High-lumi opportunities for Higgs physics

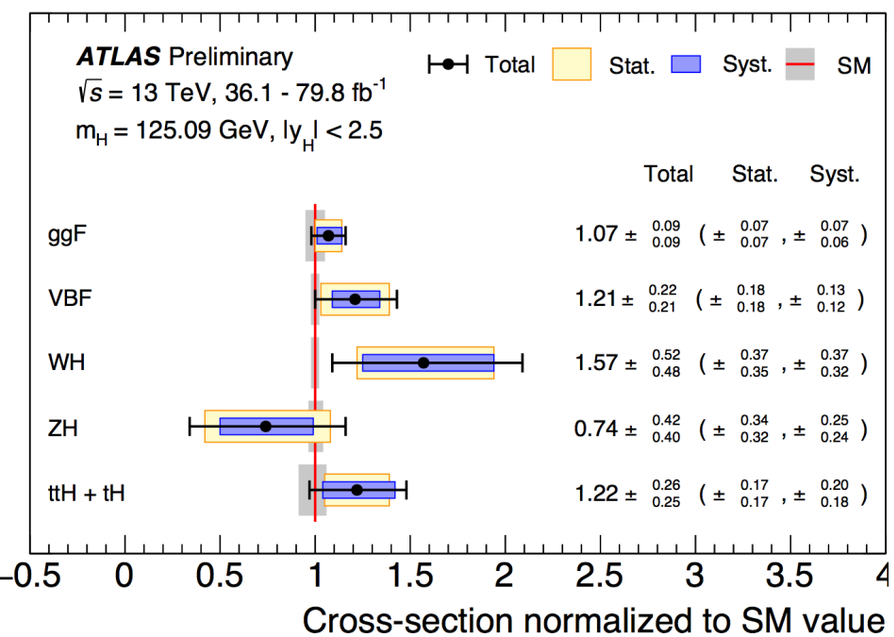
US ATLAS Workshop

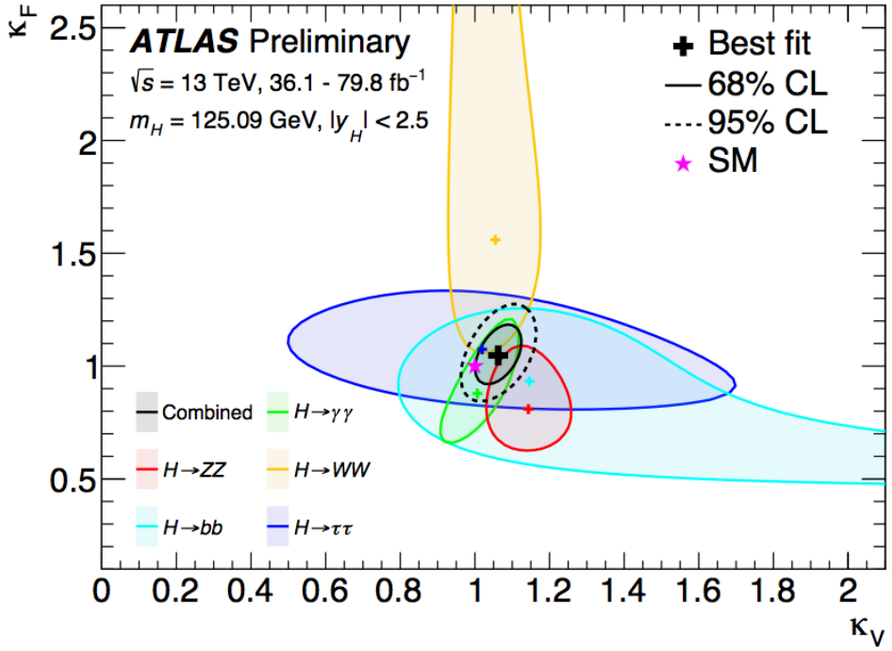
Pittsburgh - 07.30.2018

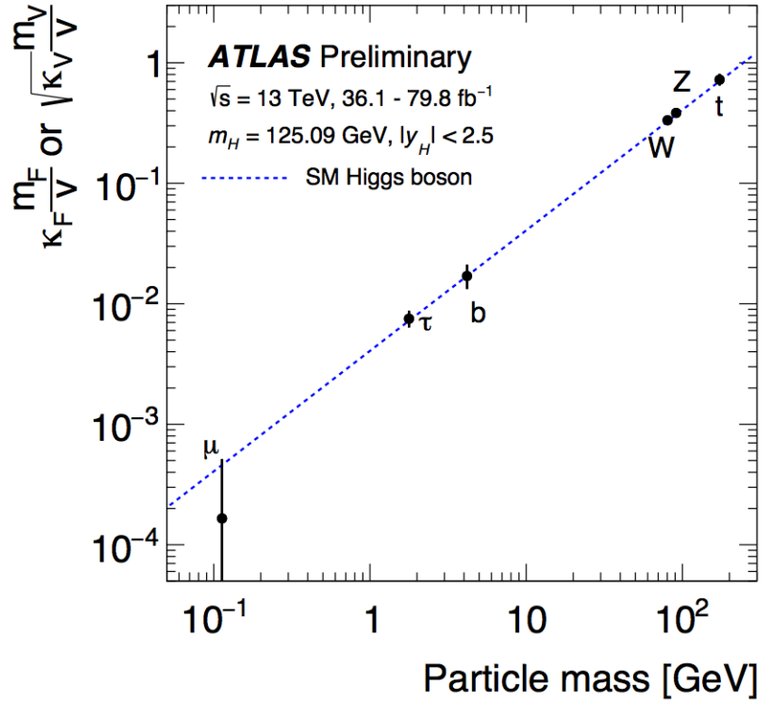
Dorival Gonçalves

Motivation

- Data tells us that we have SM-like Higgs boson

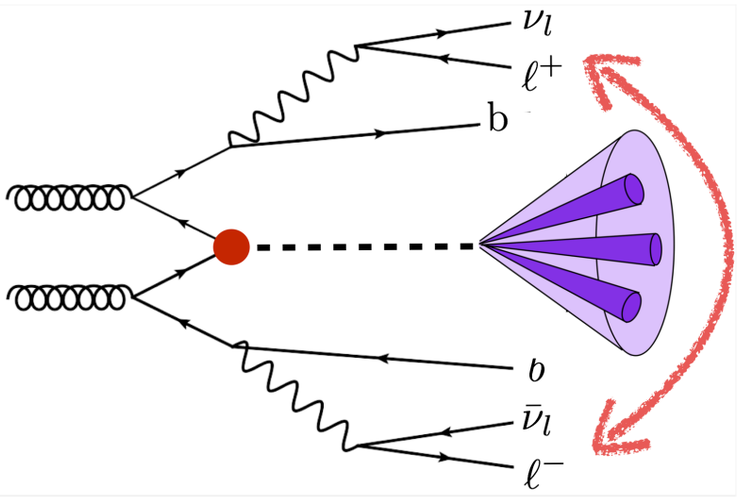




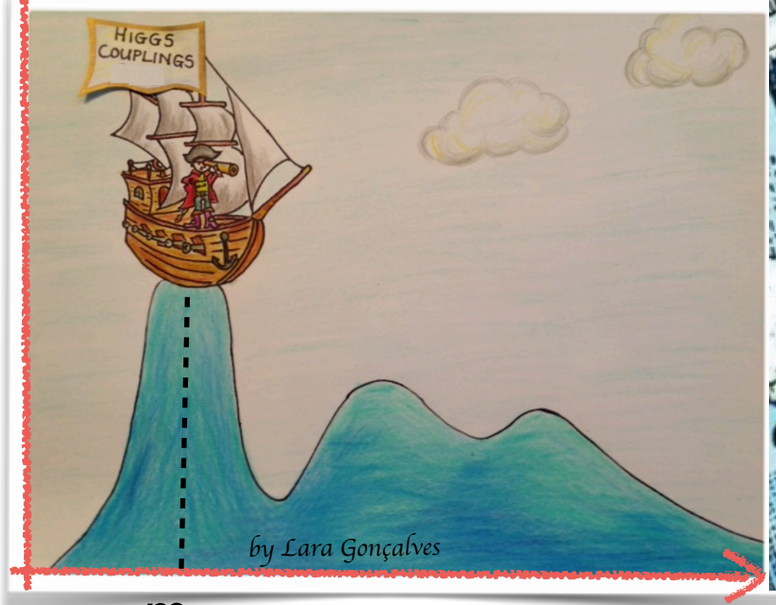


- SM could be valid all the way to exponentially high scales
- Maybe solutions to naturalness problem, DM… have taken a more subtle incarnation

Many exciting opportunities ahead!!!



direct Higgs-top CP-measurement



m_h

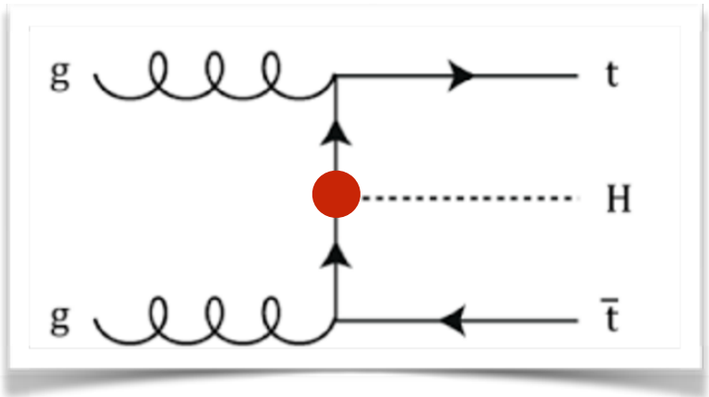
Off-shell measurements

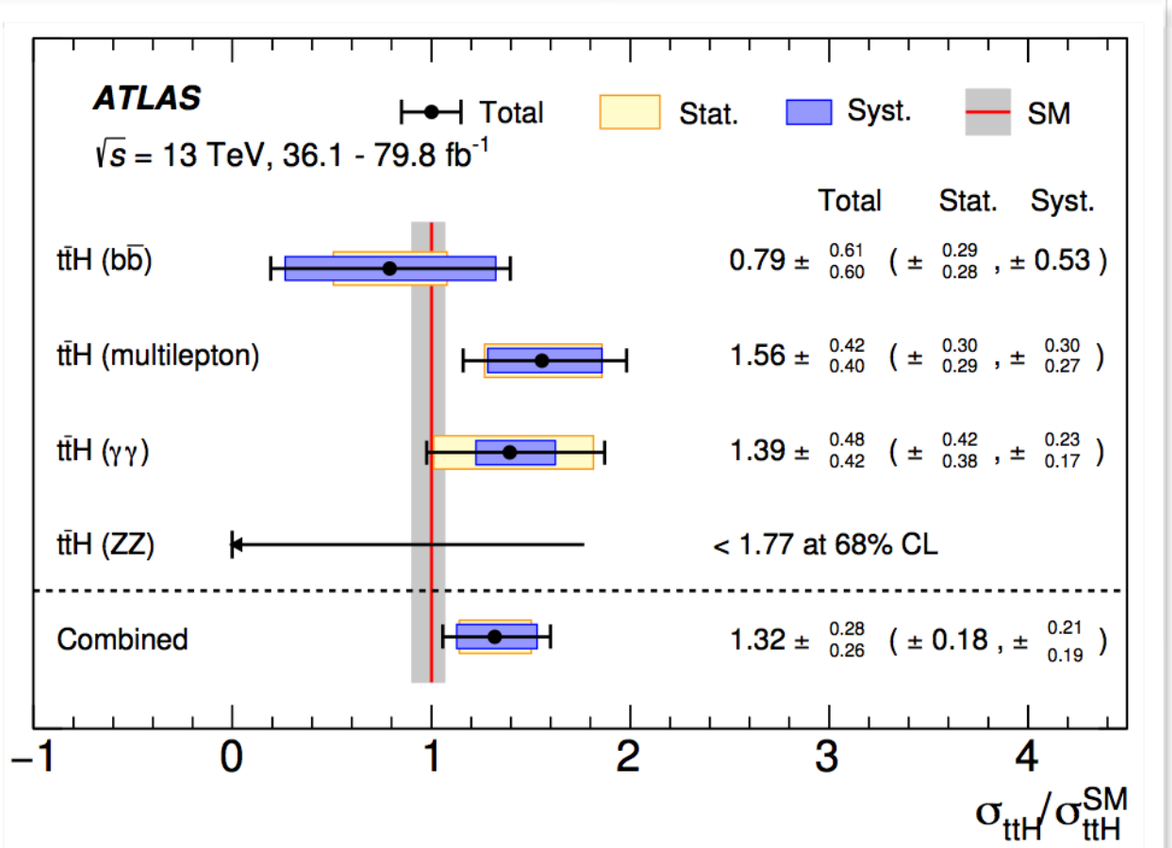
Directly Measuring ttH

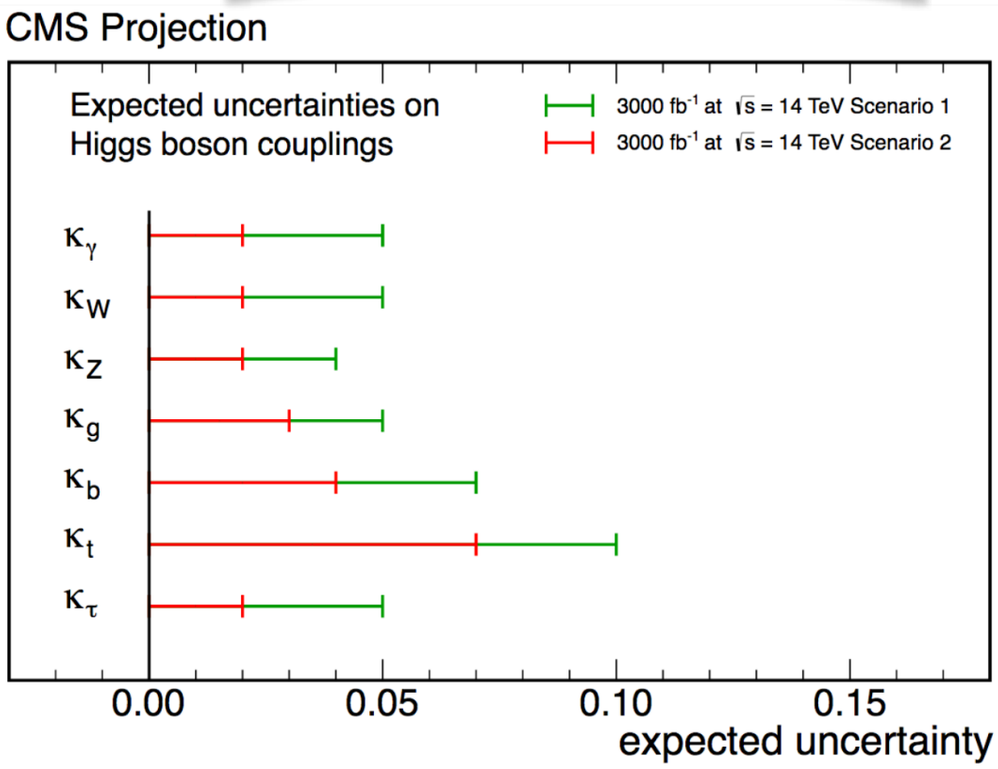
- ttH channel observation:

  6.3σ observed (5.1σ expected) – ATLAS

  5.2σ observed (4.2σ expected) – CMS







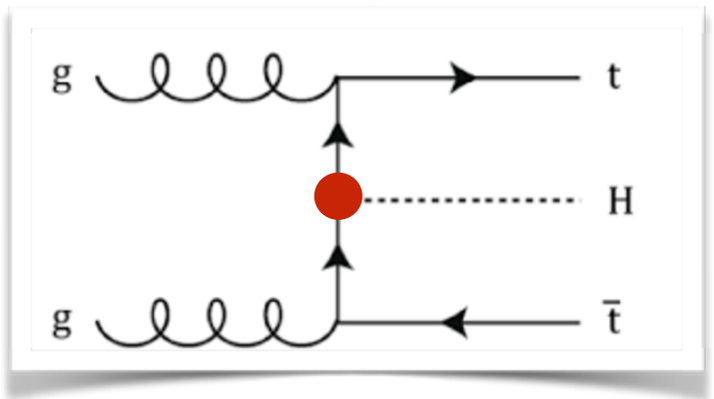
- Expected precisions:
  - Scenario I: systematic uncertainties same as now
  - Scenario II: theoretical uncertainty divided by 1/2 and systematic by 1/sqrt(L)

