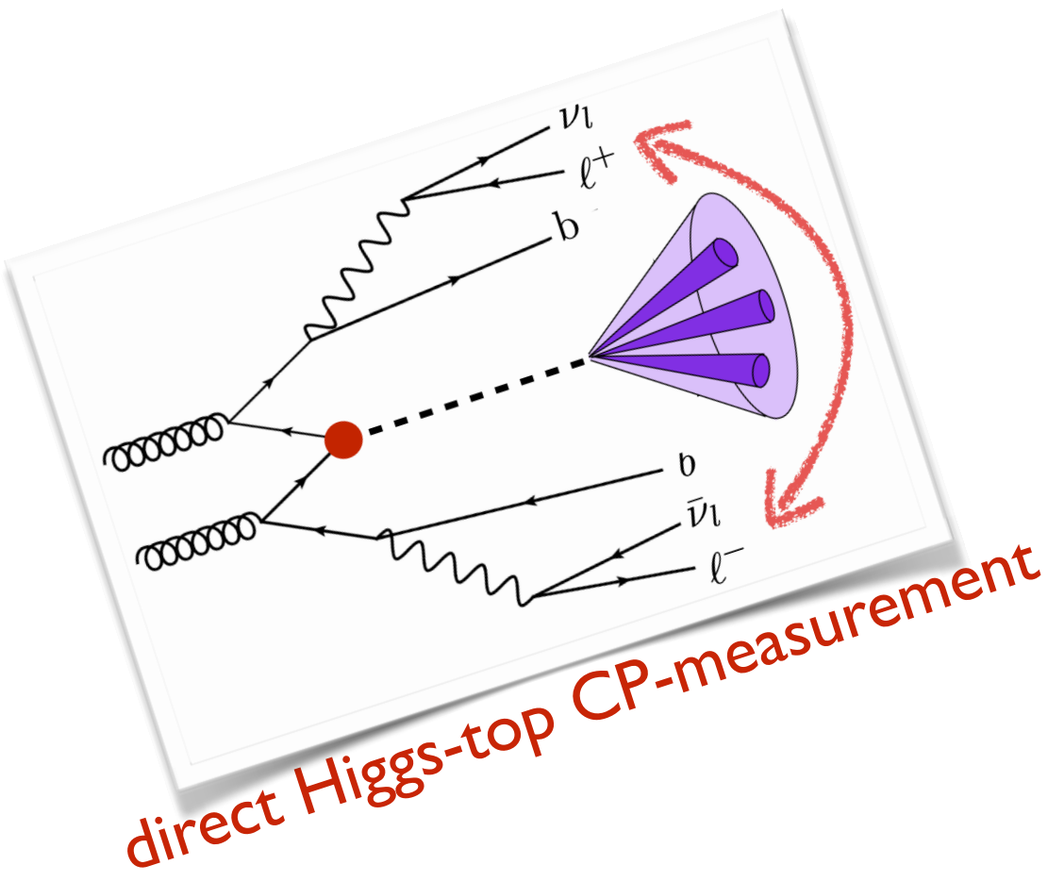
Higgs couplings at high energies

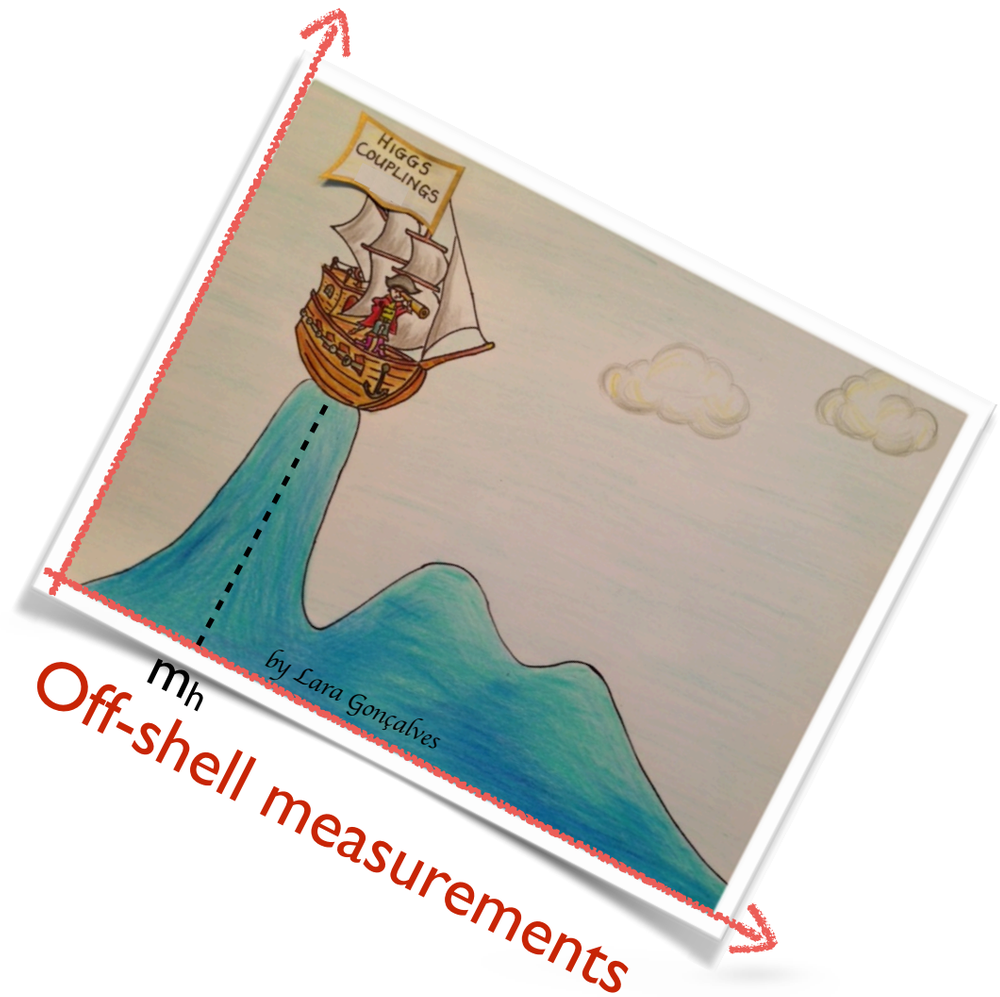
HL/HE LHC Meeting

Fermilab - 04.05.2018

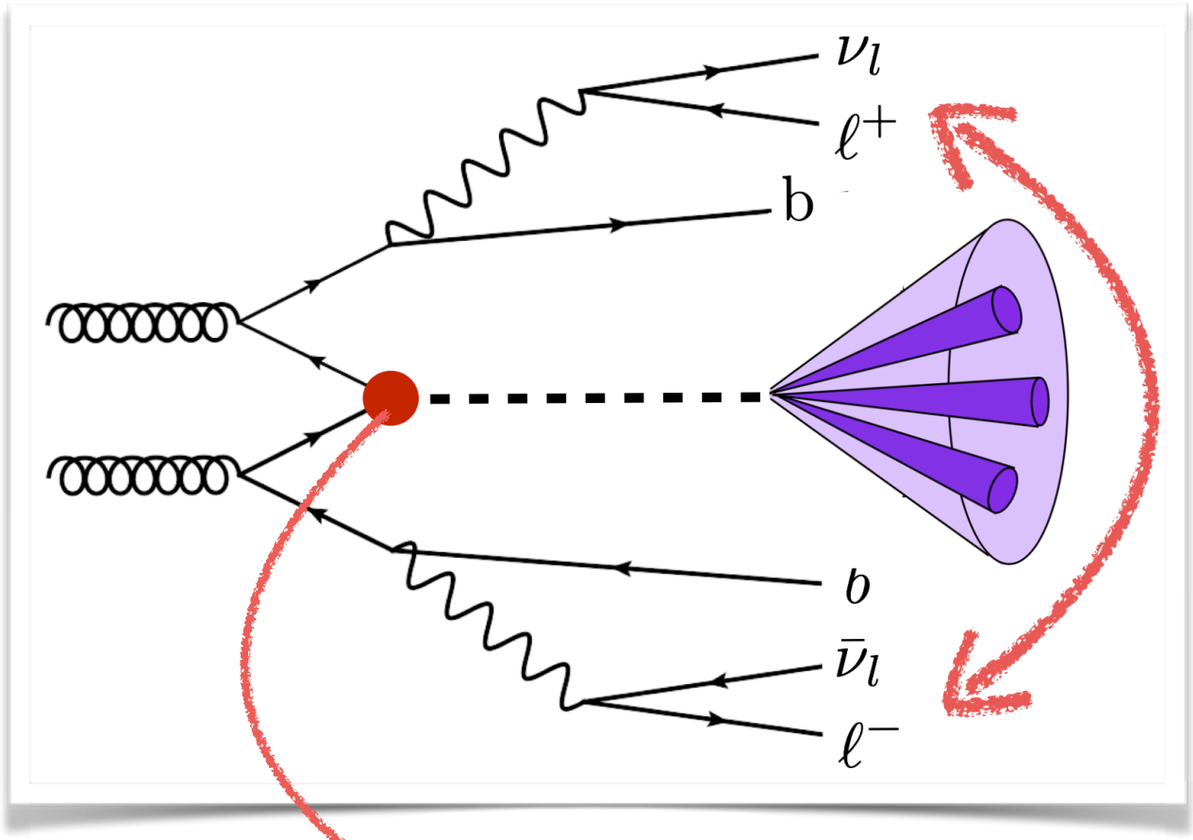
Dorival Gonçalves

Many exciting opportunities ahead!!!





