Higgs pair production at future colliders

Michihisa Takeuchi (Kavli IPMU, Univ. of Tokyo)

at IAS Hongkong, on 10th Jan. 2019

LHC & Future Colliders

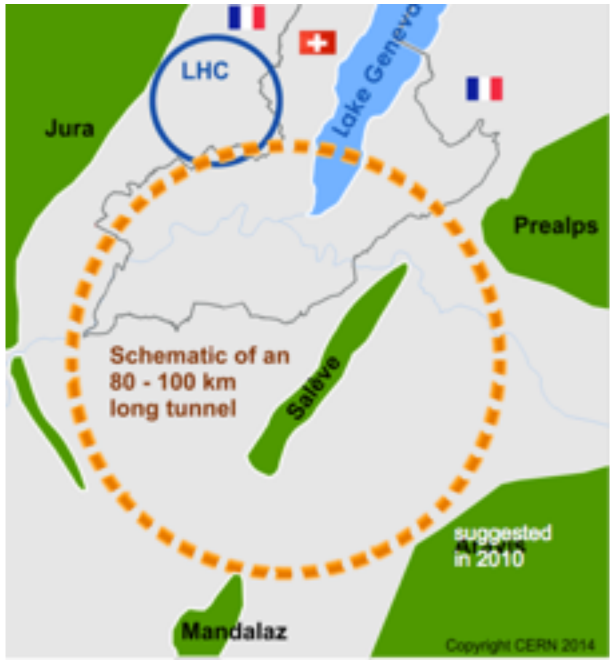
LHC: 14 TeV 3 ab^{-1} (or 4ab^{-1}) 8T dipole ~2039

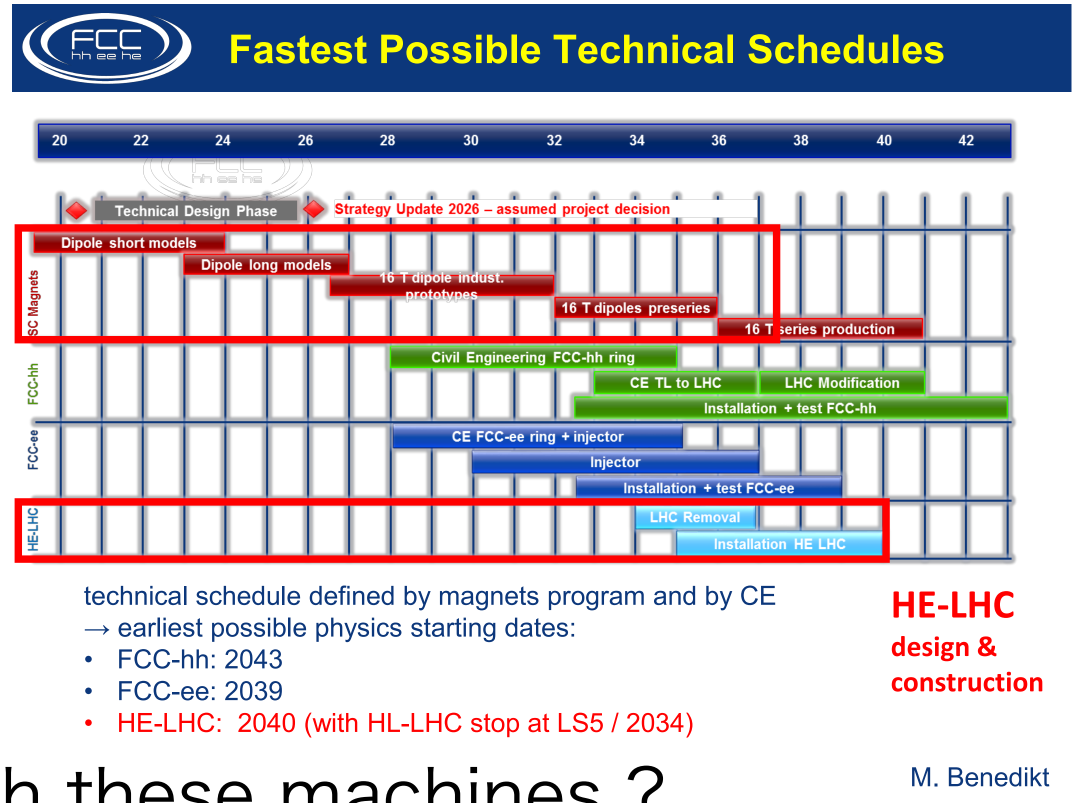
ILC: 250GeV 2 ab^{-1} , (500GeV, 1TeV, 2TeV, …)

HE-LHC: 27 TeV 15 ab^{-1} 16T dipole 2040~

100TeV collider: 100 TeV 30 ab^{-1} x3-4 long tunnel 16T dipole 2043~

CERN (or in China?)



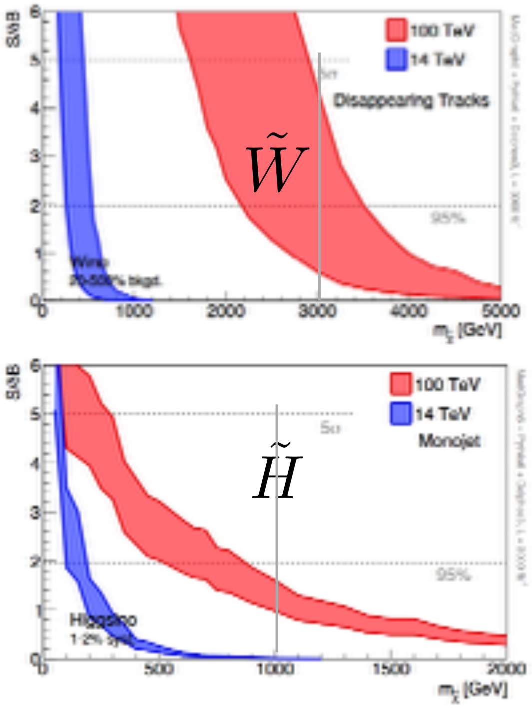

Fastest Possible Technical Schedules

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

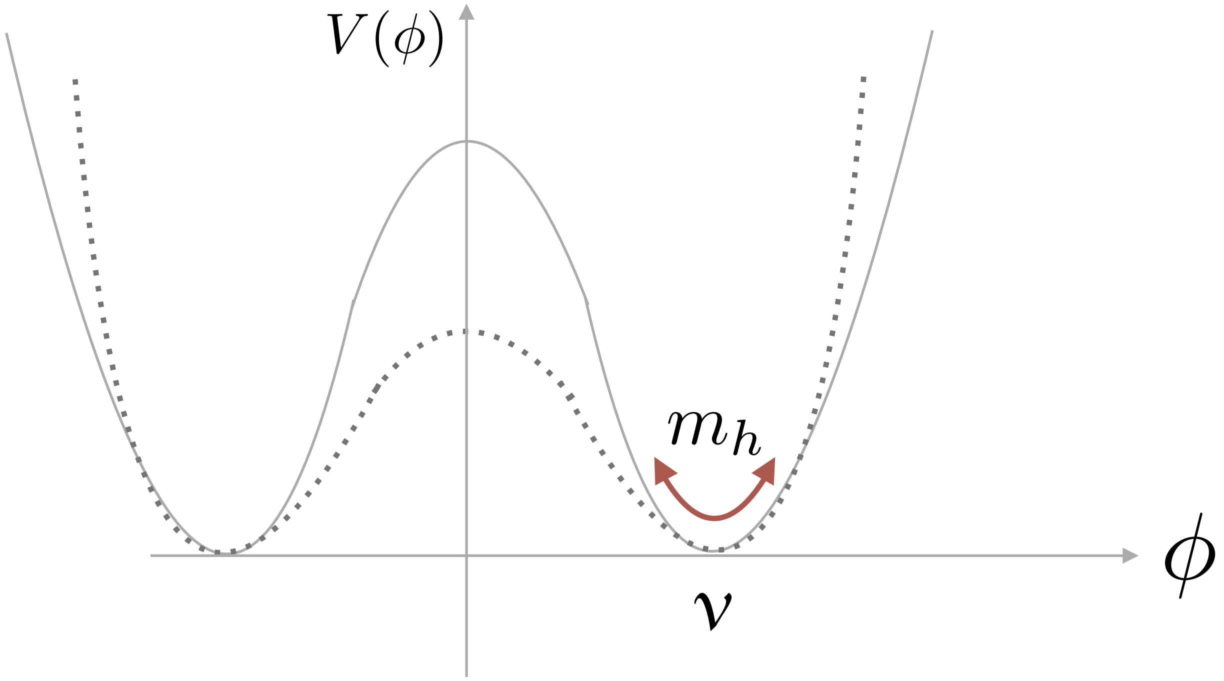


What do we search for with these machines ?

Reaches/Precision obviously improves. Can we answer qualitative yes/no question?

ex) Thermal WIMP DM can be fully searched?

Higgs potential shape



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

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

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

$$\lambda_4 = 6\lambda$$

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

global Higgs potential shape might be different from simple $\lambda\phi^4 + \mu\phi^2$

for example, ϕ^6 term

HE-LHC (27TeV , 15 ab^{-1}):

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

arXiv:1802.04319 [D. Goncalves, T. Han, F. Kling, T. Plehn, MT]

How accurate λ measurement would be interesting？

EWSB phase transition at early universe

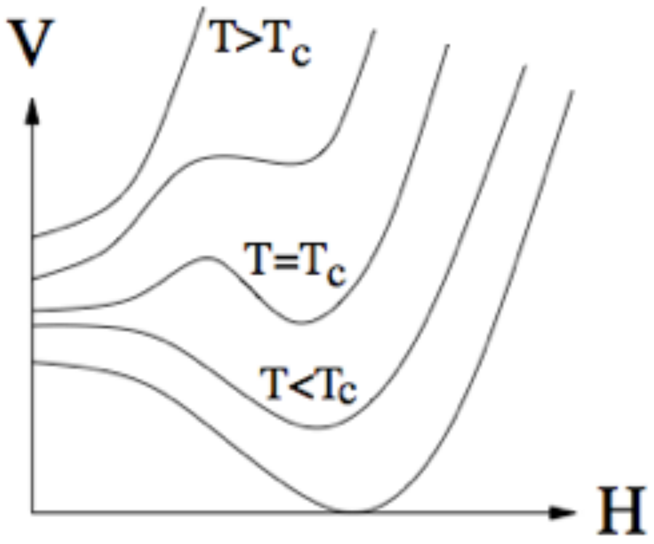
finite temp. effective higgs potential

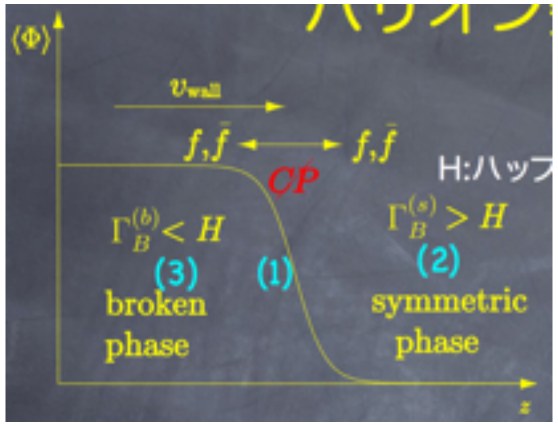
$$V(h)=\frac{\lambda}{4}h^4+\lambda v h^3+\cdots=\frac{\lambda_4}{4!}h^4+\frac{\lambda_3}{3!}h^3+$$

