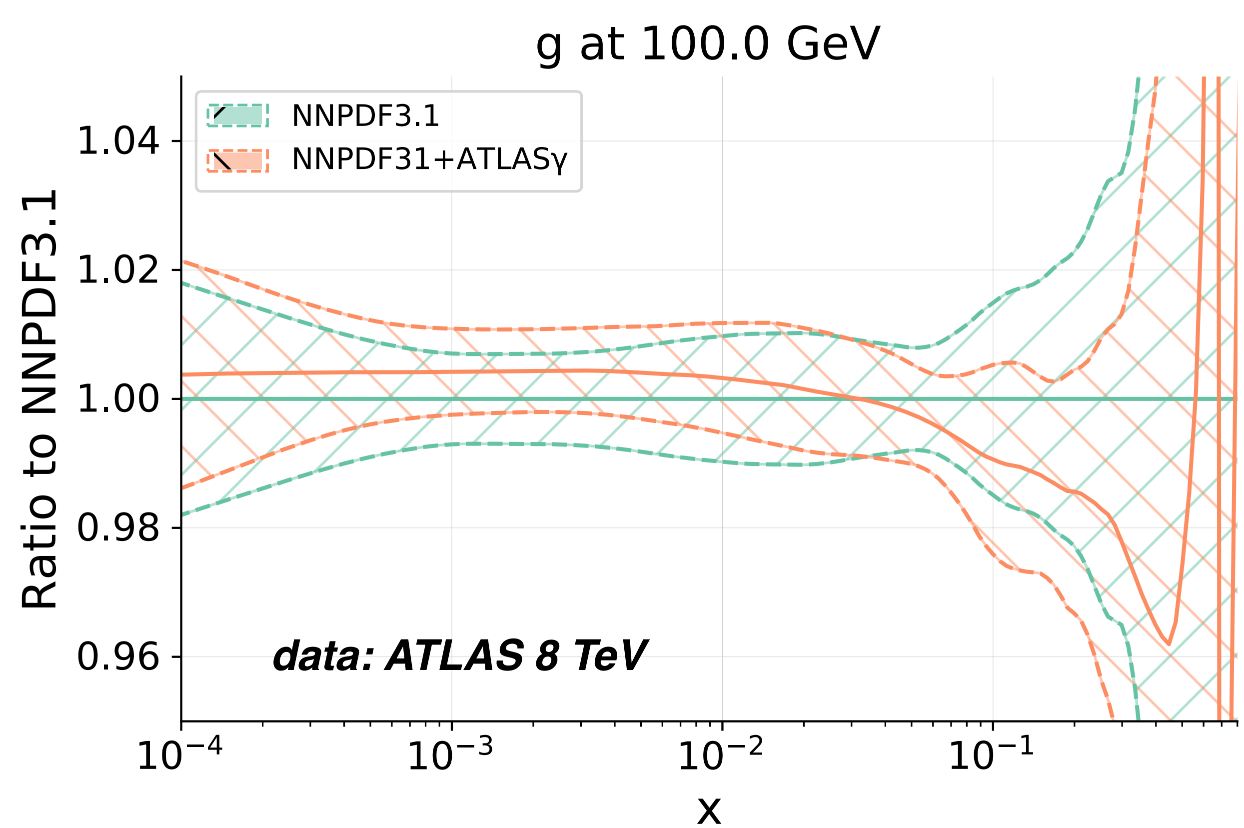
Czakon, Hartland, Mitov, Nocera, JR 16

Gluon PDF from direct photons

- Revisited the impact of LHC **direct photon data** into the global PDF fit
  Campbell, JR, Slade, Williams 18
- Theory based on **NNLO QCD** and **LL electroweak** calculations
- Moderate impact on medium-*x* gluon
- Good **consistency** with other gluon-sensitive experiments in NNPDF3.1



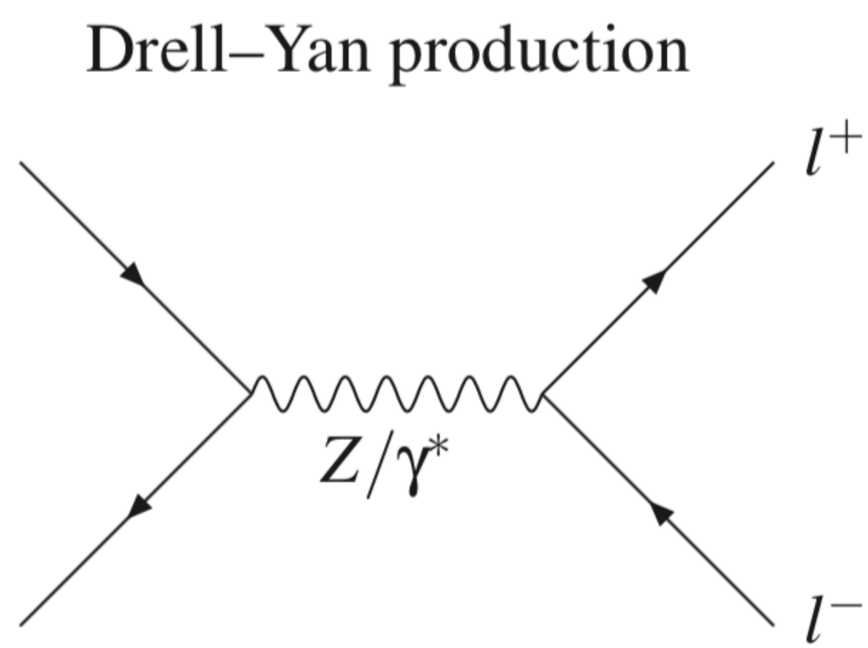
	NNPDF3.1	NNPDF3.1+ATLASγ
Fixed-target lepton DIS	1.207	1.203
Fixed-target neutrino DIS	1.081	1.087
HERA	1.166	1.169
Fixed-target Drell-Yan	1.241	1.242
Collider Drell-Yan	1.356	1.346
Top-quark pair production	1.065	1.049
Inclusive jets	0.939	0.915
Z p_T	0.997	0.980
Total dataset	**1.148**	**1.146**



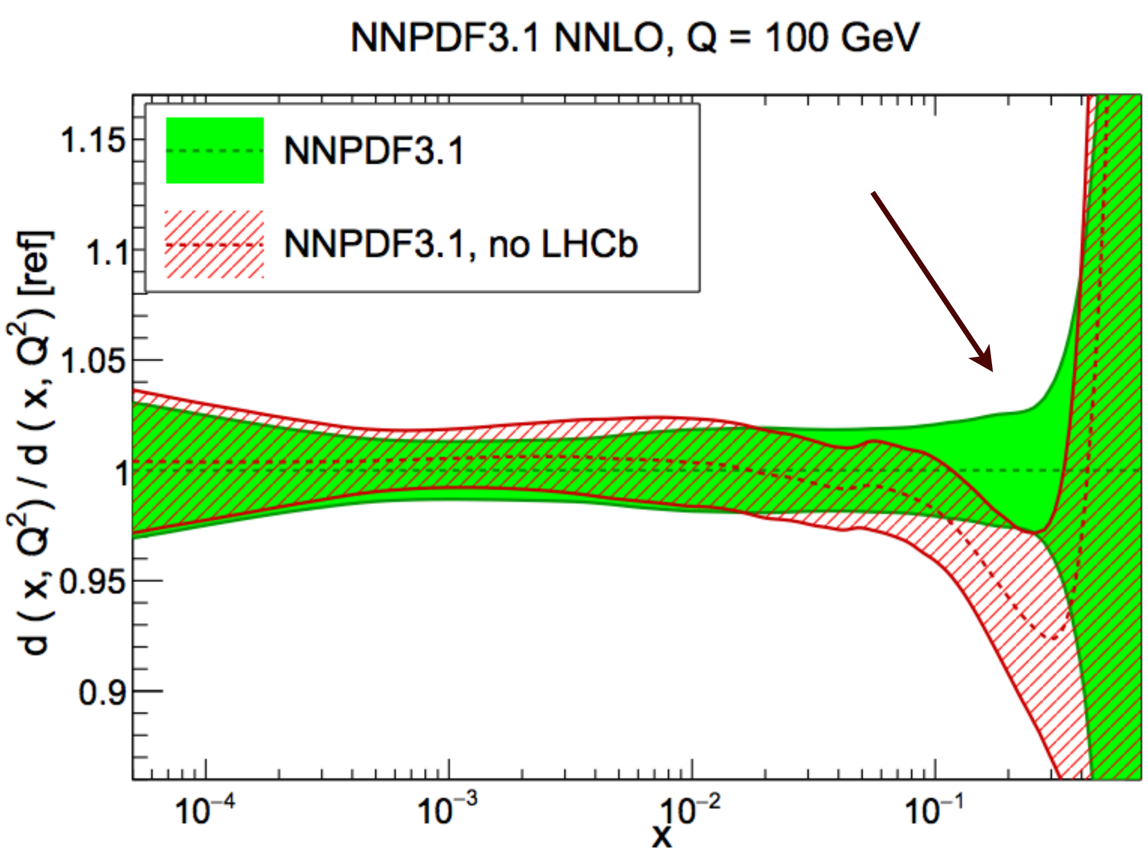
Flavour separation from forward W,Z

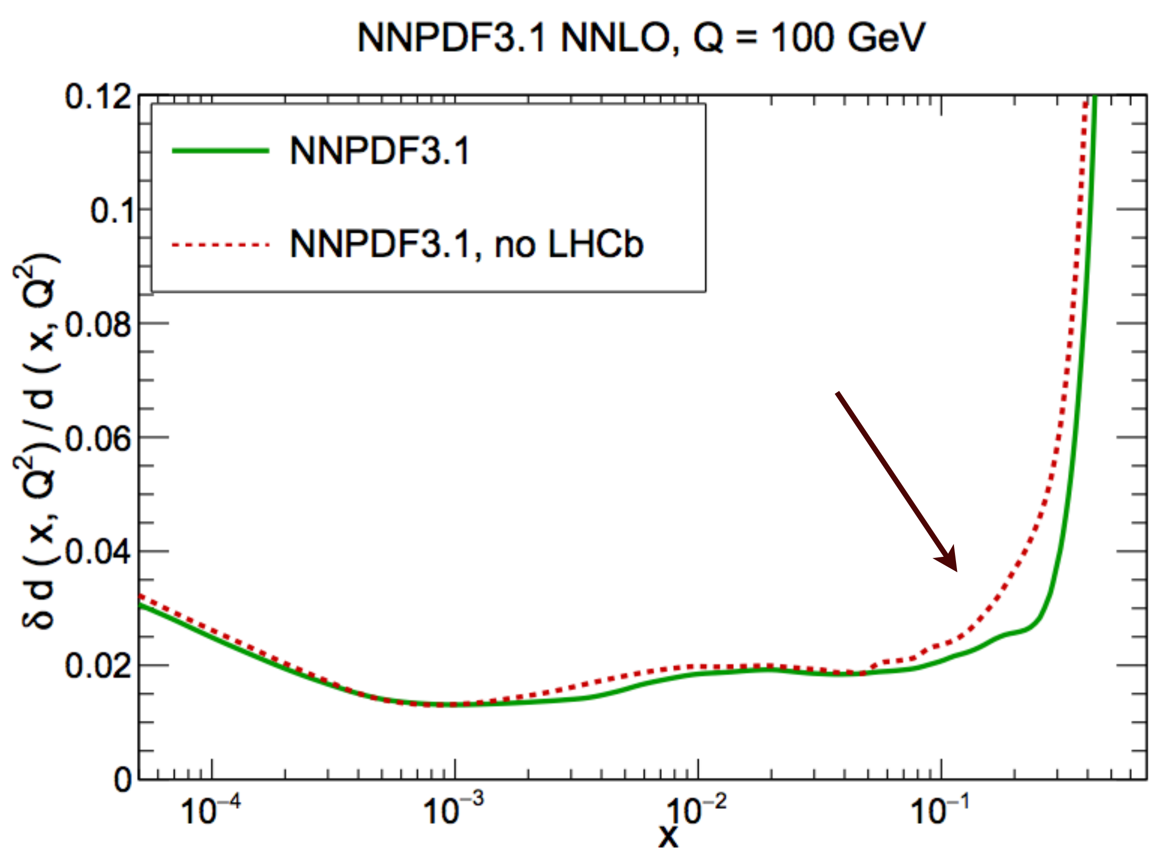
- **Forward coverage** of LHCb: unique sensitivity to small-*x* and large-*x* regions beyond that of ATLAS/CMS

- Specially important to disentangle **quark flavour at large-*x***



NNPDF 17



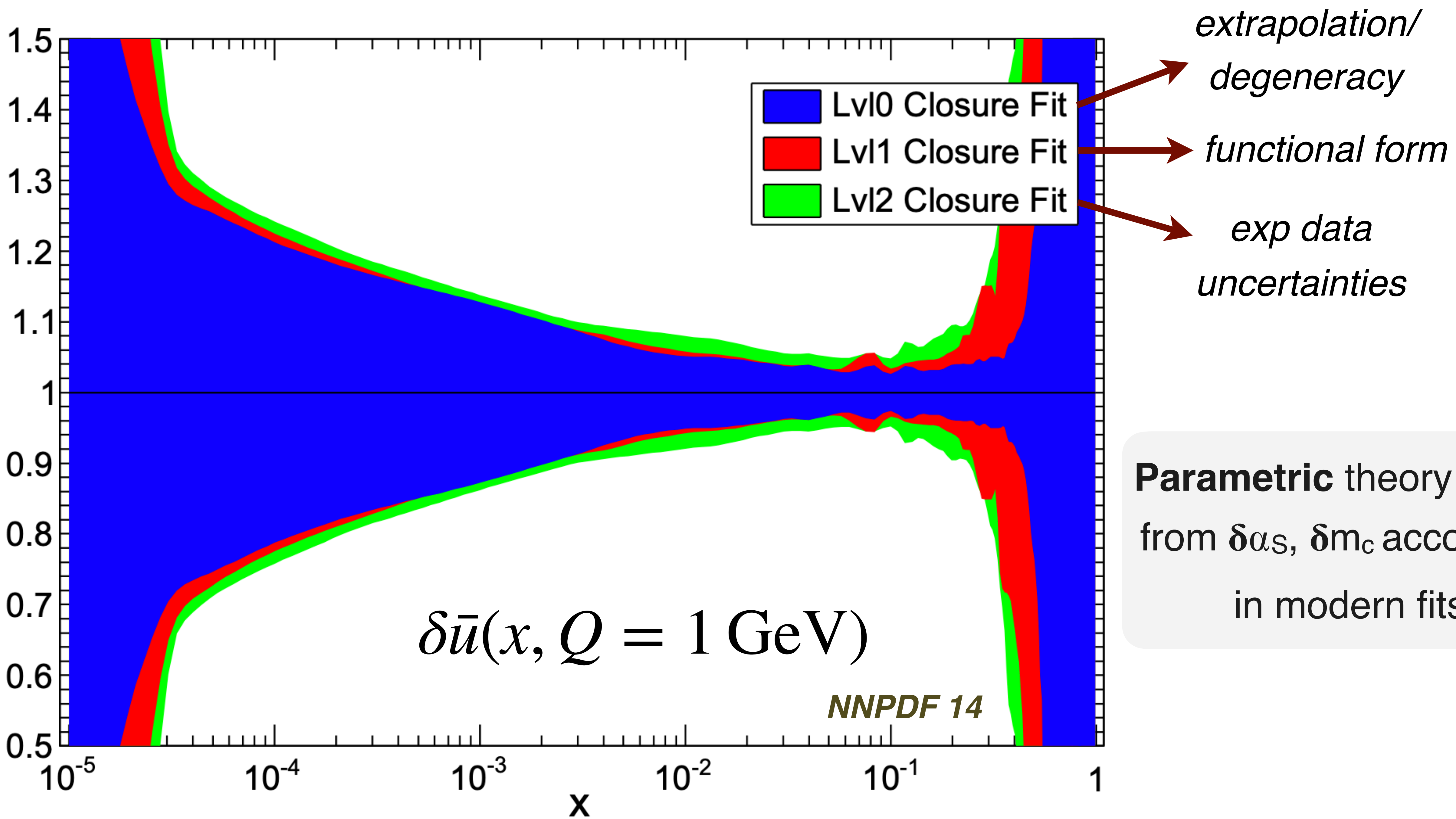


Parton Distributions with theoretical uncertainties

NNPDF Collaboration, in preparation

PDF uncertainties

PDF uncertainties receive contributions from **different sources**:



Parametric theory errors from $\delta\alpha_S$, δm_c accounted in modern fits

Theory uncertainties on PDFs from **Missing Higher Orders** (MHOs) never quantified!

Theory uncertainties from MHOs

At any finite order, perturbative QCD calculations depend on the unphysical **renormalisation** and **factorisation scales**

$$\sigma(\mu_R, \mu_F) = \sum_{k=0}^{n} \sum_{i,j}^{n_f} \alpha_s^{p+k}(\mu_R)\, \widetilde{\sigma}^{(k)}(\mu_R, \mu_F) \otimes q_i(\mu_F) \otimes q_j(\mu_F) + \mathcal{O}\left(\alpha_s^{p+n+1}\right)$$

In PDF fits, both scales are set to a fixed value, the typical **momentum transfer of the process *Q*,** and the MHOUs are ignored

$$\sigma(\mu_R = Q, \mu_F = Q) = \sum_{k=0}^{n} \sum_{i,j}^{n_f} \alpha_s^{p+k}(Q)\, \widetilde{\sigma}^{(k)}(Q) \otimes q_i(Q) \otimes q_j(Q)$$

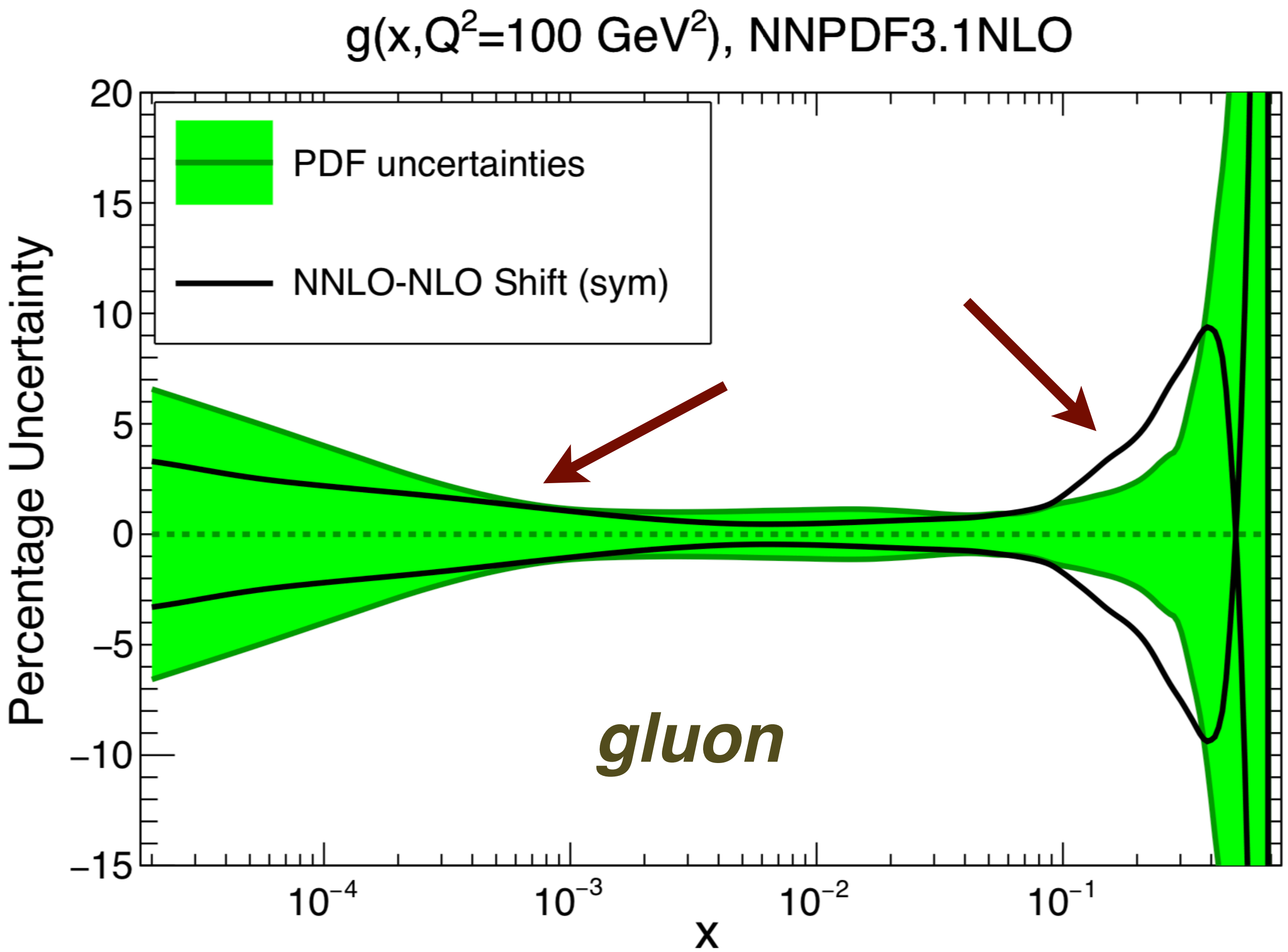
At order **N^{k}LO**, the dependence on the two scales is determined by the **N^{k-1}LO** splitting functions and partonic cross-sections by imposing:

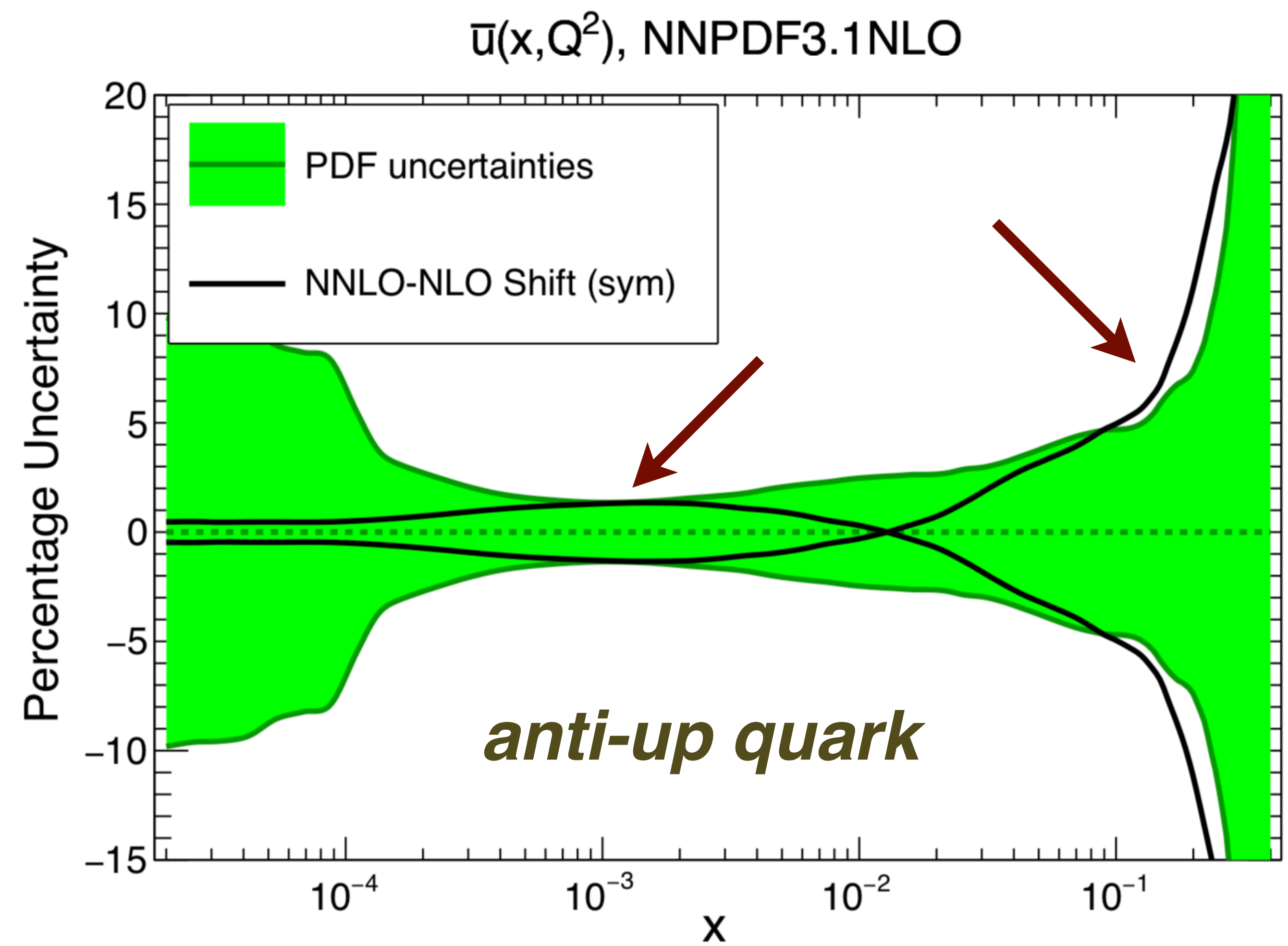
$$\sigma(\mu_R, \mu_F) = \sigma(Q, Q) + \mathcal{O}\left(\alpha_s^{p+n+1}\right)$$

*Scale variations provide an **estimate of the perturbative MHOs***

Theory uncertainties from MHOs

How severe is **ignoring MHOUs** in modern global PDFs fits?





Shift between **NLO and NNLO PDFs** comparable or larger than PDF errors

Given the high precision of modern PDF determinations, **accounting for MHOUs** is most urgent

Option #1: PDF fits with scale variations

Perform PDF fits where **theory calculations** are constructed by exploring a range of values for the **renormalisation** and **factorisation scales**

3-points

$$\sigma(\mu_R = Q, \mu_F = Q)$$ central scales

$$\sigma(\mu_R = 2Q, \mu_F = 2Q) \qquad \sigma(\mu_R = Q/2, \mu_F = Q/2)$$

7-points

$$\sigma(\mu_R = 2Q, \mu_F = Q) \qquad \sigma(\mu_R = Q, \mu_F = 2Q)$$

$$\sigma(\mu_R = Q/2, \mu_F = Q) \qquad \sigma(\mu_R = Q, \mu_F = Q/2)$$

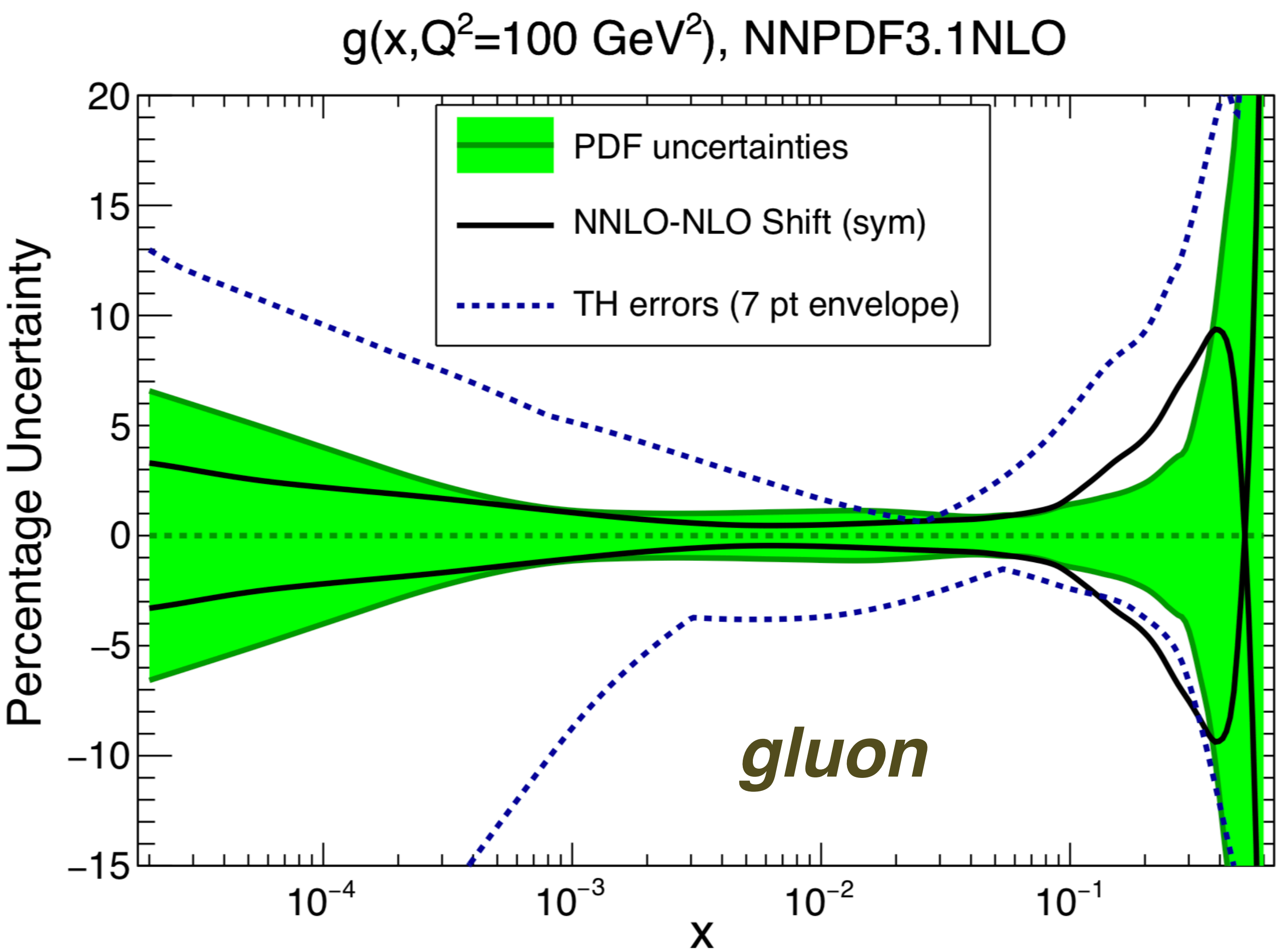
9-points

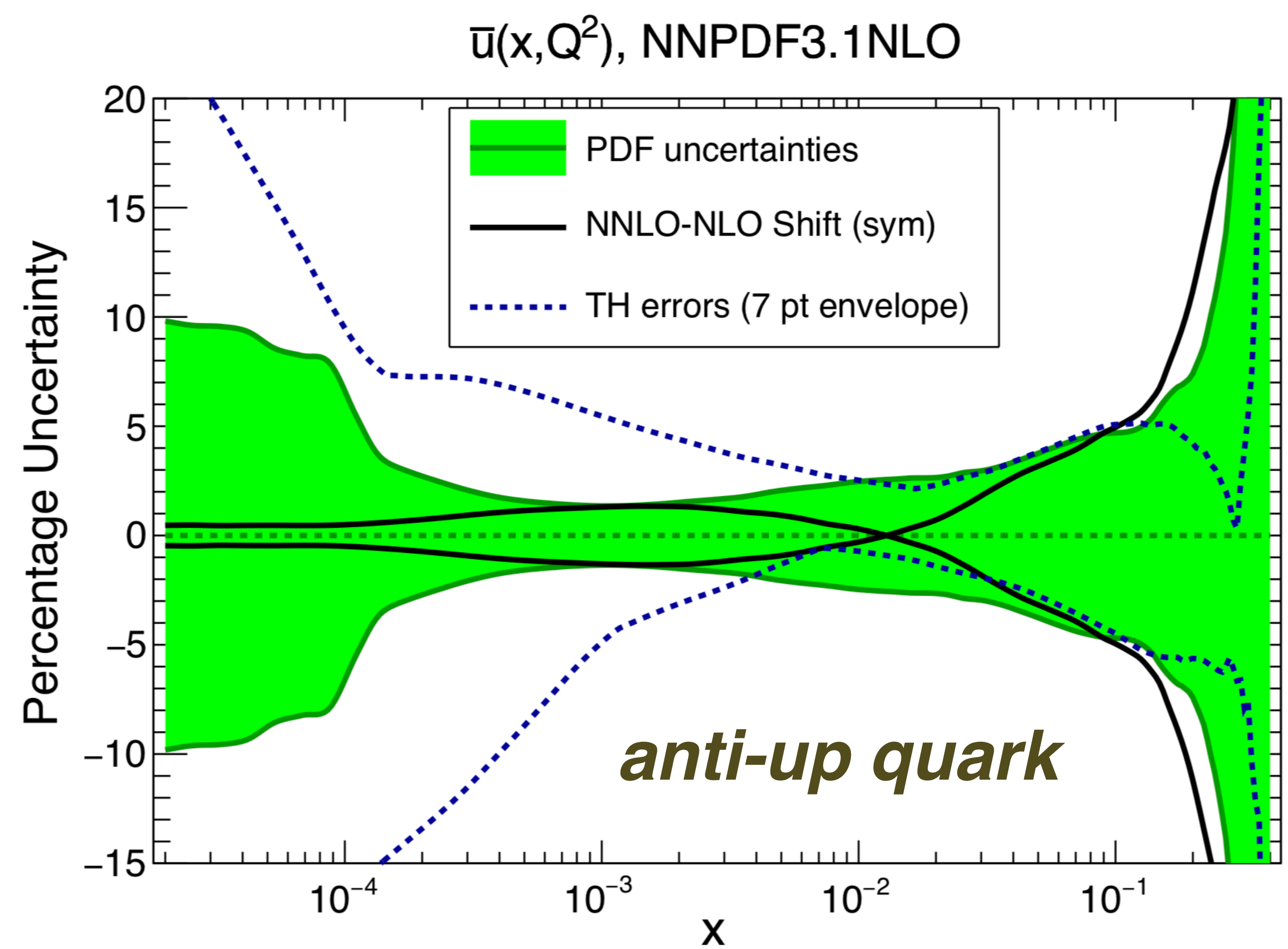
$$\sigma(\mu_R = 2Q, \mu_F = Q/2) \qquad \sigma(\mu_R = Q/2, \mu_F = 2Q)$$

Define the theory error due to MHOUs from **envelope of the scale-varied PDFs**

Option #1: PDF fits with scale variations

Perform PDF fits where **theory calculations** are constructed by exploring a range of values for the **renormalisation** and **factorisation scales**





- The 7pt envelope seems to work fine in most cases (perhaps too conservative?)
- Non-trivial **theory-induced correlations** between e.g. DIS and collider processes
- **CPU-intensive**, and cumbersome or LHC applications - can we do better?

Option #2: theory covariance matrix

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

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

Different scale variation prescriptions possible, e.g, the **5-point prescription**

$$\mathrm{cov}^{(\rm th)}_{ij} = \frac{1}{2}\left(\Delta_i(+,0)\Delta_j(+,0) + \Delta_i(-,0)\Delta_j(-,0)^2 + \Delta_i(0,+)\Delta_j(0,+)^2 + \Delta_i(0,+)\Delta_j(0,+)^2\right)$$

$$\Delta_i(-,0) \equiv \sigma_i(\mu_R = Q/2, \mu_F = Q) - \sigma_i(\mu_R = Q, \mu_F = Q)$$

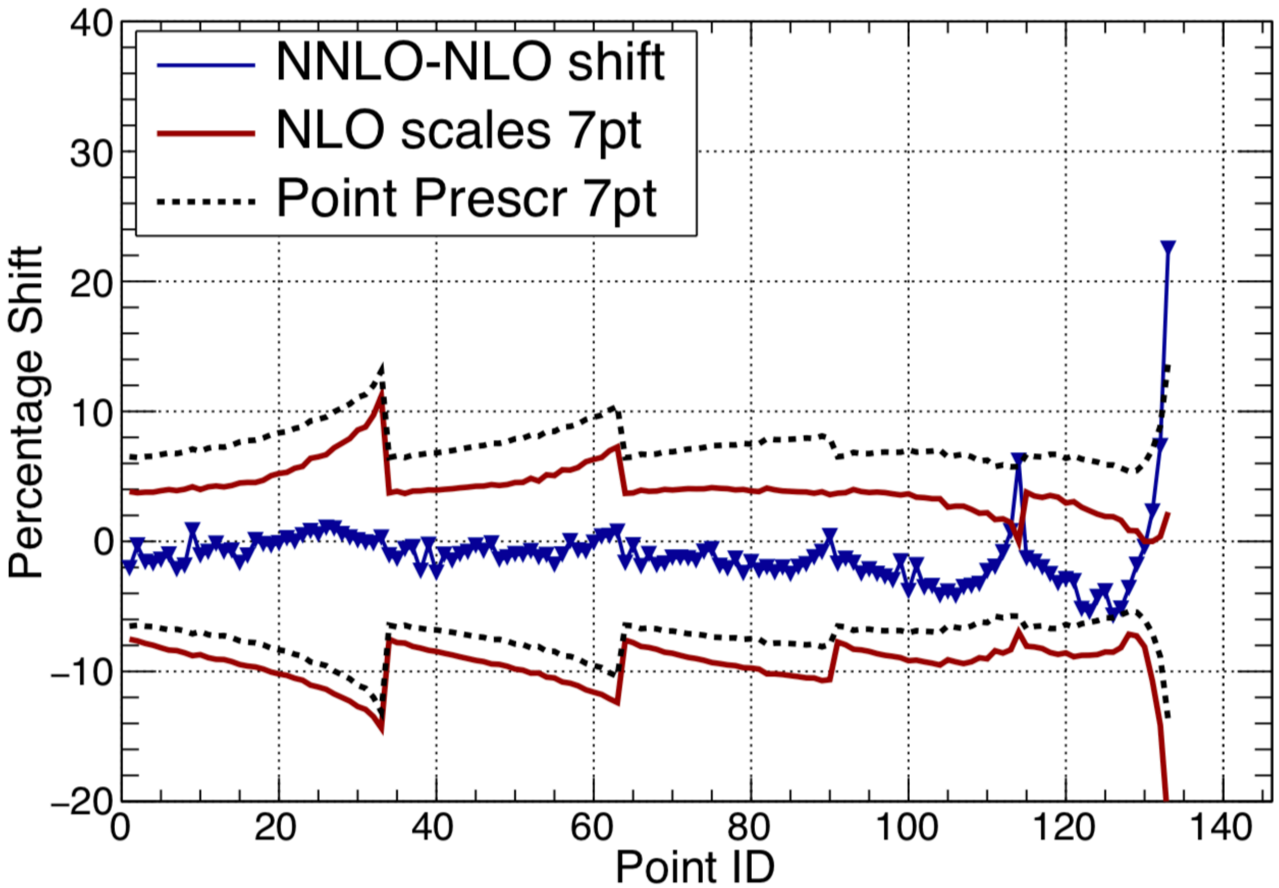
$$\Delta_i(+,+) \equiv \sigma_i(\mu_R = 2Q, \mu_F = 2Q) - \sigma_i(\mu_R = Q, \mu_F = Q)$$

Different **scale correlation patterns** expected in different processes e.g. DIS and jets

