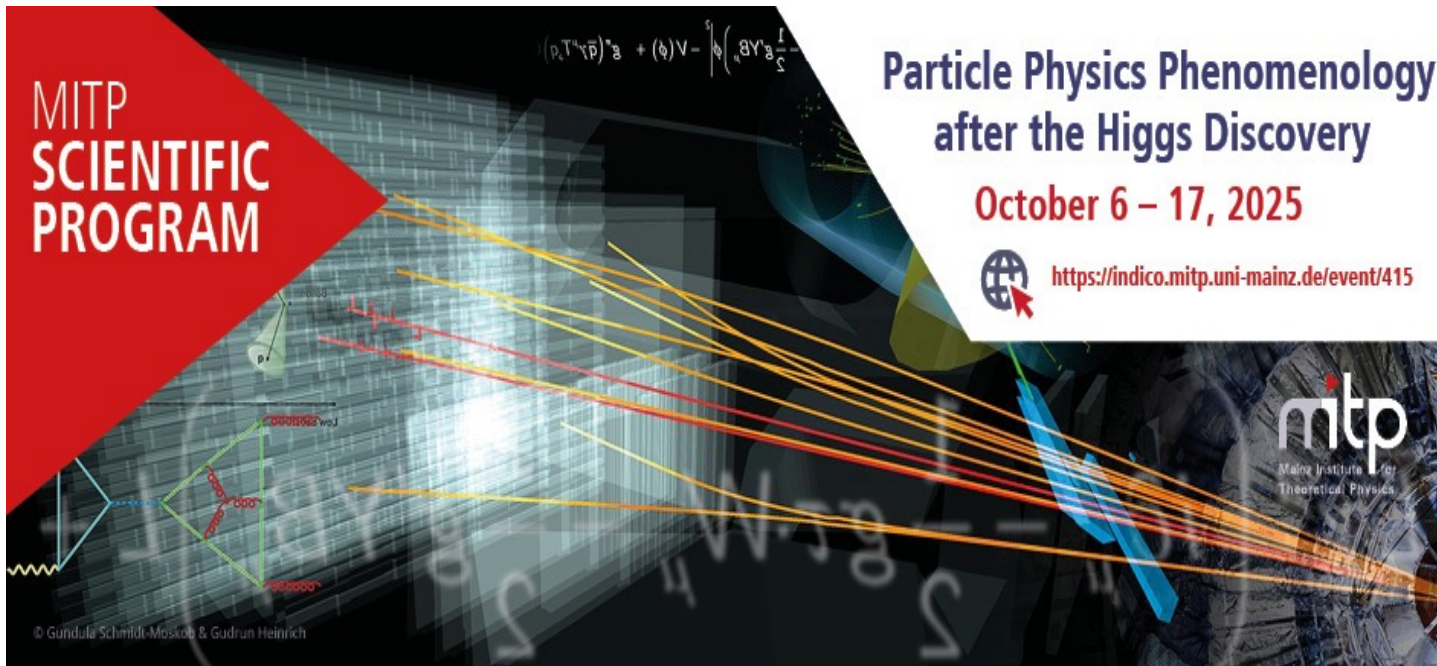


Future directions in collider physics

Progress and Perspectives after the Higgs-boson discovery



Mainz - October 9, 2025

Laura Reina
Florida State University
and
INFN – University of Rome 1

FSU | DEPARTMENT
OF PHYSICS

 **SAPIENZA**
UNIVERSITÀ DI ROMA

 U.S. DEPARTMENT OF
ENERGY

 **INFN**

Higgs boson as central to the Standard Model and a unique liaison to physics beyond it

The Higgs-boson discovery and physics program have been transformative by

- Establishing a crucial building block of the SM
- Providing a strong connection to physics beyond the SM
- **Pushing the boundaries of precision phenomenology** both in accuracy and breadth

Higgs central to the Standard Model of particle physics

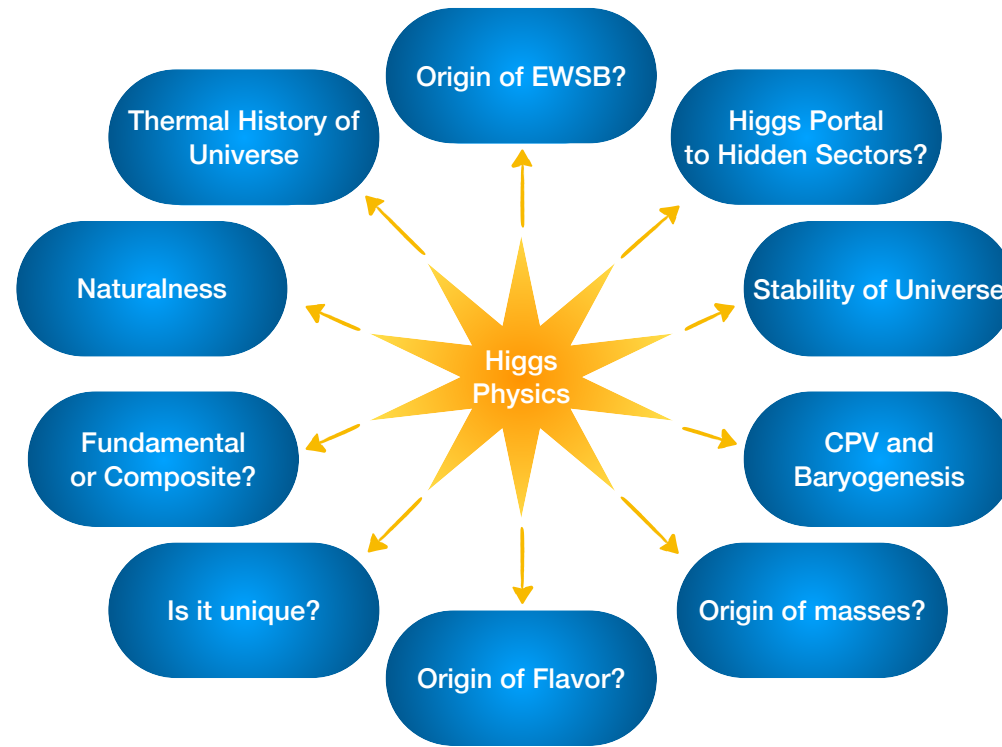
$$\begin{aligned}\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i\bar{\psi}\not{D}\psi + \text{h.c.} \\ & + \chi_i^\dagger y_{ij} \chi_j \phi + \text{h.c.} \\ & + |D_\mu \phi|^2 - V(\phi)\end{aligned}$$

The Standard Model Lagrangian depends on 19 free parameters, **15 of which are in the scalar sector!**

Higgs mass, Higgs self-coupling, fermion masses, CKM angles and phase

half of it is about Higgs!

Higgs central to exploring beyond the Standard Model



[Snowmass 2021 Energy Frontier's Report arXiv:2211.11084](#)

The discovery of the Higgs boson has sharpened the big open questions and given us a unique handle on BSM physics.

Consolidating the SM consistency at the quantum level

For M_W we combine:

- ❑ All LEP 2 measurements
- ❑ Previous Tevatron average
- ❑ ATLAS and LHCb early measurements
- ❑ CDF [$M_W=(80.4335\pm0.0094)$ GeV]
- ❑ ATLAS [$M_W=(80.3665\pm0.016)$ GeV]
- ❑ CMS [$M_W=(80.3602\pm0.010)$ GeV]

$$M_W = 80.366 \pm 0.0080 \text{ GeV (without CDF)}$$

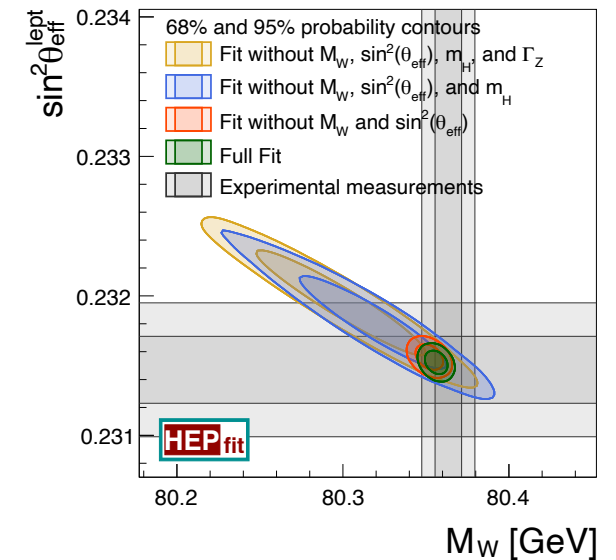
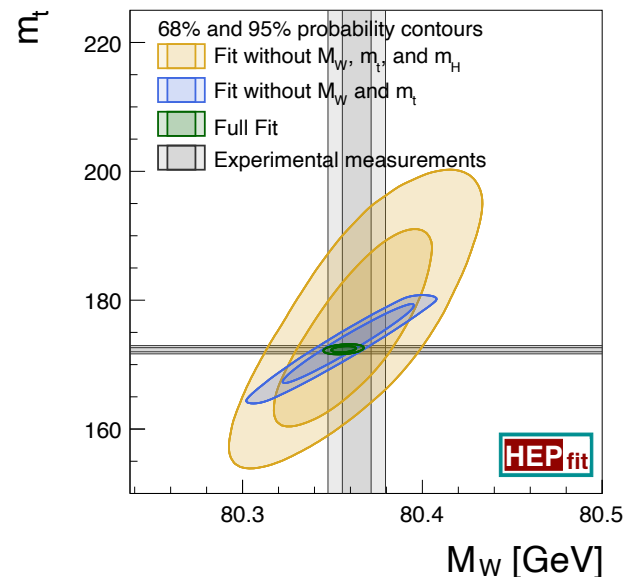
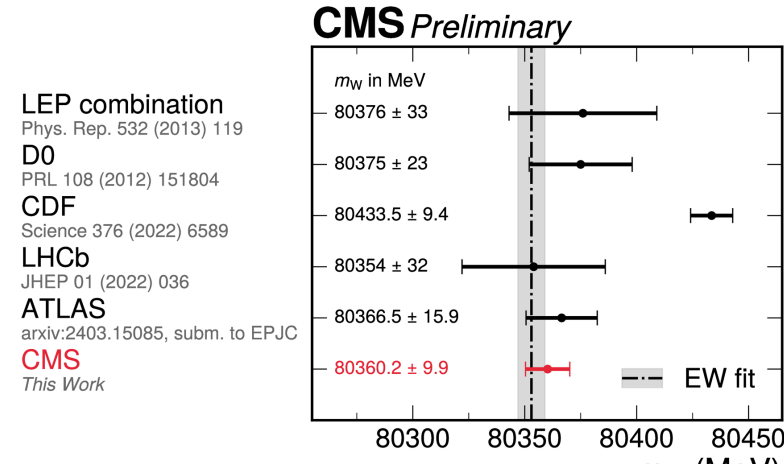
$$80.356 \pm 0.0045 \text{ GeV (from fit)}$$

For m_t we combine:

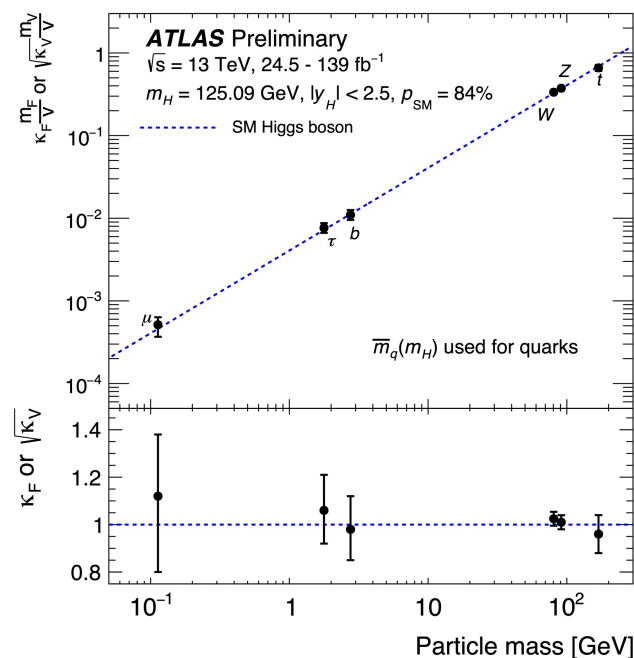
- ❑ 2016 Tevatron combination
- ❑ ATLAS Run 1 and early Run2 results
- ❑ CMS Run 1 and early Run 2 results
- ❑ CMS l+j [$m_t=(171.77\pm0.38)$ GeV]
- ❑ CMS l+j boosted [$m_t=(173.06\pm0.83)$ GeV]
- ❑ ATLAS l+j boosted [$m_t=172.95\pm0.53$ GeV]

$$m_t = 172.31 \pm 0.32 \text{ GeV}$$

$$172.38 \pm 0.31 \text{ GeV (from fit)}$$



Exploring Higgs couplings to probe the TeV scale

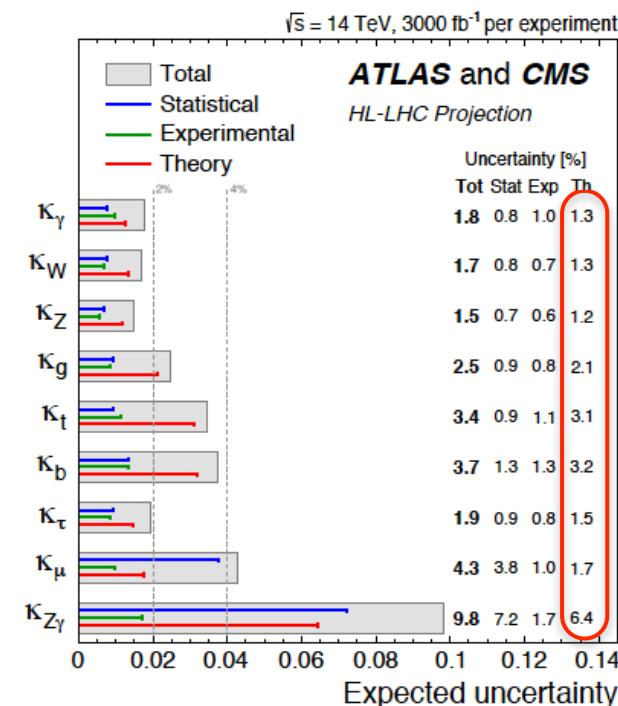
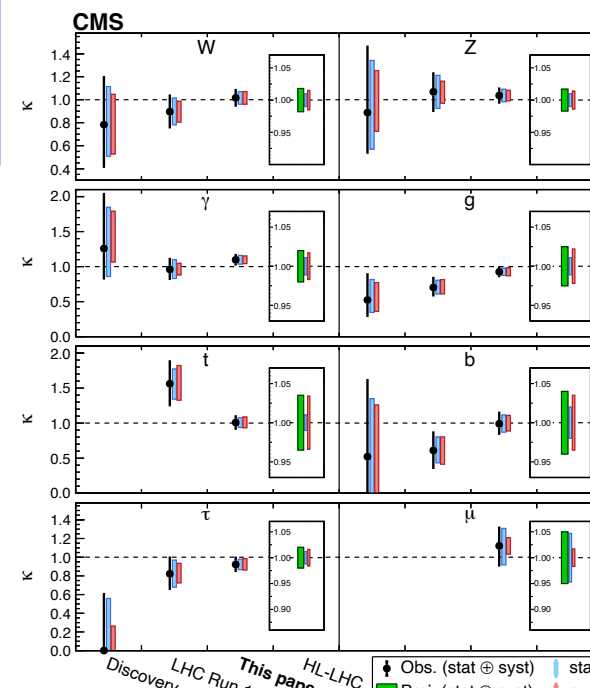


$$\kappa = g_X/g_X^{\text{SM}} = 1 + \Delta\kappa$$

$$\Delta\kappa \propto v^2/\Lambda_{\text{BSM}}^2$$

Precision on $\Delta\kappa$ reach for Λ_{BSM}

CMS, arXiv:2207.00043



- Couplings to **W/Z** at 5-10 %
- Couplings to **3rd generation** to 10-20%
- **First measurements** of 2nd generation couplings

- **HL-LHC projections** based on full Run 2 data:
 - **1.6-3.6 % on main couplings**
 - **3-7% on $H \rightarrow \mu^+ \mu^-$ and $H \rightarrow Z\gamma$**
 - **< 30% on Higgs (trilinear) self-coupling**
 - **Theory could become the main limitation**

Framework: Extend SM Lagrangian by effective interactions (ex: SMEFT)

$$\mathcal{L}_{\text{SM}}^{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \dots$$

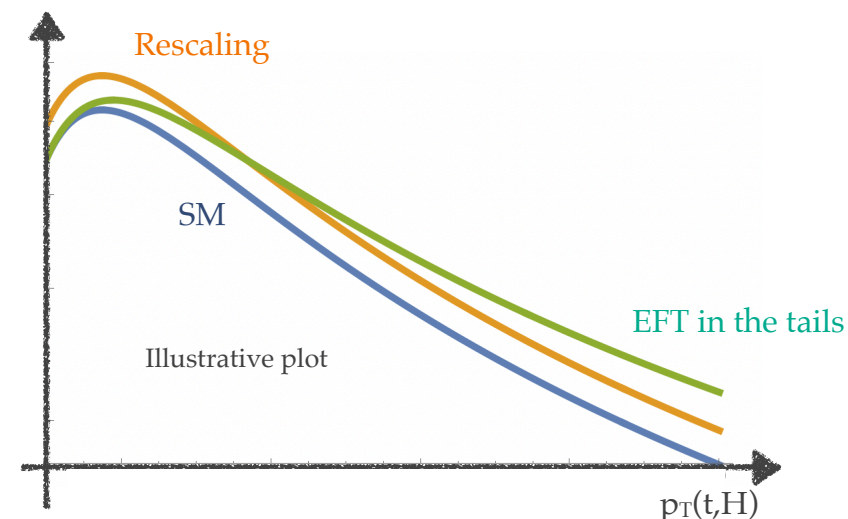
$$\mathcal{L}_d = \sum_i C_i^{(d)} \mathcal{O}_i^{(d)}, \quad [\mathcal{O}_i^{(d)}] = d$$

Built of SM fields and respecting the SM gauge symmetry.

