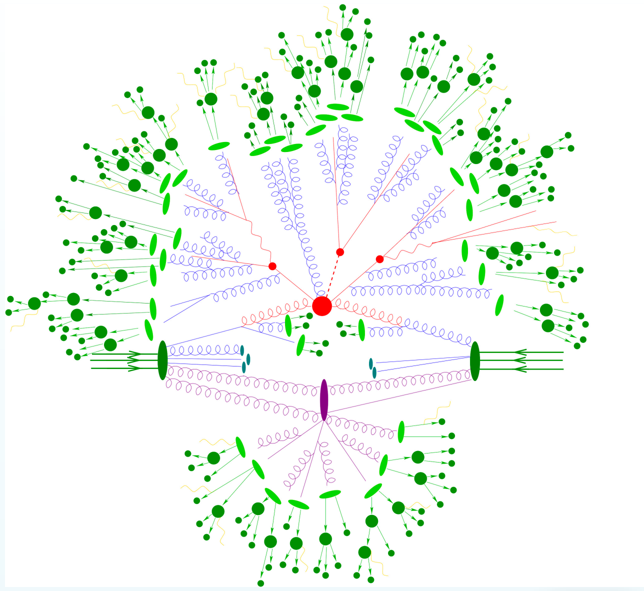
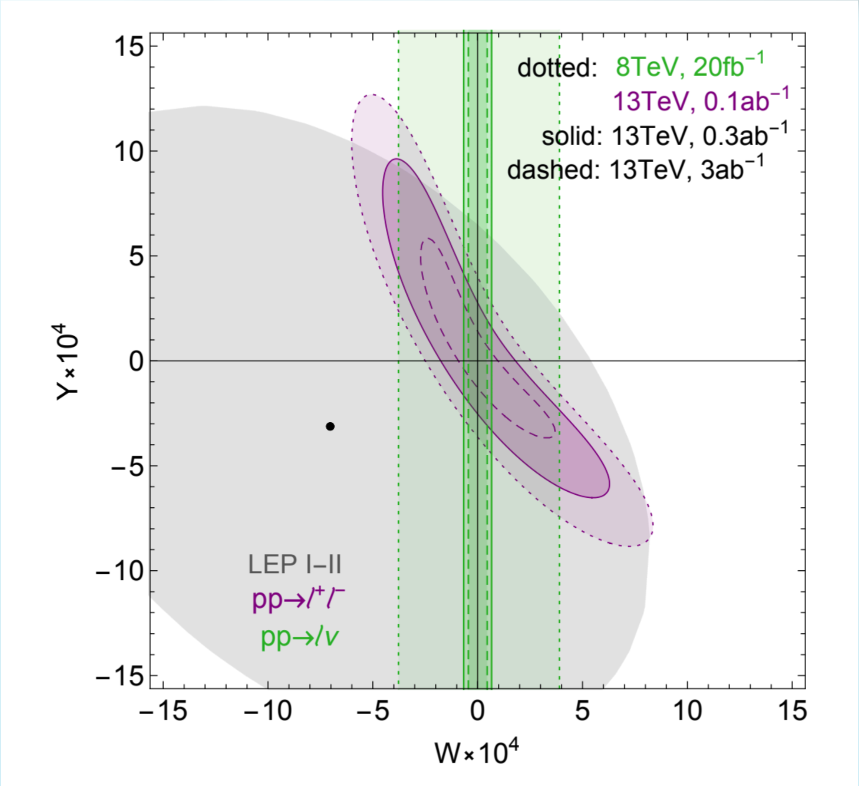
Parton Distributions and New Physics searches at the LHC

Juan Rojo
VU Amsterdam & Nikhef

Quark Confinement and the Hadron Spectrum XIII
Maynooth University, 02/08/2018



Discovery through precision at hadron colliders



Outstanding questions in Particle Physics

The Higgs boson

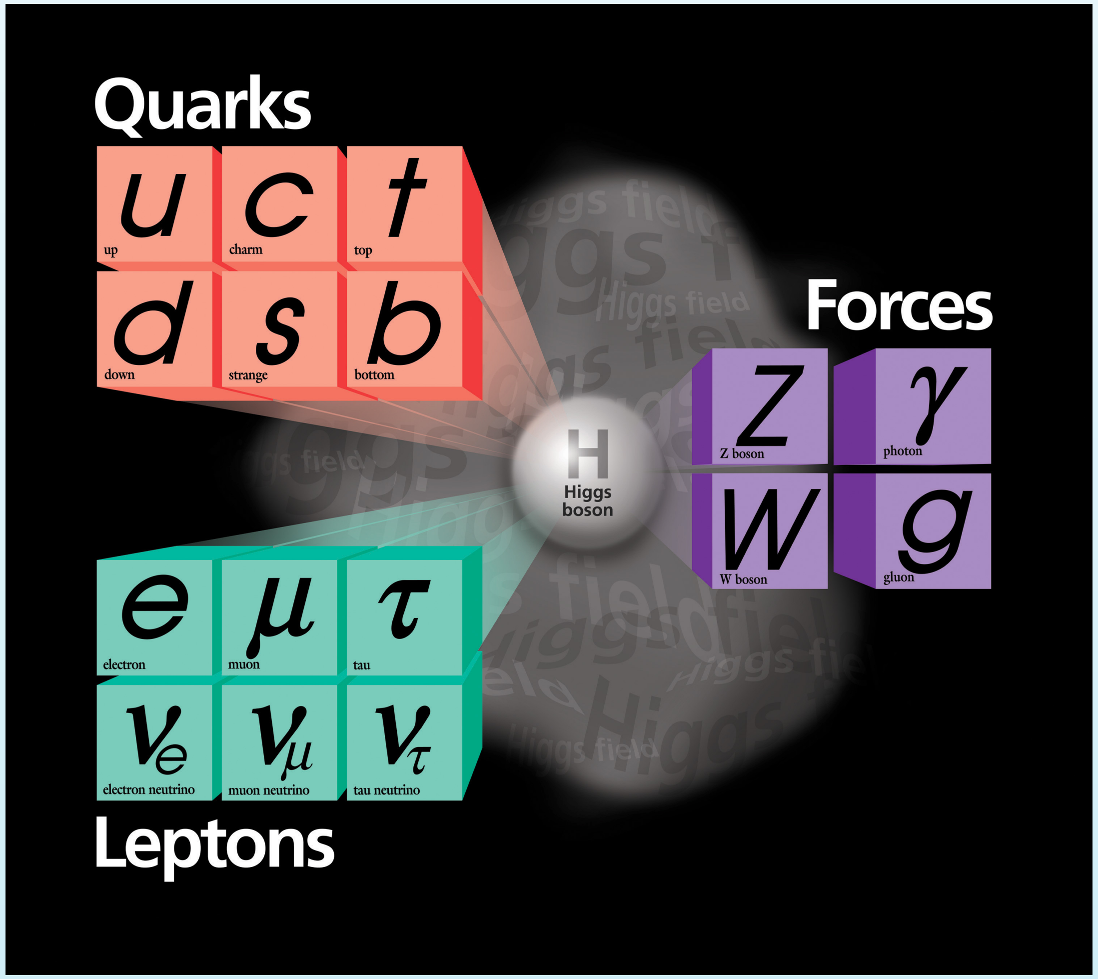
- Huge gap, 10^{17}, between **Higgs and Plank scales**
- **Elementary or composite**? Additional Higgs bosons?
- Coupling to **Dark Matter**? Role in cosmological phase transitions?
- Is the **vacuum state of the Universe** stable?

Quarks and leptons

- **Why three families?** Can we explain **masses and mixings**?
- Origin of **Matter-Antimatter asymmetry** in the Universe?
- Are **neutrinos Majorana or Dirac**? CP violation in the lepton sector?

Dark Matter

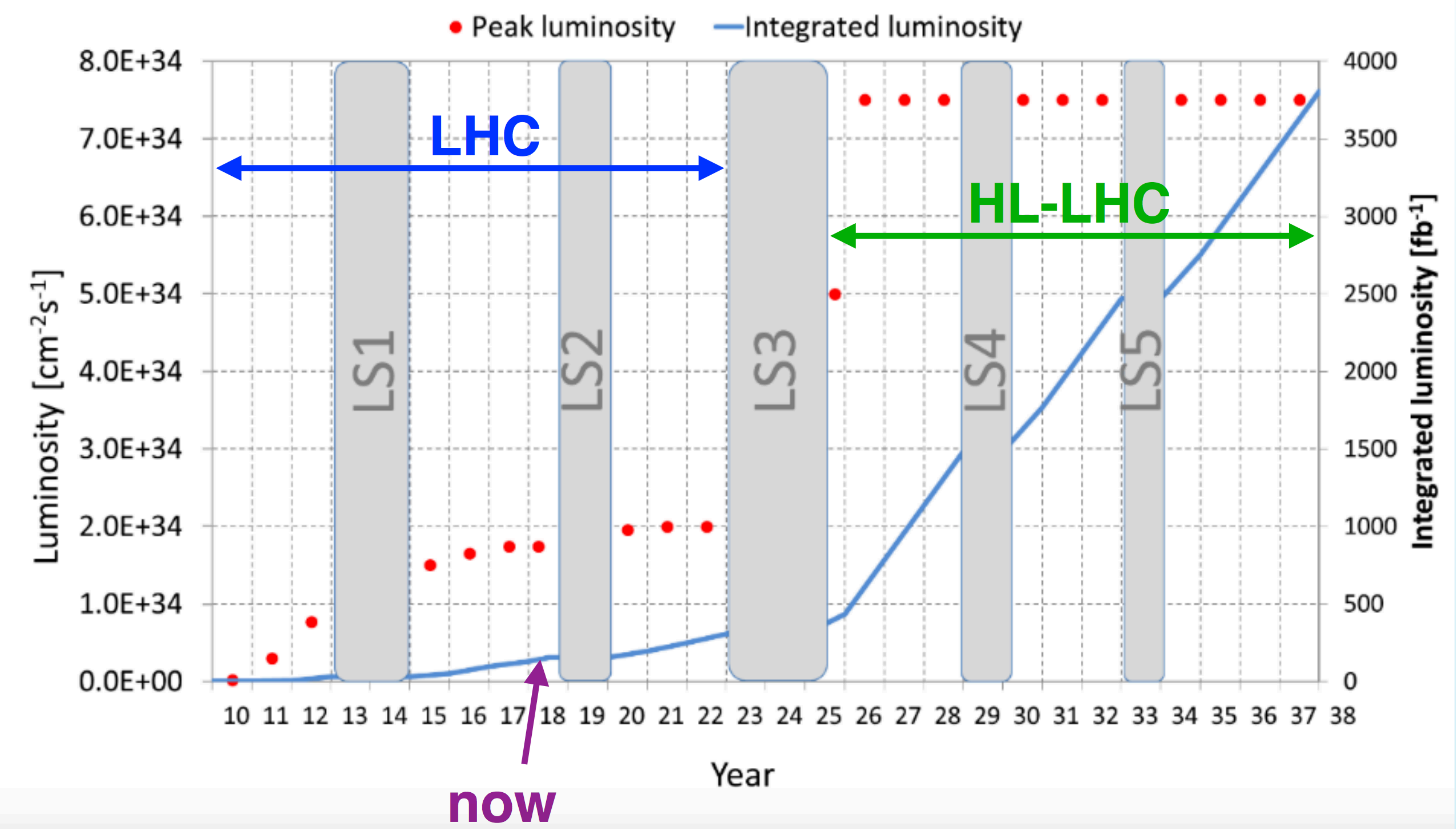
- **Weakly interacting massive particles**? Sterile neutrinos? **Extremely light particles** (axions)?
- **Interactions** with Standard Model particles?
- What is the **structure of the Dark Sector**? Is Dark Matter self-interacting?



Outstanding questions in Particle Physics

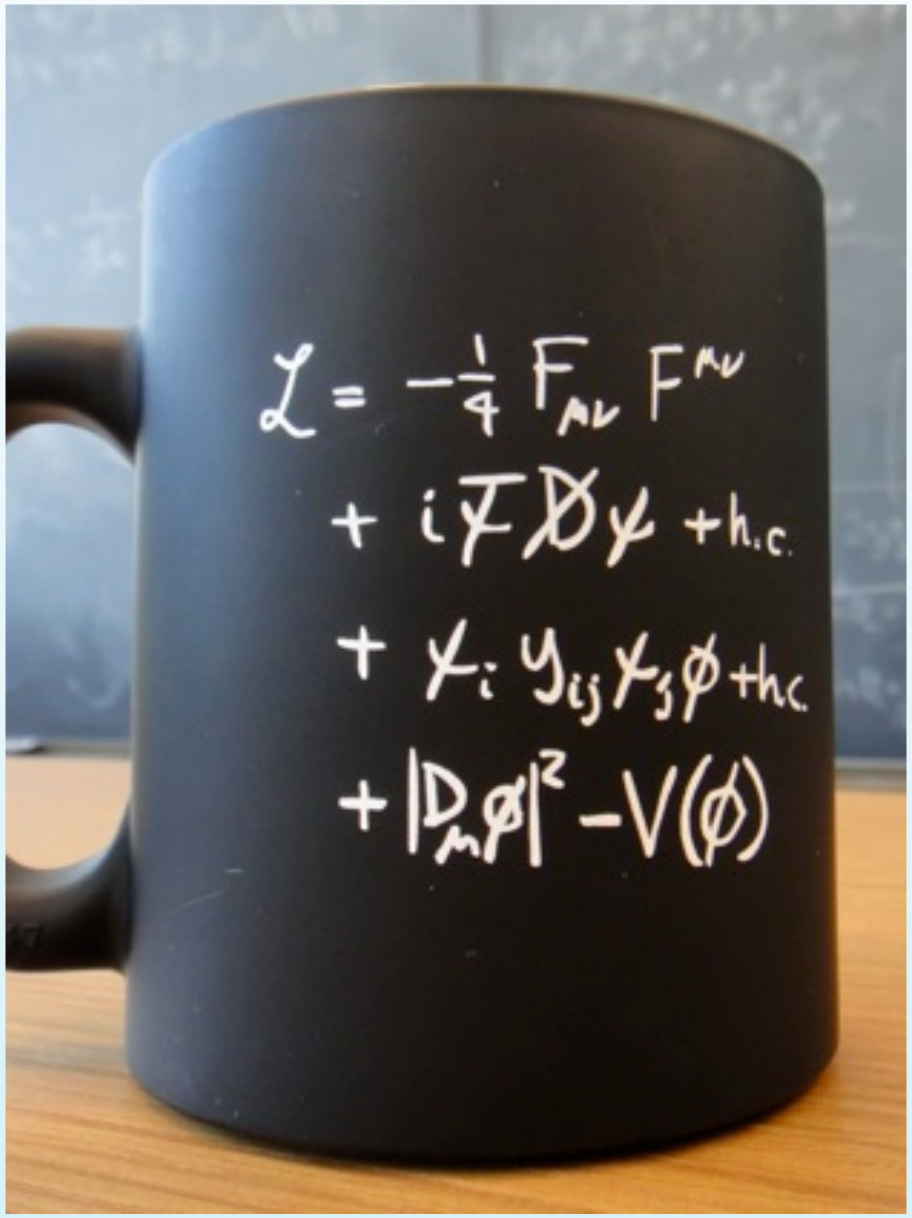
Many of these crucial questions could be addressed at the Large Hadron Collider

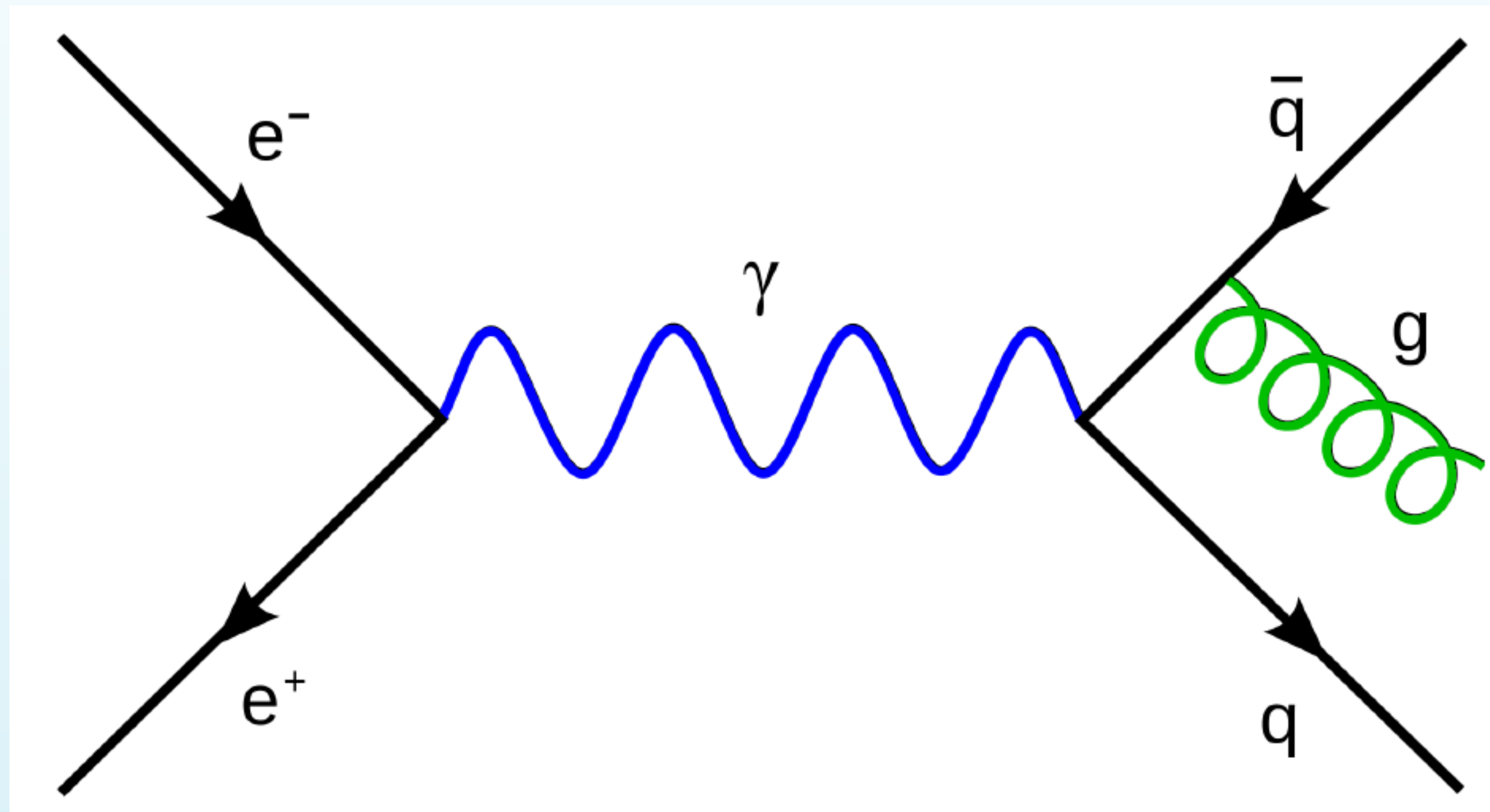
For the next 20 years, LHC will be the forefront of the exploration of the high-energy frontier!



Precision at hadron colliders?

