# Theory Challenges in QCD predictions


Quy Nhon

August 6-12, 2023

Laura Reina

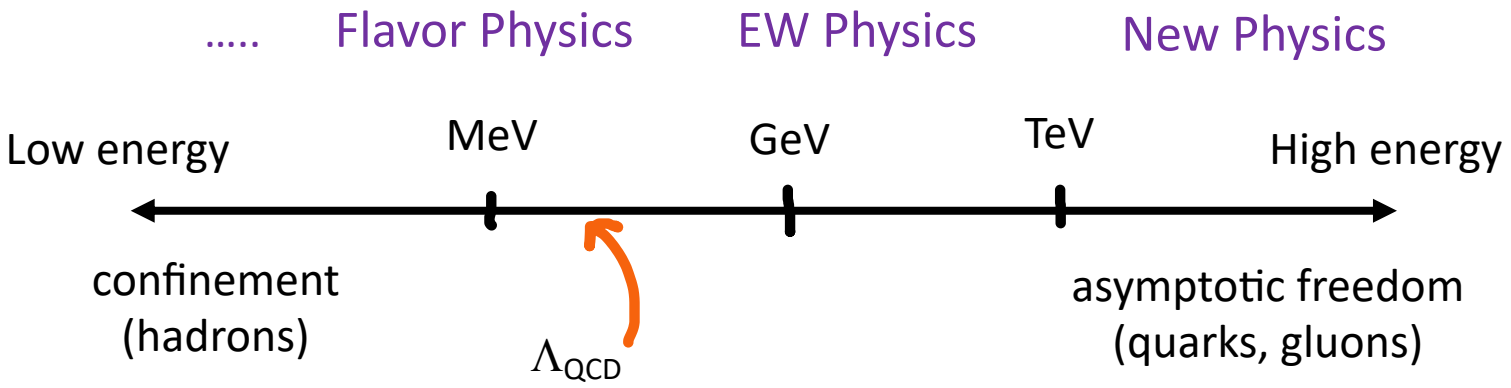
Florida State University

# A big year for QCD

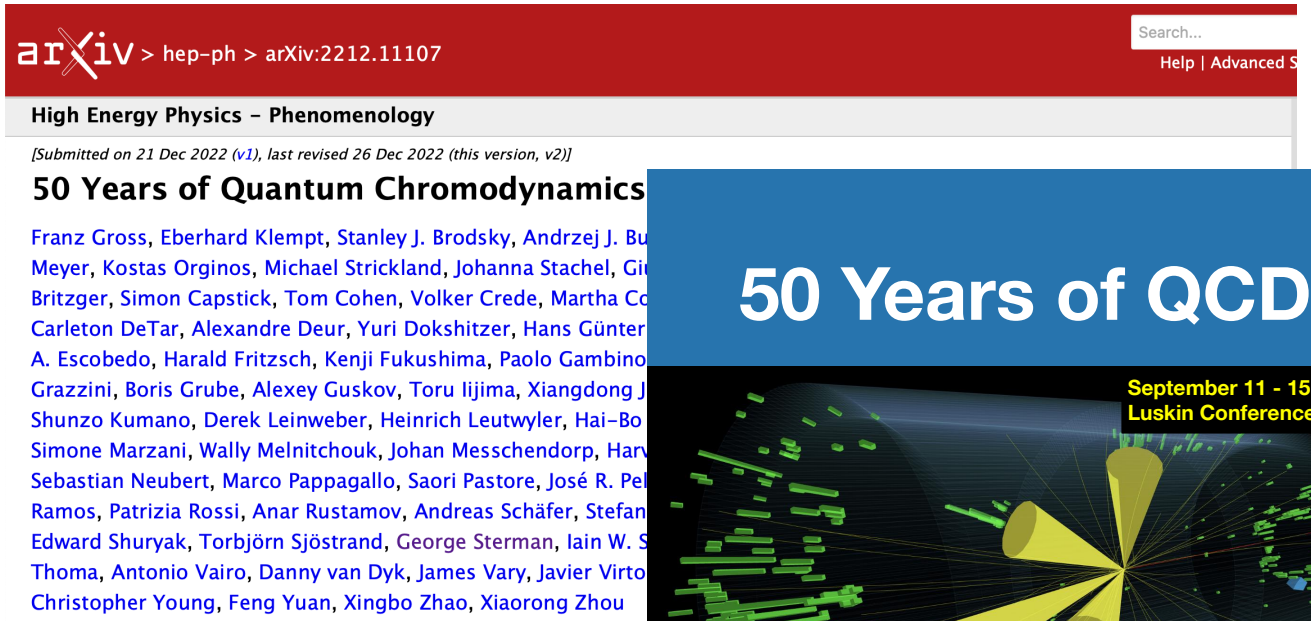
QCD was developed and defined over a brief period from 1972 - 73

The **asymptotic freedom** of strong interactions was discovered in 1973 by **D. Gross, F. Wilczek, and D. Politzer** – **Nobel Prize in 2004**

A paradigmatic QFT that can be calculated from first principles ⟶ Lattice QCD




Very different energy regimes, over multiple orders of magnitude,
spanning the full spectrum of particle physics experiments


arXiv > hep-ph > arXiv:2212.11107

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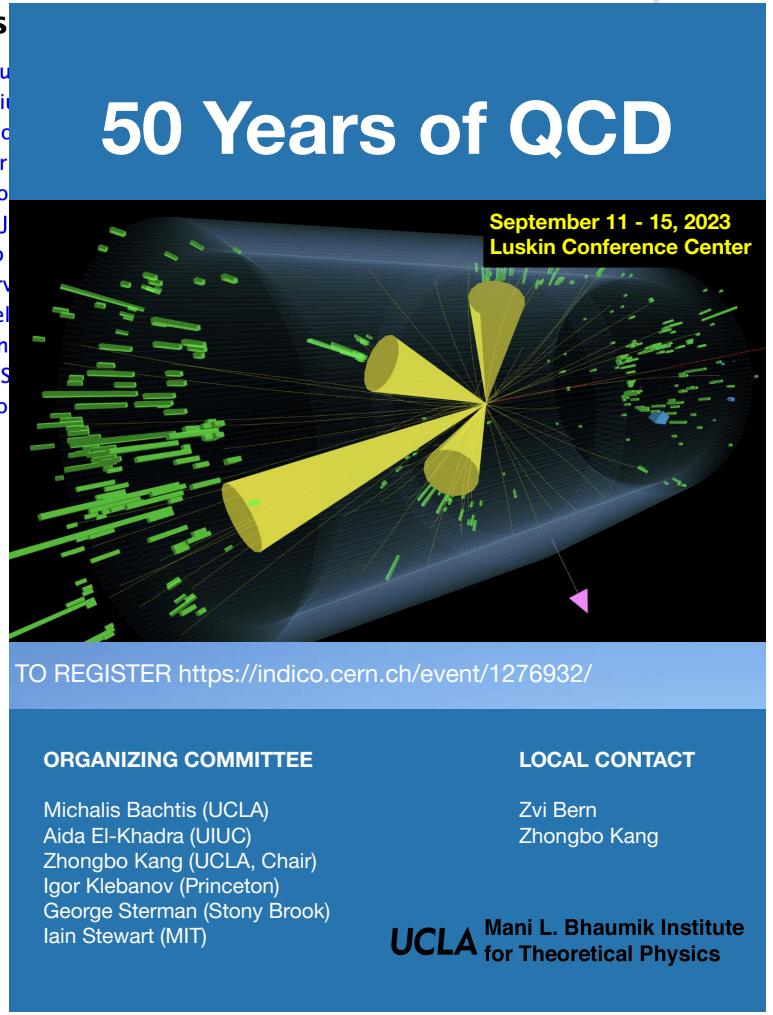
High Energy Physics – Phenomenology

[Submitted on 21 Dec 2022 (v1), last revised 26 Dec 2022 (this version, v2)]

**50 Years of Quantum Chromodynamics**

Franz Gross, Eberhard Klempt, Stanley J. Brodsky, Andrzej J. Bu
Meyer, Kostas Orginos, Michael Strickland, Johanna Stachel, Gi
Britzger, Simon Capstick, Tom Cohen, Volker Crede, Martha Co
Carleton DeTar, Alexandre Deur, Yuri Dokshitzer, Hans Günter
A. Escobedo, Harald Fritzsch, Kenji Fukushima, Paolo Gambino
Grazzini, Boris Grube, Alexey Guskov, Toru Iijima, Xiangdong J
Shunzo Kumano, Derek Leinweber, Heinrich Leutwyler, Hai-Bo
Simone Marzani, Wally Melnitchouk, Johan Messchendorp, Harv
Sebastian Neubert, Marco Pappagallo, Saori Pastore, José R. Pel
Ramos, Patrizia Rossi, Anar Rustamov, Andreas Schäfer, Stefan
Edward Shuryak, Torbjörn Sjöstrand, George Sterman, Iain W. S
Thoma, Antonio Vairo, Danny van Dyk, James Vary, Javier Virto
Christopher Young, Feng Yuan, Xingbo Zhao, Xiaorong Zhou



# Goals of QCD studies- 2023

- **Understanding strong interactions per se** (in different regimes of energy, density, …)
  - **pQCD – parton dynamics in HE-collider events** See talk by Schwartz
  - **non-perturbative QCD – PDFs,** hadronization, new states of matter, …
  - QCD phase transition – early-universe dynamics, … See talks by Grosse-Oetringhaus, Mohamty
  - Global symmetries of QCD – flavor, spectroscopy, …
  - Strong CP problem – axions, … See talks by Petrov, Schune, Ozcelik, Kim, Bianchi, Pepe, Karliner, Polyakov
- **Understanding the impact of strong interactions on anything else**
  - **Other sectors of the Standard Model**
    - SM masses and couplings See talks by d'Enterria, Liao
    - The least known of all: Higgs – EWSB See talks by Mühlleitner, Liu, di Micco
  - **New physics searches – both direct and indirect**
    - SM backgrounds
    - Precision EW physics – Global fits of the SM and beyond See talk by Silvestrini

# The (HL)-LHC and precision phenomenology

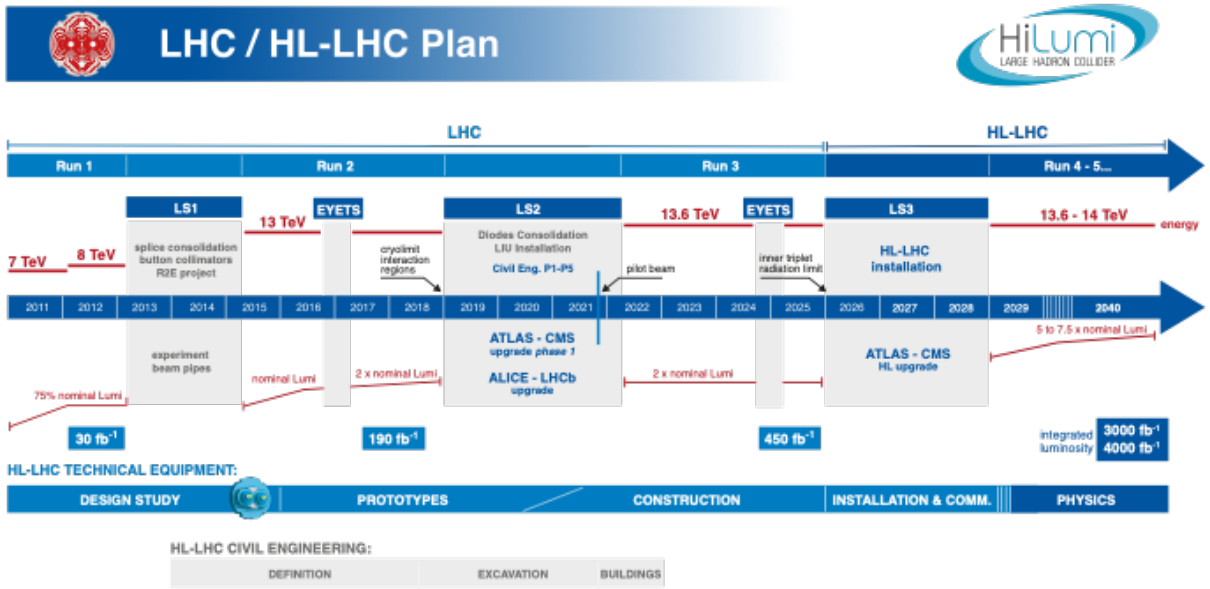
- Percent level phenomenology as the opportunity to study some of the core questions of particle physics and uncover new physics. The physics potential of the LHC greatly depends on enabling and successfully executing a broad precision phenomenology program.