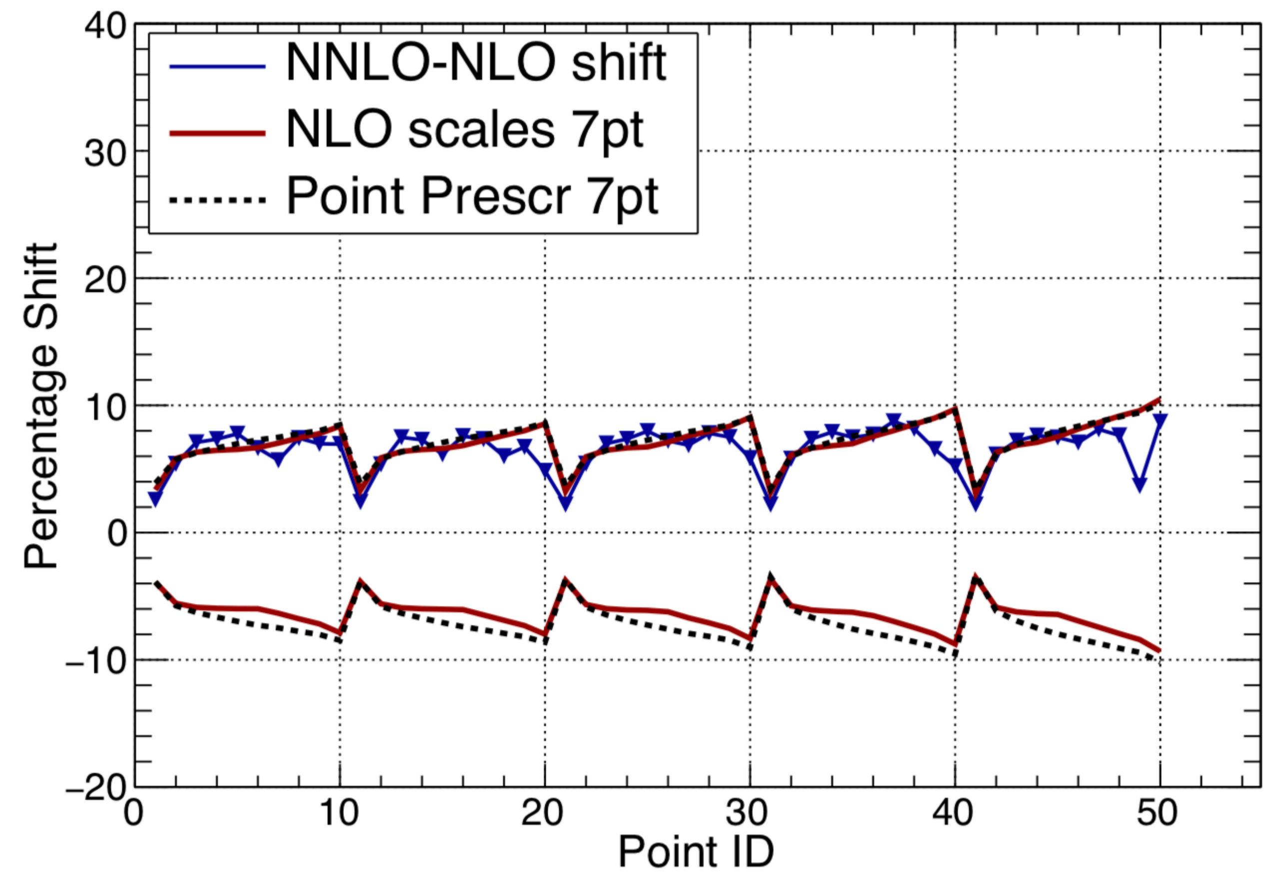
Option #2: theory covariance matrix

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

ATLAS jets 7 TeV 2011

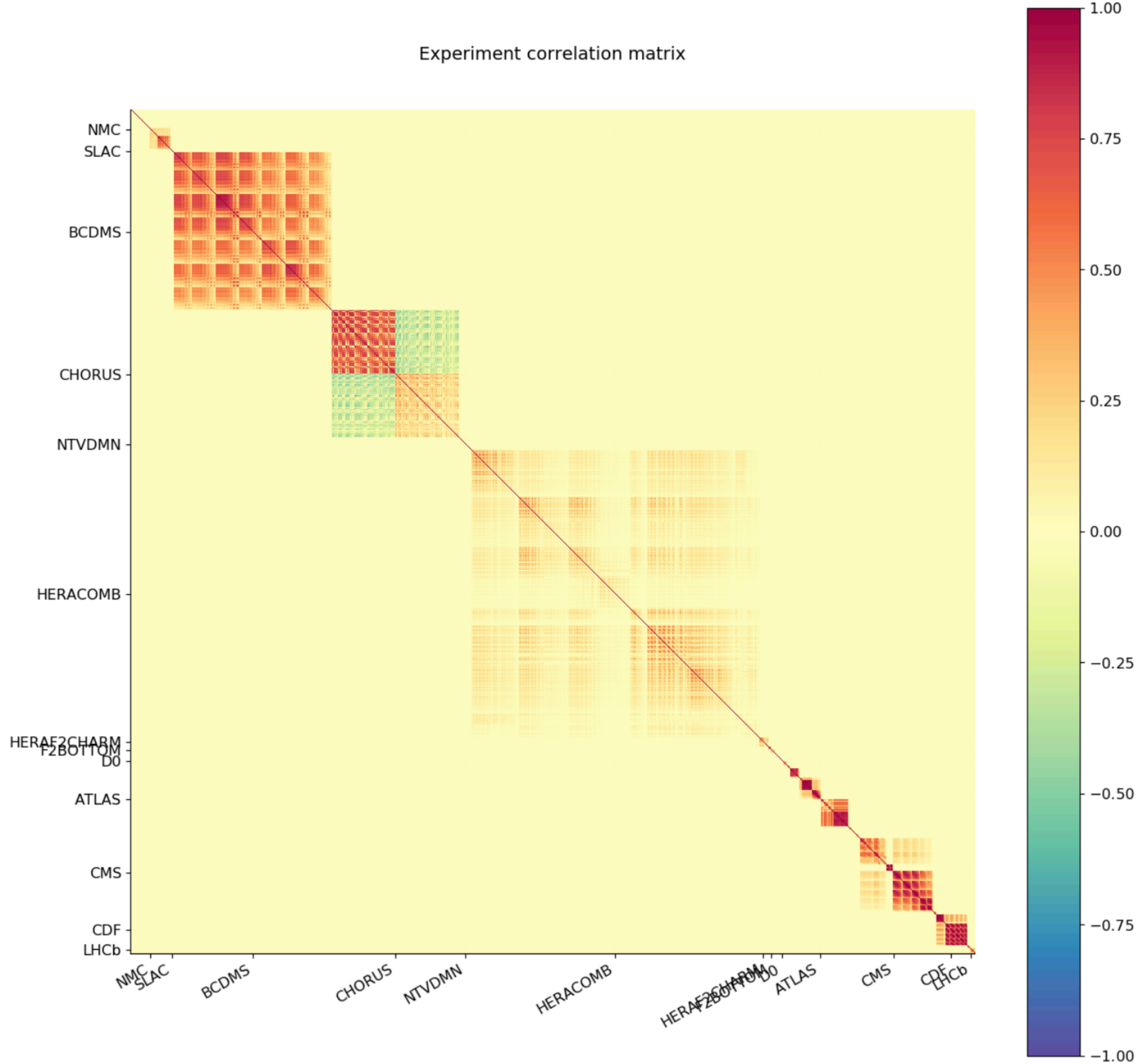


CMS Z pT 8 TeV



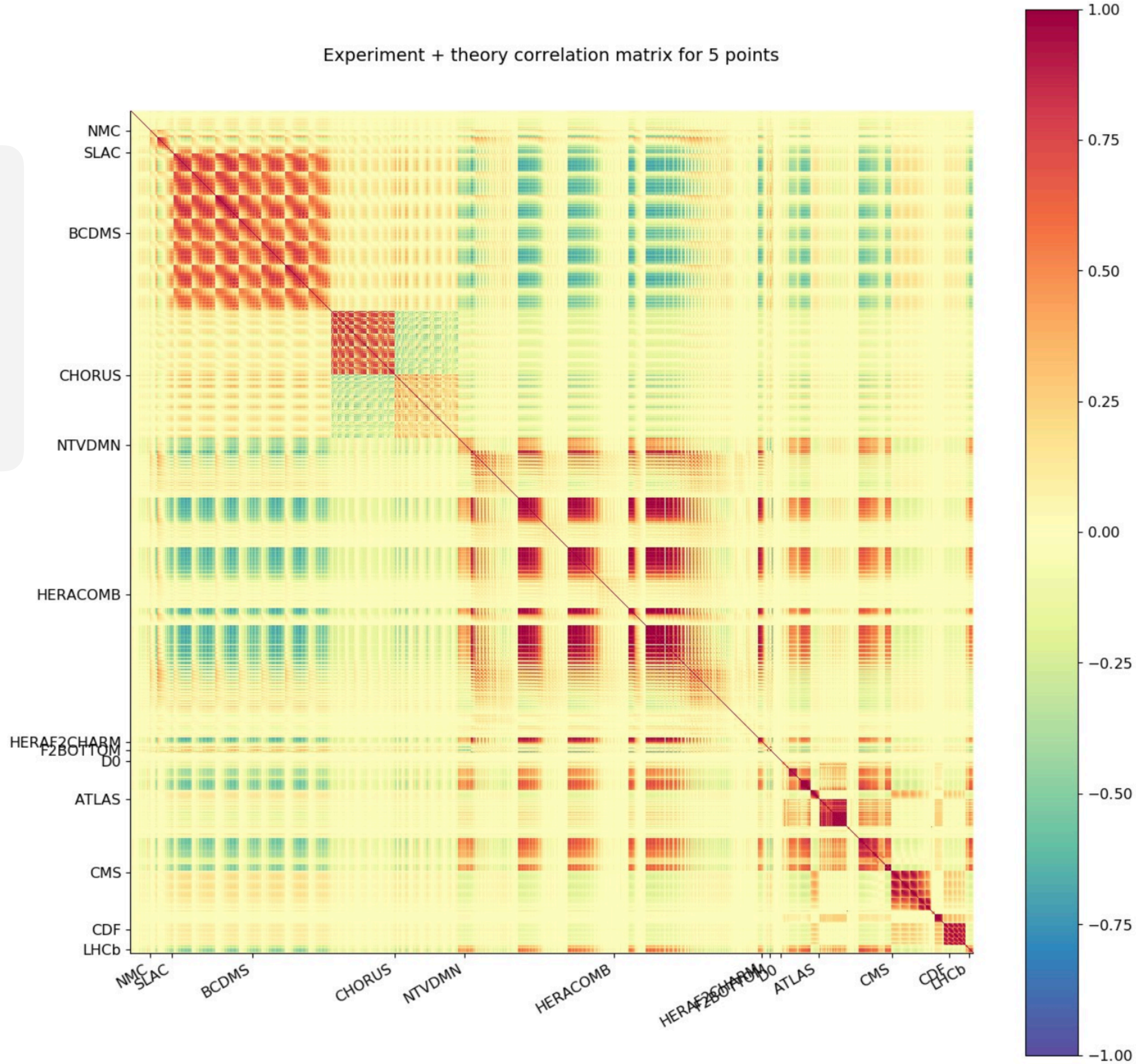
Systematic validation of the theory covariance matrix on the `exact' result, the **NNLO-NLO shift**, with the **O(5000) data points** of the global fit

Option #2: theory covariance matrix



Option #2: theory covariance matrix

Theory-induced correlations between different experiments *e.g.* DIS and LHC



NNPDF fits with theory uncertainties in preparation

Towards Ultimate PDFs at the High Lumi LHC

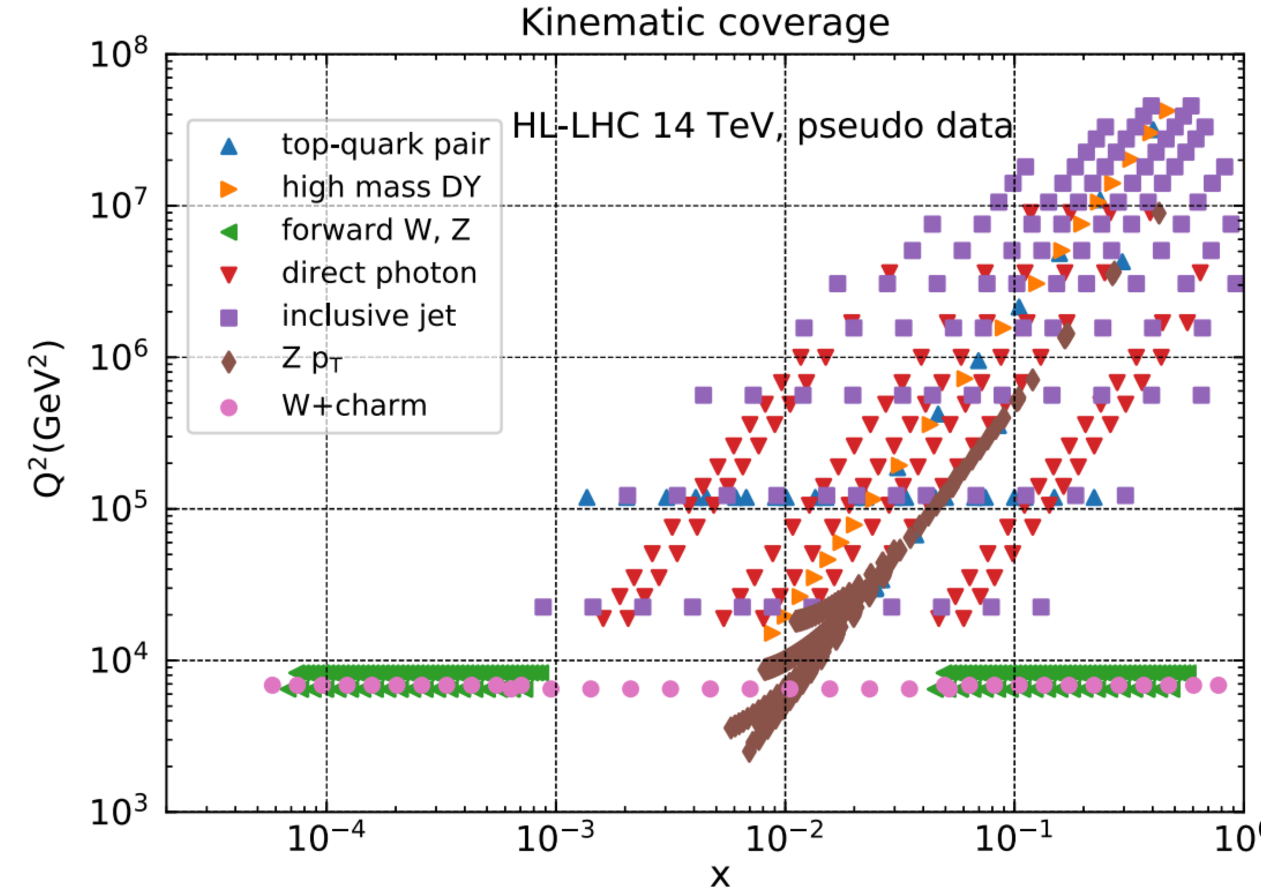
Abdul-Khalek, Bailey, Gao, Harland-Lang, JR 18
+ HL/HE-LHC Yellow Report, to appear

A luminous future

- In the framework of the update of the **European Strategy for Particle Physics**, a CERN Yellow Report will evaluate the physics potential of the **HL-LHC** (to appear in Dec 2018)

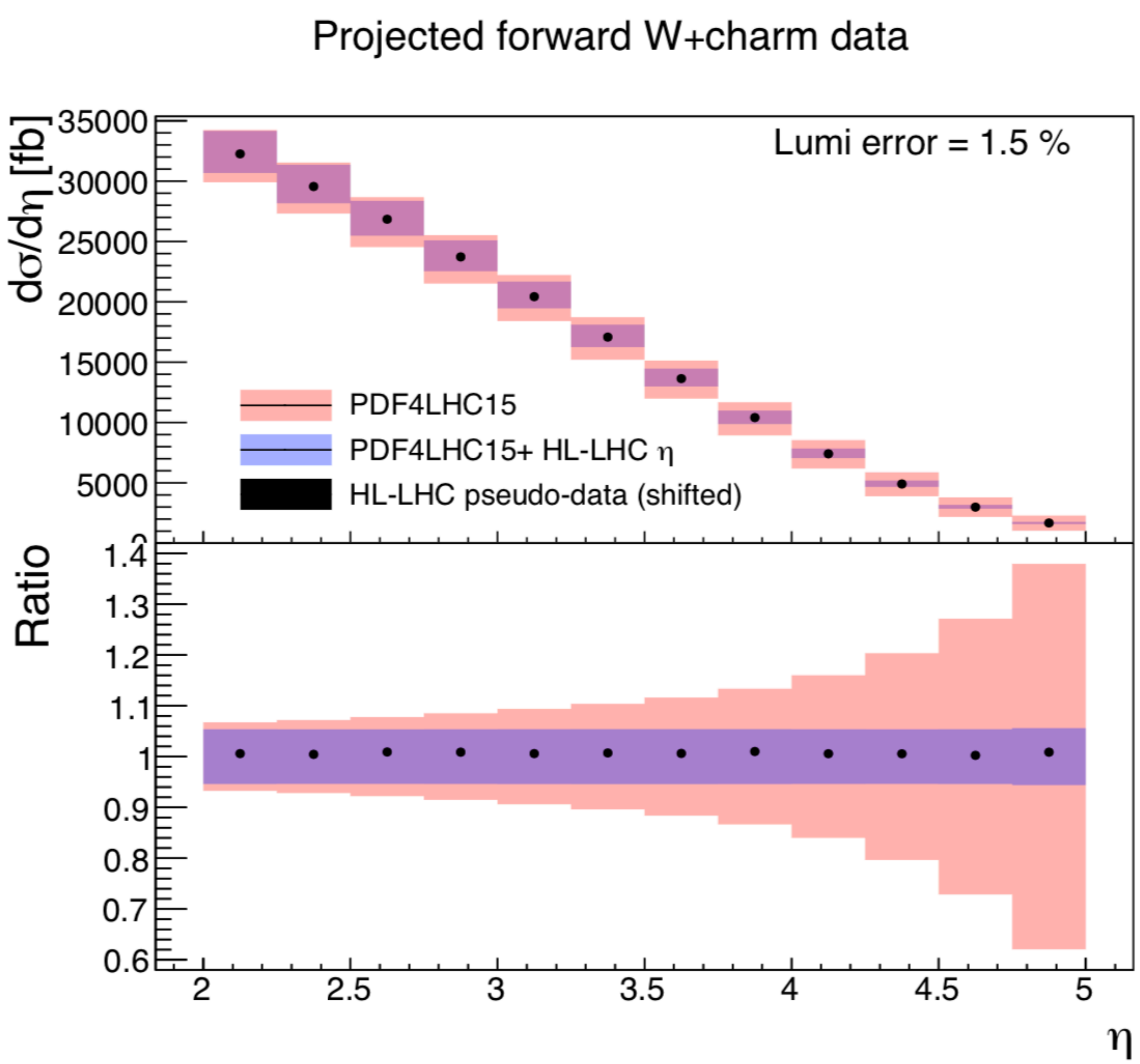
- We have studied the **impact of HL-LHC data on PDFs**, including projections with (future) LHCb measurements.

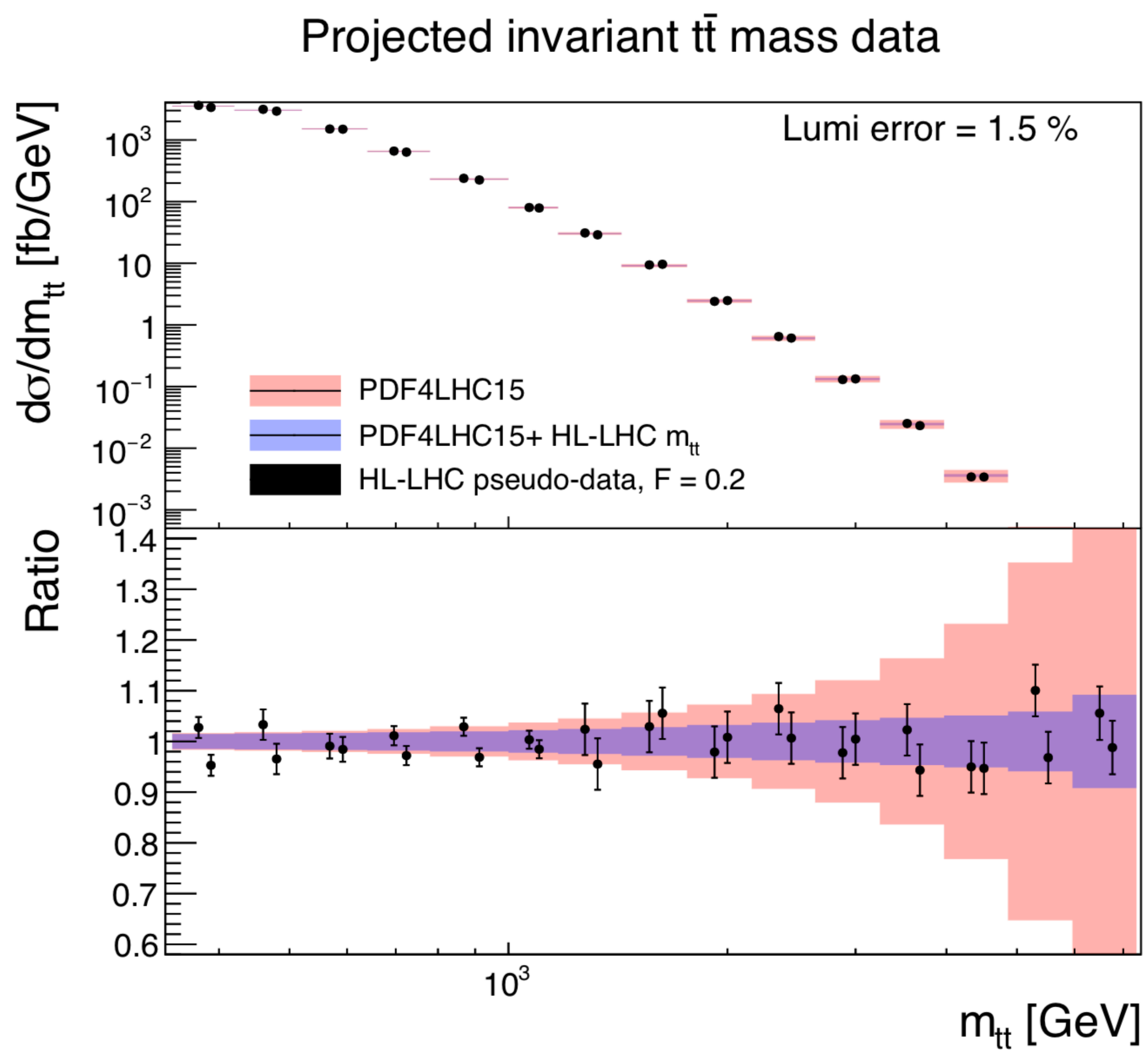
*What is the **ultimate precision** that can be expected for PDFs from **hadron collider data?***



