Higgs couplings: effects beyond total rates

Heidelberg - 10.11.2017

Dorival Gonçalves

Outline

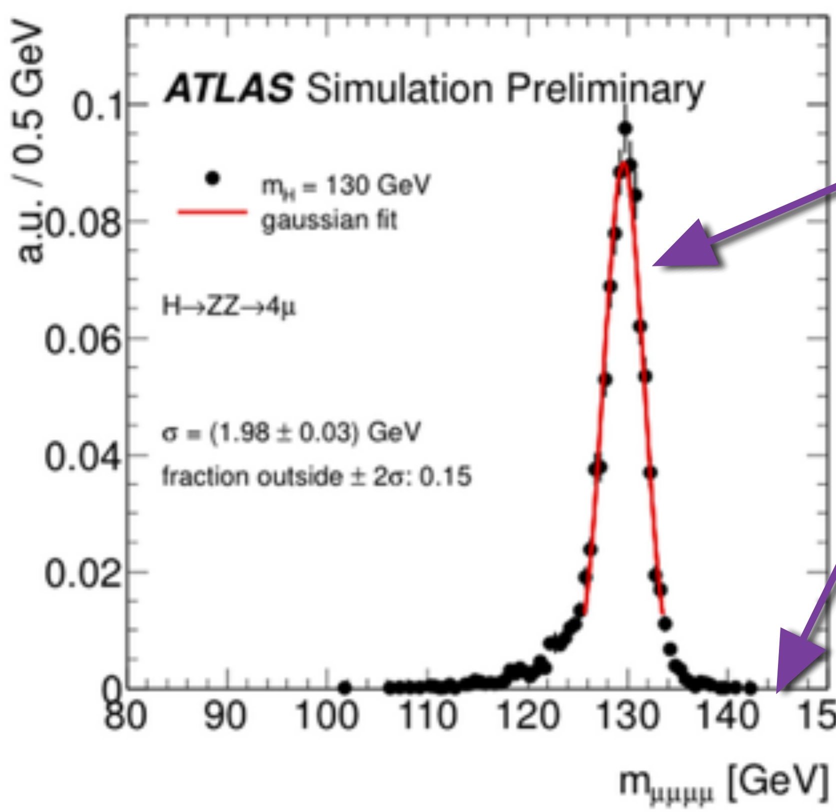
- Off-Shell Higgs
  - Theoretical ingredients
  - New probe to the Higgs portal coupling at LHC
  - WBF 100 TeV: what can we learn from it?

- Spin correlations: direct Higgs-top CP-structure measurement via ttH
  - Possible BSM applications

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 ;

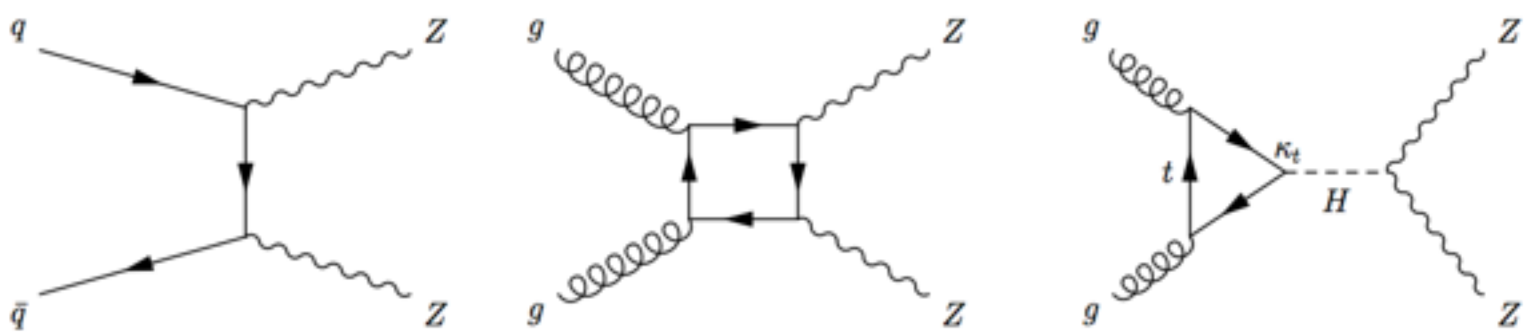
→ ZZ Threshold;

→ and top mass effects change our naive expectation

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

Theoretical ingredients

- 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

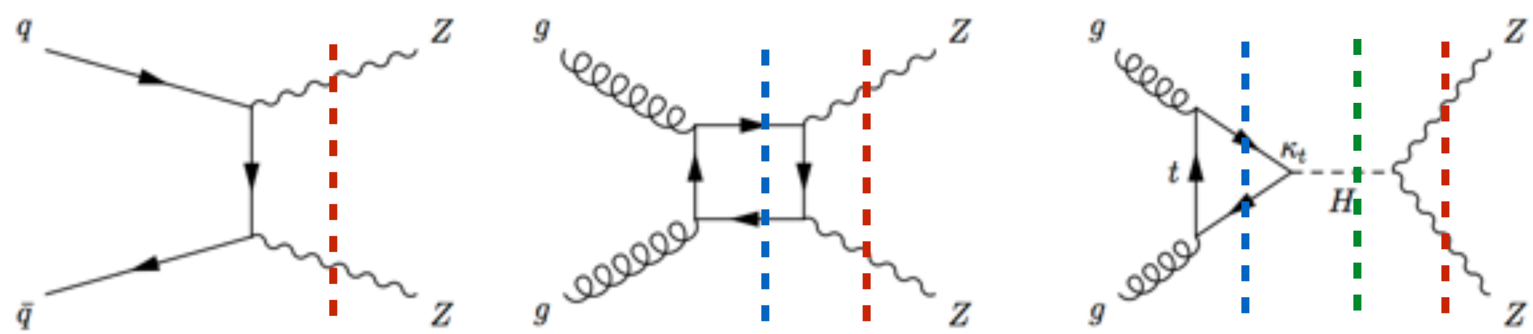
→ $|c|^2$ - Higgs signal

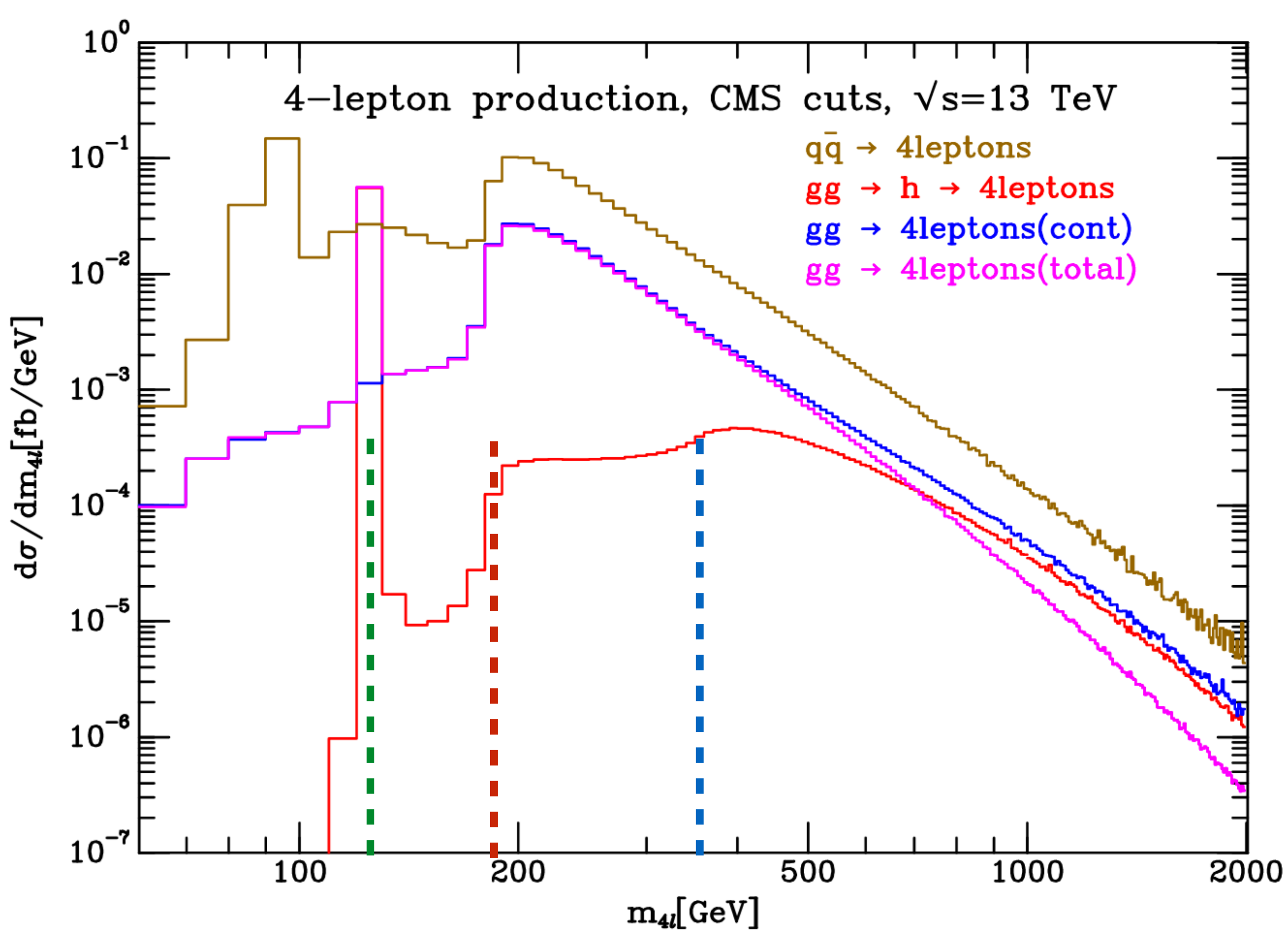
Technology is there: gg>hh
See Gudrun's talk

→ Re{b*c} - Signal/background interference large and destructive at large invariant mass
$|c|^2$ and b*c present similar perturbative QCD enhancement: $K^{NLO}_{b*c} \sim K^{NLO}_{|c|^2}$
Bonvini, Caola, Forte, Melnikov, Ridolfi (2013)

Theoretical ingredients

- Carries information on the Higgs couplings at different energy scales





Campbell, Ellis, Williams 2013

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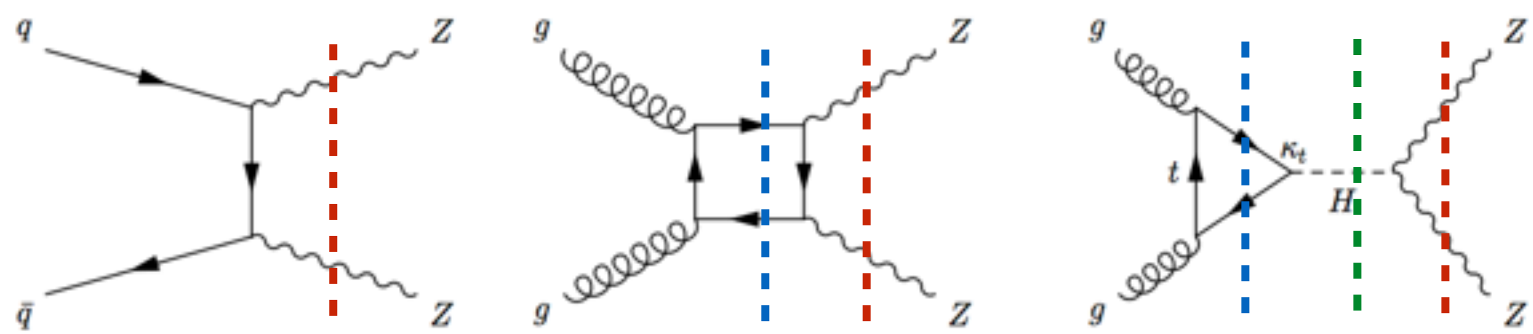


$$\mathcal{M}_t^{++00} = -2\frac{m_{4\ell}^2 - 2m_Z^2}{m_Z^2}\frac{m_t^2}{m_{4\ell}^2 - m_H^2 + i\Gamma_H m_H}\left[1 + \left(1 - \frac{4m_t^2}{m_{4\ell}^2}\right) f\left(\frac{4m_t^2}{m_{4\ell}^2}\right)\right]$$

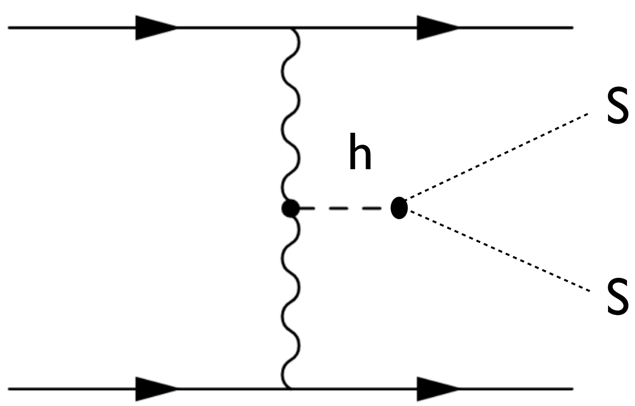
- $\mathcal{M}_t^{++00} \approx +\frac{m_t^2}{2m_Z^2}\log^2\frac{m_{4\ell}^2}{m_t^2}$ with $m_{4\ell} \gg m_t \gtrsim m_H, m_Z$
- $\mathcal{M}_c^{++00} \approx -\frac{m_t^2}{2m_Z^2}\log^2\frac{m_{4\ell}^2}{m_t^2}$ with $m_{4\ell} \gg m_t \gtrsim m_Z$.

