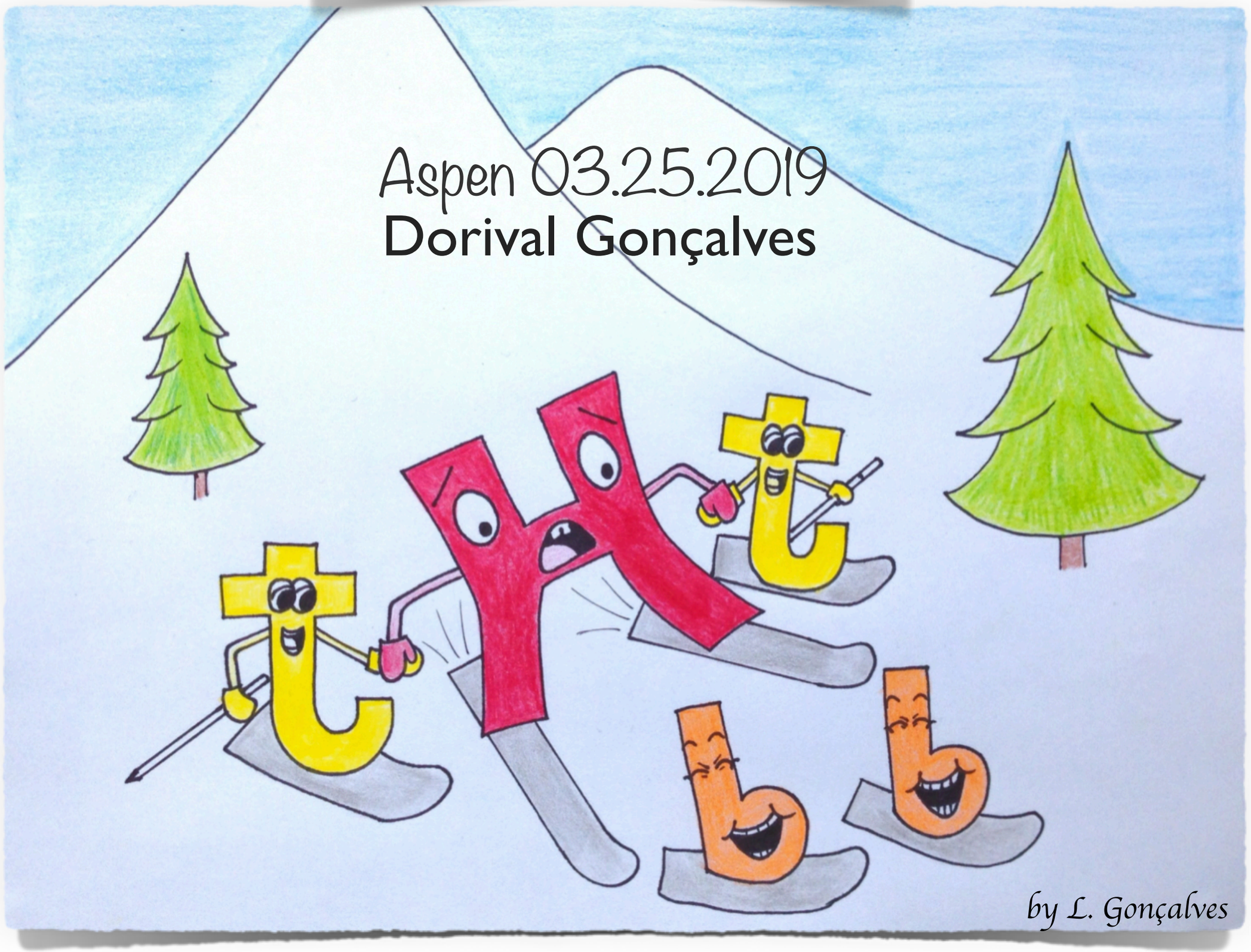
Higgs Couplings

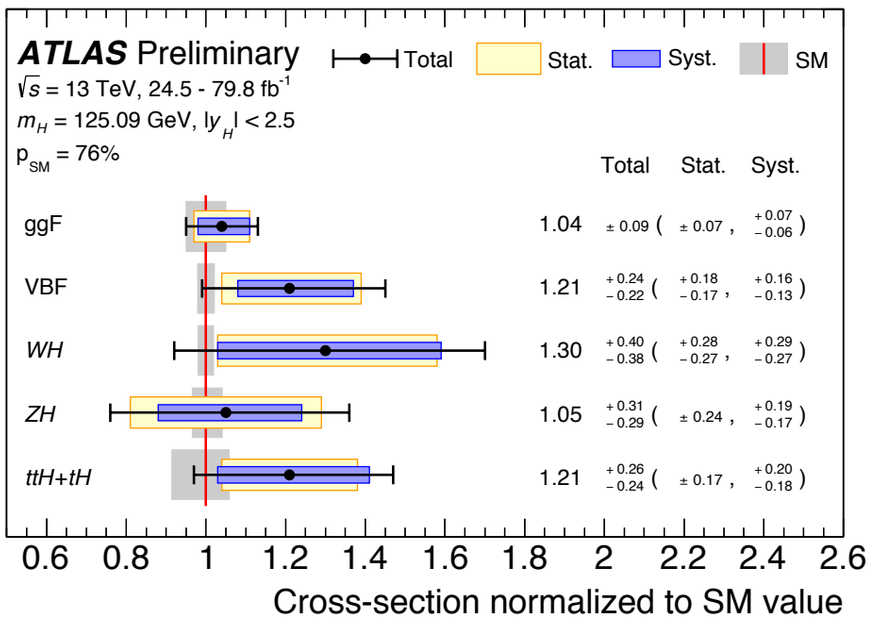
Aspen 03.25.2019

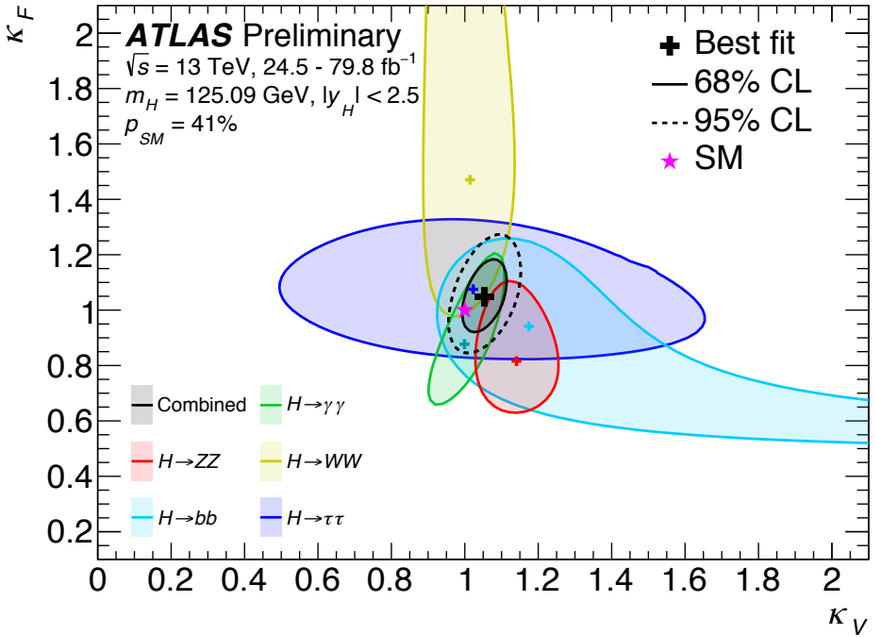
Dorival Gonçalves

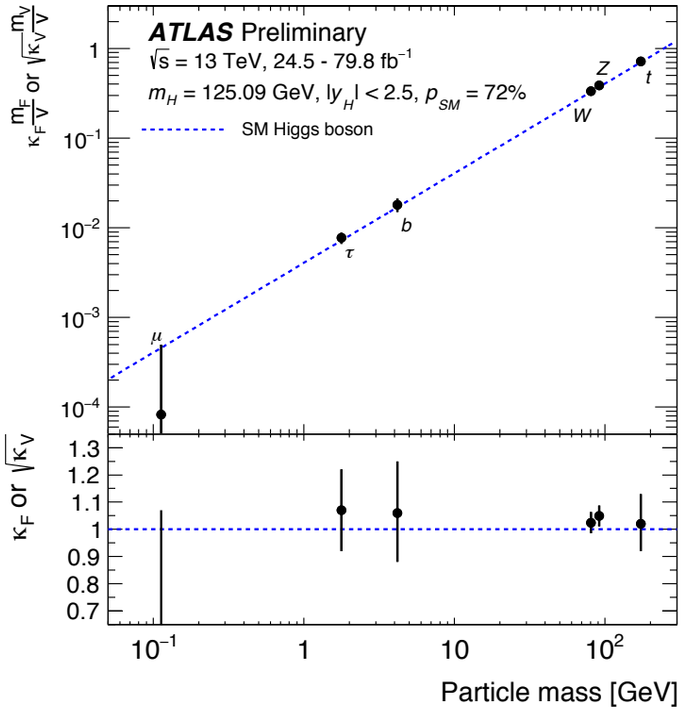


Motivation

Data tells us that we have SM-like Higgs boson



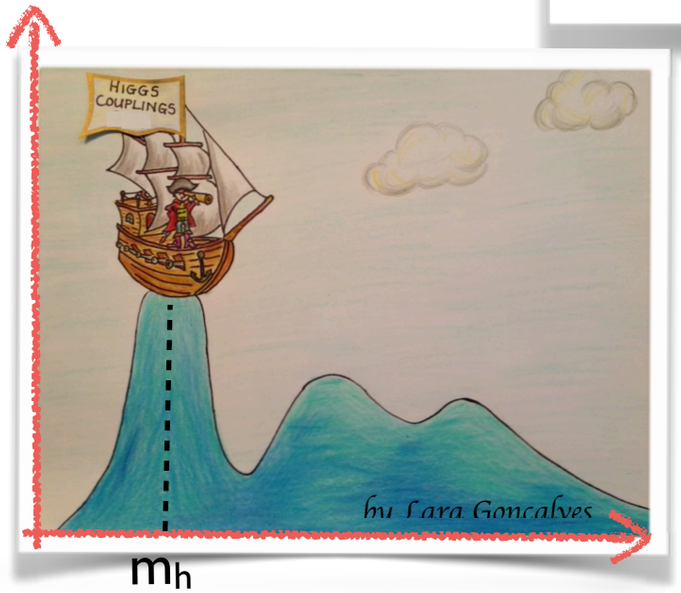




ATLAS-CONF-2019-005

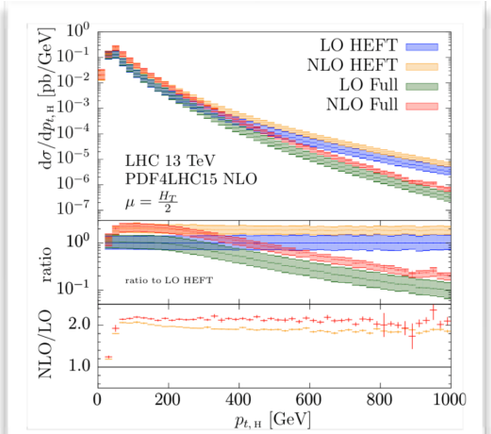
- SM could be valid all the way to exponentially high scales
- Maybe solutions to naturalness problem, DM… have taken a more subtle incarnation

Many opportunities ahead

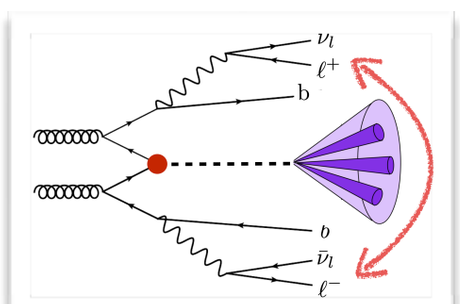


m_h

More searches



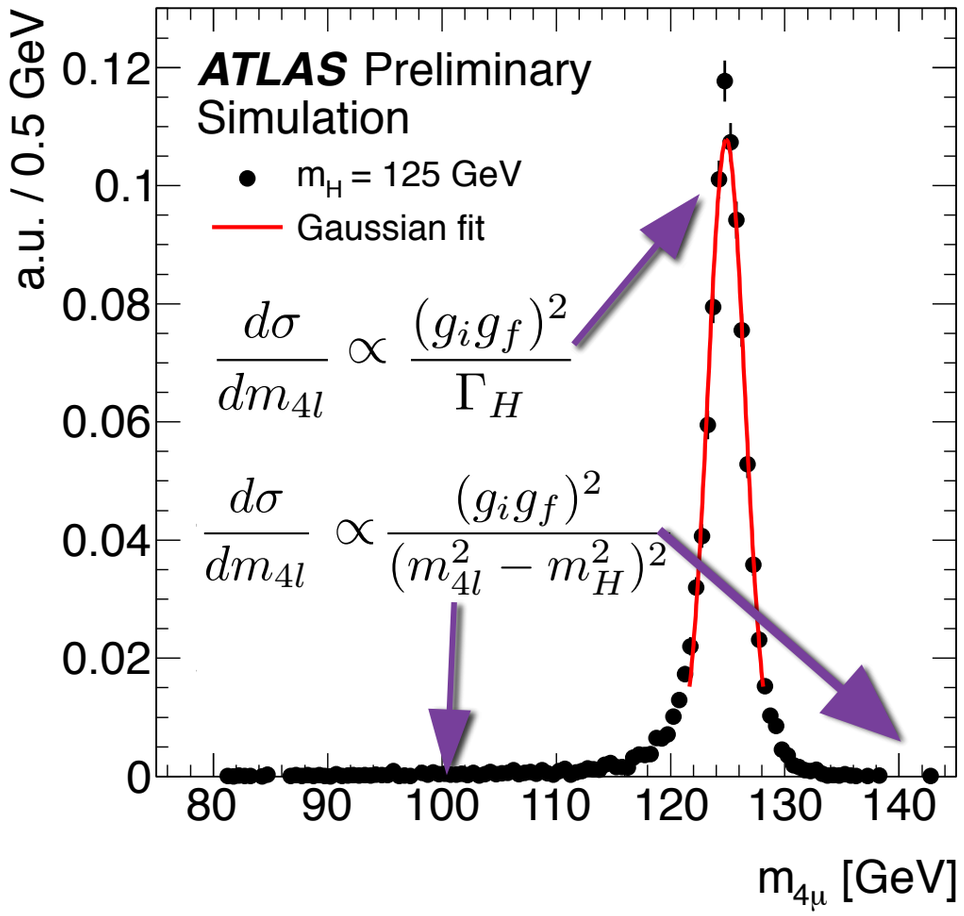
More energy & precision



More data

Off-Shell Higgs Production

- Just recently, we start to recognize the importance of the Off-Shell Higgs



→ Since $\Gamma_H/m_H \sim 3 \times 10^{-5}$ one naively expects very small off-shell rates