# Living the LHC era- Precision phenomenology

**Universal limitations**

- Luminosity — ATLAS, 2212.09379; CMS, 2104.01927
- Energy resolution (particles, jets) — ATLAS, 1703.09665; CMS, 1607.03663

**Both about 1 %**




20 -fold increase in statistics by the end of HL-LHC

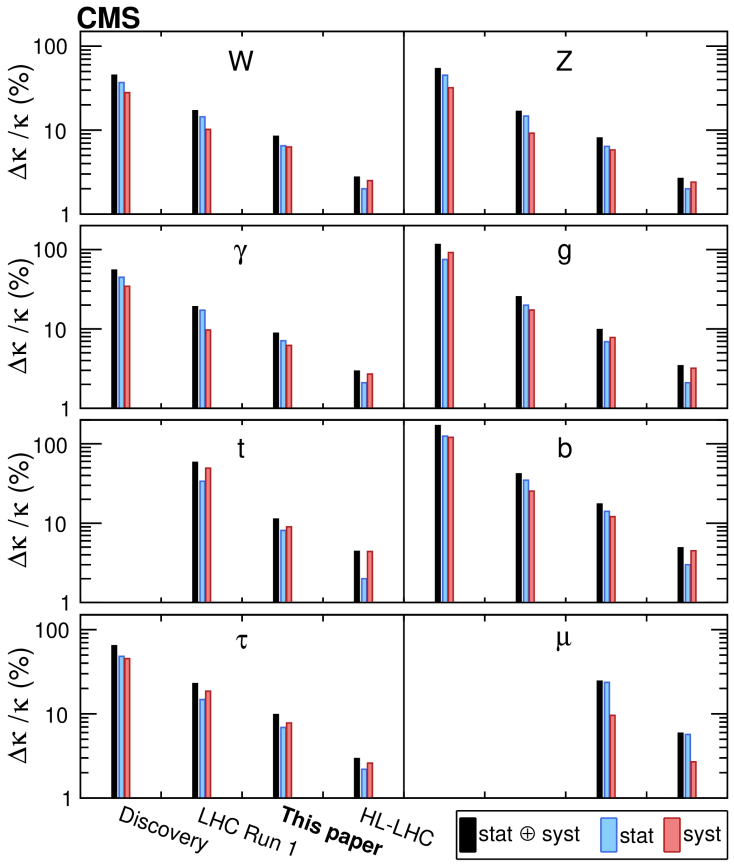
**Statistical limitations will be overcome**

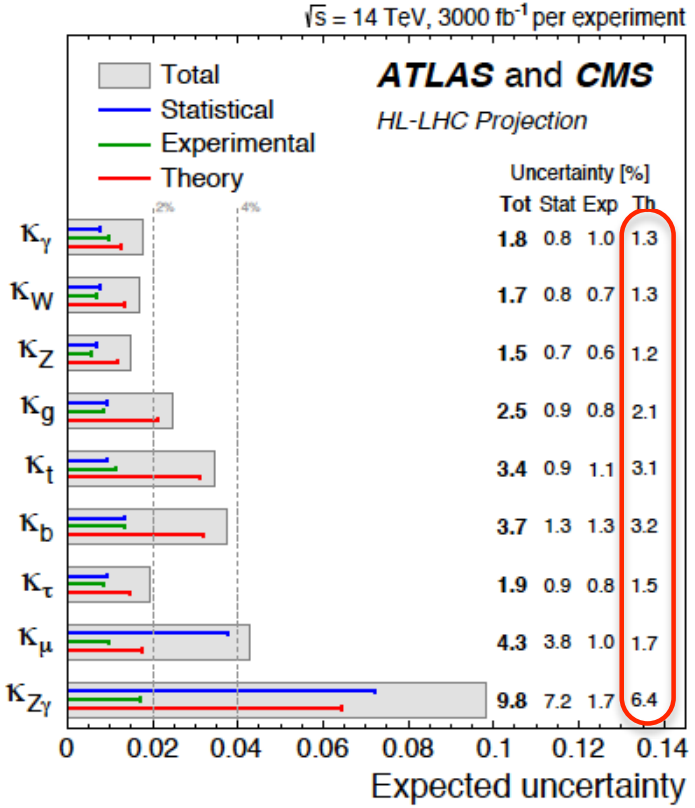
for a very large number of observables

Focus on systematics!

**Theoretical systematics could become the main limitation**

# Establishing the scalar sector of the SM and probing $\Lambda_{NP}$




$\Delta\kappa/\kappa \sim O(v^2/\Lambda^2)$

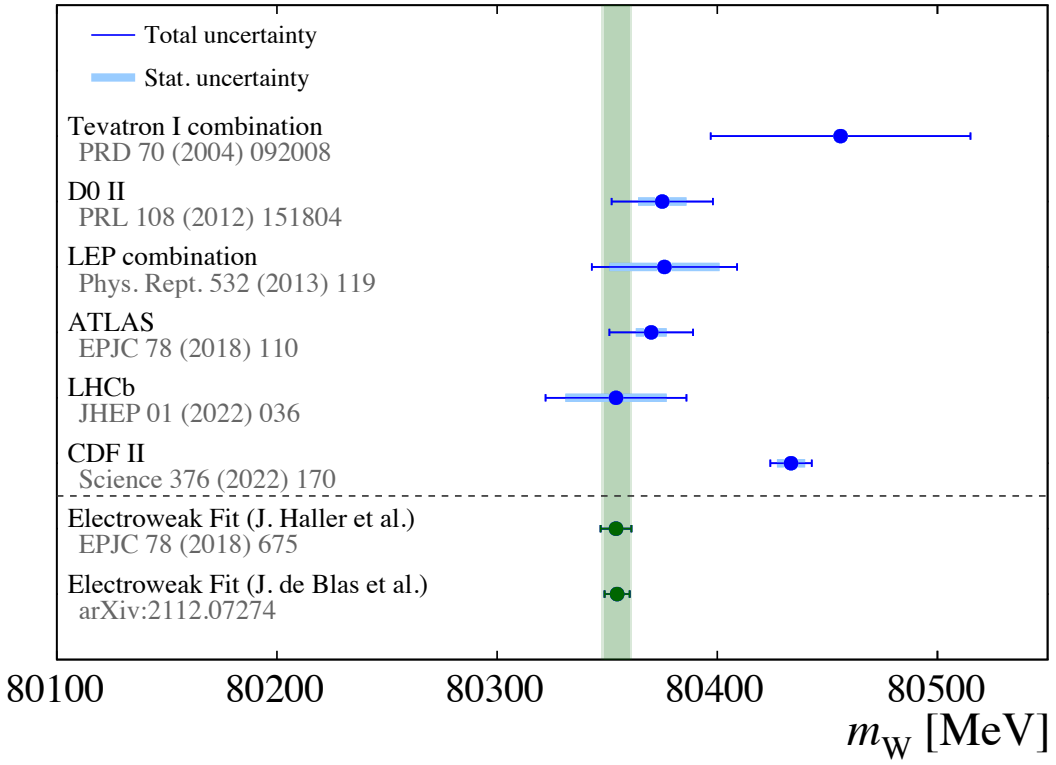
For new physics at 1 TeV expect deviations of O(6%)

Improved systematics probes higher scales

Theory could become the main limitation

Theory need to improve modeling and interpretation of LHC events, in particular when new physics may not be a simple rescaling of SM interactions