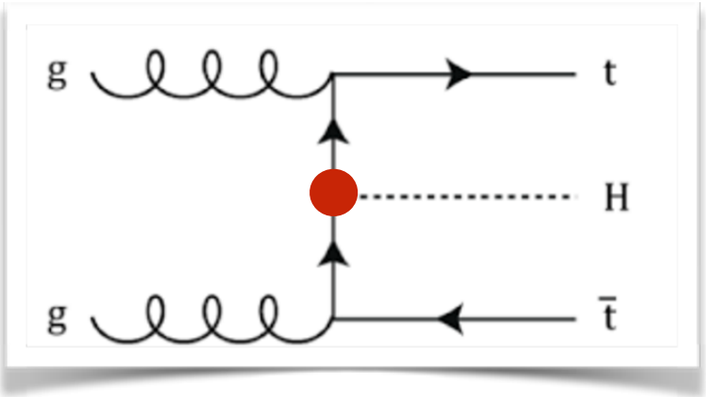
Direct Higgs-top CP-measurement

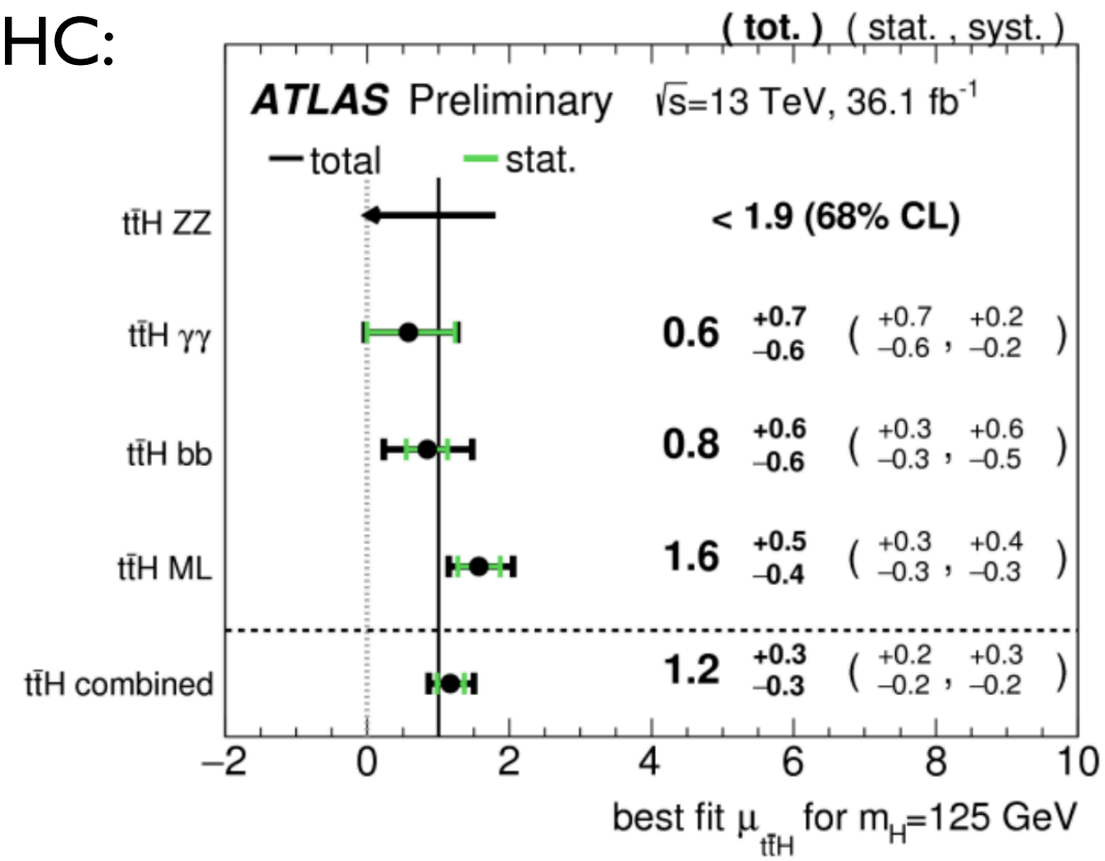


direct Higgs-top CP-measurement

Directly Measuring ttH

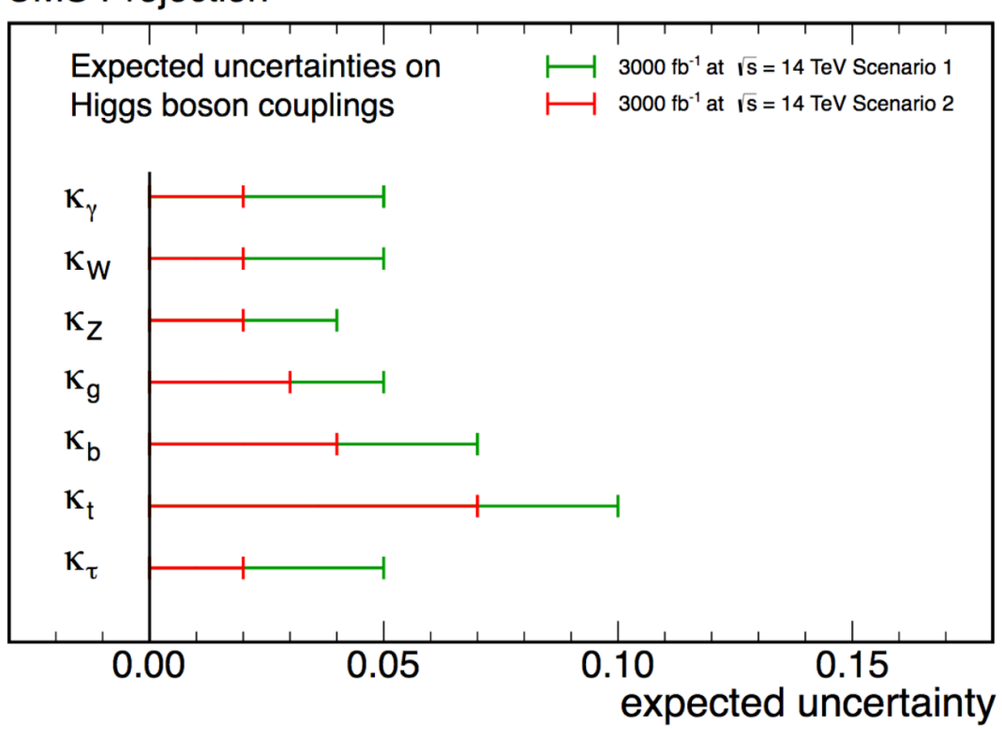
- ttH channel is around the corner at LHC:





4.2σ observed (3.8σ expected)

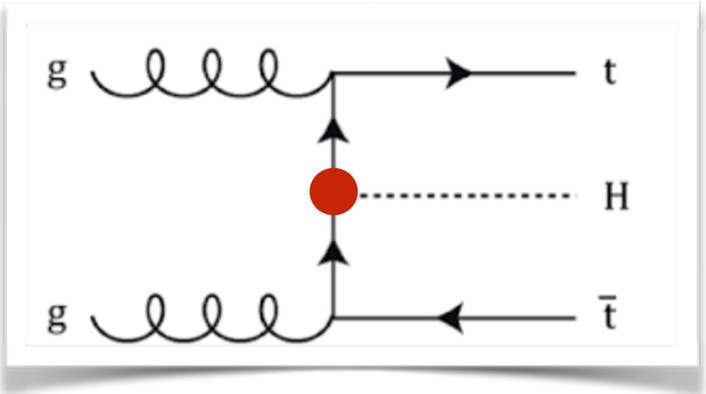
CMS Projection

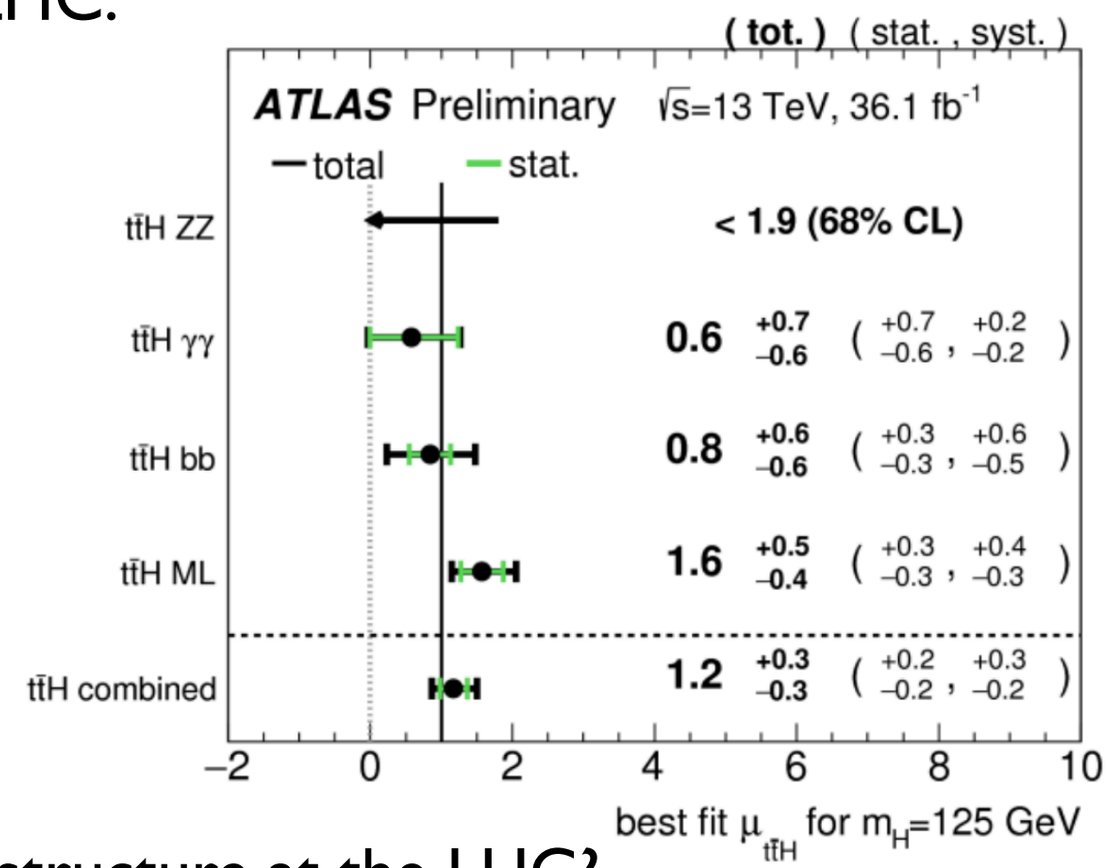


- Expected precisions
  - → Scenario I: systematic uncertainties same as now
  - → Scenario II: theoretical uncertainty divided by 1/2 and systematic by 1/sqrt(L)
- ttH(bb)/ttZ(bb) might improve it even further!

Exciting opportunities ahead!

- ttH channel is around the corner at LHC:





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

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

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

- While CP-odd H-V appears only at dim-6 or higher, CP-odd H-f can manifest at tree-level
- Mixture possible in some models, e.g., 2HDM
- Not excluded from Higgs measurements

Exciting opportunities ahead!

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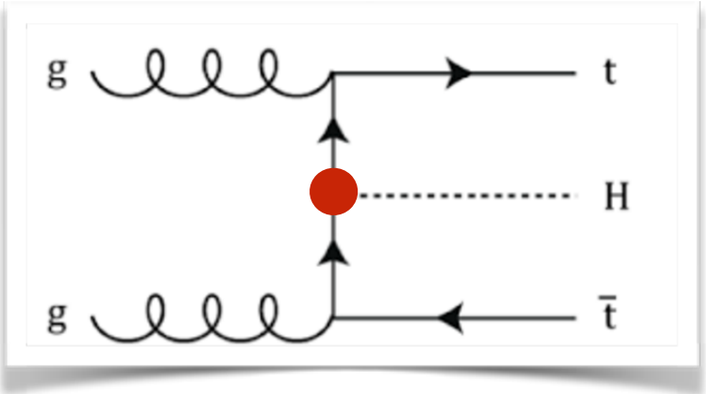

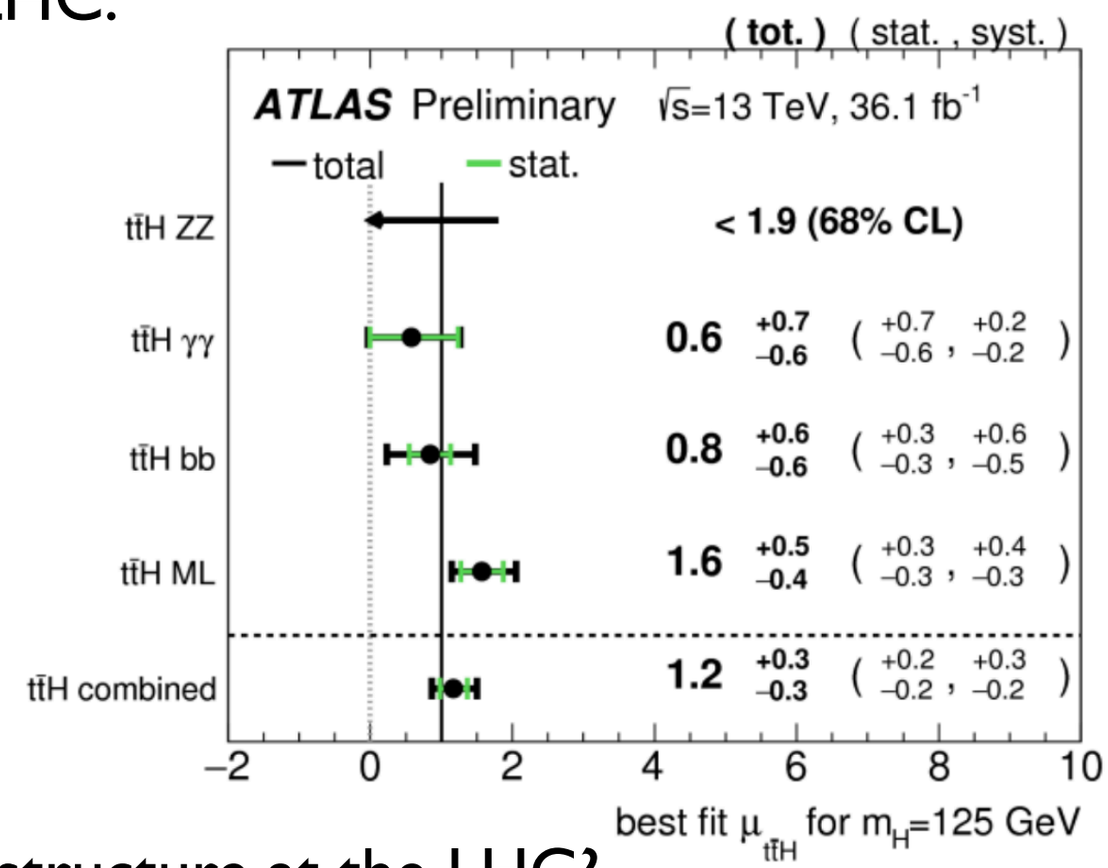

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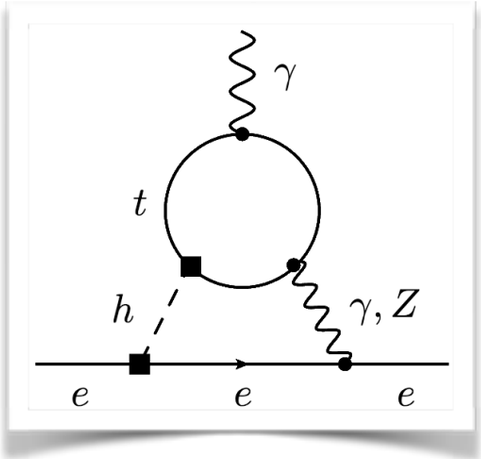

- Indirect constraints from eEDM very strong, yet assume:
  - Coupling strength/structure to light fermions
  - No other states in the spectrum

Directly Measuring $t\bar{t}H$

- 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)

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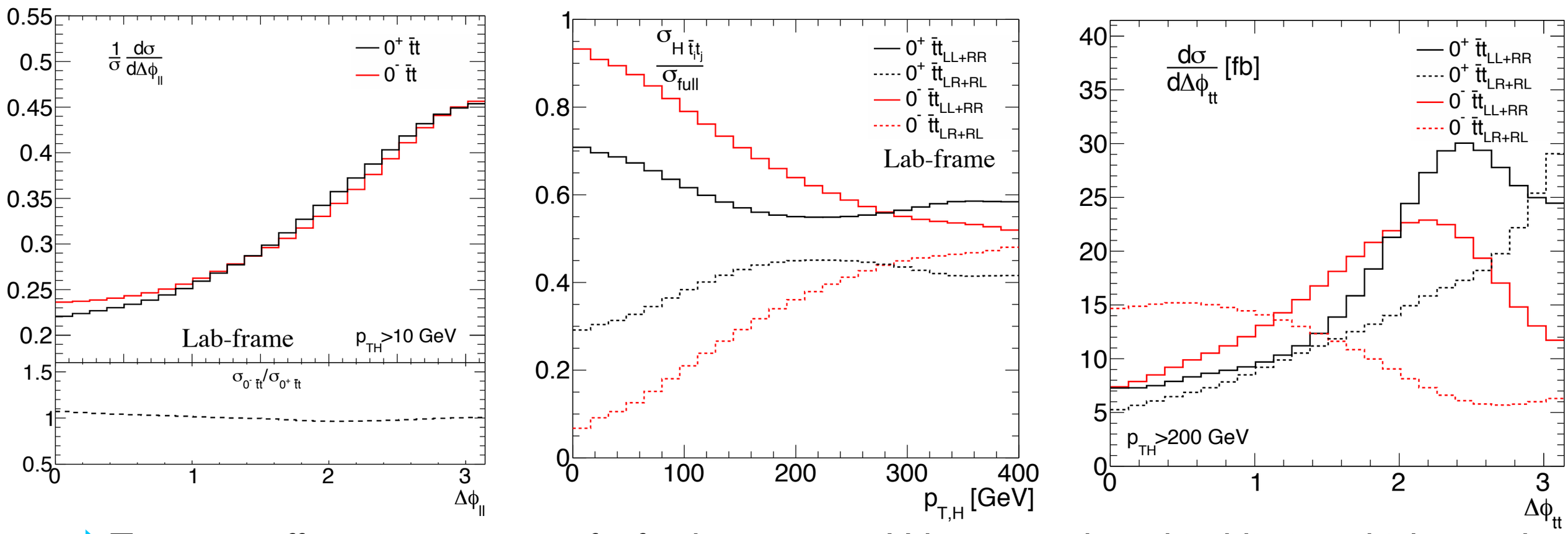

