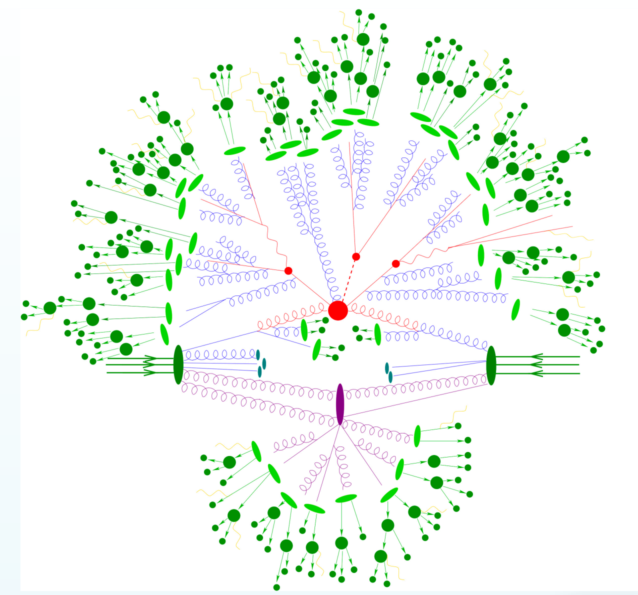
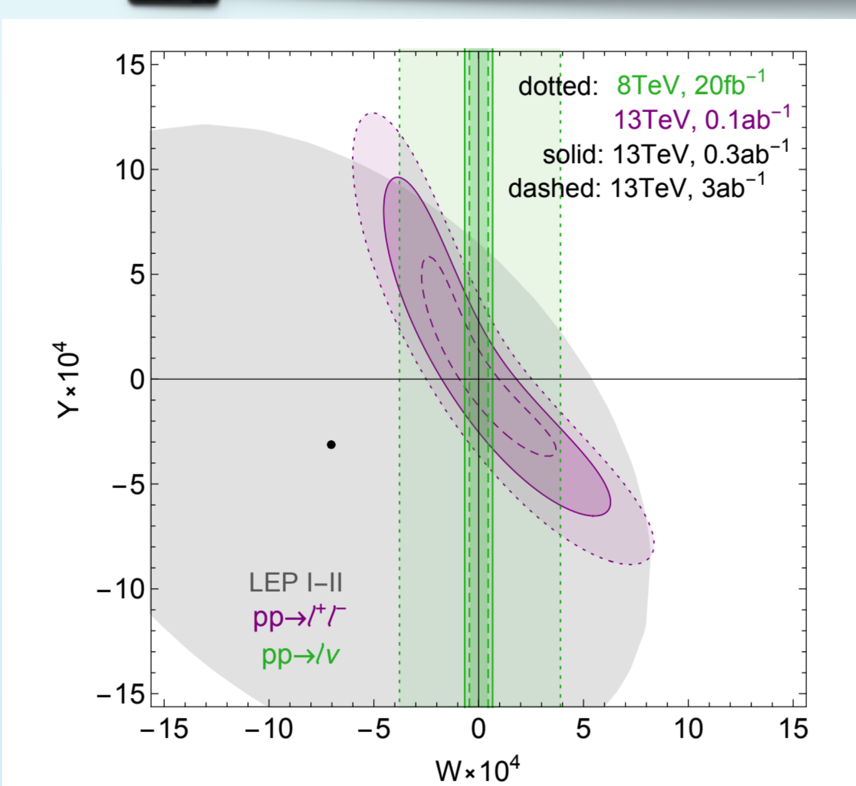
Discovery through precision at the LHC

VU Amsterdam & Nikhef

5th KSETA Plenary Workshop
Offenburg, 26th of February 2018

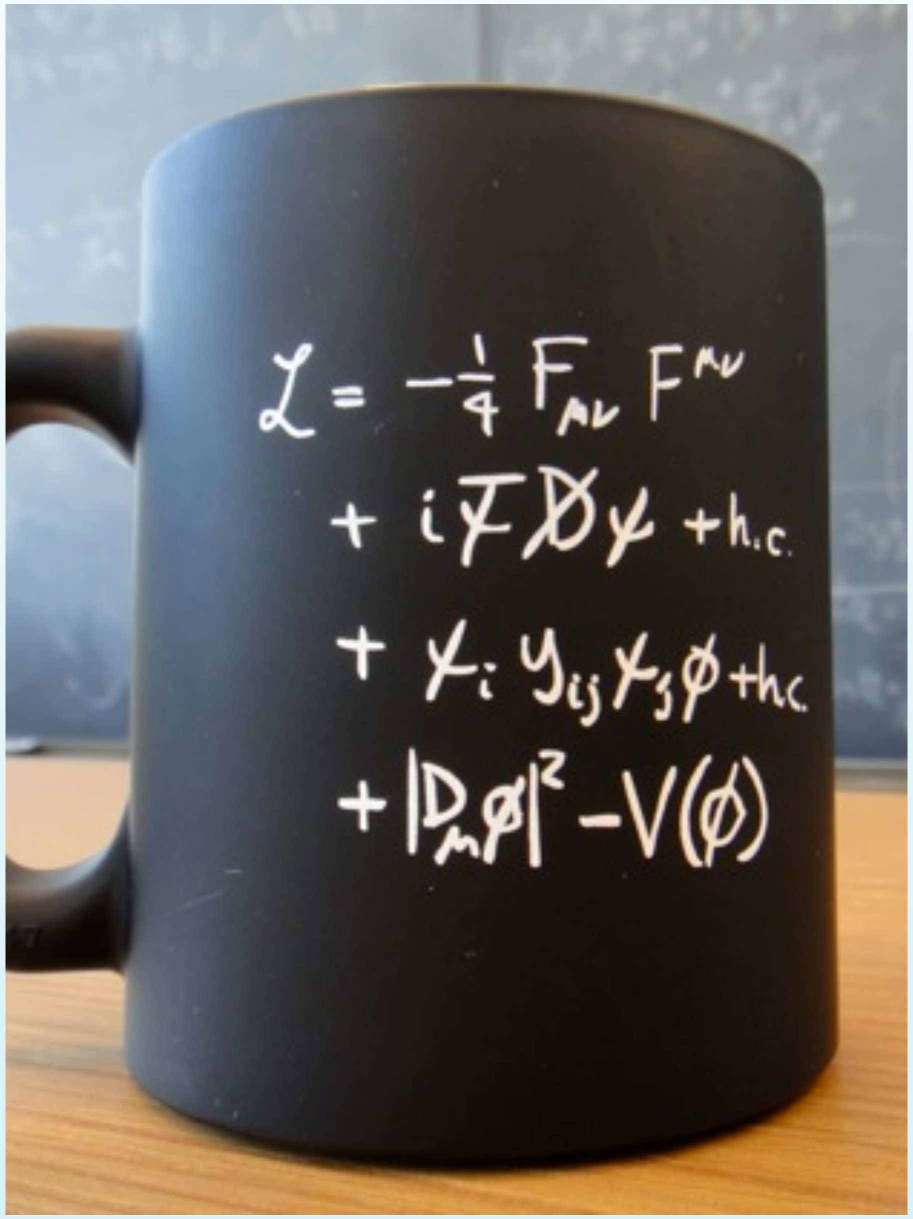


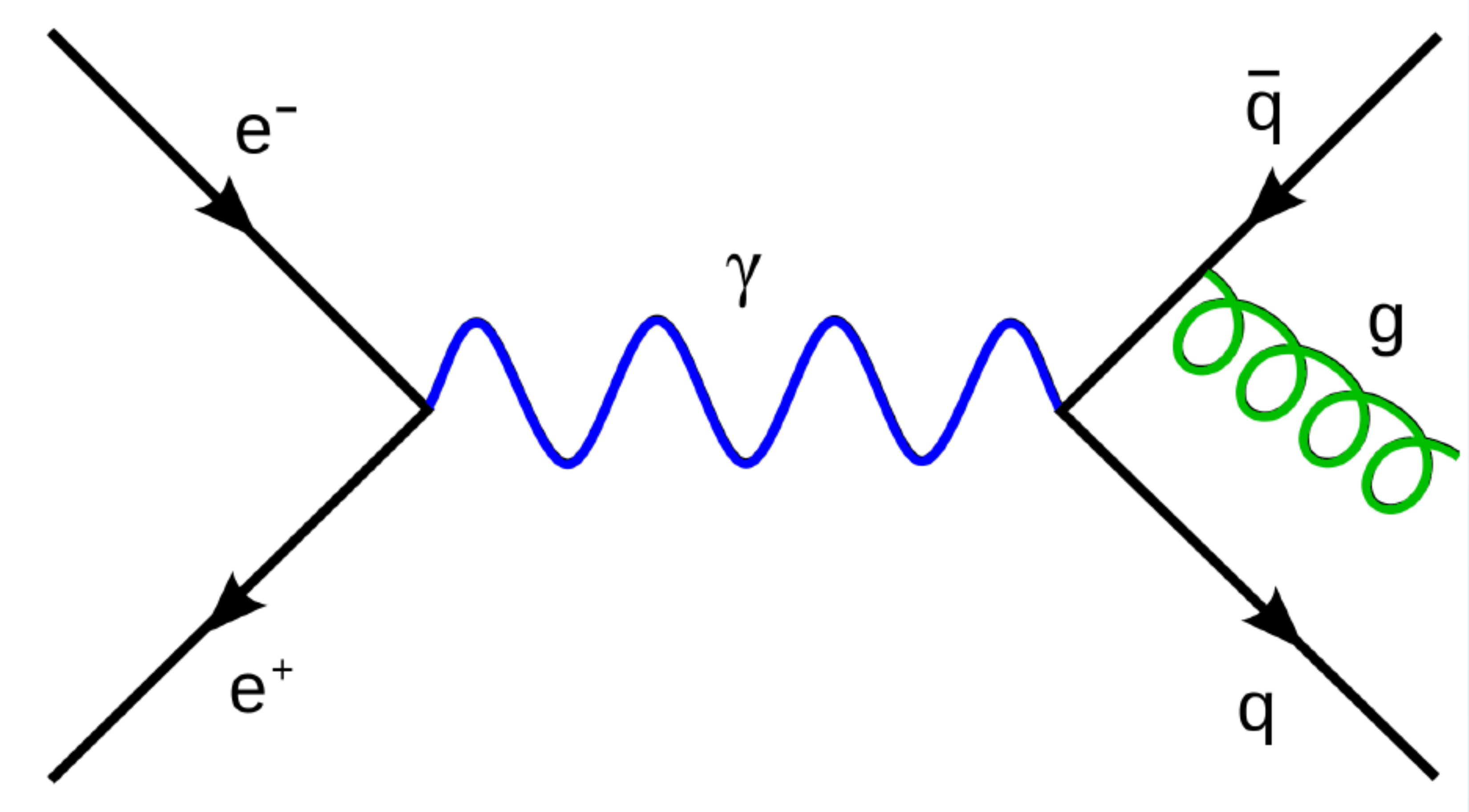
Why precision?



Precision at hadron colliders?

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





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

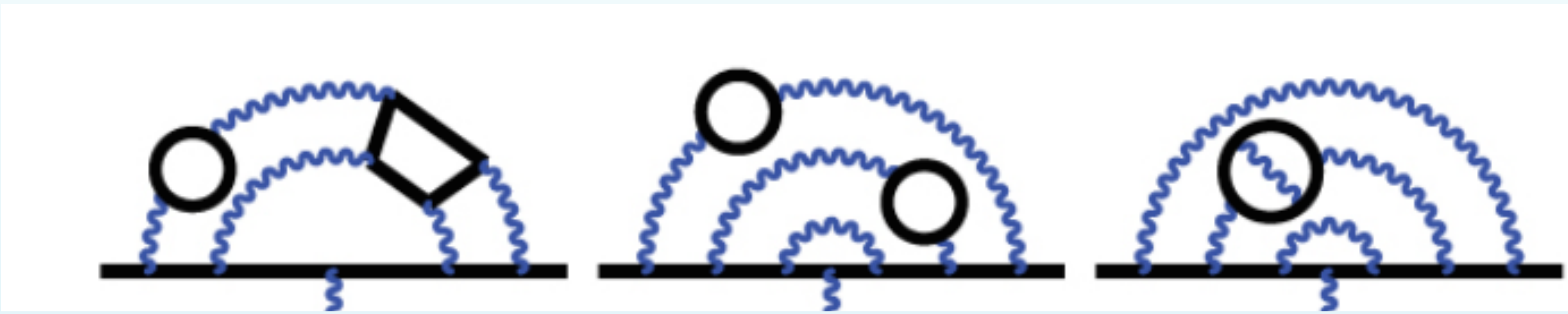
Quantum Electrodynamics and lepton colliders are ideal for **high-precision measurements**

Precision at hadron colliders?

QED leads to high-precision predictions such as the **anomalous magnetic moment of the electron**

$$a_{\text{exp}} = 0{,}00115965218073 \pm 0{,}00000000000028$$

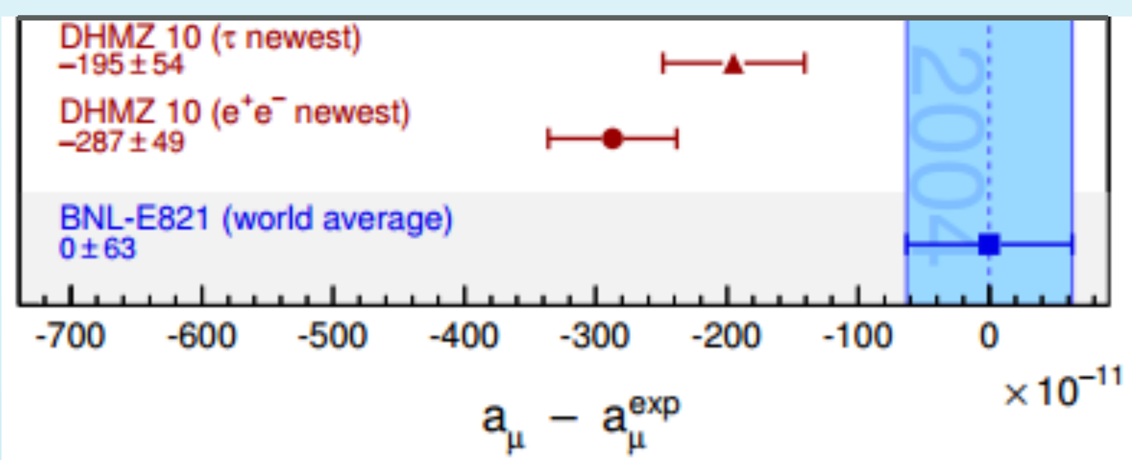
$$a_{\text{teo}} = 0{,}00115965218178 \pm 0{,}00000000000077$$

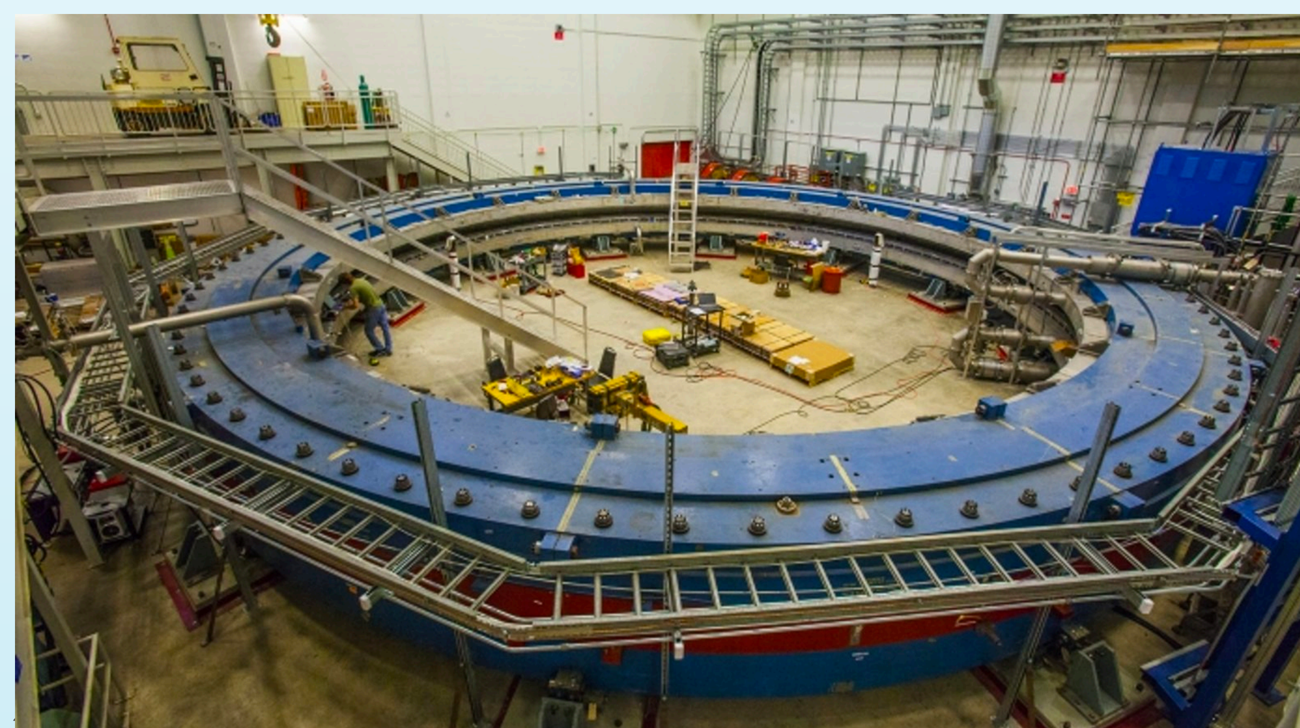


One of the most accurate predictions ever provided by any scientific theory!

This accuracy could be key for new discoveries!

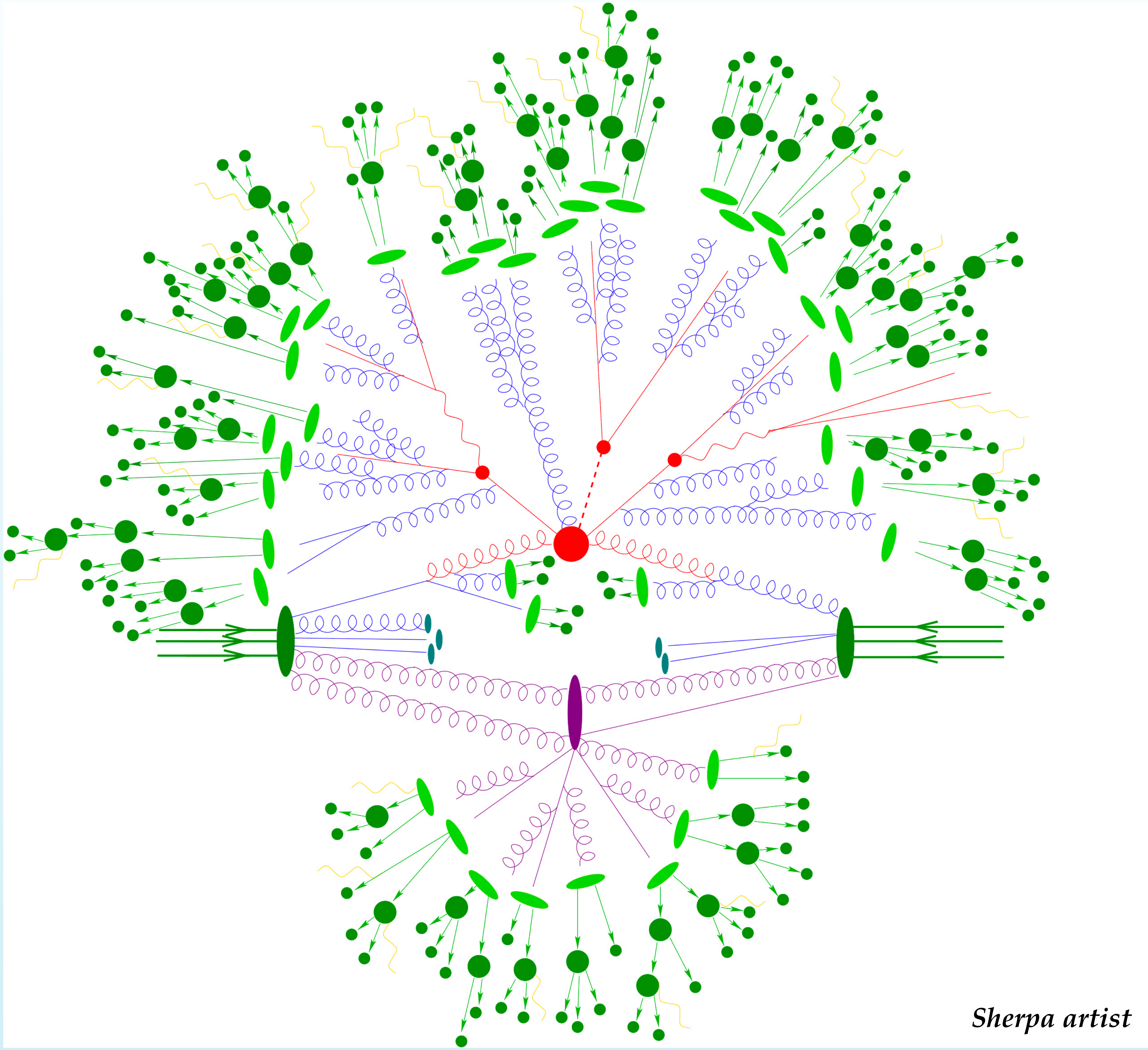
i.e. **muon g-2 experiment @ BNL and FNAL**





Precision at hadron colliders?

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

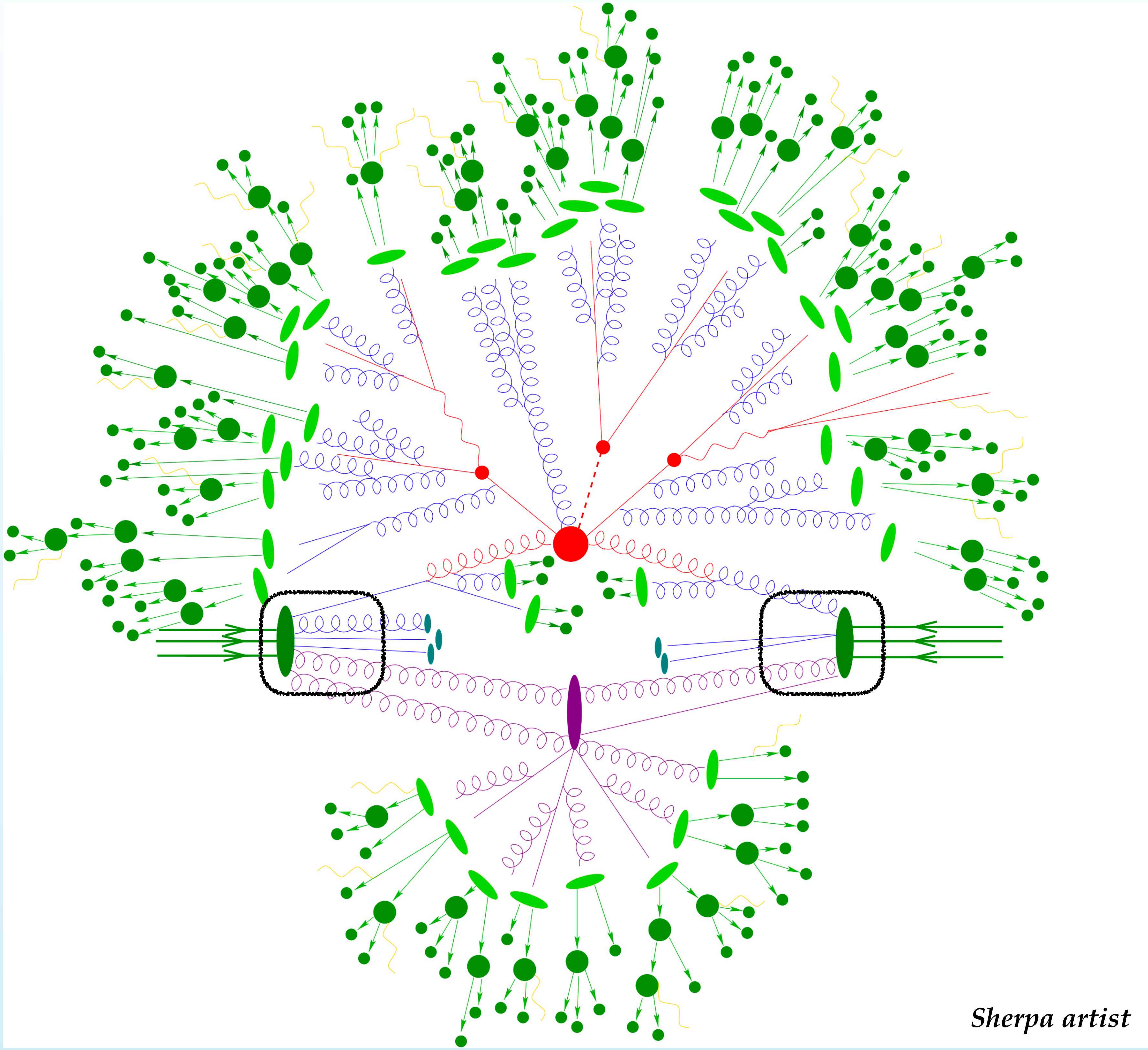


Sherpa artist

Precision at hadron colliders?

