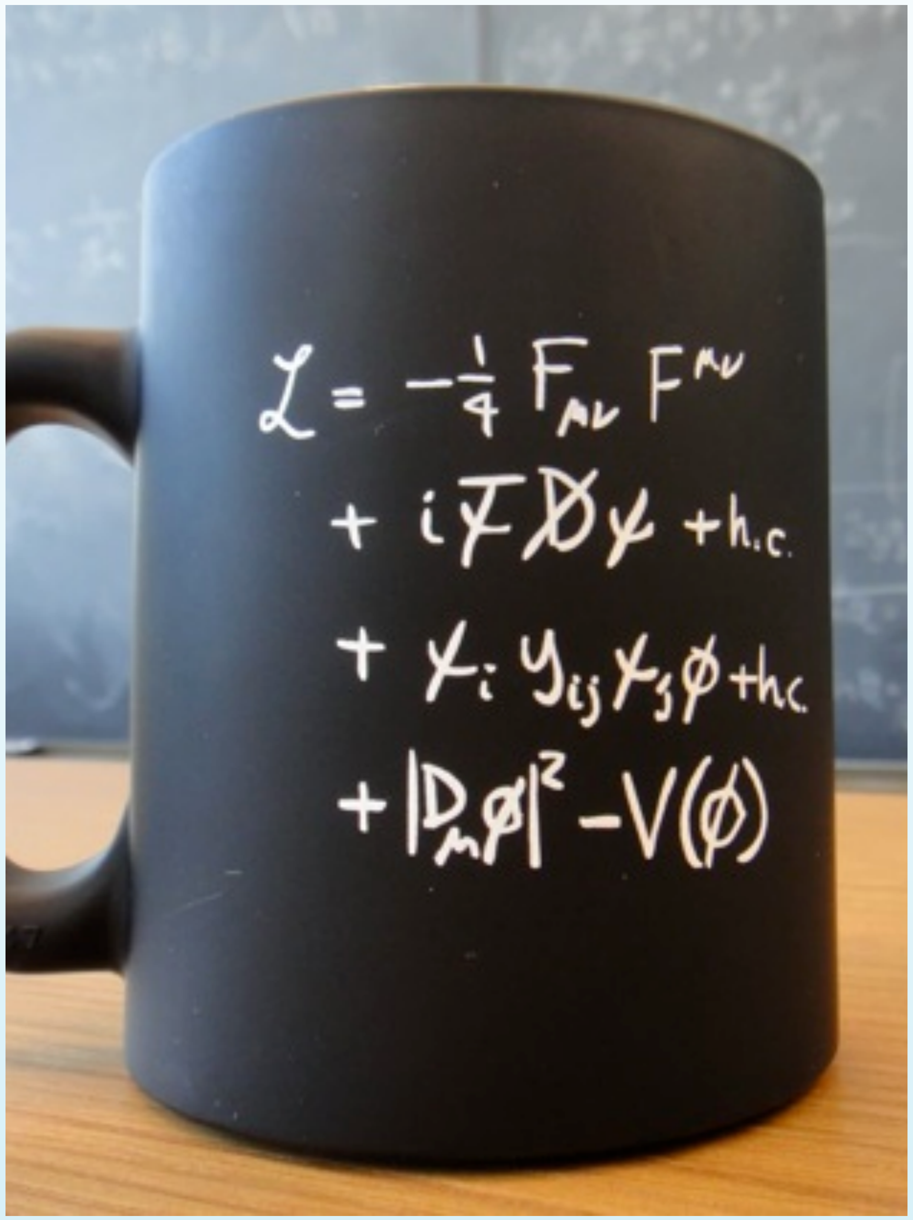
Precision QCD processes at the LHC

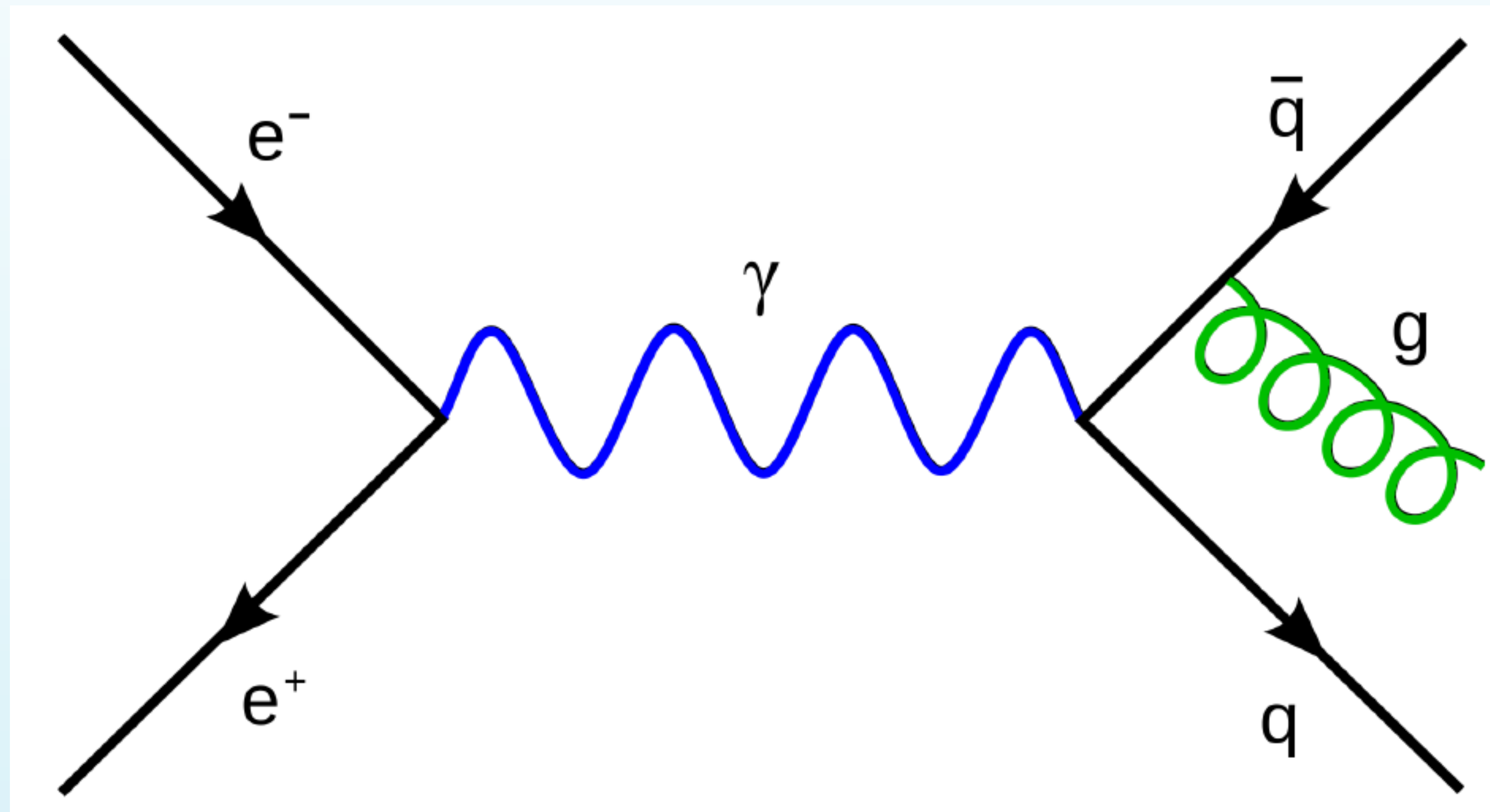
VU Amsterdam & Theory group, Nikhef

International Committee for Future Accelerators (ICFA) 2017 Seminar
Ottawa, 7th of November 2017

Precision at hadron colliders?

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





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

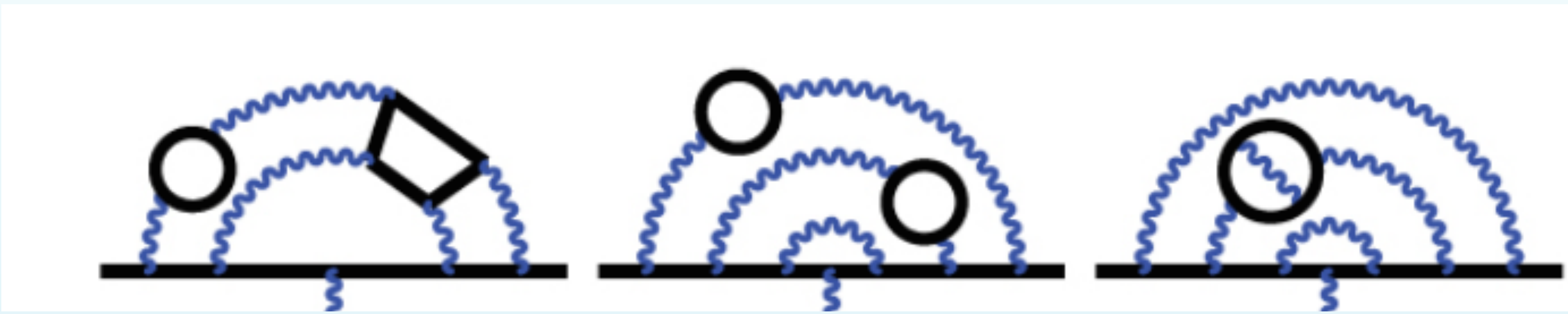
Quantum Electrodynamics and lepton colliders are ideal for **high-precision measurements**

Precision at hadron colliders?

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

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

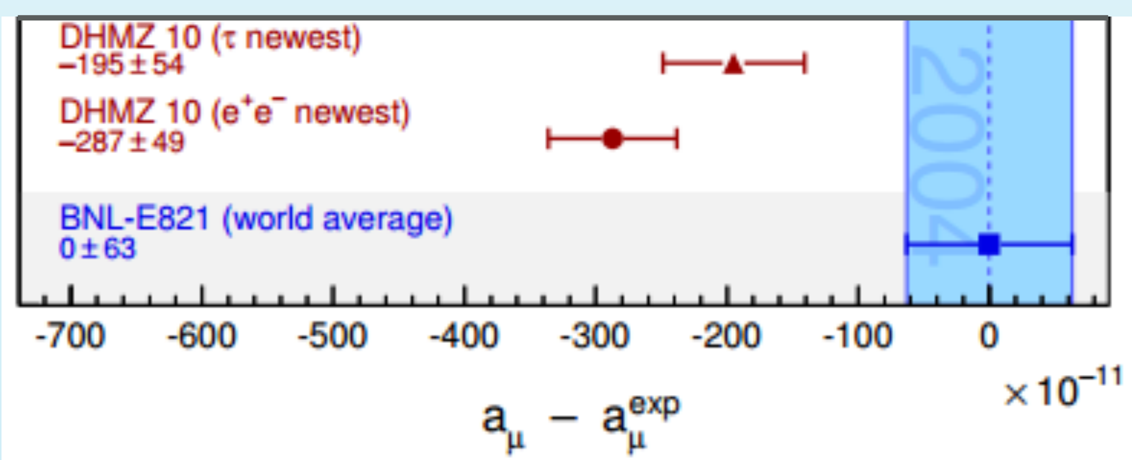
$$a_{\text{teo}} = 0{,}00115965218178 \pm 0{,}00000000000077$$

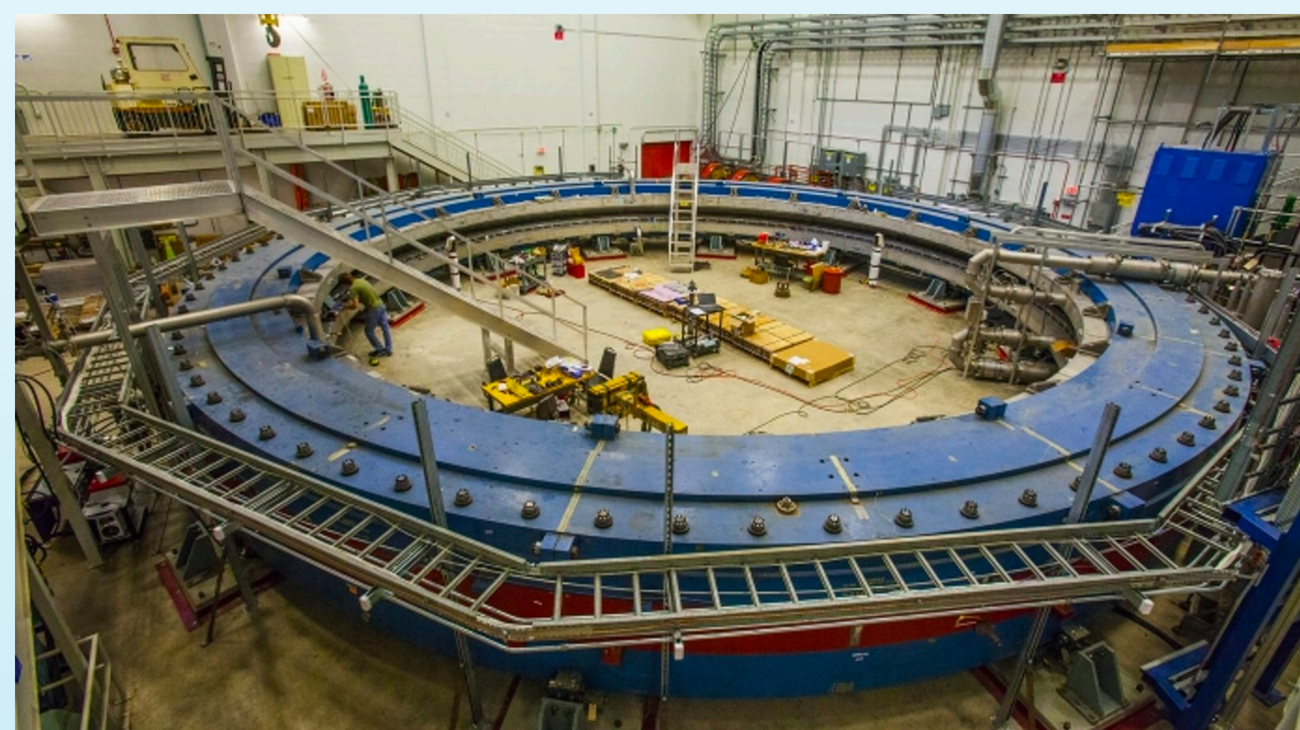


One of the most accurate predictions ever provided by any scientific theory!

This accuracy could be key for new discoveries!

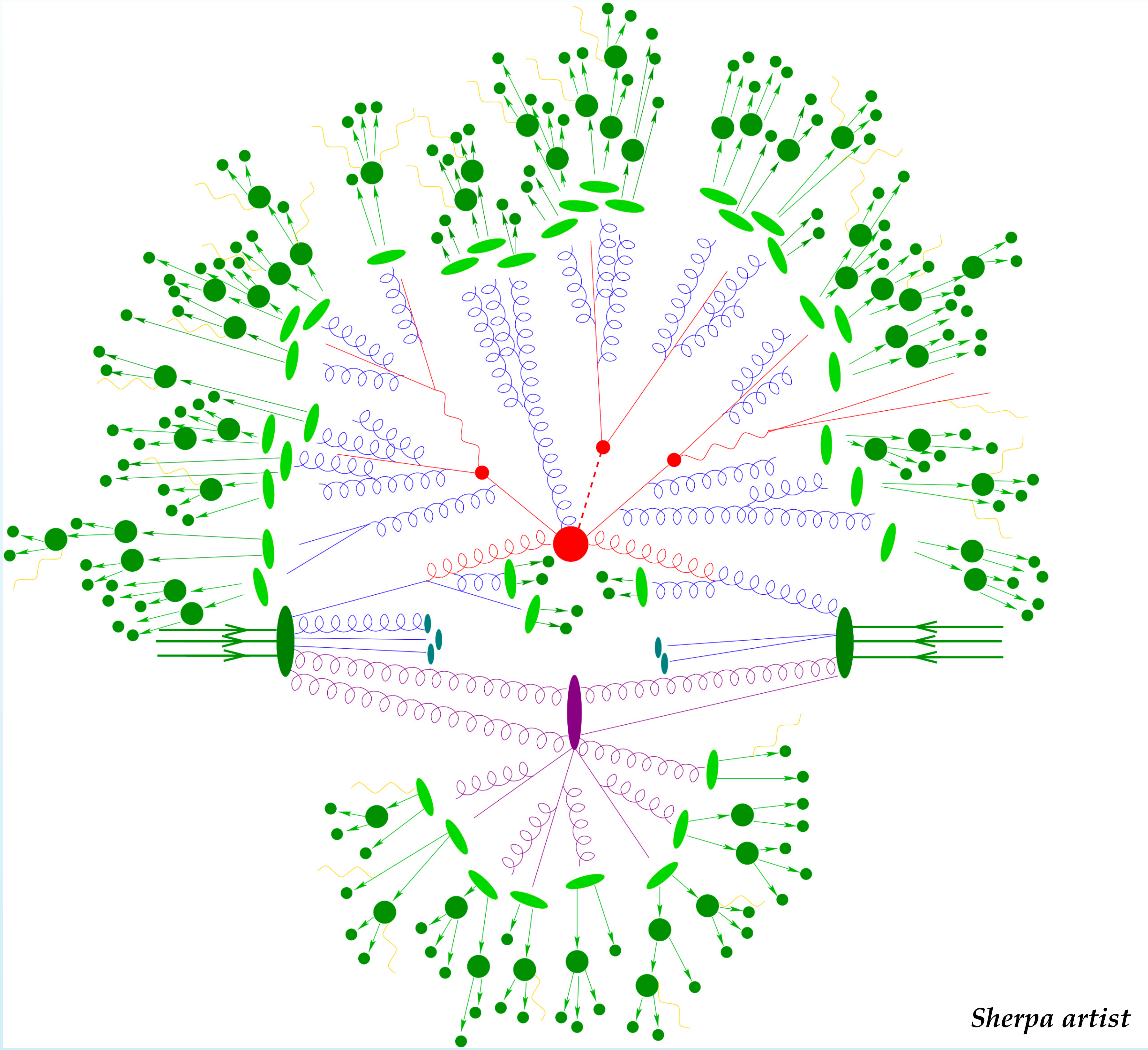
i.e. **muon g-2 experiment @ BNL and FNAL**





Precision at hadron colliders?

