Theory Challenges in QCD predictions

Quy Nhon
August 6-12, 2023

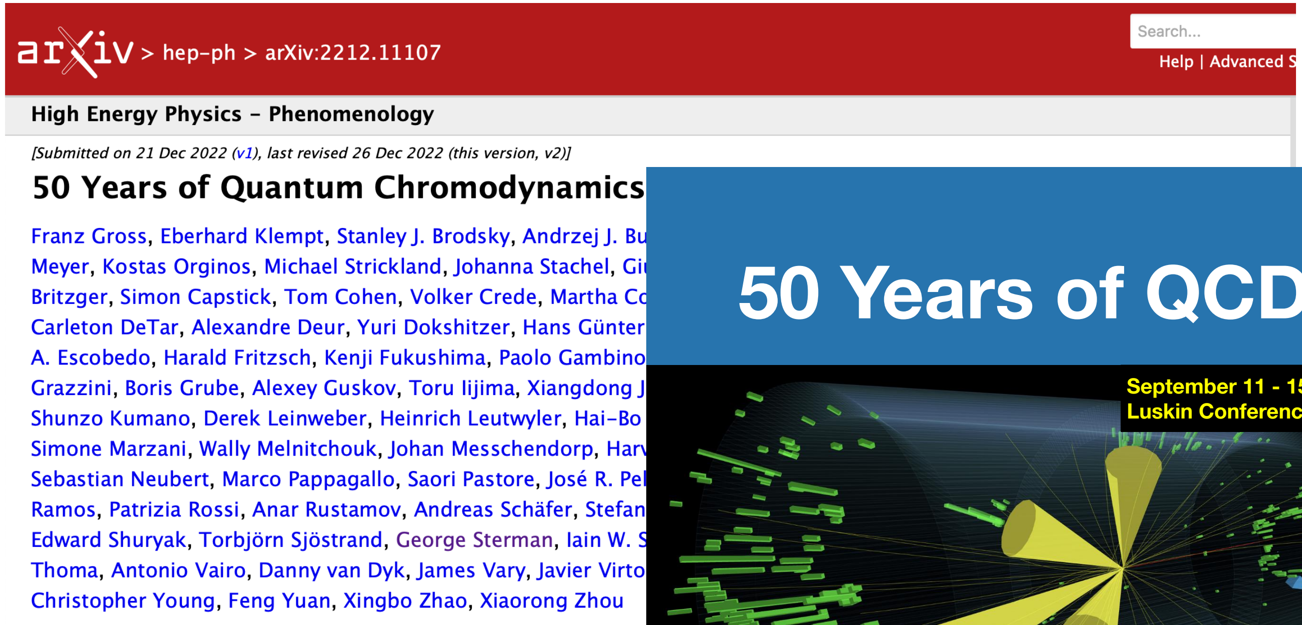
Laura Reina
Florida State University

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



arXiv > hep-ph > arXiv:2212.11107

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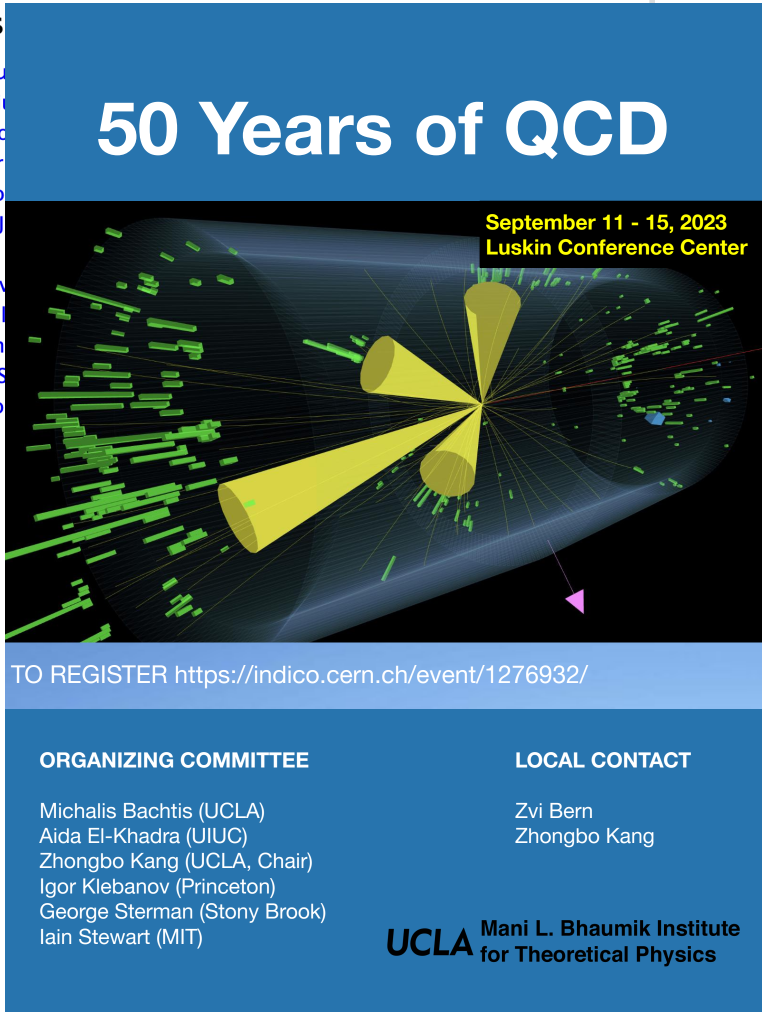
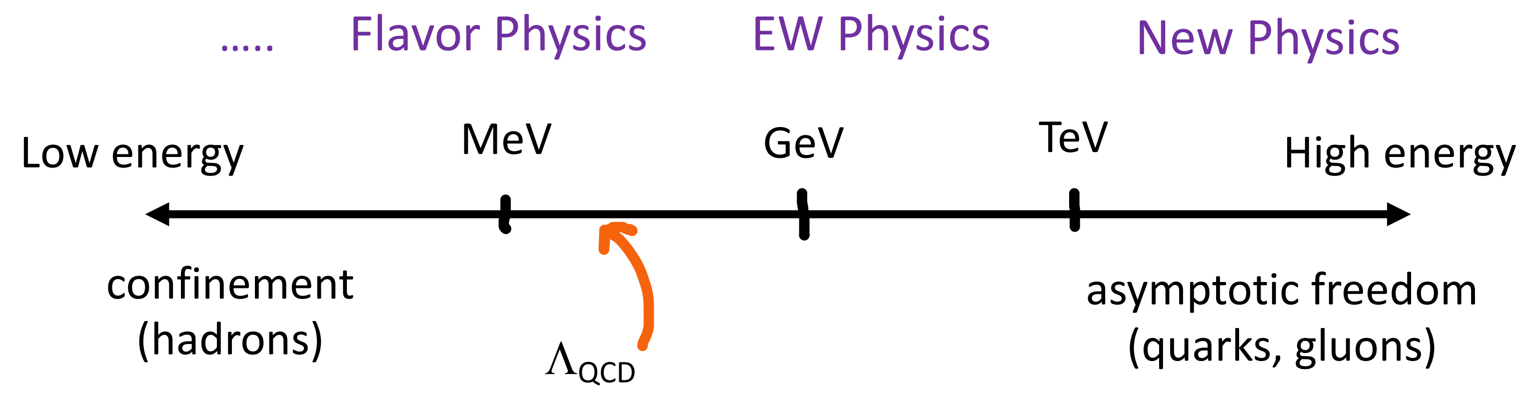
High Energy Physics – Phenomenology

[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. Pe
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





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

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

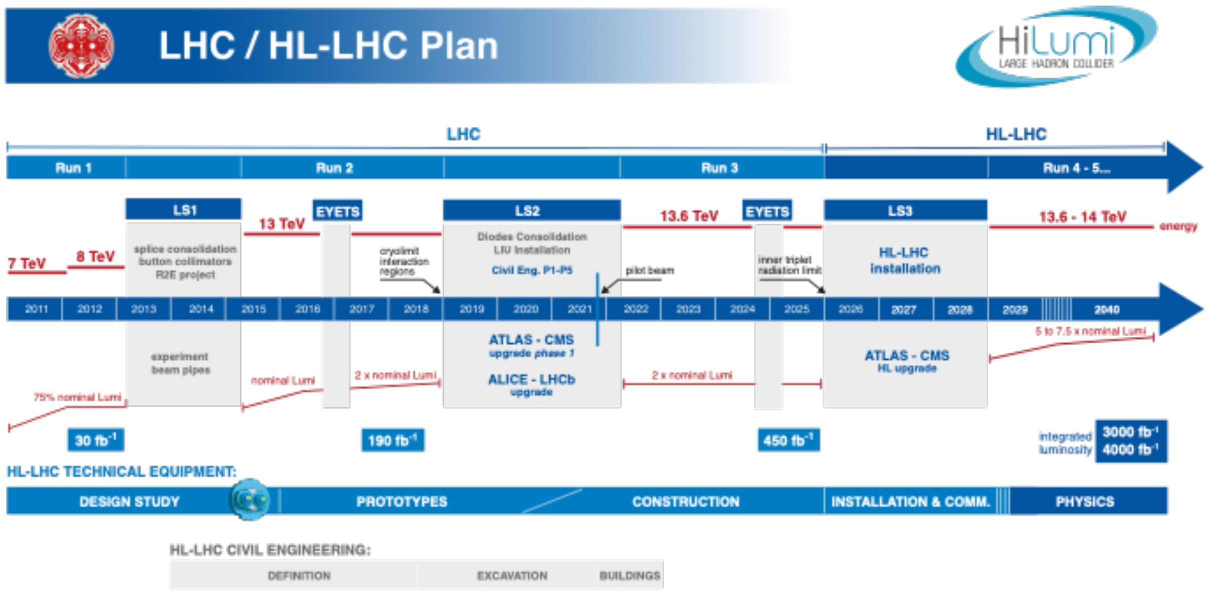
- Percent level phenomenology as the opportunity to study some of the core questions of particle physics and uncover new physics. The physics potential of the LHC greatly depends on enabling and successfully executing a broad precision phenomenology program.

