



European Research Council  
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# Higgs Hunting 2026

## Theory Concluding Talk

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(CERN)



Orsay/Paris 16-18 September 2026

## The Higgs hunter's program in the years

I

### **HUNTING FOR THE HIGGS SECTOR**

---

(Pre-)discovery era

II

### **HUNTING INSIDE THE HIGGS SECTOR**

---

Exploring the Higgs

III

### **HUNTING WITH THE HIGGS SECTOR**

---

A new discovery tool



I don't suppose I have to dwell on those days as everyone here surely knows how things unfolded. But just in case:

Higgs Hunting [2010](#), [2011](#), [2012](#)

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HUNTING FOR  
THE HIGGS SECTOR

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HUNTING WITH  
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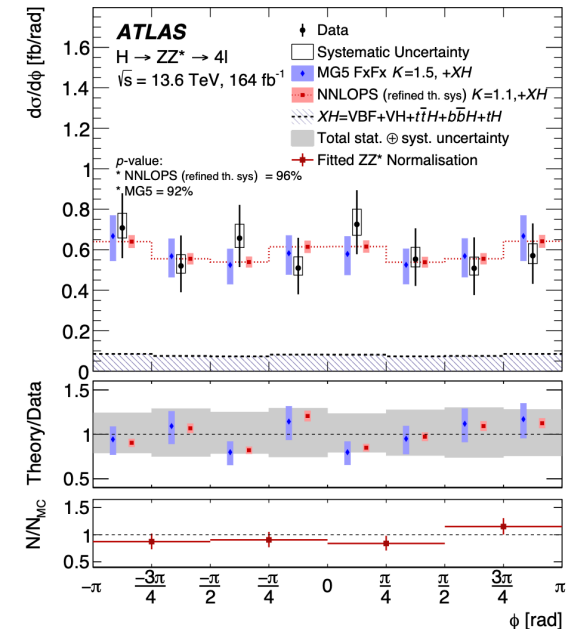
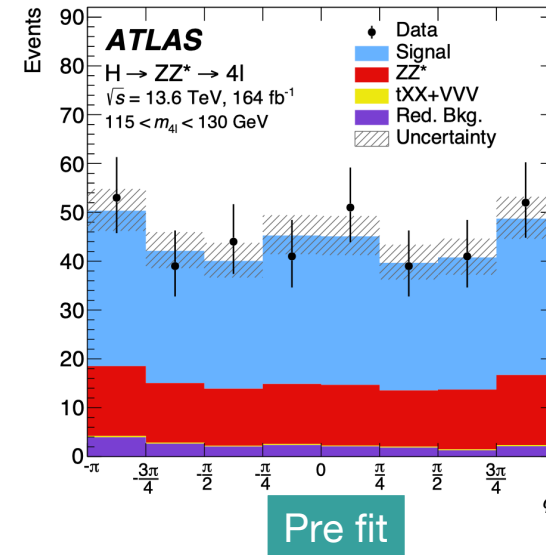
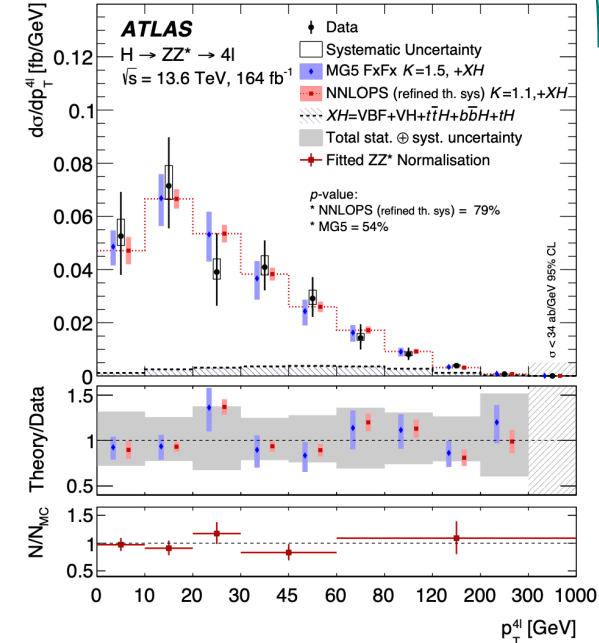
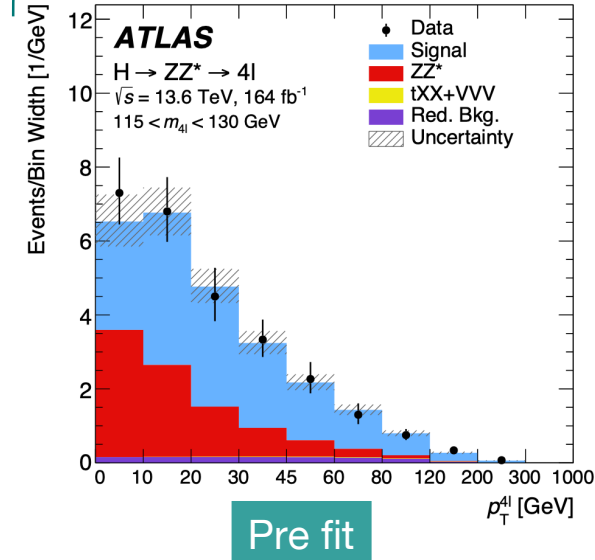
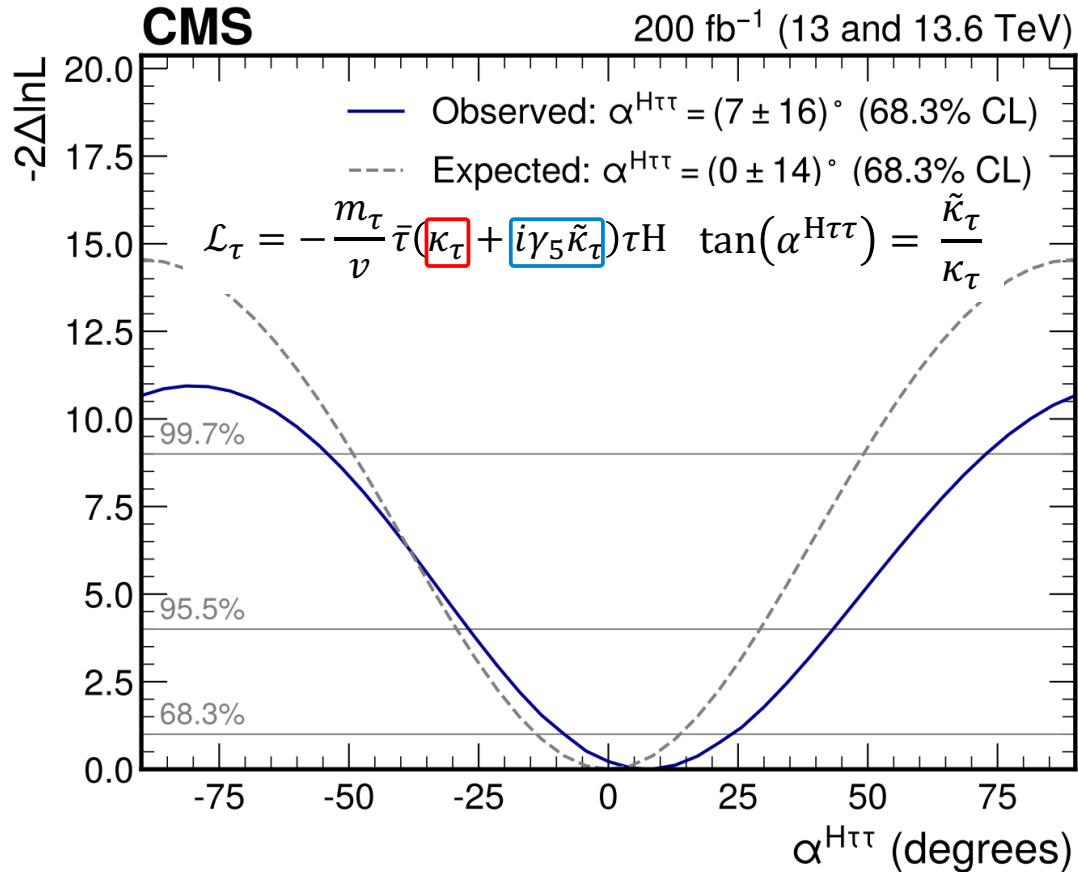
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A new discovery tool

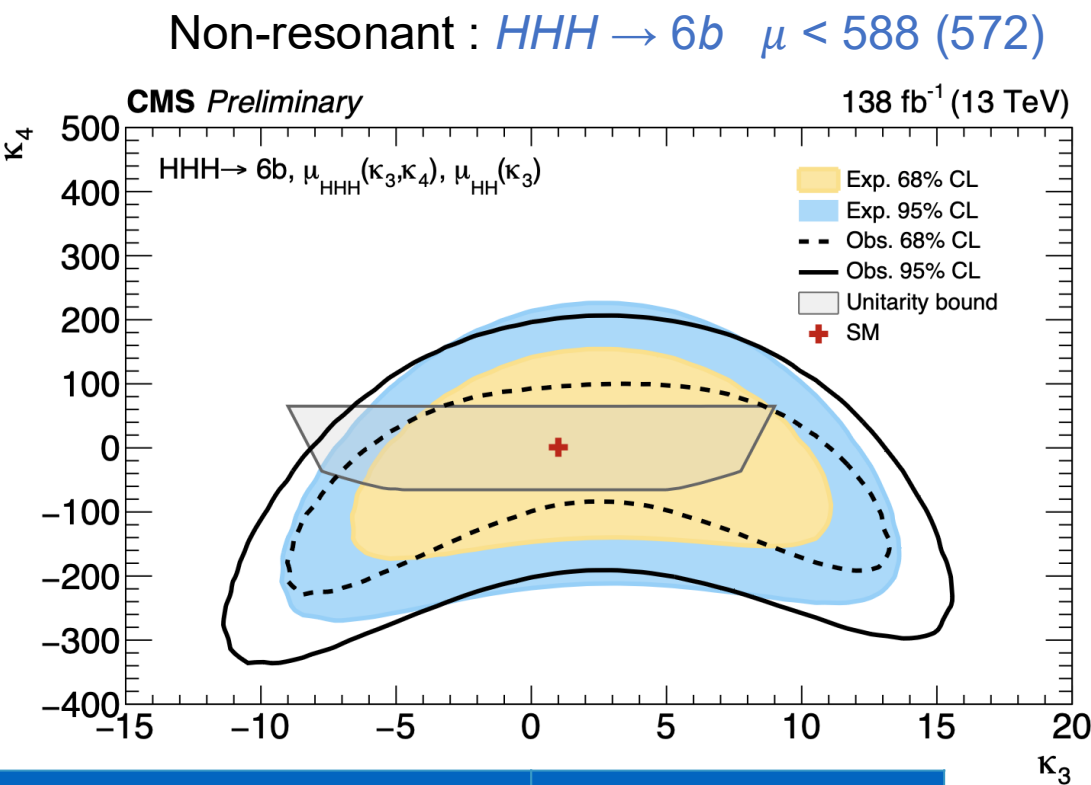
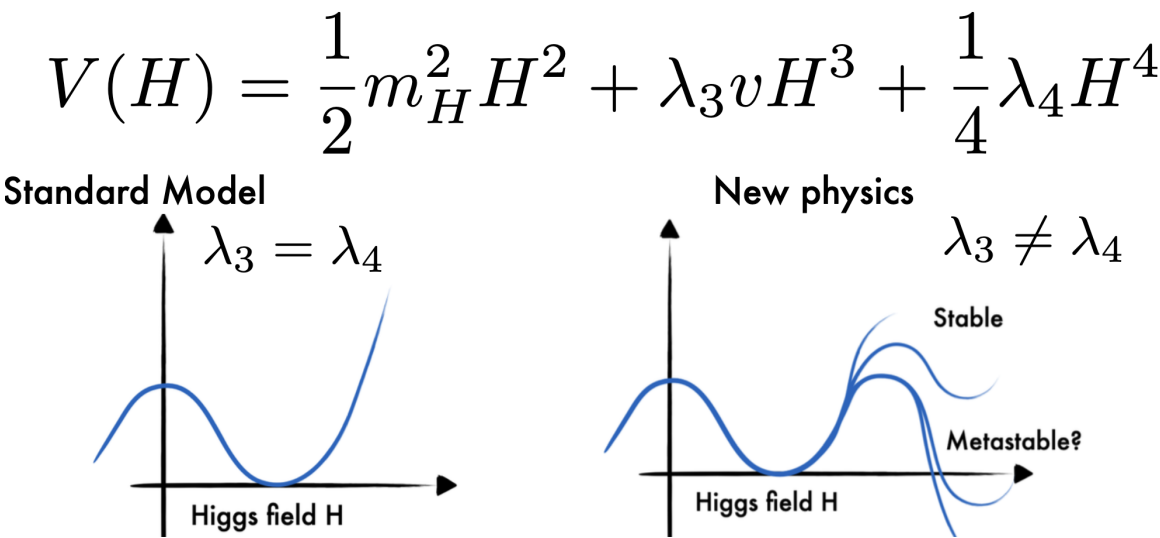
# FROM SIGNAL STRENGTH TO HIGGS TOMOGRAPHY

The study of the Higgs sector has quickly shifted to a thorough analysis of its properties and coupling to SM particles, and an increasingly accurate knowledge of the kinematics of its decay products

$$\alpha^{H\tau\tau} = 7 \pm 16 \text{ (stat)} \stackrel{+3}{-2} \text{ (bbb)} \pm 2 \text{ (syst)}^\circ$$



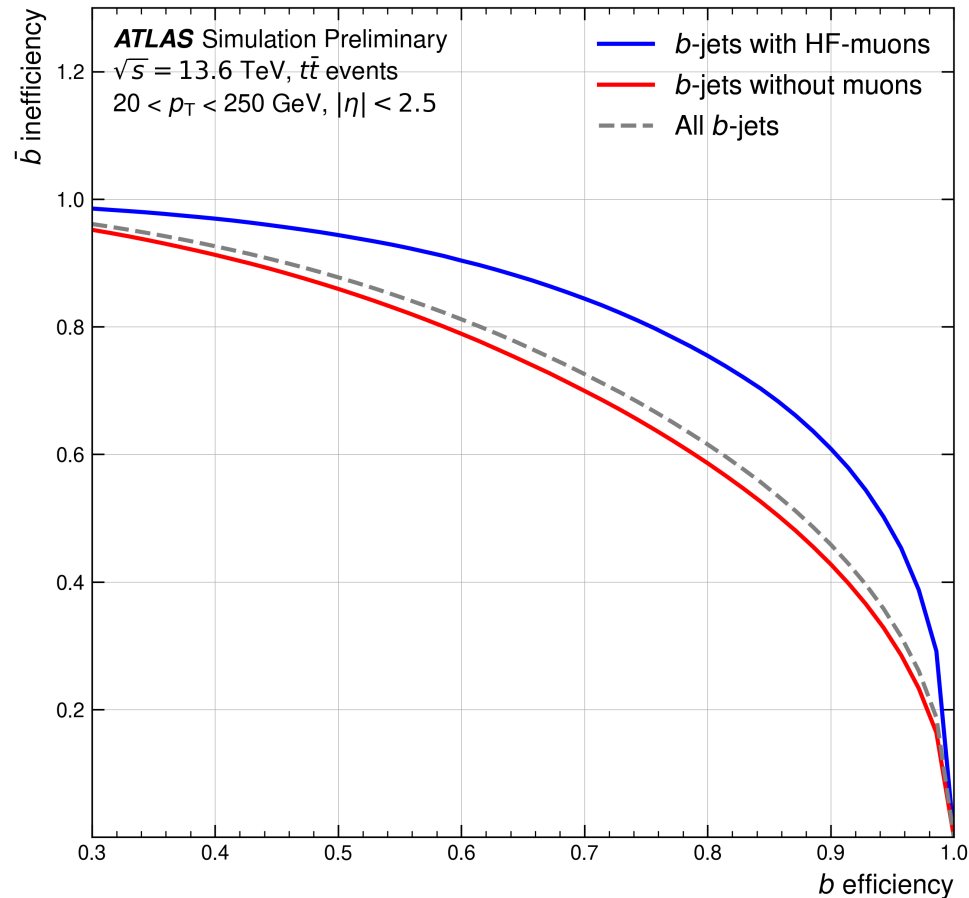
# EXPERIMENTS ARE BITING INTO THE POTENTIAL



| Channel                                  | $\kappa_\lambda$ 95% CL Observed | $\kappa_\lambda$ 95% CL Expected | Reference          |
|------------------------------------------|----------------------------------|----------------------------------|--------------------|
| ATLAS+CMS Comb Run 2                     | [-0.71,6.1]                      | [-1.3,6.7]                       | arxiv:2602.23991   |
| CMS 4b Run 2 + 62 fb-1 Run 3             | [-4.1,9.6]                       | [-3.2,9.8]                       | arxiv:2604.27044   |
| CMS 2b2 $\tau$ Run 2 + 172 fb-1 Run 3    | [-2.5,9.4]                       | [-1.5,8.4]                       | CMS-PAS-HIG-25-008 |
| CMS 2b2 $\gamma$ 62 fb-1 Run 3           | [-6.1,12.8]                      | [-3.6,10.5]                      | CMS-PAS-HIG-25-007 |
| ATLAS bb $\tau\tau$ Run 2 + 56fb-1 Run 3 | [-3.4,2.6]U[5.5,10.1]            | [-1.7,8.5]                       | arXiv:2607.26879   |

