Higgs Precision Physics – Decays

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What does decay have to do with precision?

What does decay have to do with precision?

1. **Intro: Higgs precision studies**
2. **SM prediction for Higgs decays**
3. **Higgs production at e^+e^- colliders**
4. **SM input parameters**
5. **Theory calculations**
6. **Beyond the SM**

Higgs precision studies

Higgs physics is entering the precison era:

Determination of Higgs couplings from Higgs production and decay:

	LHC* (2020)	HL-LHC*	CEPC	FCC-ee
hbb	18%	3.7%	1.0%	0.4%
hcc	–	–	1.9%	0.7%
$h\tau\tau$	15%	1.9%	1.2%	0.5%
$h\mu\mu$	–	4.3%	5%	6%
hWW	9%	1.7%	1.1%	0.2%
hZZ	8%	1.5%	0.25%	0.15%
$h\gamma\gamma$	9%	1.8%	1.6%	1.5%
hgg	10%	2.5%	1.2%	0.8%

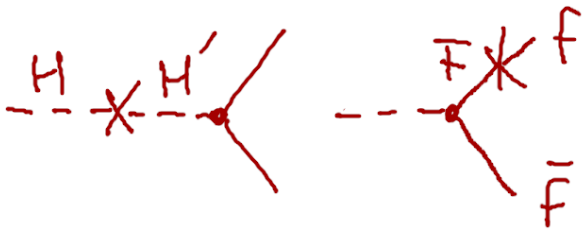
CERN-LPCC-2018-04, PDG '20

* assuming no exotic decays

New physics reach

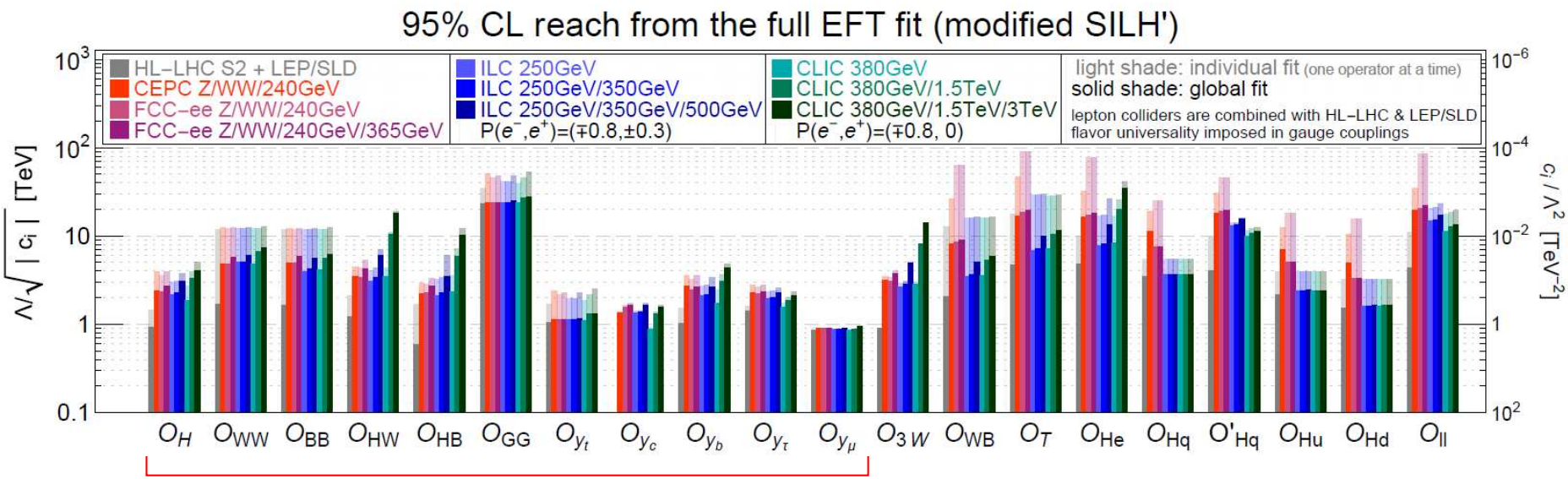
Precision $\equiv$ large mass scales

- Example: mixing with a heavy particle, $\theta \sim \frac{m_{\rm SM}}{M}$



- Model-independent formulation through effective field theory (EFT)

→ lecture by V. Sanz

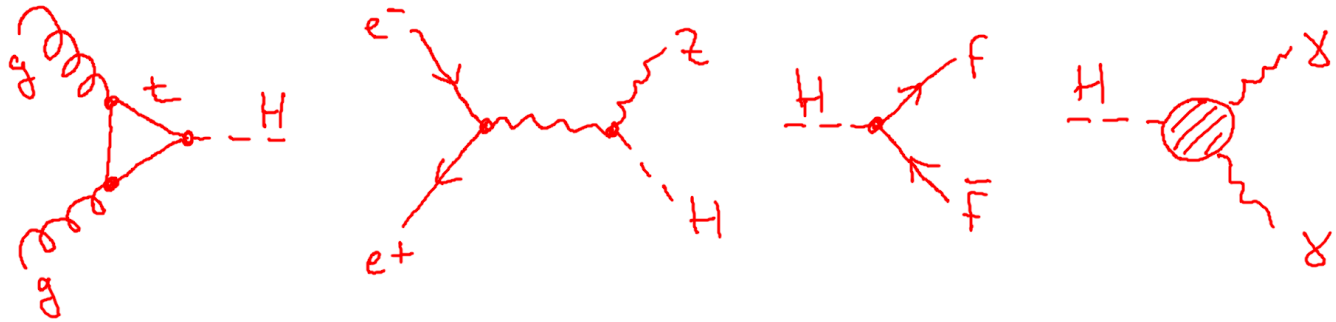


de Blas, Durieux, Grojean, Gu, Paul '19

Higgs production and decay

- Access to Higgs interactions through production and decay

  → S Gori, B. Mistlberger

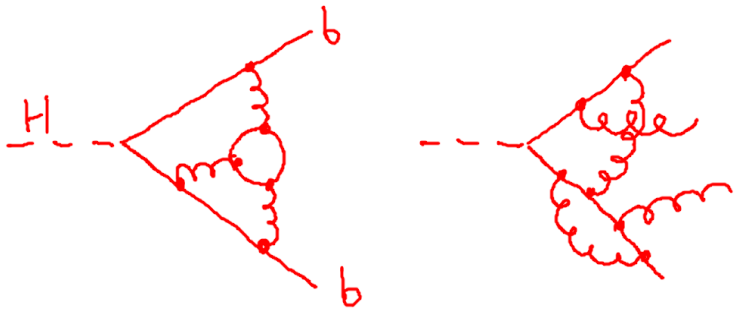


- Most couplings only accessible in decays $(b, c, \tau, \mu, \gamma, Z)$
- Decay ratios can reduce systematics, e.g. $\dfrac{\sigma[pp \to H \to \gamma\gamma]}{\sigma[pp \to H \to ZZ]}$
- $\mathcal{O}(\%)$ BSM effects → need SM predictions with higher-order corrections