➡ Top mass effects in presence of a further massive H boson pushes chiral limit to higher scales

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

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

Buckley, **DG** (PRL–2015)

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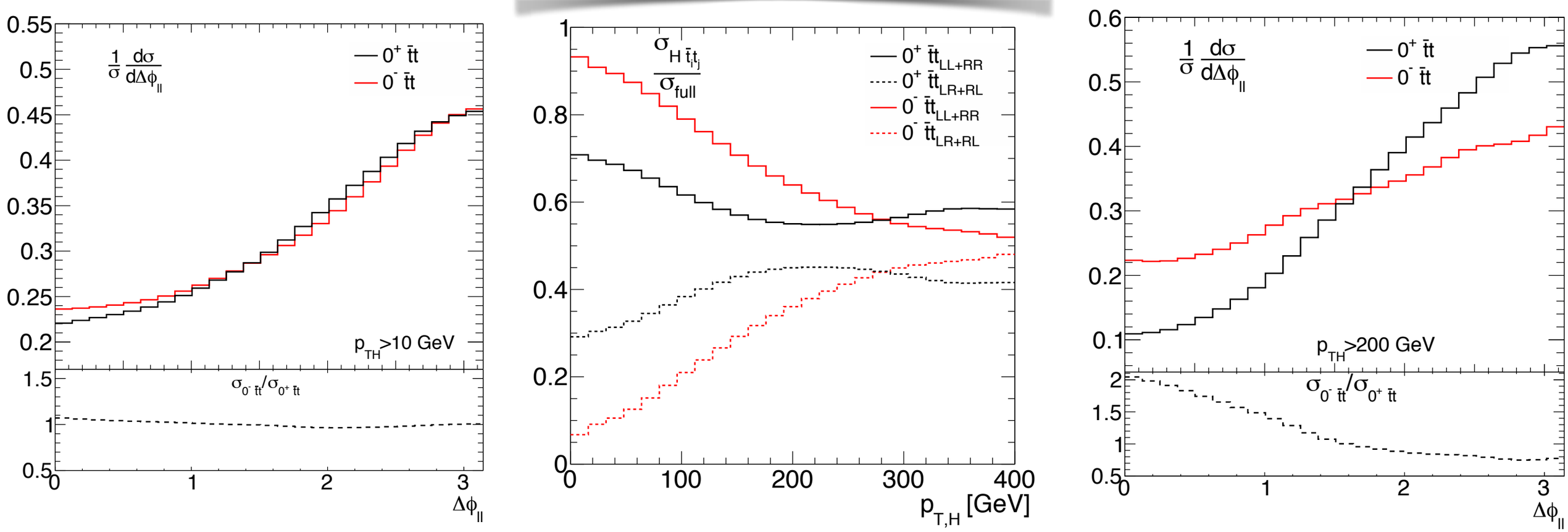


- Boosted Higgs (p_{TH}>200GeV) nicely match with H>bb BDRS algorithm
- No previous study with dileptonic ttH(bb) via BDRS in the literature

Buckley, **DG** (PRL–2015)

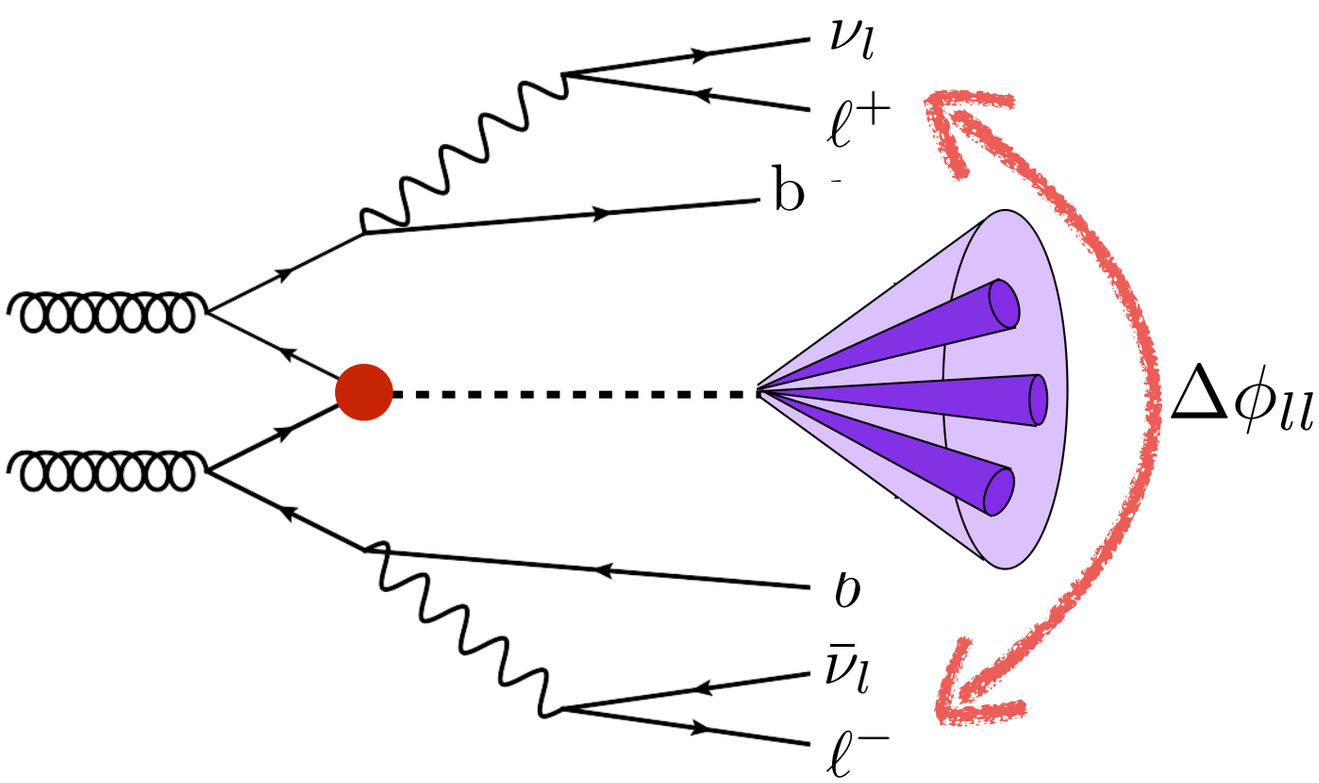
Plehn, Salam, Spannowsky (2009)

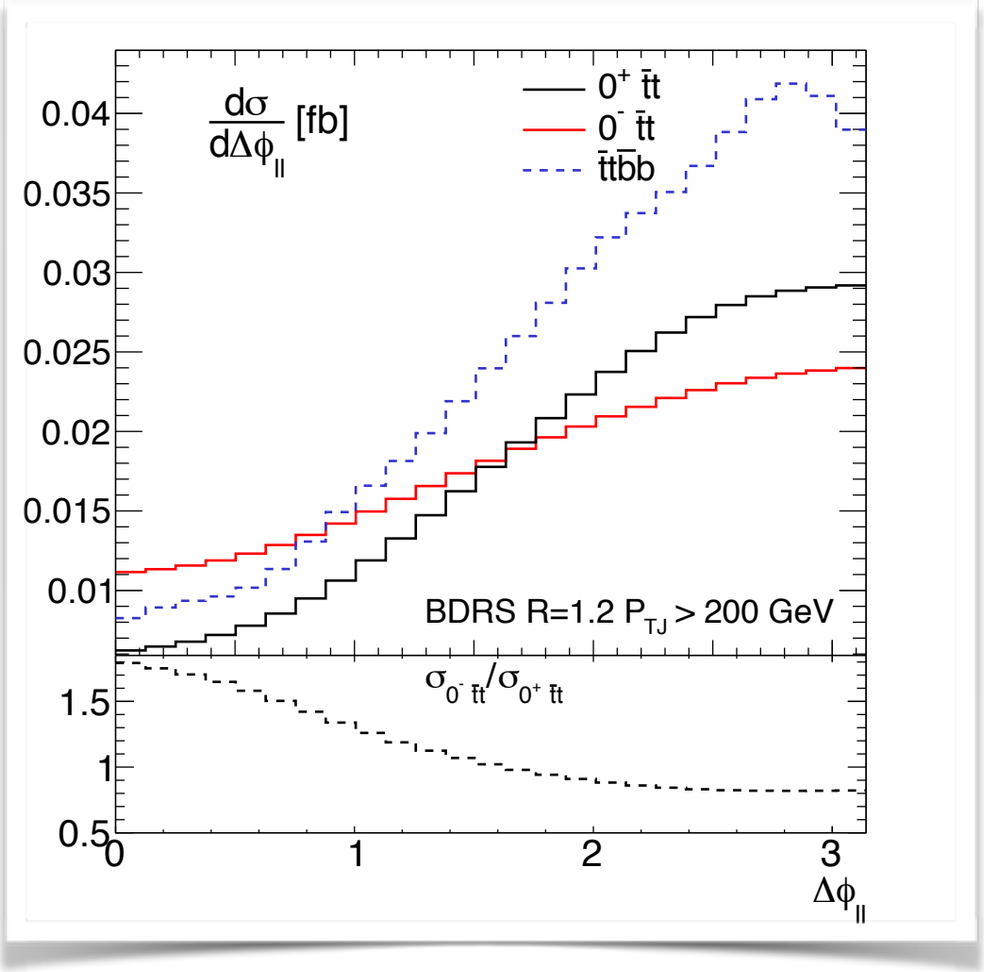
Directly Measuring $t\bar{t}H$

- Higgs candidate is genuinely <u>part of a multi-jet system:</u>

  Proper modelling of the QCD emissions indispensable requirement for robust analysis

➡ Signal & backgrounds are @NLO (MC@NLO), accounting for spin correlation on top decays





BDRS H-tag, $p_{T\ell} > 15$ GeV, $|\eta_\ell| < 2.5$
$p_{Tj} > 30$ GeV, $|\eta_j| < 2.5$, $n_j \geq 2$, $n_l = 2$
two extra b-tags (four in total)
$|m_H^{\rm BDRS} - m_H| < 10$ GeV, $m_{b\bar{b}} > 110$ GeV

- The full analysis and higher-order effects did not degrade our observable!

Buckley, **DG** (PRL–2015)

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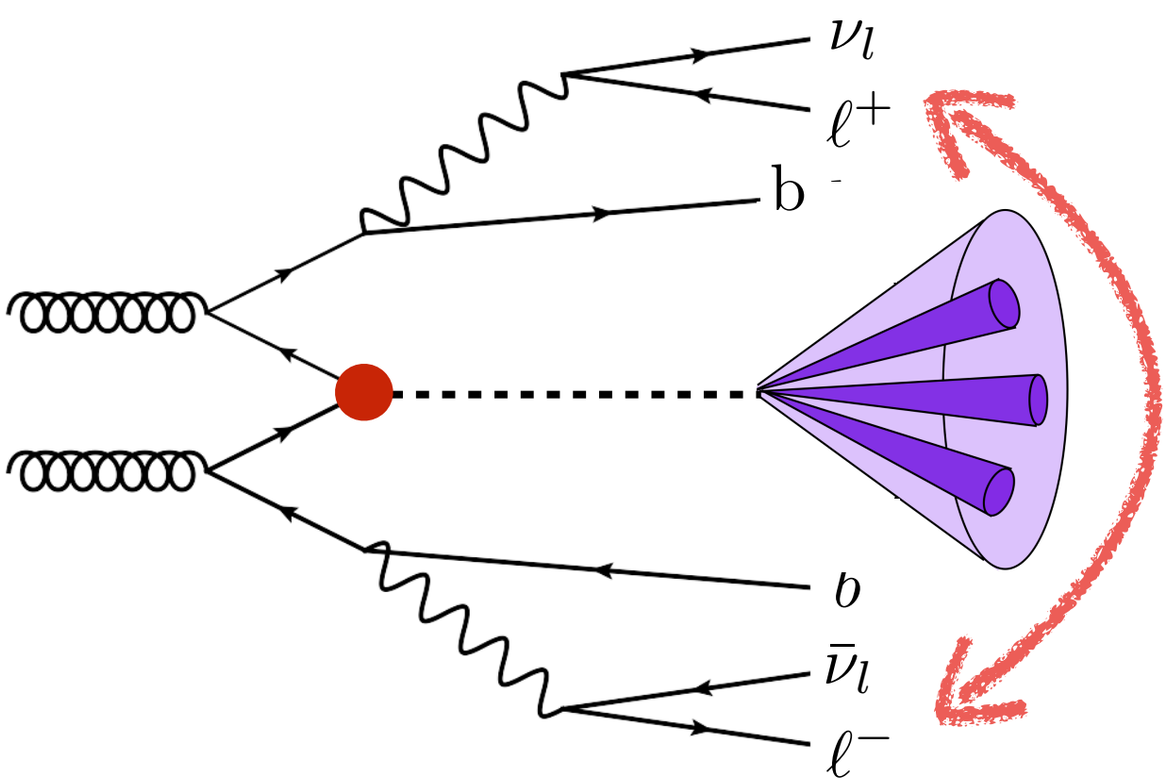