Off-Shell Higgs Production

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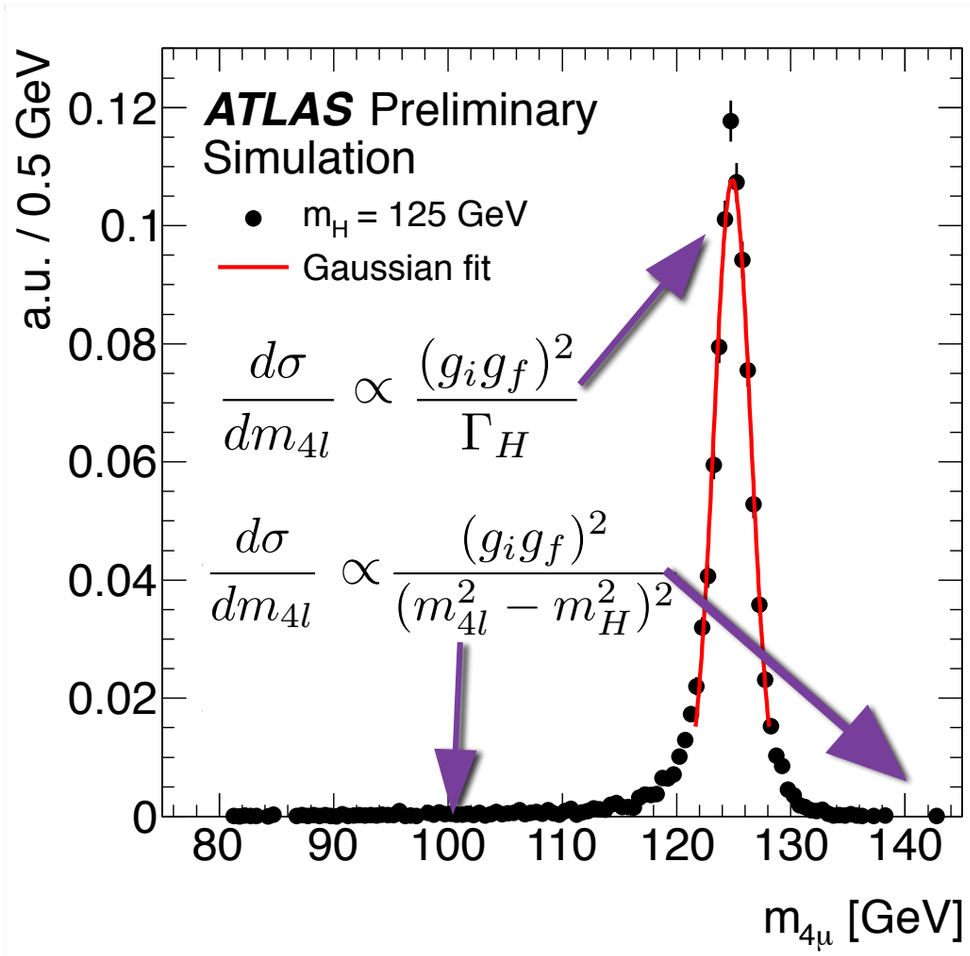
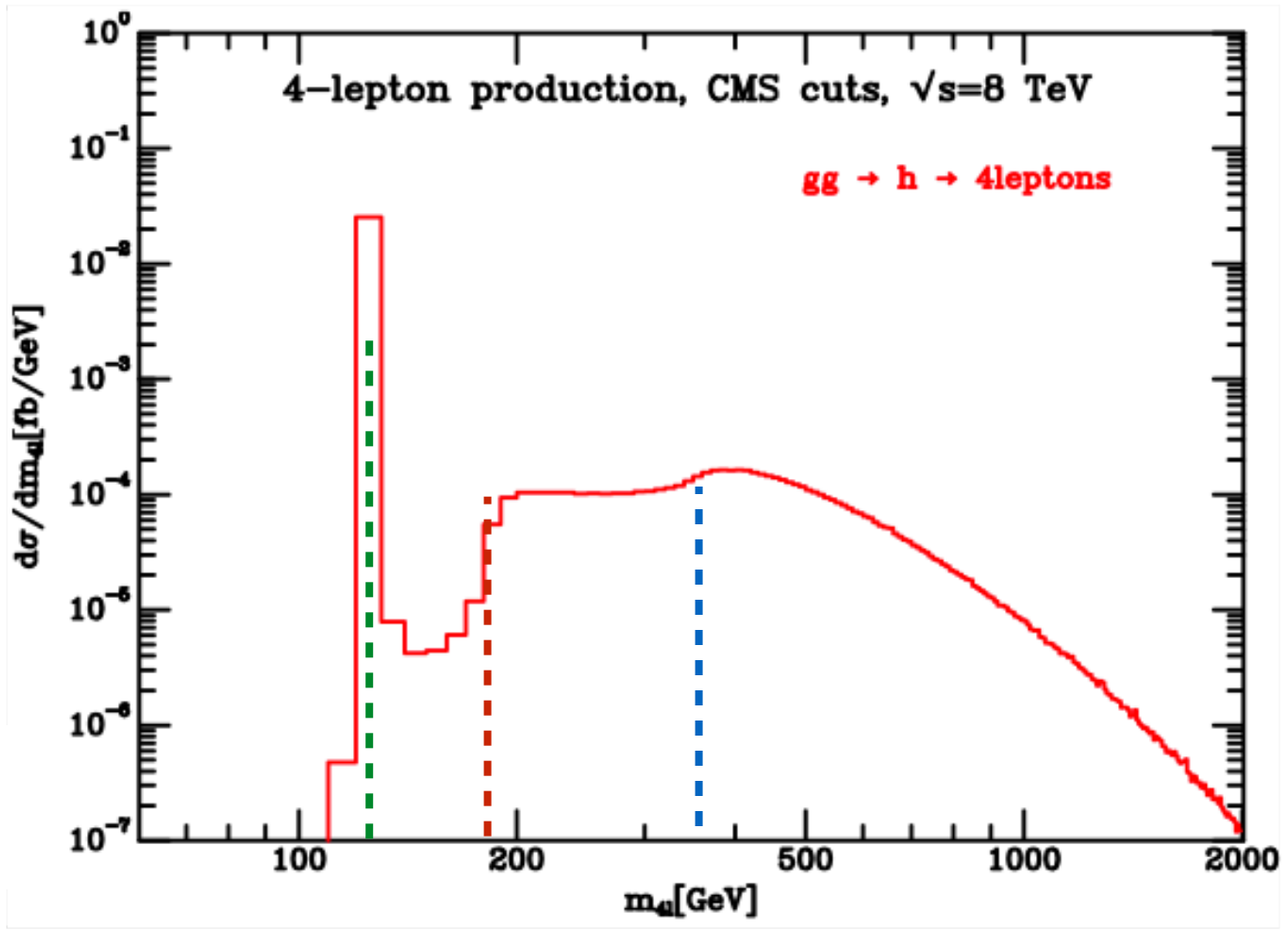


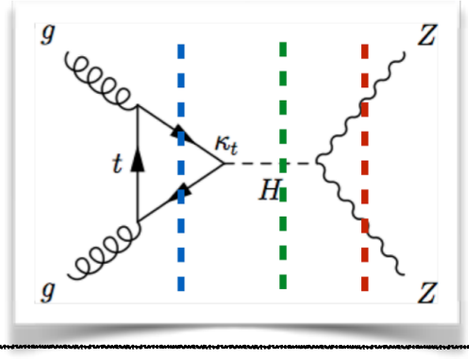


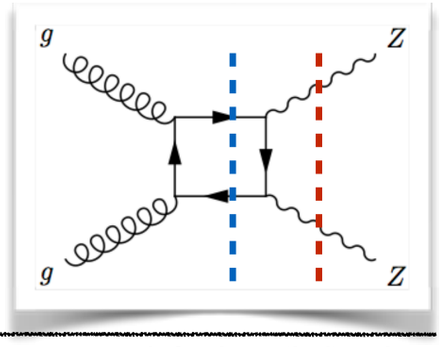
Campbell, Ellis, Williams 2013

- Spectacular fail of the NWA: $\frac{\sigma^{off-shell}_{H\to 4\ell}}{\sigma_{H\to 4\ell}} \sim 15\%$

→ $2m_Z$ and $2m_t$ thresholds

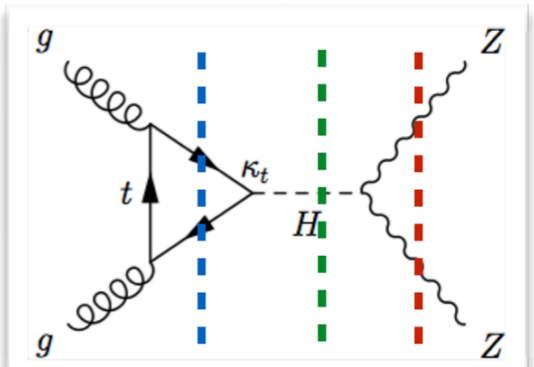
→ Interference $gg \to H^* \to ZZ$ with background $gg \to ZZ$





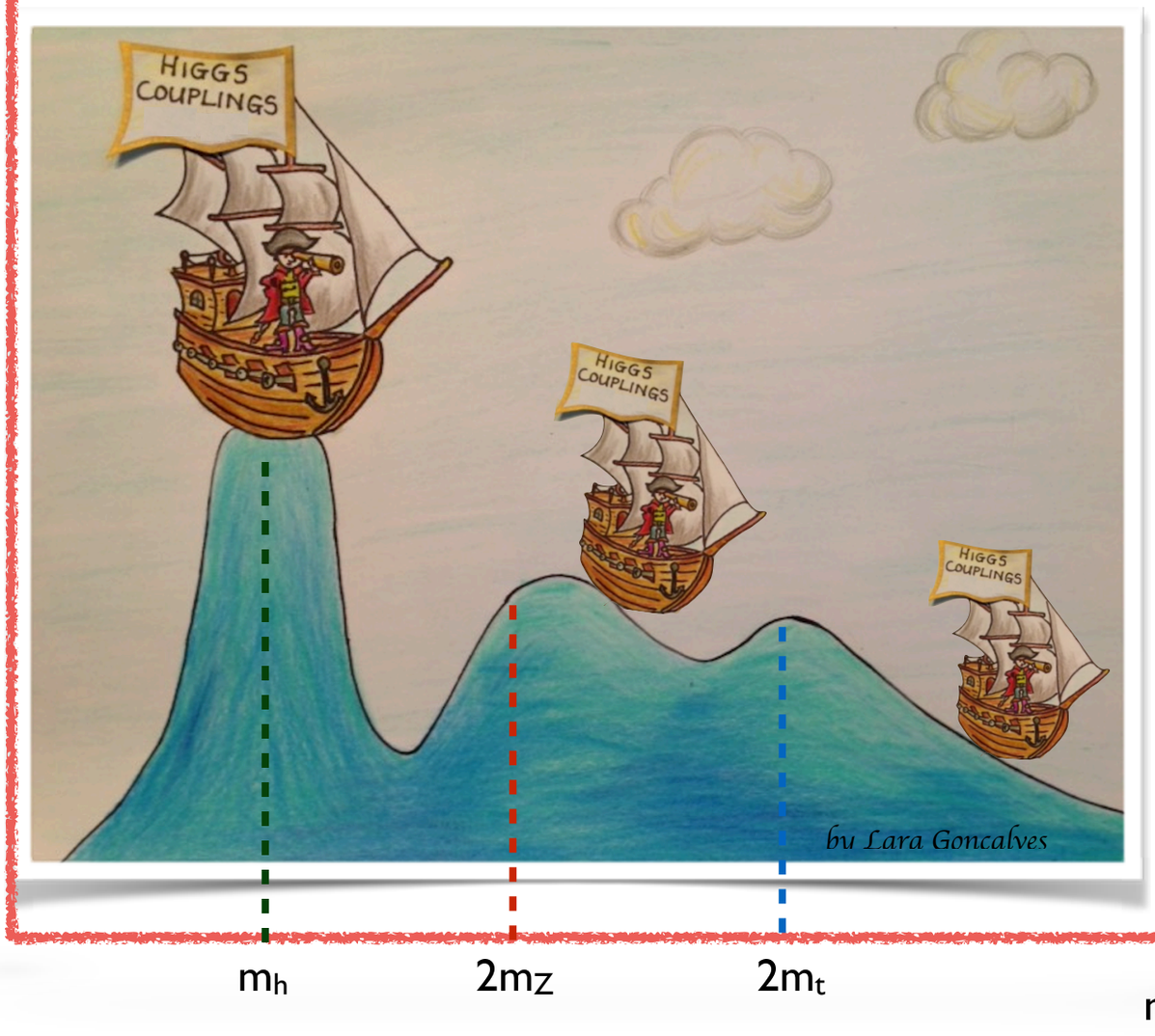
Off-Shell Higgs Production

- Off-shell Higgs carries information on the H couplings at different energy scales
- → Hidden states could show up in the scale dependence of Higgs couplings, or more broadly in Higgs production processes through quantum corrections