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 %



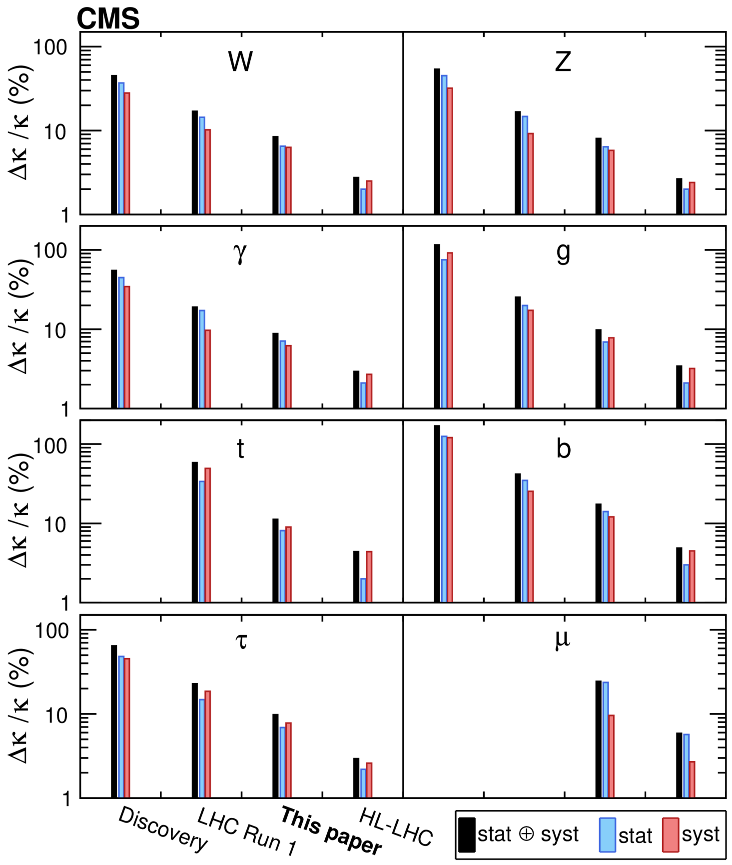
20 -fold increase in statistics by the end of HL-LHC

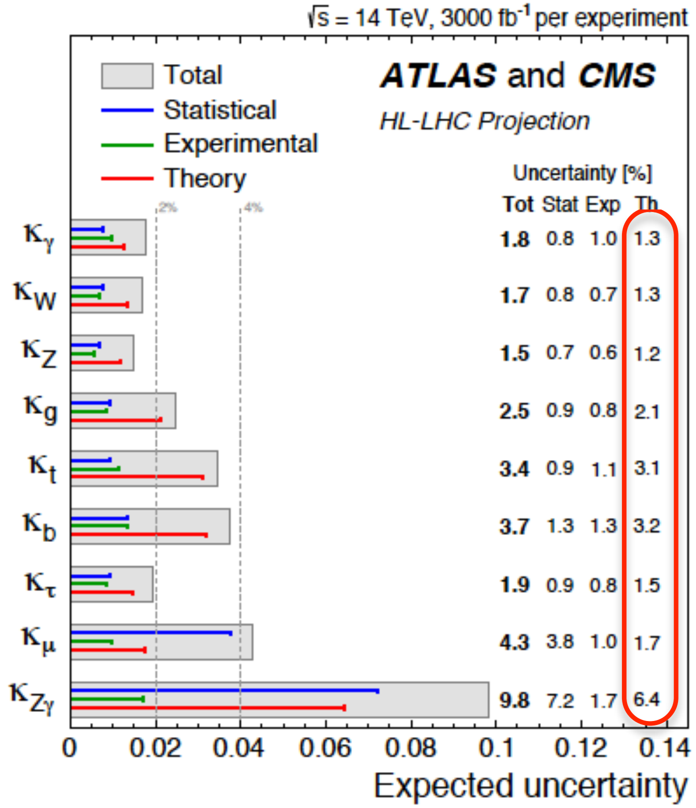
Statistical limitations will be overcome for a very large number of observables

Focus on systematics!

Theoretical systematics could become the main limitation

Establishing the scalar sector of the SM and probing Λ_{NP}





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

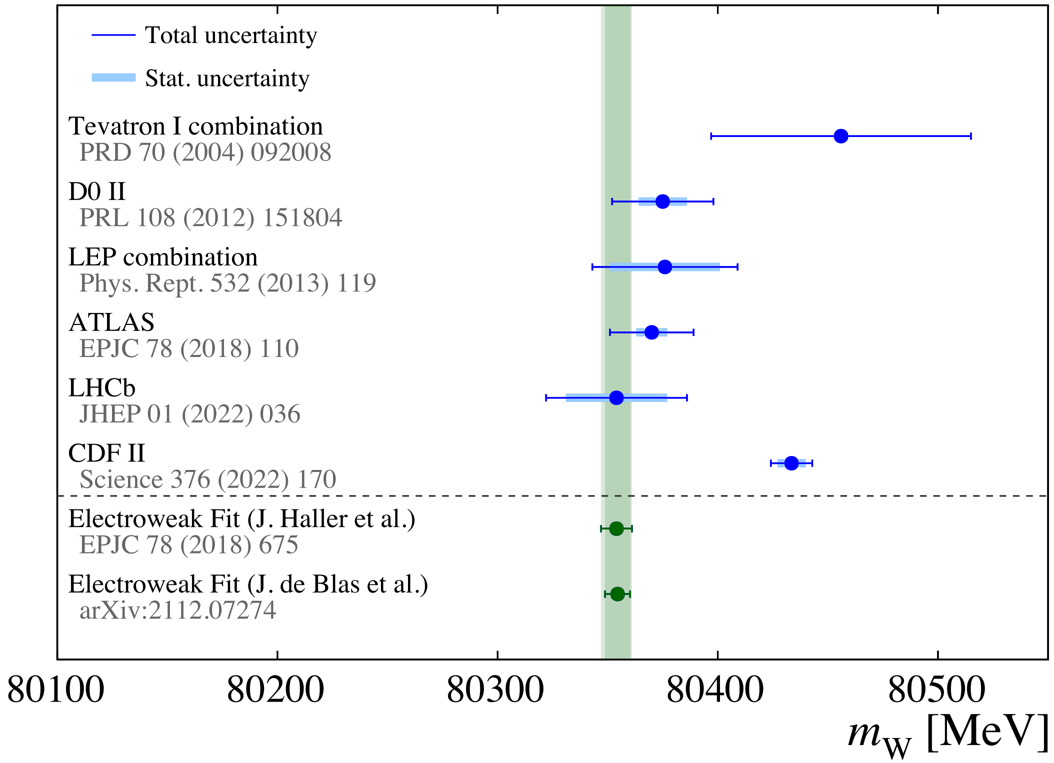
For new physics at 1 TeV expect deviations of O(6%)

