Double Higgs production at the LHC and Beyond

Giuliano Panico
IFAE Barcelona

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HH production processes

Several production channels but tiny cross section in the SM

✦ leading: **gluon fusion**

$$\sigma^{\rm GF}_{\rm 14TeV} \simeq 40 \text{ fb}$$

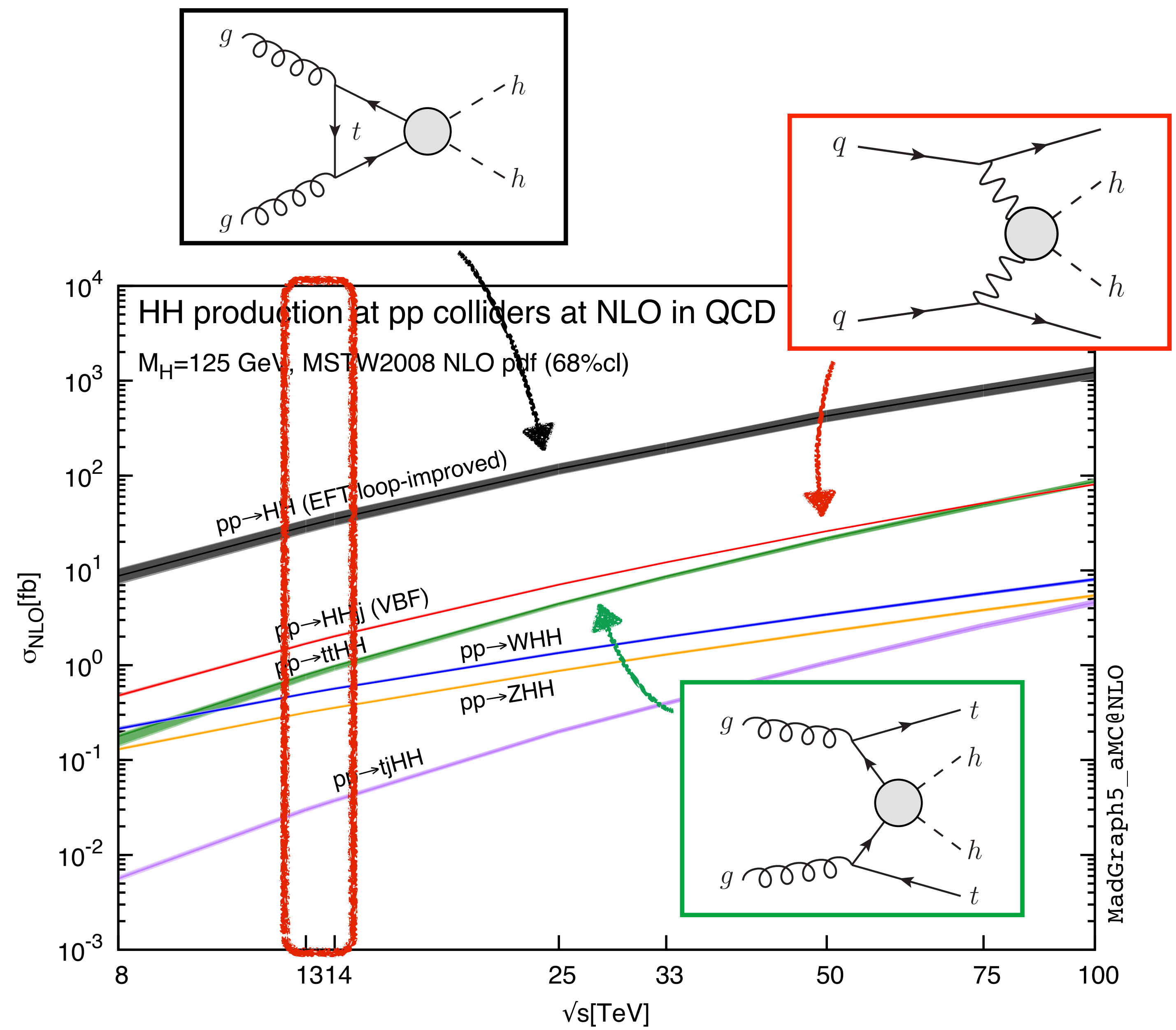
✦ potentially interesting:

- **vector boson fusion** (VBF)

$$\sigma^{\rm VBF}_{\rm 14TeV} = 1.94^{+2.3\%}_{-2.6\%}(scale) \text{ fb}$$

- **ttHH** production

$$\sigma^{\rm ttHH}_{\rm 14TeV} = 0.949^{+1.7\%}_{-4.5\%}(scale) \text{ fb}$$



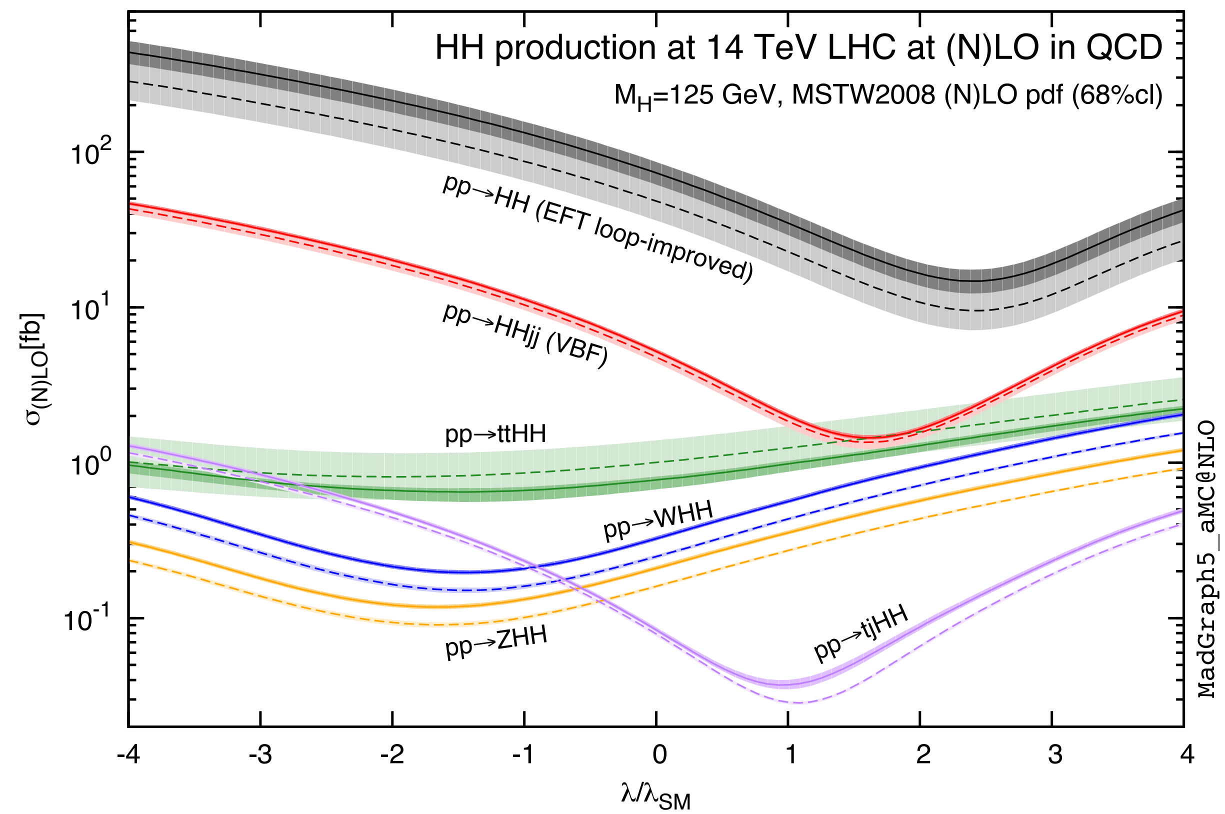
Why double Higgs?

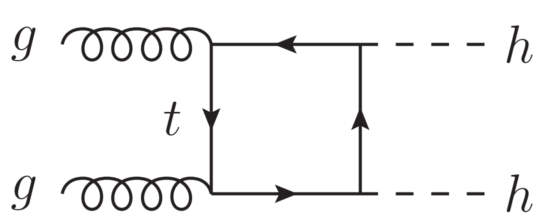
<u>Obvious answer</u>: directly accessing the **Higgs potential!**

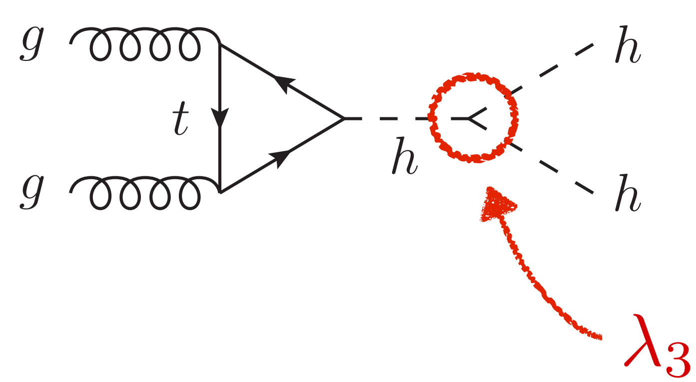
$$\mathcal{L} = -\frac{1}{2}m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

Significant dependence in the production rates

- ✦ in gluon fusion destructive interference







Why double Higgs?

<u>Less obvious answers</u>:

- extract **non-linear couplings** not accessible in single Higgs
- alternative measurement of **single-Higgs vertices**
- probe the **strength of EWSB dynamics** at high energy $E \gg m_h$