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

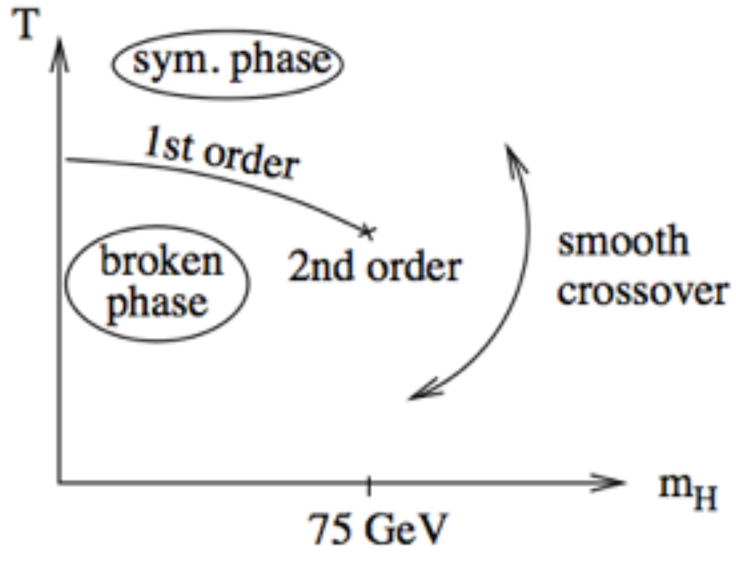
in the SM $\lambda_{\rm SM}\approx 1/8.$

$$\lambda_4=6\lambda \qquad \lambda_3=6\lambda v=\frac{3m_h^2}{v}$$





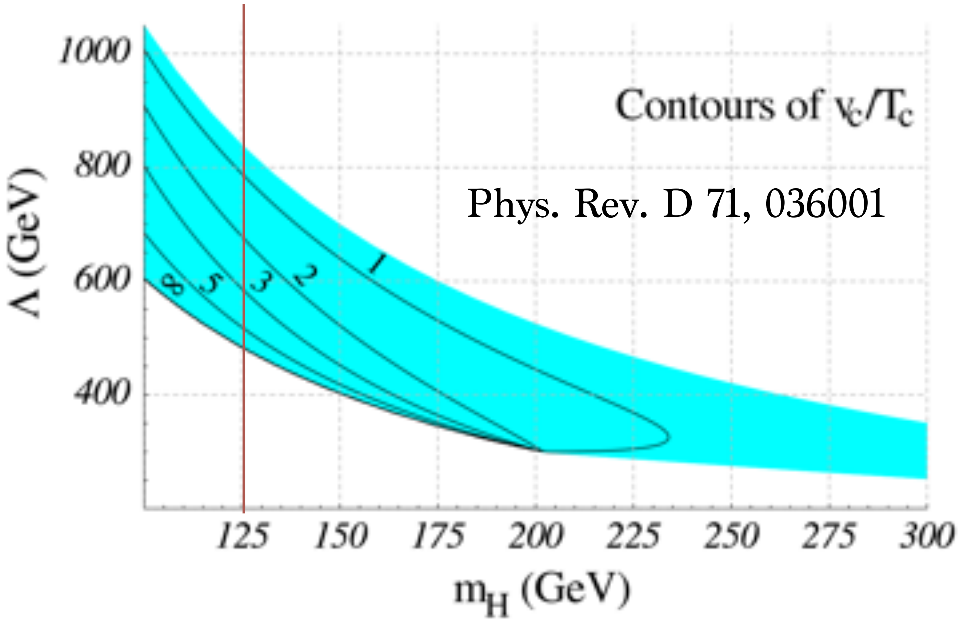
For EW baryogenesis successful strong 1st order PT ($v_c/T_c > 1$) required (necessary condition)

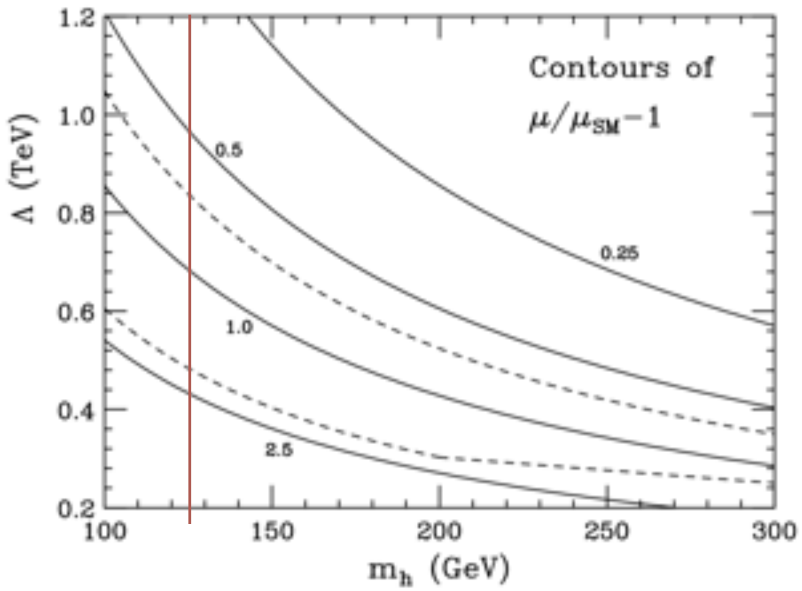


125 GeV Higgs is too heavy for EWBG successful

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 λ_3 required

[C. Grojean, G. Servant, J. Wells]

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

To exclude this EWBG scenario, 70% level measurements required for λ_3

the statement is rather general

[Phys.Rev. D97 (2018) no.7, 075008
M. Reichert, A. Eichhorn, H. Gies, J. M. Pawlowski, T. Plehn, M. M. Scherer]

$$V_{k=\Lambda} = \frac{\mu^2}{2}\phi^2 + \frac{\lambda_4}{4}\phi^4 + \Delta V,$$

$$\Delta V_6 = \lambda_6 \frac{\phi^6}{\Lambda^2}, \qquad \Delta V_8 = \lambda_6 \frac{\phi^6}{\Lambda^2} + \lambda_8 \frac{\phi^8}{\Lambda^4},$$

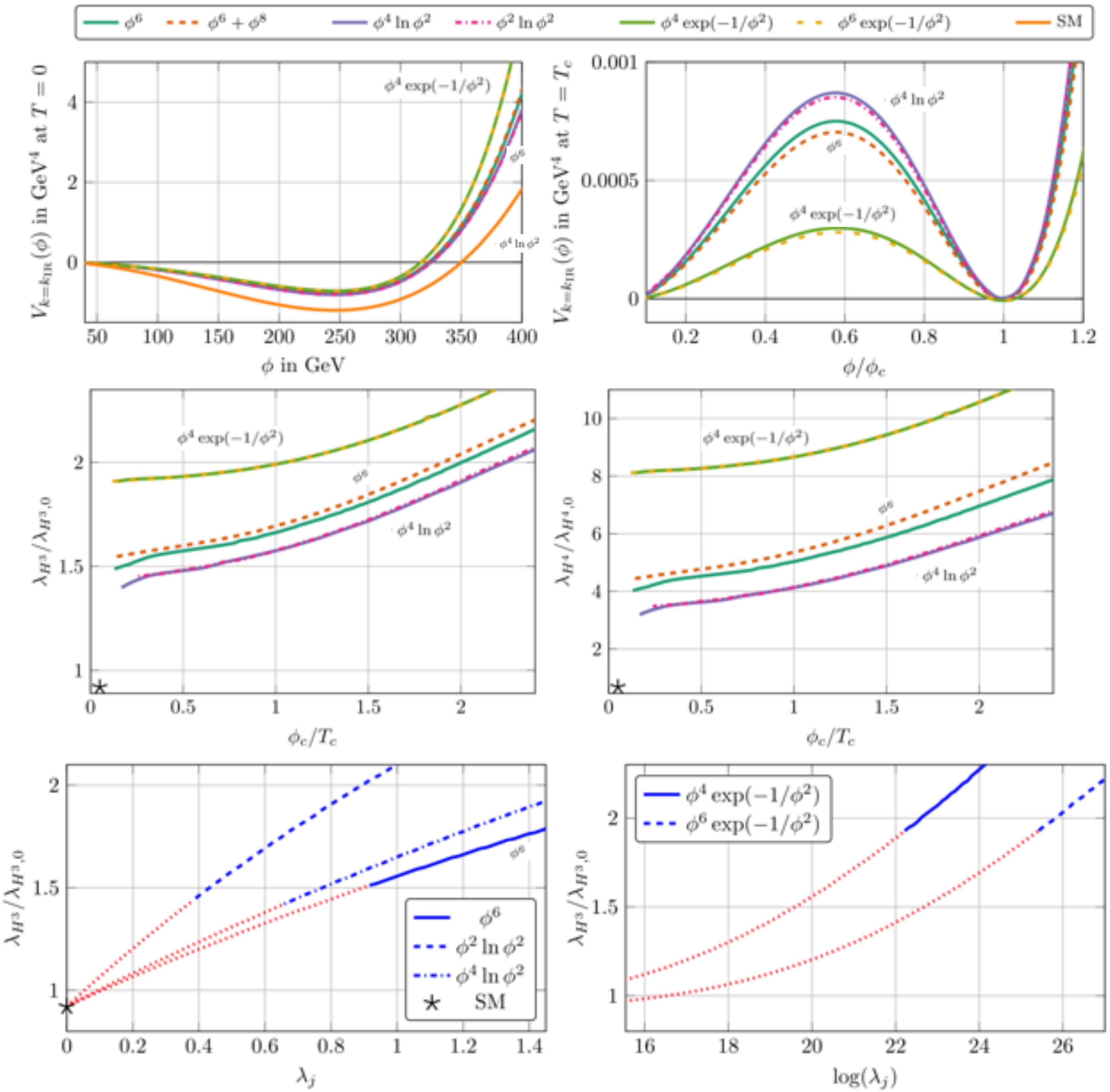
$$\Delta V_{\ln,2} = -\lambda_{\ln,2} \frac{\phi^2 \Lambda^2}{100} \ln \frac{\phi^2}{2\Lambda^2},$$

$$\Delta V_{\ln,4} = \lambda_{\ln,4} \frac{\phi^4}{10} \ln \frac{\phi^2}{2\Lambda^2},$$

$$\Delta V_{\exp,4} = \lambda_{\exp,4} \phi^4 \exp\left(-\frac{2\Lambda^2}{\phi^2}\right),$$

$$\Delta V_{\exp,6} = \lambda_{\exp,6} \frac{\phi^6}{\Lambda^2} \exp\left(-\frac{2\Lambda^2}{\phi^2}\right).$$

Considering 3 types of potentials



strong 1st order PT → O(1) deviation in λ_3 required

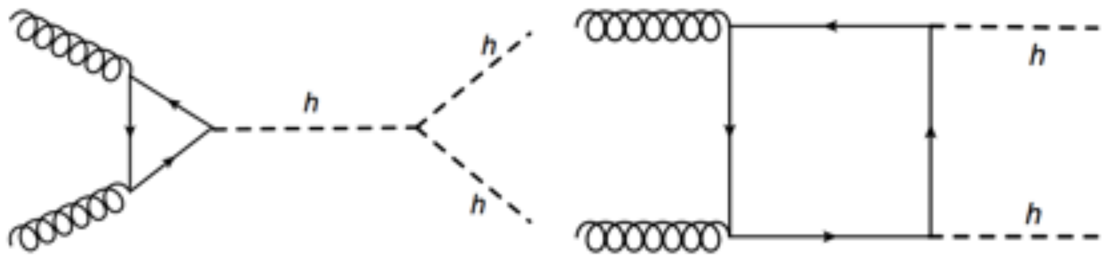
$$\lambda_3 = \frac{3m_h^2}{v} + \frac{6v^3}{\Lambda^2} \gtrsim 1.7\lambda_{3,\mathrm{SM}}$$

To exclude this EWBG scenario, 70% level measurements required for λ_3

λ sensitivity at HL-LHC

the lowest process involving the self coupling at LHC

Higgs pair production $pp \to hh$



40 fb = 120k events in full lifetime of LHC

hh decays:

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

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

$b\bar{b}WW$

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

$4W$.