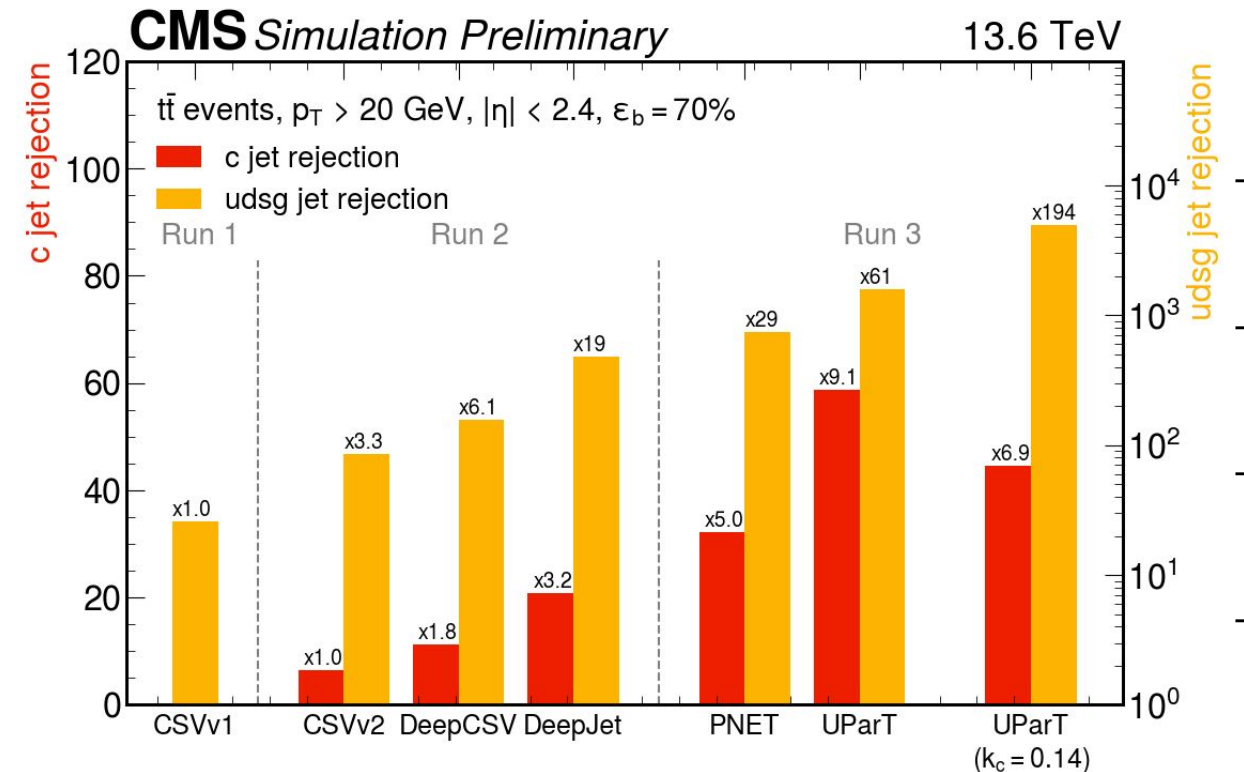
## MORE INFORMATION PER COLLISION: EVOLUTION OF ANALYSIS TECHNIQUES

e.g. jet tagging



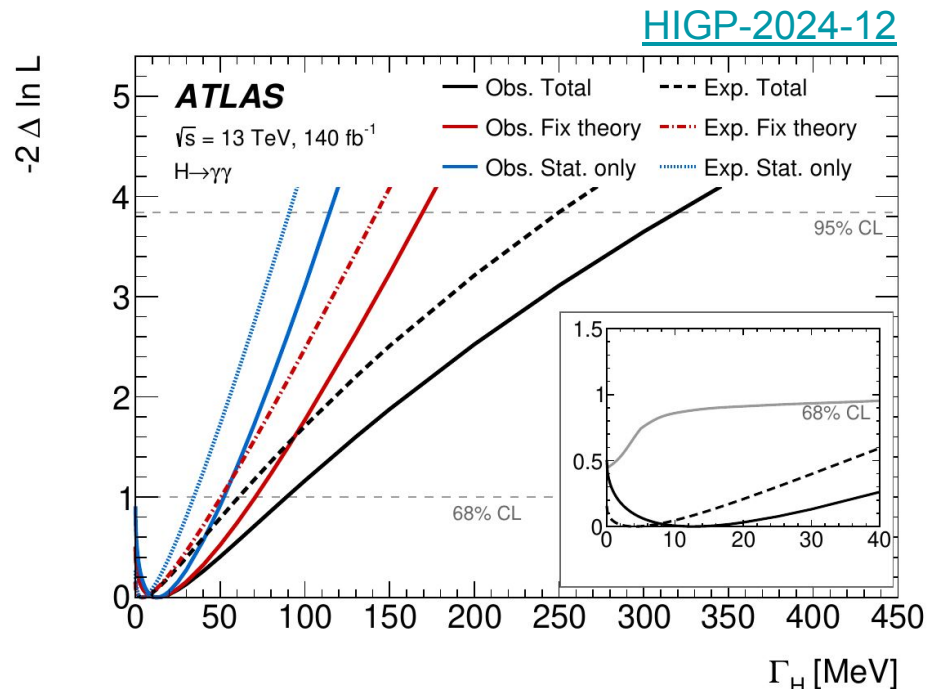
CMS: “All analyses show improvements exceeding luminosity gain”

ATLAS: “Improvements in sensitivity no longer come only from larger datasets”



- **New charge ID for heavy quarks:**
  - works even for jets without leptons
  - 50% eff. vs 13% mistag efficiency for  $b$ -quarks

“A unified approach for jet tagging in Run 3 at  $\sqrt{s}=13.6$  TeV in CMS,” CMS DP-2024/066



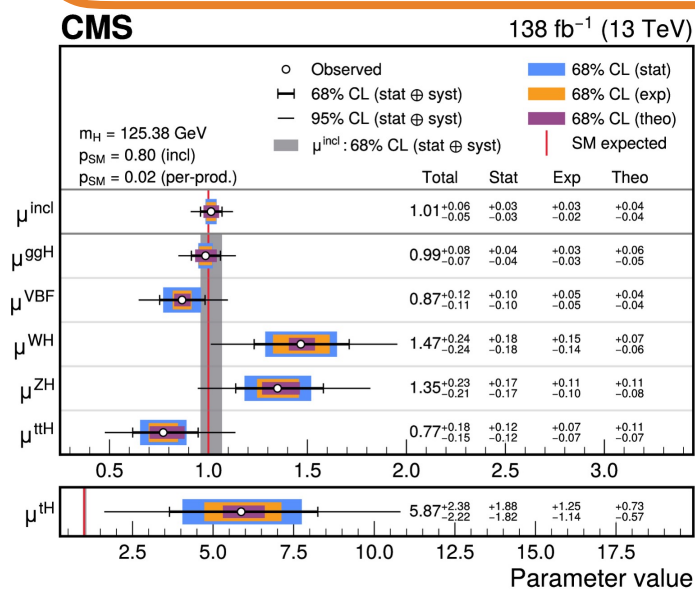
**High-Luminosity LHC projection:**  
 expected 95% CL upper limit of **21 MeV**

- Parameterize  $gg \rightarrow \gamma\gamma$  process in terms of width  $\rightarrow$  report observed (expected) 95% CL upper limit of **307 (258) MeV**
  - Limited by **theory uncertainties** (e.g. interference NLO $\rightarrow$ NNLO k-factor of 1.64)

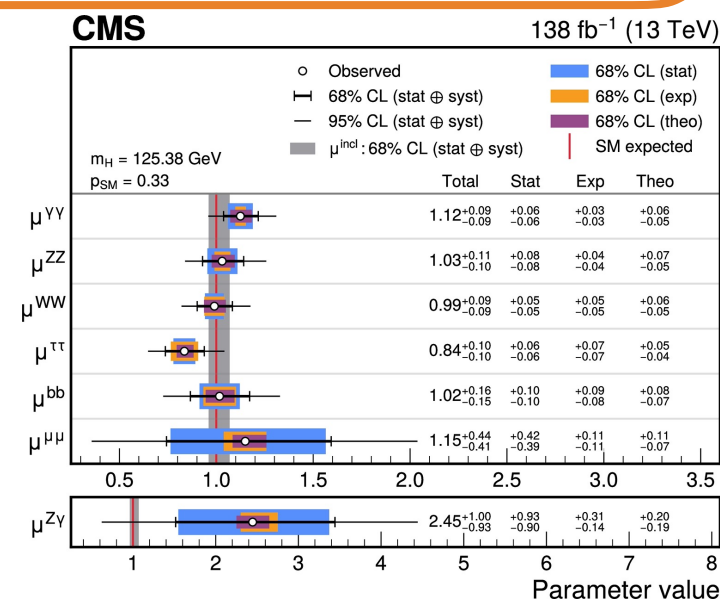
$$\mu^{\text{incl}} = 1.014^{+0.055}_{-0.053} = 1.014^{+0.040}_{-0.039} (\text{theo})^{+0.025}_{-0.024} (\text{exp}) \pm 0.028 (\text{stat})$$

**5% precision :**

Dominant uncertainty: signal theory uncertainty (on signal modelling affecting the measurement, and SM prediction)



slight upward deviation in WH,  
 ZH, and tH of roughly  $2\sigma$



$\mu^{\mu\mu}$  with  $<40\%$  precision ( $3\sigma$  evidence)  
 $\mu^{\text{Z}\gamma}$  gives an upward deviation ( $2.7\sigma$ )





## Is the Standard Model a model, a theory, or what ?

*Several colleagues argue that, with the discovery of the Higgs, the SM must now be called Standard Theory*

For the person on the street, “**theory**” sounds less robust, established and reliable than “**model**” (as in “*in theory you are right, **but** ...*” or “*well, this is **your** theory...*”)....

Eg, from the Britannica Dictionary

### **Theory**

- 1.an idea or set of ideas that is *intended to explain* facts or events
- 2.an idea that is suggested or presented as *possibly true but that is not known or proven to be true*

### **Model**

a set of ideas and numbers that *describe* the past, present, or future state of something

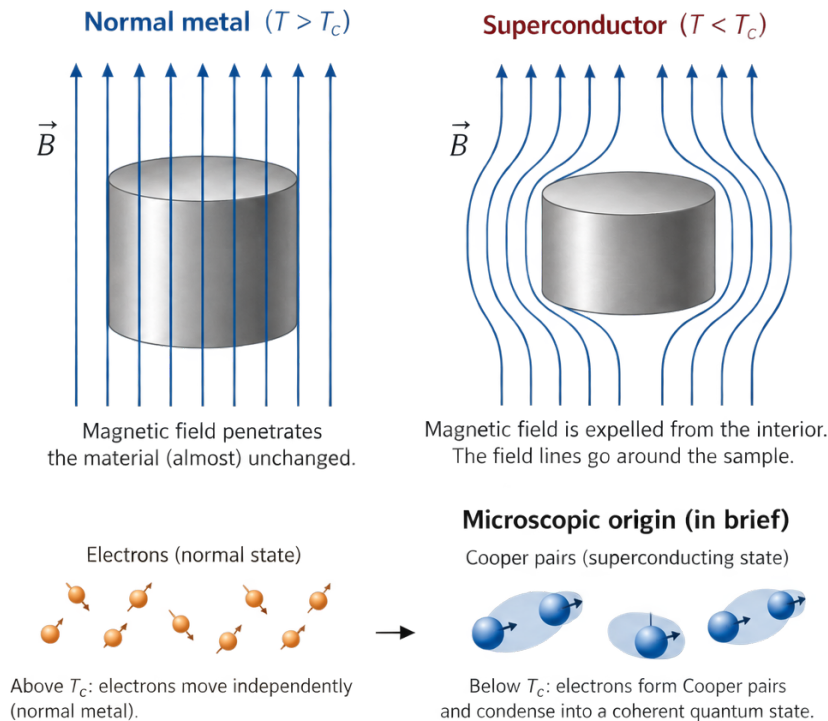
So, I'd rather stick to **Model**....

**But there is a deeper reason** why I believe the SM **still is** a model.

More precisely, I would actually define the SM as **the theory of** weak interactions, but just **a model for** electroweak symmetry breaking



Semantics aside, although so far the data suggests otherwise, it is hard/impossible to imagine that the minimal model for the SM Higgs potential is the end of the story (ditto for Yukawas). It is our duty to figure out where it comes from



*A famous example from electromagnetism...*

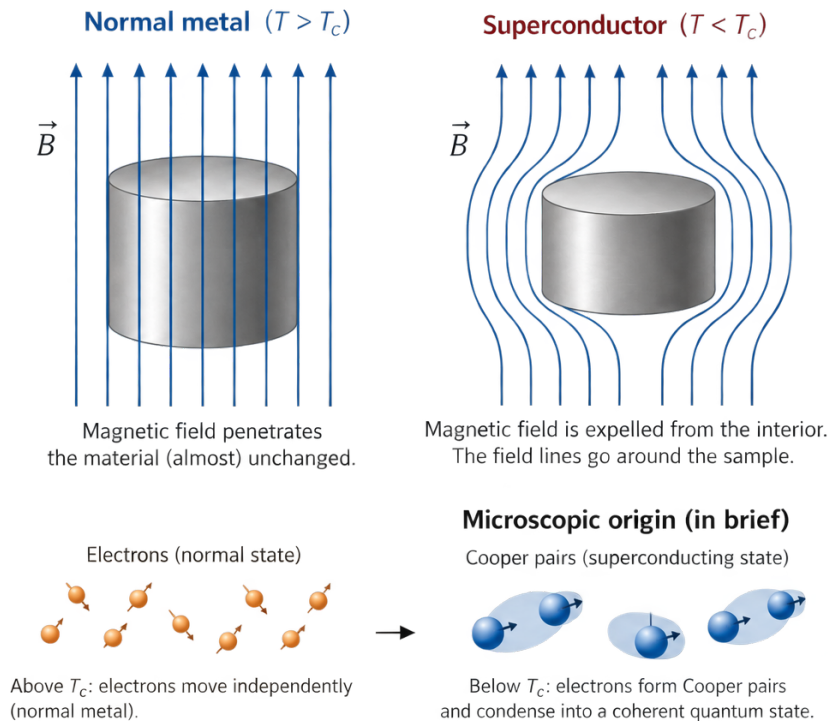
*Ginzburg, Landau Zh. Eksp. Teor. Fiz. 20 (1950) 1064-1082, Phys. Z. Sowjetunion*

Consider first a uniform superconductor in the absence of a magnetic field, and suppose that  $\Psi$  is independent of position. The free energy of the superconductor is then in accordance with the general theory of second-order phase transitions, dependent only on  $|\Psi|^2$  and may be expanded in series form in the neighbourhood of  $T_c$ . Thus near  $T_c$  we may write for the free energy  $F_{so}$ ,

$$F_{so} = F_{no} + \alpha |\Psi|^2 + \frac{\beta}{2} |\Psi|^4. \quad (6)$$

In equilibrium  $\partial F_{so}/\partial |\Psi|^2 = 0$ ,  $\partial^2 F_{so}/\partial^2 |\Psi|^2 > 0$ , and in addition we must have that  $|\Psi|^2 = 0$  for  $T \geq T_c$  and  $|\Psi|^2 > 0$  for  $T < T_c$ . It follows therefore that  $\alpha_c = 0$ ,  $\beta_c > 0$ , and for  $T < T_c$ ,  $\alpha < 0$ . Thus in equilibrium,

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# What kind of the Higgs sector can lead EW Baryogenesis?

An extended Higgs sector, which realizes

- 1<sup>st</sup> OPT (Non-decoupling property)
- CP violation

2 Higgs doublet models  
Singlet extension  
Real triplet extension  
...

Constraints from current experimental data

EW Precision Tests  
Flavor Changing Neutral Currents  
EDMs  
LHC

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A new discovery tool

The field of Higgs physics has now undoubtedly reached the necessary level of maturity to promote the Higgs boson to a precision discovery tool. While this has been long awaited, the results at this conference establish the end of Run 3 as a clear transition point into this new era

So far no compelling deviations from the SM.  
Does that make the Higgs less interesting?

So far no compelling deviations from the SM.  
Does that make the Higgs less interesting?

Quite the opposite



### A scalar field responsible for EWSB leaves many open questions about NP

SM + Appelquist-Carazzone Theorem



Decoupling of NP at high scales  
(the Higgs looks SM like)

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i \rightarrow \delta\sigma \sim \frac{v^2, E^2}{\Lambda^2}$$

... and yet, NP leaves a fingerprint on the Higgs sector

① Higgs mass remembers high scales even if NP decouples

$$\rightarrow \delta m_H^2 \sim \frac{g_*^2}{(4\pi)^2} M^2 \text{ (naturalness)}$$

② NP doesn't decouple if most of its mass is from EWSB

$$\frac{\partial \ln M}{\partial \ln v} \xrightarrow{M \gg M_W} \not\rightarrow 0 \text{ (NP not too heavy if perturbative)}$$

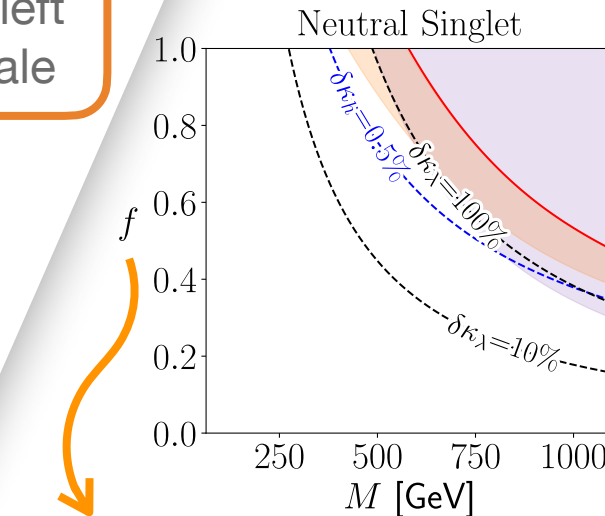
③ Does nature have a linear Higgs doublet, and analyticity at  $H \rightarrow 0$  (SMEFT) or a more general EWSB sector (HEFT)?

