Prospects for Measuring Higgs self-coupling at FCC 100 TeV hadron collider

Weiming Yao (LBNL)

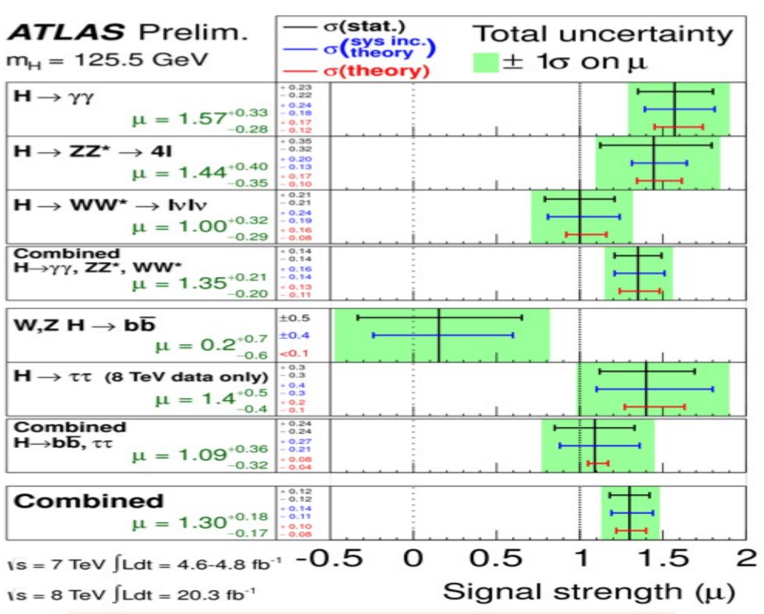
Outline

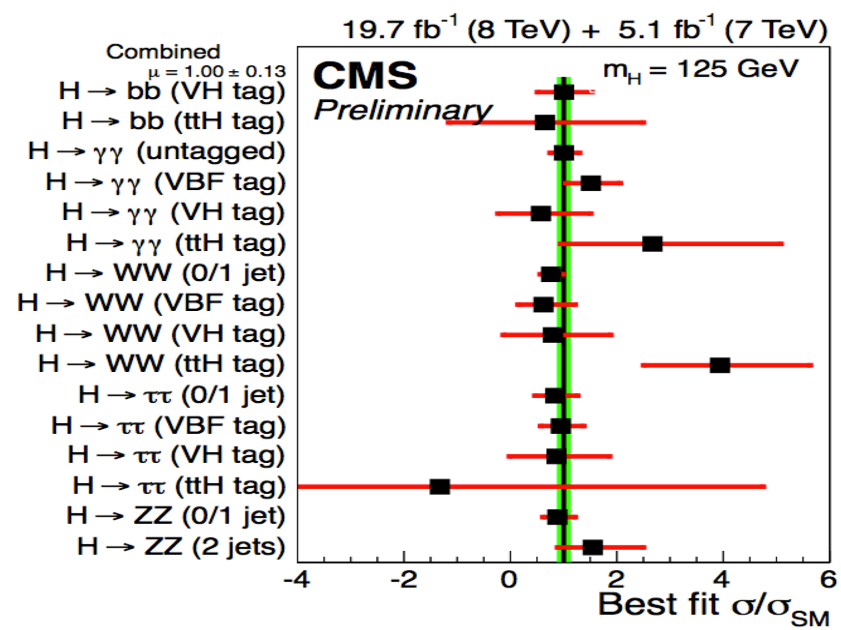
- Introduction
- Review the current status on Higgs trilinear coupling
- What we learn from HL-LHC studies
- Prospects for 100 TeV
- Implications of BSM
- Conclusion

Disclaim: There are many studies on di-higgs phenomenology after Higgs discovery and I apologize if I miss your paper.

