SMEFT (at NLO) : EW, Higgs, and Top

Fabio Maltoni
Université catholique de Louvain, Università di Bologna

Multa novit vulpes, verum echinus unum magnum

[Archilocus, Erasmo, Berlin]

Multa novit vulpes, verum echinus unum magnum

[Archilocus, Erasmo, Berlin]

the foxes draw on a variety of experiences and for them the world cannot be boiled down to a single idea

Multa novit vulpes, verum echinus unum magnum

[Archilocus, Erasmo, Berlin]

the foxes draw on a variety of experiences and for them the world cannot be boiled down to a single idea

the hedgehogs view the world through the lens of a single defining idea

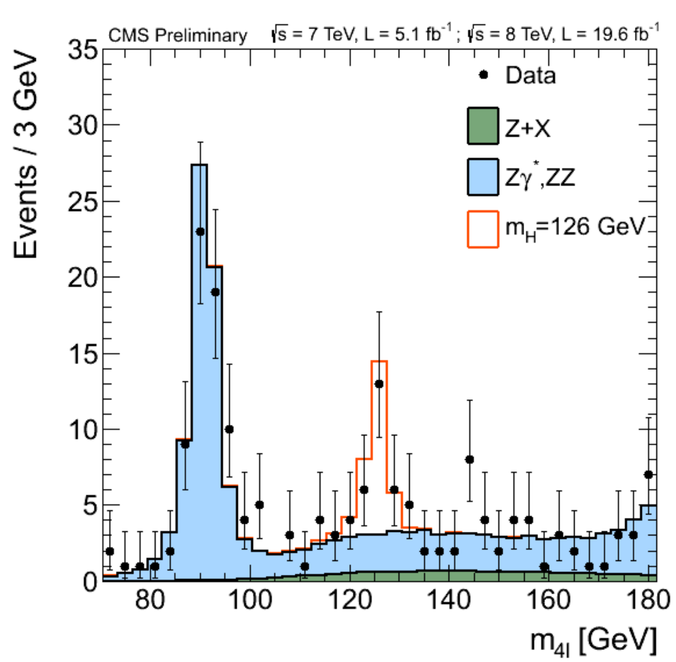
Searching for new physics

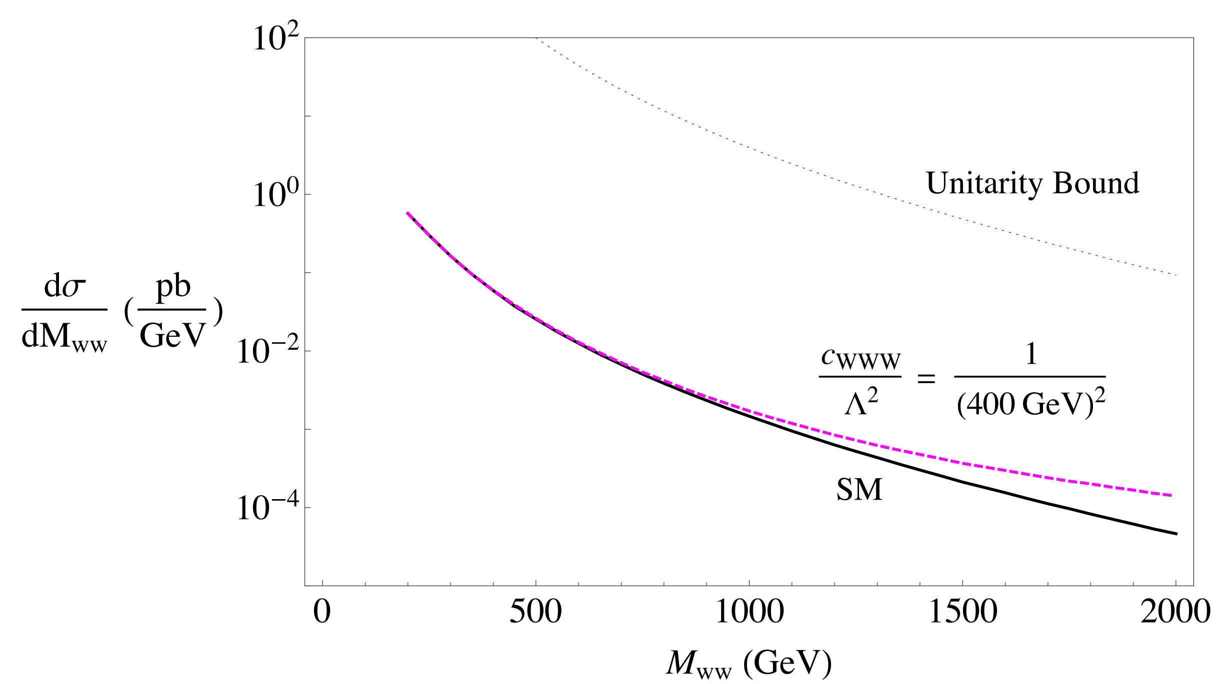
Model-dependent	⟷	**Model-independent**
SUSY, 2HDM, ED,...		simplified models, EFT, ...
Search for new states	⟷	**Search for new interactions**
specific models, simplified models		anomalous couplings, EFT...
Exotic signatures	⟷	**Standard signatures**
precision measurements		rare processes

Search for New Physics at the LHC

Two main strategies for searching new physics

Search for new states ⟷ **Search for new interactions**

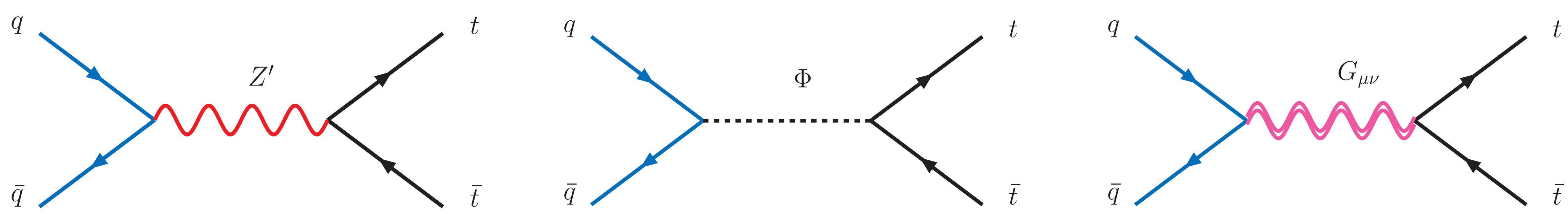




Example: ttbar

Very interesting and rich history of searches for resonances in ttbar and many proposals and results since the first days of the LHC. Higher masses can be reached by boosted top tagging techniques.

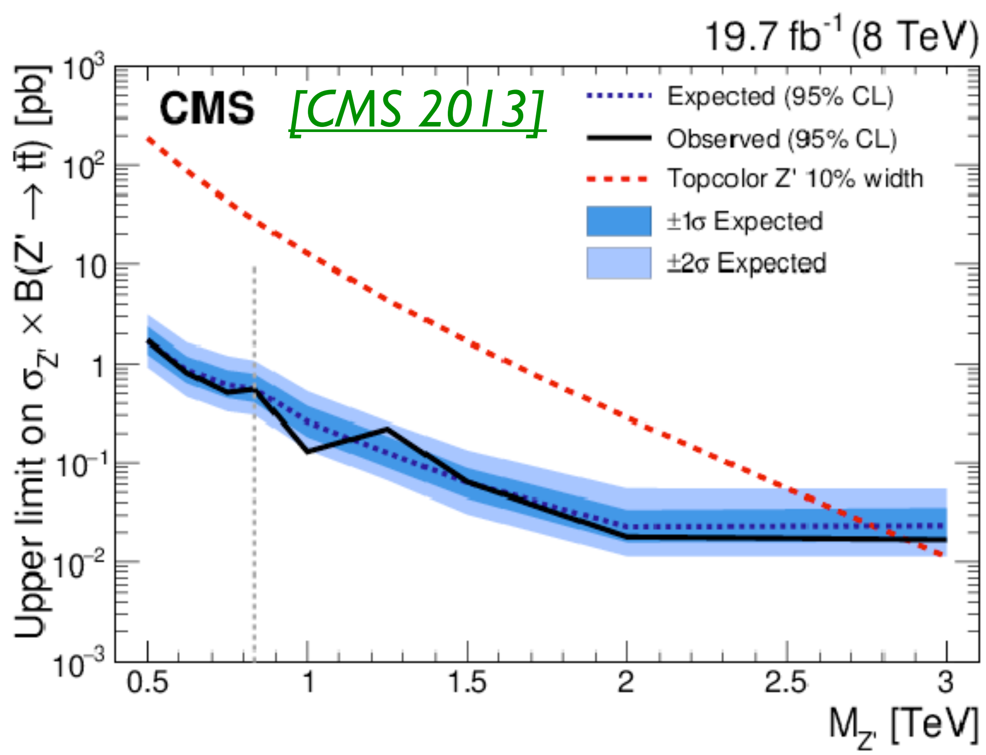
Limits on models that feature a clear BW peak (Z', coloron) with a fixed width are continuously improved by the increase in energy and luminosity:

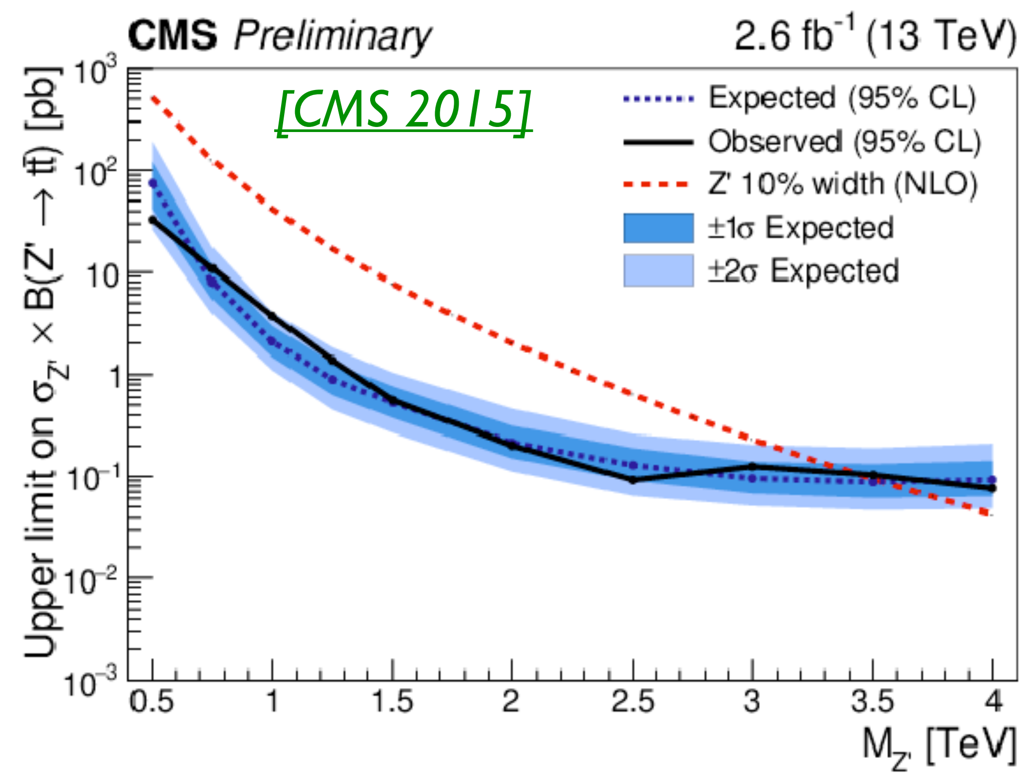


Resonances in ttbar

Very interesting and rich history of searches for resonances in ttbar and many proposals and results since the first days of the LHC. Higher masses can be reached by boosted top tagging techniques.

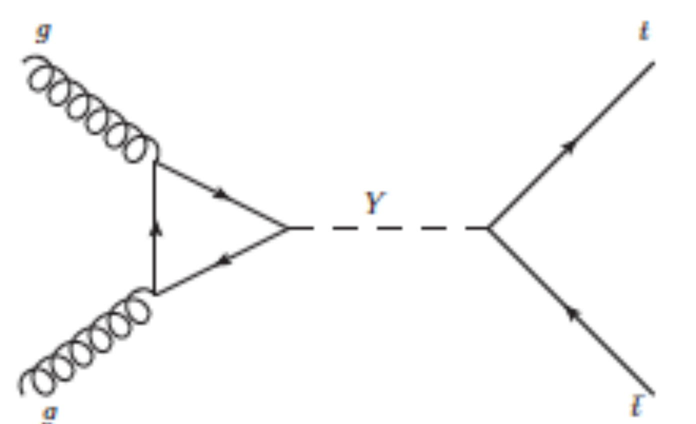
Limits on models that feature a clear BW peak (Z', coloron) with a fixed width are continuously improved by the increase in energy and luminosity:



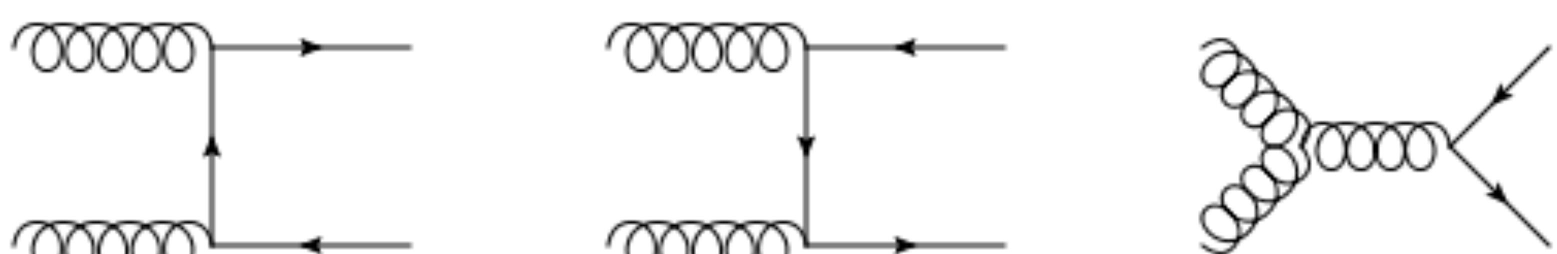


Resonances in ttbar

Imagine a new scalar exists which couples mostly to top quark, similar to the SM Higgs, but it is heavier than $2m_t$. It would be produced as the SM Higgs via gluon fusion and then mostly decay to top quarks:

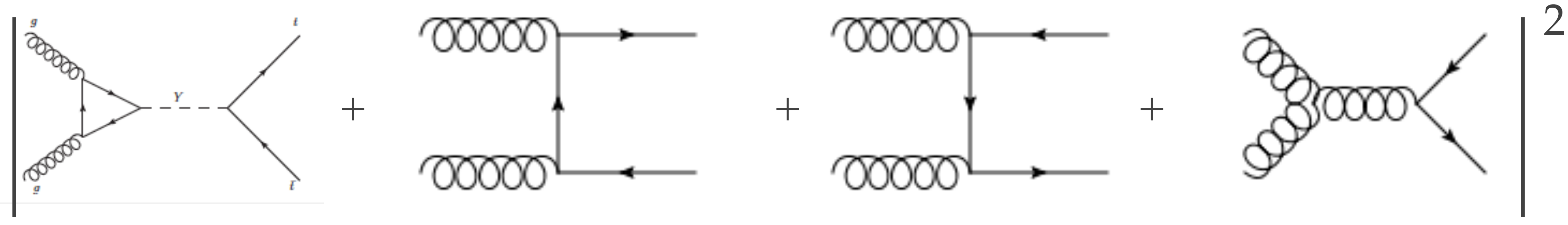


giving rise to a peak in the invariant mass distribution of m(tt). However, this process interferes with the QCD background:



Resonances in ttbar

|Amp|^2=



Taking our previous calculation of the SM amplitude and adding the scalar production:

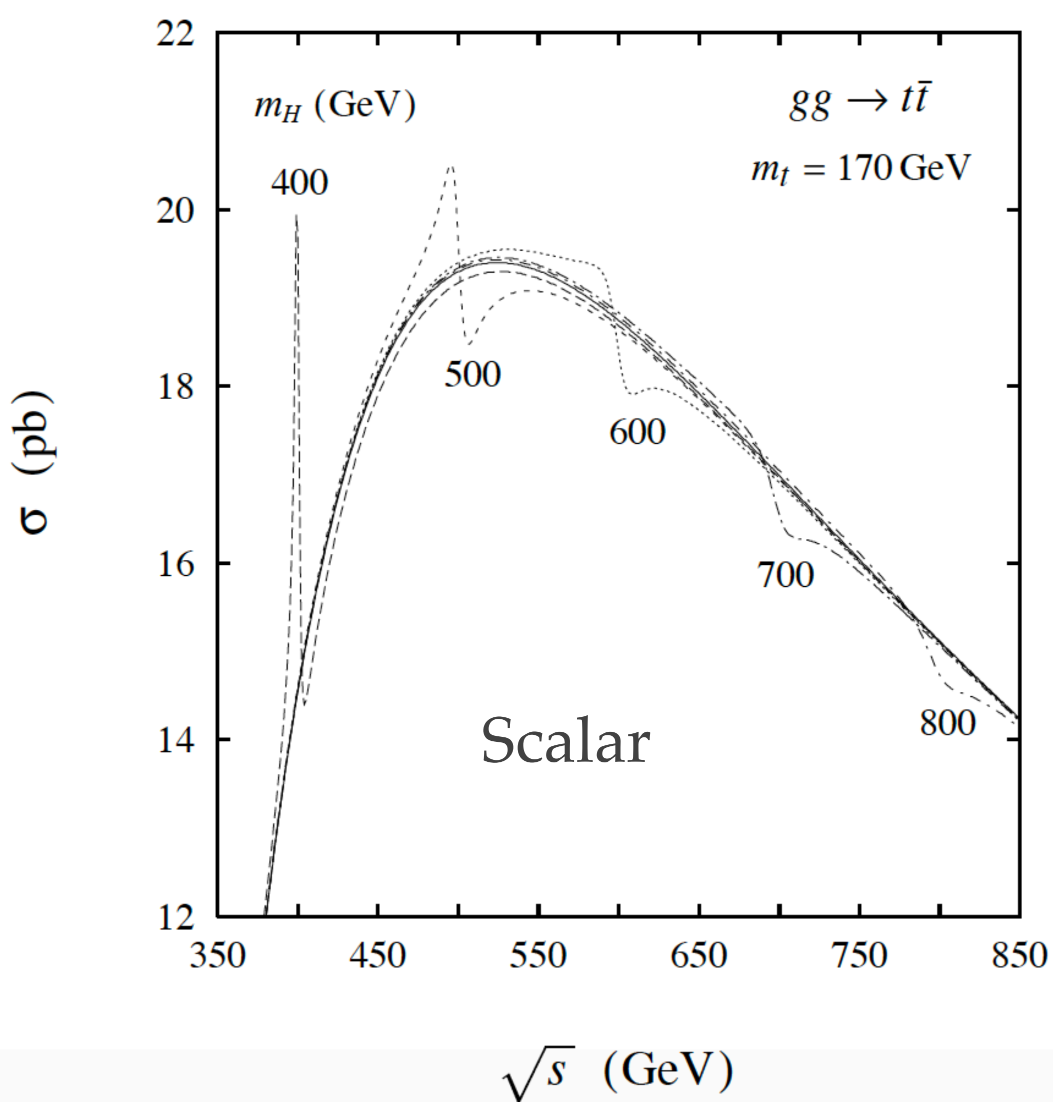
$$\hat{\sigma}(s) = \frac{\alpha_s^2 G_F^2 m^2 s^2}{768\,\pi^3}\beta^3 \left|\frac{N(s/m^2)}{s-m_H^2+im_H\Gamma_H(s)}\right|^2$$ ← BW resonance

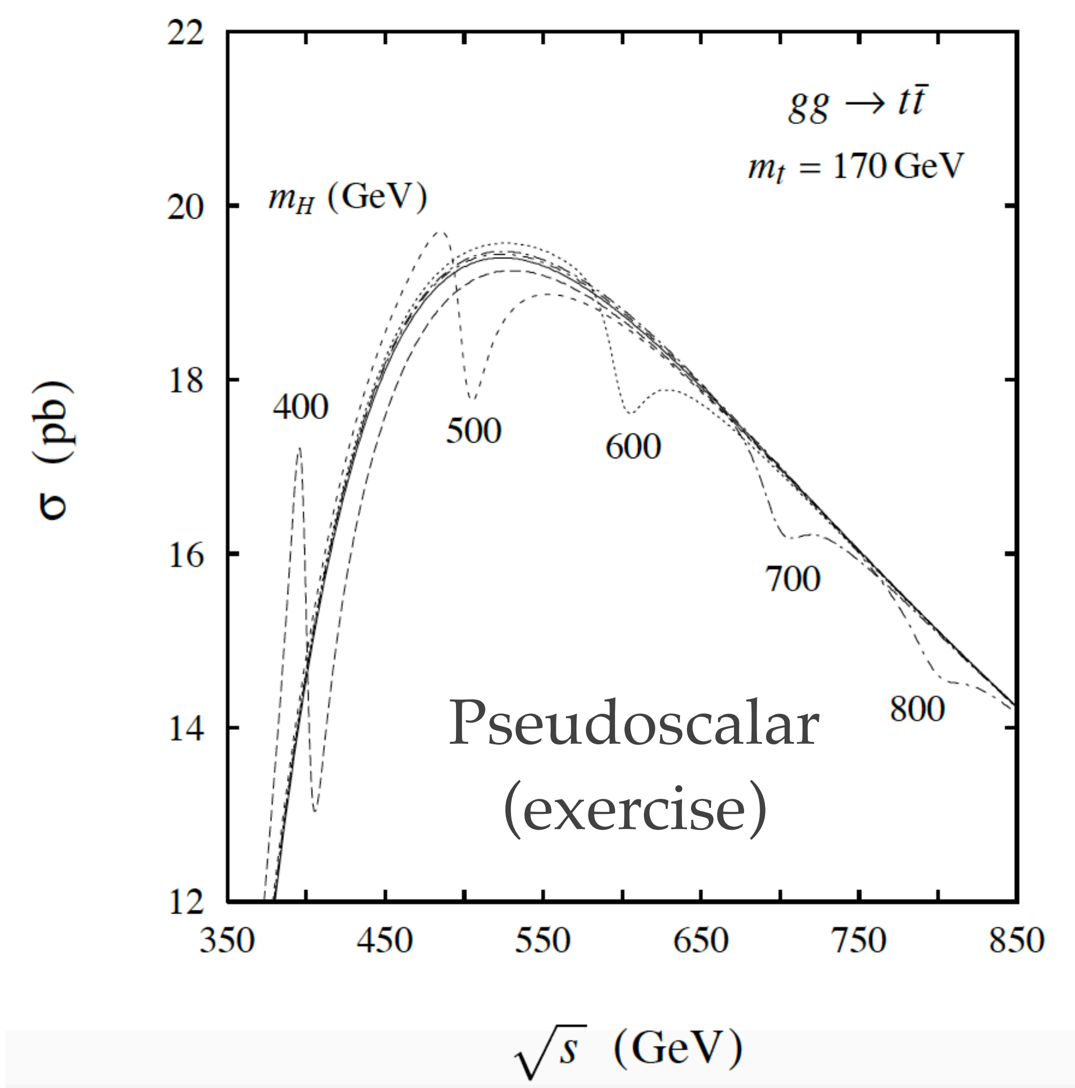
$$-\frac{\alpha_S^2 G_F m^2}{48\pi\sqrt{2}}\beta^2 \ln\frac{1+\beta}{1-\beta}\ \mathrm{Re}\left[\frac{N(s/m^2)}{s-m_H^2+im_H\Gamma_H(s)}\right]$$ ← Interference

$$+\hat{\sigma}_{\mathrm{SM}}(s)$$ ← SM

$$N(s/m^2) = \frac{3}{2}\frac{m^2}{s}\left[4-\left(1-\frac{4m^2}{s}\right)I(s/m^2)\right] \qquad I(s/m^2) = \left[\ln\frac{1+\beta}{1-\beta}-i\pi\right]^2 \qquad (s>4m^2)$$