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



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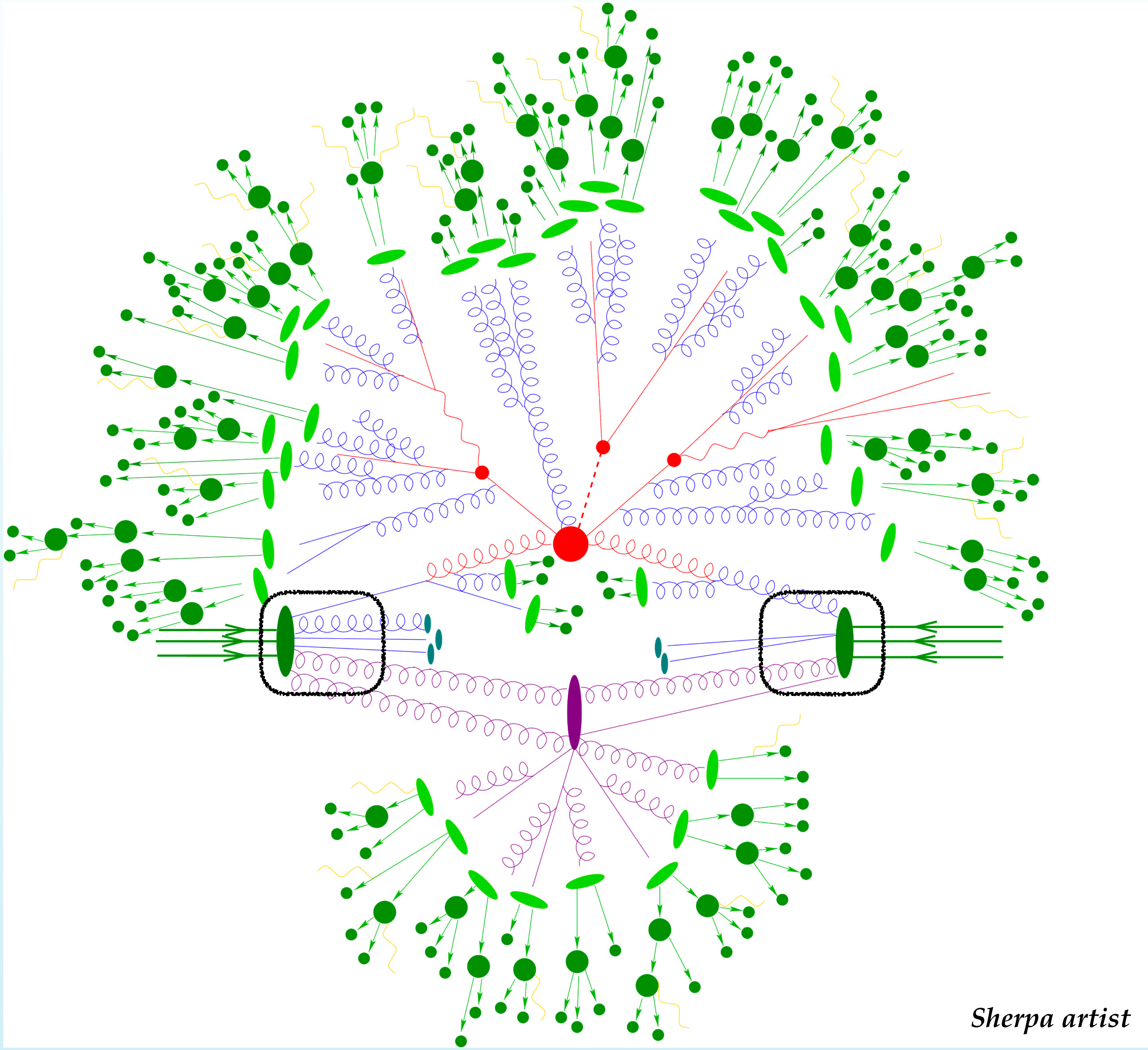
- initial state: **non-perturbative** proton's parton distributions

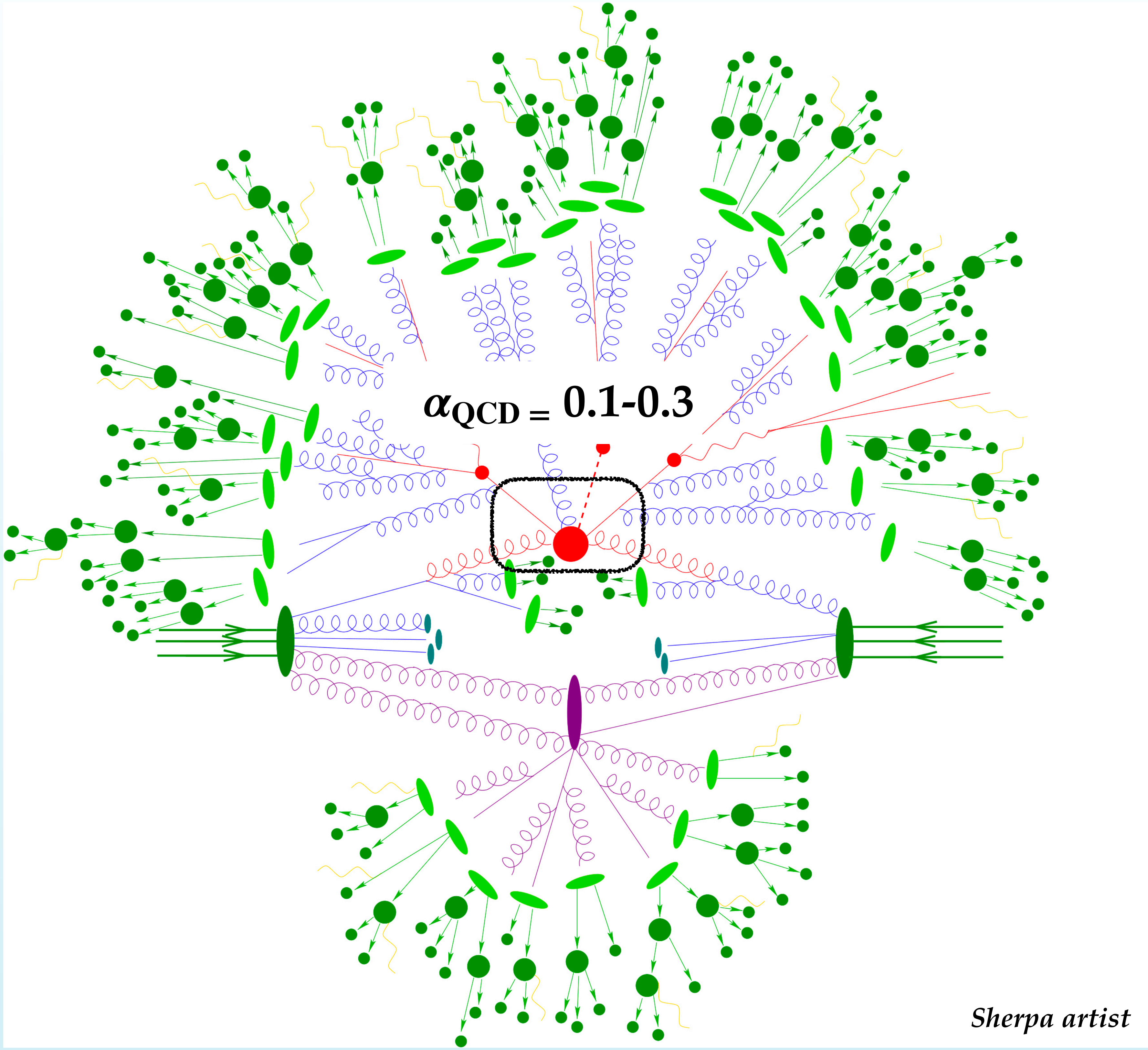


Sherpa artist

Precision at hadron colliders?

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

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



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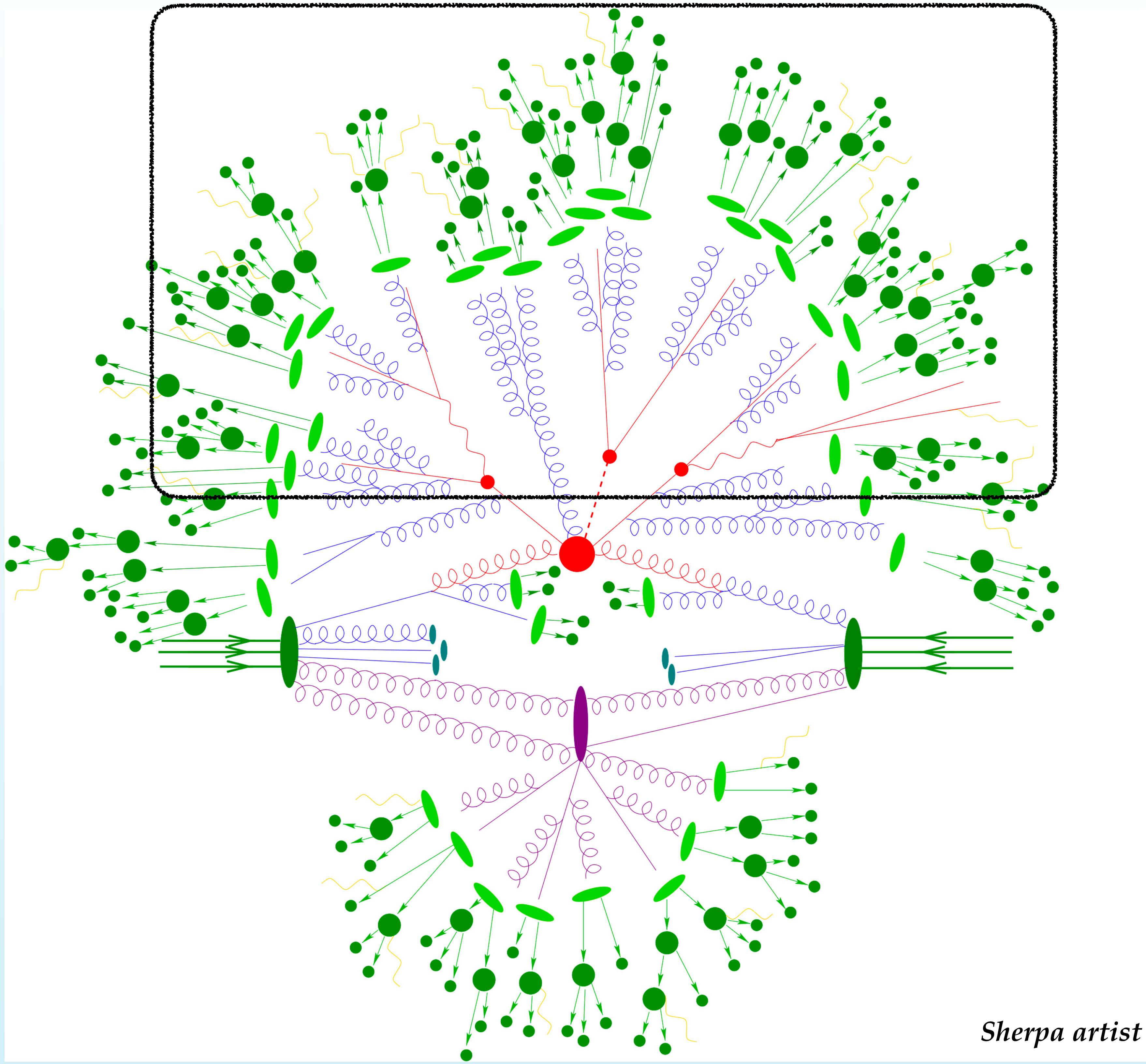

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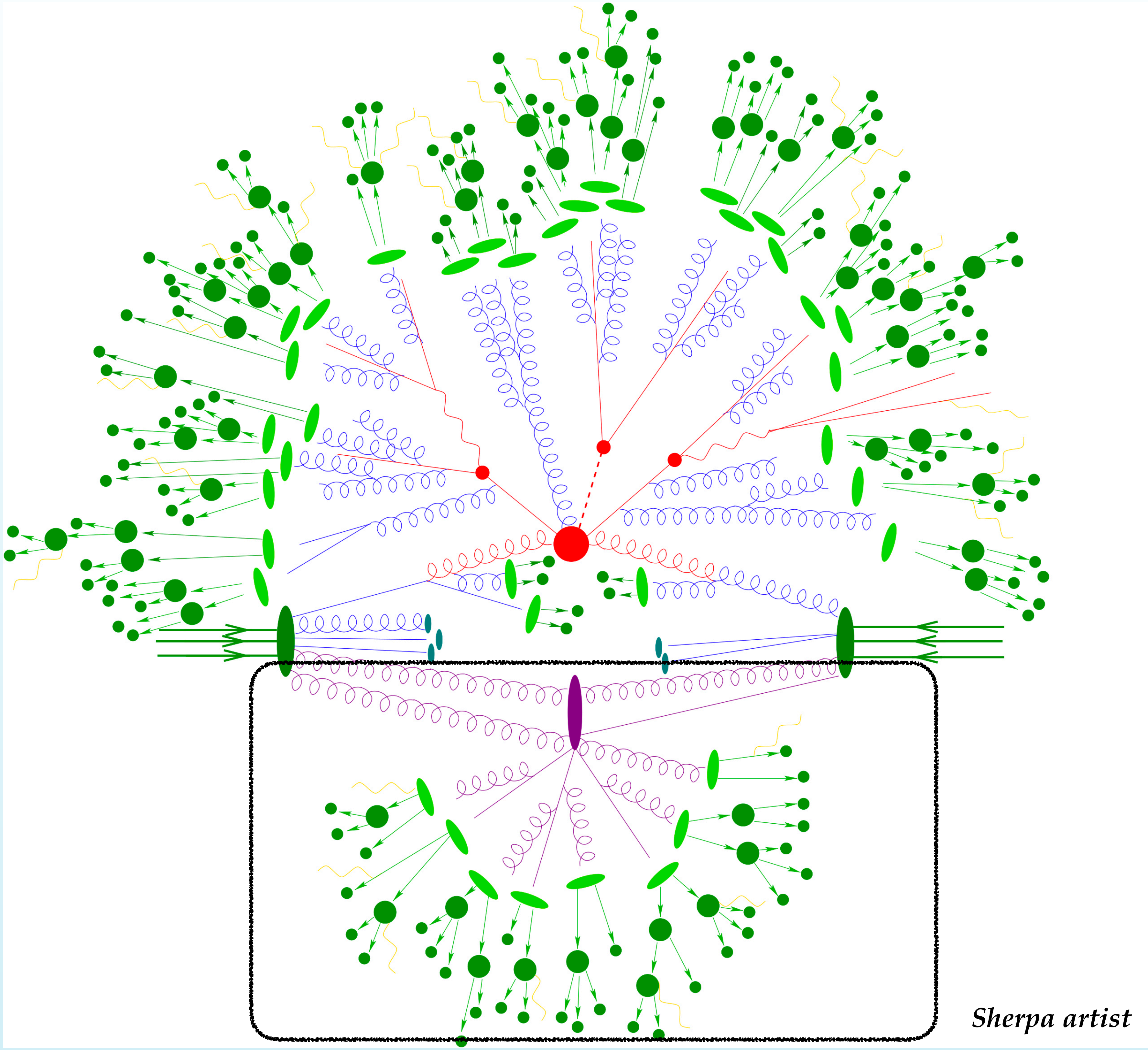

