



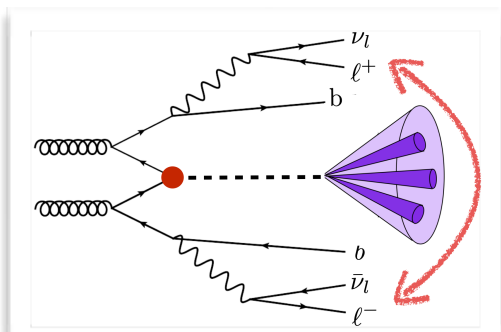
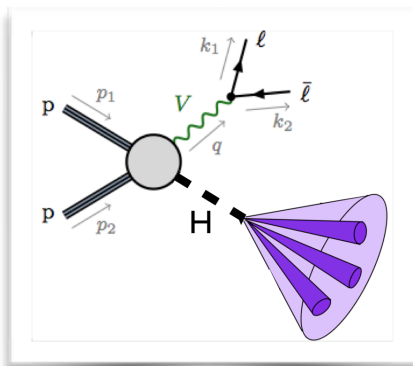
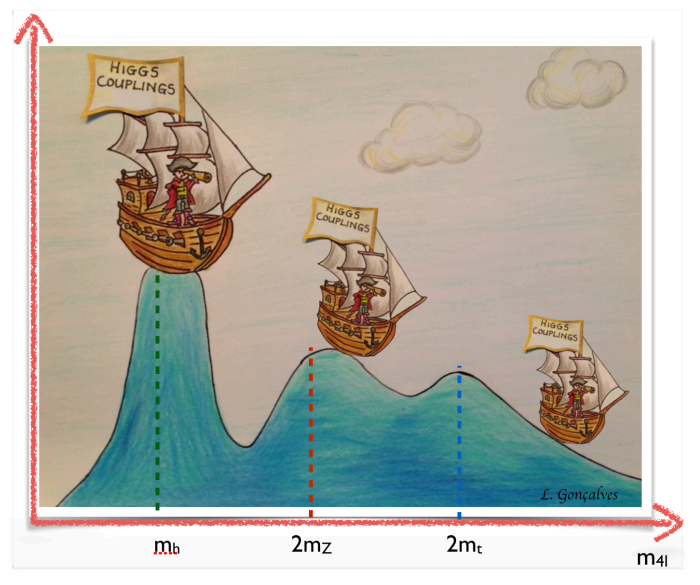
Importance of differential distributions in Higgs physics



LHCP 21.05.2019
Dorival Gonçalves

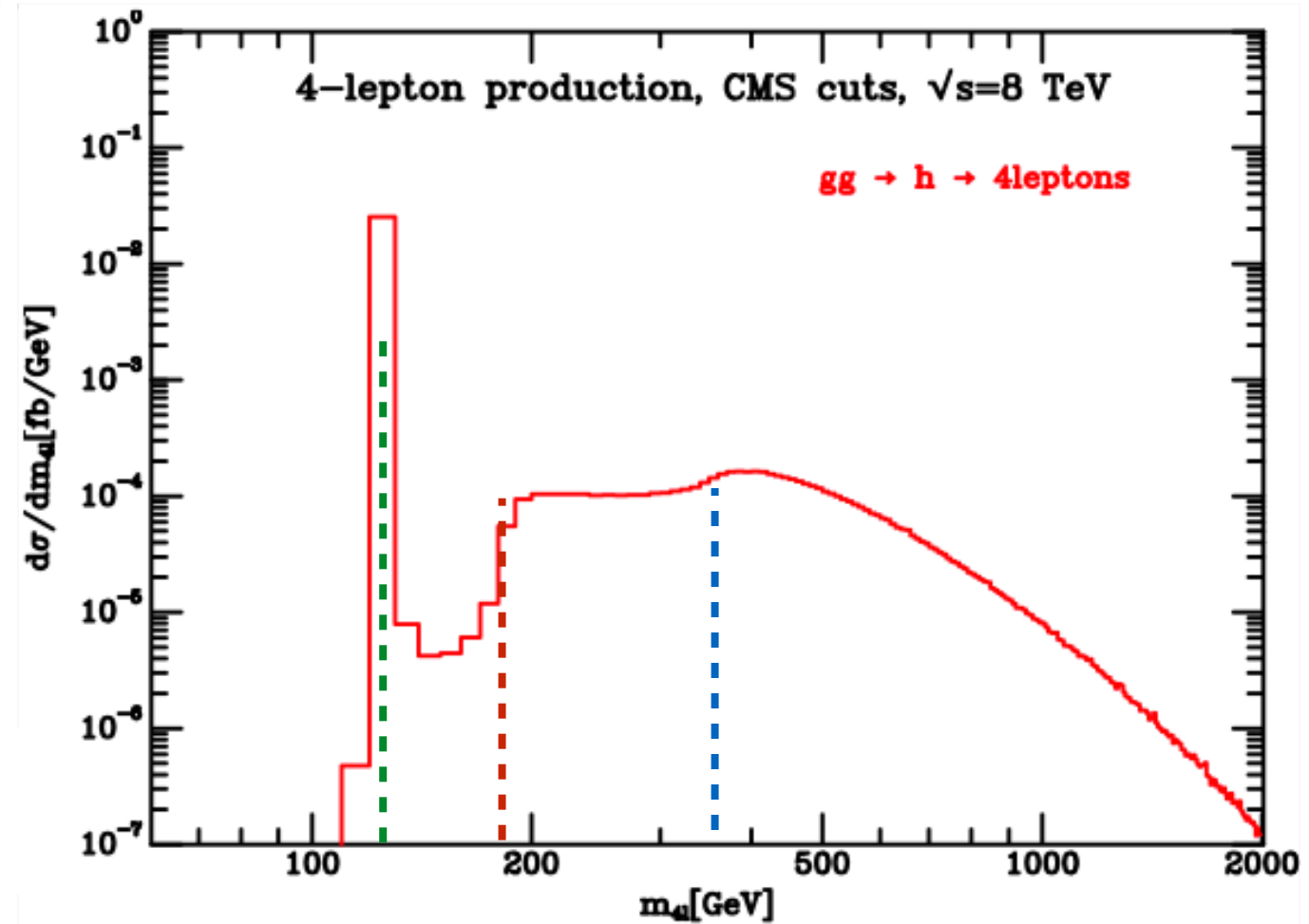
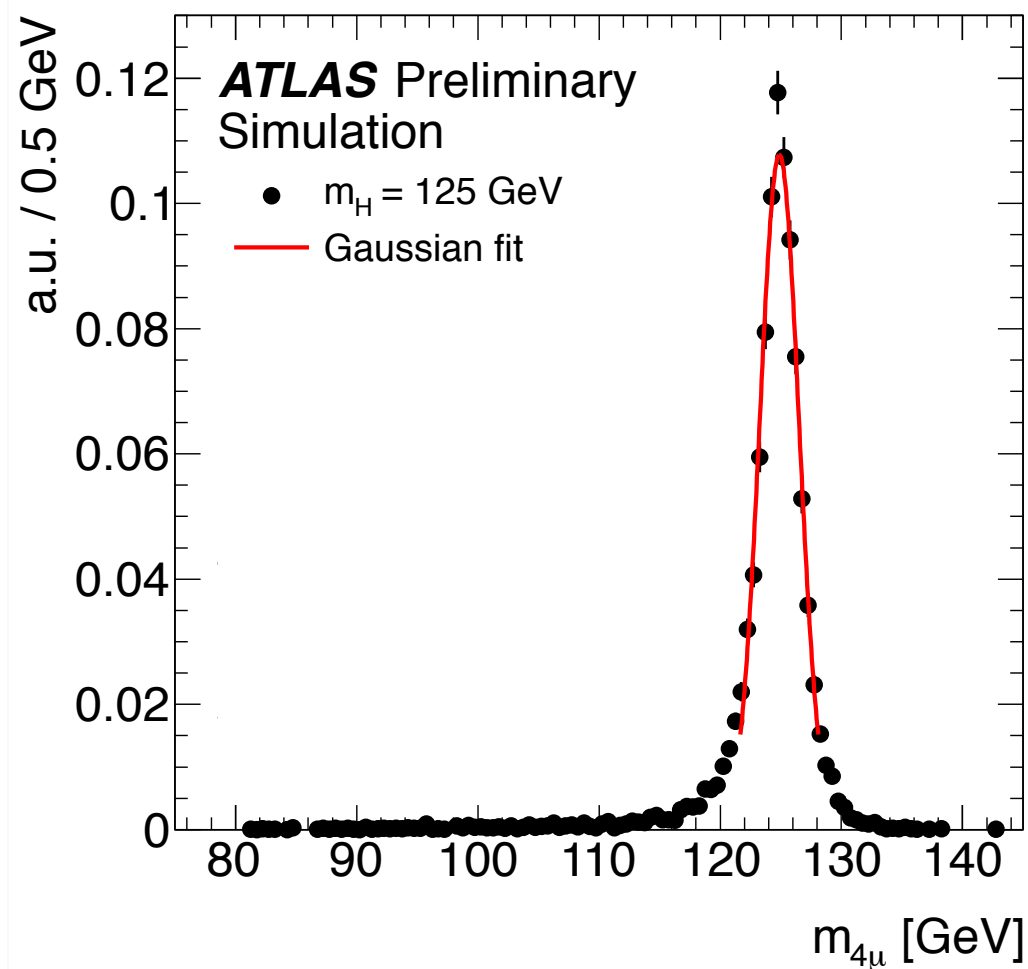


Many opportunities ahead



Off-Shell Higgs Production

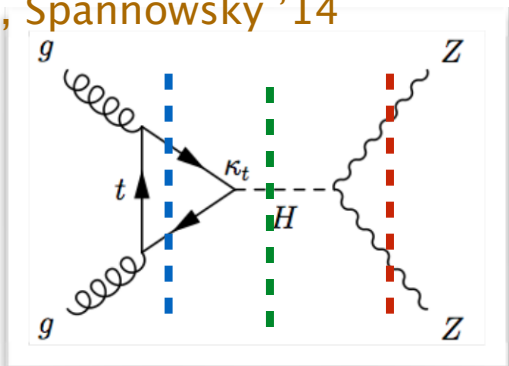
Since $\Gamma_H/m_H \sim 3 \times 10^{-5}$ one naively expects very small off-shell rates



Campbell, Ellis, Williams '13; Kauer, Passarino '12;
Caola, Melnikov '13; Englert, Spannowsky '14

