1st future Hadron Collider Workshop CERN

Double Higgs production in gluon fusion @ 14 TeV & 100 TeV

Minho Son

EPFL, Lausanne

Work in progress with Azatov, Contino, DelRe,Meridiani, Micheli, Panico

Higgs has been discovered

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But we keep seeing nothing. What should we do?

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While one can directly search for new particles, we will stick to the measurement of Higgs couplings which is another place where NP can hide

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Higgs multiplicty →

Jet multiplicty ↓

Single h	Double h	Triple H
h	hh	hhh
h+j	hh+j	
h+jj	hh+jj	

- also roughly indicates possible initial states/related kinematics
- Jet multiplicity might be replaced with V=W,Z, top, etc…

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	Single h		Double h		Triple H	
	h	$\sim 50\ \mathrm{pb}^{gg}$	hh	$\sim 34\ \mathrm{fb}^{gg}$	hhh	$\sim 44\ \mathrm{ab}^{gg}$
	h+j	$\sim 2\ \mathrm{fb}^{p_T(j)>100}$	hh+j			
	h+jj	$\sim 15\ \mathrm{pb}^{VBF}$	hh+jj	$\sim 2\ \mathrm{fb}^{VBF}$		

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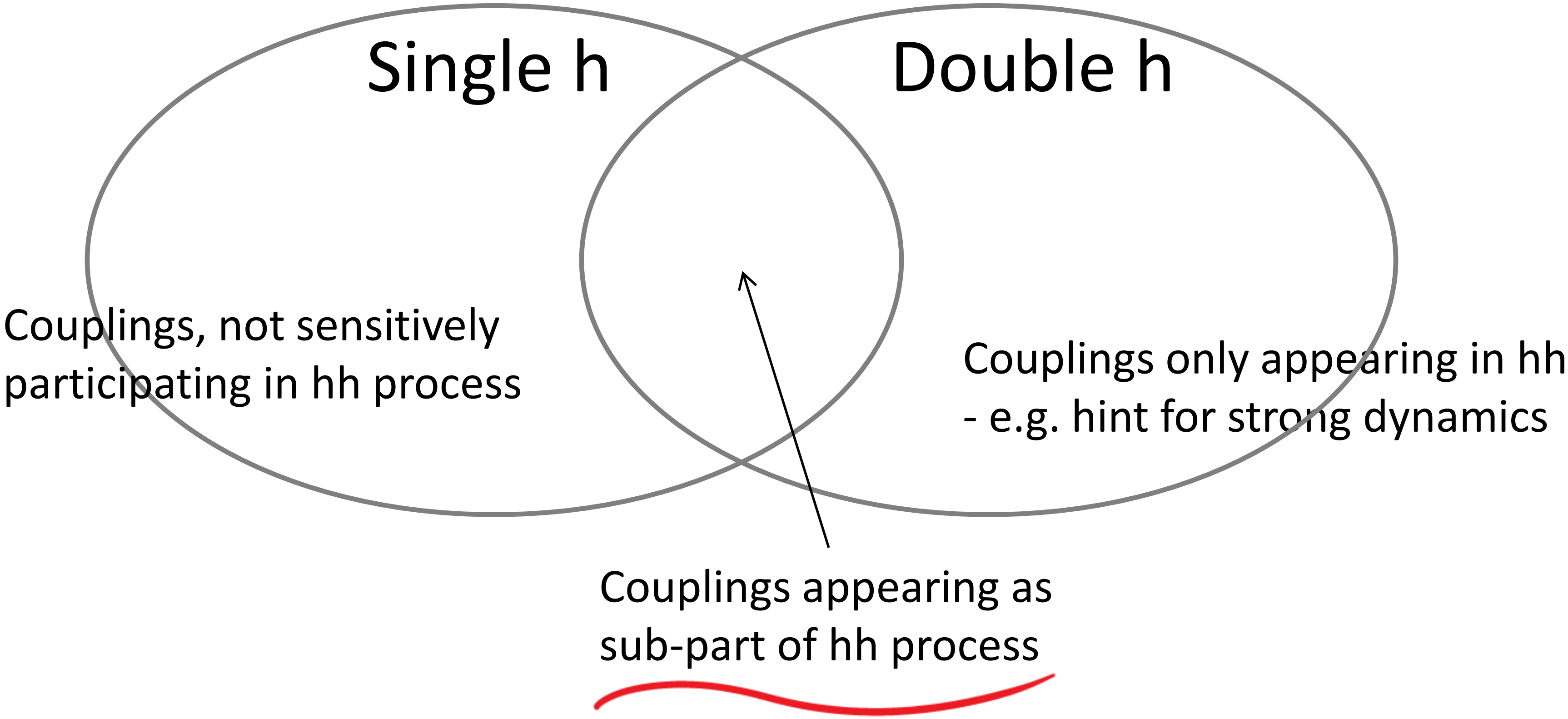
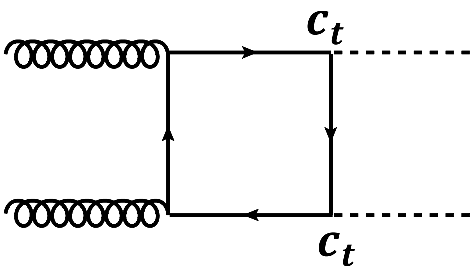
What can we learn from gg-hh ?

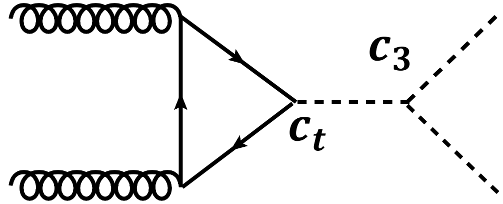
"Practically" speaking …

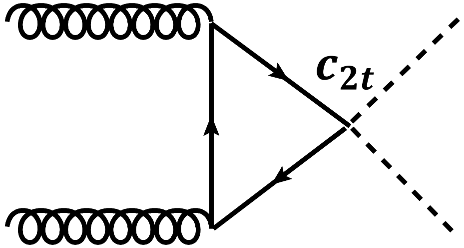


The boundary varies with assumptions

$gg \to hh$ process







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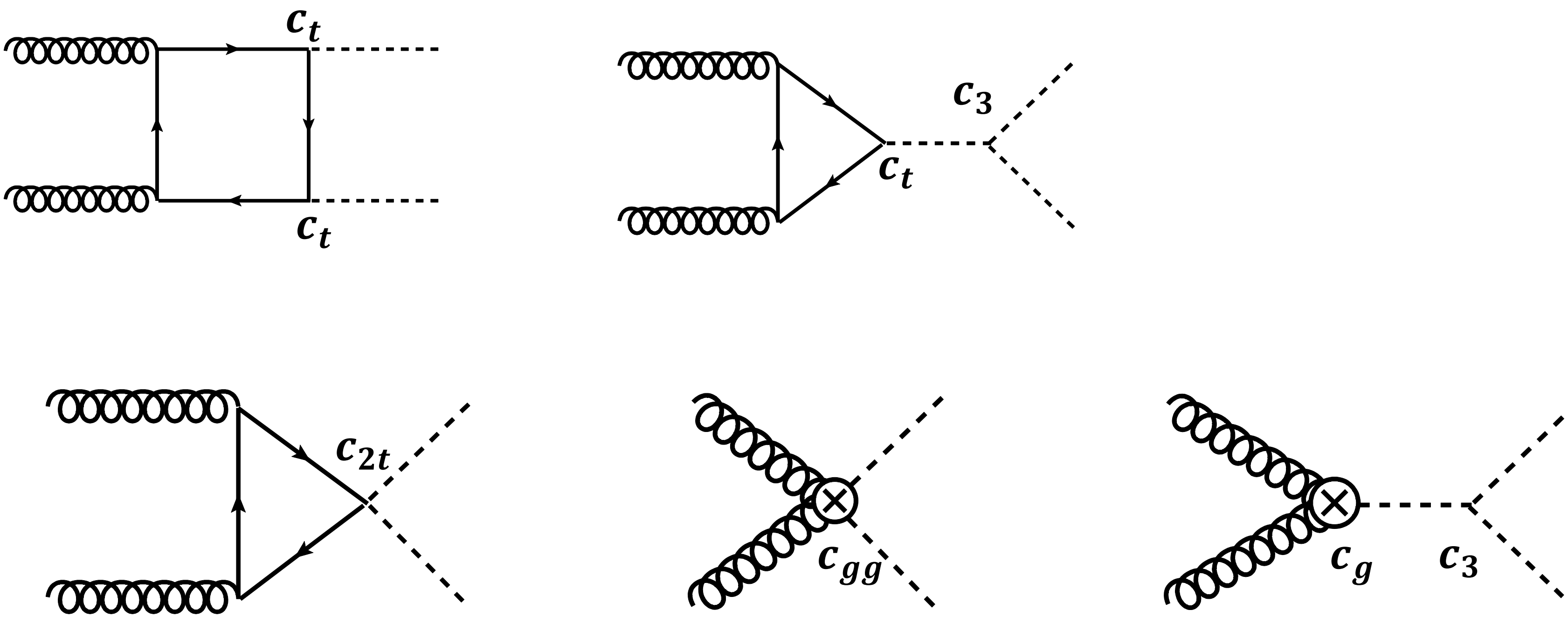

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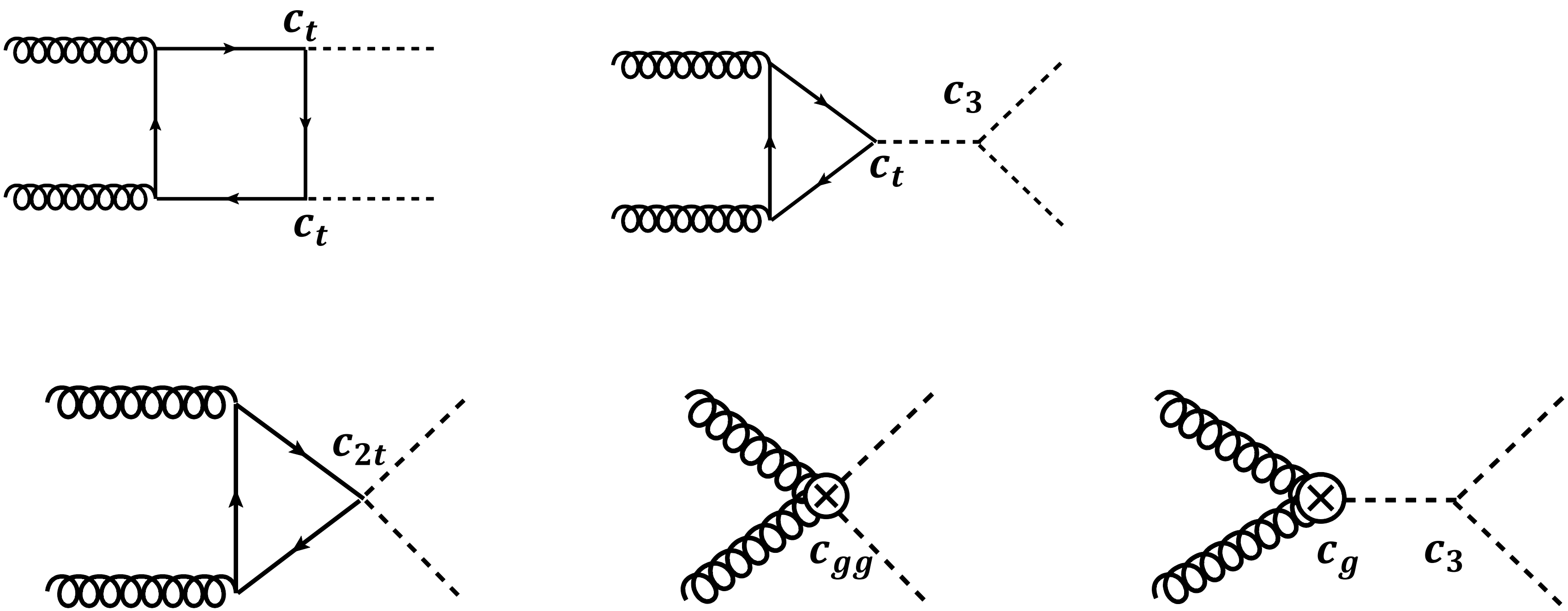
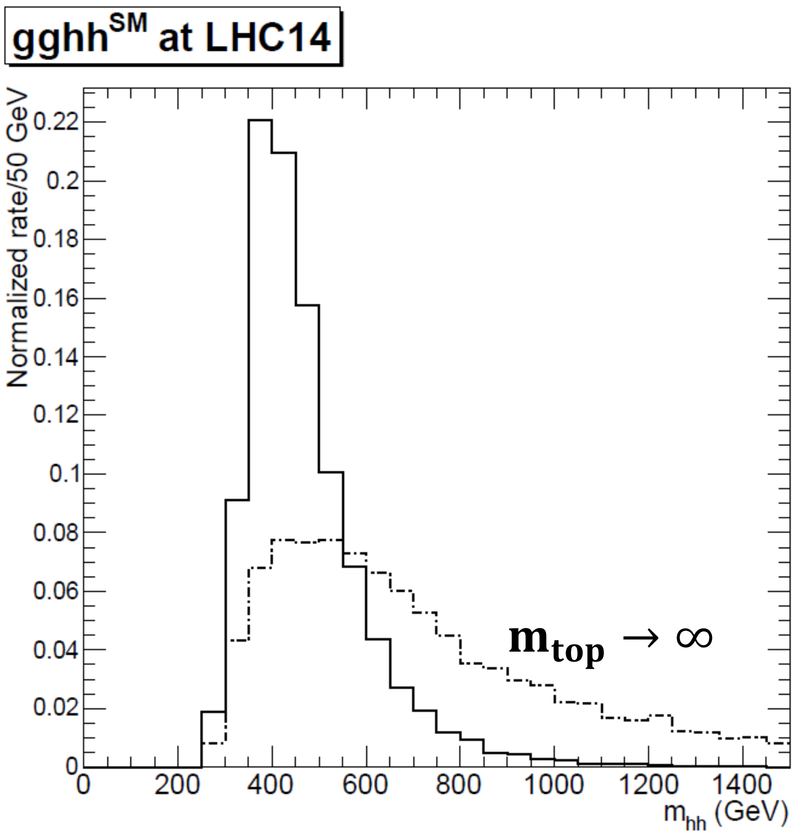


