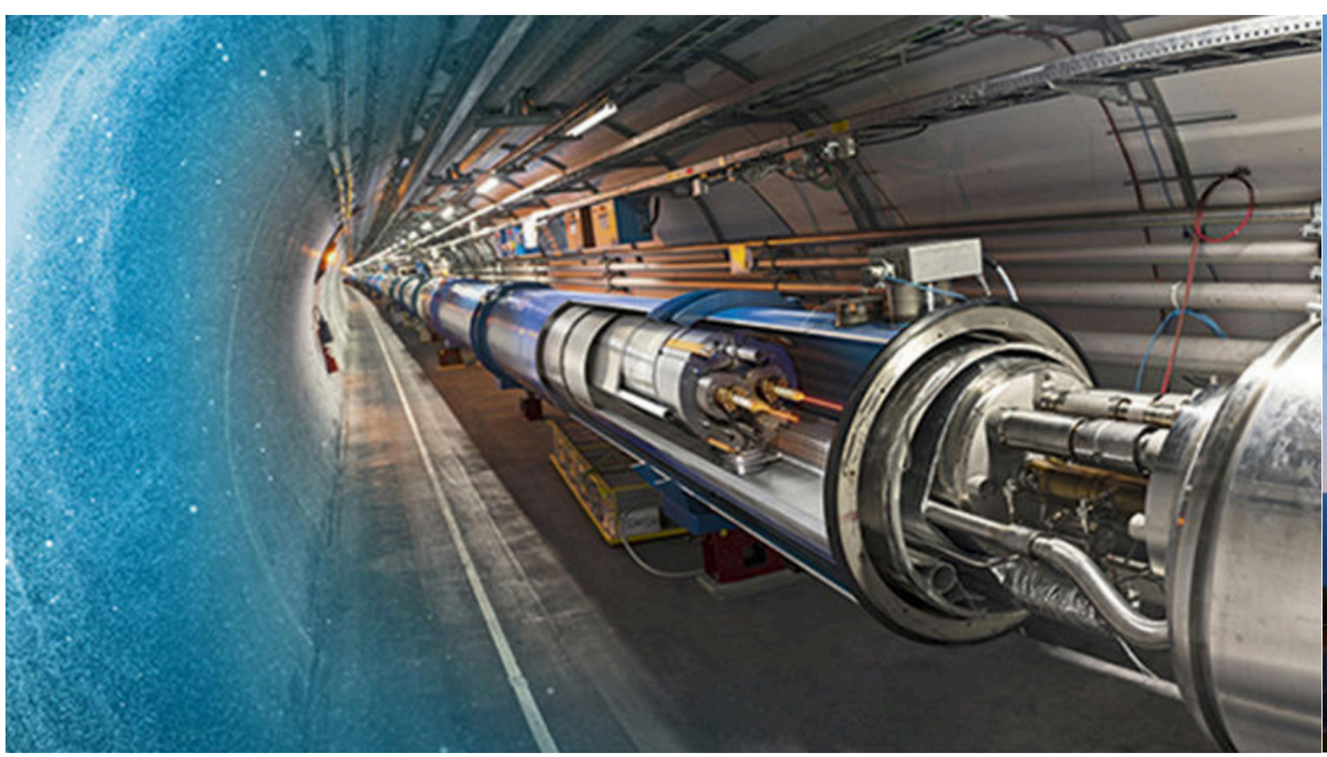
Double Higgs production

HL/HE LHC workshop

CERN - 18.06.2018

Dorival Gonçalves

Based on work with T. Han, F. Kling, T. Plehn, M. Takeuchi arxiv:1802.04312



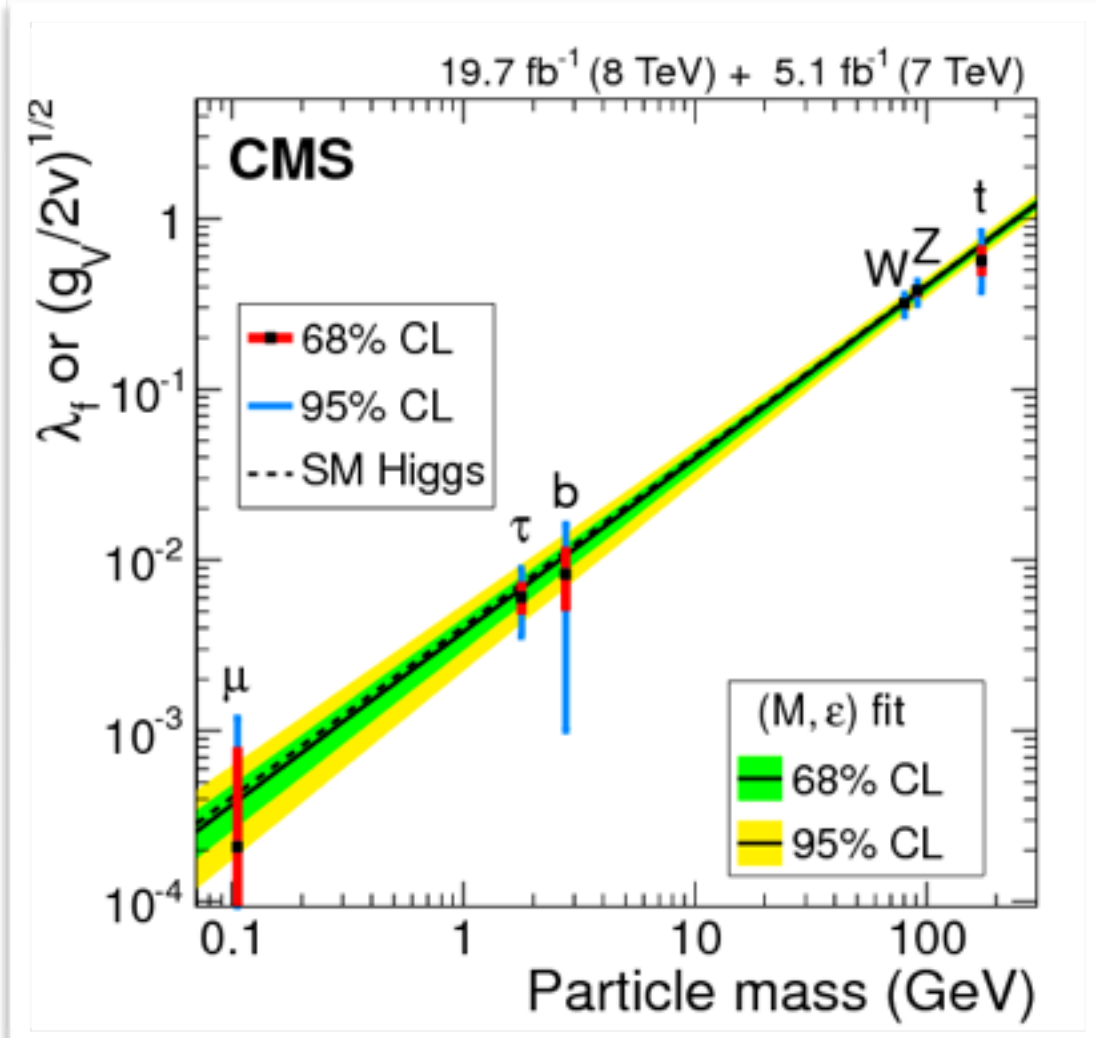
Motivation

- The properties of the Higgs sector are uniquely determined in the SM
  Any deviation would be a smoking gun signature for physics beyond SM

Goal: few percent precision *in* ***Higgs couplings measurements***

Huge experimental & theoretical effort

→ Higgs couplings to fermions and gauge bosons so far compatible with SM



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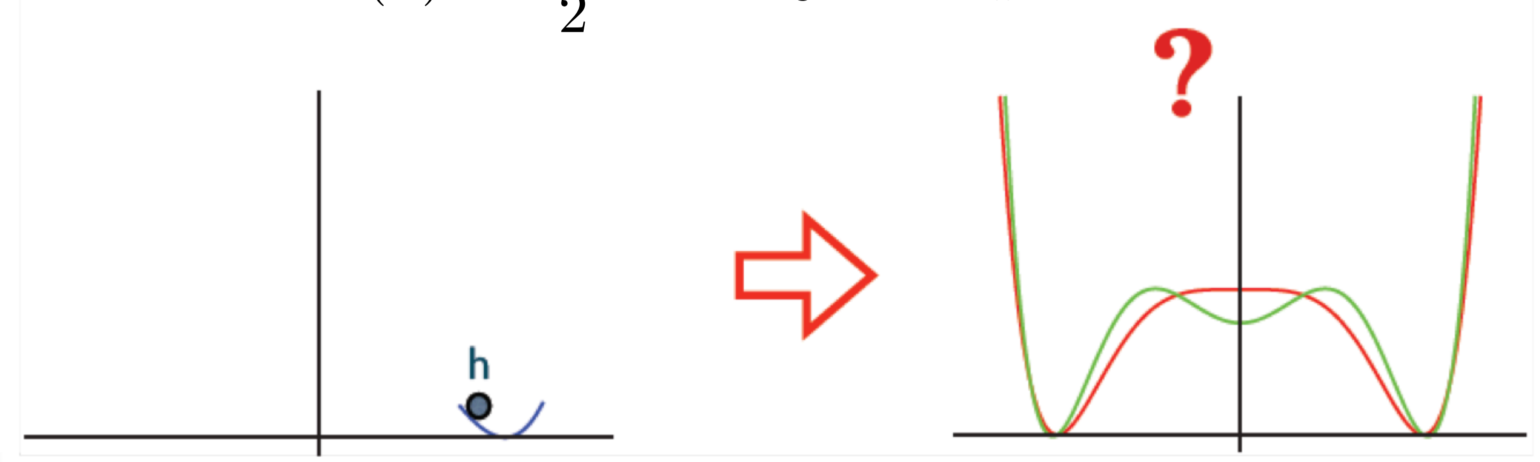
Goal: few percent precision** in **Higgs couplings measurements

