Precision collider phenomenology
(theory precision for collider experiments)

- Precision is **intrinsic to a predictive theory,** such as the Standard Model (SM).
- **Percent-level collider phenomenology** offers a **unique opportunity to explore some of the core questions of particle physics and uncover new physics**.
- The **physics potential of the (HL-)LHC and future colliders greatly depends on** enabling and successfully executing **a broad precision phenomenology program**.
- Precision **requires theory and experiments to reach comparable accuracy**.

Precision phenomenology at the (HL)-LHC

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!

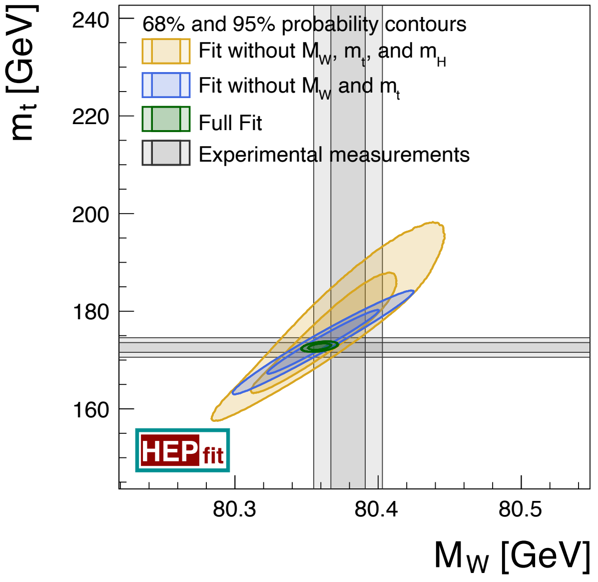
Theoretical systematics could become the main limitation

Precision intrinsic to a predictive theory: SM global fits

A recent challenge: CDF new M_W measurement

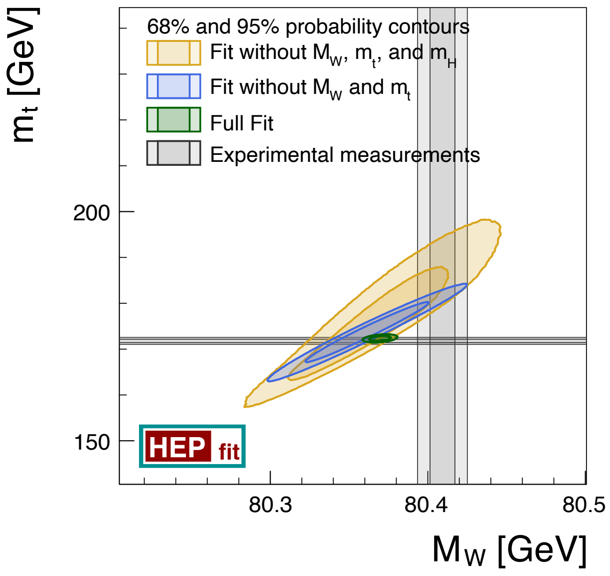
Tensions could become real indications of NP effects with the precision of the HL-LHC or of a future e^+e^- machine, if theory match the precision of experiments.

before (pull 1.8σ)



M_W=80.379 ±0.012 GeV

after (pull 6.1σ)



M_W=80.409 ±0.008 GeV

De Blas et al. [2204.04204]

EWPO uncertainties	Current theory error	Projected theory error	Current param. error	Projected param. error Scenario 1	Projected param. error Scenario 2
Δm_W (MeV)	4	1	5	2.8	0.6
$\Delta\Gamma_Z$ (MeV)	0.4	0.1	0.5	0.3	0.1
$\Delta \sin^2\theta^\ell_{\rm eff}$ $(\times 10^5)$	4.5	1.5	4.2	3.7	1.1
ΔA_ℓ $(\times 10^5)$	32	11	30	25	7.5
δR_ℓ $(\times 10^3)$	6	1.5	6	3.2	1.3

EWPO Uncertainties	Current	HL-LHC
Δm_W (MeV)	12 / 9.4†	5
Δm_Z (MeV)	2.1	
$\Delta\Gamma_Z$ (MeV)	2.3	
Δm_t (GeV)	0.6*	0.2

Quantity	current	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha(m_Z)^{-1}$ $(\times 10^3)$	17.8*	17.8*		3.8 (1.2)	17.8*	
Δm_W (MeV)	12*	0.5 (2.4)		0.25 (0.3)	0.35 (0.3)	
Δm_Z (MeV)	2.1*	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1*
Δm_H (MeV)	170*	14		2.5 (2)	5.9	78
$\Delta\Gamma_W$ (MeV)	42*	2		1.2 (0.3)	1.8 (0.9)	
$\Delta\Gamma_Z$ (MeV)	2.3*	1.5 (0.2)	0.12	0.004 (0.025)	0.005 (0.025)	2.3*

Snowmass 2021 EWK TG Report – 2209.08078

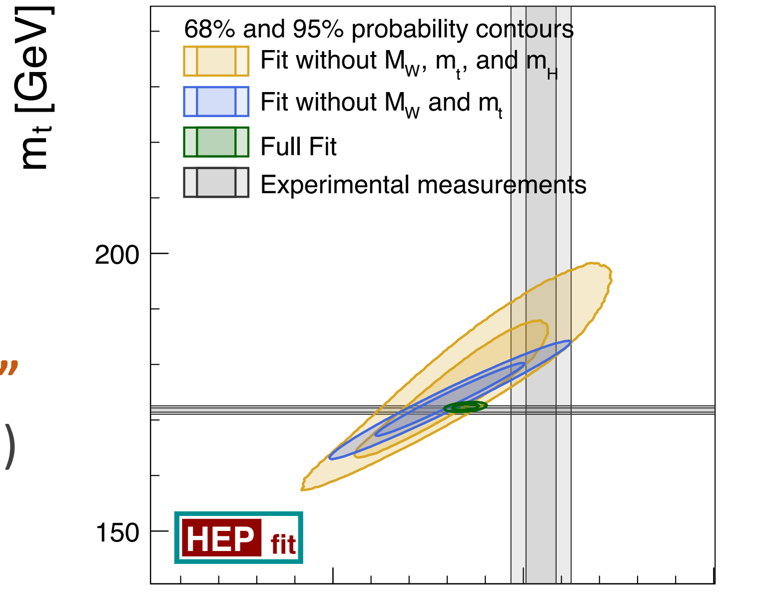
EW global fit of the SM - excerpt

J. de Blas et al. 2112.07274, 2204.04204, plus updates

For M_W we combine:
- ❑ All LEP 2 measurements;
- ❑ Previous Tevatron average
- ❑ ATLAS and LHCb measurements
- ❑ CDF measurement [M_W=(80.4335±0.0094) GeV]
- ❑ ATLAS measurement [M_W=(80.360±0.016) GeV]

M_W = 80.409 ± 0.008 GeV (**standard**, with CDF)
M_W = 80.360± 0.012 GeV (**standard**, without CDF)

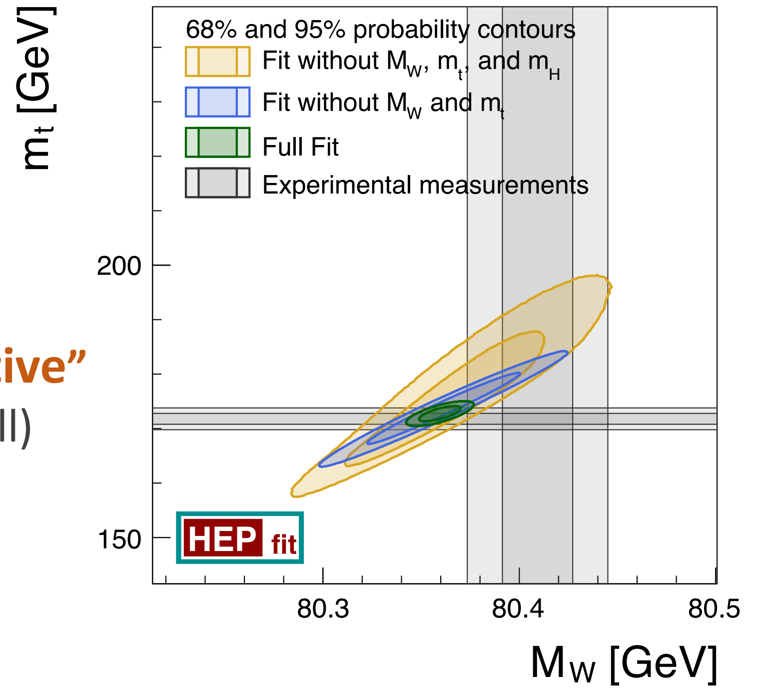
"**standard**"
(6.1 σ pull)



For m_t we combine:
- ❑ 2016 Tevatron combination
- ❑ ATLAS Run 1 and Run2 results
- ❑ CMS Run 1 and Run 2 results
- ❑ Recent CMS l+j measurement [m_t=(171.77±0.38) GeV]

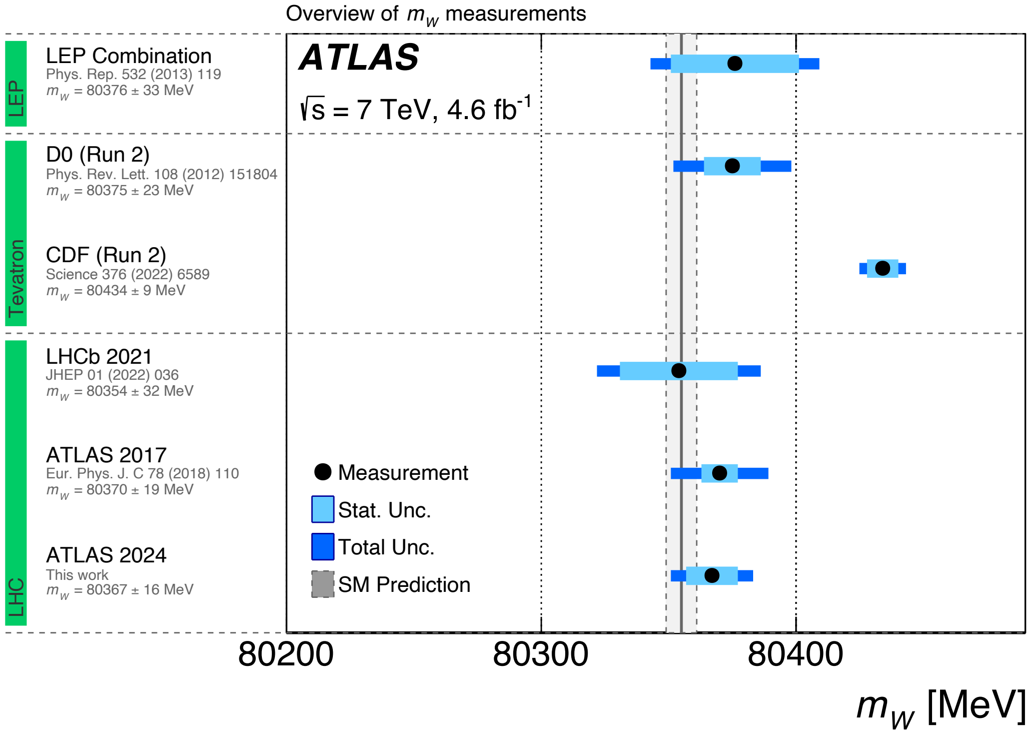
m_t = 172.61 ±0.58 GeV (**standard**)

"**conservative**"
(3.0 σ pull)



Due to tension between LEP, Tevatron, and LHC measurements consider also a **conservative** error of δM_W=18 MeV and δm_t=1 GeV (à la PDG)