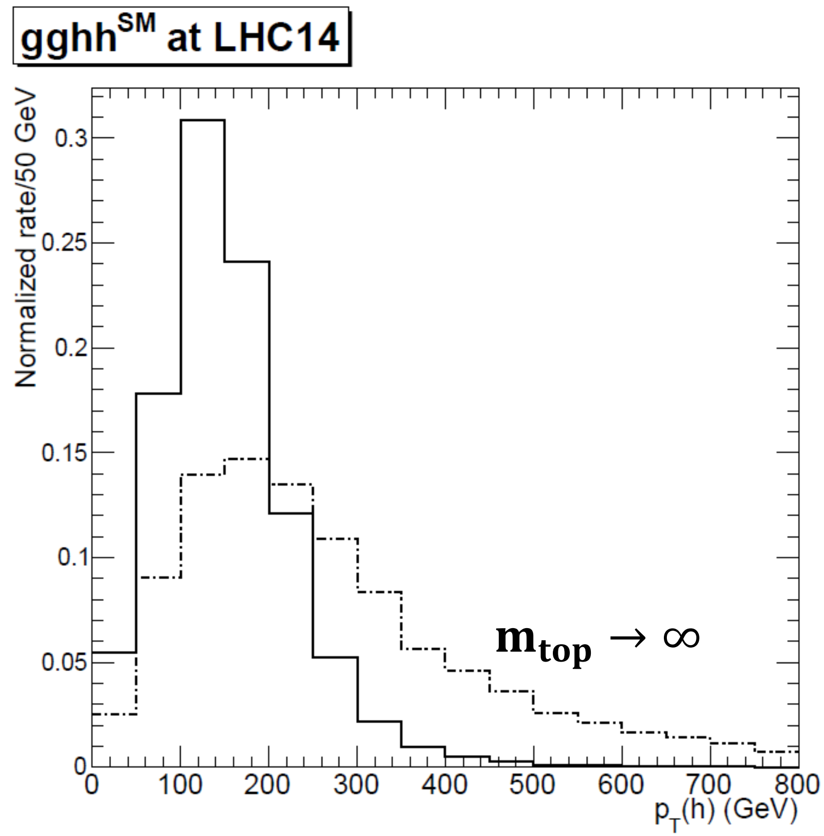
Five parameters are involved

What's the connection of these pars. to NP?

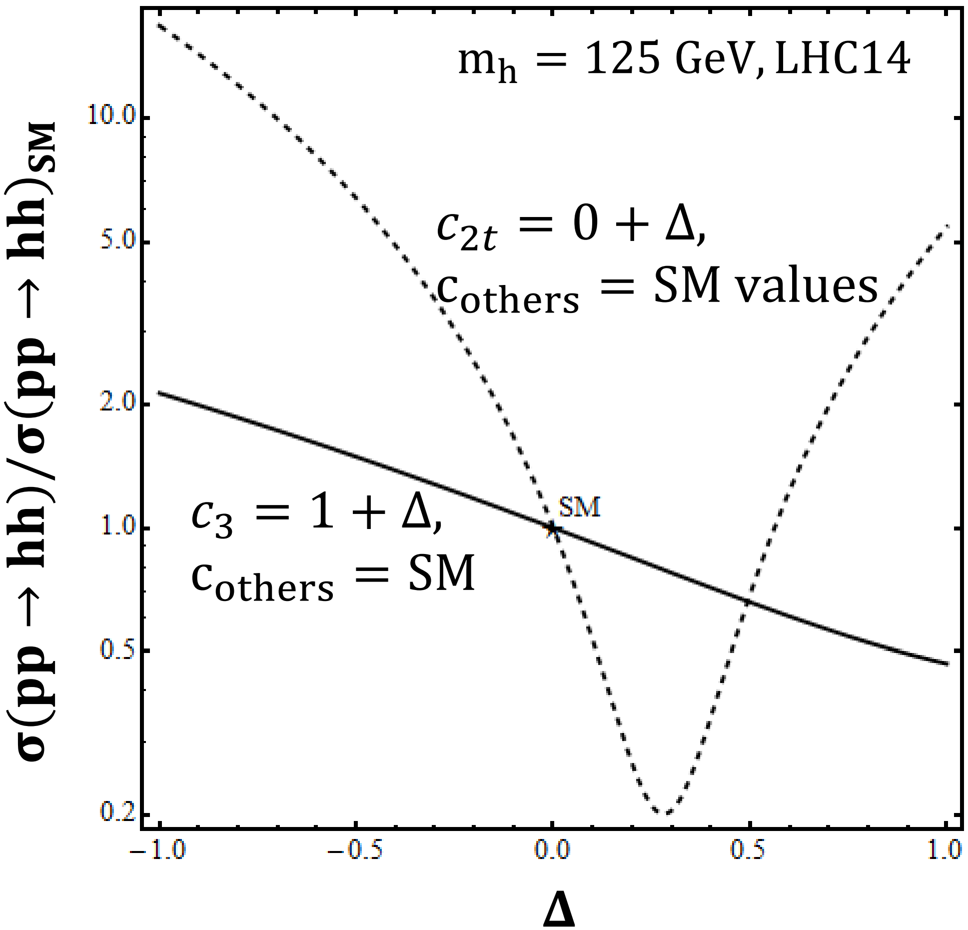
: How do we systematically study the effects of those pars ?

I. Resolving finite top loop makes big differences in differential distributions





II. Cross section is more sensitive to c_{2t} than to c_3



Higgs Effective Field Theory (HEFT)

: Model Independent Approach

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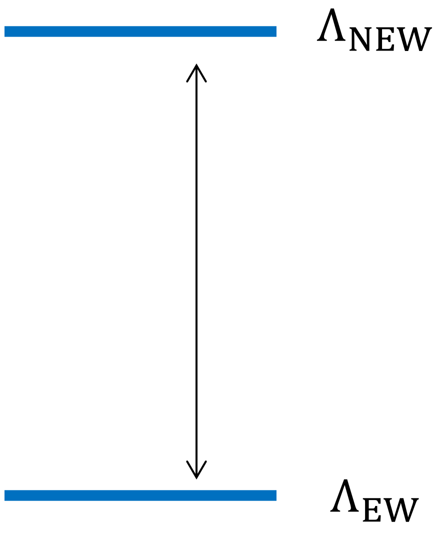
Assumption: Separation of scale



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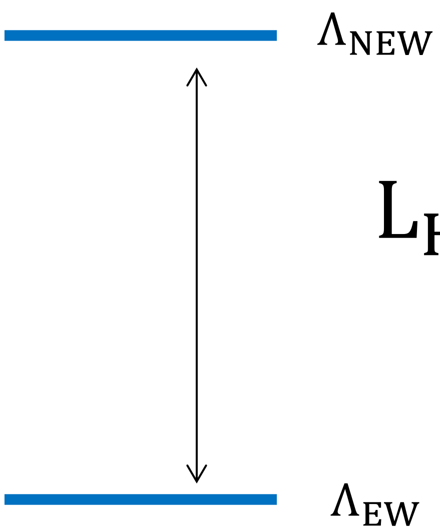

$$\mathrm{L}_{\mathrm{HEFT}} = \mathrm{L}_{\mathrm{pheno.}} + \mathrm{h\ d.o.f.}$$

: Systematic derivative and h expansions

Non-linear Lagrangian

$L_{HEFT} = L_{pheno.} + h$ d.o.f. =

$$\frac{1}{2}\left(\partial_\mu h\right)^2 + \frac{v^2}{4} Tr\left|D_\mu \Sigma\right|^2 \left(1 + 2\, a\, \frac{h}{v} + b\, \frac{h^2}{v^2} + \cdots\right)$$

$$-\mathrm{m_t}\overline{t_L}\Sigma\left(1 + c_t\, \frac{h}{v} + c_{2t}\frac{h^2}{v^2} + \cdots\right) t_R + h.c. + \text{other fermions}$$

$$-\frac{g_s^2}{4\pi^2 v^2}\left(c_g v\, h + \frac{1}{2} c_{gg} h^2\right) G^a_{\mu\nu}\mathrm{G}^{a\mu\nu}$$

$$-\frac{1}{2} m_h^2 h^2 - \mathrm{c}_3 \frac{1}{6}\left(\frac{3\, m_h^2}{v}\right) h^3 - d_4 \frac{1}{24}\left(\frac{3\, m_h^2}{v^2}\right) h^4 + \cdots$$

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SM: $\mathrm{c_t} = 1,\ \mathrm{d_3} = 1,\ \mathrm{c_{2t}} = 0, \mathrm{c_g}, \mathrm{c_{gg}} = 0$

NDA $\delta \mathrm{c_i} \sim \mathrm{O}\left(\frac{\mathrm{g}_*^2 \mathrm{v}^2}{\mathrm{m}_*^2}\right) \quad \sim O\left(\frac{v^2}{f^2} \equiv \xi\right)$

SILH basis

: useful when we are in the vicinity of SM point

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Expand around

SM point in terms of H $: c_t = 1, c_3 = 1, c_{2t} = 0, c_g, c_{gg} = 0$

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Expand around

SM point in terms of H $: c_t = 1,\ c_3 = 1,\ c_{2t} = 0, c_g, c_{gg} = 0$

E.g. $L_{dim4} \times \frac{|H|^2}{f^2} =$

$$\frac{\bar{c}_H}{2v^2}\, \partial_\mu |H|^2 \partial^\mu |H|^2, \quad \frac{\bar{c}_u}{v^2} y_u \bar{\psi} H \psi |H|^2, \quad \frac{\bar{c}_6}{v^2} |H|^4 |H|^2, \quad \frac{\bar{c}_g g_s^2}{m_W^2} |H|^2 G^{a\mu\nu} G^a_{\mu\nu}$$

$$c_t = 1 - \frac{1}{2}\bar{c}_H - \bar{c}_u, \qquad c_{2t} = 0 - \frac{1}{2}\bar{c}_H - \frac{3}{2}\bar{c}_u, \qquad c_3 = 1 + \bar{c}_6 - \frac{3}{2}\bar{c}_H$$