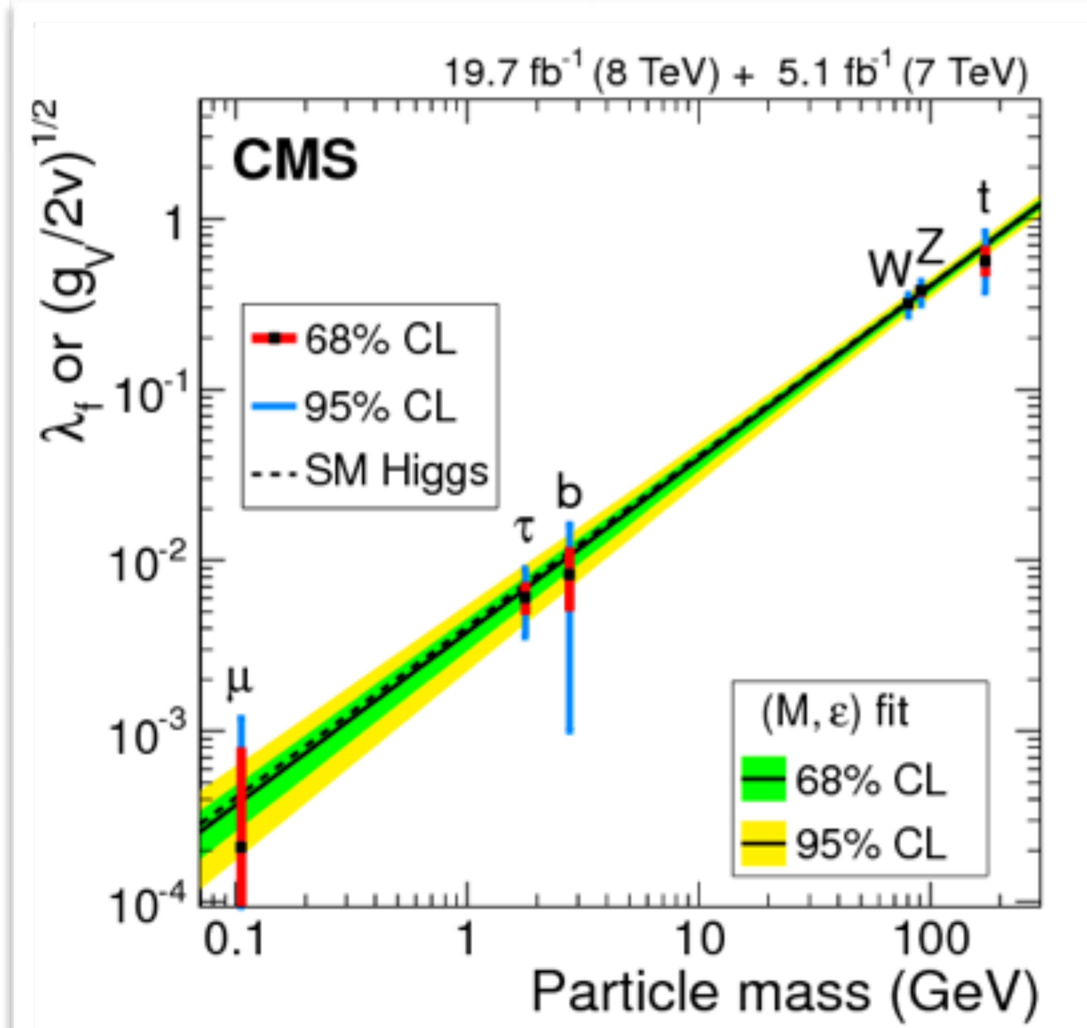
Huge experimental & theoretical effort

➡ Higgs couplings to fermions and gauge bosons so far compatible with SM

➡ However, we still lack understanding of Higgs potential

$$V(h) = \frac{m_h^2}{2}h^2 + \lambda_3 h^3 + \lambda_4 h^4 + \ldots$$



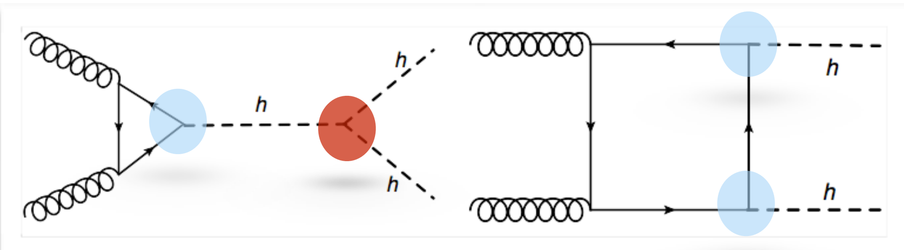


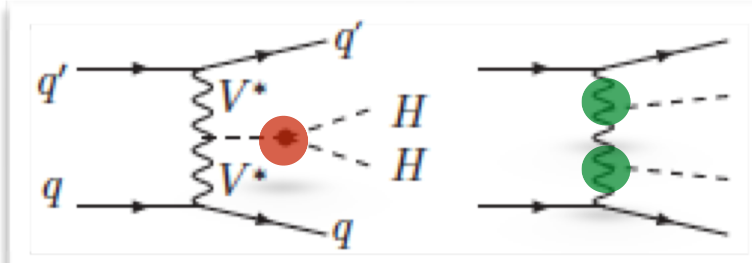
➡ Elementary scalar self-interaction has never been measured

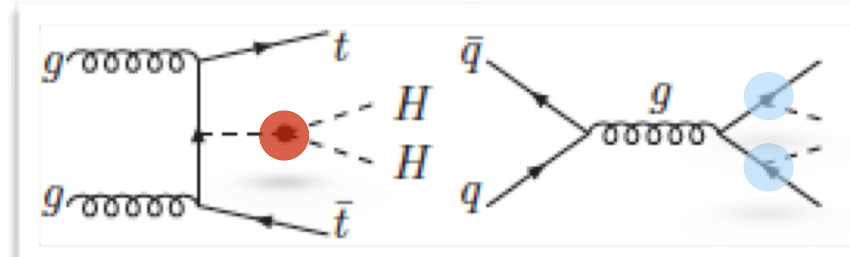
➡ Could probe the nature of the EW phase transition: 1st vs. 2nd order