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

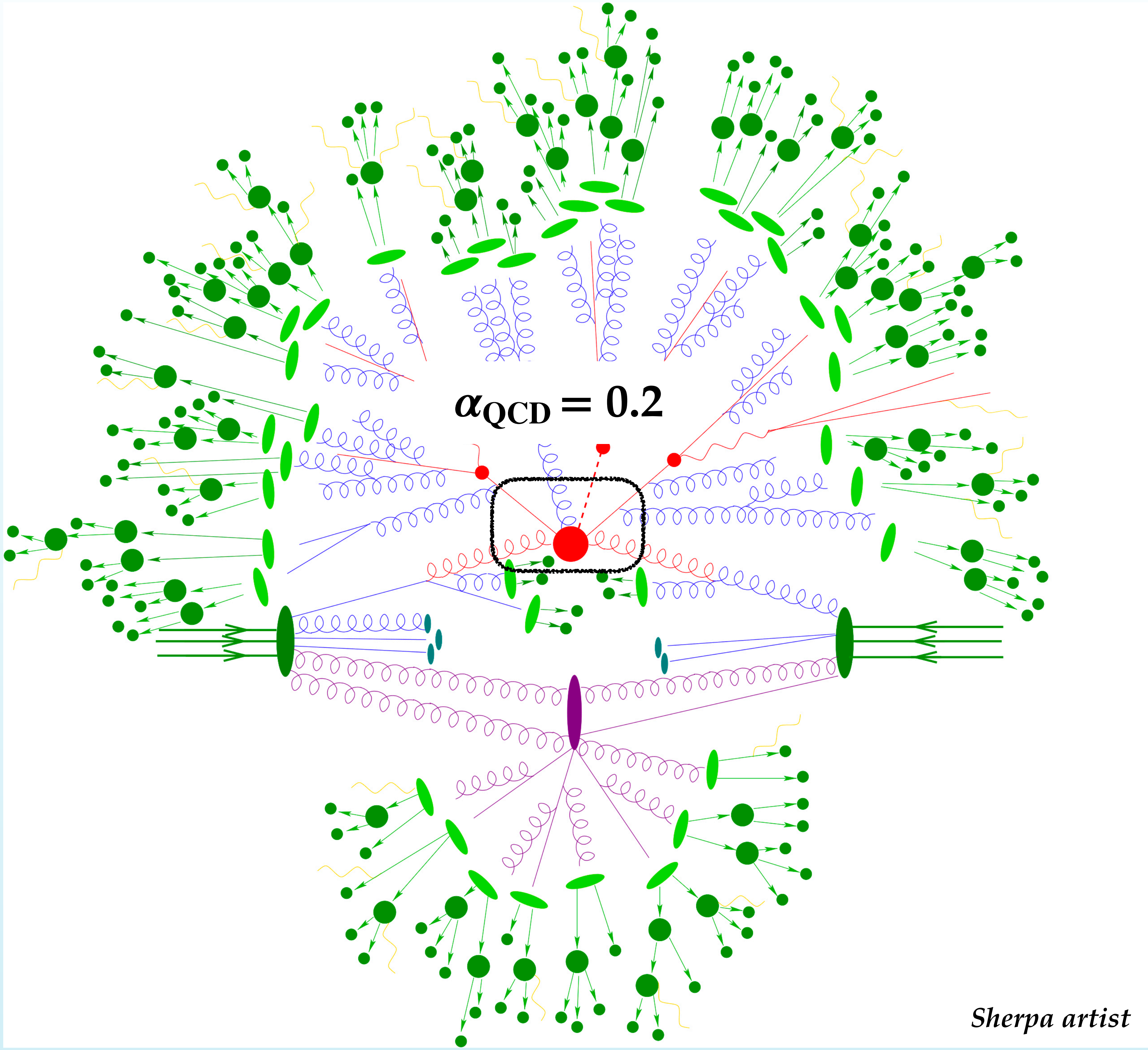
- initial state: **non-perturbative** proton's parton distributions



Precision at hadron colliders?

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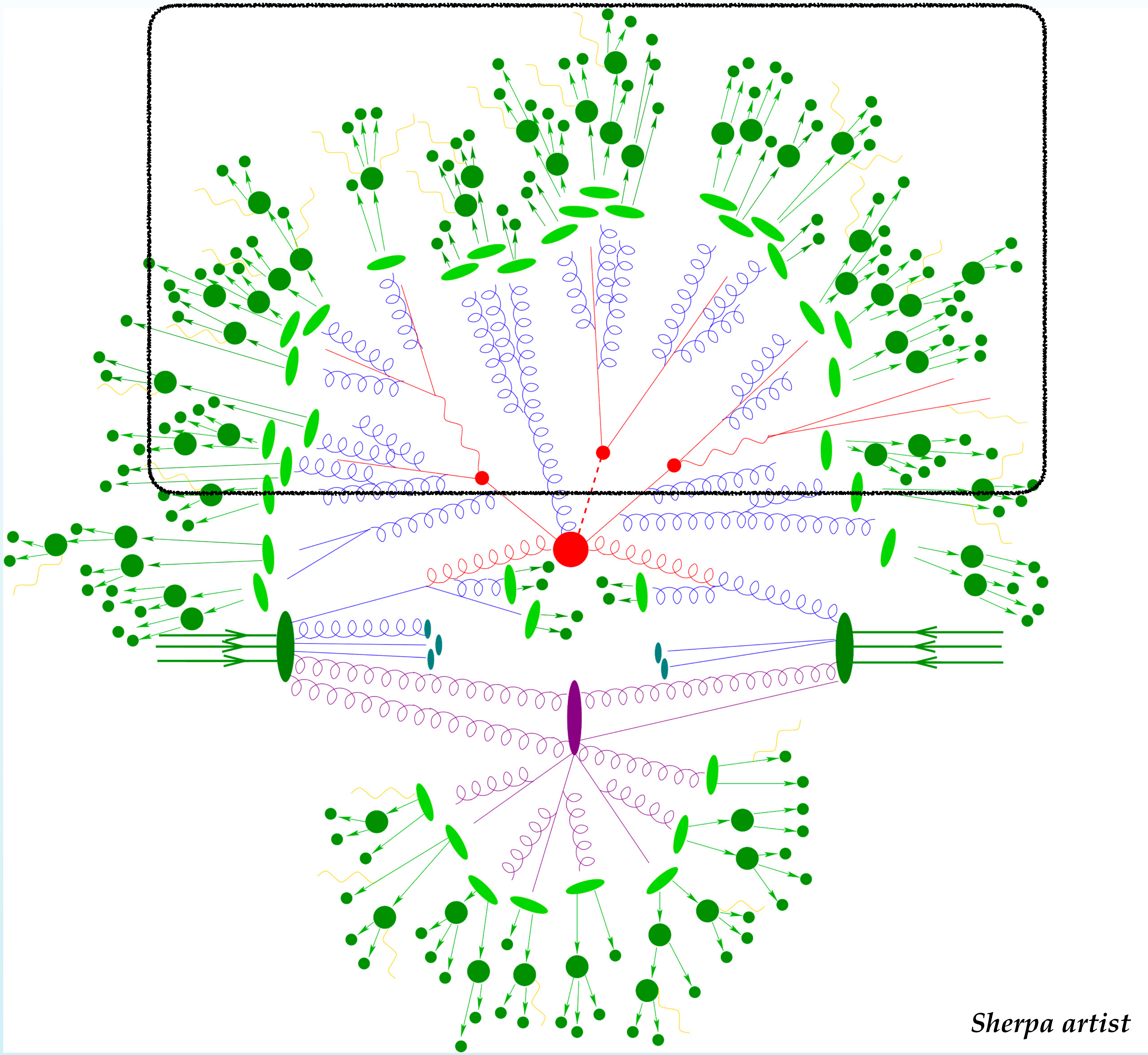
- parton showering and hadronization



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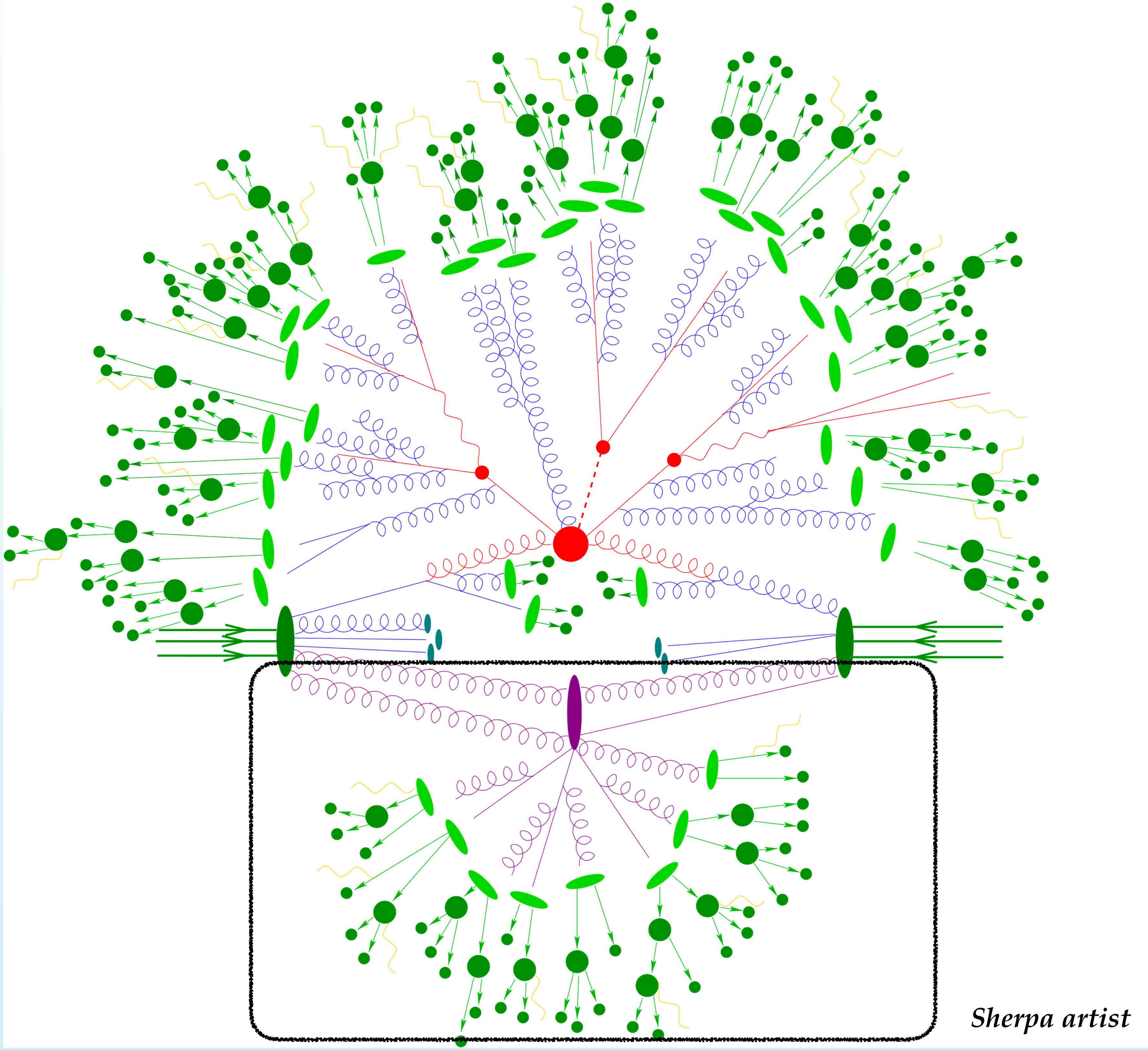
- plus lots of poorly understood non-perturbative effect: **background noise** such multiple parton intercations, pile-up….



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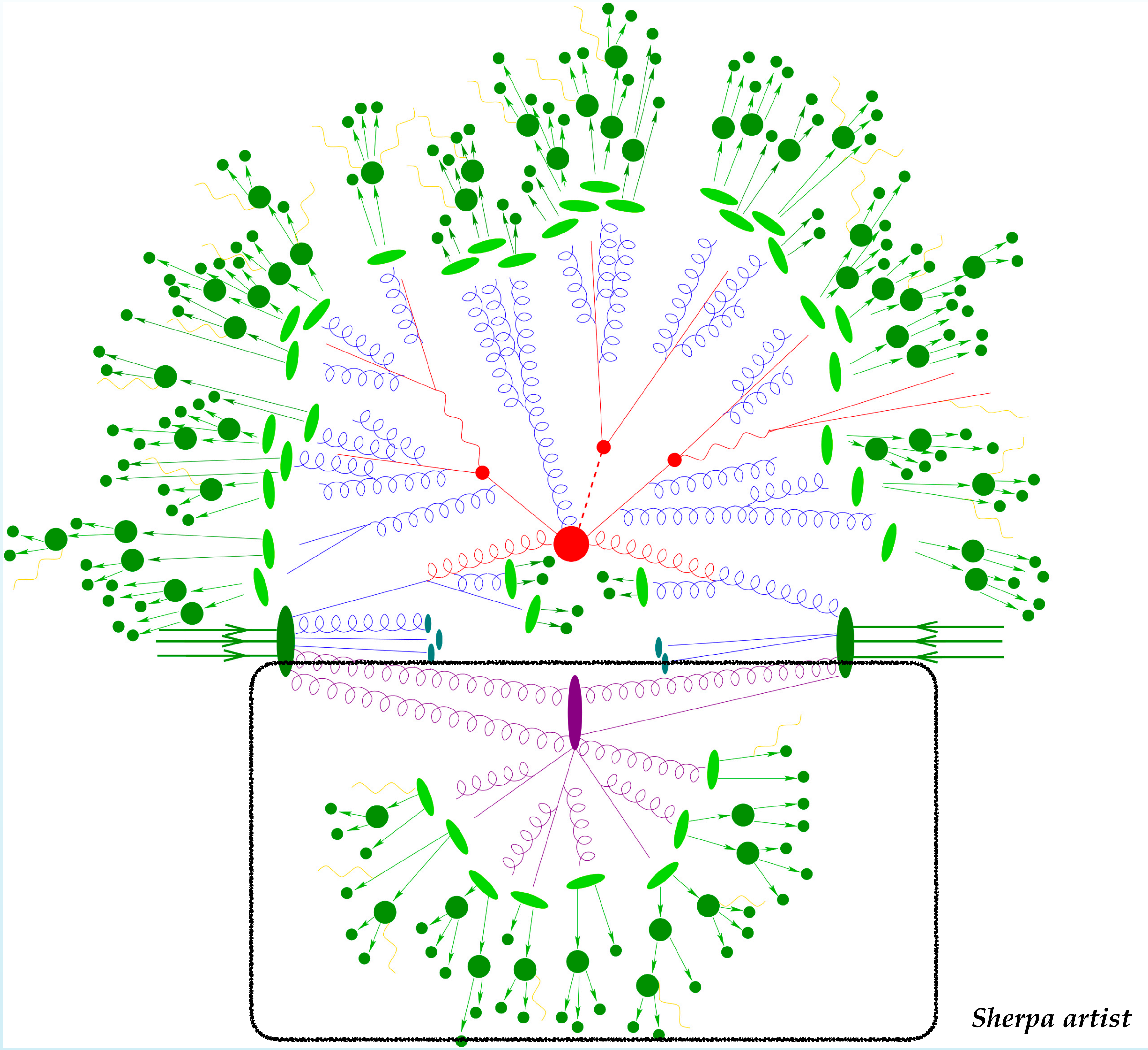
Can we really aim for precision physics at LHC?



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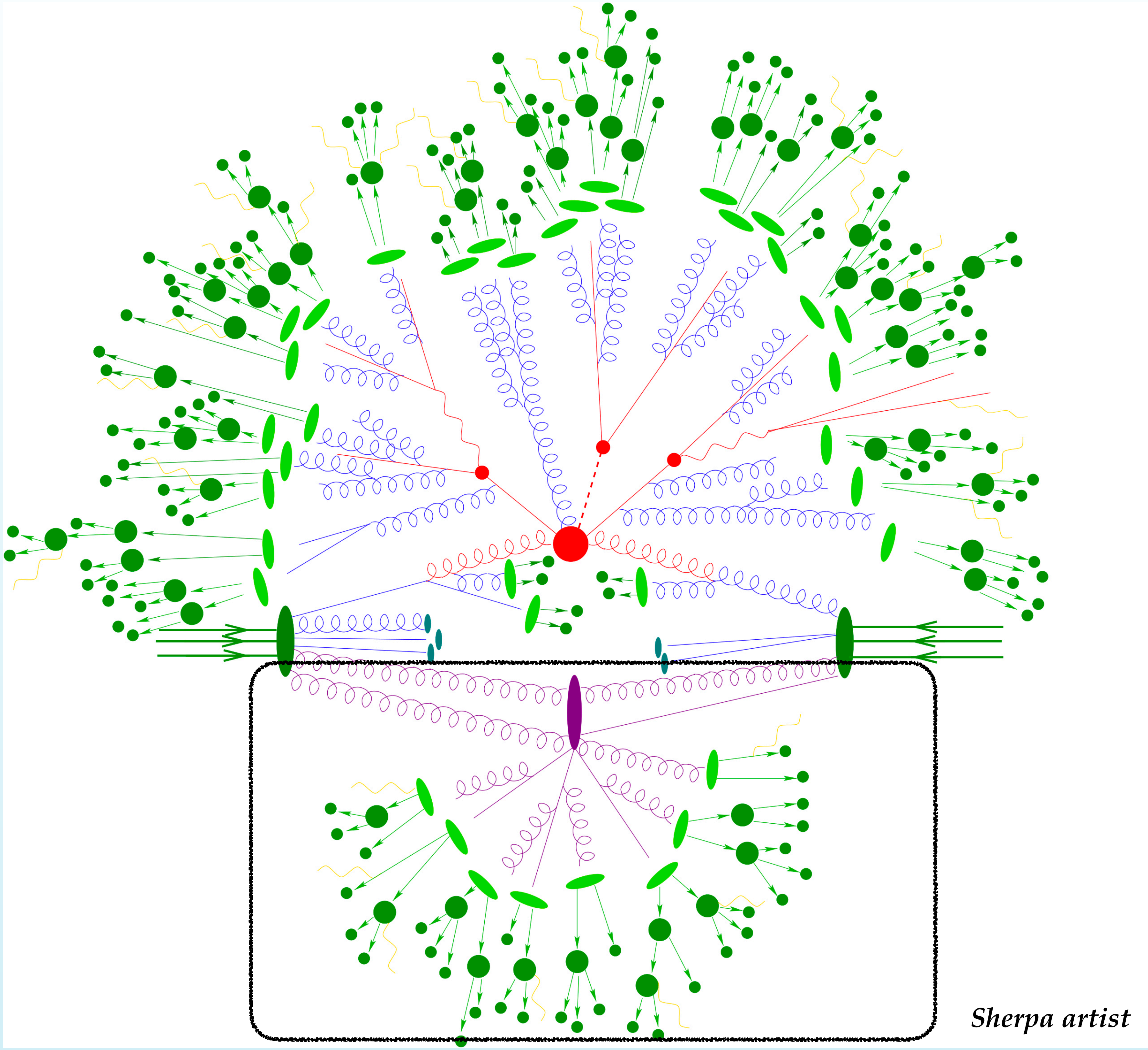


Beyond the SM

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):

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

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:

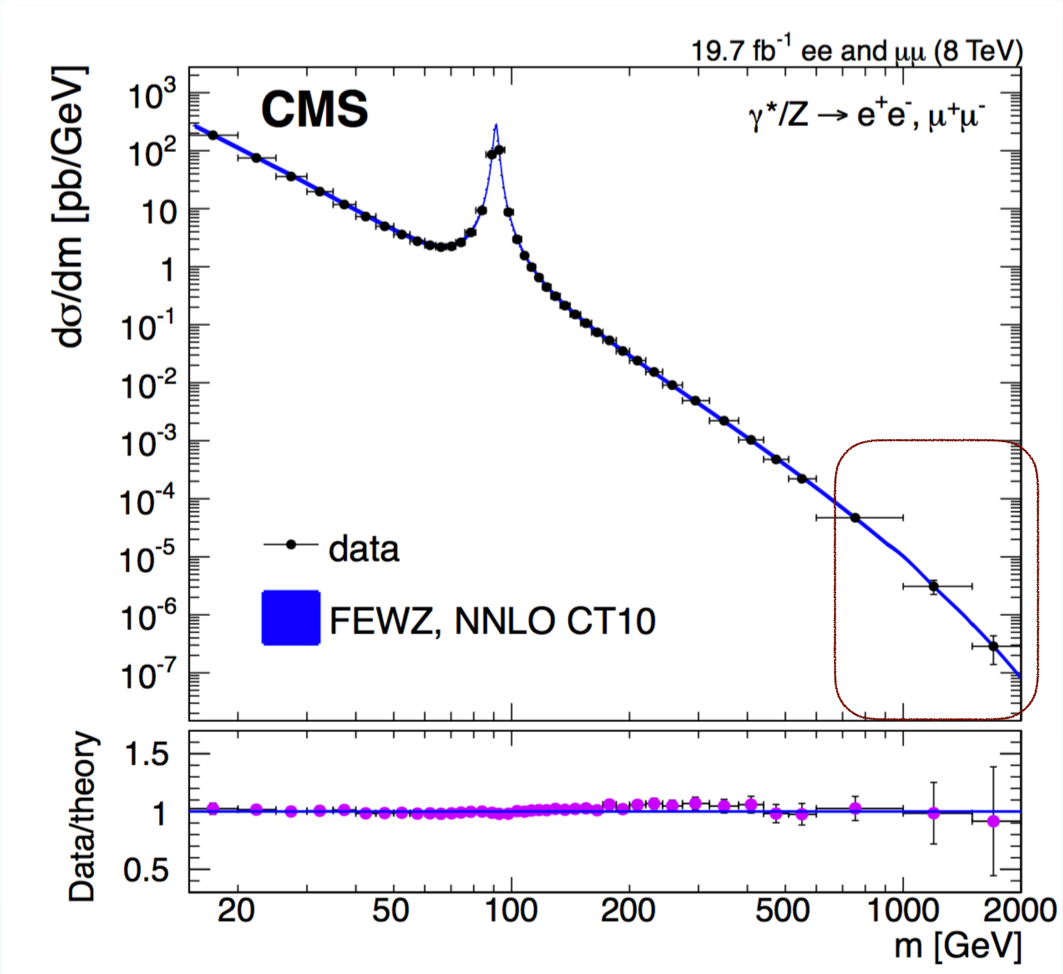
$$g_s f^{abc} G_\mu^{\nu,a} G_\nu^{\rho,b} G_\rho^{\mu,c} \qquad -\frac{Z}{2m_W^2}(D_\mu G^{\mu\nu,a})^2 \qquad \mathcal{Q}_{qq}^{(1)} \propto (\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$$

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**

Why precision at the LHC?

To enhance the discovery potential of new **Beyond the Standard Model physics!**

- BSM physics could manifest as **subtle deviations** wrt to the Standard Model predictions
- Even for high-mass resonances, theory uncertainties **degrade or limit many BSM searches**
- The robustness of **global stress-tests of the SM** (electroweak fit, SM Effective Field Theory analysis) relies crucially in high-precision theoretical calculations



Generic SMEFT expansion

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

For $\mathbf{E} \simeq \mathbf{1}$ **TeV**, a measurement with $\delta\sigma/\sigma \simeq \mathbf{10\%}$ is sensitive to $\epsilon \simeq \mathcal{O}(\mathbf{0.1\%})$!