→ Destructive interference

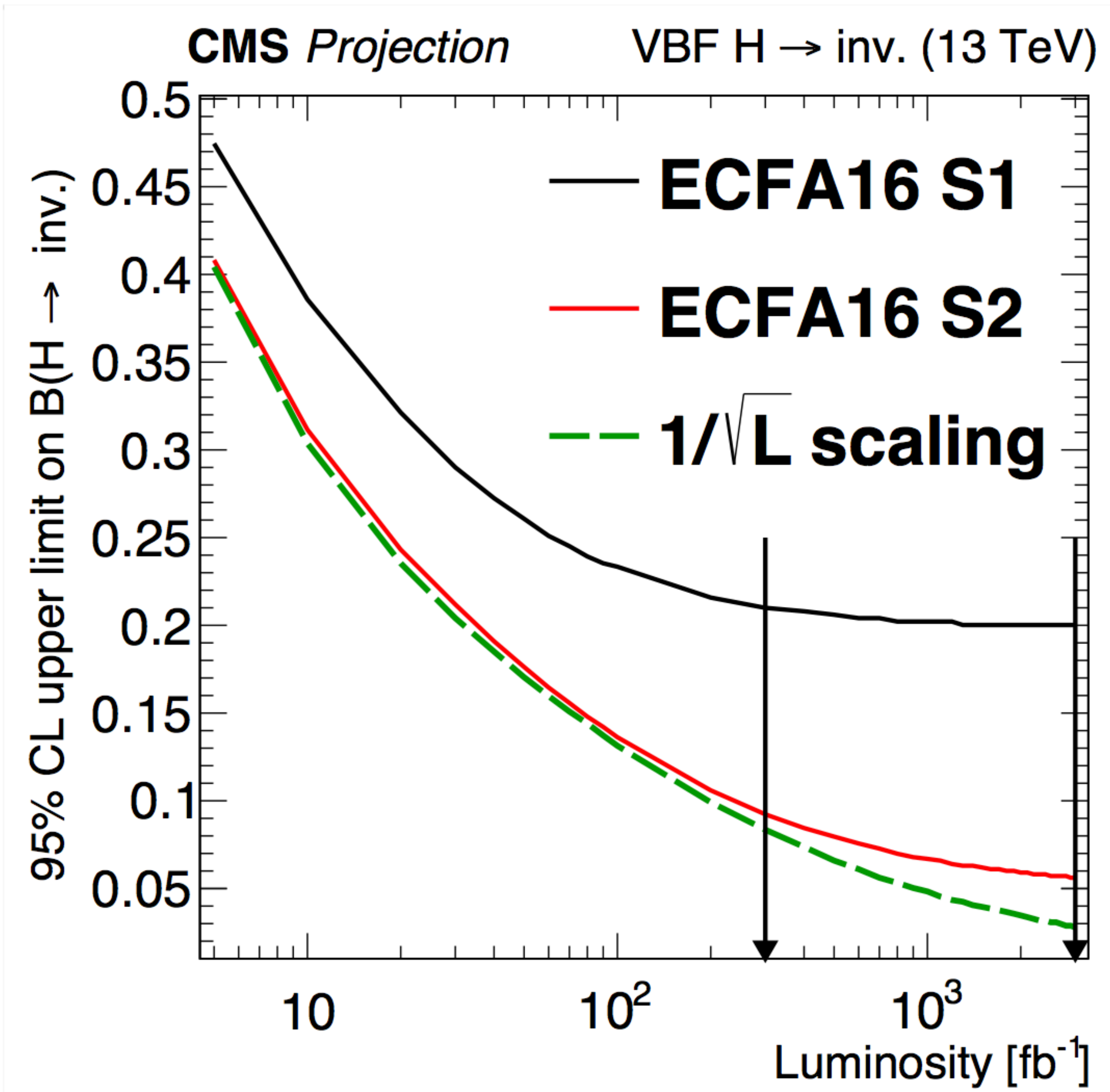
→ The Higgs does what he is expected to do! (Quigg, Lee, Thacker 1977)

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
See Ben & di Maria's talk



DG, Han, Mukhopadhyay (2017)

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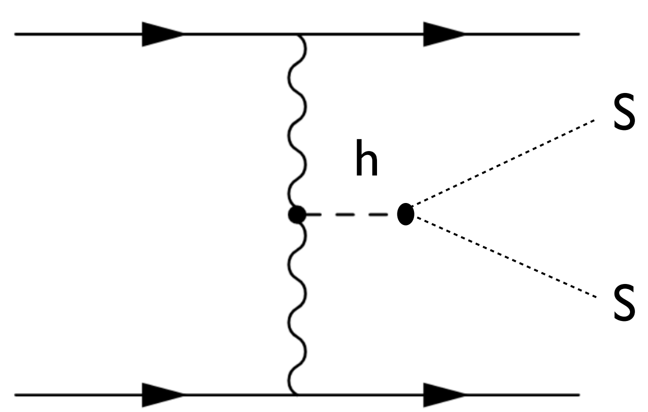

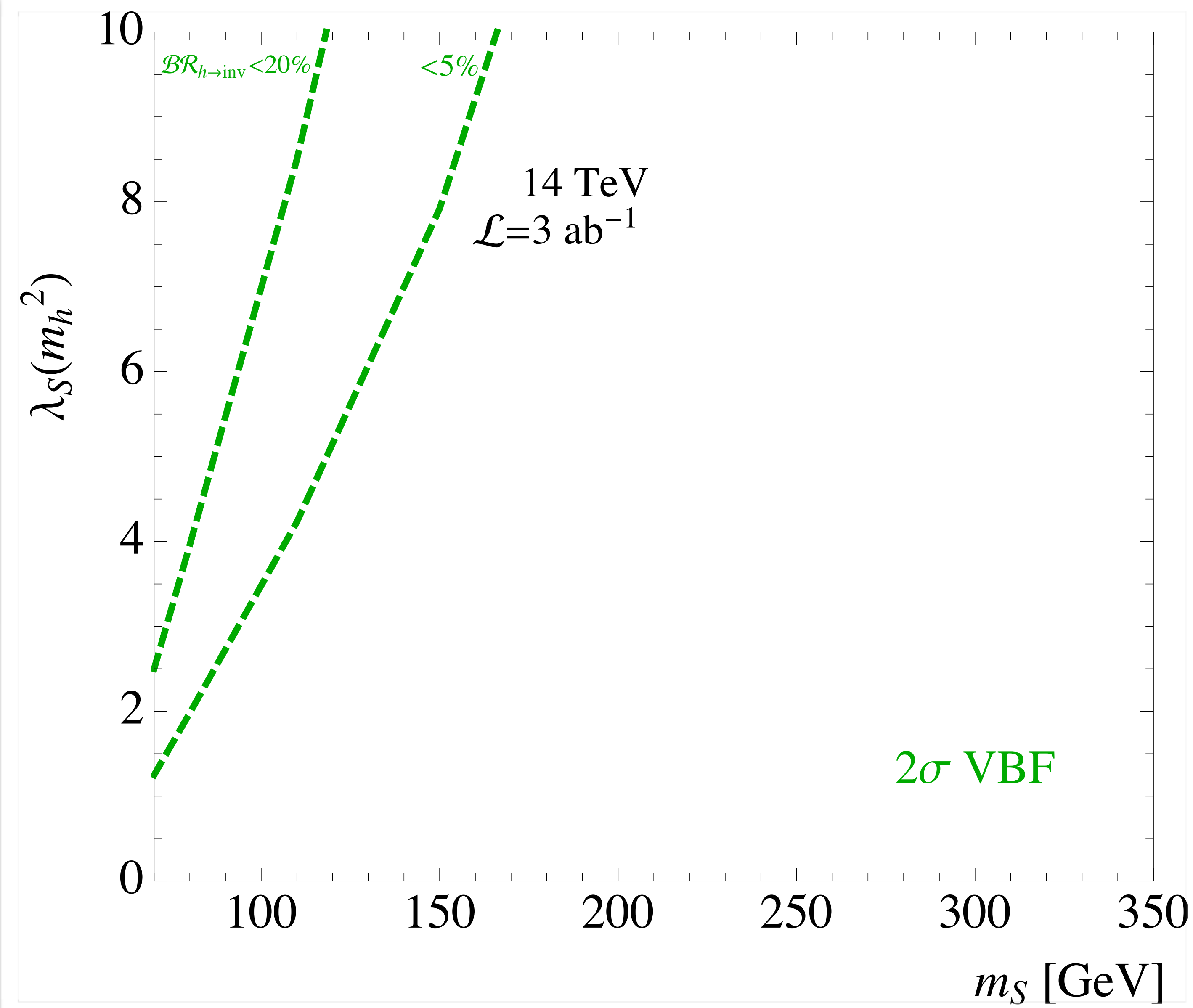

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→ $m_h < 2m_S$: sensitivity BW suppressed

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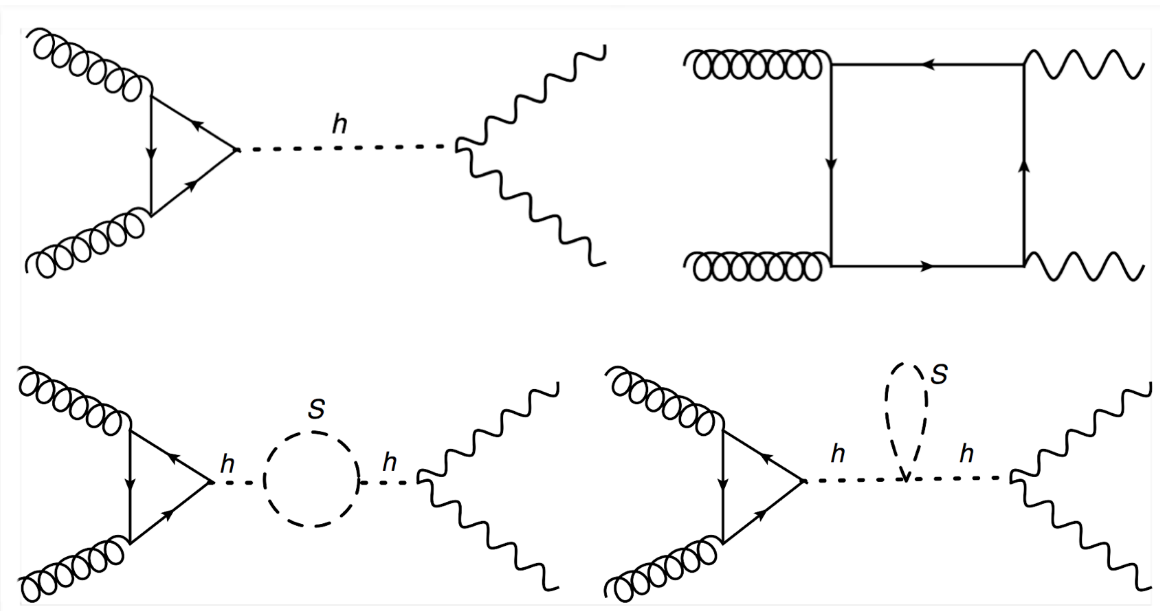

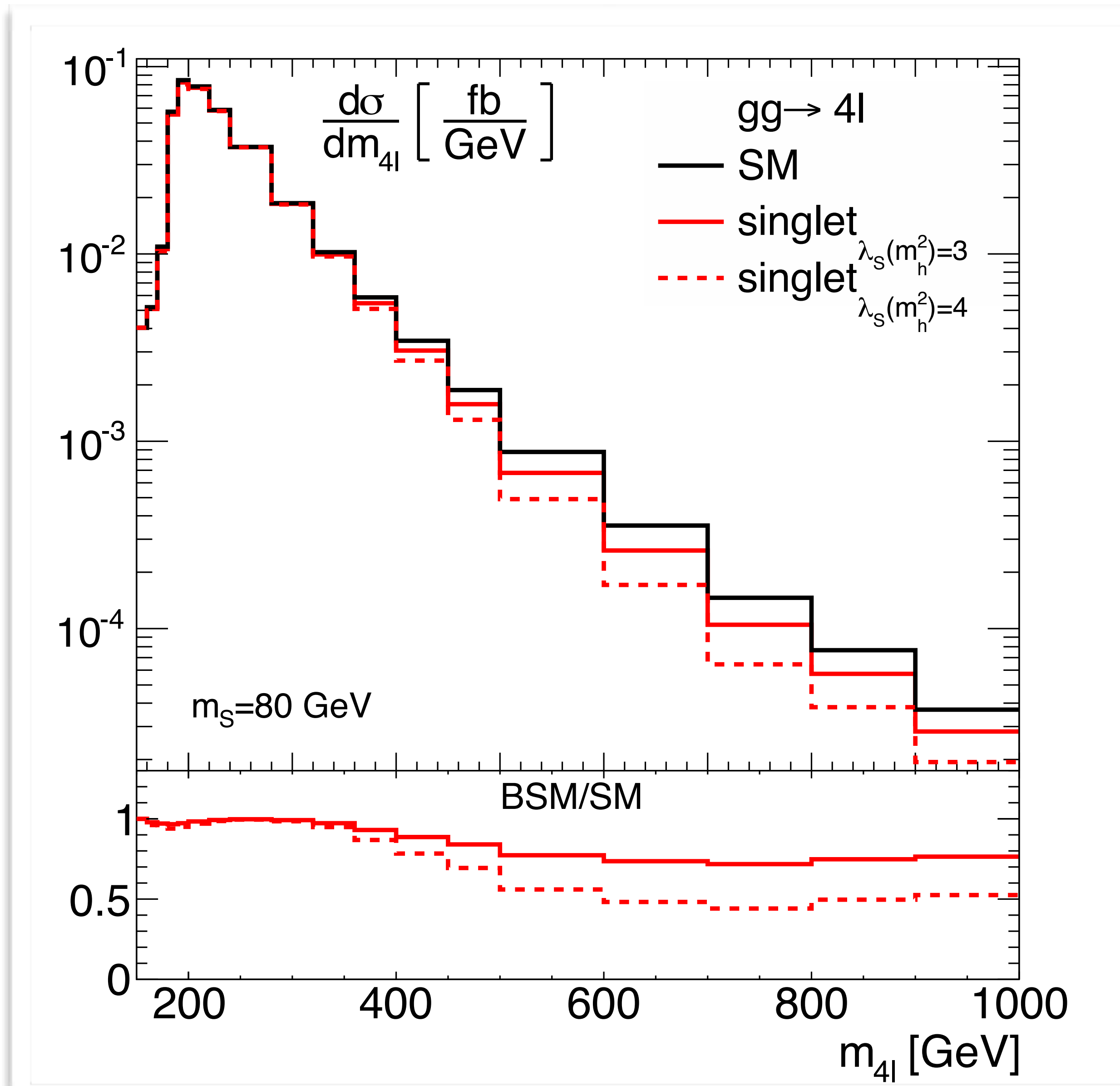

- Separably renormalizable, UV finite, gauge-invariant subset
- Corrections are also at $\delta\sigma^{NLO}_{gg\to 4l} \propto \lambda_S^2$ order

DG, Han, Mukhopadhyay (2017)

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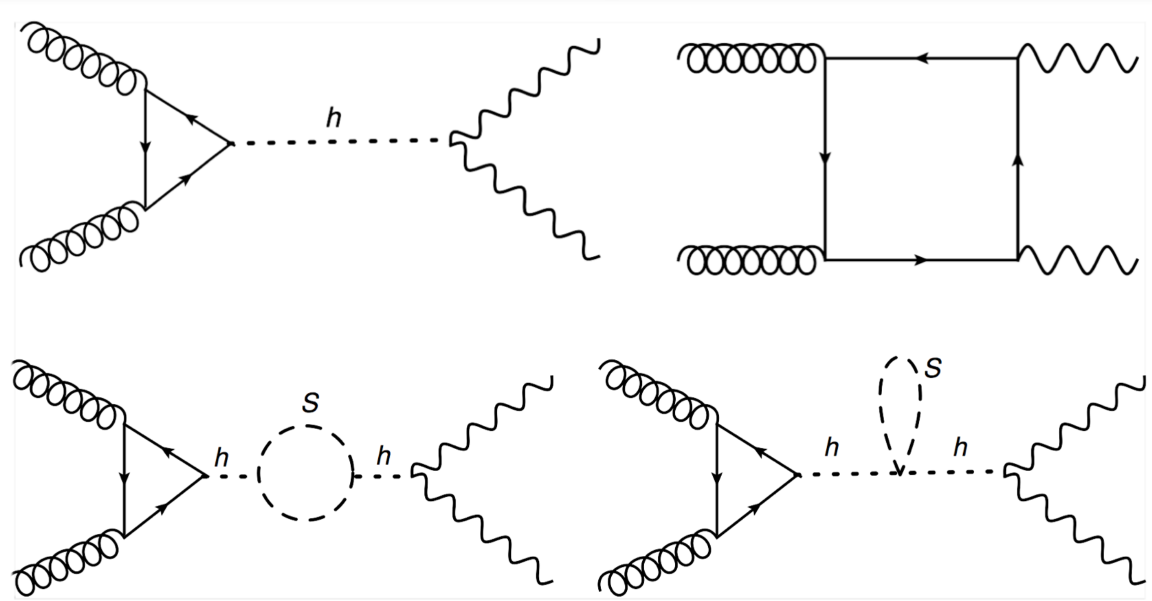

