

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**.

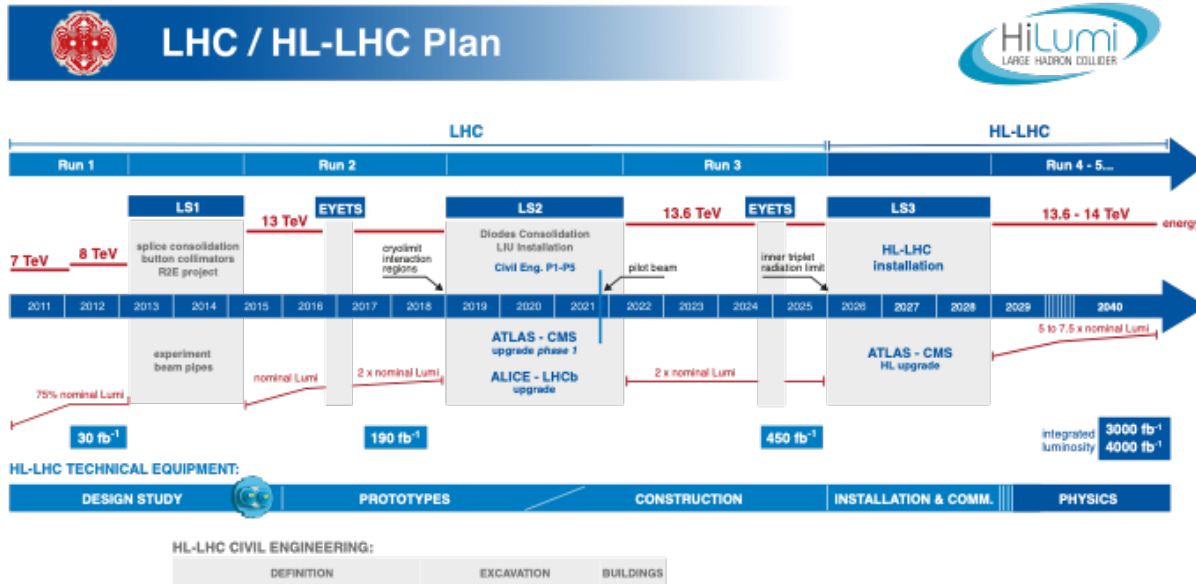
Precision phenomenology at the (HL)-LHC

Universal limitations

Luminosity
Energy resolution
(particles, jets)

ATLAS, 2212.09379
CMS, 2104.01927
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

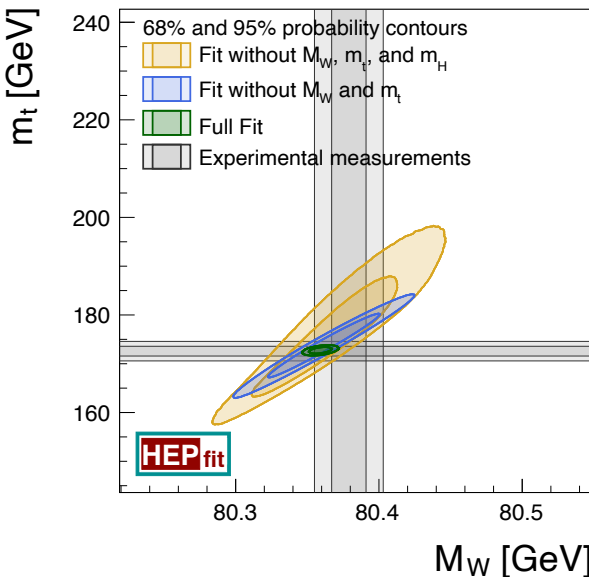
Precision intrinsic to a predictive theory: SM global fits

A recent challenge: CDF new M_W measurement

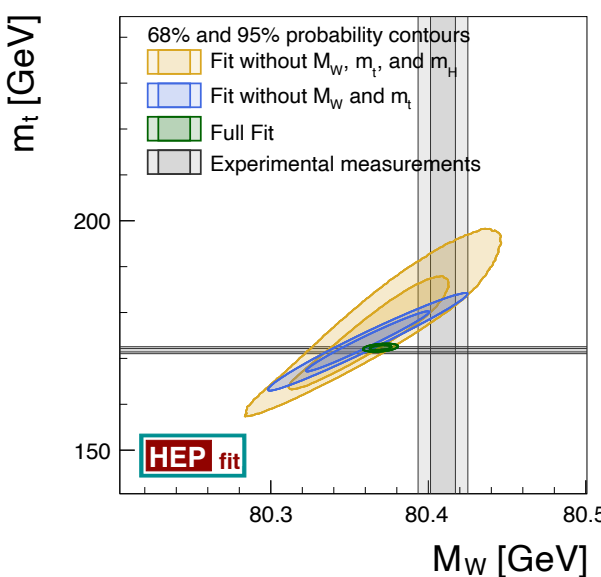
Tensions could become real indications of NP effects with the precision of the HL-LHC or of a future e^+e^- machine, if theory match the precision of experiments.

before (pull 1.8σ)

after (pull 6.1σ)



$$M_W = 80.379 \pm 0.012 \text{ GeV}$$



$$M_W = 80.409 \pm 0.008 \text{ GeV}$$

De Blas et al. [2204.04204]

EWPO uncertainties	Current theory error	Projected theory error	Current param. error	Projected param. error	
				Scenario 1	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
$\Delta \sin^2 \theta_{\text{eff}}^\ell (\times 10^5)$	4.5	1.5	4.2	3.7	1.1
$\Delta A_\ell (\times 10^5)$	32	11	30	25	7.5
$\delta R_\ell (\times 10^3)$	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*

EW global fit of the SM - excerpt

For M_W we combine:

- ☐ All LEP 2 measurements;
- ☐ Previous Tevatron average
- ☐ ATLAS and LHCb measurements
- ☐ CDF measurement [$M_W=(80.4335\pm 0.0094)$ GeV]
- ☐ ATLAS measurement [$M_W=(80.360\pm 0.016)$ GeV]

$M_W = 80.409 \pm 0.008$ GeV (**standard**, with CDF)
 $M_W = 80.360 \pm 0.012$ GeV (**standard**, without CDF)

For m_t we combine:

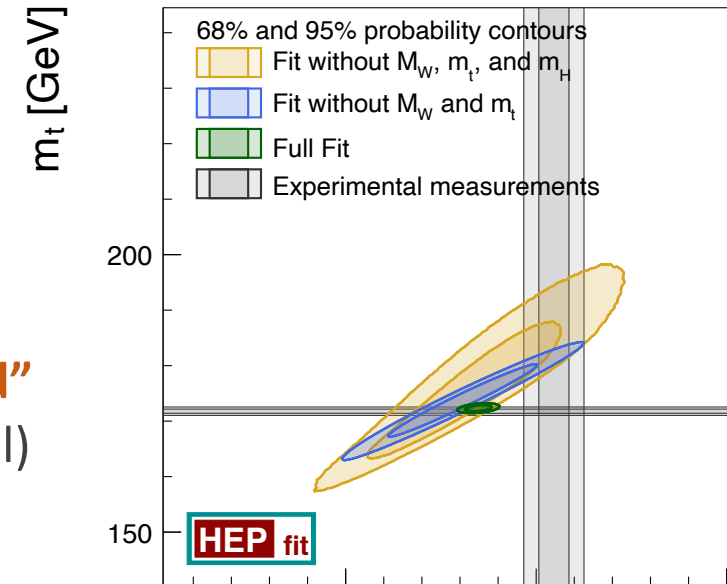
- ☐ 2016 Tevatron combination
- ☐ ATLAS Run 1 and Run2 results
- ☐ CMS Run 1 and Run 2 results
- ☐ Recent CMS $l+j$ measurement [$m_t=(171.77\pm 0.38)$ GeV]

$m_t = 172.61 \pm 0.58$ GeV (**standard**)

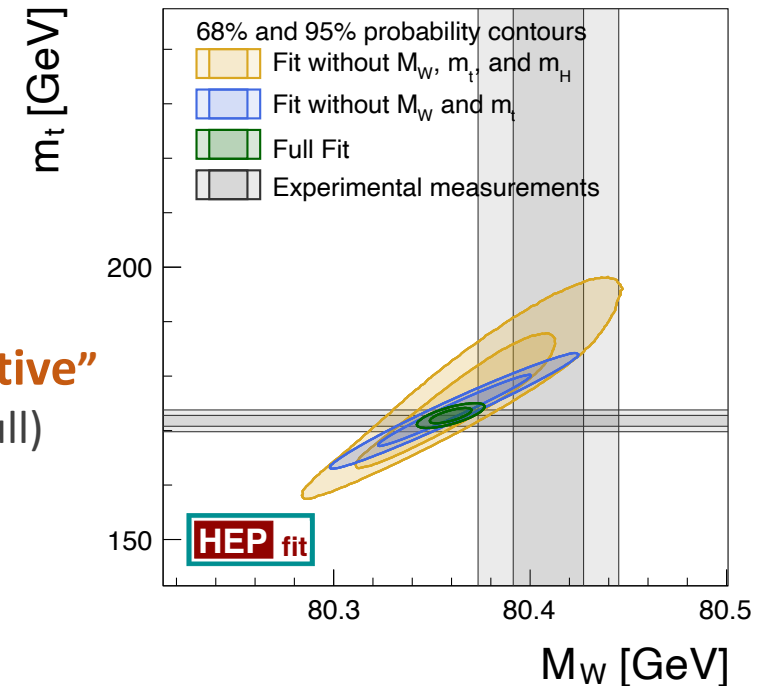
Due to tension between LEP, Tevatron, and LHC measurements consider also a **conservative** error of $\delta M_W=18$ MeV and $\delta m_t=1$ GeV (à la PDG)

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

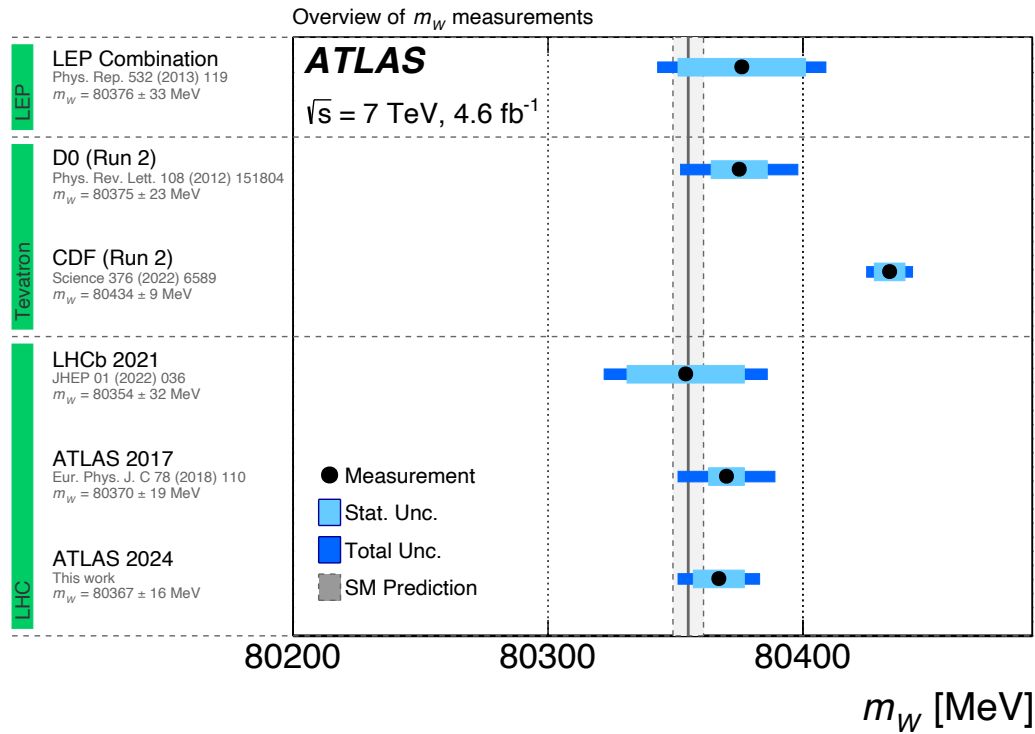
“standard”
(6.1 σ pull)



“conservative”
(3.0 σ pull)