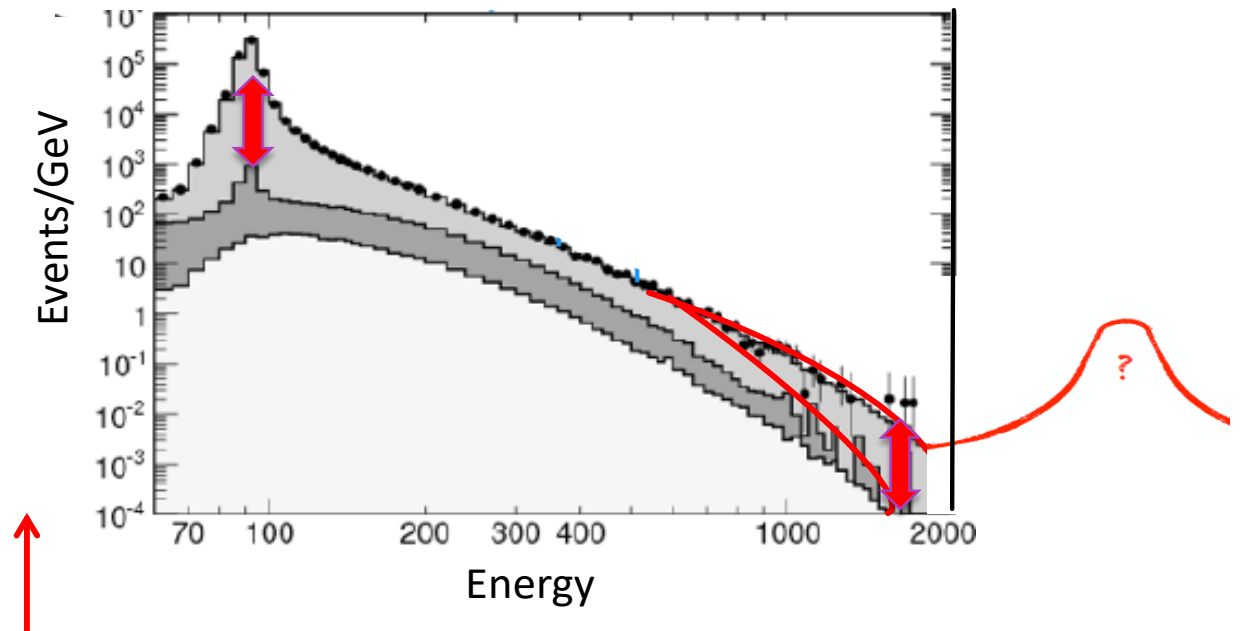
Expansion in $(v, E)/\Lambda$: **affects all SM observables** at both low and high energy

- **SM masses and couplings** → **rescaling**
- **Shapes of distributions** → more visible in **tails of distributions**

Under the assumption that new physics leaves at scales $\Lambda > \sqrt{s}$

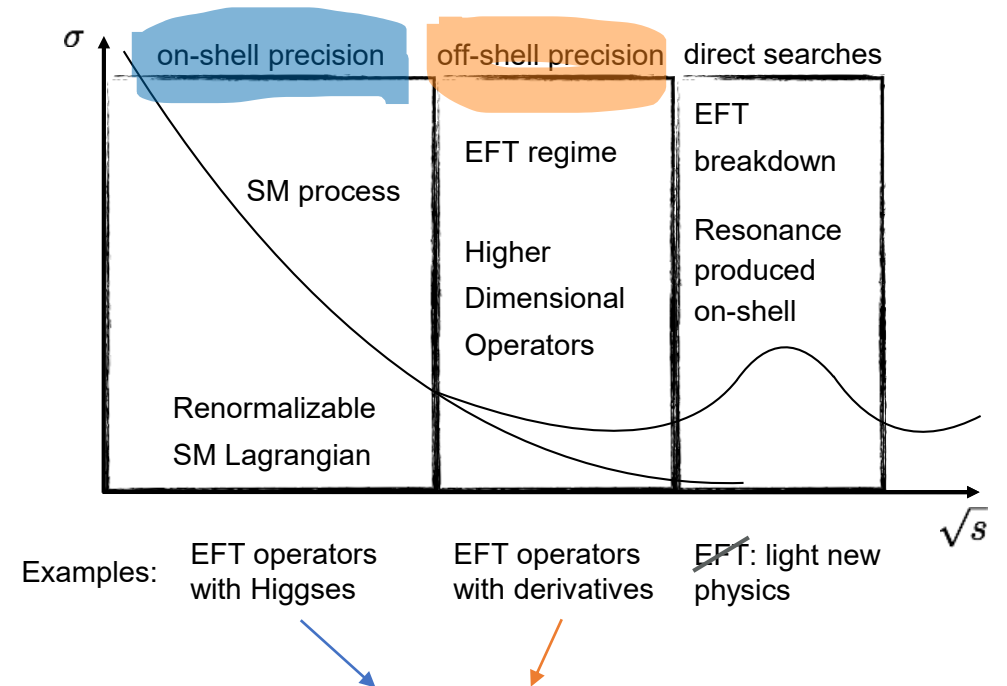


Beyond total rates



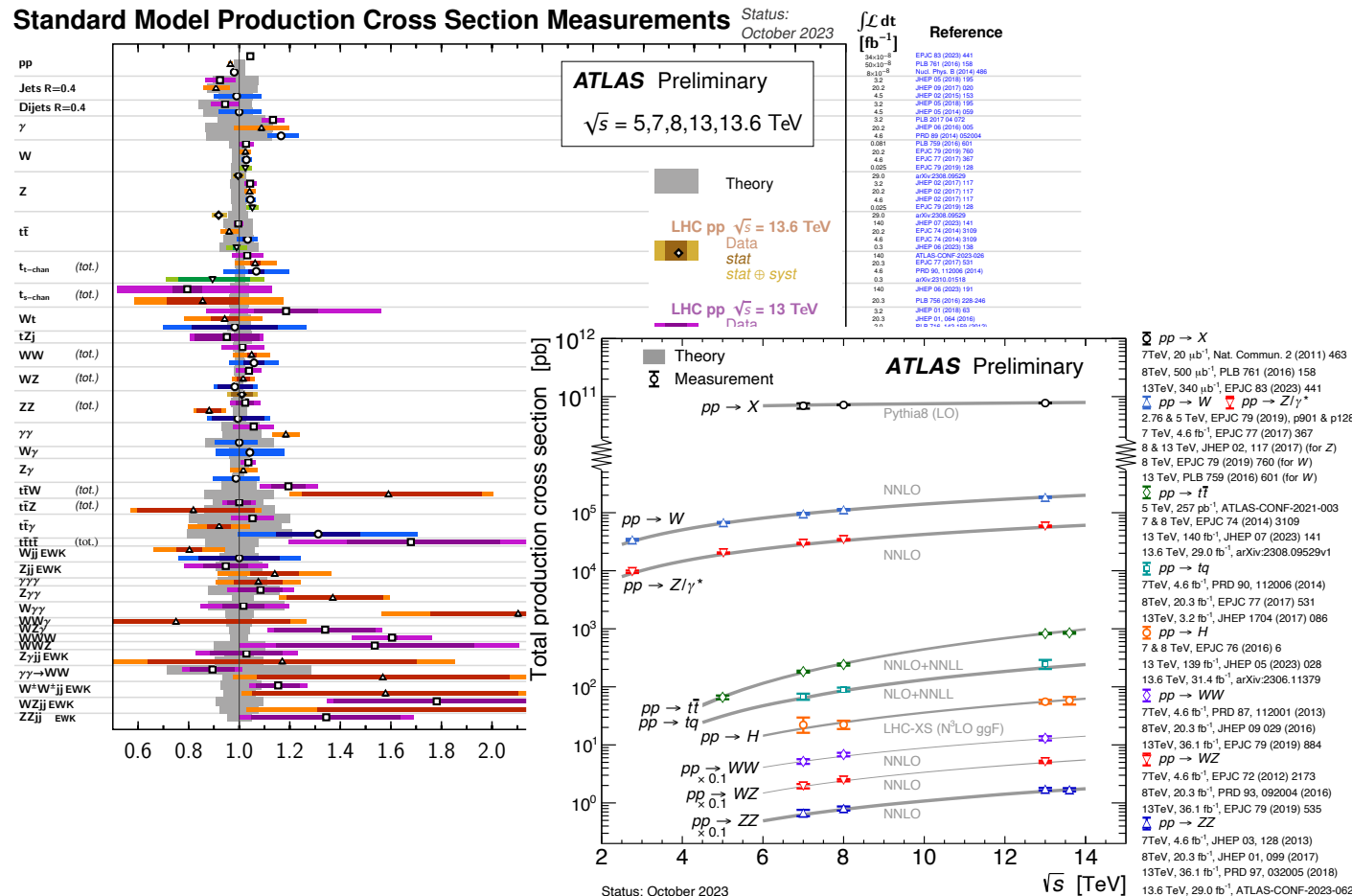
Need SM precision calculations at differential level both at **lower energy**, where rates are large and at **higher energy** where rates are small, but effects of new physics may be more visible.

See Malgorzata's, Tobias's, Thomas's talks



Crucial to control NP sensitive regions

The LHC legacy – Exploring new physics over a broad spectrum of observables



- A **wealth of high-quality data** now available from a **broad spectrum of experiments and observations**.
- **Powerful new ideas** are **boosting the accuracy of both theoretical and experimental results**.
- **Major decisions for future projects are being made (Snowmass/P5, ESPP)** based on current results and technologies, future projections, and theoretical guidance.



Message: the Higgs-boson discovery has established the LHC legacy and defined a new era of precision physics

Future Directions

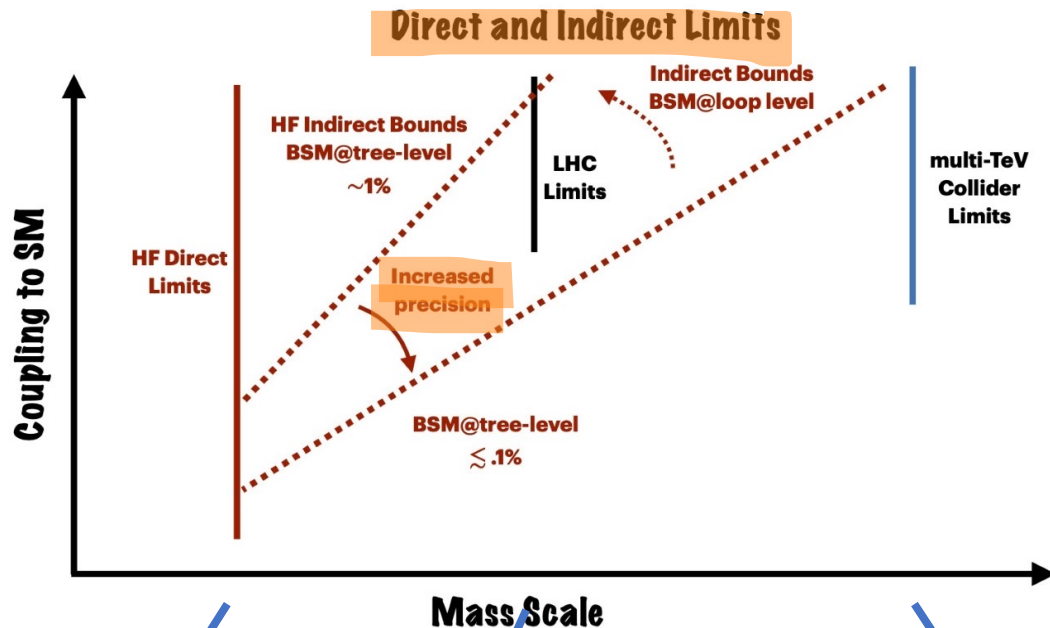
Improved Energy and Precision

The **Higgs-boson discovery** has shaped future directions

Future directions: energy and precision

Answering the big Open Questions via energy and precision

- **Origin of the EW scale** (SSB via Higgs mechanism, naturalness, flavor)
- Origin of Baryon Asymmetry, Dark Matter, Dark Energy
- ...



Given the level of consistency of the SM, and no clear evidence of new particles in LHC searches so far, we expect new physics effects to be small.

Nothing can replace direct discovery, for which energy is a major factor, but ...

Precision affects the sensitivity to both direct and indirect effects of new physics since it enhances sensitivity to small deviations.

Higgs-boson factories (up to 1 TeV c.o.m. energy)

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP	Start Date	
					Const.	Physics
HL-LHC	pp	14 TeV		3		2027
ILC & C ³	ee	250 GeV	$\pm 80/\pm 30$	2	2028	2038
		350 GeV	$\pm 80/\pm 30$	0.2		
		500 GeV	$\pm 80/\pm 30$	4		
		1 TeV	$\pm 80/\pm 20$	8		
CLIC	ee	380 GeV	$\pm 80/0$	1	2041	2048
CEPC	ee	M_Z		50	2026	2035
		$2M_W$		3		
		240 GeV		10		
		360 GeV		0.5		
FCC-ee	ee	M_Z		75	2033	2048
		$2M_W$		5		
		240 GeV		2.5		
		$2 M_{\text{top}}$		0.8		
μ -collider	$\mu\mu$	125 GeV		0.02		

Snowmass EF wiki: <https://snowmass21.org/energy/start>

Snowmass 21: EF Benchmark Scenarios

Multi-TeV colliders (> 1 TeV c.o.m. energy)

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP	Start Date	
					Const.	Physics
HE-LHC	pp	27 TeV		15		
FCC-hh	pp	100 TeV		30	2063	2074
SppC	pp	75-125 TeV		10-20		2055
LHeC	ep	1.3 TeV		1		
FCC-eh	ep	3.5 TeV		2		
CLIC	ee	1.5 TeV	$\pm 80/0$	2.5	2052	2058
		3.0 TeV	$\pm 80/0$	5		
μ -collider	$\mu\mu$	3 TeV		1	2038	2045
		10 TeV		10		

Timelines are taken from the Collider ITF
report ([arXiv: 2208.06030](https://arxiv.org/abs/2208.06030))

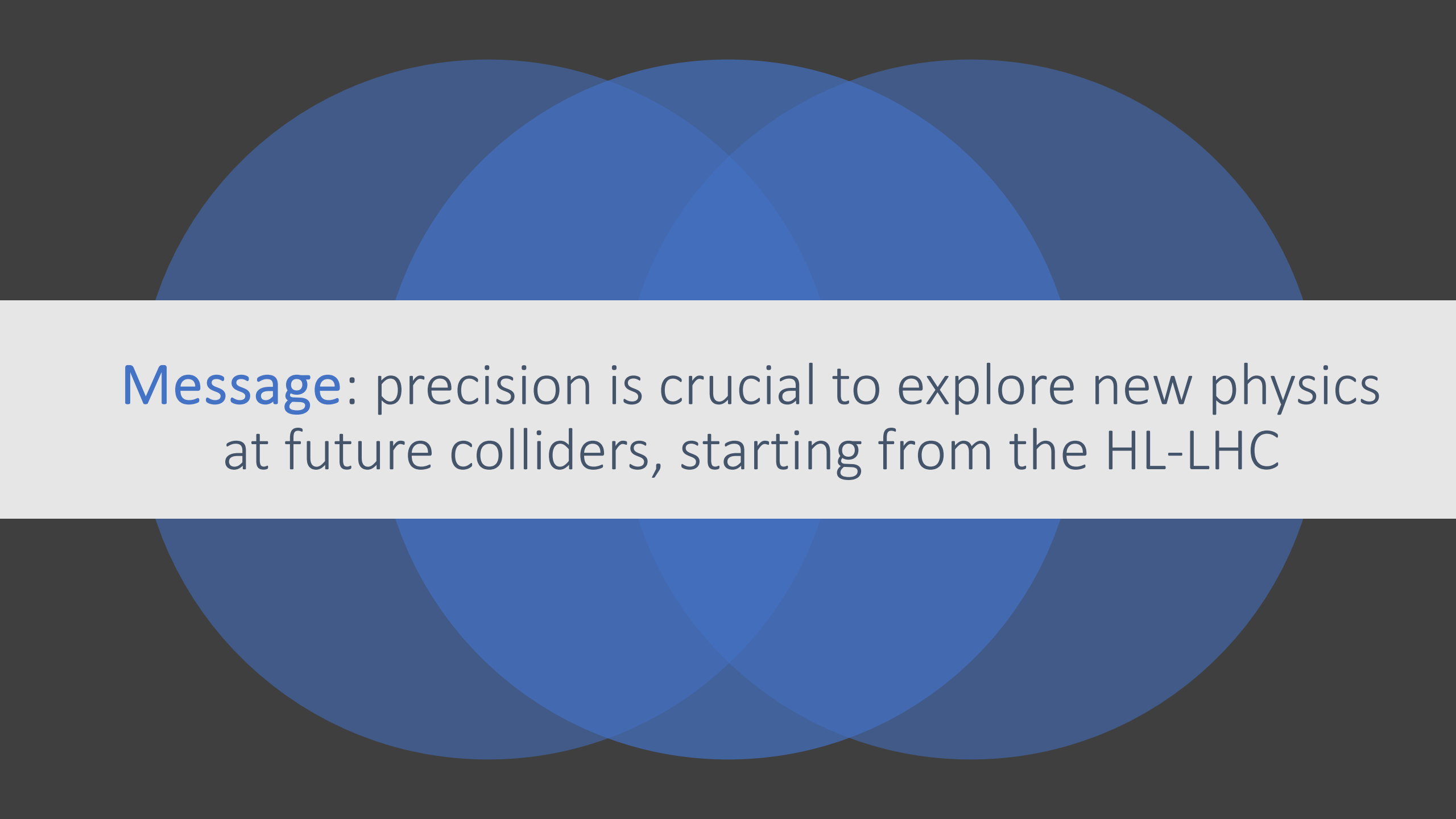
ESPP recent document: Physics Briefing Book

