Report from the LHC Higgs Cross Section Low Mass group

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for the LHCHXSLM working group
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Mandate of the group

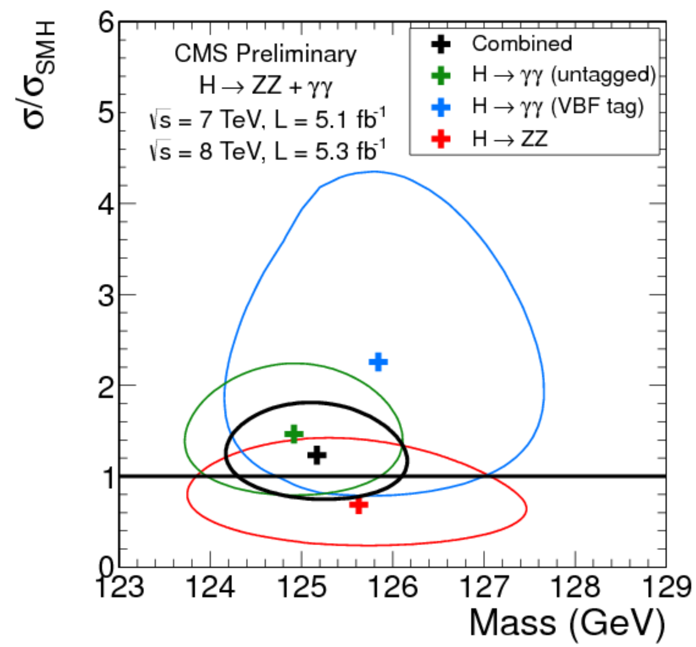
- **Issues concerning σ*BR, in particular issues connected to the decays $H\rightarrow\gamma\gamma$, $\tau\tau$, bb, WW and ZZ**

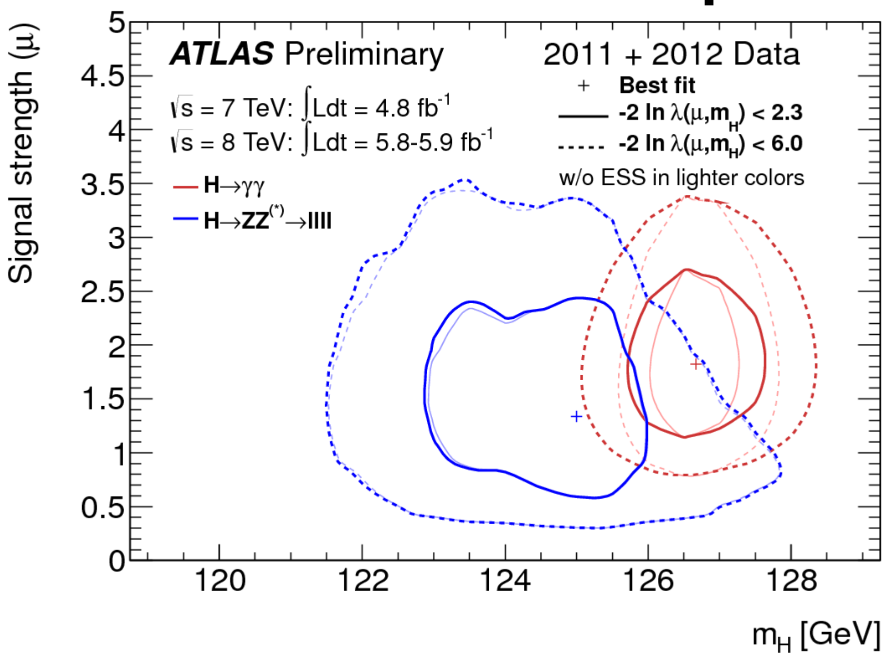
- **Higgs property measurements:**
  - **Higgs mass, width**
  - **σ*BR**
  - **J^PC**
  - **couplings (HVV, Yukawa, trilinear, quartic)**

- **As the Higgs results were already shown, the focus of this talk is on the strategy**

Mass and width

- "Peak" observed for m_H ~ 125-127 GeV
- Expected width for a SM Higgs: $\Gamma_{SM}(m_H)$ ~ 4 MeV
- Expected experimental resolution ~1 GeV
- Are theory uncertainties important?
  - Theory uncertainty on the mass should be roughly of order $\Gamma_{SM}(m_H)$
  - Nothing in the pattern of observed channels indicates that the real width could be several orders of magnitude larger (if its a Higgs) → theory uncertainties most likely negligible
- **Direct measurement/limit on the width nevertheless important !**





