Offshell 2021 - Theory ideas

Precision, complexity, and the quest for new physics

Laura Reina

Florida State University

OFFSHELL 2021

THE VIRTUAL HEP CONFERENCE

RUN 4 HL LHC

Block A: July 6, 2021

Later Today: Block B: "Theory Ideas" by Nathaniel Craig

Particle physics in the LHC era: a unique time

So much of the LHC physics potential is ahead of us:

↪ c.o.m. energy will increase from 13 TeV to 14 TeV.

↪ 2-fold increase in statistics by the end of Run 3.

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

Energy Frontier: Exploring the TeV scale

- **LHC Run 1**: the **Higgs discovery** has been a game changer.
- **LHC Run 2**: **a wealth of new measurements**.
  - ▷ Improved precision measurements of SM processes, total and differential rates.
  - ▷ Entering the era of precision Higgs physics.
  - ▷ More stringent bounds on new physics scenarios.
- The **LHC Run 3** and the **HL-LHC** are **a reality**.
- Updated scenarios for **future colliders are being proposed** based on LHC results, HL-LHC projections, and theory recommendations.
- Intriguing results coming from **rare processes**, **flavour physics**, **cosmology**, ... can give important indications.

With no evidence of new physics or a preferred way beyond the Standard Model progress crucially relies on **Precision Physics**

Particle physics and precision in the LHC era

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Particle physics and precision in the LHC era

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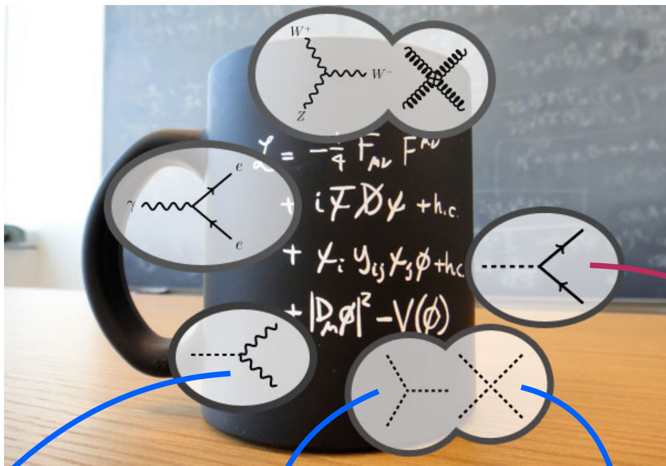
The SM is a very predictive theory

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

$\mathcal{L}_{QCD} \rightarrow \{g_s\}$

$\mathcal{L}_{EW} \rightarrow \{g_1, g_2, \mu, \lambda\} + \{y_f, V_{CKM}\}$



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

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

$\mathcal{L}_{EW}^{\text{gauge}} \longrightarrow 1^{\text{st}}$ line

$\mathcal{L}_{EW}^{\text{ferm}} \longrightarrow 2^{\text{nd}}$ line

$\mathcal{L}_{EW}^{Yukawa} \longrightarrow 3^{\text{rd}}$ line $\longleftarrow$ flavour

$\mathcal{L}_{EW}^{scalar} \longrightarrow 4^{\text{th}}$ line $\longleftarrow$ EWSB

where:

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

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

with ($\mu^2 < 0$):

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

($v = (\sqrt{2}G_F)^{-1/2}$ with G_F from μ-decay)

Lagrangian parameters all constrained by precision measurements:

$$\{g_1, g_2, \mu, \lambda\} \xrightarrow{e.g.} \{M_Z, M_W, G_F, M_H\} \text{ or } \{\alpha, M_Z, G_F, M_H\}$$

$$\{y_f, V_{CKM}\} \rightarrow \{m_f + \text{flavour}\}$$

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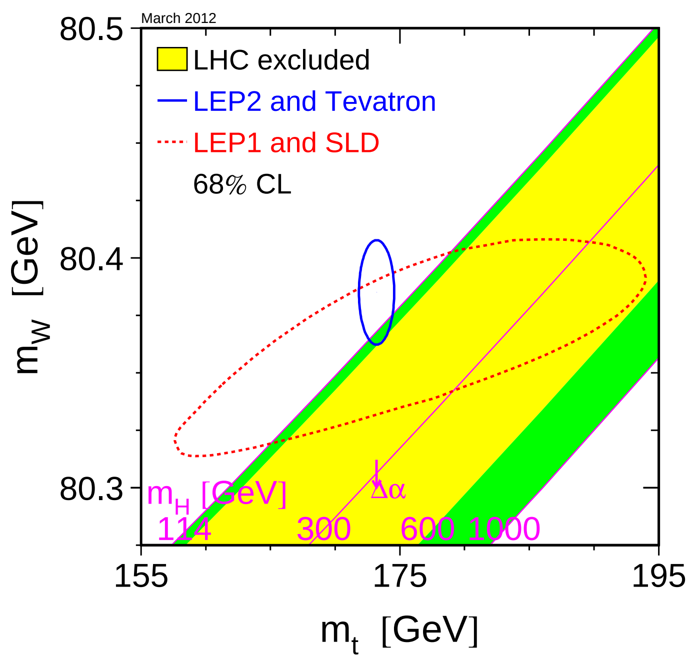
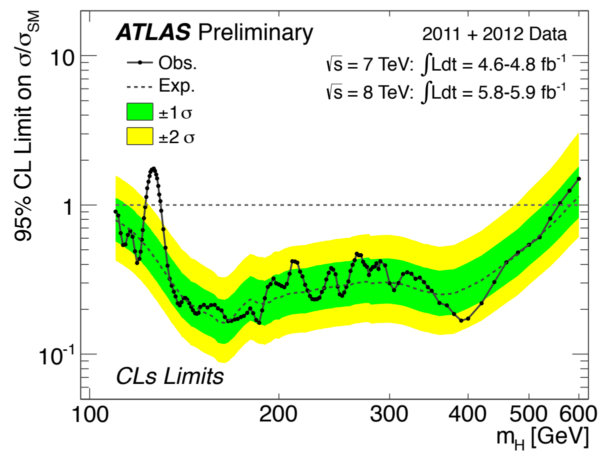
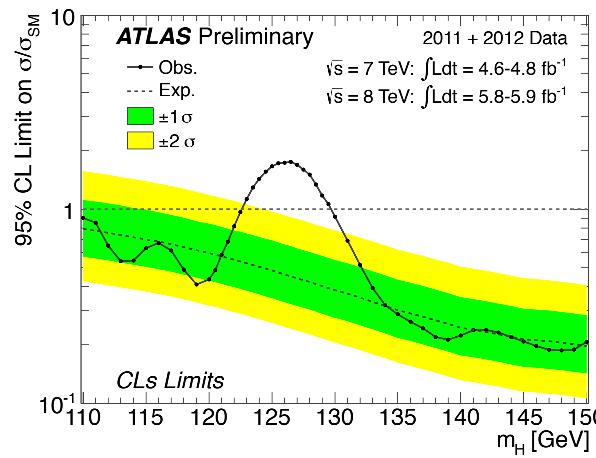
Higgs boson: a remarkable prediction of precision EW fits

Confirmed by a discovery only made possible by the synergy of experimental and theoretical accuracy.







$\Downarrow$

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

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

Measured in Run I of the LHC: $\boxed{M_{\rm H} = 125.09 \pm 0.24 \quad \text{GeV}}$

Key Question: What is the origin of the EW scale?

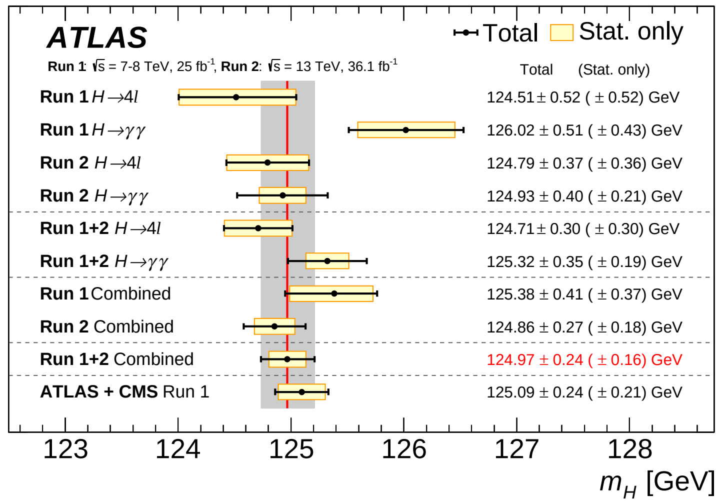
The Higgs discovery has given us a unique handle on BSM physics and any future plan needs to make the most out of it.

- Why the $M_H \ll M_{pl}$ hierarchy problem? What are the implications for Naturalness?
- Can we uncover the nature of UV physics from precision Higgs measurements (mass, width, couplings)?
- Can the Higgs give us insight into flavor and vice versa?
- Can we measure the shape of the Higgs potential?
- Can constraints come from other effects of the EW phase transition (ex. gravitational waves)?

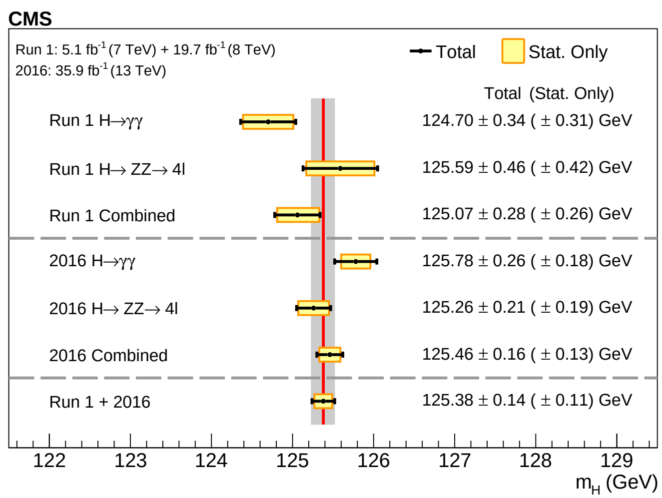
These theory-motivated benchmarks will influence future directions in both theory and experiments at the Energy Frontier. Pursuing them can change our understanding of BSM physics.