Non resonant

$gg \to hh$

$pp \to hh + jj$

- explore **extended Higgs sectors**

Resonant

$pp \to H \to hh$

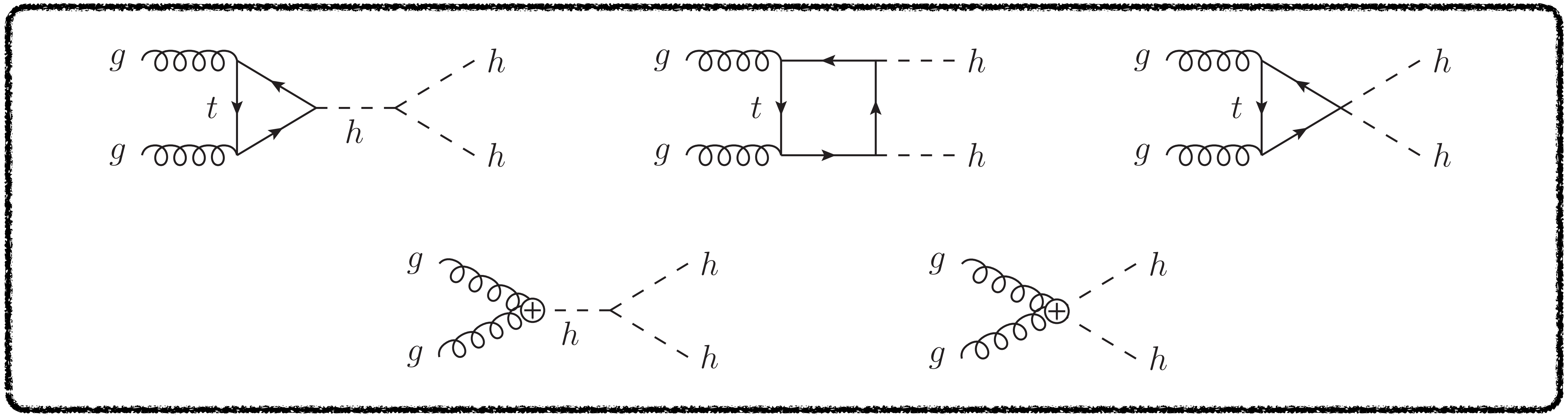
Non-resonant processes

The Gluon Fusion channel

The Higgs effective Lagrangian

Several vertices contribute to double Higgs production in GF

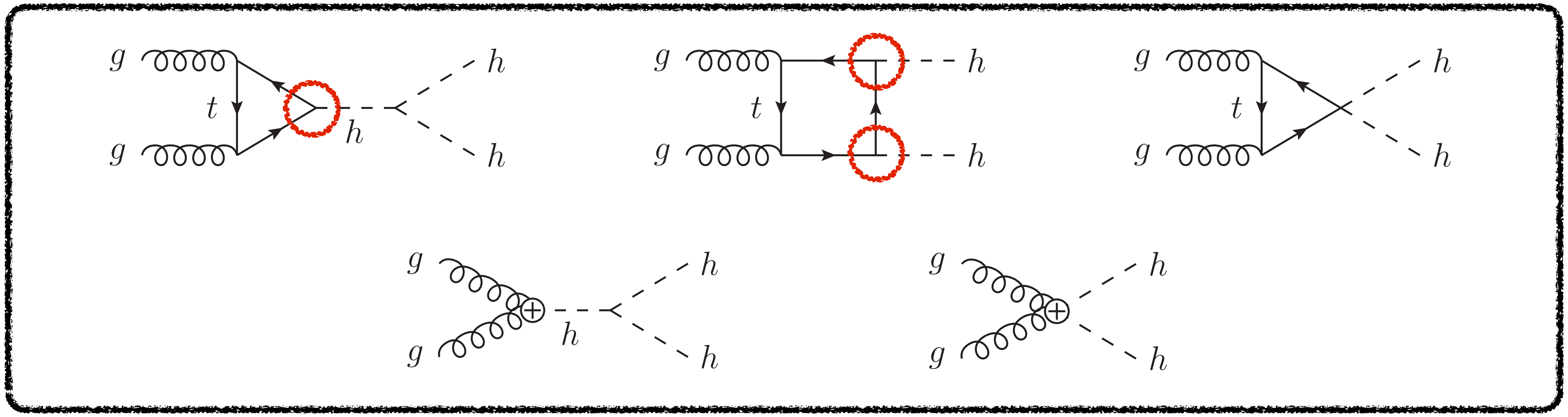
$$\mathcal{L} \supset -m_t \bar{t} t \left(c_t \frac{h}{v} + c_{2t} \frac{h^2}{2v^2} \right) - \lambda_3 \frac{m_h^2}{2v} h^3 + \frac{g_s^2}{4\pi^2} \left(c_g \frac{h}{v} + c_{2g} \frac{h^2}{2v^2} \right) G_{\mu\nu} G^{\mu\nu}$$



Modified single Higgs couplings

Several vertices contribute to double Higgs production in GF

$$\mathcal{L} \supset -m_t \bar{t}t \left(c_t \frac{h}{v} + c_{2t} \frac{h^2}{2v^2} \right) - \lambda_3 \frac{m_h^2}{2v} h^3 + \frac{g_s^2}{4\pi^2} \left(c_g \frac{h}{v} + c_{2g} \frac{h^2}{2v^2} \right) G_{\mu\nu} G^{\mu\nu}$$

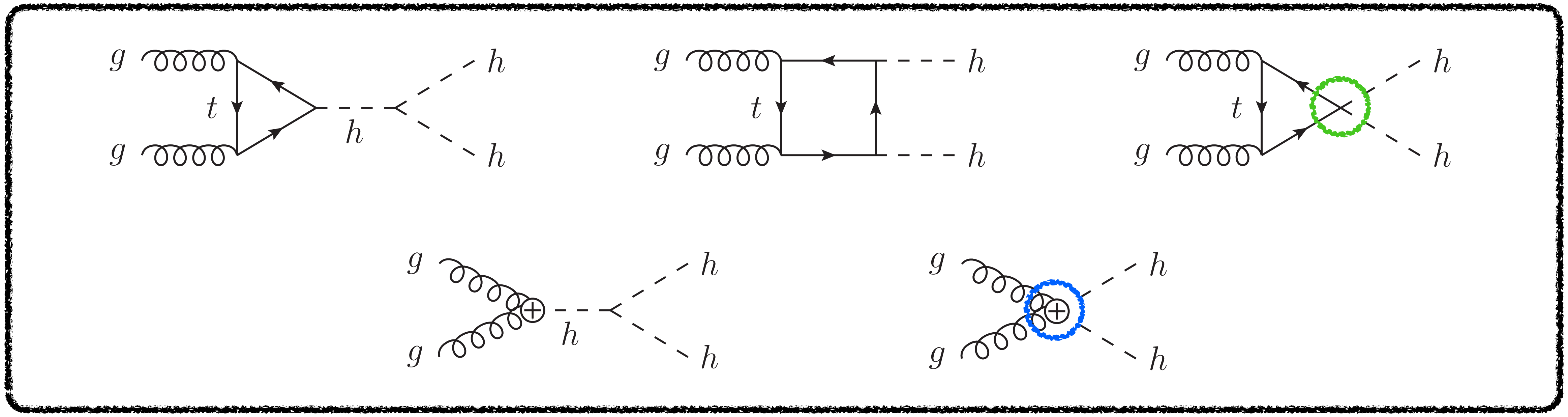


- modifications of the single Higgs couplings can affect HH production (eg. $\bar{t}th$)

Non-linear Higgs couplings

Several vertices contribute to double Higgs production in GF

$$\mathcal{L} \supset -m_t \bar{t}t \left(c_t \frac{h}{v} + c_{2t} \frac{h^2}{2v^2} \right) - \lambda_3 \frac{m_h^2}{2v} h^3 + \frac{g_s^2}{4\pi^2} \left(c_g \frac{h}{v} + c_{2g} \frac{h^2}{2v^2} \right) G_{\mu\nu} G^{\mu\nu}$$



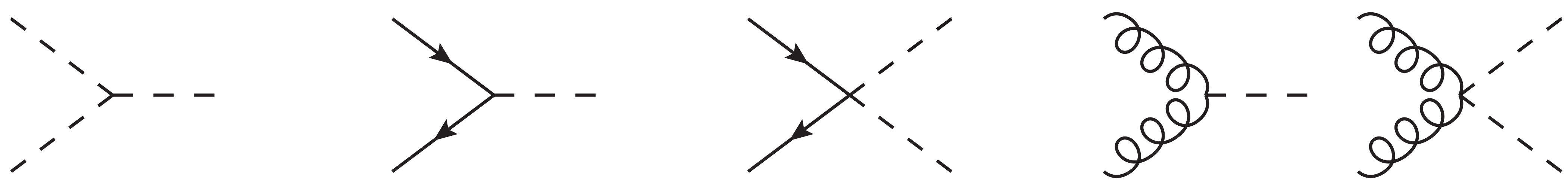
- modifications of the single Higgs couplings can affect HH production (eg. $\bar{t}th$)
- some vertices can be probed independently only in HH processes (eg. $\bar{t}thh$, $h^2 G_{\mu\nu} G^{\mu\nu}$)

Parametrization for a doublet Higgs

If the Higgs is part of an SU(2) doublet the number of independent operators is reduced

Buchmuller and Wyler; …
Giudice et al.; Grzadkowski et al.

$$\mathcal{L} \supset \frac{\bar{c}_H}{2v^2}[\partial_\mu (H^\dagger H)]^2 + \frac{\bar{c}_u}{v^2} y_u H^\dagger H \bar{q}_L H^c u_R - \frac{\bar{c}_6}{v^2}\frac{m_h^2}{2v^2}(H^\dagger H)^3 + \frac{\bar{c}_g}{m_w^2} g_s^2 H^\dagger H G_{\mu\nu} G^{\mu\nu}$$

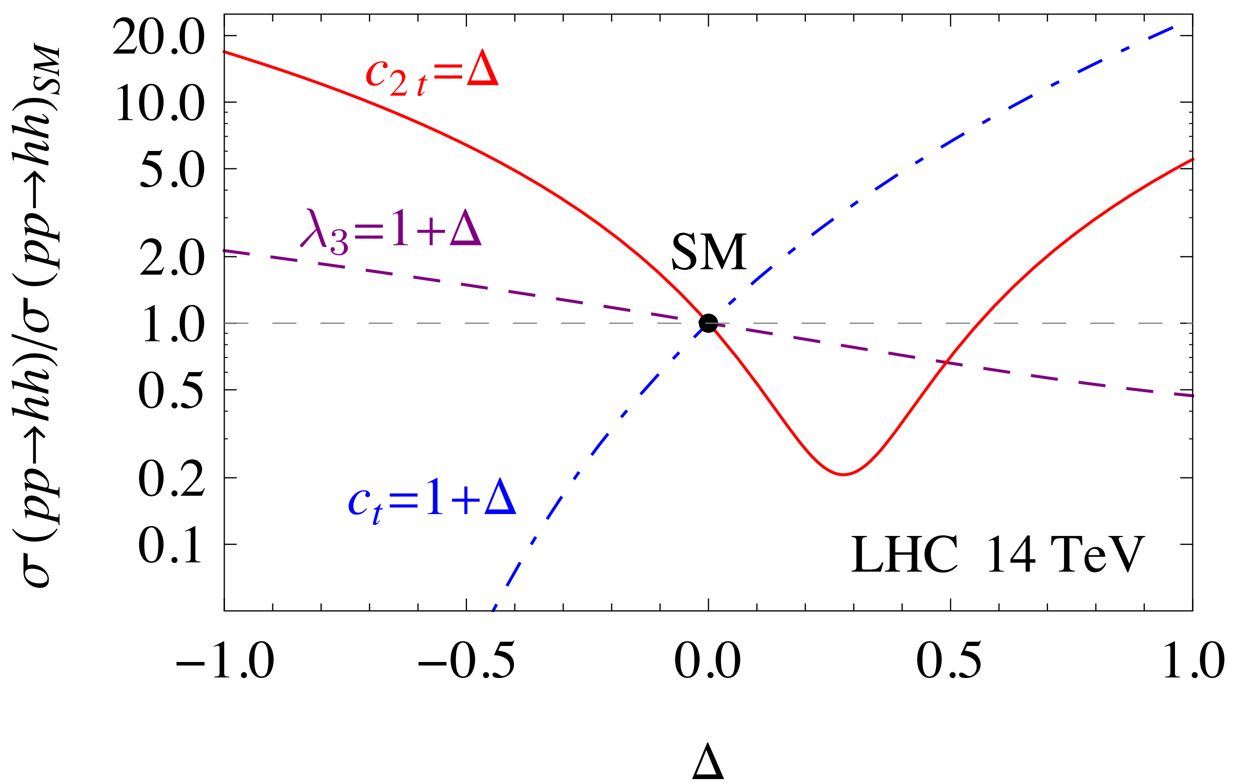


$c_3 \simeq 1 - \frac{3}{2}\bar{c}_H + \bar{c}_6$ $\quad$ $c_t \simeq 1 - \frac{\bar{c}_H}{2} - \bar{c}_u$ $\quad$ $c_{2t} \simeq -\frac{1}{2}(\bar{c}_H + 3\bar{c}_u)$ $\quad$ $c_g = c_{2g} = \bar{c}_g \left(\frac{4\pi}{\alpha_2}\right)$

- ✦ requires an additional expansion in Higgs powers

Dependence on Higgs couplings

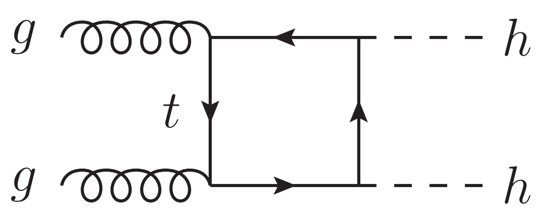
- mild dependence on λ_3
  - effects mostly at threshold
- strong dependence on top couplings c_t and c_{2t}
  - affect peak and tail of m_{hh}



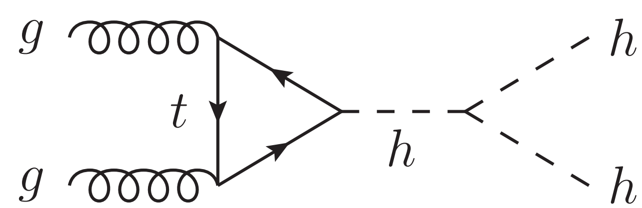
- Shape analysis could disentangle the various interactions

In many BSM scenarios **modifications to all Higgs couplings** arise simultaneously and have comparable size

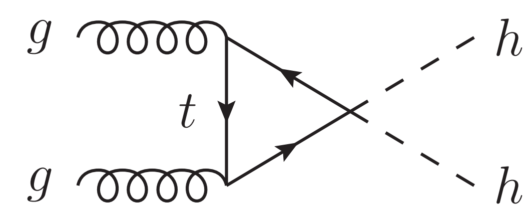
Behaviour of amplitudes



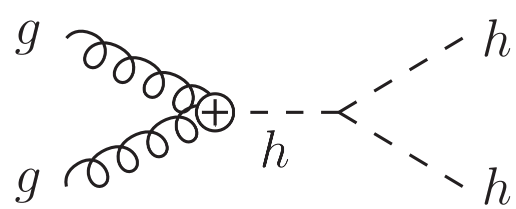
$\sim c_t^2 \times const.$



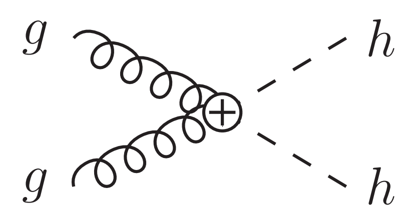
$\sim c_t c_3 \times \frac{m_h^2}{\hat{s}} \log^2\left(\frac{m_t^2}{\hat{s}}\right)$