$$\sigma_{\text{on}} \propto \frac{g_i^2(m_h^2)g_f^2(m_h^2)}{m_h\Gamma_h}$$

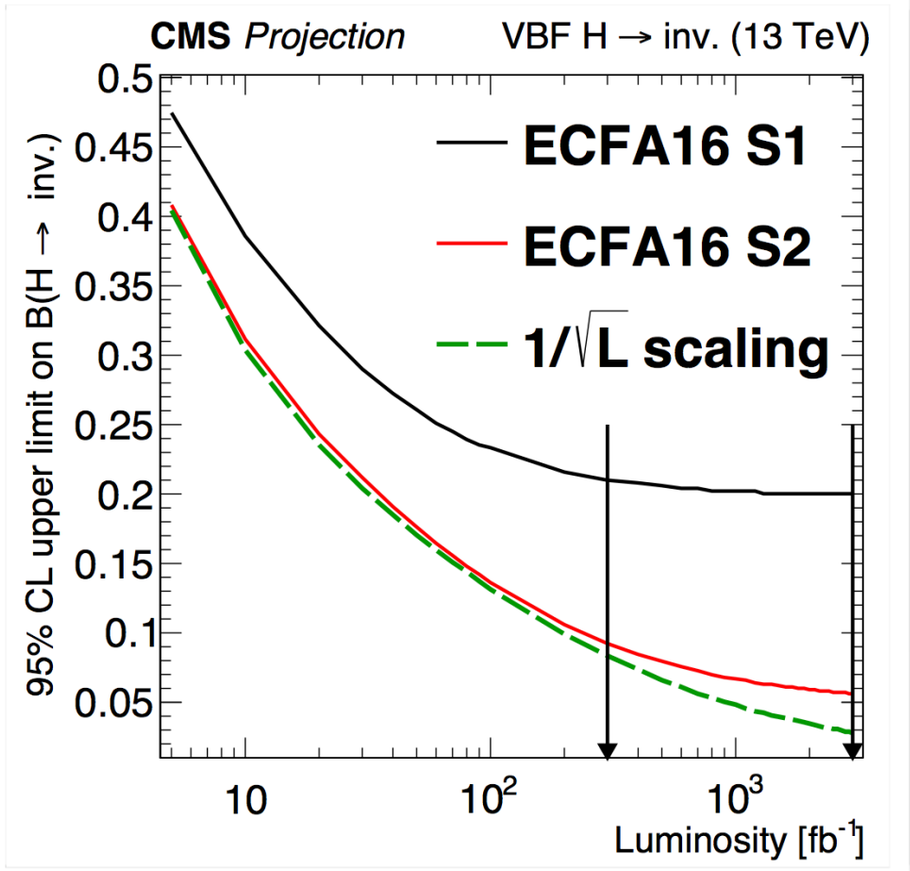
$$\sigma_{\text{off}} \propto \frac{g_i^2(Q^2)g_f^2(Q^2)}{Q^2}$$

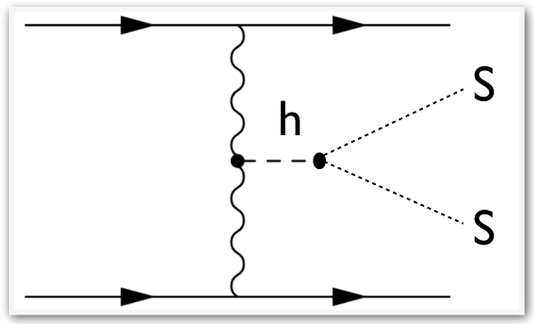


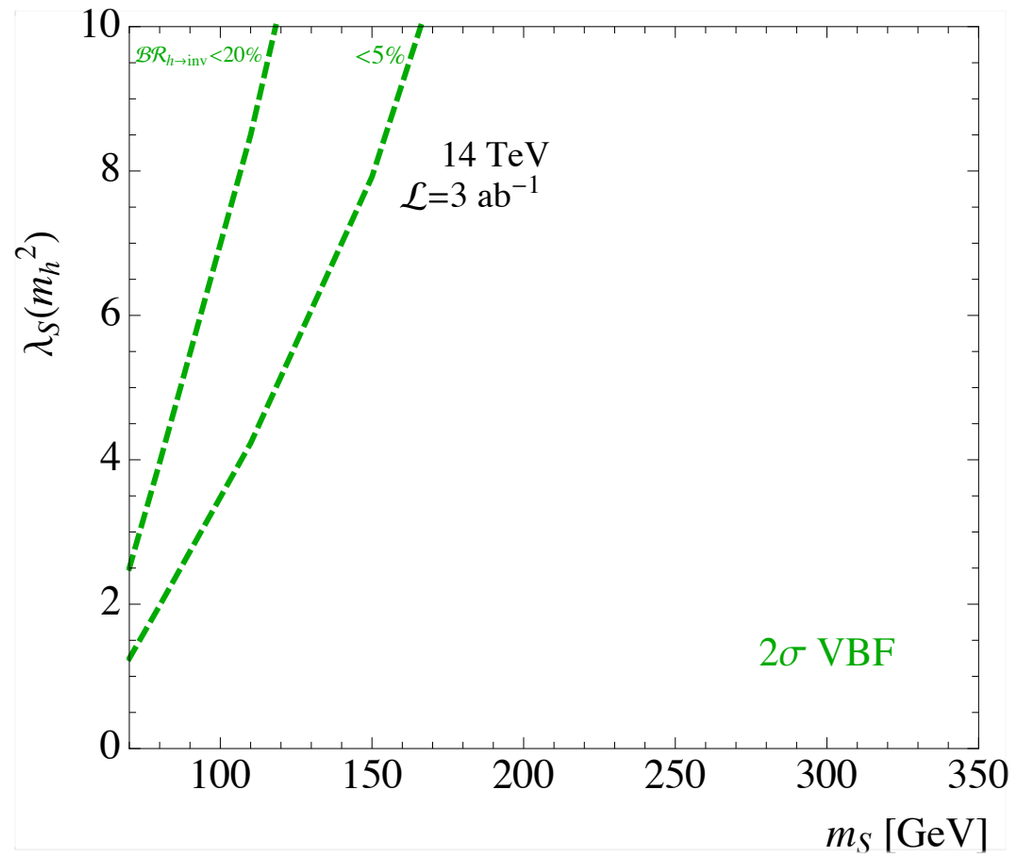
Off-shell probe to Higgs Portal

$\mathcal{L} \supset \partial_\mu S \partial^\mu S^* - \mu^2 |S|^2 - \lambda_S |S|^2 |H|^2$ with $\mathcal{Z}_2$ symmetry

The Higgs may serve as a "portal" to a "Hidden sector"







$m_h > 2m_S$: strong VBF bounds

$m_h < 2m_S$: sensitivity BW suppressed

DG, Han, Mukhopadhyay (PRL'17)

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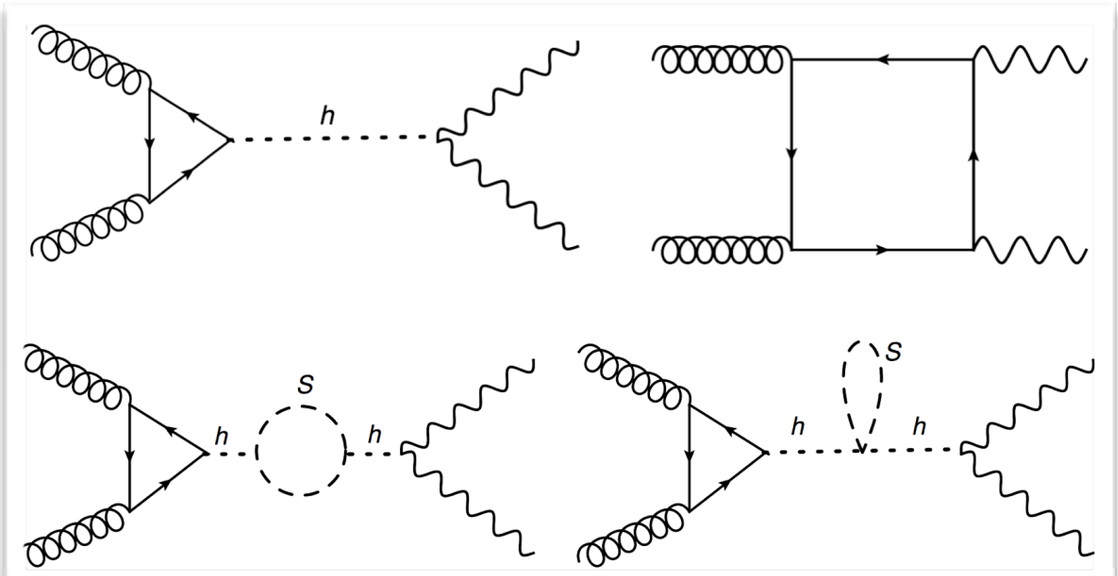
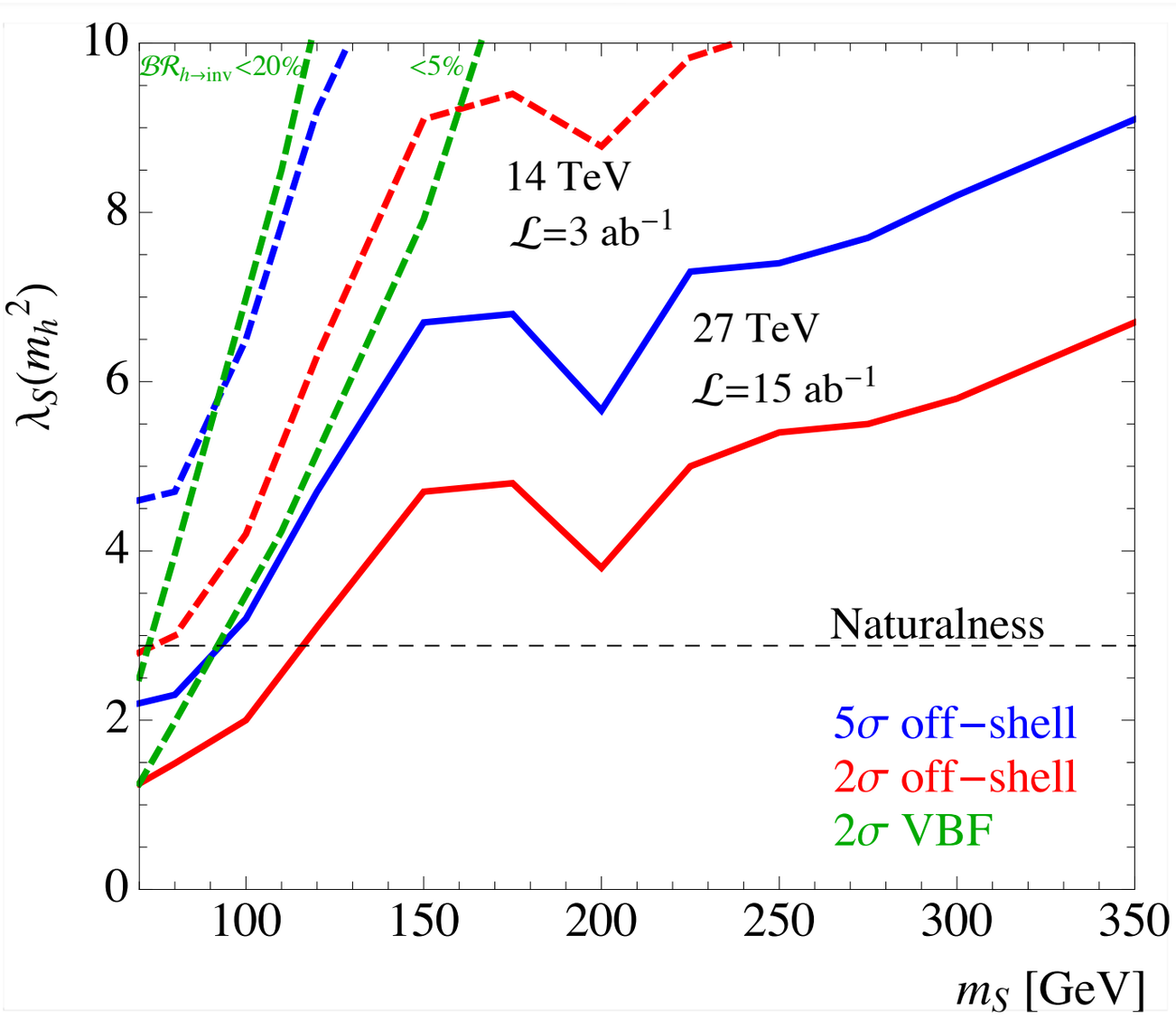


- Separably renormalizable and gauge-invariant subset
- Corrections are also at $\delta\sigma^{NLO}_{gg\to 4l} \propto \lambda_S^2$ order



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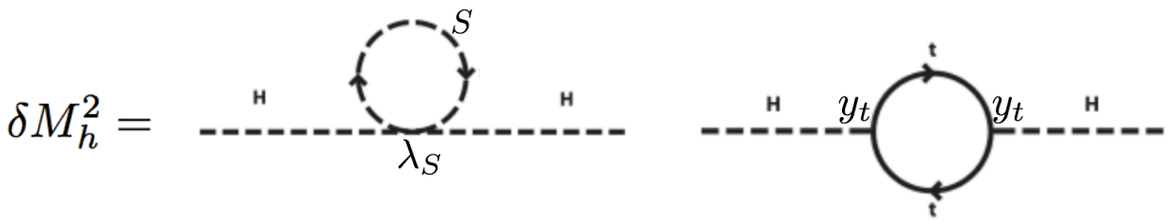
Off-shell probe to Naturalness:

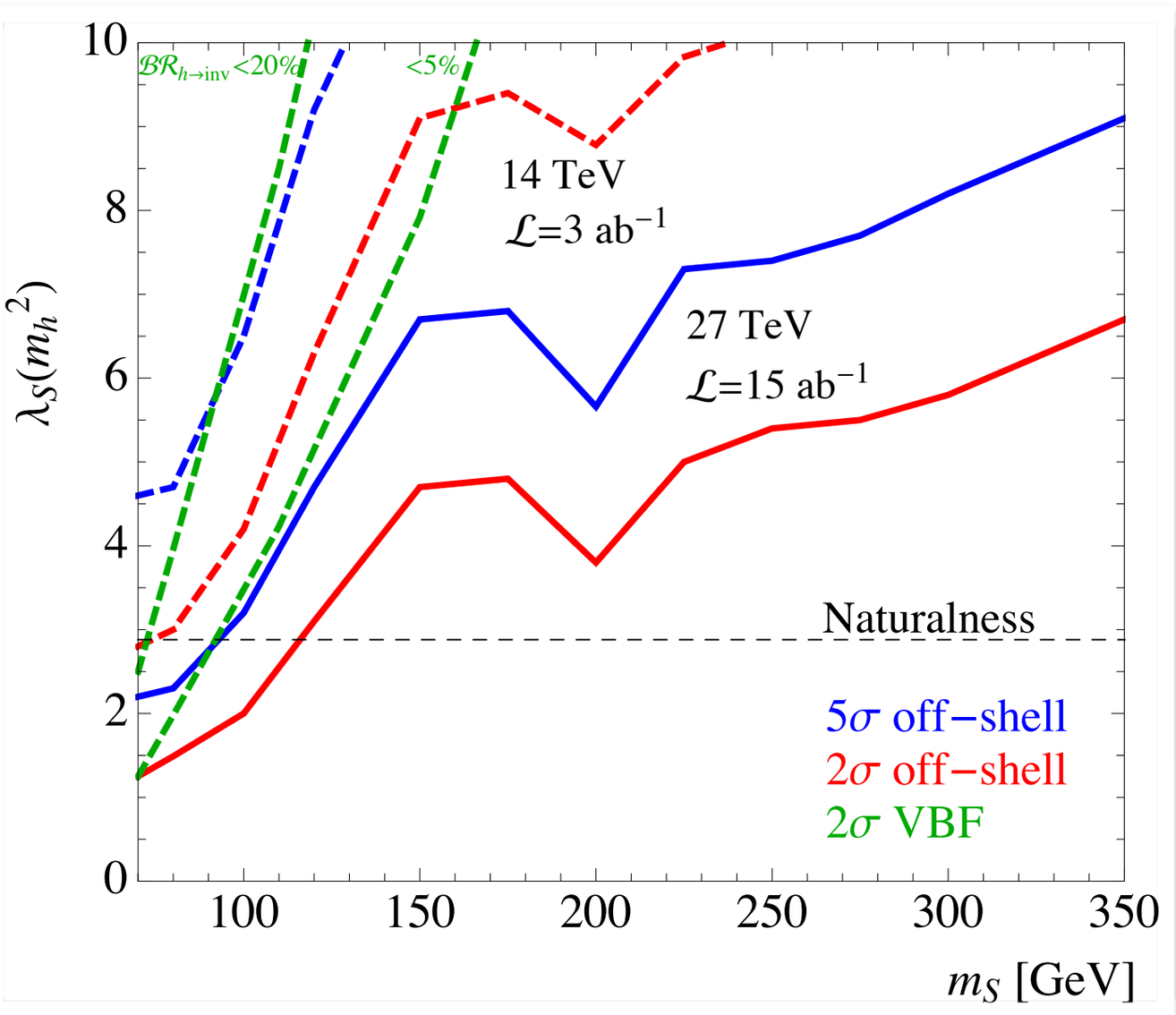


$$\delta M_h^2 = \frac{1}{16\pi^2}(\lambda_S - 2N_c y_t^2)\Lambda^2$$

If $\lambda_S(\Lambda^2) = 6y_t^2(\Lambda^2)$ singlet is like stop
Alleviate the "little hierarchy" problem

Higgs factory near ZH threshold ($e^+e^- \to ZH$)

Craig, McCullough, Englert (2015)



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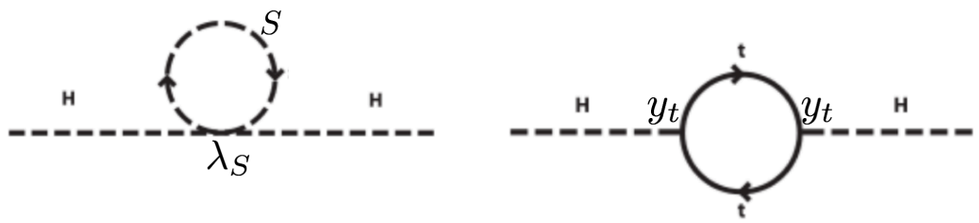
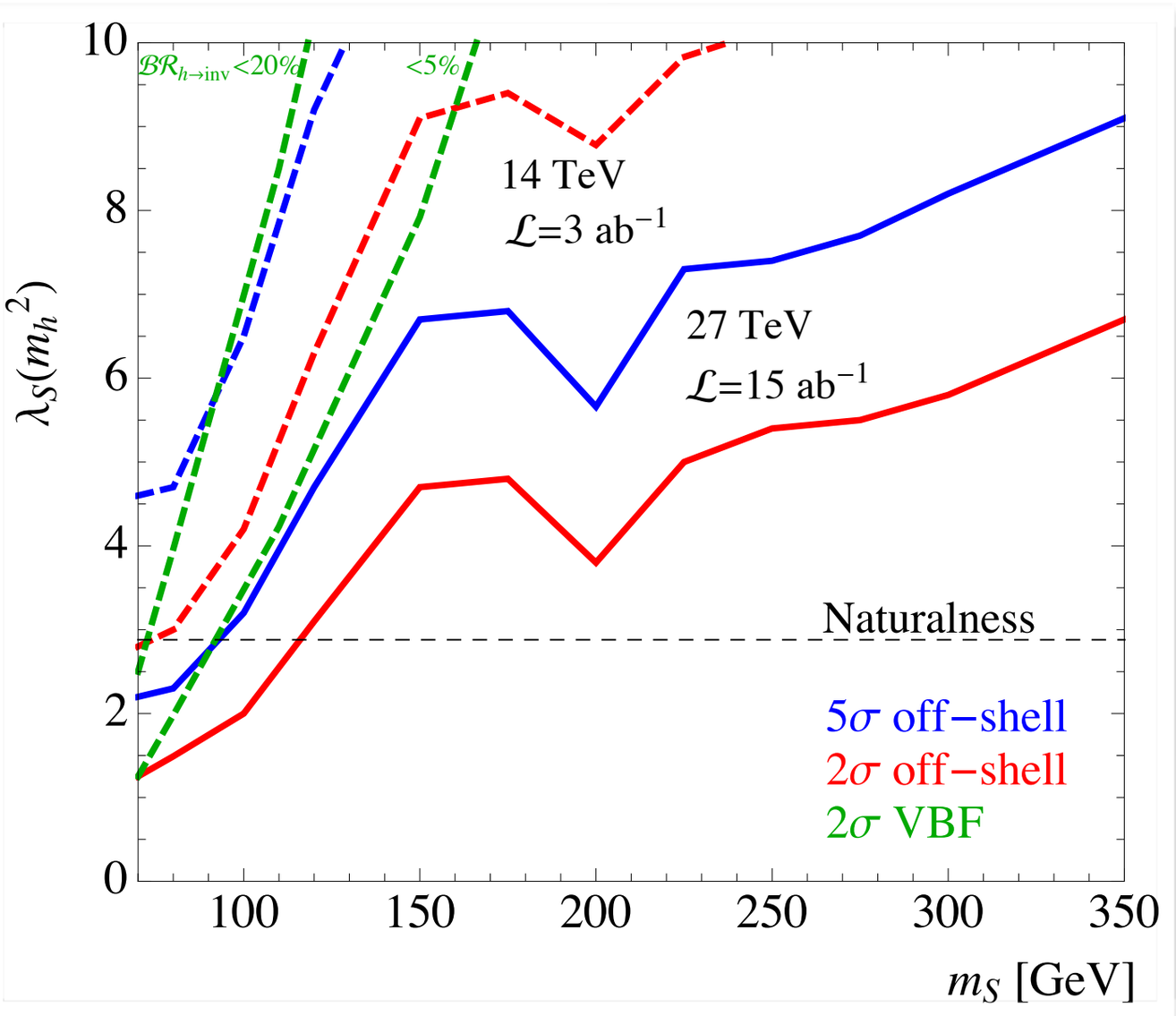
- Off-shell probe to Naturalness:

$\delta M_h^2 =$ 

$$\delta M_h^2 = \frac{1}{16\pi^2}(\lambda_S - 2N_c y_t^2)\Lambda^2$$

- Scalar singlet presents connections to DM & EW baryogenesis (1st order phase transition)
  J. McDonald (2007); C.P. Burgess et al. (2000)
  Batell, Gori, Wang (2011); Curtin, Meade, Yu (2014)

- Works for the maximally hidden scenario!



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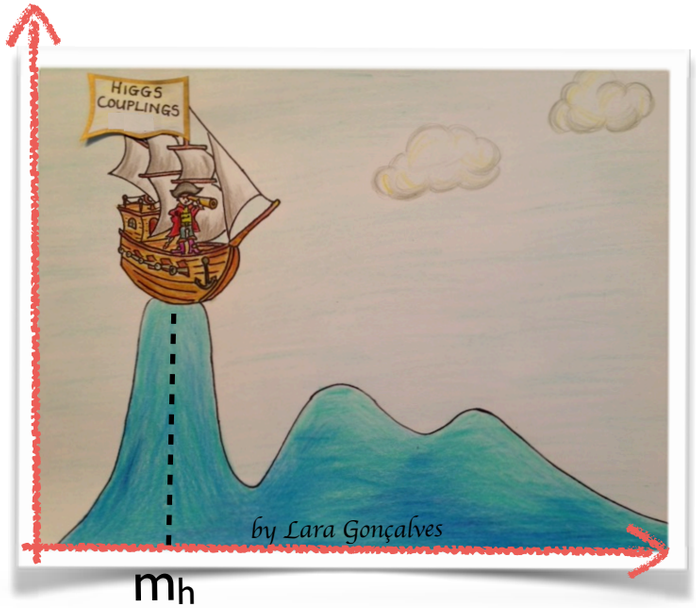
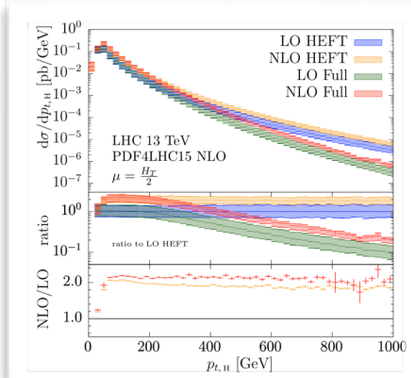
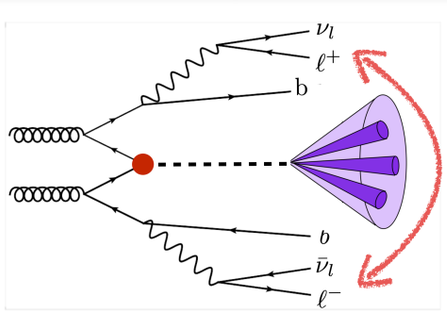


m_h

More searches



More energy & precision



More data

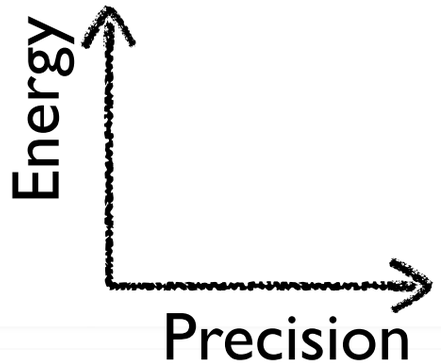
The power of kinematics

- Precision vs. sensitivity: sensitivity to BSM may not require extreme precision at LHC
  - Inclusive h-production or h-decay:

$$\frac{\delta\sigma}{\sigma_{SM}} \sim \left(\frac{m_h}{\Lambda}\right)^2 \quad \Rightarrow \quad \frac{\delta\sigma}{\sigma_{SM}} \sim 1\% \qquad \Lambda \sim 1.25 \text{ TeV}$$

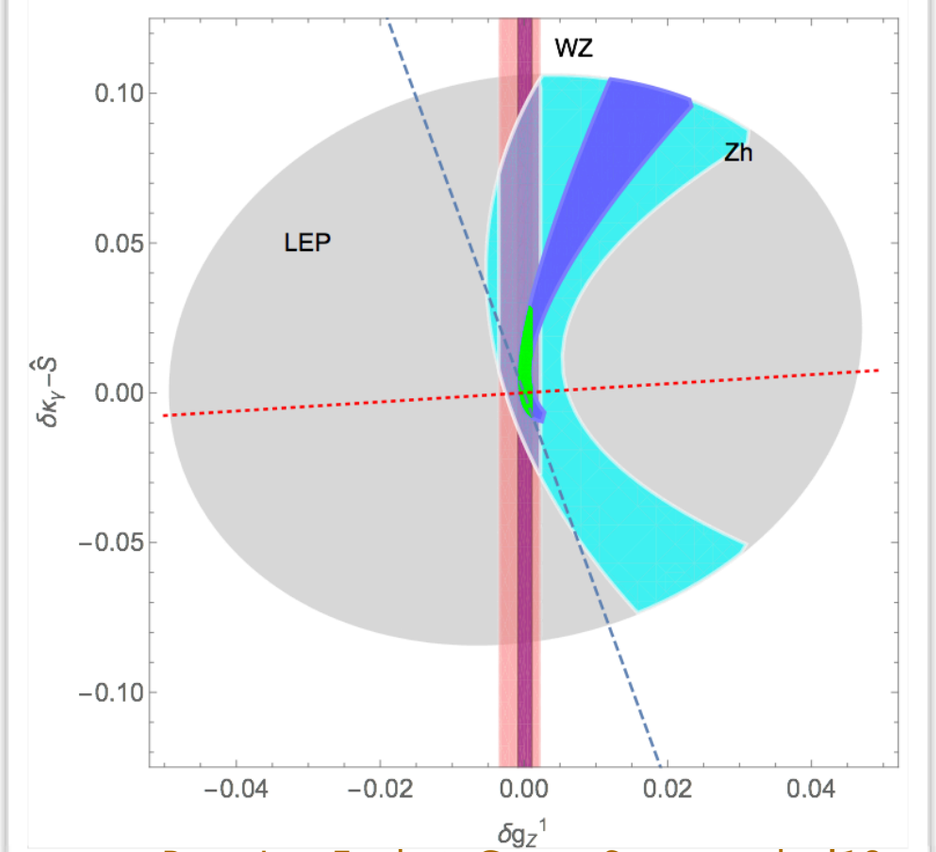
  - Boosted or off-shell Higgs (e.g. E~625 GeV):

$$\frac{\delta\sigma}{\sigma_{SM}} \sim \left(\frac{E}{\Lambda}\right)^2 \quad \Rightarrow \quad \frac{\delta\sigma}{\sigma_{SM}} \sim 25\% \qquad \Lambda \sim 1.25 \text{ TeV}$$