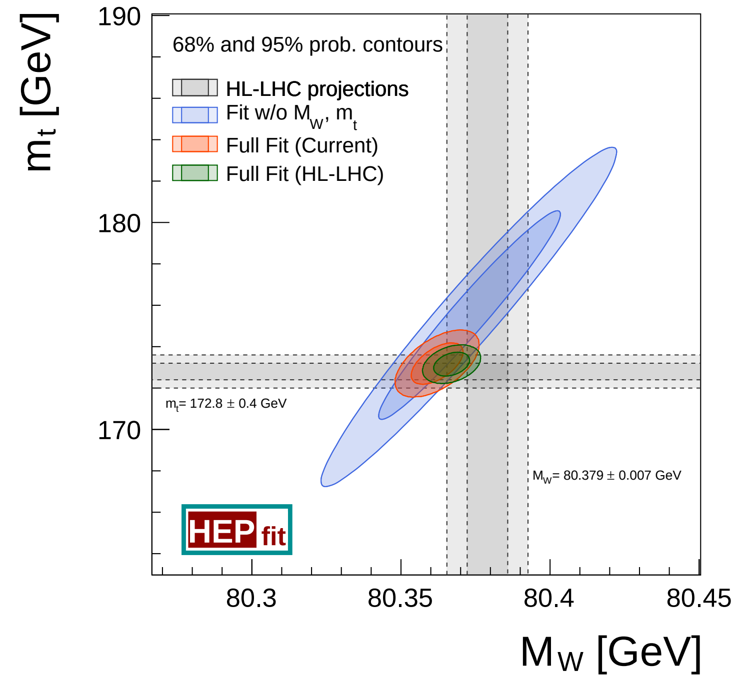
$\hookrightarrow$ See N. Craig's talk

LHC Run 1+Run 2: M_H promoted to EW precision observable



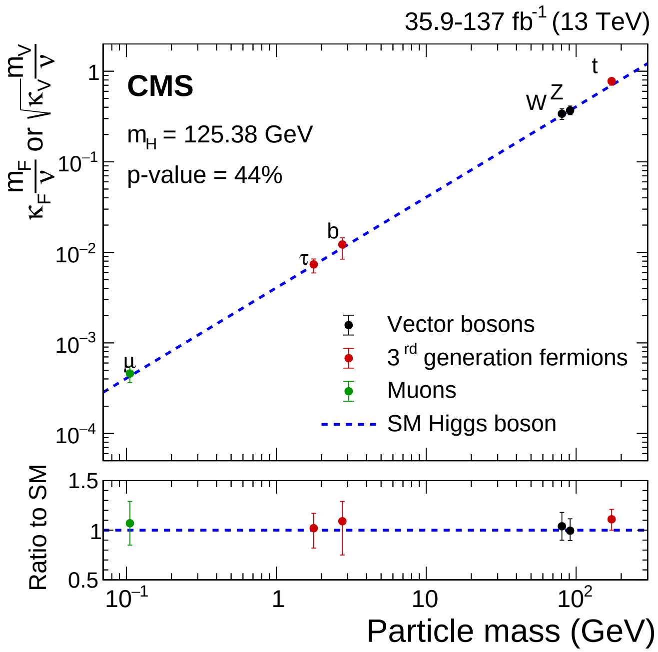
Crucial to realize the EW precision program of the HL-LHC.



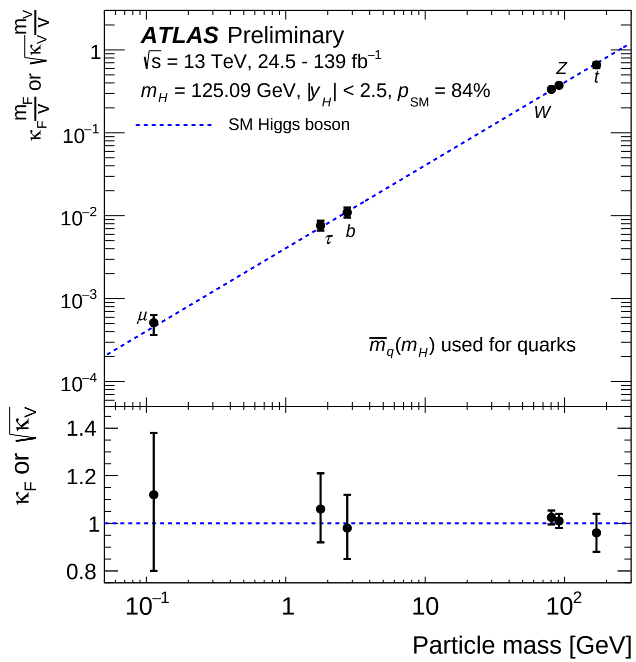


Effects of New Physics can now be more clearly disentangled in both EW observables and Higgs-boson couplings $\longleftrightarrow$ probing EWSB

LHC Run 1+Run 2: first measurement of Higgs couplings



[CMS, JHEP 01 (2021) 148]



[ATLAS-CONF-2020-027]

κ_i	ATLAS	CMS	HL-LHC
κ_Z	$1.02^{+0.06}_{-0.06}$	$0.99^{+0.11}_{-0.12}$	1.5%
κ_W	$1.05^{+0.06}_{-0.06}$	$1.10^{+0.12}_{-0.17}$	1.7%
κ_t	$0.96^{+0.08}_{-0.08}$	$1.11^{+0.12}_{-0.10}$	3.4%
κ_b	$0.98^{+0.14}_{-0.13}$	$-1.10^{+0.33}_{-0.23}$	3.7%
κ_τ	$1.06^{+0.15}_{-0.14}$	$1.01^{+0.16}_{-0.20}$	1.9%
κ_μ	$1.12^{+0.26}_{-0.32}$	$1.07^{+0.22}_{-0.22}$	4.3%

$$\kappa_i = \frac{g_{Hi}}{g_{Hi}^{\rm SM}}$$

→ Higgs couplings to gauge bosons measured to 5-10% level.

→ Higgs couplings to 3^{rd}-generation fermions measured at 10-25% level.

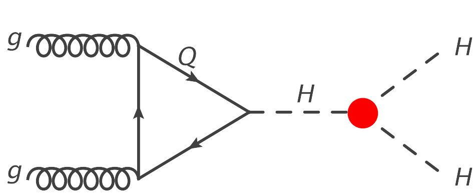
→ **Projections for HL-LHC look impressive!**

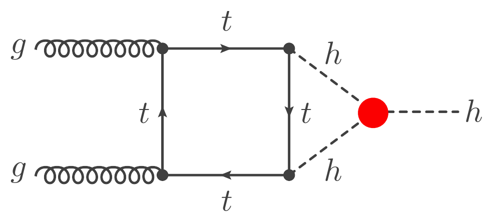
→ Ultimate challenge: measuring the Higgs self-coupling(s).

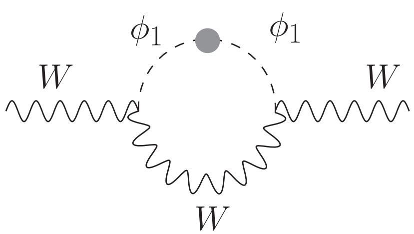
The ultimate challenge: measuring the Higgs potential

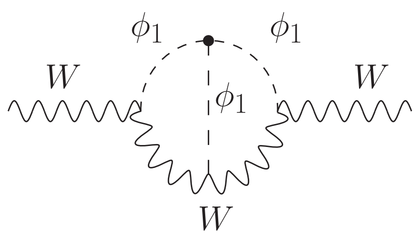
Difficult measurement: high multiplicity, severe backgrounds.

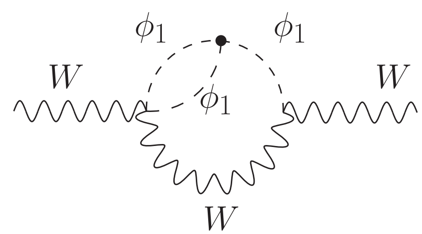
Complex, very rich theoretical structure.

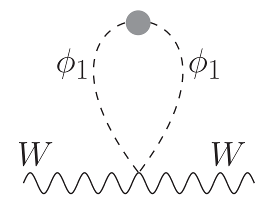












Collider	Accuracy on κ_λ	Running Years
HL-LHC	50%	12
HE-LHC	10-20%	20
ILC(500)	27%	21
CLIC(1500)	36%	15
CLIC(3000)	+11%, -7%	23
FCC(hh)	5%	13

Higgs self-coupling(s) $\leftrightarrow$ EWSB

- $\hookrightarrow$ Double vs single H production?
- $\hookrightarrow$ Indirect measurement?
- $\hookrightarrow$ Can we measure both λ_3 and λ_4?

Odds can change by exploring all ideas!