SM global fits: the M_W puzzle

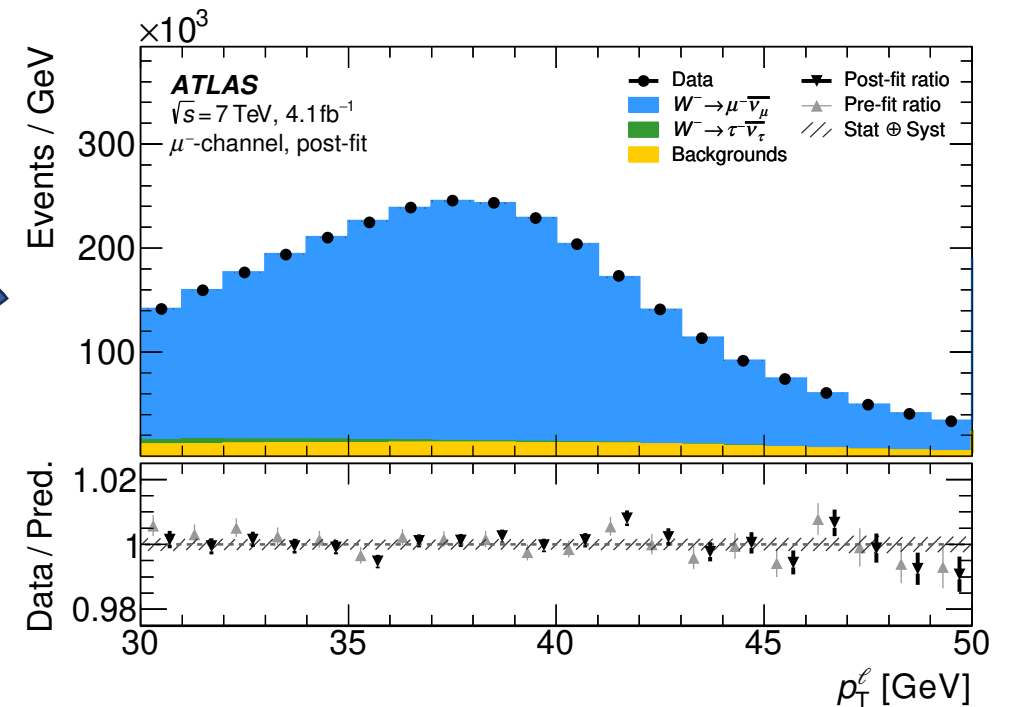


Mass measured by fitting template distributions of transverse momentum and mass

Template fitting is acceptable if theory describes data with high accuracy

ATLAS, 2403.15085

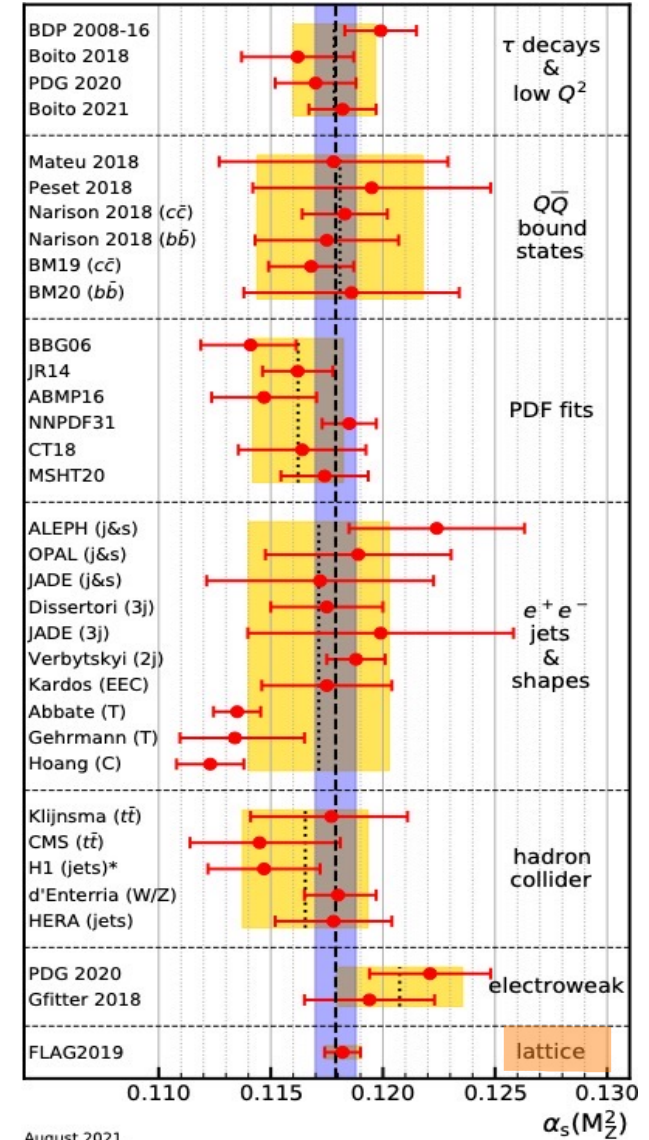
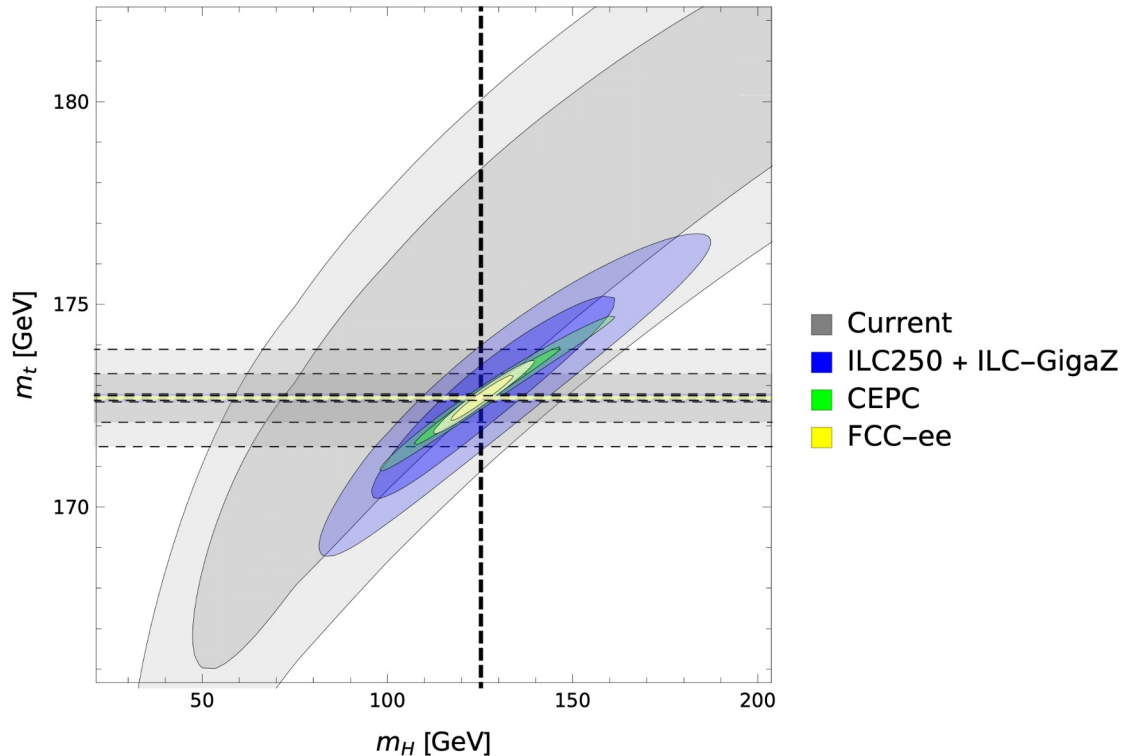
$\Delta M_W \sim 10$ MeV \rightarrow 0.1% control on kinematic distributions



More constraining parameters

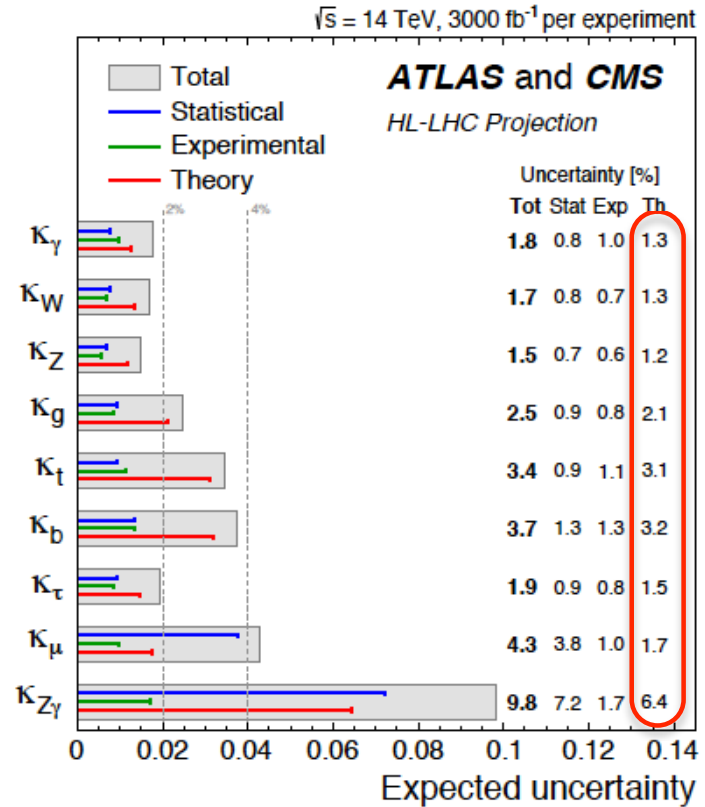
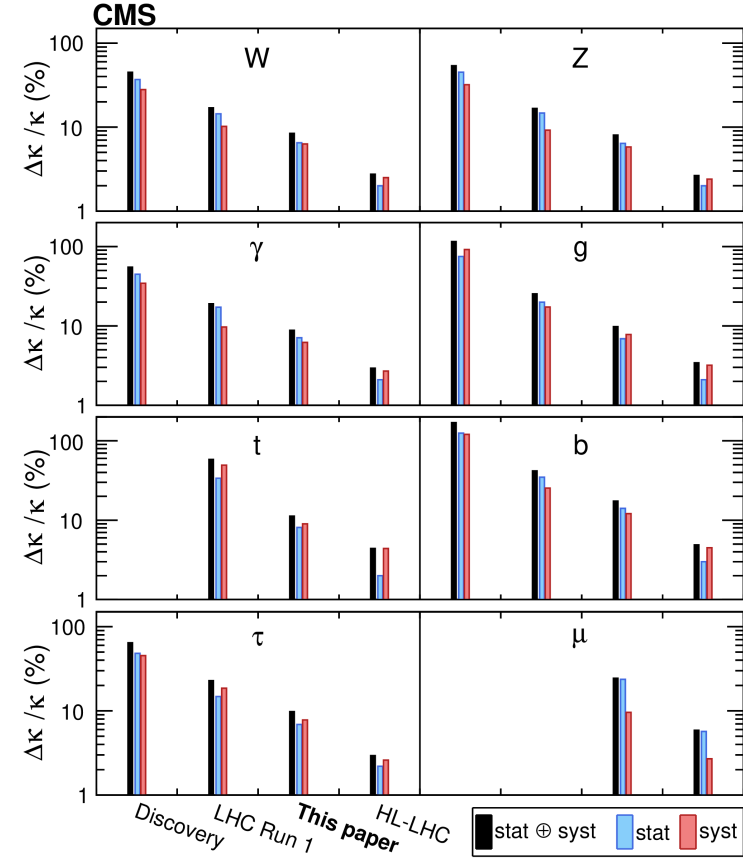
Parameter	HL-LHC	ILC 500	FCC-ee	FCC-hh
\sqrt{s} [TeV]	14	0.5	0.36	100
Yukawa coupling y_t (%)	3.4	2.8	3.1	1.0
Top mass m_t (MeV/%)	170/0.10	50/0.031	40/0.025	–

Snowmass 2021 EF TG Report,
2209.11267 and 2208.09078



August 2021

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%)

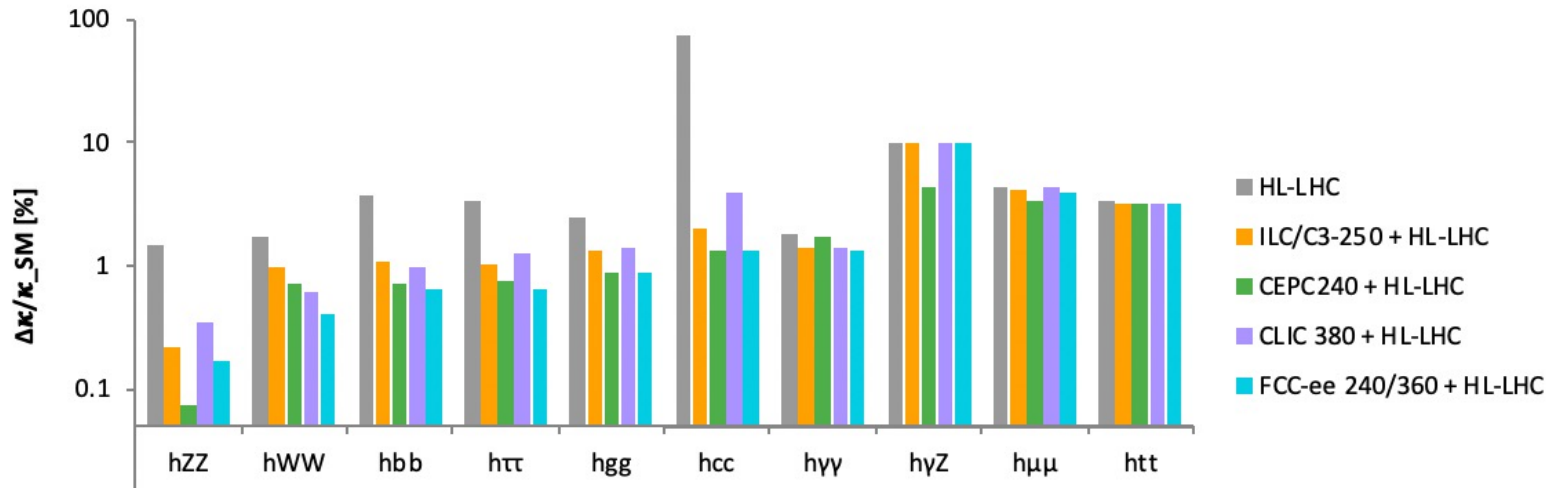
Improved systematics
probes higher scales