Resonances in ttbar

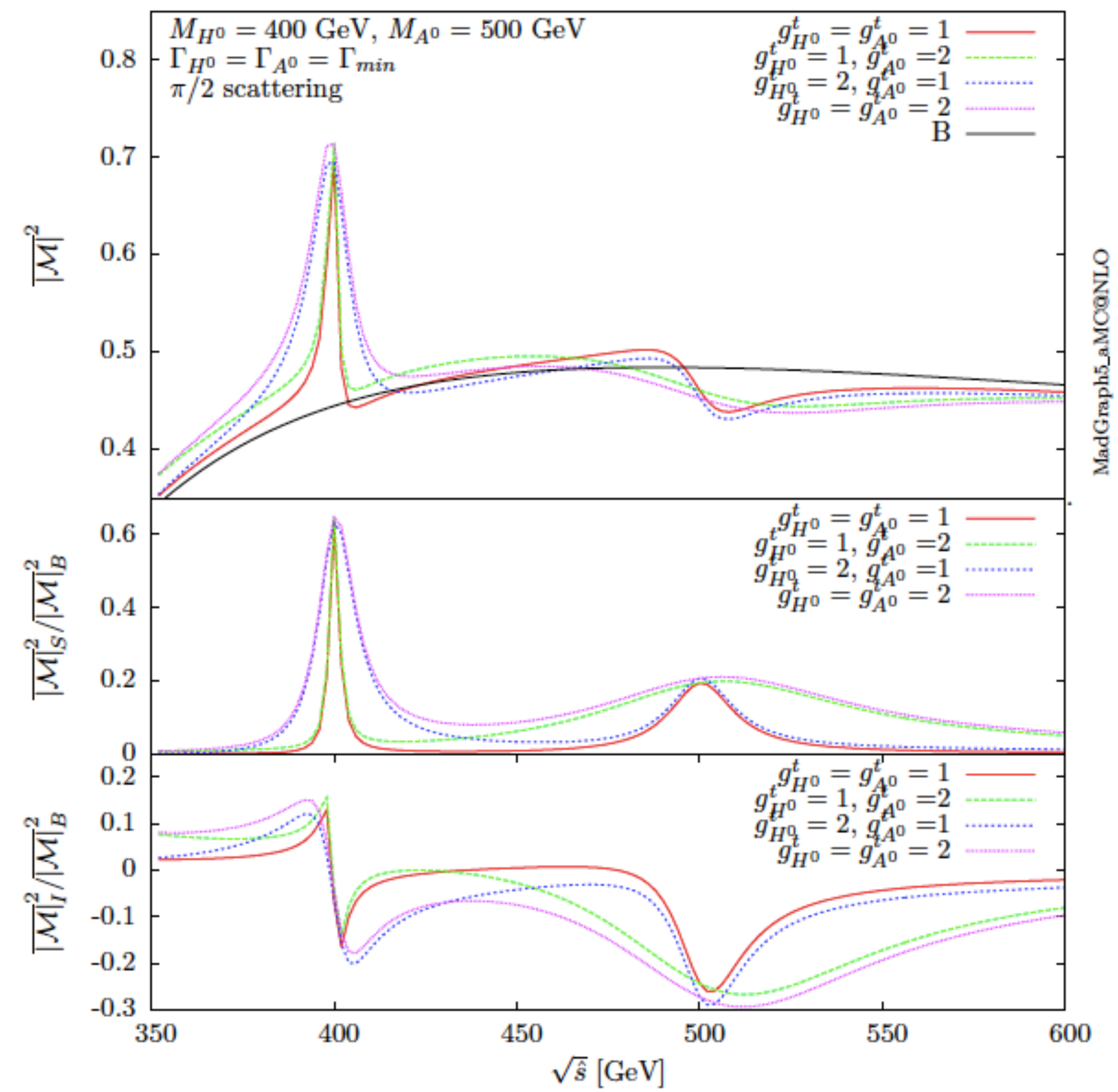




Peaks but also peak-dip and dip only structures. "Easy" to discover independently of the precise knowledge of the SM. However, needs accurate theory to characterise it.

Resonances in ttbar

2. Analysis technology to look for BW peaks in place. Now it is time to consider more complicated situations, like peak-dip or even dips.



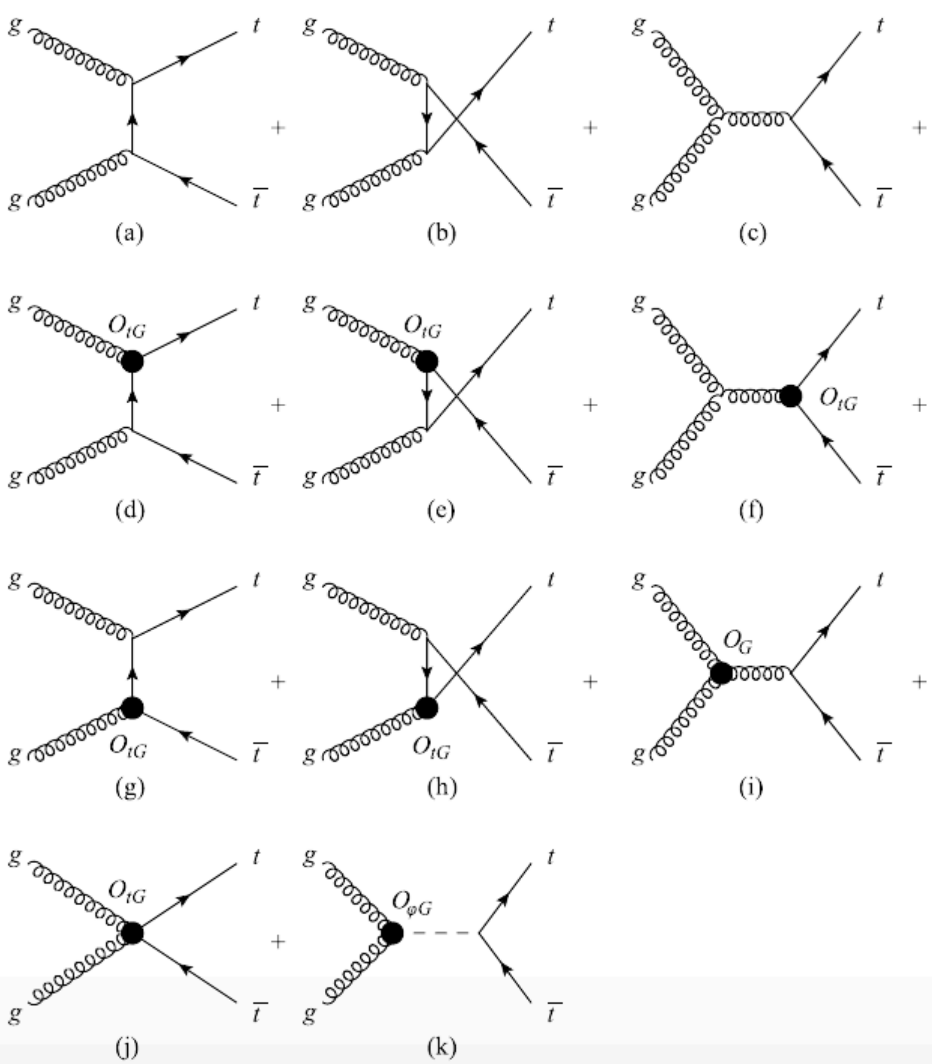
EFT in ttbar

$$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^A t)\tilde{\phi}G^A_{\mu\nu}$$

$$O_G = f_{ABC}G^{A\nu}_{\mu}G^{B\rho}_{\nu}G^{C\mu}_{\rho}$$

$$O_{\phi G} = \frac{1}{2}(\phi^+\phi)G^A_{\mu\nu}G^{A\mu\nu}$$

Three operators of dim=6 that enter tt



$$\beta = \sqrt{1 - 4m_t^2/\hat{s}}$$

$$\hat{\sigma}_{gg\to t\bar{t}} = \frac{\pi\alpha_s^2\beta}{48\hat{s}}\left(31\beta + \left(\frac{33}{\beta} - 18\beta + \beta^3\right)\ln\left[\frac{1+\beta}{1-\beta}\right] - 59\right)$$

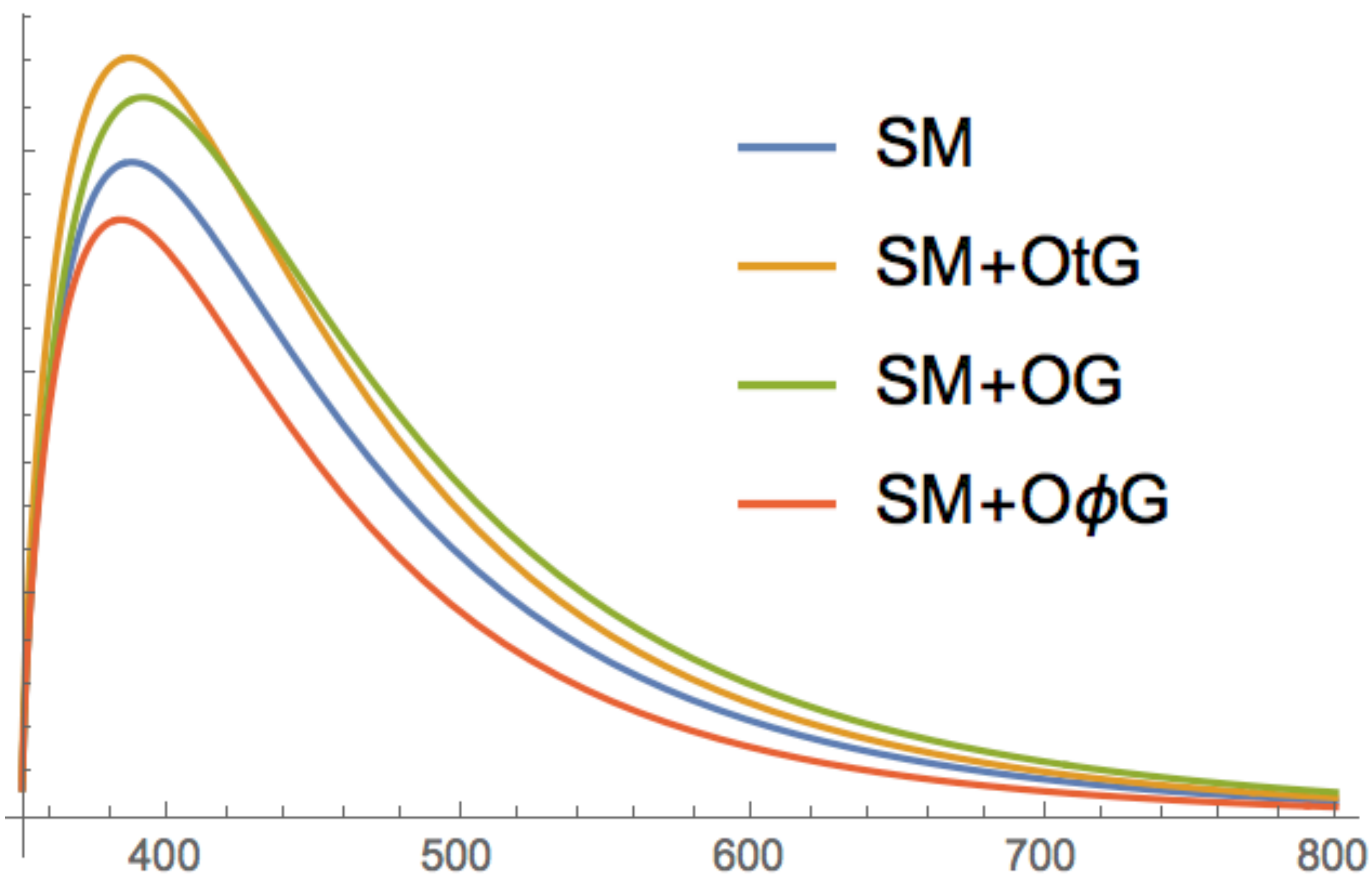
$$+ \mathrm{Re}C_{tG}\frac{g_s^3 v\sqrt{1-\beta^2}}{48\sqrt{2}\pi\Lambda^2\sqrt{s}}\left(8\ln\frac{1+\beta}{1-\beta} - 9\beta\right)$$

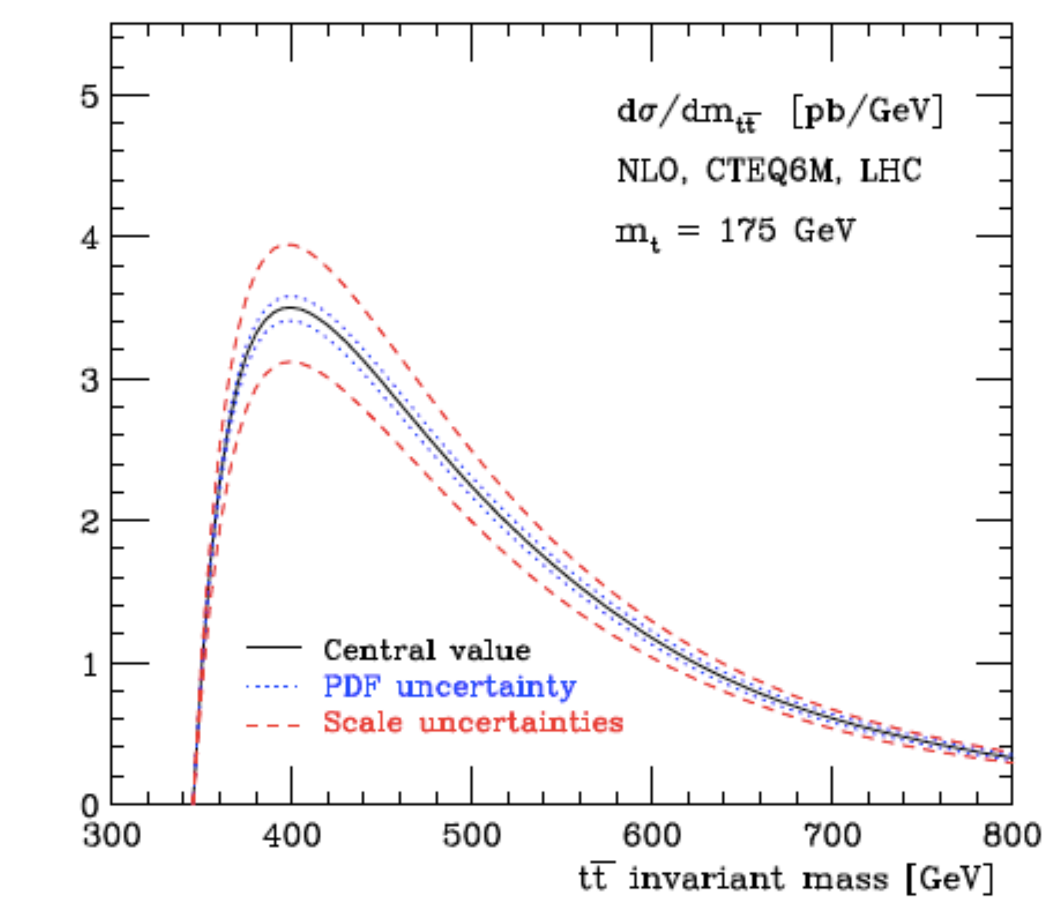
$$+ C_G\frac{9g_s^3(1-\beta^2)}{256\pi\Lambda^2}\left(\ln\frac{1+\beta}{1-\beta} - 2\beta\right)$$

$$- C_{\phi G}\frac{g_s^2 s\beta^2(1-\beta^2)}{256\pi\Lambda^2(s-m_h^2)}\ln\frac{1+\beta}{1-\beta}$$

EFT in ttbar

These new interactions lead to deformations of the SM distributions.



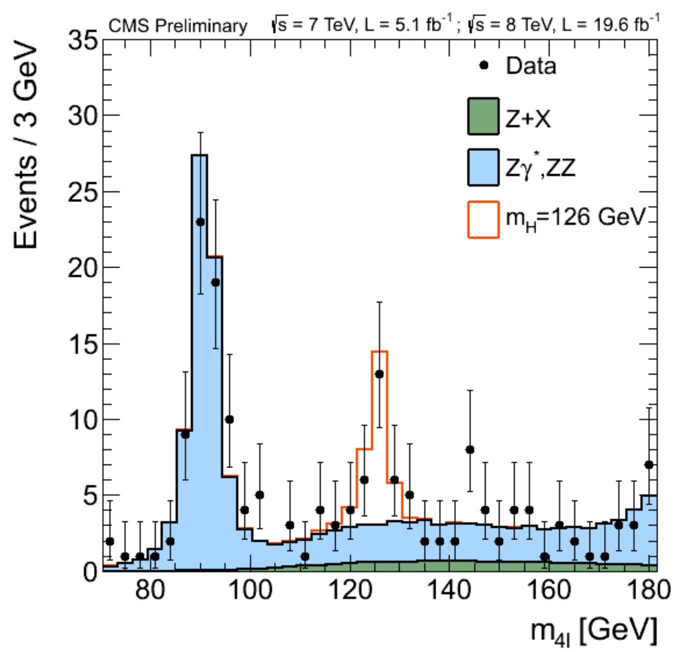


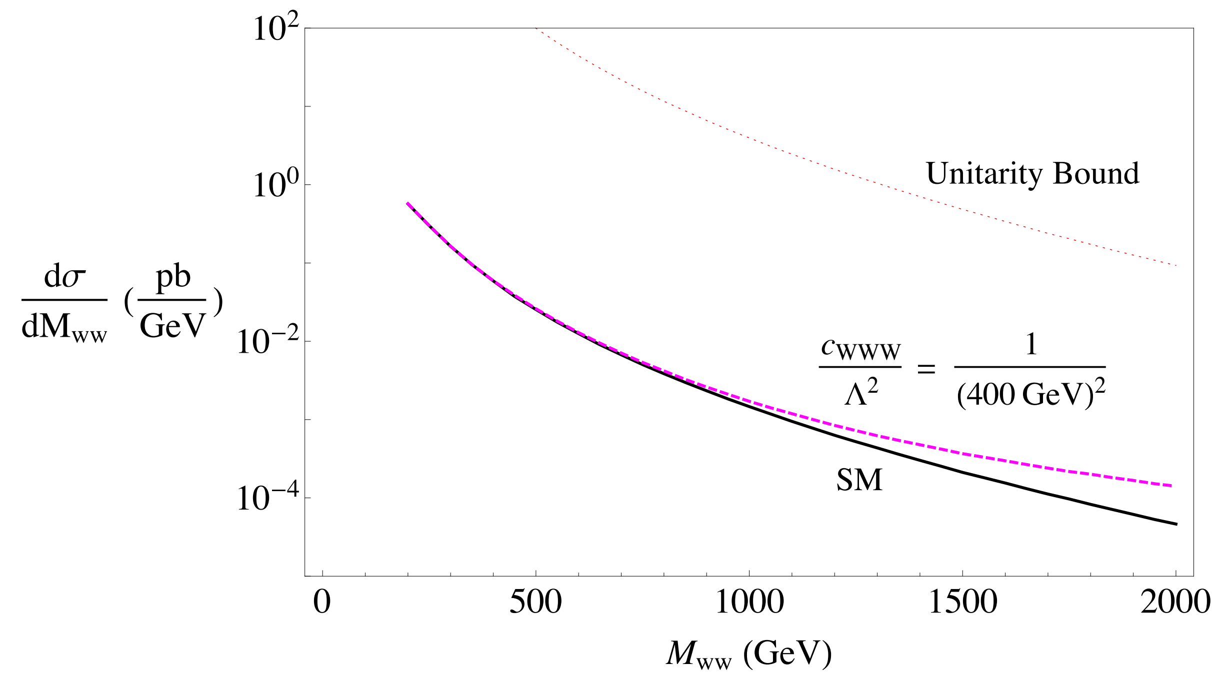
Need to know the SM distributions extremely well as well as the EFT ones!

Search for New Physics at the LHC

Two main strategies for searching new physics

Search for new states ⟷ **Search for new interactions**





"Peak" or more complicated structures searches. Need for **descriptive MC** for discovery = Discovery is data driven. Later need precision for characterisation.

Deviations are expected to be small. Intrinsically a precision measurement. Needs for **predictive MC** and accurate predictions for SM and EFT.