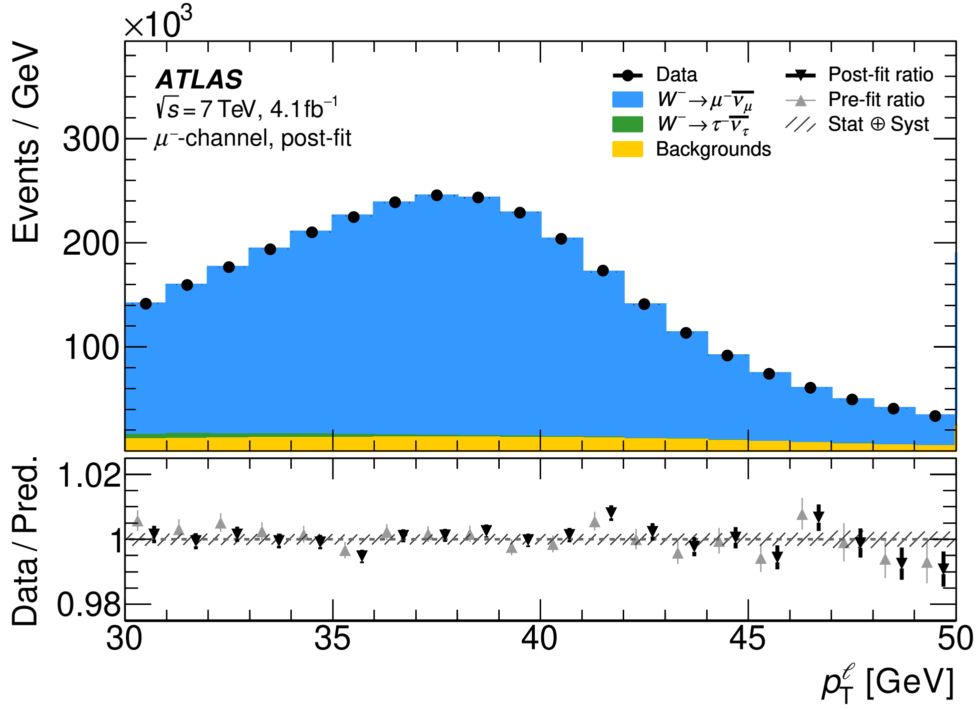
SM global fits: the M_W puzzle



ATLAS, 2403.15085

Mass measured by fitting template distributions of transverse momentum and mass

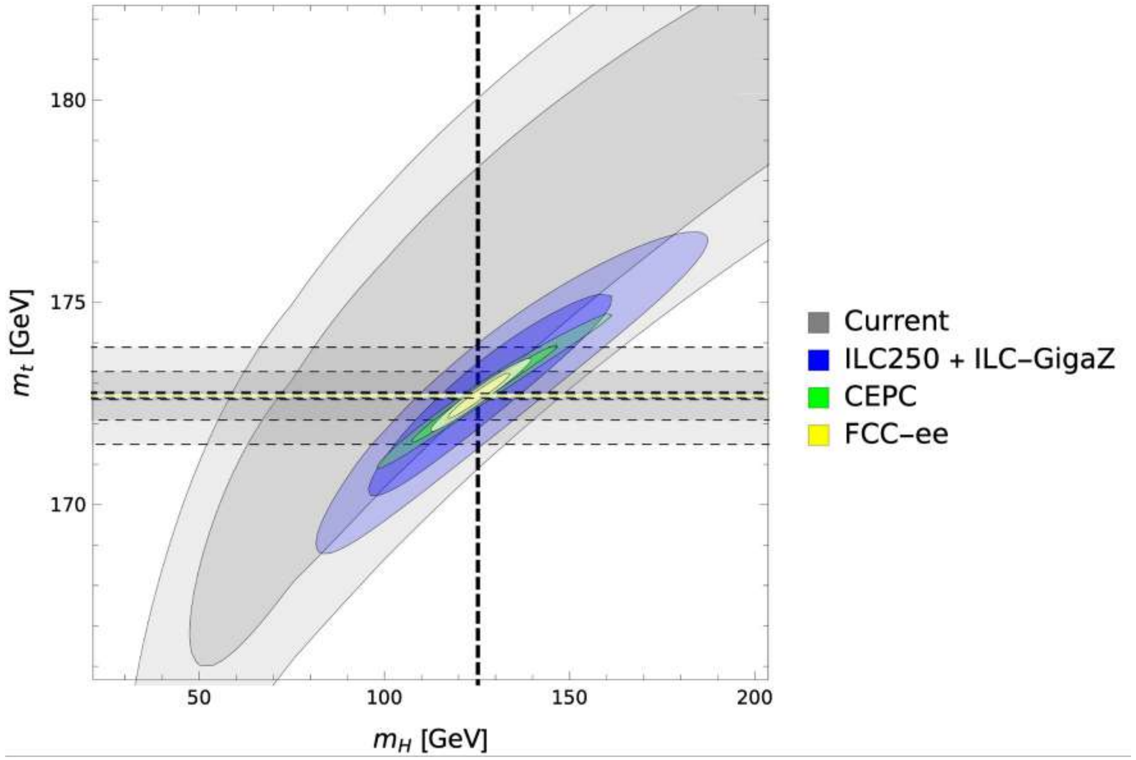
Template fitting is acceptable if theory describes data with high accuracy



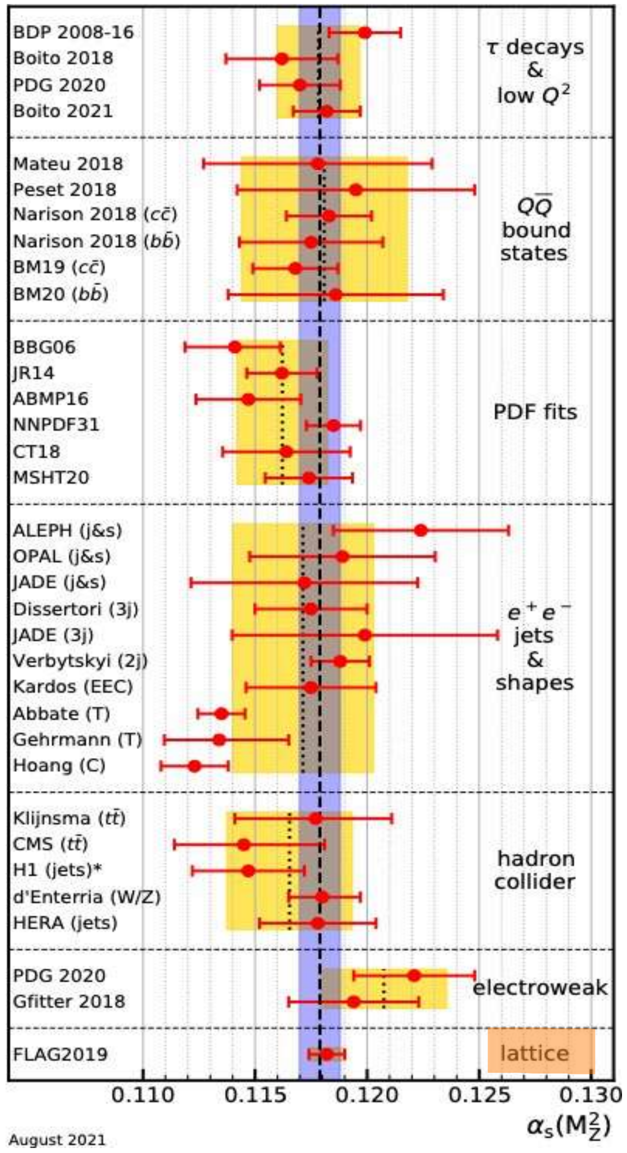
ΔM_W~10 Mev → 0.1% control on kinematic distributions

More constraining parameters

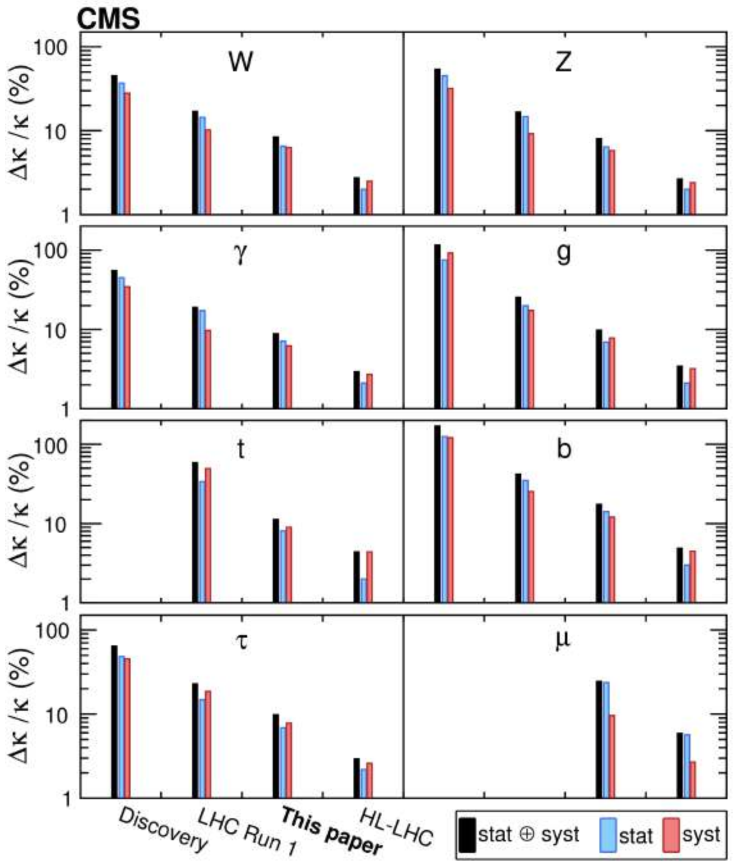
Parameter	HL-LHC	ILC 500	FCC-ee	FCC-hh
$\sqrt{s}$ [TeV]	14	0.5	0.36	100
Yukawa coupling y_t (%)	3.4	2.8	3.1	1.0
Top mass m_t (MeV/%)	170/0.10	50/0.031	40/0.025	–

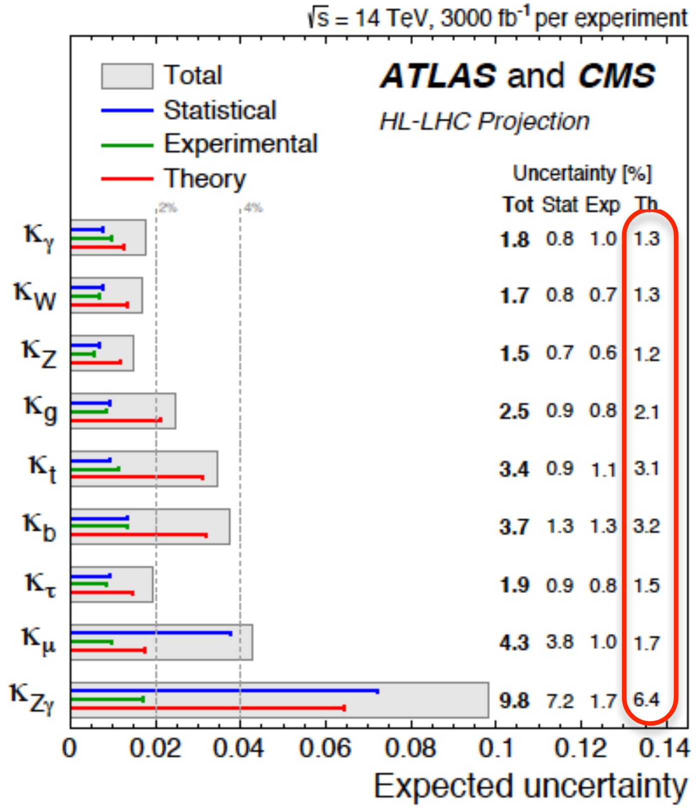


Snowmass 2021 EF TG Report, 2209.11267 and 2208.09078



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%)

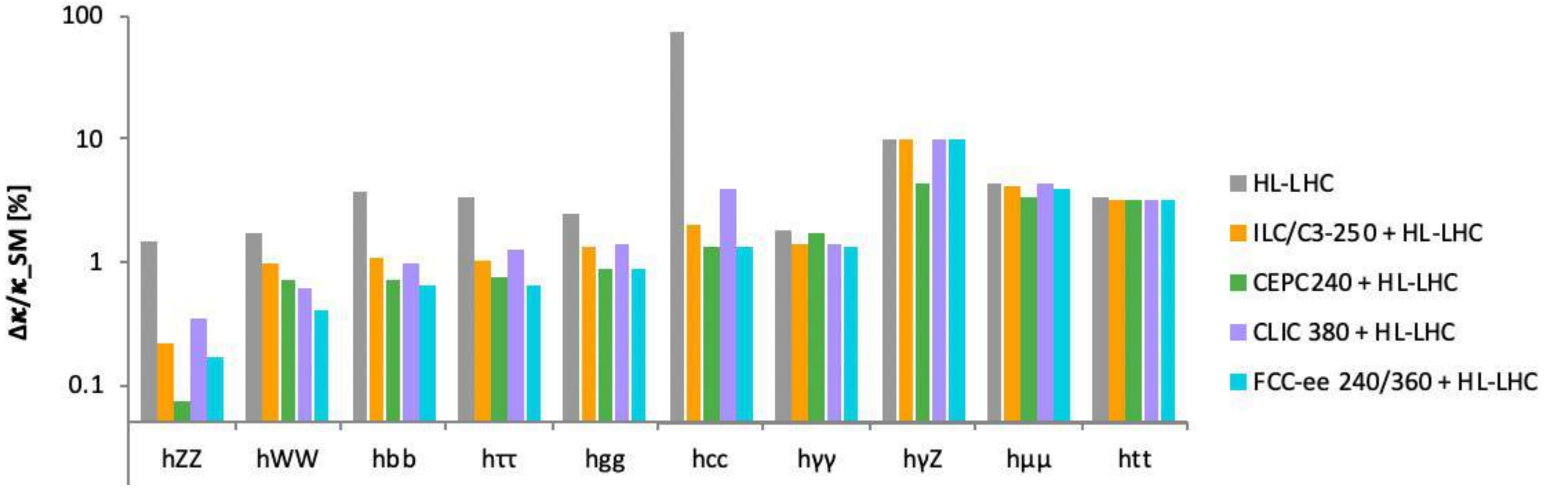
Improved systematics probes higher scales

Theory could become the main limitation

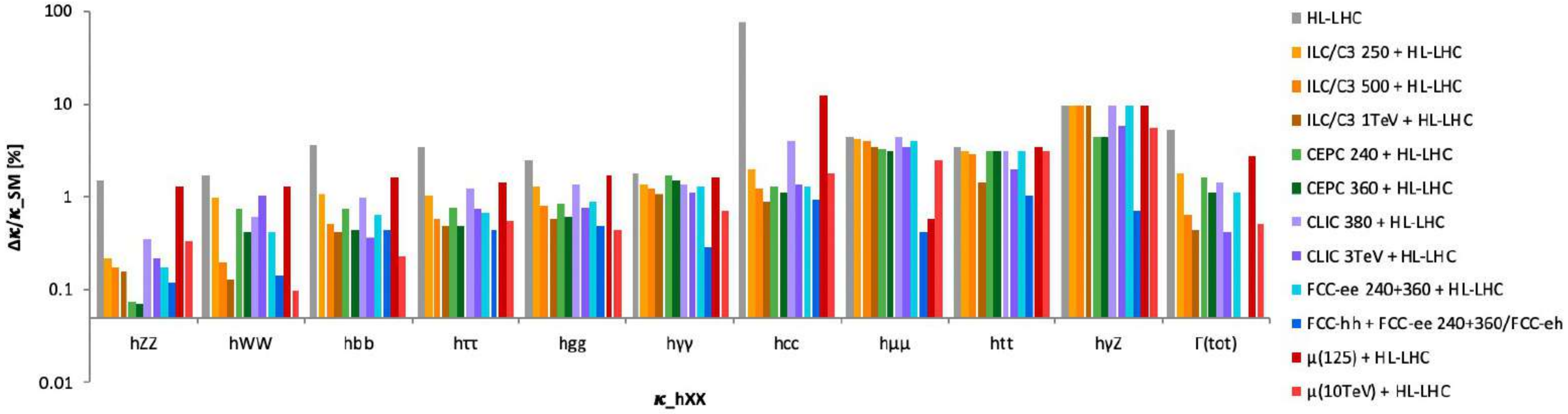
Theory need to improve modeling and interpretation of LHC events, in particular when new physics may not be a simple rescaling of SM interactions