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

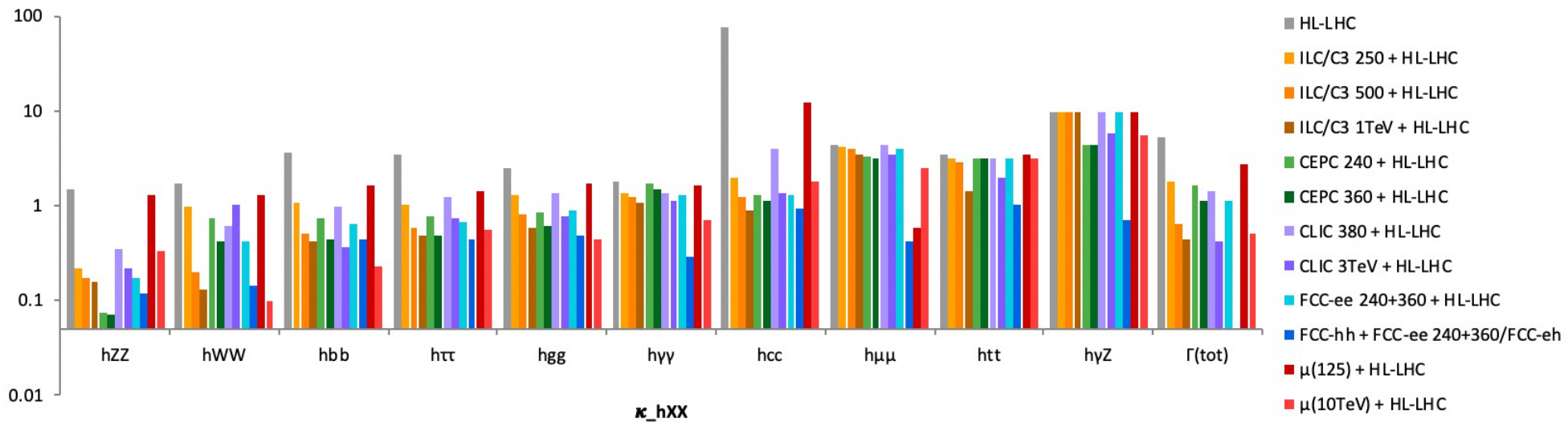
Reach of future colliders for Higgs couplings: a closer look

Based on full Run 2 dataset analyses



Initial stages of future e^+e^- machines

From Snowmass 2021 EF
Higgs Topical Group Report
arXiv:2209.07510

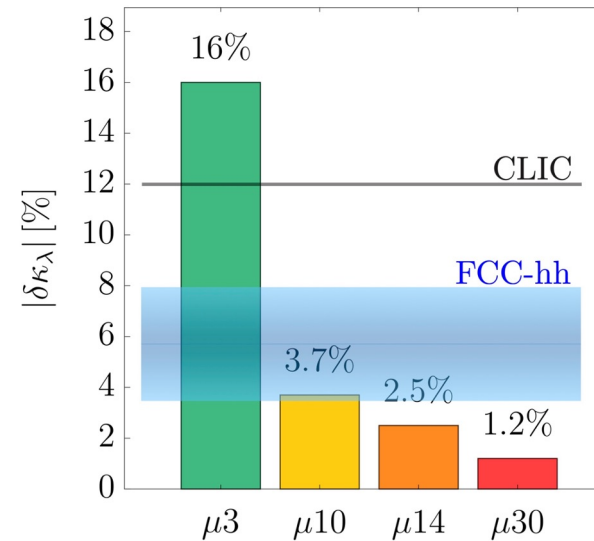


Final reach of all considered future colliders

Reach for Higgs self-coupling

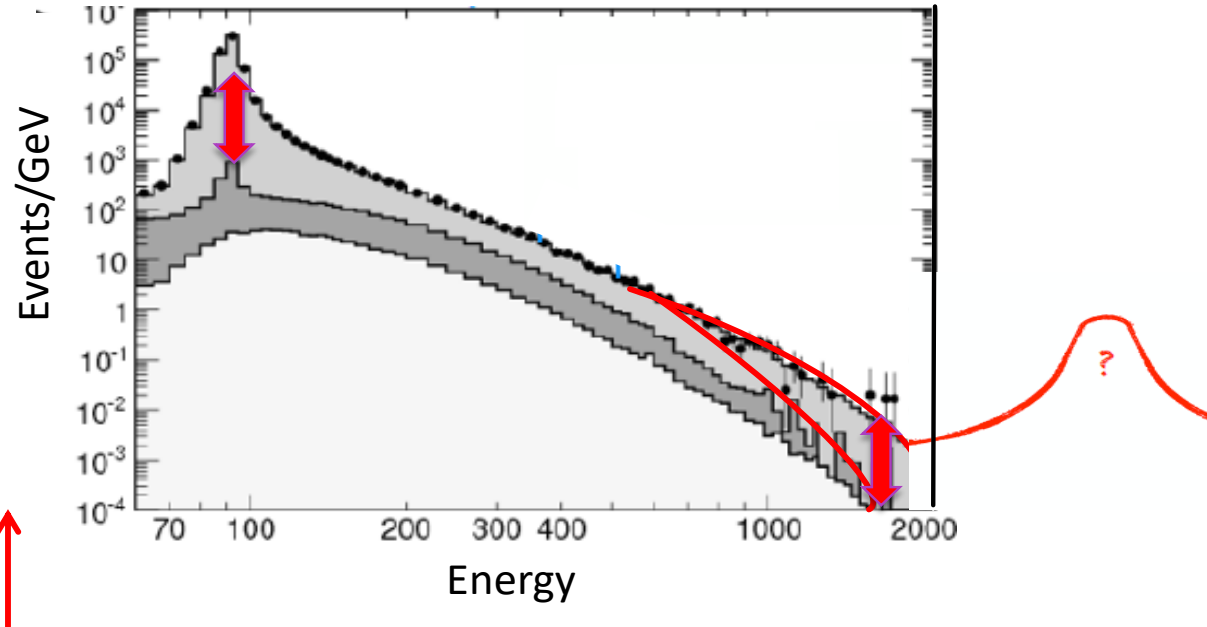
collider	Indirect- h	hh	combined
HL-LHC	100-200%	50%	50%
ILC ₂₅₀ /C ³ -250	49%	—	49%
ILC ₅₀₀ /C ³ -550	38%	20%	20%
CLIC ₃₈₀	50%	—	50%
CLIC ₁₅₀₀	49%	36%	29%
CLIC ₃₀₀₀	49%	9%	9%
FCC-ee	33%	—	33%
FCC-ee (4 IPs)	24%	—	24%
FCC-hh	-	2.9-5.5%	2.9-5.5%
μ (3 TeV)	-	15-30%	15-30%
μ (10 TeV)	-	4%	4%

- ATLAS and CMS HL-LHC updated
- FCC-hh updated [arXiv:2004.03505](https://arxiv.org/abs/2004.03505)
- Added MuC reach:



[arXiv:2203.07256](https://arxiv.org/abs/2203.07256)

Beyond total rates

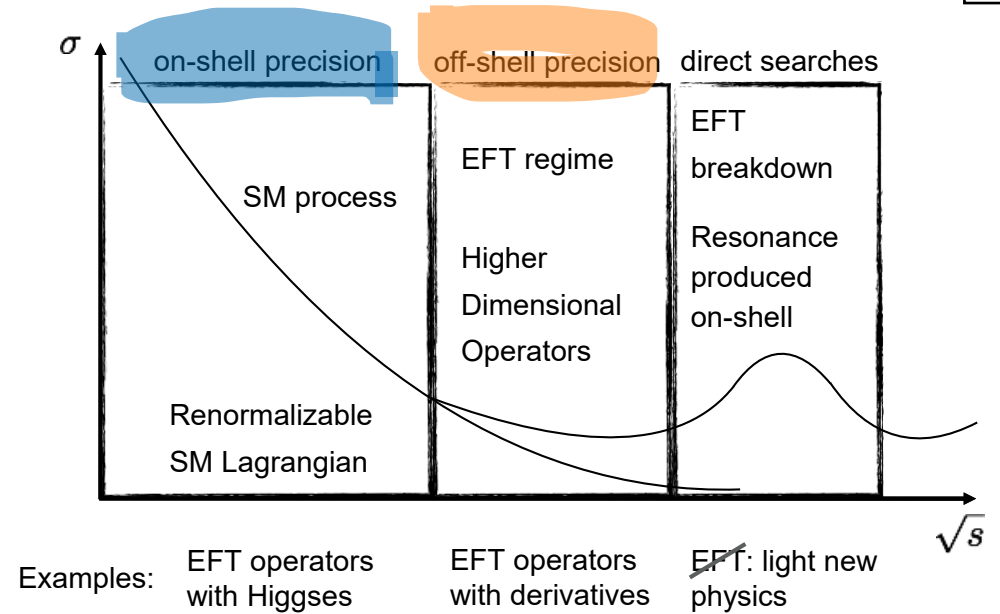


Need SM precision calculations at differential level both at **lower energy**, where rates are large and at **higher energy** where rates are small but effects of new physics may be more visible.

Extending the SM via effective interactions above the EW scale \rightarrow **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



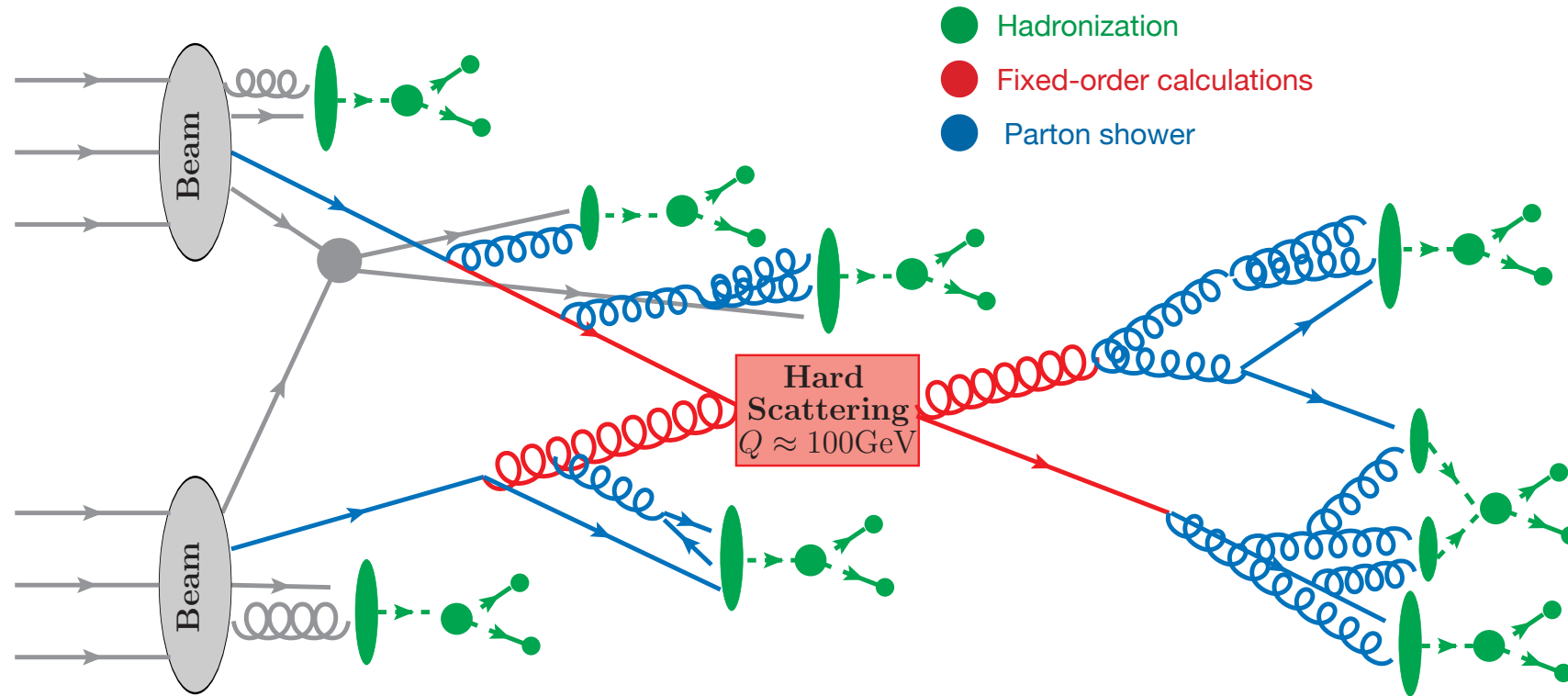
Crucial to control EFT sensitive regions