冨嶽三十六景 神奈川沖浪裏
北斎改為一筆

Plan for today's lecture

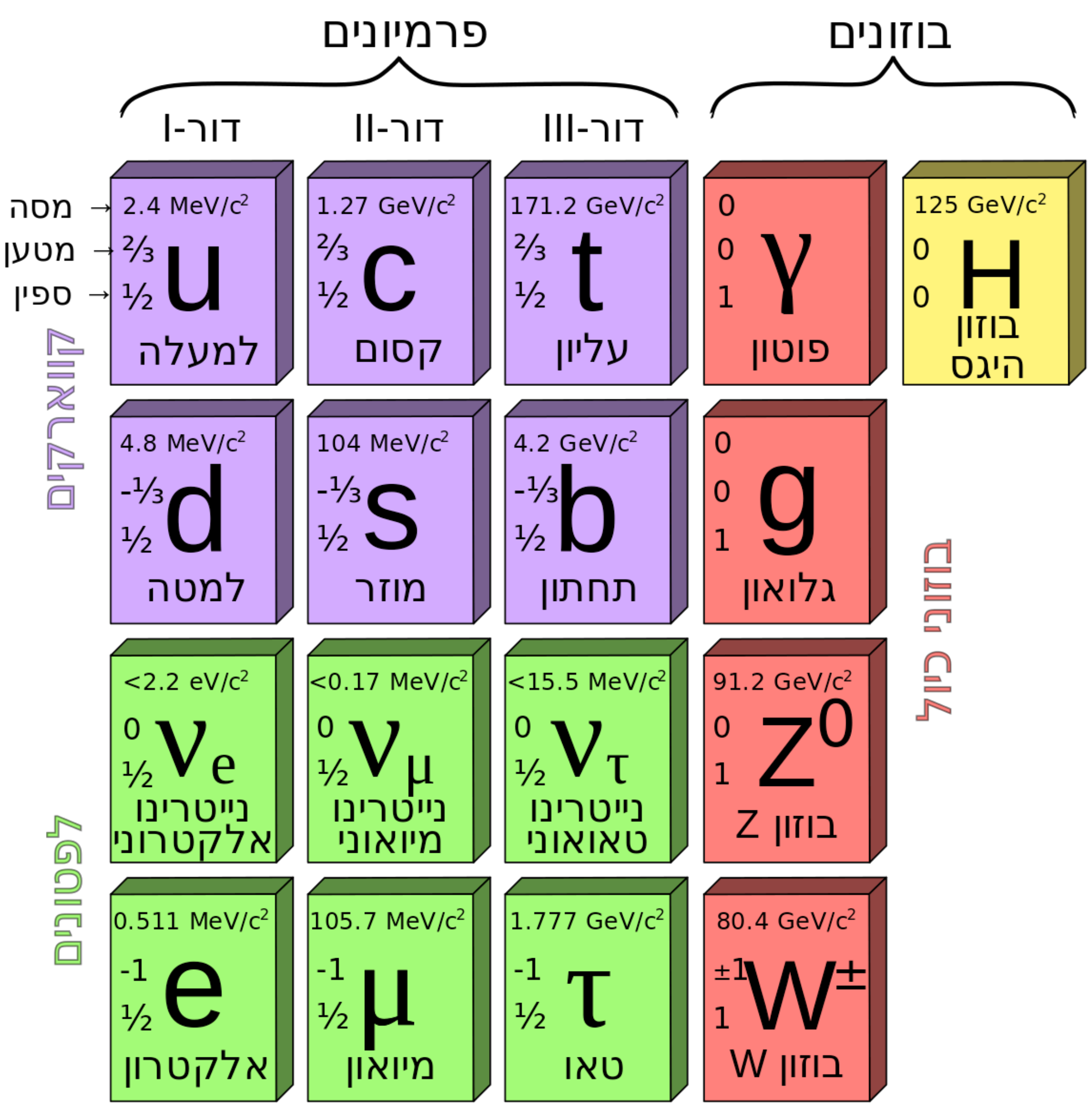
- Review of the Standard Model
- SMEFT essentials

Plan for today's lecture

- Review of the Standard Model
- SMEFT essentials

Standard Model

The SM in a nutshell



- $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge symmetries.
- Matter is organised in chiral multiplets of the fundamental representation of the gauge groups.
- The $SU(2) \times U(1)$ symmetry is spontaneously broken to EM.
- Yukawa interactions are present that lead to fermion masses and CP violation.
- Neutrino masses can be accommodated in two distinct ways.
- Anomaly free.
- Renormalisable = valid to “arbitrary” high scales.

Masses

Gauge invariance and renormalizability completely determine the kinetic terms for the gauge bosons

$$\mathcal{L}_{YM} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W_a^{\mu\nu}$$

$$\begin{aligned} B^{\mu\nu} &= \partial^\mu B^\nu - \partial^\nu B^\mu \\ W^a_{\mu\nu} &= \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g\, \epsilon^{abc}\, W_{b,\mu}\, W_{c,\nu} \end{aligned}$$

The gauge symmetry does NOT allow any mass terms for $W^\pm$ and Z.

Mass terms for gauge bosons

$$\mathcal{L}_{mass} = \frac{1}{2}\, m_A^2\, A_\mu\, A^\mu$$

are not invariant under a gauge transformation

$$A^\mu \;\rightarrow\; U(x) \left(A^\mu + \frac{i}{g}\, \partial^\mu \right) U^{-1}(x)$$

However, the gauge bosons of weak interactions are massive (short range of weak interactions).

Masses

Actually, the story is bit more subtle than this...

- One can still realise the gauge symmetry in a non-linear way, as a gauged non-linear sigma model. In this case one groups the goldstone bosons into a triplet π whose interactions are described by

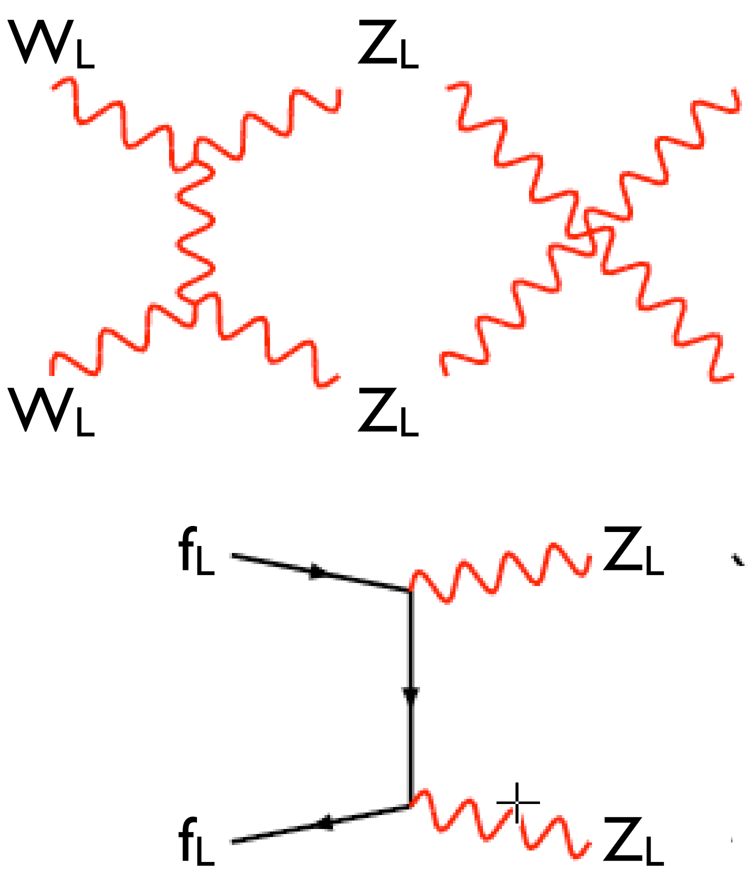
$$\mathcal{L} = \frac{v^2}{4} \mathrm{Tr}(D^\mu \Sigma)^\dagger D_\mu \Sigma$$

with $D^\mu \Sigma = \partial^\mu \Sigma + i(g/2)\sigma \cdot W^\mu \Sigma - i(g'/2)\Sigma \sigma^3 B^\mu$ and $\Sigma = \exp(i\sigma \cdot \pi / v)$

For the fermions one writes $\mathcal{L} = -m_f \bar{F}_L \Sigma \begin{pmatrix} 0 \\ 1 \end{pmatrix} f_R + \mathrm{H.c.}$

The unitarity bound

[Chanowitz, Gallard.1985]
[Appelquist, Chanowitz,1989]



$$a_0 \sim \frac{s}{v^2}$$

$$a_0 \sim \frac{\sqrt{s} m_f}{v^2}$$

Inelastic tree-level amplitudes for longitudinal W and Z and fermions violate unitarity at a scale:

$$\Lambda_{EWSB} = \sqrt{8\pi} v$$

Our effective description contains information on where it is going to fail.

Only case we know of where unknown physics has to appear below 1 TeV.

BEH mechanism

We give mass to the gauge bosons through the Brout-Englert-Higgs mechanism: generate mass terms from the kinetic energy term of a scalar doublet field Φ that undergoes a broken-symmetry process.

Introduce a complex scalar doublet: four scalar real fields

$$
\begin{aligned}
\Phi &= \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \qquad\qquad Y(\Phi) = 1 \\
\mathcal{L}_{\text{Higgs}} &= (D_\mu \Phi)^\dagger (D^\mu \Phi) - V\left(\Phi^\dagger \Phi\right) \\
D^\mu &= \partial^\mu - i g W_i^\mu \frac{\sigma^i}{2} - i g' \frac{Y(\Phi)}{2} B^\mu \\
V\left(\Phi^\dagger \Phi\right) &= -\mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi\right)^2, \qquad\qquad \mu^2, \lambda > 0
\end{aligned}
$$

- The reason why $Y(\Phi) = 1$ is not to break electric-charge conservation.
- Charge assignment for the Higgs doublet through $Q = T_3 + Y/2$. The potential has a minimum in correspondence of

$$
|\Phi|^2 = \frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2}
$$

v is called the vacuum expectation value (VEV) of the neutral component of the Higgs doublet.

The Higgs potential

The scalar potential

$$V\left(\Phi^\dagger\Phi\right) = -\mu^2\Phi^\dagger\Phi \; + \; \lambda\left(\Phi^\dagger\Phi\right)^2$$

expanded around the vacuum state

$$\Phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

becomes

$$V \;=\; \frac{1}{2}\left(2\lambda v^2\right)H^2 \;+\; \lambda v H^3 \;+\; \frac{\lambda}{4}H^4 + \text{const}$$

- the scalar field H gets a mass

$$m_H^2 = 2\lambda v^2 \qquad\qquad v^2 = \mu^2/\lambda$$

- there is a term of cubic and quartic self-coupling.

Note: this means that $\lambda_3 = \lambda_4 = \lambda$ in the SM. To have (independent) deviations of the trilinear or quadrilinear, one needs to deform the potential with a BSM hypothesis.

Vector boson masses and couplings

$$(D^\mu\Phi)^\dagger D_\mu\Phi = \frac{1}{2}\partial^\mu H\partial_\mu H + \left[\left(\frac{gv}{2}\right)^2 W^{\mu+}W^-_\mu + \frac{1}{2}\frac{(g^2+g'^2)\,v^2}{4}Z^\mu Z_\mu\right]\left(1+\frac{H}{v}\right)^2$$

- The W and Z gauge bosons have acquired masses

$$m_W^2 = \frac{g^2v^2}{4} \qquad m_Z^2 = \frac{(g^2+g'^2)\,v^2}{4} = \frac{m_W^2}{\cos^2\theta_W}$$

From the measured value of the Fermi constant G_F

$$\frac{G_F}{\sqrt{2}} = \left(\frac{g}{2\sqrt{2}}\right)^2\frac{1}{m_W^2} \quad\Longrightarrow\quad v = \sqrt{\frac{1}{\sqrt{2}G_F}} \approx 246.22\ \text{GeV}$$

- the photon stays massless

- HWW and HZZ couplings from $2H/v$ term (and $HHWW$ and $HHZZ$ couplings from H^2/v^2 term)

$$\mathcal{L}_{HVV} = \frac{2m_W^2}{v}W^+_\mu W^{-\mu}H + \frac{m_Z^2}{v}Z^\mu Z_\mu H \equiv g m_W W^+_\mu W^{-\mu}H + \frac{1}{2}\frac{g m_Z}{\cos\theta_W}Z^\mu Z_\mu H$$

Fermion masses and couplings

A direct mass term is not invariant under $\mathrm{SU}(2)_L$ or $\mathrm{U}(1)_Y$ gauge transformation

$$m_f \bar{\psi}\psi = m_f \left(\bar{\psi}_R \psi_L + \bar{\psi}_L \psi_R\right)$$

Generate fermion masses through Yukawa-type interactions terms

$$\begin{aligned} \mathcal{L}_{\text{Yukawa}} &= -\Gamma_d^{ij} \bar{Q}_L'^{i} \Phi d_R'^{j} - \Gamma_d^{ij*} \bar{d}_R'^{i} \Phi^\dagger Q_L'^{j} \\ &\quad -\Gamma_u^{ij} \bar{Q}_L'^{i} \Phi_c u_R'^{j} + \text{h.c.} \\ &\quad -\Gamma_e^{ij} \bar{L}_L^{i} \Phi e_R^{j} + \text{h.c.} \end{aligned}$$

$$\Phi_c = i\sigma_2 \Phi^* = \frac{1}{\sqrt{2}} \begin{pmatrix} v + H(x) \\ 0 \end{pmatrix}$$

where Q', u' and d' are quark fields that are generic linear combination of the mass eigenstates u and d and Γ_u, Γ_d and Γ_e are 3×3 complex matrices in generation space, spanned by the indices i and j.

$$M^{ij} = \Gamma^{ij} \frac{v}{\sqrt{2}}$$

Fermion masses and couplings

We can make the following change of fermionic fields

$$f'_{Li} = \left(U_L^f\right)_{ij} f_{Lj} \qquad\qquad f'_{Ri} = \left(U_R^f\right)_{ij} f_{Rj}$$

$$\begin{aligned} \mathcal{L}_{\text{Yukawa}} &= -\sum_{f',i,j} \bar{f}'^{\,i}_L\, M_f^{ij}\, f'^{\,j}_R \left(1+\frac{H}{v}\right) + \text{h.c.} \\ &= -\sum_{f,i,j} \bar{f}^i_L \left[\left(U_L^f\right)^\dagger M_f\, U_R^f\right]_{ij} f_R^j \left(1+\frac{H}{v}\right) + \text{h.c.} \\ &= -\sum_f m_f \left(\bar{f}_L f_R + \bar{f}_R f_L\right)\left(1+\frac{H}{v}\right) \end{aligned}$$

- We succeed in producing fermion masses and we got a fermion-antifermion-Higgs coupling proportional to the fermion mass.
- Notice that the fermionic field redefinition preserves the form of the kinetic terms in the Lagrangian ($\bar{\psi}\,\partial\!\!\!/\,\psi = \bar{\psi}_R\,\partial\!\!\!/\,\psi_R + \bar{\psi}_L\,\partial\!\!\!/\,\psi_L$ invariant for left and right field unitary transformation).
- The Higgs Yukawa couplings are flavor diagonal: no flavor changing Higgs interactions.

Fermion masses and couplings

We can make the following change of fermionic fields

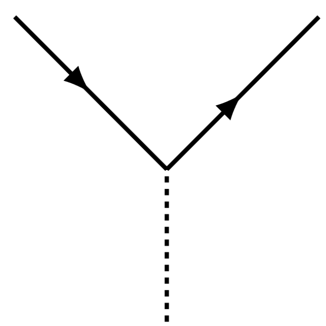
$$f'_{Li} = \left(U_L^f\right)_{ij} f_{Lj} \qquad\qquad f'_{Ri} = \left(U_R^f\right)_{ij} f_{Rj}$$

$$\begin{aligned}
\mathcal{L}_{\text{Yukawa}} &= -\sum_{f',i,j} \bar{f}'^{\,i}_L\, M_f^{ij}\, f'^{\,j}_R \left(1+\frac{H}{v}\right) + \text{h.c.} \\
&= -\sum_{f,i,j} \bar{f}^i_L \left[\left(U_L^f\right)^\dagger M_f\, U_R^f\right]_{ij} f^j_R \left(1+\frac{H}{v}\right) + \text{h.c.} \\
&= -\sum_f m_f\, (\bar{f}_L f_R + \bar{f}_R f_L)\left(1+\frac{H}{v}\right)
\end{aligned}$$

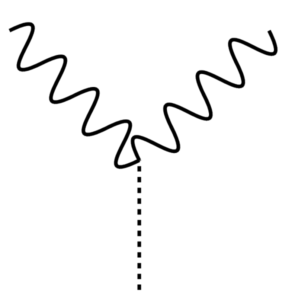
Note: this means that the mass and the Yukawa are linked.

- We succeed in producing fermion masses and we got a fermion-antifermion-Higgs coupling proportional to the fermion mass.
- Notice that the fermionic field redefinition preserves the form of the kinetic terms in the Lagrangian ($\bar\psi \partial\!\!\!/ \psi = \bar\psi_R \partial\!\!\!/ \psi_R + \bar\psi_L \partial\!\!\!/ \psi_L$ invariant for left and right field unitary transformation).
- The Higgs Yukawa couplings are flavor diagonal: no flavor changing Higgs interactions.

Higgs couplings

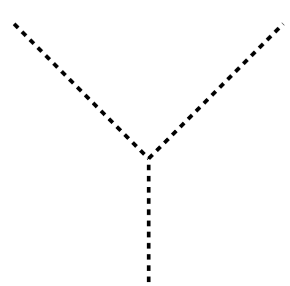


$$i\, m_f / v$$



$$i g m_W g_{\mu\nu} = 2 i\, v g_{\mu\nu} \cdot m_W^2 / v^2$$

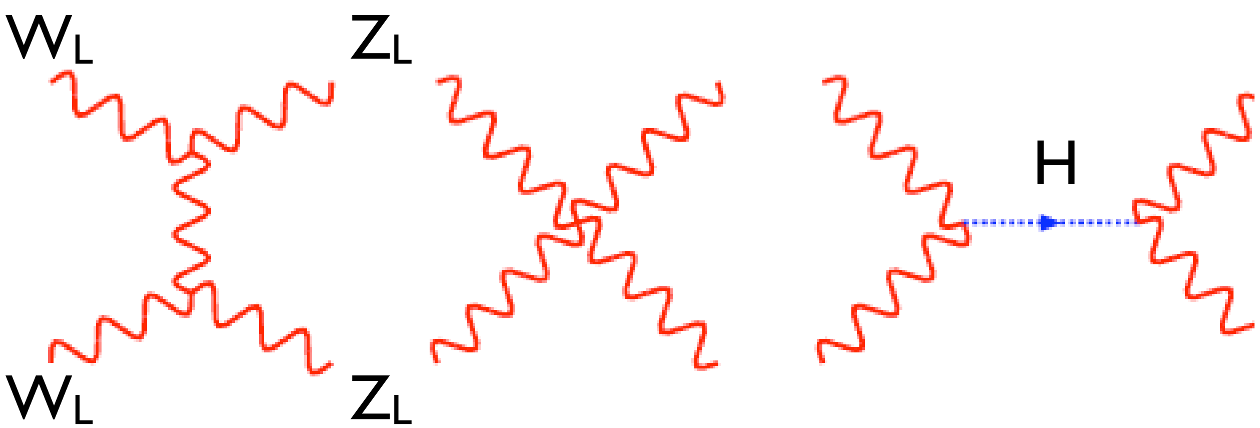
$$i g \frac{m_Z}{\cos\theta_W} g_{\mu\nu} = 2 i v g_{\mu\nu} \cdot m_Z^2 / v^2$$



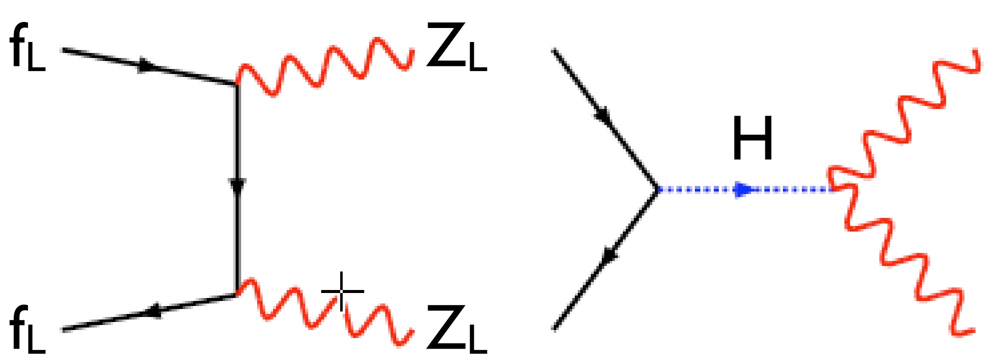
$$-3\, i v \cdot m_h^2 / v^2$$

1. The coupling to fermions is proportional to the mass.
2. The coupling to bosons is proportional to the mass squared.
3. Four-point couplings HHVV and HHHH are also predicted from the gauge symmetry and the structure of the Higgs potential.
4. Couplings to photons and gluons are loop (Vs and quarks) induced.