Process	Kinematics	N_{dat}	f_{corr}	f_{red}	Baseline
$Z\ p_T$	$20\,\text{GeV} \le p_T^{ll} \le 3.5$ TeV $12\,\text{GeV} \le m_{ll} \le 150$ GeV $\lvert y_{ll}\rvert \le 2.4$	338	0.5	(0.4, 1)	[52] (8 TeV)
High-mass Drell-Yan	$p_T^{l1(2)} \ge 40(30)$ GeV $\lvert\eta^l\rvert \le 2.5$, $m_{ll} \ge 116$ GeV	32	0.5	(0.4, 1)	[47] (8 TeV)
Top quark pair	$m_{t\bar{t}} \simeq 5$ TeV, $\lvert y_t\rvert \le 2.5$	110	0.5	(0.4, 1)	[50] (8 TeV)
W+charm (central)	$p_T^{\mu} \ge 26$ GeV, $p_T^c \ge 5$ GeV $\lvert\eta^{\mu}\rvert \le 2.4$	12	0.5	(0.2, 0.5)	[24] (13 TeV)
W+charm (forward)	$p_T^{\mu} \ge 20$ GeV, $p_T^c \ge 20$ GeV $p_T^{\mu+c} \ge 20$ GeV $2 \le \eta^{\mu} \le 4.5$, $2.2 \le \eta^c \le 4.2$	10	0.5	(0.4, 1)	LHCb projection
Direct photon	$E_T^{\gamma} \lesssim 3$ TeV, $\lvert\eta_{\gamma}\rvert \le 2.5$	118	0.5	(0.2, 0.5)	[55] (13 TeV)
Forward W, Z	$p_T^l \ge 20$ GeV, $2.0 \le \eta^l \le 4.5$ $60\,\text{GeV} \le m_{ll} \le 120$ GeV	90	0.5	(0.4, 1)	[49] (8 TeV)
Inclusive jets	$\lvert y\rvert \le 3$, $R = 0.4$	58	0.5	(0.2, 0.5)	[61] (13 TeV)
Total		768			

HL-LHC constraints from LHCb





Forward W+charm

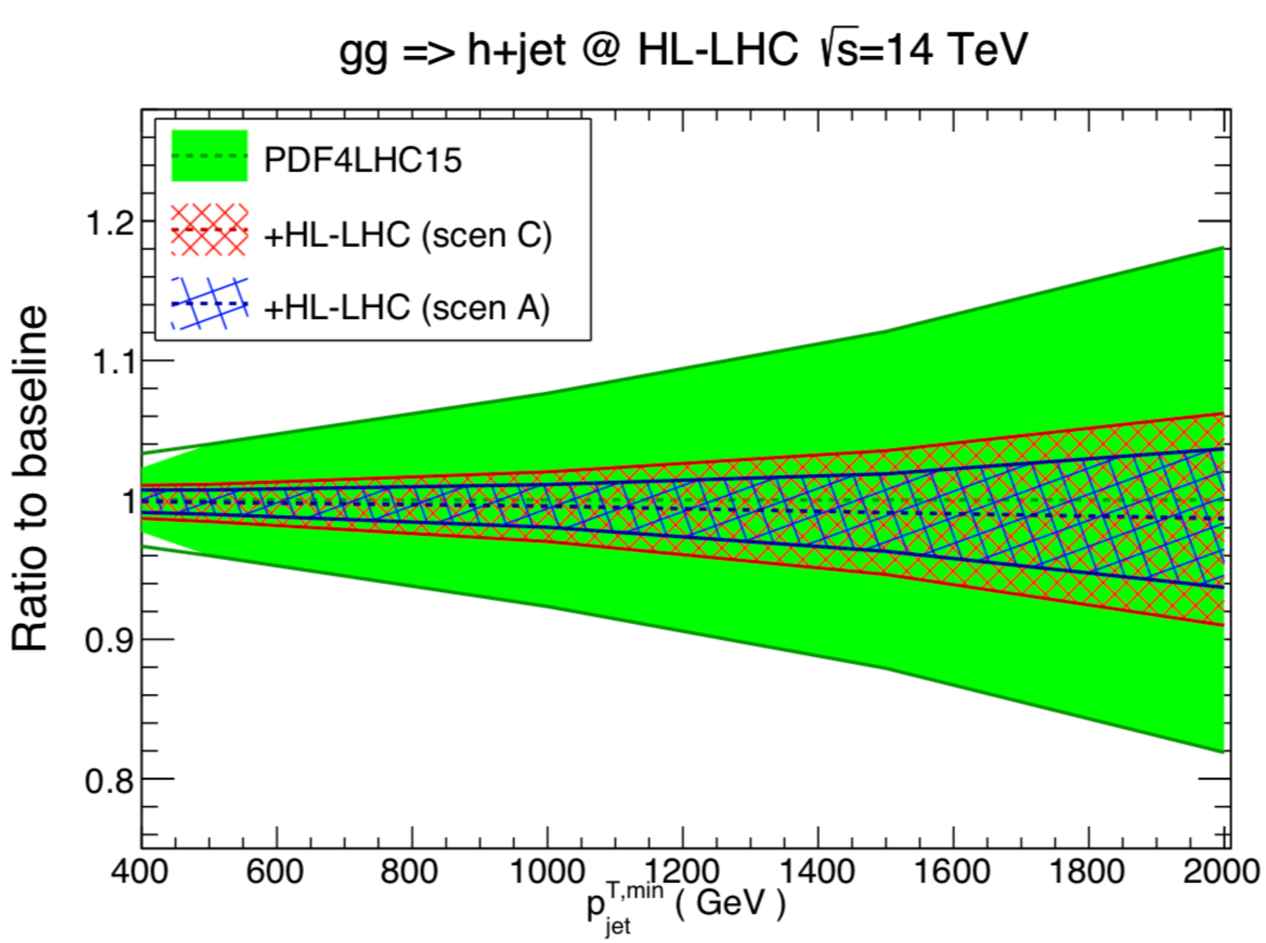
Top quark pair production

HL-LHC measurements will be specially useful to constrain the **gluon** and **quark flavour separation** in the large-*x* region, including strangeness

HL-LHC constraints on PDFs

***Reduction factor** for PDF uncertainties in luminosities as compared to PDF4LHC15*

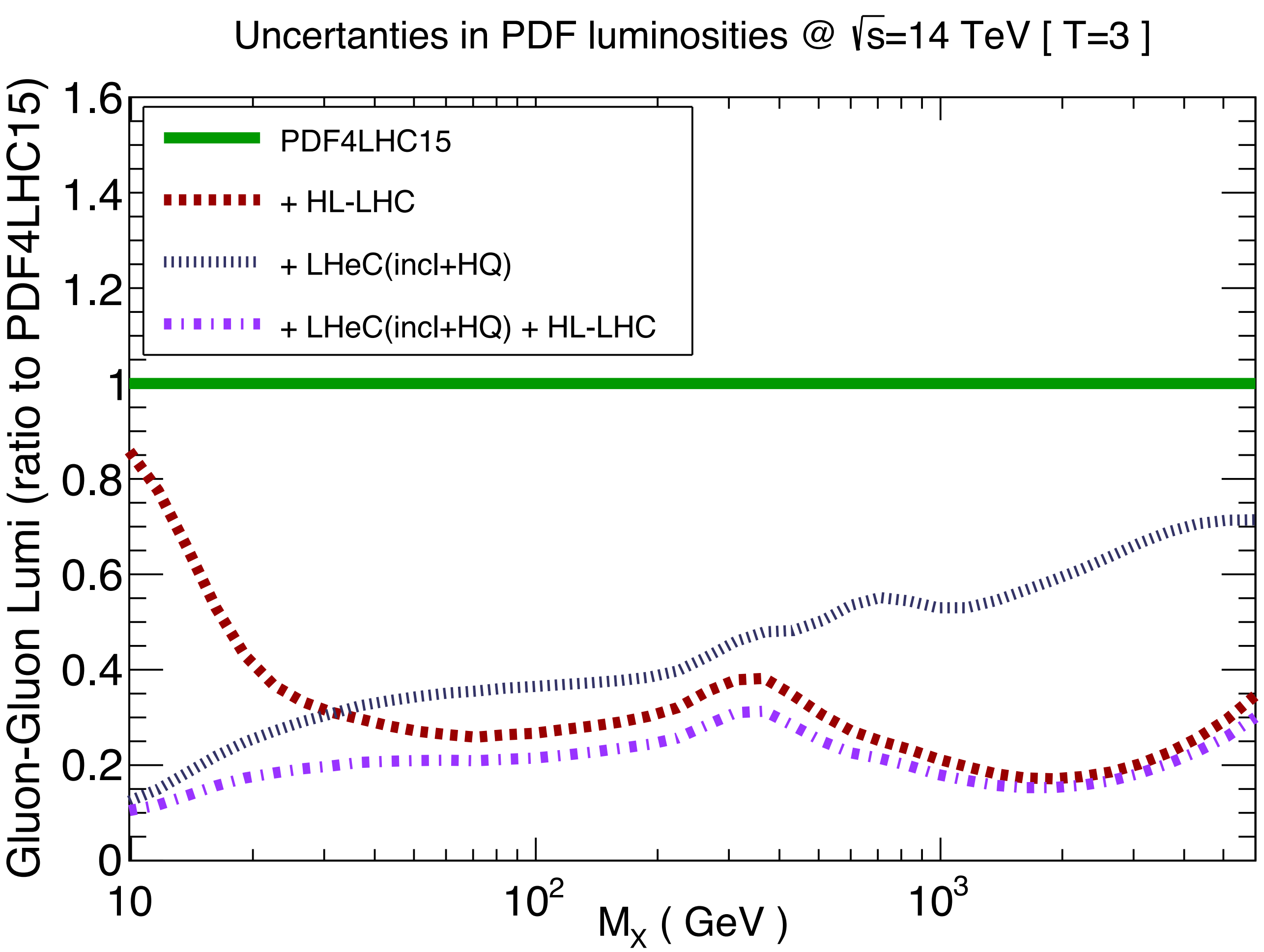
Ratio to baseline	10 GeV $\leq M_X \leq$ 40 GeV	40 GeV $\leq M_X \leq$ 1 TeV	1 TeV $\leq M_X \leq$ 6 TeV
gluon–gluon	0.50 (0.60)	0.28 (0.40)	0.22 (0.34)
gluon–quark	0.66 (0.72)	0.42 (0.45)	0.28 (0.37)
quark–quark	0.74 (0.79)	0.37 (0.46)	0.43 (0.59)
quark–antiquark	0.71 (0.76)	0.31 (0.40)	0.50 (0.60)
strange–antistrange	0.34 (0.44)	0.19 (0.30)	0.23 (0.27)
strange–antiup	0.67 (0.73)	0.27 (0.38)	0.38 (0.43)

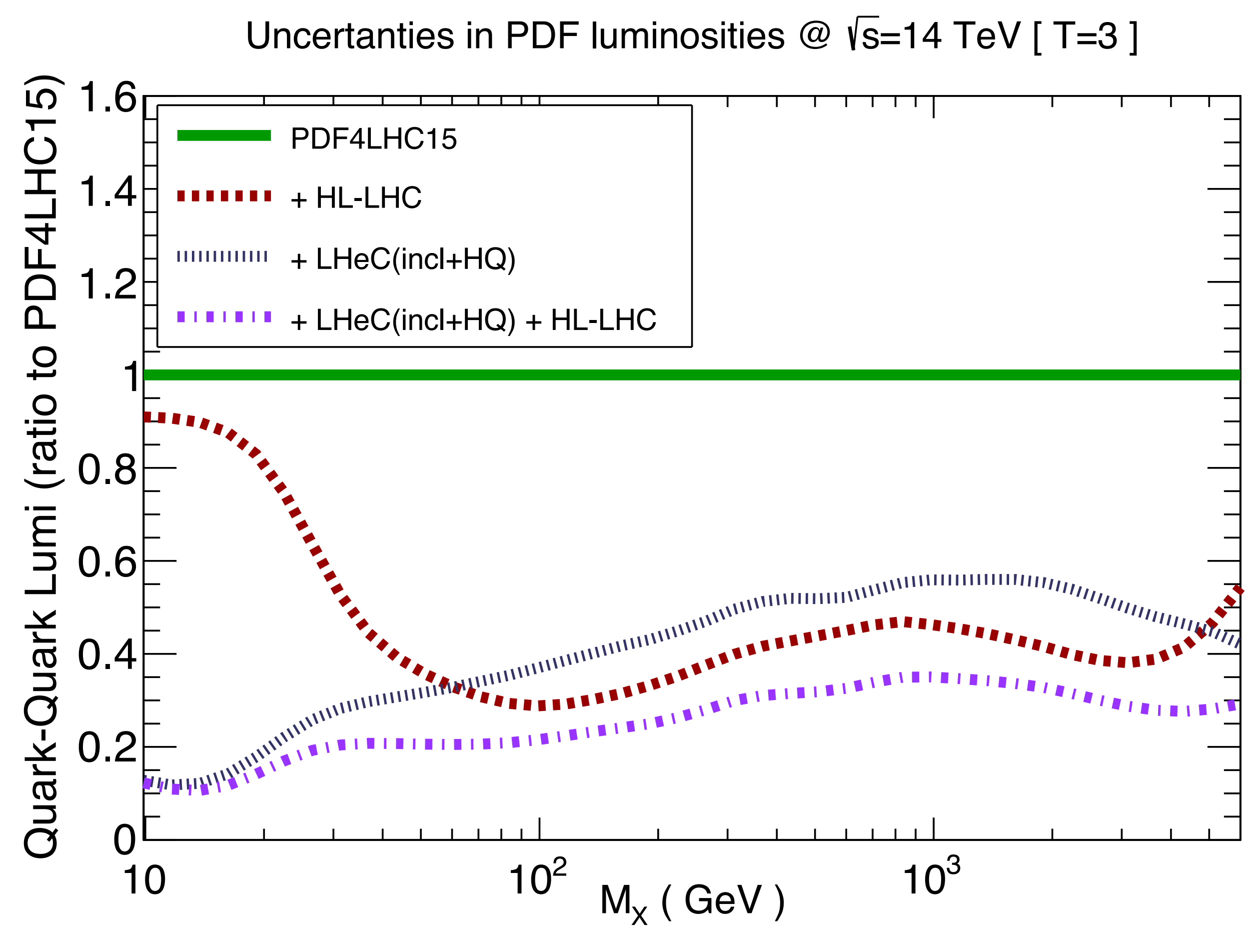


HL-LHC data will lead to **stringent constraints on PDFs**, reducing uncertainties by up to a **factor 5**, and making possible precise predictions of central processes such as **Higgs p_T**

HL-LHC and the LHeC

Compare with projections for the **Large Hadron electron Collider (LHeC),** a lepton-proton collider proposed to operate in sync with the HL-LHC





The LHeC would provide **fully complementary information** on PDFs with different exp/th systematics and reduced risk of **BSM contamination**

A SMEFT global analysis of the top quark sector

Based on work in progress with:
Nathan P. Hartland, Fabio Maltoni, Emanuele R. Nocera,
Emma Slade, Eleni Vryodinou, Cen Zhang

The Standard Model EFT

- Heavy bSM physics beyond the direct reach of the LHC can be **parametrised in a model-independent** in terms of complete basis of **higher-dimensional operators**

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

- Some operators induce **growth with the partonic centre-of-mass energy**: increased sensitivity in LHC cross-sections in the TeV region

$$\sigma(E) = \sigma_{\rm SM}(E)\left(1 + \sum_i^{N_{d6}} \omega_i \frac{c_i\, m_{\rm SM}^2}{\Lambda^2} + \sum_i^{N_{d6}} \widetilde{\omega}_i \frac{c_i\, E^2}{\Lambda^2} + \mathcal{O}\left(\Lambda^{-4}\right)\right)$$

- The number of SMEFT operators is large: **59 non-redundant operators at dimension 6** with Minimal Flavour Violation, **> 2000 operators** without any flavour assumption

- A global SMEFT analysis needs to explore a **huge complicated parameter space**

From PDF fits to SMEFT analyses

- In global PDF fits, LHC cross-sections (incl. top) are used to **constrain the input PDFs**

$$\sigma^{(\mathrm{th})}\left(Q,\{a_k\}\right) = \sum_{ij} \Gamma_{ij}\left(\alpha_s, Q, Q_0\right) \otimes q_i(x, Q_0, \{a_k\}) \otimes q_j(x, Q_0, \{a_k\})$$

- The PDF parameters ***{a_k}*** are determined from the **minimisation** of a figure of merit

$$\chi^2(\{a_k\}) = \sum_{m,n}^{n_{\mathrm{dat}}} \left(\sigma_n^{(\mathrm{exp})} - \sigma_n^{(\mathrm{th})}\{a_k\}\right) (\mathrm{cov})^{-1}_{mn} \left(\sigma_m^{(\mathrm{exp})} - \sigma_m^{(\mathrm{th})}\{a_k\}\right)$$

- If one now fixes the input PDFs (determined from a different set of data) and includes SMEFT effects, one can **exploit the same PDF fitting approach** to carry out a global SMEFT fit

$$\sigma^{(\mathrm{th})}\left(Q,\{c_k\}\right) = \left(1 + \sum_{k}^{N_{d6}} \frac{c_k \kappa_k}{\Lambda^2} + \sum_{k,l}^{N_{d6}} \frac{c_k c_l \widetilde{\kappa}_{kl}}{\Lambda^4}\right) \sum_{ij} \Gamma_{ij}\left(\alpha_s, Q, Q_0\right) \otimes q_i(x, Q_0) \otimes q_j(x, Q_0)$$

$$\chi^2(\{c_k\}) = \sum_{m,n}^{n_{\mathrm{dat}}} \left(\sigma_n^{(\mathrm{exp})} - \sigma_n^{(\mathrm{th})}\{c_k\}\right) (\mathrm{cov})^{-1}_{mn} \left(\sigma_m^{(\mathrm{exp})} - \sigma_m^{(\mathrm{th})}\{c_k\}\right)$$

Recipe for a global PDF fit

Theory

(N)NLO QCD + NLO EW for xsecs

NNLO for DGLAP evolution

Heavy quark mass effects

Data

Deep-inelastic scattering

Drell-Yan, jet, top quark production

Fixed target and collider measurements

Global PDF analysis

Delivery

Publicly available in **LHAPDF**

Automated plotting and stat analysis

New data incorporated without redoing fit

Methodology

Faithful **uncertainty estimate**

Flexible parametrizations

Validated on **pseudo-data** (closure test)