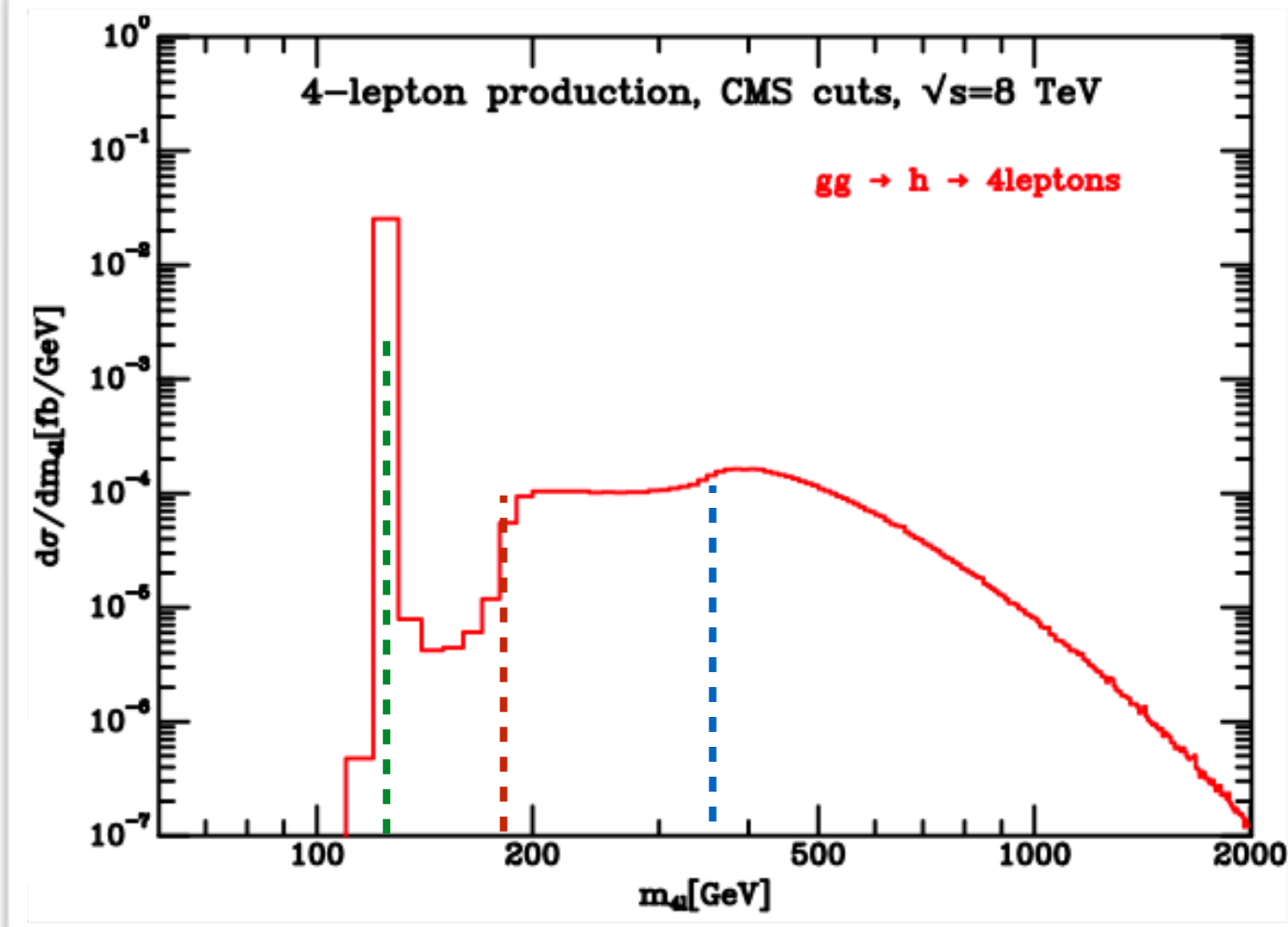
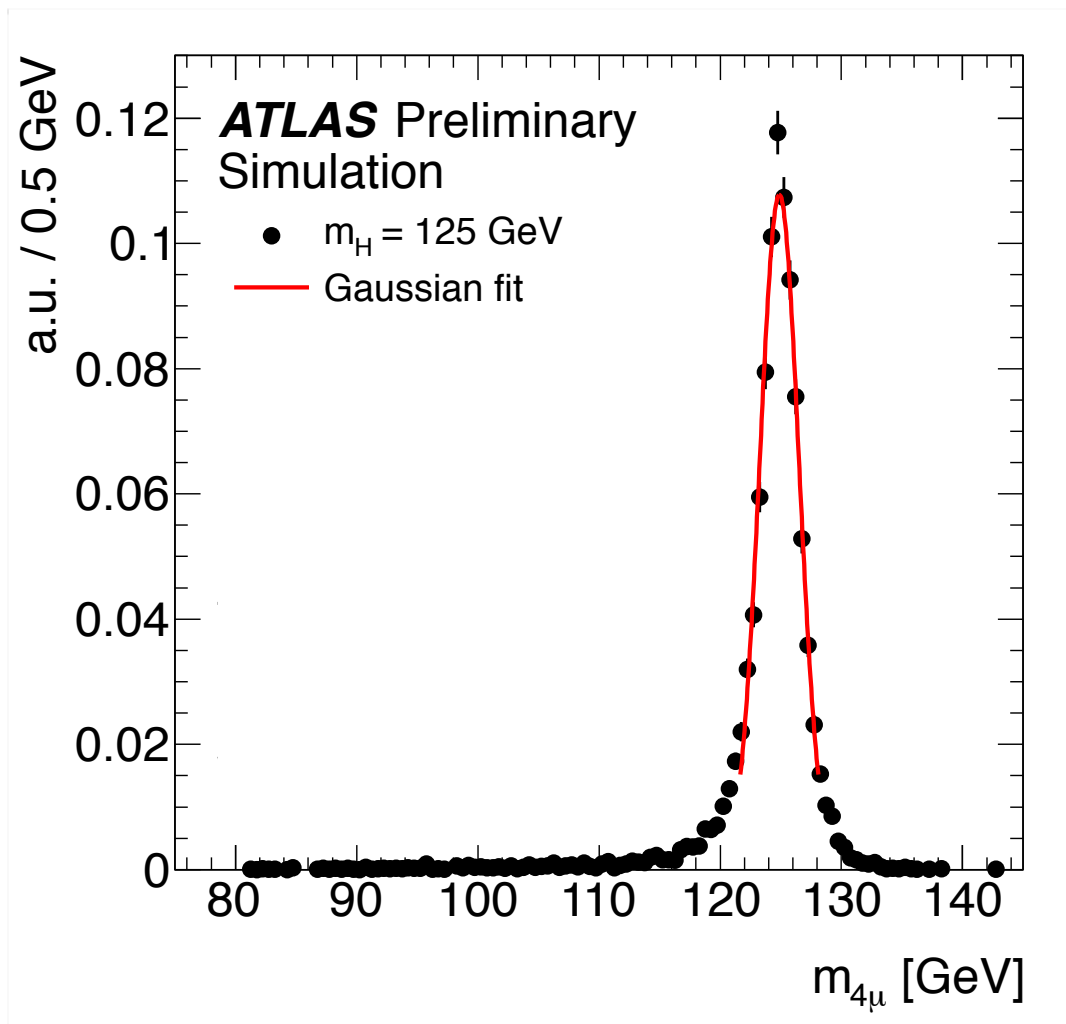
Spectacular fail of the NWA: $\frac{\sigma_{H \rightarrow 4\ell}^{off-shell}}{\sigma_{H \rightarrow 4\ell}} \sim 15\%$

→ $2m_t$ and $2m_Z$ thresholds



Off-Shell Higgs Production

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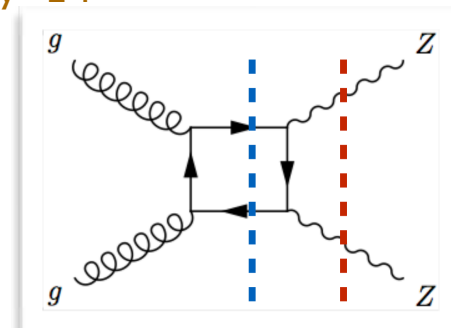
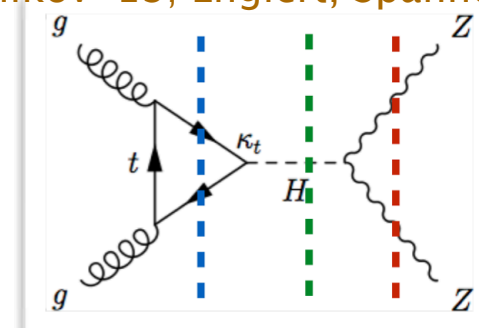


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Spectacular fail of the NWA: $\frac{\sigma_{H \rightarrow 4\ell}^{off-shell}}{\sigma_{H \rightarrow 4\ell}} \sim 15\%$