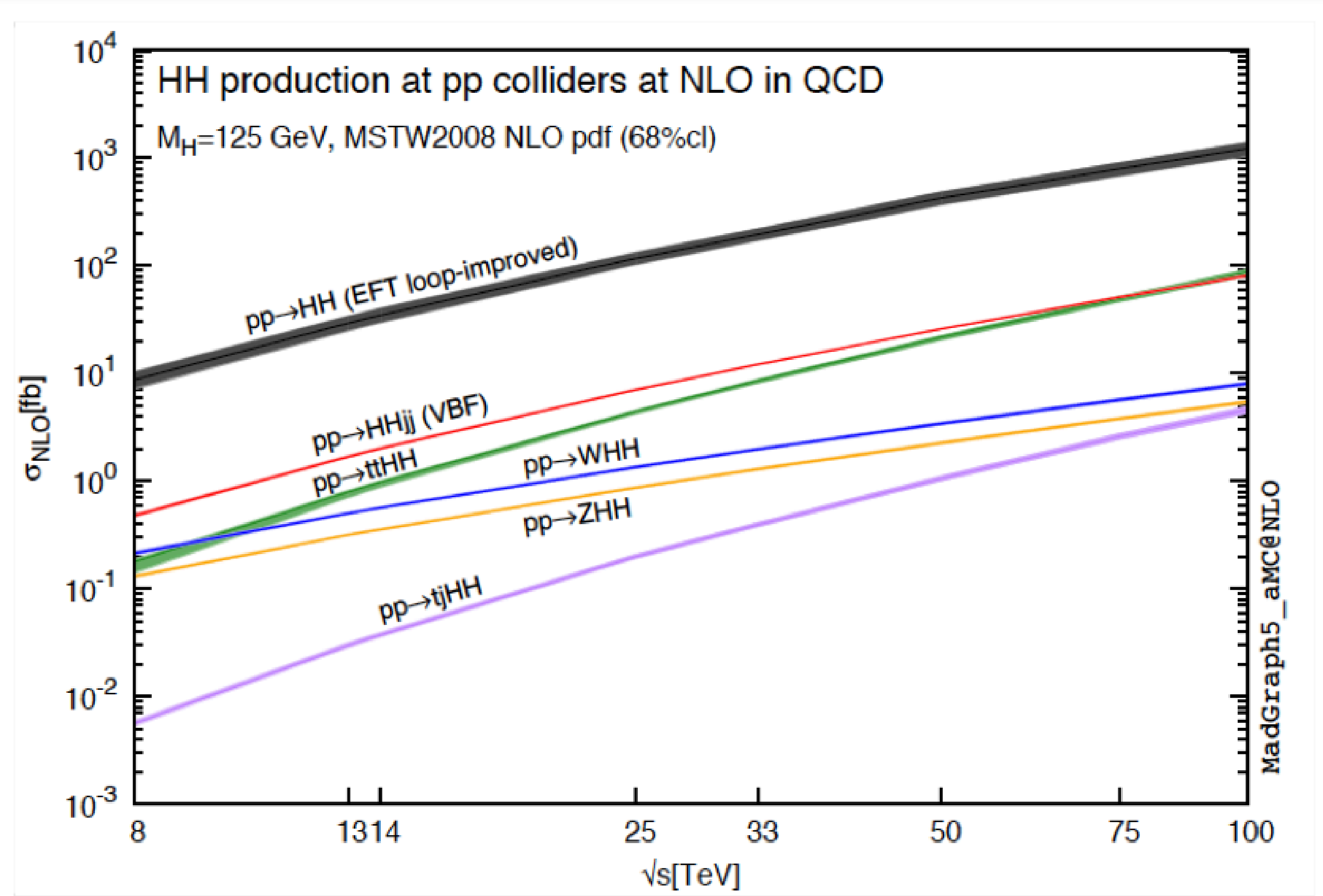
Double Higgs production

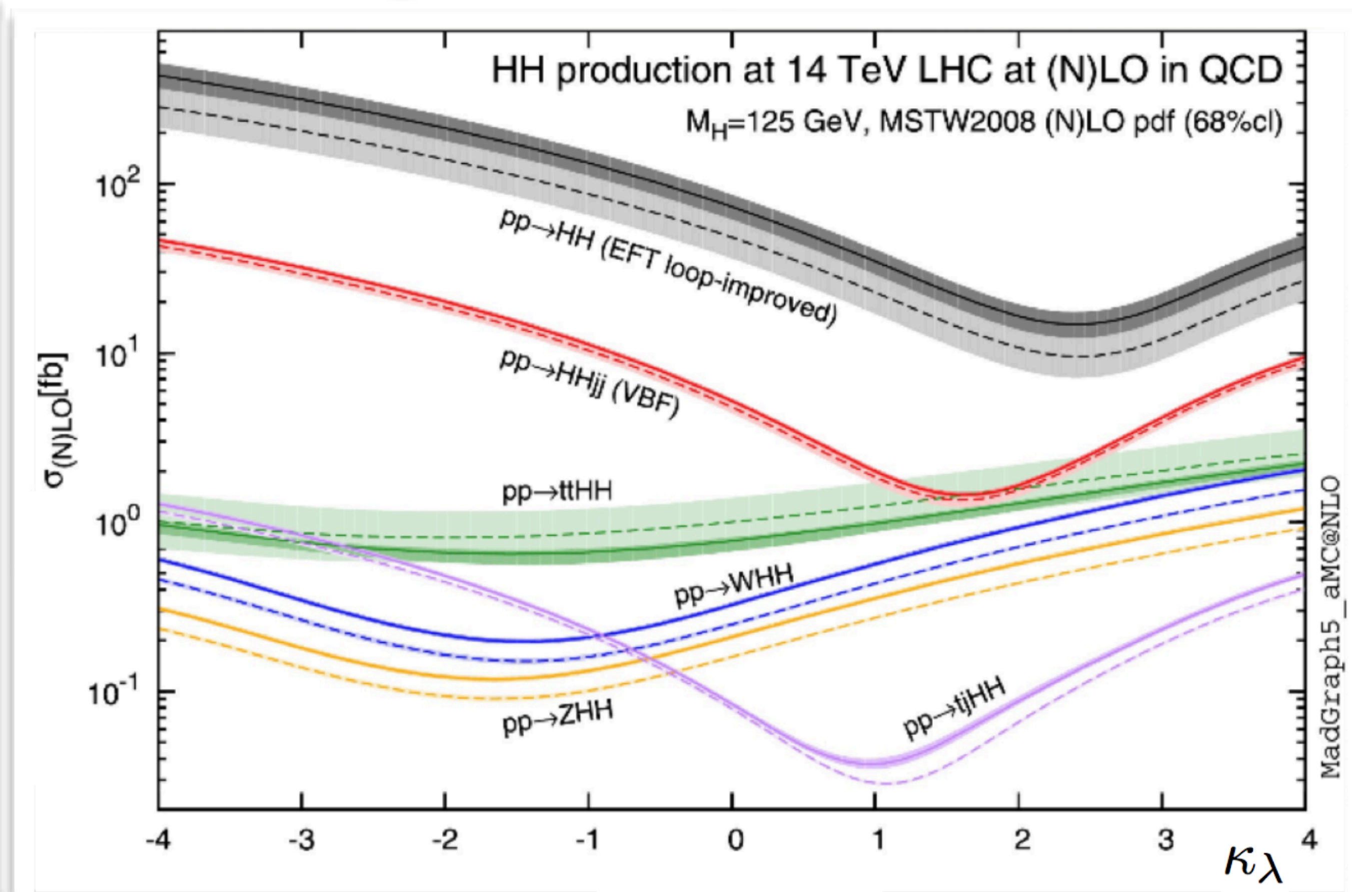
- **Double Higgs production** fundamental to **reconstruct Higgs potential**





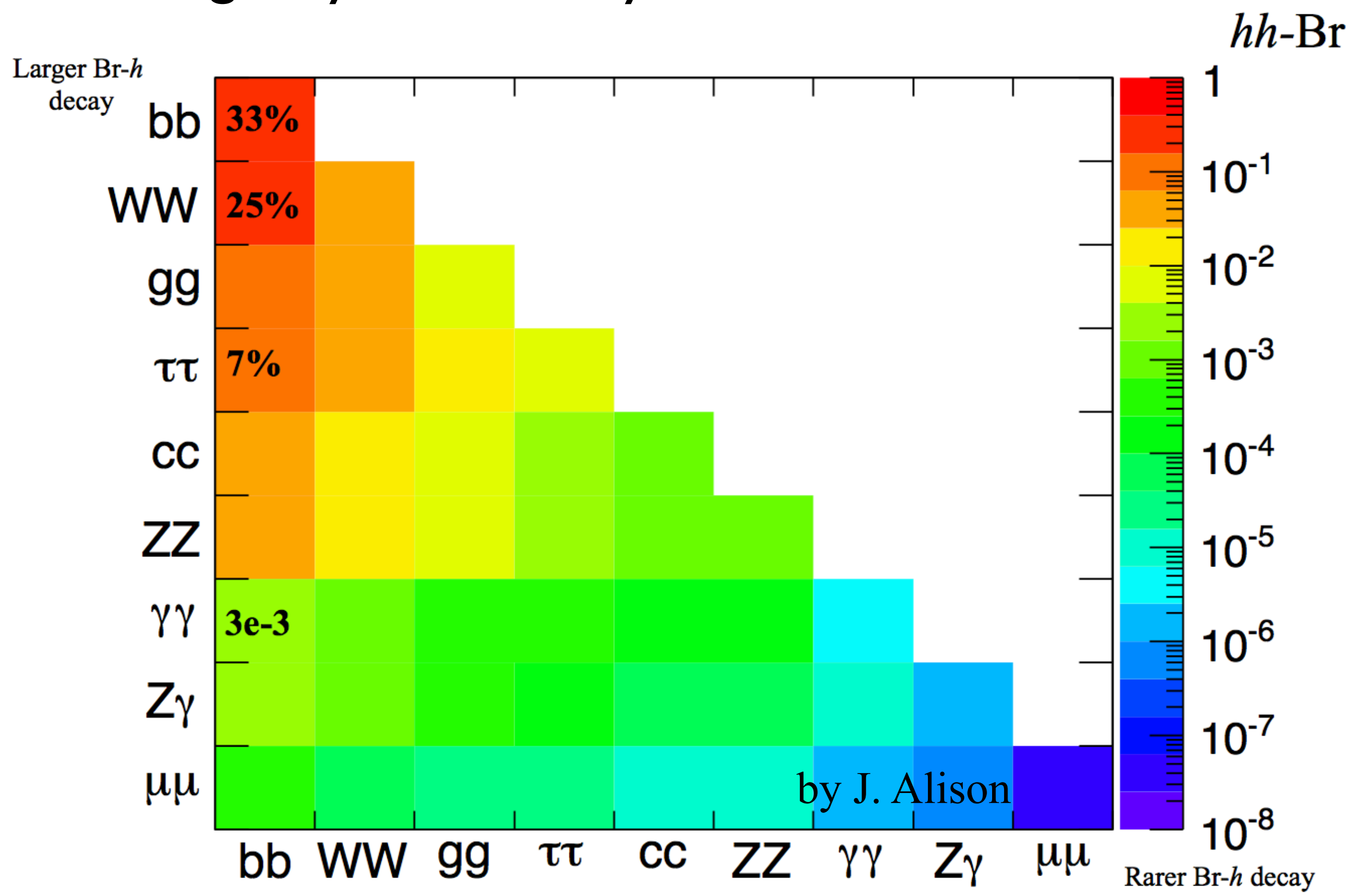






Double Higgs decays

- HH displays phenomenologically rich variety of final states:



- Huge theoretical & experimental effort exploring promising final states: bbγγ, bb$\tau\tau$, 4b, bbWW…

→ Theoretical studies as well as current analyses point to bbγγ as the most promising signature at LHC

Complementarity

H(bb)	H(γγ)
Largest Branching ratio	Limited Branching ratio
High b-tagging efficiency	Excellent mass resolution

Double Higgs decays

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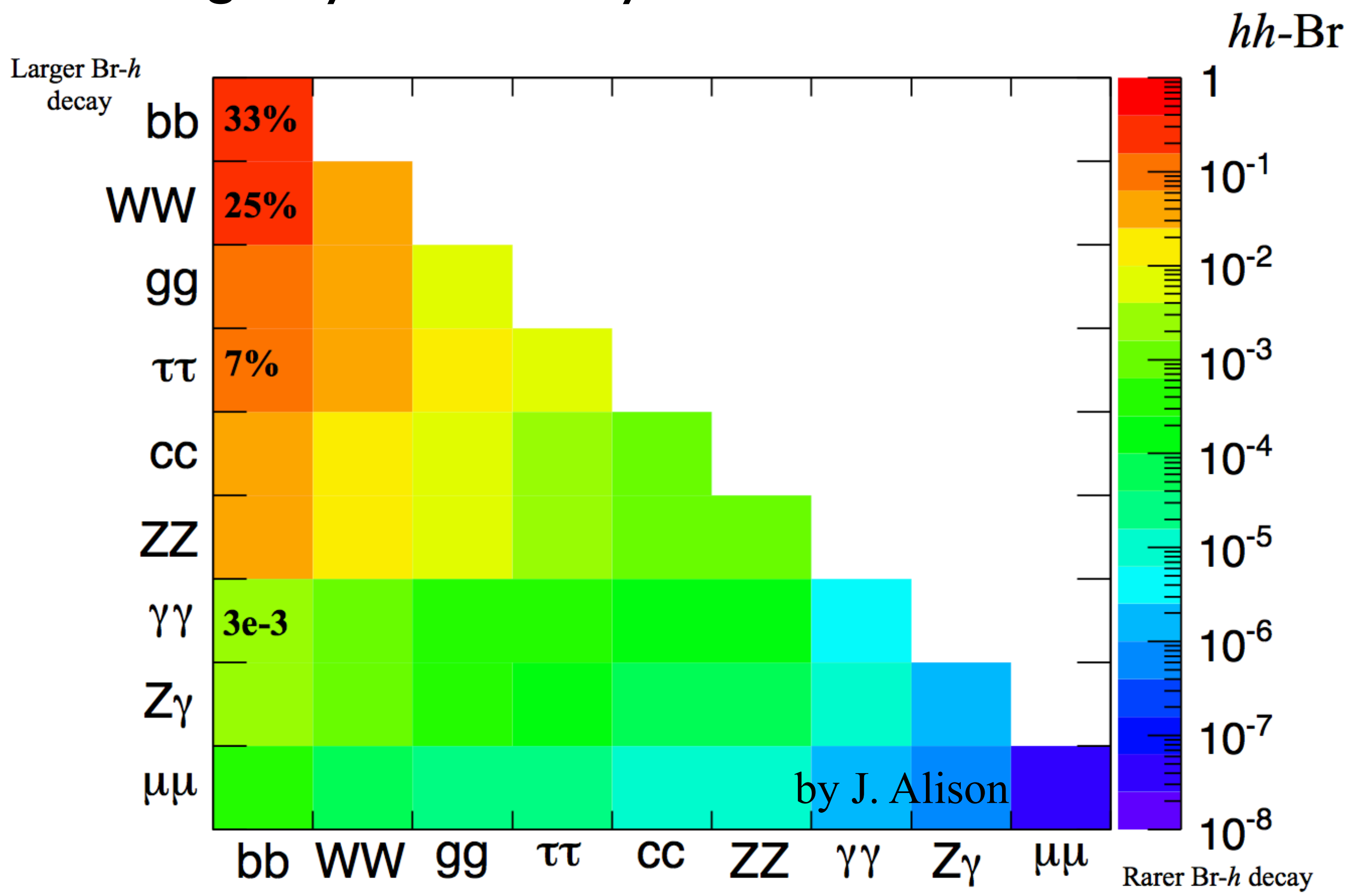
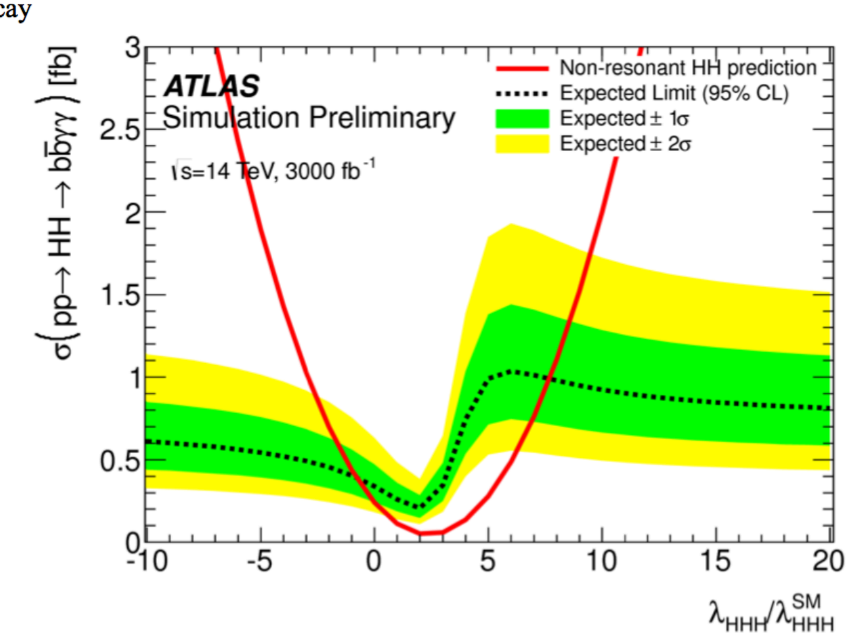


