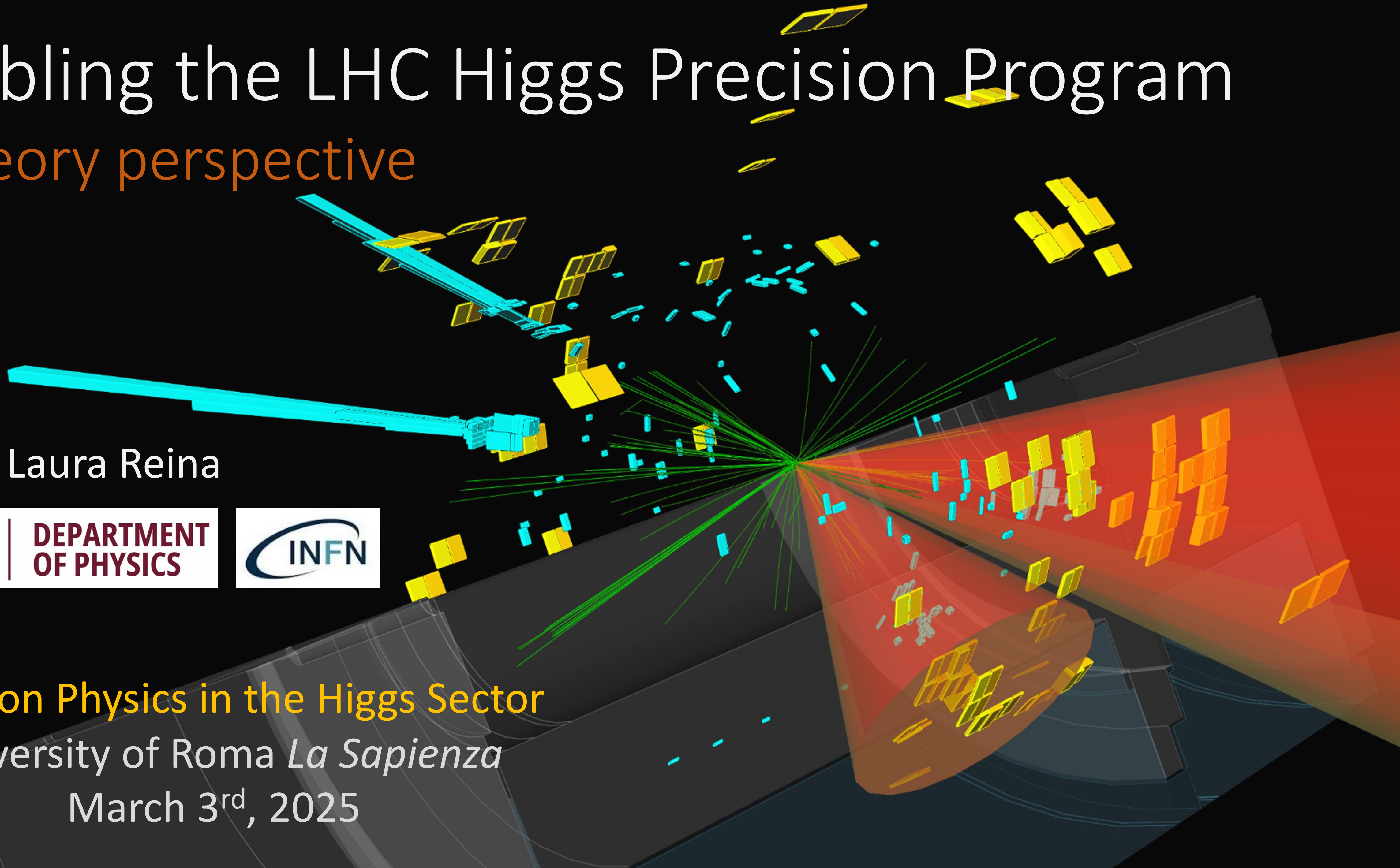
Enabling the LHC Higgs Precision Program

A theory perspective



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INFN

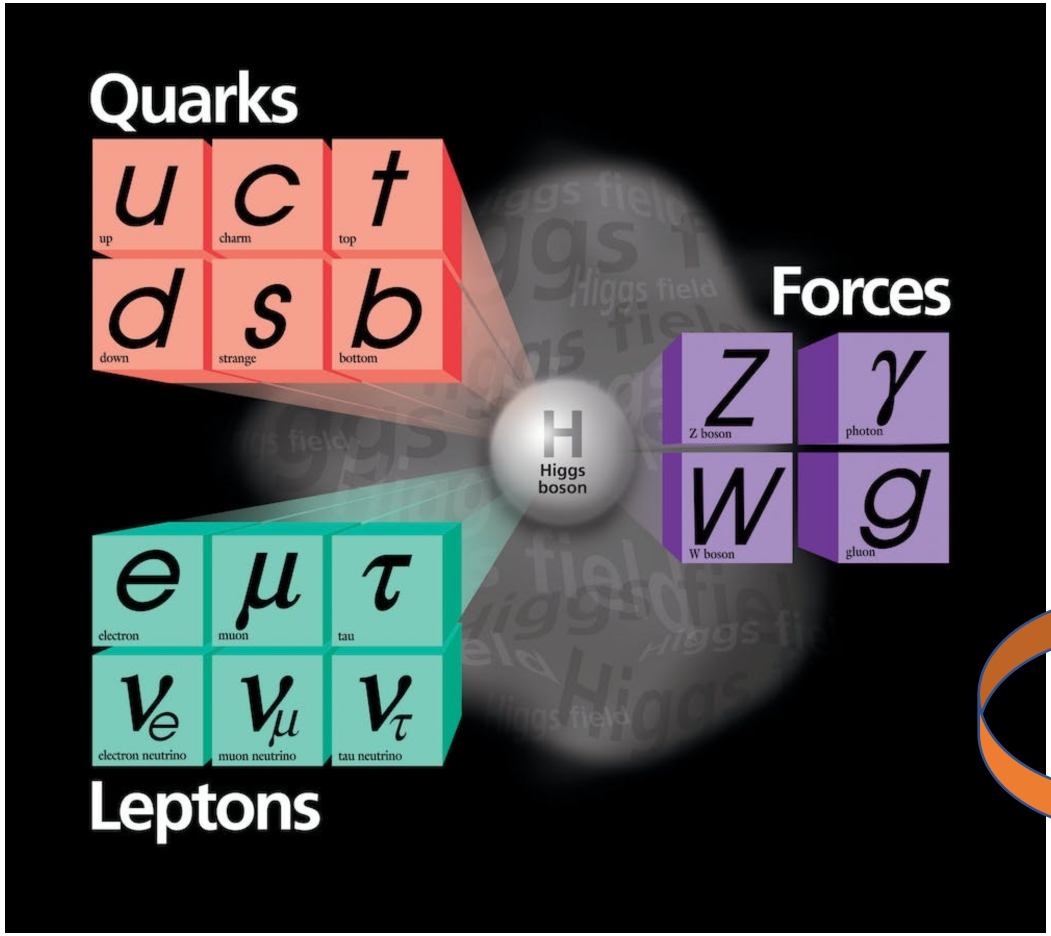
Precision Physics in the Higgs Sector

University of Roma *La Sapienza*

March 3rd, 2025

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

Higgs central to 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 → $m_g = 0$

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

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

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

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

Higgs central to the Standard Model of particle physics

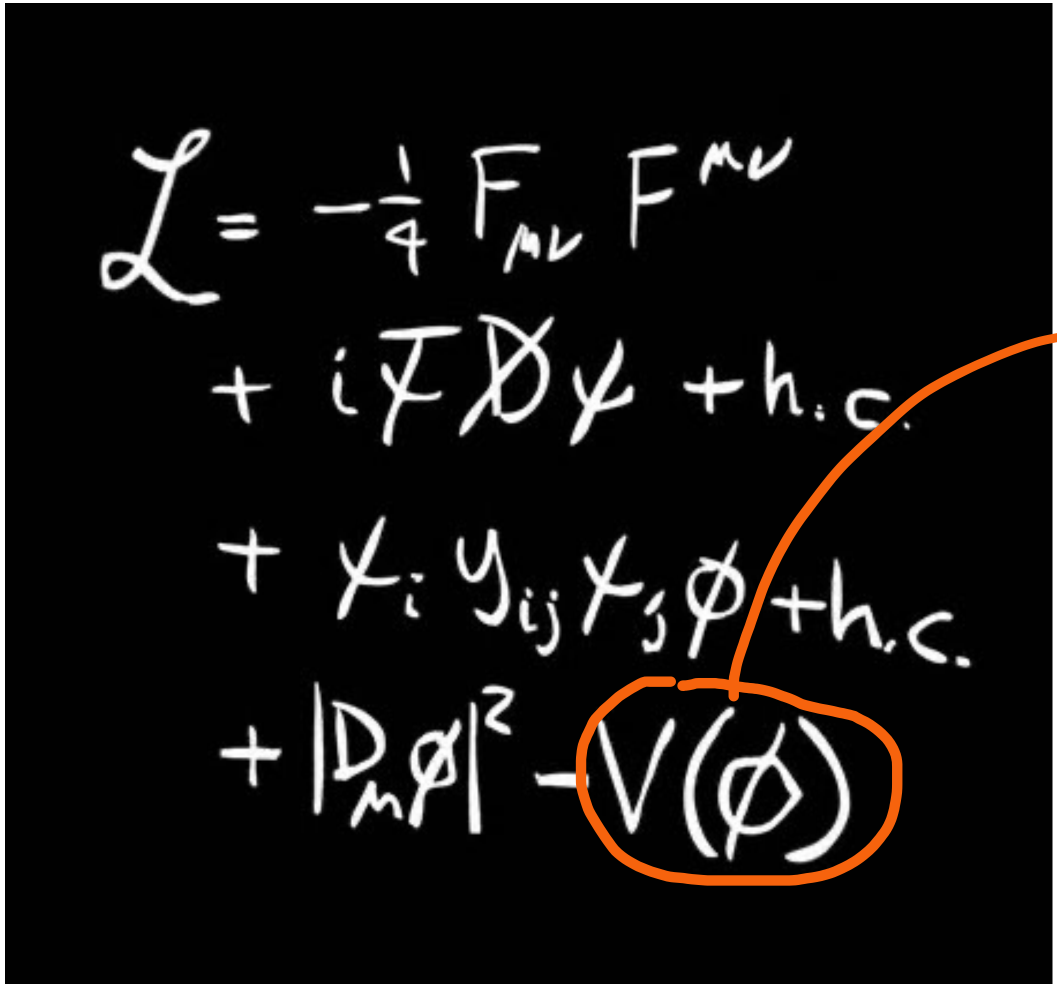
$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi + h.c. \\
& + \psi_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

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

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

half of it is about Higgs!

Higgs central to the Standard Model of particle physics

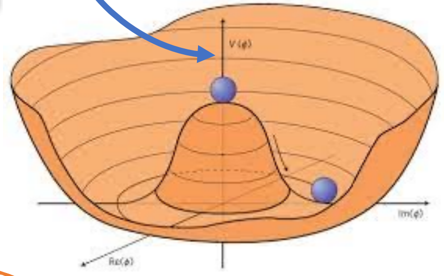


The **SM arbitrarily postulates**

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

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

Why? $(\mu^2 < 0)$



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

$$V(\phi) = \frac{M_H^2}{2} H^2 + \lambda H^3 + \frac{\lambda}{4} H^4$$

$$(M_H^2 = -2\mu^2) \quad \rightarrow +O(\Lambda_{UV}{}^2)$$

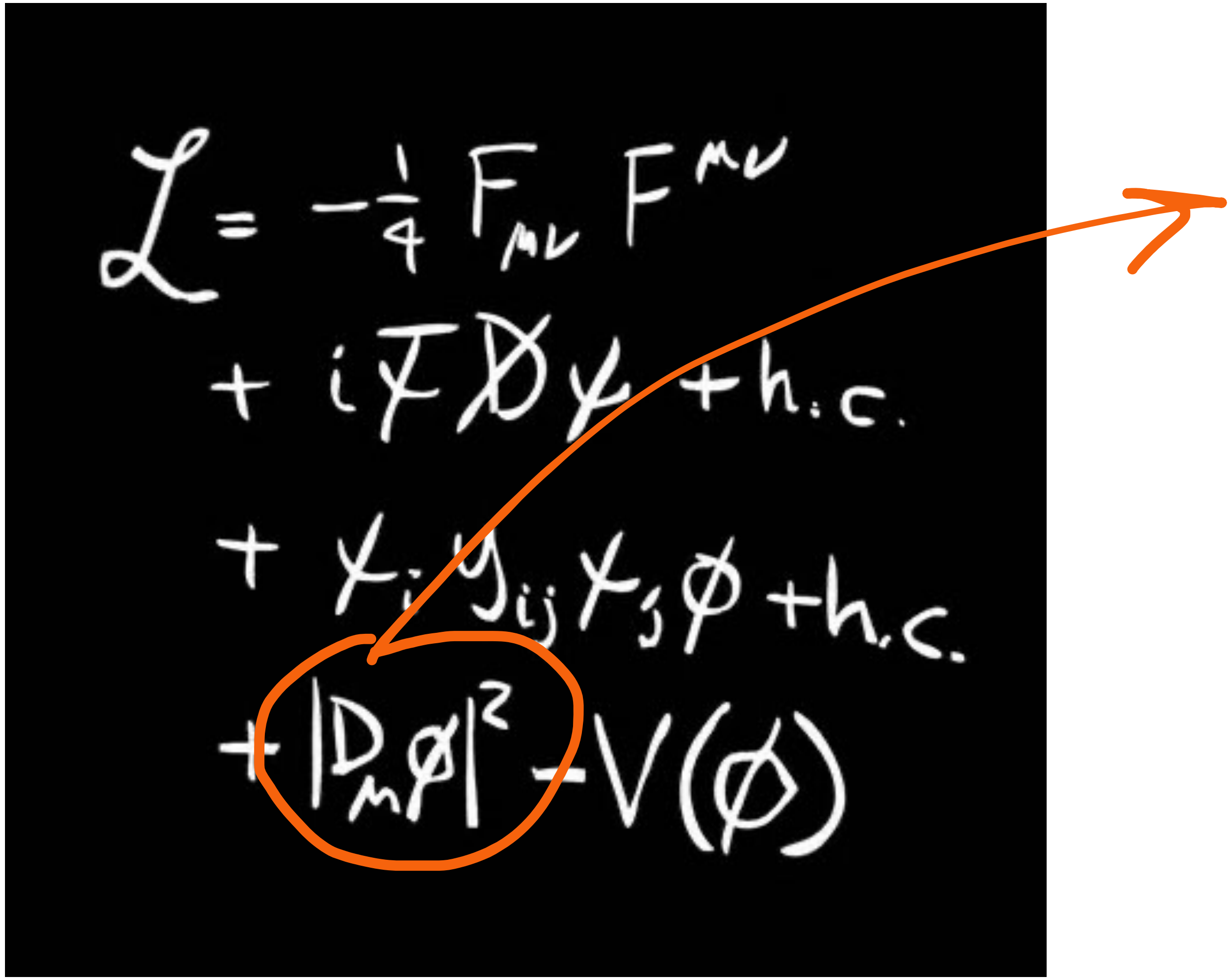
Why $M_H \sim \Lambda_{EW}$?

But **it could be an effective theory**

$$V(\phi) = \frac{M_H^2}{2} H^2 + \lambda_3 H^3 + \lambda_4 H^4$$

Ultimate test! $\lambda_3 \neq \lambda_4$?

Higgs central to the Standard Model of particle physics



Couplings to gauge bosons:

- Minimal gauge invariant coupling
- Strict relations between masses and gauge couplings

$$g_{HVV} \sim \frac{M_V^2}{v} \qquad g_{HHVV} \sim \frac{M_V^2}{v^2}$$

Consistency of the SM at the quantum level requires a complex scalar doublet (ϕ) to

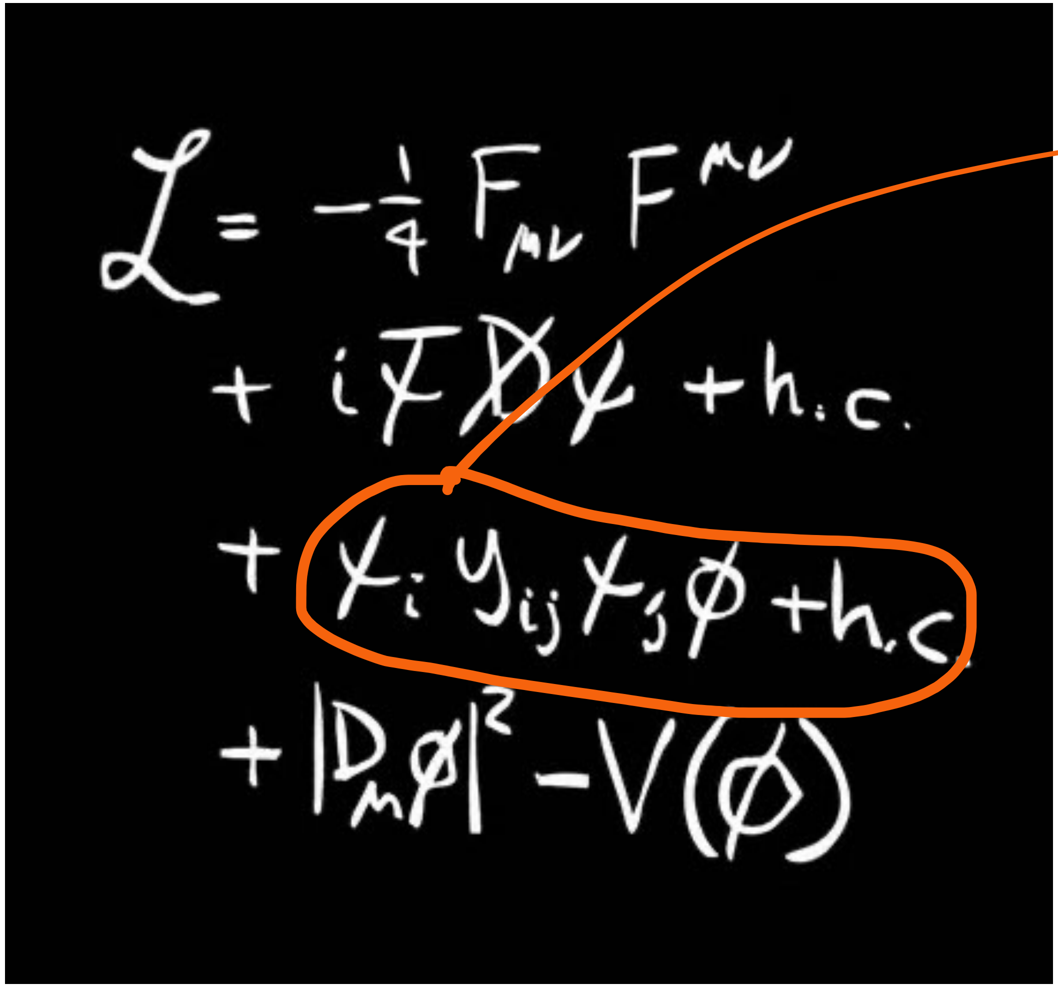
- Avoid unitarity violation in $VV \to VV$ scattering
- Account for loop-effects in W and Z propagators
- …

Crucial tests of this paradigm:

✓ **EW precision tests**

- **Direct measurement of Higgs couplings to W and Z!**

Higgs central to the Standard Model of particle physics



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

Yukawa couplings

$$\phi \rightarrow H + v$$

fermion masses

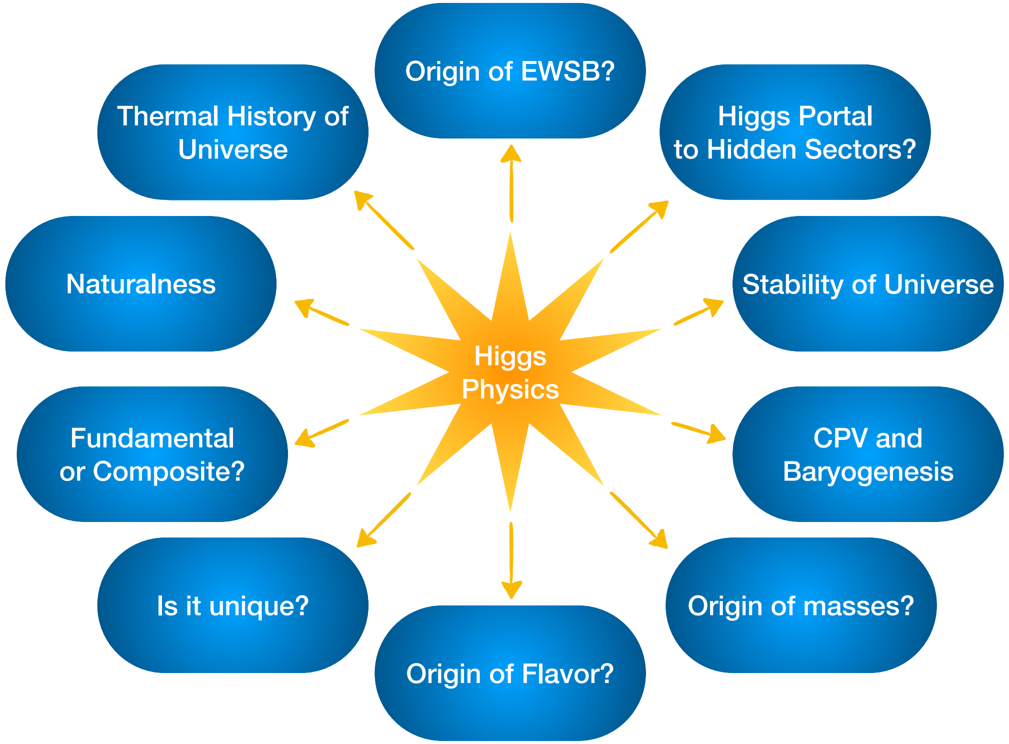
$$y_{ij} \rightarrow \frac{m_f}{v}\delta_{ij}$$

Couplings to Fermions:

- Yukawa interaction: **Is this a new force?**
- **Why the hierarchy of Yukawa couplings?**
- **Why the hierarchy of fermion masses**?
- Rotation to mass eigenstates: **origin of flavor dynamics**! in charged gauge currents (CKM)

Arbitrary, intriguing, and unexplained!