$\sim c_{2t} \times \log^2\left(\frac{m_t^2}{\hat{s}}\right)$



$\sim c_g c_3 \frac{\alpha_s}{4\pi} \times const.$



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

- Different behaviour at high energy $\sqrt{\hat{s}} = m_{hh} \gg 2m_h$
- Dependence on Higgs trilinear suppressed in the tail
  - events at threshold more sensitive to Higgs trilinear,
    events at large m_{hh} more important to determine the other operators

Final states

GF is the hh production channel with highest cross section

$$\sigma^{\rm SM}_{\rm 14TeV} \simeq 39.5 \text{ fb}$$

Full LO: Glover, van der Bij '88
Full NLO: Borowka, Greiner et al.'16
Approximate NNLO + NNLL: De Florian, Mazzitelli '13, '15; Grigo, Melnikov, Steinauser '14; Grigo, Hoff, Steinauser '15; Shao, Li, Wang '13

Many final states with reasonable number of events at HL-LHC

✦ golden channel: $b\bar{b}\gamma\gamma$

- small number of events
- clean final state (small bkg)
- can access total cross section

✦ other modes:

$$b\bar{b}\tau^+\tau^-, \quad b\bar{b}WW^*, \quad b\bar{b}b\bar{b}$$

- larger cross section
- large bkg
- may be useful to probe tail of distribution (boosted jet techniques)

decay channel	BR	events (3 ab^{-1})
$b\bar{b}b\bar{b}$	33%	40000
$b\bar{b}WW^*$	25%	31000
$b\bar{b}\tau^+\tau^-$	7.3%	8900
$ZZb\bar{b}$	3.1%	3800
$WW^*\tau^+\tau^-$	2.7%	3300
$ZZWW^*$	1.1%	1300
$b\bar{b}\gamma\gamma$	0.26%	320

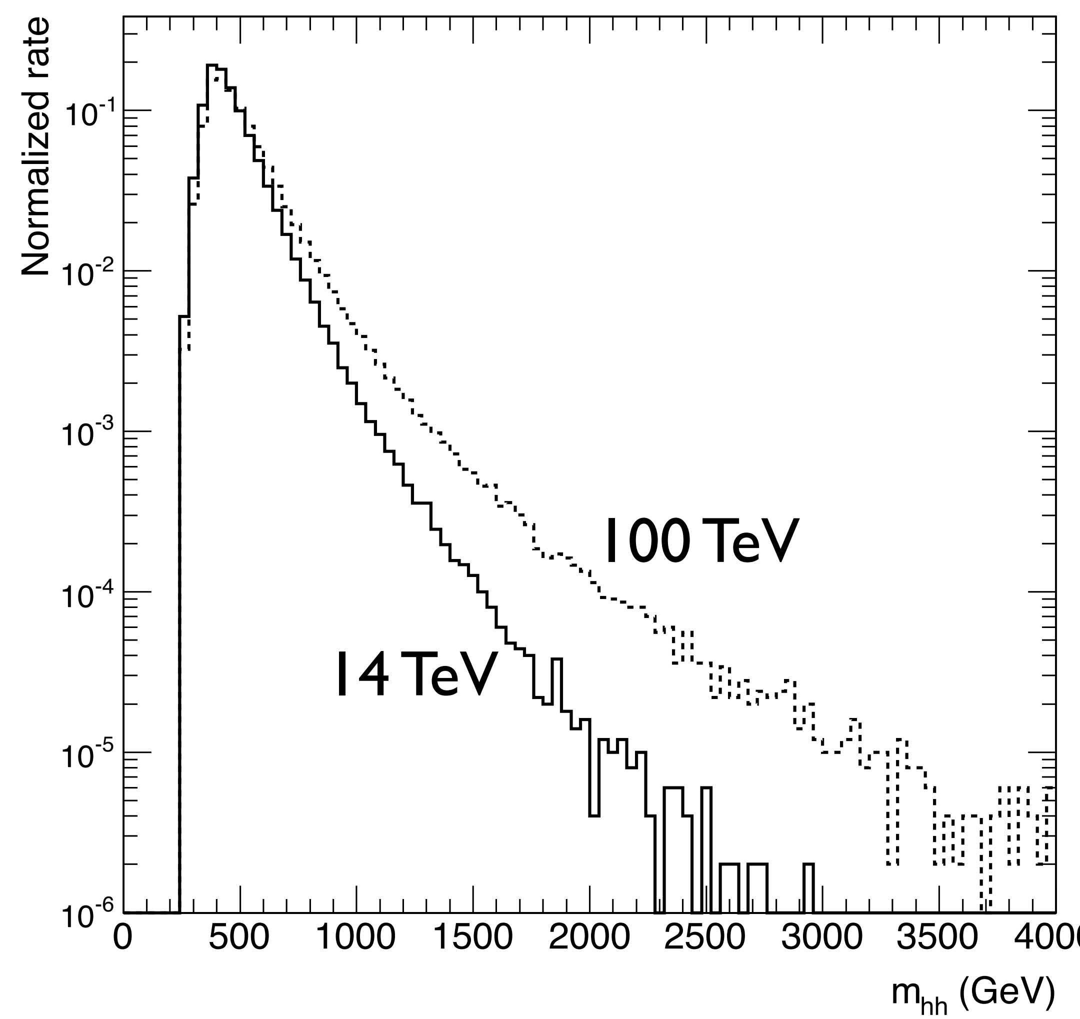
Gluon Fusion at 100 TeV

- huge increase in cross section (~40 times 14 TeV)

$$\sigma^{\rm SM}_{100{\rm TeV}} \simeq 1400 \ {\rm fb}$$

- similar shape at threshold and around the peak

- significant increase in the high m_{hh} tail



(Partial) List of theoretical analyses

- $hh \to b\bar{b}\gamma\gamma$

  Baur, Plehn, Rainwater hep-ph/0310056
  Baglio, Djouadi, Grober, Mullheitner, Quevillon et al. 1212.5581
  Yao 1308.6302
  Barger, Everett, Jackson, Shaughnessy 1311.2931
  Azatov, Contino, Panico, Son 1502.00539
  Kling, Plehn, Schichtel 1607.07441

- $hh \to b\bar{b}\tau^+\tau^-$

  Baur, Plehn, Rainwater hep-ph/0304015
  Dolan, Englert, Spannowsky 1206.5001
  Baglio, Djouadi, Grober, Mullheitner, Quevillon et al. 1212.5581
  Barr, Dolan, Englert, Spannowsky 1309.6318
  Goertz, Papaefstathiou, Yang, Zurita 1410.3471

- $hh \to b\bar{b}WW^*$

  Dolan, Englert, Spannowsky 1206.5001
  Baglio, Djouadi, Grober, Mullheitner, Quevillon et al. 1212.5581
  Papaefstathiou, Yang, Zurita 1209.1489

- $hh \to b\bar{b}b\bar{b}$

  de Lima, Papaefstathiou, Spannowsky 1404.7139

- comprehensive study at 100 TeV:

  Contino et al., "Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies", 1606.09408

The Golden Channel $b\bar{b}\gamma\gamma$

The Higgs trilinear at HL-LHC

Tiny cross section: $\sigma_{\rm SM}(HH \to b\bar{b}\gamma\gamma) \simeq 0.1 \text{ fb}$

Main backgrounds:

events after selection (CMS analysis FTR-15-002)

see also ATLAS: PHYS-PUB-2014-019, PHYS-PUB-2015-46

		events after selection
resonant	ZH	3.4
	$t\bar{t}H$	1.6
	$b\bar{b}H$	0.8
non resonant	$b\bar{b}\gamma\gamma$	10.4
	$b\bar{b}j\gamma$	6.3
	$jj\gamma\gamma$	2.1
	$b\bar{b}jj$	1.1
	$t\bar{t}\gamma$	1.2
	total	24.8

signal events: 9.0

Only $\mathcal{O}(1)$ determination of λ_3 is possible

✦ Some improvement possible with multivariate techniques Kling, Plehn, Schichten '16

$$\frac{\lambda}{\lambda_{\rm SM}} \in [0.4, 1.7] \qquad \text{at} \;\; 68\% \text{ CL}$$

Prospects at 100 TeV

Sizeable cross section: $\sigma_{\rm SM}(HH \to b\bar{b}\gamma\gamma) \simeq 3.6\ \rm fb$

Main backgrounds:

(Contino et al. 1606.09408)

see also Kling, Plehn, Schichten '16

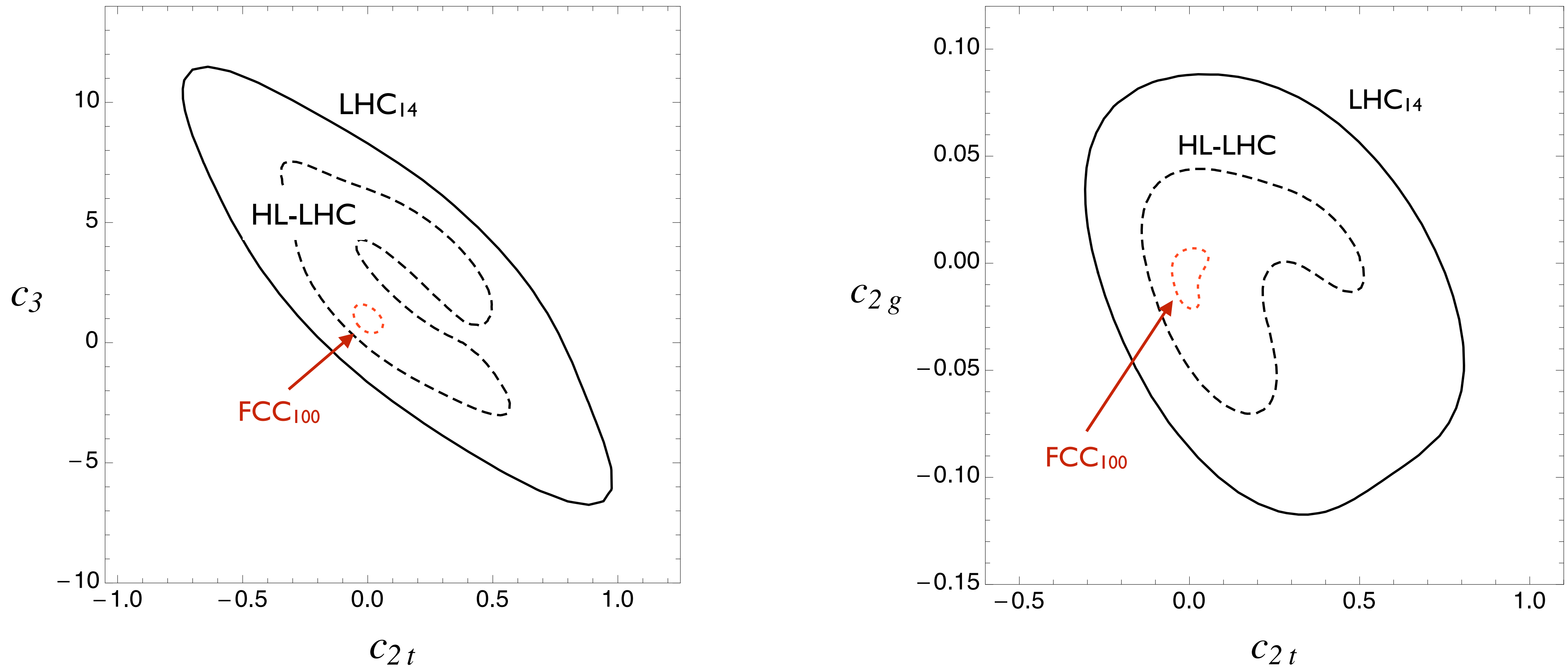
		events after selection with $20\ \rm ab^{-1}$
res.	$t\bar{t}H$	3250
non res.	$b\bar{b}j\gamma$	9300
	$jj\gamma\gamma$	3250
	$b\bar{b}\gamma\gamma$	2000
	total	17800

signal events: 7400

- Good precision on **SM cross section**: $\sim 2\%$ at 68% CL
- Good determination of **Higgs trilinear**: $\sim 4.5\%$ at 68% CL