SM predictions for Higgs decays

Reviews: 1404.0319, 1906.05379

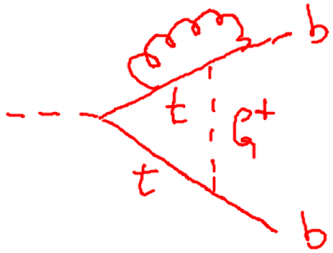
hbb: [HL-LHC: 7%, FCC-ee: 0.8%]



- $\mathcal{O}(\alpha_s^4)$ QCD corrections
  $21\% + 4\% + 0.2\% - 0.15\%$
  Baikov, Chetyrkin, Kühn '05

- $\mathcal{O}(\alpha)$ QED+EW, $< 0.5\%$
  Dabelstein, Hollik '92; Kniehl '92

- leading $\mathcal{O}(\alpha^2)$ and $\mathcal{O}(\alpha\alpha_s)$ for large m_t
  $< 0.5\%$ (use for error estimate)
  Kwiatkowski, Steinhauser '94
  Butenschoen, Fugel, Kniehl '07



Current theory error: $\Delta_{th} < 0.4\%$

With full 2-loop: $\Delta_{th} \sim 0.2\%$

$h\tau\tau$: [HL-LHC: 3.8%, FCC-ee: 1.1%] $\rightarrow$ Similar, but no QCD

SM predictions for Higgs decays

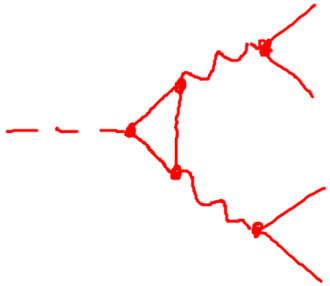
hWW*/hZZ*: [HL-LHC: 3.4%, FCC-ee: 0.4%]

- $m_H < 2m_W \rightarrow$ one or both W/Z must be off-shell
- Need full process $h \rightarrow 4f$
- Differential distributions contain more info

  $\rightarrow$ S. Gori

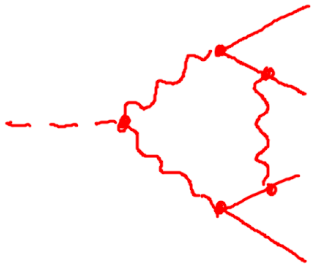
  - complete $\mathcal{O}(\alpha) + \mathcal{O}(\alpha_s)$ for $h \rightarrow 4f$
    $\rightarrow$ MC implementation for distributions

    Bredenstein, Denner, Dittmaier, Weber '06



  - leading $\mathcal{O}(\alpha^2)$, $\mathcal{O}(\alpha\alpha_s)$ and $\mathcal{O}(\alpha\alpha_s^2)$ for large m_t
    $\rightarrow$ Small (0.2%) effect

    Kniehl, Spira '95; Kniehl, Steinhauser '95
    Djouadi, Gambino, Kniehl '97; Kniehl, Veretin '12



Theory error: $\Delta_{\text{th,EW}} < 0.3\%$, $\Delta_{\text{th,QCD}} < 0.5\%$

With NNLO final-state QCD corrections: $\Delta_{\text{th,QCD}} < 0.1\%$

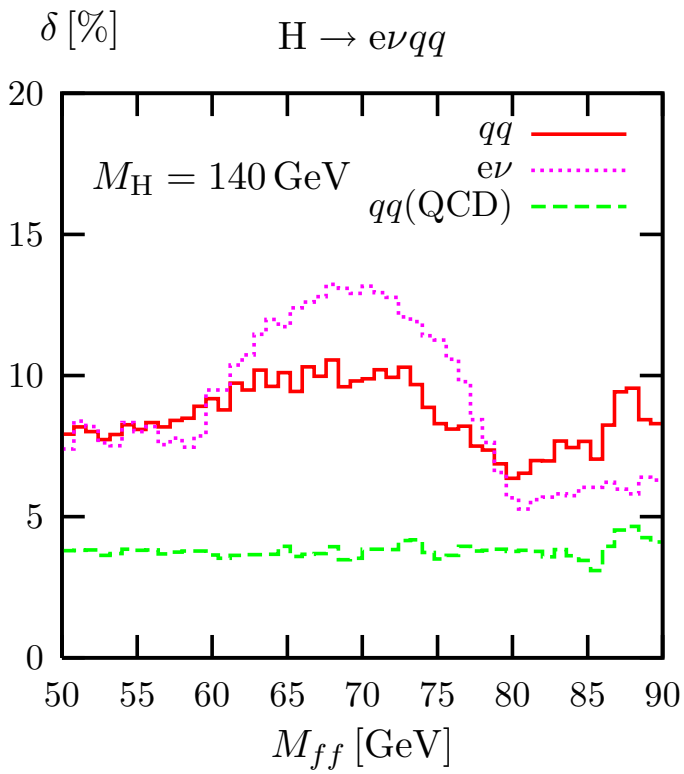
SM predictions for Higgs decays

hWW*/hZZ*:

- Non-trivial effects in distributions

  Bredenstein, Denner, Dittmaier, Weber '06

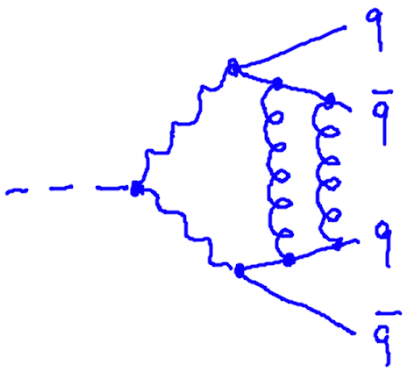
  → Larger theory uncertainty?