Higgs central to exploring beyond the Standard Model

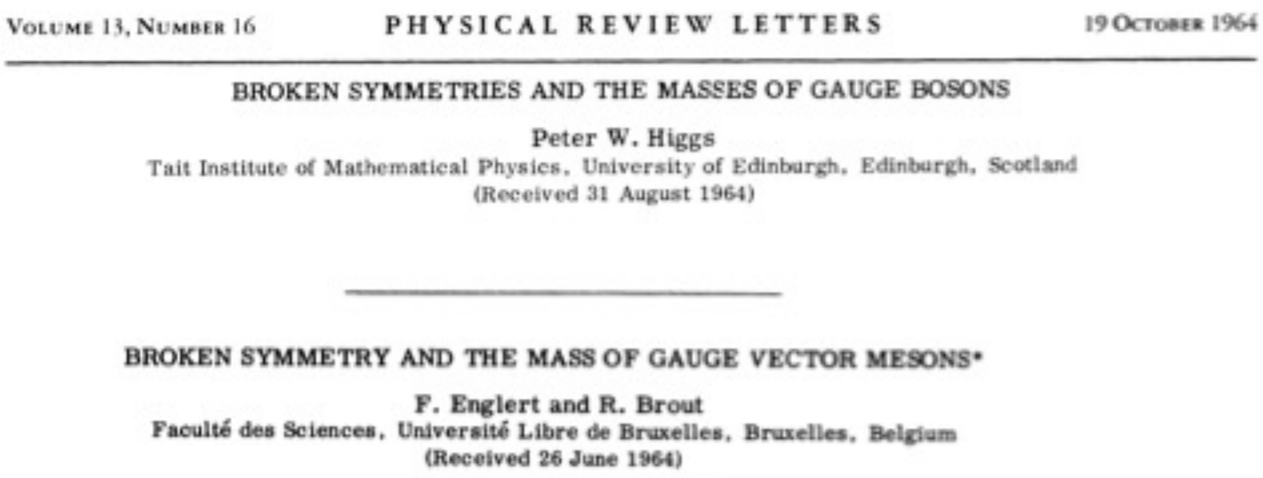


[Snowmass 2021 Energy Frontier's Report arXix:2211.11084]

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

Higgs central to the LHC physics program

From Higgs discovery to Higgs precision physics


VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

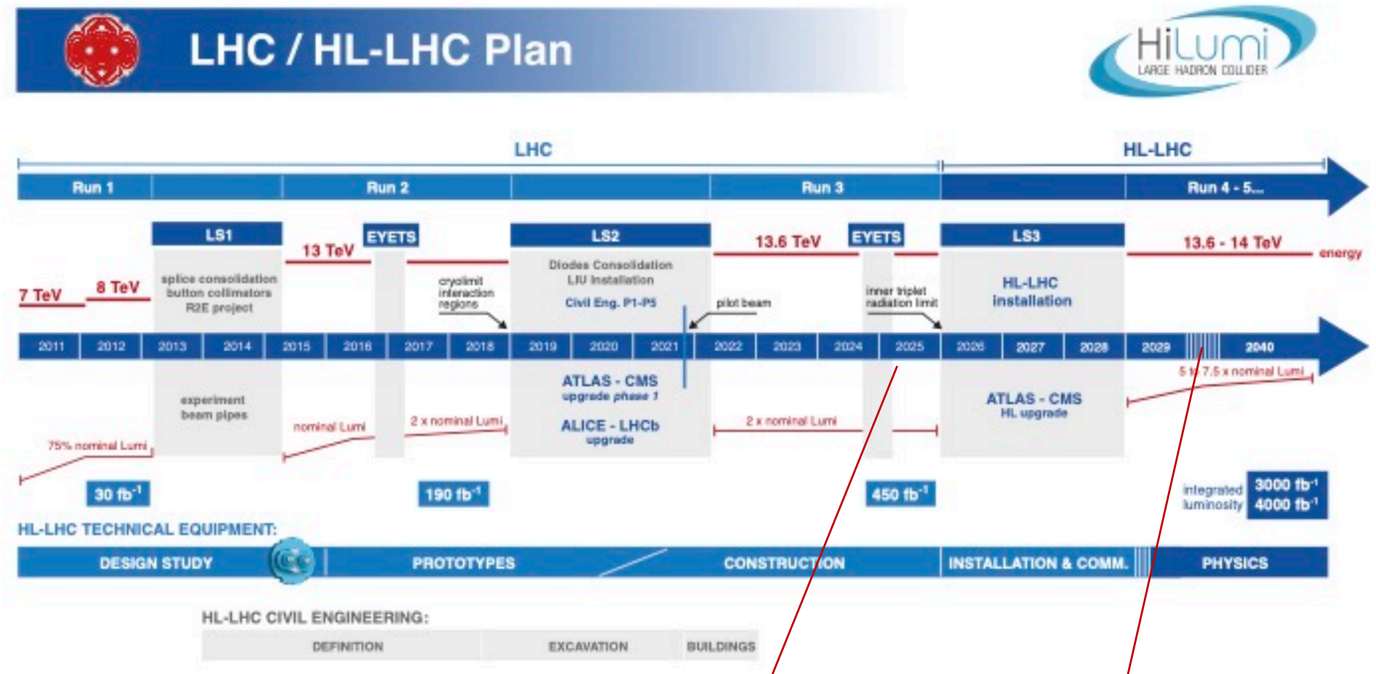
2012: discovery

2013: Nobel Prize

CERN 10 years HIGGS boson discovery

More than ten years later
Where do we stand?

The LHC era: exploring the TeV scale



We are only here

Many years of HL running ahead of us

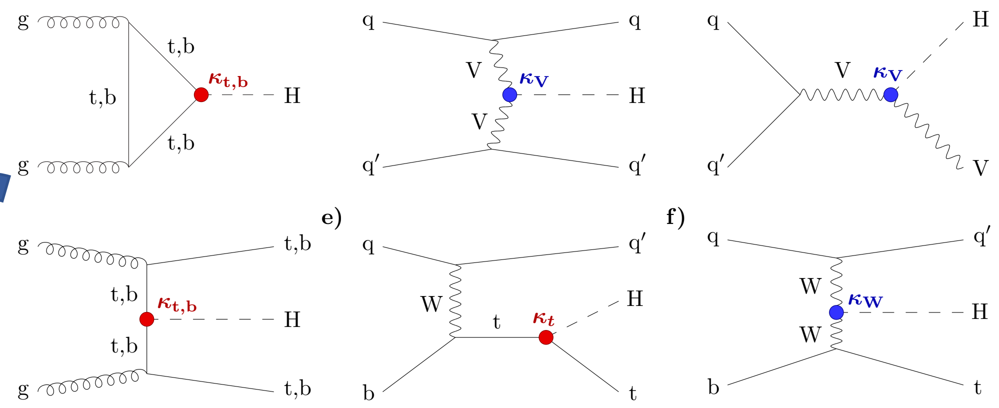
Higgs physics has been at the core of the LHC physics program

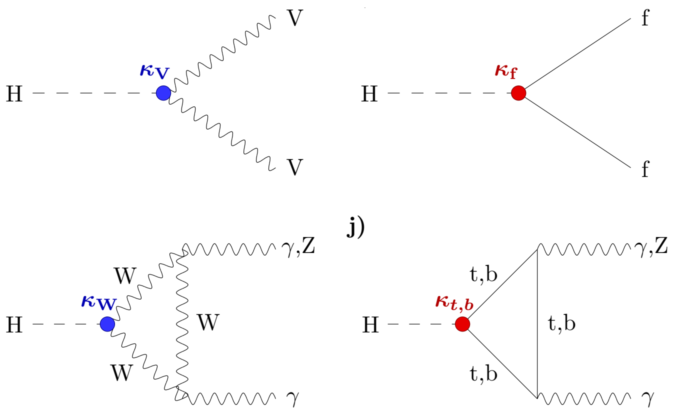
- **Run 1**: **Higgs discovery**
- **Run 2**: **Higgs couplings**
  - outperformed expectations
- **Run 3 to HL-LHC**
  - **Higgs precision program**

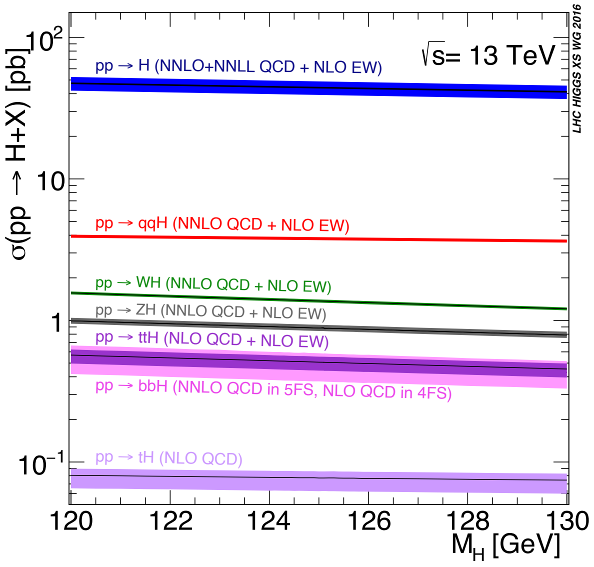
→ 2-fold increase in statistics by the end of Run 3

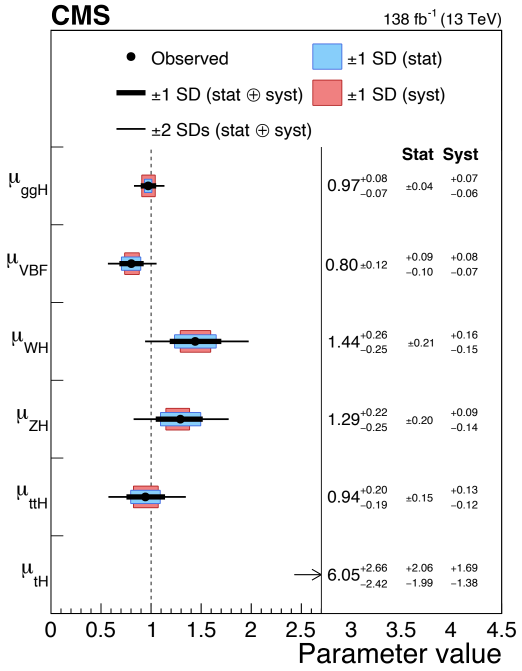
→ 20-fold increase in statistics by the end of HL-LHC!

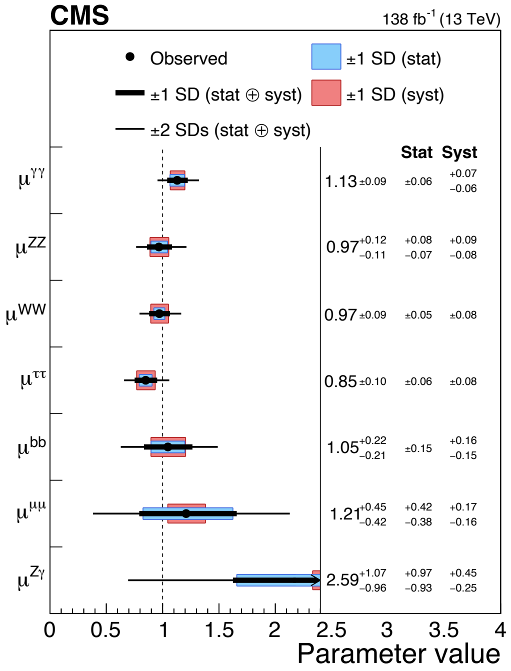
SM Higgs production and decay at the LHC

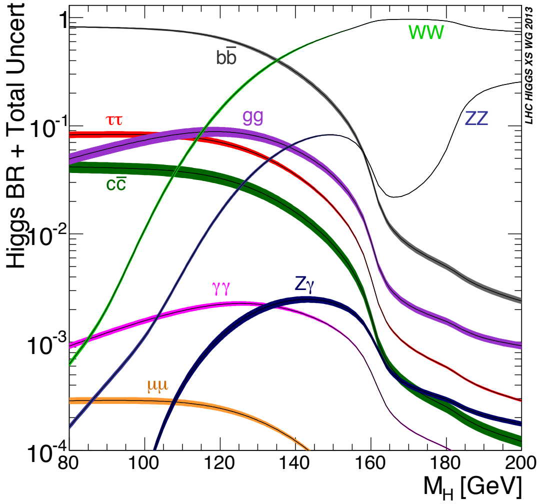










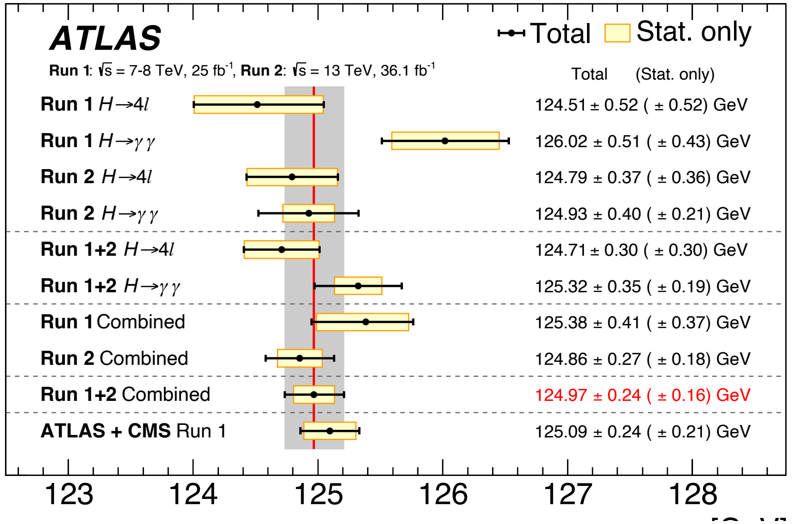


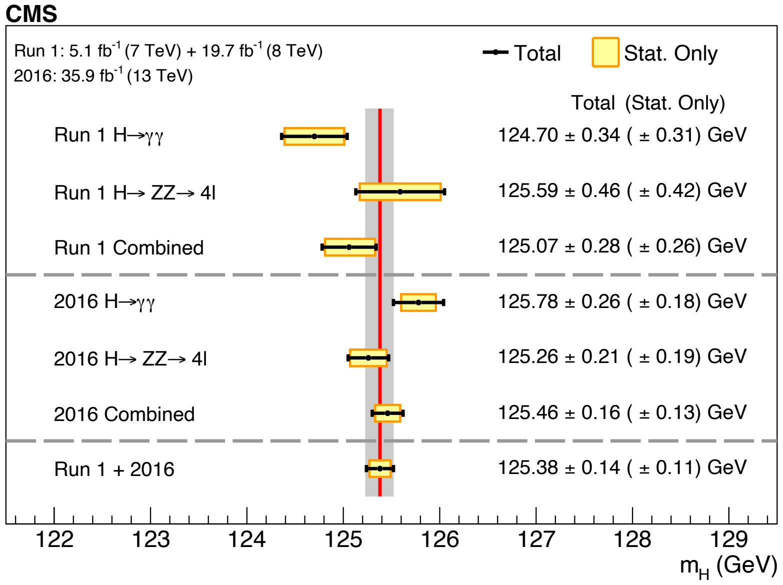
$$\mu_X = X / X_{SM}$$

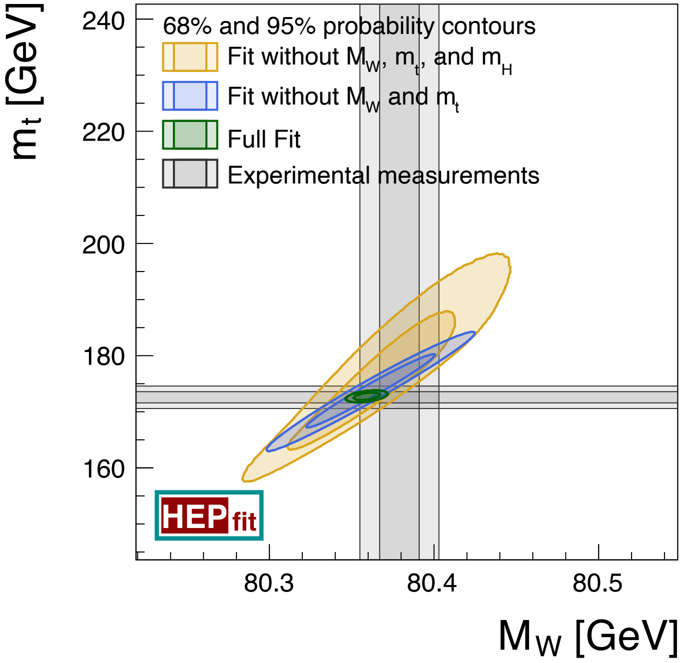
CMS, arXiv:2207.00043

Run 1+2

From discovery to precision physics

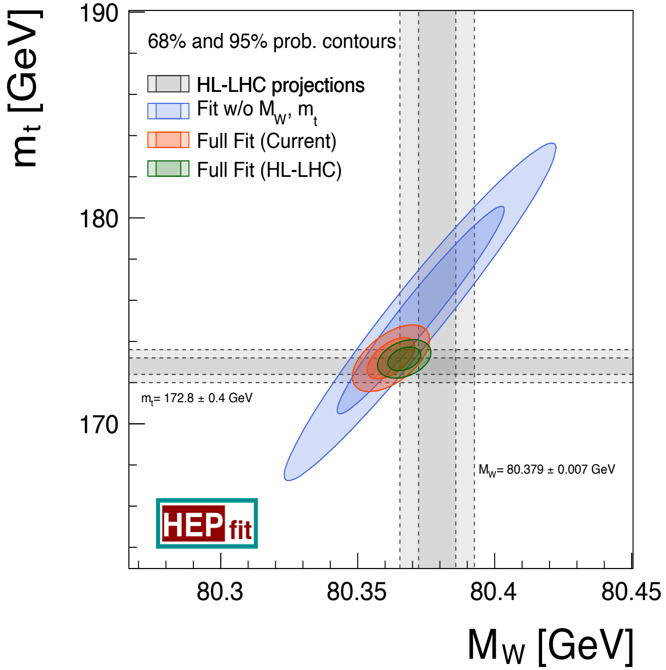






De Blas et al. [2204.04204]

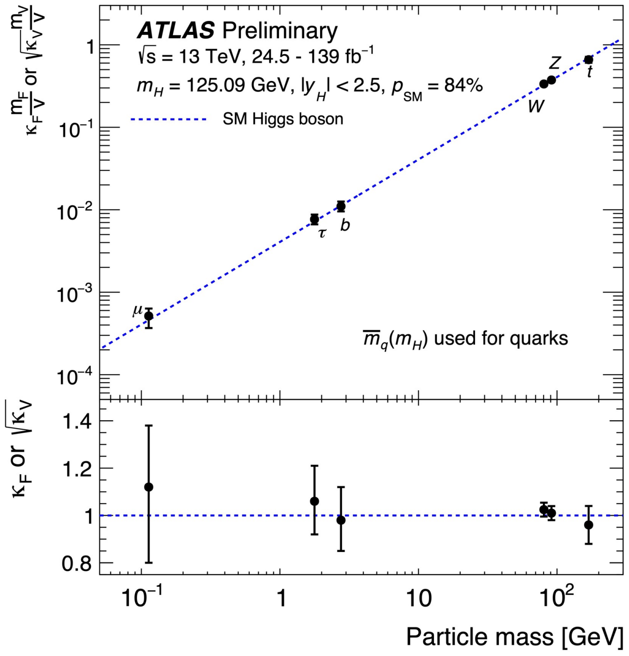
De Blas et al. HL/HE-LHC Report [1902.04070]



M_H promoted to EW precision observable

Run 2 Zooming in on couplings to probe the TeV scale

CMS, arXiv:2207.00043

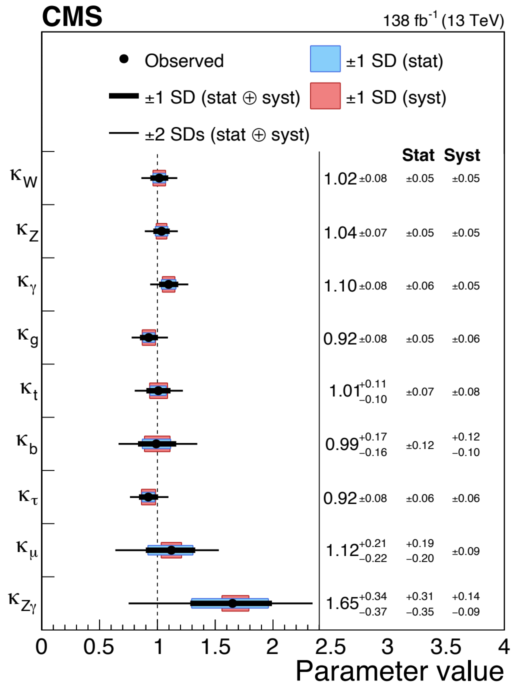


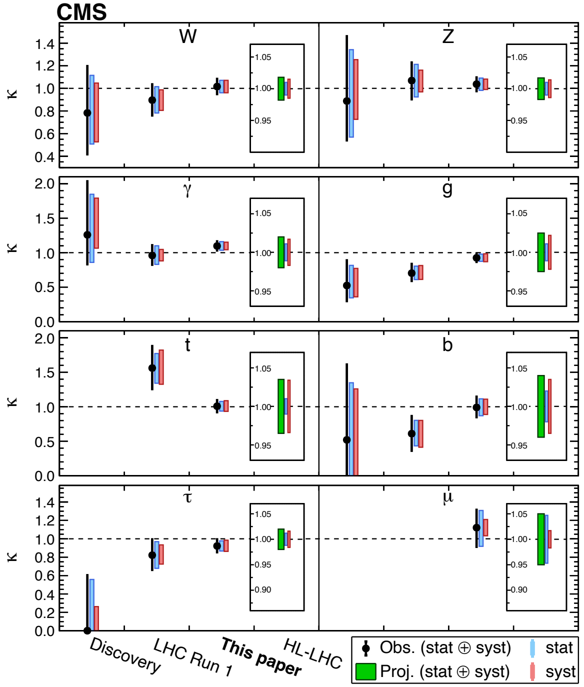
$\kappa = g_X / g_X^{SM} = 1 + \Delta\kappa$

