Effective field theory approach to double Higgs production via gluon fusion

$@\ \mathbf{14\ TeV}\ \ \&\ \mathbf{100\ TeV}$

Minho Son

EPFL, Lausanne

Work in progress with A. Azatov, R. Contino, G. Panico

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We were expecting to see new physics coming along with Higgs discovery, e.g. based on Naturalness argument.
But we keep seeing nothing. What should we do?

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e.g. within LHC reach or beyond reach? search style depends on it.

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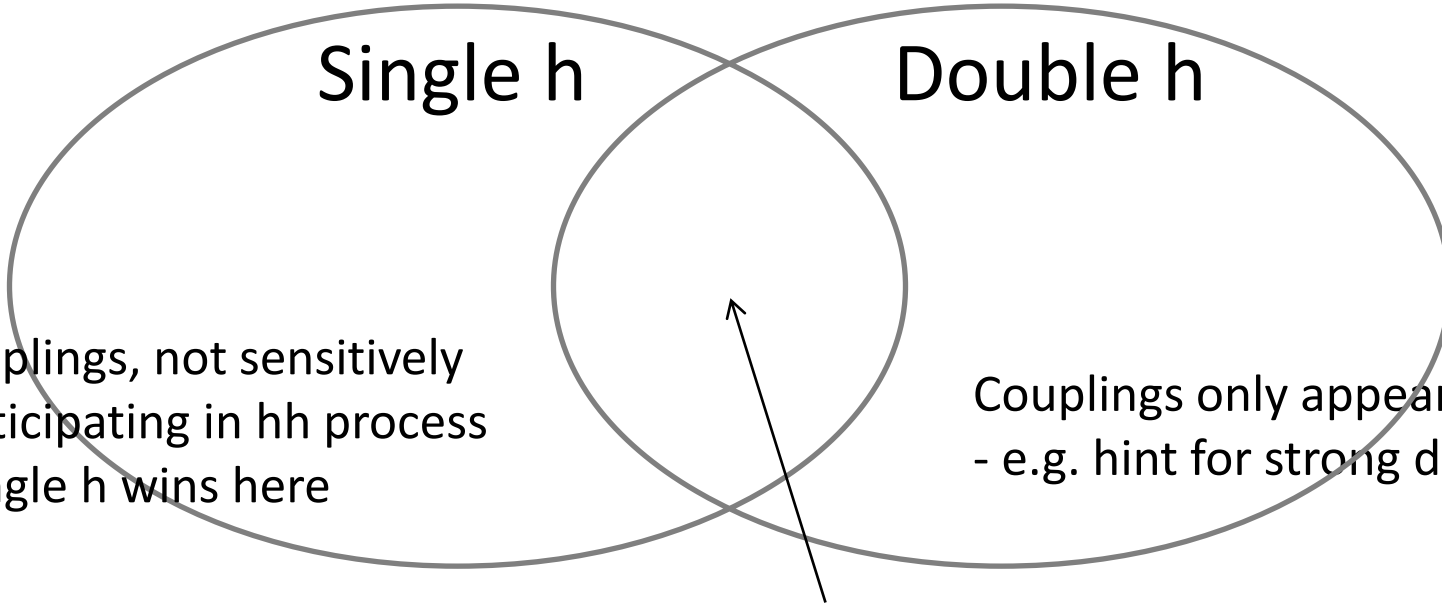
While one should directly search for new particles, we will stick to the measurement of Higgs couplings which is another place where NP can hide. We will do this in the context of HEFT

What can we learn from gg-hh ?

“Practically” speaking …



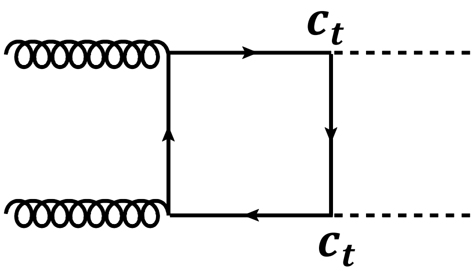
Couplings, not sensitively participating in hh process
: single h wins here

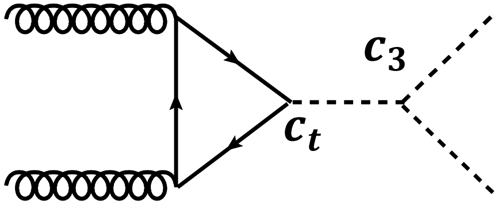
Couplings only appearing in hh
- e.g. hint for strong dynamics

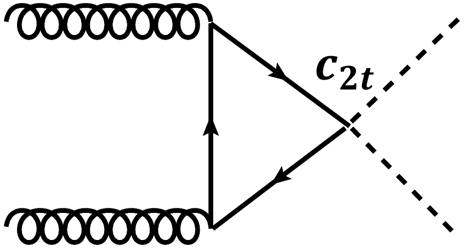
Couplings, accessible by both h and hh processes
: who’s doing better?

