

# Higgs pair production at future colliders

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at SUSY2018, on 25th July 2018

# LHC & Future Colliders

LHC: 14 TeV  $3 \text{ ab}^{-1}$  (or  $4 \text{ ab}^{-1}$ )

8T dipole ~2039

HE-LHC: 27 TeV  $15 \text{ ab}^{-1}$

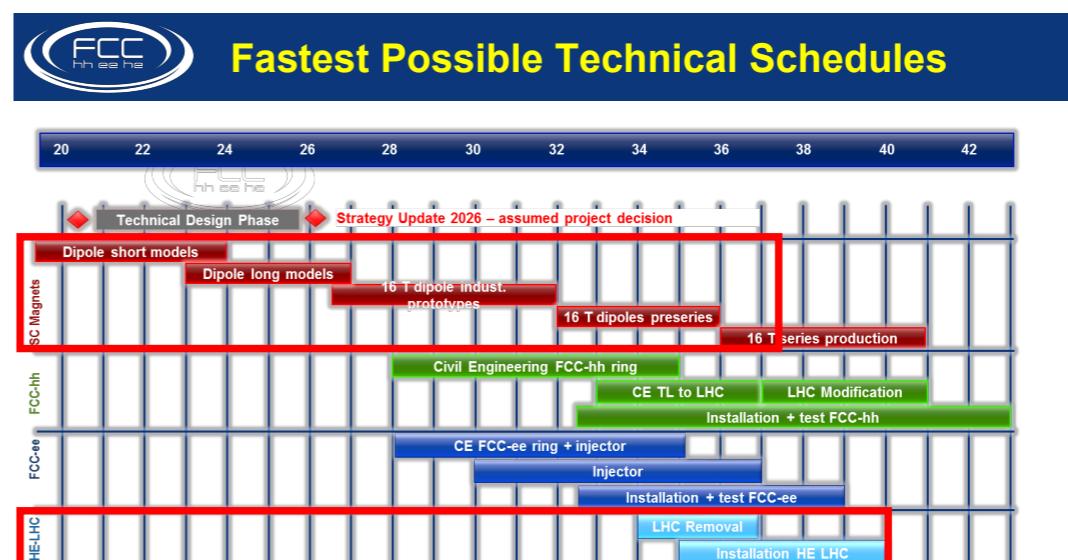
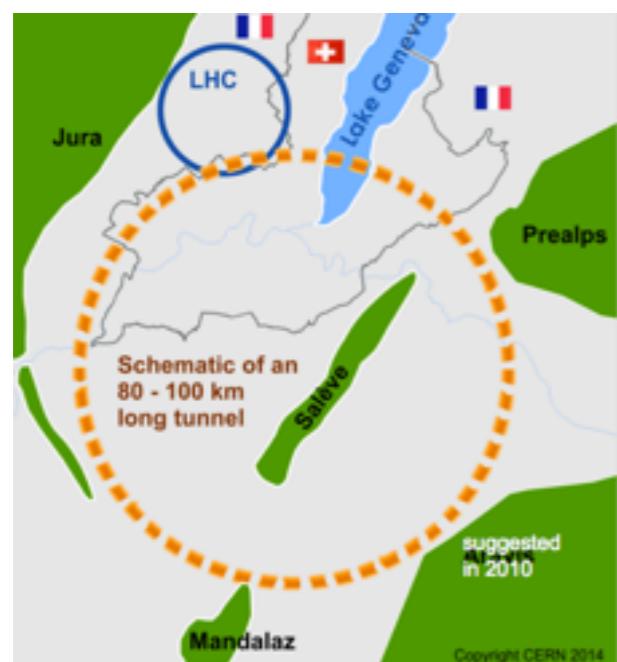
16T dipole 2040~

100TeV collider: 100 TeV  $30 \text{ ab}^{-1}$

x3-4 long tunnel

16T dipole 2043~

CERN (or in China?)



technical schedule defined by magnets program and by CE  
→ earliest possible physics starting dates:

- FCC-hh: 2043
- FCC-ee: 2039
- HE-LHC: 2040 (with HL-LHC stop at LS5 / 2034)

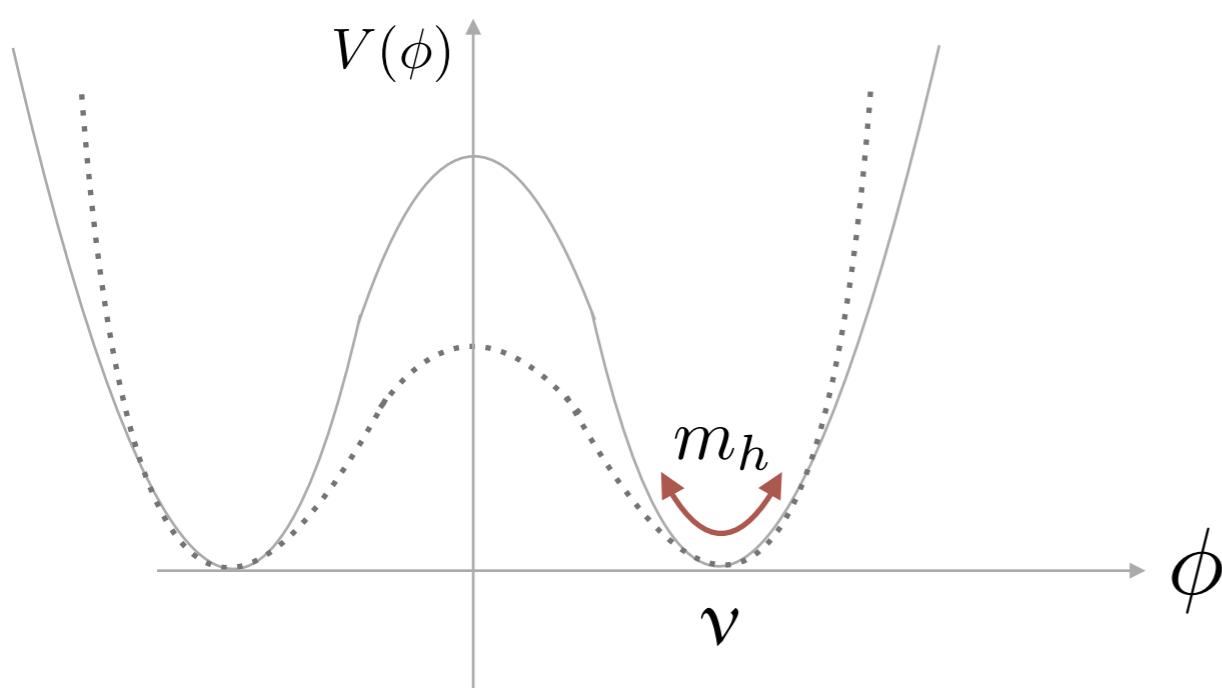
**HE-LHC**  
**design &**  
**construction**

M. Benedikt

What do we search for with these machines ?

Can we answer qualitative yes/no question?