NDA $\bar{c}_6, \bar{c}_H, \bar{c}_u \sim \left(\frac{v}{f}\right)^2 \equiv \xi, \quad \bar{c}_g \times \frac{4\pi^2}{\alpha_2} = \xi \times \frac{y_t^2}{g_*^2}$

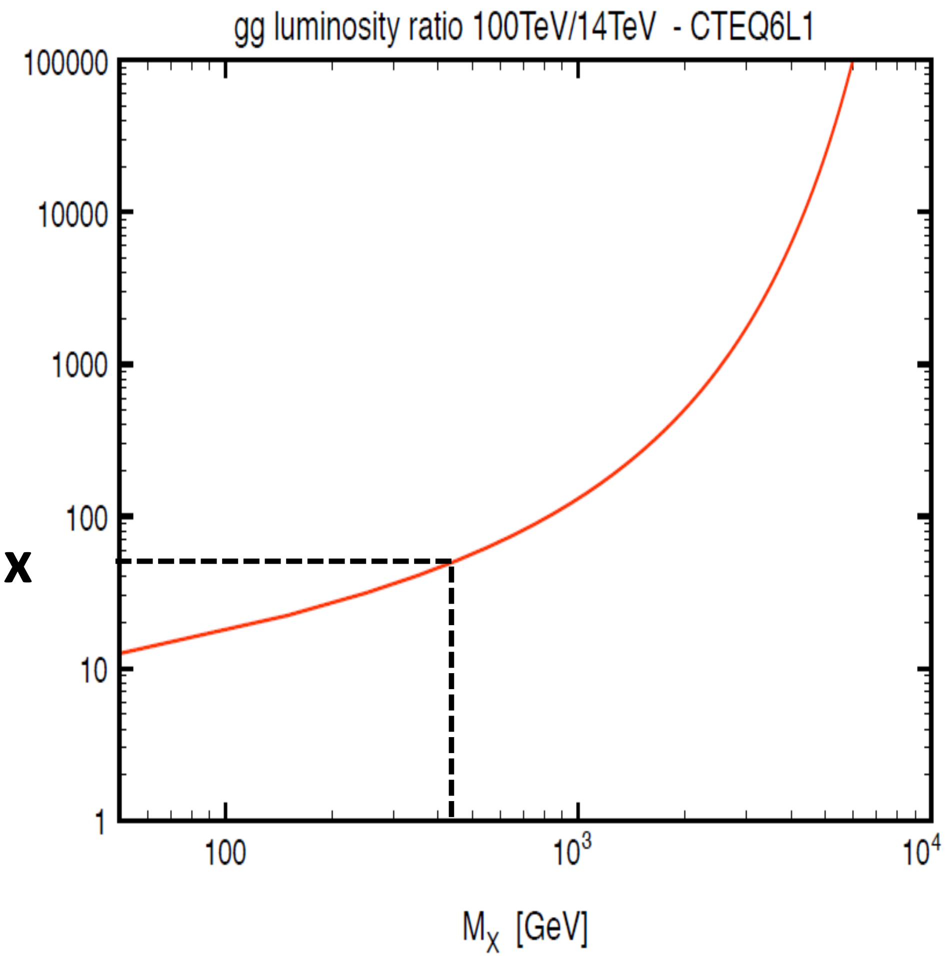
When upgrading Energy

14TeV → 100 TeV

7x

	14 TeV					100 TeV
$gg \to HH^f(\lambda=1)$	33.8 fb	207 fb (6.1)	298 fb (8.8)	609 fb (18)	980 fb (29)	1.42 pb (42)

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsEuropeanStrategy

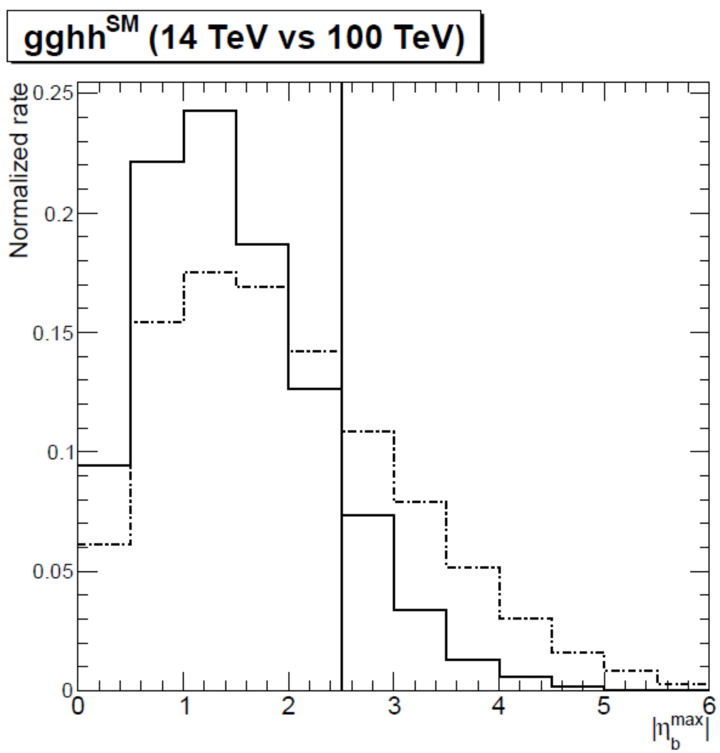


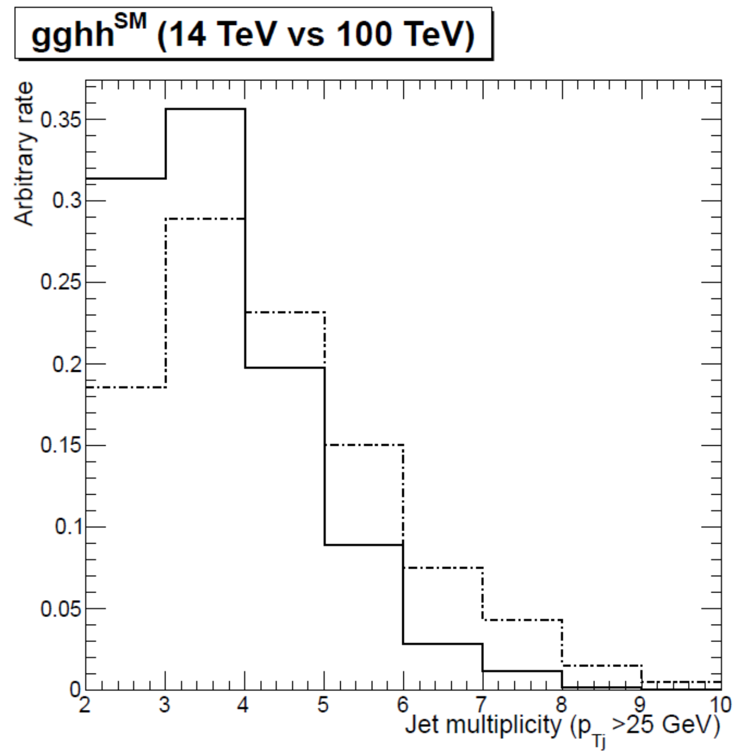
∼40-50 x

Main kinematics remain same under 7x

But there are some changes here and there …

Events leaking to higher eta region





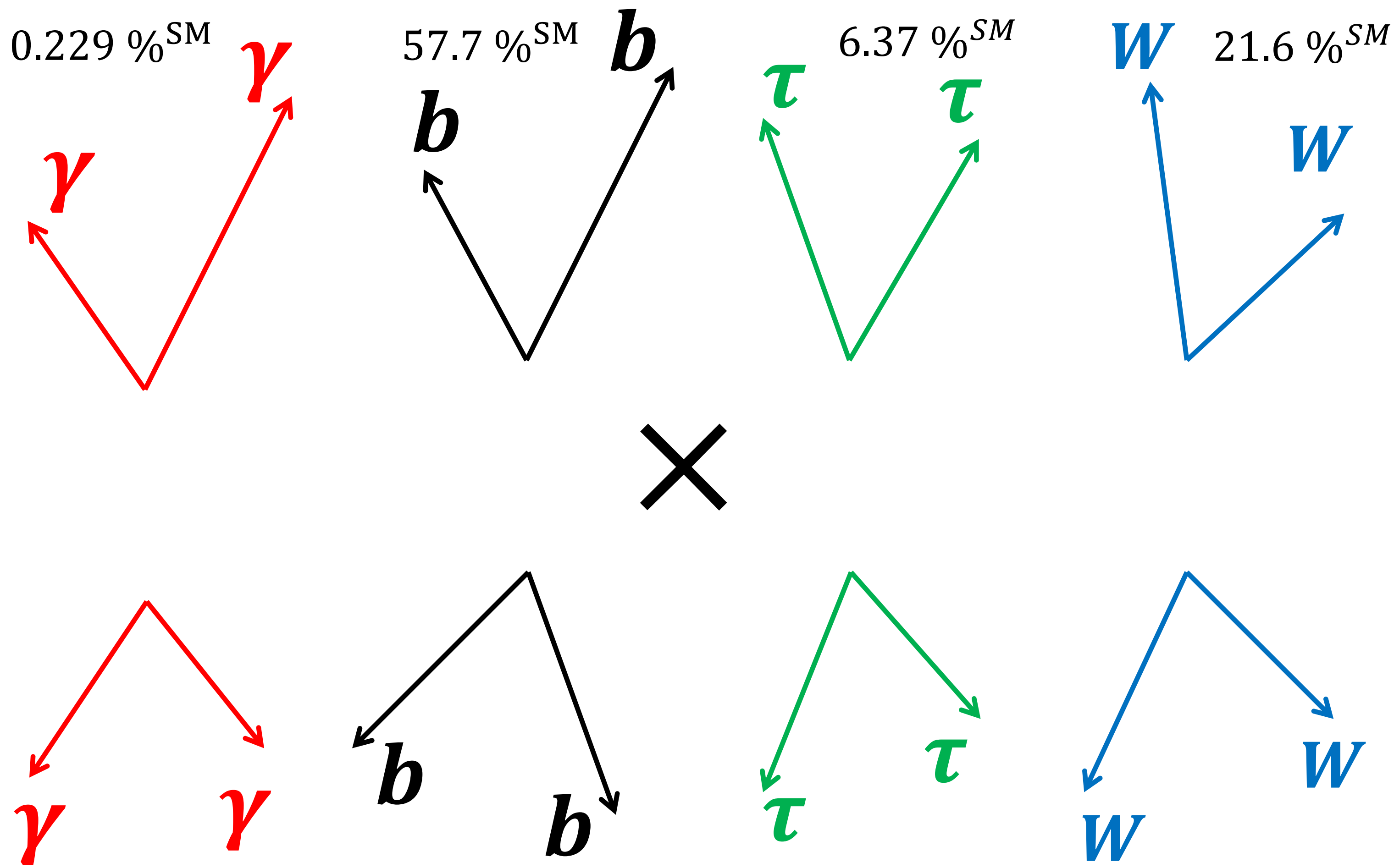
More radiations, higher jet multiplicity