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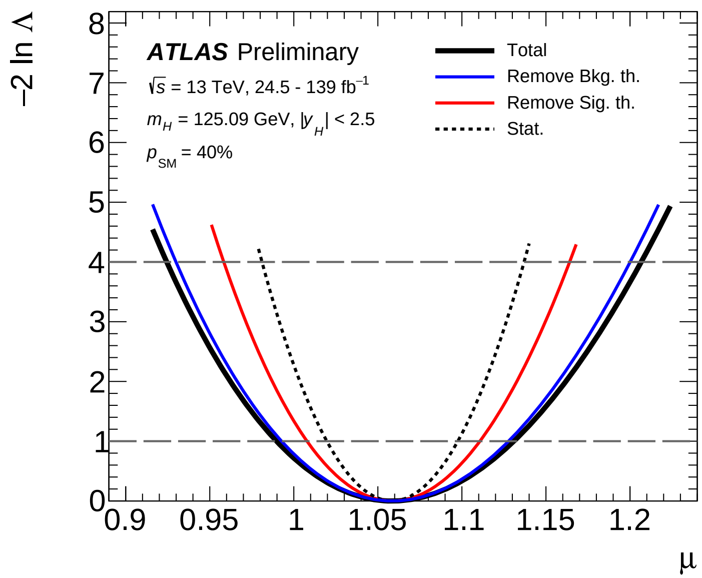
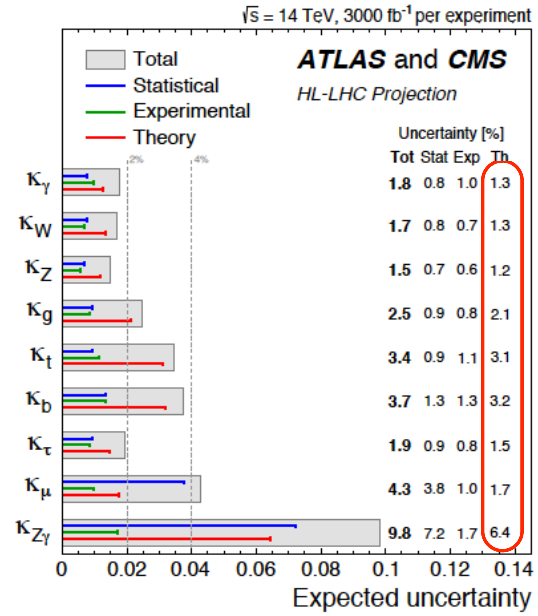
Th. vs Exp. accuracy: Higgs-boson couplings





HL-LHC (S2: Theory syst. half of LHC)

Error dominated by Theory systematics

$$\mu_{if} = \frac{\sigma_i}{\sigma_i^{SM}} \times \frac{B_f}{B_f^{SM}}$$

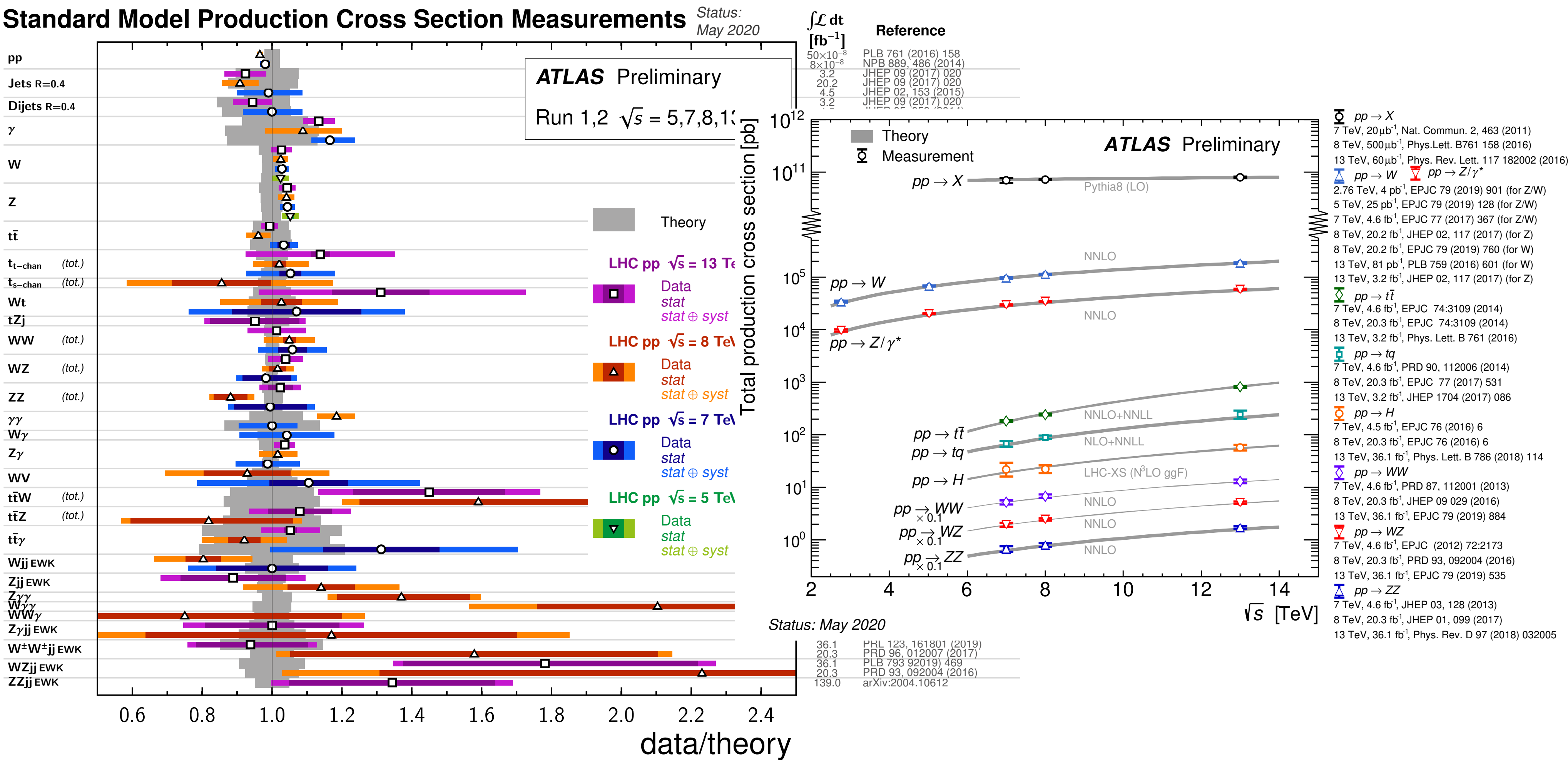
$$\mu = 1.06 \pm 0.07 \text{ (combined)}$$

LHC: Large Theory systematics

$$\kappa = \frac{g_{HX}}{g_{HX}^{SM}} = 1 + \Delta\kappa \longrightarrow \Delta\kappa \approx O\left(\frac{v}{\Lambda}\right)$$

$\hookrightarrow$ **Higher precision probes higher Λ**

Th. vs Exp. accuracy: a broad spectrum of SM processes



For all processes, theory accuracy should be a % level by HL-LHC time.

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What does complexity mean for theory?

Embracing complexity in modelling and interpreting LHC events.

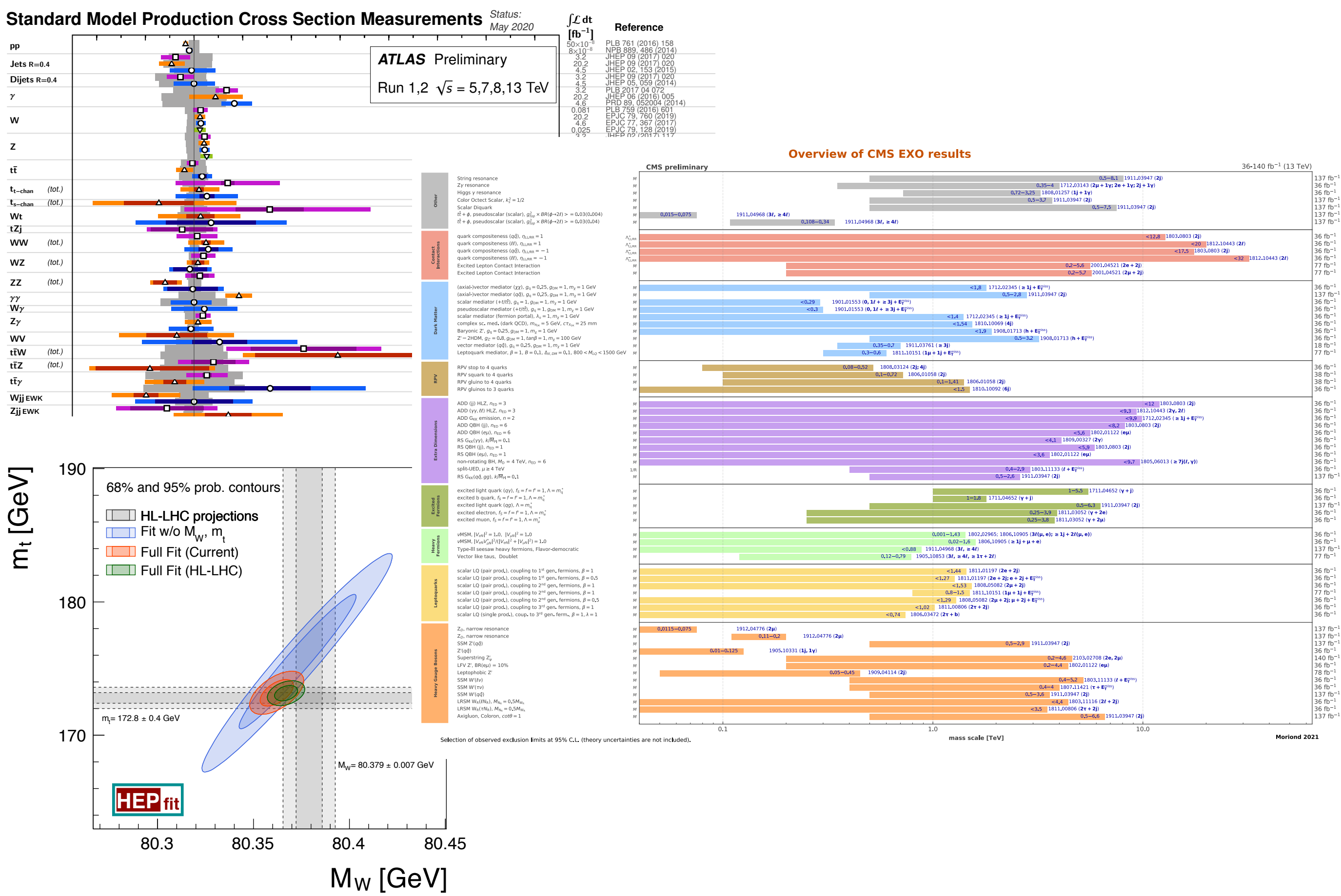
- Push precision for *standard candles* and improve description of key processes.
  - Higher-order perturbative QCD and EW corrections.
    - **N^2LO QCD** for all processes (total rates and distributions) and **N^3LO QCD** for keystone processes ($gg \to H$, $pp \to \gamma^*/Z/W^\pm$,...).
    - **NLO EW+QCD corrections** for all processes.
    - **Improved PDF** (>NLO QCD, QED)
    - **Resummation** of specific kinematic- or cut-induced large (logarithmic) corrections needs to be included.
    - Effects previously neglected need to be reconsidered (mass effects, . . .).
    - **NNLO+PS matching to parton-shower Monte Carlo** event generators
  - Precision extended to high-multiplicity processes.
    - Include accurate modelling of final-state decays.
    - Study off-shell effects.
  - Non-pertubative effects.
- Use cutting-edge techniques to extract more information from otherwise difficult data.
  - Precursor: jet substructure.
  - New approach to QCD dynamics via ML/DL techniques.
  - ML/AI algorithms to select difficult signals.