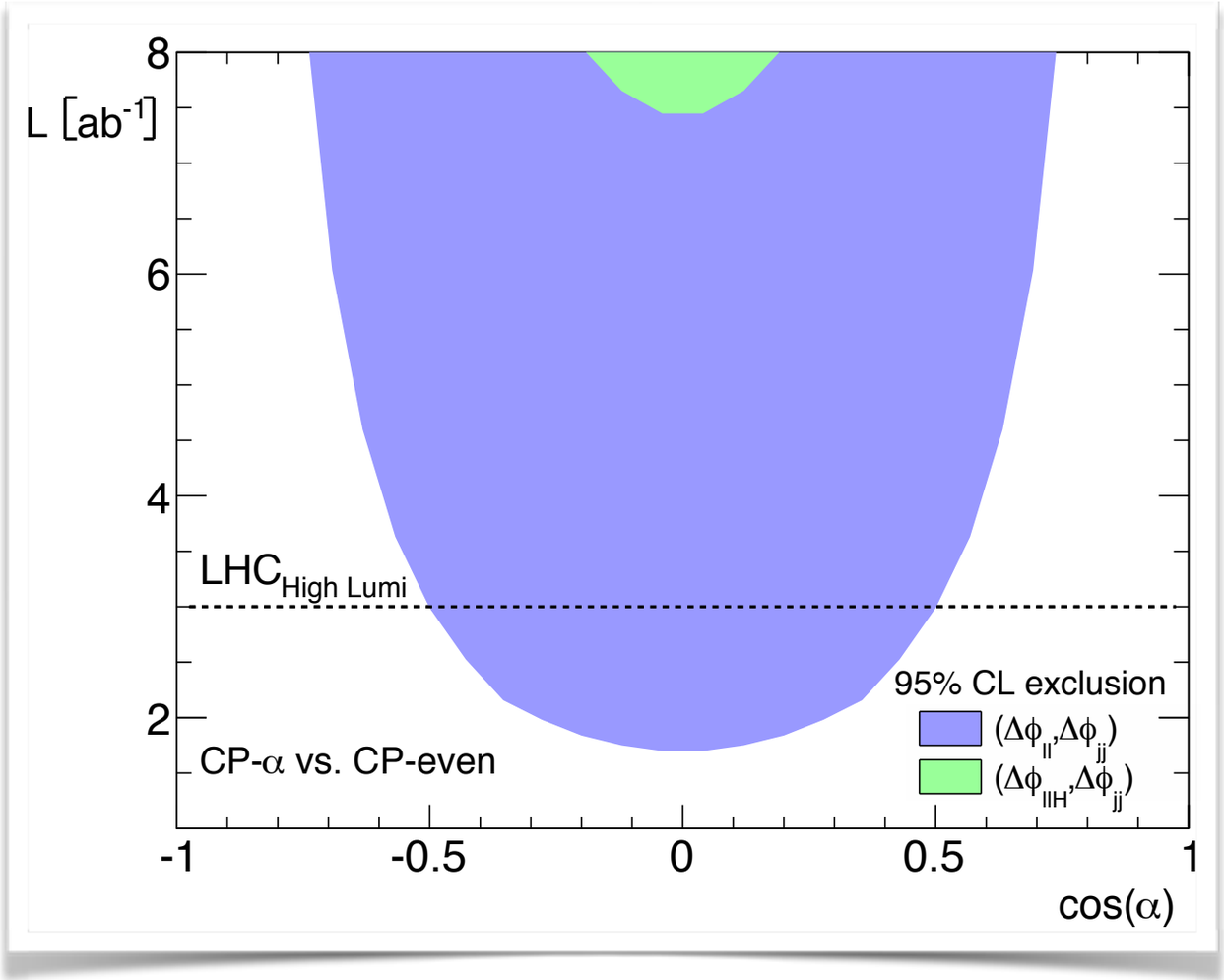

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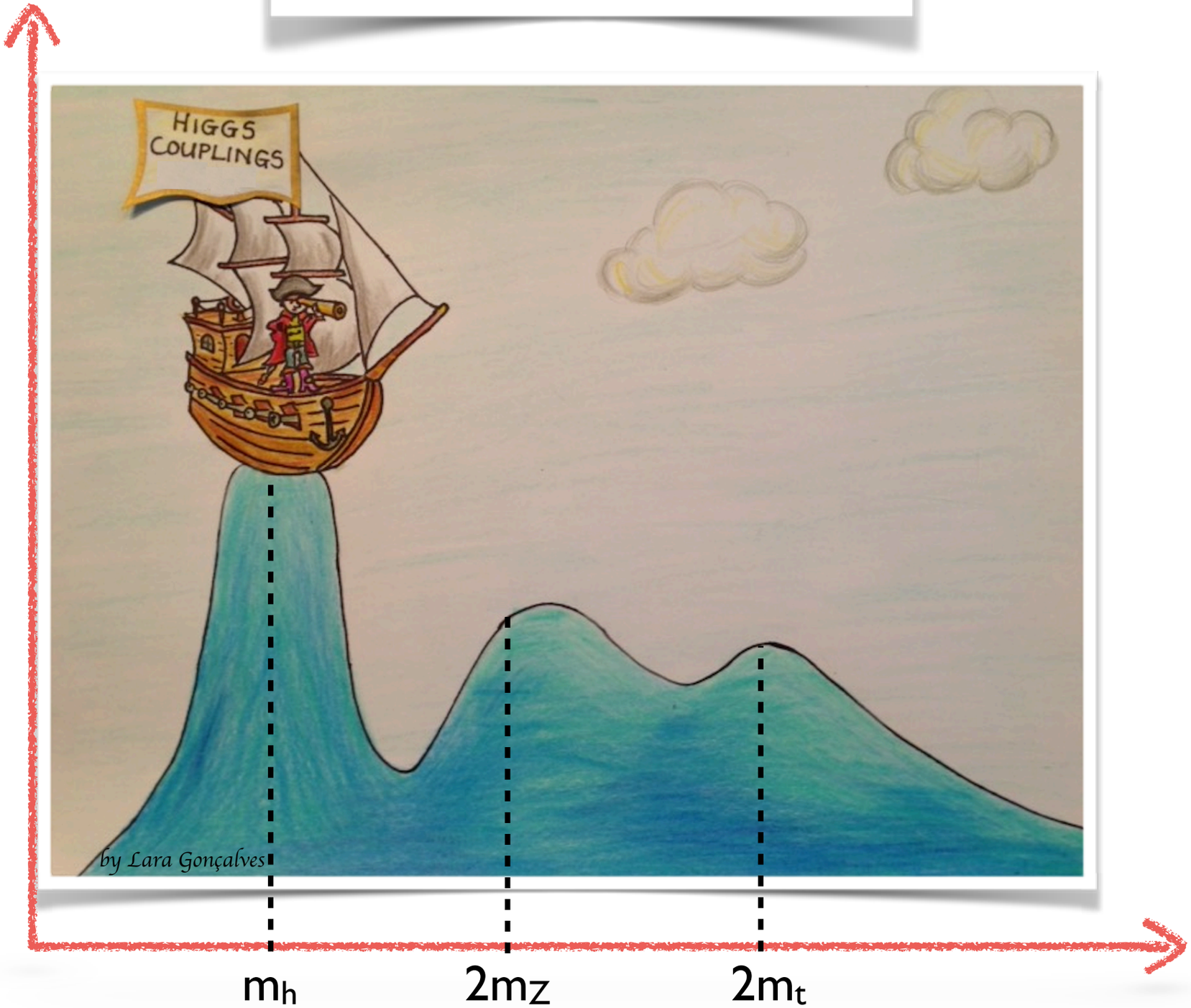
Buckley, **DG** (PRL–2015), Lopez-val, **DG** (2016)

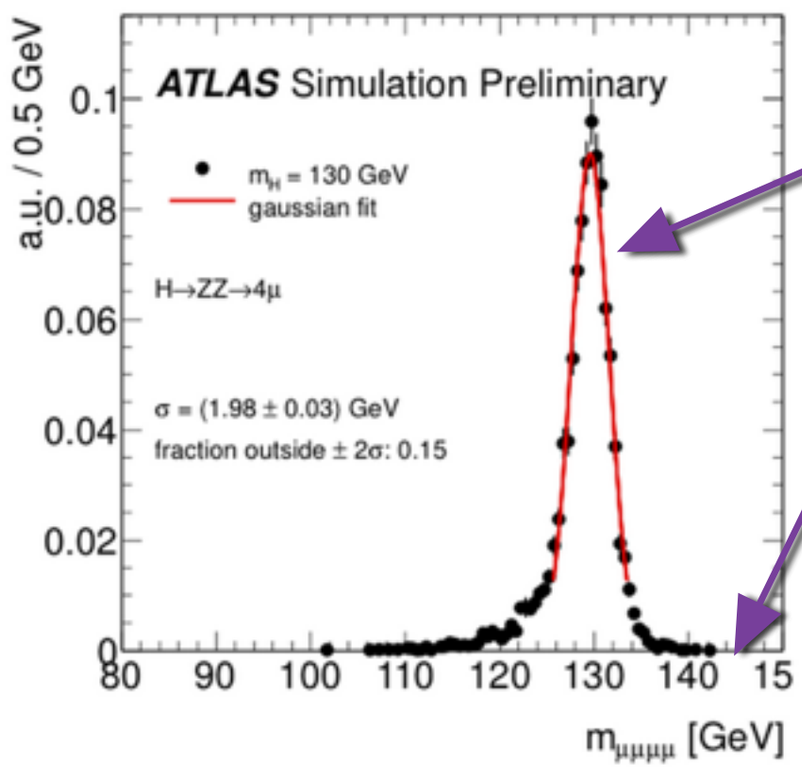
Off-shell Higgs



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 ;

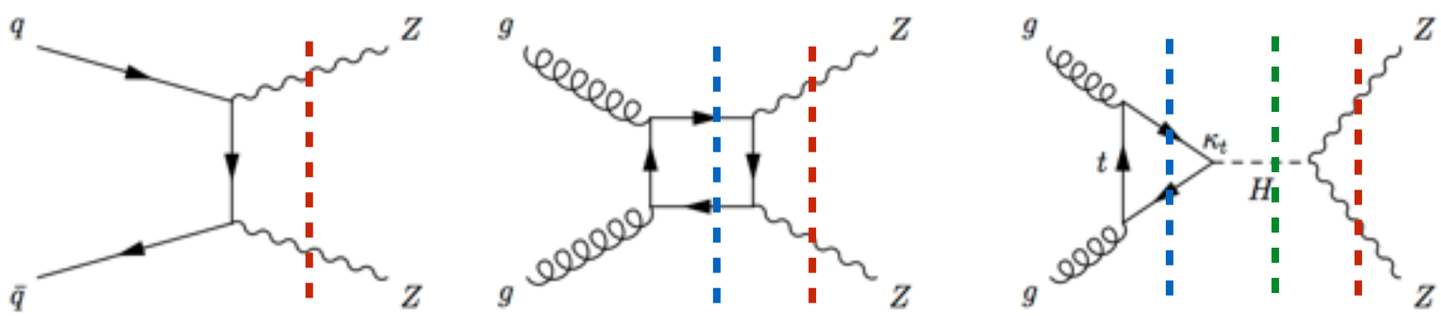
→ ZZ Threshold;

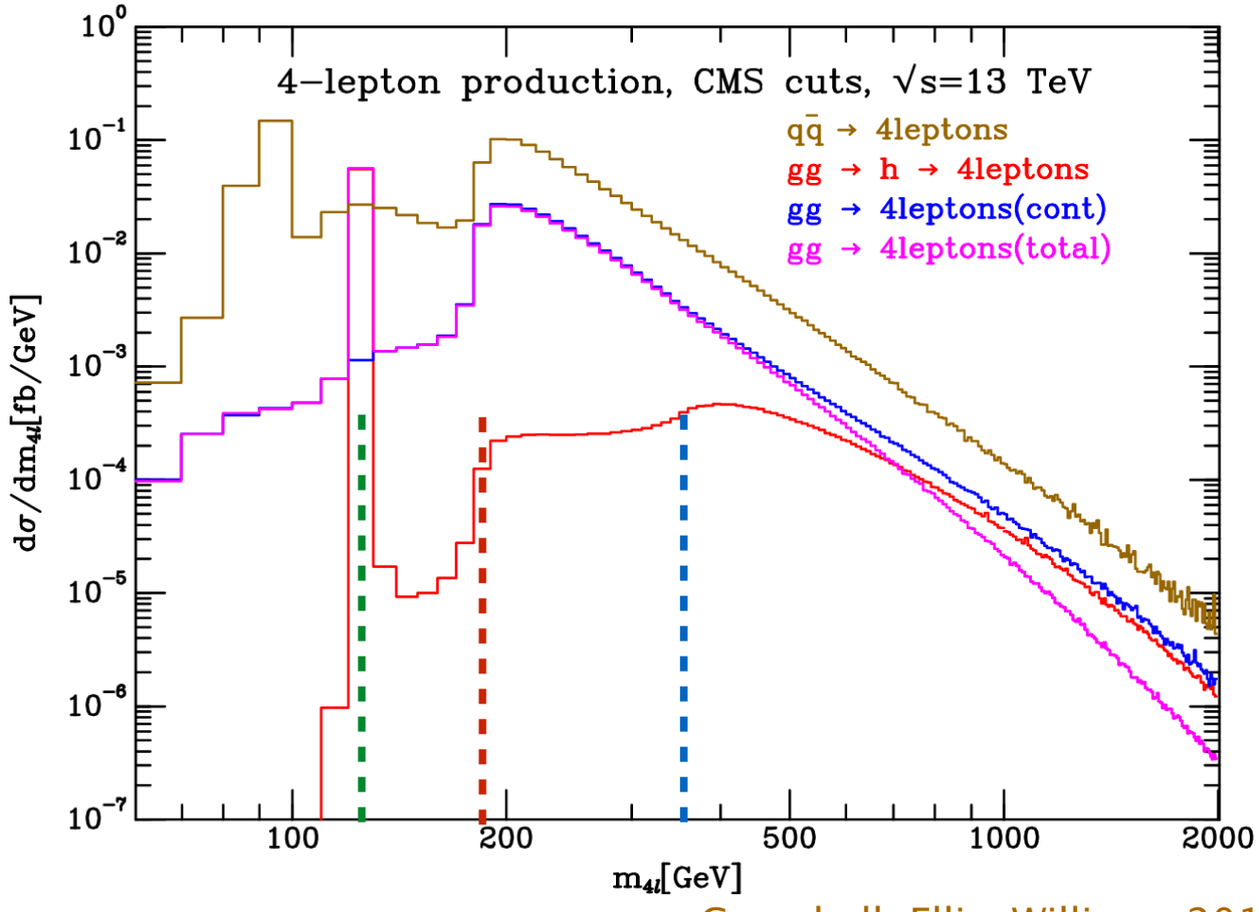
→ and top mass effects change our naive expectation