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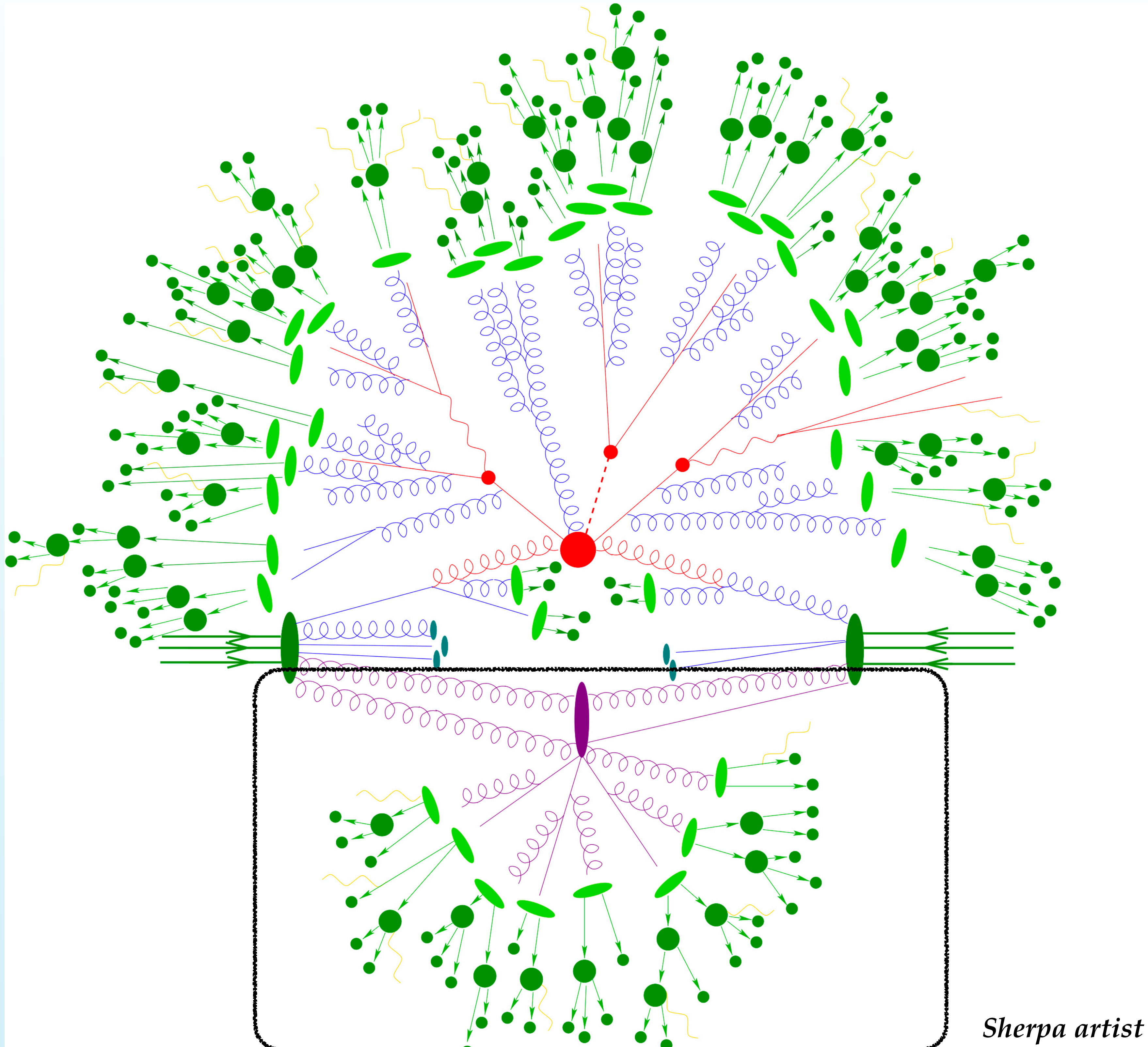
Can we really aim for precision physics at LHC?



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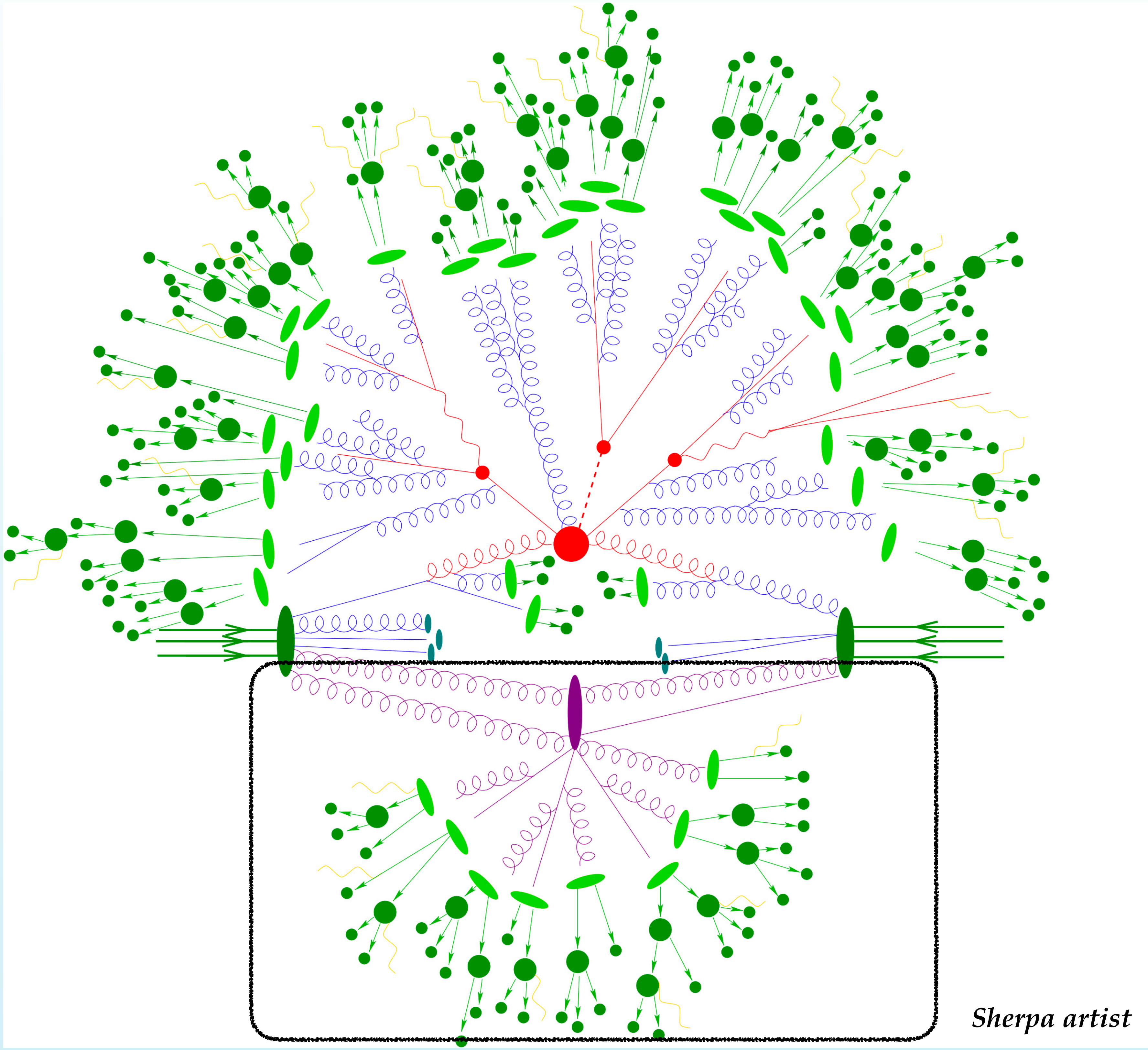
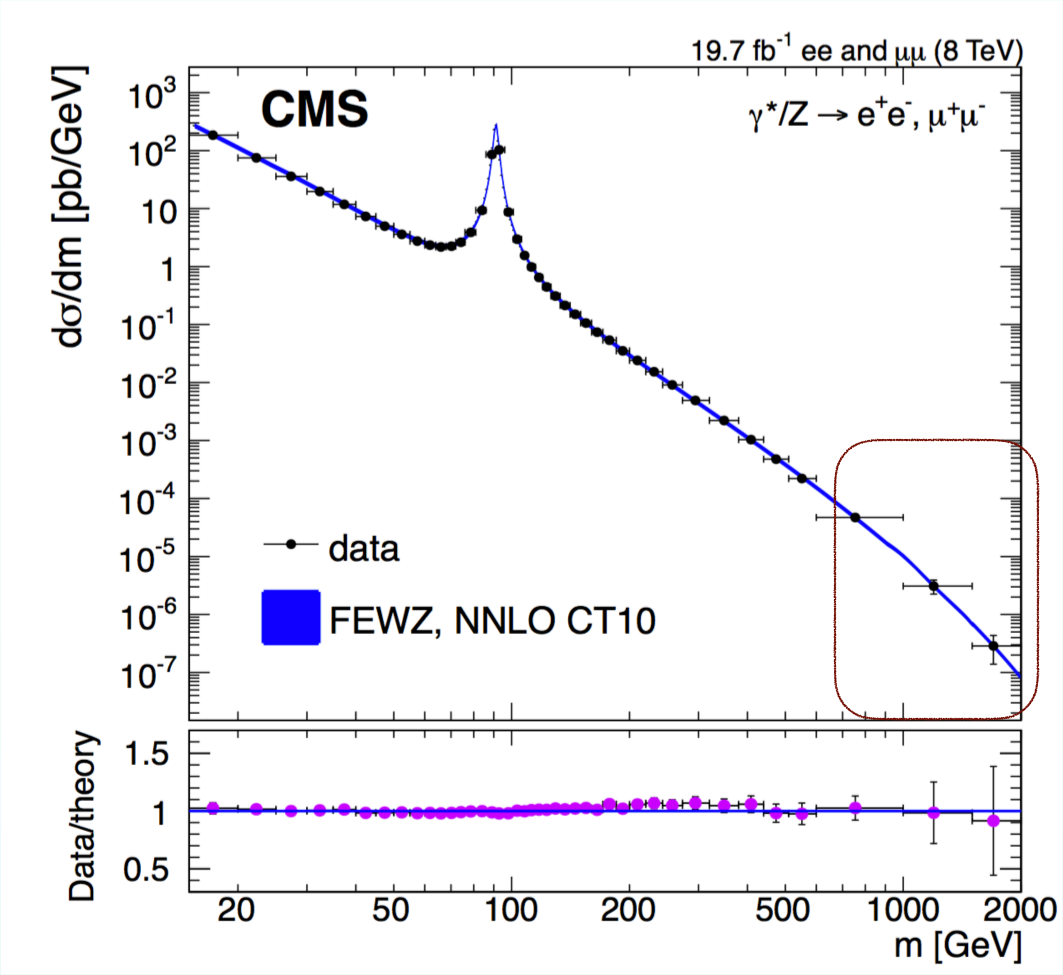


Sherpa artist

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

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

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

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 ***completely automated***

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

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

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Easy, textbook calculations

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

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 ***completely automated***

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

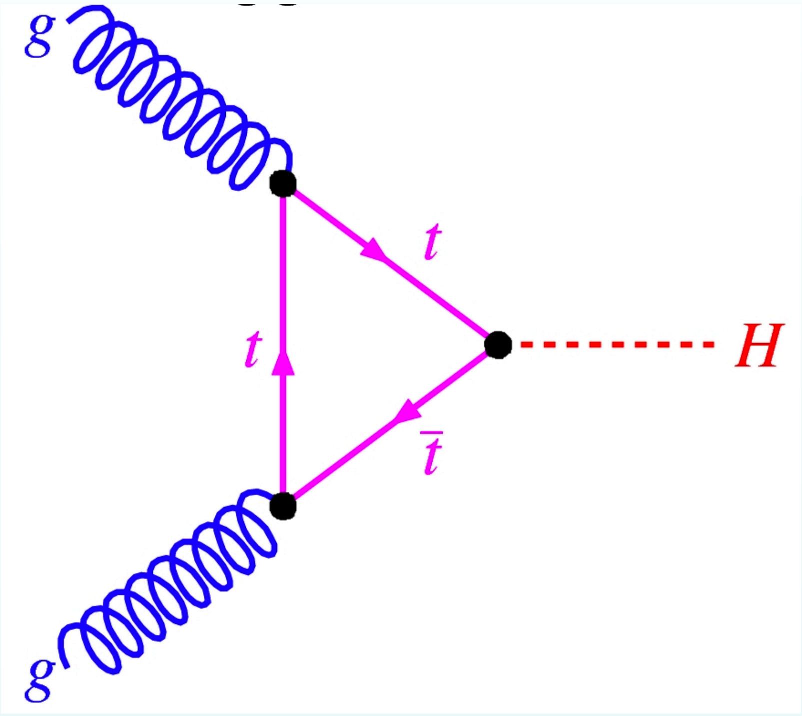
$$\frac{\sigma(pp \to X)}{\sigma_0} = 1 + \alpha_{\rm qcd}\,\sigma_1 + \alpha_{\rm qcd}^2\,\sigma_2 + \alpha_{\rm qcd}^3\,\sigma_3 + \ldots$$