- HL-LHC projections:

	$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$ @95%CL	
$bb\gamma\gamma_{w/o\ sys}$	[-0.8, 7.7]	ATL-PHYS-PUB-2017-001
$bb\tau\tau$	[-4.0, 12.0]	ATL-PHYS-PUB-2015-046
4b	[-3.5, 11]	ATL-PHYS-PUB-2016-024



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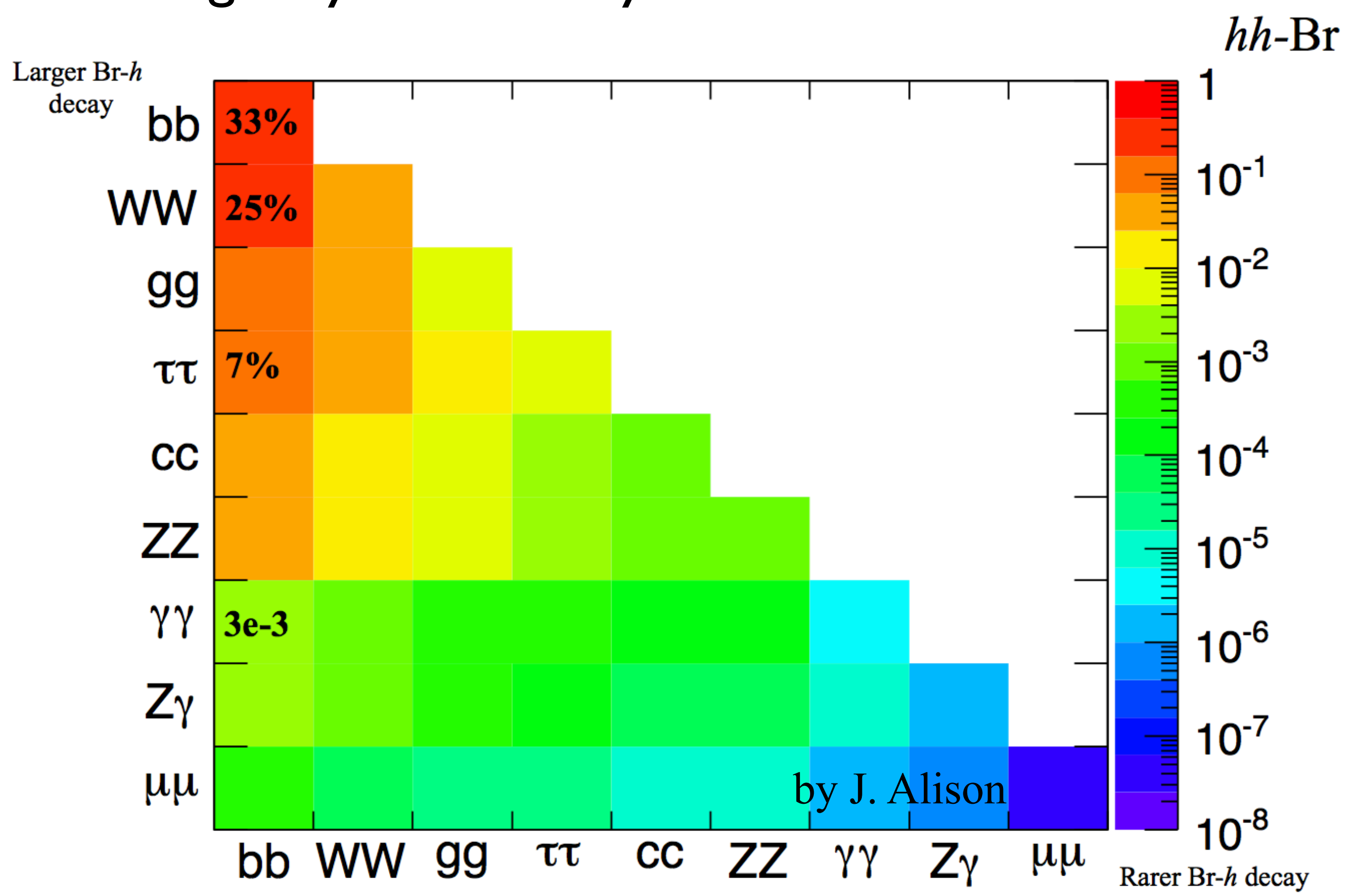

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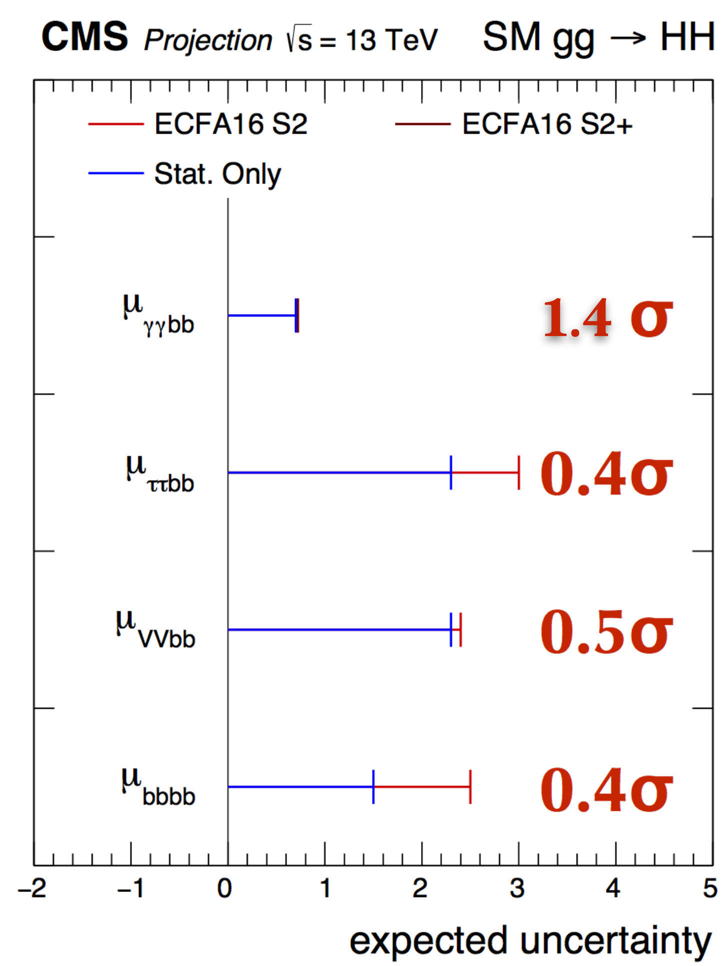
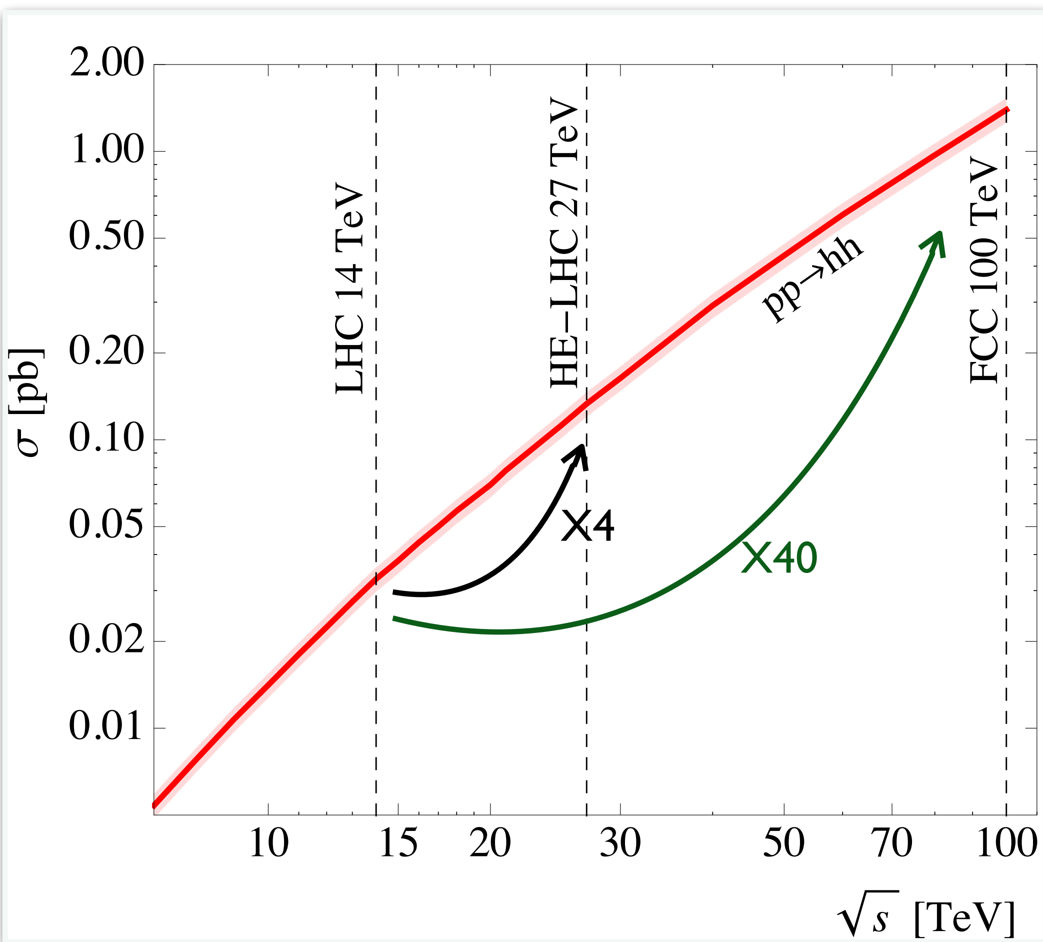