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

Theoretical ingredients

- Carries information on the Higgs couplings at different energy scales

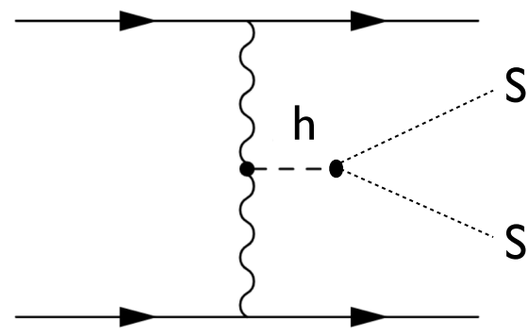


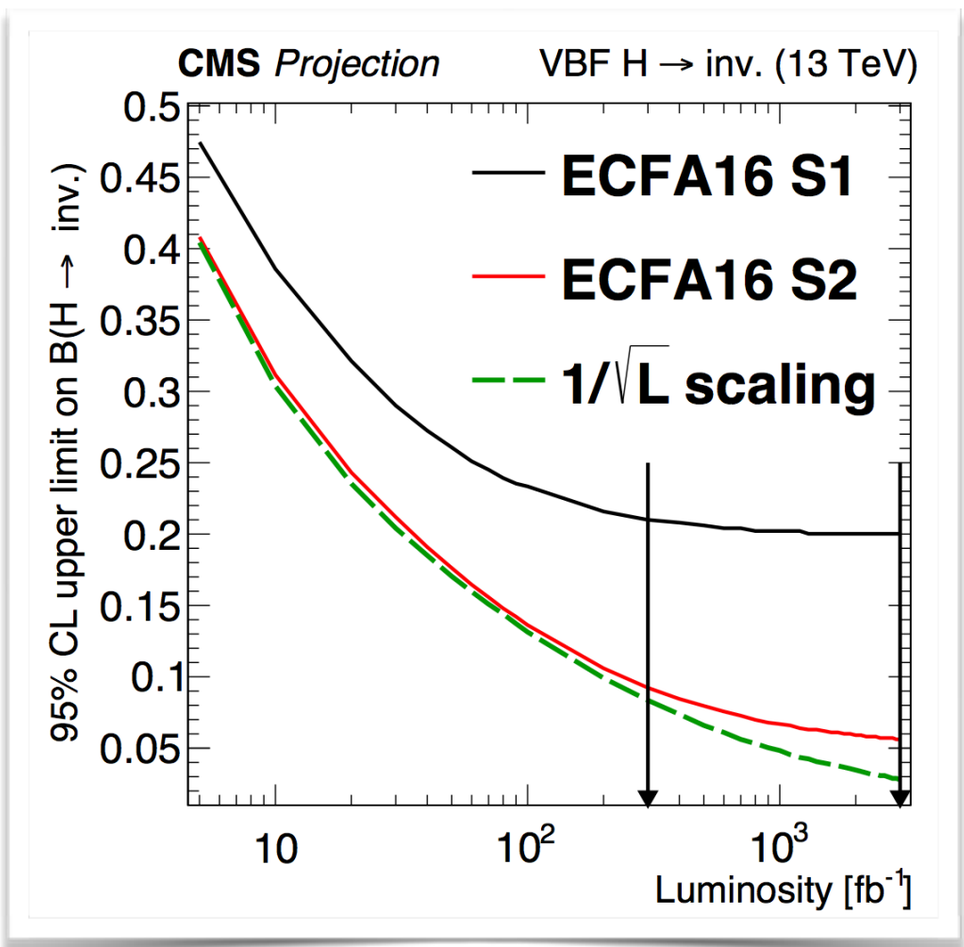


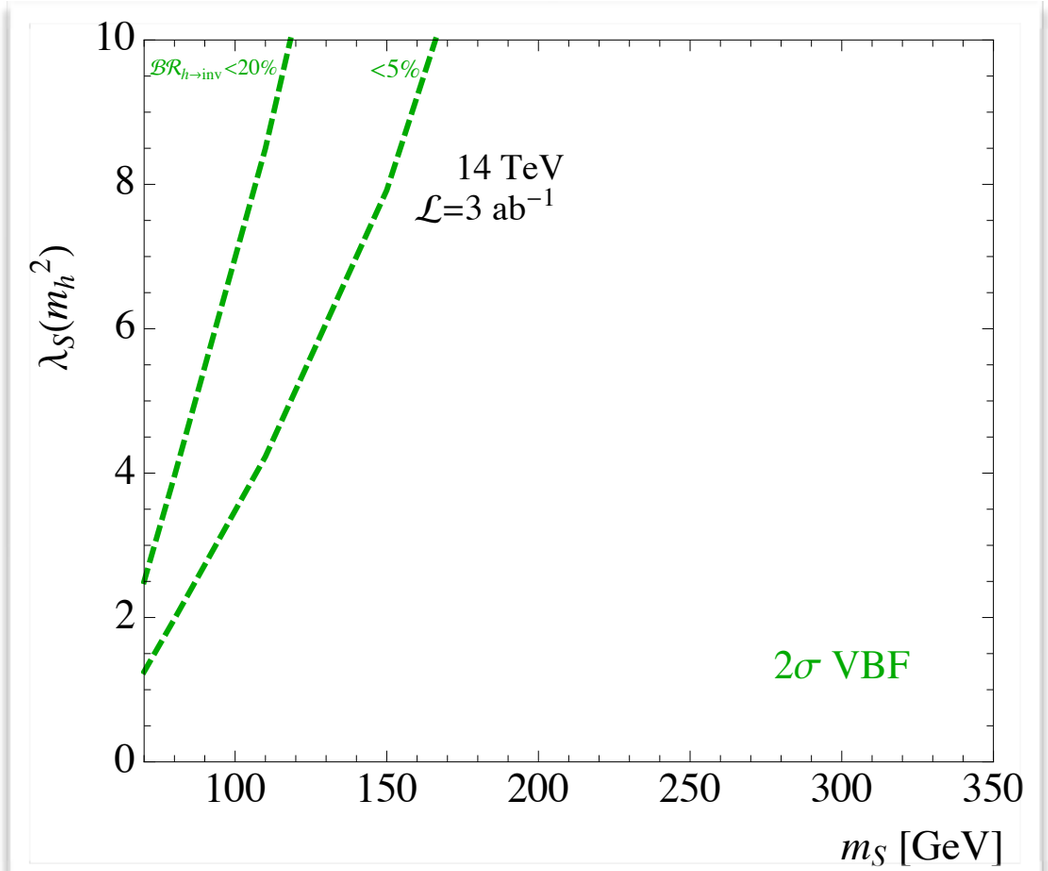
Campbell, Ellis, Williams 2013

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







→ $m_h > 2m_S$: strong VBF bounds

→ $m_h < 2m_S$: sensitivity BW suppressed

DG, Han, Mukhopadhyay (PRL–2017)

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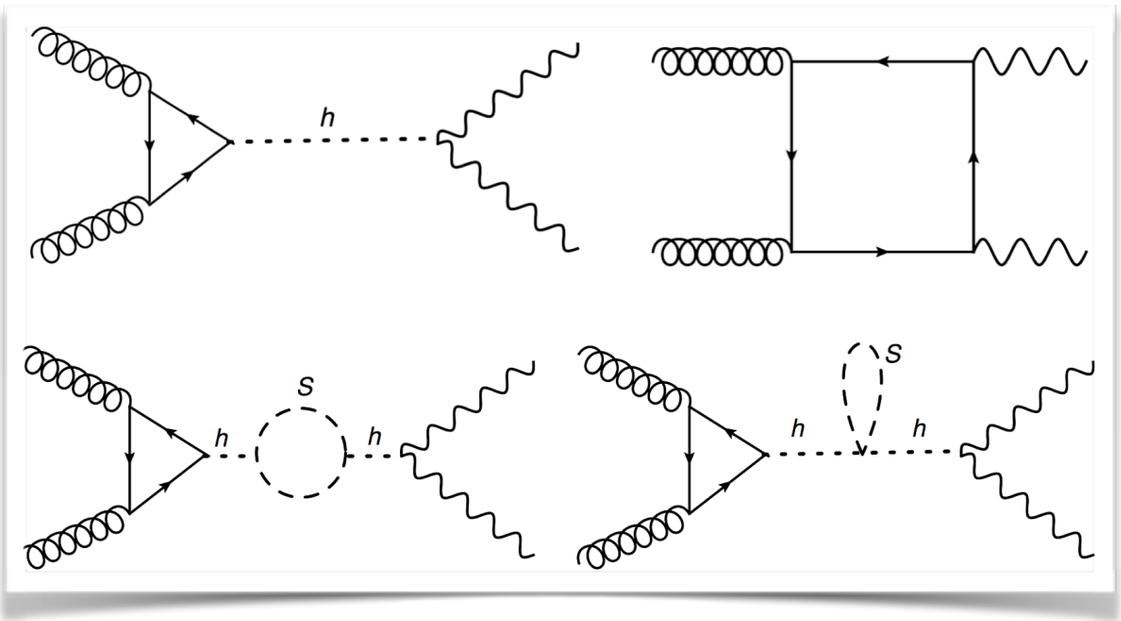

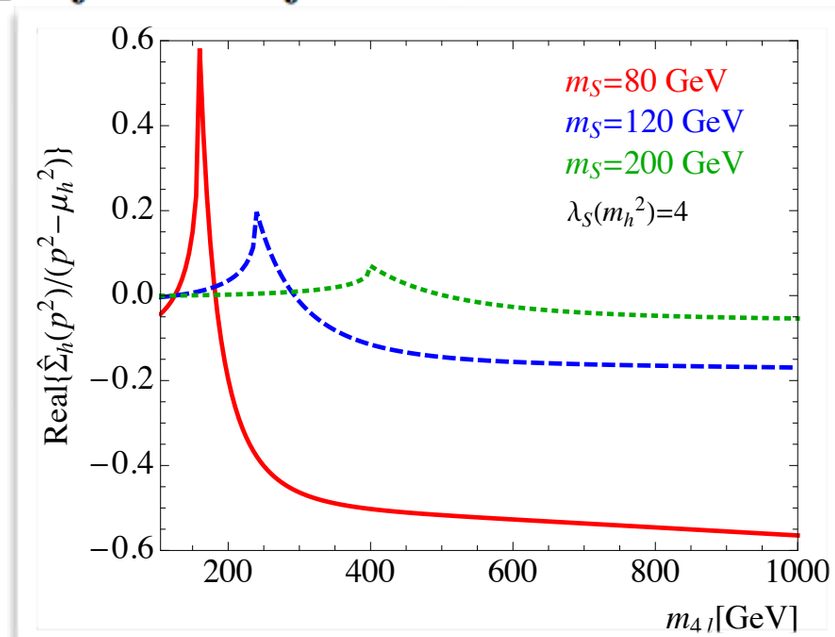

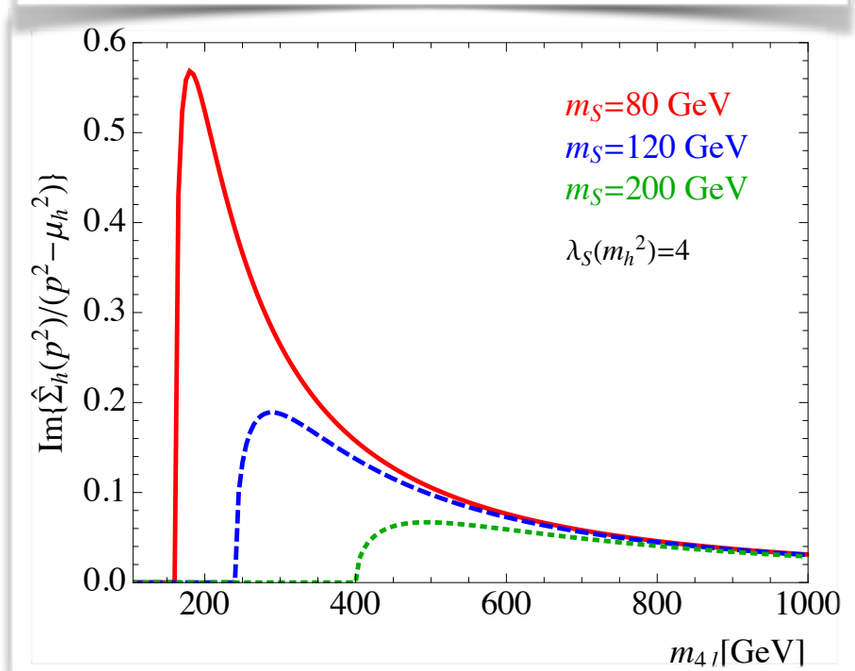

- Separably renormalizable, UV finite, gauge-invariant subset
- Corrections are also at $\delta\sigma^{NLO}_{gg\to 4l} \propto \lambda_S^2$ order

DG, Han, Mukhopadhyay (PRL–2017)