Leading Order (Born level)
Easy, textbook calculations

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

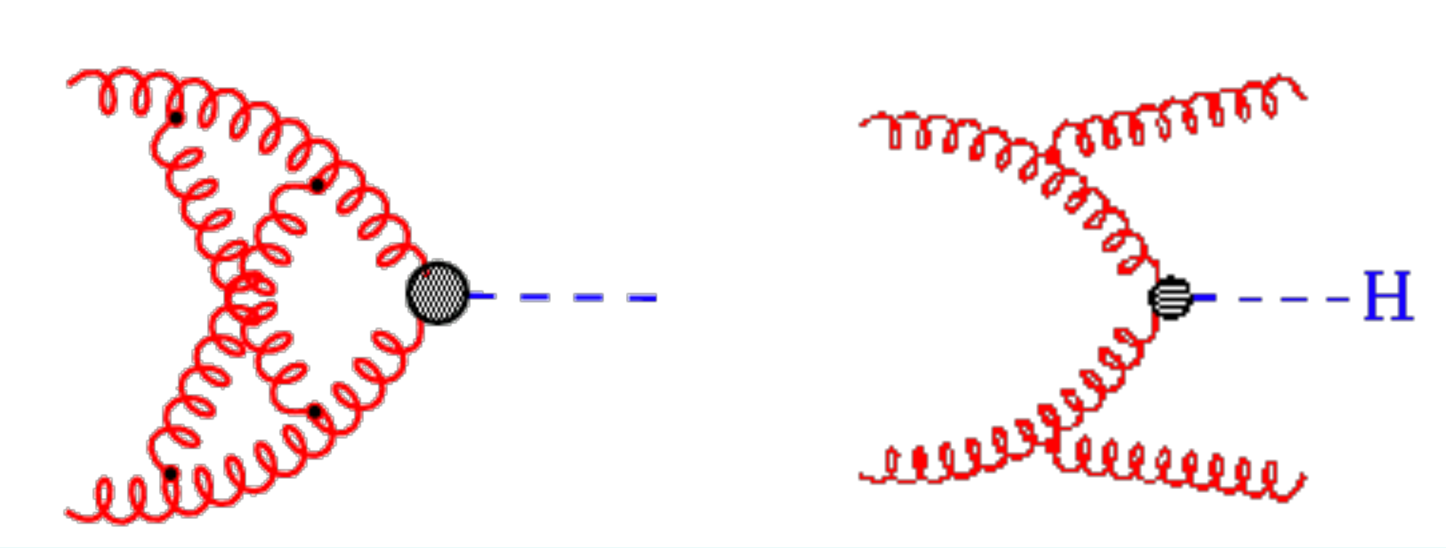
Loops and more loops

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

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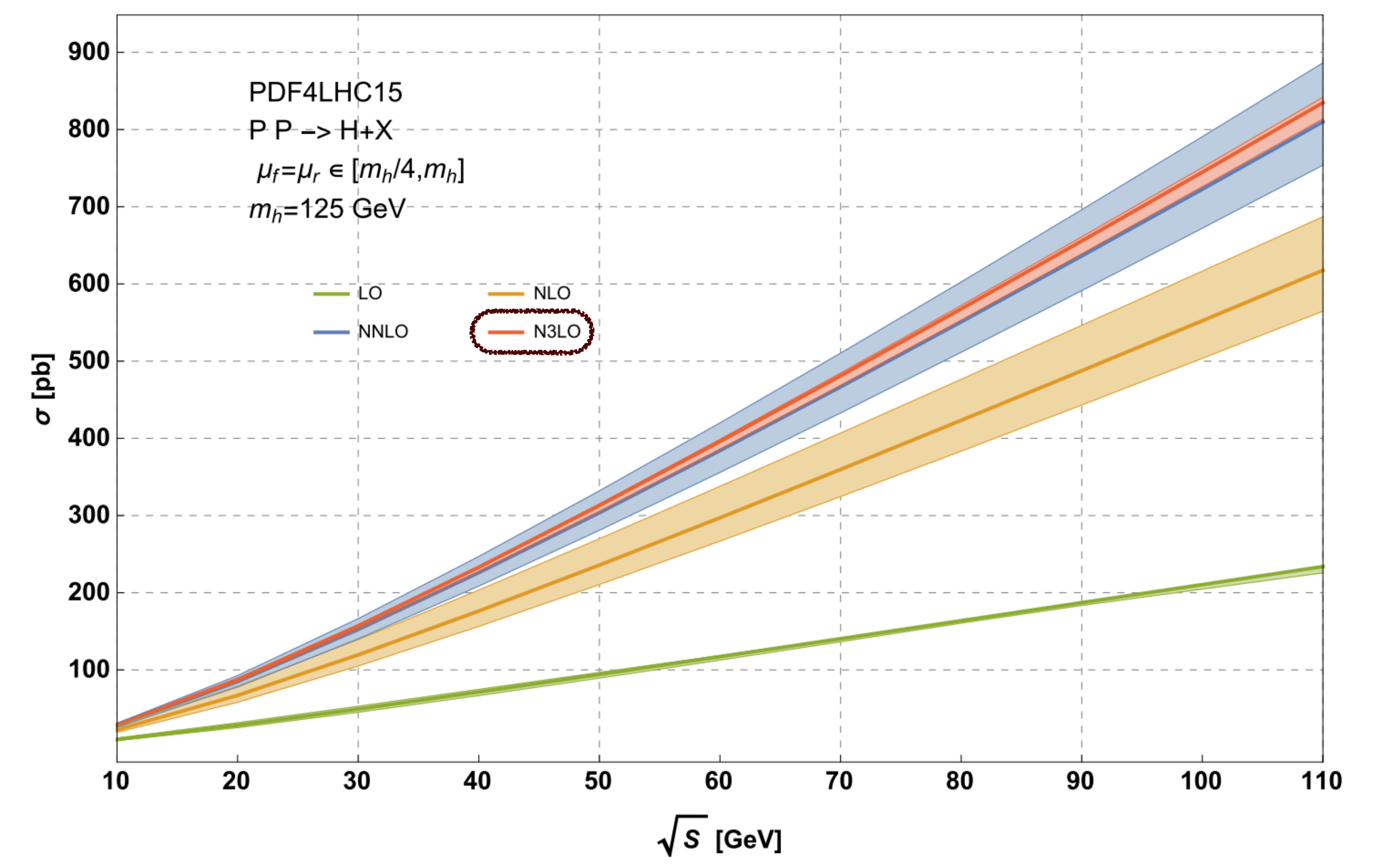
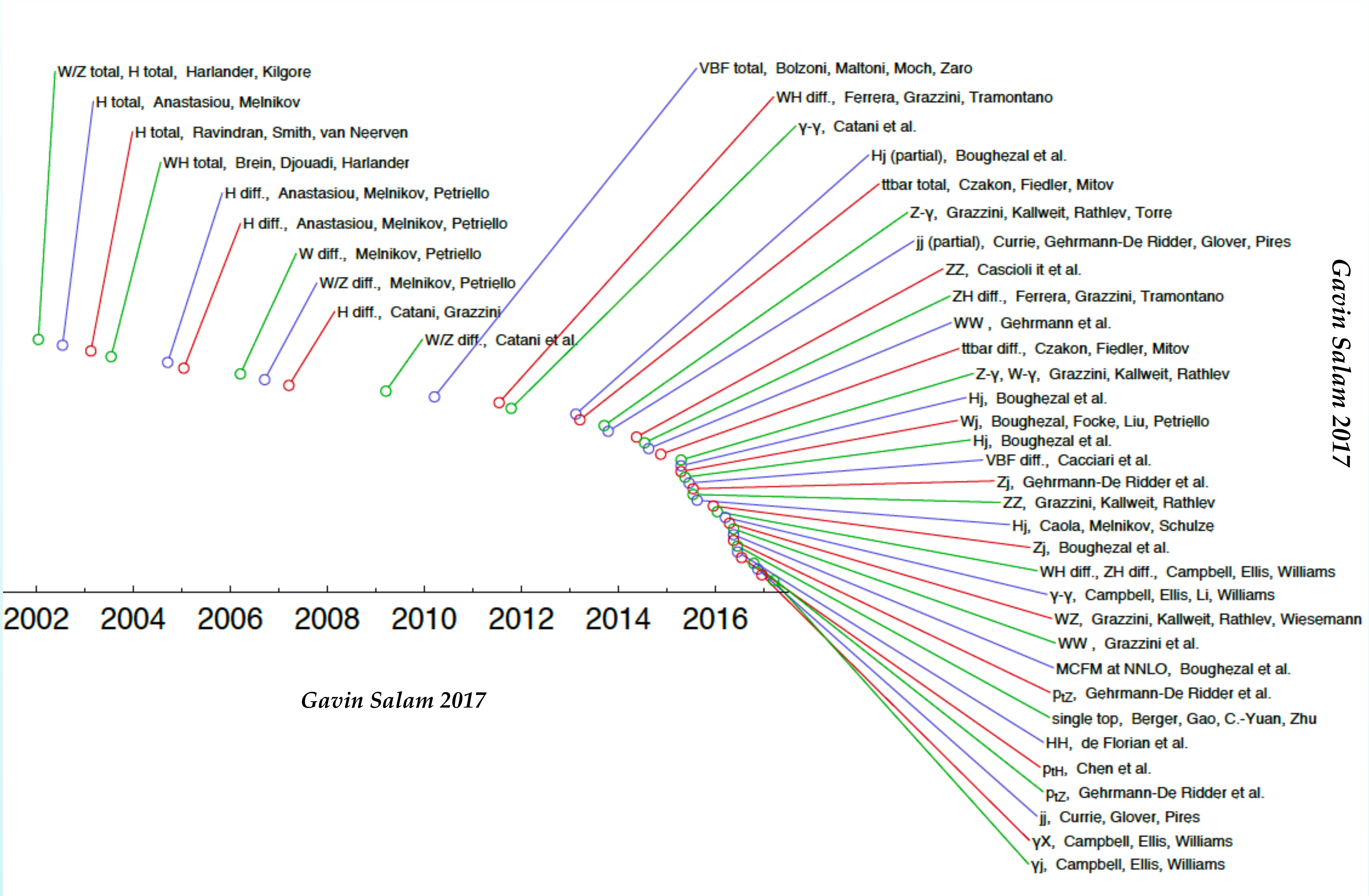


Anastasiou et al. 15-16

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

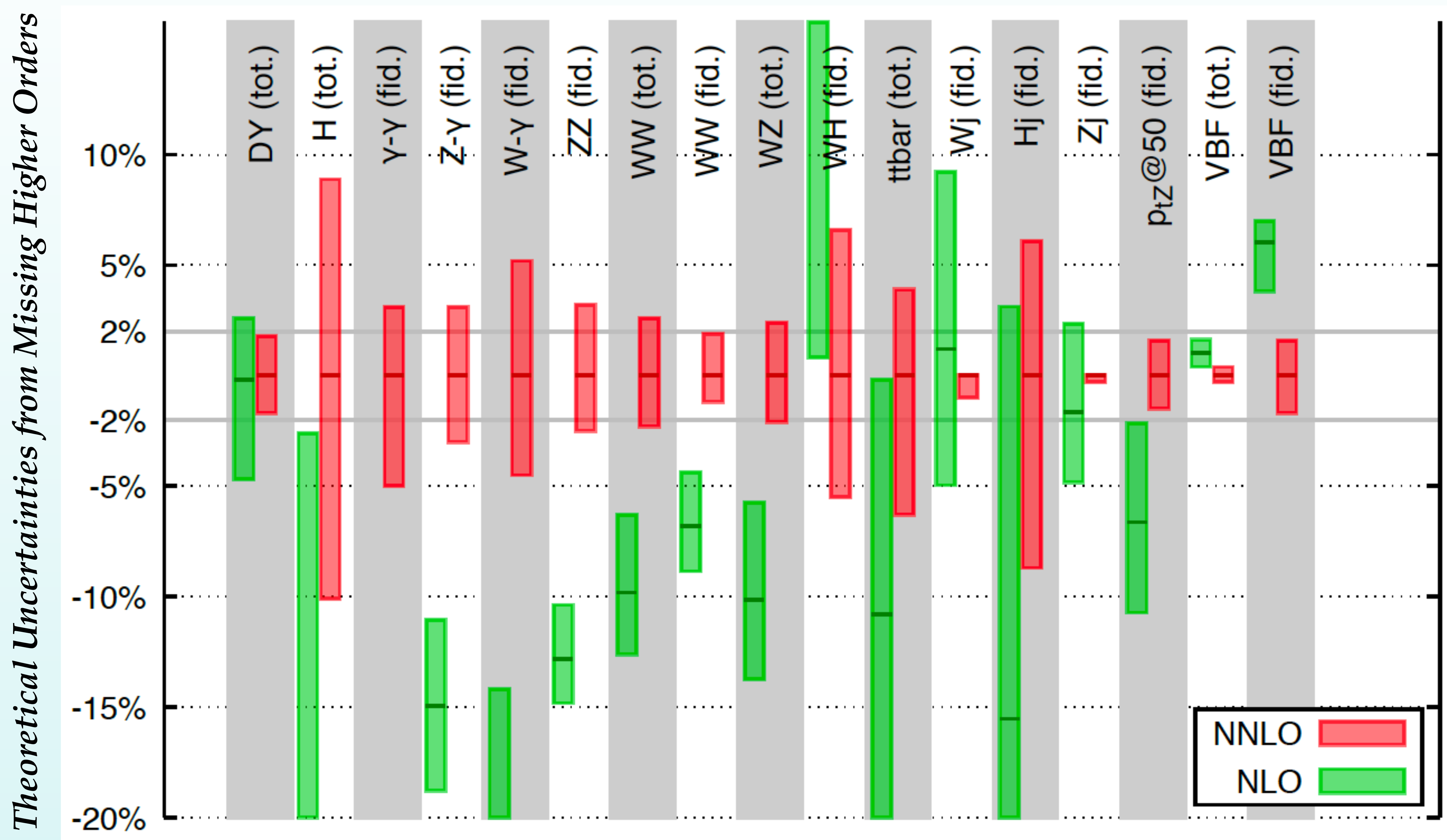
Pushing the QCD precision frontier

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



Pushing the QCD precision frontier

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



Gavin Salam 2017

LHC phenomenology at 1% precision is within reach!

Pushing the QCD precision frontier

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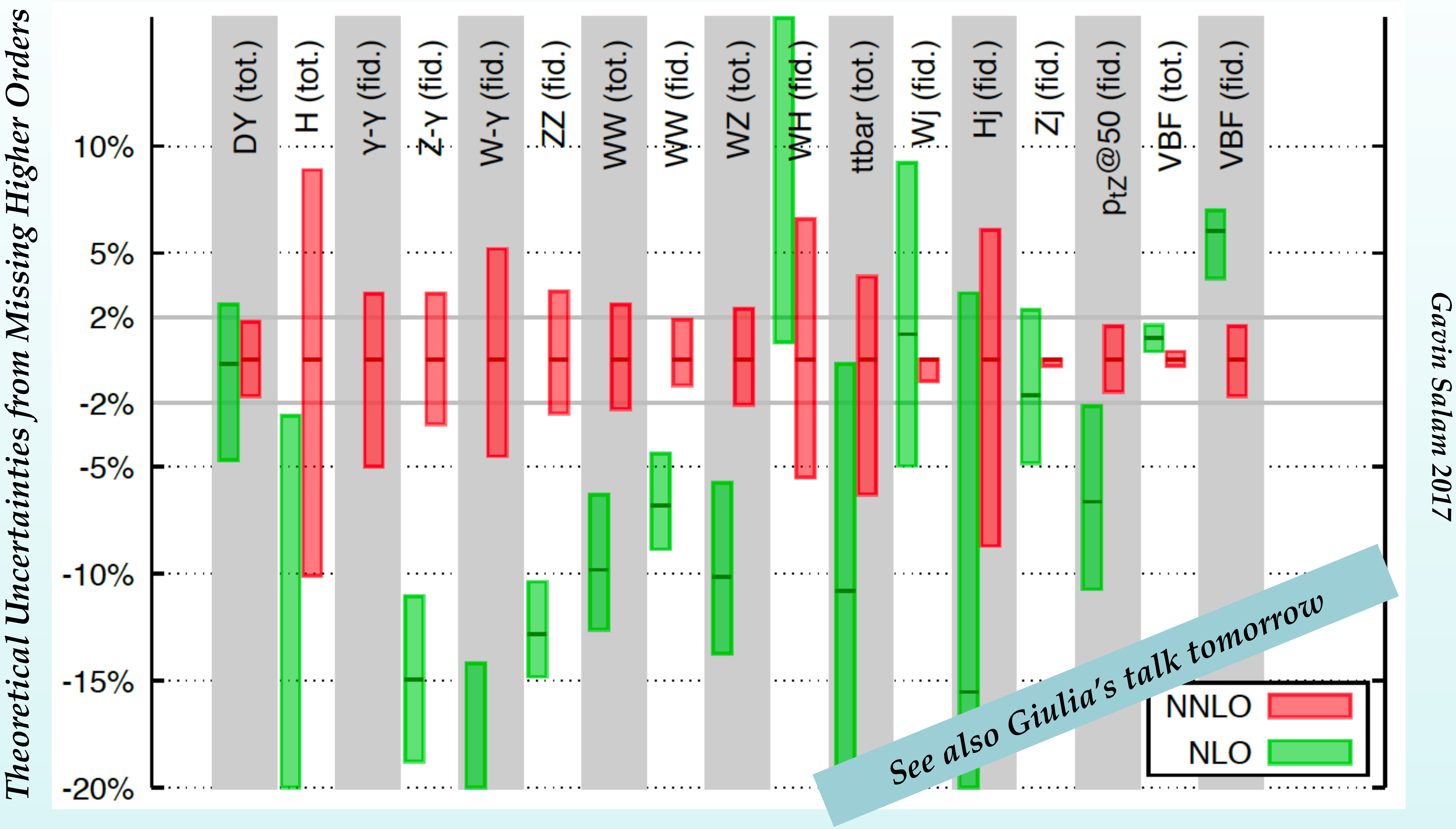


LHC phenomenology at 1% precision is within reach!