Reach of future colliders for Higgs couplings: a closer look

Based on full Run 2 dataset analyses



Initial stages of future e^+e^- machines



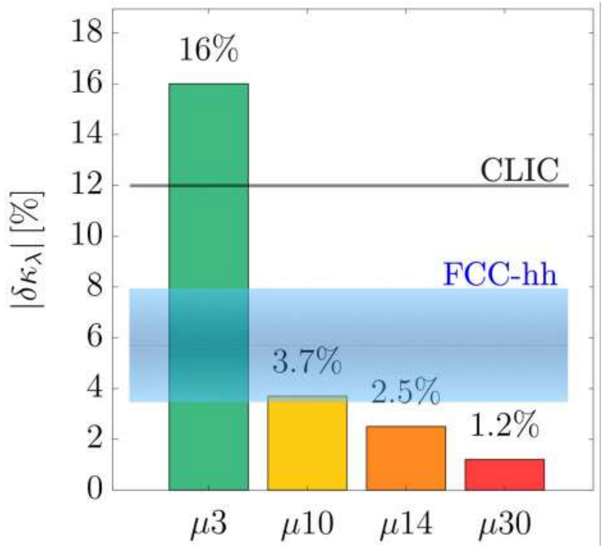
Final reach of all considered future colliders

From Snowmass 2021 EF Higgs Topical Group Report arXiv:2209.07510

Reach for Higgs self-coupling

collider	Indirect-h	hh	combined
HL-LHC	100-200%	50%	50%
ILC_{250}/C^3-250	49%	–	49%
ILC_{500}/C^3-550	38%	20%	20%
$CLIC_{380}$	50%	–	50%
$CLIC_{1500}$	49%	36%	29%
$CLIC_{3000}$	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
FCC-hh	-	2.9-5.5%	2.9-5.5%
μ(3 TeV)	-	15-30%	15-30%
μ(10 TeV)	-	4%	4%

- ATLAS and CMS HL-LHC updated
- FCC-hh updated arXiv:2004.03505
- Added MuC reach:



arXiv:2203.07256

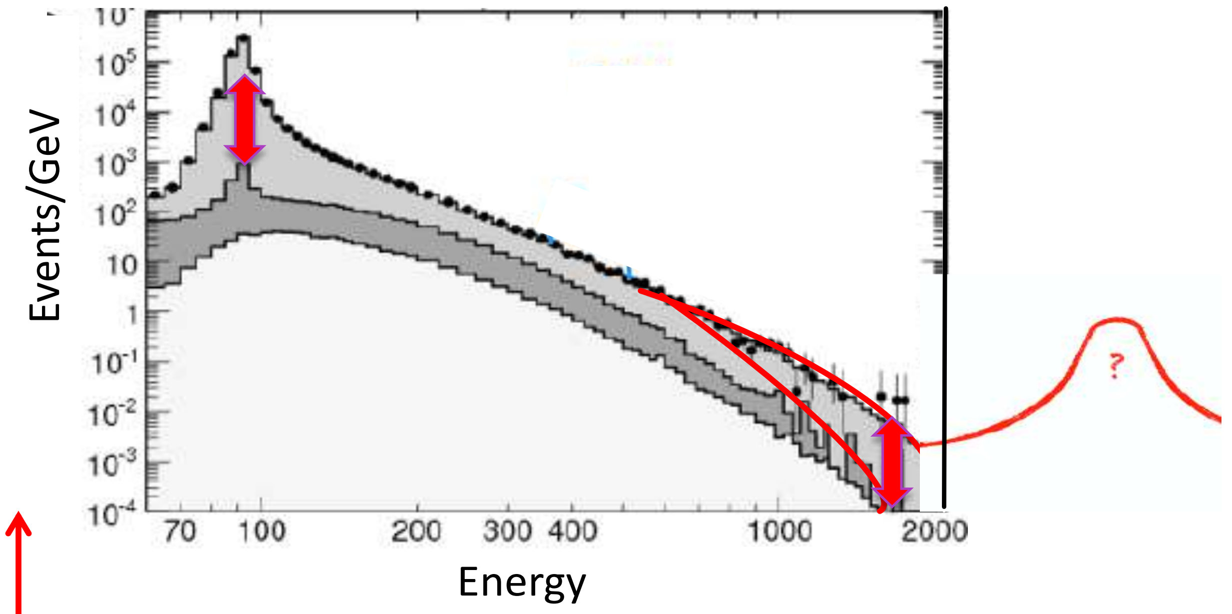
Beyond total rates

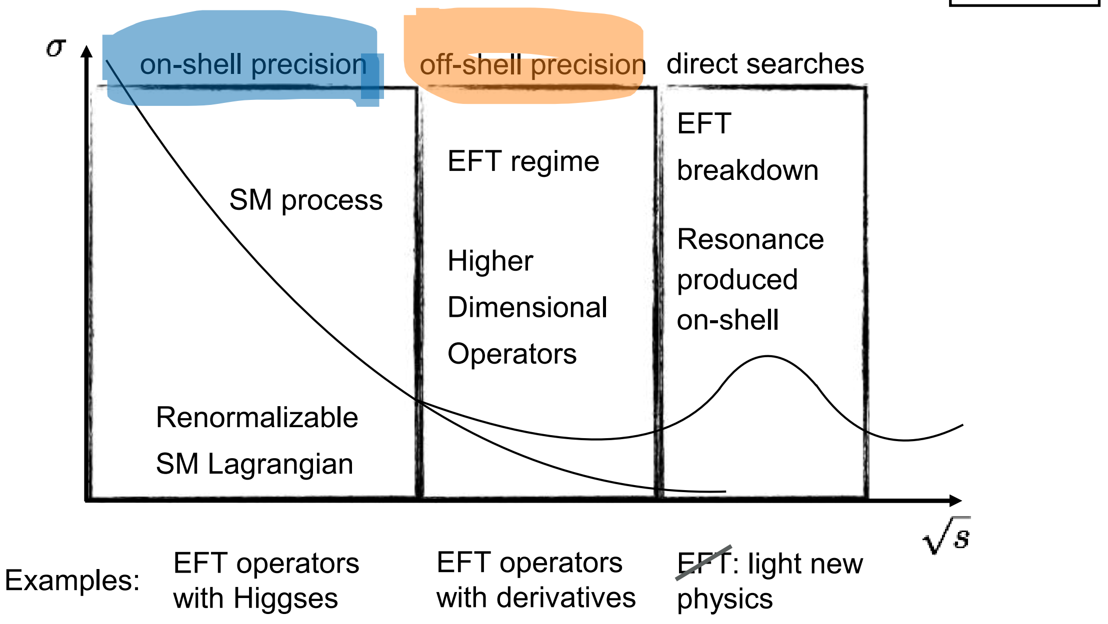
Extending the SM via effective interactions above the EW scale $\longrightarrow$ **SMEFT**

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \left(\frac{1}{\Lambda^2} \sum_i C_i O_i + \text{h.c.} \right) + O(\Lambda^{-4})$$

dim=6

dim>8





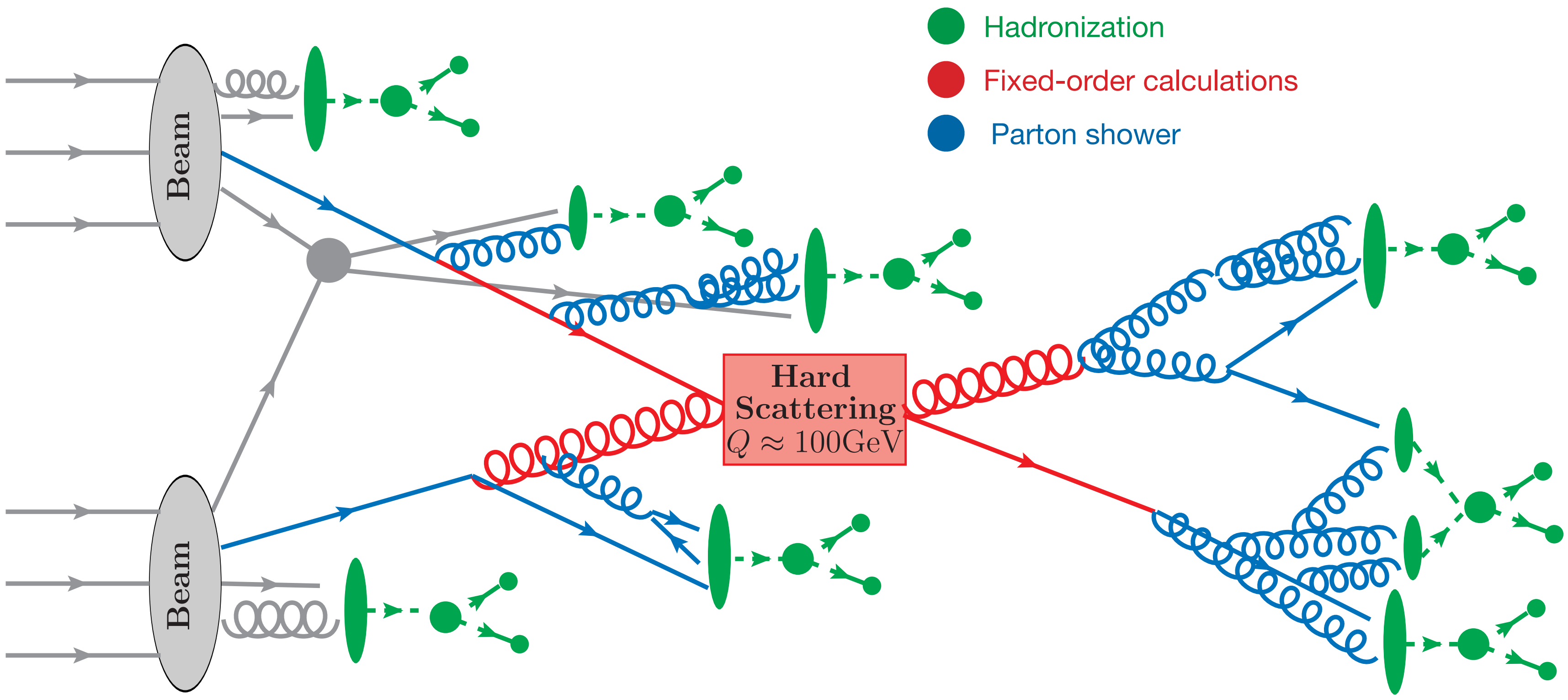
Need SM precision calculations at differential level both at **lower energy,** where rates are large and at **higher energy** where rates are small but effects of new physics may be more visible.

Crucial to control EFT sensitive regions

Theory 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 tackle future challenges.

Dissecting the challenge



From S. Ferrario Ravasio, RADCOR 2023

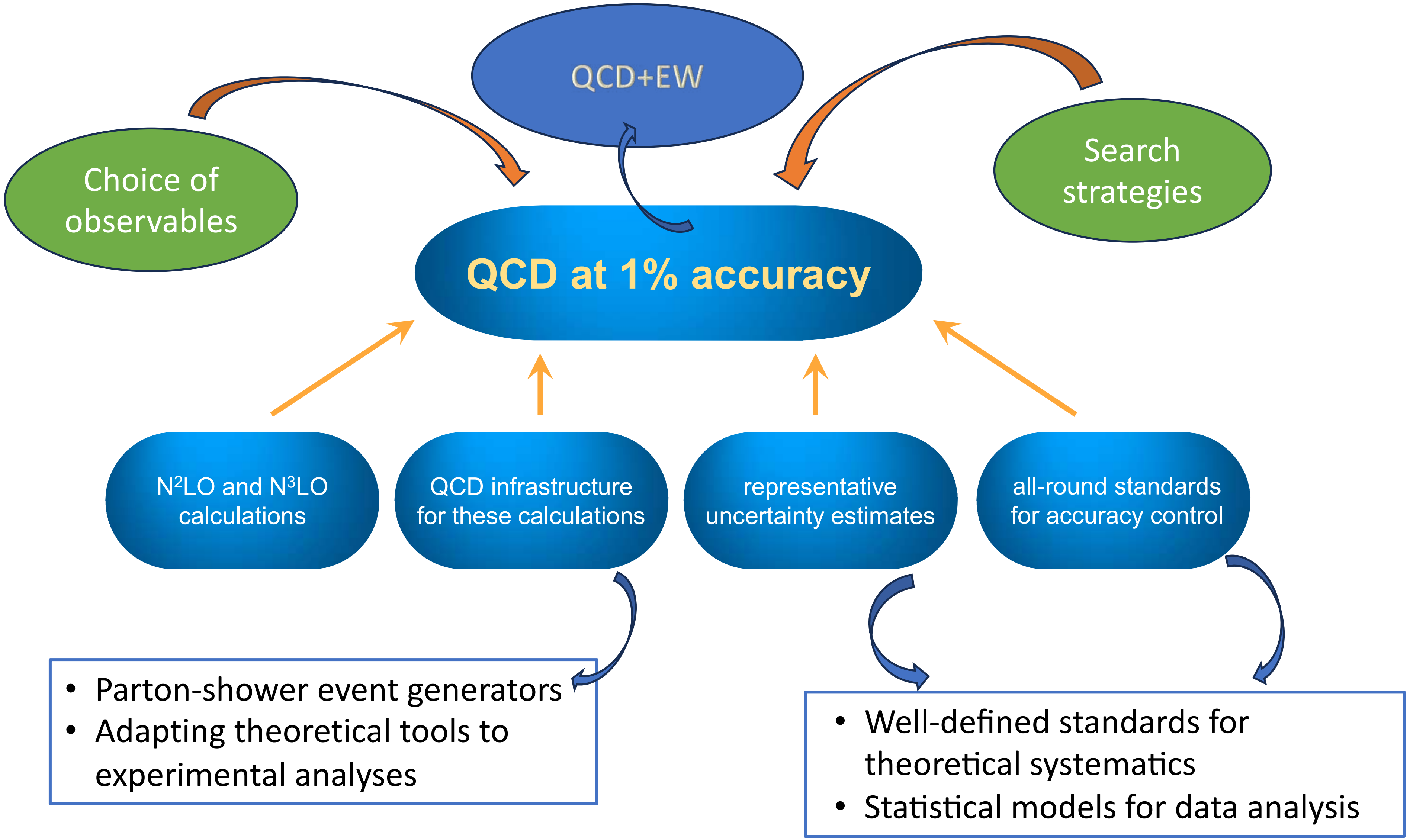
$$d\sigma = \sum_{ij} \int dx_1\, dx_2\, f_{p,i}(x_1) f_{p,j}(x_2) \widehat{d\sigma}(x_1 x_2 s) + O((\Lambda_{QCD}/Q)^p)$$