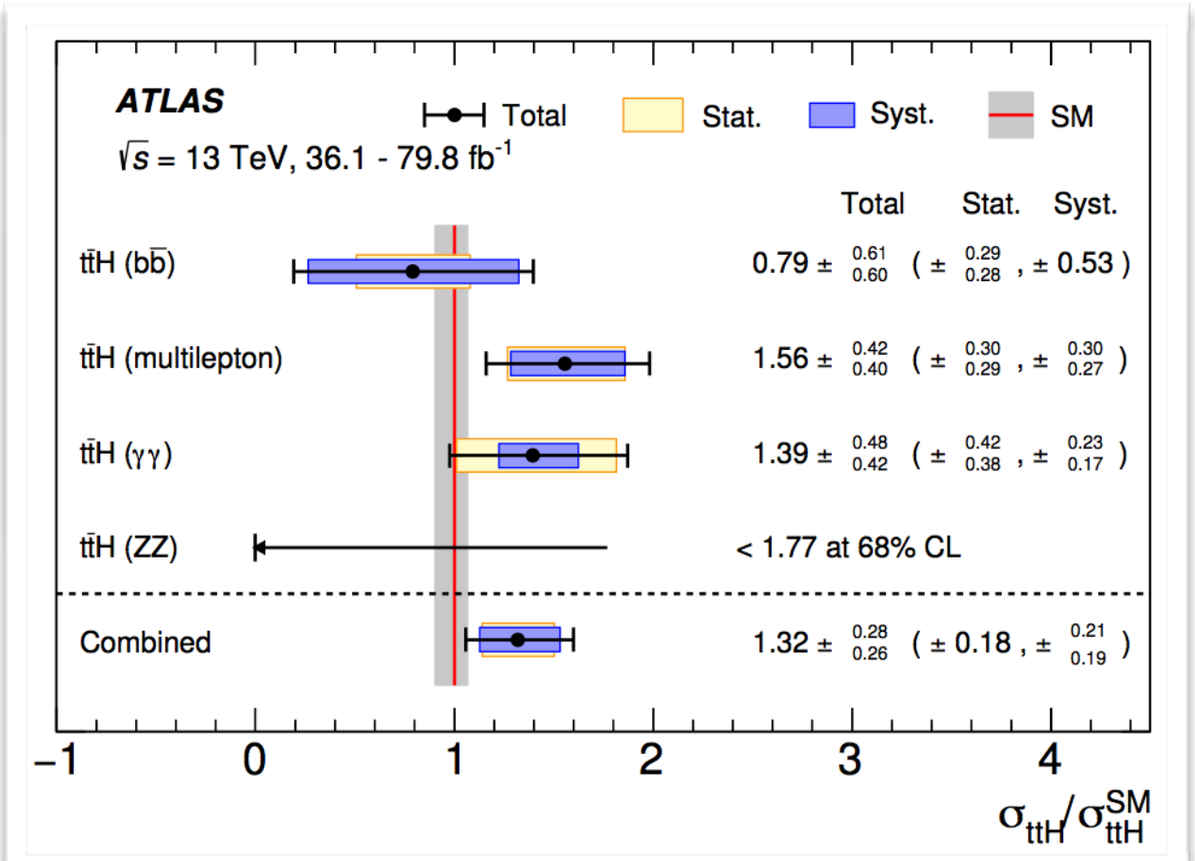
Directly Measuring ttH

- ttH channel observation:

  6.3σ observed (5.1σ expected) – ATLAS

  5.2σ observed (4.2σ expected) – CMS





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

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

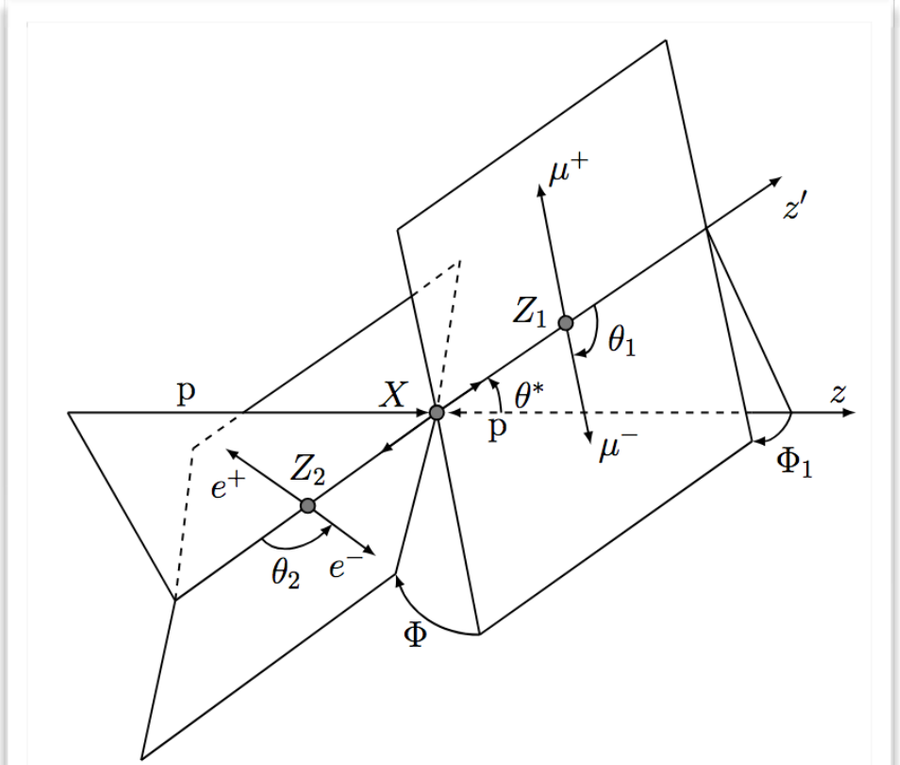
Buckley, DG (PRL-2015), Lopez-val, DG (2016)
J. Ellis, Hwang, Sakurai, Takeuchi (2014)
Boudjemaa, Godbole, Guadagnoli,Mohan (2015)

CPV - collider constraints

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

Gritsan, Melnikov Schulze, et al (2013)

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

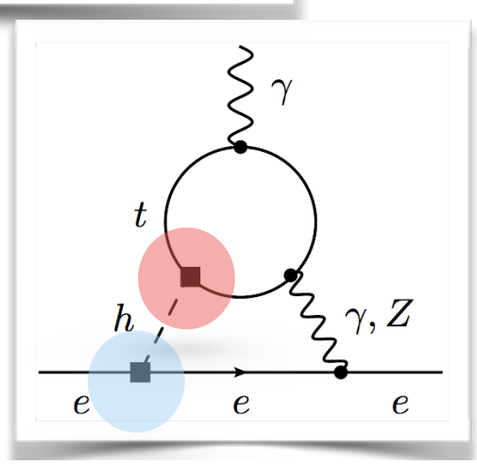


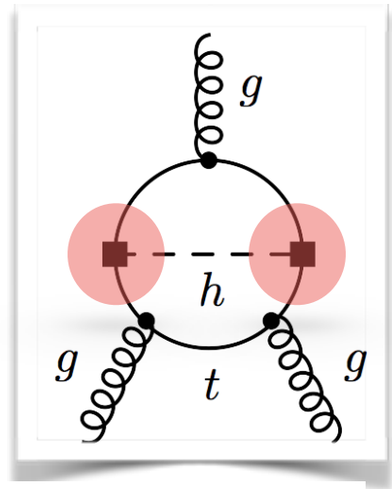
- While CP-odd HVV is loop suppressed, CP-odd Hff can manifest at tree-level:
  - Mixture possible in some models, e.g., 2HDM
  - Not excluded from Higgs measurements
  - Top quark is the first obvious candidate

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

CPV - EDM constraints

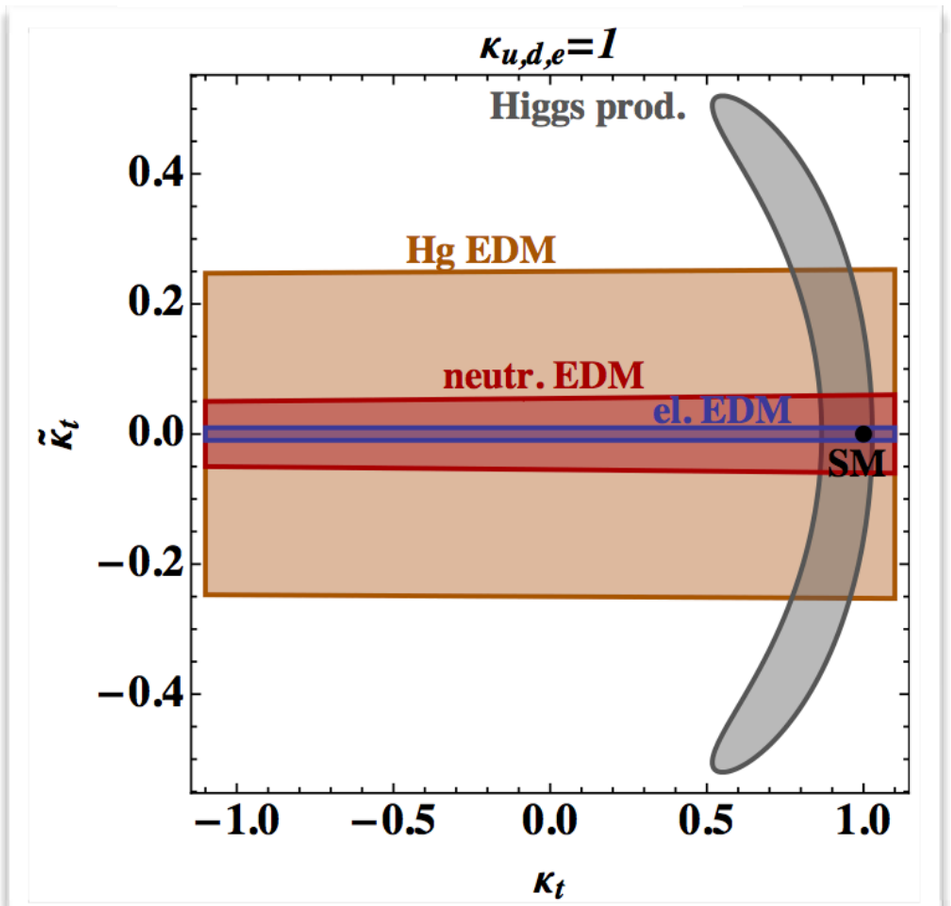
- Indirect constraints from eEDM very strong, yet assume:
  - → No other states in the spectrum
  - → Coupling strength/structure to light fermions

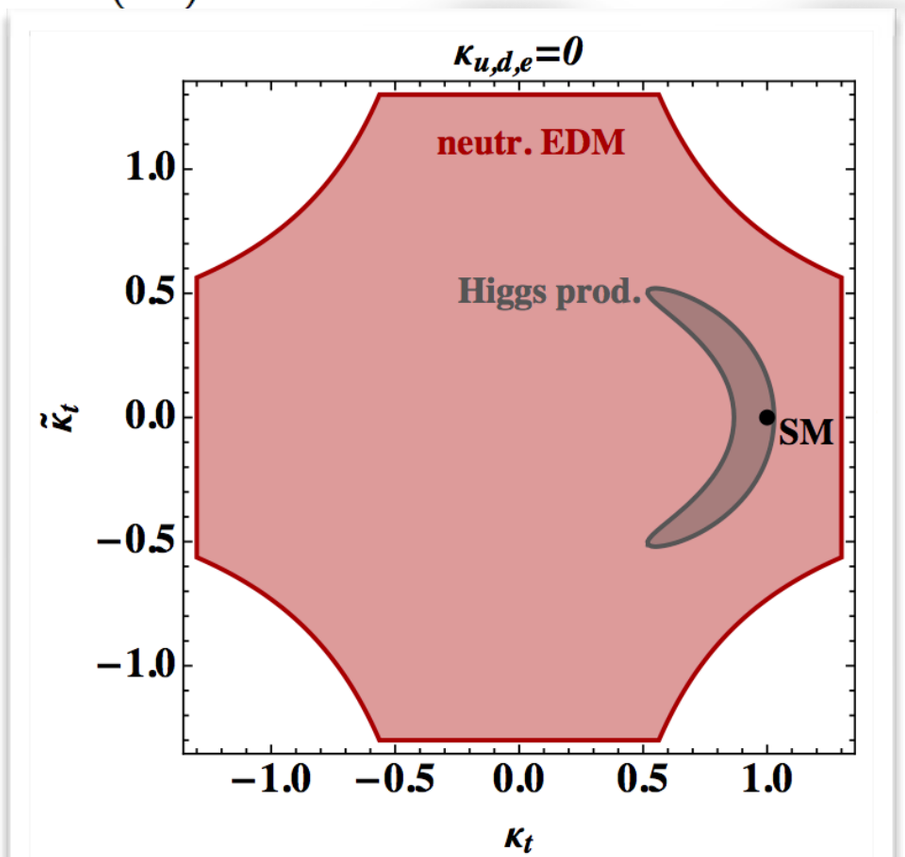




$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}}\left(\kappa_f\,\bar{f}f + i\tilde{\kappa}_f\,\bar{f}\gamma_5 f\right)h$$

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





- → Model dependent interpretation

Brod, Haisch, Zupan (2013)

Direct CP measurement of Higgs-top coupling

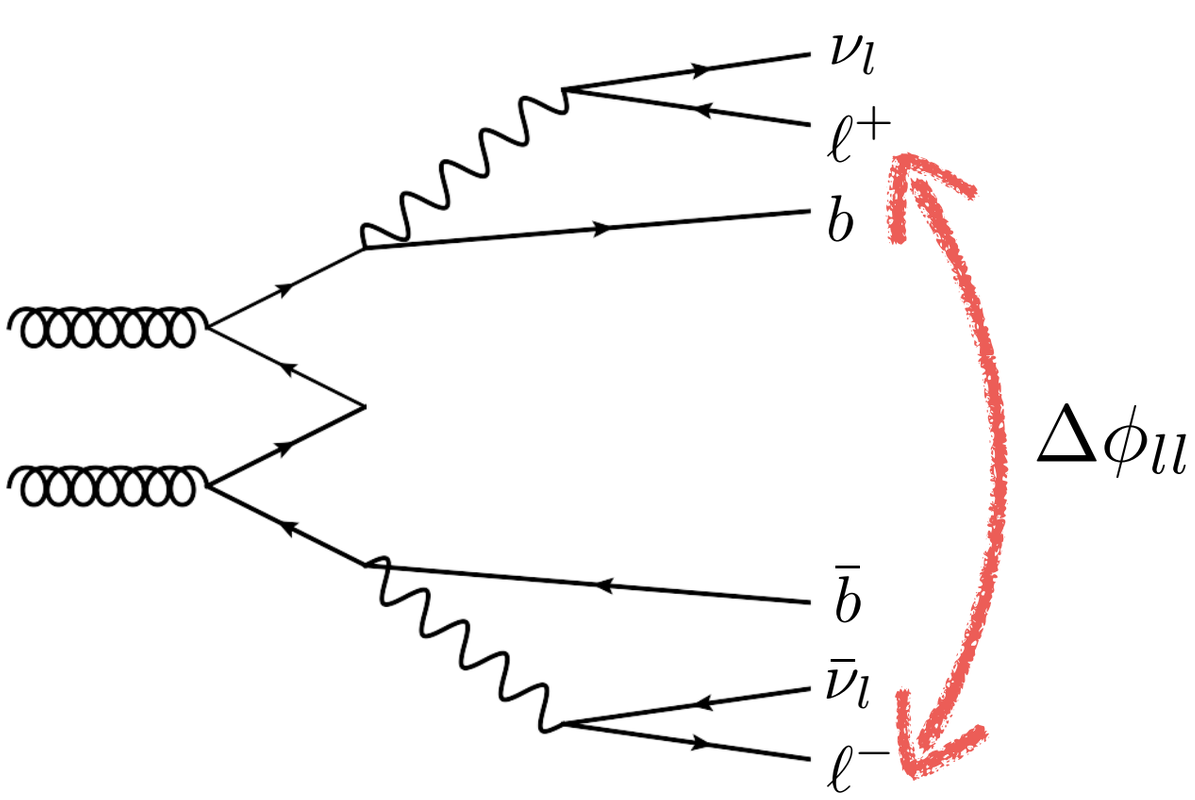
- Proposal looking only at the signal and at parton level via angular correlations