## A WINDOW ON NEW PHYSICS

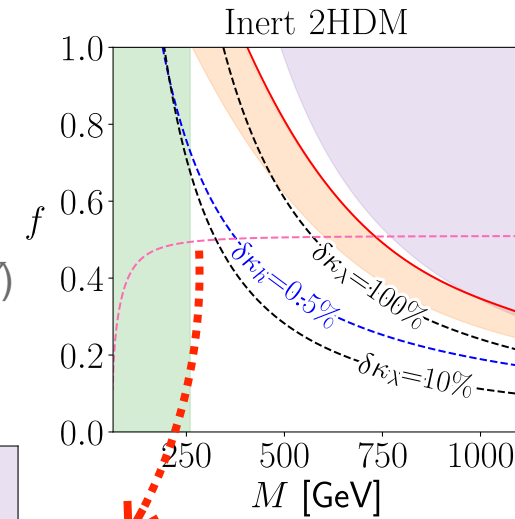
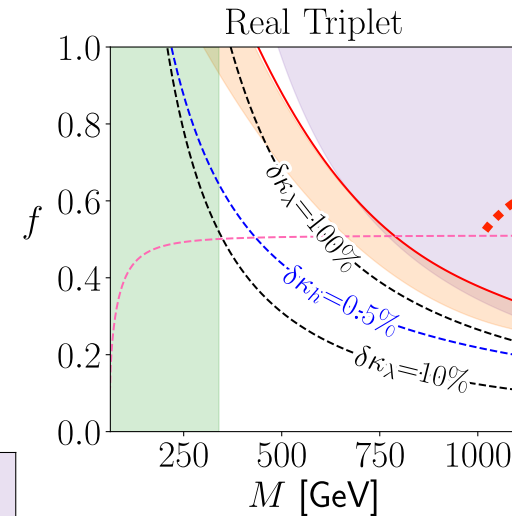
The absence/pattern of deviations in Higgs measurements informs us of how high-scale NP is connected to EWSB.

There is immense value in scrutinizing the Higgs sector, esp. multi-H observables. Significant portions of parameter space left unexplored even at or below the TeV scale

- excl. by unitarity
- probed by FCCee ( $\Delta W, \Delta Y$ )
- 1<sup>st</sup> order PT allowed



fraction of mass from EWSB



bound detectable  
by LISA

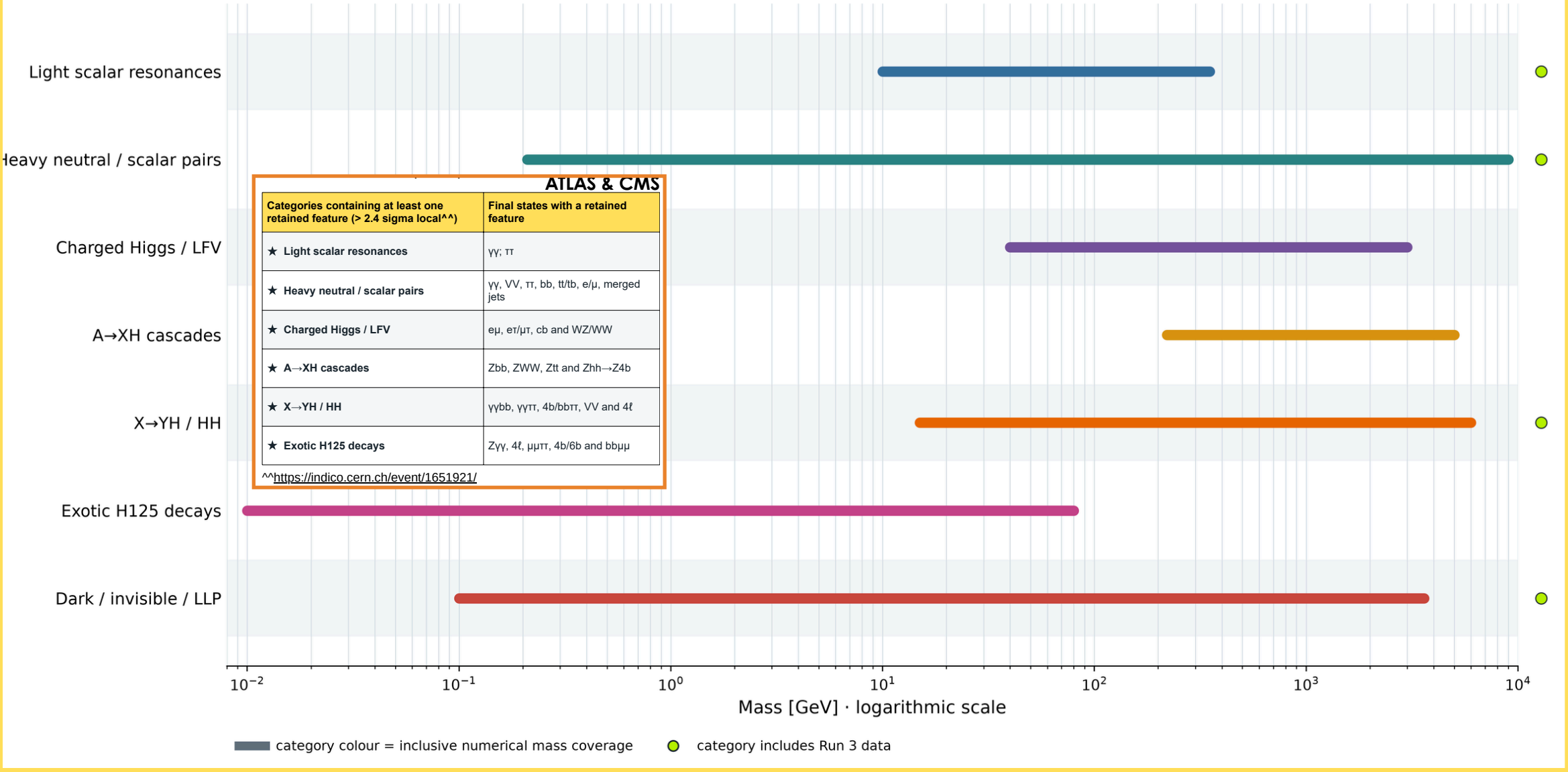
e.g. Parameter space for sub-TeV Loryons, especially neutral scalars, remains rather unexplored, and it will be hard to probe it even at future particle colliders

Crawford, Sutherland '24

cf. also Banta, Cohen, Craig, Lu, Sutherland '21

ATLAS & CMS

RUN 3



# THE HIGGS AS A PORTAL TO LIGHT NEW PHYSICS: LIGHT ACCIDENTS

Light scalars can emerge as accidental flat directions in the tree-level potential in a SB, for instance when there are more tree-level zero modes than Goldstone Bosons ( $N_0 > N_{GB}$ ).  
Accidental scalar mass is loop suppressed

e.g. large reps like SU(2) five-plet in a dark sector

Possible applications:

- ① Little hierarchy (second symmetry breaking)
- ② Stable light(est) scalars as DM candidates
- ③ Accidentally flat potential could be exploited for inflation



$$G_D = \text{SU}(2)_D \times \text{U}(1)_D : \quad \phi = (\phi_1, \phi_2, \phi_3, \phi_4, \phi_5)_1$$

$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 + \kappa \left[ (\phi^\dagger \phi)^2 - |\phi^T \phi|^2 \right] + \delta (\phi^\dagger T^a \phi)^2$$

No symmetry larger than  $G_D$

$$\text{VEV: } \begin{cases} \langle \phi_1 \rangle = v \sin \alpha \\ \langle \phi_3 \rangle = v \cos \alpha \end{cases}$$

$$5 \text{ massive} + \begin{cases} 4 \text{ NGBs} + \mathbf{1 \text{ accident}} \left( G_D \rightarrow I \right), \alpha \neq 0 \\ 3 \text{ NGBs} + \mathbf{2 \text{ accidents}} \left( G_D \rightarrow \text{U}(1)'_D \right), \alpha = 0 \end{cases}$$

# THE HIGGS AS A PORTAL TO LIGHT NEW PHYSICS: SEARCH FOR CP-ODD SCALARS IN QUARKONIA

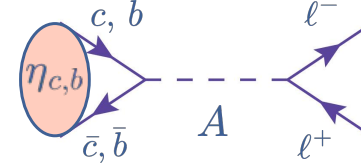
New idea to search for light CP-odd scalars by exploiting their mixing with pseudo-scalar mesons. e.g. light ( $< m_H/2$ ) CP-odd Higgs in 2HDM

Search via theory (lattice) vs. data comparison:

- ① Masses, branching fractions & widths
- ② Leptonic decays of pseudo-scalar quarkonia
- ③ Radiative decays of quarkonium

$$\mathcal{L}_A \supset i \frac{m_f}{v} \xi_A^f A (\bar{f} \gamma_5 f) - \frac{m_A^2}{2} A^2$$

A can be a mediator



A can mix with pseudoscalar mesons

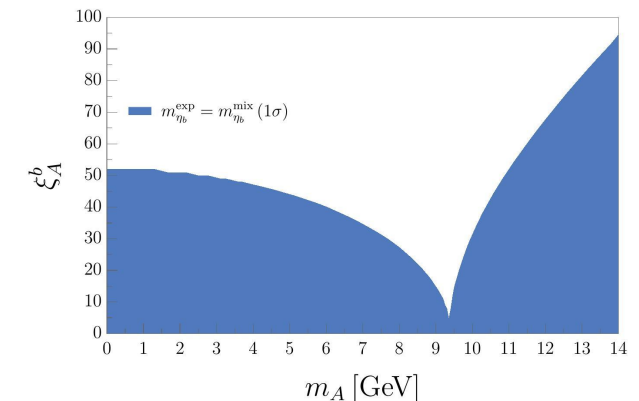
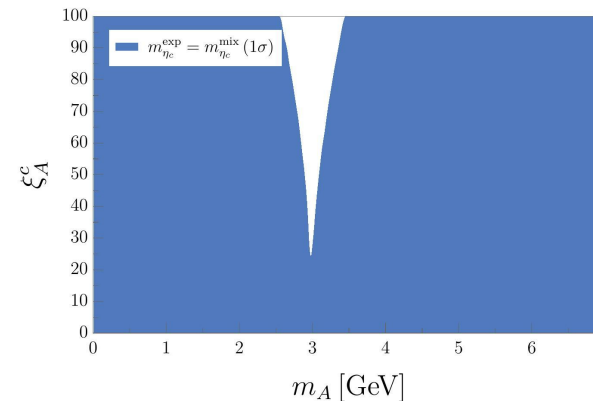
$$\langle A | \mathcal{L}_A | \eta_q \rangle = \frac{\xi_A^q}{2v} f_{\eta_q} m_{\eta_q}^2 = \delta m^2$$

$$\begin{pmatrix} \eta_{c,b}^{\text{phys}} \\ A^{\text{phys}} \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \eta_{c,b}^0 \\ A^0 \end{pmatrix}$$

$$m_{\eta^{\text{phys}}}^2 \approx \frac{1}{2} \left( m_{\eta^0}^2 + m_{A^0}^2 \pm \sqrt{4\delta m^4 + (m_{\eta^0}^2 - m_{A^0}^2)^2} \right)$$

[MeV]

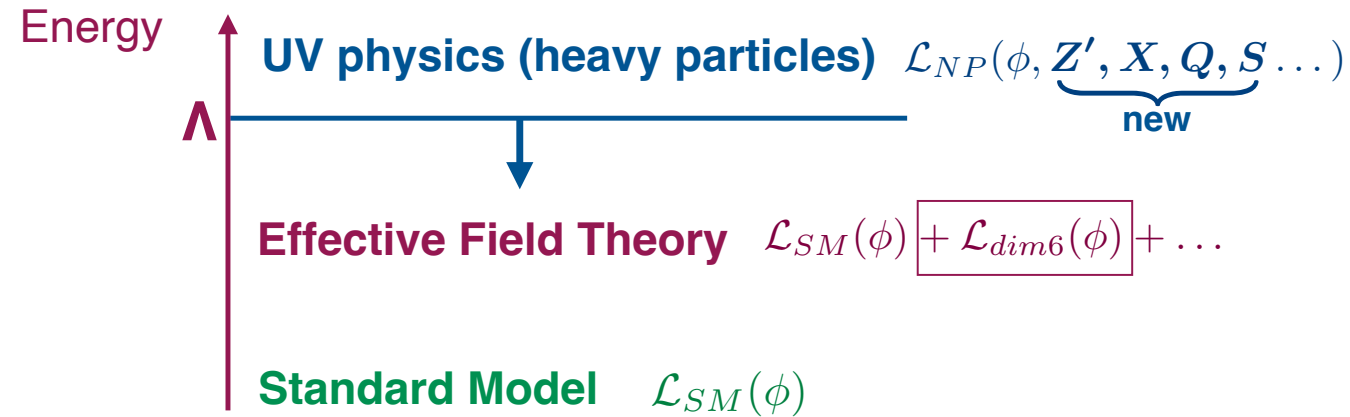
| $m_{\eta_c^{\text{phys}}}$ | $m_{\eta_c^0}$   | $m_{\eta_b^{\text{phys}}}$ | $m_{\eta_b^0}$   |
|----------------------------|------------------|----------------------------|------------------|
| $2984.1 \pm 0.4$           | $2976.6 \pm 1.1$ | $9398.7 \pm 2.0$           | $9402.9 \pm 2.5$ |



EFTs are the tool of choice to parametrize heavy NP in a model-independent way. Full structure of the theory, including important mixing across observables is provided. In practice, choices are made in global fits to reduce the size of op. basis, e.g.

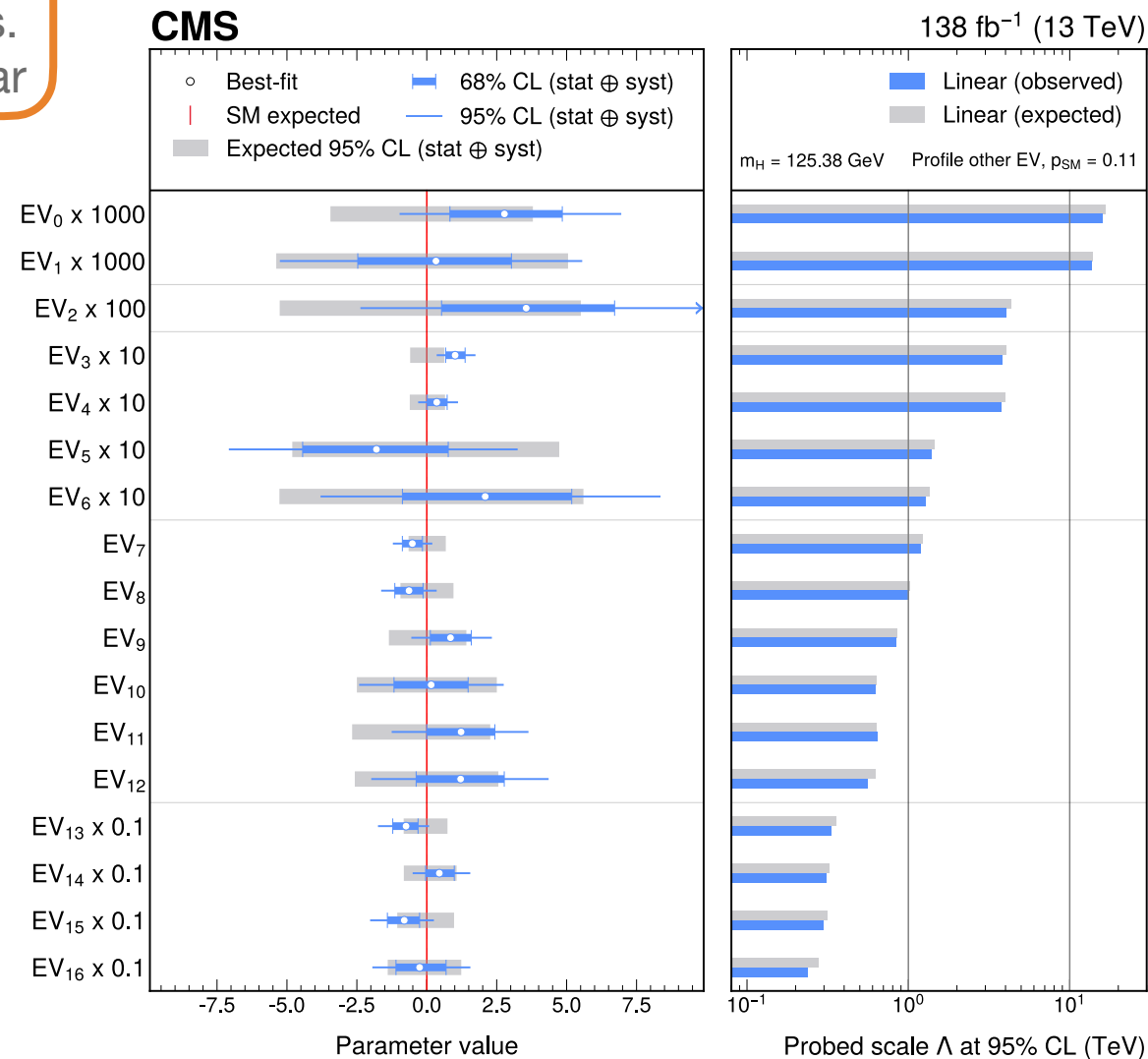
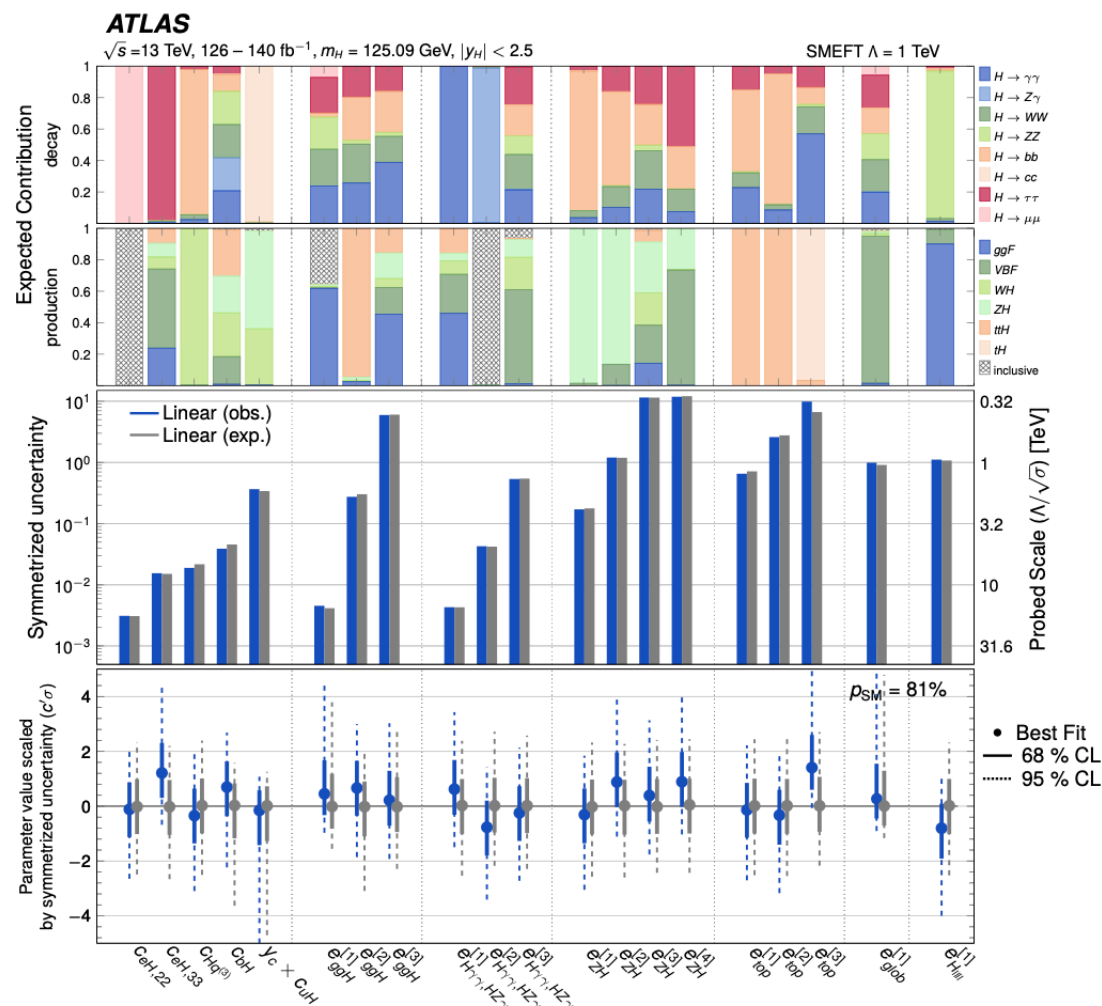
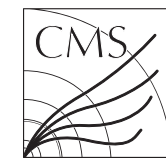
- ① Assumptions on Higgs and EWSB, e.g. linear doublet and decoupling NP in SMEFT
- ② Flavor symmetries of EFT basis & Yukawas
- ③ Typically fits remove flat directions in op. space with little-to-no sensitivity