The Higgs restores unitarity



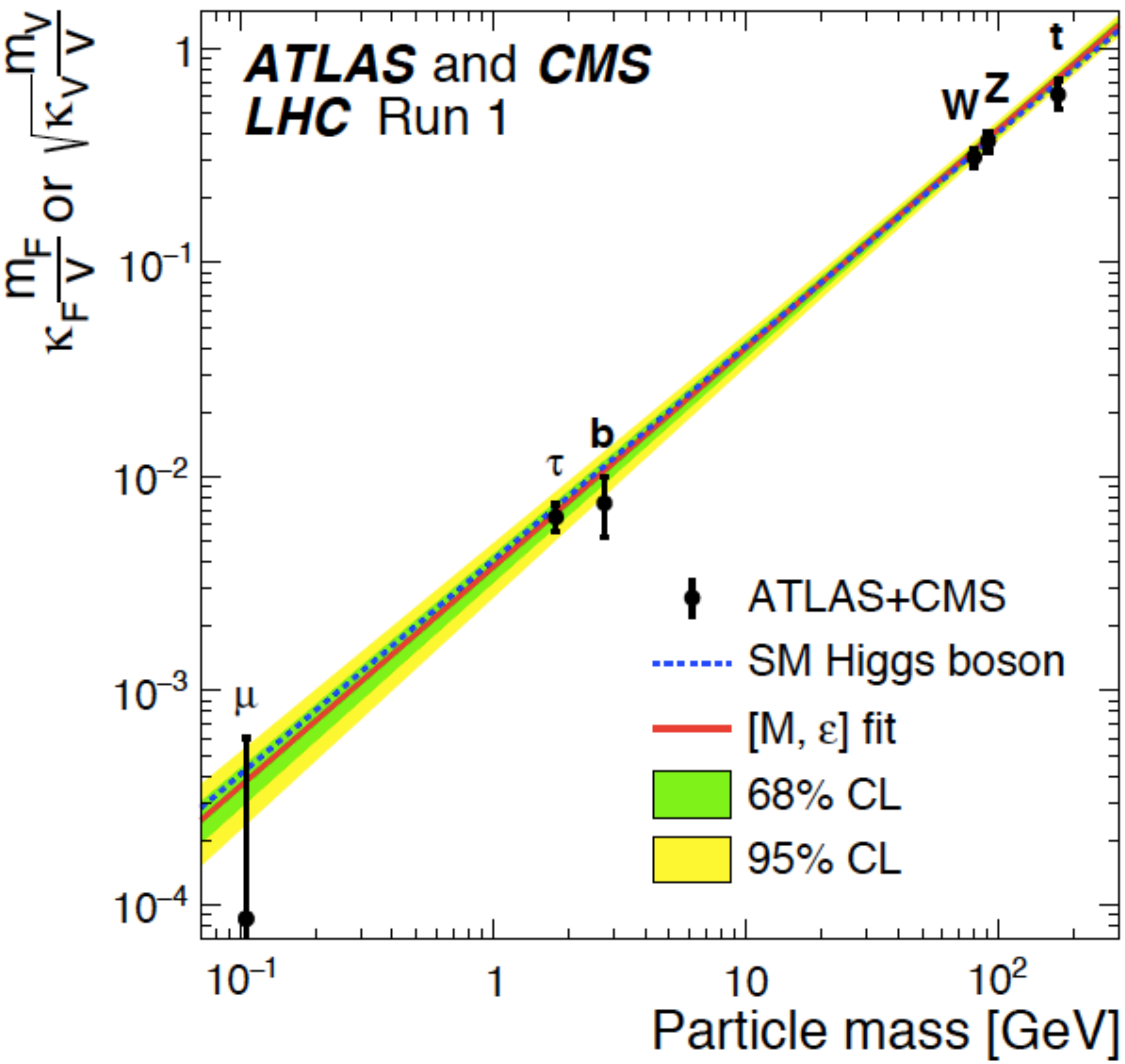
$$a_0 \sim \frac{s}{v^2} - \frac{s}{v^2} \sim \frac{m_H^2}{v^2}$$



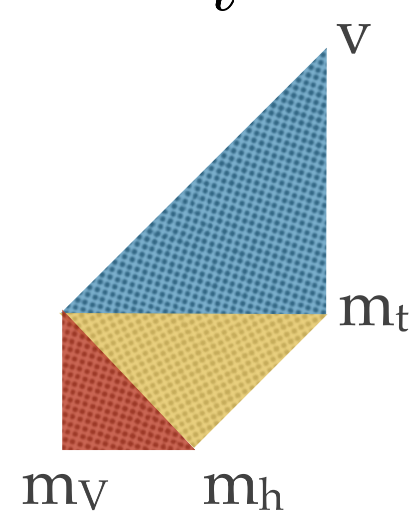
$$a_0 \sim \frac{\sqrt{s}m_f}{v^2} - \frac{\sqrt{s}m_f}{v^2} \sim \frac{m_f^2}{v^2}$$

SM is a linearly realised gauge theory which valid up to arbitrary high scales (if m_H<<1 TeV).

Higgs couplings



$$\frac{v}{m_t} = \frac{m_t}{m_h} = \frac{m_h}{\bar{m}_V} = \sqrt{2}$$

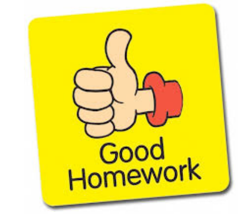


$$r = 2^{\frac{2\theta}{\pi}}$$

SM logarithmic spiral

- Measurements only on vector bosons and 3rd generation fermions
- We don't know the couplings to 2nd and 1st generation
- We don't know the self couplings

Review questions: SM



1. What are the hypercharge assignments of the fermions in the SM? Can you explain in an elevator ride the anomaly cancellation mechanism in the SM? And its implications?

2. It is often said that a mass term for a gauge boson violates the gauge symmetry. What is the usual argument? Is this really true for an abelian gauge group? Is this true for non-abelian gauge group? Why?

3. Can I write a "SM" for which is SU(2)xU(1) invariant, yet does not contain the Higgs field? If so, how? Is it unitary?

4. If a mass term for the fermions is introduced that does not respect the EW gauge symmetry, at which scale the model will end to be valid?

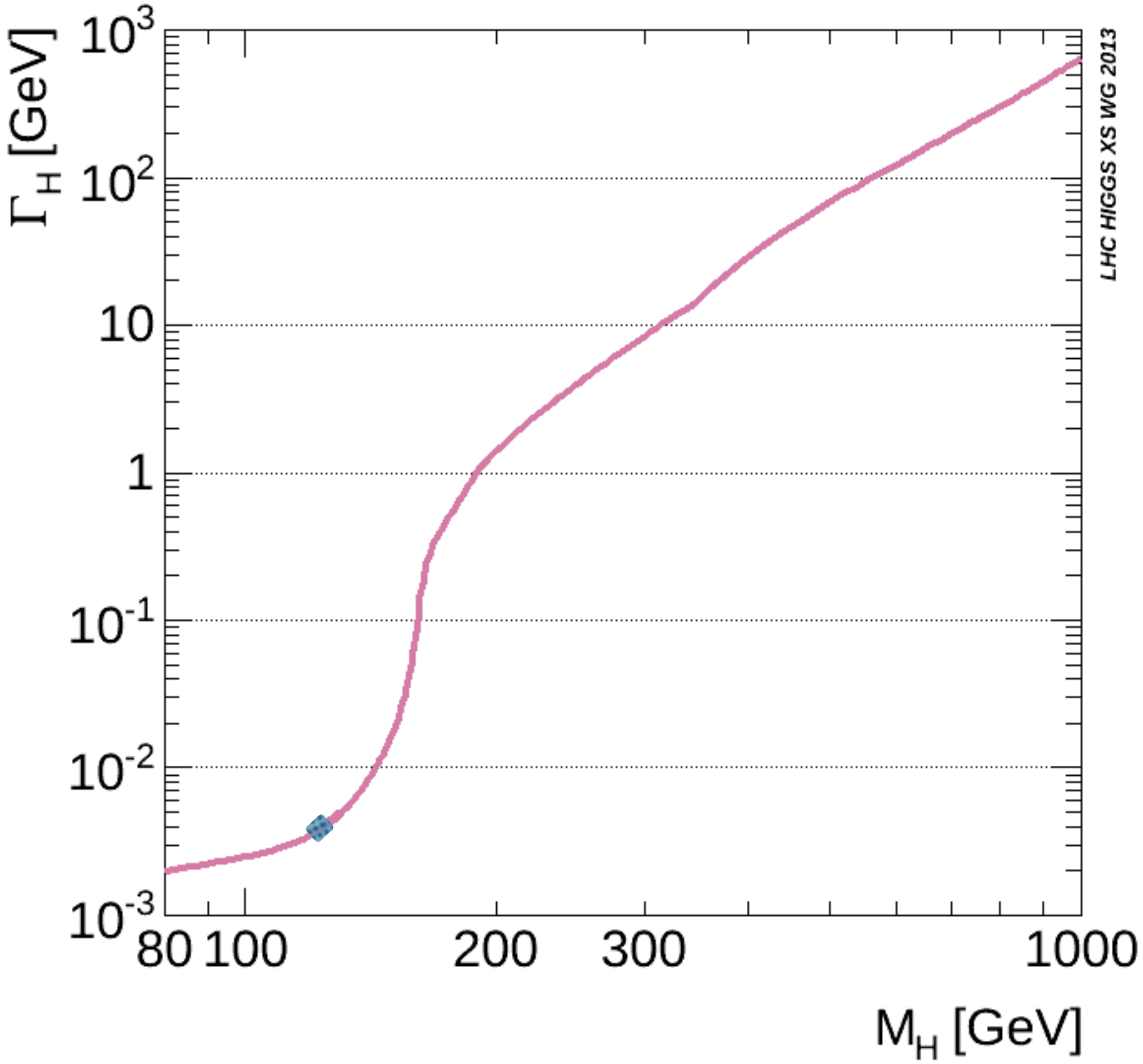
5. What is the mass of the Goldstones in the SM? What is a shift symmetry? Can you describe the mysterious analogy of the SM EW sector with QCD at low-energy?

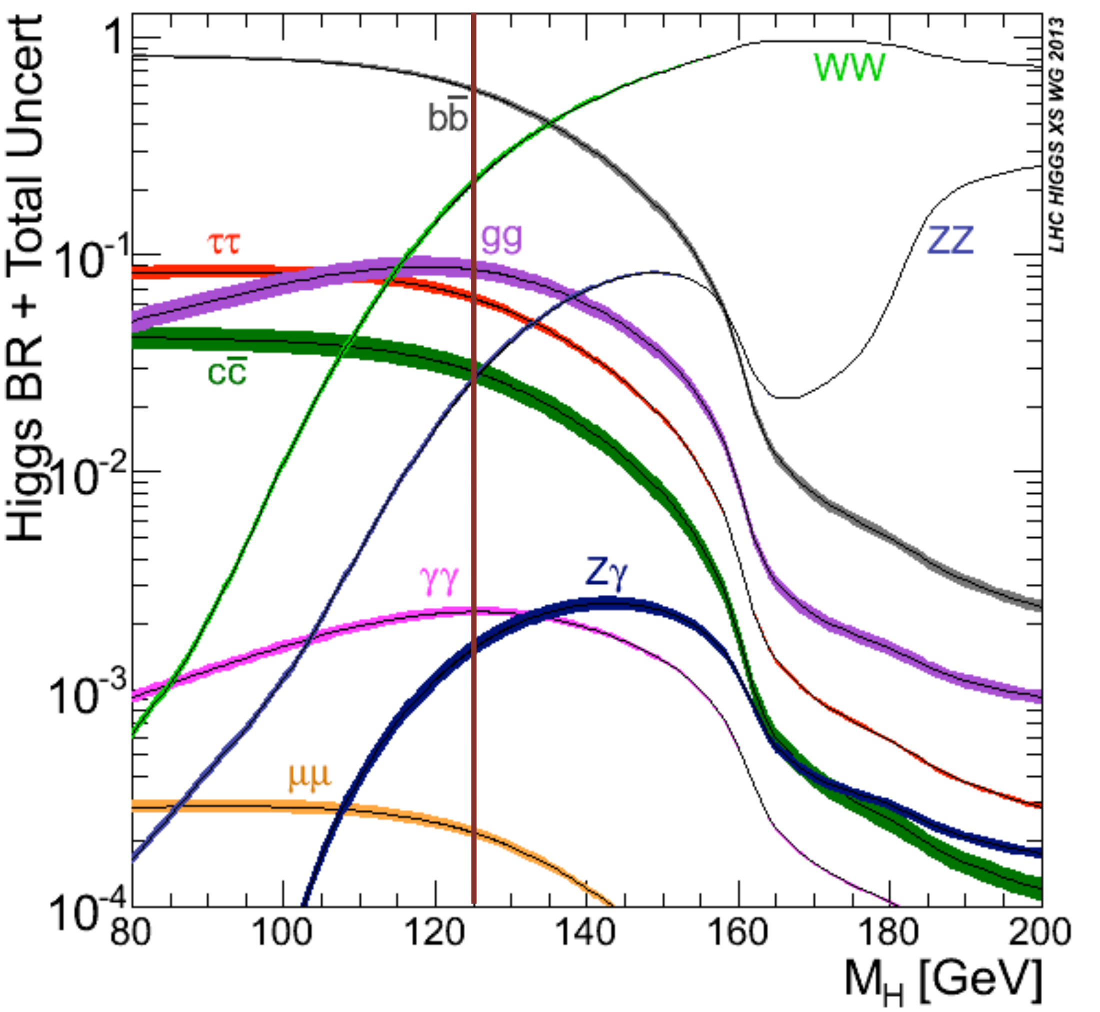
7. List the options that exist to give mass to neutrinos in a renormalizable way and by adding higher-dimensional operators.

8. Define as a “SM portal” a combination of SM fields which is a gauge singlet and has dimension less than four. How many of such portals do exist?