# Higgs potential shape



We know the local structure around VEV,  
( $v$  and higgs mass)

$$V(h) = \frac{\lambda}{4}h^4 + \lambda vh^3 + \dots = \frac{\lambda_4}{4!}h^4 + \frac{\lambda_3}{3!}h^3 +$$

$$\lambda_{\text{SM}} \approx 1/8.$$

$$\lambda_4 = 6\lambda$$

$$\lambda_3 = 6\lambda v = \frac{3m_h^2}{v}$$

global Higgs potential shape might be different from simple  $\lambda\phi^4 + \mu\phi^2$   
for example,  $\phi^6$  term

HE-LHC (27TeV , 15 ab<sup>-1</sup>):

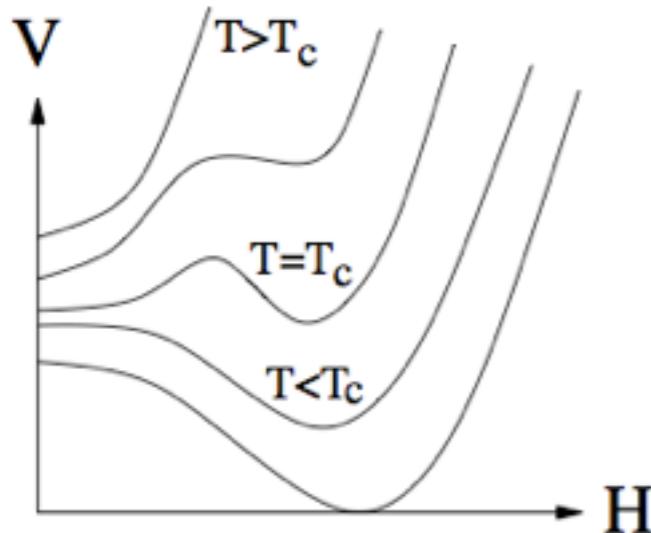
the machine for the Higgs self coupling measurement  
at the sensitivity able to answer the interesting question

# How accurate $\lambda$ measurement would be interesting ?

## EWBG phase transition at early universe

finite temp. effective higgs potential  $V(h) = \frac{\lambda}{4}h^4 + \lambda vh^3 + \dots = \frac{\lambda_4}{4!}h^4 + \frac{\lambda_3}{3!}h^3 + \dots$

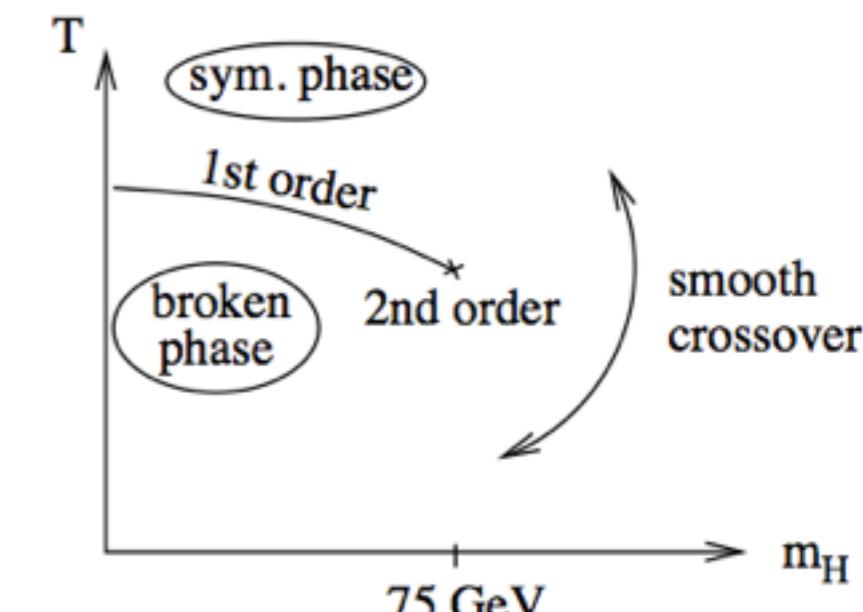
$$V_{\text{tot}} \cong m_H^2(T)H^2 - ETH^3 + \lambda H^4$$



in the SM  $\lambda_{\text{SM}} \approx 1/8$ .

$$\begin{aligned}\lambda_4 &= 6\lambda \\ \lambda_3 &= 6\lambda v = \frac{3m_h^2}{v}\end{aligned}$$

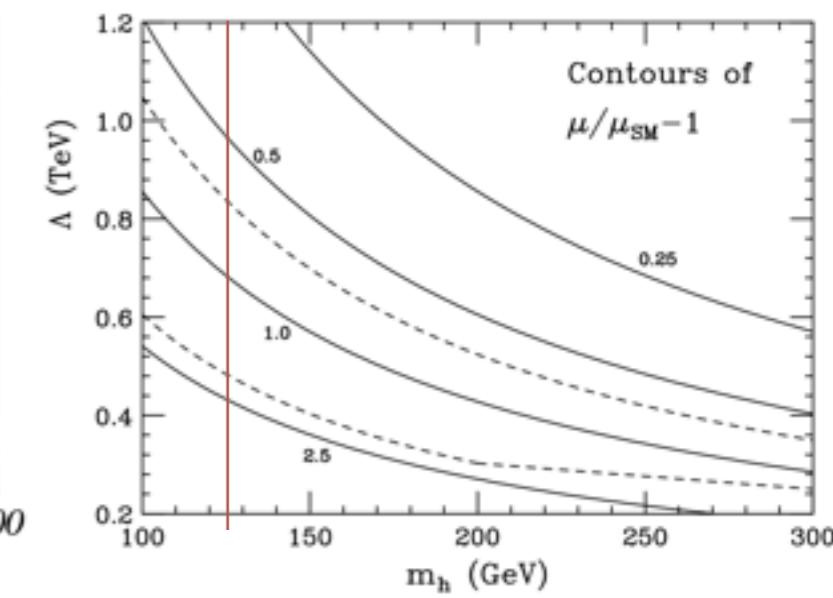
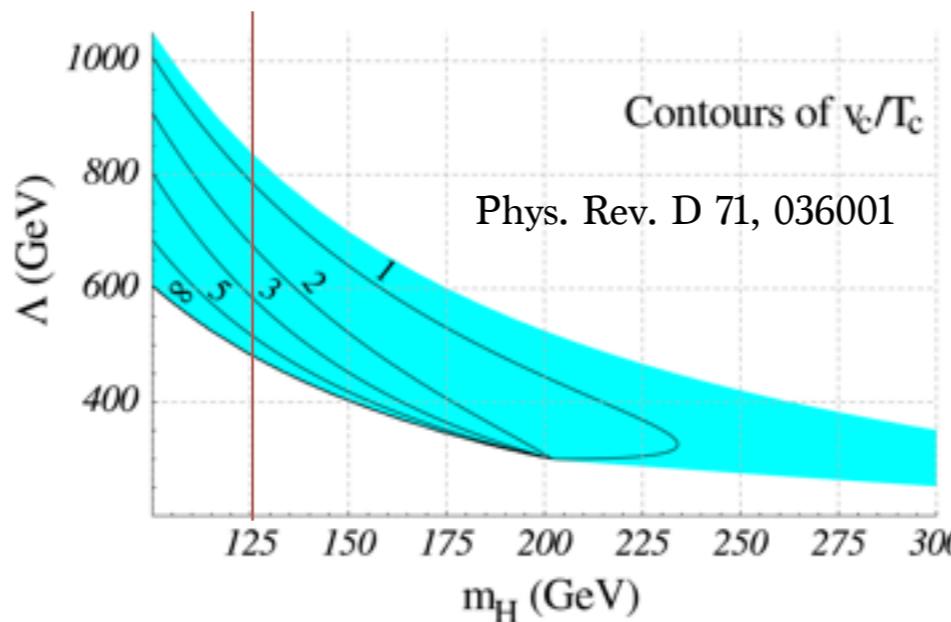
For EW baryogenesis successful  
strong 1st order PT ( $v_c/T_c > 1$ )  
required (necessary condition)



