Multiple Higgs Production at the LHC

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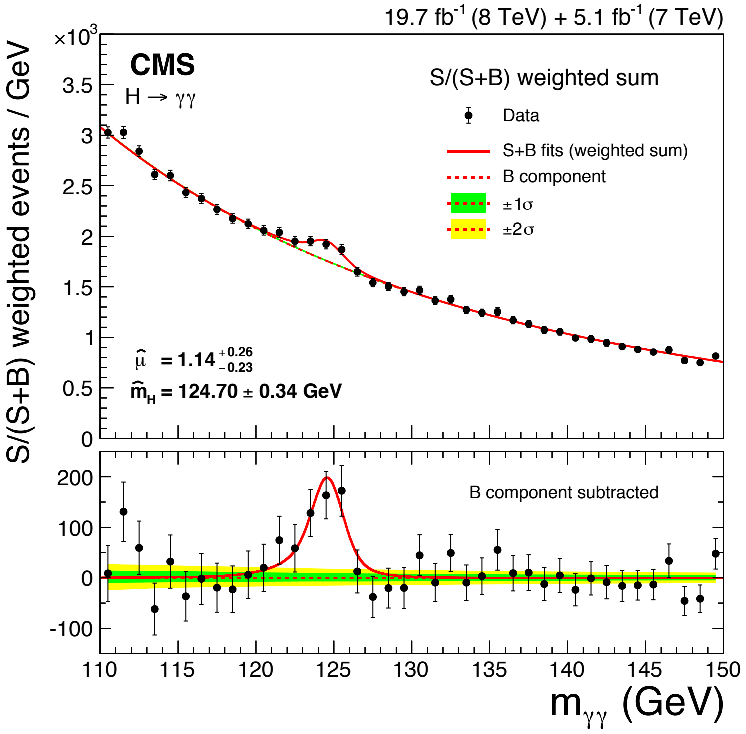
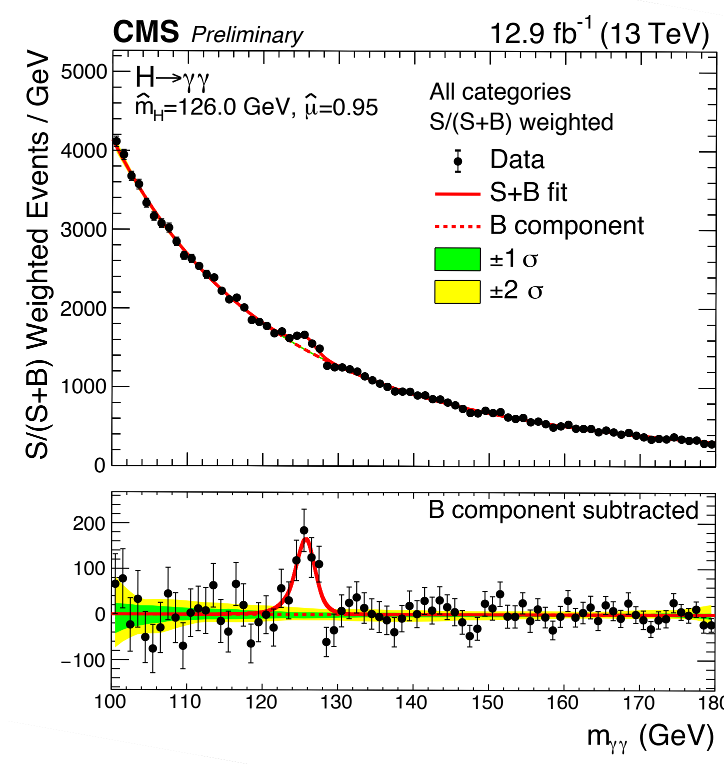
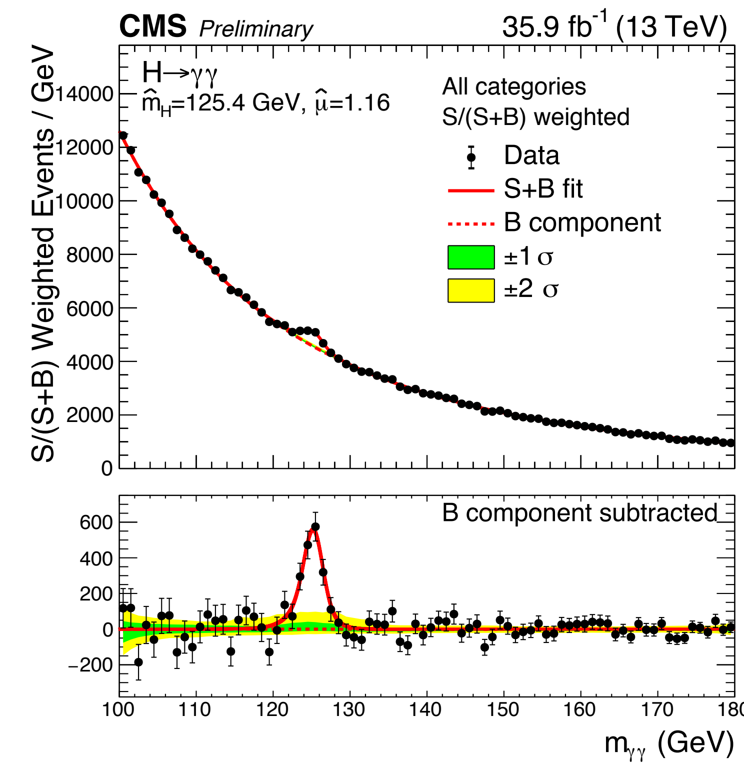
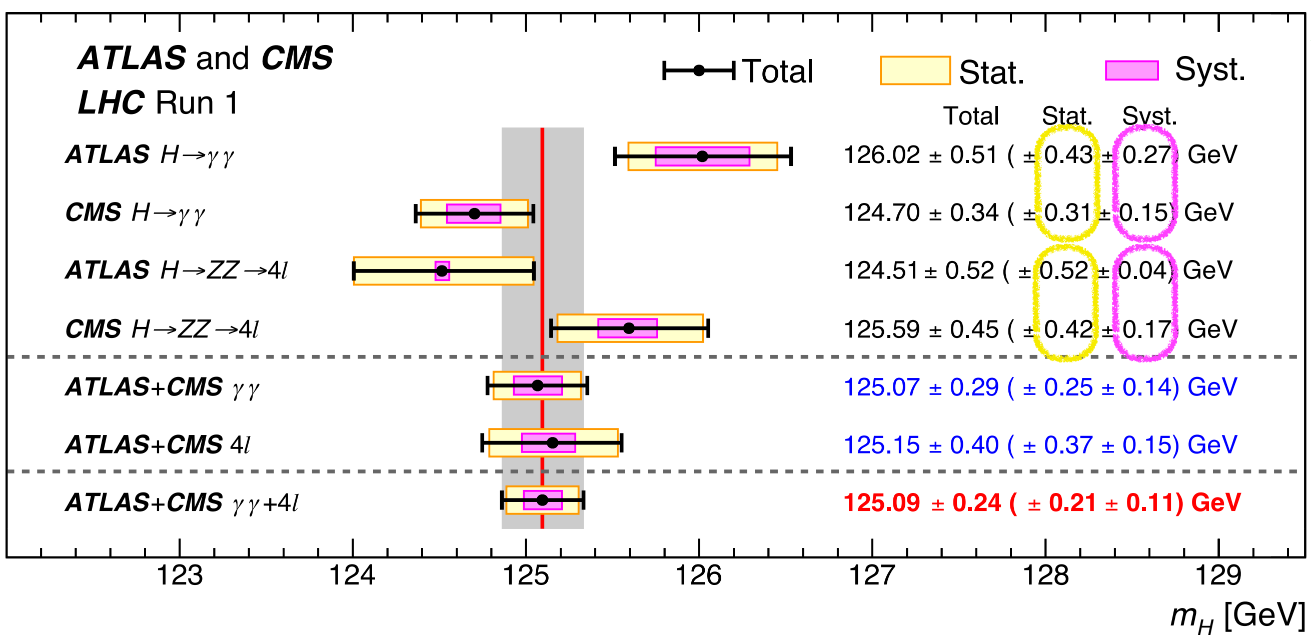
Higgs discovered, re-discovered and re-re-discovered