Marco Farina, HL/HE LHC workshop

BSM physics might very well hiding itself in the tails of distributions

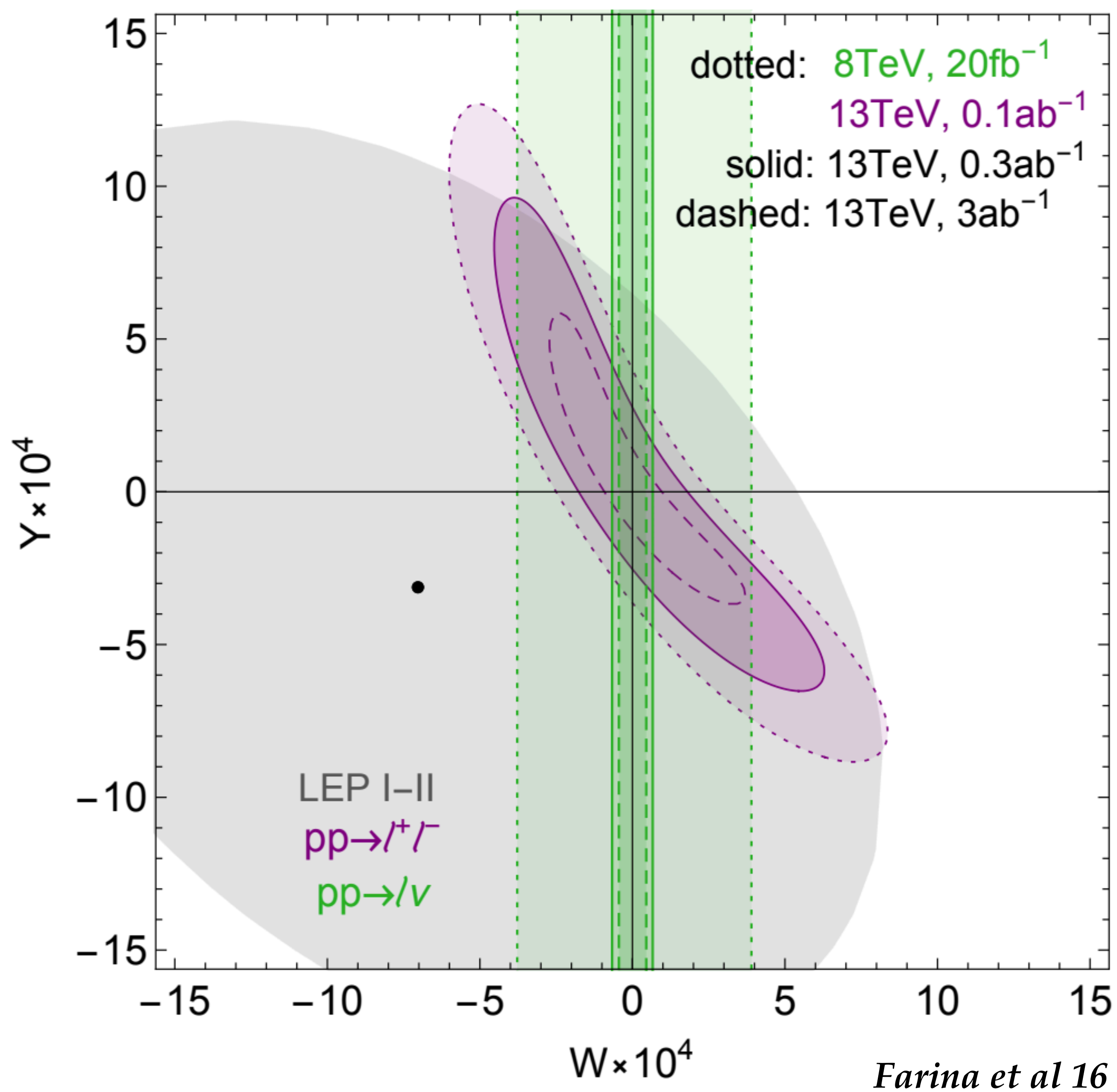
Energy helps accuracy

Recent progress in theoretical calculations has demonstrated that the LHC is not only a discovery machine: it can (and should!) **carry out a precision physics program**

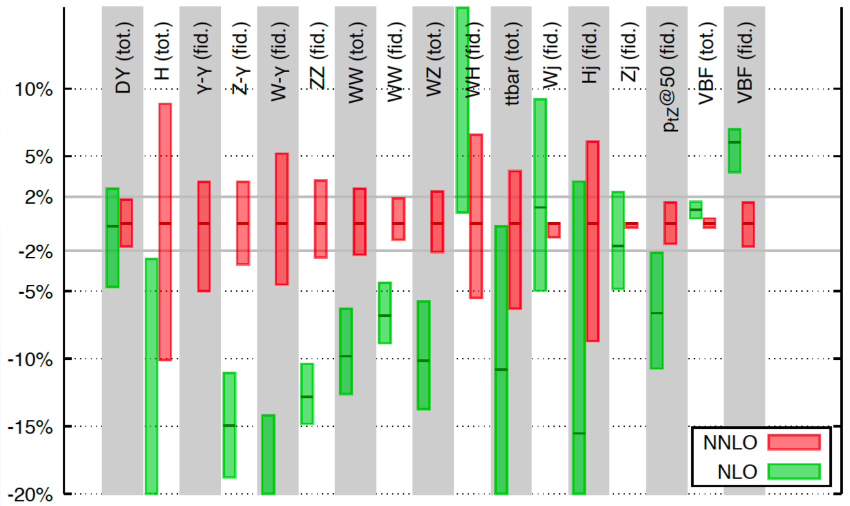
- **Electroweak precision tests** at the LHC are possible
- Constraints on some SMEFT EW operators can markedly **improve LEP bounds**
- Exploiting **increase in partonic energy**

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

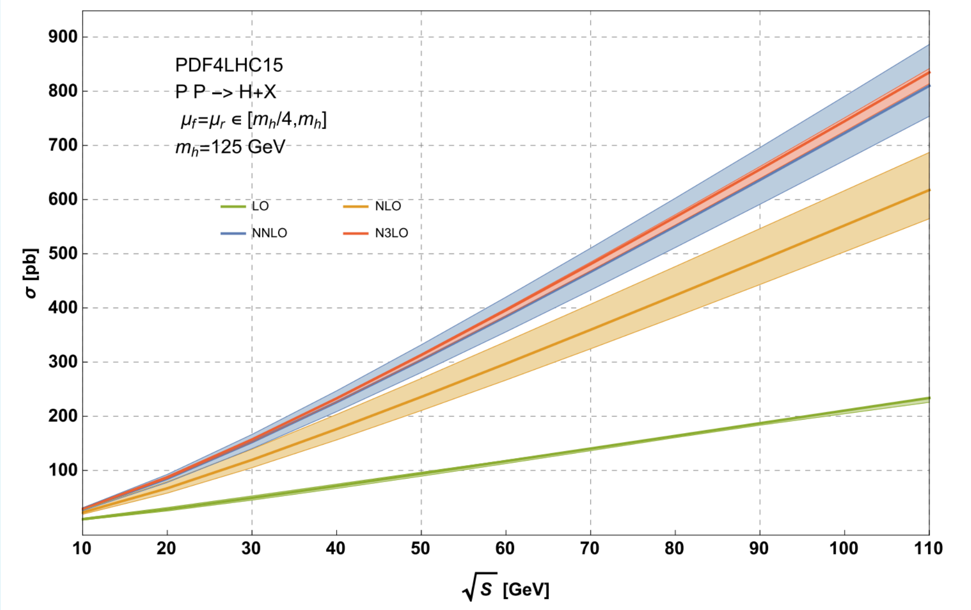
W	$-\frac{\mathrm{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2$
Y	$-\frac{\mathrm{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$



Farina et al 16



Precision QCD and perturbative matrix elements



Loops and more loops

Perturbative calculations in QCD organised as a **series expansion in the strong coupling**

$$\frac{\sigma(pp \to X)}{\sigma_0} = 1$$

Leading Order (Born level)
Easy, textbook calculations

Loops and more loops

Perturbative calculations in QCD organised as a **series expansion in the strong coupling**

Next-to-Leading Order (NLO)
More tricky, now ***mostly automated***

$$\frac{\sigma(pp \to X)}{\sigma_0} = 1 + \alpha_{\rm qcd}\,\sigma_1$$

Leading Order (Born level)
Easy, textbook calculations

Loops and more loops

ie **Higgs production with up to three extra particles** in the final state with **MG5_aMC**

Process		Syntax	Cross section (pb)			
Single Higgs production			LO 13 TeV		NLO 13 TeV	
g.1	$pp \to H$ (HEFT)	`p p > h`	$1.593 \pm 0.003 \cdot 10^{1}$	$^{+34.8\%}_{-26.0\%}$ $^{+1.2\%}_{-1.7\%}$	$3.261 \pm 0.010 \cdot 10^{1}$	$^{+20.2\%}_{-17.9\%}$ $^{+1.1\%}_{-1.6\%}$
g.2	$pp \to Hj$ (HEFT)	`p p > h j`	$8.367 \pm 0.003 \cdot 10^{0}$	$^{+39.4\%}_{-26.4\%}$ $^{+1.2\%}_{-1.4\%}$	$1.422 \pm 0.006 \cdot 10^{1}$	$^{+18.5\%}_{-16.6\%}$ $^{+1.1\%}_{-1.4\%}$
g.3	$pp \to Hjj$ (HEFT)	`p p > h j j`	$3.020 \pm 0.002 \cdot 10^{0}$	$^{+59.1\%}_{-34.7\%}$ $^{+1.4\%}_{-1.7\%}$	$5.124 \pm 0.020 \cdot 10^{0}$	$^{+20.7\%}_{-21.0\%}$ $^{+1.3\%}_{-1.5\%}$
g.4	$pp \to Hjj$ (VBF)	`p p > h j j $$ w+ w- z`	$1.987 \pm 0.002 \cdot 10^{0}$	$^{+1.7\%}_{-2.0\%}$ $^{+1.9\%}_{-1.4\%}$	$1.900 \pm 0.006 \cdot 10^{0}$	$^{+0.8\%}_{-0.9\%}$ $^{+2.0\%}_{-1.5\%}$
g.5	$pp \to Hjjj$ (VBF)	`p p > h j j j $$ w+ w- z`	$2.824 \pm 0.005 \cdot 10^{-1}$	$^{+15.7\%}_{-12.7\%}$ $^{+1.5\%}_{-1.0\%}$	$3.085 \pm 0.010 \cdot 10^{-1}$	$^{+2.0\%}_{-3.0\%}$ $^{+1.5\%}_{-1.1\%}$
g.6	$pp \to HW^{\pm}$	`p p > h wpm`	$1.195 \pm 0.002 \cdot 10^{0}$	$^{+3.5\%}_{-4.5\%}$ $^{+1.9\%}_{-1.5\%}$	$1.419 \pm 0.005 \cdot 10^{0}$	$^{+2.1\%}_{-2.6\%}$ $^{+1.9\%}_{-1.4\%}$
g.7	$pp \to HW^{\pm}j$	`p p > h wpm j`	$4.018 \pm 0.003 \cdot 10^{-1}$	$^{+10.7\%}_{-9.3\%}$ $^{+1.2\%}_{-0.9\%}$	$4.842 \pm 0.017 \cdot 10^{-1}$	$^{+3.6\%}_{-3.7\%}$ $^{+1.2\%}_{-1.0\%}$
g.8*	$pp \to HW^{\pm}jj$	`p p > h wpm j j`	$1.198 \pm 0.016 \cdot 10^{-1}$	$^{+26.1\%}_{-19.4\%}$ $^{+0.8\%}_{-0.6\%}$	$1.574 \pm 0.014 \cdot 10^{-1}$	$^{+5.0\%}_{-6.5\%}$ $^{+0.9\%}_{-0.6\%}$
g.9	$pp \to HZ$	`p p > h z`	$6.468 \pm 0.008 \cdot 10^{-1}$	$^{+3.5\%}_{-4.5\%}$ $^{+1.9\%}_{-1.4\%}$	$7.674 \pm 0.027 \cdot 10^{-1}$	$^{+2.0\%}_{-2.5\%}$ $^{+1.9\%}_{-1.4\%}$
g.10	$pp \to HZj$	`p p > h z j`	$2.225 \pm 0.001 \cdot 10^{-1}$	$^{+10.6\%}_{-9.2\%}$ $^{+1.1\%}_{-0.8\%}$	$2.667 \pm 0.010 \cdot 10^{-1}$	$^{+3.5\%}_{-3.6\%}$ $^{+1.1\%}_{-0.9\%}$
g.11*	$pp \to HZjj$	`p p > h z j j`	$7.262 \pm 0.012 \cdot 10^{-2}$	$^{+26.2\%}_{-19.4\%}$ $^{+0.7\%}_{-0.6\%}$	$8.753 \pm 0.037 \cdot 10^{-2}$	$^{+4.8\%}_{-6.3\%}$ $^{+0.7\%}_{-0.6\%}$
g.12*	$pp \to HW^{+}W^{-}$ (4f)	`p p > h w+ w-`	$8.325 \pm 0.139 \cdot 10^{-3}$	$^{+0.0\%}_{-0.3\%}$ $^{+2.0\%}_{-1.6\%}$	$1.065 \pm 0.003 \cdot 10^{-2}$	$^{+2.5\%}_{-1.9\%}$ $^{+2.0\%}_{-1.5\%}$
g.13*	$pp \to HW^{\pm}\gamma$	`p p > h wpm a`	$2.518 \pm 0.006 \cdot 10^{-3}$	$^{+0.7\%}_{-1.4\%}$ $^{+1.9\%}_{-1.5\%}$	$3.309 \pm 0.011 \cdot 10^{-3}$	$^{+2.7\%}_{-2.0\%}$ $^{+1.7\%}_{-1.4\%}$
g.14*	$pp \to HZW^{\pm}$	`p p > h z wpm`	$3.763 \pm 0.007 \cdot 10^{-3}$	$^{+1.1\%}_{-1.5\%}$ $^{+2.0\%}_{-1.6\%}$	$5.292 \pm 0.015 \cdot 10^{-3}$	$^{+3.9\%}_{-3.1\%}$ $^{+1.8\%}_{-1.4\%}$
g.15*	$pp \to HZZ$	`p p > h z z`	$2.093 \pm 0.003 \cdot 10^{-3}$	$^{+0.1\%}_{-0.6\%}$ $^{+1.9\%}_{-1.5\%}$	$2.538 \pm 0.007 \cdot 10^{-3}$	$^{+1.9\%}_{-1.4\%}$ $^{+2.0\%}_{-1.5\%}$
g.16	$pp \to Ht\bar{t}$	`p p > h t t~`	$3.579 \pm 0.003 \cdot 10^{-1}$	$^{+30.0\%}_{-21.5\%}$ $^{+1.7\%}_{-2.0\%}$	$4.608 \pm 0.016 \cdot 10^{-1}$	$^{+5.7\%}_{-9.0\%}$ $^{+2.0\%}_{-2.3\%}$
g.17	$pp \to Htj$	`p p > h tt j`	$4.994 \pm 0.005 \cdot 10^{-2}$	$^{+2.4\%}_{-4.2\%}$ $^{+1.2\%}_{-1.3\%}$	$6.328 \pm 0.022 \cdot 10^{-2}$	$^{+2.9\%}_{-1.8\%}$ $^{+1.5\%}_{-1.6\%}$
g.18	$pp \to Hb\bar{b}$ (4f)	`p p > h b b~`	$4.983 \pm 0.002 \cdot 10^{-1}$	$^{+28.1\%}_{-21.0\%}$ $^{+1.5\%}_{-1.8\%}$	$6.085 \pm 0.026 \cdot 10^{-1}$	$^{+7.3\%}_{-9.6\%}$ $^{+1.6\%}_{-2.0\%}$
g.19	$pp \to Ht\bar{t}j$	`p p > h t t~ j`	$2.674 \pm 0.041 \cdot 10^{-1}$	$^{+45.6\%}_{-29.2\%}$ $^{+2.6\%}_{-2.9\%}$	$3.244 \pm 0.025 \cdot 10^{-1}$	$^{+3.5\%}_{-8.7\%}$ $^{+2.5\%}_{-2.9\%}$
g.20*	$pp \to Hb\bar{b}j$ (4f)	`p p > h b b~ j`	$7.367 \pm 0.002 \cdot 10^{-2}$	$^{+45.6\%}_{-29.1\%}$ $^{+1.8\%}_{-2.1\%}$	$9.034 \pm 0.032 \cdot 10^{-2}$	$^{+7.9\%}_{-11.0\%}$ $^{+1.8\%}_{-2.2\%}$

Loops and more loops

Perturbative calculations in QCD organised as a **series expansion in the strong coupling**

Next-to-Leading Order (NLO)
More tricky, now ***mostly automated***

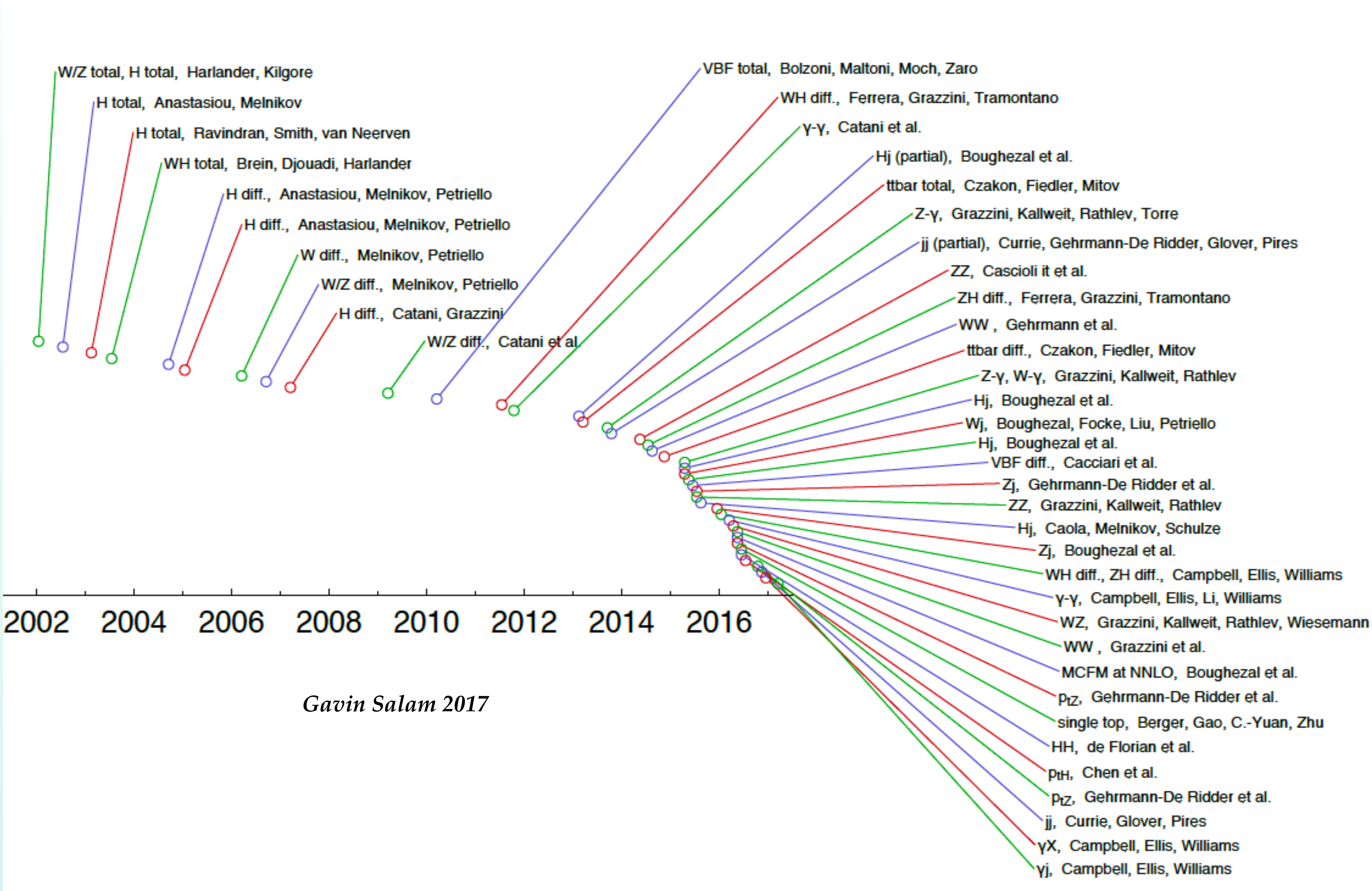
$$\frac{\sigma(pp \to X)}{\sigma_0} = 1 + \alpha_{\rm qcd}\,\sigma_1 + \alpha_{\rm qcd}^2\,\sigma_2$$

Leading Order (Born level)
Easy, textbook calculations

NNLO: Very difficult, but now ***becoming standard***

Pushing the QCD precision frontier

Explosion of (N)NNLO QCD calculations in last years: **NNLO is now the standard at the LHC**



Gavin Salam 2017

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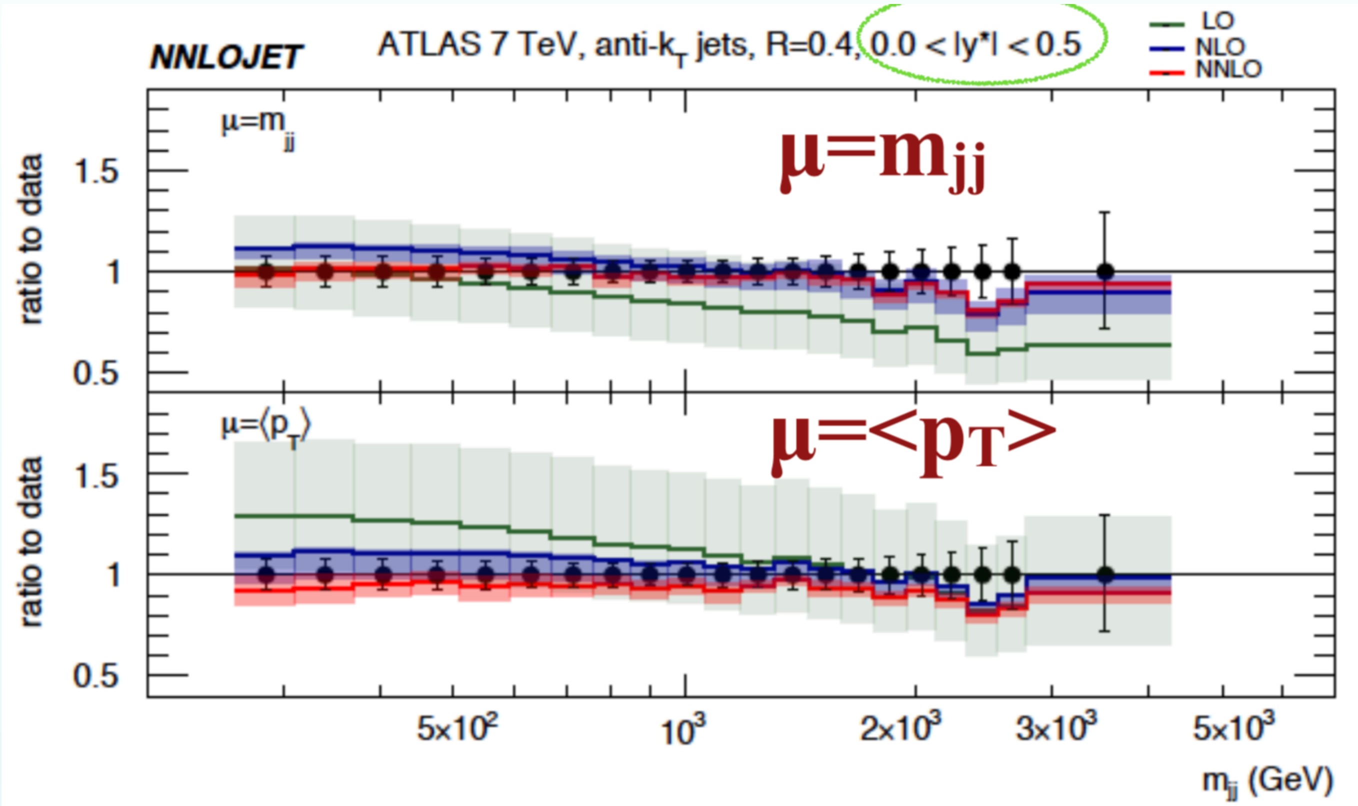

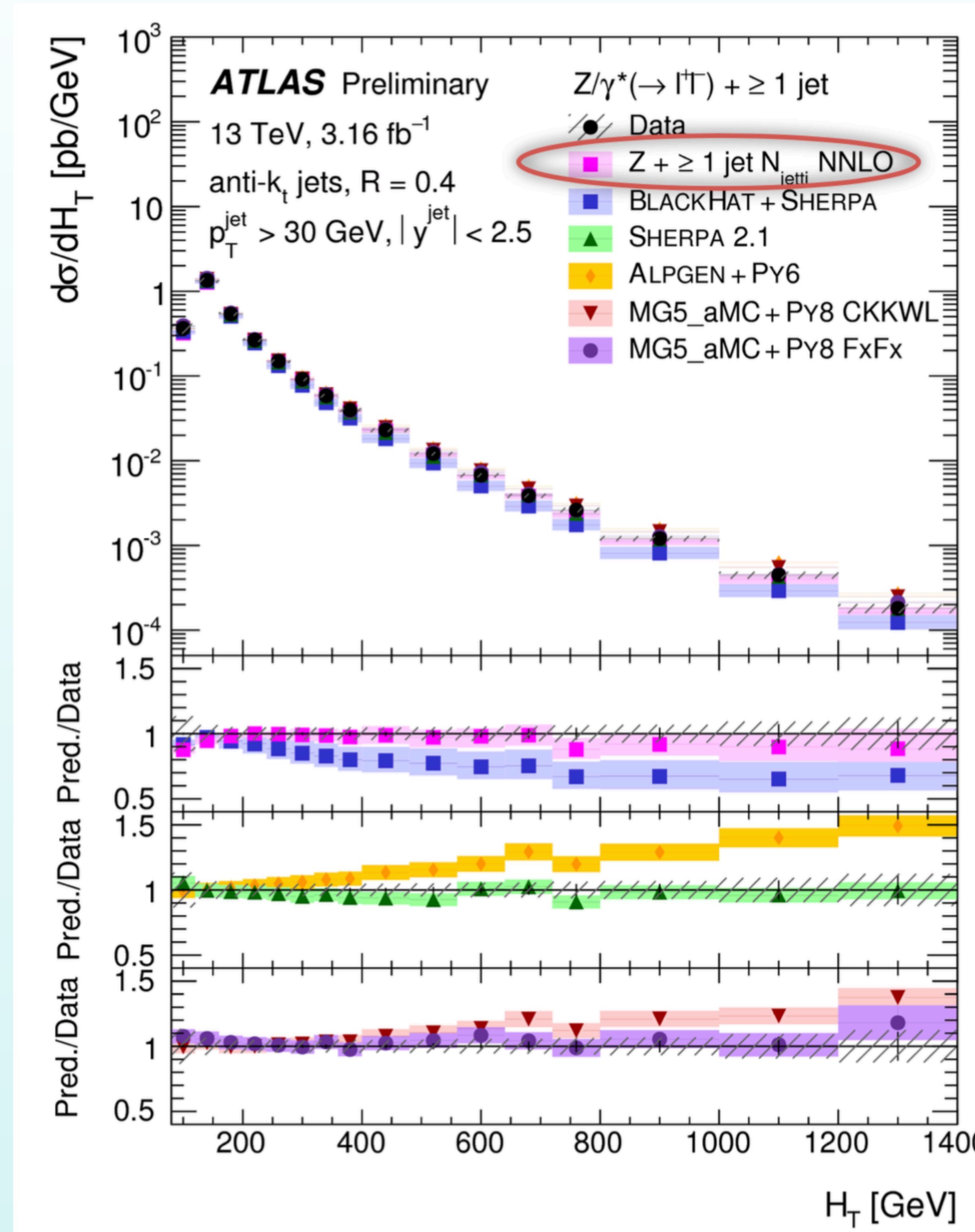

- **Improved agreement** with experimental data
- Reduced theoretical uncertainties (MHOUs)
- Allows **extraction of SM inputs** (PDFs, α_S) and **more stringent BSM constraints**