- Non-perturbative color reconnection effects

  → No impact on decay rate, but on distributions

  → Difficult to model, currently done with MC programs such as PYTHIA/HERWIG



SM predictions for Higgs decays

hWW*/hZZ*:

- Intermediate W/Z can become on-shell

  $\rightarrow$ regularize divergencies in $\dfrac{1}{p^2 - m_V^2}$ $(V = W, Z)$

- One option: *complex mass scheme*

  $m_V^2 \rightarrow \mu_V^2 \equiv m_V^2 - i\, m_V \Gamma'_V$ everywhere,

  incl. relations like $g = \frac{e}{s_W} = \frac{e}{\sqrt{1 - m_W^2/m_Z^2}}$ Denner, Dittmaier, Roth, Wieders '05

  $\rightarrow$ preserves gauge invariance, consistent to all orders

$$\frac{d\Gamma}{d(p^2)} \propto \frac{1}{(p^2 - m_V^2)^2 + m_V^2 \Gamma_V'^2}$$

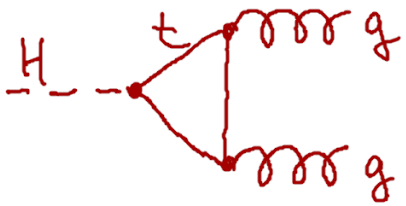
- In experimental analyses: $\dfrac{d\Gamma}{d(p^2)} \propto \dfrac{1}{(p^2 - M_V^2)^2 + p^4 M_V^2/\Gamma_V^2}$

$$m_Z = M_Z \Big/ \sqrt{1 + \Gamma_Z^2/M_Z^2} \approx M_Z - 34 \text{ MeV}$$

$$\Gamma'_Z = \Gamma_Z \Big/ \sqrt{1 + \Gamma_Z^2/M_Z^2} \approx \Gamma_Z - 0.9 \text{ MeV}$$

SM predictions for Higgs decays

hgg: [HL-LHC: 5%, FCC-ee: 1.6%]

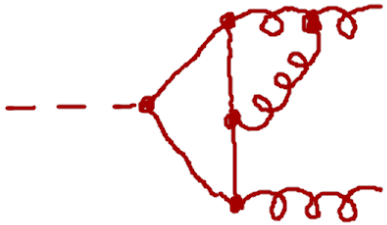


- Loop-induced process in the SM

$$\Gamma[h \to gg] = \frac{y_t^2 \alpha_s^2 m_t^2}{4\pi^3 m_H}\left[1 + \left(1 - \frac{4m_t^2}{m_H^2}\right)\arcsin^2 \frac{m_H}{2m_t}\right]^2$$
$$\approx \frac{\alpha_s^2 m_H^3}{72\pi^3 v^2} \qquad \left(m_H \ll 2m_t,\ y_t = \frac{\sqrt{2}}{v} m_t\right)$$

For heavy BSM quark:

$$\delta\Gamma[h \to gg] \approx \frac{y_{hQQ}^2 \alpha_s^2 m_H^3}{144\pi^3 M_Q^2}$$



- N^{n}LO corrections require (n+1)-loop diagrams
  - $\mathcal{O}(\alpha_s)$ exact result — Djouadi, Graudenz, Spira, Zerwas '95
  - Use large m_t expansion, used for $\mathcal{O}(\alpha_s^2)$ — Schreck, Steinhauser '07
    $\to$ fast convergence (m_t^{-4} term is $\sim 1\%$ of m_t^0 term)
  - $\mathcal{O}(\alpha_s^3)$ with low-energy theorem (equiv. to 1st term in large m_t exp.)
    Baikov, Chetyrkin '06

SM predictions for Higgs decays

hgg:

- **Low-energy theorem:** for $m_t \to \infty$ top loop becomes effective hgg interaction:

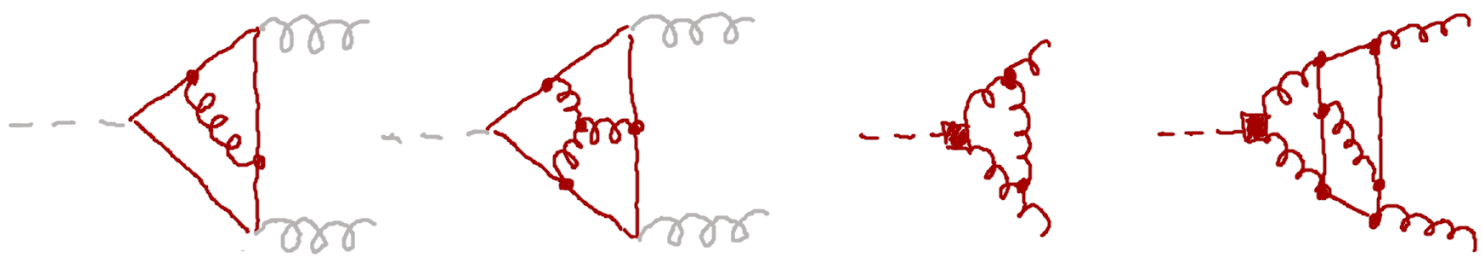
$$\mathcal{L}_{\text{eff}} = \frac{C_{hg}}{v} h G^{\mu\nu} G_{\mu\nu} \qquad \text{LO SM res.:} \quad C_{hg} = -\frac{\alpha_s}{12\pi} \tag{1}$$

$$\Gamma[h \to gg] = \frac{2 C_{hg}^2 m_H^3}{\pi v^2} \tag{2}$$

Gauge-invariant form:

$$\mathcal{L}_{\text{eff}} = \frac{C_{hg}}{v^2} (\phi^\dagger \phi) G^{\mu\nu} G_{\mu\nu}, \qquad \phi = \left(G^+, \frac{v+h+G^0}{\sqrt{2}}\right)^\top \tag{3}$$

- Higher orders:
  - corrections to C_{hg} (zero external momentum)
  - corrections to (2) with effective hgg cpl.