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

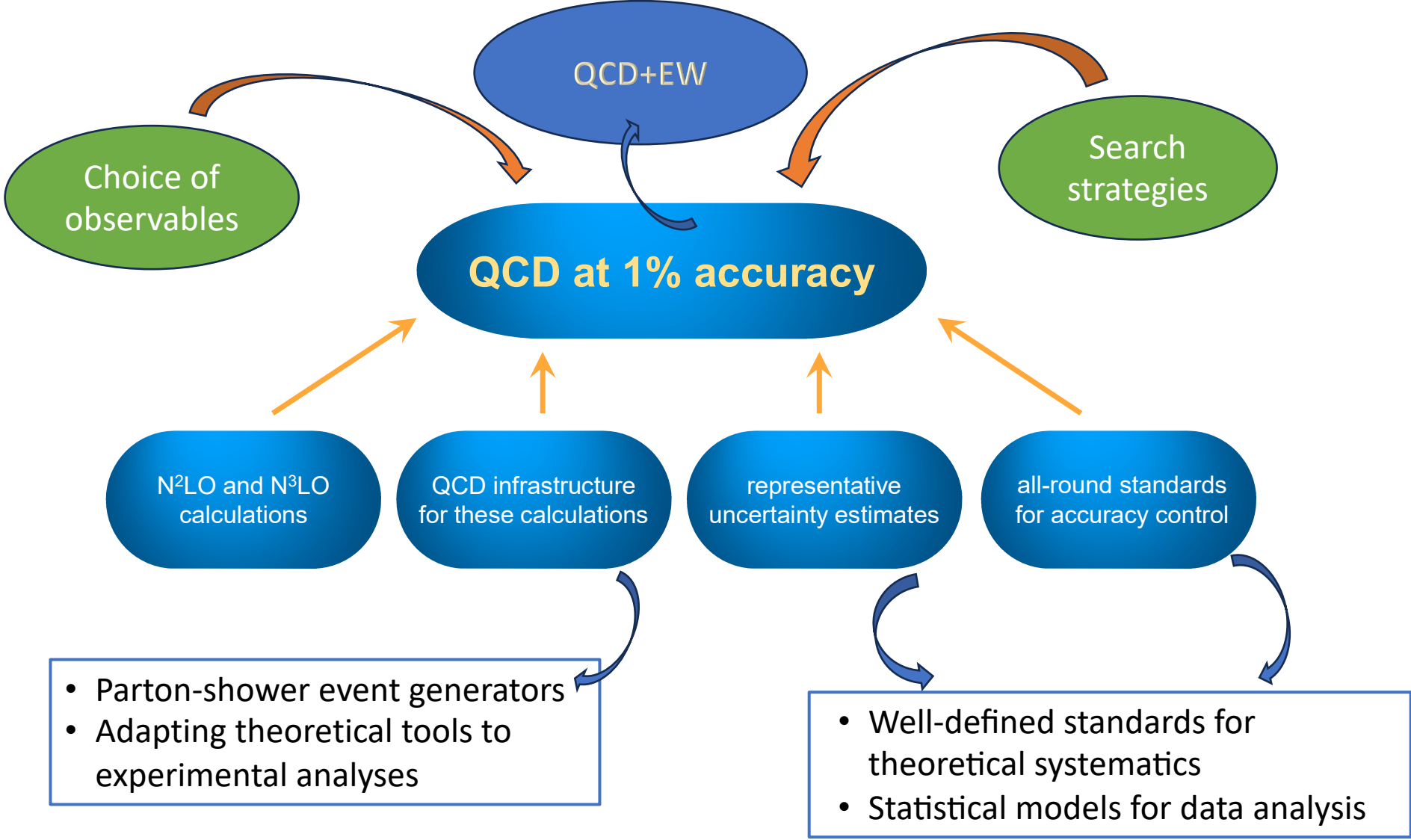
$$d\sigma = \sum_{ij} \int dx_1 dx_2 f_{p,i}(x_1) f_{p,j}(x_2) \widehat{d\sigma}(x_1 x_2 s) + O((\Lambda_{QCD}/Q)^p)$$

Parton Distribution
Functions (PDF)

hard-scattering partonic
xsection (pQCD+EW)

Hadronization,
non-p QCD

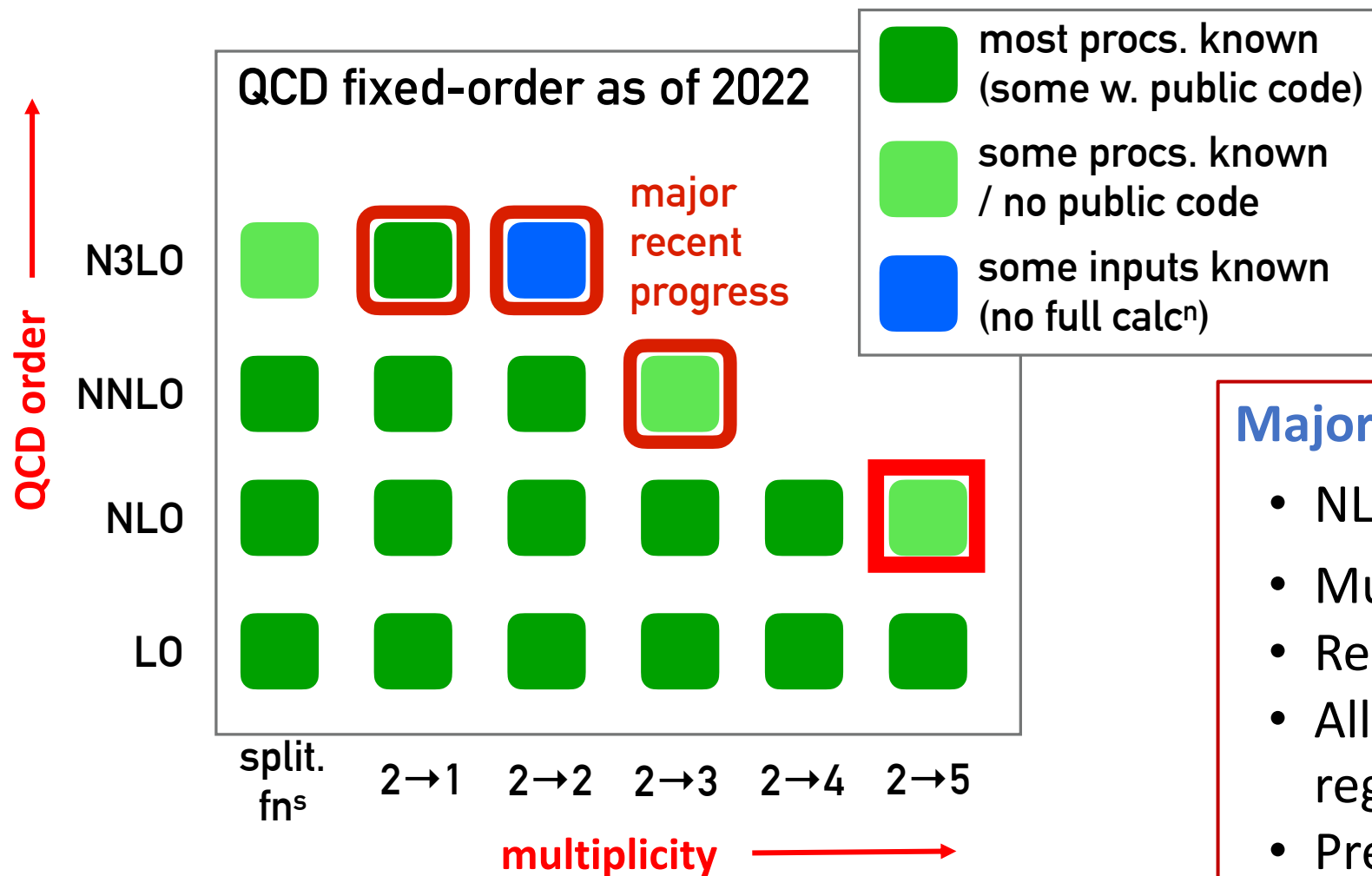
Many components to percent precision



N^XLO predictions - state of the art

For a complete summary of existing and auspicious results see

[Les Houches list \[Huss et al., 2207.02122, updated 2023\]](#)



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

Major challenges and progress:

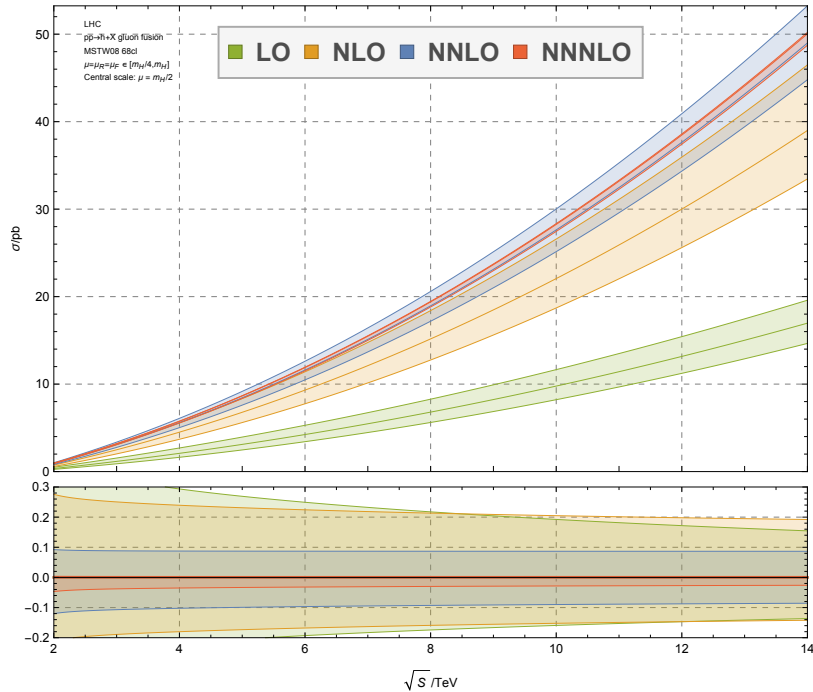
- NLO EW and mixed NLO QCD+EW
- Multiloop scattering amplitudes
- Real emission → IR subtraction
- All-order resummations in specific regions of phase space
- Predictions for fiducial regions

From G. Salam, ICHEP 2022 (slightly modified)

Higgs production via gg fusion at N³LO

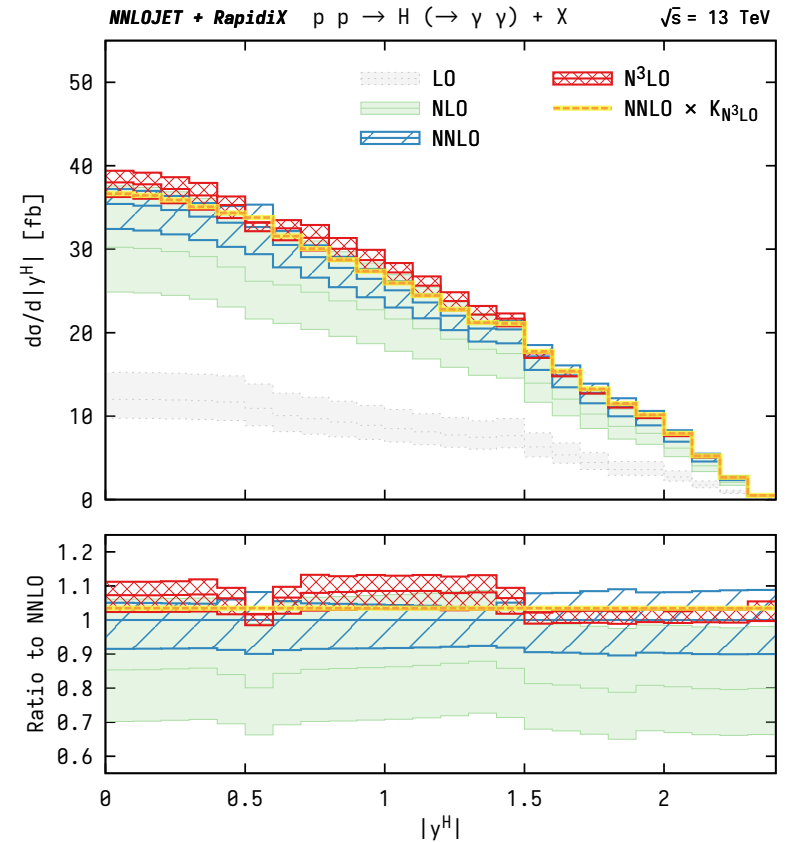
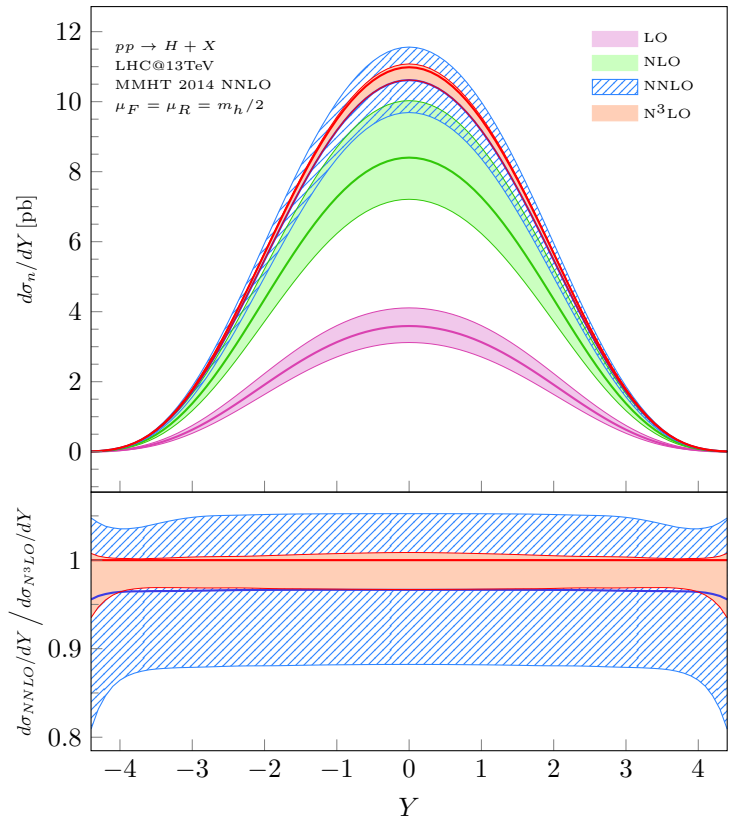
Continuous progress on a crucial process