High-energy **lepton colliders** involve **elementary particles** without substructure



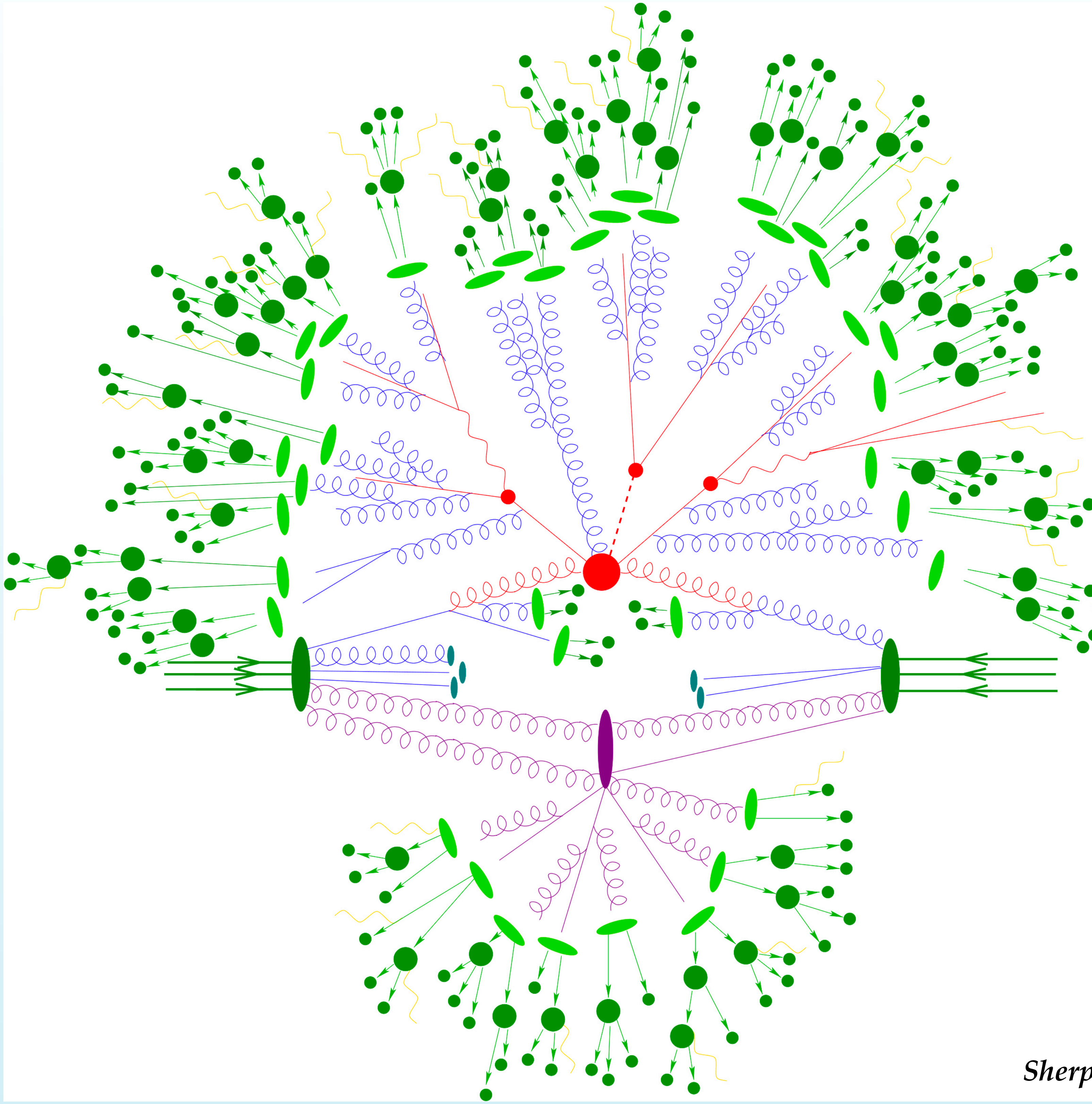


Clean initial state, well-behaved perturbative expansion ($\boldsymbol{\alpha_{\rm QED} \gtrsim 0.01}$)

Quantum Electrodynamics and lepton colliders are ideal for **high-precision measurements**

Precision at hadron colliders?

Hadron colliders offer **excellent energy reach**, but also **very messy environment:**

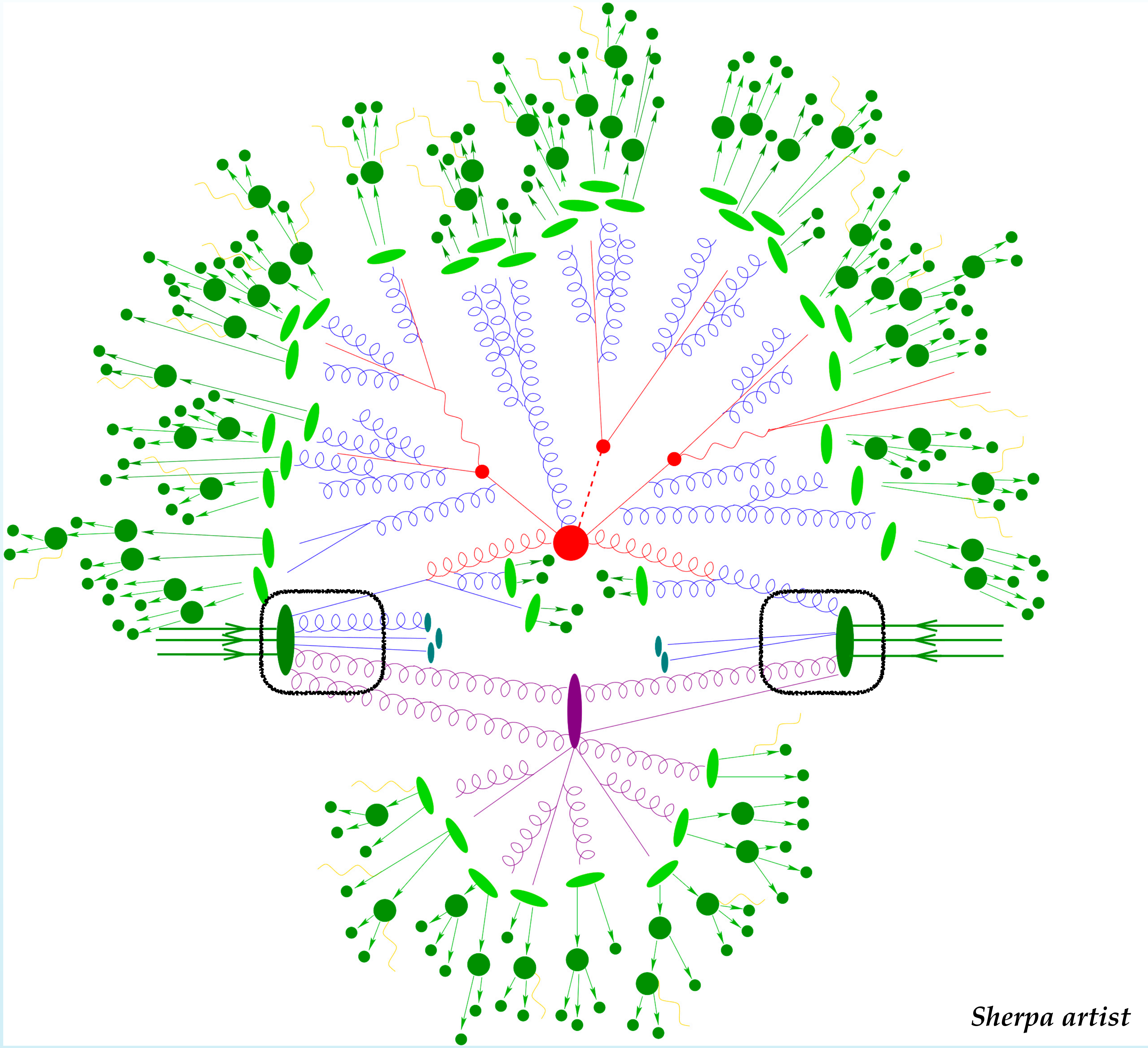


Sherpa artist

Precision at hadron colliders?

Hadron colliders offer **excellent energy reach**, but also **very messy environment:**

- initial state: **non-perturbative** proton's parton distributions



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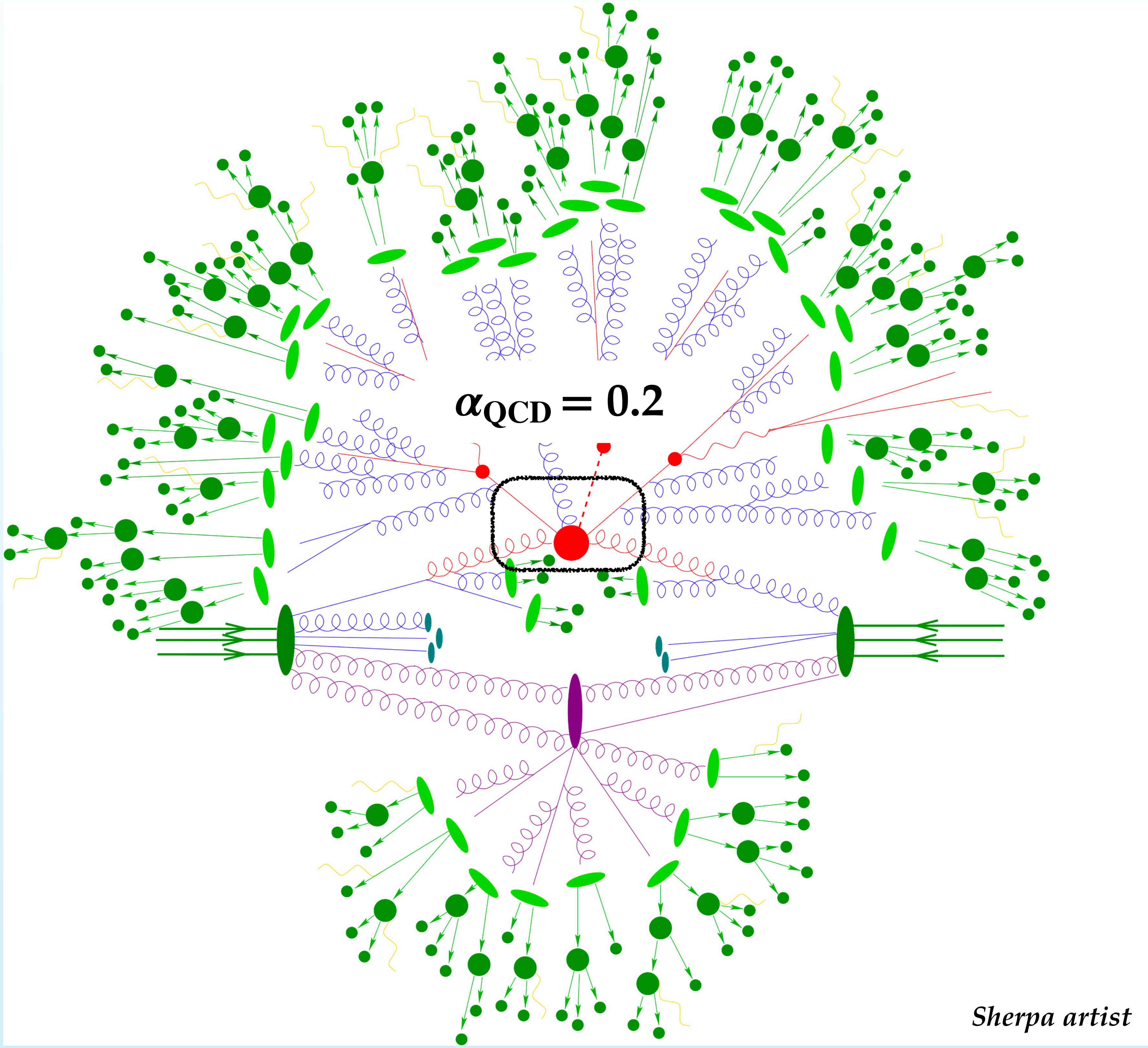
Hadron colliders offer **excellent energy reach**, but also **very messy environment:**

- initial state: **non-perturbative** proton's parton distributions
- quark-gluon hard-scattering: **slow perturbative convergence**



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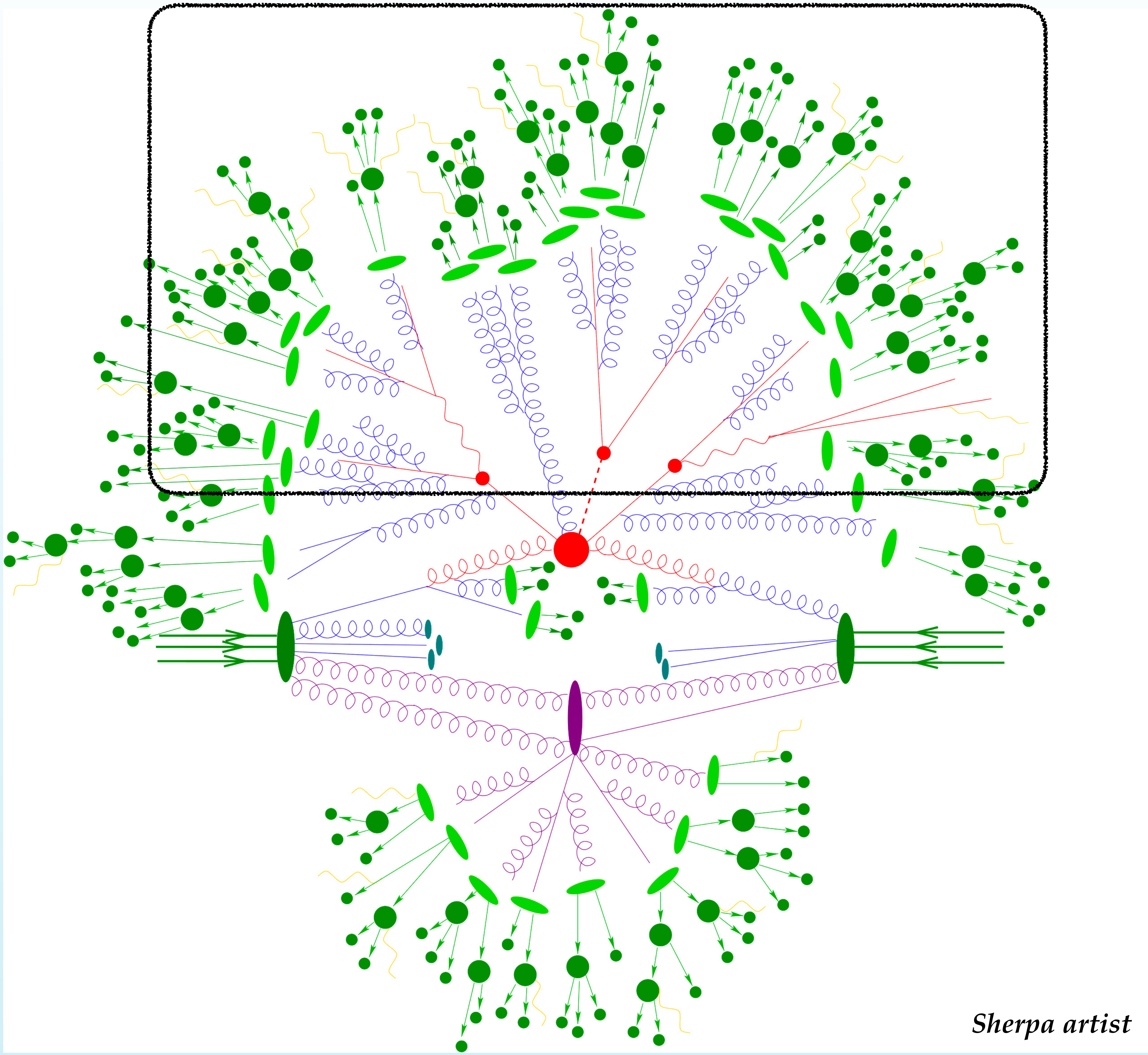

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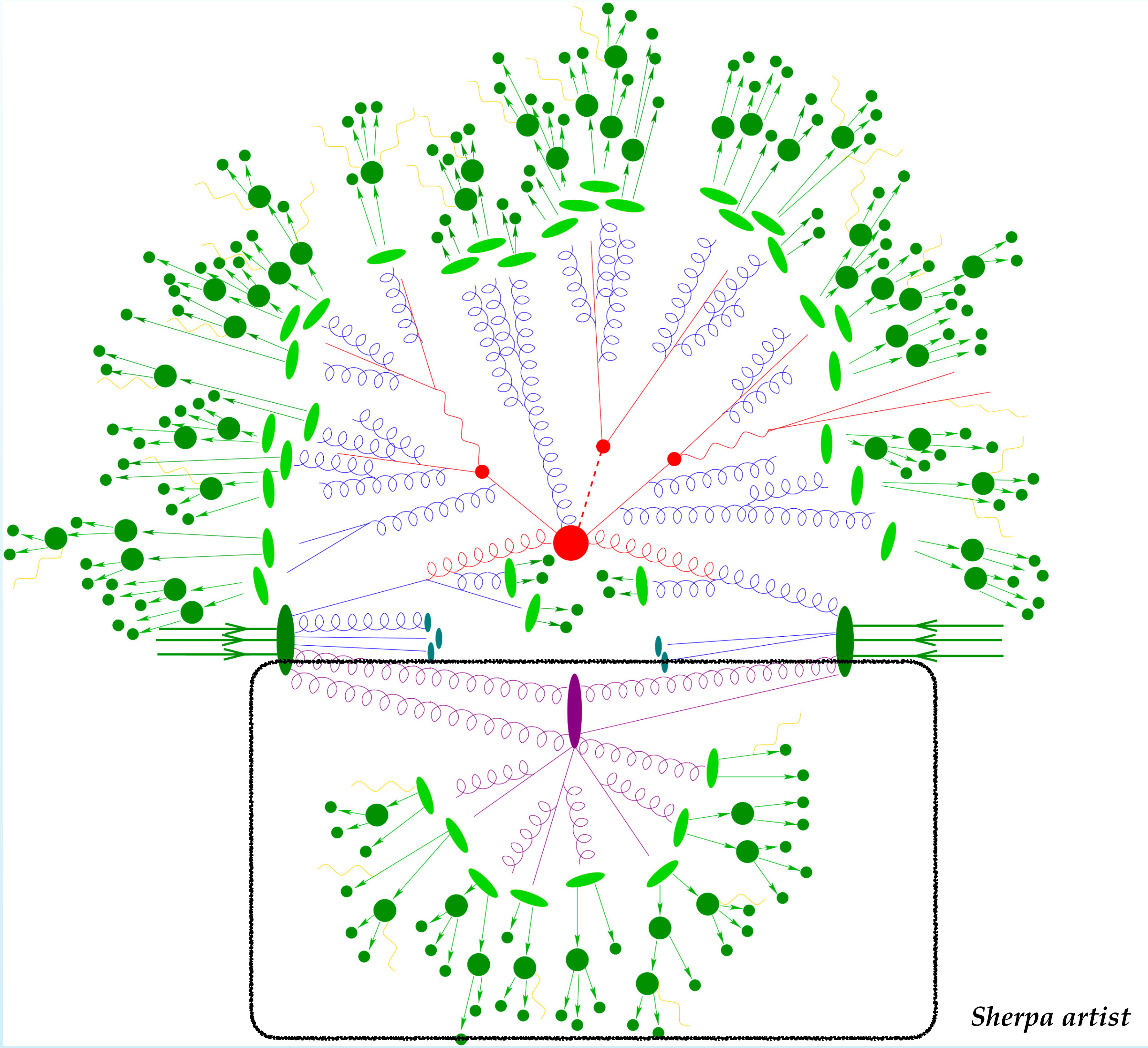
- plus lots of poorly understood non-perturbative effect: **background noise** such multiple parton intercations, pile-up….



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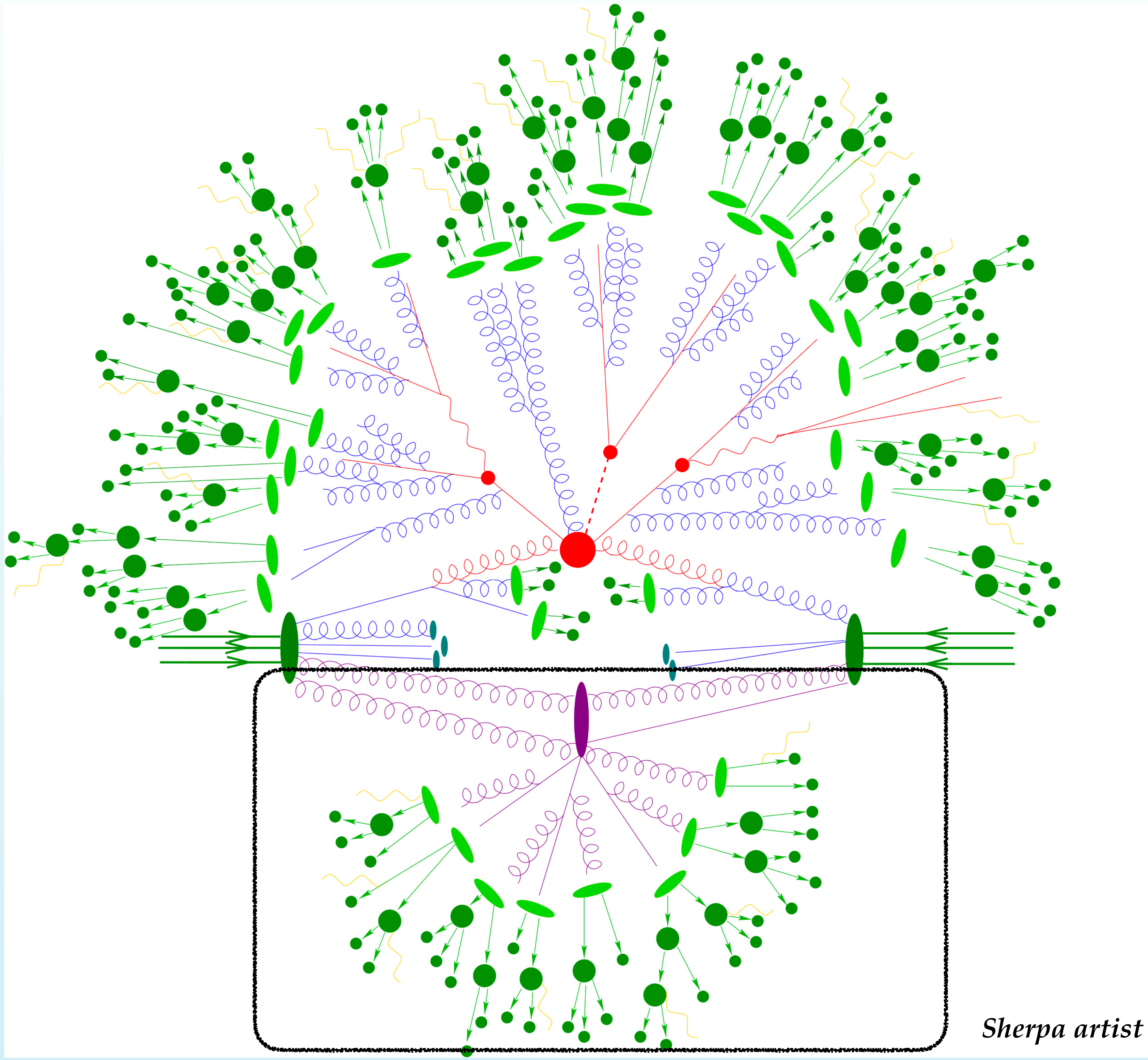
Can we really aim for precision physics at LHC?