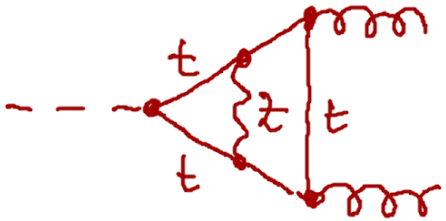


SM predictions for Higgs decays

hgg:

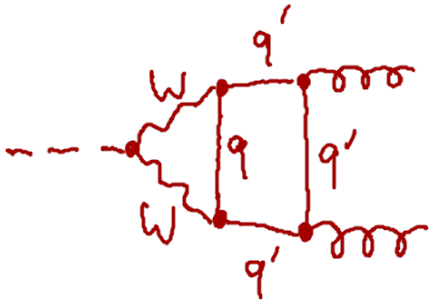
- **EW corrections:**
  - Can use expansion or low-energy theorem for top-quark contributions

    Degrassi, Maltoni '04



  - Direct 2-loop calculation for (dominant) light-quark contributions

    Aglietti, Bonciani, Degrassi, Vicini '04; Degrassi, Maltoni '04



QCD corrections: $65\% + 20\% + 2\%$

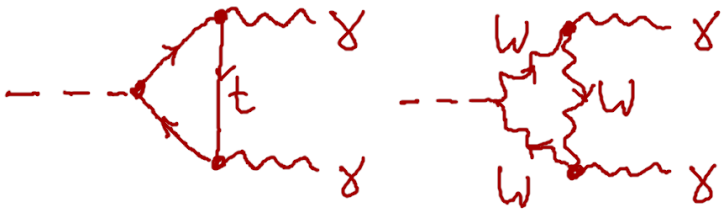
EW corrections: $\sim 5\%$

Theory error (dominated by QCD): $\Delta_{\rm th} \approx 3\%$

With $\mathcal{O}(\alpha_s^4)$ in large m_t-limit (4-loop massless QCD diags.): $\Delta_{\rm th} \approx 1\%$

SM predictions for Higgs decays

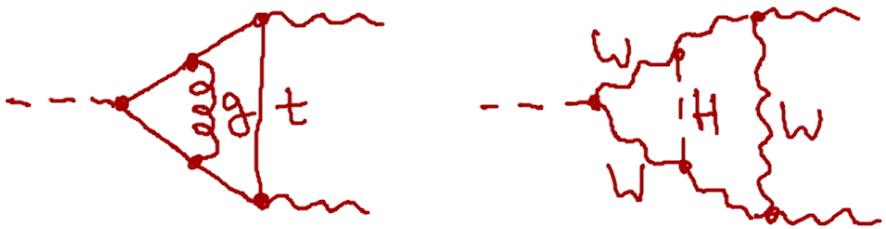
$h\gamma\gamma$: [HL-LHC: 3.6%, FCC-ee: 3.0%]



- Top+W loop at LO
  - $\mathcal{O}(\alpha_s^2)$ QCD corrections (with large m_t expansion)

    Zheng, Wu '90; Djouadi, Spira, v.d.Bij, Zerwas '91
    Dawson, Kauffman '93; Maierhöfer, Marquard '12
  - NLO EW

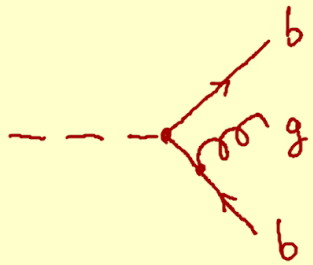
    Aglietti, Bonciani, Degrassi, Vicini '04; Degrassi, Maltoni '04
    Actis, Passarino, Sturm, Uccirati '08

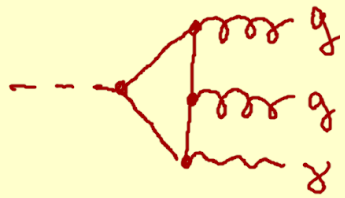


Theory error: $\Delta_{th} < 1\%$

Real vs. pseudo observables

- $\Gamma \to XX$ is not a real observable
- Effect of detector acceptance and isolation criteria,
  in particular for extra gluon (jet) and photon radiation
- Effect of selection cuts to reduce backgrounds
- Monte-Carlo tools needed to simulate these effects





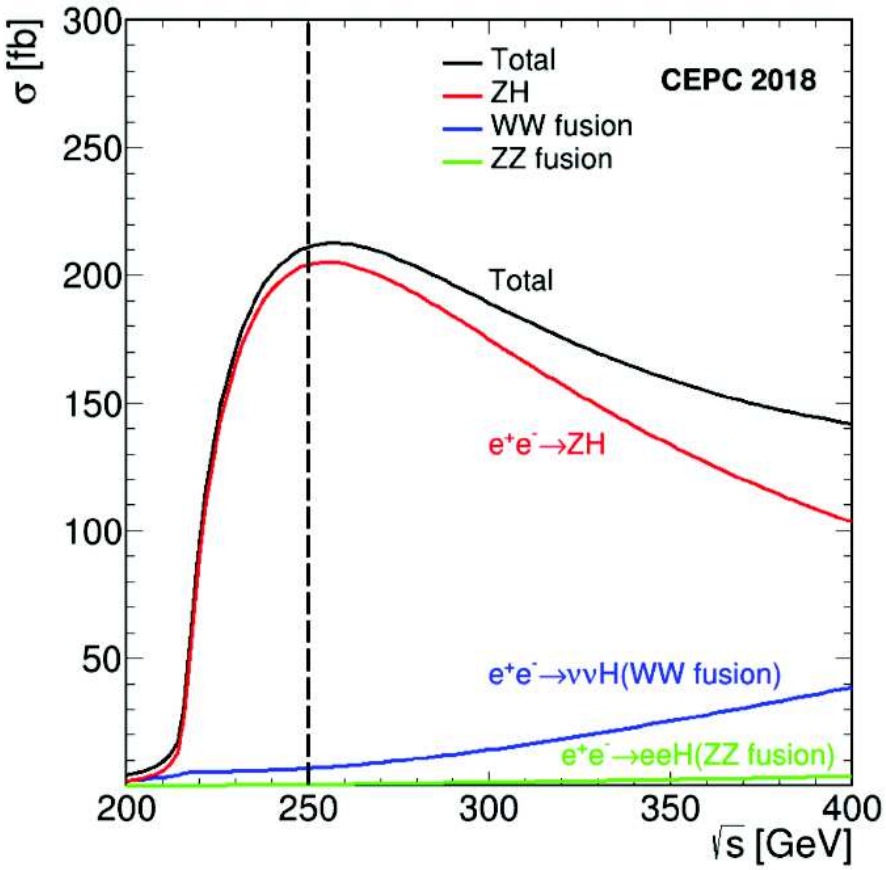
- **Current LHC studies:**
  rad. corrections in decay, only parton shower for γ, g emission;
  differential rates corrected (reweighted) with fixed-order results