Backbone of indirect NP searches at LHC and future colliders, great progress in recent years



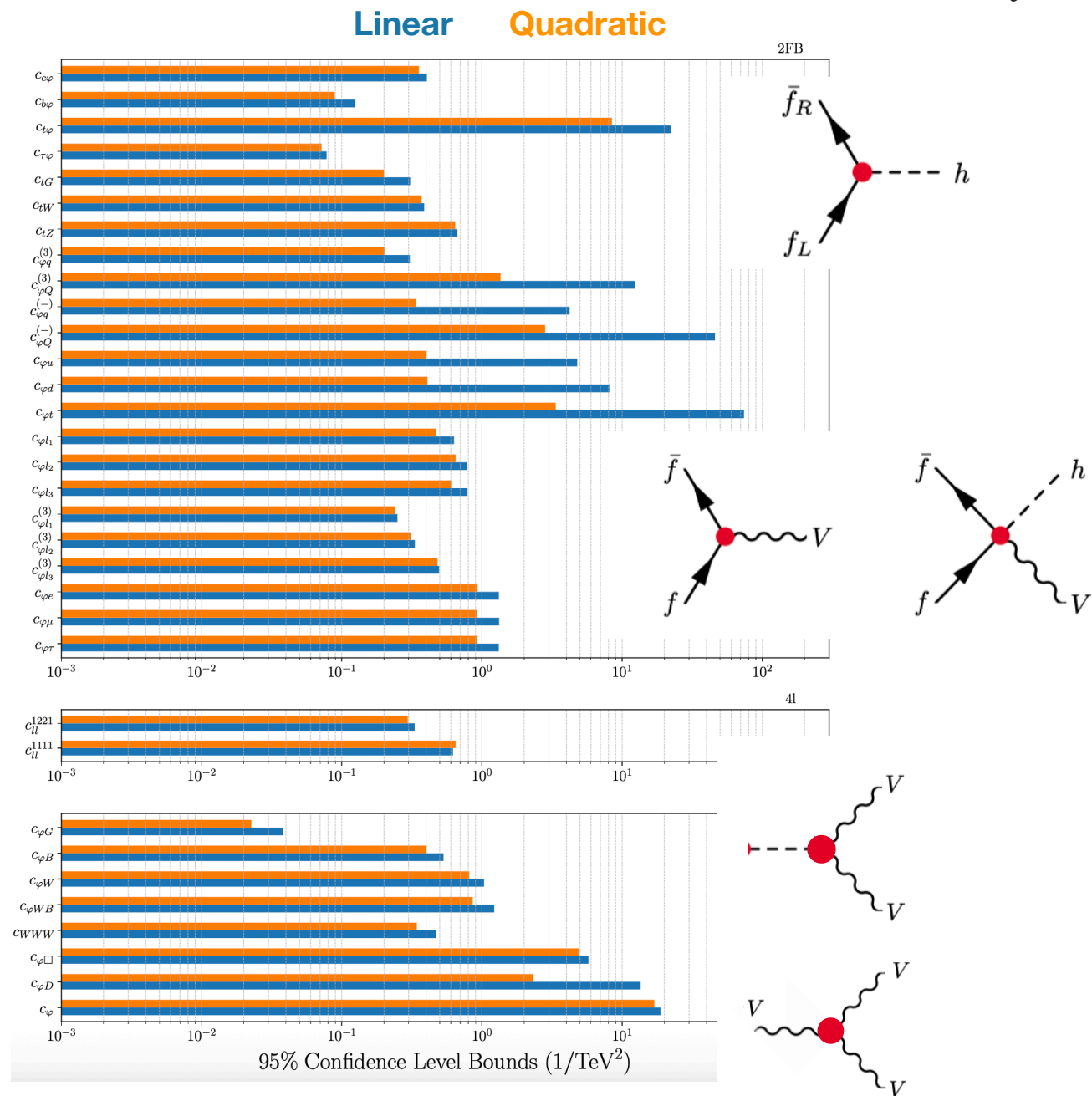
## AN INDIRECT DETECTOR HEAVY NEW PHYSICS

Often global fits performed by exp. collaborations cannot be directly compared to those of theory groups: different treatment of errors, principal component analysis, op. basis. Except perhaps that no deviation from SM is observed so far





Impact of dimension-8 ops often significant (also encode additional kinematic information). There is no consensus on how to handle this: upper bound on  $C/\Lambda^2$ ? systematic uncertainty on the fit?...



# RADIATIVE CORRECTIONS AND RG FLOW IN SMEFT

- Higher Orders in QCD/EW couplings and in the  $1/\Lambda^2$  expansion
- EFT is a QFT, renormalisable order-by-order in  $1/\Lambda^2$

$$\mathcal{O}(\alpha_s, \alpha_{ew}) + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_s}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_{ew}}{\Lambda^2}\right) \longrightarrow \text{Does this matter?}$$

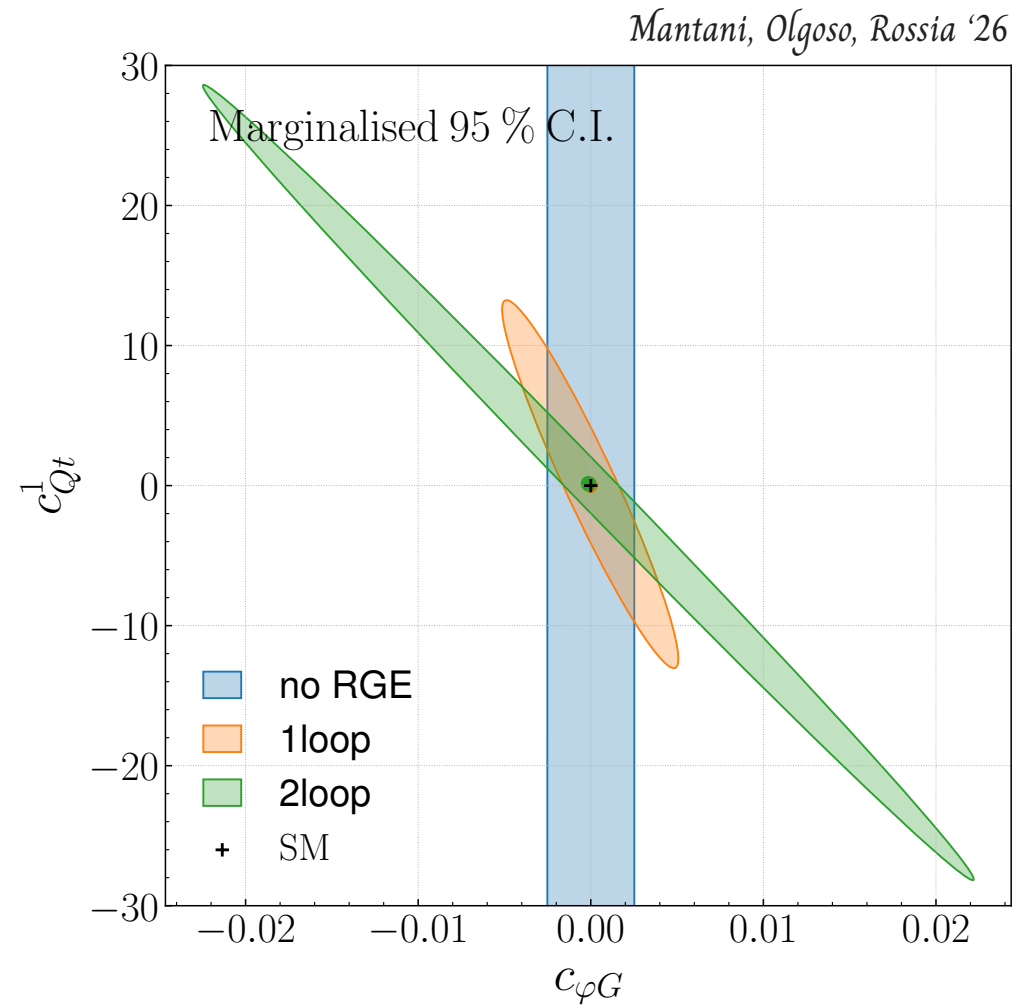
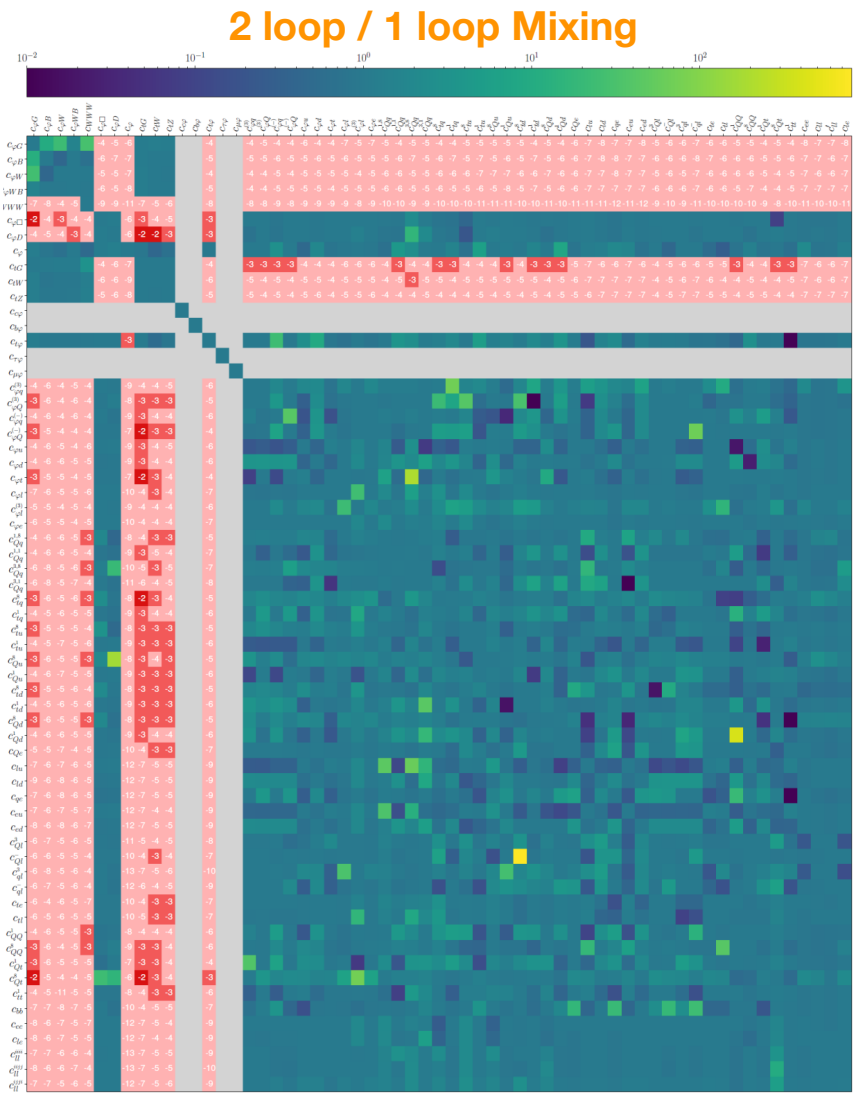
- Higher-order terms in the EFT expansion can also be added by considering higher-dimension operators
- Renormalisation Group Running and mixing

$$\Delta \text{Obs}_n = \text{Obs}_n^{\text{EXP}} - \text{Obs}_n^{\text{SM}} = \sum_i \frac{c_i^6(\mu)}{\Lambda^2} a_{n,i}^6(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right) \quad \text{How about this } \mu?$$

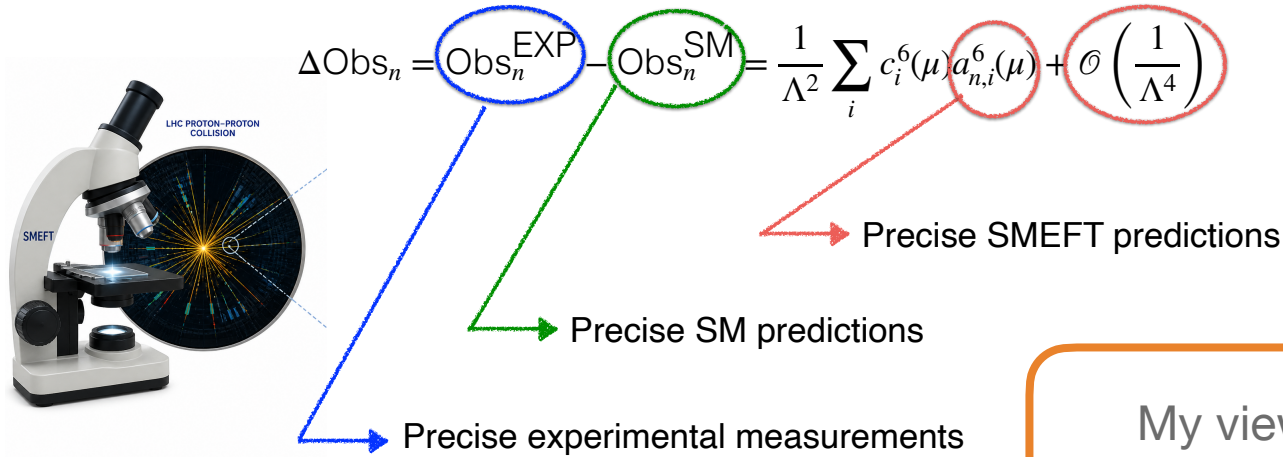
1-loop: (Alonso) Jenkins et al arXiv:1308.2627, 1310.4838, 1312.2014,

2-loop: Born, Fuentes-Martin, Thomsen 2601.19974

In addition, as precision grows, corrections to the EFT parametrization start becoming relevant, with visible effects in recent global fits for specific classes of operators



### EFT pathway to New Physics

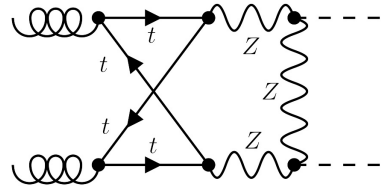


My view: We reached a point in time where global fits demand highly specialized expertise from both EP (e.g. uncertainties & correlations) and TH (e.g. higher orders, EFT aspects, dim-8, th. unc.) communities, both critical to the success of this program at HL-LHC.

LS3 should be an opportunity to devise a framework for closer synergistic EP/TH collaboration on these aspects, so that legacy analyses will be performed optimally.