$\hookrightarrow$ See N. Craig's talk

- Parametrize new physics in terms of more general effective interactions.
  - Parametrize BSM via EFT extension of SM Lagrangian.

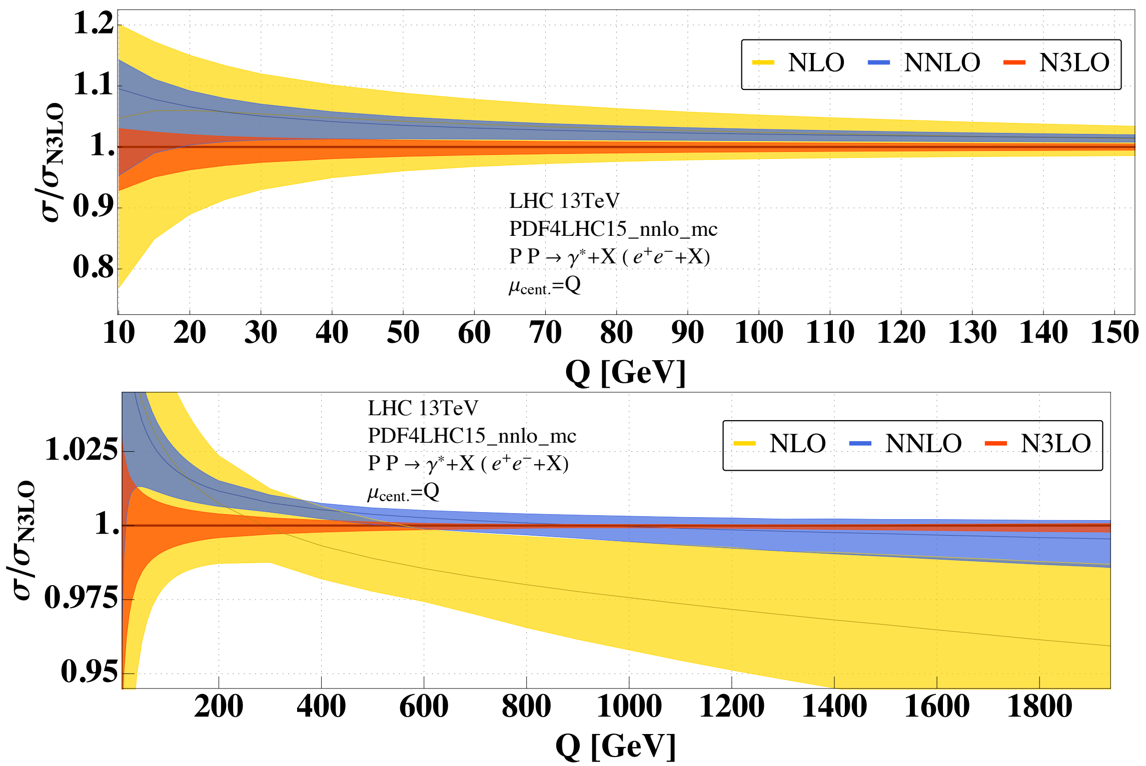
$$\mathcal{L}_{\rm SM}^{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

  - Constrain parameter space via SM fits and direct search results.
  - Connect to flavour physics within usual EFT language (SMEFT $\rightarrow$ WET).
  - Account for NP effects at all levels (signal, background, PDF fits, ...)



DY at N^3LO: a standard candle

For luminosity measurements, detector calibration, PDFs measurements, new physics searches.

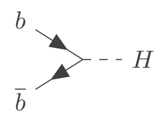
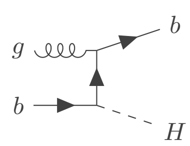
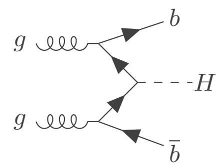
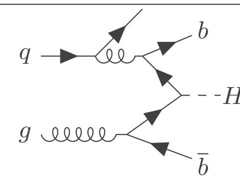


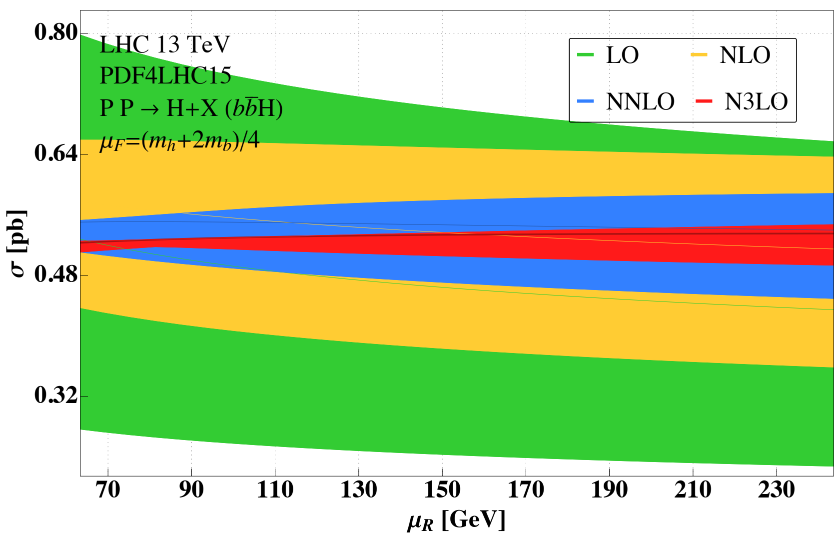
[Duhr, Dulat, Mistlberger, arXiv:2001.07717]

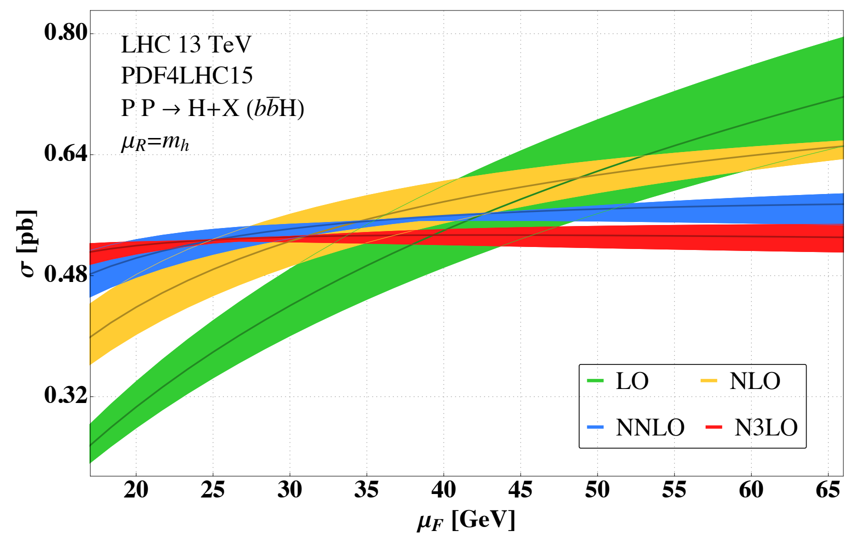
- ↪ N^3LO effects at percent level over the entire Q range.
- ↪ Very reduced scale dependence, but naive scale variation underestimates residual theoretical uncertainty → Need for N^3LO PDF
- ↪ **Need for revision of traditional assessment of theory uncertainty and consequences for PDF determination.**

$b\bar{b} \to H$ at N^{3}LO: closing in on the b-quark Yukawa coupling

Consistent matching (FONNL) of 4FS and 5FS calculations including all known QCD corrections: %-level effects with respect to partial matchings.

				
4FS	–	–	LO	NLO
5FS	LO	NLO	NNLO	N^{3}LO



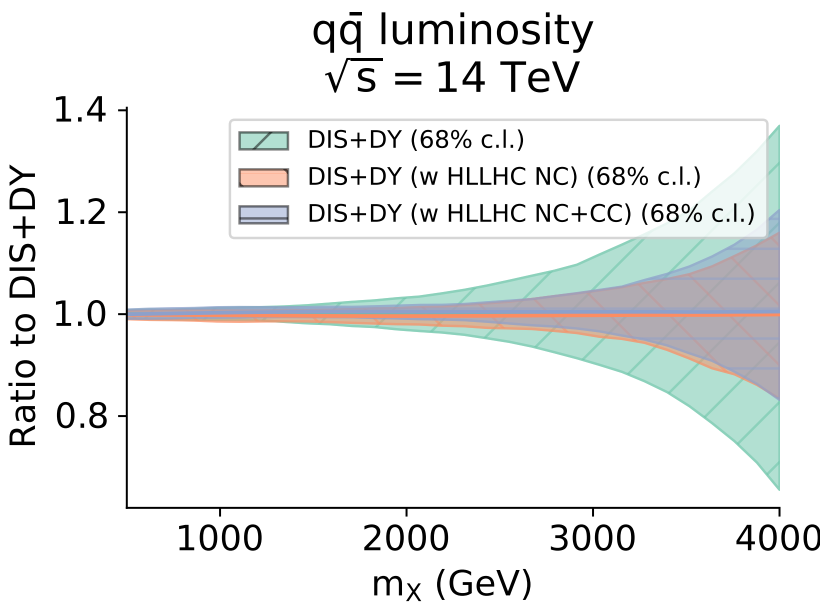


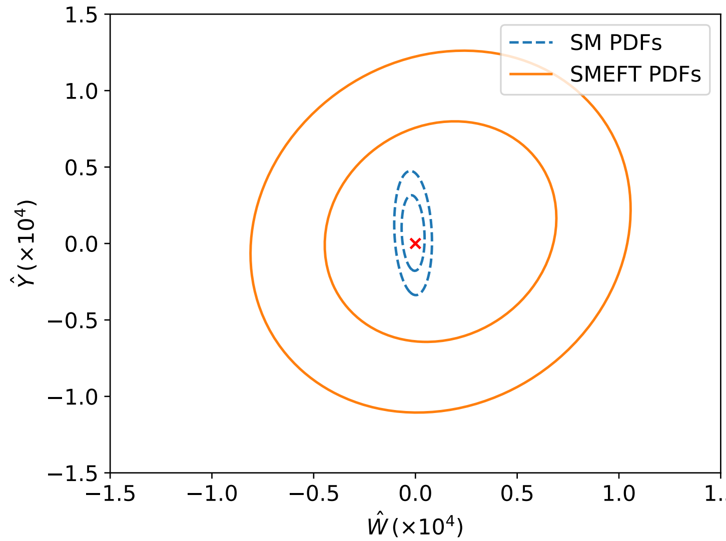
[Duhr, Dulat, Hirschi, Mistlberger, arXiv:2004.04752]

- ↪ Very reduced scale dependence. Validate choice of low energy factorization scale.
- ↪ Open possibilities of similar studies for other b initiated processes (e.g. $Z + b$ jets) → precision measurement of b PDF with high luminosity.