σ*BR

- **Currently σ*BR related results are made public by the experiments in the form of best-fit μ for the different channels**

- **However the evaluation of the sharing of contributions from different initial states is driven by the SM**

- **Different categories have different sensitivities/efficiencies to the various SM Higgs production modes, but in almost no case they are pure in one production channel**
  $\rightarrow$ μ actually determined for an analysis selection
  If we want to remove some of the SM dependence in understanding the different μ
  $\rightarrow$ coupling measurements

Measuring the Higgs couplings

Topic of long discussion within the group

Rough outline of current strategy:

1) Search for deviations from the SM Higgs hypothesis

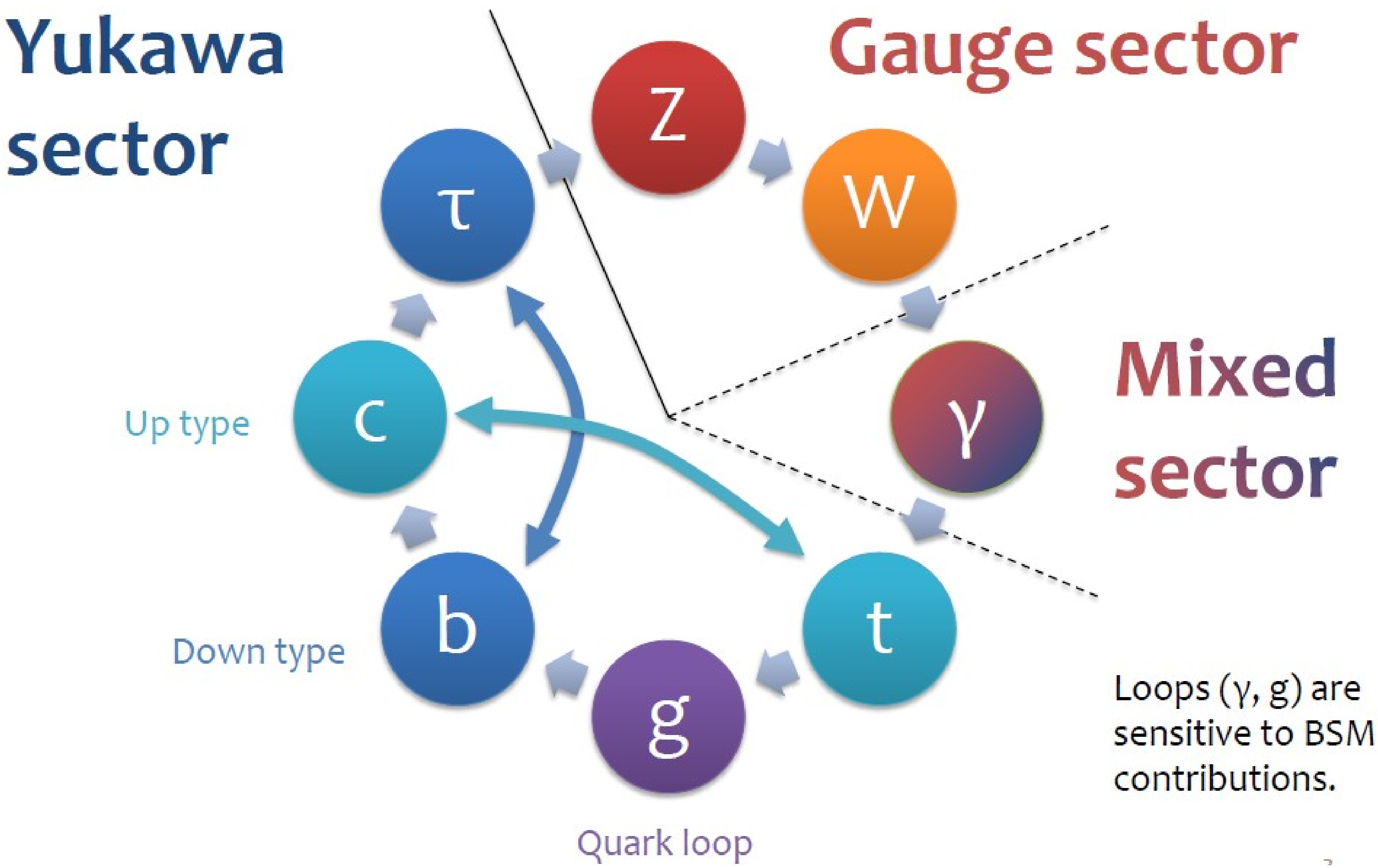
- **Start from the most precise SM σ*BR calculations**
- **Apply production and decay mode scale factors that correspond at LO to a Higgs gauge or Yukawa coupling**
- **As the data is not sufficiently powerful yet, run various benchmarks with different scale factor combinations that test possible BSM Higgs effects**