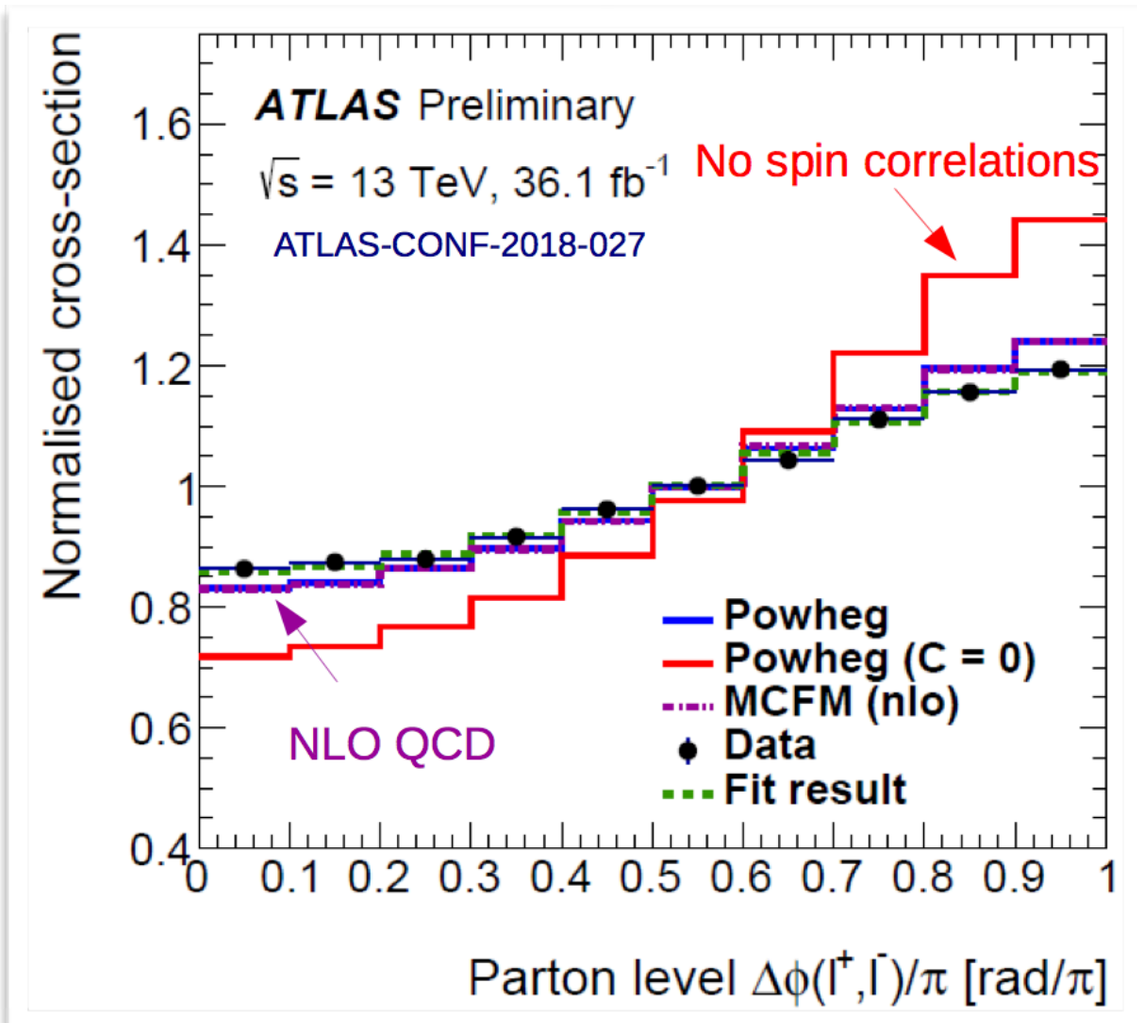
J. Ellis, Hwang, Sakurai, Takeuchi (2014);
Boudjemaa, Godbole, Guadagnoli,Mohan (2015)

$$\Delta\phi_{ll} = sign[\vec{p}_t.(\vec{p}_{l-} \times \vec{p}_{l+})]arccos[|(\hat{\vec{p}}_{l+} \times \hat{\vec{p}}_t).(\hat{\vec{p}}_{l-} \times \hat{\vec{p}}_t)|]|_{t\bar{t}}$$

- Analogous situation to correlated vs uncorrelated top decays

Parke, Mahlon (1996,2010)





Direct CP measurement of Higgs-top coupling

- Proposal looking only at the signal and at parton level via angular correlations

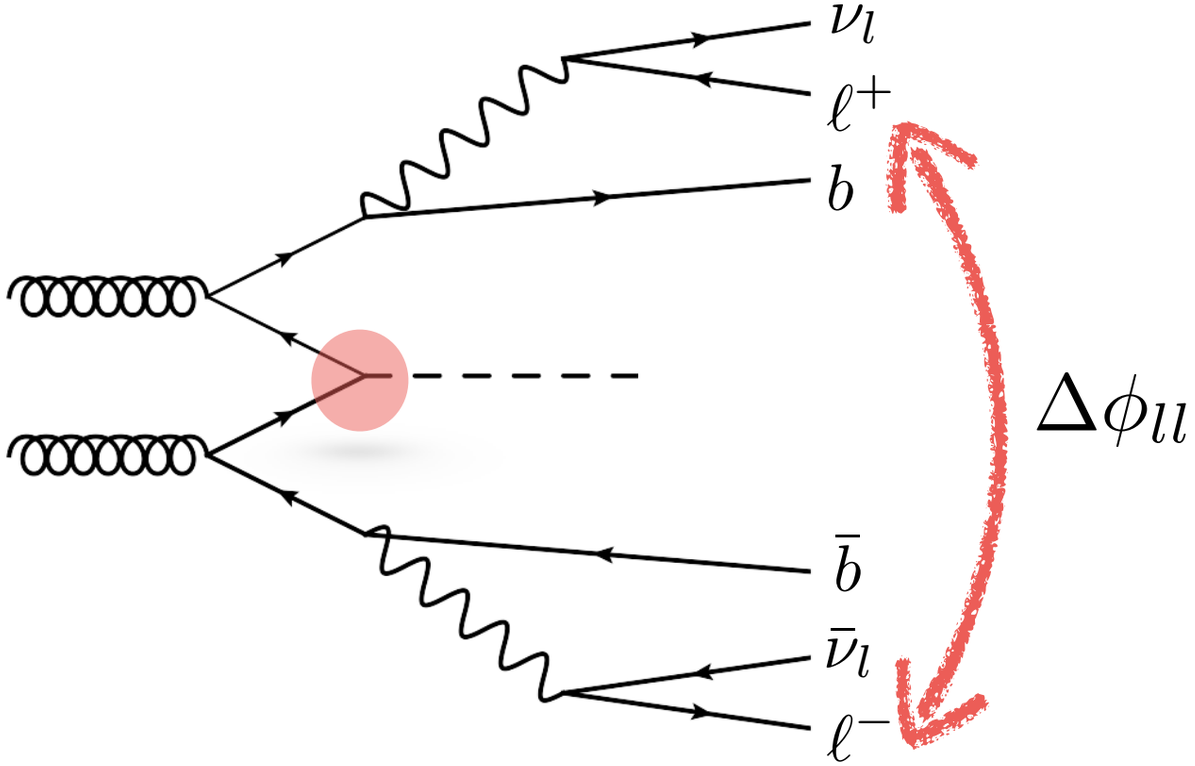
J. Ellis, Hwang, Sakurai, Takeuchi (2014);

Boudjemaa, Godbole, Guadagnoli,Mohan (2015)

$$\Delta\phi_{ll} = sign[\vec{p}_t.(\vec{p}_{l-} \times \vec{p}_{l+})]arccos[|(\hat{\vec{p}}_{l+} \times \hat{\vec{p}}_t).(\hat{\vec{p}}_{l-} \times \hat{\vec{p}}_t)|]|_{t\bar{t}}$$

- Analogous situation to correlated vs uncorrelated top decays

Parke, Mahlon (1996,2010)



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

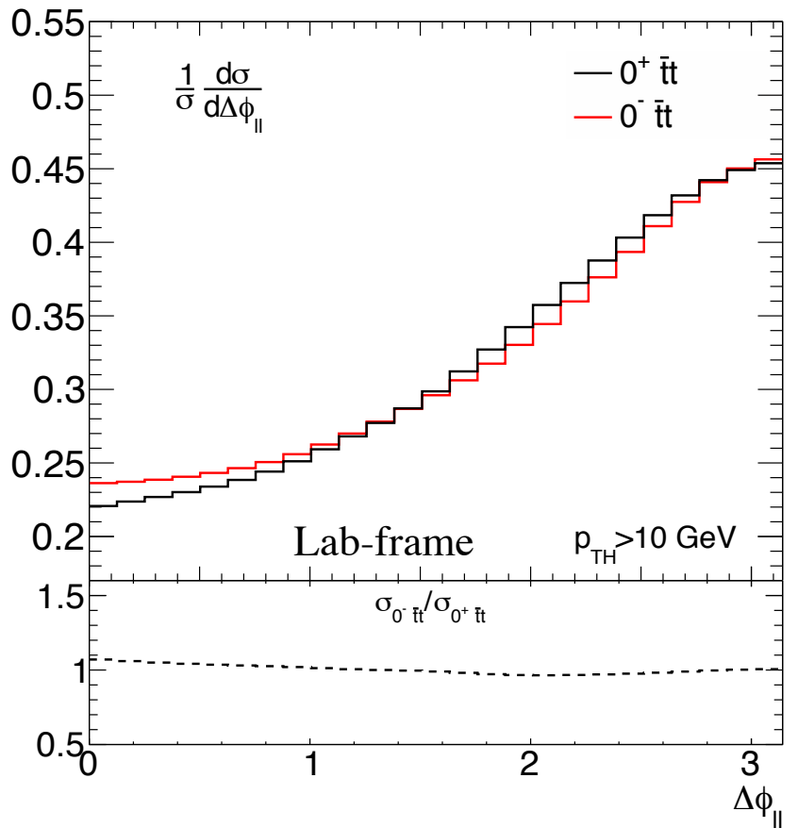
Direct CP measurement of Higgs-top coupling

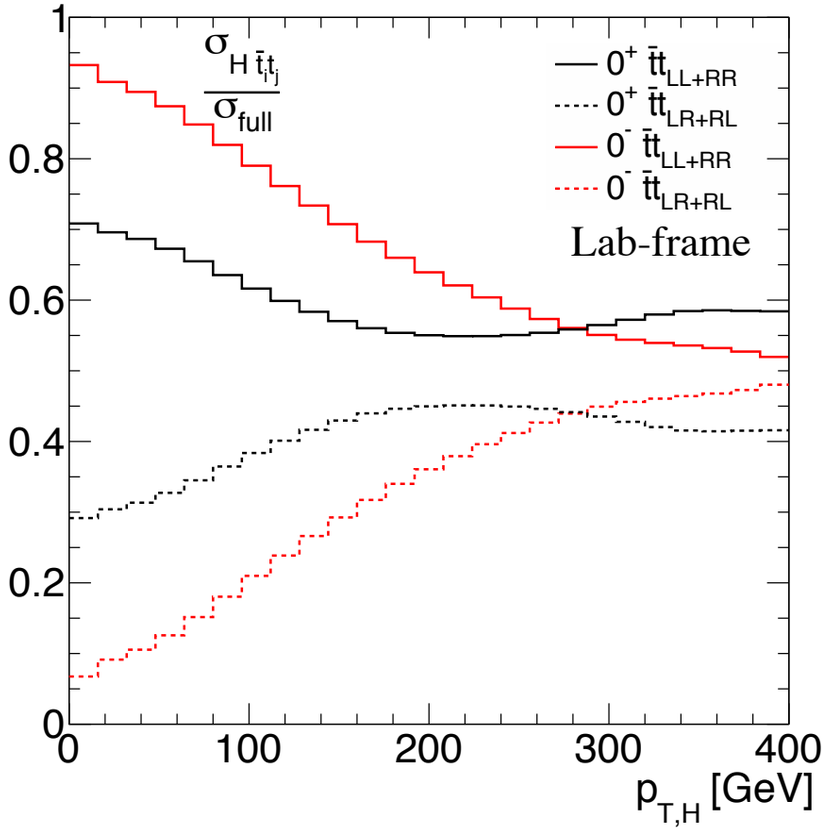
- Spin correlations of top and anti-top affected by nature of interaction

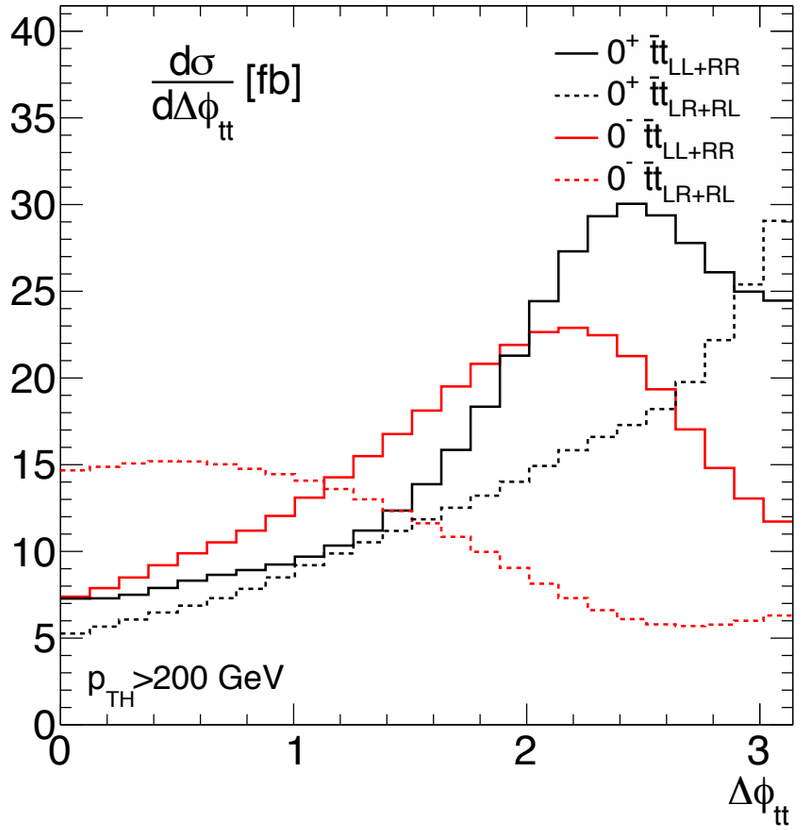
$\Delta\phi_{tt}$ distribution directly reflects on $\Delta\phi_{ll}$:

Parke, Mahlon (2010)

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







➡ Top mass effects in presence of a further massive H boson pushes chiral limit to higher scales

$$\mathcal{M}_{0^+ t\bar{t}_{LR+RL}} \propto \sin\left(\frac{\Delta\phi_{tt}}{2}\right)$$

$$\mathcal{M}_{0^- t\bar{t}_{LR+RL}} \propto \cos\left(\frac{\Delta\phi_{tt}}{2}\right)$$

Buckley, DG (PRL-2015)