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

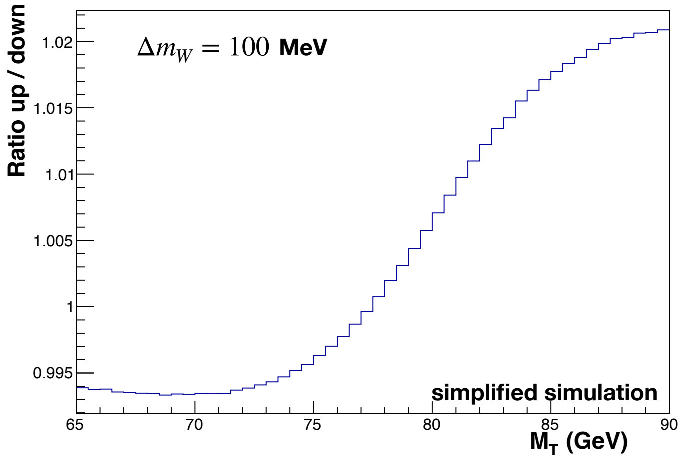


LHCb-FIGURE-2022-003

Mass measured by fitting template distributions of transverse momentum and mass

Template fitting is acceptable if theory describes data with high accuracy

ΔM_W~ 100 MeV → 1-2 % change in the spectrum



C. Hays, ICHEP 2022

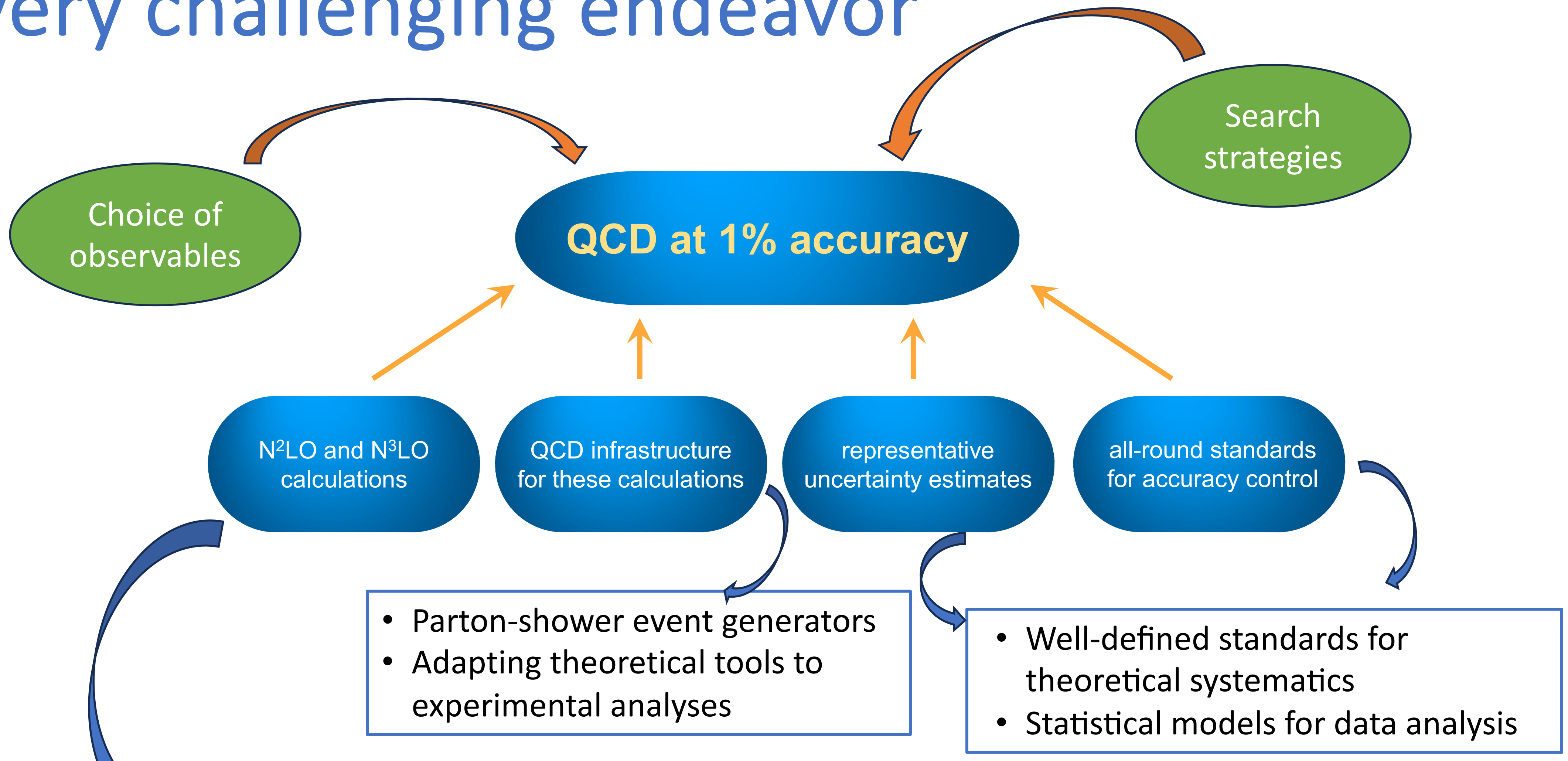
ΔM_W~10 Mev → 0.1% control on kinematic distributions

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)

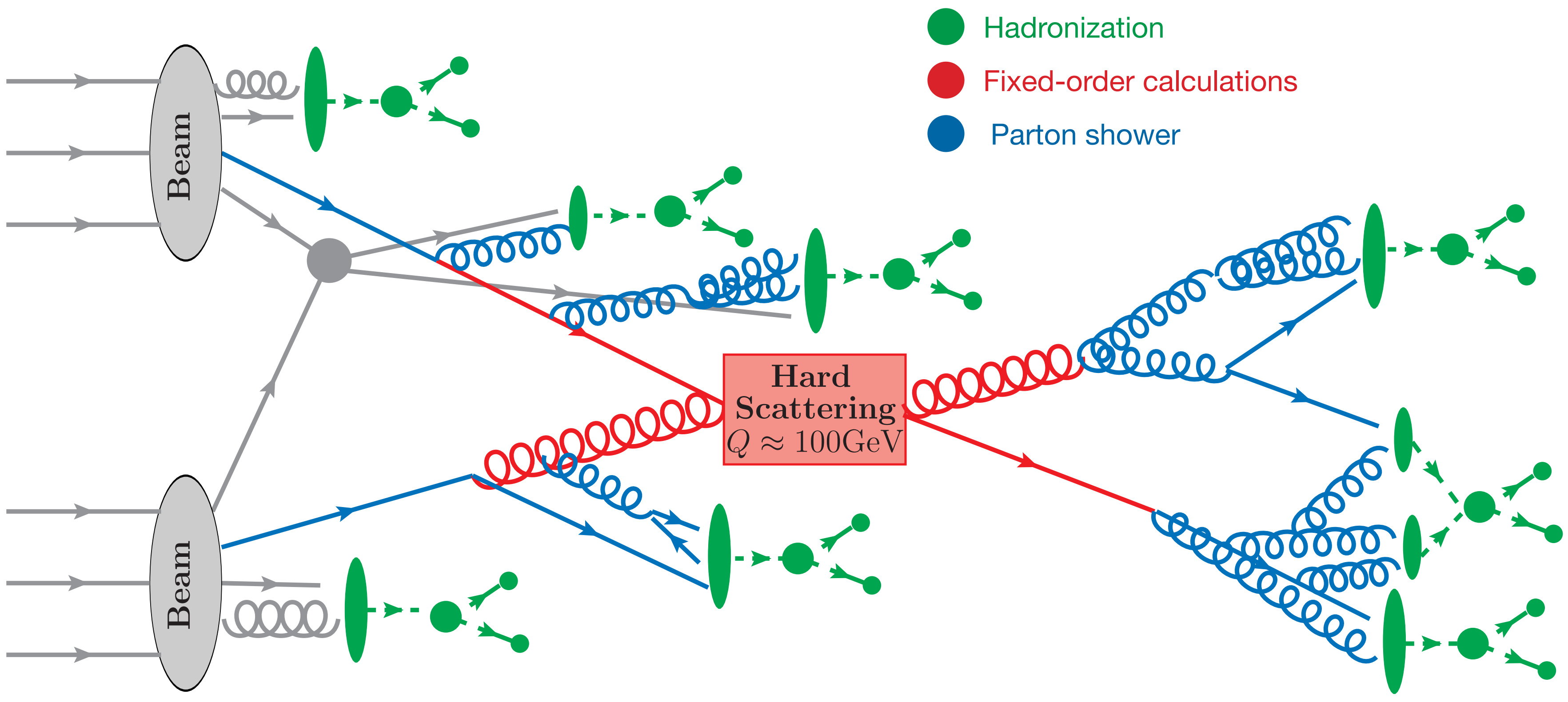
hard-scattering partonic xsec (pQCD)

Hadronization, non-p QCD

Snowmass Report of QCD Topical Groups, 2209.14872

Dissecting the challenge

From S. Ferrario Ravasio, RADCOR 2023



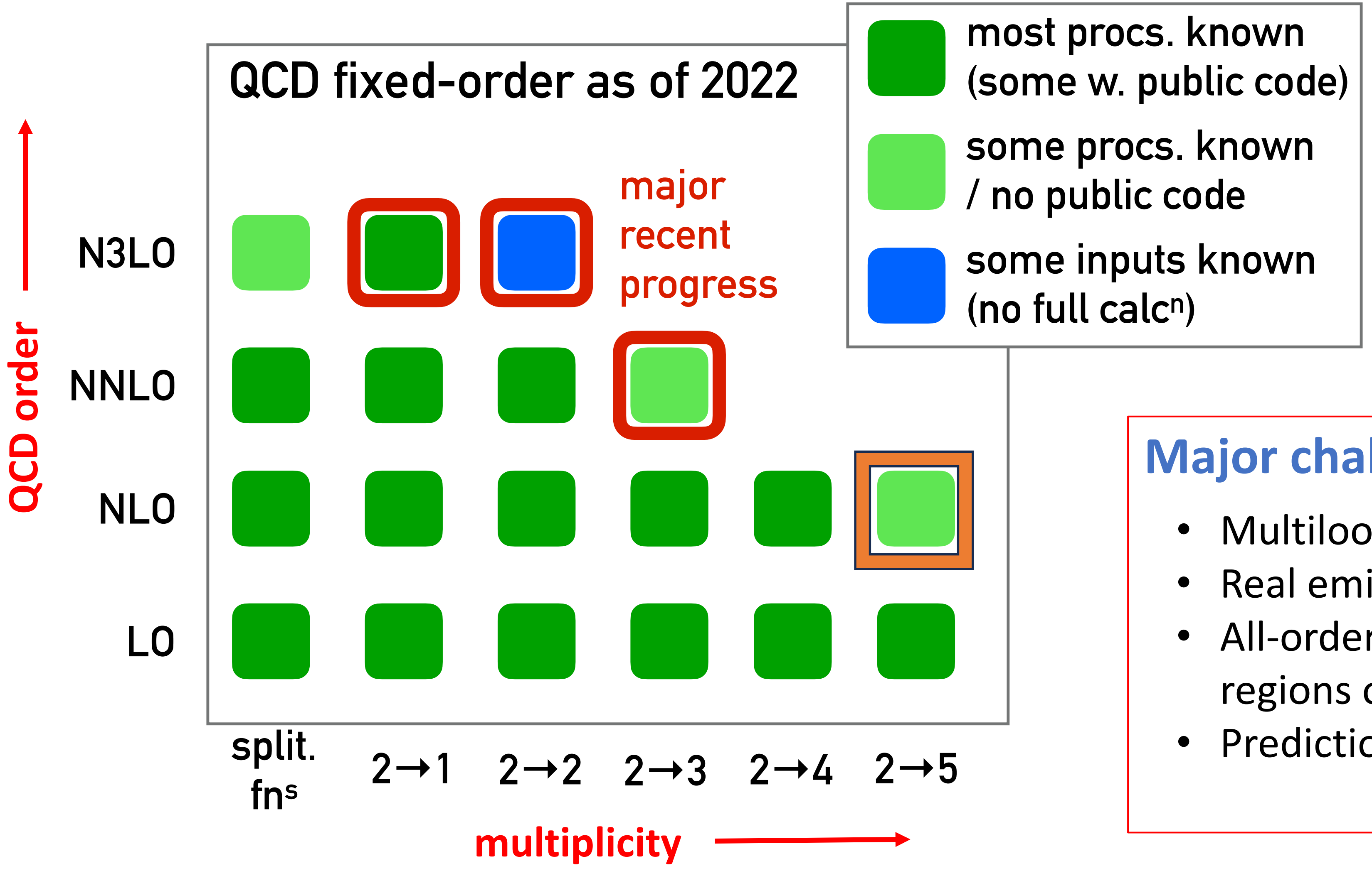
$$\sigma = \sum_{ij} \int dx_1\, dx_2\, f_{p,i}(x_1) f_{p,j}(x_2) \hat{\sigma}(x_1 x_2 s) + O((\Lambda_{QCD}/Q)^p)$$