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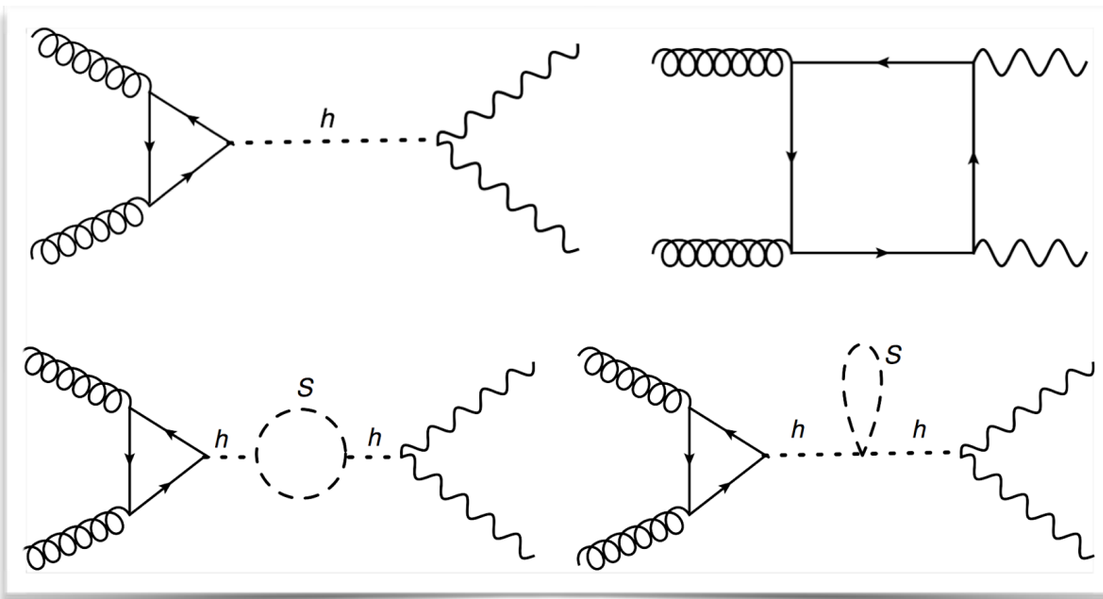

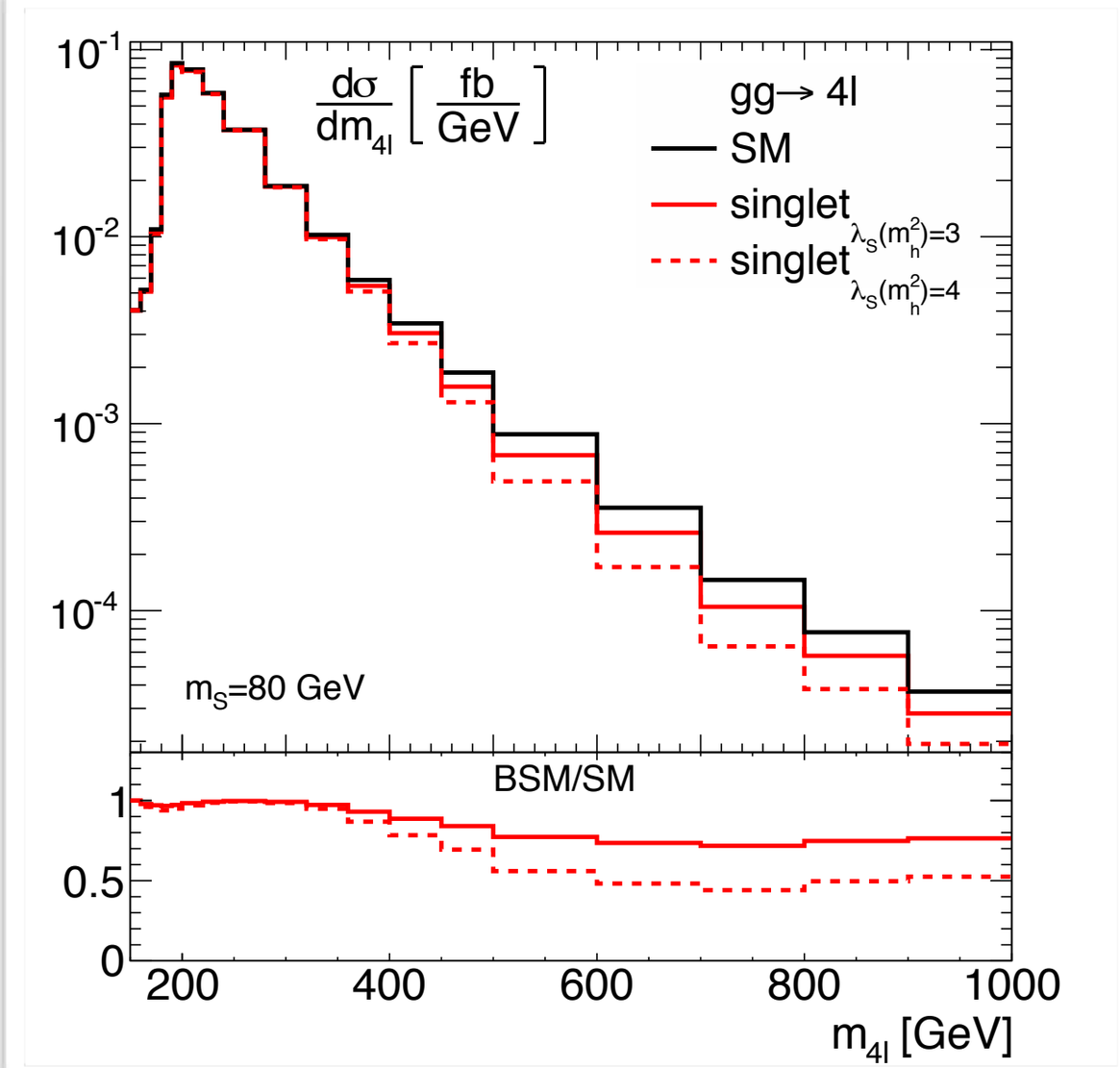

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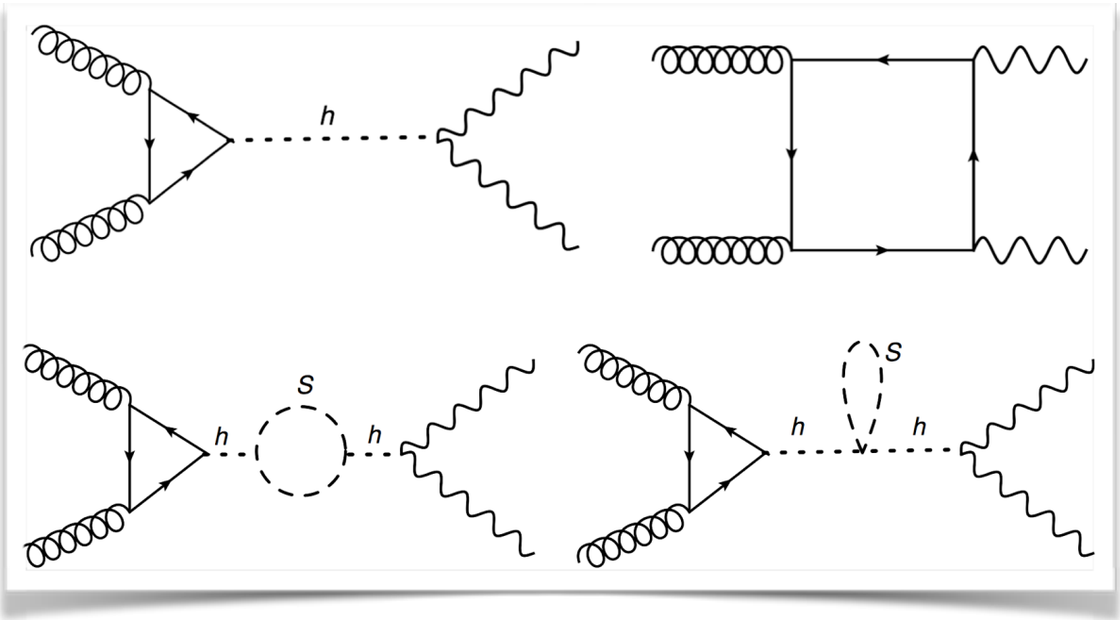
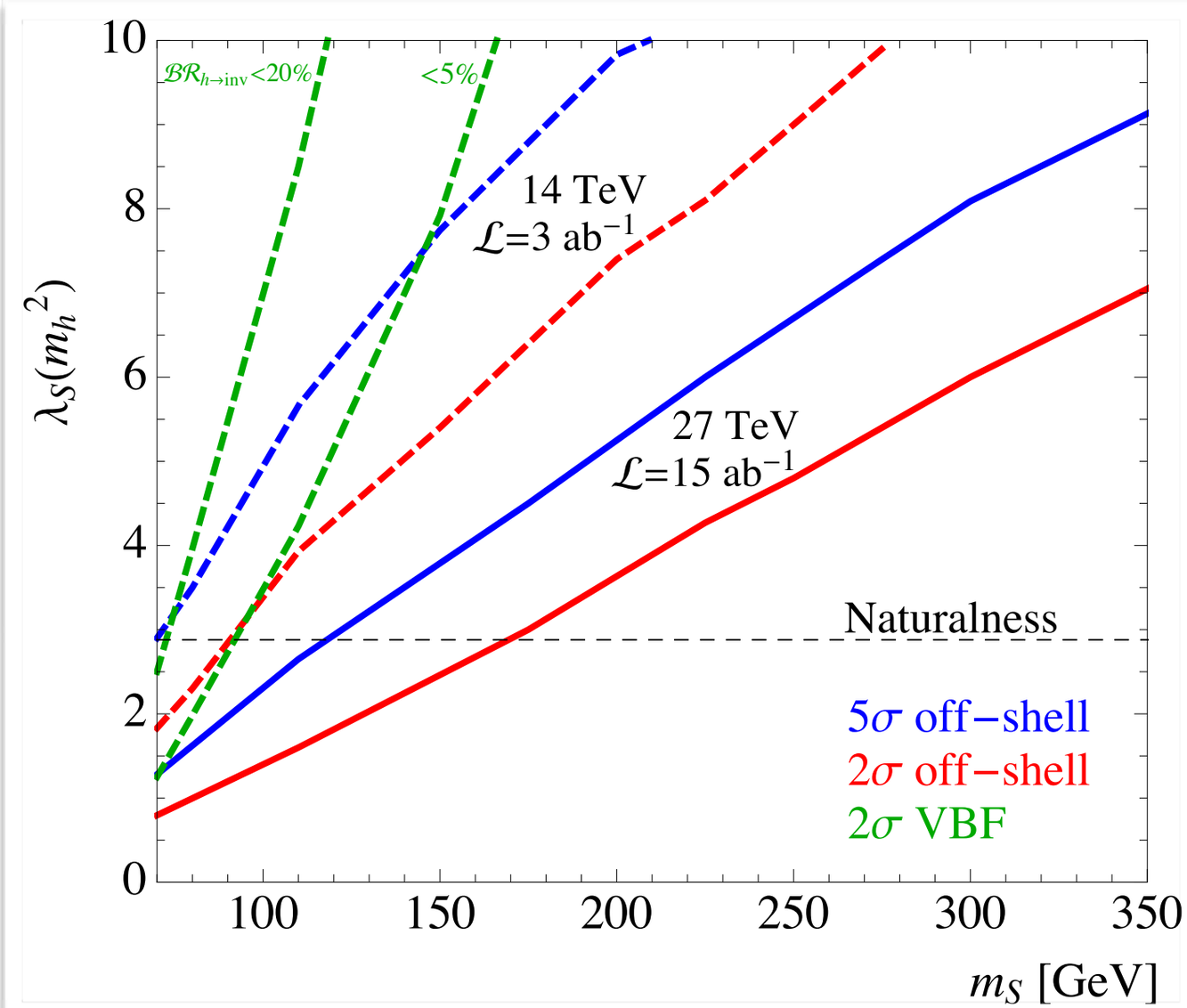




- New states could have a direct connection to Naturalness:

$$\delta M_h^2 = \frac{1}{16\pi^2}(\lambda_S - 2N_c y_t^2)\Lambda^2 + \frac{6N_c y_t^2}{16\pi^2} m_t^2 \log\frac{\Lambda^2}{m_t^2} - \frac{1}{16\pi^2}\left(\lambda_S m_S^2 + \lambda_S^2 v^2\right)\log\frac{\Lambda^2}{m_S^2},$$

- Works for the maximally hidden scenario!
  If we add extra charges, e.g., stop case the off-shell effects tend to be larger

$e^+e^- \to ZH$ study: Craig, McCullough, Englert (2015) DG, Han, Mukhopadhyay (PRL–2017)