Loops and more loops

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Next-to-Leading Order (NLO)
More tricky, now ***mostly automated***

N3LO: stop dreaming,
forget about this! (***or not?***)

$$\frac{\sigma(pp \to X)}{\sigma_0} = 1 + \alpha_{\rm qcd}\,\sigma_1 + \alpha_{\rm qcd}^2\,\sigma_2 + \alpha_{\rm qcd}^3\,\sigma_3 + \ldots$$

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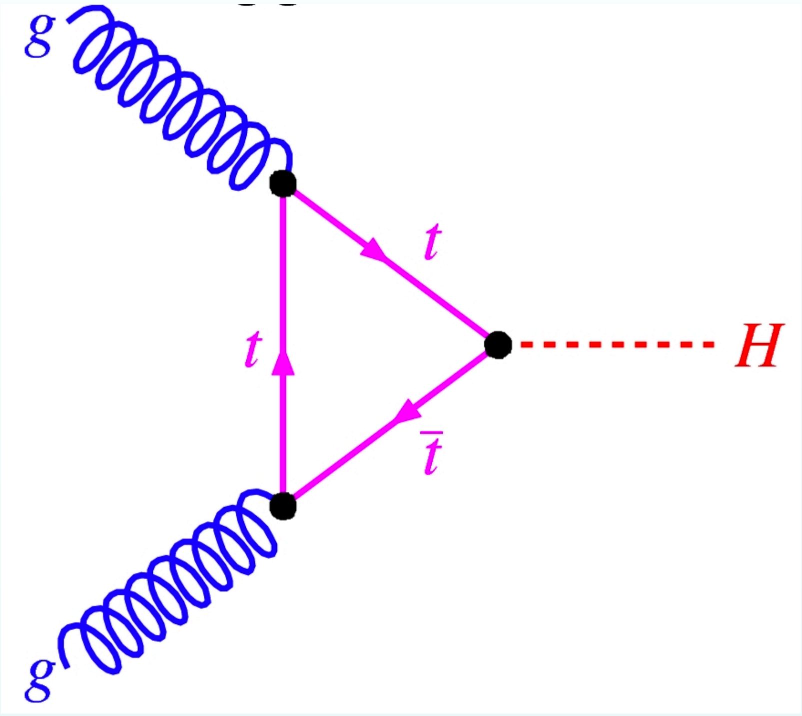
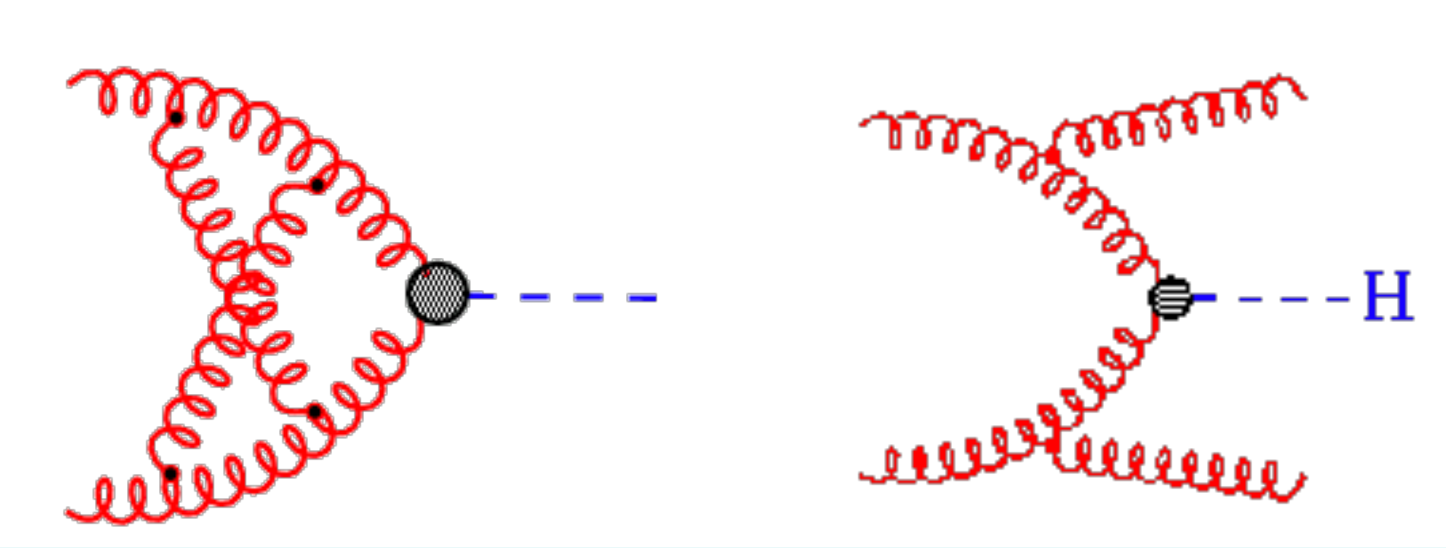
Loops and more loops

Case example: **Higgs production in gluon fusion**, dominant channel at the LHC



Until 2015, cross-section was known up to **two loops** (NNLO)

Calculation required **O(1000) interference diagrams** and **O(47000) loop and phase space integrals**



Loops and more loops

How difficult could it be to compute one more perturbative order, *i.e.*, N3LO?

NNLO: **O(1000) interference diagrams** and **O(47000) loop and phase space integrals**

N3LO: **O(10^5) interference diagrams** and **O(10^8) loop and phase space integrals**

Hopeless??

Loops and more loops

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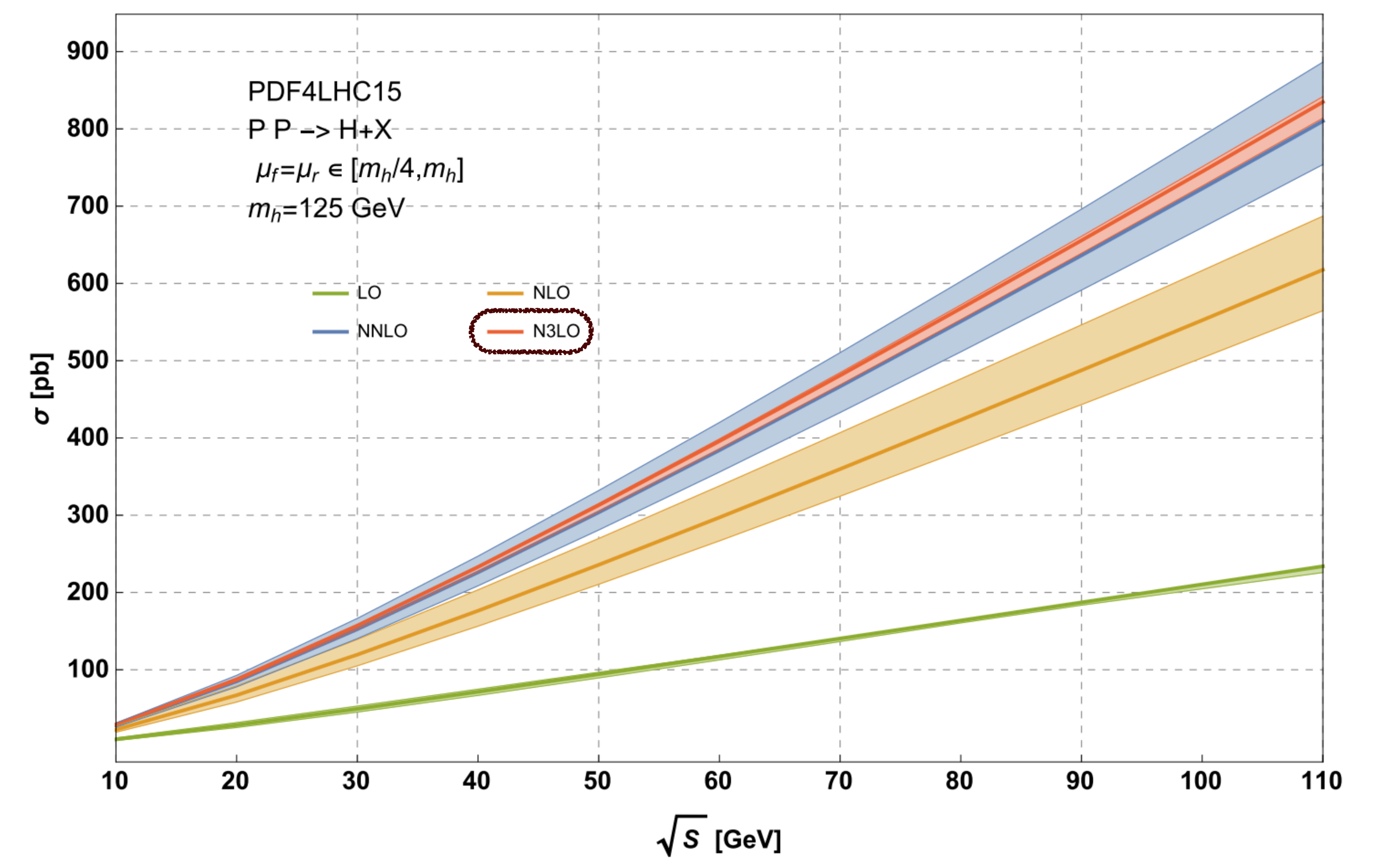
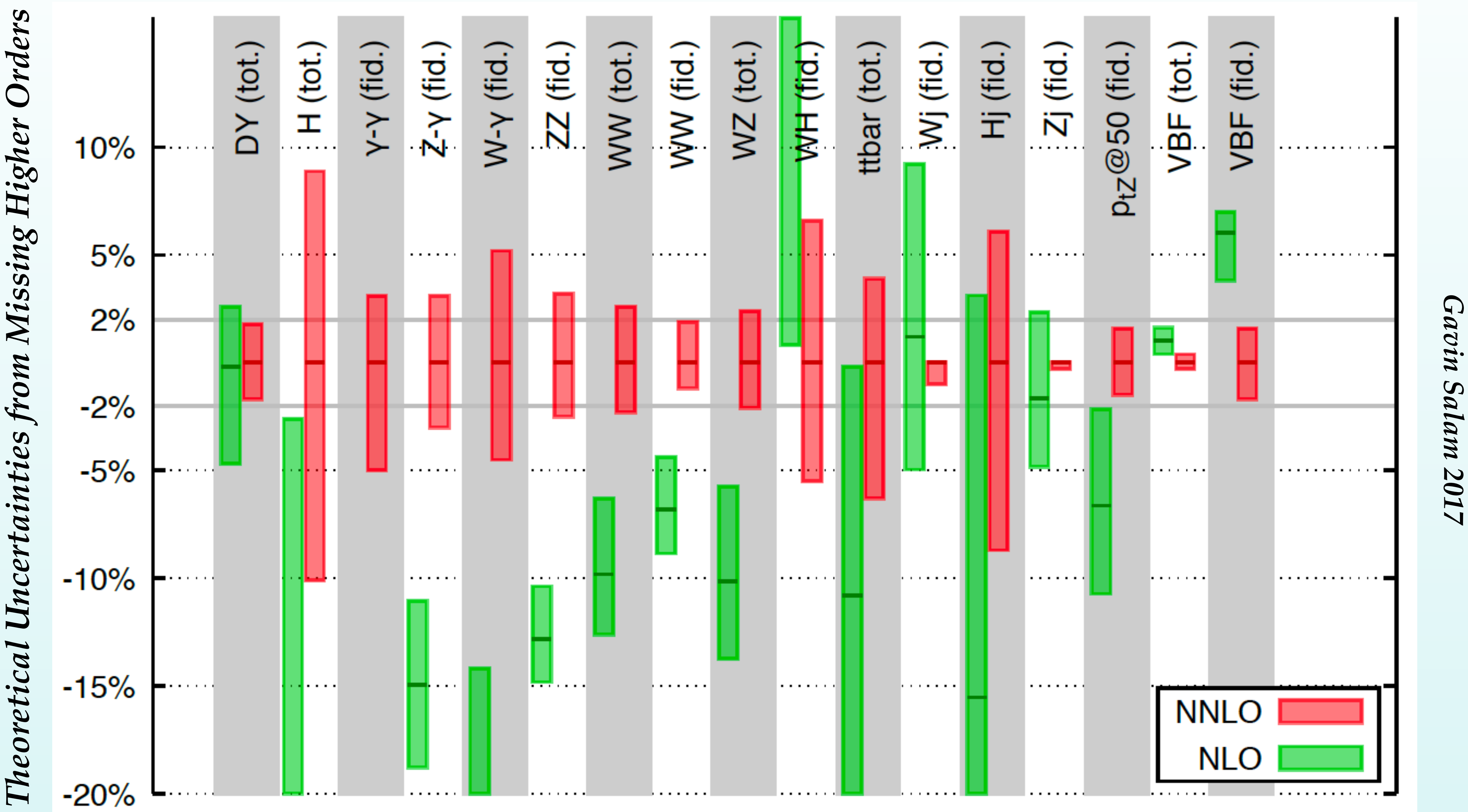


Anastasiou et al. 15-16

Theory error reduced to few-percent: **boosting discovery potential of Higgs coupling measurements!**

Pushing the QCD precision frontier

Higher order QCD calculations allow a much superior **exploitation of the LHC physics output**



LHC phenomenology at 1% precision is within reach!

We have come a long way ....

Example: gg → gggg

background to the detection of W^+W^- pairs in their nonleptonic decays. The cross sections for the elementary two→four processes have not been calculated, and their complexity is such that they may not be evaluated in the foreseeable future. It is worthwhile to seek estimates of the four-jet cross sections, even if these are only reliable in restricted regions of phase space.

Supercollider physics

(1984)

E. Eichten

Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510

I. Hinchliffe

Lawrence Berkeley Laboratory, Berkeley, California 94720

K. Lane

The Ohio State University, Columbus, Ohio 43210

C. Quigg

Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510

Eichten *et al.* summarize the motivation for exploring the 1-TeV ($=10^{12}$ eV) energy scale in elementary particle interactions and explore the capabilities of proton-(anti)proton colliders with beam energies between 1 and 50 TeV. The authors calculate the production rates and characteristics for a number of conventional processes, and discuss their intrinsic physics interest as well as their role as backgrounds to more exotic phenomena. The authors review the theoretical motivation and expected signatures for several new phenomena which may occur on the 1-TeV scale. Their results provide a reference point for the choice of machine parameters and for experiment design.

IV. ELECTROWEAK PHENOMENA

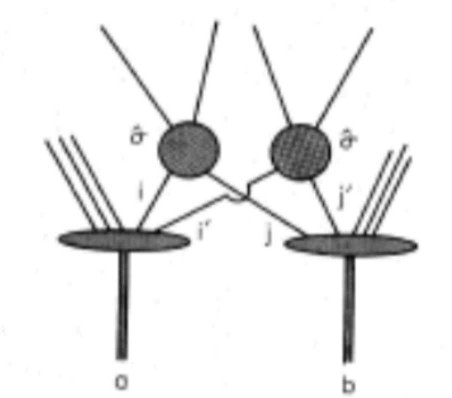
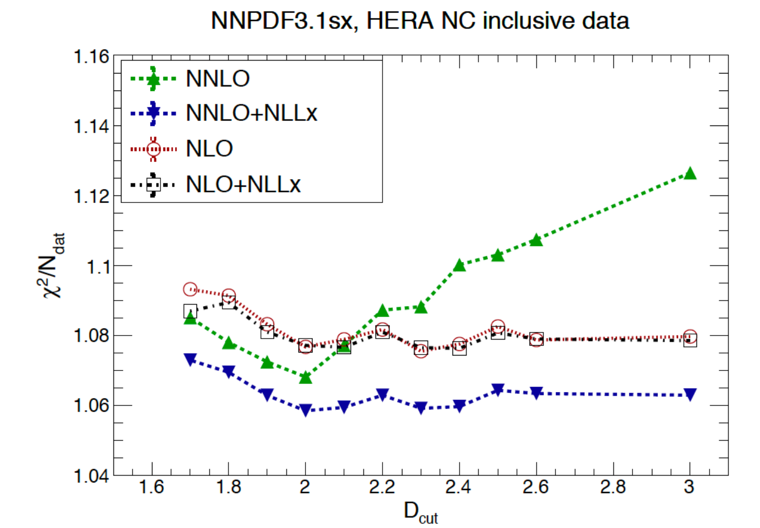
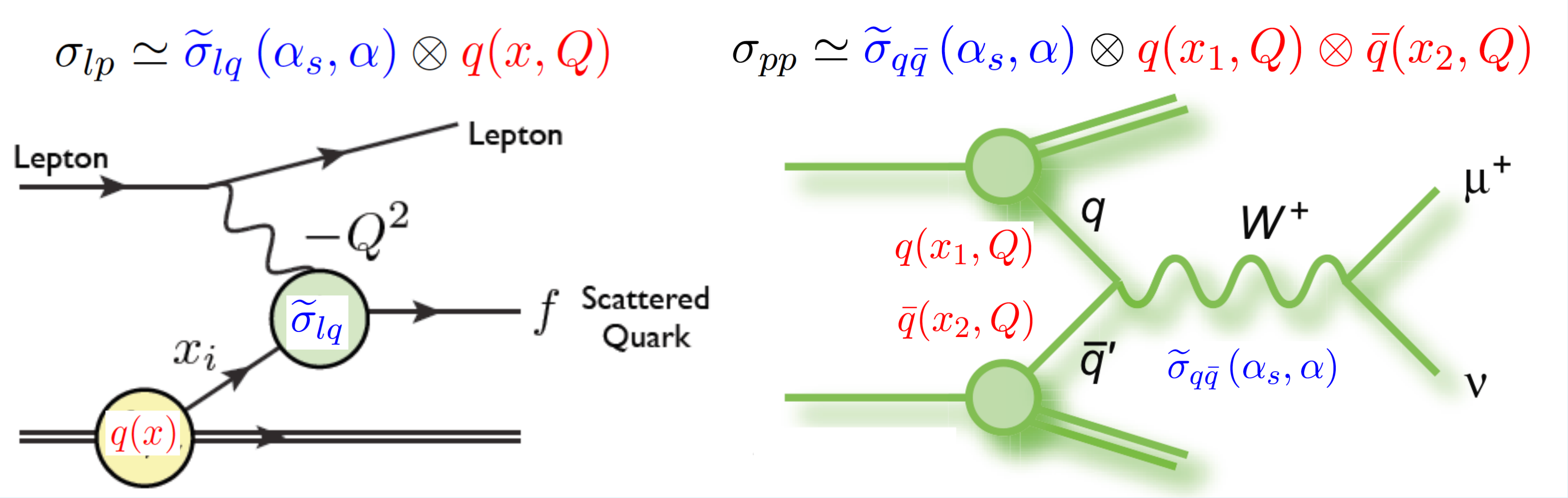


FIG. 103. Four-jet topology arising from two independent parton interactions.

Zanderighi ICFA workshop 2017

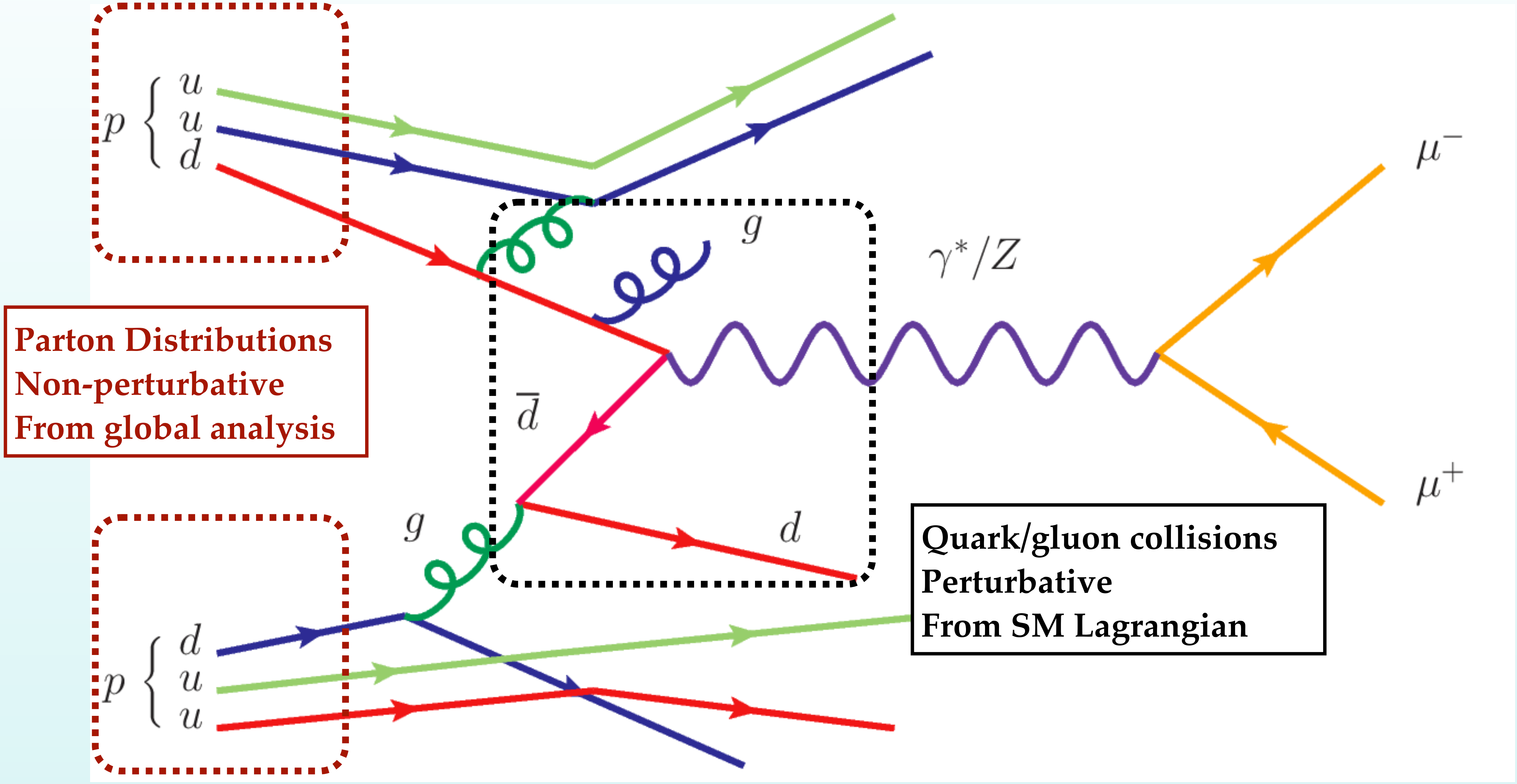


Precision QCD and the proton structure



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

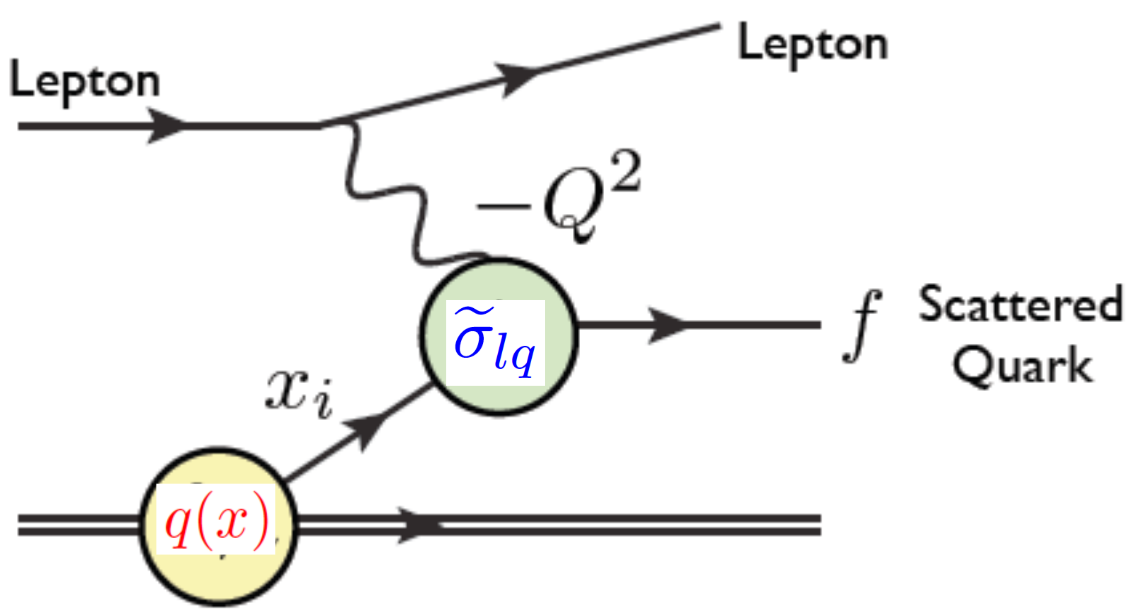
g(x,Q)*: Probability** of **finding a gluon inside a proton**, carrying a fraction ***x of the proton momentum when probed at energy ***Q***