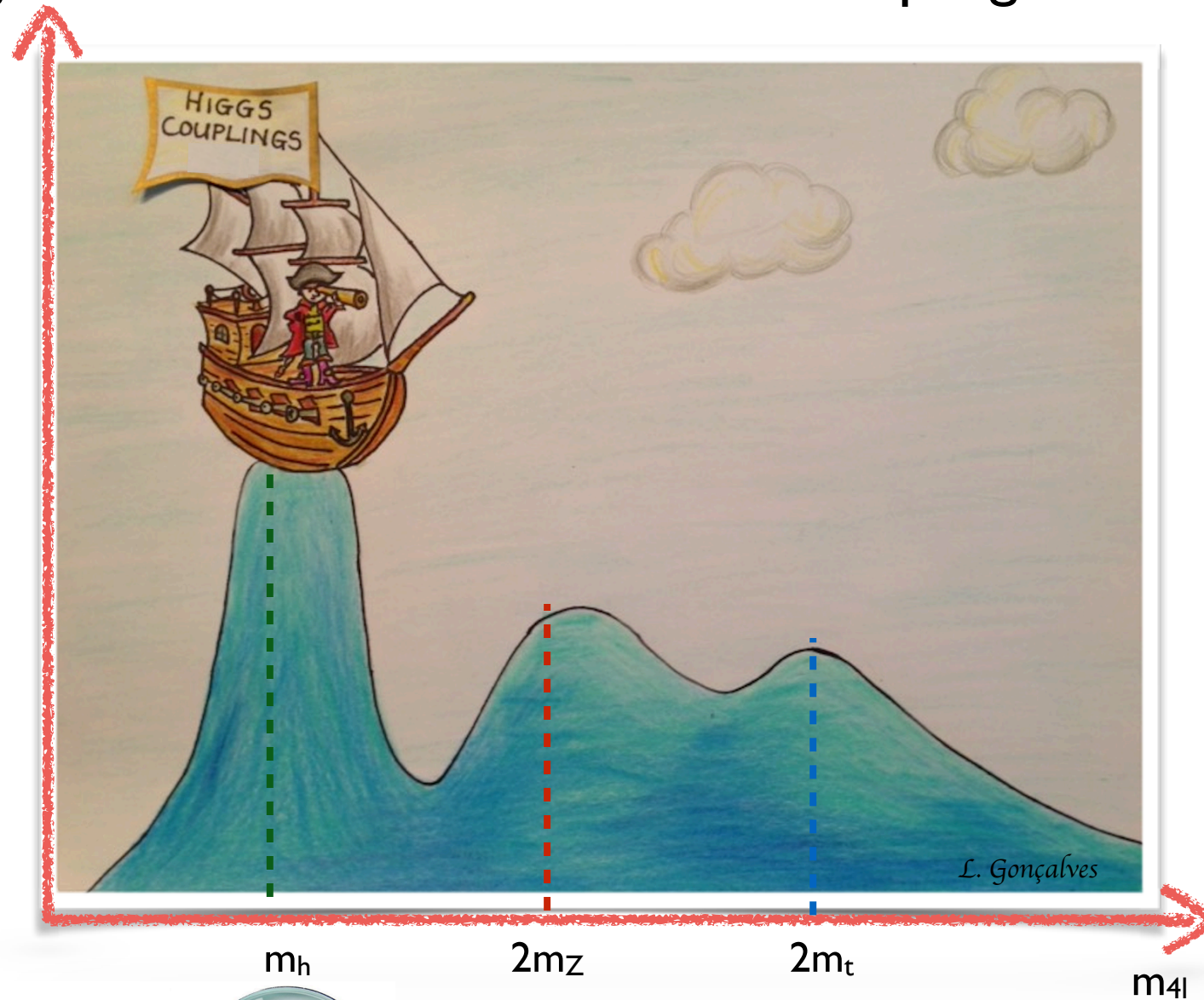
→ $2m_t$ and $2m_Z$ thresholds

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



Off-Shell Higgs Production

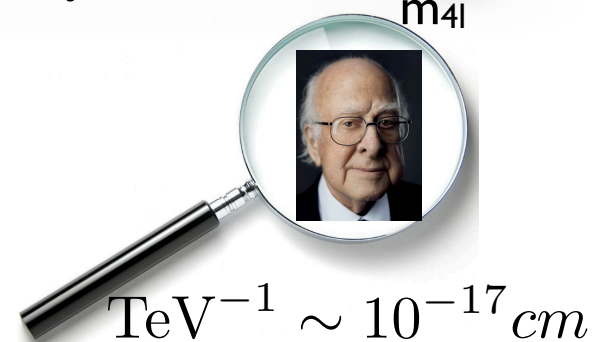
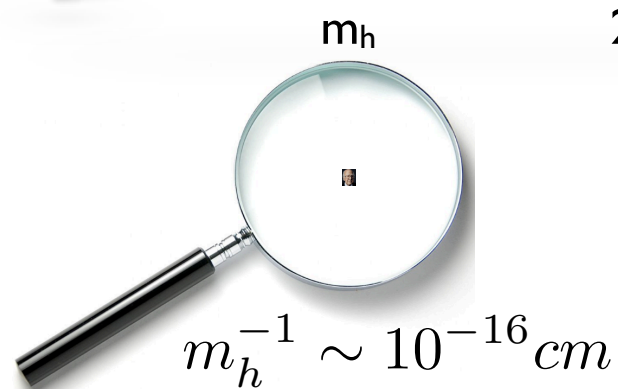
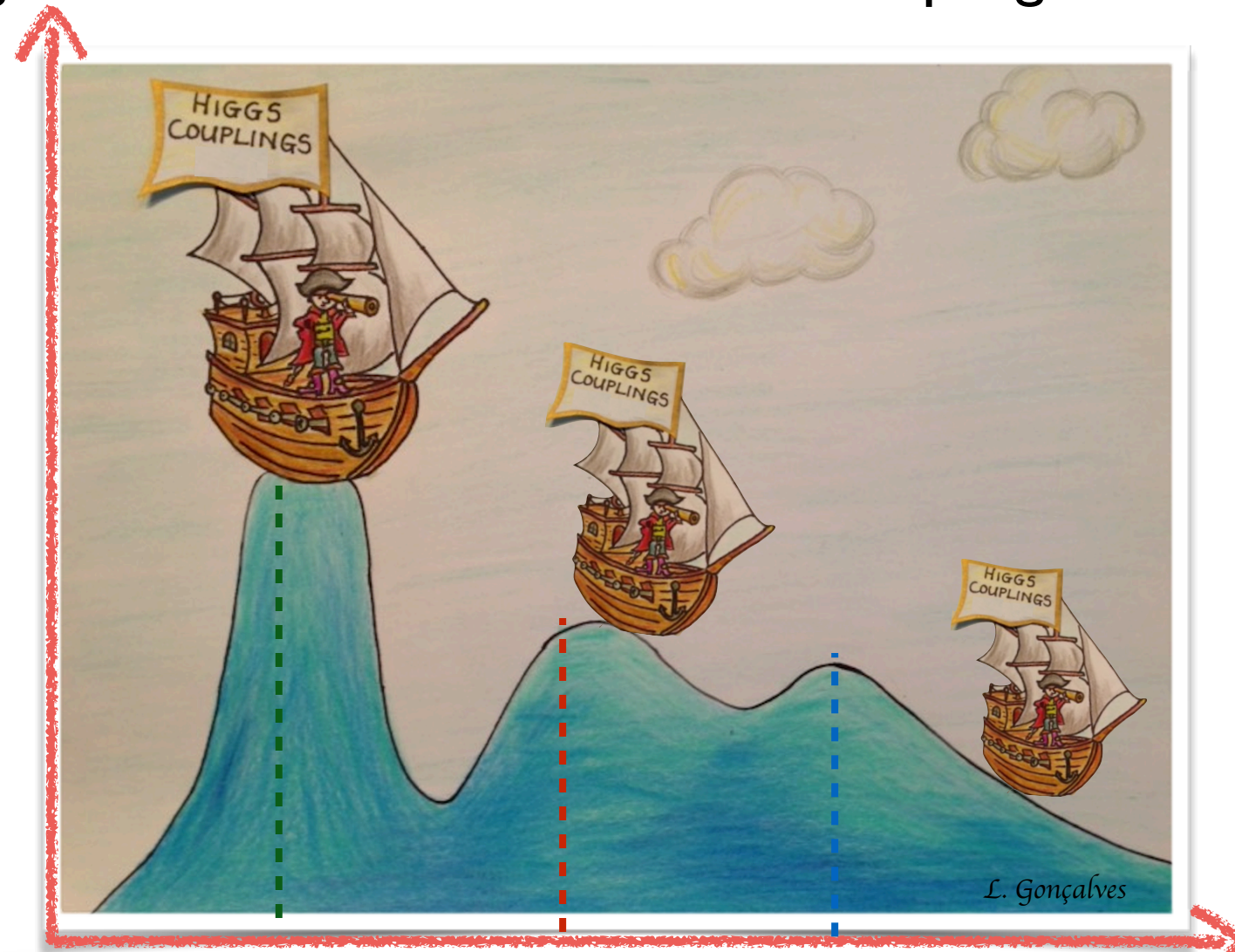
- Off-shell Higgs carries information on the H couplings at different energy scales



$m_h^{-1} \sim 10^{-16} \text{ cm}$

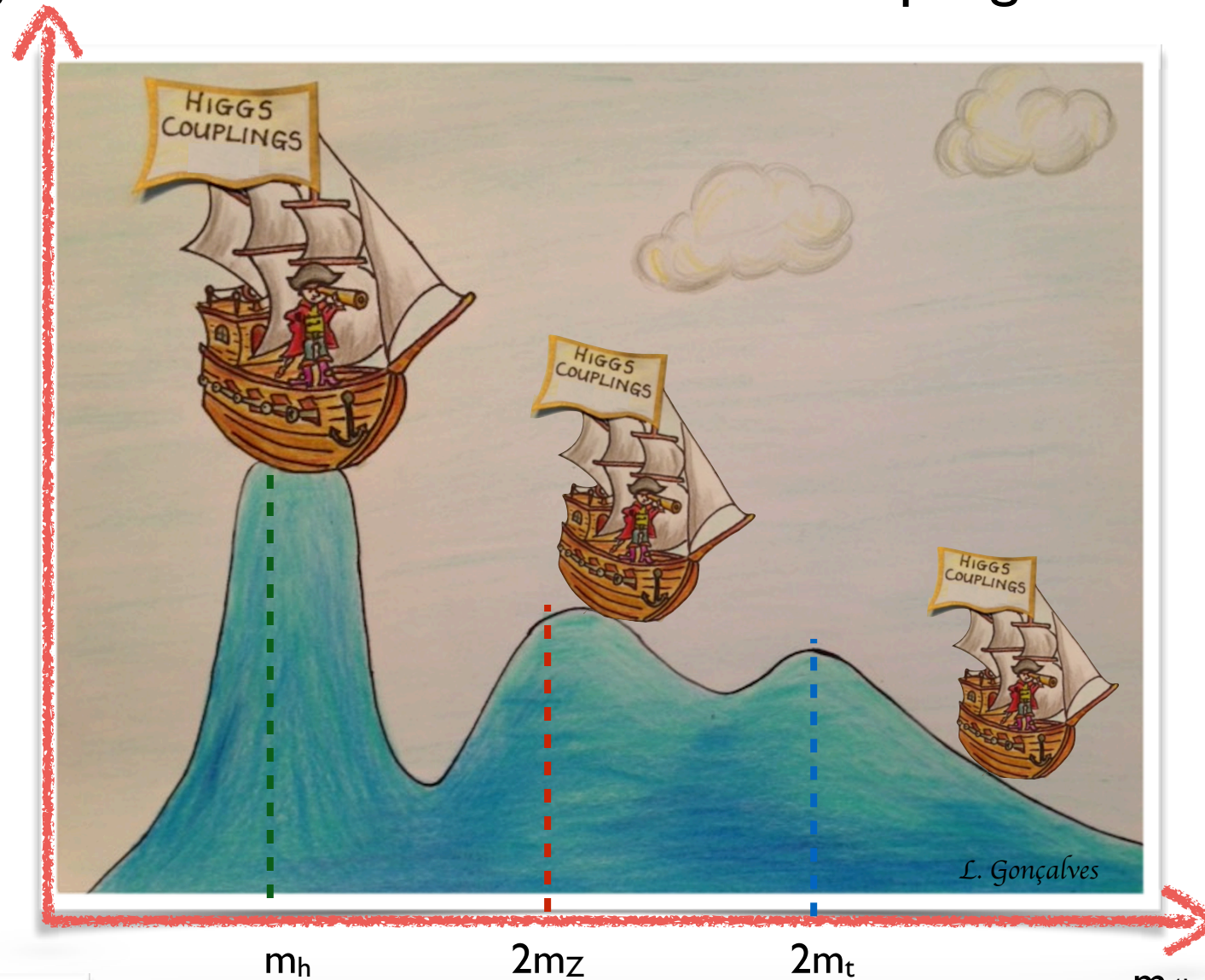
Off-Shell Higgs Production

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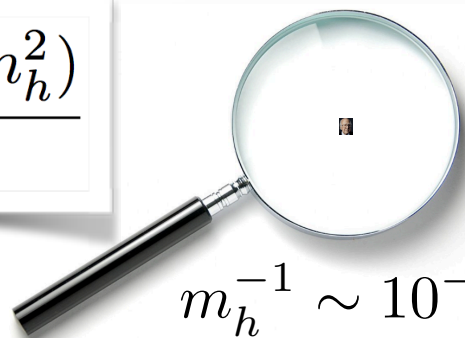