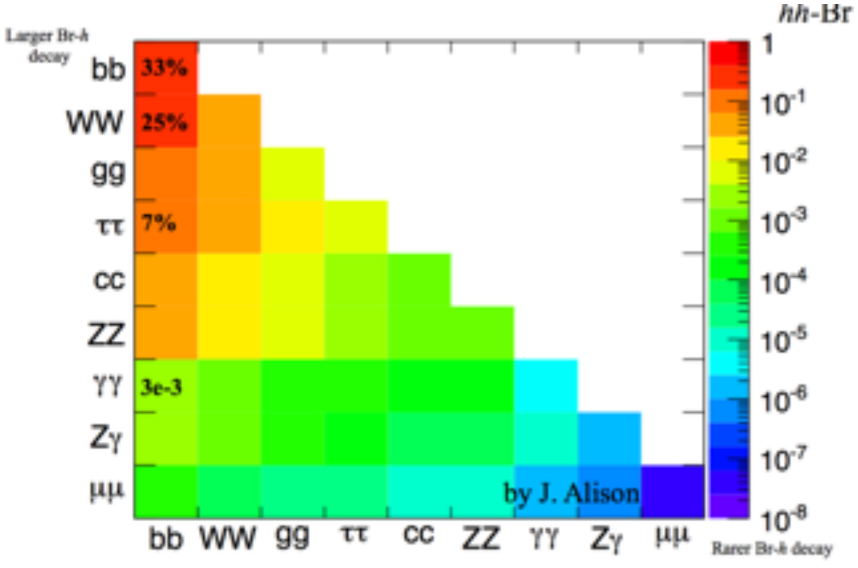
Best sensitivity channel

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 $\kappa_\lambda = \frac{\lambda}{\lambda_{\mathrm{SM}}}$.

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

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

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

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

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

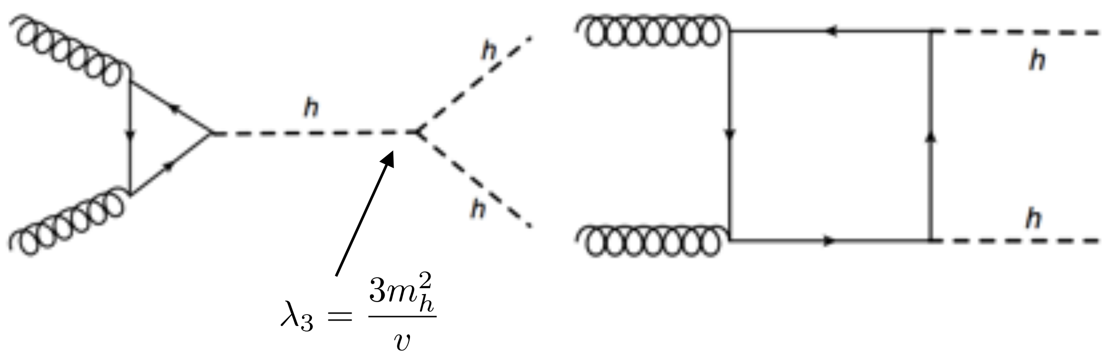
$$\kappa_\lambda \approx 1^{+75\%}_{-60\%}$$

not satisfactory at all.

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

three phase space

strong destructive interference



$$\mathcal{M} = \kappa_\lambda y_t \mathcal{M}_\triangle + y_t^2 \mathcal{M}_\Box$$

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

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

$$\frac{\alpha_S}{12\pi} G^{\mu\nu} G_{\mu\nu} \log(1+\frac{h}{v})$$

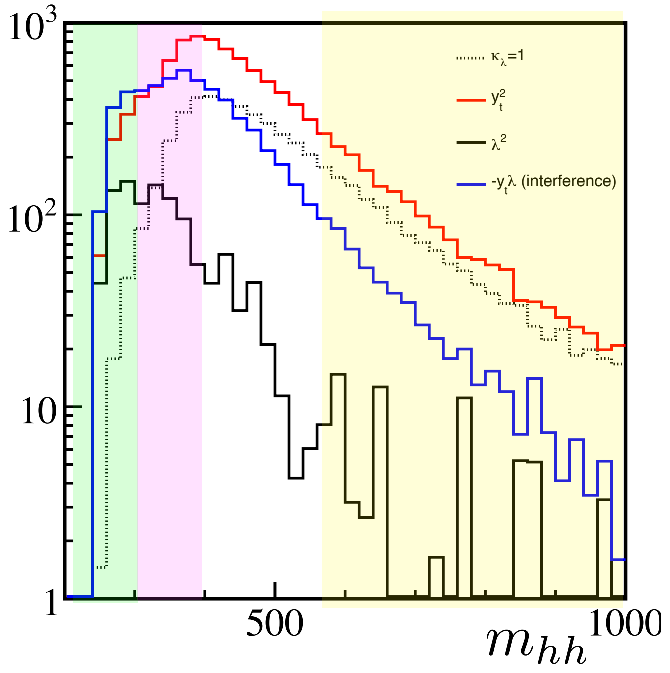
$$\log(1+\frac{h}{v}) = \frac{h}{v} - \frac{h^2}{2v^2} + \cdots$$

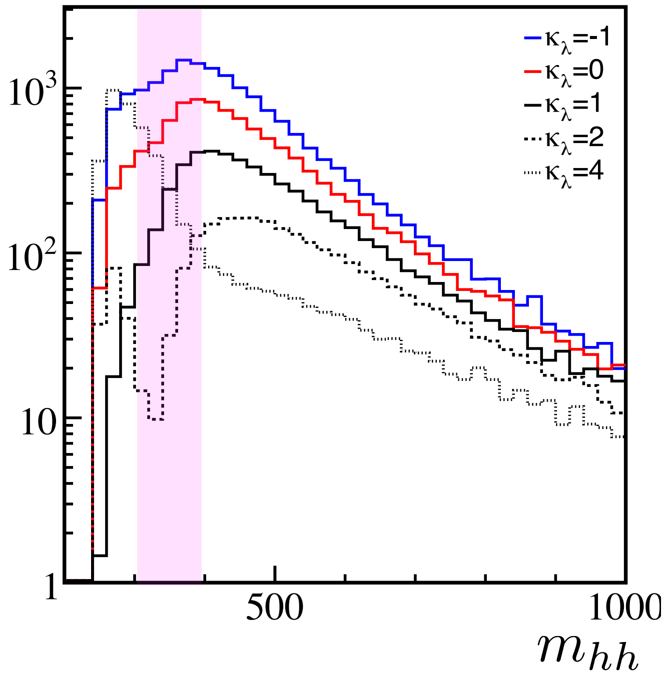
$$m_{hh}^{(\mathrm{abs})} \approx 2m_t\,.$$

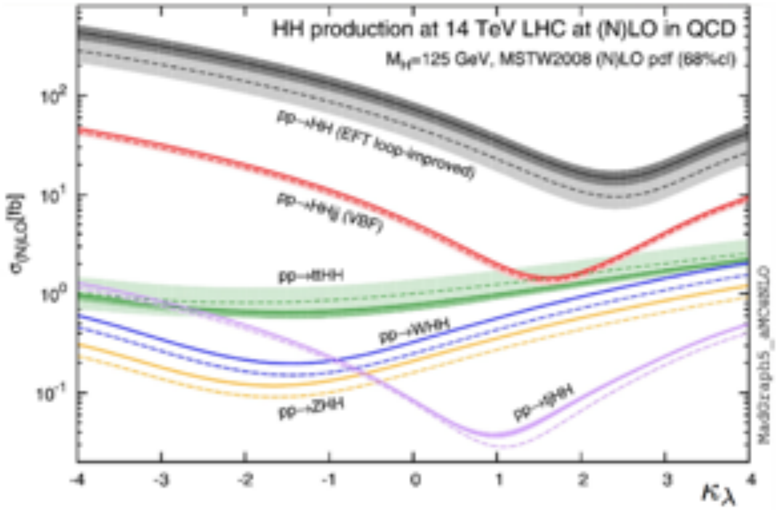
absorptive imaginary parts lead to a significant dip

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

box contributions decay slower





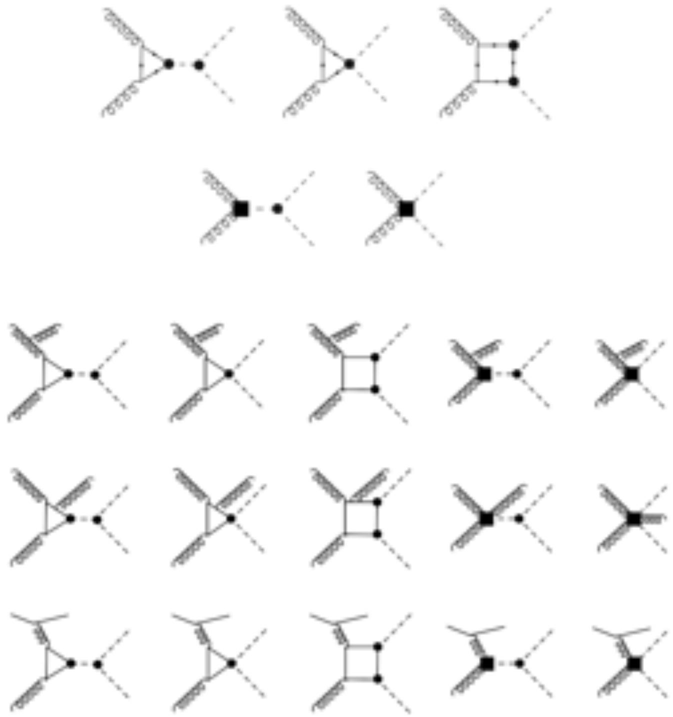


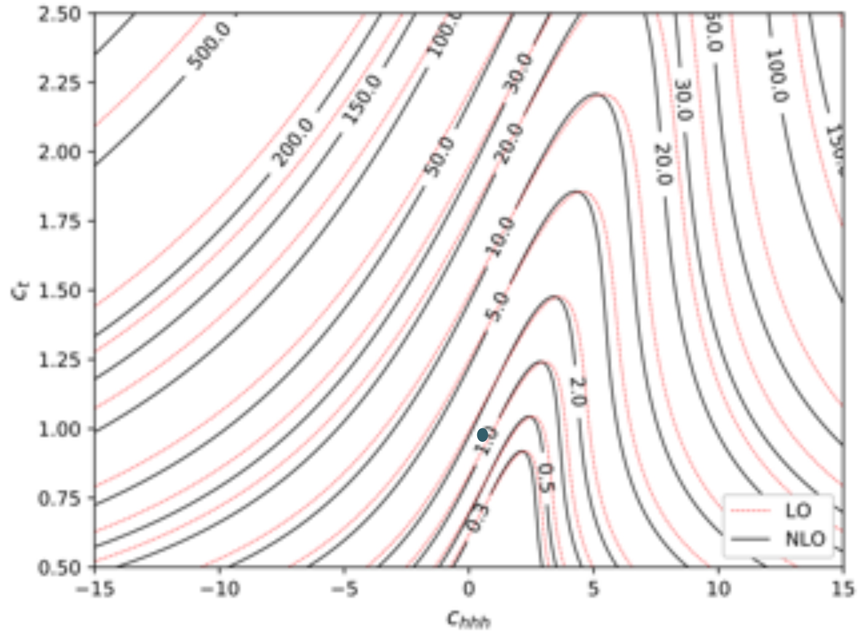
Since they are scalar particles, only m_{hh} distribution has the information at LO.