Fit to non-linear Higgs couplings

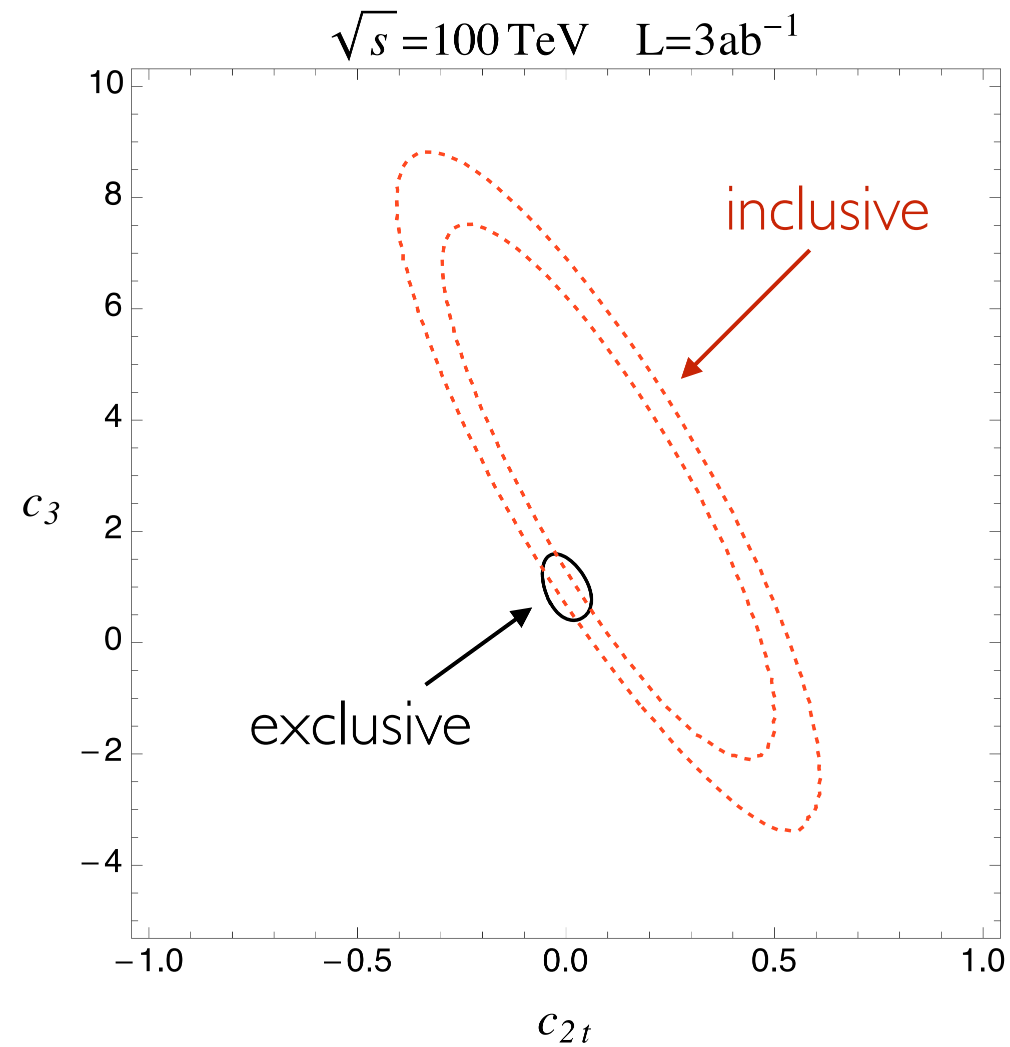
Determination of c_3, c_{2t} and c_{2g}

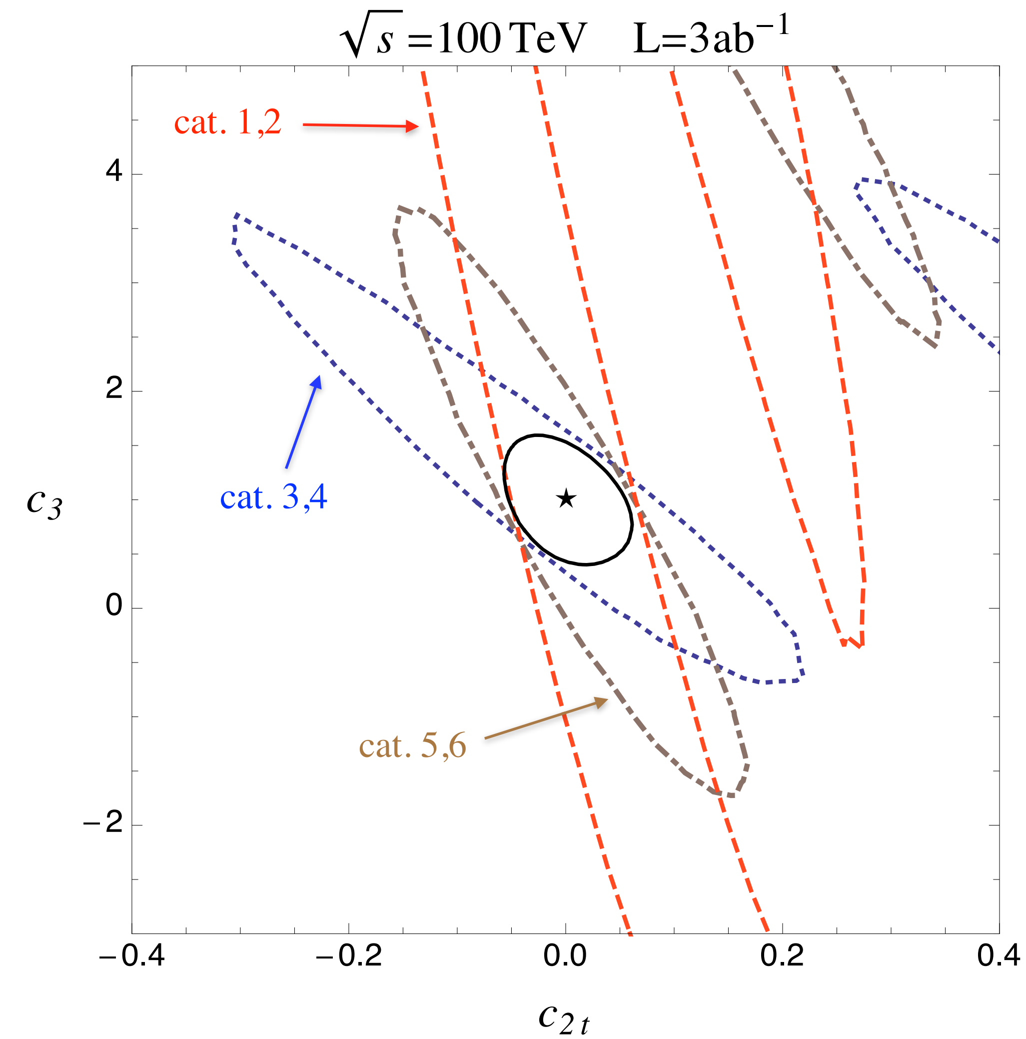


- ✦ Correlation between Higgs trilinear and top couplings
- ✦ Good precision on contact interactions to top and gluons

benchmark scenarios:			
	LHC14	$\sqrt{s} = 14$ TeV ,	$\mathrm{L} = 300\ \mathrm{fb}^{-1}$
	HL-LHC	$\sqrt{s} = 14$ TeV ,	$\mathrm{L} = 3\ \mathrm{ab}^{-1}$
	FCC100	$\sqrt{s} = 100$ TeV ,	$\mathrm{L} = 3\ \mathrm{ab}^{-1}$

Exclusive vs inclusive analysis

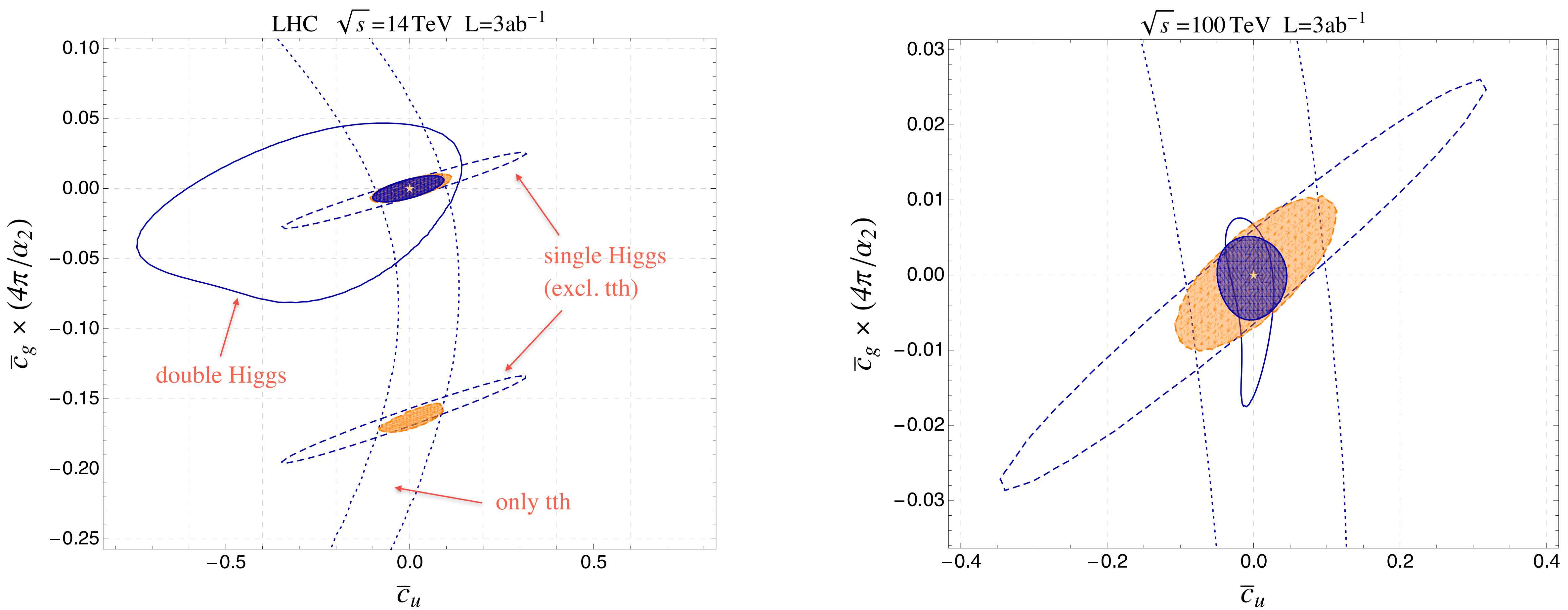




Exclusive analysis is crucial at FCC_{100}

category	1	2	3	4	5	6
m_{hh} [GeV]	250 - 400	400 - 550	550 - 700	700 - 850	850 - 1000	1000 -

Operators in the Higgs doublet basis



- Double Higgs measurement can resolve the degeneracy in c_g
- At FCC$_{100}$ can be competitive with $t\bar{t}h$ for the determination of the top Yukawa $\bar{c}_u$ (if precision from single Higgs similar to the LHC one)

orange region: single Higgs incl. $t\bar{t}h$

blue region: single + double Higgs

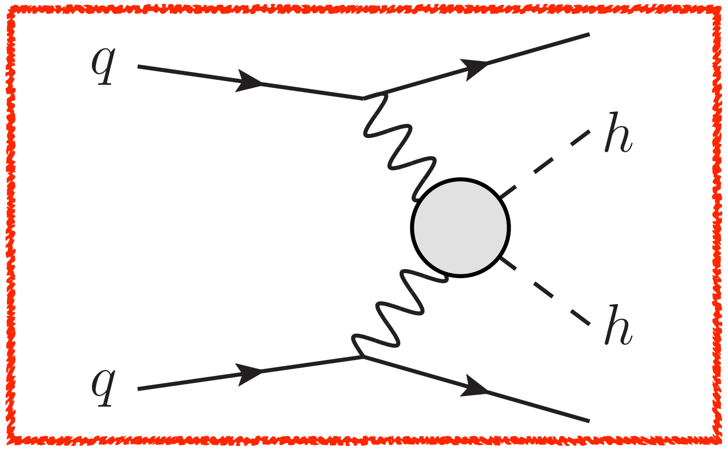
Non-resonant processes

The Vector Boson Fusion channel

results from Contino, Rojo, work in progress (courtesy of R. Contino)