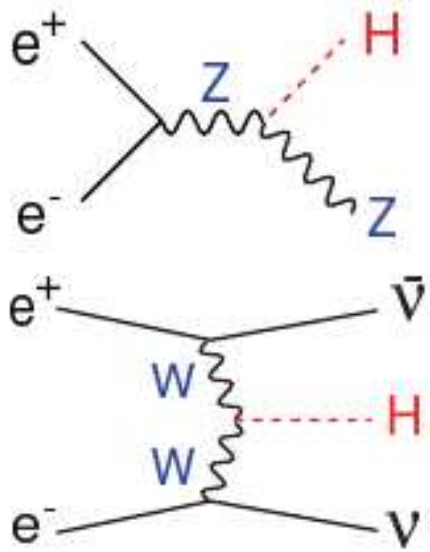
- **More accurate procedure:**
  Implement fixed-order rad. corr. in MC program,
  matching to avoid double counting with parton shower

Catani, Krauss, Kuhn, Webber '01
Nason '04; Frixione, Nason, Oleari '07

Higgs production at e^+e^- colliders

- hZ production: dominant at $\sqrt{s} \sim 240$ GeV
- WW fusion: sub-dominant but useful for constraining h width Han, Liu, Sayre '13





SM predictions for Higgs production

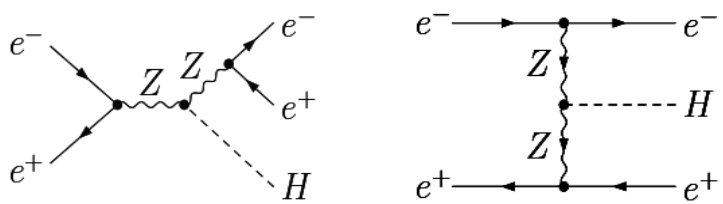
hZ production: [CEPC: 0.5%, FCC-ee: 0.3%]

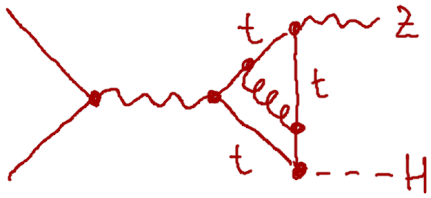
- $\mathcal{O}(\alpha)$ corr. to hZ production and h, Z decay

  Kniehl '92; Denner, Küblbeck, Mertig, Böhm '92
  Consoli, Lo Presti, Maiani '83; Jegerlehner '86
  Akhundov, Bardin, Riemann '86

- $\Gamma_H/m_H \approx 4 \times 10^{-5}$, $\Gamma_Z/m_Z \approx 0.025$ $\Rightarrow$ include off-shell Z effects
  Technology for $\mathcal{O}(\alpha)$ corr. to $hf\bar{f}$ production available

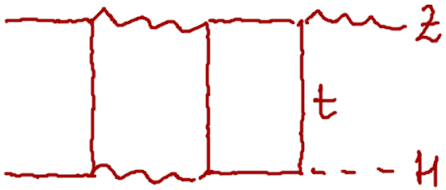
  Boudjema et al. '04
  Denner, Dittmaier, Roth, Weber '03





- $\mathcal{O}(\alpha\alpha_s)$ corrections

  Gong et al. '16; Chen, Feng, Jia, Sang '18



Theory error: $\Delta_{\rm th} \sim O(1\%)$

With full 2-loop corrections for $ee \to HZ$:
$\Delta_{\rm th} \lesssim O(0.3\%)$

Freitas, Song '21; Li, Wang, Wu '21

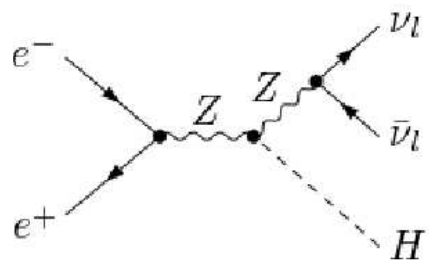
SM predictions for Higgs production

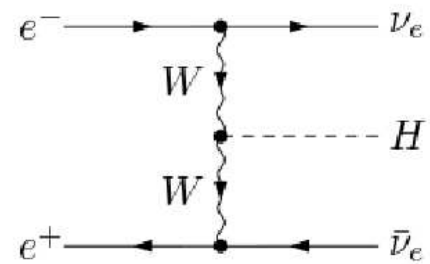
WW fusion:

- $\mathcal{O}(\alpha)$ corrections

Belanger et al. '02; Denner, Dittmaier, Roth, Weber '03

Theory error: $\Delta_{\text{th}} \sim O(1\%)$?





Full NNLO calc. for 2→3 process is very challenging, but may not be needed

SM input parameters

SM predictions for Higgs decays need measured input parameters

Reviews: 1906.05379, 2012.11642

- $M_Z,\ M_W$: current precision $< 0.1\%$ $\rightarrow$ negligible impact
- m_t: Most precise measurement at LHC: $\delta m_t \sim 0.3$ GeV

  Additional theory error from scheme translation Hoang, Plätzer, Samitz '18

  $\rightarrow$ Total uncertainty $\delta m_t \sim 0.5$ GeV

  $\rightarrow$ Negligible impact because m_t only appears in loops

SM input parameters

SM predictions for Higgs decays need measured input param

Reviews: 1906.05379, 2012.11642

- M_H: high precision important for $h \to WW^*, ZZ^*$

  amplitude $\propto \dfrac{1}{p_1^2 - m_V^2}$, $\quad p_1 \sim m_H - m_V$ (both V, V^* at rest)

  $\Gamma_{VV^*} =$ [energy]

  $$\Rightarrow \quad \Gamma_{VV^*} \propto \frac{[\text{energy}]^5}{|p_1^2 - m_V^2|^2} \sim \frac{m_H^5}{[(m_H - m_V)^2 - m_V^2]^4}$$

  Uncertainty $\delta m_H \quad \Rightarrow \quad \dfrac{\delta\Gamma_{VV^*}}{\Gamma_{VV^*}} = \dfrac{m_H - 6m_V}{m_H - 2m_V}\dfrac{\delta m_H}{m_H} \approx 10\dfrac{\delta m_H}{m_H}$

  $\delta m_H = 0.2$ GeV $\quad \Rightarrow \quad \dfrac{\delta\Gamma_{VV^*}}{\Gamma_{VV^*}} = 1.6\%$

  CEPC/FCC-ee/ILC can achieve $\delta m_H \lesssim 20$ MeV $\quad \Rightarrow \quad \dfrac{\delta\Gamma_{VV^*}}{\Gamma_{VV^*}} \lesssim 0.2\%$

SM input parameters

- α_s: important for $h \to gg$ (also $h \to q\bar{q}$)

  $\delta\alpha_s = 0.001 \qquad \Rightarrow \qquad \frac{\delta\Gamma_{gg}}{\Gamma_{gg}} \approx 3\%$

  Methods for α_s determination: d'Enterria, Skands, et al. '15

  - Most precise determination using Lattice QCD:

    $\alpha_s = 0.1184 \pm 0.0006$ HPQCD '10

    $\alpha_s = 0.1185 \pm 0.0008$ ALPHA '17

    $\alpha_s = 0.1179 \pm 0.0015$ Takaura et al. '18

    $\alpha_s = 0.1172 \pm 0.0011$ Zafeiropoulos et al. '19

    $\to$ Difficulty in evaluating systematics

  - e^+e^- event shapes and DIS: $\alpha_s \sim 0.114$

    Alekhin, Blümlein, Moch '12; Abbate et al. '11; Gehrmann et al. '13

    $\to$ Subject to sizeable non-pertubative power corrections

    $\to$ Systematic uncertainties in power corrections?