The boundary varies with assumptions and capability

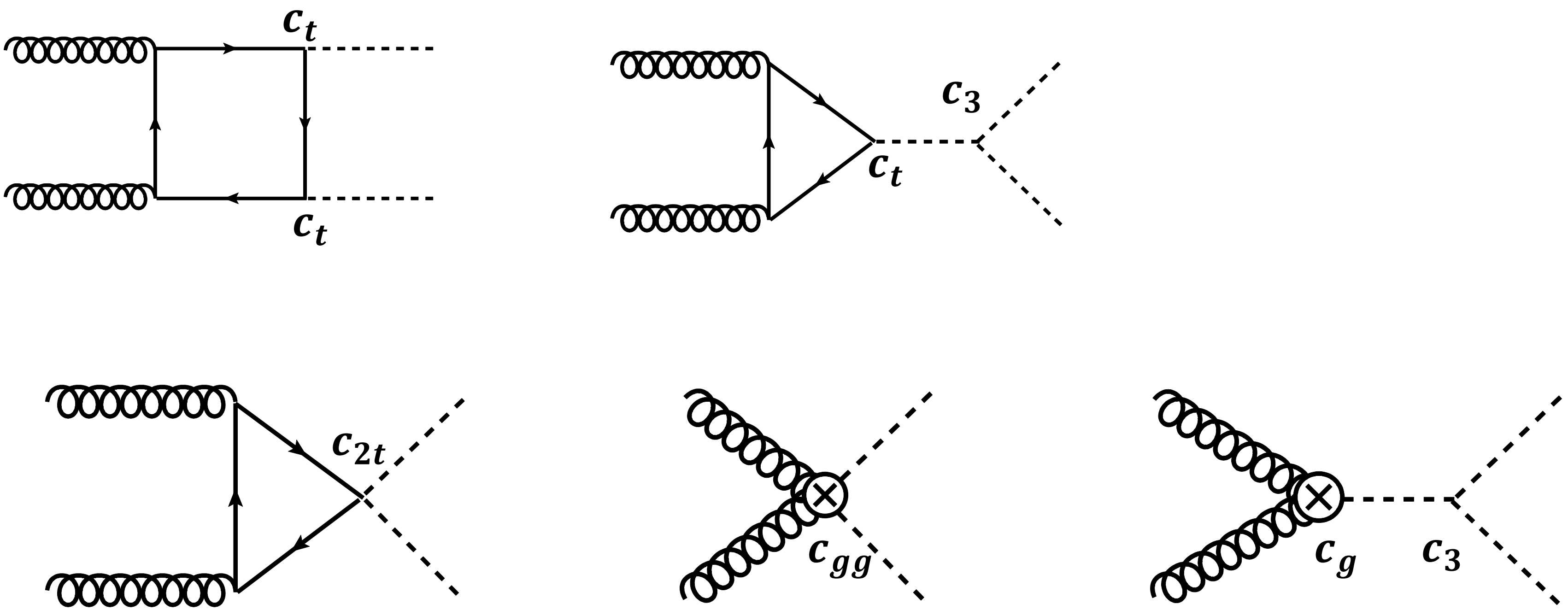
$gg \to hh$ process



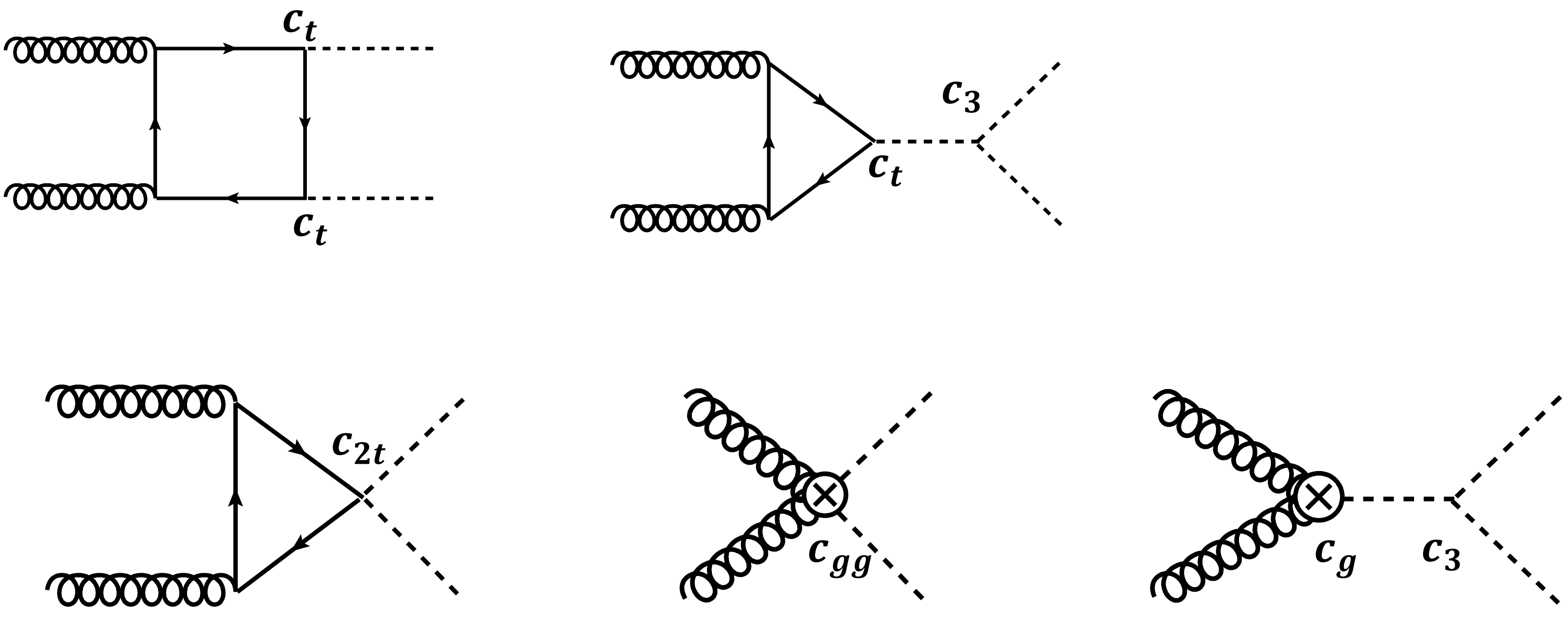




$gg \to hh$ process



$gg \to hh$ process

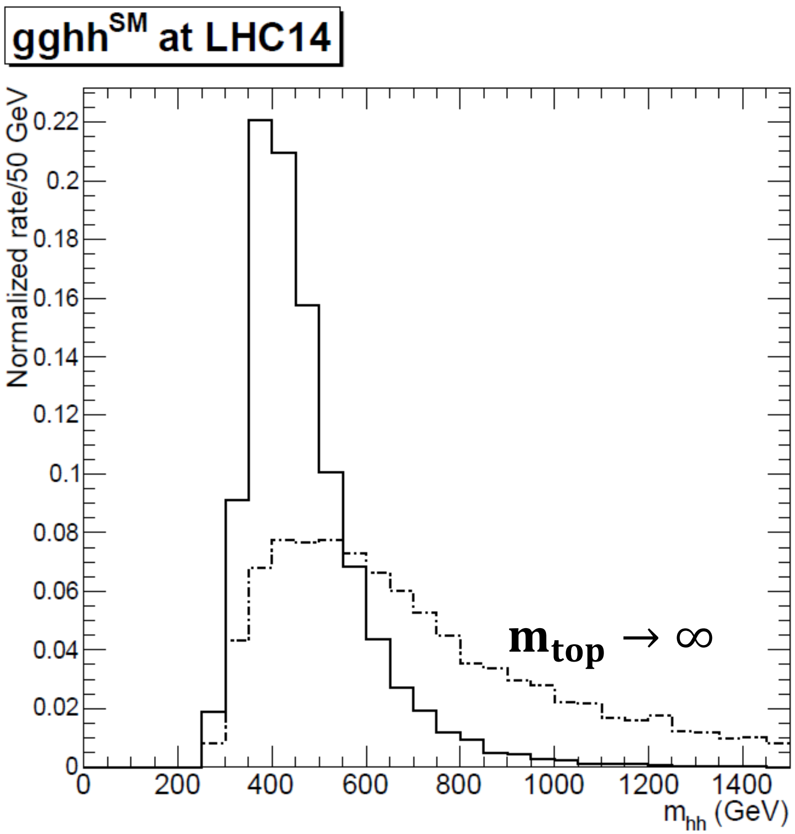


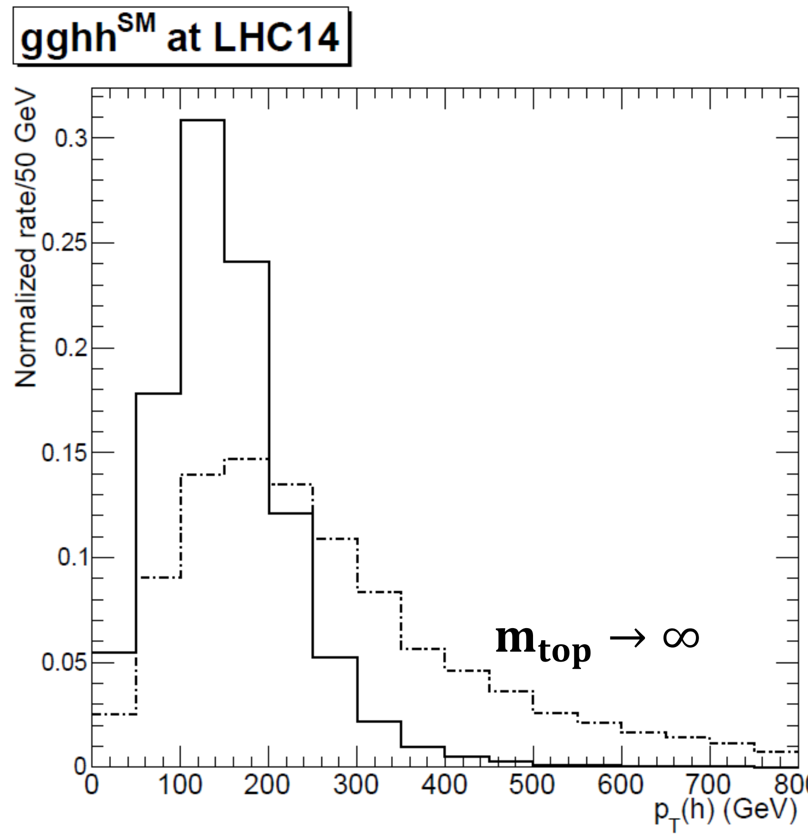
Five parameters are involved

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

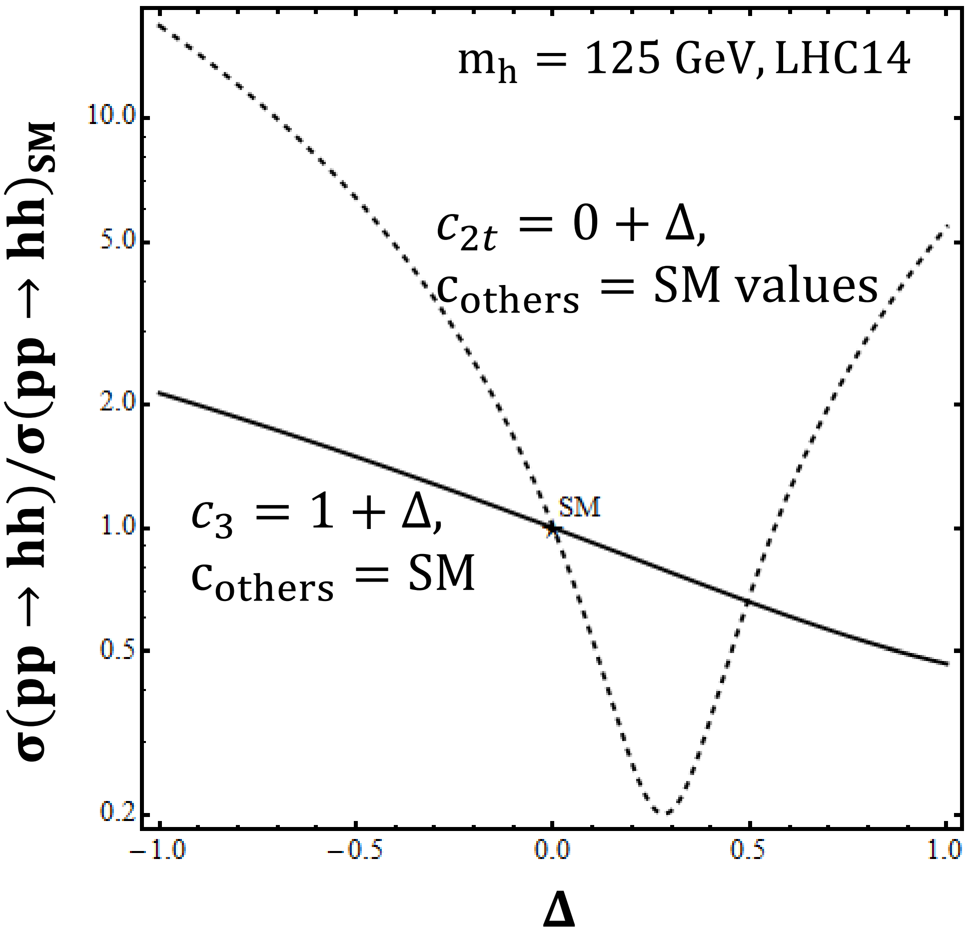
: How do we systematically study the effects of those pars ?

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

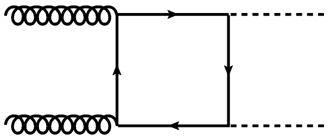




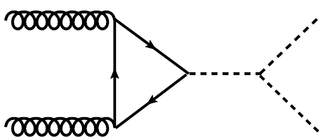
II. Cross section is more sensitive to c_{2t} than to c_3



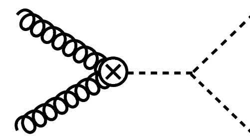
III. All parameters are sensitive to the different energy scale !!



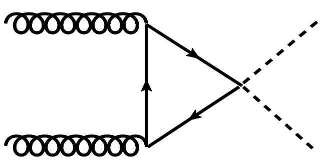
$\sim c_t^2 \frac{\alpha_s}{4\pi} y_t^2$



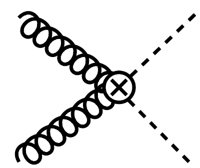
$\sim c_t c_3 \frac{\alpha_s}{4\pi} y_t^2 m_h^2 \frac{m_h^2}{\hat{s}} \left(\log \frac{m_t^2}{\hat{s}} + i\pi \right)^2$



$\sim c_g c_3 \frac{m_h^2}{\hat{s}}$



$\sim c_{t2} \frac{\alpha_s}{4\pi} y_t^2 \left(\log \frac{m_t^2}{\hat{s}} + i\pi \right)^2$



$\sim c_{2g}$

This makes $\mathbf{m_{hh}} (= \sqrt{\hat{s}})$ perfect shape variable

Double Higgs process can probe arbitrarily high new physics scale via $\mathbf{m_{hh}}$ (as long as it does not violate validity of EFT)

Higgs Effective Field Theory (HEFT)

: Model Independent Approach

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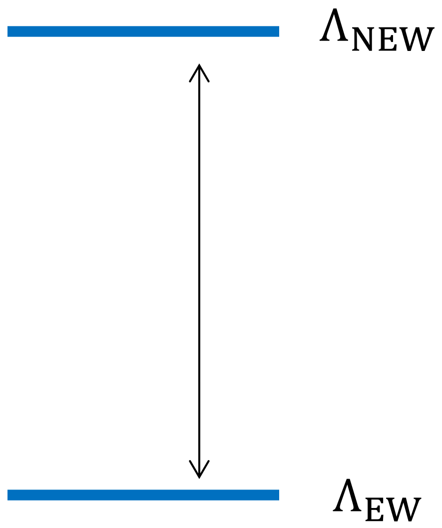
Assumption: Separation of scale



Higgs Effective Field Theory (HEFT)

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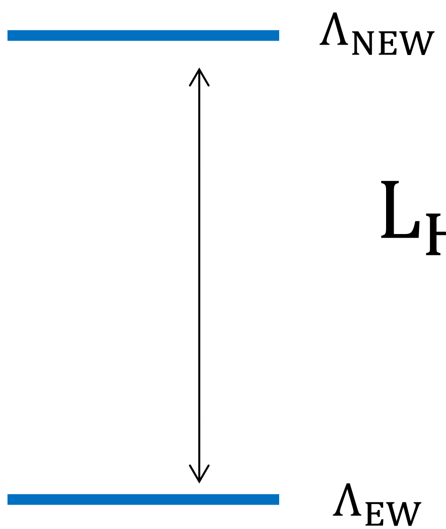

$$\mathrm{L}_{\mathrm{HEFT}} = \mathrm{L}_{\mathrm{pheno.}} + \mathrm{h}\ \text{d.o.f.}$$

: Systematic derivative and h expansions

Non-linear Lagrangian

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

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

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

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

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

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SM: $\mathrm{c_t} = 1,\ \mathrm{c_3} = 1,\ \mathrm{c_{2t}} = 0, \mathrm{c_g}, \mathrm{c_{2g}} = 0$

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 : $c_t = 1, c_3 = 1, c_{2t} = 0, c_g, c_{2g} = 0$

SILH basis

: useful when we are in the vicinity of SM point

Expand around

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

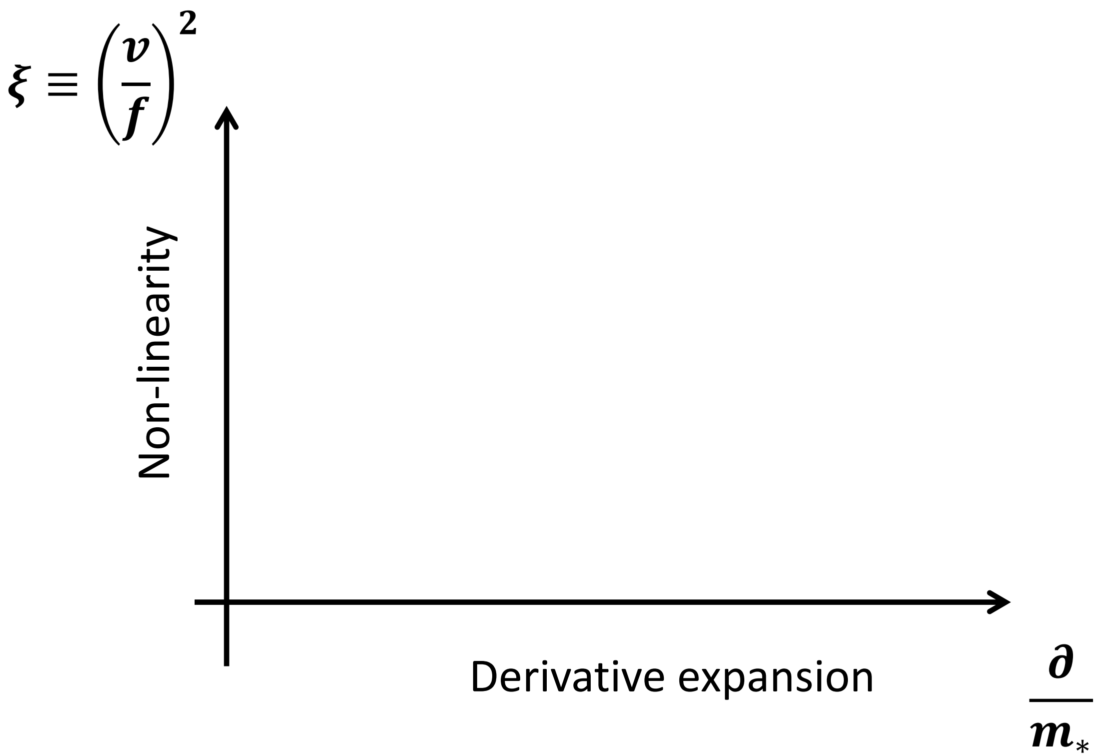
E.g. $L_{dim4} \times \frac{|H|^2}{f^2} =$