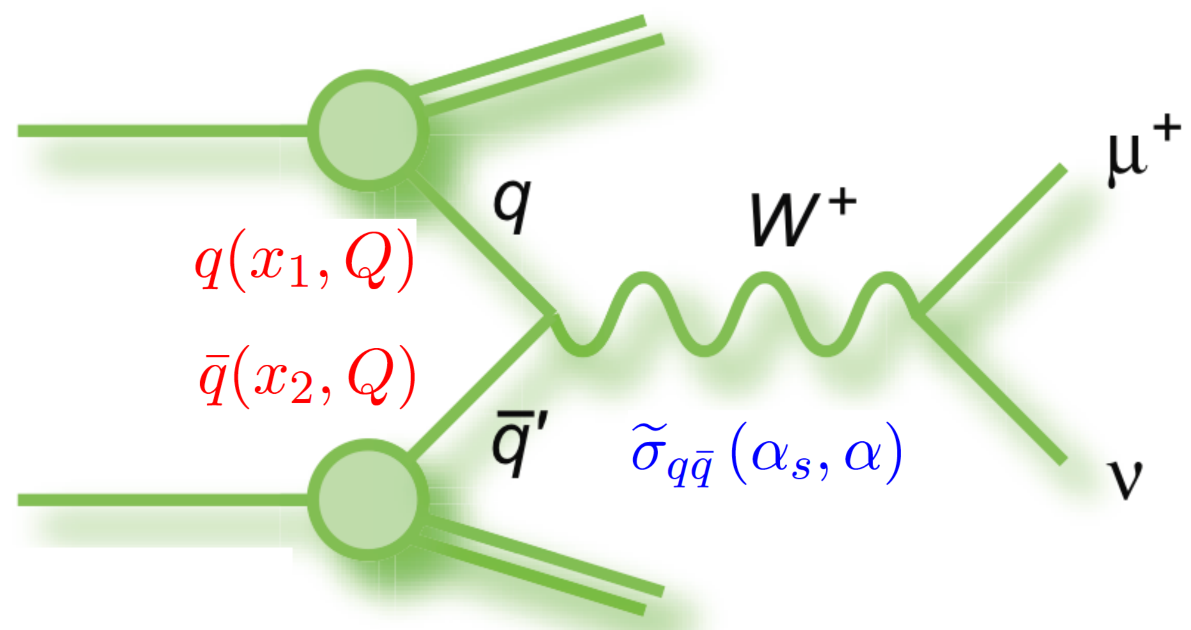
***x*: Fraction of the proton's momentum**

PDFs *determined by* ***non-perturbative QCD dynamics***
Extract from experimental data within a ***global analysis***

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

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





Extract PDFs from lepton-proton collisions

Use PDFs to predict proton-proton cross-sections

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 with energy ***Q***

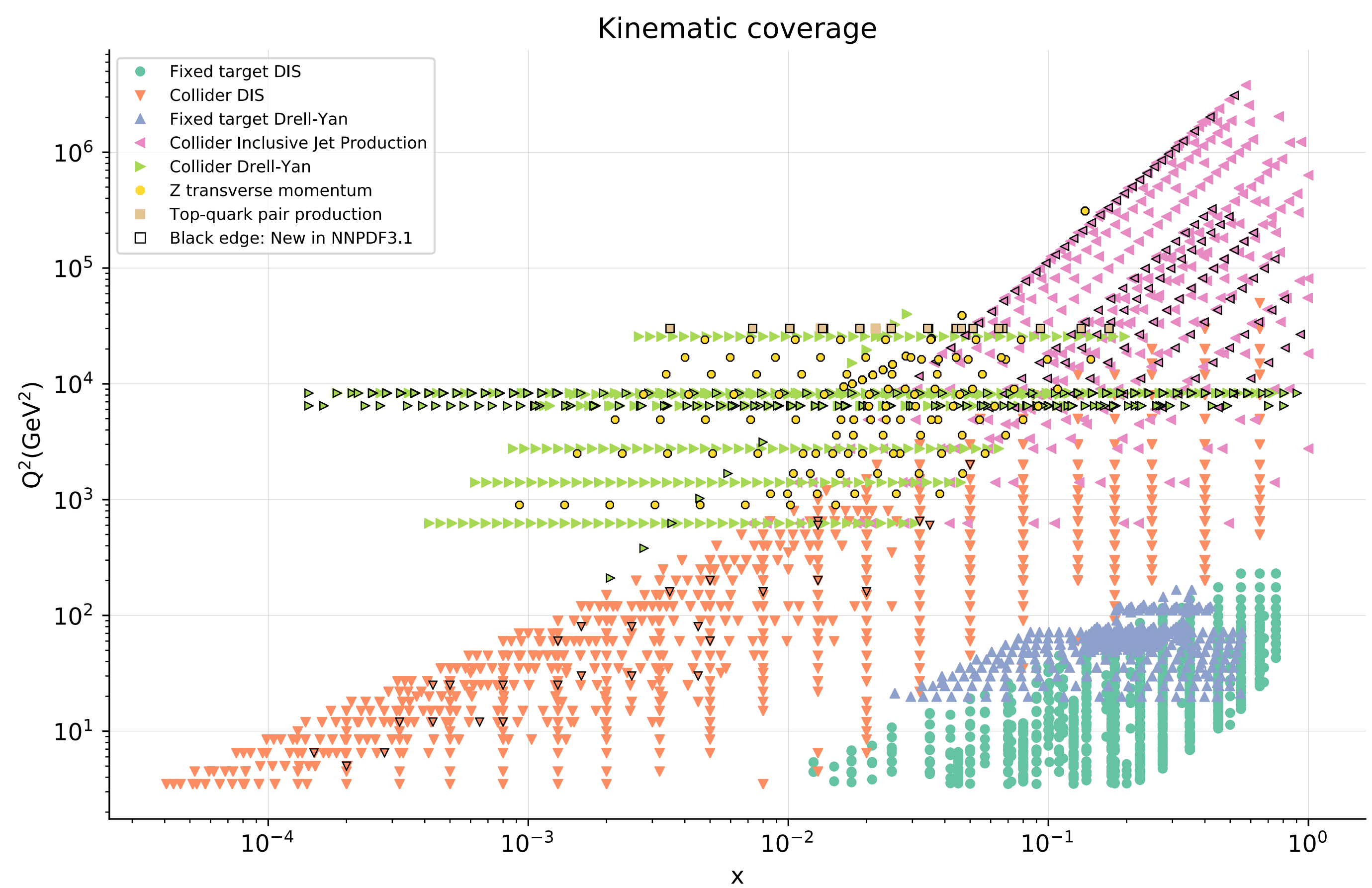
x: **Fraction of the proton's momentum**

PDFs** determined by **non-perturbative QCD dynamics
*Extract from experimental data within a **global analysis***

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

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

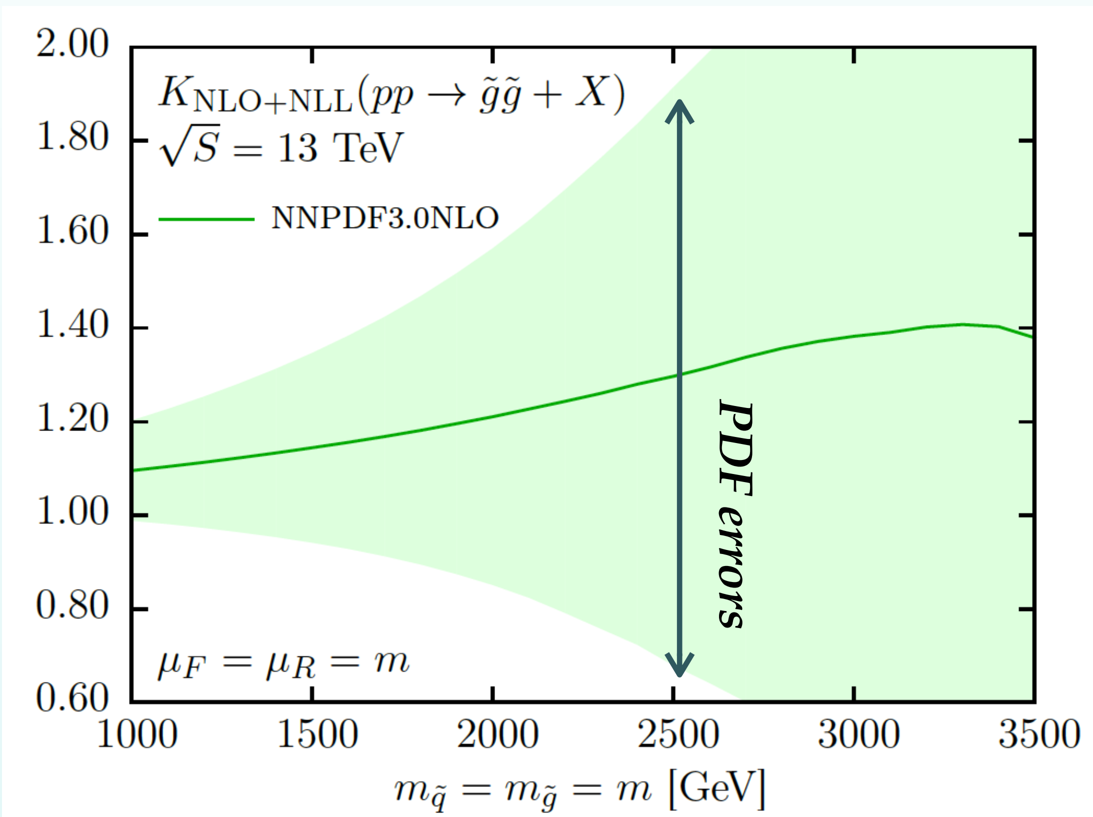
yet still $\chi^2/N_{\mathrm{dat}} \approx \mathbf{1}$!



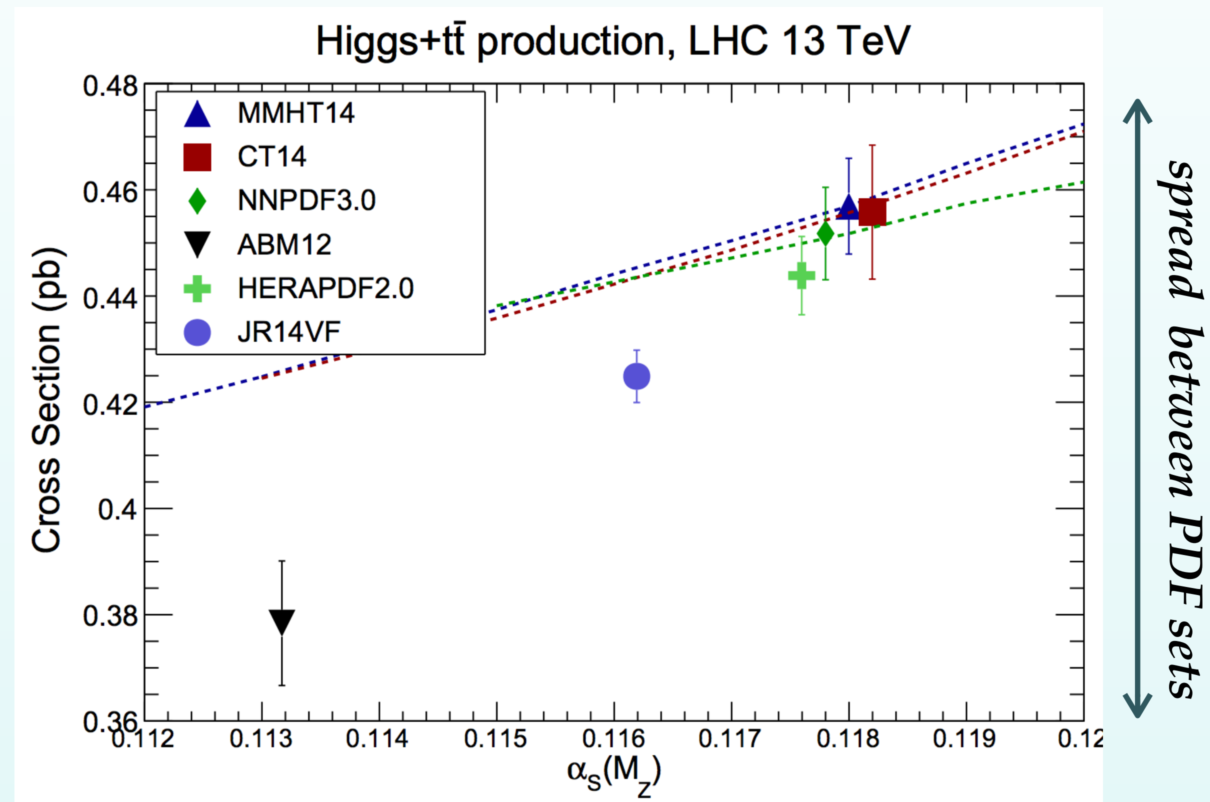
Why precision PDFs?

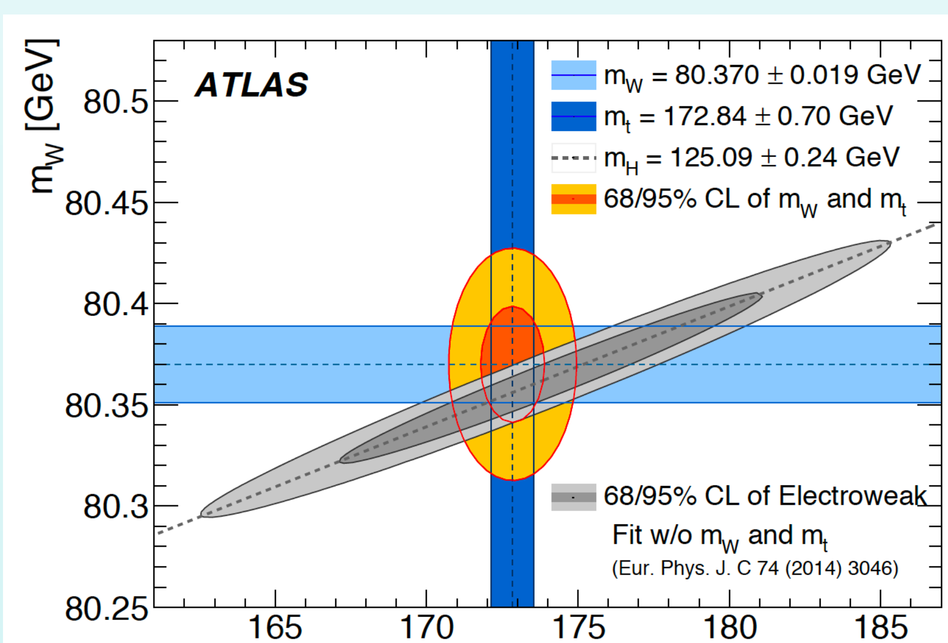
Ultimate accuracy of LHC calculations limited by **knowledge of proton structure**

heavy SUSY particle production



Higgs couplings





W mass determination

Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5

[HL-LHC forecast]

The Structure of the Proton in the LHC Precision Era

Jun Gao[a], Lucian Harland-Lang[b], Juan Rojo[c,d]

[a]*Institute of Nuclear and Particle Physics,*
Shanghai Key Laboratory for Particle Physics and Cosmology,
School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai, China
[b]*Department of Physics and Astronomy, University College London, WC1E 6BT, United Kingdom*
[c]*Department of Physics and Astronomy, VU University, De Boelelaan 1081, 1081HV Amsterdam, The Netherlands*
[d]*Nikhef, Science Park 105, NL-1098 XG Amsterdam, The Netherlands*

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

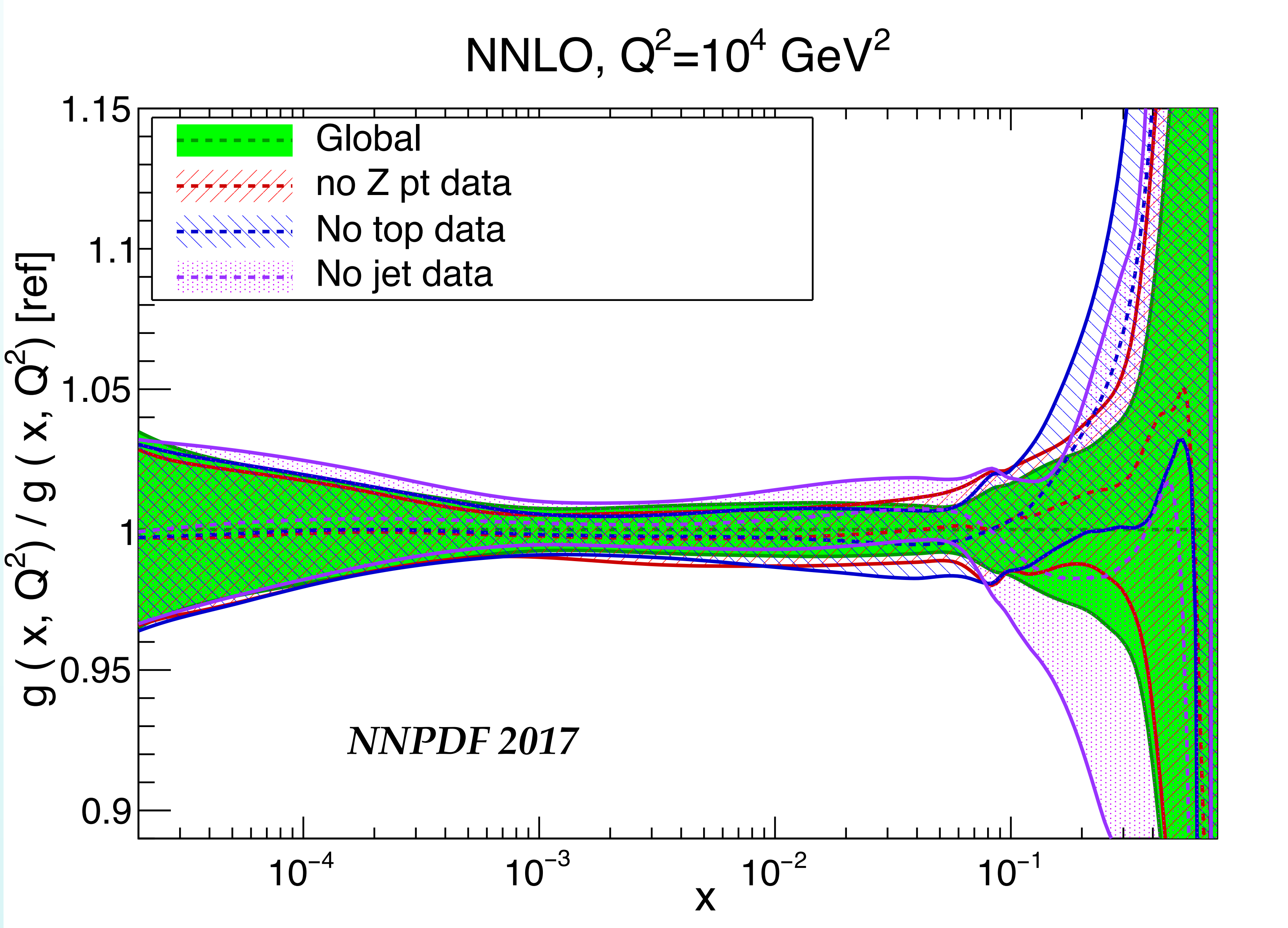
166 pages, 82 figures, > 500 references, to appear in Physics Reports

Only time for a brief snapshot here!

Progress in PDF determination

Many exciting **recent developments in global PDF analysis**: constraints from LHC measurements, statistical validation of PDF uncertainties, the strange and charm content of the proton ….

Precision NNLO gluon at large-x
from combining top, jet and Z p_T LHC data



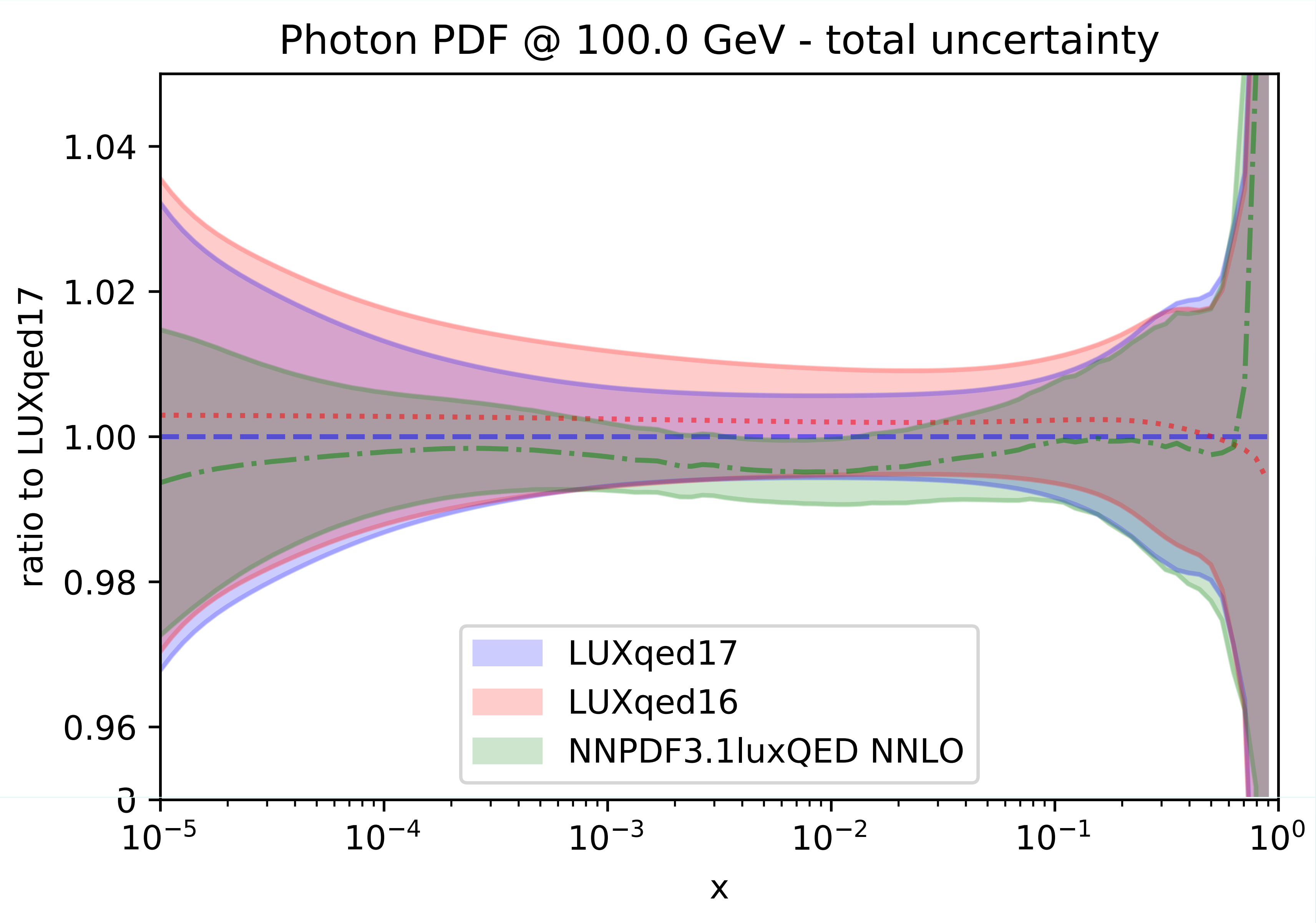
Progress in PDF determinations allows fully exploiting higher-order QCD calculations

Progress in PDF determination

Many exciting **recent developments in global PDF analysis**: constraints from LHC measurements, statistical validation of PDF uncertainties, the strange and charm content of the proton ….