2) Analyze data using a BSM effective Lagrangian

- **Once any deviation from the SM is found in 1), the baseline σ*BR calculations are no longer valid**
- **Postulate consistent BSM Lagrangian and fit BSM couplings to the data**

Search for deviations from the SM Higgs hypothesis

- **Attach some scale factor to each LO Higgs coupling**
- **Can motivate these LO scale factors also by higher dim. operators**
- **Accessible at LHC through initial or final state for a SM Higgs W, Z, t, b, τ, g (gluon), γ, eventually also μ**



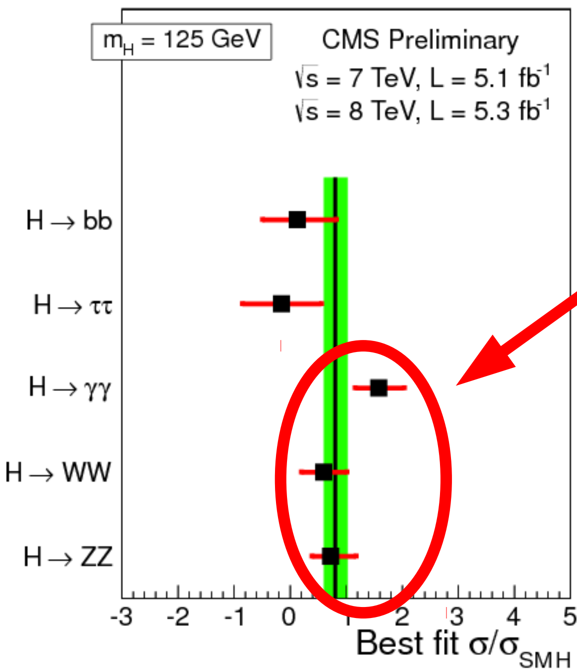
Search for deviations from the SM Higgs hypothesis

- **Start from the best calculate SM σ*BR** (with (N)NLO and (N)NLL)
- **Dress with scale factors C_W, C_Z, C_γ, C_g, C_τ, C_t, C_b, $C_{inv/undet}$**
- **Total width: $C_H(C_X)=1/\Gamma_H * (C_W*\Gamma W + C_Z*\Gamma Z + \ldots + C_{inv/undet})$**
- **Some "complicated" functions for VBF+loops (only LO):**
  $C_{VBF}(C_X)=f_{VBF}(C_W,C_Z)$
  $C_\gamma(C_X)=f_\gamma(C_W,C_t,C_\gamma^{new})$ → **can fit just C_γ or fit loop contributions**
  $C_g(C_X)=f_g(C_t,C_b,C_g^{new})$ → **can fit just C_g or fit loop contributions**
- **General examples:**

$$\sigma(gg\to H\to\gamma\gamma, m_H) = \sigma_{SM}(gg\to H\to\gamma\gamma, m_H) * C_g * C_\gamma / C_H$$
$$\sigma(VBF\ H\to\gamma\gamma, m_H) = \sigma_{SM}(VBF\ H\to\gamma\gamma, m_H) * C_{VBF} * C_\gamma / C_H$$
$$\sigma(gg\to H\to ZZ, m_H) = \sigma_{SM}(gg\to H\to ZZ, m_H) * C_g * C_Z / C_H$$
$$\sigma(VBF\ H\to\tau\tau, m_H) = \sigma_{SM}(VBF\ H\to\tau\tau, m_H) * C_{VBF} * C_\tau / C_H$$
$$\sigma(W/Z\ H\to bb, m_H) = \sigma_{SM}(W/Z\ H\to bb, m_H) * C_{W/Z} * C_b / C_H$$
$$\sigma(XX\to H\to YY, m_H) = \sigma_{SM}(XX\to H\to YY, m_H) * C_X * C_Y / C_H$$