- Example 1: Only way to compete with LEP in the TGC sensitivity is to go to high energies
  - $ZH \longrightarrow G^0 H$
  - $WH \longrightarrow G^+ H$
  - $WW \longrightarrow G^+ G^-$
  - $WZ \longrightarrow G^+ G^0$

Franceschini, Panico, Pomarol, Riva, Wulzer '17;
Butter, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, Plehn, Rauch '16



Banerjee, Englert, Gupta, Spannowsky '18

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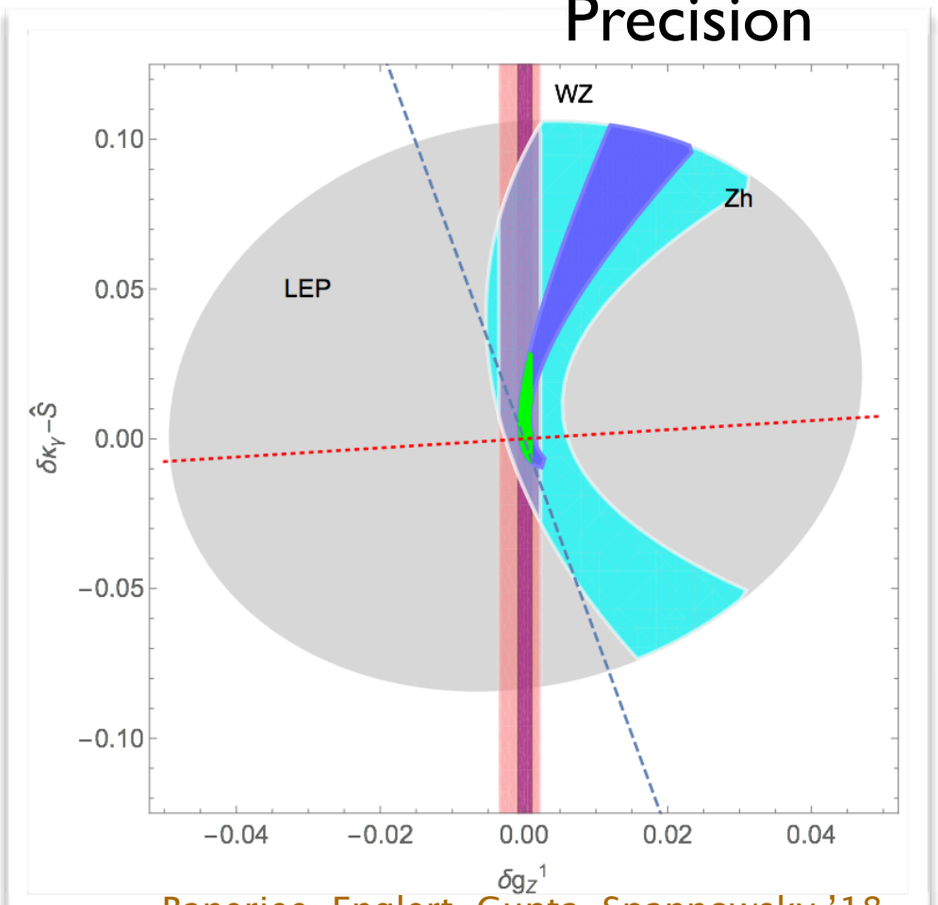
- Example 1: We cannot look at only piece of the puzzle! Combining Higgs & diboson data at high energies significantly improve sensitivity to new physics

Franceschini, Panico, Pomarol, Riva, Wulzer '17;
Butter, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, Plehn, Rauch '16



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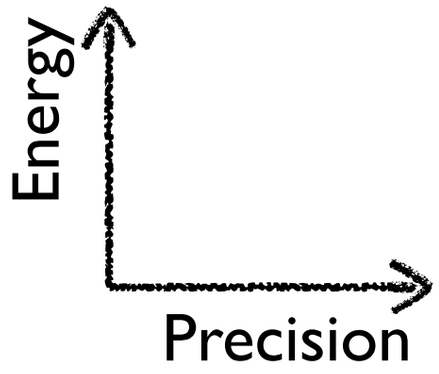
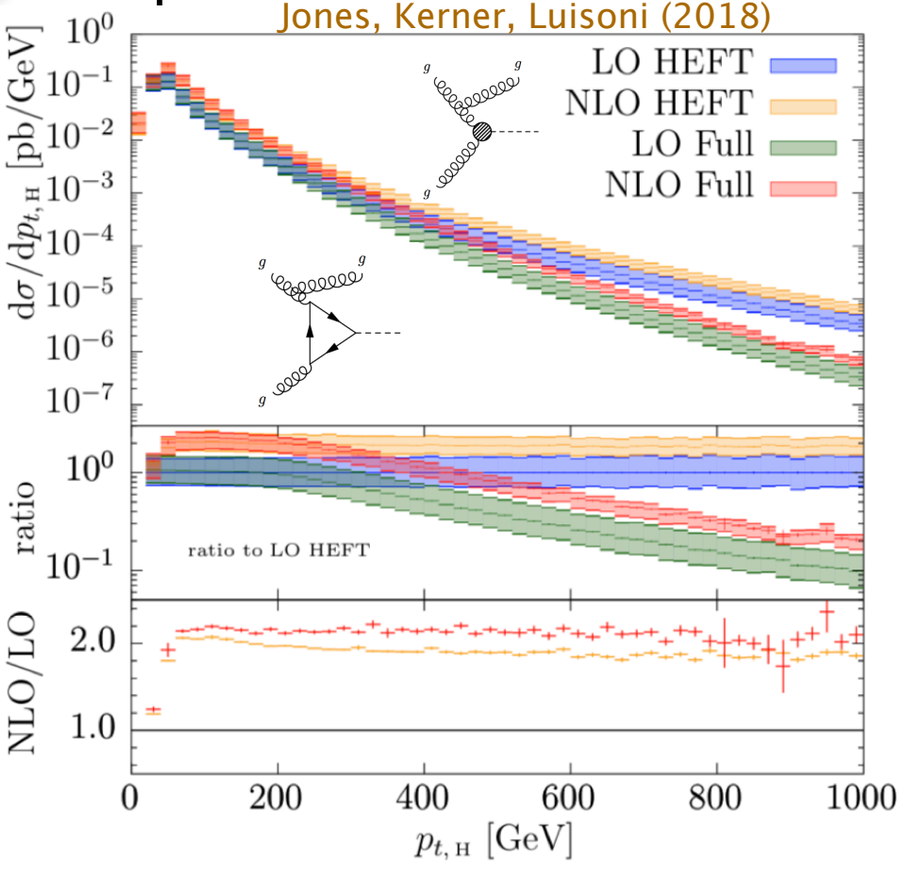
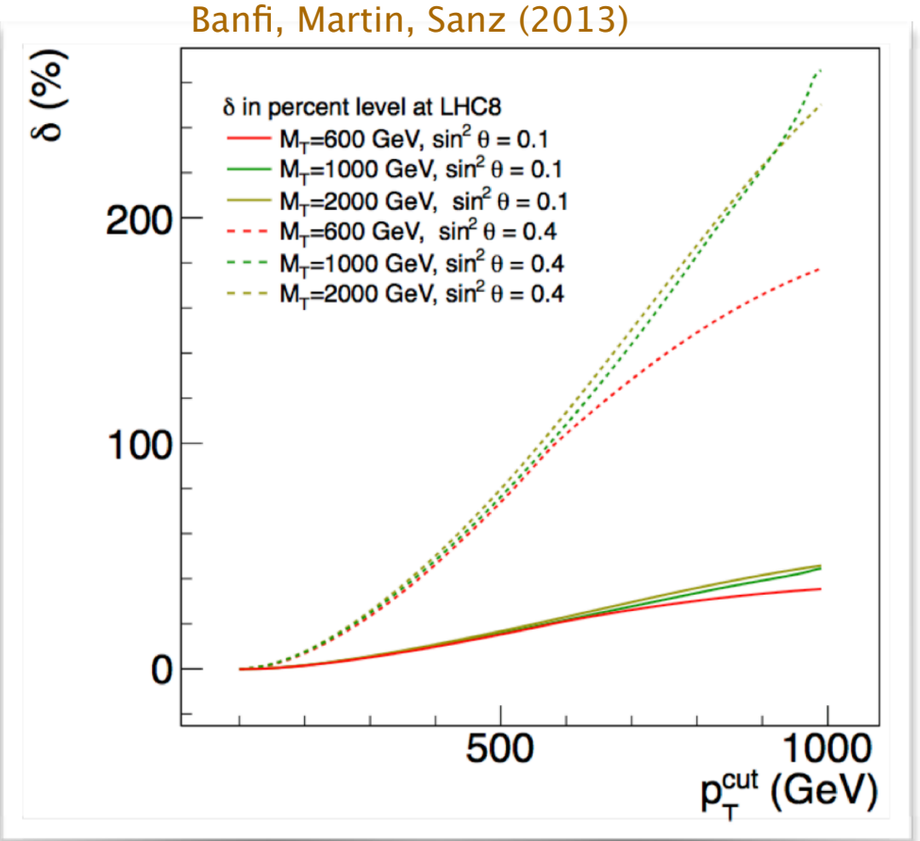


- Example 2:

Jones, Kerner, Luisoni (2018)



Banfi, Martin, Sanz (2013)



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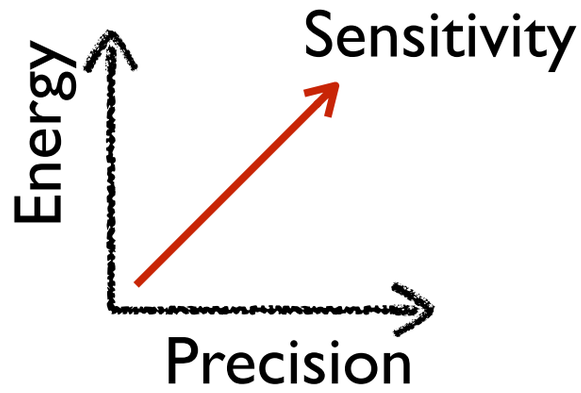

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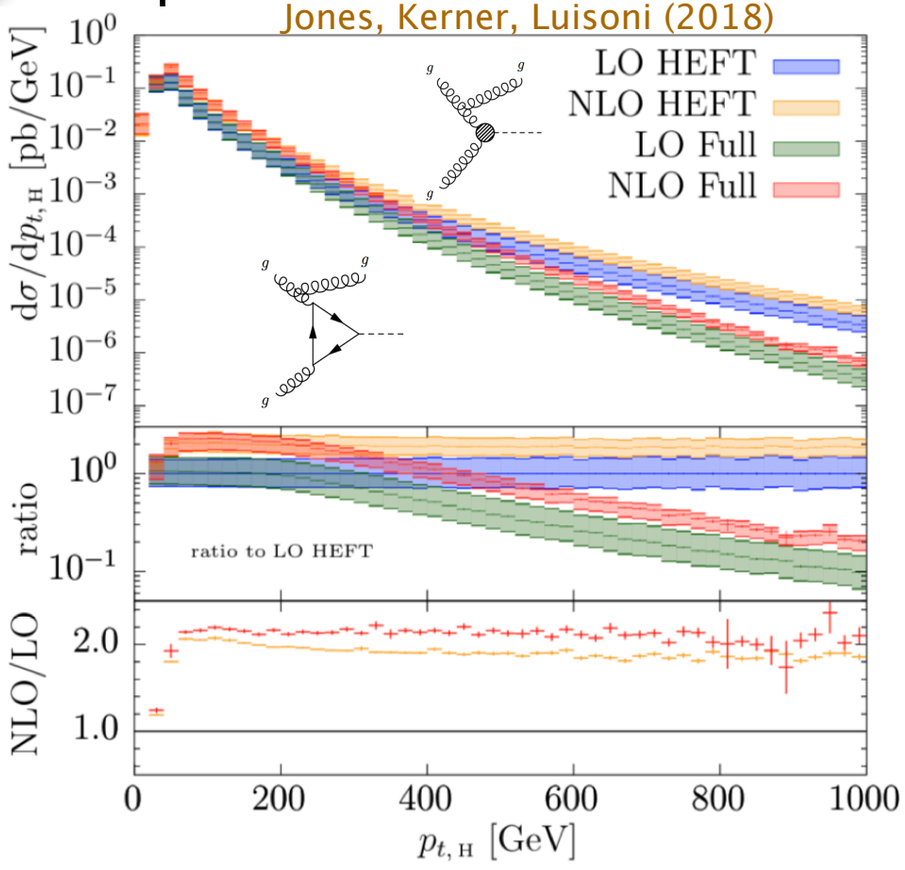


→ First exact NLO calculation

→ QCD corrections approximately factorize:

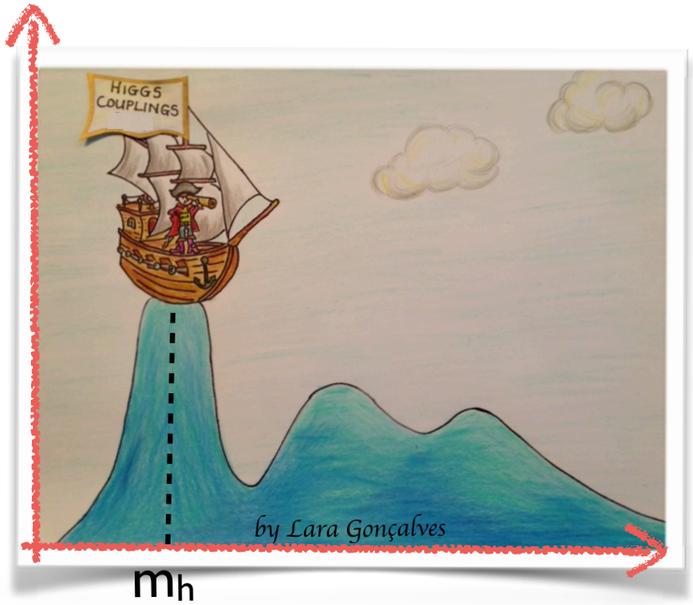
$$\left(\frac{NLO}{LO}\right)_{HEFT} \sim \left(\frac{NLO}{LO}\right)_{Full}$$

