HH AT FUTURE COLLIDERS

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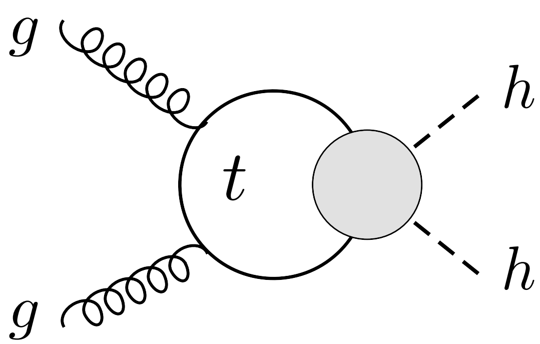
EPFL & CERN

‘Higgs Pair Production at Colliders’, Mainz, 27-30 April 2015

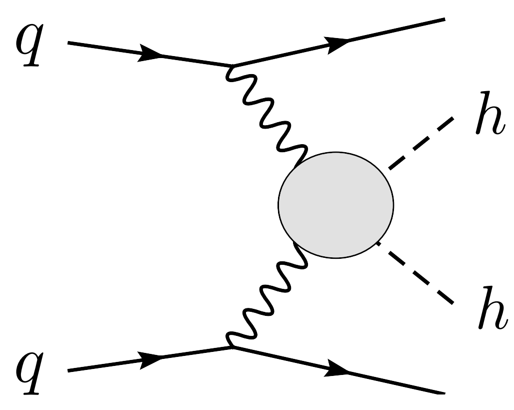
Processes for double Higgs production

pp colliders (HL-LHC, FCC-hh)

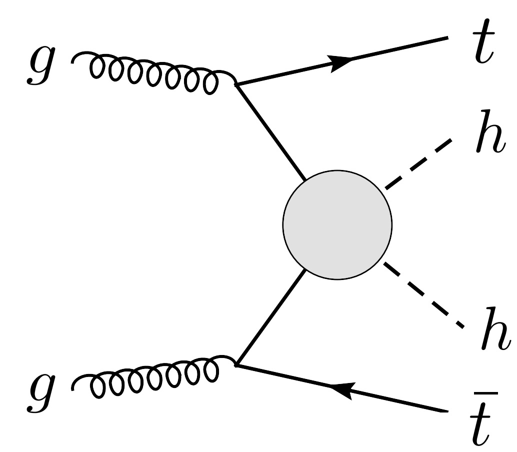
Gluon Fusion (GF)



Vector Boson Fusion (VBF)

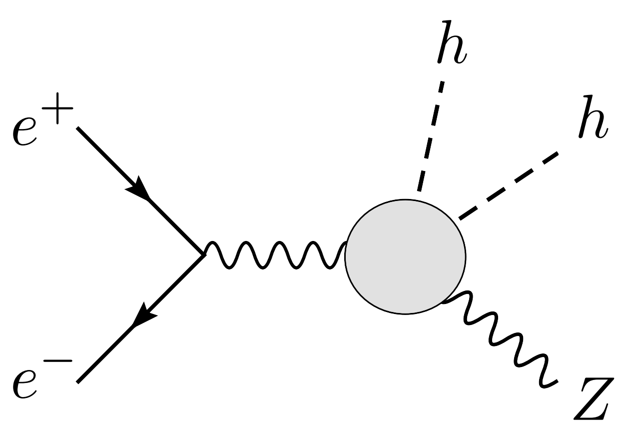


tthh associated production



e[+]e[-] colliders (ILC, FCC-ee, CLIC)

Double HiggsStrahlung (DHS)



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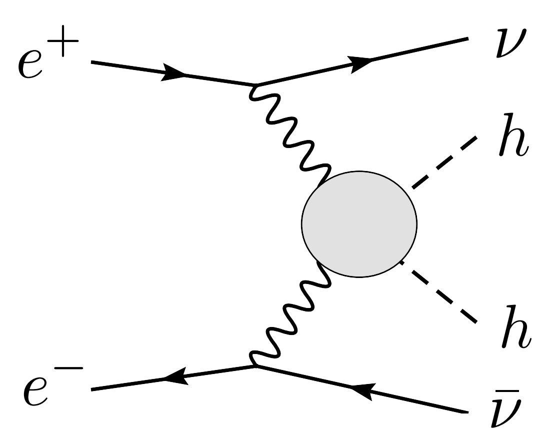
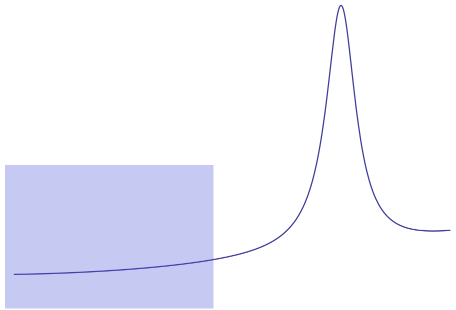


On the use of Effective Field Theory

- EFT ideal framework for low-energy machines with high precision (e^+e^-, HL-LHC)

Cannot access directly the new states → probe their tail effects with high-precision measurements



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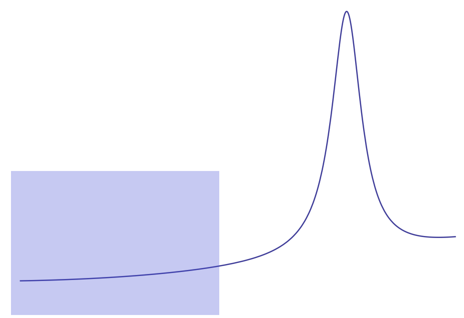

- Primary goal of a 100TeV pp collider (FCC-hh) is to open produce new states

Cannot use EFT in general, need to explicitly include the new states in the calculations

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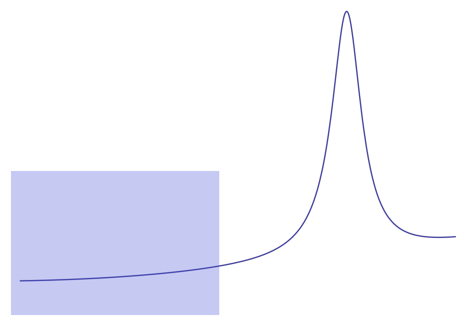

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  Cannot use EFT in general, need to explicitly include the new states in the calculations

  <u>Exception</u>: study of Higgs properties near threshold (low energy)

  ☞ EFT useful to give universal effective description of the contribution from new states in terms of a few local operators

  No need of complete and accurate knowledge of mass spectrum, couplings etc.

On the use of Effective Field Theory

- Going above threshold helps extracting the NP contribution

Effects from heavy New Physics scale like:

on-shell single production $$\frac{\delta c}{c} \sim \frac{g_*^2}{g_{SM}^2}\frac{m_h^2}{m_*^2}$$

2→2 processes $$\frac{\delta \mathcal{A}}{\mathcal{A}} \sim \frac{g_*^2}{g_{SM}^2}\frac{E^2}{m_*^2}$$

$m_* =$ scale of NP

$g_* =$ coupling strength of new states with the Higgs boson

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☞ Making use of differential distributions (exclusive analysis) is key to maximize the sensitivity on New Physics

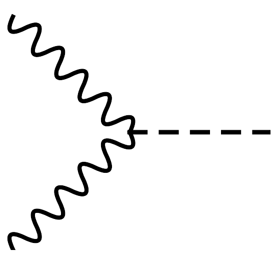
Region of interest: $$m_h \ll E \ll m_*$$

Effective Lagrangian for a Higgs doublet

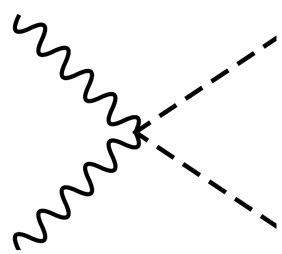
Buchmuller and Wyler NPB 268 (1986) 621
⋮
Giudice et al. JHEP 0706 (2007) 045
Grzadkowski et al. JHEP 1010 (2010) 085

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

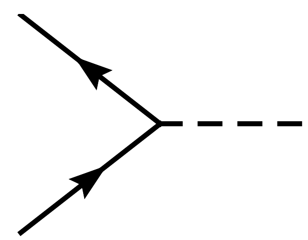
$$\supset \frac{\bar{c}_H}{2v^2}[\partial_\mu (H^\dagger H)]^2 + \frac{\bar{c}_u}{v^2} y_u \, H^\dagger H \, \bar{q}_L H^c u_R - \frac{\bar{c}_6}{v^2}\frac{m_h^2}{2v^2}(H^\dagger H)^3 + \frac{\bar{c}_g \, g_S^2}{m_W^2} \, H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$



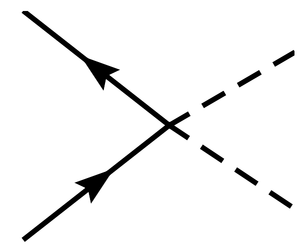
$$c_V = 1 - \frac{\bar{c}_H}{2}$$



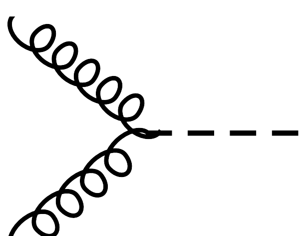
$$c_{2V} = 1 - 2\bar{c}_H$$

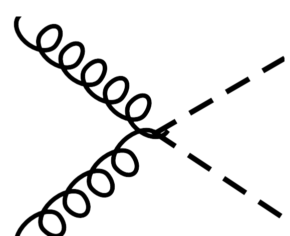


$$c_t \simeq 1 - \frac{\bar{c}_H}{2} - \bar{c}_u$$

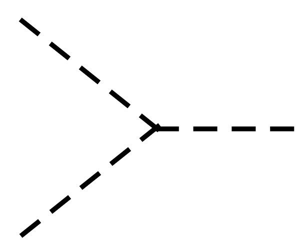


$$c_{2t} \simeq -\frac{1}{2}(\bar{c}_H + 3\bar{c}_u)$$





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



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

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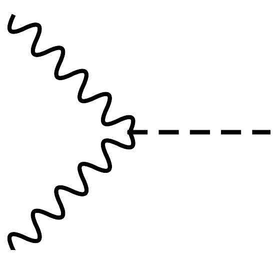
In the unitary gauge:

$$\mathcal{L} \supset \left(m_W^2 W_\mu^2 + \frac{m_Z^2}{2} Z_\mu^2 \right) \left(1 + 2 c_V \frac{h}{v} + c_{2V} \frac{h^2}{v^2} \right) - m_t \bar{t} t \left(1 + c_t \frac{h}{v} + c_{2t} \frac{h^2}{2v^2} \right)$$
$$- c_3 \frac{m_h^2}{2v} h^3 + \frac{g_s^2}{4\pi^2} \left(c_g \frac{h}{v} + c_{2g} \frac{h^2}{2v^2} \right) G_{\mu\nu}^a G^{a\,\mu\nu}$$



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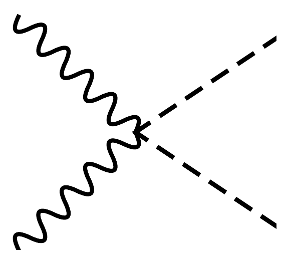

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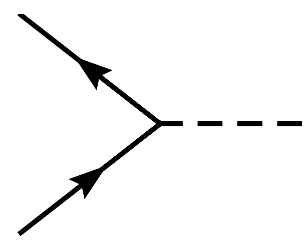

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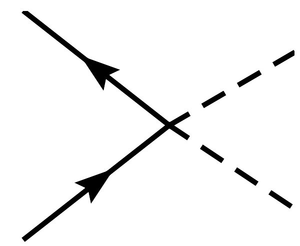

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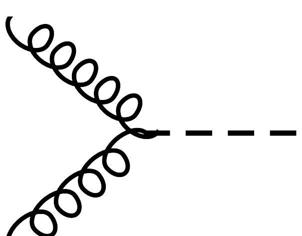

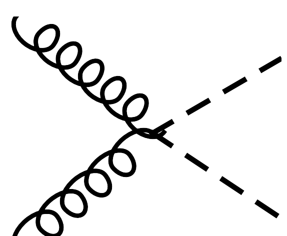

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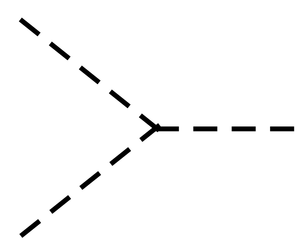


$$c_3 \simeq 1 - \frac{3}{2} \bar{c}_H + \bar{c}_6$$

HH at future Hadron Colliders

References (for FCC_{100}):

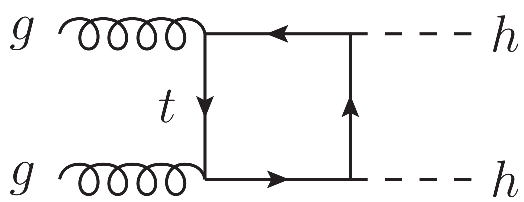
Baglio, Djouadi, Groeber, Muehlleitner, Quevillon, Spira JHEP 1304 (2013) 151
W. Yao arXiv:1308.6302 (Snowmass Summer Study 2013)
Barr, Dolan, Englert, de Lima, Spannowsky   arXiv:1412.7154
Azatov, R.C., Panico, Son   arXiv:1502.00539

Benchmark scenarios:

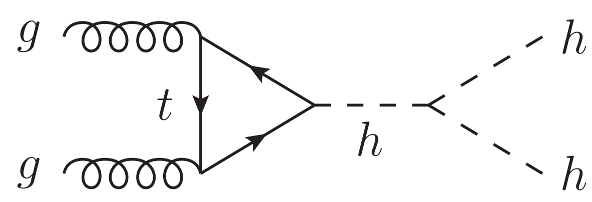
LHC_{14}:	$\sqrt{s} = 14\,\mathrm{TeV},\ L = 300\,\mathrm{fb}^{-1}$
HL-LHC:	$\sqrt{s} = 14\,\mathrm{TeV},\ L = 3\,\mathrm{ab}^{-1}$
FCC_{100}:	$\sqrt{s} = 100\,\mathrm{TeV},\ L = 3\,\mathrm{ab}^{-1}$

Double Higgs production via gluon fusion

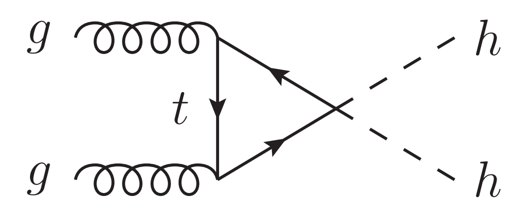
Results from: Azatov, R.C., Panico, Son arXiv:1502.00539



$$\sim c_t^2 \times const.$$



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



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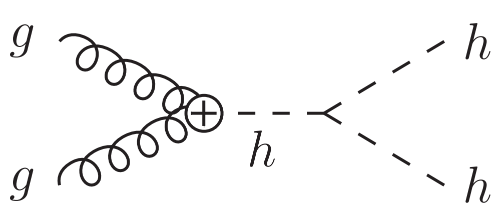
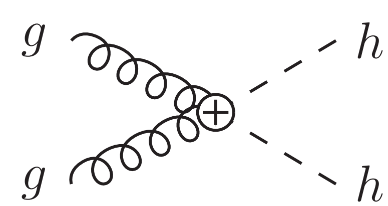


$$\sim c_g c_3 \frac{\alpha_s}{4\pi} \times const.$$



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

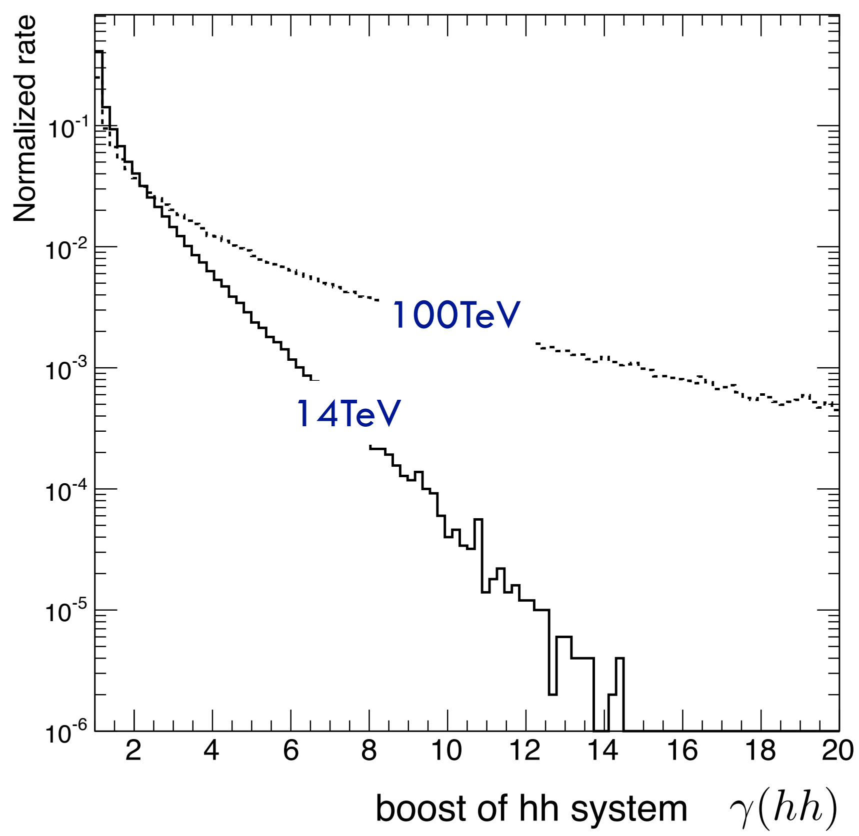
- various contributions scale differently at large $\sqrt{\hat{s}} = m_{hh}$

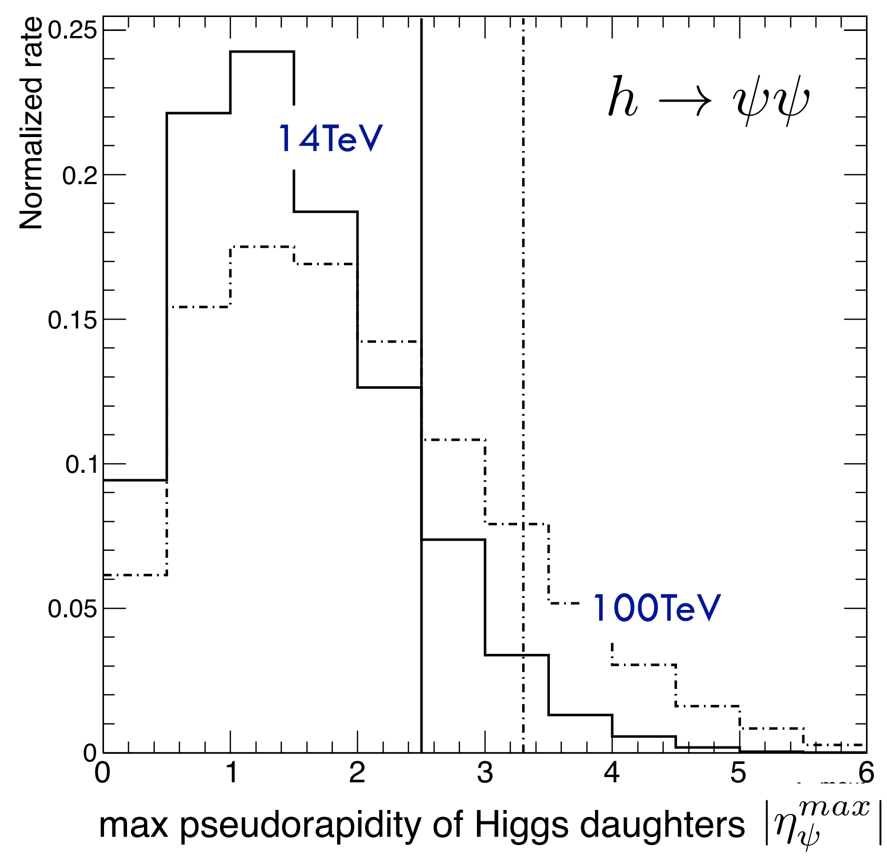
- triangle diagram with Higgs trilinear coupling *suppressed* at high energies

Kinematics of the signal

Two main differences occur when going from 14TeV to 100TeV:

1. Larger boost of the (hh) system → Higher fraction of Higgs decay products goes outside detector region





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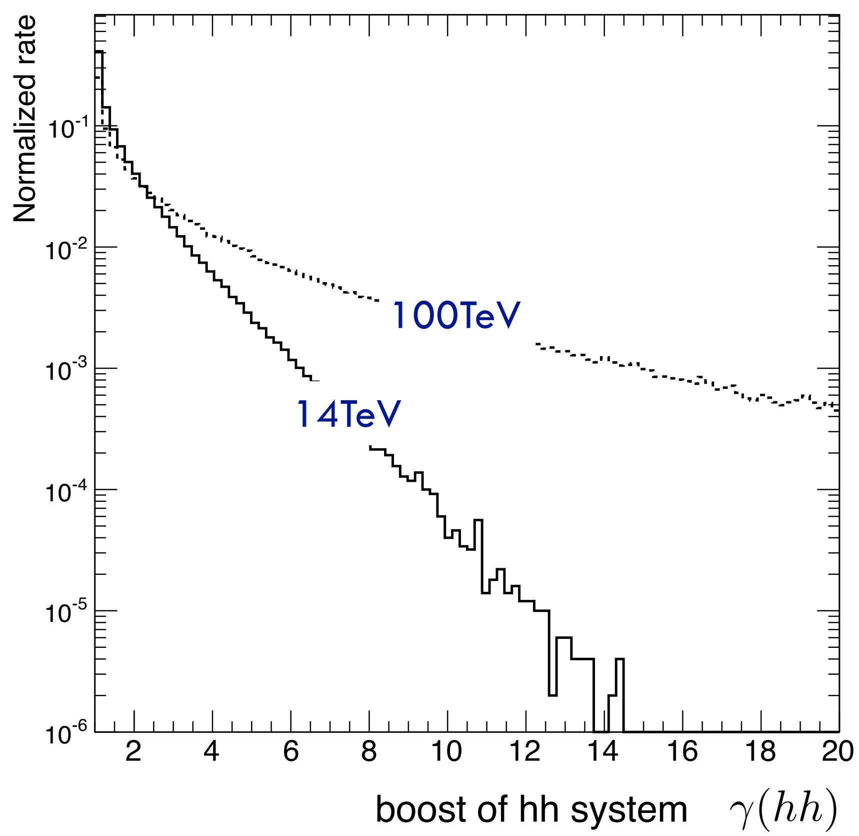