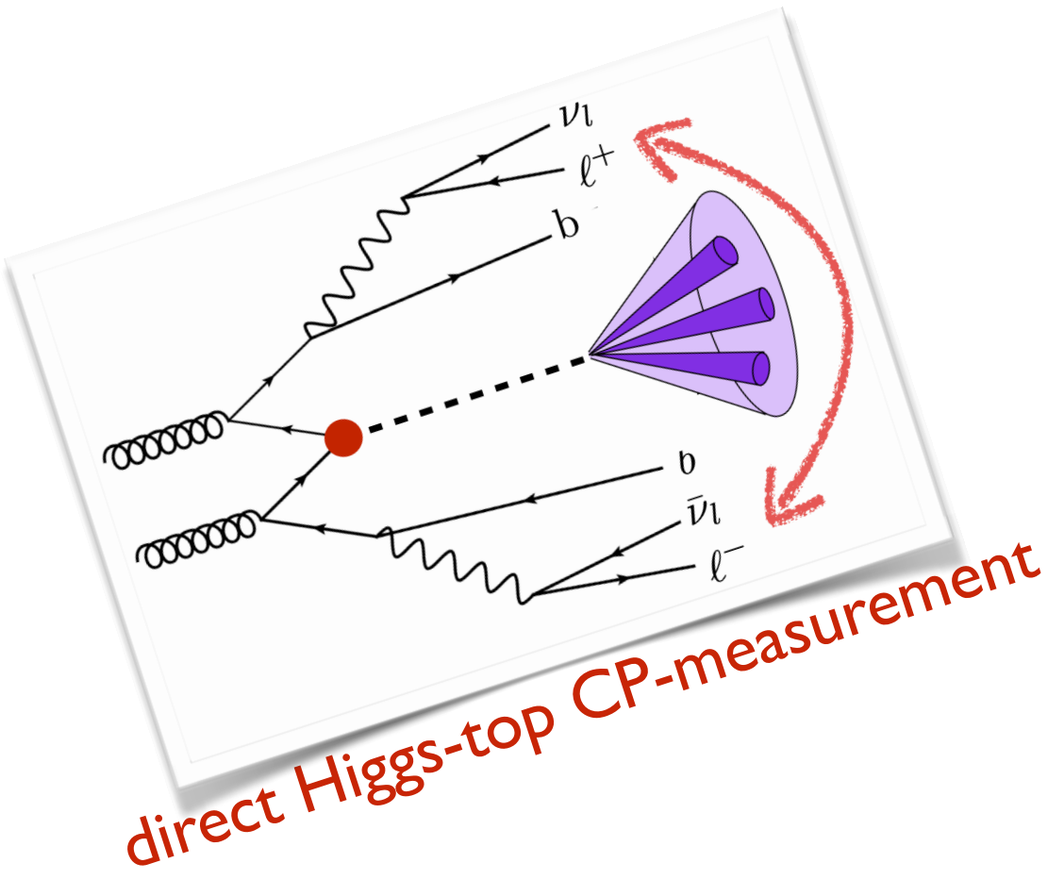
Summary

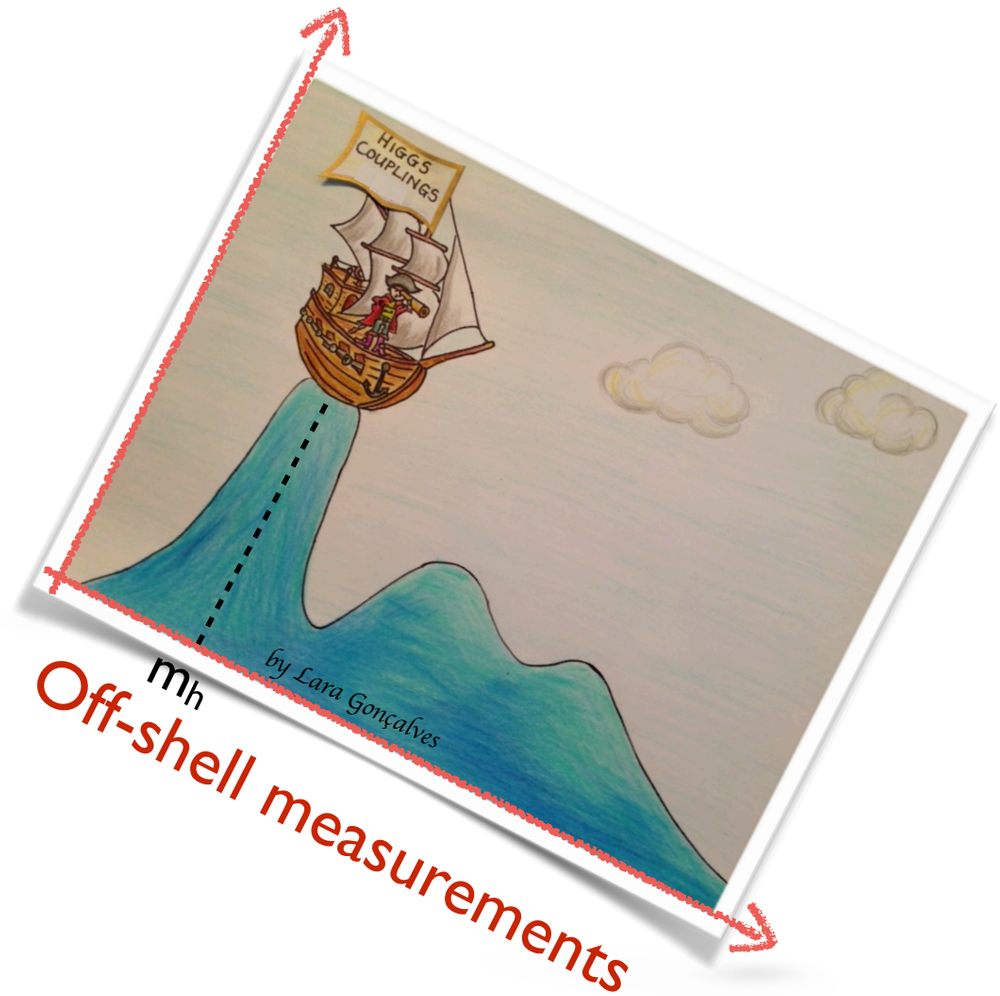
HL/HE-LHC give very energetic Higgses with significant statistics, opening several Pheno possibilities

- Direct Higgs-top CP-measurement:
  - We can go beyond the *direct* Higgs-top strength analysis, probing also *directly* its CP-structure via spin correlation from the top decays
  - Boosted Higgs analysis nicely match with CP-structure measurement

- Off-shell Higgs:
  - Relevant probe to new physics that goes beyond the usual H-width measurement or bump hunt
  - We illustrate this via a maximally hidden scenario that can display connections to the hierarchy problem

Many exciting opportunities ahead!!!





… and learning many more in the other talks!!!

Thank you for your attention!

Backup

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  Proper modelling of the QCD emissions indispensable requirement for robust analysis

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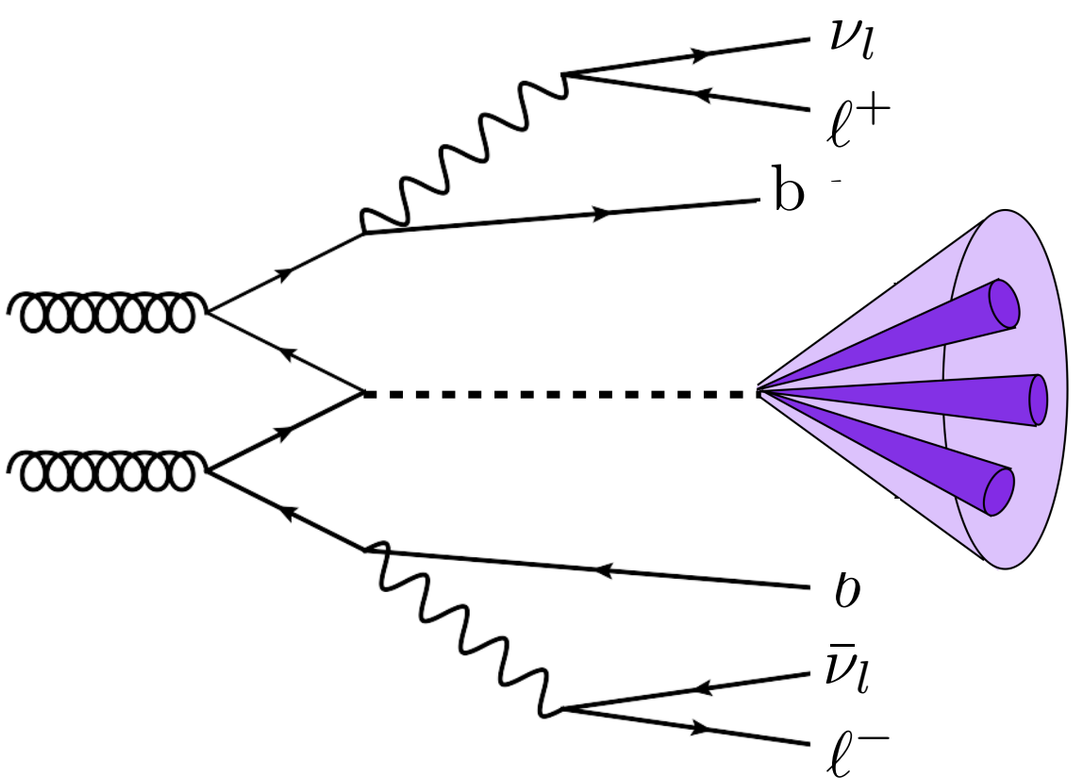

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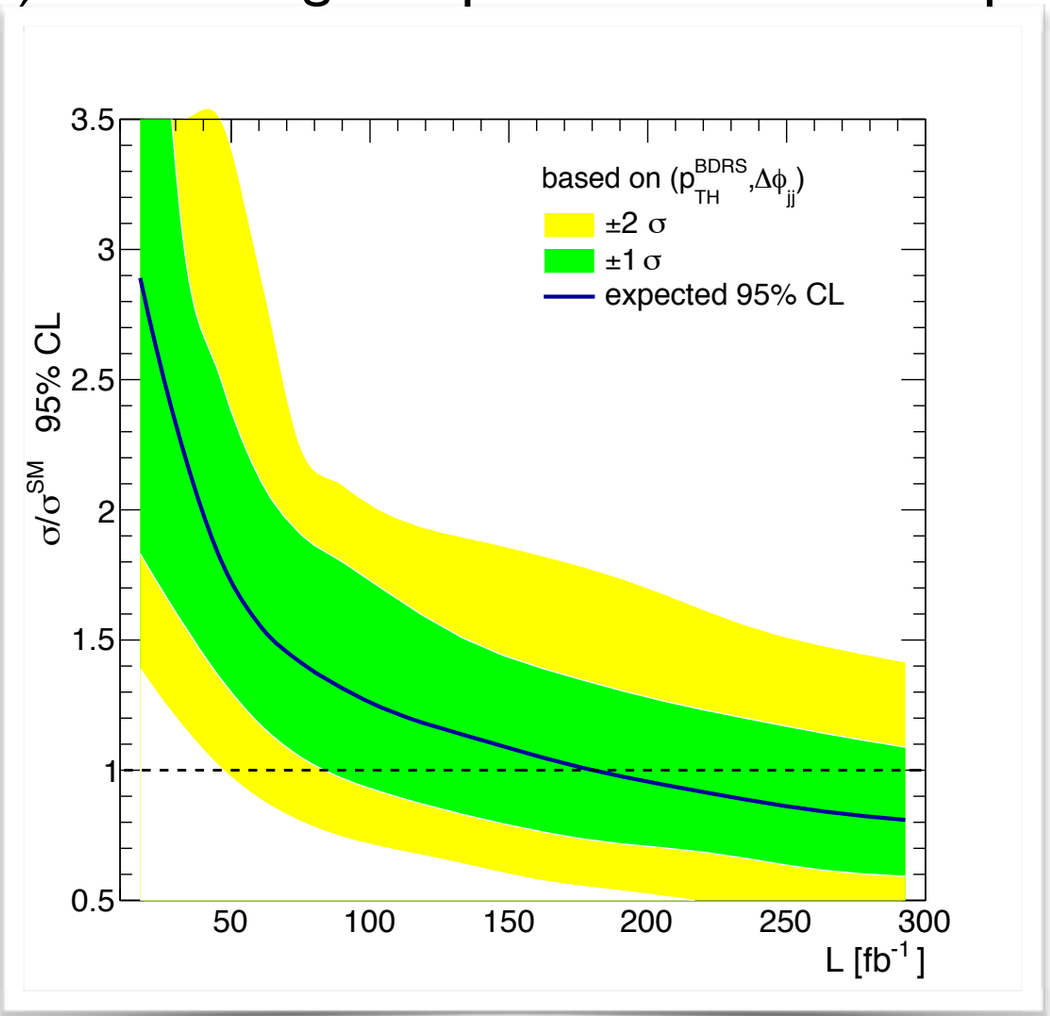

- We can see the ttH with L~175 fb^{-1} @95% CL

Buckley, **DG** (PRL–2015)

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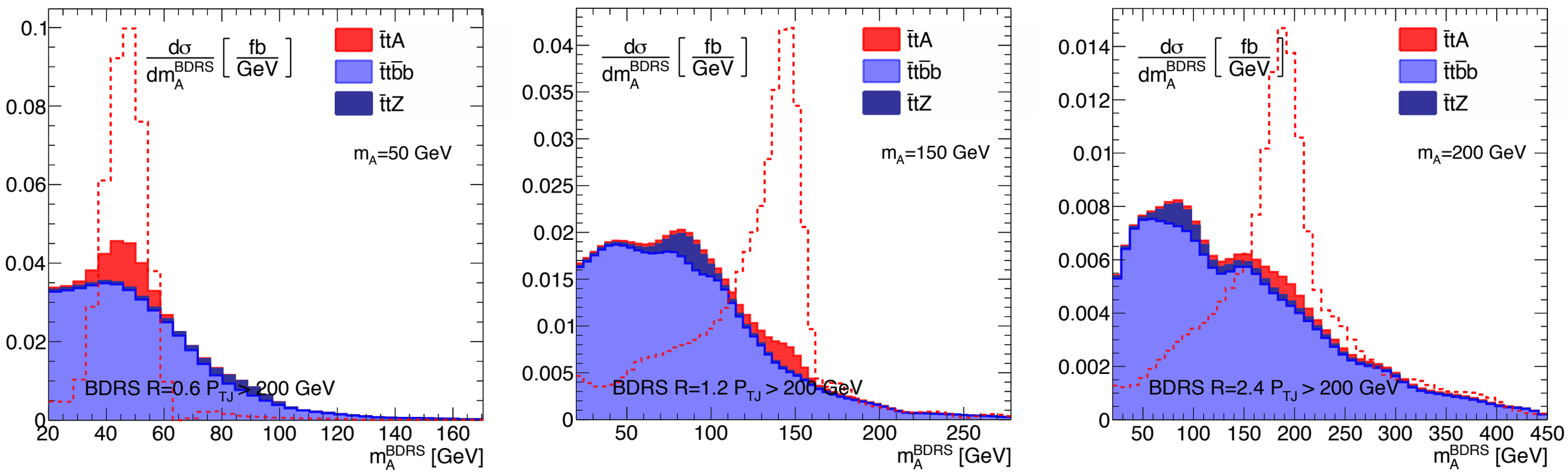
- Seeking for light pseudoscalars: ttA(bb) can <u>direct</u> access the Yukawa and explore low m_A