Future colliders

- Despite of the huge effort, it is far from satisfactory in probing the **Higgs potential**, HH falls short in precision in comparison to other Higgs property measurements

Clear motivation for a higher energy colliders

HL-LHC: 14 TeV 3 ab^{-1} | HE-LHC: 27 TeV 15 ab^{-1} | 100 TeV 30 ab^{-1}



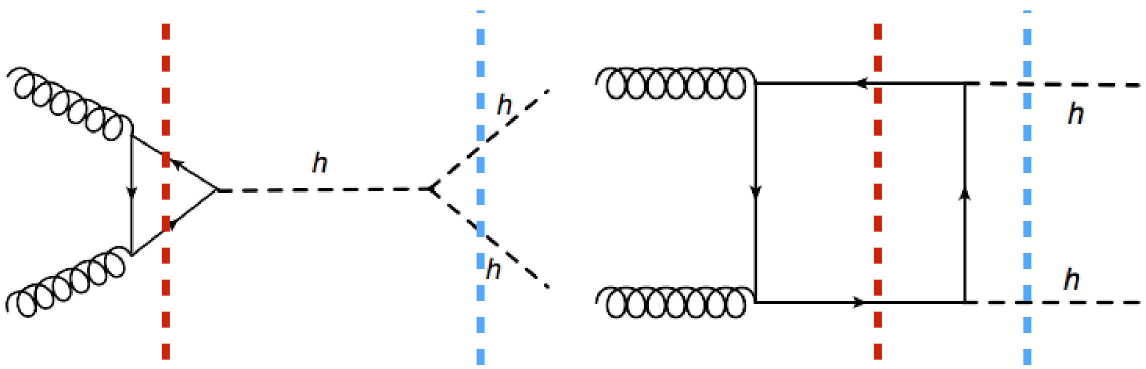
→ Factor 4 at 27 TeV in cross section and factor 40 at 100 TeV

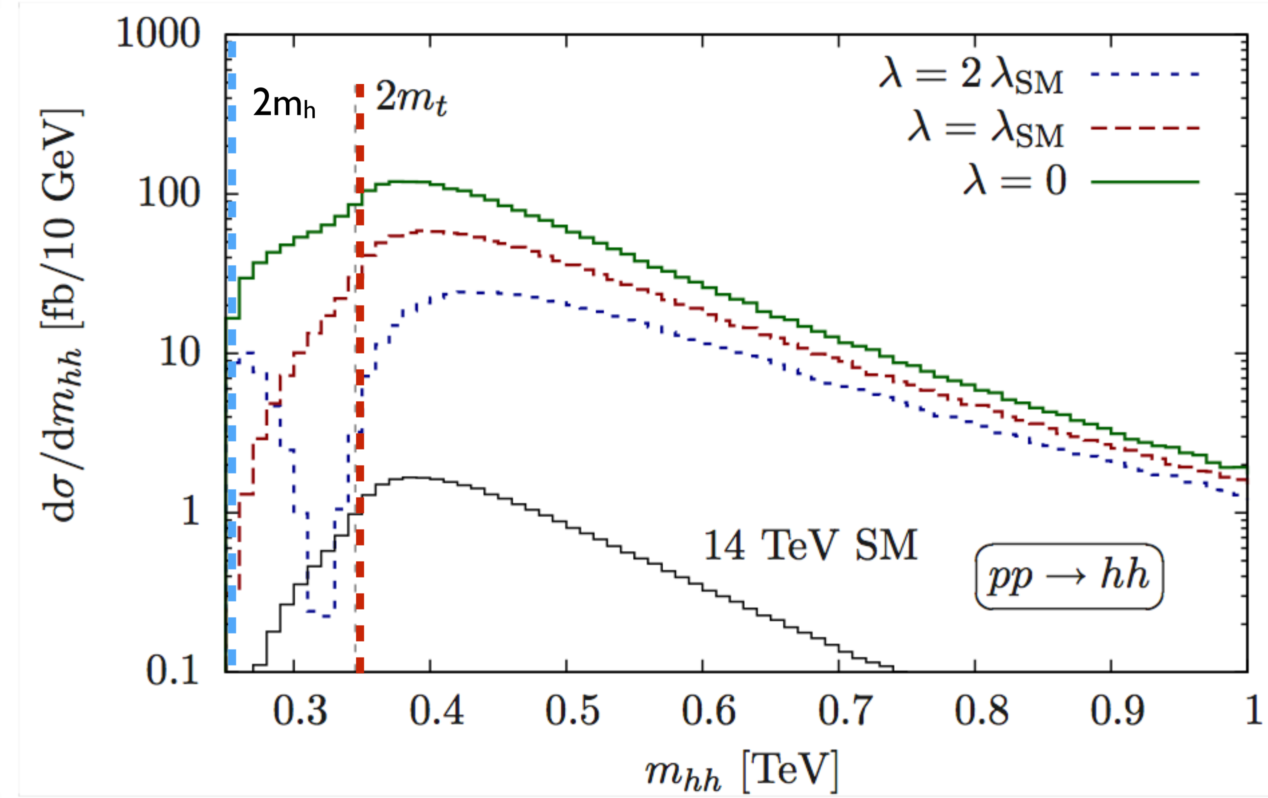
Accounting for the projected luminosities, this implies in an event increase

DG, Han, Kling, Plehn, Takeuchi (2018)

→ Increased energy and luminosity turns Higgs pair production into a valid channel for precision measurements

Where the sensitivities come from?





Barr, Dolan, Englert, Lima, Spannowsky (2014)

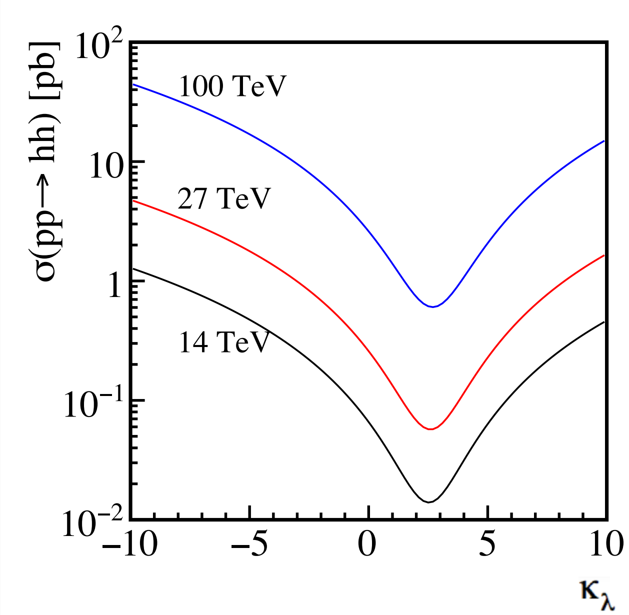
- Three distinctive phase space regimes:

→ $m_{hh}^{(\mathrm{th})} \approx 2m_h$

$$\frac{\alpha_s}{12\pi v}\left(\frac{\kappa_\lambda \lambda_{\mathrm{SM}}}{s-m_h^2} - \frac{1}{v}\right) \rightarrow \frac{\alpha_s}{12\pi v^2}(\kappa_\lambda - 1) \overset{\mathrm{SM}}{=} 0$$

→ $m_{hh}^{(\mathrm{abs})} \approx 2m_t$

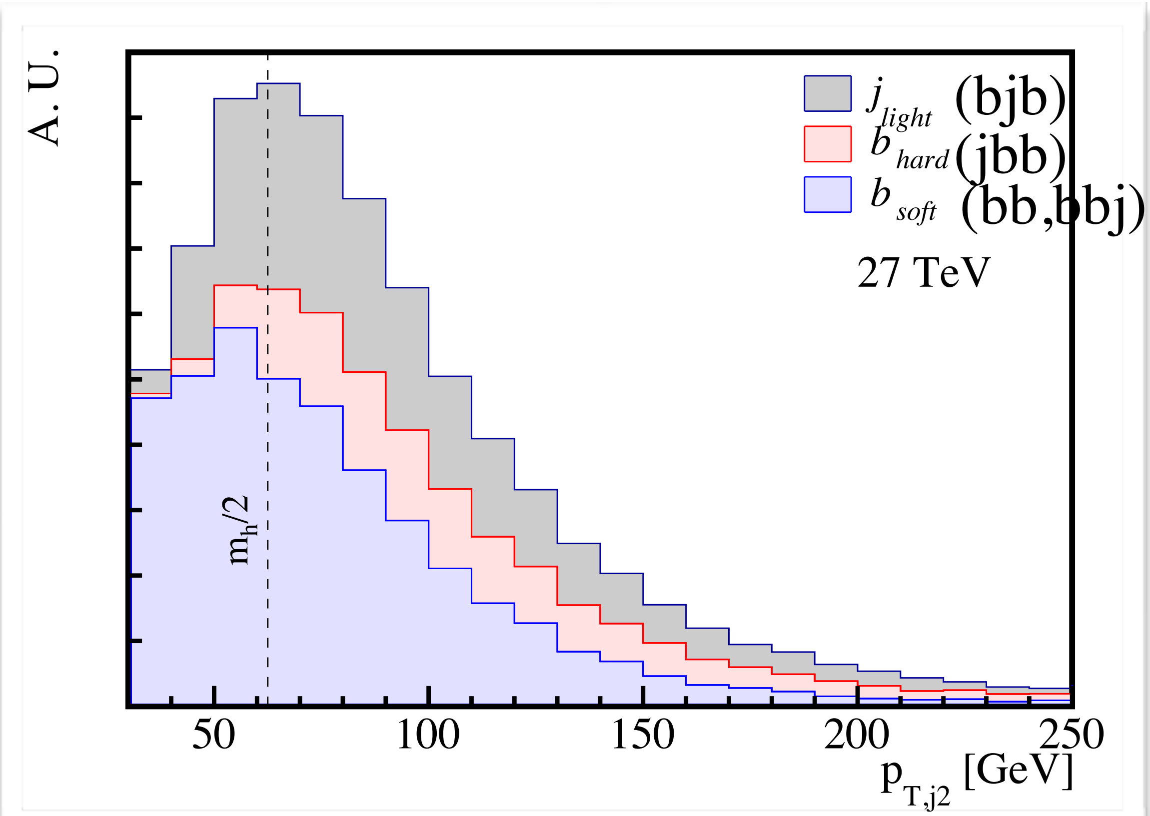
→ $m_{hh}^{(\mathrm{high})} \gg m_h, m_t$