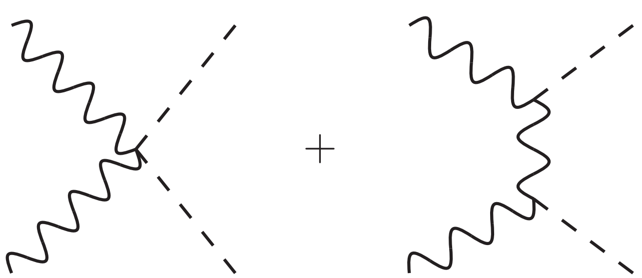
Testing the strength of EWSB

VBF can test perturbative unitarization

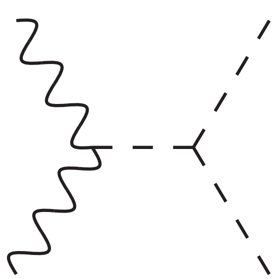


$$\mathcal{L} \supset \left(m_W^2 W_\mu^2 + \frac{m_Z^2}{2} Z_\mu^2 \right) \left(1 + 2c_V \frac{h}{v} + c_{2V} \frac{h^2}{v^2} \right)$$

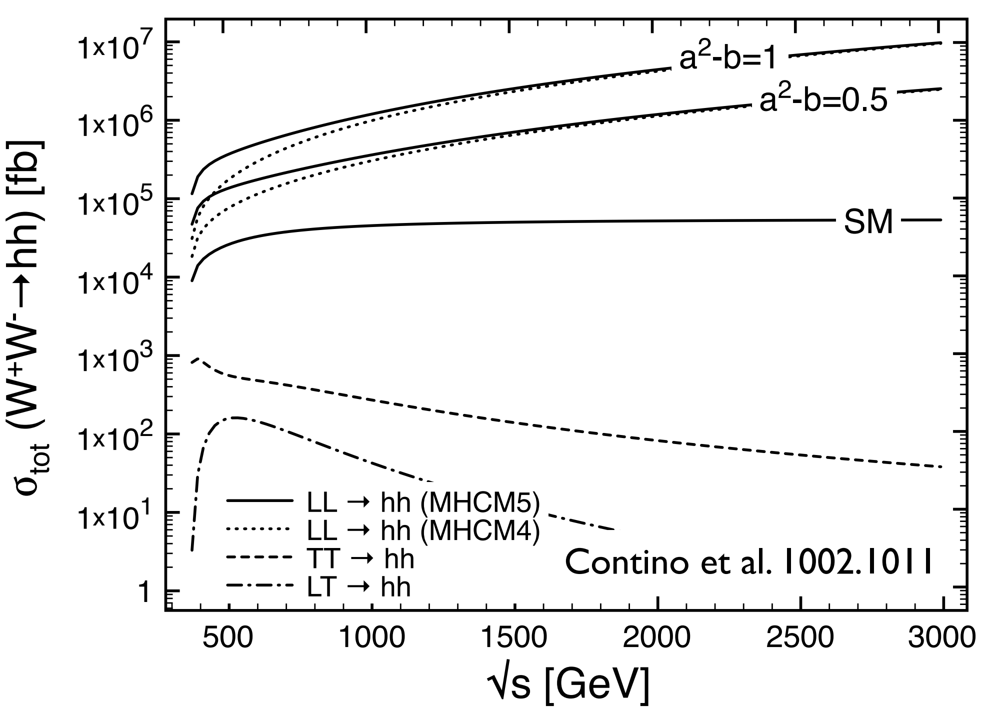
- Cross section grows at high m_{hh} if the couplings are modified (in the SM $c_V = c_{2V} = 1$)



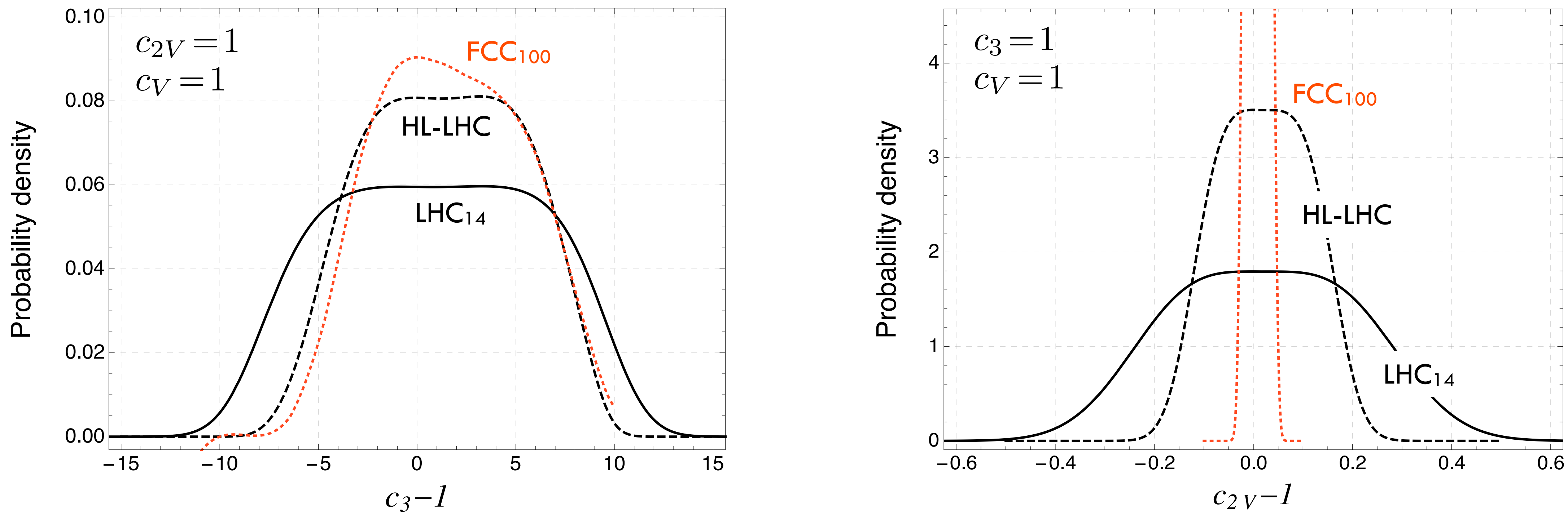
$$\sim \frac{\hat{s}}{v^2}(c_V^2 - c_{2V})$$



$$\sim \frac{m_h^2}{v^3}\lambda_3 c_V$$



Higgs couplings from VBF



Best channel: $hh \to 4b$

- huge background, sensitive only if deviations much larger than SM
- poor precision on Higgs trilinear (not competitive with GF)
- FCC_{100} can provide good bounds on $\Delta c_{2V} \equiv c_{2V} - 1$

68% probability intervals on Δc_{2V}

LHC_{14}	HL-LHC	FCC_{100}
[-0.18, 0.22]	[-0.08, 0.12]	[-0.01, 0.03]

Resonant processes

Scalar Singlet production

Additional scalar singlet

Extensions of the Higgs sector are quite common in BSM scenarios

Additional **singlet** ϕ is often present (eg. NMSSM, Twin Higgs, …)

results taken from Buttazzo, Sala, Tesi, 1505.05488
see also references therein

- Couplings controlled by the mixing with the Higgs

couplings to SM
$$\frac{g_{\phi ff}}{g_{hff}^{\mathrm{SM}}} = \frac{g_{\phi VV}}{g_{hVV}^{\mathrm{SM}}} = \sin\gamma = \left(\frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}\right)^{1/2}$$

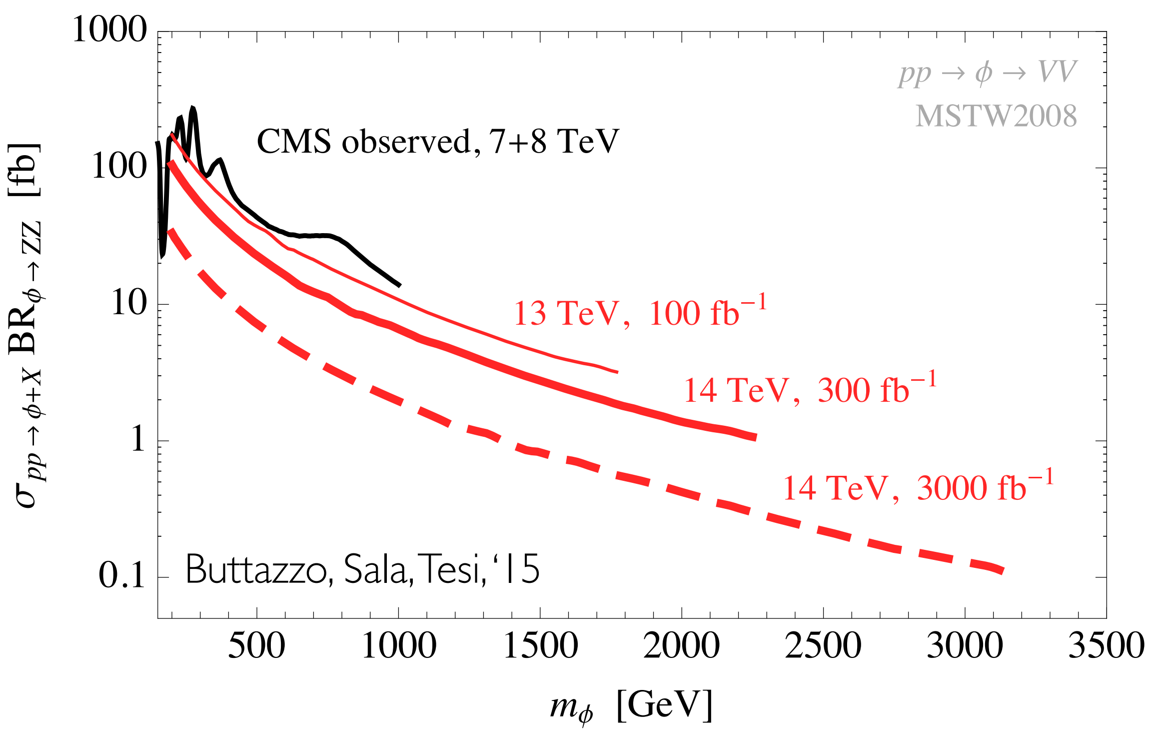
coupling to the Higgs
$$g_{\phi hh}$$

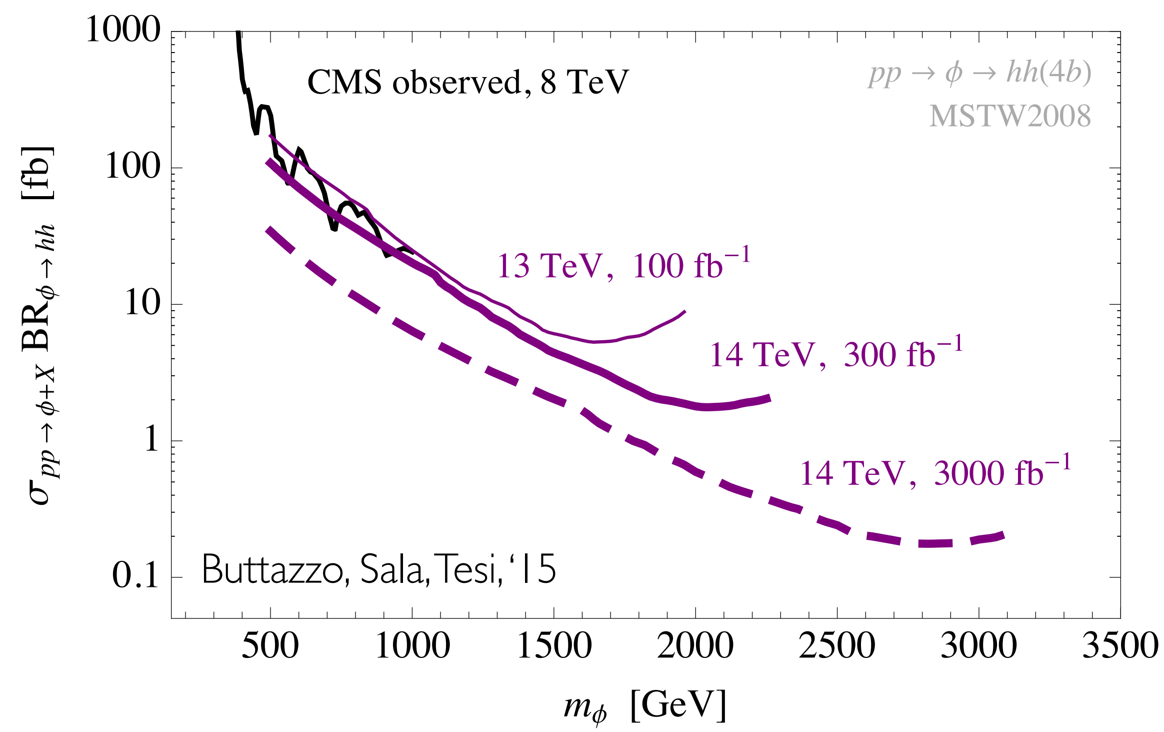
- Main decay channels

$$\mathrm{BR}(\phi \to hh) = \mathrm{BR}(\phi \to ZZ) = \frac{1}{2}\mathrm{BR}(\phi \to WW) = \frac{1}{4}\,, \qquad \text{for} \quad m_\phi \gg m_W$$