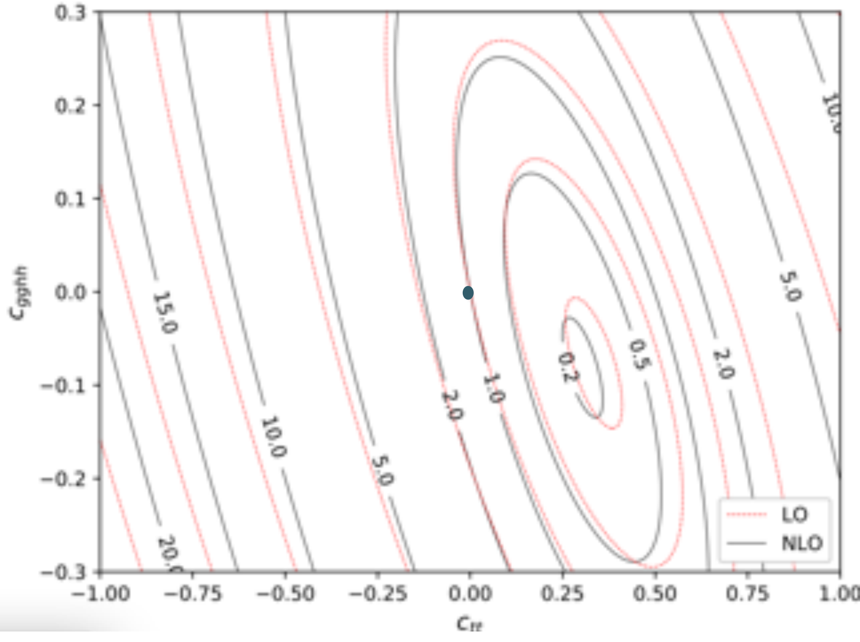
Theory prediction at NLO

include EFT couplings and full mt dependence [arXiv: 1806.05162]

$$\mathcal{L} \supset -m_t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{v^2} \right) \bar{t}\, t - c_{hhh} \frac{m_h^2}{2v} h^3 + \frac{\alpha_s}{8\pi} \left(c_{ggh} \frac{h}{v} + c_{gghh} \frac{h^2}{v^2} \right) G^a_{\mu\nu} G^{a,\mu\nu} \,.$$



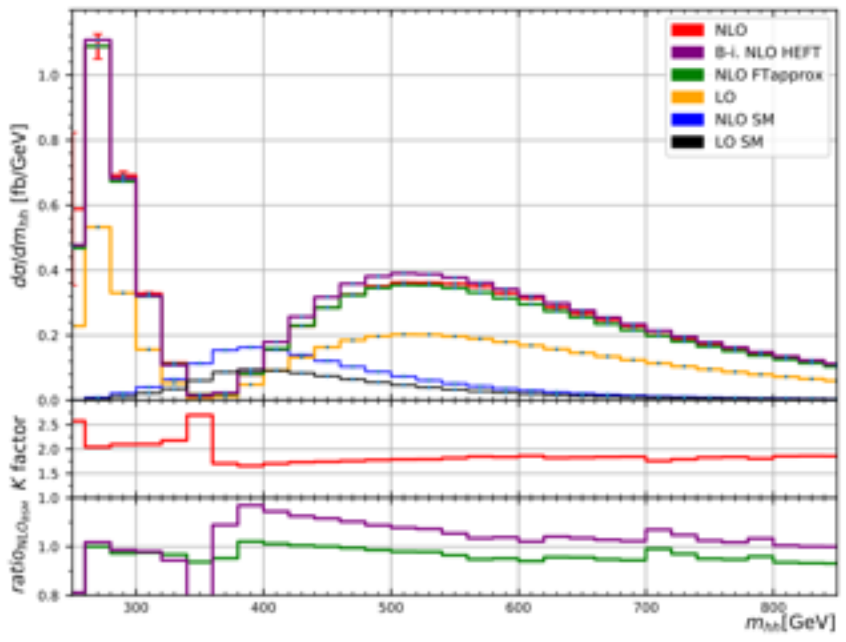




$$\sigma/\sigma_{SM} = A_1\, c_t^4 + A_2\, c_{tt}^2 + A_3\, c_t^2 c_{hhh}^2 + A_4\, c_{ggh}^2 c_{hhh}^2 + A_5\, c_{gghh}^2 + A_6\, c_{tt} c_t^2 + A_7\, c_t^3 c_{hhh}$$
$$+ A_8\, c_{tt} c_t\, c_{hhh} + A_9\, c_{tt} c_{ggh} c_{hhh} + A_{10}\, c_{tt} c_{gghh} + A_{11}\, c_t^2 c_{ggh} c_{hhh} + A_{12}\, c_t^2 c_{gghh}$$
$$+ A_{13}\, c_t c_{hhh}^2 c_{ggh} + A_{14}\, c_t c_{hhh} c_{gghh} + A_{15}\, c_{ggh} c_{hhh} c_{gghh} \,. \quad (2.7)$$

$$\Delta\sigma/\sigma_{SM} = A_{16}\, c_t^3 c_{ggh} + A_{17}\, c_t c_{tt} c_{ggh} + A_{18}\, c_t c_{ggh}^2 c_{hhh} + A_{19}\, c_t c_{ggh} c_{gghh}$$
$$+ A_{20}\, c_t^2 c_{ggh}^2 + A_{21}\, c_{tt} c_{ggh}^2 + A_{22}\, c_{ggh}^3 c_{hhh} + A_{23}\, c_{ggh}^2 c_{gghh} \,.$$

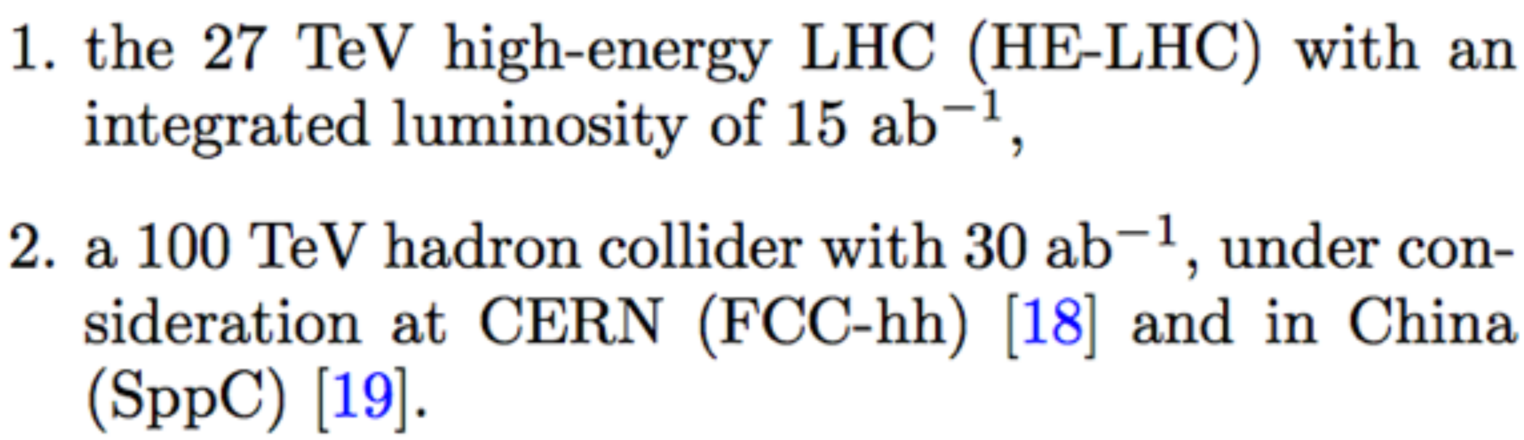
$c_{hhh} = 7.5, c_t = 1, c_{tt} = -1, c_{ggh} = c_{gghh} = 0.$



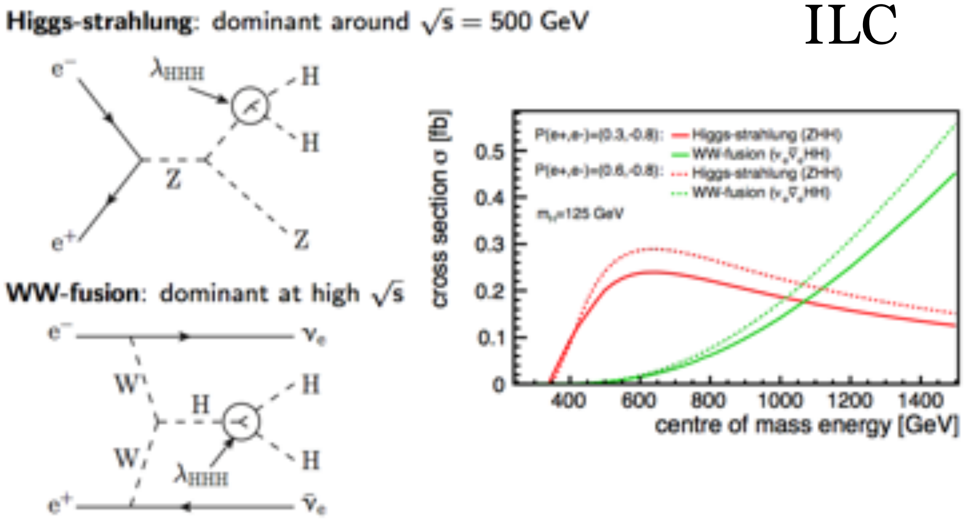
K-factor can be large up to 3, depending on the phase space

