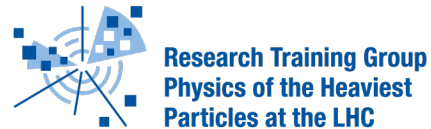


Global fits of the SM and beyond

Constraining new physics via global fits of the
Standard Model (SM) and the SM Effective Field Theory (SMEFT)



Laura Reina
(Florida State University)



RTG Colloquium, May 28, 2024

Global fits of precision measurements

- The **symmetry structure** of the Standard Model defines **specific relations among couplings and masses**.
- The **renormalizability** of the theory assures that tree-level relations are modified by **finite calculable corrections**.
- **Precision measurements** of masses and couplings via multiple observables:
 - Test the consistency of the theory at the quantum level
 - Indirectly probe new physics via virtual effects

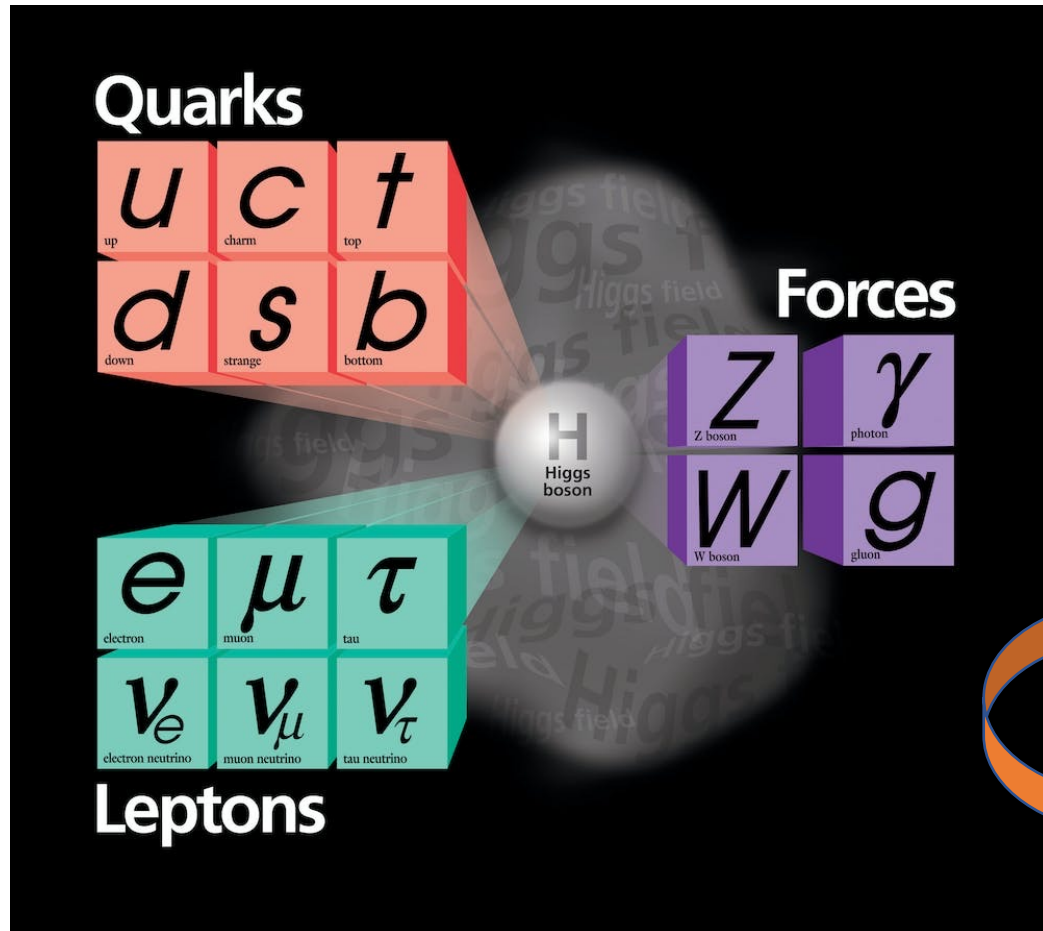
A comprehensive program of precision physics (EW, top, Higgs, flavor, ...) can be a very powerful tool to explore physics beyond the Standard Model

The Standard Model at a glance

A minimal theory of elementary particles with high predictivity.

A very successful history of precision physics leading to predictions confirmed by discoveries and now pointing to the model's intrinsic limitations.

The Standard Model of particle physics



A very minimal quantum field theory describing strong, weak, and electromagnetic interactions, based on a local (gauge) symmetry

$$SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_C \times U(1)_Q$$

Strong interactions: gluons $\rightarrow m_g = 0$

Electromagnetic interactions: photon $\rightarrow m_\gamma = 0$

Weak interactions: $W^\pm$ and $Z \rightarrow M_W, M_Z \neq 0$

Due to the presence of a scalar field whose potential spontaneously breaks the gauge symmetry of electroweak interactions and gives origin to massive gauge bosons (W,Z)

The Higgs boson (H) is the physical particle associated with such field

SM: a very constrained pattern

$$\mathcal{L}_{SM} = \mathcal{L}_{QCD} + \mathcal{L}_{EW}$$

$\{g_s\}$

$\{g_1, g_2, \mu, \lambda\} + \{y_f, V_{CKM}\}$

$$\mathcal{L}_{EW} = \mathcal{L}_{EW}^{gauge} + \mathcal{L}_{EW}^{ferm} + \mathcal{L}_{EW}^{Yukawa} + \mathcal{L}_{EW}^{scalar}$$

$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$

$$\langle \phi \rangle = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \xrightarrow{\text{SSB}} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ H + v \end{pmatrix}$$

$(\mu^2 < 0)$

$v = (-\mu^2 / \lambda)^{1/2}$

Higgs interactions

particle masses

$\mathcal{L}_{EW}^{gauge}$

W^+, W^-, Z

$\mathcal{L}_{EW}^{ferm}$

e, ν_e

$\mathcal{L}_{EW}^{Yukawa}$

$-i \frac{m_f}{v} = i y_f$

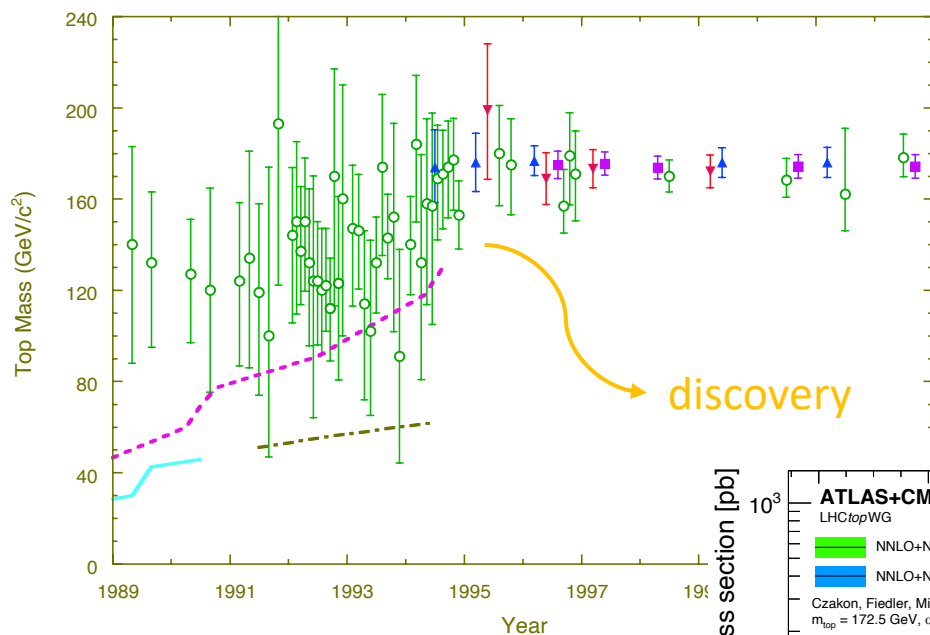
$\mathcal{L}_{EW}^{scalar}$

$-2i \frac{M_V^2}{v} g^{\mu\nu}$
 $-3i \frac{M_H^2}{v} = -6i v \lambda$
 $-3i \frac{M_H^2}{v^2} = -6i \lambda$

SM: unique pattern of Higgs couplings and particle masses

Top

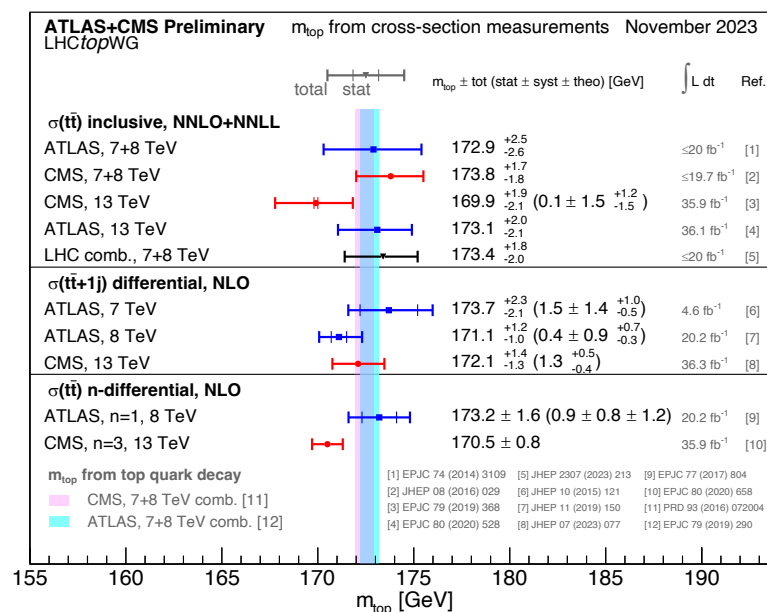
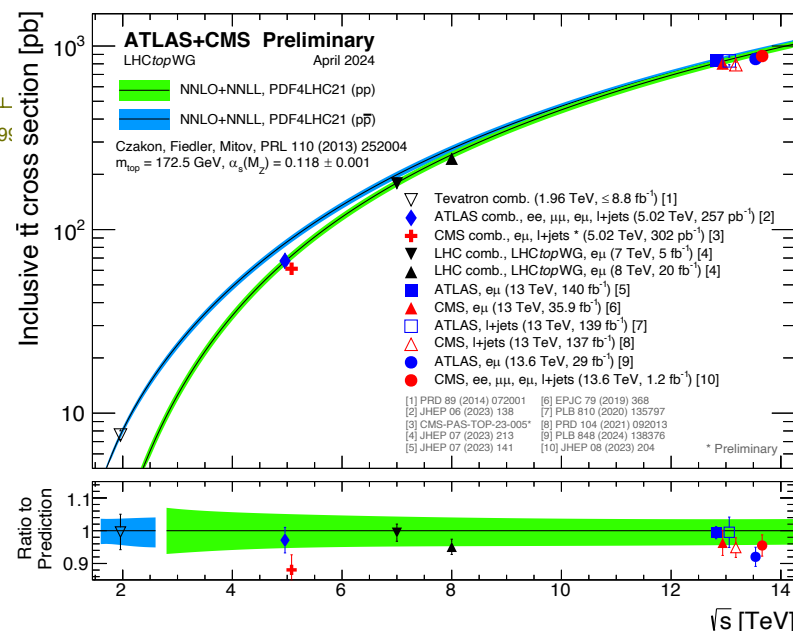
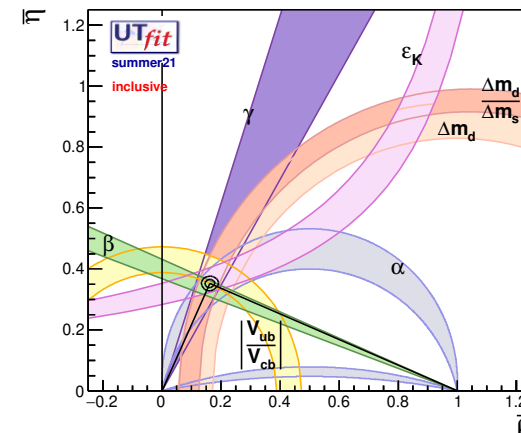
From prediction to discovery to precision



C. Quigg [hep-ph/0404228]

M_t becomes a crucial input in precision fits of the SM (including flavor)

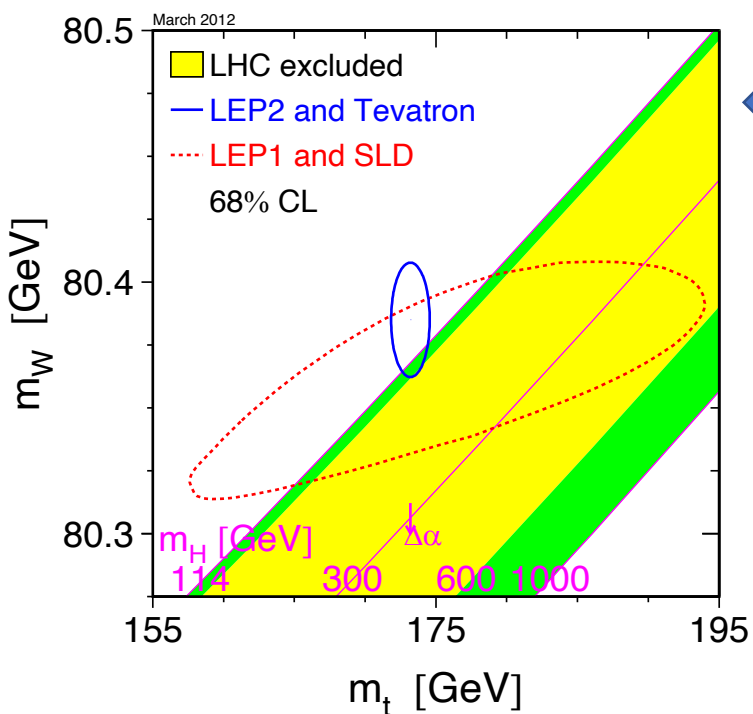
green dots $\longrightarrow$ indirect fits
 blue triangles $\longrightarrow$ CDF
 red triangles $\longrightarrow$ D0
 purple squares $\longrightarrow$ world average
 lines $\longrightarrow$ various lower bounds



Anomalies in Top-quark EW couplings (W,Z,H) possible hint of BSM physics

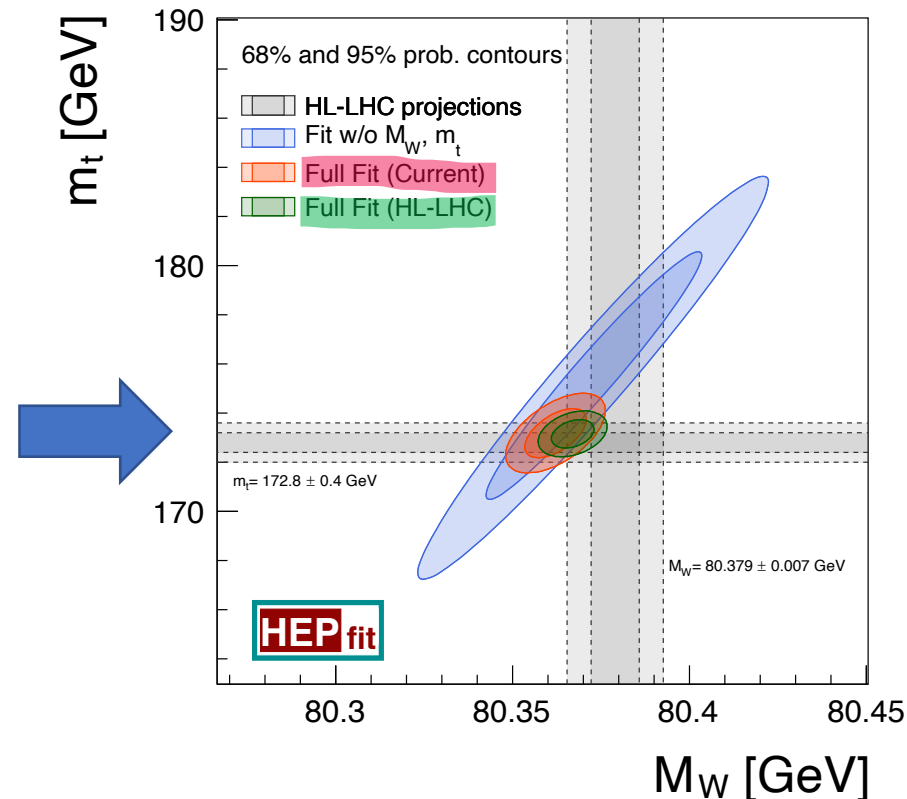
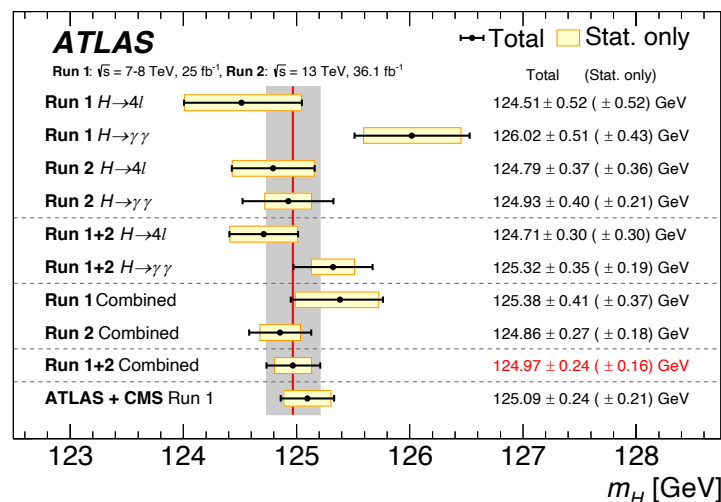
From prediction to discovery to precision

Global fits of precision EW observables gave us strong indications of where to find the SM Higgs boson and we now use its mass as one of the EW precision observables of the EW global fit to constrain new physics.



$$M_H = 94^{+29}_{-24} \text{ GeV}$$

$$M_H < 152 (171) \text{ GeV}$$



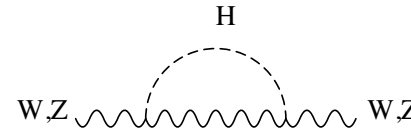
The big open questions

The SM weaknesses are its strength: less satisfactory aspects that we should investigate

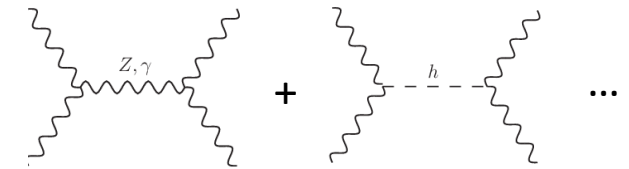
The scalar sector of the SM is still very mysterious

The Higgs is necessary to the consistency of the SM as a quantum theory, W and Z have longitudinal components that can be problematic without a Higgs:

➤ Loop corrections are not finite without a Higgs



➤ Scattering amplitudes grows with energy: unitarity violation



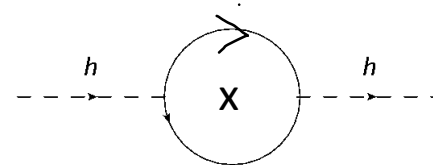
But the origin of SSB and ultimately of the EW scale is unexplained by the SM

➤ Why the Higgs potential? Why $\mu^2 < 0$?

➤ Dynamical origin? What induces it?

➤ Why $M_H = 125$ GeV? → Hierarchy problem - Naturalness

➤ Mass of scalar not protected by symmetry, receives large quantum corrections



$$\Delta M_H^2 \propto \pm \frac{\lambda_X}{16\pi^2} M_X^2$$

Yukawa couplings to fermions: an even deeper mystery

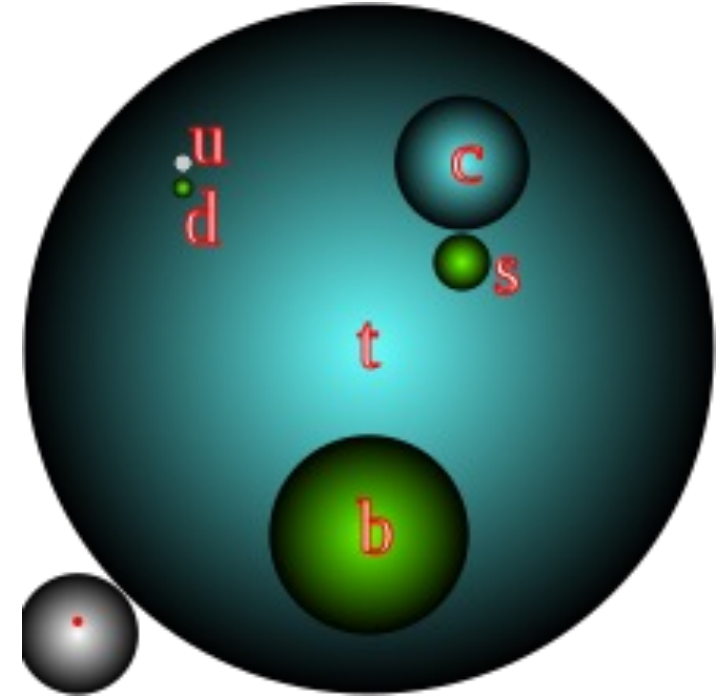
$$L_{Yuk} = y_{ij} \bar{\psi}_L^i \phi \psi_R^j + h.c.$$

Diagram illustrating the Yukawa coupling and its consequences:

- $\phi \rightarrow H + \nu$ (Higgs boson and neutrino)
- Yukawa couplings (indicated by orange arrows)
- fermion masses (indicated by blue arrows)

- Why the hierarchy of fermion masses?
- Why the hierarchy of Yukawa couplings?
(arbitrary in the SM)
- Why flavor-diagonal scalar couplings? $\leftrightarrow$ Why one Higgs?
(With more than one Higgs mass and current eigenstates can be different)

$$y_{ij} \rightarrow \frac{m_f}{v} \delta_{ij} = y_f$$

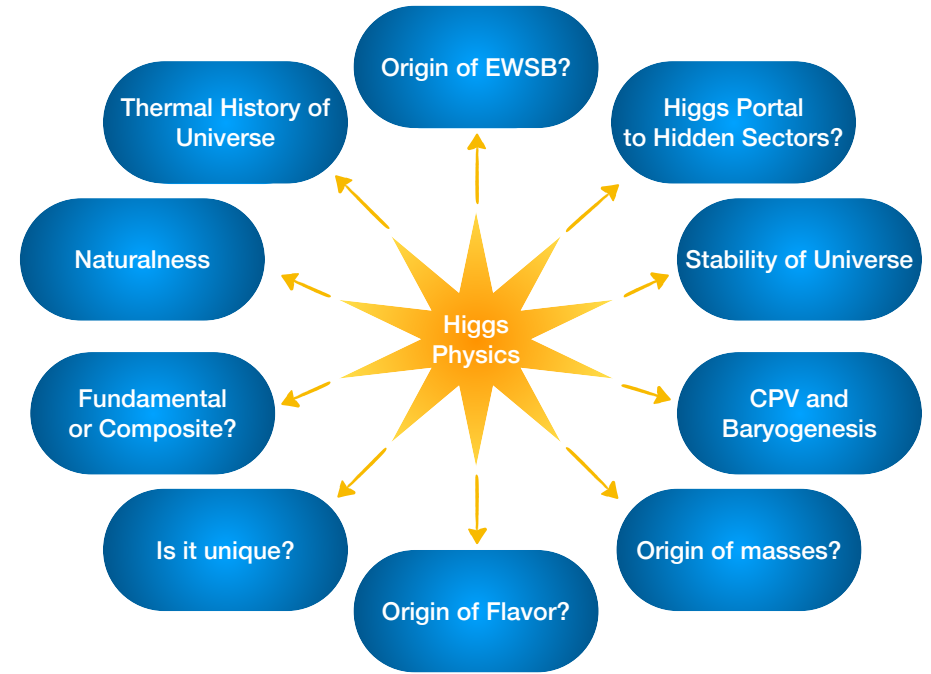


➤ Is this a new force all together??