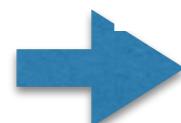
125 GeV Higgs is  
too heavy for EWBG successful

Considering new physics by dim.6 op.

$$V(\Phi) = \lambda \left( \Phi^\dagger \Phi - \frac{v^2}{2} \right)^2 + \frac{1}{\Lambda^2} \left( \Phi^\dagger \Phi - \frac{v^2}{2} \right)^3$$



strong 1st order PT



O(1) deviation in  $\lambda_3$  required  
[C. Grojean, G. Servant, J. Wells]

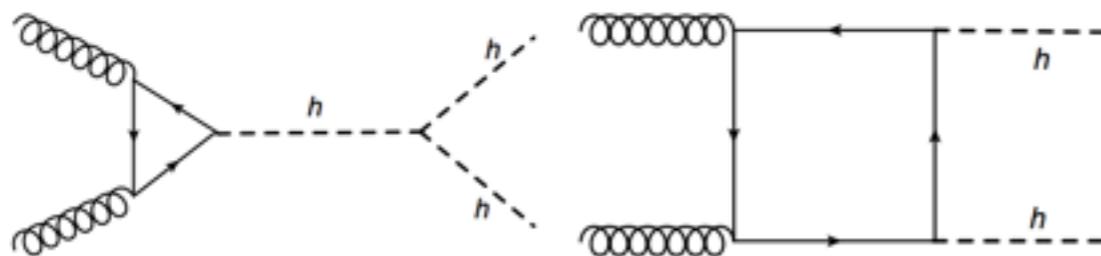
$$\lambda_3 = \frac{3m_h^2}{v} + \frac{6v^3}{\Lambda^2} \gtrsim 1.7\lambda_{3,\text{SM}}$$

To exclude this EWBG scenario, 70% level measurements required for  $\lambda_3$

# $\lambda$ sensitivity at HL-LHC

the lowest process involving the self coupling at LHC

Higgs pair production  $pp \rightarrow hh$



40 fb = 120k events in full lifetime of LHC

$hh$  decays:

$b\bar{b}\gamma\gamma$

$b\bar{b}\tau\tau$

$b\bar{b}WW$

$b\bar{b}b\bar{b}$

$4W$ .

Best sensitivity channel

$bb$  : large BR

$\gamma\gamma$ : clean channel

0.1 fb including BR=0.26%

(300 events in full lifetime of LHC)

the final sensitivity at HL-LHC on  $\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$ .

using only total rate [ATL-PHYS-PUB-2017-001,CMS-PAS-FTR-16-002]

$$-0.8 < \kappa_\lambda < 7.7 \text{ . at 95% CL}$$

using full kinematics [Phys. Rev. D 95, 035026, F. Kling, T. Plehn, P. Schichtel]

$$-0.2 < \kappa_\lambda < 2.6 \text{ , at 95% CL}$$

$$0.4 < \kappa_\lambda < 1.75 \text{ at 68% CL}$$

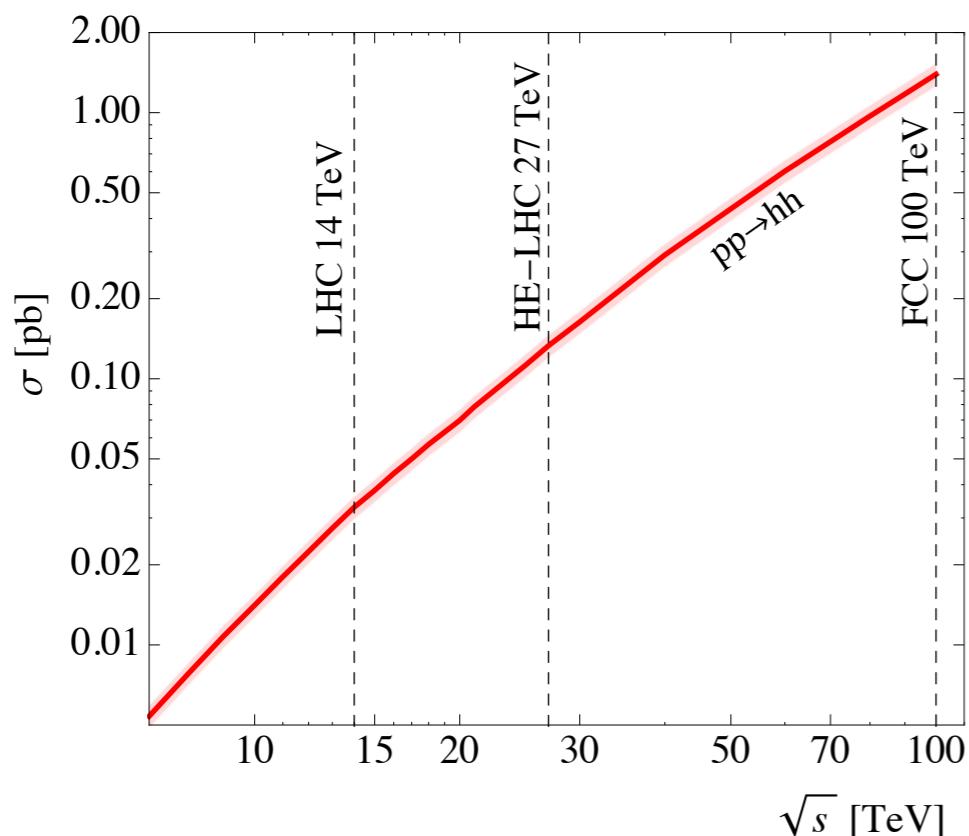
$$\kappa_\lambda \approx 1^{+75\%}_{-60\%}$$

not satisfactory at all.

after selection, based on  $O(10)$  events ~3% acceptance

# HE-LHC and 100 TeV colliders

1. the 27 TeV high-energy LHC (HE-LHC) with an integrated luminosity of  $15 \text{ ab}^{-1}$ ,
2. a 100 TeV hadron collider with  $30 \text{ ab}^{-1}$ , under consideration at CERN (FCC-hh) [18] and in China (SppC) [19].



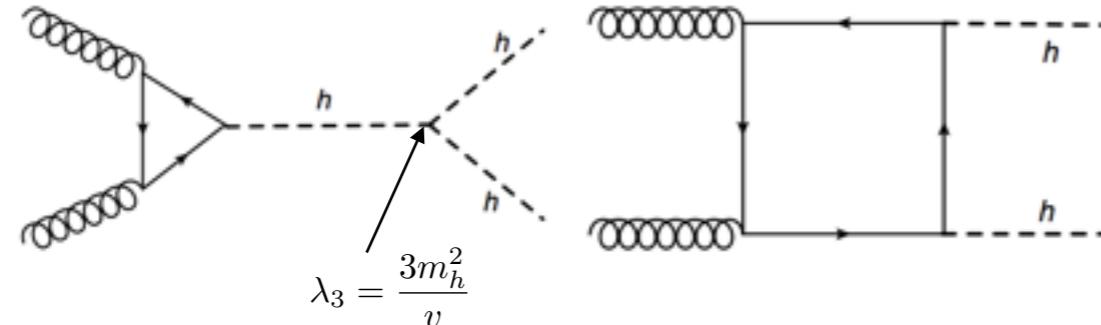
in cross section compared with 14TeV  
factor 4 (27TeV)  
factor 40 (100TeV)