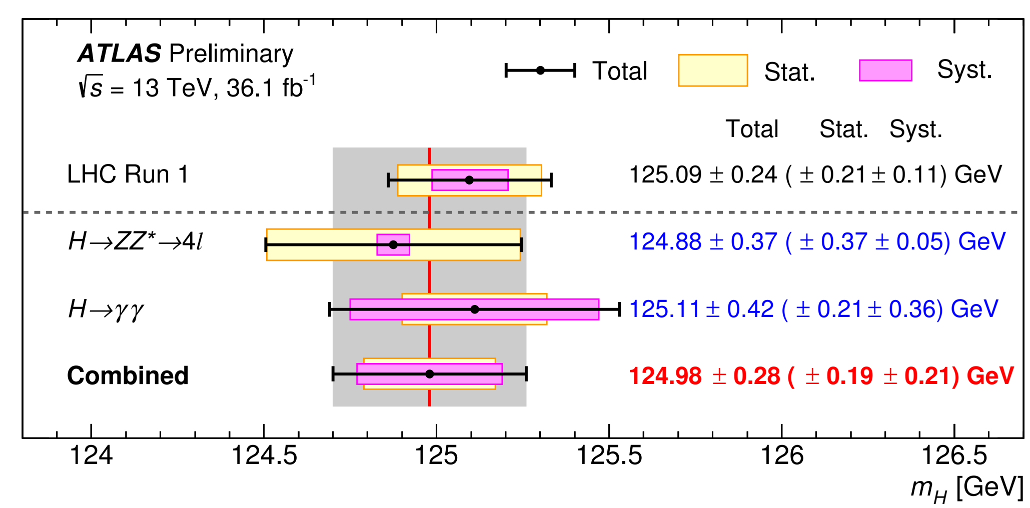




- Run 1 mass combination: ATLAS and CMS (2015)   125.09 GeV

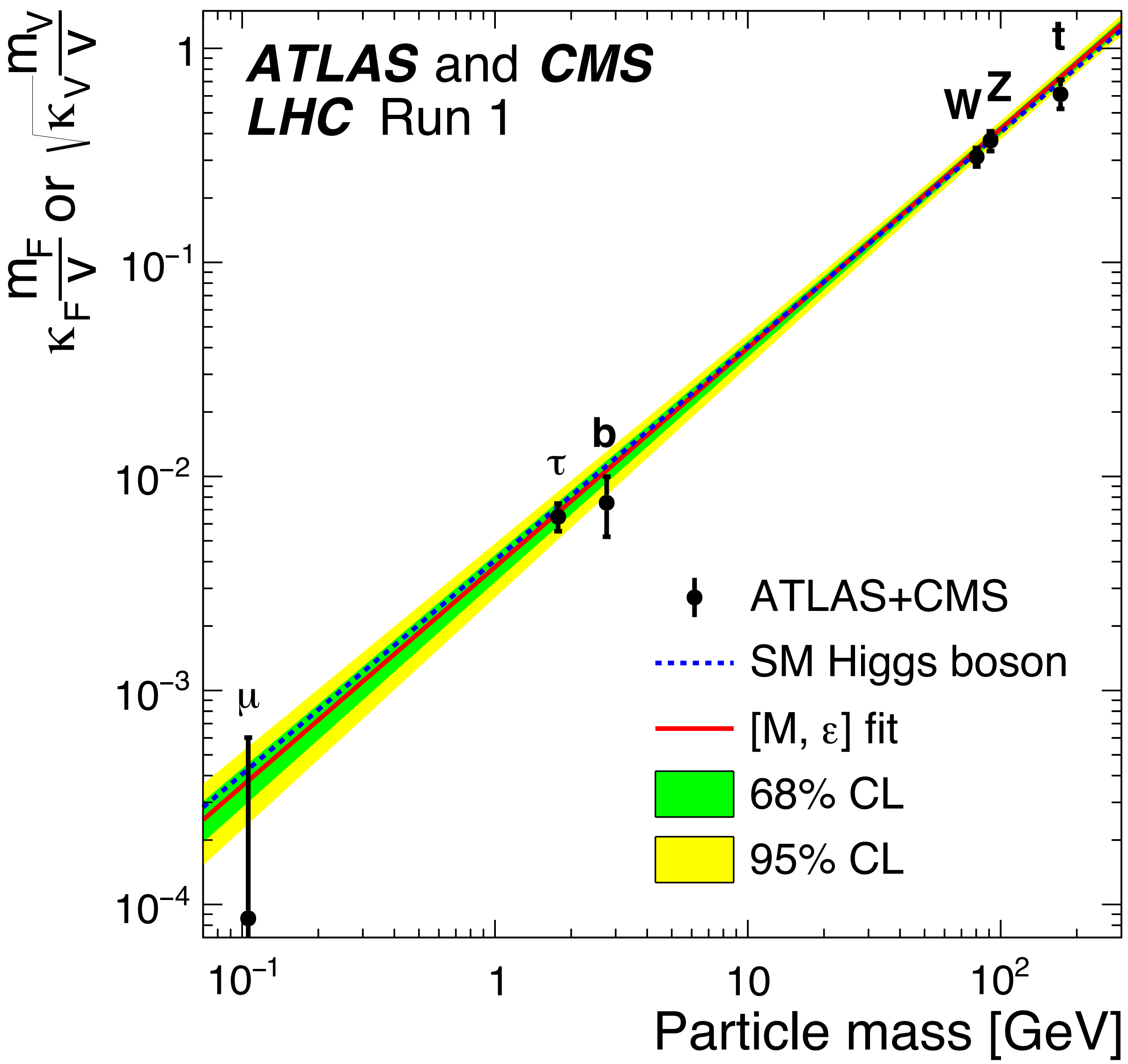


now similar precision in one exp

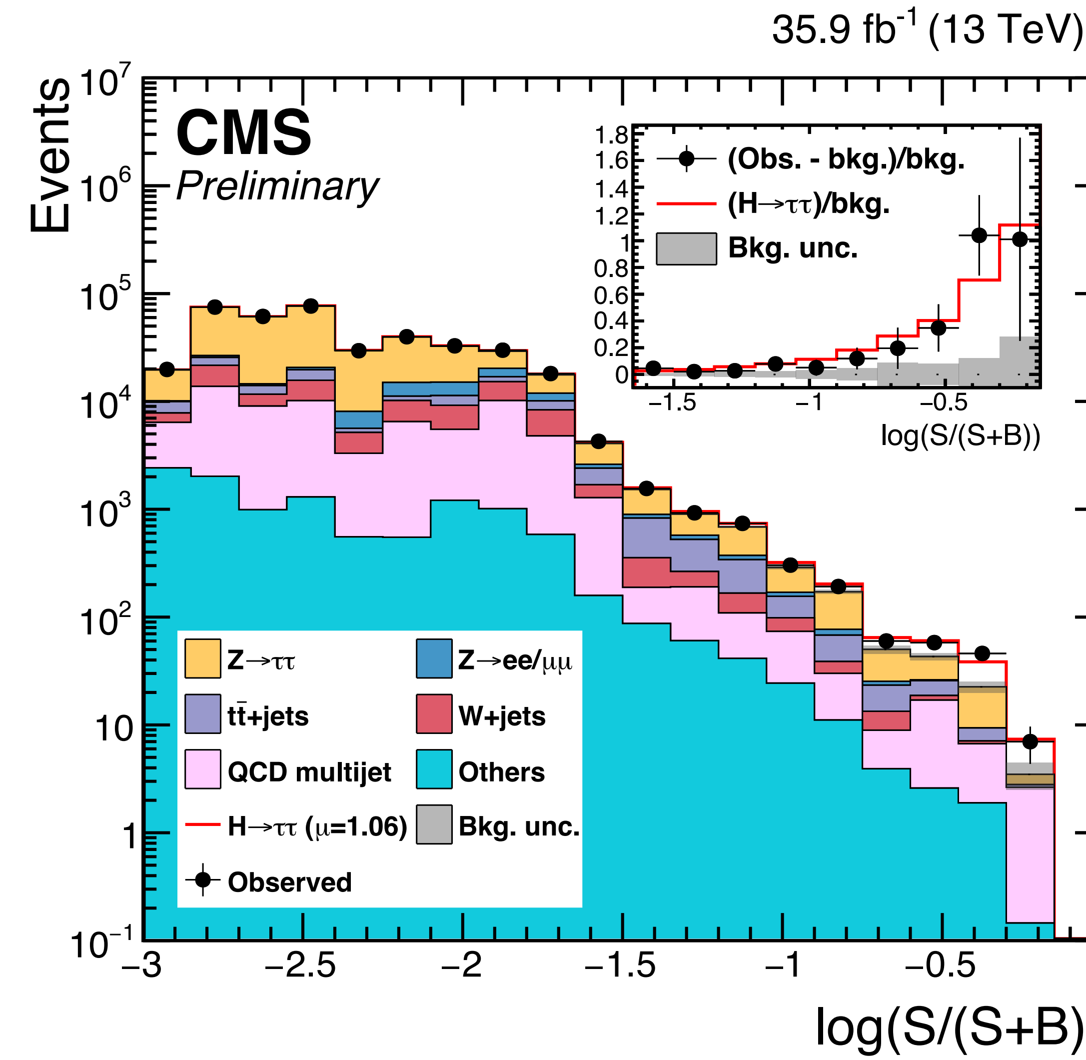


- Uncertainty in mass ~ 0.2% , better than for top (~0.5%)!