Initial state: Parton Distributions

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

$$g(x, Q)$$

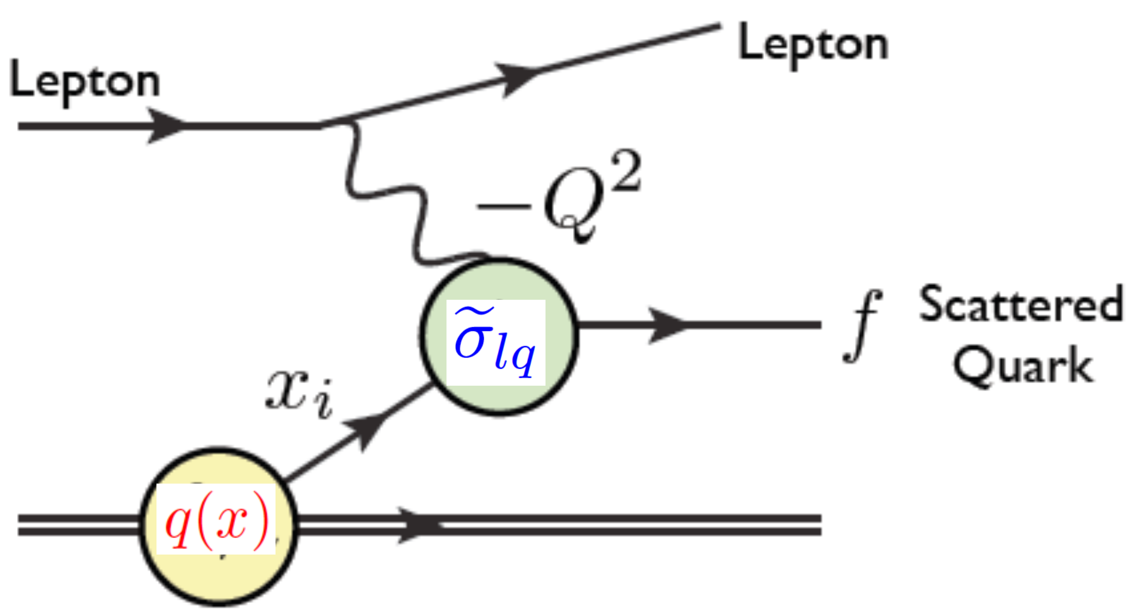
g(x,Q) : **Probability** of **finding a gluon inside a proton**, carrying a fraction ***x*** of the proton momentum when probed at energy ***Q***

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

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

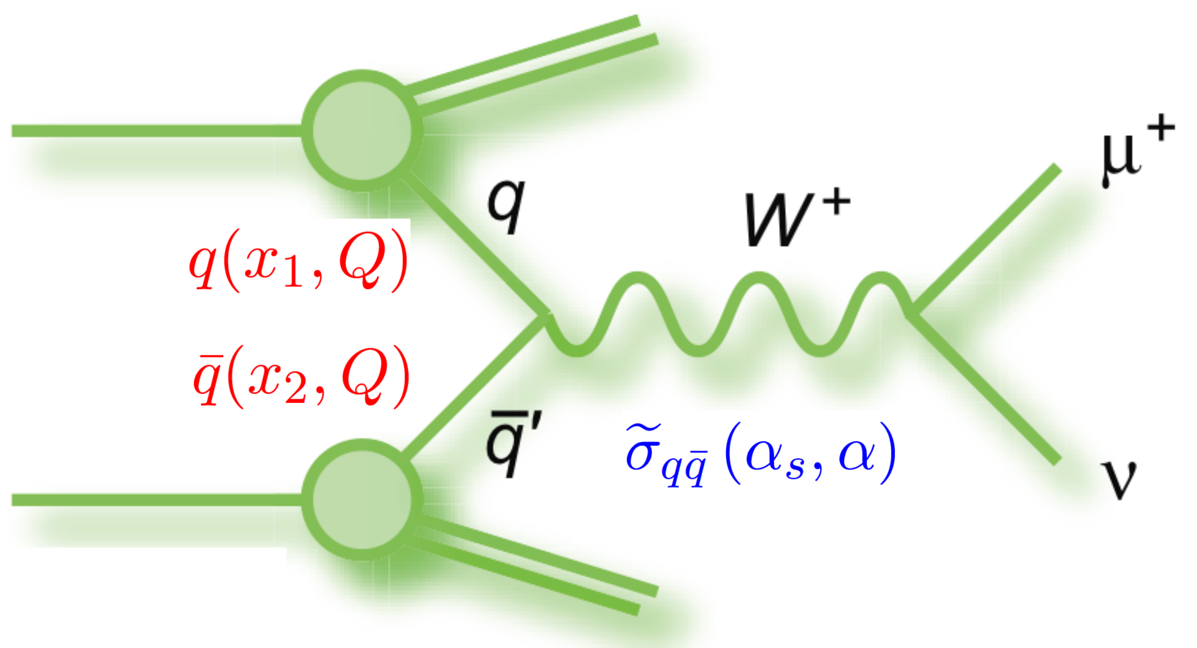
PDFs** determined by **non-perturbative QCD dynamics
*Extract from experimental data within a **global analysis***

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



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

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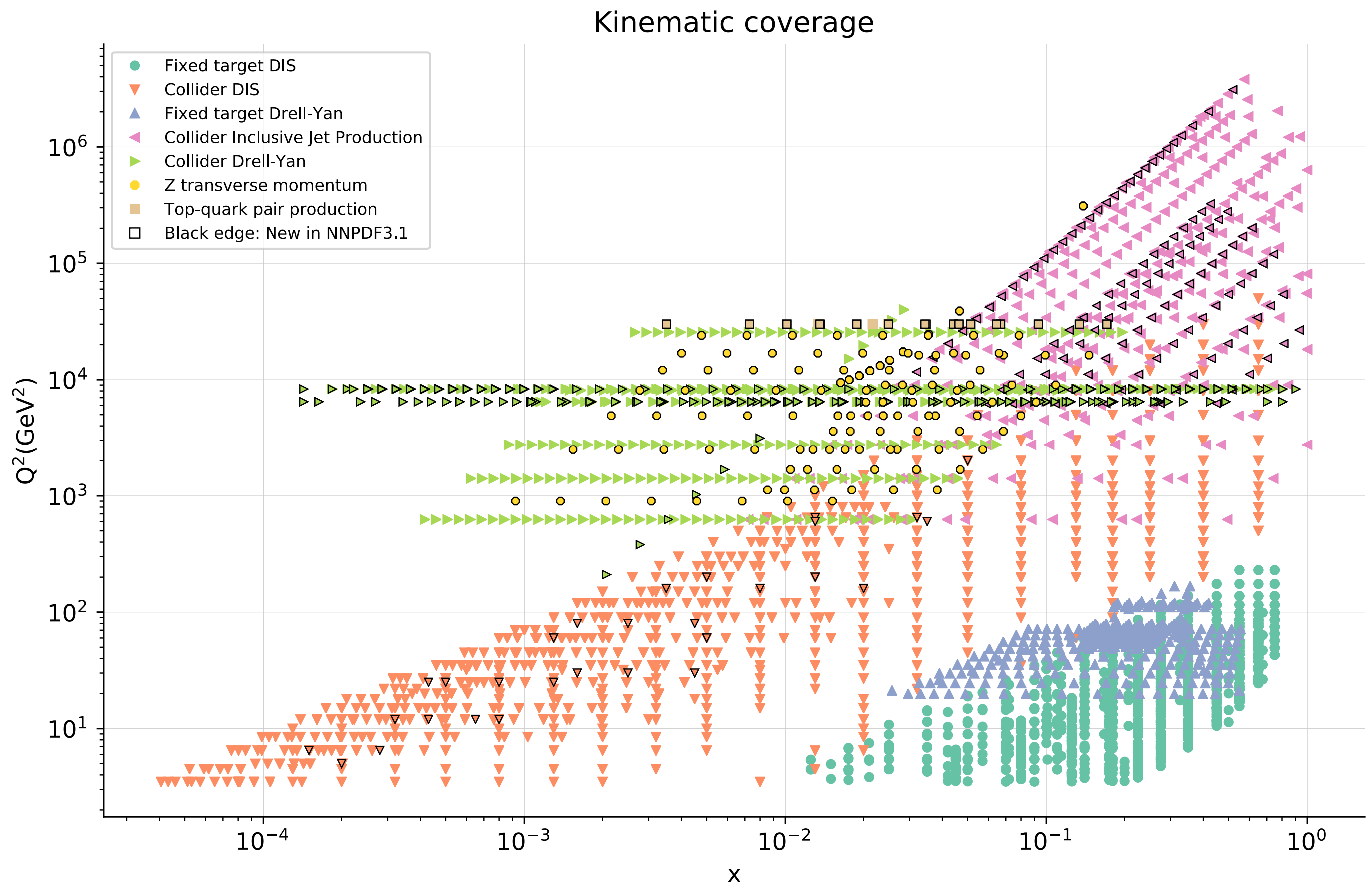
PDFs *determined by* ***non-perturbative QCD dynamics***
Extract from experimental data within a ***global analysis***

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

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

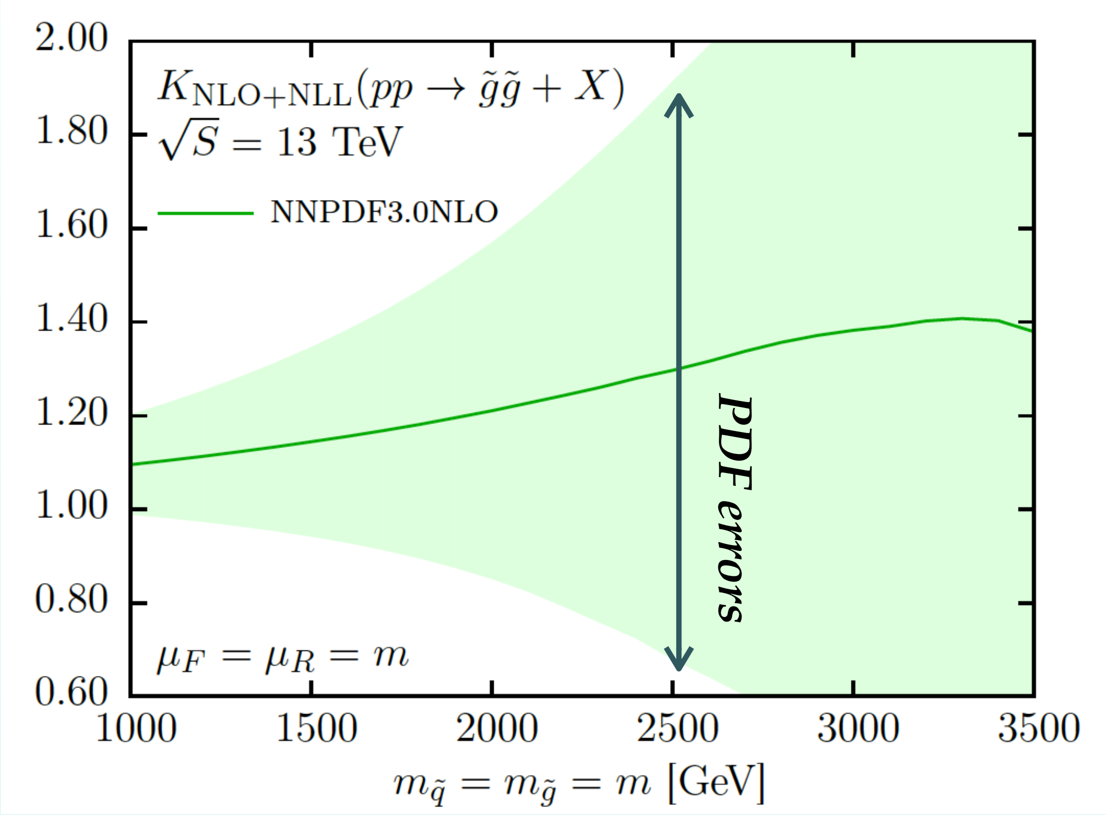
yet still $\chi^2/N_{dat} \approx 1$!



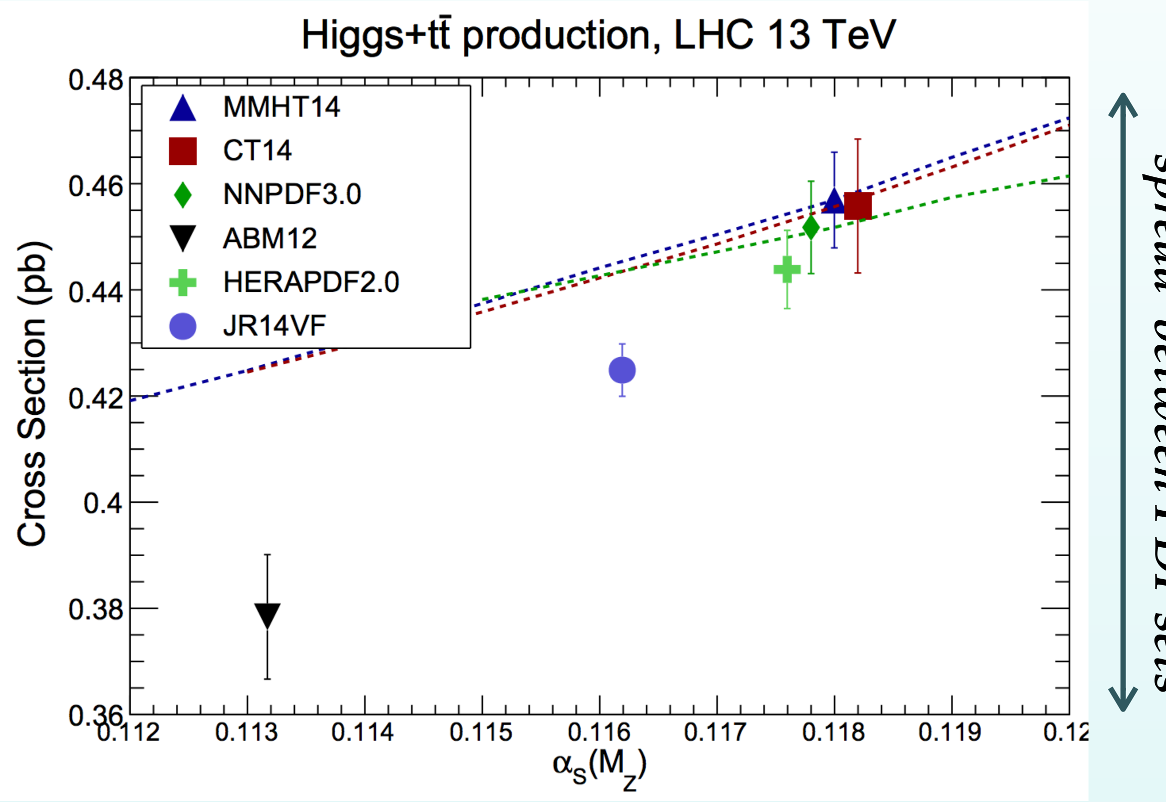
Why precision PDFs?

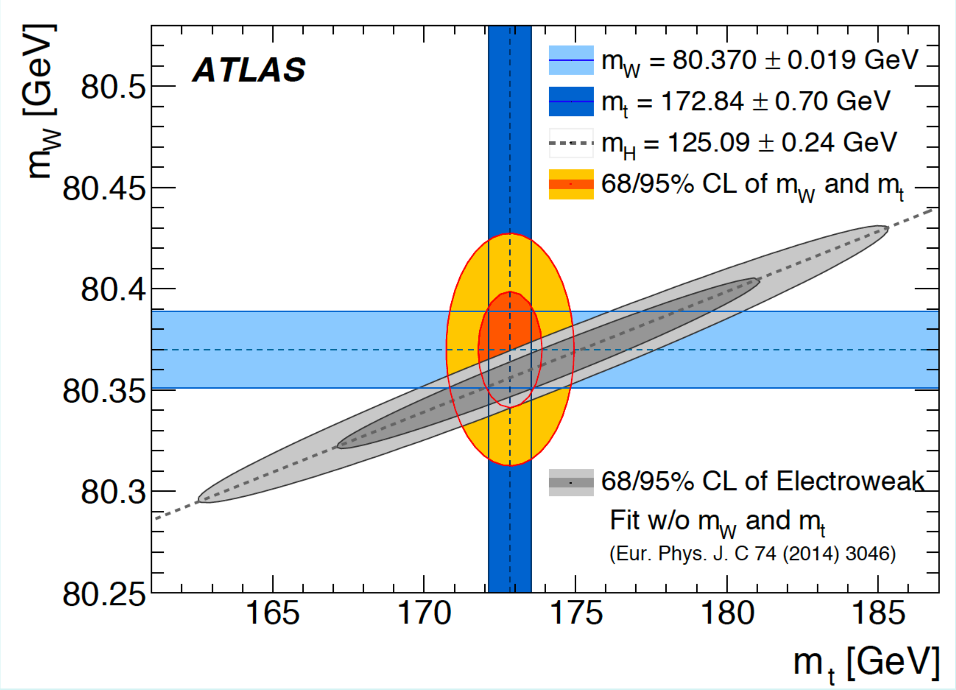
Ultimate accuracy of LHC calculations limited by **knowledge of proton structure**

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

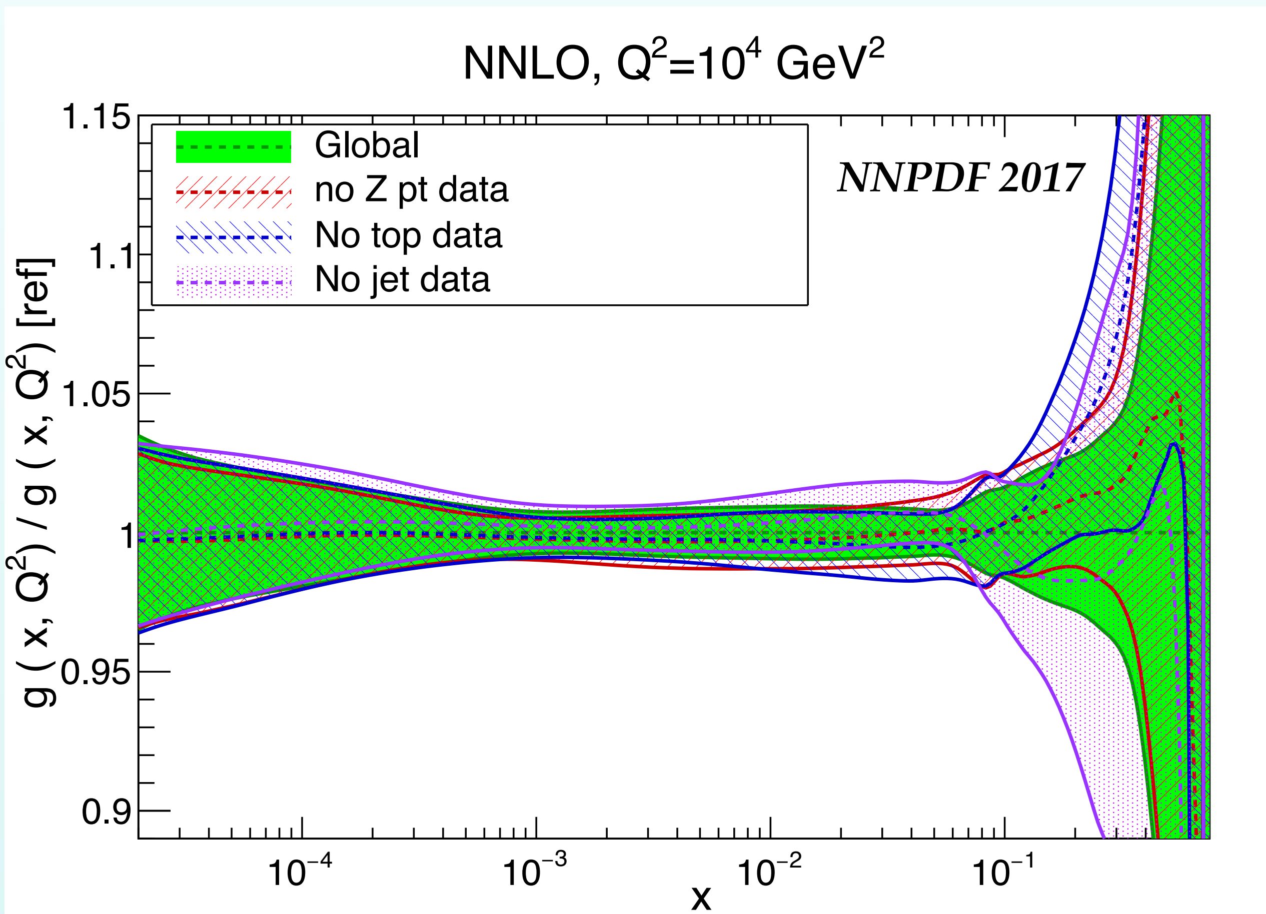
[HL-LHC forecast]

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 ….