# SM global fits: solving the $M_W$ puzzle



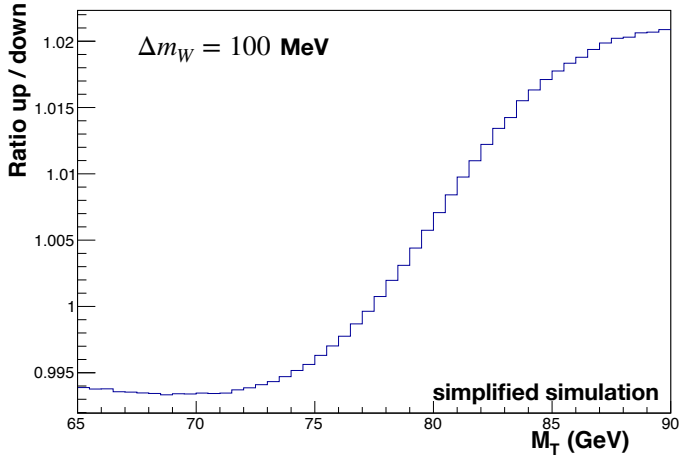

LHCb-FIGURE-2022-003

Mass measured by fitting template distributions of transverse momentum and mass

Template fitting is acceptable if theory describes data with high accuracy

$\Delta M_W$~ 100 MeV → 1-2 % change in the spectrum

$\Delta M_W$~10 Mev → 0.1% control on kinematic distributions



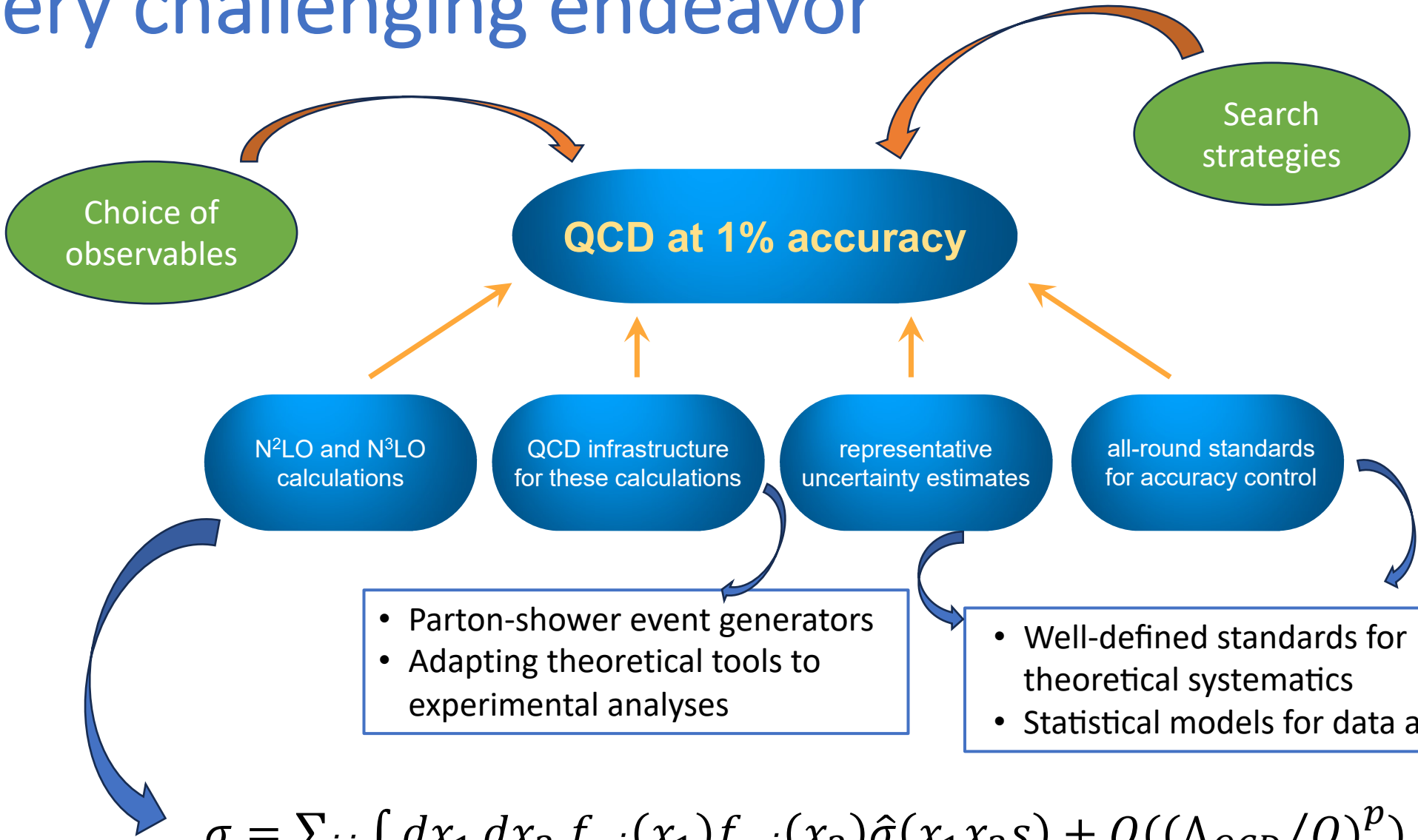

C. Hays, ICHEP 2022

**How to achieve that?**

# QCD for percent-level phenomenology

- A realm where mathematical progress and phenomenological studies and intuition are strongly intertwined and have brought so much progress, paving the way to tackling future challenges.

# A very challenging endeavor




$$\sigma = \sum_{ij} \int dx_1\, dx_2\, f_{p,i}(x_1) f_{p,j}(x_2) \hat{\sigma}(x_1 x_2 s) + O((\Lambda_{QCD}/Q)^p)$$

Parton Distribution Functions (PDF)

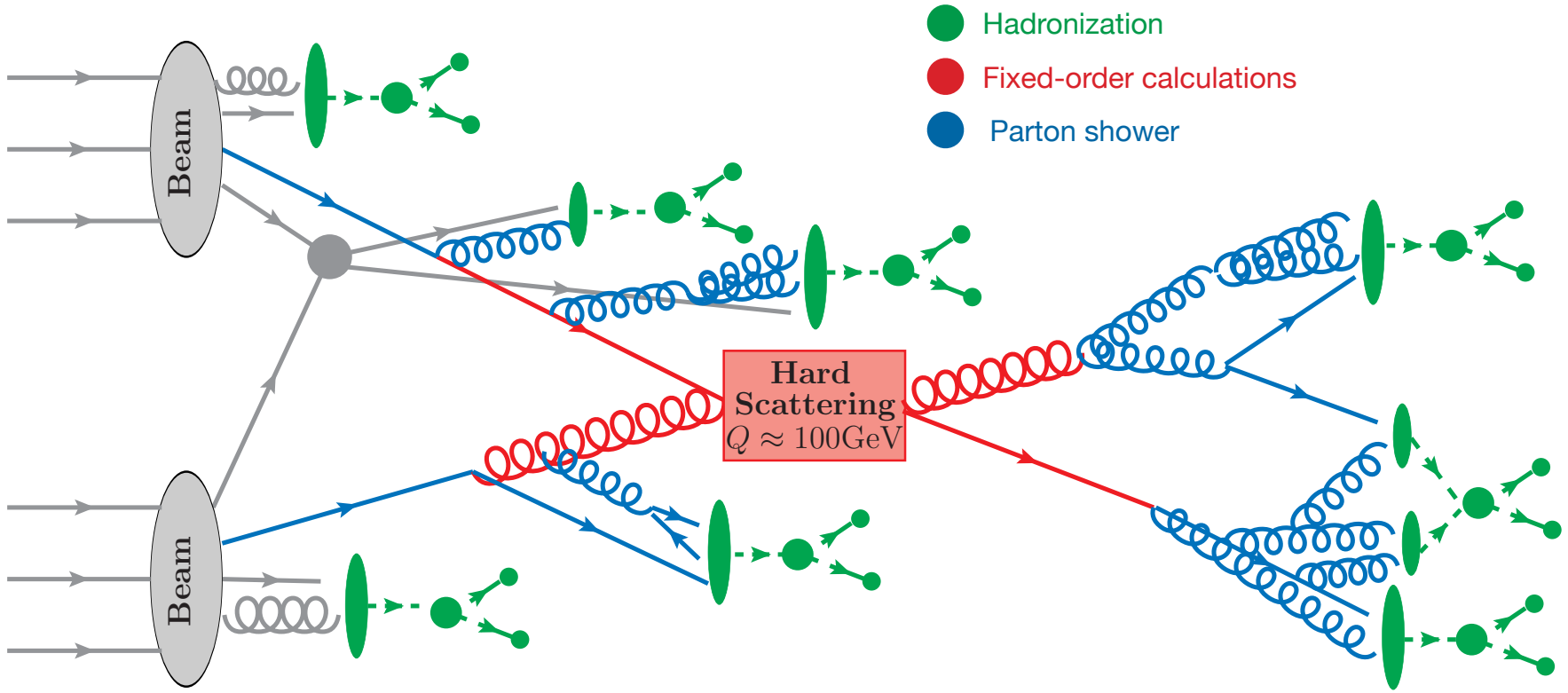
hard-scattering partonic xsec (pQCD)

Hadronization, non-p QCD

Snowmass Report of QCD
Topical Groups, 2209.14872

# Dissecting the challenge

From S. Ferrario Ravasio, RADCOR 2023

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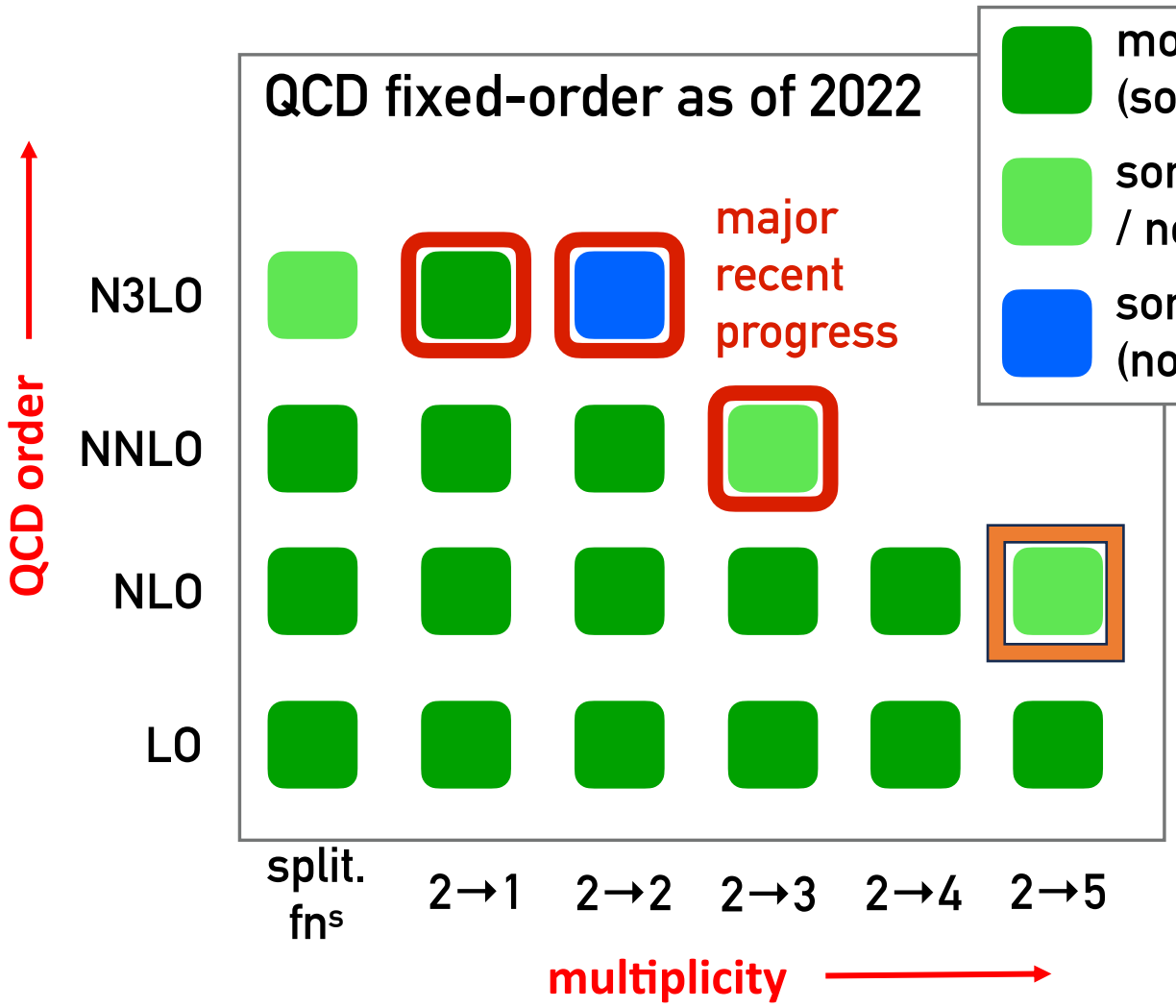
Parton Distribution Functions (PDF)

hard-scattering partonic xsec (pQCD)

Hadronization, non-p QCD

# QCD predictions: N$^X$LO state of the art



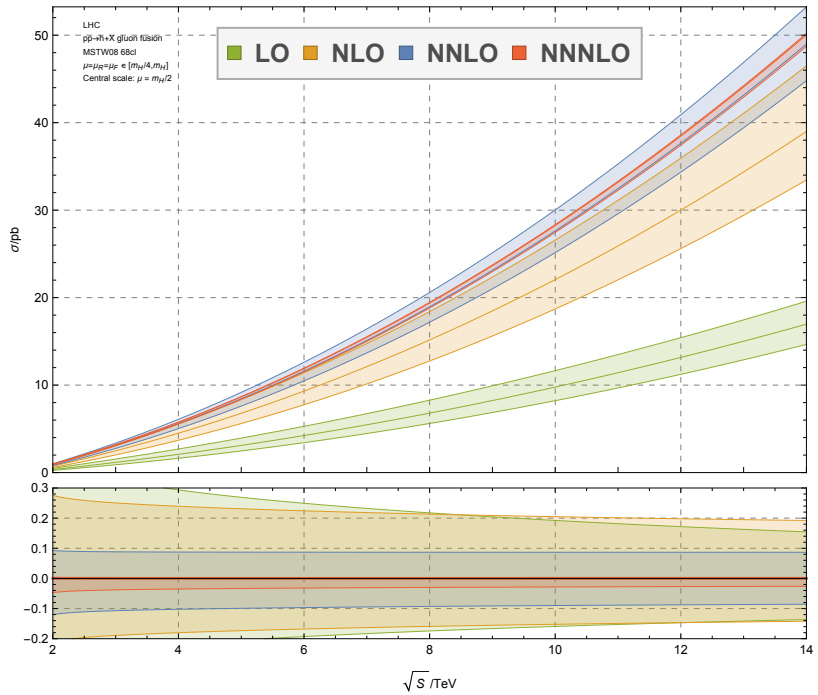

Still a good summary for 2023, with much progress in red-circled boxes

**Major challenges and progress:**

- Multiloop scattering amplitudes
- Real emission → IR subtraction
- All-order resummations in specific regions of phase space
- Predictions for fiducial regions