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

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

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

Validity of HEFT



Non-linear basis: only derivative expansion

SILH basis: expansion on both

Validity of HEFT

$$A(gg \to hh) \sim \left(\frac{\alpha_s}{4\pi}\right) \times \left[y_t^2 \left(1 + O\left(\frac{v^2}{f^2}\right)\right) + g_6^2(E) + g_8^2(E) + \ \dots \right]$$

$$g_6^2(E) \sim \bar{c}_g \frac{4\pi}{\alpha_2} \frac{E^2}{v^2} \sim \frac{\lambda^2 E^2}{m_*^2}$$

$$O_{dim-6} = GGhh \times \frac{\lambda^2}{g_*^2}$$

$$\frac{\lambda^2}{g_*^2} \quad \text{vs.} \quad \frac{E^2}{m_*^2}$$

$$g_8^2(E) \sim \bar{c}_{gD0,2} \frac{4\pi}{\alpha_2} \frac{E^4}{v^2 m_W^2} \sim \frac{g_*^2 E^4}{m_*^4}$$

$$O_{dim-8} = GG\partial h \partial h$$

Energy Hierarchy and Validity of HEFT

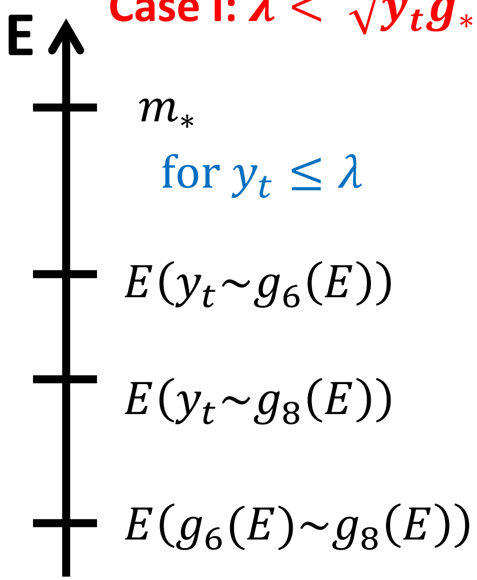
$$E\left(y_t^2 \sim g_6^2(E)\right) = m_* \frac{y_t}{\lambda} = m_* \sqrt{\frac{y_t}{g_*}} \times \left(\frac{\sqrt{y_t g_*}}{\lambda}\right)$$

$$E\left(y_t^2 \sim g_8^2(E)\right) = m_* \sqrt{\frac{y_t}{g_*}}$$

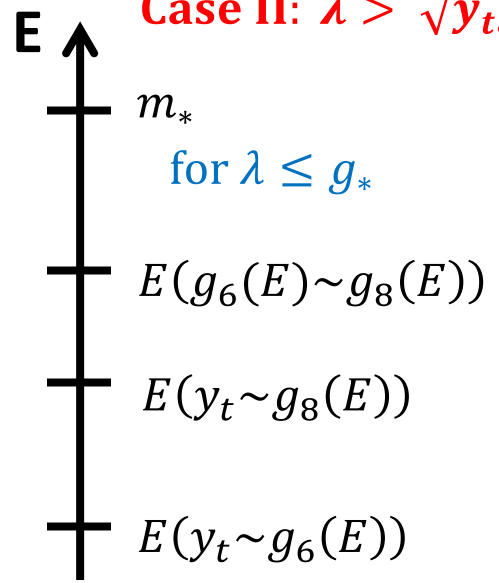
$$E\left(g_6^2(E) \sim g_8^2(E)\right) = \lambda f = m_* \frac{\lambda}{g_*} = m_* \sqrt{\frac{y_t}{g_*}} \times \left(\frac{\lambda}{\sqrt{y_t g_*}}\right)$$

$\frac{\sqrt{y_t g_*}}{\lambda}$ controls hierarchy

Case I: $\lambda < \sqrt{y_t g_*}$



Case II: $\lambda > \sqrt{y_t g_*}$



Two scenarios

$$E\left(y_t^2 \sim g_6^2(E)\right) = m_* \frac{y_t}{\lambda} = m_* \sqrt{\frac{y_t}{g_*}} \times \left(\frac{\sqrt{y_t g_*}}{\lambda}\right)$$

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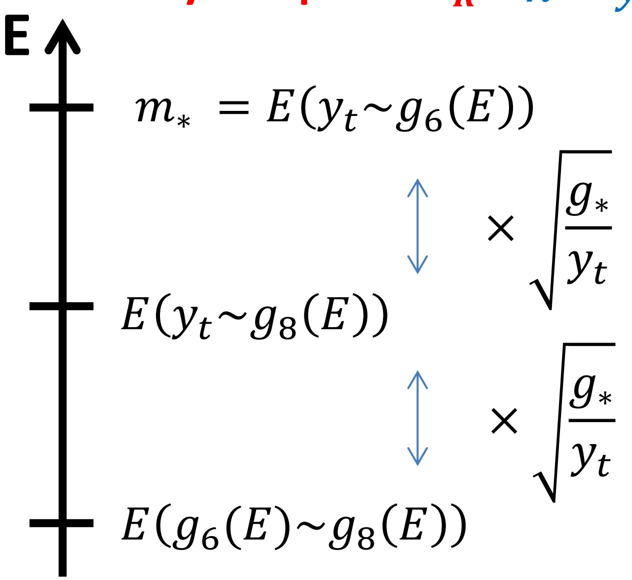
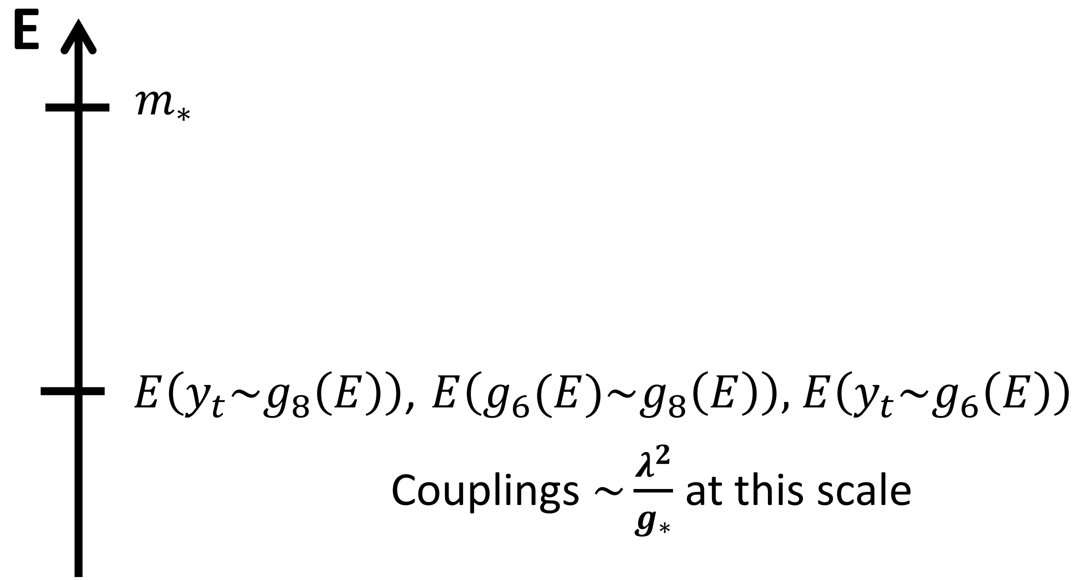
Fully composite t_R $\lambda = y_t$



Partially composite t_L & t_R $\lambda = \sqrt{y_t g_*} < g_*$



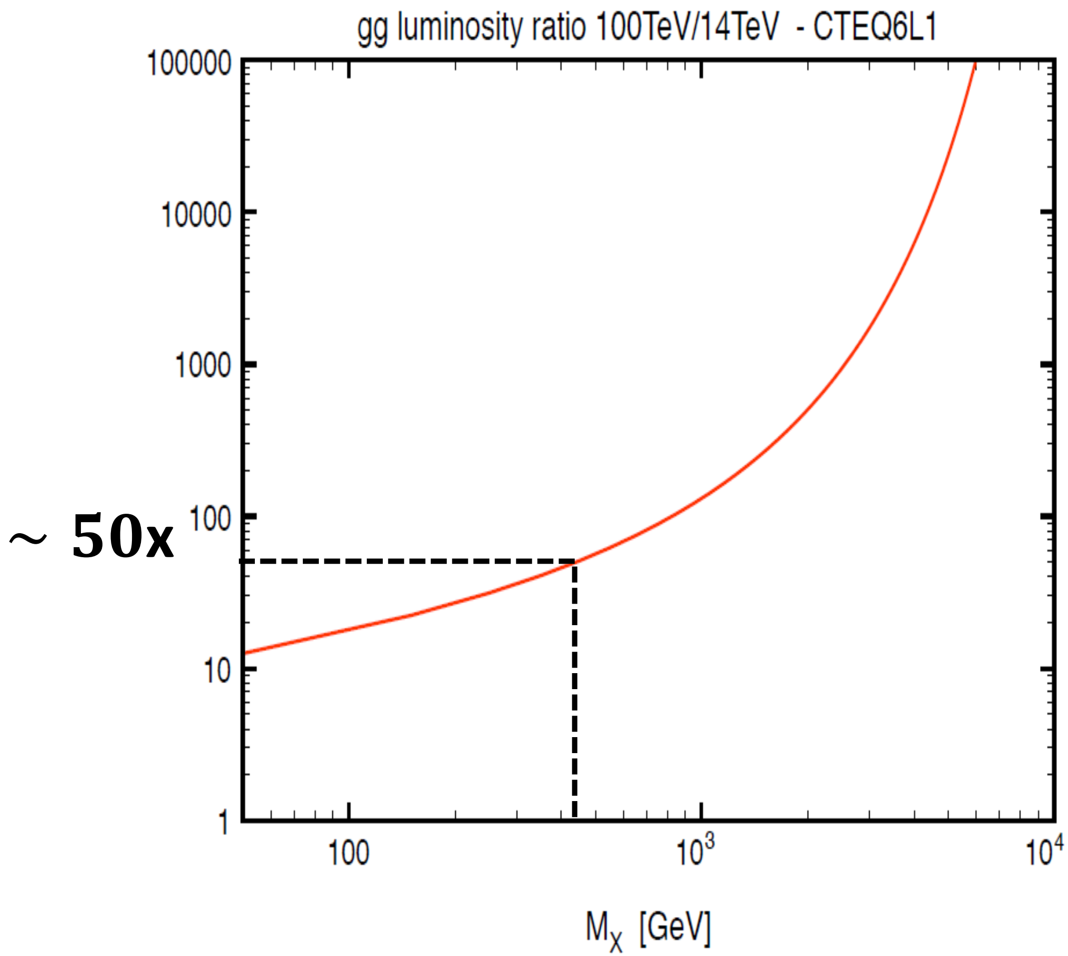
When upgrading Energy

14TeV → 100 TeV

7x

	14 TeV					100 TeV
gg → *HH*^{f}(*λ*=1)	33.8 fb	207 fb (6.1)	298 fb (8.8)	609 fb (18)	980 fb (29)	1.42 pb (42)

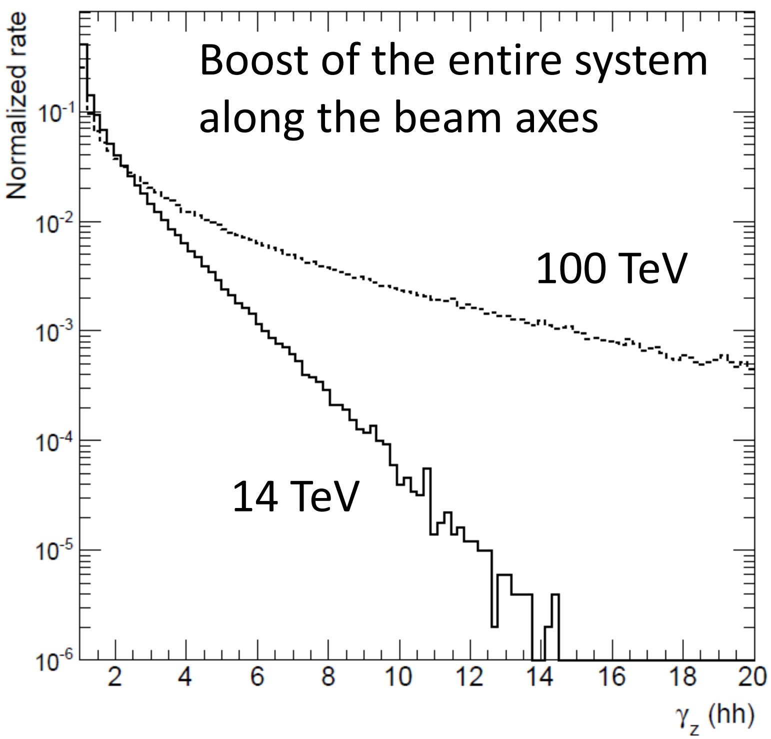
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsEuropeanStrategy