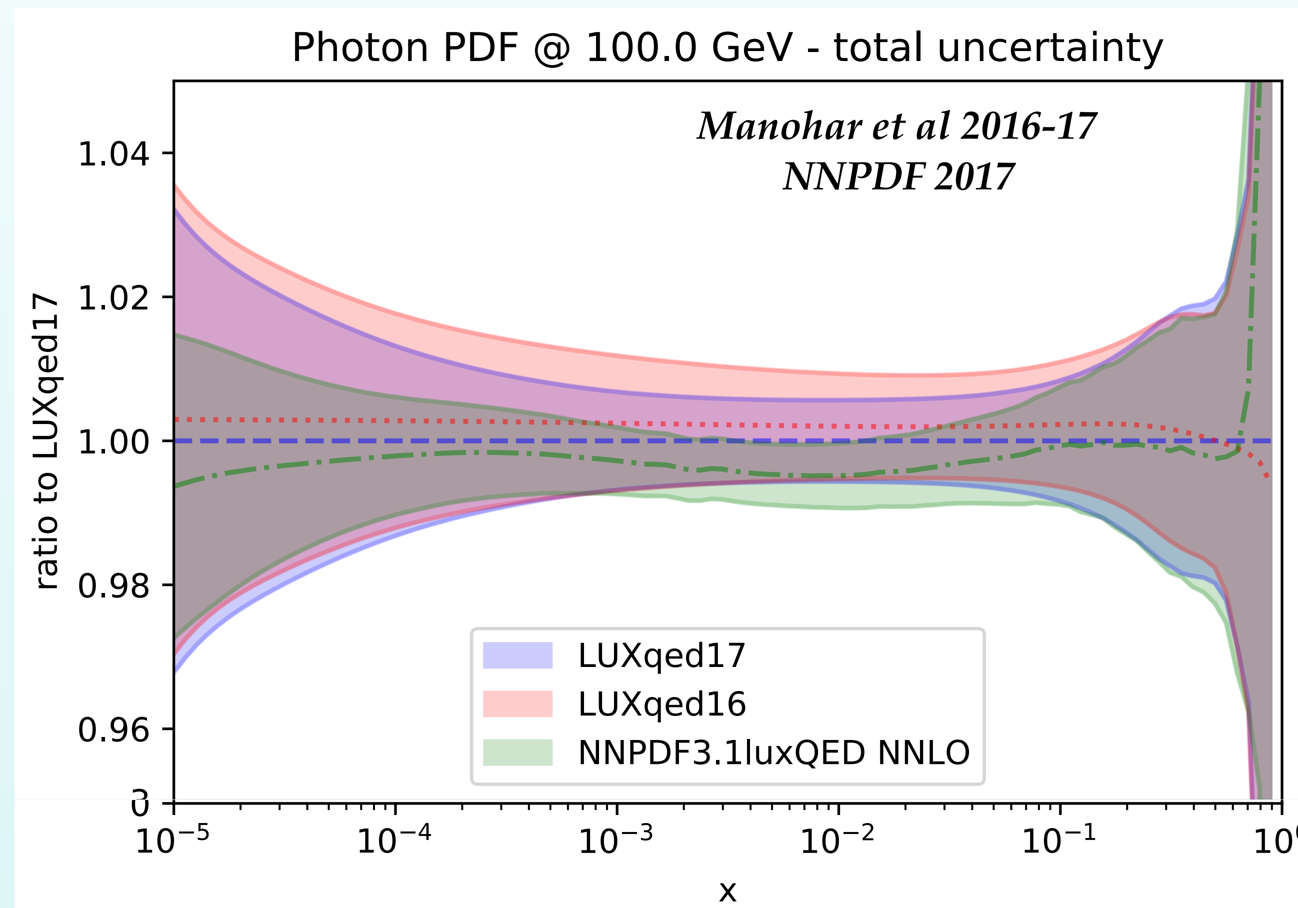
Precision NNLO gluon at large-x

from combining top, jet and Z p_T LHC data



Photon PDF with few % errors

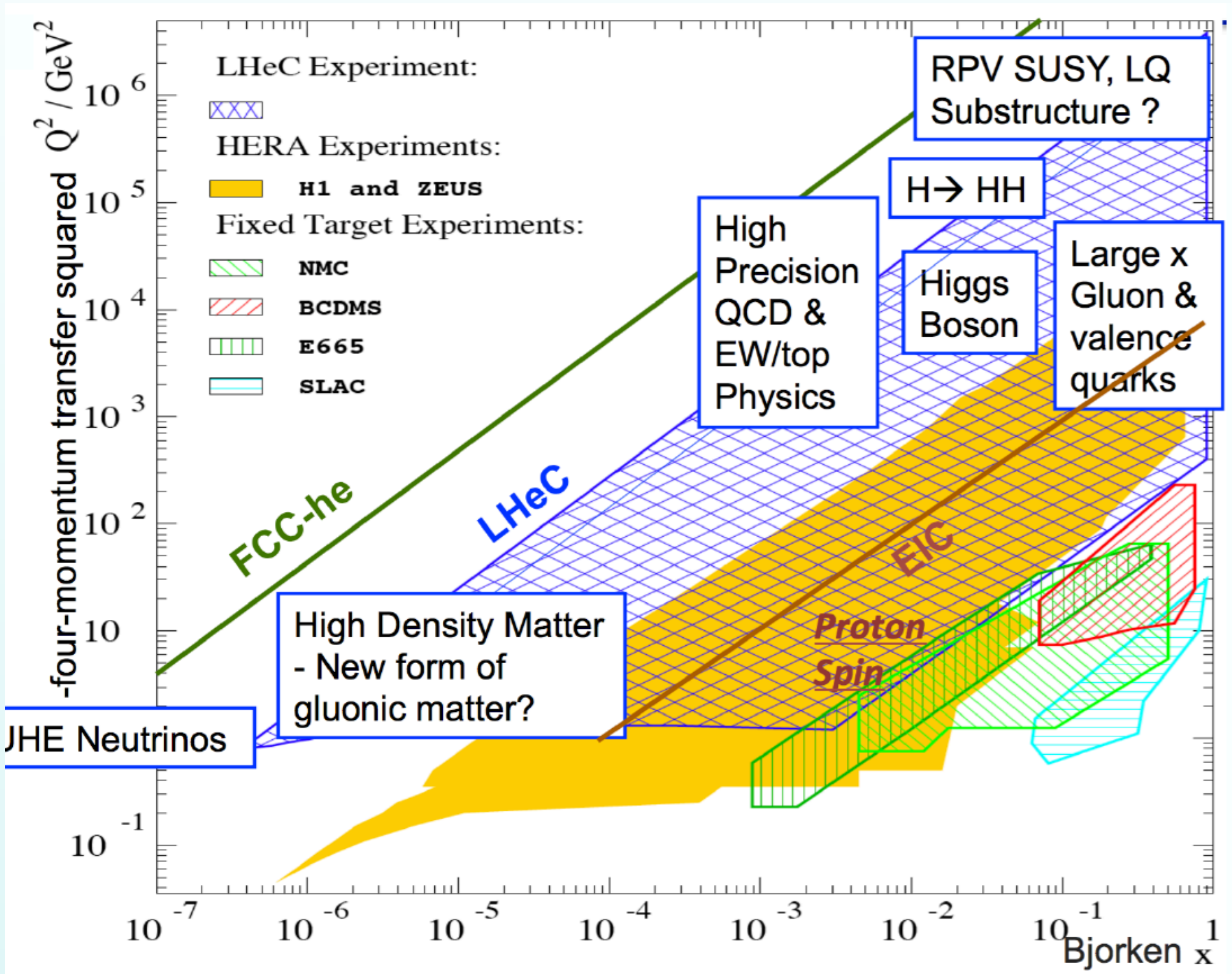
Crucial to complement electroweak calculations

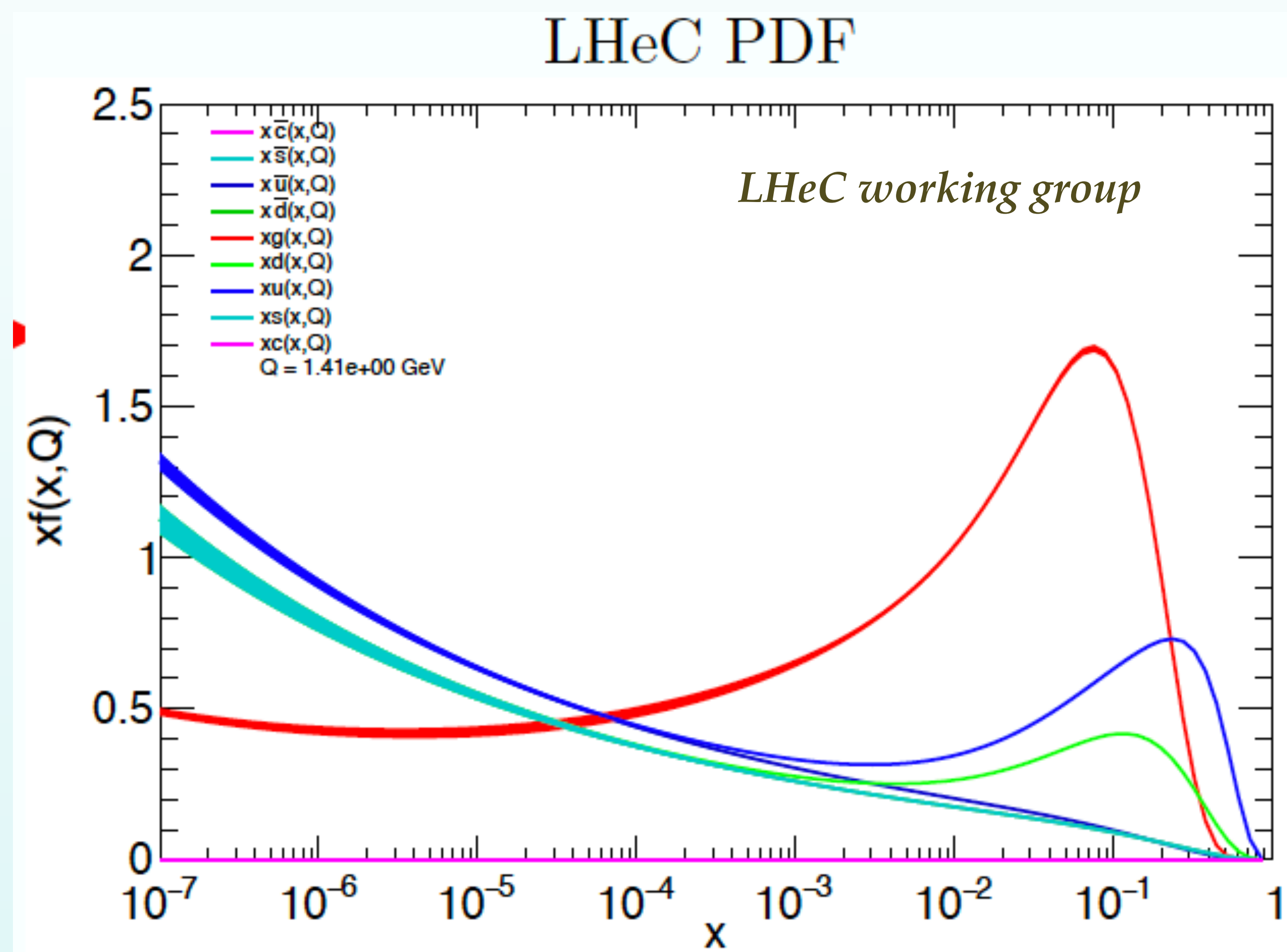


Progress in PDF determinations allows fully exploiting higher-order QCD calculations

LHeC: the ultimate proton microscope

HERA DIS structure function measurements provide **backbone of modern PDF analyses**

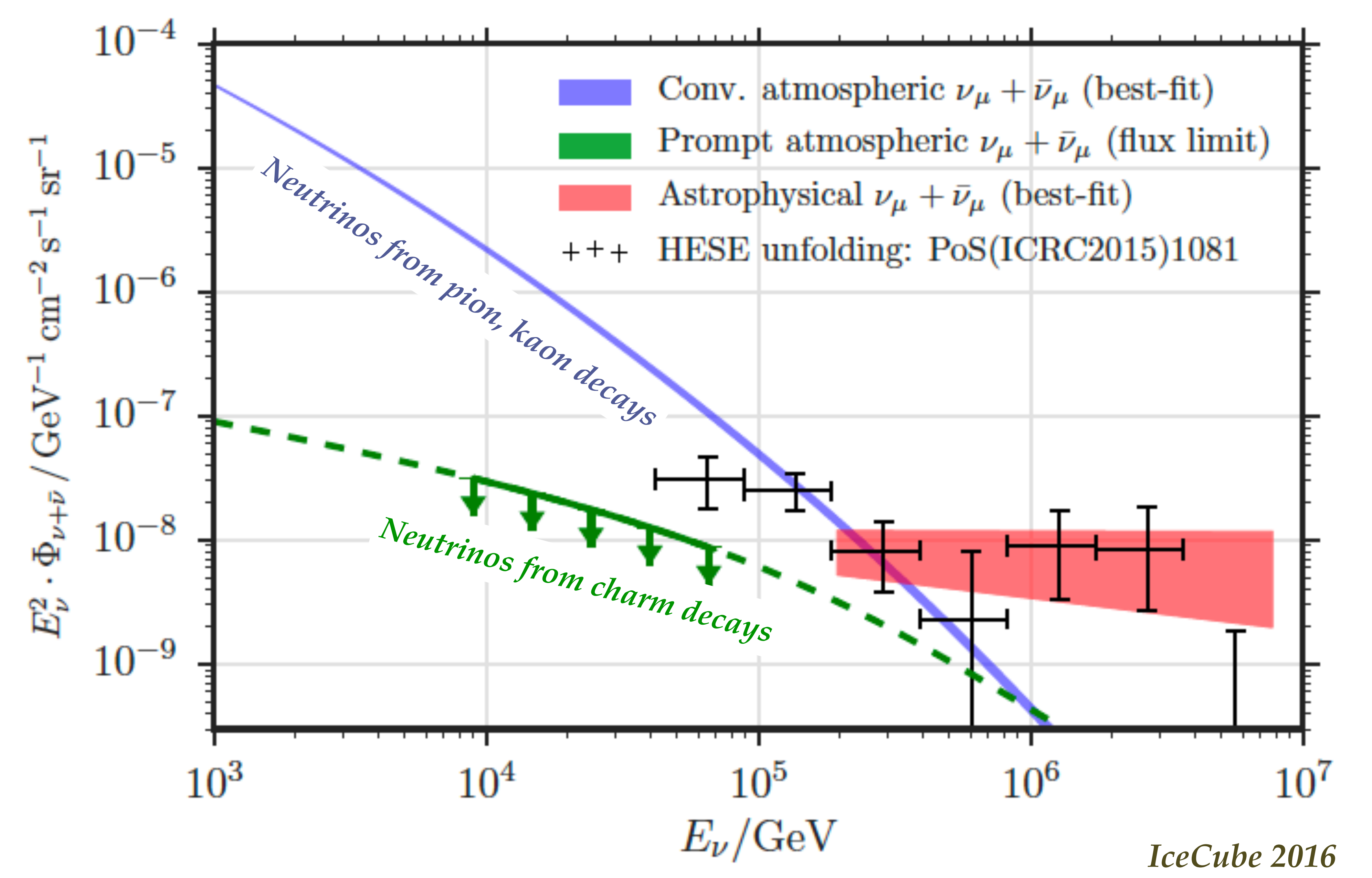




Higher energy lepton-hadron colliders such as the LHeC would allow unprecedented precision in our **understanding of the proton structure**

See also Tanja's talk tomorrow

Precision QCD and … neutrino astronomy?