(CERN-ESU-2025-001, 30 September 2025)

e^+e^- projects	Energies (GeV)								FCC-hh	CLIC Muon Collider	Muon Collider Plasma Collider
	91	160	240	365	380	550	1000	1500	85 TeV	3 TeV	10 TeV
FCC-ee	X	X	X	X							
LCF-250	X		X								
LCF-250+550	X		X	X		X					
CLIC-380					X						
CLIC-380+1500					X			X			
LEP 3	X	X	X (230)								
ep collider											
LHeC											
High-energy options											
FCC-ee + FCC-hh (85 TeV)	X	X	X	X					X		
FCC-hh (85 TeV)									X		
LCF + 1 TeV option	X		X			X	X				
LCF + High-energy lepton collider	X		X			X					X
CLIC + 3 TeV					X			X		X	
Muon Collider										X	X
LEP3 + FCC-hh (85 TeV)	X	X	X(230)						X		
LEP3 + High-energy lepton collider	X	X	X(230)								X
LHeC + FCC-hh (85 TeV)									X		

Some new benchmarks
FCC-hh (85 TeV)
LEP3

Several combined scenarios



Message: precision is crucial to explore new physics
at future colliders, starting from the HL-LHC

Precision collider phenomenology

Raising to the challenge

Future collider projections are impressive. Theoretical predictions depends on:

- **Parametric uncertainties** (on SM parameters)
- **Theoretical uncertainties** (perturbative and non-perturbative quantum effects in collider observables)
- **Interpretation of established deviations** (model specific/model agnostic)

All need to be controlled to **reach (sub)percent level precision** and **enable a future collider precision program.**

EW precision fits: stressing the SM and beyond to unprecedented level

Current and projected experimental precision (e^+e^-)

Observable	Current	FCC-ee	LCF	LEP3
Δm_Z (keV)	2000	4 (100)	200	7.5 (100)
$\Delta \Gamma_Z$ (keV)	2300	4 (12)	125	7.5 (23)
$\delta R_\mu (\times 10^{-6})$ $R_\mu \equiv \frac{\Gamma_{\text{had}}}{\Gamma_\mu}$	1600	2.4 (2.3)	90 (90)	4.5 (2.3)
$\delta R_b (\times 10^{-6})$ $R_b \equiv \frac{\Gamma_b}{\Gamma_{\text{had}}}$	3300	1.2 (1.6)	70 (60)	2.2 (3.0)
$\Delta \sin^2 \theta_W (\times 10^6)$	130	0.4 (0.5)	2.7 (2.3)	0.75 (0.95)
$\Delta \alpha(m_Z)^{-1} (\times 10^3)$	14	0.8, 3.8	—	1.4, 7.3
Δm_W (keV)	9900	180 (160)	500 (1600)	430 (700)
$\Delta \Gamma_W$ (keV)	42000	270 (200)	2000	650 (500)

Current and projected theoretical precision (e^+e^-)

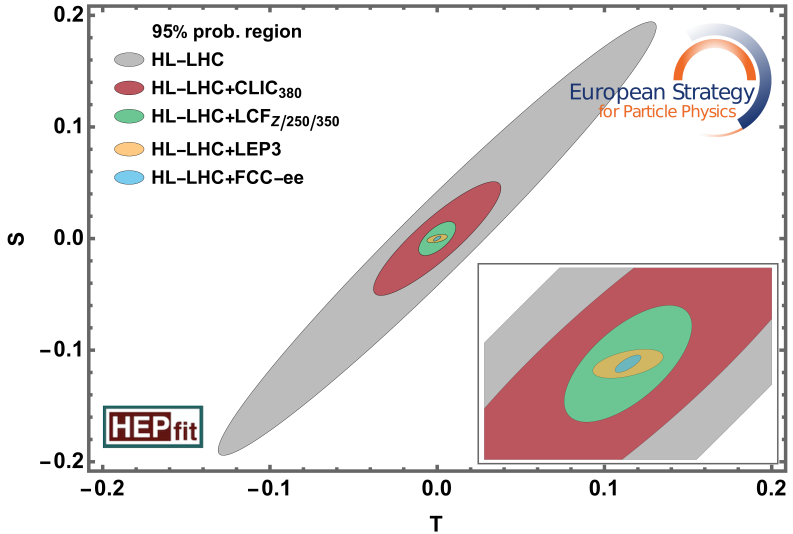
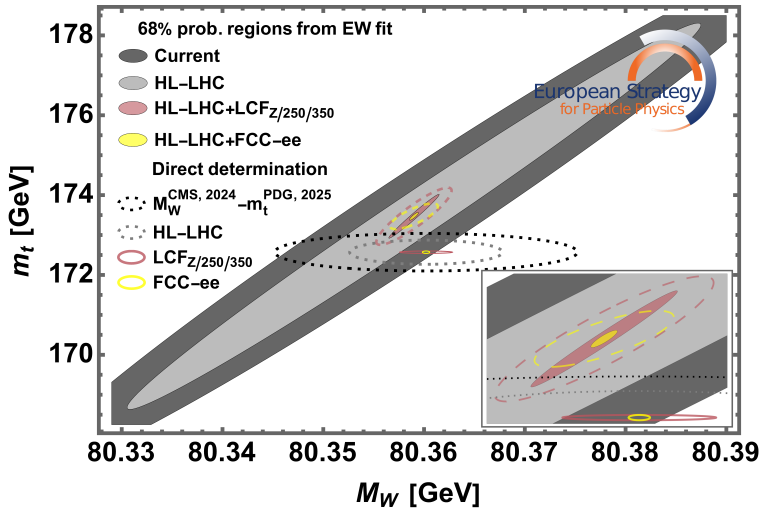
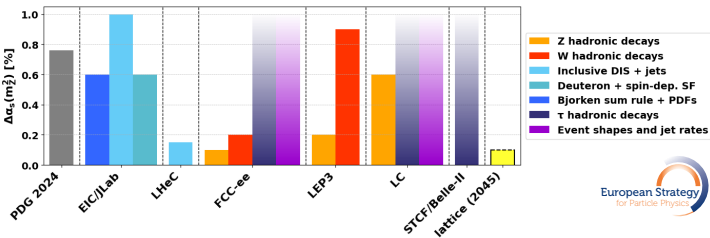
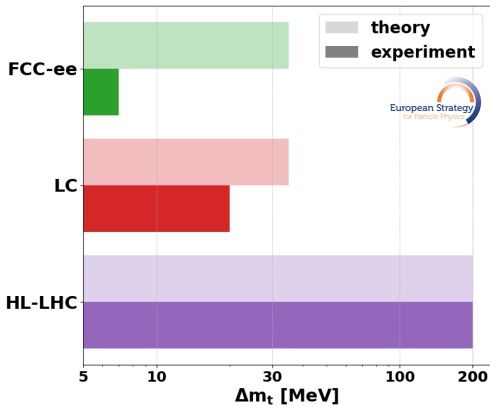
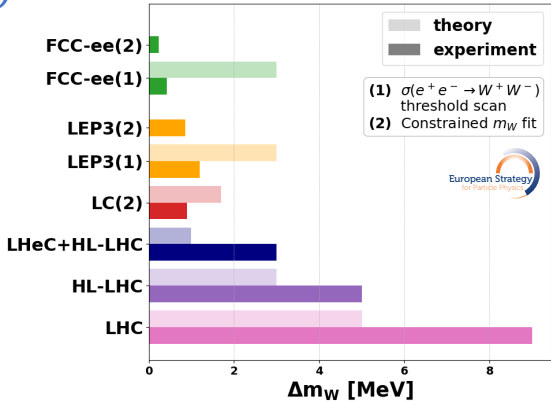
Observable	Current	Conservative	Aggressive
Γ_Z (MeV)	0.23	0.035	—
m_Z (MeV)	0.3	0.03	—
$R_\ell (10^{-3})$	12	0.4	—
$R_b (10^{-4})$	4.4	0.44	0.09
$R_c (10^{-4})$	17	1.7	0.34
σ_{had} (pb)	25	1.7	—
$A_{\text{FB}}^\ell (10^{-4})$	6	0.43	—
$A_{\text{FB}}^b (10^{-4})$	1.5	0.32	0.028
$A_{\text{FB}}^c (10^{-4})$	1.1	0.23	0.021

From extraction
(background,
ISR/FSR)

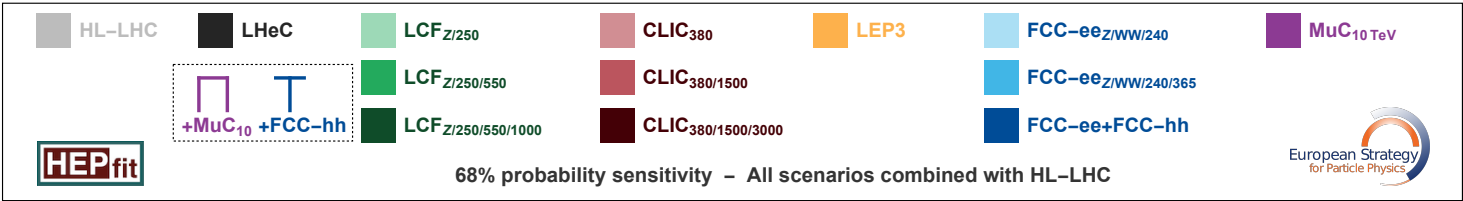
Observable	Current	Conservative	Aggressive
Γ_Z (MeV)	0.4	0.08	0.016
$R_\ell (10^{-3})$	6.0	1.2	0.2
$R_b (10^{-4})$	1.0	0.2	0.035
$R_c (10^{-4})$	0.5	0.1	0.02
σ_{had} (pb)	6	1.6	0.3
$\sin^2 \theta_{\text{eff}} (10^{-5})$	4.5	0.7	0.06
m_W (MeV)	4.0	1.0	0.1

From SM
prediction

Parametric uncertainties

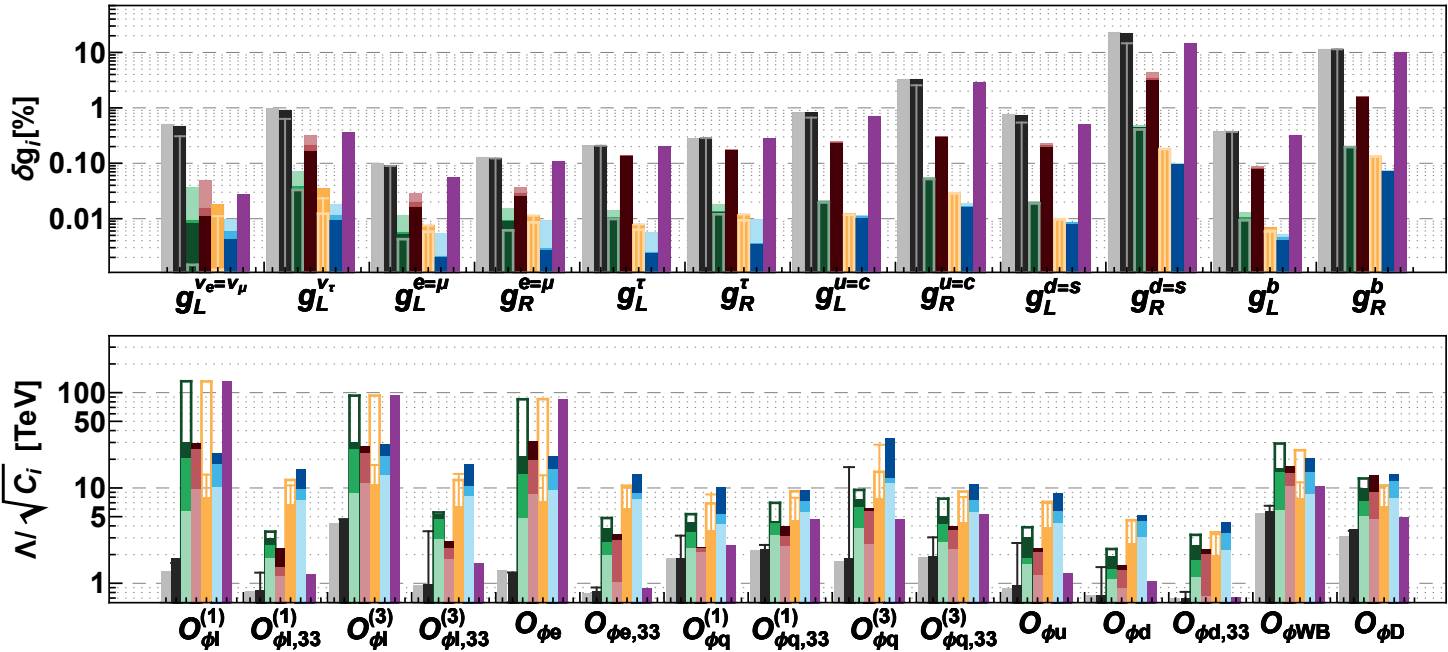


Precision reach on EW couplings



Crucial to test our understanding of HL-LHC precision measurements.

The obtainable precision from EWPO strongly depends on the **assumptions made in the evaluation of theoretical uncertainties.**



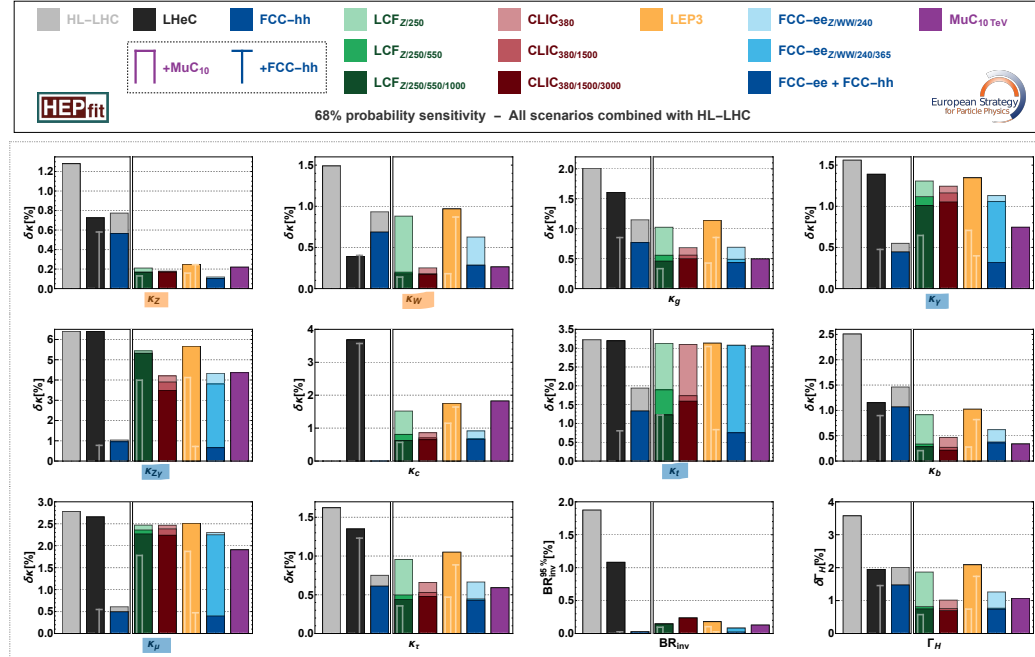
The interpretation is a case by case choice

Assuming theory errors improve as follows

Quantity	Current	Conservative	Aggressive
m_t (MeV)	35	30	—
m_W (MeV)	3	0.6	—
$\alpha_s(m_Z)$ (10^{-3})	1	0.3	0.1
$\alpha(m_Z)/\alpha(0)$ (10^{-4})	< 1	< 0.5	0.1 - 0.3

“conservative”: assuming theory improvements likely to be achieved building on and extending existing computational methods.
“aggressive”: requires more fundamental advances in techniques and tools.

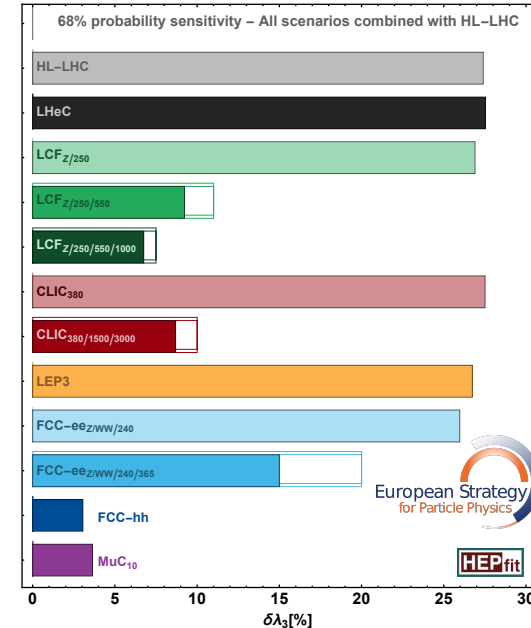
Precision reach on Higgs-boson couplings



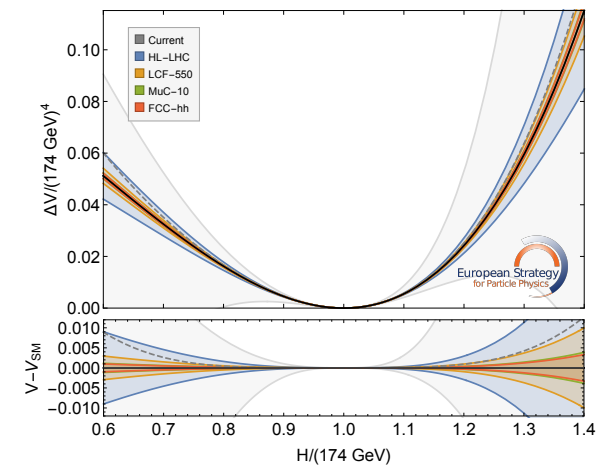
➤ **Per-mille** precision level for κ_V

➤ But in other cases: κ_μ , $\kappa_{Z\gamma}$, κ_γ , or even κ_t
(if next e^+e^- collider runs below the $t\bar{t}H$ threshold)
It will be the HL-LHC legacy (until FCC-hh)

The ultimate goal: the Higgs self-coupling (λ_3)



In the domain of the FCC-hh or
a 10 TeV $\mu^+\mu^-$ collider



Assuming theory errors improve as follows

Process	Current	Conservative	Aggressive
$H \rightarrow bb/cc$ (%)	< 0.4	0.2	0.1
$H \rightarrow \tau\tau/\mu\mu$ (%)	< 0.3	< 0.1	—
$H \rightarrow WW^*/ZZ^*$ (%)	0.5	0.3	—
$H \rightarrow gg$ (%)	3.2	1.0	0.5
$H \rightarrow \gamma\gamma$ (%)	< 1.0	< 1.0	0.4
$H \rightarrow Z\gamma$ (%)	1.5	1.5	—
$e^+e^- \rightarrow ZH$ (%)	0.3	< 0.1	—
$e^+e^- \rightarrow \nu\bar{\nu}H$ (%)	~ 1	~ 0.1	—



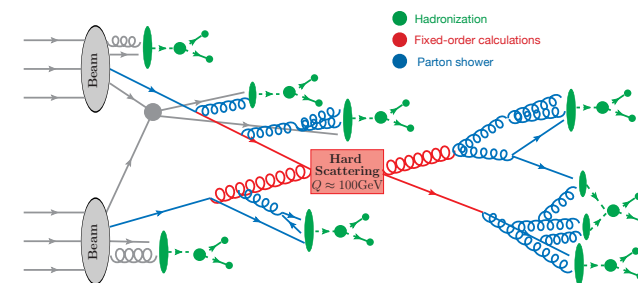
Message: the HL-LHC precision program should be our focus, and it is a complex task

Establishing theoretical uncertainties for percent-level phenomenology

The **future of precision physics** relies on the ability of theoretical predictions to **describe and interpret the complexity of LHC events** with accuracy comparable (or smaller) than the experimental systematics.