Off-Shell Higgs Production

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



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



$$m_h^{-1} \sim 10^{-16} \text{ cm}$$

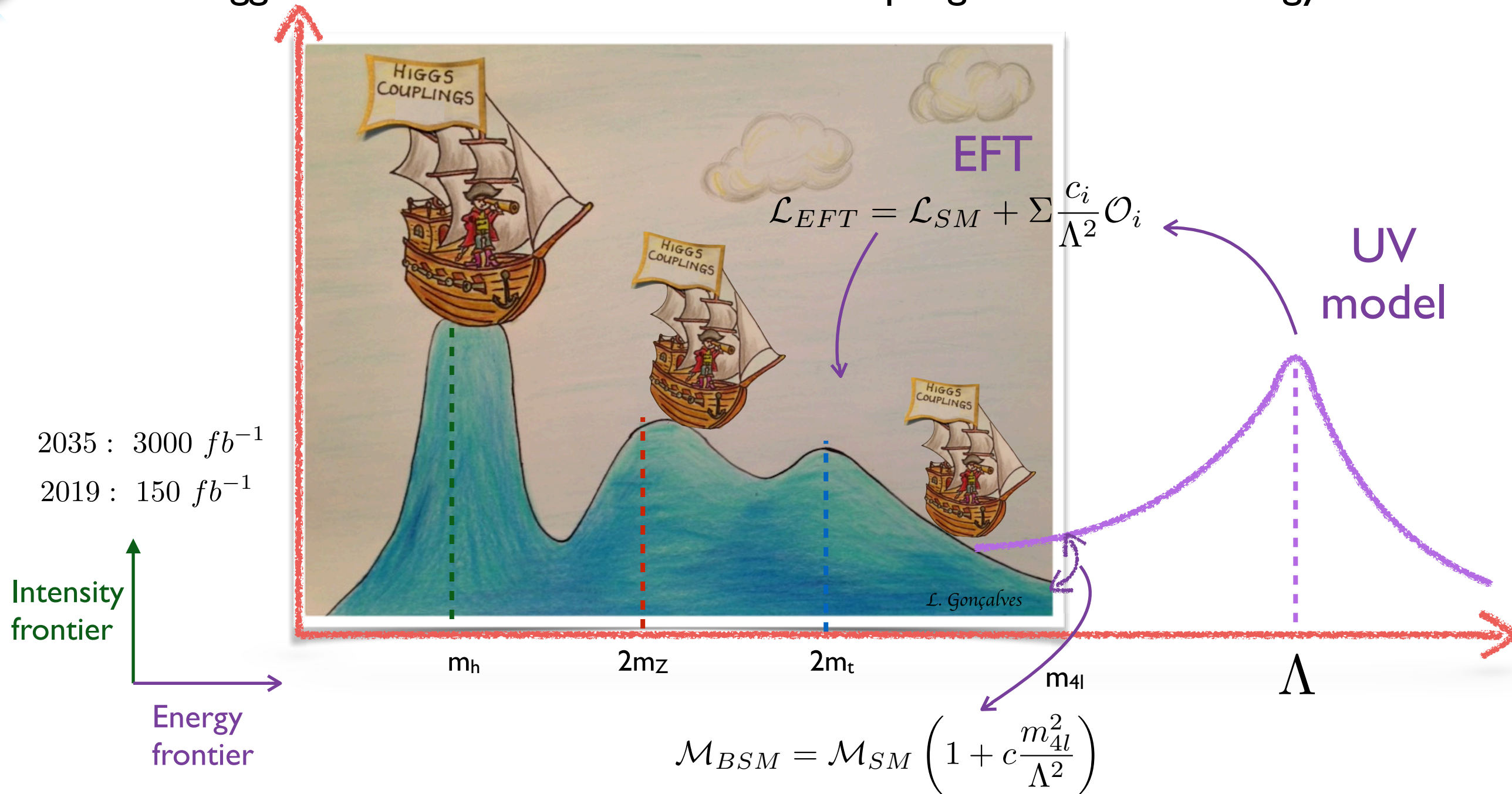


$$\text{TeV}^{-1} \sim 10^{-17} \text{ cm}$$

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

What is the new physics scale?

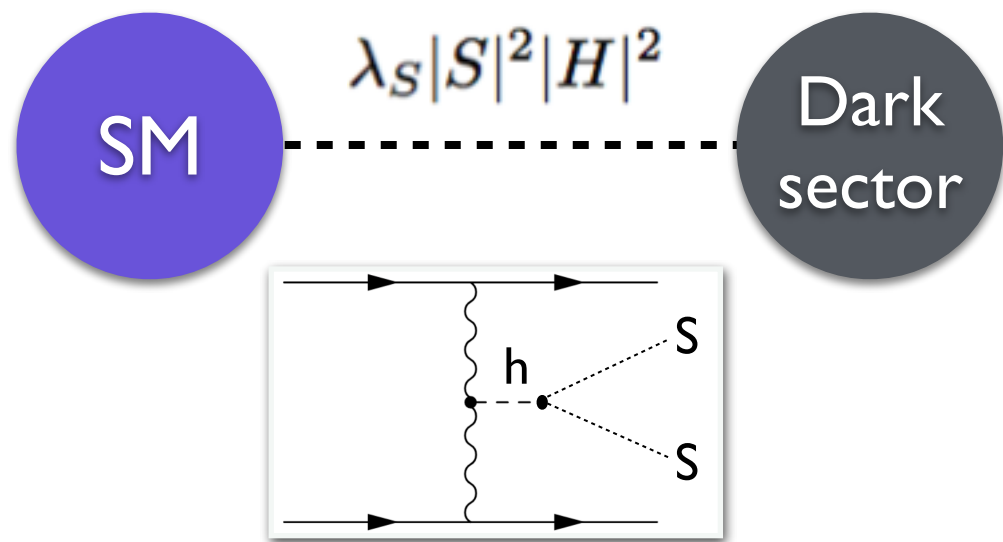
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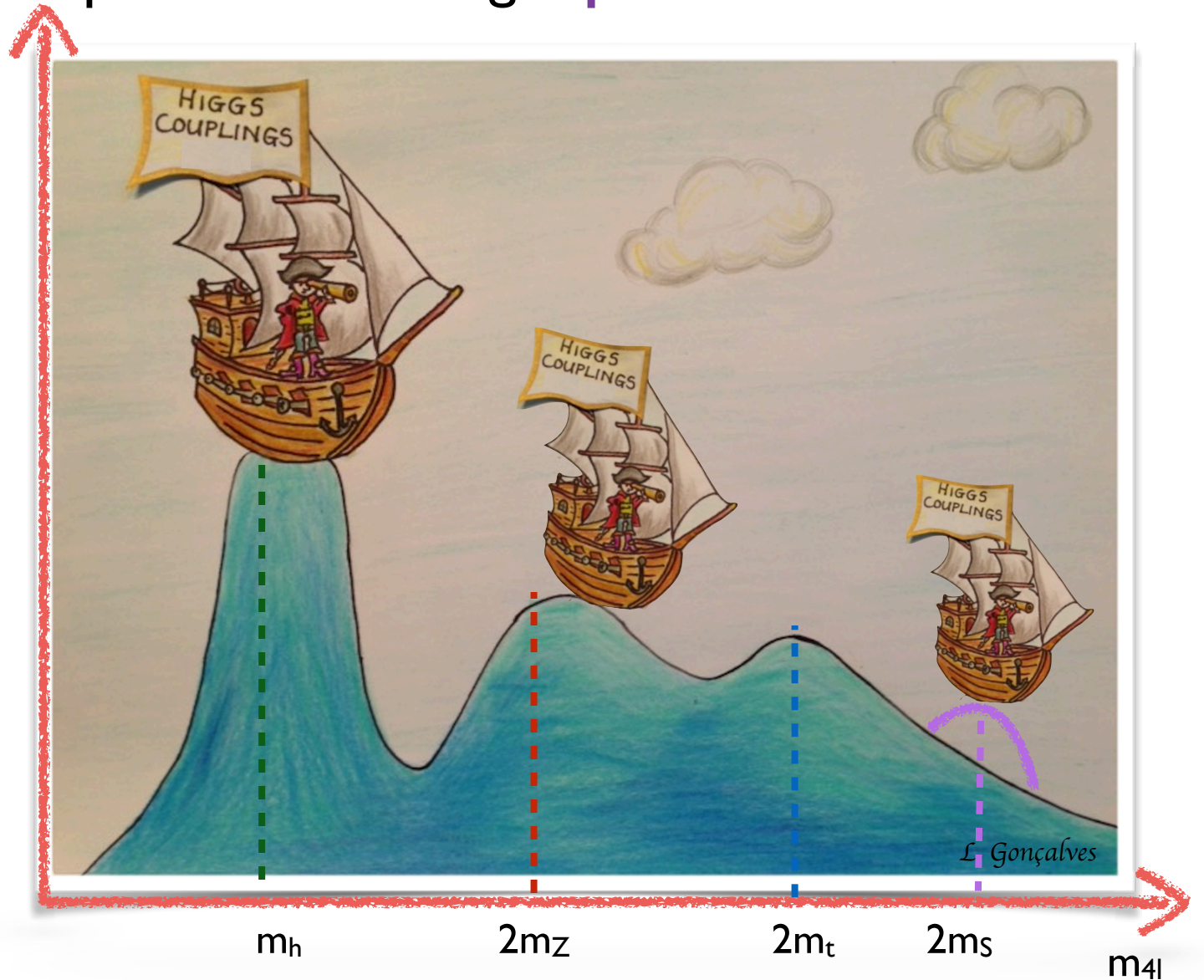
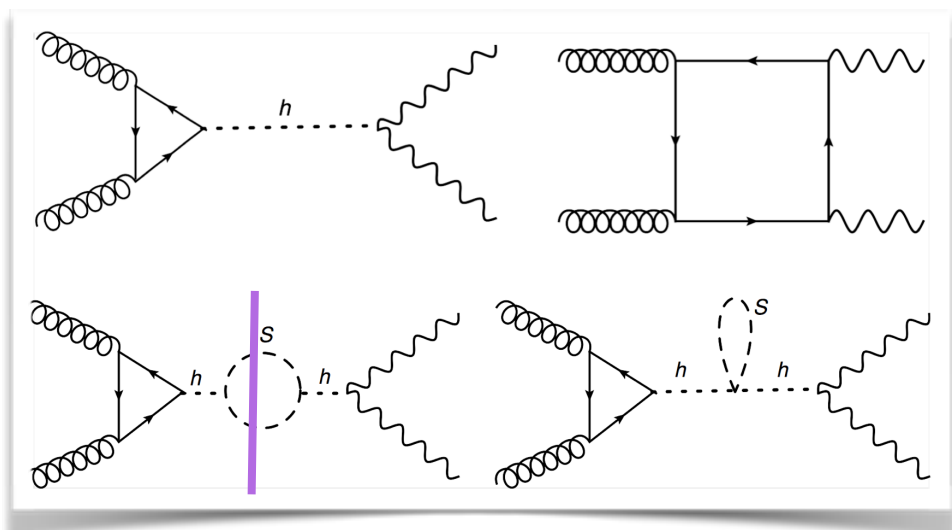
Buschmann, **Gonçalves**, Kuttimalai, Schonherr, Krauss, Plehn '14; Azatov, Grojean, Paul, Salvioni '14
 Englert, Soreq, Spannowsky '14; Corbett, Eboli, **Gonçalves**, Fraile, Plehn, Rauch '15

Is it a portal to a hidden world?