differential distribution for 23terms available at arxiv

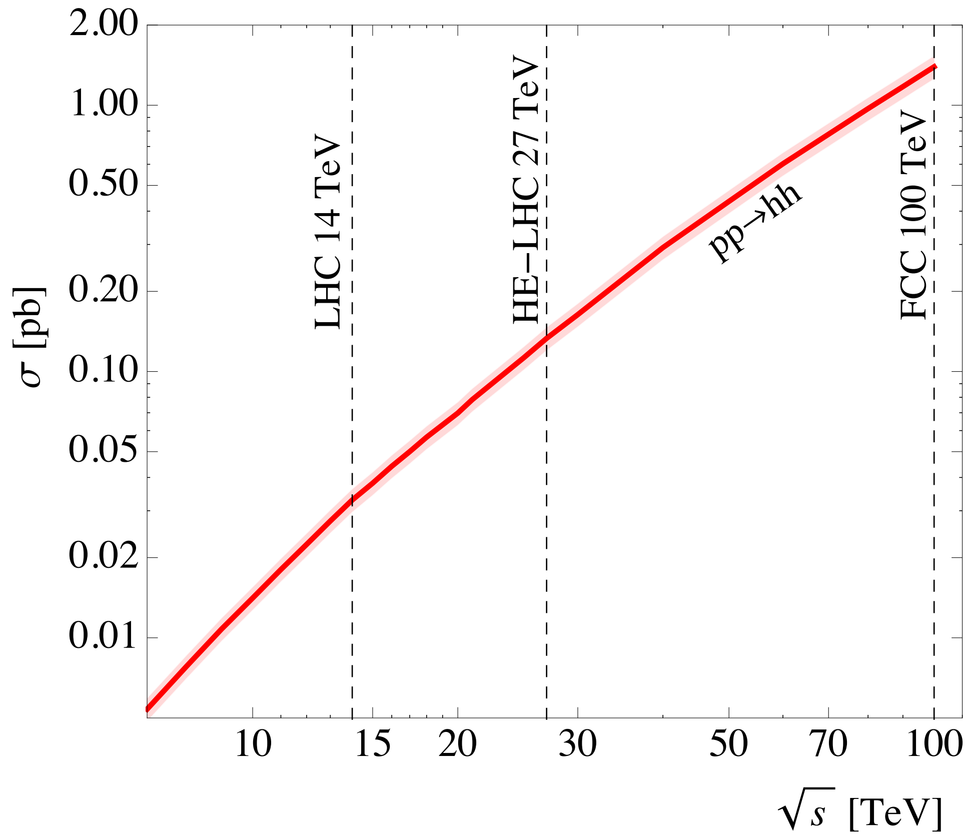
HE-LHC and 100 TeV colliders



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



ILC



in cross section compared with 14TeV

factor 4 (27TeV)

factor 40 (100TeV)

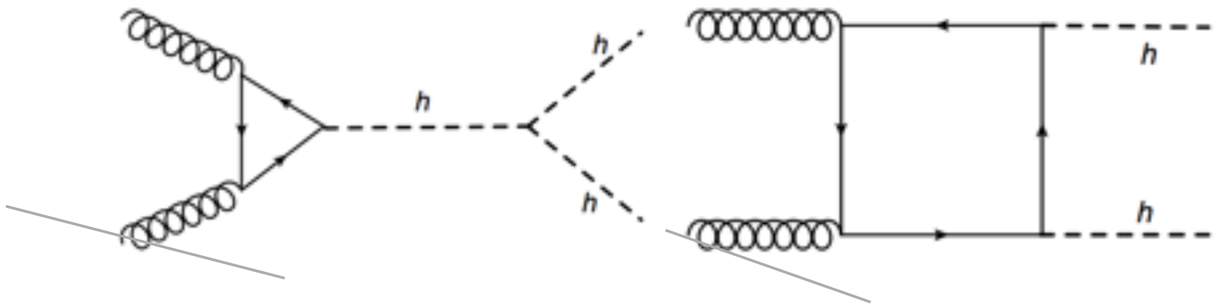
in event numbers

14 TeV → 27 TeV → 100 TeV

x20 x20

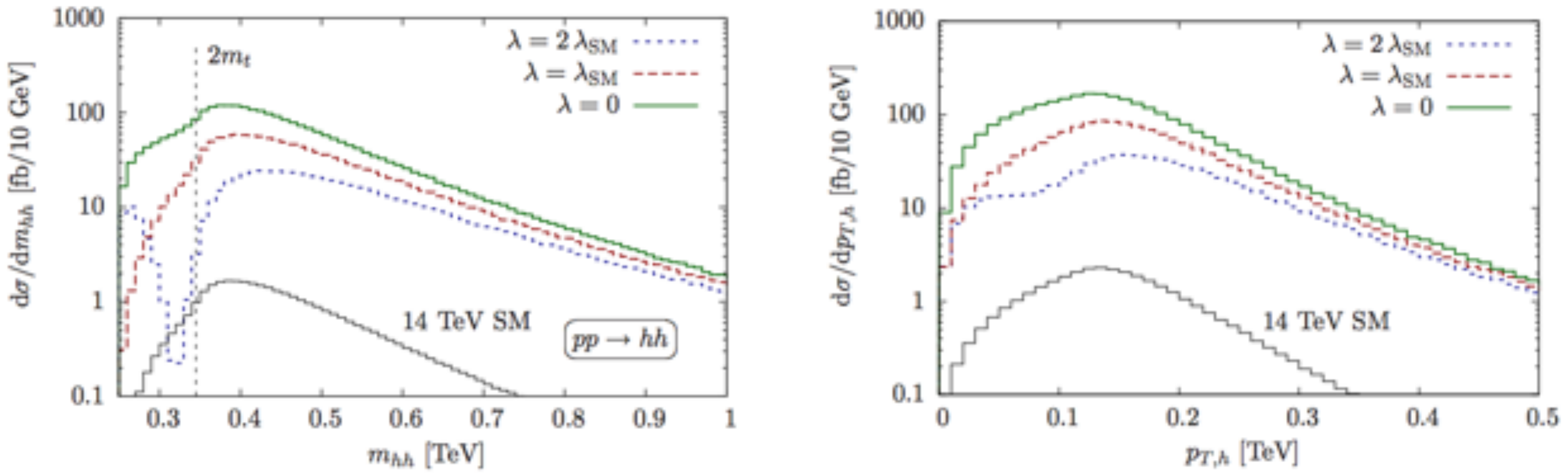
boosted HH + j

[arXiv:1412.7154, A. J. Barr, M. J. Dolan, C. Englert, D. F. de Lima, M. Spannowsky]

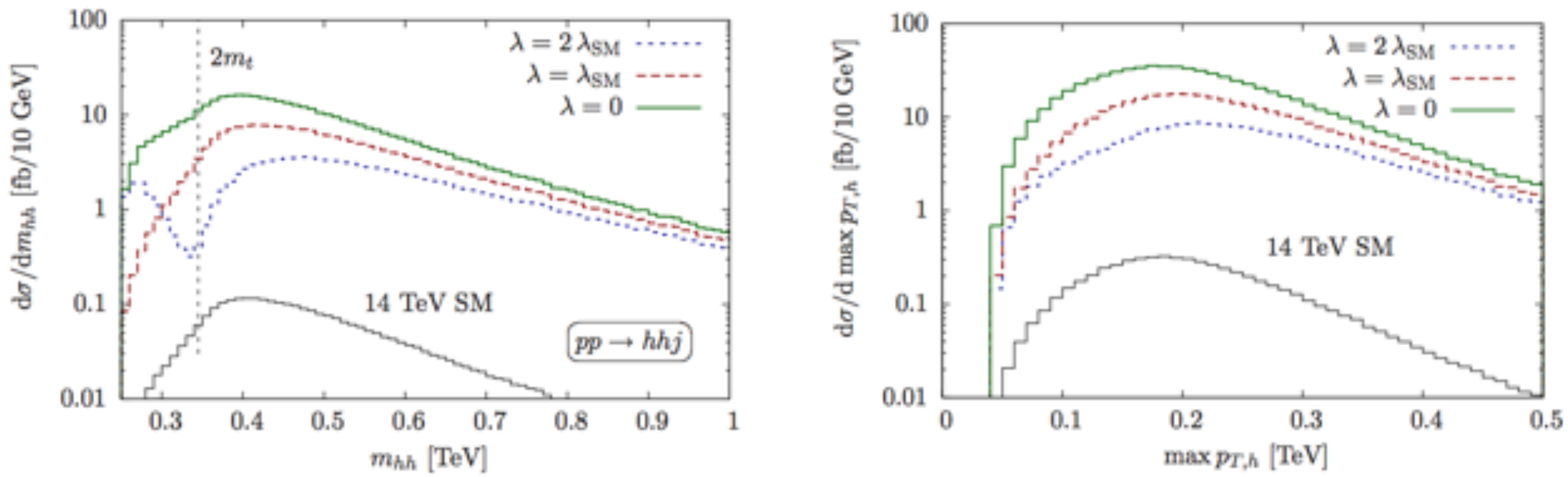


Boosting HH system provide possible S/B improvement

HH events



HH + j events



large p_{T,H}

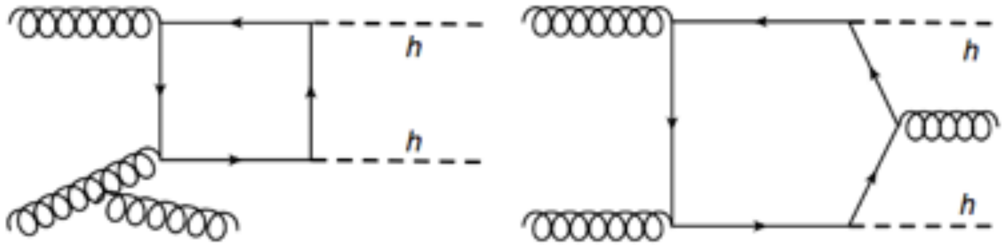
keeping mHH structure

requiring 1 additional jet reduce the number of remaining events

properly simulate the 3rd jet important

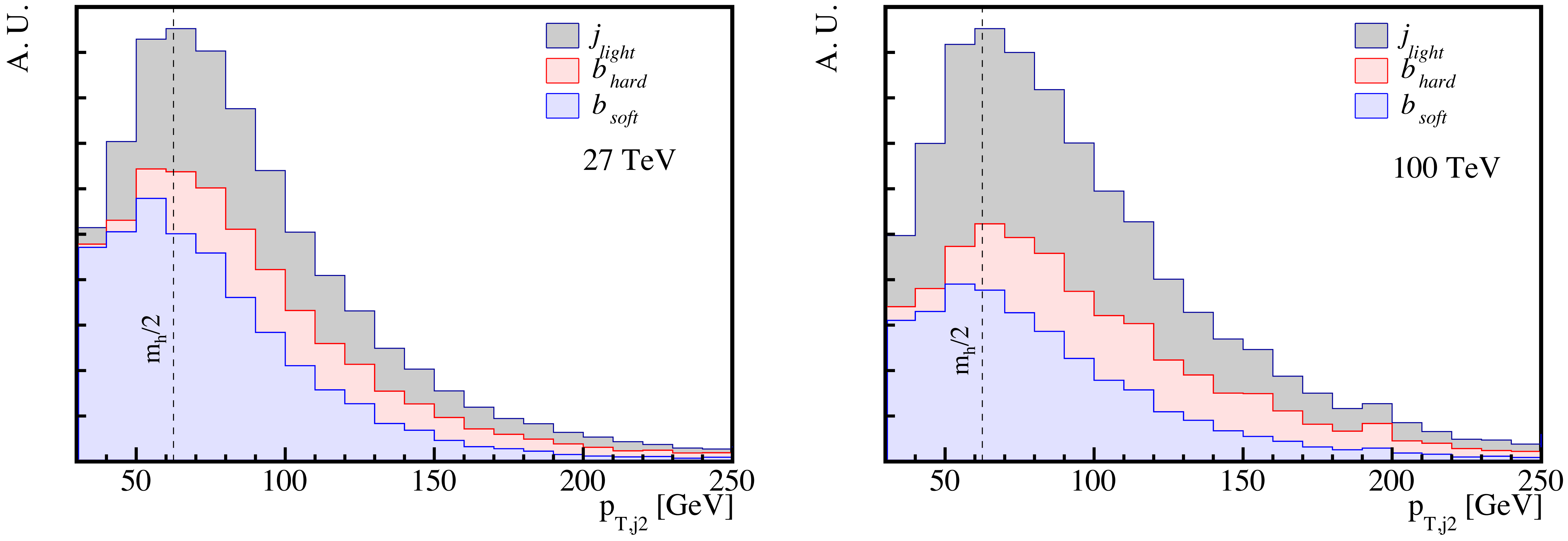
All Signal/BG samples simulated with 1 additional jet in MLM matching