The big open questions

What is the origin of the EW scale?

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



- Why the $M_H \ll M_{\text{planck}}$ **hierarchy problem**?
- What are the implications for **Naturalness**?
- Can we uncover the origin of BSM physics from precision measurement of Higgs properties (couplings, width, ...). **Elementary vs composite? One Higgs? More?**
- Can we measure the shape of the **Higgs potential** → **Higgs self coupling(s)**
- Can Higgs properties give us **insights on flavor** and vice versa?
 - Couplings to heavy flavors (bottom, **top**, ..)
 - Couplings to light quarks and leptons

Beyond Higgs, exploring the TeV scale with collider physics

Exploring the TeV scale: enabling the LHC physics program and beyond

The LHC era: exploring the TeV scale



We are only here

Many years of HL running ahead of us

- 2-fold increase in statistics by the end of Run 3
- 20-fold increase in statistics by the end of HL-LHC!

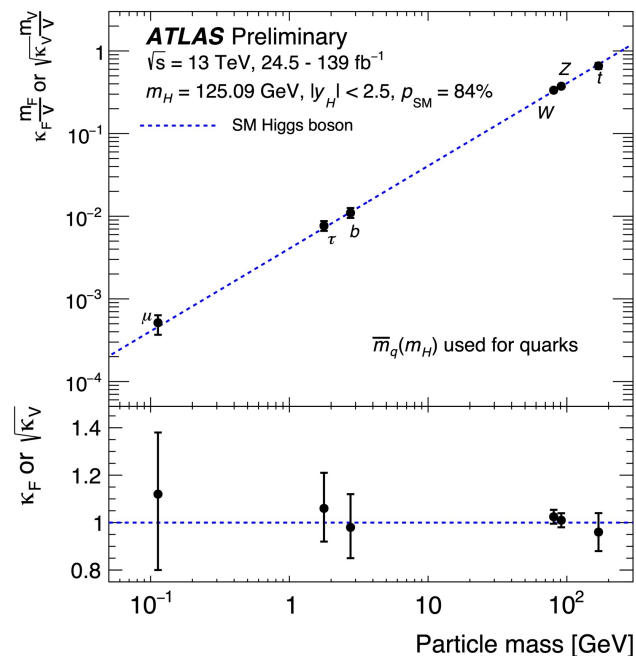
Indirectly via Higgs and Top:

- Run 2 delivery for Higgs couplings outperformed expectations
- LHC will define top physics till the next high-energy collider
 - $e^+e^- > 500$ GeV
 - $pp@100$ TeV
 - $\mu^+\mu^- > 10$ TeV

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

Reach % level precision

Example: zooming in on Higgs couplings



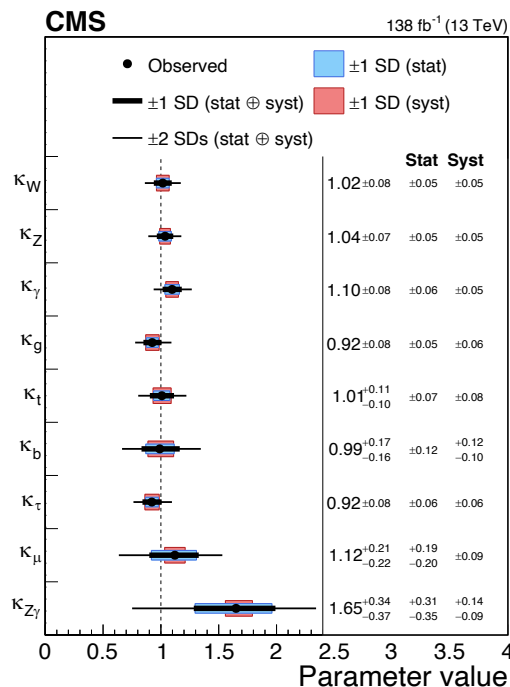
$$\kappa = g_X / g_X^{\text{SM}} = 1 + \Delta\kappa$$

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

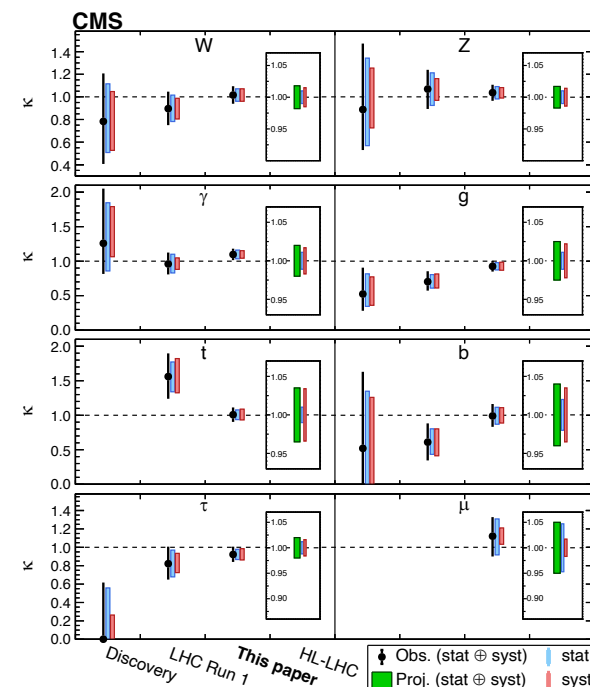
Precision on $\Delta\kappa$



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 from partial Run 2 data (YR):
 - 2-5 % on most couplings
 - < 50% on Higgs self-coupling.
- Full Run2 results drastically improve partial Run 2 results: better projections expected

Beyond a simple rescaling of SM-coupling

Extend SM Lagrangian by effective interactions (ex. SM EFT)

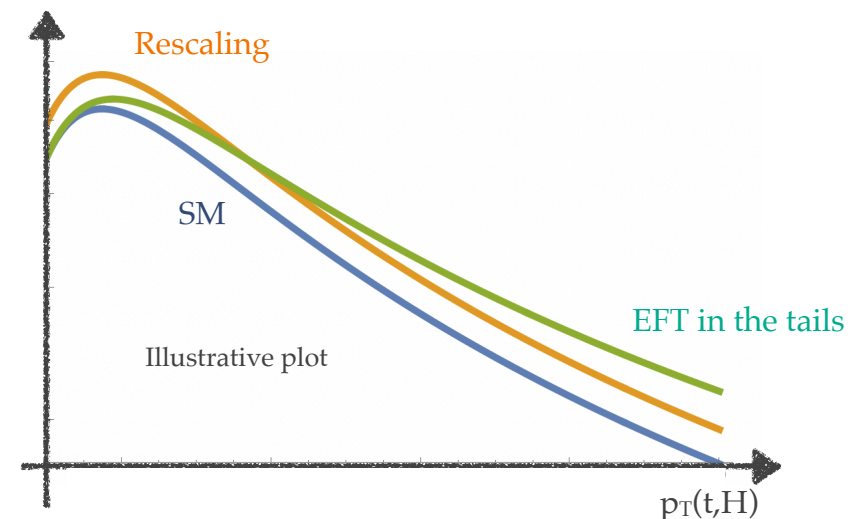
$$\mathcal{L}_{\text{SM}}^{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \dots$$

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

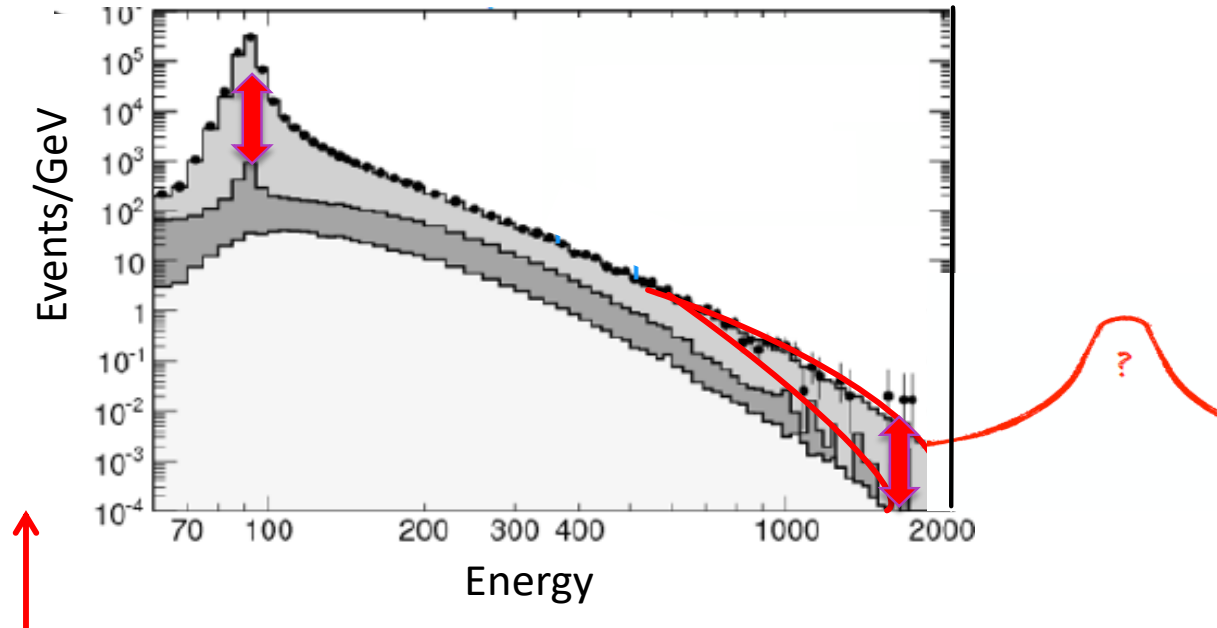
Under the assumption that new physics leaves at scales $\Lambda > \sqrt{s}$

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**



Beyond total rates



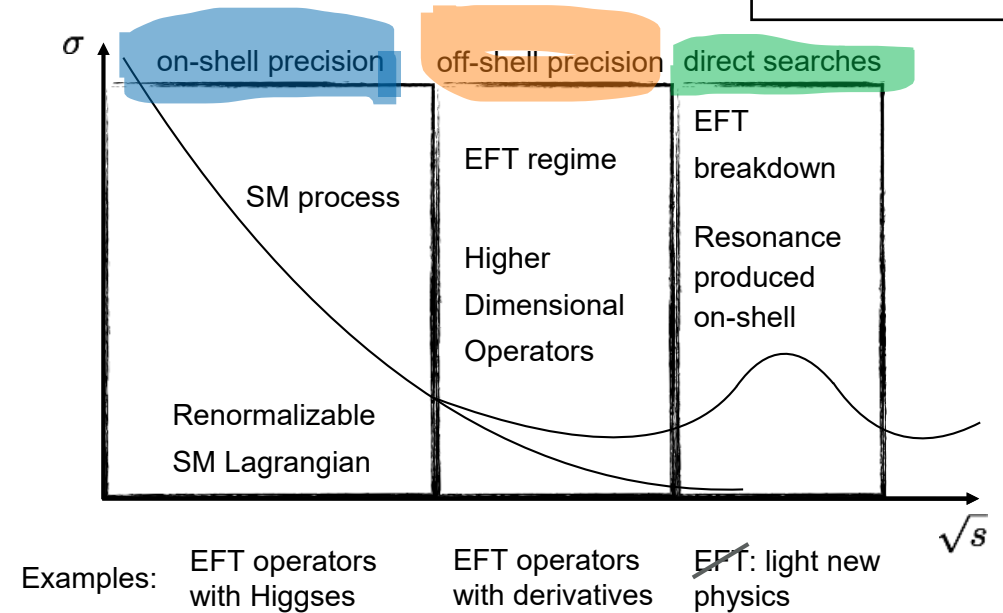
Need SM precision calculations at differential level both at **lower energy**, where rates are large and at **higher energy** where rates are small but effects of new physics may be more visible.

Extending the SM via effective interactions above the EW scale → **SMEFT**

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

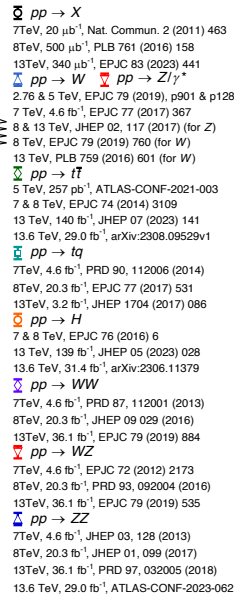
dim=6

dim=8 and above



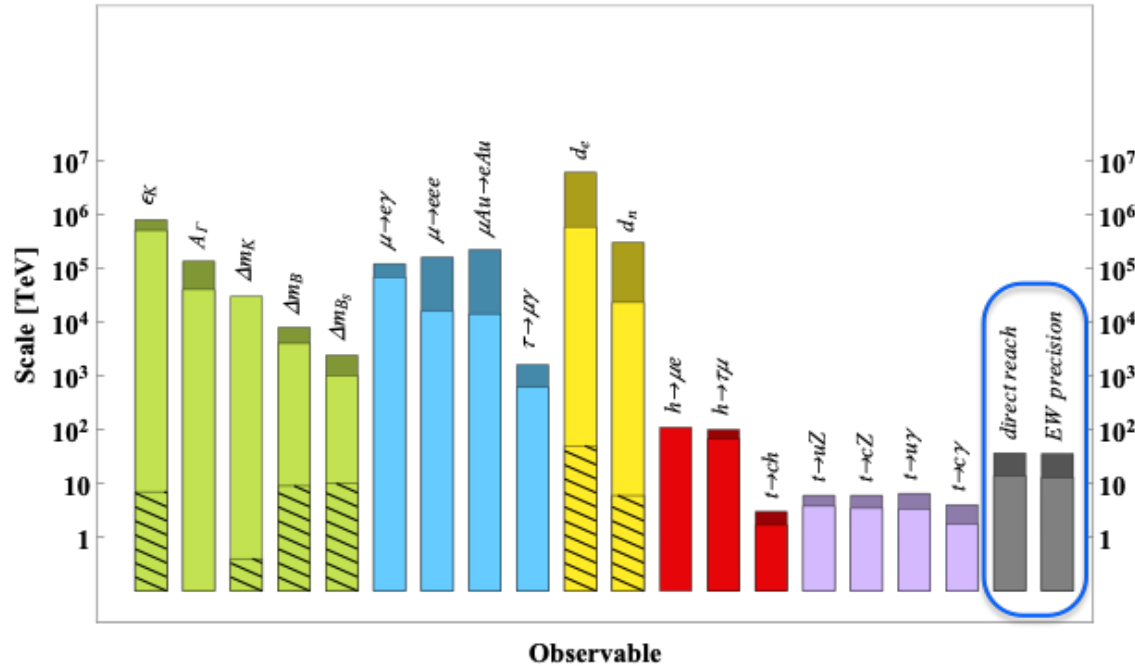
Crucial to control EFT sensitive regions

$\int_{[a, b]} \mathcal{L} \, dt$ **Reference**

[illegible]

The realization of this program largely depend on theoretical progress

Emphasizing the breadth of collider physics

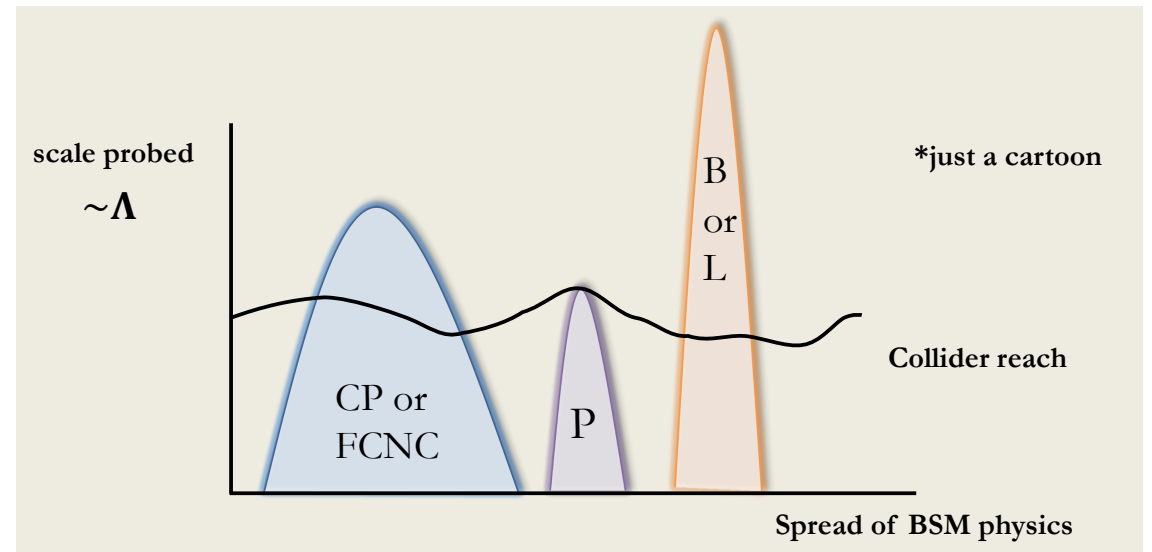


[European Strategy, arXiv:1910.11775]

Any new physics hypothesis will have to stand the test of colliders

Colliders may not be able to indirectly probe scales as high as e.g. flavor physics, but they provide a huge spectrum of measurements

 **complementarity**

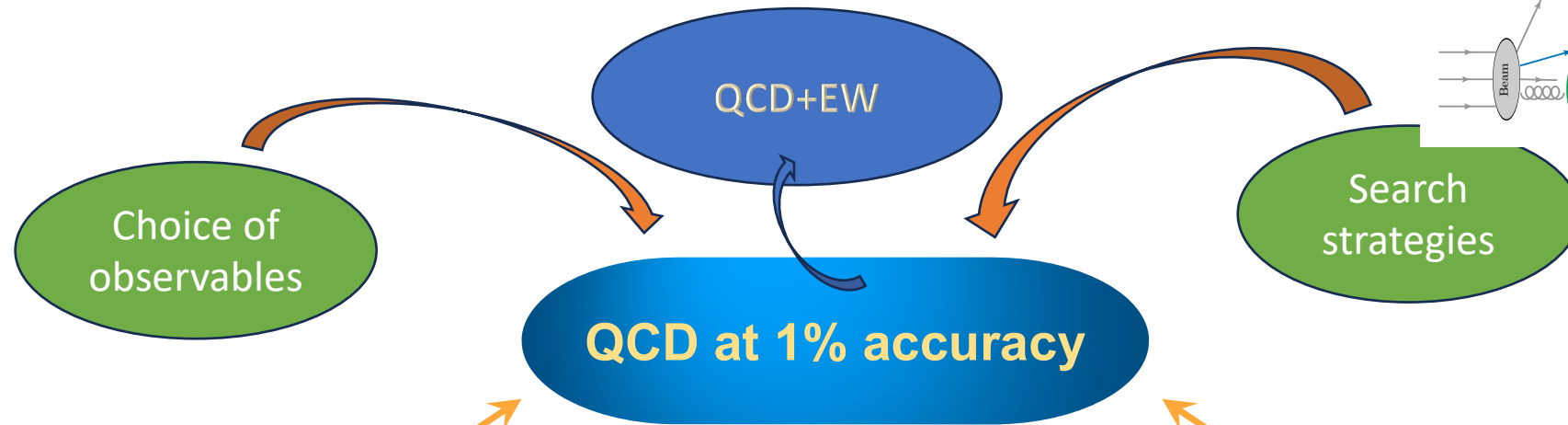


[J. de Vries, talk at Snowmass 21 CPM]

Theory has come a long way

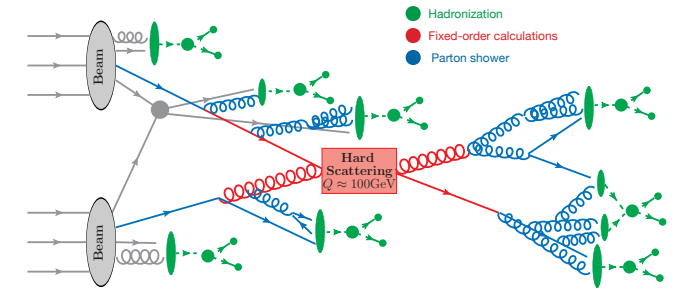
Aiming for percent level precision at the HL-LHC