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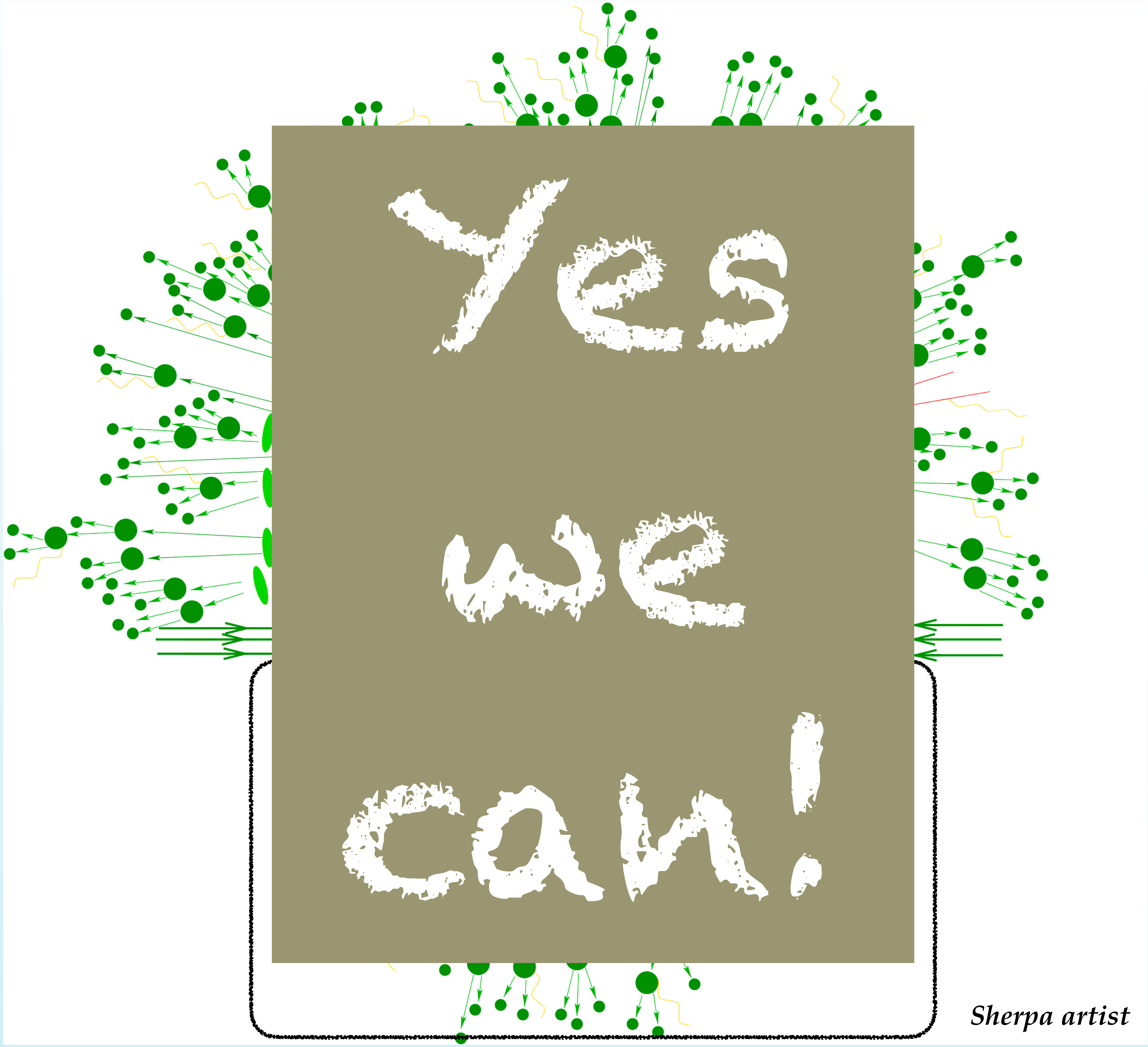

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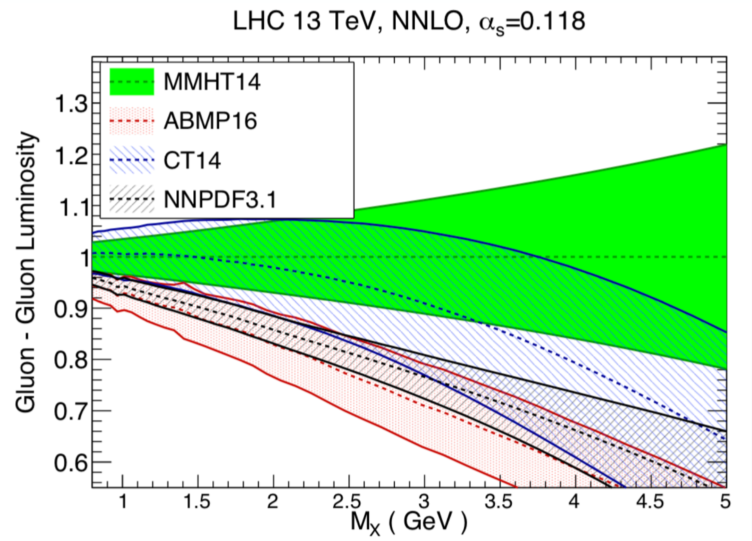
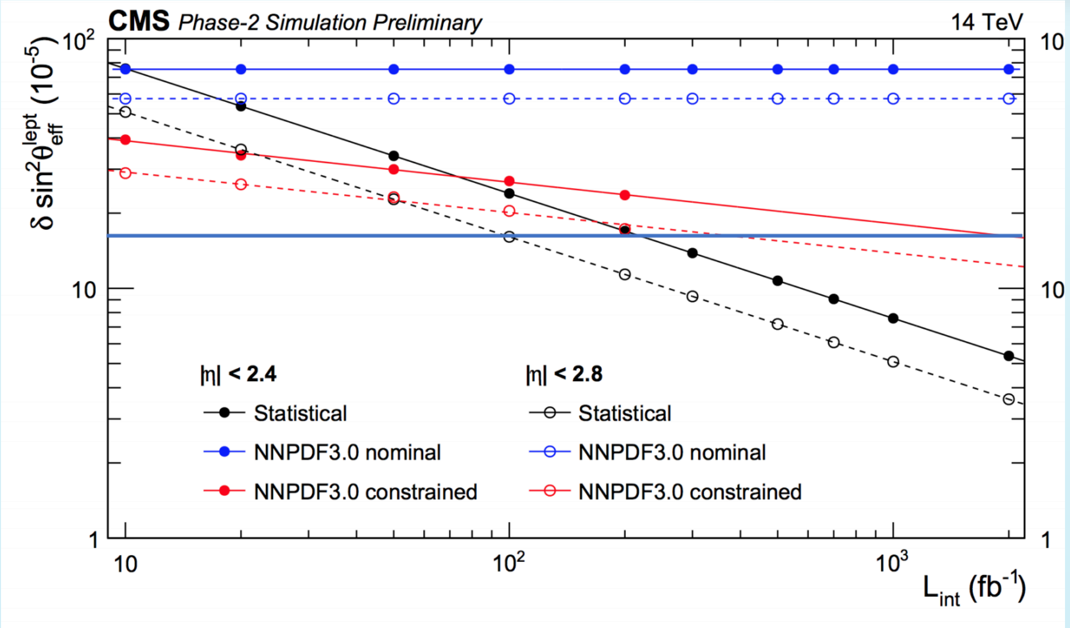
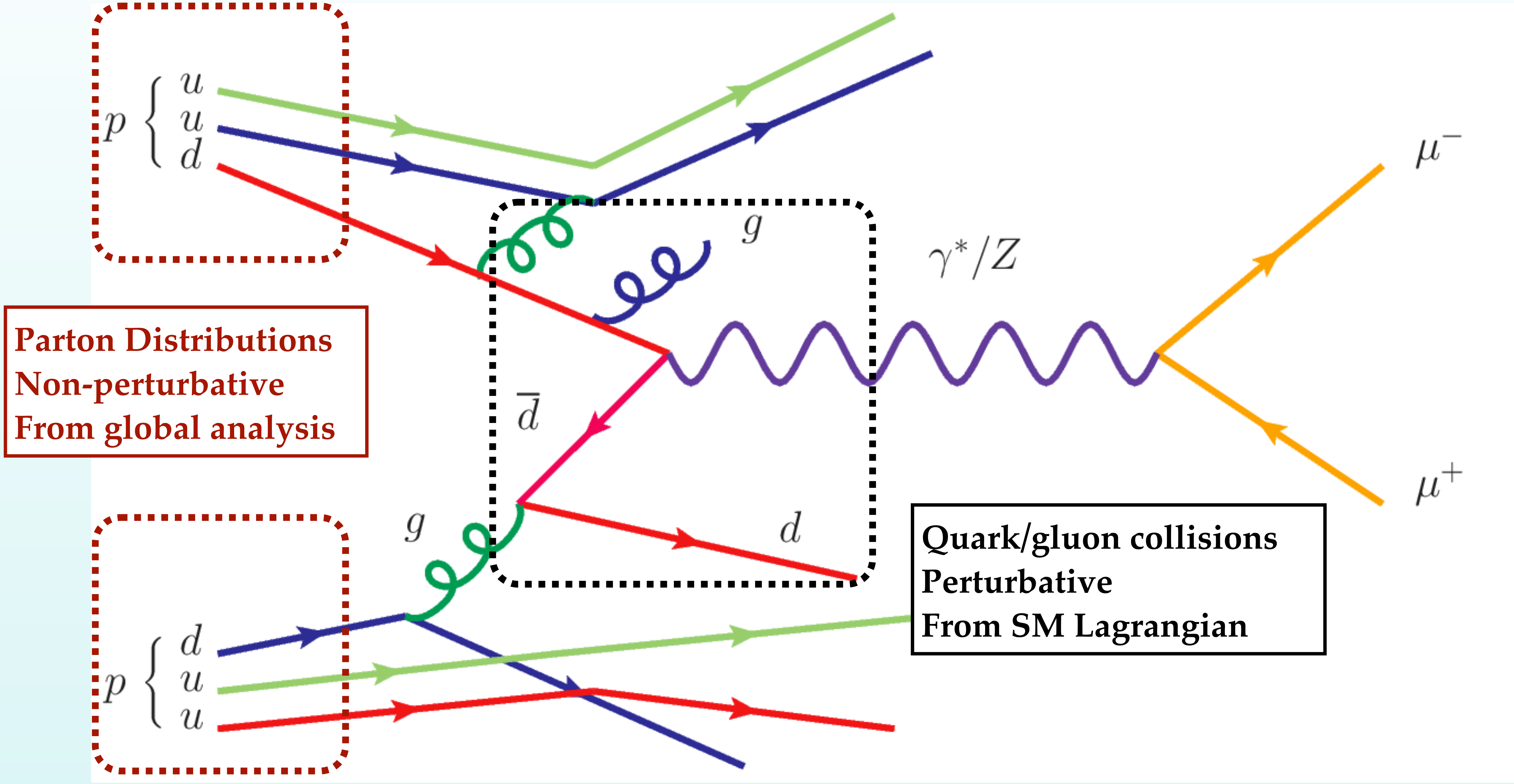


Parton Distributions and BSM searches at the LHC



anatomy of hadronic collisions

In high-energy **hadron colliders** the collisions involve **composite particles** (protons) with internal substructure (quarks and gluons): the LHC is actually a **quark/gluon collider!**



Calculations of **cross-sections** in hadron collisions require the combination of **perturbative cross-sections** with **non-perturbative parton distribution functions (PDFs)**

the inner life of protons

Distribution of energy that **quarks and gluons carry inside proton** quantified by **Parton Distributions**

$$g(x, Q)$$

Q: Energy of the quark/gluon collision
Inverse of the resolution length

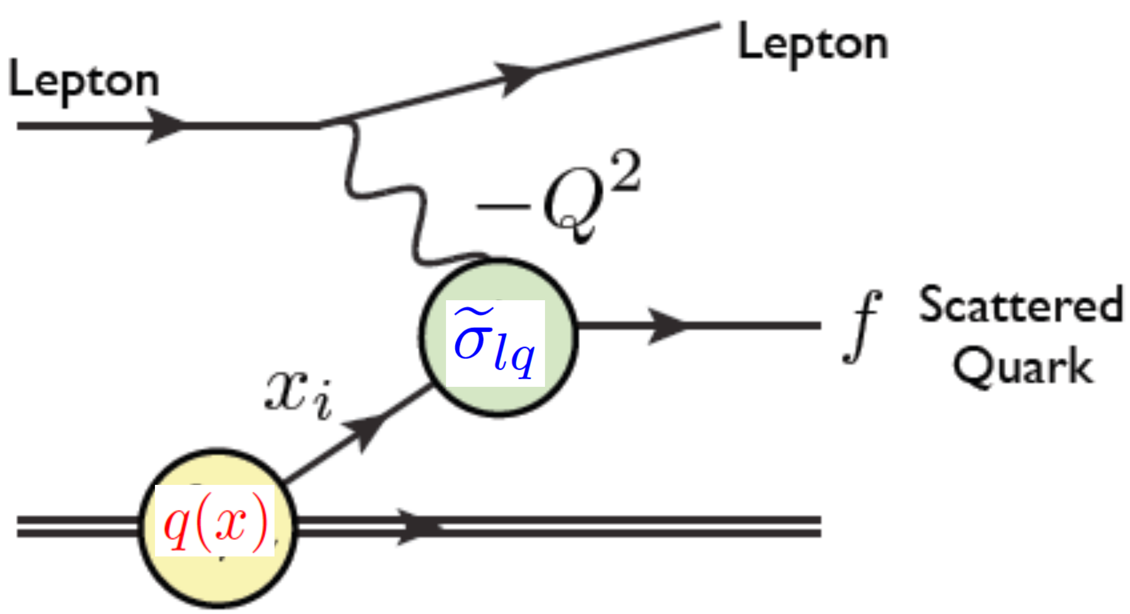
g(x,Q) : **Probability** of **finding a gluon inside a proton**, carrying a fraction *x* of the proton momentum when probed at energy *Q*

***x*: Fraction of the proton's momentum**

PDFs** determined by **non-perturbative QCD dynamics

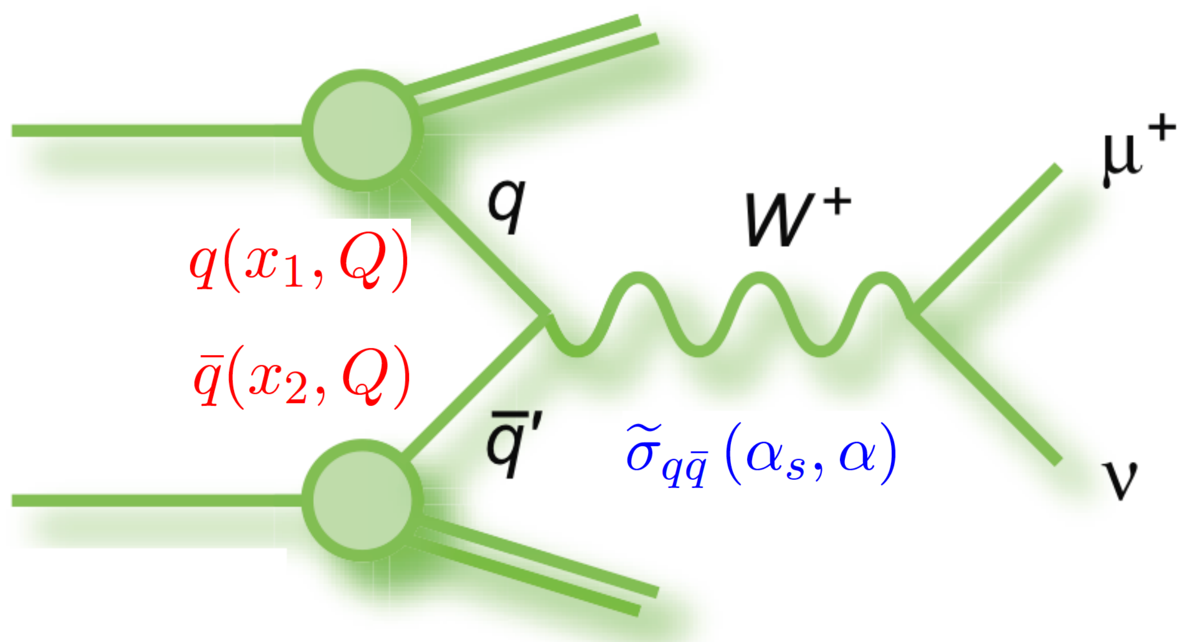
*Extract from experimental data within a **global analysis***

$$\sigma_{lp} \simeq \widetilde{\sigma}_{lq}\left(\alpha_s, \alpha\right) \otimes q(x, Q)$$



Extract PDFs from lepton-proton collisions

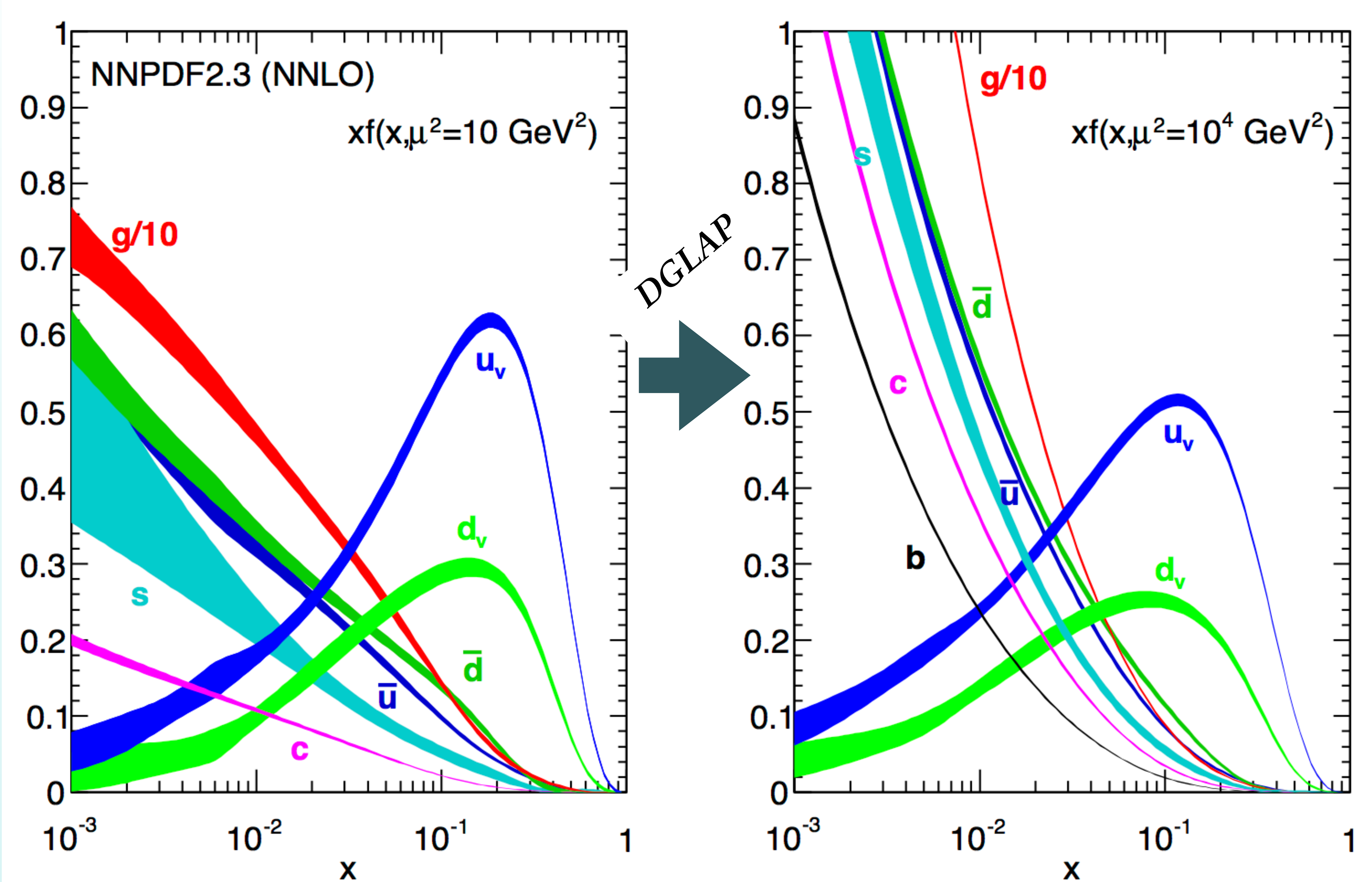
$$\sigma_{pp} \simeq \widetilde{\sigma}_{q\bar{q}}\left(\alpha_s, \alpha\right) \otimes q(x_1, Q) \otimes \bar{q}(x_2, Q)$$