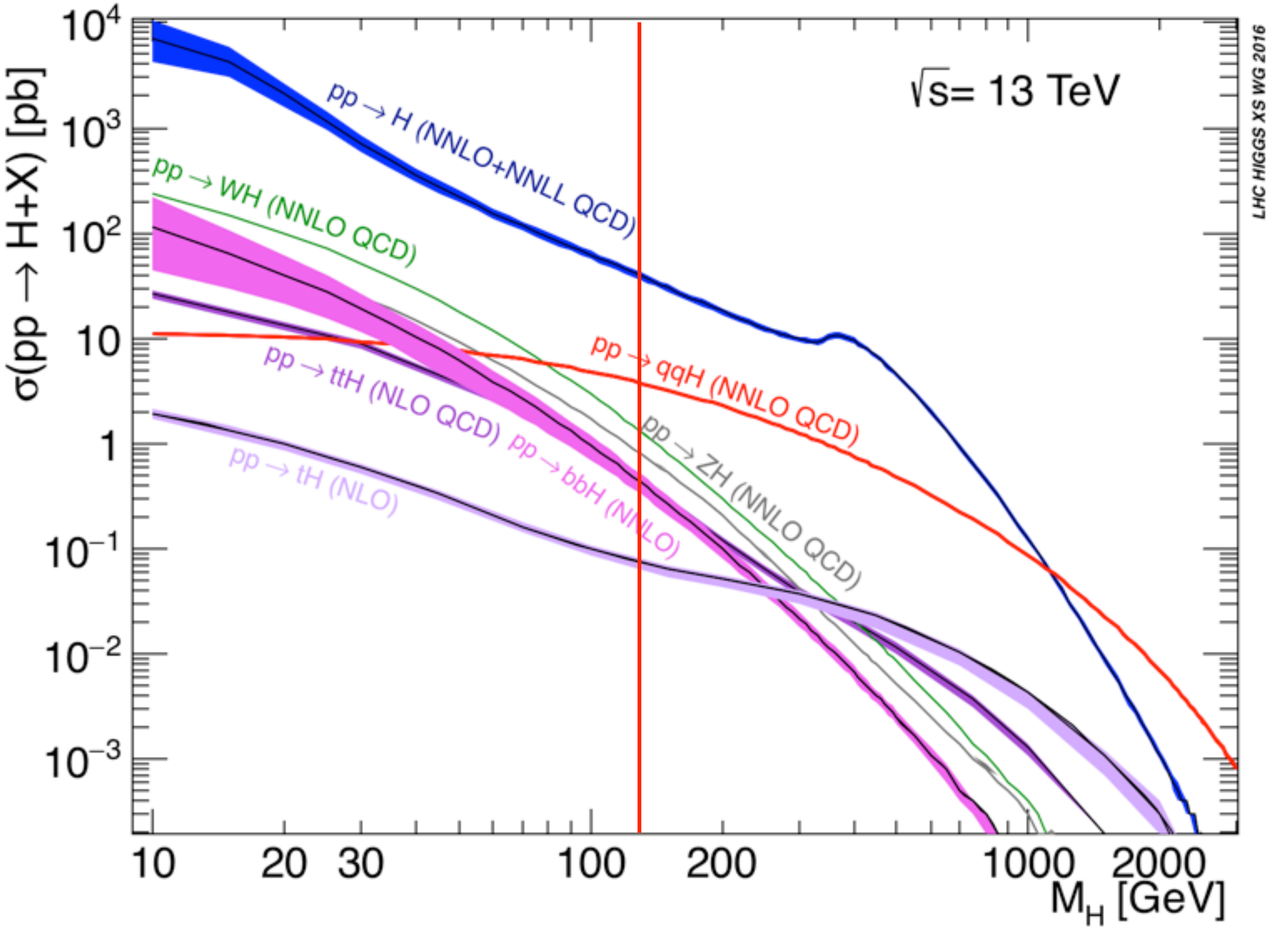
Higgs Boson

Higgs decays

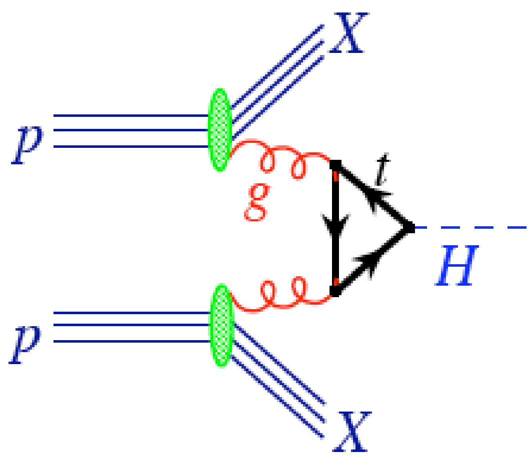




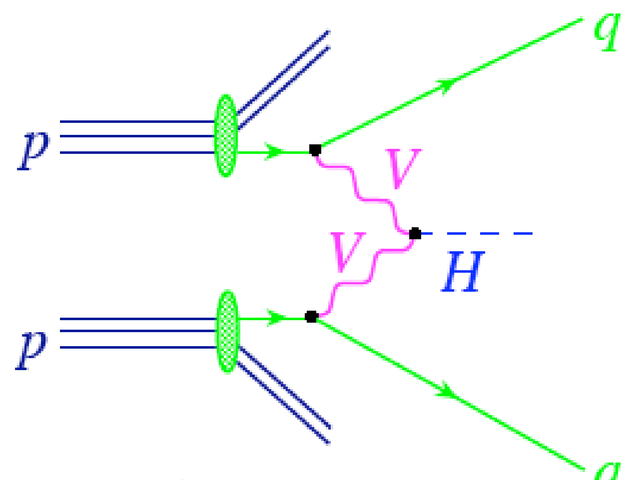
Higgs production at the LHC



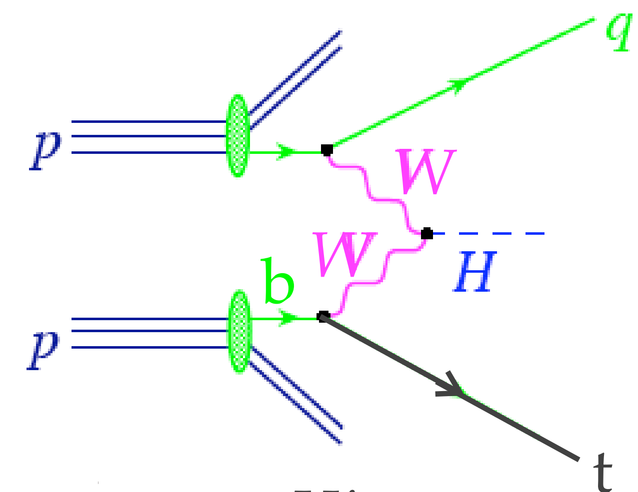
Higgs production channels



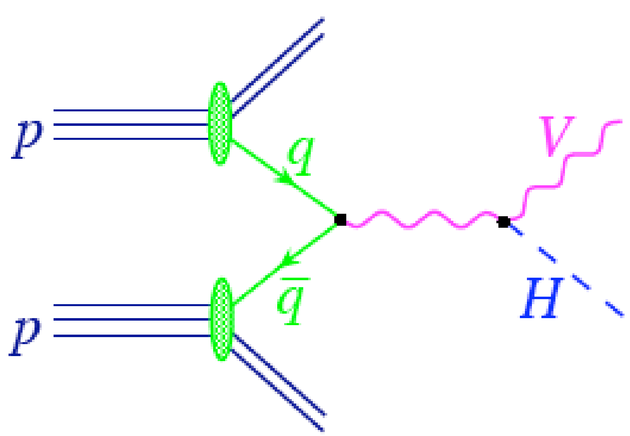
Gluon fusion



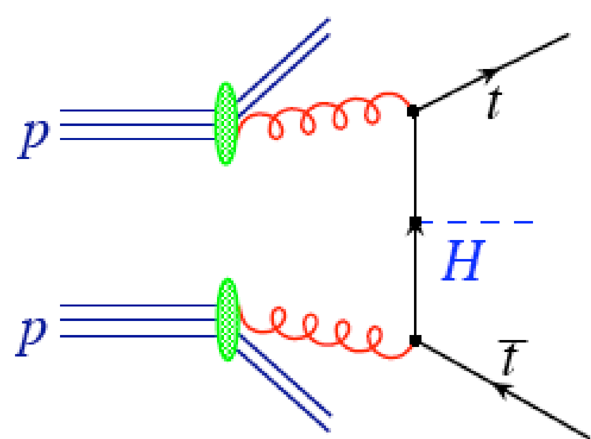
Weak-Boson Fusion



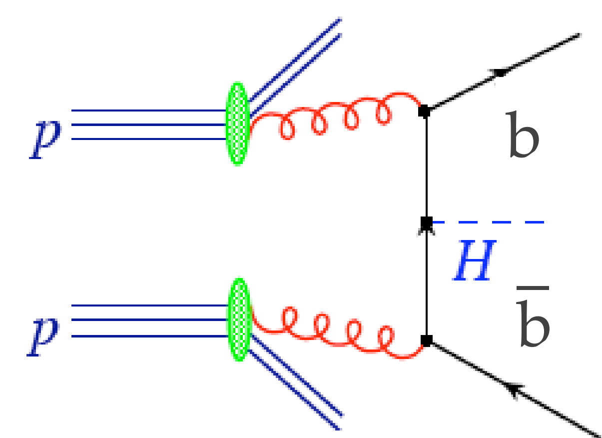
tHj



Higgs Strahlung

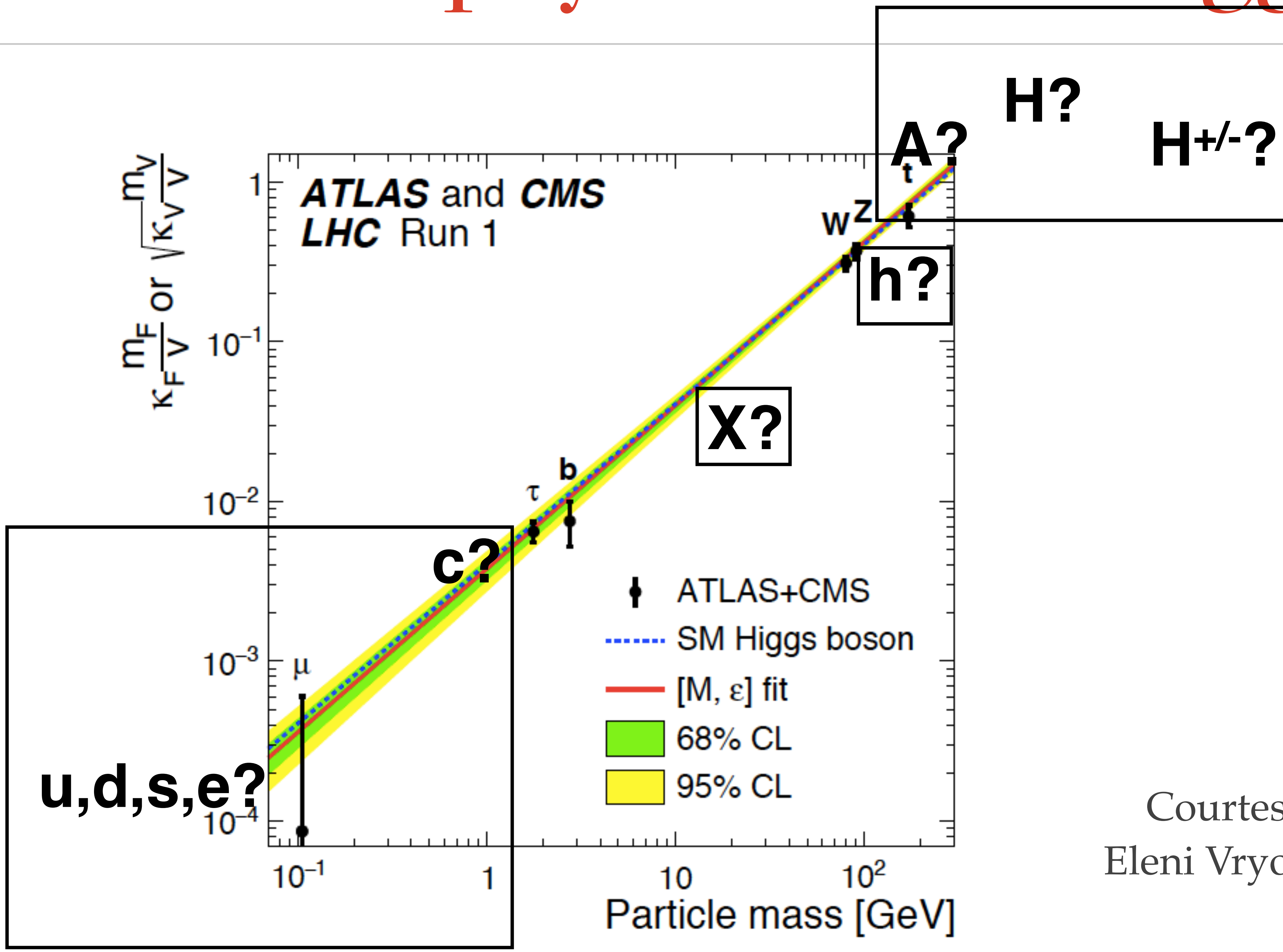


$t\bar{t}H$



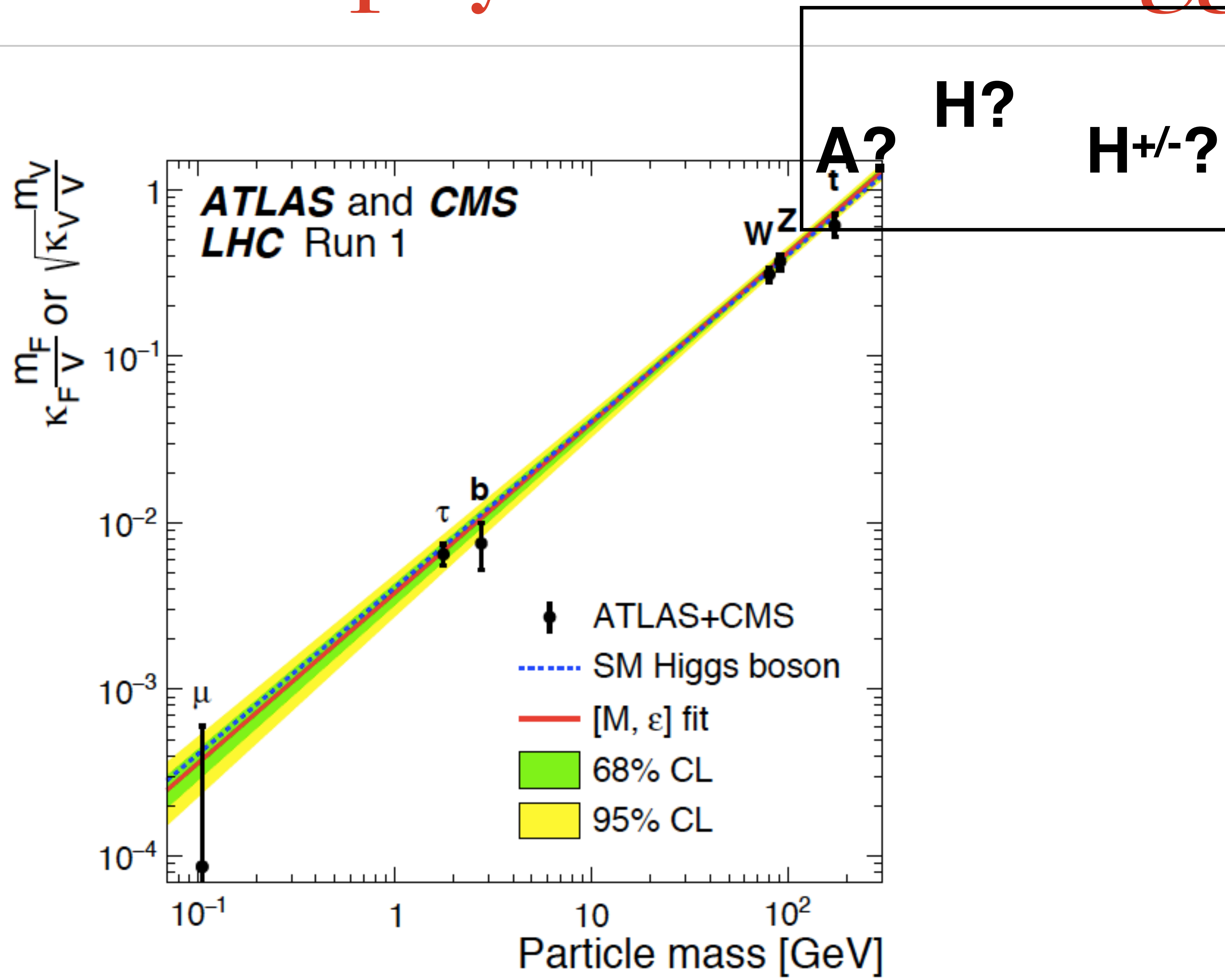
bbH

Search for new physics via the Higgs



Courtesy of
Eleni Vryonidou

Search for new physics via the Higgs



Direct vs indirect searches

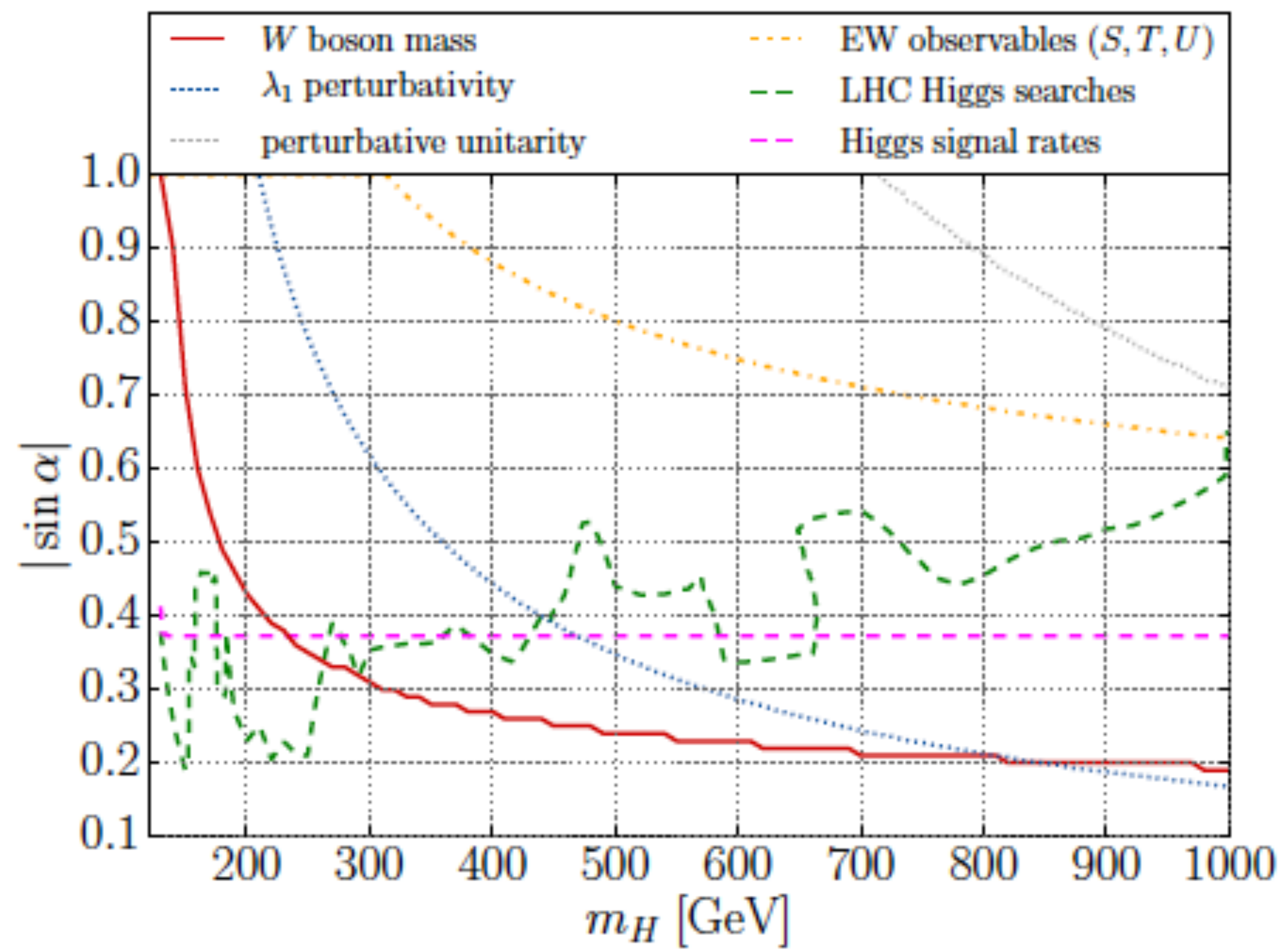
Adopting a simple model one can compare the reach for direct vs indirect measurements. Again adding a singlet :

$$V(\Phi, S) = -m^2\Phi^\dagger\Phi - \mu^2 S^2 + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2 S^4 + \lambda_3\Phi^\dagger\Phi S^2 \qquad m_h,\ m_H,\ \sin\alpha,\ \tan\beta,\ v$$

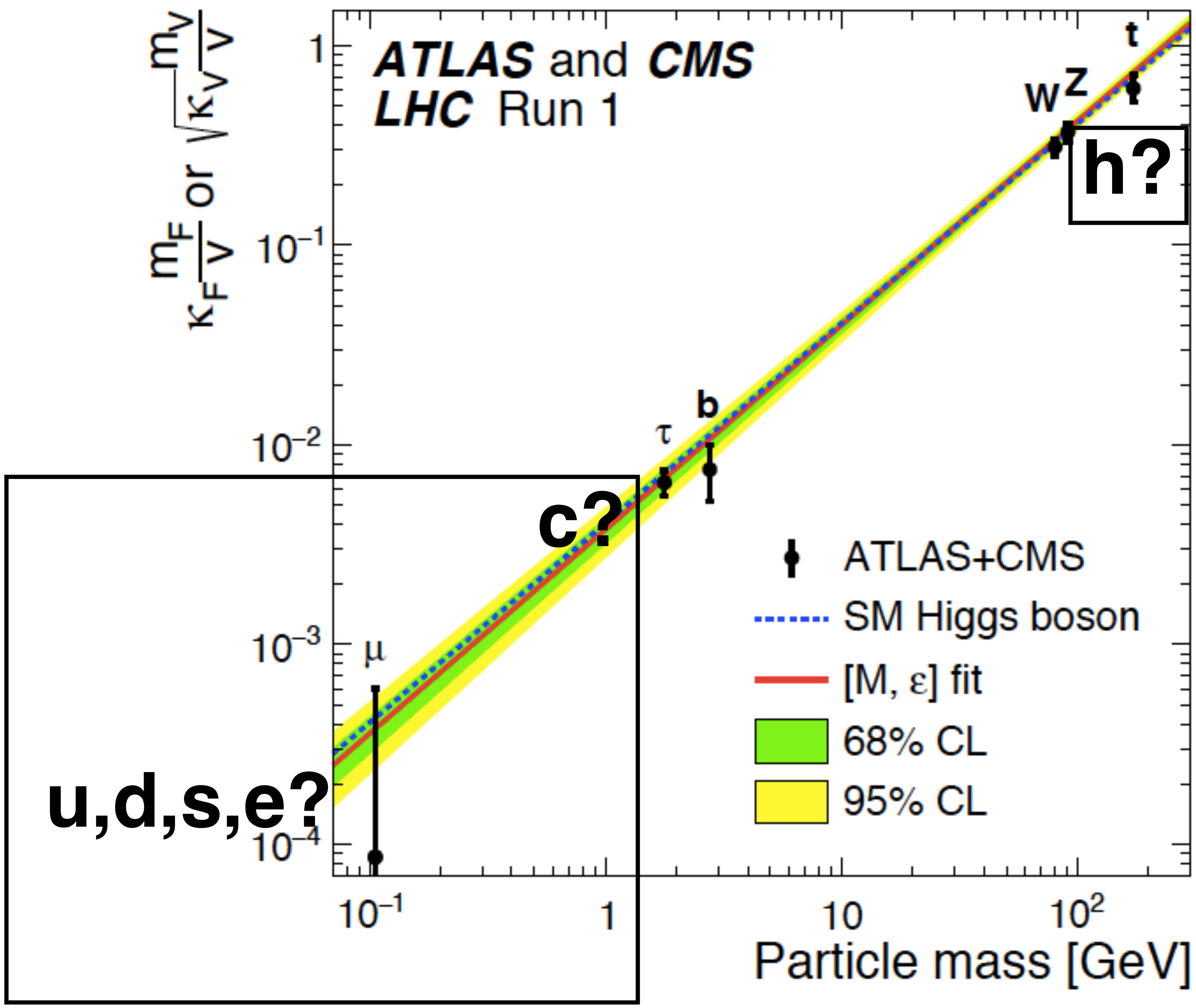
Heavy Higgs searches

vs

Light Higgs signal strengths



Phase I (exploration) : examples



Search for new interactions

- Such a programme is based on large set of measurements, both in the exploration and in the precision phases:

  - **PHASE I (EXPLORATION):**
    Bound Higgs SM couplings

  - **PHASE II (SIMPLE DEFORMATIONS):**
    Stress test the SM: Look for deviations wrt dim=4 SM (rescaling factors)

  - **PHASE III (EFT DEFORMATIONS):**
    Interpret measurements in terms of an EFT

- Rare SM processes (induced by small interactions, such as those involving the Higgs with first and second fermion generations or flavour changing neutral interactions) are still in the exploration phase.

- For interactions with vector boson and third generation fermions we are ready to move to phase II.

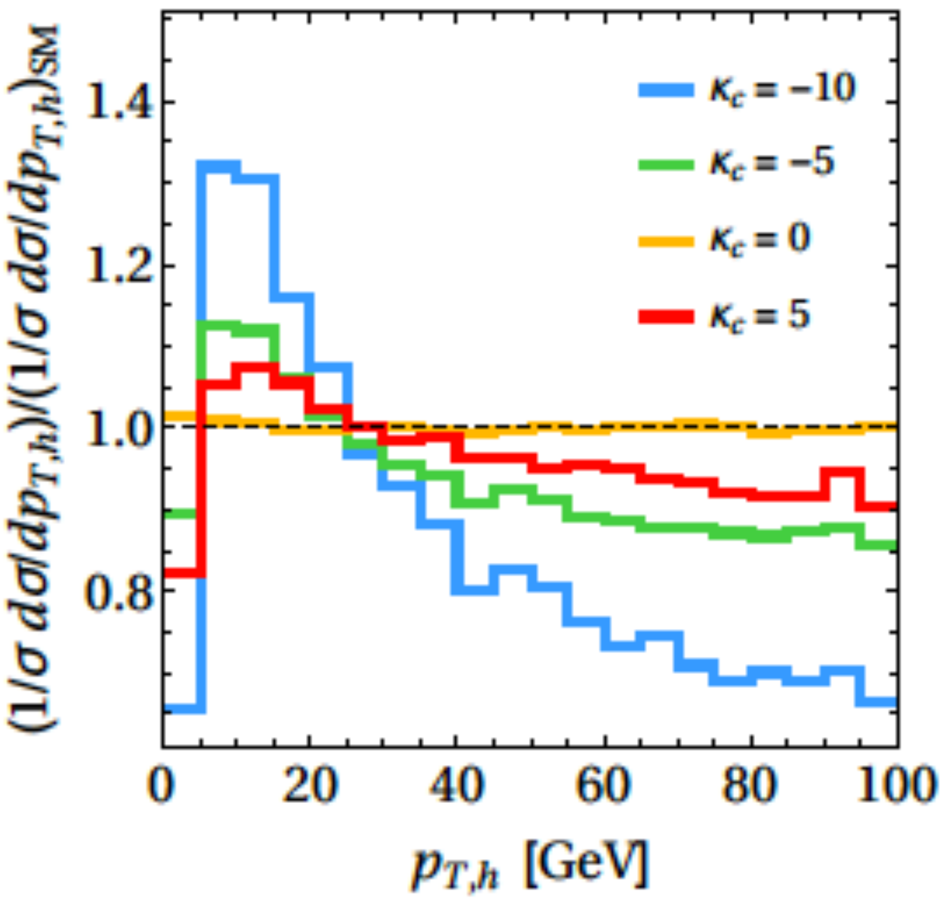
Phase I (exploration) : examples

- H self-interactions
- Second generation Yukawas: ccH, μμH
- Flavor off-diagonal int.s : tqH, ll'H, …
- HZγ
- Top self-interactions : 4top interactions
- Top neutral gauge interactions
- Top FCNC's
- Top CP violation

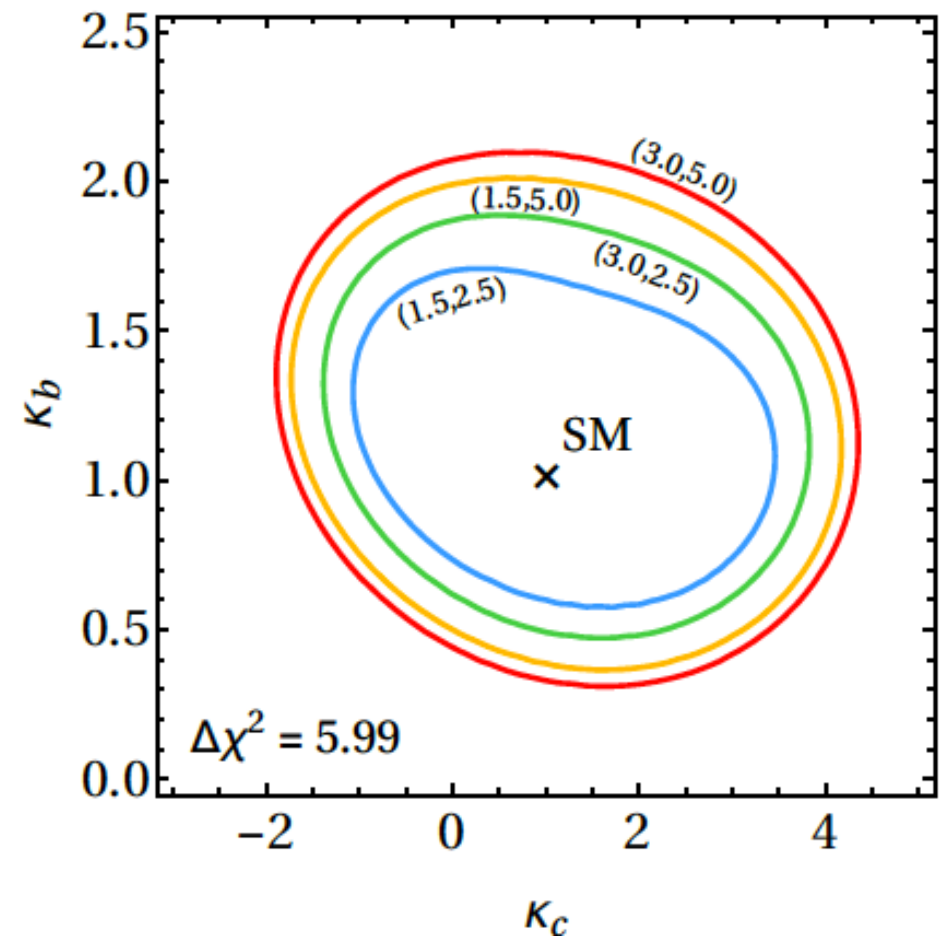
Second generation

Using kinematic distributions i.e. the Higgs pT

Bishara et al.1606.09253



Bishara et al.1606.09253



Inclusive Higgs decays i.e VH + flavour tagging (limited by c-tagging) gives a limit of 110 x SM expectation

$$ZH(H \to c\bar{c})$$

(for evidence of bottom couplings: ATLAS: arXiv:1708.03299 and CMS: arXiv:1708.04188)

Higgs potential 101

To go Beyond the SM, one can parametrise a generic potential by expanding it in series:

$$V^{\mathrm{BSM}}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 + \sum_n \frac{c_{2n}}{\Lambda^{2n-4}}(\Phi^\dagger\Phi - \frac{v^2}{2})^n$$

so that the basic relations remain the same as in the SM:

$$\begin{cases} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{cases}$$

while the λ_3 and λ_4 are modified with respect to the SM values:

$$\begin{cases} \lambda_3 = \kappa_\lambda \lambda_3^{\mathrm{SM}} \\ \lambda_4 = \kappa_{\lambda_4} \lambda_4^{\mathrm{SM}} \end{cases}$$

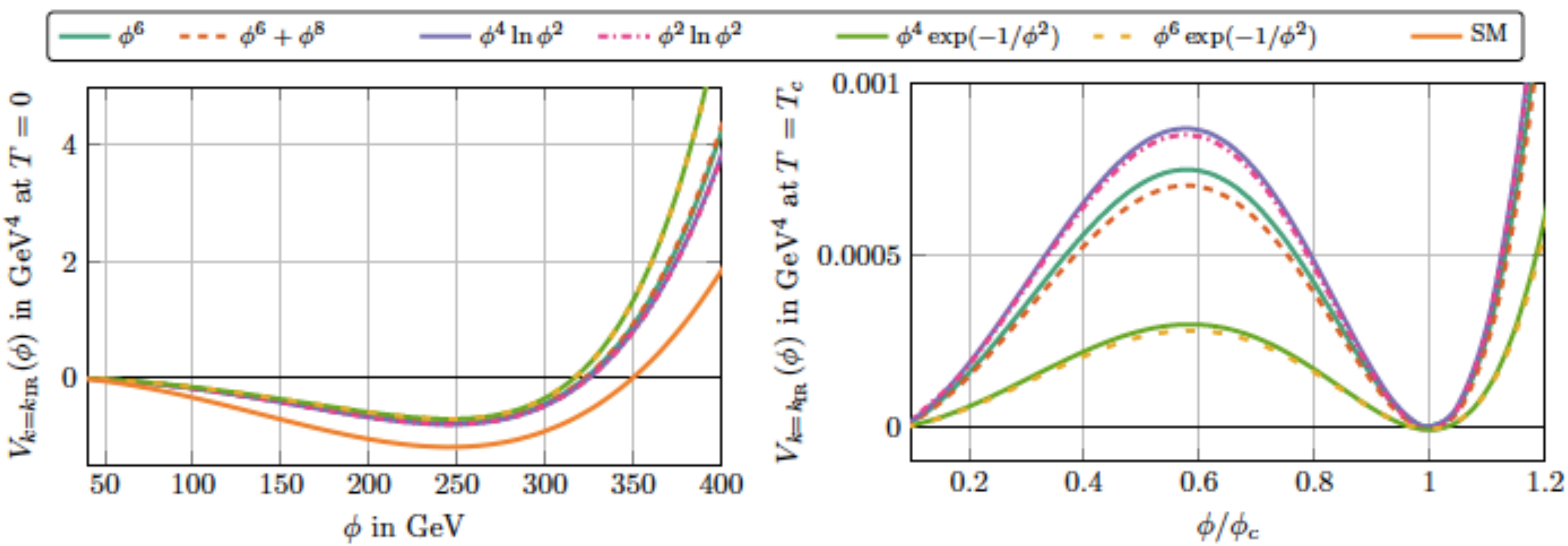
So for example: adding c_6 only

$$\begin{cases} \kappa_\lambda = 1 + \dfrac{c_6 v^2}{\lambda\Lambda^2} \\ \kappa_{\lambda_4} = 1 + \dfrac{6 c_6 v^2}{\lambda\Lambda^2} = 6\kappa_\lambda - 5 \end{cases}$$

i.e., in this case λ_3 and λ_4 are related.