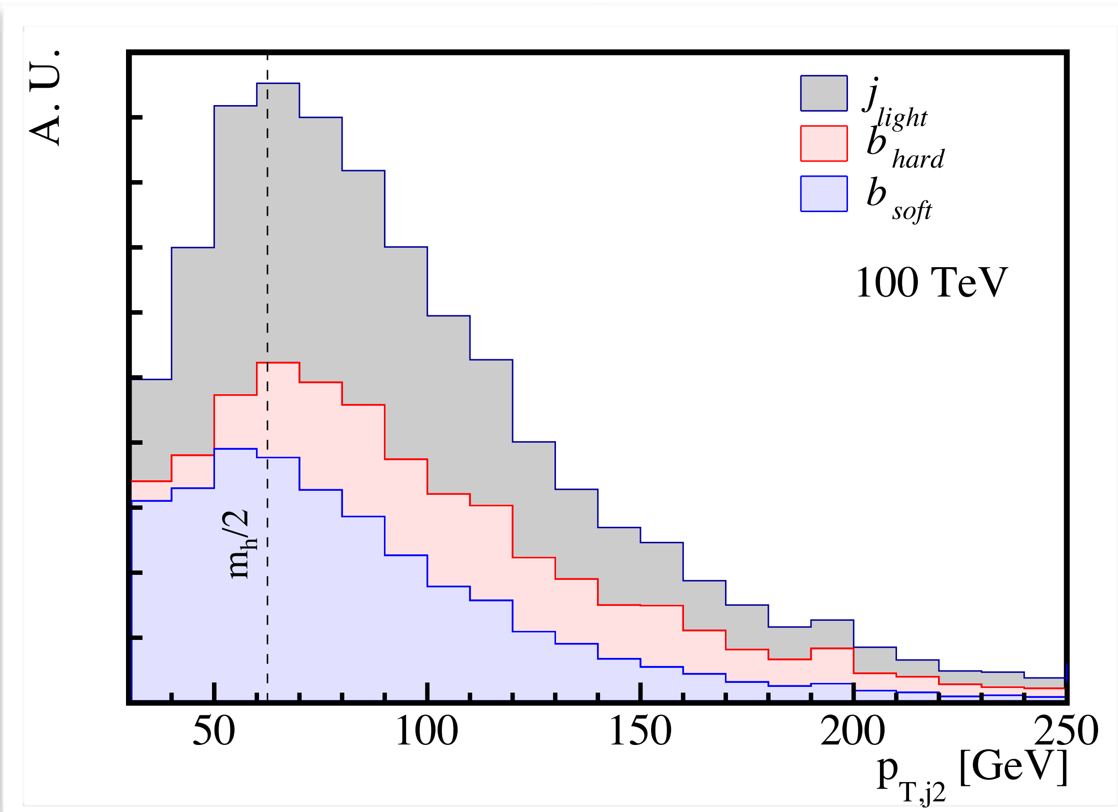


DG, Han, Kling, Plehn, Takeuchi (2018)

Detector level analysis

- The Higgs tend to produce soft decays $p_{Tb} \sim m_h/2$. Cheap to produce extra harder jet at HE colliders



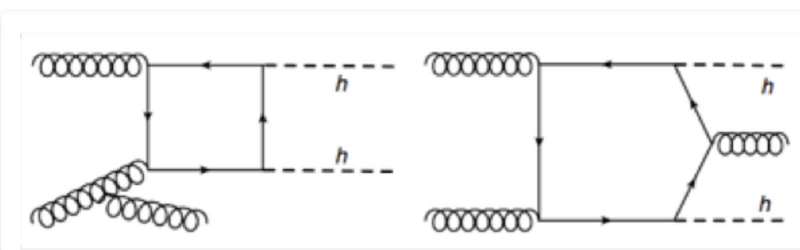


DG, Han, Kling, Plehn, Takeuchi (2018)

→ Two H(bb) decay products not always found in hardest two jets

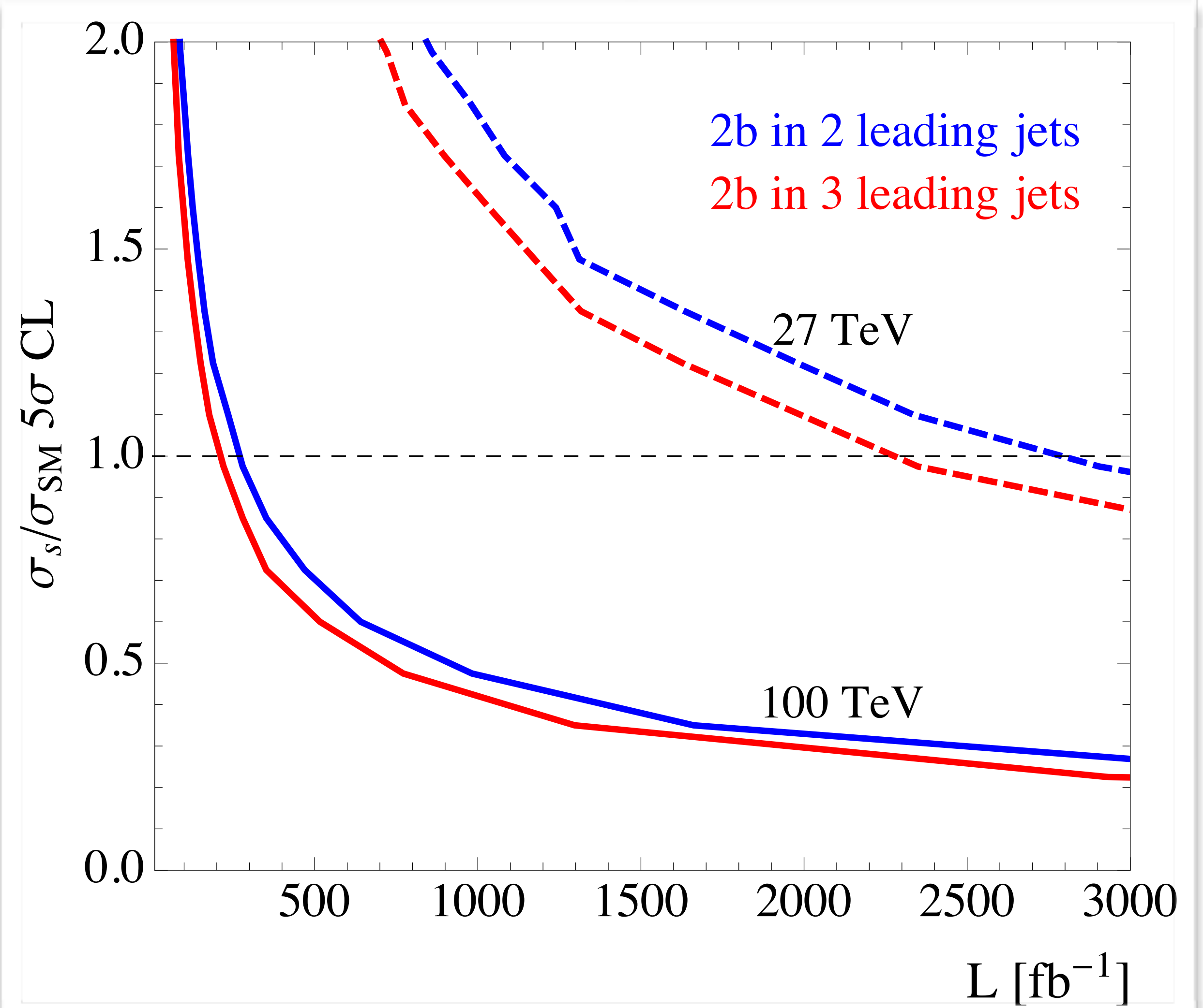
We simulate all samples (Signal &Background) merged up to one jet

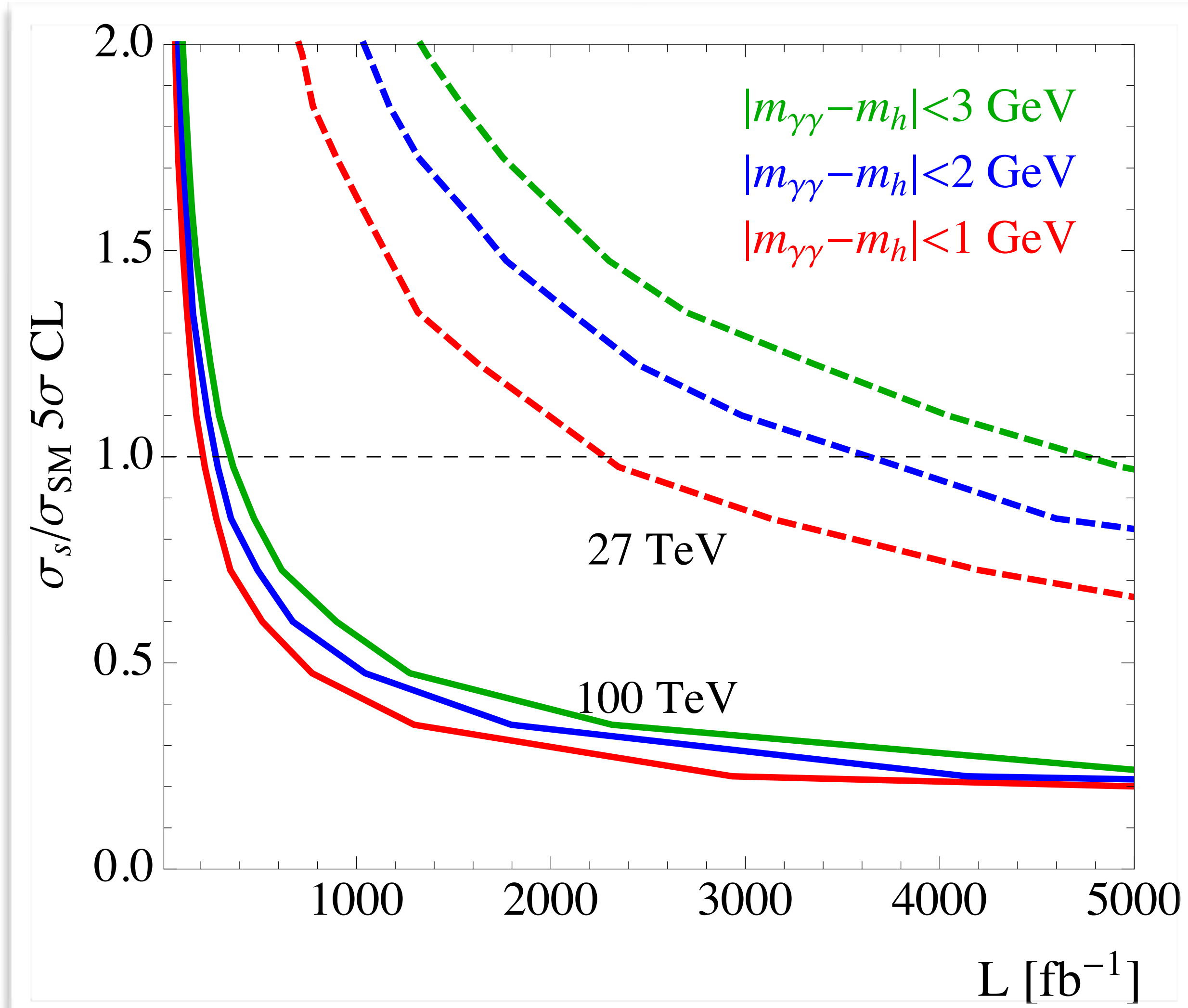
→ Divide analysis in two sub-samples: (bb,bbj) & (bjb,jbb)