- 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



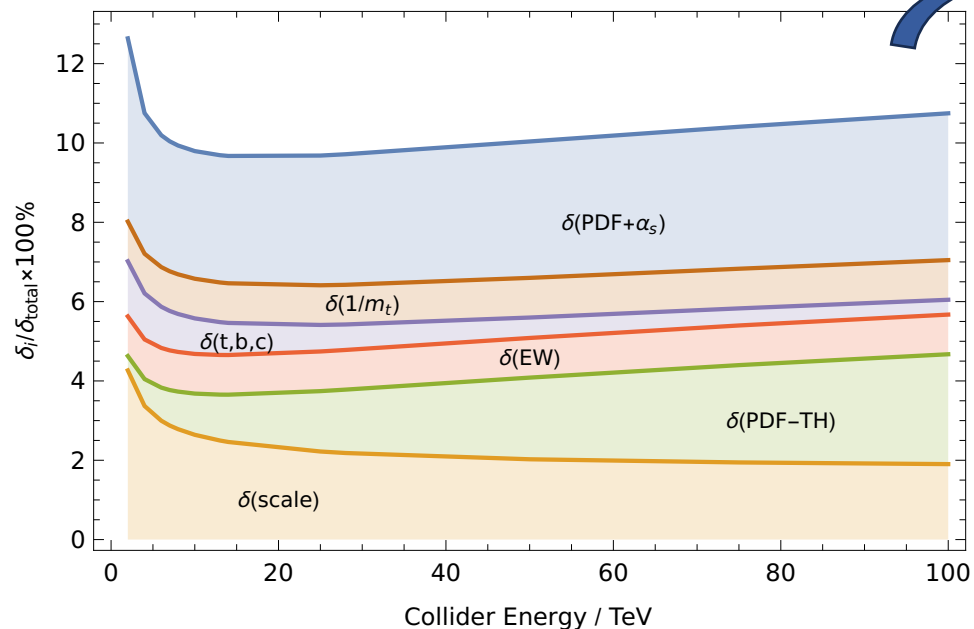
Anastasiou, Duhr, Dulat,
 Herzog, Mistlberger
 1503.06056

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)

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

Future challenges:

- **N3LO PDF!** → $\delta(\text{PDF-TH})$
- Light-quark mass effects → $\delta(b,c)$
- 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

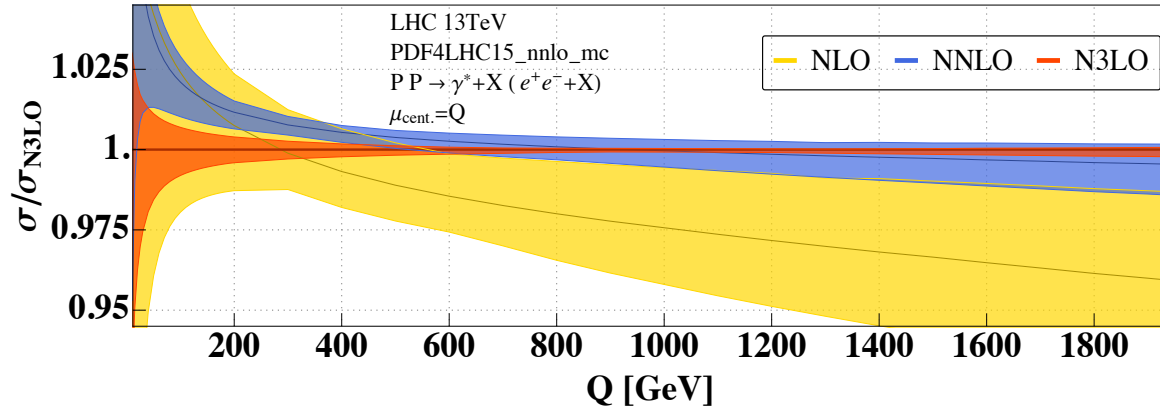
Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer, 2010.09451

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

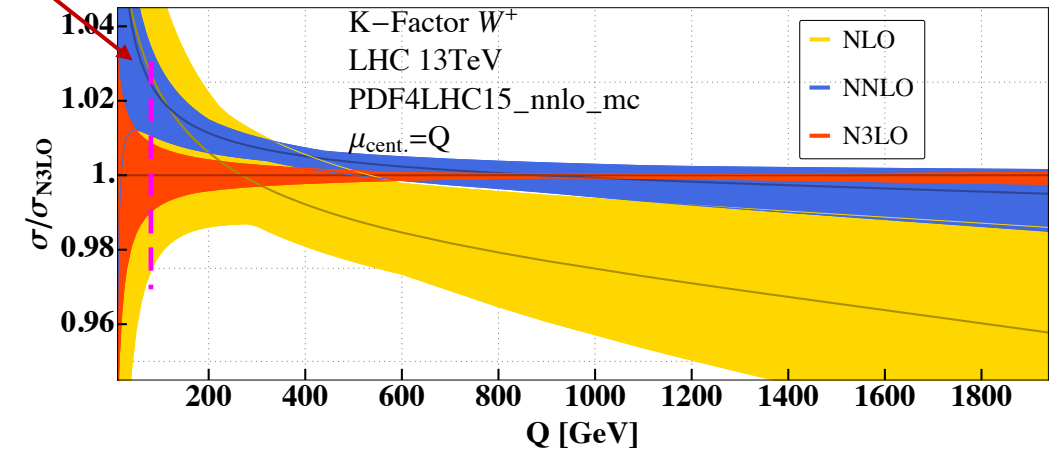
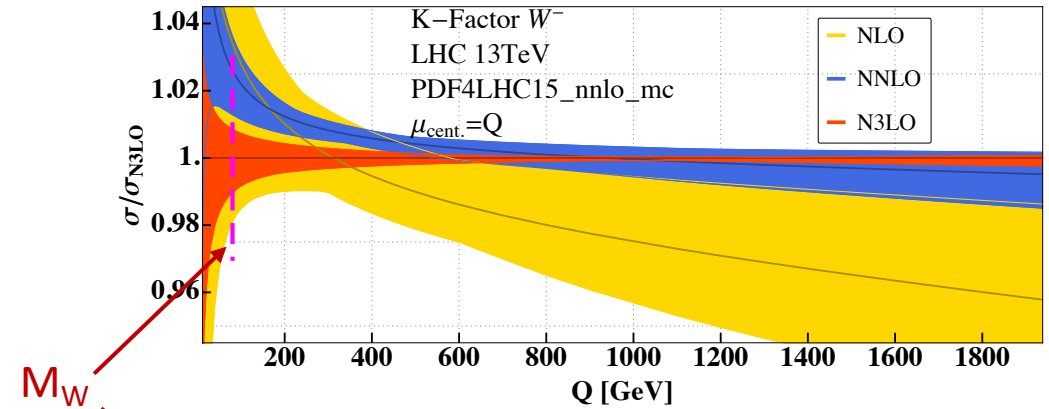
DY@N3LO QCD – Duhr, Dulat, Mistlberger, 2001.07717, 2007.13313

DY at N³LO – input to PDF fits and M_W measurement

NC-DY



CC-DY



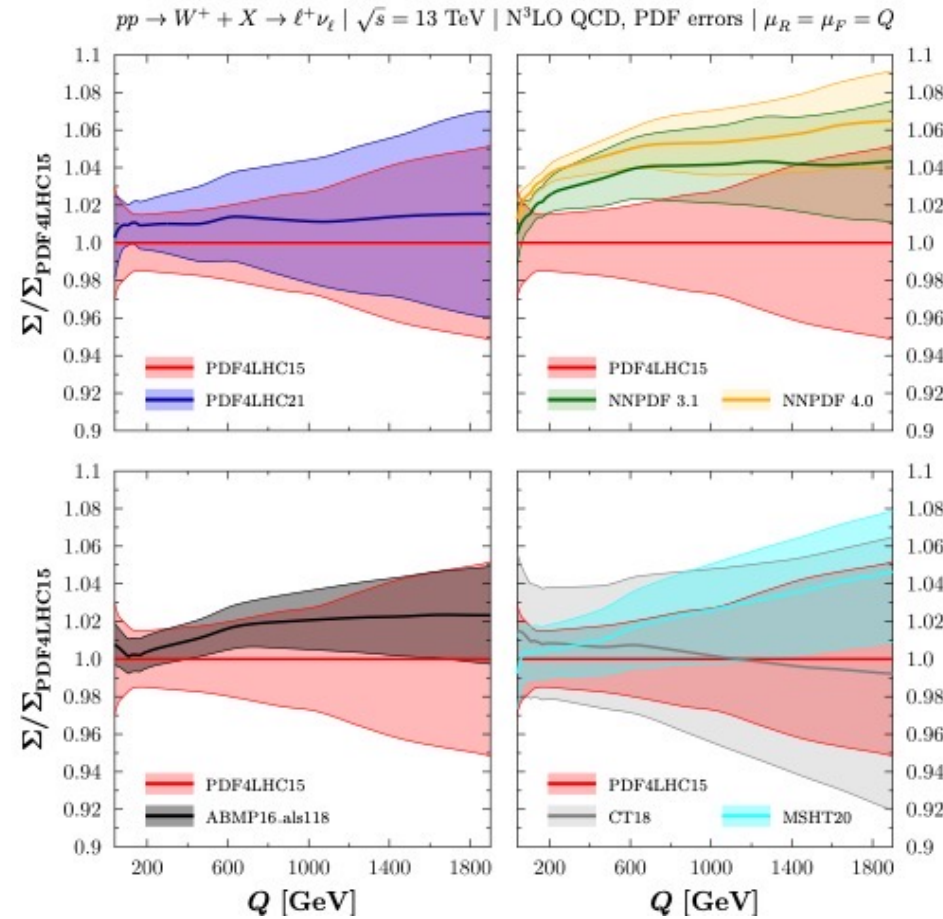
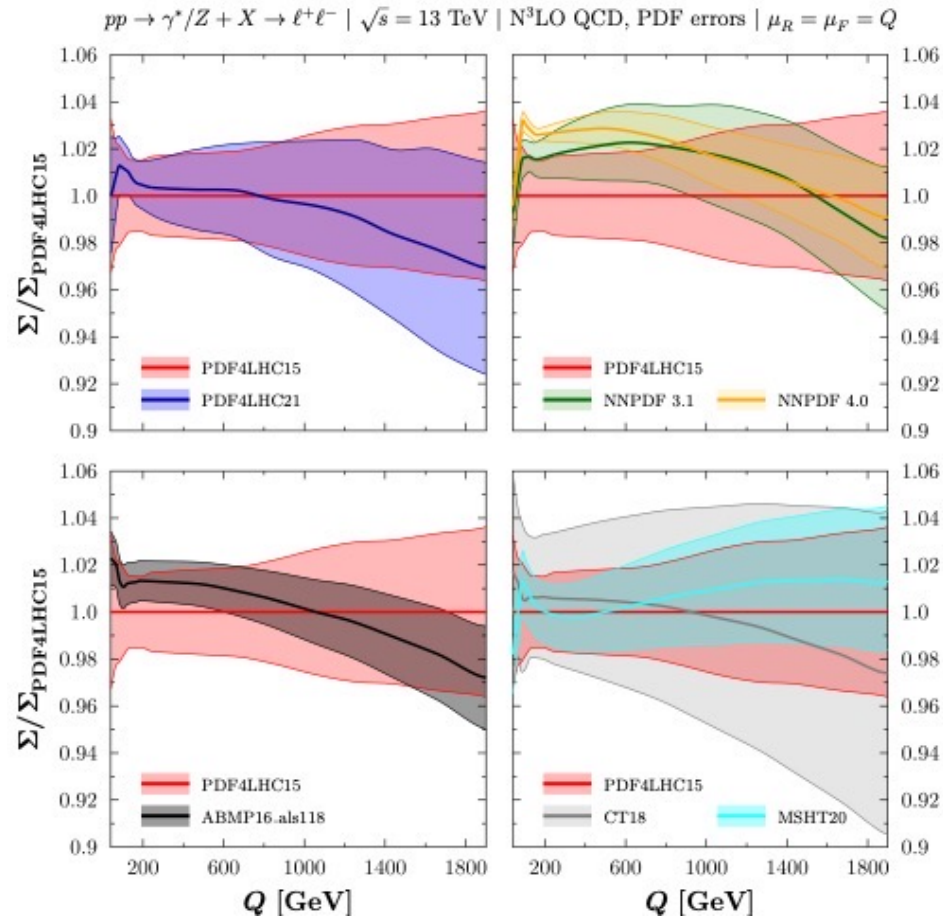
Duhr, Dulat, Mistlberger, 2001.07717