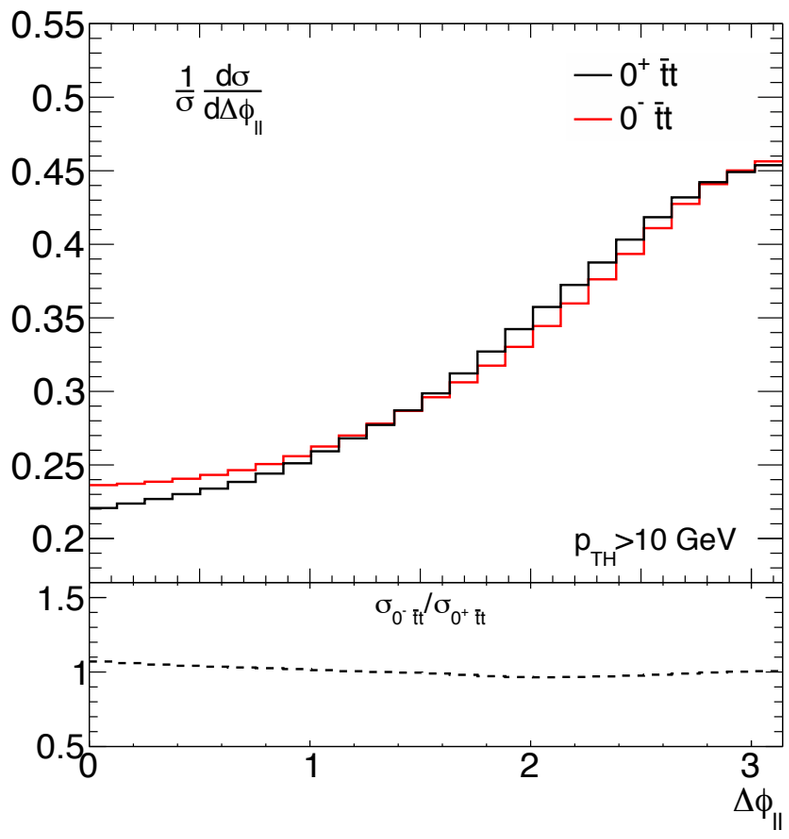
Direct CP measurement of Higgs-top coupling

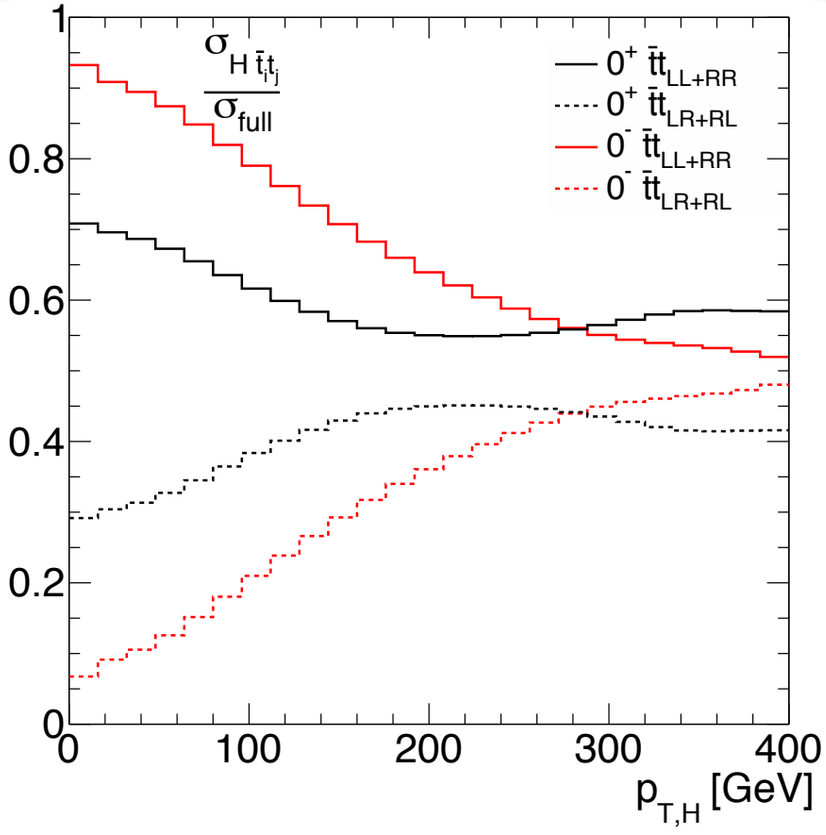
- Spin correlations of top and anti-top affected by nature of interaction

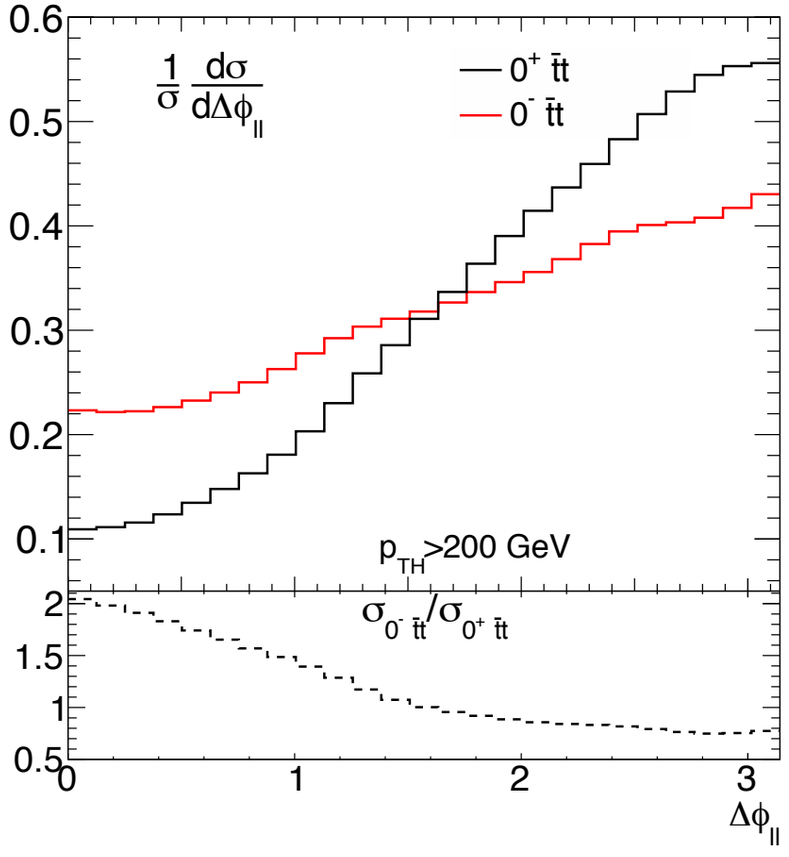
$\Delta\phi_{tt}$ distribution directly reflects on $\Delta\phi_{ll}$:

Parke, Mahlon (2010)

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







➡ Boosted Higgs (p_{TH}>200GeV) nicely match with H>bb BDRS algorithm

Buckley, DG (PRL–2015)

Plehn, Salam, Spannowsky (2009)

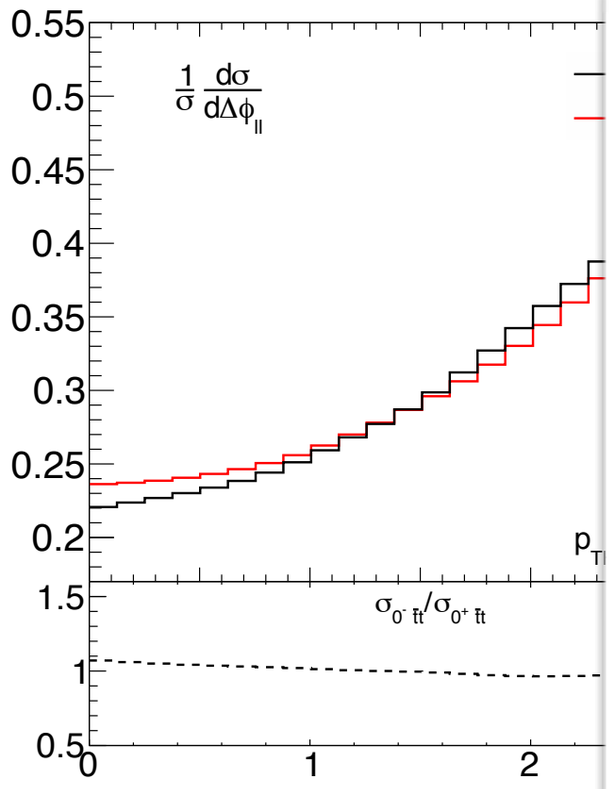
Direct CP measurement of Higgs-top coupling

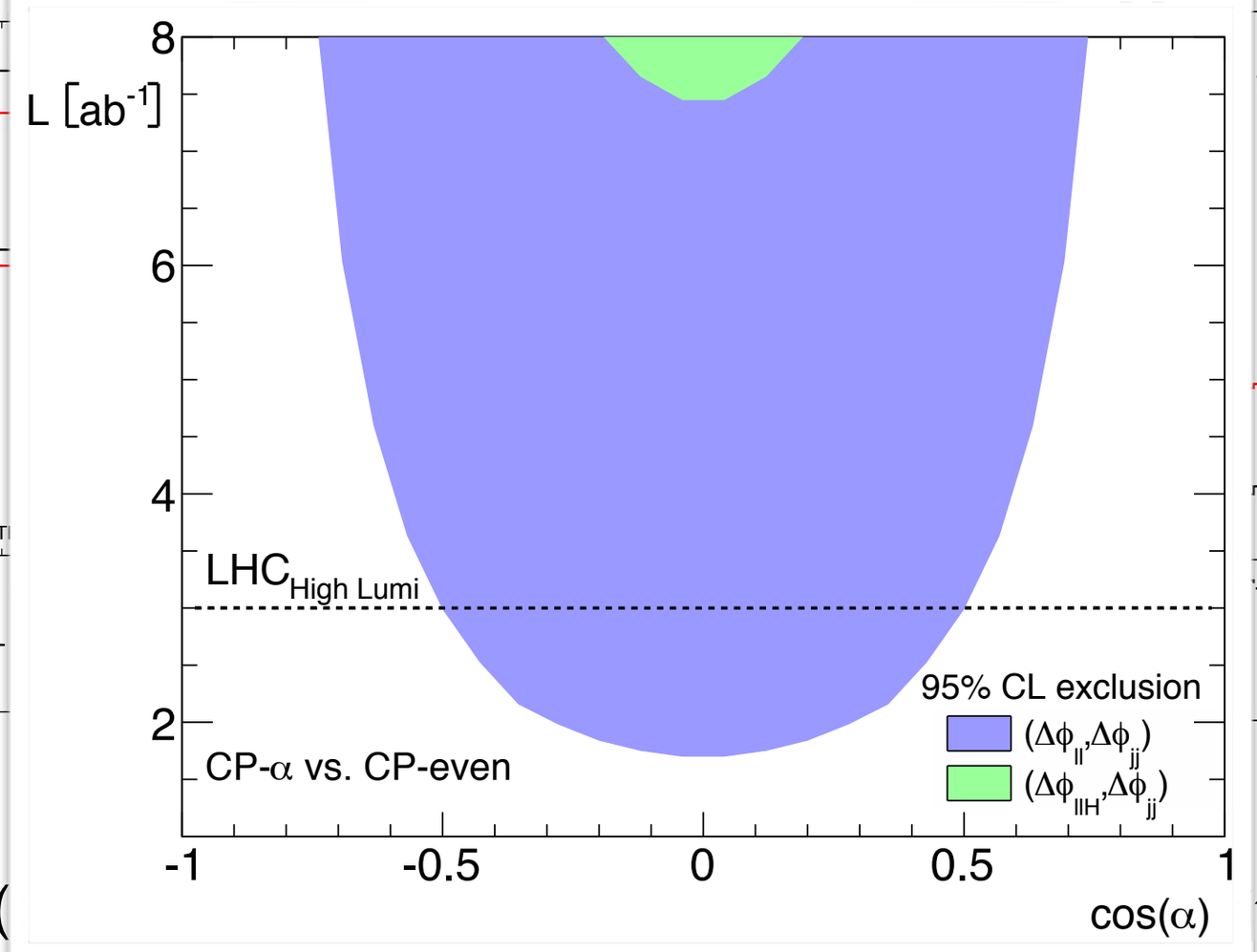
- Spin correlations of top and anti-top affected by nature of interaction

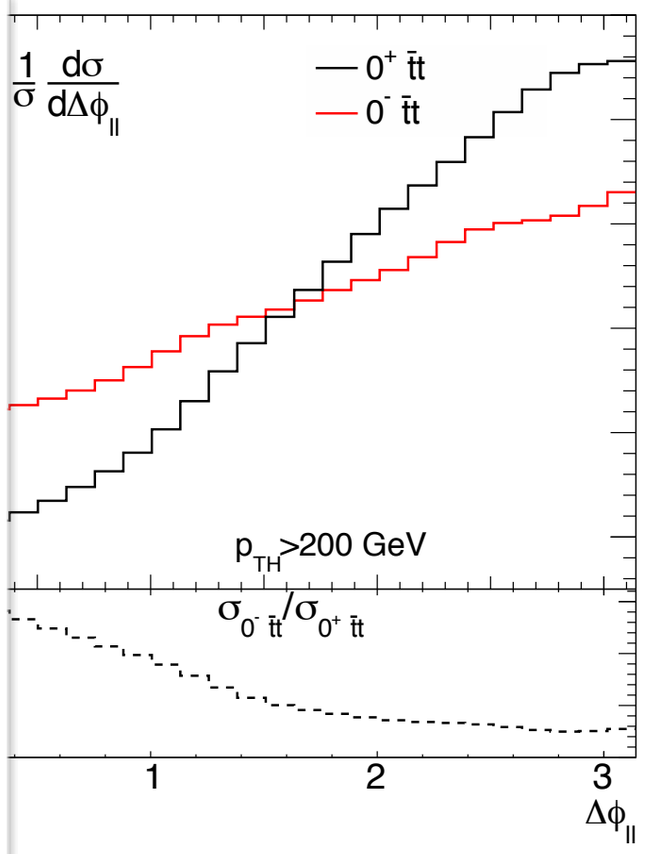
$\Delta\phi_{tt}$ distribution directly reflects on $\Delta\phi_{ll}$:

Parke, Mahlon (2010)