Use PDFs to predict proton-proton cross-sections

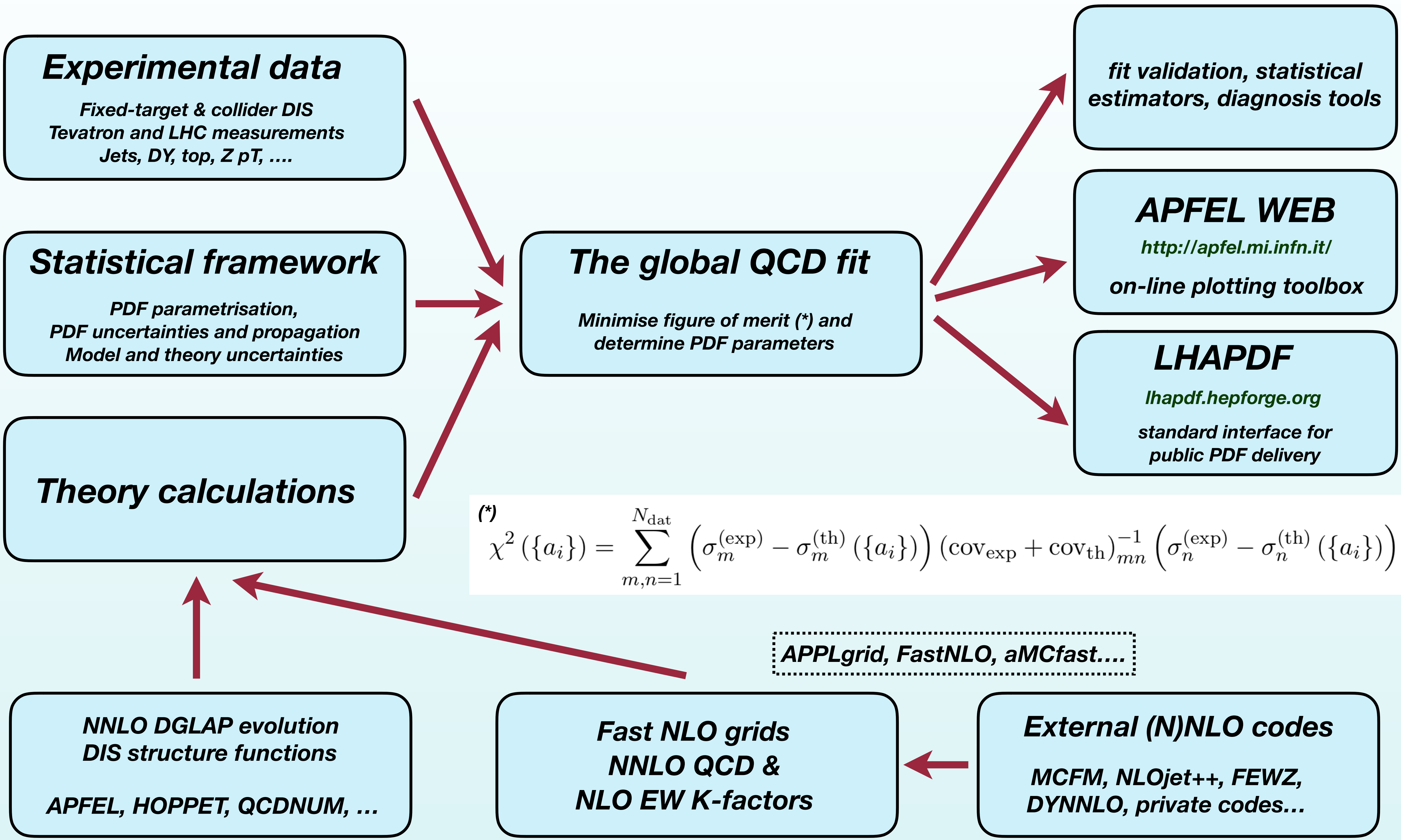
the inner life of protons

Determine the PDFs at some low scale $Q_0 \simeq m_p \simeq 1$ GeV



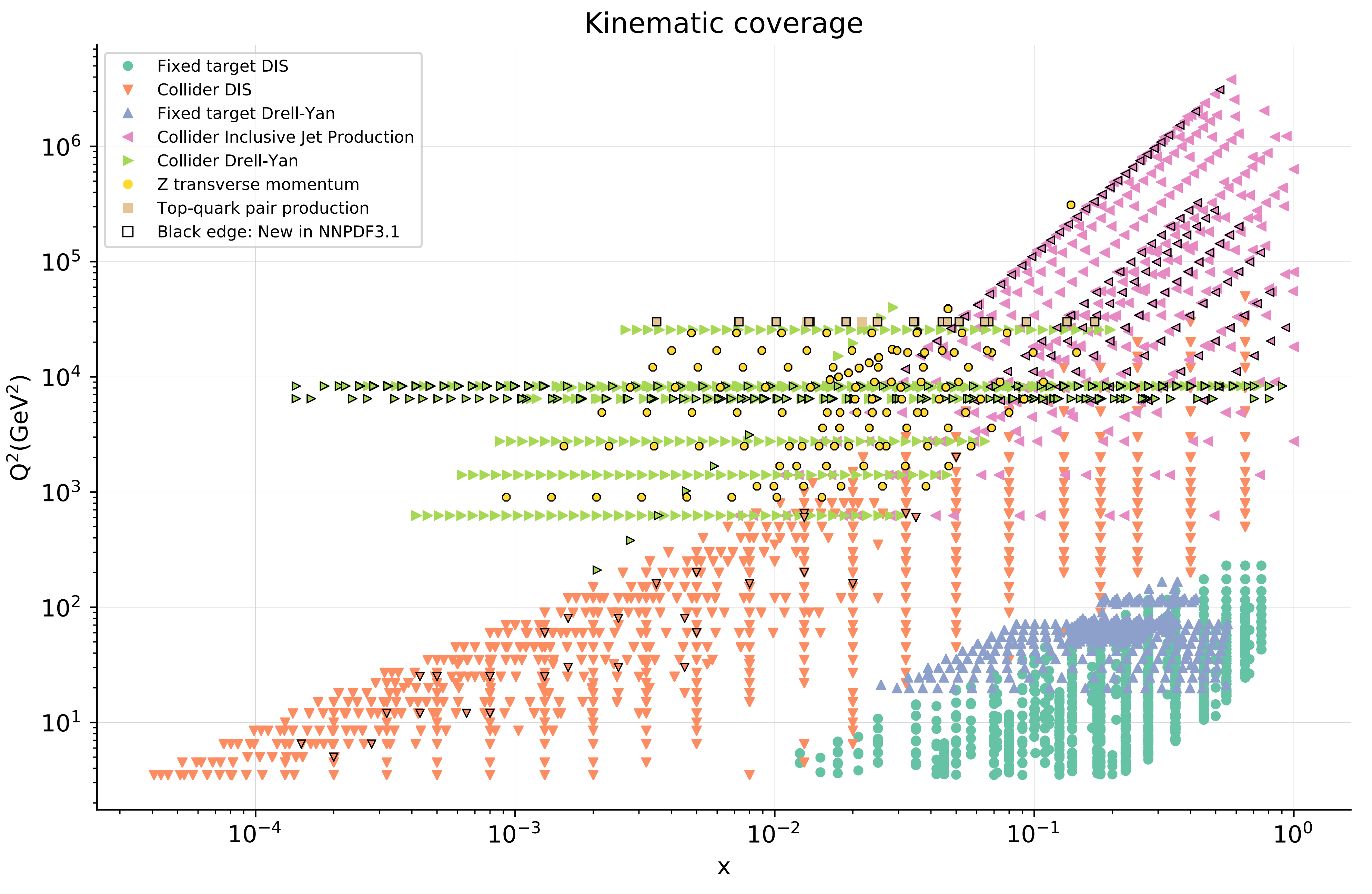
… and then evolve upwards using DGLAP to predict LHC cross-sections

The global QCD fit machinery



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

The global QCD fit machinery



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 still $\chi^2/N_{dat} \approx$ **1** !

PDFs and Higgs boson profiling

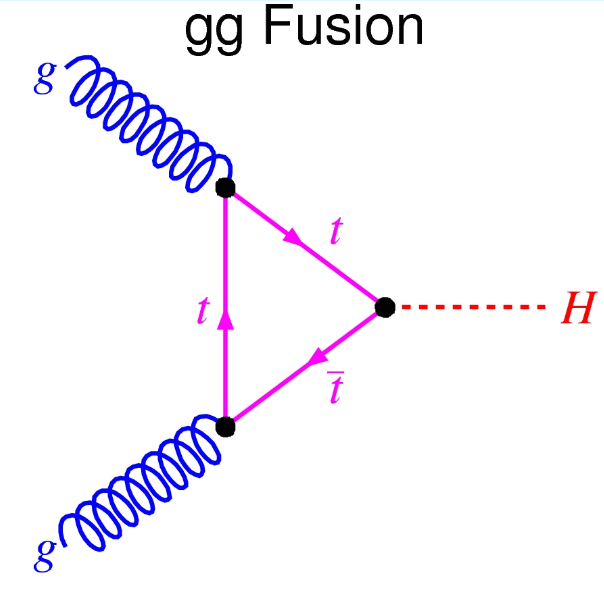
Within the **Standard Model,** the properties of the Higgs sector are **uniquely determined**

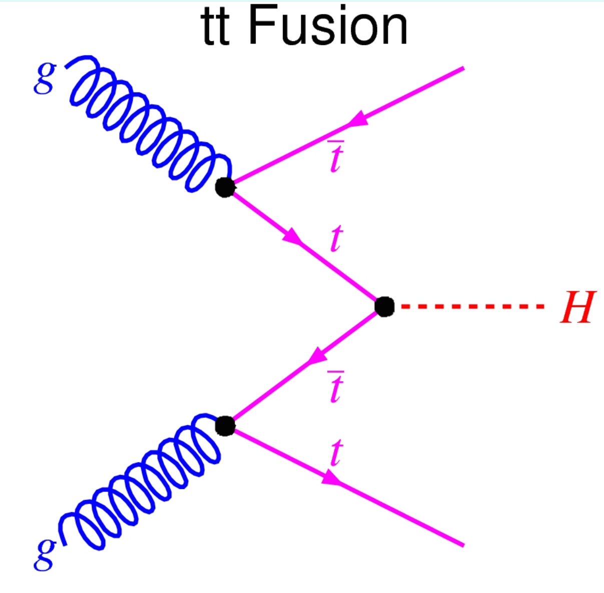
Any deviation from the tight SM predictions would be a **smoking gun for Physics beyond the SM**

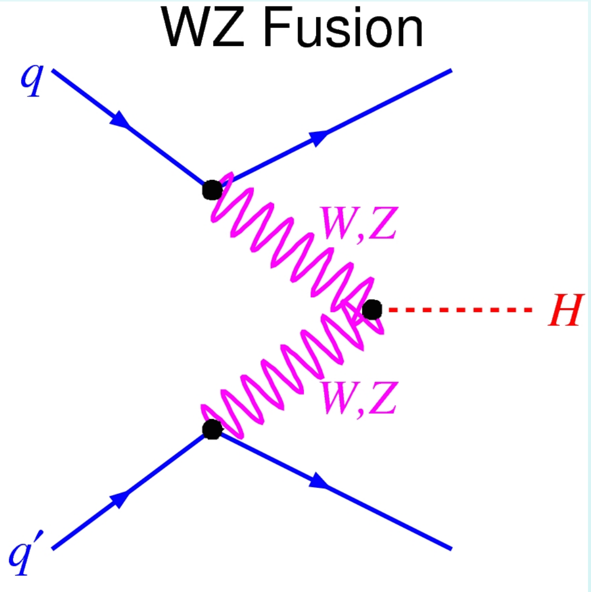
BSM model	Deviations in Higgs coupling to		
	W, Z weak bosons	bottom quarks	photons
New heavy Higgs boson	6%	6%	6%
Two-Higgs Doublet model	1%	10%	1%
Composite Higgs	-3%	-9%	-9%
New heavy top-like quark	-2%	-2%	+2%

A ***precision of a few percent*** *in* ***Higgs couplings measurements*** *is the goal!*

This precision required both in **experimental data** and in **theory calculations** of **Higgs production**



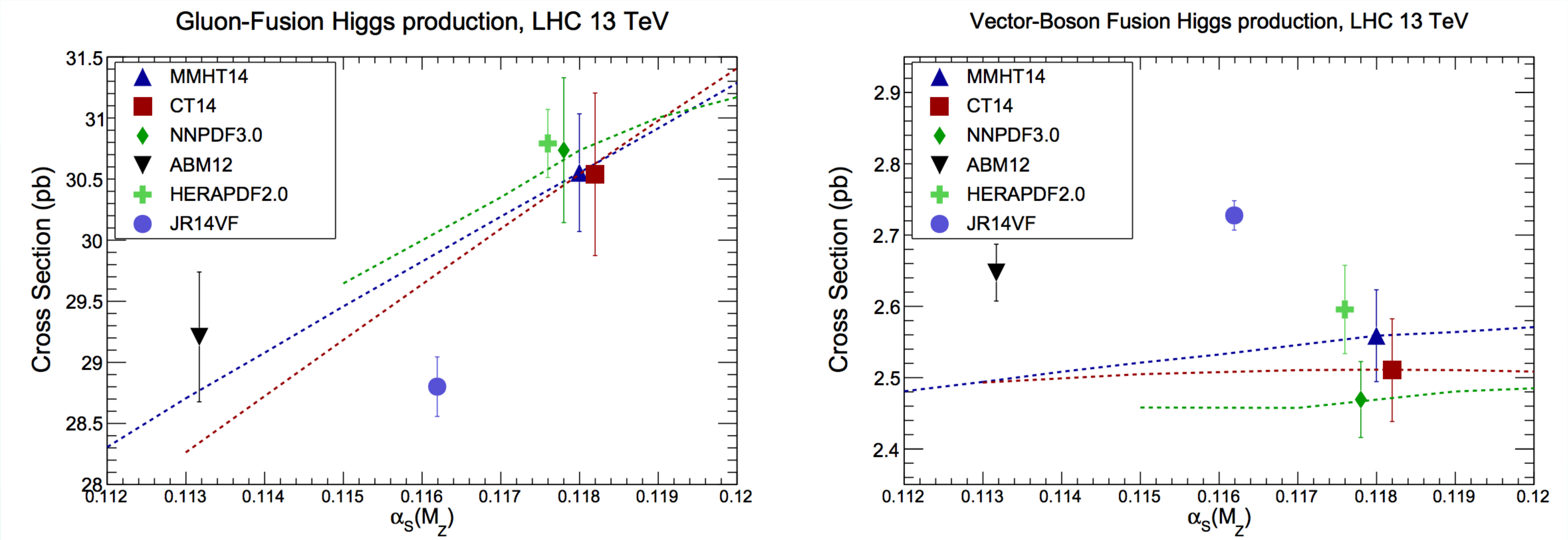




PDFs and Higgs boson profiling

PDF and α_S uncertainties are one of **dominant theory errors in Higgs cross-sections**

The better we understand PDFs, the **more discriminating Higgs measurements** become



Higgs Cross-Section Working Group Yellow Report 4

LHC measurements of **SM cross-sections** provide unique information to strengthen the Higgs boson profiling efforts

PDFs and the SMEFT

If BSM physics is **too heavy and beyond the reach of the LHC**, its effects could still be present in kinematic distributions due to virtual corrections

Generic BSM scenarios can be parametrised in a **model-independent way** in terms of higher-dimensional operators: the **SM Effective Field Theory** (SMEFT):

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \ldots$$

A large number of these operators can be directly probed at the LHC

For instance, some operators contributing to **inclusive jet, dijet, and multi-jet production** are:

$$g_s f^{abc} G_\mu^{\nu,a} G_\nu^{\rho,b} G_\rho^{\mu,c} \qquad -\frac{Z}{2m_W^2}\left(D_\mu G^{\mu\nu,a}\right)^2 \qquad \mathcal{Q}_{qq}^{(1)} \propto (\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$$

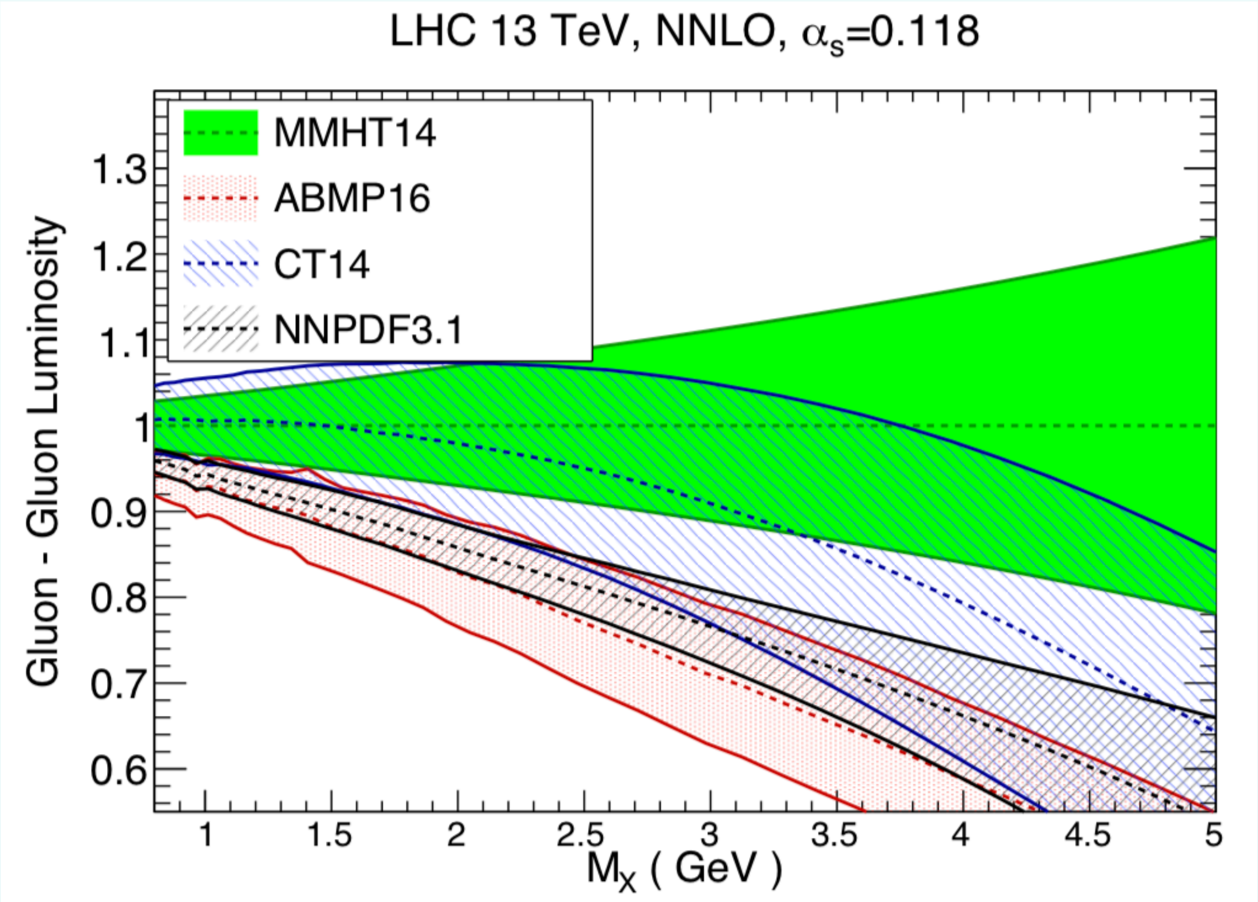
Crucially, no **dedicated searches** are required: we can exploit all the excellent measurements that the LHC has (and will) produce, provided **theoretical calculations are up to par**

