TESTING THE HIGGS BOSON THROUGH PAIR PRODUCTION

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EPFL, Lausanne & CERN

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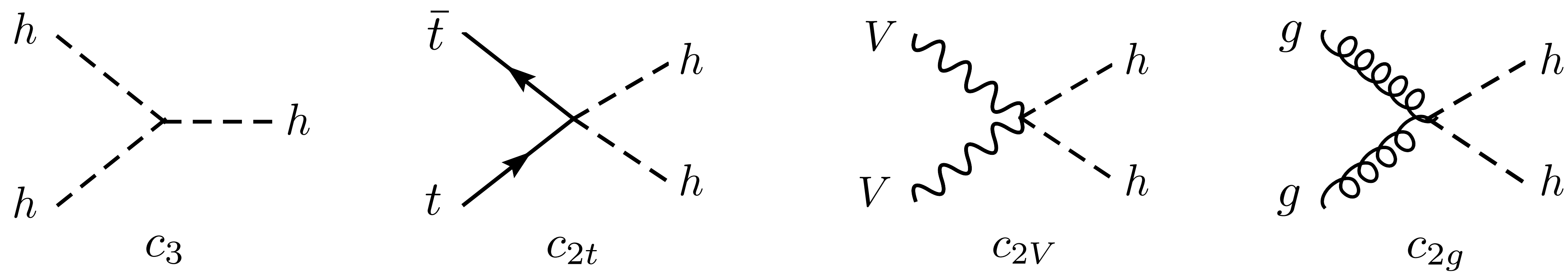
What can we learn from double-Higgs production ?

1. Measure couplings not accessible through single-Higgs processes



2. (further) Test the Higgs as an $SU(2)_L$ doublet

3. Probe the strength of EWSB dynamics at higher energies

General parametrization of Higgs couplings: non-linear Lagrangian

$$\mathcal{L} = \frac{1}{2}\partial_\mu h\,\partial^\mu h - \frac{1}{2}m_h^2 h^2 - c_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + \dots$$
$$- \sum_{\psi=u,d,l} m_{\psi^{(i)}}\,\bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi\frac{h}{v} + c_{2\psi}\frac{h^2}{v^2} + \dots\right)$$
$$+ \left(m_W^2\,W_\mu^+W^{-\,\mu} + \frac{1}{2}m_Z^2\,Z_\mu Z^\mu\right)\left(1 + 2c_V\,\frac{h}{v} + c_{2V}\,\frac{h^2}{v^2} + \dots\right)$$
$$+ \frac{\alpha_s}{\pi}G^a_{\mu\nu}G^{a\mu\nu}\left(c_g\frac{h}{v} + \frac{c_{gg}}{2}\frac{h^2}{v^2} + \dots\right) + \dots$$

- Assumptions: 1) spin-0, custodial singlet Higgs ; 2) New Physics is heavy
- All terms can be dressed up with EW Nambu-Goldstone bosons and made manifestly invariant under $SU(2)_L \times U(1)_Y$
- Naively: $$\delta c_i \equiv (c_i - 1) \sim O\left(\frac{g_*^2 v^2}{m_*^2}\right)$$

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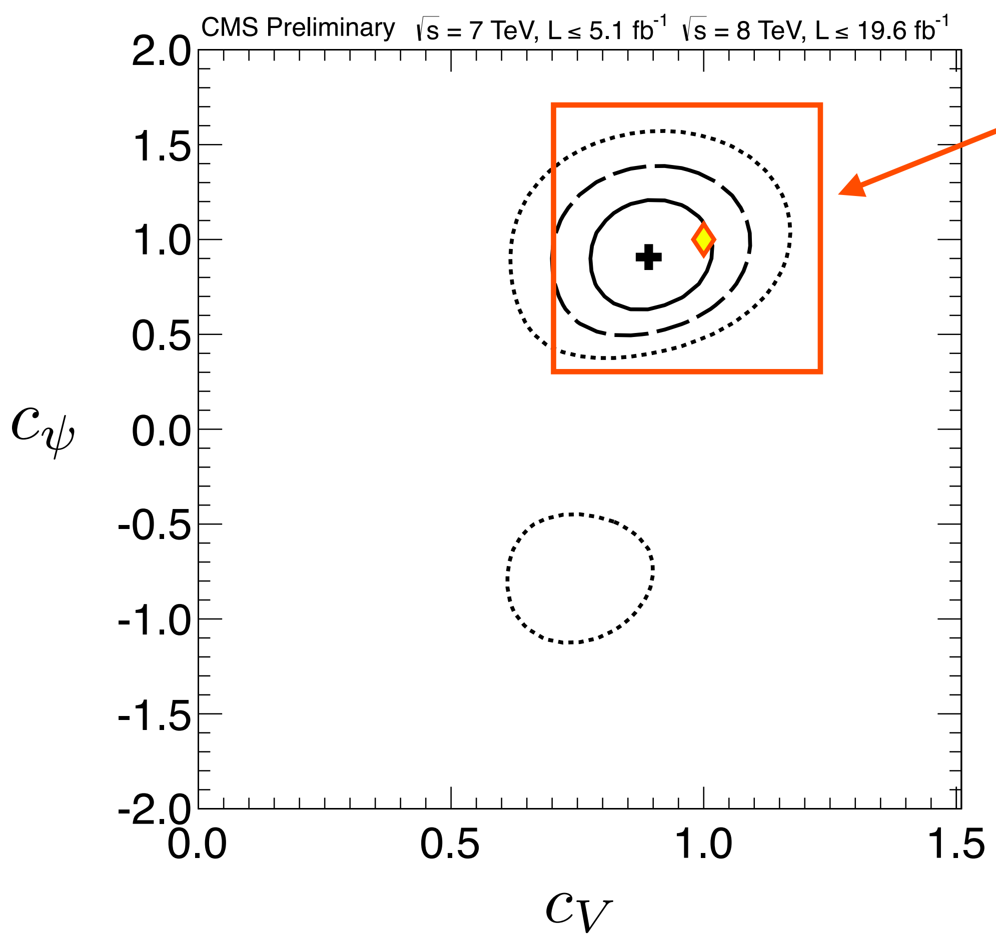

Current data constrain single-Higgs couplings to be close to the SM point

$$\delta c_i \lesssim O(20-30\%)$$

The SM point is special in that the theory stays weakly-coupled up to very high scales

How to live near the SM point:

1. The new boson is part of an $SU(2)_L$ doublet

$$H = e^{i\pi/v}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

2. There is a gap between the NP scale and m_h

Effective Lagrangian for a Higgs doublet

Buchmuller and Wyler NPB 268 (1986) 621

⋮

Giudice et al. JHEP 0706 (2007) 045

Grzadkowski et al. JHEP 1010 (2010) 085

$$\mathcal{L} = \mathcal{L}_{SM} + \Delta\mathcal{L}_{(6)} + \Delta\mathcal{L}_{(8)} + \ldots$$

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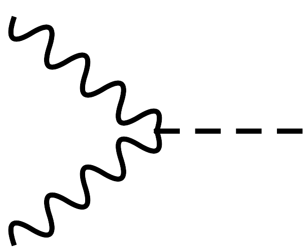
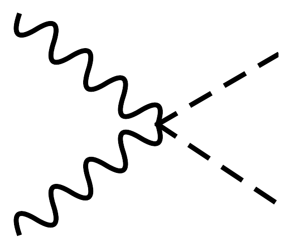
$$\mathcal{L} = \mathcal{L}_{SM} + \Delta\mathcal{L}_{(6)} + \Delta\mathcal{L}_{(8)} + \ldots$$

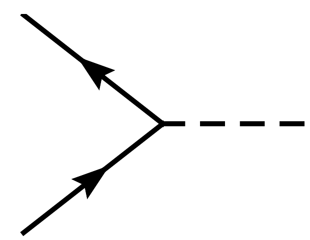
$$\supset \frac{\bar{c}_H}{2v^2}[\partial_\mu(H^\dagger H)]^2 + \frac{\bar{c}_u}{v^2} y_u\, H^\dagger H\, \bar{q}_L H^c u_R - \frac{\bar{c}_6 \lambda}{v^2}(H^\dagger H)^3 + \frac{\bar{c}_g\, g_S^2}{m_W^2}\, H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$



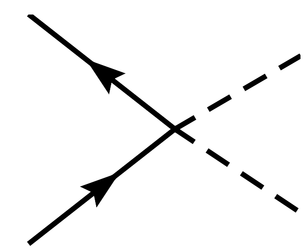
$$c_V = 1 - \frac{\bar{c}_H}{2}$$



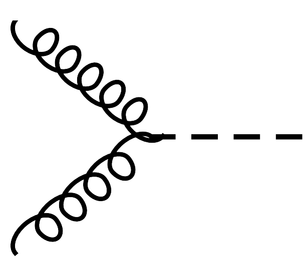
$$c_{2V} = 1 - 2\bar{c}_H$$

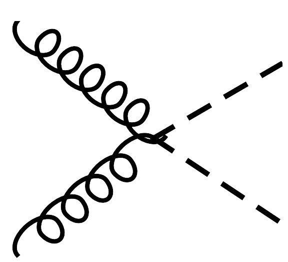


$$c_t \simeq 1 - \frac{\bar{c}_H}{2} - \bar{c}_u$$

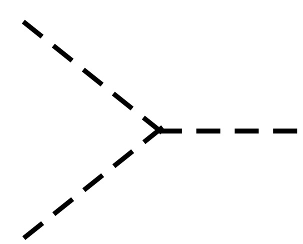


$$c_{2t} \simeq -\frac{1}{2}\left(\bar{c}_H + 3\bar{c}_u\right)$$





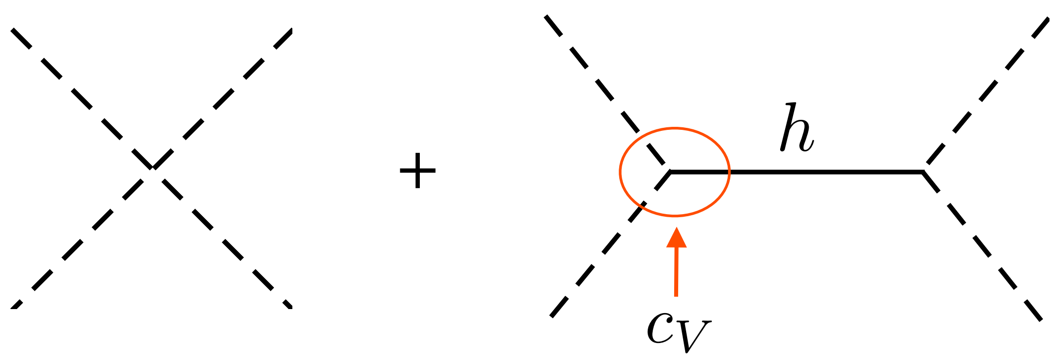
$$c_g = c_{2g} = \bar{c}_g \left(\frac{4\pi}{\alpha_2}\right)$$



$$c_3 \simeq 1 - \frac{3}{2}\bar{c}_H + \bar{c}_6$$

Strength of EWSB dynamics

EWSB sector $= \{\, \chi \,,\, h \,, \ldots \}$



$$A(s) = \frac{s}{v^2}(1 - c_V^2) - c_V^2\, \frac{m_h^2}{v^2}\, \frac{s}{s - m_h^2 + i\Gamma_h m_h} \equiv g^2(\sqrt{s})$$

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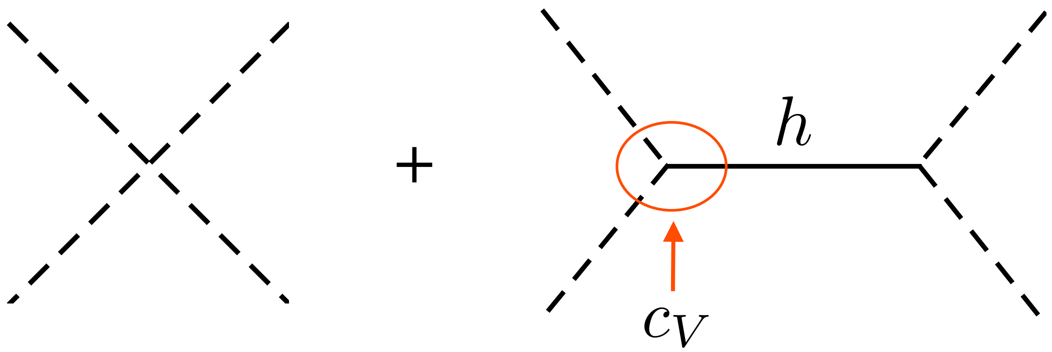