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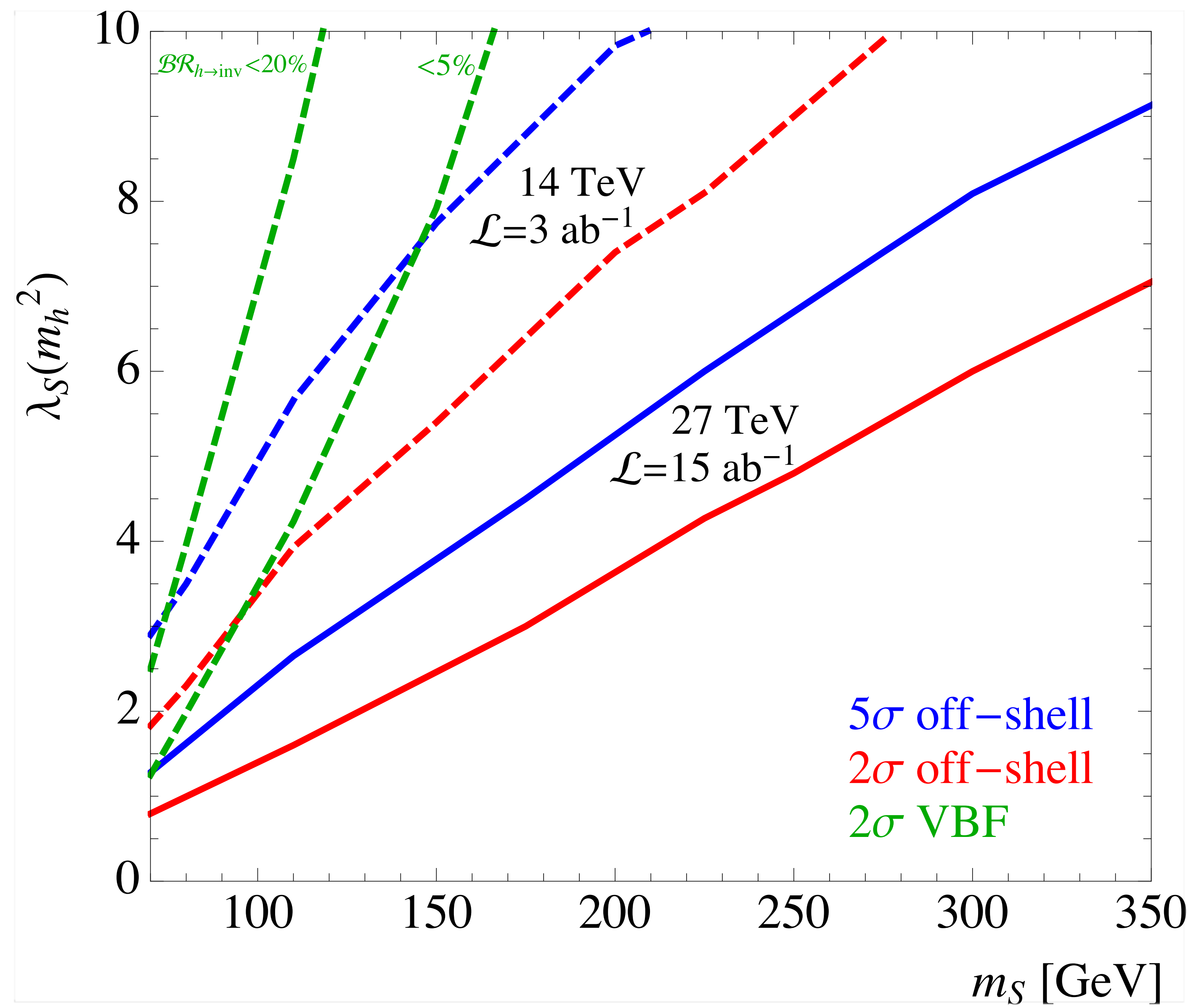

DG, Han, Mukhopadhyay (2017)

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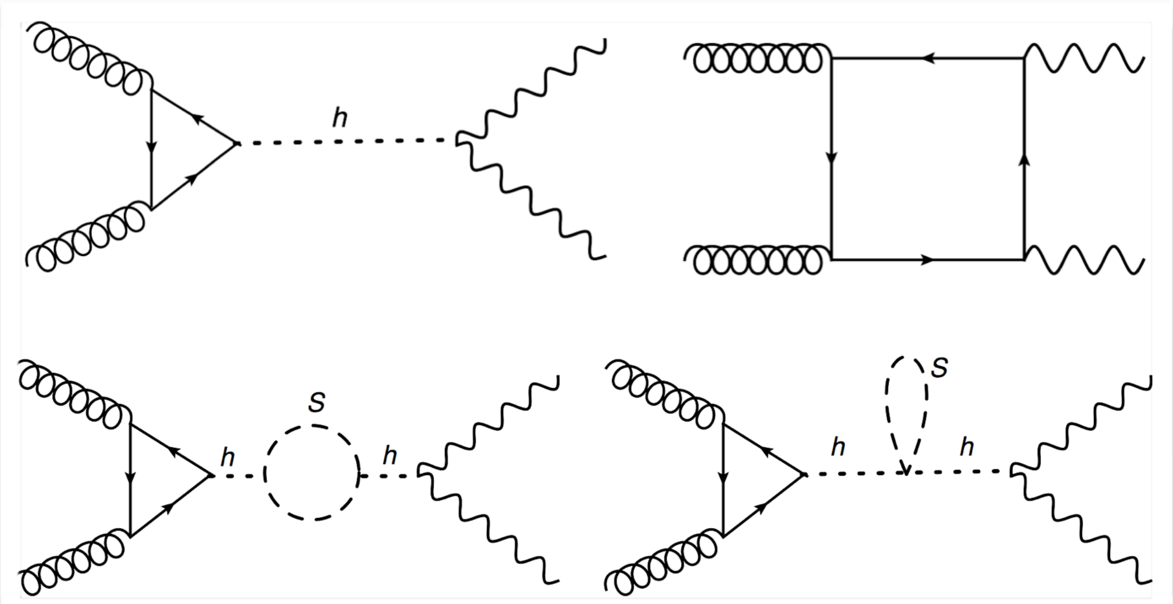
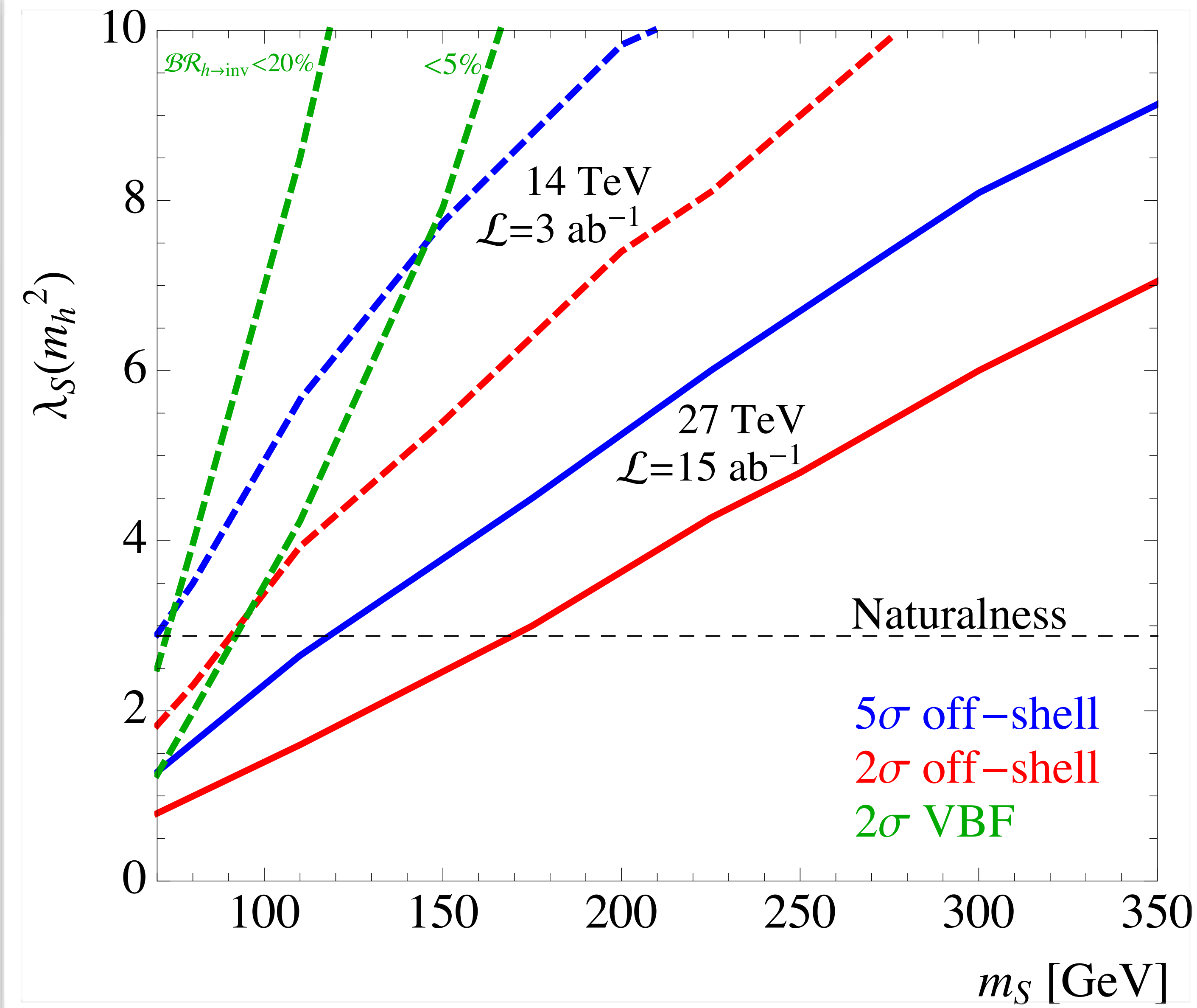


- $$\delta M_h^2 = \frac{1}{16\pi^2}(\lambda_S - 2N_c y_t^2)\Lambda^2 + \frac{6N_c y_t^2}{16\pi^2} m_t^2 \log\frac{\Lambda^2}{m_t^2} - \frac{1}{16\pi^2}\left(\lambda_S m_S^2 + \lambda_S^2 v^2\right)\log\frac{\Lambda^2}{m_S^2},$$

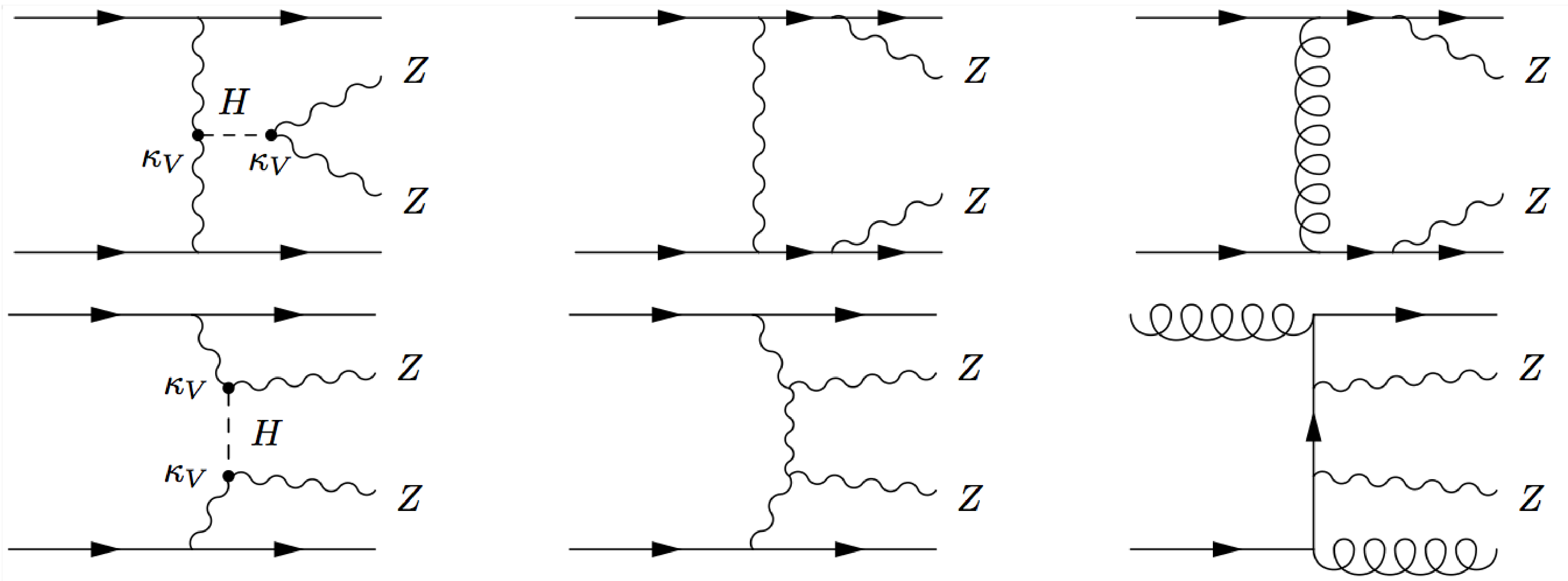


DG, Han, Mukhopadhyay (2017)

Future: off-shell WBF

- WBF presents exclusively tree-level Higgs-EW boson couplings

→ More model independent



(a) $ZZjj_{\mathrm{EW,only\text{-}H}}$ (b) $ZZjj_{\mathrm{EW,no\text{-}H}}$ (c) $ZZjj_{\mathrm{QCD}}$