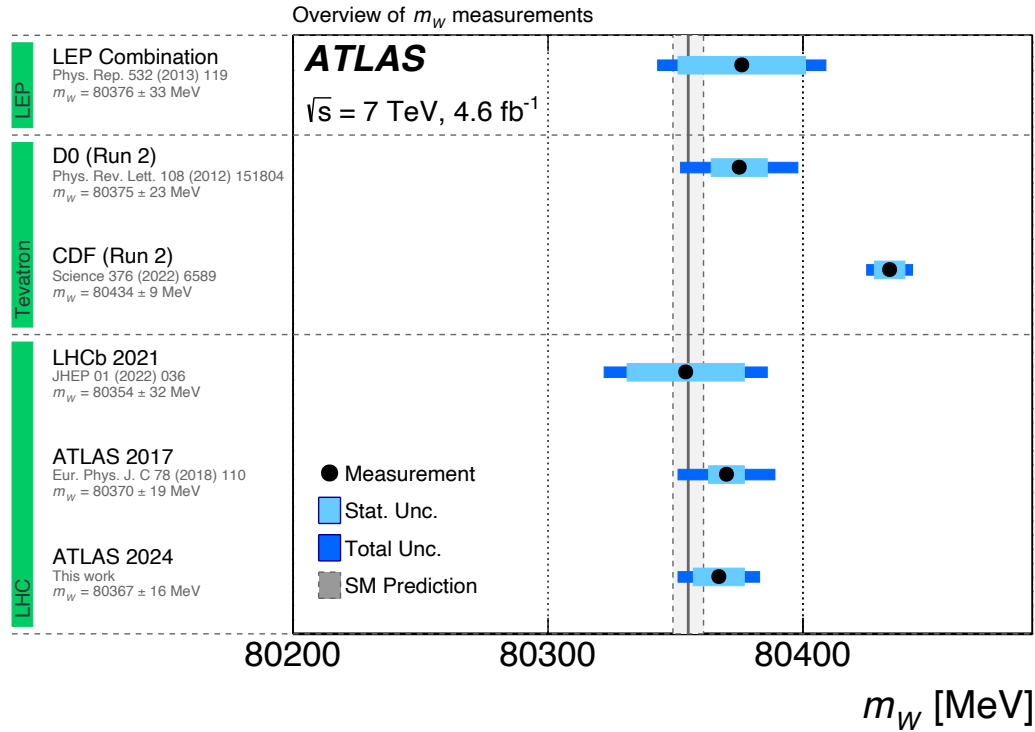
Embracing the complexity of modelling and interpreting collider events at percent-level is a multi-prong task

- **Push precision for standard candles** and **improve description of key processes**.
 - Higher-order perturbative QCD and EW corrections, at differential/fiducial level
 - Consider signatures, i.e. consider off-shell instead of on-shell production
 - Consistently match to PDF and Parton Shower event generators
 - Estimate non-perturbative effects
 - Remove approximations at all levels
- Use **cutting edge techniques** to study **signal/background properties** (AI/ML, ...)
- **Parametrize new physics effects** in terms of **more general effective interactions** (EFT) and explore as many BSM directions as possible. New physics can be anywhere and give origin to correlated effects.



To illustrate the point: a few recent examples from LHC precision phenomenology

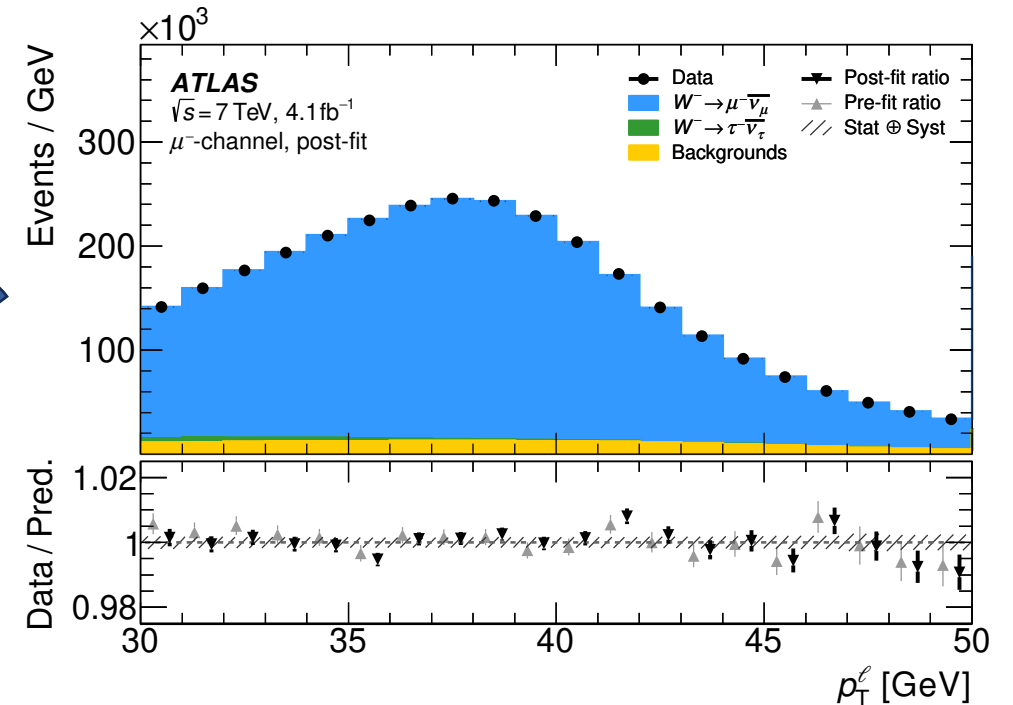
SM global fits: the M_W puzzle



ATLAS, 2403.15085

Mass measured by fitting template distributions of transverse momentum and mass

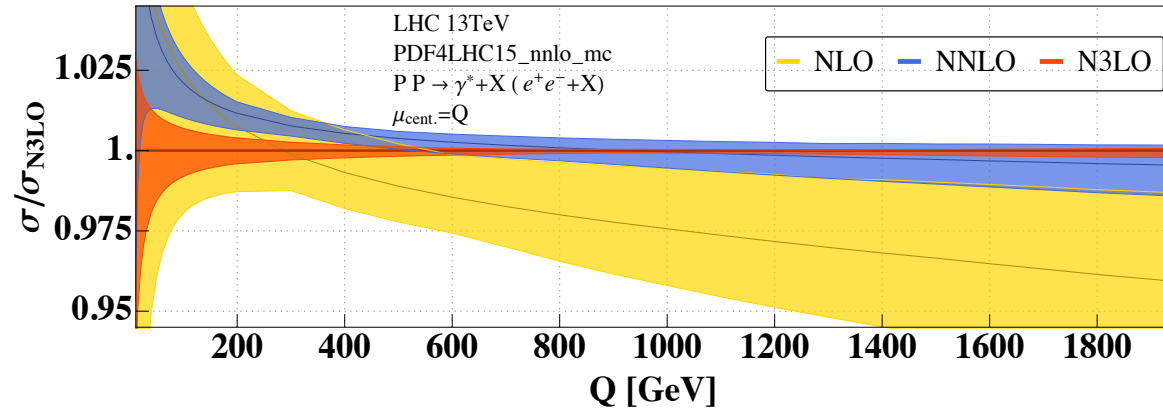
Template fitting is acceptable if theory describes data with high accuracy



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

DY at N³LO – input to PDF fits and M_W measurement

NC-DY

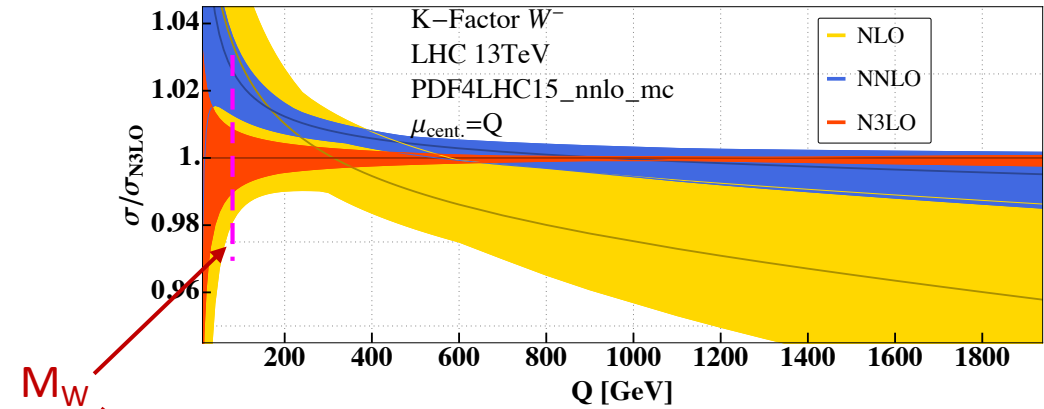


Duhr, Dulat, Mistlberger, 2001.07717

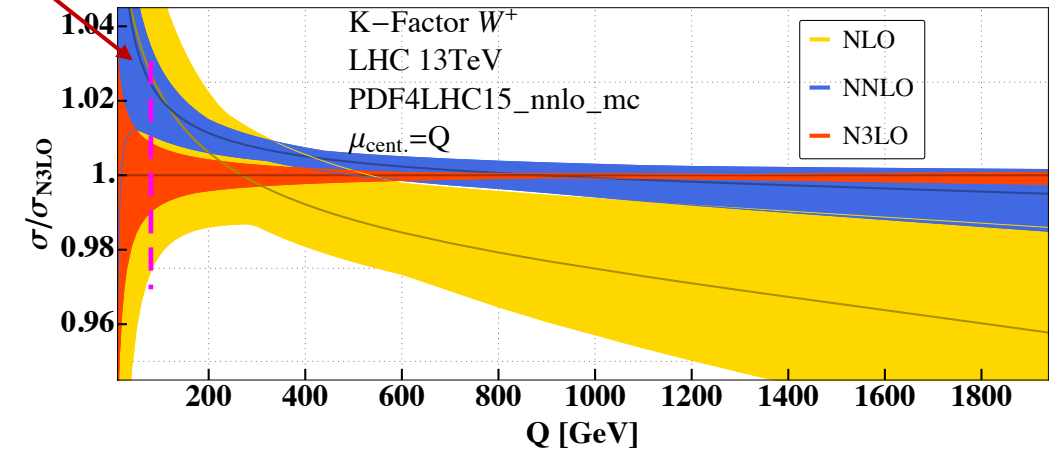
- Scale dependence: non-uniform behavior in all Q -regions
- Important input for PDFs (not yet included)
- **Region around $Q \sim M_W$: reconsider how to estimate theoretical uncertainty from scale variation**

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

CC-DY

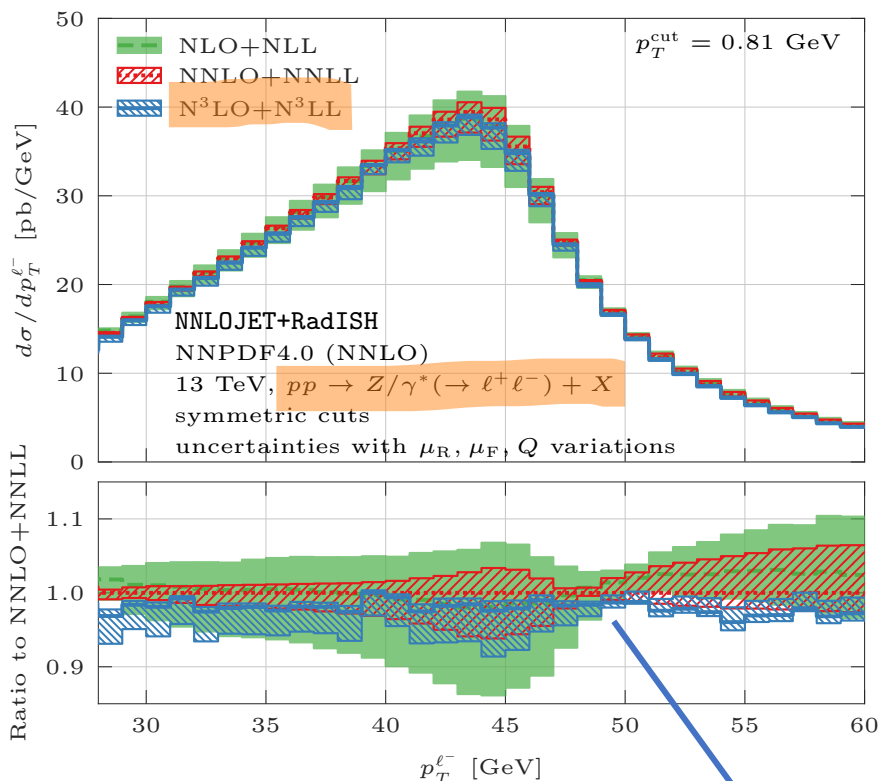


M_W



Duhr, Dulat, Mistlberger, 2007.13313

DY at N³LO+N³LL – differential



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

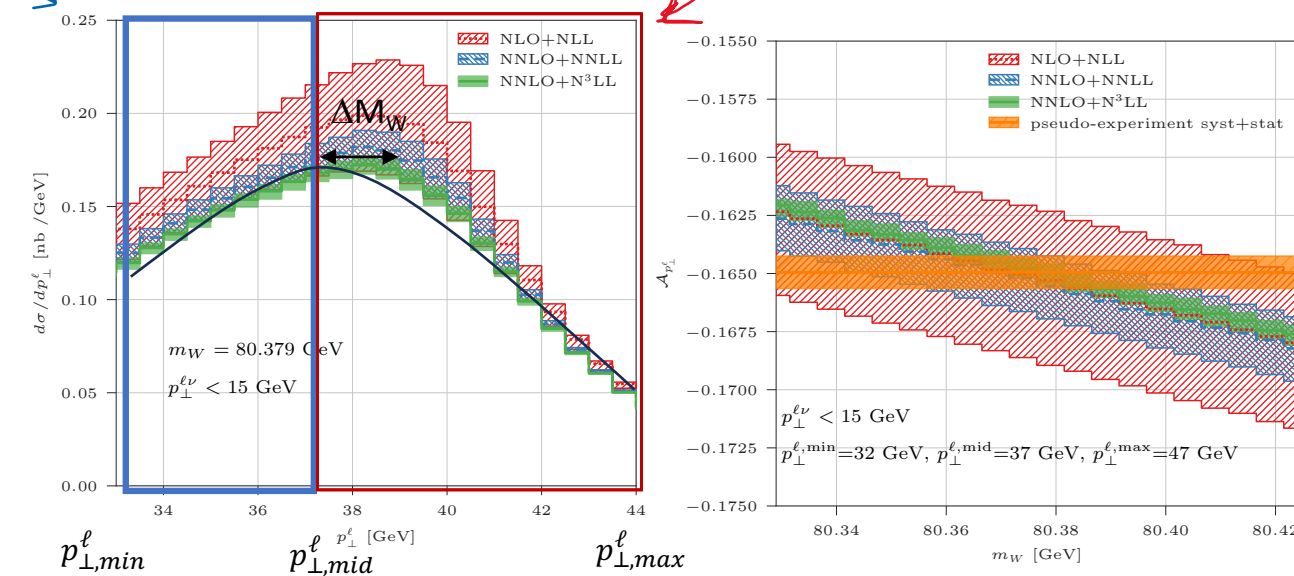
Challenging to control theoretical
uncertainties below percent level!

Consider different observable?