Direct searches

Direct searches can exploit the VV and hh channels



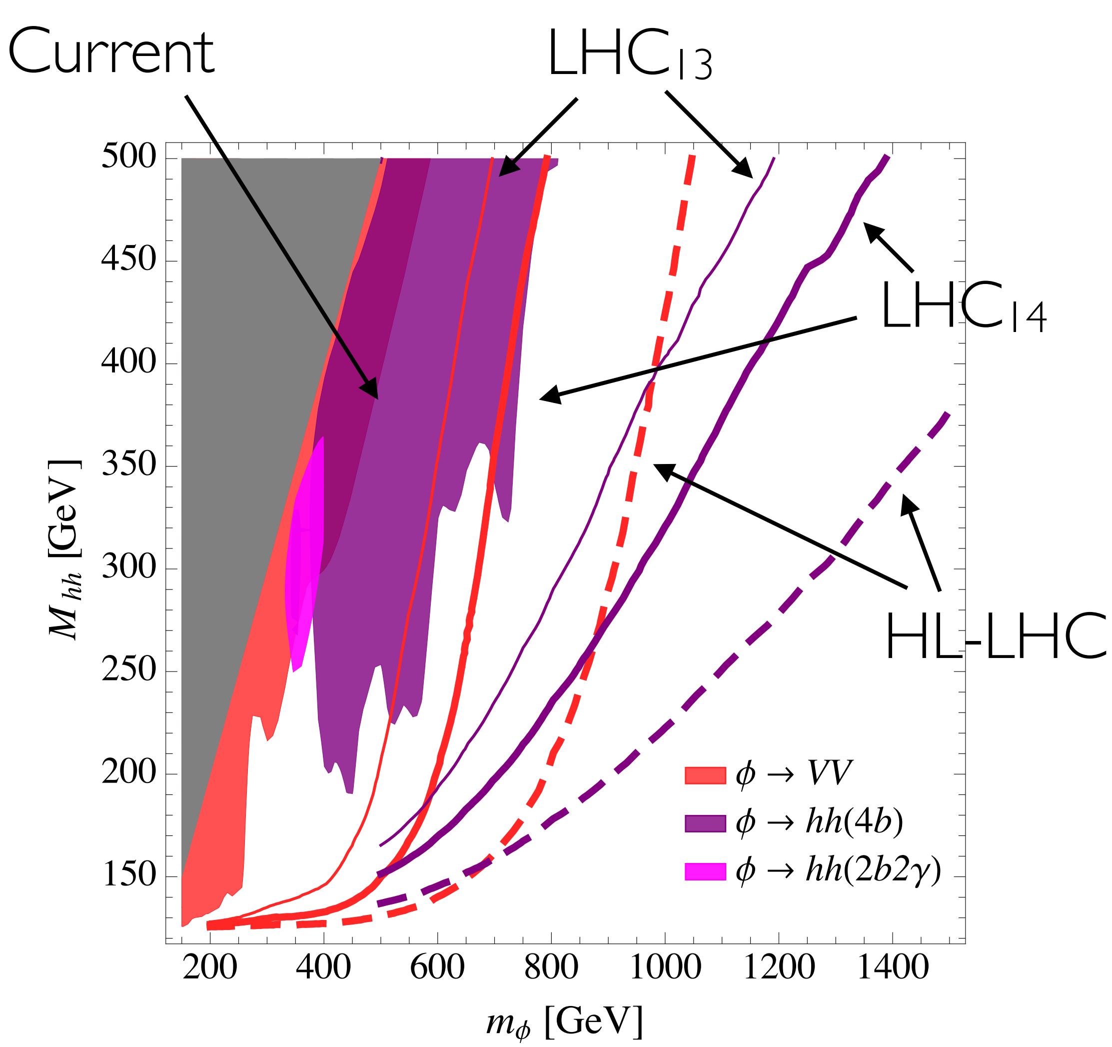


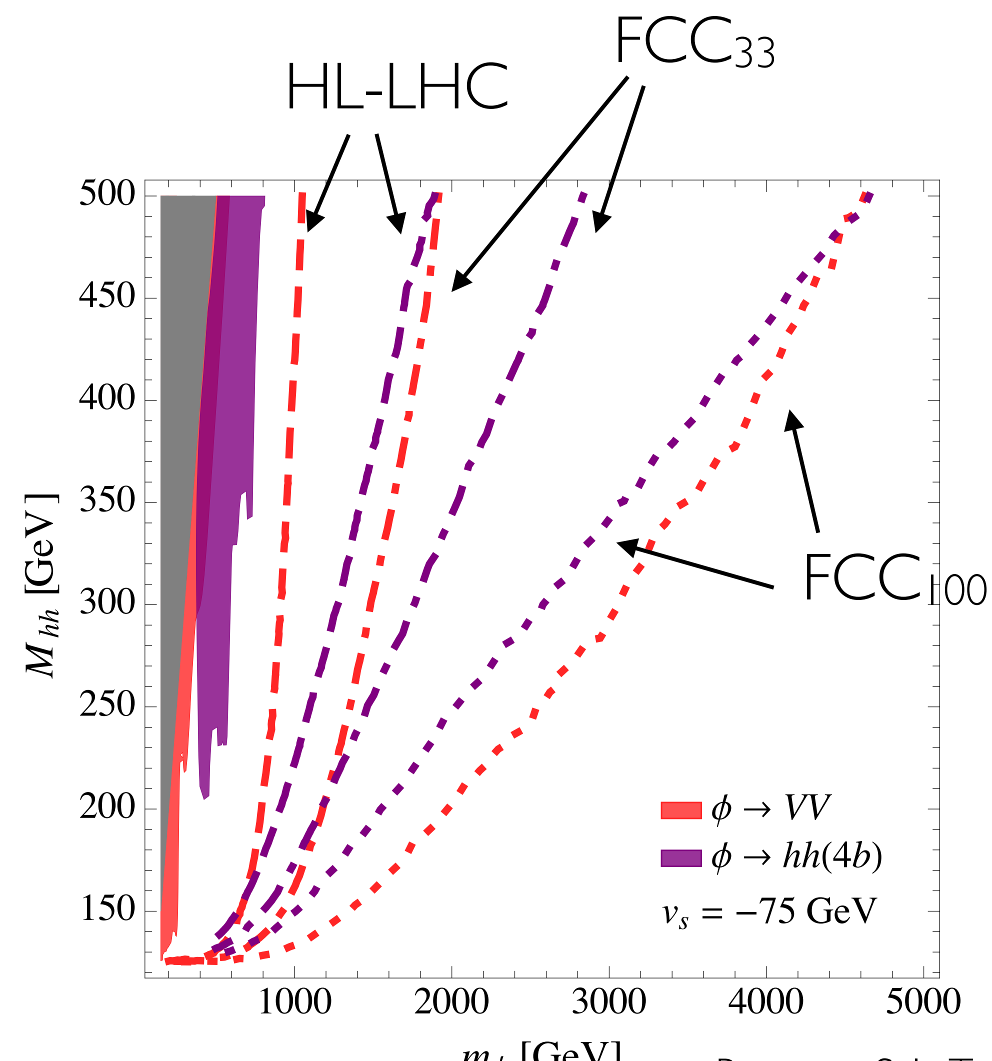
Current experimental analyses in the $\phi \to hh(4b)$ channel

8 TeV	ATLAS	CONF-2014-005
	CMS	1503.04114
13 TeV	ATLAS	CONF-2016-049

Reach of direct searches

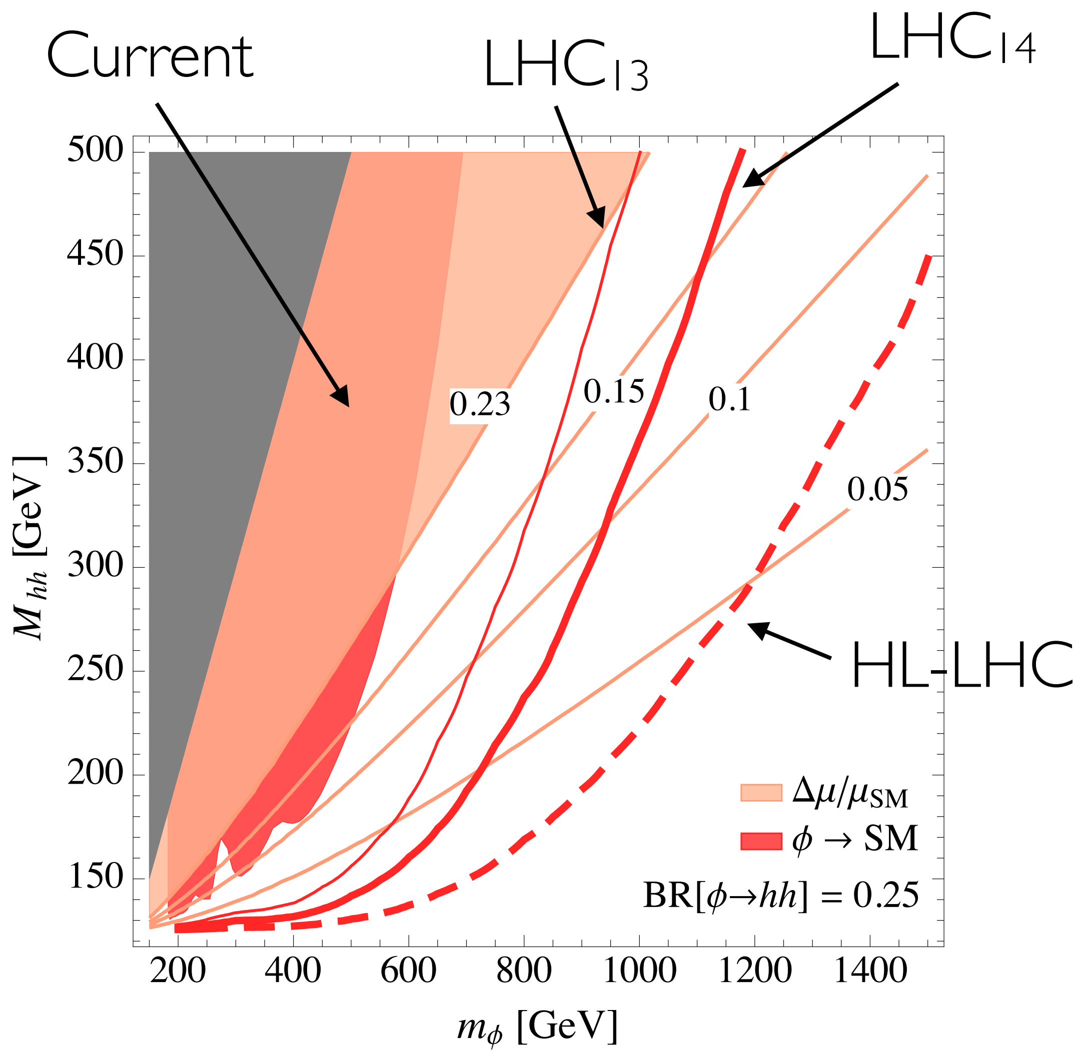
In some regions of the parameter space, the $\phi \to hh(4b)$ channel give the best reach