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

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

Duhr, Dulat, Mistlberger, 2007.13313

DY at N³LO – dedicated PDF study



Overall consistency among different sets

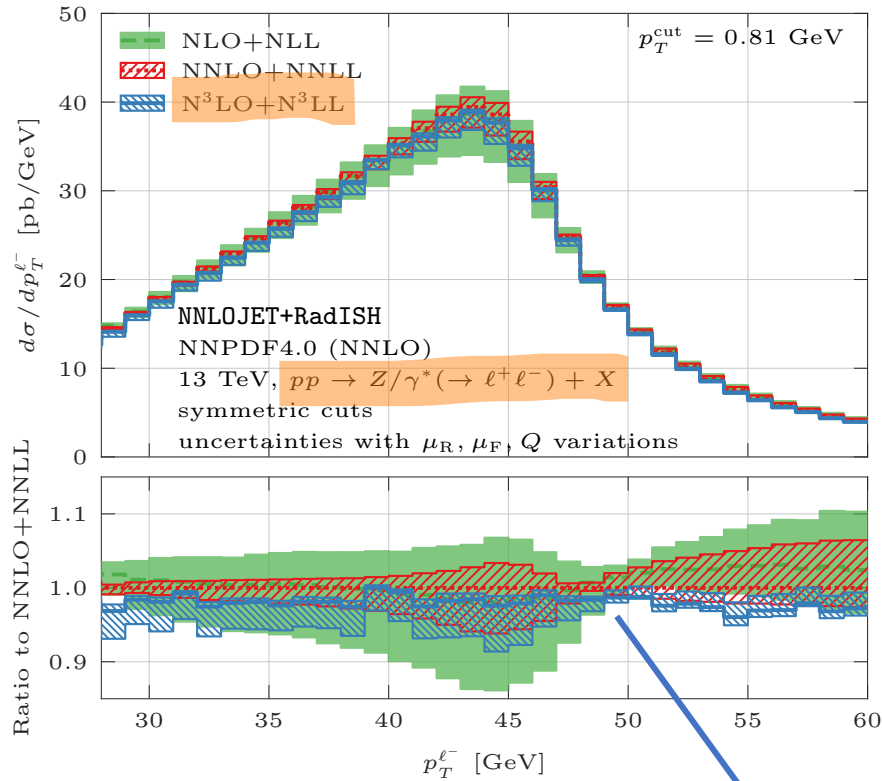
Large variation in error bands

Systematics introduced by choosing different sets can be substantial

Baglio, Duhr, Mistlberger, Szafron, 2209.06138
(n3lox – 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 N³LO+N³LL – differential



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

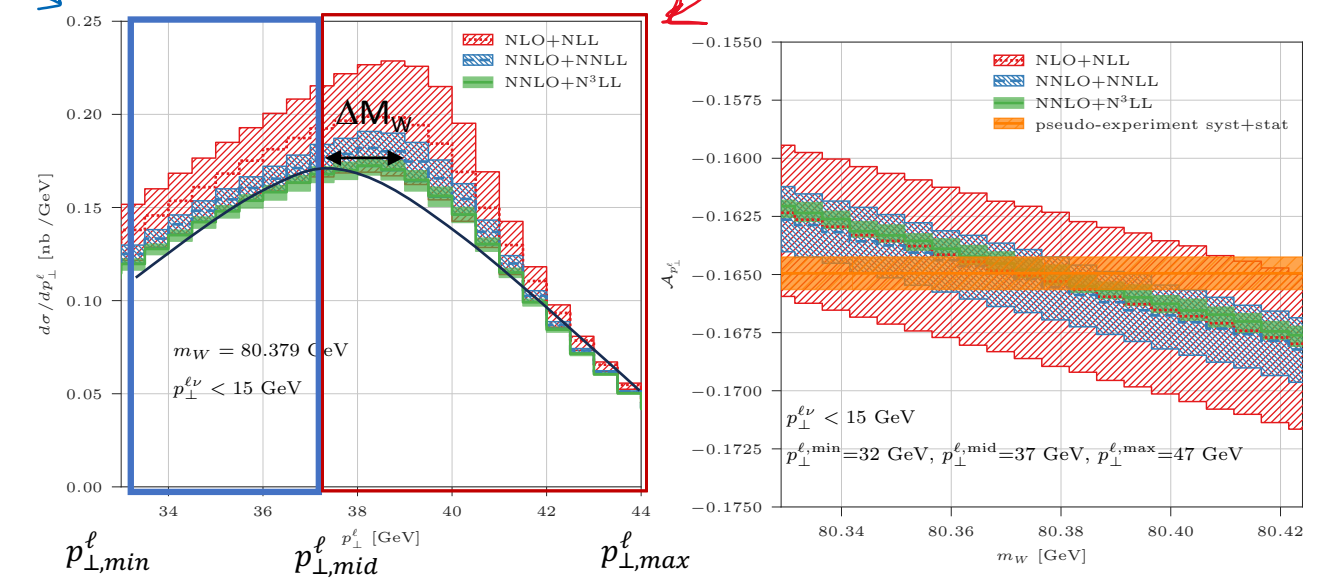
Challenging to control theoretical uncertainties below percent level!

Consider different observable?

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

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

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

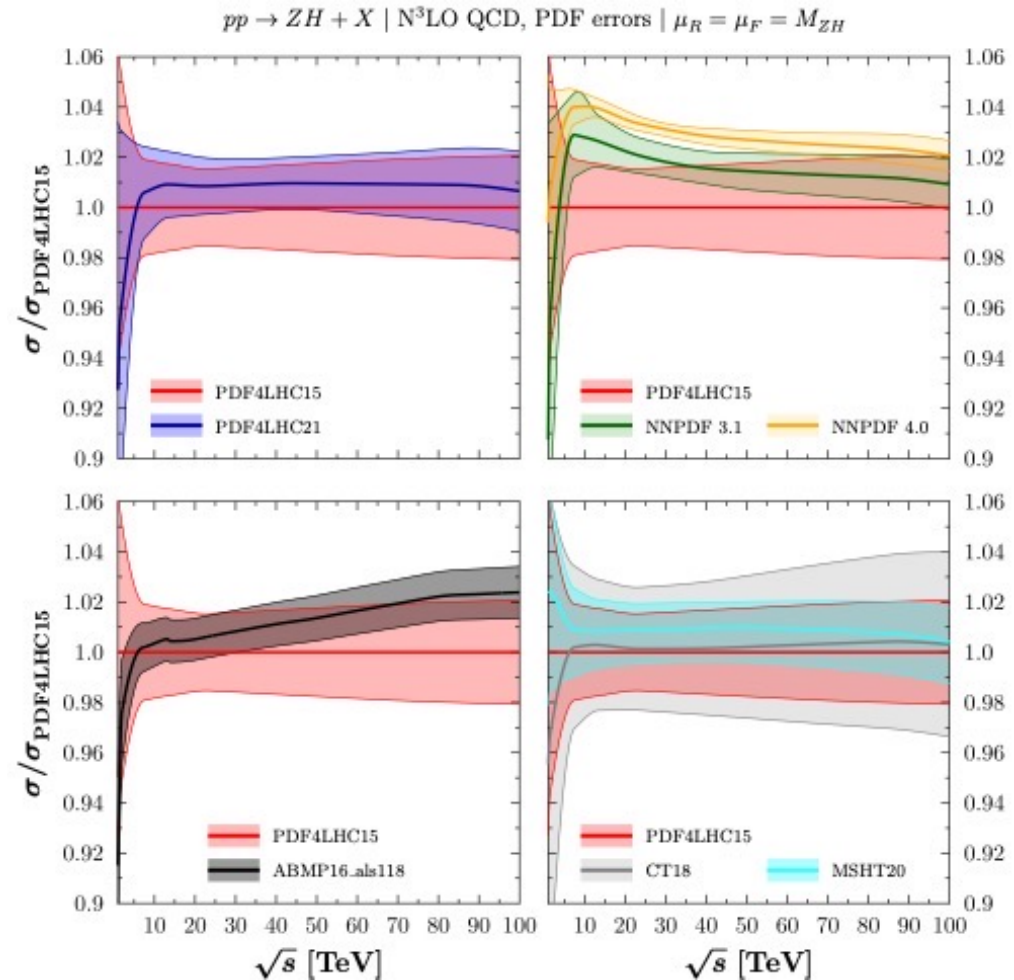
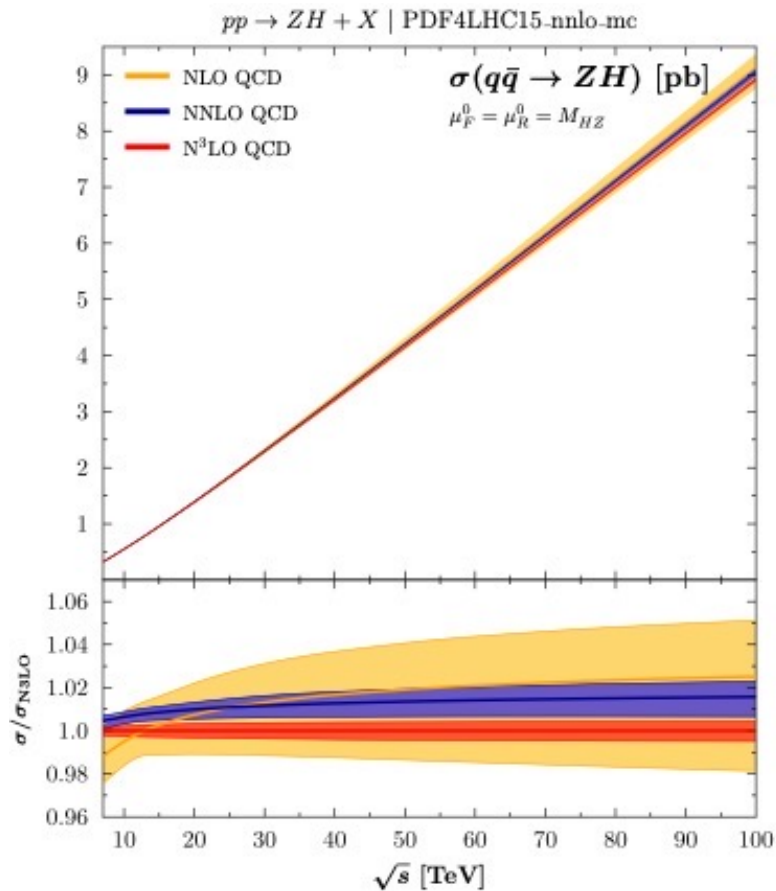


Rottoli, Torrielli, Vicini, 2301.04059

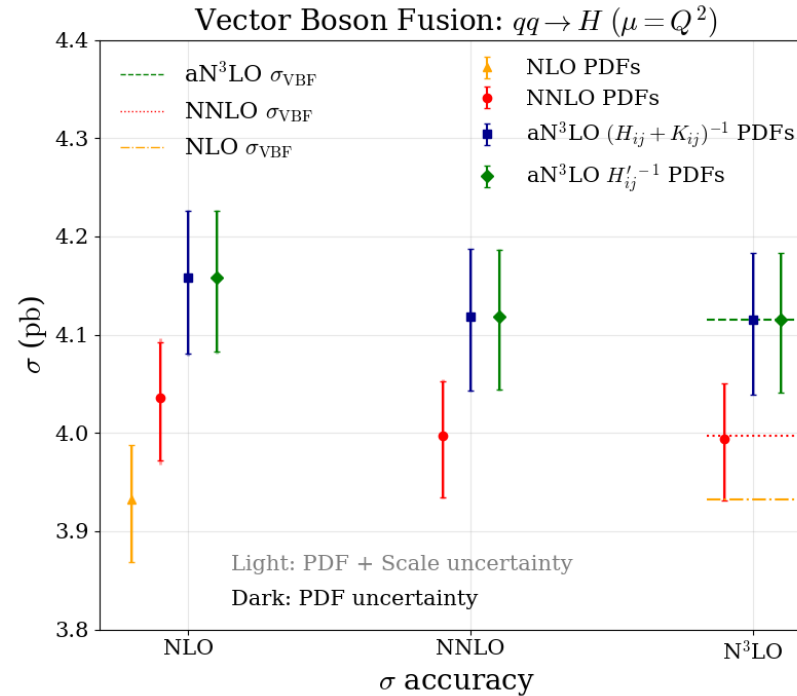
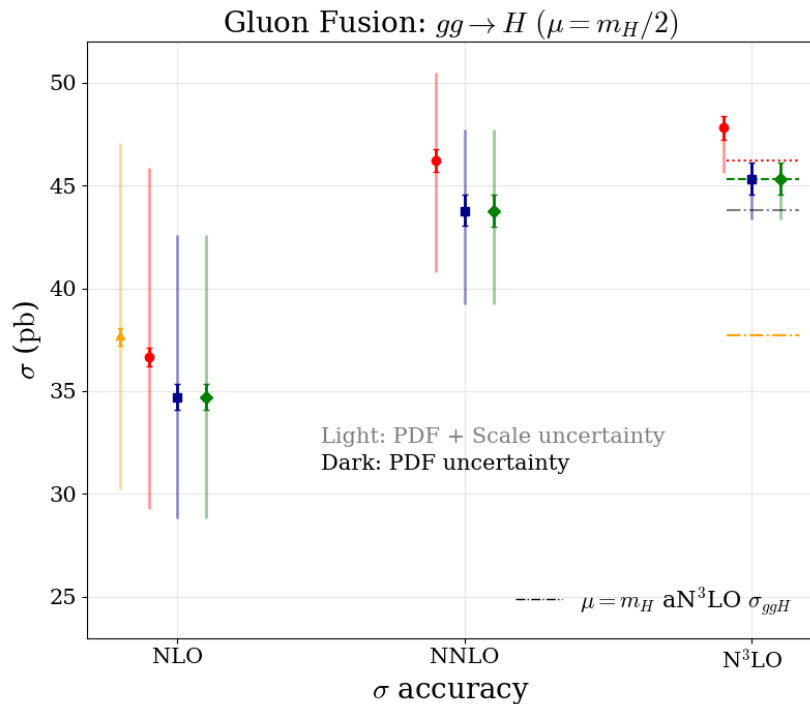
$\Delta M_W \sim \pm 15 \text{ MeV}$ feasible

VH at N³LO, first complete calculation

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



PDF – first approximate N³LO sets



aN³LO → MSHT20aN³LO

McGowan, Cridge, Harland-Lang, Thorne, 2207.04739

- **Gluon fusion to H:** the increase in the cross section prediction at N³LO is compensated by the N³LO PDF, suggesting a cancellation between terms in the PDF and cross section theory at N³LO → **matching orders matters!**
- **Vector Boson Fusion:** no relevant change in going from N²LO to N³LO PDF, due to different partonic channel involved.