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

Precision on Δκ

reach for Λ_{BSM}



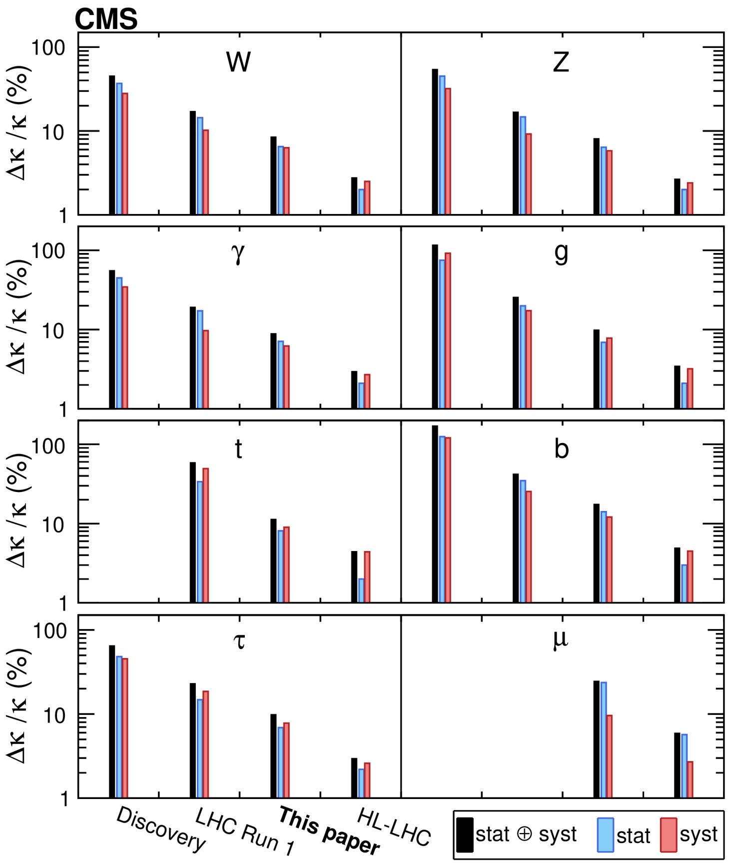


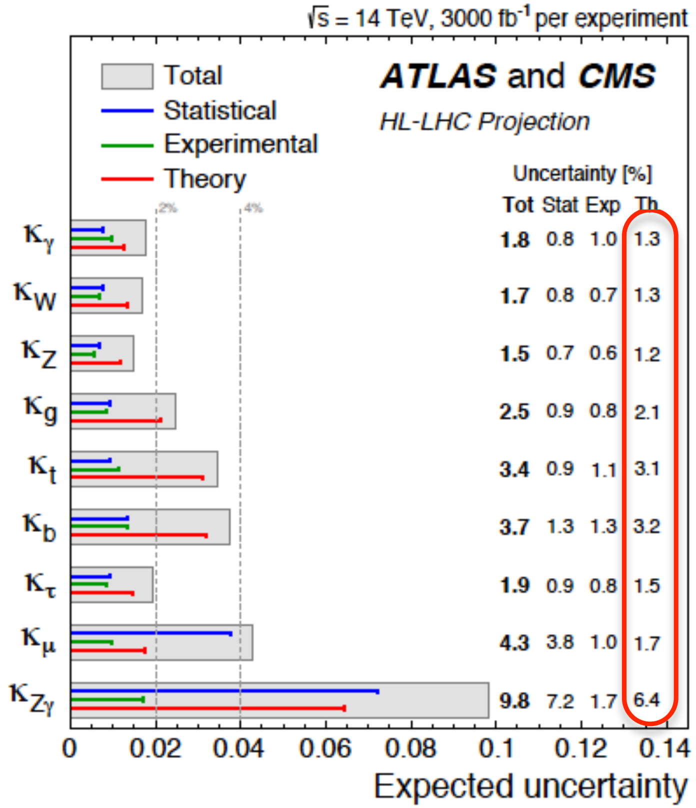
- Couplings to **W/Z at 5-10 %**
- Couplings to **3rd generation to 10-20%**
- **First measurements of 2nd generation** couplings

- **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

Run 2 and beyond

per-cent level systematic uncertainties





$$\Delta\kappa/\kappa \sim O(v^2/\Lambda^2)$$

For new physics at 1 TeV expect deviations of O(6%)

Improved systematics probes higher scales

Theory could become the main limitation

Theory need to improve modeling and interpretation of LHC events, in particular when new physics may not be a simple rescaling of SM interactions

Run 2 and beyond

Beyond SM coupling rescaling

Framework: Extend SM Lagrangian by effective interactions (SMEFT)

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

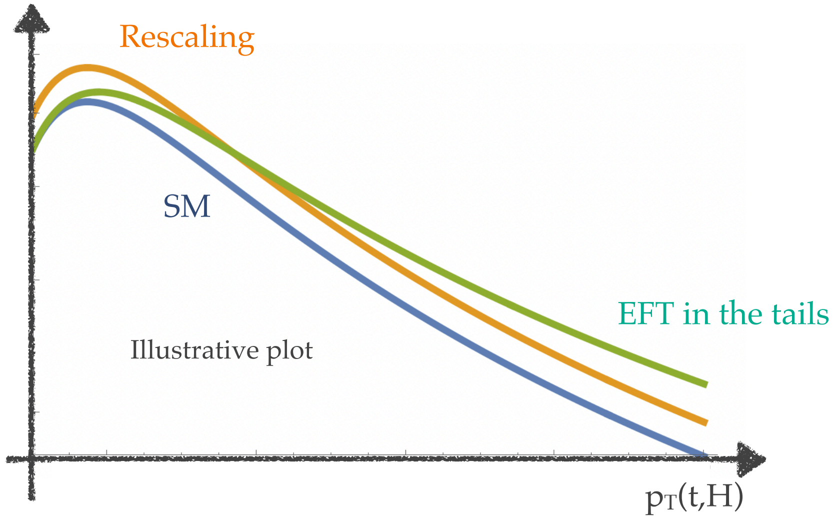
$$\mathcal{L}_d = \sum_i C_i^{(d)} \mathcal{O}_i^{(d)}, \quad \left[\mathcal{O}_i^{(d)}\right] = d$$

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

Built of SM fields and respecting the SM gauge symmetry.

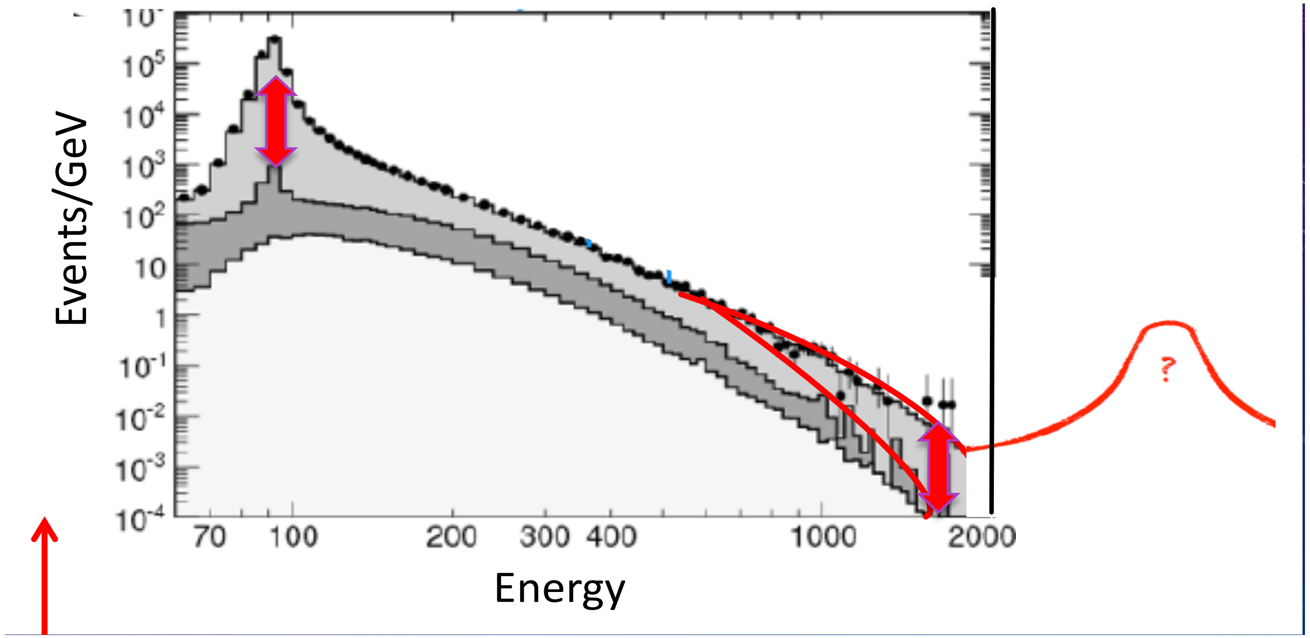
Expansion in $(v, E)/\Lambda$: **affects all SM observables** at both low and high energy

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



Beyond total rates

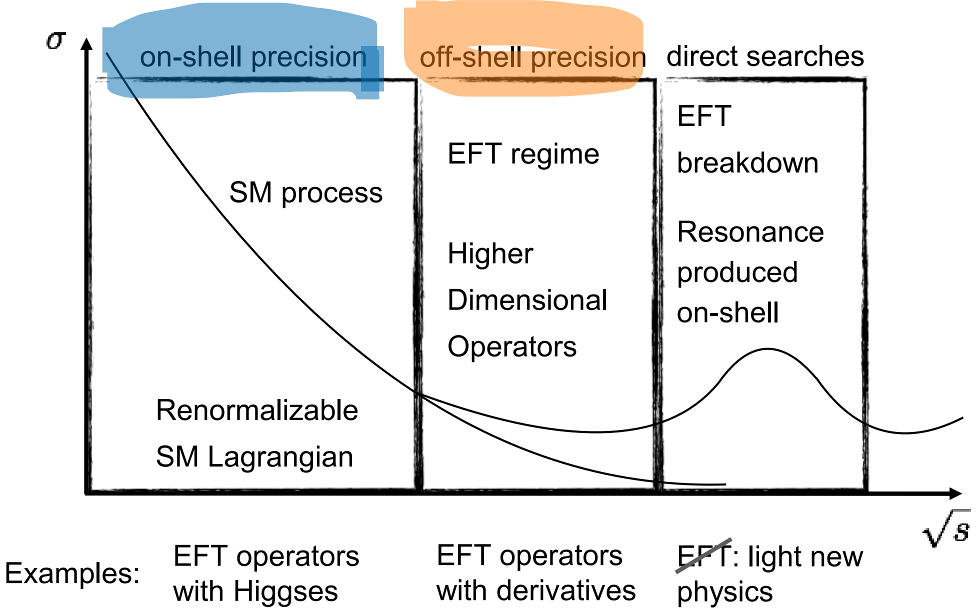
Extending the SM via effective interactions above the EW scale ⟶ **SMEFT**



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

dim=6

dim>8



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.

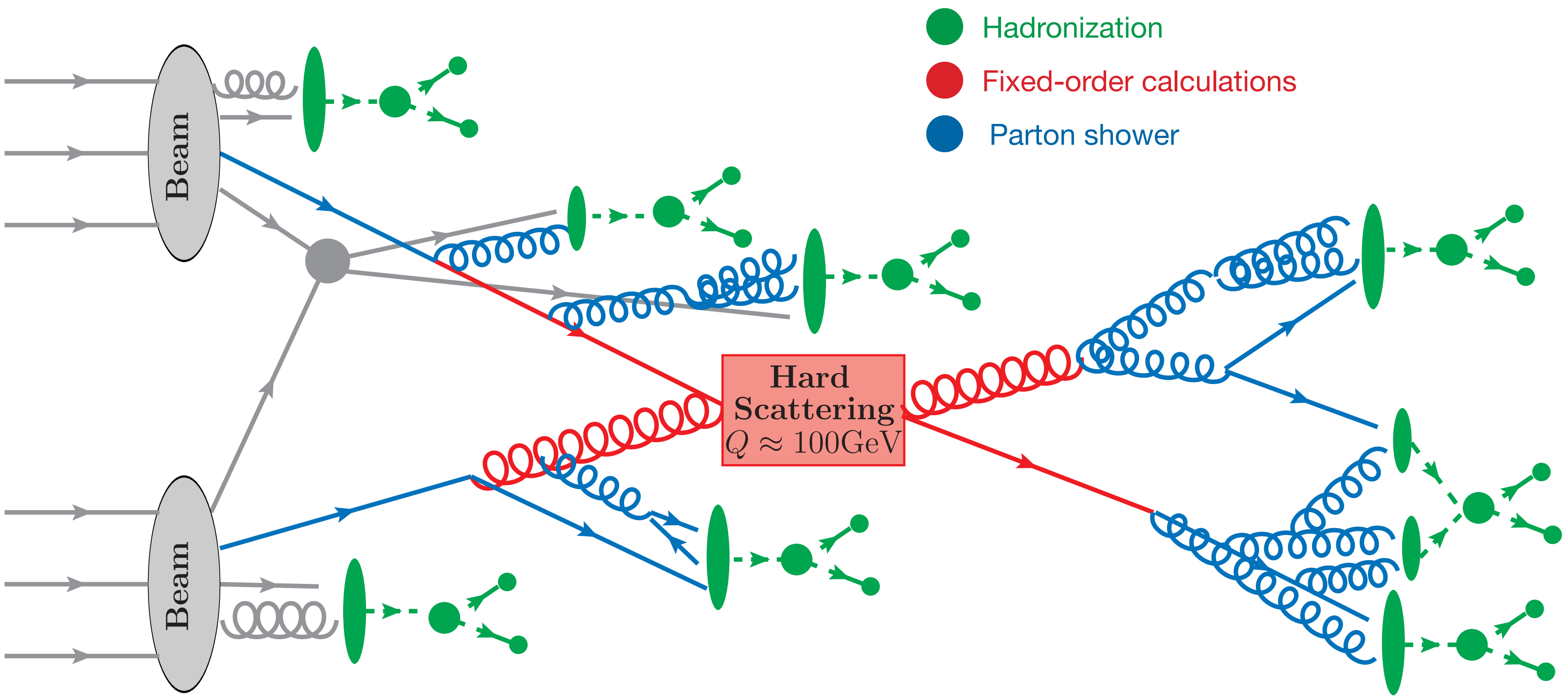
Crucial to control EFT sensitive regions

Enabling the LHC Higgs precision program

Theory for percent-level phenomenology

Understand and reduce theoretical uncertainties: **a multi-pronged challenge**

Dissecting the challenge



From S. Ferrario Ravasio, RADCOR 2023

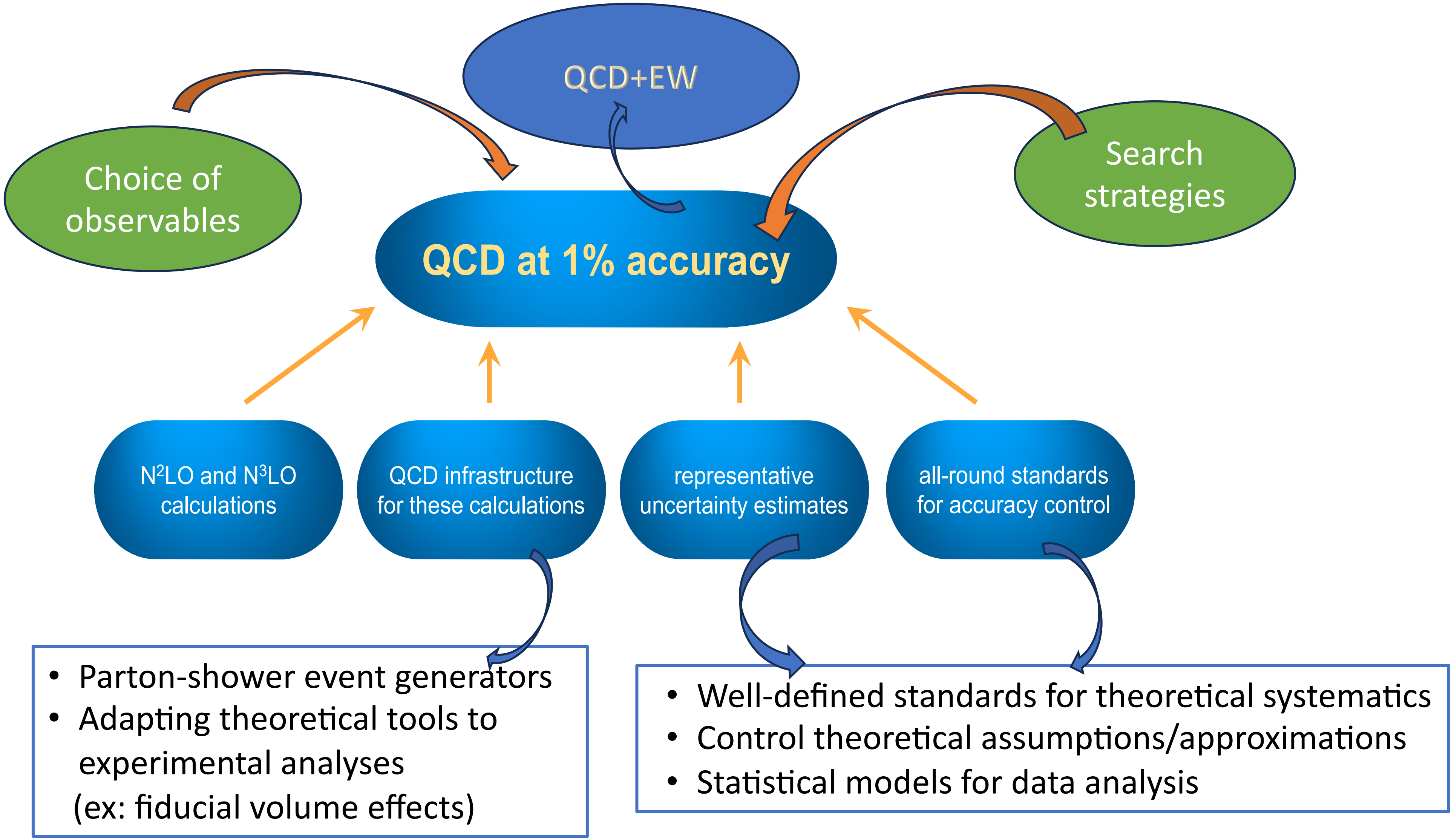
$$d\sigma = \sum_{ij} \int dx_1\, dx_2\, f_{p,i}(x_1) f_{p,j}(x_2) \widehat{d\sigma}(x_1 x_2 s) + O((\Lambda_{QCD}/Q)^p)$$

Parton Distribution Functions (PDF)

hard-scattering partonic xsection (pQCD+EW)

Hadronization, non-p QCD

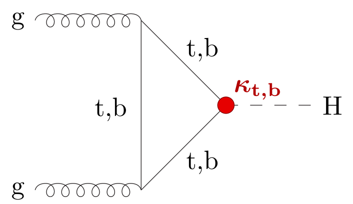
Multiple components to percent accuracy



Snowmass Report of QCD Topical Groups, 2209.14872

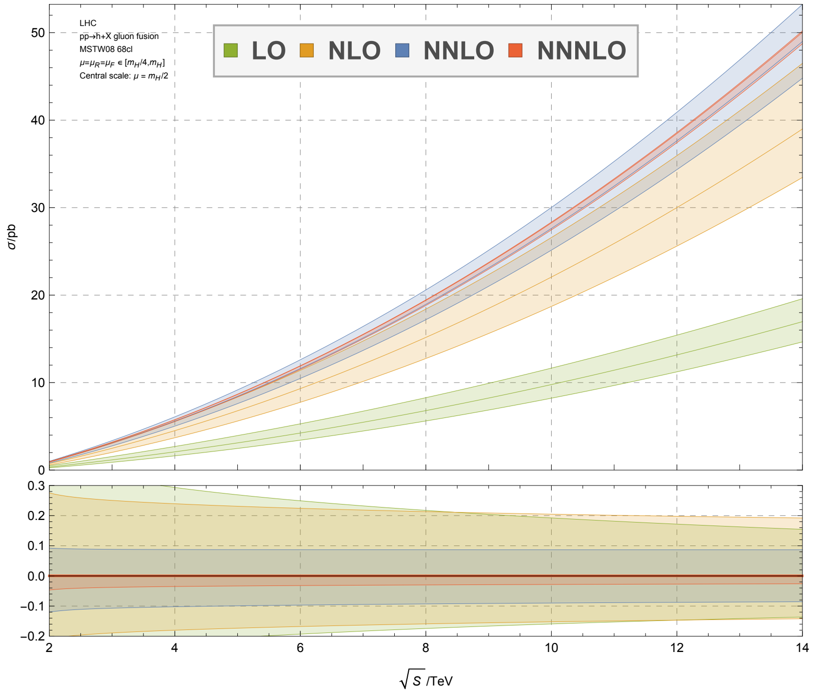
Examples to illustrate the path towards percent precision

gg fusion: the need for precision

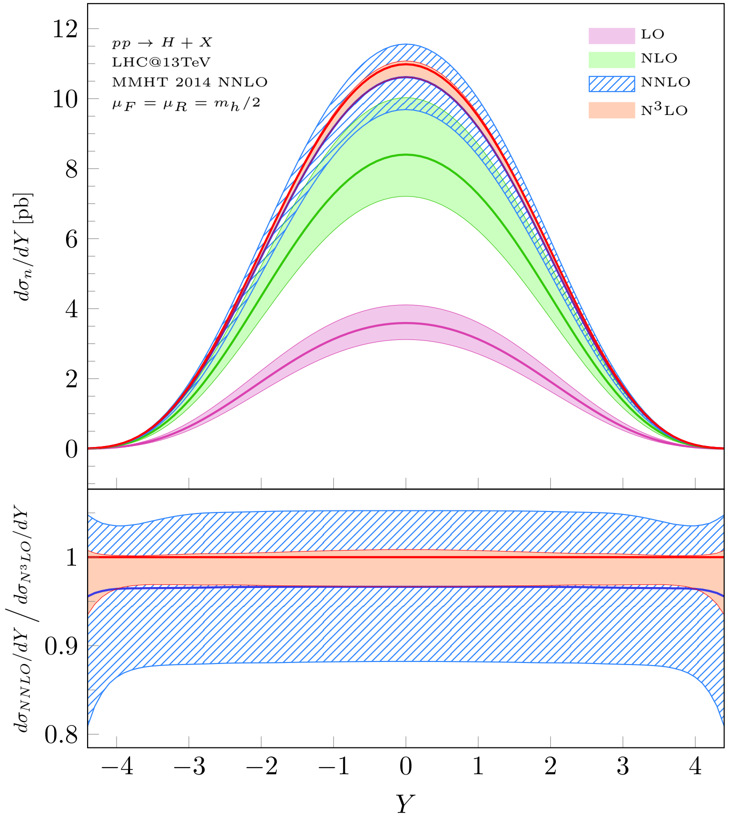


Continuous progress on a crucial process

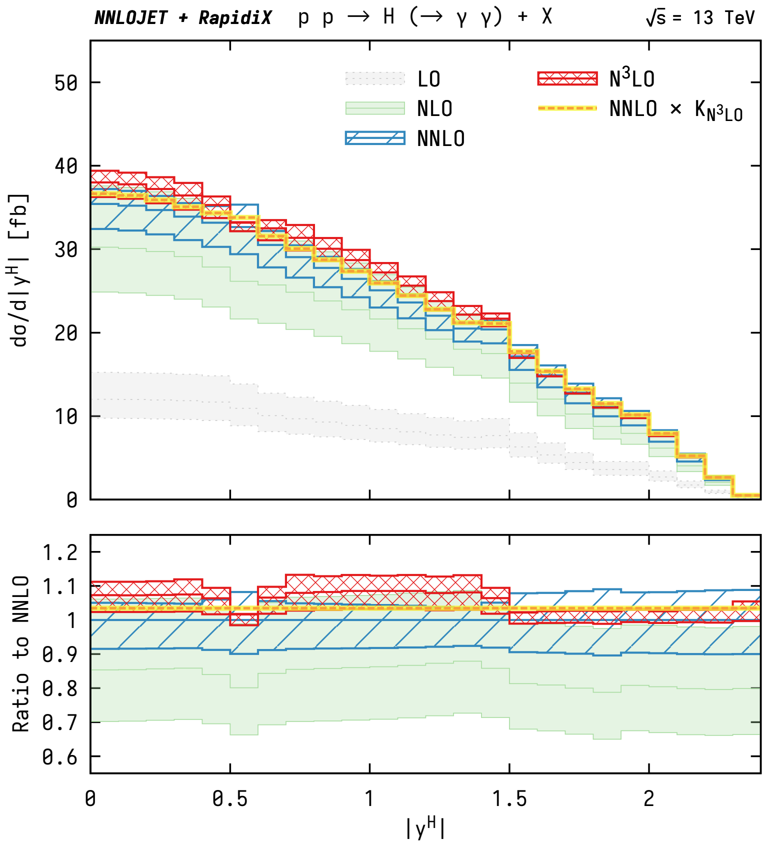
- The main Higgs production mode, crucial to all measurements
- A benchmark test of QCD, and QCD+EW
- **An excellent testing ground to probe theoretical accuracy**