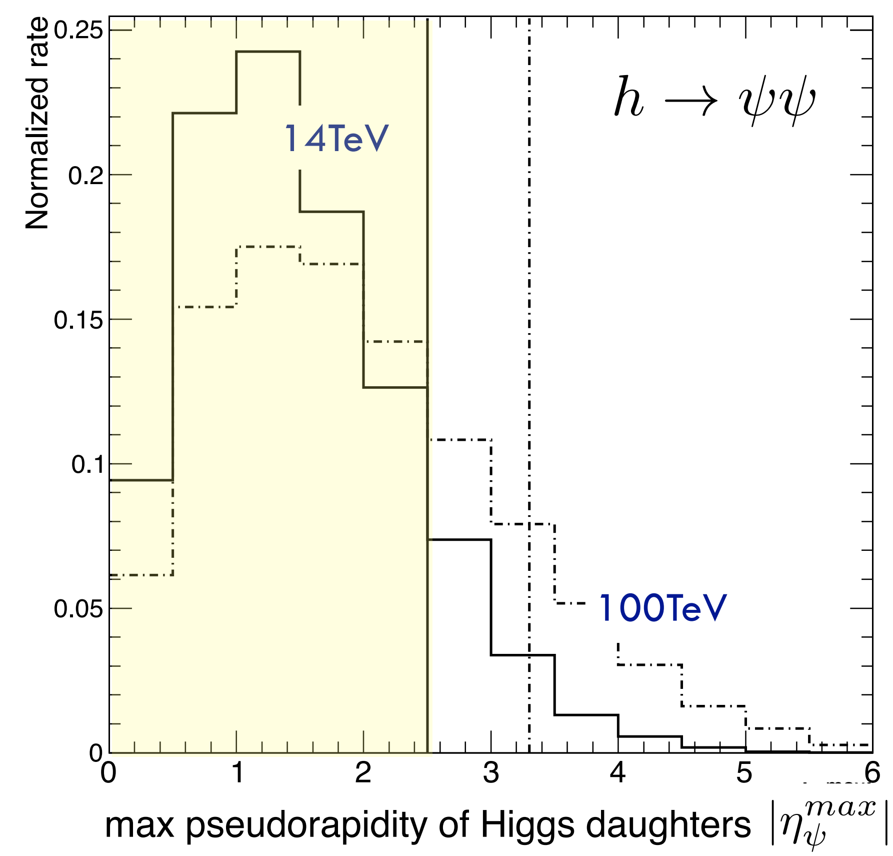

Fraction of Higgs decay products with $|\eta| > 2.5$: 13% at LHC → 30% at 100TeV

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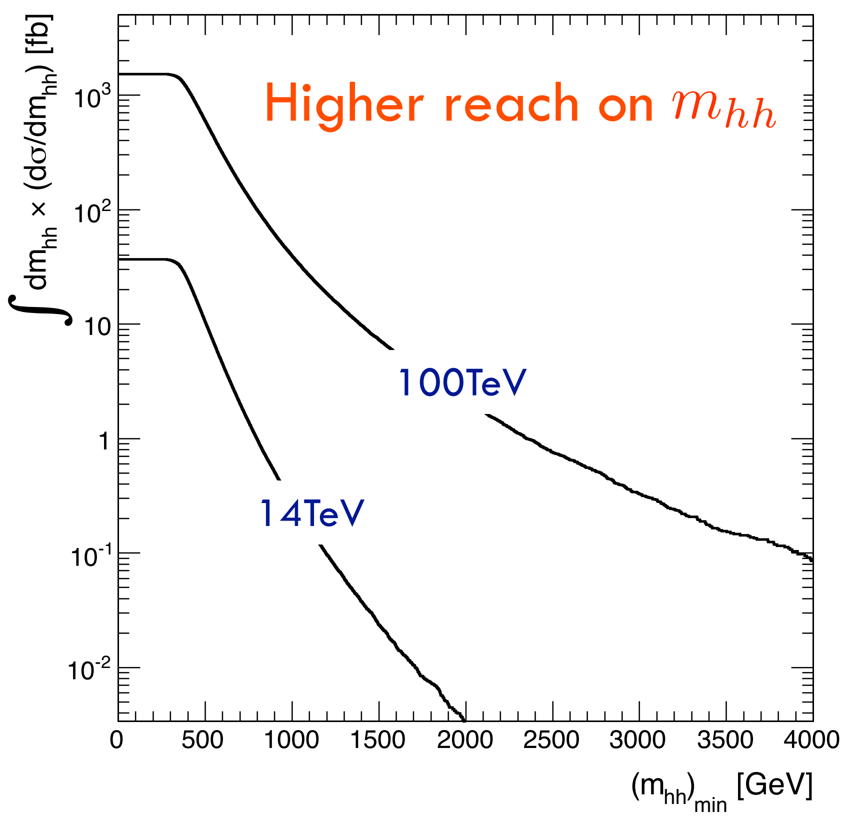
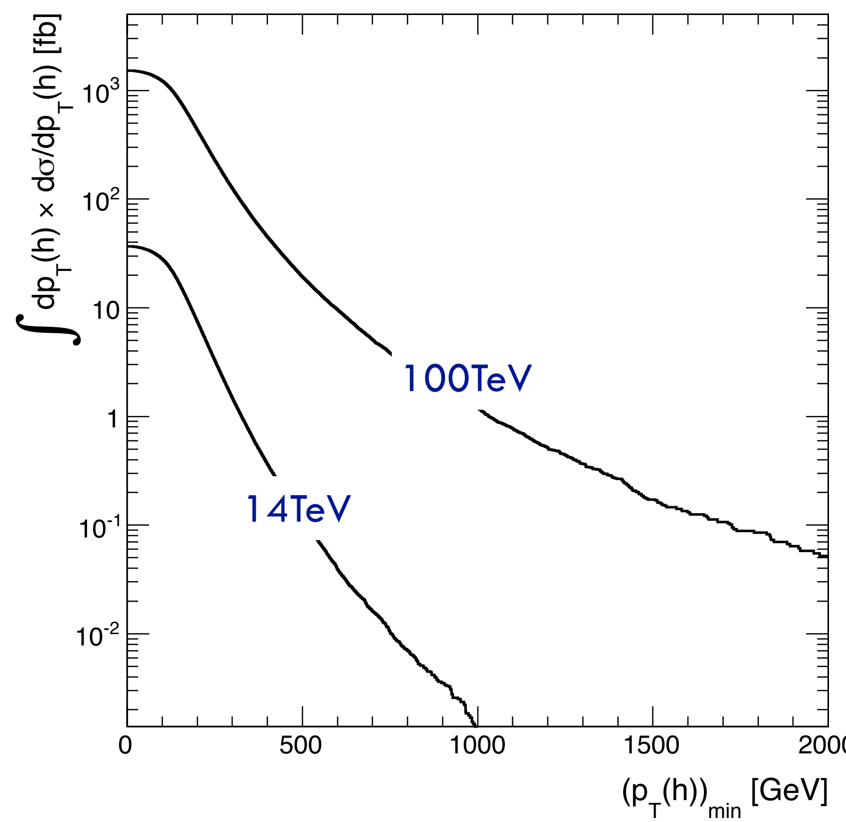
2. Larger invariant mass of the (hh) system





- requiring at least 5 events
- including 10% efficiency due to kinematic cuts

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]	< 1340 (4290)	< 1280 (4170)	< 1039 (3235)	< 558 (1552)
$p_T(h)$ [GeV]	< 575 (2000)	< 550 (1890)	< 440 (1430)	< 210 (664)

Assumed luminosity: $L = 3\,\text{ab}^{-1}$. Numbers in parenthesis are for a 100TeV collider

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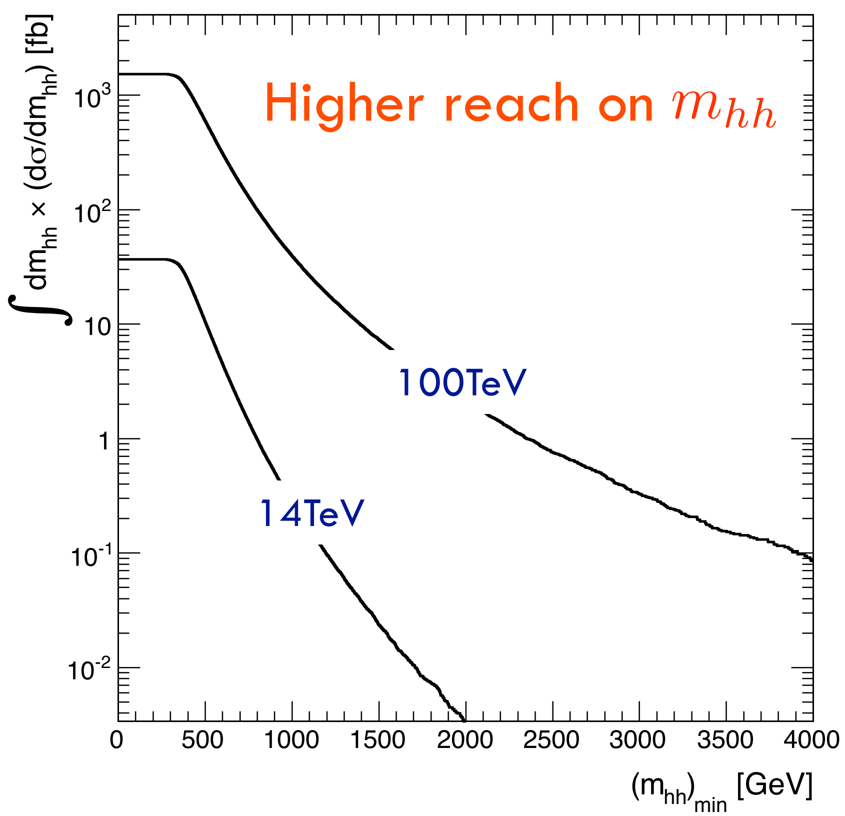

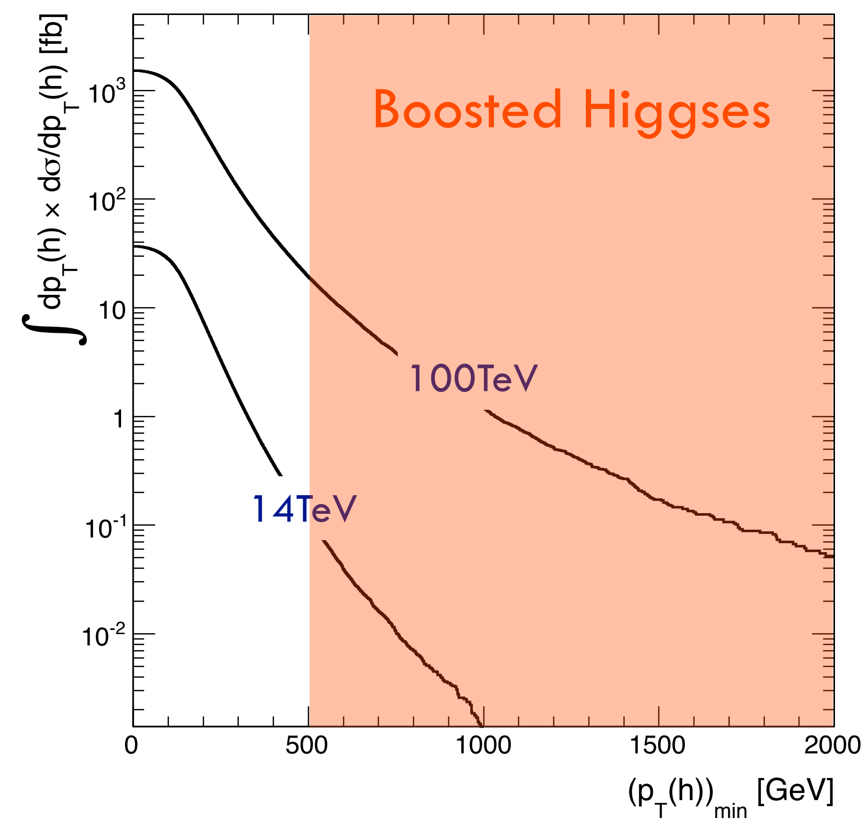

$$\Delta R \sim \frac{2m_h}{p_T(h)}$$

$\Delta R \lesssim 0.5$ for

$p_T(h) \gtrsim 500\,\mathrm{GeV}$

jet substructure techniques crucial at 100TeV

- requiring at least 5 events
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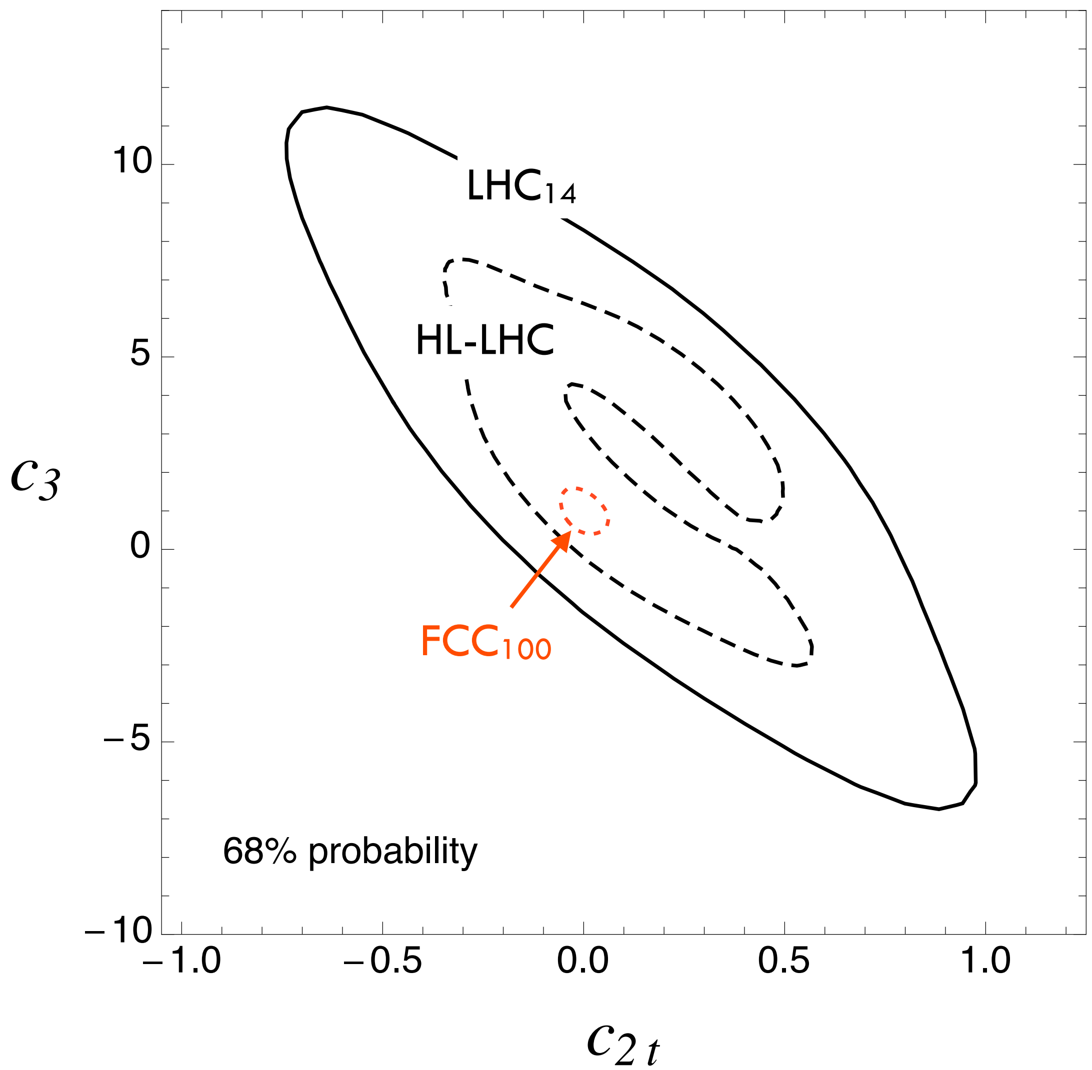
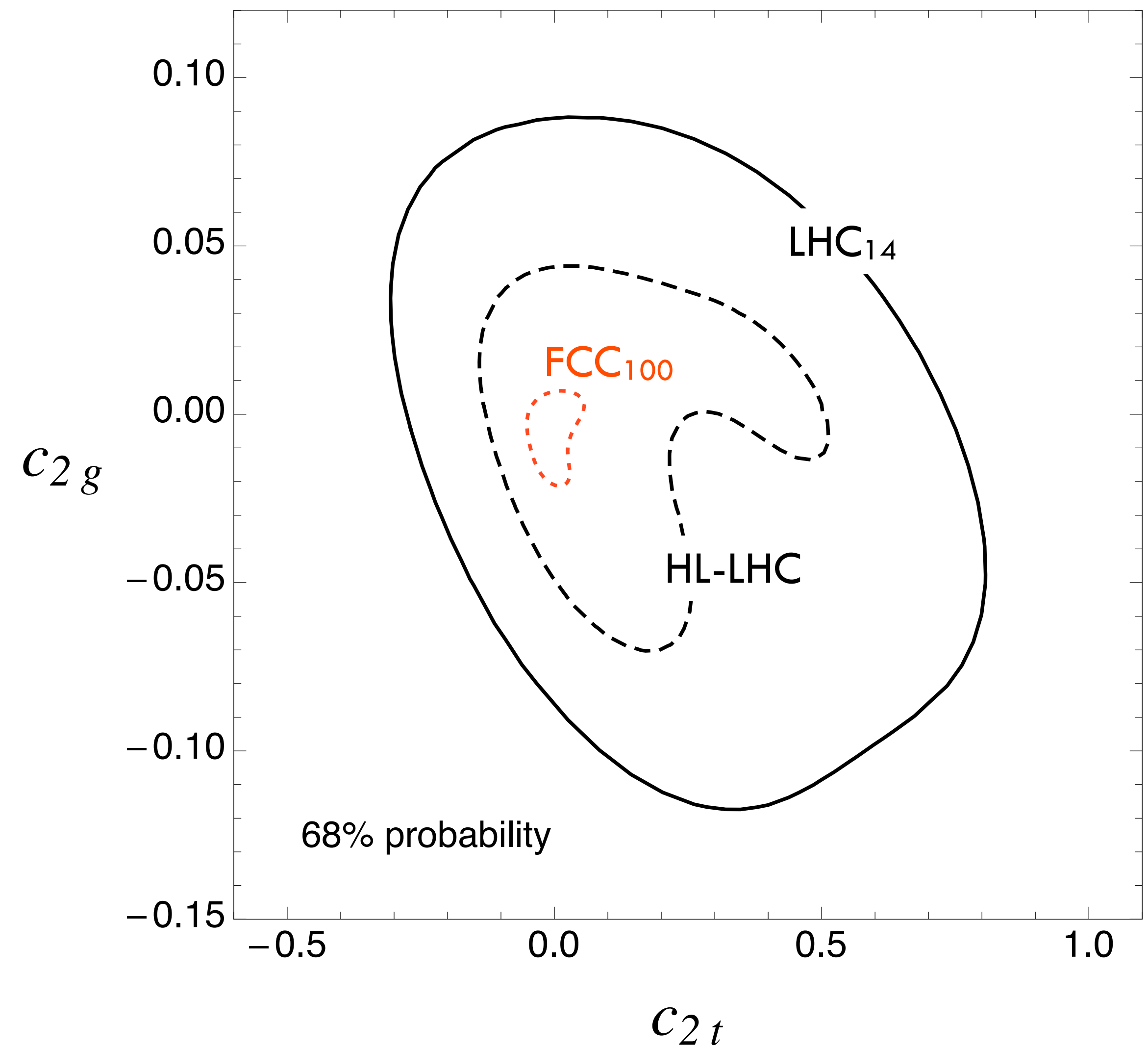
Higgs couplings from the $b\bar{b}\gamma\gamma$ channel

- Precision on couplings c_3, c_{2t}, c_{2g} (accessible only through double-Higgs production)





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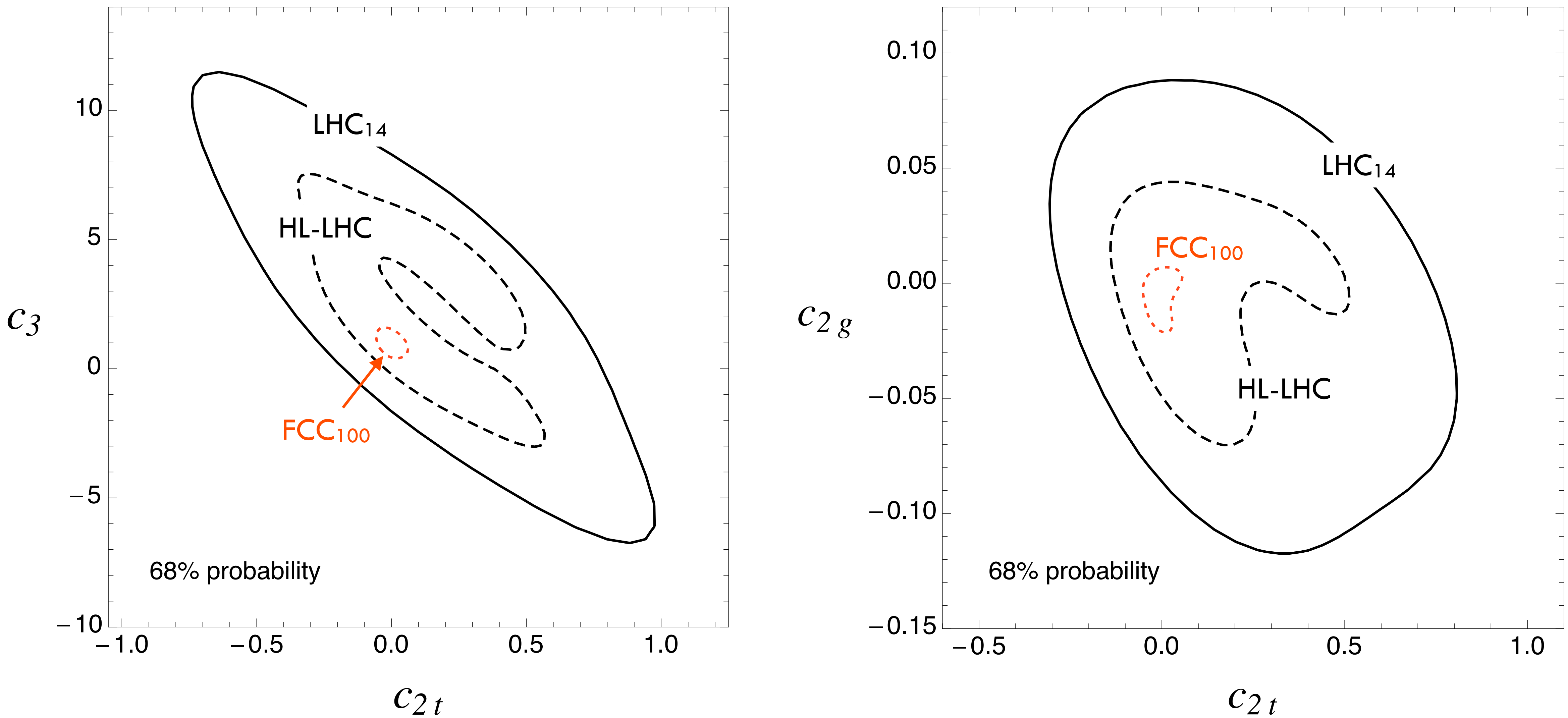

- Huge improvement of the precision on the Higgs trilinear c_3 at 100TeV
- Much better precision on c_{2t}, c_{2g}