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



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

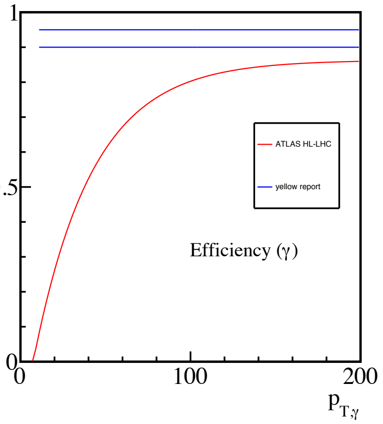
two photons, two b-jets

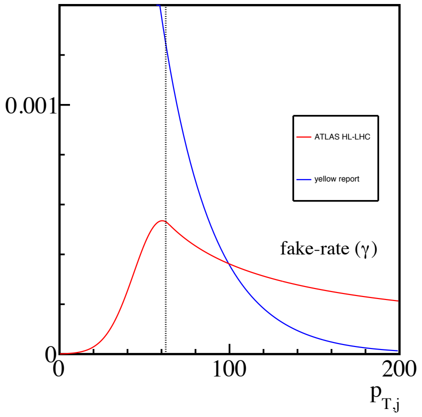
$$\epsilon_{\gamma\to\gamma} = 0.863 - 1.07\cdot e^{-p_{T,\gamma}/34.8\text{ GeV}}\ ,$$

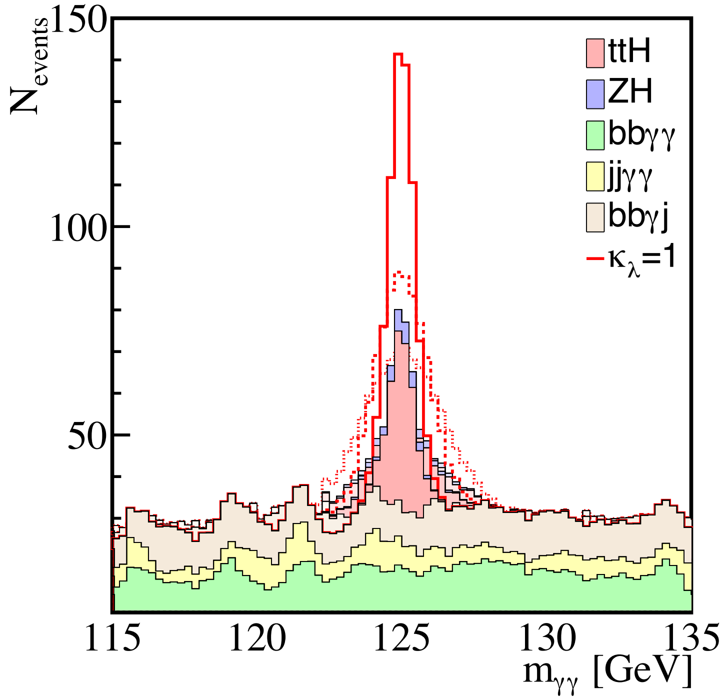
$$\epsilon_{j\to\gamma} = \begin{cases} 5.3\cdot 10^{-4}\exp\left(-6.5\left(\frac{p_{T,j}}{60.4\text{ GeV}}-1\right)^2\right)\ , & \text{pT<65GeV} \\ 0.88\cdot 10^{-4}\left[\exp\left(-\frac{p_{T,j}}{943\text{ GeV}}\right)+\frac{248\text{ GeV}}{p_{T,j}}\right]\ , & \text{pT>65GeV} \end{cases}$$

reducing fake photon important (esp. low pT)

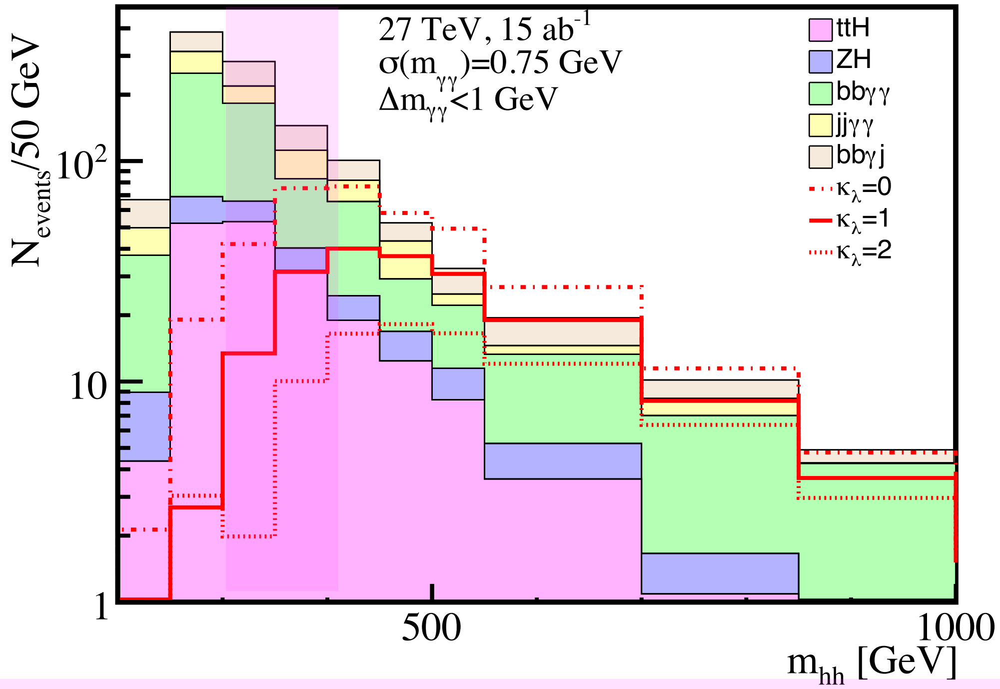
both pairs provide higgs mass

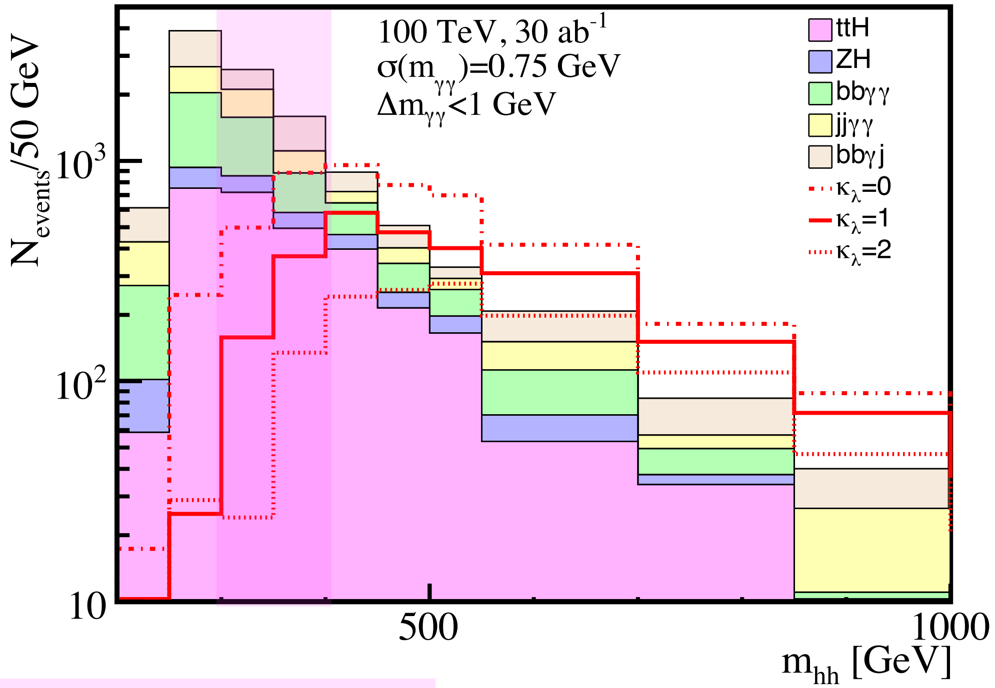






Higgs Signal/BG: peaked
continuum BG: flat
(controllable by side-bands)