in event numbers



# three phase space

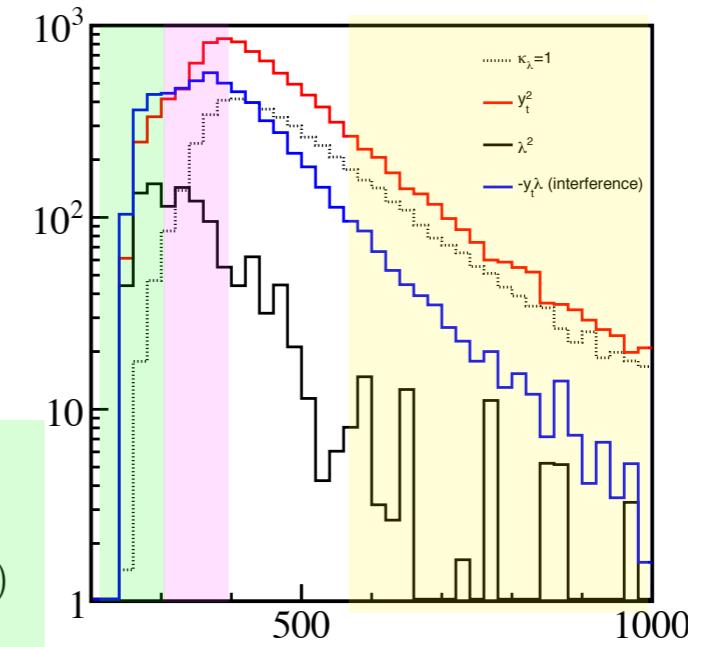
strong destructive interference  $\mathcal{M} = \kappa_\lambda \mathcal{M}_\Delta + y_t^2 \mathcal{M}_\square$



$$m_{hh}^{(\text{th})} \approx 2m_h$$

$$\frac{\alpha_s}{12\pi v} \left( \frac{\kappa_\lambda \lambda_{\text{SM}}}{s - m_h^2} - \frac{1}{v} \right) \rightarrow \frac{\alpha_s}{12\pi v^2} (\kappa_\lambda - 1) \stackrel{\text{SM}}{=} 0 .$$

$$\begin{aligned} & \frac{\alpha_s}{12\pi} G^{\mu\nu} G_{\mu\nu} \log\left(1 + \frac{h}{v}\right) \\ & \log\left(1 + \frac{h}{v}\right) = \frac{h}{v} - \frac{h^2}{2v^2} + \dots \end{aligned}$$

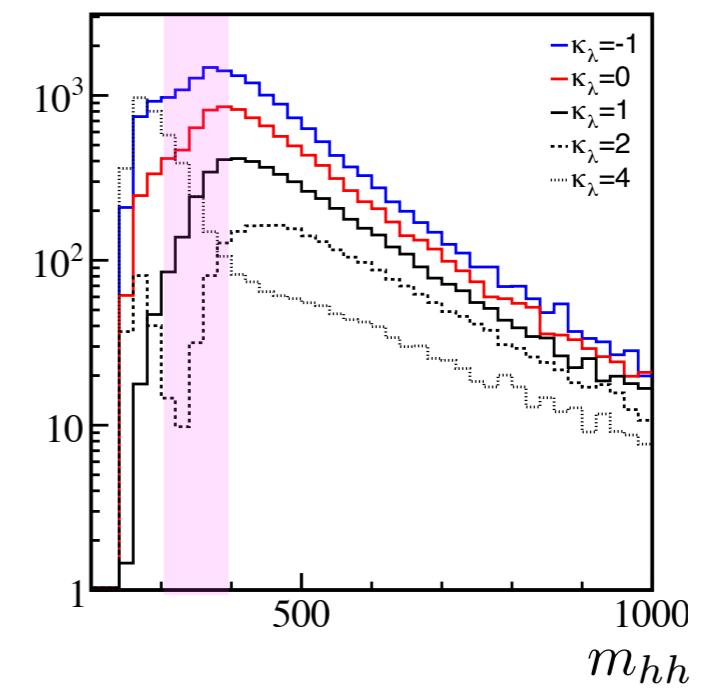


$$m_{hh}^{(\text{abs})} \approx 2m_t .$$

absorptive imaginary parts lead to a significant dip

$$m_{hh}^{(\text{high})} \gg m_h, m_t .$$

box contributions decay slower

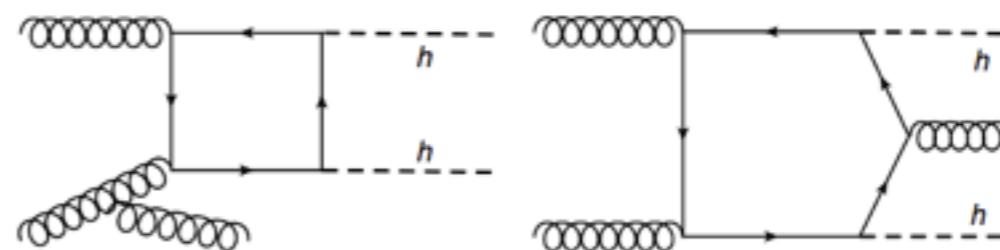


Since they are scalar particles, only  $m_{hh}$  distribution has the information at LO.