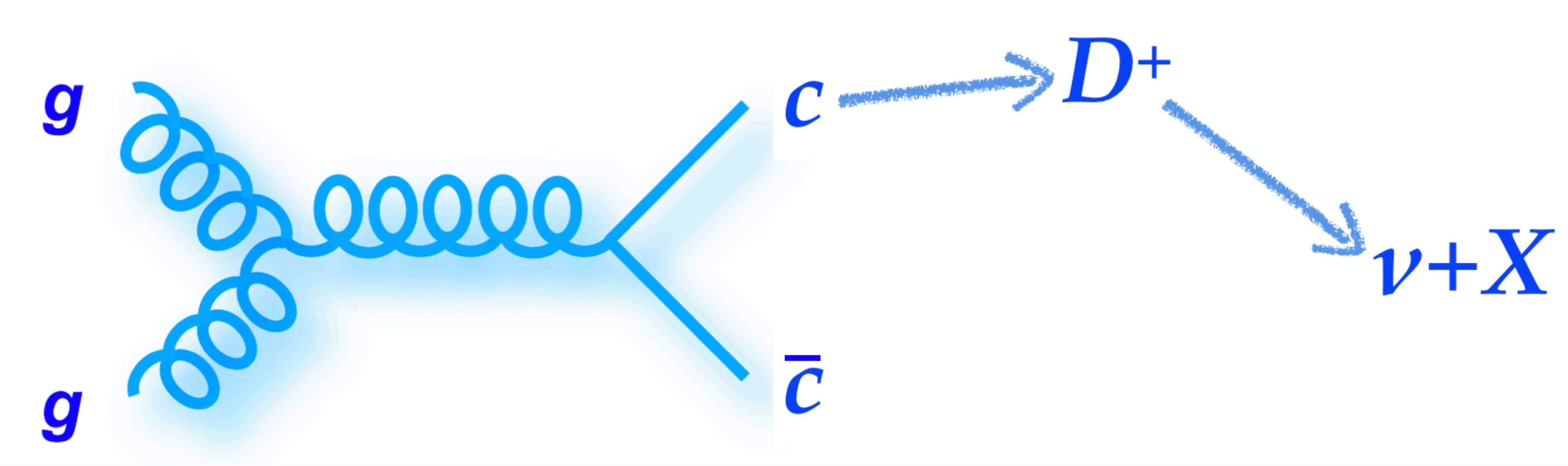


Detection of ultra-high energy neutrinos represents the beginning of **neutrino astronomy**: new window to the Universe!

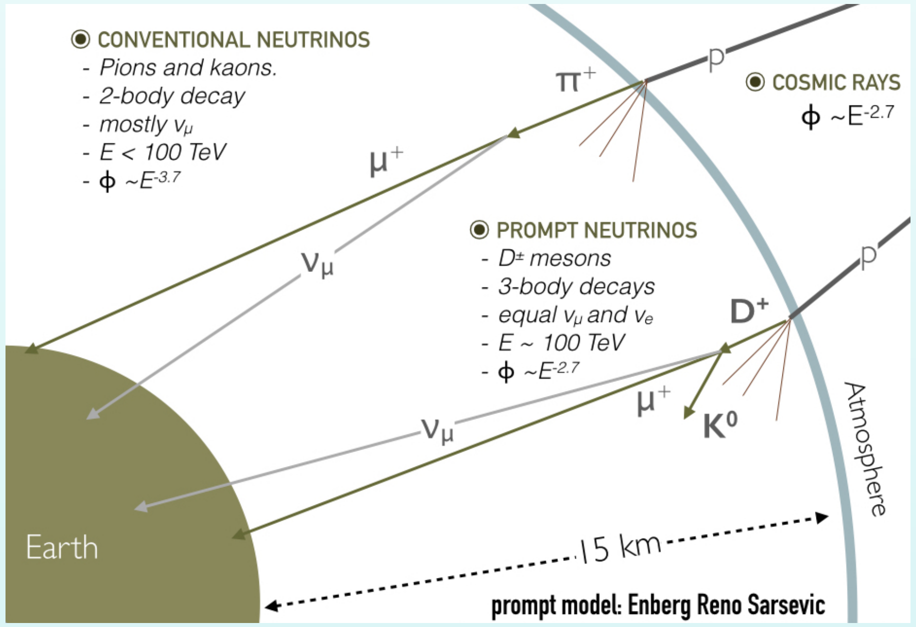
However, the dominant background, **prompt neutrinos from charm decays**, never been detected…

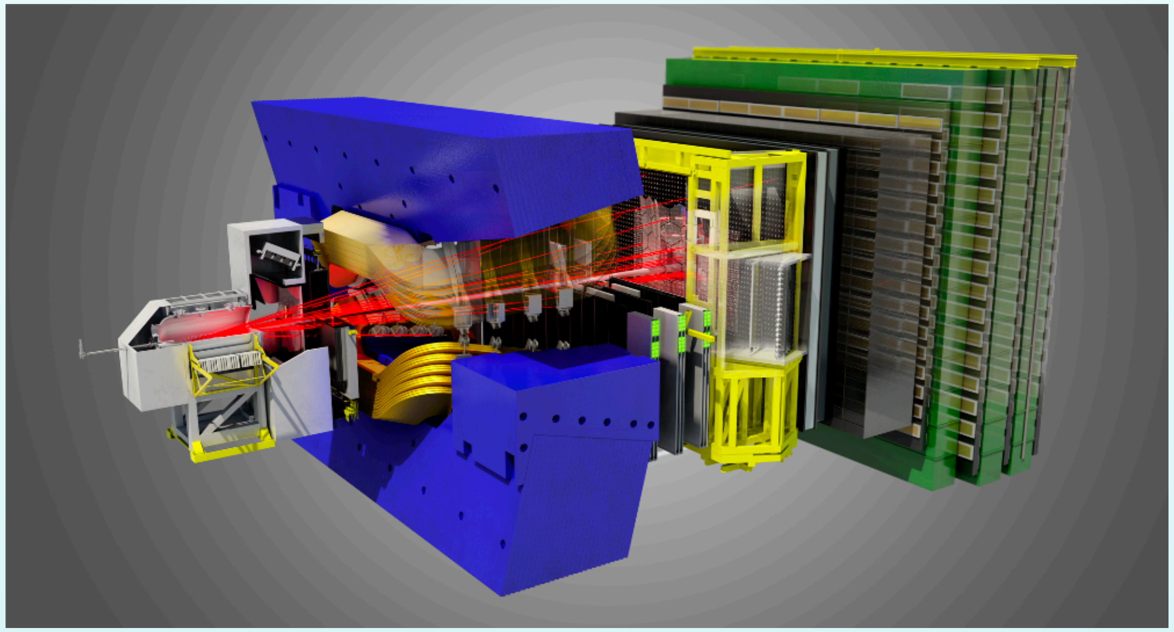
Precision QCD and ... neutrino astronomy?

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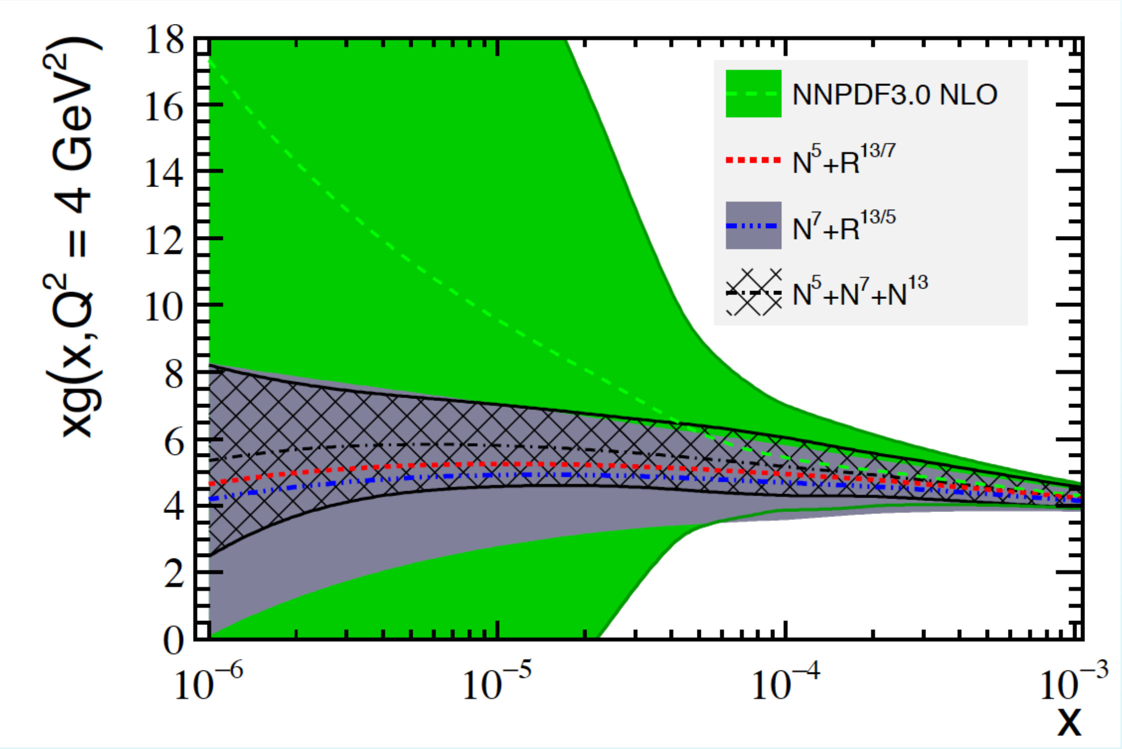
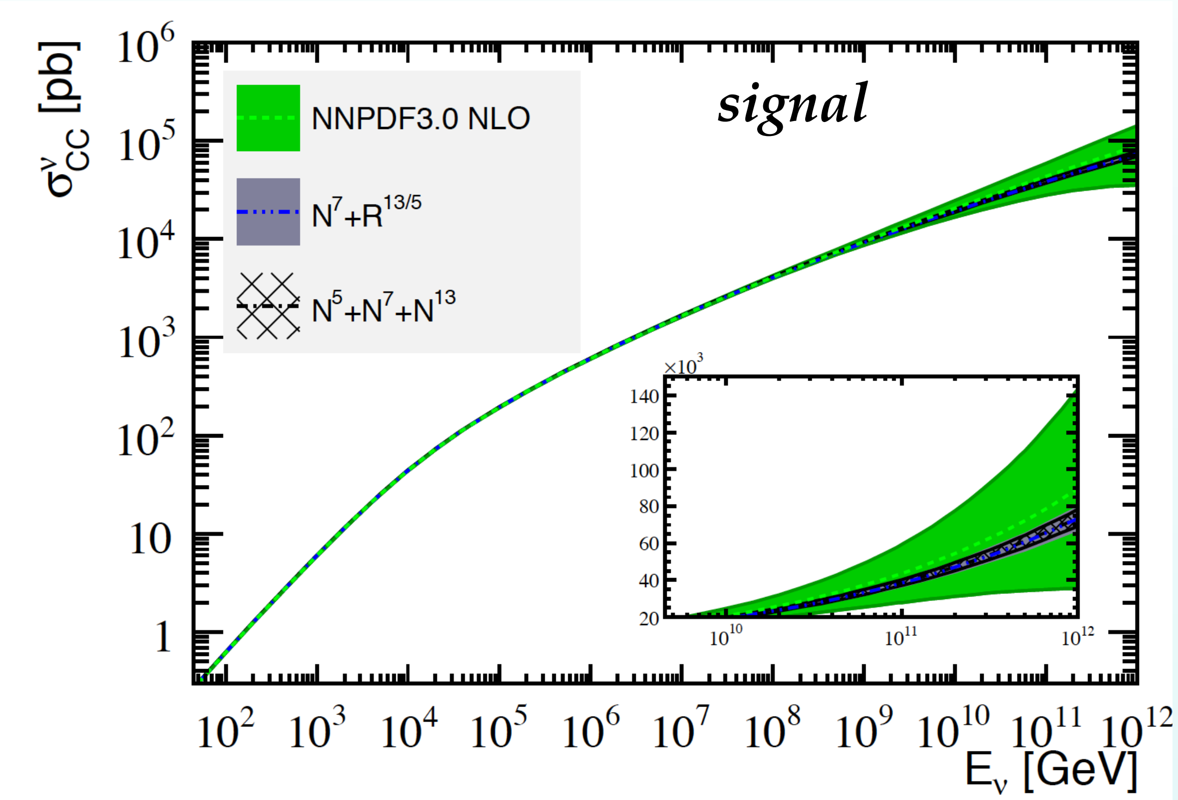
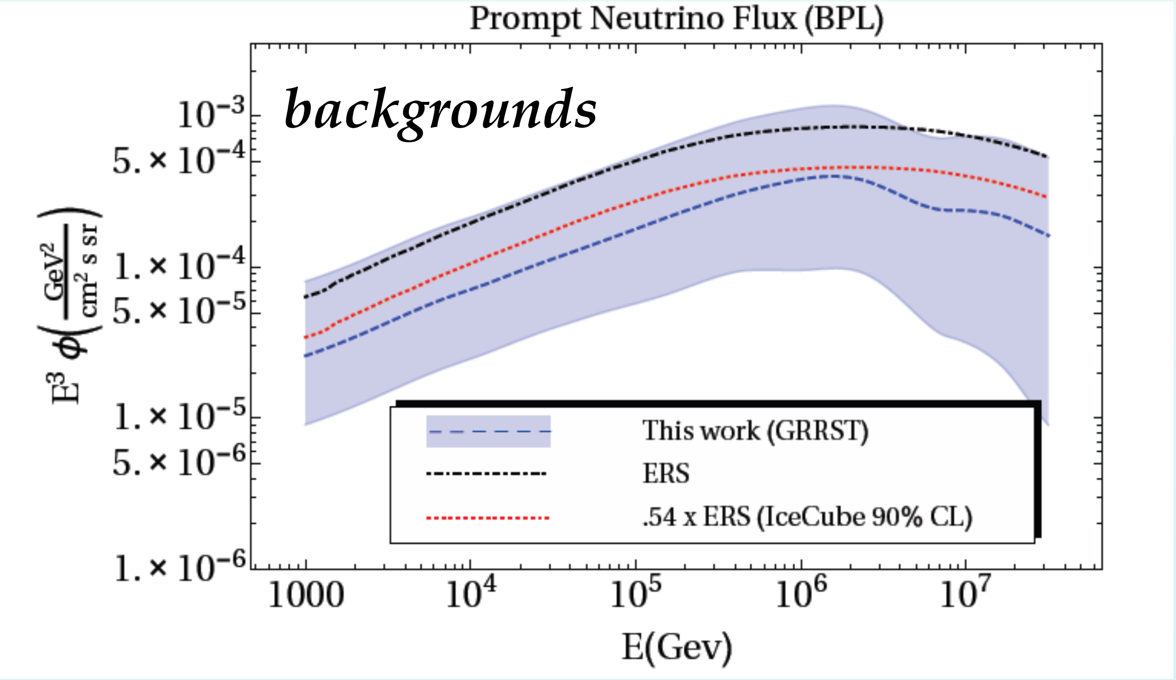
Precision determination of small-x gluon from charm production art LHCb