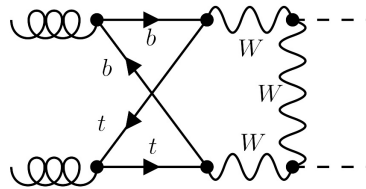
# A SENSITIVE PROBE REQUIRES A PRECISE BASELINE: PRECISION THEORY<sup>†</sup>

## Multi-scale/loops amplitudes



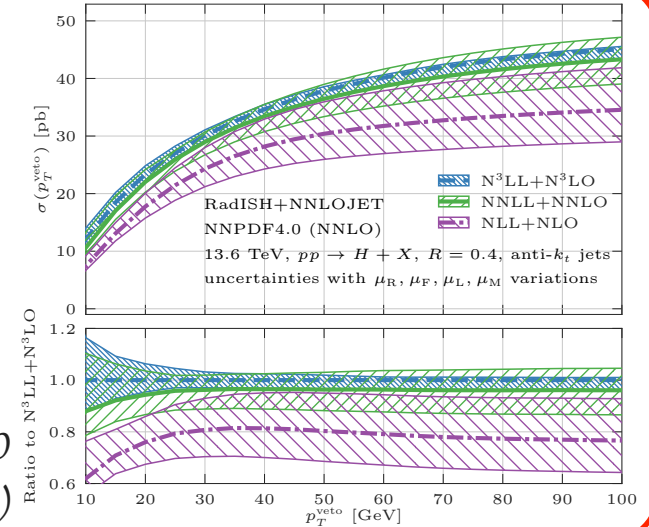
e.g.  $\mathcal{N}^{\text{LO}}$  EW for  $H\bar{H}$

Bi et al. '24, Heinrich et al. '24, Bhattacharya et al. '25,  
Davies et al. '22-'26, Bonetti et al. '25-'26



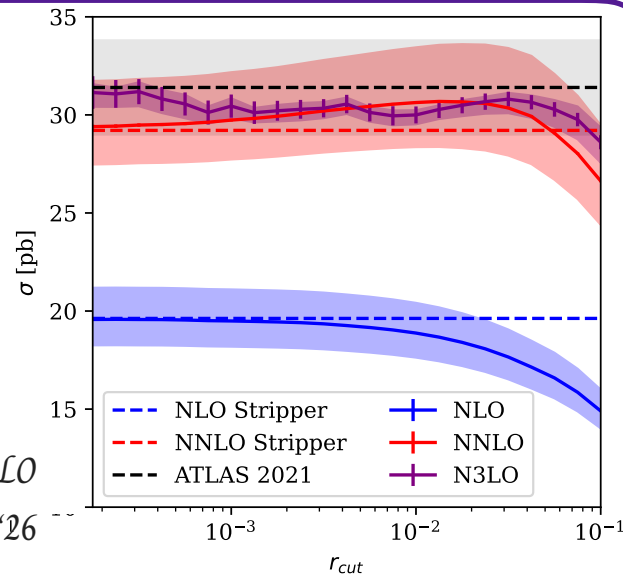
## Factorization & resummation

e.g. jet-veto XS at  $\mathcal{N}^3\text{LL}+\mathcal{N}^3\text{LO}$   
Abreu et al. (coming soon)



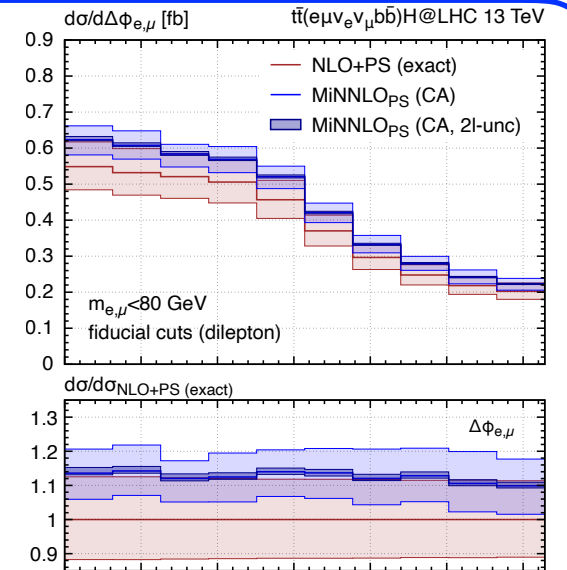
## IR subtraction for real radiation

e.g.  $\gamma\gamma$  at  $\mathcal{N}^3\text{LO}$   
Czakon et al. '26



## Higher-order Monte Carlo

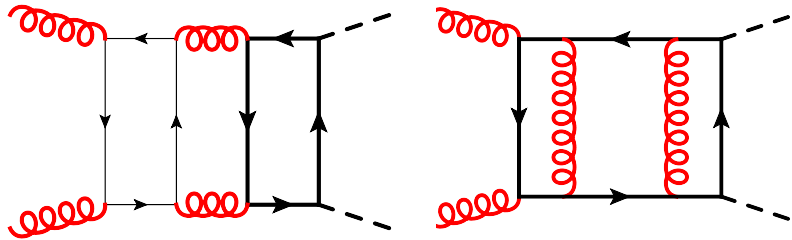
e.g.  $\text{MINNLO}_{\text{PS}}$  for  $t\bar{t}H$   
Biello et al. '26



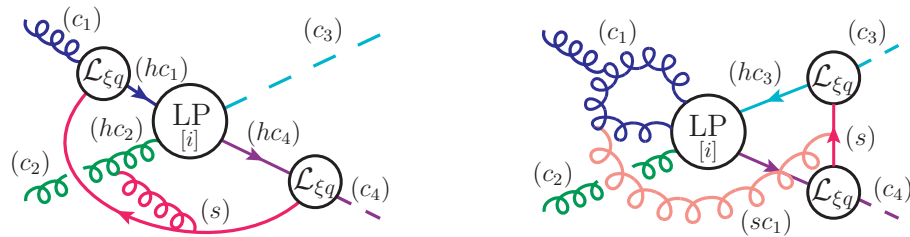
<sup>†</sup>  $\mathcal{N}^{\text{B}}$ : Advancements in designing better observables and fiducial cuts are just as important

# SHARPENING THE TOOLS

e.g. Exploitation of scale hierarchies for accurate/fast approximations

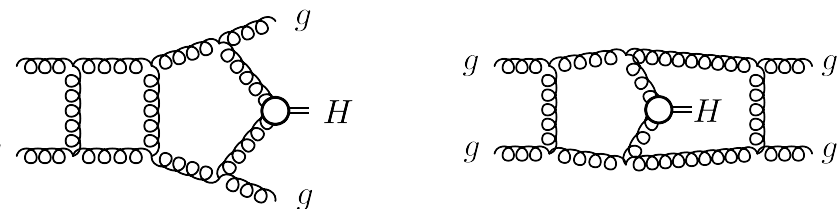


e.g. towards NNLO QCD for  $gg \rightarrow H\bar{H}$   
Davies, Schönwald, Steinhauser '23-'25



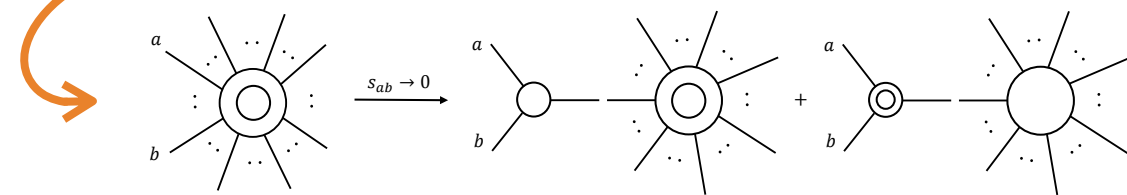
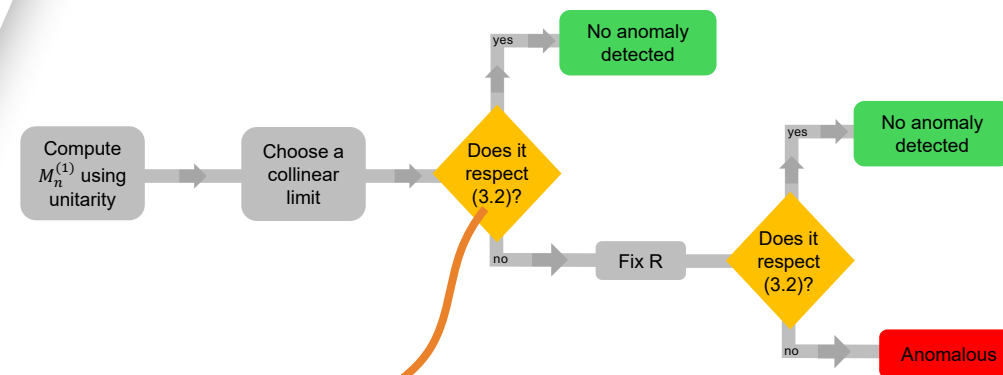
e.g. EFT for  $H\bar{H}$  amplitudes at high energy  
Jaskiewicz, Jones, Szafron, Ulrich '24

e.g. Rational reconstruction of  $H+jj$  amplitudes (LC)  
De Laurentis, Ita, Kuschke, Ruf, Sotnikov '26

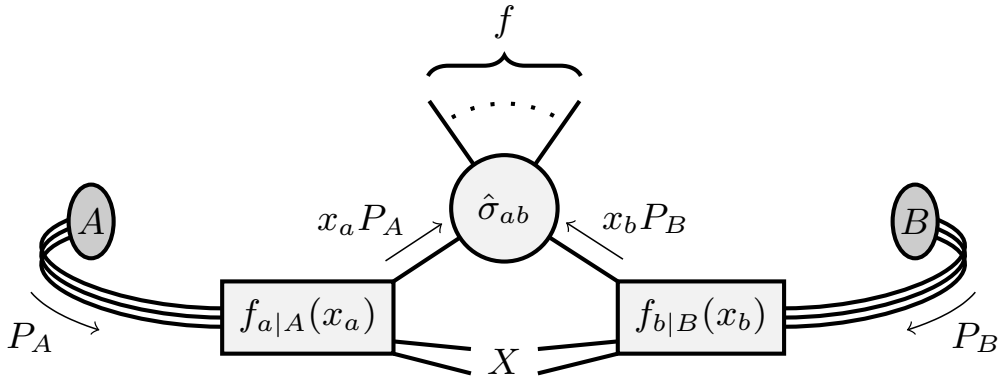


Advancements in the understanding of QFTs and its perturbative structure has been the backbone of these critical developments. Paramount to continue the exploration

e.g. Collinear factorization as a probe of gauge anomaly cancellation



## HOW FAR CAN WE PUSH THEORY PRECISION AT THE LHC?



$$d\sigma = \int dx_a dx_b f_{a|A}(x_a) f_{b|B}(x_b) d\hat{\sigma}_{ab}(x_a, x_b) + \mathcal{O}\left(\frac{\Lambda^n}{Q^n}\right)$$

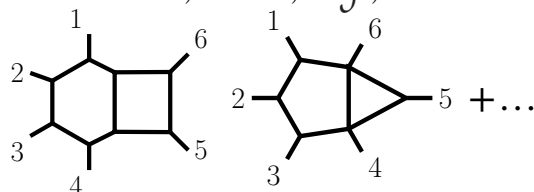


Remarkable progress in perturbative QFT  
boosted our control over the  
partonic cross section  
(QCD & EW radiative corrections)

# AN EXAMPLE: QCD AMPLITUDES FOR $2 \rightarrow n$ SCATTERING AT LHC

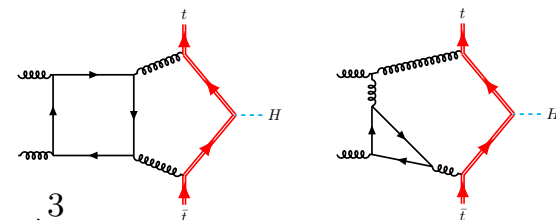
Towards 6-point amplitudes

*Abreu, Monni, Page, Usovitsch '24; Henn, Matijašić, Miczajka, Peraro, Xu, Zhang '21-'25*  
 + *Carrôlo, Chicherin, Yang '25*

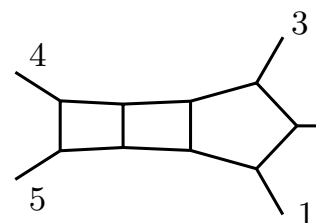


*e.g. ttH: Febres Cordero, Figueiredo, Kraus, Page, Reina '23;*  
*Agarwal, Heinrich, Jones, Kerner, Klein, Lang, Magerya, Olsson '24*

Massless processes available,  
 current work towards reactions  
 with 1, 2, 3 massive particles

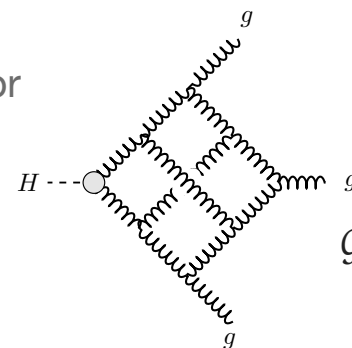


Massless planar  $2 \rightarrow 3$   
 integrals known



*Chicherin, Wu, Wu, Xu, Zhang, Zhang '25*

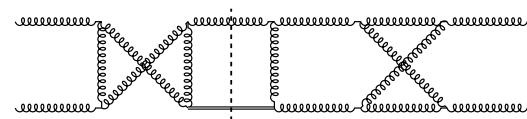
Amplitudes known for  
 $\gamma\gamma$ ,  $\gamma j$ ,  $jj$  and  $H/V+j$



*e.g.  $H+j$ :*

*Guan, Mistlberger, Ruf '26*

First steps towards  
 H cross section @  $N^4LO$



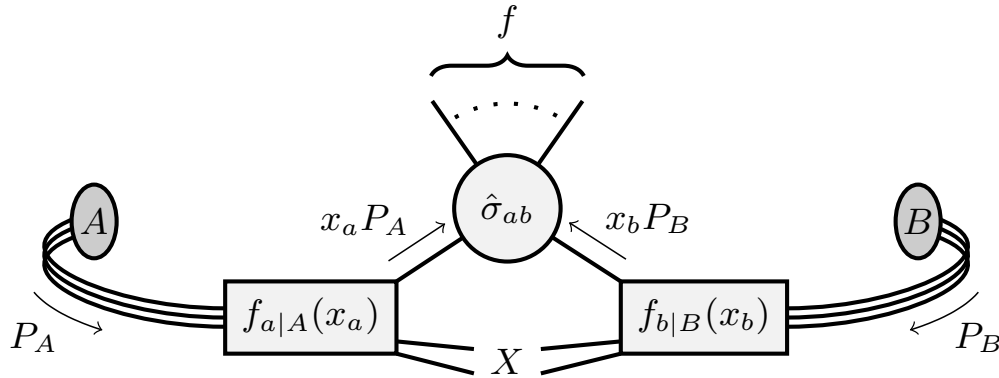
*e.g.  $RVVxV$  corrections:  
 Mistlberger, Suresh '25*

State of the art of QCD corr<sup>ns</sup> to  $2 \rightarrow n$  scattering at the LHC

NB: challenges in efficient computation of multi-scale processes also remain at  $NLO$ , though conceptually solved



## HOW FAR CAN WE PUSH THEORY PRECISION AT THE LHC?



$$d\sigma = \int dx_a dx_b f_{a|A}(x_a) f_{b|B}(x_b) d\hat{\sigma}_{ab}(x_a, x_b) + \mathcal{O}\left(\frac{\Lambda^n}{Q^n}\right)$$

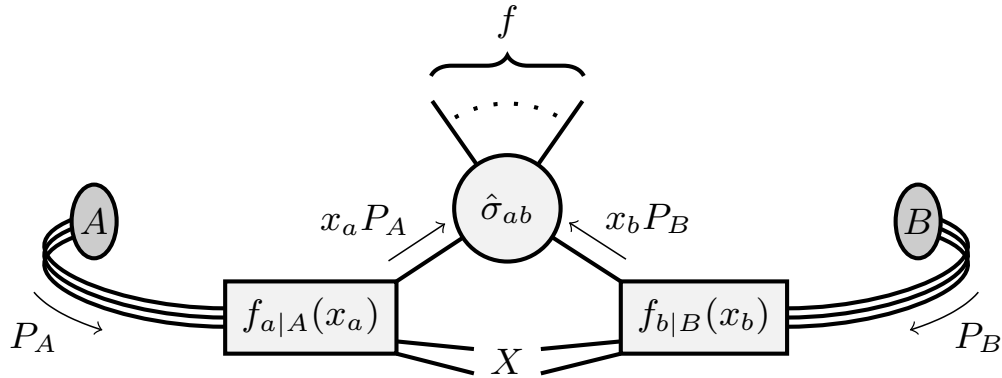


However, many open challenges on the path to %-level pheno

Ongoing program to extend their understanding to differential observables. Their robust control is among the main challenges for HL-LHC and, later, FCCee

- ① Non perturbative (power) corrections
- ② Violations of collinear factorization
- ③ Parametric uncertainties & parton densities
- ④ Theory uncertainties

# HOW FAR CAN WE PUSH THEORY PRECISION AT THE LHC?



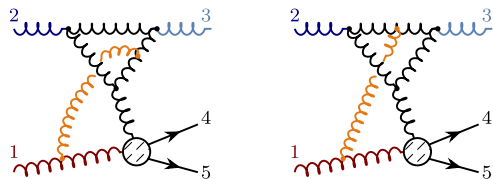
$$d\sigma = \int dx_a dx_b f_{a|A}(x_a) f_{b|B}(x_b) d\hat{\sigma}_{ab}(x_a, x_b) + \mathcal{O}\left(\frac{\Lambda^n}{Q^n}\right)$$



However, many open challenges on the path to %-level pheno

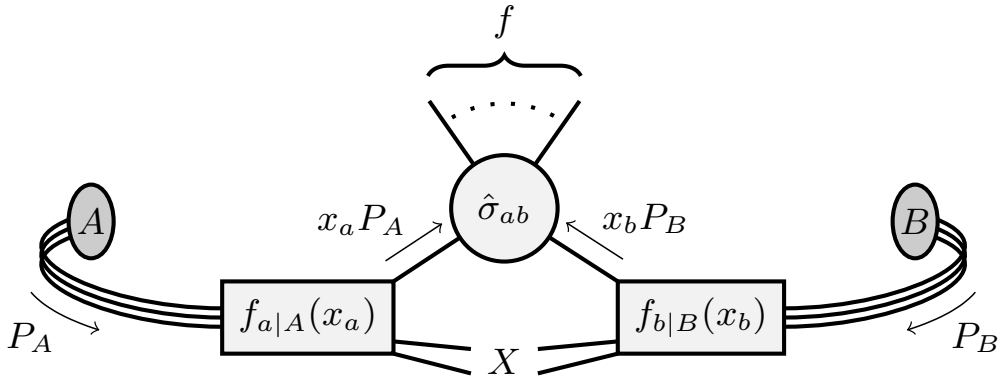
Recent research on factorization suggests that N<sup>3</sup>LO phenomenology may be unhindered, with the question being postponed by one order. Will this set the ultimate TH precision for LHC?

*e.g. 2-loop splitting amps: Buccioni, Fang, Yan '26*



- ① Non perturbative (power) corrections
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$$d\sigma = \int dx_a dx_b f_{a|A}(x_a) f_{b|B}(x_b) d\hat{\sigma}_{ab}(x_a, x_b) + \mathcal{O}\left(\frac{\Lambda^n}{Q^n}\right)$$



However, many open challenges on the path to %-level pheno

- ① Non perturbative (power) corrections
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## E.G. HOW WELL DO WE KNOW THE GLUON PDF IN HIGGS PRODUCTION?

Impact of aN<sup>3</sup>LO PDFs on ggH XS is substantial (further  $\simeq -1\%$  from QED).