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$= 0$

- For an elementary Higgs boson

$$\boxed{c_V = 1}$$

$$g(E) \to \frac{m_h}{v}$$ ⟵ weak

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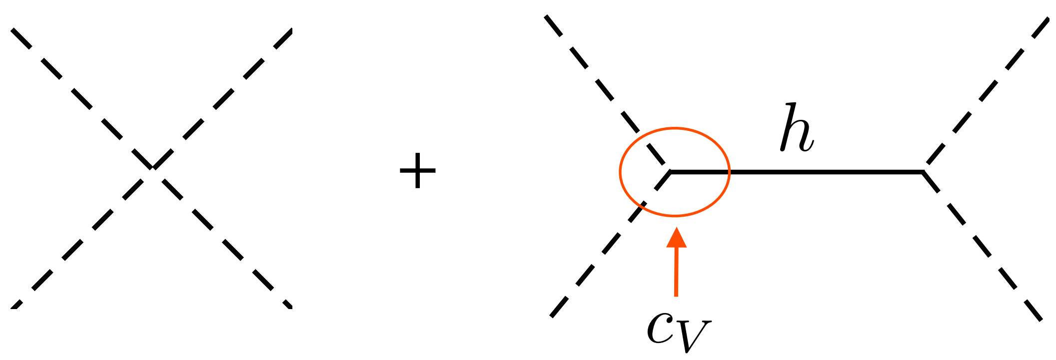

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- For a composite Higgs

$$f^2 \left| \partial_\mu\, e^{i\pi/f} \right|^2 = |D_\mu H|^2 + \frac{1}{2f^2}\left[\partial_\mu (H^\dagger H)\right]^2 + \ldots$$

$$f y\, \bar\psi e^{i\pi/f} \psi = y\, \bar\psi H \psi + \frac{y}{f^2}(H^\dagger H)\bar\psi H\psi + \ldots$$

$$\bar c_H\,, \bar c_u = O\left(\frac{v^2}{f^2}\right)$$

Strength of EWSB dynamics

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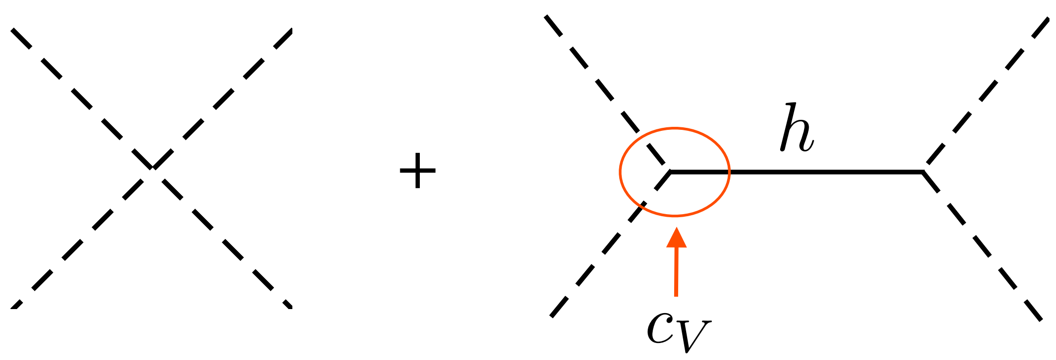

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- For a composite Higgs

$$(1 - c_V^2) \equiv \delta \neq 0$$

coupling strength grows with energy: $g(E) \sim \frac{E}{v}\sqrt{\delta}$

EWSB dynamics becomes fully non-perturbative at energies: $\Lambda_S = \frac{4\pi v}{\sqrt{\delta}}$

Strength of EWSB dynamics

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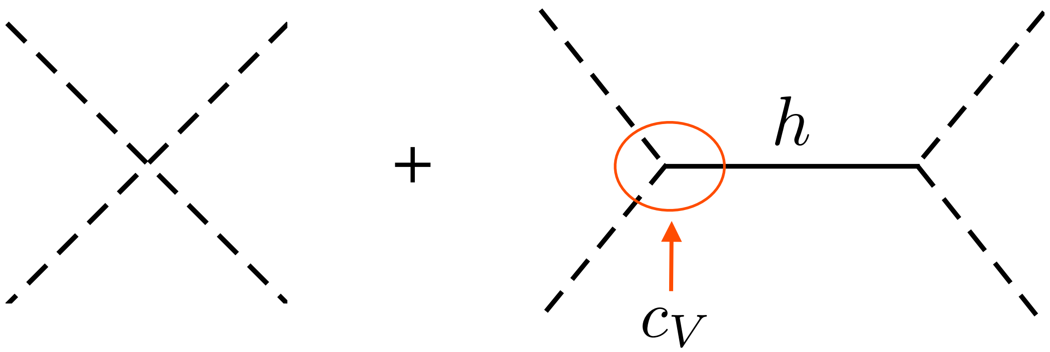

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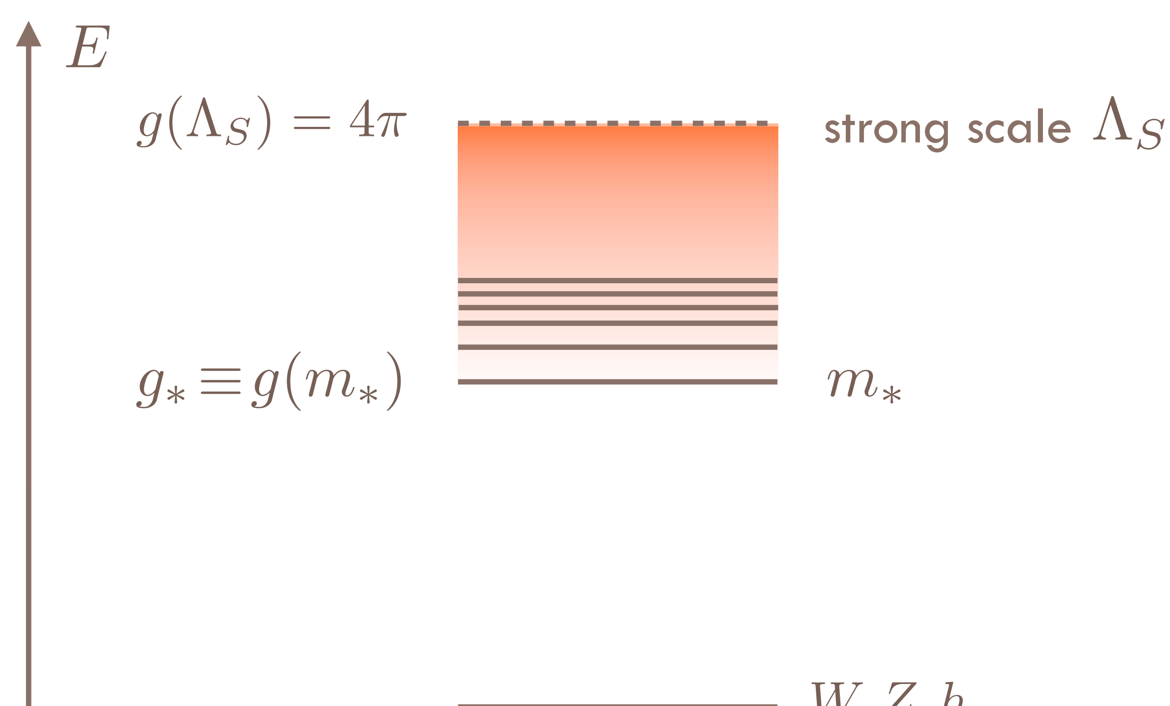
Energy cartoon



Strength of EWSB dynamics

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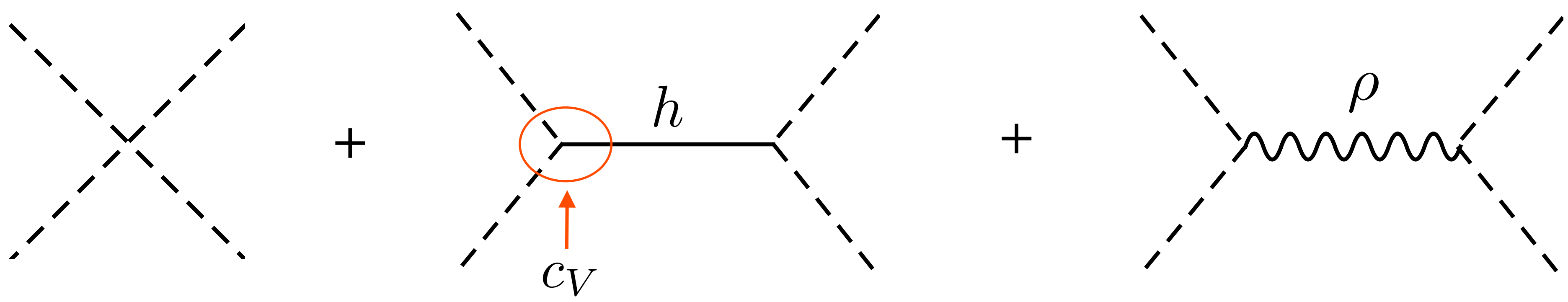

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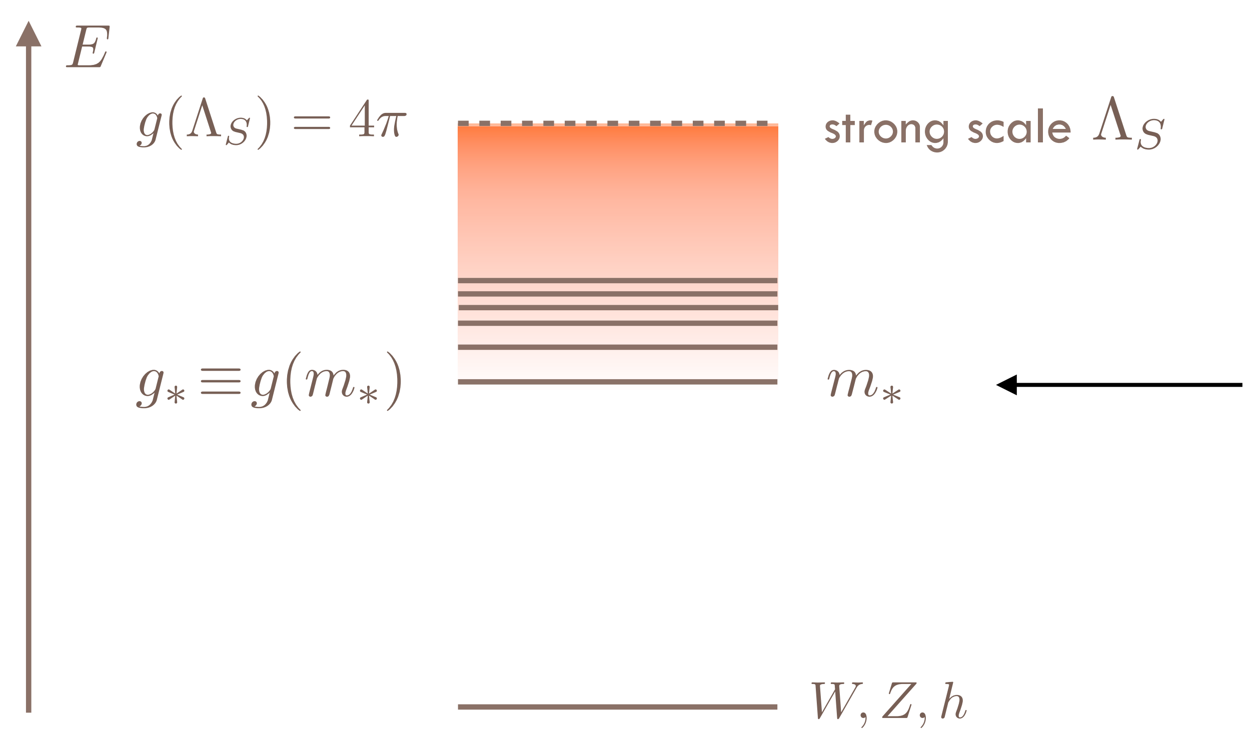

new states appear at the scale $m_* < \Lambda_S$ and saturate the growth of the coupling strength