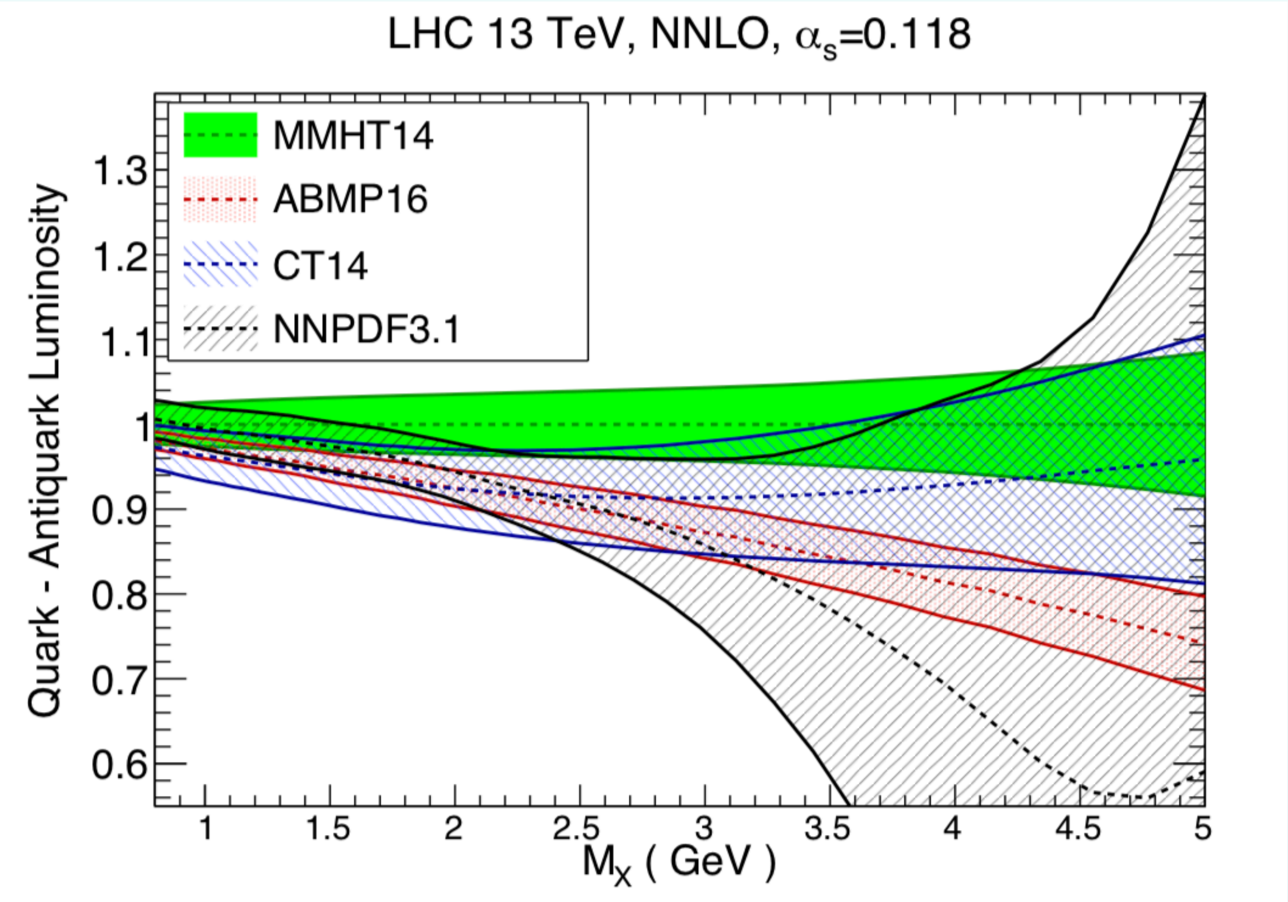
PDFs and the SMEFT

Several SMEFT operators lead to **corrections which grow with the energy:** enhanced sensitivity at the LHC via the **TeV tails of differential cross-sections**

$$\sigma(E) = \sigma_{SM}(E)\left(1 + \epsilon\frac{m_{SM}^2}{m_W^2} + \epsilon\frac{E^2}{m_W^2} + \ldots\right)$$

… but PDF uncertainties blow up in the TeV region due to **limited experimental constraints at large x**





Improved PDFs allow **extending the SMEFT parameter space** accessible at the LHC

PDFs and the SMEFT

Several SMEFT operators lead to **corrections which grow with the energy:**
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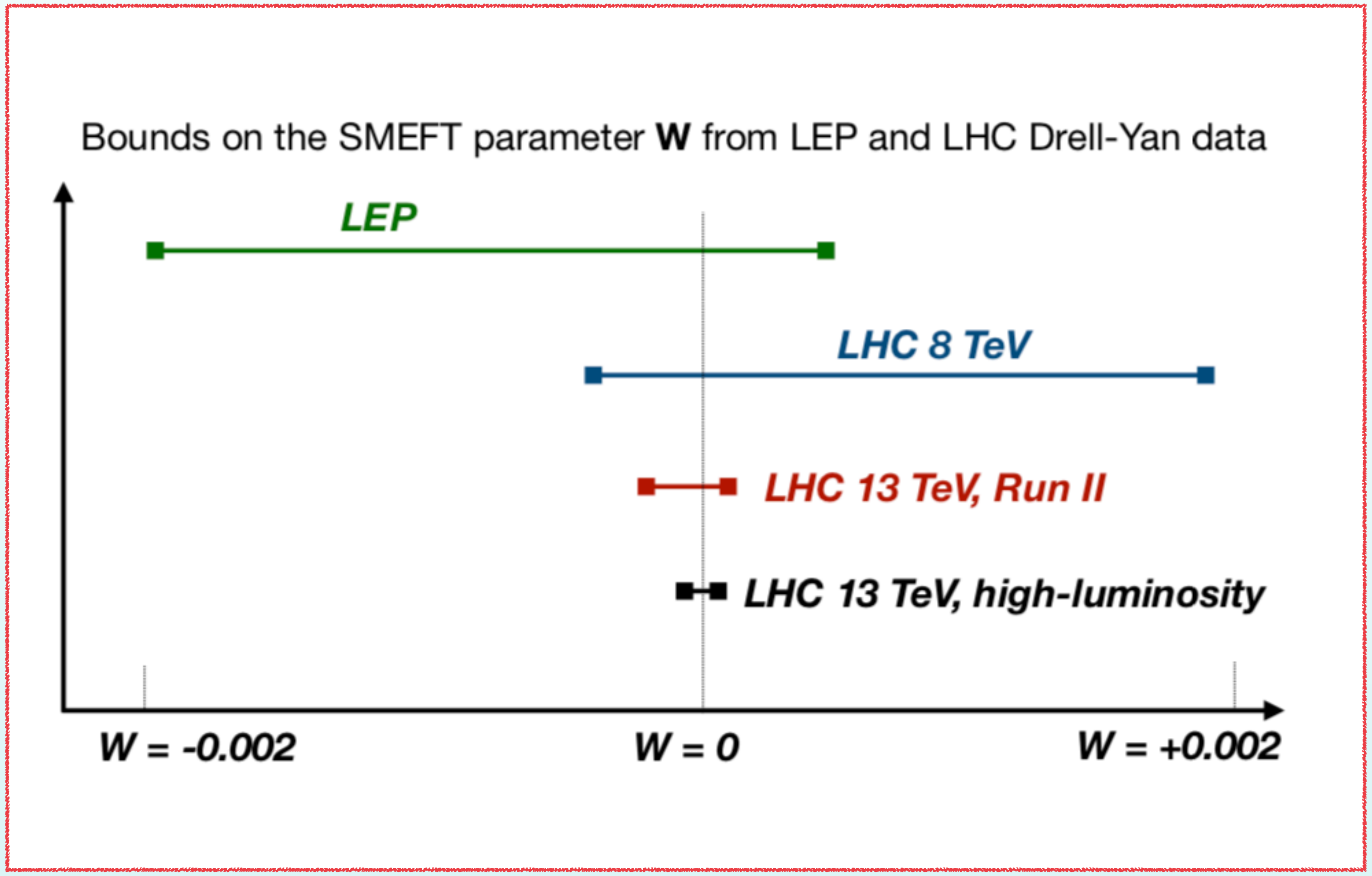
$$\sigma(E) = \sigma_{SM}(E)\left(1 + \epsilon\frac{m_{SM}^2}{m_W^2} + \epsilon\frac{E^2}{m_W^2} + \ldots\right)$$

constraints on "oblique" operators from high-mass ATLAS and CMS Drell-Yan (NC and CC) data

W	$-\frac{\mathrm{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2$
Y	$-\frac{\mathrm{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$

Farina et al 16

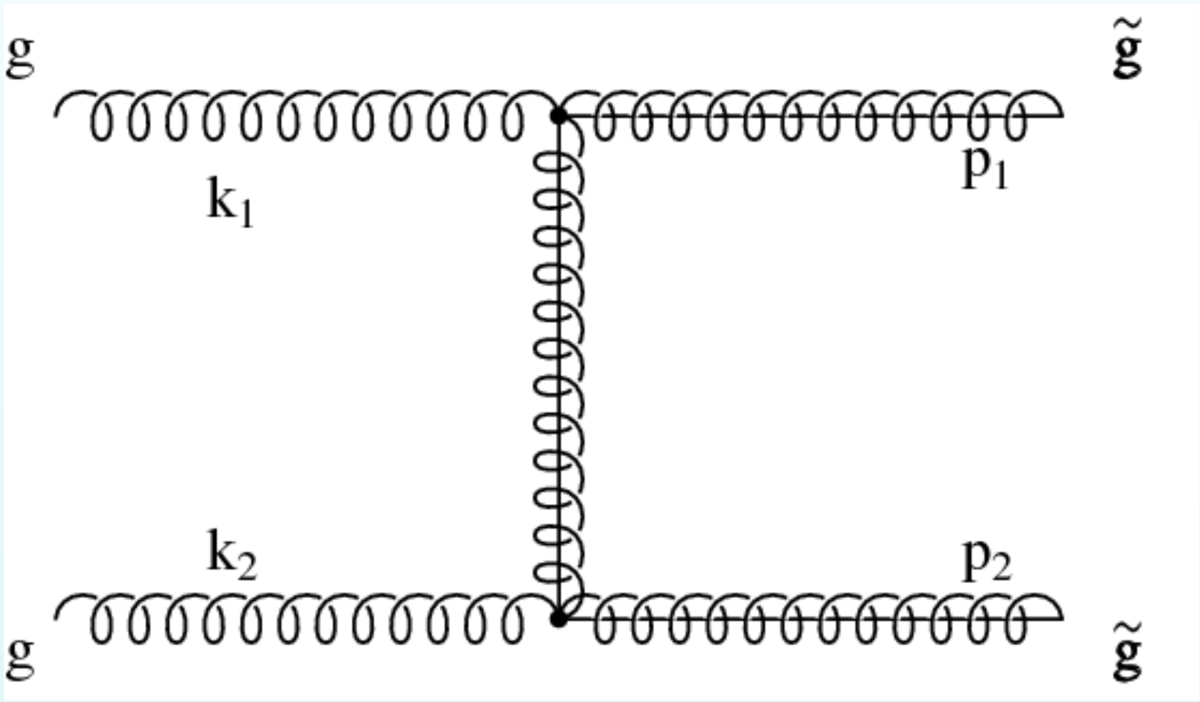


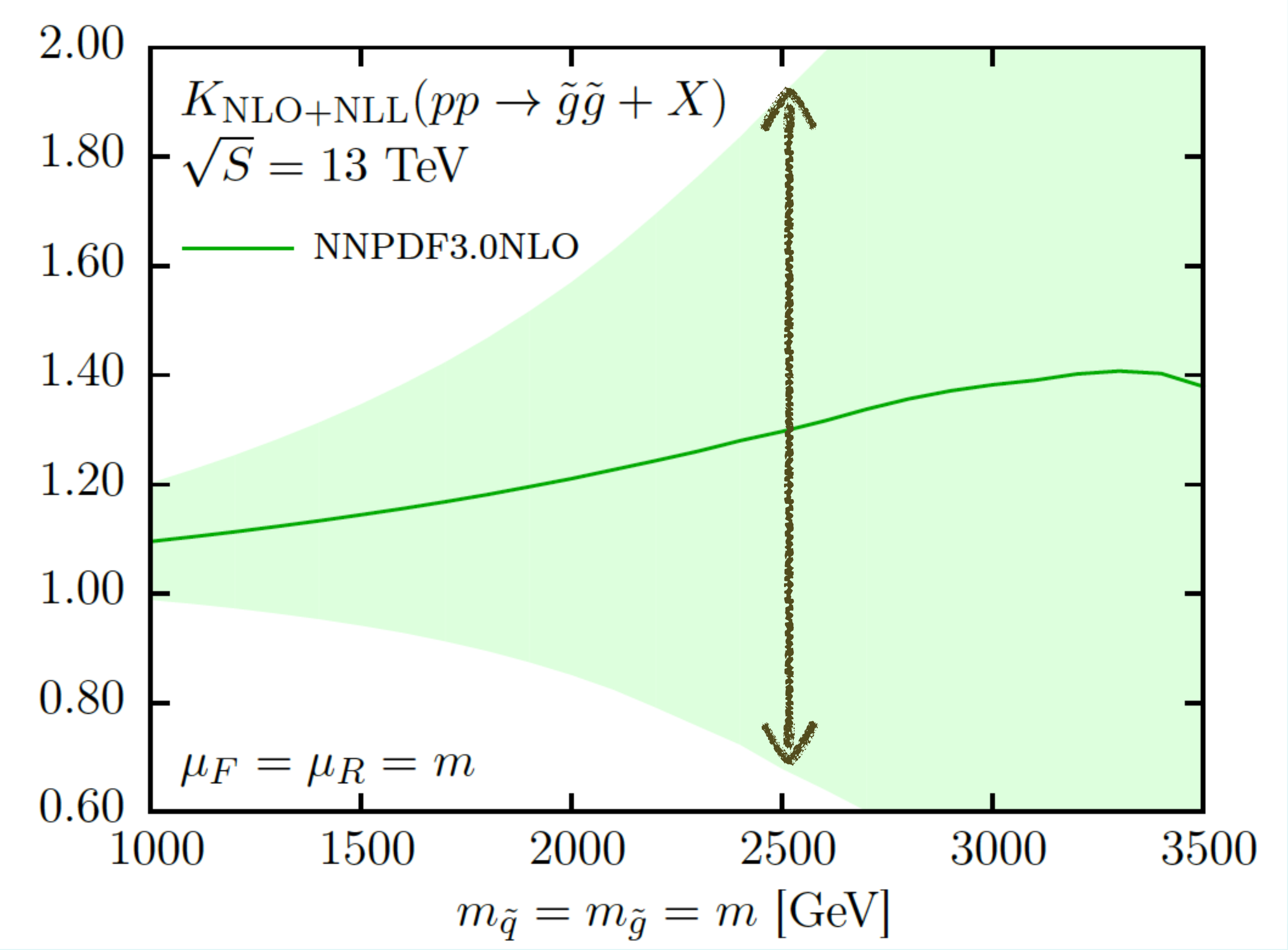
Fully exploiting the SMEFT program only possible if PDF uncertainties under control

PDFs and high-mass BSM resonances

The production of **TeV-scale resonances**, expected in many BSM scenarios, also affected by **large PDF uncertainties**

gluino pair production at the LHC





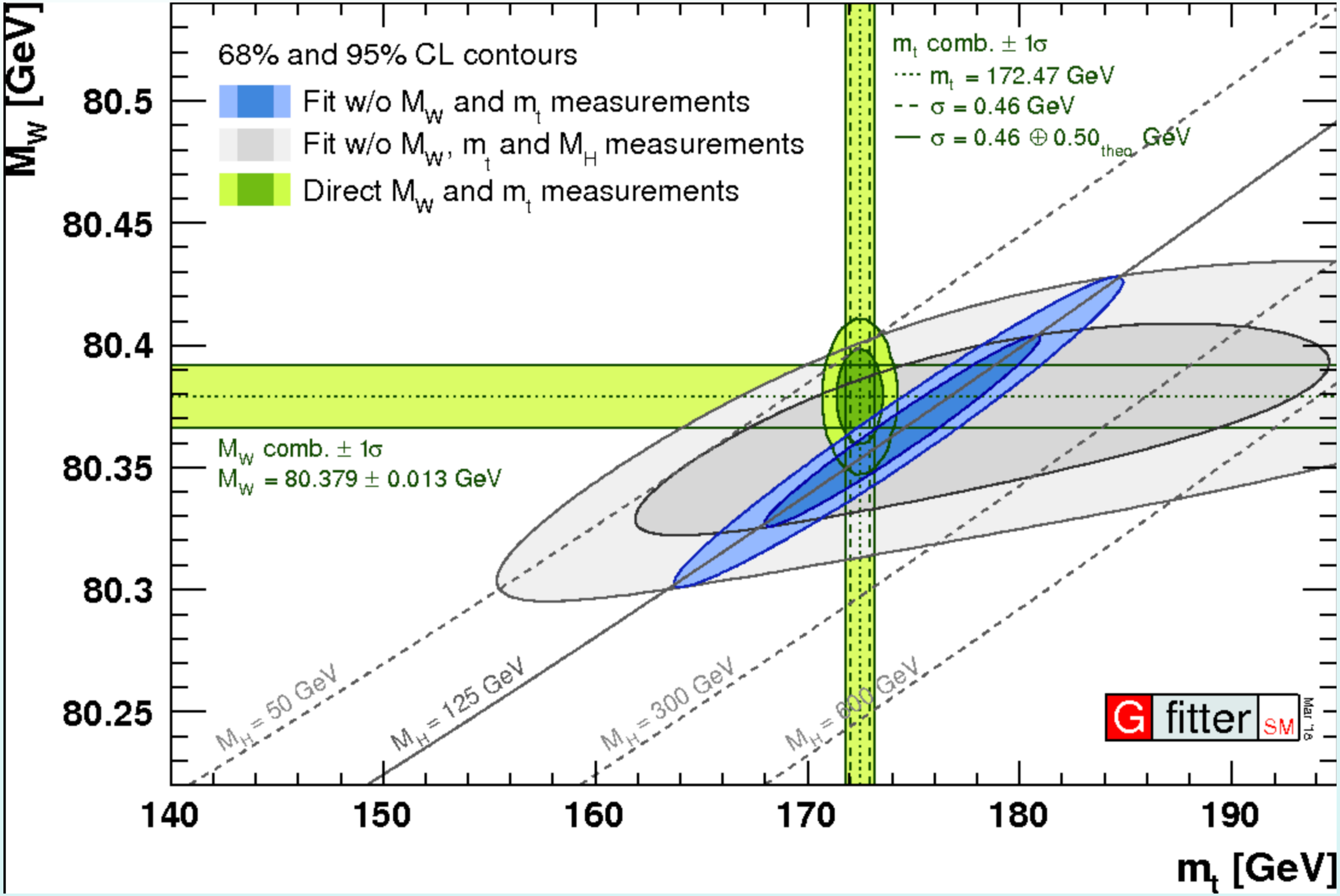
Beenakker, Borchensky, Kramer, Kulesza, Laenen, Marzani, JR 15

*Unless we **improve PDF uncertainties**, even if we discover New Physics, it will be extremely **difficult to characterise the underlying BSM model***