$gg \to hh$

Phenomenology

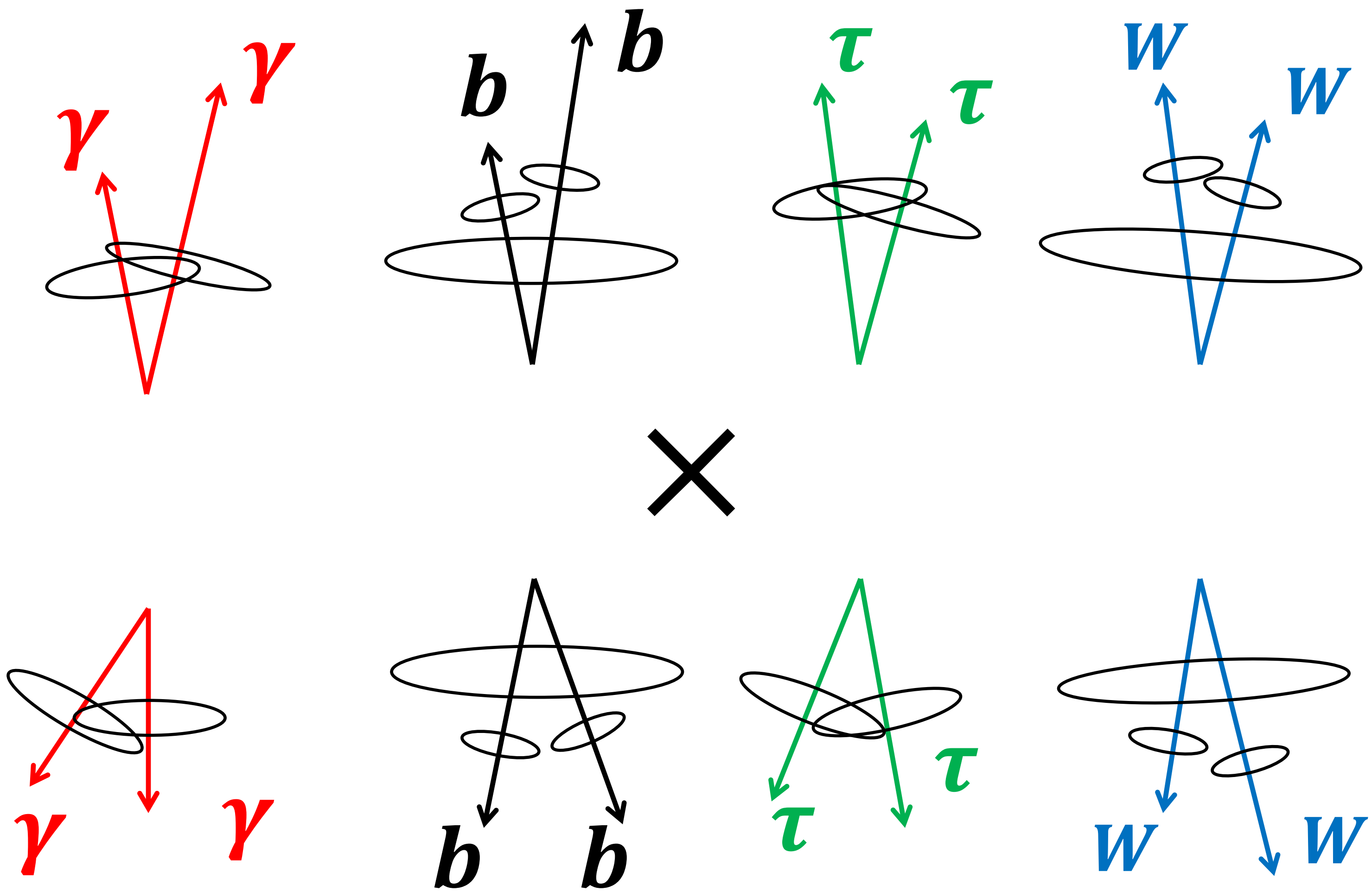
Zoo of $gg \to hh$ decay

Consider the best channel or multiple comparable channels



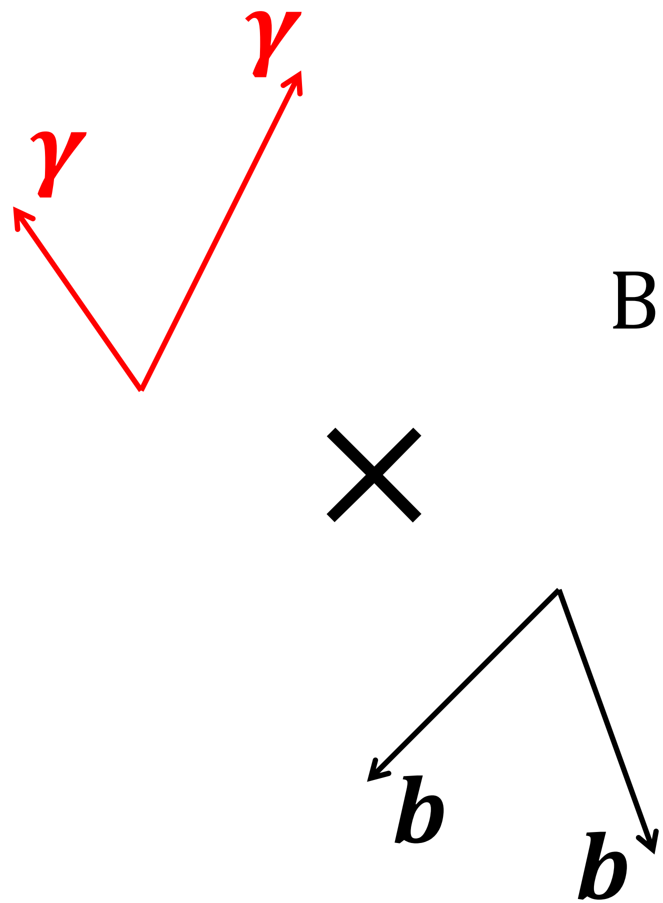
Boosted kinematics could help ??

If your signal rate/kinematics allows,
e.g. Energy-growing VV-hh process, 100TeV



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

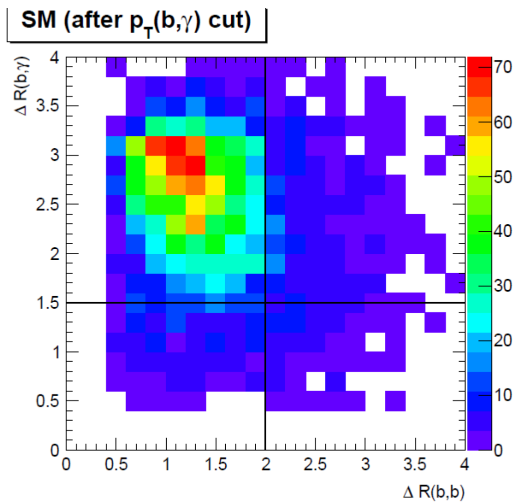
In this work we focus on



$$\mathrm{BR}(\mathrm{b\bar{b}}\gamma\gamma)_{\mathrm{SM}} = 0.27\%$$

; small but clean!

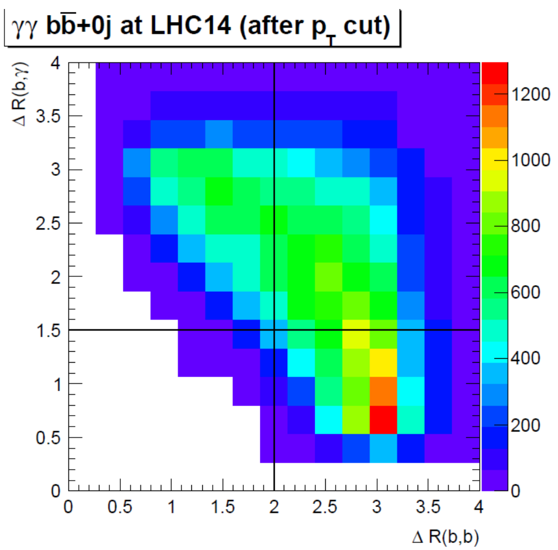
Acceptance cuts @14TeV

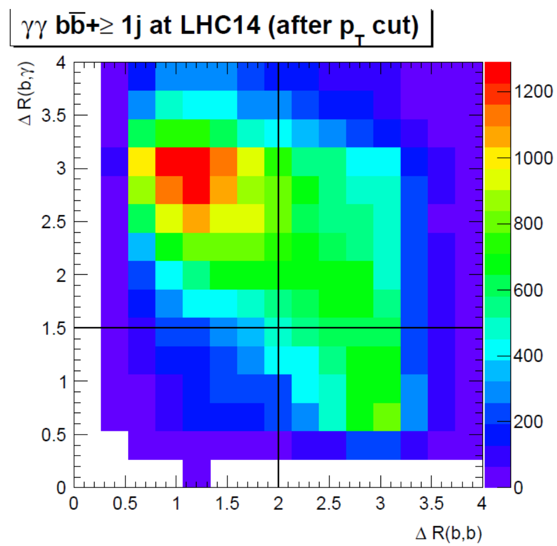


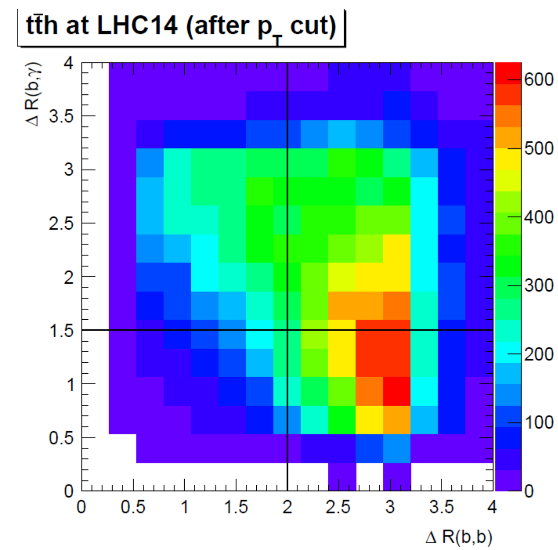
$$p_T(b,\gamma)^{max} > 50\ GeV,$$
$$p_T(b,\gamma)^{min} > 30\ GeV$$

$$\Delta R(b,b) < 2, \qquad \Delta R(\gamma,\gamma) < 2$$
$$\Delta R(b,\gamma) > 1.5$$

$$\epsilon_b = 0.7, \qquad \zeta_j = 0.01$$





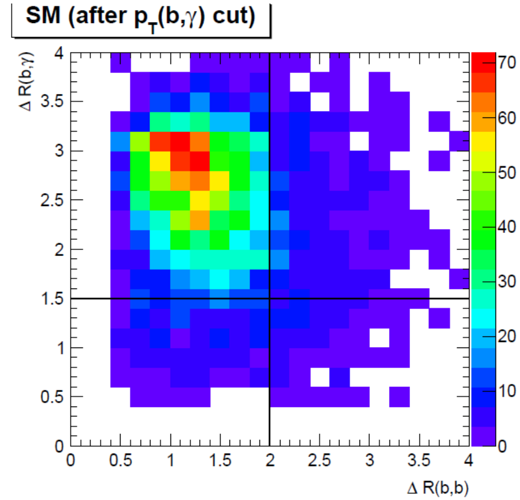


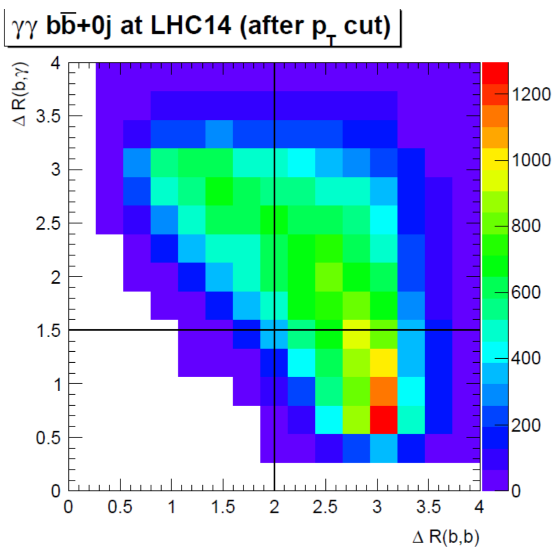
Acceptance cuts @100TeV

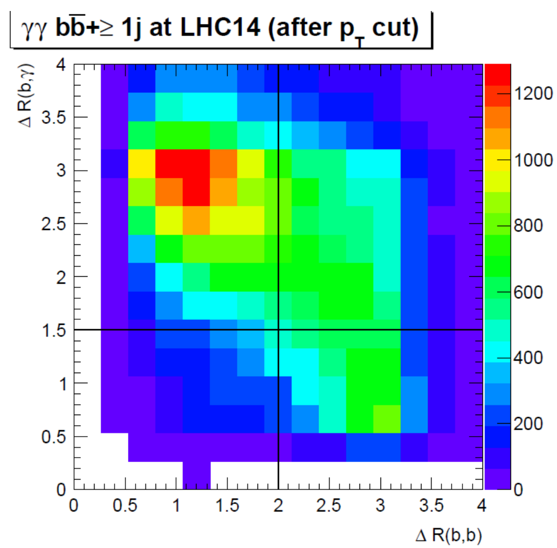
$$p_T(b,\gamma)^{max} > 50\ GeV \rightarrow 60\ GeV$$
$$p_T(b,\gamma)^{min} > 30\ GeV \rightarrow 40\ GeV$$