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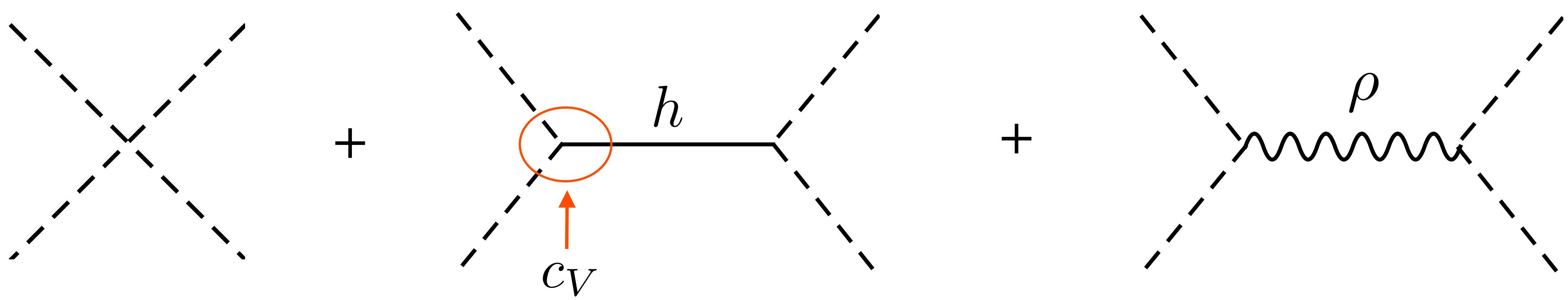

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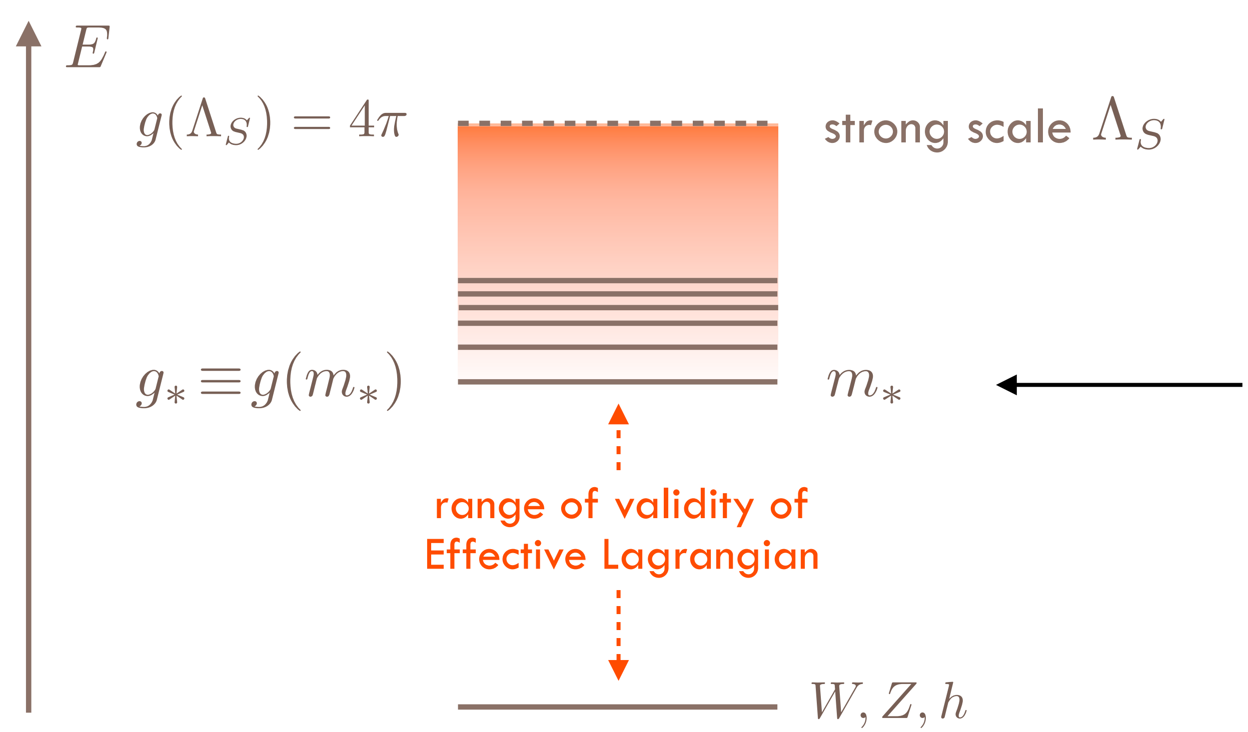

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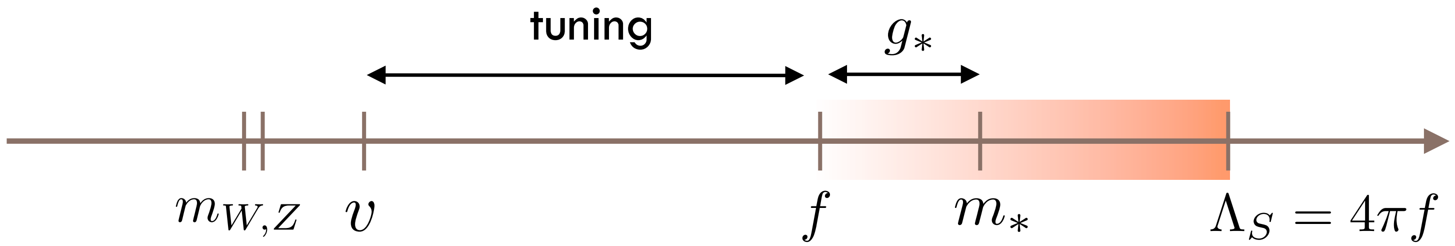
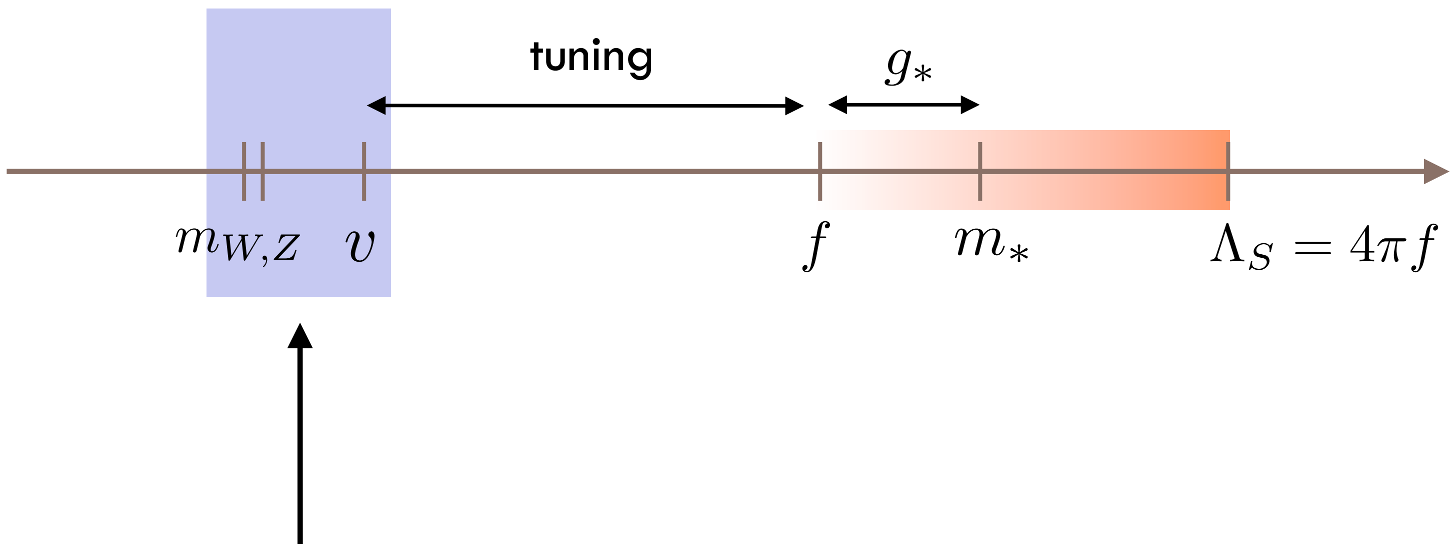
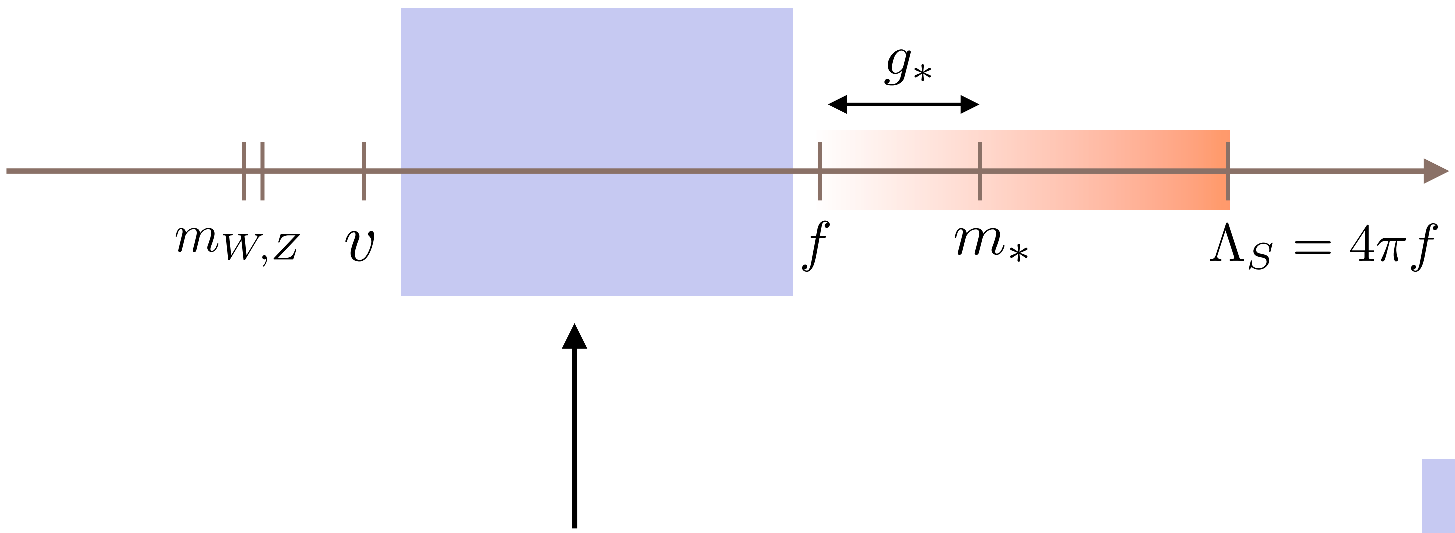

tuning
g_*
$m_{W,Z}$
v
f
m_*
$\Lambda_S = 4\pi f$



Higgs couplings from single-Higgs processes

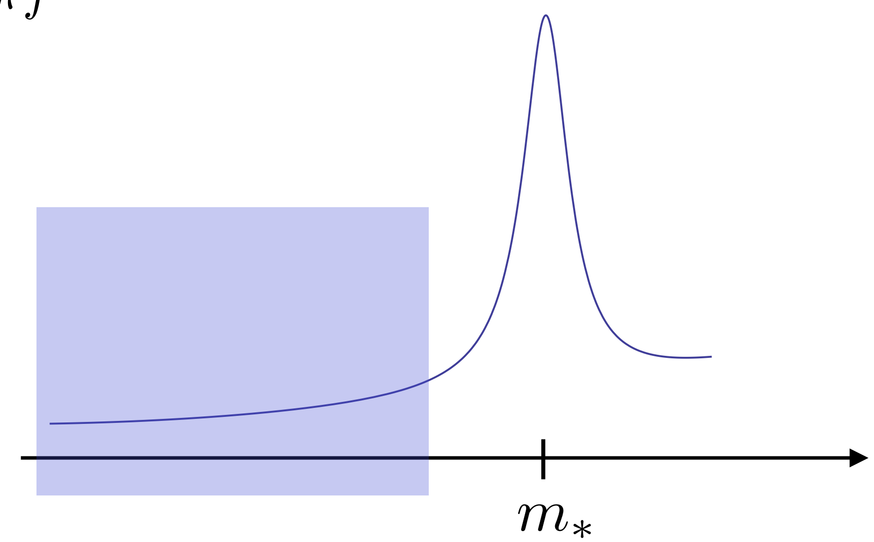
$$g(E = m_h) = \frac{m_h}{v}\sqrt{\delta}$$