SM input parameters

- α_s:
  - Hadronic τ decays: $\alpha_s = 0.119 \pm 0.002$ PDG '18

    $\rightarrow$ Non-perturbative uncertainties in OPE and from duality violation

    Pich '14; Boito et al. '15,18

  - Electroweak precision ($R_\ell = \Gamma_Z^{\rm had}/\Gamma_Z^\ell$):

    $\alpha_s = 0.120 \pm 0.003$ PDG '18

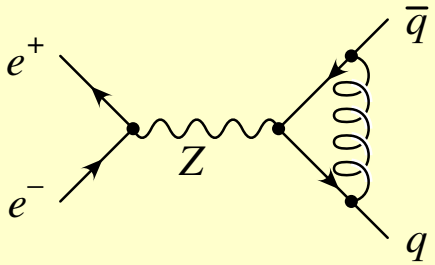
    $\rightarrow$ No (negligible) non-perturbative QCD effects

    FCC-ee: $\delta R_\ell \sim 0.001$

    $\Rightarrow \quad \delta\alpha_s < 0.0001$

    Theory input: N^{3}LO EW corr. + leading N^{4}LO

    to keep $\delta_{\rm th} R_\ell \lesssim \delta_{\rm exp} R_\ell$



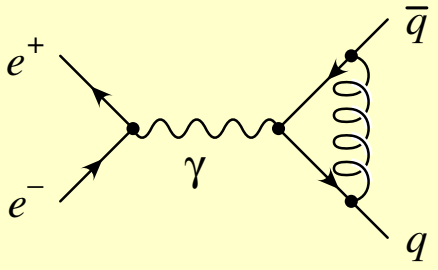
Caviat: R_ℓ could be affected by new physics

SM input parameters

- α_s:
  - $R = \frac{\sigma[ee\to\text{had.}]}{\sigma[ee\to\mu\mu]}$ at lower $\sqrt{s}$

    e.g. CLEO ($\sqrt{s} \sim 9$ GeV): $\alpha_s = 0.110 \pm 0.015$

    Kühn, Steinhauser, Teubner '07



    $\rightarrow$ dominated by s-channel photon, less room for new physics

    $\rightarrow$ QCD still perturbative

    naive scaling to 50 ab^{-1} (BELLE-II): $\delta\alpha_s \sim 0.0001$

- m_b, m_c: From quarkonia spectra using Lattice QCD

  $\delta m_b^{\overline{\text{MS}}} \sim 30$ MeV, $\delta m_c^{\overline{\text{MS}}} \sim 25$ MeV

  LHC HXSWG '16

  $\Rightarrow \quad \frac{\delta\Gamma_{bb}}{\Gamma_{bb}} \approx 1.4\%, \quad \frac{\delta\Gamma_{cc}}{\Gamma_{cc}} \approx 4.0\%$

  $\rightarrow$ estimated improvements $\delta m_b^{\overline{\text{MS}}} \sim 13$ MeV, $\delta m_b^{\overline{\text{MS}}} \sim 7$ MeV

  Lepage, Mackenzie, Peskin '14

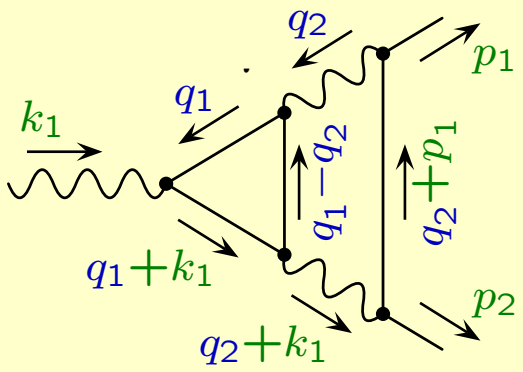
  $\Rightarrow \quad \frac{\delta\Gamma_{bb}}{\Gamma_{bb}} \approx 0.4\%, \quad \frac{\delta\Gamma_{cc}}{\Gamma_{cc}} \approx 0.4\%$

Theory uncertainties

- Theory error estimate is not well defined, ideally $\Delta_{\text{th}} \ll \Delta_{\text{exp}}$
- Common methods:
  - Count prefactors (α, N_c, N_f, ...)
  - Extrapolation of perturbative series
    e.g. assume $\frac{\Gamma_{\text{NNNLO}}}{\Gamma_{\text{NNLO}}} \sim \frac{\Gamma_{\text{NNLO}}}{\Gamma_{\text{NLO}}}$
  - Renormalization scale dependence
    (for $\overline{\text{MS}}$ renormalization, widely used for QCD)
  - Renormalization scheme dependence
    e.g. compare $\overline{\text{MS}}$ and OS renormalization

Theory calculations

Experimental precision requires inclusion of **multi-loop corrections** in theory



Integrals over loop momenta:

$$\int d^4q_1 d^4q_2 \; f(q_1, q_2, p_1, k_1, ..., m_1, m_2, ...)$$

Computer algebra tools:

- Generation of diagrams, $\mathcal{O}(1000) - \mathcal{O}(10000)$
- Lorentz and Dirac algebra
- Integral simplification (e.g. symmetries)

} not a limiting factor

Evaluation of loop integrals:

- Analytical
- Approximate (expansions)
- Numerical

Analytic calculations

- Mostly used for diagrams with few mass scales
- Reduce to **master integrals** with integration-by-parts and other identities

  Chetyrkin, Tkachov '81; Gehrmann, Remiddi '00; Laporta '00; ...

  Public programs:

`Reduze`	von Manteuffel, Studerus '12
`FIRE`	Smirnov '13,14
`LiteRed`	Lee '13
`KIRA`	Maierhoefer, Usovitsch, Uwer '17

  → Large need for computing time and memory

- Evaluate master integrals with differential equations or Mellin-Barnes rep.