PDFs and precision EWK measurements

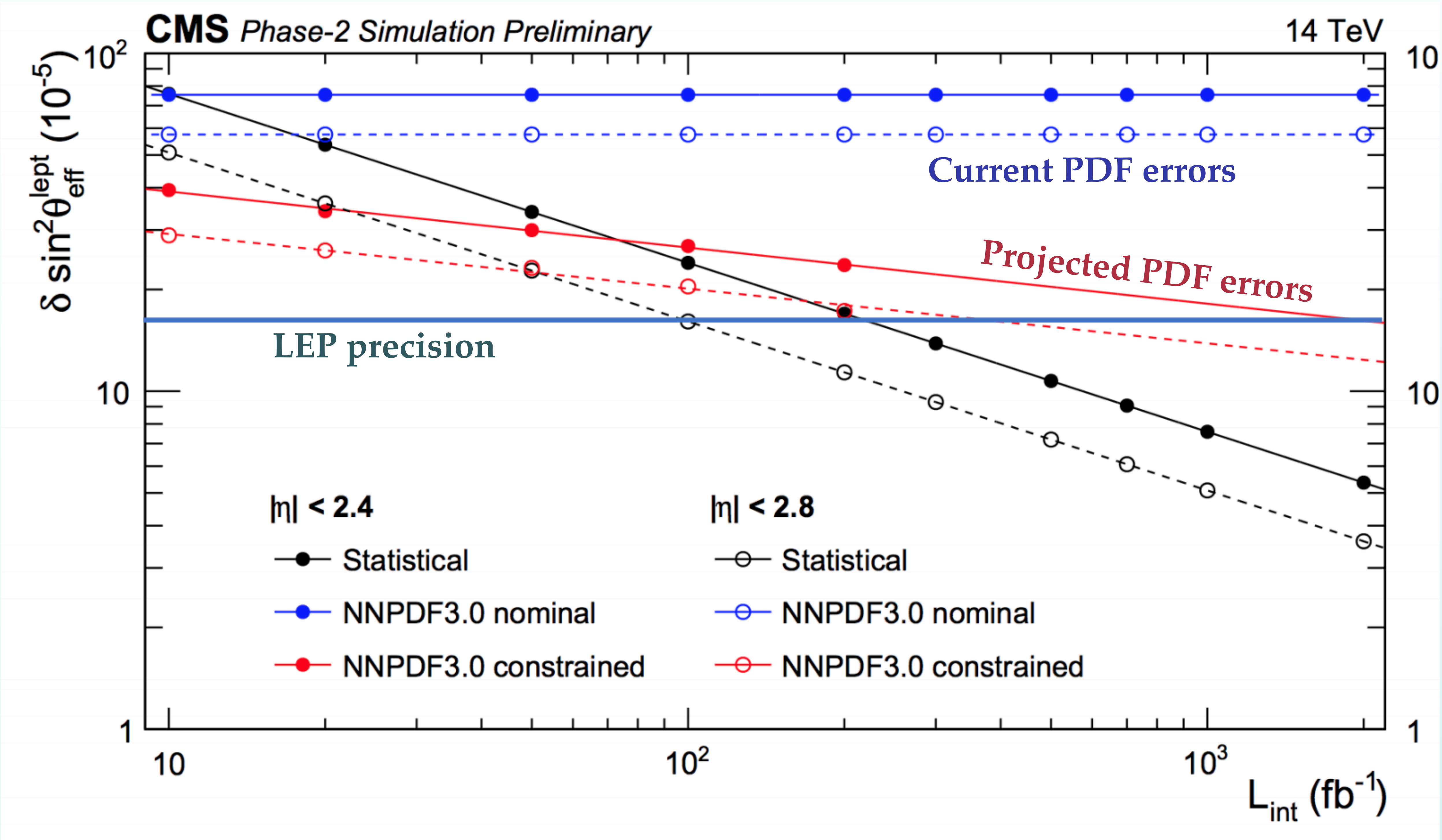
The SM is **over-constrained** once $\mathbf{M_W}$, $\mathbf{m_t}$ **and** $\mathbf{M_H}$ have been determined

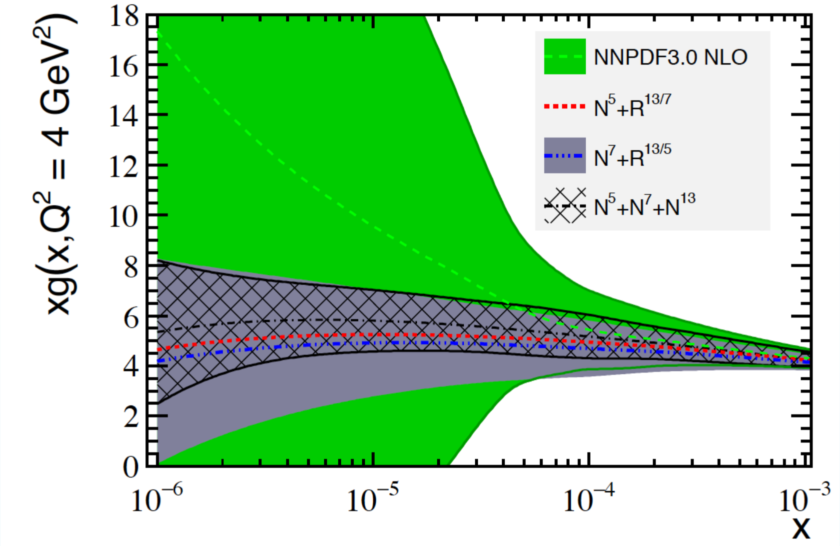
High-precision measurements of $\mathbf{m_t}$ **and** $\mathbf{M_H}$ can be used to stress-test the SM



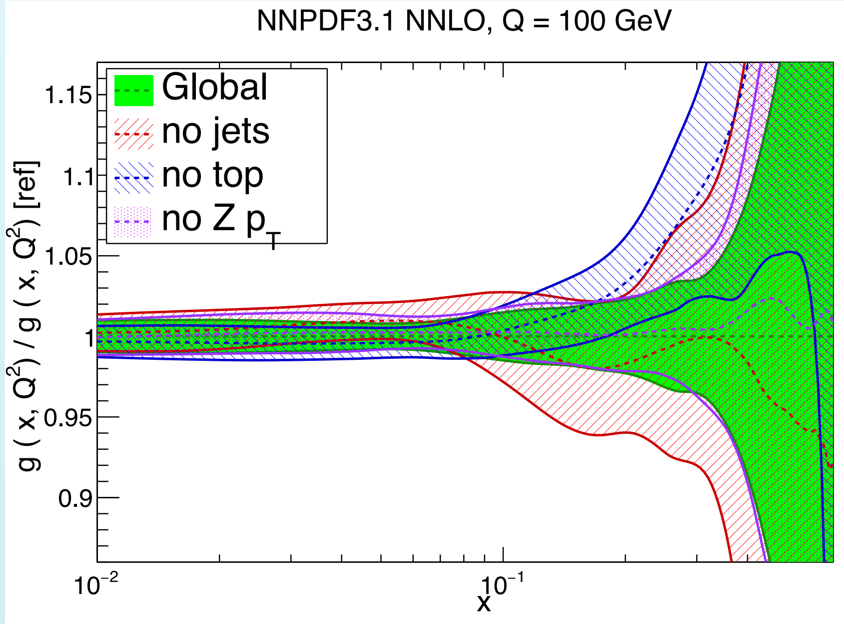
PDFs and precision EWK measurements

With improved PDFs, **direct measurements of the Weinberg mixing angle** at the LHC are expected to i**mprove the current best bounds** from LEP/SLD





Progress in PDF determinations



The Structure of the Proton in the LHC Precision Era

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arXiv:1709.04922v1 [hep-ph] 14 Sep 2017

Abstract

We review recent progress in the determination of the parton distribution functions (PDFs) of the proton, with emphasis on the applications for precision phenomenology at the Large Hadron Collider (LHC). First of all, we introduce the general theoretical framework underlying the global QCD analysis of the quark and gluon internal structure of protons. We then present a detailed overview of the hard-scattering measurements, and the corresponding theory predictions, that are used in state-of-the-art PDF fits. We emphasize here the role that higher-order QCD and electroweak corrections play in the description of recent high-precision collider data. We present the methodology used to extract PDFs in global analyses, including the PDF parametrization strategy and the definition and propagation of PDF uncertainties. Then we review and compare the most recent releases from the various PDF fitting collaborations, highlighting their differences and similarities. We discuss the role that QED corrections and photon-initiated contributions play in modern PDF analysis. We provide representative examples of the implications of PDF fits for high-precision LHC phenomenological applications, such as Higgs coupling measurements and searches for high-mass New Physics resonances. We conclude this report by discussing some selected topics relevant for the future of PDF determinations, including the treatment of theoretical uncertainties, the connection with lattice QCD calculations, and the role of PDFs at future high-energy colliders beyond the LHC.

Keywords: Parton Distributions, Quantum Chromodynamics, Large Hadron Collider, Higgs boson, Standard Model, Electroweak theory

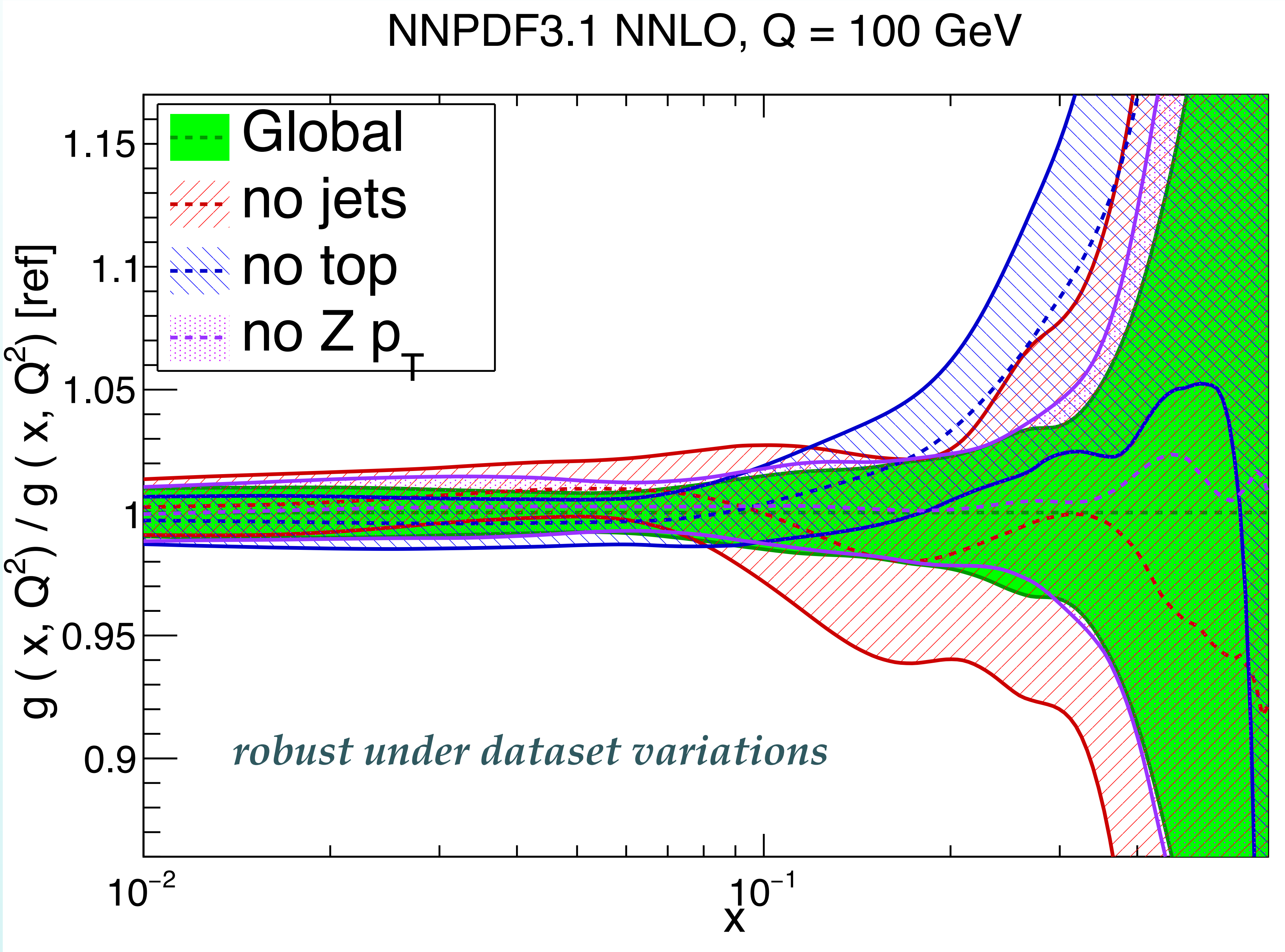
170 pages, 82 figures, > 500 references (Physics Reports)

Only time for a very brief snapshot here!

Constraints from LHC data

LHC measurements have provided in the recent years a wealth of information on the PDFS

Illustrated by the **large-*x* gluon**, now constrained by **three independent processes**: jets, top, $Z\ p_T$



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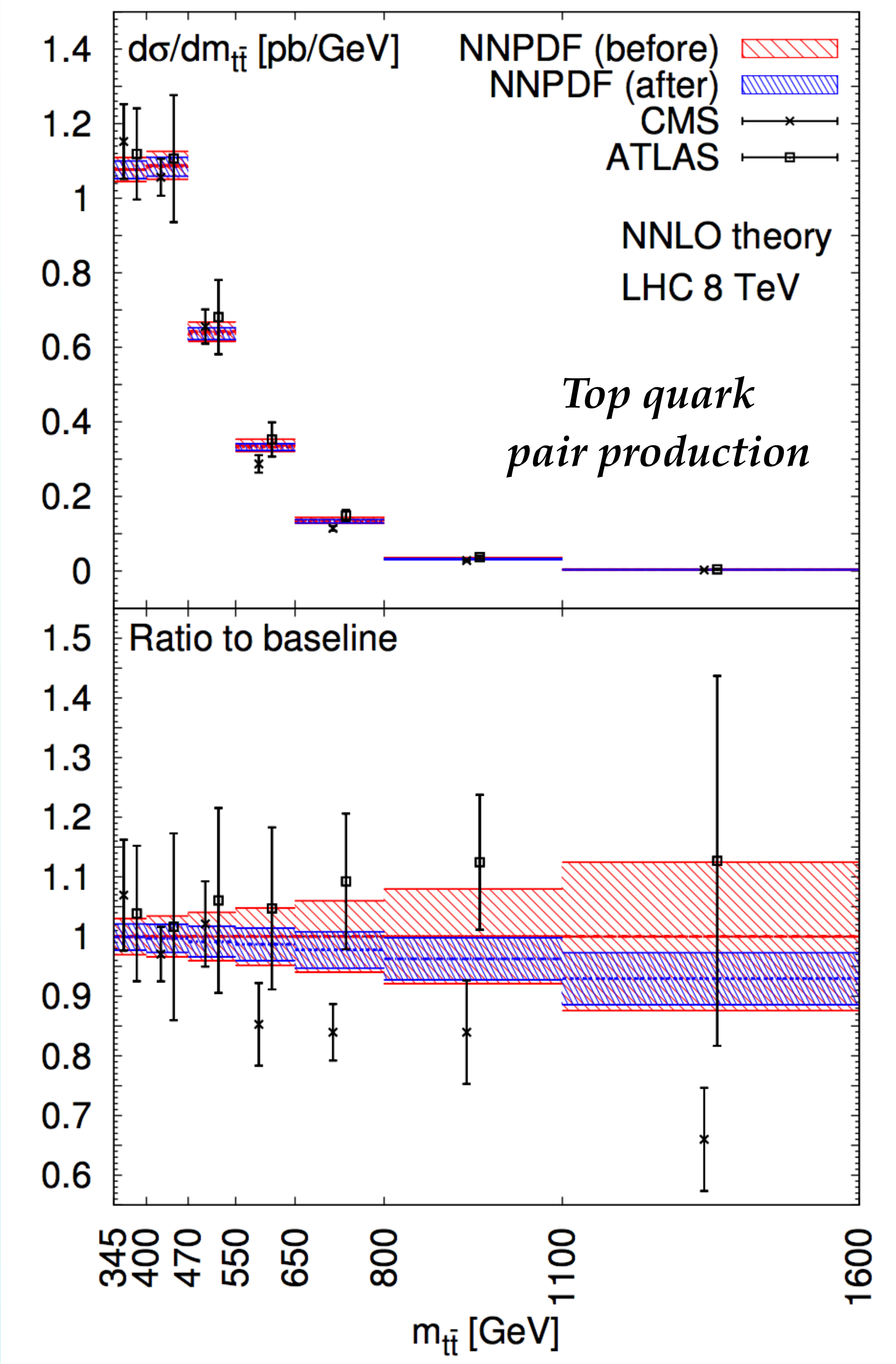
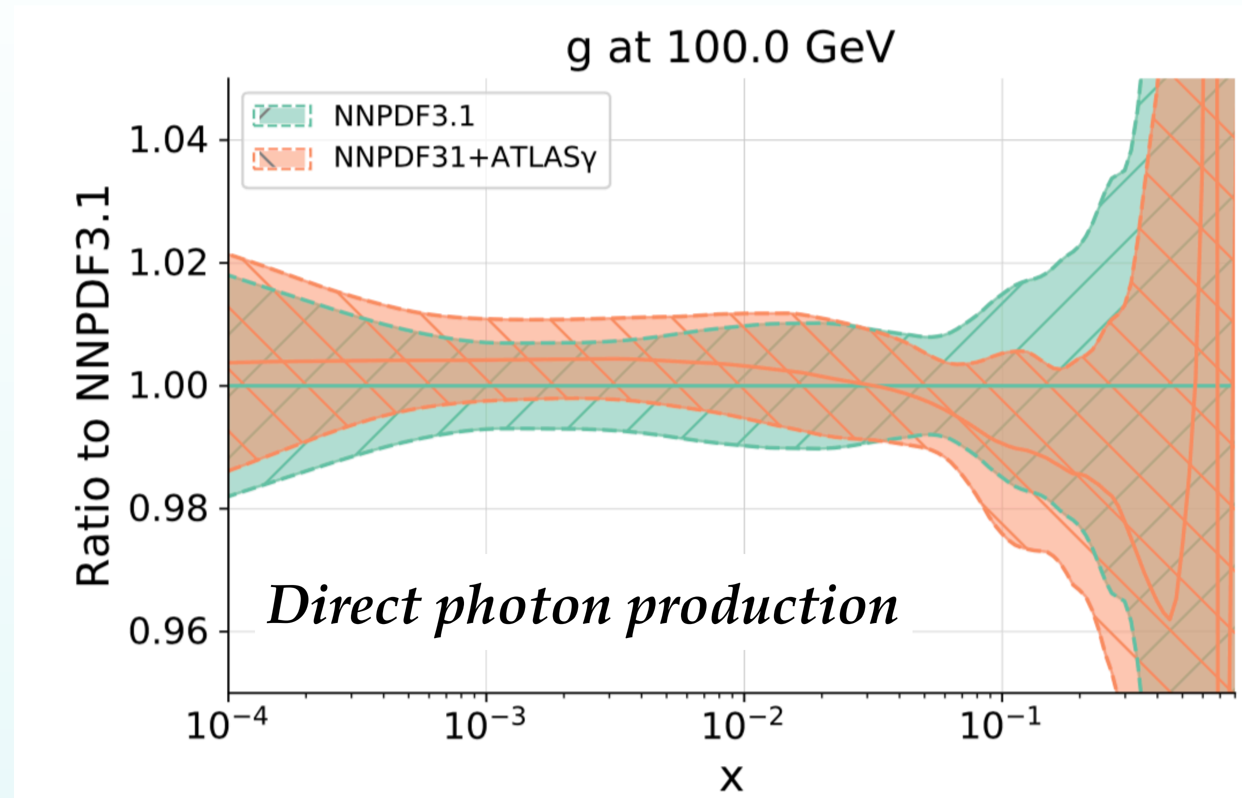
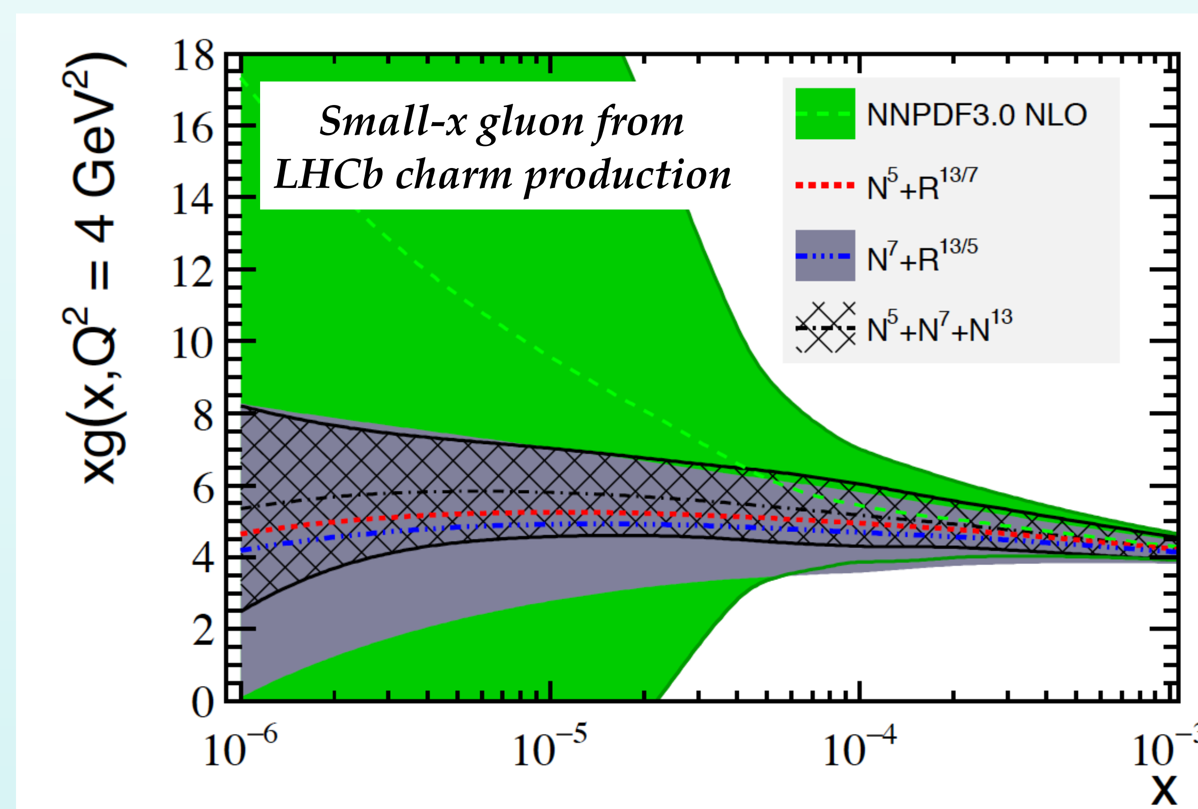
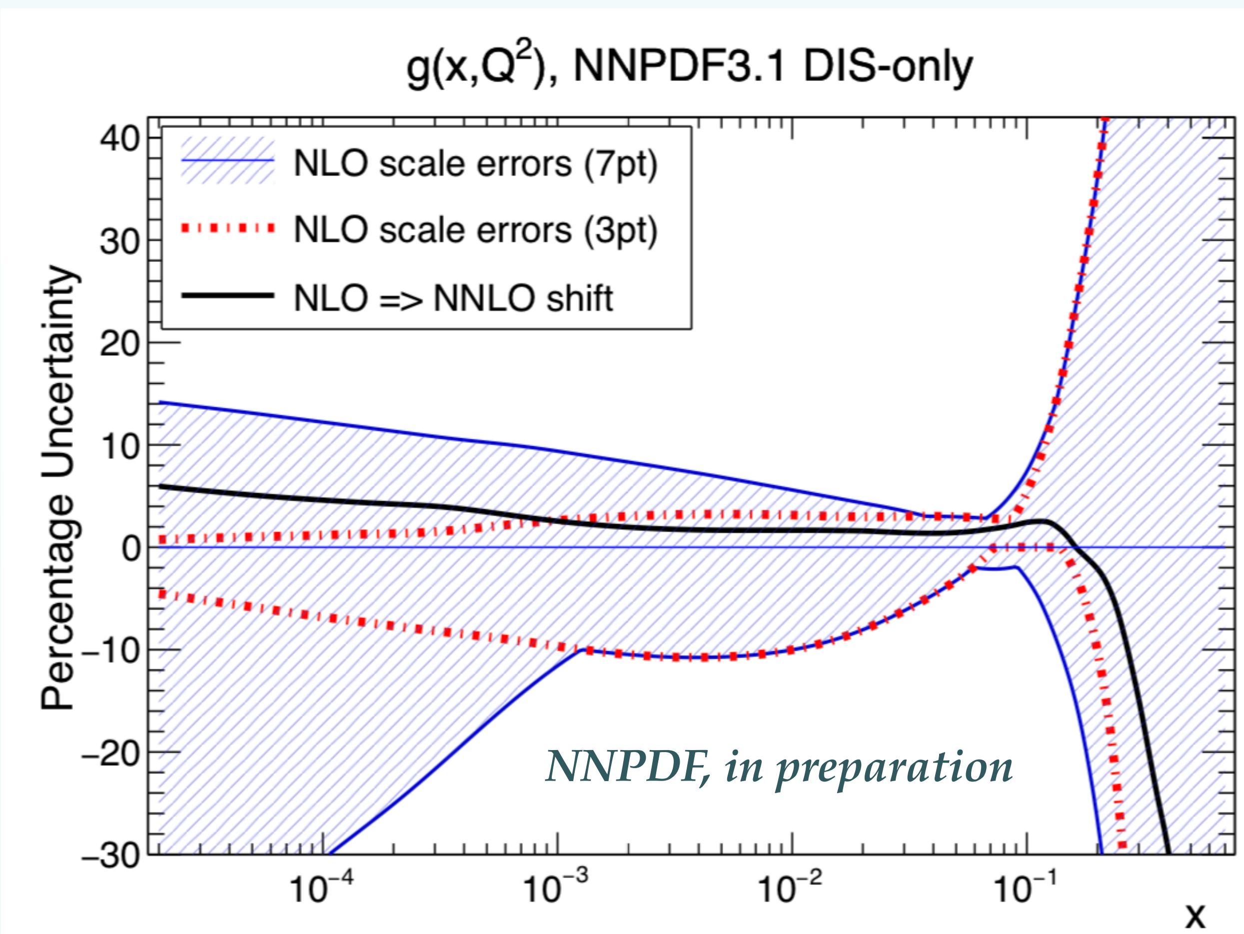