→ Relevant to many studies, e.g., H(bb)+jets

CMS PAS HIG-17010

→ Best prediction: multiplicative combination $NNLO_{HEFT}$ with NLO_{full}

NNLO HEFT see: Boughezal,Caola et al. '15; Boughezal et al. '15; Chen et al. '16…



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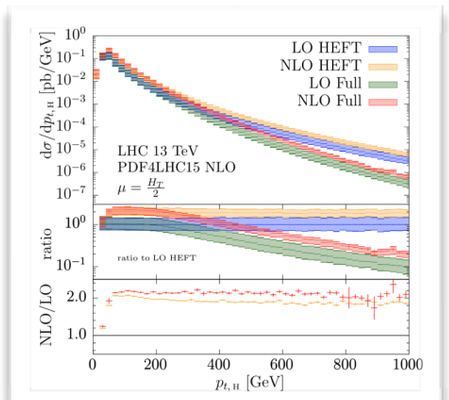

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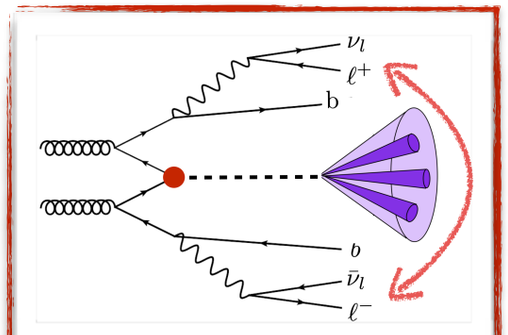


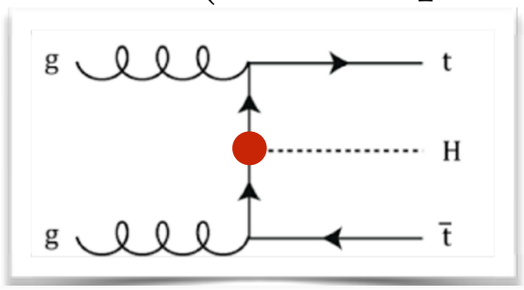
More data

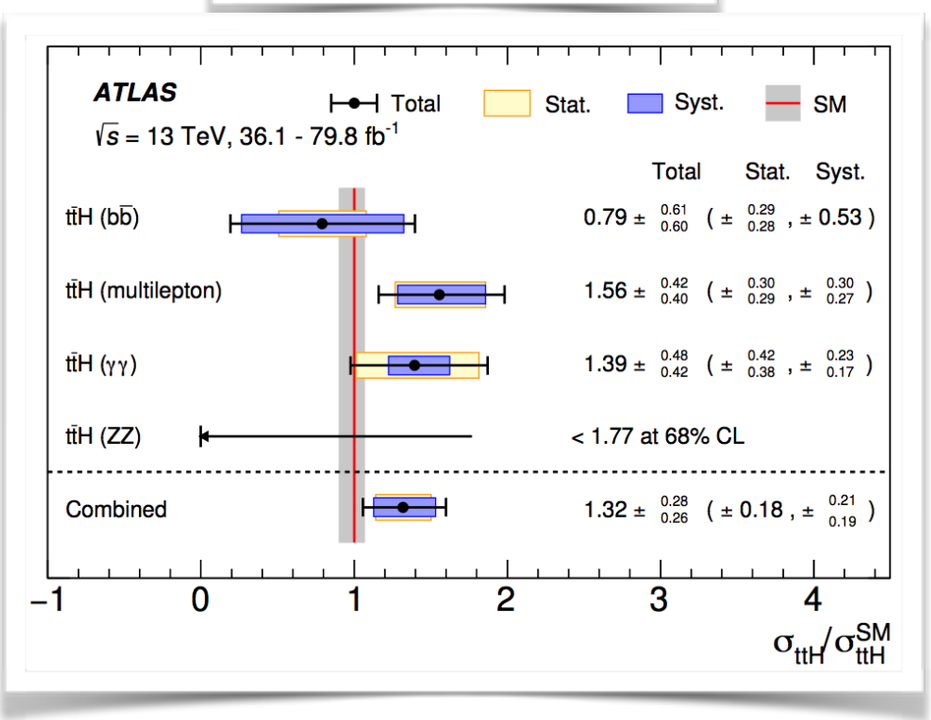
Direct Higgs-top measurement

- ttH channel observation (2018):

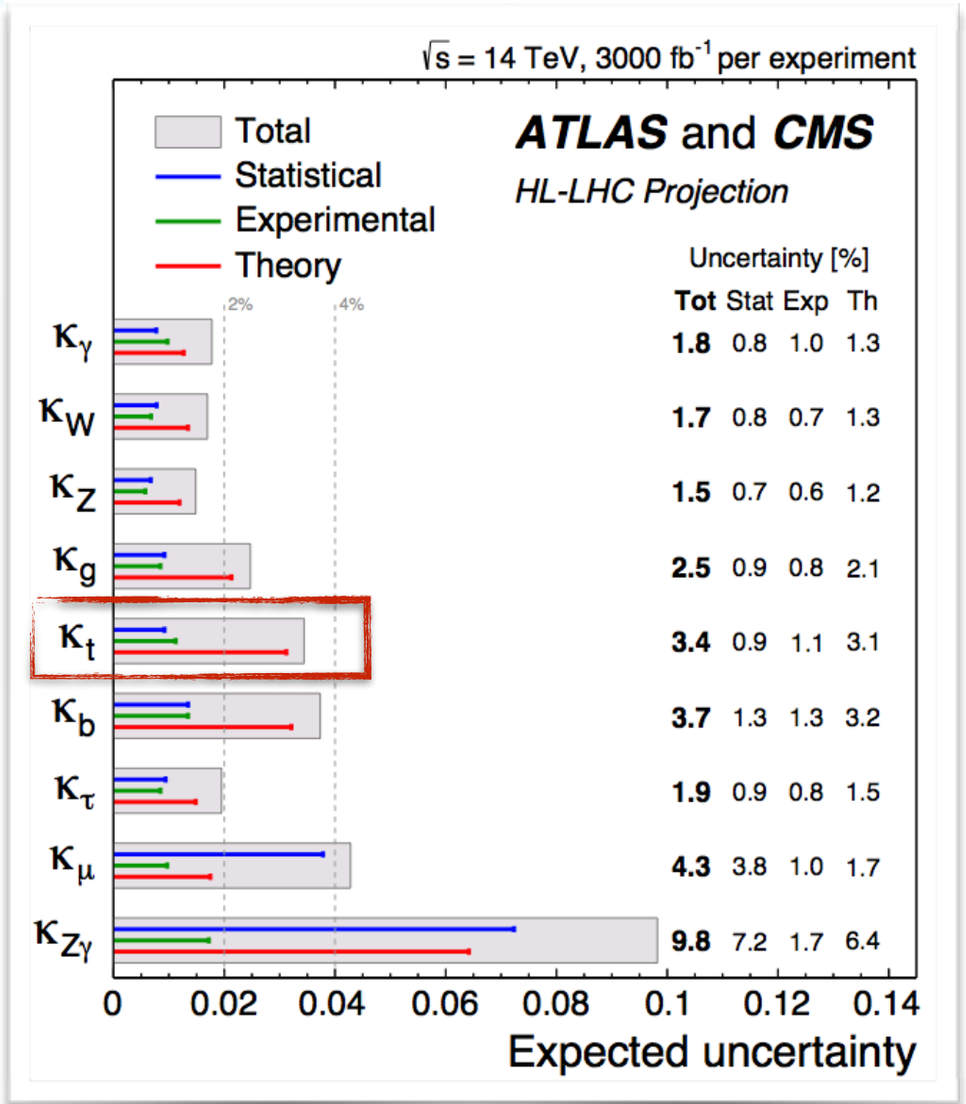
  6.3σ observed (5.1σ expected) – ATLAS

  5.2σ observed (4.2σ expected) – CMS





- Expected HL-LHC precisions:



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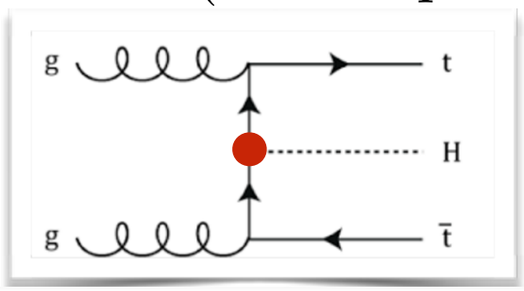

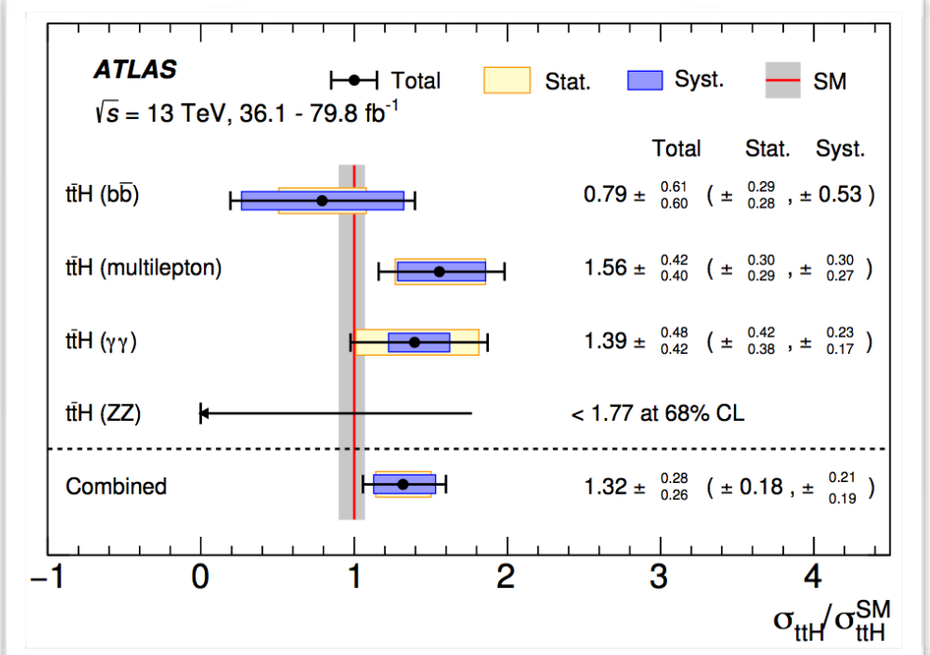

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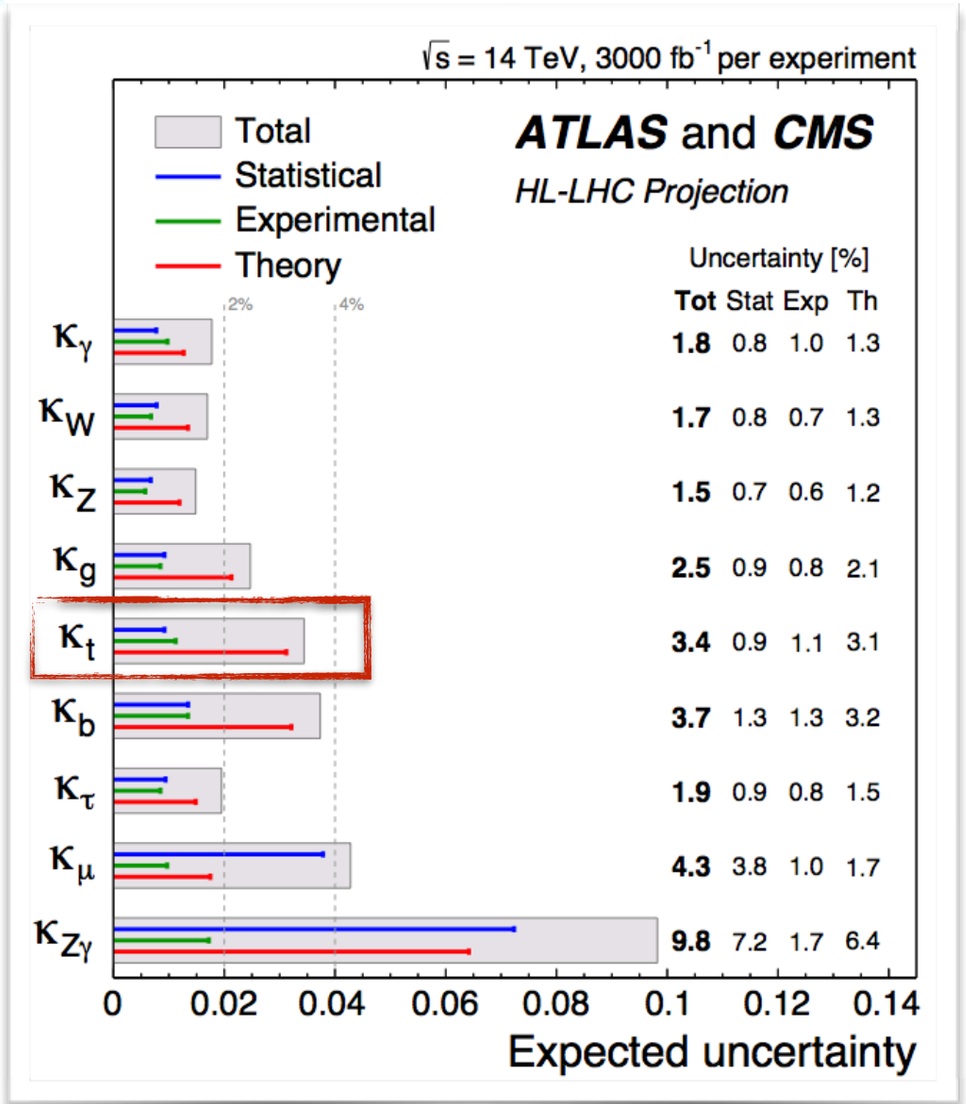


- Can we go beyond and directly measure Higgs-top CP structure at the LHC?