Many components to percent precision



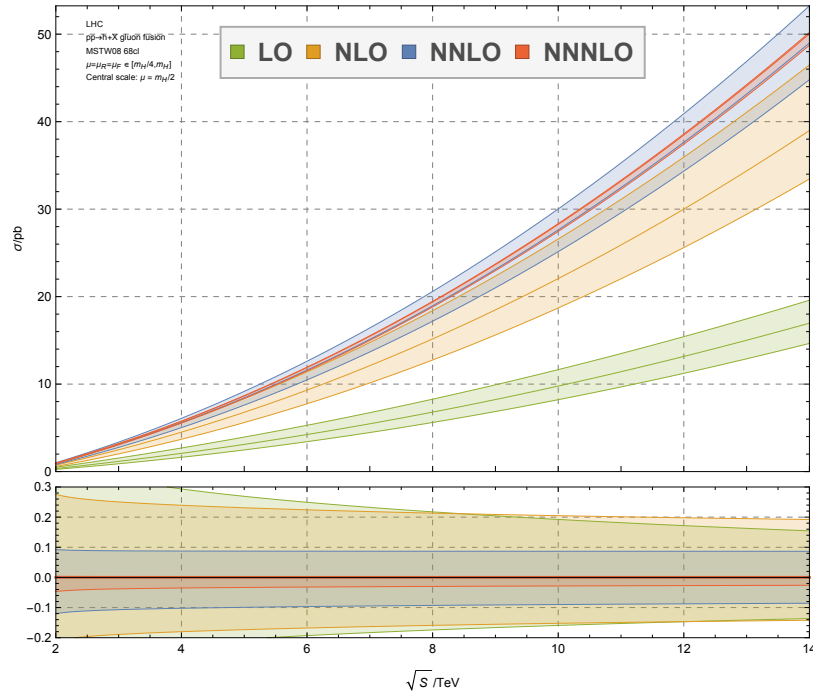
- Parton-shower event generators
- Adapting theoretical tools to experimental analyses

- Well-defined standards for theoretical systematics
- Statistical models for data analysis



Snowmass Report of QCD
Topical Groups, 2209.14872

Higgs production via gg fusion at N³LO

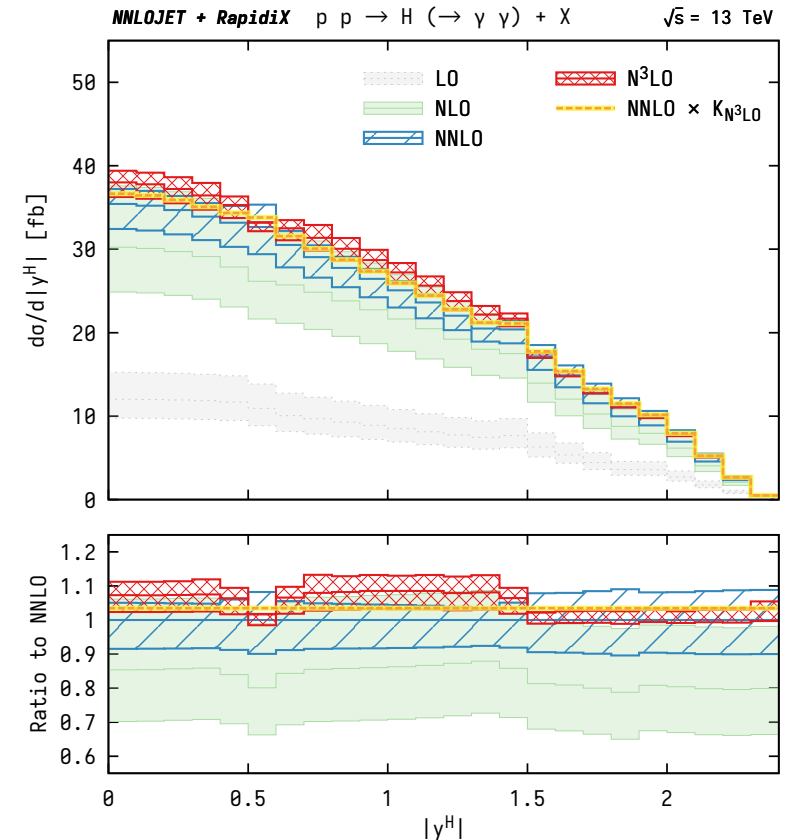
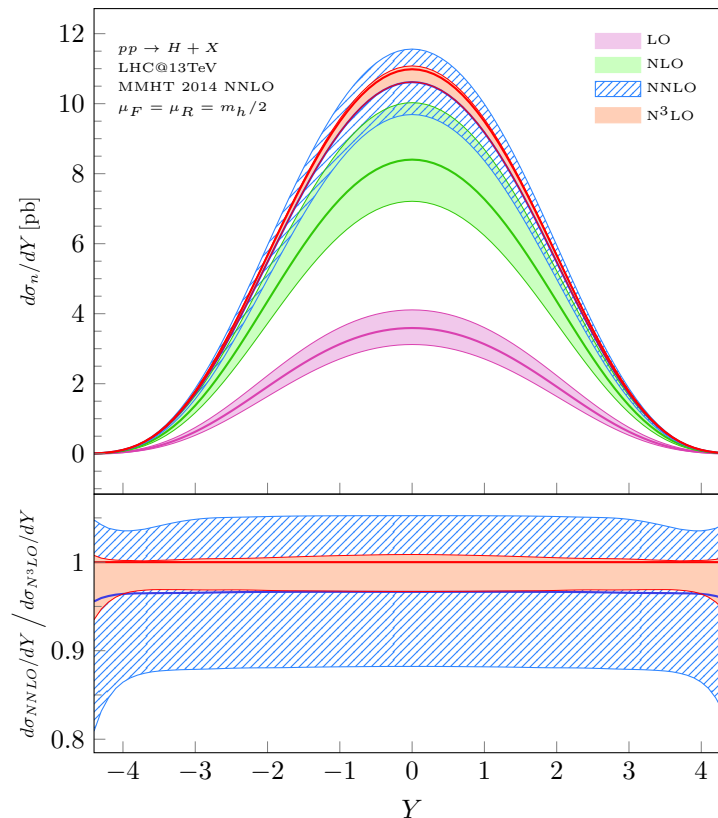


Anastasiou, Duhr, Dulat,
Herzog, Mistlberger
1503.06056

Dulat, Mistlberger, Pelloni
1810.09462

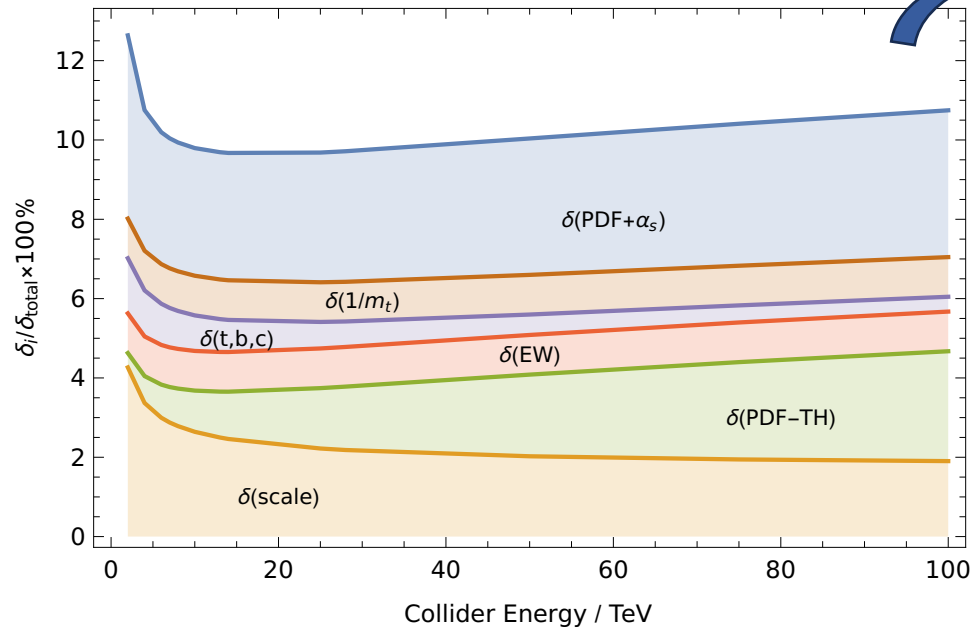
Continuous progress on a crucial process

- 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

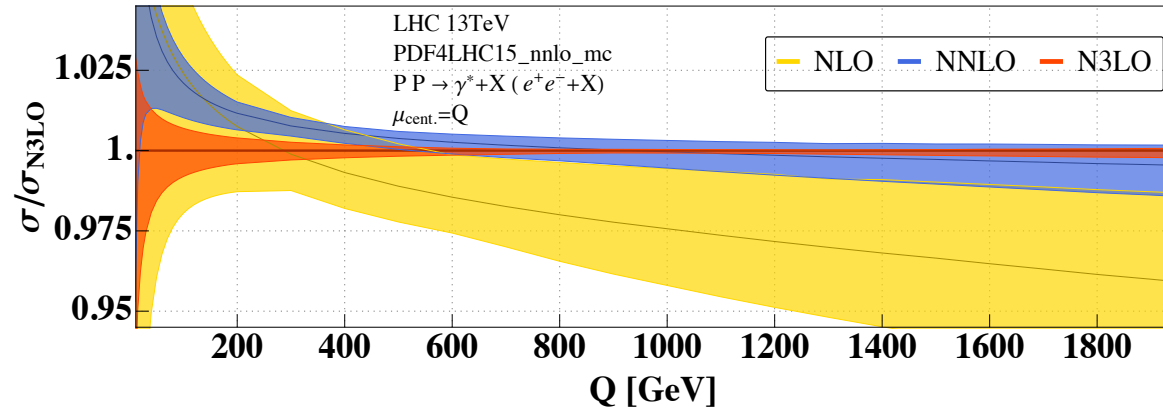
Becchetti, Bonciani, Del Duca, Hirschi,
Moriello, Schweitzer, 2010.09451

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

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

DY at N³LO – input to PDF fits and M_W measurement

NC-DY

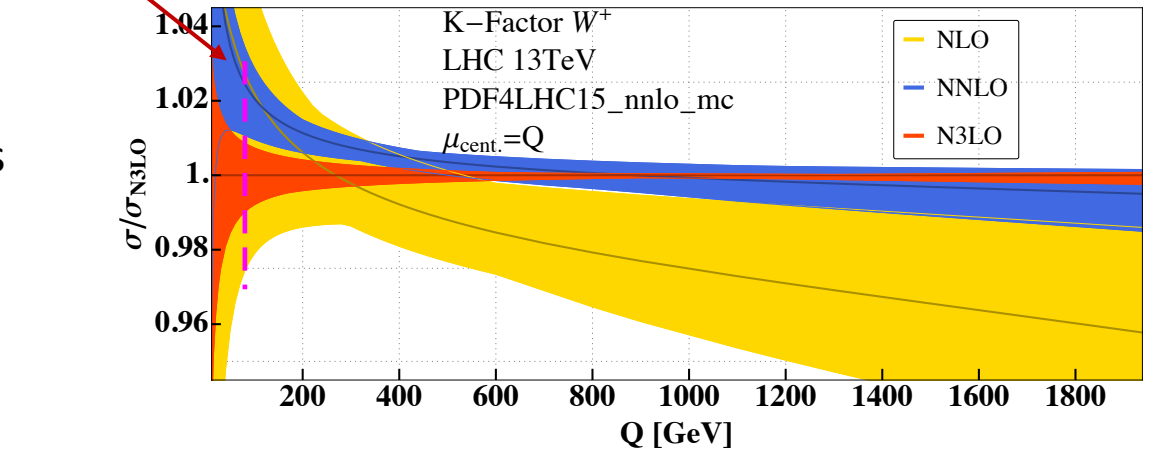
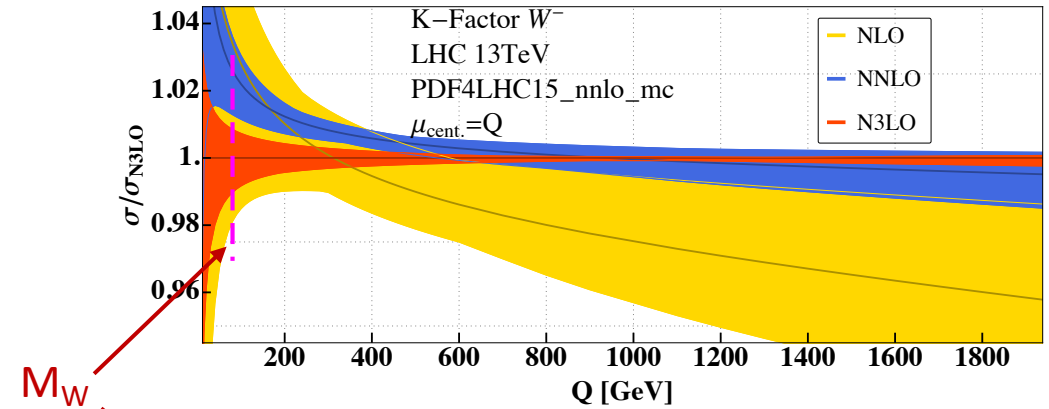


Duhr, Dulat, Mistlberger, 2001.07717

- 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**

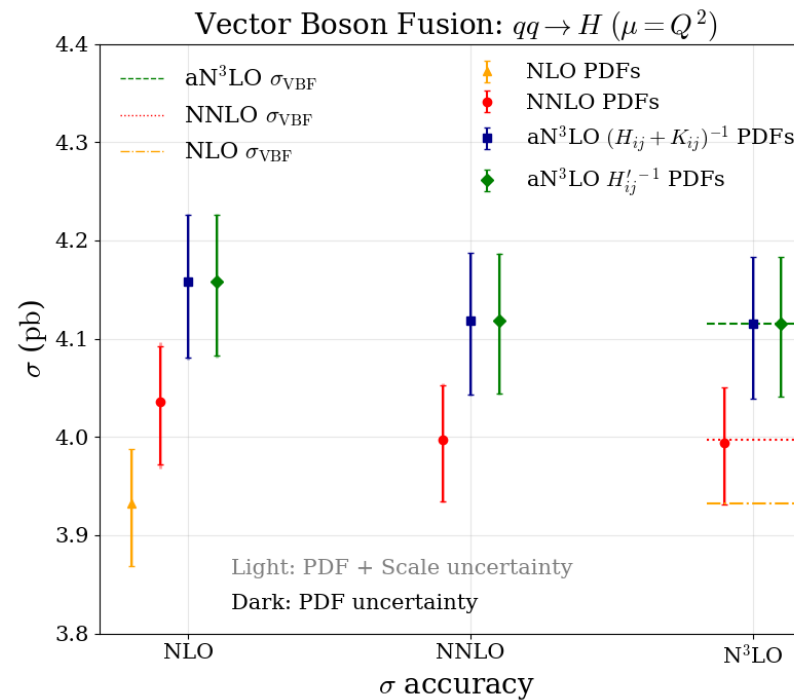
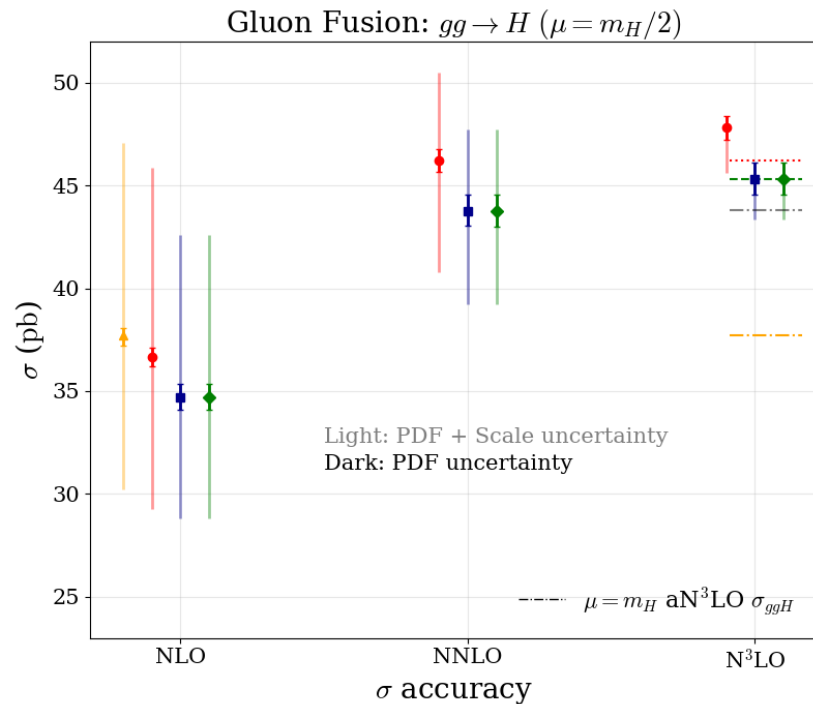
Recall from before: **need 0.1% accuracy in template distributions in order to achieve $\Delta M_W \sim 10$ MeV**

CC-DY



Duhr, Dulat, Mistlberger, 2007.13313

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

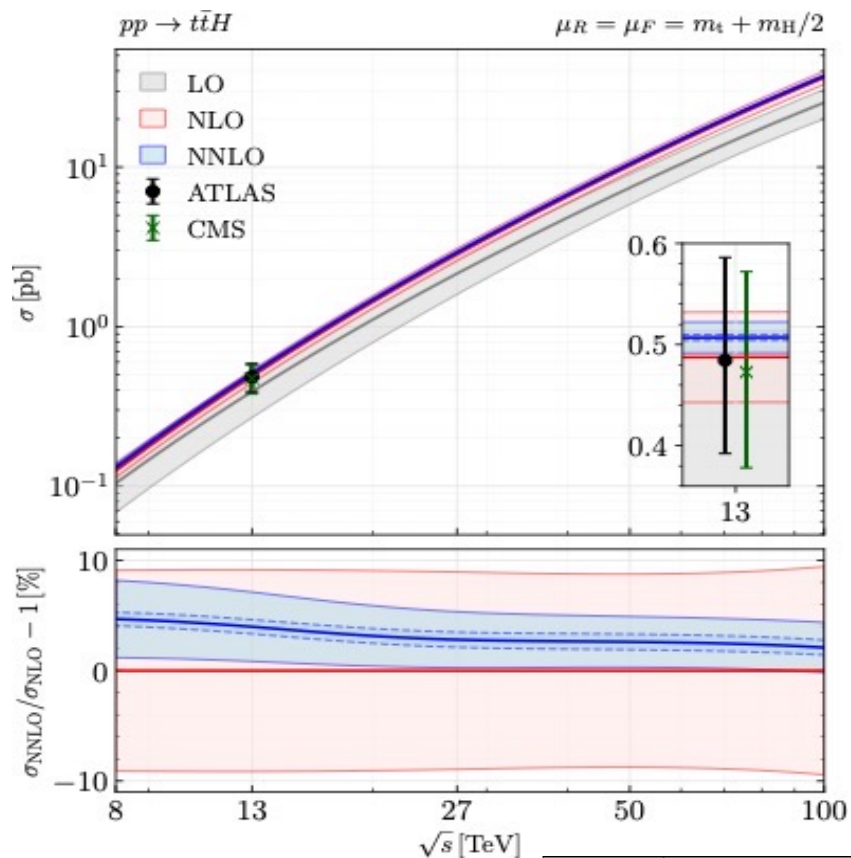
Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini, 2210.07846