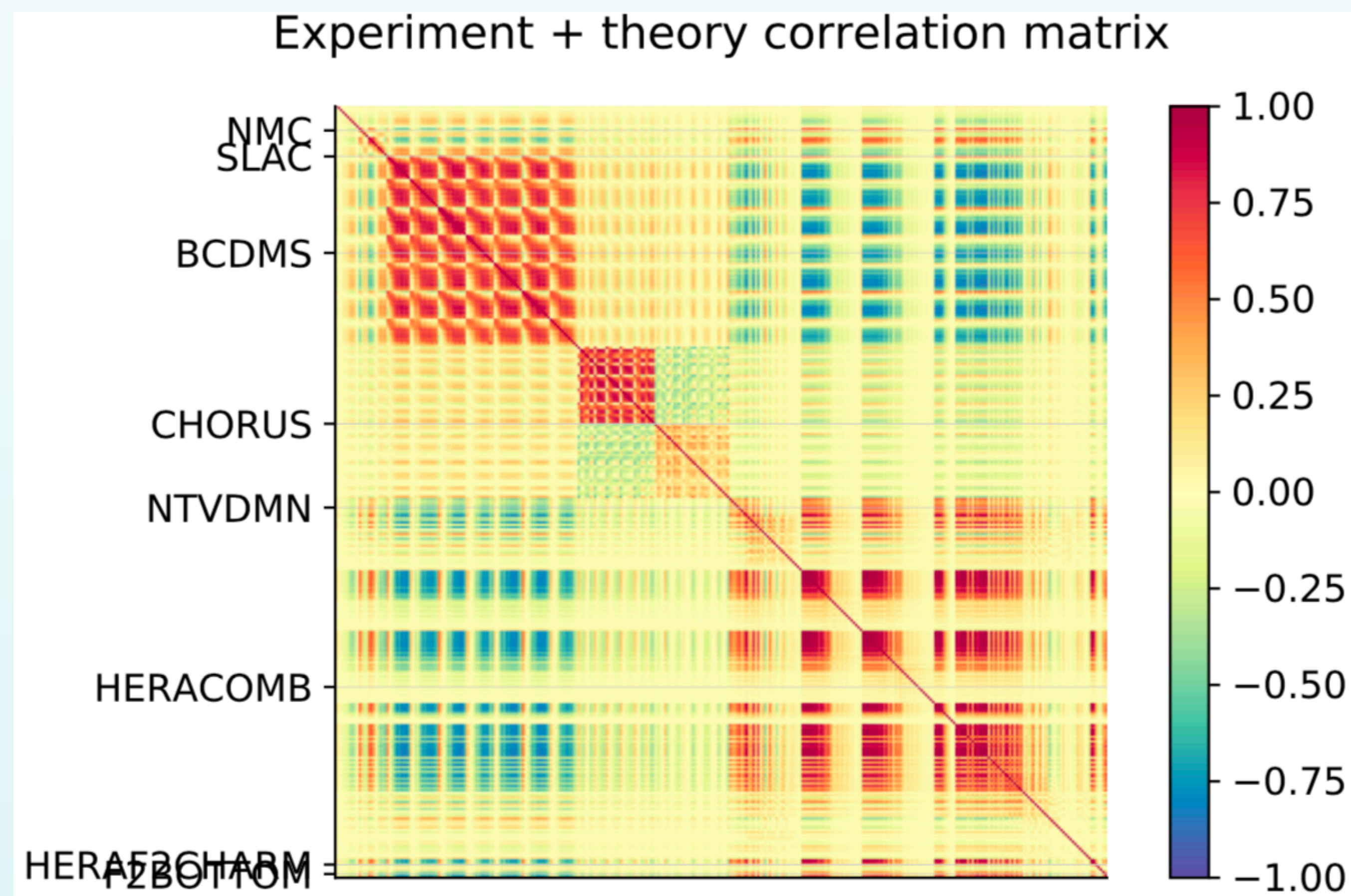




Parton Distributions with Theory Uncertainties

- Theoretical uncertainties from perturbative **missing higher orders (MHO)** neglected in PDF fits
- Ongoing work towards PDF fits with MHO based on constructed an **EXP+TH covariance matrix**
- Validated with **PDF fits with scale variations** and with **exact NLO => NNLO shift**



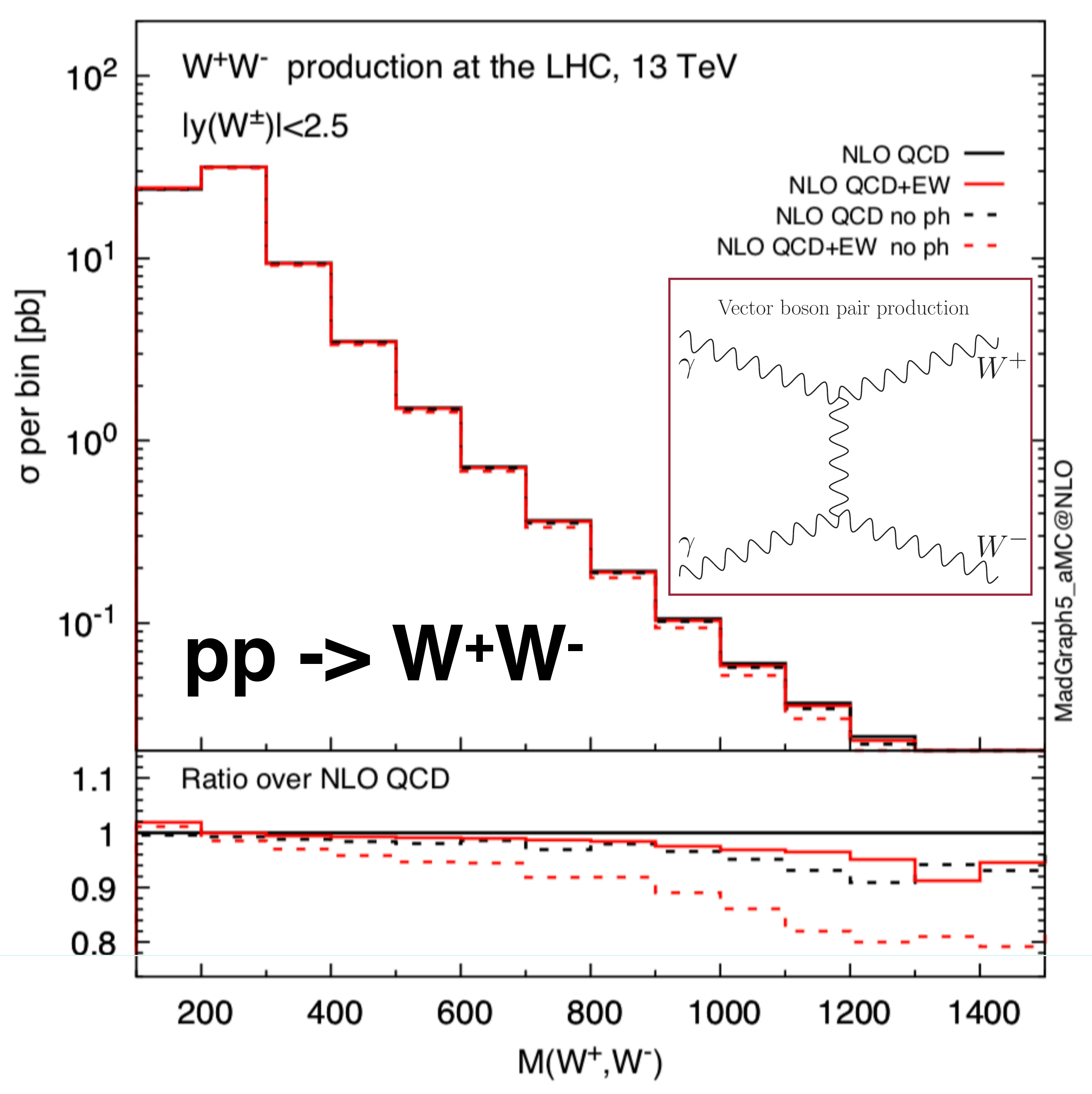


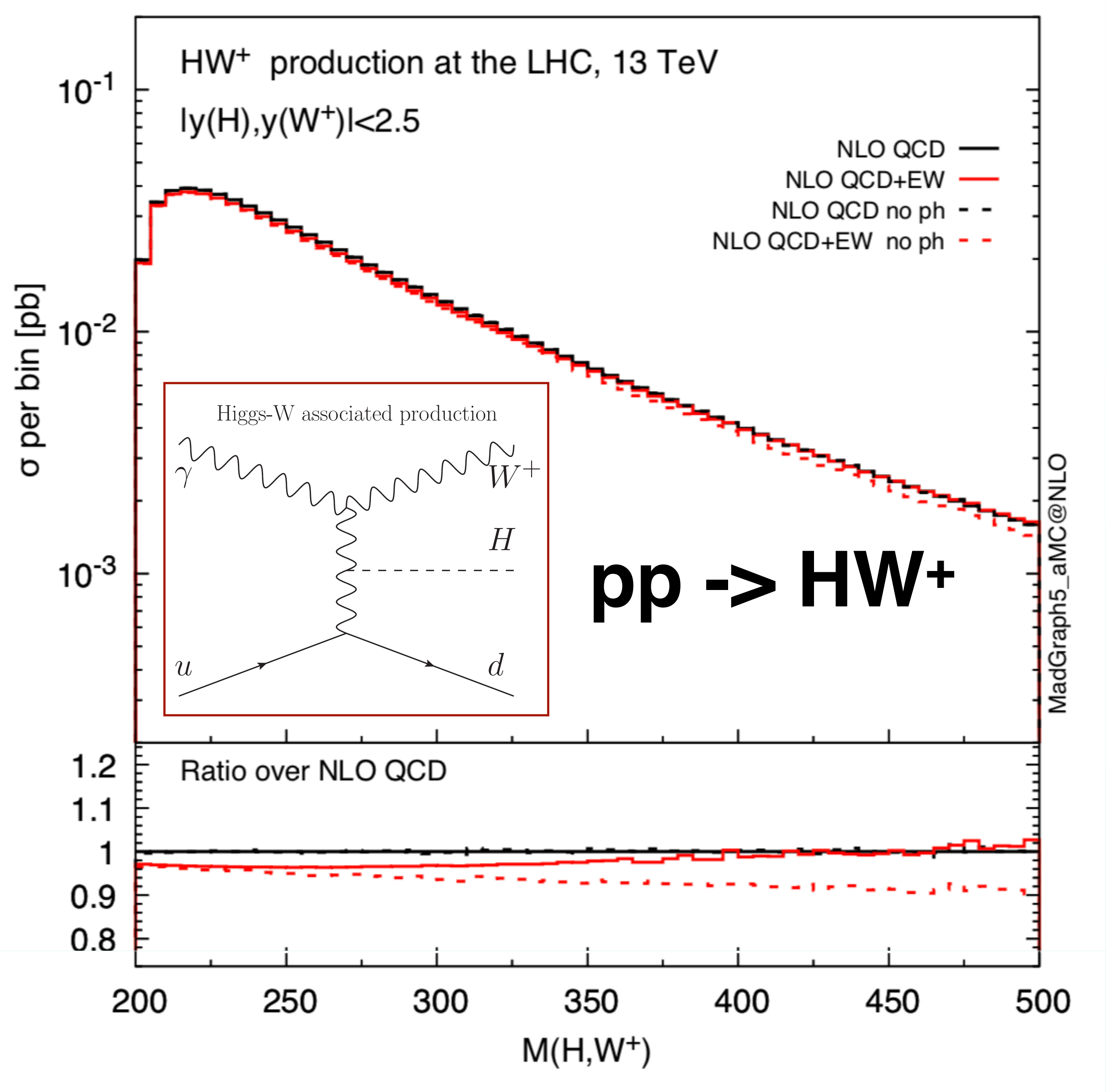
New theory-induced correlations between experiments

Photon-initiated processes at the LHC

- The proton contains not only quarks and gluons, but also photons: the **LHC is also a photon collider!**
- At high mass **PI contributions and NLO EW corrections have opposite sign**
- This seems to be the case for many processes: **once PI effects included, NLO EW corrections small**

NNPDF3.1_luxQED



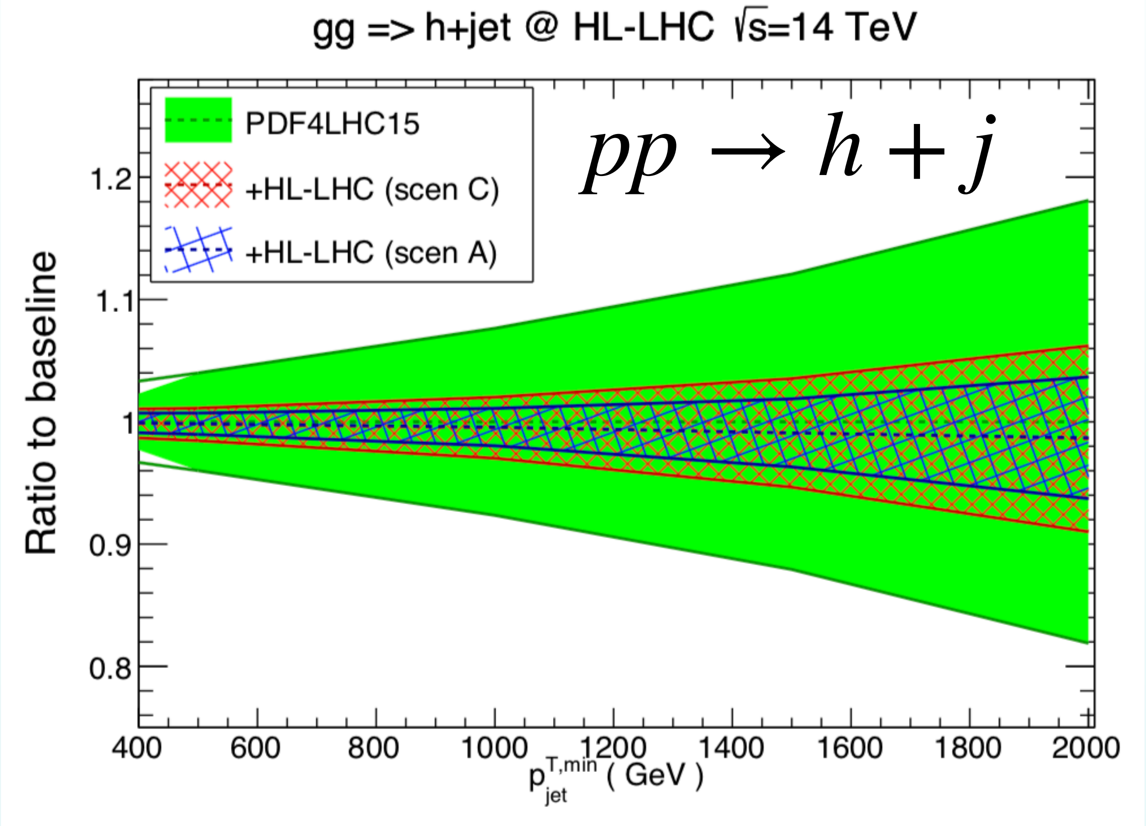


Bertone, Carrazza, Pagani, Rojo, Vicini, Zaro (in preparation)