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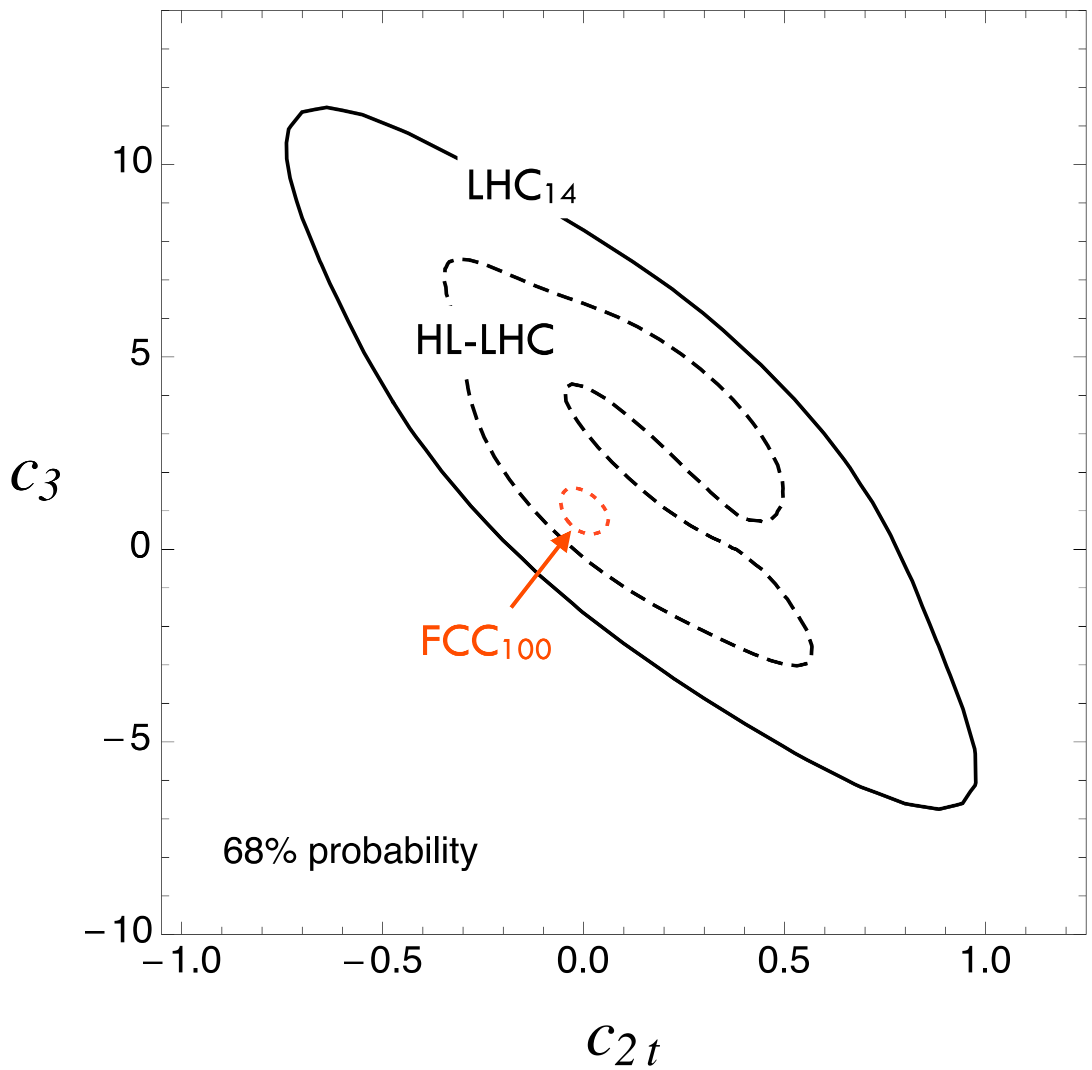
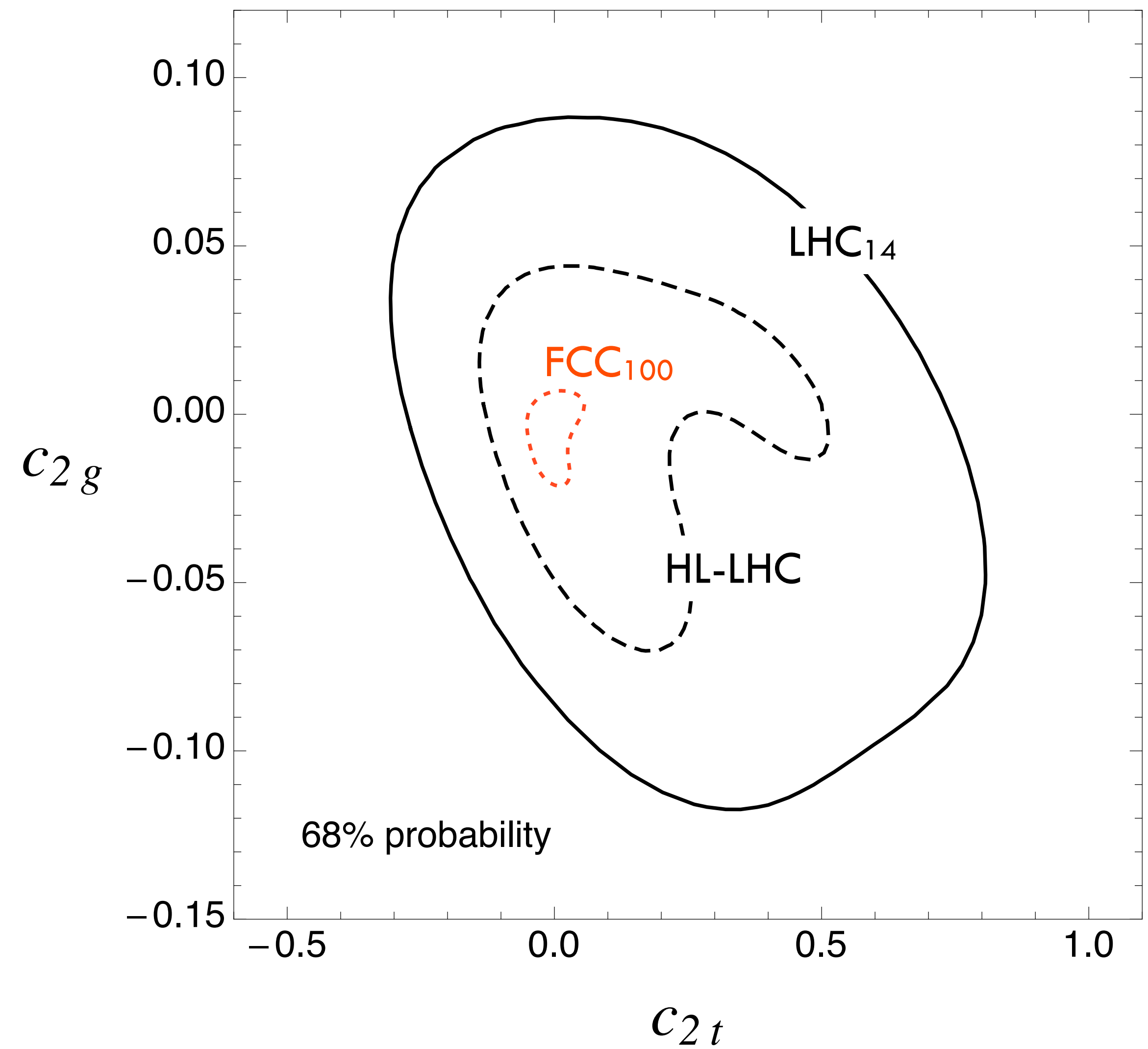
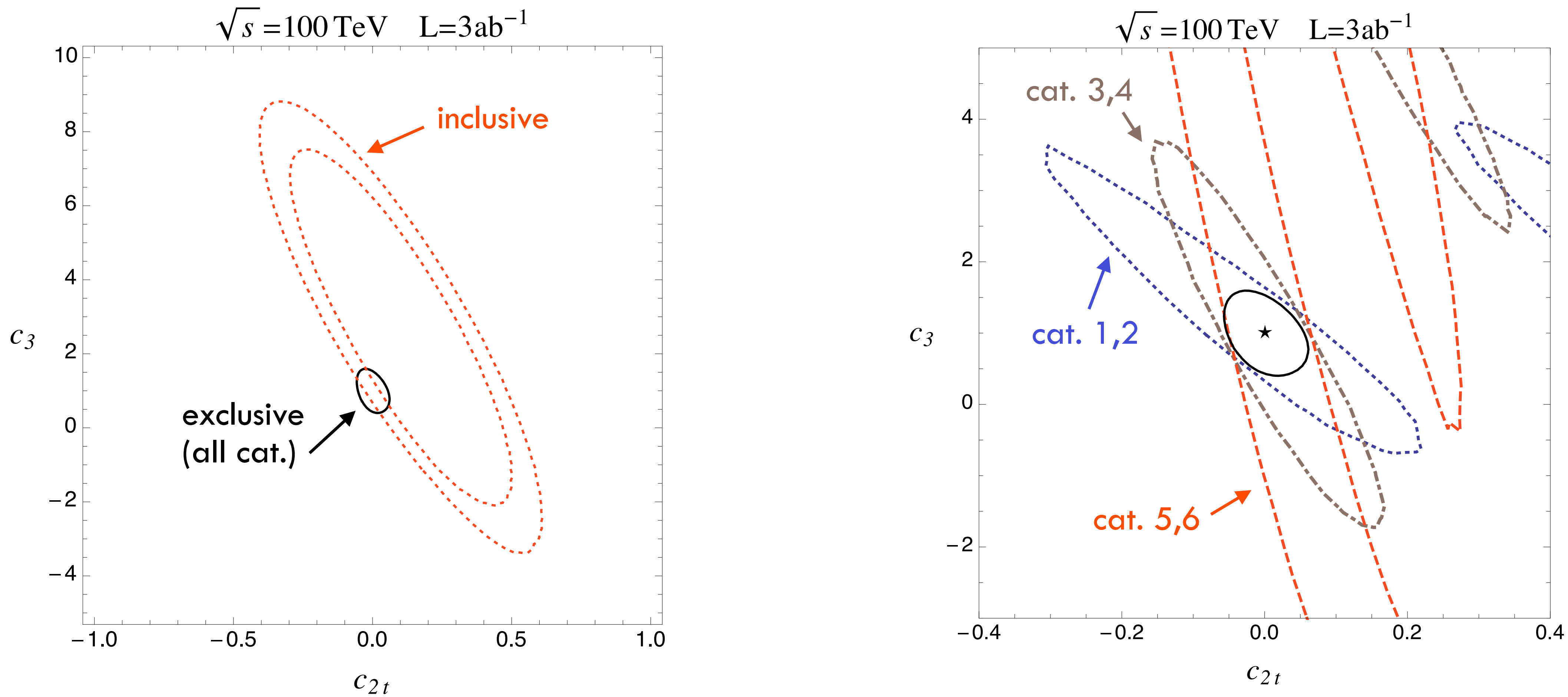




Naive (SILH) estimates: $(c_3 - 1),\ c_{2t} \sim \frac{v^2}{f^2}$ $\quad c_{2g} \sim \frac{v^2}{f^2} \times \frac{\lambda^2}{g_*^2}$ $\quad f \equiv \frac{m_*}{g_*}$

- Exclusive vs inclusive analysis (with traditional jet reconstruction)

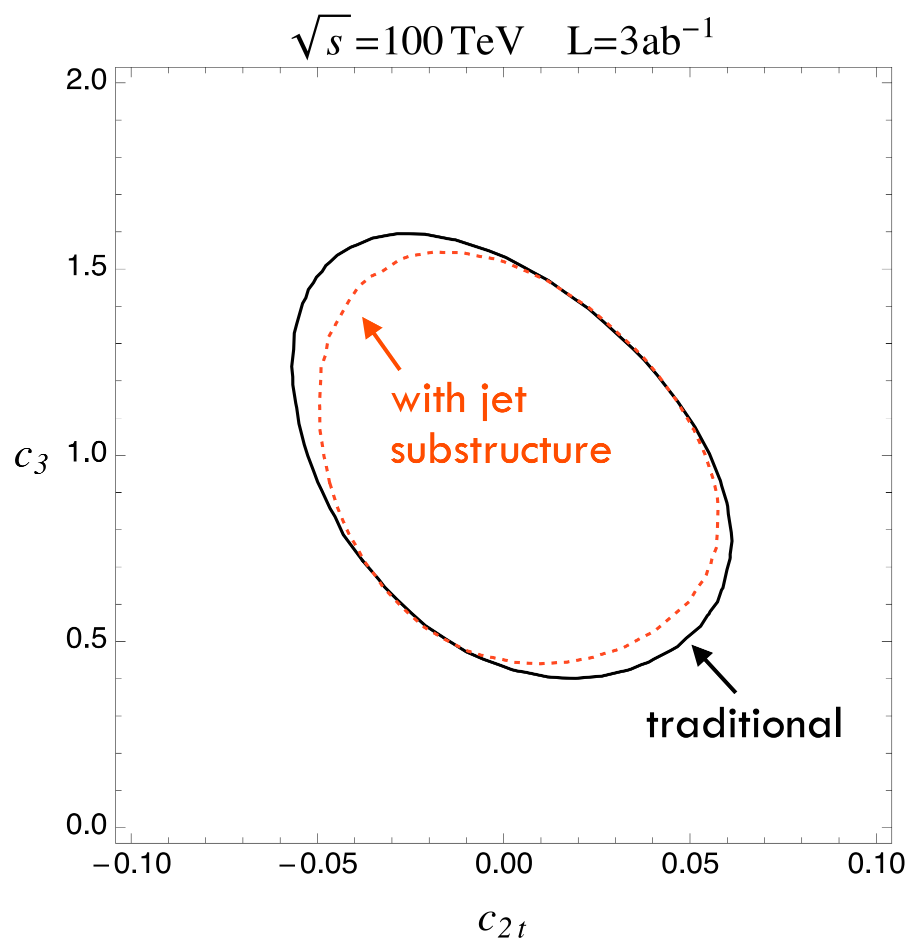


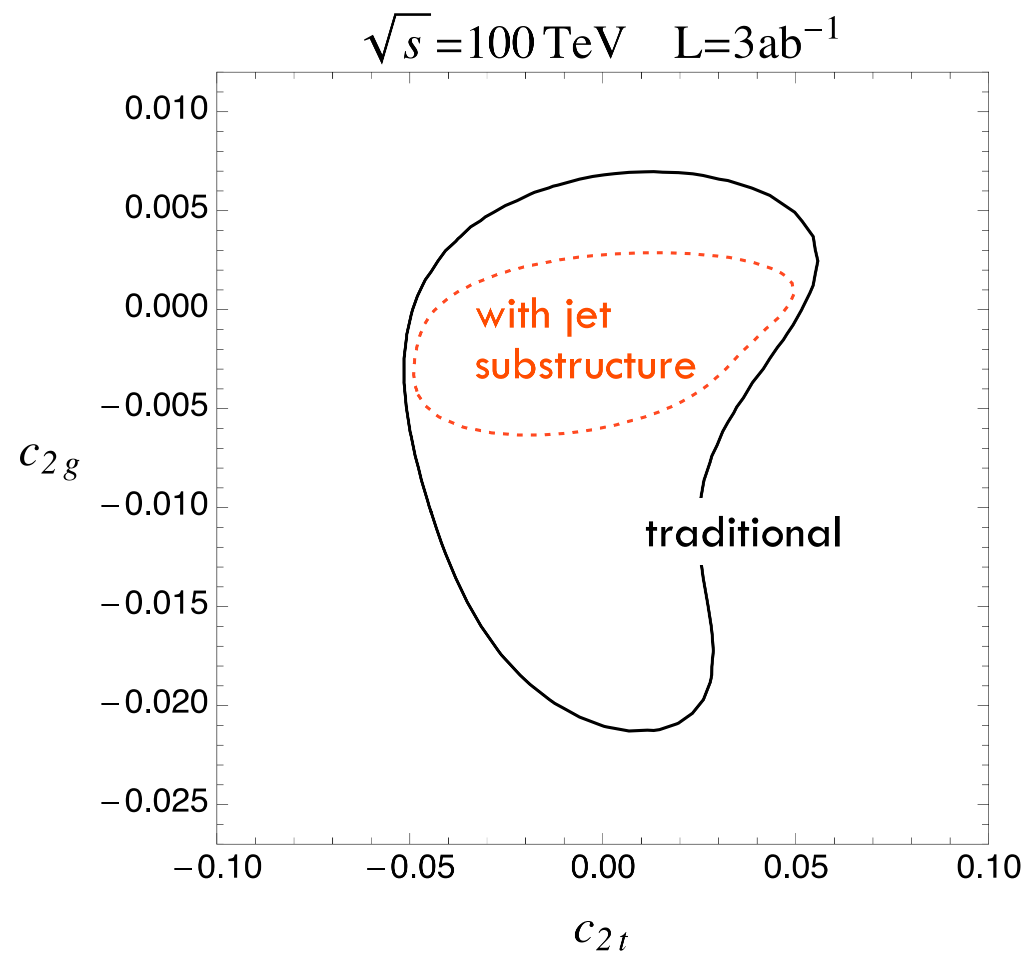
category	1	2	3	4	5	6
$m_{hh}^{\rm reco}$ [GeV]	250 – 400	400 – 550	550 – 700	700 – 850	850 – 1000	1000–

Exclusive analysis is crucial at 100TeV

Notice: even setting $c_{2t} = 0$ exclusive analysis required to remove degenerate solution for c_3

- Improvement from jet substructure

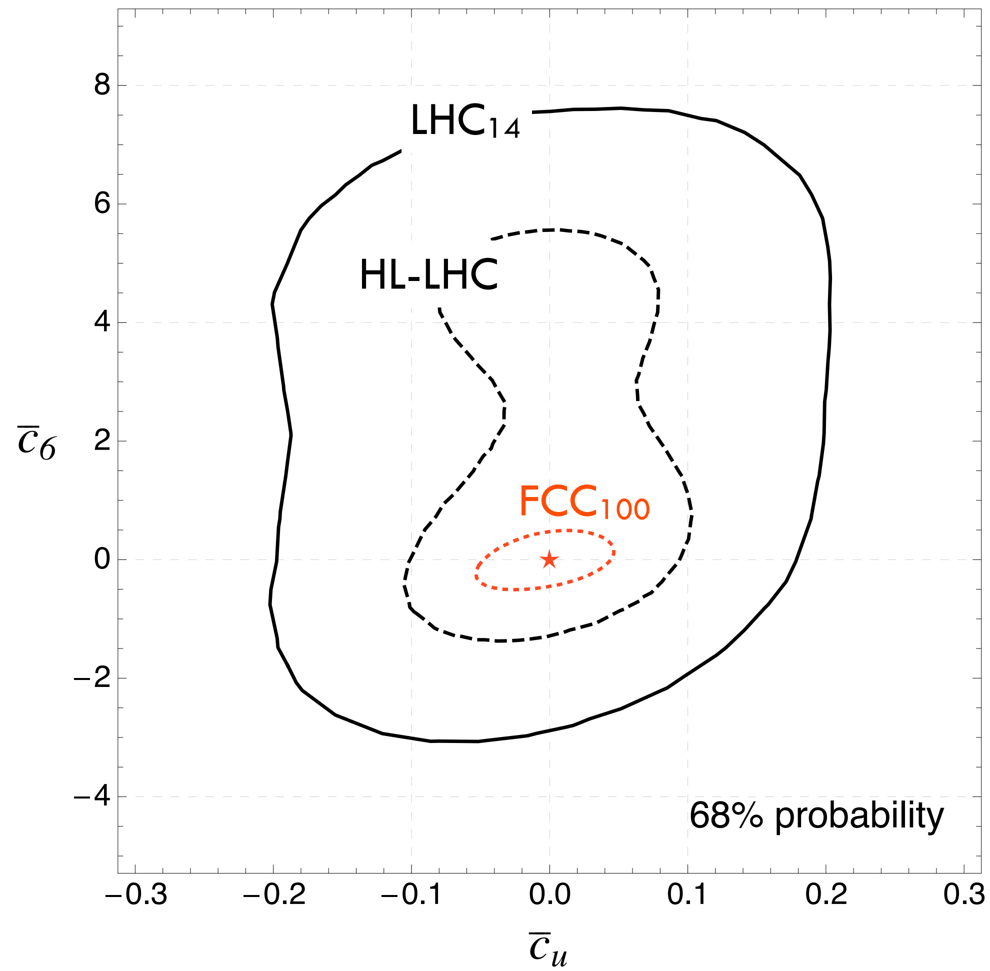


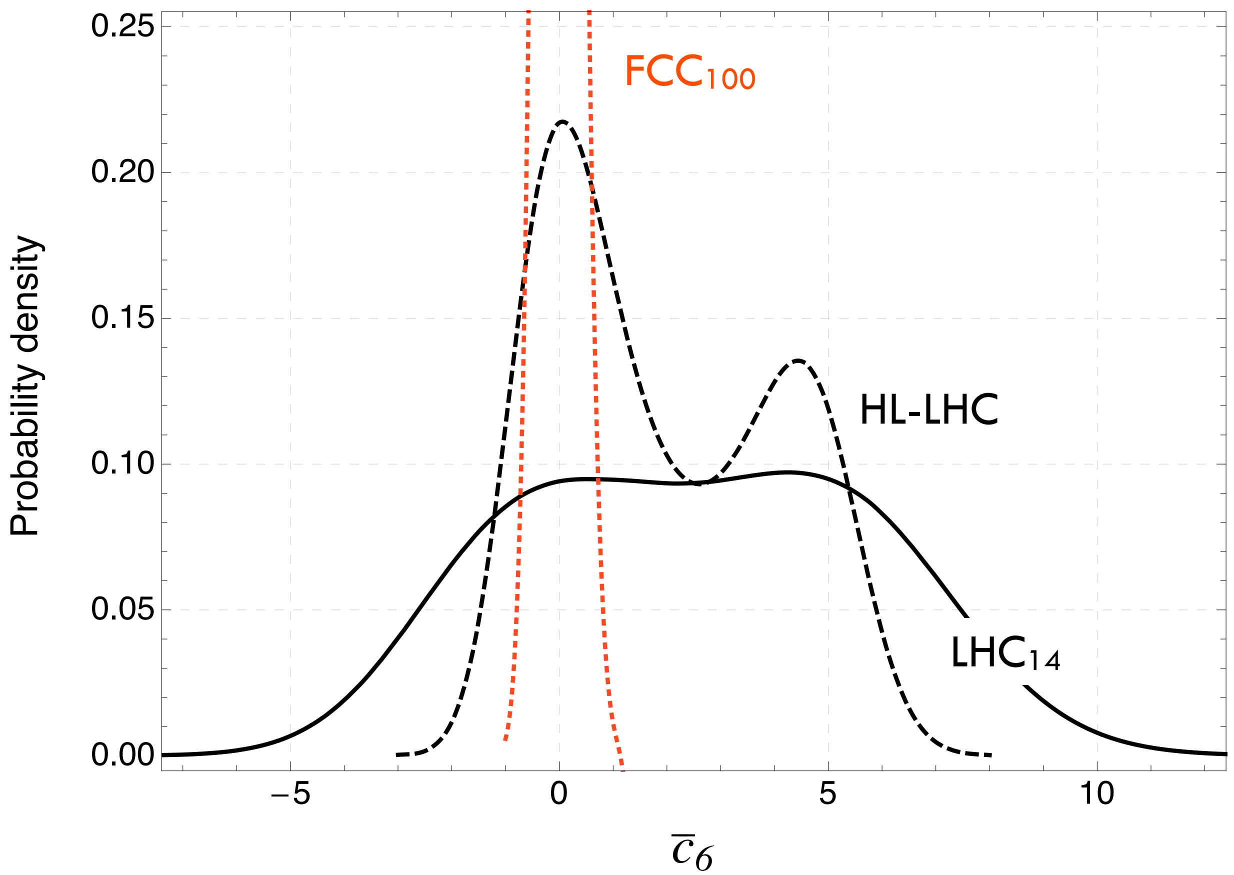


category	$m_{hh}^{\rm reco}$ [TeV]	
	Traditional	Boosted
1	0.25 – 0.40	1.0 – 1.2
2	0.40 – 0.55	1.2 – 1.4
3	0.55 – 0.70	1.4 – 1.6
4	0.70 – 0.85	1.6 – 1.8
5	0.85 – 1.00	1.8 –

Jet substructure key to extract c_{2g} but not crucial to determine c_3 and c_{2t}

- Constraining dim-6 operators: $\bar{c}_u$ vs $\bar{c}_6$ $(\bar{c}_6 = c_3 - 1)$