$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha\right) t \; H$$

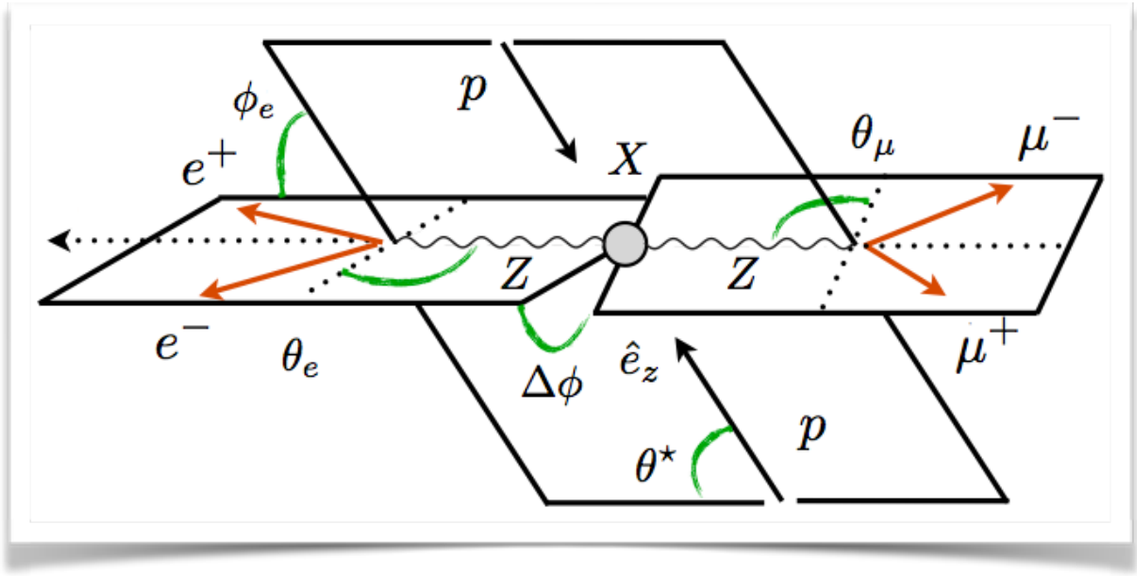
CP-violation

- At LHC CPV HVV interaction is already extensively tested (clean target H→4leptons)

  Gritsan, Melnikov, Schulze, et al (2010)

  Englert, DG, Mawatari, Plehn (2012)…

$$\mathcal{L}_0 = g_1^{(0)}\, HV_\mu V^\mu - \frac{g_2^{(0)}}{4}\, H\, V_{\mu\nu} V^{\mu\nu} - \frac{g_3^{(0)}}{4}\, A\, V_{\mu\nu} \tilde{V}^{\mu\nu}$$



- While CP-odd HVV is loop suppressed, CP-odd Hff can manifest at tree-level:
  - → Mixture possible in some models, e.g., 2HDM
  - → Not excluded from Higgs measurements
  - → t-quark and τ are the first obvious candidates

$$\mathcal{L} \supset -\frac{m_f}{v} K h \bar{f} (\cos\alpha + i\gamma_5 \sin\alpha) f$$

Buckley, DG (PRL–2015)

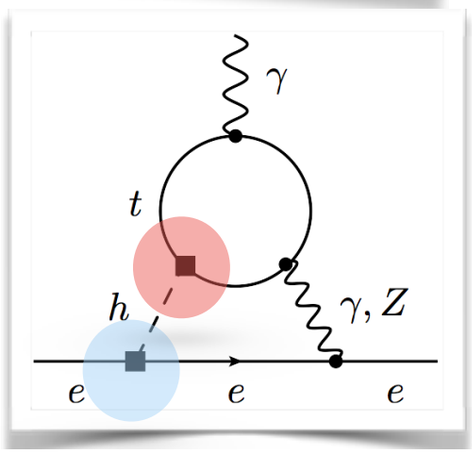
Harnik, Martin, Okui, Primulando, Yu (2013)

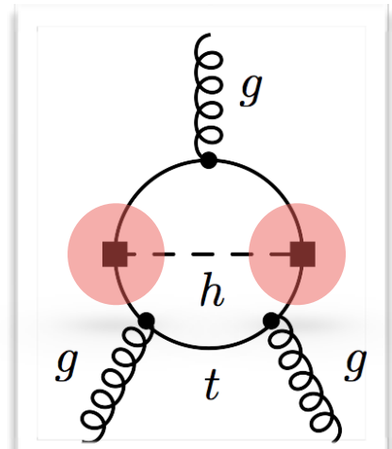
Han, Mukhopadhyay, Mukhopadhyaya, Wu (2016)

CP-violation: EDM constraints

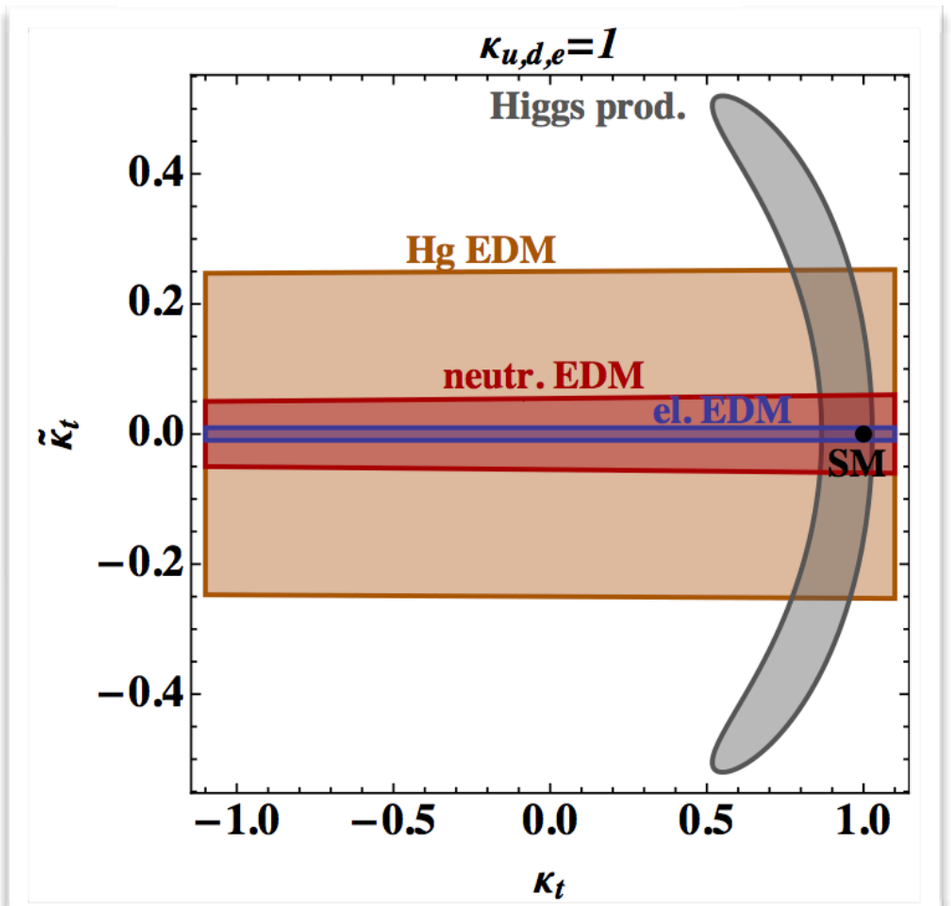
- Indirect constraints from eEDM very strong, yet assume:
  - → No other states in the spectrum
  - → Coupling strength/structure to light fermions

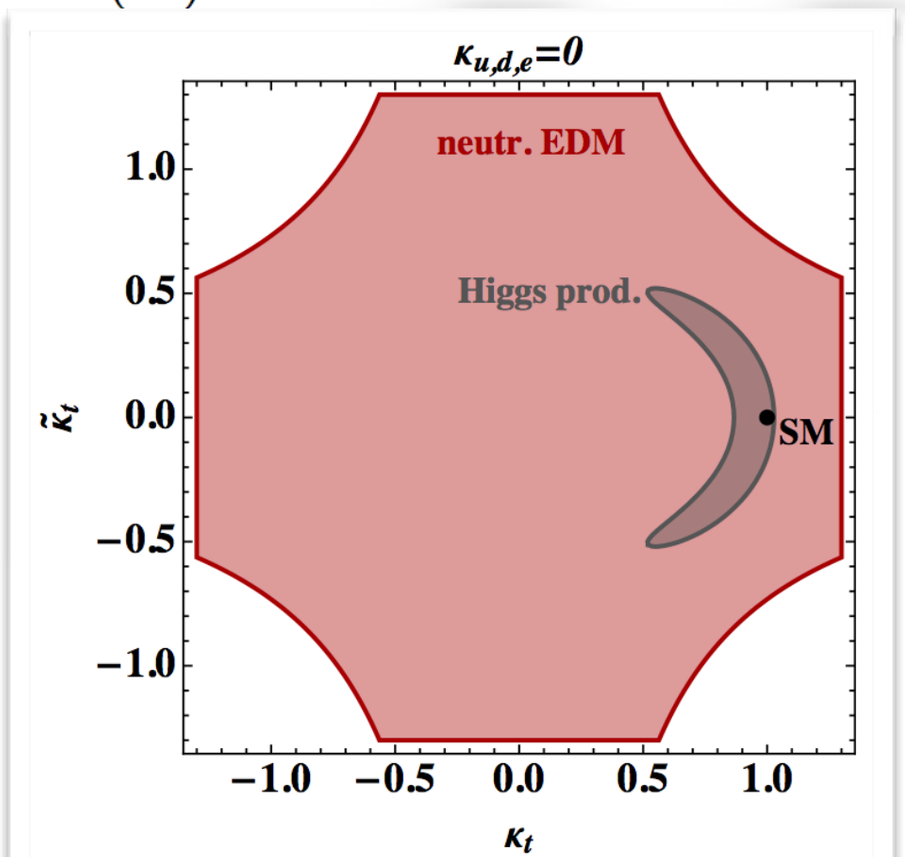
$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}}\left(\kappa_f\,\bar{f}f + i\tilde{\kappa}_f\,\bar{f}\gamma_5 f\right)h$$





$$\frac{d_e}{e} = \frac{16}{3}\frac{\alpha}{(4\pi)^3}\sqrt{2}G_F m_e\left[\kappa_e\tilde{\kappa}_t\, f_1(x_{t/h}) + \tilde{\kappa}_e\kappa_t\, f_2(x_{t/h})\right]$$



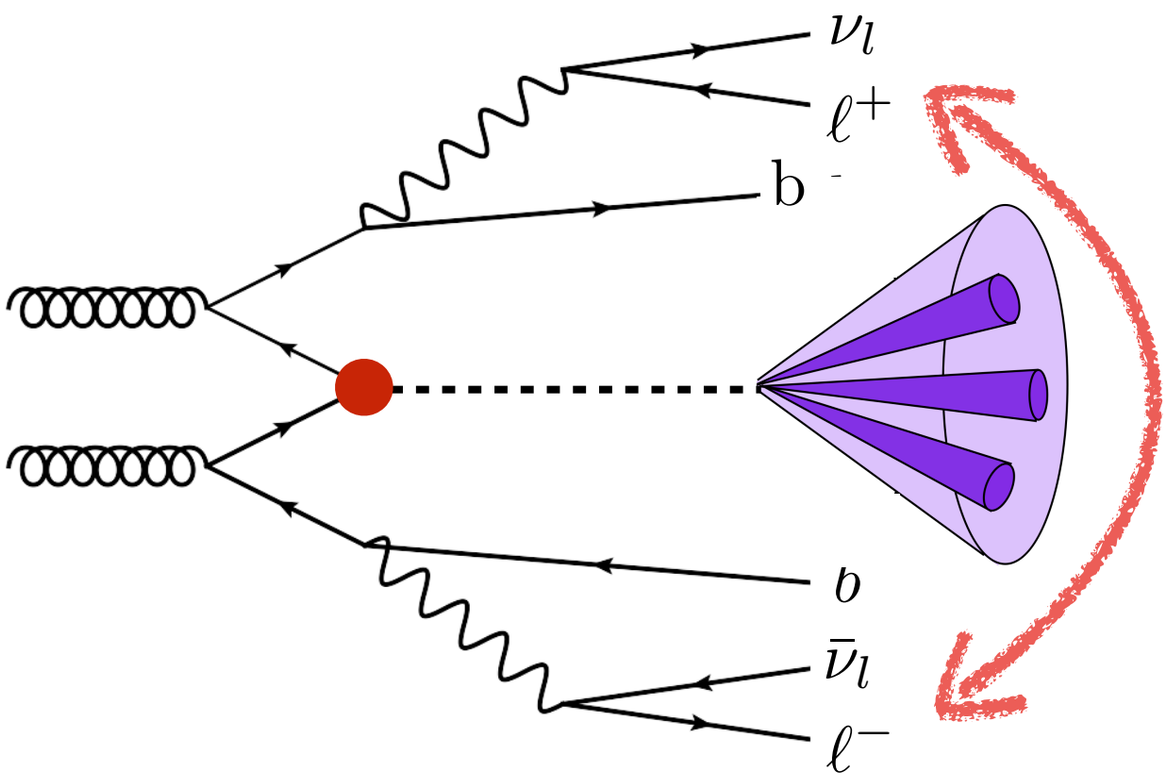


Brod, Haisch, Zupan (2013)