Probing the Higgs potential

- Doing a binned log-likelihood analysis for the m_{hh} distribution at 27 TeV and 100TeV for $pp \to h(bb)h(\gamma\gamma)$





HH discovery pushed from 2.8 ab^{-1} to 2.3 ab^{-1} at 27 TeV HE-LHC

Photon and b-jet invariant mass resolution important for the detector design

HH discovery: 27 TeV 2.3 - 5 ab^{-1}; 100 TeV collider 0.2 - 0.3 ab^{-1}

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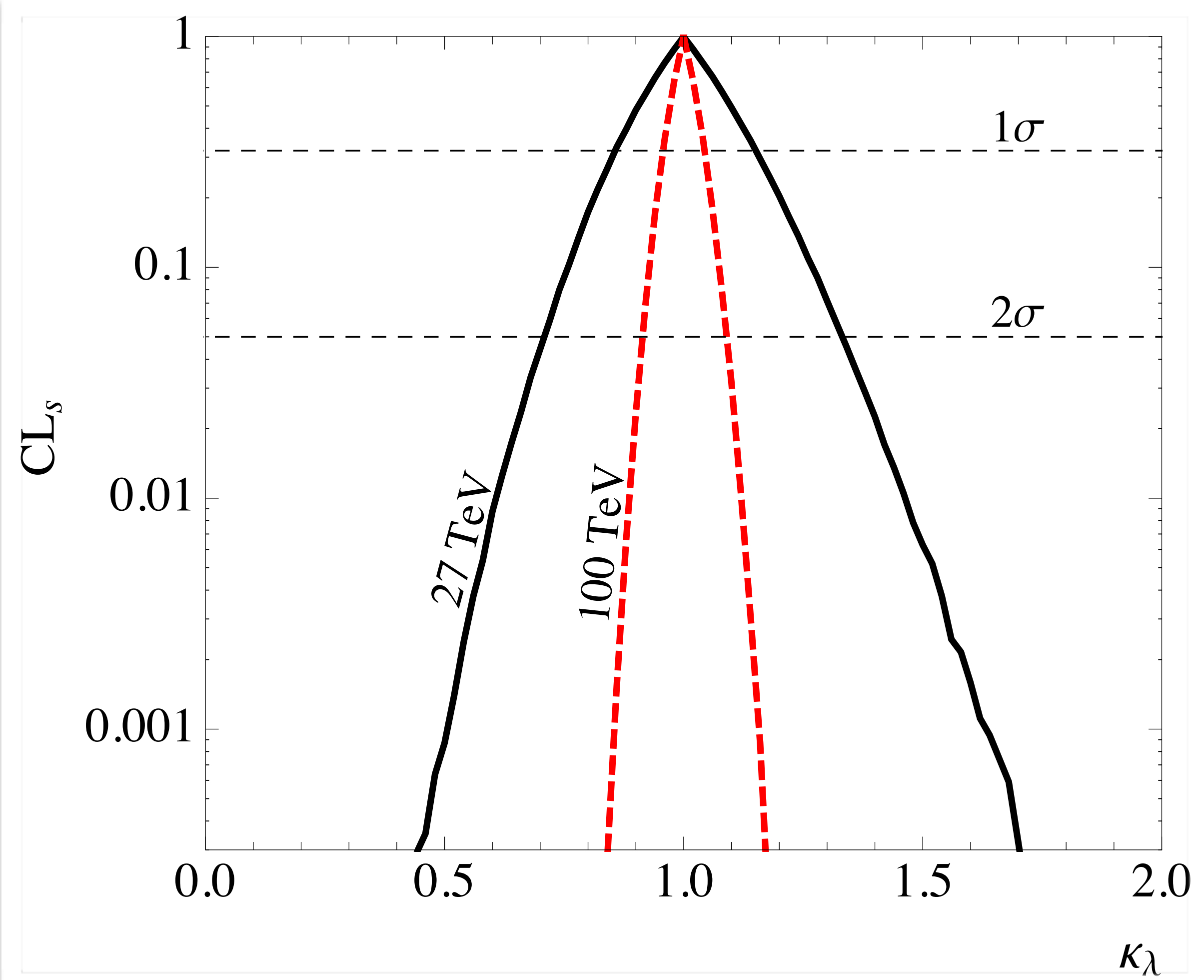


DG, Han, Kling, Plehn, Takeuchi (2018)

→ m_{hh} shape analysis removes degeneracies from rate-based measurement → symmetric error bars

→ Uncertainty measurement for the Higgs self-coupling:

- HE-LHC: $\kappa_\lambda \approx 1 \pm 15\%\ (1\sigma),\ 30\%\ (2\sigma)$
- FCC-100TeV: $\kappa_\lambda \approx 1 \pm 5\%\ (1\sigma),\ 10\%\ (2\sigma)$