Rethinking global PDF fits vis-à-vis theory accuracy

↪ See recent talk by M. Ubiali at RADCOR 2021.



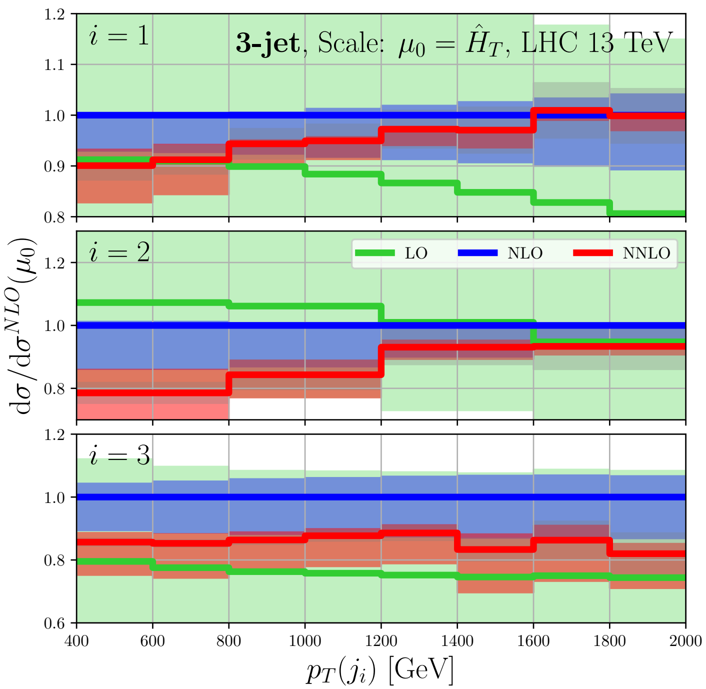


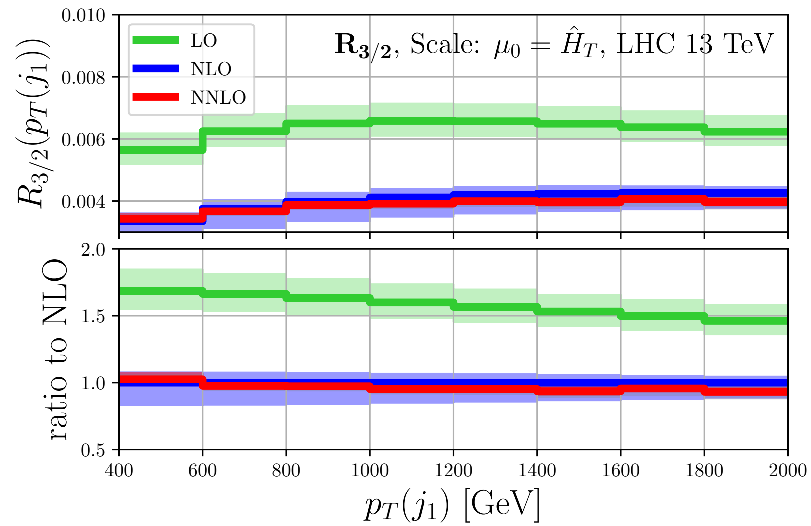
[Greljo et al., arXiv:2104.02723]

- PDF fit based on DIS, DY on-shell and low-mass data from ATLAS, CMS and LHCb.
- + Run 1 and Run 2 ATLAS and CMS high mass NC DY data.
- + HL-LHC projections for NC and CC DY data.
- SM predictions at NNLO QCD + NLO EW and SMEFT corrections added via local K-factors.
- **Clear impact of simultaneous fit of PDFs and SMEFT coefficients** ($W, Y \to$ EW oblique corrections).

3-jet production at N^2LO: precision jet physics

Multi-jet rates: essential information for pQCD and modelling of jet production.





[Czakon, Mitov, Poncelet, arXiv:2106.05331]

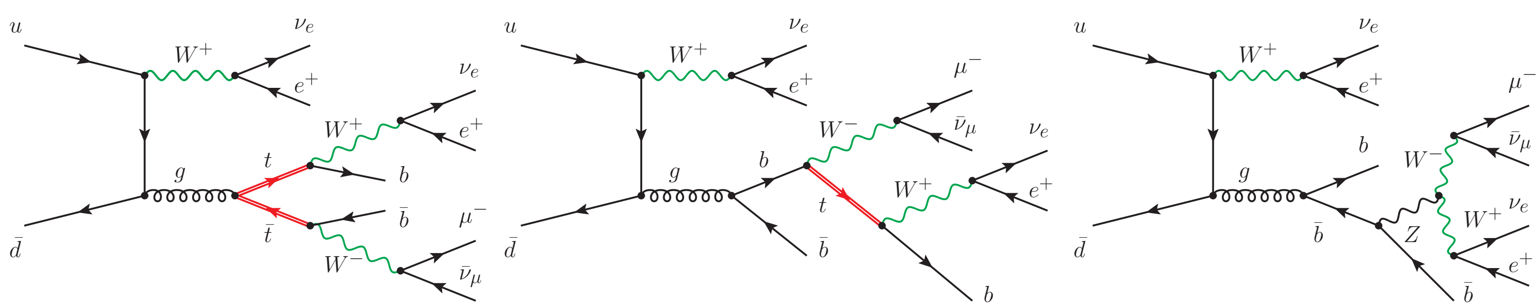
- ↪ The first N^2LO $2 \to 3$ full QCD calculation (with 5 colored partons at tree level).
- ↪ A technical milestone with a unique phenomenological impact: jet event shapes, α_s, scale setting in multi-jet production, ...
- ↪ Reduction of theoretical error to % level.

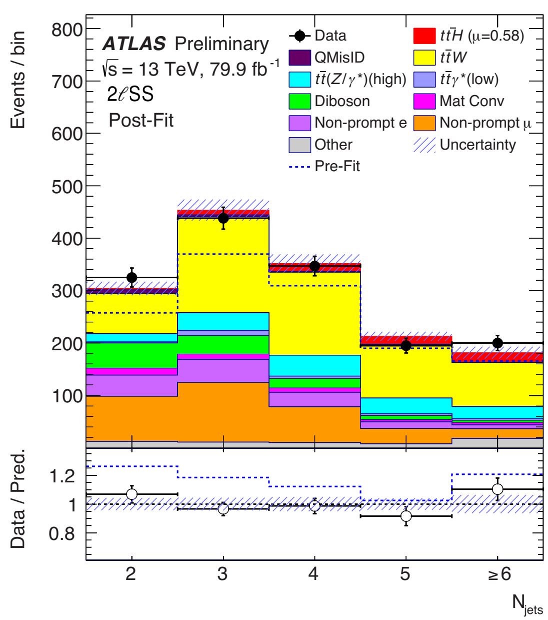
The N^2LO QCD program is moving fast!

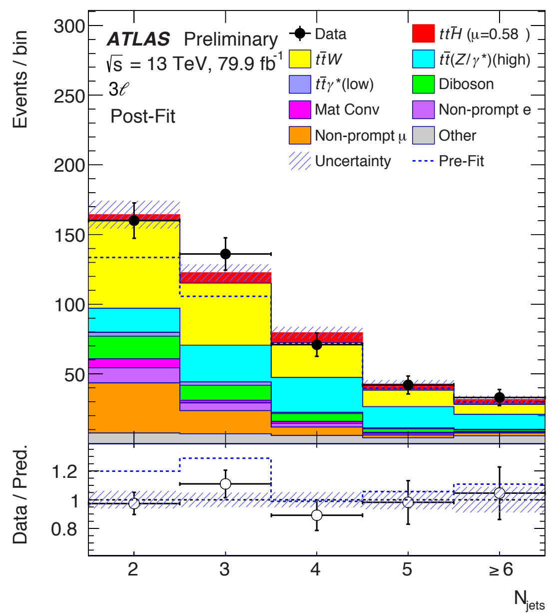
Next major challenge: $2 \to 3$ processes with massive particles (e.g. $t\bar{t} + X$)

$t\bar{t}W^{\pm}$ complex signature: precision needs high-multiplicity

Important to establish top-quark EW couplings (as $t\bar{t}Z$), and **major background in $t\bar{t}H$ multi-lepton signatures (2lSS, 3l)**.







Disagreement between data and simulations.