→ However, it presents very weak bounds at LHC

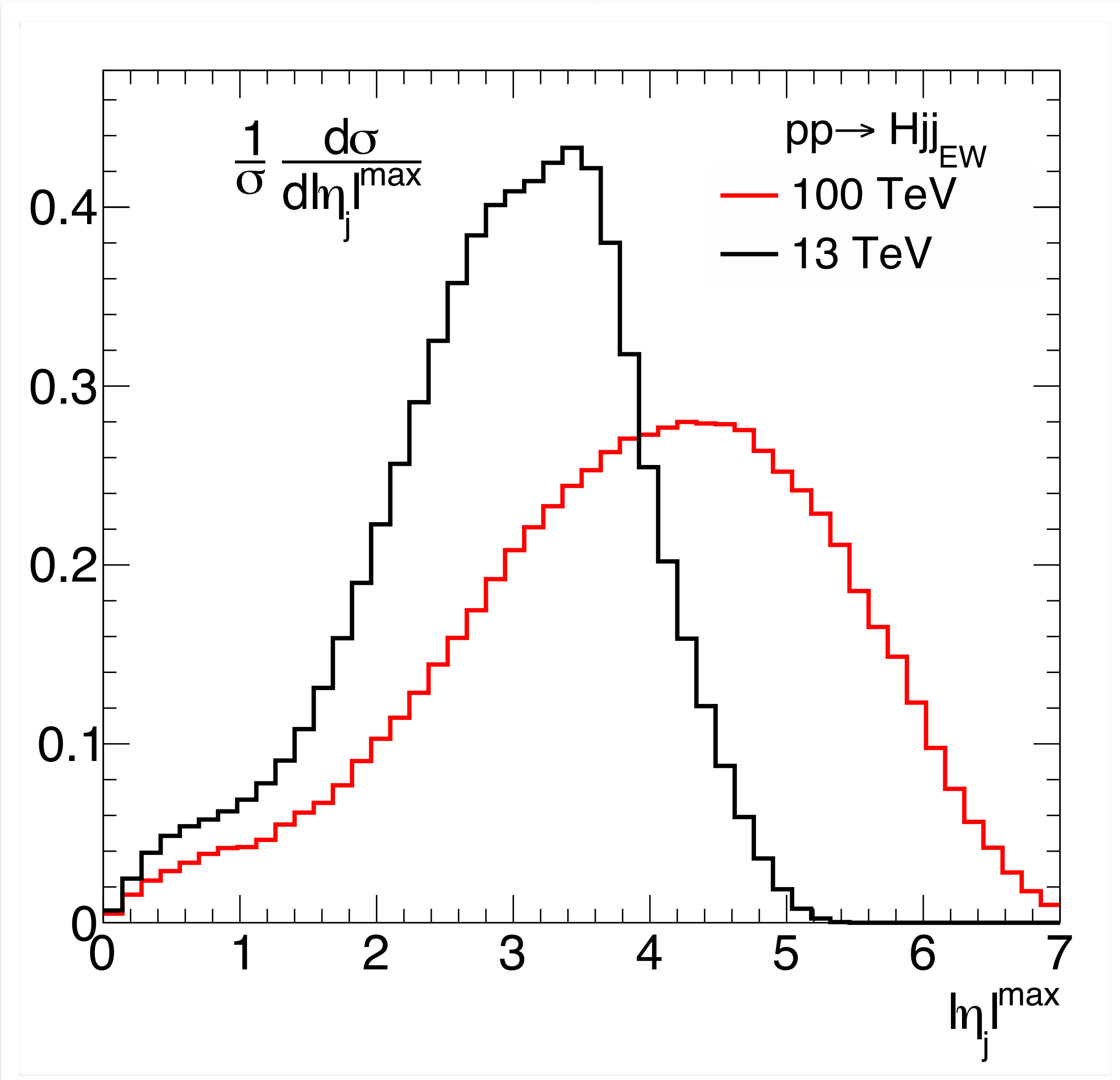
Run-I $\Gamma_H/\Gamma_{H,SM}<60$, whereas GF channel $\Gamma_H/\Gamma_{H,SM}<6.5$ (CMS)

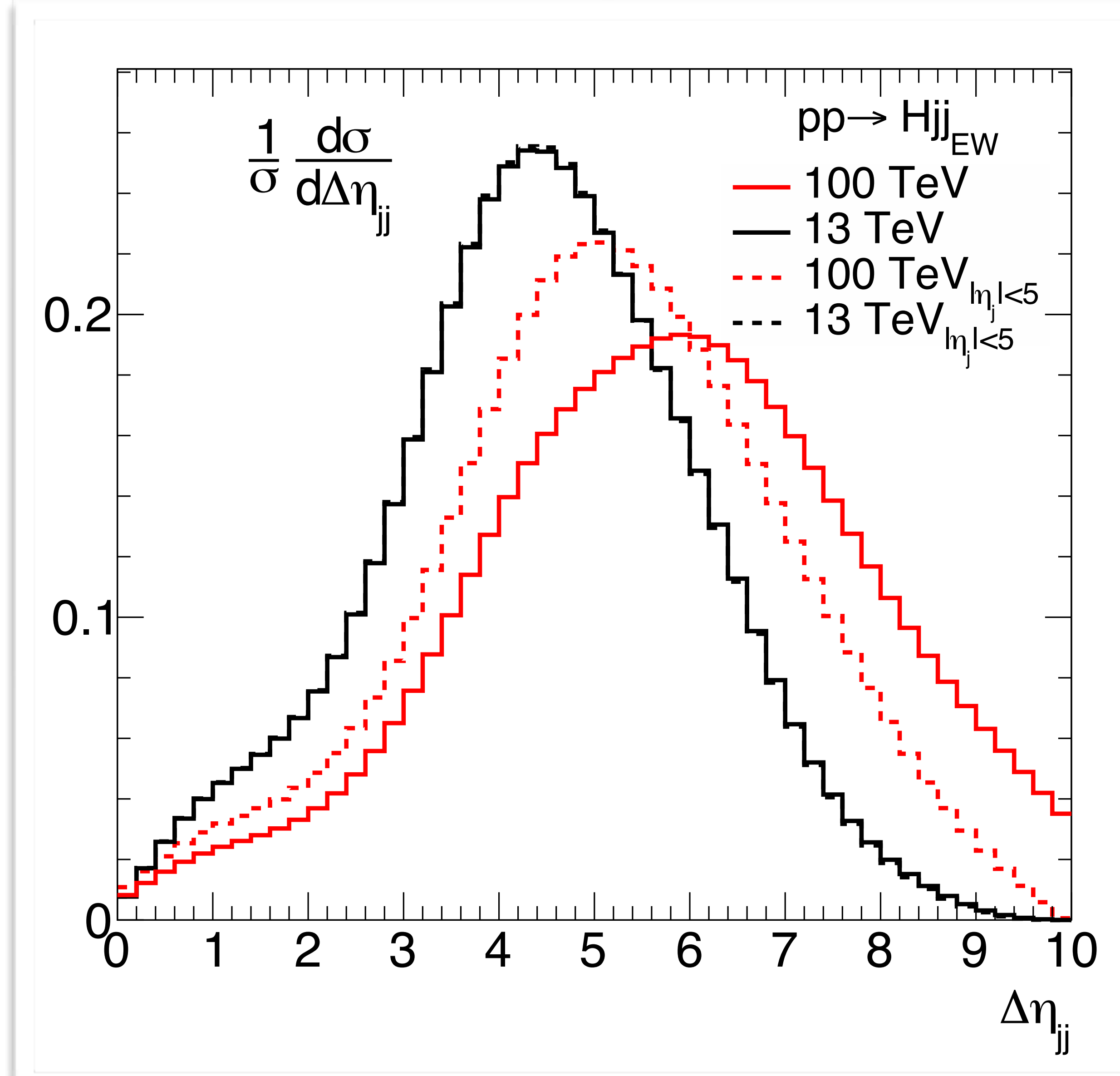
→ What can we do with it at the 100 TeV collider?

DG, Thompson, Plehn (2017)

Future: off-shell WBF

- Tagging jet kinematics at 100 TeV



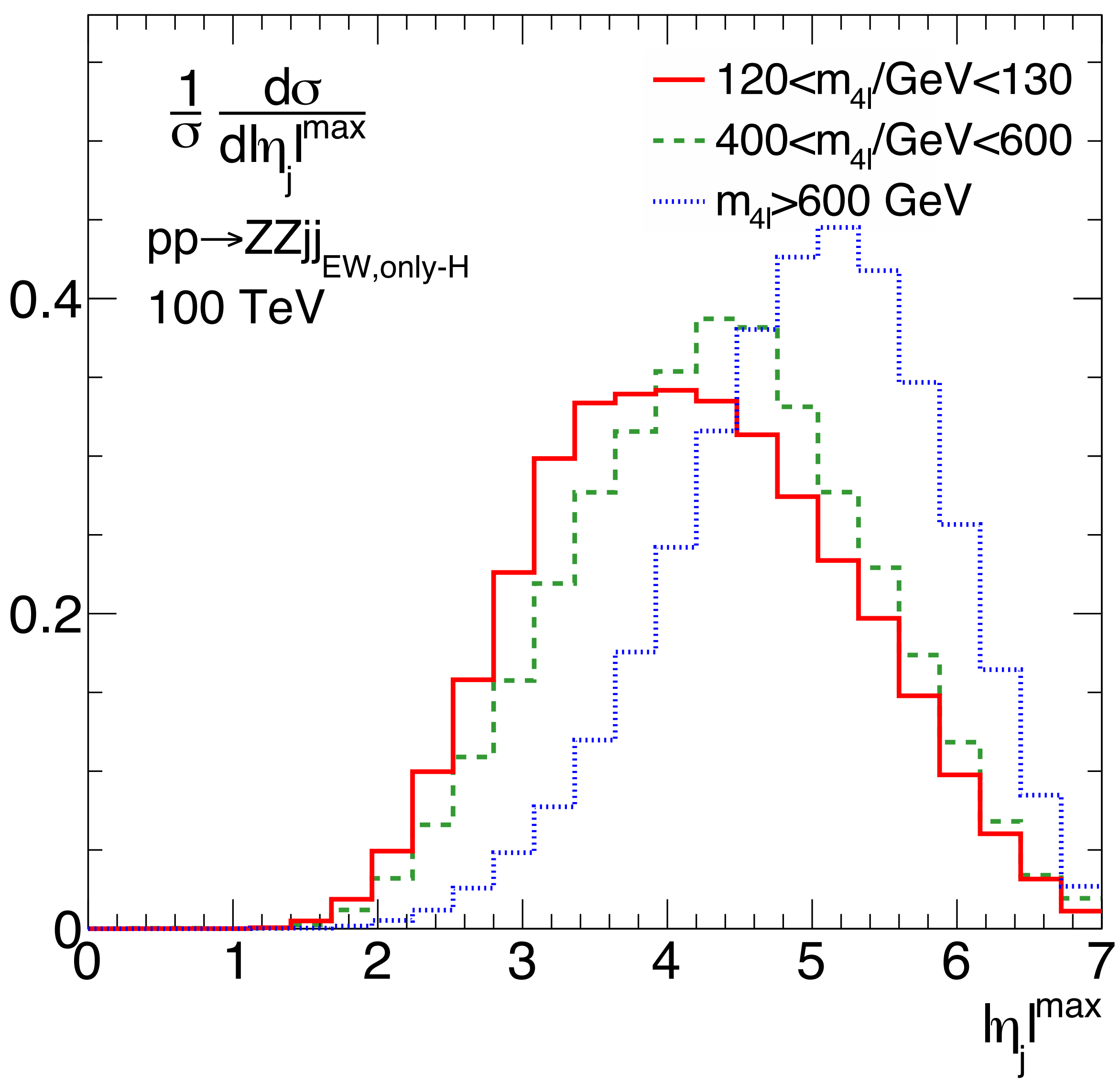


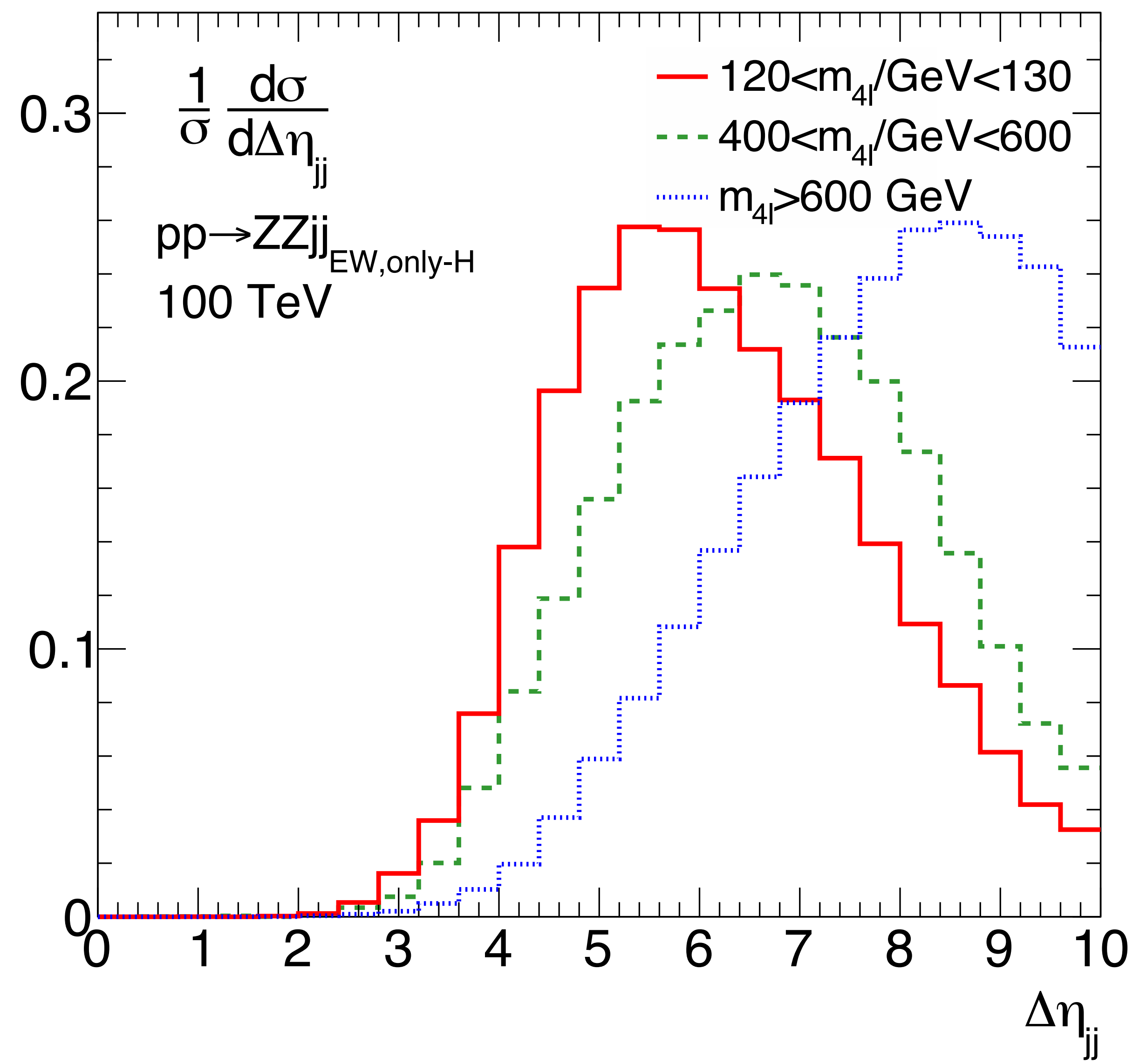
→ Tagging jets are even more forward at 100TeV