Parton Distribution Functions (PDF)

hard-scattering partonic xsec (pQCD)

Hadronization, non-p QCD

QCD predictions: N^XLO state of the art



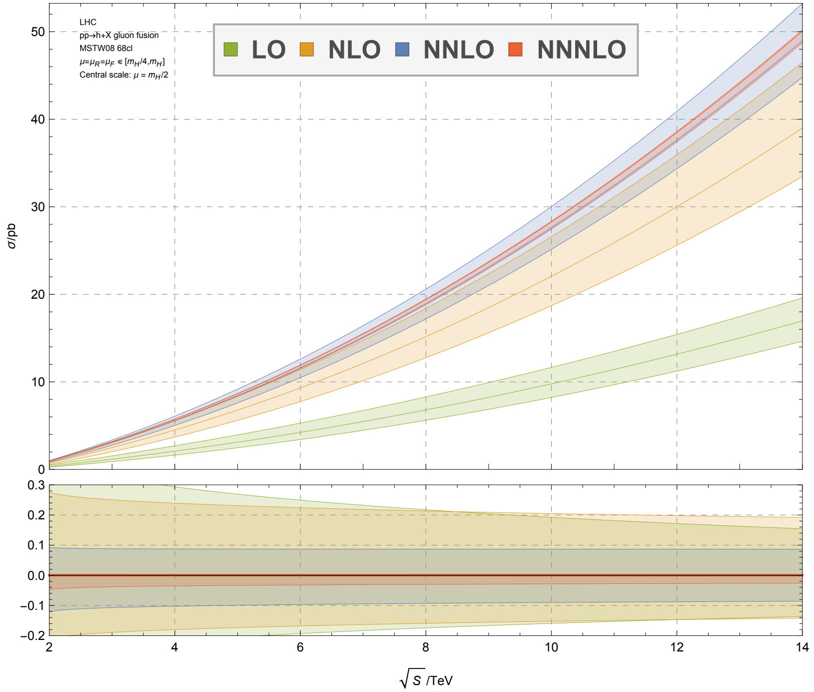
From G. Salam, ICHEP 2022 (slightly modified)

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

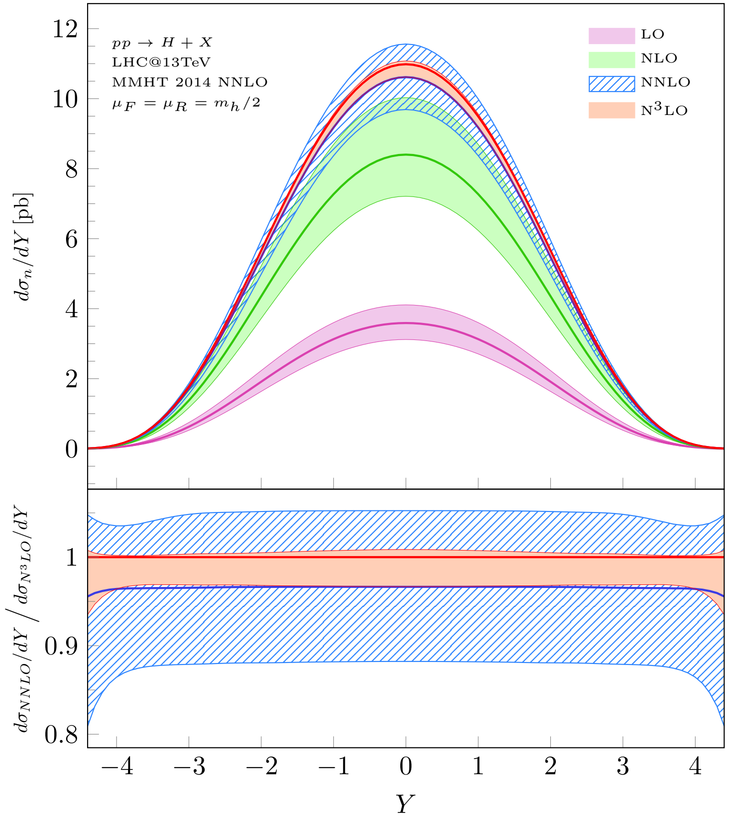
Higgs production via gg fusion at N^3LO

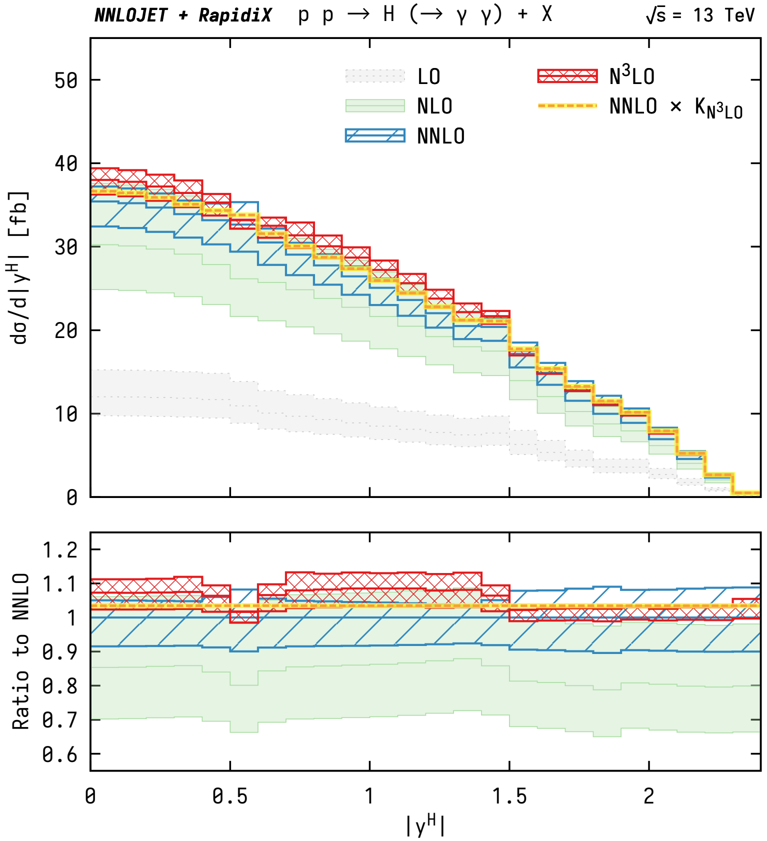


Anastasiou, Duhr, Dulat, Herzog, Mistlberger 1503.06056

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

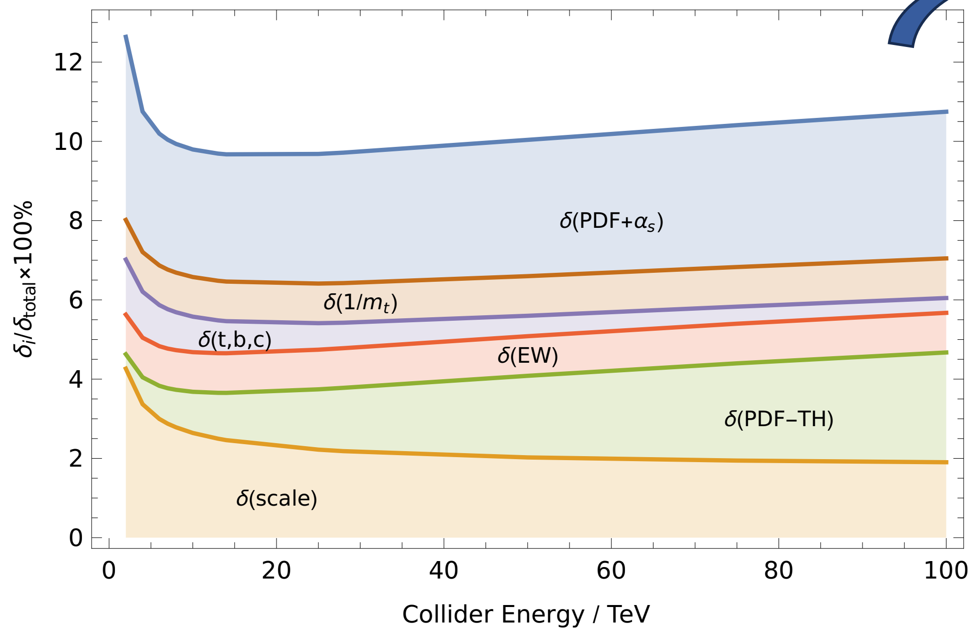




Dulat, Mistlberger, Pelloni 1810.09462

Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni, 2102.07607

… crucial to map residual uncertainties



LHC @ 13 TeV

Dulat, Lazopoulos, Mistlberger
1802.00827 (iHixis)

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

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

Future challenges:

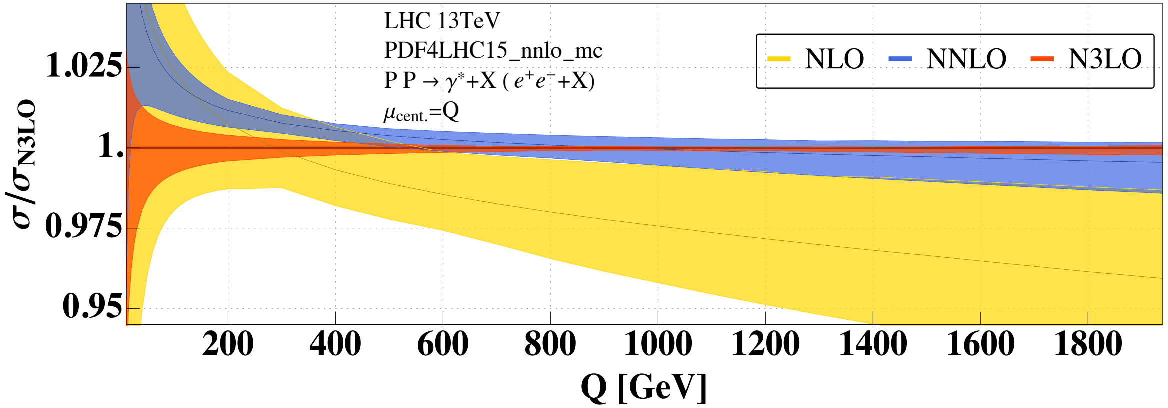
- **N3LO PDF!** → δ(PDF-TH)
- Light-quark mass effects → δ(b,c)
- More EW corrections
- Large logs resummation (fiducial)?