- Based on N³LO 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 N³LO results
- Including PDF uncertainty from missing higher-orders (MHOU) as theoretical uncertainty in the fit

NNLO for $2 \rightarrow 3$ processes

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

Major impact on LHC phenomenology

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

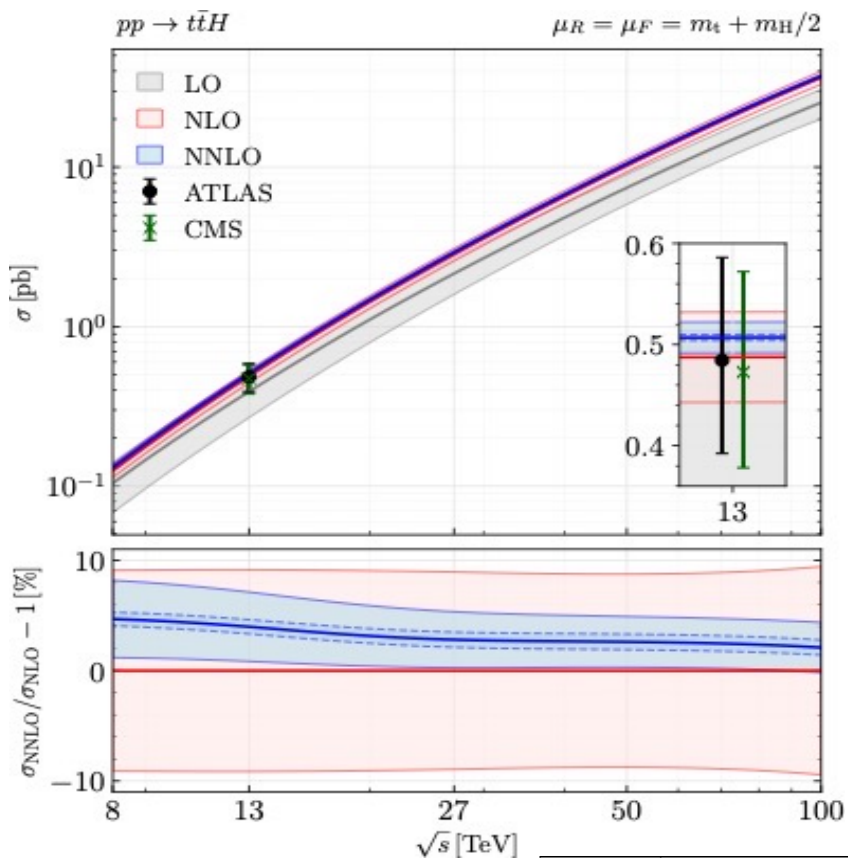
Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini, 2210.07846

Major 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

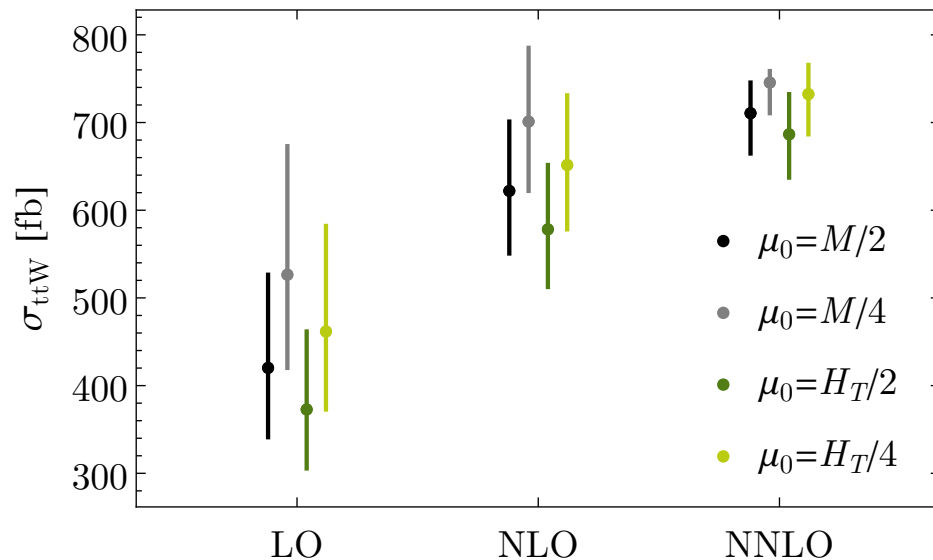


Catani et al., 2210.07846

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) $^{+0.1\%}_{-2.2\%}$

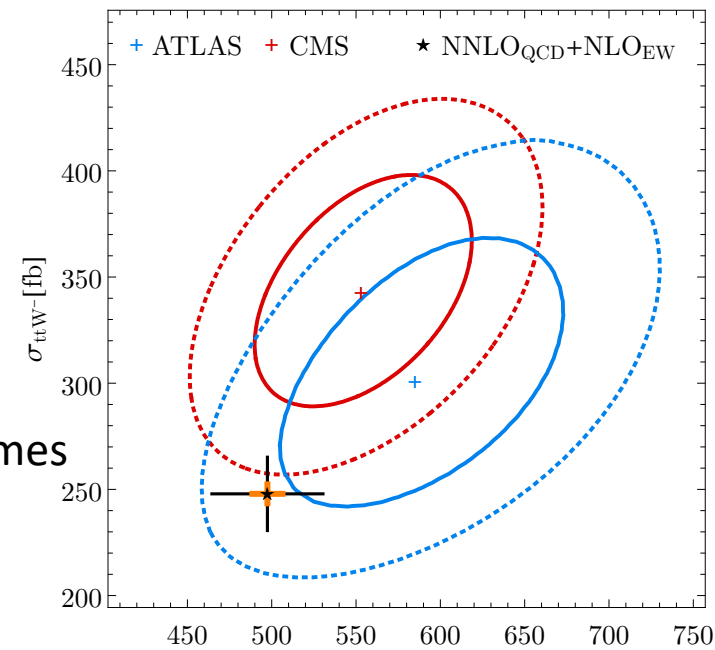
Buonocore et al., 2306.16311



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

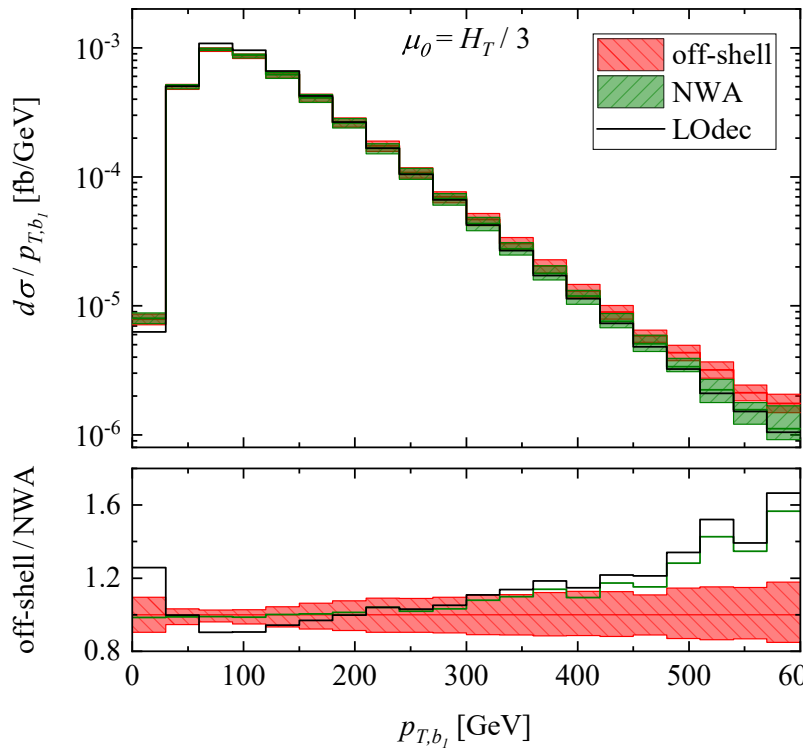
Ratio $\sigma_{t\bar{t}W^+}/\sigma_{t\bar{t}W^-}$ in very good agreement with ATLAS measurement

Comparison in fiducial volumes may give further insight



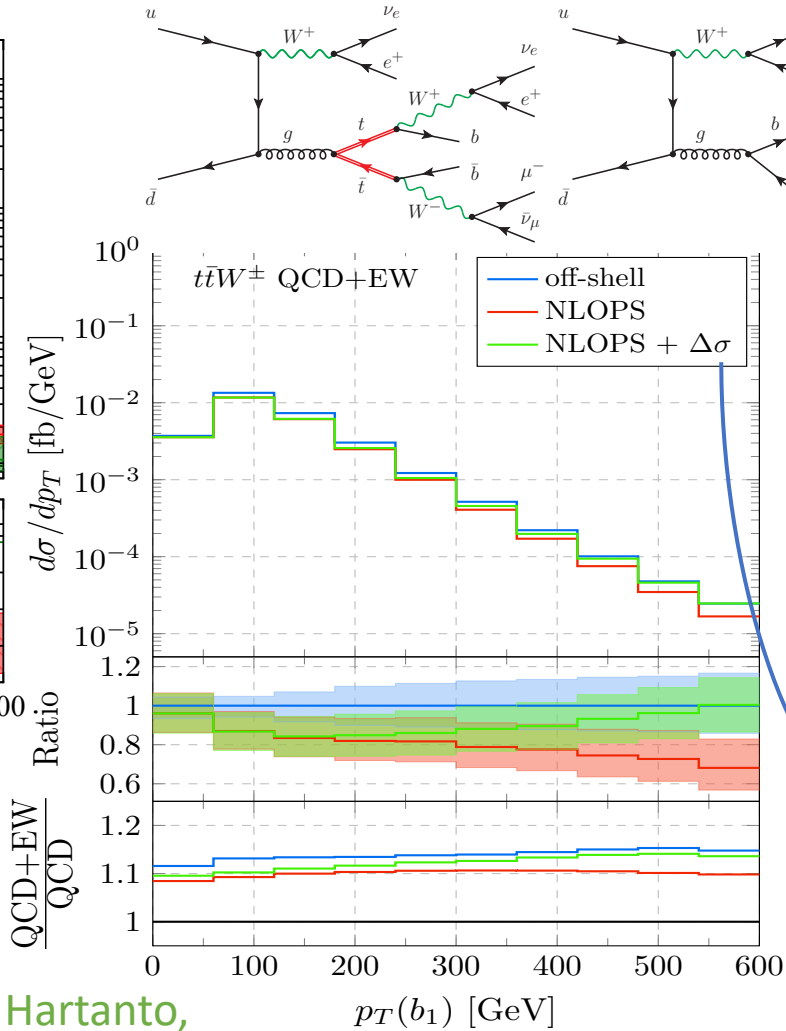
NLO: push the multiplicity challenge

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

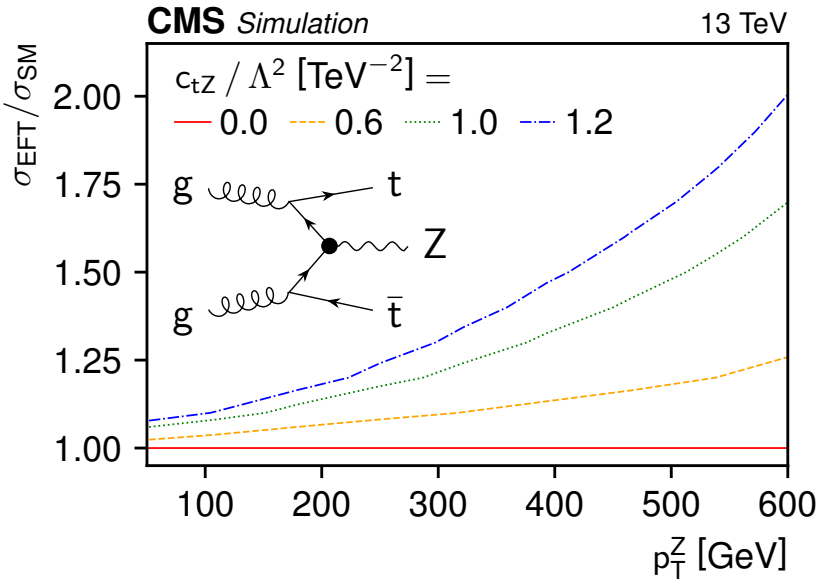
Off-shell effects most relevant in tails and end-points of distributions, where new physics effects can be hidden