Parton Distribution Functions (PDF)

hard-scattering partonic xsection (pQCD+EW)

Hadronization, non-p QCD

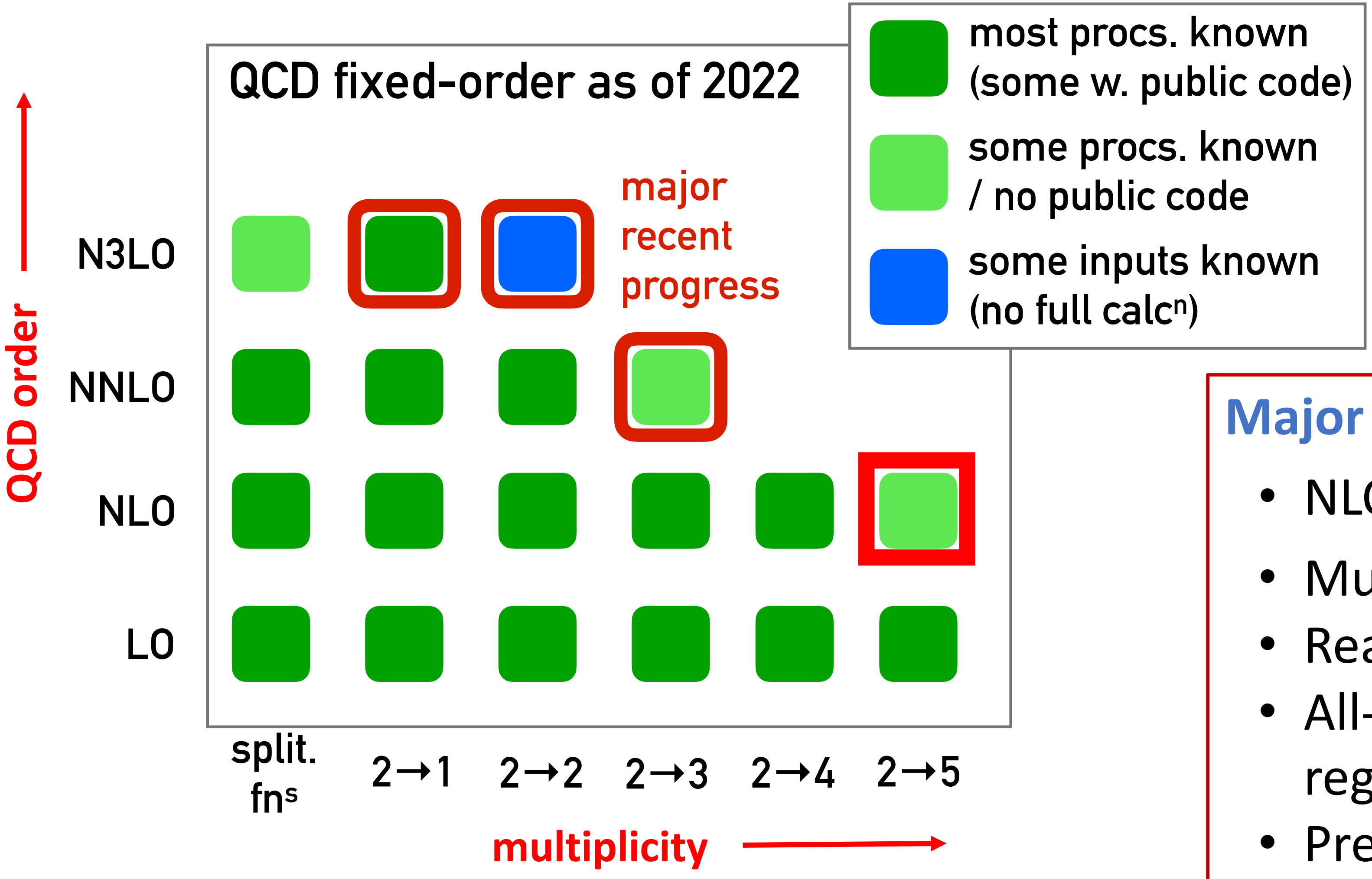
Many components to percent precision



Snowmass Report of QCD Topical Groups, 2209.14872

N^XLO predictions - state of the art

For a complete summary of existing and auspicable results see
Les Houches list [Huss et al., 2207.02122, updated 2023]



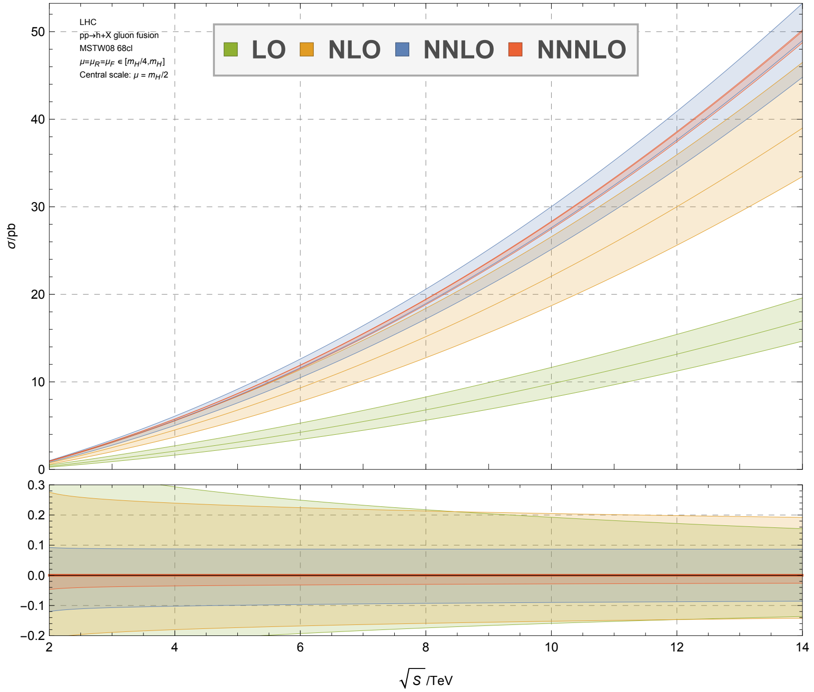
From G. Salam, ICHEP 2022 (slightly modified)

Still a good summary for 2024, with much progress in red-circled boxes

Major challenges and progress:

- NLO EW and mixed NLO QCD+EW
- Multiloop scattering amplitudes
- Real emission → IR subtraction
- All-order resummations in specific regions of phase space
- Predictions for fiducial regions

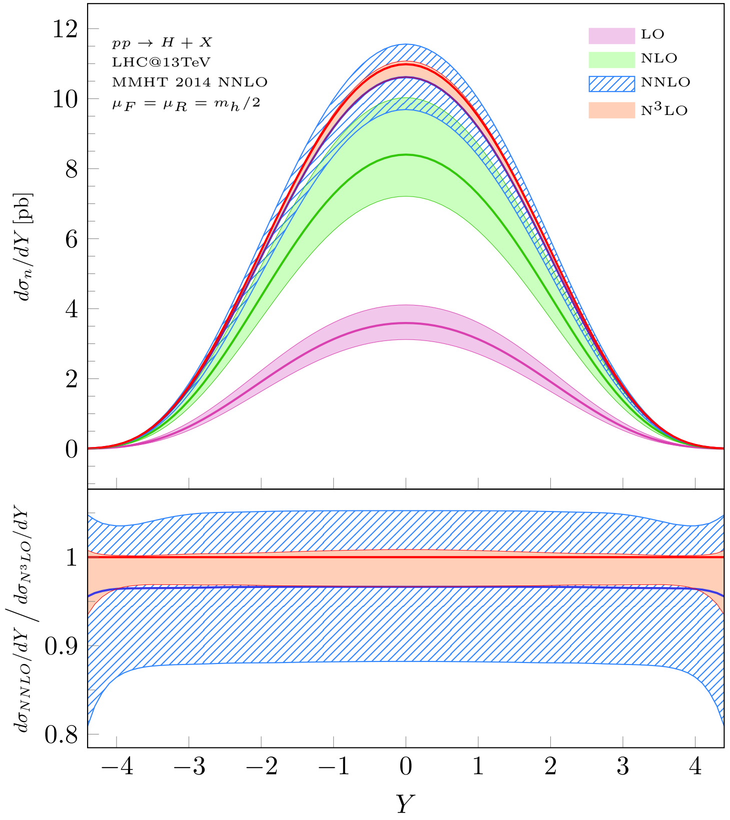
Higgs production via gg fusion at N^3LO



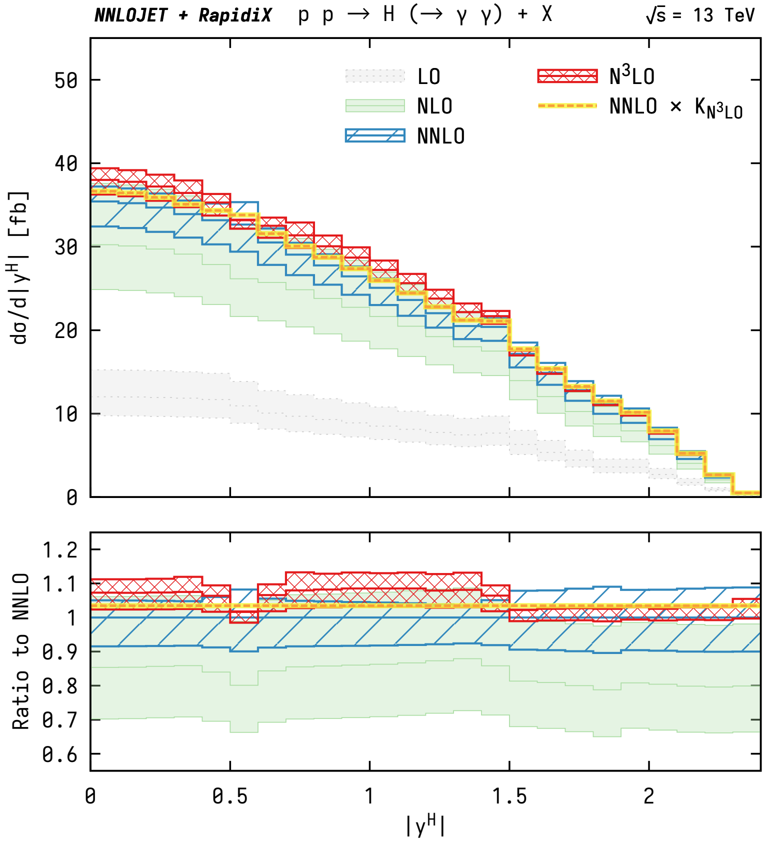
Anastasiou, Duhr, Dulat, Herzog, Mistlberger 1503.06056