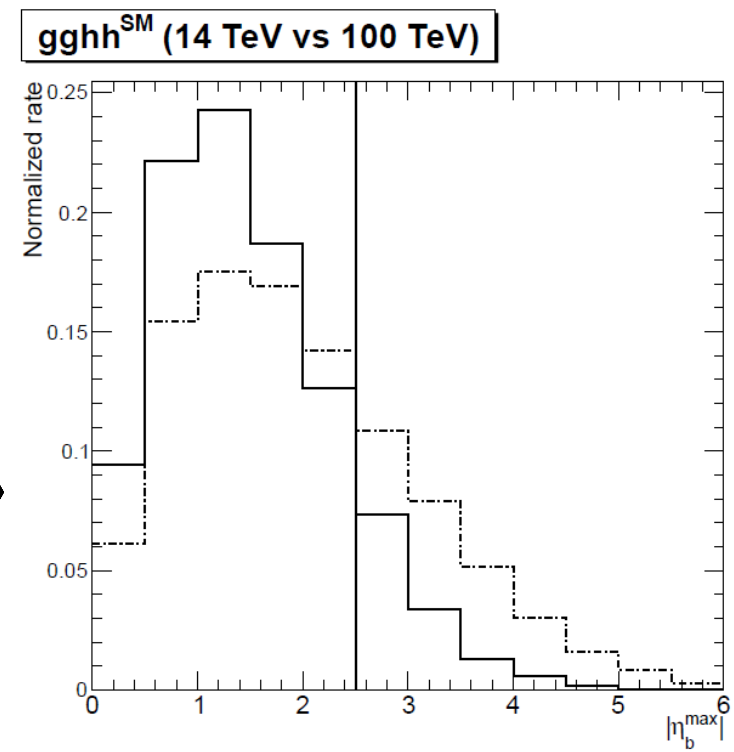


Main kinematics remain same under 7x

But there are some changes here and there …

Large imbalance in x_i, x_j in gluon PDF



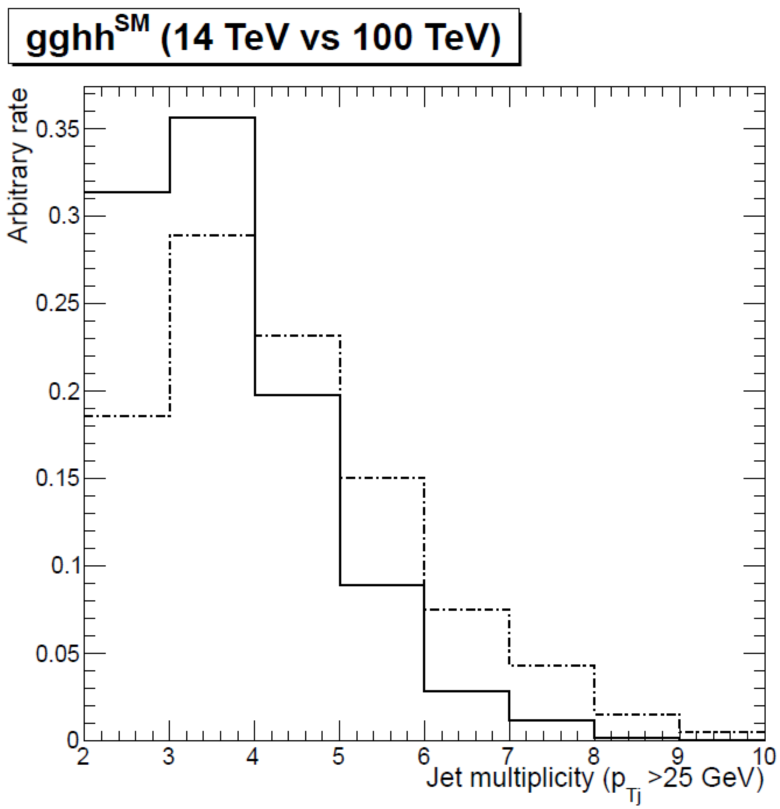


Events leaking to higher eta region

Main kinematics remain same under 7x

But there are some changes here and there …

More radiations, higher jet multiplicity

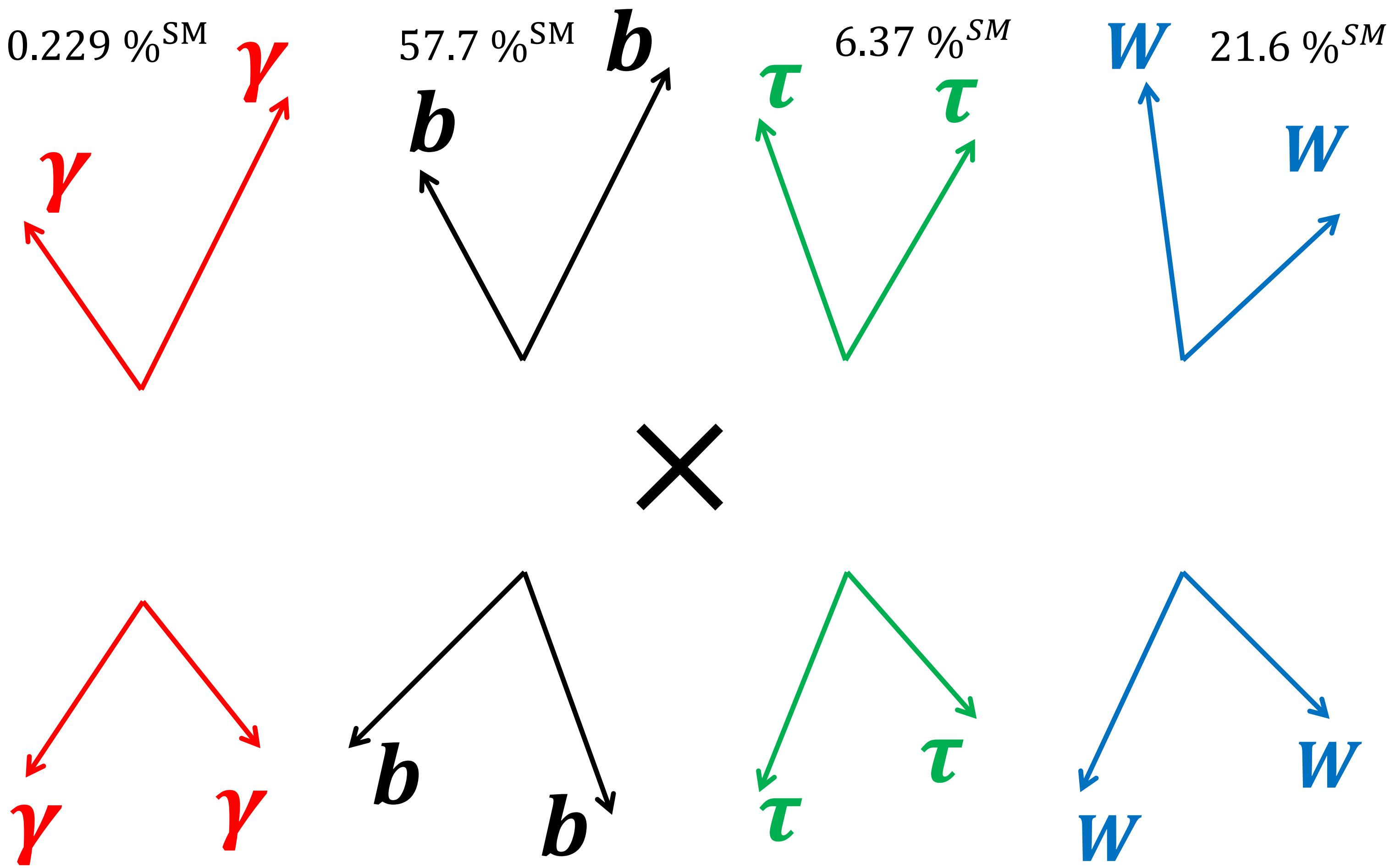


$$gg \to hh$$

Phenomenology

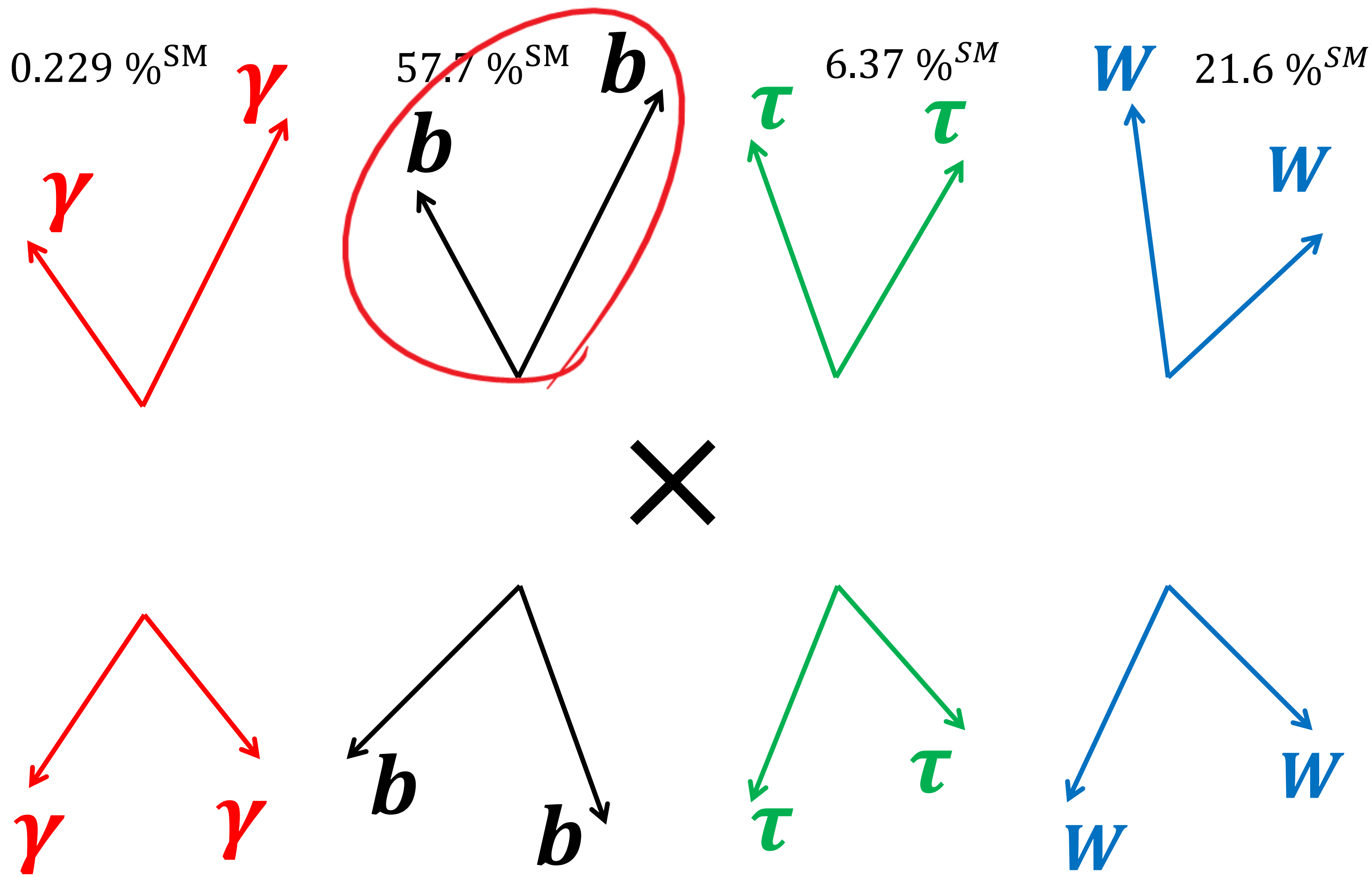
Zoo of $gg \to hh$ decay

Consider the best channel or multiple comparable channels



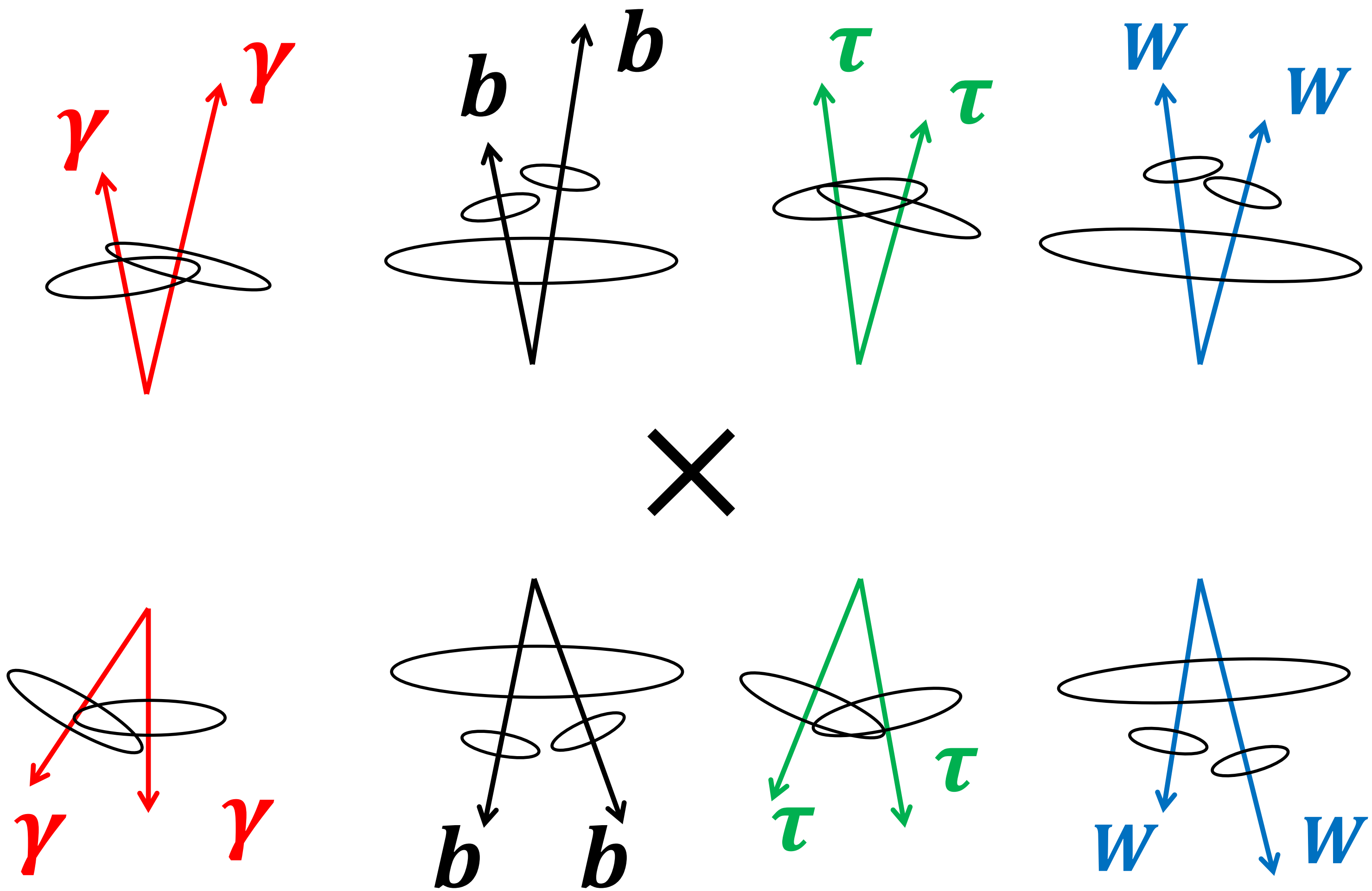
Zoo of $gg \to hh$ decay