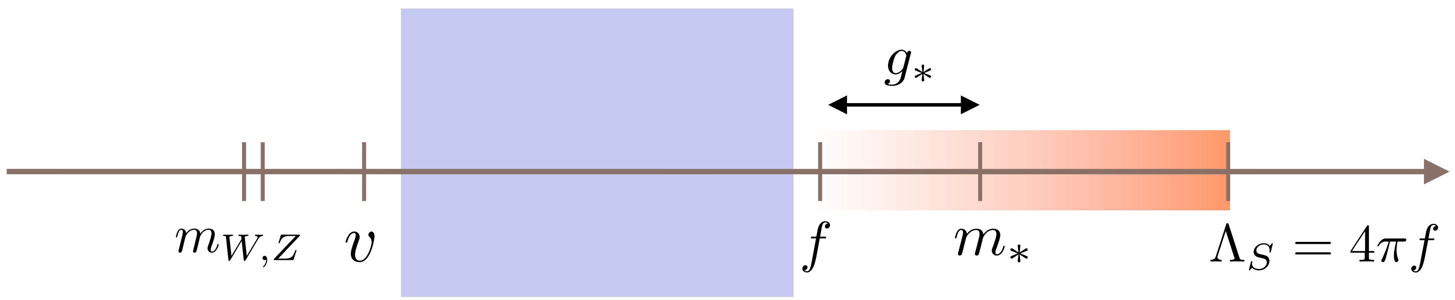
$$\delta = O\left(\frac{v^2}{f^2}\right)$$



Double Higgs production

$$\mathcal{A} = g^2(\sqrt{\hat{s}})\left(1 + O\left(\frac{\hat{s}}{m_*^2}\right)\right)$$





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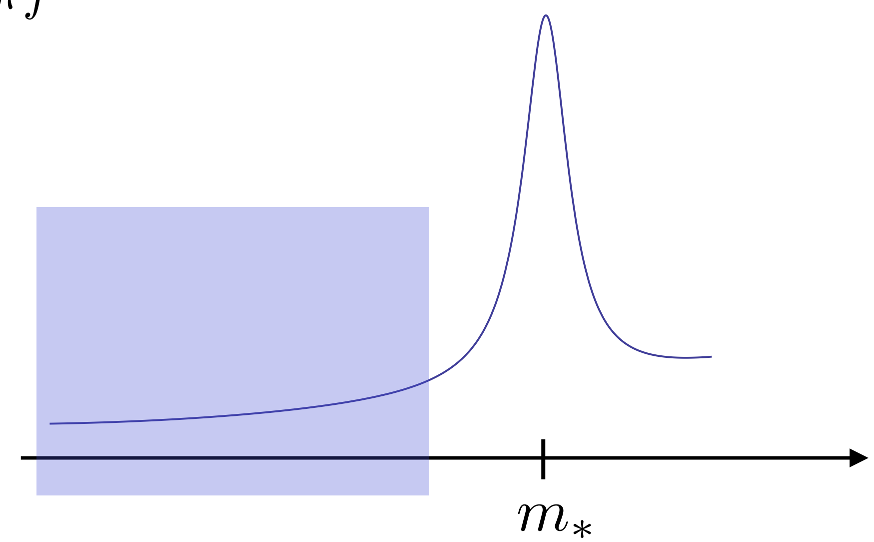
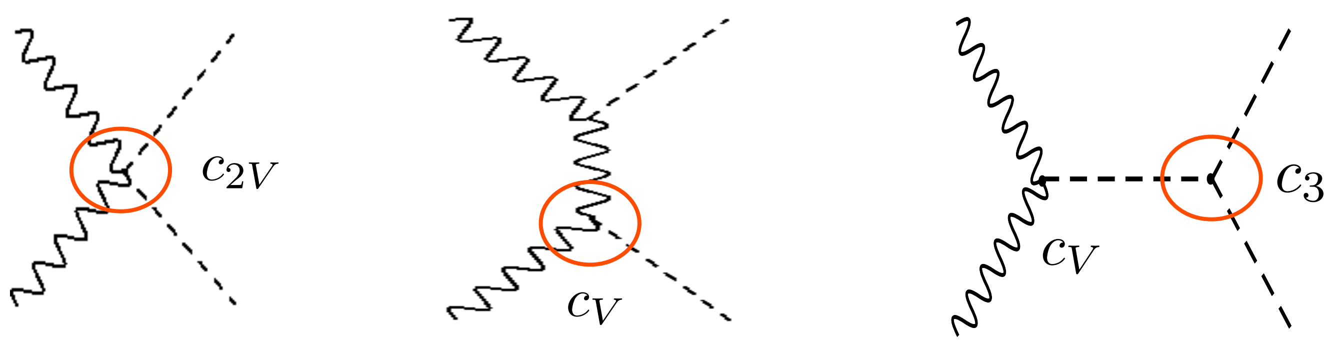
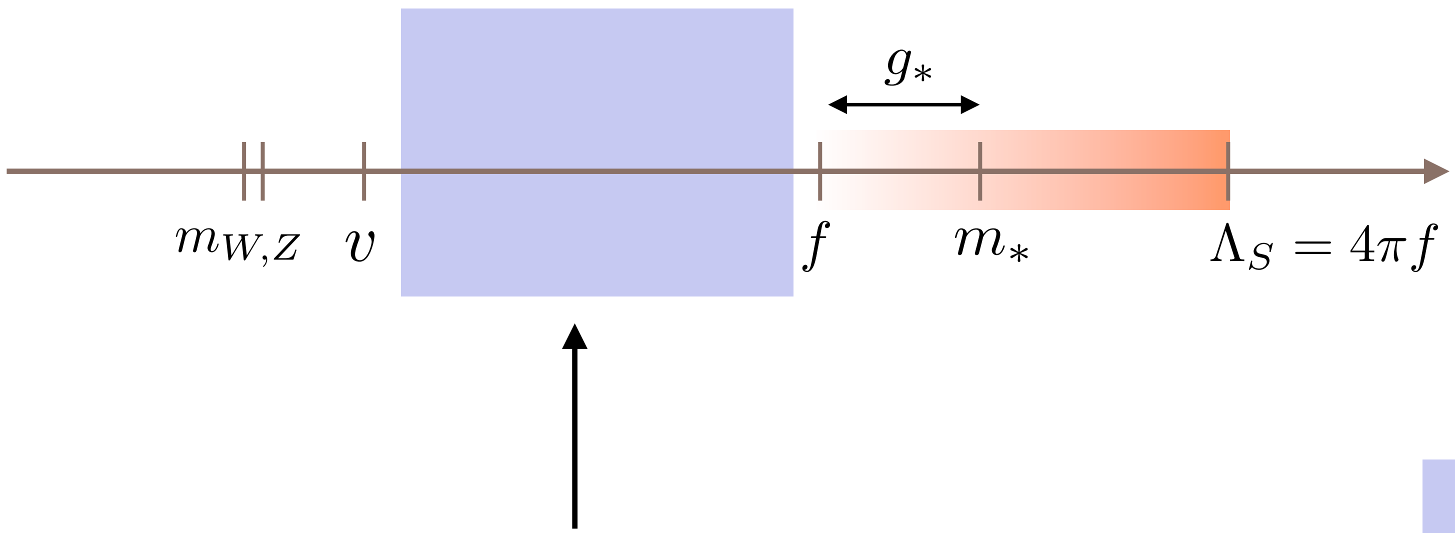


Vector boson fusion



$$g^2(\sqrt{\hat{s}}) = \frac{\hat{s}}{v^2}\left(c_V^2 - c_{2V}\right) \equiv \frac{\hat{s}}{v^2}\delta_{hh}$$



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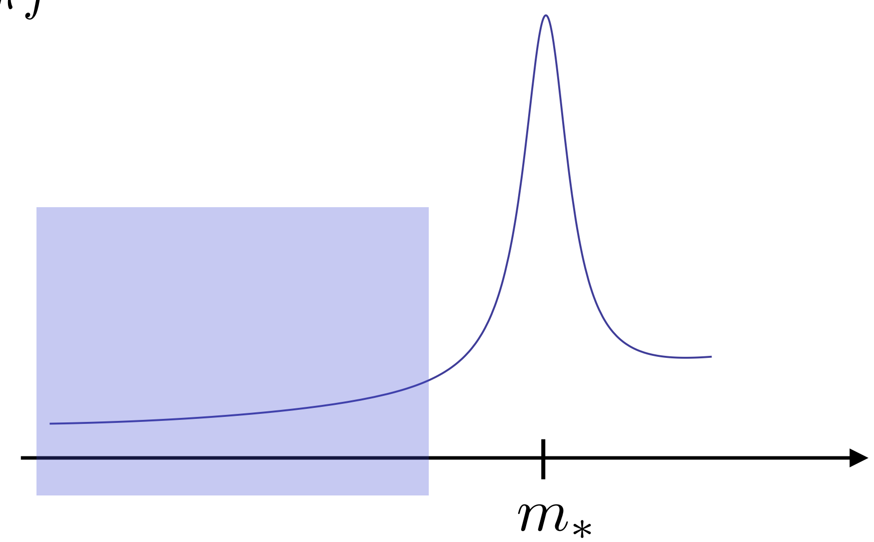

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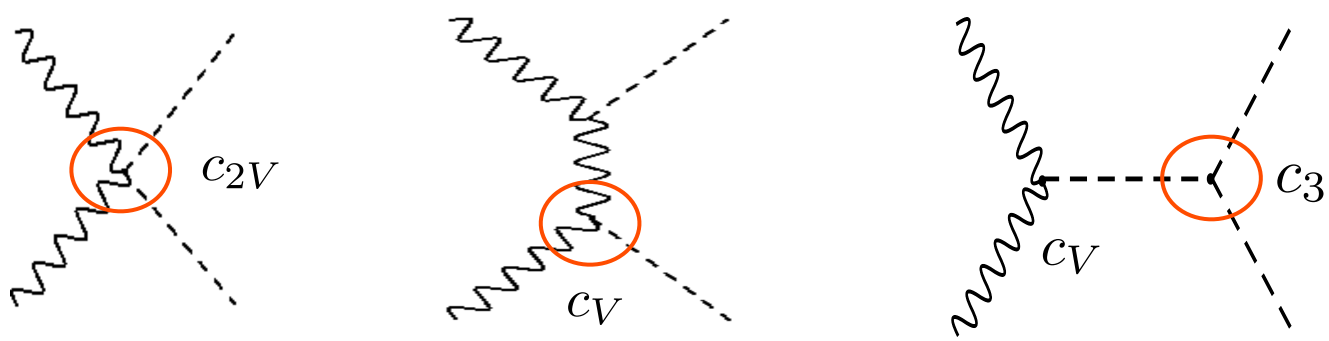


$$g^2(\sqrt{\hat{s}}) = \frac{\hat{s}}{v^2}\left(c_V^2 - c_{2V}\right) \equiv \frac{\hat{s}}{v^2}\delta_{hh}$$