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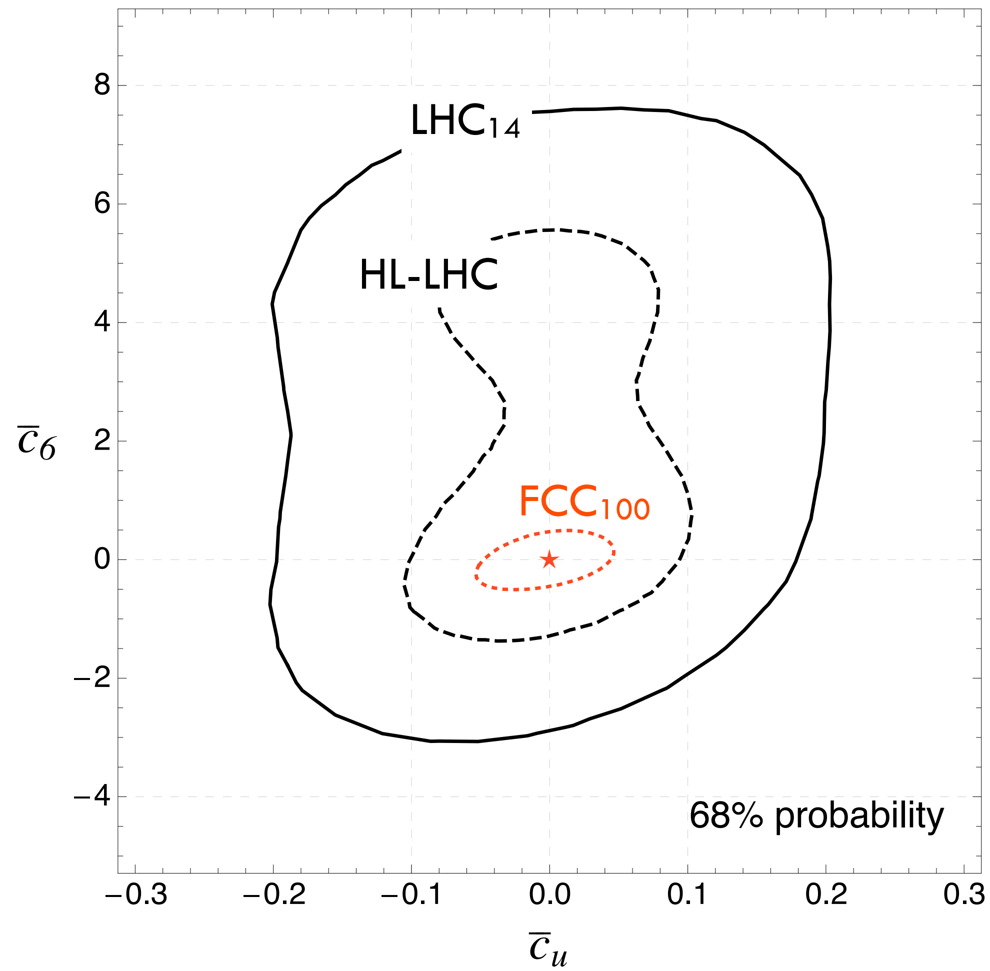

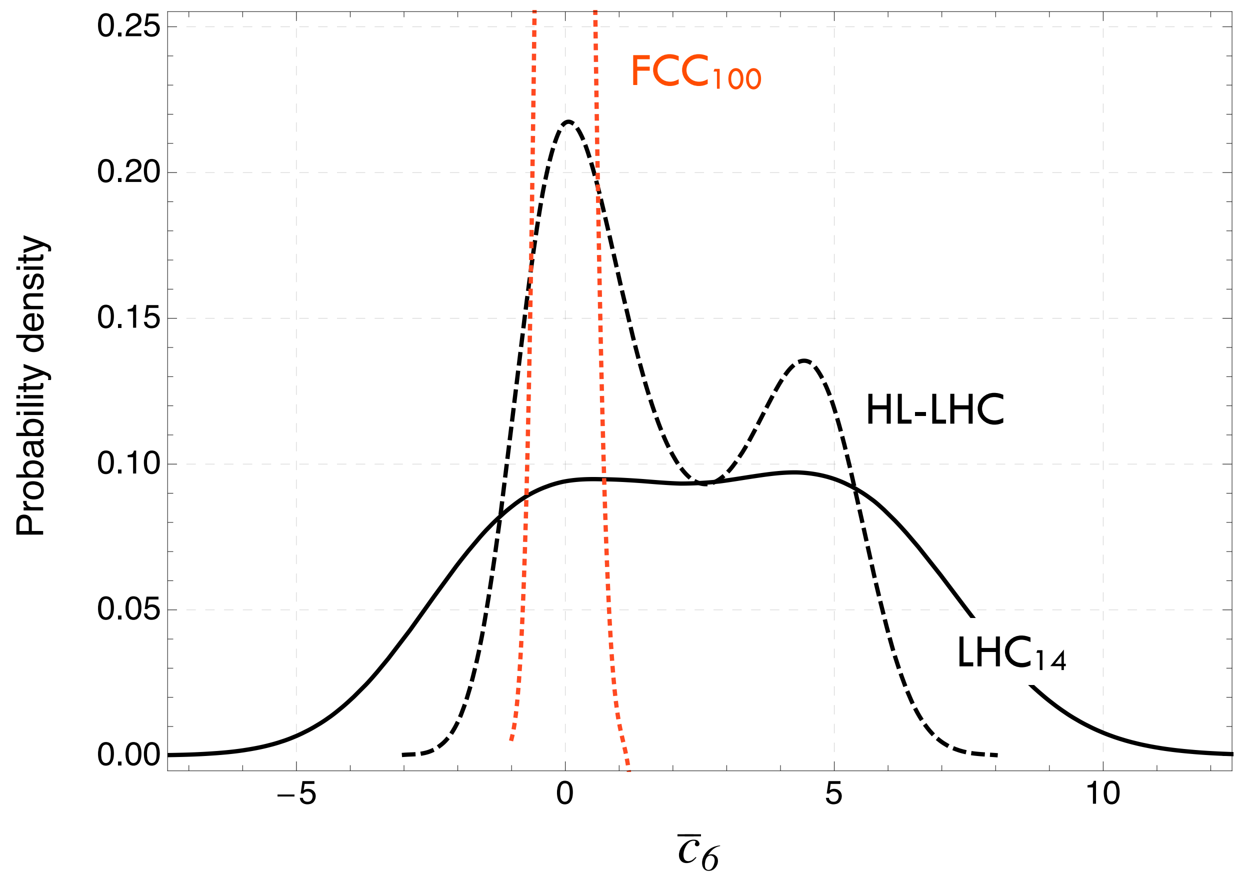

68% probability intervals on $\bar{c}_6$:

(obtained by marginalizing over the other parameters)

LHC_{14}	HL-LHC	FCC_{100}
$[-1.2, 6.1]$	$[-1.0, 1.8] \cup [3.5, 5.1]$	$[-0.33, 0.29]$

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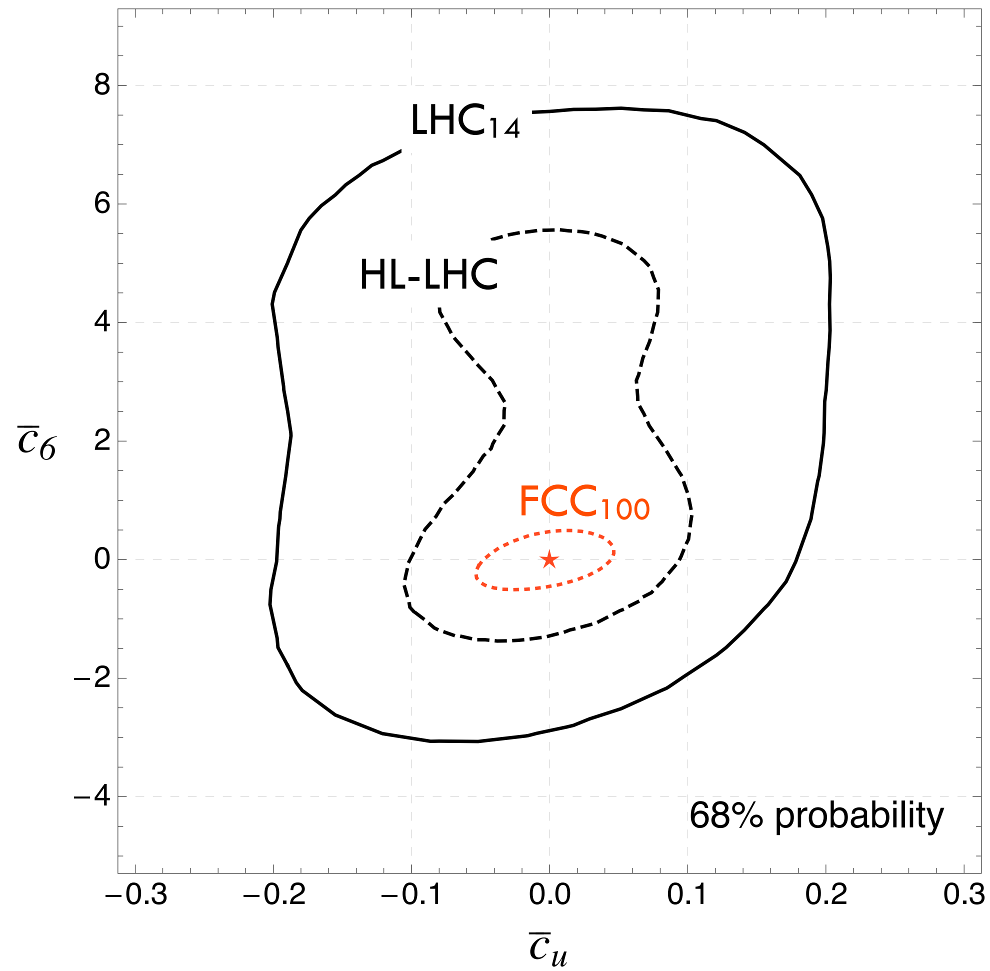

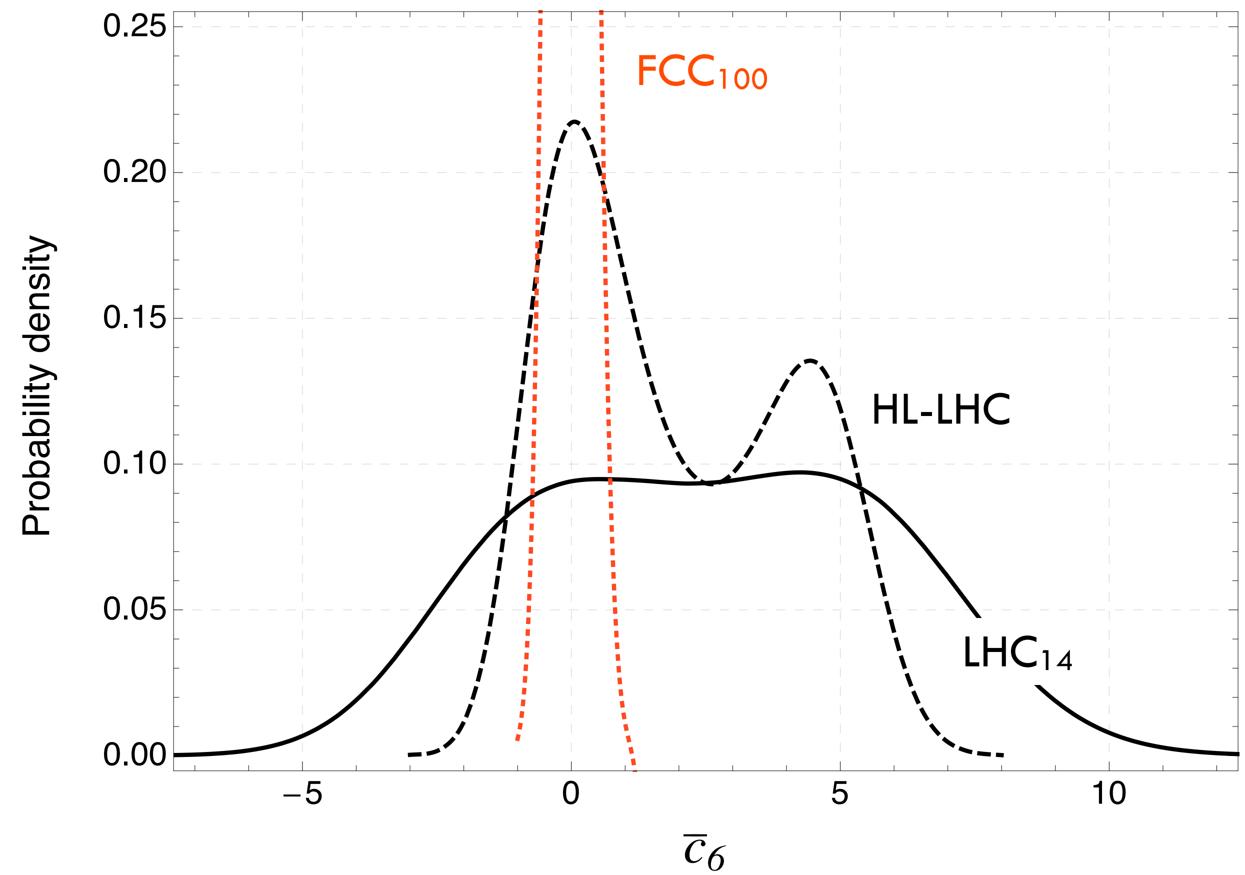

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second solution

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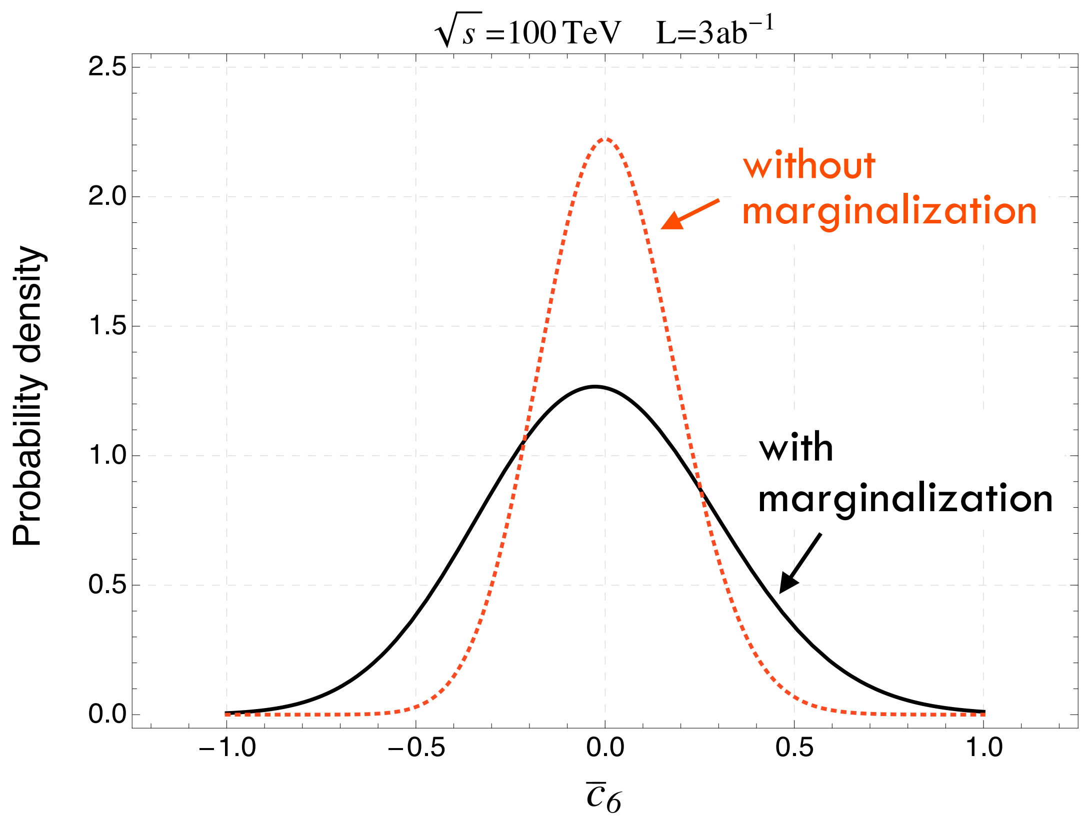

Marginalization over $\bar{c}_H, \bar{c}_u, \bar{c}_d, \bar{c}_g$ has significant impact on the precision on $\bar{c}_6$

	with marginalization	without marginalization
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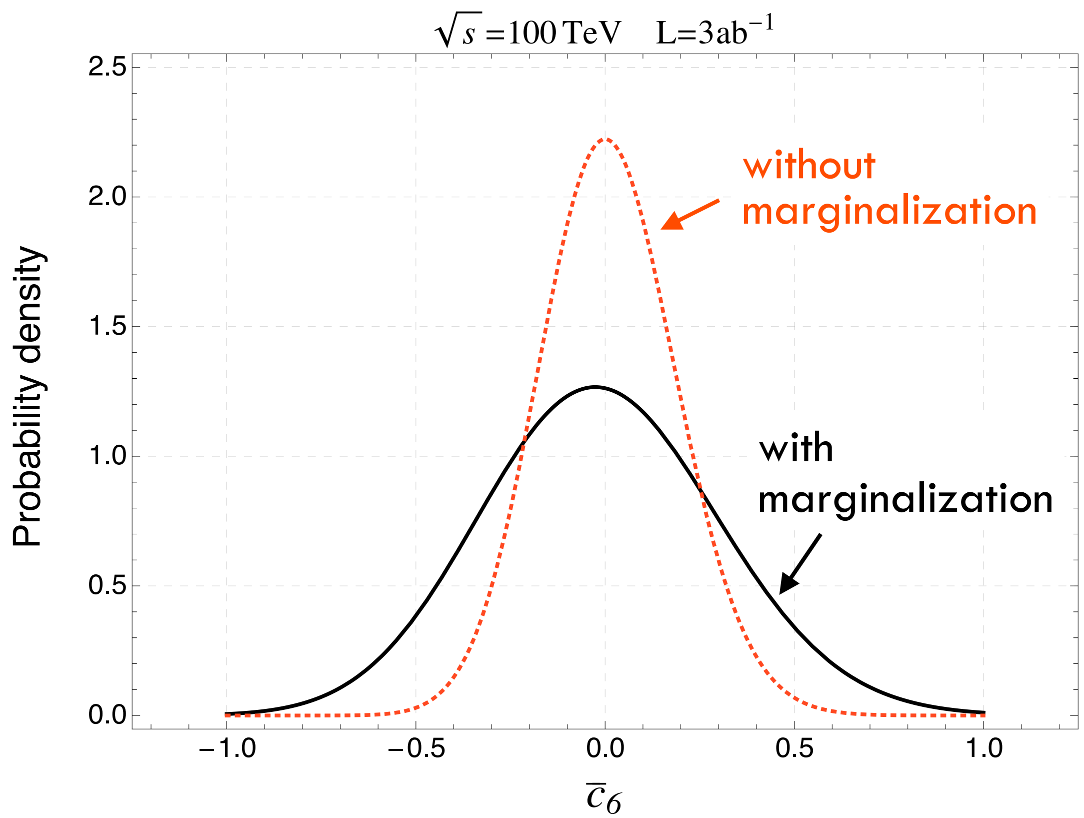

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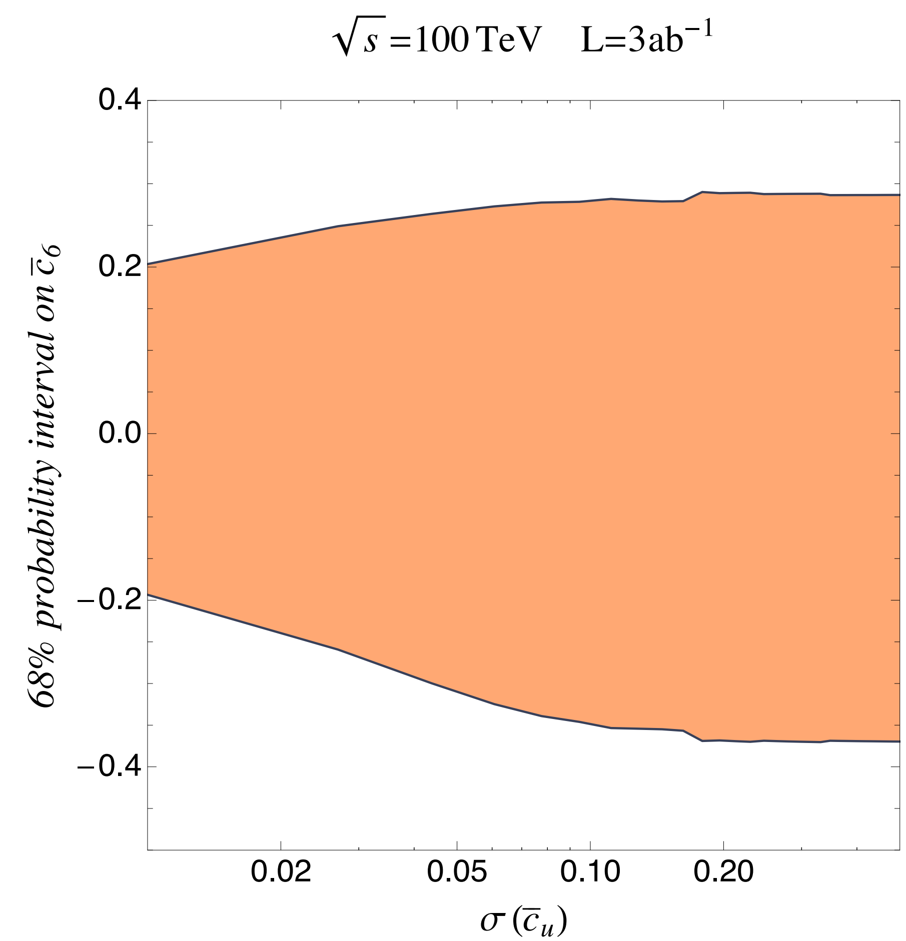

Notice: for a Higgs doublet the uncertainty on the top Yukawa coupling (ttH) reflects on an uncertainty on ttHH

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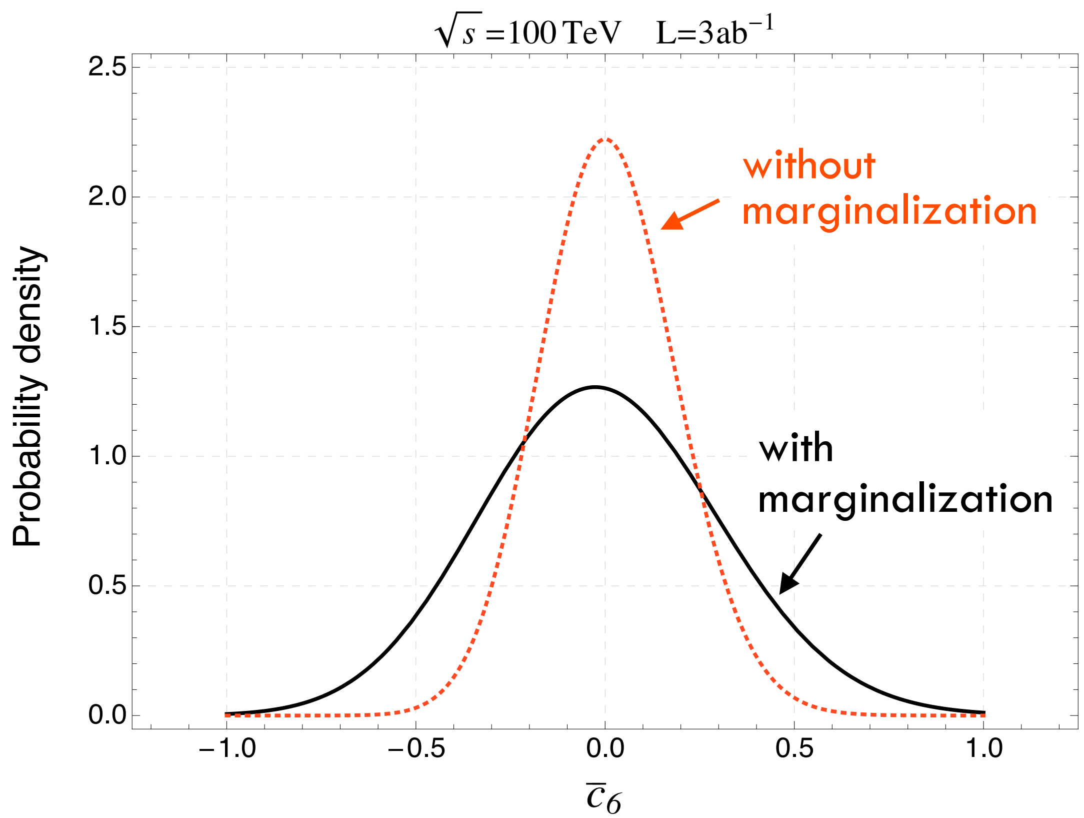