  Kotikov '91; Remiddi '97; Smirnov '00,01; Henn '13; ...

  → Result in terms of Goncharov polylogs / multiple polylogs

  → Some problems need iterated elliptic integrals / elliptic multiple polylogs

  Broedel, Duhr, Dulat, Trancredi '17,18

  Ablinger er al. '17

  → Even more classes of functions needed in future?

Asymptotic expansions

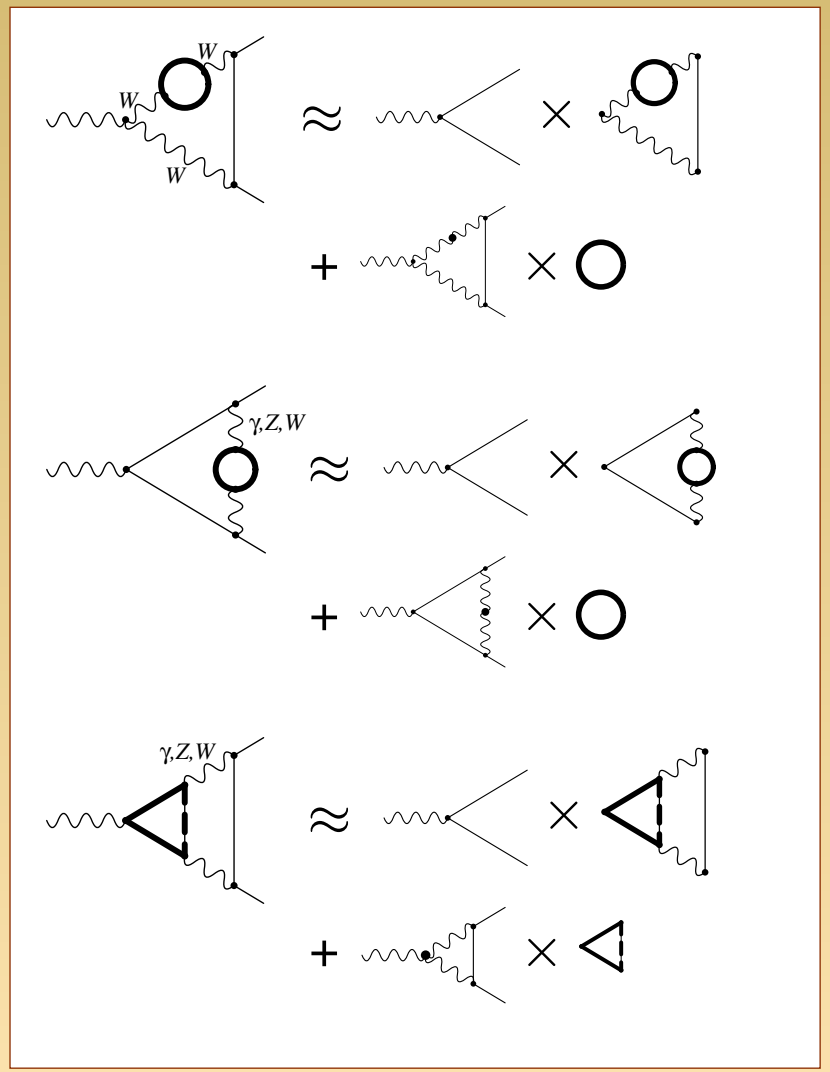
- Exploit large mass/momentum ratios, *e. g.* $M_Z^2/m_t^2 \approx 1/4$
- Evaluate coeff. integrals analytically
- Fast numerical evaluation

→ Public programs:

`exp` Harlander, Seidensticker, Steinhauser '97
`asy` Pak, Smirnov '10

→ Possible limitations:

- no appropriate mass/momentum ratios
- bad convergence
- impractical if too many mass/mom. scales



Numerical integration

Challenge 1: presence of UV/IR divergencies

- Remove through subtraction terms

$$\underbrace{\int d^4q_1 d^4q_2\,(f - f_{\text{sub}})}_{\text{finite}} + \underbrace{\int d^4q_1 d^4q_2\, f_{\text{sub}}}_{\text{solve analytically}}$$

Cvitanovic, Kinoshita '74
Levine, Park, Roskies '82
Bauberger '97
Nagy, Soper '03
Awramik, Czakon, Freitas '06
Becker, Reuschle, Weinzierl '10
Sborlini et al. '16
...

- Remove through variable transformations:

a) Sector decomposition

Public programs: `(py)SecDec` Carter, Heinrich '10; Borowka et al. '12,15,17
`FIESTA` Smirnov, Tentyukov '08; Smirnov '13,15

b) Mellin-Barnes representations

Public programs: `MB/MBresolve` Czakon '06; Smirnov, Smirnov '09
`AMBRE/MBnumerics` Gluza, Kajda, Riemann '07
Dubovyk, Gluza, Riemann '15
Usovitsch, Dubovyk, Riemann '18

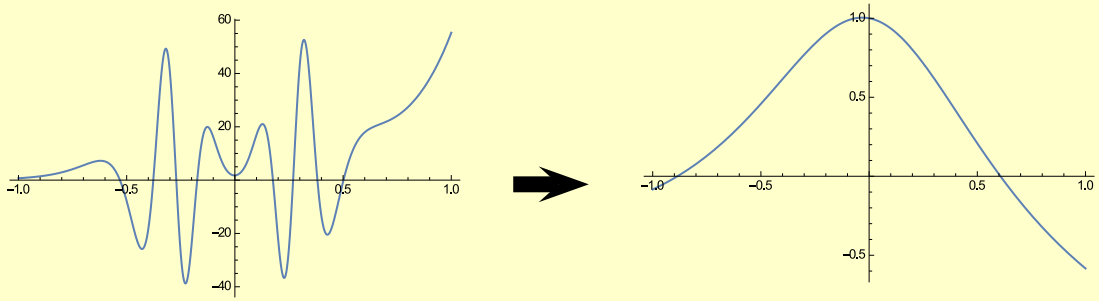
Numerical integration

Challenge 2: stability and convergence

- Integration in momentum space: $4L$ dimensions ($L =$ # of loops)
- Integration in Feynman parameters: $P - 1$ dimensions ($P =$ # of propagators)

$\rightarrow$ Multi-dim. integrals need large computing resources and converge slowly

- Variable transformations to avoid singularities and peaks



Loop calculations: Summary

Analytical techniques and expansions:

Complexity increases with ...

... more loops;

... more external particles;

... **more different masses**

Numerical techniques:

Complexity increases with ...