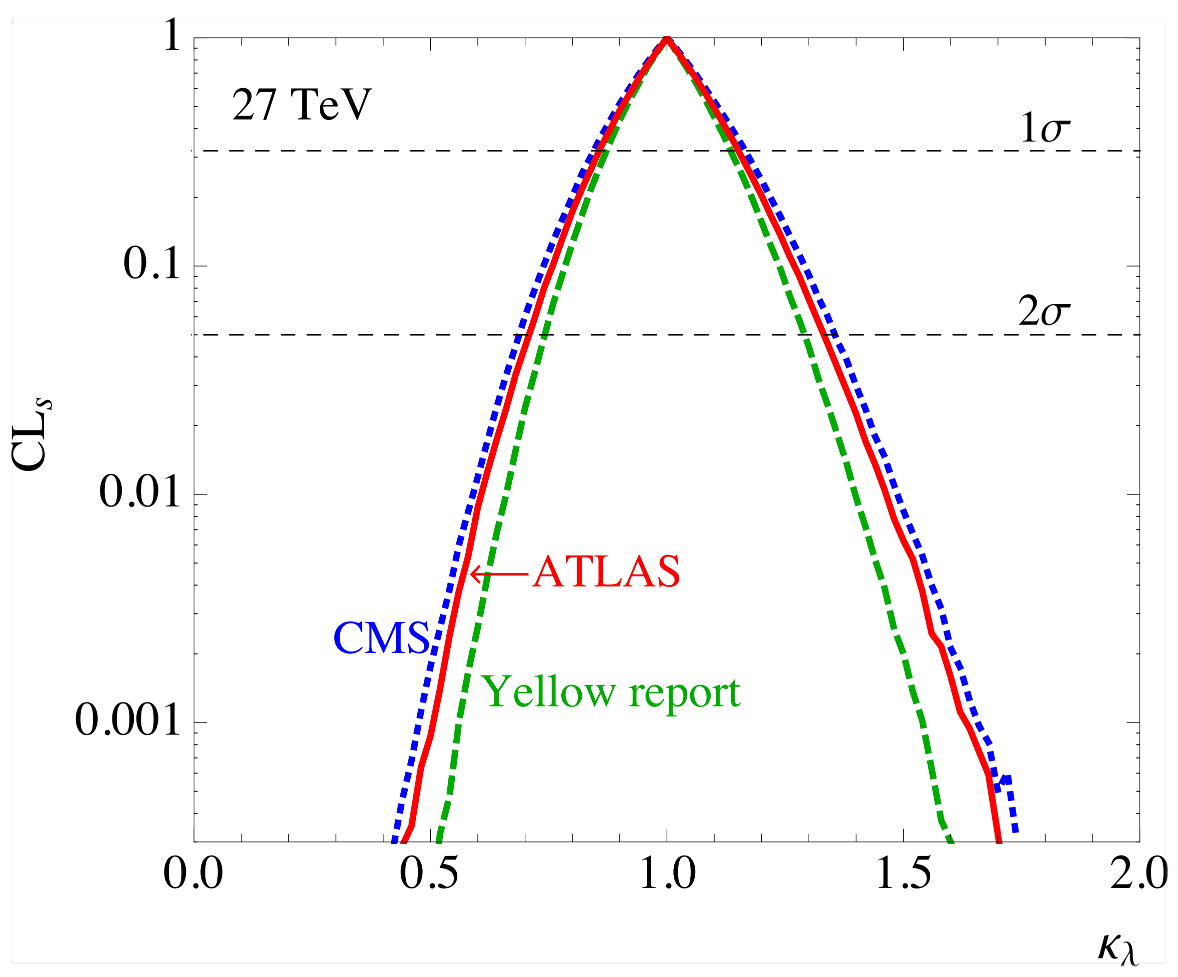
HE-LHC give very competitive results

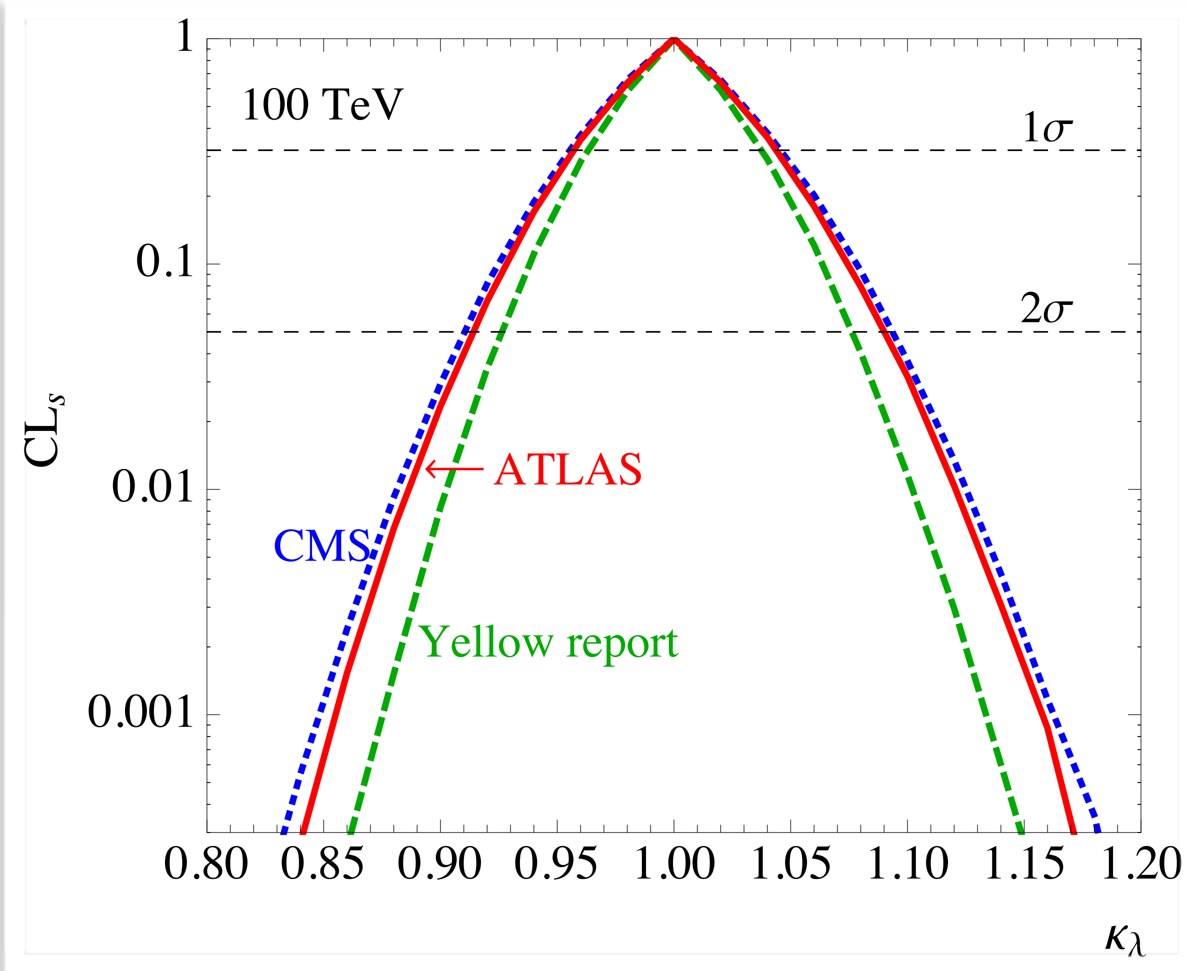
Probing the Higgs potential

- Dependence on detector parameter choice

  Conservative: HL-LHC performance projections from ATL-PHYS-PUB-2016-026

  More optimistic parameter choice: FCC CERN Yellow Report





→ Only moderate changes on the bounds for these parameter choices

DG, Han, Kling, Plehn, Takeuchi (2018)

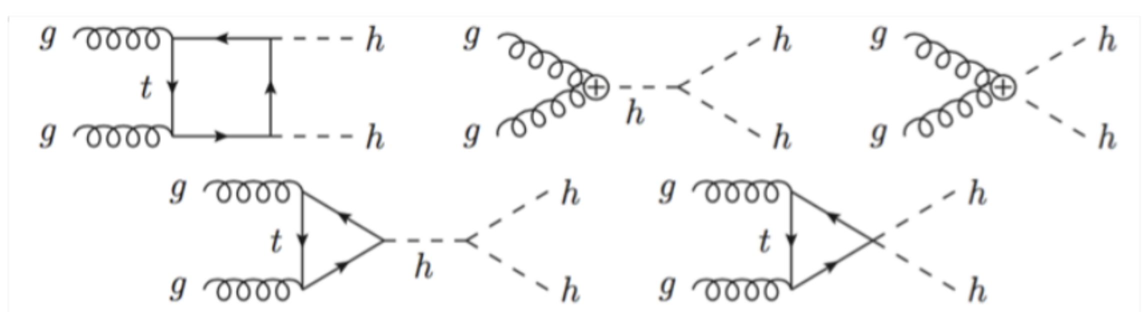
Double Higgs production in EFT

- Dim-6 Lagrangian relevant to HH production:

$$\mathcal{L}_{non-lin} \supset -m_t \bar{t}t \left(c_t \frac{h}{v} + c_{2t} \frac{h^2}{v^2} \right) - c_3 \frac{m_h^2}{2v} h^3 + \frac{g_s^2}{4\pi^2} \left(c_g \frac{h}{v} + c_{2g} \frac{h^2}{2v^2} \right) G^a_{\mu\nu} G^{a\,\mu\nu}$$

→ Non-linear EFT: $c_t, \ c_{2t}, \ c_3, \ c_g, \ c_{2g}$ independent parameters

→ Linear EFT (Higgs is a doublet): $c_g, \ c_t, c_3$ independent parameters. $c_g = c_{gg}; \ c_{2t} = -\frac{3m_t}{2v} c_t$



- EFT - divide and conquest:

→ $c_t, \ c_g$ can be constrained by single Higgs production

→ c_3, c_{2g}, c_{2t} need HH production for constraints

Azatov, Contino, Panico, Son (2015)

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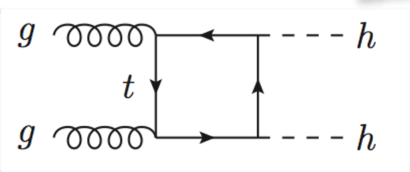
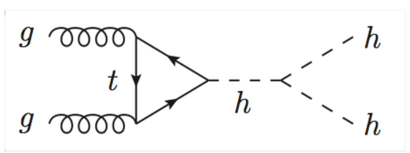
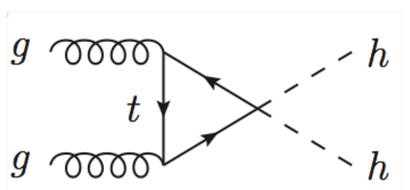


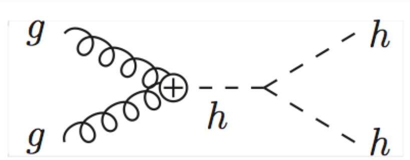
$$\sim c_t^2 \frac{\alpha_s}{4\pi} y_t^2$$



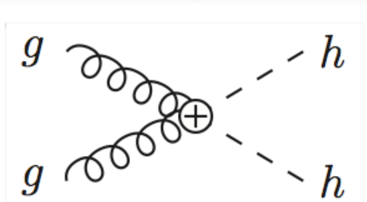
$$\sim c_t c_3 \frac{\alpha_s}{4\pi} y_t^2 \frac{m_h^2}{\hat{s}} \left(\log \frac{m_t^2}{\hat{s}} + i\pi \right)^2$$



$$\sim c_{2t} \frac{\alpha_s}{4\pi} y_t^2 \left(\log \frac{m_t^2}{\hat{s}} + i\pi \right)^2$$

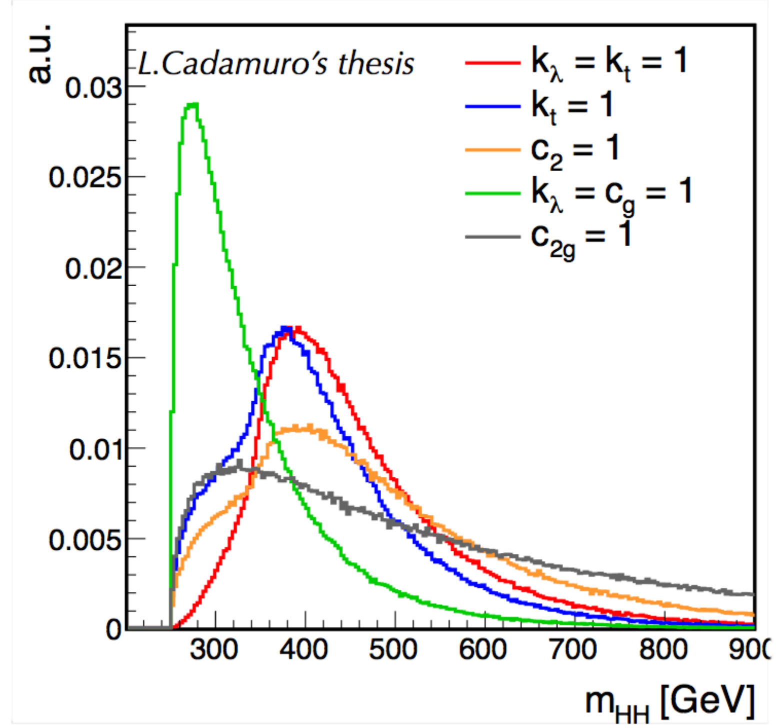


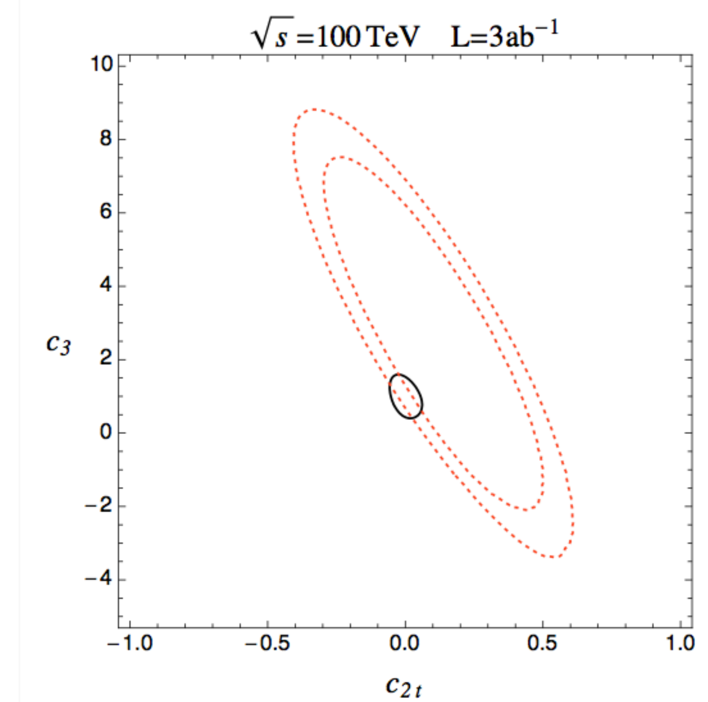
$$\sim c_g c_3 \frac{\alpha_s}{4\pi} \frac{m_h^2}{v^2}$$



$$\sim c_{2g} \frac{\alpha_s}{4\pi} \frac{\hat{s}}{v^2}$$

➡ Shape analysis can significantly improve the fits:





Azatov, Contino, Panico, Son (2015)

Summary

Triple Higgs couplings is a key benchmark for the LHC and future colliders

- The HE-LHC and FCC combination of increased energy and luminosity turn the **Higgs pair production** into a valid channel for **precision measurements** ⟶ Finally probe the Higgs potential!
- The m_{hh} shape analysis remove degeneracies and enhance the triple coupling sensitivity
- HE-LHC would rapidly reach a 5σ observation with 2.3 ab^{-1}. It displays competitive sensitivities to FCC

⟶ HE-LHC: $\kappa_\lambda \approx 1 \pm 15\%\ (1\sigma),\ 30\%\ (2\sigma)$
⟶ FCC-100TeV: $\kappa_\lambda \approx 1 \pm 5\%\ (1\sigma),\ 10\%\ (2\sigma)$

Thank you for your attention!