Photon PDF with few % errors

Crucial to complement electroweak calculations

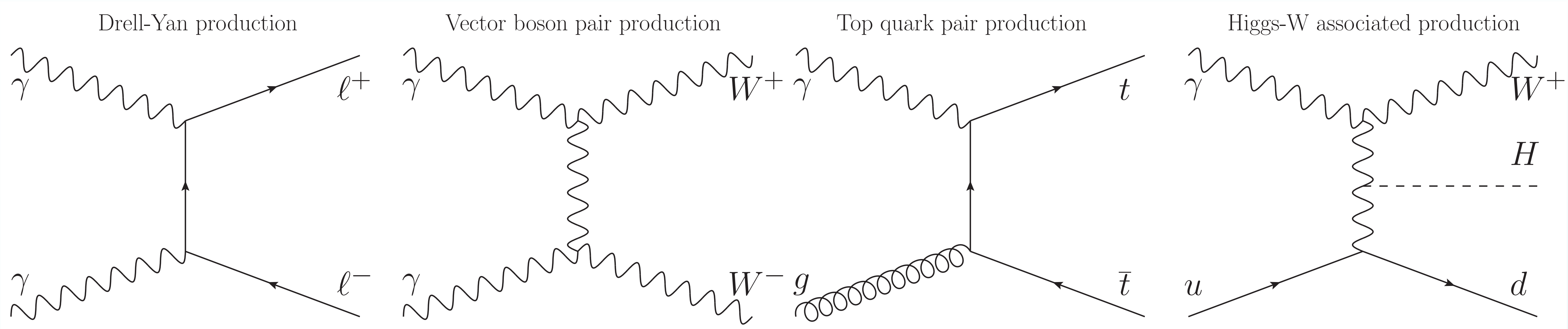


Manohar, Nason, Salam, Zanderighi 16-17

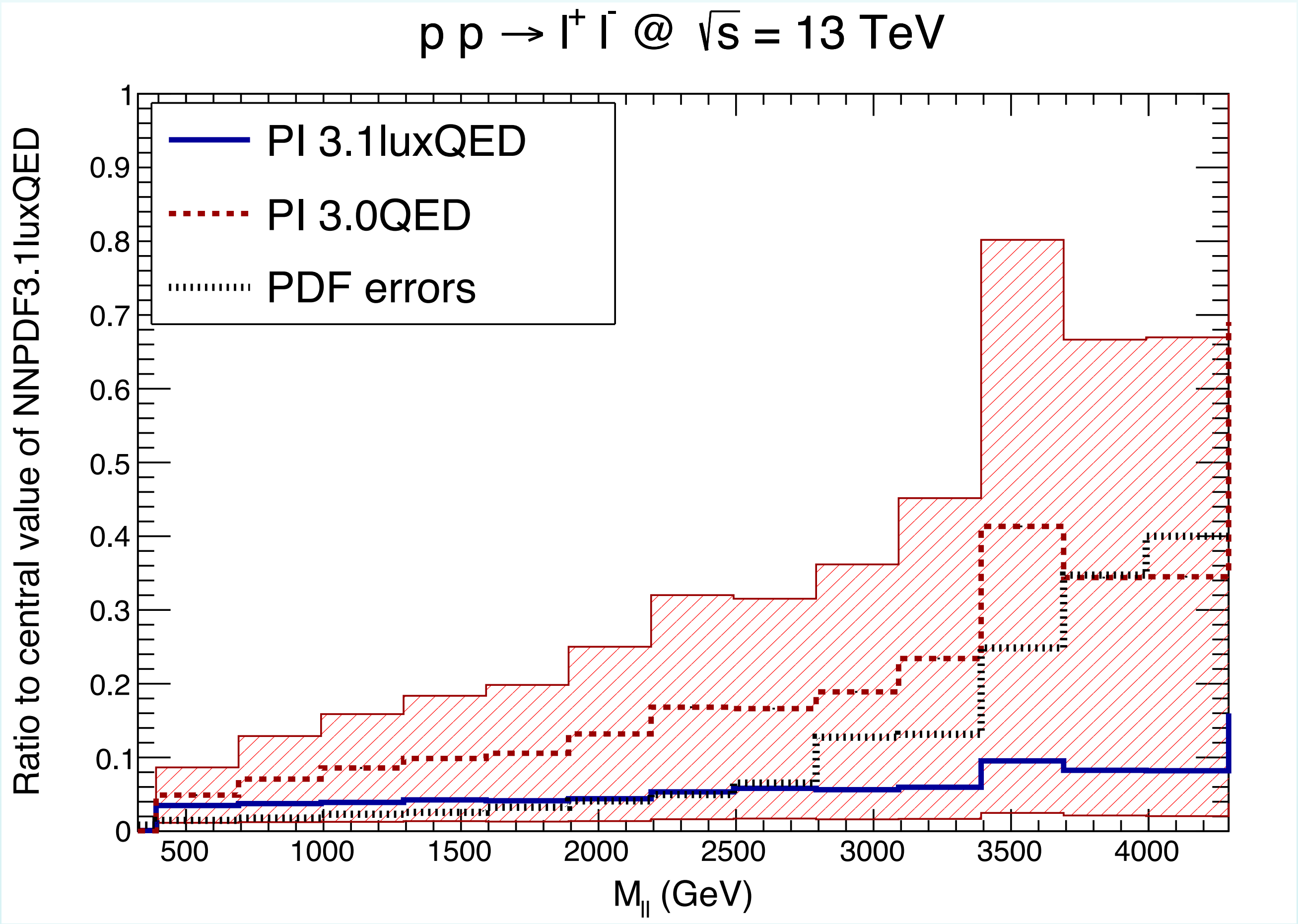
Bertone, Carrazza, Hartland, JR 17

Progress in PDF determinations allows fully exploiting higher-order QCD calculations

Photon-initiated processes at the LHC

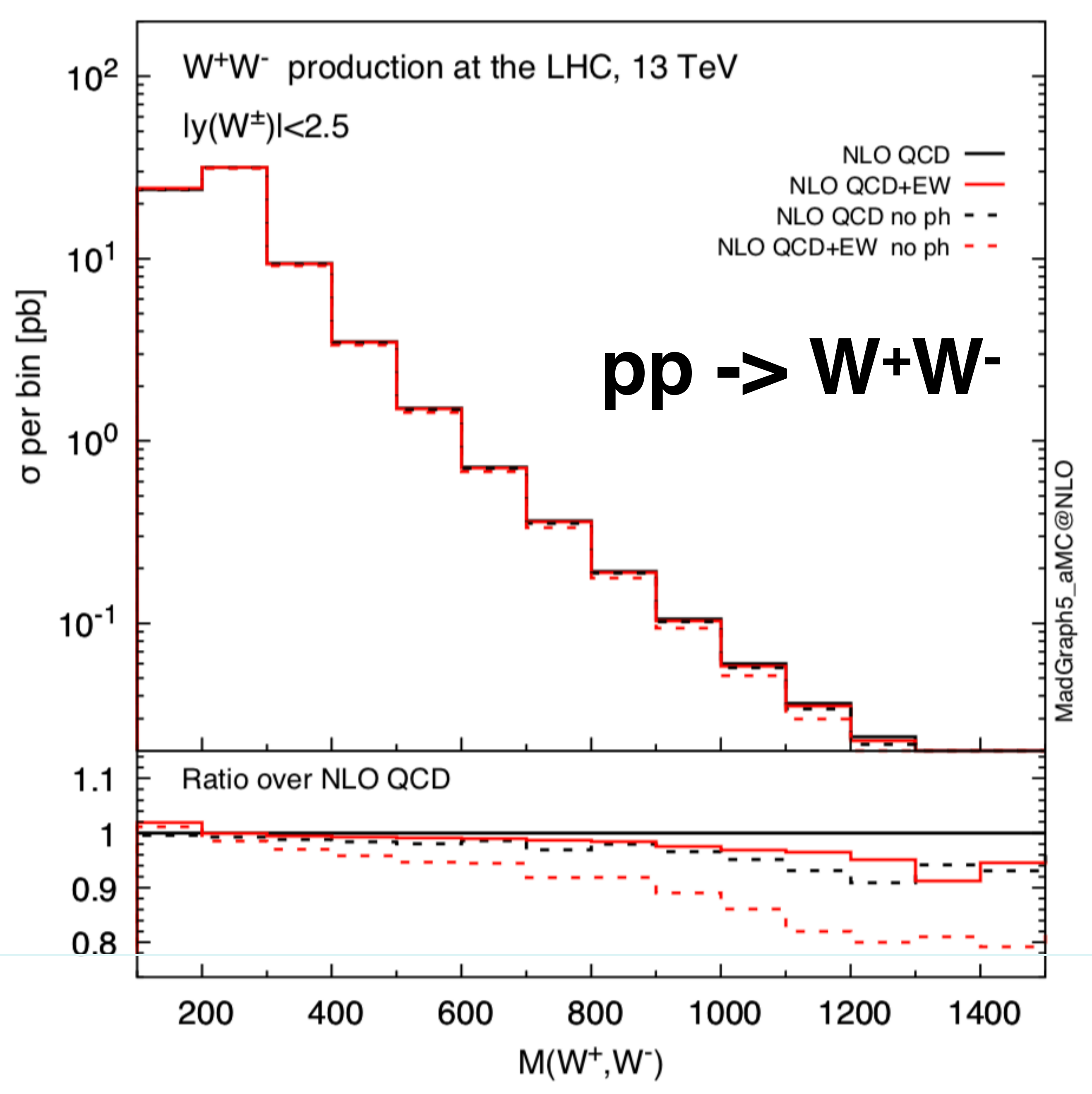


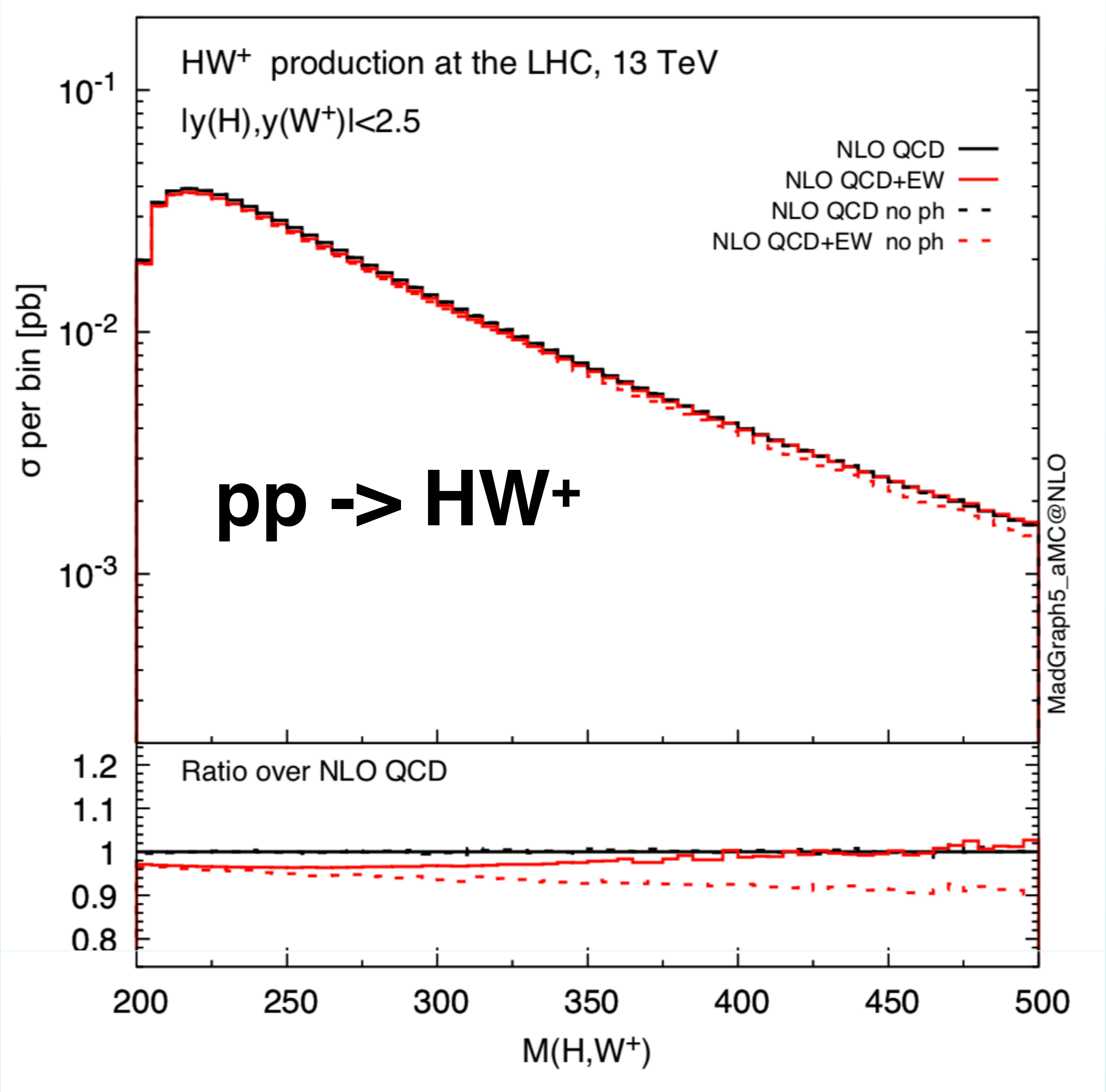
- NNPDF3.1luxQED results are **consistent** with NNPDF3.0QED, with **much reduced uncertainties**
- PI effects can be up to **10% (Drell-Yan) and 30% (WW) at the LHC**, with opposite sign wrt **EW corrections**



Photon-initiated processes at the LHC

- At high mass **PI contributions and NLO EW corrections have opposite sign**, and thus in general one expects a partial cancellation among them
- This seems to be the case for many processes: **once PI effects included, NLO EW corrections rather small**





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

Parton distributions with BFKL resummation

- **Perturbative fixed-order QCD calculations** have been extremely successful in describing a wealth of data from proton-proton and electron-proton collisions

- There are theoretical reasons that eventually we need to go beyond DGLAP: at small-x, **logarithmically enhanced terms in *1/x* become dominant** and need to be resummed to all orders

- ***BFKL/high-energy/small-x resummation*** can be matched to the **DGLAP collinear framework**, and thus be included into a standard PDF analysis

DGLAP Evolution in Q²

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

BFKL Evolution in x

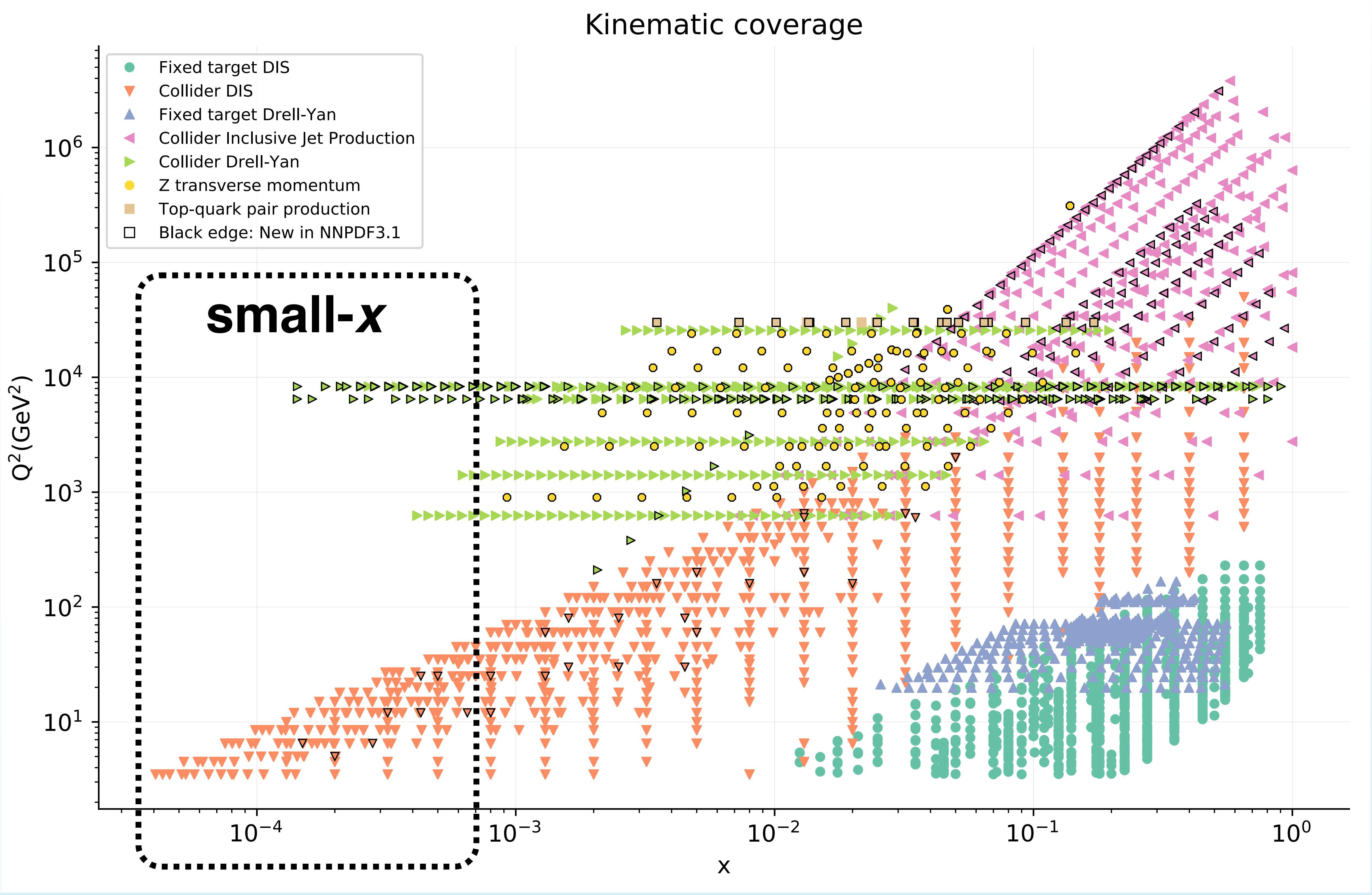
$$-x\,\frac{d}{dx}\, f_+(x,\mu^2) = \int_0^\infty \frac{d\nu^2}{\nu^2}\, K\left(\frac{\mu^2}{\nu^2}, \alpha_s\right) f_+(x,\nu^2)$$

Within small-*x* resummation, the **N^{k}LO fixed-order DGLAP splitting functions** are complemented with the **N^{h}LL*x* contributions from BKFL**

ABF, CCSS, TW + others, 94-08

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

A new world at small-x



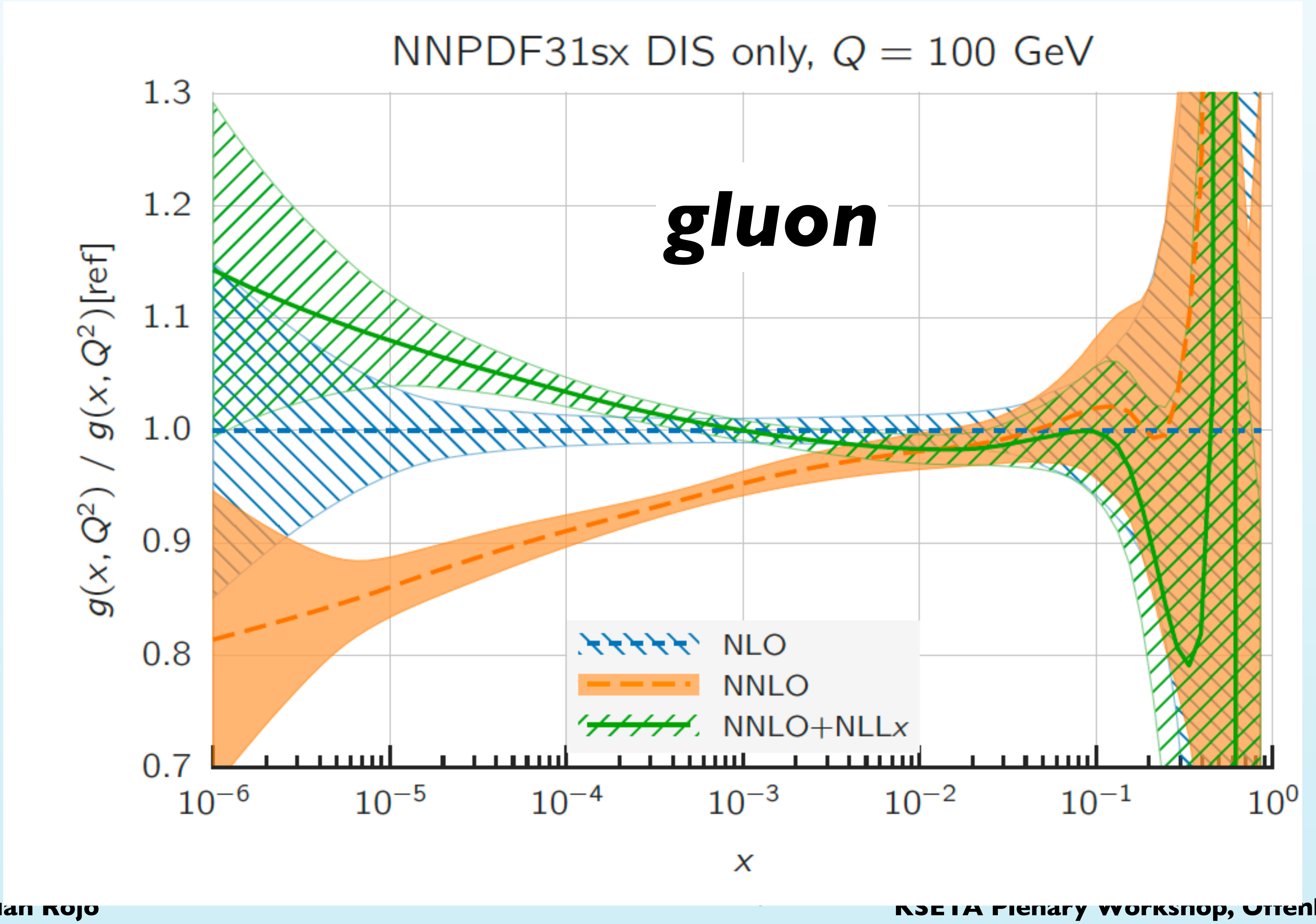
A new world at small-x

- Ultimately, the need for (or lack of) BKFL resummation in ***ep* and *pp* collider data** can only be assessed by performing a **global PDF analysis based on (N)NLO+NLLx theory**

- Theoretical tools are now available: **HELL for NLLx resummation**, interfaced to **APFEL**

APFEL: Bertone, Carrazza, JR 13 *HELL: Bonvini, Marzani, Peraro, Muselli 16-17*

- NNPDF3.1 (N)NLO+NLL fits **stabilise the perturbative PDF expansion at small-*x***, in particular for the gluon, and markedly improve the **fit quality to the small-*x* HERA data**