# properly simulate the 3rd jet important

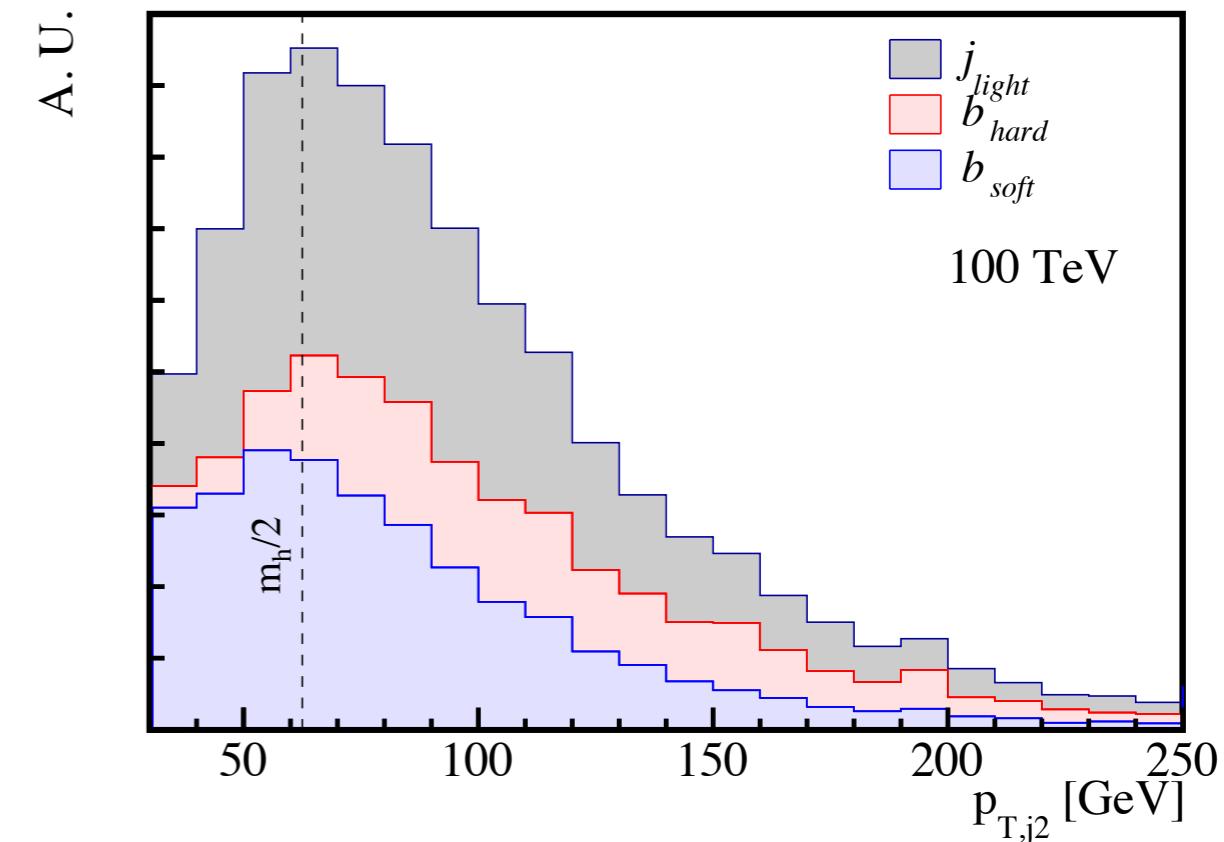
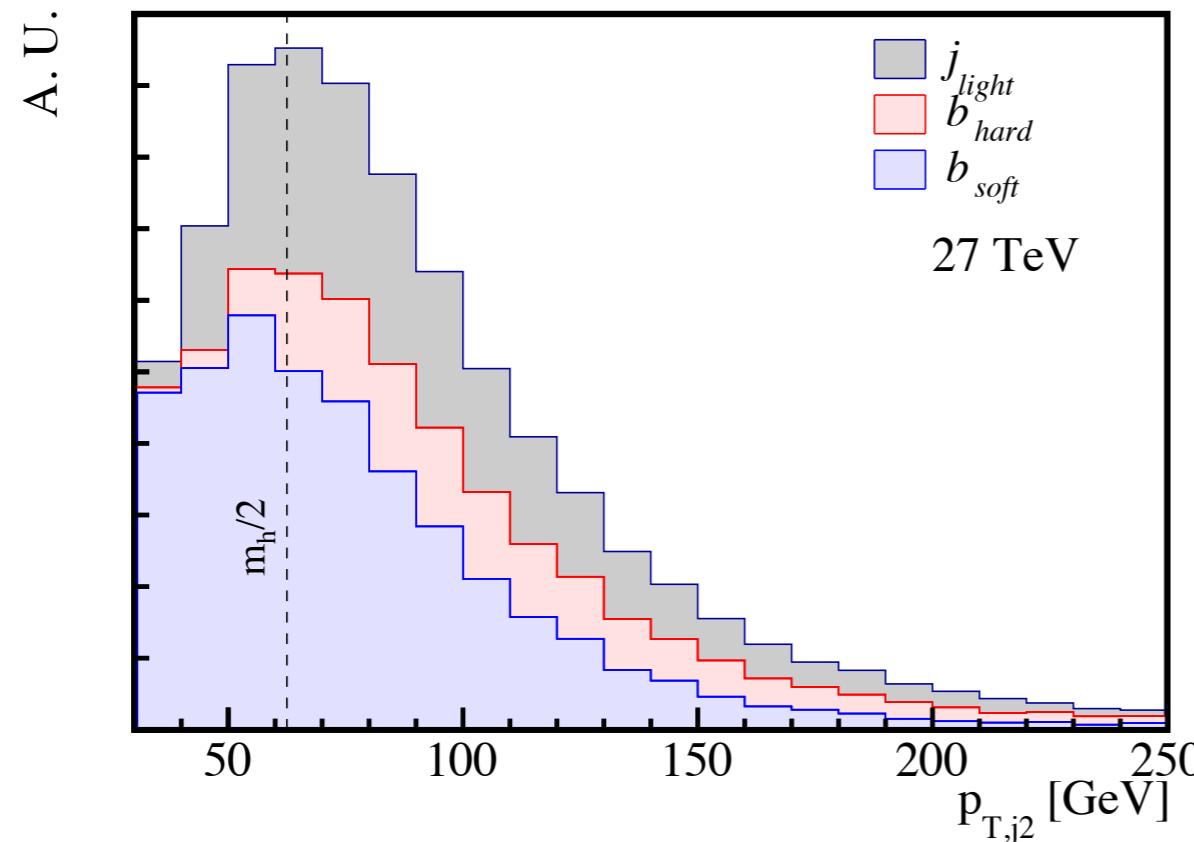
All Signal/BG samples simulated with 1 additional jet in MLM matching

$$pp \rightarrow hh \rightarrow b\bar{b} \gamma\gamma + X.$$



two H decay products not always found in the hardest two jets (b from H has intrinsic pT ~ 60GeV)

origin of the second jet for 27 TeV and 100 TeV



Requiring two b-tags in three hardest jets important! (50% acceptance higher)

# Event selection

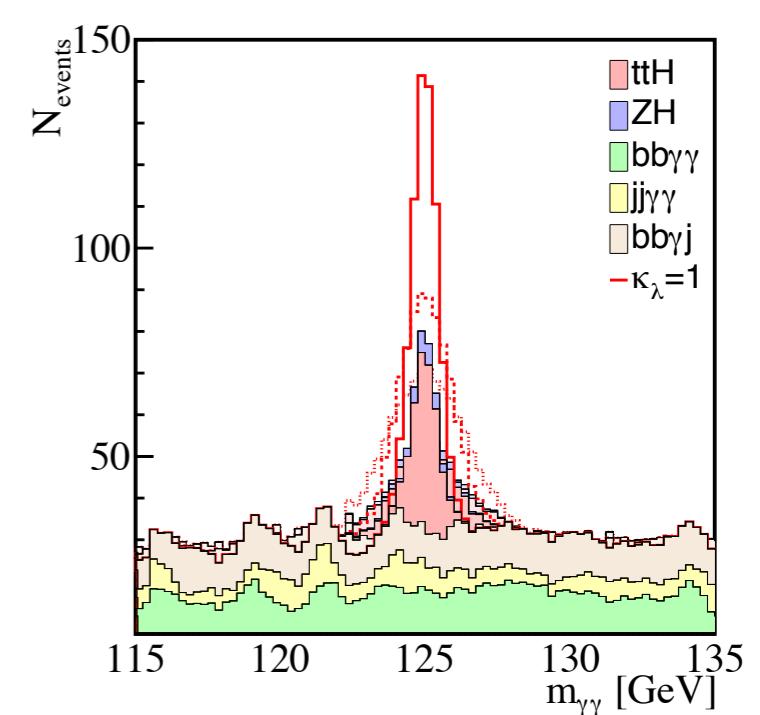
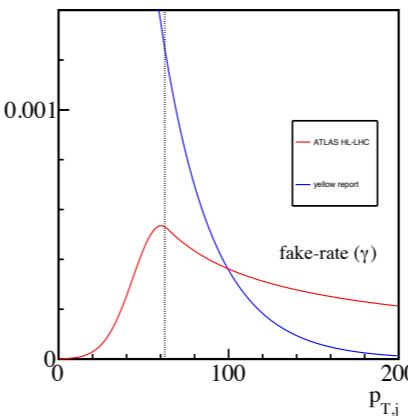
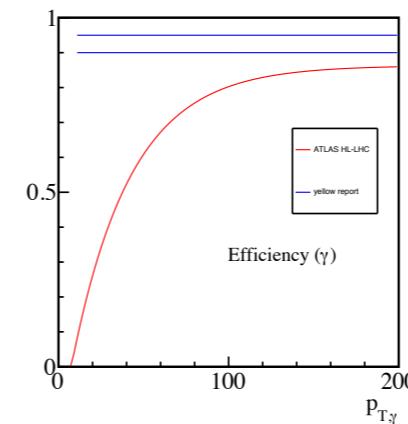
two photons, two b-jets

$$\epsilon_{\gamma \rightarrow \gamma} = 0.863 - 1.07 \cdot e^{-p_{T,\gamma}/34.8 \text{ GeV}},$$