Anastasiou, Duhr, Dulat, Herzog, Mistlberger 1503.06056

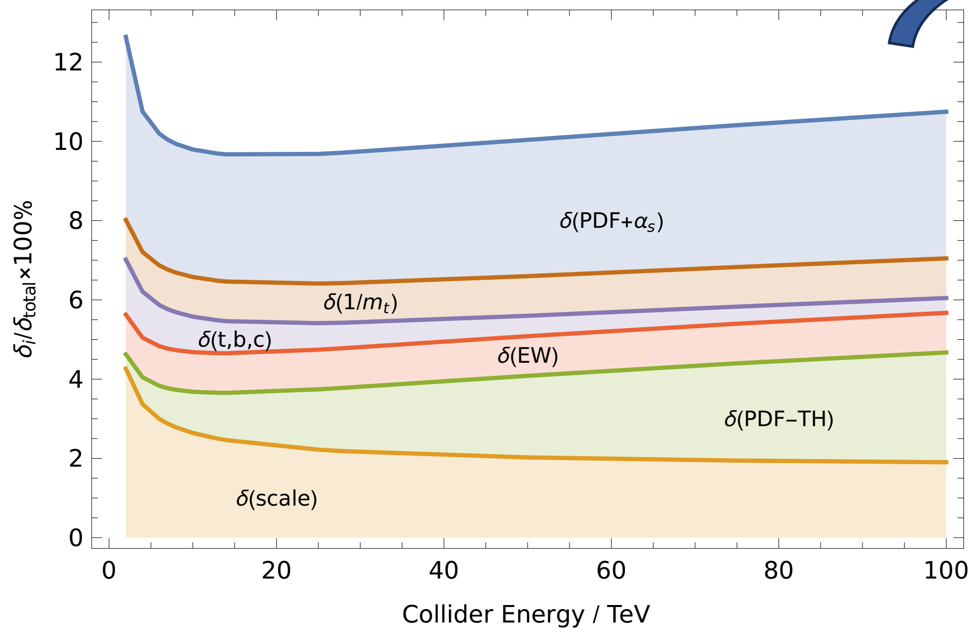


Dulat, Mistlberger, Pelloni 1810.09462



Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni, 2102.07607

… a clear map of residual uncertainties



LHC @ 13 TeV

Dulat, Lazopoulos, Mistlberger
1802.00827 (iHixis)

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

Uncertainty removed by calculation of exact NNLO m_t dependence and top-bottom interference

Czakon, et al. 2105.04436, 2312.09896, 2407.12413

Reduced uncertainty to 0.26% by calculation of NLO mixed QCD+EW

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

Future challenges:

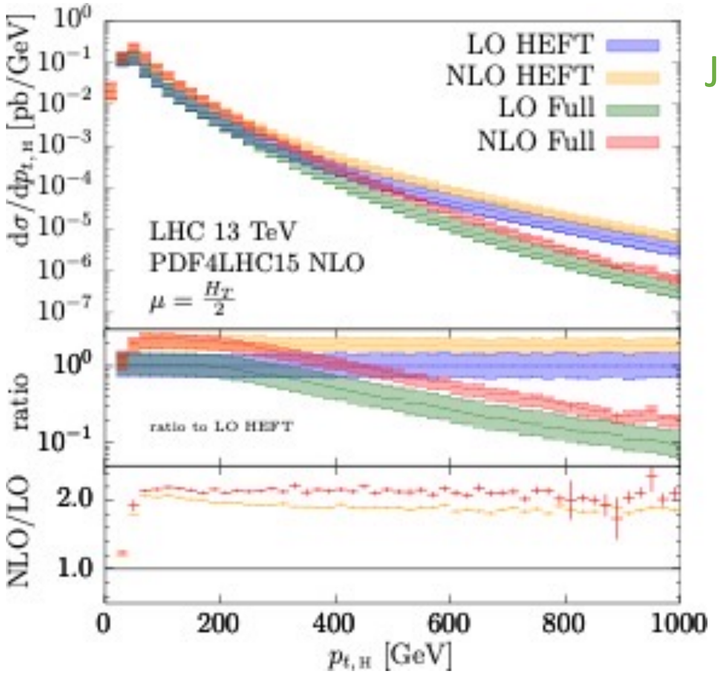
- **N3LO PDF!** → δ(PDF-TH)
- More EW corrections
- Large logs resummation (fiducial)?

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

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

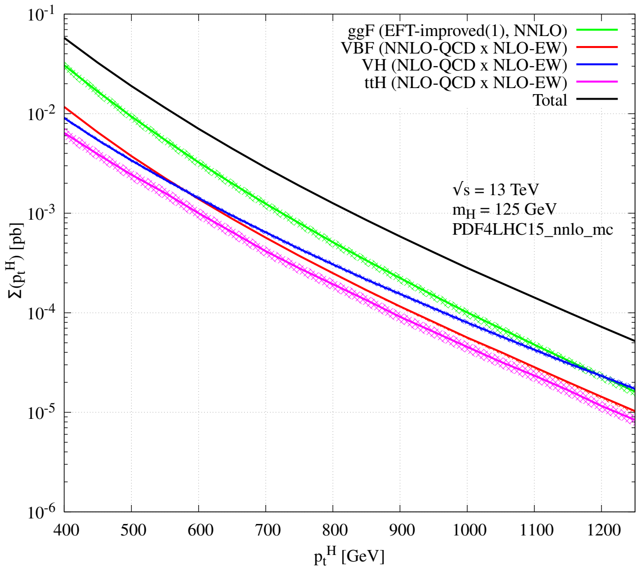
Higgs p_T spectrum (H+j)

Observing the H in different kinematic regimes:
high p_T region particularly interesting for new physics effects



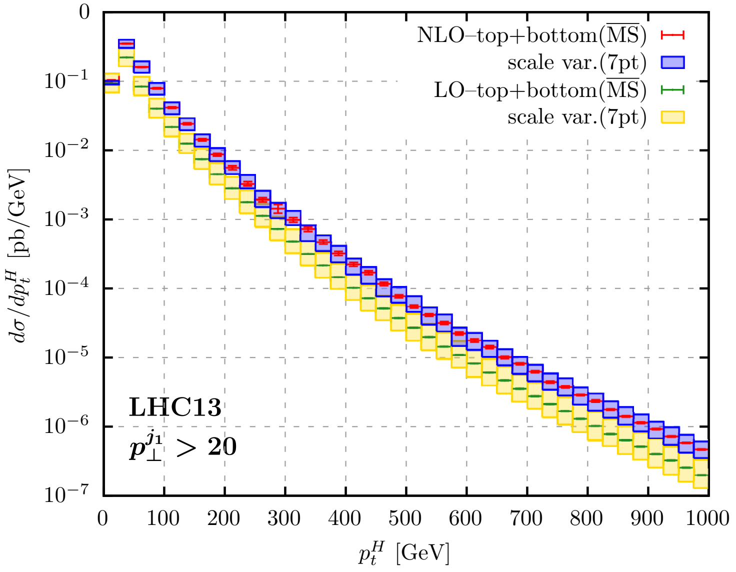
Jones, Kerner, Luisoni, arXiv:1802.00349

Kudashkin, Lindert, Melnikov, Wever, arXiv:1801.08226



Other channel matters at high p_T

Becker et al., arXiv:2005.07762



Bonciani, et al., arXiv:2206.10490

In the high p_T region:

- **Need full m_t dependence**
- Clear deviation from HEFT, but similar K-factors

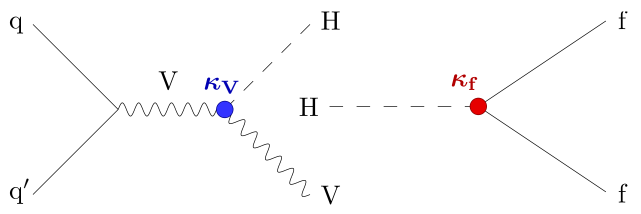
Exact top+bottom contributions with on-shell and running masses:

- interference and NLO effects cancel at high p_T
- non-trivial shape effects at low p_T.

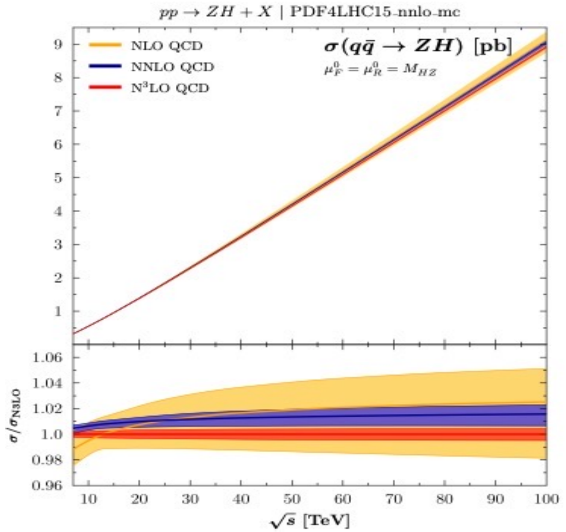
$VH(H \to b\bar{b})$, access to y_b

Dominant at high p_T

Need to account for mass effects: **both m_t and m_b!**

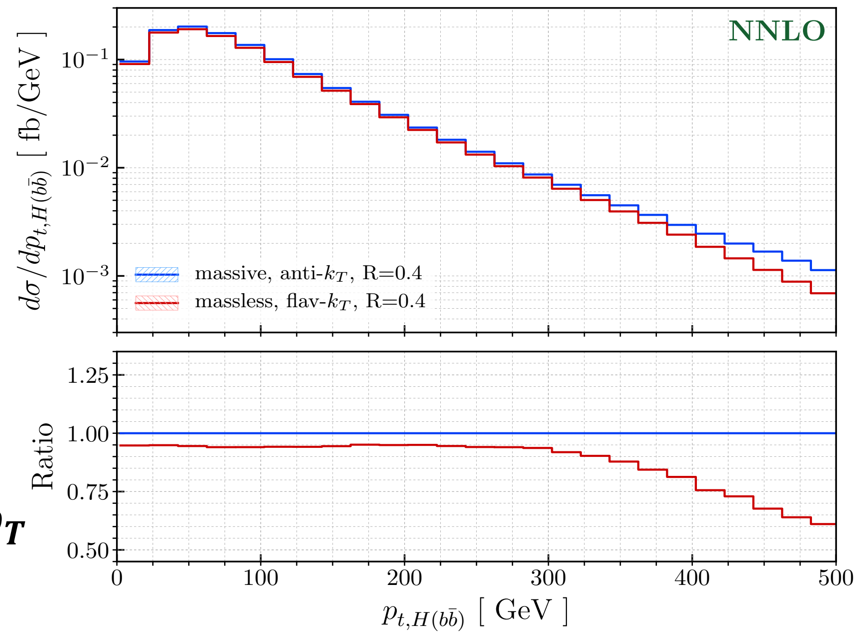


Scale uncert.: <1%
PDF+α_s: 2 – 3%



Baglio, Duhr, Mistlberger, Szafron, arXiv:2209.06138

Order	b quarks	$\sigma_{\rm fid}$ [fb]	$\sigma_{\rm fid}$(boosted) [fb]
LO	massive	$22.623^{+0.845}_{-1.047}$	$3.735^{+0.000}_{-0.016}$
	massless	$22.501^{+0.796}_{-1.007}$	$3.638^{+0.000}_{-0.009}$
NLO	massive	$25.364(1)^{+0.778}_{-0.756}$	$4.586(1)^{+0.158}_{-0.141}$
	massless	$24.421(1)^{+0.852}_{-0.879}$	$4.333(1)^{+0.165}_{-0.154}$
NNLO	massive	$24.225(4)^{+0.642}_{-0.742}$	$4.530(2)^{+0.071}_{-0.096}$
	massless	$22.781(3)^{+0.791}_{-0.898}$	$4.207(1)^{+0.097}_{-0.116}$



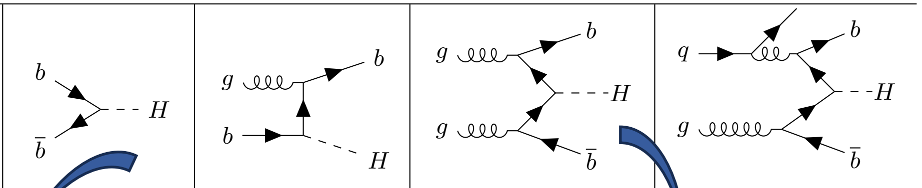
O(6%) m_b effect on total rates, up to O(25%) on high- p_T tail of distributions, once fiducial cuts applied (2 b jets)

Due to $H \to b\bar{b}g$ radiative decays (**different collinear patterns**) when combined with clustering algorithm.

Behring, Bizoń, Caola, Melnikov. Röntsch. arXiv:2003.08321

$H + b$ jets at N3LO, measuring y_b

Higgs couplings to b quark modified in many BSM models
(also background to pp $\rightarrow HH \rightarrow Hb\bar{b}$)

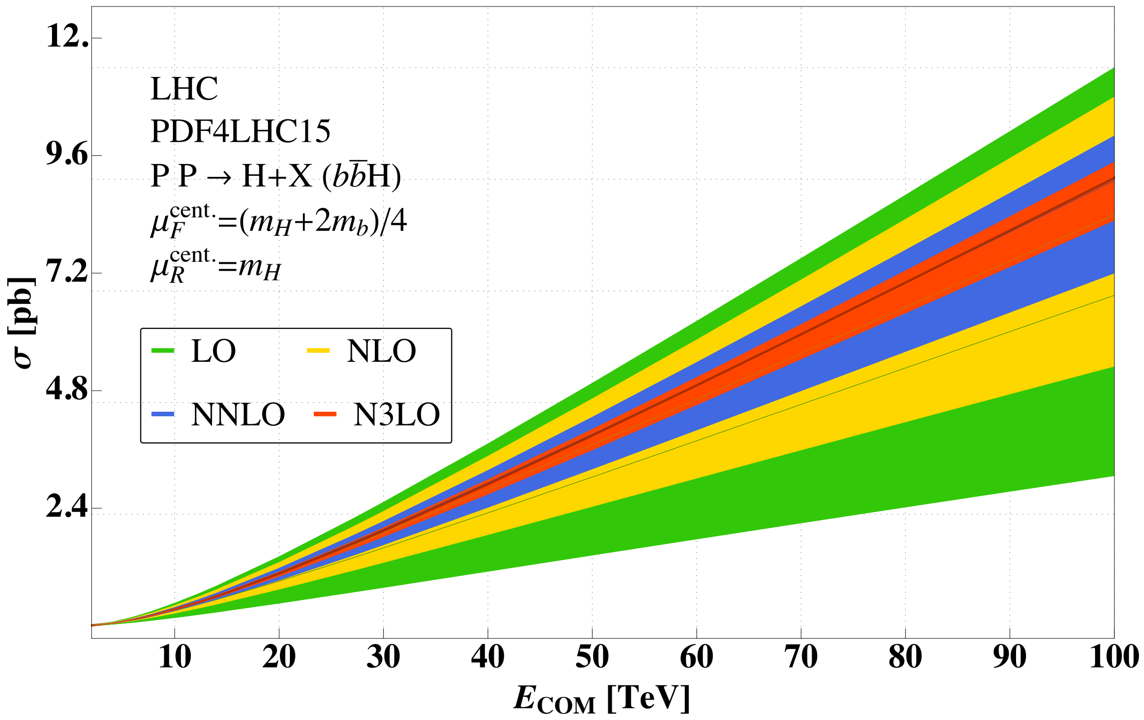


4FS	–	–	LO	NLO
5FS	LO	NLO	NNLO	N^{3}LO

Resummation of collinear $\log(\frac{\mu^2}{m_b^2})$ in b-PDF

b quark in final state starting at LO (better for H+b jets)

Duhr, Dulat, Hirschi, Mistlberger, arXiv:2004.04752



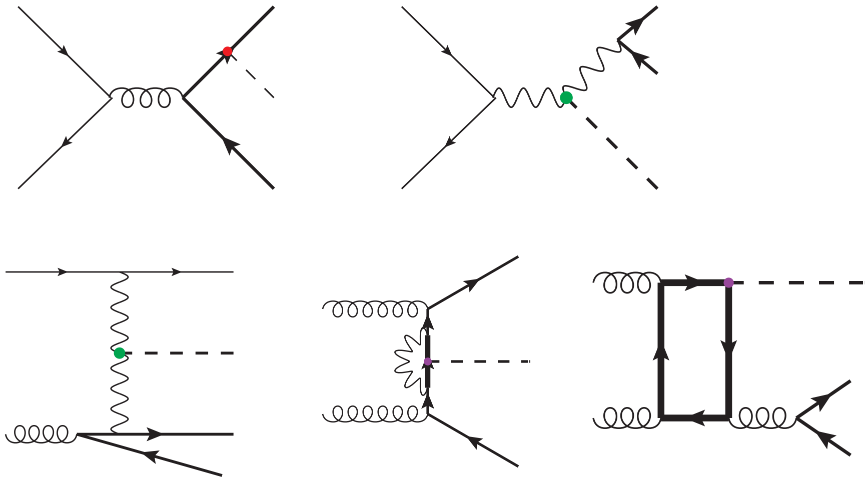
- A long history of calculations in both 4FS and 5FS, matched using various recipes.
- **At N3LO possible consistent matching** through third order in α_s. **Theoretical prediction well understood.**

… deploying new techniques to interpret complex signatures

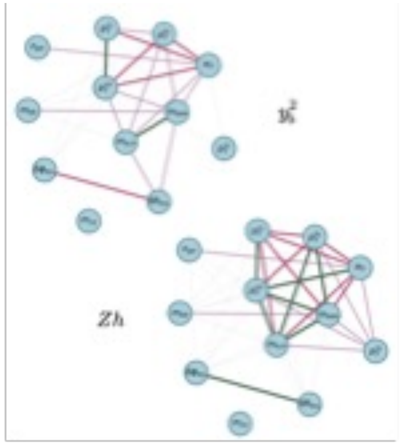
The case of **bbH production including QCD+EW corrections**
The extraction of y_b seems lost

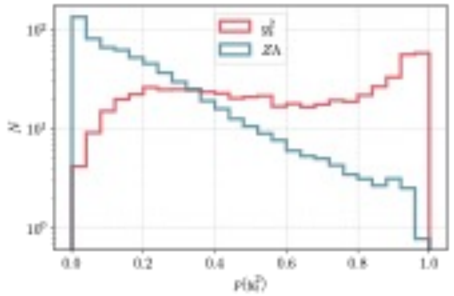
``RIP Hbb'' [Pagani et al., arXiv:2005.10277]

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



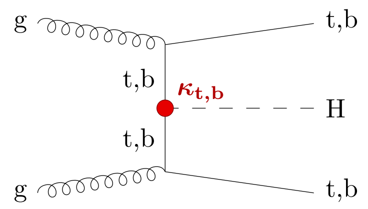
A kinematic-shape based analysis based on game theory (Shapley values) and BDT techniques opened new possibilities
“Resurrecting Hbb with kinematic shapes”
[Grojean et al., arXiv:2011.13945]





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

$t\bar{t}H$ (and $t\bar{t}W$) at NNLO: measuring y_t



First NNLO results for multi-scale processes: $t\bar{t}H, t\bar{t}W$

3 massive final-state particles

Buonocore, Devoto, Grazzini, Kallweit, Mazzitelli, Rotoli, Savoini , 2306.16311

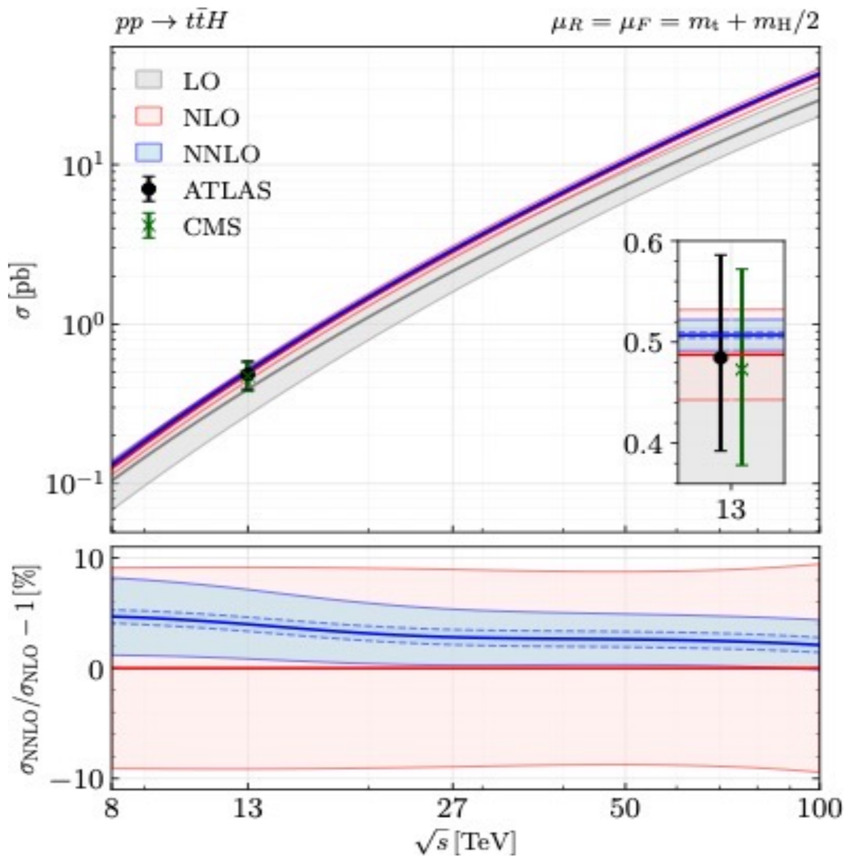
Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini , 2210.07846

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 exact 2-loop amplitudes

Febres Cordero, Figueiredo, Krauss, Page, Reina, 2312.08131
Buccioni, Kreer, Liu, Tancredi, 2312.10015
Agarwal, Heinrich, Jones, Kerner, Klein, 2402.03301