At 14TeV we are forced to select one bb pair due to small signal rate



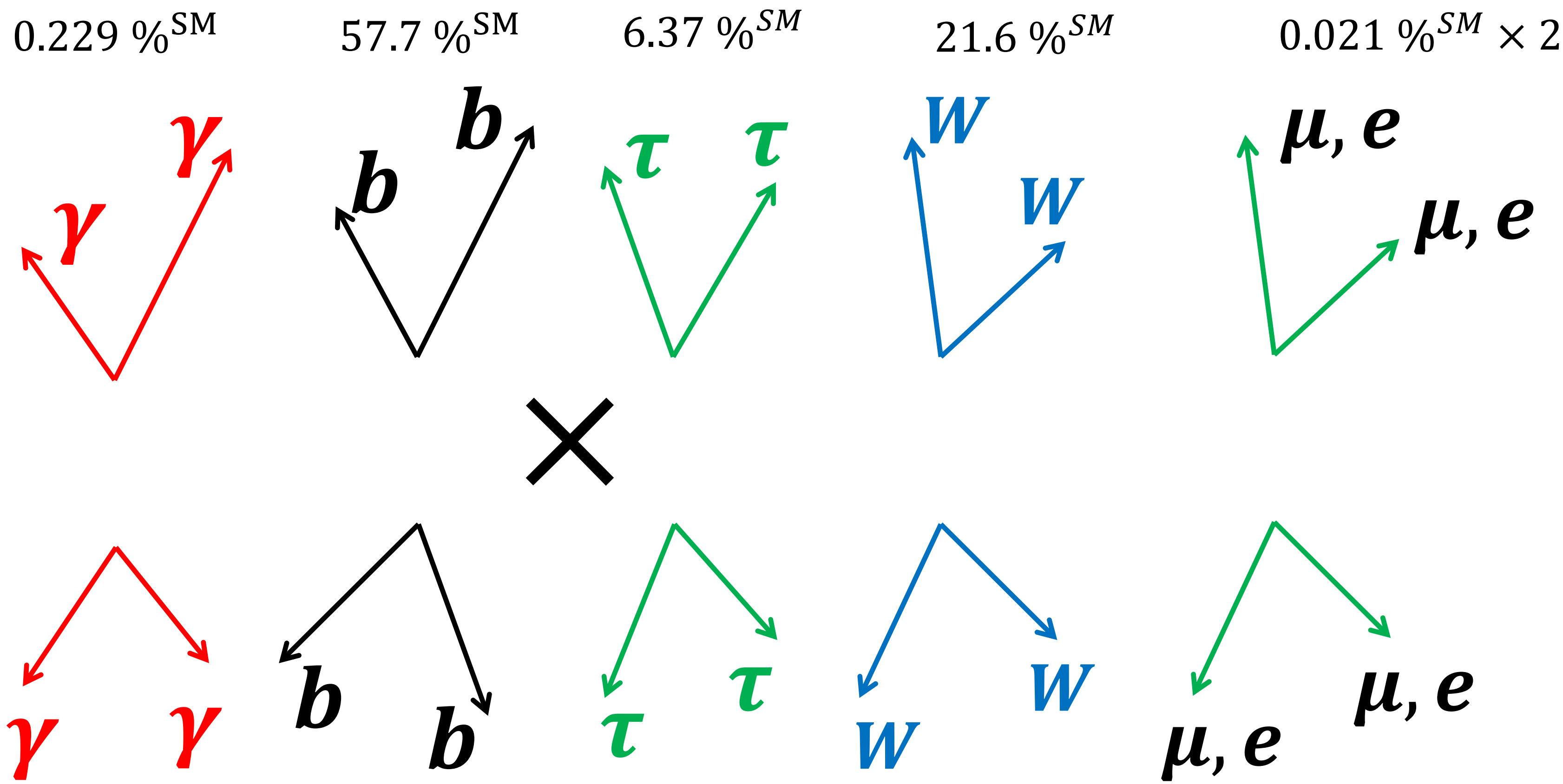
Boosted kinematics could help ??

becomes relevant If your signal rate/kinematics allows,
e.g. Process growing with the energy (VBF, …), 100 TeV

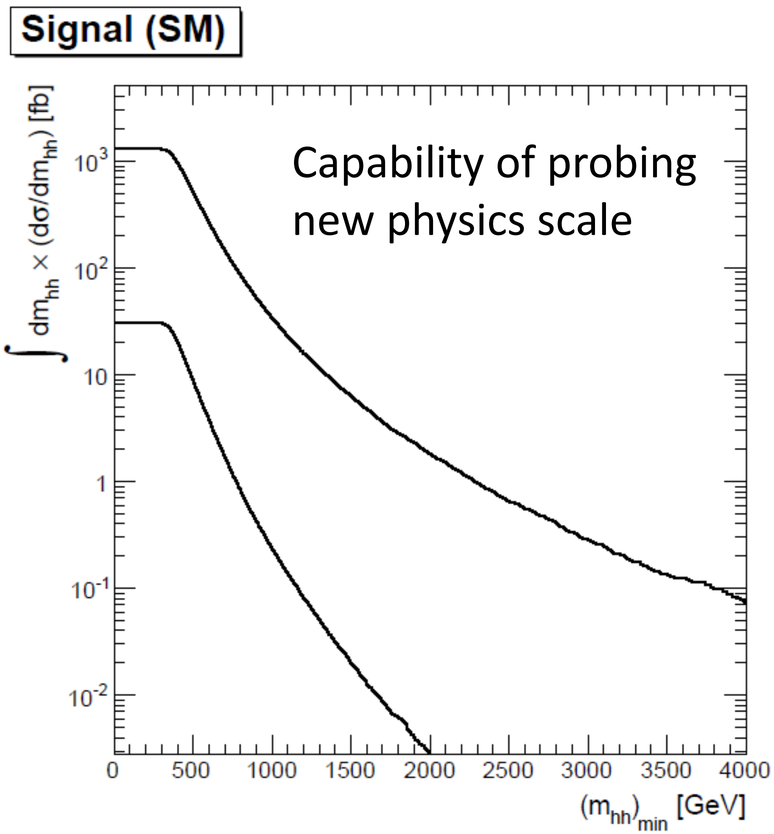


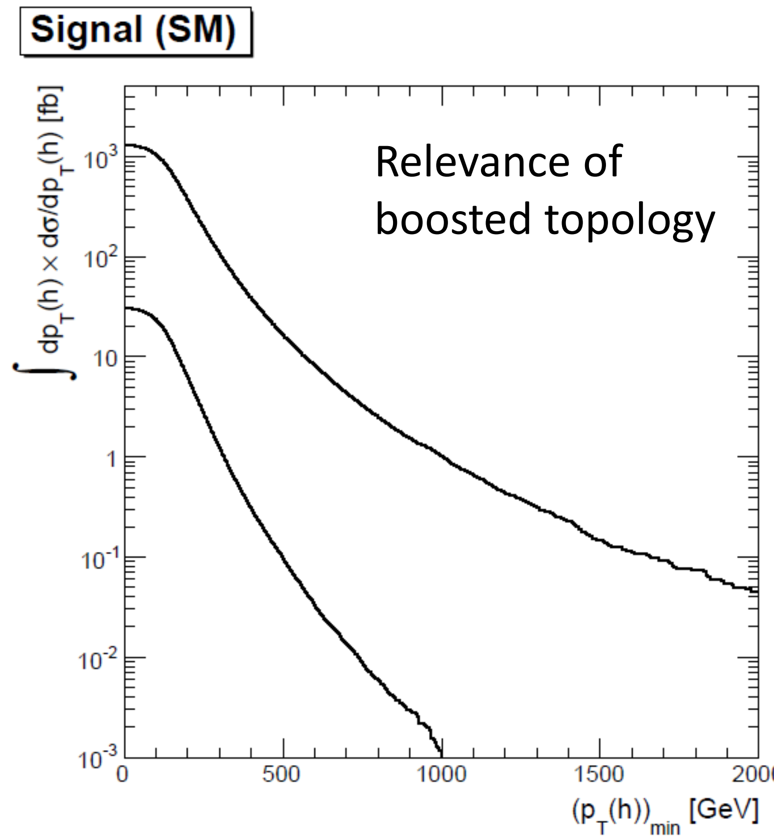
More exotic process ?? **@ higher energy collider**

Higher signal rate opens up new set of rare final state channels
We do not have to select always one of bb pair



Let us be more specific

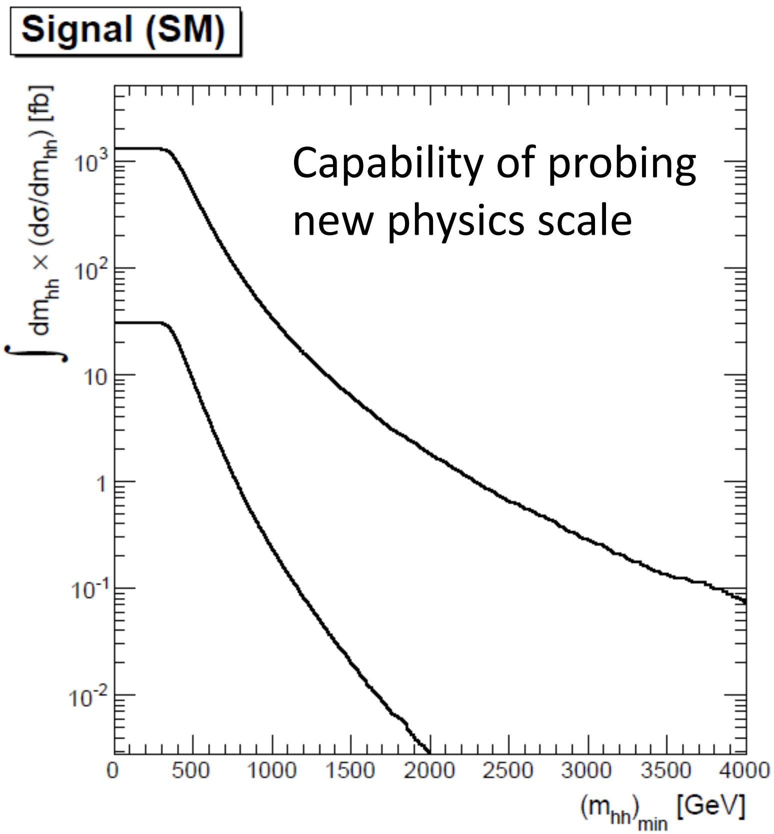


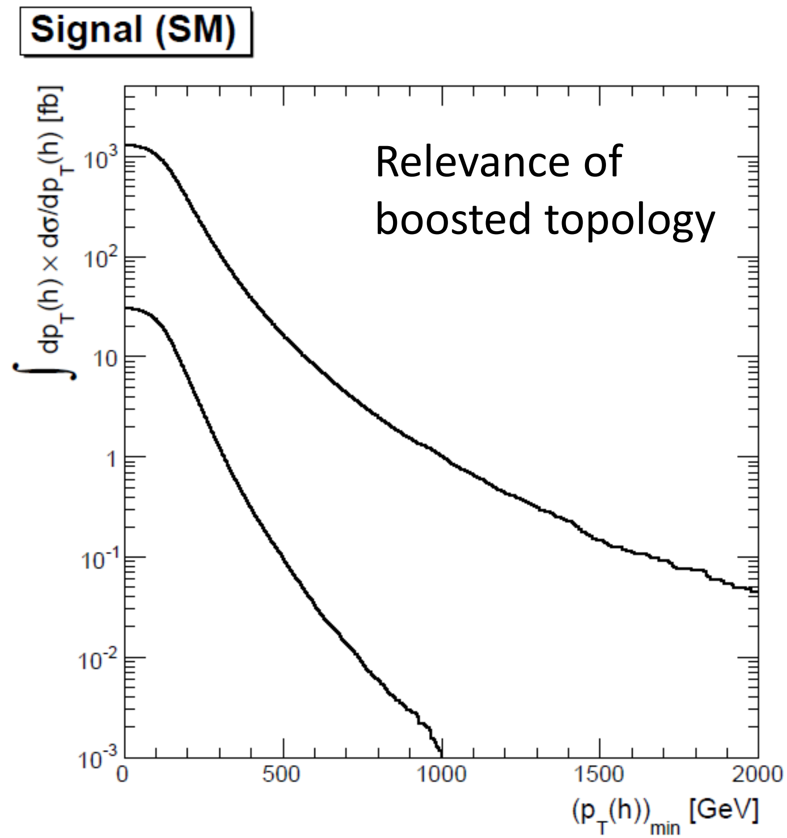


Demanding at least some fixed number events
can be translated into the various scales