Baryogenesis

Remember that to generate a matter-antimatter asymmetry in the Universe the three Sakharov conditions have to be satisfied (B violation, first-order phase transition (out-of-equilibrium), C and CP violation). The SM potential leads to 2nd order phase transitions.

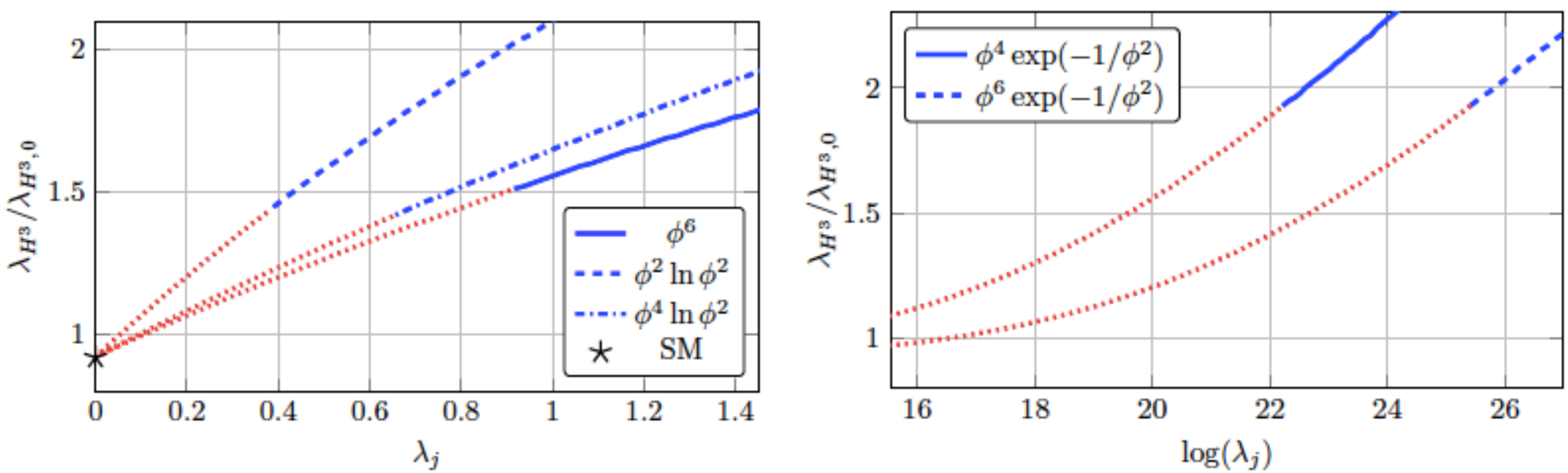


Reichert et al. 1711.00019

A trilinear coupling above 1.5*SM value allows a 1st order transition.

Baryogenesis

Remember that to generate a matter-antimatter asymmetry in the Universe the three Sakharov conditions have to be satisfied (B violation, first-order phase transition (out-of-equilibrium), C and CP violation). The SM potential leads to 2nd order phase transitions.

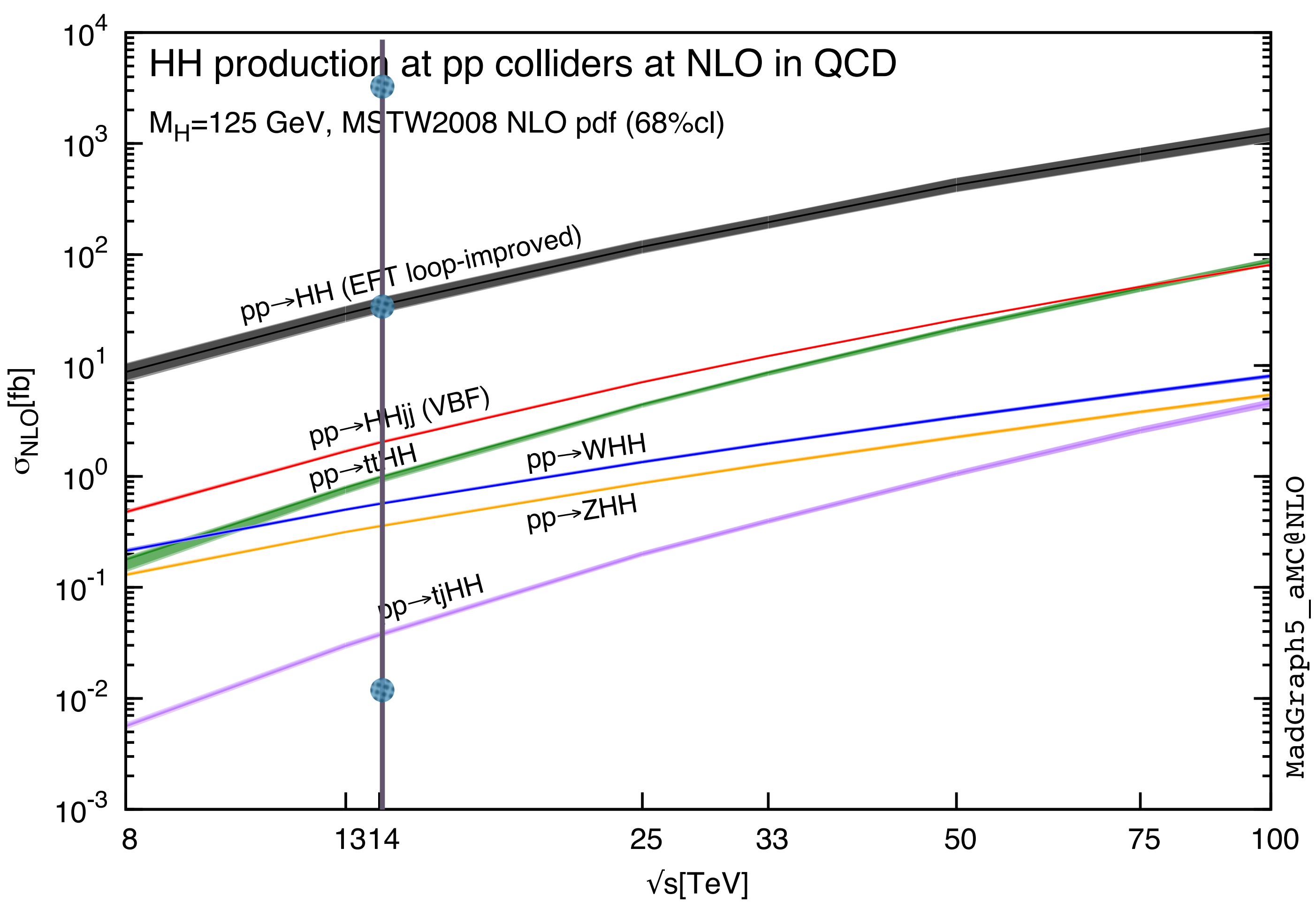


Reichert et al. 1711.00019

A trilinear coupling above 1.5*SM value allows a 1st order transition.

Phase I : Higgs self-coupling

[Frederix et al. '14]

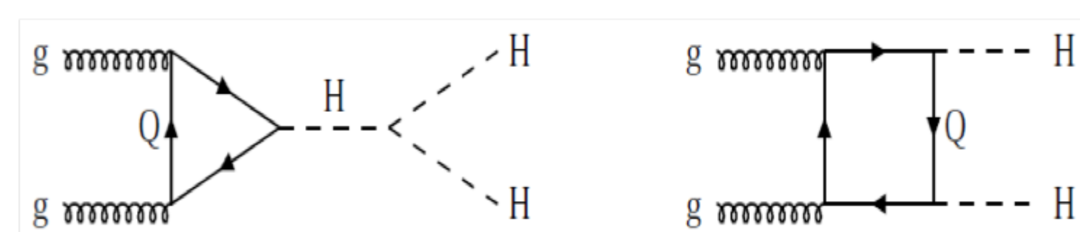


At 14 TeV from gg fusion:

$$\sigma_H = 55 \text{ pb}$$

$$\sigma_{HH} = 44 \text{ fb}$$

$$\sigma_{HHH} = 110 \text{ ab}$$

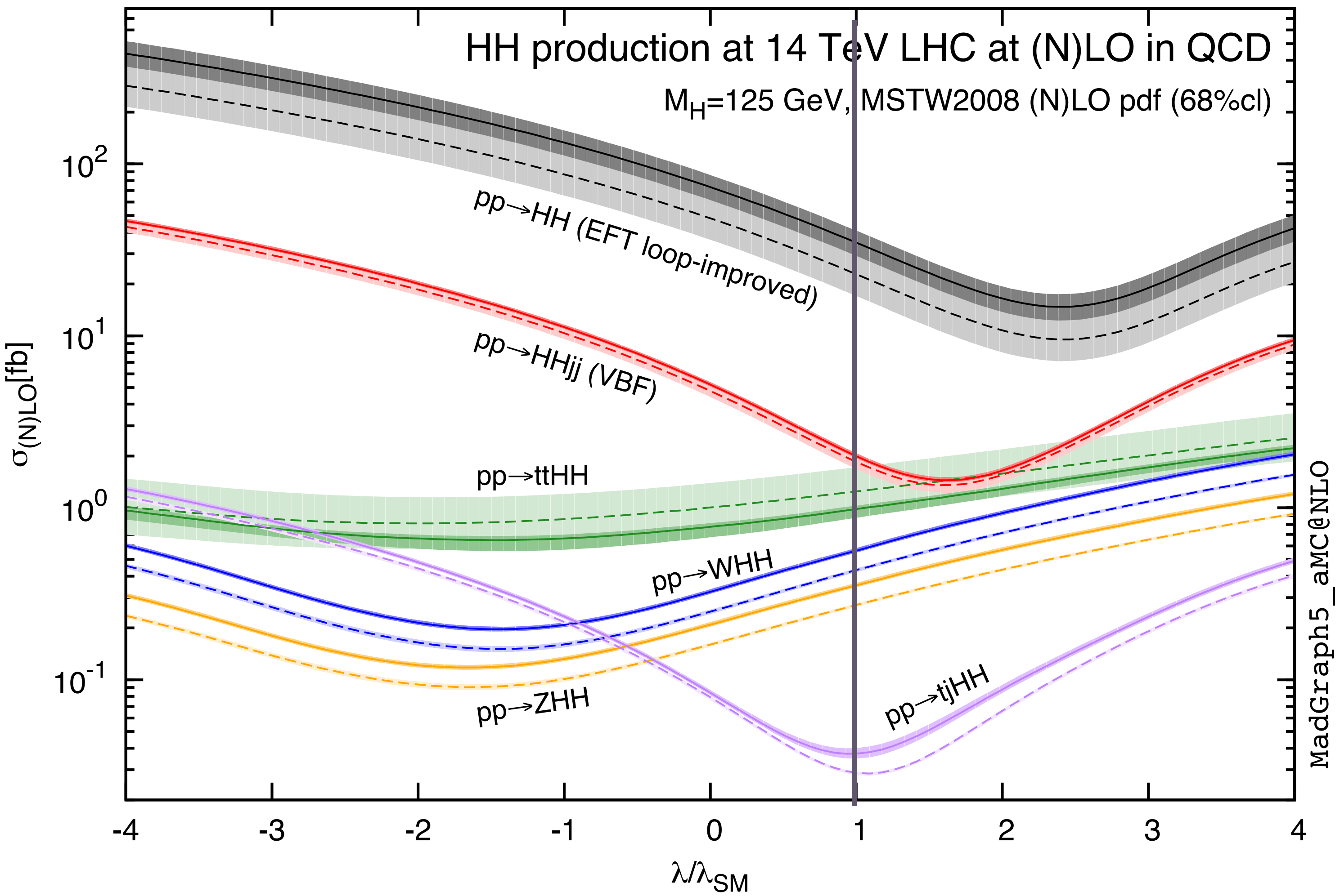


As in single Higgs many channels contribute in principle.

Cross sections for HH(H) increase by a factor of 20(60) at a FCC.

Phase I : Higgs self-coupling

[Frederix et al. '14]



Many channels, but small cross sections.

Current limits are on σ_{SM} (gg→HH) channel in various H decay channels:

CMS : $\sigma/\sigma_{SM} < 19$ (bbγγ) [EPS2017]
ATLAS : $\sigma/\sigma_{SM} < 13$ (bbbb). [Moriond18]

Remarks:

1. Interpretations of these bounds in terms of BSM always need additional assumptions on how the SM has been deformed.
2. The current most common assumption is just a change of λ_3 which leads to a change in σ as well as of distributions:

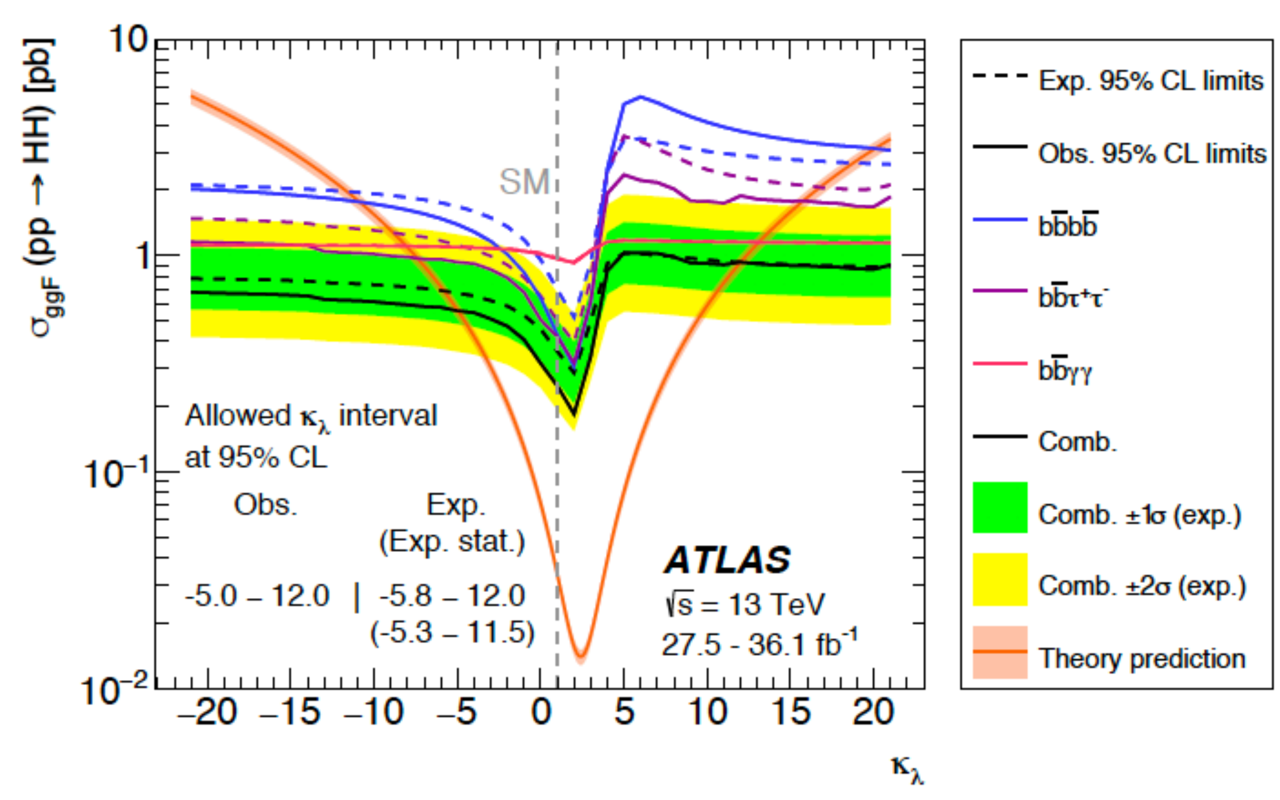
$$\sigma = \sigma_{SM}[1 + (\kappa_\lambda - 1)A_1 + (\kappa_\lambda^2 - 1)A_2]$$

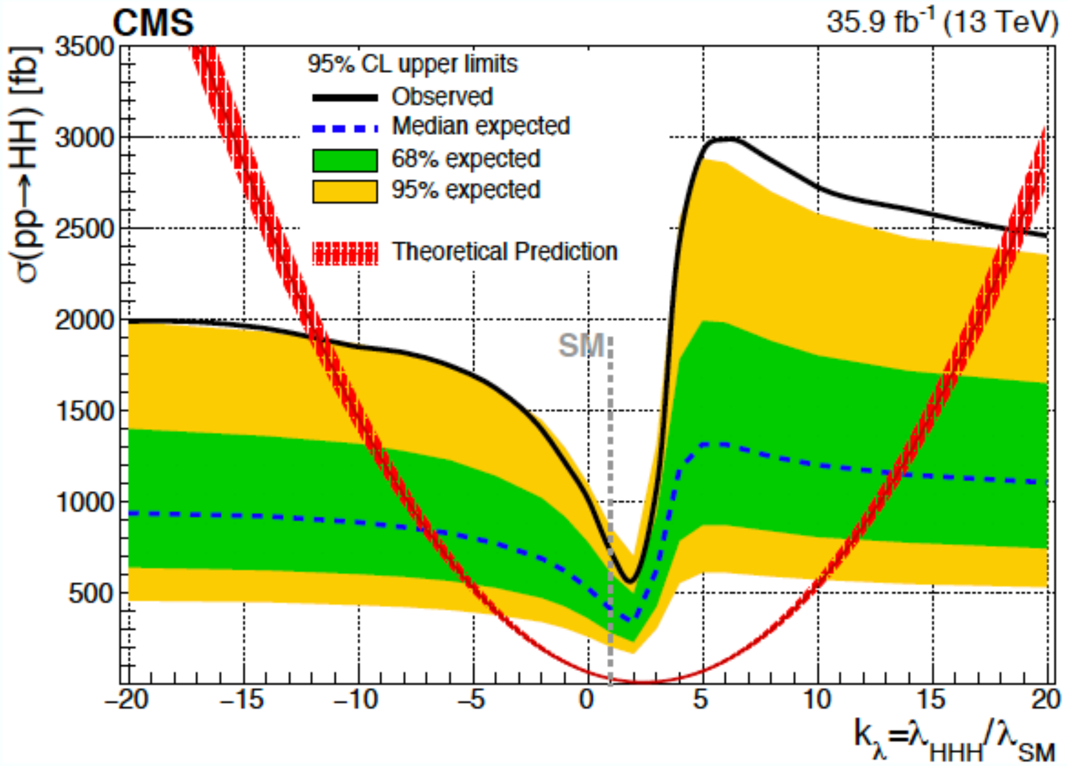
Note: due to shape changes, it is not straightforward to infer a bound on λ_3 from σ(HH), even when $\sigma_{BSM}=\sigma(\lambda_3)$ only is assumed.