... more loops;

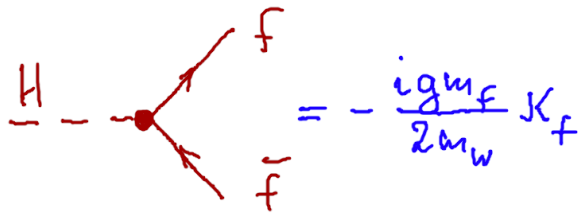
... more external particles;

... **fewer masses**

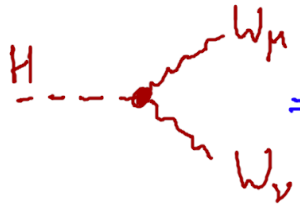
Deviations from SM predictions

"Kappa framework"

- Multiply Higgs Feynman rules with factor $\kappa_X \neq 1$:



$$= -\frac{i g m_f}{2 m_W} \kappa_f$$



$$= i g m_W g_{\mu\nu} \kappa_W$$

- breaks gauge-invariance
  $\rightarrow$ in general not possible to compute EW corrections

Effective field theory framework

$\rightarrow$ V. Sanz

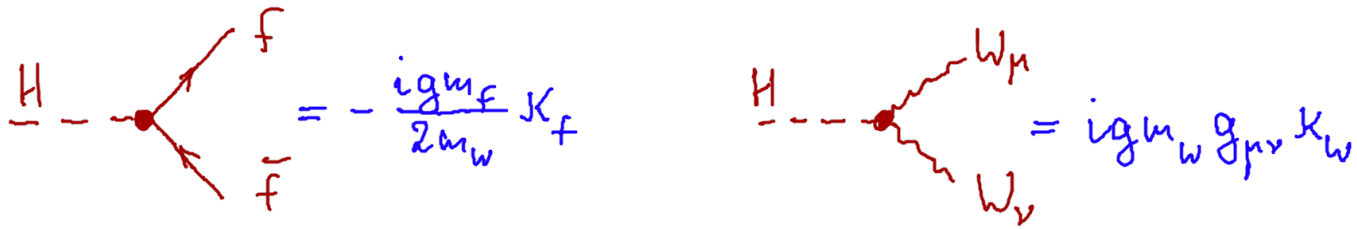
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{d=5}^{\infty} \frac{1}{\Lambda^{d-4}} \sum_i c_i \, \mathcal{O}_i^{(d)}$$

- Operators required to satisfy SM gauge invariance
- Valid description for energies $E \ll \Lambda$ ($\Lambda \sim$ mass of heavy particles)
- Leading contribution to Higgs physics: $d = 6$
- **SMEFT**: Higgs doublet as in SM
- **HEFT**: Higgs and Goldstone bosons treated independently

Deviations from SM predictions

"Kappa framework"

- Multiply Higgs Feynman rules with factor $\kappa_X \neq 1$:



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BSM physics: radiative corrections?

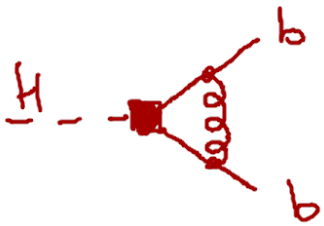
No conclusive BSM evidence in Higgs physics

→ BSM effects are small

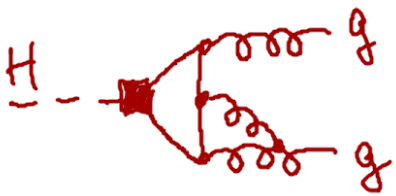
→ ignore rad. corr. to BSM contributions (?)

But some higher-order effects can be significant:

- Large SM QCD corrections to LO operator insertions:



$\delta_{\rm QCD} \sim 20\%$



$\delta_{\rm QCD} \sim 50...100\%$

→ Practical calculations similar to SM

- New operators appearing in loops:

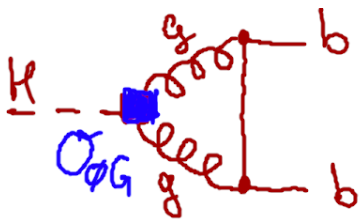
e.g.

SMEFT for $h \to b\bar{b}$

Example 1: hgg operator in $h \to b\bar{b}$

Gauld, Pecjak, Scott '16
Cullen, Pecjak, Scott '19

$$\frac{\delta\Gamma_{bb}}{\Gamma_{bb}} = C_F \frac{\alpha_s}{\pi} \frac{v^2}{\Lambda^2} c_{\phi G} \ln^2 \frac{m_b^2}{m_H^2} \approx 2.4 \frac{v^2}{\Lambda^2} c_{\phi G}$$

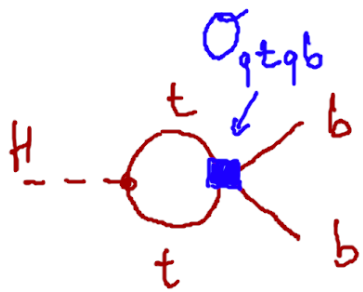


[Note: $c_{\phi G}$ expected to be loop-induced]

Example 2: $ttbb$ operator in $h \to b\bar{b}$

Gauld, Pecjak, Scott '15
Cullen, Pecjak, Scott '19

$$\frac{\delta\Gamma_{bb}}{\Gamma_{bb}} \approx 1.75 \frac{v^2}{\Lambda^2} c^{(1)}_{qtqb}$$



[Note: $c^{(1)}_{qtqb}$ also makes a contribution to m_b, and fine-tuning arguments suggest it shouldn't be large]

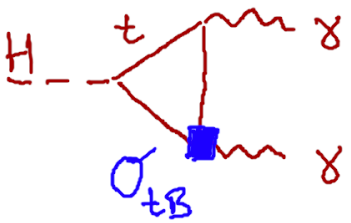
SMEFT for $h \to \gamma\gamma$

Example 3: dipole-type γ-top operator in $h \to \gamma\gamma$

Vryonidou, Zhang '18
Dawson, Giardino '19

$$\frac{\delta\Gamma_{bb}}{\Gamma_{bb}} \approx \mathcal{O}(10-20) \times \frac{v^2}{\Lambda^2} c_{tB}^{(1)}$$

[Note: c_{tB} expected to be loop-induced]



Backup slides

SMEFT operators in Warsaw basis

Grzadkowski, Iskrzynski, Misiak, Rosiek '10

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star (\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

SMEFT operators in Warsaw basis

Grzadkowski, Iskrzynski, Misiak, Rosiek '10

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

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		