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





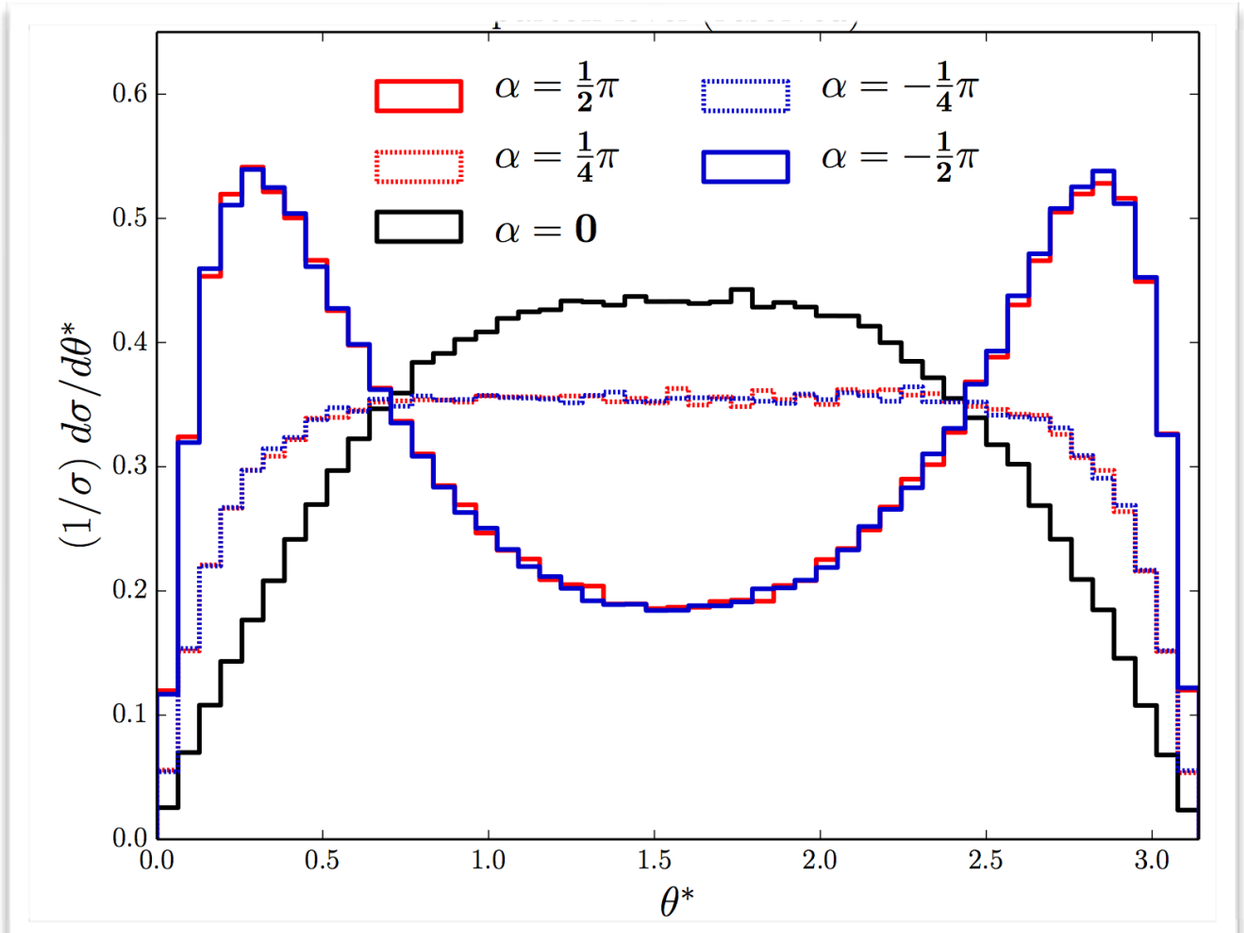


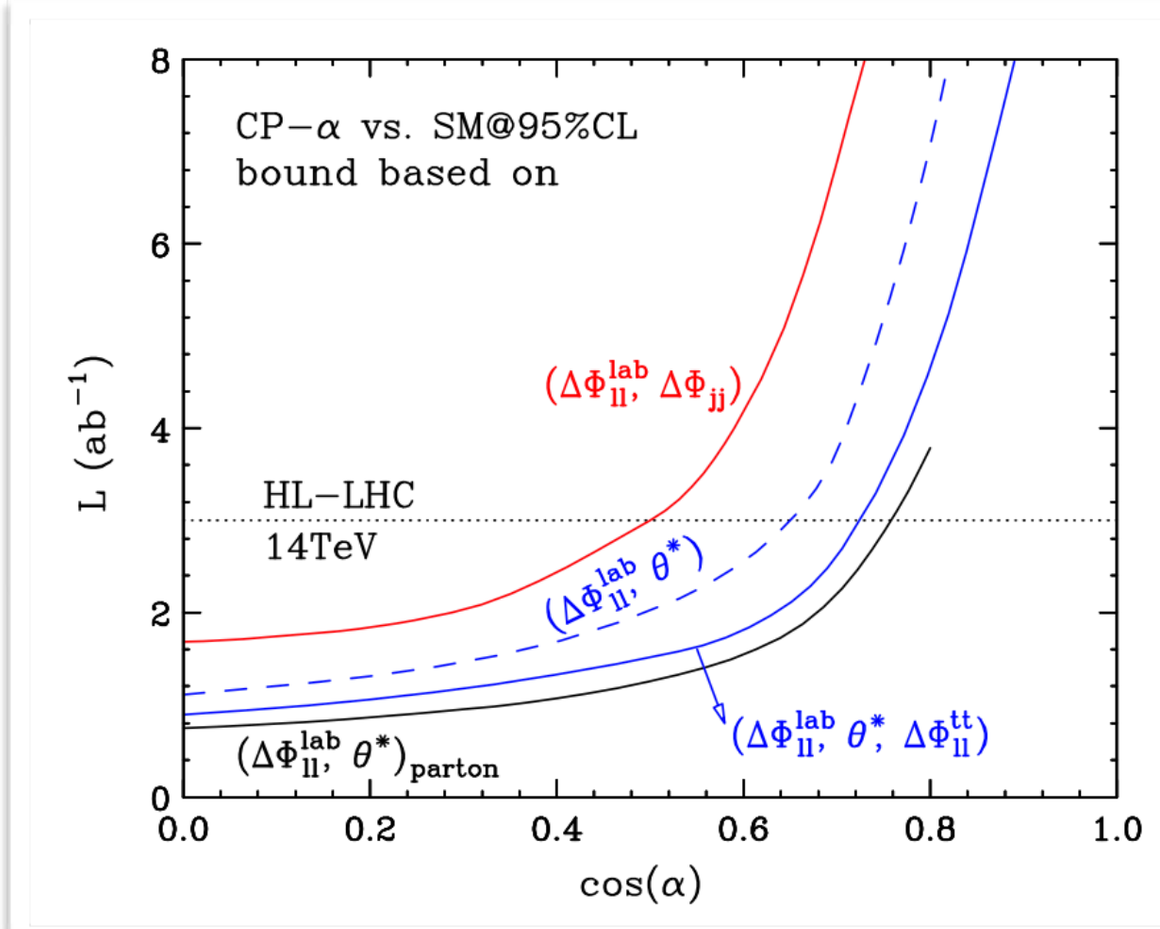
→ Boosted Higgs (thm

Buckley, DG (PRL-2015)

Multivariate analysis problem

- Rich final state with many more relevant observables:





- New powerful observables can be defined at tt CM frame, e.g, θ*
- At the HL-LHC, we can probe the top Yukawa CP up to cosα=0.7

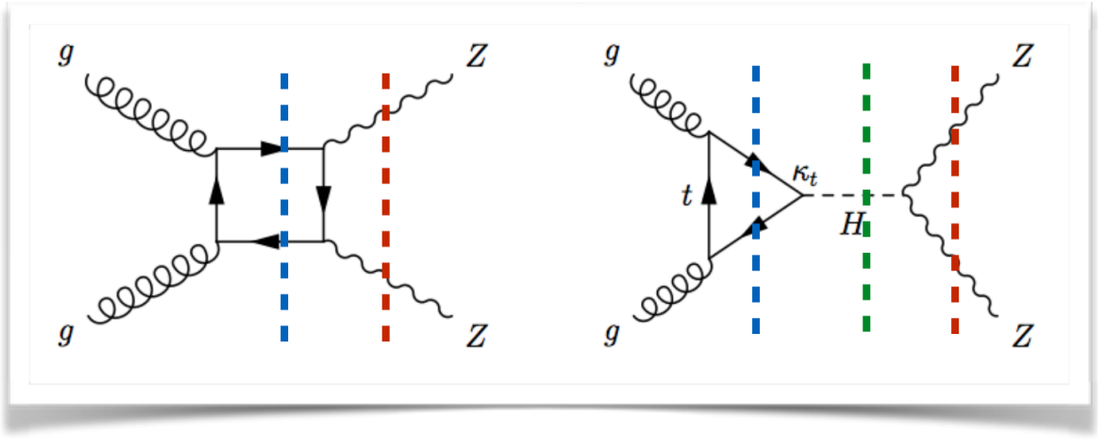
DG, Kong, Kim (2018)

Gritsan, Rontsch, Schulze, Xiao (2016); Amor dos Santos et al. (2017)

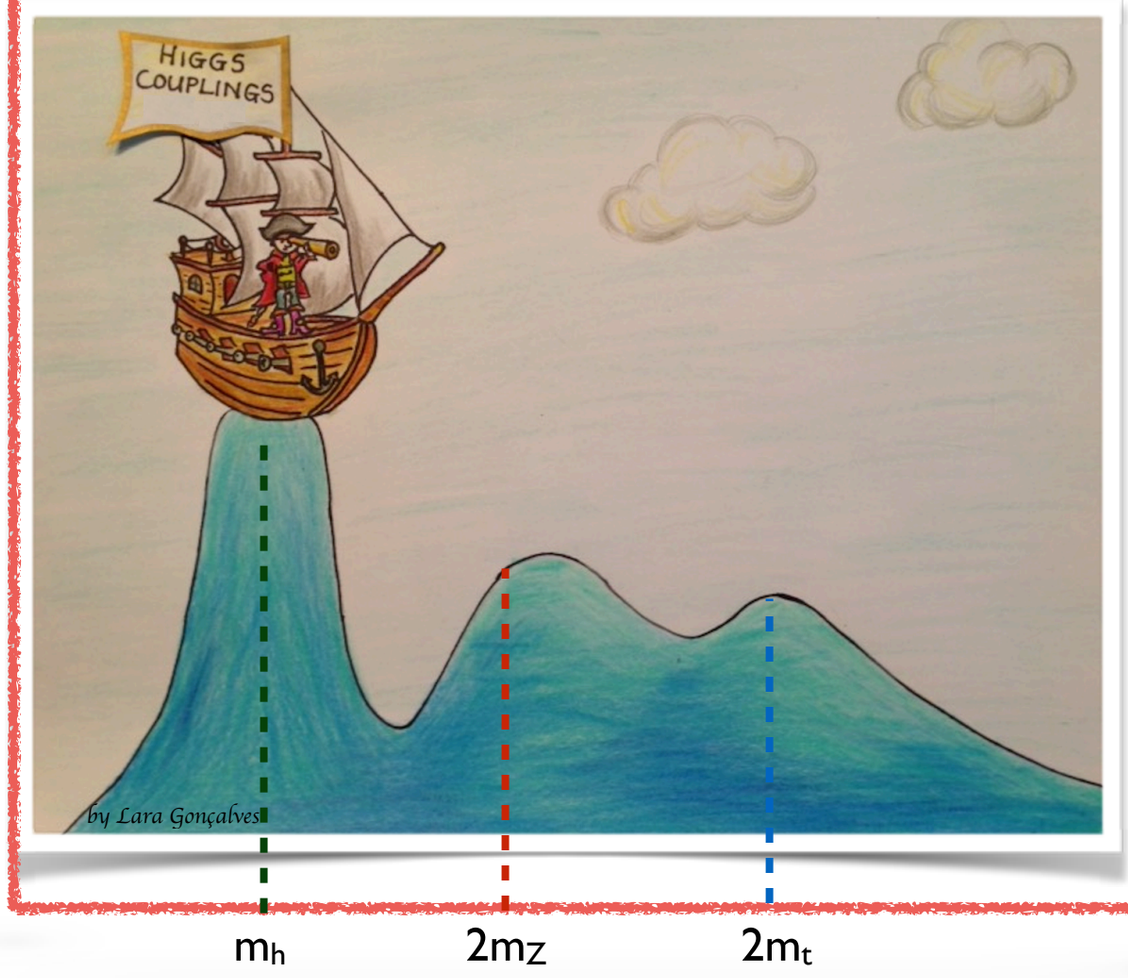
Off-Shell Higgs Production

- Hidden states could show up in the scale dependence of Higgs couplings, or more broadly in Higgs production processes through quantum corrections

→ Off-shell Higgs carries information on the H couplings at different energy scales



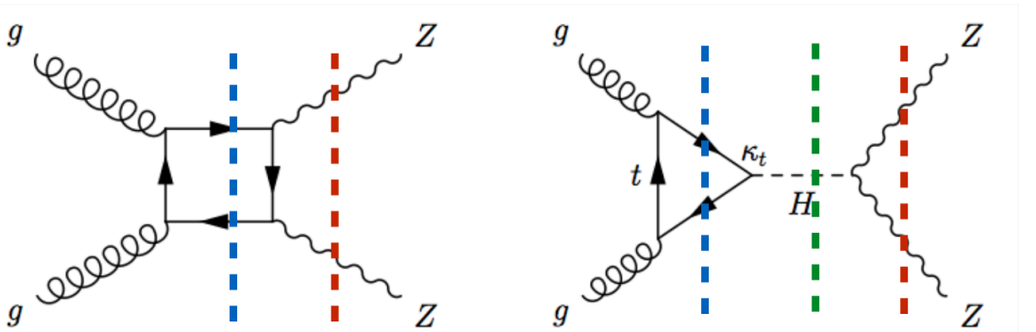
$$\sigma_{\rm on} \propto \frac{g_i^2(m_h^2)g_f^2(m_h^2)}{m_h\Gamma_h}$$



Off-Shell Higgs Production

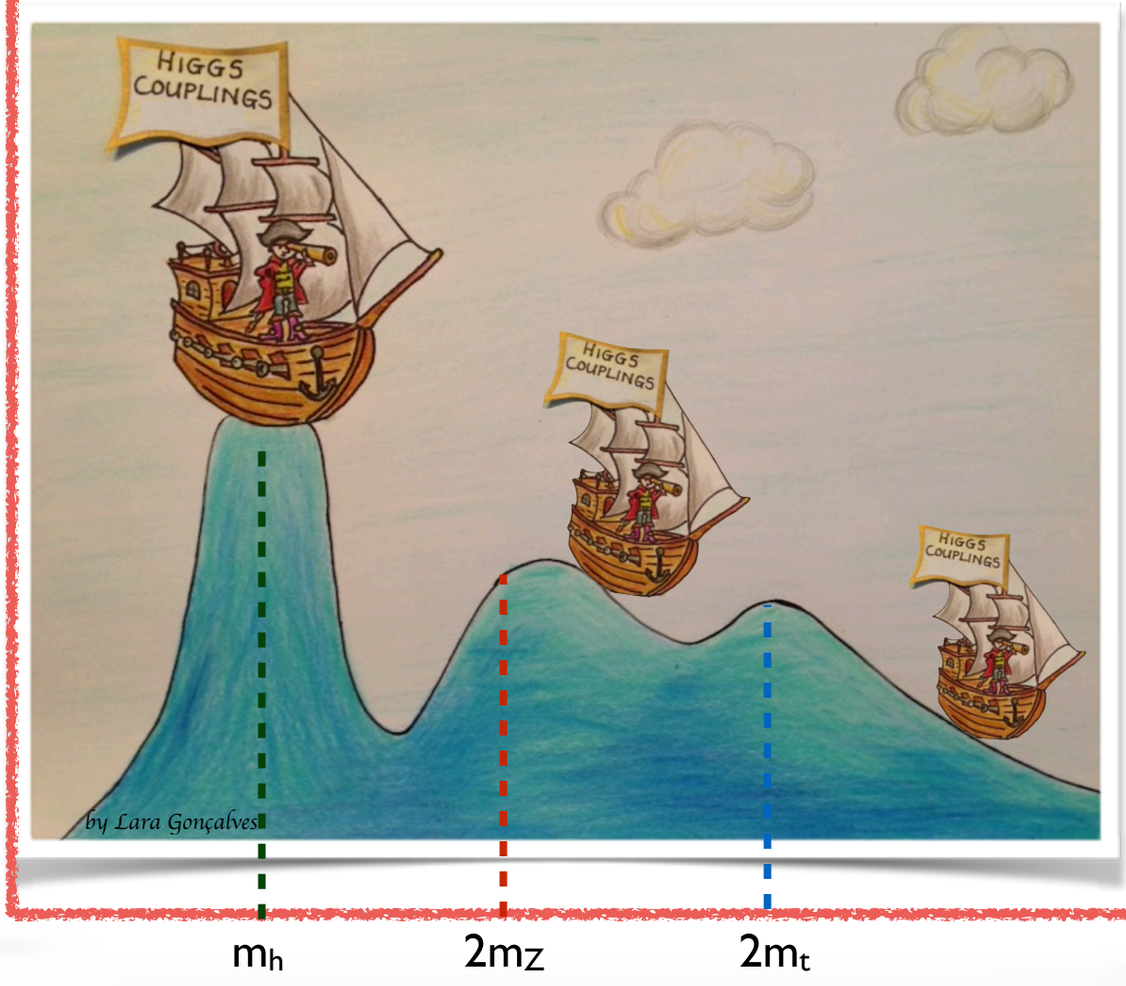
- Hidden states could show up in the scale dependence of Higgs couplings, or more broadly in Higgs production processes through quantum corrections

→ Off-shell Higgs carries information on the H couplings at different energy scales