$t\bar{t}H$ and $t\bar{t}W$ at NNLO

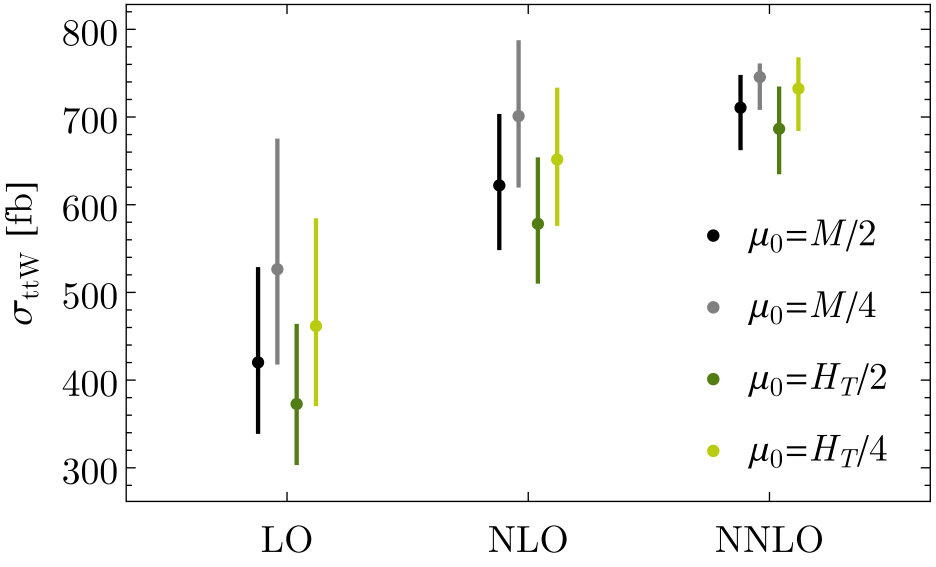


Catani et al., 2210.07846

Theoretical uncertainty reduced to 3% level
(not counting approx. 2-loop)

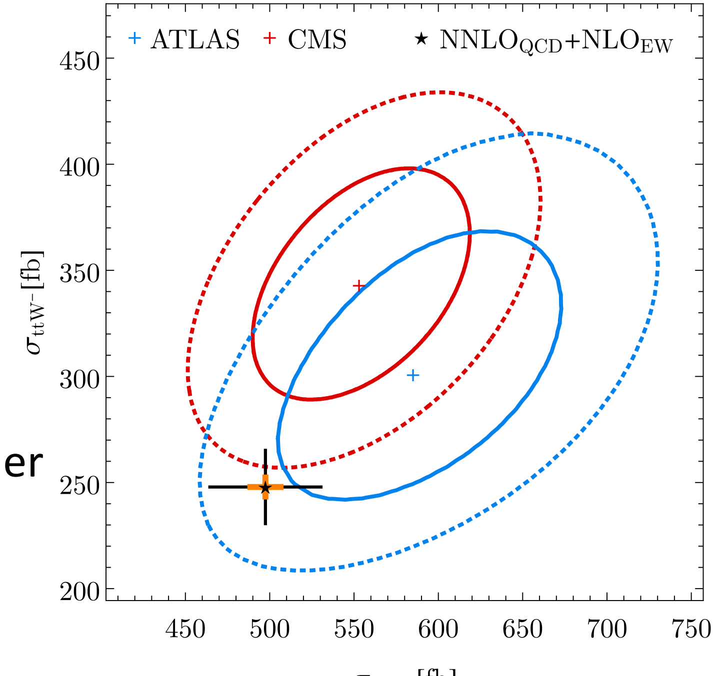
σ [pb]	$\sqrt{s} = 13$ TeV	$\sqrt{s} = 100$ TeV
σ_{LO}	$0.3910\,^{+31.3\%}_{-22.2\%}$	$25.38\,^{+21.1\%}_{-16.0\%}$
σ_{NLO}	$0.4875\,^{+5.6\%}_{-9.1\%}$	$36.43\,^{+9.4\%}_{-8.7\%}$
σ_{NNLO}	$0.5070\,(31)\,^{+0.9\%}_{-3.0\%}$	$37.20(25)\,^{+0.1\%}_{-2.2\%}$

Buonocore et al., 2306.16311



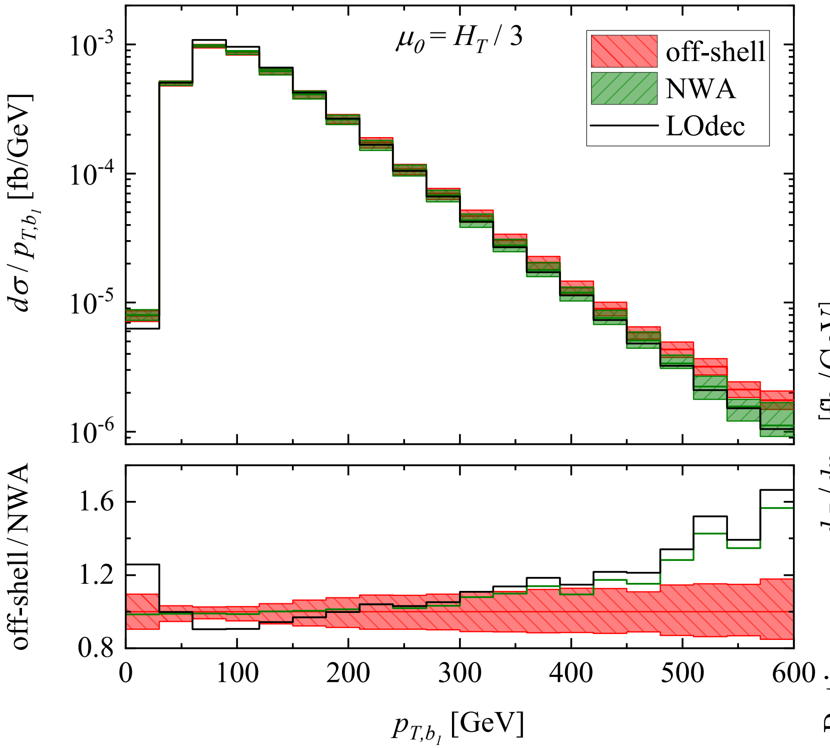
NNO QCD+NLO EW within at most 2σ of exp. measurement.

Comparison in fiducial volumes may give further insight

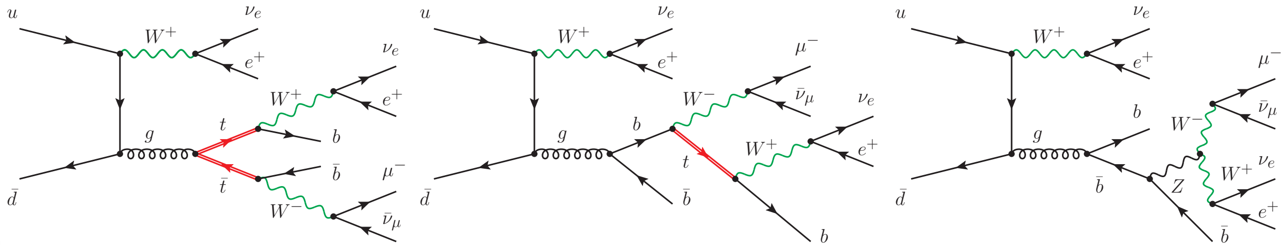


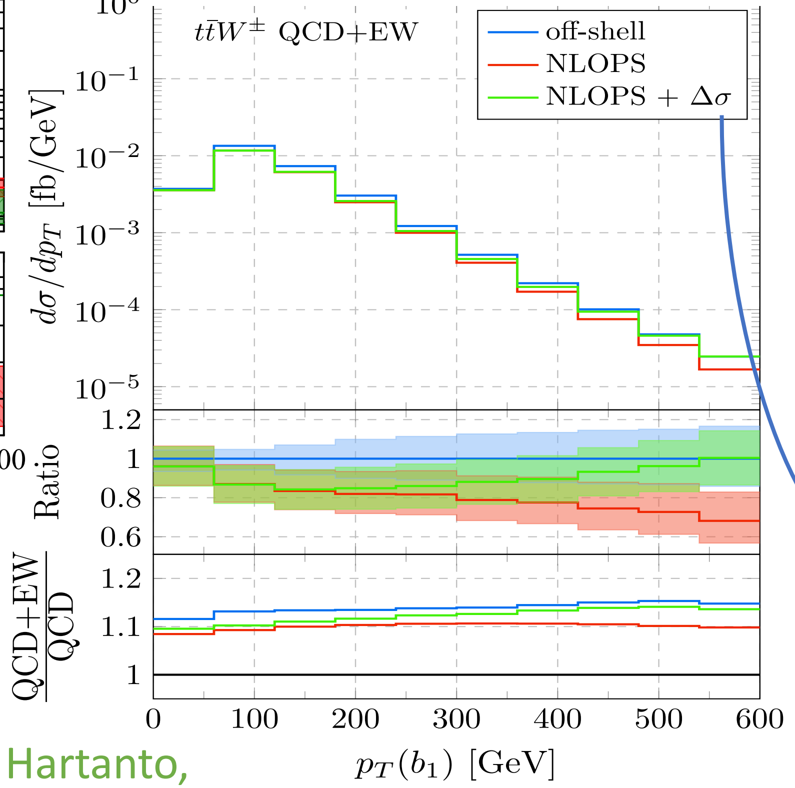
$t\bar{t}X$@NLO: push the multiplicity challenge

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

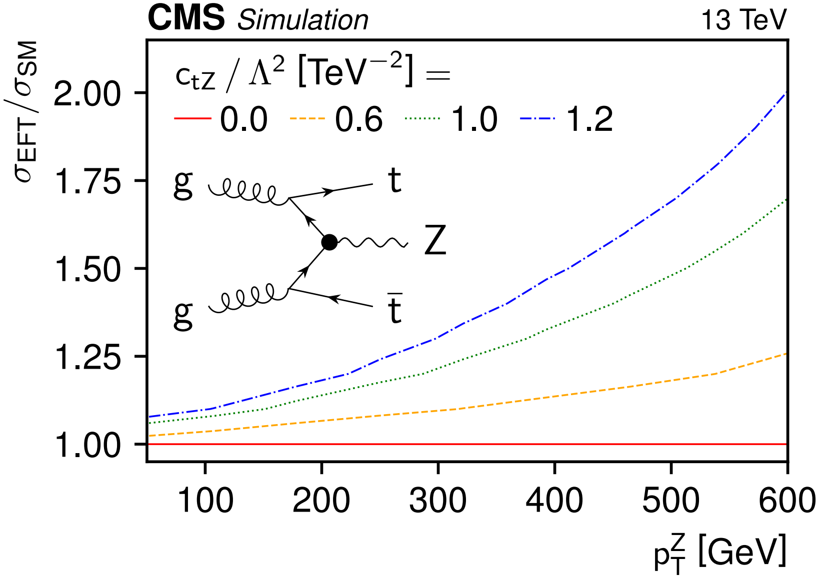
Off-shell effects most relevant in tails and end-points of distributions, where new physics effects can be hidden

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

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

… exploring boosted kinematics and off-shell signatures

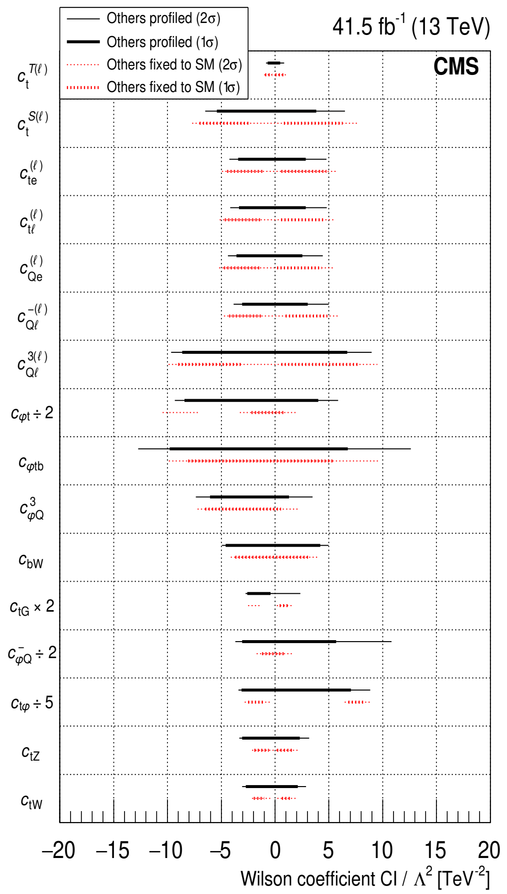
Top pair + boosted Z/H



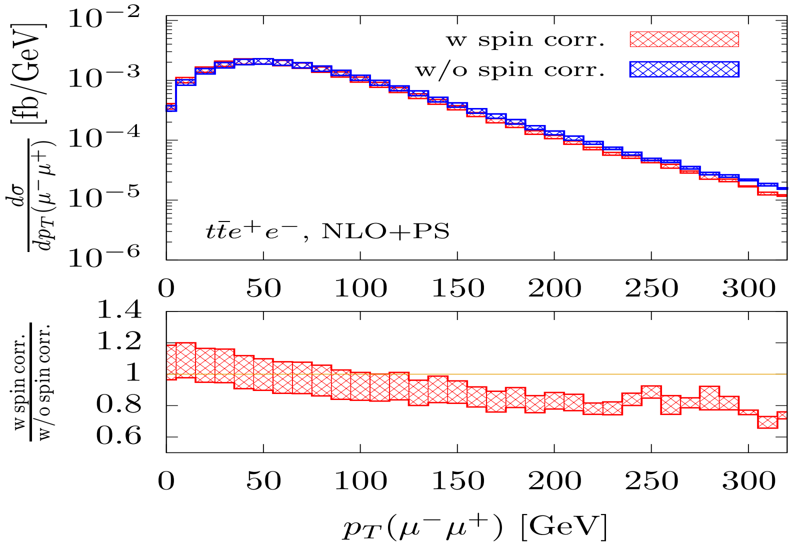
$$\delta\eta_{SM} \sim g^2_{BSM}\frac{E^2}{M^2}$$

Effects in tails of distributions but also anomalous shapes

Top+additional leptons

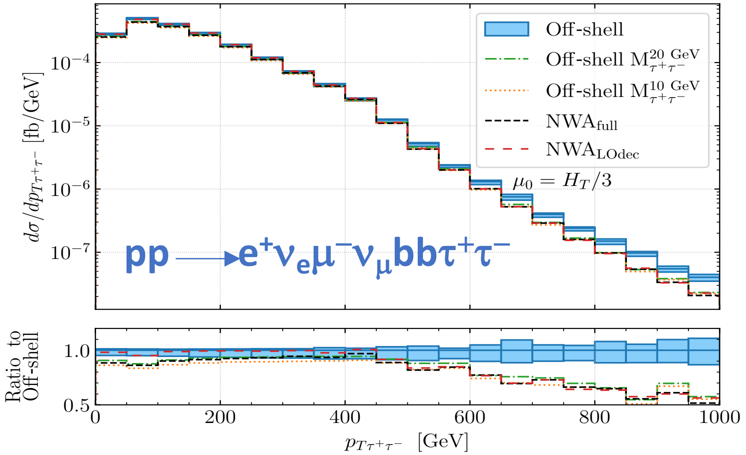


[CMS: arXiv:2012.04120]



M. Ghezzi et al. [2112.08892]

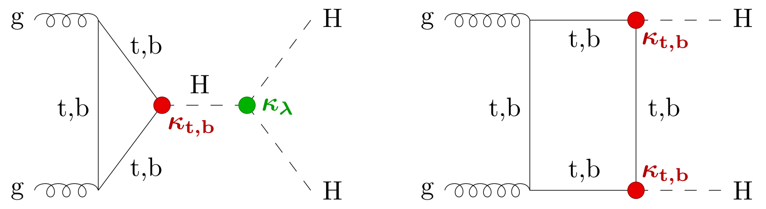
Off-shell studies



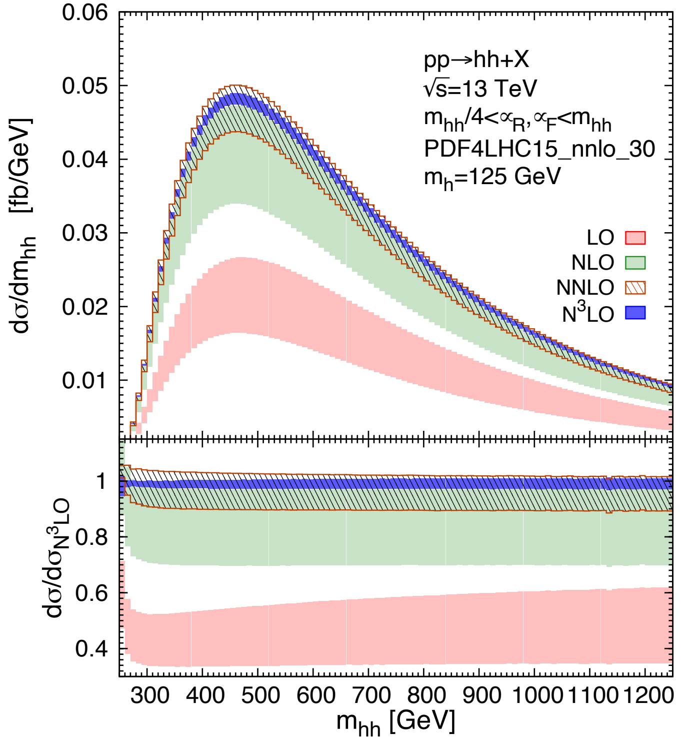
G. Bevilacqua et al. [2203.15688]

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

HH and HHH production



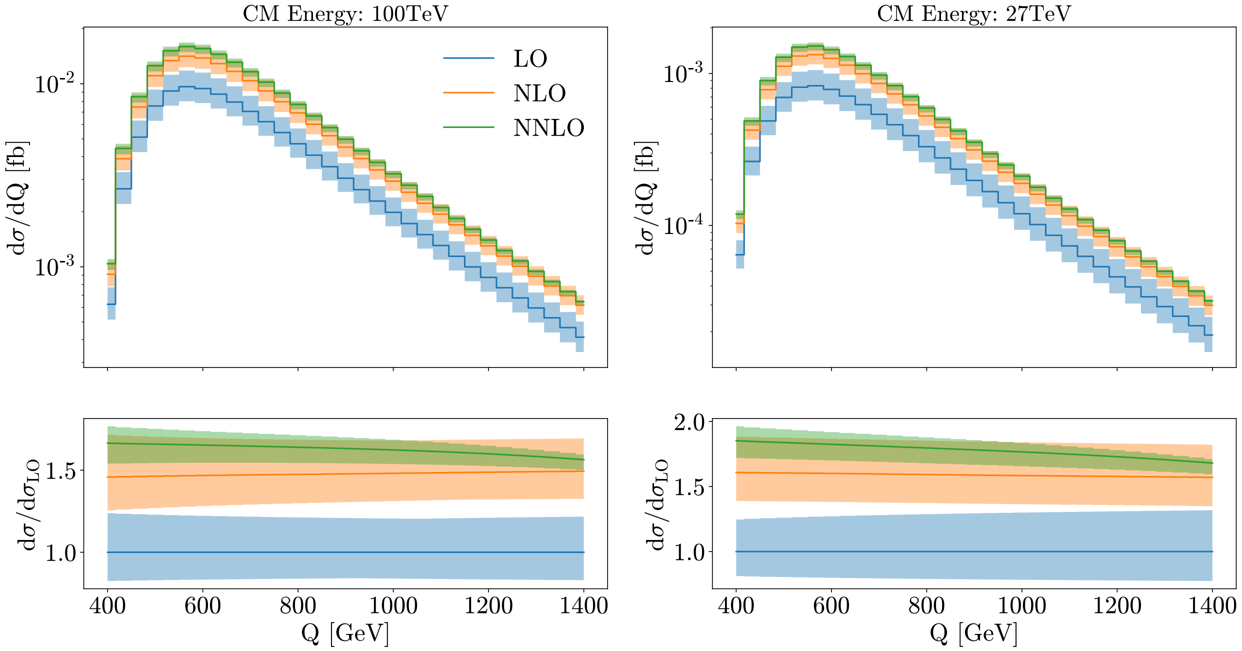
Sensitive to λ_3



$\sqrt{s}$ / Order	13 TeV	14 TeV	27 TeV	100 TeV
LO	$13.80^{+31\%}_{-22\%}$	$17.06^{+31\%}_{-22\%}$	$98.22^{+26\%}_{-19\%}$	$2015^{+19\%}_{-15\%}$
NLO	$25.81^{+18\%}_{-15\%}$	$31.89^{+18\%}_{-15\%}$	$183.0^{+16\%}_{-14\%}$	$3724^{+13\%}_{-11\%}$
NNLO	$30.41^{+5.3\%}_{-7.8\%}$	$37.55^{+5.2\%}_{-7.6\%}$	$214.2^{+4.8\%}_{-6.7\%}$	$4322^{+4.2\%}_{-5.3\%}$
N^3LO	$31.31^{+0.66\%}_{-2.8\%}$	$38.65^{+0.65\%}_{-2.7\%}$	$220.2^{+0.53\%}_{-2.4\%}$	$4438^{+0.51\%}_{-1.8\%}$

Chen, Li, Shao, Wang, arXiv:1909.06808

Sensitive to λ_4

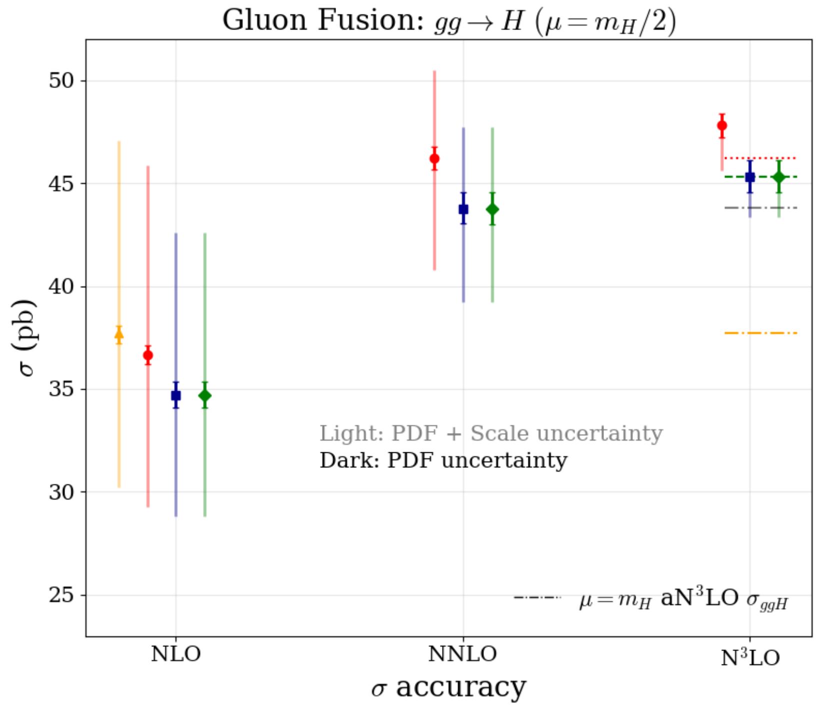


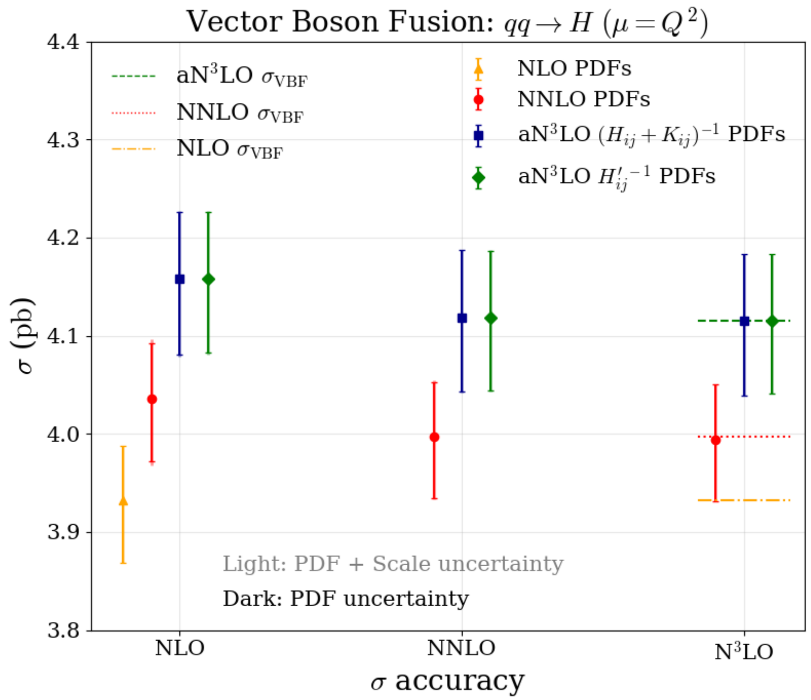
$\text{NNLO}_{\text{Best}}$	$0.103^{+5\%}_{-8\%}$	$0.501^{+5\%}_{-7\%}$	$5.56^{+5\%}_{-6\%}$