From G. Salam, ICHEP 2022 (slightly modified)

# Higgs production via gg fusion at N$^3$LO

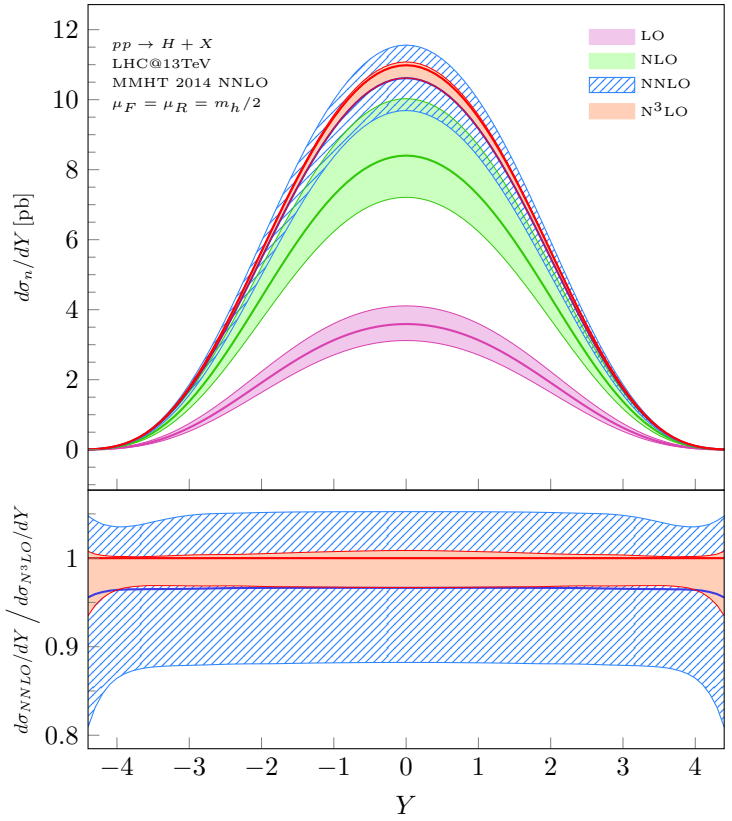


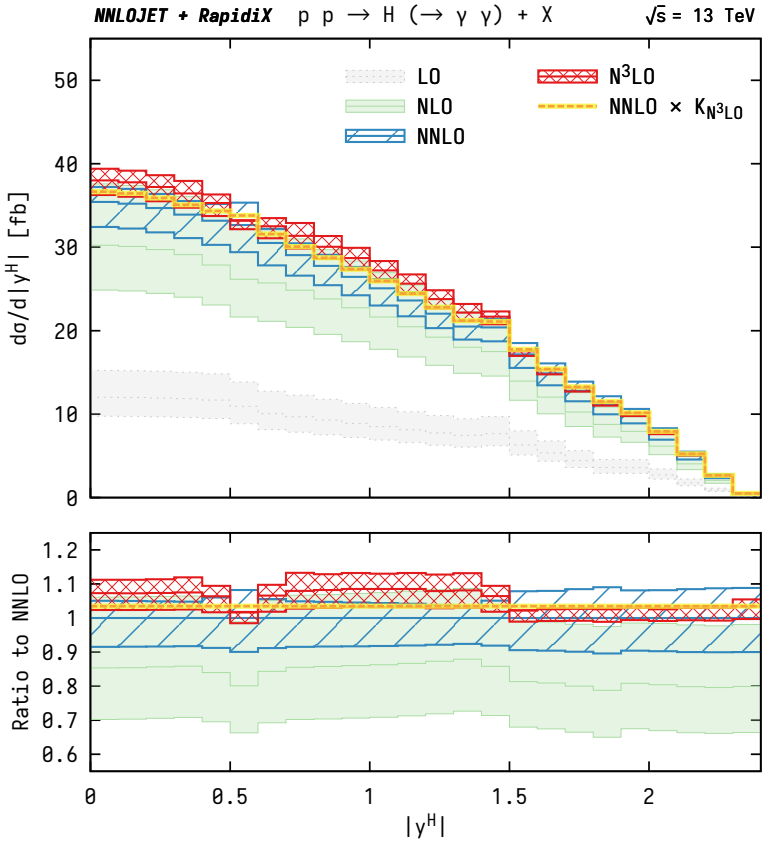

Anastasiou, Duhr, Dulat, Herzog, Mistlberger 1503.06056

Dulat, Mistlberger, Pelloni 1810.09462

**A strong case to demonstrate the need for higher-order QCD**

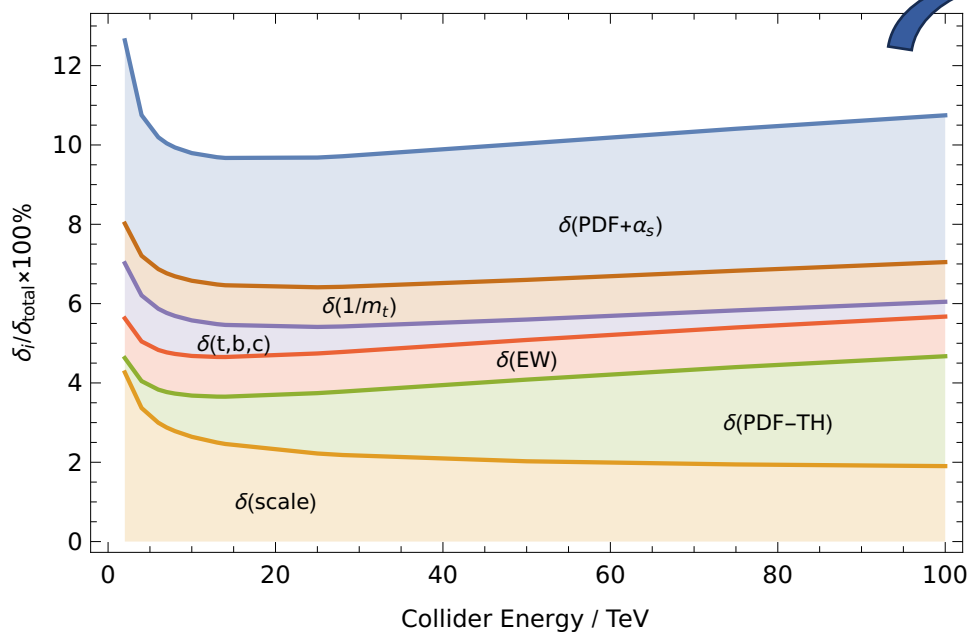
- The leading Higgs production mode
- A benchmark test of QCD, including H+j production
- An excellent testing ground to probe theoretical accuracy




Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni, 2203.01565

# … crucial to map residual uncertainties




LHC @ 13 TeV

Dulat, Lazopoulos, Mistlberger
1802.00827 (iHixis)

$$
\begin{aligned}
\delta(\text{theory}) &= {}^{+0.13pb}_{-1.20pb} \quad {}^{(+0.28\%)}_{(-2.50\%)} \quad \delta(\text{scale}) \\
&+ \pm 0.56pb \quad (\pm 1.16\%) \quad \delta(\text{PDF-TH}) \\
&+ \pm 0.49pb \quad (\pm 1.00\%) \quad \delta(\text{EWK}) \\
&+ \pm 0.41pb \quad (\pm 0.85\%) \quad \delta(\text{t,b,c}) \\
&+ \pm 0.49pb \quad (\pm 1.00\%) \quad \delta(1/m_t) \\
&= {}^{+2.08pb}_{-3.16pb} \quad {}^{(+4.28\%)}_{(-6.5\%)} \,, \\
\delta(\text{PDF}) &= \pm 0.89\text{pb} \quad (\pm 1.85\%) \,, \\
\delta(\alpha_S) &= {}^{+1.25pb}_{-1.26pb} \quad {}^{(+2.59\%)}_{(-2.62\%)} \,.
\end{aligned}
$$

**Future challenges**:

- **N3LO PDF!** → δ(PDF-TH)
- Light-quark mass effects → δ(b,c)
- More EW corrections
- Large logs resummation (fiducial)?

Uncertainty removed by calculation of exact NNLO $m_t$ dependence

Czakon, Harlander, Klappert, Nieggetied, 2105.04436

Reduced uncertainty to 0.26% by calculation of NLO mixed QCD+EW

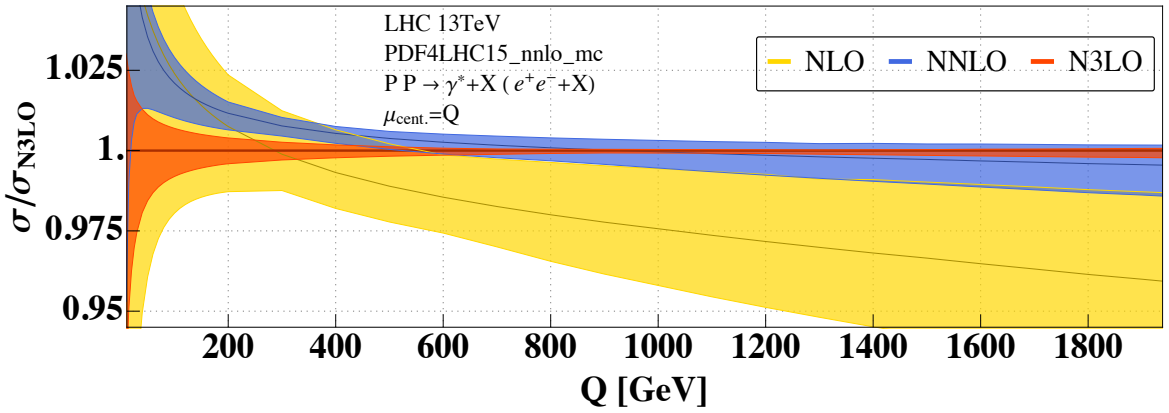
Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer, 2010.09451

4-loop splitting functions (low moments) – Moch, Ruijl, Ueda, Vermaseren, Vogt, 2111.15561