Couplings



Observation Of H→ττ



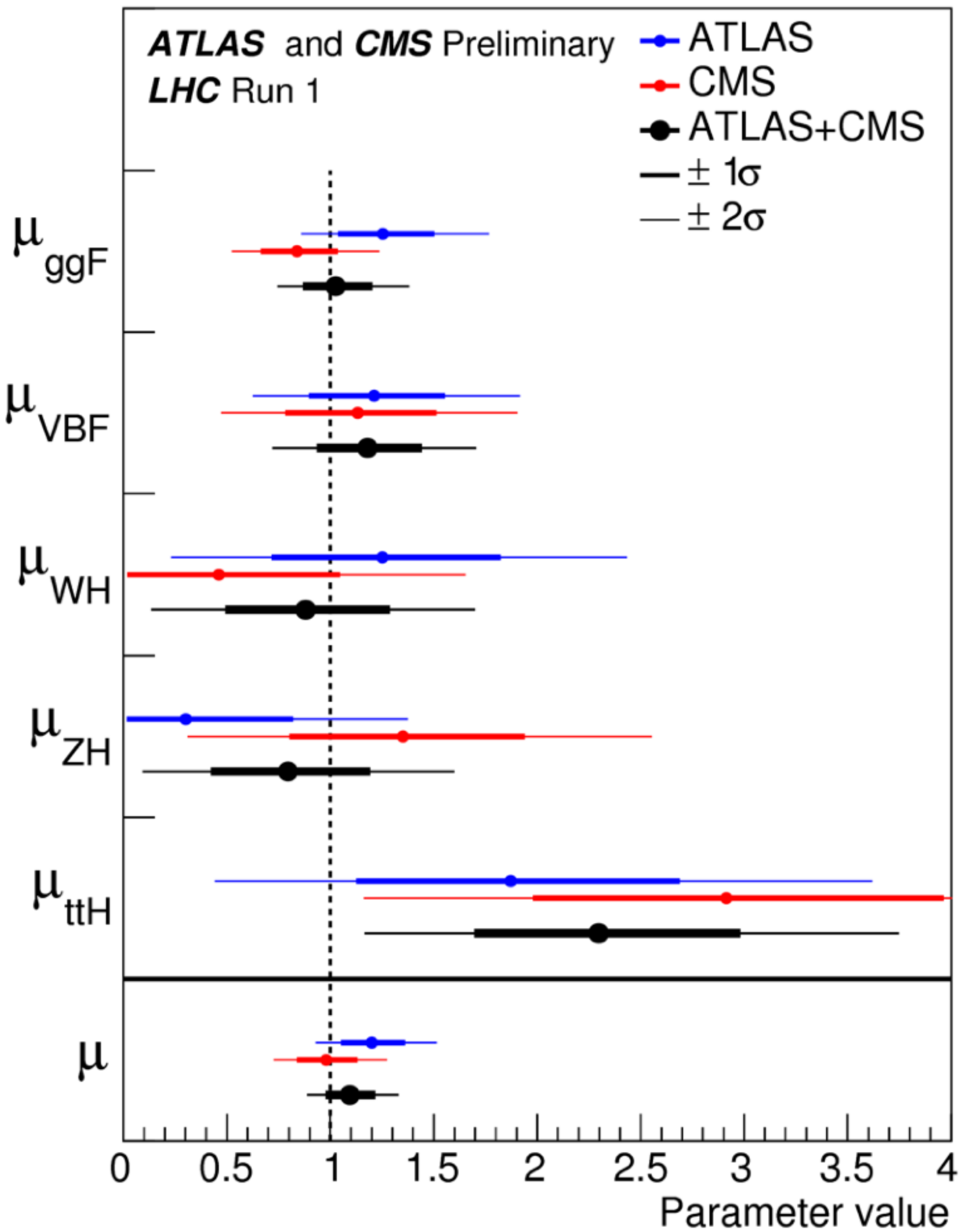
Observed significance is 4.9 σ

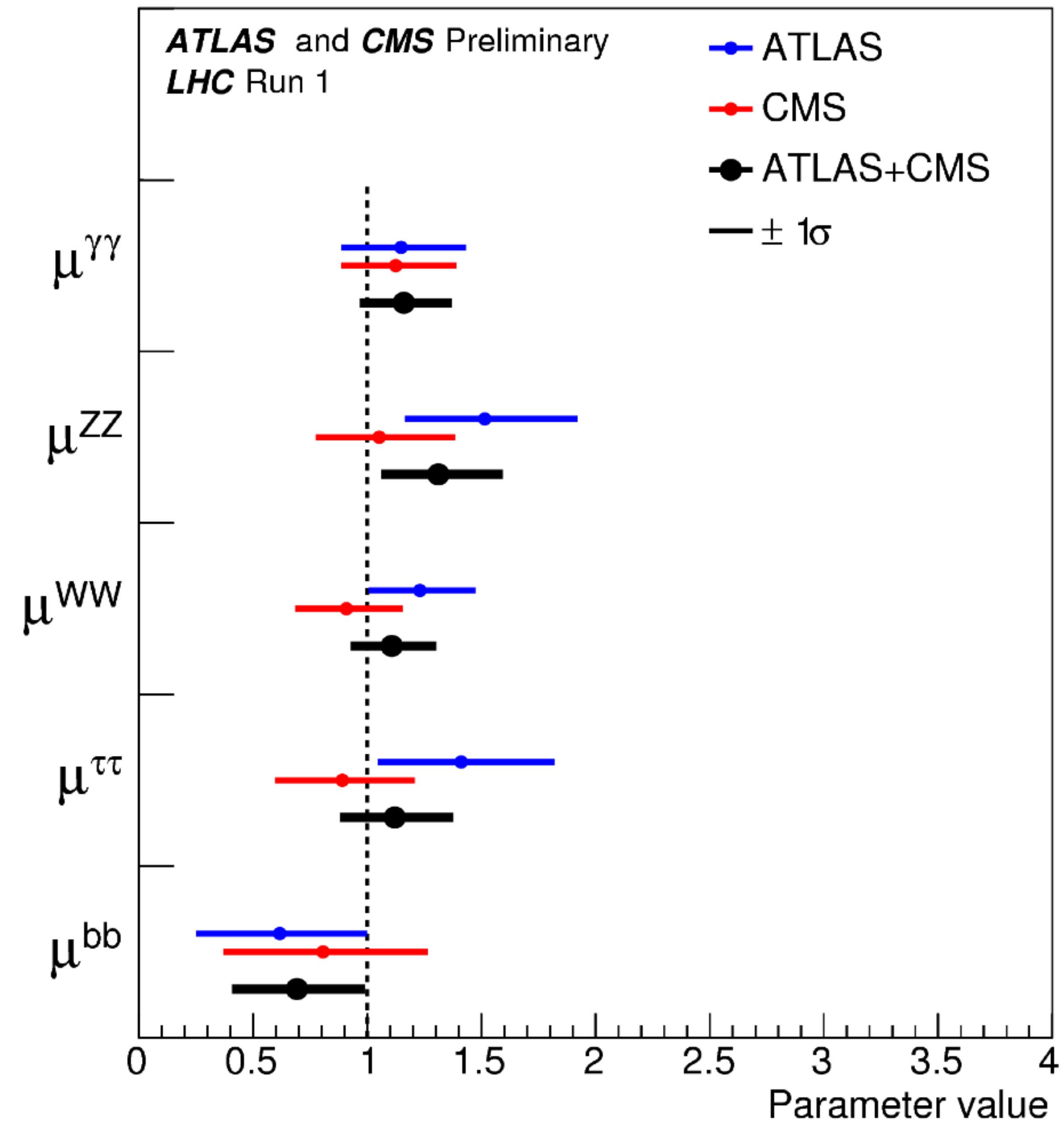
5.9 when combined with CMS Run1

Best Fit signal strength : 1.06 ± 0.25

Cross sections in "agreement" with SM in all channels (large errors yet)