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



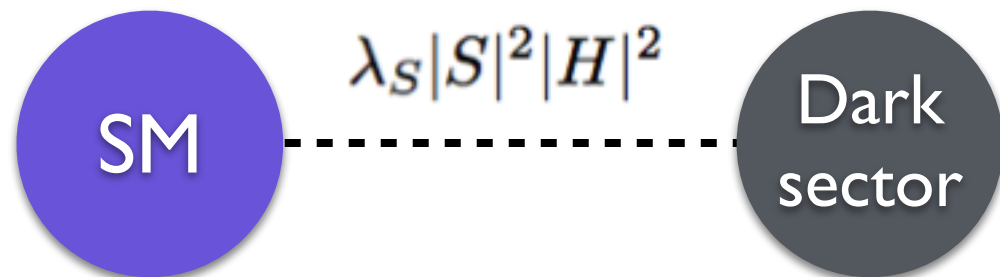
- $m_h > 2m_S$: strong sensitivity
- $m_h < 2m_S$: sensitivity **suppressed**



Gonçalves, Han, Mukhopadhyay (PRL '18, PRD '18)

Is it a portal to a hidden world?

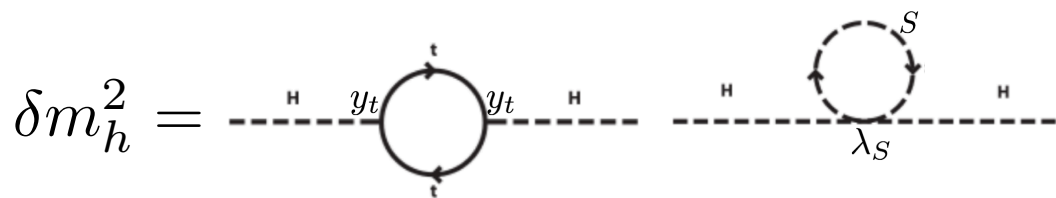
- Hidden states could show up in the scale dependence of Higgs couplings, or more broadly in Higgs production processes through **quantum corrections**



Is it natural?

Off-shell probe to Naturalness:

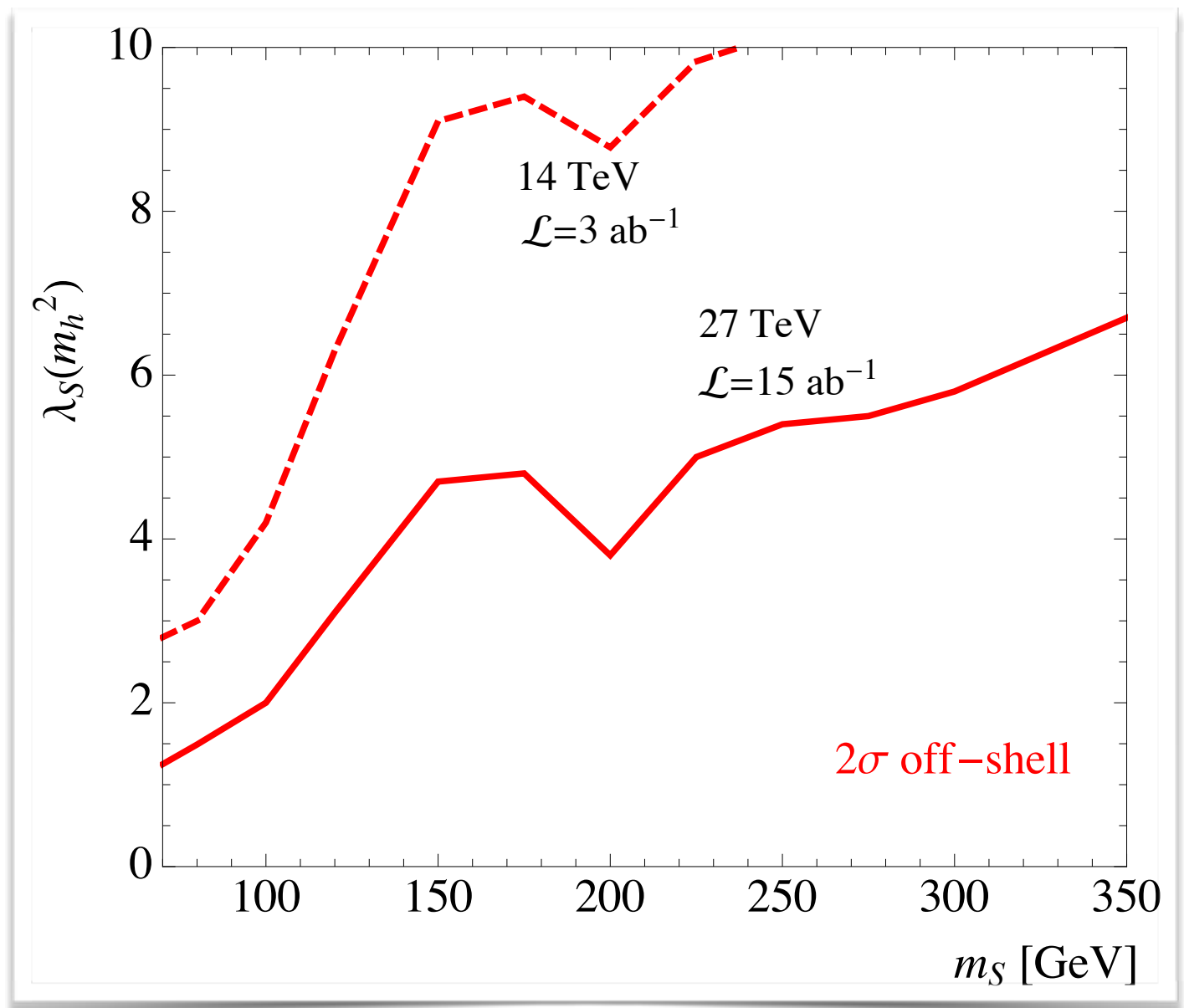
$$m_h^2 = (m_h^0)^2 + \delta m_h^2$$



$$\delta m_h^2 = \frac{\Lambda^2}{16\pi^2} (-6y_t^2 + \lambda_S)$$

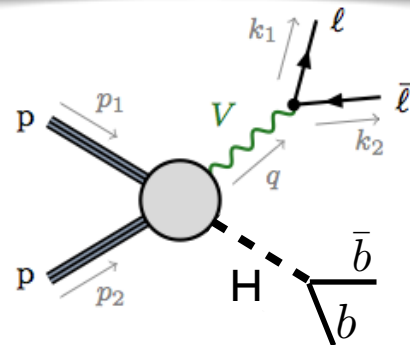
→ If $\lambda_S(\Lambda^2) = 6y_t^2(\Lambda^2)$ singlet is like stop
Alleviate the “**little hierarchy**” problem

Works for the maximally hidden scenario!

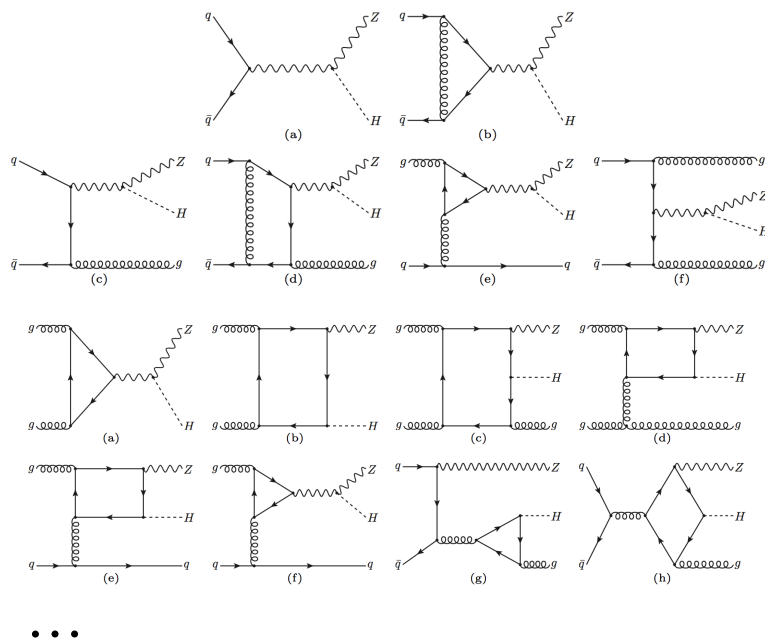


Gonçalves, Han, Mukhopadhyay (PRL '18, PRD '18)

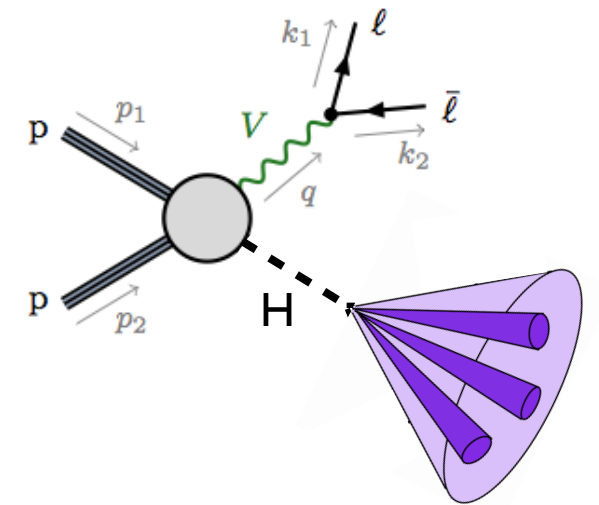
Paths towards precision



Higher order calculations



Efficient analysis technics



QCD corrections are dynamic and fundamental for robust predictions

Astill, Bizoń, Re, Zanderighi '18

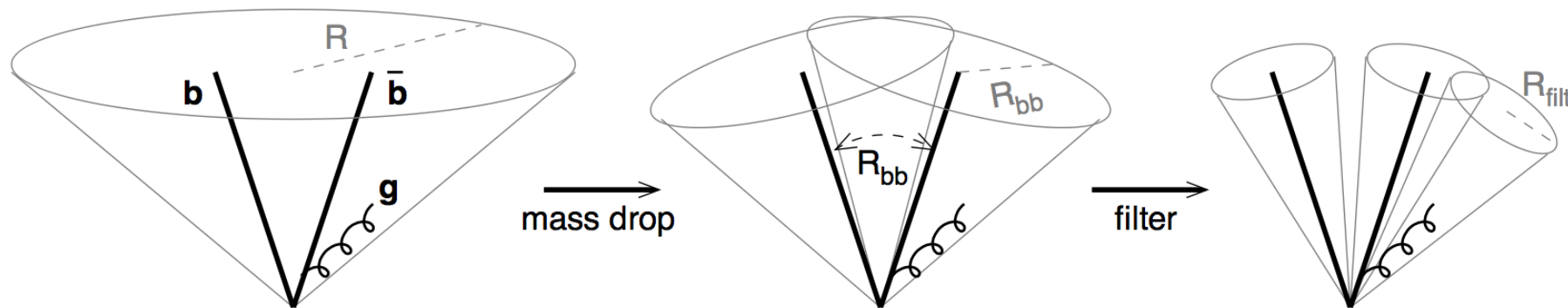
Gonçalves, Krauss, Kuttimalai, Maierhoefer '15