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

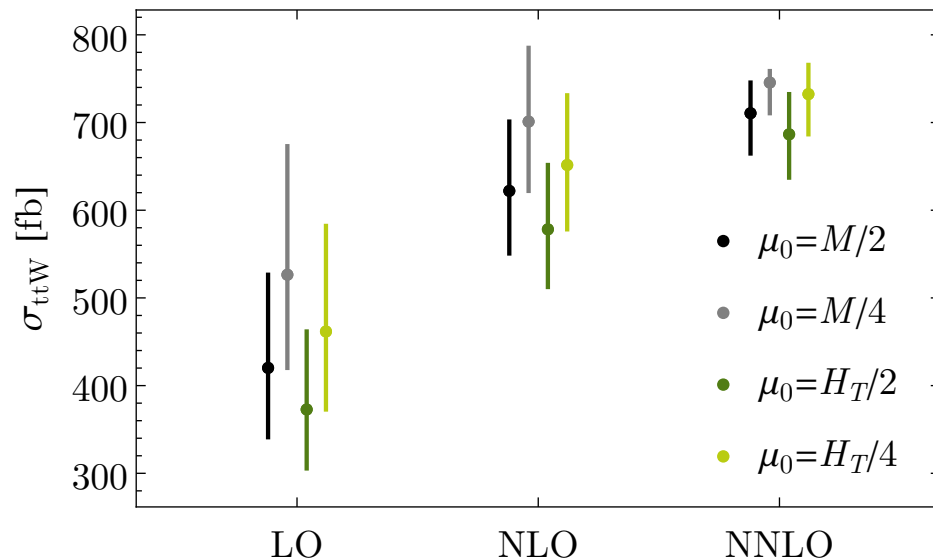


Catani et al., 2210.07846

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

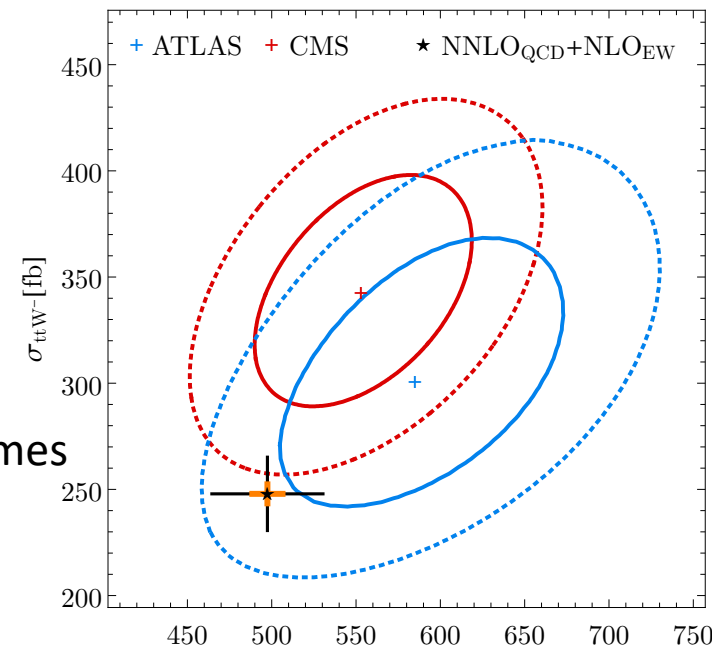
Buonocore et al., 2306.16311



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

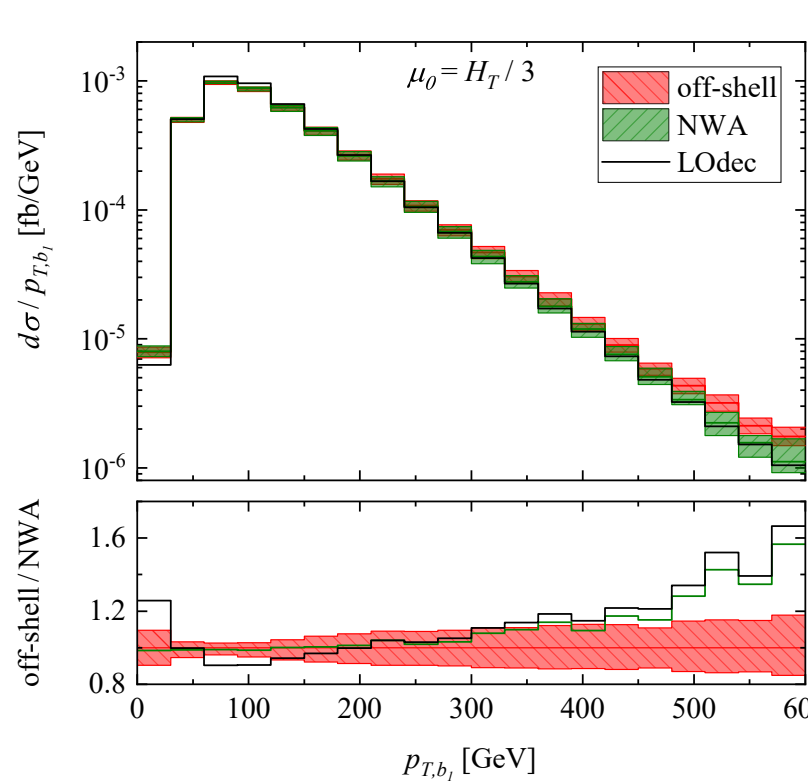
Ratio $\sigma_{t\bar{t}W^+}/\sigma_{t\bar{t}W^-}$ in very
good agreement with ATLAS
measurement

Comparison in fiducial volumes
may give further insight



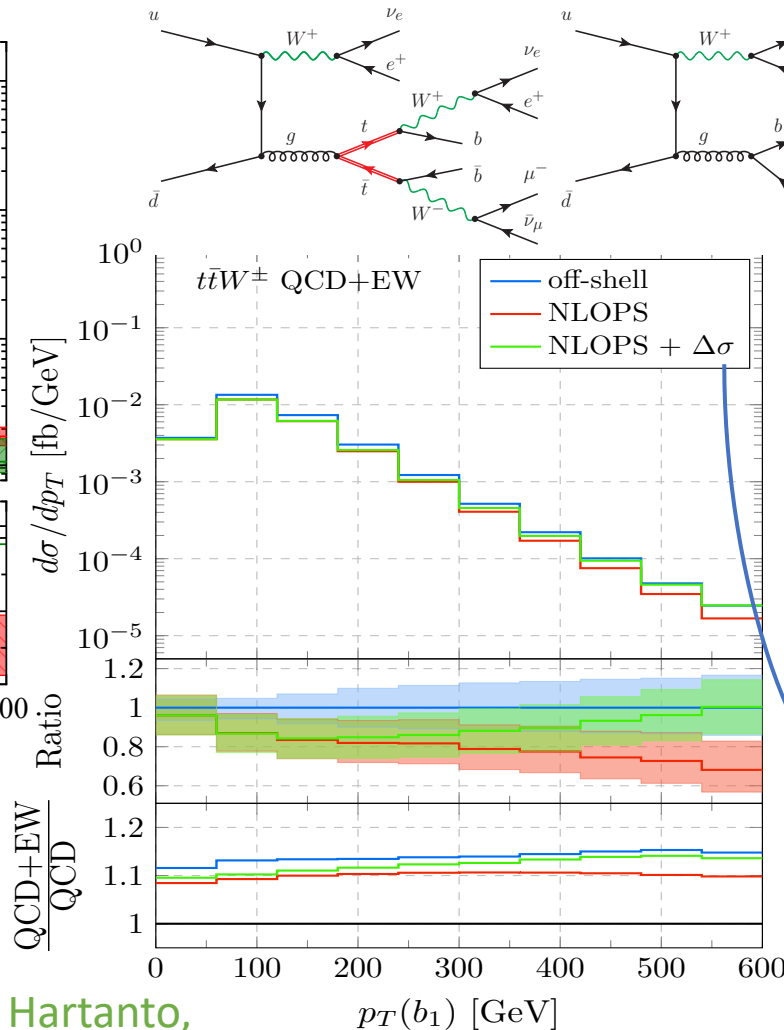
NLO: push the multiplicity challenge

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

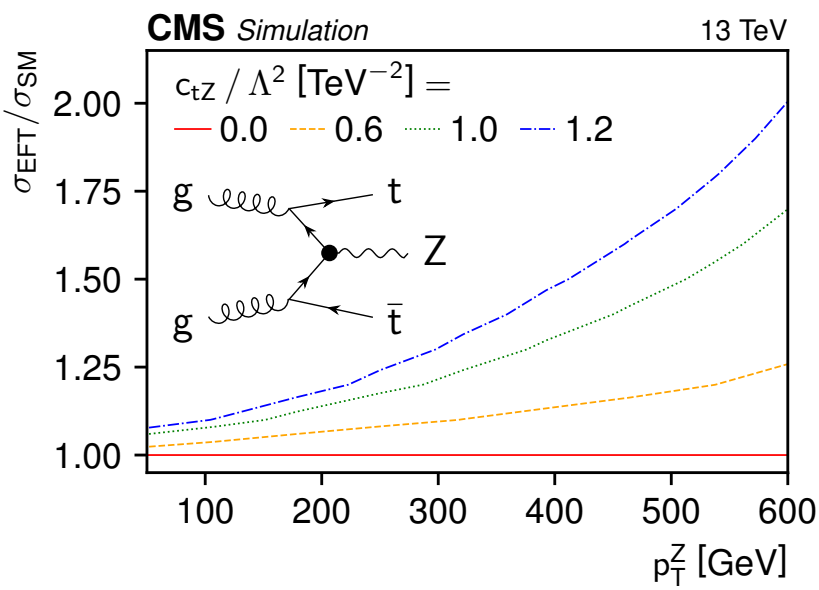
Off-shell effects most relevant in tails
and end-points of distributions, where
new physics effects can be hidden

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

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

... exploring boosted kinematics and off-shell signatures

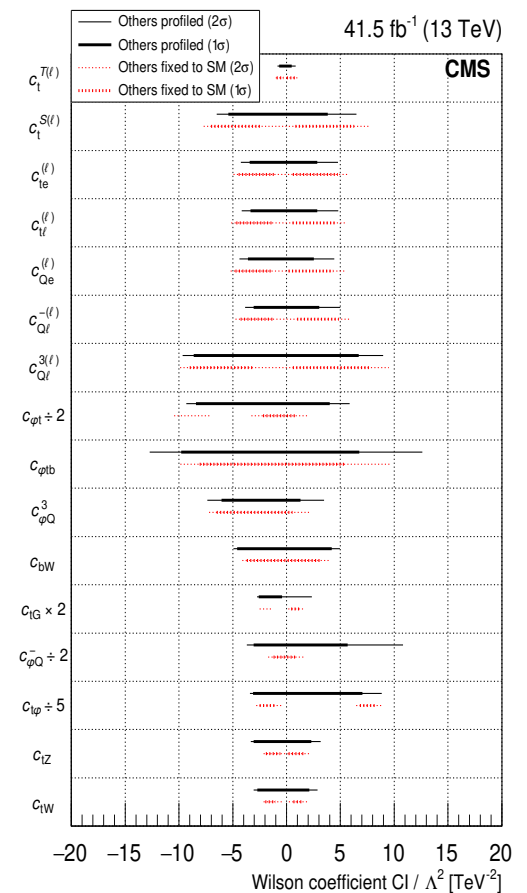
Top pair + boosted Z/H



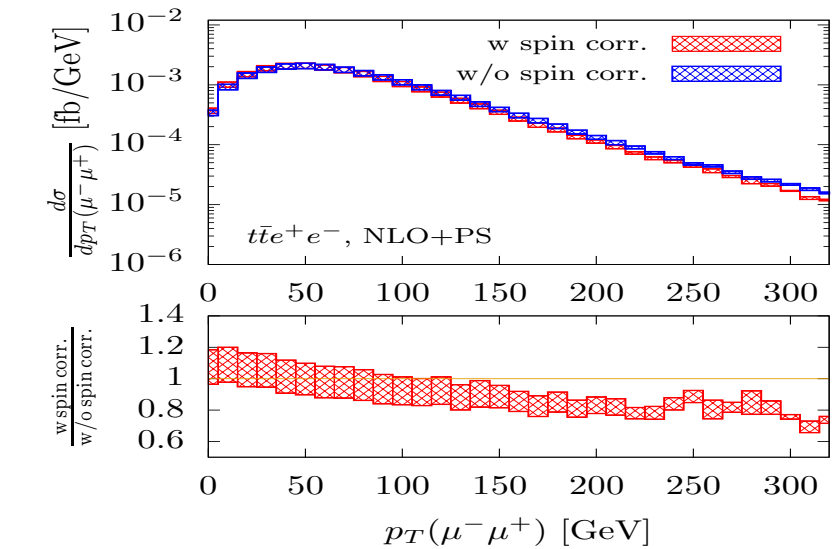
$\delta\eta_{\text{SM}} \sim g_{\text{BSM}}^2 \frac{E^2}{M^2}$

Effects in tails of distributions but also anomalous shapes

Top+additional leptons

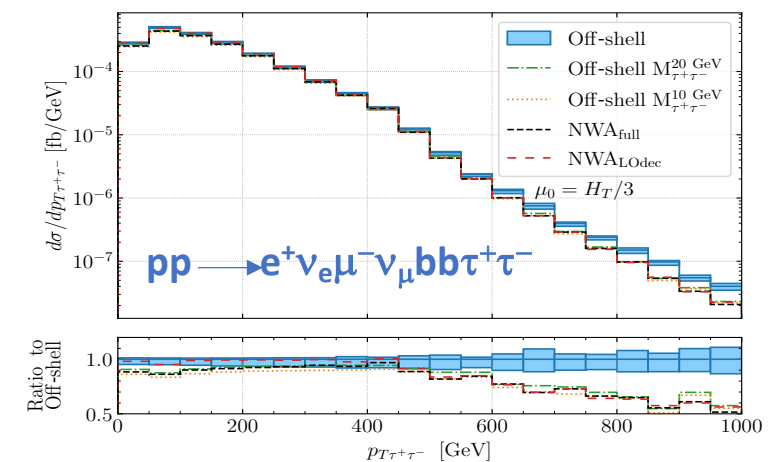


[CMS: arXiv:2012.04120]



M. Ghezzi et al. [2112.08892]

Off-shell studies



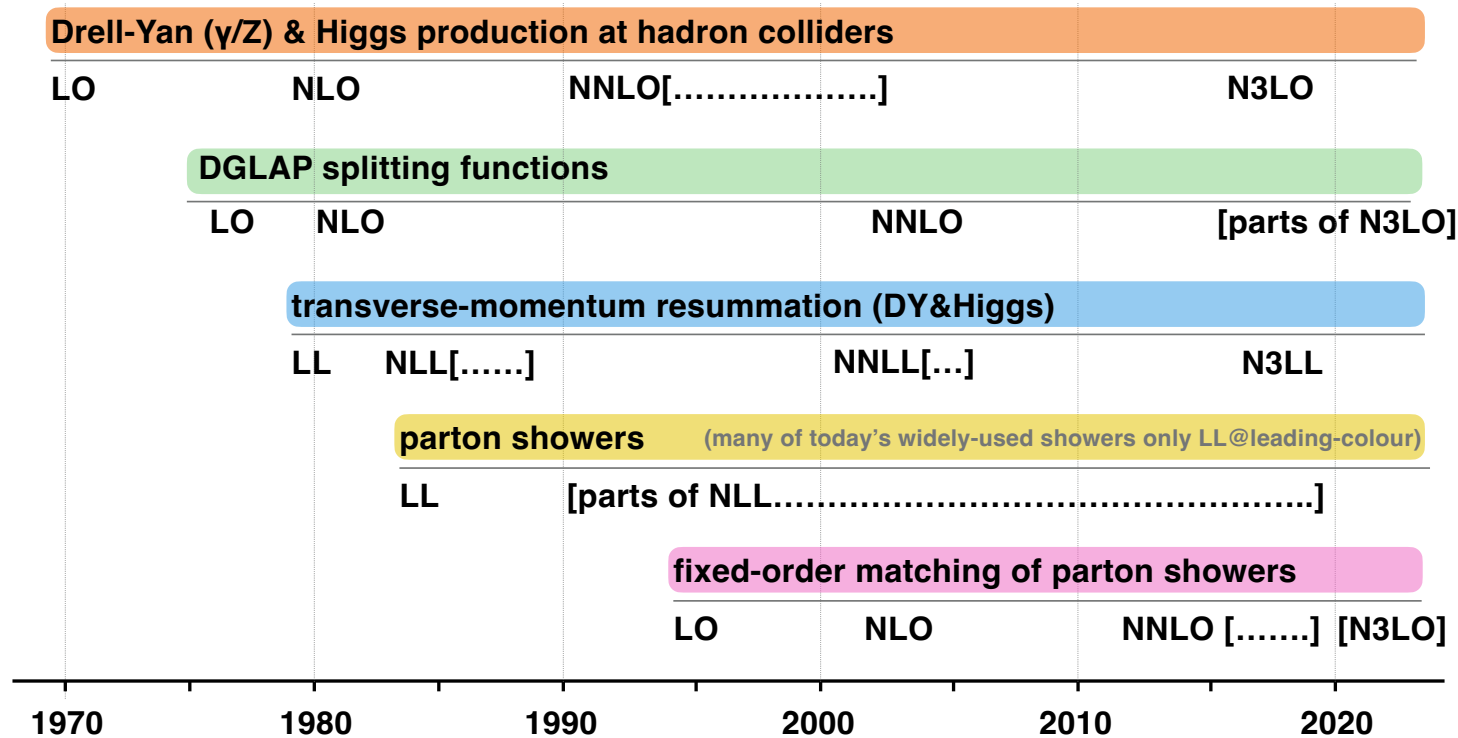
G. Bevilacqua et al. [2203.15688]

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

Parton-shower event generators

It's time for better Parton Showers!

Slide from G. Salam



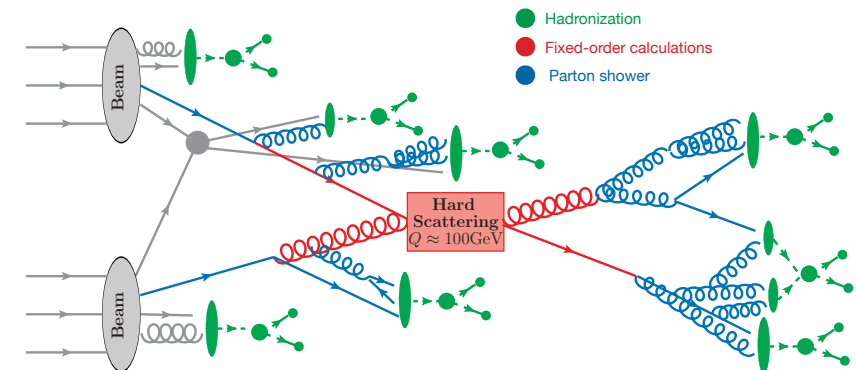
Crucial ingredient to reproduce the complexity of collider events

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



Global fits of the SM and beyond

From EW precision fits to global fits of EW, Higgs, top, and flavor observables in the framework of the SM effective field theory (SMEFT)

Need a framework

Open-source tool

Statistical framework based on a Bayesian MCMC analysis as implemented in

BAT (Bayesian Analysis Toolkit)

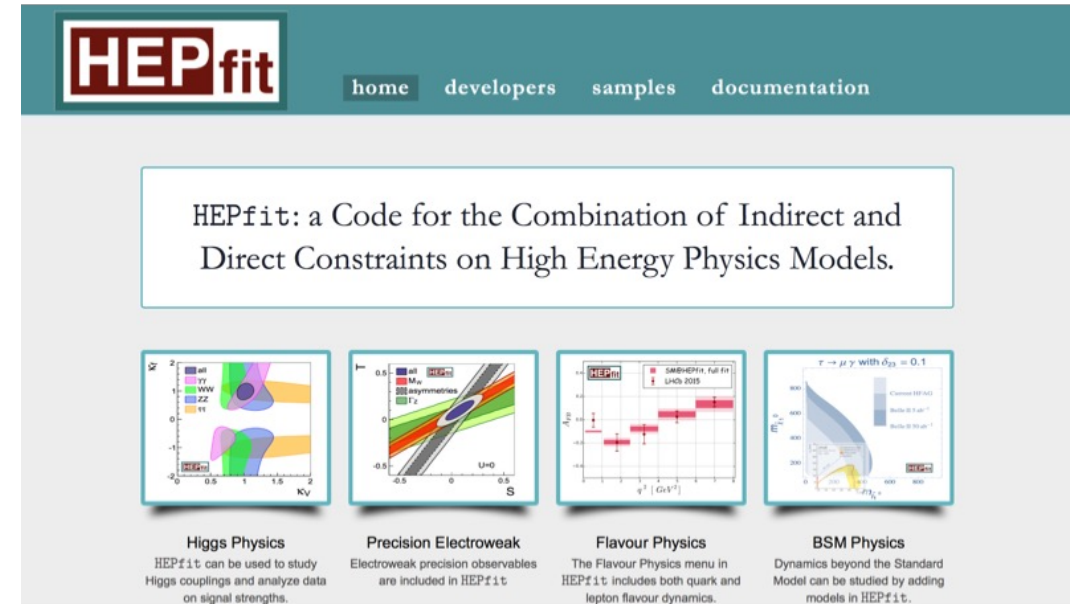
Caldwell et al., arXiv:0808.2552

Supports SM (fully implemented) and BSM models, some already implemented (e.g. dim-6 SMEFT).

Used for several global fit and future collider projections.