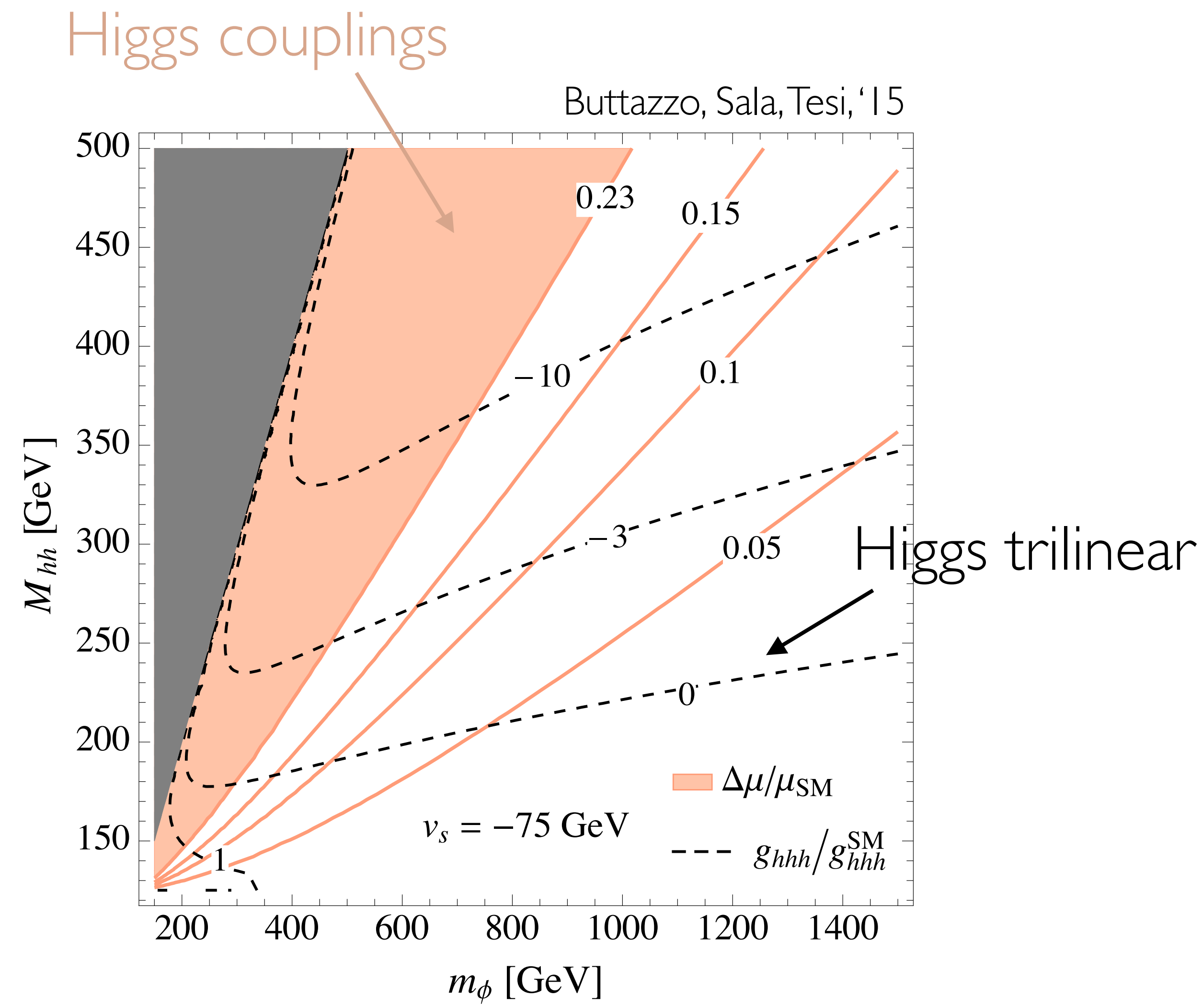




Buttazzo, Sala, Tesi, '15

Deviations in the Higgs couplings





- ✦ Direct searches can be competitive with indirect constraints from Higgs couplings deviations
- ✦ Sizeable deviations in the Higgs trilinear coupling expected

Conclusions

Conclusions

Double Higgs production can give access to a rich landscape of phenomena both in the SM and Beyond

✦ **Non-resonant** processes

- probe Higgs potential (in particular Higgs trilinear)
- access non-linear Higgs couplings
- test the strength of EWSB at high energy
- small cross section:

  limited precision at LHC

  good prospects at future high energy colliders (eg. FCC_{100})

✦ **Resonant** processes

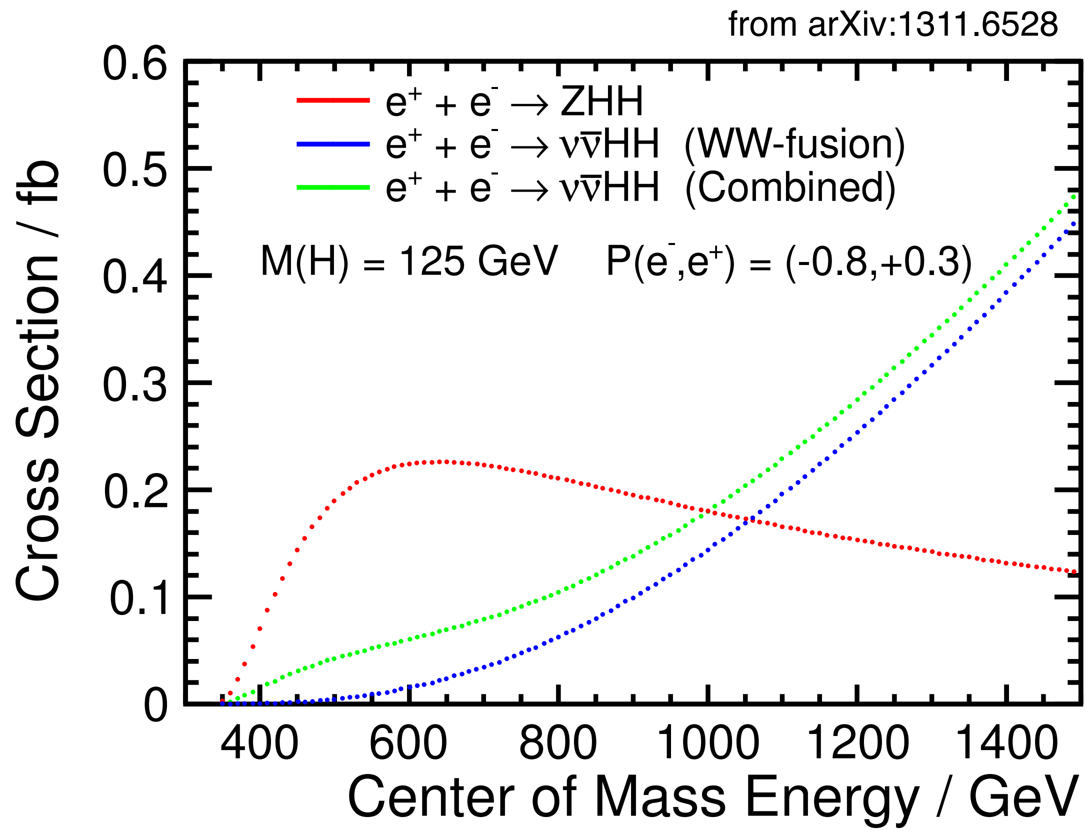
- test extended Higgs sectors
- good reach possible at HL-LHC

Backup

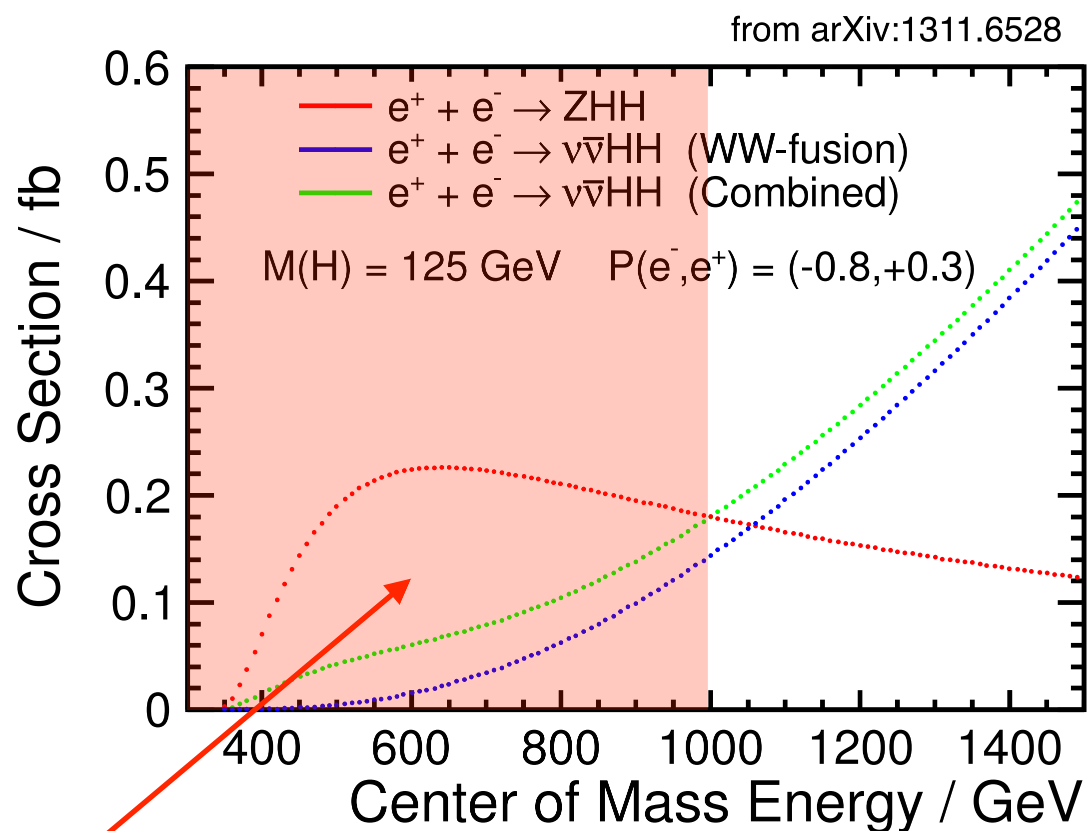
Non-resonant processes

Double Higgs at e^+e^- Colliders

Main production channels

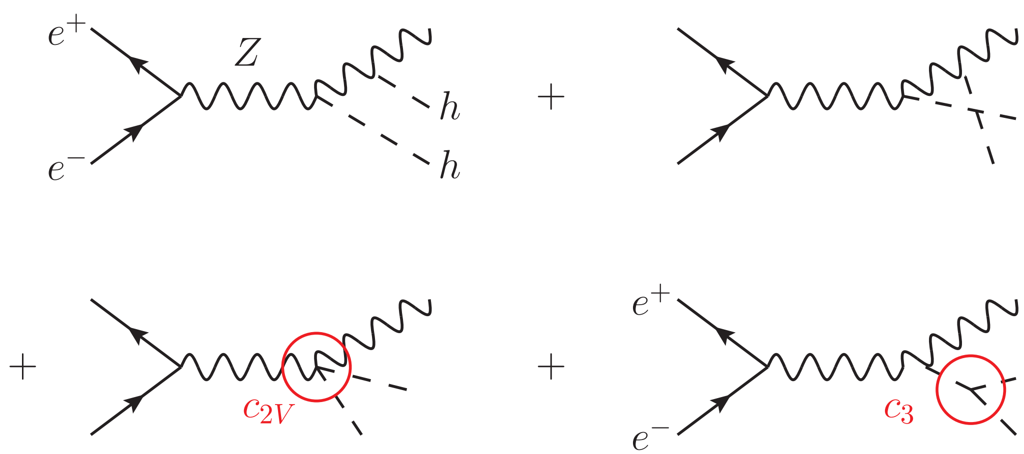


Main production channels



Double Higgs-strahlung (DHS)