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

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

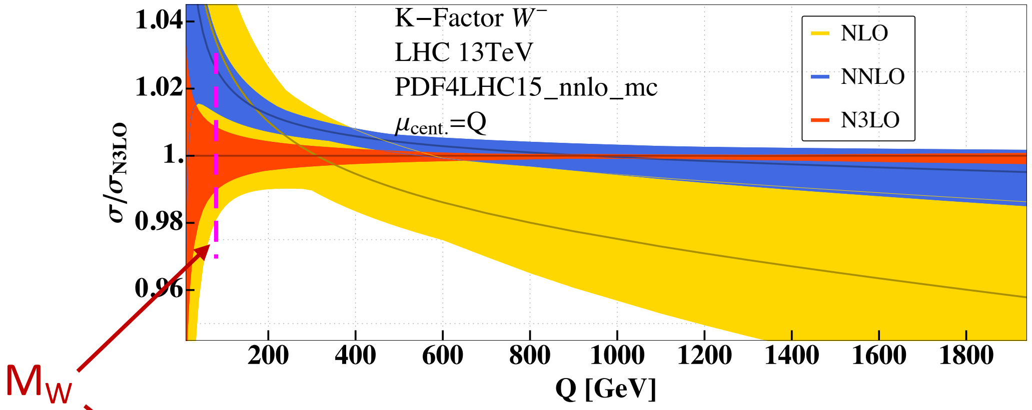
DY at N^3LO – input to PDF fits and M_W measurement

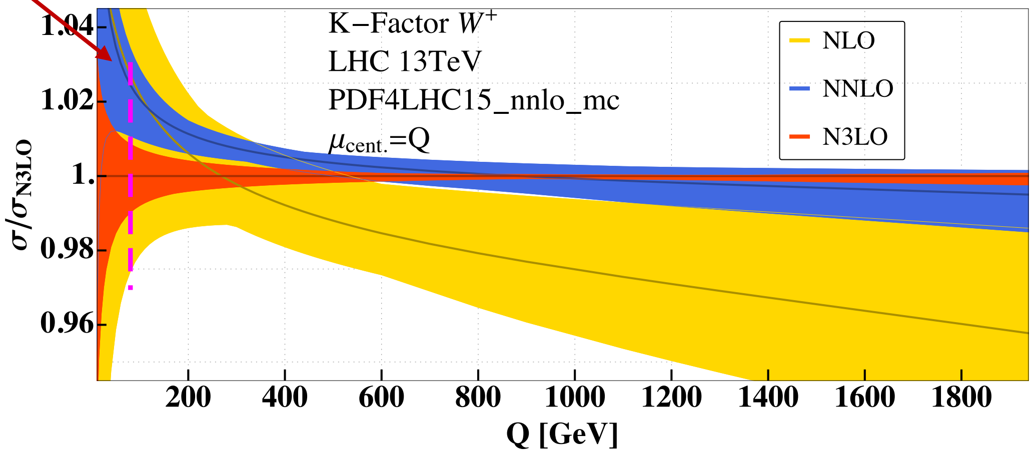
NC-DY



Duhr, Dulat, Mistlberger, 2001.07717

CC-DY



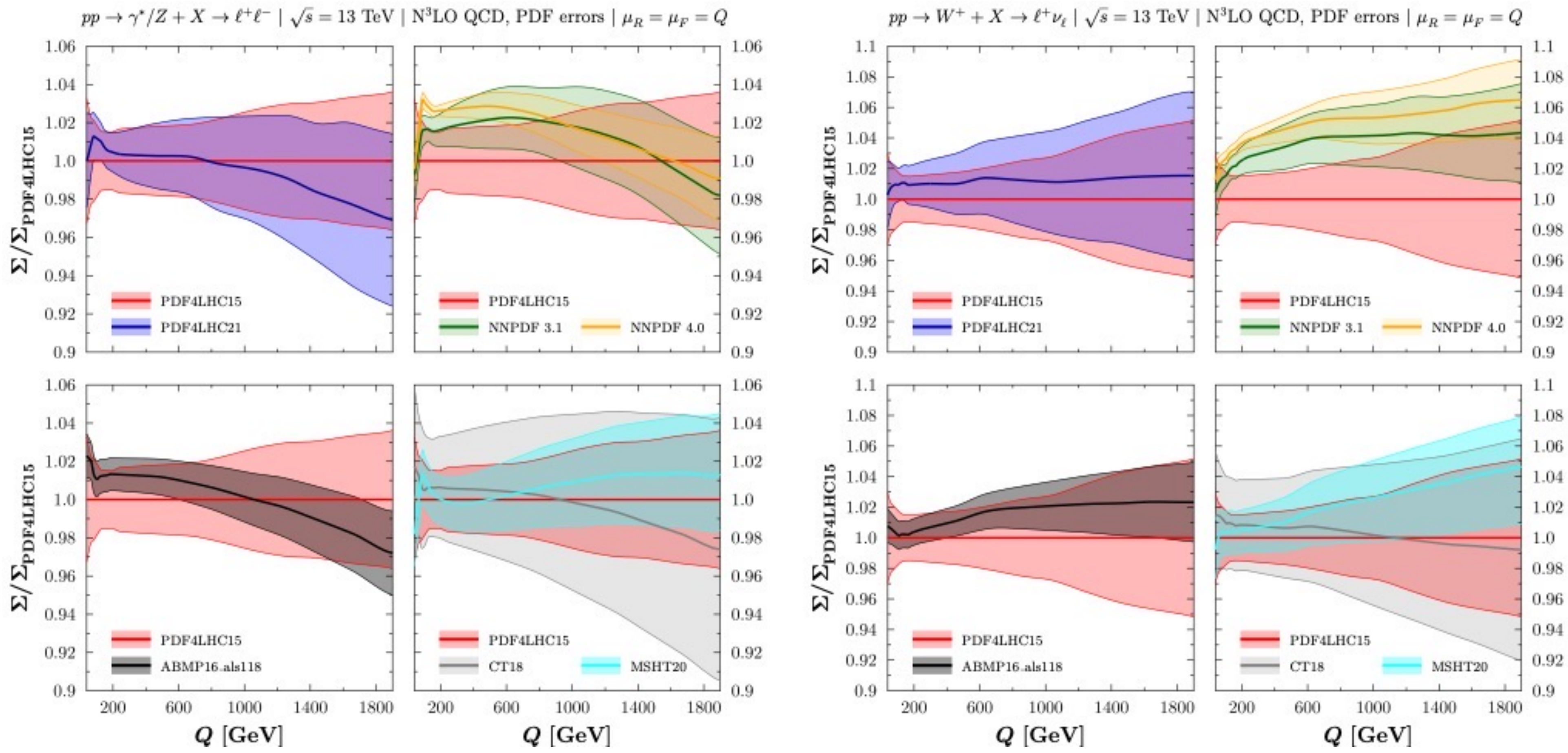


- Scale dependence: non-uniform behavior in all Q-regions
- Important input for PDFs (not yet included)
- **Region around Q~M_W: reconstruce how to estimate theoretical uncertainty from scale variation**

Recall from before: **need 0.1% accuracy in template distributions in order to achieve ΔM_W~10 MeV**