characteristic structure should appear in low m_{hh} region

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

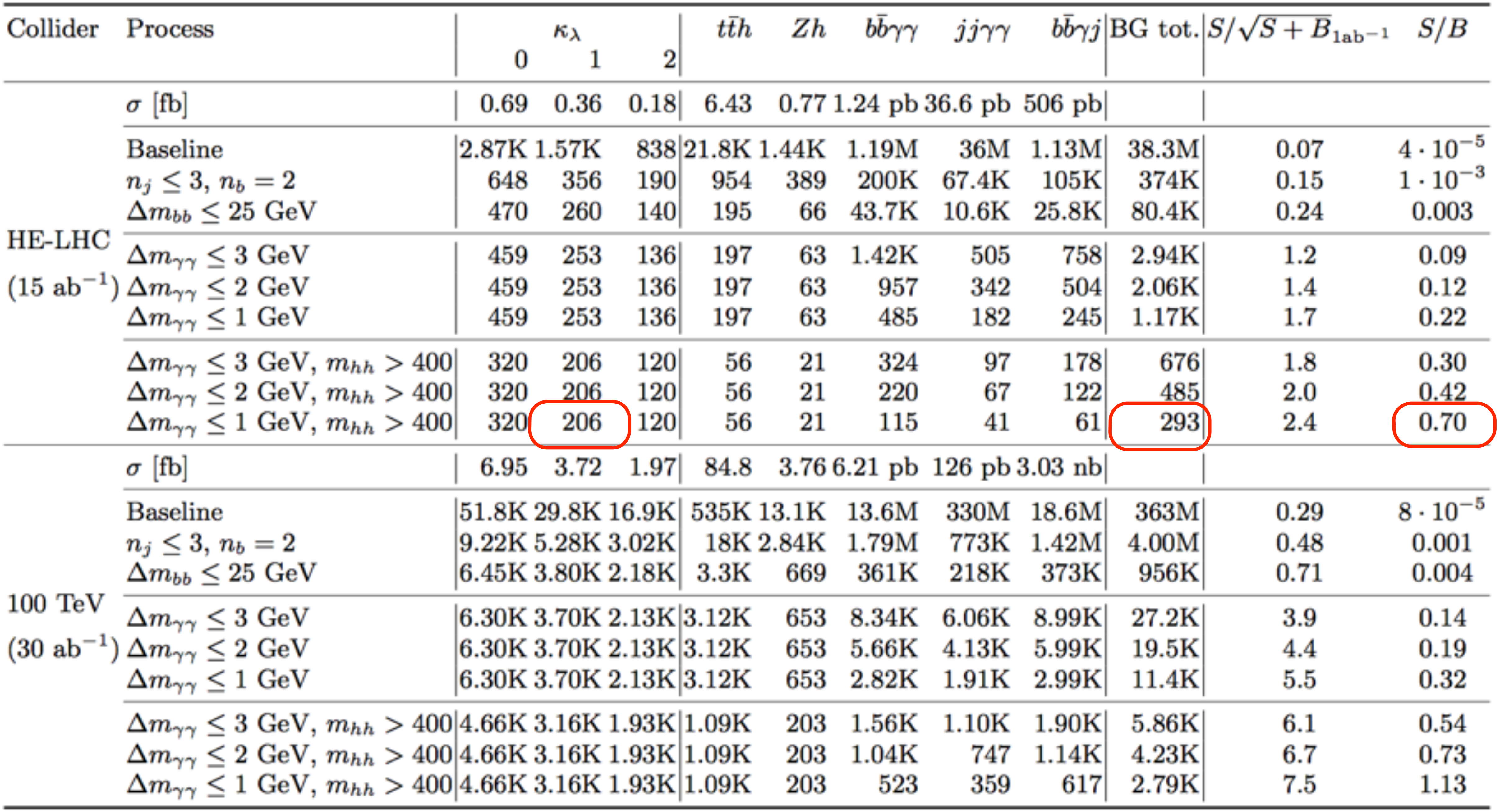
We have to require $m_{hh} > 400\text{GeV}$

JHEP 1502 (2015) 016
[A. Barr, M. Dolan, C. Englert,
D. Ferreira de Lima, M. Spannowsky]

Results

Baseline: $p_{T,j} > 30$ GeV, $|\eta_j| < 2.5$,
$p_{T,\gamma} > 30$ GeV, $|\eta_\gamma| < 2.5$,
$\Delta R_{\gamma\gamma,\gamma j,jj} > 0.4$.

$\epsilon_b = 70\%$ $\epsilon_c = 15\%$ $\epsilon_j = 0.3\%$



Collider	Process	κ_λ 0	1	2	$t\bar{t}h$	Zh	$b\bar{b}\gamma\gamma$	$jj\gamma\gamma$	$b\bar{b}\gamma j$	BG tot.	$S/\sqrt{S+B}_{1\text{ab}^{-1}}$	S/B
HE-LHC (15 ab^{-1})	σ [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	$1 \cdot 10^{-3}$
	$\Delta m_{bb} \leq 25$ GeV	470	260	140	195	66	43.7K	10.6K	25.8K	80.4K	0.24	0.003
	$\Delta m_{\gamma\gamma} \leq 3$ GeV	459	253	136	197	63	1.42K	505	758	2.94K	1.2	0.09
	$\Delta m_{\gamma\gamma} \leq 2$ GeV	459	253	136	197	63	957	342	504	2.06K	1.4	0.12
	$\Delta m_{\gamma\gamma} \leq 1$ GeV	459	253	136	197	63	485	182	245	1.17K	1.7	0.22
	$\Delta m_{\gamma\gamma} \leq 3$ GeV, $m_{hh} > 400$	320	206	120	56	21	324	97	178	676	1.8	0.30
	$\Delta m_{\gamma\gamma} \leq 2$ GeV, $m_{hh} > 400$	320	206	120	56	21	220	67	122	485	2.0	0.42
	$\Delta m_{\gamma\gamma} \leq 1$ GeV, $m_{hh} > 400$	320	206	120	56	21	115	41	61	293	2.4	0.70
100 TeV (30 ab^{-1})	σ [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
	$\Delta m_{bb} \leq 25$ GeV	6.45K	3.80K	2.18K	3.3K	669	361K	218K	373K	956K	0.71	0.004
	$\Delta m_{\gamma\gamma} \leq 3$ GeV	6.30K	3.70K	2.13K	3.12K	653	8.34K	6.06K	8.99K	27.2K	3.9	0.14
	$\Delta m_{\gamma\gamma} \leq 2$ GeV	6.30K	3.70K	2.13K	3.12K	653	5.66K	4.13K	5.99K	19.5K	4.4	0.19
	$\Delta m_{\gamma\gamma} \leq 1$ GeV	6.30K	3.70K	2.13K	3.12K	653	2.82K	1.91K	2.99K	11.4K	5.5	0.32
	$\Delta m_{\gamma\gamma} \leq 3$ 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
	$\Delta m_{\gamma\gamma} \leq 2$ GeV, $m_{hh} > 400$	4.66K	3.16K	1.93K	1.09K	203	1.04K	747	1.14K	4.23K	6.7	0.73
	$\Delta m_{\gamma\gamma} \leq 1$ GeV, $m_{hh} > 400$	4.66K	3.16K	1.93K	1.09K	203	523	359	617	2.79K	7.5	1.13

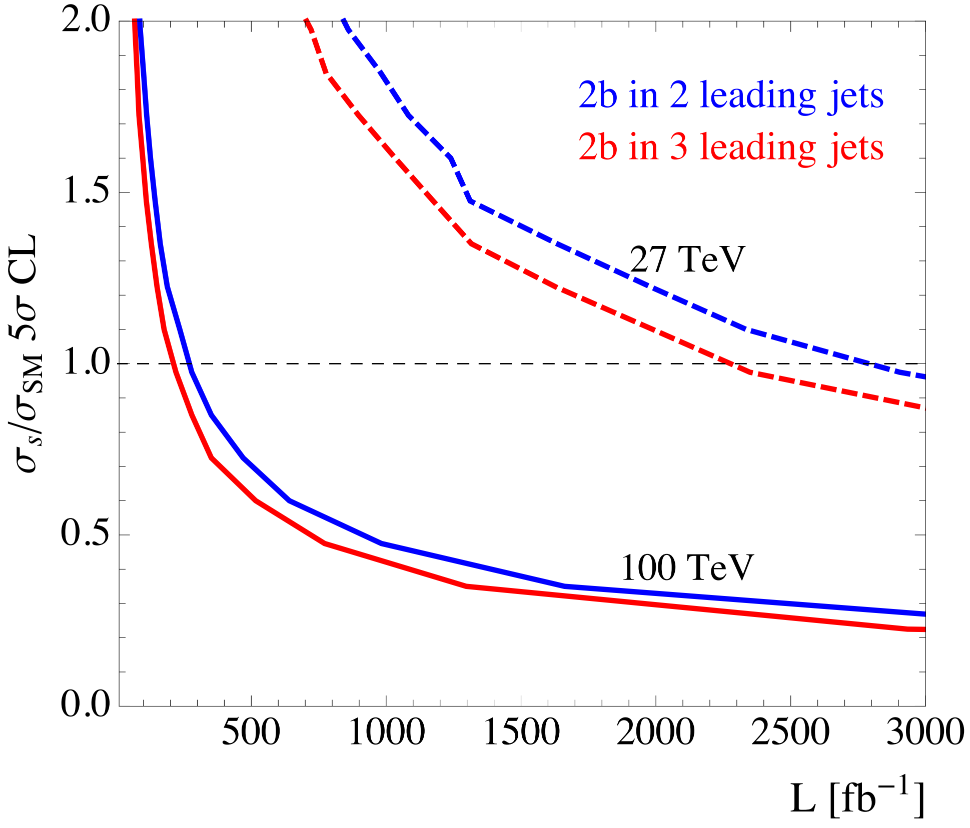
including 3rd jets in the analysis important

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

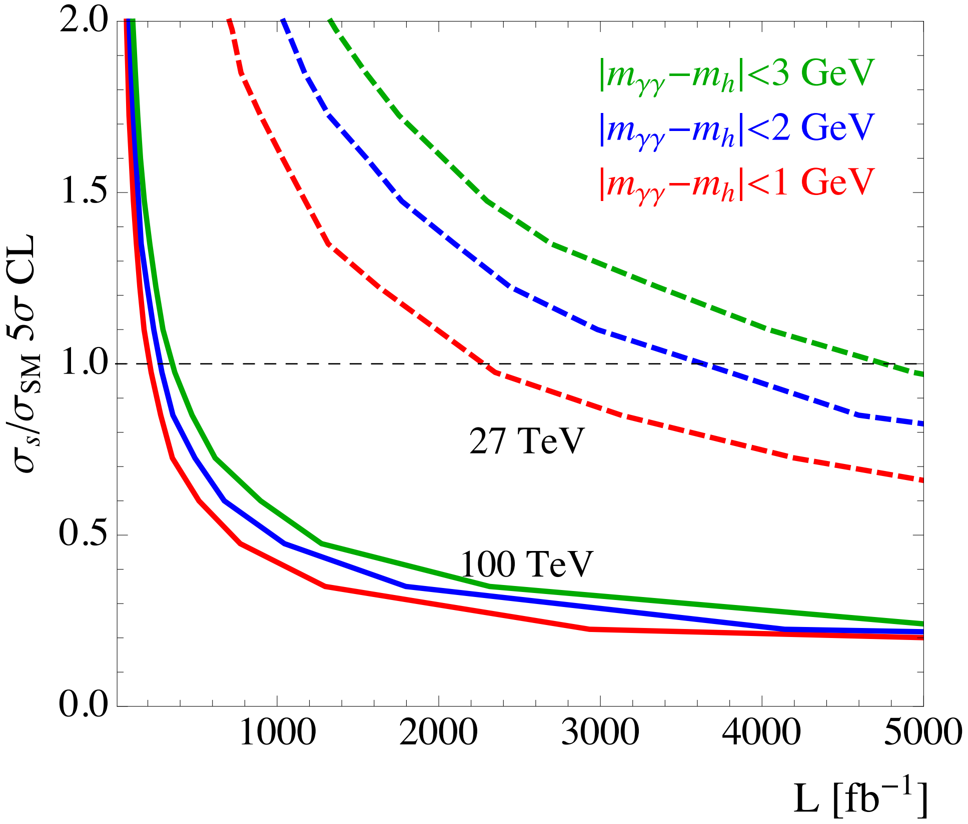


sub-samples (bb, bbj) and (jbb, bjb)