Continuous progress on a crucial process

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

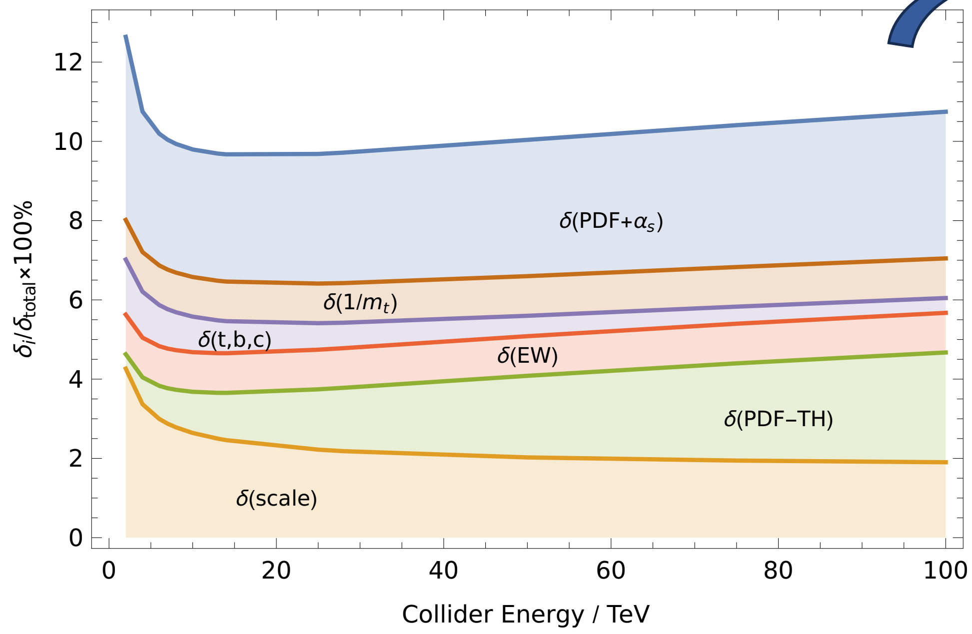


Dulat, Mistlberger, Pelloni 1810.09462



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

… crucial to map residual uncertainties



LHC @ 13 TeV

Dulat, Lazopoulos, Mistlberger
1802.00827 (iHixis)

$$
\begin{array}{rclll}
\delta(\text{theory}) & = & {}^{+0.13pb}_{-1.20pb} & \left({}^{+0.28\%}_{-2.50\%}\right) & \delta(\text{scale}) \\
 & + & \pm0.56pb & (\pm1.16\%) & \delta(\text{PDF-TH}) \\
 & + & \pm0.49pb & (\pm1.00\%) & \delta(\text{EWK}) \\
 & + & \pm0.41pb & (\pm0.85\%) & \delta(\text{t,b,c}) \\
 & + & \pm0.49pb & (\pm1.00\%) & \delta(1/m_t) \\
 & = & {}^{+2.08pb}_{-3.16pb} & \left({}^{+4.28\%}_{-6.5\%}\right), & \\
\delta(\text{PDF}) & = & \pm0.89\text{pb} & (\pm1.85\%), & \\
\delta(\alpha_S) & = & {}^{+1.25pb}_{-1.26pb} & \left({}^{+2.59\%}_{-2.62\%}\right). &
\end{array}
$$

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

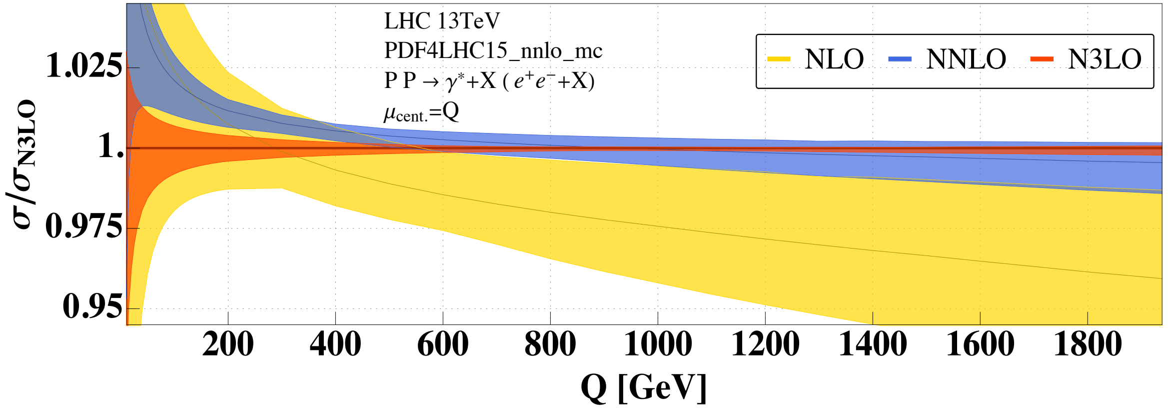
Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer, 2010.09451

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

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

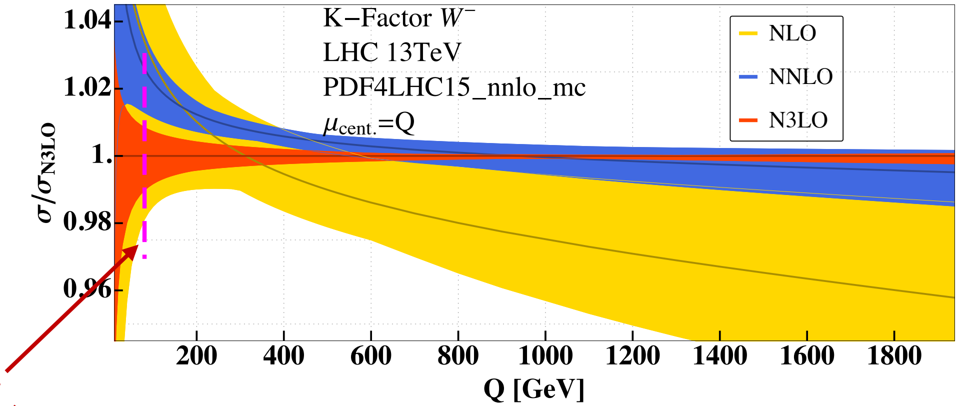
DY at N^3LO – input to PDF fits and M_W measurement

NC-DY

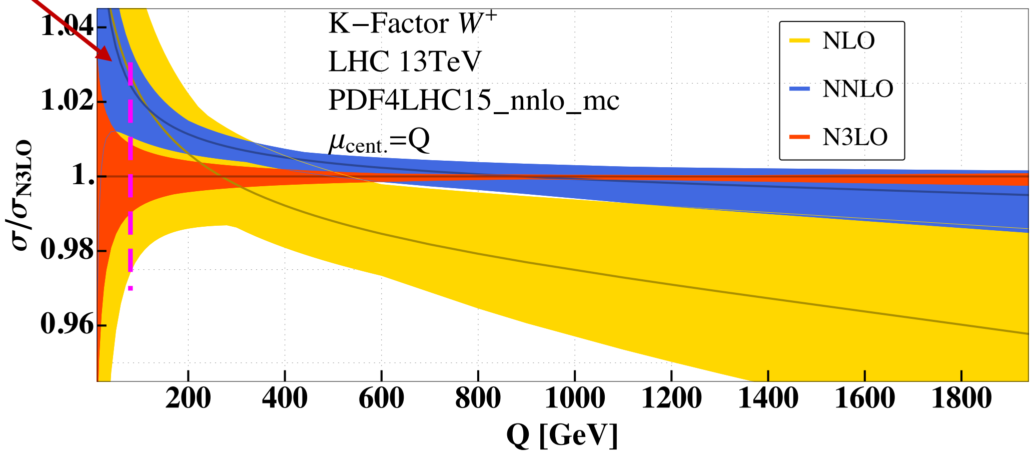


Duhr, Dulat, Mistlberger, 2001.07717

CC-DY



M_W

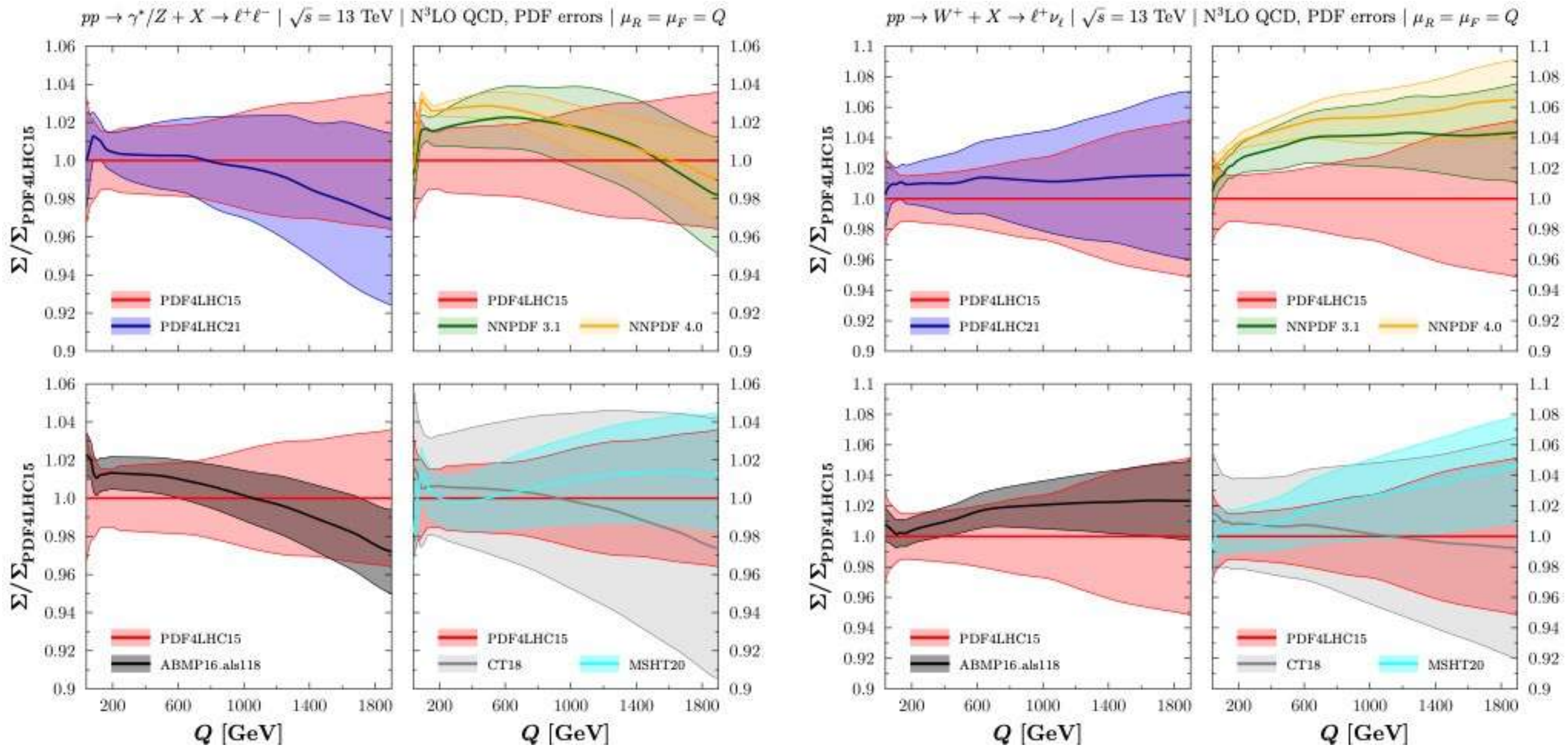


- Scale dependence: non-uniform behavior in all Q-regions
- Important input for PDFs (not yet included)
- **Region around Q~M_W: reconsider how to estimate theoretical uncertainty from scale variation**

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

Duhr, Dulat, Mistlberger, 2007.13313

DY at N^{3}LO – dedicated PDF study



Overall consistency among different sets

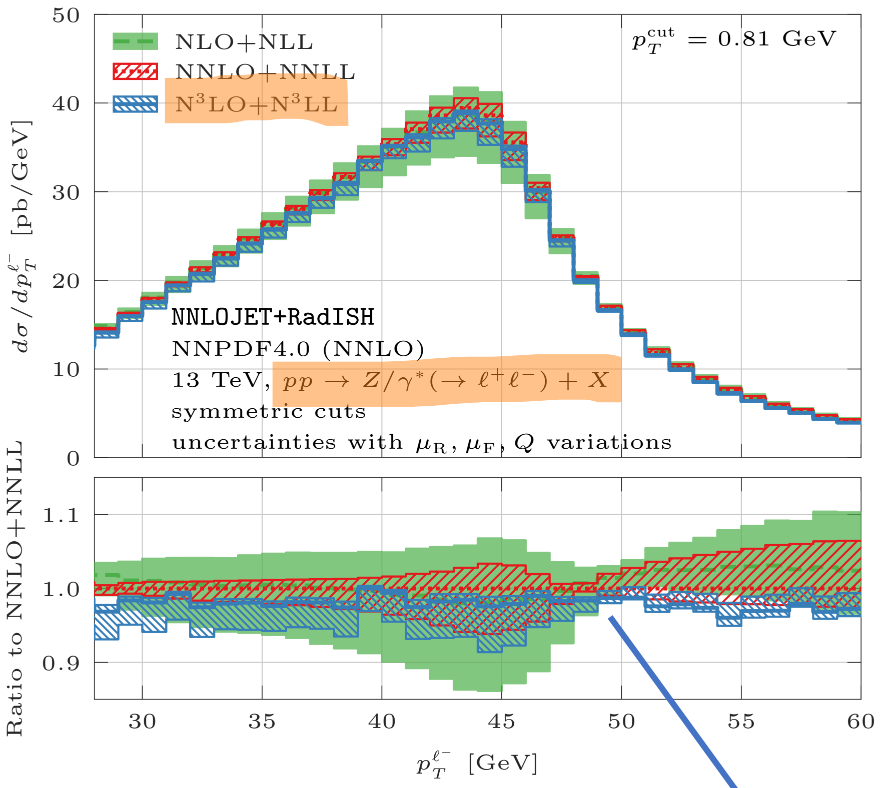
Large variation in error bands

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

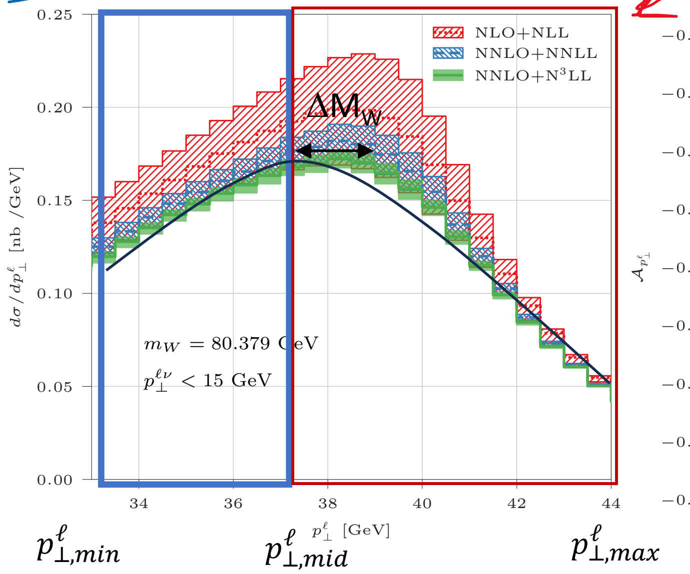
Challenging to control theoretical uncertainties below percent level!