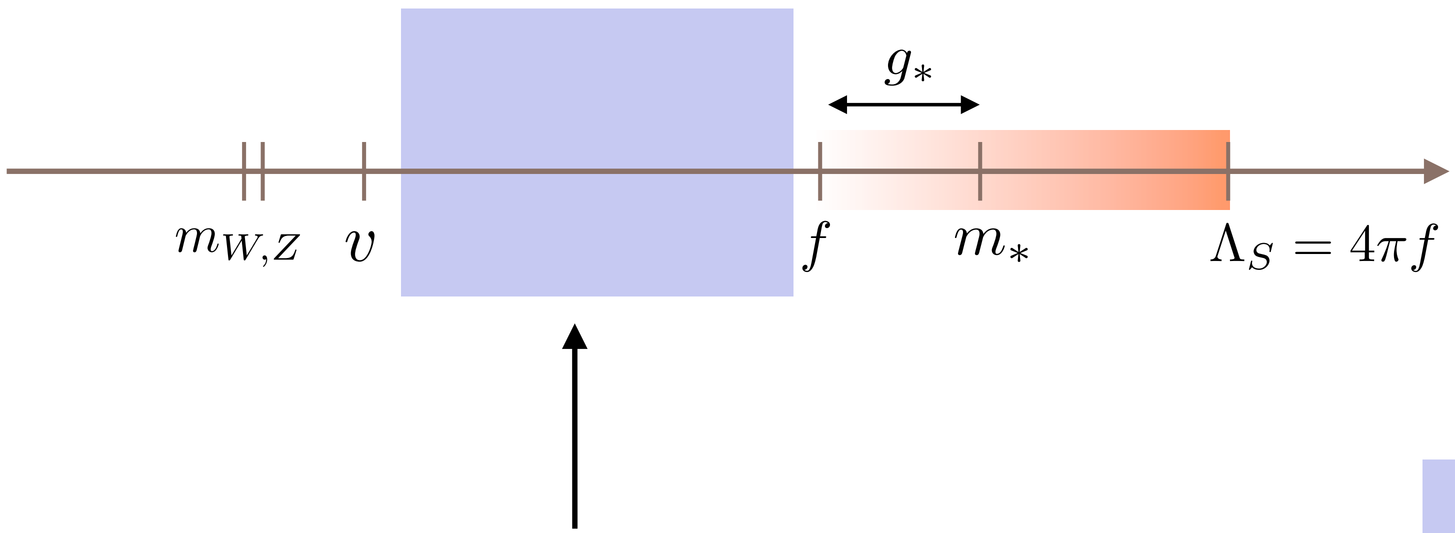
Can put lower bound on coupling strength g_*

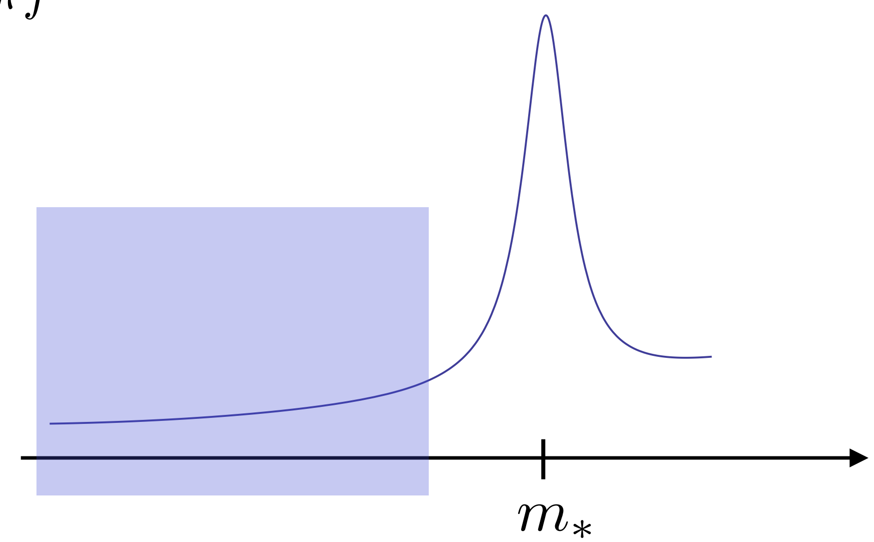
$\delta_{hh} = \delta_{hh}^{exp}$ *and* no new states below a scale M ($m_* > M$) ➡

$$g_* > \frac{M}{v}\sqrt{\delta_{hh}^{exp}}$$

Ex: $\delta_{hh}^{exp} = 0.1$
$M = 2\,\mathrm{TeV}$

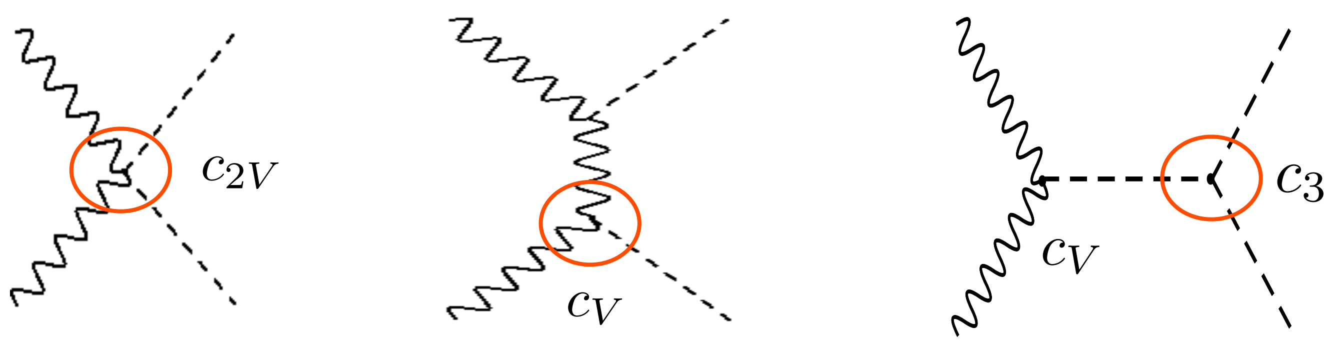
$g_* > 2.6$





Double Higgs production $\mathcal{A} = g^2(\sqrt{\hat{s}})\left(1 + O\left(\frac{\hat{s}}{m_*^2}\right)\right)$

Vector boson fusion



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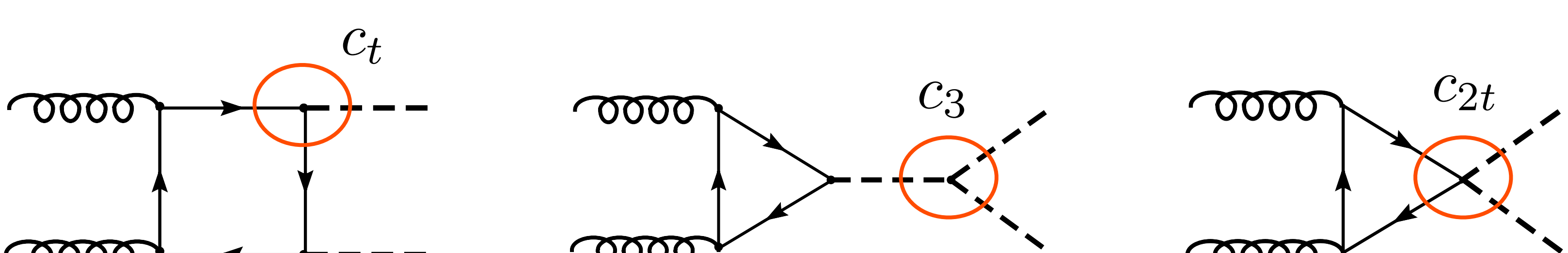
Gluon fusion



$$g^2(\sqrt{\hat{s}}) \sim \frac{\alpha_s}{4\pi} y_t^2 (1 + \delta c_i)$$

Double Higgs production via VBF at pp colliders

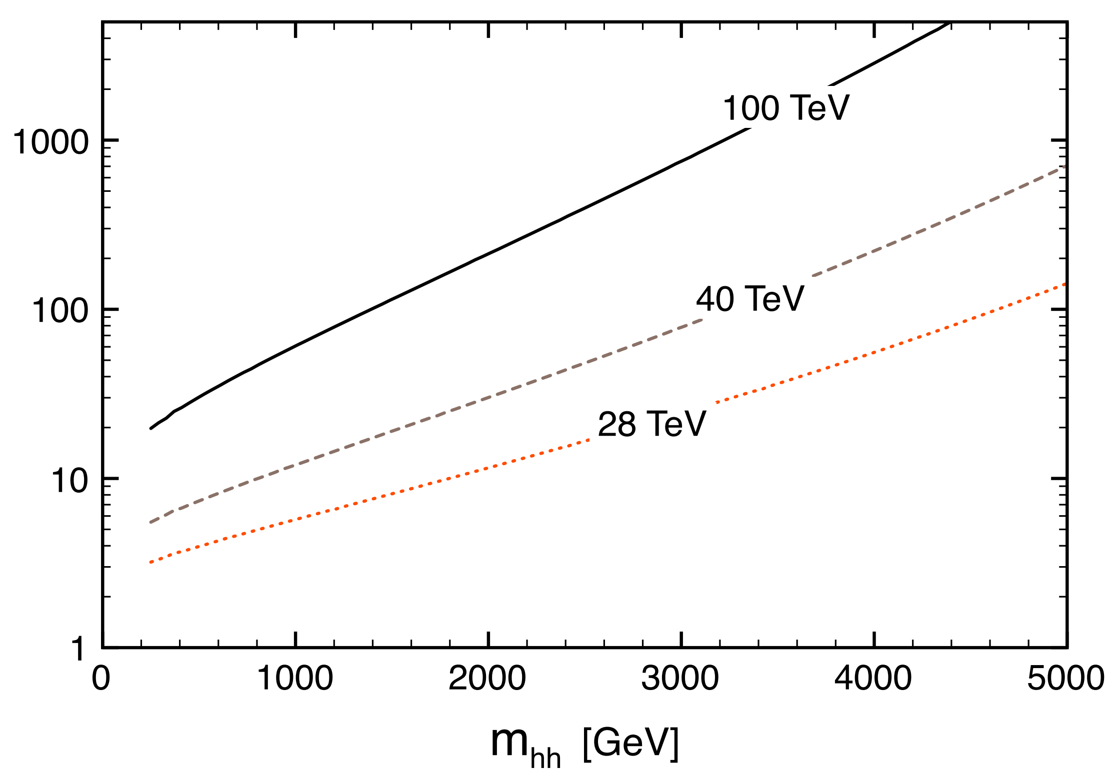
work in progress with O. Bondu, A. Massironi, J. Rojo

	14 Tev	100 Tev
$\sigma(pp \to hhjj)$ [SM]	1.5 fb	54 fb

$$BR(hh \to 4b) = 33\%$$

$$BR(hh \to bb\,\tau_h\tau_h) = 3.1\%$$

WW luminosity ratio



Strategy of analysis:

- Final states included: $hh \to 4b$, $hh \to bb\,\tau_h\tau_h$

- Jets reconstructed using BDRS mass-drop tagger

  Butterworth et al. arXiv:0802.2470

  Events classified by number of mass drops (fat jets)

$hh \to 4b$	boosted	2 MD
	semi-boosted	1 MD + 2 b-jets
	resolved	4 b-jets
$hh \to bb\,\tau_h\tau_h$	boosted	1 MD + 2 τ-jets
	resolved	2 b-jets + 2 τ-jets

- Final events classified in bins of m_{hh} to enhance sensitivity on Higgs couplings