Paths towards precision

BR($H \rightarrow bb$) $\sim 58\%$: Largest, yet very challenging Higgs decay (overwhelming QCD backgrounds)

Jet substructure revolution

Butterworth, Davison, Rubin, Salam (2008) - **BDRS method**



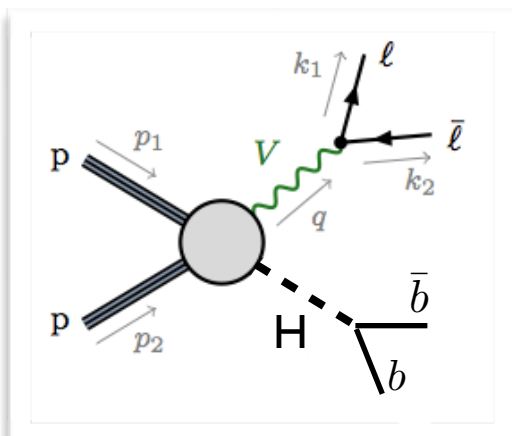
Despite the huge theoretical/experimental effort, it is still challenging to access the BR($H \rightarrow bb$)

Only last year, ATLAS/CMS claimed observation (and it required a major combination with several channels)

Data

Analysis

Current sensitivity

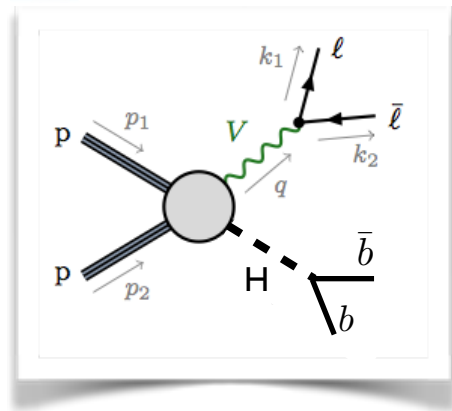


Channel	Significance	
	Exp.	Obs.
VBF+ggF	0.9	1.5
$t\bar{t}H$	1.9	1.9
VH	5.1	4.9
$H \rightarrow bb$ Combination	5.5	5.4

ATLAS '18

Role of the Z polarization in the $H \rightarrow bb$ measurement

Z polarization displays a rich amount of information (8 multipoles coef.) and is **not systematically limited**

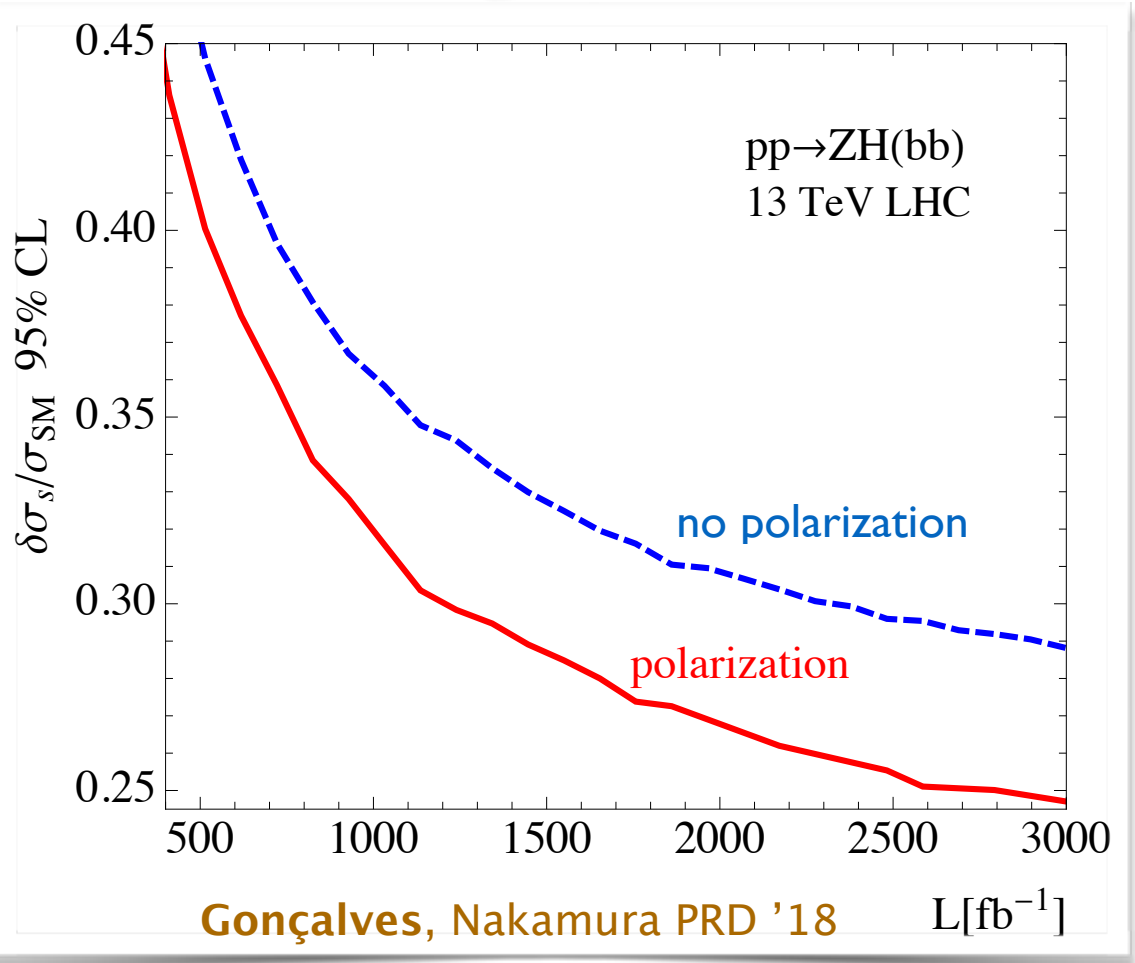


$$\ell^-(\ell^+) : \frac{m_{\ell\ell}}{2} (1, \pm \sin \theta \cos \phi, \pm \sin \theta \sin \phi, \pm \cos \theta)$$

$$\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta d\phi} = 1 + \cos^2 \theta + A_1(1 - 3 \cos^2 \theta) + A_2 \sin 2\theta \cos \phi + A_3 \sin^2 \theta \cos 2\phi$$

$$+ A_4 \cos \theta + A_5 \sin \theta \cos \phi + A_6 \sin \theta \sin \phi + A_7 \sin 2\theta \sin \phi + A_8 \sin^2 \theta \sin 2\phi$$

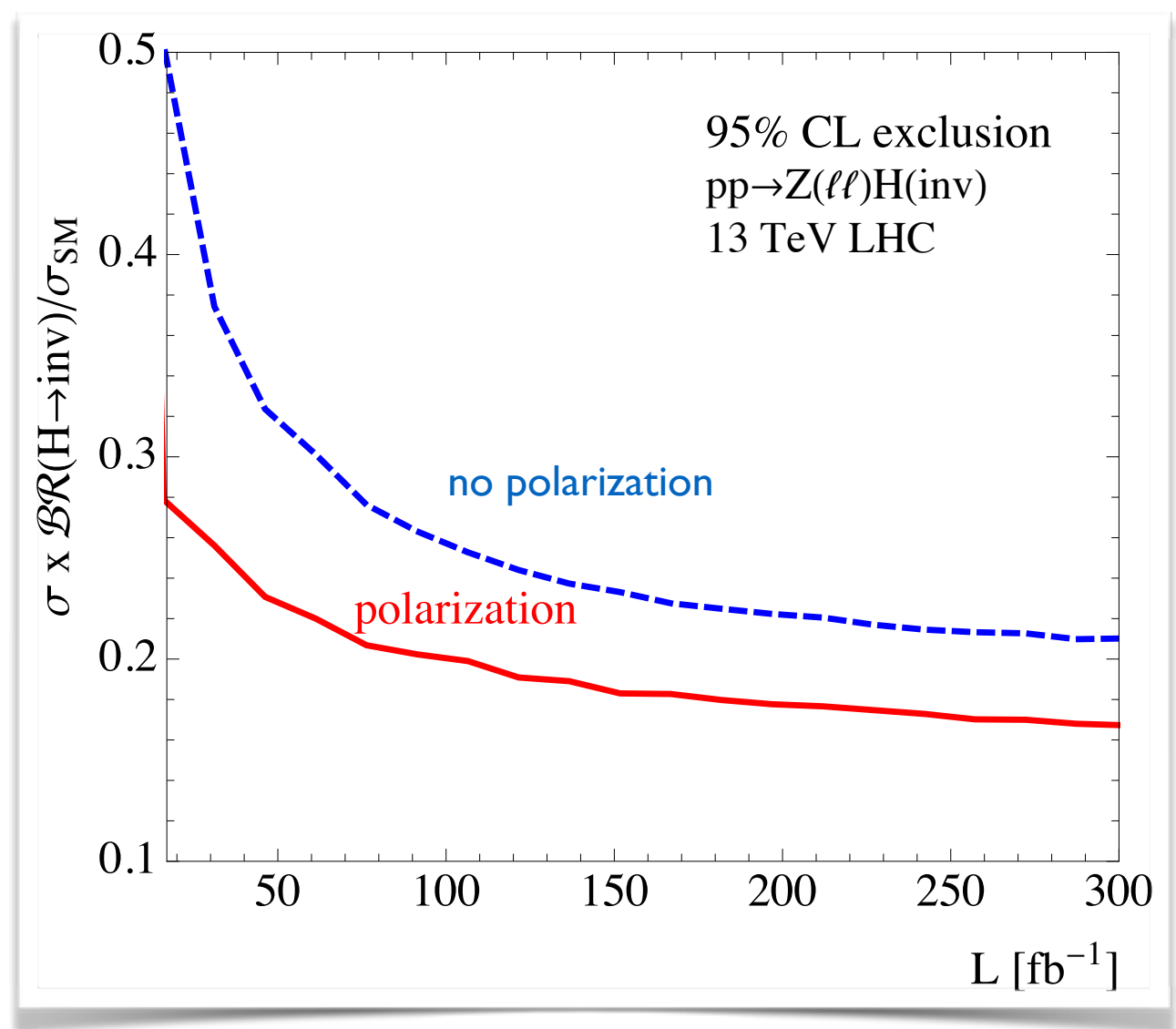
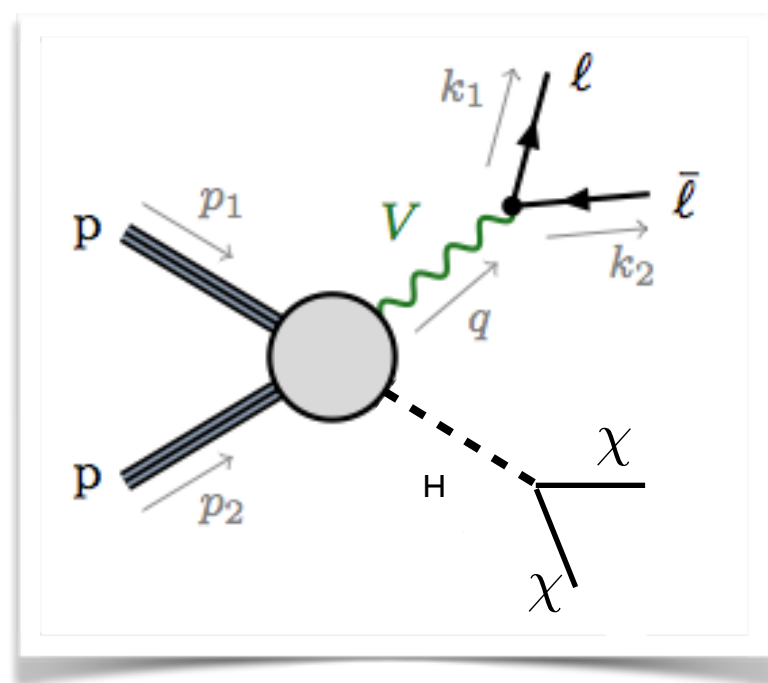
Hagiwara, Hikasa, Kai (1984)