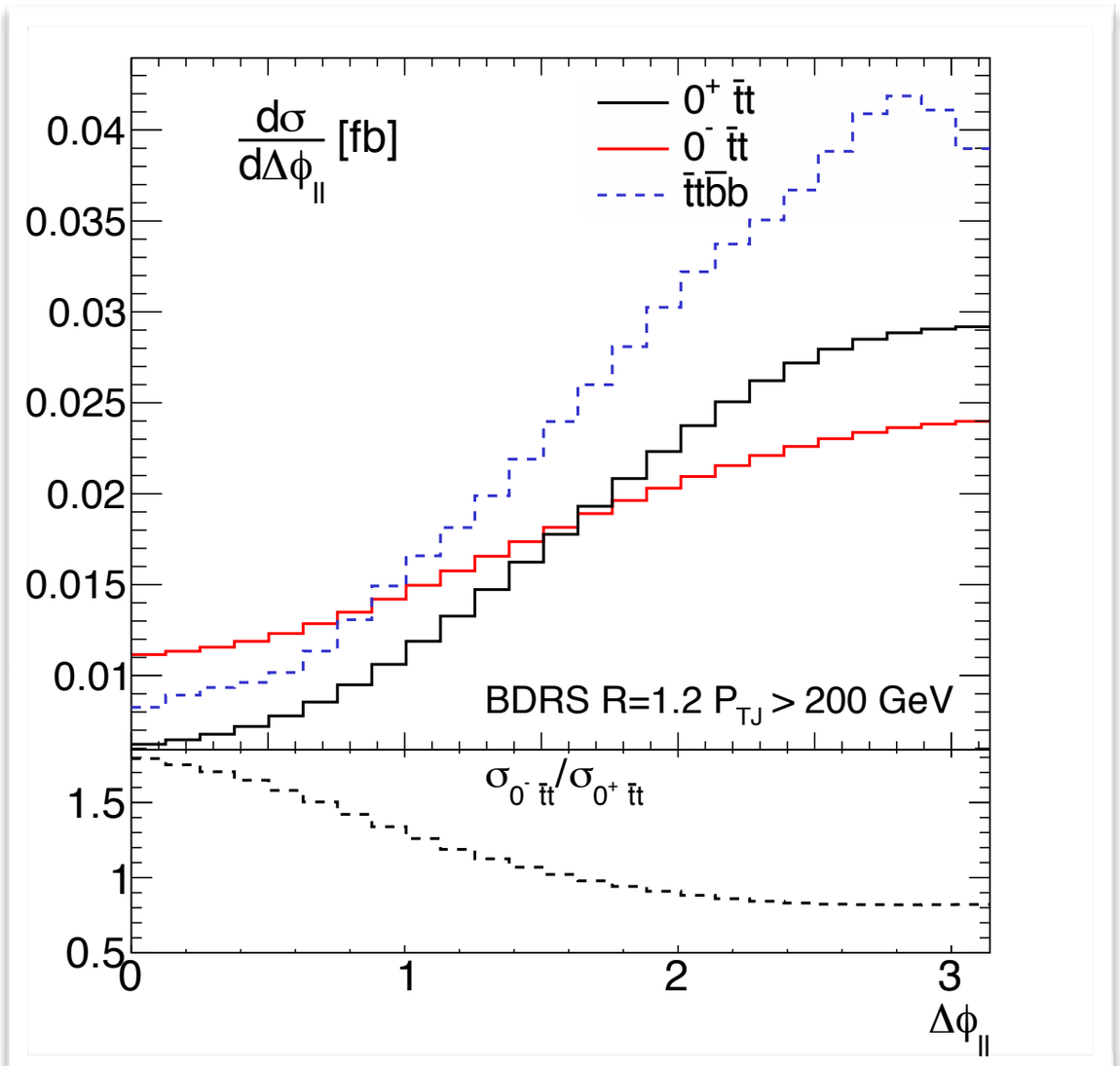
Higgs-top CP measurement via ttH

- Analogous situation to correlated vs uncorrelated top decays

  Parke, Mahlon (1996,2010)



$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha\right) t \; H$$



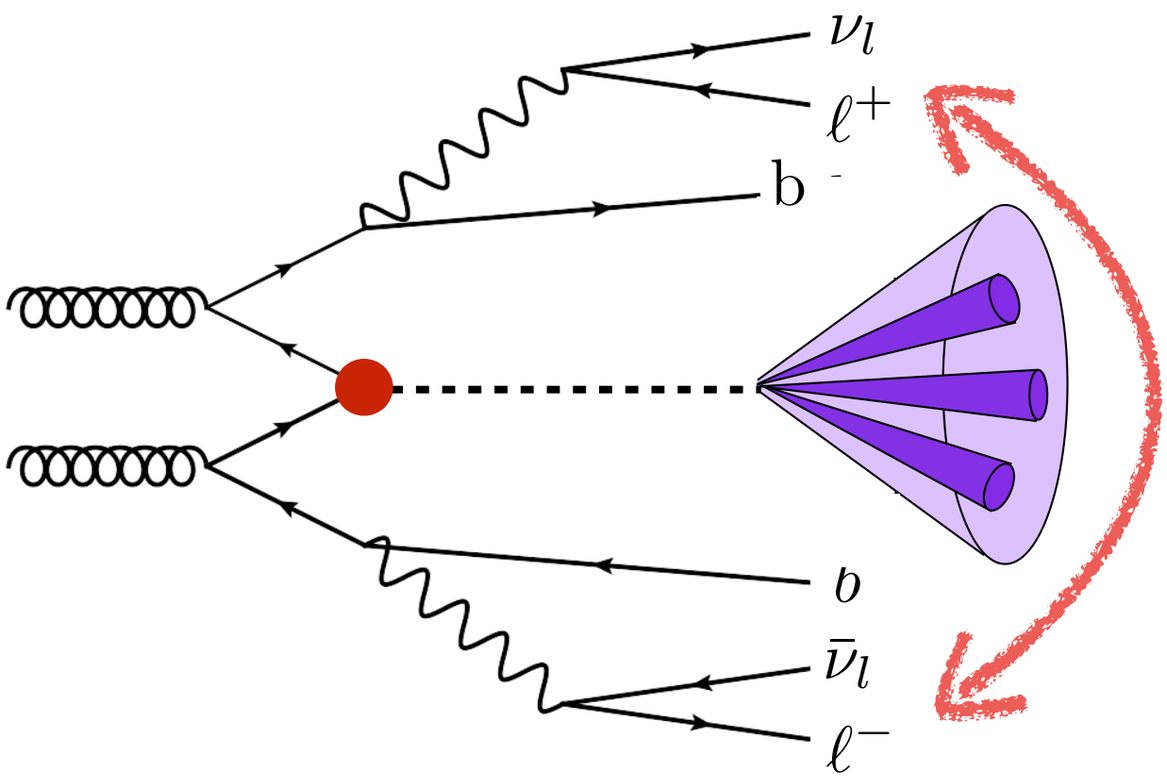
Buckley, DG (PRL–2015)

➡ Boosted Higgs study nicely match with Higgs-top CP-measurement

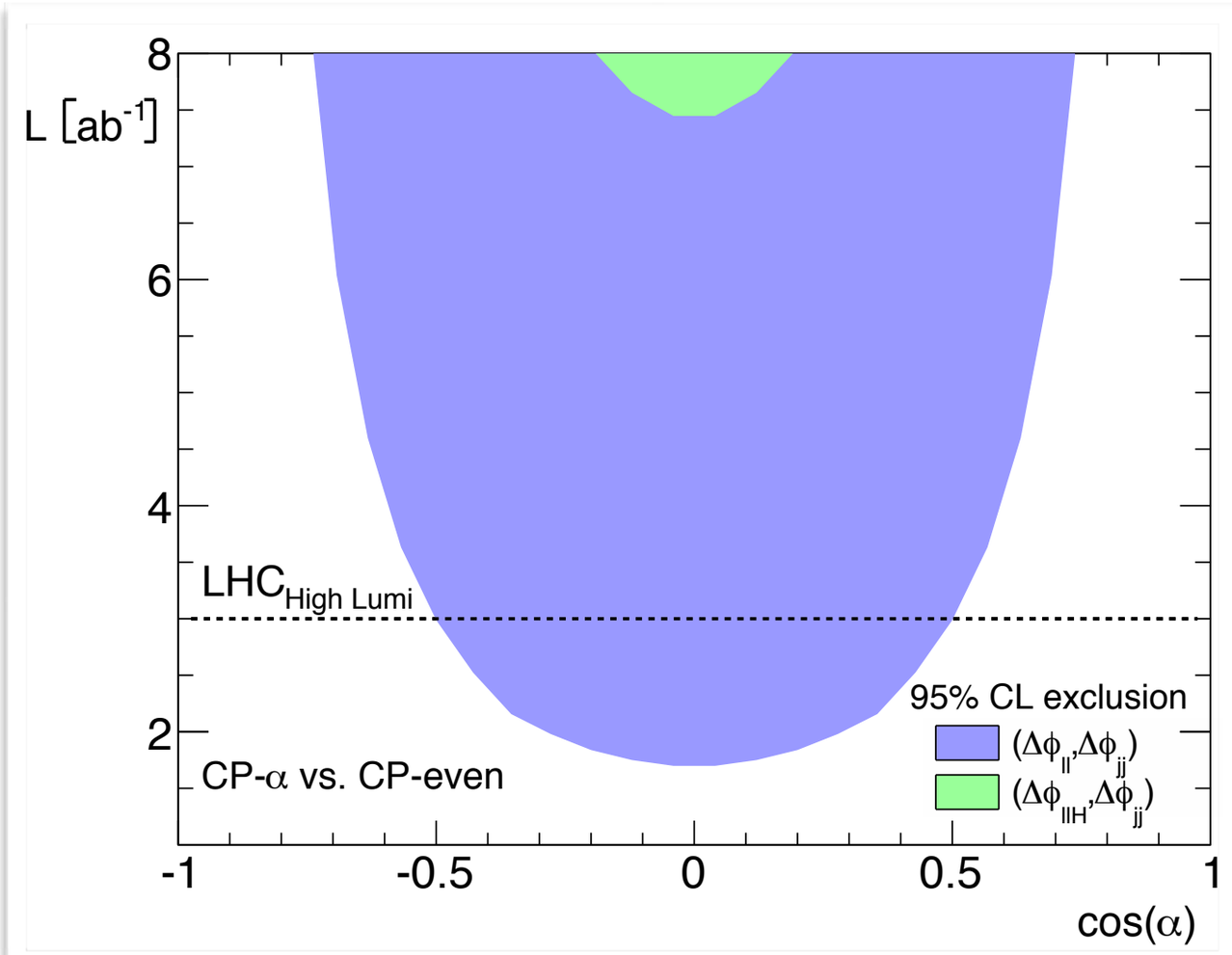
Higgs-top CP measurement via ttH

- Analogous situation to correlated vs uncorrelated top decays

  Parke, Mahlon (1996,2010)



$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha\right) t \; H$$



Buckley, DG (PRL-2015)

- New powerful observables and reconstruction: sensitive to |cosα|<0.7

  DG, Kong, Kim '18; Gritsan, Rontsch, Schulze, Xiao '16

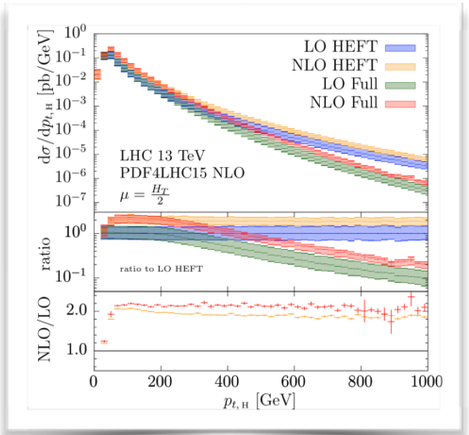
Summary

The Higgs boson is a new particle type. Likely a portal to new physics!

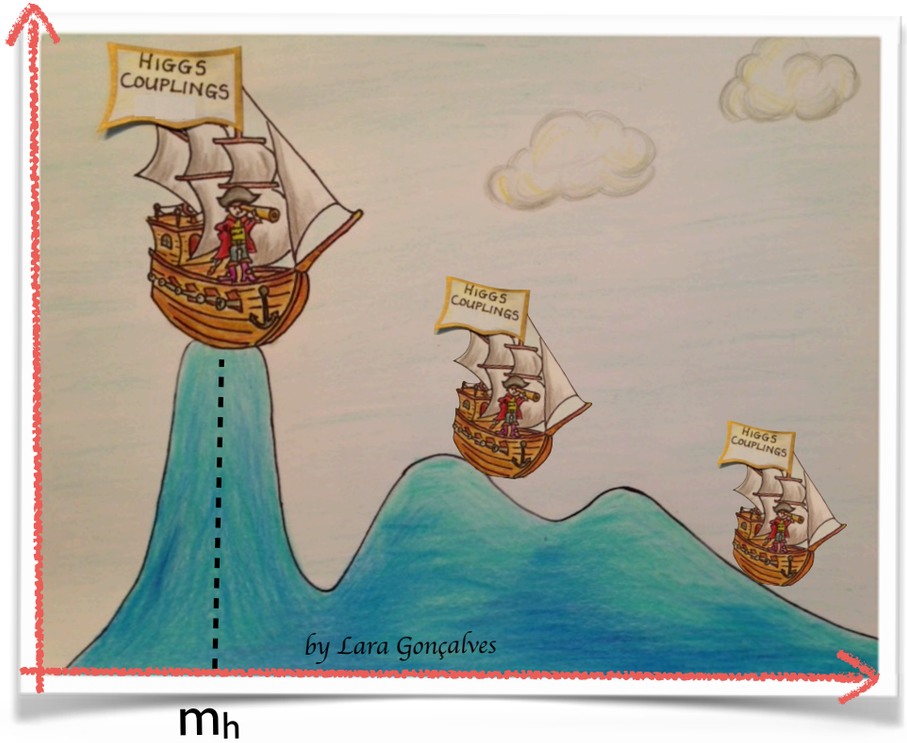
- **More searches:** Off-shell Higgs - New probe to the maximally hidden Higgs portal scenario. May display connections to hierarchy problem, DM…

- **More energy & precision:** Going after *sensitivity* instead of only precision opens new opportunities

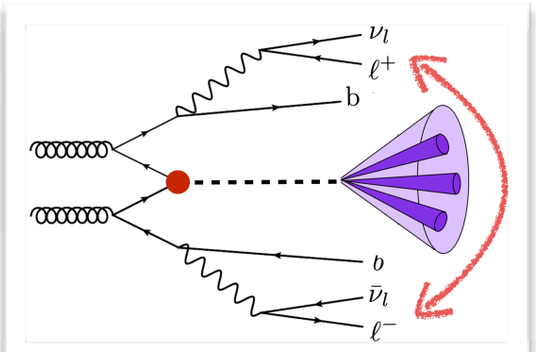
- **More data:** Analogously to the Higgs-top signal strength measurement, ttH provides a direct probe Higgs-top CP-structure. Relevant target for the forthcoming experimental analyses



More energy & precision



More searches



More data

Thank you for your attention!