Double Higgs production via VBF at pp colliders

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Cuts

$$p_{Tj} \geq 25 \text{ GeV}\,, \quad p_{Tb} \geq 25 \text{ GeV}\,, \quad p_{T\tau} \geq 25 \text{ GeV}$$

$$|\eta_j| \leq 4.5\,, \quad |\eta_b| \leq 2.5\,, \quad |\eta_\tau| \leq 2.5$$

$$\Delta R_{jb} \geq 0.4\,, \quad \Delta R_{bb} \geq 0.2\,, \quad \Delta R_{j\tau} \geq 0.4\,, \quad \Delta R_{b\tau} \geq 0.4\,, \quad \Delta R_{\tau\tau} \geq 0.2\,,$$

$$m_{jj} \geq 800 \text{ GeV}\,, \qquad \Delta R_{jj} \geq 4.0\,.$$

Efficiencies

$$\epsilon_b = 0.7 \qquad \epsilon_\tau = 0.7$$

$$\zeta_b = 0.01 \qquad \zeta_\tau = 0.04$$

Higgs reconstruction

$$|m(\tau\tau) - m_h| < 20\,\text{GeV}$$

$$|m(bb) - m_h| < 0.15\,m_h$$

Double Higgs production via VBF: results at the LHC

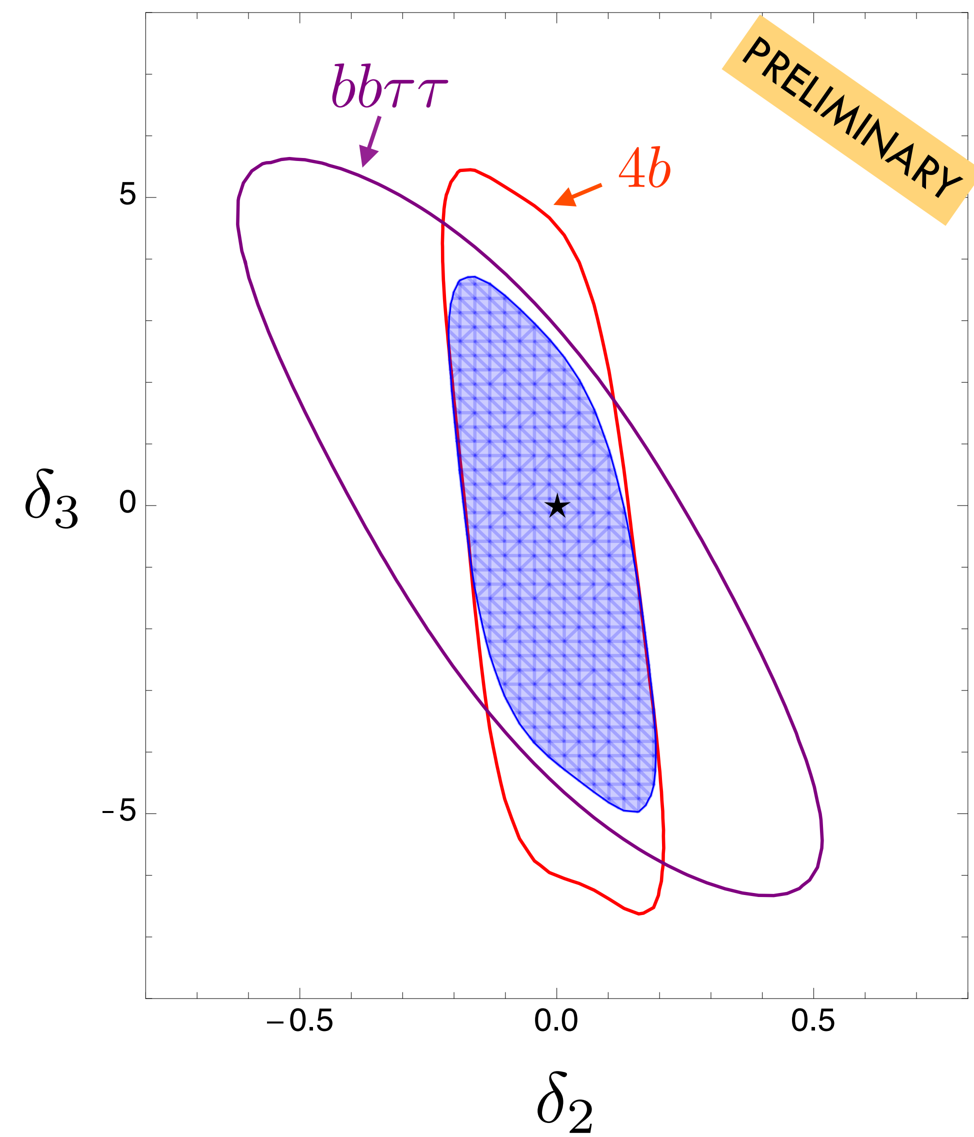
work in progress with O. Bondu, A. Massironi, J. Rojo

Number of events with 3ab^{-1} after cuts

	Bins of m_{hh}				
	I	II	III	IV	V
$hh \to 4b$ [SM]	4.1	3.7	0.8	1.2	1.8
$4b2j$	3.5×10^4	2.7×10^3	630	225	25
$hh \to 2b2\tau$ [SM]	0.3	0.3	0.06	0.09	0.09
$ttjj$	61	2.4	0.3	0.1	0.02

Bins [GeV]: 250, 500, 750, 1000, 1500

LHC 14TeV L=3ab^{-1}



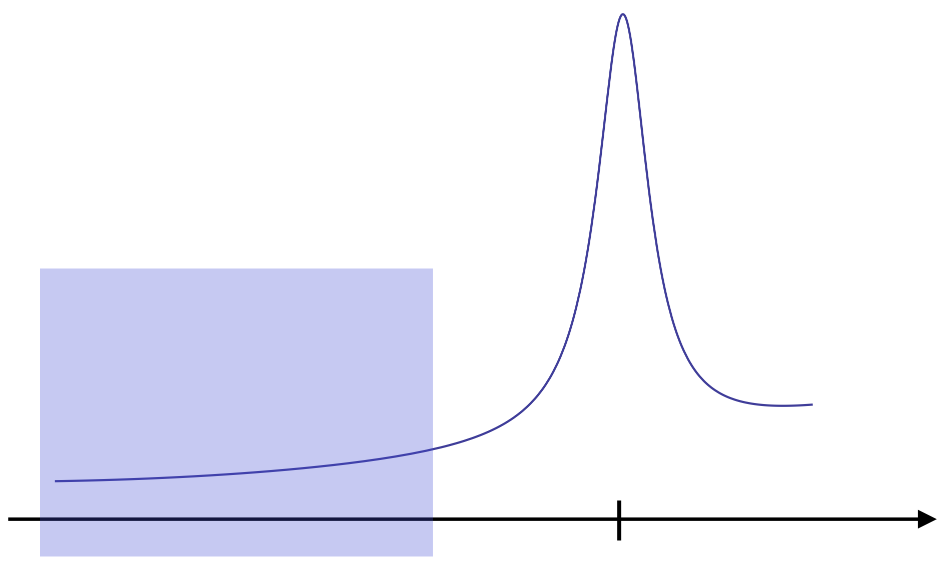
20% precision on δ_2 ($f \sim 550\,\mathrm{GeV}$),
mostly from events with $m_{hh} \sim 1.5\,\mathrm{TeV}$

Sensitive to trilinear Higgs couplings
~4 times larger than in the SM

$$\delta_2 \equiv 1 - c_{2V}/c_V^2$$
$$\delta_3 \equiv 1 - c_3/c_V$$

Validity of EFT description

R. Rattazzi, talk at "BSM physics opportunities at 100TeV", Cern 2014"



$$\mathcal{A}(VV \to hh) = g^2(E)\left(1 + O\left(\frac{E^2}{m_*^2}\right)\right)$$

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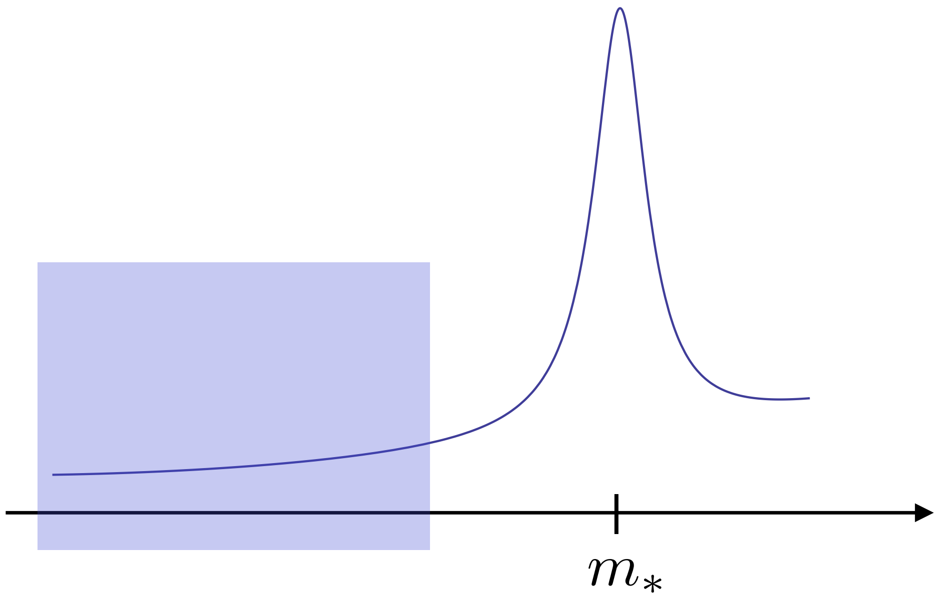

$$\mathcal{A}(VV \to hh) = g^2(E)\left(1 + O\left(\frac{E^2}{m_*^2}\right)\right)$$

$$g(E) = \frac{E}{v}\sqrt{\delta_2} \sim \frac{E}{f}$$

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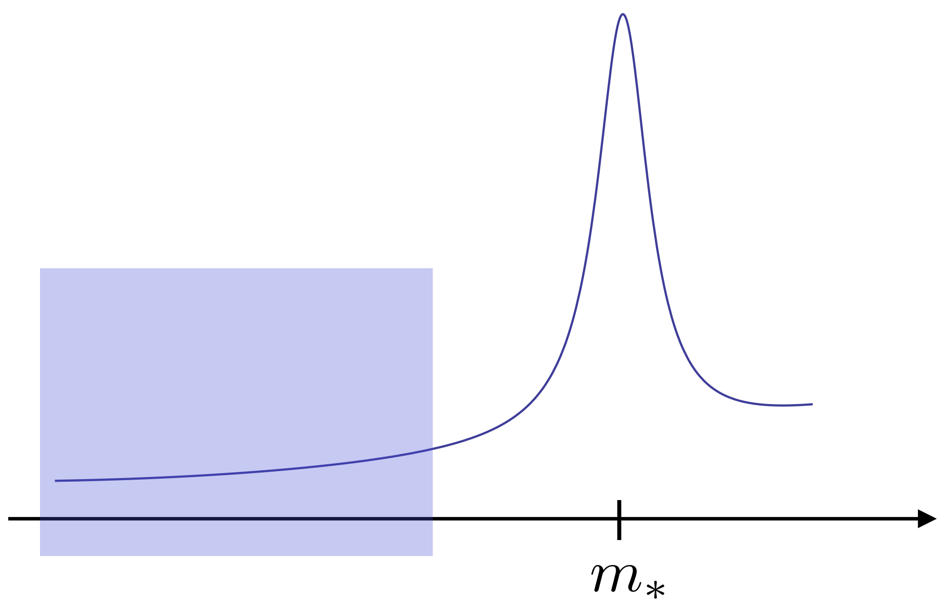

$$\mathcal{A}(VV \to hh) = g^2(E)\left(1 + O\left(\frac{E^2}{m_*^2}\right)\right)$$

$$g(E) = \frac{E}{v}\sqrt{\delta_2} \sim \frac{E}{f}$$

$$\sim \left(\frac{g(E)}{g_*}\right)^2$$

negligible if $g(E) \ll g_*$

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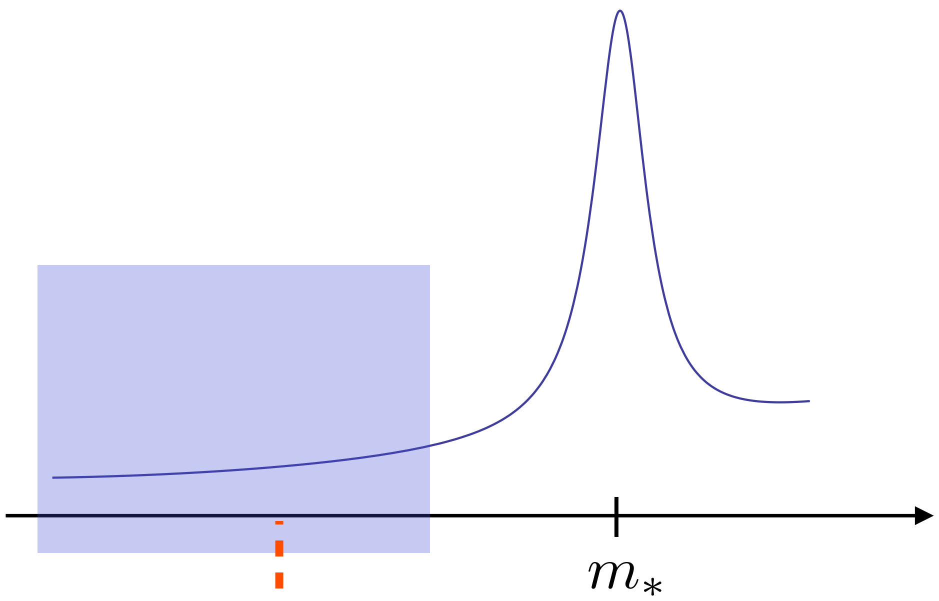