- ➡ Lepton angular distribution works as an analyser, probing **underlying production dynamics** encoded in the A_i coefficients: ZH(bb) vs Zbb
- ➡ It relies only on lepton reconstruction with small experimental uncertainties. It can be promptly included in the ATLAS and CMS studies

Boosting the $H \rightarrow \text{inv}$ searches with Z boson polarization

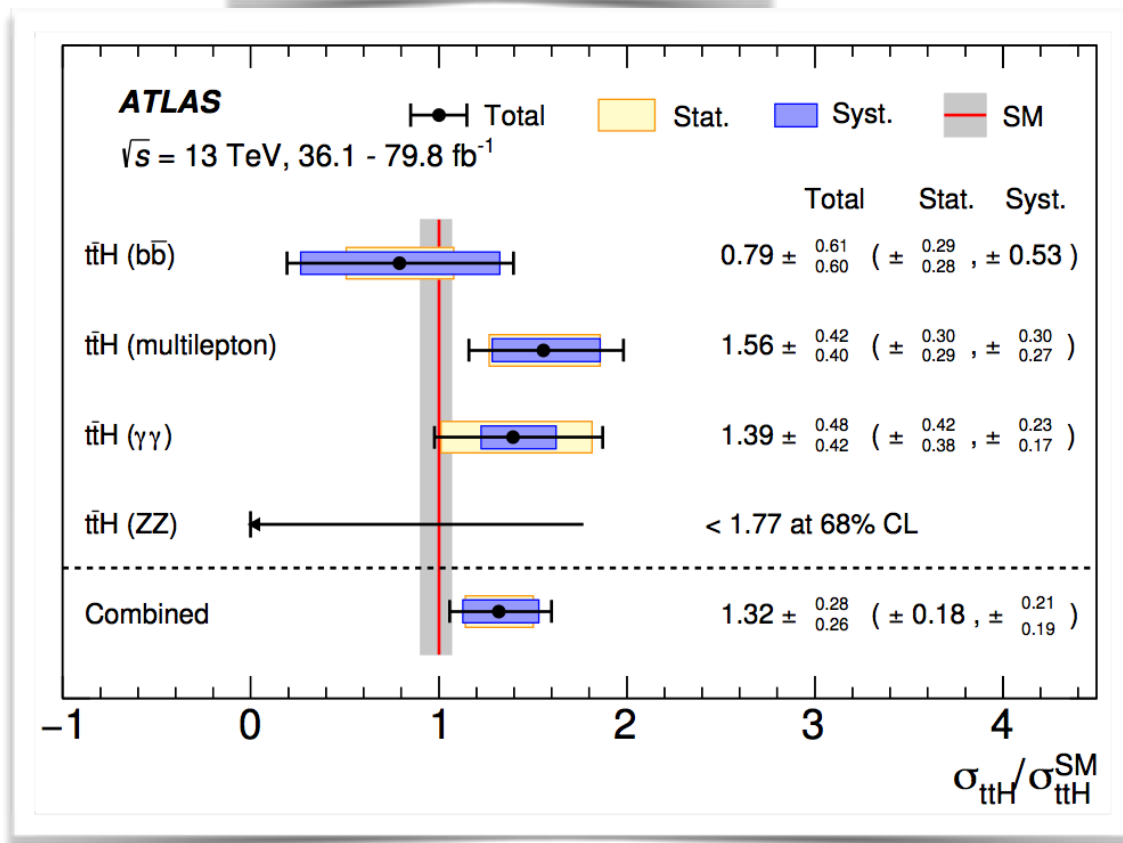
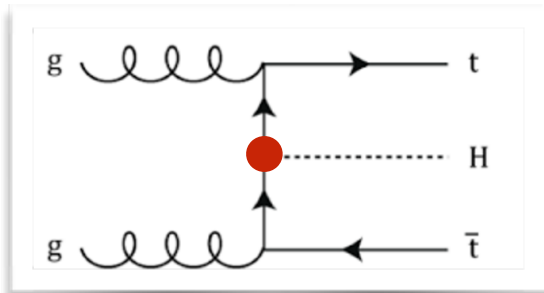
- It directly generalizes to other relevant searches such as $Z(\ell\bar{\ell})H(\text{inv})$:
Does not depend on the Higgs decay, only on the Z polarization



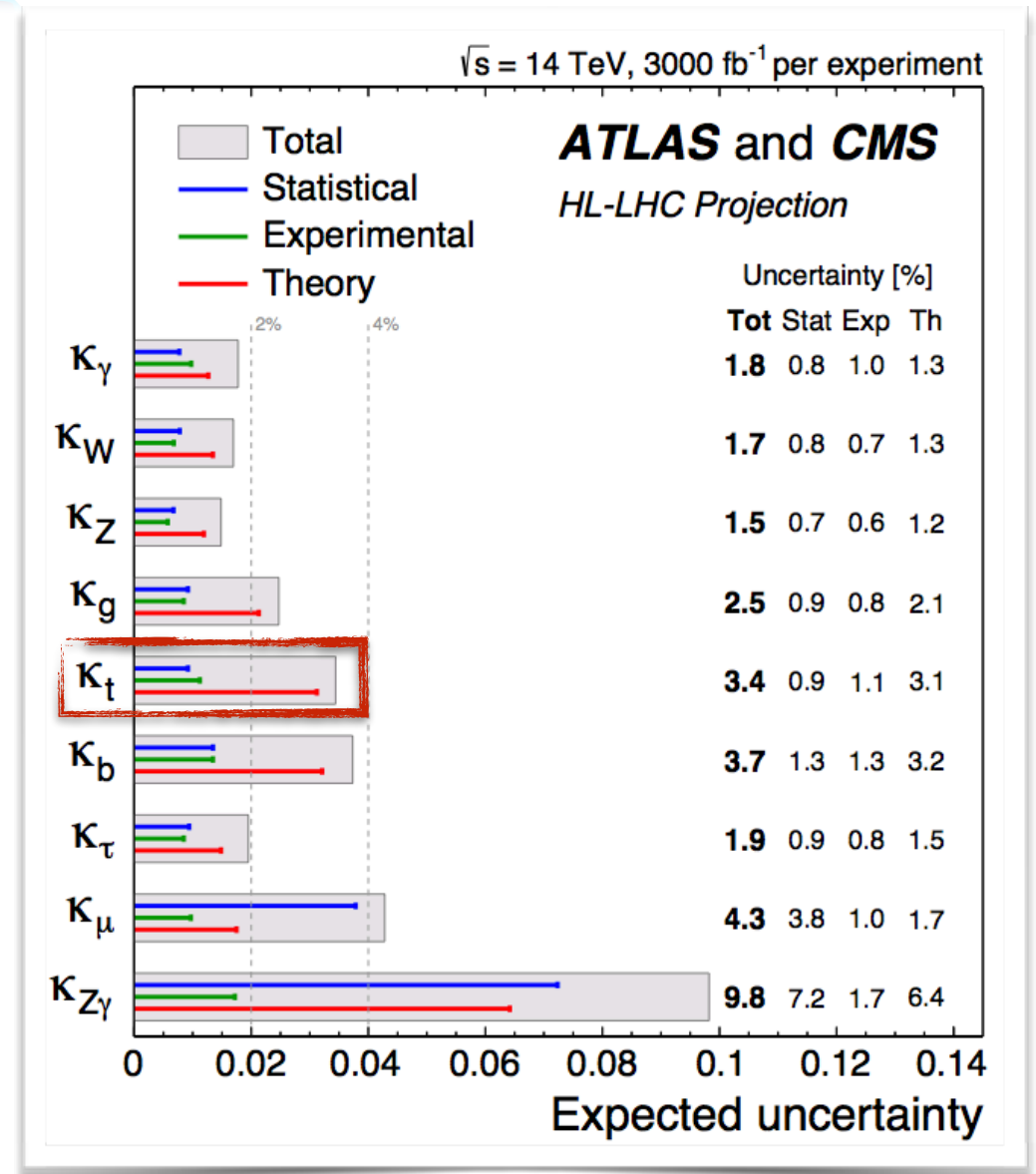
Gonçalves, Nakamura PRD '19

Direct CP measurement of Higgs-top coupling

ttH channel observation (2018):



Expected HL-LHC precisions:

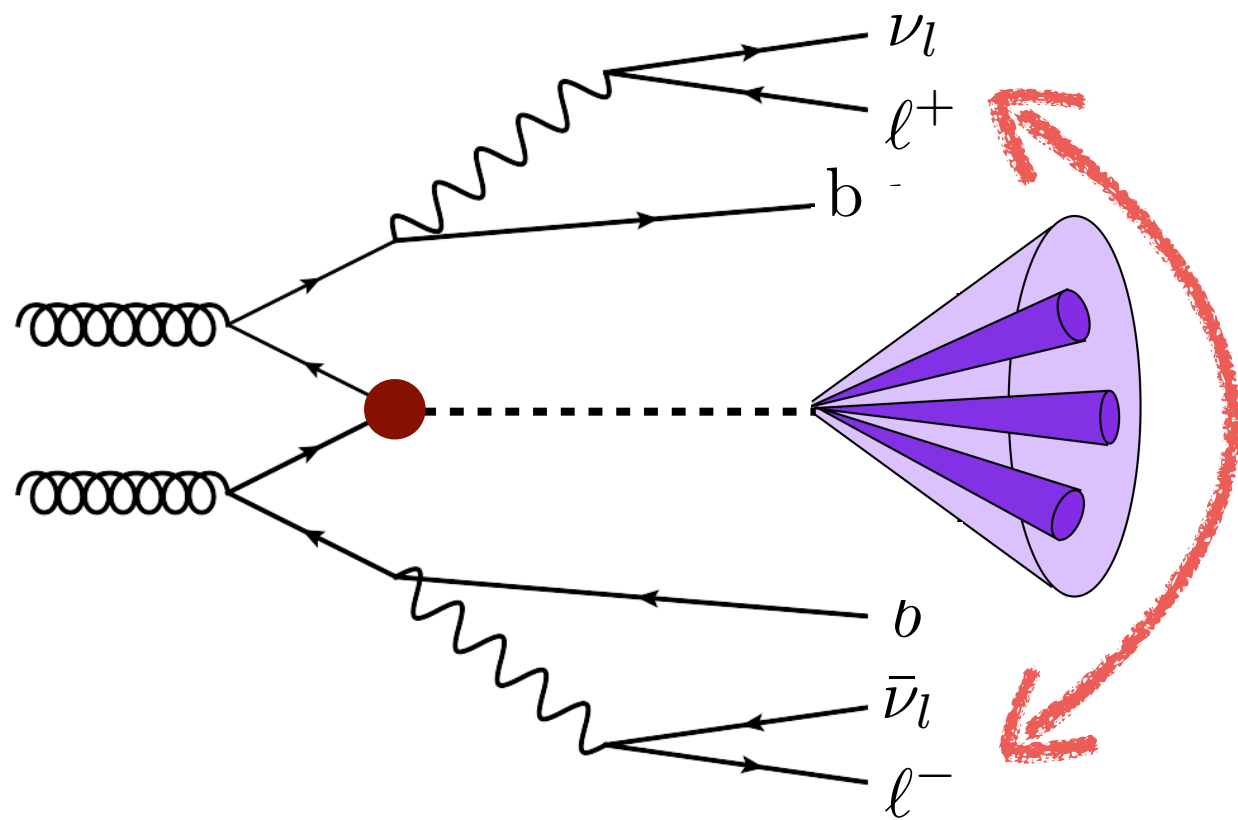


Can we go beyond and directly measure Higgs-top CP structure at the LHC?