dominant below 1 TeV



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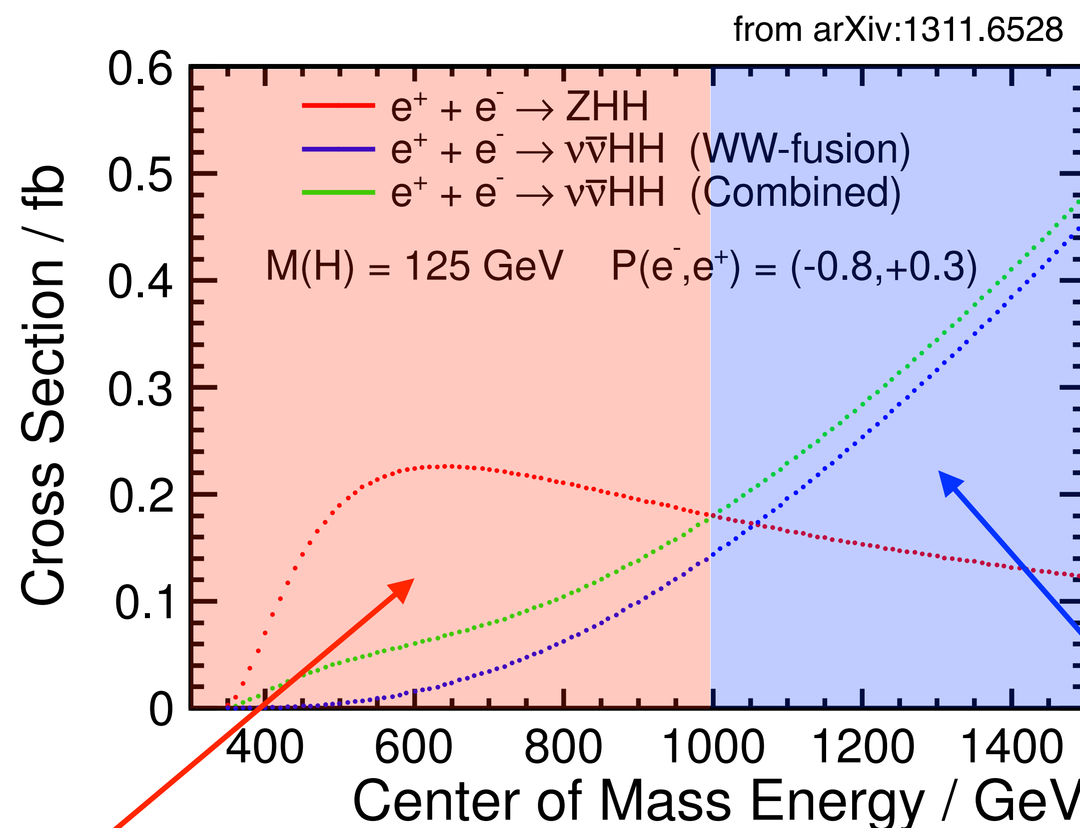

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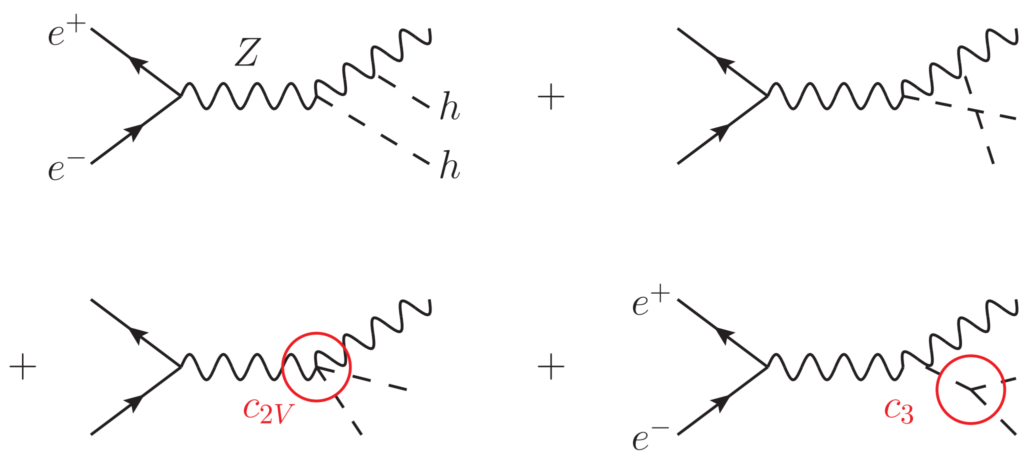
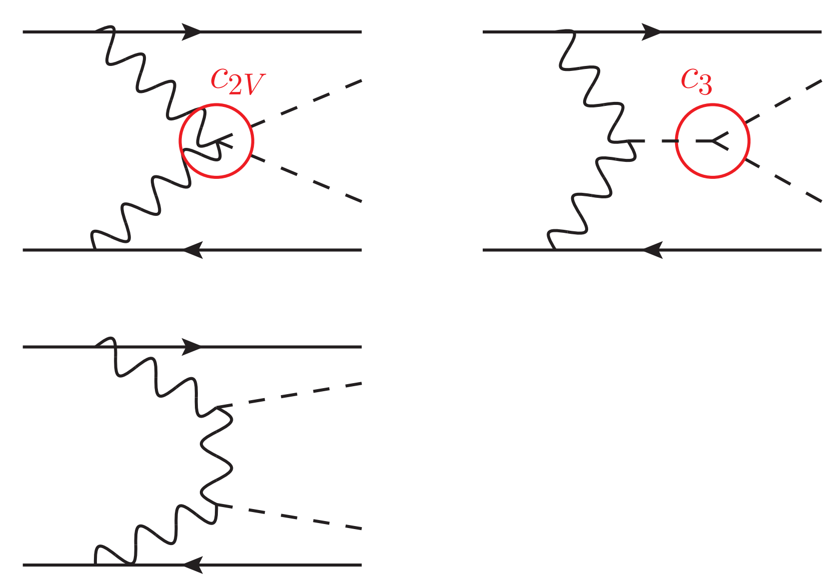


Vector Boson Fusion (VBF)

dominant above 1 TeV



Expected precision on c_3 and c_{2V}

	COM energy	Precision	Process	Reference
ILC	500 GeV $[L = 500\ \mathrm{fb}^{-1}]$	$\Delta c_3 \sim 104\%$	DHS	ILC TDR, Volume 2, arXiv:1306.6352
	1 TeV $[L = 1\ \mathrm{ab}^{-1}]$	$\Delta c_3 \sim 28\%$	VBF	ILC TDR, Volume 2, arXiv:1306.6352
		$\Delta c_{2V} \sim 20\%$	DHS	Contino et al., JHEP 1402 (2014) 006
CLIC	1.4 TeV $[L = 1.5\ \mathrm{ab}^{-1}]$	$\Delta c_3 \sim 24\%$	VBF	Roloff (CLICdp Coll.), talk at LCWS14
		$\Delta c_{2V} \sim 7\%$		
	3 TeV $[L = 2\ \mathrm{ab}^{-1}]$	$\Delta c_3 \sim 12\%$		
		$\Delta c_{2V} \sim 3\%$		

FCC$_{100}$ allows for better precision

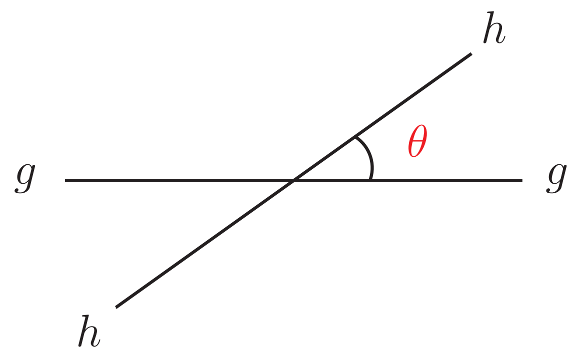
- higher energy reach (useful for Δc_{2V})
- higher luminosity at threshold (useful for Higgs trilinear)

Gluon Fusion channel

Angular dependence

The angular distribution

The signal is also characterised by the angle between the Higgs pair and the beam axis in the c.o.m. frame



Scattering due to two partial waves $J_z = 0$ and $J_z = \pm 2$

$$\frac{d\sigma}{d\cos\theta} \sim const. \quad (J_z = 0) \qquad\qquad \frac{d\sigma}{d\cos\theta} \sim \sin^2\theta \quad (J_z = \pm 2)$$

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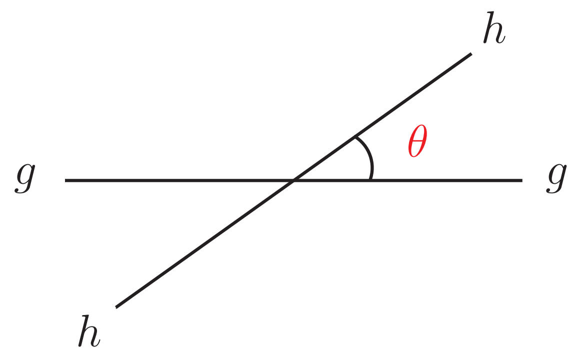

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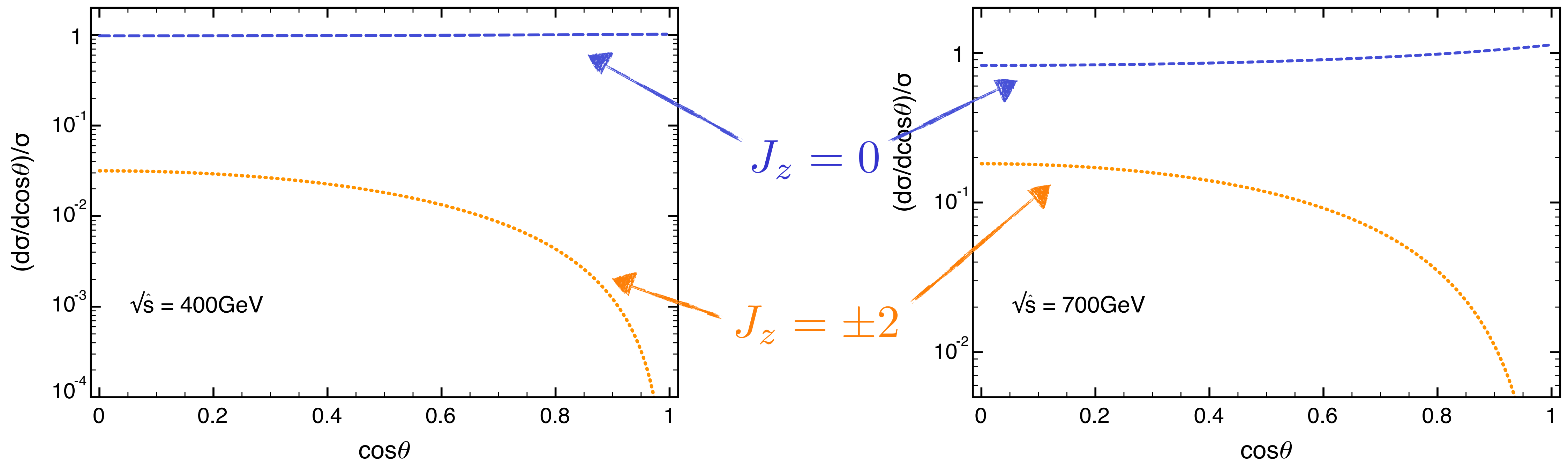
- in the SM the $J_z = \pm 2$ amplitude comes only from the box diagram and is quite suppressed



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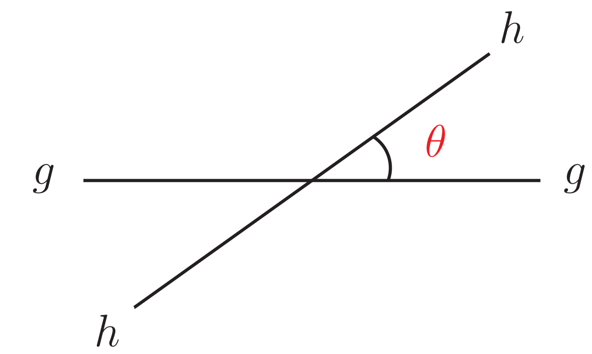

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$$\frac{d\sigma}{d\cos\theta} \sim const. \quad (J_z = 0) \qquad \frac{d\sigma}{d\cos\theta} \sim \sin^2\theta \quad (J_z = \pm 2)$$

- ✦ in the SM the $J_z = \pm 2$ amplitude comes only from the box diagram and is quite suppressed

- ✦ the BSM diagrams coming from dim. 6 operators only generate contributions with $J_z = 0$

  ➡ angular analysis not useful to disentangle NP effects
  (possible exception dim. 8 operators, extremely hard at LHC)