Signal strength $\mu = \dfrac{\sigma}{\sigma_{SM}}$ similar for Run 2





$$\frac{\sigma}{\sigma_{SM}} \equiv \mu = 1.09 \pm 0.07(stat) \pm .04(syst)$$
$$\pm .03(th\ bckd)^{+.07}_{-.06}(th\ signal)$$

WHY MULTIPLE HIGGS?

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Scalar Symmetry Breaking potential in the SM:

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

Self coupling fixed by measurement of the Higgs mass and VEV!

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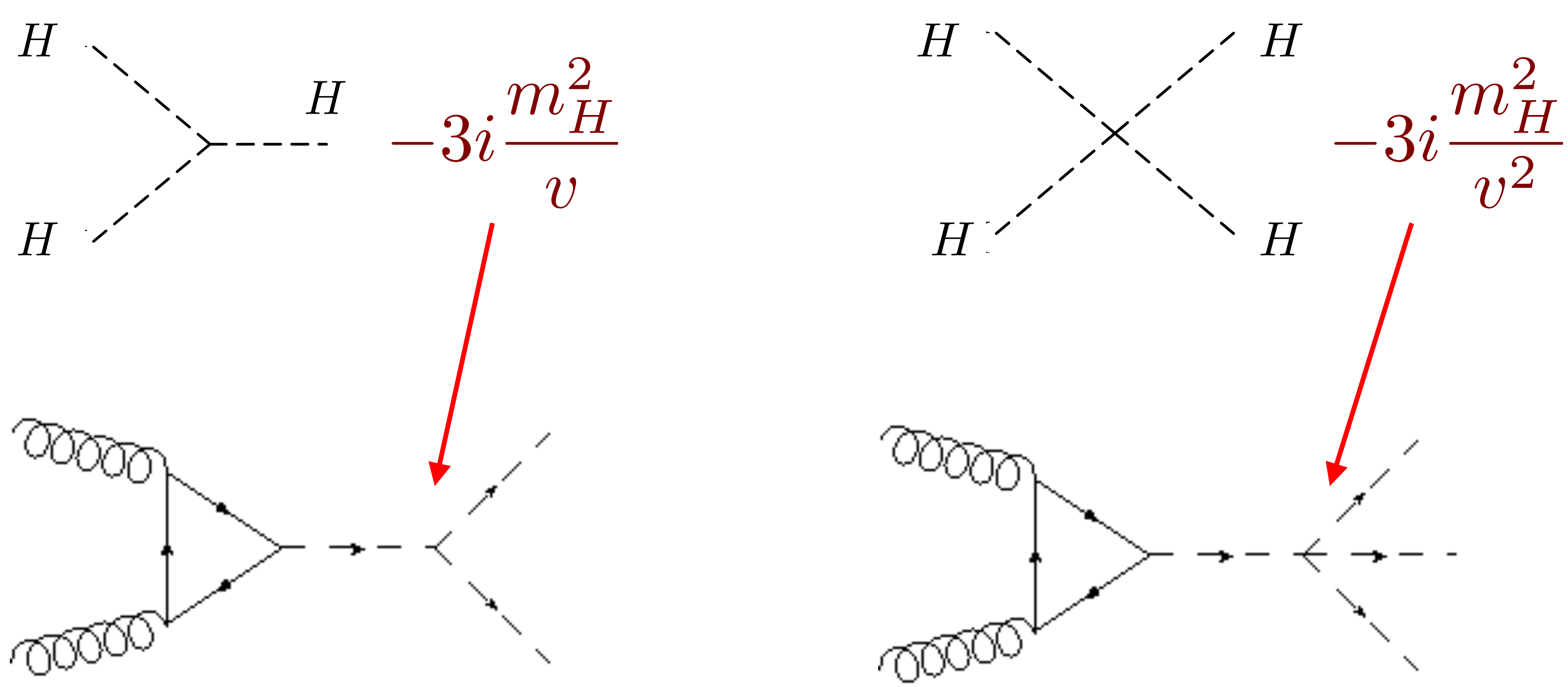
To be seen in:



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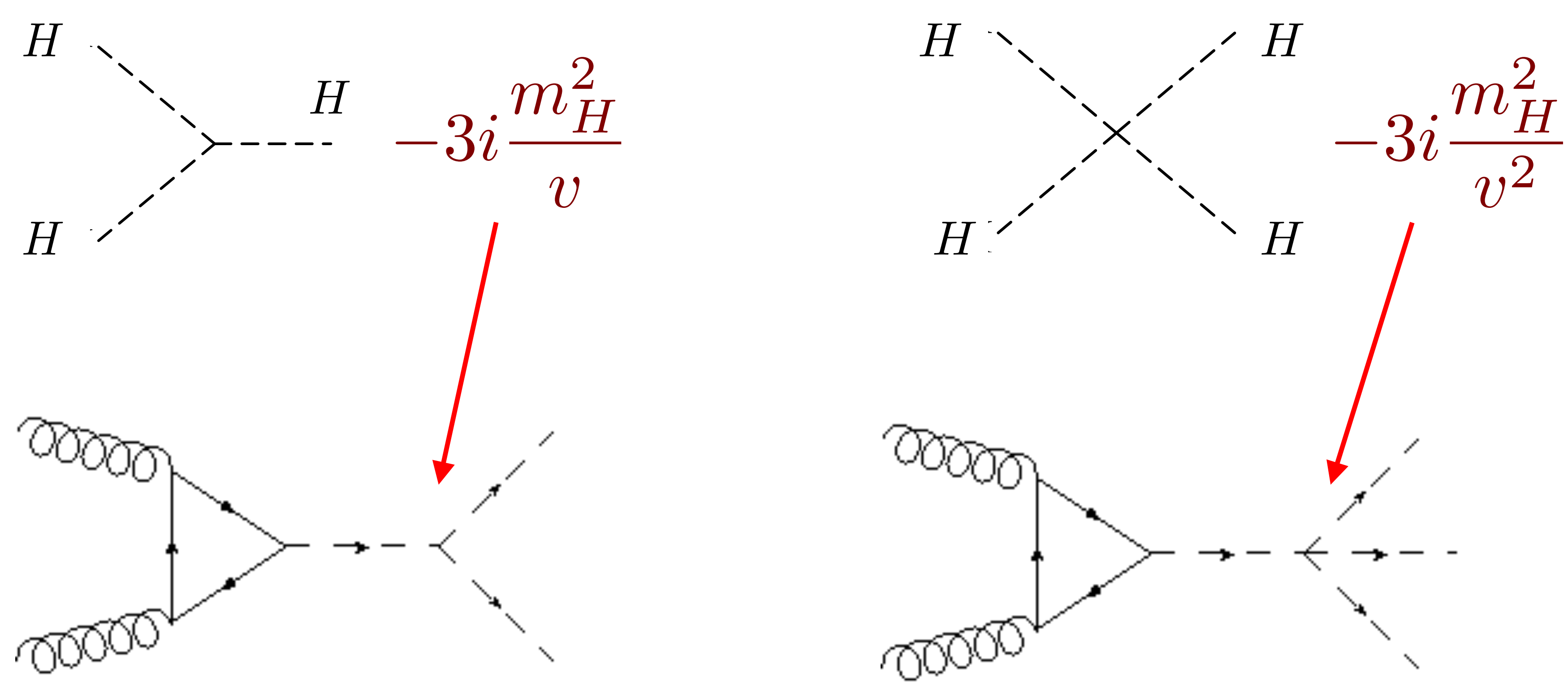