New release will include EW, Higgs, top, and flavor observables in the SM and the SMEFT with

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



<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

Allwicher et al, 2311.00020

Cirigliano et al. 2311.00021

Bartocci et al. 2311.04963

EW Global fit: general framework

- Set of **input parameters** (α or M_W scheme):
 - Fixed: G_F , α
 - Floating: M_W , M_Z , M_H , m_t , $\alpha_s(M_Z)$, $\Delta\alpha_{\text{had}}^{(5)}$
- **Compute EW Precision Observables** (EWPO), including all known higher-order SM corrections:
 - 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)
- Perform **best fit to EW precision data** through different fitting procedures and compare with experimental measurements.
- Parametrize **new physics** effects on EWPO (tree-level) and **constrain deviations** in terms of chosen parameters:
 - Oblique parameters : S,T, U
 - **Effective interactions: SMEFT**
 -



focus of this talk

EW Observables: Theoretical parametrization

- **Analytic** theoretical predictions of **Z and W boson observables**.
- Z-pole observables:

$$\sin^2 \theta_{eff,l} = \frac{1}{4} \left(1 - \frac{g_{V,l}}{g_{A,l}} \right)$$

$$A_f = \frac{2 \left(\frac{g_{V,f}}{g_{A,f}} \right)}{1 + \left(\frac{g_{V,f}}{g_{A,f}} \right)^2} \quad \left\{ \quad A_{FB,f} = \frac{3}{4} A_e A_f \right.$$

$$\Gamma_{Z,f} = N_f \frac{G_F M_Z^3}{24\sqrt{2}\pi} 4 [(g_{V,f})^2 + (g_{A,f})^2] \quad \left\{ \quad \sigma_{had}^0 = \frac{12\pi}{M_Z^2} \frac{\Gamma_e \Gamma_{had}}{\Gamma_Z^2} \quad R_e^0 = \frac{\Gamma_{had}}{\Gamma_e} \quad R_{q,\nu}^0 = \frac{\Gamma_{q,\nu}}{\Gamma_{had}} \right.$$

all in terms
of Z-fermion
couplings

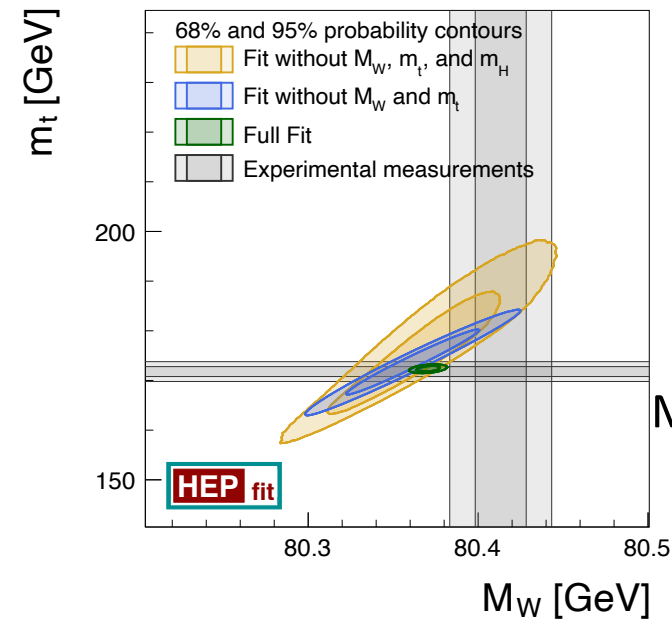
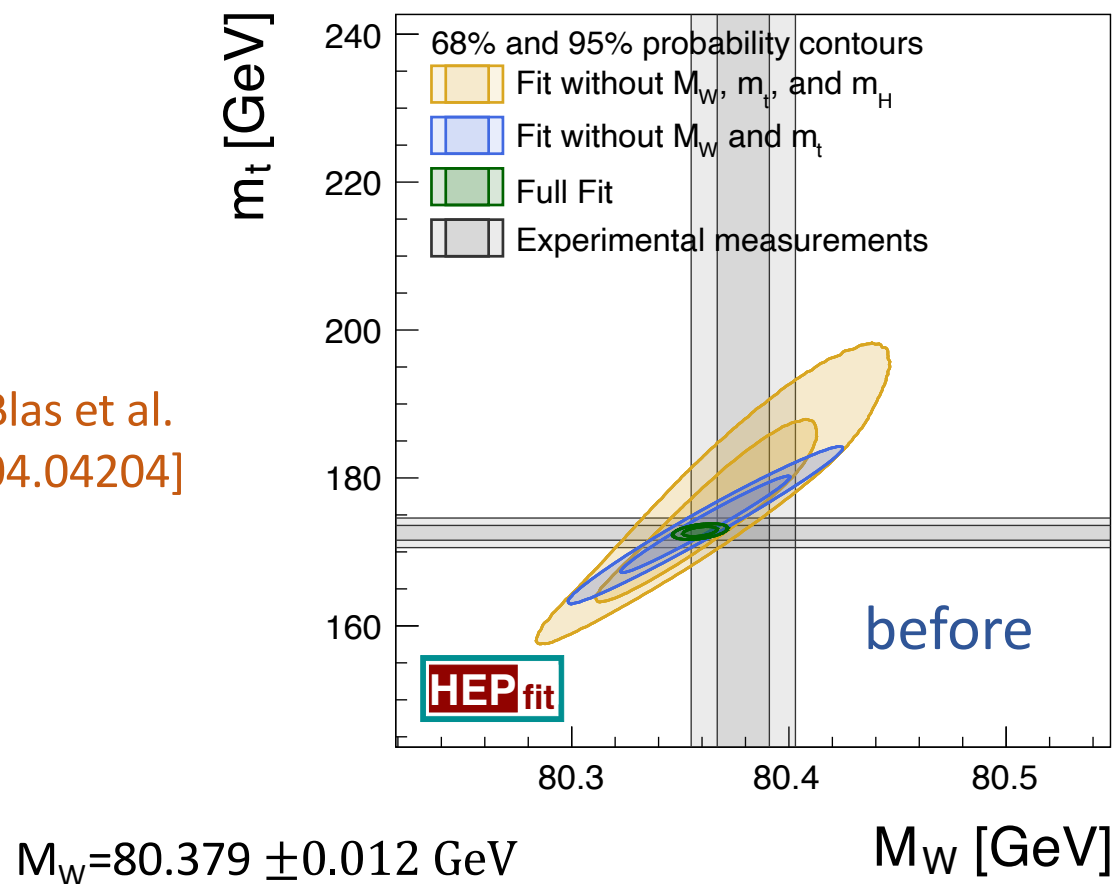


- **Functions of all the parameters of the model** (masses, couplings) through SM quantum corrections

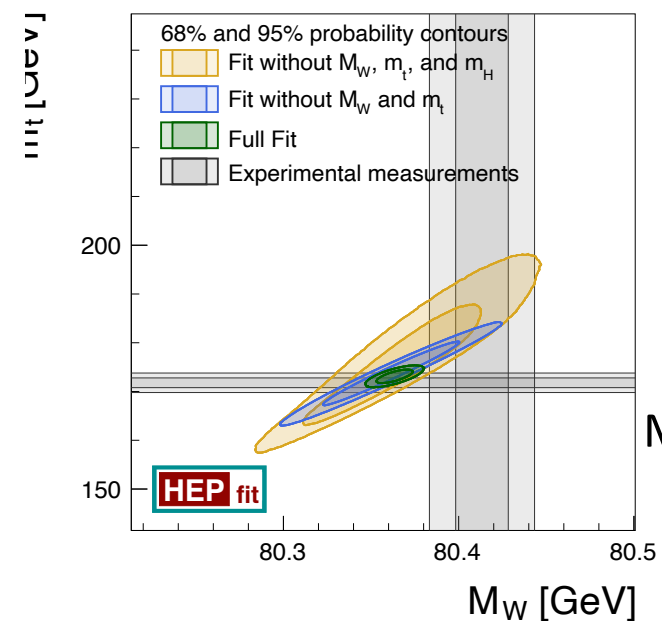
Stress-testing the SM

A recent challenge: CDF new M_W measurement

De Blas et al.
[2204.04204]



after
"standard"



after
"conservative"

EW global fit of the SM- exerpt

For M_W we combine:

- ❑ All LEP 2 measurements;
- ❑ Previous Tevatron average
- ❑ ATLAS and LHCb measurements
- ❑ CDF measurement [$M_W=(80.4335\pm0.0094)$ GeV]
- ❑ ATLAS measurement [$M_W=(80.360\pm0.0016)$ GeV]

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

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

“standard”
(6.1 σ pull)

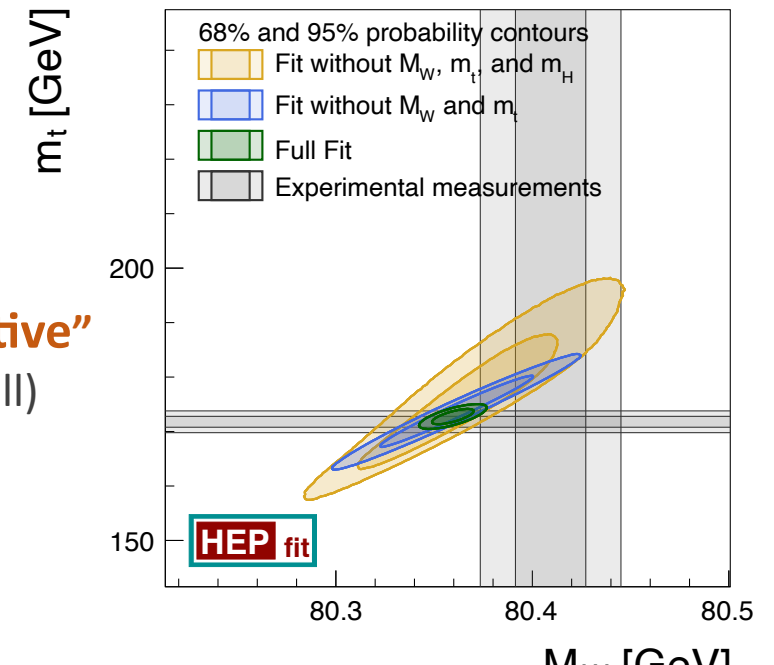
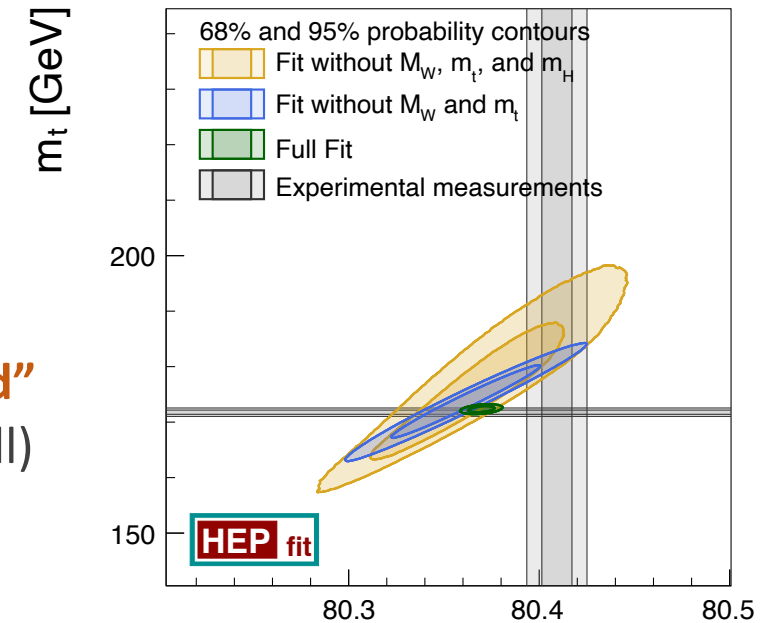
For m_t we combine:

- ❑ 2016 Tevatron combination
- ❑ ATLAS Run 1 and Run2 results
- ❑ CMS Run 1 and Run 2 results
- ❑ Recent CMS $l+j$ measurement [$m_t=(171.77\pm0.38)$ GeV]

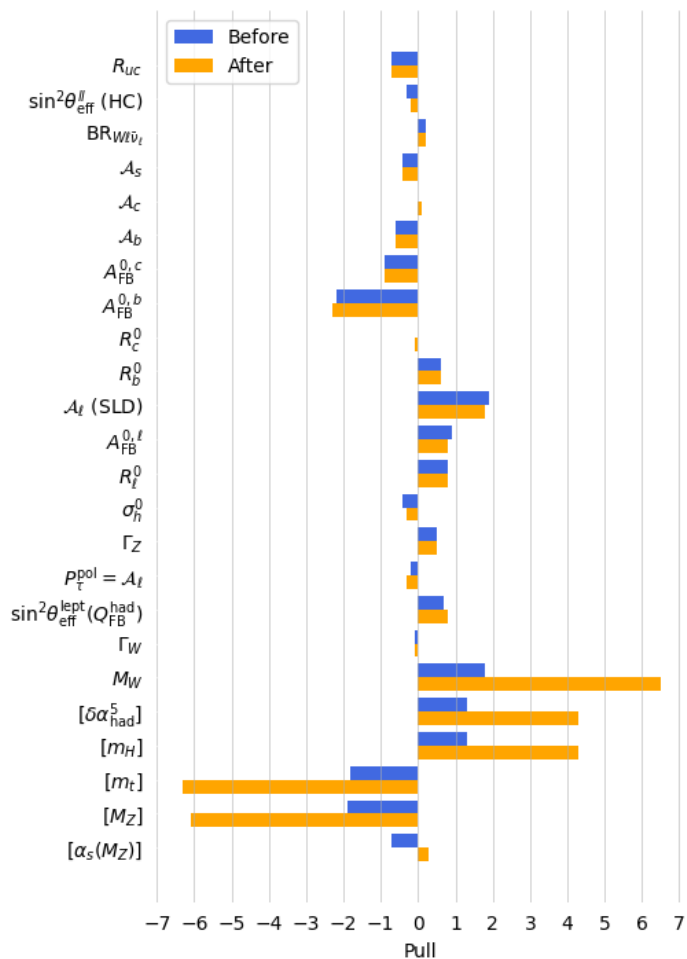
$m_t = 172.71 \pm 0.58$ GeV (**standard**)

“conservative”
(3.0 σ pull)

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)



EW global fit results- example



“standard” scenario

	Measurement	Posterior	Indirect/Prediction	Pull	Full Indirect	Pull	Full Prediction	Pull
$\alpha_s(M_Z)$	0.1177 ± 0.0010	0.11763 ± 0.00095 [0.11577, 0.11946]	0.1170 ± 0.0028 [0.1116, 0.1225]	0.2	0.1217 ± 0.0047 [0.1126, 0.1310]	-0.8	0.1177 ± 0.0010 [0.1157, 0.1197]	0.0
$\delta\alpha_{\text{had}}^5$	0.02766 ± 0.00010	0.027541 ± 0.000096 [0.027352, 0.027730]	0.02624 ± 0.00033 [0.02559, 0.02689]	4.1	0.02793 ± 0.00068 [0.02661, 0.02926]	-0.4	0.02766 ± 0.00010 [0.02746, 0.02786]	0.0
M_Z [GeV]	91.1875 ± 0.0021	91.1910 ± 0.0020 [91.1870, 91.1949]	91.2287 ± 0.0068 [91.2154, 91.2421]	-5.8	91.210 ± 0.039 [91.134, 91.287]	-0.6	91.1875 ± 0.0021 [91.1834, 91.1916]	0.0
m_t [GeV]	171.79 ± 0.38	172.34 ± 0.37 [171.61, 173.06]	180.9 ± 1.5 [178.0, 183.8]	-5.9	186.7 ± 9.5 [168.0, 205.1]	-1.6	171.80 ± 0.38 [171.05, 172.54]	0.0
m_H [GeV]	125.21 ± 0.12	125.2 ± 0.12 [124.97, 125.44]	94.0 ± 5.0 [83.3, 104.3]	4.1	241.2 ± 121.3 [100.8, 626.8]	-0.8	125.21 ± 0.12 [124.97, 125.45]	0.0
M_W [GeV]	80.4093 ± 0.0079	80.3696 ± 0.0045 [80.3608, 80.3786]	80.3499 ± 0.0056 [80.3390, 80.3609]	6.1	80.4089 ± 0.0078 [80.3934, 80.4241]	0.0	80.3496 ± 0.0037 [80.3386, 80.3608]	6.1
Γ_W [GeV]	2.085 ± 0.042	2.08896 ± 0.00052 [2.08793, 2.08999]	2.08896 ± 0.00052 [2.08896, 2.08896]	-0.1	2.0940 ± 0.0023 [2.0896, 2.0984]	-0.2	2.08744 ± 0.00059 [2.08627, 2.08859]	0.0
$\sin^2 \theta_{\text{eff}}^l$ (HC)		0.231474 ± 0.00005 [0.231366, 0.231583]			0.23146 ± 0.00014 [0.23119, 0.23173]	0.8	0.231558 ± 0.000062 [0.231558, 0.231558]	0.7
$P_{\tau}^{\text{pol}} = \mathcal{A}_{\tau}$		0.14739 ± 0.00044 [0.14654, 0.14825]			0.1475 ± 0.0011 [0.1454, 0.1496]	-0.3		
Γ_Z [GeV]		2.49454 ± 0.00064 [2.49328, 2.49580]			2.4953 ± 0.0020 [2.4912, 2.4993]	0.1		
σ_h^0 [nb]	41.480 ± 0.033	41.4892 ± 0.0077 [41.4742, 41.5042]	$41.4758, 41.5072$		41.462 ± 0.030 [41.403, 41.522]	0.4	$41.4766, 41.5081$	
R_{ℓ}^0	20.767 ± 0.025		20.7451 ± 0.0086 [20.7281, 20.7621]	0.8	20.760 ± 0.022 [20.717, 20.802]	0.2	20.7468 ± 0.0087 [20.7298, 20.7637]	0.7
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010		0.016284 ± 0.000096 [0.016097, 0.016476]	0.8			0.01615 ± 0.00011 [0.01594, 0.01636]	1.0
$\mathcal{A}_{\ell}$ (SLD)	0.1513 ± 0.0021	0.14742 ± 0.00045 [0.14654, 0.14832]		1.8			0.14675 ± 0.00049 [0.14580, 0.14770]	2.1
R_b^0	0.21629 ± 0.00066	0.215894 ± 0.000100 [0.215697, 0.216090]	0.21589 ± 0.00010 [0.21569, 0.21609]	0.6			0.21591 ± 0.00010 [0.21571, 0.21611]	0.6
R_c^0	0.1721 ± 0.0030	0.172198 ± 0.000054 [0.172093, 0.172302]	0.172199 ± 0.000054 [0.172094, 0.172304]	-0.1			0.17189 ± 0.000054 [0.172084, 0.172295]	-0.1
$A_{\text{FB}}^{0,b}$	0.0996 ± 0.0016	0.10334 ± 0.00031 [0.10273, 0.10393]	0.10335 ± 0.00032 [0.10273, 0.10398]	-2.3	0.10338 ± 0.00077 [0.10189, 0.10489]	-2.1	0.10288 ± 0.00034 [0.10220, 0.10354]	-2.0
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035	0.07384 ± 0.00023 [0.07339, 0.07428]	0.07385 ± 0.00024 [0.07339, 0.07432]	-0.9	0.07391 ± 0.00059 [0.07275, 0.07507]	-0.9	0.07348 ± 0.00025 [0.07298, 0.07398]	-0.8
$\mathcal{A}_b$	0.923 ± 0.020	0.934768 ± 0.000040 [0.934690, 0.934845]	0.934769 ± 0.000040 [0.934691, 0.934846]	-0.6	0.93460 ± 0.00016 [0.93428, 0.93492]	-0.6	0.934721 ± 0.000041 [0.934642, 0.934801]	-0.6
$\mathcal{A}_c$	0.670 ± 0.027	0.66795 ± 0.00021 [0.66753, 0.66837]	0.66795 ± 0.00022 [0.66753, 0.66838]	0.1	0.66817 ± 0.00054 [0.66711, 0.66921]	0.1	0.66766 ± 0.00022 [0.66722, 0.66810]	0.1
$\mathcal{A}_s$	0.895 ± 0.091	0.935675 ± 0.000039 [0.935597, 0.935752]	0.935674 ± 0.000040 [0.935597, 0.935752]	-0.4	0.935714 ± 0.000099 [0.935523, 0.935907]	-0.5	0.935621 ± 0.000041 [0.935541, 0.935702]	-0.5
$\text{BR}_{W\ell\bar{\nu}_{\ell}}$	0.10860 ± 0.00090	0.108388 ± 0.000022 [0.108345, 0.108431]	0.108388 ± 0.000022 [0.108344, 0.108431]	0.2	0.10829 ± 0.00011 [0.10807, 0.10850]	0.3	0.108386 ± 0.000023 [0.108340, 0.108432]	0.2
$\sin^2 \theta_{\text{eff}}^l$ (HC)	0.23143 ± 0.00025	0.231474 ± 0.000055 [0.231366, 0.231583]	0.231477 ± 0.000056 [0.231366, 0.231588]	-0.2	0.23146 ± 0.00014 [0.23119, 0.23173]	-0.1	0.231558 ± 0.000062 [0.231436, 0.231679]	-0.5
R_{uc}	0.1660 ± 0.0090	0.172220 ± 0.000031 [0.172158, 0.172282]	0.172220 ± 0.000031 [0.172158, 0.172282]					

Experimental values used as inputs

Result of the fit not using the corresponding measurement

Results of the global fit

Predictions using measurements of SM parameters

Result of the fit not using any measurements of SM parameters

Beyond the SM: {S,T,U}

$$S = -16\pi\Pi_{30}^{\text{NP}'}(0) = 16\pi[\Pi_{33}^{\text{NP}'}(0) - \Pi_{3Q}^{\text{NP}'}(0)]$$