Gauld, JR 16

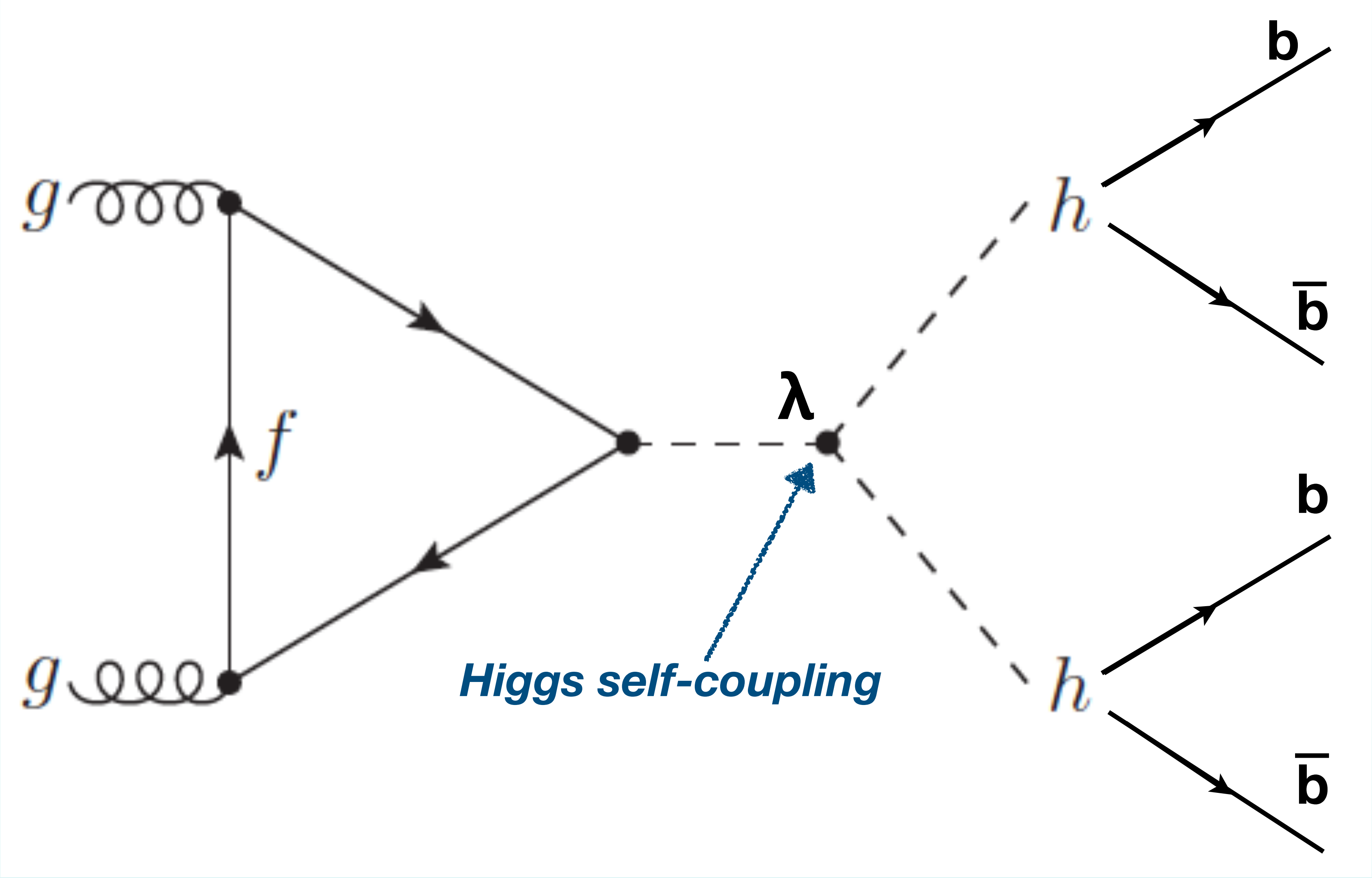




Progress in precision QCD benefits other fields beyond collider physics (i.e. also nuclear physics)

Machine Learning to Discover New Physics

QCD calculations supplemented by **advanced Machine Learning algorithms** lead to enhanced efficiency for a number of crucial tasks such as signal over background discrimination

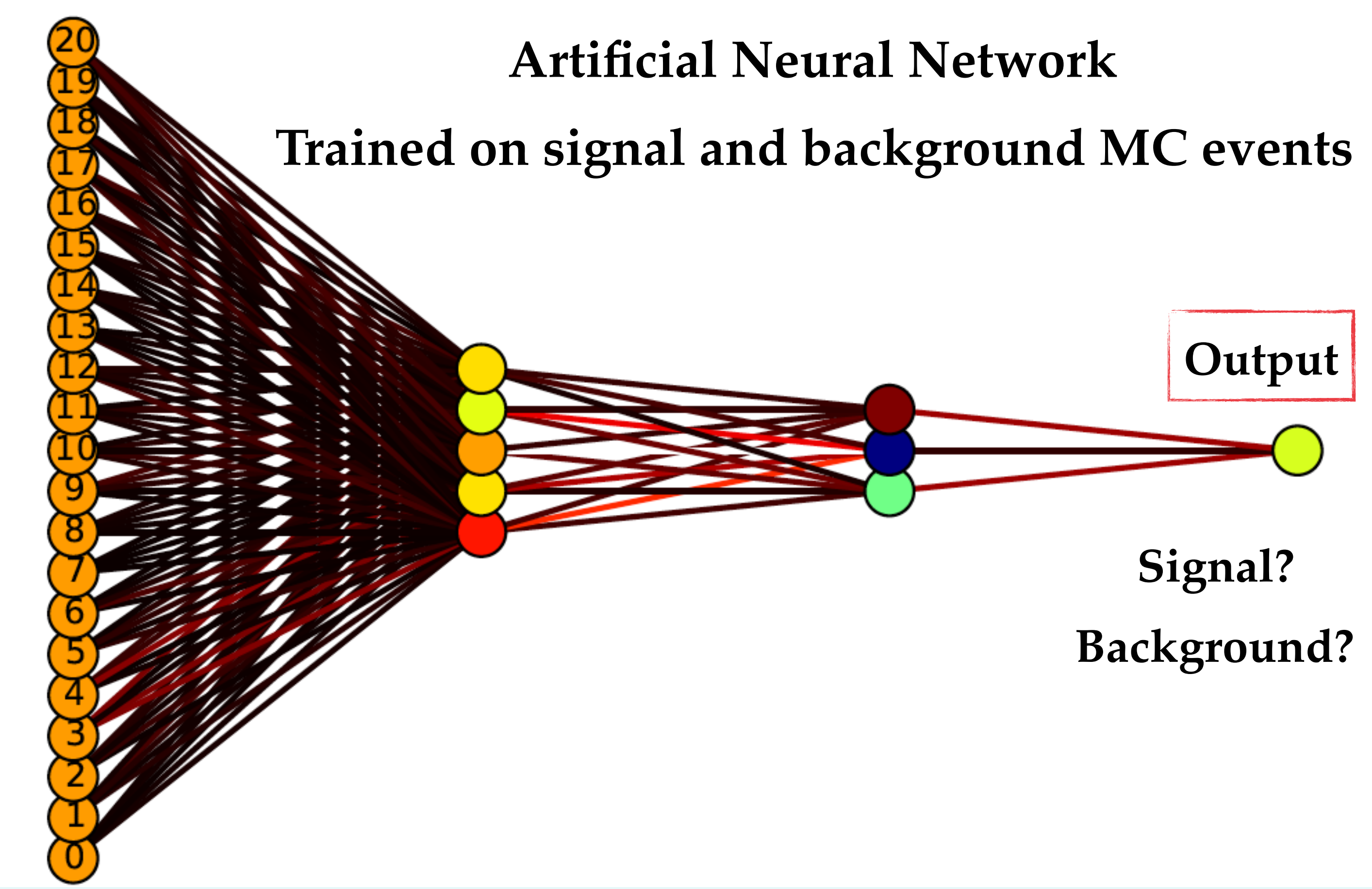


Consider **Higgs pair production in the 4b final state**: unique sensitivity to the (unknown!) **Higgs boson self-coupling**, but need to deal with an **overwhelming QCD background ≈ 10^7 times larger**

Machine Learning to Discover New Physics

Input

Higgs p_T
Higgs m
di-Higgs m
ECF
τ_{12}
Subjet p_T
***b*-tagging**
…..

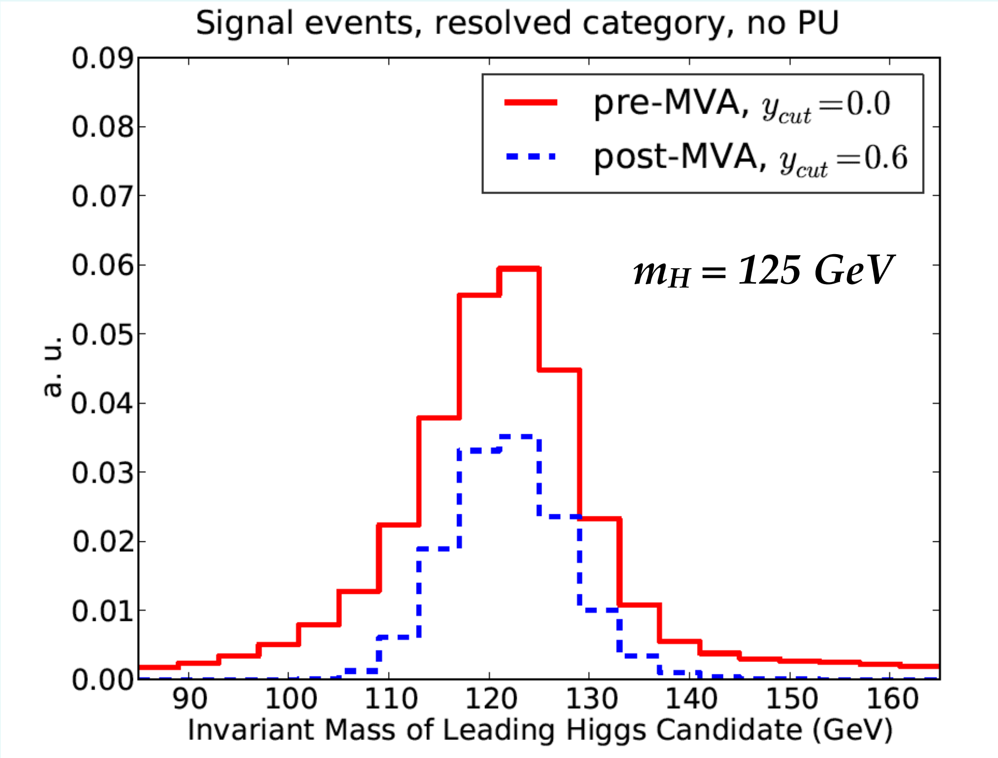


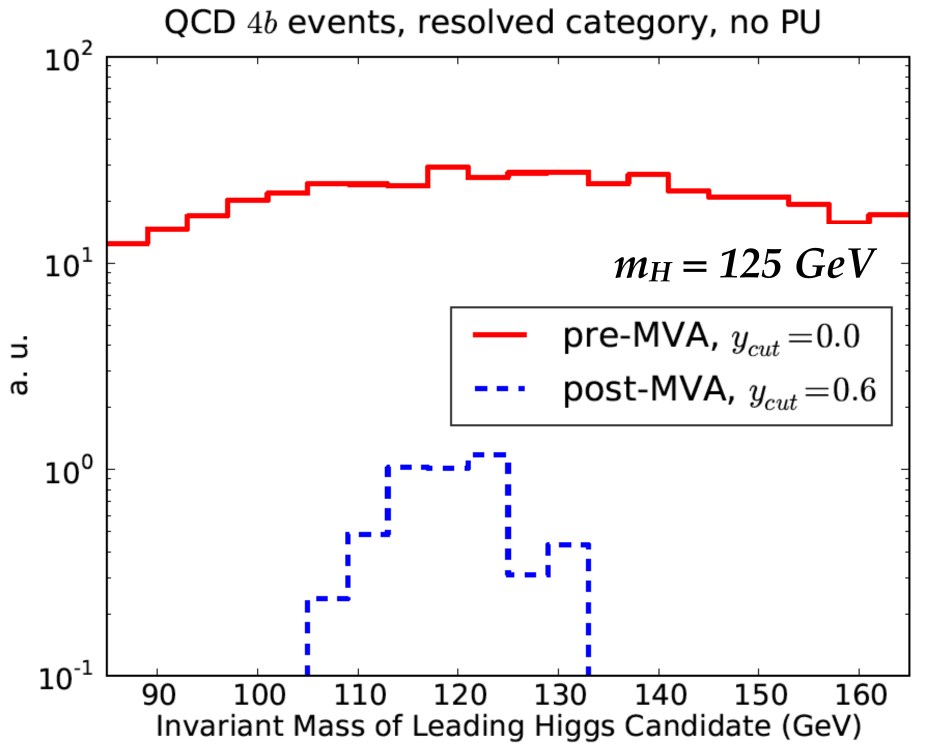
Post-ANN significance

$$\left(\frac{S}{\sqrt{B_{4b}}}\right)_{\rm tot} \simeq 4.7\ (1.5)$$

$$\mathcal{L} = 3000\ (300)\ \text{fb}^{-1}$$

*Combining **state-of-the-art QCD with ML tools** boosts LHC discovery potential*





Enhancing sensitivity down to *truly irreducible* background:
i.e. ***ANN sculpts Higgs mass peak in QCD events***

Behr, Bortoletto, Frost, Hartland, Issever, JR 15

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

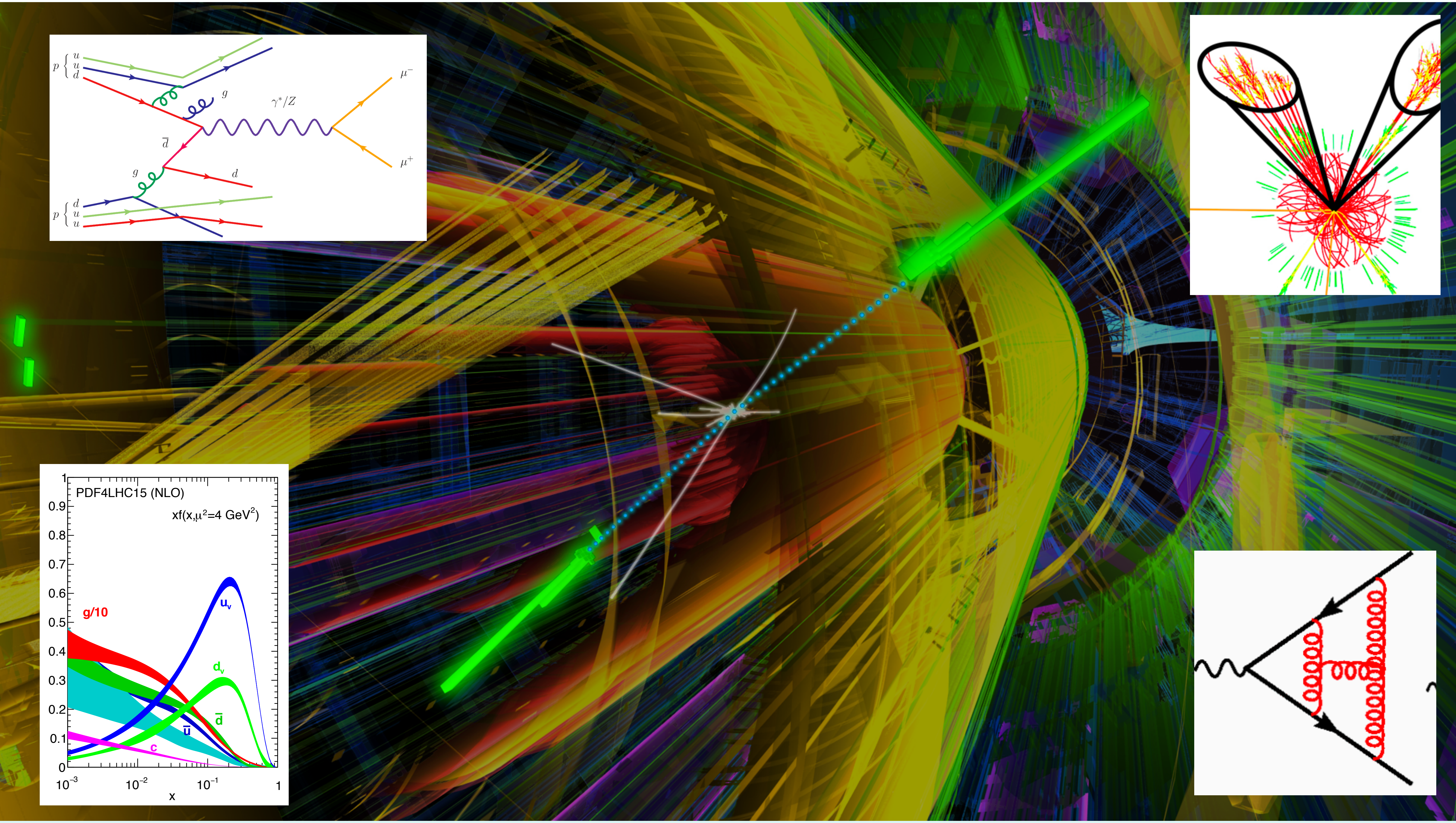
- ☑ Detailed mapping of the proton structure: **few-percent errors in most PDFs in relevant LHC range**, including gluon and photon

- ☑ 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!

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