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If max sensitivity on δ_2 comes from events with invariant mass $\sim E$

$m_* > E$ ⇨

$$\delta_2 < \left(\frac{g_*^2 v^2}{E^2}\right) = 0.54\left(\frac{g_*}{3}\right)^2\left(\frac{1\,\mathrm{TeV}}{E}\right)^2$$

$$4\pi \gtrsim g_* > \frac{E}{v}\sqrt{(\delta_2)_{min}} \equiv g_{min}$$

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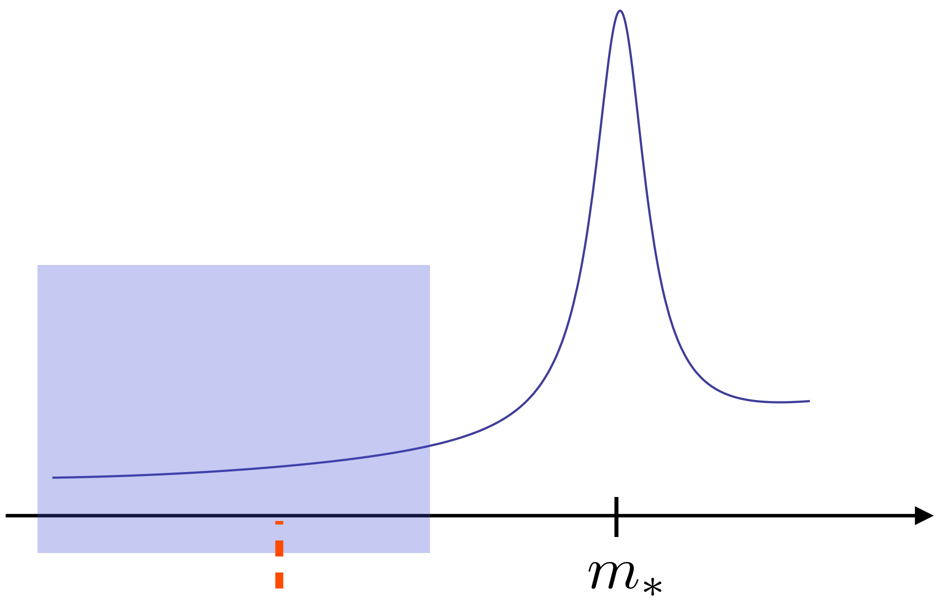

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For our analysis at the LHC L=3ab^{-1}:

$$E \sim 1.5\,\mathrm{TeV}$$
$$(\delta_2)_{min} \sim 0.2$$
$$(f > 550\,\mathrm{GeV})$$

$$\Rightarrow \quad \delta_2 < 0.24\left(\frac{g_*}{3}\right)^2$$
$$4\pi \gtrsim g_* > g_{min} = 2.7$$

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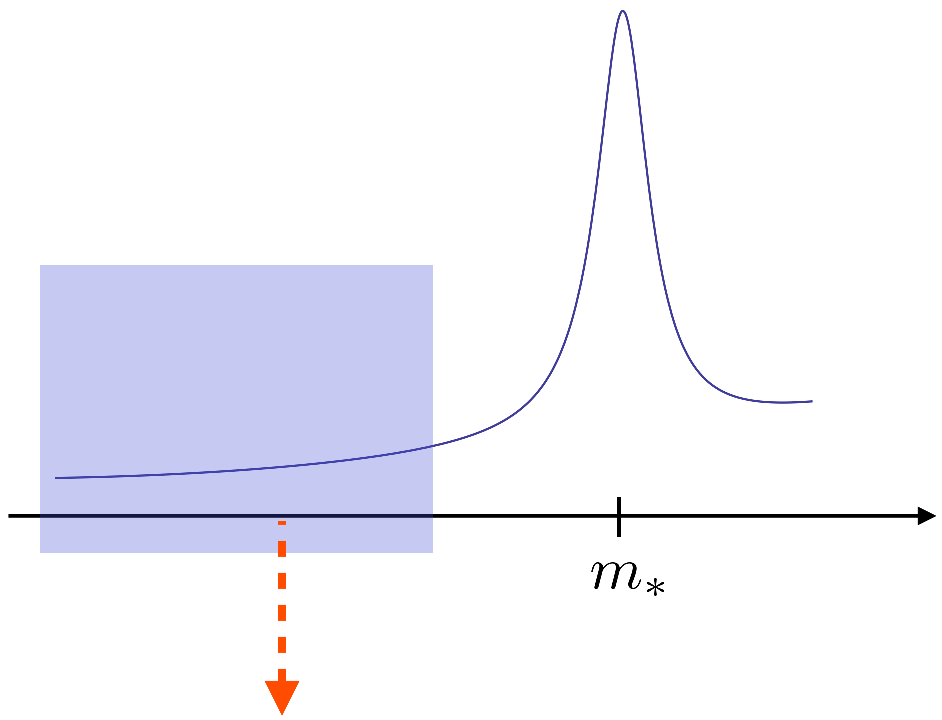

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In general: Study of Higgs properties via EFT in double Higgs production better justified at high-precision machines (such as e^+e^- colliders)

Double Higgs via VBF at CLIC 3TeV

Process: $e^+e^- \to \nu\bar{\nu}\, hh \to \nu\bar{\nu}\, 4b$

- Background negligible (req. good mass res. h vs Z)
  (largest processes: $hZ\nu\bar{\nu}$, $ZZ\nu\bar{\nu}$, ZZe^+e^-)

- Final events classified in 4 categories of m_{hh}, H_T
  to enhance sensitivity on Higgs couplings

Results with 1ab^{-1}

5% precision on δ_2 ($f \sim 1.1\,\mathrm{TeV}$)

30% precision on δ_3

RC, Grojean, Pappadopulo, Rattazzi, Thamm JHEP 1402 (2014) 006

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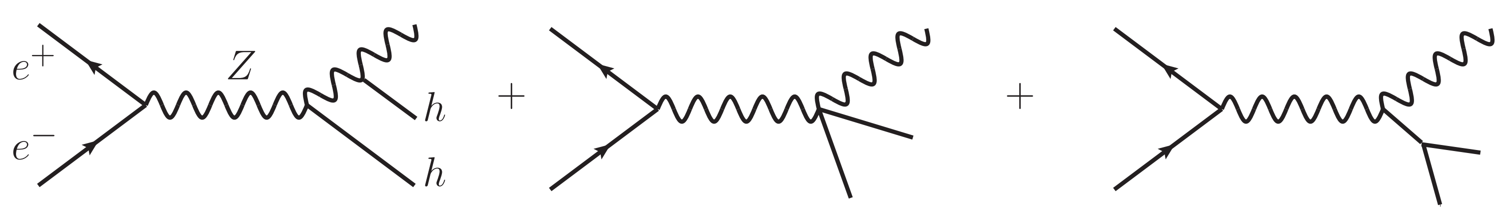
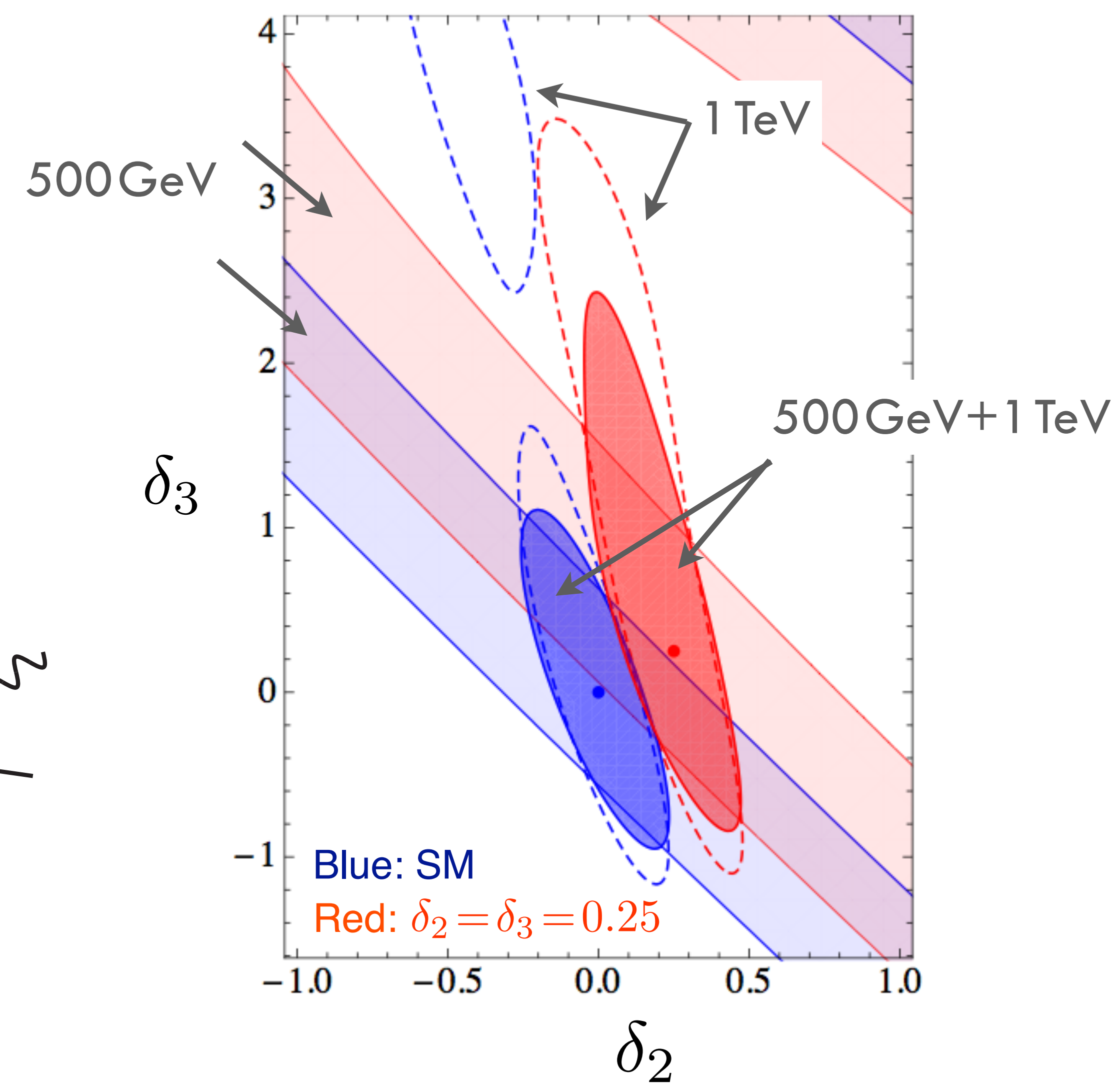
Double Higgs-strahlung at the ILC

Assuming
$$\sqrt{s} = 500\,\mathrm{GeV} + 1\,\mathrm{TeV}$$
$$L = 1\,\mathrm{ab}^{-1}$$
$$c_V^2 (BR(b\bar{b})/BR(b\bar{b})_{SM}) = 1$$





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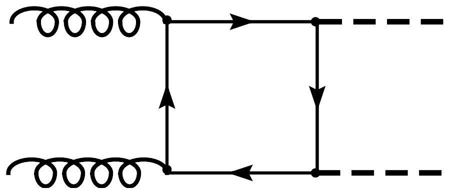
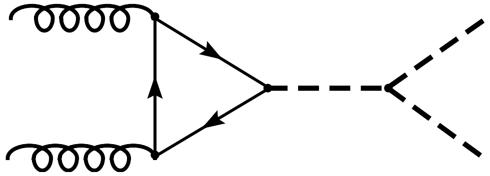
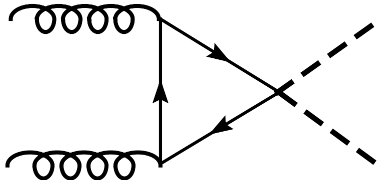
Double Higgs production via gluon fusion