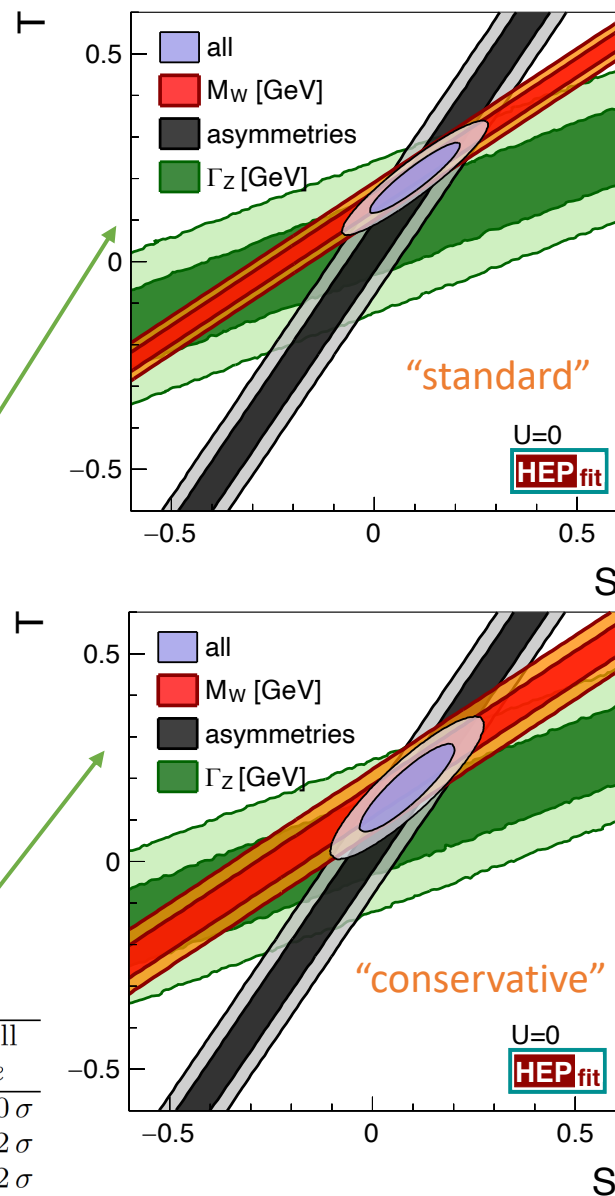
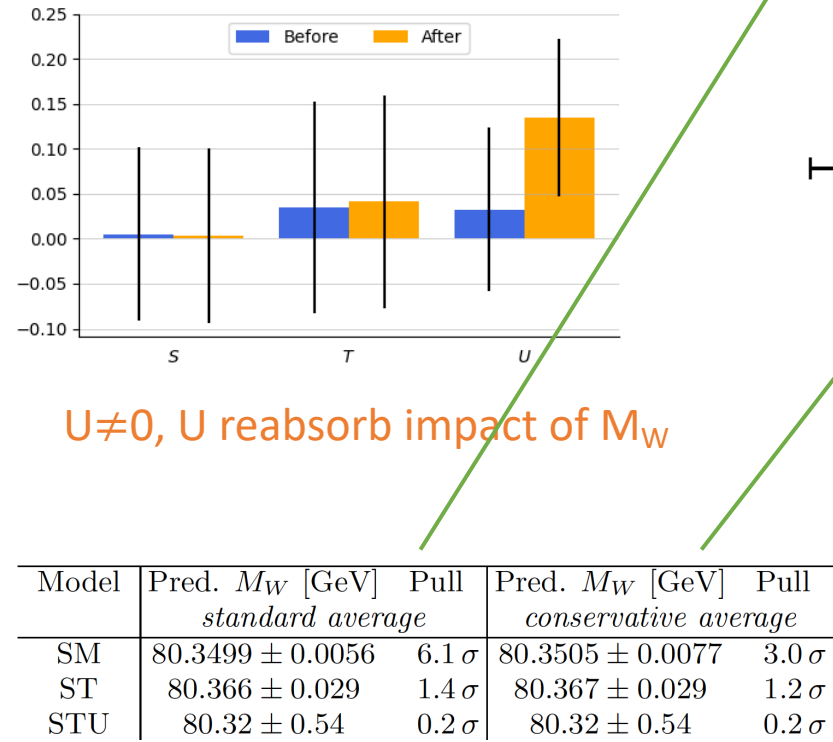
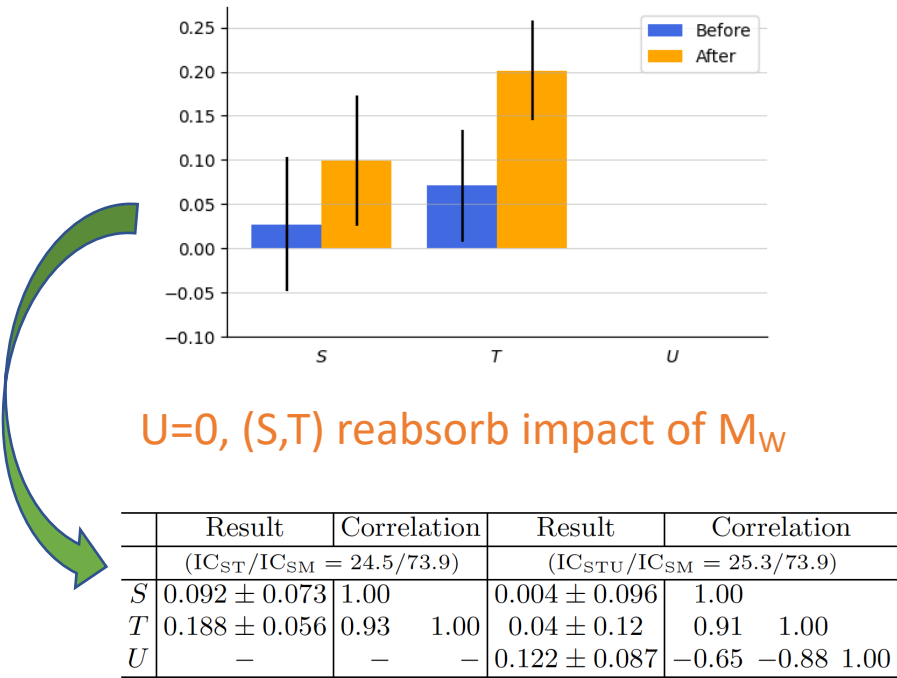
$$T = \frac{4}{s_W^2 c_W^2 M_Z^2} [\Pi_{11}^{\text{NP}}(0) - \Pi_{33}^{\text{NP}}(0)]$$

$$U = 16\pi[\Pi_{11}^{\text{NP}'} - \Pi_{33}^{\text{NP}'}(0)]$$

$$g_{\text{SM}} + \Delta g \begin{cases} \Delta g^{Zf\bar{f}} \propto (S,T) \\ \Delta g^{Wf'\bar{f}} \propto (S,T,U) \end{cases}$$



$$\mathcal{O} = \mathcal{O}_{\text{SM}} + \Delta\mathcal{O}_{\text{NP}}(S,T,U)$$



Beyond the SM: SMEFT (d=6)

$$\mathcal{O}_{\phi l}^{(1)} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi) (\bar{l}_L \gamma^\mu l_L) \ ,$$

$$\mathcal{O}_{\phi l}^{(3)} = (\phi^\dagger i \overleftrightarrow{D}_\mu^i \phi) (\bar{l}_L \sigma_i \gamma^\mu l_L) \ ,$$

$$\mathcal{O}_{\phi e} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi) (\bar{e}_R \gamma^\mu e_R) \ ,$$

$$\mathcal{O}_{\phi q}^{(1)} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi) (\bar{q}_L \gamma^\mu q_L) \ ,$$

$$\mathcal{O}_{\phi q}^{(3)} = (\phi^\dagger i \overleftrightarrow{D}_\mu^i \phi) (\bar{q}_L \sigma_i \gamma^\mu q_L)$$

$$\mathcal{O}_{\phi u} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi) (\bar{u}_R \gamma^\mu u_R) \ ,$$

$$\mathcal{O}_{\phi d} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi) (\bar{d}_R \gamma^\mu d_R) \ ,$$

$$\mathcal{O}_{\phi WB} = (\phi^\dagger \sigma_i \phi) W_{\mu\nu}^i B^{\mu\nu} \ ,$$

$$\mathcal{O}_{\phi D} = (\phi^\dagger D^\mu \phi)^* (\phi^\dagger D_\mu \phi) \ ,$$

$$\mathcal{O}_l = (\overline{l}_L \gamma^\mu l_L)(\overline{l}_L \gamma^\mu l_L)$$

Zff/Wff
vertex
corrections

W/Z propagators $\longleftrightarrow$ S,T

 G_F

Very loose prediction of M_W from $\Gamma_W(M_W)$

Model	Pred. M_W [GeV]	Pull	Pred. M_W [GeV]	Pull
	<i>standard average</i>		<i>conservative average</i>	
SMEFT	80.66 ± 1.68	-0.1σ	80.66 ± 1.68	-0.1σ

Only 8 independent combinations enter EWPO

$$\begin{aligned}\hat{C}_{\varphi f}^{(1)} &= C_{\varphi f}^{(1)} - \frac{Y_f}{2} C_{\varphi D}, \quad f = l, q, e, u, d, \\ \hat{C}_{\varphi f}^{(3)} &= C_{\varphi f}^{(3)} + \frac{c_w^2}{4s_w^2} C_{\varphi D} + \frac{c_w}{s_w} C_{\varphi WB}, \quad f = l, q, \\ \hat{C}_{ll} &= \frac{1}{2} ((C_{ll})_{1221} + (C_{ll})_{2112}) = (C_{ll})_{1221},\end{aligned}$$

[illegible]

Parameter	Before (Blue)	After (Orange)
$\hat{C}_{\varphi L1}$	0.00	0.00
$\hat{C}_{\varphi L3}$	-0.02	-0.05
$\hat{C}_{\varphi e}$	0.00	0.00
$\hat{C}_{\varphi Q1}$	-0.02	-0.02
$\hat{C}_{\varphi Q3}$	-0.08	-0.10
$\hat{C}_{\varphi u}$	0.08	0.09
$\hat{C}_{\varphi d}$	-0.62	-0.62
$\hat{C}_{LL}$	0.00	-0.02

Parameter	Before (Blue)	After (Orange)
$C_{\phi L1}$	-0.002	-0.002
$C_{\phi L3}$	-0.005	-0.015
$C_{\phi e}$	0.005	0.005
$C_{\phi Q1}$	0.020	0.020
$C_{\phi Q3}$	0.005	0.005
$C_{\phi u}$	0.035	0.035
$C_{\phi d}$	-0.085	-0.085
C_{LL}	0.005	0.025
$C_{\phi WB}$	-0.005	-0.010
$C_{\phi D}$	-0.010	-0.035

No substantial impact of new mt and MW measurements, within uncertainty of the fit.

Adding Higgs observables lifts the degeneracy



Extended set of coefficients constrained independently by the global fit

[illegible]

Beyond EW fits: adding Higgs, top, DY, di-boson, flavor

Constraining new physics through the spectrum of LHC measurements and beyond

- Higgs boson observables

- Signal strengths.
- Simplified Template Cross Sections (STXS)

$$\mu_{ij} = \frac{\sigma_i \times Br_j}{(\sigma_i \times Br_j)_{SM}}$$

Preliminary results in this talk

- 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

- $pp \rightarrow W, Z \rightarrow f_i \bar{f}_j$
- $pp \rightarrow WZ, WW, ZZ, Z\gamma$

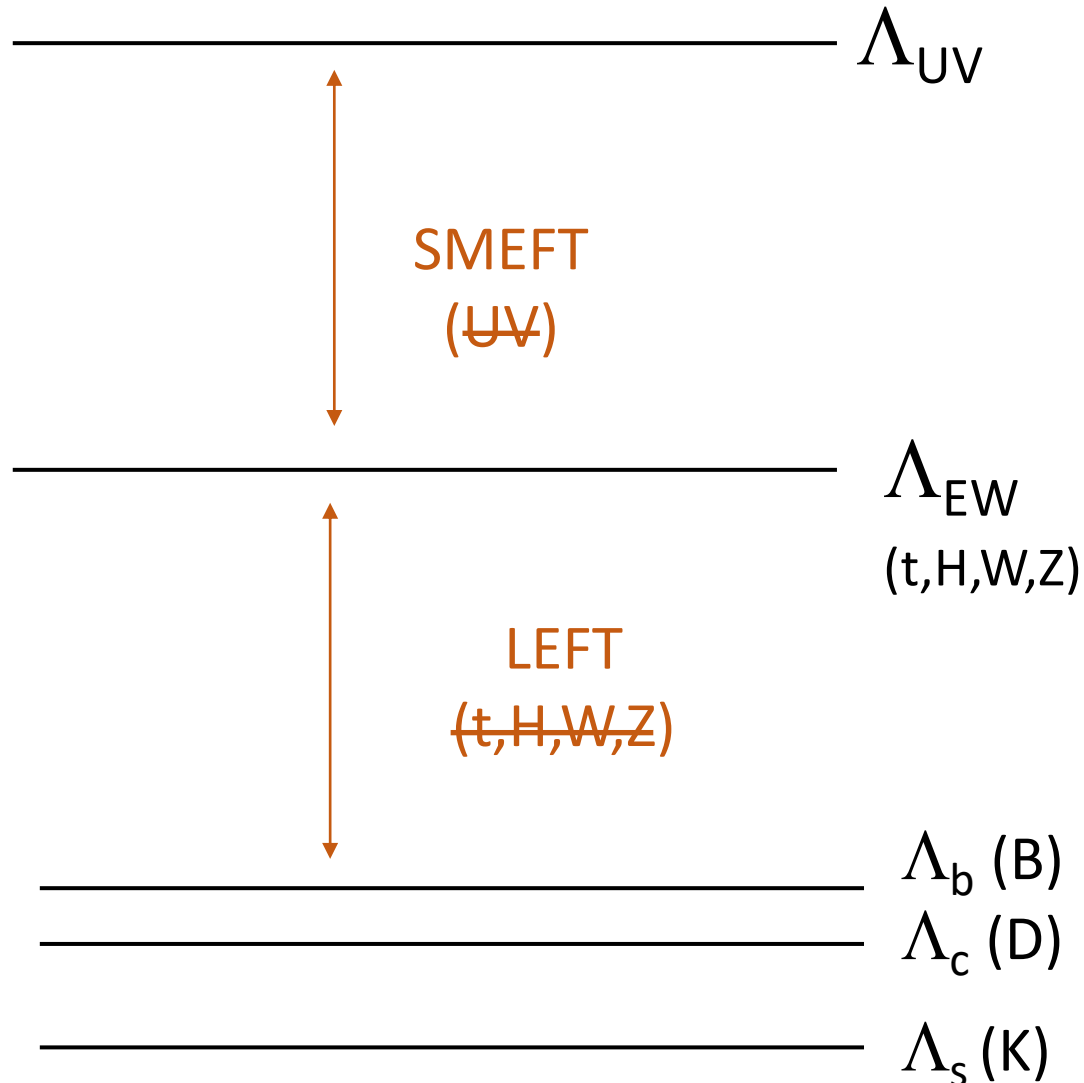
- Flavor observables

- $\Delta F=2: \Delta MB_{d,s}, D^0 - \bar{D}^0, \epsilon_K$
- Leptonic decays: $B_{d,s} \rightarrow \mu^+ \mu^-$, $B \rightarrow \tau \nu$, $D \rightarrow \tau \nu$, $K \rightarrow \mu \nu$, $\pi \rightarrow \mu \nu$
- Semi-leptonic decays: $B \rightarrow D^{(*)} l \nu$, $K \rightarrow \pi \nu \bar{\nu}$, $B \rightarrow K \nu \bar{\nu}$, $B, K \rightarrow \pi l \nu$
- Radiative B decays ($B \rightarrow X_{s,d} \gamma$)

Still being tested

Beyond EW fits – Higgs, top, flavor observables

Connecting far apart scales naturally lends itself to the EFT framework



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

RGE

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i,d} \frac{C_{i,d}^{\text{SMEFT}}}{\Lambda^2} \mathcal{O}_{i,d}^{\text{SMEFT}}$$

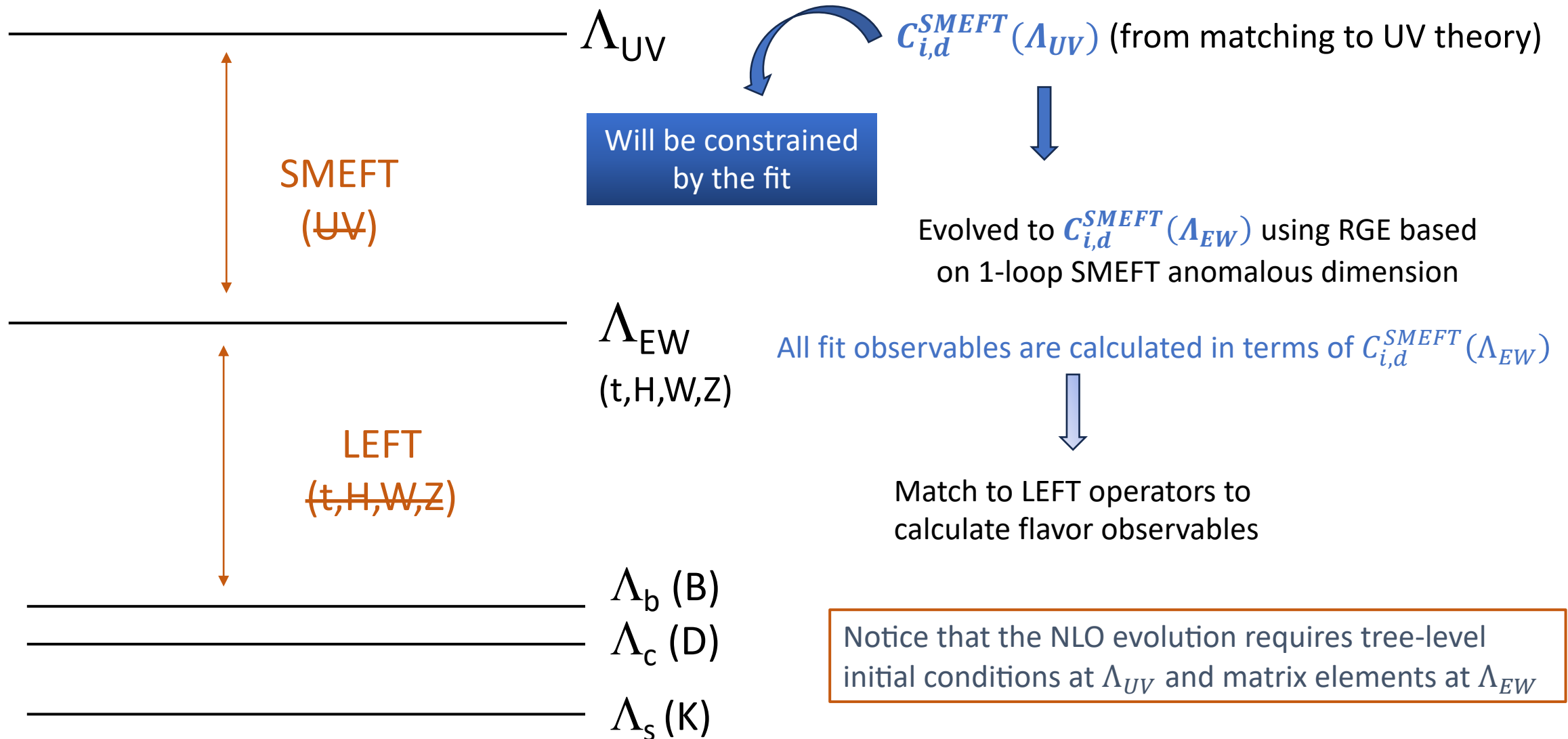
RGE

$$\mathcal{L}_{\text{LEFT}} = \mathcal{L}_{\text{QCD+QED}} + \sum_{i,d} \frac{C_{i,d}^{\text{LEFT}}}{v^2} \mathcal{O}_{i,d}^{\text{LEFT}}$$

Operators mix through RGE and what we really want to know is the SMEFT structure at the high scale

Beyond EW fits – Higgs, top, flavor observables

Connecting far apart scales naturally lends itself to the EFT framework



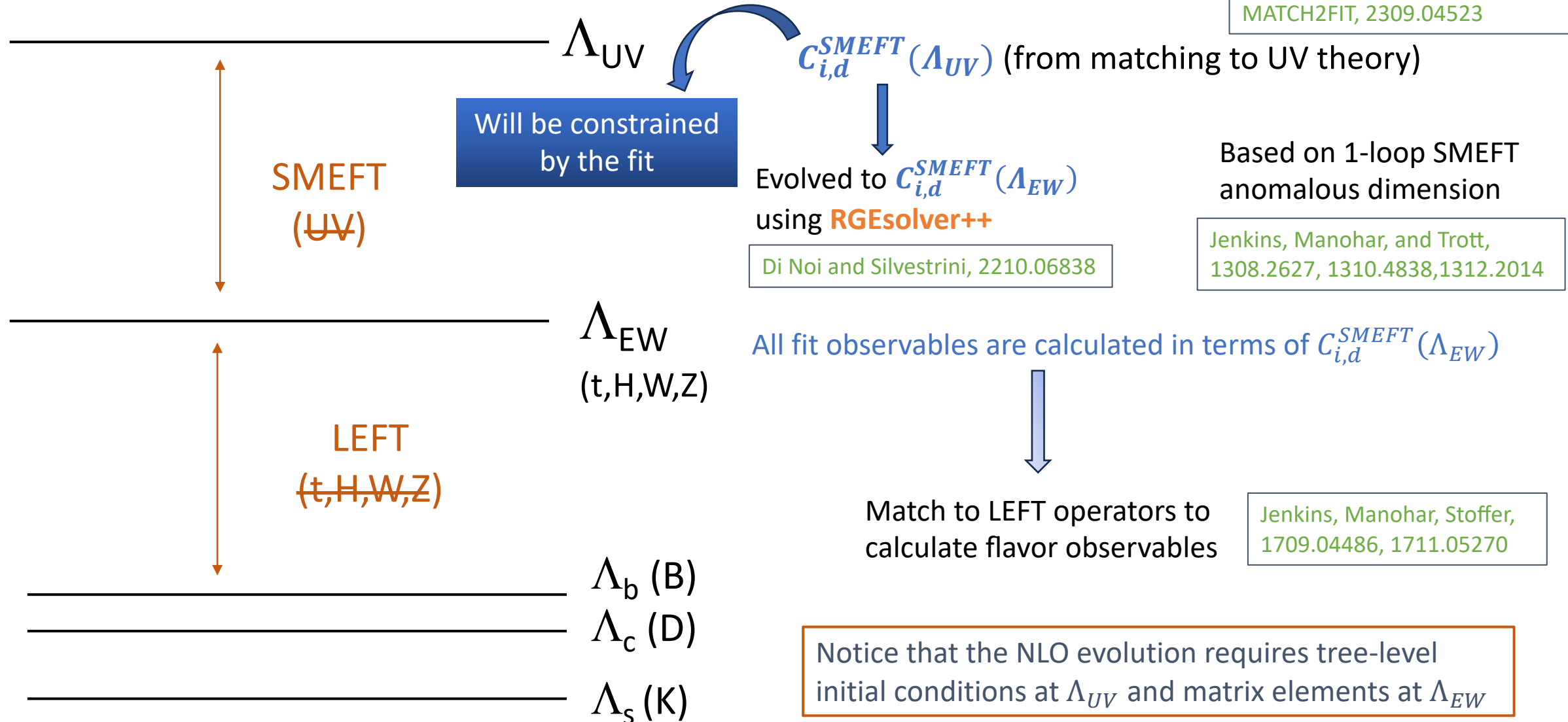
Beyond EW fits – Higgs, top, flavor observables

Connecting far apart scales naturally lends itself to the EFT framework

Starting with specific UV models:

[Matchmakereft, 2112.10787](#)

[MATCH2FIT, 2309.04523](#)



The SMEFT framework for this study

Grzadkowski, Iskrzynski,
Misiak, Rosiek, 1008.4884

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

“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

Higgs field and Mh

Yukawa couplings

vff, Hff

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
$\mathcal{O}_G$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$\mathcal{O}_\varphi$	$(\varphi^\dagger \varphi)^3$	$\mathcal{O}_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p \varphi e_r)$
$\mathcal{O}_W$	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$\mathcal{O}_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p \tilde{\varphi} u_r)$
		$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$\mathcal{O}_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p \varphi d_r)$
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$\mathcal{O}_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$\mathcal{O}_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$\mathcal{O}_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$\mathcal{O}_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$\mathcal{O}_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$\mathcal{O}_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$\mathcal{O}_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$\mathcal{O}_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
		$\mathcal{O}_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$\mathcal{O}_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
		$\mathcal{O}_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$\mathcal{O}_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
		$\mathcal{O}_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$\mathcal{O}_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
		$\mathcal{O}_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$\mathcal{O}_{\varphi ud}$	$(\tilde{\varphi}^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{ed}^{(1)}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

4-fermion interactions: tt, ttH, DY

- Dim-6 operators only, including linear and quadratic effects
- Obeying SM symmetries, CP even
- Assuming $U(2)^5$ flavor symmetry (3rd generation singled out)
- One Higgs doublet of $SU(2)_L$, SSB linearly realized.