Recent results

$\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$

-5.0 < κλ < 12	***Observed***	***-11.8 < κλ < 18.8***
-5.8 < κλ < 12	*Expected*	*-7.1 < κλ < 13.6*





- Strong shape effects with κ_λ variations
- Soft spectra for $\kappa_\lambda \approx 5 \rightarrow$ difficult to constrain anomalous positive values

Phase II : Higgs couplings combination

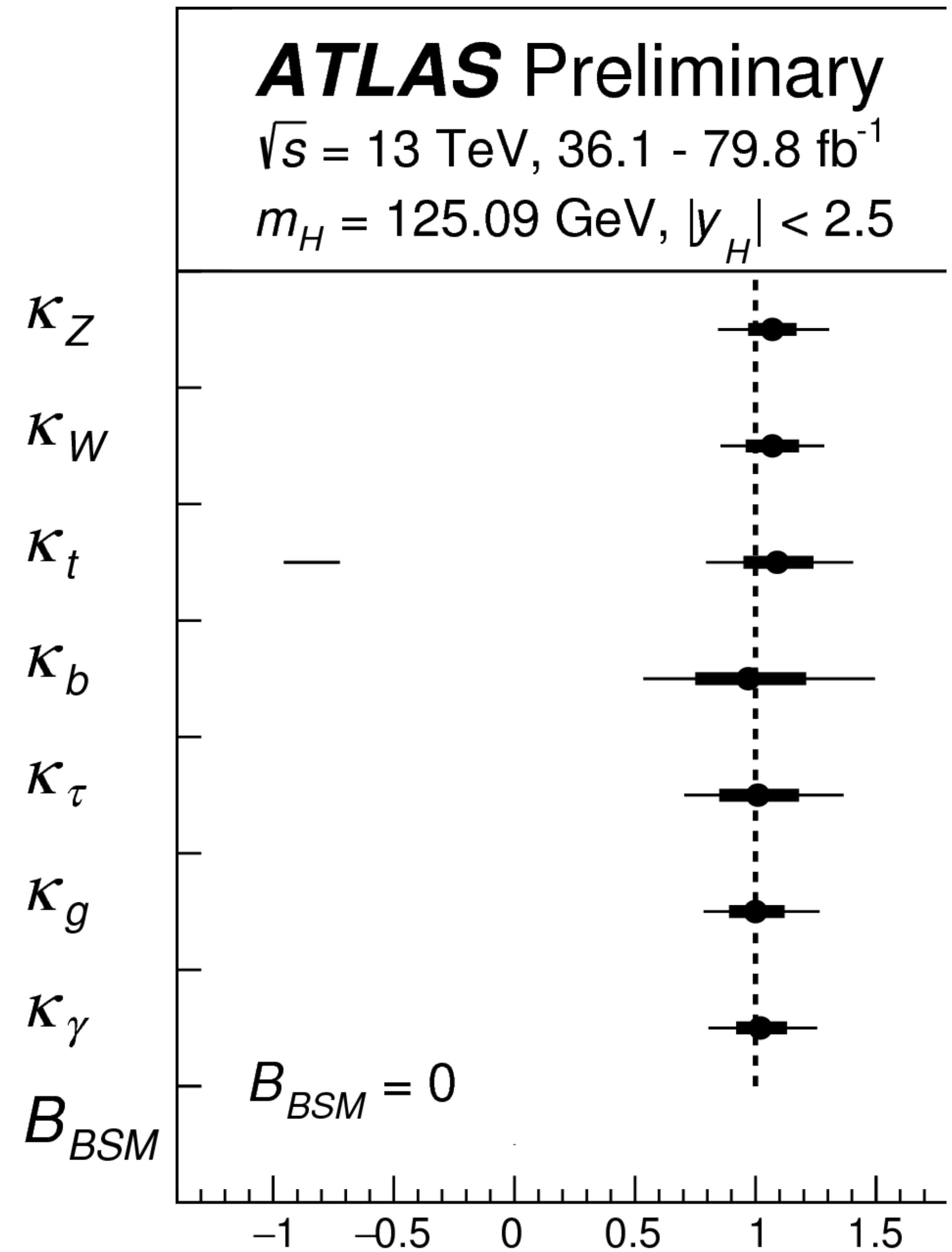
A few formulas:

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

$$\kappa_H^2 \equiv \sum_j \frac{\kappa_j^2 \Gamma_j^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}}$$

$$\Gamma_H = \frac{\Gamma_H^{\mathrm{SM}} \cdot \kappa_H^2}{1 - (BR_{inv} + BR_{unt})}$$



If $Br_{\mathrm{BSM}}>0$ we need an extra condition on the overall scaling to break a flat direction

Phase II : Higgs couplings combination

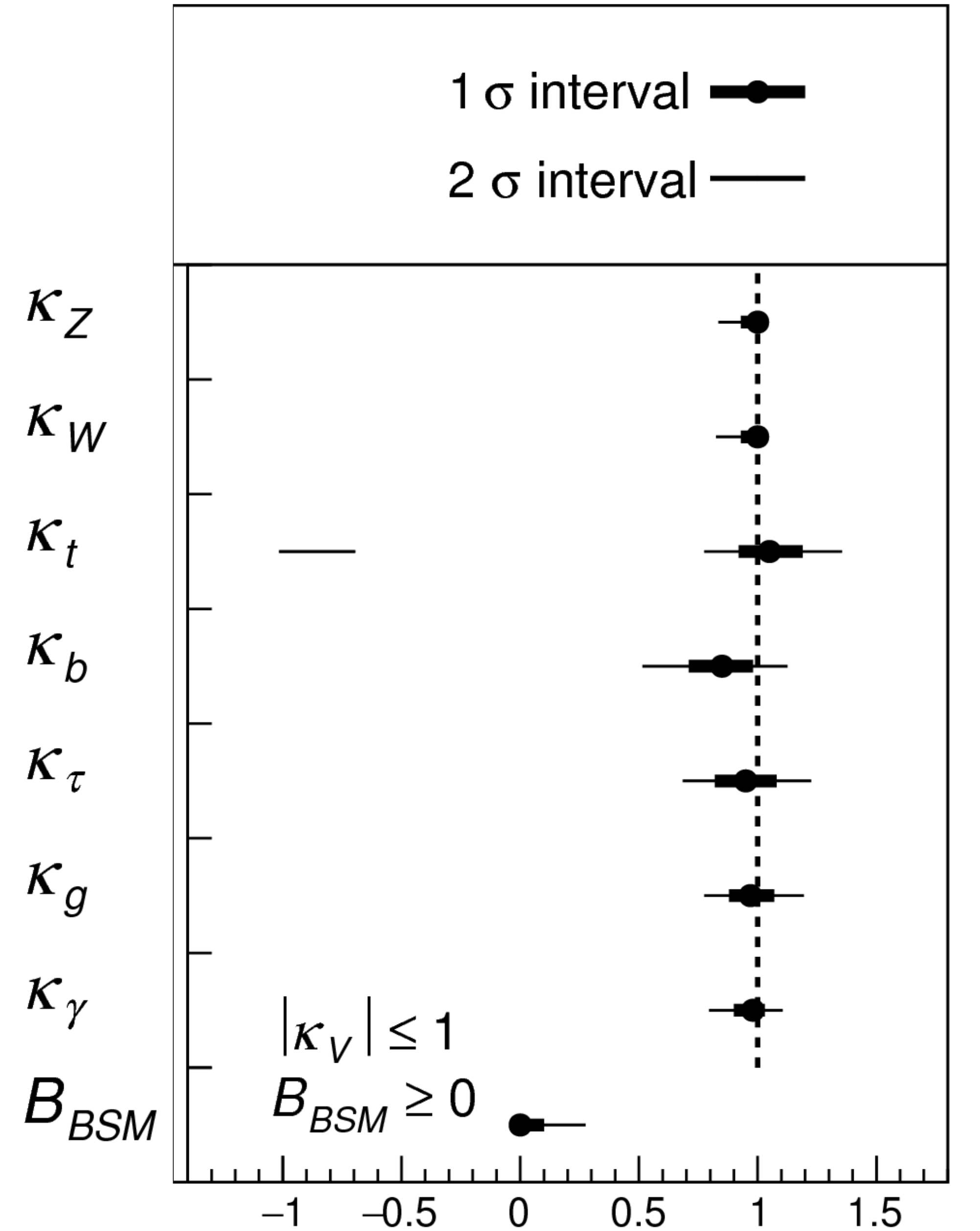
A few formulas:

$$(\sigma\cdot \mathrm{BR})(i\to \mathrm{H}\to f)=\frac{\sigma_i\cdot\Gamma_f}{\Gamma_H}$$

$$(\sigma\cdot \mathrm{BR})(i\to \mathrm{H}\to f)=\frac{\sigma_i^{SM}\kappa_i^2\cdot\Gamma_f^{SM}\kappa_f^2}{\Gamma_H^{SM}\kappa_H^2}\quad\to\quad \mu_i^f\equiv\frac{\sigma\cdot\mathrm{BR}}{\sigma_{\mathrm{SM}}\cdot\mathrm{BR}_{\mathrm{SM}}}=\frac{\kappa_i^2\cdot\kappa_f^2}{\kappa_H^2}$$

$$\kappa_H^2\equiv\sum_j\frac{\kappa_j^2\Gamma_j^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}}$$

$$\Gamma_H=\frac{\Gamma_H^{\mathrm{SM}}\cdot\kappa_H^2}{1-(BR_{inv}+BR_{unt})}$$



If $\mathrm{Br}_{\mathrm{BSM}}>0$ we need an extra condition on the overall scaling to break a flat direction

Phase II : Future prospects

[De Blas et al. 1905.03764]

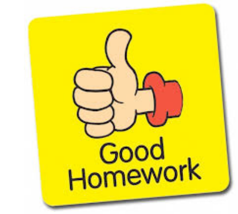
kappa-3 scenario	HL-LHC	HL-LHC + LHeC	HL-LHC + HE-LHC (S2)	HL-LHC + HE-LHC (S2')
$1 \geq \kappa_W > (68\%)$	0.985	0.996	0.988	0.992
$1 \geq \kappa_Z > (68\%)$	0.987	0.993	0.989	0.993
κ_g (%)	±2.	±1.6	±1.6	±1.
κ_γ (%)	±1.6	±1.4	±1.2	±0.82
$\kappa_{Z\gamma}$ (%)	±10.	±10. *	±5.5	±3.7
κ_c (%)	–	±3.7	–	–
κ_t (%)	±3.2	±3.2 *	±2.6	±1.6
κ_b (%)	±2.5	±1.2	±2.	±1.4
κ_μ (%)	±4.4	±4.4 *	±2.2	±1.5
κ_τ (%)	±1.6	±1.4	±1.2	±0.77
$\mathrm{BR_{inv}}$ (<%, 95% CL)	1.9	1.1	1.8 *	1.5 *
$\mathrm{BR_{unt}}$ (<%, 95% CL)	inferred using constraint $\lvert\kappa_V\rvert \leq 1$			
	4.	1.3	3.3	2.4

Phase II : Future prospects

[De Blas et al. 1905.03764]

kappa-3 scenario	HL-LHC+ ILC_{250}	ILC_{500}	ILC_{1000}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	FCC-ee_{240}	FCC-ee_{365}	FCC-ee/eh/hh
κ_W [%]	1.0	0.29	0.24	0.73	0.40	0.38	0.88	0.88	0.41	0.19
κ_Z[%]	0.29	0.22	0.23	0.44	0.40	0.39	0.18	0.20	0.17	0.16
κ_g[%]	1.4	0.85	0.63	1.5	1.1	0.86	1.	1.2	0.9	0.5
κ_γ [%]	1.4	1.2	1.1	1.4∗	1.3	1.2	1.3	1.3	1.3	0.31
$\kappa_{Z\gamma}$ [%]	10.∗	10.∗	10.∗	10.∗	8.2	5.7	6.3	10.∗	10.∗	0.7
κ_c [%]	2.	1.2	0.9	4.1	1.9	1.4	2.	1.5	1.3	0.96
κ_t [%]	3.1	2.8	1.4	3.2	2.1	2.1	3.1	3.1	3.1	0.96
κ_b [%]	1.1	0.56	0.47	1.2	0.61	0.53	0.92	1.	0.64	0.48
κ_μ [%]	4.2	3.9	3.6	4.4∗	4.1	3.5	3.9	4.	3.9	0.43
κ_τ [%]	1.1	0.64	0.54	1.4	1.0	0.82	0.91	0.94	0.66	0.46
BR_{inv} (<%, 95% CL)	0.26	0.23	0.22	0.63	0.62	0.62	0.27	0.22	0.19	0.024
BR_{unt} (<%, 95% CL)	1.8	1.4	1.4	2.7	2.4	2.4	1.1	1.2	1.	1.

Review questions: Higgs



1. Determine the scaling of the partial widths of the Higgs with respect to the Higgs mass and the final state particle mass for fermions and vector bosons.

2. Calculate the width of a pseudo-scalar into two gluons at one-loop or via the EFT.

3. List the most salient features (size, typical signatures, backgrounds, coupling information, status of the predictions) of the each of the main production mechanisms for the Higgs boson at the LHC.

4. Brainstorm on other Higgs subleading production mechanisms at the LHC. Imagine a reason why the could be interesting/useful. Guess-estimate their cross sections first, then check it with an automatic MC tool.

5. Brainstorm on how new physics could modify the couplings of the Higgs to the SM particles. Make a list of simple modification/additions to the SM and determine how the couplings, production and decay of the Higgs would be modified.

Top quark

The top is special

The top is special

In the SM is the **only** quark with a “natural mass”:

$$m_{top} = y_t\, v/\sqrt{2} \approx 174 \text{ GeV} \Rightarrow y_t \approx 1$$

i.e., it “strongly” interacts with the Higgs sector.

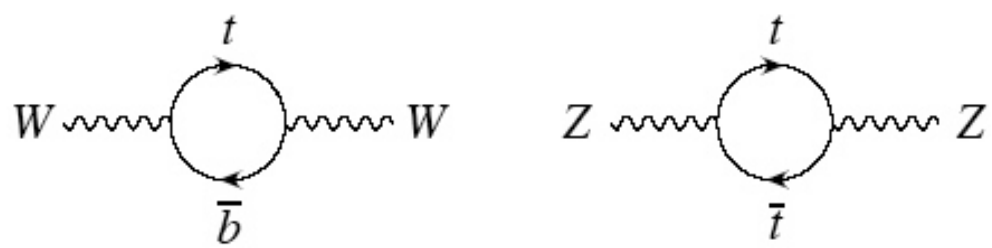
Therefore:

- It gives large corrections to EW observables.
- It points to a mass generation mechanism at low scales.
- It destabilises the Higgs mass.
- It allows to excite the Higgs boson (production).
- It deforms the Higgs potential at high energy.
- It decays semi-weakly.

Precision EW measurements

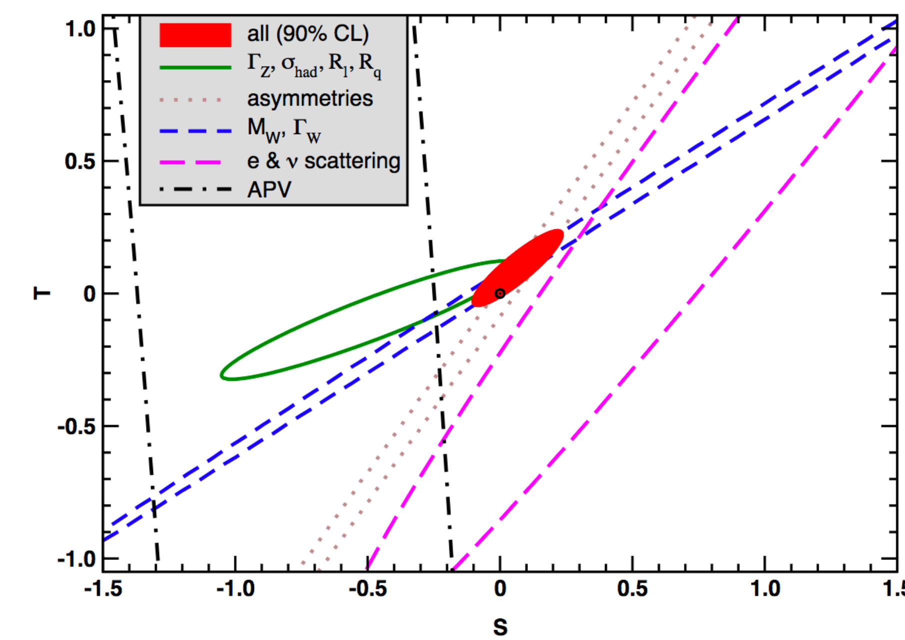
Indirect evidence for the existence of particles not yet detected can be inferred from quantum corrections. At tree level mW=mZ cos θW. At one loop:

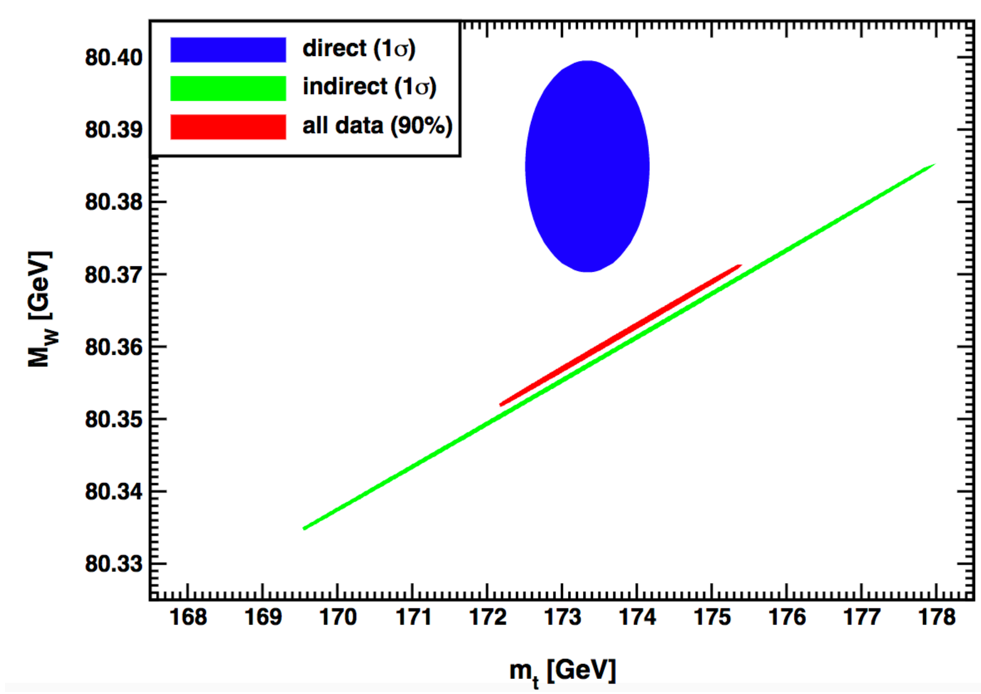
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$



$$\Delta r_{\rm top}=-\frac{3\alpha}{16\pi}\frac{\cos^2\theta_W}{\sin^4\theta_W}\frac{m_t^2}{m_W^2}$$

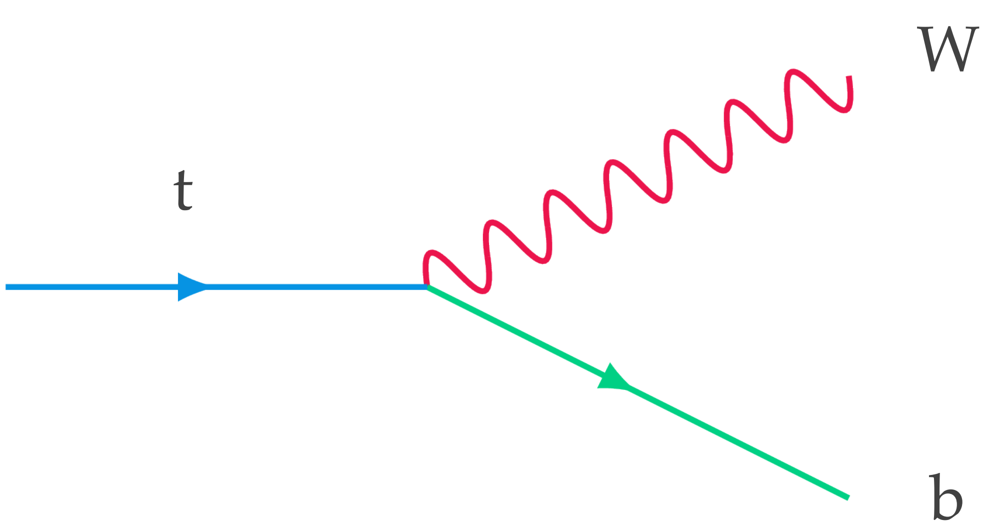
$$\Delta r_{\rm Higgs}=+\frac{11\alpha}{48\pi\sin^2\theta_W}\log\frac{m_H^2}{m_W^2}$$





The top is special

Thanks to its large mass it is the only quark that decays before hadronising



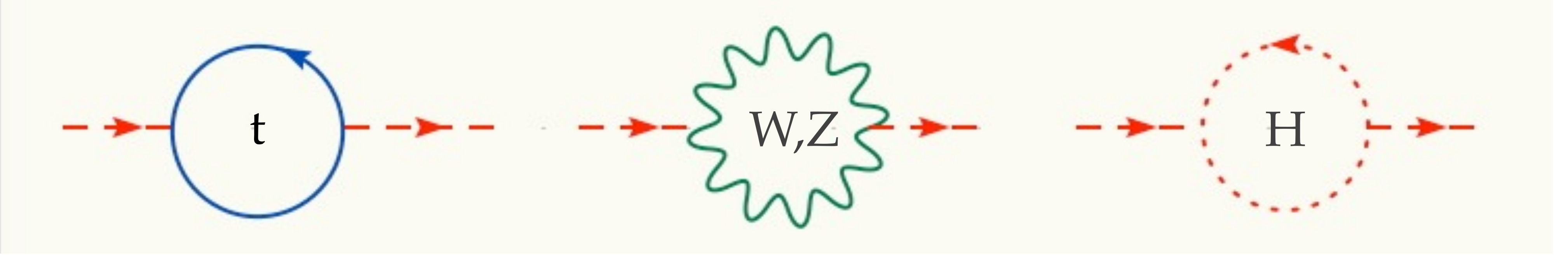
b

$\tau_{had} \approx h/\Lambda_{QCD} \approx 2 \bullet 10^{-24}$ s
$\tau_{top} \approx h/\ \Gamma_{top} = 1/(GF\ m_t^3\ |Vtb|2/8\pi\sqrt{2}) \approx 5 \bullet 10^{-25}$ s
(with $h = 6.6\ 10^{-25}$ GeV s)

(Compare with $\tau_b \approx (GF^2\ mb^5\ |V_{bc}|^2\ )^{-1} \approx 10^{-12}$ s)

Naturalness in the SM

The Higgs mass is renormalised additively. Using a cutoff the regularization :