BECAUSE IS FUNDAMENTAL TO TEST THE SCALAR POTENTIAL

SM is an effective theory:

Let’s move to higher dimension operators

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SM EFT: Warsaw basis $\rightarrow$ 2499 non-redundant 6-dim operators

Phenomenological use: Subsets, e.g. SILH $\subset$ Warsaw

Relevant for HH production: H-top & H-G interactions

$$\mathcal{L}_6^{\rm SILH} \supset \frac{\bar{c}_H}{2v^2}\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H) + \frac{\bar{c}_u}{v^2}y_t(H^\dagger H\bar{q}_L H^c t_R + h.c.) - \frac{\bar{c}_6}{6v^2}\frac{3M_h^2}{v^2}(H^\dagger H)^3 + \bar{c}_g\frac{g_s^2}{M_W^2}H^\dagger H G^{a\,\mu\nu}G^a_{\mu\nu},$$

Giudice et al. 2007

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Giudice et al. 2007

HEFT: Interactions that involve the Higgs singlet only:

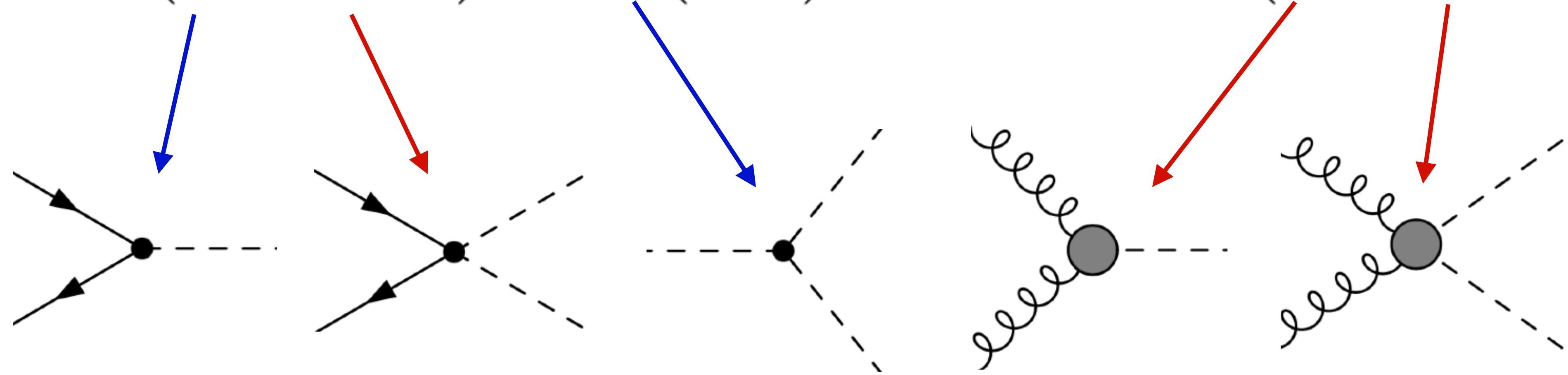
$$\mathcal{L}_{\text{non-lin}} \supset -M_t\,\bar{t}t\left(c_t\frac{h}{v} + c_{tt}\frac{h^2}{2v^2}\right) - c_3\frac{1}{6}\left(\frac{3M_h^3}{v}\right)h^3 + \frac{\alpha_s}{\pi}G^{a\,\mu\nu}G^a_{\mu\nu}\left(c_g\frac{h}{v} + c_{gg}\frac{h^2}{2v^2}\right)$$

Non-linear realization of EWSM

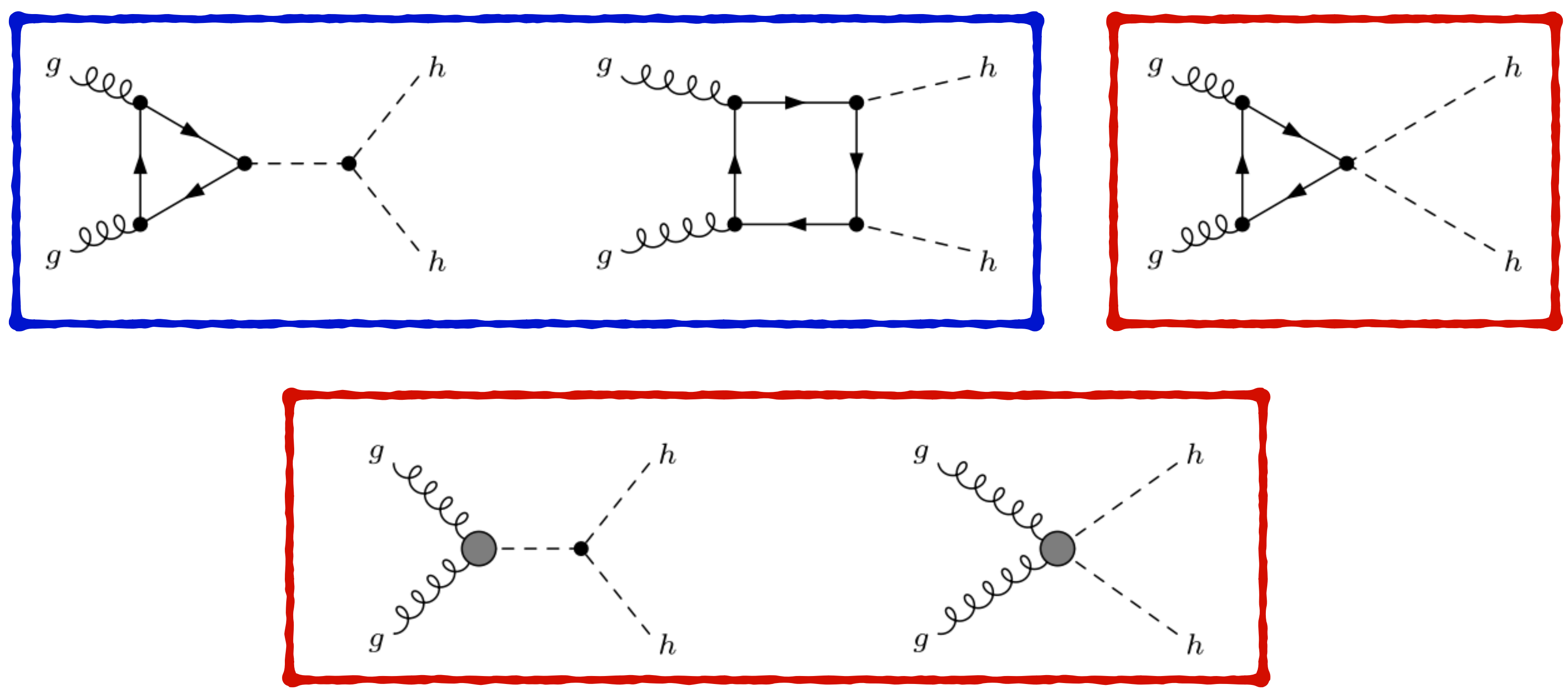
Contino et al. 2010

Linearly (in $\Lambda^{-1}_{\text{EFT}}$) equivalent if $c_g = c_{gg}$

$$\mathcal{L}_{\text{non-lin}} \supset -M_t\,\bar{t}t\left(c_t\frac{h}{v}+c_{tt}\frac{h^2}{2v^2}\right)-c_3\frac{1}{6}\left(\frac{3M_h^3}{v}\right)h^3+\frac{\alpha_s}{\pi}G^{a\,\mu\nu}G^a_{\mu\nu}\left(c_g\frac{h}{v}+c_{gg}\frac{h^2}{2v^2}\right)$$