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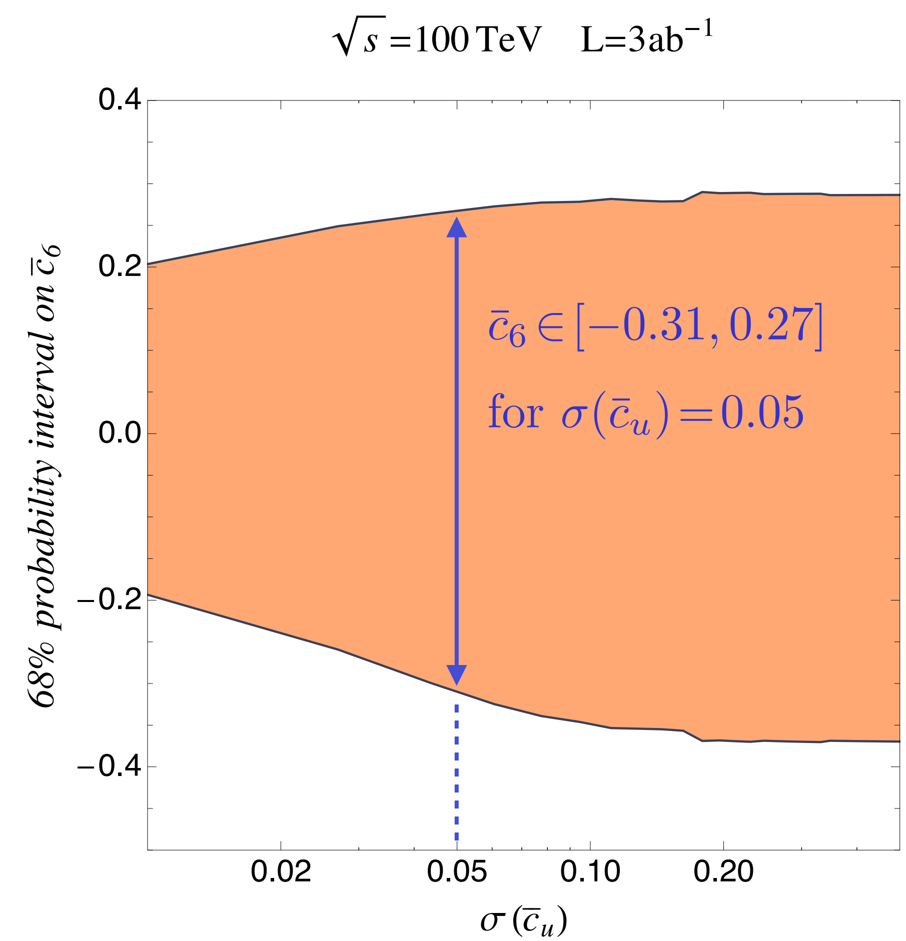

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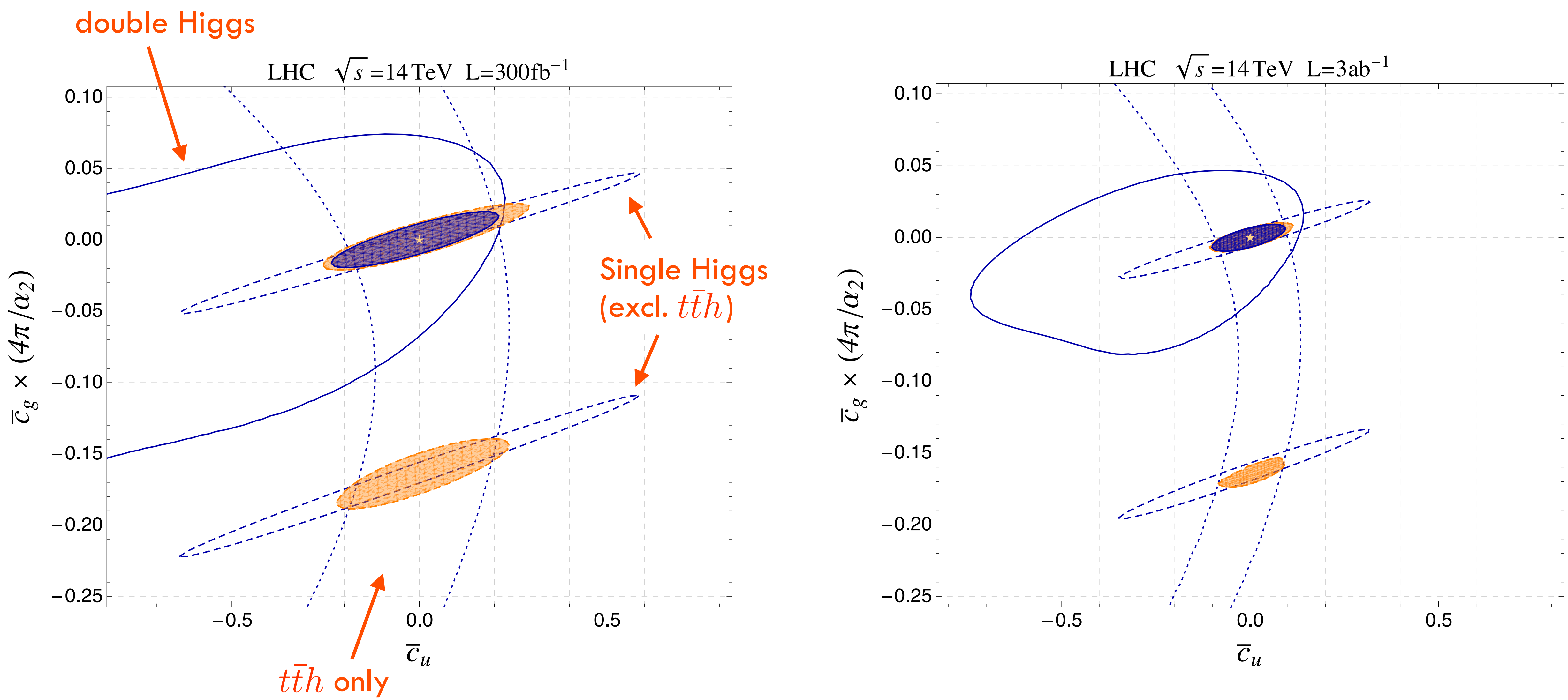

Orange region:
single Higgs incl. $t\bar{t}h$

Blue region:
single+double Higgs

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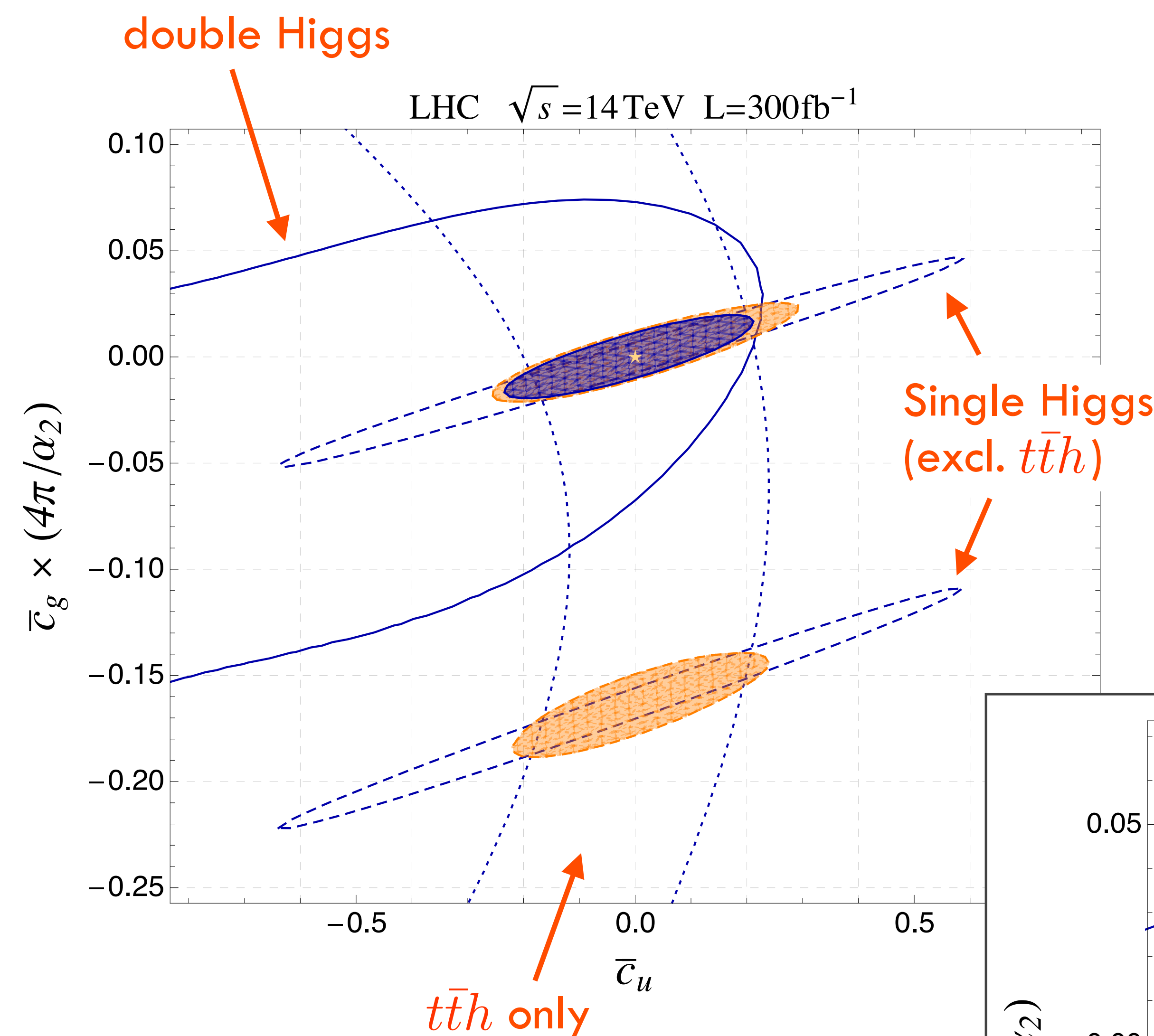

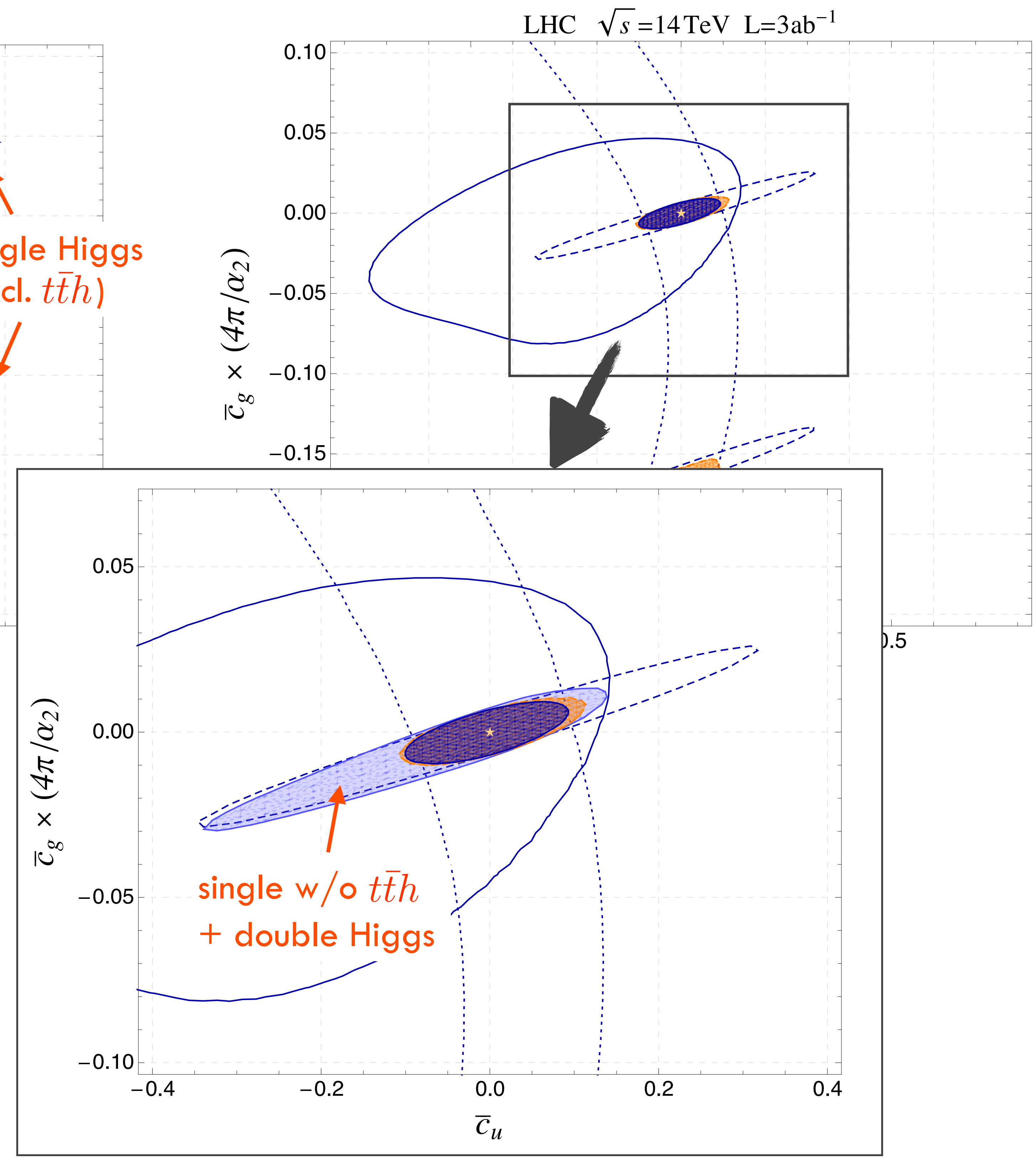

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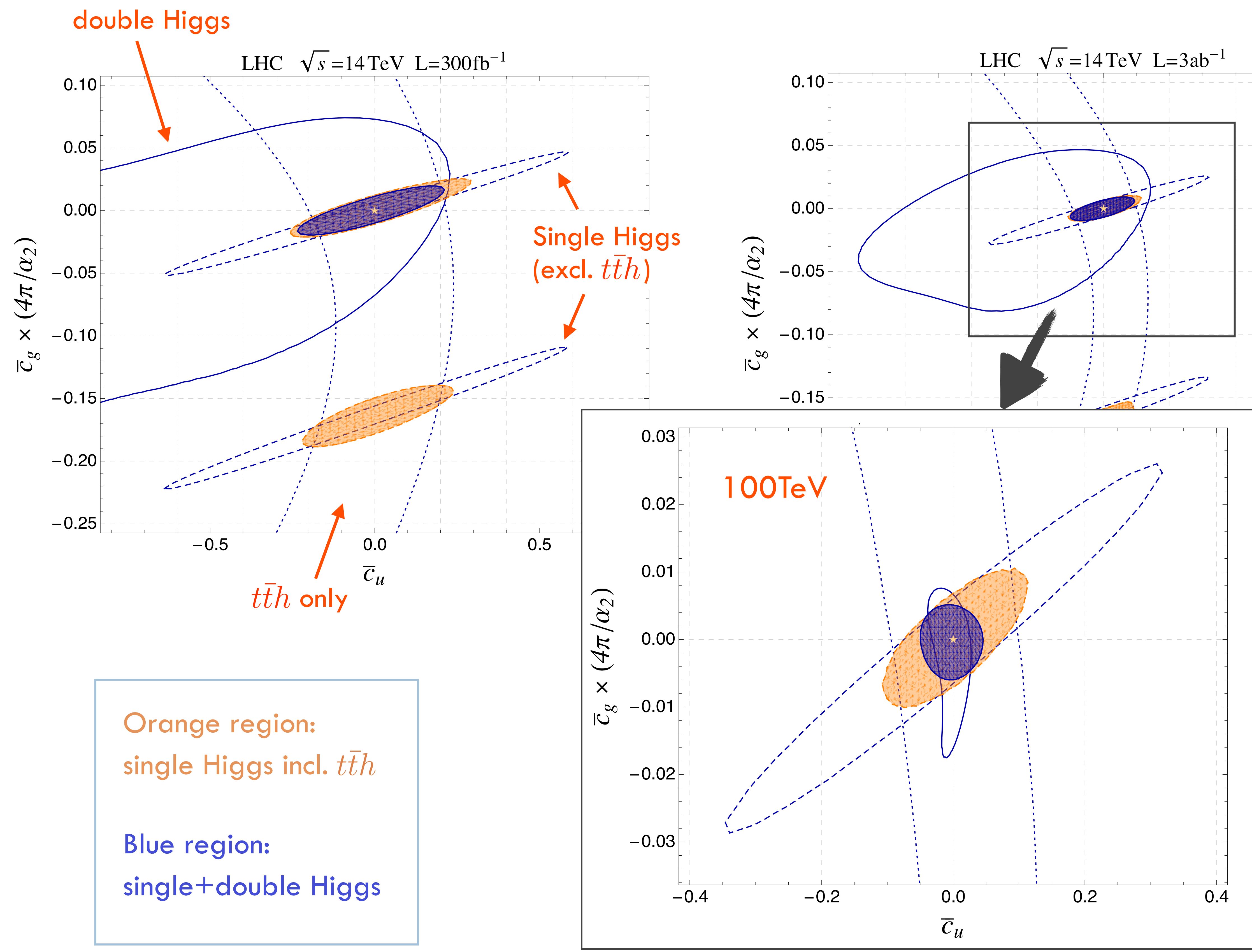
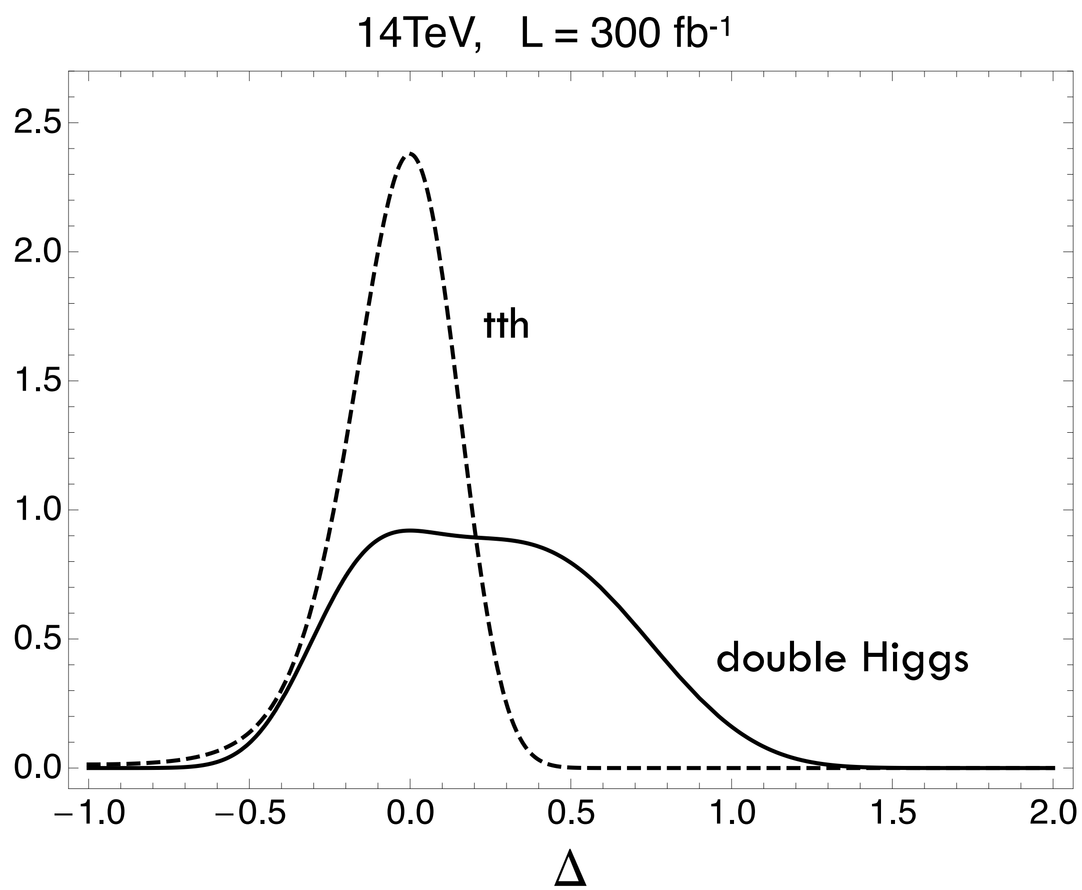
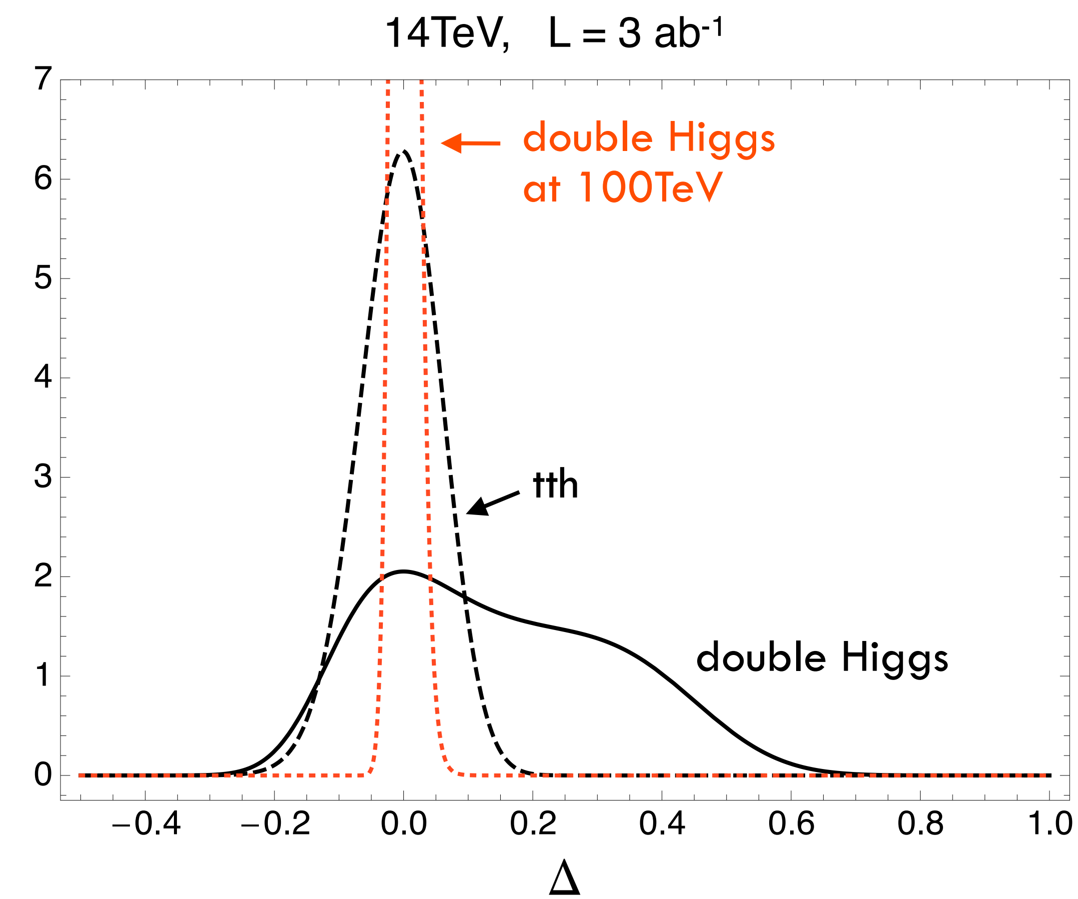