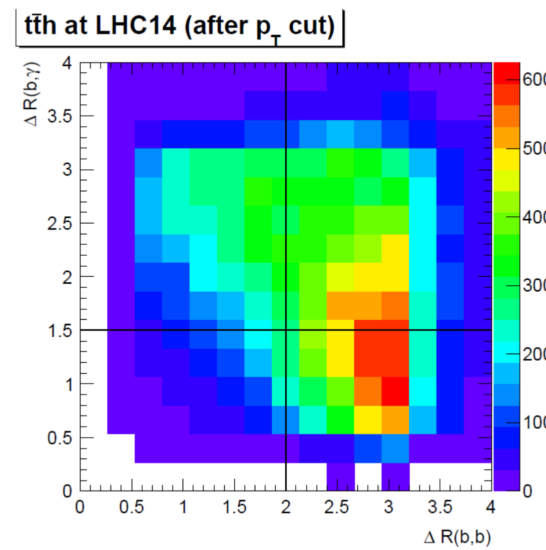
$$\Delta R(b,b) < 2, \qquad \Delta R(\gamma,\gamma) < 2$$
$$\Delta R(b,\gamma) > 1.5$$

$$\epsilon_b = 0.7, \qquad \zeta_j = 0.01$$

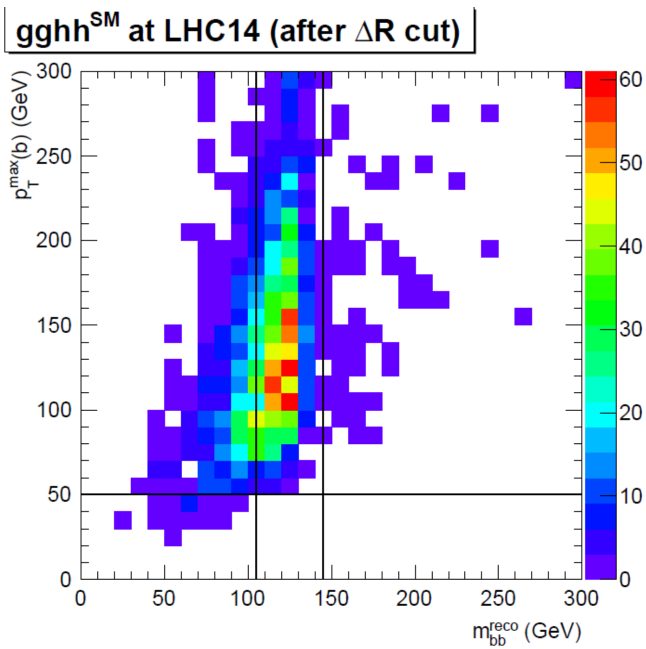






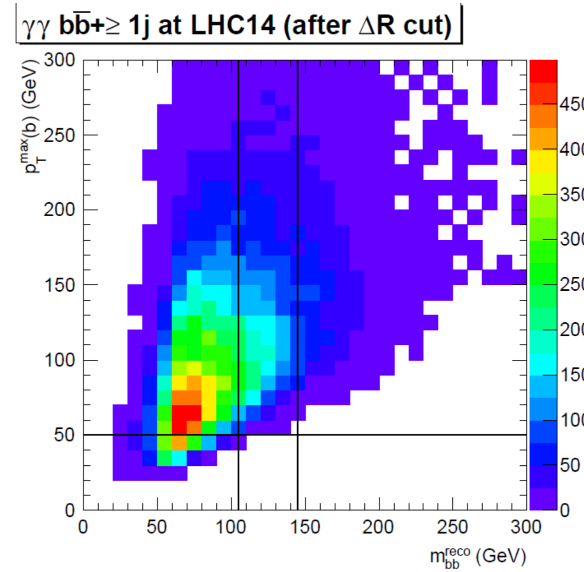


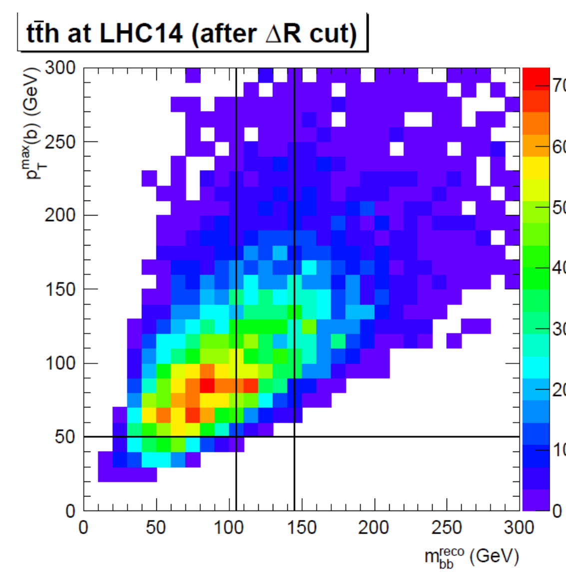
Signal mass windows



$$105\text{GeV} < m_{bb}^{reco} < 145\ \text{GeV}$$

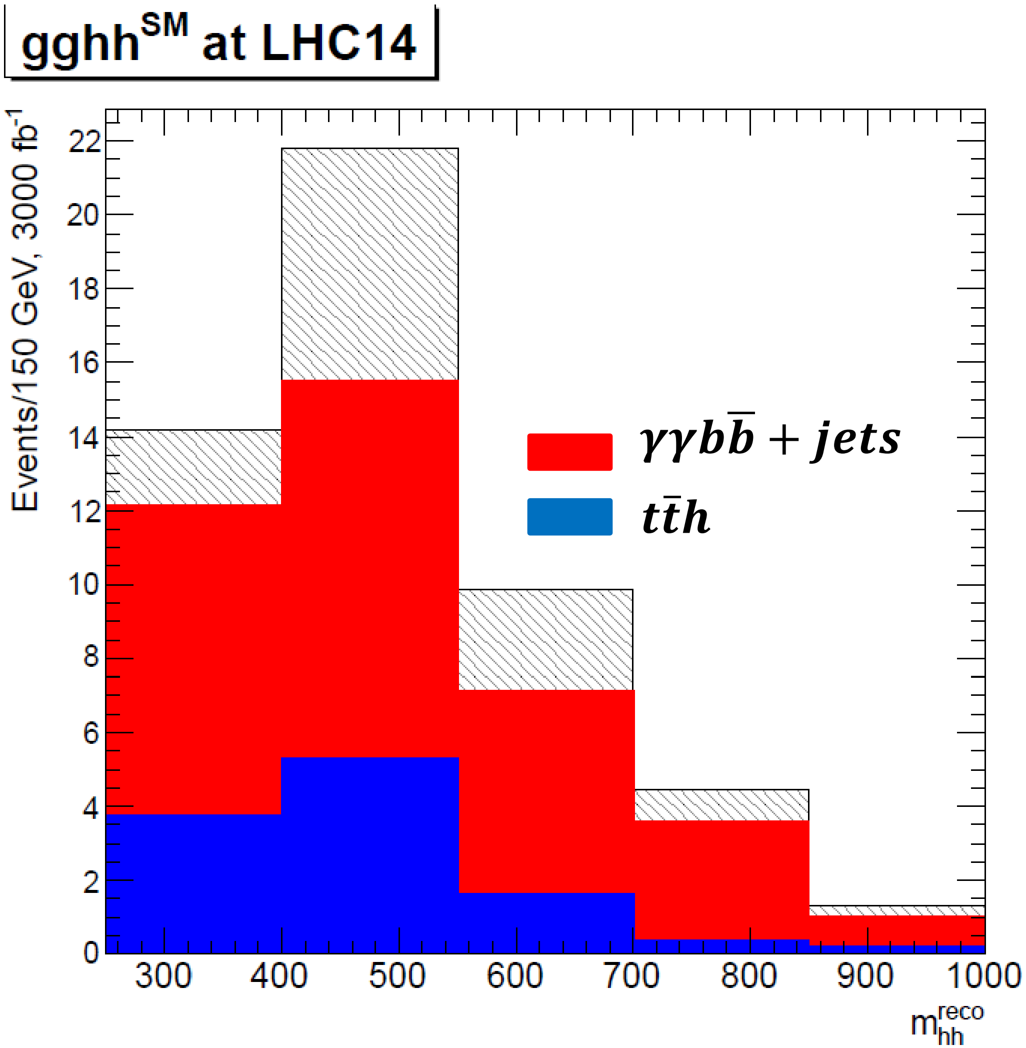
$$120\text{GeV} < m_{\gamma\gamma}^{reco} < 130\ \text{GeV}$$





One more relevant thing …

Binning m_{hh} dist. can improve sensitivity



Other backgrounds are not shown

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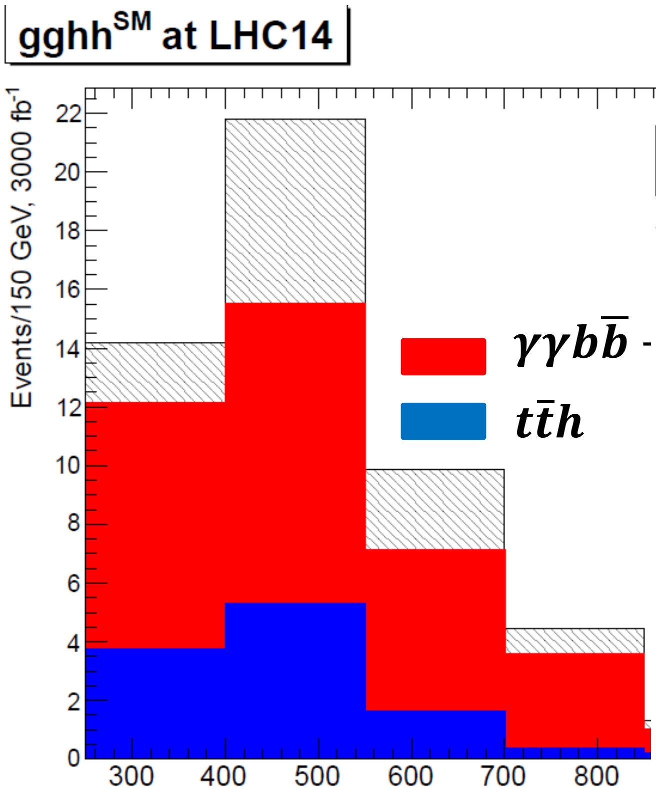
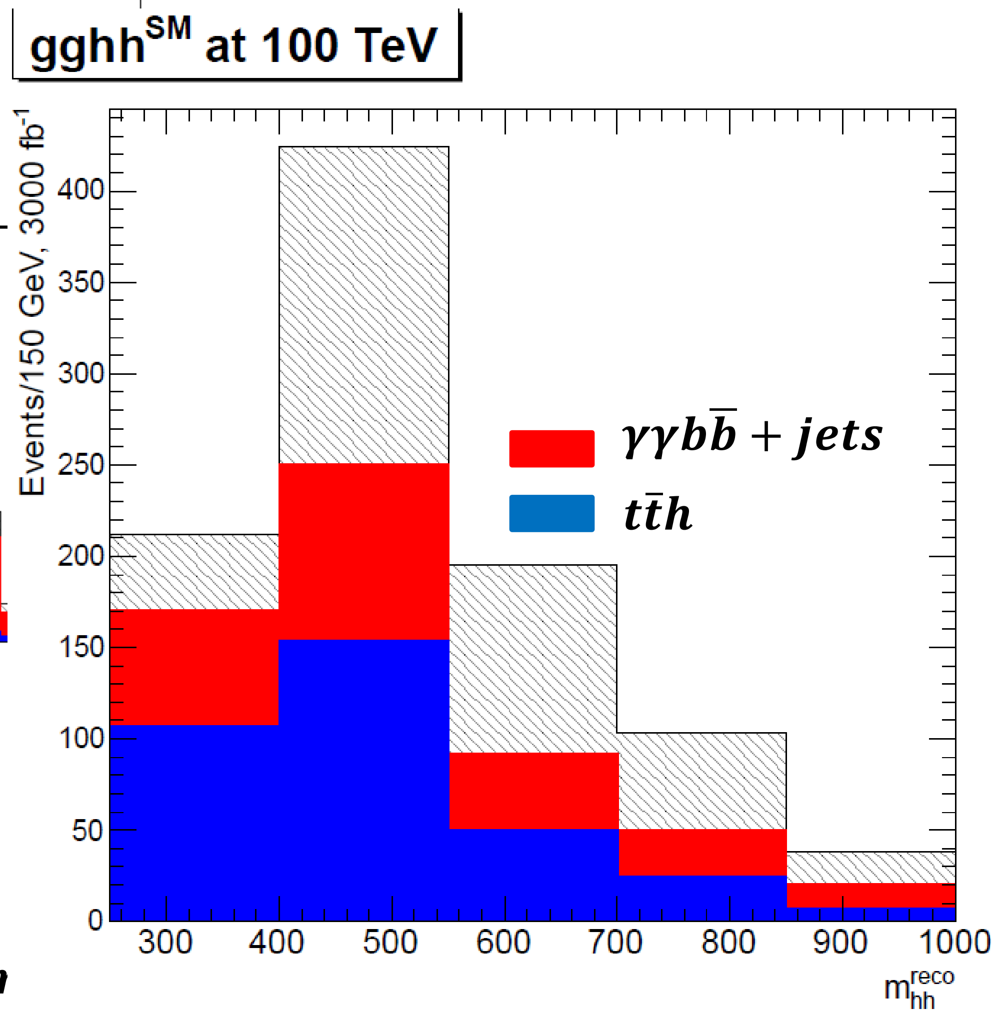