Towards ultimate PDFs at hadron colliders

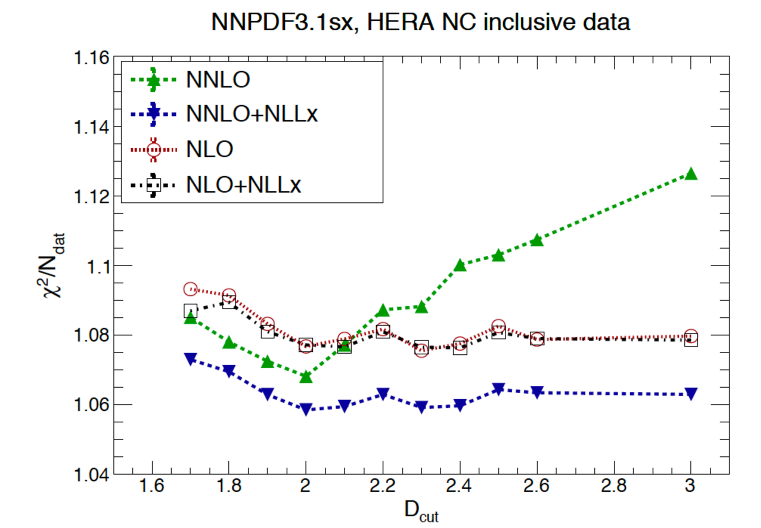
The HL-LHC with 3 ab^{-1} will lead to a **dramatic improvement** of the PDF uncertainties

Process	Kinematics	$N_{\rm dat}$
$Z\ p_T$	$20\ \text{GeV} \le p_T^{ll} \le 3.5\ \text{TeV}$ $12\ \text{GeV} \le m_{ll} \le 150\ \text{GeV}$ $\lvert y_{ll}\rvert \le 2.4$	338
high-mass Drell-Yan	$p_T^{l1(2)} \ge 40(30)\ \text{GeV}$ $\lvert\eta^l\rvert \le 2.5,\ m_{ll} \ge 116\ \text{GeV}$	32
top quark pair	$\lvert y_t\rvert \le 2.4$	52
W+charm (central)	$p_T^\mu \ge 26\ \text{GeV},\ p_T^c \ge 5\ \text{GeV}$ $\lvert\eta^\mu\rvert \le 2.4$	12
W+charm (forward)	$p_T^\mu \ge 20\ \text{GeV},\ p_T^c \ge 20\ \text{GeV}$ $p_T^{\mu+c} \ge 20\ \text{GeV}$ $2 \le \eta^\mu \le 5,\ 2.2 \le \eta^c \le 4.2$	12
Direct photon	$E_T^\gamma \lesssim 3\ \text{TeV},\ \lvert\eta_\gamma\rvert \le 2.5$	118
Forward W, Z	$p_T^l \ge 20\ \text{GeV},\ 2.0 \le \eta^l \le 4.5$ $2.0 \le y_{ll} \le 4.5$ $60 \le m_{ll} \le 120\ \text{GeV}$	90
Inclusive jets	$\lvert y\rvert \le 3,\ R = 0.4$	58

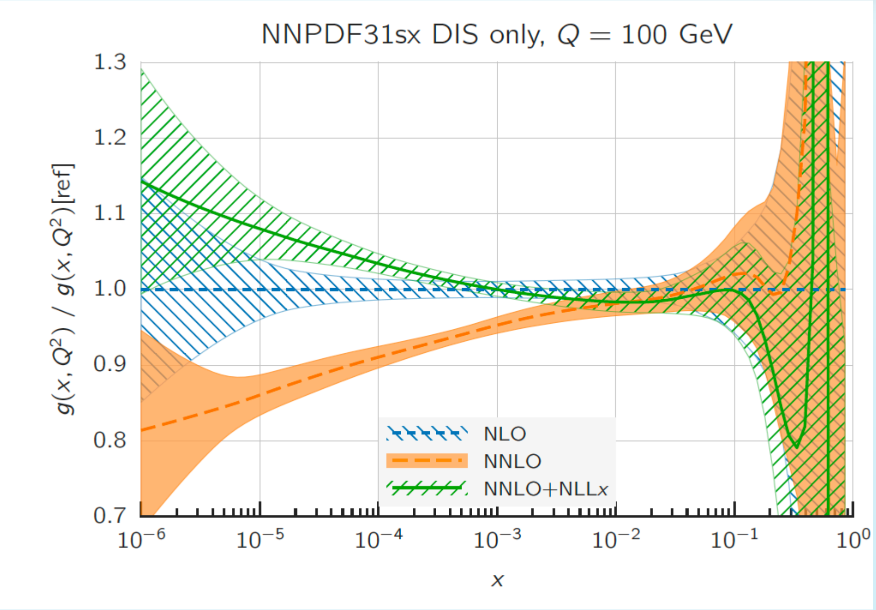


Abdul-Khalek, Bailey, Gao, Harland-Lang, JR
to appear un the HL/HE-LHC Yellow Report

- Generated projections for **HL-LHC pseudo-data**
- Included them on **PDF4LHC15** using Hessian profiling
- Study pheno implications for important processes such as **Higgs production**



Discovering ``New Physics" from the global QCD analysis



Discovering New Physics within QCD

How we can ensure that we are not ``**fitting way" BSM effects** in the global PDF analysis?

Our recent discovery of **BFKL effects in HERA data** illustrates how this can be achieved!

- At small-x, **logarithmically enhanced terms in *1/x* become dominant** and need to be resummed
- **BFKL/high-energy/small-x resummation** can be matched to the **DGLAP collinear framework**
- Until recently**,** no conclusive evidence for the onset of BFKL dynamics had been provided

DGLAP Evolution in Q^2

$$\mu^2 \frac{\partial}{\partial \mu^2} f_i(x,\mu^2) = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(\mu^2)\right) f_j(z,\mu^2),$$

BFKL Evolution in x

$$-x\frac{d}{dx} f_+(x,\mu^2) = \int_0^\infty \frac{d\nu^2}{\nu^2} K\left(\frac{\mu^2}{\nu^2}, \alpha_s\right) f_+(x,\nu^2)$$

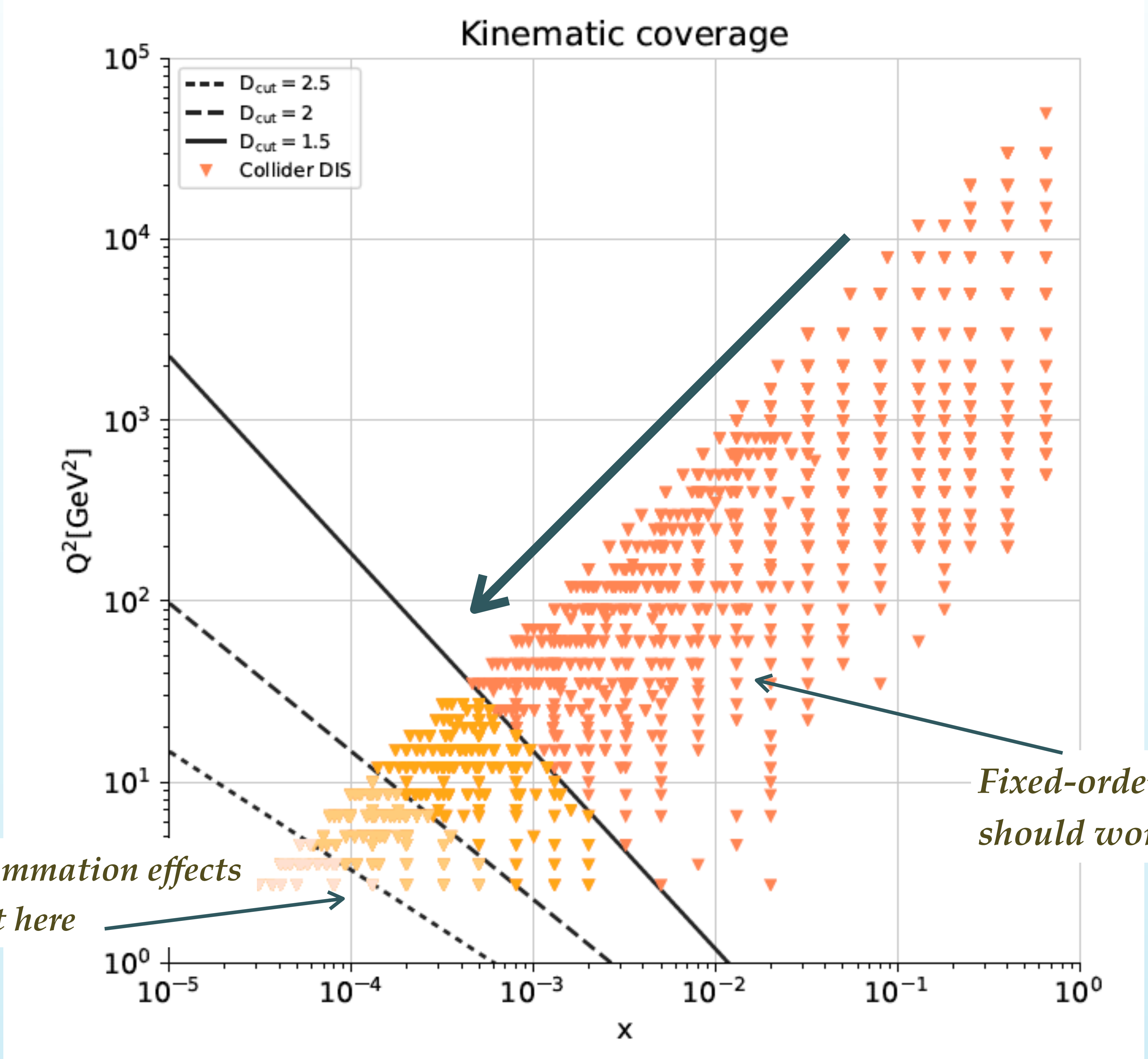
Within small-*x* resummation, the **N^kLO fixed-order DGLAP splitting functions** are complemented with the **N^hLL*x* contributions from BKFL**

$$P_{ij}^{\mathrm{N}^k\mathrm{LO}+\mathrm{N}^h\mathrm{LL}x}(x) = P_{ij}^{\mathrm{N}^k\mathrm{LO}}(x) + \Delta_k P_{ij}^{\mathrm{N}^h\mathrm{LL}x}(x),$$

ABF, CCSS, TW + others, 94-08

Evidence for BFKL dynamics in HERA data

In order to assess the impact of small-x resummation for the description of the **small-*x* and Q^2 HERA data,** compute the χ^2 **removing data points in the region where resummation effects are expected**



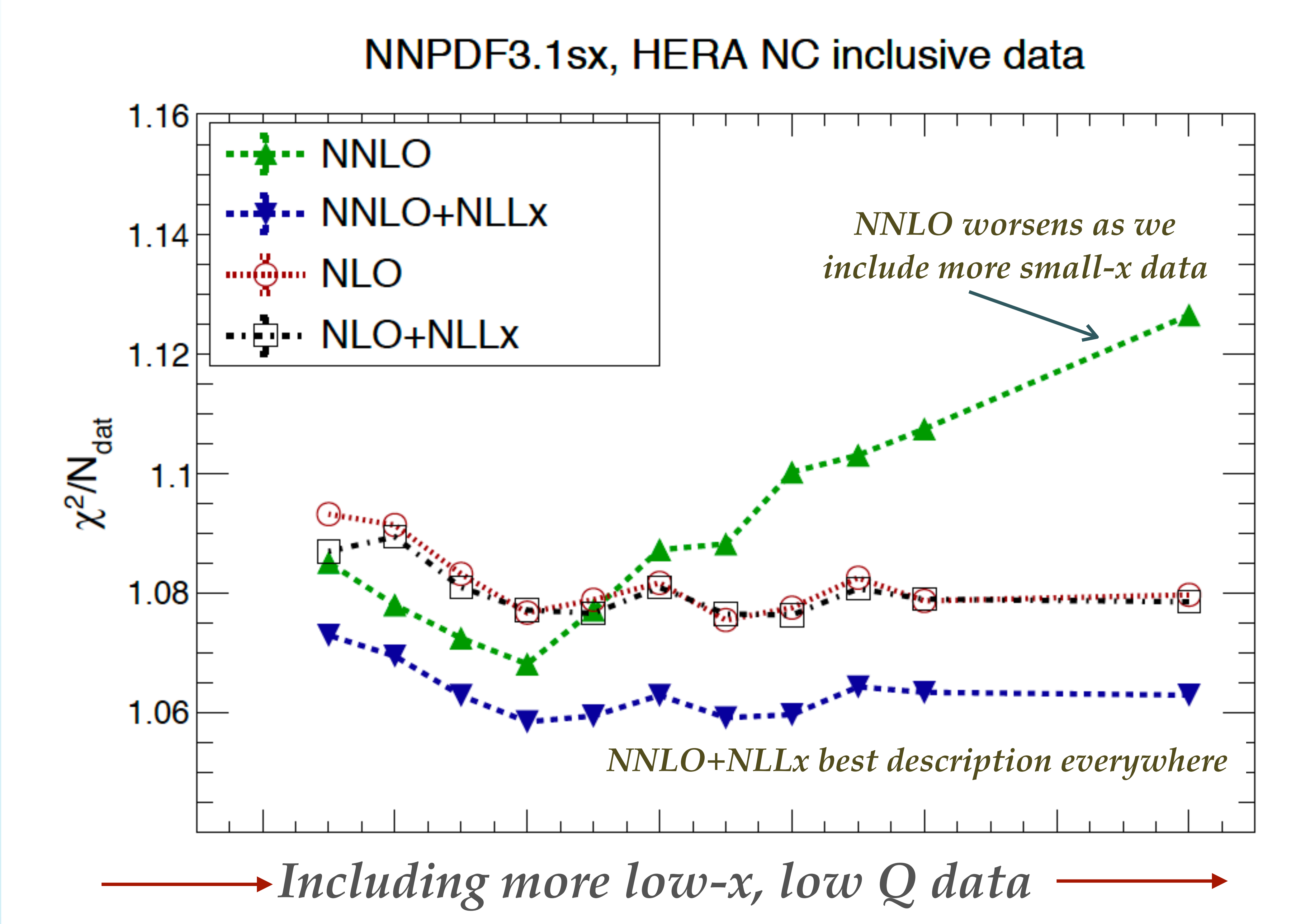
Fixed-order theory should work fine here

Small-x BFKL resummation effects could be important here

Evidence for BFKL dynamics in HERA data

Using **NNLO+NLLx theory, the NNLO instability at small-x of the χ^2 disappears**

Excellent fit quality to **inclusive and charm HERA** data achieved in the **entire (x,Q²) region**



Science
Life and Physics

After 40 years of studying the strong nuclear force, a revelation

This was the year that analysis of data finally backed up a prediction, made in the mid 1970s, of a surprising emergent behaviour in the strong nuclear force

Jon Butterworth

@jonmbutterworth
Thu 28 Dec 2017 17.30 GMT

529 | 59

In the mid 1970s, four Soviet physicists, Batlisky, Fadin, Kuraev and Lipatov, made some predictions involving the strong nuclear force which would lead to their initials entering the lore. “BFKL” became a shorthand for a difficult-to-

Jon Butterworth, The Guardian

PDFs and BSM physics at the LHC

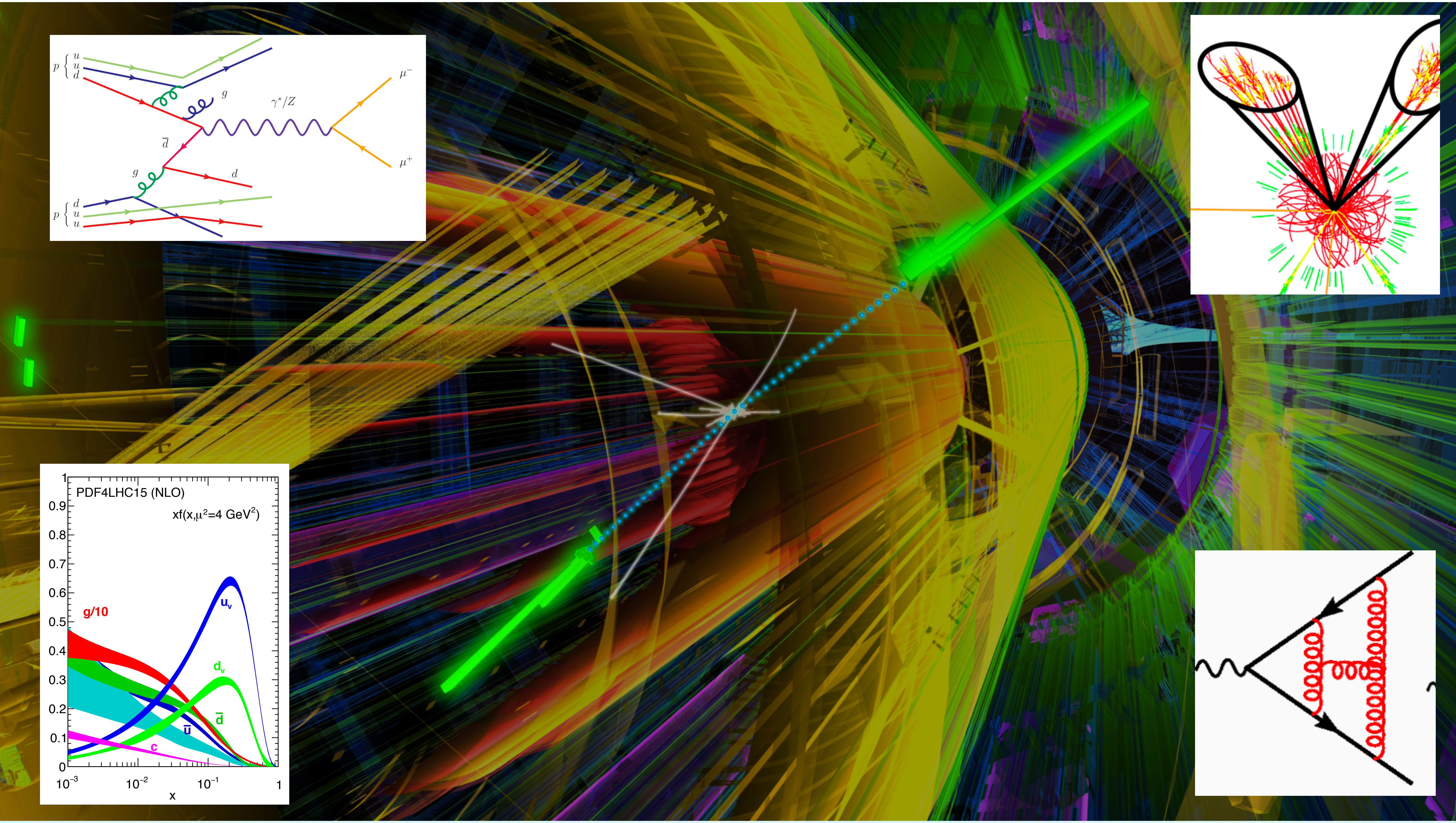
☑ Recent progress both from the **theoretical** and **experimental** sides have realised the dream of turning the **LHC into a high-precision experiment**

☑ A **detailed mapping of the proton structure** is essential for a wide variety of **BSM searches**, both direct (high-mass resonances) and indirect (SMEFT, Higgs couplings, electroweak parameters)

☑ The LHC provides unique opportunities to **constrain the quark and gluon PDFs**

☑ Parton distributions could be the key for **unravelling new physics at the LHC!**

Fascinating times to explore the high-energy frontier!



equipped with our high-precision QCD toolbox!

Fascinating times to explore the high-energy frontier!

Thanks for your attention!

equipped with our high-precision QCD toolbox!