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

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

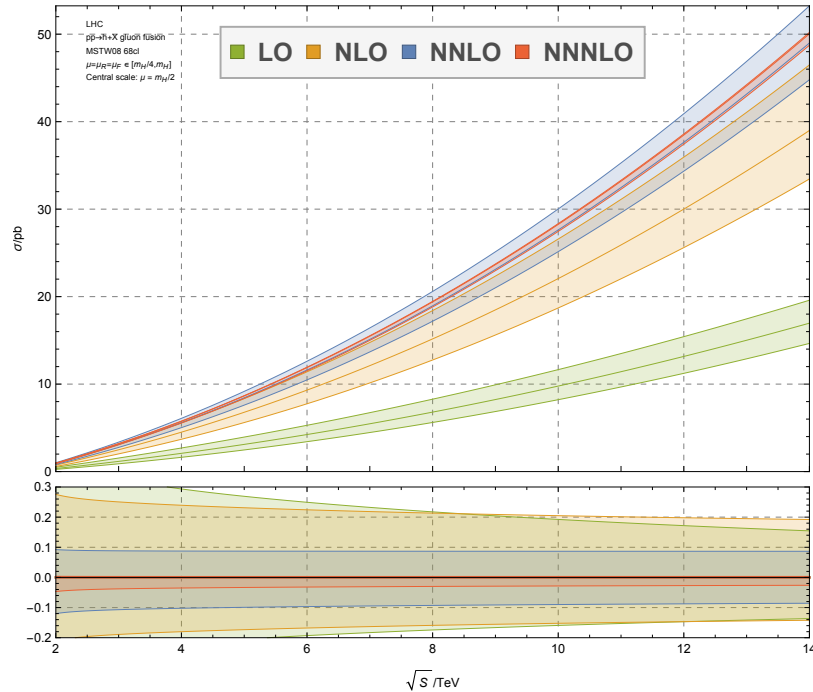
Shift in jacobian peak
by $\Delta M_W/2$



Rottoli, Torrielli, Vicini, 2301.04059

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

Higgs production via gg fusion at N³LO

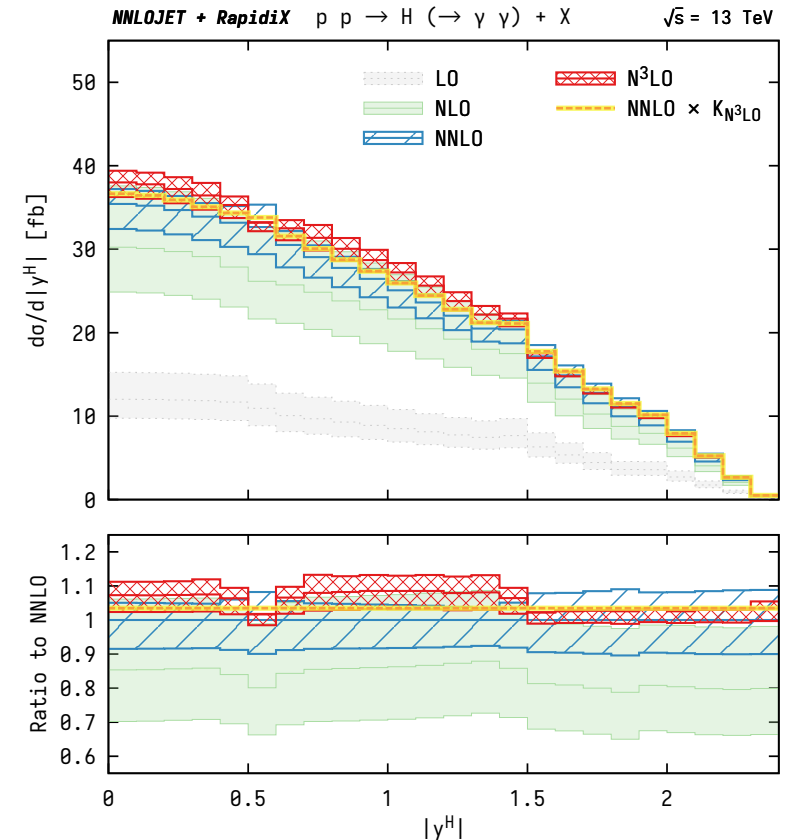
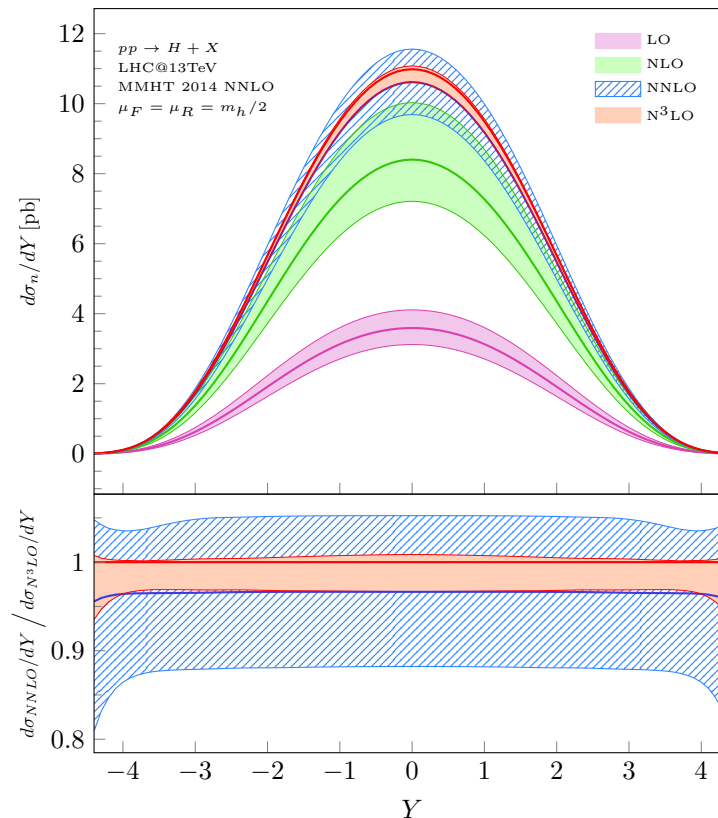


Anastasiou, Duhr, Dulat,
Herzog, Mistlberger
1503.06056

Dulat, Mistlberger, Pelloni
1810.09462

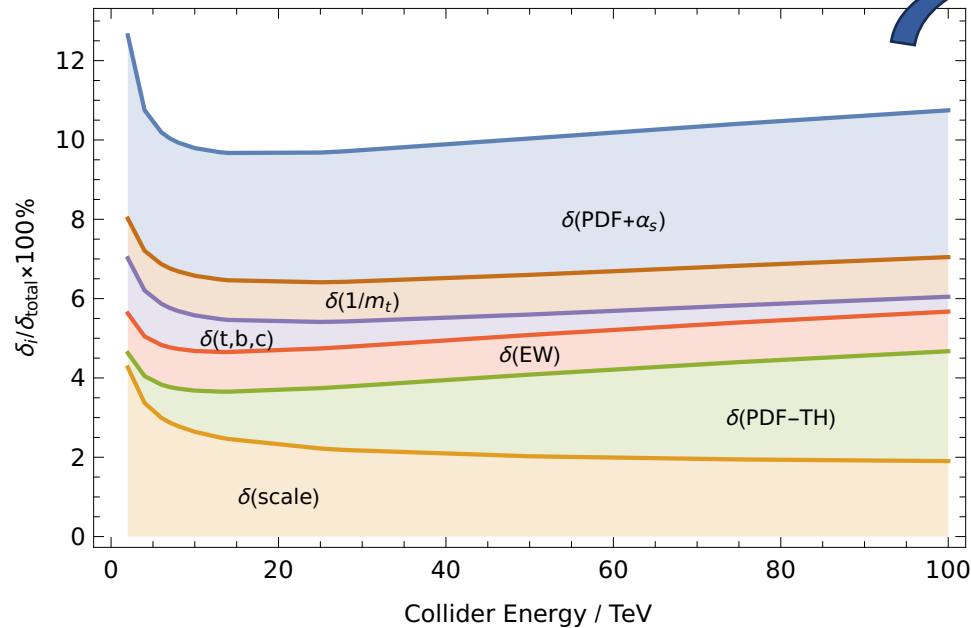
Continuous progress on a crucial process

- 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



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

NNLO for $2 \rightarrow 3$ processes at the core of the LHC program

- 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: $b\bar{b}W, t\bar{t}W, t\bar{t}H, \dots$

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

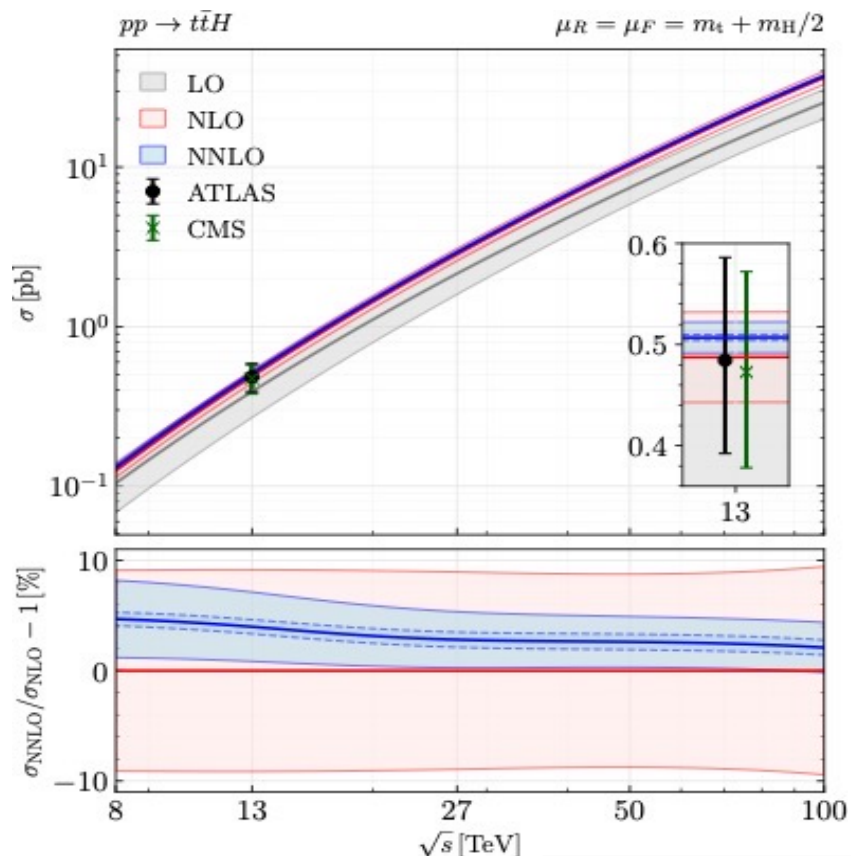
Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini, 2210.07846

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 (a)NNLO

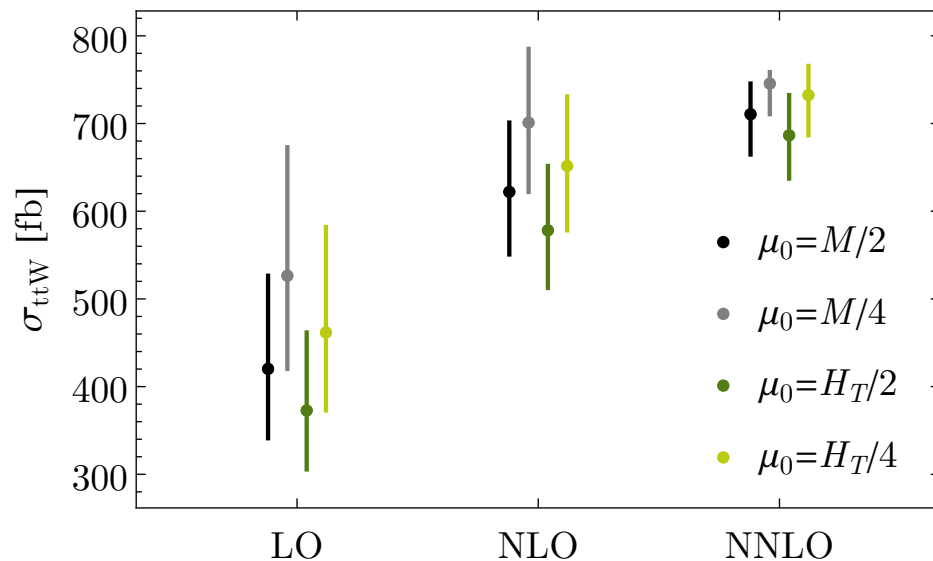


Catani et al., 2210.07846

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

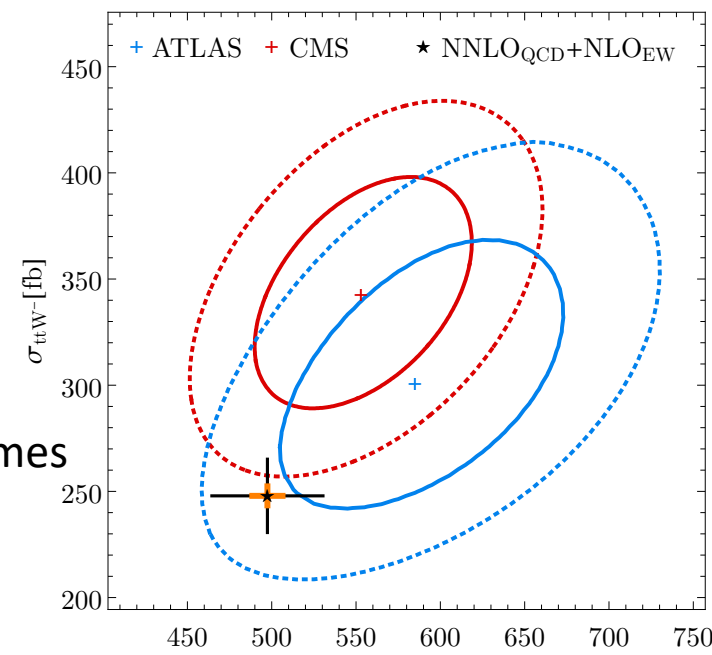
Buonocore et al., 2306.16311



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

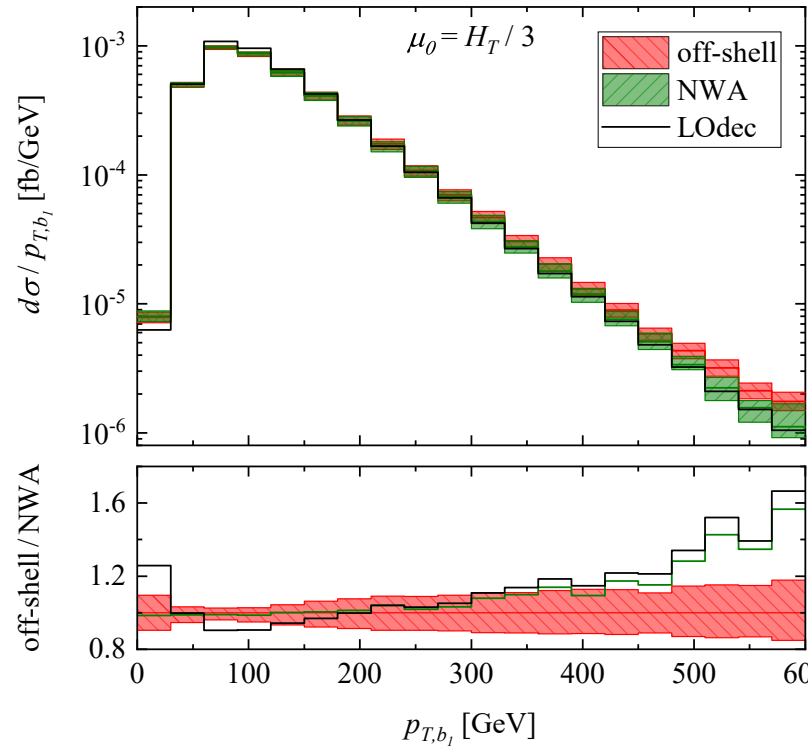
Ratio $\sigma_{t\bar{t}W^+}/\sigma_{t\bar{t}W^-}$ in very good agreement with ATLAS measurement