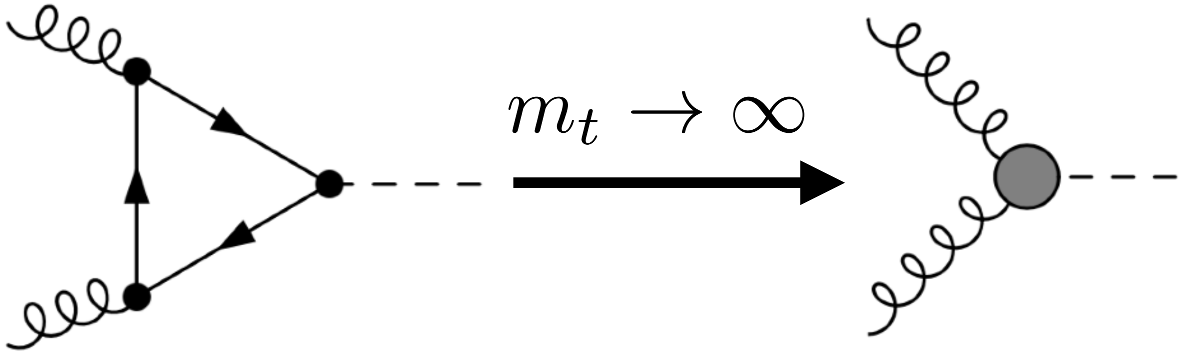


LO:

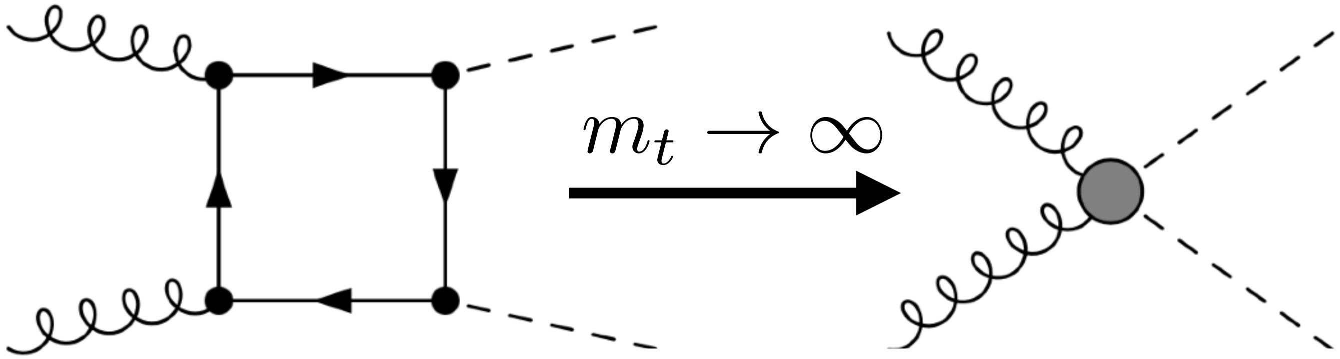


QCD Corrections: Too difficult → Use HTL and rescale by Born

These include virtual NNLO corrections

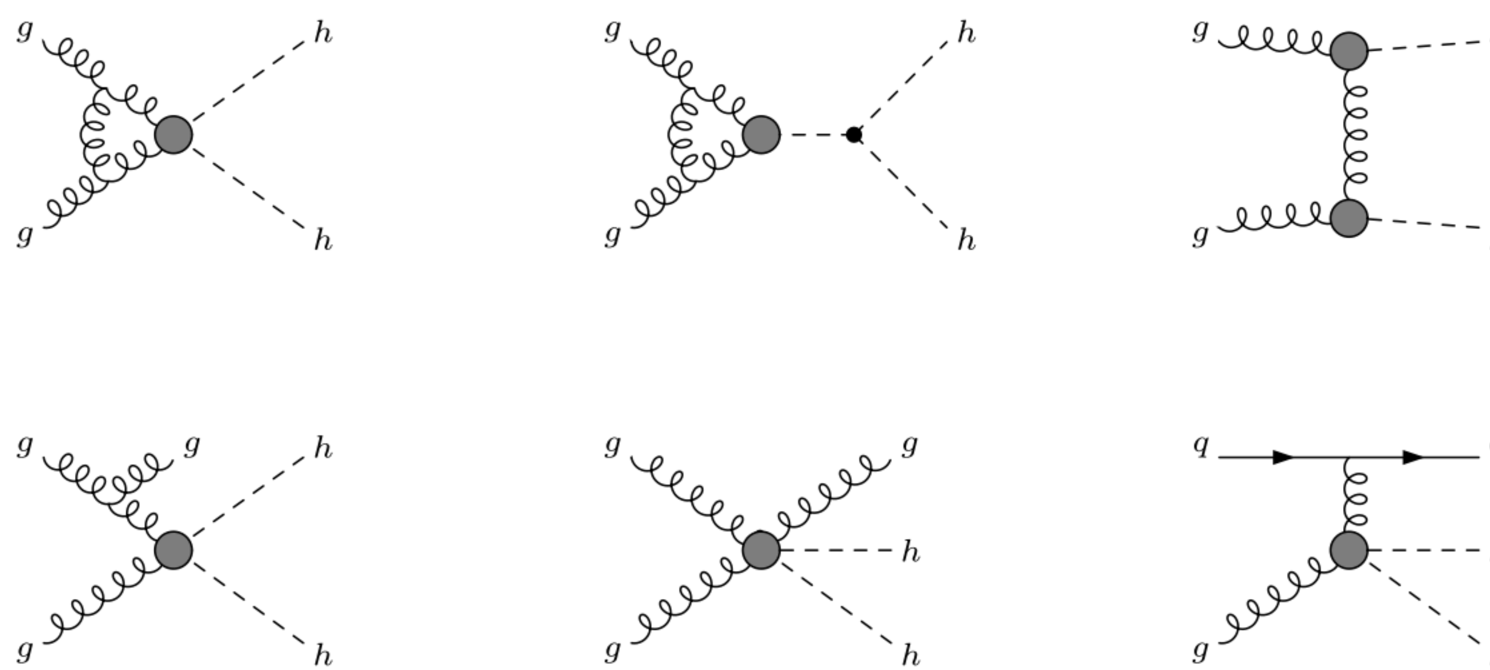


$$C_H = 1 + \frac{11}{4}\frac{\alpha_s}{\pi} + \left(\frac{\alpha_s}{\pi}\right)^2 \left[\frac{2777}{288} + \frac{19}{16}\log\frac{\mu_R^2}{M_t^2} + N_f\left(-\frac{67}{96} + \frac{1}{3}\log\frac{\mu_R^2}{M_t^2}\right)\right] + \mathcal{O}(\alpha_s^3)$$



$$C_{HH} = C_H + \left(\frac{\alpha_s}{\pi}\right)^2 \left(\frac{35}{24} + \frac{2}{3}N_f\right) + \mathcal{O}(\alpha_s^3)$$

NLO:



What we did?

Adapted the double Higgs result to the EFT

(arXiv:hep-ph/1704.05700 - DdF, IF, JM)