Duhr, Dulat, Mistlberger, 2007.13313

DY at N^3LO – dedicated PDF study



Overall consistency among different sets

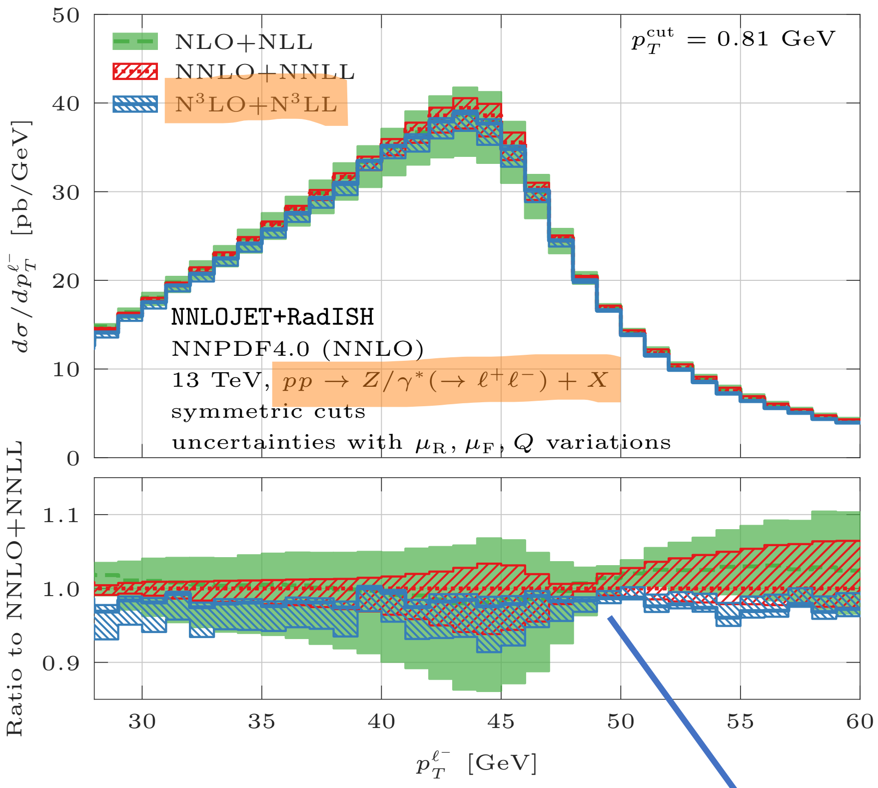
Large variation in error bands

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

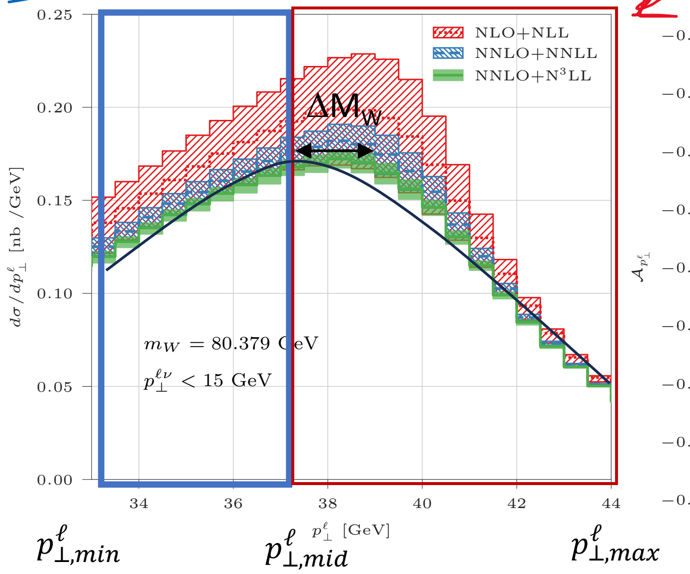
Challenging to control theoretical uncertainties below percent level!

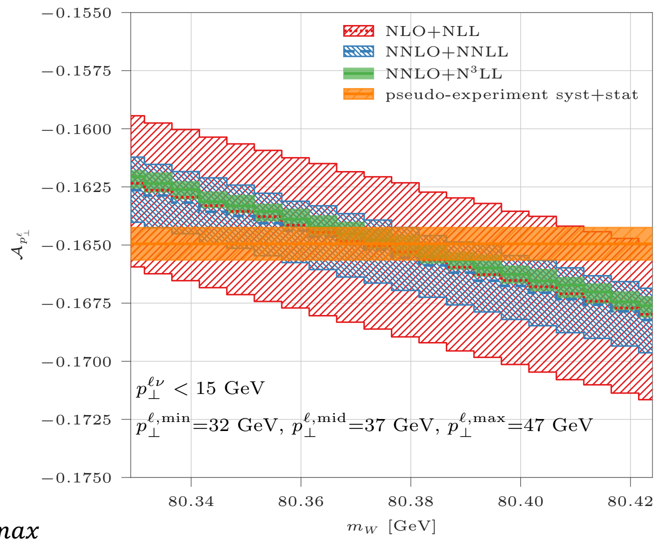
Consider different observable?

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

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

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



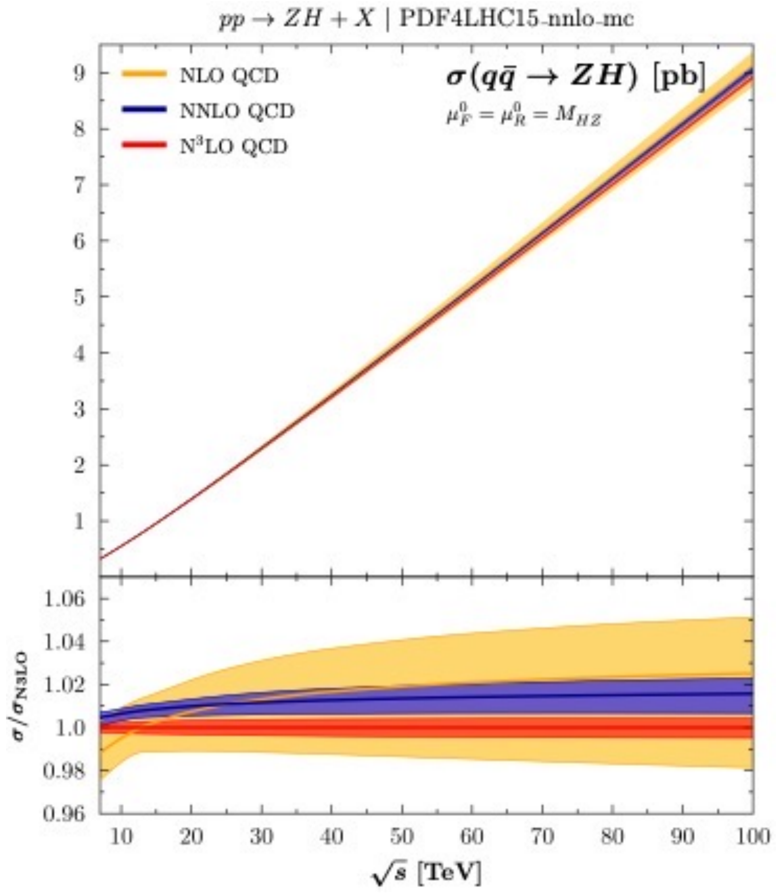


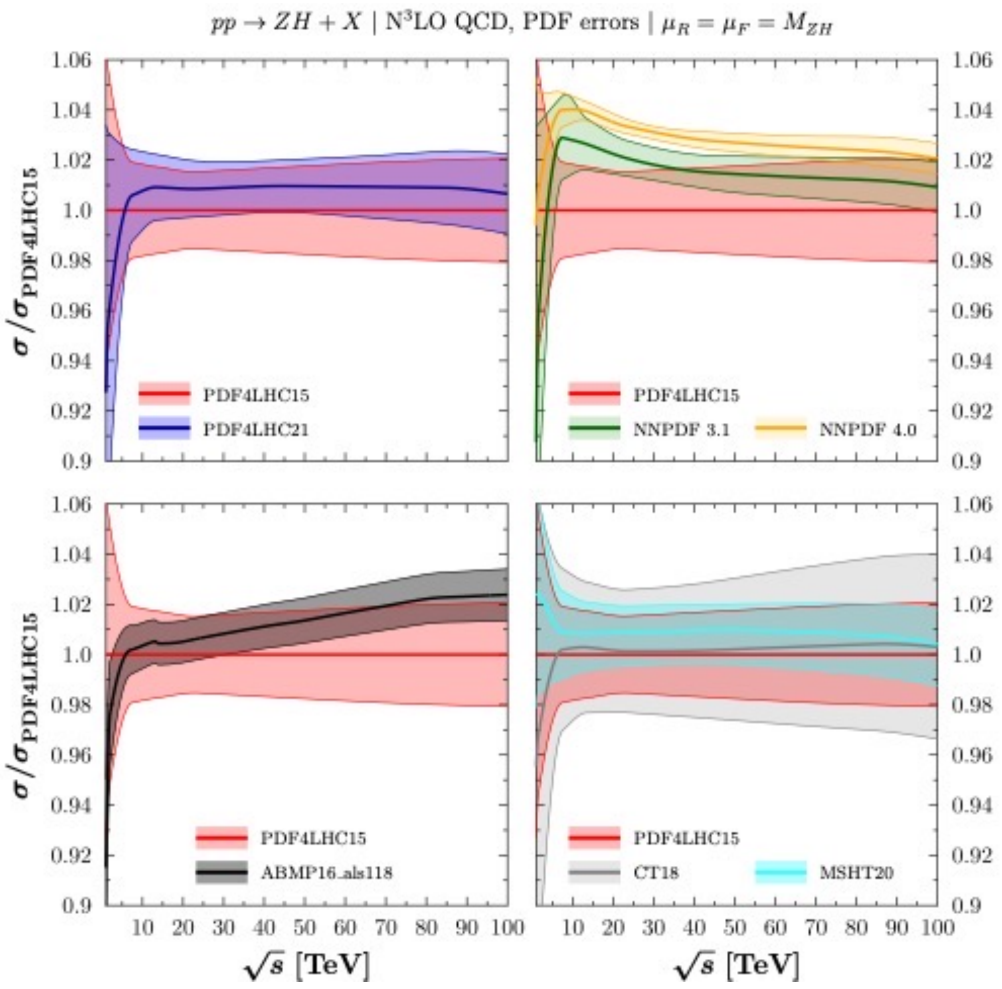
Rottoli, Torrielli, Vicini, 2301.04059

ΔM_W~$\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

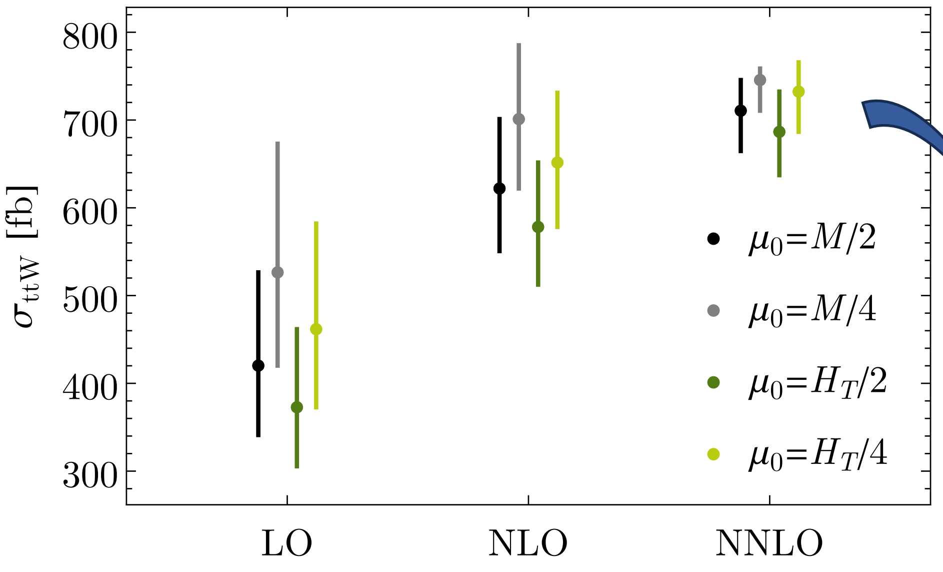
Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini , 2210.07846