De Florian, Fabre, Mazzitelli.arXiv:1912.02760

Beyond specific processes

PDF – first approximate N^3LO sets





aN^{3}LO → MSHT20aN^{3}LO

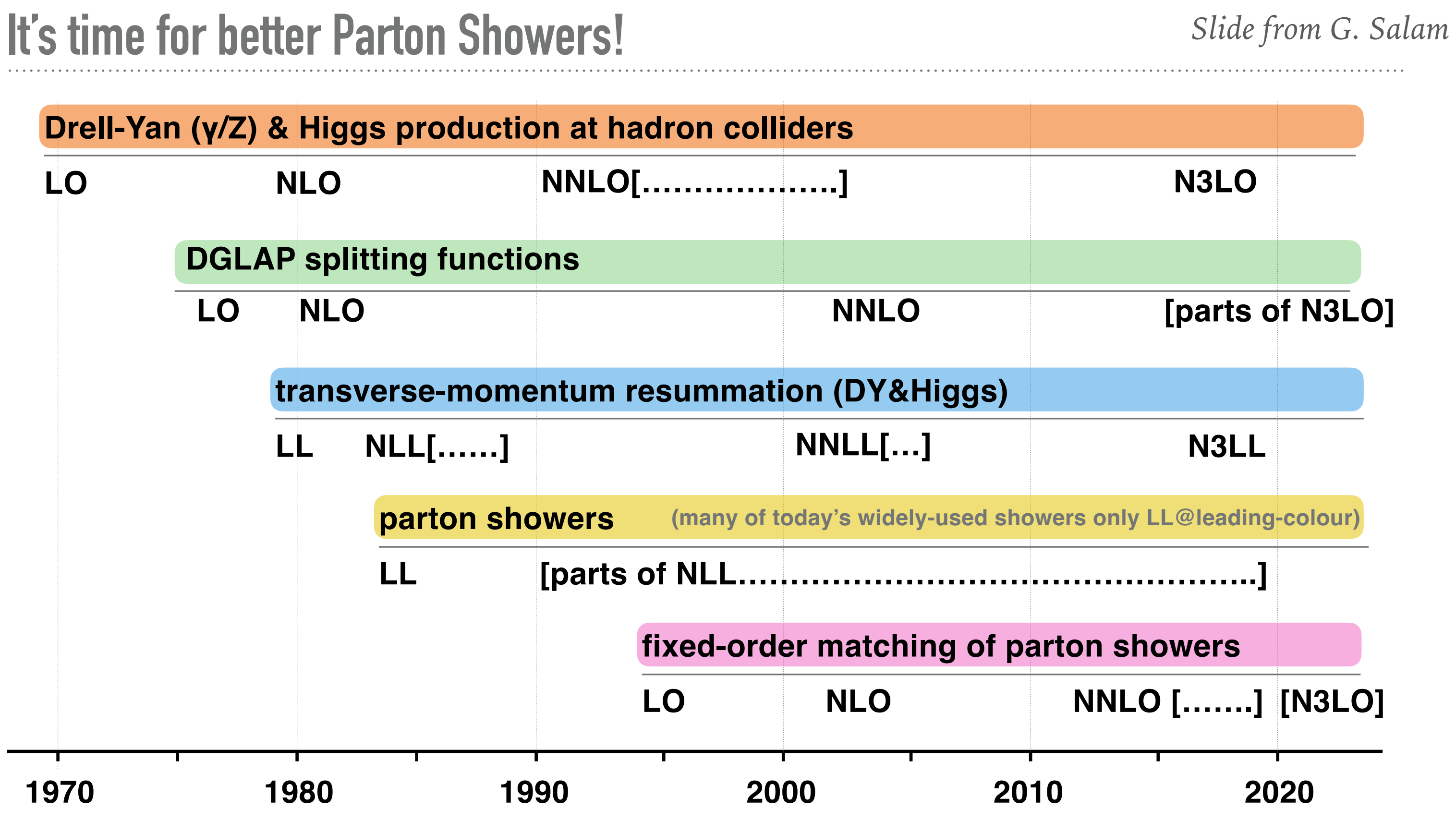
McGowan, Cridge, Harland-Lang, Thorne, 2207.04739

- Based on N^{3}LO 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 N^{3}LO results
- Including PDF uncertainty from missing higher-orders (MHOU) as theoretical uncertainty in the fit

➢ **Gluon fusion to H**: the increase in the cross section prediction at N^{3}LO is compensated by the N^{3}LO PDF, suggesting a cancellation between terms in the PDF and cross section theory at N^{3}LO → **matching orders matters!**

➢ **Vector Boson Fusion**: no relevant change in going from N^{2}LO to N^{3}LO PDF, due to different partonic channel involved.

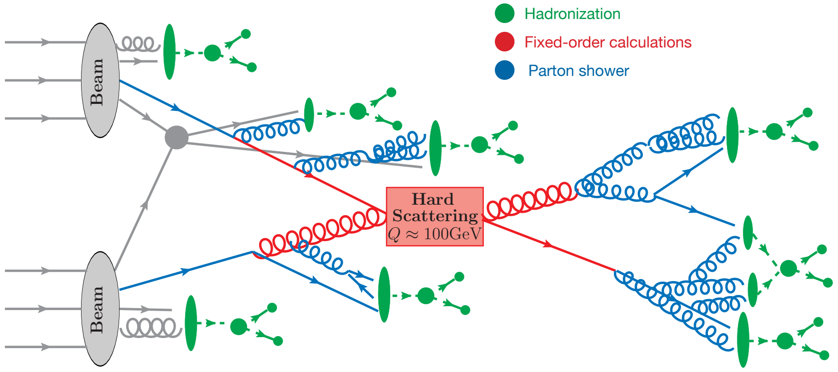
Parton-shower event generators



Crucial ingredient to reproduce the complexity of collider events

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

From S. Ferrario Ravasio, RADCOR 2023



- ➢ Standard PS are Leading Logarithmic (LL) → becoming a limitation
- ➢ Several groups aiming for NLL hadron-collider PS

Nagy&Soper, PanScales, Holguin- Forshaw-Platzer, Herren-Höche-Krauss- Reichelt

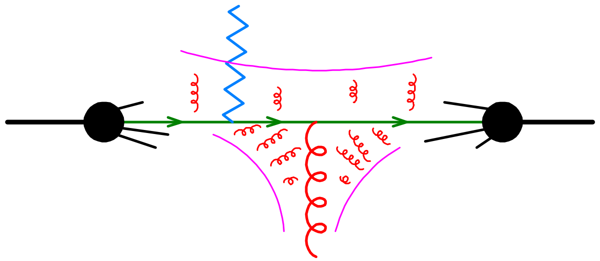
More challenges: non-perturbative effects $O((\Lambda_{QCD}/Q)^p)$

Estimate of “p” for all relevant processes crucial to LHC precision program

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

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

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



- Z transverse-momentum distributions

  Ferrario Ravasio, Limatola, Nason, 2011.14114

- Observables that are inclusive with respect to QCD radiation

  Caola, Ferrario Ravasio, Limatola, Melnikov, Nason, 2108.08897, same+Ozcelik 2204.02247

Summary

- **The Higgs discovery has been fundamental in opening new avenues to explore physics beyond the SM** and the Higgs-physics program ahead of us promises to start answering some of the remaining fundamental questions in particle physics.
- **Collider physics** remains as a **unique and necessary test of BSM scenarios,** both via direct and indirect evidence of new physics effects.
- Both direct and indirect searches for new physics effects will rely on the **percent level precision** of the HL-LHC and of the necessary theoretical predictions.
- **Matching the precision expected by the HL-LHC (and future Higgs factories) is a remarkable challenge** that brings theoretical prediction to a **multi-component new level of accuracy.**

Supplemental Material

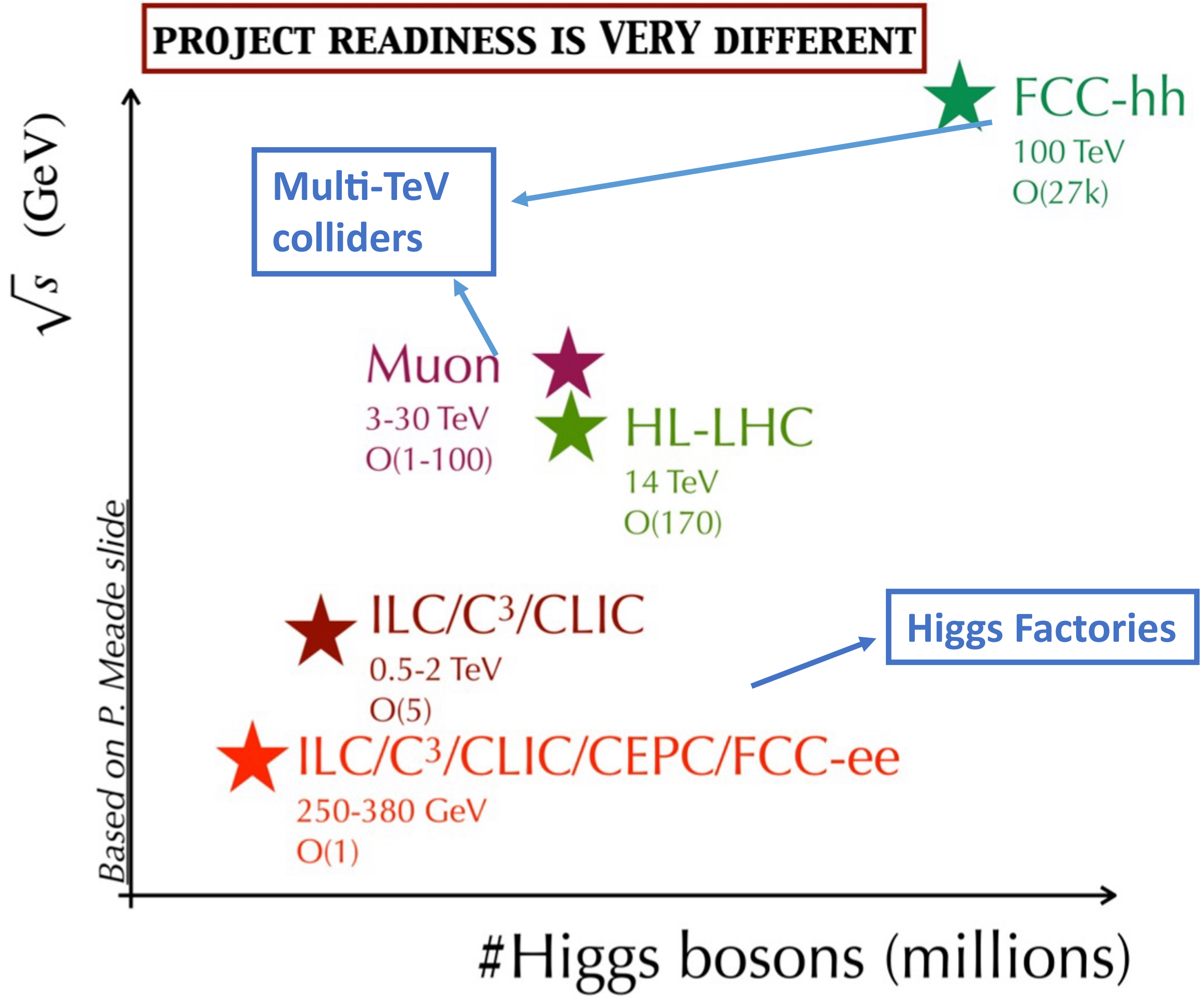
Beyond the HL-LHC: proposed future colliders

Lepton colliders

- **Circular e+e-** (CEPC, FCC-ee)
  - **90-350 GeV**
  - *strongly limited by synchrotron radiation above 350– 400 GeV*
- **Linear e+e-** (ILC, CLIC, C^3)
  - **250 GeV — > 1 TeV**
  - *Reach higher energies, and can use polarized beams*
- **μ+μ-**
  - **3-30 TeV**

Hadron colliders

- **75-200 TeV** (FCC-hh)



Snowmass 21:
EF Benchmark Scenarios

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

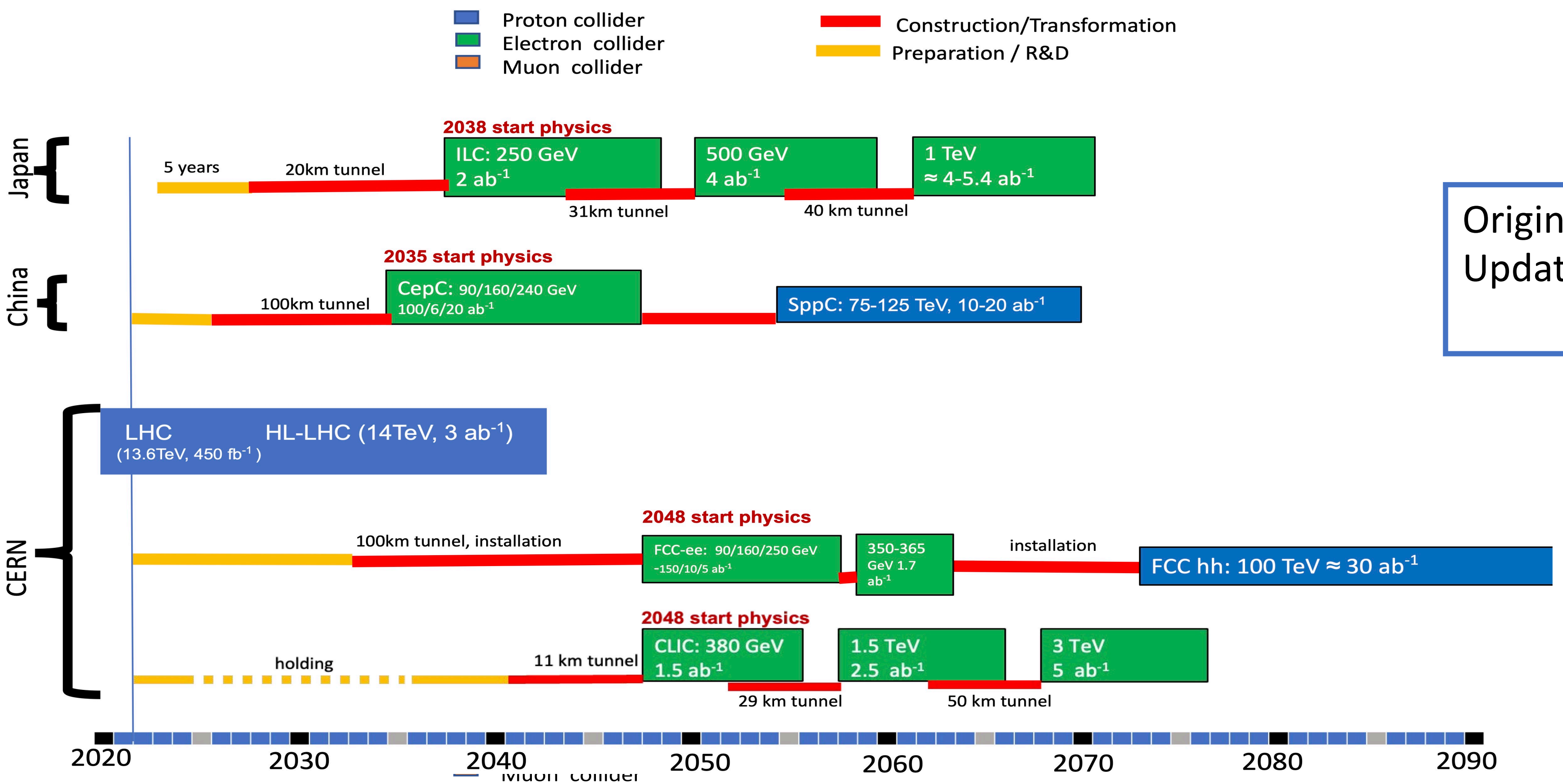
Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\rm int}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HL-LHC	pp	14 TeV		3		2027
ILC & C^3	ee	250 GeV	$\pm80/\pm30$	2	2028	2038
		350 GeV	$\pm80/\pm30$	0.2		
		500 GeV	$\pm80/\pm30$	4		
		1 TeV	$\pm80/\pm20$	8		
CLIC	ee	380 GeV	$\pm80/0$	1	2041	2048
CEPC	ee	M_Z		50	2026	2035
		$2M_W$		3		
		240 GeV		10		
		360 GeV		0.5		
FCC-ee	ee	M_Z		75	2033	2048
		$2M_W$		5		
		240 GeV		2.5		
		$2\ M_{top}$		0.8		
μ-collider	$\mu\mu$	125 GeV		0.02		

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

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

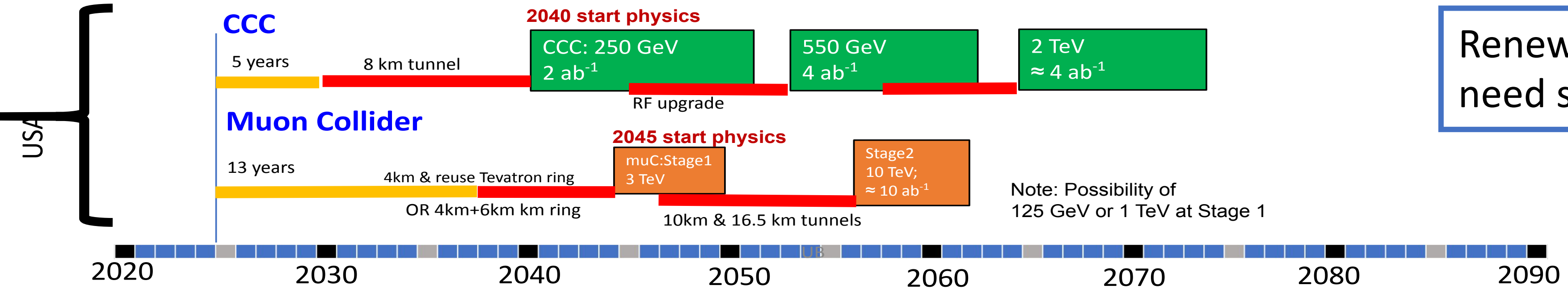
Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$. e^-/e^+	$\mathcal{L}_{\rm int}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HE-LHC	pp	27 TeV		15		
FCC-hh	pp	100 TeV		30	2063	2074
SppC	pp	75-125 TeV		10-20		2055
LHeC	ep	1.3 TeV		1		
FCC-eh		3.5 TeV		2		
CLIC	ee	1.5 TeV	$\pm80/0$	2.5	2052	2058
		3.0 TeV	$\pm80/0$	5		
μ-collider	$\mu\mu$	3 TeV		1	2038	2045
		10 TeV		10		

Timelines are taken from the Collider ITF report (arXiv: 2208.06030)



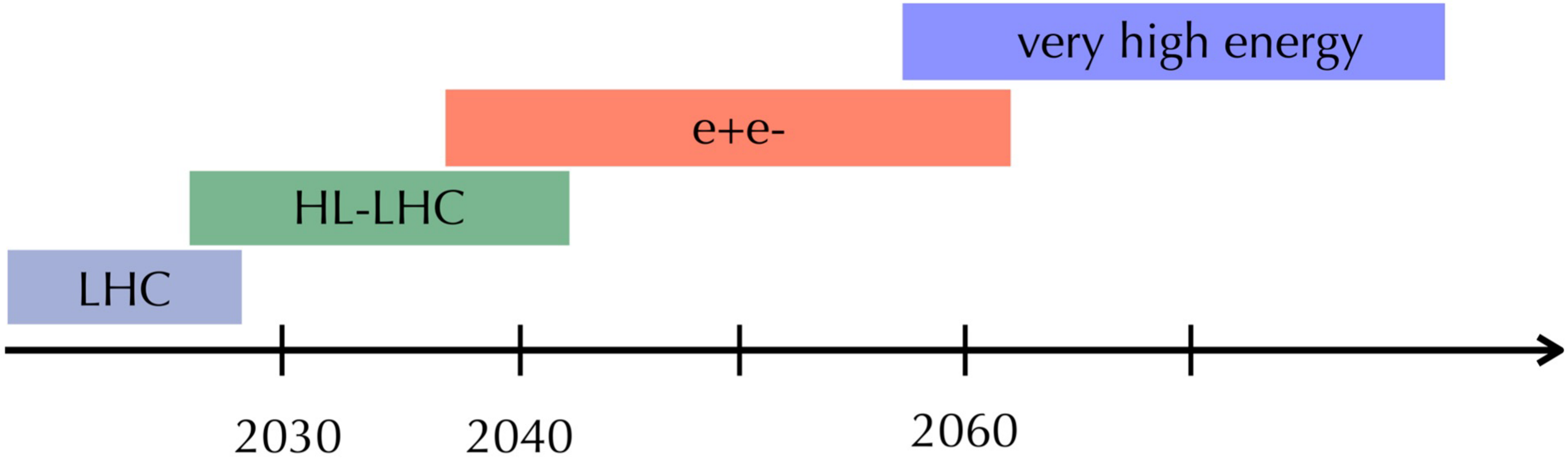
Original timeline from ESG
Updated during Snowmass 2021
(see EF Report)