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

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

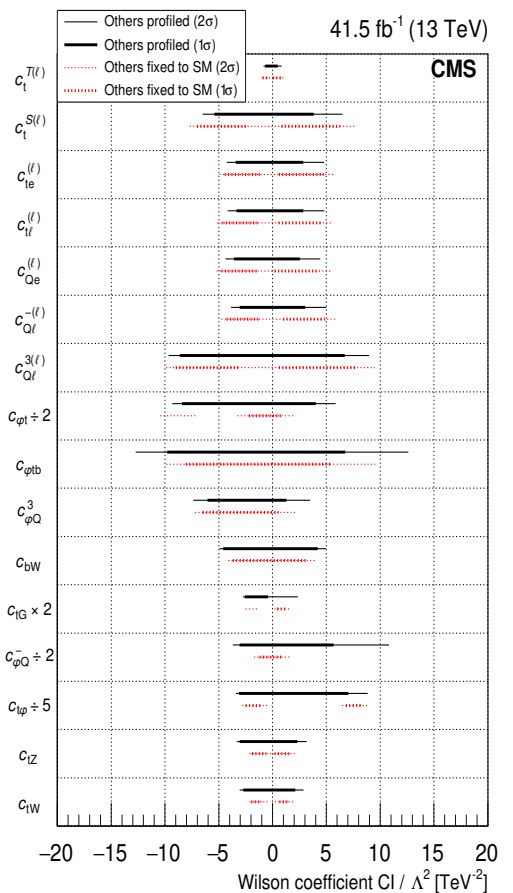
... exploring boosted kinematics and off-shell signatures

Top pair + boosted Z/H

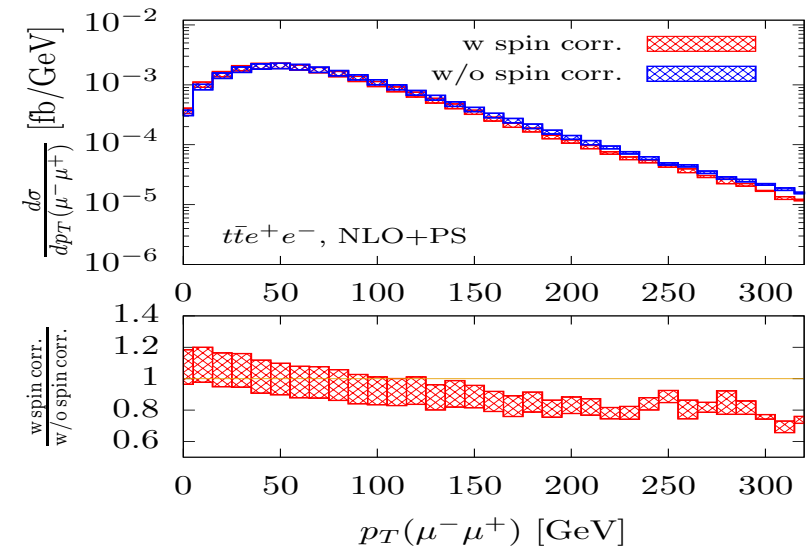


$\delta\eta_{\text{SM}} \sim g_{\text{BSM}}^2 \frac{E^2}{M^2}$ Effects in tails of distributions but also anomalous shapes

Top+additional leptons

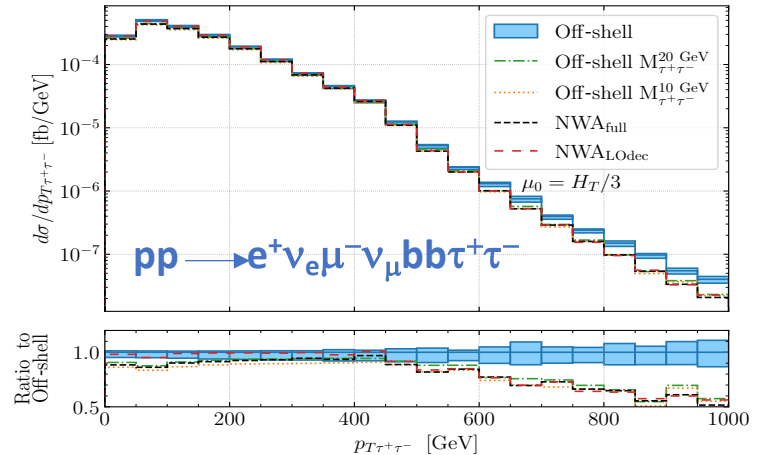


[CMS: arXiv:2012.04120]



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

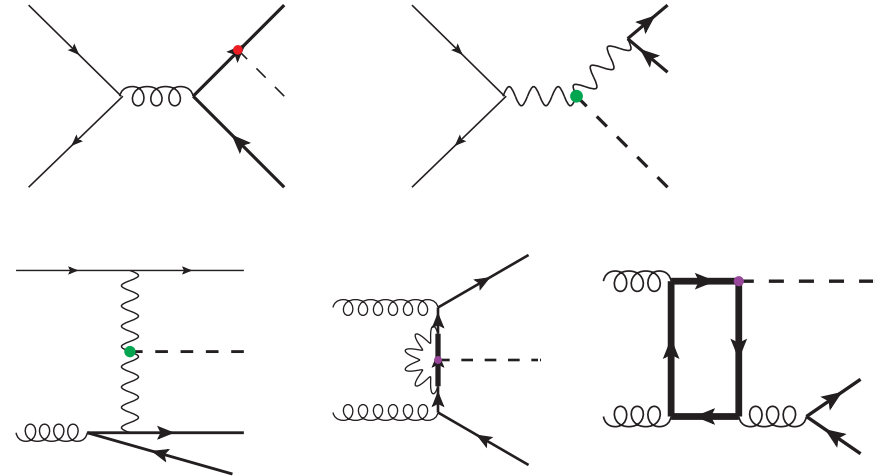
... deploying new techniques to interpret complex signatures

The case of **bbH** production including QCD+EW corrections

The extraction of y_b seems lost

“RIP Hbb” [Pagani et al., arXiv:2005.10277]

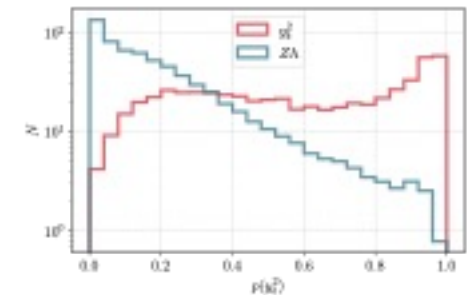
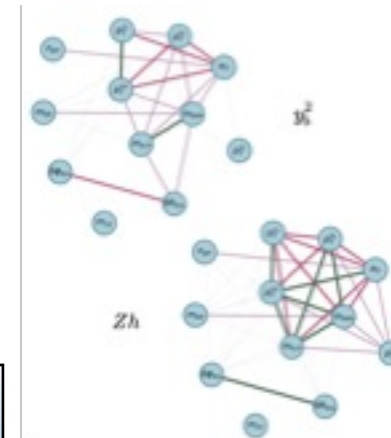
ratios	$\frac{\sigma(y_b^2)}{\sigma(y_b^2)+\sigma(\kappa_Z^2)} \equiv \frac{\sigma_{\text{NLO}_{\text{QCD+EW}}}}{\sigma_{\text{NLO}_{\text{all}}}}$ (y_b vs. κ_Z)	$\frac{\sigma(y_b^2)}{\sigma(y_b^2)+\sigma(y_t^2)+\sigma(y_b y_t)}$ (y_b vs. y_t)	$\frac{\sigma(y_b^2)}{\sigma(y_b^2)+\sigma(y_t^2)+\sigma(y_b y_t)+\sigma(\kappa_Z^2)}$ (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]

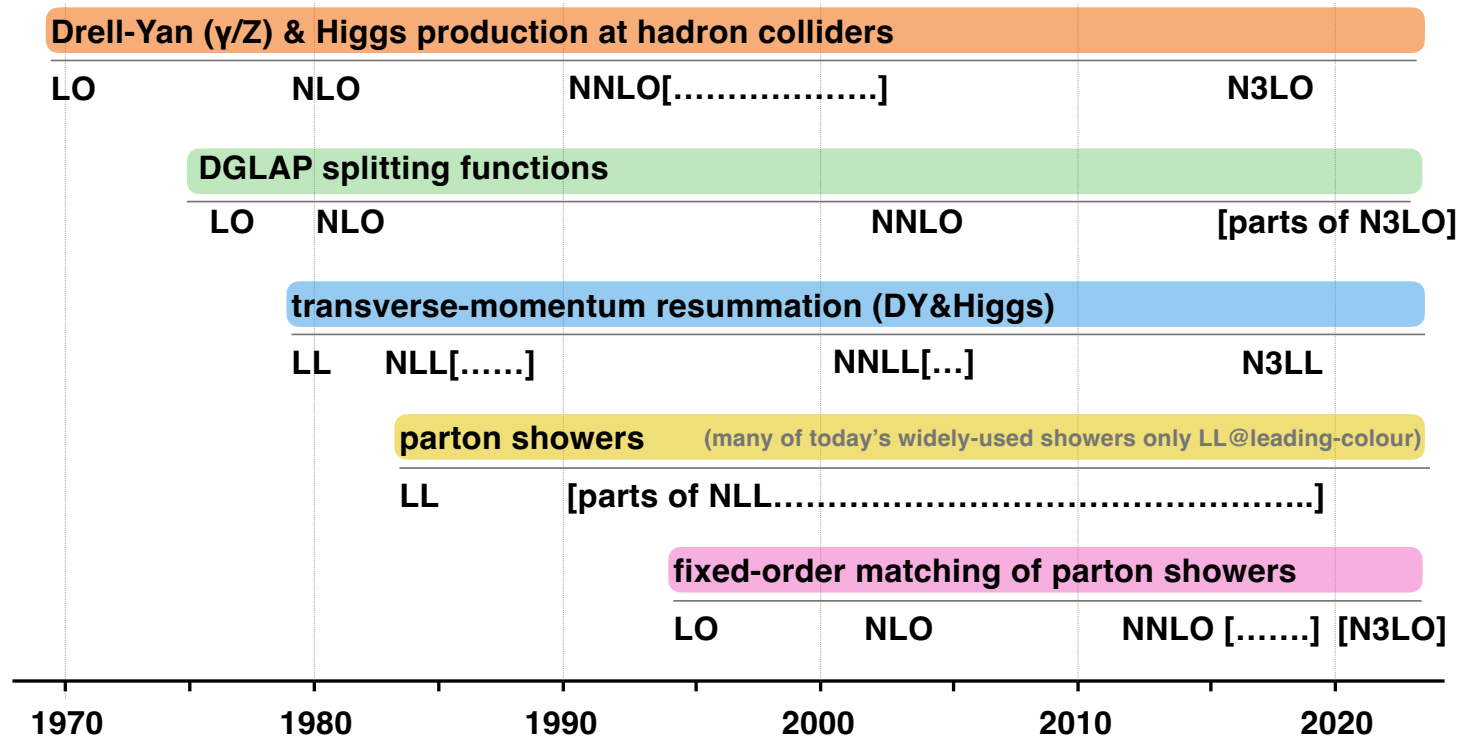


New techniques will open the possibility of turning problematic processes into powerful probes of the quantum structure of the SM

Parton-shower event generators

It's time for better Parton Showers!

Slide from G. Salam



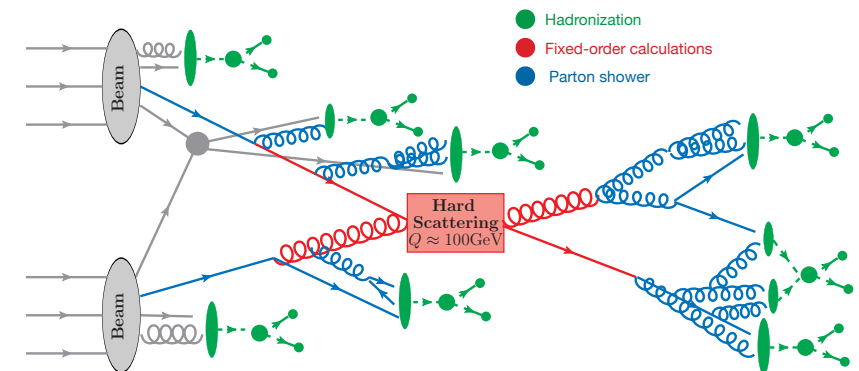
Crucial ingredient to reproduce the complexity of collider events

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

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



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

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

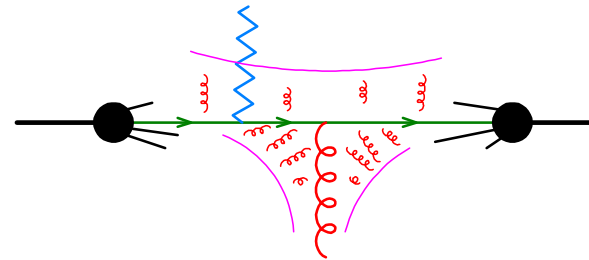
No general theory. Direct calculations have shown that there are no linear non-pert power corrections in:

- 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.