DG, Thompson, Plehn (2017)

Future: off-shell WBF

- $VV \to VV$ at higher energies $m_{4\ell} \gg m_V$ $\quad \frac{\mathcal{A}_{LL}}{\mathcal{A}_{TT}} \sim \frac{m_{4\ell}^2}{m_V^2}$ Dawson (1985)





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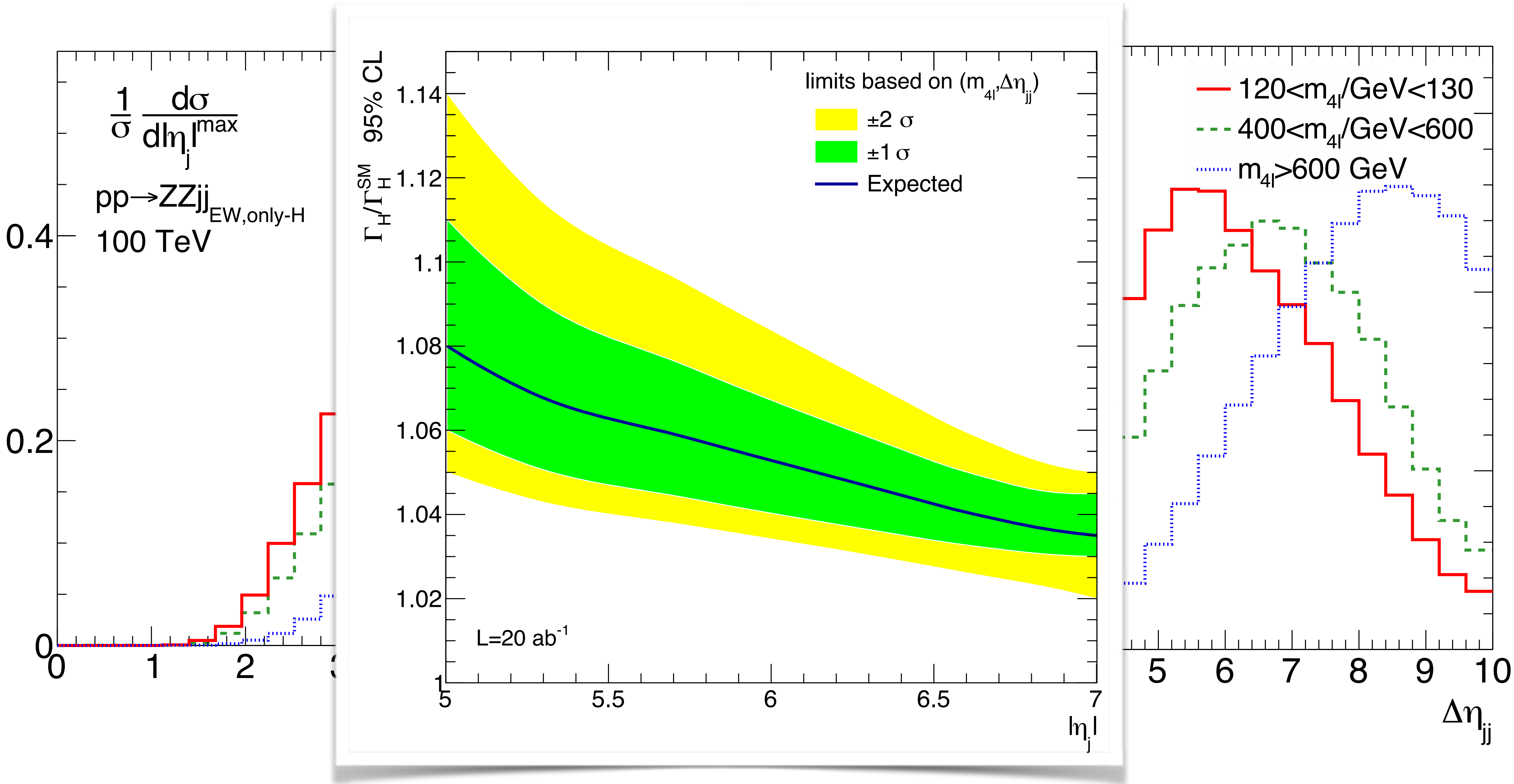
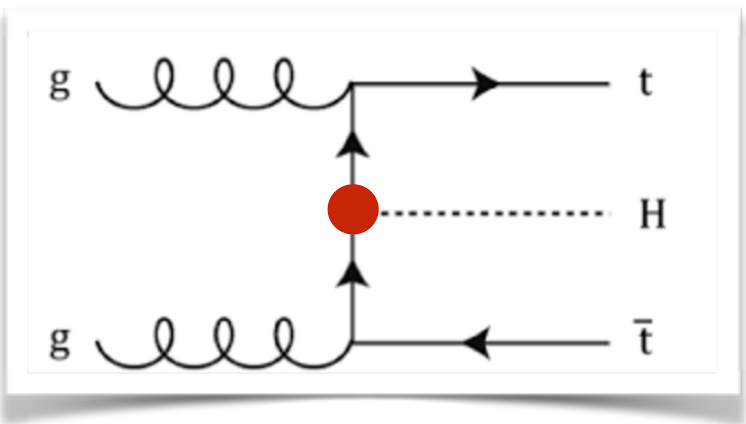
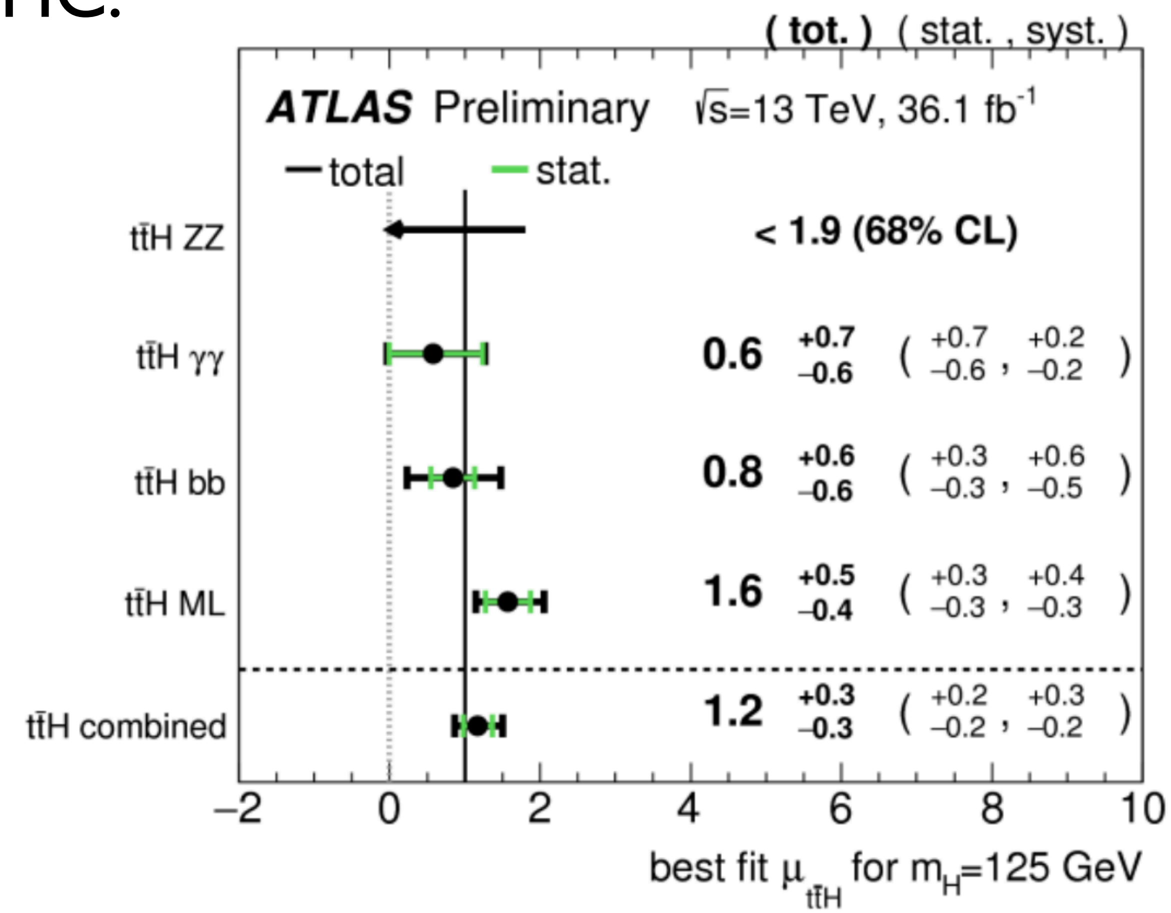


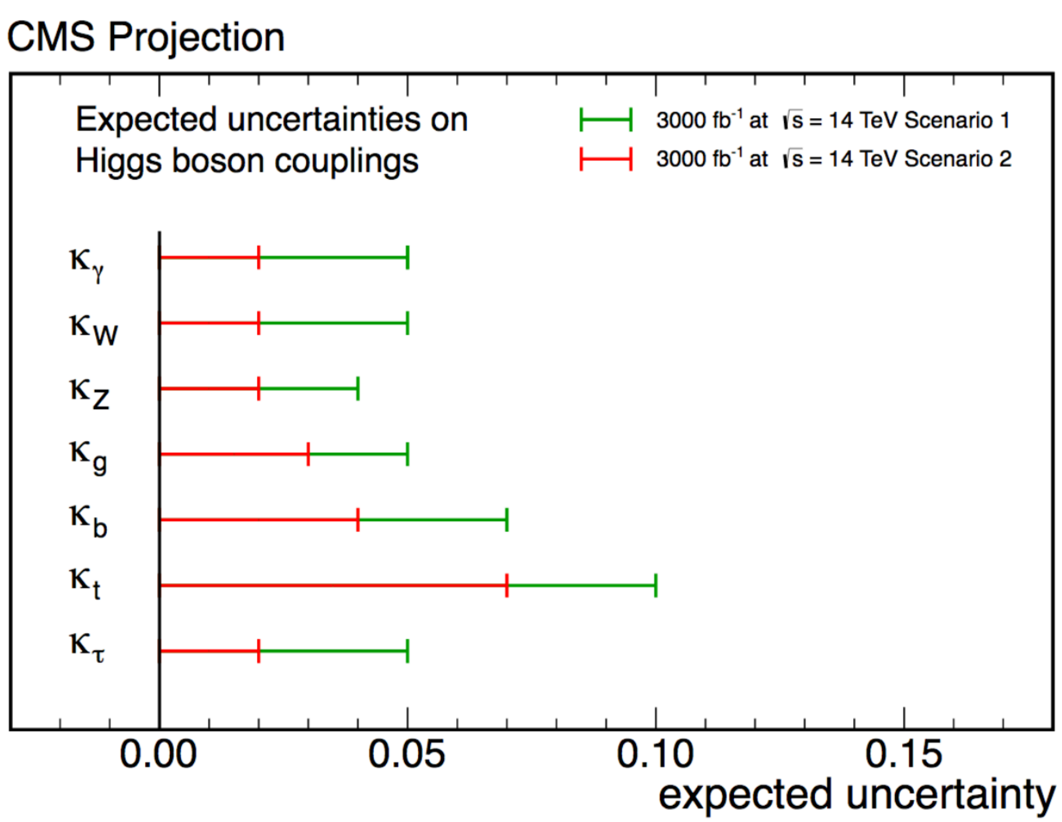
DG, Thompson, Plehn (2017)

Exciting opportunities ahead!

- ttH channel is around the corner at LHC:







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

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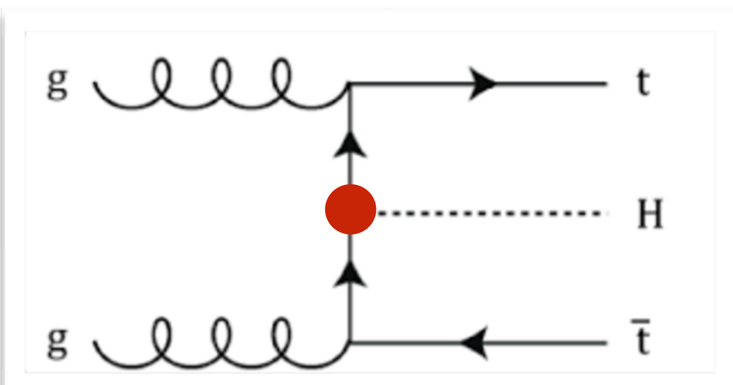

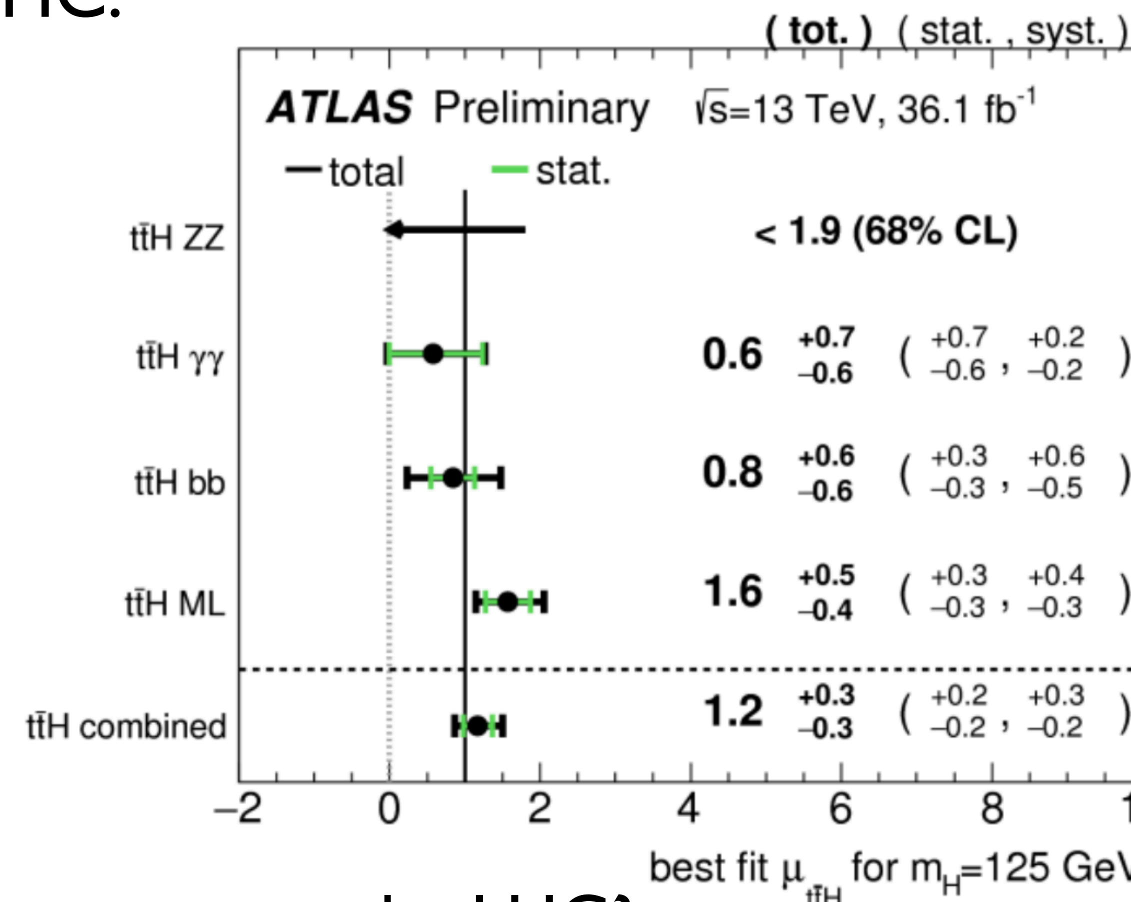

- Can we directly measure Higgs-top CP structure at the LHC?