Recipe for a global SMEFT fit

Theory

(N)NLO QCD + NLO EW for SM xsecs

NLO QCD for SMEFT contributions

State-of-the-art PDFs without top data

Data

Top quark production

Higgs, VV, electroweak

Low-energy, flavour

Global SMEFT analysis

Delivery

Derived bounds can be compared with

specific UV completions

New data incorporated without redoing fit

Methodology

Faithful **uncertainty estimate**

Avoiding under- and over-fitting

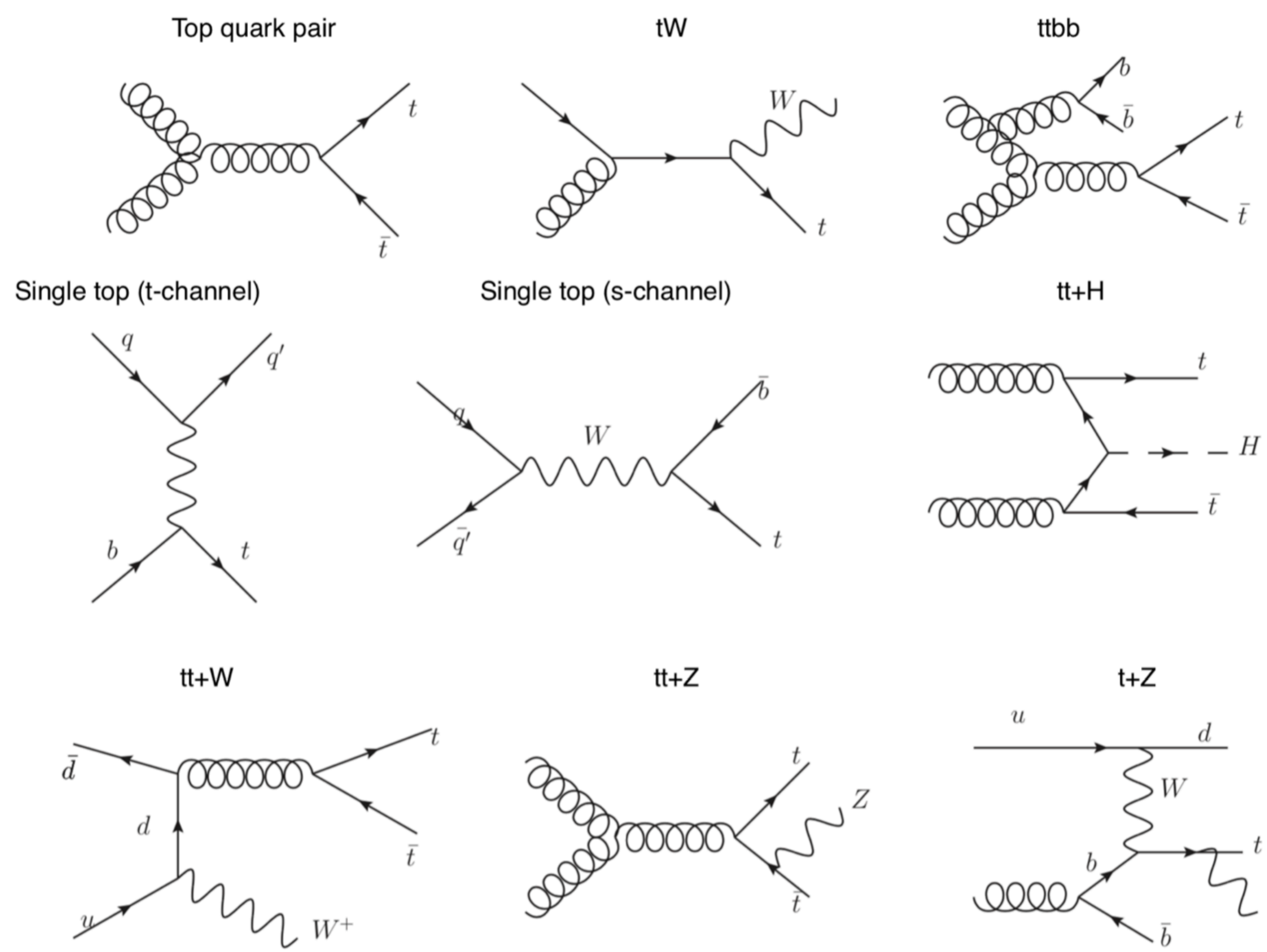
Validated on **pseudo-data** (closure test)

The top quark sector of the SMEFT

Notation	Sensitivity at $\mathcal{O}(\Lambda^{-2})$ ($\mathcal{O}(\Lambda^{-4})$)								
	$t\bar{t}$	single-top	tW	tZ	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$t\bar{t}t\bar{t}$	$t\bar{t}b\bar{b}$
OQQ1								✓	✓
OQQ8								✓	✓
OQt1								✓	✓
OQt8								✓	✓
OQb1								(✓)	✓
OQb8								(✓)	✓
Ott1								✓	✓
Otb1								(✓)	✓
Otb8								✓	✓
OQtQb1									
OQtQb8									
O81qq	✓				✓	✓	✓	✓	✓
O11qq	✓				(✓)	(✓)	(✓)	✓	✓
O83qq	✓	✓		(✓)	✓	✓	✓	✓	✓
O13qq	✓	✓		✓	(✓)	(✓)	(✓)	✓	✓
O8qt	✓				✓	✓	✓	✓	✓
O1qt	✓				(✓)	(✓)	(✓)	✓	✓
O8ut	✓					✓	✓	✓	✓
O1ut	✓					(✓)	(✓)	✓	✓
O8qu	✓					✓	✓	✓	✓
O1qu	✓					(✓)	(✓)	✓	✓
O8dt	✓					✓	✓	✓	✓
O1dt	✓					(✓)	(✓)	✓	✓
O8qd	✓					✓	✓	✓	✓
O1qd	✓					(✓)	(✓)	✓	✓
OtG	✓				✓	✓	✓	✓	✓
OtW		✓	✓	✓					
ObW		(✓)	(✓)						
OtZ				✓		✓			
Off		(✓)	(✓)	(✓)					
Ofq3		✓	✓	✓		✓			
OpQM				✓		✓			
Opt				✓		✓	✓		
Otp							✓		

A large number of different dimension-6 SMEFT operators modify **top production at LHC**

$$\sigma(E) = \sigma_{\rm SM}(E)\left(1 + \sum_i^{N_{d6}} \kappa_i \frac{c_i}{\Lambda^2} + \sum_{i,j}^{N_{d6}} \widetilde{\kappa}_{ij} \frac{c_i c_j}{\Lambda^4}\right)$$



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OQQ1								✓	✓
OQQ8								✓	✓
OQt1								✓	✓
OQt8								✓	✓
OQb1								(✓)	✓
OQb8								(✓)	✓
Ott1								✓	✓
Otb1								(✓)	✓
Otb8								✓	✓
OQtQb1									
OQtQb8									
O81qq	✓				✓	✓	✓	✓	✓
O11qq	✓				(✓)	(✓)	(✓)	✓	✓
O83qq	✓	✓		(✓)	✓	✓	✓	✓	✓
O13qq	✓	✓		✓	(✓)	(✓)	(✓)	✓	✓
O8qt	✓				✓	✓	✓	✓	✓
O1qt	✓				(✓)	(✓)	(✓)	✓	✓
O8ut	✓					✓	✓	✓	✓
O1ut	✓					(✓)	(✓)	✓	✓
O8qu	✓					✓	✓	✓	✓
O1qu	✓					(✓)	(✓)	✓	✓
O8dt	✓					✓	✓	✓	✓
O1dt	✓					(✓)	(✓)	✓	✓
O8qd	✓					✓	✓	✓	✓
O1qd	✓					(✓)	(✓)	✓	✓
OtG	✓				✓	✓	✓	✓	✓
OtW		✓	✓	✓					
ObW		(✓)	(✓)						
OtZ				✓		✓			
Off		(✓)	(✓)	(✓)					
Ofq3		✓	✓	✓		✓			
OpQM				✓		✓			
Opt				✓		✓	✓		
Otp							✓		

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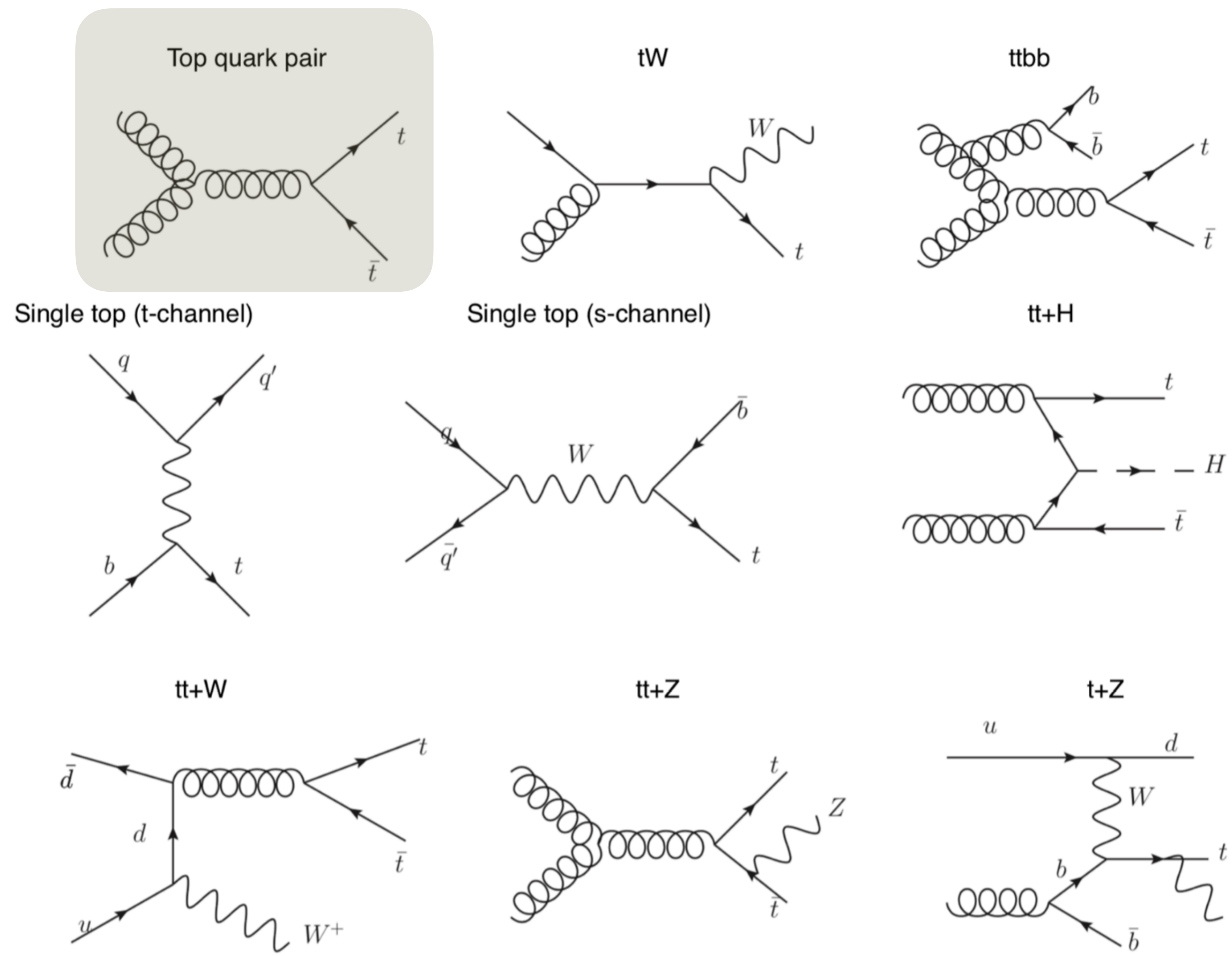

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OQt1								✓	✓
OQt8								✓	✓
OQb1								(✓)	✓
OQb8								(✓)	✓
Ott1								✓	✓
Otb1								(✓)	✓
Otb8								✓	✓
OQtQb1									
OQtQb8									
O81qq	✓				✓	✓	✓	✓	✓
O11qq	✓				(✓)	(✓)	(✓)	✓	✓
O83qq	✓	✓		(✓)	✓	✓	✓	✓	✓
O13qq	✓	✓		✓	(✓)	(✓)	(✓)	✓	✓
O8qt	✓				✓	✓	✓	✓	✓
O1qt	✓				(✓)	(✓)	(✓)	✓	✓
O8ut	✓					✓	✓	✓	✓
O1ut	✓					(✓)	(✓)	✓	✓
O8qu	✓					✓	✓	✓	✓
O1qu	✓					(✓)	(✓)	✓	✓
O8dt	✓					✓	✓	✓	✓
O1dt	✓					(✓)	(✓)	✓	✓
O8qd	✓					✓	✓	✓	✓
O1qd	✓					(✓)	(✓)	✓	✓
OtG	✓				✓	✓	✓	✓	✓
OtW		✓	✓	✓					
ObW		(✓)	(✓)						
OtZ				✓		✓			
Off		(✓)	(✓)	(✓)					
Ofq3		✓	✓	✓		✓			
OpQM				✓		✓			
Opt				✓		✓	✓		
Otp							✓		

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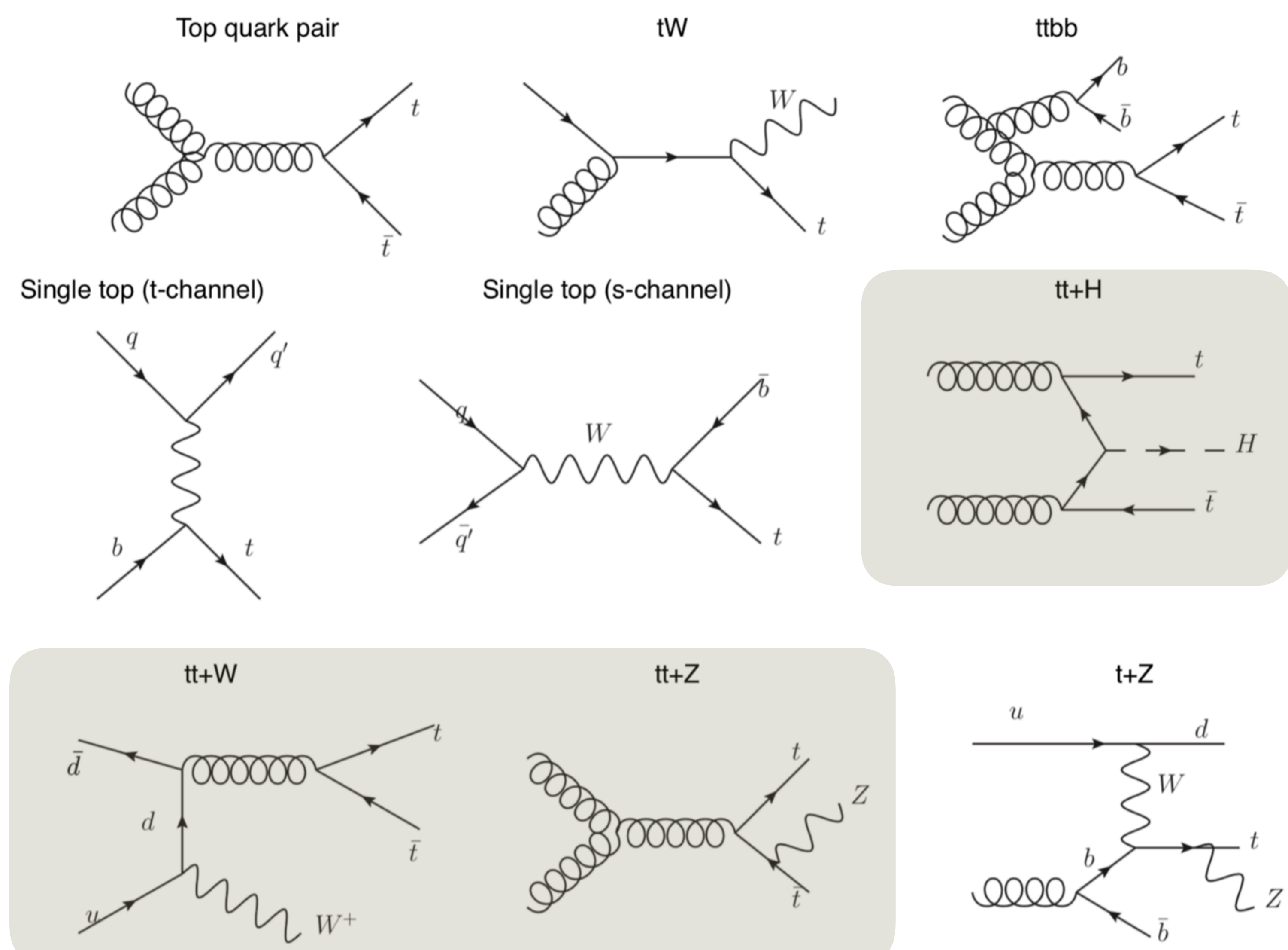

The top quark sector of the SMEFT

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OQQ1								✓	✓
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OQt1								✓	✓
OQt8								✓	✓
OQb1								(✓)	✓
OQb8								(✓)	✓
Ott1								✓	✓
Otb1								(✓)	✓
Otb8								✓	✓
OQtQb1									
OQtQb8									
O81qq	✓				✓	✓	✓	✓	✓
O11qq	✓				(✓)	(✓)	(✓)	✓	✓
O83qq	✓	✓		(✓)	✓	✓	✓	✓	✓
O13qq	✓	✓		✓	(✓)	(✓)	(✓)	✓	✓
O8qt	✓				✓	✓	✓	✓	✓
O1qt	✓				(✓)	(✓)	(✓)	✓	✓
O8ut	✓					✓	✓	✓	✓
O1ut	✓					(✓)	(✓)	✓	✓
O8qu	✓					✓	✓	✓	✓
O1qu	✓					(✓)	(✓)	✓	✓
O8dt	✓					✓	✓	✓	✓
O1dt	✓					(✓)	(✓)	✓	✓
O8qd	✓					✓	✓	✓	✓
O1qd	✓					(✓)	(✓)	✓	✓
OtG	✓				✓	✓	✓	✓	✓
OtW		✓	✓	✓					
ObW		(✓)	(✓)						
OtZ				✓		✓			
Off		(✓)	(✓)	(✓)					
Ofq3		✓	✓	✓		✓			
OpQM				✓		✓			
Opt				✓		✓	✓		
Otp							✓		