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

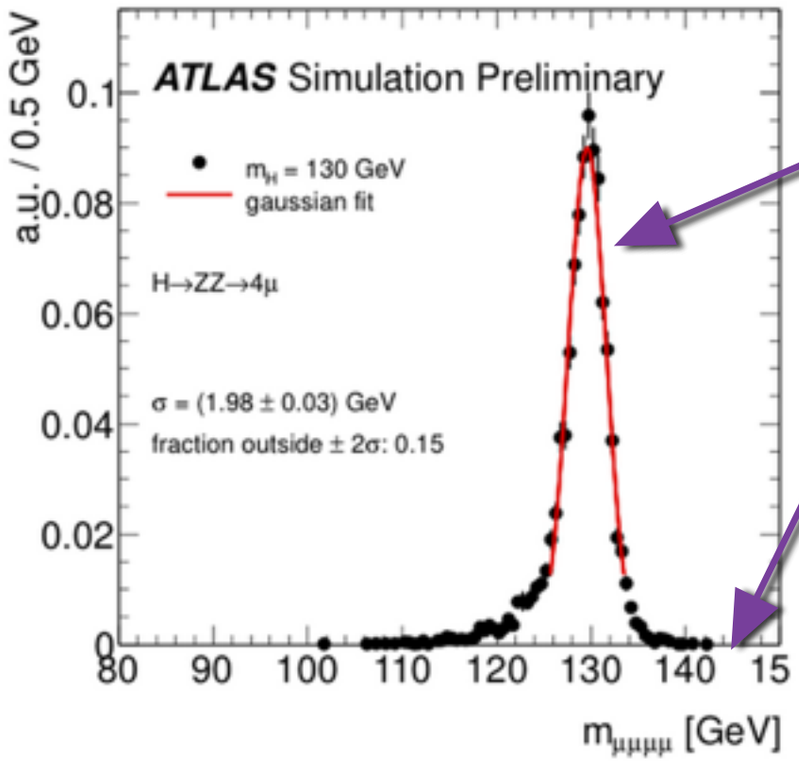
$$\sigma_{\text{off}} \propto \frac{g_i^2(Q^2)g_f^2(Q^2)}{Q^2}$$



Off-Shell 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



$$\frac{d\sigma}{dm_{4l}} \sim \frac{(g_i g_f)^2}{\Gamma_H}$$

$$\frac{d\sigma}{dm_{4l}} \sim \frac{(g_i g_f)^2}{(m_{4l}^2 - m_H^2)^2}$$

- However, at least 15% of the H→4l cross-section comes from m_{4l}>300 GeV

  Spectacular fail of Narrow Width Approximation

→ Interference with background: gg→h*→ZZ with gg→ZZ ;

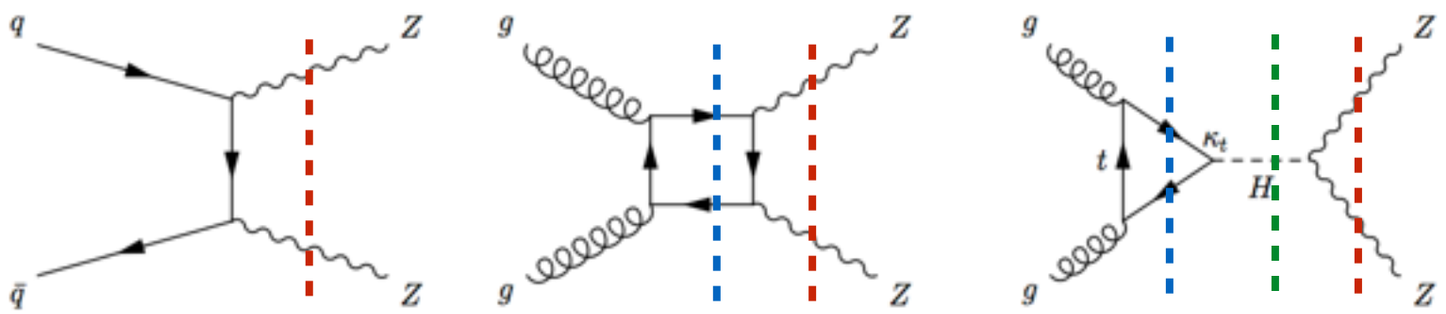
→ ZZ Threshold;

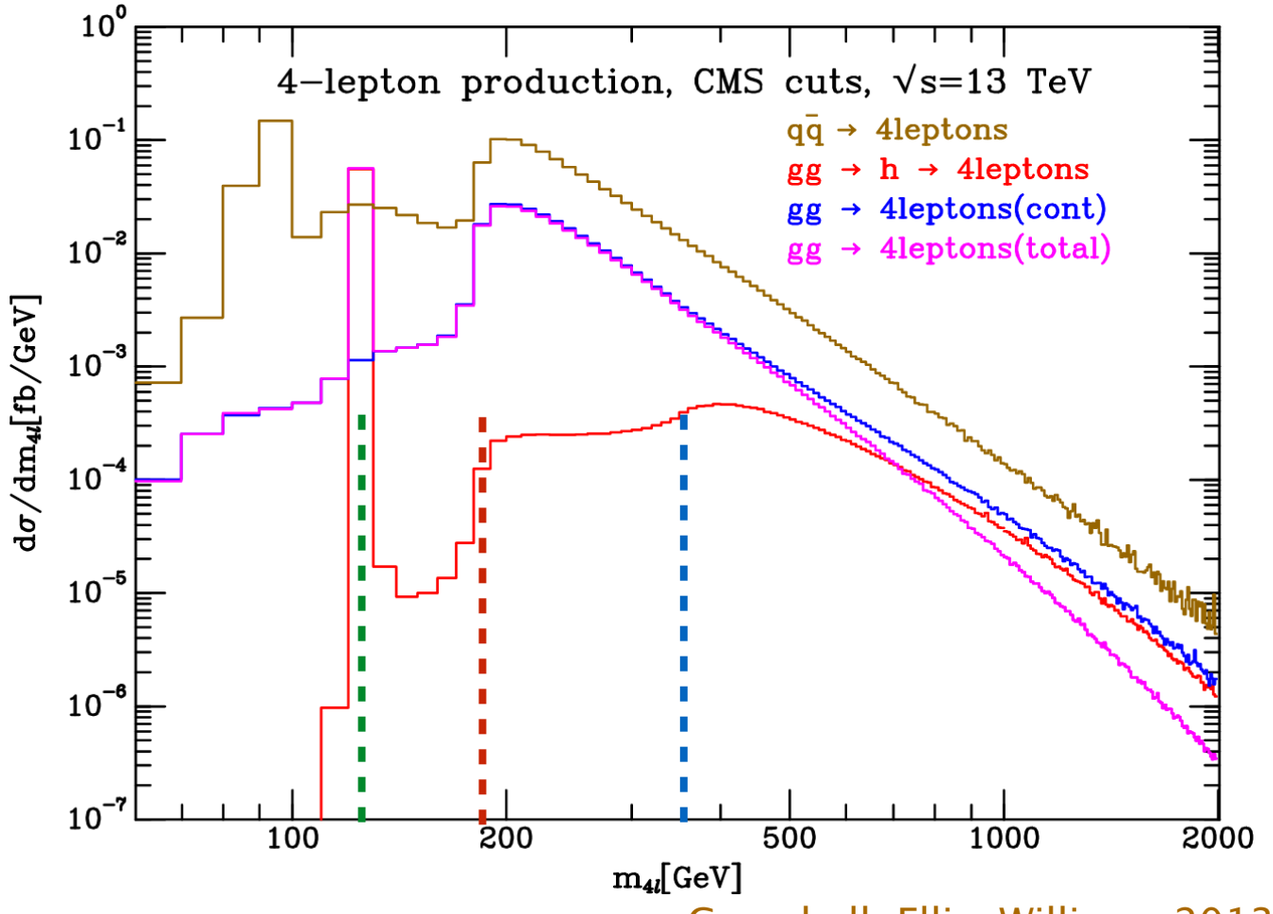
→ and top mass effects change our naive expectation

Kauer, Passarino 2012
Caola, Melnikov 2013
Campbell, Ellis, Williams 2013

Off-Shell Higgs Production

- Carries information on the Higgs couplings at different energy scales





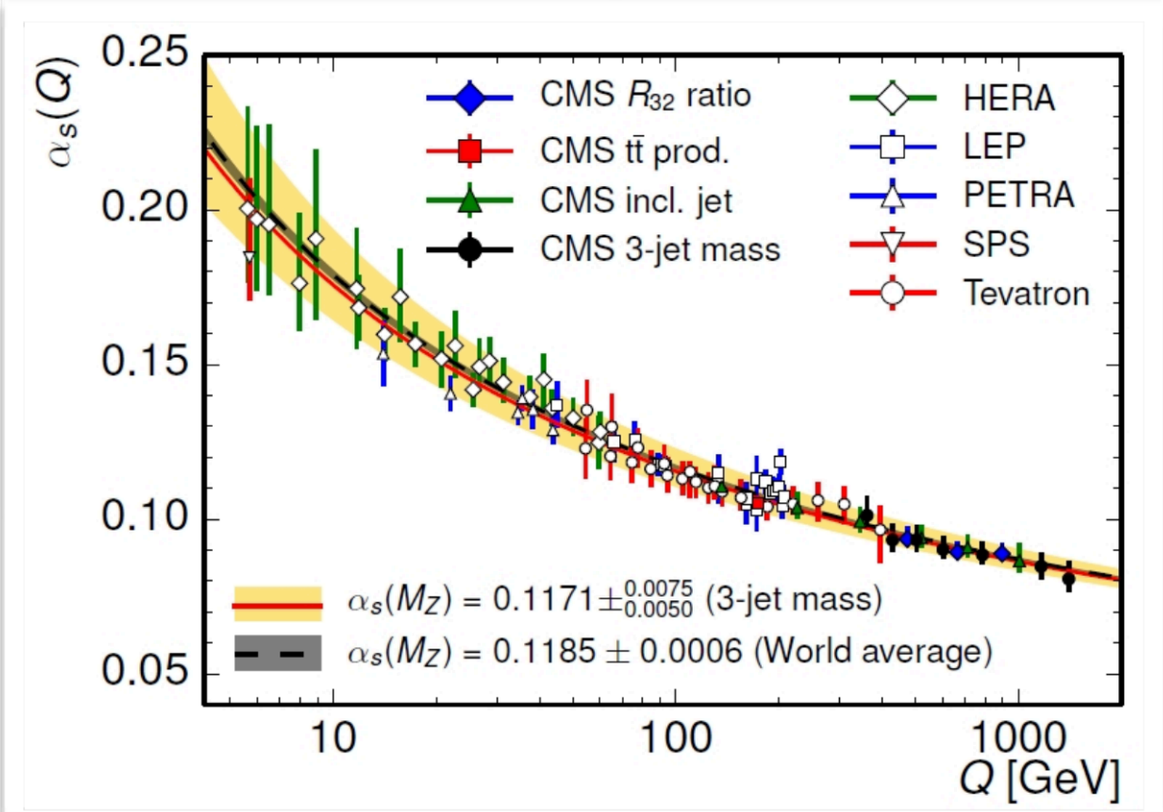
Campbell, Ellis, Williams 2013

Case study 1: Weakly Coupled Scenario RG Evolution

- Couplings evolve with the scale

→ Different running than the SM could be an indication of new physics (e.g., Gluino mass bounds) Kaplan, Schwartz (2008)

→ This probe works independent of production or decay modes of the new states, as long as they contribute to RG evolution of couplings



Alves, Galloway, Ruderman, Walsh (2014); Berger, Nadolsky, Olness, Pumplin (2004);Sannino, Spanno et al. (2014)

Can we use the off-shell Higgs to probe BSM deviations on the running of H couplings?

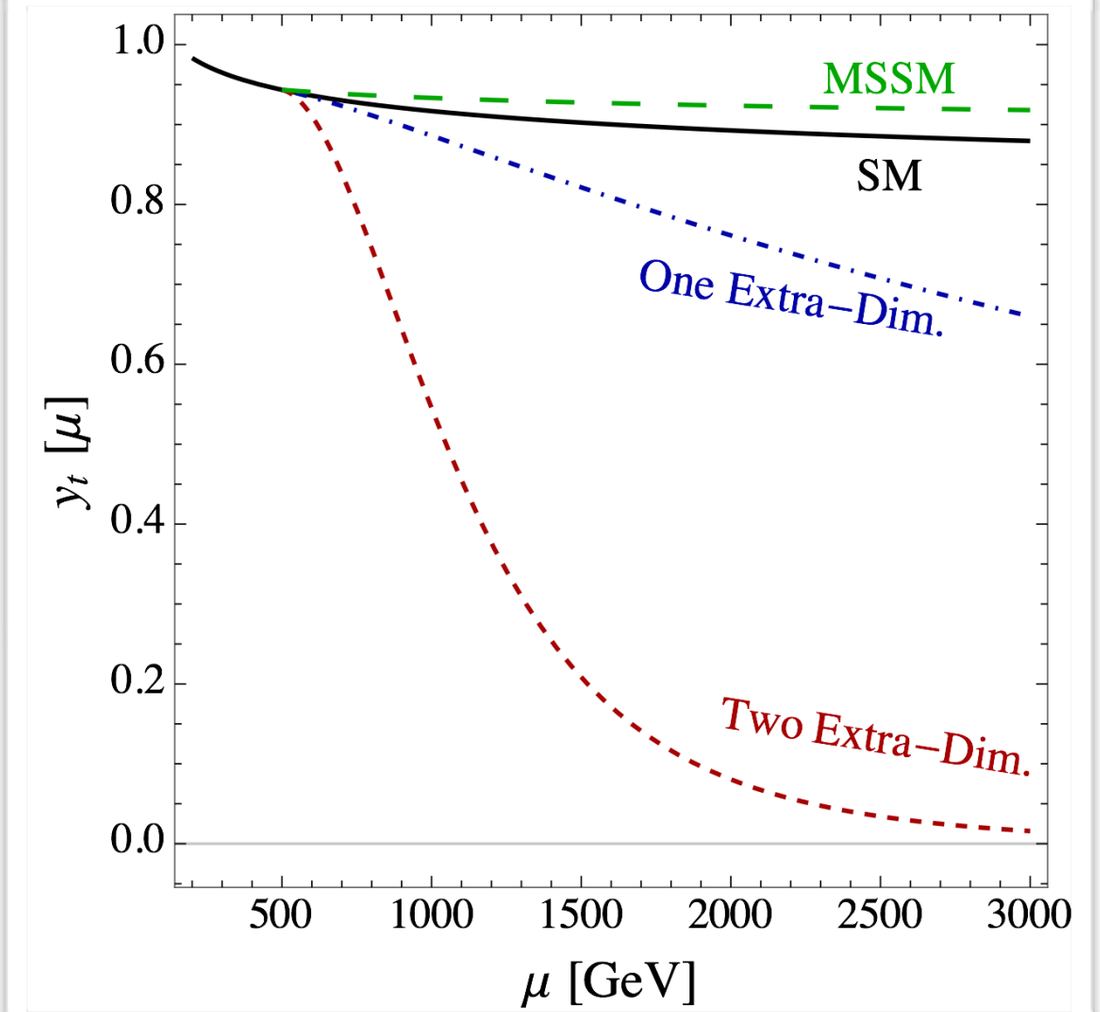
$$\sigma_{\rm on} \propto \frac{g_i^2(m_h^2) g_f^2(m_h^2)}{m_h \Gamma_h}$$