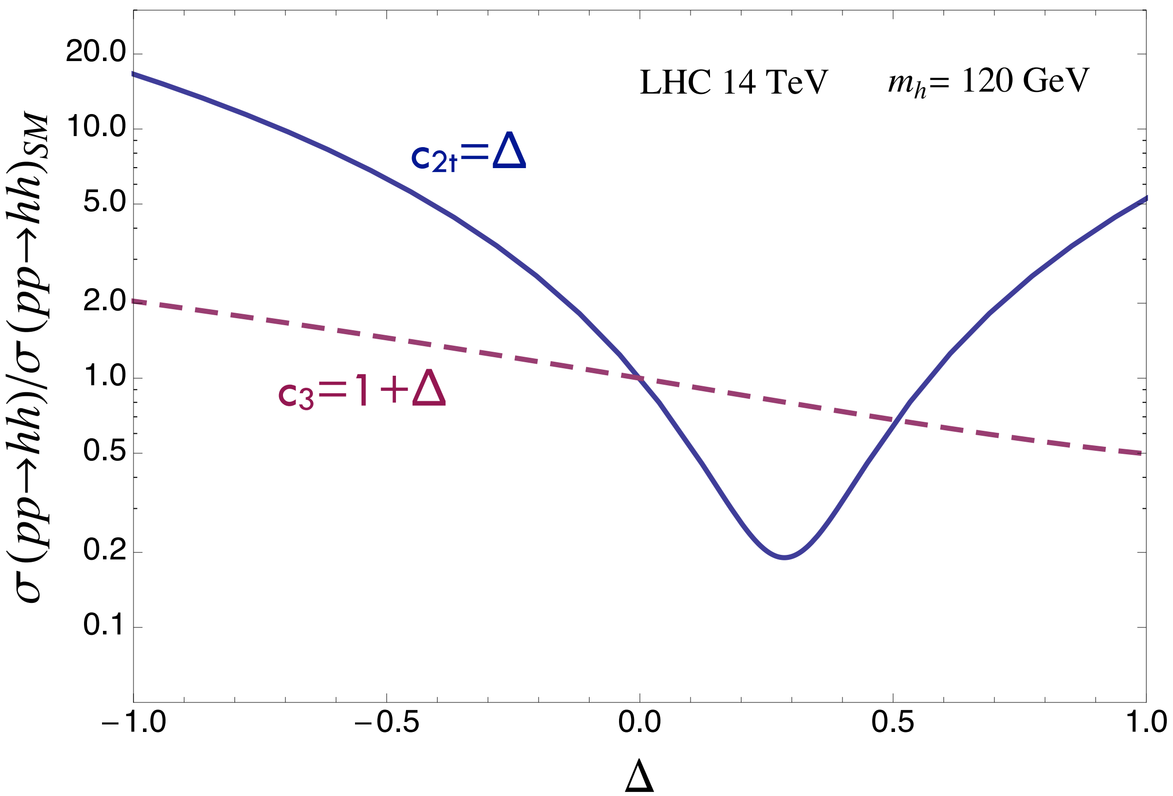
$\sim c_t^2 \times const.$



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



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



RC, Ghezzi, Moretti, Panico, Piccinini, Wulzer
JHEP 1208 (2012) 154

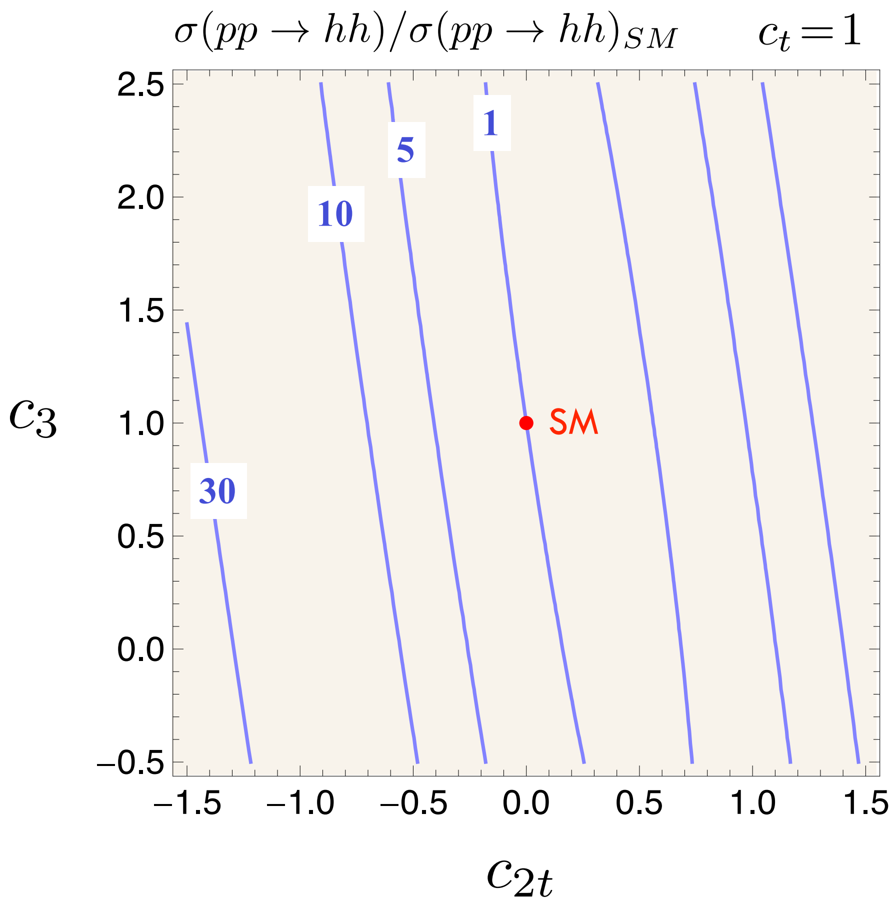
Suppression of SM triangle diagram at high-energy implies:

much stronger sensitivity on c_{2t} than on c_3

[First noticed by:
Dib, Rosenfeld, Zerwekh, JHEP 0605 (2006) 074
Grober and Muhlleitner, JHEP 1106 (2011) 020]

$$\sigma(pp \to hh + X)_{SM} = 28.7\,\text{fb}$$

(NLO $K = 2$ incl.)



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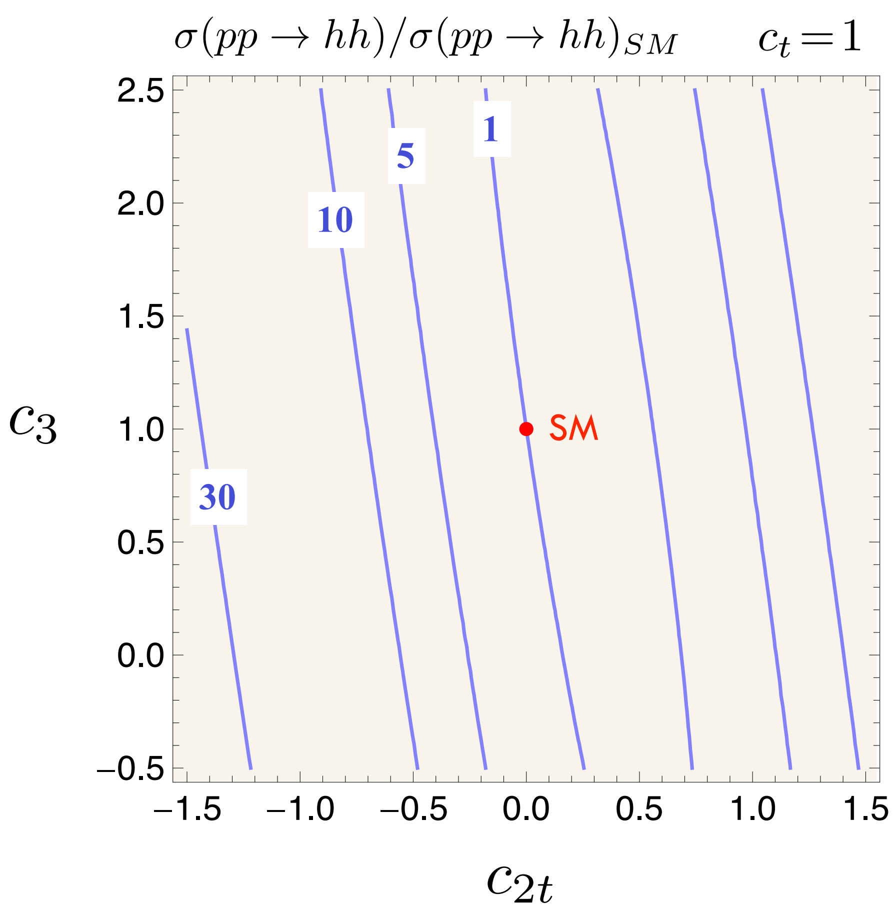

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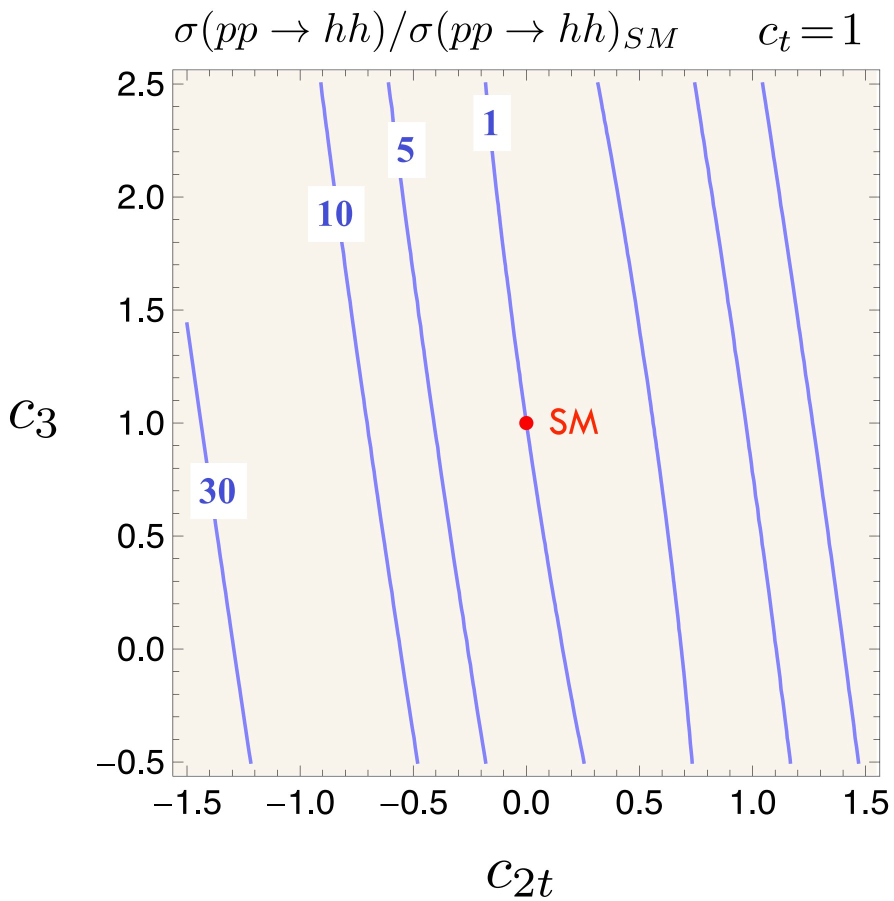

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➡ **See talk by Minho Son on Tuesday**

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- Double Higgs-strahlung at the ILC with 500GeV+1TeV:

  Precision: *VVhh* at 20% ; *hhh* at 100%

Conclusions (continued)

- Double Higgs production gives the opportunity to:

  i) measure Higgs couplings not accessible in single production;

  ii) probe the strength of EWSB dynamics

- Double Higgs production via gluon fusion:

  – Best process to extract trilinear coupling at the LHC

  – Extremely sensitive to *Vhh* coupling, competes with single-Higgs in constraining $\bar{c}_u$

  68% probability intervals on *hhh* from $hh \to b\bar{b}\gamma\gamma$:

  LHC 300fb^{-1}: $\bar{c}_3 \in [-1.5, 6.0]$

  LHC 3ab^{-1}: $\bar{c}_3 \in [-0.98, 1.8] \cup [3.4, 5.3]$

  100TeV 3ab^{-1}: $\bar{c}_3 \in [-0.27, 0.24]$