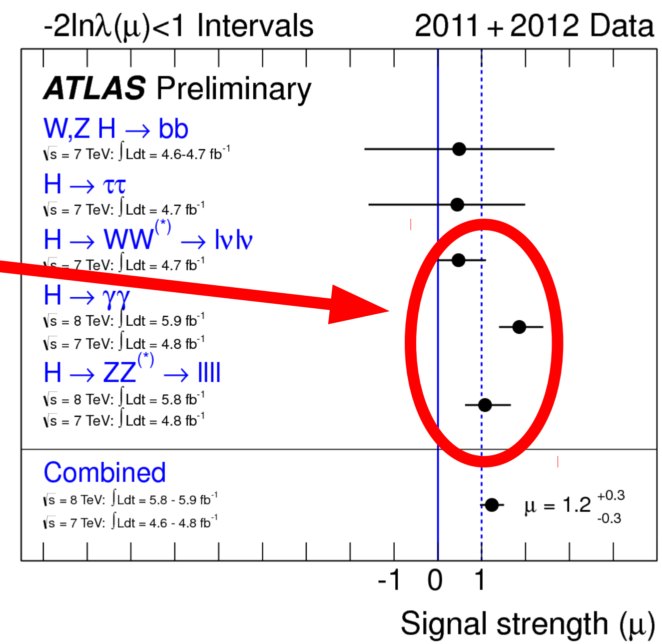
Confronting with current LHC reality

- Even with perfect measurements, not all C_X could be measured independently: some ambiguity with the total width always remains without assumptions
- Currently data is by far not strong enough to give meaningful results for more than 2-3 independent C_X



Best channels with $\Delta\mu/\mu<100\%$ mostly dominated by inclusive (ggF) production

→ effectively we have only 3-4 independent measurements

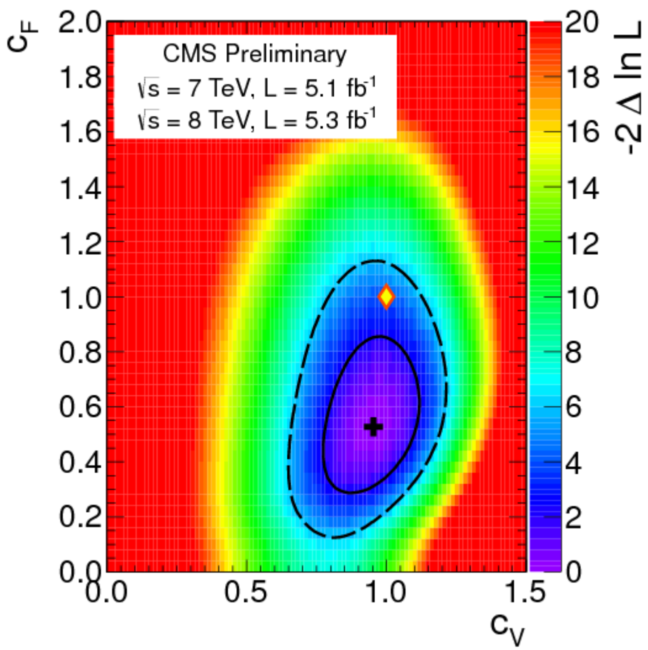


- Need to chose several benchmarks that combine C_X parameters and then test different aspects of where deviations from the SM could appear

Possible benchmark: C_V, C_F

- **Assumptions:**
  - **No new physics contributions to gg→H or H→γγ loops**
  - **No new physics decay modes (e.g. H→invisible or undetectable)**
  - **Parameters:**

    $C_V = C_W = C_Z$; $C_\gamma(C_X)$, $C_g(C_F)$; $C_F = C_\tau = C_t = C_b = C_c$; $C_{inv} = 0$
- **Given the current data, best determined, but uncertainties still large**



Production	Decay	LO SM ($m_H = 125$ GeV), $\Gamma(H) \sim 1/C_F^2$	
VH	$H \to bb$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to \tau\tau$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to \tau\tau$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
ggH	$H \to ZZ$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to WW$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to WW$	$\sim \frac{C_V^2 \times C_V^2}{C_F^2}$	$\sim C_V^4/C_F^2$
ggH	$H \to \gamma\gamma$	$\sim \frac{C_F^2 \times (8.6C_V - 1.8C_F)^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to \gamma\gamma$	$\sim \frac{C_V^2 \times (8.6C_V - 1.8C_F)^2}{C_F^2}$	$\sim C_V^4/C_F^2$