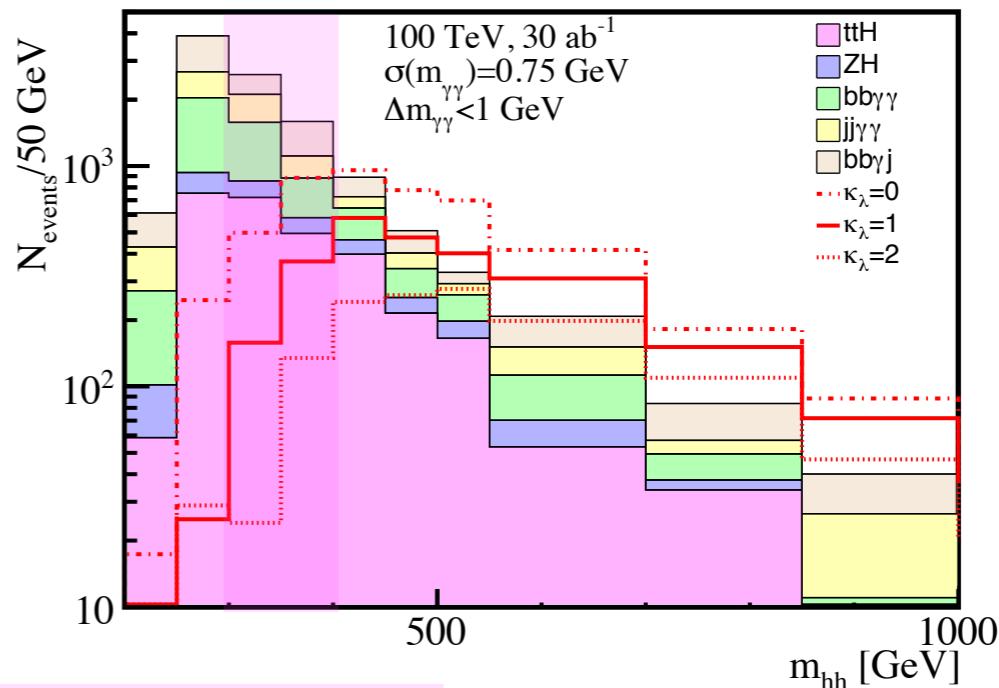
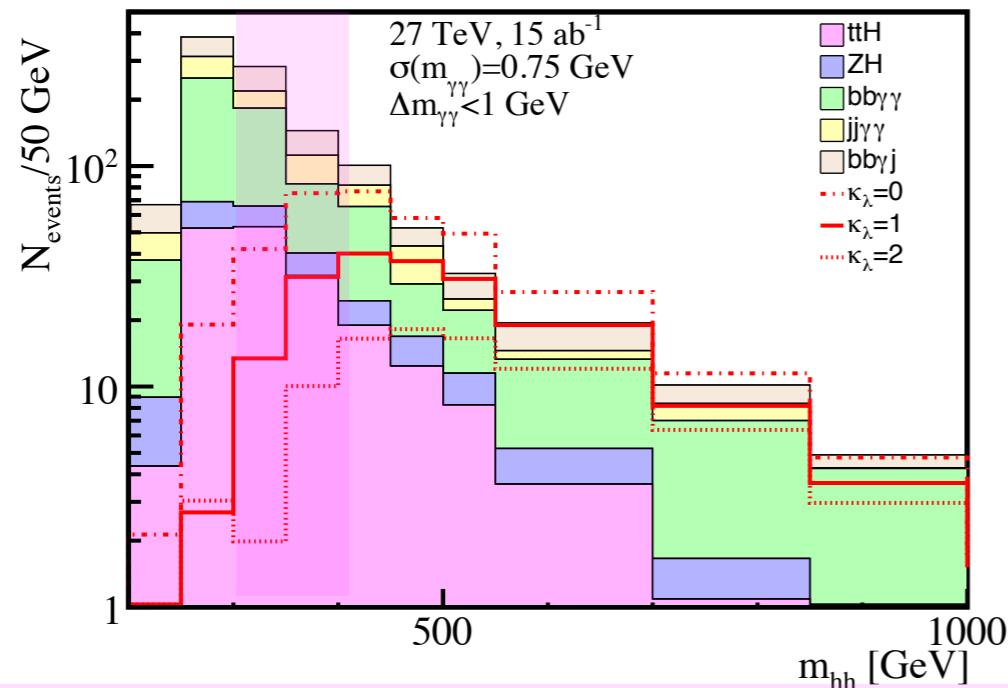
$$\epsilon_{j \rightarrow \gamma} = \begin{cases} 5.3 \cdot 10^{-4} \exp\left(-6.5\left(\frac{p_{T,j}}{60.4 \text{ GeV}} - 1\right)^2\right), & pT < 65 \text{ GeV} \\ 0.88 \cdot 10^{-4} \left[\exp\left(-\frac{p_{T,j}}{943 \text{ GeV}}\right) + \frac{248 \text{ GeV}}{p_{T,j}}\right], & pT > 65 \text{ GeV} \end{cases}$$

reducing fake photon important (esp. low pT)

both pairs provide higgs mass



Higgs Signal/BG: peaked  
continuum BG: flat  
(controllable by side-bands)



characteristic structure should appear in low  $m_{hh}$  region

but very difficult to access it due to too huge BG (cf. using jet recoil)

We have to require  $m_{hh} > 400 \text{ GeV}$

# Results

Baseline:  $p_{T,j} > 30 \text{ GeV}, |\eta_j| < 2.5,$   $\epsilon_b = 70\%$   $\epsilon_c = 15\%$   $\epsilon_j = 0.3\%$   
 $p_{T,\gamma} > 30 \text{ GeV}, |\eta_\gamma| < 2.5,$   
 $\Delta R_{\gamma\gamma, \gamma j, jj} > 0.4.$