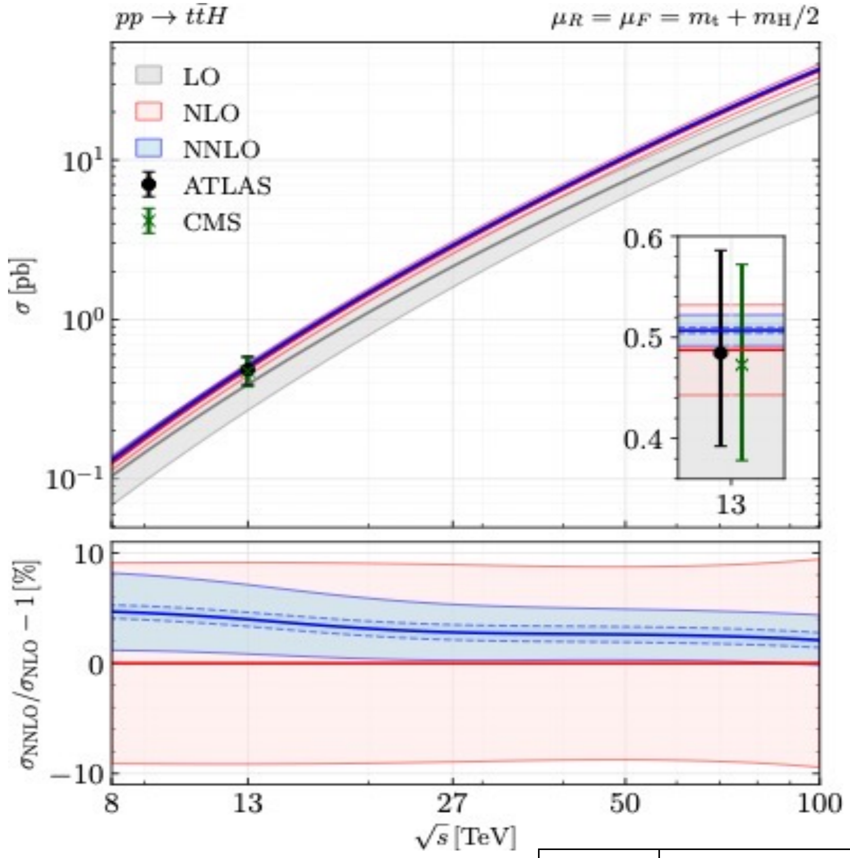
Major impact on LHC phenomenology

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

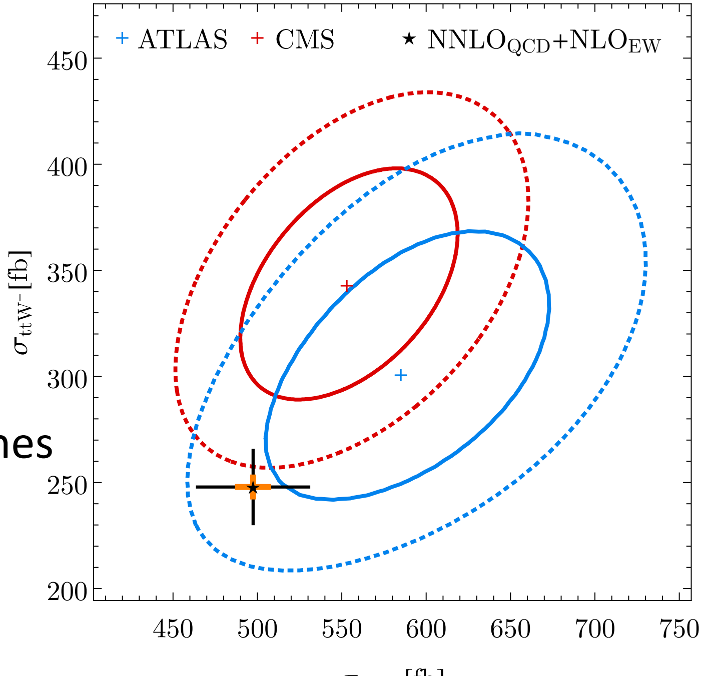
Buonocore et al., 2306.16311





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



Catani et al., 2210.07846

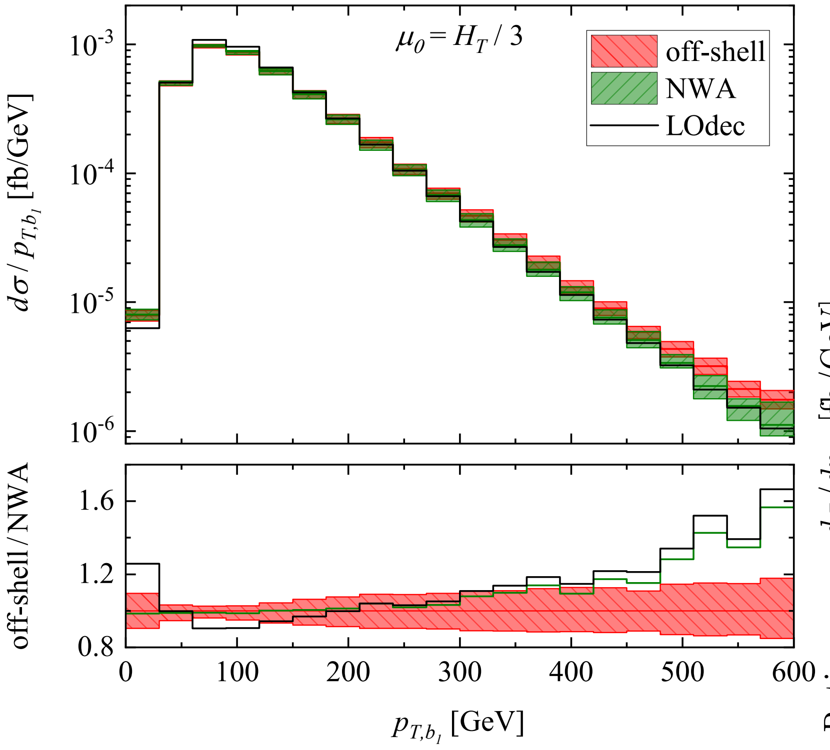
Theoretical uncertainty reduced to 3% level

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

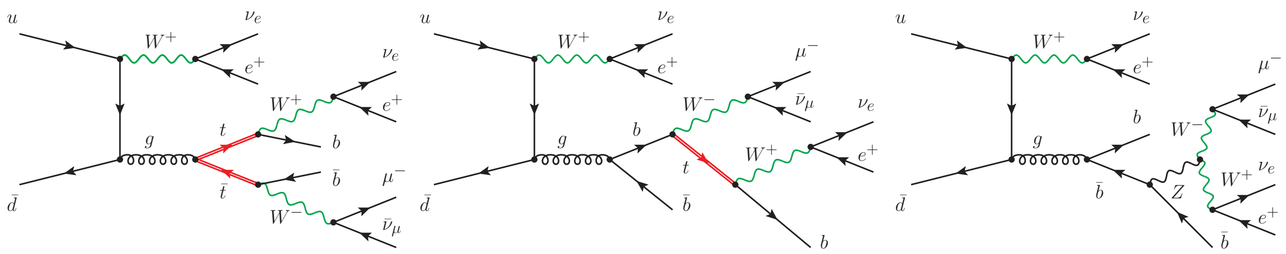
Comparison in fiducial volumes may give further insight