Comparison in fiducial volumes may give further insight



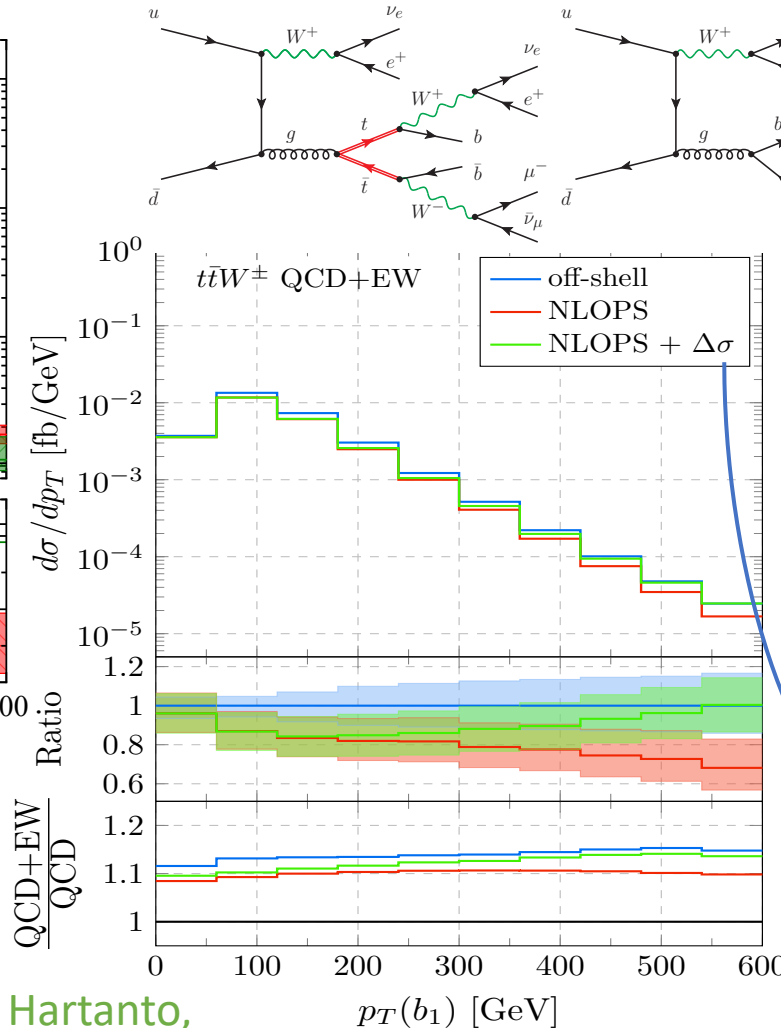
NLO: push the multiplicity challenge

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

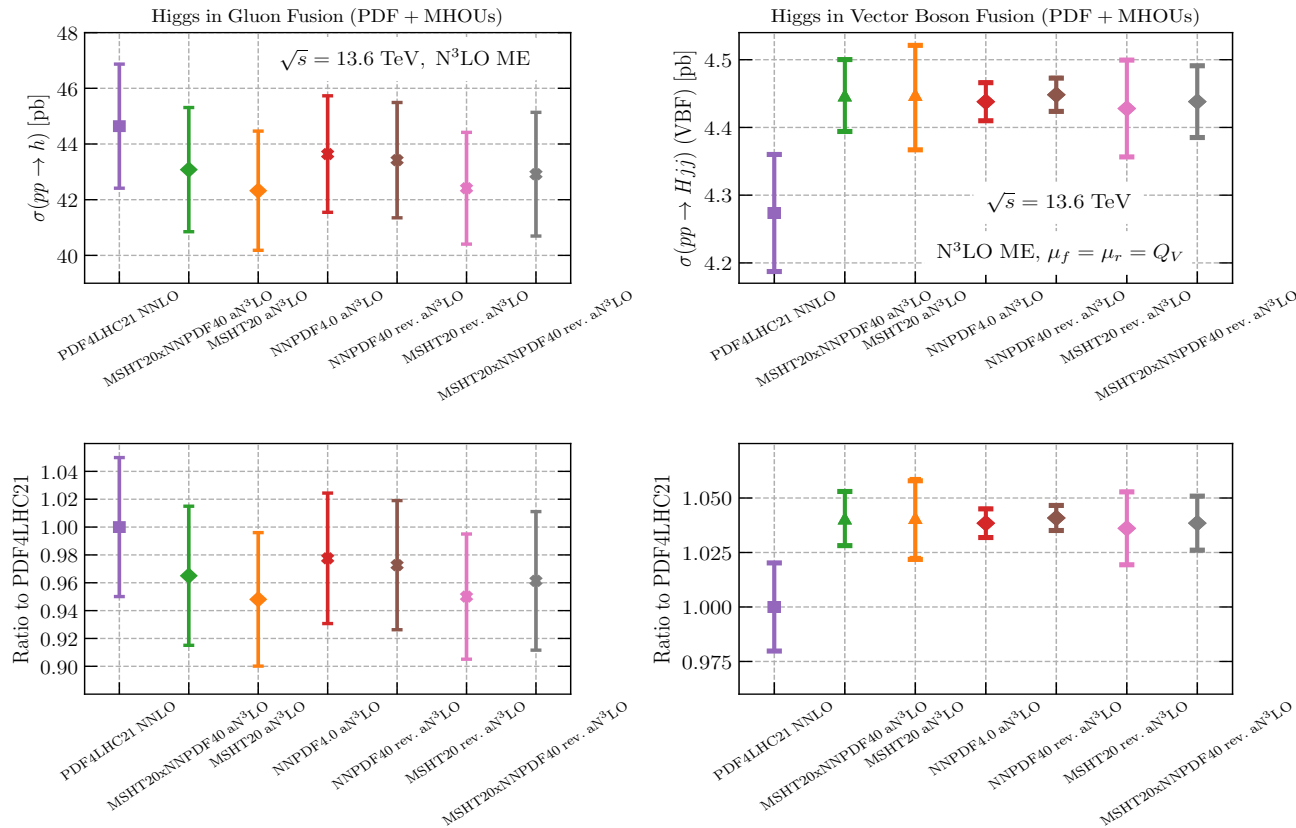
Off-shell effects most relevant in tails
and end-points of distributions, where
new physics effects can be hidden

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

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

Reducing $\delta(\text{PDF-TH})$: towards consistent matching with N³LO PDF

McGowan, Cridge, Harkland-Lang, Thorne, 2207.04739 (MSHT); NNPDF 2402.18635; MSHT+NNPDF 2411.05373



- Based on N³LO approximation to structure functions and DGLAP evolution

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

- 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

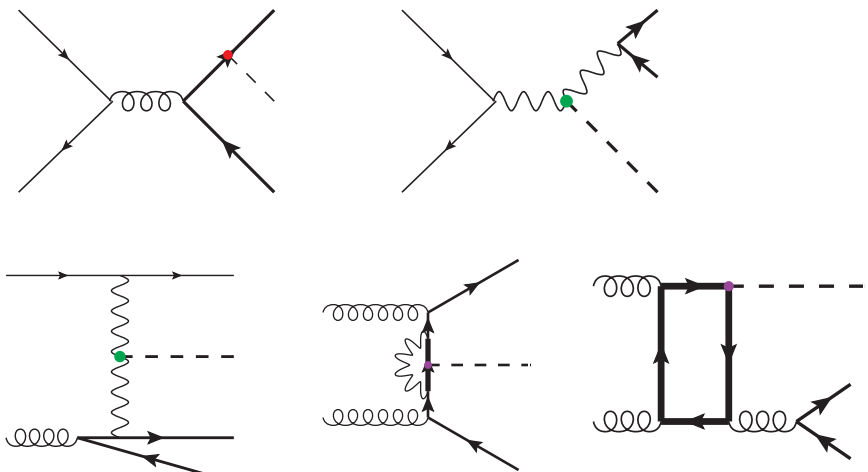
- **Gluon fusion to H**: the increase in the cross-section prediction at N³LO is compensated by the N³LO PDF, suggesting a cancellation between terms in the PDF and cross section theory at N³LO → **matching orders matters!**
- **Vector Boson Fusion**: no relevant change in going from N²LO to N³LO PDF,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

... 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]

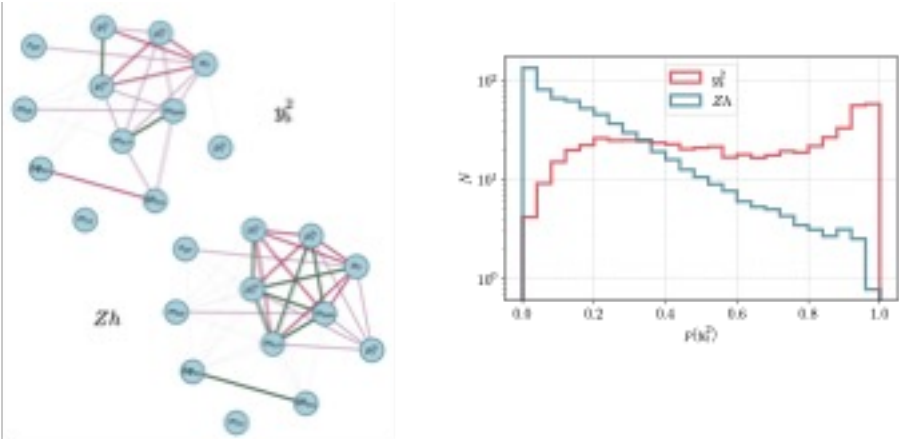
ratios	$\frac{\sigma(y_b^2)}{\sigma(y_b^2)+\sigma(\kappa_Z^2)} \equiv \frac{\sigma_{\text{NLO QCD+EW}}}{\sigma_{\text{NLO all}}}$ (y_b vs. κ_Z)	$\frac{\sigma(y_b^2)}{\sigma(y_b^2)+\sigma(y_t^2)+\sigma(y_b y_t)}$ (y_b vs. y_t)	$\frac{\sigma(y_b^2)}{\sigma(y_b^2)+\sigma(y_t^2)+\sigma(y_b y_t)+\sigma(\kappa_Z^2)}$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

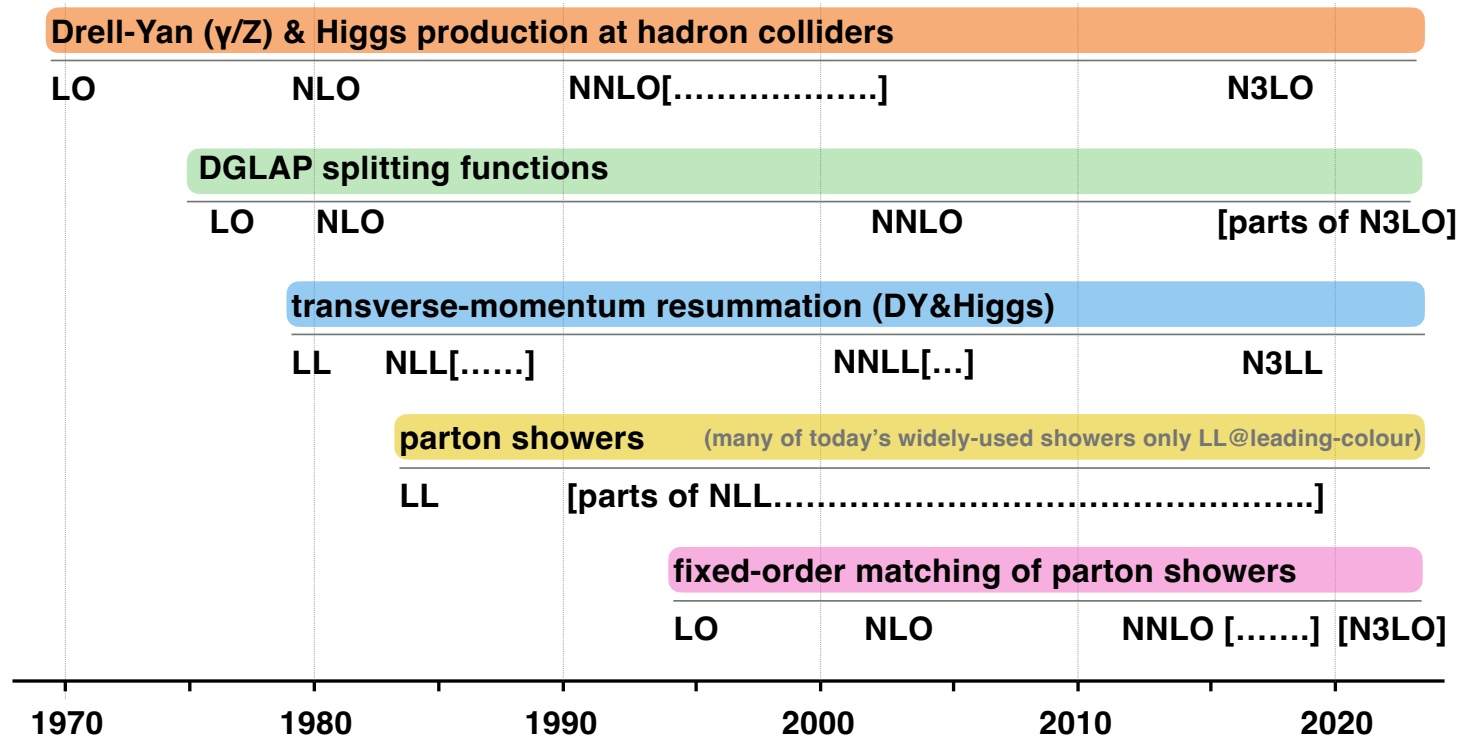


New techniques will open the possibility of turning problematic processes into powerful probes of the quantum structure of the SM

Parton-shower event generators

It's time for better Parton Showers!

Slide from G. Salam



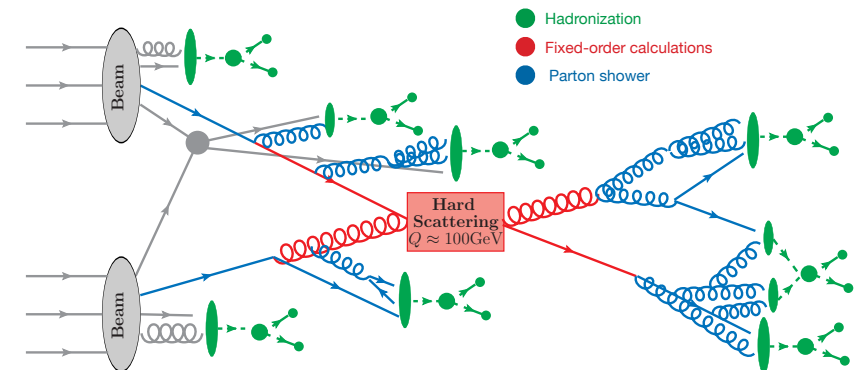
Crucial ingredient to reproduce the complexity of collider events

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.

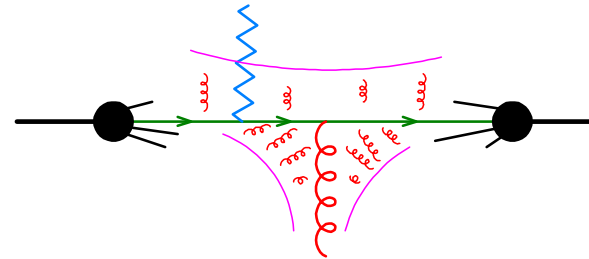
No general theory. Direct calculations have shown that there are no linear non-pert power corrections in:

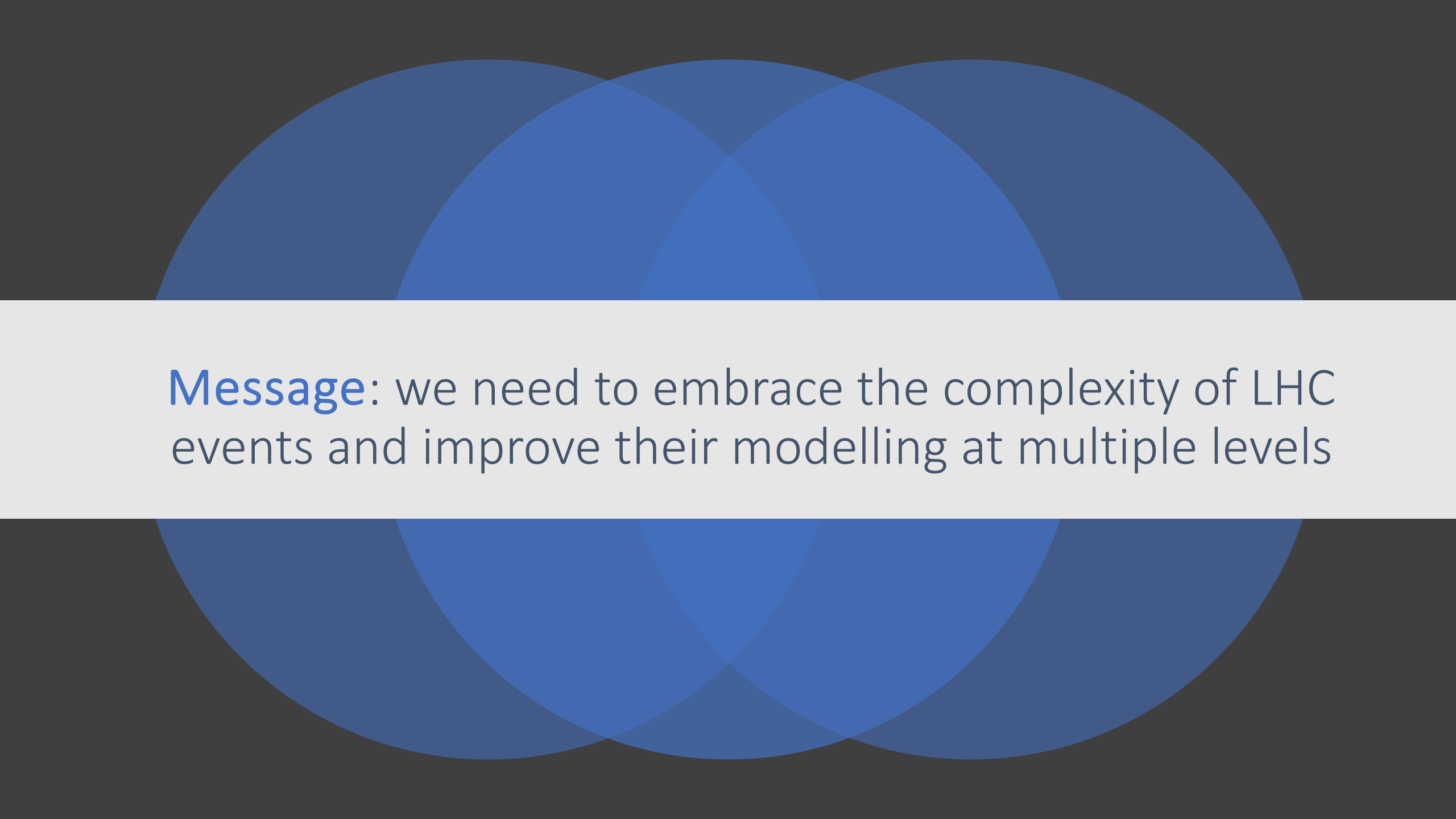
- Z transverse-momentum distributions

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





Message: we need to embrace the complexity of LHC events and improve their modelling at multiple levels

Beyond EW precision fits: global precision fits

Constraining new physics through a broad spectrum of collider and flavour observables

• EW precision observables

- Z-pole observables (LEP/SLD): Γ_Z , $\sin^2\theta_{\text{eff}}$, A_l , A_{FB} , ...
- W observables (LEP II, Tevatron, LHC): M_W , Γ_W
- m_t , M_H , $\sin^2\theta_{\text{eff}}$ (Tevatron/LHC)

Including recent LHC measurements of m_t and M_W

• Higgs boson observables

- Production and decay rates
- Simplified Template Cross Sections (STXS)

• Top quark observables

- $pp \rightarrow t\bar{t}, t\bar{t}Z, t\bar{t}W, t\bar{t}\gamma, tZq, t\gamma q, tW, \dots$