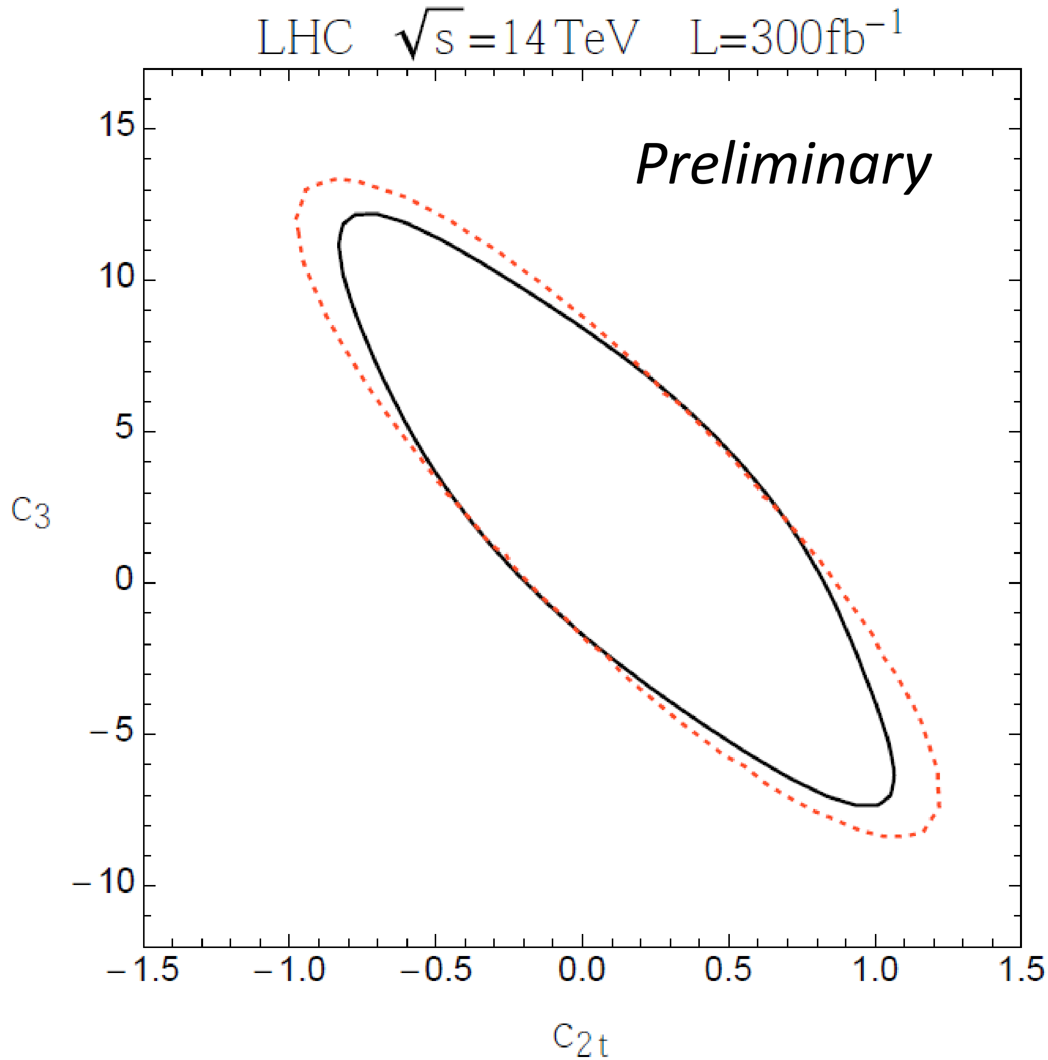
Other backgrounds ar

Sensitivity

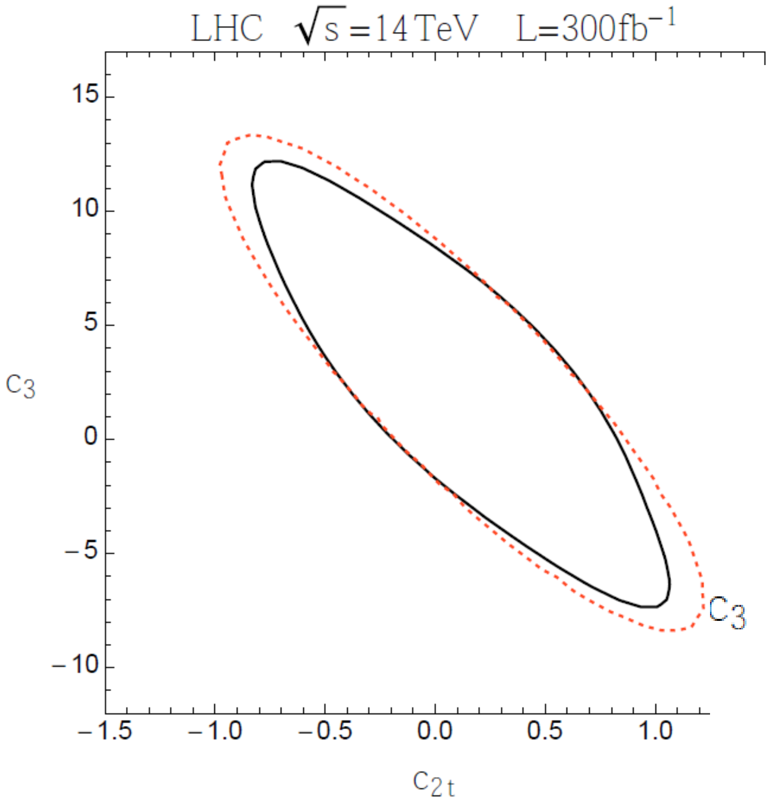
@ (HL) LHC14

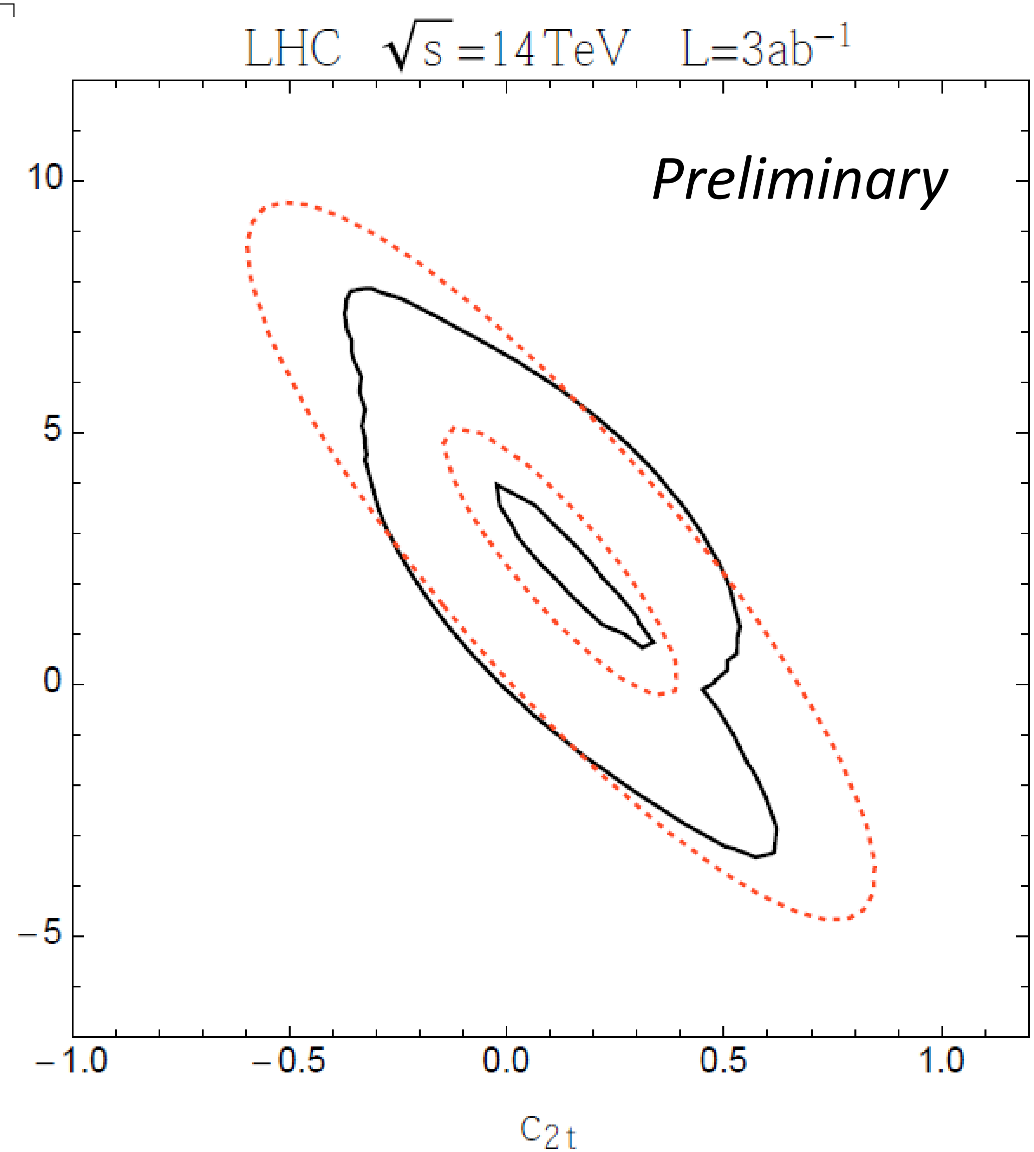
& 100 TeV

Sensitivity @ 14 TeV, using 300/fb

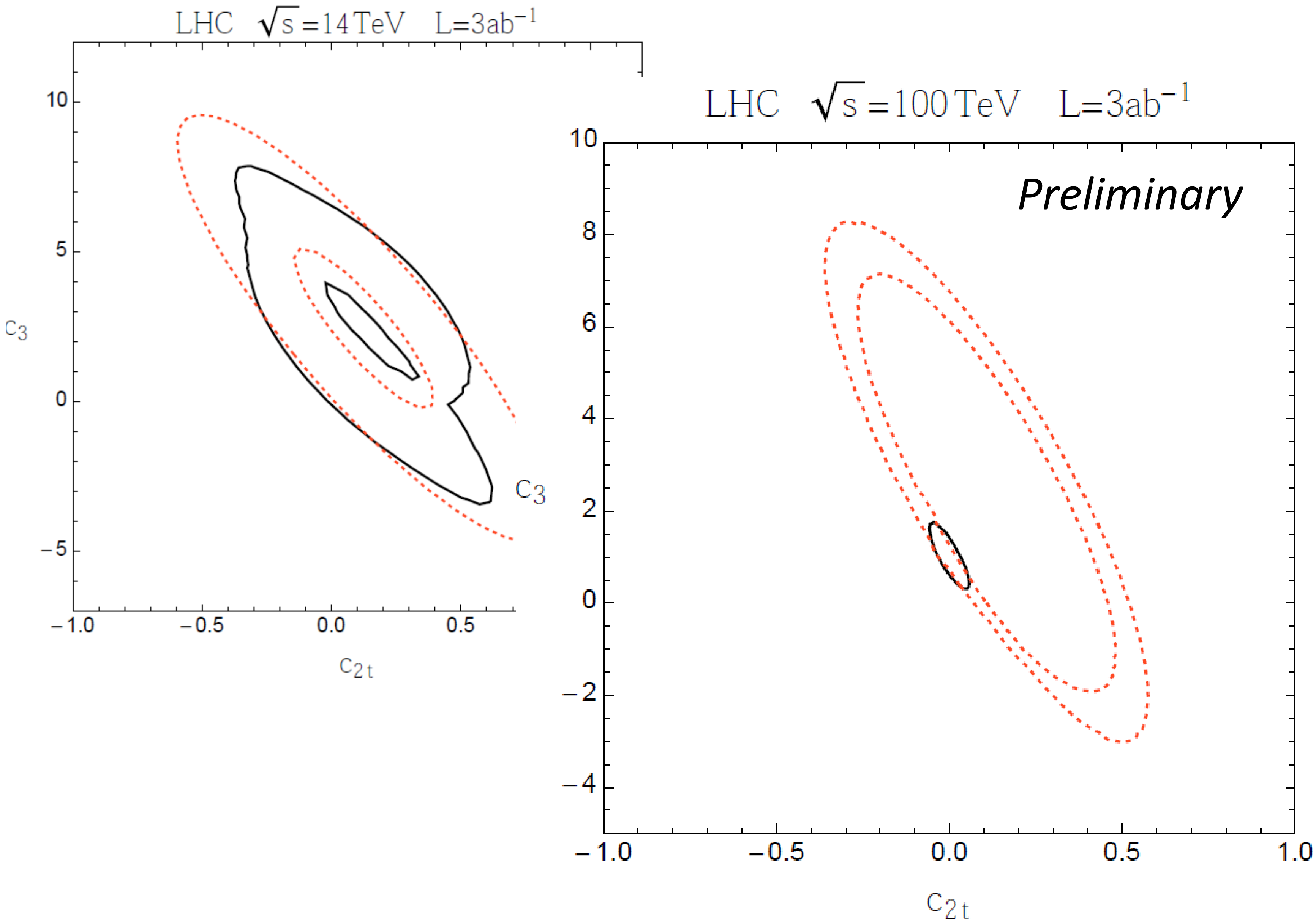


Sensitivity @ 14 TeV, using 3000/fb

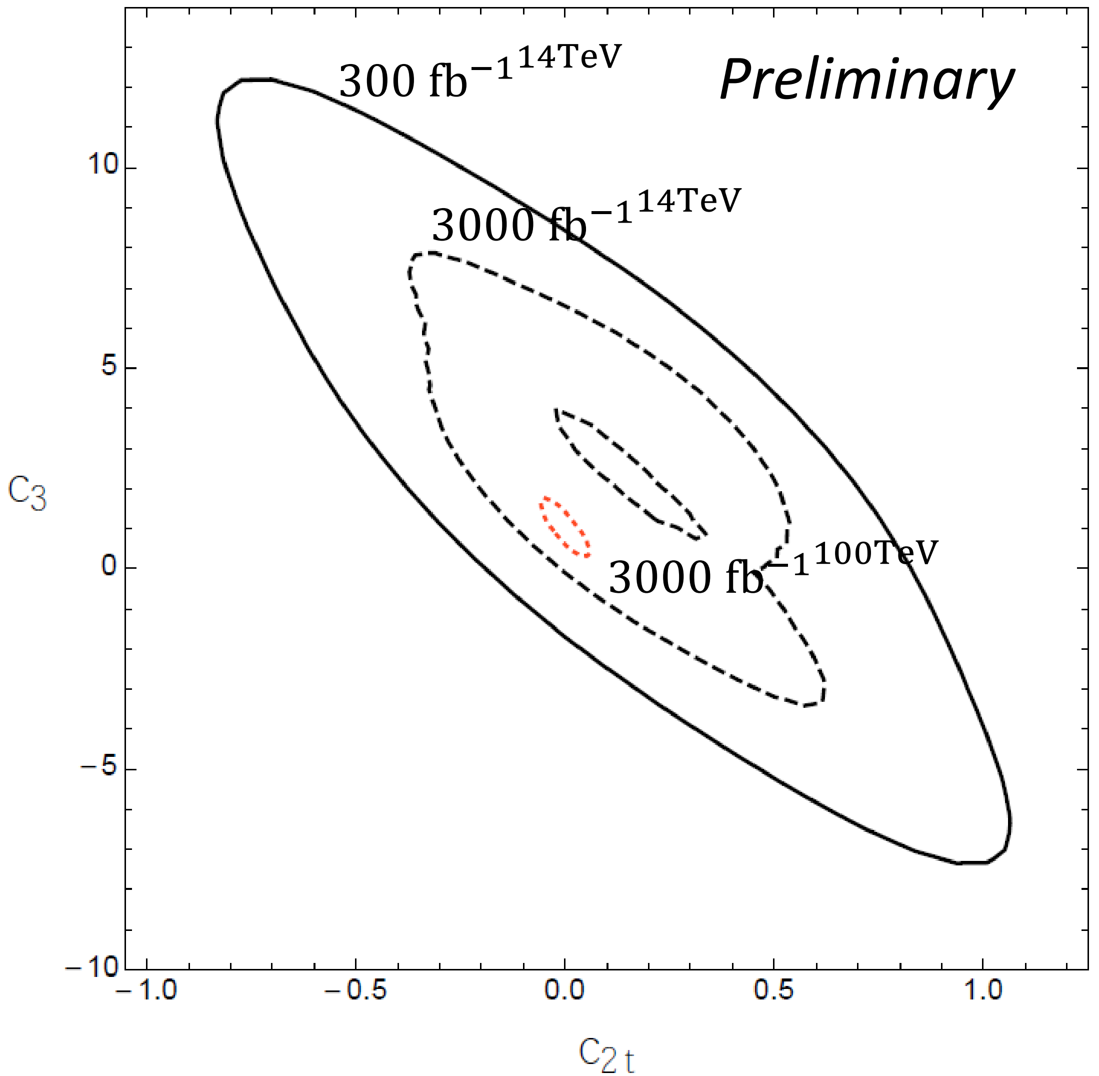




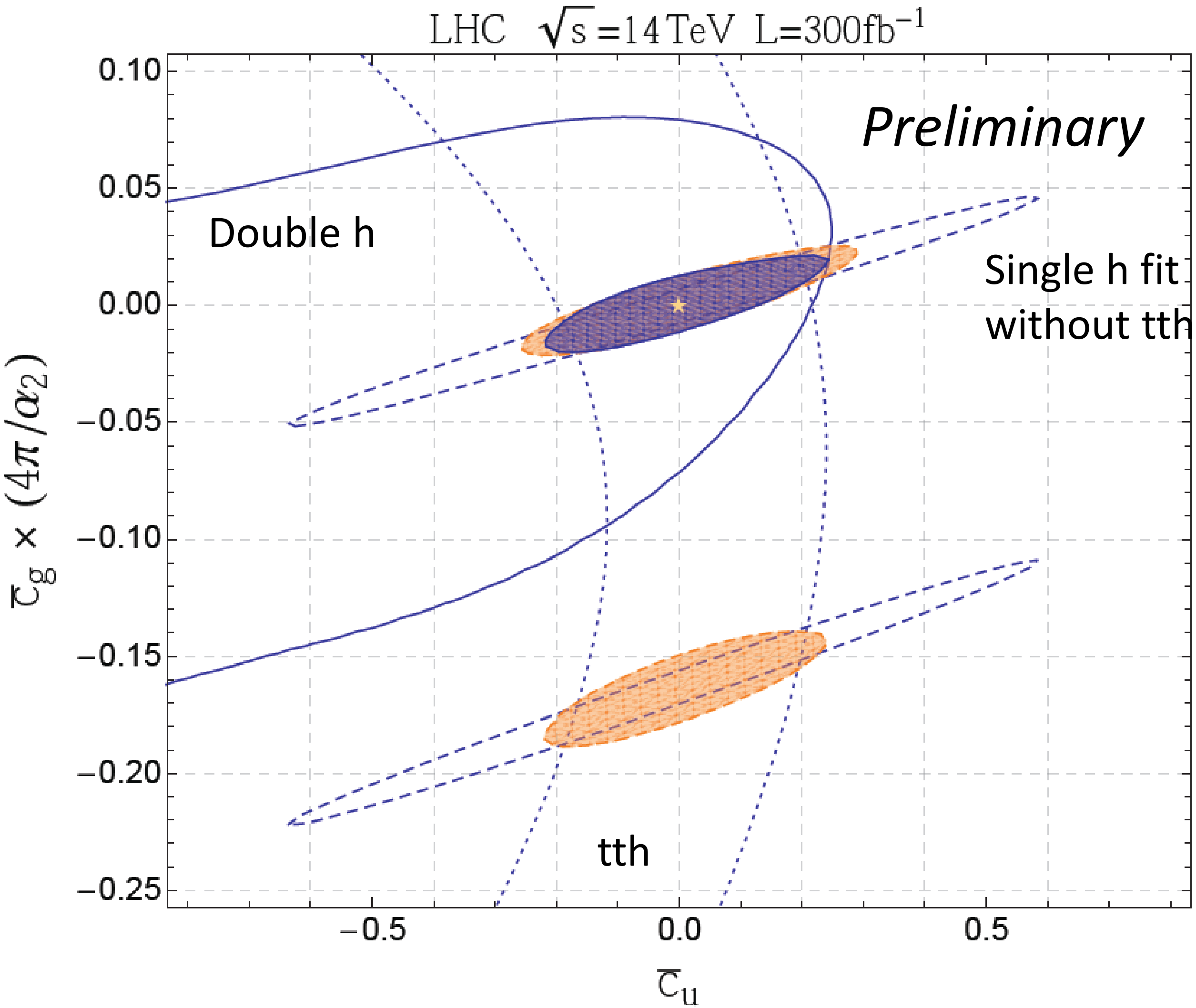
Sensitivity @ 100 TeV, using 3000/fb



Evolution of c3 and c2t under 14 TeV → 100 TeV



Sensitivity @ 14 TeV, using 300/fb