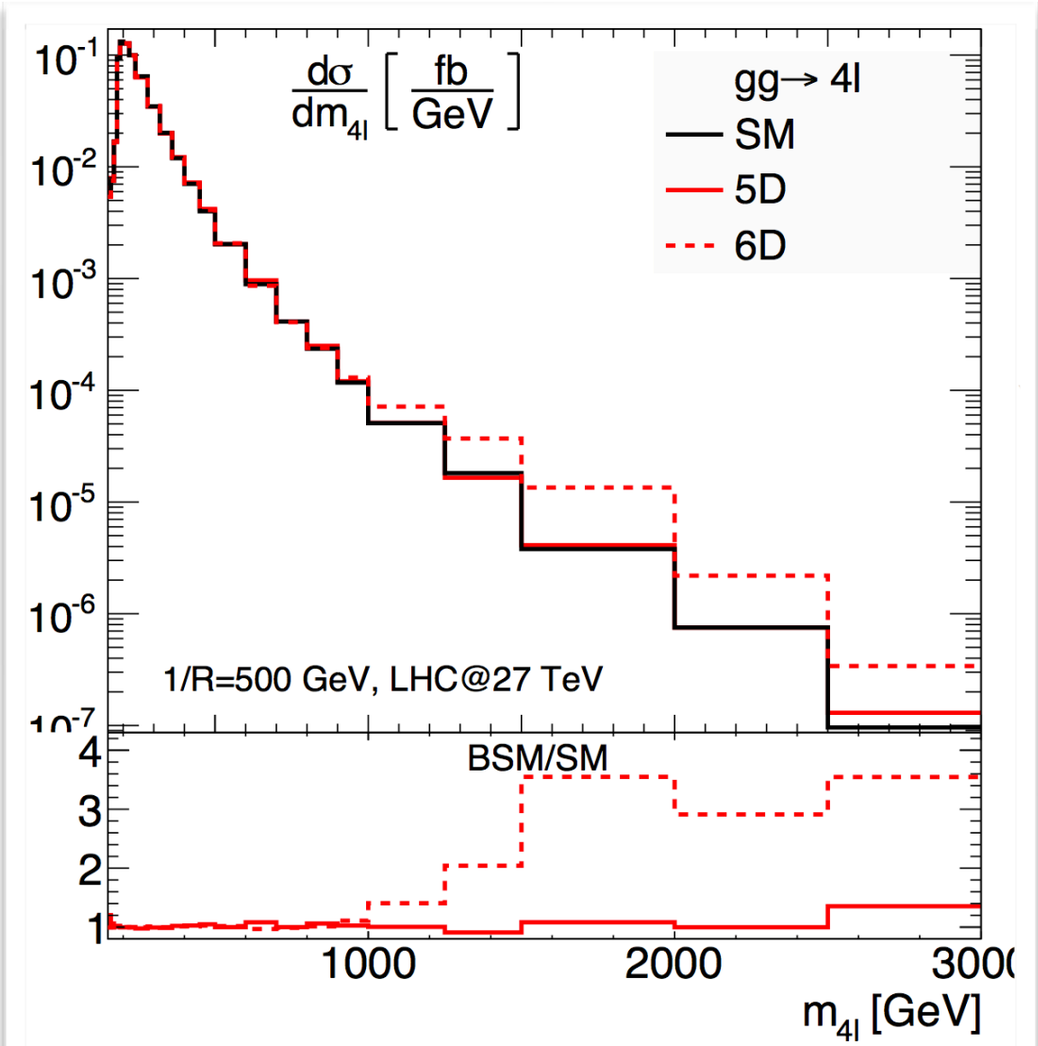
$$\sigma_{\rm off} \propto \frac{g_i^2(Q^2) g_f^2(Q^2)}{Q^2}$$

DG, Han, Mukhopadhyay (2018)

Case study 1: Weakly Coupled Scenario RG Evolution

$$\beta_Q = \beta_Q^{\rm SM} + \sum_{\text{s: massive new states}} \theta(\mu - M_s)(N_s \beta_{s,Q}^{\rm NP})$$



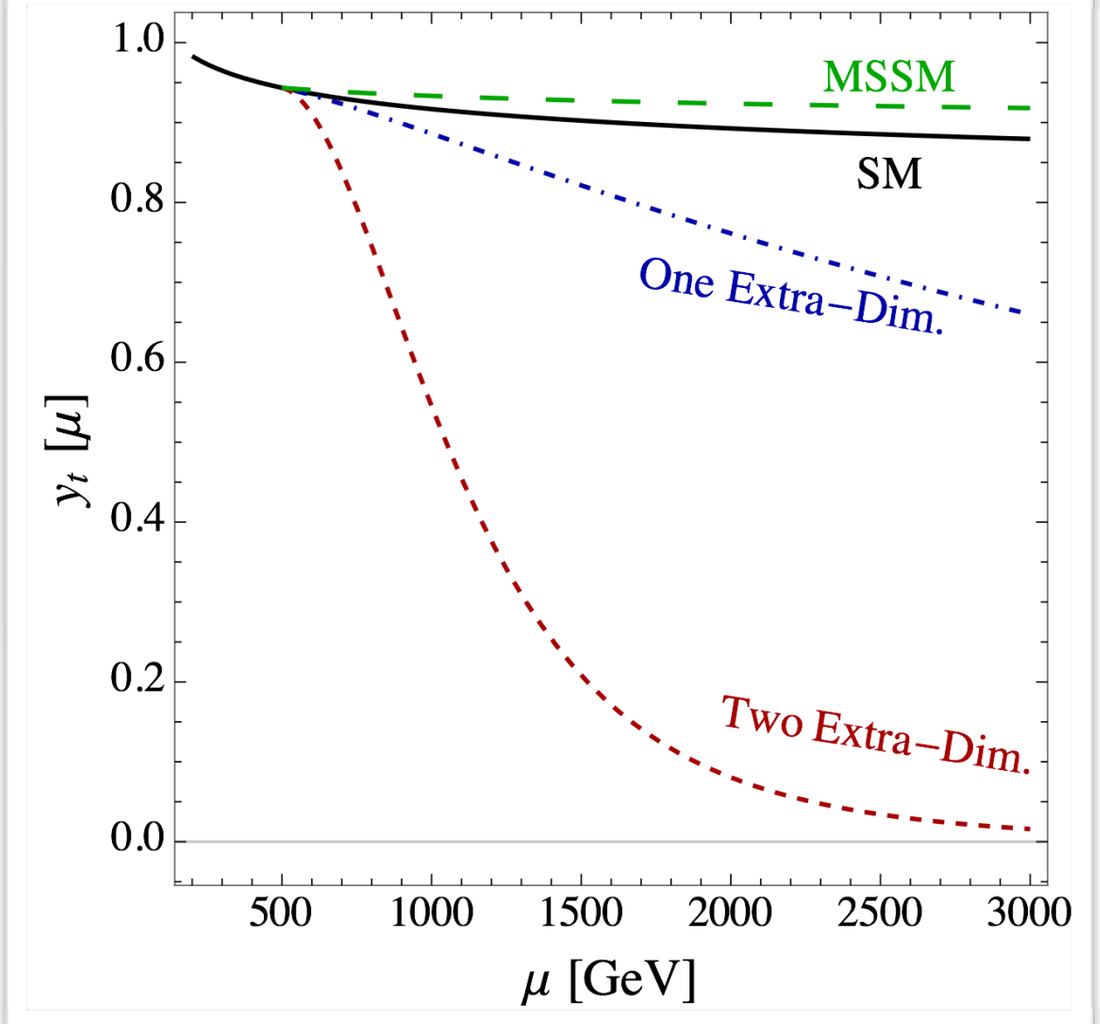


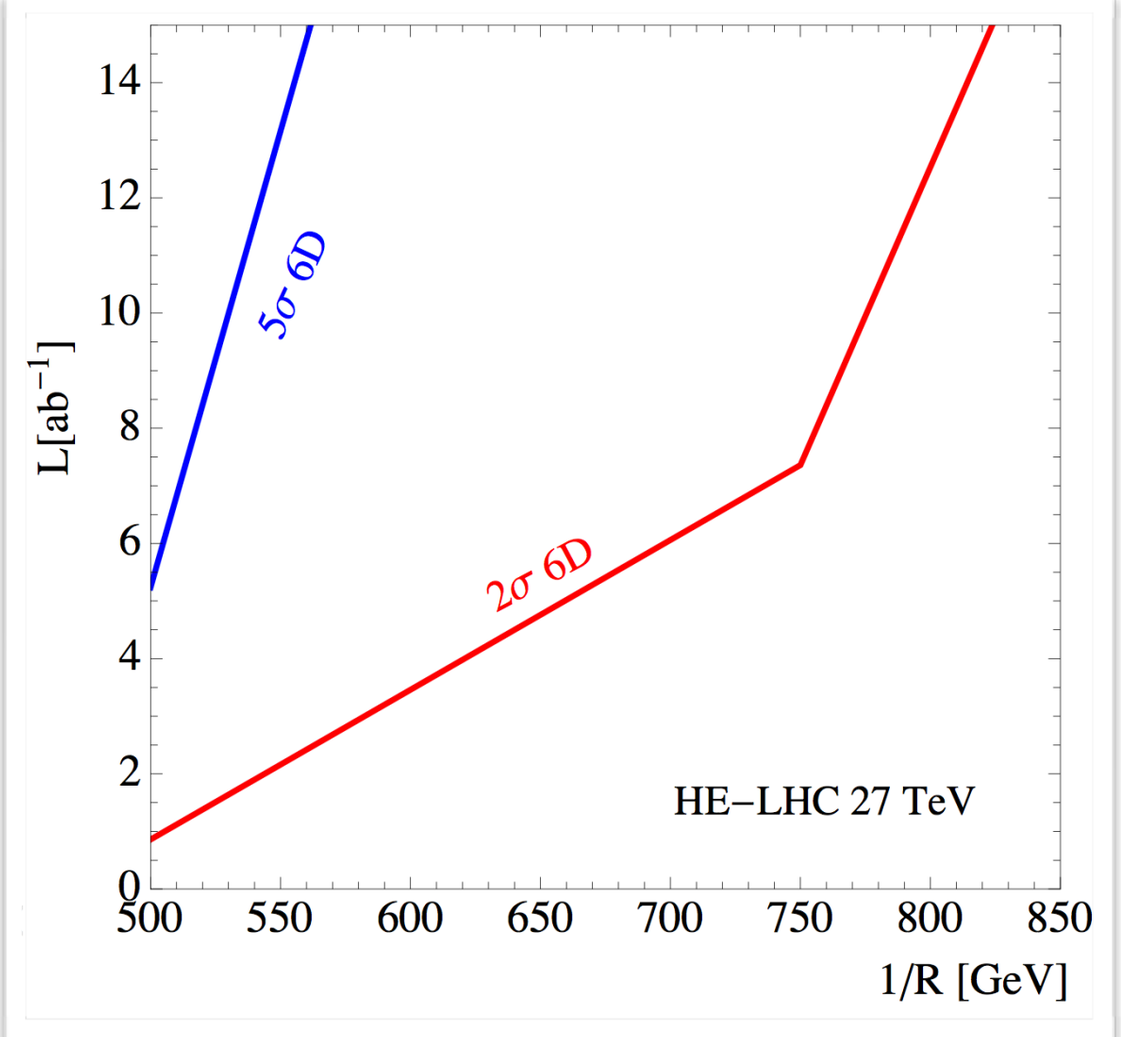
Suppressed Yukawa → small signal & interference → Larger off-shell rate

DG, Han, Mukhopadhyay (2018)

Case study 1: Weakly Coupled Scenario RG Evolution

$$\beta_Q = \beta_Q^{\rm SM} + \sum_{\text{s: massive new states}} \theta(\mu - M_s)(N_s \beta_{s,Q}^{\rm NP})$$





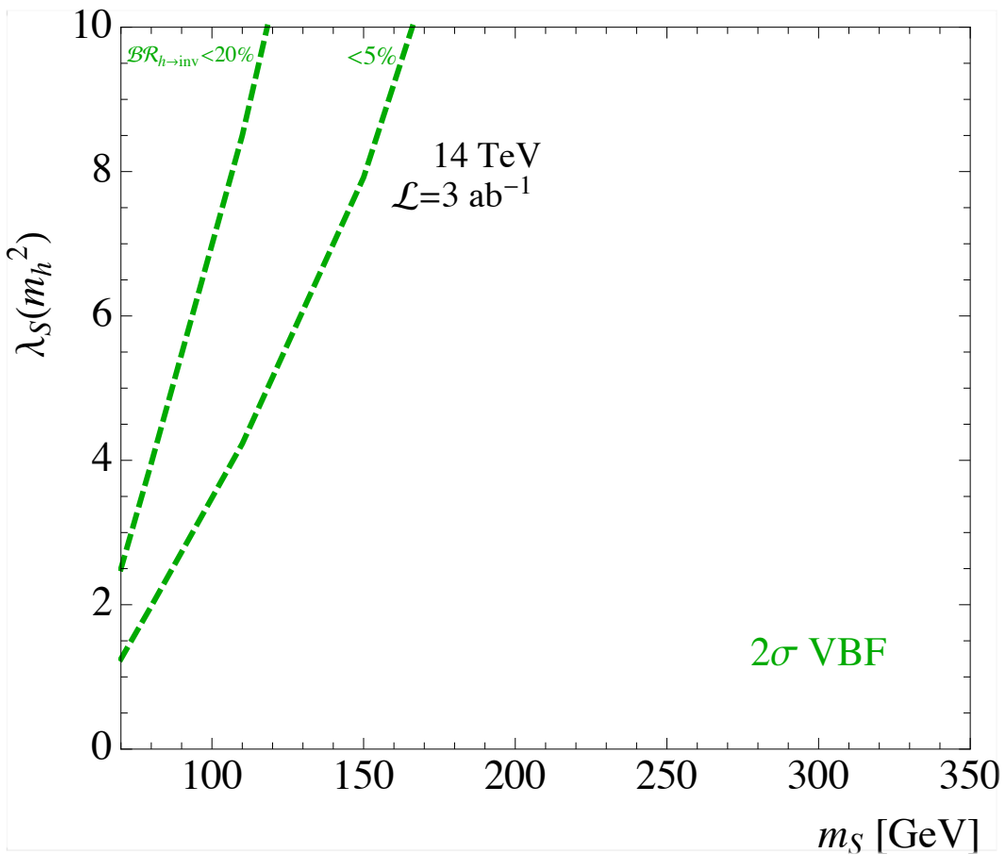
Suppressed Yukawa → small signal & interference → Larger off-shell rate

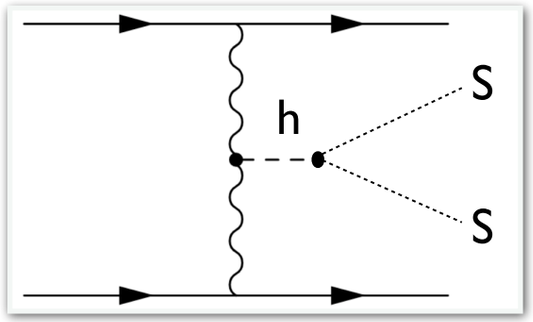
DG, Han, Mukhopadhyay (2018)

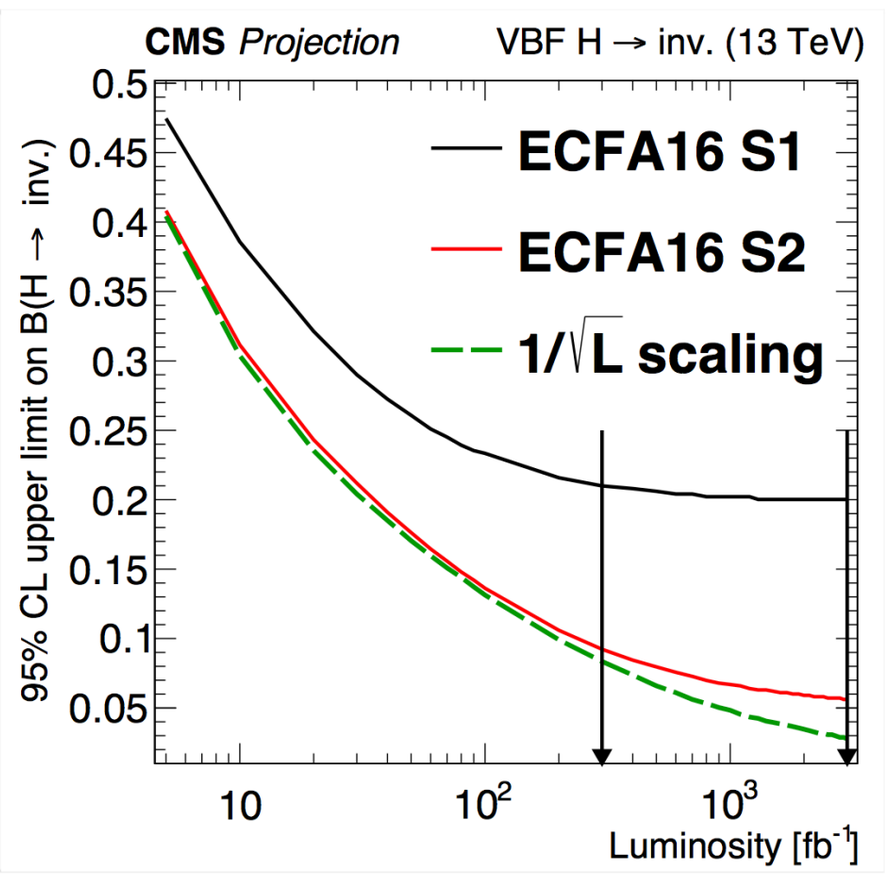
Case study 2: Off-shell probe to Higgs Portal