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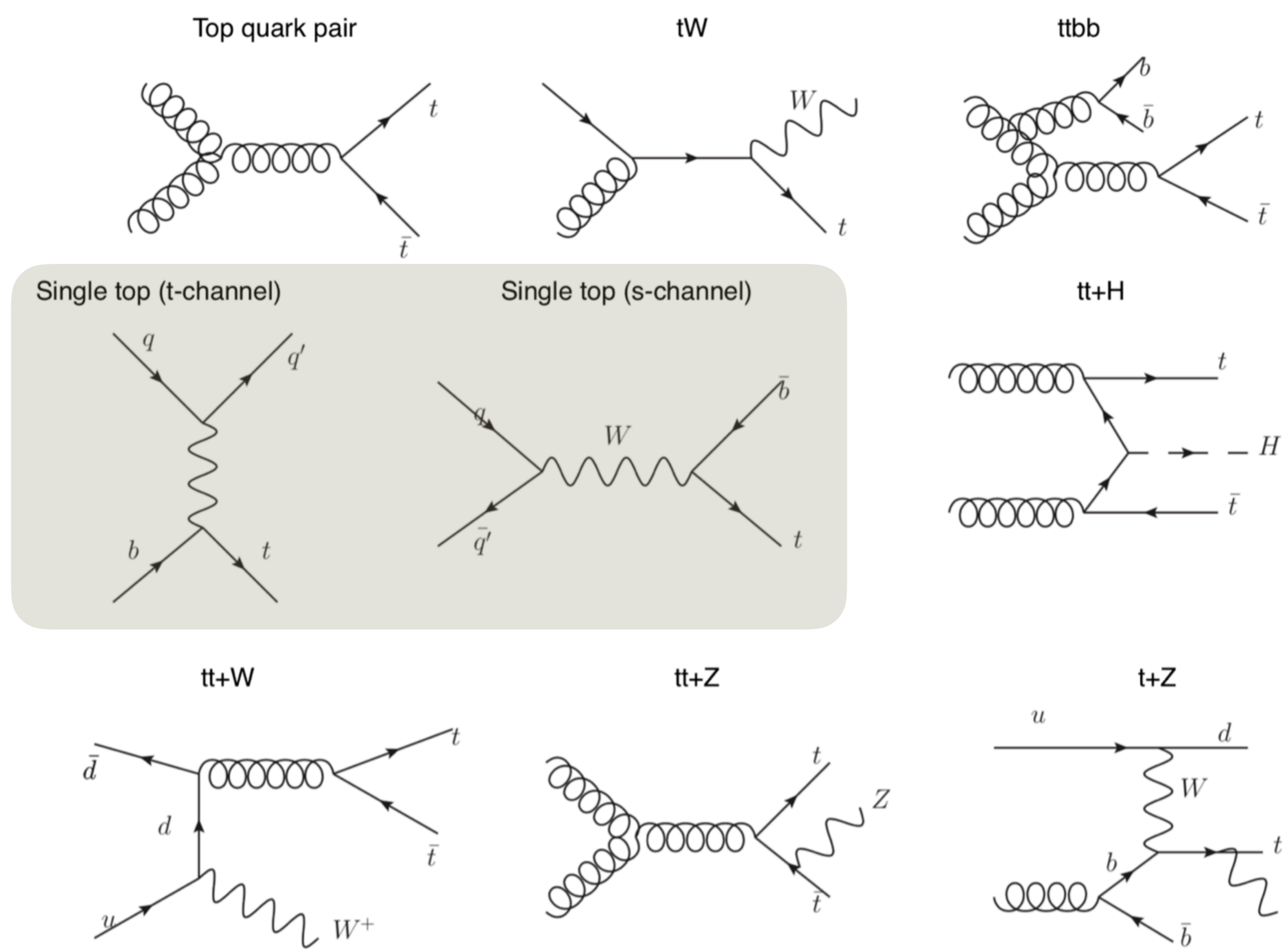
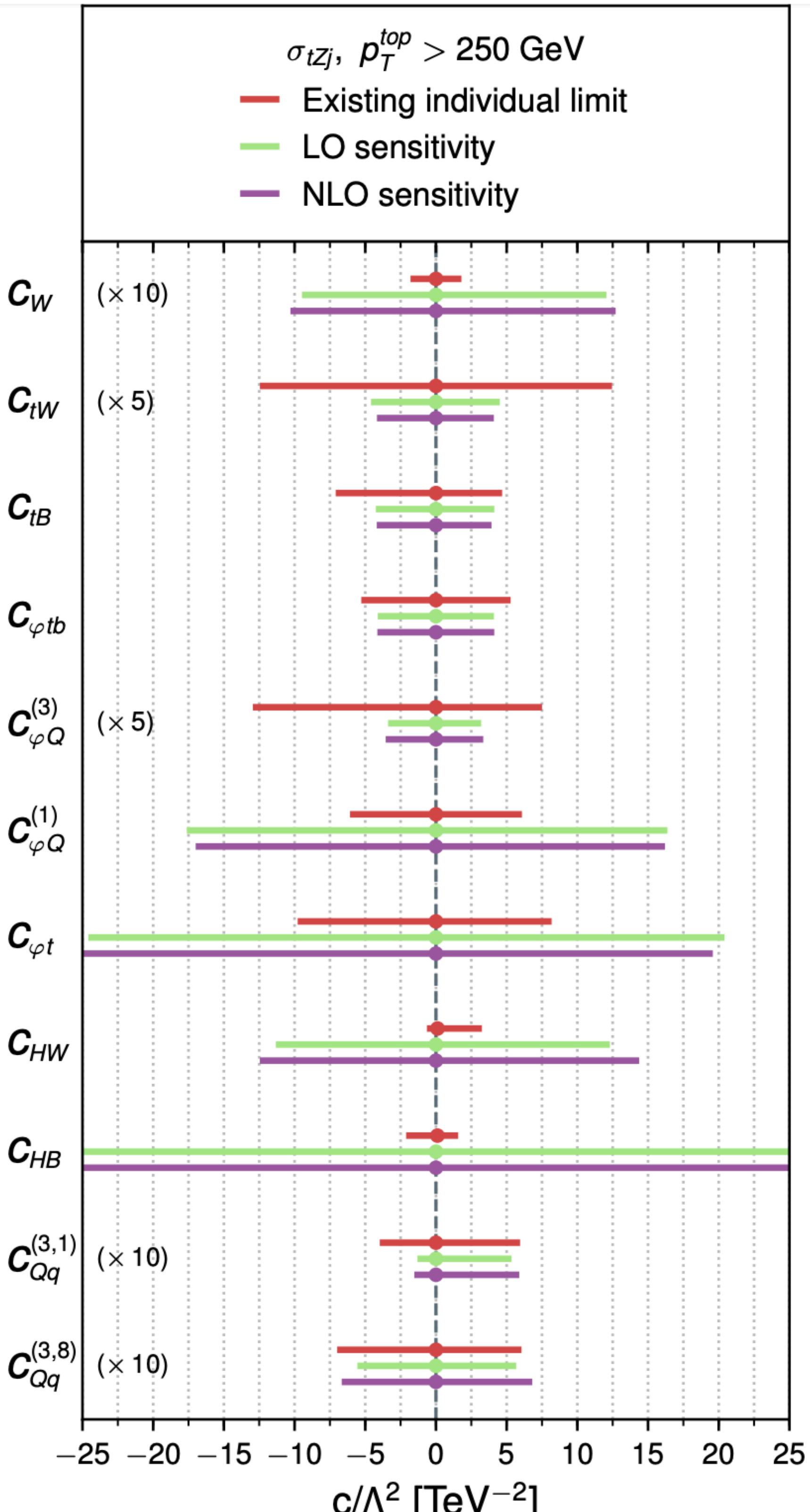


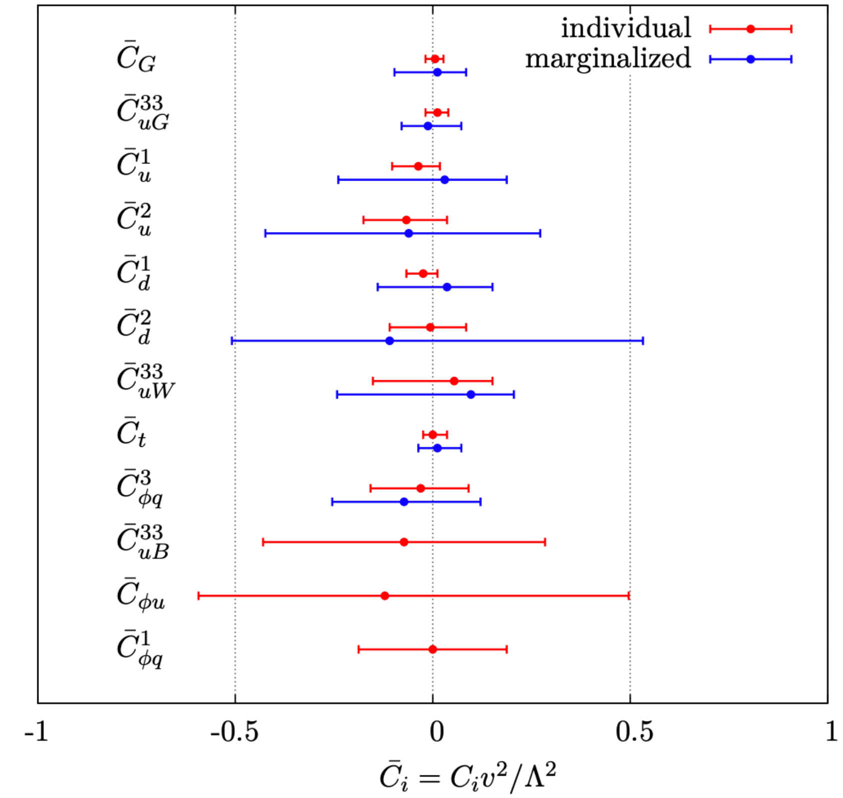
SMEFT constraints from top data

Exploit **rarer processes** at LHC eg ***t+Z+j***



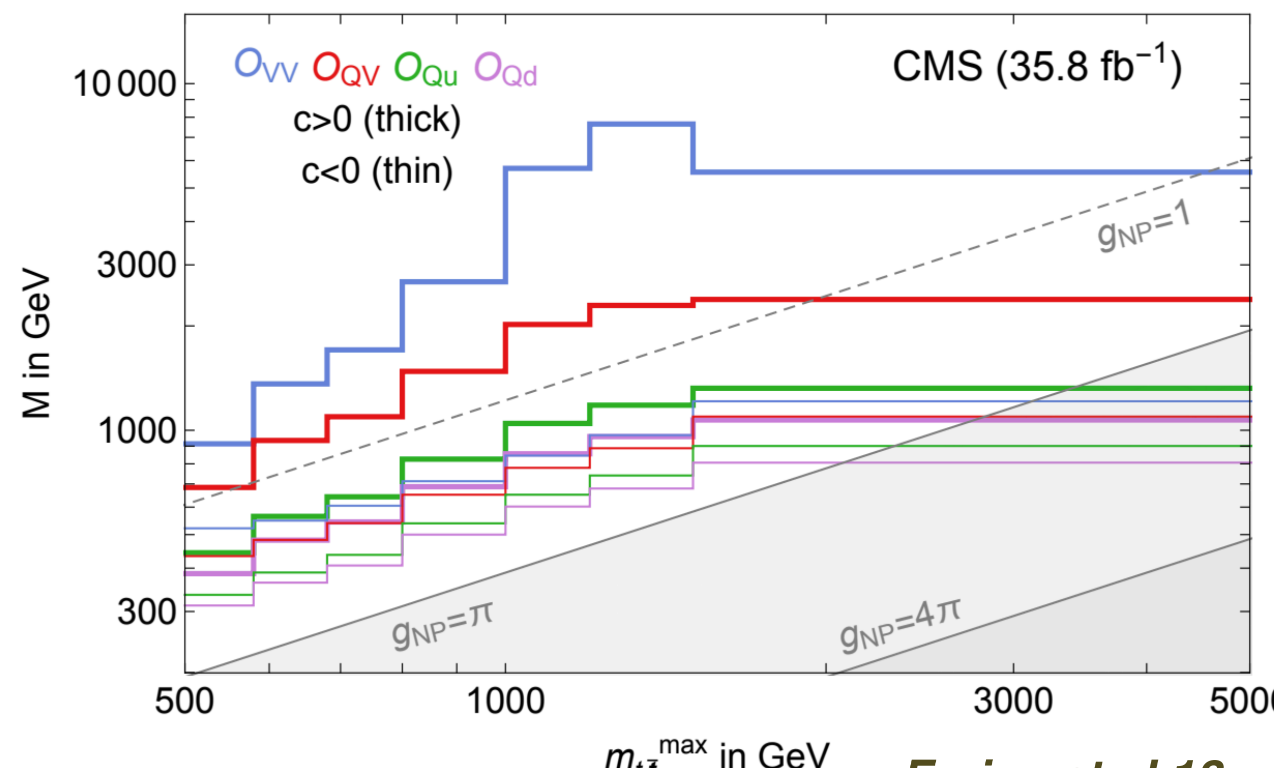
Degrande et al 18

Combine **different processes** in global fit



TopFitter 15

Enhance sensitivity from **high-energy m_{tt} tail**



Farina et al 18

SMEFiT structure

Stand-alone **Python code**, which exploits functionalities of the **NNPDF framework**

NNPDF code

- **Experimental data** and covariance matrices
- **NLO** APPLgrids + **NNLO** C-factors (for processes used in PDF fit)

aMC@NLO

- NLO **QCD** (benchmark)
- LO, NLO **SMEFT**
- Both **O(Λ^{-2})** and **O(Λ^{-4})** from ***d=6*** **operators**

MCFM

- NLO **QCD** (consistent choice of PDFs)
- Cross-checks of **aMC@NLO**

Python analysis code

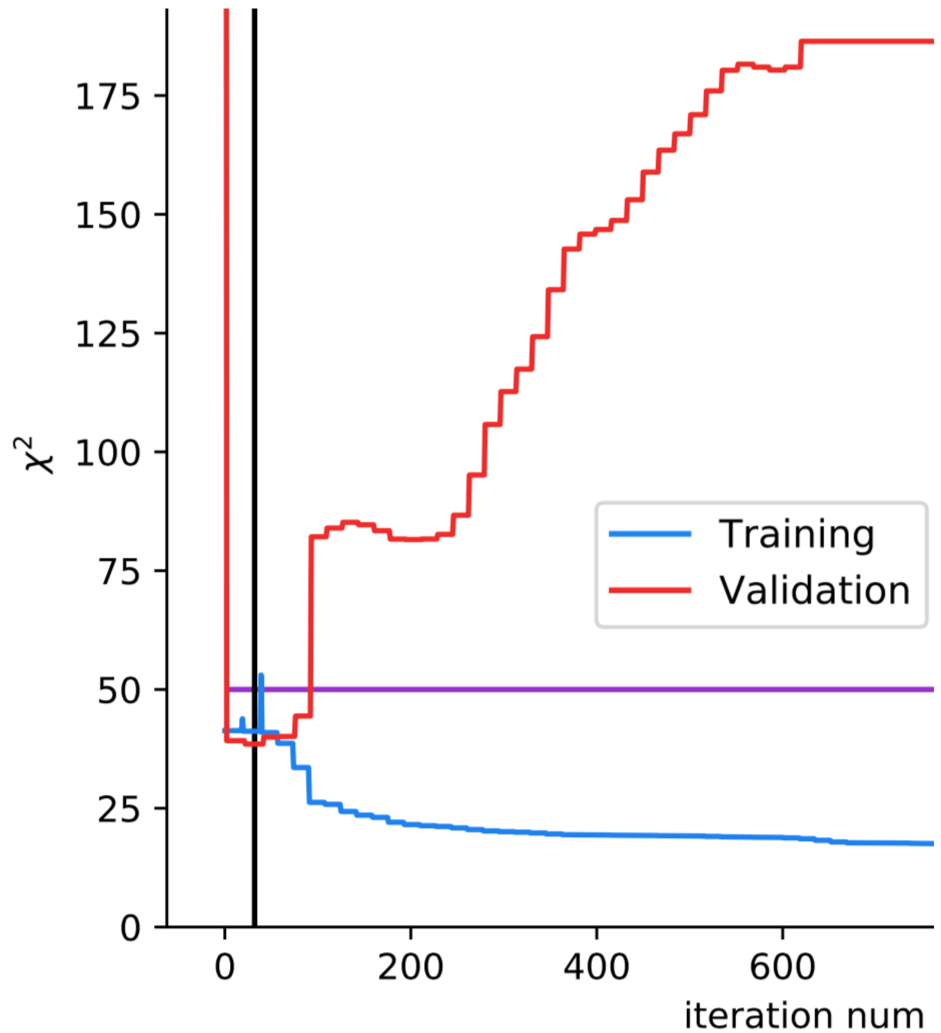
- Assemble **theory predictions** for generic SMEFT Wilson coefficients
- **Optimisation** with Sequential Quadratic Programming (**SciPy**)
- Look-back **cross-validation stopping**
- **Monte Carlo replicas** for uncertainty propagation

Fitting methodology

- Generate large sample of **Monte Carlo replicas** to construct the **probability distribution** in the space of experimental top quark measurements

$$\mathcal{O}_i^{(\mathrm{art})(k)} = S_{i,N}^{(k)} \mathcal{O}_i^{(\mathrm{exp})} \left(1 + \sum_{\alpha=1}^{N_{\mathrm{sys}}} r_{i,\alpha}^{(k)} \sigma_{i,c}^{(\mathrm{sys})} + r_i^{(k)} \sigma_i^{(\mathrm{stat})} \right) , \quad k = 1, \ldots, N_{\mathrm{rep}}$$

- **Cross-validation stopping** to avoid both under- and over-fitting

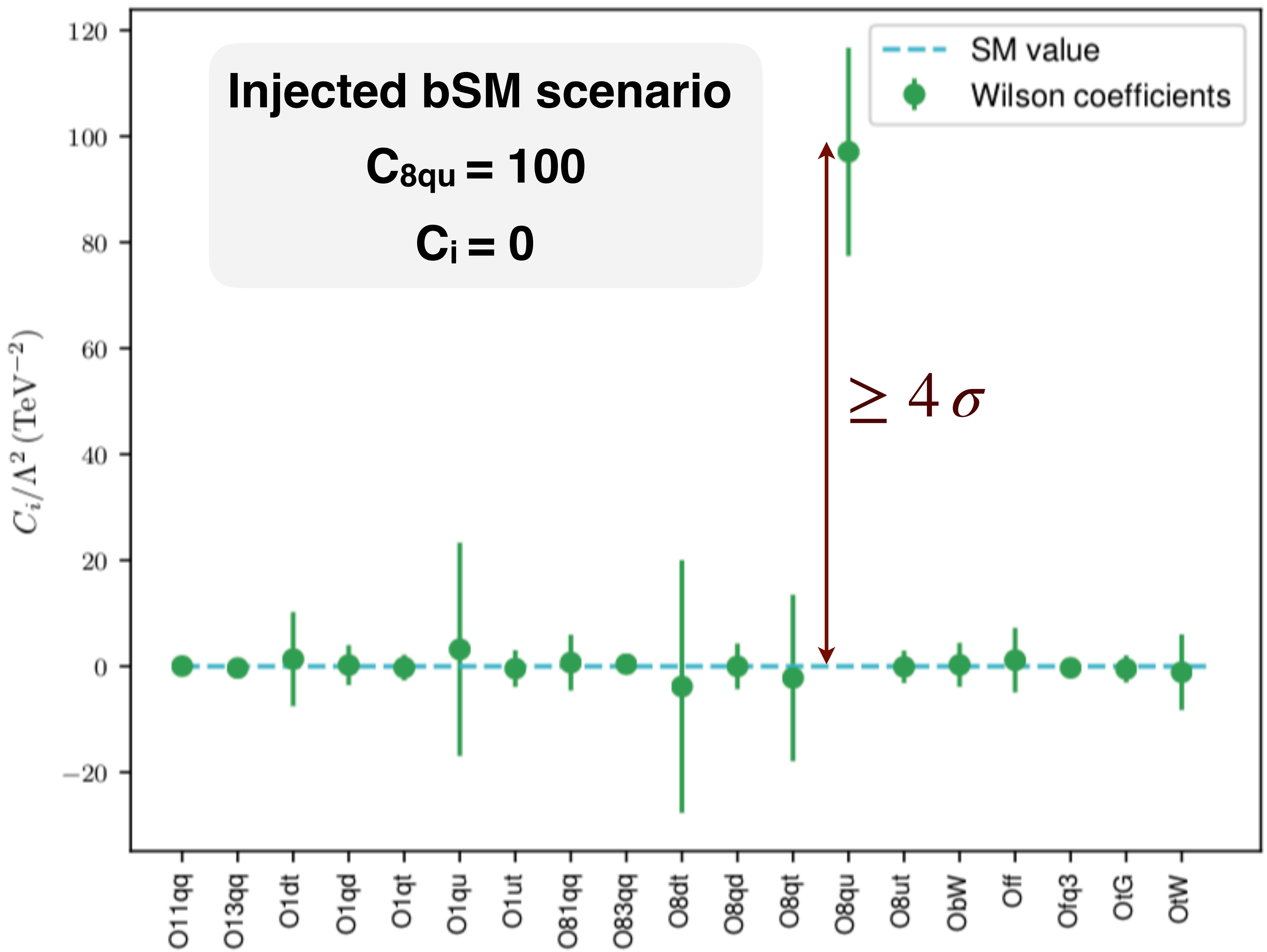


- Methodology validated with pseudo-data based on **closure tests**: decouple from possible data incompatibilities, theory limitations, or **genuine bSM effects**

- **PDF uncertainties** included in the χ^2 definition and MC sampling

Closure Tests

- Generate **pseudo-data based** on a given scenario (SM or BSM) and check that the correct (known) results are reproduced after the fit
- Allows quantifying the **expected statistical significance** for BSM deviations