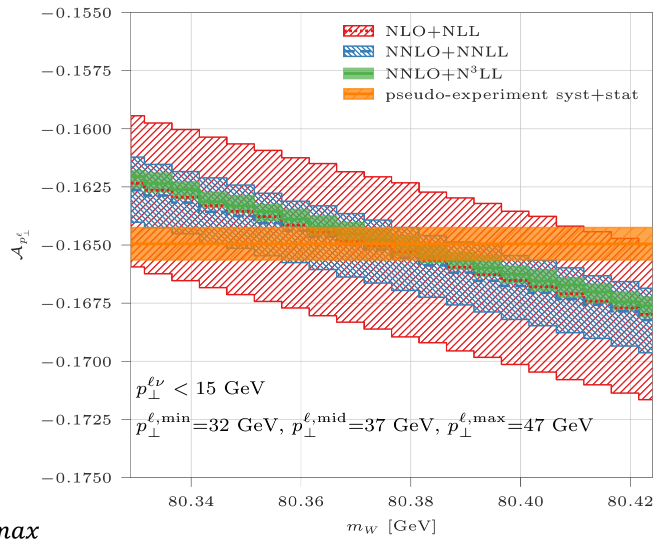
Consider different observable?

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

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

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



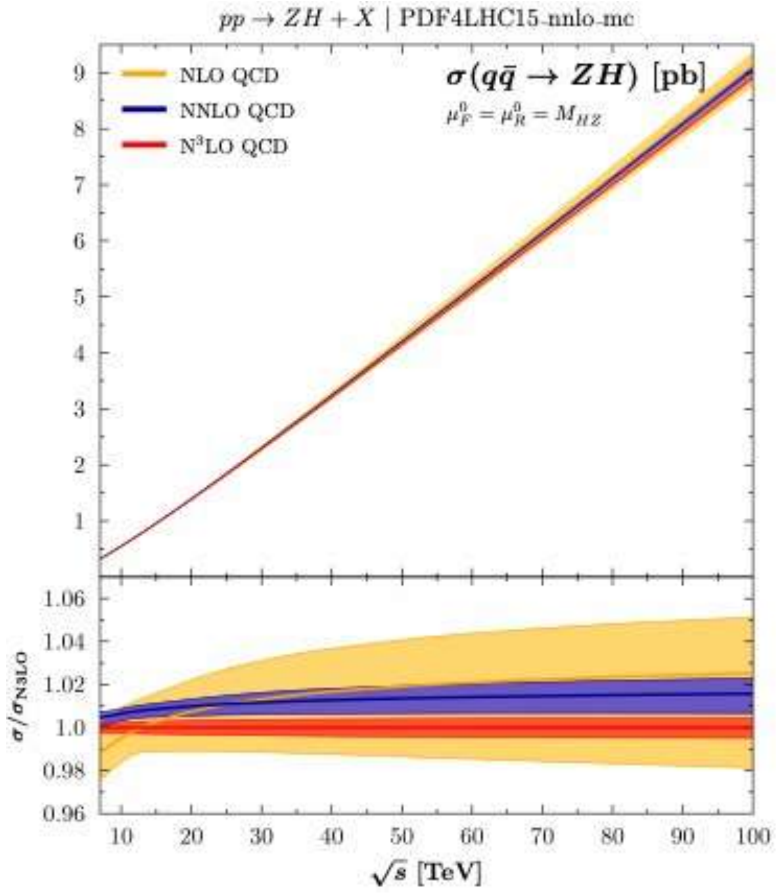


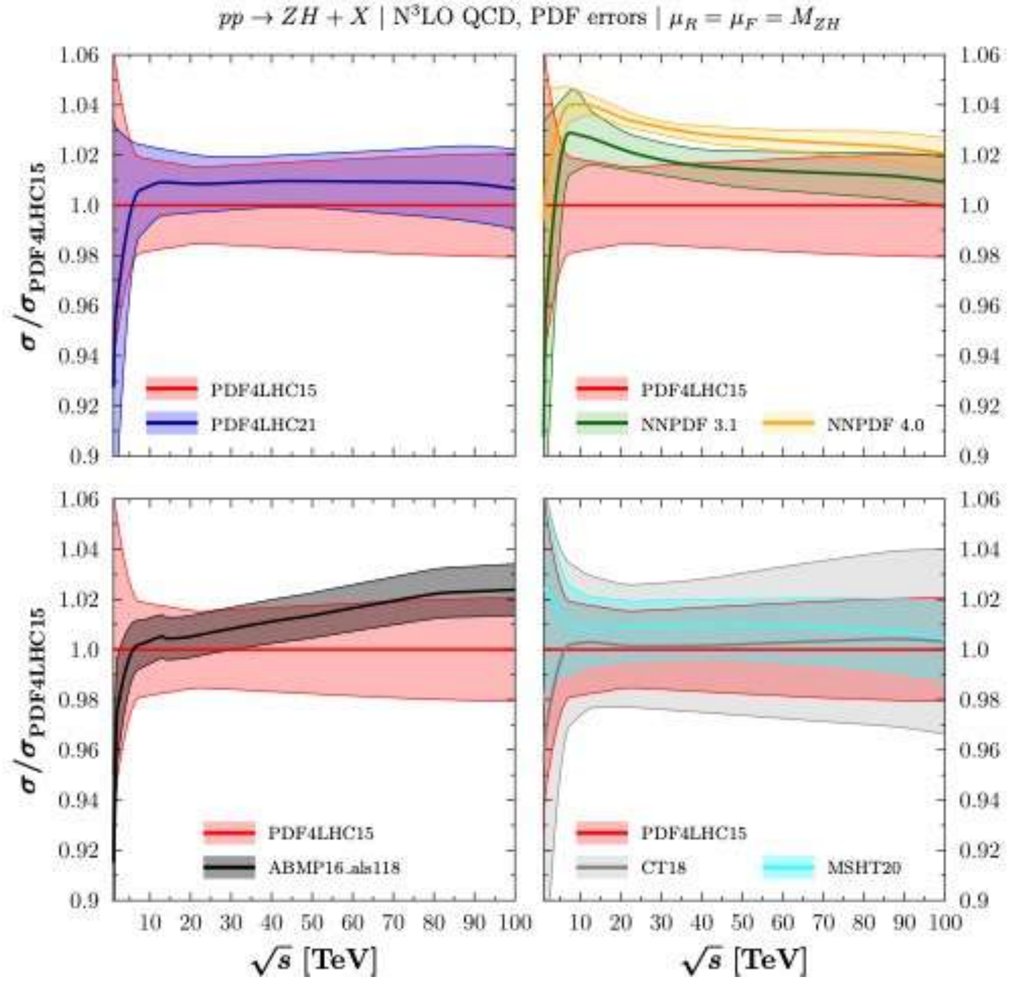
Rottoli, Torrielli, Vicini, 2301.04059

ΔM_W~±15 MeV feasible

VH at N^{3}LO, first complete calculation

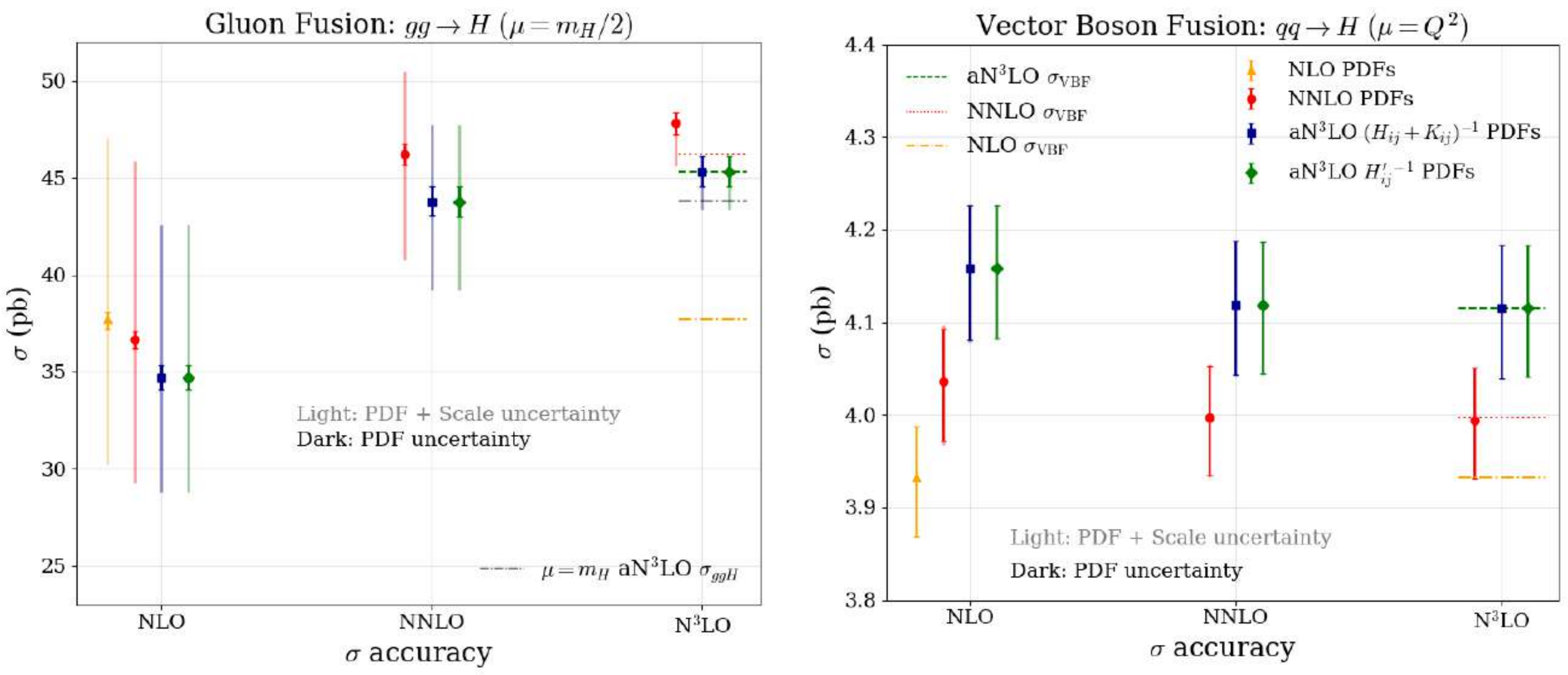
Same color structure as DY, same characteristic behavior, same lesson learnt in assessing theoretical uncertainties





Baglio, Duhr, Mistlberger, Szafron, 2209.06138

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.

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

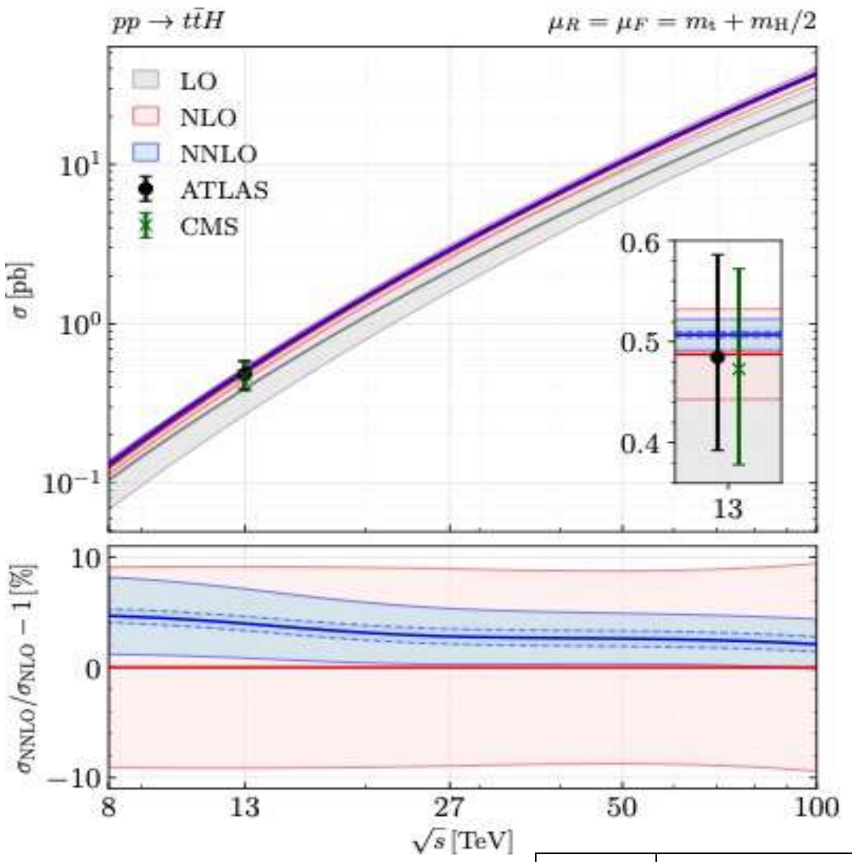
Major impact on LHC phenomenology

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

Very recently first results for 2-loop amplitudes

Febres Cordero, Figueiredo, Krauss, Page, Reina, 2312.08131
Buccioni, Kreer, Liu, Tancredi, 2312.10015
Agarwal, Heinrich, Jones, Kerner, Klein, 2402.03301