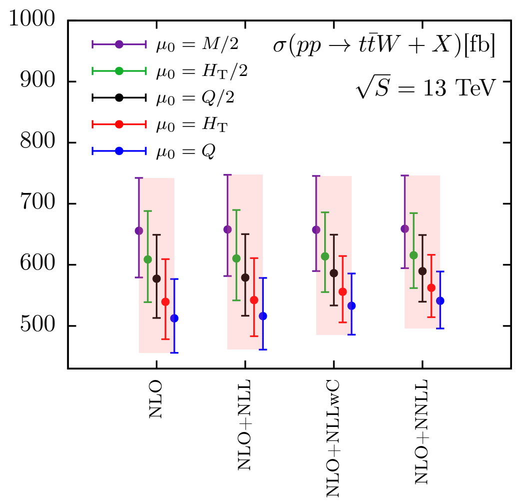
⇓

Significant normalization of $t\bar{t}W$ background needed

$\lambda_{ttW} \simeq$1.2-1.7

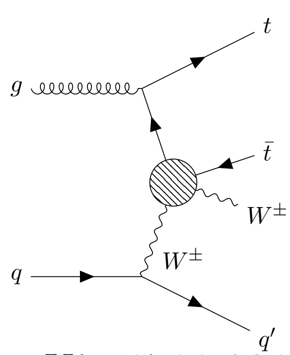
[ATLAS-CONF-2019-045]

Expected large QCD corrections, at the moment only captured through multi-jet merging → need N^2LO



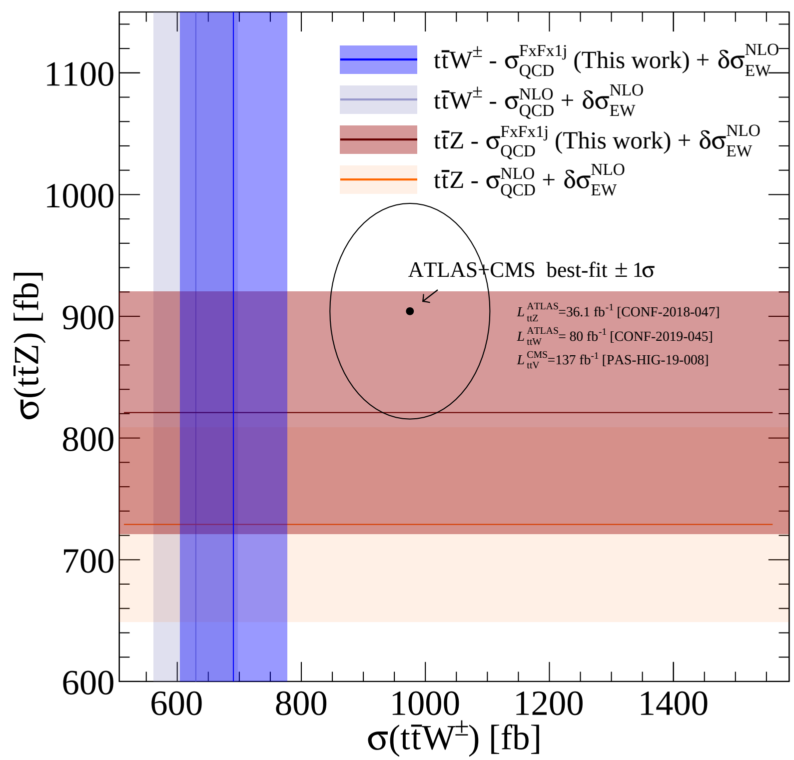
[Kulesza et al., arXiv:2001.03031]

Sizable (10%) NLO EW corrections due to t-channel rescattering



[Frederix et al., arXiv:1711.02116]

⇒ Still tension in LHC $t\bar{t}W$ measurements:

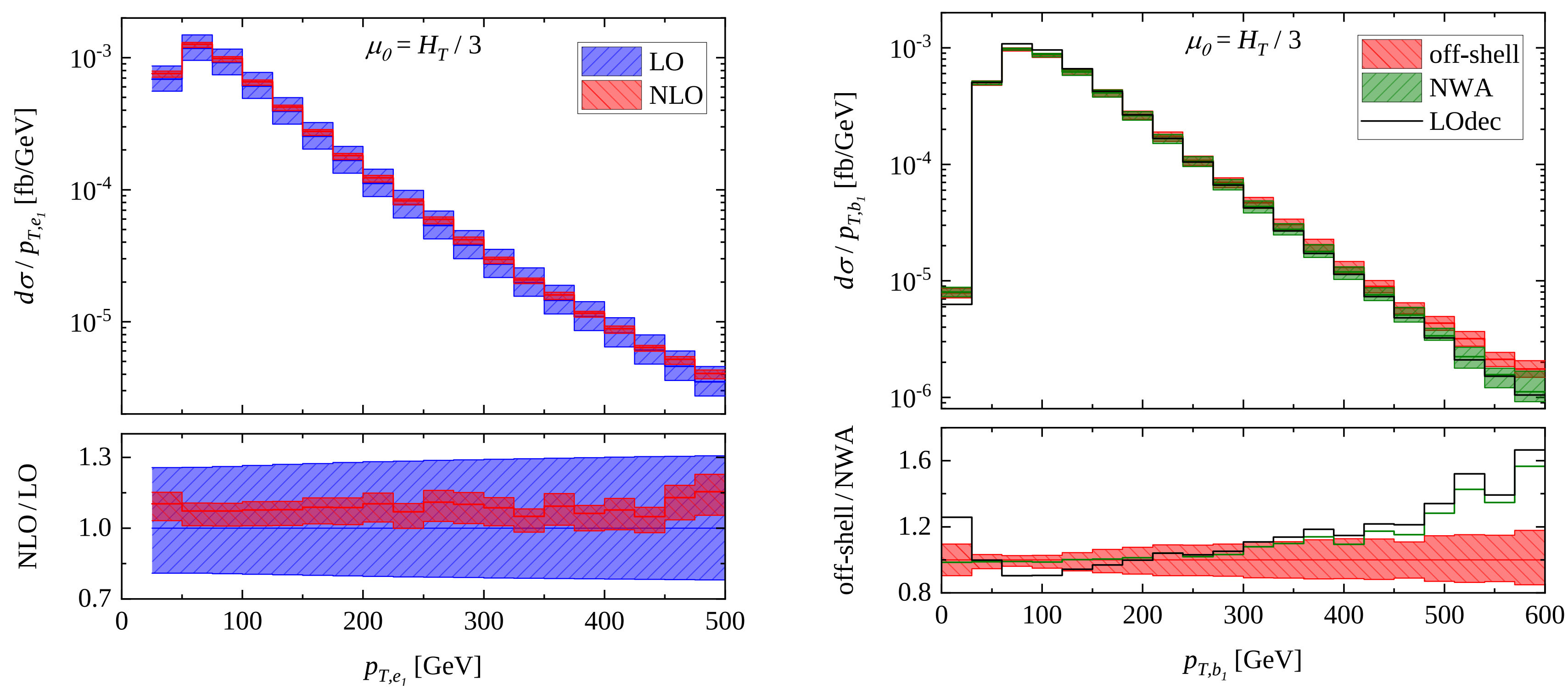


[Buddenbrock, Ruiz, Mellado, arXiv:2009.00032]

⇒ Study modelling of specific fiducial volumes (3l and 2lSS).

Beyond stable tops

Off-shell fixed order NLO QCD calculation of $3l$ signature: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu e^+\nu_e b\bar{b}$



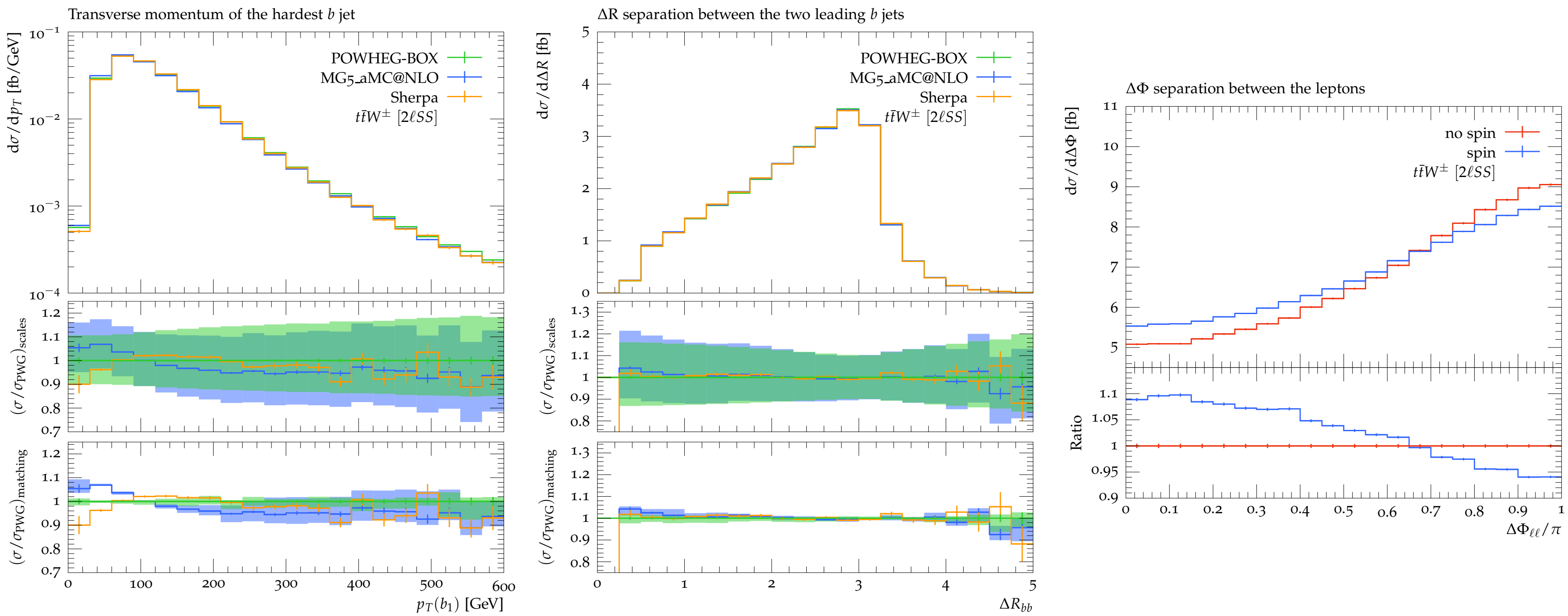
[Bevilacqua, Bi, Hartanto, Kraus, Worek, arXiv:2005.09427]

(See also: Denner, Pellicciolì, arXiv:2007.12089 and 2102.03246)

- ↪ Off-shell: uncertainty below 10% independently of scale choice (fixed/dynamic).
- ↪ Large off-shell effects in the tails of distributions.

Beyond fixed order and stable tops: parton-shower+ LO decays.

NLO QCD and leading EW contributions in calculation of $2lSS$.