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

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

→ 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

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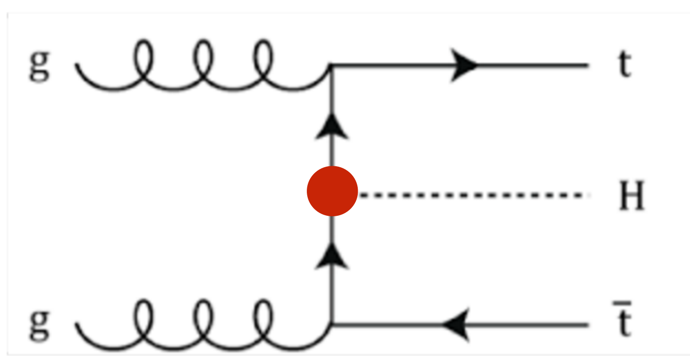

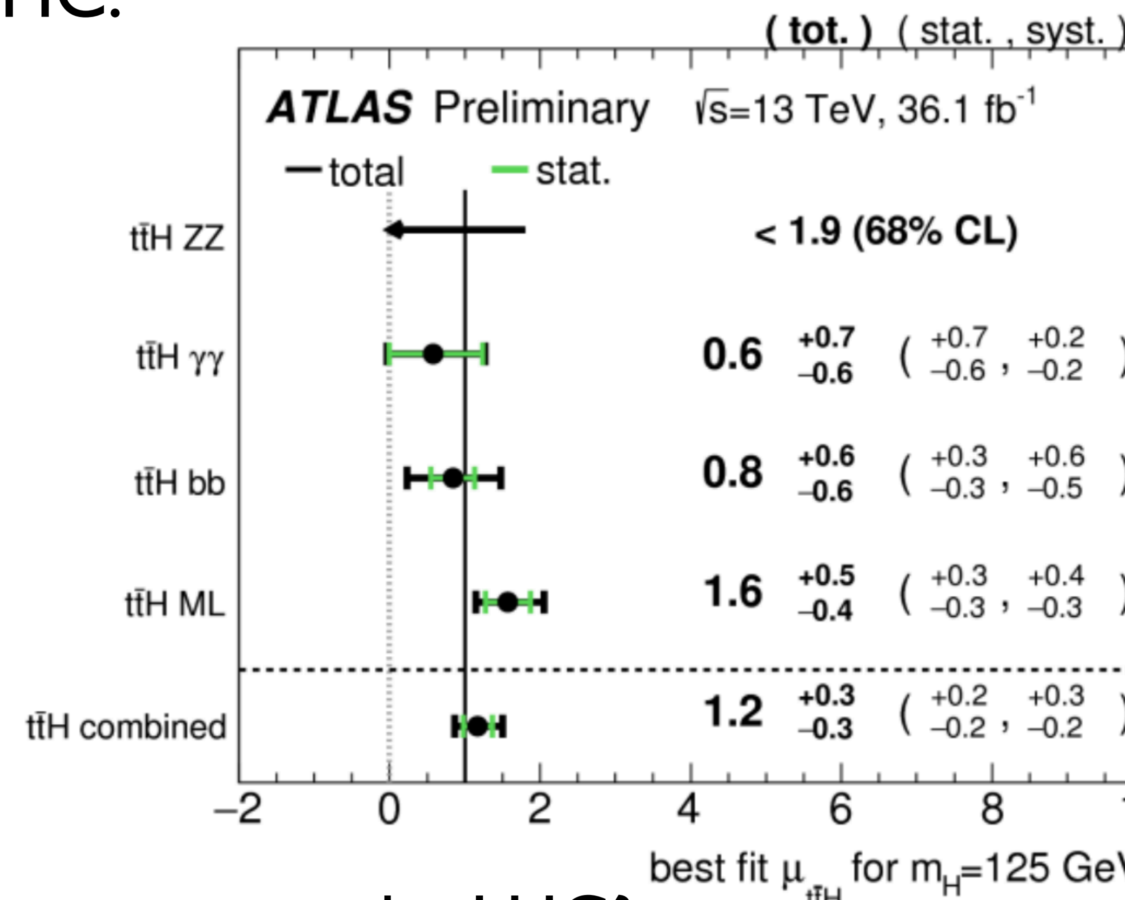

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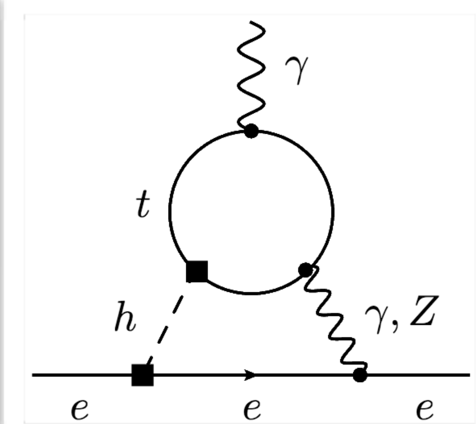

- Indirect constraints from eEDM very strong, yet assume:
  - → Coupling strength/structure to light fermions
  - → No other states in the spectrum

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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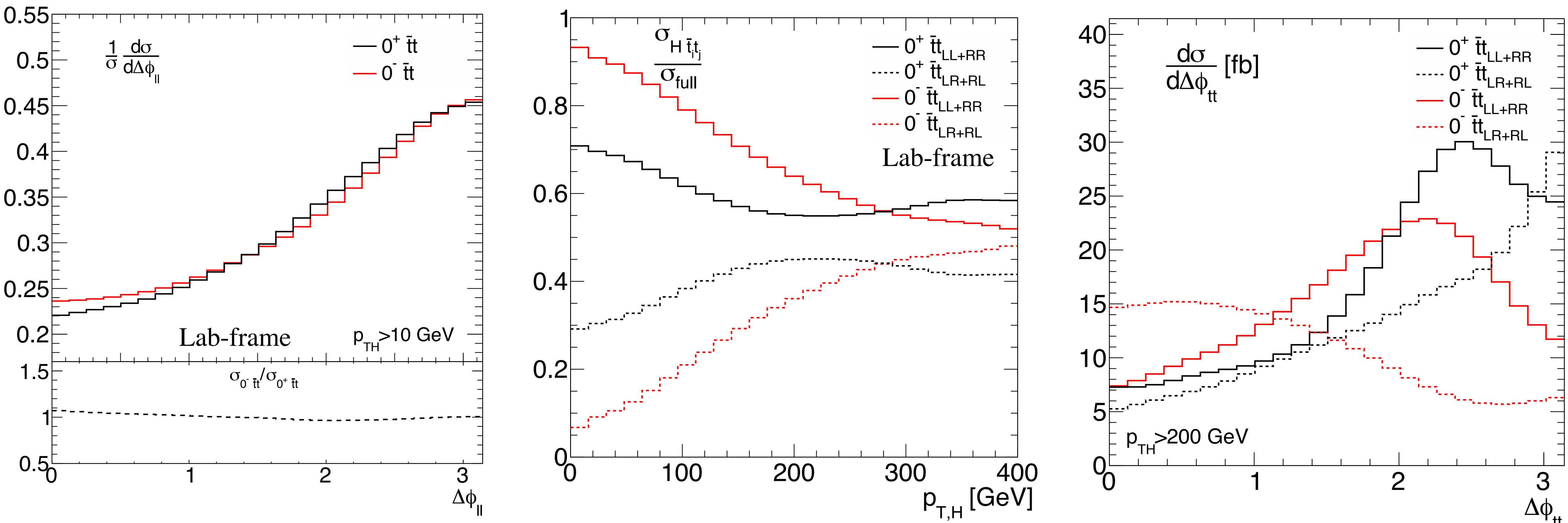

➡ Top mass effects in presence of a further massive H boson pushes chiral limit to higher scales

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

Buckley, DG (2015)

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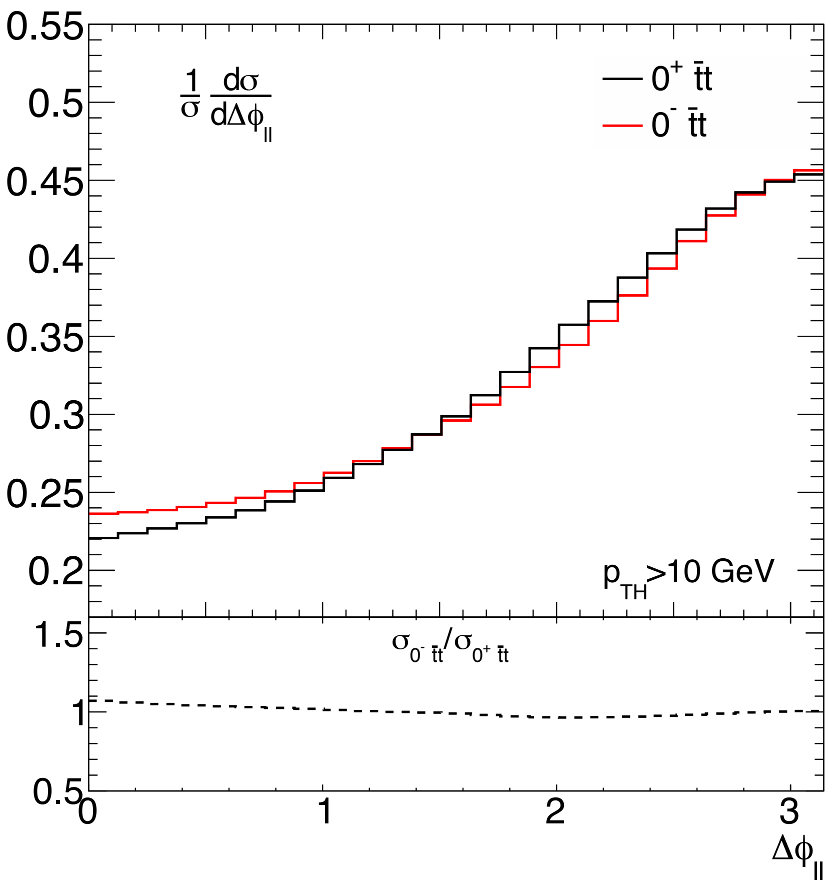
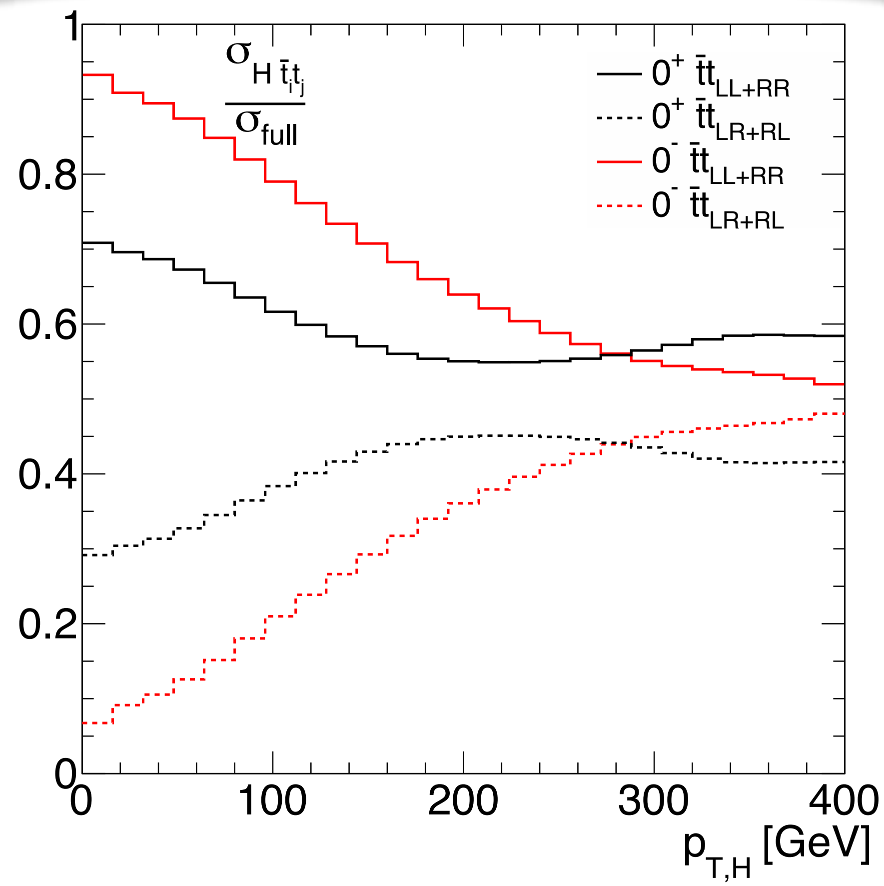
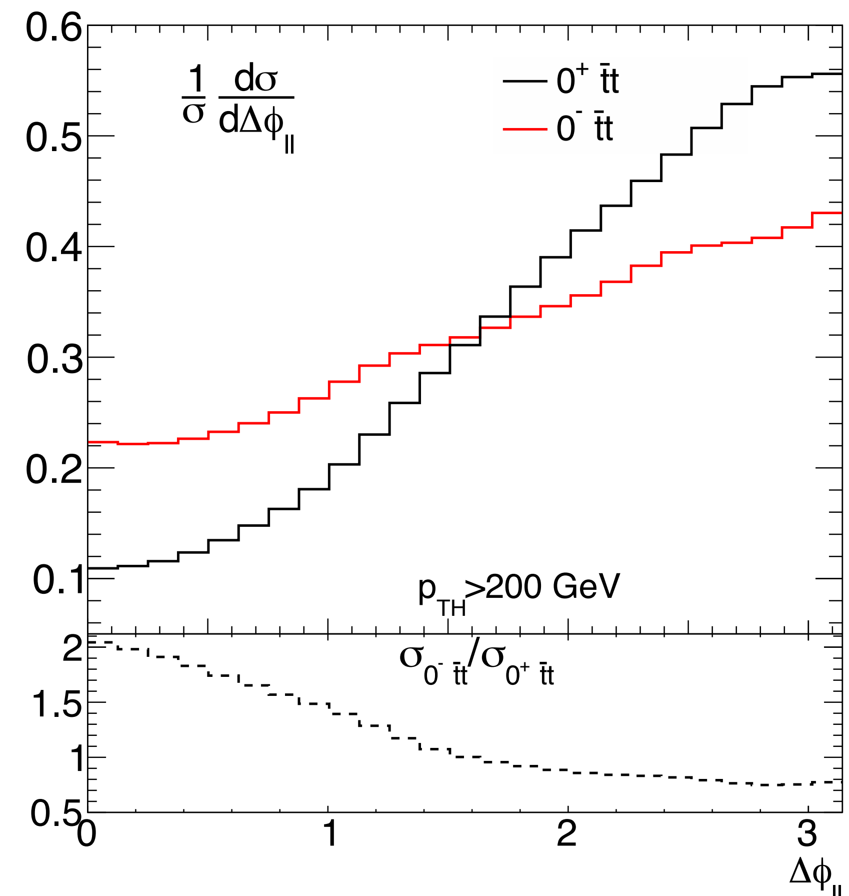