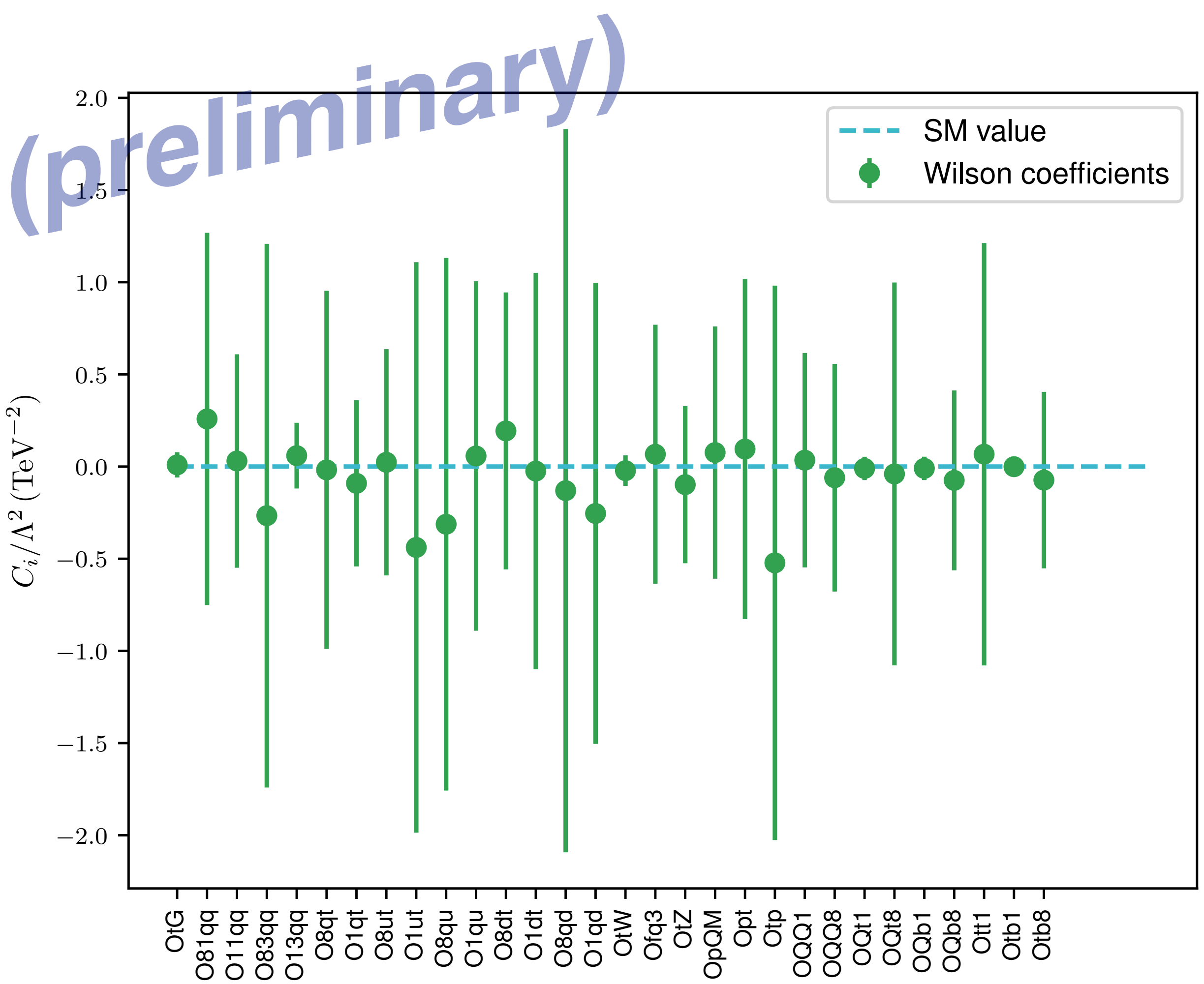
Fit quality

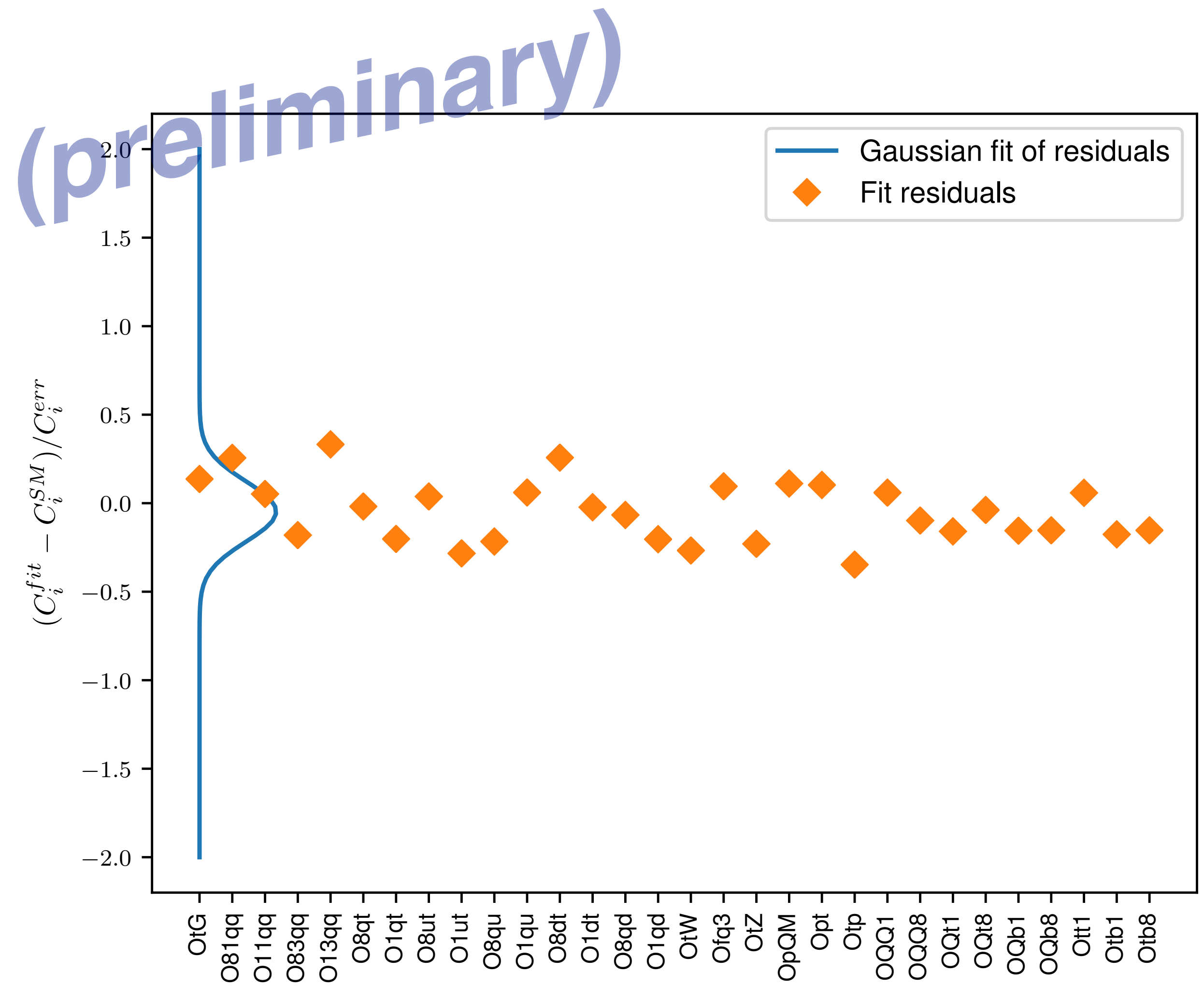
(preliminary)

- **Good agreement** between theory (SM and SMEFT) and data for most datasets
- For the **102 fitted cross-sections**, we find χ^2/n_{dat} *of* **0.81 (0.76) before (after) fit**
- Including SMEFT effects tend to improve agreement with data: need to quantify how **significant** this improvement is

Dataset	$\chi^2/n_{\rm dat}$ (prior)	$\chi^2/n_{\rm dat}$ (fit)	$n_{\rm dat}$
ATLAS_tt_8TeV_ljets [$m_{t\bar{t}}$]	1.51	1.44	7
CMS_tt_8TeV_ljets [y_t]	1.17	1.21	10
CMS_tt2D_8TeV_dilep [$(m_{t\bar{t}}, y_t)$]	1.38	1.38	16
CMS_tt_13TeV_ljets2 [$y_{t\bar{t}}$]	0.25	0.23	8
CMS_tt_13TeV_dilep [$y_{t\bar{t}}$]	0.26	0.26	6
CMS_tt_13TeV_ljets_2016 [y_t]	0.07	0.08	11
ATLAS_WhelF_8TeV	1.98	1.13	3
CMS_WhelF_8TeV	0.31	0.42	3
CMS_ttbb_13TeV	5.00	3.99	1
CMS_tttt_13TeV	0.05	0.08	1
ATLAS_tth_13TeV	1.61	1.11	1
CMS_tth_13TeV	0.34	0.09	1
ATLAS_ttZ_8TeV	1.32	1.18	1
ATLAS_ttZ_13TeV	0.01	0.01	1
CMS_ttZ_8TeV	0.04	0.06	1
CMS_ttZ_13TeV	0.90	0.94	1
ATLAS_ttW_8TeV	1.34	1.24	1
ATLAS_ttW_13TeV	0.82	0.81	1
CMS_ttW_8TeV	1.54	1.46	1
CMS_ttW_13TeV	0.03	0.02	1
CMS_t_tch_8TeV_dif	0.11	0.21	6
ATLAS_t_tch_8TeV [y_t]	0.91	0.61	4
ATLAS_t_tch_8TeV [$y_{\bar{t}}$]	0.40	0.33	4
ATLAS_t_sch_8TeV	0.08	0.23	1
CMS_t_tch_13TeV_dif [y_t]	0.46	0.48	4
CMS_t_sch_8TeV	1.26	1.16	1
ATLAS_tW_inc_8TeV	0.02	0.00	1
CMS_tW_inc_8TeV	0.00	0.01	1
ATLAS_tW_inc_13TeV	0.52	0.62	1
CMS_tW_inc_13TeV	4.29	3.26	1
ATLAS_tZ_inc_13TeV	0.00	0.02	1
CMS_tZ_inc_13TeV	0.66	0.64	1
Total	**0.81**	**0.76**	**102**

Fit results

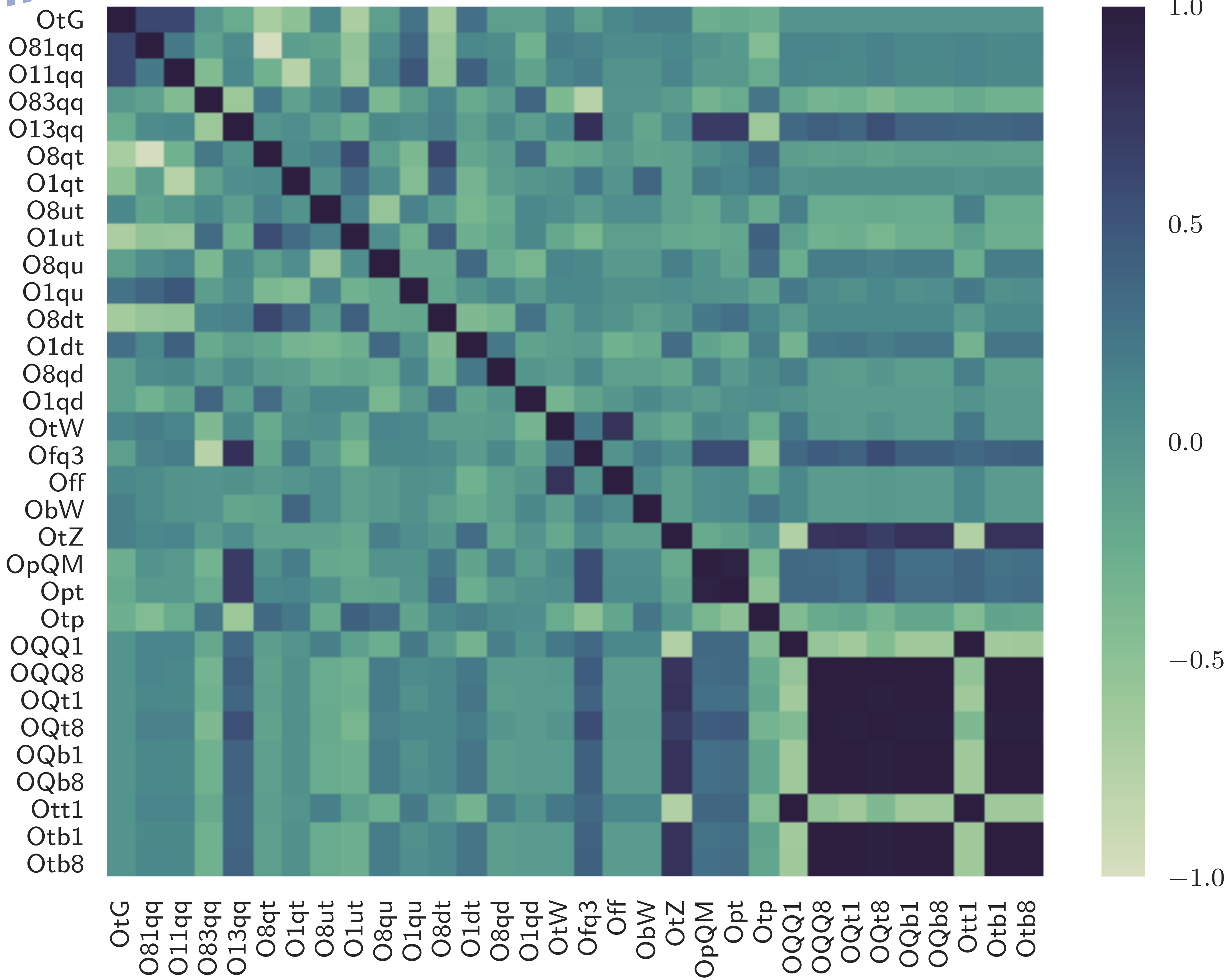




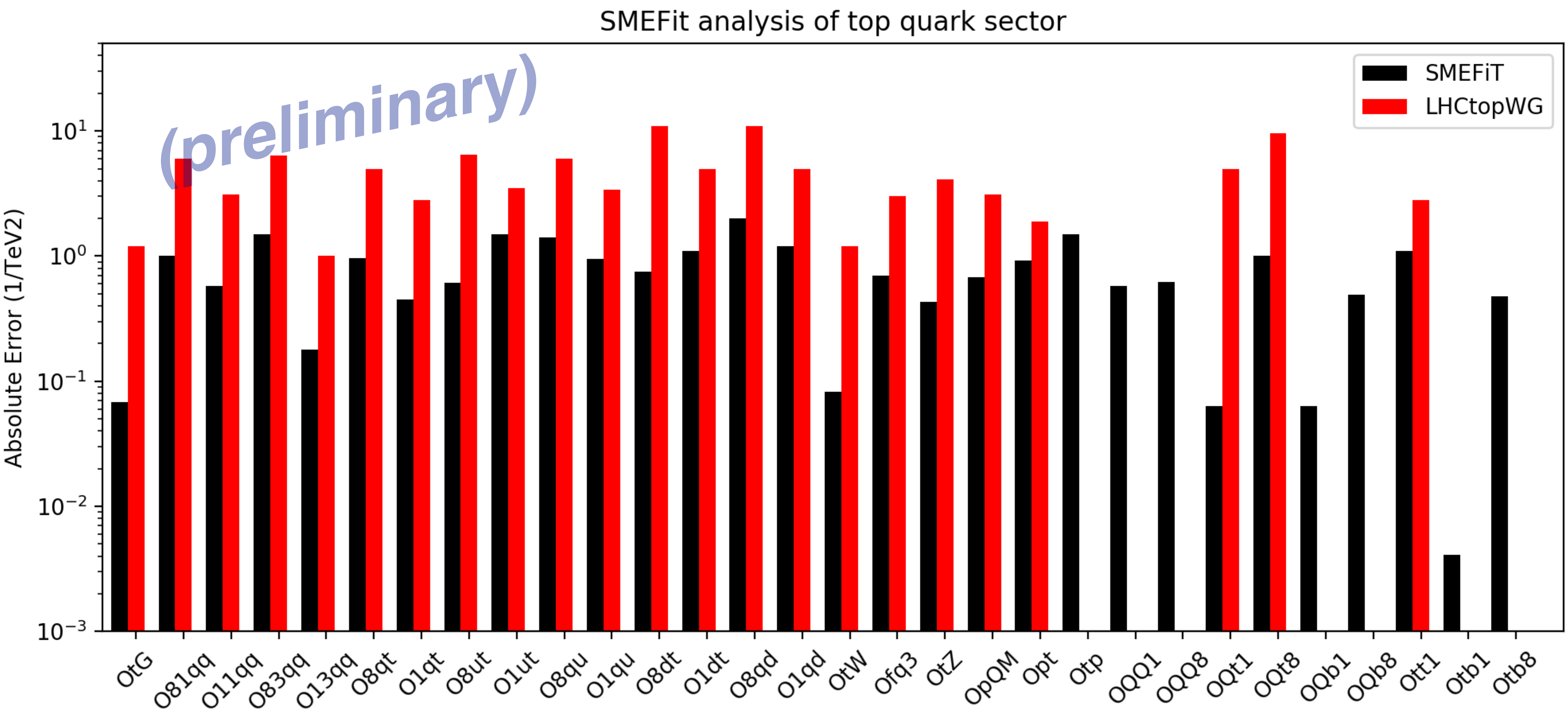
- Agreement with the SM expectation **within uncertainties**
- Bounds on individual operators are in general largely **correlated among them**
- Large differences between the bounds obtained from each operator

Correlations

(preliminary)

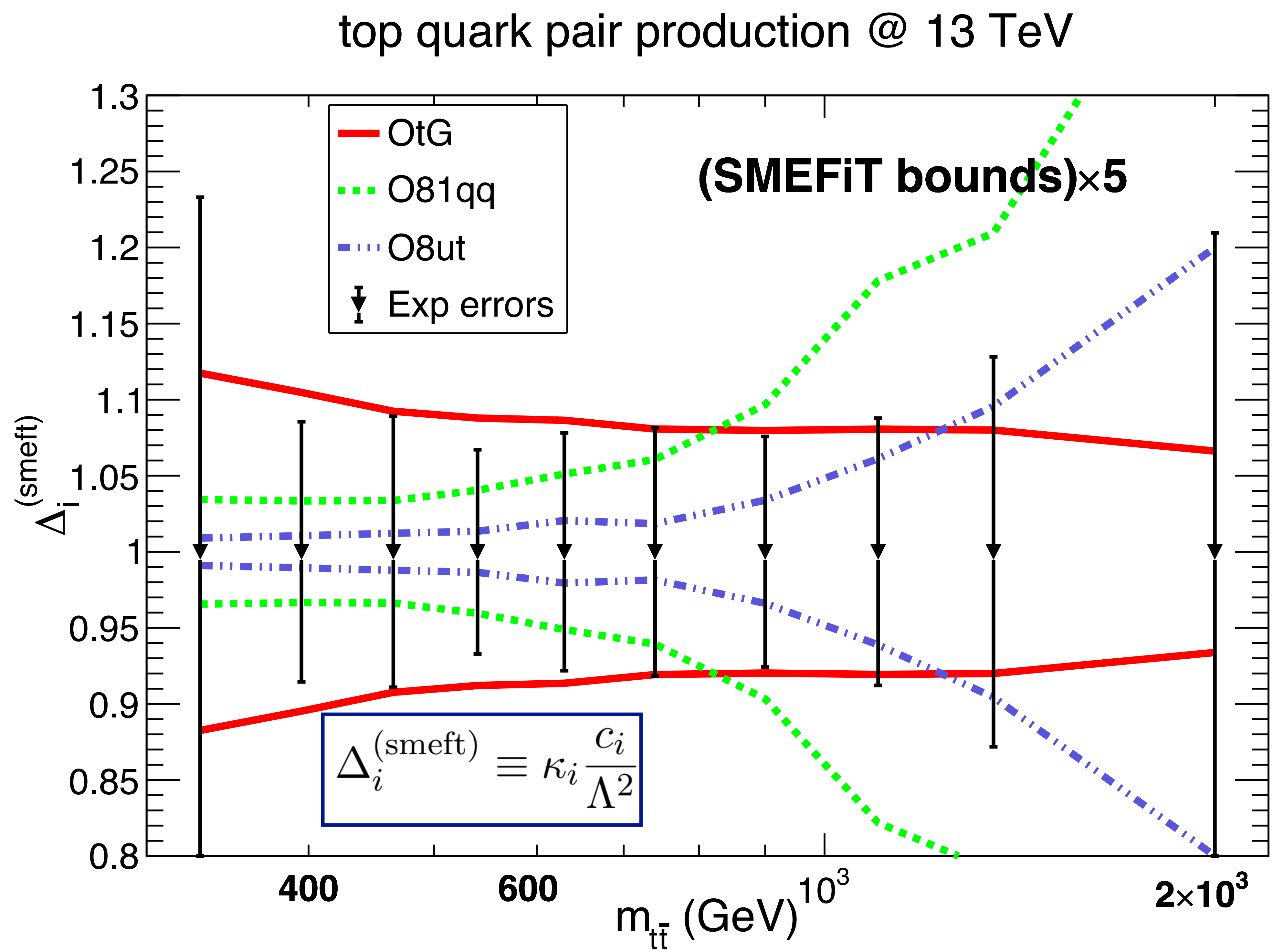


Comparison with previous bounds



- Compare to bounds reported in the LHC Top WG EFT note (same flavour assumptions)
- **Improvement** found (more stringent bounds) in all fitted degrees of freedom
- For some specific operators **our bounds are the first ones** to be reported

High-energy behaviour



Energy-growing effects enhance sensitivity to SMEFT effects with **TeV-scale cross-sections** but need to be careful to ensure **validity of EFT description**

Summary and outlook (part II)

- The accurate determination of the **quark and gluon structure of the proton** is an essential ingredient for LHC phenomenology

- LHC data provides **stringent constraints on PDFs**

- PDFs with **theoretical uncertainties**: the next milestone for global QCD analyses

- At the HL-LHC, theory calculations with **1% PDF uncertainties** are within reach

- The **SMEFiT** framework is a novel approach for global analyses of the SMEFT, which exploits expertise from the NNPDF fits