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

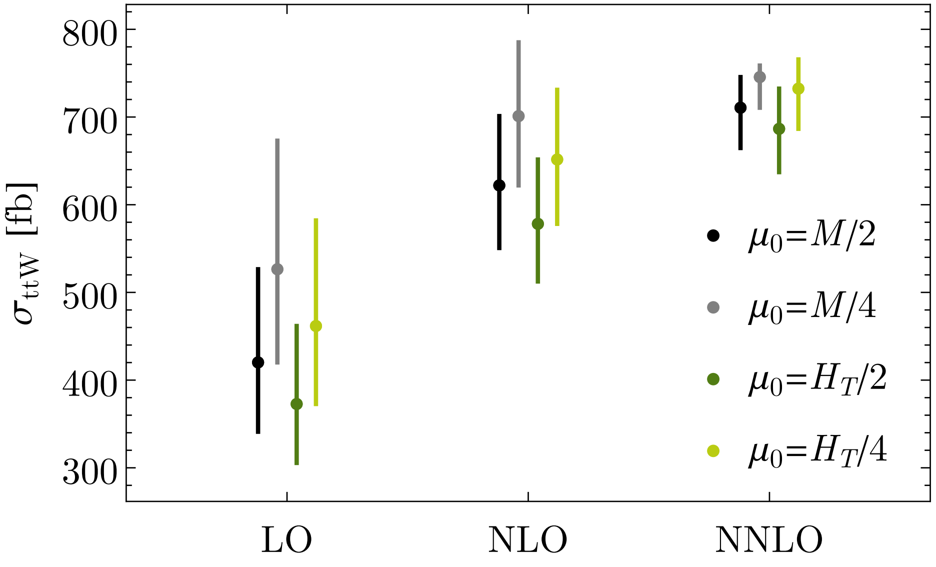


Catani et al., 2210.07846

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}	$0.5070\,(31)^{+0.9\%}_{-3.0\%}$	$37.20(25)^{+0.1\%}_{-2.2\%}$

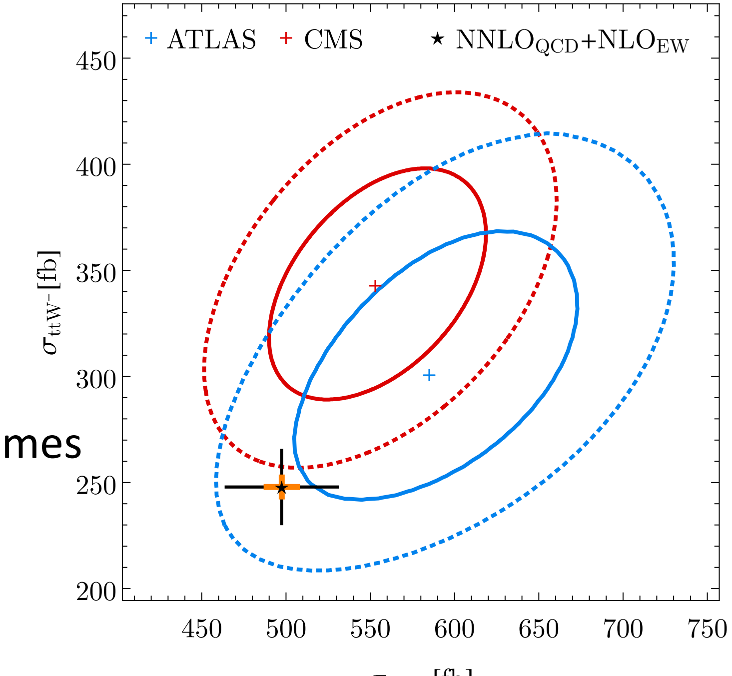
Buonocore et al., 2306.16311



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

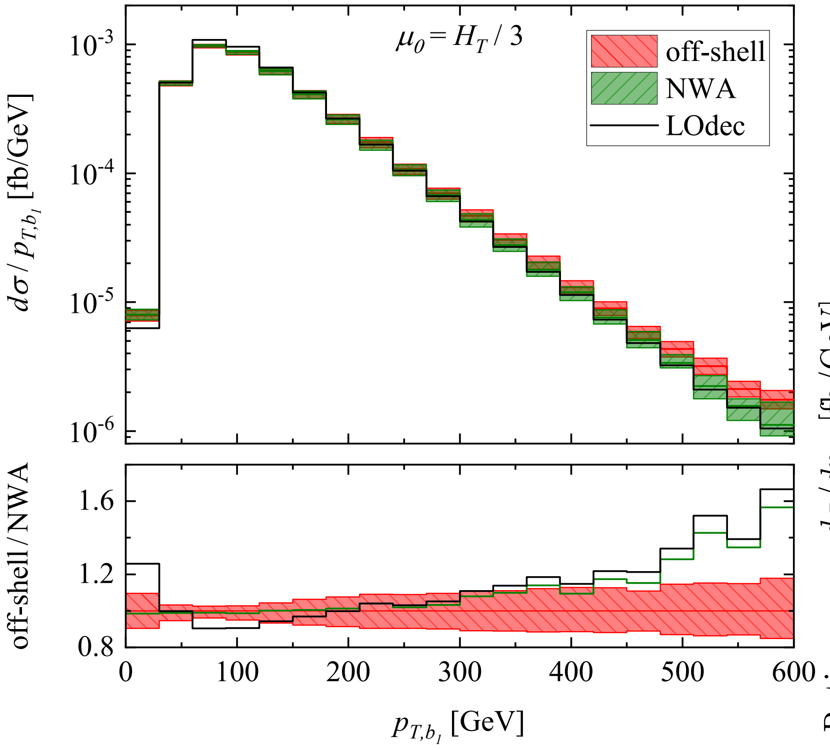
Ratio $\sigma_{t\bar{t}W^+}/\sigma_{t\bar{t}W^-}$ in very good agreement with ATLAS measurement

Comparison in fiducial volumes may give further insight

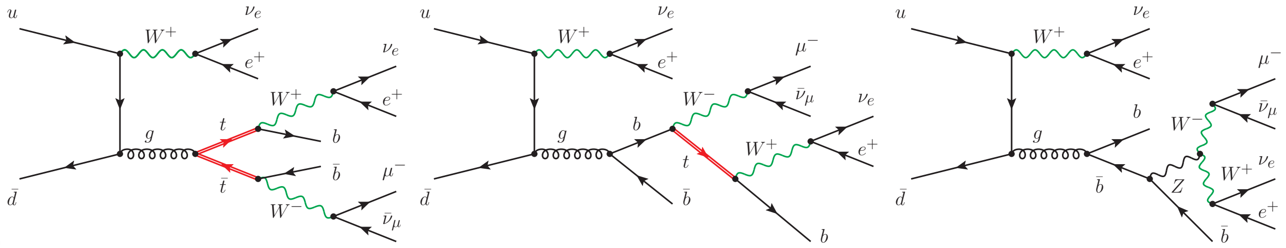


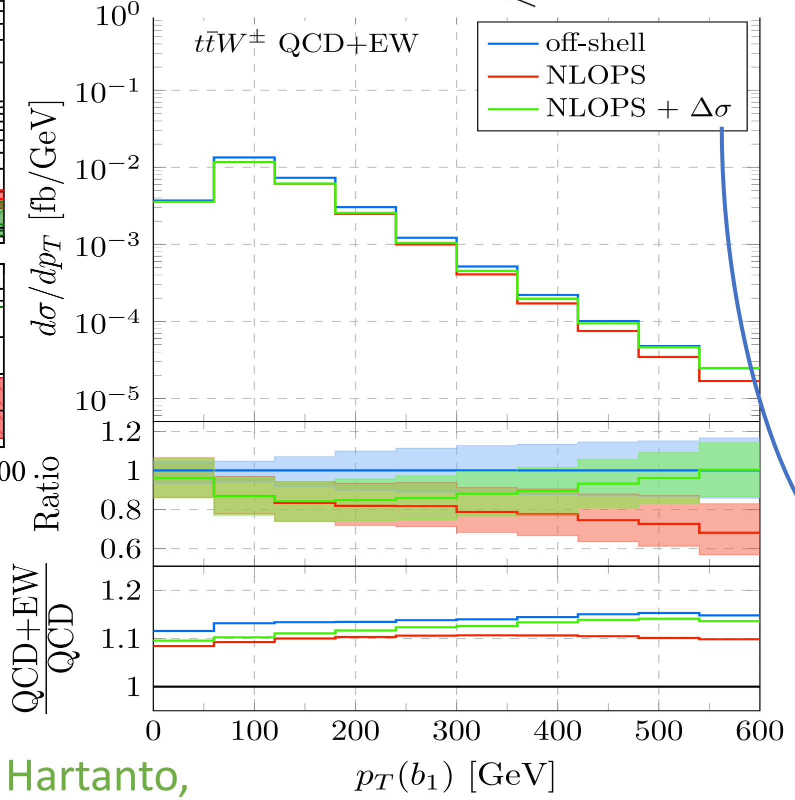
NLO: push the multiplicity challenge

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

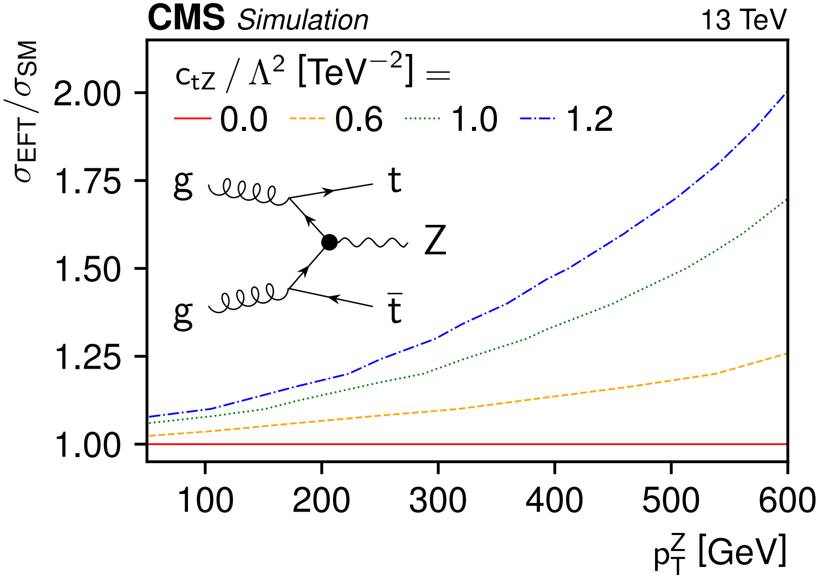
Off-shell effects most relevant in tails and end-points of distributions, where new physics effects can be hidden

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

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

… exploring boosted kinematics and off-shell signatures

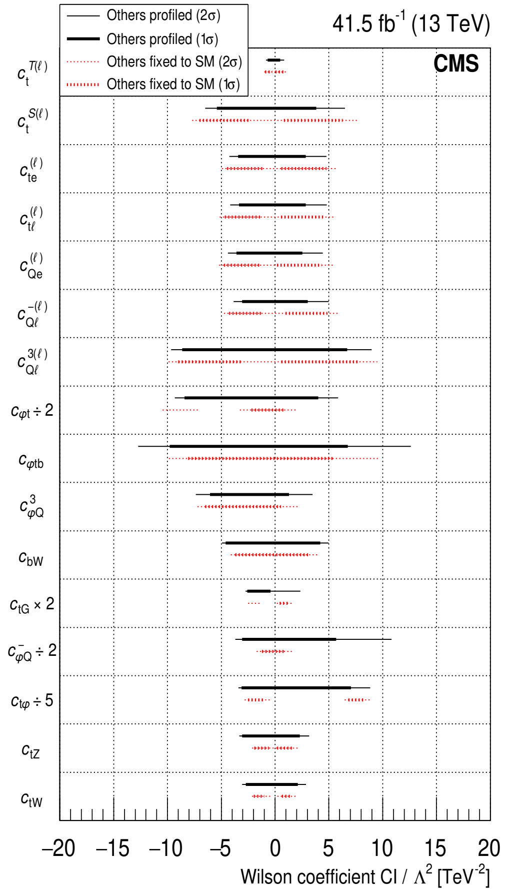
Top pair + boosted Z/H



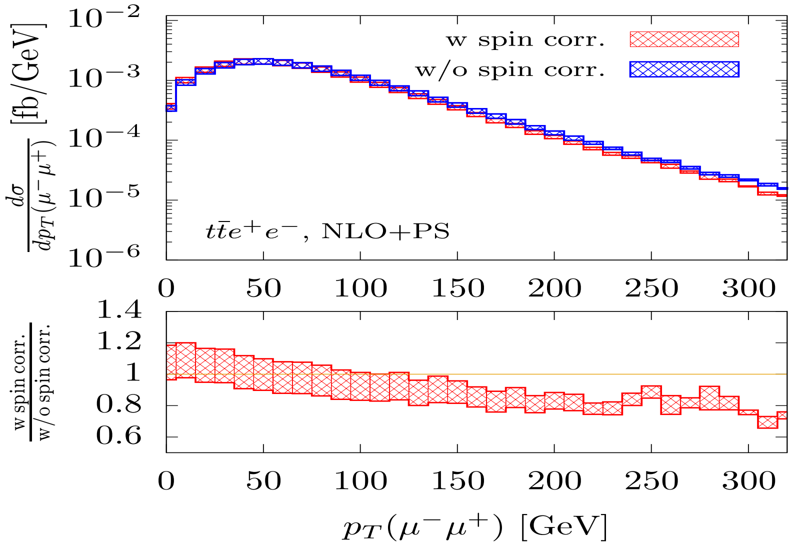
$$\delta\eta_{SM} \sim g^2_{BSM} \frac{E^2}{M^2}$$