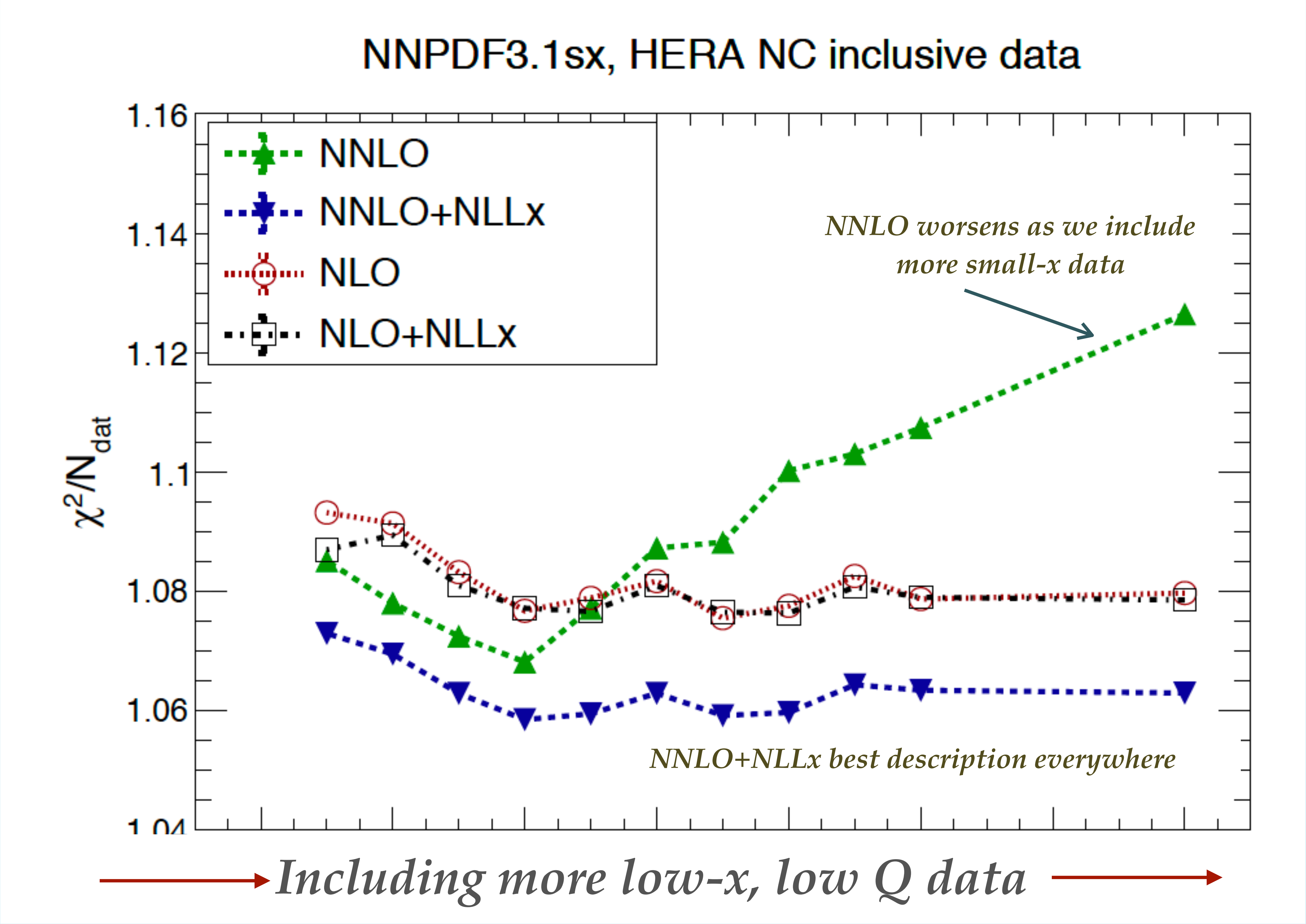


Ball, Bertone, Bonvini, Marzani, JR,Rottoli 16

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,Q^2) region**



Nunca es tarde si la dicha es buena

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-

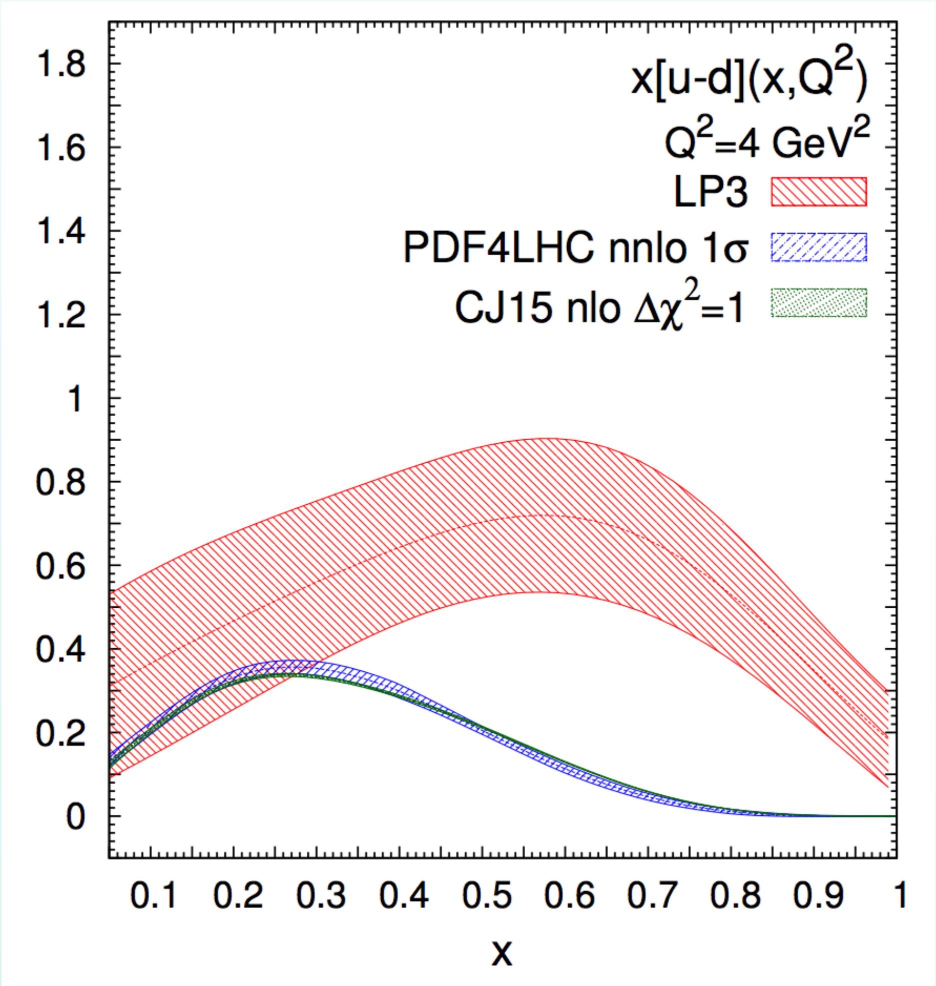
Jon Butterworth, the Guardian, 28/12/2018

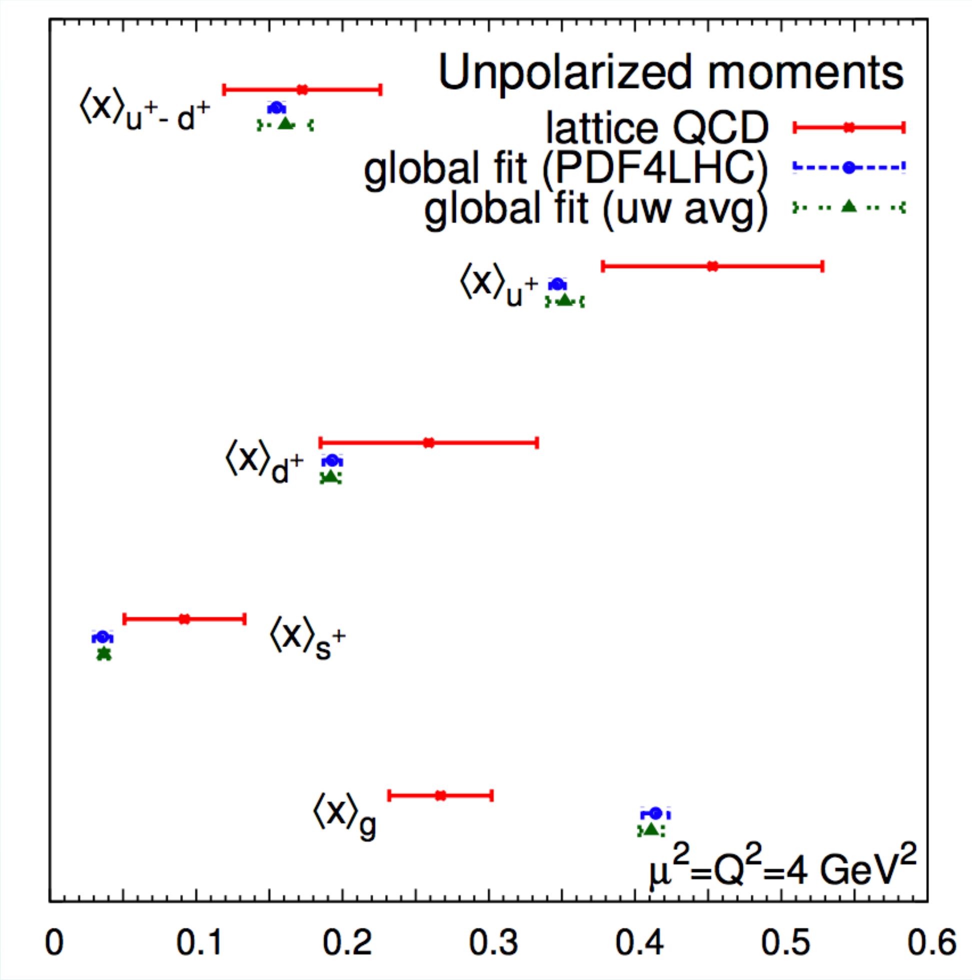
Parton distributions and lattice QCD calculations: a community white paper

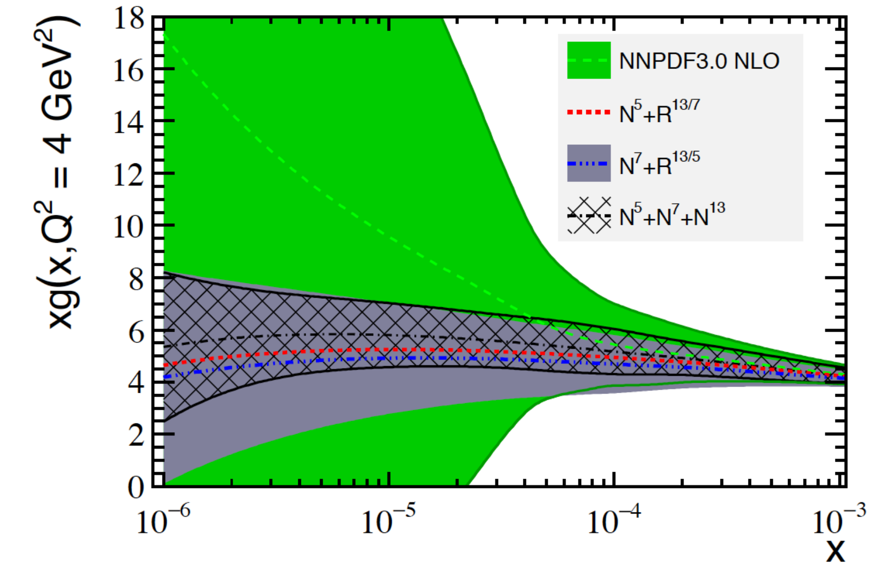
arXiv:1711.07916

Huey-Wen Lin[1,2], Emanuele R. Nocera[3,4], Fred Olness[5], Kostas Orginos[6,7], Juan Rojo[8,9] (editors),

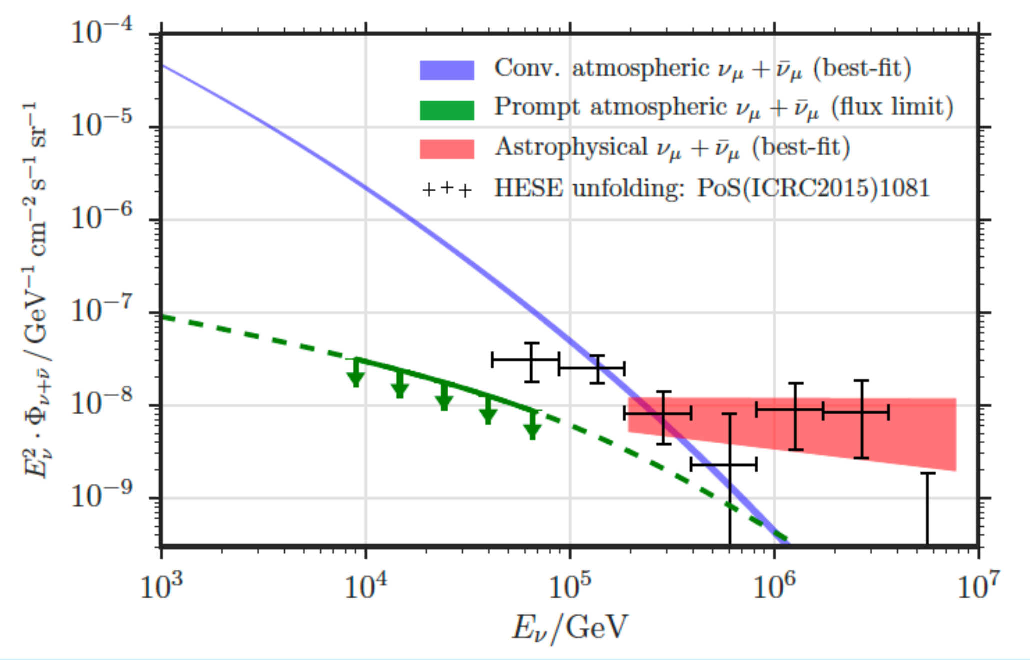
- A complementary approach to understand the proton structure is provided by **lattice QCD**
- Recent progress both in improved calculations of **PDF Mellin moments** and **direct x-space calculations**
- Future calculations could be added to the global fit as **additional theory constraints**







Precision QCD beyond particle colliders



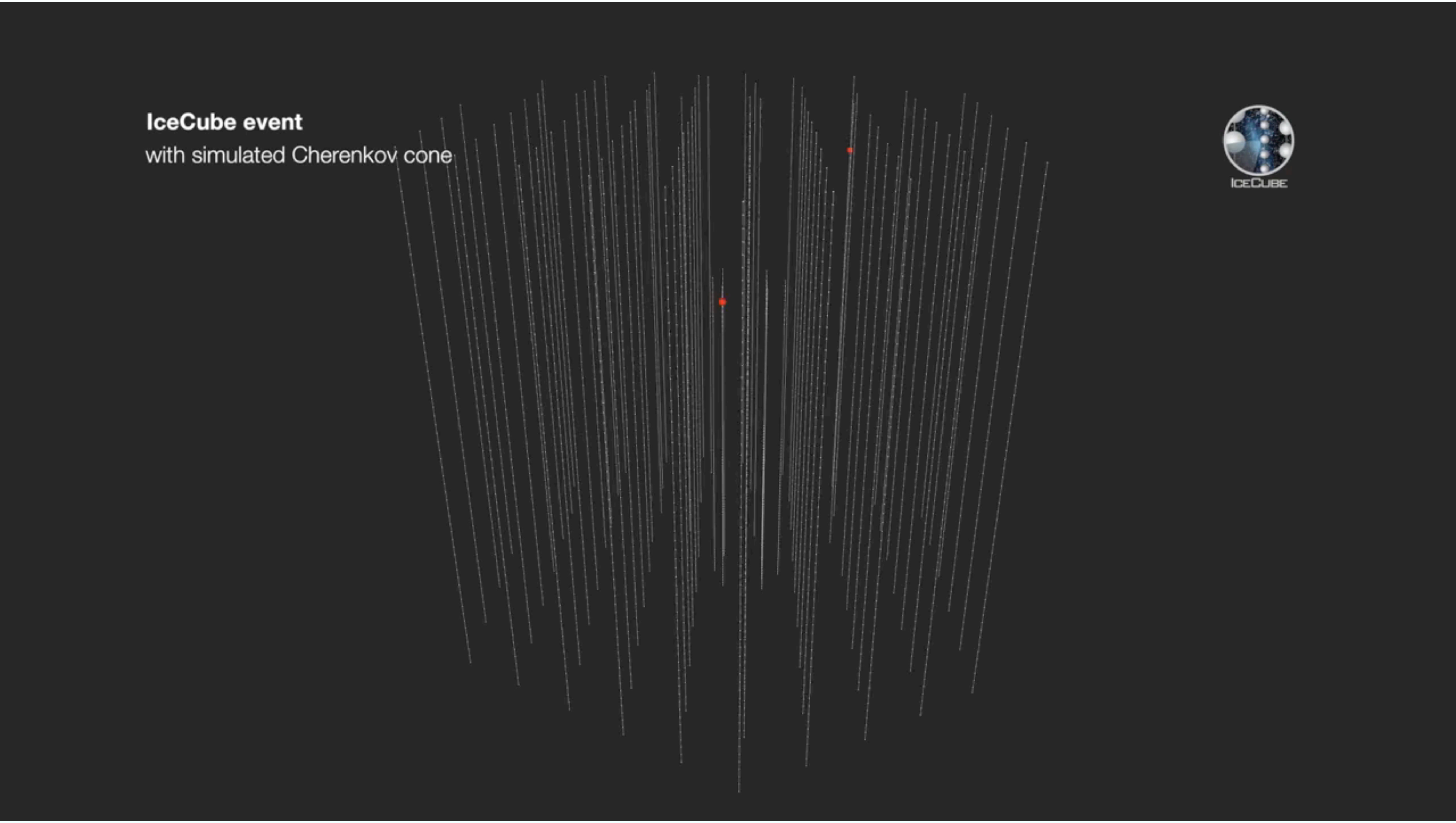
the neutrino universe

Observation of ultra-high energy (UHE) neutrino events at **IceCube** heralds start of **neutrino astronomy**

*Neutrinos are not **deflected or attenuated**: unique probes of extreme astrophysical events*

the neutrino universe

Observation of ultra-high energy (UHE) neutrino events at **IceCube** heralds start of **neutrino astronomy**



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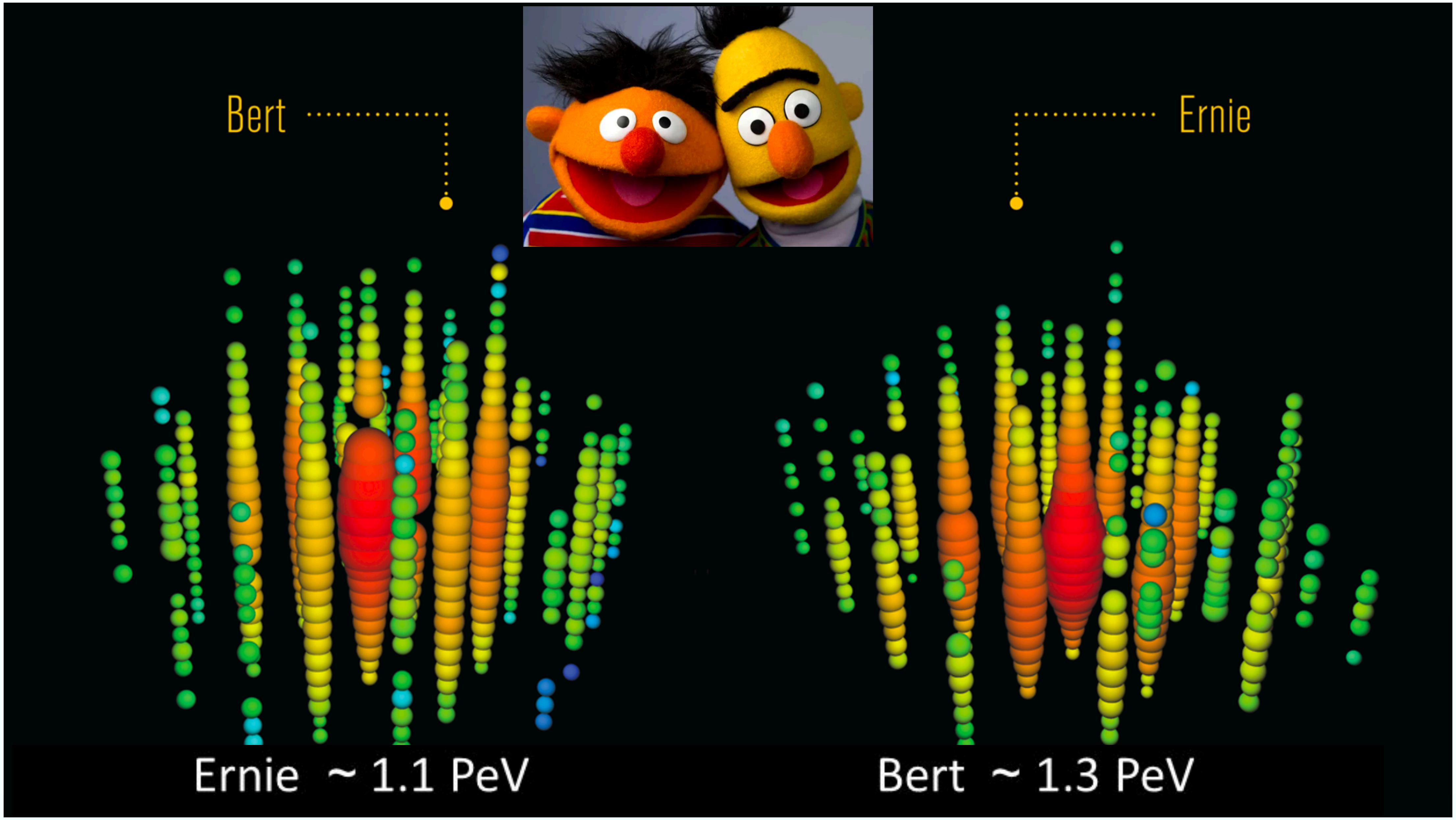
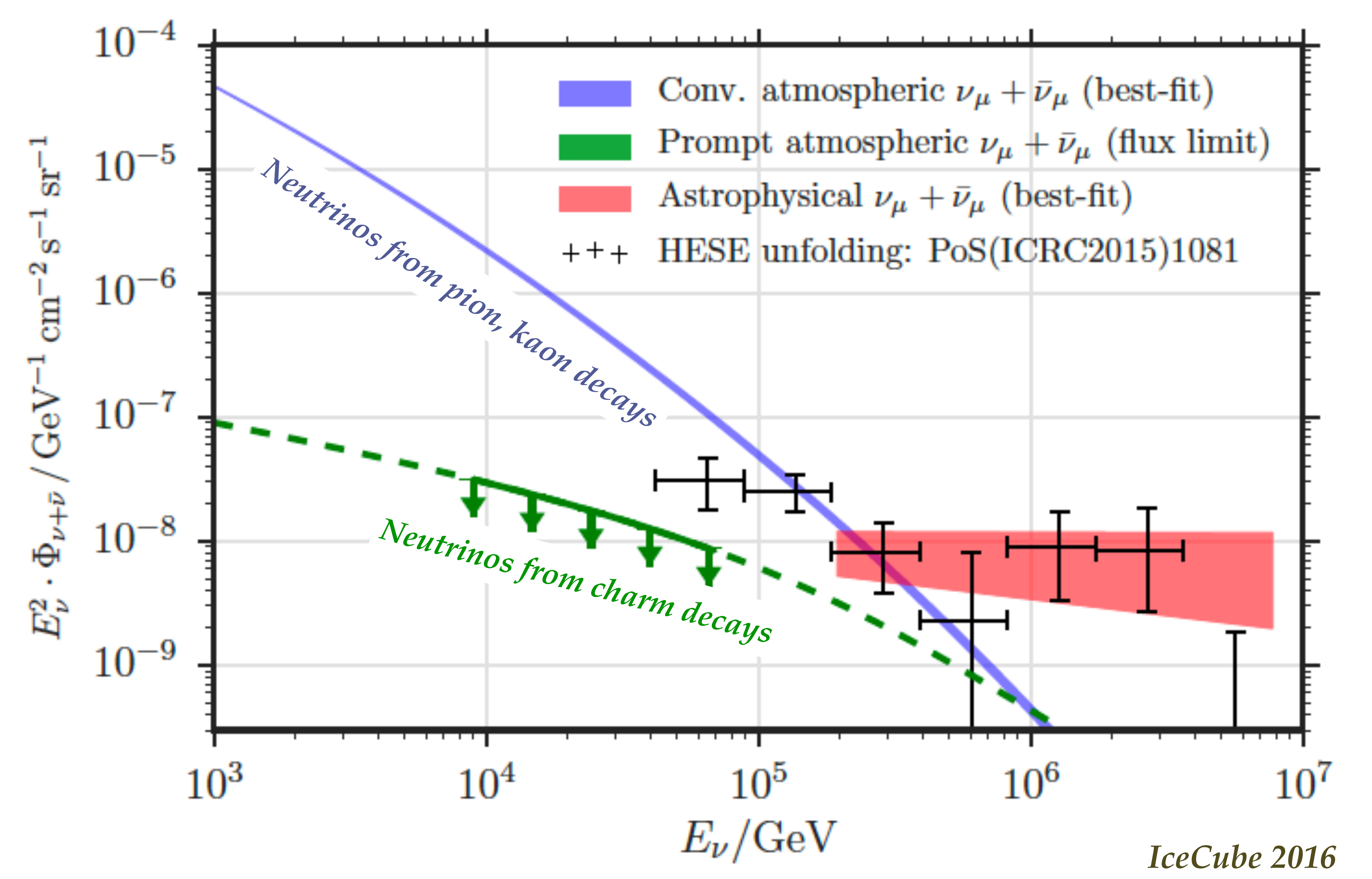


Same centre-of-mass energy than in proton-proton collisions at the TeV!

Precision QCD and … neutrino astronomy?

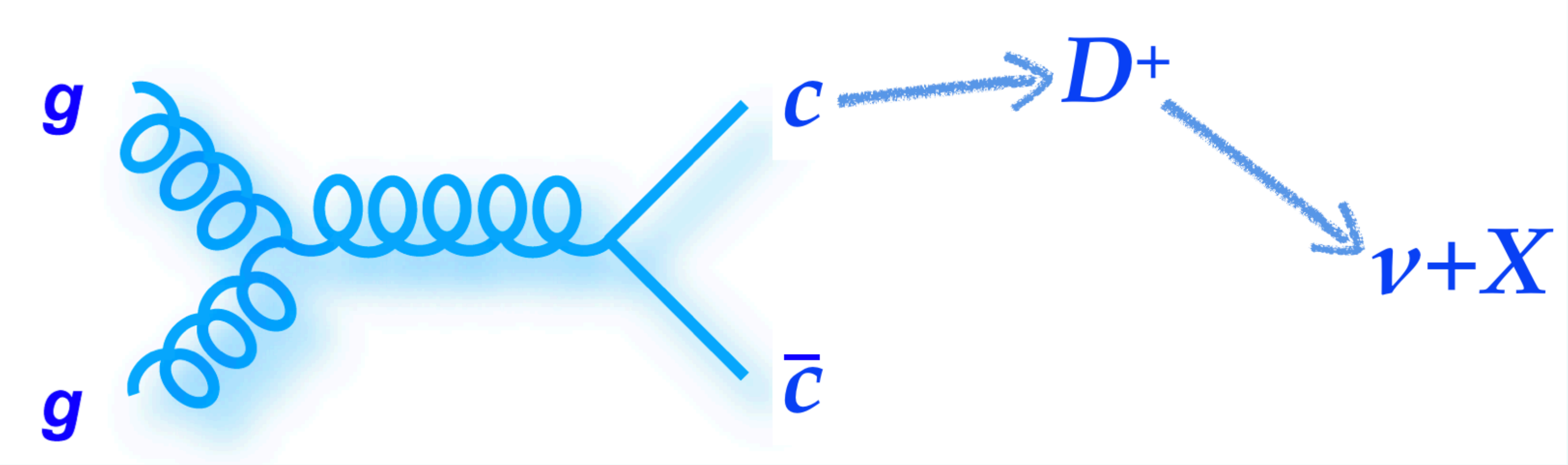


Detection of ultra-high energy neutrinos represents the beginning of **neutrino astronomy**: new window to the Universe!