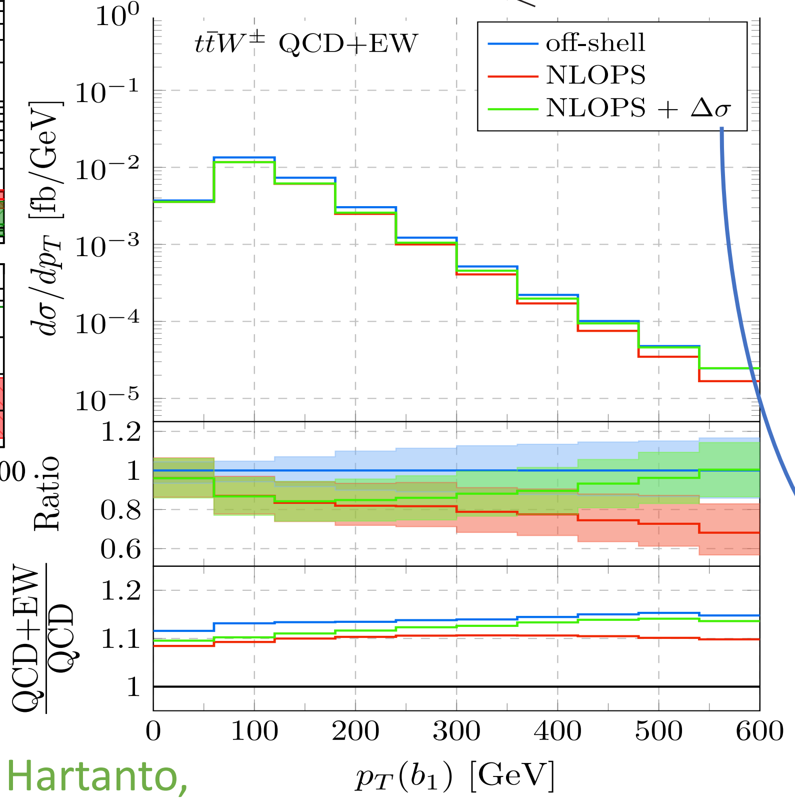
NLO: push the multiplicity challenge

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

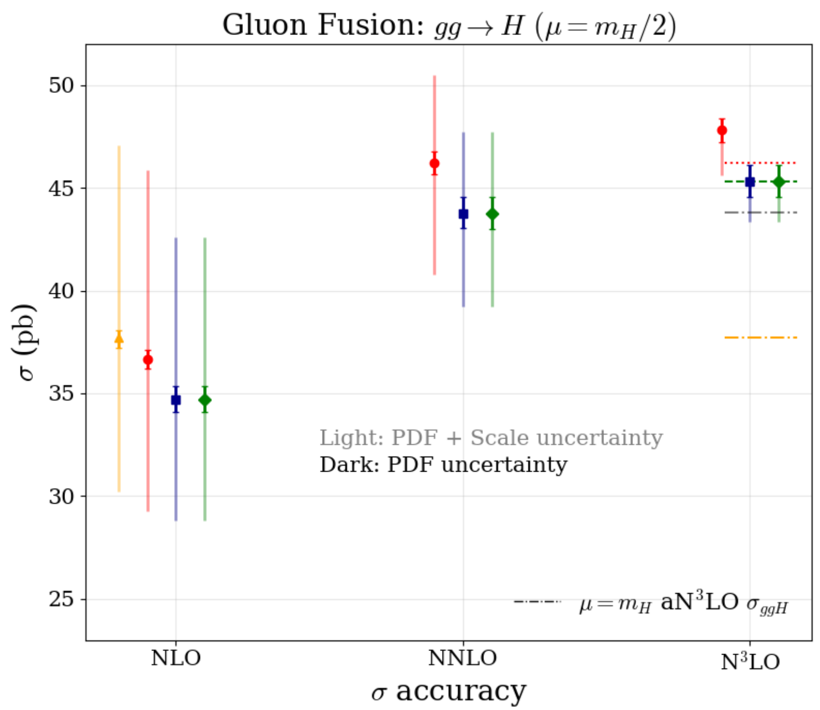
$$\frac{d\sigma^{th}}{dX} = \frac{d\sigma^{NLO+PS}}{dX} + \frac{d\Delta_{off-shell}}{dX}$$

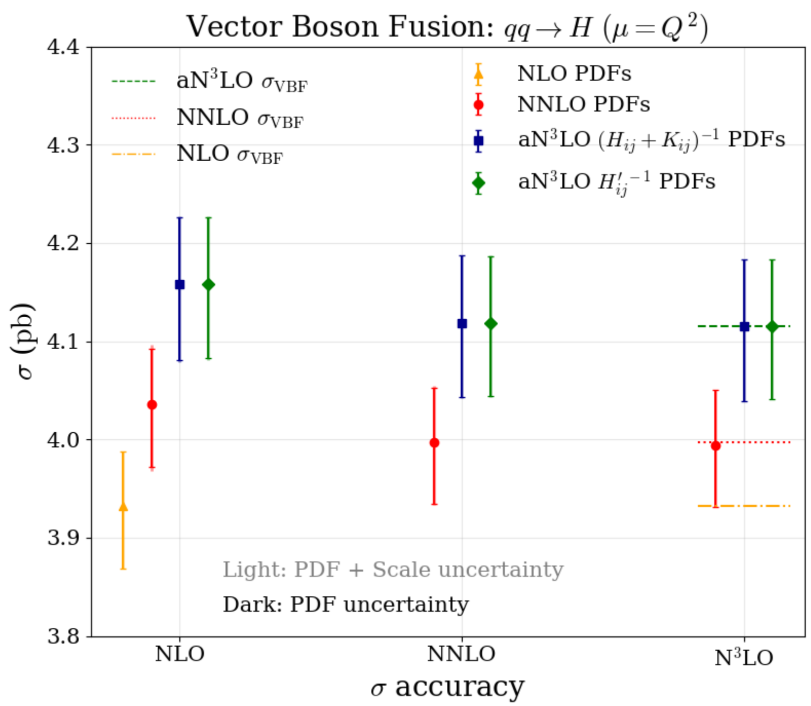
$$\frac{d\Delta_{off-shell}}{dX} = \frac{d\sigma^{NLO}_{off-shell}}{dX} - \frac{d\sigma^{NLO}_{NWA}}{dX}$$

PDF – first approximate N^{3}LO sets

aN^{3}LO → MSHT20aN^{3}LO

McGowan, Cridge, Harland-Lang, Thorne, 2207.04739



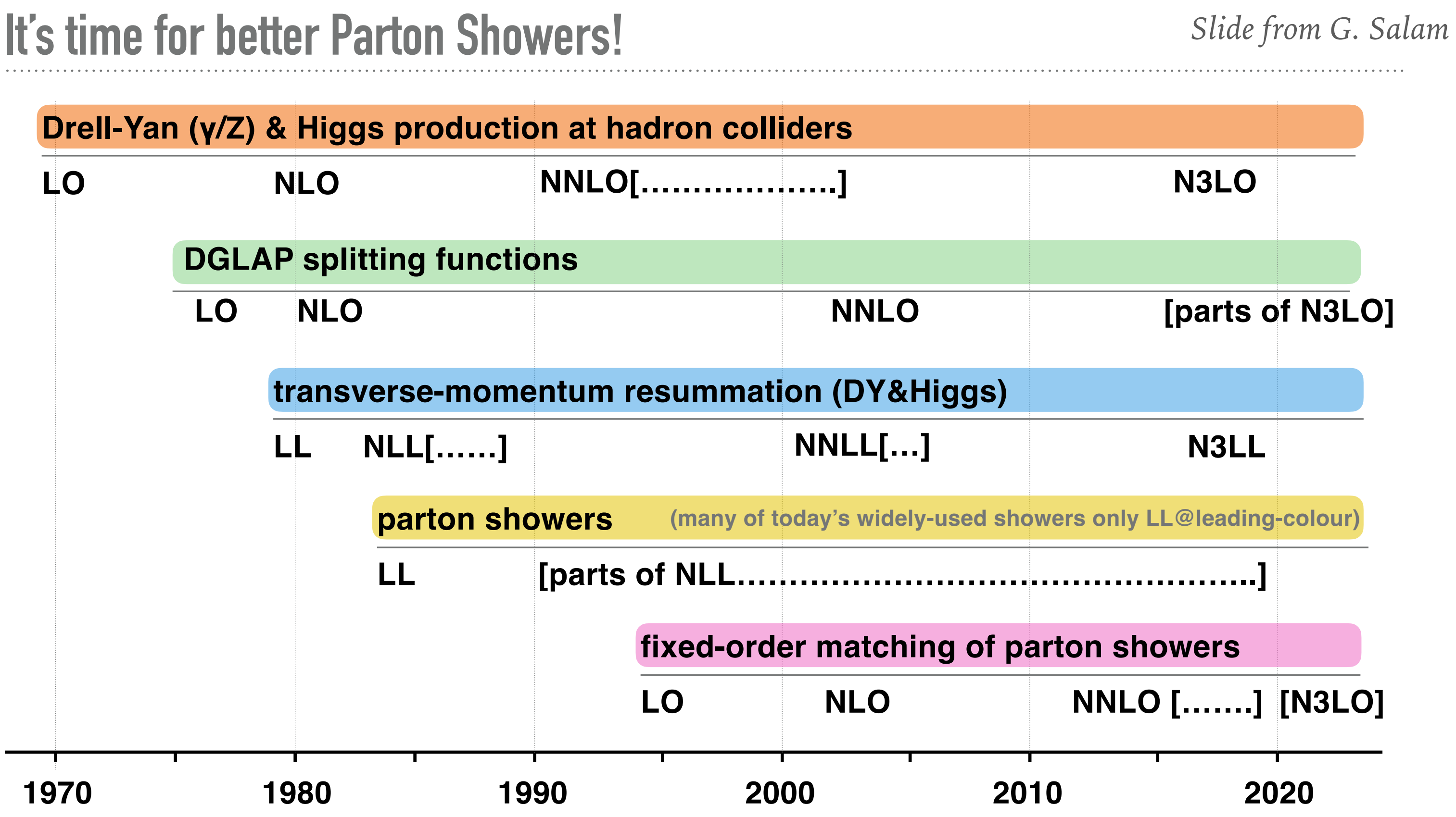


- Based on N^{3}LO approximation to structure functions and DGLAP evolution
- Making use of all available knowledge to constrain PDF parametrization, including both exact, resummed, and approximate estimates of N^{3}LO results
- Including PDF uncertainty from missing higher-orders (MHOU) as theoretical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

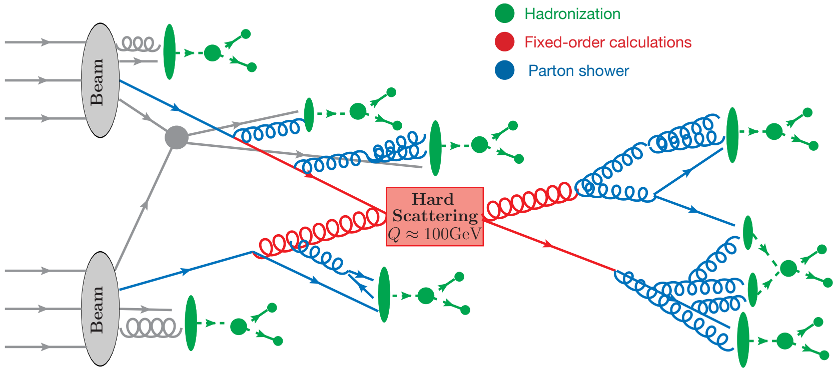
Parton-shower event generators



From S. Ferrario Ravasio, RADCOR 2023

Crucial ingredient to reproduce the complexity of collider events

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



- ➢ 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

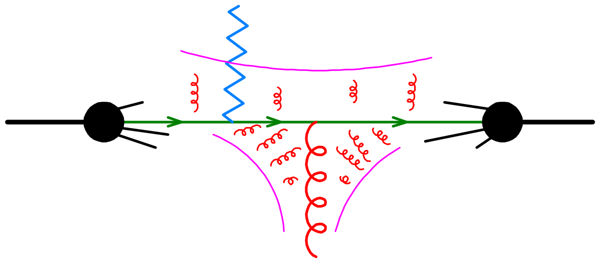
More challenges: non-perturbative effects $O((\Lambda_{QCD}/Q)^p)$

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.