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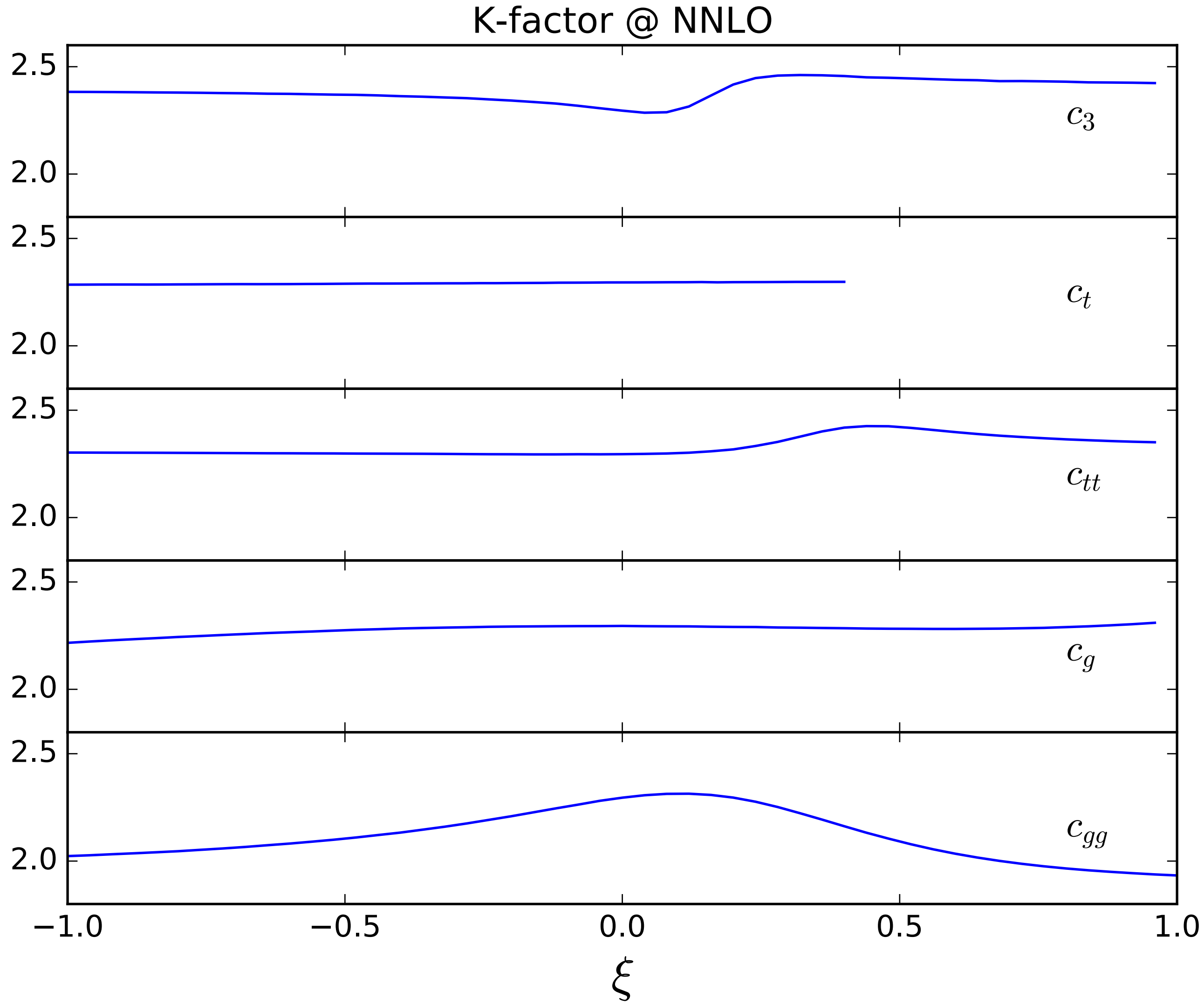
NNLO K-Factor



Maximum departure from SM:

$$\Delta K^{c_3} \approx 7.2\% \quad \text{at } c_3 = 4.20\,,$$

$$\Delta K^{c_{tt}} \approx 5.7\% \quad \text{at } c_{tt} = 0.66\,,$$

$$\Delta K^{c_g} \approx 3.4\% \quad \text{at } c_g = -0.15\,,$$

$$\Delta K^{c_t} \approx 0.5\% \quad \text{at } c_t = 0.65\,.$$

Global maximum:

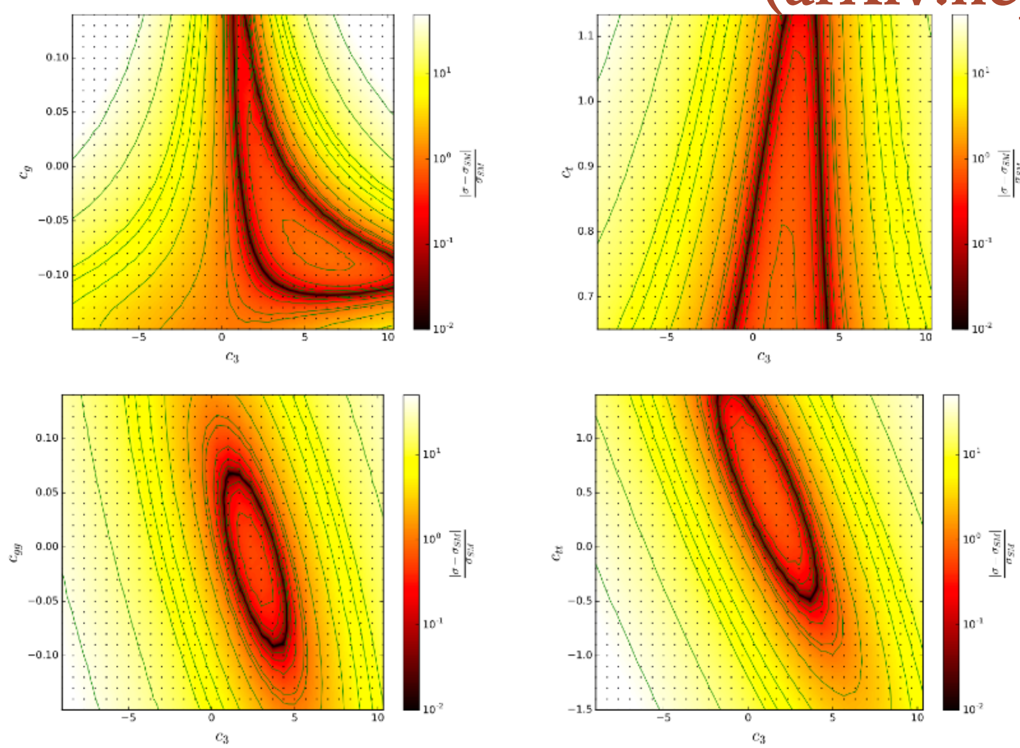
$$\Delta K^{\max} \approx 84\%$$ ⟶ EFT NNLO calculation relevant!!!

$$\text{at } c_3 = 7.0,\ c_t = 1.15,\ c_{tt} = 0.1,\ c_g = -0.09,\ c_{gg} = 0.02$$

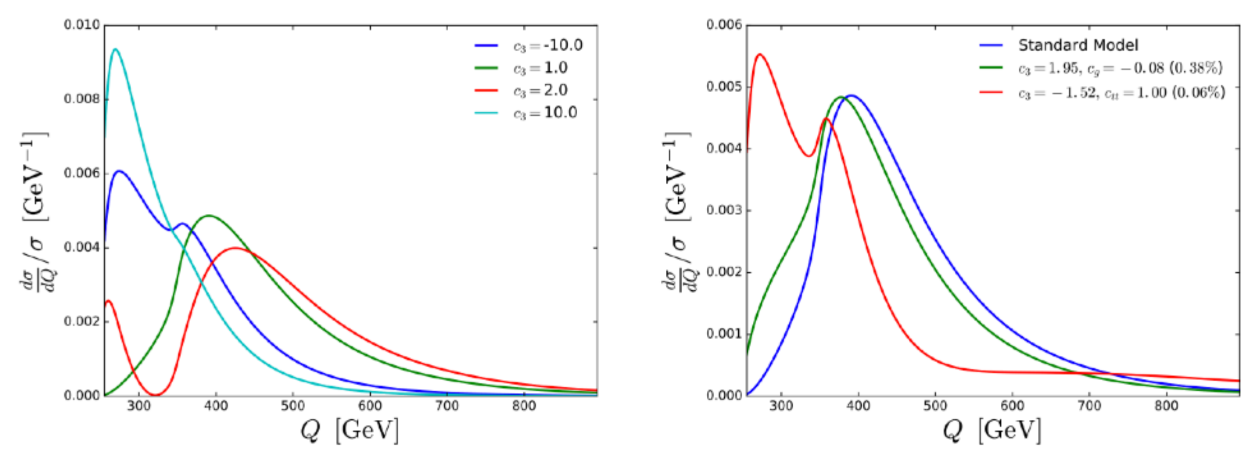
ADAPTED THE DOUBLE HIGGS RESULT TO THE EFT

(arXiv:hep-ph/1704.05700 - DdF, IF, JM)

Degeneracy structure preserved after inclusion of m_t effects (in Born) and NNLO radiative corrections.



Breaking of degeneracy in differential distributions



(a) (b)

Figure 4: Invariant mass distribution of the produced Higgs boson pair plotted for (a) different values of its self-coupling, and (b) different combinations of anomalous couplings that are degenerate with the SM. The relative deviation from the SM of the total cross section in (b) is specified between brackets on the label.

What about triple Higgs?