$$\mathbf{E.g.}\ \boldsymbol{\sigma} \geq \frac{\mathbf{5\ Events}}{\mathbf{BR(hh \to X) \times \epsilon_s \times 3000\ fb^{-1}}}$$

Let us be more specific!

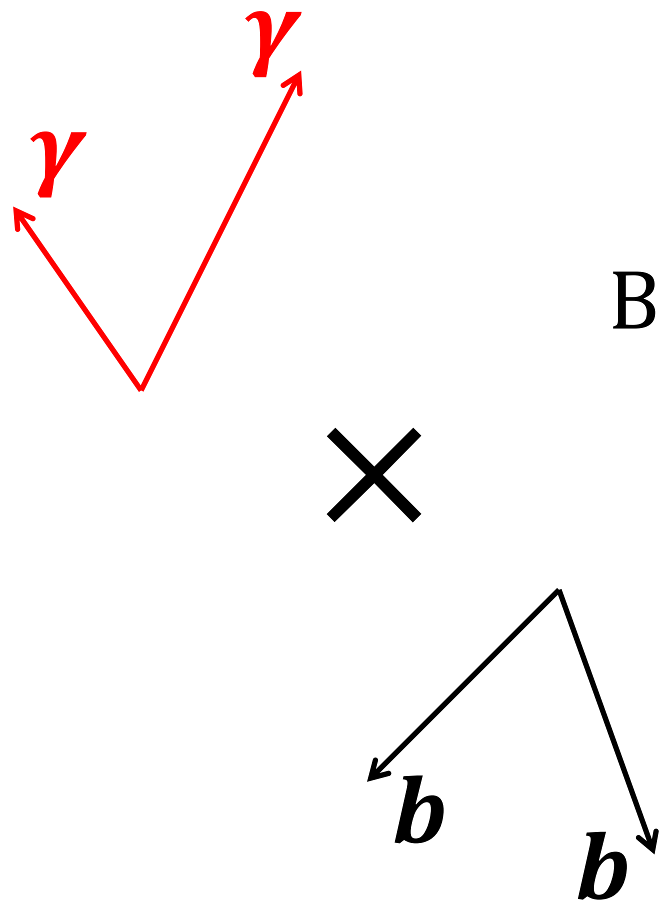




Channel	$b\bar{b}b\bar{b}$ (33.3%)	$b\bar{b}WW^*$(24.9%)	$b\bar{b}\tau^+\tau^-$(7.35%)	$\gamma\gamma b\bar{b}$ (0.264%)
Cross section	> 0.05 fb	> 0.067 fb	> 0.227 fb	> 6.31 fb
m_{hh} [GeV]	< 1300 (4200)	< 1240 (4070)	< 1006 (3141)	< 538 (1499)
$p_T(h)$ [GeV]	< 560 (1900)	< 530 (1830)	< 424 (1399)	< 200 (640)

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

We focus on



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

; small but clean!

Our traditional jet-based analysis on the process is something you can easily imagine