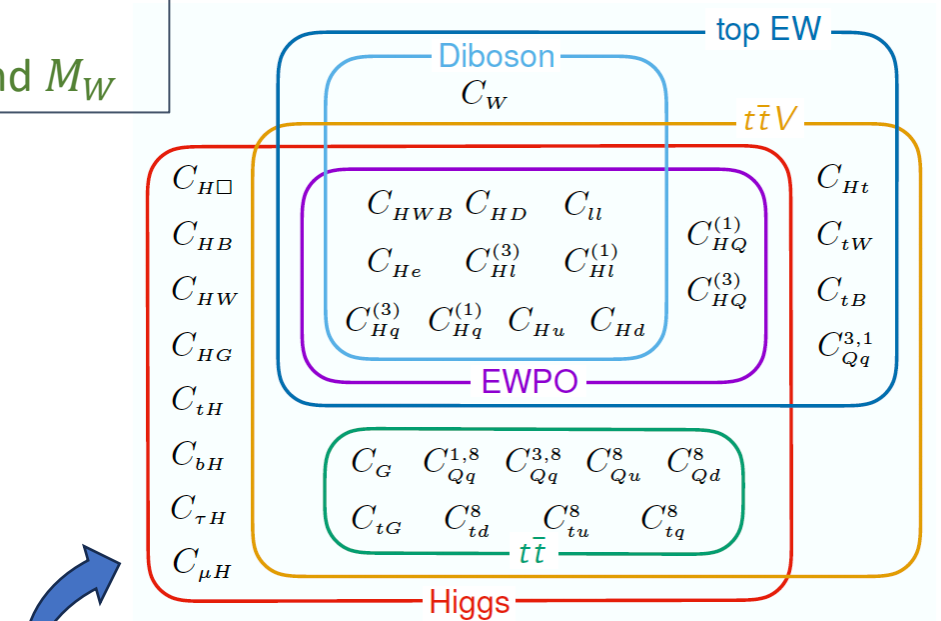
• Drell-Yan, Di-boson measurements

- $pp \rightarrow W, Z \rightarrow f_i f_j$
- $pp \rightarrow WZ, WW, ZZ, Z\gamma$

• Flavour observables

- $\Delta F=2$: $\Delta m_{B_{d,s}}$, $A_{sl}^{s,d}$, $D^0 - \bar{D}^0(\phi_{12}^M)$, ε_K
- Leptonic decays: $B_s \rightarrow \mu^+ \mu^-$, $B \rightarrow \tau \nu$, $K \rightarrow \ell \nu$, $\pi \rightarrow \ell \nu$
- Semi-leptonic decays: $B \rightarrow D^{(*)} \ell \nu$, $B \rightarrow \pi \ell \nu$, $K \rightarrow \pi \ell \nu$
- Radiative B decays: $B \rightarrow X_{s,d} \gamma$

ATLAS and CMS Run 1+2 results

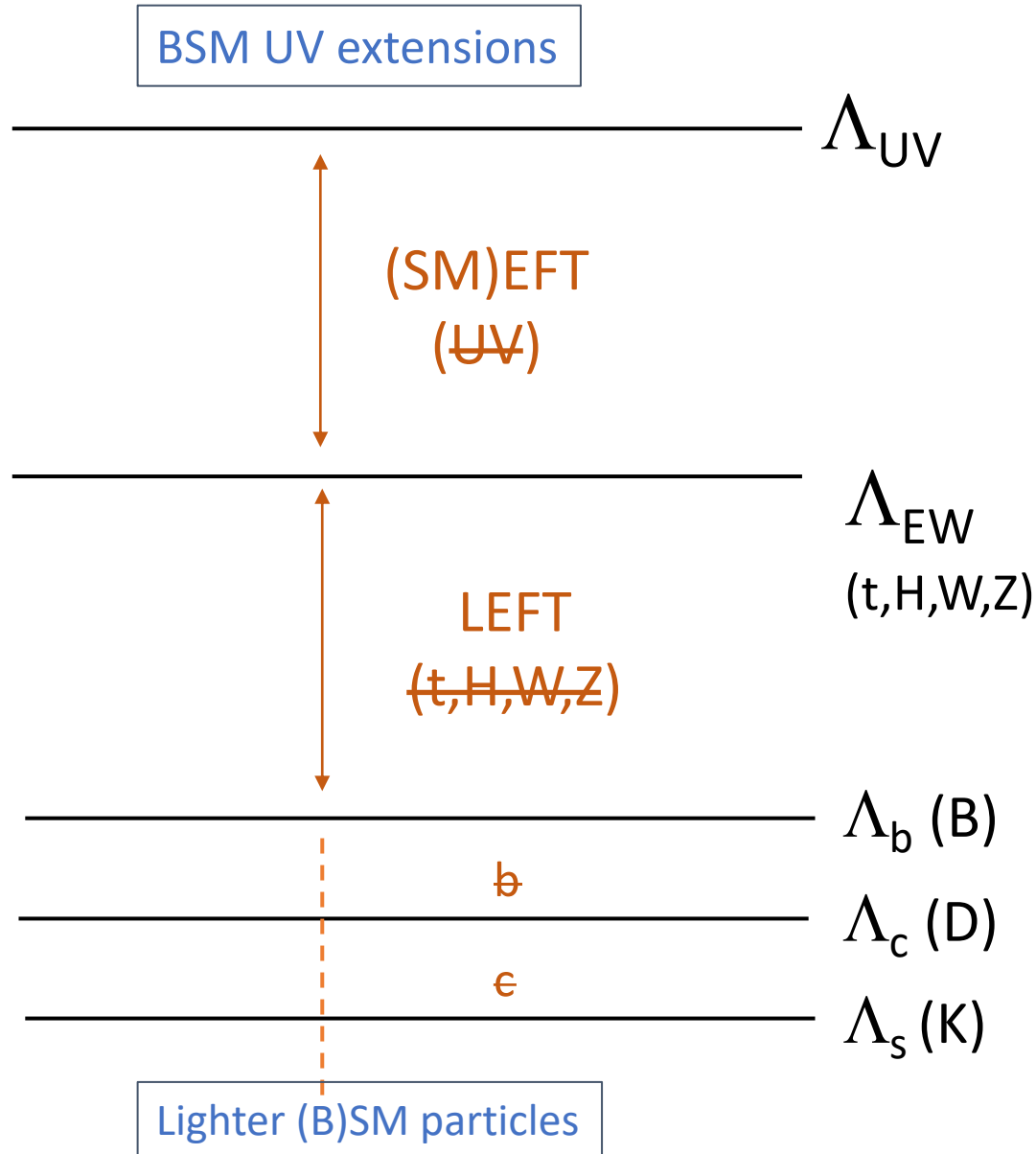


Flavor involves almost all of them either directly or through RGE

Exp: PDG, HFLAV

Th: best available predictions

Connecting far apart scales: the EFT picture



Heavy physics decouples and leaves effective contact interactions of $\dim > 4$



RGE

EFT operators in terms of SM fields

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{i,d} \frac{C_{i,d}^{SMEFT}}{\Lambda^{d-4}} O_{i,d}^{SMEFT}$$



RGE

WC depend on $m_t, M_W, M_Z, M_H, \dots M_X$

$$\mathcal{L}_{LEFT} = \mathcal{L}_{QED+QCD} + \sum_{i,d} \frac{C_{i,d}^{LEFT}}{\Lambda_{EW}^{d-4}} O_{i,d}^{LEFT}$$

Calculate physical processes at each scale and derive constraints on the UV theory

The HEPfit framework

Open-source tool

Statistical framework based on a Bayesian MCMC analysis as implemented in

BAT (Bayesian Analysis Toolkit)

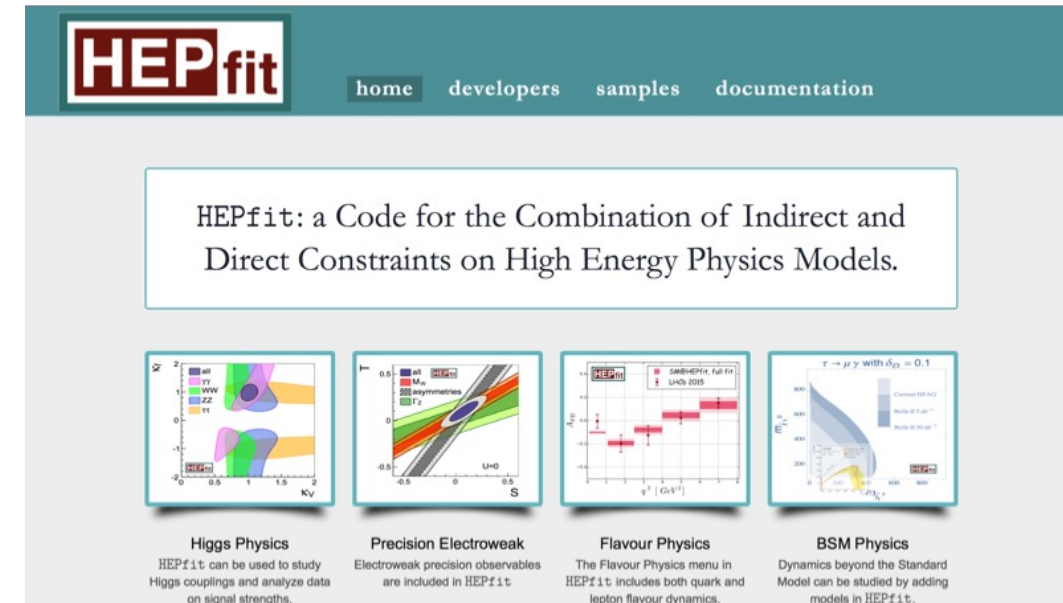
Caldwell et al., arXiv:0808.2552

Supports SM (fully implemented) and BSM models, in particular the dim-6 SMEFT

Used for several global fits and future collider projections

New release includes EW, Higgs, top, and flavour observables in the SM and the SMEFT with

- ☐ SM predictions at NLO or higher
- ☐ SMEFT at tree level (dim-6 operators only)
- ☐ Linear (and quadratic) effects from dim-6 operators
- ☐ RGE running of the SMEFT Wilson Coefficients



<http://hepfit.roma1.infn.it>

J. De Blas et al., 1910.14012

Other existing frameworks for SMEFT global fits:

SMEFiT, Celada et al. 2105.00006, 2302.06660, 2404.12809

Fitmaker, Ellis et al. 2012.02779

Aebischer et al., 1810.07698

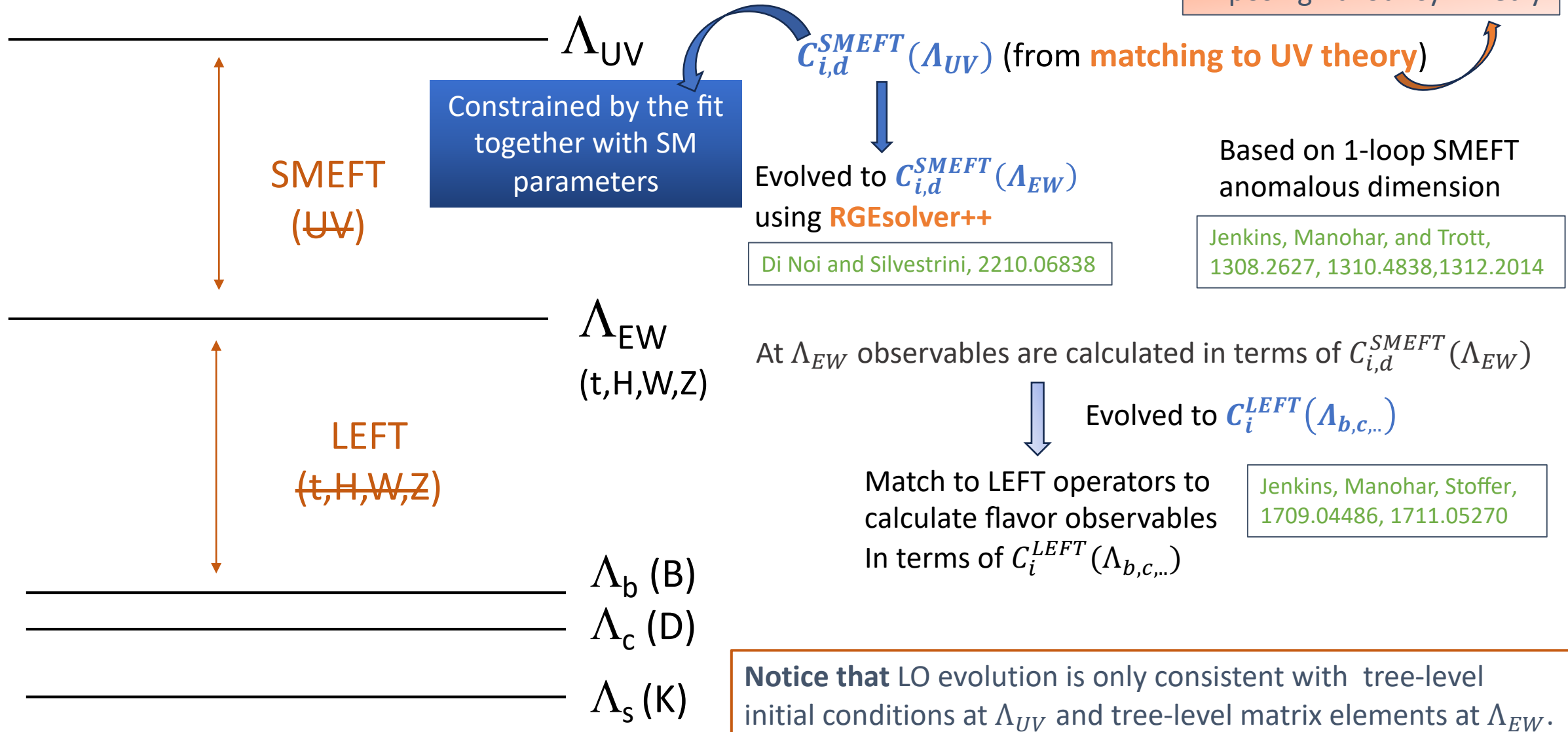
Allwicher et al, 2311.00020

Cirigliano et al. 2311.00021

Bartocci et al. 2311.04963

Beyond EW fits – Higgs, top, flavour observables

Connecting far apart scales naturally lends itself to the EFT framework



The SMEFT framework for this study

Higgs field and Mh

Yukawa couplings

Vff, Hff

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{C_i}{\Lambda^2} Q_i + \dots$$

Grzadkowski, Iskrzynski,
Misiak, Rosiek, 1008.4884

“Warsaw” basis

$$\begin{aligned} \mathcal{L}_{SM}^{(4)} = & -\frac{1}{4}G_{\mu\nu}^A G^{A,\mu\nu} - \frac{1}{4}W_{\mu\nu}^I W^{I,\mu\nu} - \frac{1}{4}B_{\mu\nu} B^{\mu\nu} \\ & + (D_\mu \varphi)^\dagger (D^\mu \varphi) + m^2 \varphi^\dagger \varphi - \frac{1}{2} \lambda (\varphi^\dagger \varphi)^2 \\ & + i (\bar{l}'_L \not{D} l'_L + \bar{e}'_R \not{D} e'_R + \bar{q}'_L \not{D} q'_L + \bar{d}'_R \not{D} d'_R) \\ & - (\bar{l}'_L \Gamma_e e'_R \varphi + \bar{q}'_L \Gamma_u u'_R \tilde{\varphi} + \bar{q}'_L \Gamma_d d'_R \varphi) + h.c. \end{aligned}$$

with covariant derivative:

$$D_\mu = \partial_\mu + ig_s G_\mu^A \mathcal{T}^A + ig_W W_\mu^I T^I + ig_1 B_\mu Y$$

gauge fields
and masses,
HVV, VVV

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
$\mathcal{O}_G$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$\mathcal{O}_\varphi$	$(\varphi^\dagger \varphi)^3$	$\mathcal{O}_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p \varphi e_r)$
$\mathcal{O}_W$	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$\mathcal{O}_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p \tilde{\varphi} u_r)$
		$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$\mathcal{O}_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p \varphi d_r)$
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$\mathcal{O}_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$\mathcal{O}_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$\mathcal{O}_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$\mathcal{O}_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$\mathcal{O}_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$\mathcal{O}_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$\mathcal{O}_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$\mathcal{O}_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
		$\mathcal{O}_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$\mathcal{O}_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
		$\mathcal{O}_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$\mathcal{O}_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
		$\mathcal{O}_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$\mathcal{O}_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
		$\mathcal{O}_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$\mathcal{O}_{\varphi ud}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

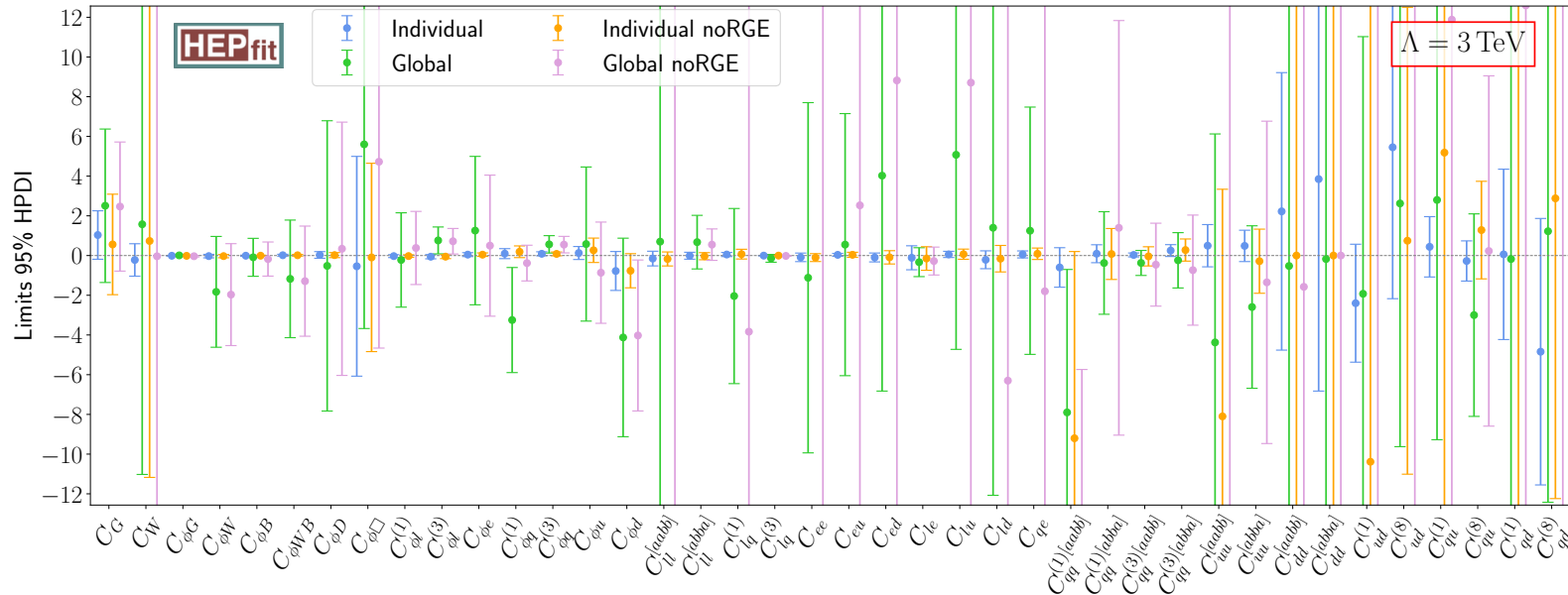
$(\bar{L}R)(\bar{L}R)$	$(\bar{L}R)(\bar{R}L)$
$\mathcal{O}_{quqd}^{(1)[prst]} = (\bar{q}_p^i u_r) \epsilon_{ij} (\bar{q}_s^j d_t)$	$\mathcal{O}_{ledq}^{[prst]} = (\bar{l}_p^i e_r) (\bar{d}_s q_{ti})$
$\mathcal{O}_{quqd}^{(8)[prst]} = (\bar{q}_p^i T^A u_r) \epsilon_{ij} (\bar{q}_s^j T^A d_t)$	
$\mathcal{O}_{lequ}^{(1)[prst]} = (\bar{l}_p^i e_r) \epsilon_{ij} (\bar{q}_s^j u_t)$	
$\mathcal{O}_{lequ}^{(3)[prst]} = (\bar{l}_p^i \sigma_{\mu\nu} e_r) \epsilon_{ij} (\bar{q}_s^j \sigma^{\mu\nu} u_t)$	