Proposals emerging from Snowmass 2021 for a US based collider



Renewed interest in lepton colliders:
need supporting R&D in near future

Beyond the HL-LHC: projections for Higgs couplings

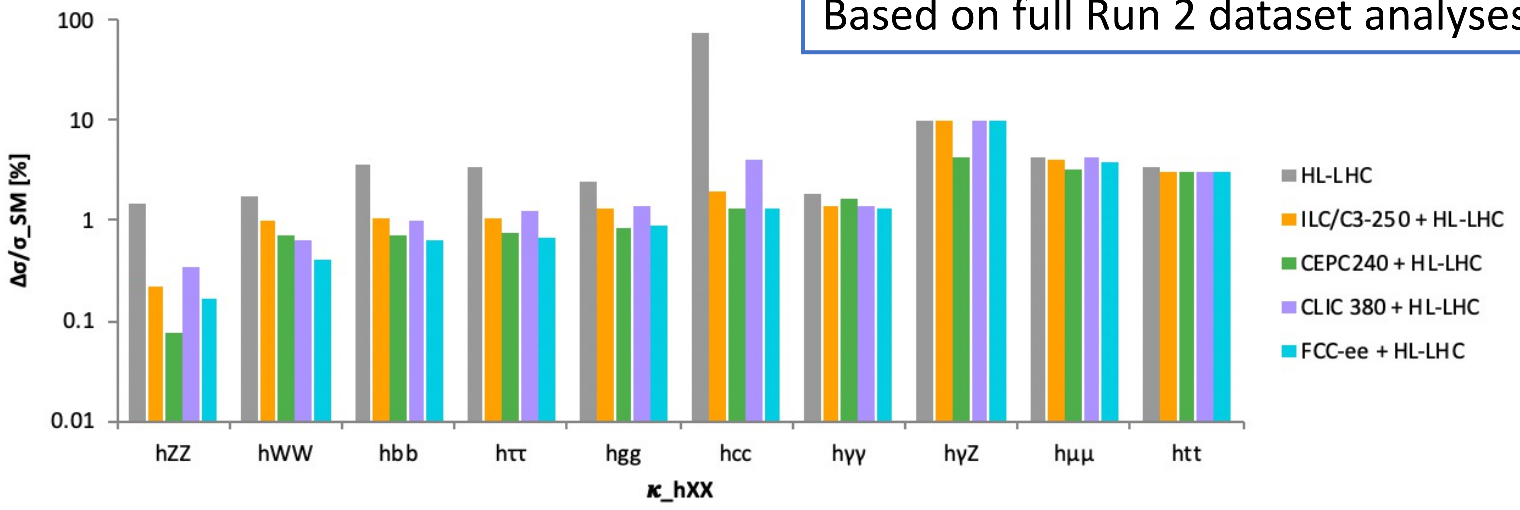


H couplings to:	**O(5-15)%**	**O(0.1-1)%**	**O(1)‰**
H self-coupling to	**<O(50)%**	**O(20)%**	**O(1)%**

From C. Vernieri – Snowmass 21 EF Workshop - Brown U. - March 2022

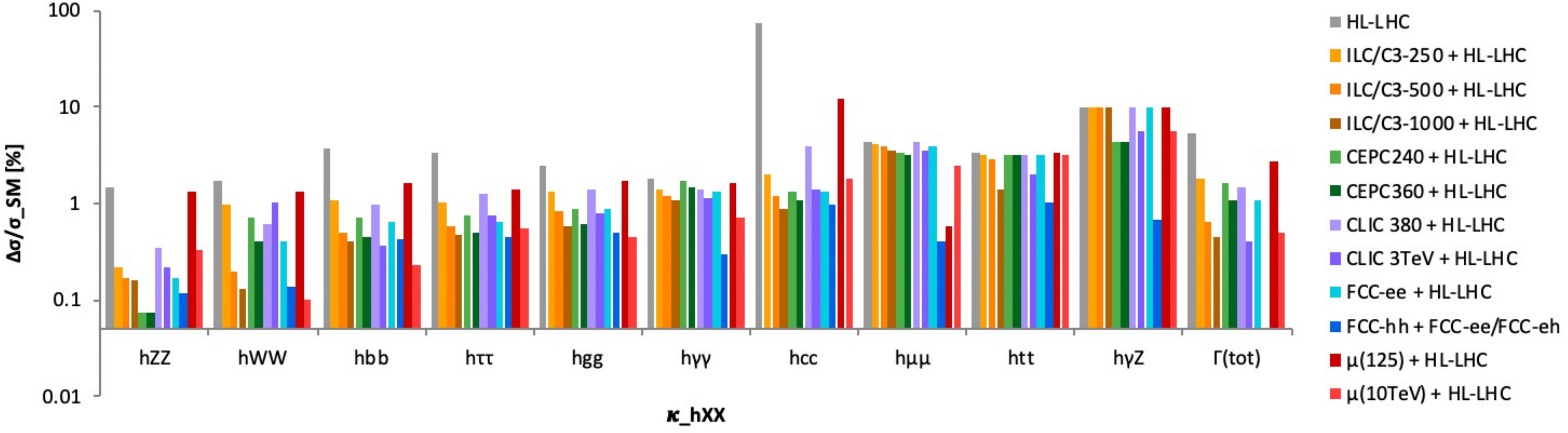
Reach of future colliders for Higgs couplings: a closer look

Based on full Run 2 dataset analyses



Initial stages of future e+e- machines

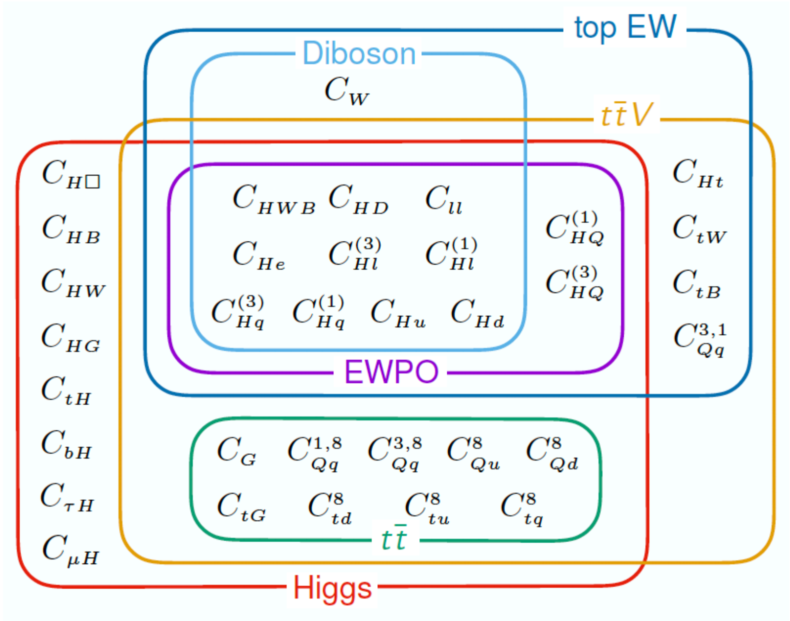
From Snowmass 2021 EF Higgs Topical Group Report arXiv:2209.07510



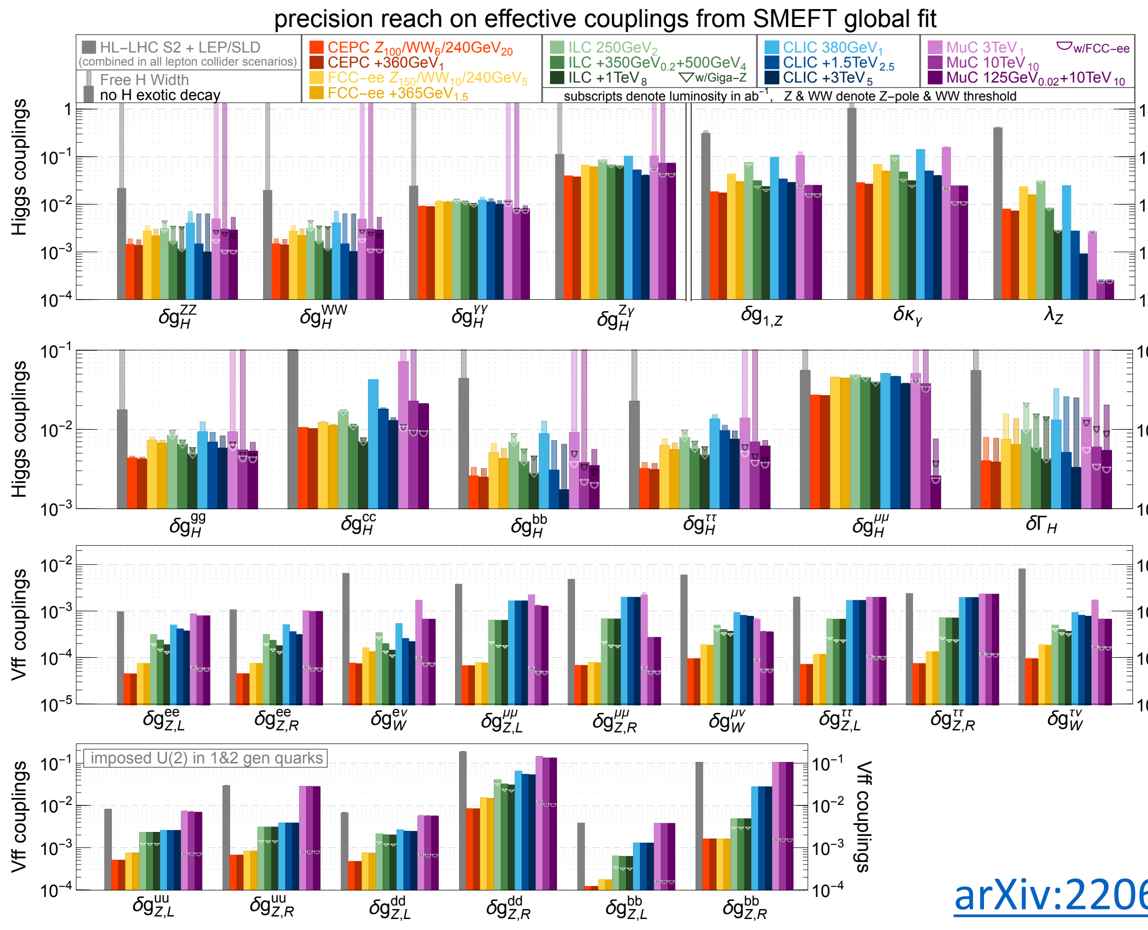
Final reach of all considered future colliders

Constraining BSM via global EFT fits

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



EW + Higgs



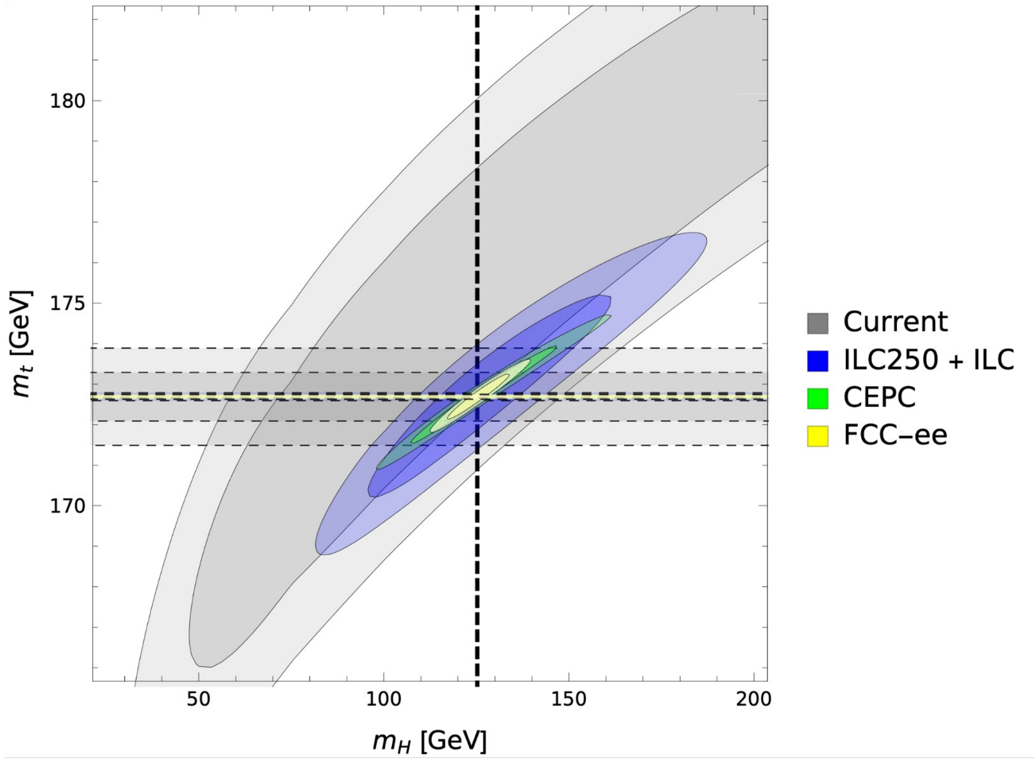
[arXiv:2206.08326](https://arxiv.org/abs/2206.08326)

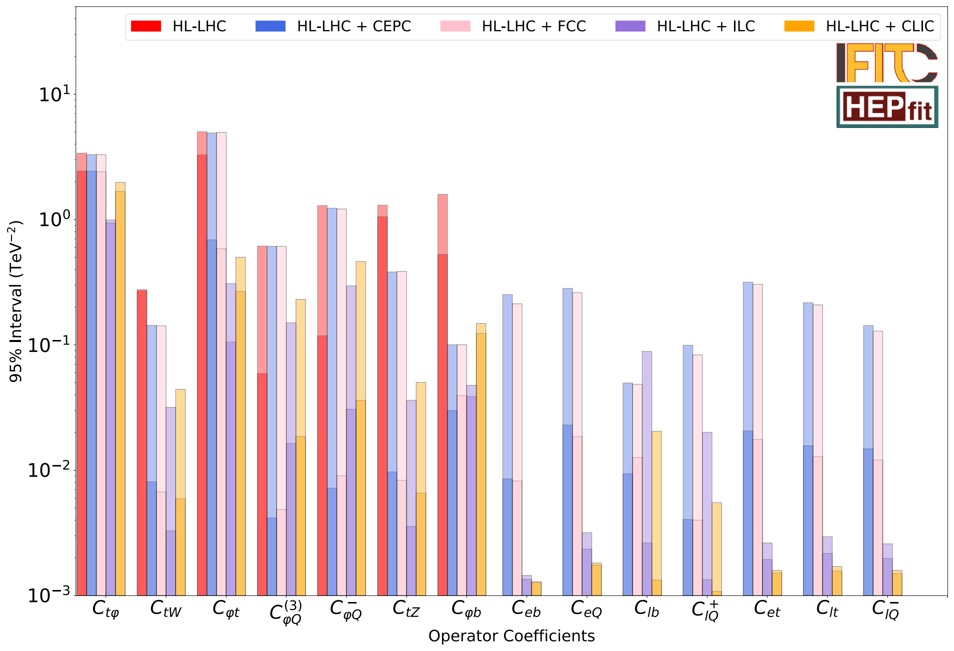
EFT connects different processes with large correlations: pattern of coefficients give insights on underlying BSM model

Interplay with top-quark precision measurements

Parameter	HL-LHC	ILC 500	FCC-ee	FCC-hh
$\sqrt{s}$ [TeV]	14	0.5	0.36	100
Yukawa coupling y_t (%)	3.4	2.8	3.1	1.0
Top mass m_t (%)	0.10	0.031	0.025	–
Left-handed top-W coupling $C^3_{\phi Q}$ (TeV^{-2})	0.08	0.02	0.006	–
Right-handed top-W coupling C_{tW} (TeV^{-2})	0.3	0.003	0.007	–
Right-handed top-Z coupling C_{tZ} (TeV^{-2})	1	0.004	0.008	–
Top-Higgs coupling $C_{\phi t}$ (TeV^{-2})	3	0.1	0.6	
Four-top coupling c_{tt} (TeV^{-2})	0.6	0.06	–	0.024

Stress testing the SM and exploring anomalous couplings

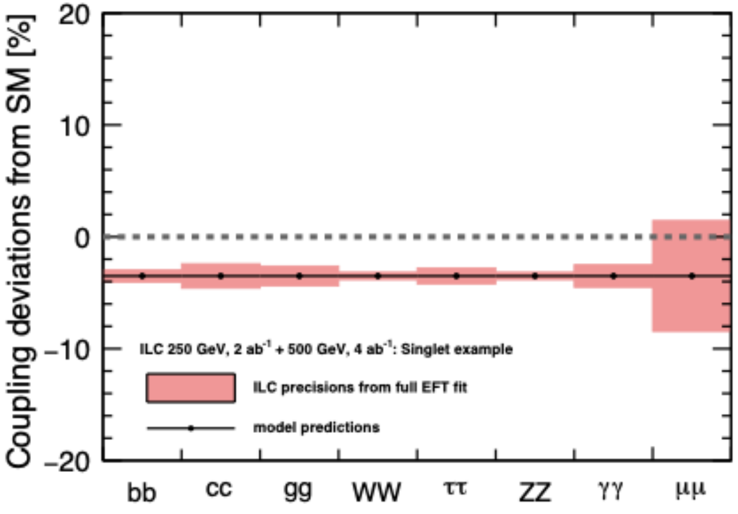




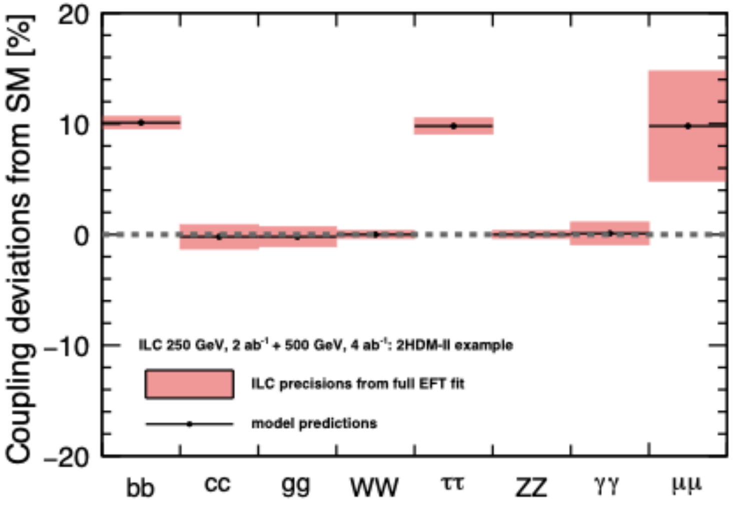
From Snowmass 2021 EF HF and EW TG's Reports arXiv:2209.11267, arXiv:2209.08078

Disentangling models from EFT patterns

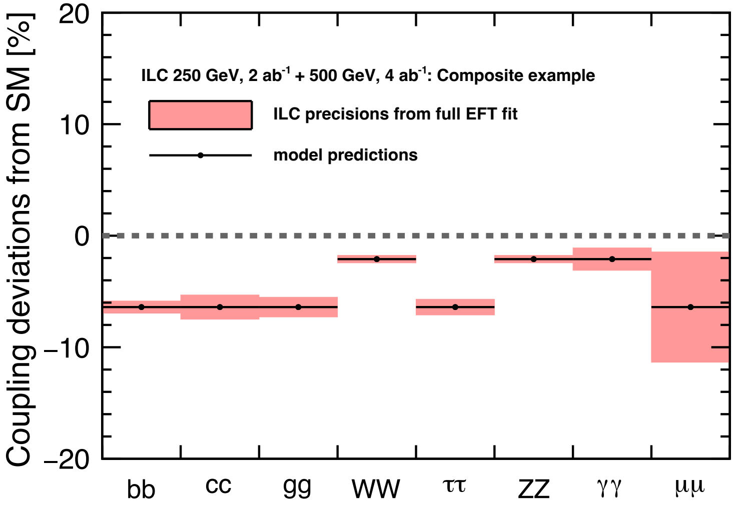
The "inverse Higgs" problem



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



2HDM-II
(MH=600 GeV, tanβ=7)

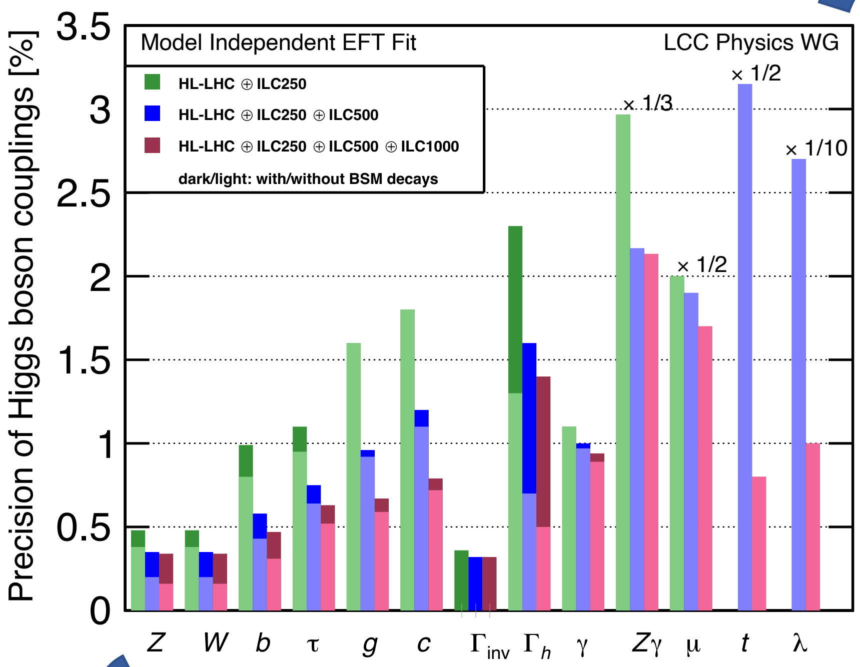


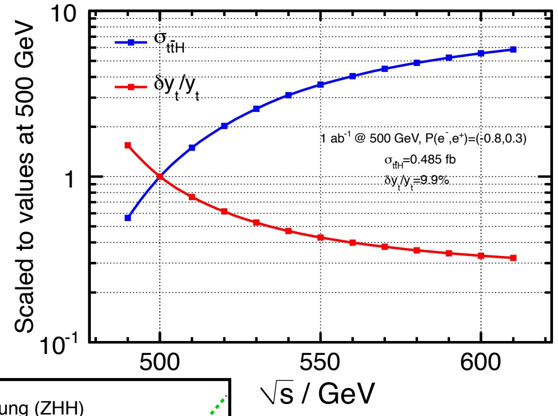
Composite Higgs
(f=1.2 TeV)

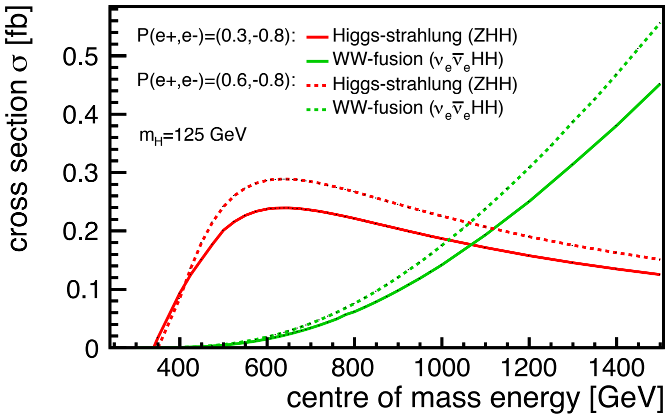
Snowmass 2021: ILC white paper (arXiv: 2203.07622)