- Breaking the degeneracy of single Higgs: tth vs double Higgs ($hh \to bb\gamma\gamma$)

Line of degeneracy of single Higgs production:

$$c_t = 1 + \Delta \qquad c_{2t} = \frac{3}{2}\Delta \qquad c_g = c_{2g} = \frac{3}{8}c_\gamma = -\frac{\Delta}{12}$$





$(-0.18,\ 0.16)$ ⟷ tth

$(-0.21,\ 0.58)$ ⟷ double Higgs

$(-0.02,\ 0.02)$ ⟷ double Higgs at 100TeV

$(-0.07,\ 0.06)$ ⟷ tth

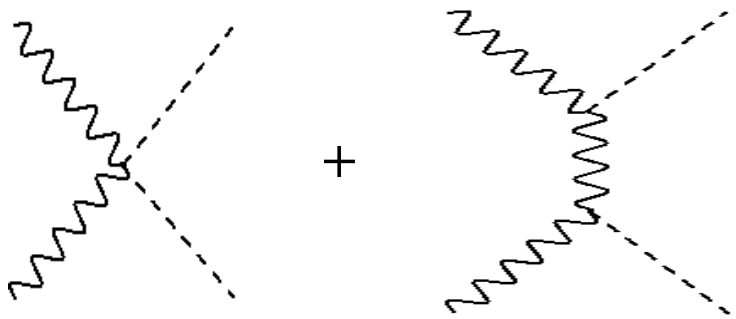
$(-0.1,\ 0.3)$ ⟷ double Higgs

68% probability intervals

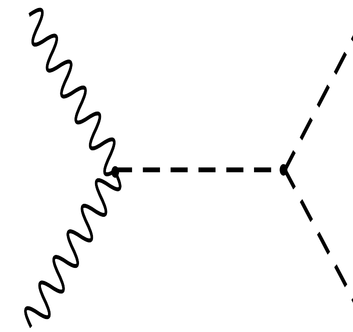
Double Higgs production via Vector Boson Fusion

Results from: R.C. and J. Rojo, work in progress

(see also: Bondu et al. proceeding of Les Houches 2013)



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



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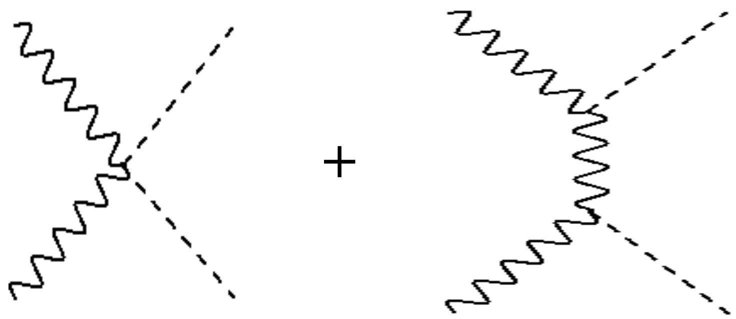

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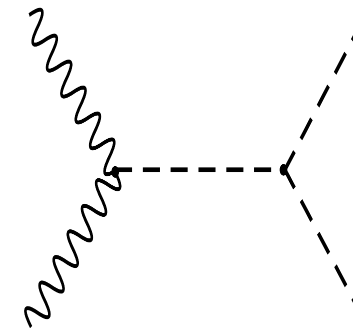

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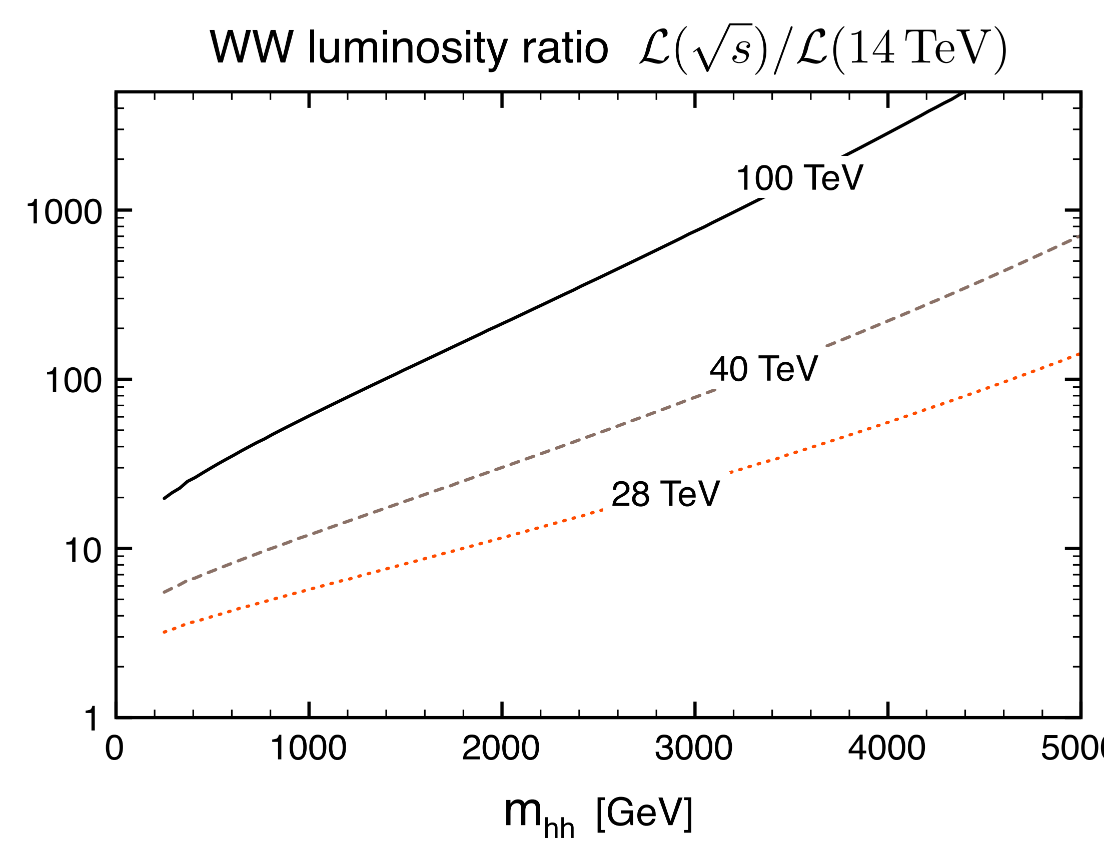
Higher rate due to higher WW luminosity

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



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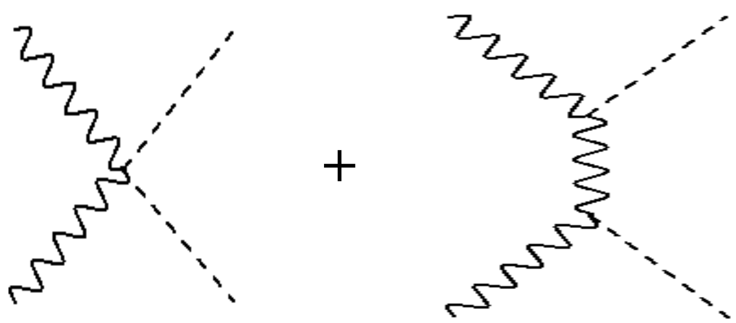

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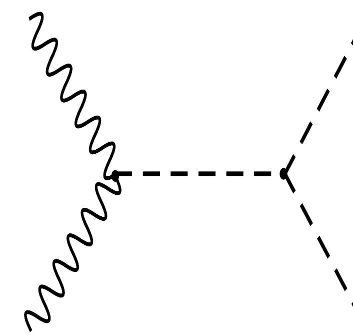

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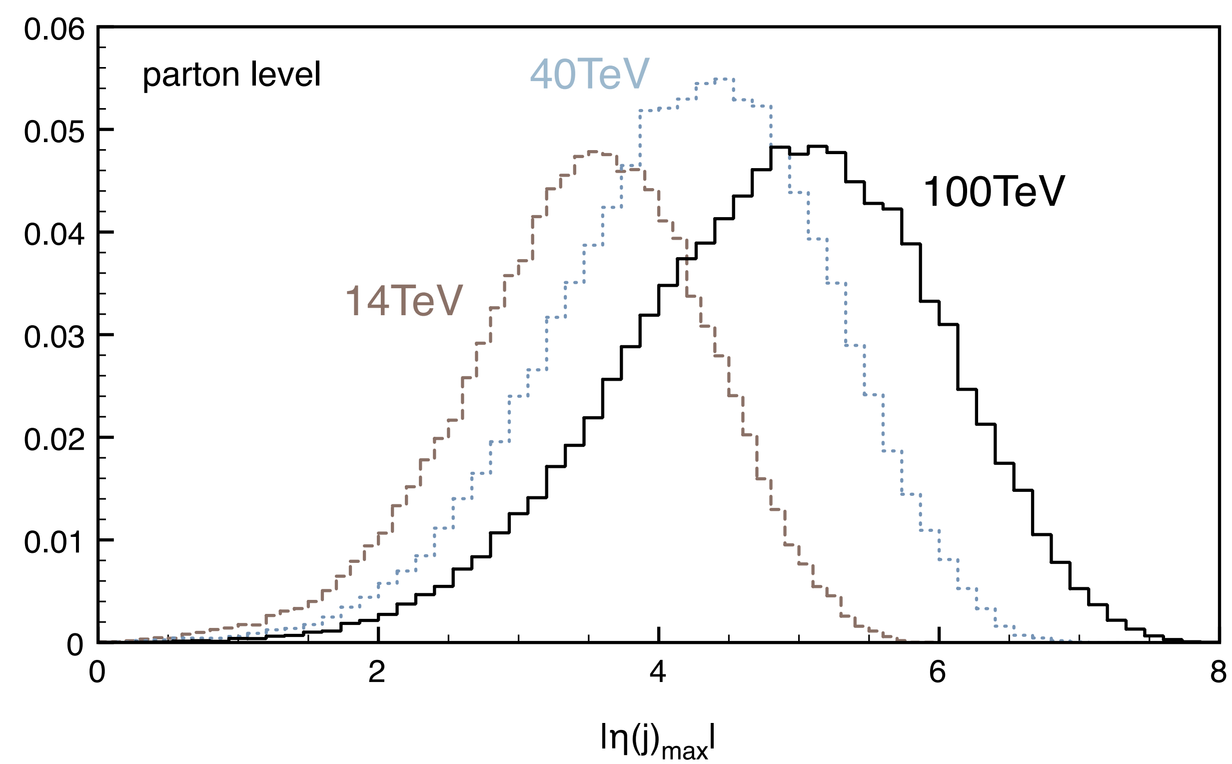
Study of double Higgs via VBF at 100TeV requires a dedicated detector in the very forward region



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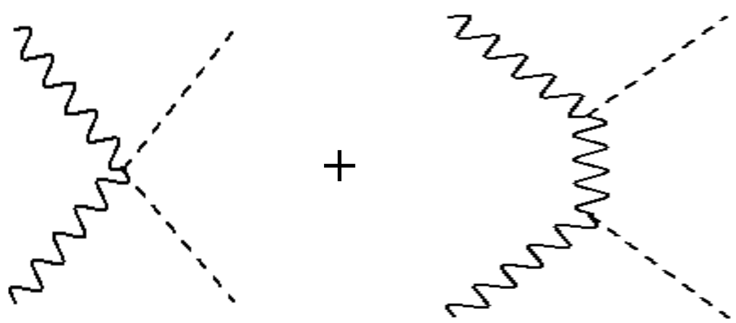

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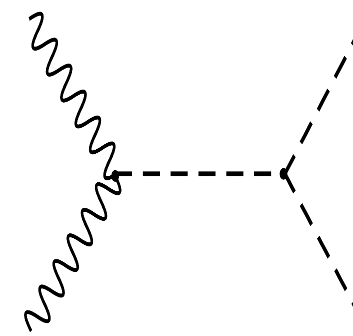

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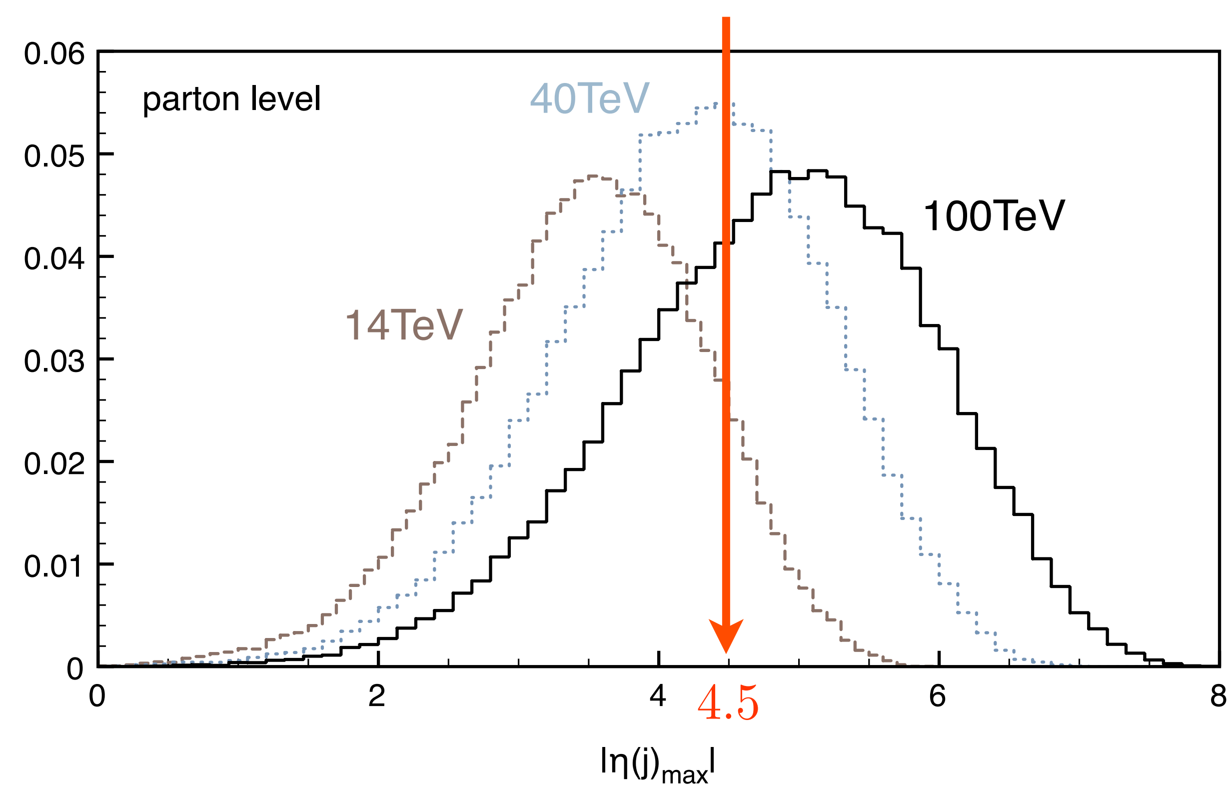
~67% of signal events at 100TeV has $|\eta(j)_{max}| > 4.5$



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

PRELIMINARY

14 TeV	$m(hh)$ [GeV] 250 – 500	500 – 750	750 – 1000	1000 – 1500	> 1500
$hh \to 4b$ [SM]	6.6	4.1	1.6	0.68	0.18
$4b2j$	9.8×10^3	557	203	101	15

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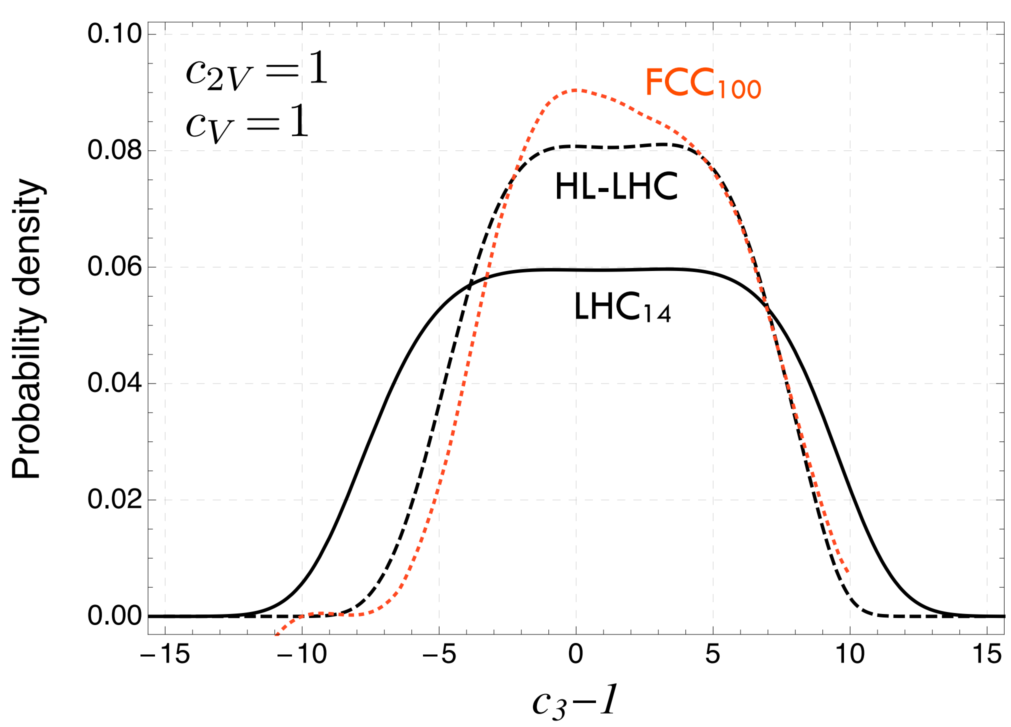

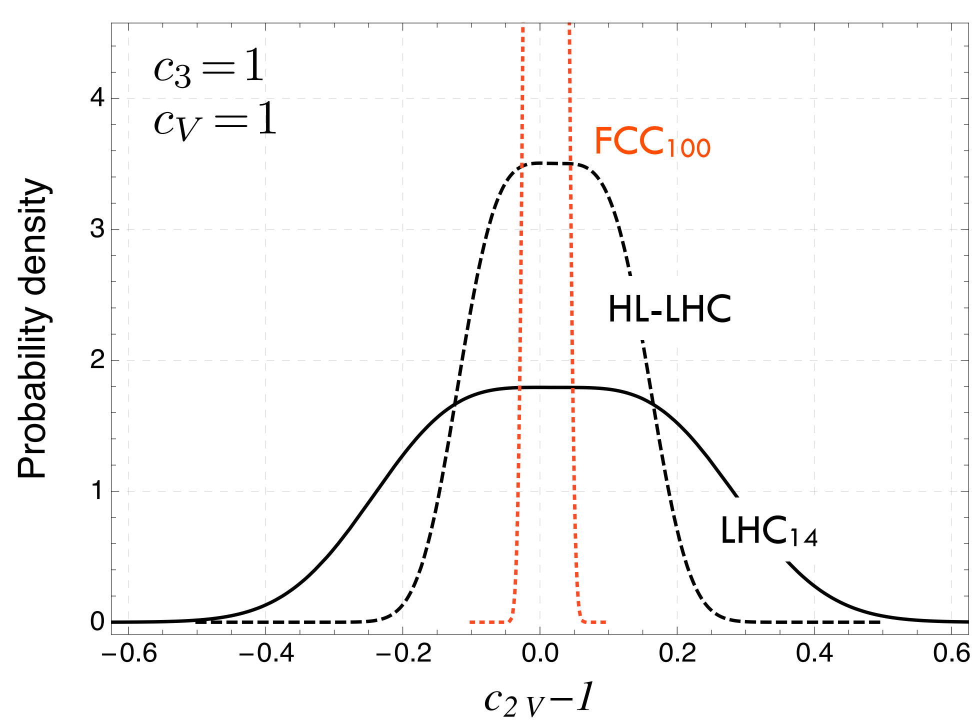

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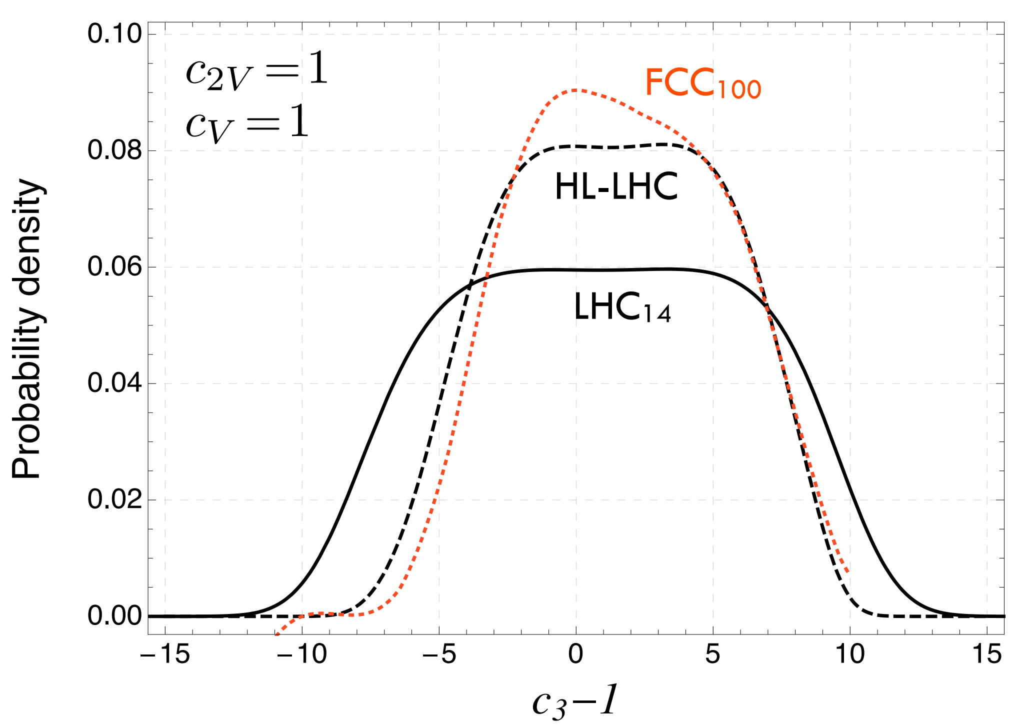
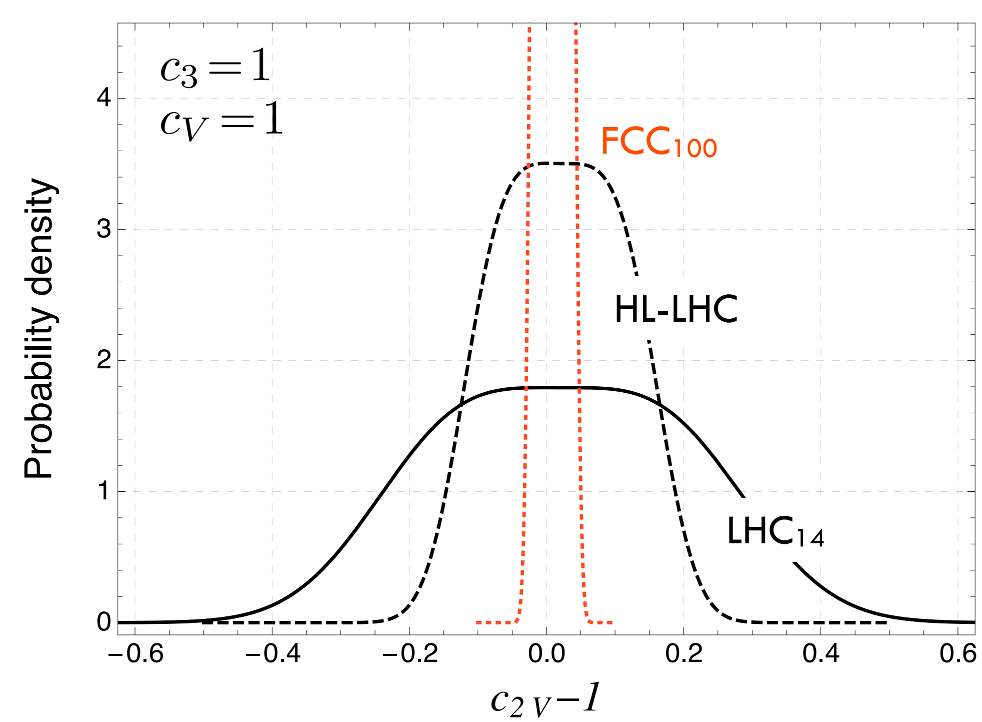