**DY@N3LO QCD** – Duhr, Dulat, Mistlberger, 2001.07717, 2007.13313

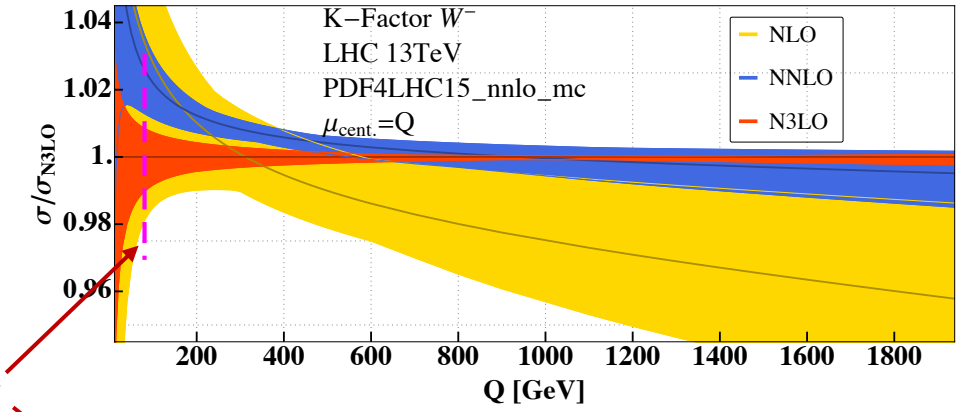
# DY at N$^3$LO – input to PDF fits and $M_W$ measurement

## NC-DY

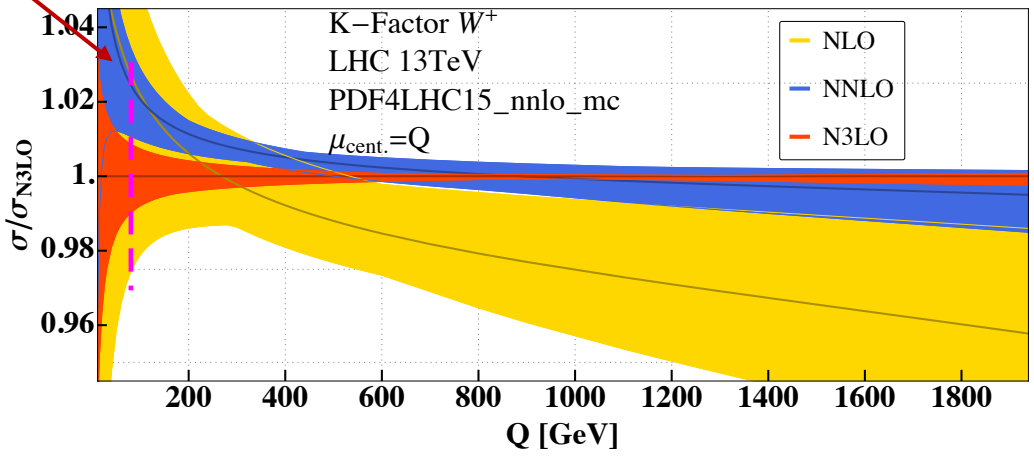



Duhr, Dulat, Mistlberger, 2001.07717

## CC-DY




$M_W$

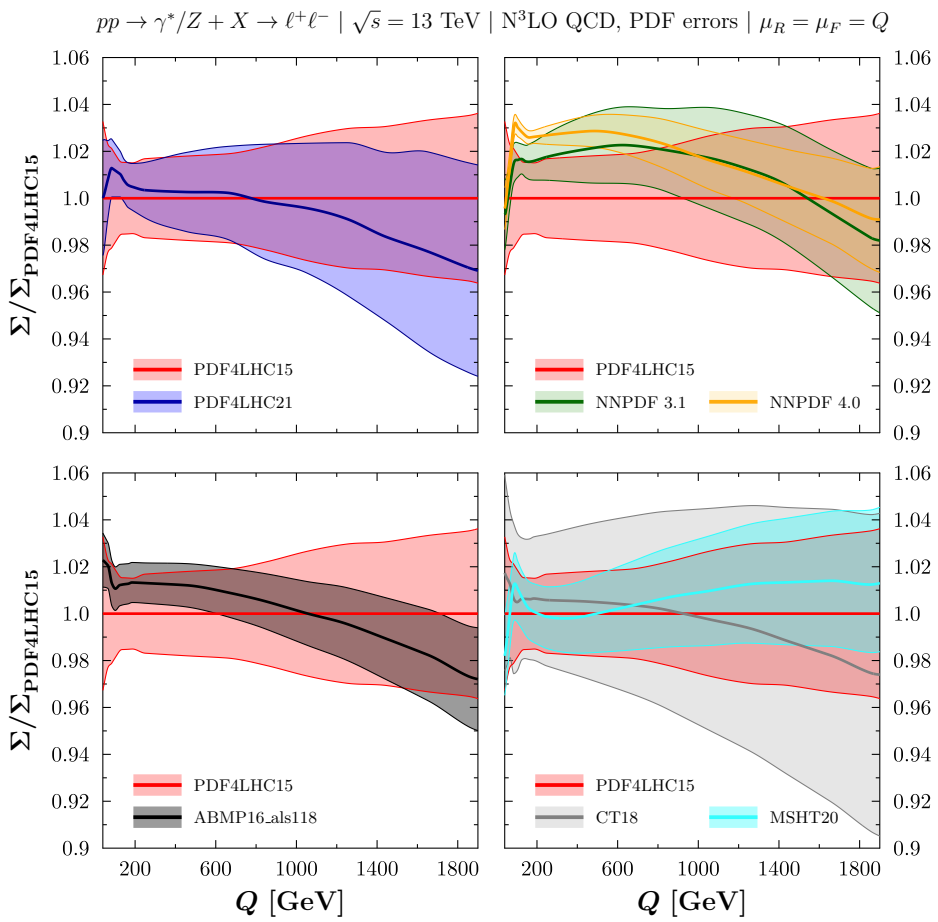


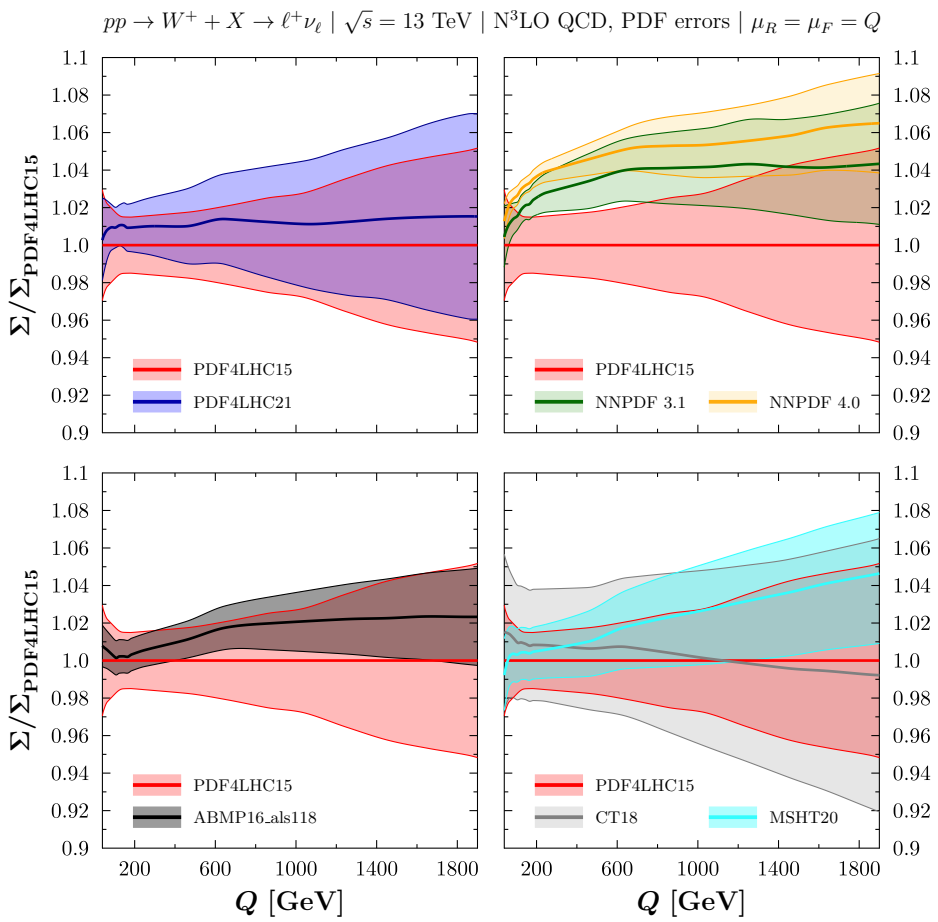

Duhr, Dulat, Mistlberger, 2007.13313

- Scale dependence: non-uniform behavior in all Q-regions
- Important input for PDFs (not yet included)
- **Region around Q~$M_W$: reconsider how to estimate theoretical uncertainty from scale variation**

Recall from before: **need 0.1% accuracy in template distributions in order to achieve $\Delta M_W$~10 MeV**

# DY at N$^3$LO – dedicated PDF study




Overall consistency among different sets

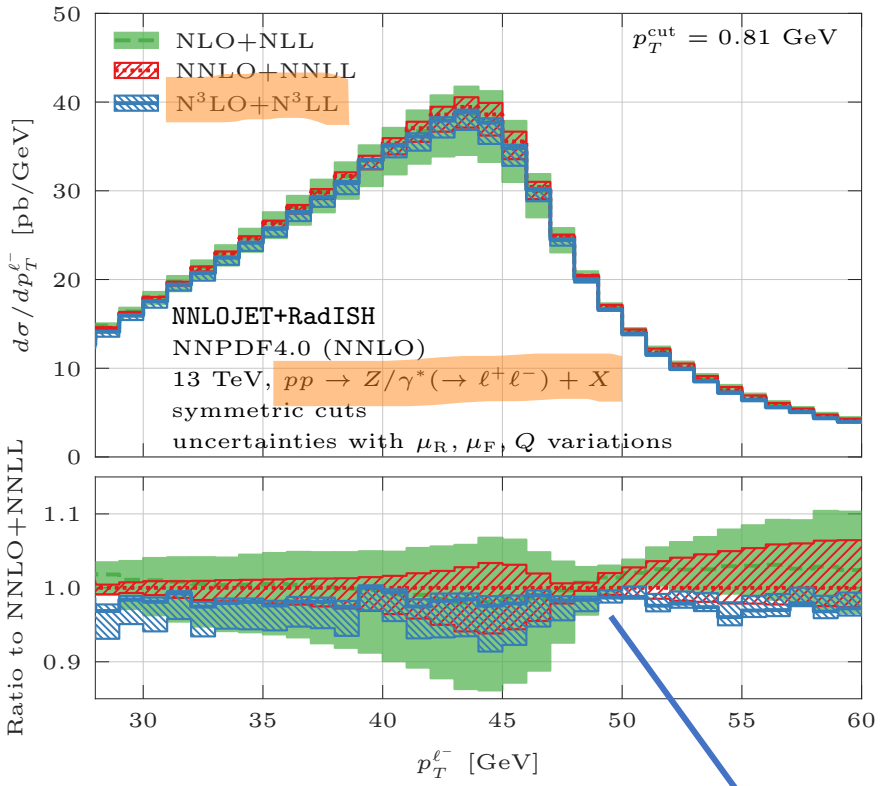
Large variation in error bands

Systematics introduced by choosing different sets can be substantial

Baglio, Duhr, Mistlberger, Szafron, 2209.06138
(n3loxs – public numerical code)

Different patterns observed in CC vs NC cannot be ignored for precision measurements, since the introduced bias can be sizable at percent level.