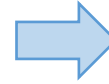
Direct and indirect SMEFT effects

Example: scalar sector

$$\mathcal{L}_\varphi = \underbrace{(D_\mu \varphi)^\dagger (D^\mu \varphi)}_{\text{kinetic}} + \underbrace{m^2 (\varphi^\dagger \varphi) - \frac{\lambda}{2} (\varphi^\dagger \varphi)^2 + \hat{C}_\varphi (\varphi^\dagger \varphi)^3 + \hat{C}_{\varphi \square} (\varphi^\dagger \varphi) \square (\varphi^\dagger \varphi)}_{\text{mass and self-energy}} + \underbrace{\hat{C}_{\varphi D} (\varphi^\dagger D_\mu \varphi)^* (\varphi^\dagger D^\mu \varphi)}_{\text{Higgs trilinear}}$$

VEV identified from the minimization of $V(\varphi)$:

$$\bar{v} = \sqrt{\frac{2m^2}{\lambda}} \left(1 + \frac{3m^2 \hat{C}_\varphi}{2\lambda^2} + \frac{63m^4 \hat{C}_\varphi^2}{8\lambda^4} + \dots \right)$$



$$\varphi = \begin{pmatrix} 0 \\ \frac{\bar{v}+h}{\sqrt{2}} \end{pmatrix}$$

Expansion of SU(2) scalar doublet around the VEV and Higgs field (unitary gauge)

Shift on the Higgs field identified from the normalization of its kinetic-term:

$$\bar{h} \equiv Z_h h = \left(1 + \frac{\bar{v}^2}{4} (\hat{C}_{\varphi D} - 4\hat{C}_{\varphi \square}) - \frac{\bar{v}^4}{32} (\hat{C}_{\varphi D} - 4\hat{C}_{\varphi \square})^2 + \dots \right) h$$

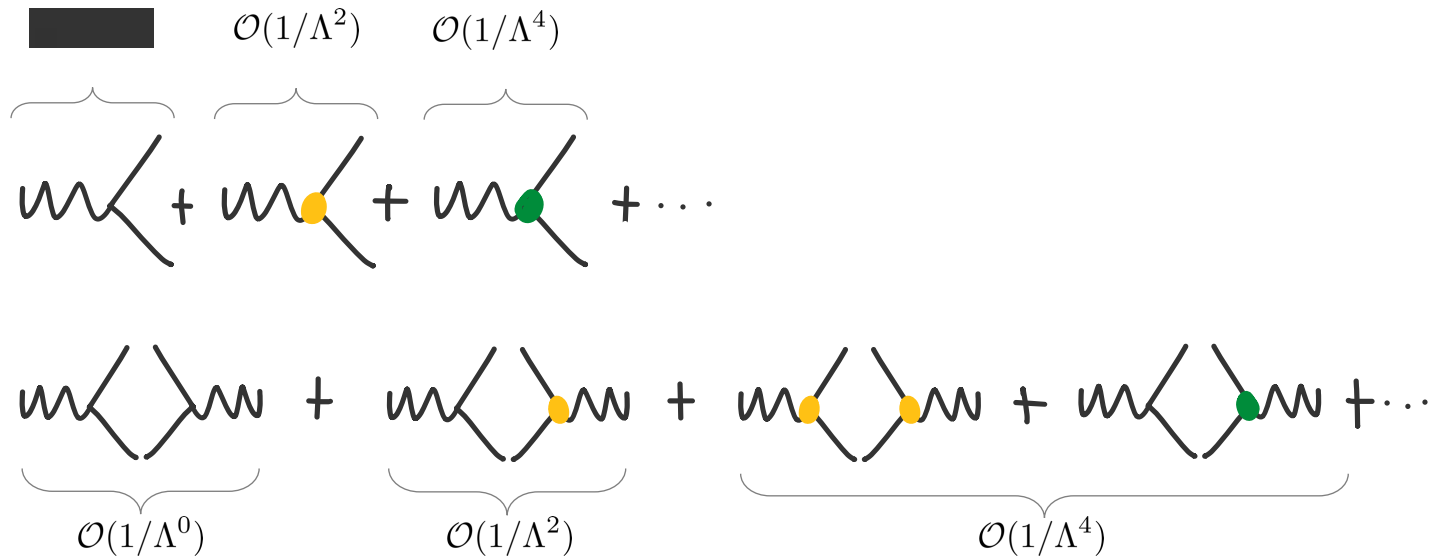
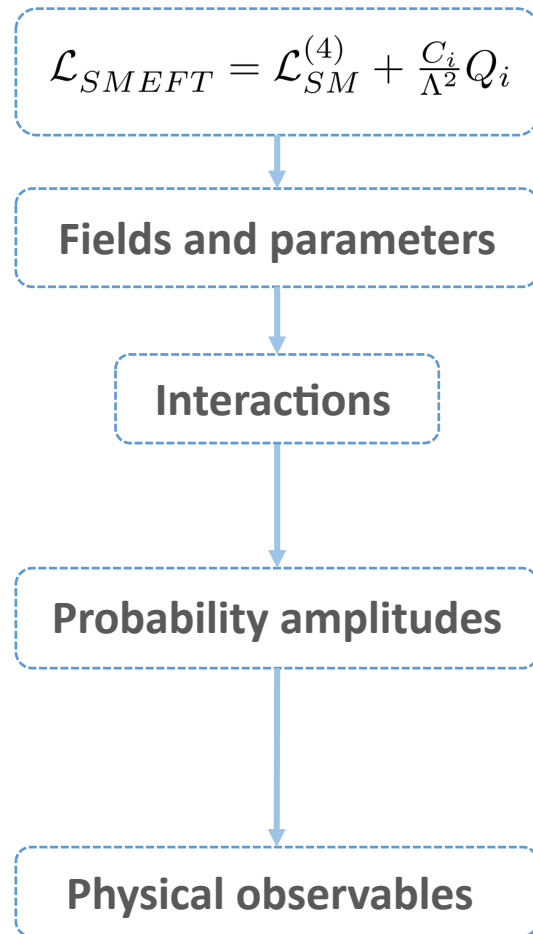
Shift on the physical mass of the Higgs field identified from the normalization of its mass-term:

$$M_h^2 = \lambda \bar{v}^2 - \bar{v}^4 \left(3\hat{C}_\varphi - 2\hat{C}_{\varphi \square} \lambda + \frac{1}{2} \hat{C}_{\varphi D} \lambda \right) - \frac{\bar{v}^6}{2} (4\hat{C}_{\varphi \square} - \hat{C}_{\varphi D}) \left(3\hat{C}_\varphi - 2\hat{C}_{\varphi \square} \lambda + \frac{1}{2} \hat{C}_{\varphi D} \lambda \right) + \dots$$

Direct effect on hVV interaction

$$\hat{C}_{\varphi D} (\varphi^\dagger D_\mu \varphi)^* (\varphi^\dagger D^\mu \varphi) \longrightarrow V^\mu V_\mu h$$

SMEFT predictions



$$O_{SMEFT} = O_{SM} + \underbrace{\Delta O^{(1)}}_{\text{yellow}} + \underbrace{\Delta O^{(2)}}_{\text{yellow-green}} + \dots$$

SMEFT predictions

A given observable will be written as

$$O_{\text{SMEFT}} = O_{\text{SM}} + \Delta O^{(1)} + \Delta O^{(2)} + \dots$$

SM: including SM
higher-order corrections

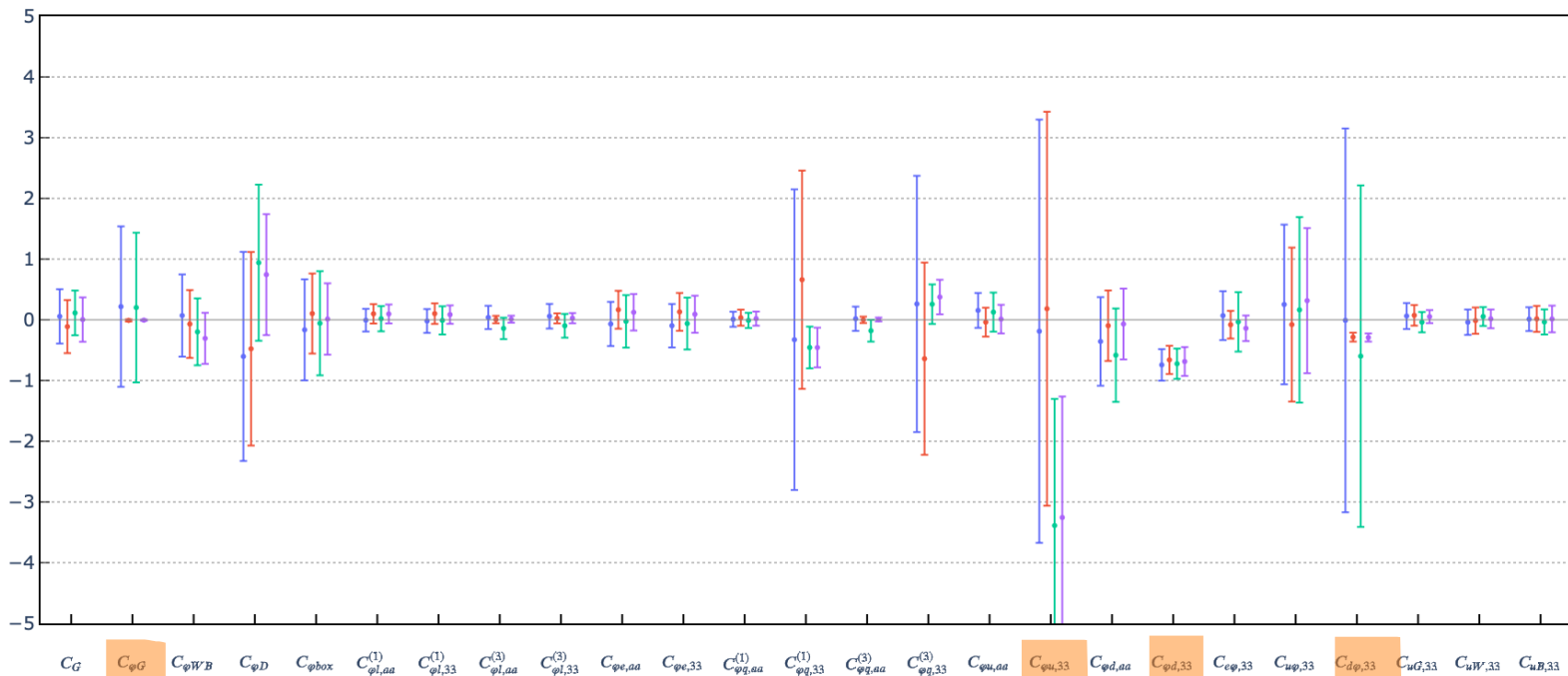
SMEFT: tree level

Observables have been calculated either analytically and via parametrizations reported in the literature (e.g. EW observables) or obtained using various tools (MG5_aMC@NLO with **SMEFTci2**, a new UFO file developed for this study, Feynart+Feyncalc for loop-induced Higgs decays, ...)

See also, SmeftFR-v3, Dedes et al. 2302.01353

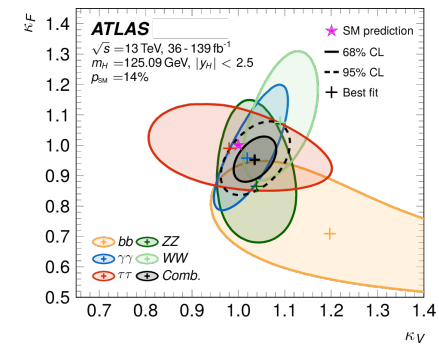
Including direct and indirect SMEFT effects from dim-6 operators up to $O(1/\Lambda^4)$, by **A. Goncalves**

Example of Preliminary results

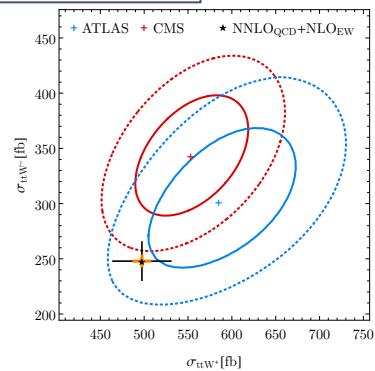


- EW Observables
- EW & Higgs Observables
- EW & Top-quark Observables
- EW, Higgs & Top-quark Observables

De Blas et al.
In preparation



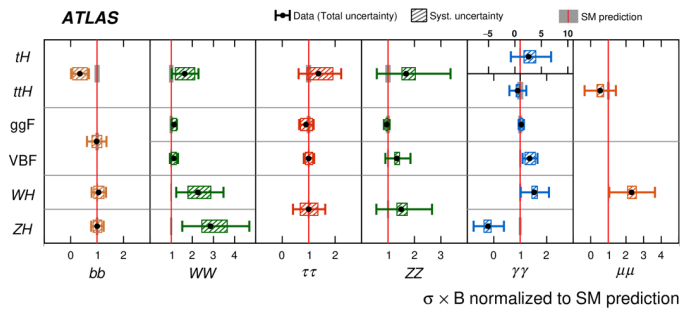
Highly constrained from ggH
RGE effects visible



Effect of V_{tt} ($V=Z,W,\gamma$)

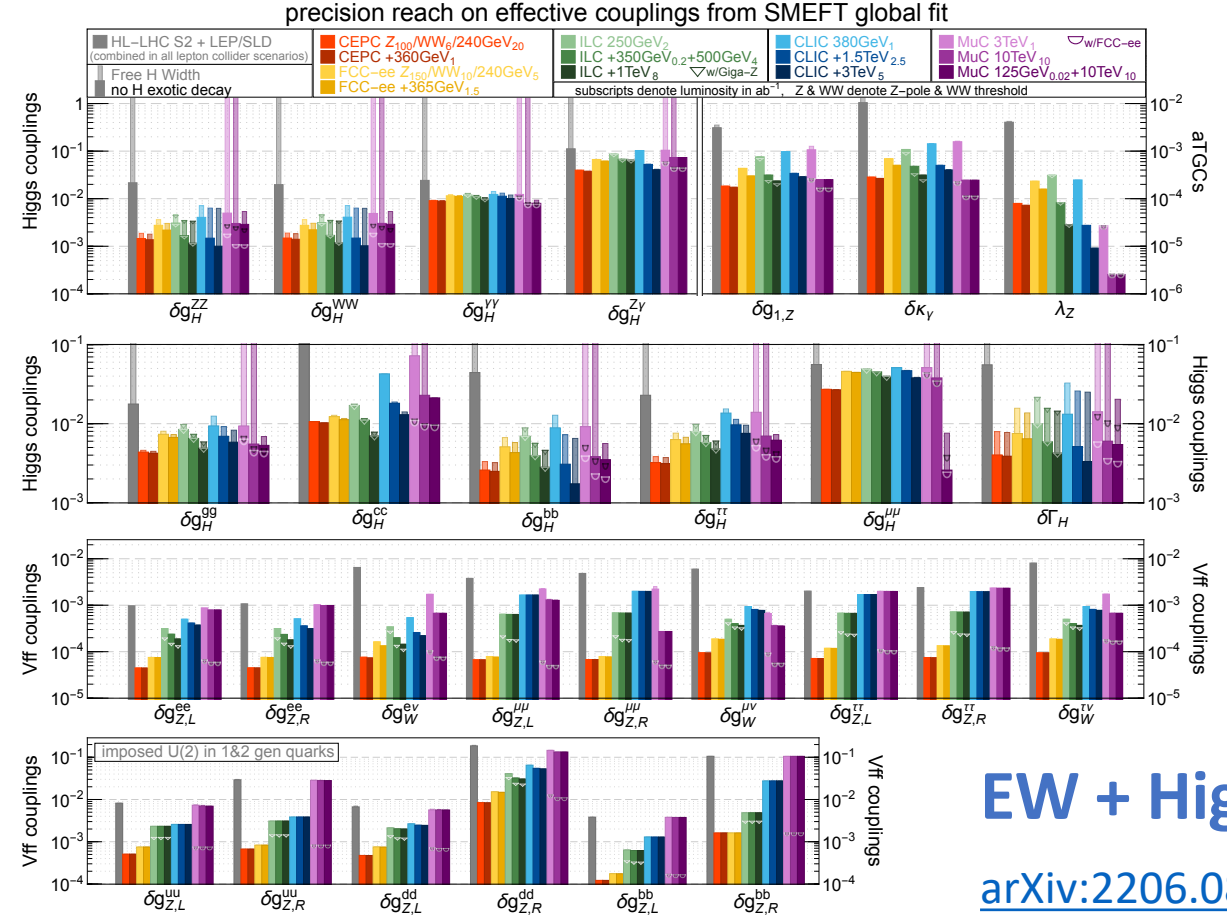
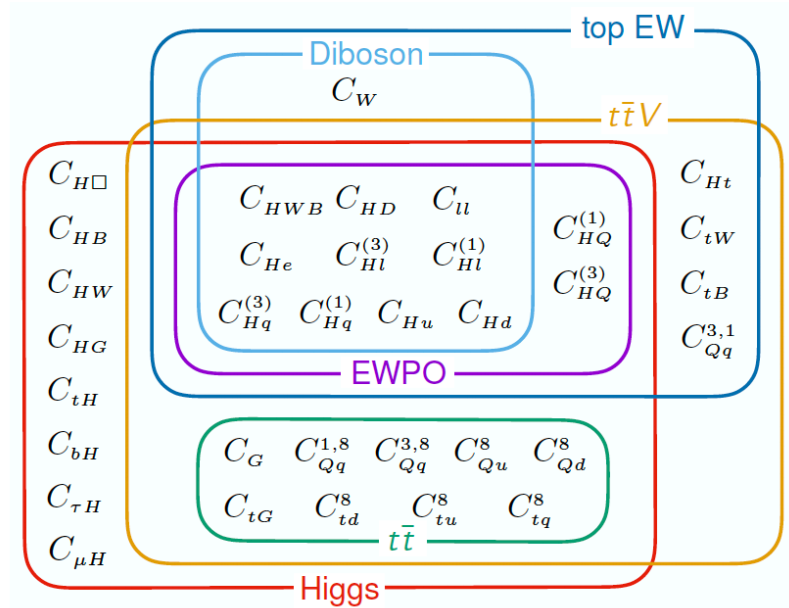
Driven by EW

Effect on H to bb



Projecting back on EW and Higgs couplings

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



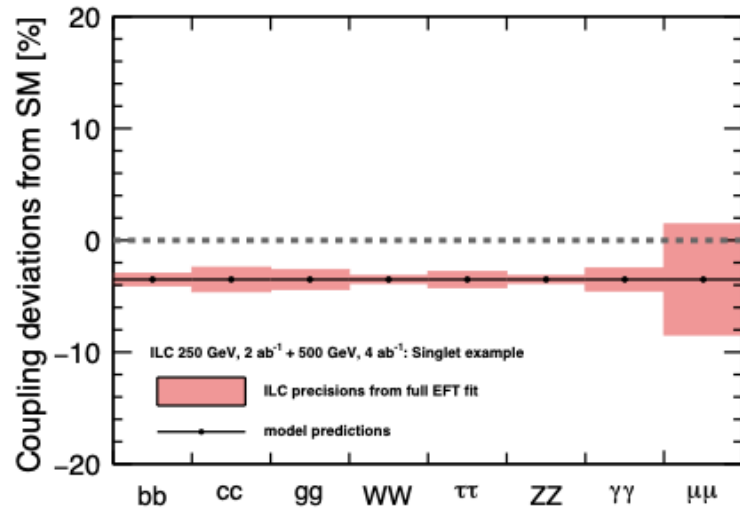
EW + Higgs

[arXiv:2206.08326](https://arxiv.org/abs/2206.08326)

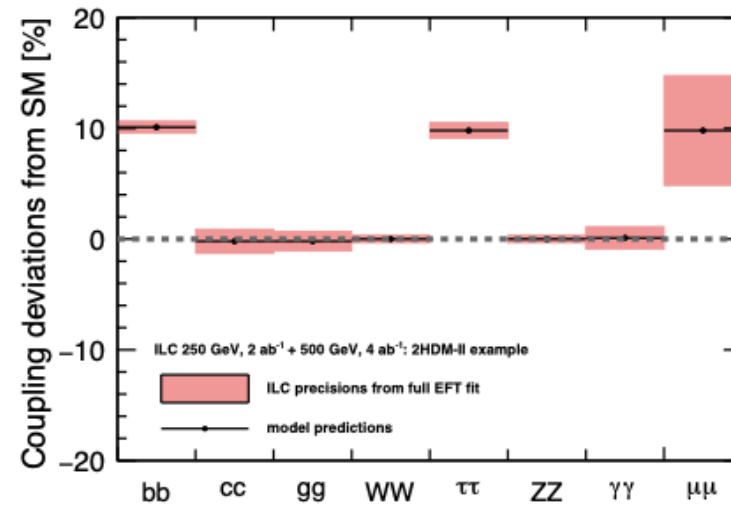
EFT connects different processes with large correlations: pattern of coefficients give insights on underlying BSM model