Collider	Process	$\kappa_\lambda$			$t\bar{t}h$	$Zh$	$b\bar{b}\gamma\gamma$	$jj\gamma\gamma$	$b\bar{b}\gamma j$	BG tot.	$S/\sqrt{S+B}_{\text{lab}^{-1}}$	$S/B$
		0	1	2								
HE-LHC (15 ab $^{-1}$ )	$\sigma$ [fb]	0.69	0.36	0.18	6.43	0.77	1.24 pb	36.6 pb	506 pb			
	Baseline	2.87K	1.57K	838	21.8K	1.44K	1.19M	36M	1.13M	38.3M	0.07	$4 \cdot 10^{-5}$
	$n_j \leq 3, n_b = 2$	648	356	190	954	389	200K	67.4K	105K	374K	0.15	$1 \cdot 10^{-3}$
	$\Delta m_{bb} \leq 25 \text{ GeV}$	470	260	140	195	66	43.7K	10.6K	25.8K	80.4K	0.24	0.003
	$\Delta m_{\gamma\gamma} \leq 3 \text{ GeV}$	459	253	136	197	63	1.42K	505	758	2.94K	1.2	0.09
	$\Delta m_{\gamma\gamma} \leq 2 \text{ GeV}$	459	253	136	197	63	957	342	504	2.06K	1.4	0.12
	$\Delta m_{\gamma\gamma} \leq 1 \text{ GeV}$	459	253	136	197	63	485	182	245	1.17K	1.7	0.22
	$\Delta m_{\gamma\gamma} \leq 3 \text{ GeV}, m_{hh} > 400$	320	206	120	56	21	324	97	178	676	1.8	0.30
	$\Delta m_{\gamma\gamma} \leq 2 \text{ GeV}, m_{hh} > 400$	320	206	120	56	21	220	67	122	485	2.0	0.42
	$\Delta m_{\gamma\gamma} \leq 1 \text{ GeV}, m_{hh} > 400$	320	206	120	56	21	115	41	61	293	2.4	0.70
100 TeV (30 ab $^{-1}$ )	$\sigma$ [fb]	6.95	3.72	1.97	84.8	3.76	6.21 pb	126 pb	3.03 nb			
	Baseline	51.8K	29.8K	16.9K	535K	13.1K	13.6M	330M	18.6M	363M	0.29	$8 \cdot 10^{-5}$
	$n_j \leq 3, n_b = 2$	9.22K	5.28K	3.02K	18K	2.84K	1.79M	773K	1.42M	4.00M	0.48	0.001
	$\Delta m_{bb} \leq 25 \text{ GeV}$	6.45K	3.80K	2.18K	3.3K	669	361K	218K	373K	956K	0.71	0.004
	$\Delta m_{\gamma\gamma} \leq 3 \text{ GeV}$	6.30K	3.70K	2.13K	3.12K	653	8.34K	6.06K	8.99K	27.2K	3.9	0.14
	$\Delta m_{\gamma\gamma} \leq 2 \text{ GeV}$	6.30K	3.70K	2.13K	3.12K	653	5.66K	4.13K	5.99K	19.5K	4.4	0.19
	$\Delta m_{\gamma\gamma} \leq 1 \text{ GeV}$	6.30K	3.70K	2.13K	3.12K	653	2.82K	1.91K	2.99K	11.4K	5.5	0.32
	$\Delta m_{\gamma\gamma} \leq 3 \text{ GeV}, m_{hh} > 400$	4.66K	3.16K	1.93K	1.09K	203	1.56K	1.10K	1.90K	5.86K	6.1	0.54
	$\Delta m_{\gamma\gamma} \leq 2 \text{ GeV}, m_{hh} > 400$	4.66K	3.16K	1.93K	1.09K	203	1.04K	747	1.14K	4.23K	6.7	0.73
	$\Delta m_{\gamma\gamma} \leq 1 \text{ GeV}, m_{hh} > 400$	4.66K	3.16K	1.93K	1.09K	203	523	359	617	2.79K	7.5	1.13

including 3rd jets in the analysis important

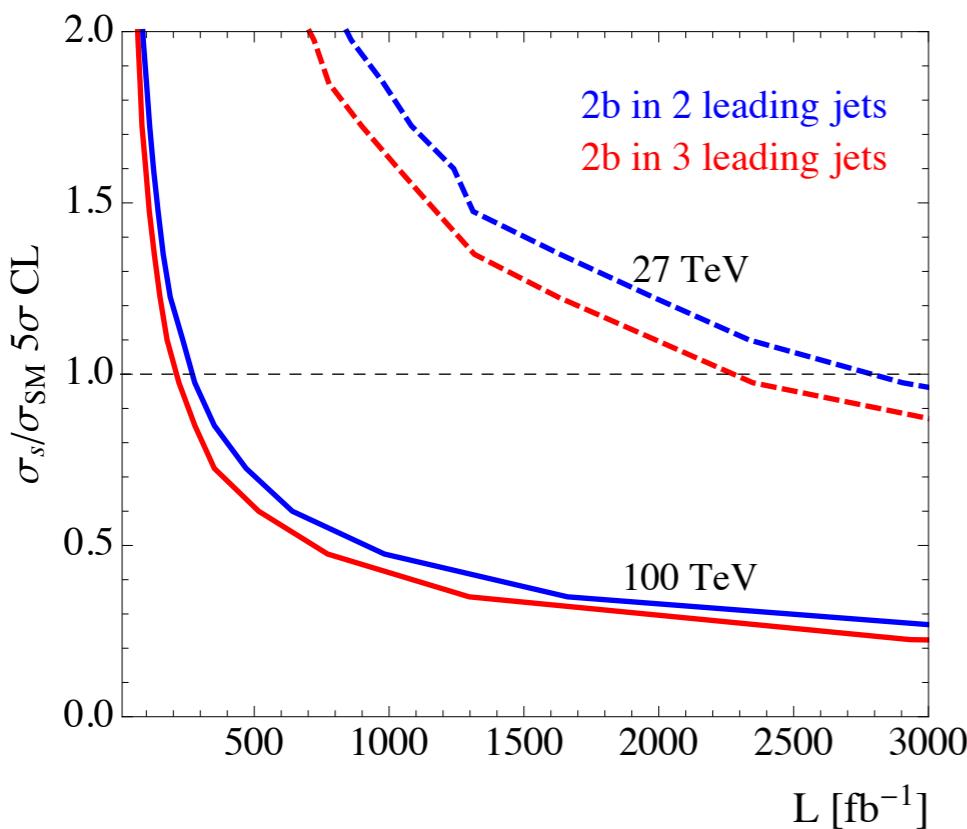
narrowing di-photon mass range effective to reach S/B ~ 1.

(the resolution 0.75, 1.5, 2.25 GeV assumed corresponding to the 1,2,3 GeV range)

[Note: 1.5GeV is already achieved at the LHC.]

4th jet veto mainly for reducing ttH BG.