Introduction

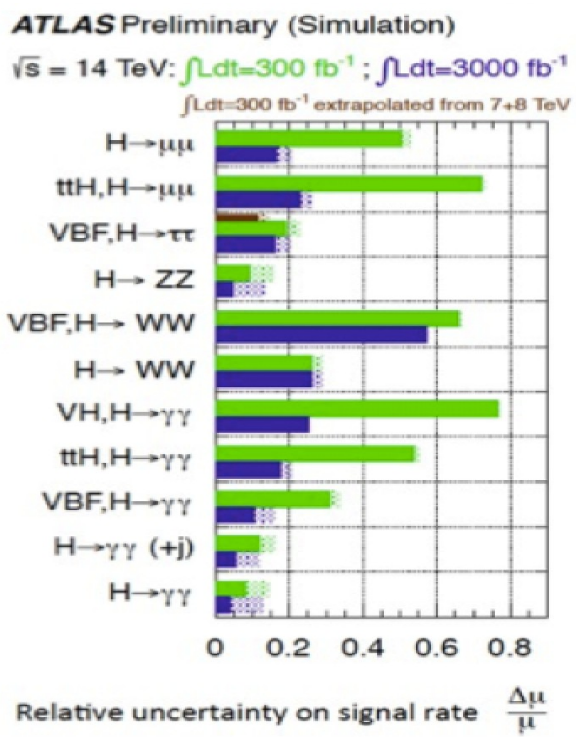
- ATLAS and CMS discovered a new boson at 125 GeV in July, 2012
- The results are consistent with SM Higgs boson so far.
- LHC/HL-LHC will provide unprecedented and unparalleled physics opportunities for testing the validity of SM and search for BSM.
- But very likely, we need future FCC to explore the energy frontier.



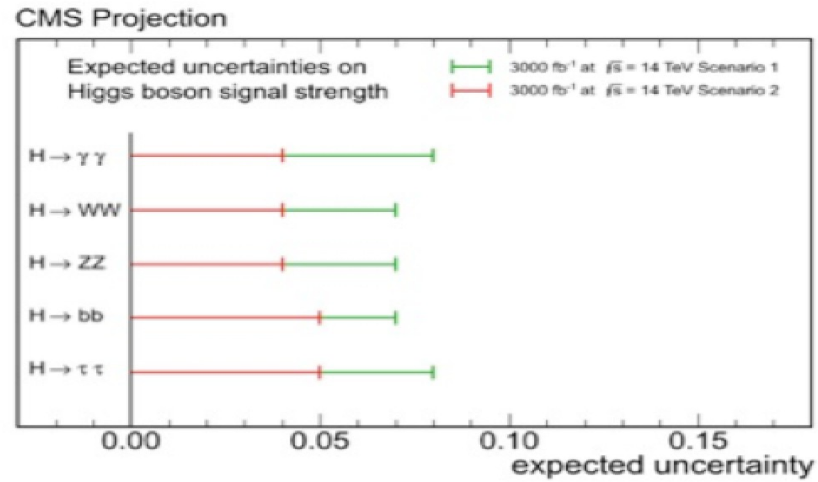


What can we learn from HL-LHC

- Determine the Higgs couplings to a few % level.
- Typical deviation for new physics: $\Delta \frac{g}{g_{SM}} < 5\% \left(\frac{1TeV}{\Lambda}\right)^2$
- For a 5 sigma deviation, require <1% precision



Based on parametric simulation

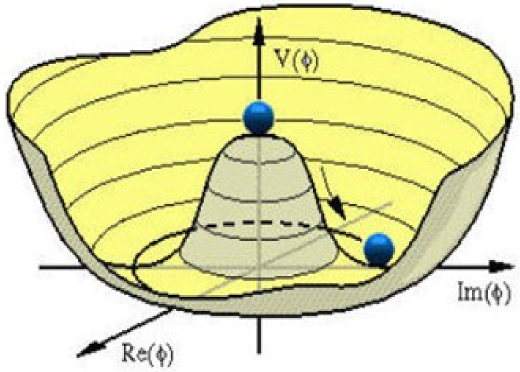


$L\,(fb^{-1})$	$H\to\gamma\gamma$	$H\to WW$	$H\to ZZ$	$H\to bb$	$H\to\tau\tau$	$H\to Z\gamma$	$H\to inv.$
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[6, 17]

Assumptions on systematic uncertainties
Scenario 1: no change
Scenario 2: Δ theory / 2, rest ∝ 1/√L

Extrapolated from 2011/12 results

Probing the Higgs Potential



- From the scalar potential before EWSB:
  - $V(\Phi)=-\mu^2|\Phi|^2 + \lambda|\Phi|^4$
- $V(\Phi)$ after EWSB with $M_h^2 = 2\mu^2$, $v^2 = \mu^2/\lambda$
  - $\Phi=(0,(v+h)/\sqrt{2})$
  - $V(h)=1/2M_h^2h^2 + 1/2M_h^2/v\, h^3 + 1/8M_h^2/v^2h^4$ + Const
- Trilinear and Quartic Higgs coupling:
  - $\lambda_{hhh}=3M_h^2/v$
  - $\lambda_{hhhh}=3M_h^2/v^2$
- Within SM, everything known: $\lambda_{hhh}\sim0.13$.