Difference between sets larger at aN<sup>3</sup>LO (3-4%) than at NNLO (1-2%), and increase at fiducial level

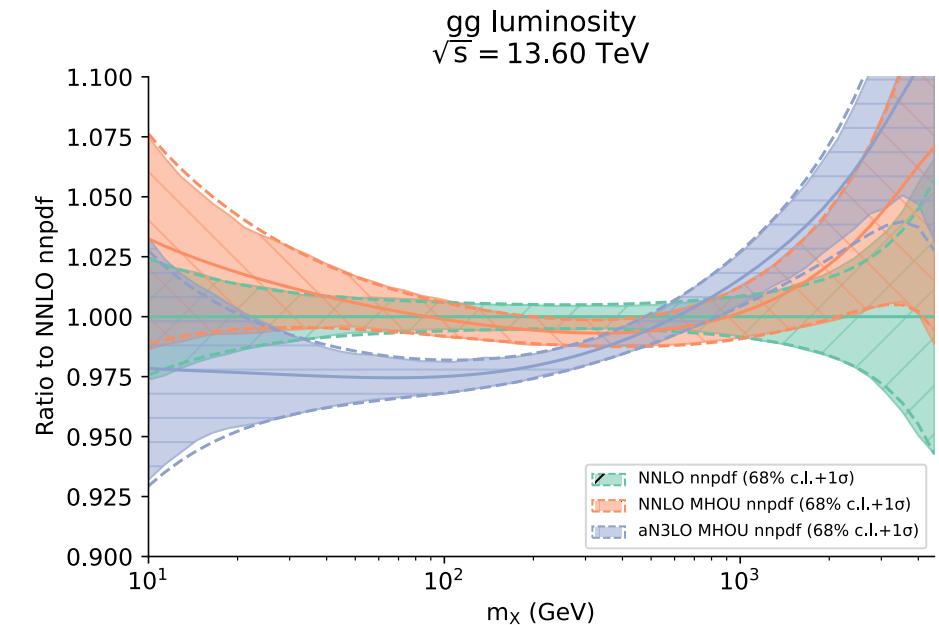
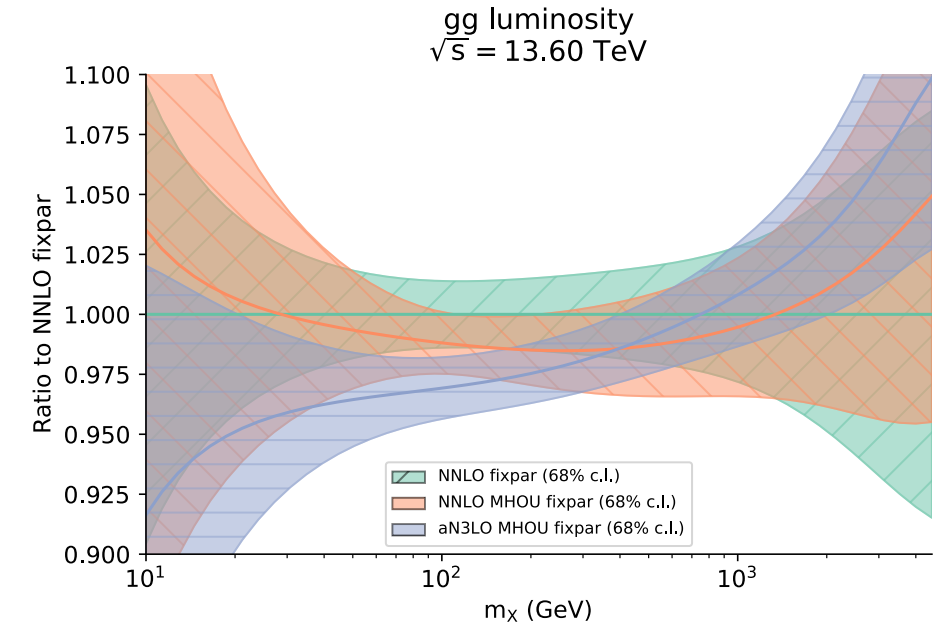
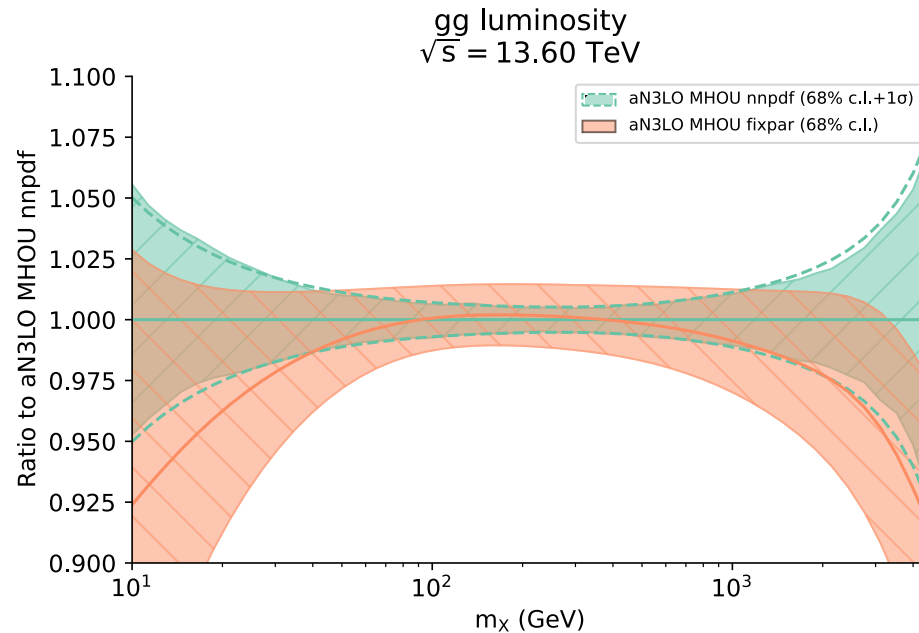
Credits: Stephen Jones @ [PDF4LHC/HXSWG meeting](#) '26

| (aN <sup>3</sup> LO PDF $\otimes$ N <sup>3</sup> LO HTL) vs (NNLO PDF $\otimes$ N <sup>3</sup> LO HTL) |                            |        |         |                                      |        |         |
|--------------------------------------------------------------------------------------------------------|----------------------------|--------|---------|--------------------------------------|--------|---------|
| $\sqrt{s}$ [TeV]                                                                                       | aN <sup>3</sup> LO vs NNLO |        |         | aN <sup>3</sup> LO vs PDF4LHC21 NNLO |        |         |
|                                                                                                        | MSHT20xNNPDF40             | MSHT20 | NNPDF40 | MSHT20xNNPDF40                       | MSHT20 | NNPDF40 |
| 7                                                                                                      | -4.2%                      | -6.0%  | -2.0%   | -5.2%                                | -6.8%  | -3.2%   |
| 13.6                                                                                                   | -3.8%                      | -5.2%  | -2.1%   | -4.2%                                | -5.9%  | -2.2%   |
| 100                                                                                                    | -0.7%                      | +0.6%  | -1.6%   | -1.0%                                | -0.7%  | -1.0%   |
| (aN <sup>3</sup> LO PDF $\otimes$ N <sup>3</sup> LO HTL) vs (NNLO PDF $\otimes$ NNLO HTL)              |                            |        |         |                                      |        |         |
| $\sqrt{s}$ [TeV]                                                                                       | aN <sup>3</sup> LO vs NNLO |        |         | aN <sup>3</sup> LO vs PDF4LHC21 NNLO |        |         |
|                                                                                                        | MSHT20xNNPDF40             | MSHT20 | NNPDF40 | MSHT20xNNPDF40                       | MSHT20 | NNPDF40 |
| 7                                                                                                      | -0.8%                      | -2.6%  | +1.5%   | -1.8%                                | -3.5%  | +0.3%   |
| 13.6                                                                                                   | -0.5%                      | -1.9%  | +1.3%   | -0.9%                                | -2.6%  | +1.2%   |
| 100                                                                                                    | +3.1%                      | +4.4%  | +2.1%   | +2.8%                                | +3.1%  | +2.8%   |

## E.G. HOW WELL DO WE KNOW THE GLUON PDF IN HIGGS PRODUCTION?

Pattern of discrepancies probably not due to fit methodology. Choices related to data sets and theory aspects (e.g. masses, VFNS, treatment of HOs, ...) likely the culprit. Are PDF errors assessed robustly?

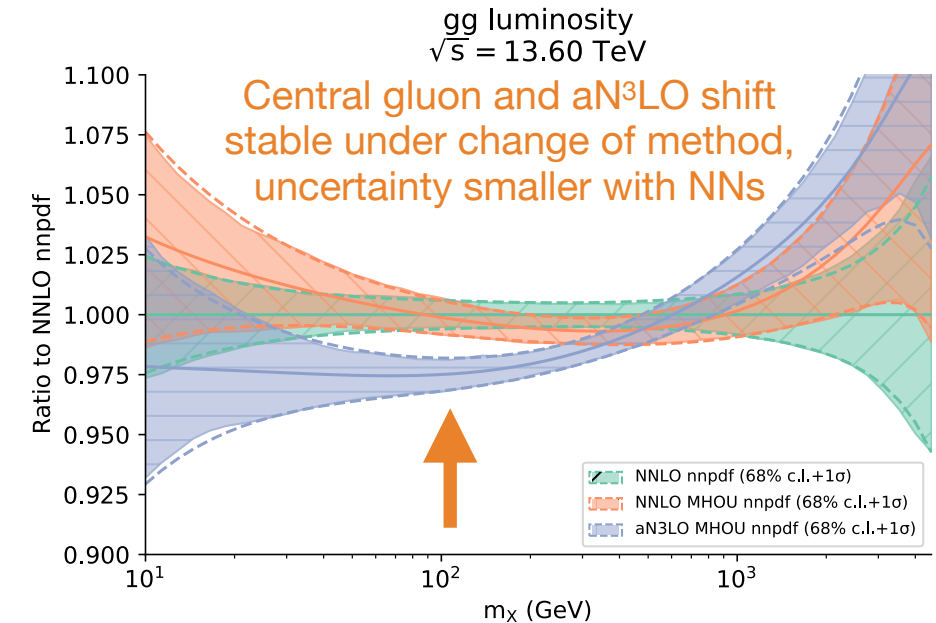
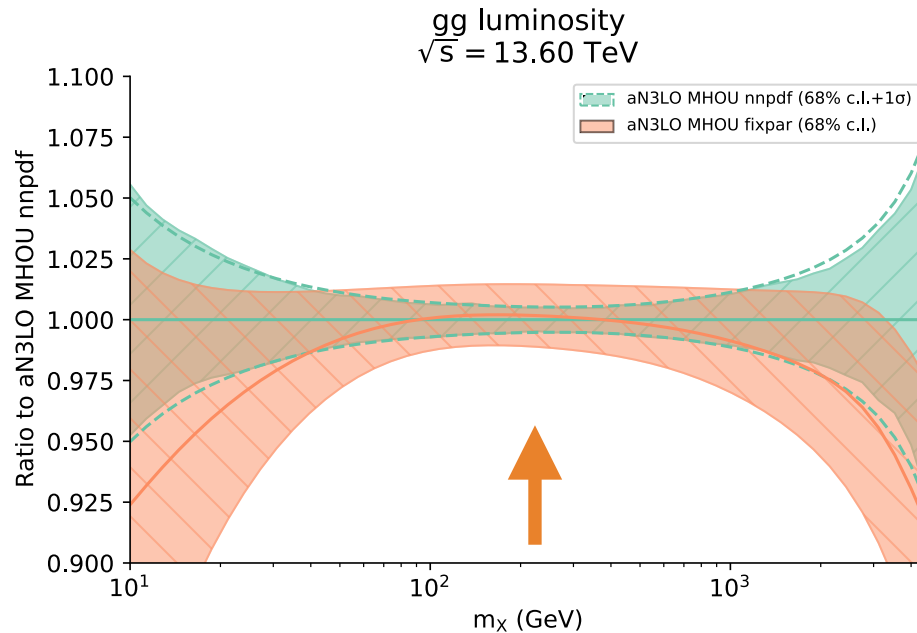
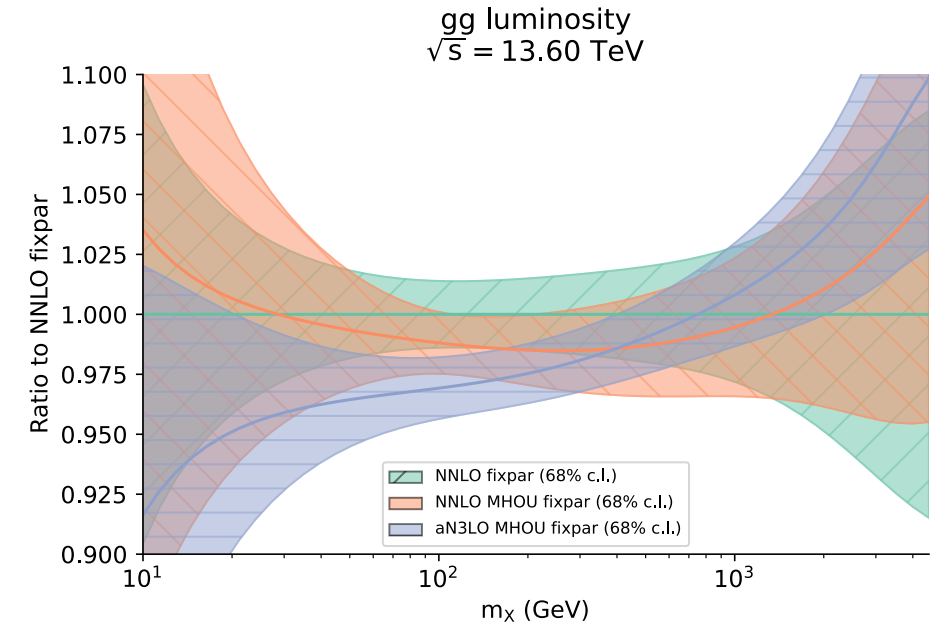
*FPDF project Cruz-Martinez, Giani, Harland-Lang '26*  
*Fixed-Chebyshev polynomial PDFs + Hessian vs. NNPDF method*



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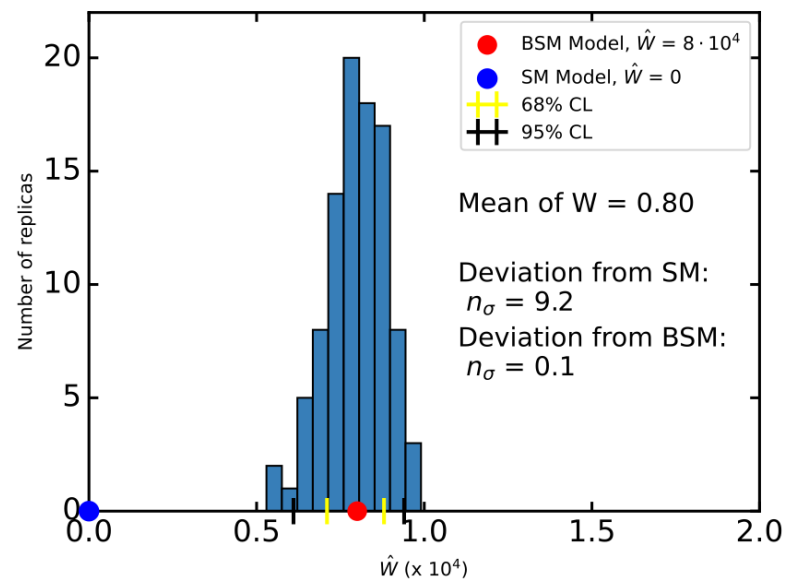
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*FPDF project Cruz-Martinez, Giani, Harland-Lang '26*  
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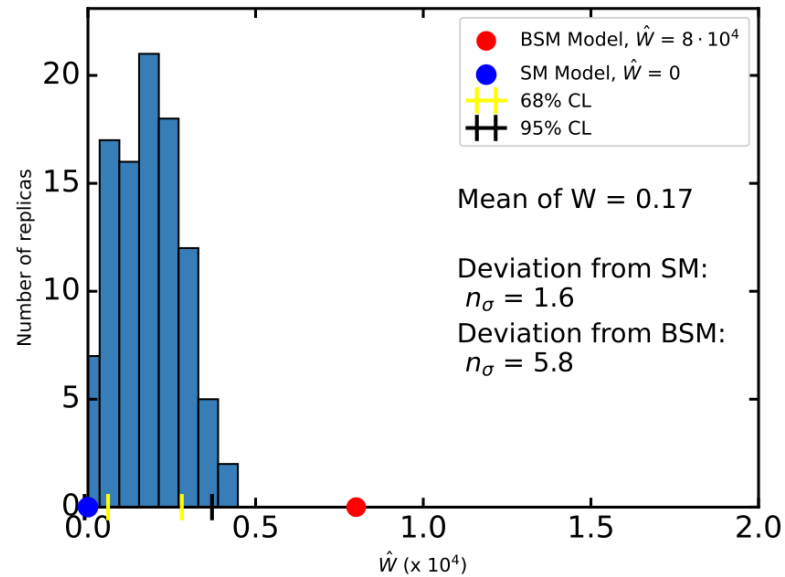
# A HUNTING TOOL IS AS GOOD AS ITS CALIBRATION

## SMEFT Fit with True PDF



## SMEFT Fit with BSM Biased PDF

- Misses new physics



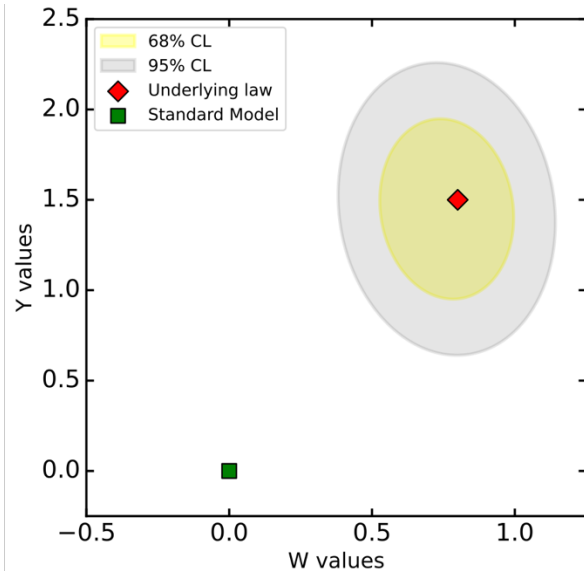
Flexible PDF  
parametrizations can absorb  
heavy NP effects washing out  
any signal in observables  
(e.g. DY mass spectrum).  
Crucial to avoid this pitfall to  
maximize HL-LHC sensitivity

$$\mathcal{L}_{true} \otimes \hat{\sigma}_{BSM} \approx \mathcal{L}_{BSM-biased} \otimes \hat{\sigma}_{SM}$$