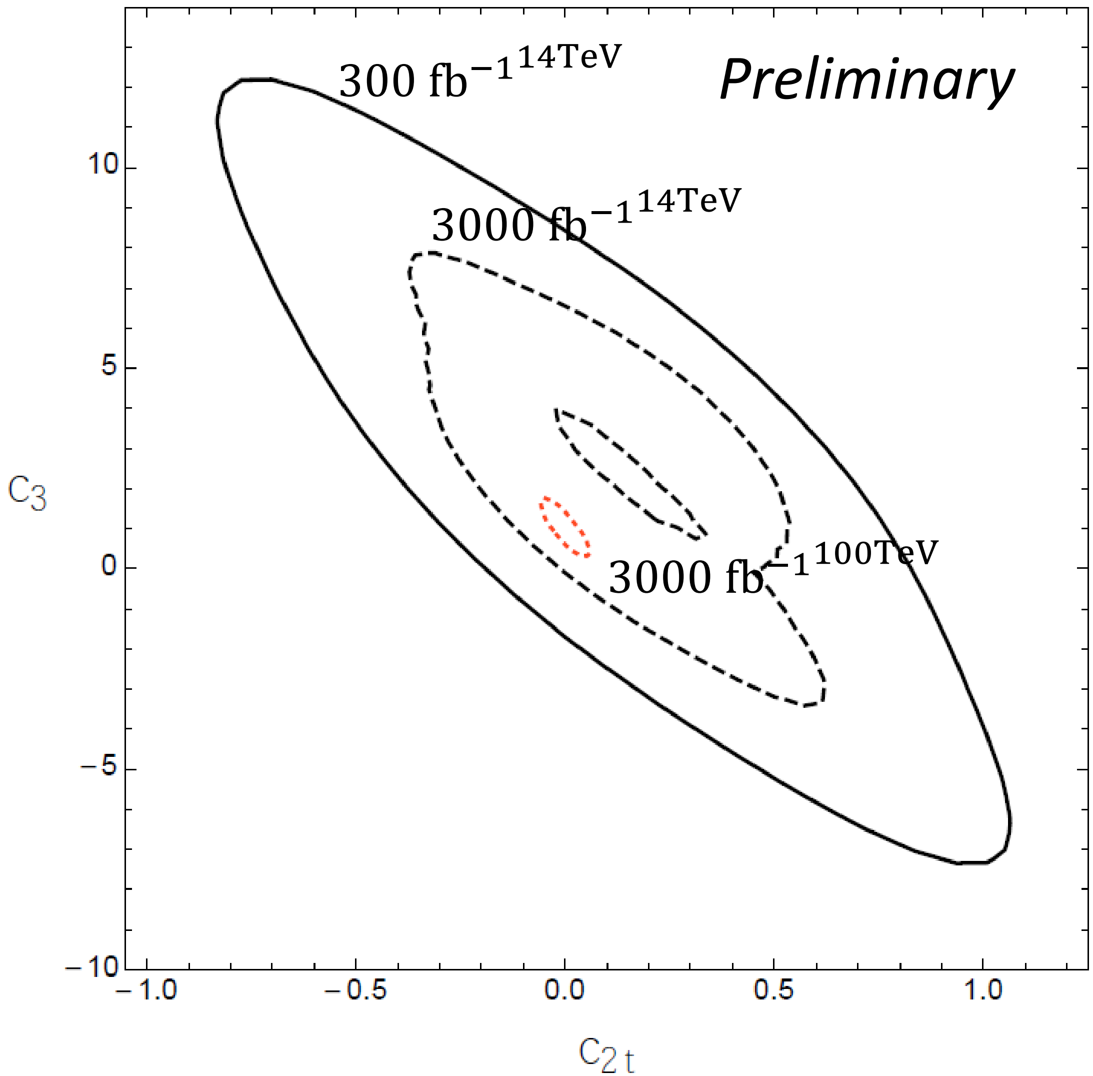
Let us skip it and save time

Sensitivity

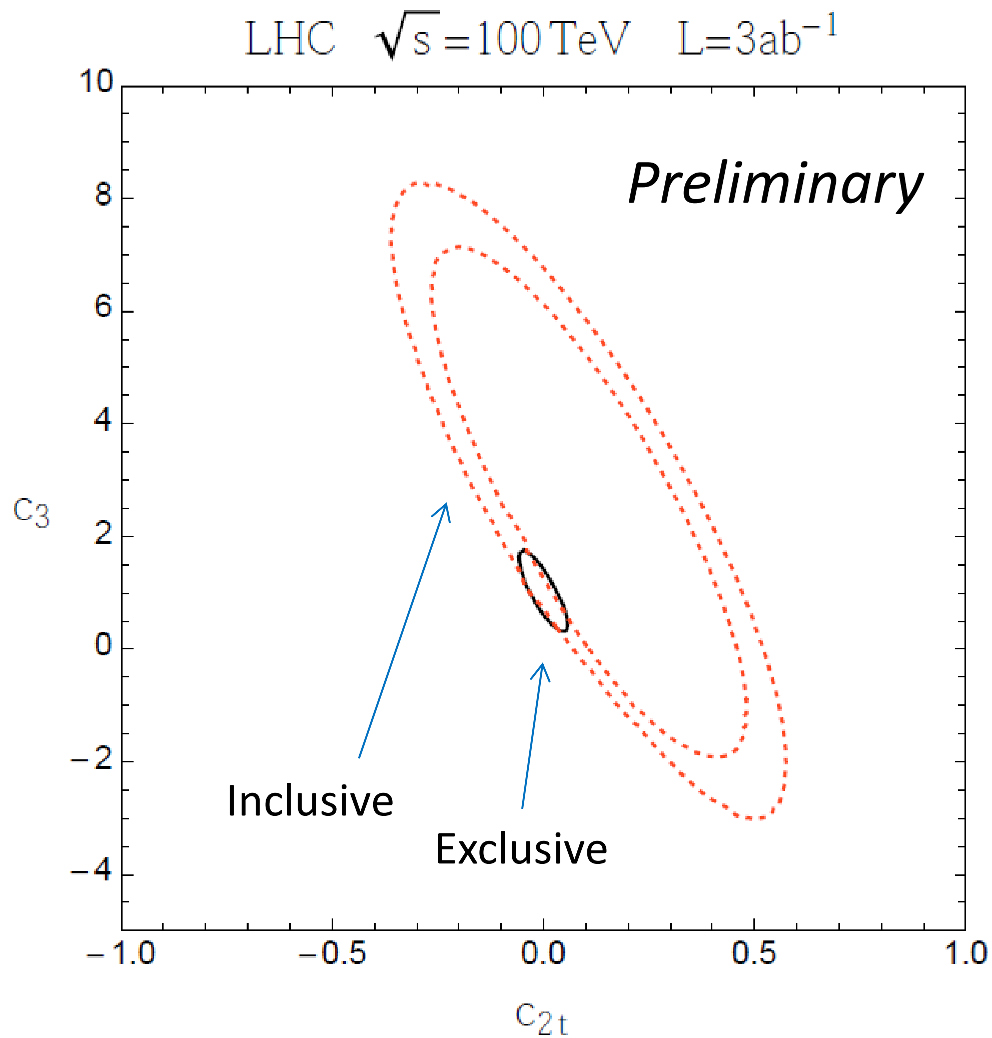
@ LHC14

& 100 TeV

Evolution of c3 and c2t under 14 TeV → 100 TeV

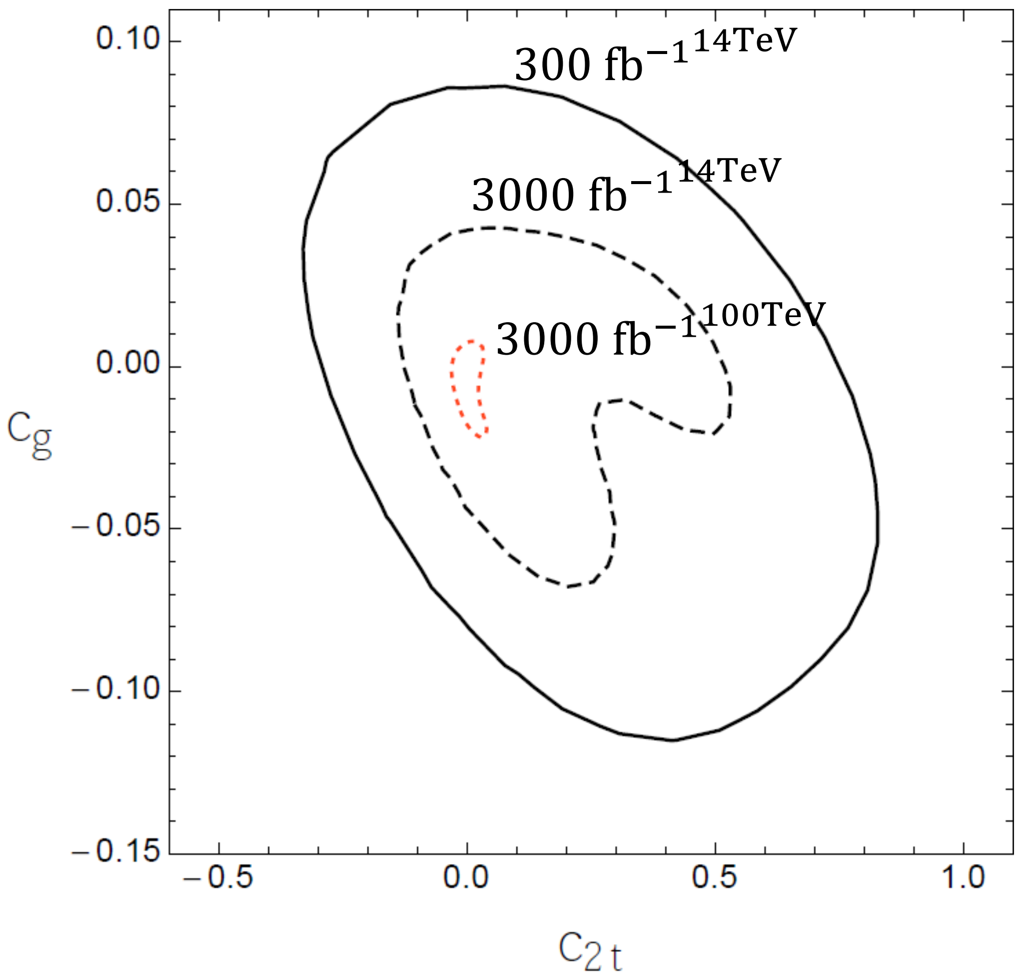


What does the shape analysis of $\mathbf{m_{hh}}$ do ?

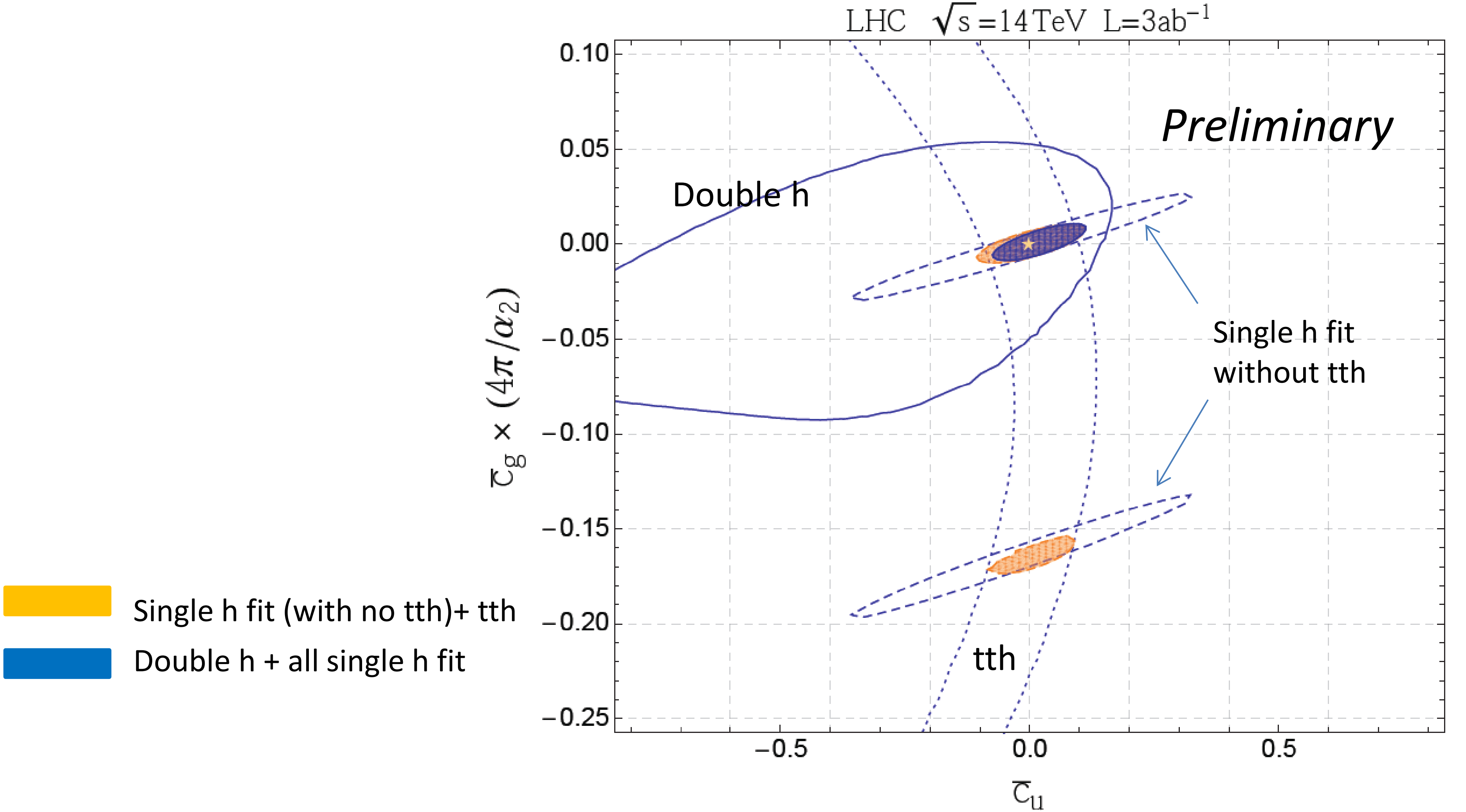


Similar improvements appear here and there

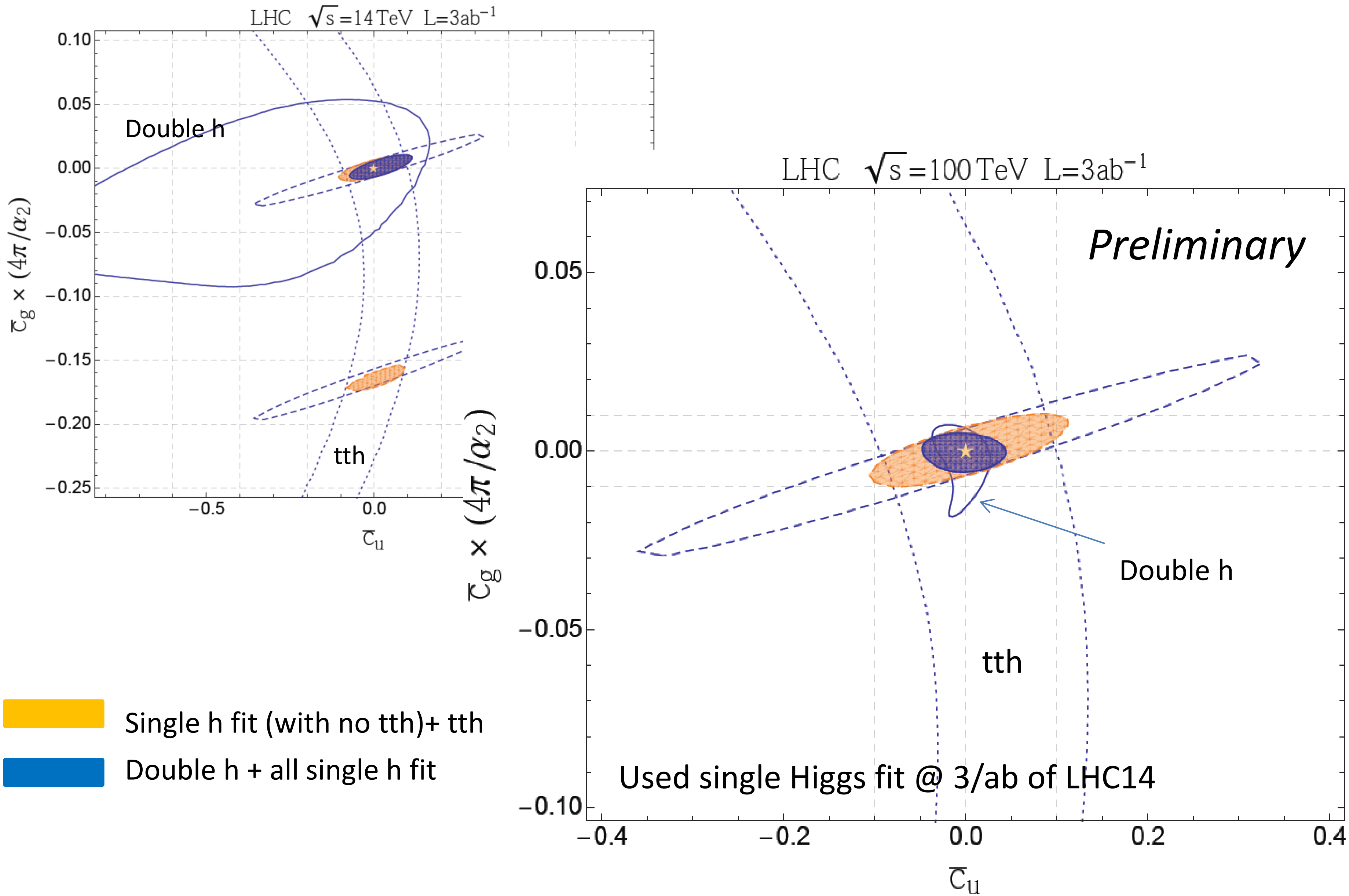
Evolution of
c2t and cg under 14 TeV → 100 TeV



Sensitivity @ 14 TeV, using 3000/fb



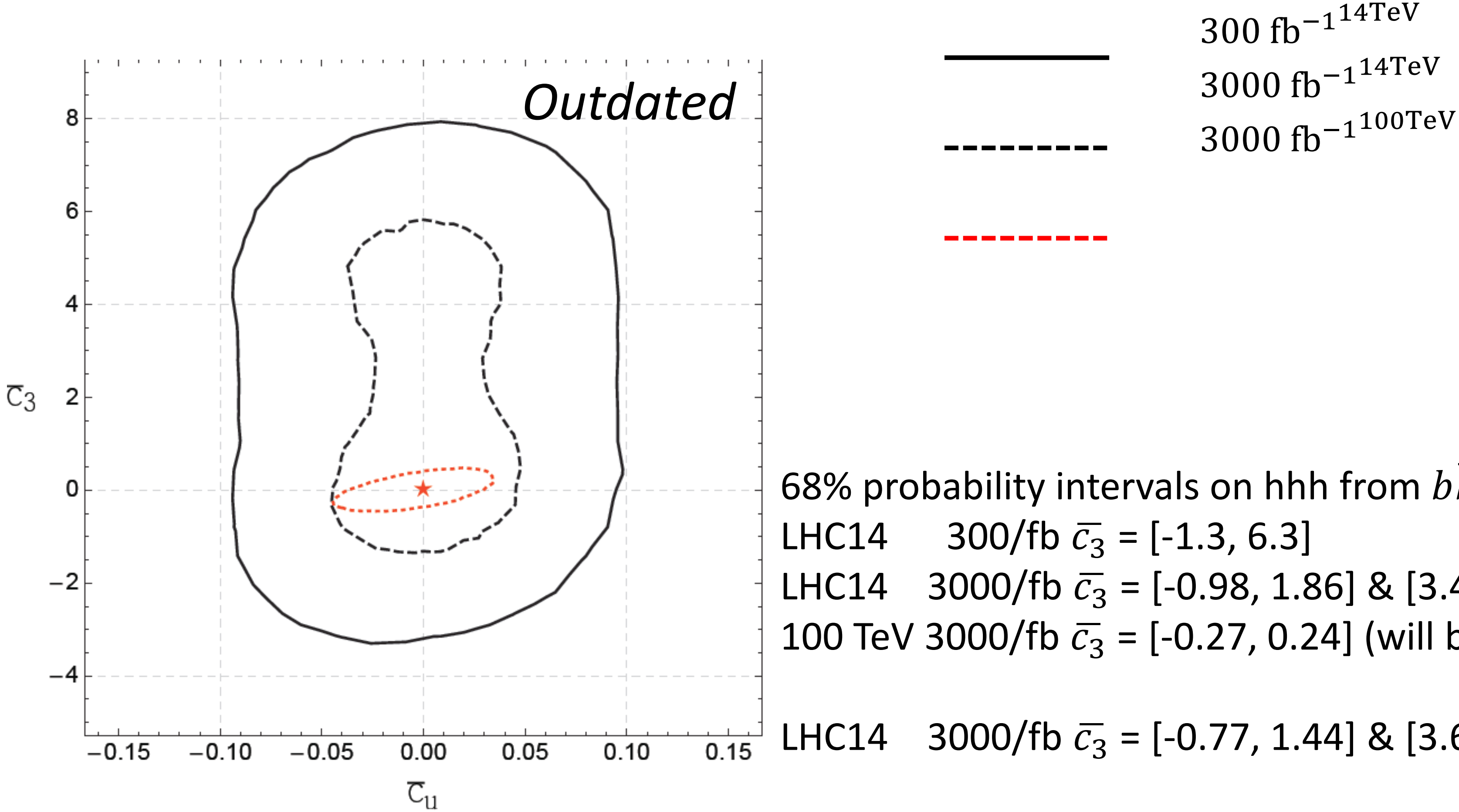
Sensitivity @ 100 TeV , using 3000/fb



Single h fit (with no tth)+ tth

Double h + all single h fit

Evolution of
c3bar and cubar under 14 TeV → 100 TeV



68% probability intervals on hhh from $b\bar{b}\gamma\gamma$

LHC14 300/fb $\bar{c_3}$ = [-1.3, 6.3]