# DY at N$^3$LO+N$^3$LL – differential




Chen, Gehrmann, Glover, Huss, Monni, Re, Rottoli, Torrielli, 2203.01565

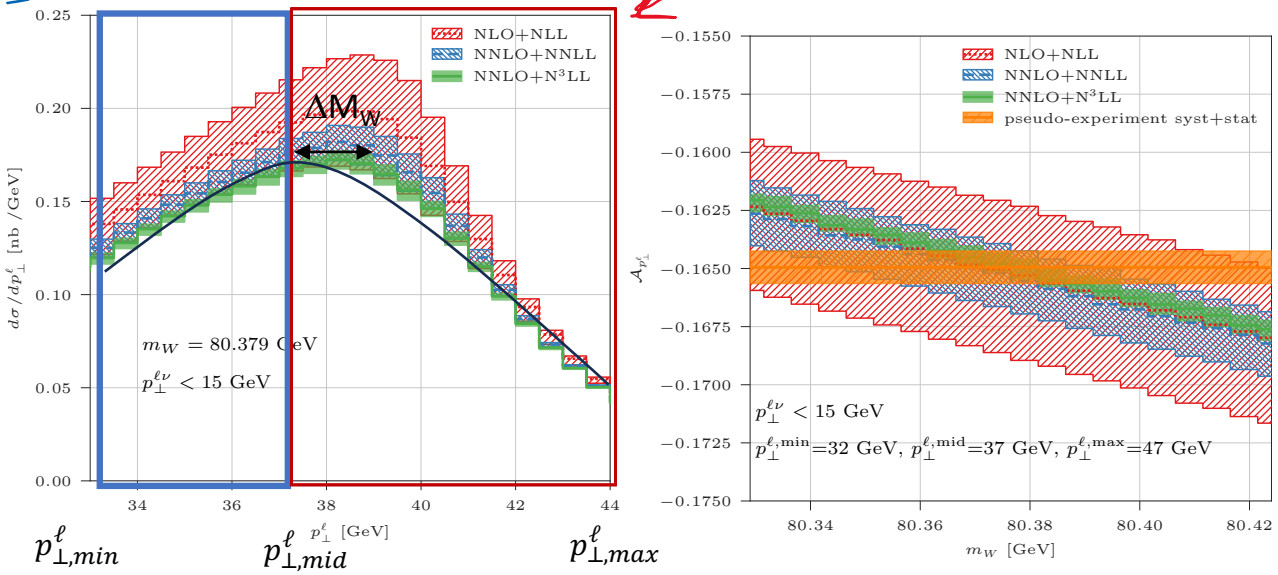
Challenging to control theoretical uncertainties below percent level!

## Consider different observable?

$$A_{p_\perp^\ell}\left(p_{\perp,min}^\ell, p_{\perp,mid}^\ell, p_{\perp,max}^\ell\right) = \frac{L-U}{L+U}$$

$$L = \int_{p_{\perp,min}^\ell}^{p_{\perp,mid}^\ell} dp_\perp^\ell \frac{d\sigma}{dp_\perp^\ell} \qquad U = \int_{p_{\perp,mid}^\ell}^{p_{\perp,max}^\ell} dp_\perp^\ell \frac{d\sigma}{dp_\perp^\ell}$$

Shift in jacobian peak by $\Delta M_W/2$

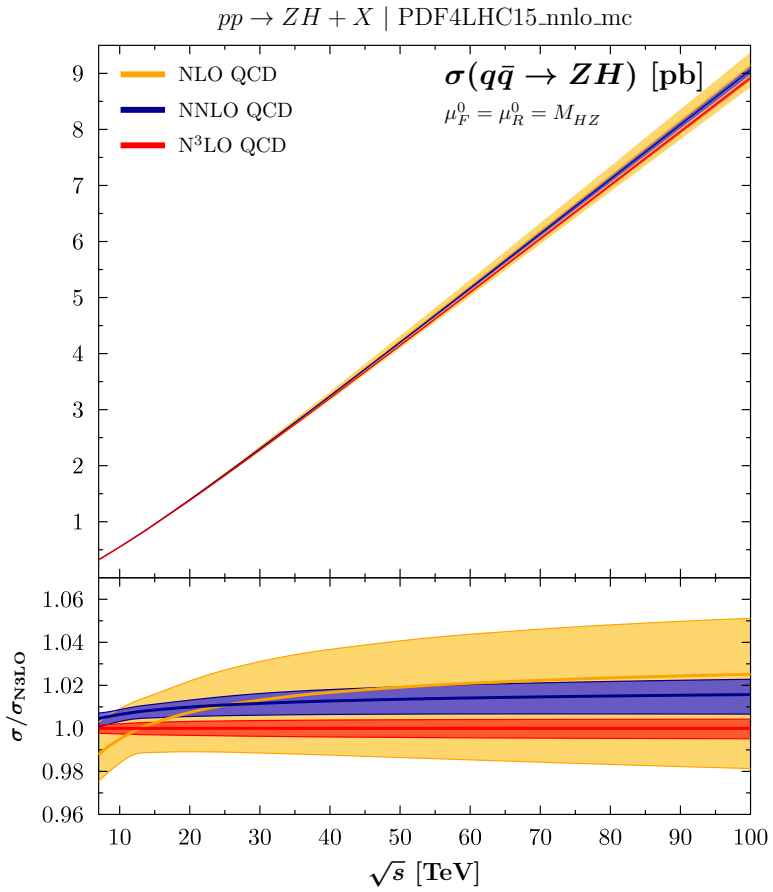


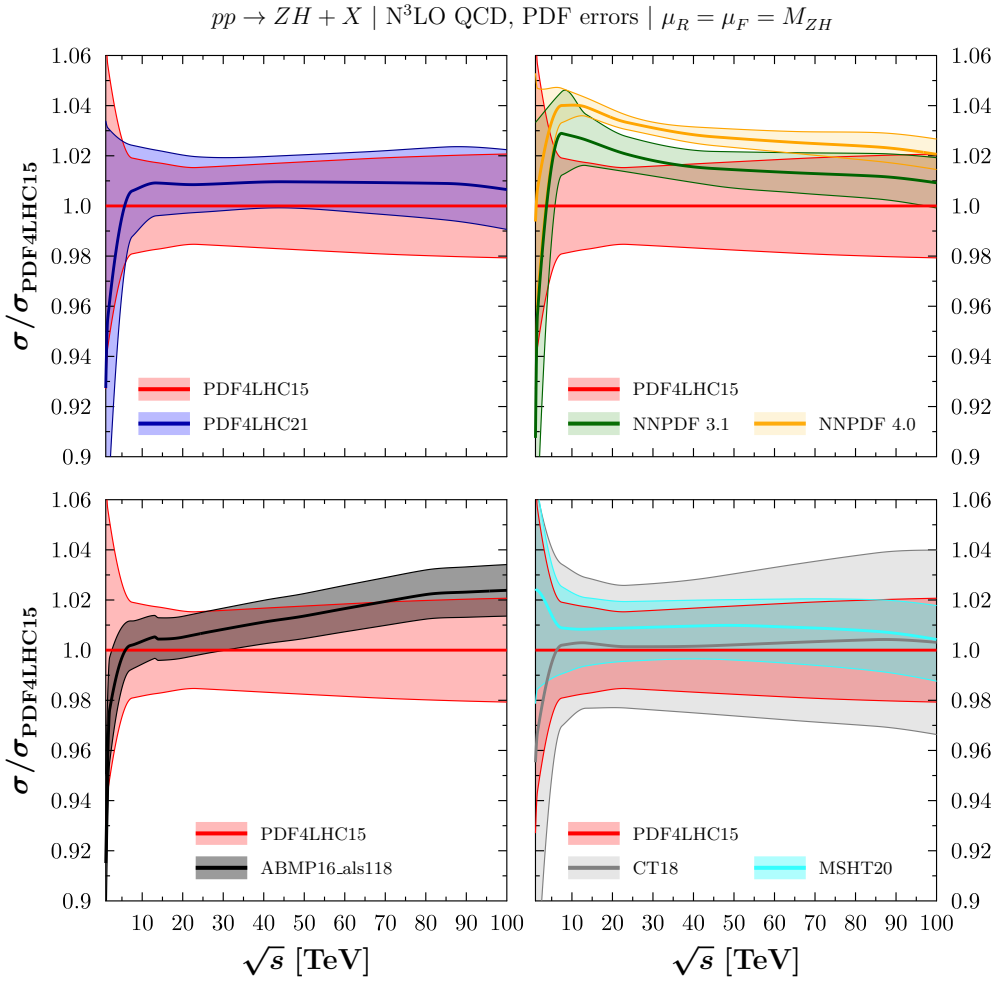

Rottoli, Torrielli, Vicini, 2301.04059

$\Delta M_W \sim \pm 15$ MeV feasible

# VH at N$^3$LO, first complete calculation

Same color structure as DY, same characteristic behavior, same lesson learnt in assessing theoretical uncertainties




Baglio, Duhr, Mistlberger, Szafron, 2209.06138

# NNLO for 2→3 processes

- Several recent results for pp → $\gamma\gamma\gamma, \gamma\gamma j, \gamma jj, jjj$
  Chawdry, Czakon, Mitov, Poncelet; Kallweit, Sotnikov, Wiesemann; Badger, Gerhmann, Marcoli, Moodie;
- Most recently first NNLO results for multi-scale processes: $b\bar{b}W, t\bar{t}W, t\bar{t}H$

1 massive final-state particle (b massless)

Hartanto, Poncelet, Popescu, Zoia 2205.01687

3 massive final-state particles

Buonocore, Devoto, Grazzini, Kallweit, Mazzitelli, Rotoli, Savoini , 2306.16311

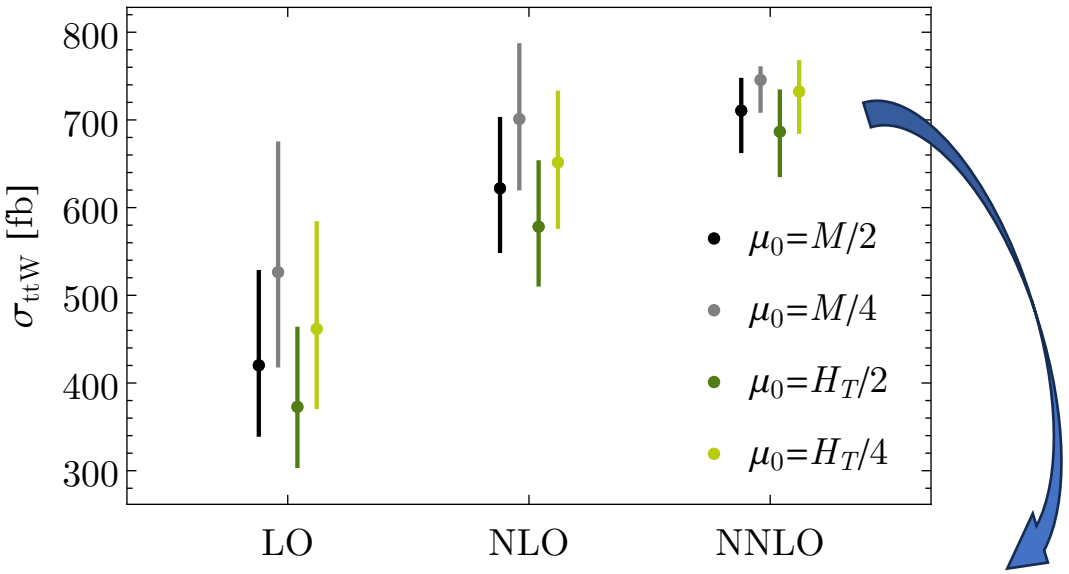
Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini , 2210.07846