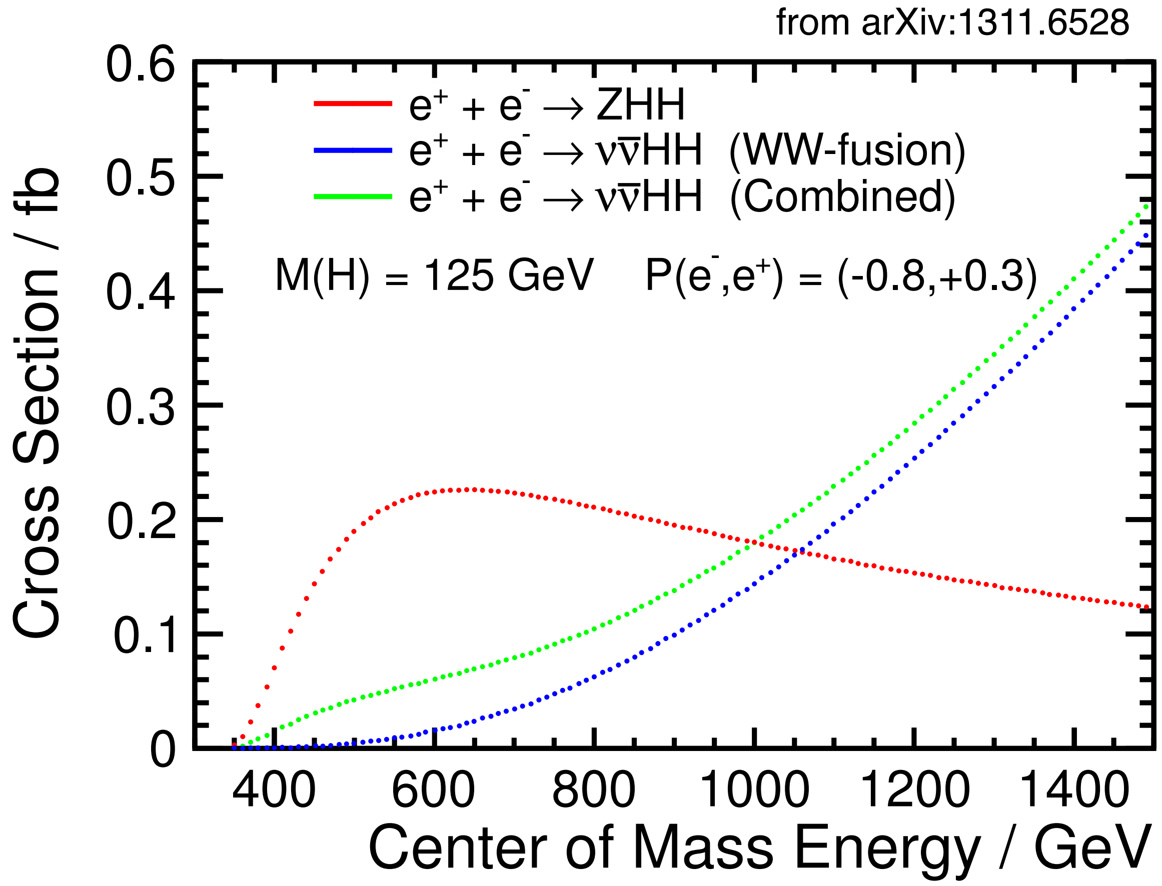
68% probability intervals on $\Delta c_{2V} \equiv c_{2V} - 1$:

(uncertainties included: 50% systematic on background, 10% on $BR(hh \to 4b)$)

LHC$_{14}$	HL-LHC	FCC$_{100}$
$[-0.18, 0.22]$	$[-0.08, 0.12]$	$[-0.01, 0.03]$

HH at future e^+e^- Colliders

Double Higgs-strahlung (DHS) vs VBF



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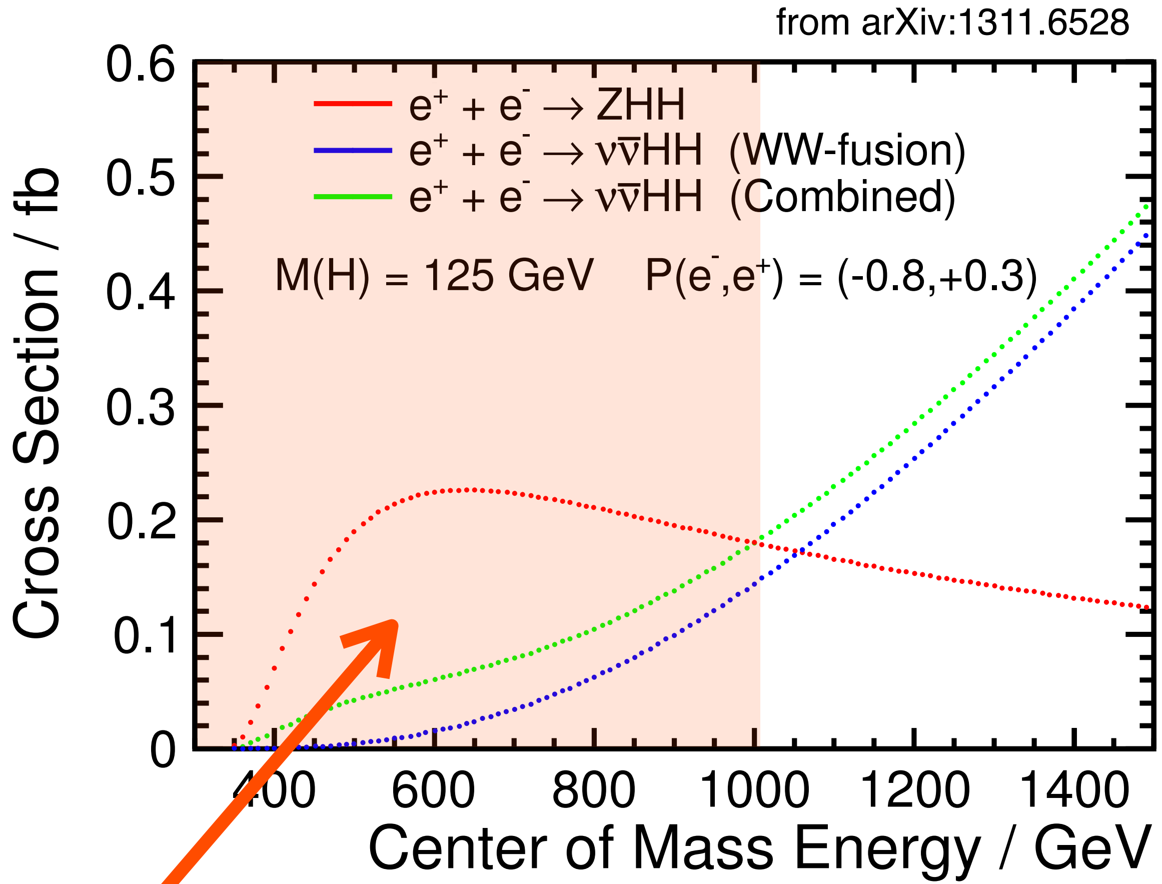
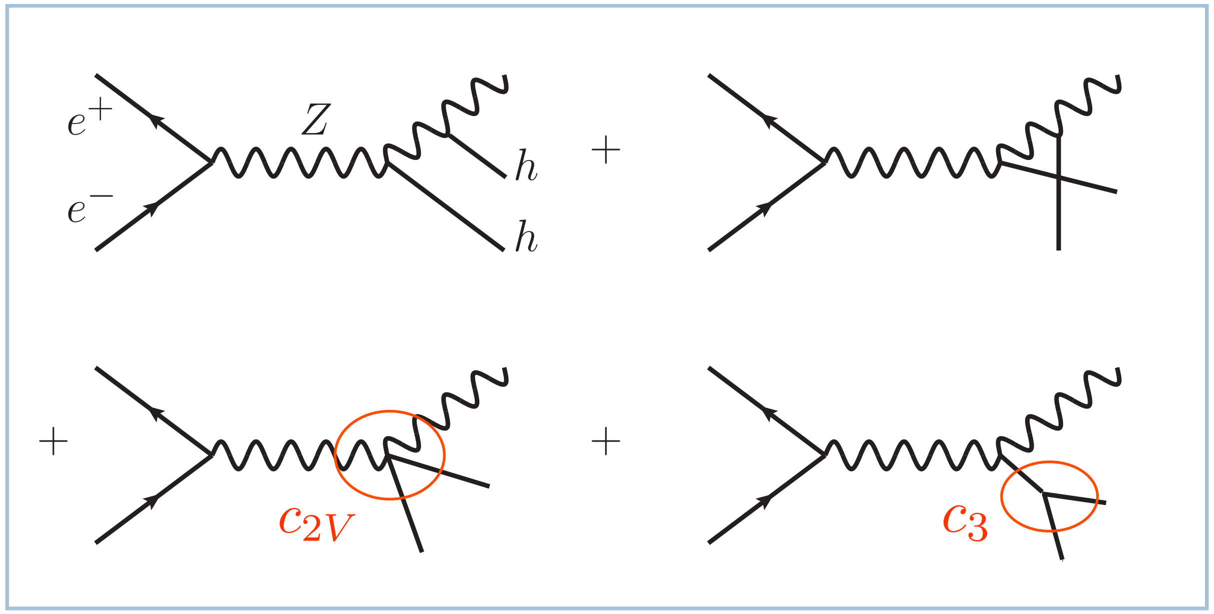


Double Higgs-strahlung dominates below 1TeV



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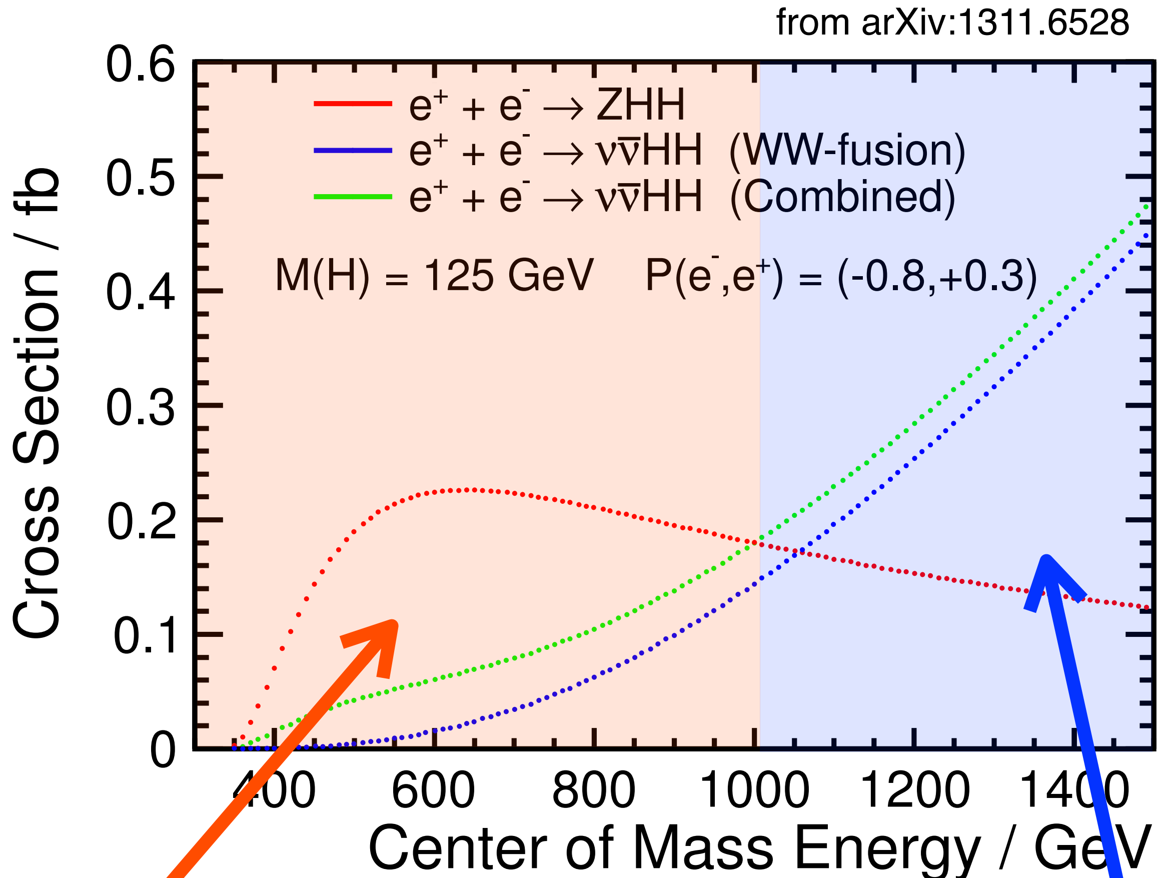

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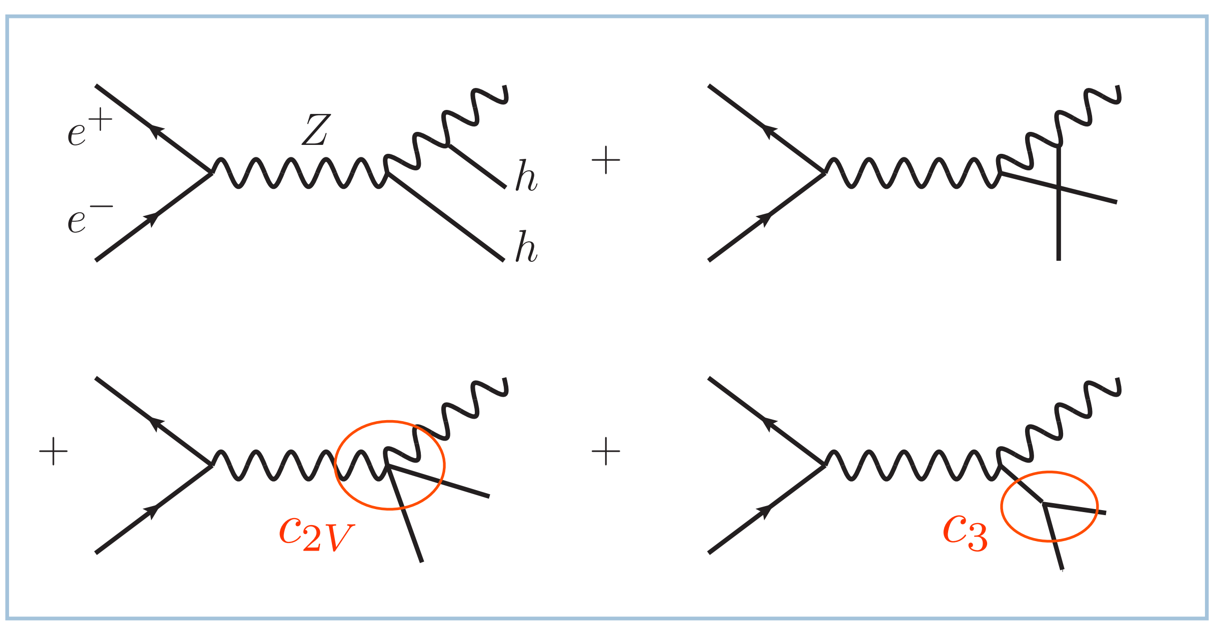
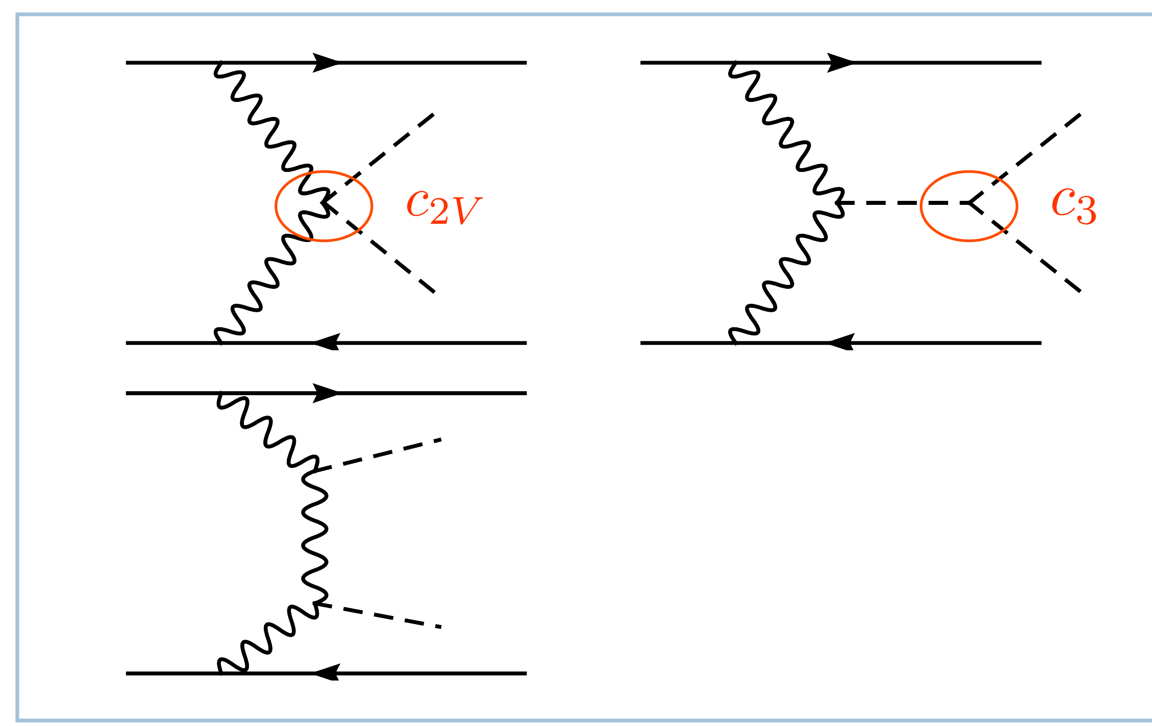
VBF important above 1TeV





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

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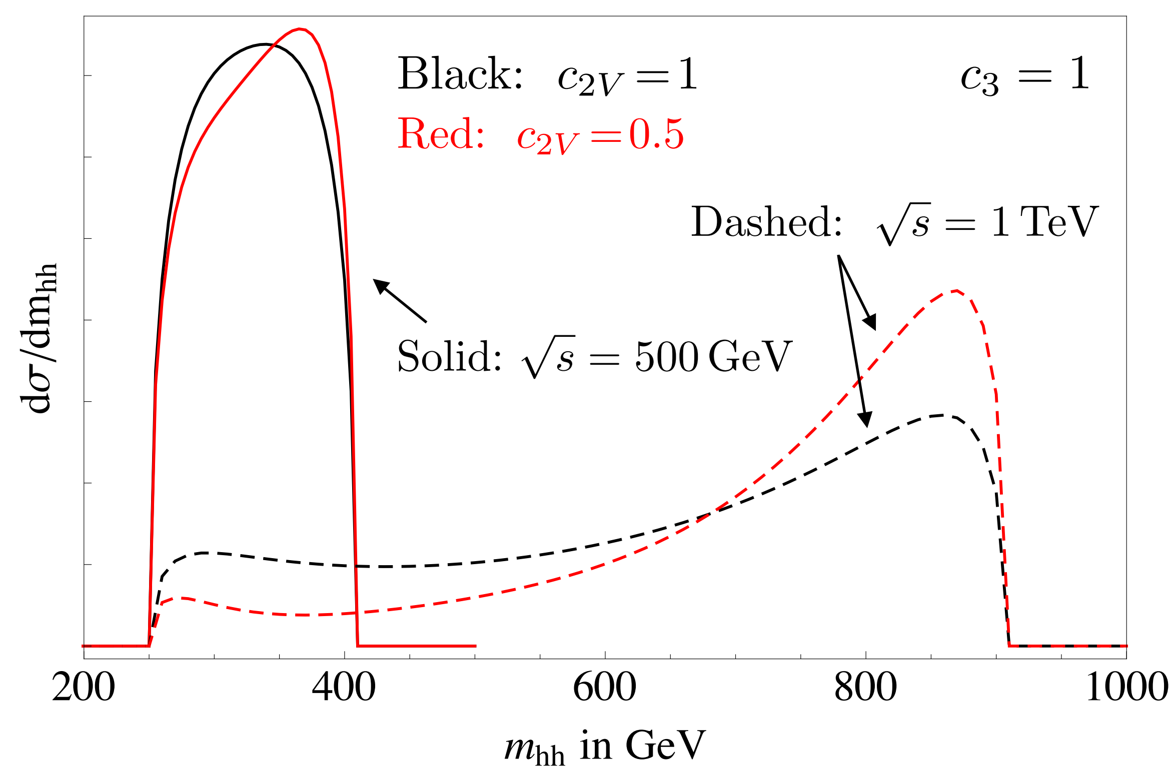