➡ Boosted Higgs (p_{TH}>200GeV) nicely match with H>bb BDRS algorithm

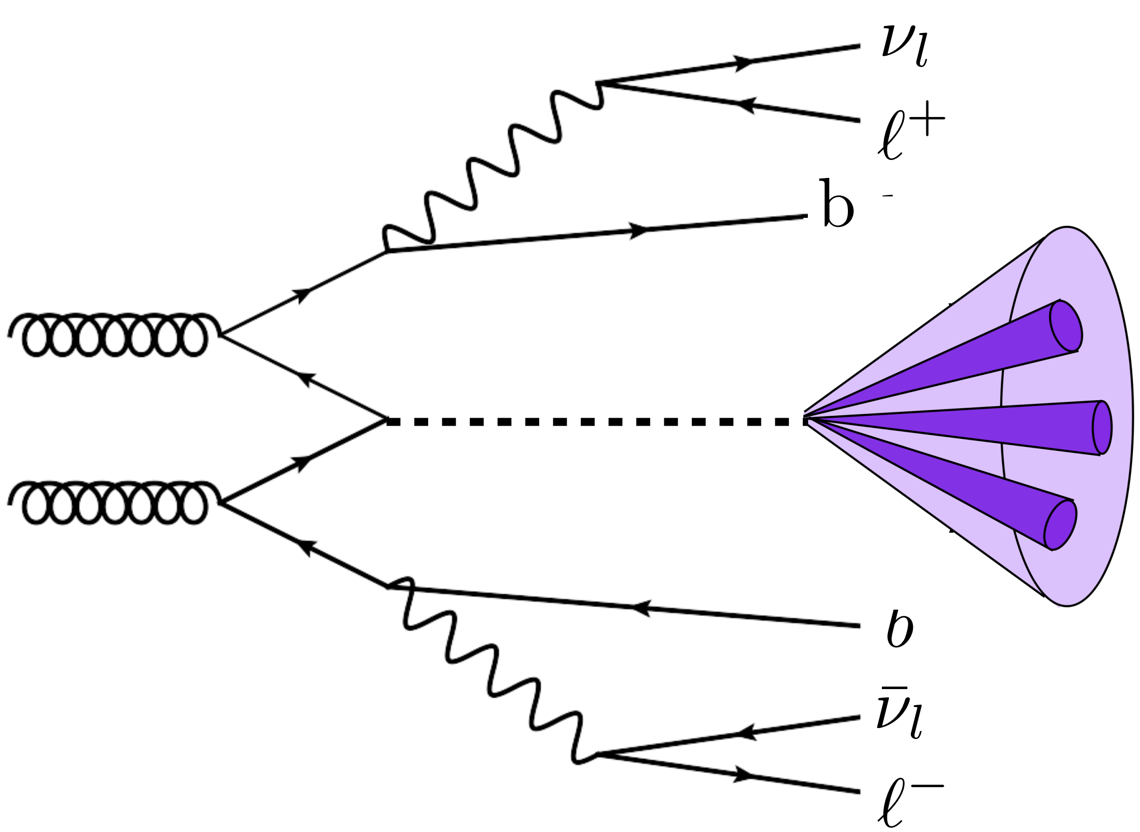
Buckley, DG (2015)
Plehn, Salam, Spannowsky (2009)

Directly Measuring $t\bar{t}H$

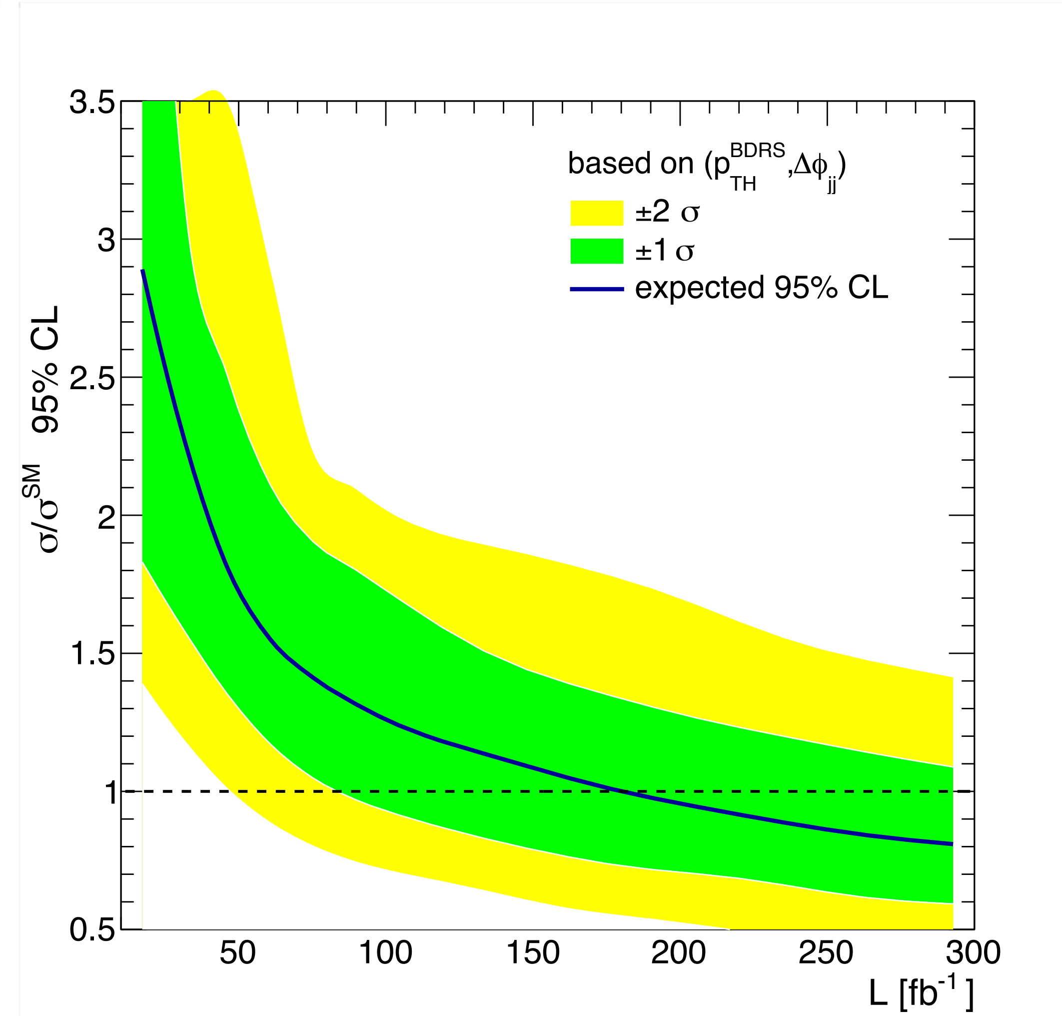
- Higgs candidate is genuinely part of a multi-jet system:

  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)
$|m_H^{\text{BDRS}} - m_H| < 10$ GeV, $m_{b\bar{b}} > 110$ GeV



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

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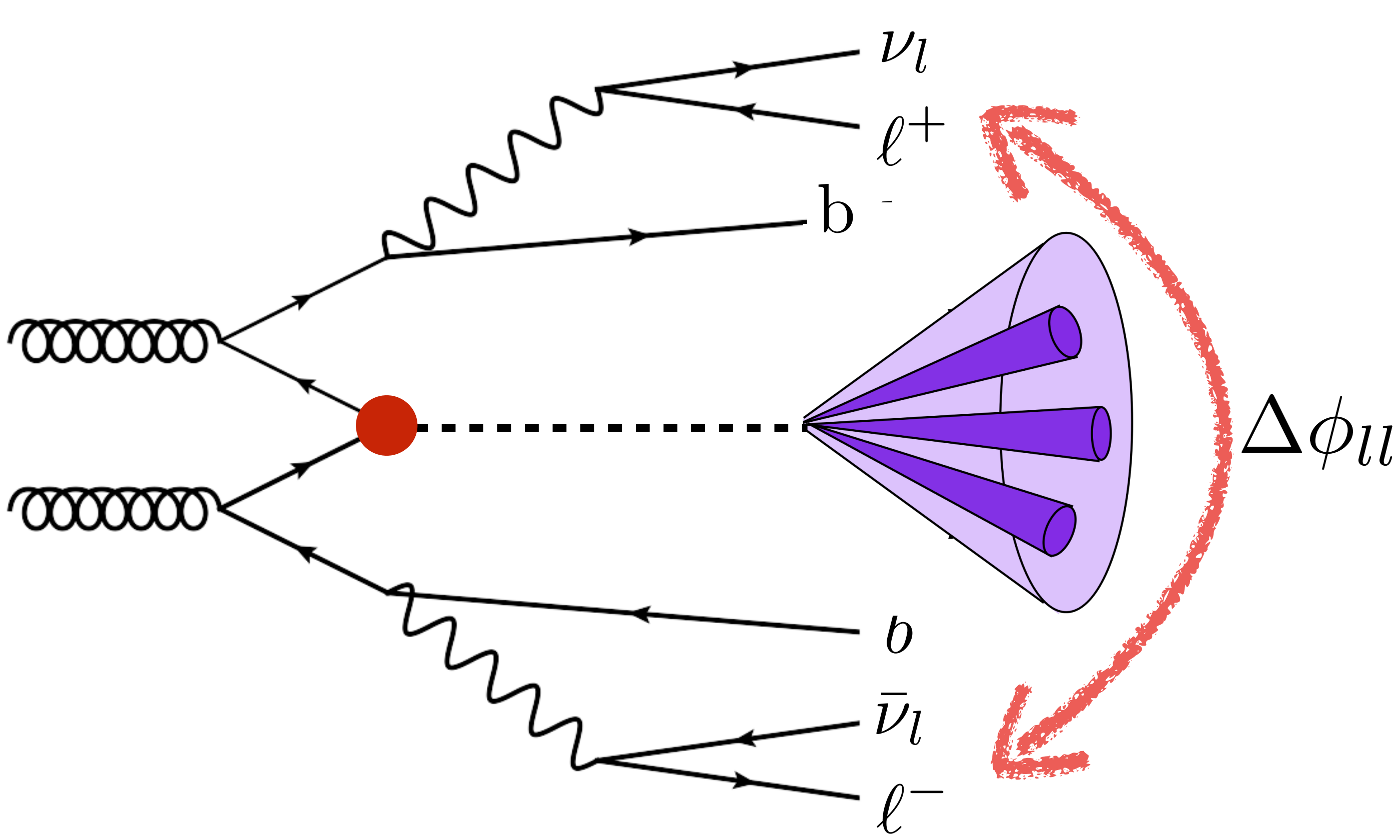

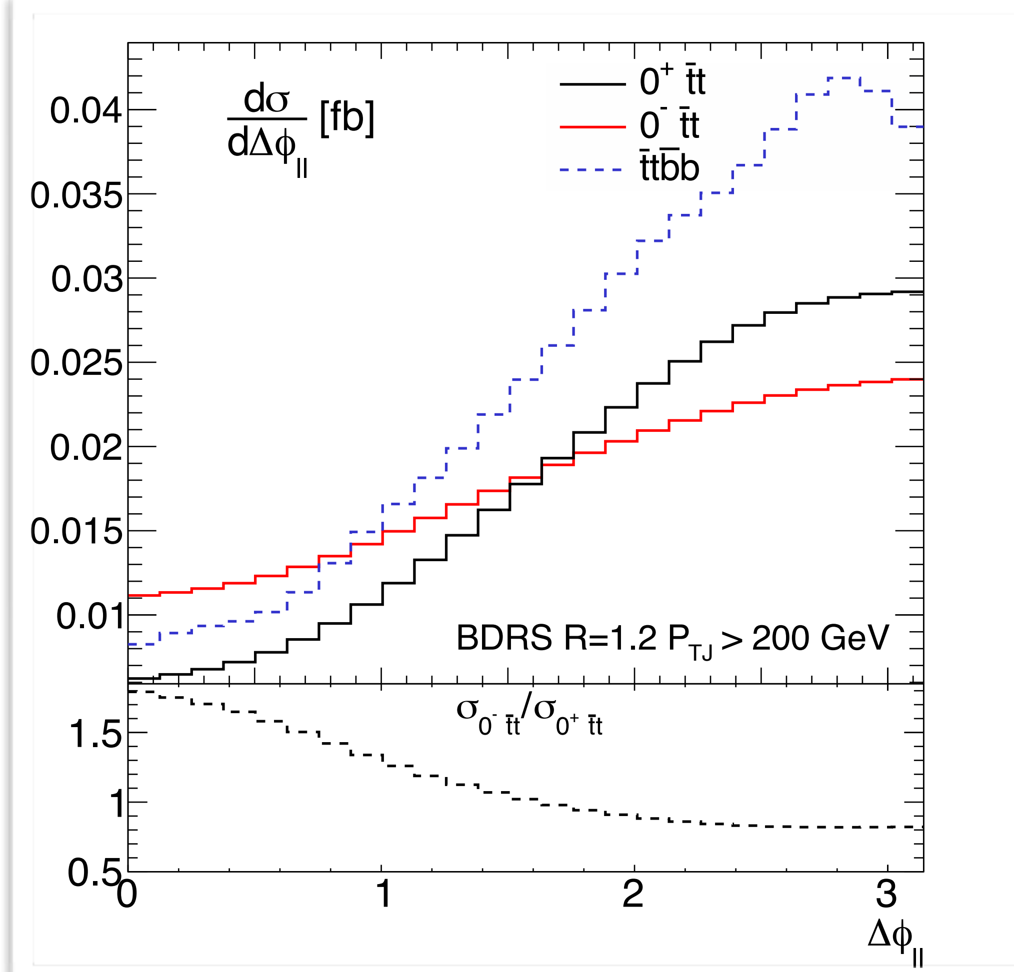

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- The full analysis and higher-order effects did not degrade our observable!