LHC14 3000/fb $\bar{c_3}$ = [-0.98, 1.86] & [3.45,5.2]

100 TeV 3000/fb $\bar{c_3}$ = [-0.27, 0.24] (will be updated)

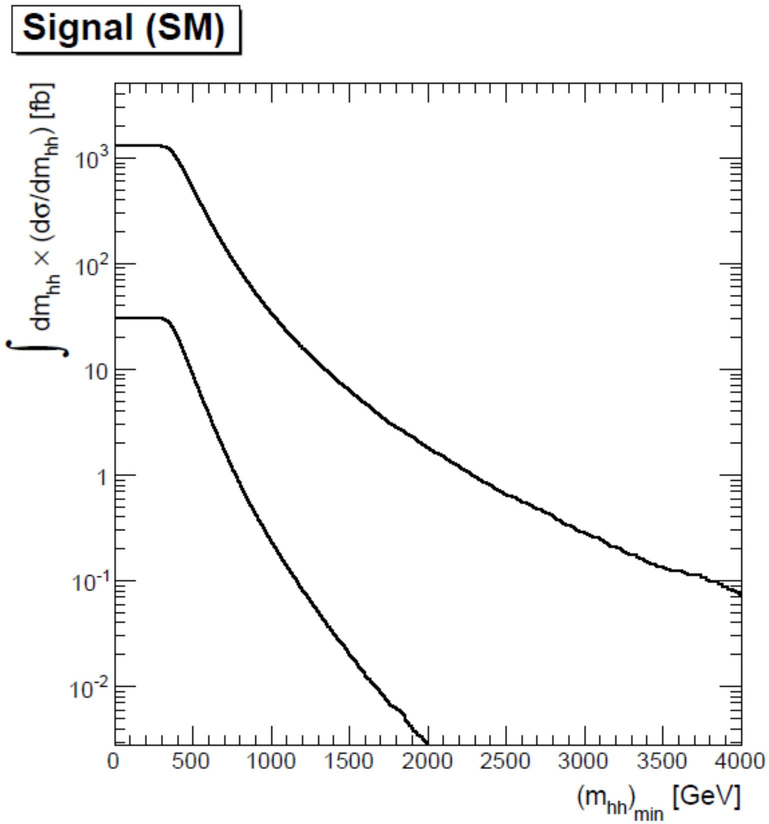
LHC14 3000/fb $\bar{c_3}$ = [-0.77, 1.44] & [3.6,5.9]

Jet Substructure

: Essential tool to probe very high new physics scale

No available plots yet
I will only sketch the issues

Let me remind you of this beautiful plot

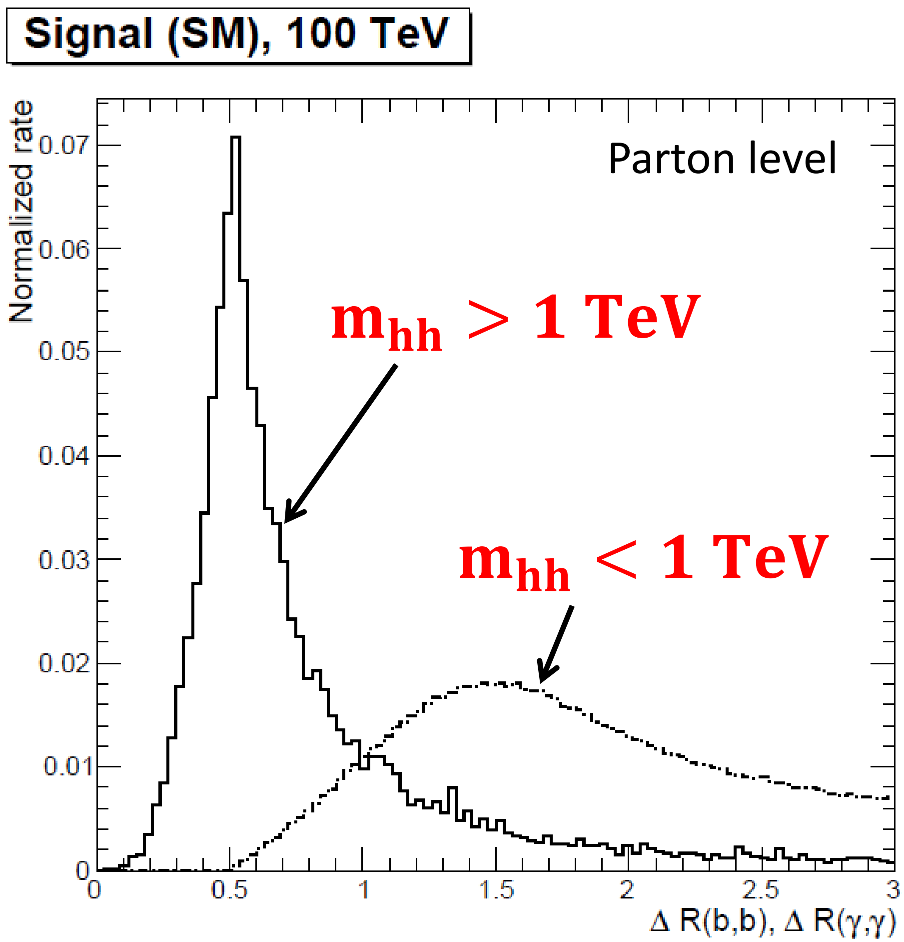


$$\sigma \geq \frac{5 \text{ Events}}{\text{BR}(hh \to X) \times \epsilon_s \times 3000\ \text{fb}^{-1}}$$

Assumed 10% signal efficiency

Channel	$b\bar{b}\tau^+\tau^-$ (7.35%)	$\gamma\gamma b\bar{b}$ (0.264%)
Cross section	> 0.227 fb	> 6.31 fb
m_{hh} [GeV]	< 1006 (3141)	< 538 (1499)
$p_T(h)$ [GeV]	< 424 (1399)	< 200 (640)

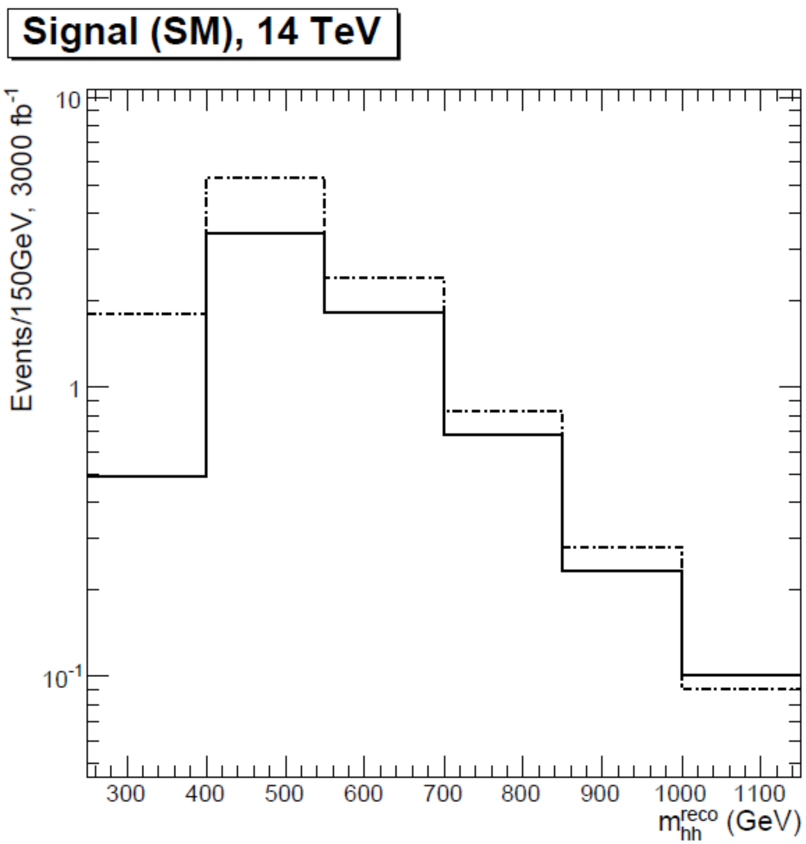
Remember this is for SM

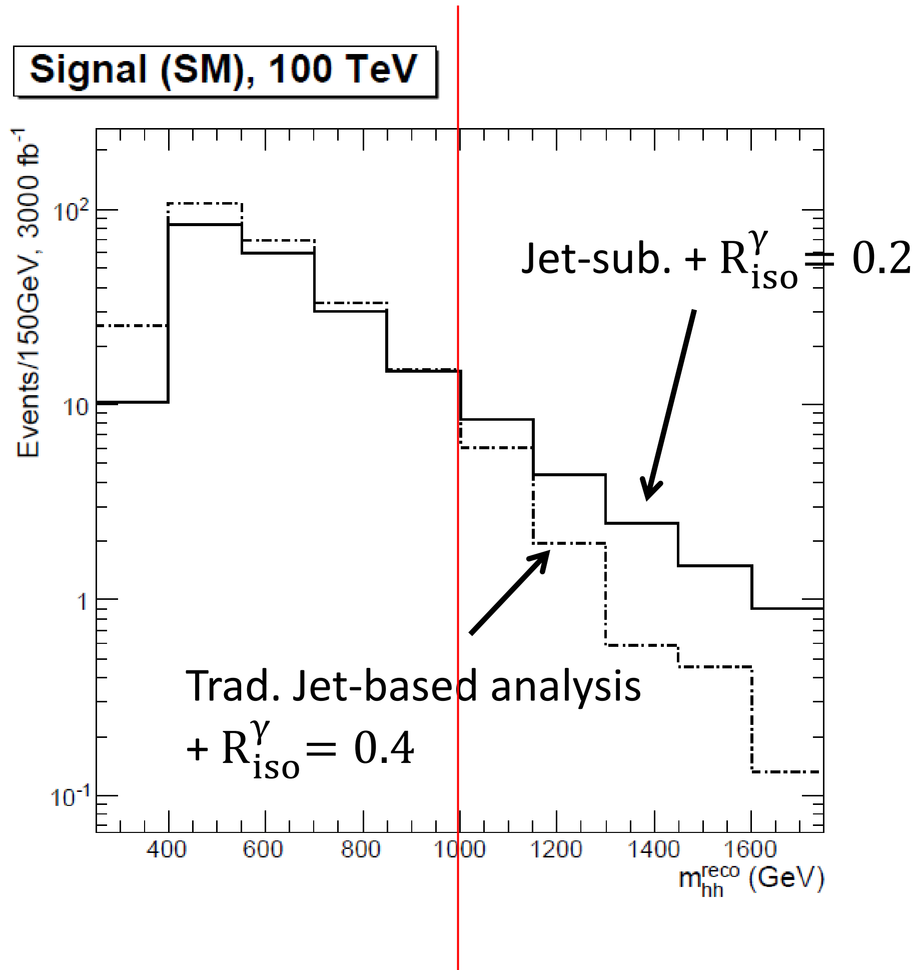


ATLAS/CMS

R_{jet} ~ 0.5/0.4

“Jet-based” vs. “jet-substructure”





Summary

Shamefully, results in this talk are still preliminary !
: see our paper for the final plots (hopefully in two weeks)

Messages from HH process

1. very challenging, but it still can compete with single Higgs fit, e.g. cubar
2. the best channel to measure the hhh coupling (but hard since it hides itself in large backgrounds)
3. very sensitive to tthh coupling etc.
4. different sensitivity of the couplings to the overall energy scale (can break degeneracy etc.)
5. can reach very high new physics scale via mHH, but it requires the modification of the analysis. E.g. Jet-sub.
6. more details in our coming paper