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Cons:

- Very low cross section (ab -> won't be seen @ LHC)
- HTL not very good approximation

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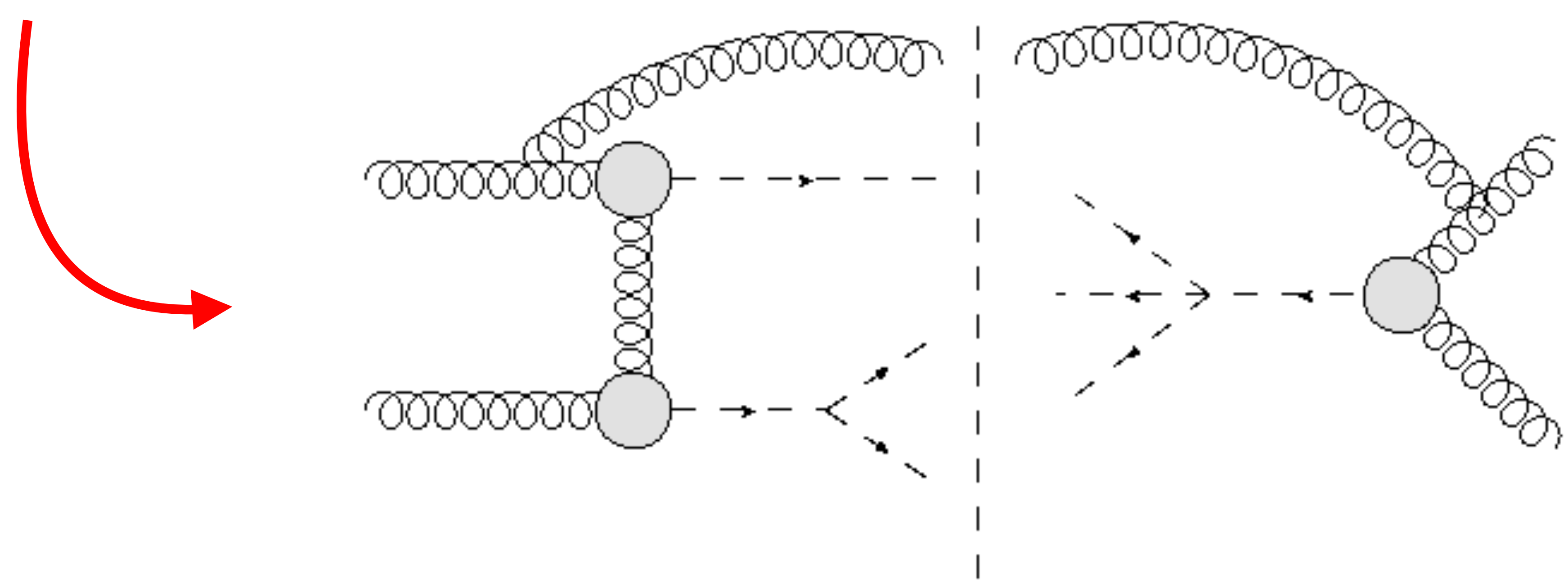
But… only NNLO (single) real emission missing to have a full calculation (arXiv:hep-ph/1610.05012 - DdF, JM)



SUMMARY

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We need precision in QCD to have good estimates & EFT's to parametrize possible deviations.

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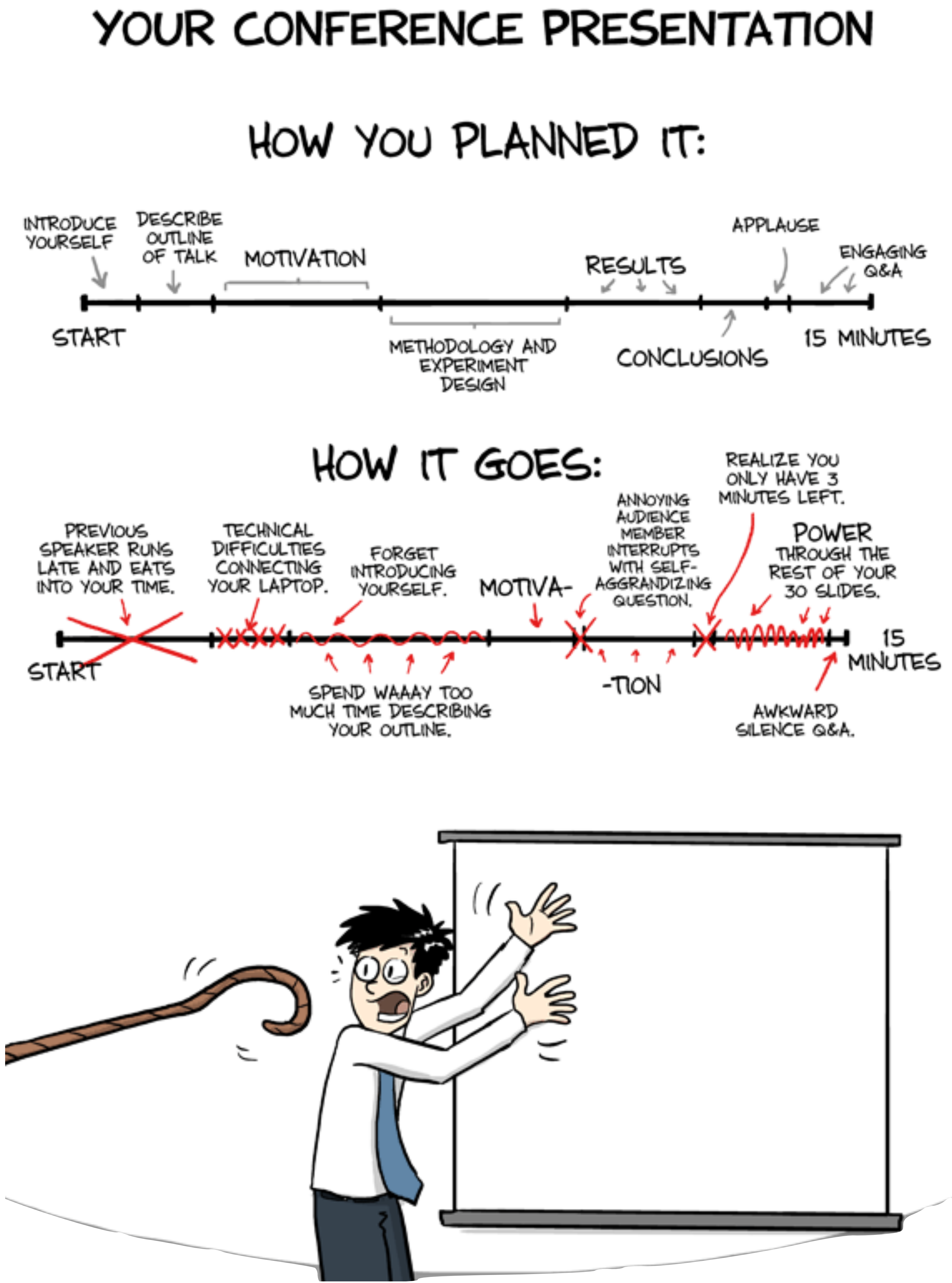
We need precision in QCD to have good estimates & EFT's to parametrize possible deviations.

We can make use of existing calculations in order to achieve precision without doing the heavy lifting.

Work in progress with Daniel and Manuel:
Mixed QCDxQED corrections to Z production. Please ask.


YOUR CONFERENCE PRESENTATION
HOW YOU PLANNED IT:
INTRODUCE YOURSELF
DESCRIBE OUTLINE OF TALK
MOTIVATION
RESULTS
APPLAUSE
ENGAGING Q&A
START
METHODOLOGY AND EXPERIMENT DESIGN
CONCLUSIONS
15 MINUTES
HOW IT GOES:
PREVIOUS SPEAKER RUNS LATE AND EATS INTO YOUR TIME.
TECHNICAL DIFFICULTIES CONNECTING YOUR LAPTOP.
FORGET INTRODUCING YOURSELF.
MOTIVA-
ANNOYING AUDIENCE MEMBER INTERRUPTS WITH SELF-AGGRANDIZING QUESTION.
REALIZE YOU ONLY HAVE 3 MINUTES LEFT.
POWER THROUGH THE REST OF YOUR 30 SLIDES.
START
SPEND WAAAY TOO MUCH TIME DESCRIBING YOUR OUTLINE.
-TION
15 MINUTES
AWKWARD SILENCE Q&A.