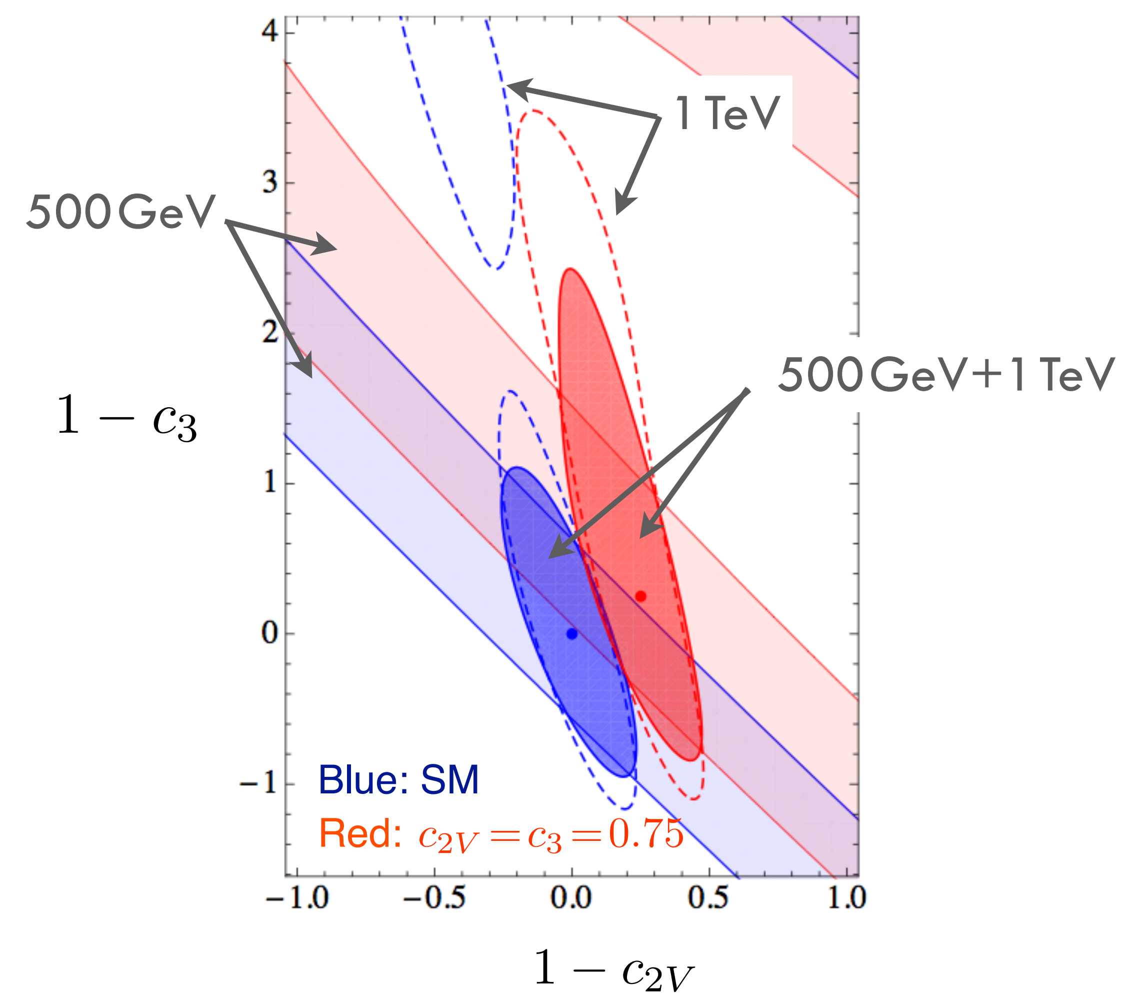

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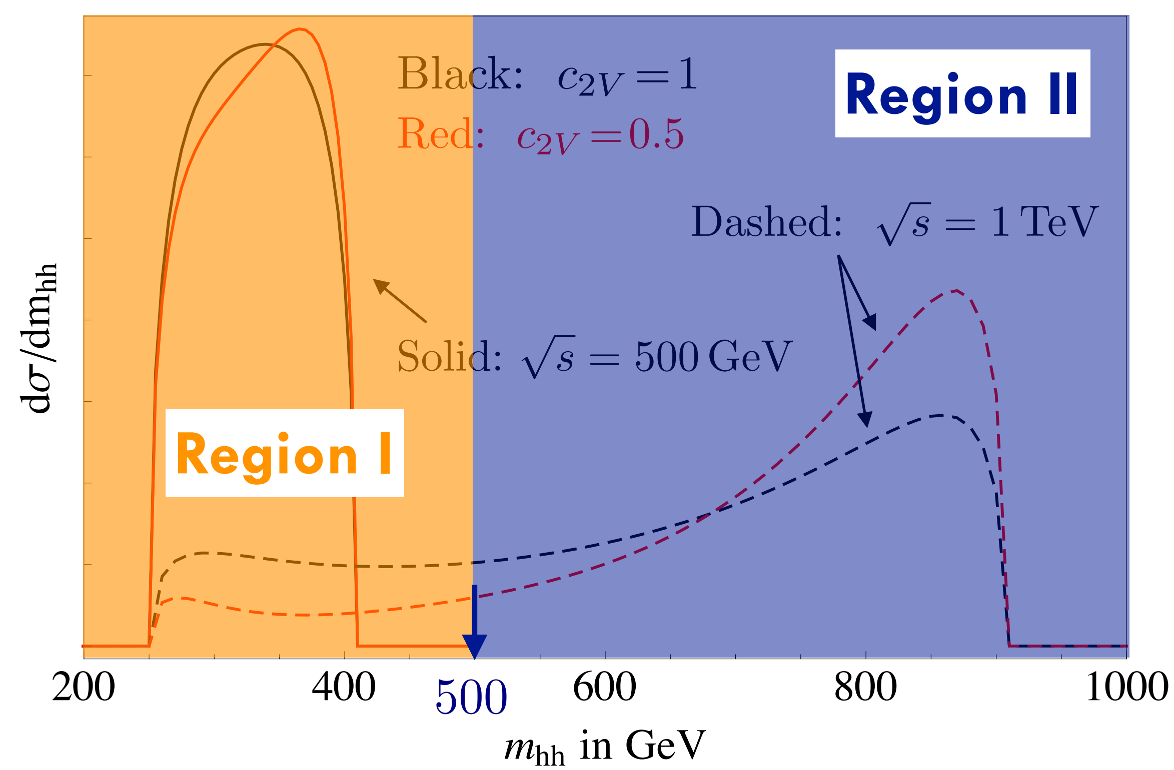

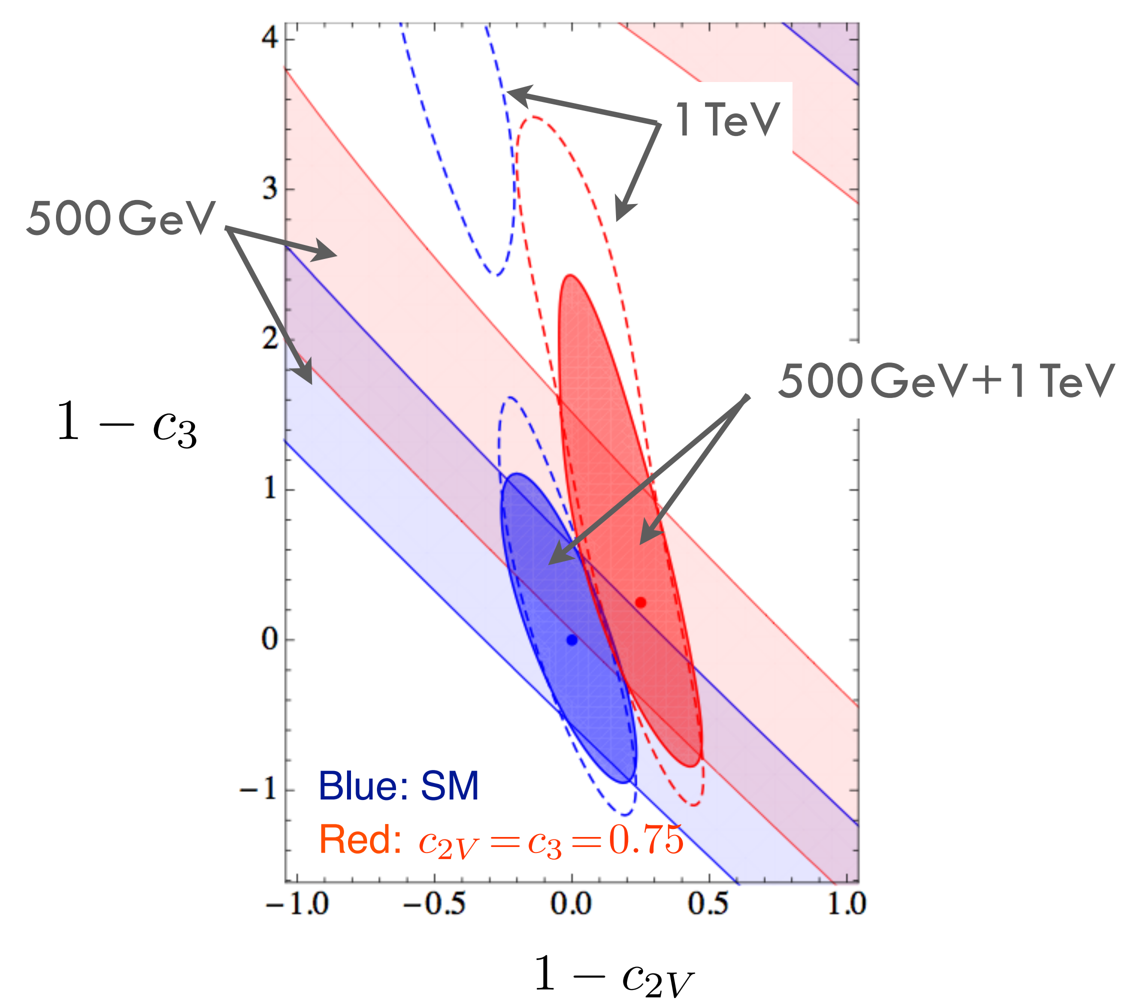

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  <u>for e^+e^- machines</u>

  - $\sqrt{s} \gtrsim 1\,\mathrm{TeV}$ necessary to measure the Higgs trilinear through VBF

Conclusions

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  - sufficient statistics to use m_{hh} distribution, hence: better precision on energy-growing interactions, degeneracies resolved

- Higher energy implies:

  - larger luminosity (through PDFs) !

  - larger forward coverage needed to fully exploit VBF, beneficial also for GF

Conclusions

- Better more energy or more Luminosity (continued) ?

for pp machines

- Higher luminosity implies:

  - sufficient statistics to use m_{hh} distribution, hence: better precision on energy-growing interactions, degeneracies resolved

- Higher energy implies:

  - larger luminosity (through PDFs) !
  - larger forward coverage needed to fully exploit VBF, beneficial also for GF
  - jet substructure techniques are key to fully exploit the larger boost

Extra slides

Sensitivity on EFT coefficients

- Three benchmark scenarios considered:

	LHC_{14}	HL-LHC	FCC_{100}
$\sqrt{s}$	14 TeV	14 TeV	100 TeV
Luminosity	$L = 300\,\mathrm{fb}^{-1}$	$L = 3\,\mathrm{ab}^{-1}$	$L = 3\,\mathrm{ab}^{-1}$

- Bayesian probability for parameters of interest constructed by fixing or marginalizing on the remaining ones

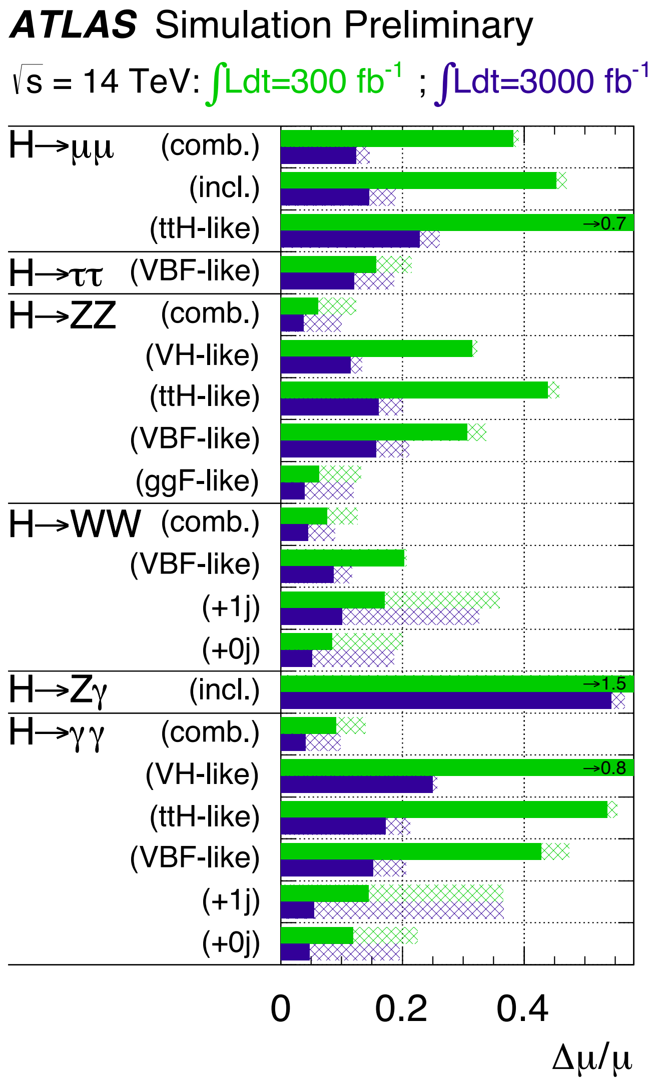
- Flat prior assumed on EFT coefficients except when they are constrained by single-Higgs data. We use ATLAS projections for 300fb^{-1} and 3ab^{-1}

  ATLAS note ATL-PHYS-PUB-2013-014 (2013)

  No theoretical uncertainties on signal or systematic errors included

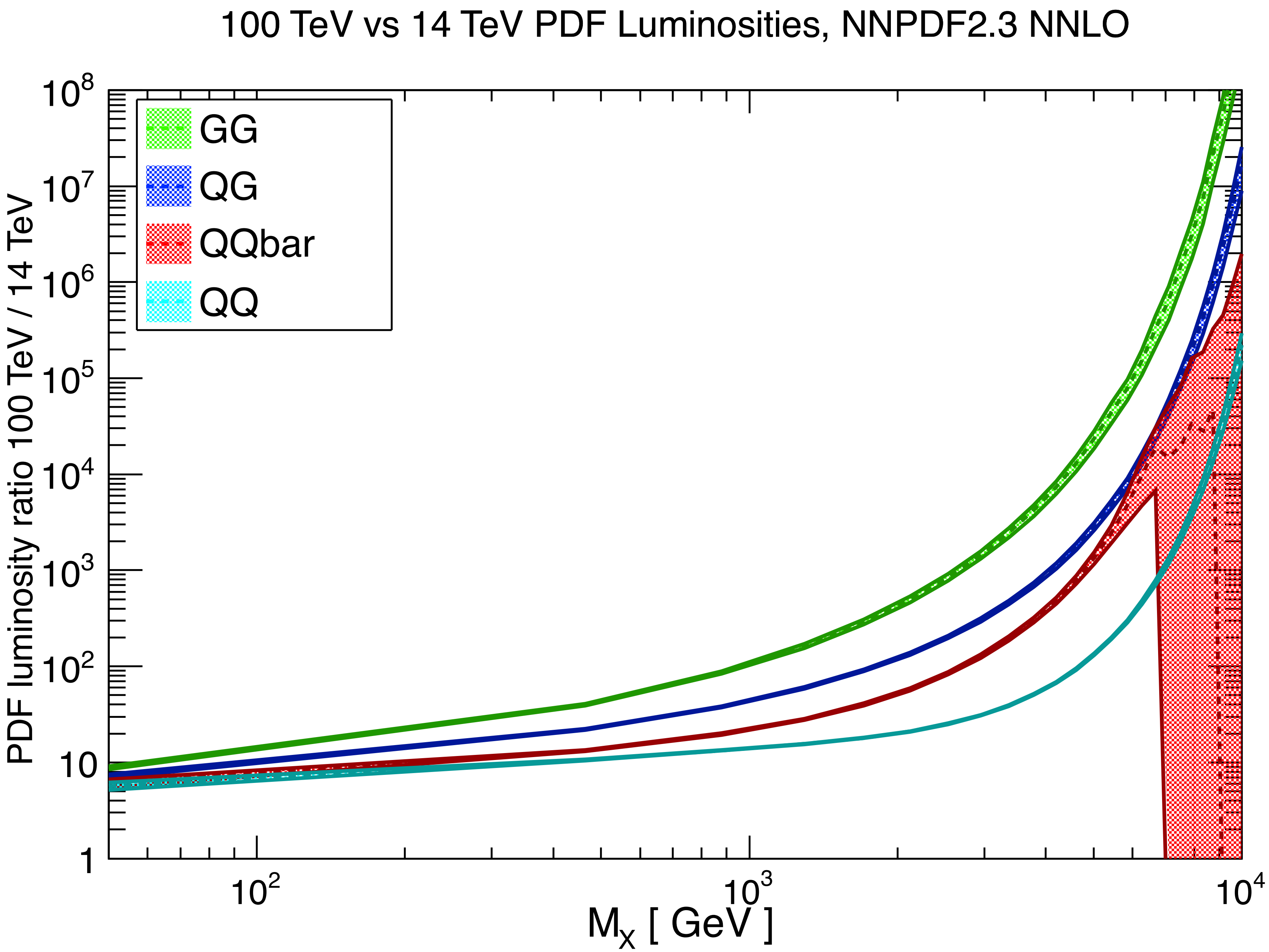
ATLAS projections at high luminosity (ATL-PHYS-PUB-2013-014)

$\Delta\mu/\mu$	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
$H \to \mu\mu$ (comb.)	0.39	0.38	0.15	0.12
(incl.)	0.47	0.45	0.19	0.15
(ttH-like)	0.73	0.72	0.26	0.23
$H \to \tau\tau$ (VBF-like)	0.22	0.16	0.19	0.12
$H \to ZZ$ (comb.)	0.12	0.06	0.10	0.04
(VH-like)	0.32	0.31	0.13	0.12
(ttH-like)	0.46	0.44	0.20	0.16
(VBF-like)	0.34	0.31	0.21	0.16
(ggF-like)	0.13	0.06	0.12	0.04
$H \to WW$ (comb.)	0.13	0.08	0.09	0.05
(VBF-like)	0.21	0.20	0.12	0.09
(+1j)	0.36	0.17	0.33	0.10
(+0j)	0.20	0.08	0.19	0.05
$H \to Z\gamma$ (incl.)	1.47	1.45	0.57	0.54
$H \to \gamma\gamma$ (comb.)	0.14	0.09	0.10	0.04
(VH-like)	0.77	0.77	0.26	0.25
(ttH-like)	0.55	0.54	0.21	0.17
(VBF-like)	0.47	0.43	0.21	0.15
(+1j)	0.37	0.14	0.37	0.05
(+0j)	0.22	0.12	0.20	0.05



	300 fb^{-1}	3 ab^{-1}
$\sigma(\bar{c}_H)$	7.9%	5.4%
$\sigma(\bar{c}_u)$	5.9%(w/$t\bar{t}h$)	5.4%(w/$t\bar{t}h$)
	20%($t\bar{t}h$)	7.7%($t\bar{t}h$)
$\sigma(\bar{c}_d)$	6.3%	4.4%

Growth of Parton Luminosity with Energy



from: J. Rojo, talk at FCC workshop, CERN 27.1.2014

Our analysis at 14TeV in a nutshell

Simulation: Parton level + Showering + Hadronization

events clustered into R=0.5 anti-k_T jets

Signal: our own code at 1-loop

Backgrounds: MadGraph5_aMC@NLO (working in LO mode)

Backgrounds included: $b\bar{b}\gamma\gamma$, $jj\gamma\gamma$ (non resonant)

$b\bar{b}h\,,\,Zh\,,\,t\bar{t}h$ (resonant)

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Matched up to 1 extra parton at the ME level

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Found large k-factor for $b\bar{b}\gamma\gamma$: $k \sim 2$

Mainly from real emissions, full NLO simulation with MadGraph5_aMC@NLO gives similar cross section (virtual corrections small)

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No matching, cross section rescaled to NLO value

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Selected events with: 2 b-tagged jets + 2 photons

efficiencies: $\epsilon_b = 0.7, \quad \epsilon_{j\to b} = 0.01, \quad \epsilon_\gamma = 0.8$

Kinematic selection for the 14TeV LHC:

basic object reconstruction:

$$p_T(j) > 25\,\mathrm{GeV}, \quad |\eta(j)| < 2.5$$

$$p_T(\gamma) > 25\,\mathrm{GeV}, \quad |\eta(\gamma)| < 2.5$$

veto on isolated leptons with

$$p_T(l) > 20\,\mathrm{GeV}, \quad |\eta(l)| < 2.5$$

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first selection:

$$p_{T>}(b), p_{T>}(\gamma) > 50 \text{ GeV}$$

$$p_{T<}(b), p_{T<}(\gamma) > 30 \text{ GeV}$$

$$60 < m_{b\bar{b}}^{\text{reco}} < 200 \text{ GeV}$$

$$60 < m_{\gamma\gamma}^{\text{reco}} < 200 \text{ GeV}$$

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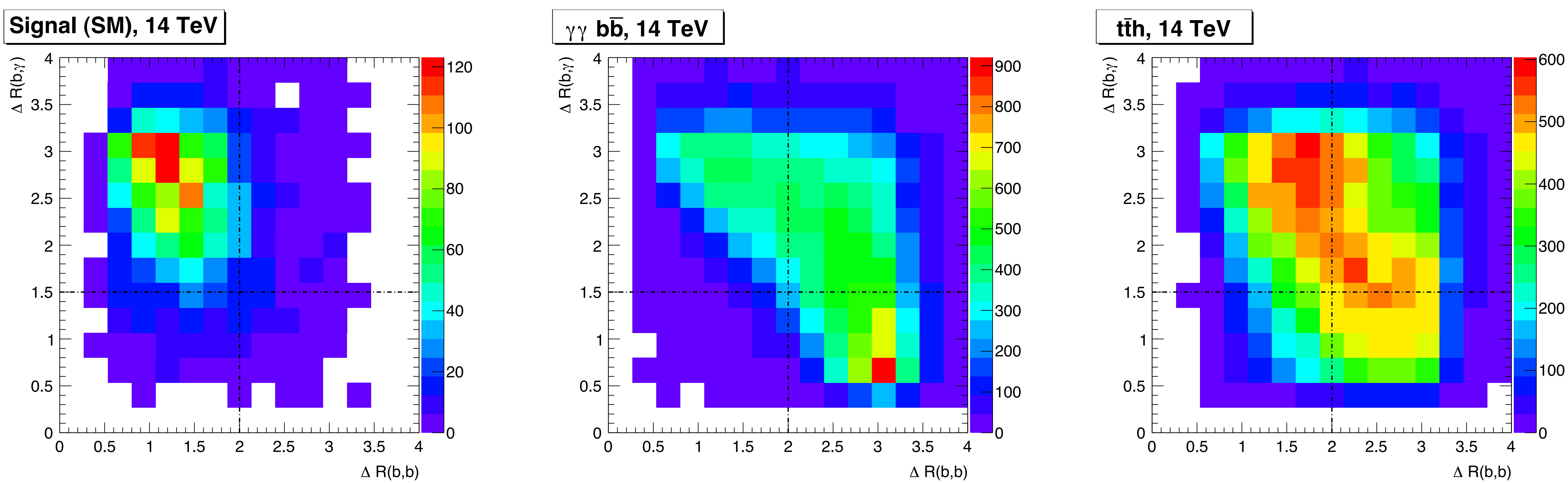

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$$p_{T<}(b), p_{T<}(\gamma) > 30 \ \mathrm{GeV} \qquad 60 < m_{\gamma\gamma}^{\mathrm{reco}} < 200 \ \mathrm{GeV}$$

angular cuts:

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

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veto on isolated leptons with

$$p_T(l) > 20\,\mathrm{GeV}, \quad |\eta(l)| < 2.5$$

first selection:

$$p_{T>}(b), p_{T>}(\gamma) > 50\ \mathrm{GeV} \qquad 60 < m_{b\bar{b}}^{\mathrm{reco}} < 200\ \mathrm{GeV}$$
$$p_{T<}(b), p_{T<}(\gamma) > 30\ \mathrm{GeV} \qquad 60 < m_{\gamma\gamma}^{\mathrm{reco}} < 200\ \mathrm{GeV}$$

angular cuts:

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

Higgs reconstruction:

$$105 < m_{b\bar{b}}^{\mathrm{reco}} < 145\ \mathrm{GeV}, \quad 120 < m_{\gamma\gamma}^{\mathrm{reco}} < 130\ \mathrm{GeV}$$

Number of events (SM signal and background) with L=3ab^{-1}

$\sqrt{s} = 14$ TeV	hh	$b\bar{b}\gamma\gamma$	$\gamma\gamma jj$	$t\bar{t}h$	$b\bar{b}h$	Zh
After first selection	25.8	6919	684	130	7.2	25.4
After angular cuts	17.8	1274	104	29	1.2	15.8
After Higgs reco.	12.8	24.2	2.21	9.9	0.40	0.41

Subdividing events in bins of m_{hh} (6 categories)

m_{hh}^{reco} [GeV]	$250-400$	$400-550$	$550-700$	$700-850$	$850-1000$	$1000-$
hh	2.14	6.34	2.86	0.99	0.33	0.17
$\gamma\gamma b\bar{b}$	7.69	10.1	3.35	1.38	1.18	0.59
$\gamma\gamma jj$	0.66	0.95	0.31	0.16	0.08	0.045
$t\bar{t}h$	3.33	4.53	1.41	0.41	0.16	0.043
$b\bar{b}h$	0.20	0.16	0.03	0.0054	0.0022	0.00054
Zh	0.13	0.19	0.067	0.021	0.009	0.0009

Only modest improvement of signal significance from veto on extra hadronic activity

Examples: $N(jets) < 4$ removes 80% of $t\bar{t}h$ keeping 70% of signal

$N(W_{had}) = 0$ removes 50% of $t\bar{t}h$ keeping 90% of signal