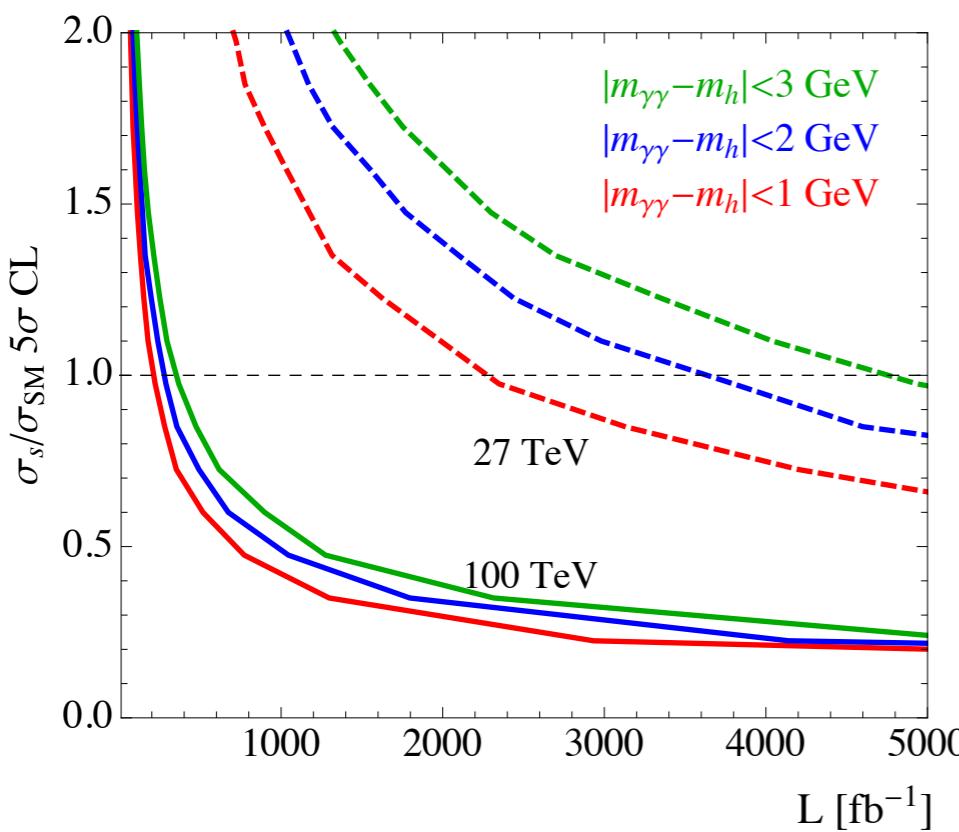
# Two important comments



sub-samples ( $bb, bbj$ ) and ( $jbb, bjb$ )

including b-tag in 3rd jet clearly improves the sensitivity

The  $5\sigma$  measurement for HE-LHC is  
 $2.8 \text{ ab}^{-1}$  to below  $2.3 \text{ ab}^{-1}$

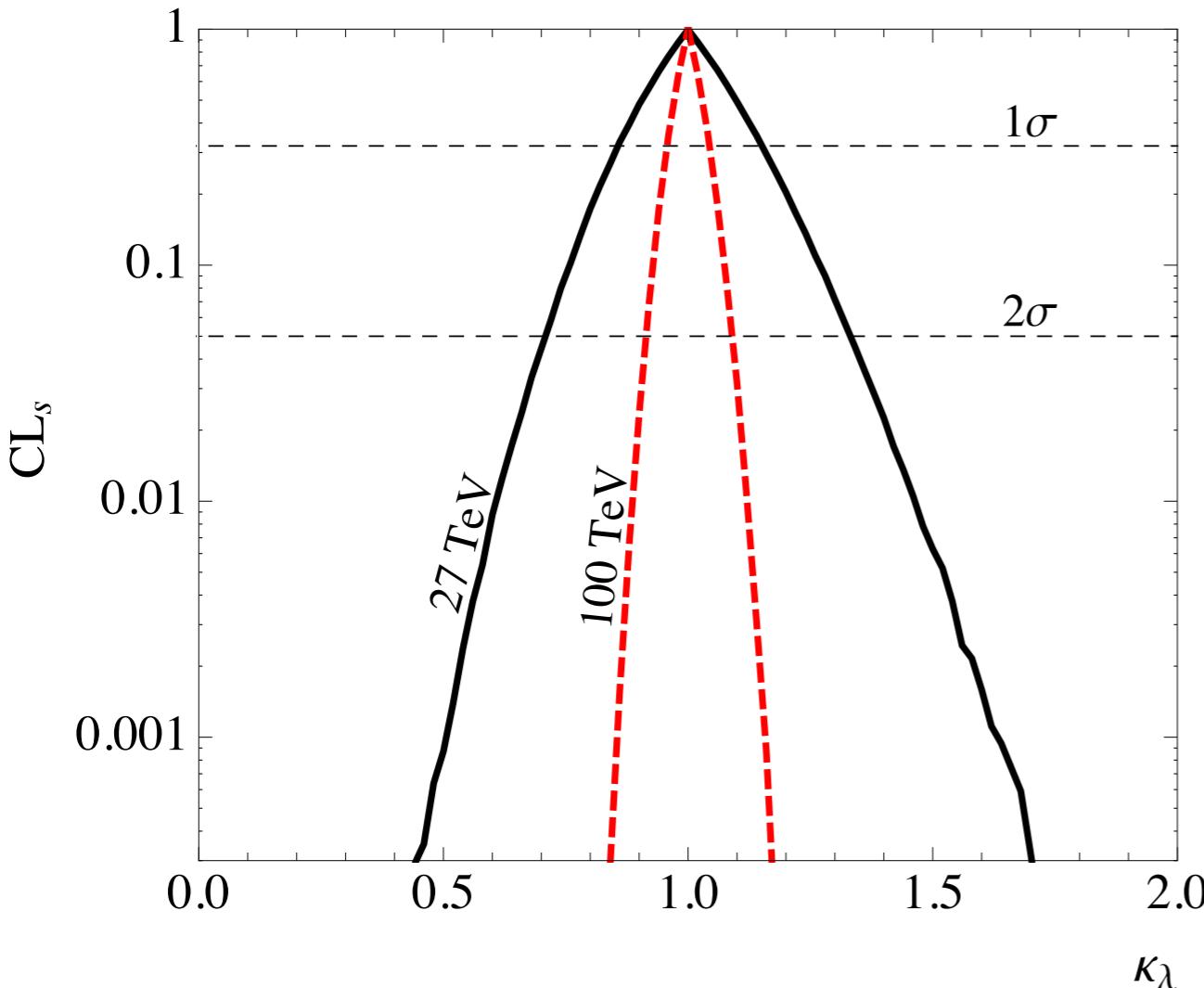


for Higgs self coupling sensitivity  
photon invariant mass resolution most important

(the resolution 0.75, 1.5, 2.25 GeV assumed  
corresponding to the 1,2,3 GeV range)  
[1.5 GeV is already achieved at LHC]

important for detector design

# sensitivity at HE-LHC



Phys. Rev. D 97, 113004 [arXiv:1802.04319]  
[D. Goncalves, T. Han, F. Kling, T. Plehn, MT]

The other channels contribute sub-dominantly.

HE-LHC, 27 TeV,  $15 \text{ ab}^{-1}$

$$\kappa_\lambda \approx 1 \pm 15\% \text{ } (1\sigma)$$

$$\kappa_\lambda \approx 1 \pm 30\% \text{ } (2\sigma)$$

conclusive sensitivity to determine whether self-coupling deviation is  $O(1)$  or not

for 100 TeV,  $30 \text{ ab}^{-1}$

$$\kappa_\lambda \approx 1 \pm 5\% (1\sigma), 10\% (2\sigma)$$

# Summary

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**HE-LHC (27TeV)** machine for Higgs self-coupling measurement  
to answer yes/no for the EW Baryogenesis

successful EWBG require the 70% enhancement on the Higgs self-coupling.

We have checked the sensitivity at HE-LHC (27TeV,  $15\text{ab}^{-1}$ )  $\sim 15\%$  [cf. 70% at HL-LHC]  
(it would be able to exclude the EWBG scenario at  $\sim 5\sigma$ )

low  $m_{hh}$  region exhibit a characteristic structure but not possible to access  
due to the huge background.

important: including 3rd jets properly, improving di-photon invariant mass resolution

We would be able to reach S/B  $\sim 1$ , and O(200) events allow the shape analysis

100TeV collider would improve the sensitivity by a factor 3,  $\sim 5\%$ .