- Proof-of-concept: SMEFT analysis of the **top quark sector**

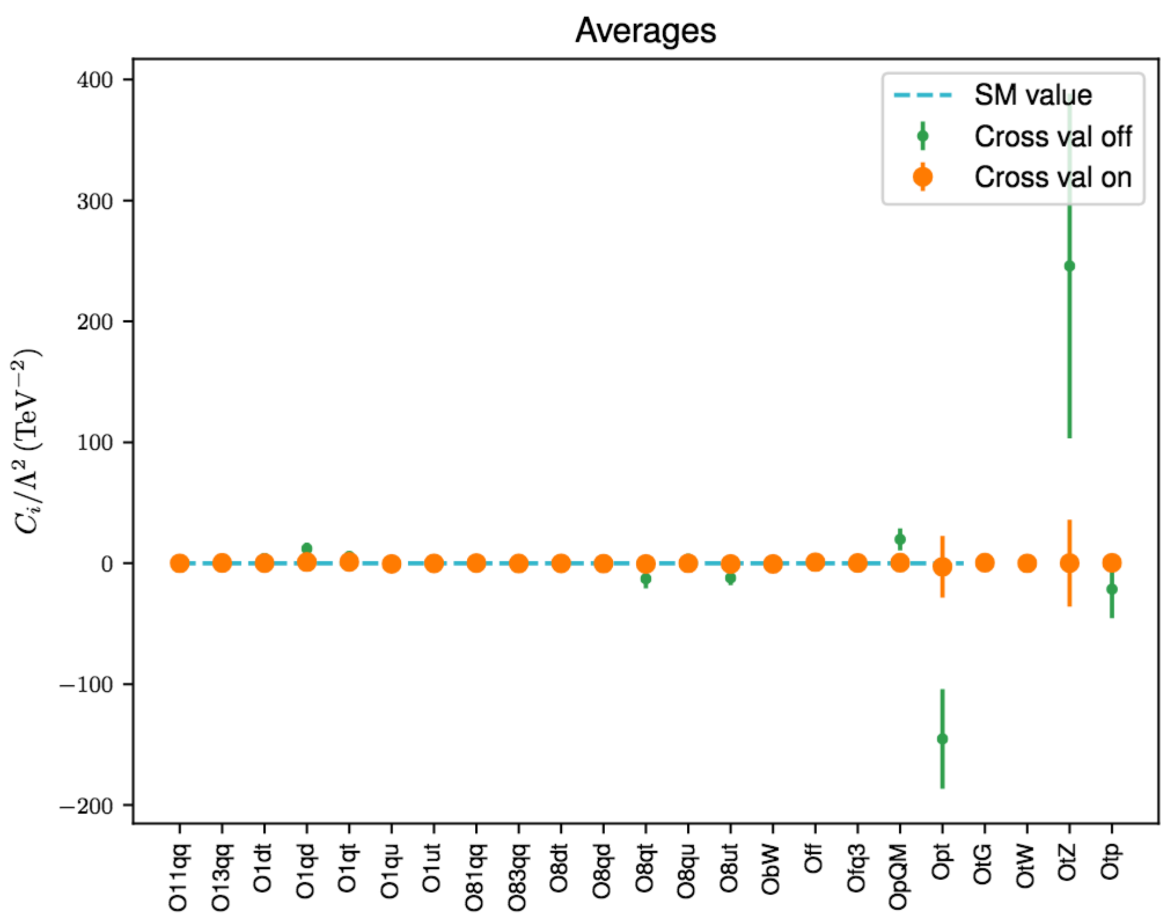
- Next steps: enlarge the operator basis and include **additional LHC cross-sections** (Higgs, electroweak, jets) as well as flavour and low-energy observables

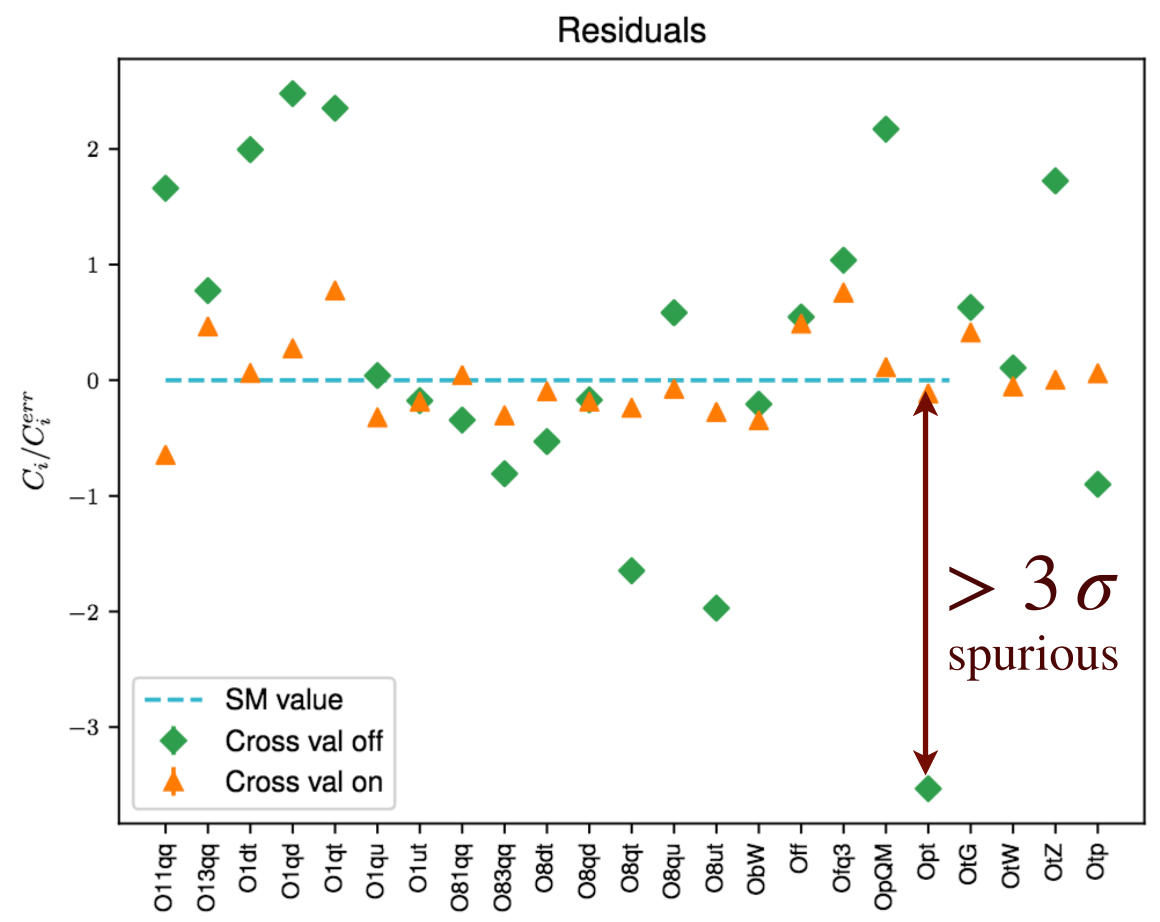
*Ultimately the **simultaneous determination of PDFs and SMEFT** degrees of freedom might be required to fully exploit the LHC potential*

Extra material

Cross-validation

- Since N_{par} is not too different from N_{dat}, overfitting will take place for an efficient optimiser
- **Artificial tensions with the SM** are likely to be generated by overfitting!
- Test the role of cross-validation in a closure test with pseudo-data generated with the SM
- Fit residuals **consistent with true result (SM)** only with cross-validation





Input dataset (I)

Process	Dataset	$\sqrt{s}$	Info	Observables	$N_{\rm dat}$	Ref
$t\bar{t}$	ATLAS_tt_8TeV_ljets	**8 TeV**	lepton+jets	$d\sigma/d\lvert y_t\rvert$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\lvert y_{t\bar{t}}\rvert$	5, 8, 7, 5	[77]
$t\bar{t}$	CMS_tt_8TeV_ljets	**8 TeV**	lepton+jets	$d\sigma/dy_t$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/dy_{t\bar{t}}$	10, 8, 7, 10	[78]
$t\bar{t}$	CMS_tt2D_8TeV_dilep	**8 TeV**	dileptons	$d^2\sigma/dy_t dp_t^T$, $d^2\sigma/dy_t dm_{t\bar{t}}$, $d^2\sigma/dp_{t\bar{t}}^T dm_{t\bar{t}}$, $d^2\sigma/dy_{t\bar{t}} dm_{t\bar{t}}$	16, 16, 16, 16	[79]
$t\bar{t}$	CMS_tt_13TeV_ljets	**13 TeV**	lepton+jets	$d\sigma/d\lvert y_t\rvert$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\lvert y_{t\bar{t}}\rvert$	7, 9, 8, 6	[83]
$t\bar{t}$	CMS_tt_13TeV_ljets2	**13 TeV**	lepton+jets	$d\sigma/d\lvert y_t\rvert$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d\lvert y_{t\bar{t}}\rvert$	11, 12, 10, 10	[85]
$t\bar{t}$	CMS_tt_13TeV_dilep	**13 TeV**	dileptons	$d\sigma/dy_t$, $d\sigma/dp_t^T$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/dy_{t\bar{t}}$	8, 6, 6, 8	[86]
$t\bar{t}$	ATLASCMS_AcMtt_8TeV	**8 TeV**	Asymm comb	$A_C(m_{t\bar{t}})$, Eq. (3.1)	6	[80]
$t\bar{t}$	ATLAS_WhelF_8TeV	**8 TeV**	W helicity fract	F_0, F_L, F_R	3	[81]
$t\bar{t}$	CMS_WhelF_8TeV	**8 TeV**	W helicity fract	F_0, F_L, F_R	3	[82]

Input dataset (II)

Process	Dataset	$\sqrt{s}$	Info	Observables	$N_{\rm dat}$	Ref
Single t	`CMS_t_tch_8TeV_inc`	**8 TeV**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$ (R_t)	2 (1)	[95]
Single t	`CMS_t_sch_8TeV`	**8 TeV**	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[96]
Single t	`ATLAS_t_sch_8TeV`	**8 TeV**	s-channel	$\sigma_{\rm tot}(t+\bar{t})$	1	[97]
Single t	`ATLAS_t_tch_8TeV`	**8 TeV**	t-channel	$d\sigma(tq)/dp_T^t, d\sigma(\bar{t}q)/dp_T^{\bar{t}}$ $d\sigma(tq)/dy_t, d\sigma(\bar{t}q)/dy_t$	5, 4 4, 4	[98]
Single t	`ATLAS_t_tch_13TeV`	**13 TeV**	t-channel	$\sigma_{\rm tot}(t), \sigma_{\rm tot}(\bar{t})$ (R_t)	2 (1)	[99]
Single t	`CMS_t_tch_13TeV_inc`	**13 TeV**	t-channel	$\sigma_{\rm tot}(t+\bar{t})$ (R_t)	1 (1)	[100]
Single t	`CMS_t_tch_8TeV_dif`	**8 TeV**	t-channel	$d\sigma/dp_T^{(t+\bar{t})}$, $d\sigma/d\|y^{(t+\bar{t})}\|$	6 6	[101]
Single t	`CMS_t_tch_13TeV_dif`	**13 TeV**	t-channel	$d\sigma/dp_T^{(t+\bar{t})}$, $d\sigma/d\|y^{(t+\bar{t})}\|$	4 4	[102]
tW	`ATLAS_tW_inc_8TeV`	**8 TeV**	inclusive	$\sigma_{\rm tot}(tW)$	1	[103]
tW	`CMS_tW_inc_8TeV`	**8 TeV**	inclusive	$\sigma_{\rm tot}(tW)$	1	[104]
tW	`ATLAS_tW_inc_13TeV`	**13 TeV**	inclusive	$\sigma_{\rm tot}(tW)$	1	[105]
tW	`CMS_tW_inc_13TeV`	**13 TeV**	inclusive	$\sigma_{\rm tot}(tW)$	1	[106]
tZ	`CMS_tZ_inc_13TeV`	**13 TeV**	inclusive	$\sigma_{\rm fid}(Wbl^+l^-q)$	1	[107]
tZ	`ATLAS_tZ_inc_13TeV`	**13 TeV**	inclusive	$\sigma_{\rm tot}(tZq)$	1	[108]

Input dataset (III)

Process	Dataset	$\sqrt{s}$	Info	Observables	$N_{\rm dat}$	Ref
$t\bar{t}b\bar{b}$	CMS_ttbb_13TeV	**13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}b\bar{b})$	1	[87]
$t\bar{t}t\bar{t}$	CMS_tttt_13TeV	**13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}t\bar{t})$	1	[88]
$t\bar{t}Z$	CMS_ttZ_8_13TeV	**8+13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	2	[89, 90]
$t\bar{t}Z$	ATLAS_ttZ_8_13TeV	**8+13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}Z)$	2	[91, 92]
$t\bar{t}W$	CMS_ttW_8_13TeV	**8+13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	2	[89, 90]
$t\bar{t}W$	ATLAS_ttW_8_13TeV	**8+13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}W)$	2	[91, 92]
$t\bar{t}H$	CMS_tth_13TeV	**13 TeV**	signal strength	$\mu_{t\bar{t}H}$	1	[93]
$t\bar{t}H$	ATLAS_tth_13TeV	**13 TeV**	total xsec	$\sigma_{\rm tot}(t\bar{t}H)$	1	[94]

The fit includes more than **100 cross-section measurements** at 8 and 13 TeV from **10 different top-quark production processes**

Theory calculations

Process	SM	Code	SMEFT	Code
$t\bar{t}$	NNLO QCD	MCFM/SHERPA NLO + NNLO K-factors	NLO QCD	MG5_aMC
single-t (t-ch)	NNLO QCD	MCFM NLO + NNLO K-factors	NLO QCD	MG5_aMC
single-t (s-ch)	NLO QCD	MCFM	NLO QCD	MG5_aMC
tW	NLO QCD	MG5_aMC	NLO QCD	MG5_aMC
tZ	NLO QCD	MG5_aMC	LO QCD + NLO SM K-factors	MG5_aMC
$t\bar{t}W(Z)$	NLO QCD	MG5_aMC	LO QCD + NLO SM K-factors	MG5_aMC
$t\bar{t}h$	NLO QCD	MG5_aMC	LO QCD + NLO SM K-factors	MG5_aMC
$t\bar{t}t\bar{t}$	NLO QCD	MG5_aMC	LO QCD + NLO SM K-factors	MG5_aMC
$t\bar{t}b\bar{b}$	NLO QCD	MG5_aMC	LO QCD + NLO SM K-factors	MG5_aMC

PDF set: **NNPDF3.1 NNLO no-top**

Operator basis

- We follow the same flavour assumptions as in the **LHC Top WG note**
- Minimal Flavour Violation (MFV), diagonal CKM, zero Yukawas for first two quark gens
- CP conservation assumed
- Include those SMEFT dimension-6 operators of Warsaw basis with **at least one top quark**
- The fit includes a total of **34 independent degrees of freedom**
- Include both **interference** and **quadratic contributions** from these operators

Class	Notation	Degree of Freedom	Operator Definition
	OQQ1	c^1_{QQ}	$2C^{1(3333)}_{qq} - \frac{2}{3}C^{3(3333)}_{qq}$
	OQQ8	c^8_{QQ}	$8C^{3(3333)}_{qq}$
	OQt1	c^1_{Qt}	$C^{1(3333)}_{qu}$
	OQt8	c^8_{Qt}	$C^{8(3333)}_{qu}$
$QQQQ$	OQb1	c^1_{Qb}	$C^{1(3333)}_{qd}$
	OQb8	c^8_{Qb}	$C^{8(3333)}_{qd}$
4-heavy	Ott1	c^1_{tt}	$C^{(3333)}_{uu}$
	Otb1	c^1_{tb}	$C^{1(3333)}_{ud}$
	Otb8	c^8_{tb}	$C^{8(3333)}_{ud}$
	OQtQb1	c^1_{QtQb}	$C^{1(3333)}_{quqd}$
	OQtQb8	c^8_{QtQb}	$C^{8(3333)}_{quqd}$
	O81qq	$c^{1,8}_{Qq}$	$C^{1(i33i)}_{qq} + 3C^{3(i33i)}_{qq}$
	O11qq	$c^{1,1}_{Qq}$	$C^{1(ii33)}_{qq} + \frac{1}{6}C^{1(i33i)}_{qq} + \frac{1}{2}C^{3(i33i)}_{qq}$
	O83qq	$c^{3,8}_{Qq}$	$C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq}$
	O13qq	$c^{3,1}_{Qq}$	$C^{3(ii33)}_{qq} + \frac{1}{6}(C^{1(i33i)}_{qq} - C^{3(i33i)}_{qq})$
	O8qt	c^8_{tq}	$C^{8(ii33)}_{qu}$
	O1qt	c^1_{tq}	$C^{1(ii33)}_{qu}$
	O8ut	c^8_{tu}	$2C^{(i33i)}_{uu}$
$QQqq$	O1ut	c^1_{tu}	$C^{(ii33)}_{uu} + \frac{1}{3}C^{(i33i)}_{uu}$
	O8qu	c^8_{Qu}	$C^{8(33ii)}_{qu}$
2-heavy-2-light	O1qu	c^1_{Qu}	$C^{1(33ii)}_{qu}$
	O8dt	c^8_{td}	$C^{8(33ii)}_{ud}$
	O1dt	c^1_{td}	$C^{1(33ii)}_{ud}$
	O8qd	c^8_{Qd}	$C^{8(33ii)}_{qd}$
	O1qd	c^1_{Qd}	$C^{1(33ii)}_{qd}$
	OtG	c_{tG}	$\mathrm{Re}\{C^{(33)}_{uG}\}$
	OtW	c_{tW}	$\mathrm{Re}\{C^{(33)}_{uW}\}$
	ObW	c_{bW}	$\mathrm{Re}\{C^{(33)}_{dW}\}$
	OtZ	c_{tZ}	$\mathrm{Re}\{-s_W C^{(33)}_{uB} + c_W C^{(33)}_{uW}\}$
$QQ+V,G,\varphi$	Off	$c_{\varphi tb}$	$\mathrm{Re}\{C^{(33)}_{\varphi ud}\}$
	Ofq3	$c^3_{\varphi Q}$	$C^{3(33)}_{\varphi q}$
2-heavy + V/h	OpQM	$c^-_{\varphi Q}$	$C^{1(33)}_{\varphi q} - C^{3(33)}_{\varphi q}$
	Opt	$c_{\varphi t}$	$C^{(33)}_{\varphi u}$
	Otp	$c_{t\varphi}$	$\mathrm{Re}\{C^{(33)}_{u\varphi}\}$

Operator basis

4-quark operators

$$O_{qq}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{q}_k\gamma_\mu q_l),$$
$$O_{qq}^{3(ijkl)} = (\bar{q}_i\gamma^\mu \tau^I q_j)(\bar{q}_k\gamma_\mu \tau^I q_l),$$
$$O_{qu}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{u}_k\gamma_\mu u_l),$$
$$O_{qu}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{u}_k\gamma_\mu T^A u_l),$$
$$O_{qd}^{1(ijkl)} = (\bar{q}_i\gamma^\mu q_j)(\bar{d}_k\gamma_\mu d_l),$$
$$O_{qd}^{8(ijkl)} = (\bar{q}_i\gamma^\mu T^A q_j)(\bar{d}_k\gamma_\mu T^A d_l),$$
$$O_{uu}^{(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{u}_k\gamma_\mu u_l),$$
$$O_{ud}^{1(ijkl)} = (\bar{u}_i\gamma^\mu u_j)(\bar{d}_k\gamma_\mu d_l),$$
$$O_{ud}^{8(ijkl)} = (\bar{u}_i\gamma^\mu T^A u_j)(\bar{d}_k\gamma_\mu T^A d_l),$$
$$^{\ddagger}O_{quqd}^{1(ijkl)} = (\bar{q}_i u_j)\,\varepsilon\,(\bar{q}_k d_l),$$
$$^{\ddagger}O_{quqd}^{8(ijkl)} = (\bar{q}_i T^A u_j)\,\varepsilon\,(\bar{q}_k T^A d_l).$$

2-quark + V/g/h operators

$$^{\ddagger}O_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger\varphi),$$
$$O_{\varphi q}^{1(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_i\gamma^\mu q_j),$$
$$O_{\varphi q}^{3(ij)} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_i\gamma^\mu\tau^I q_j),$$
$$O_{\varphi u}^{(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j),$$
$$^{\ddagger}O_{\varphi ud}^{(ij)} = (\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{u}_i\gamma^\mu d_j),$$
$$^{\ddagger}O_{uW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{\varphi}W^I_{\mu\nu},$$
$$^{\ddagger}O_{dW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,\varphi W^I_{\mu\nu},$$
$$^{\ddagger}O_{uB}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu} u_j)\quad\tilde{\varphi}B_{\mu\nu},$$
$$^{\ddagger}O_{uG}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}T^A u_j)\,\tilde{\varphi}G^A_{\mu\nu}\,,$$