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

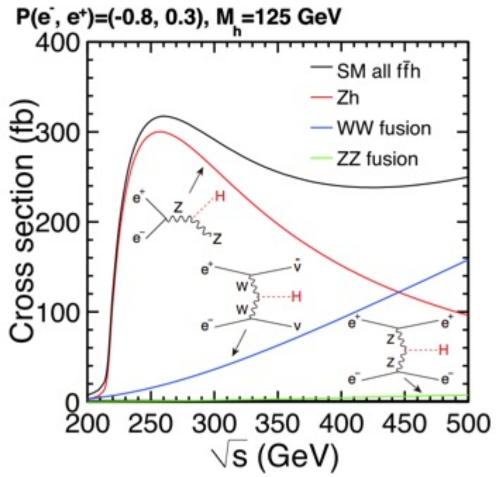
The case of e^+e^- Higgs factories



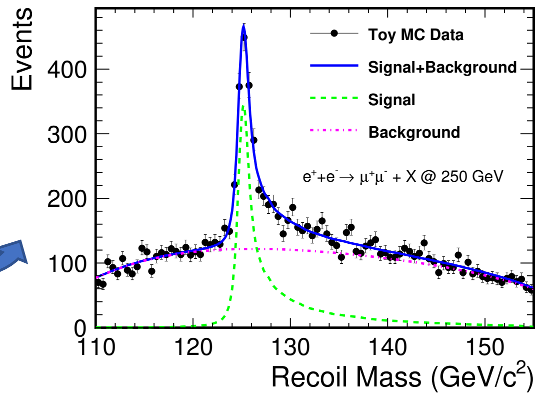


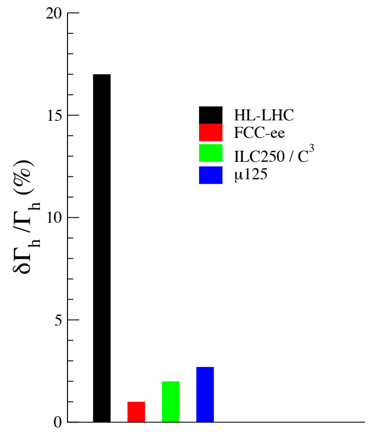


Energy matters
top-Yukawa, HH,
extended Higgs sectors
need >500 GeV

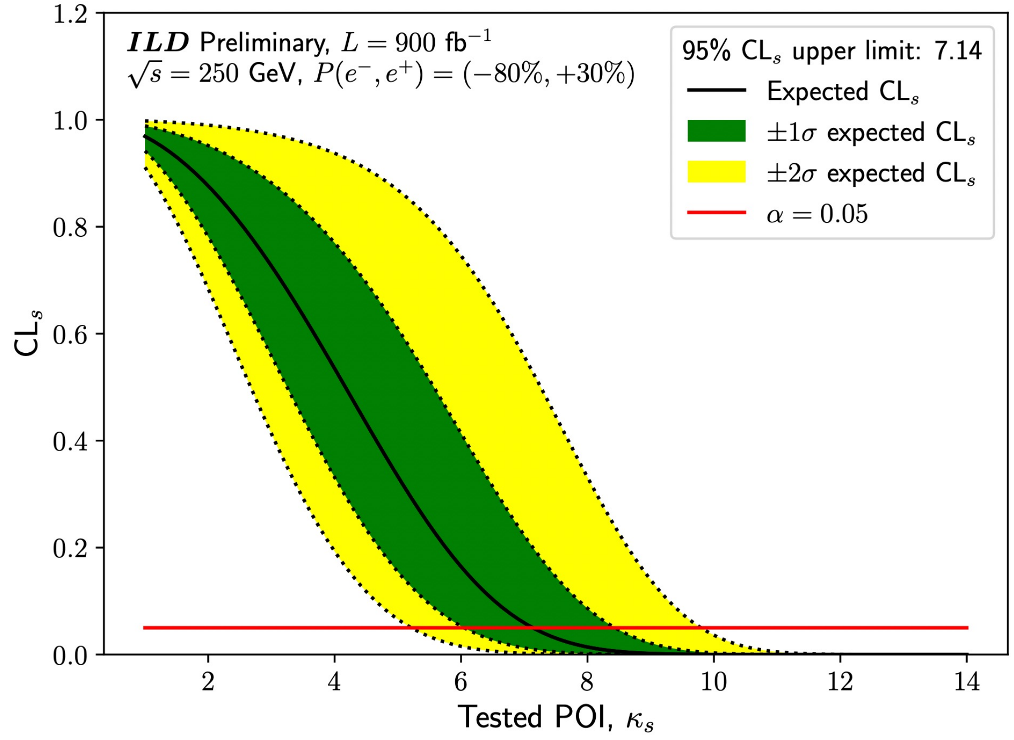


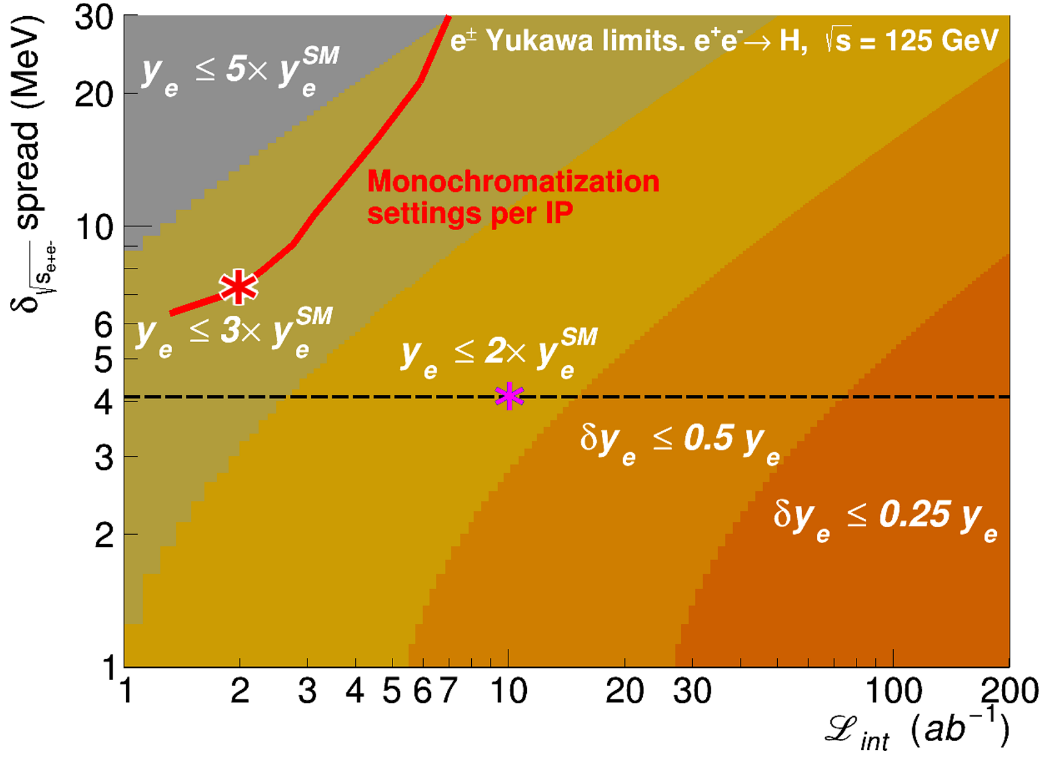
Model-independent
Γ_H measurment





Reach for light fermion Yukawa couplings: highlights





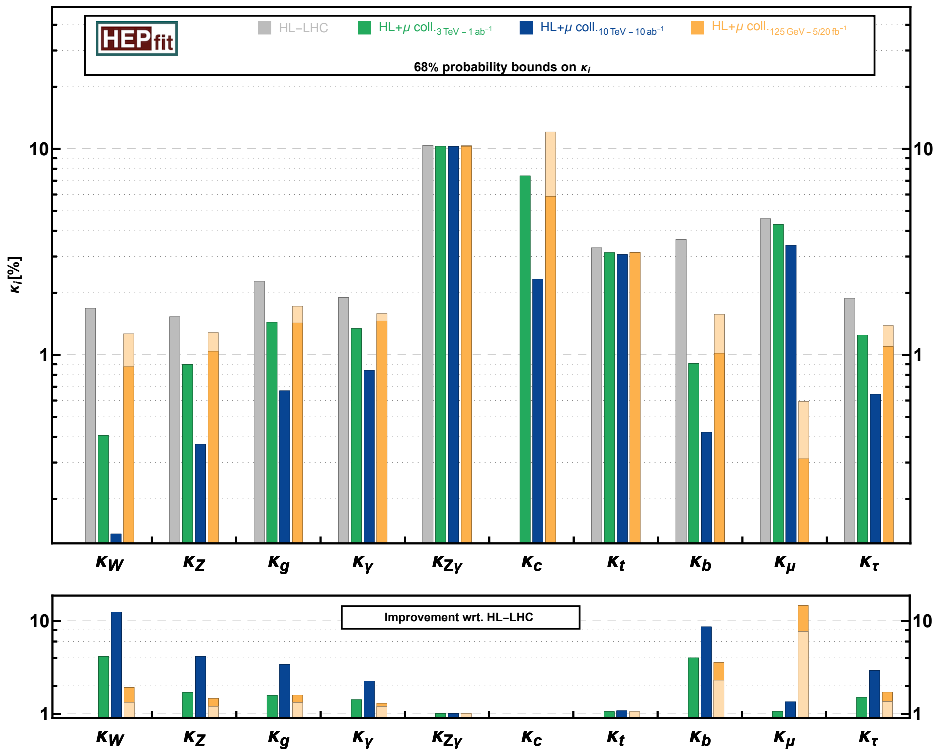
- Studying ZH with Z going to leptons and neutrinos
- $\kappa_s < 7.14$ at 95% c.l.

arXiv:2203.07535

- Electron Yukawa at FCC-ee (s-channel H)
- $\kappa_e < 1.6$ at 95% c.l.

arXiv:2107.02686

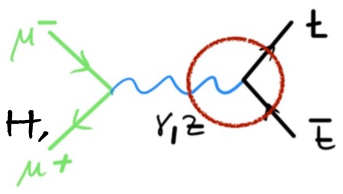
The case of a Muon Collider



- **Many stages/upgrades:**
  - 125 GeV on-Higgs resonace
  - 3 TeV
  - 10 TeV
  - >10 TeV (14, 30, … TeV)
- **Lepton collider**
  - Cleaner environment → **precision**
- **… but high energy**
  - Pushing the EF → **discovery**
- **Competitive/complementary to ~100 TeV hadron collider**
- **Contained size**
  - $M_\mu \sim 200\, m_e$ → reduced synchrotron radiation (x 1.6×10^{-9})
- **New physics regimes**
  - $E > \Lambda_{EW}$
  - EW radiation

Snowmass 21 EF Higgs TG Report (arXiv:2209.07510) & MuC Forum Report (arXiv:2209.01318)

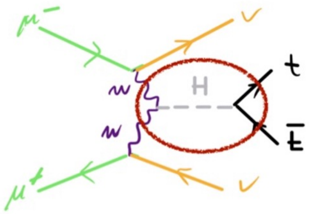
$\sqrt{s} \lesssim$ 1-5 TeV



$$\sigma_s \sim \frac{1}{s}$$

$$\sigma_s \sim \frac{1}{M^2} \log^n \frac{s}{M}$$

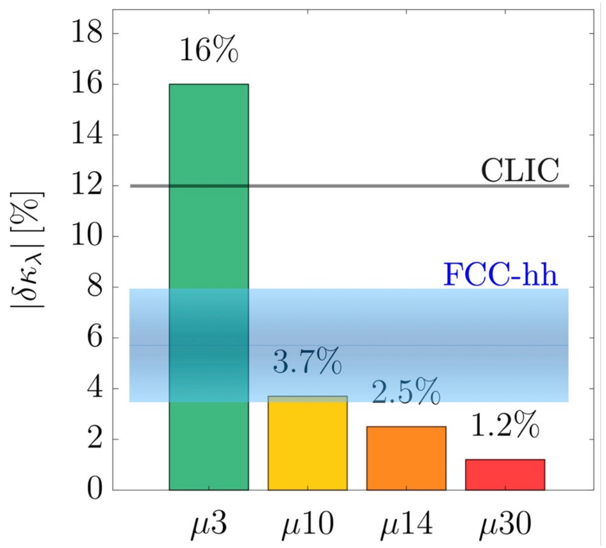
$\sqrt{s} \gtrsim$ 1-5 TeV



Reach for Higgs self-coupling

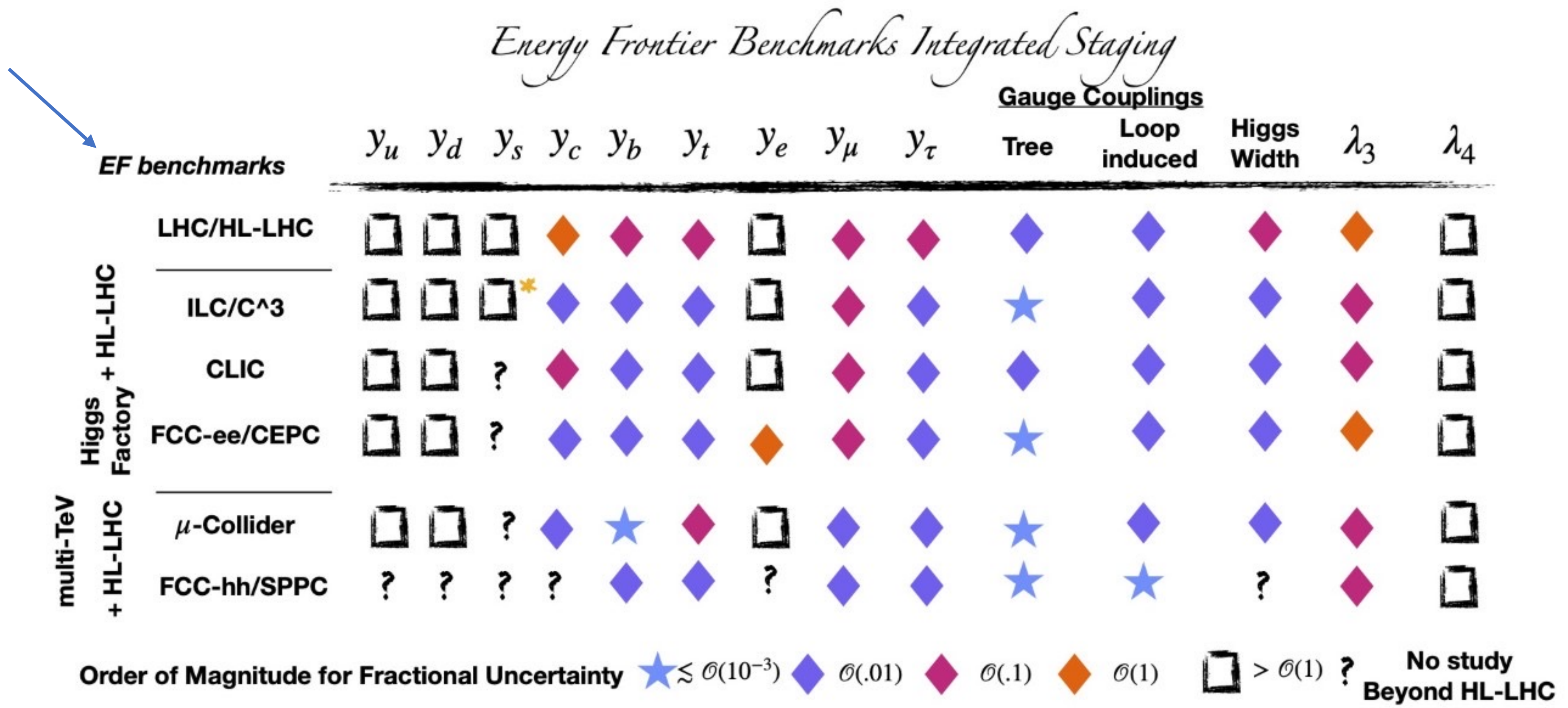
collider	Indirect-h	hh	combined
HL-LHC	100-200%	50%	50%
ILC_{250}/C^3-250	49%	–	49%
ILC_{500}/C^3-550	38%	20%	20%
$CLIC_{380}$	50%	–	50%
$CLIC_{1500}$	49%	36%	29%
$CLIC_{3000}$	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
FCC-hh	-	2.9-5.5%	2.9-5.5%
μ(3 TeV)	-	15-30%	15-30%
μ(10 TeV)	-	4%	4%

- ATLAS and CMS HL-LHC updated
- FCC-hh updated arXiv:2004.03505
- Added MuC reach:



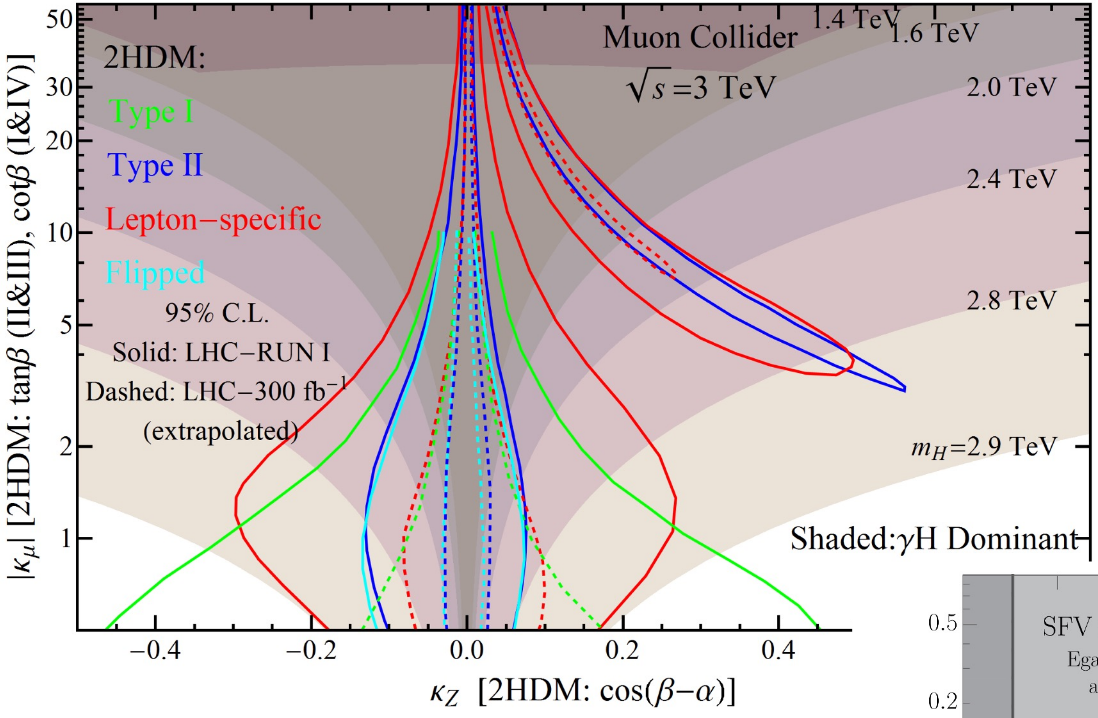
arXiv:2203.07256

Higgs precision reach of Future Colliders: a summary

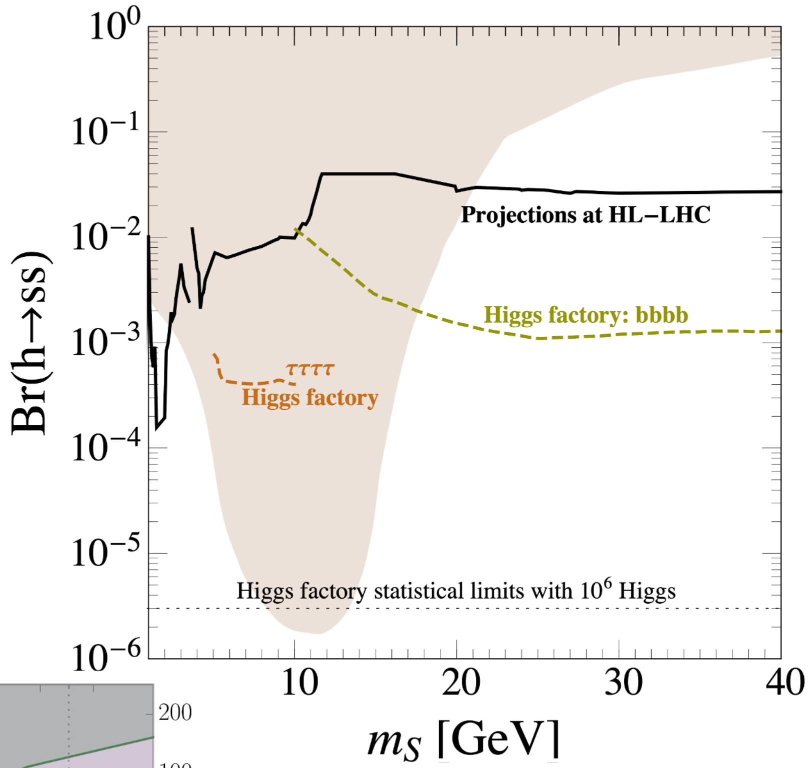


Add some conclusions

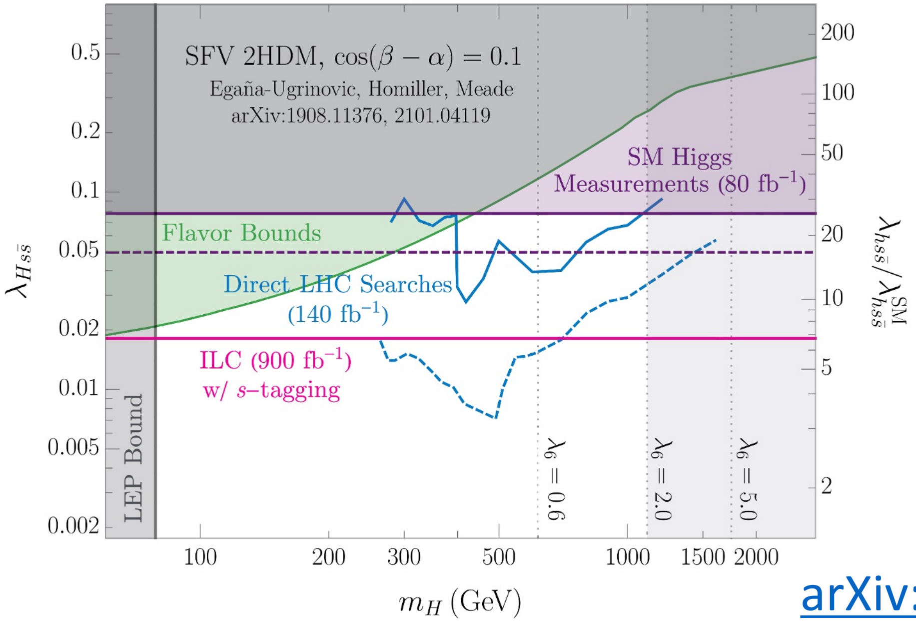
Extended Higgs sectors - direct BSM portal



arXiv:2203.07261



arXiv:2203:08206



arXiv:2203:07535

Extended Higgs sectors:
2HDM, extra singlets, …

Higgs and flavor:
probing anomalous
Hss coupling