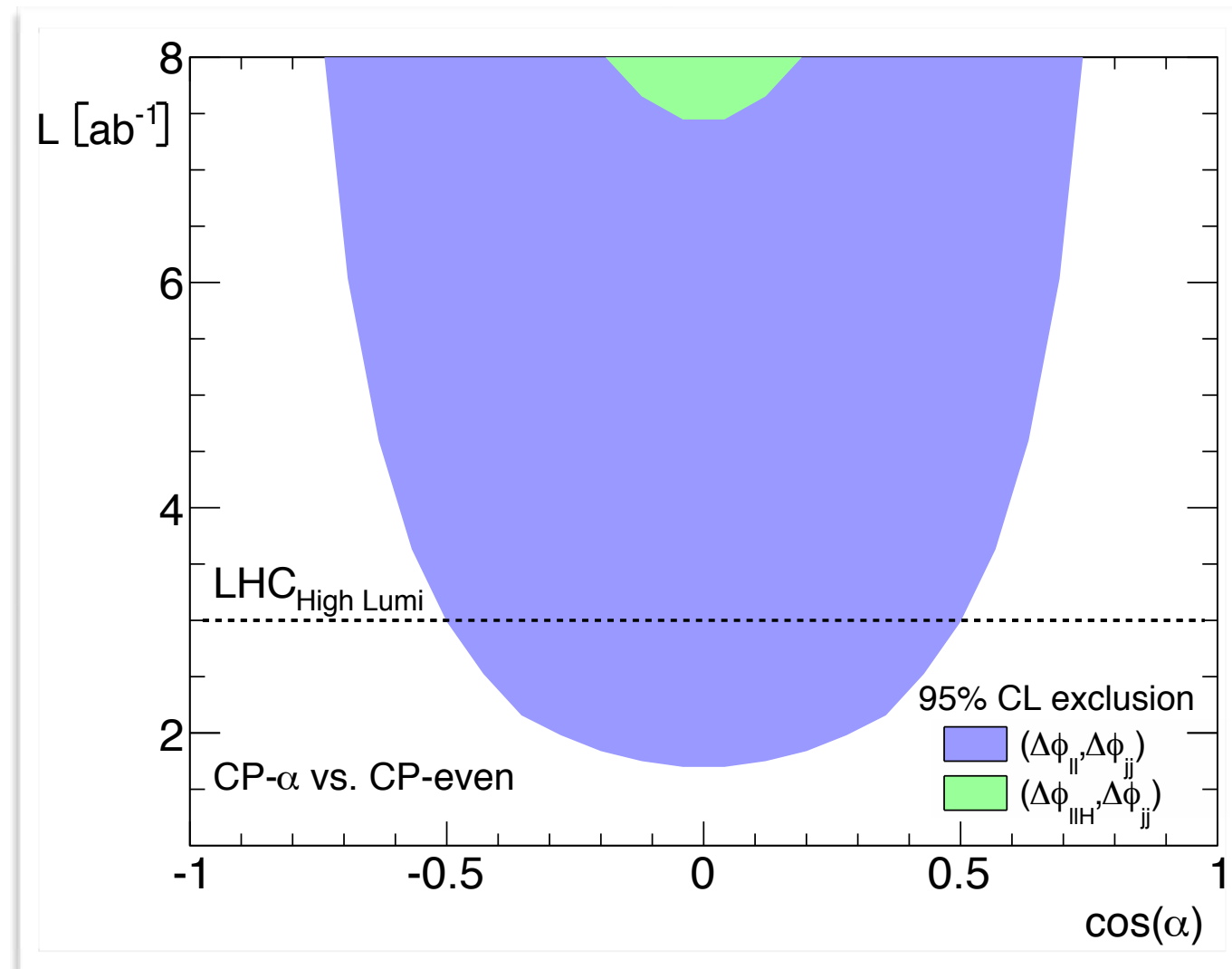
$$\mathcal{L} \supseteq -\frac{m_t}{v} K \bar{t} (\cos \alpha + i \gamma_5 \sin \alpha) t H$$

Direct CP measurement of Higgs-top coupling

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



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



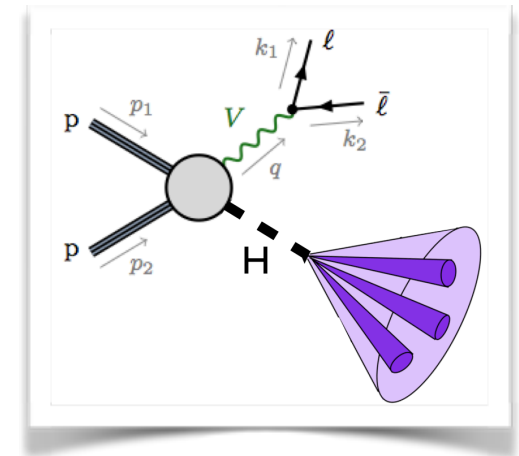
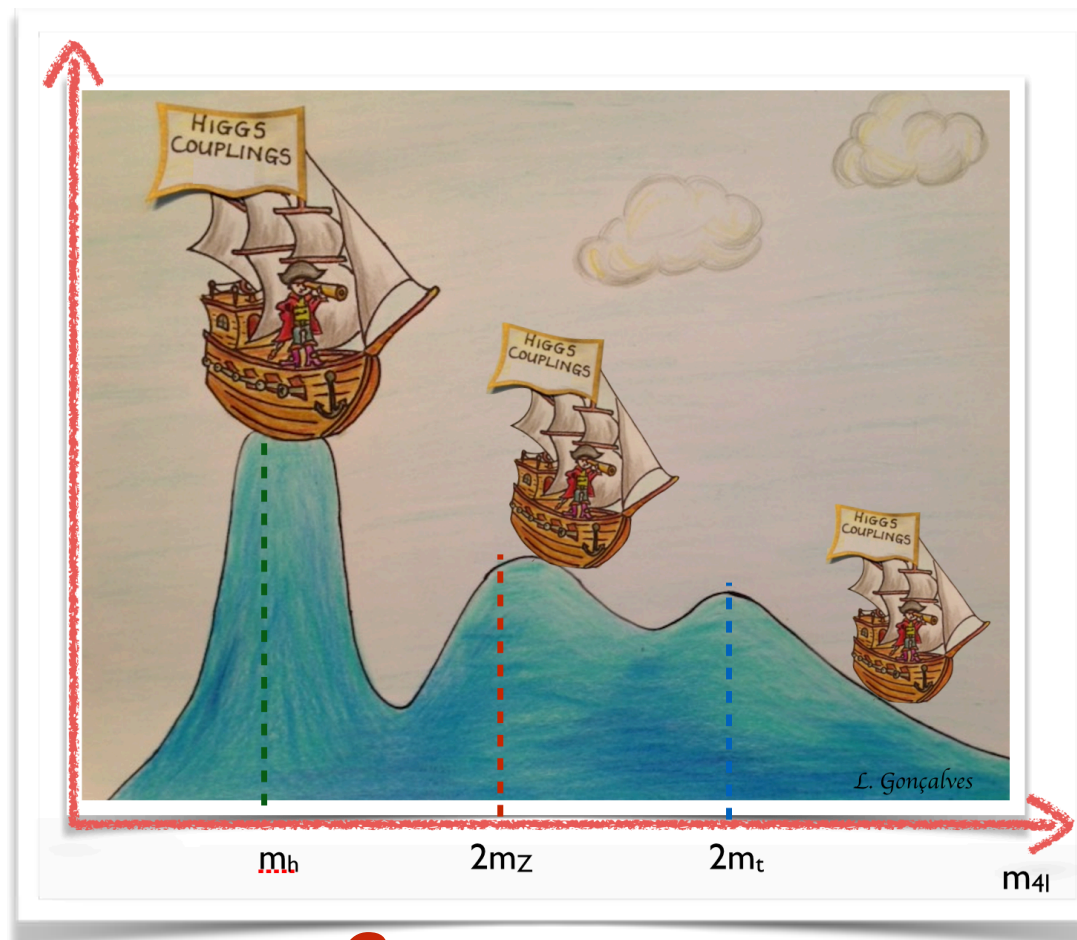
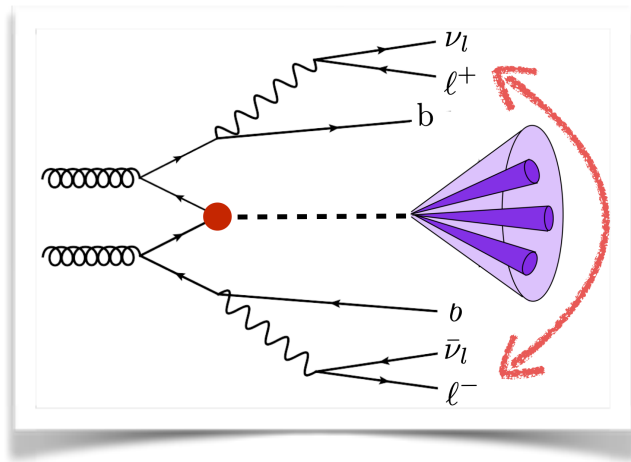
Buckley, Gonçalves (PRL '15)

- New powerful observables and reconstruction: sensitive to $|\cos \alpha| < 0.7$ Gonçalves, Kong, Kim '18

Summary

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

- **Off-shell Higgs** - New probe to the maximally hidden Higgs portal scenario. May display connections to hierarchy problem, DM...
- **Comprehensive Z polarization**: can significantly improve the LHC sensitivity to $ZH(bb)$ & $ZH(inv)$. Small experimental uncertainties. Can be promptly included in ATLAS and CMS studies
- **Direct Higgs-top CP-measurement**: Analogously to Higgs-top signal strength measurement, ttH provides direct probe Higgs-top CP-structure. **Relevant target for forthcoming experimental analyses**



Thank you for your attention!