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

The 5σ measurement for HE-LHC is

2.8 ab^{-1} to below 2.3 ab^{-1}

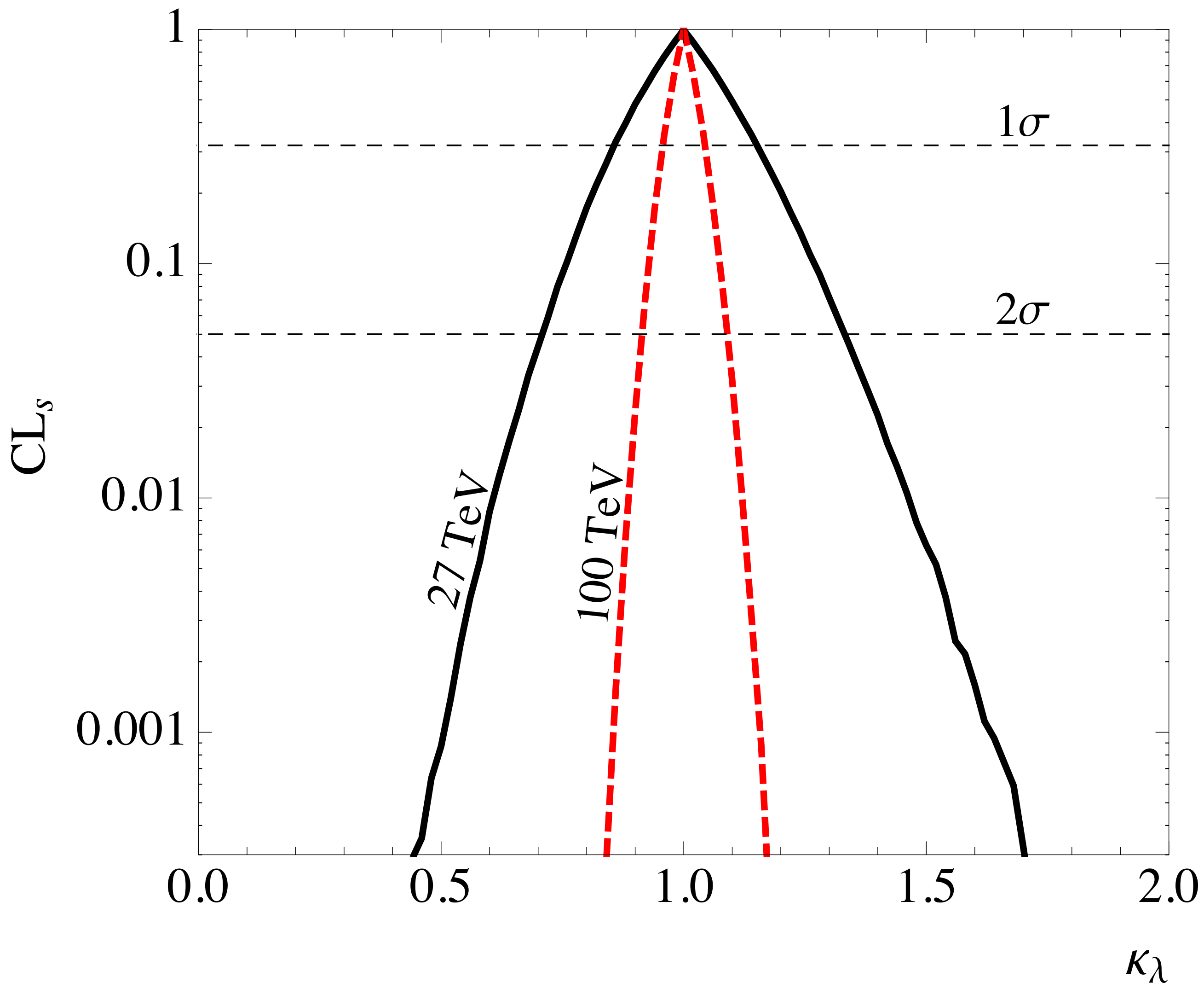


for Higgs self coupling sensitivity
photon invariant mass resolution most important

(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.

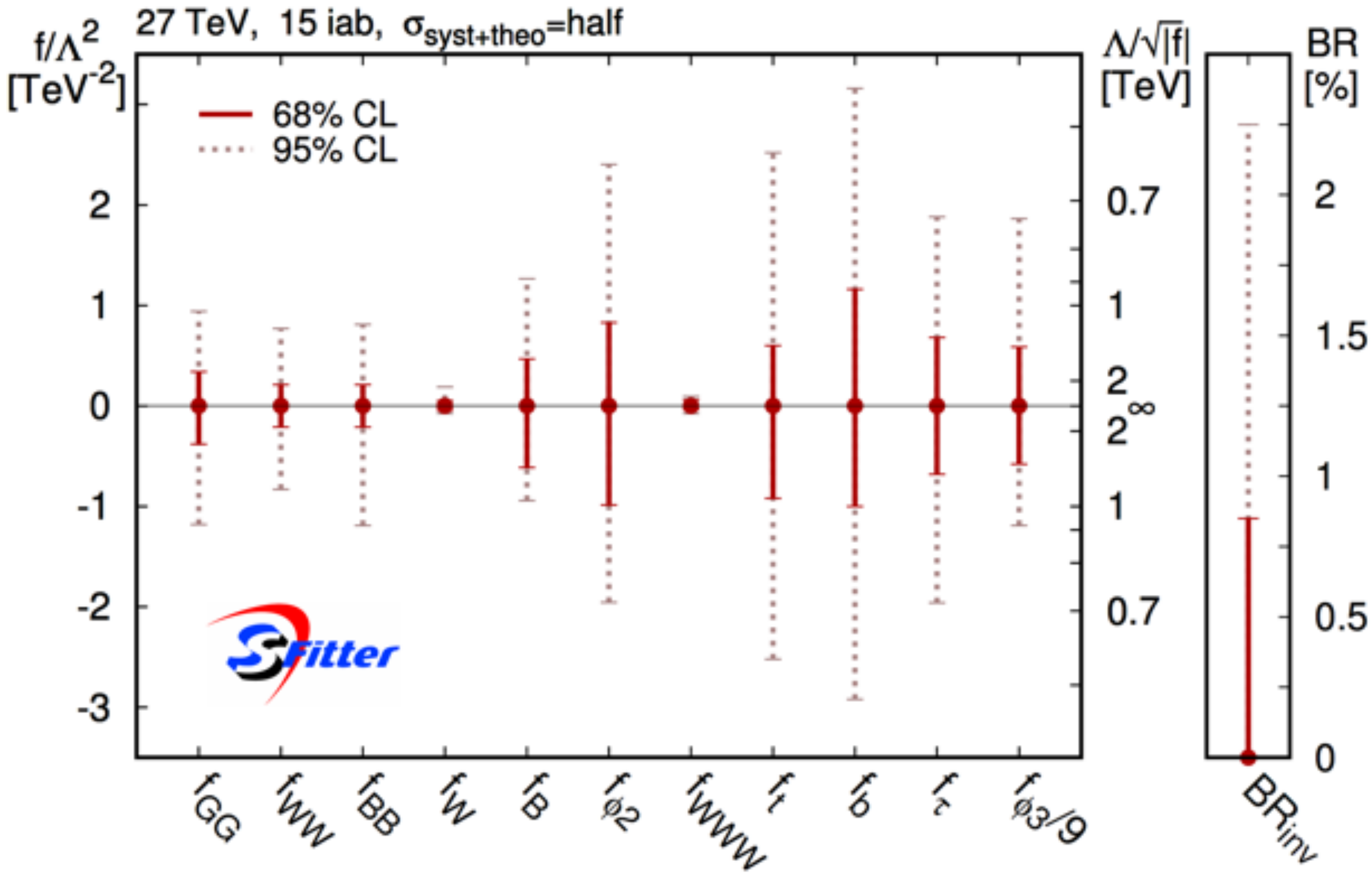
HE-LHC, 27 TeV, 15 ab^{-1}

$$\kappa_\lambda \approx 1 \pm 15\% \ (1\sigma) \qquad \kappa_\lambda \approx 1 \pm 30\% \ (2\sigma)$$

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

for 100 TeV, 30 ab^{-1} $\kappa_\lambda \approx 1 \pm 5\%(1\sigma), 10\%(2\sigma)$

global analysis for Higgs couplings at HE-LHC



[arXiv:1811.08401]

[A. Biekotter, D. Goncalves, T. Plehn, MT, D Zerwas]

$$\begin{aligned}\mathcal{L}_{\text{eff}} = & -\frac{\alpha_s}{8\pi}\frac{f_{GG}}{\Lambda^2}\mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2}\mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2}\mathcal{O}_{WW} + \frac{f_B}{\Lambda^2}\mathcal{O}_B + \frac{f_W}{\Lambda^2}\mathcal{O}_W + \frac{f_{WWW}}{\Lambda^2}\mathcal{O}_{WWW} \\ & + \frac{f_{\phi 2}}{\Lambda^2}\mathcal{O}_{\phi 2} + \frac{f_{\phi 3}}{\Lambda^2}\mathcal{O}_{\phi 3} + \frac{f_\tau m_\tau}{v\Lambda^2}\mathcal{O}_{e\phi,33} + \frac{f_b m_b}{v\Lambda^2}\mathcal{O}_{d\phi,33} + \frac{f_t m_t}{v\Lambda^2}\mathcal{O}_{u\phi,33} \\ & + \text{invisible decays},\end{aligned}$$

channel	observable	# bins	range [GeV]
$WW \to (\ell\nu)(\ell\nu)$	$m_{\ell\ell'}$	10	$0 - 4500$
$WW \to (\ell\nu)(\ell\nu)$	$p_T^{\ell_1}$	8	$0 - 1750$
$WZ \to (\ell\nu)(\ell\ell)$	m_T^{WZ}	11	$0 - 5000$
$WZ \to (\ell\nu)(\ell\ell)$	$p_T^{\ell\ell}$ (p_T^Z)	9	$0 - 2400$
WBF, $H \to \gamma\gamma$	$p_T^{\ell_1}$	9	$0 - 2400$
$VH \to (0\ell)(b\bar{b})$	p_T^V	7	$150 - 750$
$VH \to (1\ell)(b\bar{b})$	p_T^V	7	$150 - 750$
$VH \to (2\ell)(b\bar{b})$	p_T^V	7	$150 - 750$
$HH \to (b\bar{b})(\gamma\gamma)$, $2j$	m_{HH}	9	$200 - 1000$
$HH \to (b\bar{b})(\gamma\gamma)$, $3j$	m_{HH}	9	$200 - 1000$

$$\frac{\Lambda}{\sqrt{|f_{\phi 3}|}} > 430 \text{ GeV}$$ at 68%CL

15% in the self-coupling corresponds to

$$\left|\frac{\Lambda}{\sqrt{f_{\phi 3}}}\right| \sim 1 \text{ TeV}$$

Limits are diluted from one param analysis due to the cancellation between $\mathcal{O}_{\phi 2}$ and $\mathcal{O}_{\phi 3}$

$$\mathcal{O}_{\phi 3} = -(\phi^\dagger\phi)^3/3 \qquad \mathcal{O}_{\phi,2} = \frac{1}{2}\partial^\mu\left(\phi^\dagger\phi\right)\partial_\mu\left(\phi^\dagger\phi\right)$$

Summary

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, 15ab^{-1}) ~ 15% [cf. 70% at HL-LHC]
(it would be able to exclude the EWBG scenario at ~ 5σ)

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 ~ 1, and O(200) events allow the shape analysis

100TeV collider would improve the sensitivity by a factor 3, which is ~ 5%.