## A HUNTING TOOL IS AS GOOD AS ITS CALIBRATION

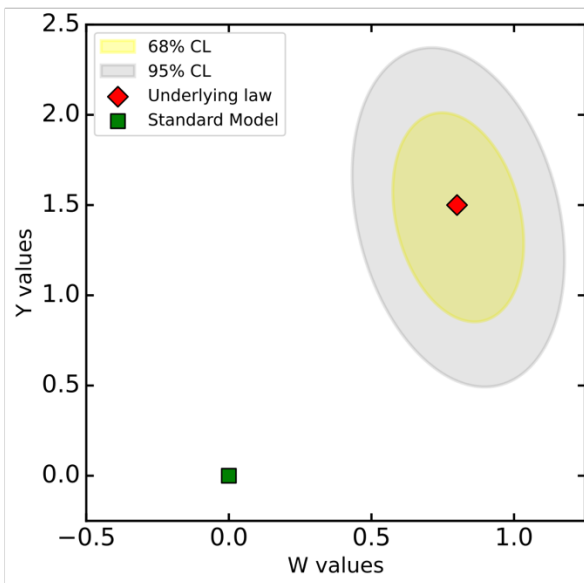
Simultaneous fit  
(no PDF assumption)

✓ Doable



SMEFT only fit  
(Conservative PDF)

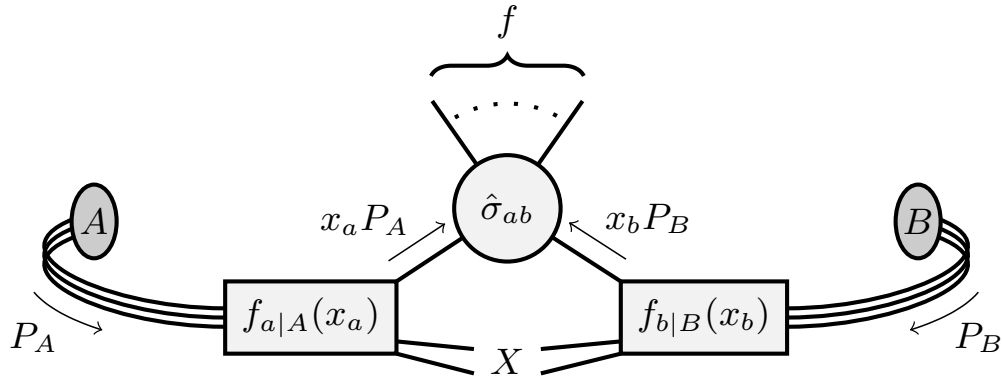
✓ Doable



Simultaneously extracting Wilson coefficients and PDFs seems optimistic, but avoids potentially conservative PDF errors by cutting out relevant datasets. Differential measurements to disentangle the effect of NP might be preferable, though harder from a statistics PoV. Either way, understanding PDF errors is paramount!



## HOW FAR CAN WE PUSH THEORY PRECISION AT THE LHC?

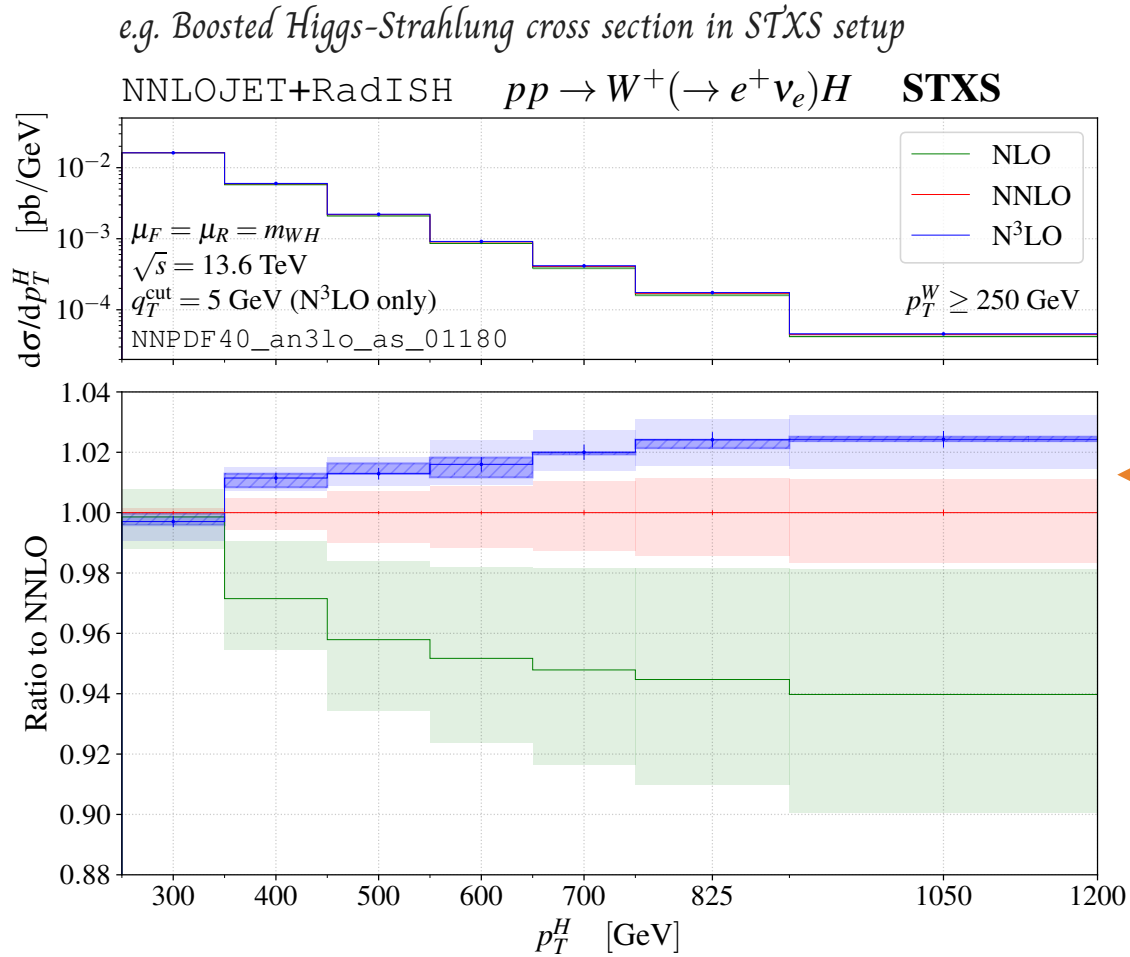


$$d\sigma = \int dx_a dx_b f_{a|A}(x_a) f_{b|B}(x_b) d\hat{\sigma}_{ab}(x_a, x_b) + \mathcal{O}\left(\frac{\Lambda^n}{Q^n}\right)$$

However, many open challenges on the path to %-level pheno

- ① Non perturbative (power) corrections
- ② Violations of collinear factorization
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- ④ Theory uncertainties

# CAN WE CONTROL THEORY UNCERTAINTIES AT % LEVEL?

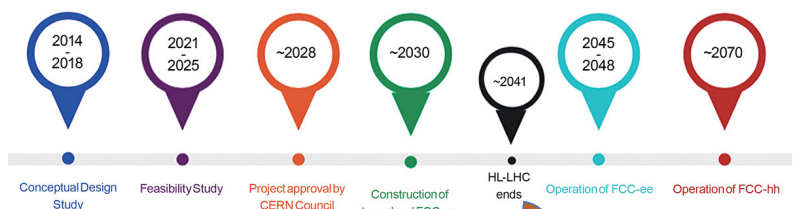


As LHC theory predictions reach few-percent precision, conventional uncertainty estimates (e.g. scale variation) become increasingly inadequate. More robust uncertainty models will be essential to exploit the HL-LHC precision physics program

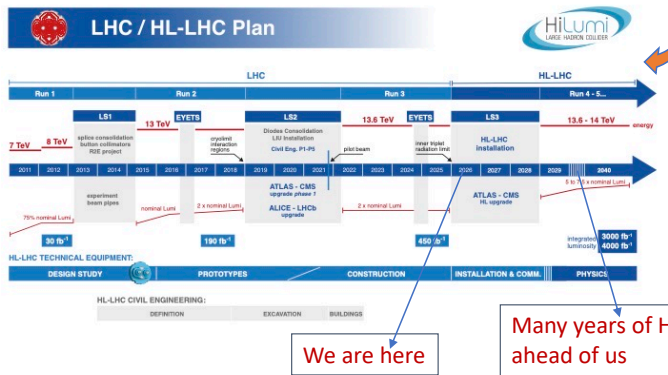
*e.g. Ongoing discussions within the [EWWG](#), soon to reach the Higgs too*

# THE FUTURE OF THE HIGGS MICROSCOPE

This is what the FCC project will realize in a synergistic way over the span of 40+ years.



Based on the LHC legacy, which is where the roadmap to the FCC starts ...



- Run 1: Higgs discovery
  - Run 2: Higgs couplings
    - outperformed expectations
  - Run 3 to HL-LHC
    - Higgs precision program
- 20-fold increase in statistics by the end of HL-LHC!

We are here

Many years of HL running ahead of us

## From Kick-off to TDR

2015

CEPC-SPPC  
Preliminary Conceptual Design Report  
Volume I - Physics & Detector

The CEPC-SPPC Study Group  
March 2015

**CEPC physics white papers:**

1. Higgs physics, arxiv:1810.09037 Chin. Phys. C 43(2019) 043002
2. Flavor physics, arxiv:2412.19743
3. New Physics Search arXiv:2505.24810
4. Electroweak physics, to be published
5. QCD, to be published

CEPC-SPPC  
Preliminary Conceptual Design Report  
Volume II - Accelerator

The CEPC-SPPC Study Group  
March 2015

**2018**

HEP-CEPC-DR-2018-01  
HEP-EP-2018-01  
HEP-AC-2018-01

**CEPC**  
Conceptual Design Report  
Volume I - Accelerator

The CEPC Study Group  
August 2018

**2018**

HEP-CEPC-DR-2018-02  
HEP-EP-2018-01  
HEP-TH-2018-01

**CEPC**  
Conceptual Design Report  
Volume II - Physics & Detector

The CEPC Study Group  
October 2018

**2023**

HEP-CEPC-DR-2023-01  
HEP-AC-2023-01

**CEPC**  
Technical Design Report  
Accelerator

The CEPC Study Group  
December 2023

**2025**

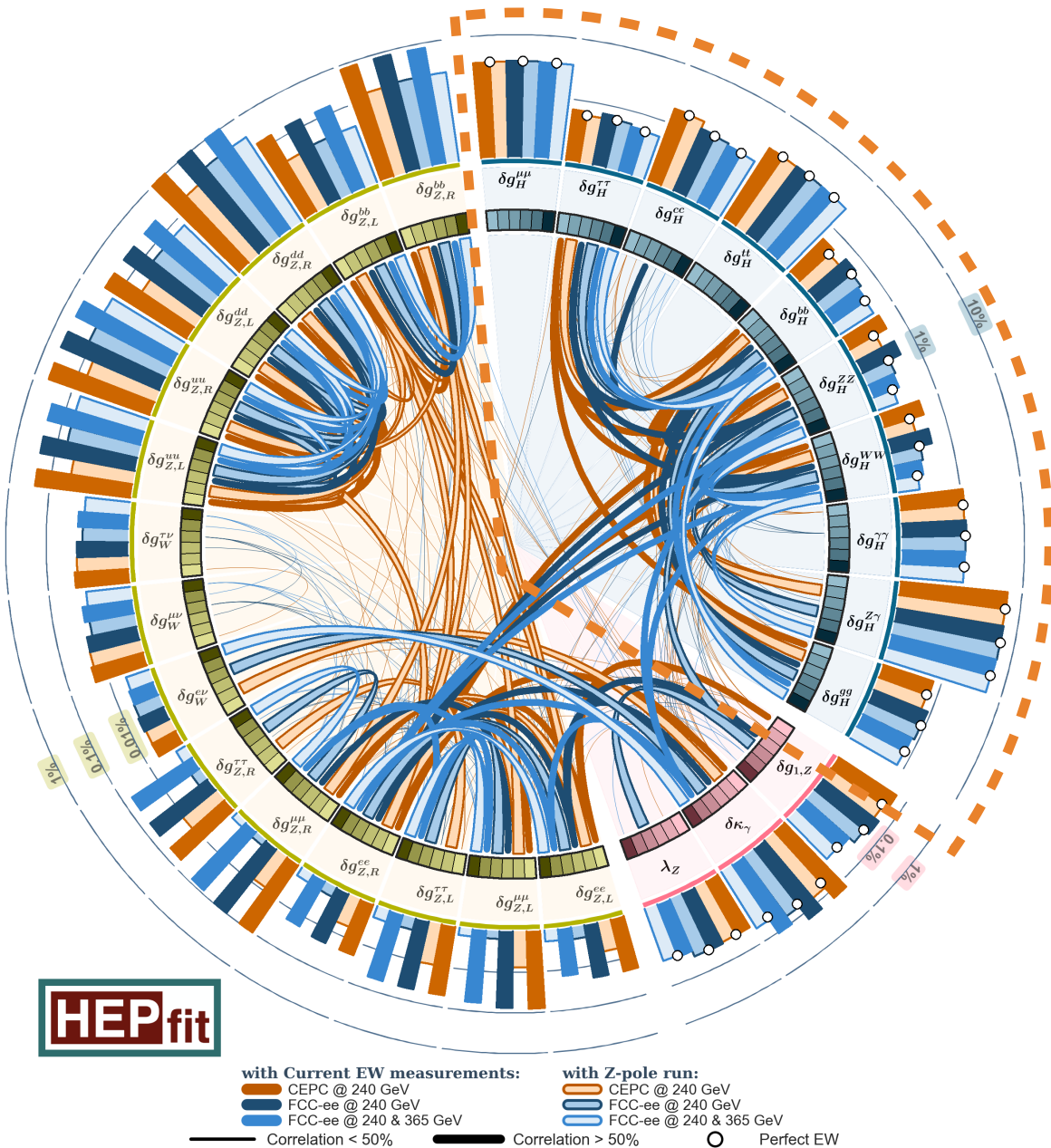
HEP-EP-EP-DR-2025-01  
HEP-EP-EP-2025-01

**CEPC Reference Detector**  
Technical Design Report

Version: V1.0.0 Initial, 2025-10-08 09:09:14Z

The CEPC Study Group  
October, 2025

<http://cepc.ihep.ac.cn>



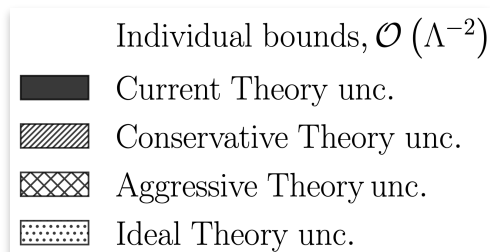
The precision reached in several key Higgs couplings and width will be instrumental to clarify the structure of the Higgs sector and corner many BSM scenarios (e.g. flavour, compositeness)

Full structure of the theory must be under perfect control to exploit the data. Mixing between processes is critical to constrain the pattern of deviations: e.g. Tera-Z and top runs are vital to constrain the Higgs sector

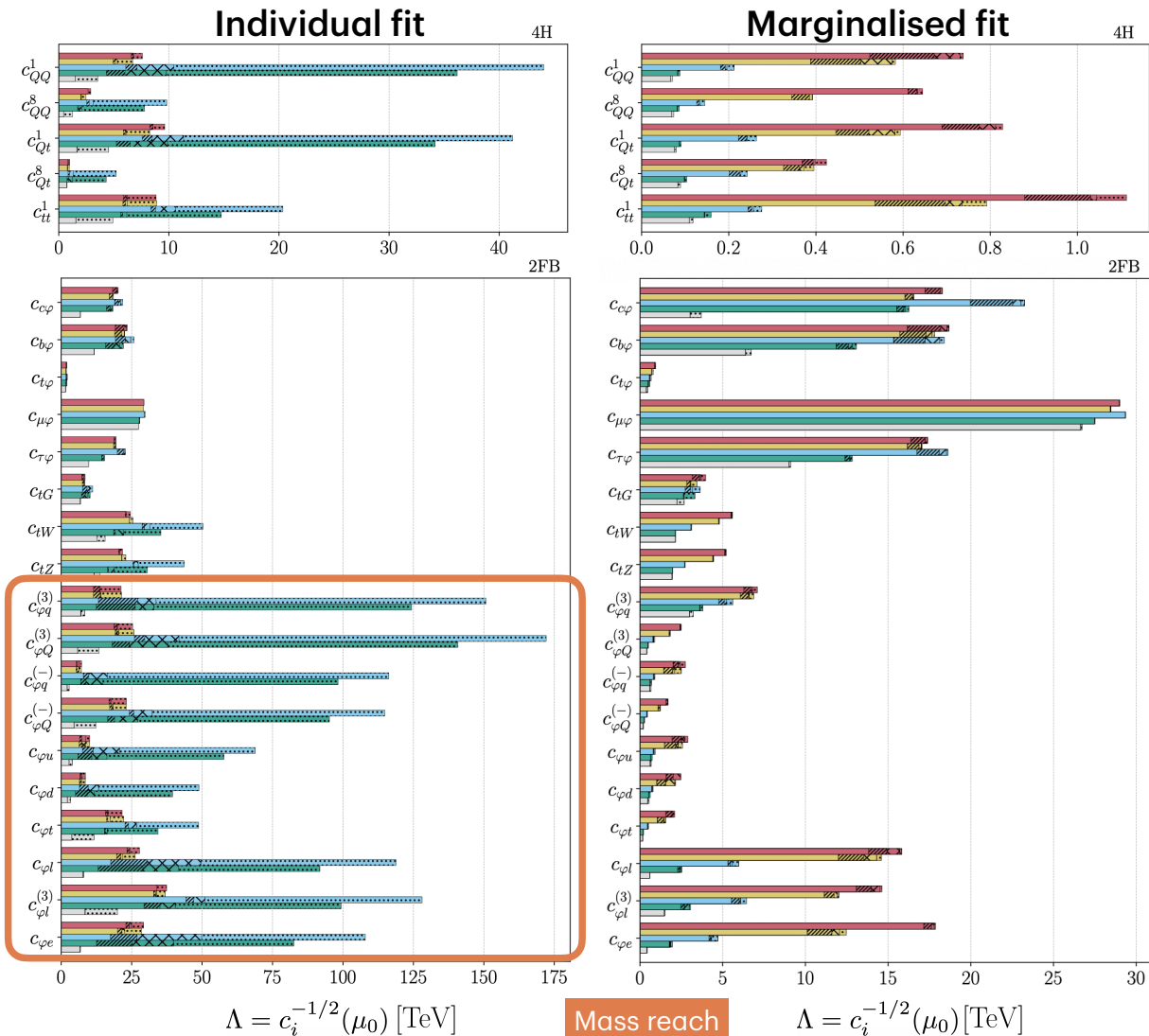
# Impact of theory uncertainties

Better theory predictions are essential to make the most of future colliders

Operators sensitive to Z-pole observables are strongly affected by theory uncertainties