[Febres Cordero, Kraus, Reina, arXiv:2101.11808]

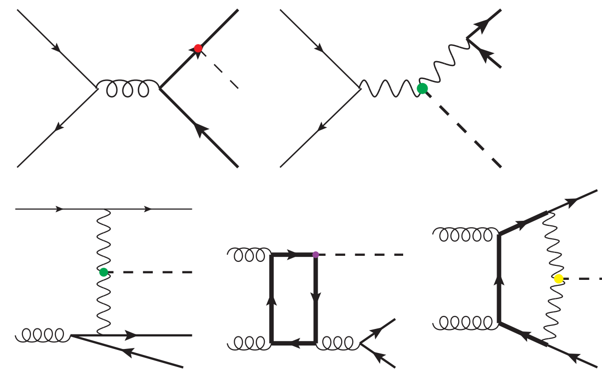
(See also: Frederix, Tsinikos, arXiv:2004.09552)

- ↪ Good consistency between different NLO QCD+PS event generators.
- ↪ Polarization effects modify shapes at 10% level, stronger in $t\bar{t}W^+$ case.
- ↪ More robust assessment of theoretical uncertainties.

$b\bar{b}H$: direct measurement of y_b obfuscated by several SM backgrounds

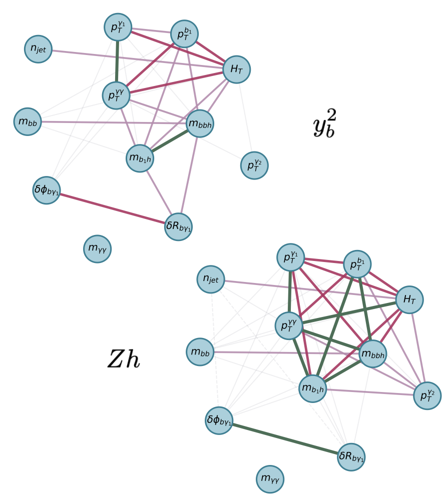
NLO QCD+EW corrections pollute the sensitivity to y_b and makes a cut base analysis hopeless: **RIP Hb$\bar{\text{b}}$** [Pagani, Shao, Zaro, arXiv:2005.10277]

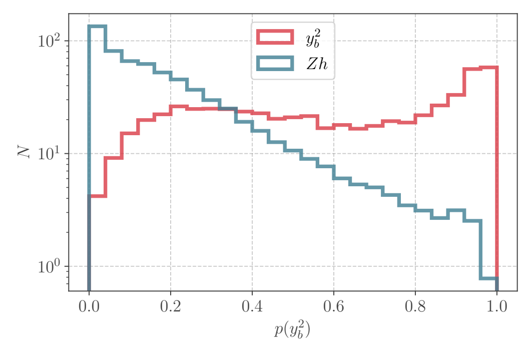
ratios	$\frac{\sigma(y_b^2)}{\sigma(y_b^2)+\sigma(\kappa_Z^2)} \equiv \frac{\sigma_{\text{NLO}_{\text{QCD+EW}}}}{\sigma_{\text{NLO}_{\text{all}}}}$ (y_b vs. κ_Z)	$\frac{\sigma(y_b^2)}{\sigma(y_b^2)+\sigma(y_t^2)+\sigma(y_b y_t)}$ (y_b vs. y_t)	$\frac{\sigma(y_b^2)}{\sigma(y_b^2)+\sigma(y_t^2)+\sigma(y_b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



A kinematic-shape based analysis based on game theory (Shapley values) and BDT opened new possibilities: **Resurrecting $b\bar{b}h$ with kinematic shapes** [Grojean, Paul, Qian, arXiv:2011.13945]

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





Parametrizing New Physics beyond specific BSM models

Extension of the SM Lagrangian by $d > 4$ effective field theory (EFT) operators:

$$\mathcal{L}_{\rm SM}^{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

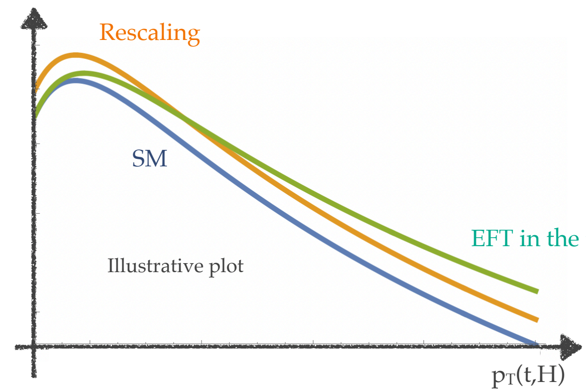
where

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

under the assumption that new physics lives at a scale $\Lambda > \sqrt{s}$.

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

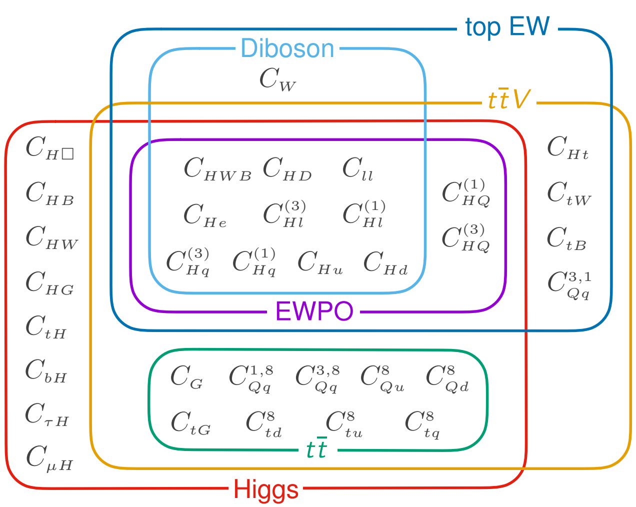
- SM masses, couplings $\rightarrow$ rescaling
- shape of distributions $\rightarrow$ more visible in high-energy tails



Systematic, yet complex approach.

$\Downarrow$

Studying correlations among operators can point to specific BSM patterns.



$\leftarrow$ [Ellis, Madigan, Mimasu, Sanz, You, arXix:2012.02779]

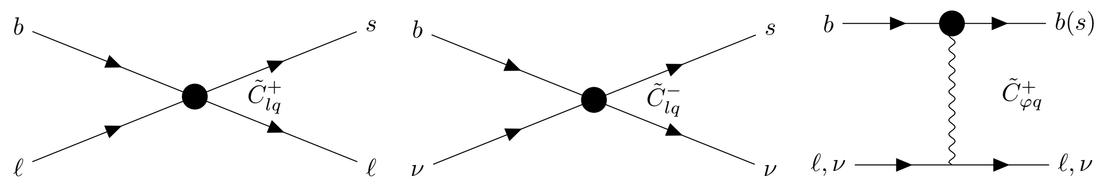
Constrain new physics via flavour observables

$$\mathcal{L}_{\rm SM}^{\rm EFT} \xrightarrow{\Lambda \ll \Lambda_{EW}} \mathcal{L}_{\rm Weak}^{\rm EFT} = \sum_{i=1}^{10} C_i^{\rm WEFT} \mathcal{O}_i^{\rm WEFT}$$

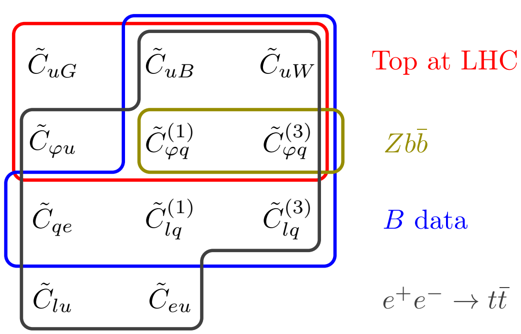
where

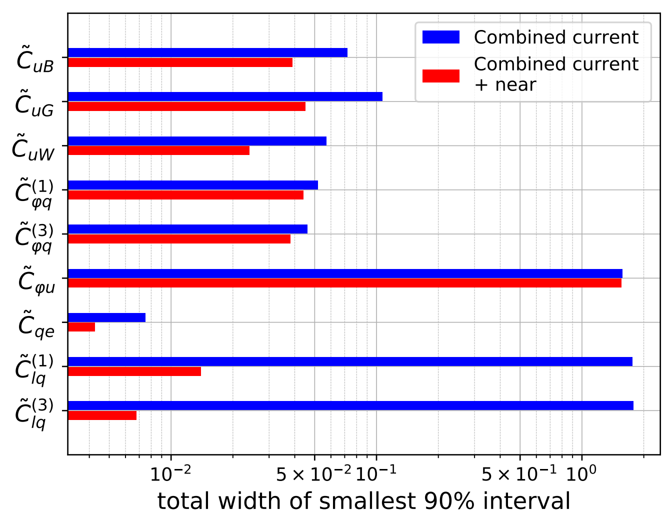
$\mathcal{O}_i^{\rm WEFT} \rightarrow$ 4-fermion operators of quarks(except t) and leptons

$C_i^{\rm WEFT} \rightarrow$ depend on $C_i^{\rm SMEFT}$



Strong constraints from B-meson semileptonic decays and intriguing relation with flavor anomalies.