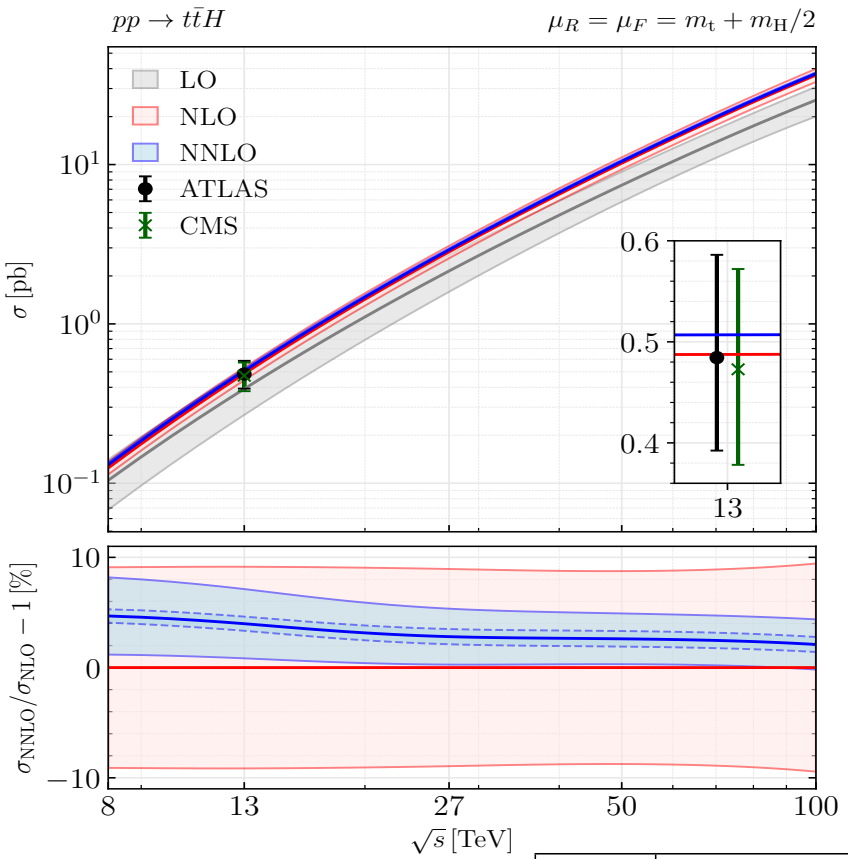
Major impact on LHC phenomenology

Major bottle neck: 2-loop 5-point amplitudes
Evaluated in $t\bar{t}W, t\bar{t}H$ calculation by soft-W/H approximation
Several groups working at providing exact 2-loop amplitudes

# $t\bar{t}W$ and $t\bar{t}H$ at NNLO

Buonocore et al., 2306.16311




Catani et al., 2210.07846

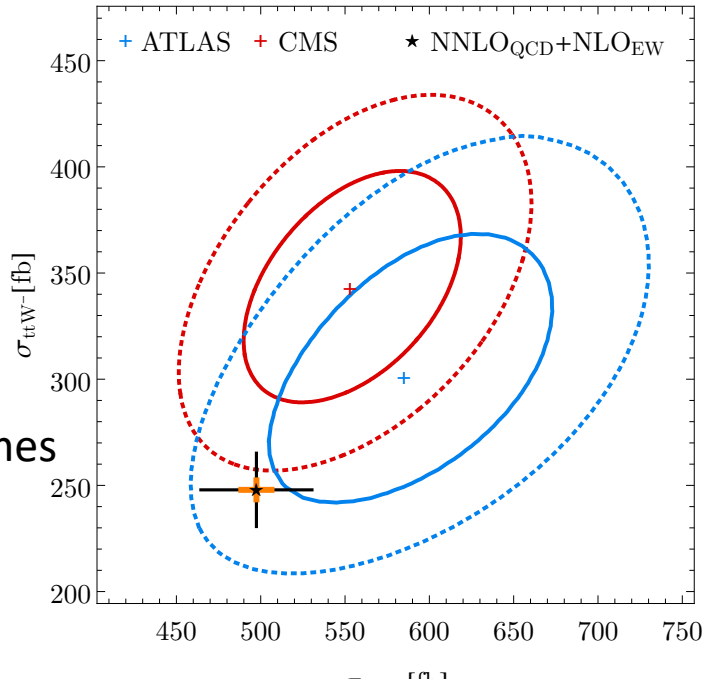
Theoretical uncertainty reduced to 3% level

| $\sigma$ [pb] | $\sqrt{s} = 13$ TeV | $\sqrt{s} = 100$ TeV |
|---|---|---|
| $\sigma_{LO}$ | $0.3910\,^{+31.3\%}_{-22.2\%}$ | $25.38\,^{+21.1\%}_{-16.0\%}$ |
| $\sigma_{NLO}$ | $0.4875\,^{+5.6\%}_{-9.1\%}$ | $36.43\,^{+9.4\%}_{-8.7\%}$ |
| $\sigma_{NNLO}$ | $0.5070\,(31)^{+0.9\%}_{-3.0\%}$ | $37.20(25)\,^{+0.1\%}_{-2.2\%}$ |

NNO QCD+NLO EW within at most 2σ of exp. measurement.

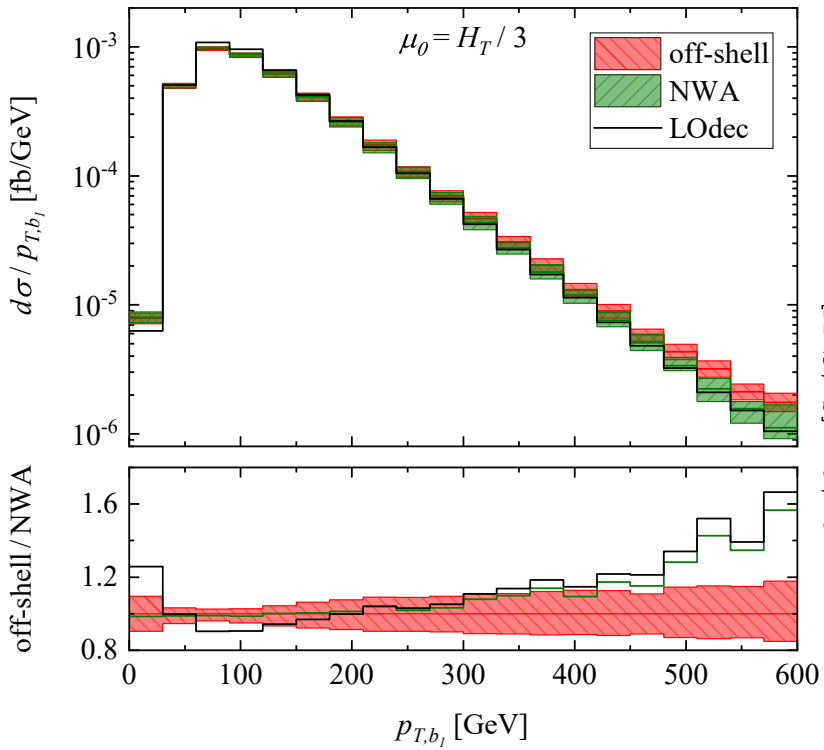
Ratio $\sigma_{t\bar{t}W^+}/\sigma_{t\bar{t}W^-}$ in very good agreement with ATLAS measurement

Comparison in fiducial volumes may give further insight

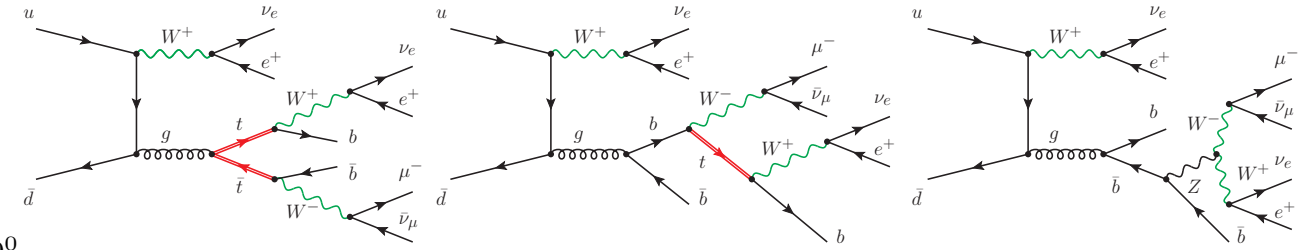


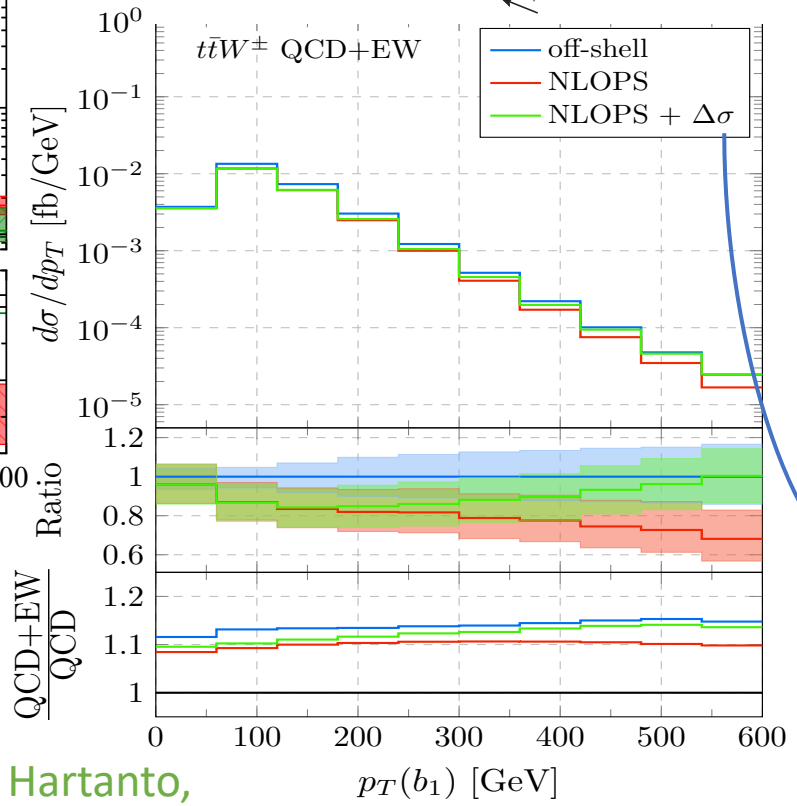
# NLO: push the multiplicity challenge

## Beyond on-shell production to match fiducial measurements




Bevilacqua, Bi, Hartanto, Kraus, Worek, 2005.09427






Bevilacqua, Bi, Febres Cordero, Hartanto, Kraus, Nasufi, LR, Worek, 2109.15181

Modelling full process crucial to match experimental fiducial cuts and estimate theoretical systematic

Off-shell effects most relevant in tails and end-points of distributions, where new physics effects can be hidden