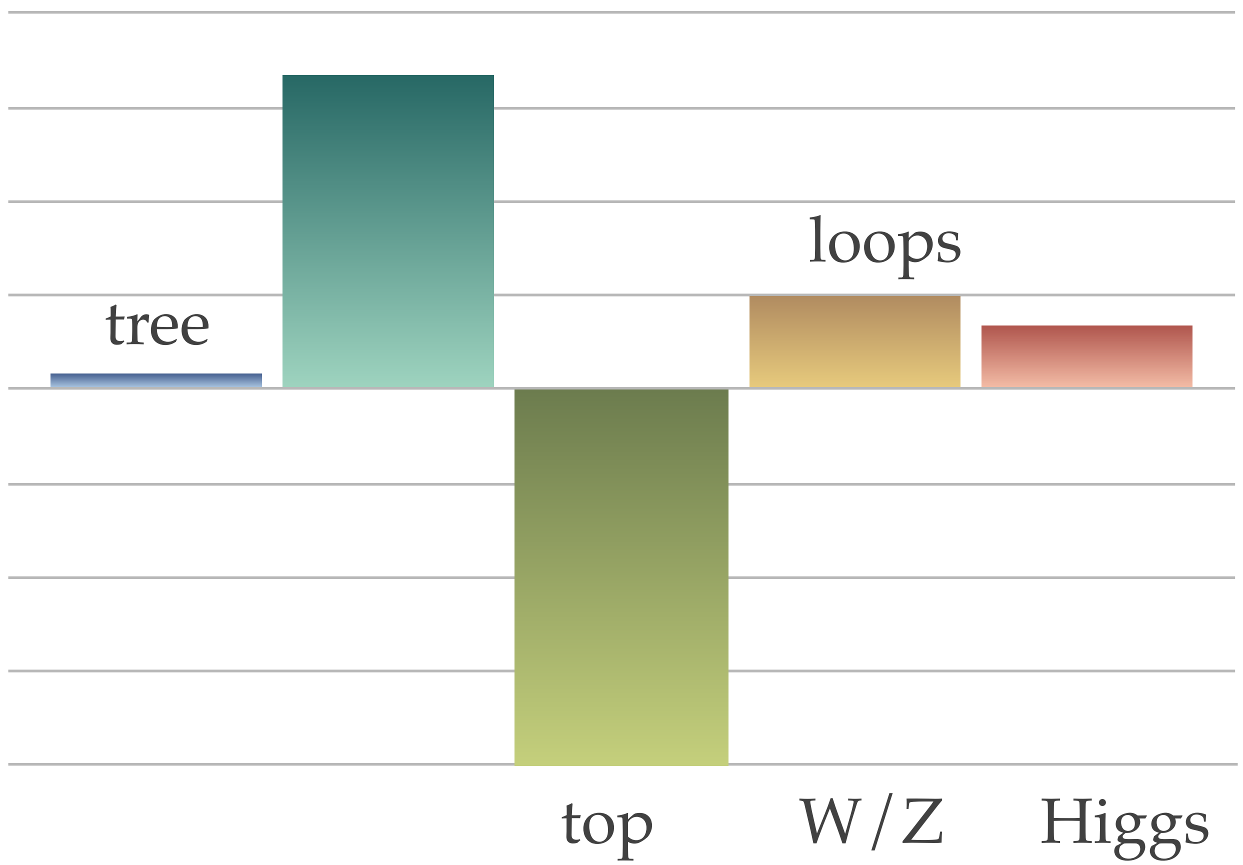
$$m_H^2 = m_{H0}^2 \qquad - \frac{3}{8\pi^2} y_t \Lambda^2 \qquad + \frac{1}{16\pi^2} g^2 \Lambda^2 \qquad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

Putting numbers, one gets:

$$(125\,\mathrm{GeV})^2 = m_{H0}^2 + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right] \left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

Naturalness in the SM

$m_H^2 \sim (125\text{ GeV})^2$

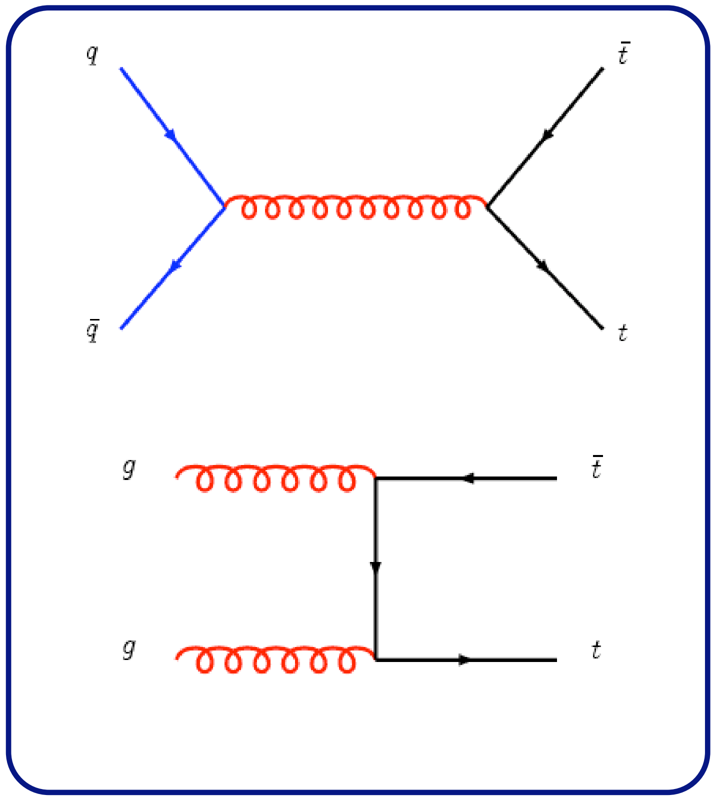
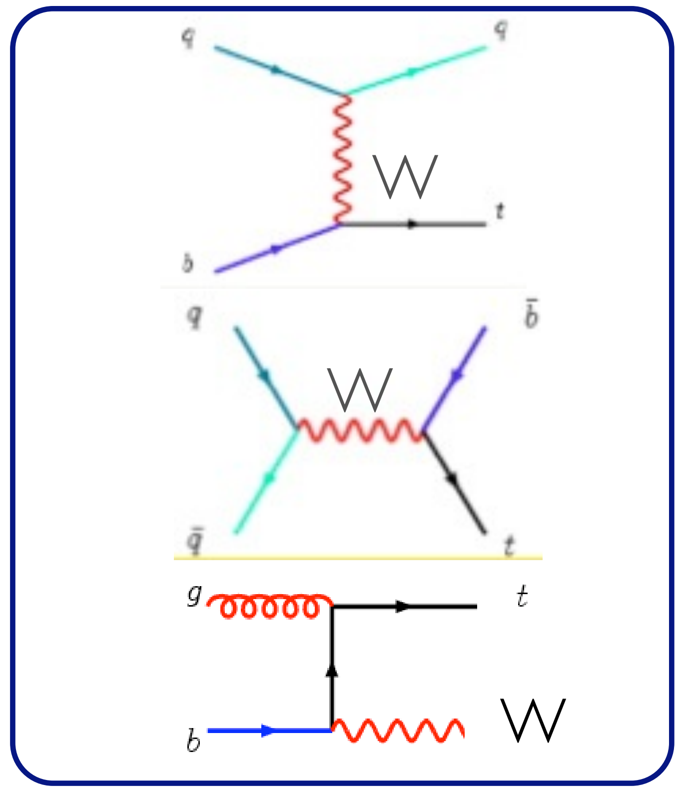
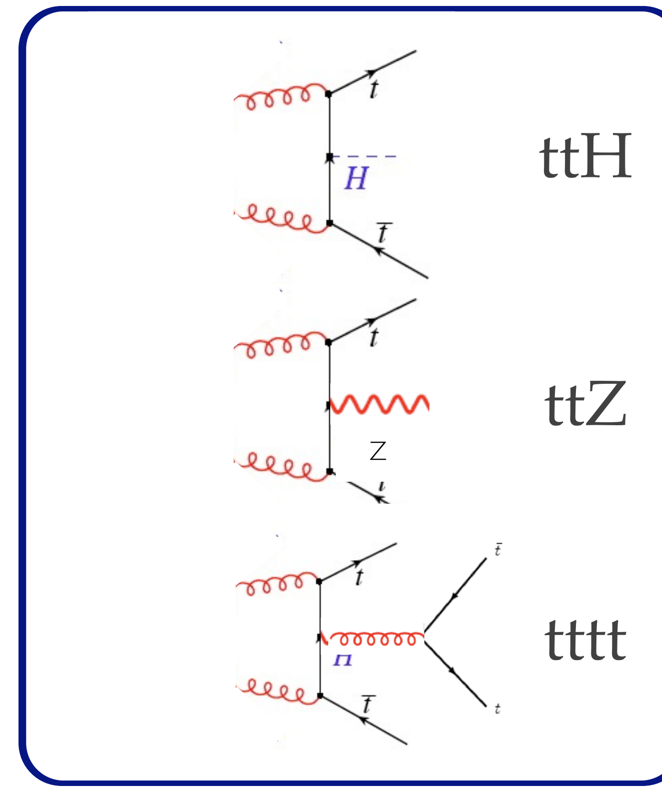


$$(125\,\text{GeV})^2 = m_{H0}^2 + \left[-(2\,\text{TeV})^2 + (700\,\text{GeV})^2 + (500\,\text{GeV})^2\right]\left(\frac{\Lambda}{10\text{TeV}}\right)^2$$

Definition of naturalness: less than 90% cancellation:

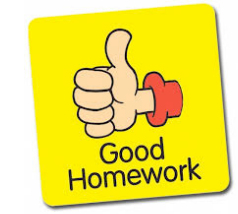
$\Lambda_t < 3\,\text{TeV}$ $\Rightarrow$ top partners must be "light"

Top production at the LHC

Strong	Weak	Associated
		
10^6	$250 \cdot 10^3$	$< (2-3) \cdot 10^3$

number of events @13TeV 1 fb^{-1}

Review questions: top



1. How does the top width scale with the top mass?

2. Is there an upper bound to the top-quark mass?

3. Imagine the top quark mass were half of its value. What would be the consequences for the SM and the LHC phenomenology?

4. How would you look for a fourth generation? Why nobody talks about its existence lately?

5. Explain the difference between a short-distance mass and the pole mass.

Plan for today's lecture

- Review of the Standard Model
- SMEFT essentials

Plan for today's lecture

- Review of the Standard Model
- SMEFT essentials

SMEFT Lagrangian: Dim=6

[Buchmuller and Wyler, 86] [Grzadkowski et al, 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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	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 Lagrangian: Dim=6

[Buchmuller and Wyler, 86] [Grzadkowski et al, 10]

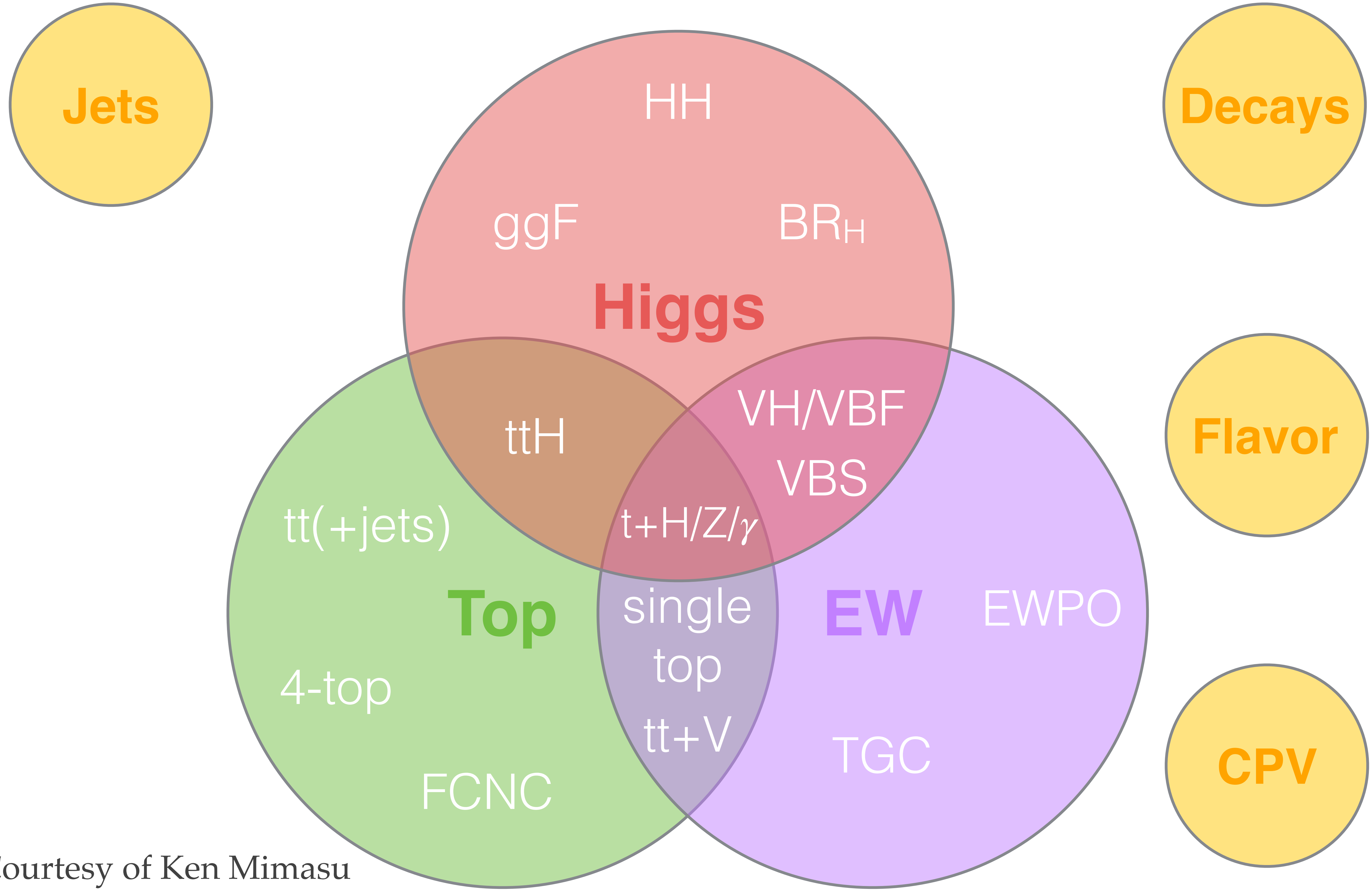
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Which interactions?

- Interactions between light fermions and gauge bosons tested at low energies and at LEP at below the per mill level.
- Self interactions of weak gauge bosons tested at LEP II High energy at the % level and can be competitive at the LHC
- Higgs interactions with gauge bosons constrained at 10% level.
- Top-quark interactions with gauge bosons and the Higgs at 10% level.
- Higgs self interactions unexplored
- Higgs interactions with light fermions unexplored.

t, H, W, Z



Courtesy of Ken Mimasu

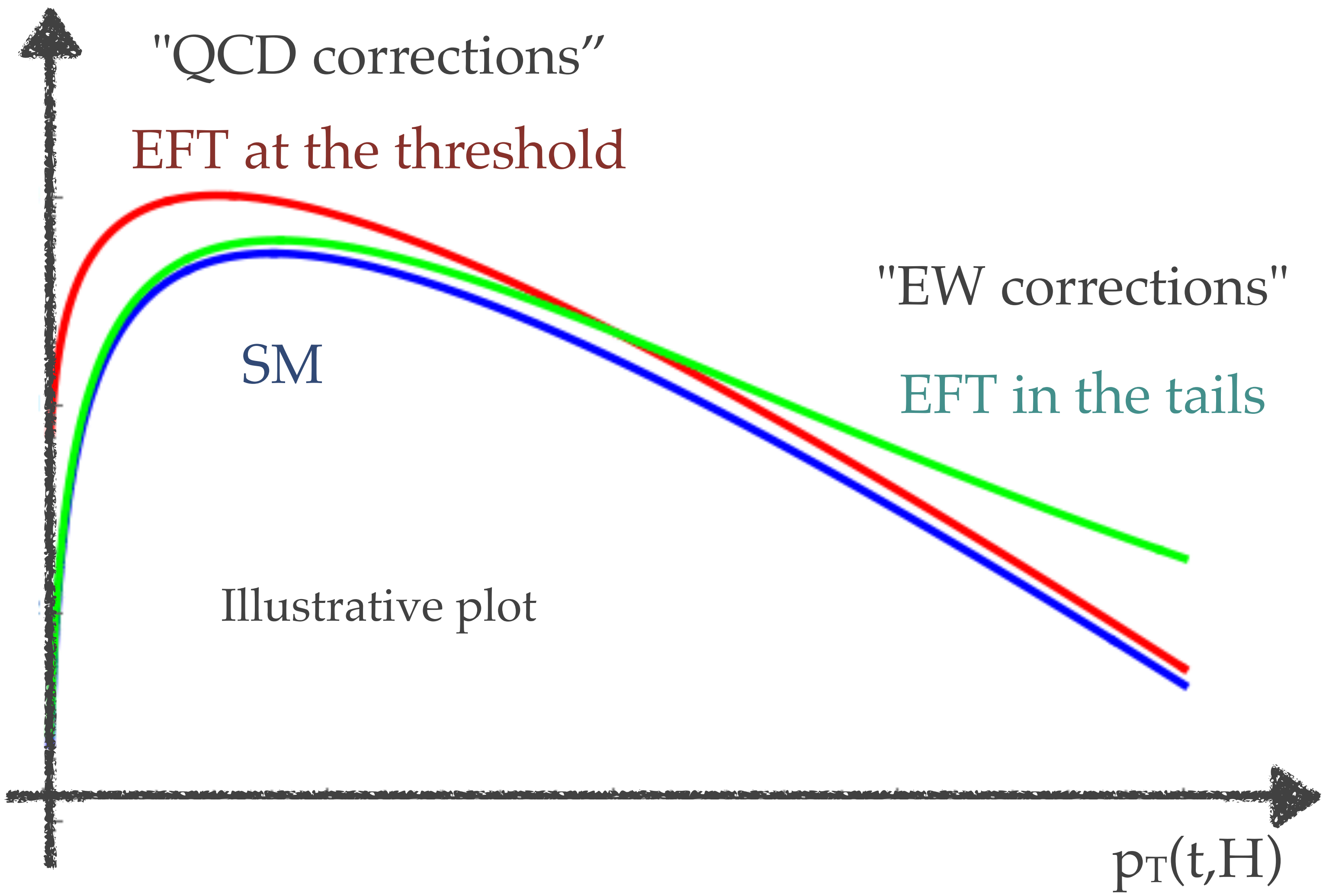
SMEFT Lagrangian: Dim=6

- Based on all the symmetries of the SM
- New physics is heavier than the resonance itself : $\Lambda > M_X$
- QCD and EW renormalisable (order by order in $1/\Lambda$)
- Number of extra couplings reduced by symmetries and dimensional analysis
- Extends the reach of searches for NP beyond the collider energy.

The EFT approach: managing unknown unknowns

- Very powerful model-independent approach.
- A **global constraining strategy** needs to be employed:
  - assume all* couplings not be zero at the EW scale.
  - identify the operators entering predictions for each observable (LO, NLO,..)
  - find enough observables (cross sections, BR's, distributions,…) to constrain all operators.
  - solve the linear (+quadratic)* system.
- Use to constrain UV-complete* models.
- The final reach on the scale of New Physics crucially depends on the THU.

SMEFT at the LHC



The expected effects can be both at threshold as well as in the tails. Some operators can affect distributions at the threshold. Some operators just lead to global rescaling of the distributions. Other induce an energy growth in the tails. The latter are the most characteristic EFT effects that are looked for.

The sensitivity to new interactions depends on a crucial way to our ability to make accurate/precise predictions for the SM observables. The reach of our interpretations will also depend on the accuracy/precision on the SMEFT predictions.

SMEFT at the LHC

S is a generic scale, which is process and operator dependent

- Large number of operators, yet a plethora of observables and final states to measure.
- Precision observables in the bulk of the distributions while tails provide sensitivity through the energy growth.
- Validity issues arise, as well as for the interpretation in terms of models.

SMEFT at the LHC

s is a generic scale, which is process and operator dependent

$$\text{Obs}_i = \text{Obs}_i^{\text{SM}} + M_{ij} \cdot \frac{s}{\Lambda^2} c_j$$

- Large number of operators, yet a plethora of observables and final states to measure.
- Precision observables in the bulk of the distributions while tails provide sensitivity through the energy growth.
- Validity issues arise, as well as for the interpretation in terms of models.

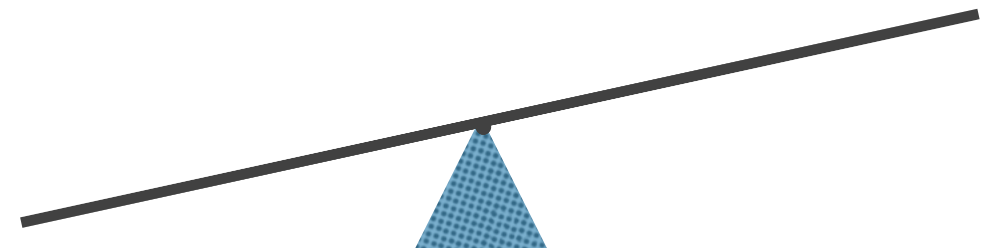
SMEFT at the LHC

s is a generic scale, which is process and operator dependent

$$\mathrm{Obs}_i = \mathrm{Obs}_i^{\mathrm{SM}} + M_{ij} \cdot \frac{s}{\Lambda^2}\, c_j$$

- Large number of operators, yet a plethora of observables and final states to measure.
- Precision observables in the bulk of the distributions while tails provide sensitivity through the energy growth.
- Validity issues arise, as well as for the interpretation in terms of models.

$$\Lambda > \sqrt{s}\sqrt{|c_i|/\delta}$$



$$|c_i| s/\Lambda^2 < \delta$$

SMEFT at the LHC

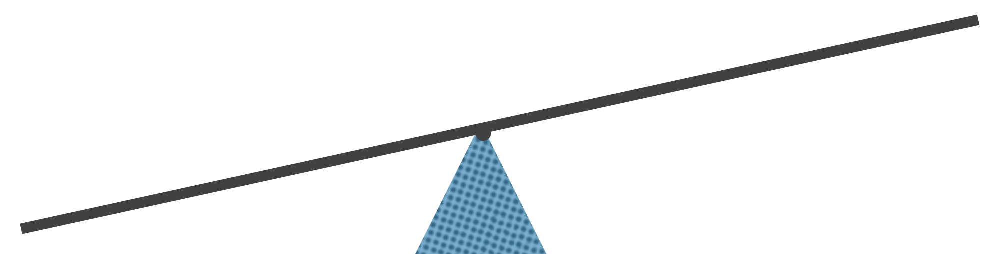
s is a generic scale, which is process and operator dependent

- Large number of operators, yet a plethora of observables and final states to measure.

$$\text{Obs}_i = \text{Obs}_i^{\text{SM}} + M_{ij} \cdot \frac{s}{\Lambda^2}\, c_j$$

- Precision observables in the bulk of the distributions while tails provide sensitivity through the energy growth.

$$\Lambda > \sqrt{s}\sqrt{|c_i|/\delta}$$



$$|c_i|s/\Lambda^2 < \delta$$

- Validity issues arise, as well as for the interpretation in terms of models.

$$\sqrt{s} < \Lambda$$