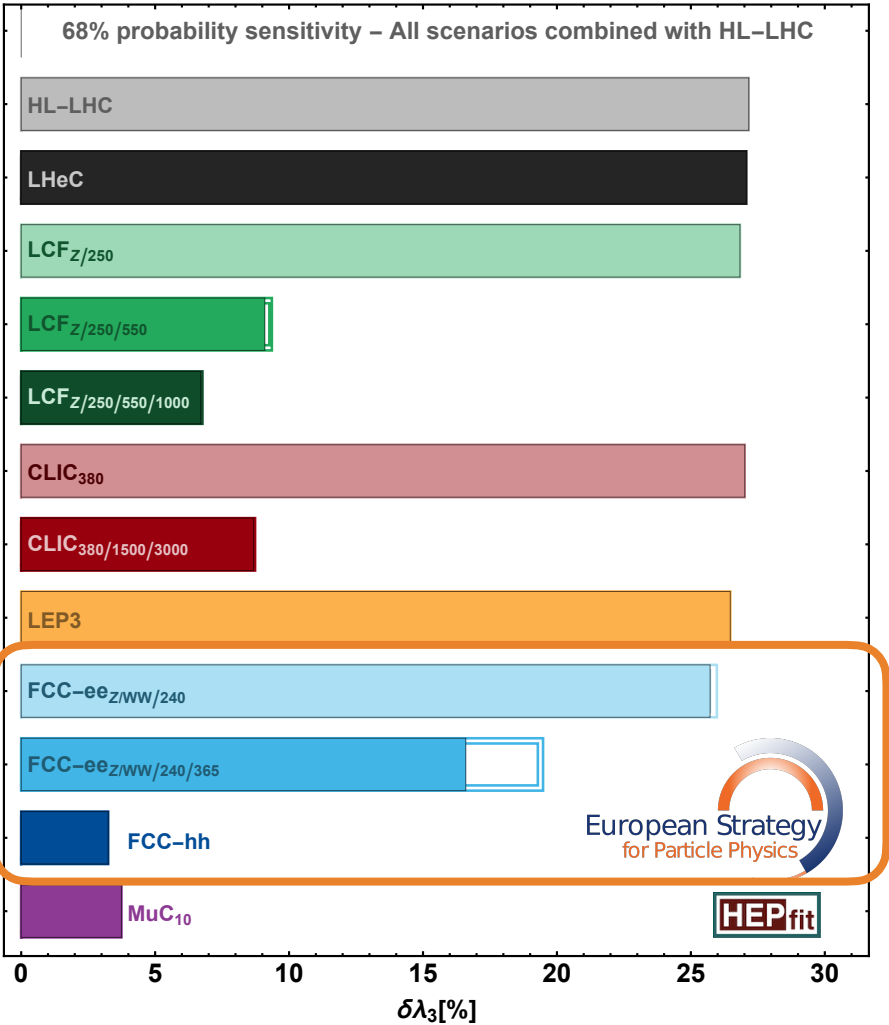


HL-LHC LEP3 FCC-ee LCF550 LCF1000

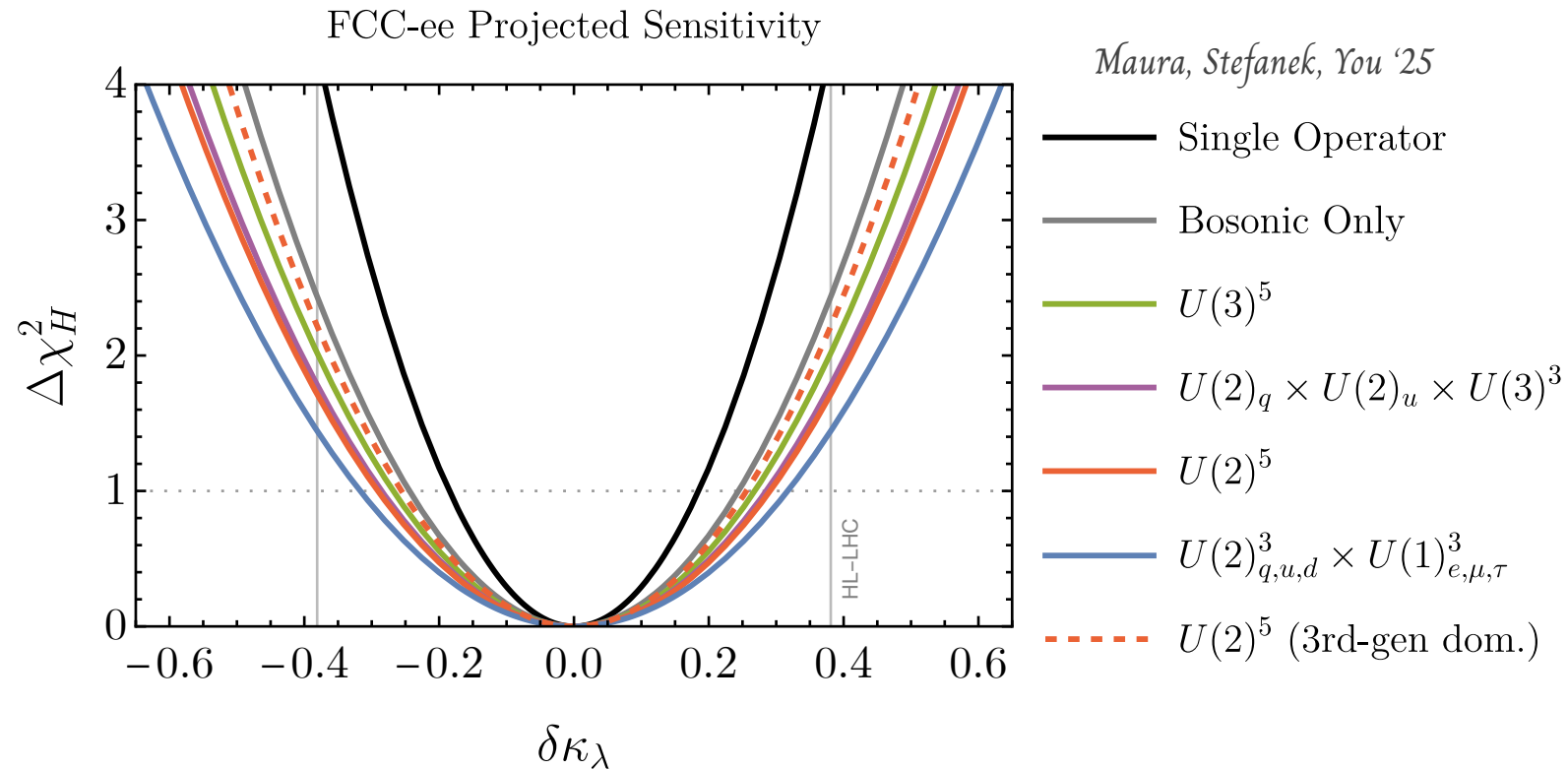


E.G. HIGGS TRILINEAR COUPLING

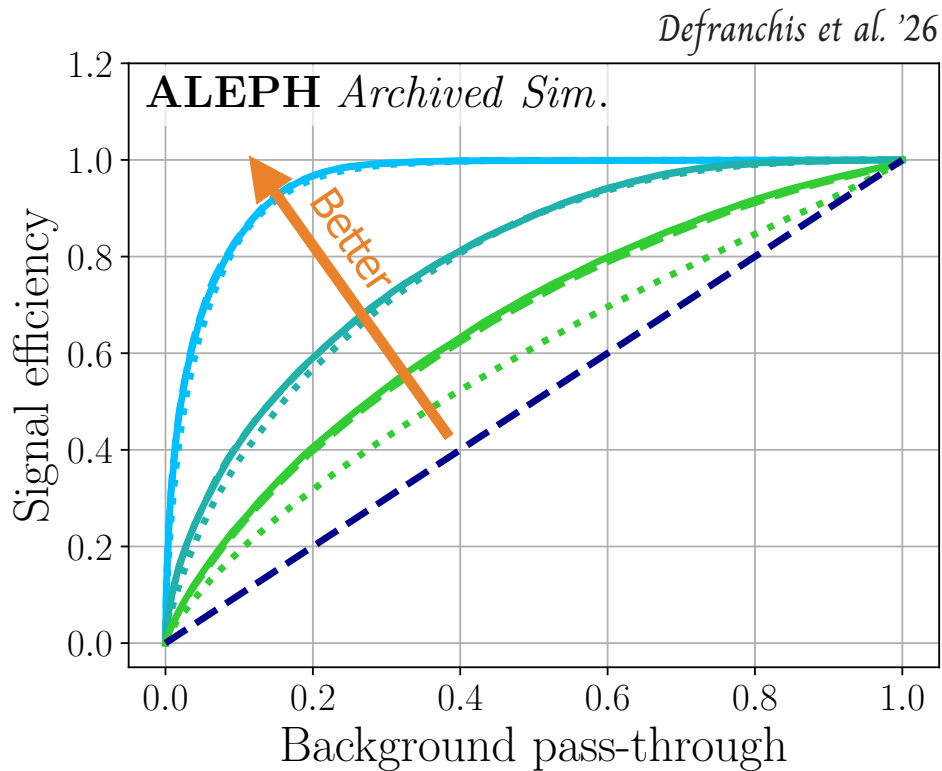
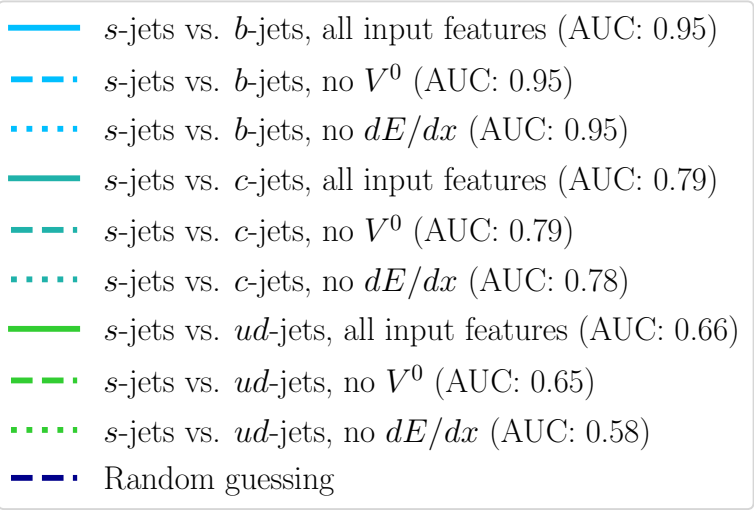
Physics Briefing Book 2511.03883



e.g. Relative bounds on  $\kappa_\lambda$  in SMEFT (w/ different flavour assumptions):  
EW corr.<sup>ns</sup> and RGE flow in SMEFT affect actual bounds,  
which may turn out to be milder than in a single-operator scenario.  
Control over EFT global fits must be perfect



STRANGE YUKAWA COUPLING



ML-based jet taggers open up tantalizing prospects for constraining the strange Yukawa, with recent studies indicating a sensitivity to  $O(<100\%)$  deviations from SM. Understanding of taggers and their training (e.g. modelling) is critical

*Physics Briefing Book 2511.03883*

| Coupling                                        | HL-LHC                 | FCC-ee               | FCC-ee + FCC-hh      |
|-------------------------------------------------|------------------------|----------------------|----------------------|
| $\kappa_Z$ (%)                                  | 1.3*                   | 0.10                 | 0.10                 |
| $\kappa_W$ (%)                                  | 1.5*                   | 0.29                 | 0.25                 |
| $\kappa_b$ (%)                                  | 2.5*                   | 0.38 / 0.49          | 0.33 / 0.45          |
| $\kappa_g$ (%)                                  | 2*                     | 0.49 / 0.54          | 0.41 / 0.44          |
| $\kappa_\tau$ (%)                               | 1.6*                   | 0.46                 | 0.40                 |
| $\kappa_c$ (%)                                  | —                      | 0.70 / 0.87          | 0.68 / 0.85          |
| $\kappa_\gamma$ (%)                             | 1.6*                   | 1.1                  | 0.30                 |
| $\kappa_{Z\gamma}$ (%)                          | 10*                    | 4.3                  | 0.67                 |
| $\kappa_t$ (%)                                  | 3.2*                   | 3.1                  | 0.75                 |
| $\kappa_u$ (%)                                  | 4.4*                   | 3.3                  | 0.42                 |
| $ \kappa_s $ (%)                                | —                      | $+29$<br>$-67$       | $+29$<br>$-67$       |
| $\Gamma_H$ (%)                                  | —                      | 0.78                 | 0.69                 |
| $\mathcal{B}_{\text{inv}} (<, 95\% \text{ CL})$ | $1.9 \times 10^{-2} *$ | $5 \times 10^{-4}$   | $2.3 \times 10^{-4}$ |
| $\mathcal{B}_{\text{unt}} (<, 95\% \text{ CL})$ | $4 \times 10^{-2} *$   | $6.8 \times 10^{-3}$ | $6.7 \times 10^{-3}$ |



What does this require from theory

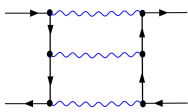
Precision for extraction from data

| Quantity                          | Current precision    | FCC-ee stat. (syst.) precision | Required theory input                                                      | Theory status as of today                                                                            | Needed theory improvement <sup>†</sup>                                       |
|-----------------------------------|----------------------|--------------------------------|----------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| $m_Z$ (MeV)                       | 2.0                  | 0.004 (0.1)                    | non-resonant $e^+e^- \rightarrow f\bar{f}$ , initial-state radiation (ISR) | NLO, ISR logarithms up to 6 <sup>th</sup> order                                                      | NNLO for $e^+e^- \rightarrow f\bar{f}$                                       |
| $\Gamma_Z$ (MeV)                  | 2.3                  | 0.004 (0.012)                  |                                                                            |                                                                                                      |                                                                              |
| $\sin^2 \theta_{\text{eff}}^\ell$ | $1.6 \times 10^{-4}$ | $1.2 (1.2) \times 10^{-6}$     |                                                                            |                                                                                                      |                                                                              |
| $m_W$ (MeV)                       | 9.9                  | 0.18 (0.16)                    | lineshape of $e^+e^- \rightarrow WW$ near threshold                        | NLO ( $e^+e^- \rightarrow 4f$ or EFT framework)                                                      | NNLO for $e^+e^- \rightarrow WW$ , $W \rightarrow f\bar{f}'$ in EFT setup    |
| HZZ coupling                      | —*                   | 0.1%                           | cross section for $e^+e^- \rightarrow ZH$                                  | NLO EW plus partial NNLO QCD/EW                                                                      | full NNLO EW                                                                 |
| $m_{\text{top}}$ (MeV)            | 290                  | 4.2 (4.9)                      | threshold scan $e^+e^- \rightarrow t\bar{t}$                               | N <sup>3</sup> LO QCD, NNLO EW, resummations up to NNLL, $\mathcal{O}(30 \text{ MeV})$ scale uncert. | Matching fixed orders with resummations, merging with MC, $\alpha_S$ (input) |

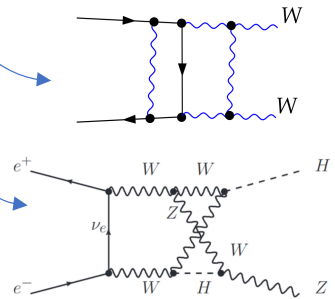
FCC feasibility study report – 2505.00272

Several building blocks:

- Initial state soft+collinear ( $\gamma$ ) radiation (ISR)
- EW+QCD corrections (h.o. + resummed)
- QCD at Z-pole: multijet xsec ( $\alpha_S(M_Z)$ )
- Improved parton-shower event generators
- Non-perturbative hadronization effects



All need to be pushed beyond LEP experience  
Lots of experience from LHC, but h.o. EW is new territory



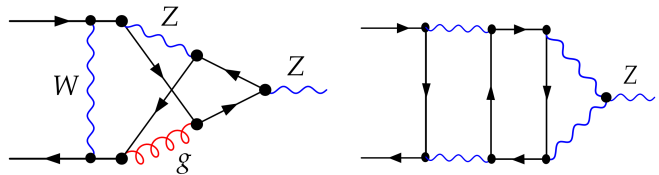
2<sup>nd</sup> order EW corrections  
↪ Extremely challenging

Precision for prediction

| Quantity                          | Required theory input                           | Theory status as of today    | Needed theory improvement <sup>†</sup>       |
|-----------------------------------|-------------------------------------------------|------------------------------|----------------------------------------------|
| $\Gamma_Z$                        | vertex corrections for $Z \rightarrow f\bar{f}$ | NNLO + partial higher orders | N <sup>3</sup> LO EW + partial higher orders |
| $\sin^2 \theta_{\text{eff}}^\ell$ |                                                 |                              |                                              |
| $m_W$                             | SM corrections to the muon decay rate           | NNLO + partial higher orders | N <sup>3</sup> LO EW + partial higher orders |

FCC feasibility study report – 2505.00272

Beyond current state of the art





The experimental and theoretical progress of the last few years has been remarkable, and the opportunities ahead of us at the HL-LHC are correspondingly rich.

But many of the questions we now want to answer sit precisely at the interface between theory and experiment: design of new observables; control and interpretation of theory uncertainties/correlations at the % level; optimal use of differential information; combination of measurements; EFTs; ensuring that increasingly sophisticated analyses remain both powerful and interpretable; ...

The time is therefore mature to (re)consider a stronger framework for this interaction, e.g. within the LHC WGs: a new layer of collaboration between the LHC experiments and the theory community, where cutting-edge analyses, theoretical developments and open questions can be discussed early, openly and constructively.

# Let's keep hunting!