4-fermion interactions: tt, ttH, DY, flavour

- Dim-6 operators only, including linear (and quadratic effects)
- Obeying SM gauge symmetry
- One Higgs doublet of $SU(2)_L$, SSB linearly realized.
- Assuming different flavor symmetries: $U(3)^5$, $U(2)^5$...; no CPV

- Lower half:** uncertainty on C_i/Λ reported as half of the 95% HPDI (high posterior density interval)
- Upper half:** lower bound on $\Lambda/\sqrt{|C_i|}$ from the maximum of the 95% HPDI of $|C_i|$
(since no interval is driven away from zero at 95% probability, we can only put a lower bound)
- Dashed lines:** perturbativity bounds ($|C_i| \sim 4\pi$)
- Red shades:** posteriors touches the edges of the prior (truncated) $\rightarrow$ need better measurements
- White shades:** posterior completely flat $\rightarrow$ need more observables

$U(3)^5$ case: individual vs global fit

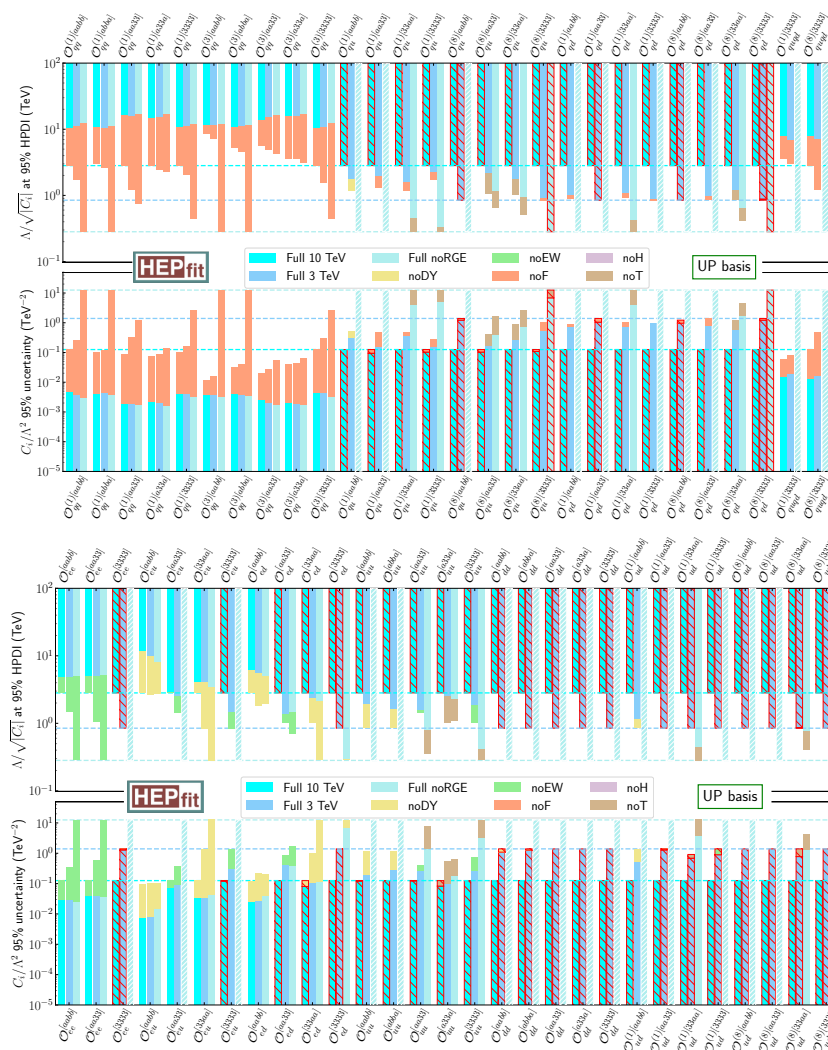
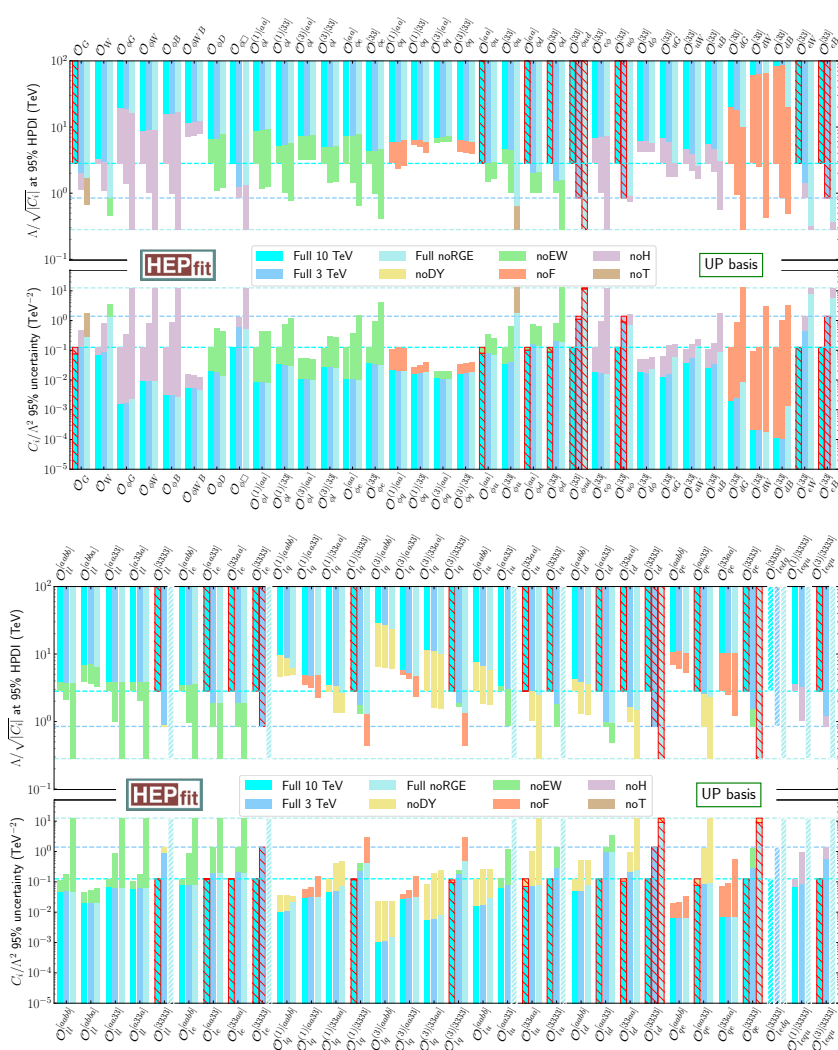


This is already relevant input to model building!

- In general (both individual and global): **adding more observables lift degeneracies but leaves strong correlations**
- Although bounds get diluted in the global fit, both with and without RGE, some cases still very well constrained, giving strong lower bounds:
- Global fits, if really global, are numerically massive. Adding all existing measurements may prevent the fit from converging or take a lot of educated choices: fine balance between higher information and better convergence.

UV theory flavor symmetry: $U(2)^5$, testing third family

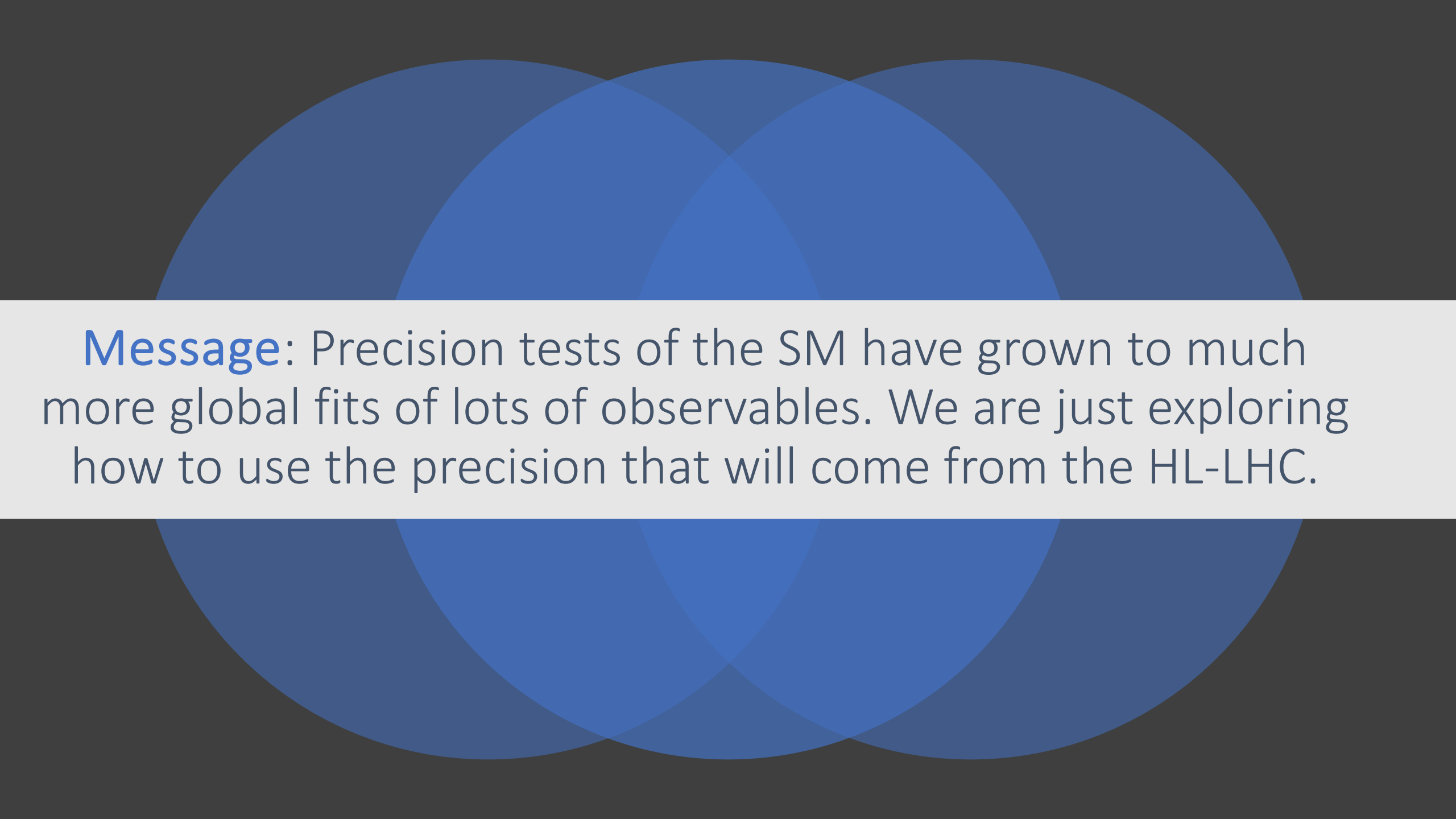
The impact of a non flavour-blind choice. More scenarios can be explored.



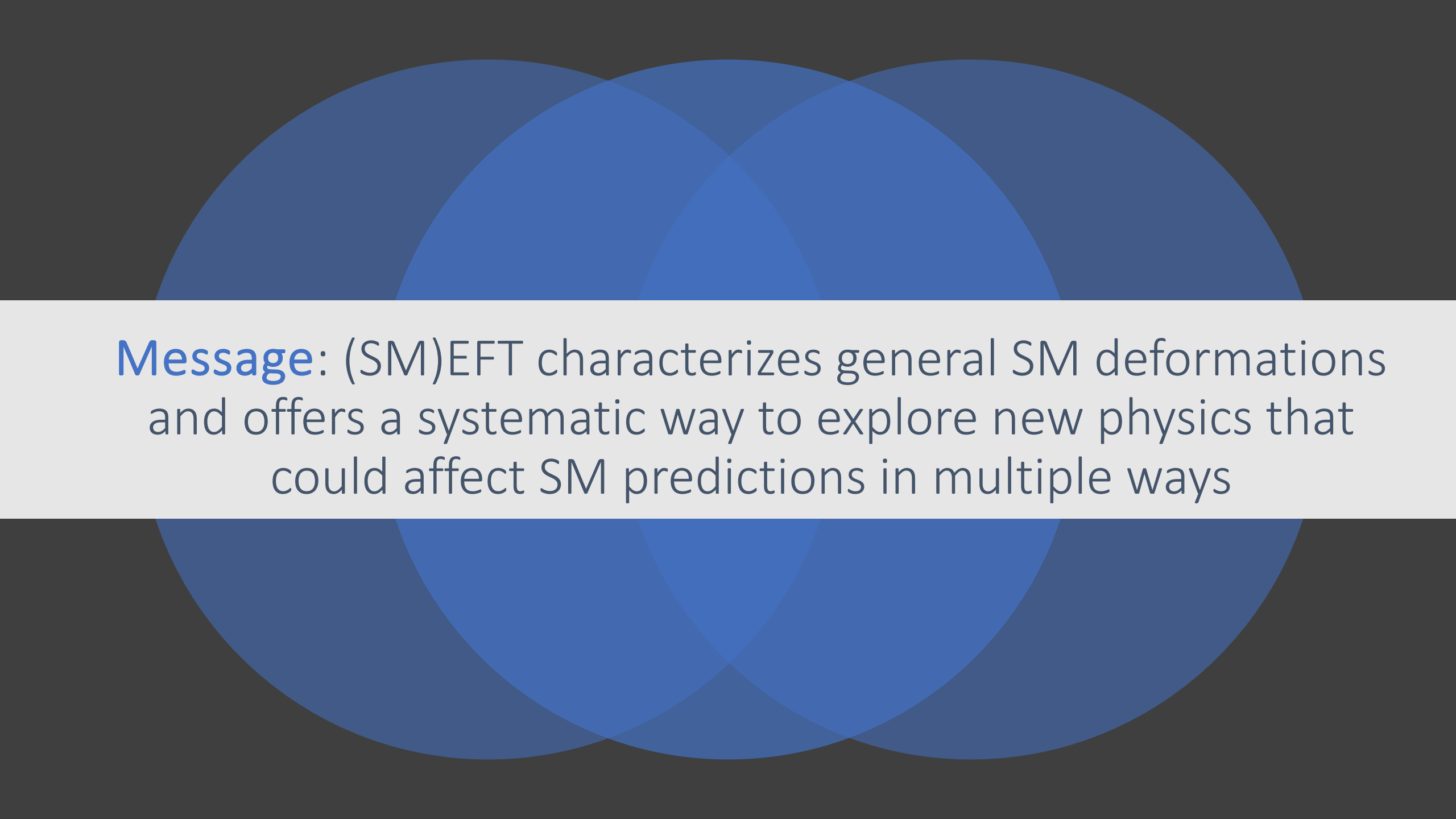
124 operators (123 if not considering $O_\phi = (\phi^\dagger \phi)^3$)

Main flavour constraints coming from:

- $B \rightarrow X_s \gamma$ (O_{dG}, O_{dW}, O_{dB})
- $B_s \rightarrow \mu^+ \mu^-$ (O_{qe}^{ijklk})
- meson mixing ($O_{qq}^{(1,3)}$)



Message: Precision tests of the SM have grown to much more global fits of lots of observables. We are just exploring how to use the precision that will come from the HL-LHC.



Message: (SM)EFT characterizes general SM deformations and offers a systematic way to explore new physics that could affect SM predictions in multiple ways

Summary and discussion

- **Collider physics** remains as a **unique and necessary test of any BSM hypotheses**, and in this context **precision phenomenology** will play a crucial role at future colliders.
 - The most important **first goal** is to **enable the physics program of the HL-LHC**
- **Increasing the theoretical accuracy on SM observables** (Higgs, top, EW, flavour) by one order of magnitude **can be crucial**
- Reaching this level of **theoretical accuracy has multiple components**, all of which have been the focus of intense theoretical work and should continue to be.
- The amount of precision observables now available gives us the possibility **for the first time** to **explore new physics via global precision fits**.
- Using an **EFT approach** seems a **natural option** (given the different scales involved) **and will become more constraining of BSM physics** with more data and higher precision.
 - Initially **bottom-up** → **Exploration**
 - Eventually **top-down** → **Precision**