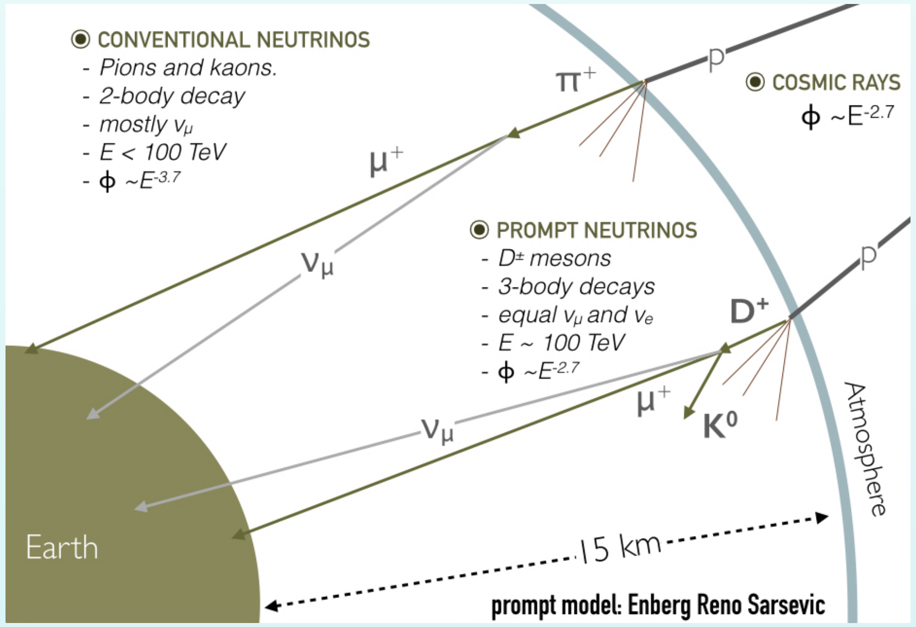
However, the dominant background, **prompt neutrinos from charm decays**, never been detected…

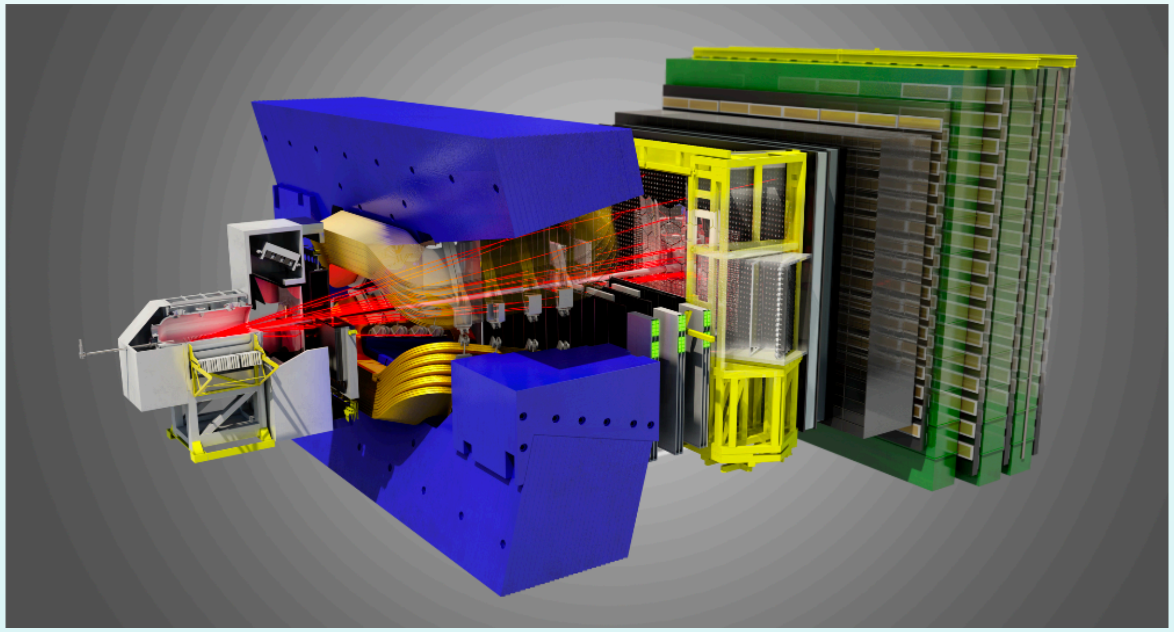
Precision QCD and … neutrino astronomy?

QCD (and the LHC) to the rescue! Include ***D* meson production data from LHCb** into PDF fit to constrain **small-*x* gluon**: precise predictions for **signal and background events at neutrino telescopes**



IceCube E_{CR} = 100 PeV —*Lorentz boost*→ *LHCb $E_{lab} \approx$ 14 TeV*





Direct overlap kinematics between charm production in UHE cosmic rays and at the LHC

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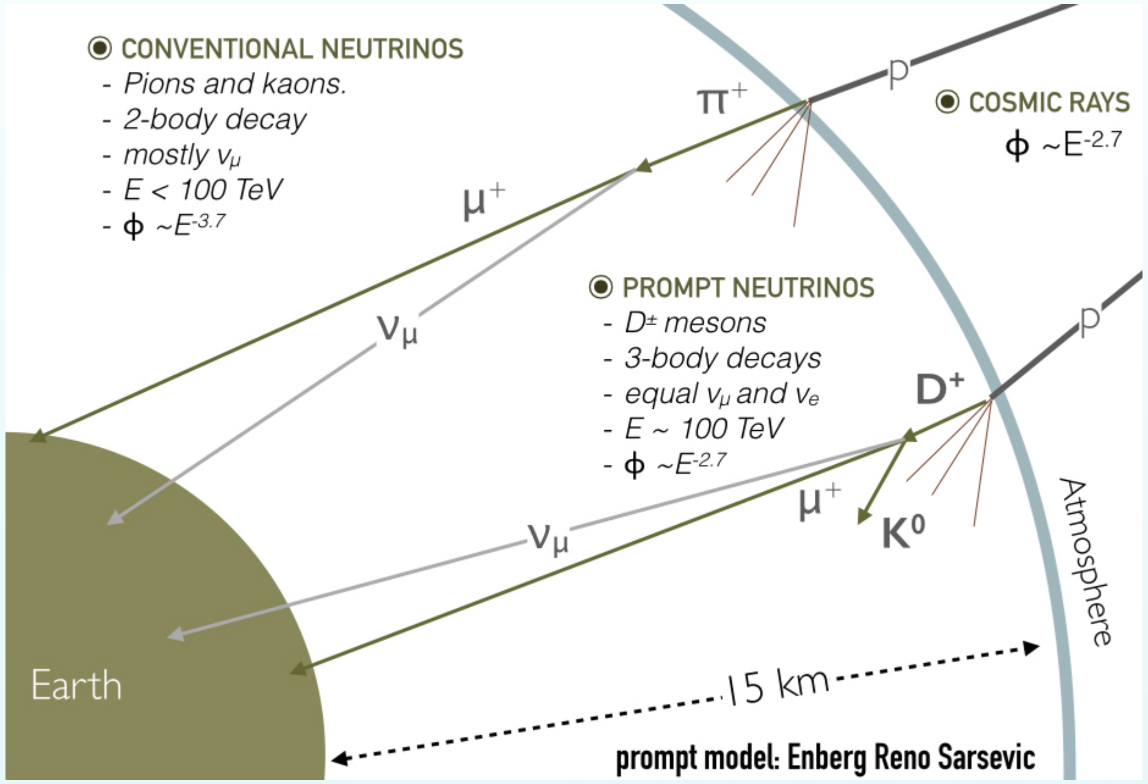
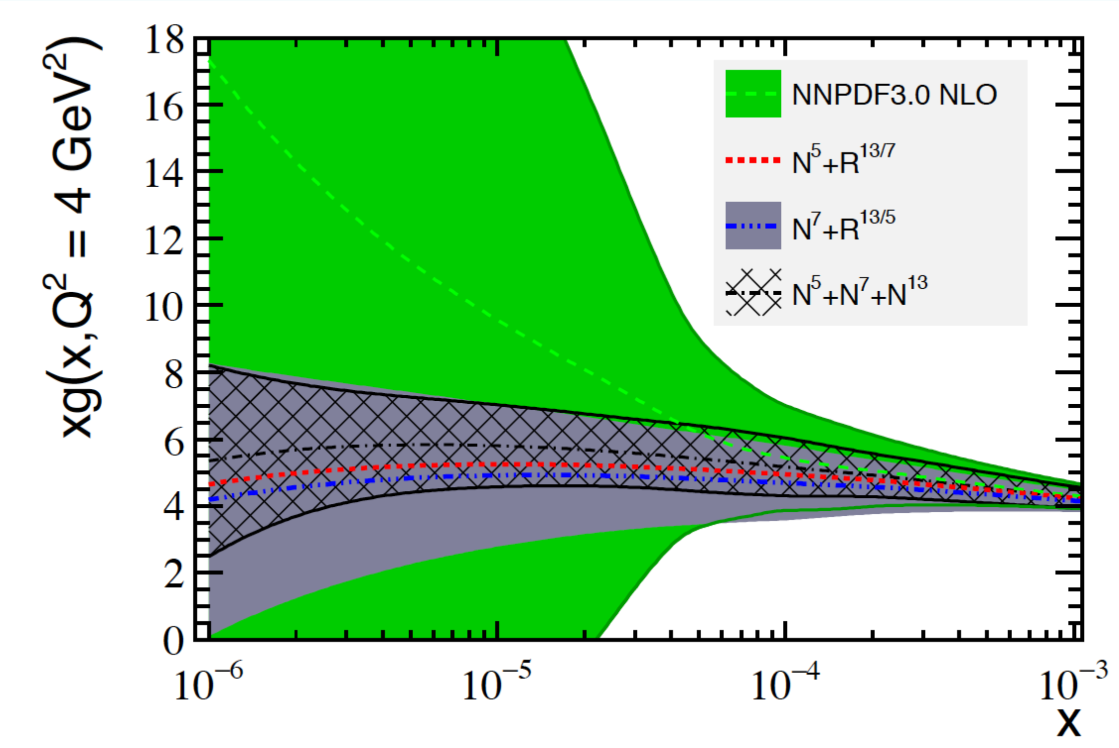
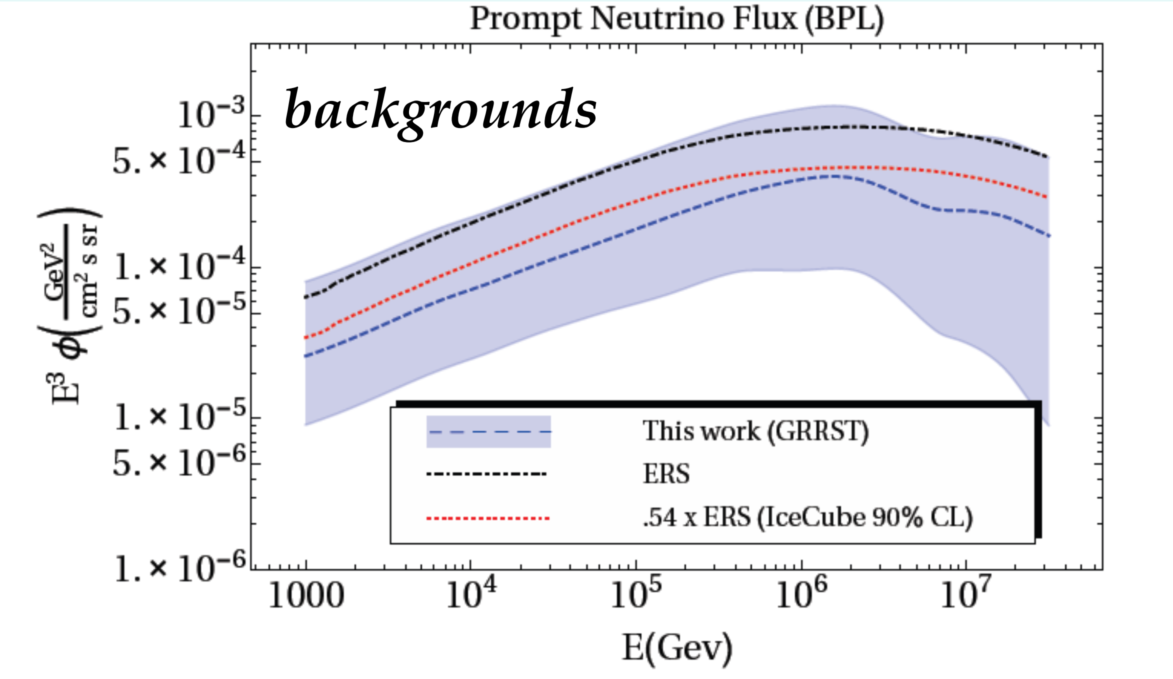


Precision determination of small-x gluon from charm production art LHCb



Gauld, JR 16



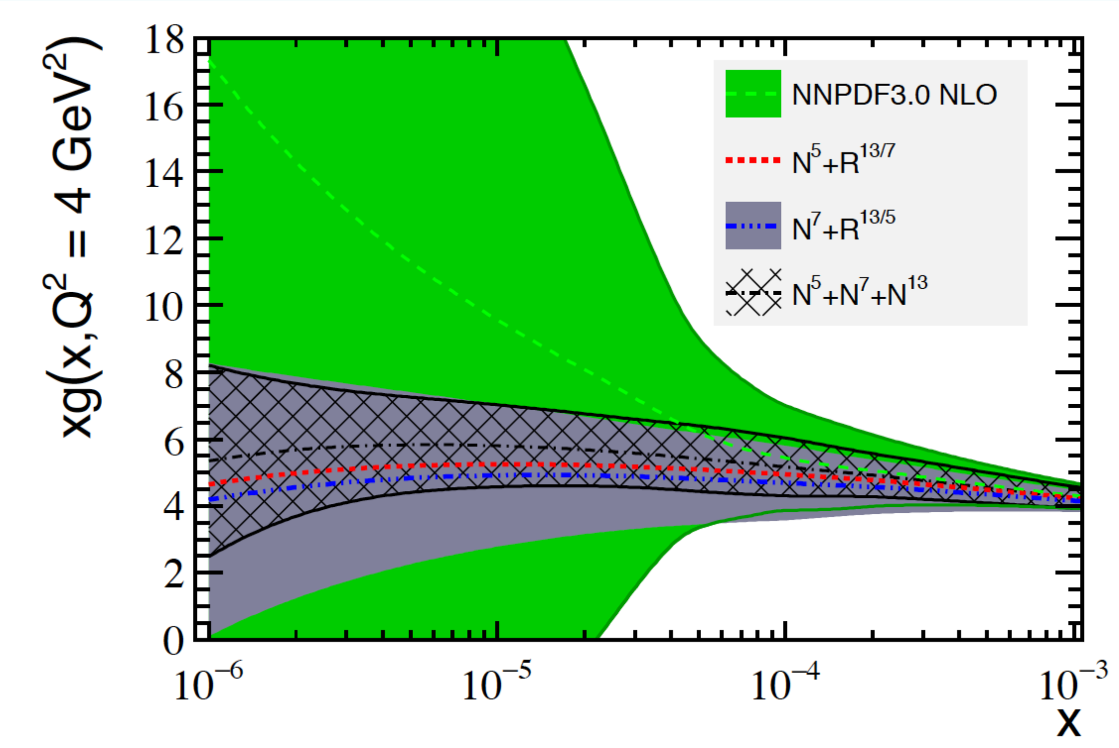
Progress in precision QCD benefits other fields beyond collider physics (i.e. also nuclear physics)

Gauld, JR, Rottoli, Sarkar, Talbert 15

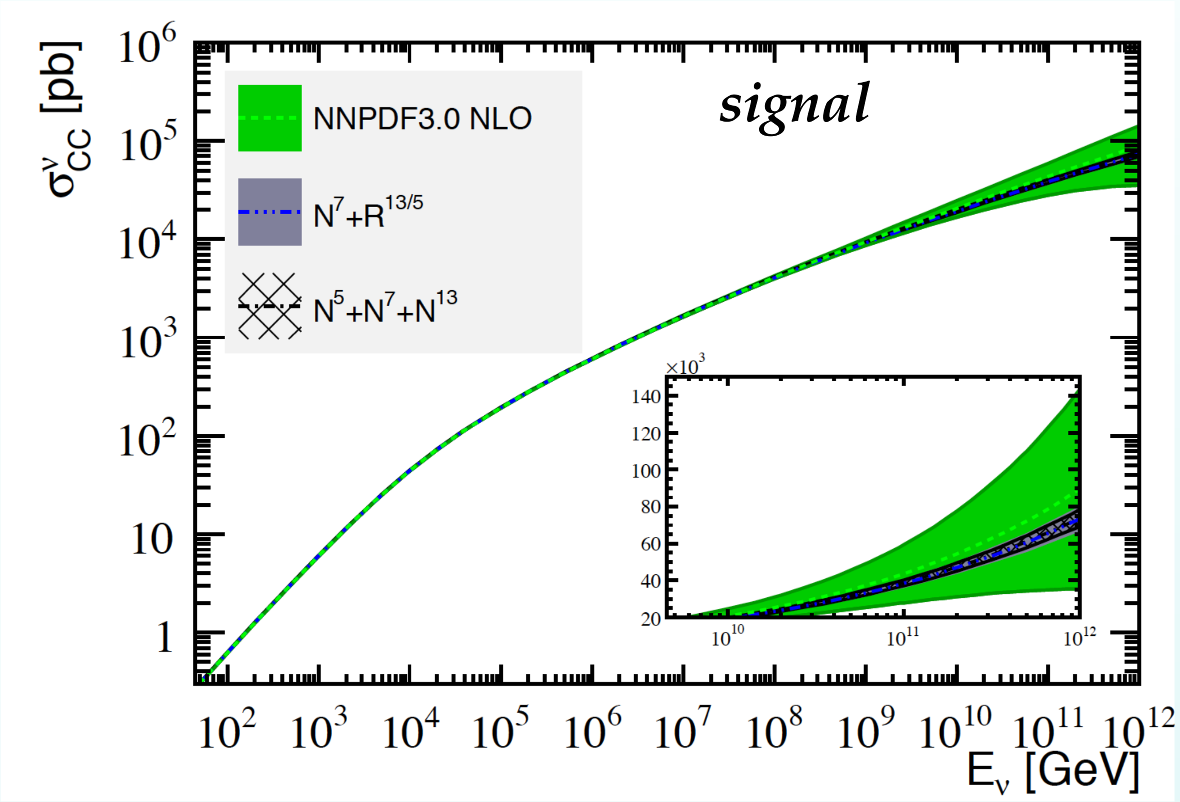
Precision QCD and … neutrino astronomy?

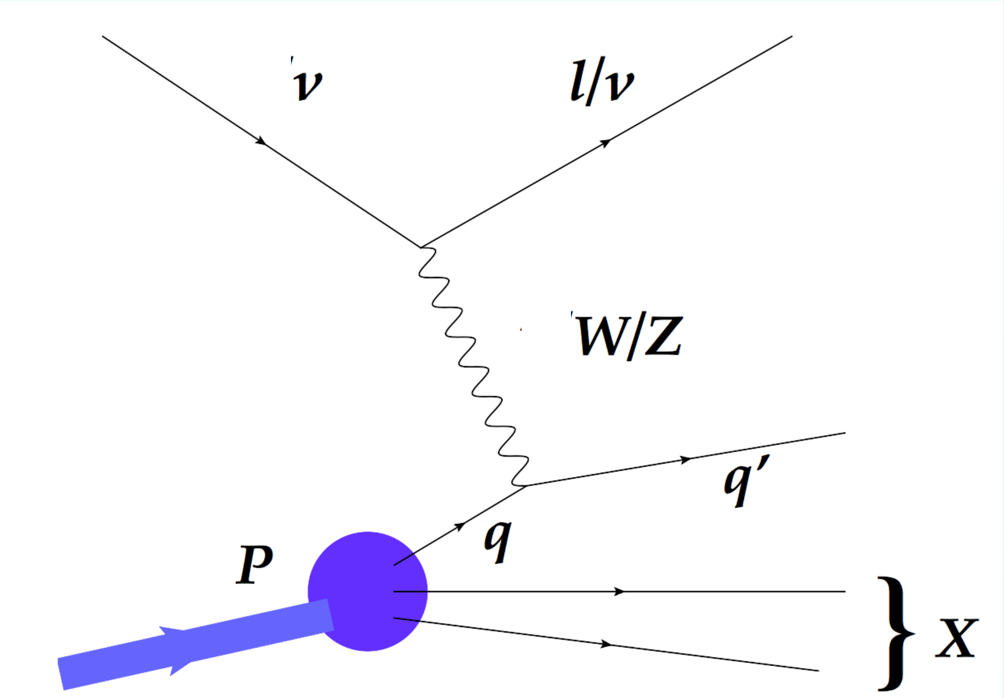
QCD (and the LHC) to the rescue! Include ***D* meson production data from LHCb** into PDF fit to constrain **small-*x* gluon**: precise predictions for **signal and background events at neutrino telescopes**

Precision determination of small-x gluon from charm production art LHCb



Gauld, JR 16





Progress in precision QCD benefits other fields beyond collider physics (i.e. also nuclear physics)

Precision QCD at the LHC

☑ Recent progress with **theoretical QCD calculation** have realised the dream of turning the **LHC into a high-precision experiment**

☑ **Two-loop QCD calculations** and beyond are now the standard for LHC processes

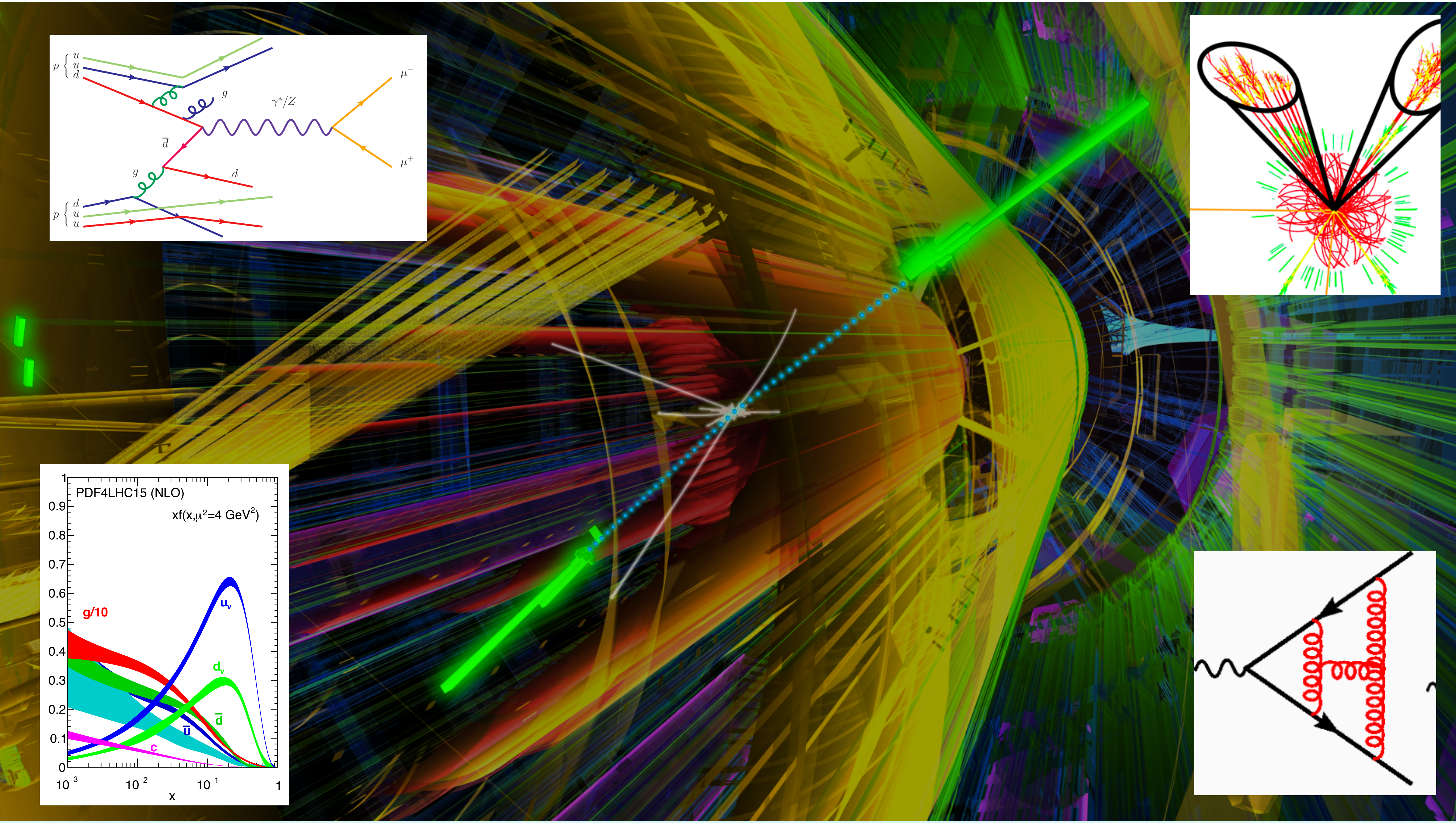
☑ Detailed mapping of the proton structure: **few-percent errors in most PDFs in relevant LHC range**, including gluon and photon

☑ Implications beyond colliders: also for **astroparticle, nuclear,** and **hadronic physics**

☑ Rich interplay with **high-performance computing** and **machine learning algorithms**

☑ Precision QCD 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!

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