  Tailoring the BDRS analysis for different m_A ranges: $R \sim 2m_A/p_{TA}$



Lopez-val, **DG** (2016)

Kozaczuk, Martin (2015); Casolino,Spannowsky(2015)

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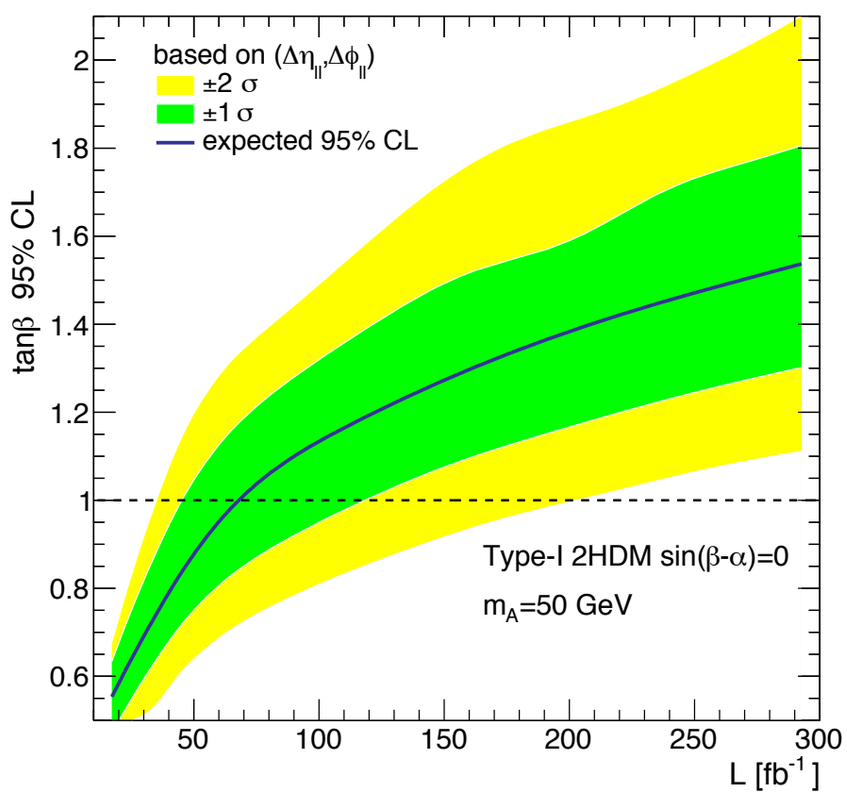
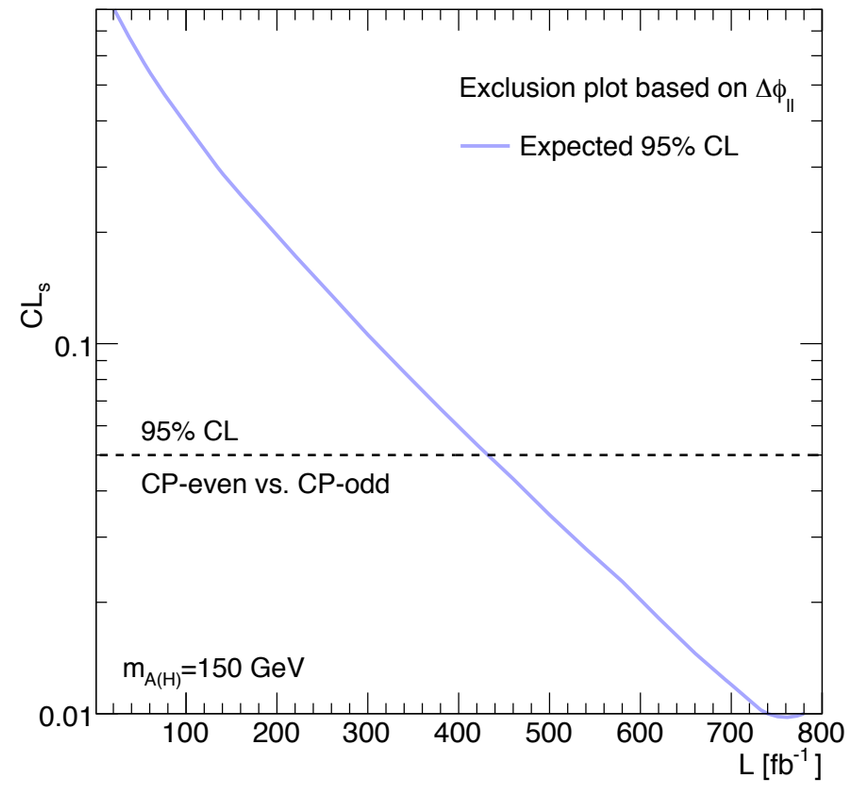
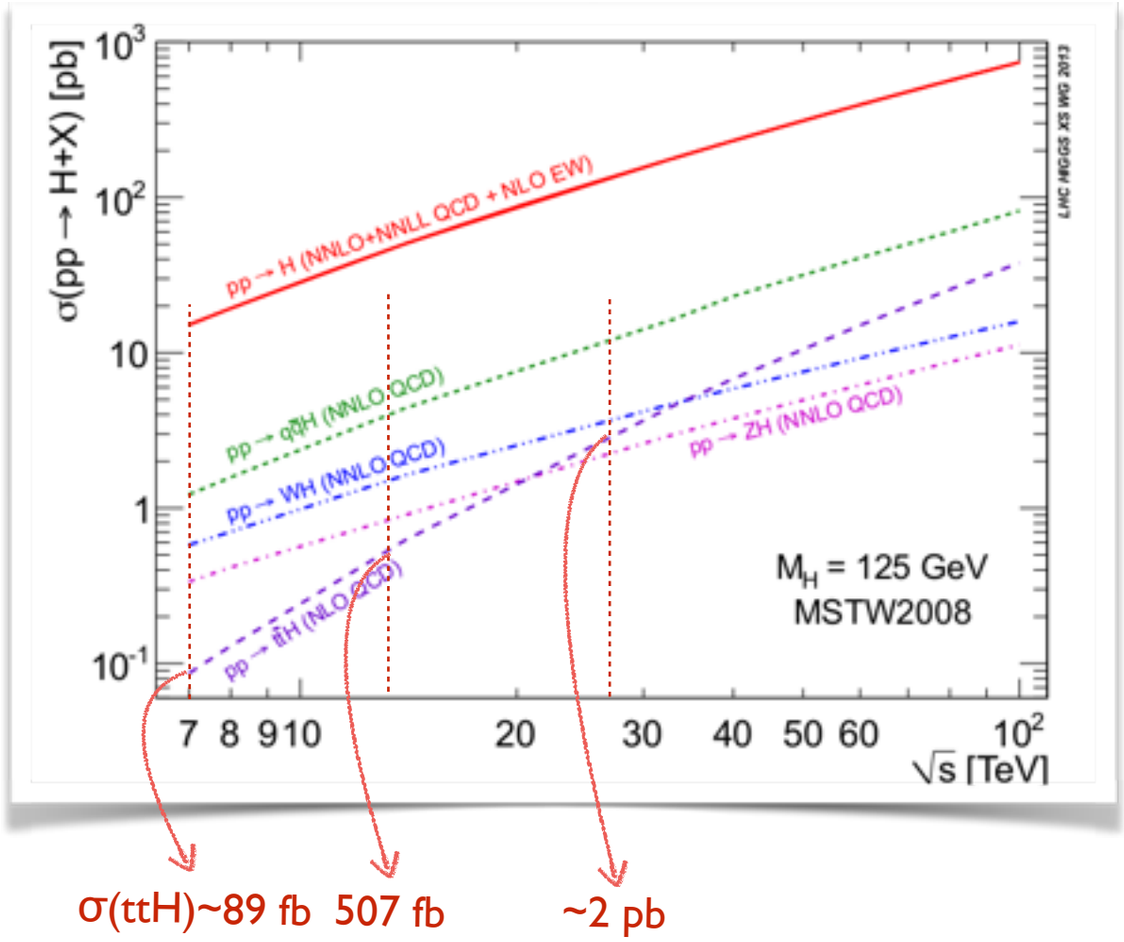




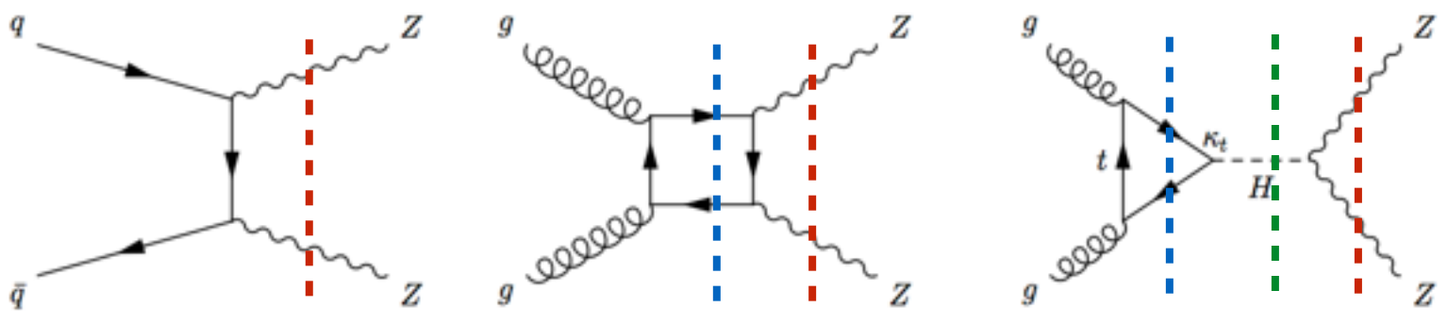
Lopez-val, DG (2016)

Backup


σ(pp → H+X) [pb]
10^3
10^2
10
1
10^{-1}
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qq̄H (NNLO QCD)
pp → WH (NNLO QCD)
pp → ZH (NNLO QCD)
pp → tt̄H (NLO QCD)
M_H = 125 GeV
MSTW2008
7 8 9 10 20 30 40 50 60 10^2
√s [TeV]
LHC HXSWG 2013
σ(ttH)~89 fb
507 fb
~2 pb

Backup

- Carries information on the Higgs couplings at different energy scales



$$\mathcal{M}_t^{++00} = -2\frac{m_{4\ell}^2 - 2m_Z^2}{m_Z^2}\frac{m_t^2}{m_{4\ell}^2 - m_H^2 + i\Gamma_H m_H}\left[1 + \left(1 - \frac{4m_t^2}{m_{4\ell}^2}\right) f\left(\frac{4m_t^2}{m_{4\ell}^2}\right)\right]$$

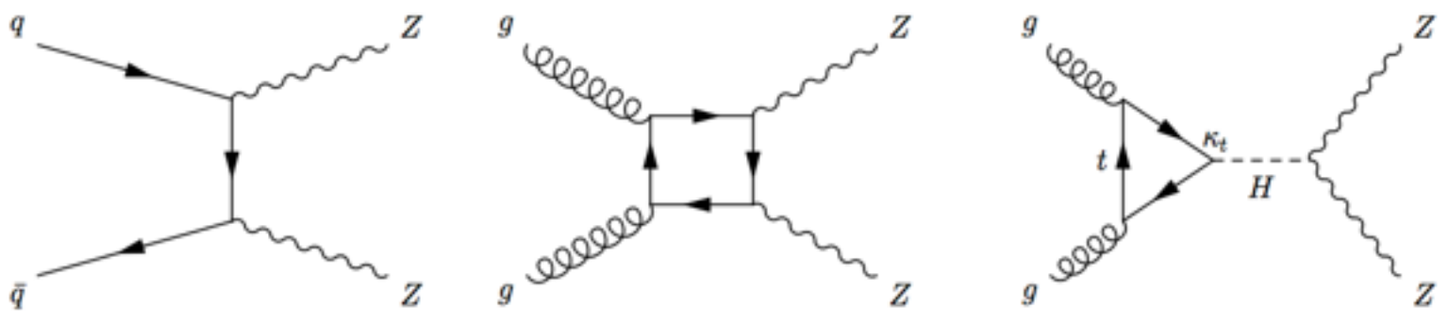
- $\mathcal{M}_t^{++00} \approx +\frac{m_t^2}{2m_Z^2}\log^2\frac{m_{4\ell}^2}{m_t^2}$ with $m_{4\ell} \gg m_t \gtrsim m_H, m_Z$
- $\mathcal{M}_c^{++00} \approx -\frac{m_t^2}{2m_Z^2}\log^2\frac{m_{4\ell}^2}{m_t^2}$ with $m_{4\ell} \gg m_t \gtrsim m_Z$.

→ Destructive interference

→ The Higgs does what he is expected to do! (Quigg, Lee, Thacker 1977)

Backup

- Signal and background components:



(a) (b) (c)

- $|a|^2$ - Background component: generated already at tree level (large) known at NNLO
  (Cascioli et. al. 2014)
- $|b+c|^2$ - (loop induced) known at NLO (w/o m_t effects). Internal masses make it a non-trivial multi-scale problem; Very important calculation for Run II
  Caola, Melnikov, Röntsch, Tancredi (2015)

→ $|b|^2$ - continuum background

→ $|c|^2$ - Higgs signal

→ Re{b*c} - Signal/background interference large and destructive at large invariant mass

Technology is there: gg>hh

$|c|^2$ and b*c present similar perturbative QCD enhancement: $K^{NLO}_{b*c} \sim K^{NLO}_{|c|^2}$
Bonvini, Caola, Forte, Melnikov, Ridolfi (2013)