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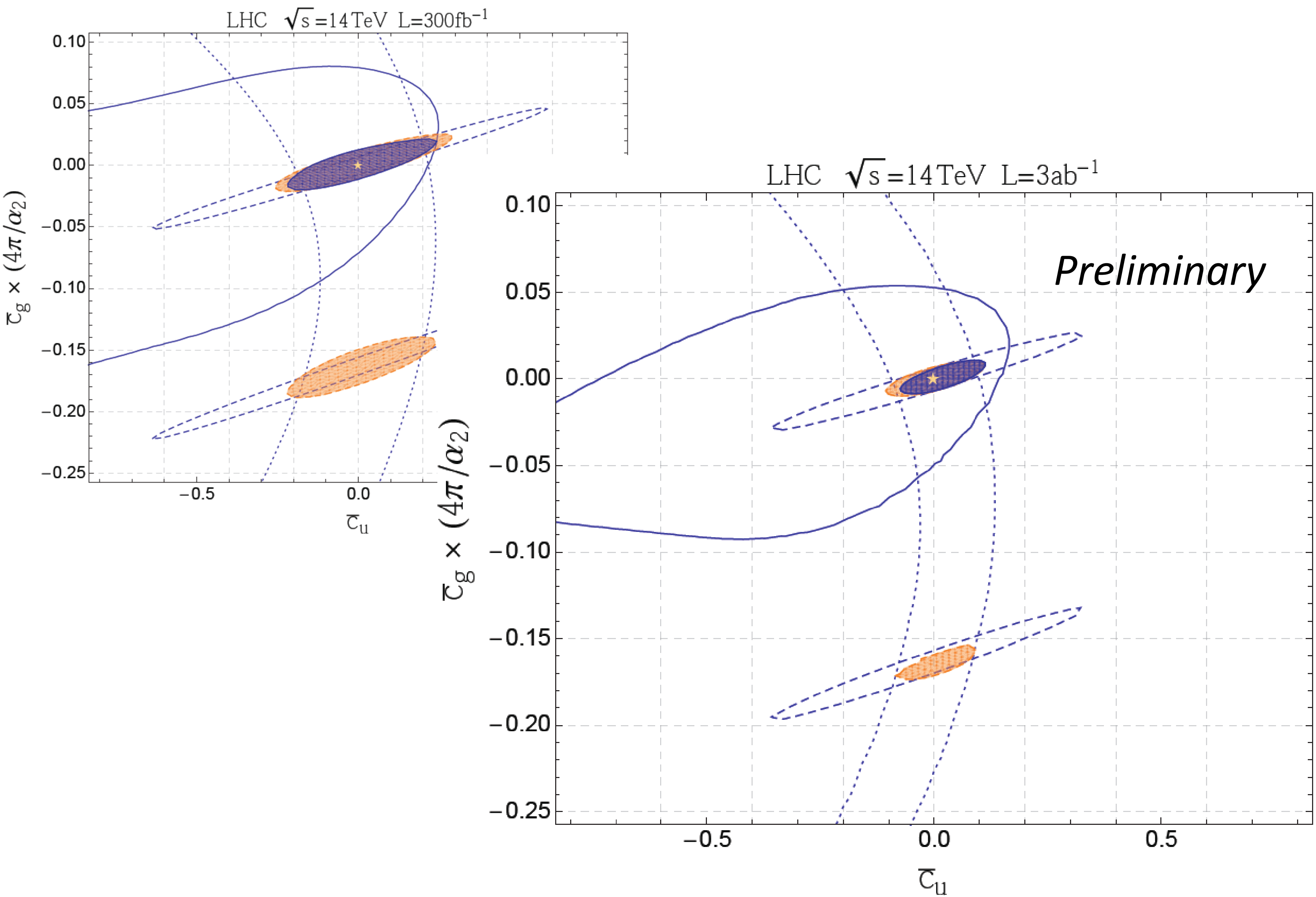
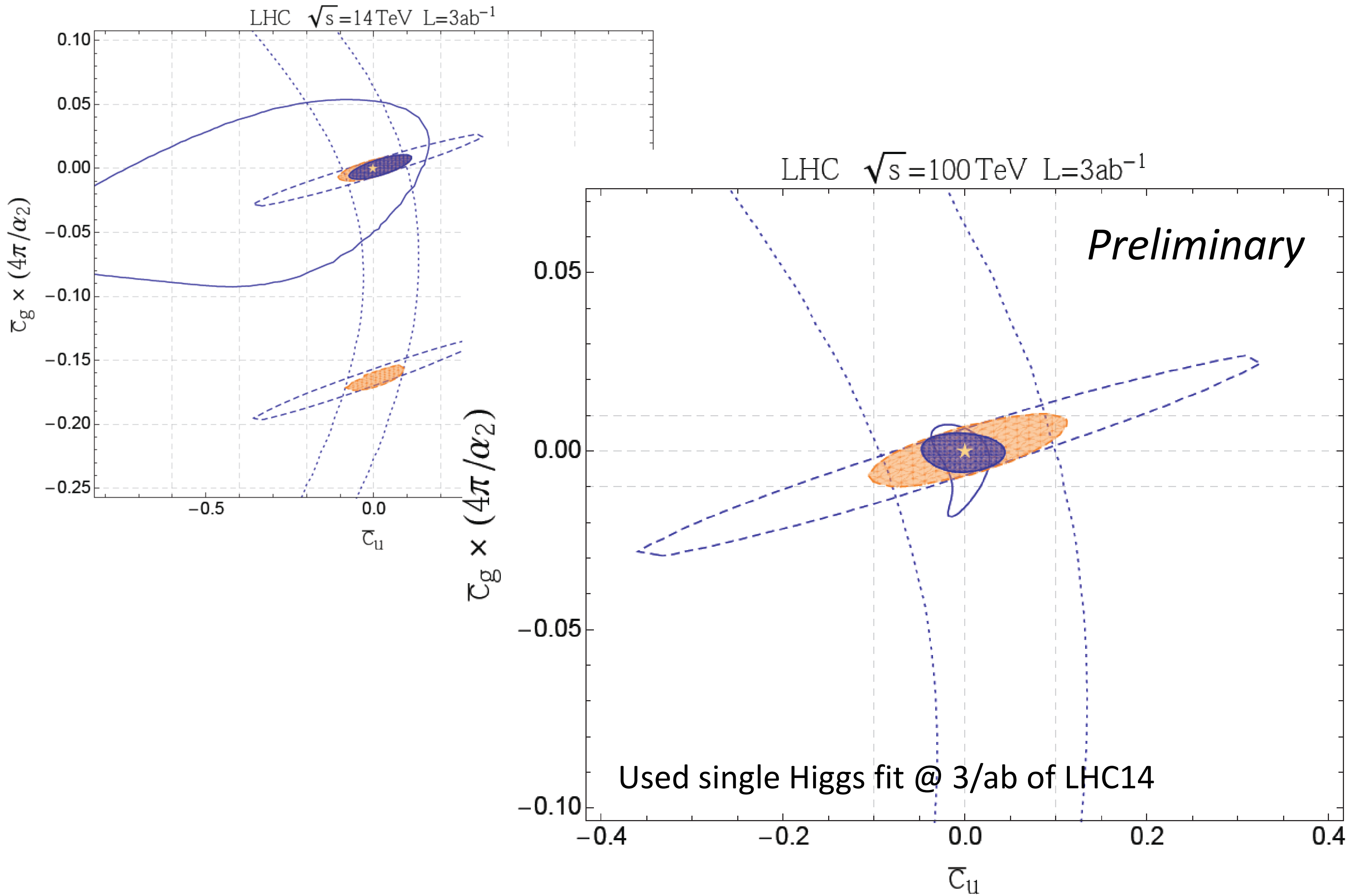
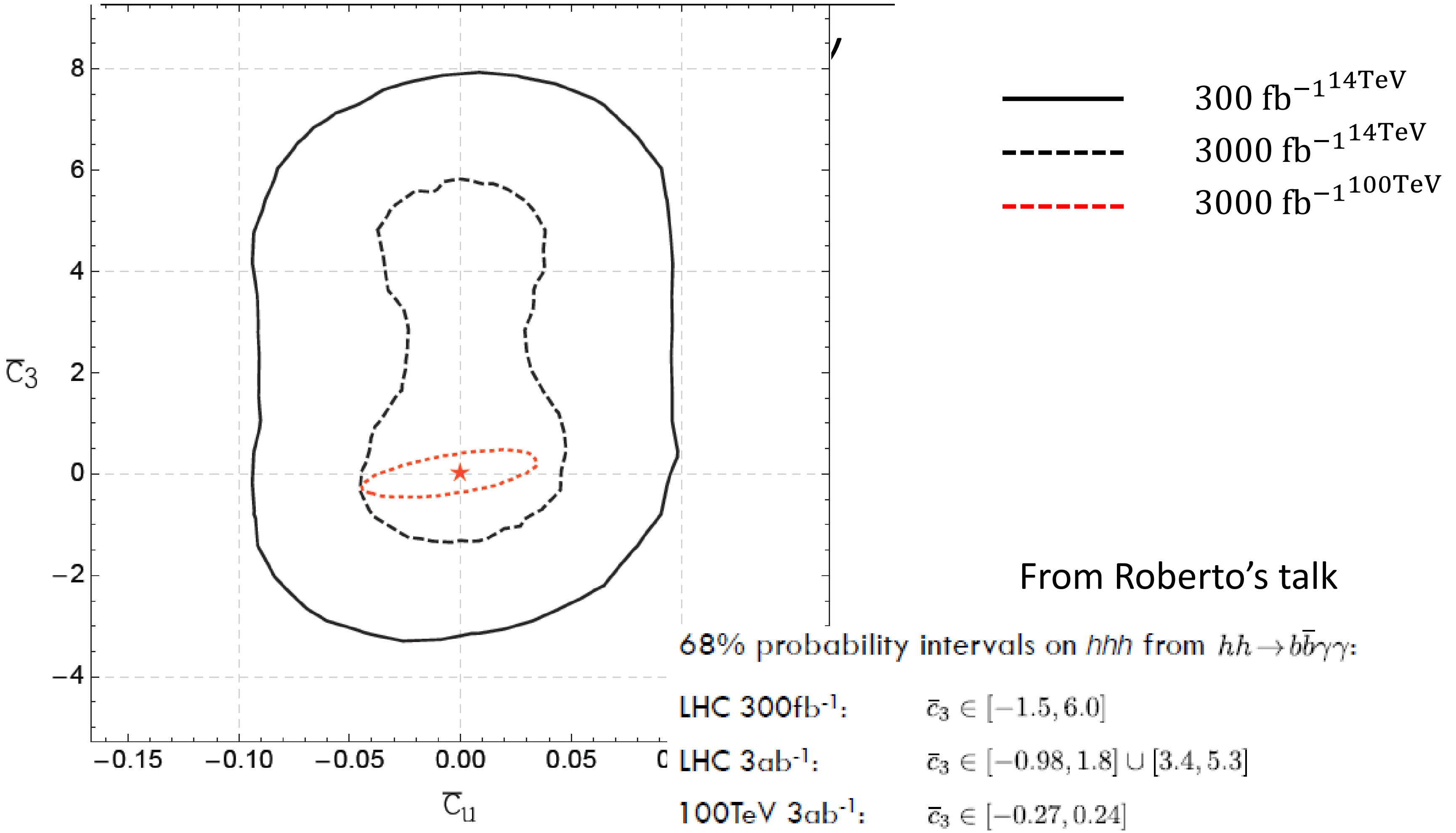


Sensitivity @ 100 TeV, using 3000/fb



Evolution of c3bar and cubar under 14 TeV → 100 TeV



From Roberto's talk

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}: $\bar{c}_3 \in [-0.27, 0.24]$

Summary

All result in this talk is preliminary !

: plots are changing day-by-day

Nevertheless there are some messages

1. hh is very challenging, but it still can compete with single Higgs fit, e.g. cubar
2. it is the best channel to measure the hhh coupling
3. It is very sensitive to tthh coupling

……

Extra Slides

Cross section
is saturated by the value at threshold

$$\sigma = \hat{\sigma}(s_0) \int_{s_0} \frac{d\hat{s}}{\hat{s}} \frac{\hat{\sigma}(\hat{s})}{\hat{\sigma}(s_0)} \rho_{AB}(\hat{s}/s \equiv \tau)$$

Kinematics determined
by threshold kinematics

"scale invariant"
if s_0 scales as s
:no benefit at all!

Upgrading energy while keeping threshold fixed makes the partonic luminosity scales accordingly

$\rho(\tau, Q^2) \sim 1/\tau^q$ for the τ range of interest