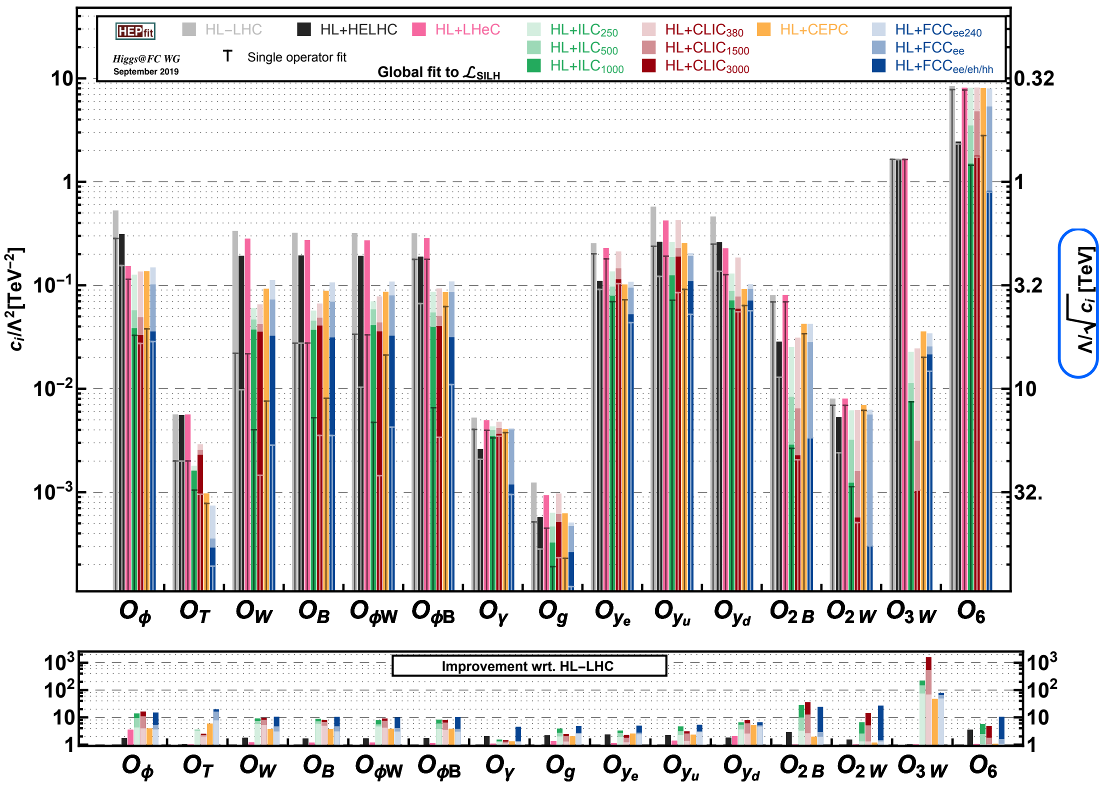


near $\rightarrow$ including HL-LHC and Belle II

[Bißman, Grunwald, Hiller,Kröninger, arXiv:2012.10456]

Bounding the scale of new physics: EFT

Global fit to EFT operators Combining EW+Higgs PO



$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d$$
with
$$\mathcal{L}_d = \sum_i C_i^{(d)} \mathcal{O}_i^{(d)}, \quad \left[\mathcal{O}_i^{(d)}\right] = d$$

$$\leftarrow \quad \mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}$$

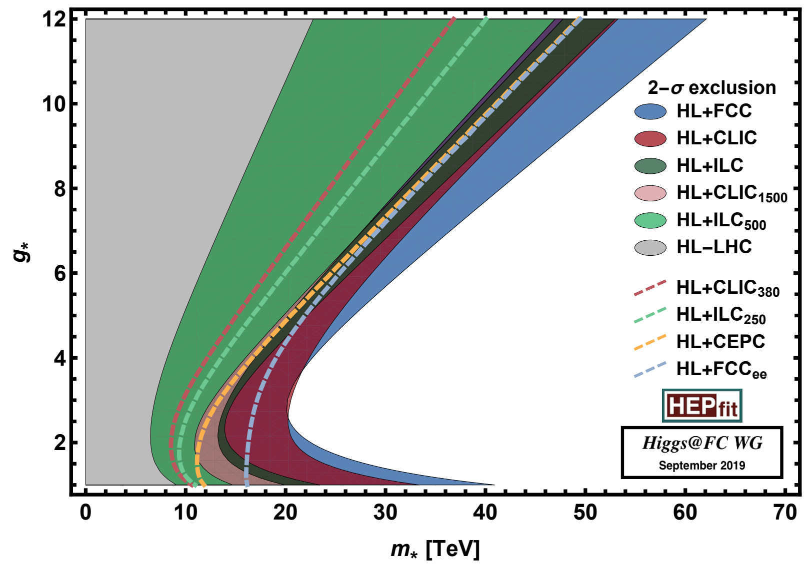
[J. de Blas et al., arXiv:1905.03764]

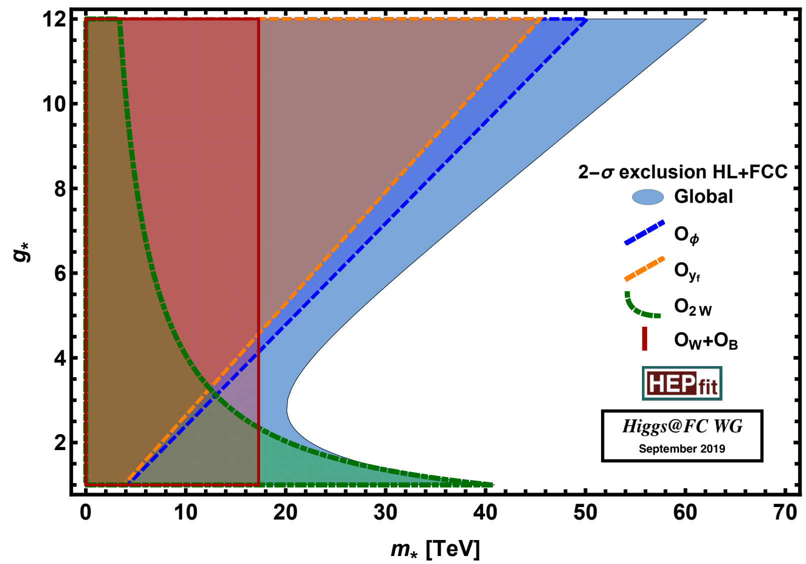
Important goals:

- ↪ Study effects of neglected higher orders in EFT: **reduce *interpretation* errors**.
- ↪ Study effects of adding **SM corrections** (QCD+EW NLO) → mixing through evolution.
- ↪ Consider **global fit**, not just single operators.
- ↪ Extend set of fitted observables (distributions, STXS, etc.).
- ↪ Study inclusion of **theory errors** and their correlations in global fits.

Bounding the scale of new physics: specific models

Example of a **composite Higgs model**:





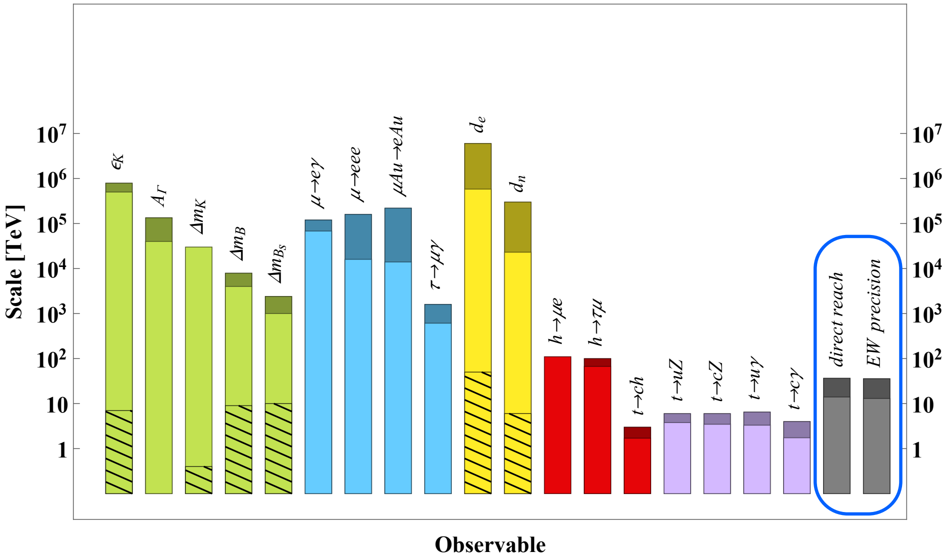
[J. de Blas et al., arXiv:1905.03764]

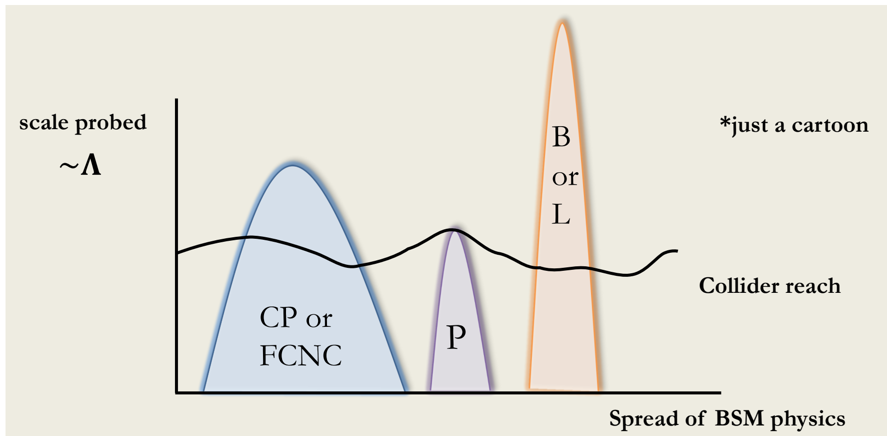
g^*, m^* $\rightarrow$ coupling and mass scale of the new resonances

$g^*, m^* \leftrightarrow \{O_\phi, O_6, O_T, O_W, O_B, O_{2W}, \ldots\}$

Bounding the scale of new physics with precision

Probing the scale of new physics with **EW+top+Higgs+Flavor** ...





[European Strategy, arXiv:1910.11775]

[J. De Vries, talk at Snowmass CPM, Oct. 2020]

- **FCNC, CP, etc.** high reach but target very specific sectors of BSM models.
- **Collider reach much broader**: test BSM models across the spectrum of all collider observables.
- **Unique complementarity** between EW precision fit and flavor observables.

Conclusions and Outlook

- After the discovery of the Higgs boson during Run 1 of the LHC, a major effort to **develop a full-fledged precision program to control SM physics at the percent level** has been growing.
- Groundbreaking new ideas and more powerful techniques allow us to take much higher challenges: **embrace the complexity of LHC events!**
- **Indirect evidence of new physics** from Higgs, top, and EW precision measurements could come from the synergy between
  - → pushing theoretical predictions to a new level of accuracy,
  - → a systematic approach to the study of new effective interactions,
  - → the intuition and experience of many years of Beyond SM searches!
- **Increasing the precision on SM observables** could **allow to test higher scales** of new physics: a factor of 10 in precision could give access to scales well above 10 TeV.
- **Direct evidence** of new physics will boost this process, as the discovery of a Higgs-boson has prompted and guided us in this new era of LHC physics.