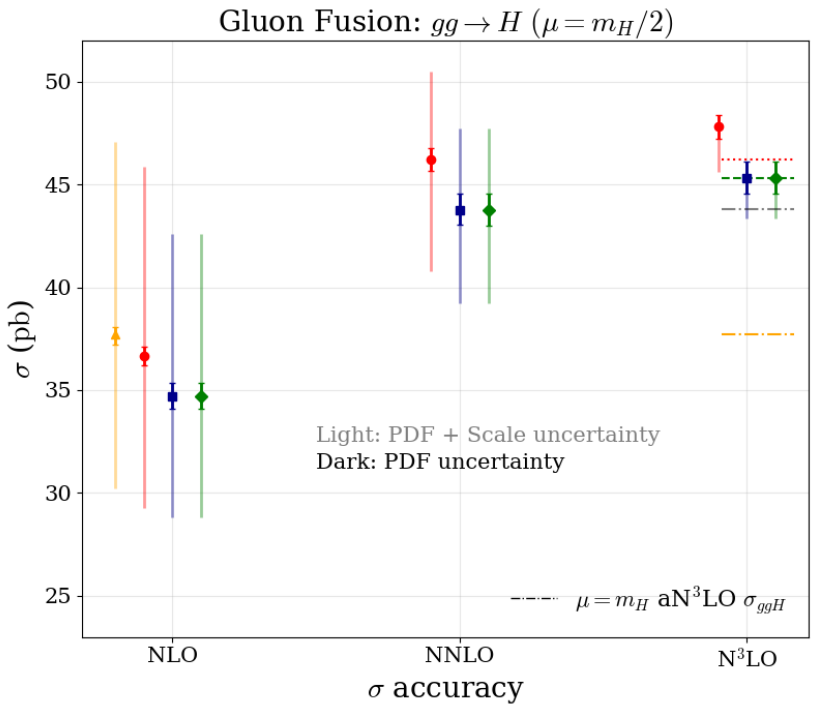
$$\frac{d\sigma^{th}}{dX} = \frac{d\sigma^{NLO+PS}}{dX} + \frac{d\Delta_{off-shell}}{dX}$$

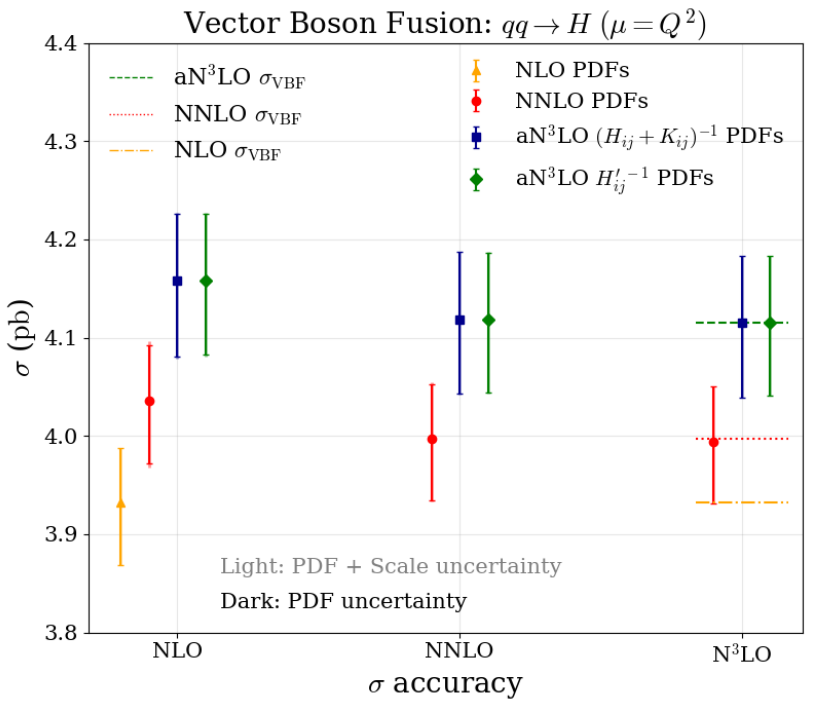
$$\frac{d\Delta_{off-shell}}{dX} = \frac{d\sigma^{NLO}_{off-shell}}{dX} - \frac{d\sigma^{NLO}_{NWA}}{dX}$$

# PDF – first approximate N$^3$LO sets

aN$^3$LO → MSHT20aN$^3$LO

McGowan, Cridge, Harland-Lang, Thorne, 2207.04739

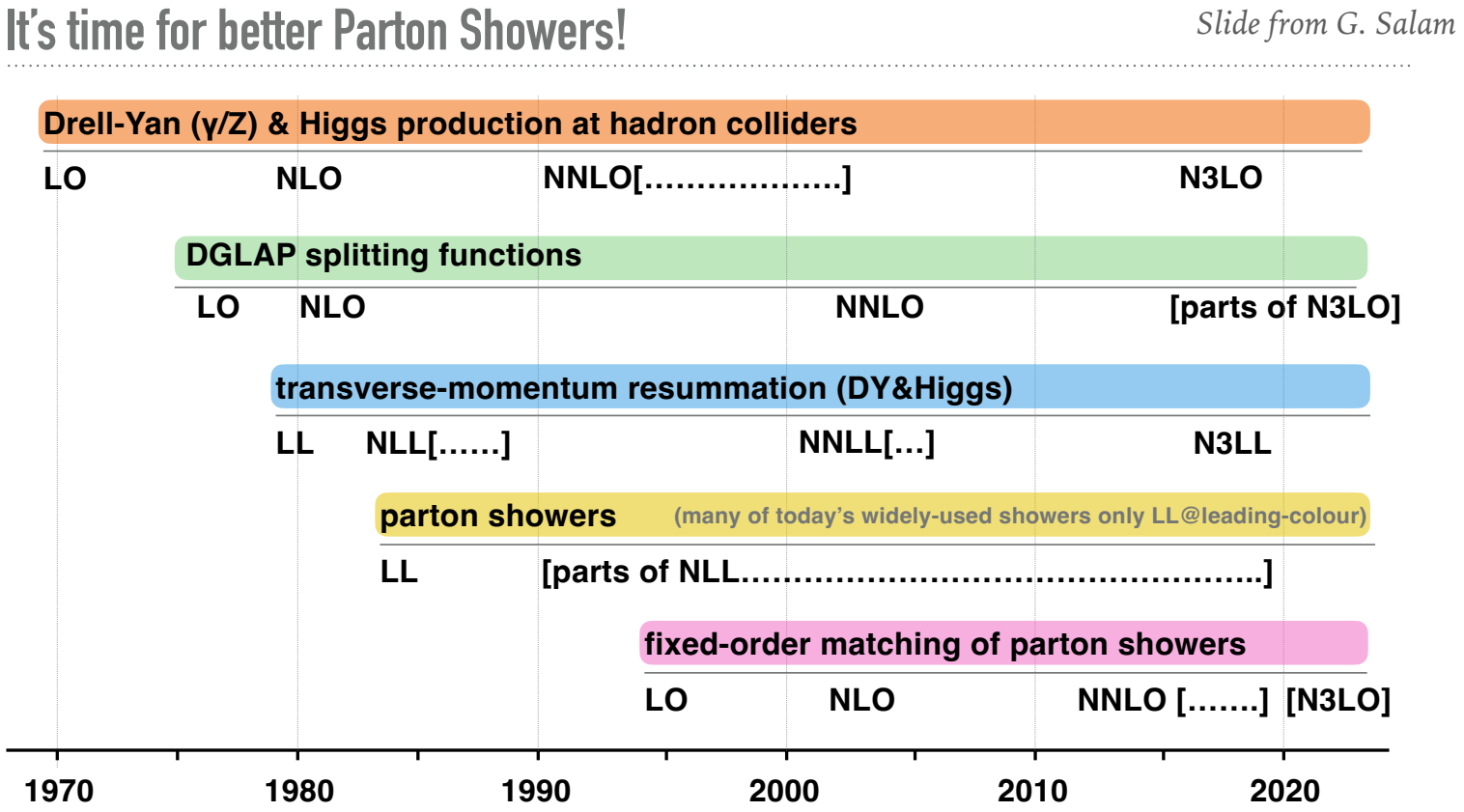



- Based on N$^3$LO approximation to structure functions and DGLAP evolution
- Making use of all available knowledge to constrain PDF parametrization, including both exact, resummed, and approximate estimates of N$^3$LO results
- Including PDF uncertainty from missing higher-orders (MHOU) as theoretical uncertainty in the fit

- **Gluon fusion to H**: the increase in the cross section prediction at N$^3$LO is compensated by the N$^3$LO PDF, suggesting a cancellation between terms in the PDF and cross section theory at N$^3$LO → **matching orders matters!**
- **Vector Boson Fusion**: no relevant change in going from N$^2$LO to N$^3$LO PDF, due to different partonic channel involved.

# Parton-shower event generators



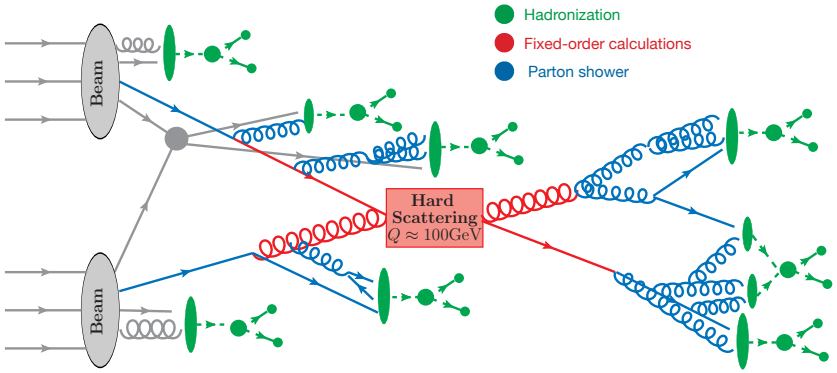

From S. Ferrario Ravasio, RADCOR 2023

- Standard PS are Leading Logarithmic (LL) → becoming a limitation
- Several groups aiming for NLL hadron-collider PS

Nagy&Soper, PanScales, Holguin- Forshaw-Platzer, Herren-Höche-Krauss- Reichelt

Crucial ingredient to reproduce the complexity of collider events

Often unknown or with poor formal accuracy (built in approx., tunings, etc.)



# More challenges: non-perturbative effects O($(\Lambda_{QCD}/Q)^p$)

Estimate of "p" for all relevant processes crucial to LHC precision program

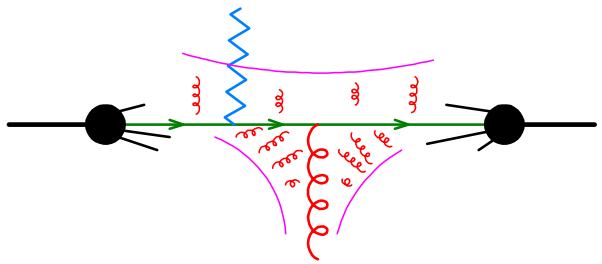
A few tens GeV < Q < a few hundreds GeV $\longrightarrow$ $(\Lambda_{QCD}/Q)^p \sim (0.01)^p - (0.001)^p$

Perturbative predictions at percent level will have to be supplemented with non-perturbative effects if $p = 1$ for a particular process or observable.

No general theory. Direct calculations have shown that there are no linear non-pert power corrections in:

- Z transverse-momentum distributions

  Ferrario Ravasio, Limatola, Nason, 2011.14114



- Observables that are inclusive with respect to QCD radiation

  Caola, Ferrario Ravasio, Limatola, Melnikov, Nason, 2108.08897, same+Ozcelik 2204.02247

# Summary and Outlook

- QCD: a mature theory that still offers plenty of conceptual challenges
- In this talk we have mainly focused on aspects of QCD predictions for collider physics
- Understanding the **multiple components of QCD predictions** becomes crucial to interpret precision measurements as well as direct searches of new physics. Of course, QCD+EW corrections will be part of the balance (not covered in this talk).
- Now accessible **high-precision measurements pose a serious challenge to theoretical predictions**
- Theoretical **development during the last few years have deeply changed traditional approaches** to QCD calculations and given results that were unimaginable only a decade ago, **giving us confidence that challenges can be met.**
- Interpreting the complexity of LHC events at with HL-LHC precision will be challenging and will require diversity of approaches.