Effects in tails of distributions but also anomalous shapes

Top+additional leptons

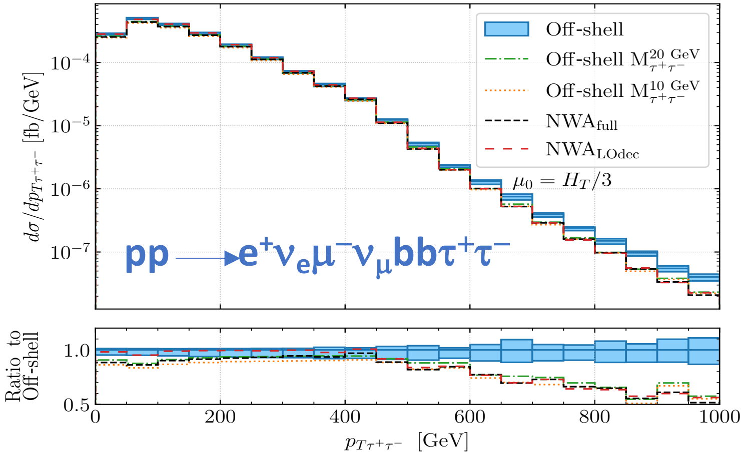


[CMS: arXiv:2012.04120]



M. Ghezzi et al. [2112.08892]

Off-shell studies



G. Bevilacqua et al. [2203.15688]

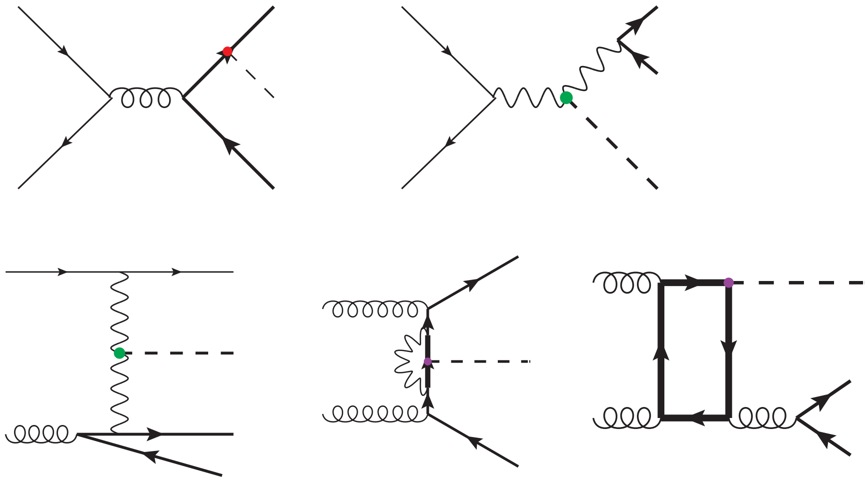
Pointing to the need for precision in modelling signatures from $t\bar{t}$+X processes in regions where on-shell calculations may not be accurate enough

… deploying new techniques to interpret complex signatures

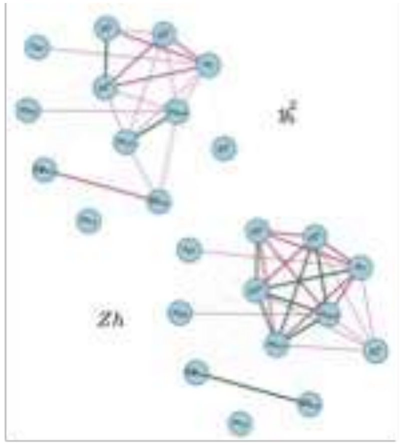
The case of **bbH production including QCD+EW corrections**
The extraction of y_b seems lost

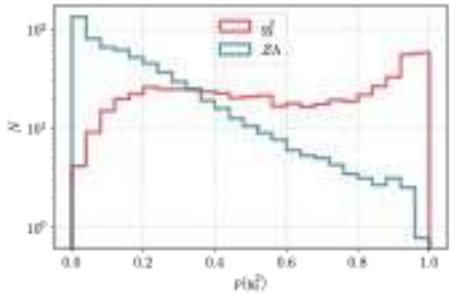
``RIP Hbb'' [Pagani et al., arXiv:2005.10277]

ratios	$\frac{\sigma(y_b^2)}{\sigma(y_b^2)+\sigma(\kappa_Z^2)} \equiv \frac{\sigma_{\mathrm{NLO}_{\mathrm{QCD+EW}}}}{\sigma_{\mathrm{NLO}_{\mathrm{all}}}}$ $(y_b$ vs. $\kappa_Z)$	$\frac{\sigma(y_b^2)}{\sigma(y_b^2)+\sigma(y_t^2)+\sigma(y_b y_t)}$ $(y_b$ vs. $y_t)$	$\frac{\sigma(y_b^2)}{\sigma(y_b^2)+\sigma(y_t^2)+\sigma(y_b y_t)+\sigma(\kappa_Z^2)}$ $(y_b$ vs. κ_Z and $y_t)$
NO CUT	0.69	0.32	0.28
$N_{j_b} \geq 1$	0.37 (0.48)	0.19	0.14
$N_{j_b} = 1$	0.46 (0.60)	0.20	0.16
$N_{j_b} \geq 2$	0.11	0.11	0.06



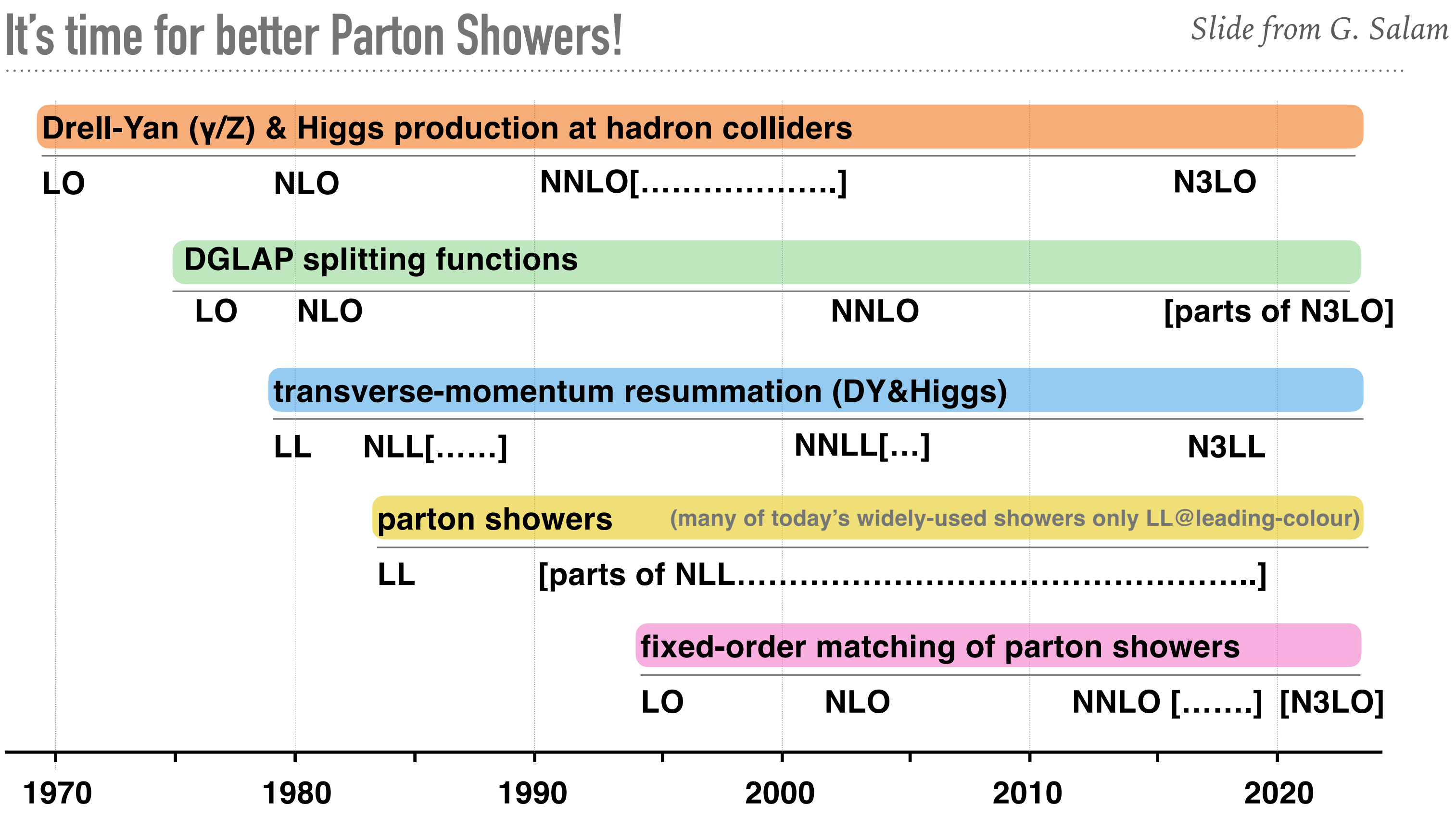
A kinematic-shape based analysis based on game theory (Shapley values) and BDT techniques opened new possibilities
"Resurrecting Hbb with kinematic shapes"
[Grojean et al., arXiv:2011.13945]





New techniques will open the possibility of turning problematic processes into powerful probes of the quantum structure of the SM

Parton-shower event generators



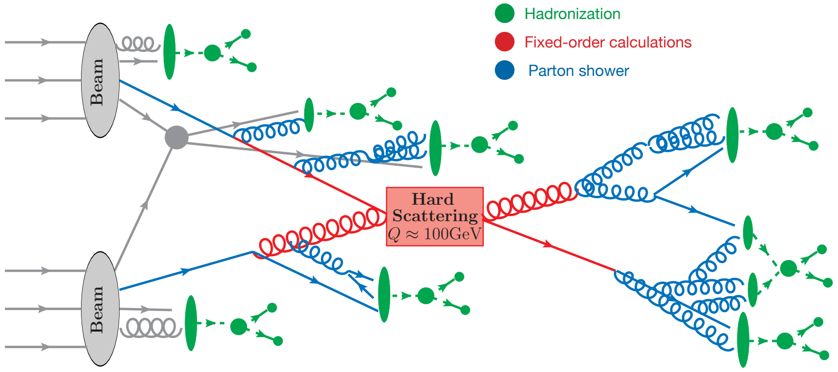
From S. Ferrario Ravasio, RADCOR 2023

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



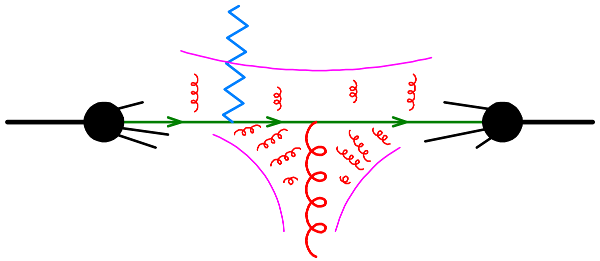
More challenges: non-perturbative effects $O((\Lambda_{QCD}/Q)^p)$

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

- **Collider physics** remains as a **unique and necessary test of any BSM hypotheses,** and in this context **precision phenomenology will play a crucial role**.
- **The HL-LHC** will accumulate 20 times what it has so far and **will deliver precision measurements beyond expectations.**
- **Increasing the theoretical accuracy on SM observables** (Higgs, top, EW**) is crucial**: a factor of 10 in precision could allow to test scale in the 10 TeV and beyond.
- Reaching this level of theoretical accuracy has **multiple components**, all of which have been the focus of **intense and highly creative theoretical work**.
- **Direct evidence of new physics could boost this process**, as the discovery of the Higgs boson has prompted us in this new era of LHC physics.

Lesson 5 "theoretical challenges for collider physics"

Knowing what enters the theoretical "modeling" of collider events, we can now discuss the level of theoretical accuracy achieved in realizing this picture and what we will need to fully enable the physics program of the (HL) LHC and future colliders.

→ See attached slides for most of today's discussion, since at this point we need to compare with LHC data and see how theory "fares" i.e. how does it raise to the challenge of interpreting what we see through the very powerful eyes of colliders.

I will articulate the discussion starting from some precise example that will show you the need of theoretical accuracy to isolate tensions in the SM or anomalies in its predictions.

- → M_W measurement
- → m_t, α_s
- → Higgs couplings
- → EFT couplings

We will then look at a series of important processes and use them to illustrate how their theoretical prediction is built and systematically improved, recognizing in each case the impact of the different building blocks that we have discussed during this lecture ($\hat{\sigma}$ hard, PDFs, Parton shower E.G., etc.)

Some general comment before we start

↳ Given a certain goal of theoretical accuracy, how do we reach it may mean different things.

As we will see, it may take:

⇒ adding higher order of SM quantum effects (LO → NLO → N^2LO → N^3LO)

↳ consistently done in all building blocks.

this is crucial to:

→ reduce scale-dependence (μ_R, μ_F)

→ extend the theoretical control of the hard process ($\hat{\sigma}_{hard}$) in the energy regime where it should be dominant

→ include all parton-level channels ($q\bar{q}, gq, gg$)

pushing the perturbative order ←

⇒ Understanding the systematic uncert. coming from other sources: PS event generators, "fiducial" cuts, etc. (many params. to control) (from exp.)

- - -

⇒ Backgrounds, not only signal, have to be controlled at the same order

↳ the importance of focusing on "signatures", not only specific processes.

pushing the inclusivity ←