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

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







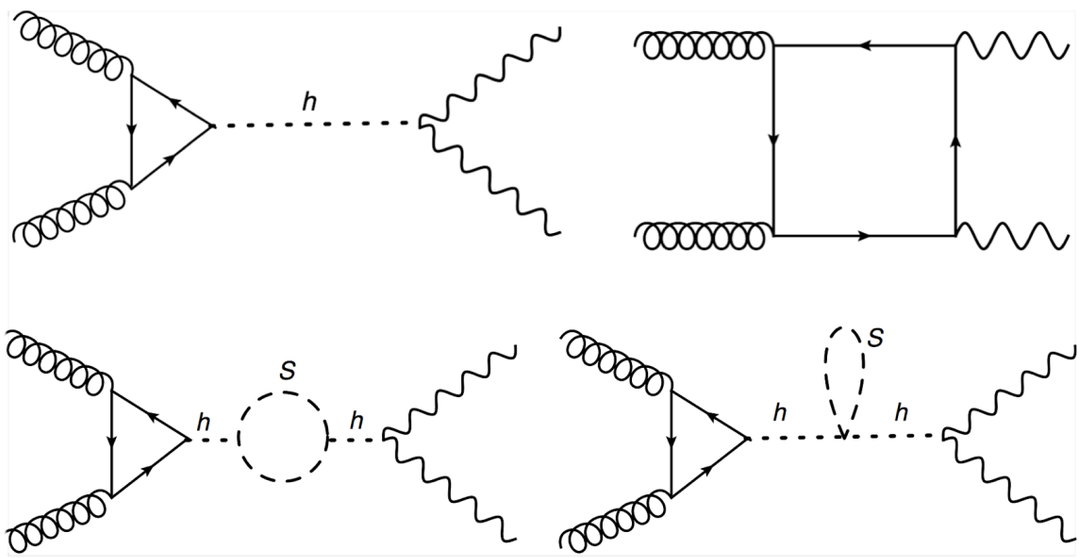
→ $m_h > 2m_S$: strong VBF bounds

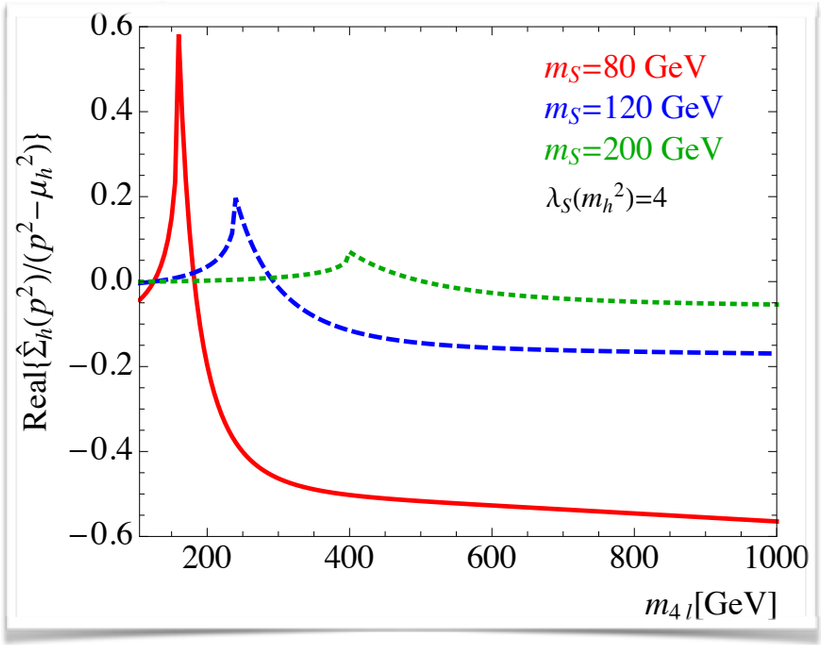
→ $m_h < 2m_S$: sensitivity BW suppressed

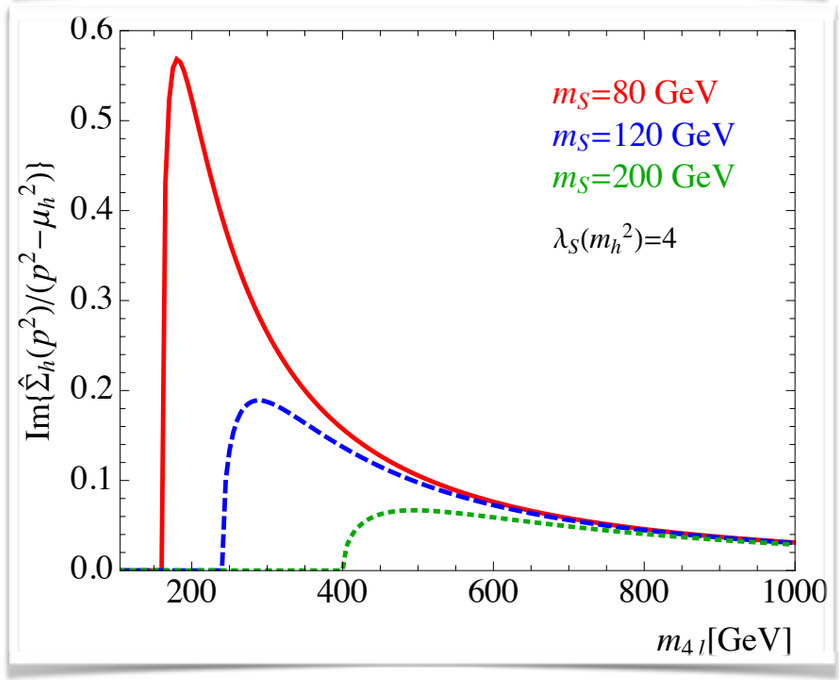
DG, Han, Mukhopadhyay (PRL–2017)

Case study 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







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

DG, Han, Mukhopadhyay (PRL–2017)

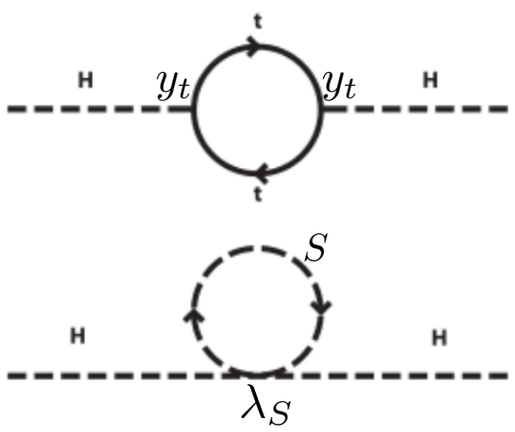
Case study 2: Off-shell probe to Higgs Portal

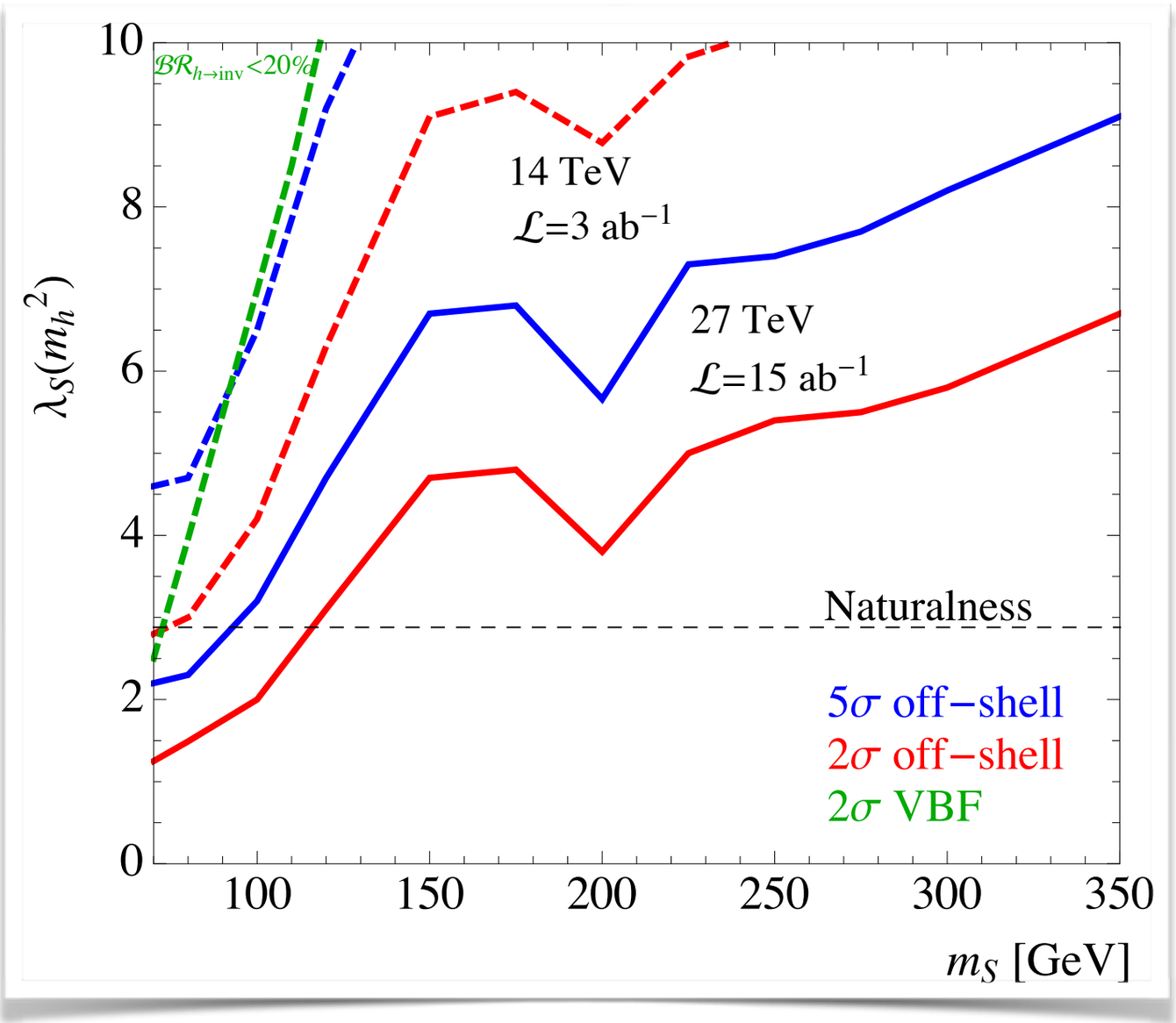
- $\mathcal{L} \supset \partial_\mu S \partial^\mu S^* - \mu^2 |S|^2 - \lambda_S |S|^2 |H|^2$ with $\mathcal{Z}_2$ symmetry

- New states could have a direct connection 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





DG, Han, Mukhopadhyay (PRL–2017)

Case study 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

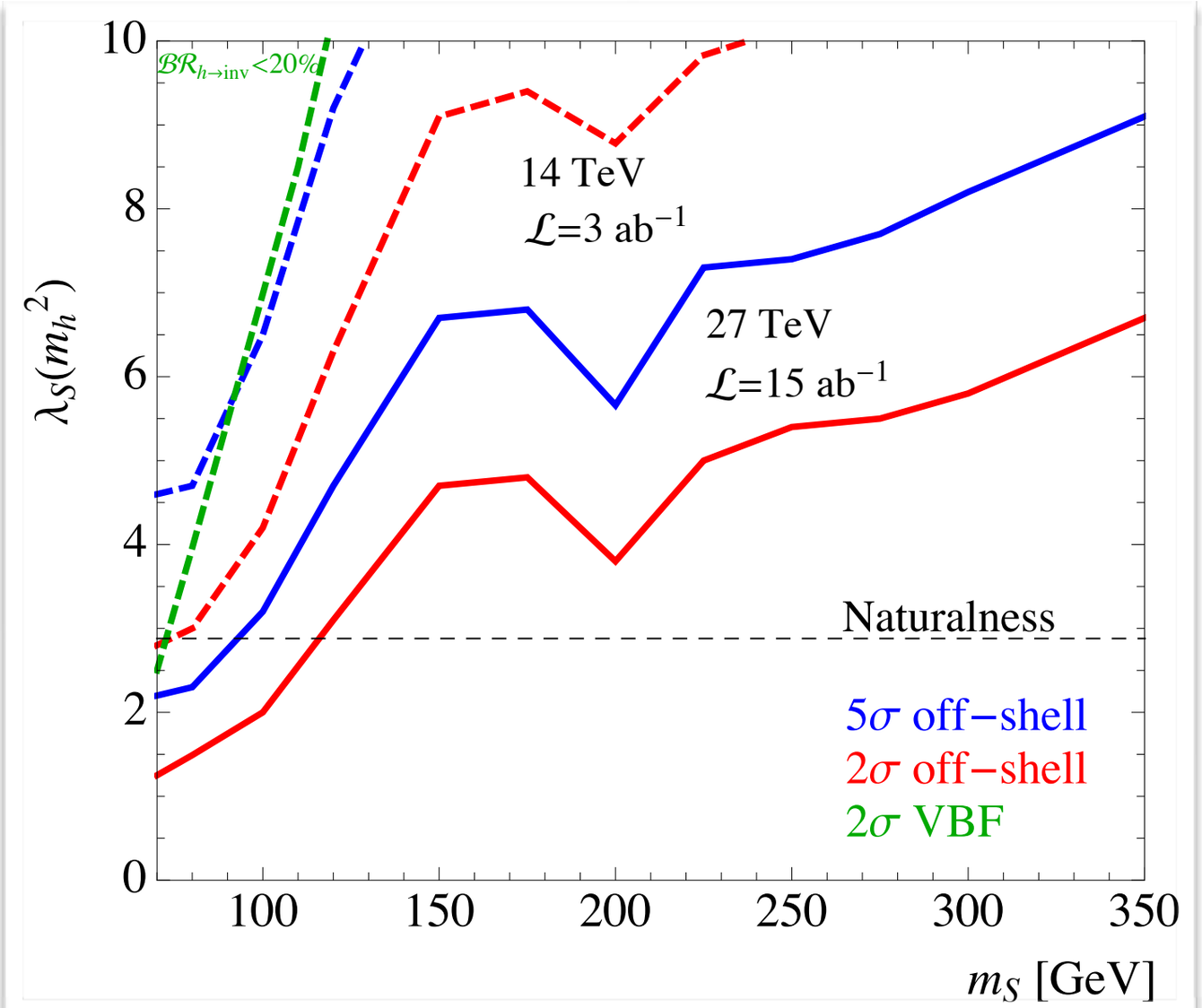
- New states could have a direct connection to Naturalness:

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

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

- 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)…

- Works for the maximally hidden scenario!



DG, Han, Mukhopadhyay (PRL-2017)

Summary

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

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

- Off-shell Higgs can provide an important probe to new physics. Hidden states could appear in the scale dependency of Higgs couplings:

→ Weakly couple running (RGE): Extra dimension ➡ asymptotically power law running!

→ New probe to the maximally hidden Higgs portal scenario. May display connections to hierarchy problem, DM…

Thank you for your attention!