Possible benchmark: C_V, C_{up} , C_{down}

- **Allow up- and down-type Yukawa couplings to be different**

- **Assumptions:**
  - **No new physics contributions to $gg \rightarrow H$ or $H \rightarrow \gamma\gamma$ loops**
  - **No new physics decay modes (e.g. $H \rightarrow$ invisible or undetectable)**
  - **Parameters:**
    $C_V = C_W = C_Z$; $C_\gamma(C_X)$, $C_g(C_X)$;
    $C_{down} = C_\tau = C_b$; $C_{up} = C_t = C_c$; $C_{inv} = 0$

- **$gg \rightarrow H$ dominated by C_t, total width dominated by C_b. Current data might just be sufficient, but where previously the C_F from $gg \rightarrow H$ and C_F from $\Gamma_H \sim \Gamma_b$ in the dominator canceled, now the ratio C_{up}/C_{down} remains in all the strong gluon fusion channels**

Possible benchmark: C_V, C_F, C_γ

- **Assumptions:**
  - **No new physics contributions to the gg→H loop**
  - **No new physics decay modes (e.g. H→invisible or undetectable)**
  - **Parameters:**
    $C_V=C_W=C_Z$; C_γ , $C_g(C_F)$; $C_F=C_\tau=C_t=C_b=C_c$; $C_{inv}=0$

- **Allows an extra degree of freedom for the H→γγ channel, which currently shows the largest deviations from the SM**

Possible benchmark: C_g, C_γ

- **Somehow orthogonal to previous benchmarks**

- **Assumptions:**
  - **No new physics decay modes (e.g. no H→invisible or H→undetectable)**
  - **Higgs couplings to known SM particles as in the SM**
  - **Parameters:**
    C_γ, C_g ; $C_W=C_Z=C_\tau=C_b=C_t=C_c=1$; $C_{inv}=0$

- **Allow for new physics contributions to gg→H or H→γγ loops**
  fit $C_\gamma(C_X, C_\gamma^{new})$, $C_g(C_X, C_g^{new})$ or just C_γ, C_g

- **gg→H→WW/ZZ only sensitive to gluon loop,**
  gg→H→γγ sensitive to both loops
  → current data should be sufficient

Benchmark "without" assumptions?

- **Combine previous (C_V, C_F) and (C_g, C_γ) benchmarks**
- **No assumption on the total width :**
  - **Need to incorporate the total width scale factor C_H somehow into the parameters**
  - **Fitted parameters R_{XY} are ratios of the previous C_X/C_Y**
- **Example**

  $R_{Vg} = C_V/C_g$; $R_{\gamma V} = C_\gamma / C_V$; $R_{FV} = C_F / C_V$; $\mu = C_g \cdot C_V / C_H = \sigma(gg \to H \to VV)$
  - $\sigma(gg \to H \to \gamma\gamma, m_H) = \sigma_{SM}(gg \to H \to \gamma\gamma, m_H) * \mu * R_{\gamma V}$
  - $\sigma(VBF\ H \to \gamma\gamma, m_H) = R_{Vg} * \sigma_{SM}(VBF\ H \to \gamma\gamma, m_H) * \mu * R_{\gamma V}$
  - $\sigma(gg \to H \to WW/ZZ, m_H) = \sigma_{SM}(gg \to H \to WW/ZZ, m_H) * \mu$
  - $\sigma(VBF\ H \to \tau\tau, m_H) = R_{Vg} * \sigma_{SM}(VBF\ H \to \tau\tau, m_H) * \mu * R_{fV}$
  - $\sigma(W/Z\ H \to bb, m_H) = R_{Vg} * \sigma_{SM}(W/Z\ H \to bb, m_H) * \mu * R_{fV}$
- **Given current data, one can expect μ and $R_{\gamma V}$ to be somehow well "measured", while R_{Vg} and R_{fV} are only determined by the weak channels → for the near future?**

What else when looking for deviations from a SM Higgs ?

- We know that some SM effects are not (completely) taken into account yet :
  - NWA/ZWA approximation
  - Strict treatment of interference effects with SM backgrounds
  - Interference effects in the signal, when C_x!=1 ?
  - NLO QCD effects in the gg→H loop when C_x!=1
  - Complete correlation of theory uncertainties given the different analysis selections
- Soon measurements will be sufficiently sensitive that these issues matter → better take them into account

What else when looking for deviations from a SM Higgs ?