Disentangling models from EFT patterns

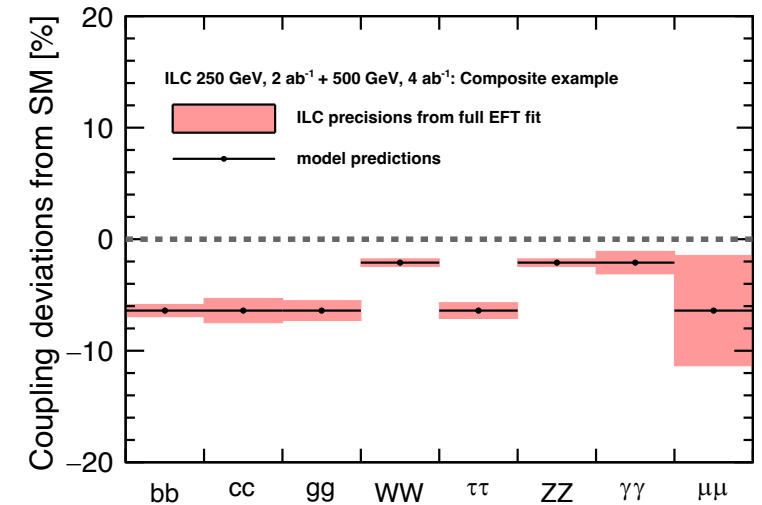
The “inverse Higgs” problem



additional scalar singlet
($m_S=2.8$ TeV, max mixing)



2HDM-II
($M_H=600$ GeV, $\tan\beta=7$)



Composite Higgs
($f=1.2$ TeV)

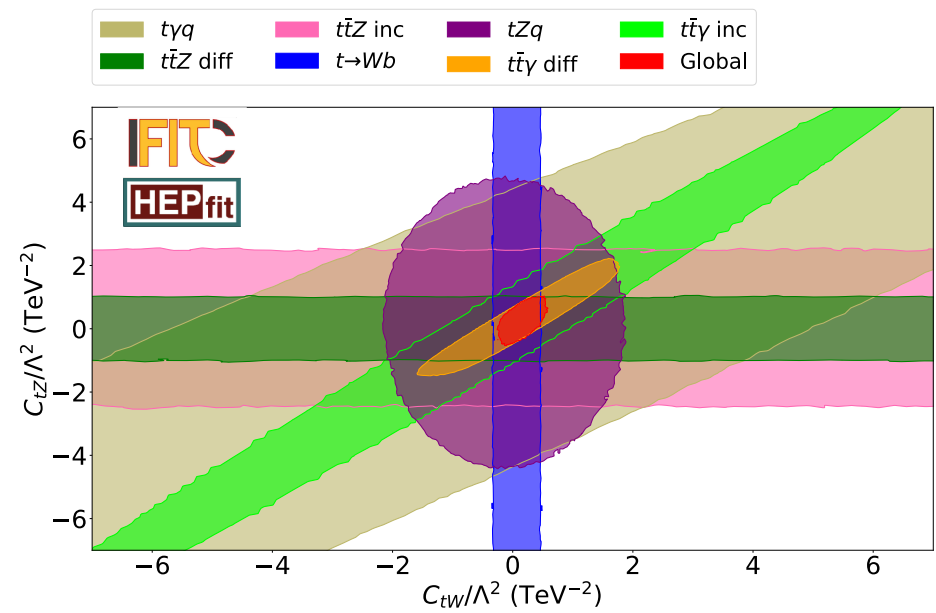
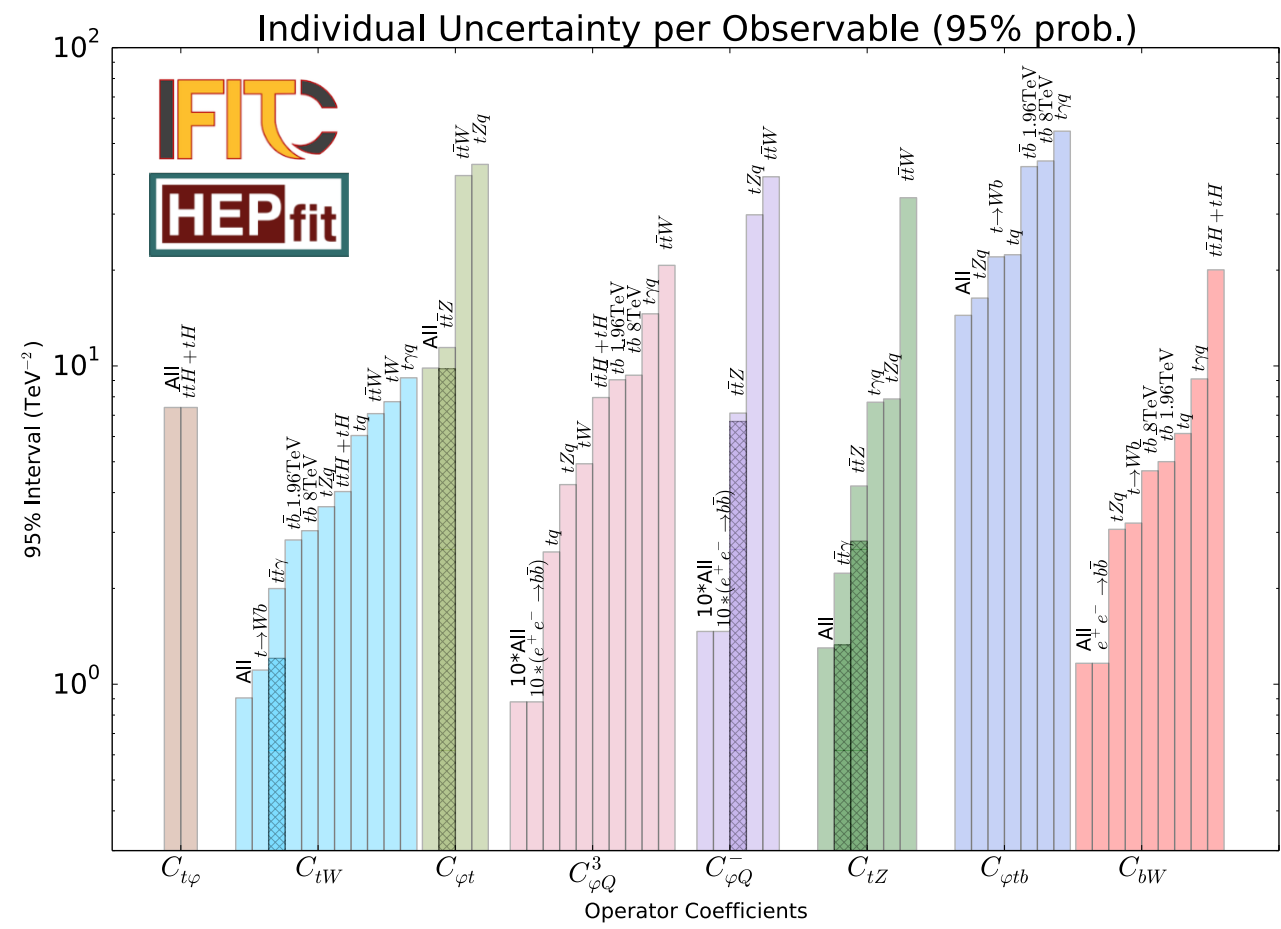
Snowmass 2021: ILC white paper ([arXiv: 2203.07622](https://arxiv.org/abs/2203.07622))

Examples to illustrate the **different patterns of Higgs coupling deviations** from **different BSM models**

EFT allows multiple probes

Global fits of top observables

V. Miralles, et al. [arXiv:2107.13917]



Kinematic distributions add substantial constraining power



Accurate modelling of $t\bar{t}+X$ differential cross sections and signatures becomes crucial

Testing the SMEFT framework

Assessing the validity of the EFT approach: relevance of higher-order terms in the EFT expansion.

Relevance of dim-6 quadratic terms – The case of EW fits

Testing the EFT expansion to dim-6. Tensions could indicate need for dim-8 in specific cases.

Analytic parametrization of Z and W observables:

$$\Gamma_{Z,f} = N_f \frac{G_F M_Z^3}{24\sqrt{2}\pi} 4 [(g_{V,f})^2 + (g_{A,f})^2]$$

$$R_e^0 = \frac{\Gamma_{had}}{\Gamma_e} \quad R_{q,\nu}^0 = \frac{\Gamma_{q,\nu}}{\Gamma_{had}}$$

$$\sigma_{had}^0 = \frac{12\pi}{M_Z^2} \frac{\Gamma_e \Gamma_{had}}{\Gamma_Z^2}$$

$$A_f = \frac{2 \left(\frac{g_{V,f}}{g_{A,f}} \right)}{1 + \left(\frac{g_{V,f}}{g_{A,f}} \right)^2} \quad A_{FB,f} = \frac{3}{4} A_e A_f$$

Z

$$\sin^2 \theta_{eff,l} = \frac{1}{4} \left(1 - \frac{g_{V,l}}{g_{A,l}} \right)$$

W[±]

$$M_W \quad \Gamma_{(W \rightarrow f_i f_j)} \quad Br W_{f_i f_j}$$

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

$$O_{SMEFT} = O_{SM} + \Delta O^{(1)} + \Delta O^{(2)} + \dots$$

$$g_{V,f} = g_{V,f}^{SM} + \Delta g_{V,f}^{(1)} + \Delta g_{V,f}^{(2)} + \dots$$

$$g_{A,f} = g_{A,f}^{SM} + \Delta g_{A,f}^{(1)} + \Delta g_{A,f}^{(2)} + \dots$$

$$m \text{ (diagram)} + m \text{ (diagram)} + m \text{ (diagram)} + \dots$$

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

$\psi^2 \varphi^2 D$	
$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{l}'_p \gamma^\mu l'_r)$
$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi) (\bar{l}'_p \tau^I \gamma^\mu l'_r)$
$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{e}'_p \gamma^\mu e'_r)$
$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{q}'_p \gamma^\mu q'_r)$
$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi) (\bar{q}'_p \tau^I \gamma^\mu q'_r)$
$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{u}'_p \gamma^\mu u'_r)$
$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{d}'_p \gamma^\mu d'_r)$
$Q_{\varphi ud}$	$i (\tilde{\varphi}^\dagger D_\mu \varphi) (\bar{u}'_p \gamma^\mu d'_r)$

Relevance of dim-6 quadratic terms – The case of EW fits

Preliminary Global Fit of EW observables at quadratic order in the dim=6 SMEFT

Observable	$C_{\varphi D}$	$C_{\varphi WB}$	$C_{\varphi L}^{(3)}$	C_{LL}	$C_{\varphi L}^{(1)}$	$C_{\varphi e}$	$C_{\varphi Q}^{(1)}$	$C_{\varphi Q}^{(3)}$	$C_{\varphi u}$	$C_{\varphi d}$	$C_{\varphi B}$	$C_{\varphi W}$	$C_{\varphi ud}$
A_l													
A_{FB}^l	✓	✓	✓	✓	✓	✓					✓	✓	
P_τ^{pol}													
$\sin \theta_{eff,l}^2$													
A_c	✓	✓	✓	✓			✓	✓	✓		✓	✓	
R_c^0													
A_b													
A_s	✓	✓	✓	✓			✓	✓		✓	✓	✓	
R_b^0													
A_{FB}^c	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	
A_{FB}^b	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	
R_l^0													
Γ_Z	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
σ_{had}^0													
M_W	✓	✓	✓	✓									
Γ_W	✓	✓	✓	✓	✓		✓			✓	✓	✓	✓
BrW													

$\mathcal{O}(1/\Lambda^4)$: degeneracy is (analytically) lifted

$\mathcal{O}(1/\Lambda^2)$: Constrain 8 independent relations

$$\hat{C}_{\varphi L}^{(3)} = \hat{C}_{\varphi L}^{(3)} + \frac{1}{4} \frac{\widetilde{c_W}^2}{\widetilde{s_W}^2} \hat{C}_{\varphi D} + \frac{\widetilde{c_W}}{\widetilde{s_W}} \hat{C}_{\varphi WB}$$

$$\hat{C}_{\varphi Q}^{(3)} = \hat{C}_{\varphi Q}^{(3)} + \frac{1}{4} \frac{\widetilde{c_W}^2}{\widetilde{s_W}^2} \hat{C}_{\varphi D} + \frac{\widetilde{c_W}}{\widetilde{s_W}} \hat{C}_{\varphi WB}$$

$$\hat{C}_{\varphi L}^{(1)} = \hat{C}_{\varphi L}^{(1)} + \frac{1}{4} \hat{C}_{\varphi D}$$

$$\hat{C}_{\varphi Q}^{(1)} = \hat{C}_{\varphi Q}^{(1)} - \frac{1}{12} \hat{C}_{\varphi D}$$

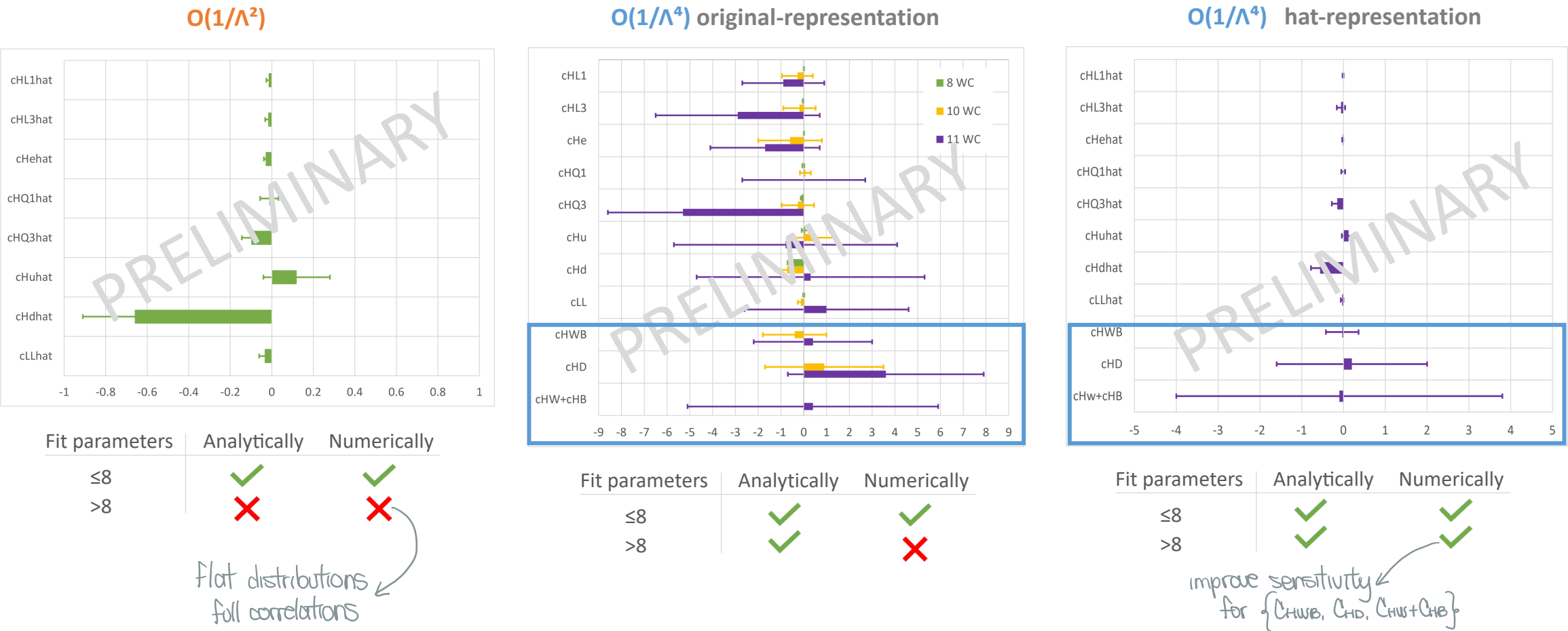
$$\hat{C}_{\varphi e} = \hat{C}_{\varphi e} + \frac{1}{2} \hat{C}_{\varphi D}$$

$$\hat{C}_{\varphi u} = \hat{C}_{\varphi e} - \frac{1}{3} \hat{C}_{\varphi D}$$

$$\hat{C}_{LL} = \hat{C}_{LL}$$

Relevance of dim-6 quadratic terms – The case of EW fits

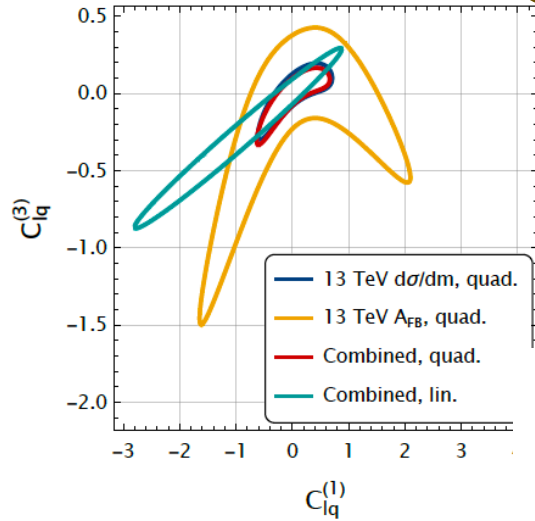
Preliminary Global Fit of EW observables at quadratic order in the dim=6 SMEFT:



Relevance of dim-8 operators – The case of DY

Increased precision allows sensitivity to SMEFT expansion beyond dim-6

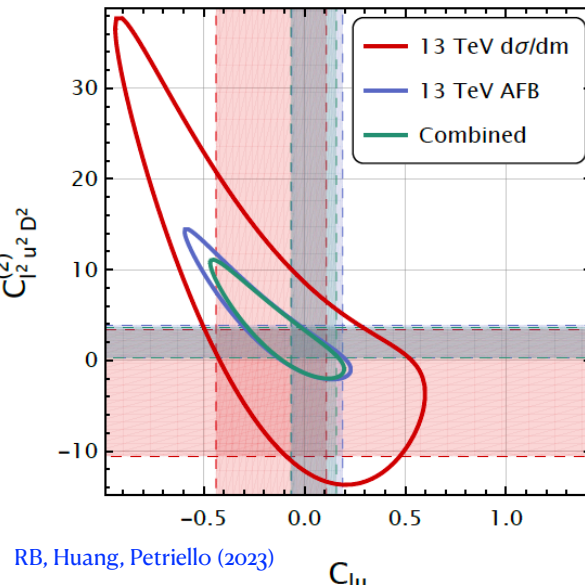
RB, Huang, Petriello (2023) $\Lambda = 4 \text{ TeV}$



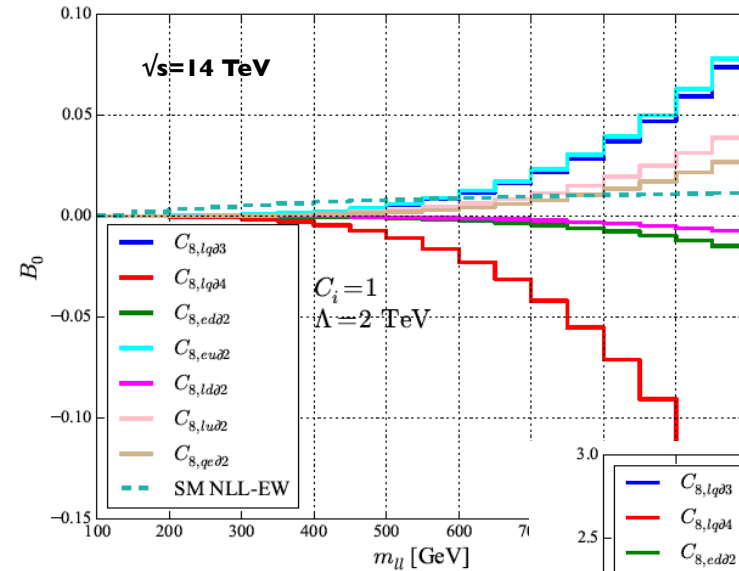
Need to explore effects of dim-8

See large effects by expanding dim-6 at quadratic order

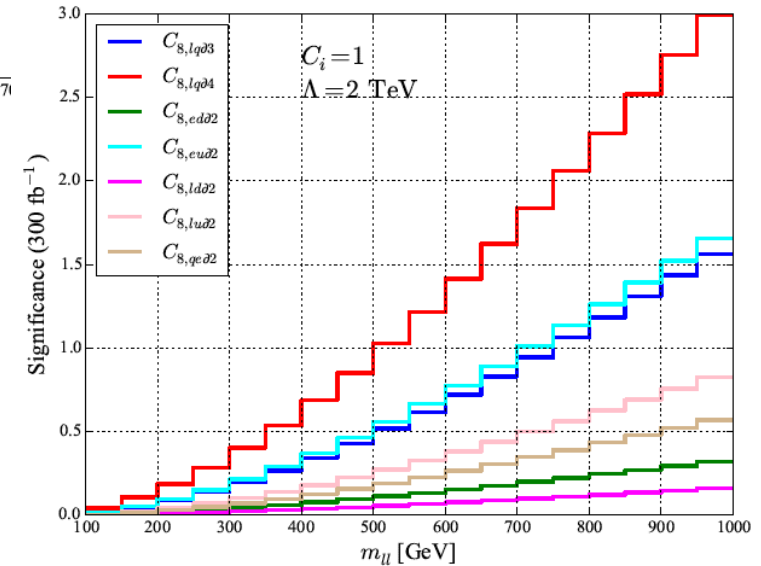
From R. Boughezal's talk at Loopfest 2024



RB, Huang, Petriello (2023)



Non-SM effects from dim-8 in angular distributions



Conclusions

- **Global fits** stress-test the SM and provide a **very strong indirect constraint on new physics**.
- Effects of new physics can then be constrained using the **broad spectrum of precision measurement available from EW, Higgs, top, flavor physics** and more.
- The **SMEFT (→LEFT) framework** can be used to connect unknown physics at the UV scale (> 1 TeV) to the EW scale and below within a **systematic framework that allows some model independence**.
- With **increasing precision** in both theory and experiments, constraints **could start to show intriguing patterns and guide future explorations**.