Buckley, DG (2015)

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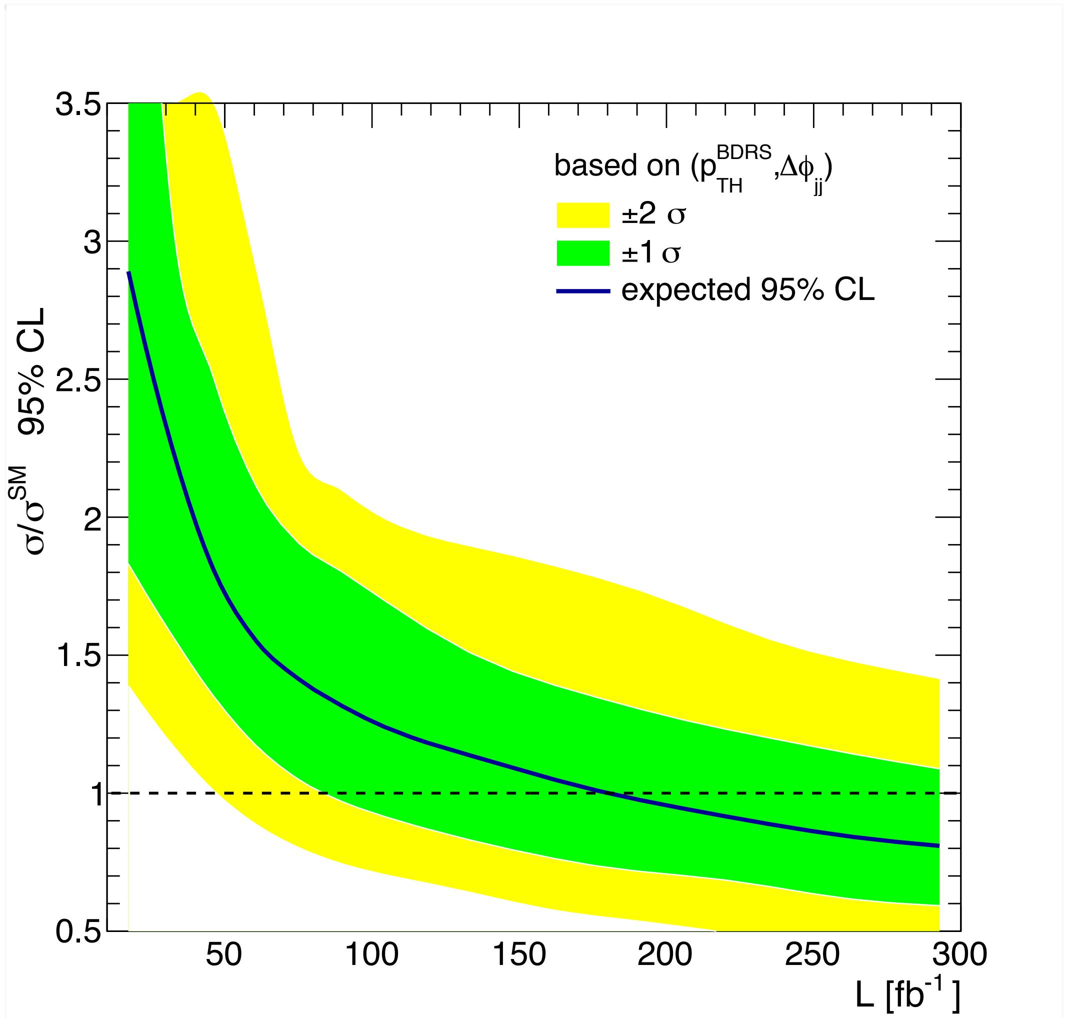

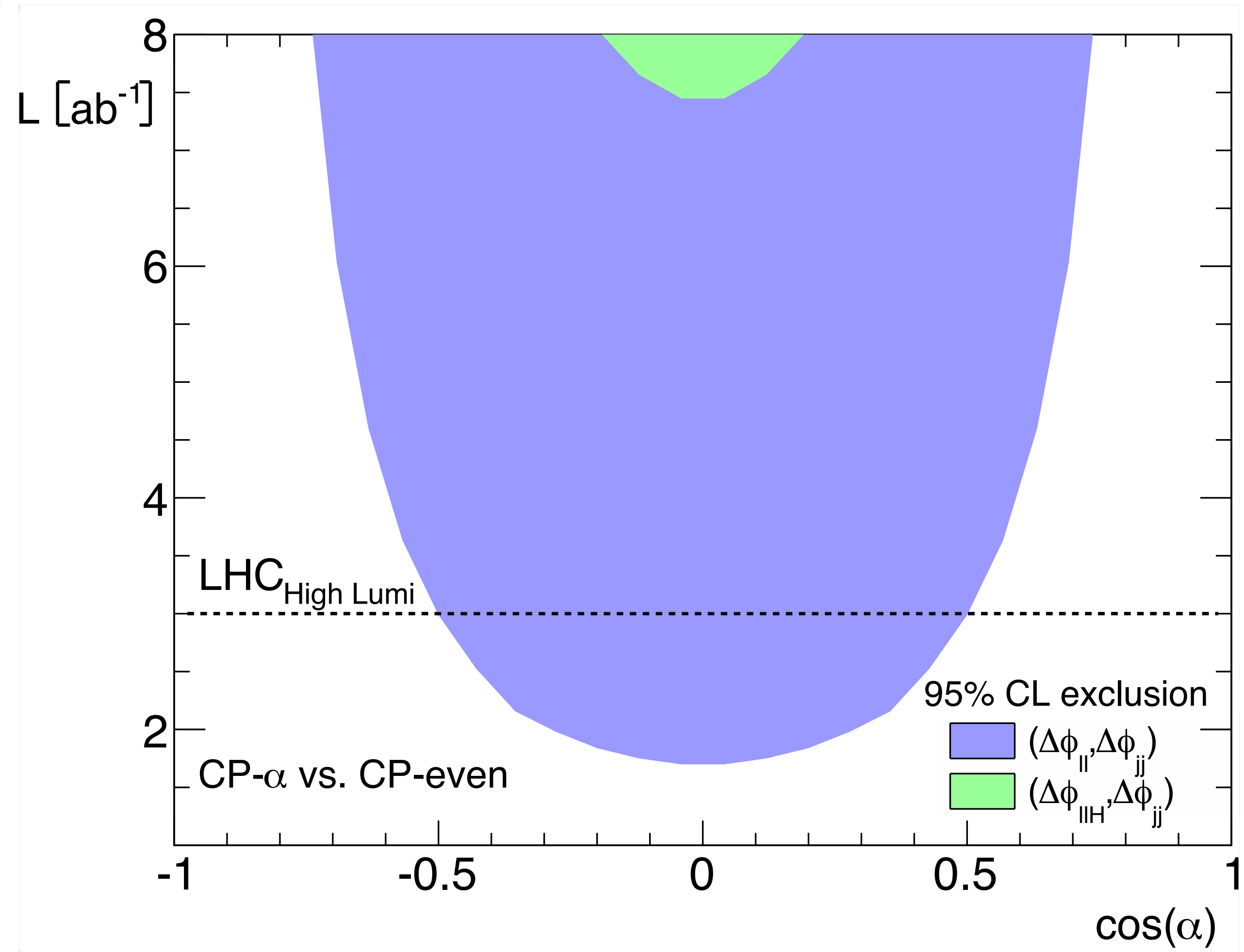

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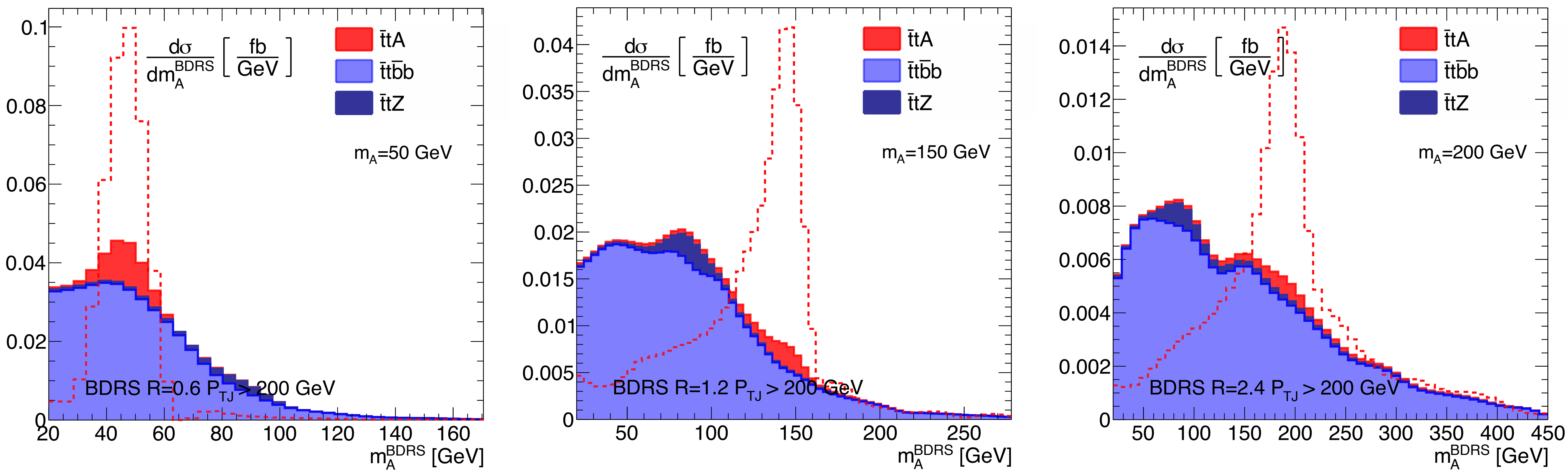
  Tailoring the BDRS analysis for different m_A ranges: $R \sim 2m_A/p_{TA}$



Lopez-val, DG (2016)

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

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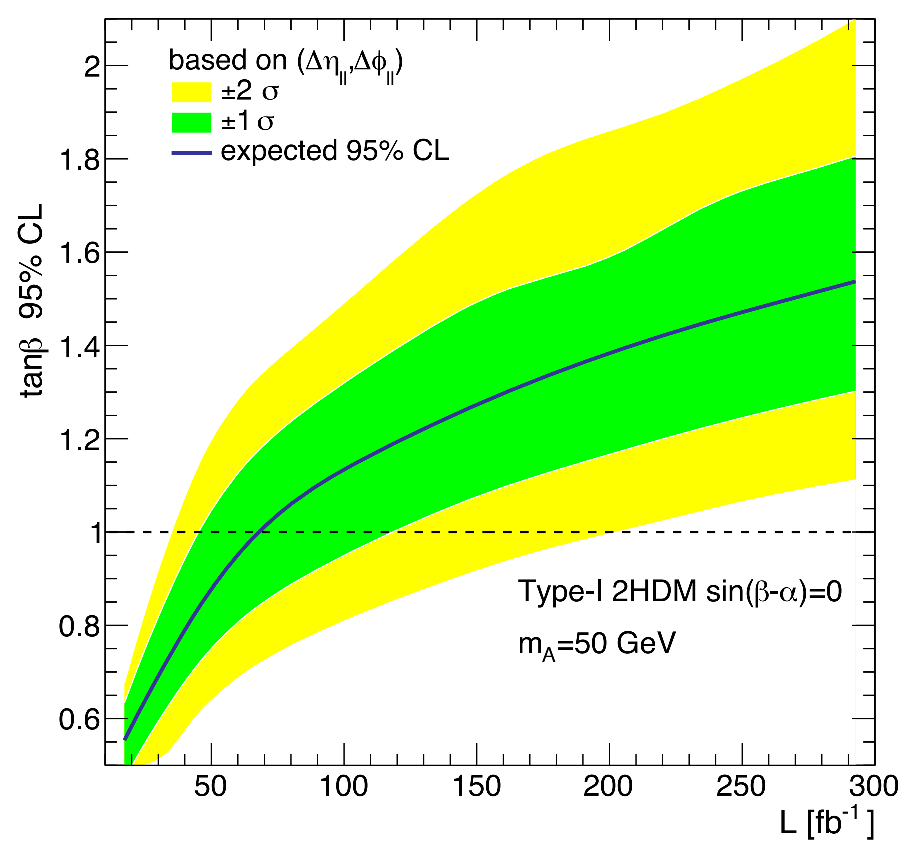

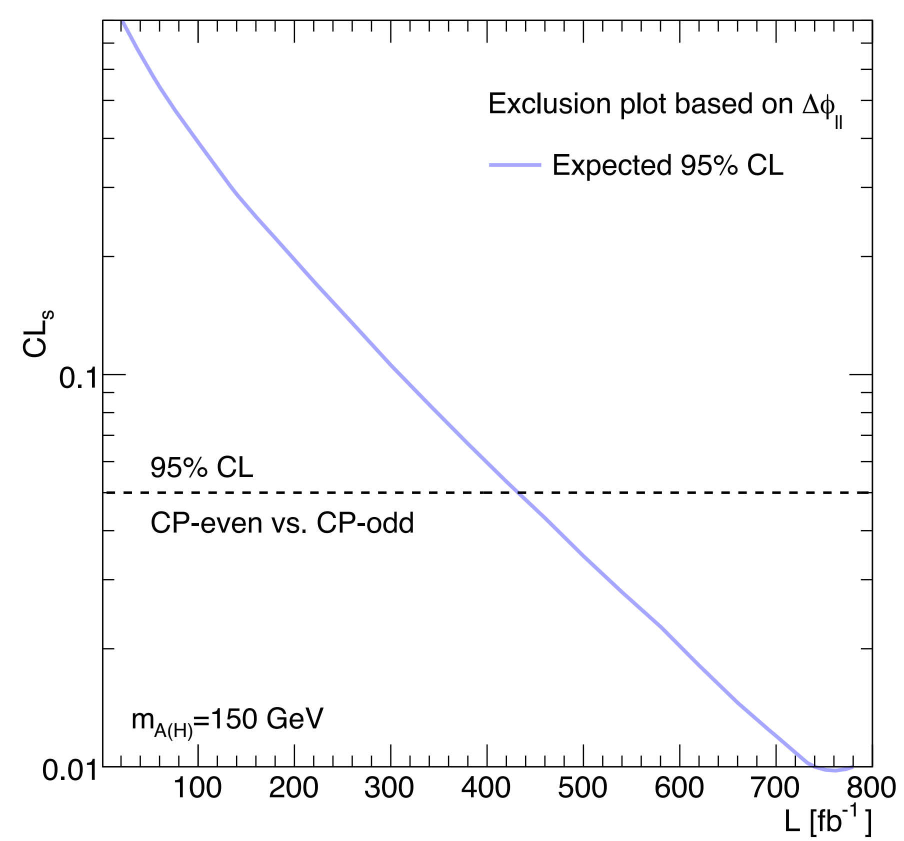

Lopez-val, DG (2016)

Summary

- LHC Run II gives very energetic Higgses with significant statistics
  Off-shell important to further explore the TeV scale

→ Off-shell probe to Higgs portal couplings provide new very promising bounds for $m_h<2m_S$

→ Width measurement is more model independent with WBF
  100TeV collider can push the width measurement to below 10%

- It is possible to access the Higgs-top CP-structure via angular correlations in ttH
  Boosted Higgs analysis nicely match with CP-structure measurement

Thank you for your attention!