- **Of course with more data, more complicated fits can be done with less/different assumptions that might probe a direction not visible in one of the "simple" benchmarks**
  → example C_W!=C_Z, C_b!=C_τ, ...
  → will be tried for sure once it is possible

- **As usual, two options for results:**
  - **Results stay compatible with SM**
    → theory and experiments "race" for precision
  - **Results show a deviation from the SM somewhere**
    → this means all underlying σ*BR computations are no longer strictly valid and also signal kinematics might be affected
    → Start fresh and question all previous Higgs "measurements"

Effective BSM Lagrangian

- **Multiplying the plain SM couplings just with constants C_x gives no valid theory**
  → C_x != 1 might be an experimental result, but not a well defined quantity in the SM
- **Need a theory that intrinsically contains the effect caused by the measured C_x → consistent BSM theories**
- **Need to redo all σ*BR calculations with these theories and fit the free BSM parameters to the data**
  → a valid BSM attempt should explain the data
  → reiterate with more data and rule out more models
- **Many BSM models are possible and were already shown during this workshop and far more will arrive**
  - **Anomalous couplings**
  - **Several Higgs**
  - **Additional particles appearing somewhere**
  - **Something playing to look like a Higgs**
  - **…**
- **Proposals will be discussed in the next LM meeting !**

Spin / CP (J^PC)

- Need to do shape analysis for signal events
- So far we have a significant amount of events to observe the total signal in some channels, but statistics is not sufficient yet for signal shape analysis
- Signal strength is not necessarily predicted
  → removes currently strongest data constrain from the measurement

- BUT: More data will turn this into a hot topic, especially once the fermion initial/final states get accessible
- Several MC generators are available, but experiments can't simply take the analysis used for the Higgs searches and recast
  → dedicated analysis needed for each initial and final state !
- not trivial to combine between channels, as different channels might see different projections of CP

- Spin/CP will move into focus in the next LHCHXSWG LM meetings
  → **more details this afternoon in “WG1: Higgs properties ”**

Summary of properties

- **Mass ? → almost there**

- **Couplings ? → in work**
  - **Search for deviations from SM expectation based on SM Higgs calculations and LO scale factors**
  - **Several benchmarks how theory aspects can already be probed with current data**
  - **If a deviation from the SM is found**
    → need to reanalyze data with consistent BSM Lagrangian
  - **Document results in the next week(s)**

- **Spin/CP? → more details this afternoon**

Information sheet

- **Light Mass group wiki:**
  https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsLightMass

- **Email list of the Light Mass group:**
  lhc-higgs-lm@cern.ch

- **LHC Higgs XS Indico:**
  https://indico.cern.ch/categoryDisplay.py?categId=2792

- **Next Light Mass meeting: 27 July**

- **We are looking forward to your contributions!**

Backup

$$\frac{\Gamma(b\bar{b})}{\Gamma_{SM}(b\bar{b})} = C_b^2 \qquad = C_F^2$$

$$\frac{\Gamma(\tau\tau)}{\Gamma_{SM}(\tau\tau)} = C_\tau^2 \qquad = C_F^2$$

$$\frac{\Gamma(WW)}{\Gamma_{SM}(WW)} = C_W^2 \qquad = C_V^2$$

$$\frac{\Gamma(ZZ)}{\Gamma_{SM}(ZZ)} = C_Z^2 \qquad = C_V^2$$

$$\frac{\Gamma(\gamma\gamma)}{\Gamma_{SM}(\gamma\gamma)} = \frac{|C_t A_t + C_b A_b + C_W A_W|^2}{|A_t + A_b + A_W|^2} \qquad = \frac{|C_F(A_t + A_b) + C_V A_W|^2}{|A_t + A_b + A_W|^2}$$

$$\frac{\Gamma(Z\gamma)}{\Gamma_{SM}(Z\gamma)} = \frac{|C_t B_t + C_b B_b + C_W B_W|^2}{|B_t + B_b + B_W|^2} \qquad = \frac{|C_F(B_t + B_b) + C_V B_W|^2}{|B_t + B_b + B_W|^2}$$

$$\frac{\sigma(ggH)}{\sigma_{SM}(ggH)} = \frac{|C_t A_t + C_b A_b|^2}{|A_t + A_b|^2} = C_F^2$$

$$\frac{\sigma(VBF)}{\sigma_{SM}(VBF)} = \frac{C_W^2 + C_Z^2 R_{VBF}}{1 + R_{VBF}} = C_V^2$$

$$\frac{\sigma(WH)}{\sigma_{SM}(WH)} = C_W^2 = C_V^2$$

$$\frac{\sigma(ZH)}{\sigma_{SM}(ZH)} = C_Z^2 = C_V^2$$

$$\frac{\sigma(t\bar{t}H)}{\sigma_{SM}(t\bar{t}H)} = C_t^2 = C_F^2$$