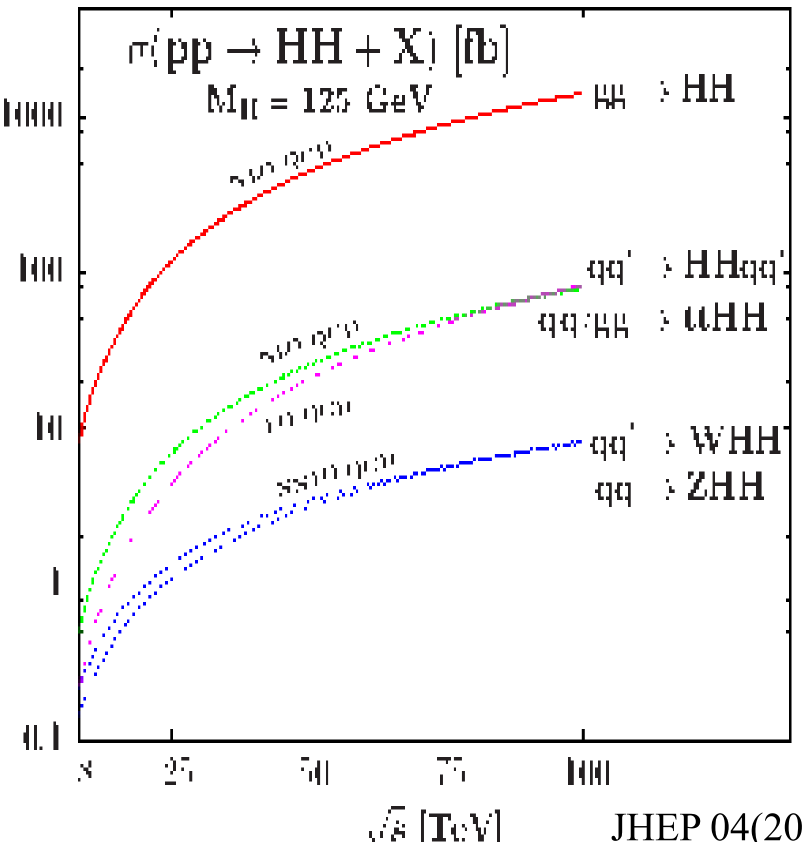
Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	-18%
Composite Higgs	Tens of %
Minimal Supersymmetry	-2% -15%
NMSSM	-25%

- BSM: max deviations ranging from few to 20% (arxiv:1305.6397)
- Targeted precision: <5% for both theory and experiments to confirm or discover the Higgs potential.

Advantage of probing Higgs Potential at 100 TeV

•The σ(pp→HH) increased significantly at 100 TeV, opens new window to measure the Higgs potential directly.

•Initial snowmass studies were encouraging, but ignoring some of detector related backgrounds, which depends on assumed detector performances.



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	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

R=σ(E)/σ(14TeV)

Recent Studies

- Many studies on di-higgs phenomenology after Higgs discovery and results are not fully understood yet.

Decay	Issues	Expectation 3000 ifb	References
$b\bar{b}\gamma\gamma$	• Signal small • BKG large & difficult to asses • Simple reconst.	$S/B \simeq 1/3$ $S/\sqrt{B} \simeq 2.5$	[Baur, Plehn, Rainwater] [Yao 1308.6302] [Baglio et al. JHEP 1304]
$b\bar{b}\tau^+\tau^-$	• tau rec tough • largest bkg tt • Boost+MT2 might help	**differ a lot** $S/B \simeq 1/5$ $S/\sqrt{B} \simeq 5$	[Dolan, Englert, MS] [Barr, Dolan, Englert, MS] [Baglio et al. JHEP 1304]
$b\bar{b}W^+W^-$	• looks like tt • Need semilep. W to rec. two H • Boost + BDT proposed	**differ a lot** best case: $S/B \simeq 1.5$ $S/\sqrt{B} \simeq 8.2$	[Dolan, Englert, MS] [Baglio et al. JHEP 1304] [Papaefstathiou, Yang, Zurita 1209.1489]
$b\bar{b}b\bar{b}$	• Trigger issue (high pT kill signal) • 4b background large difficult with MC • Subjets might help	$S/B \simeq 0.02$ $S/\sqrt{B} \leq 2.0$	[Dolan, Englert, MS] [Ferreira de Lima, Papaefstathiou, MS] [Wardrope et al, 1410.2794]
others	• Many taus/W not clear if 2 Higgs • Zs, photons no rate		

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Snowmass Studies

- Expected precisions on the trilinear Higgs coupling assuming all other Higgs coupling are SM-like and no other new physics contributions.
- Individual Collider:

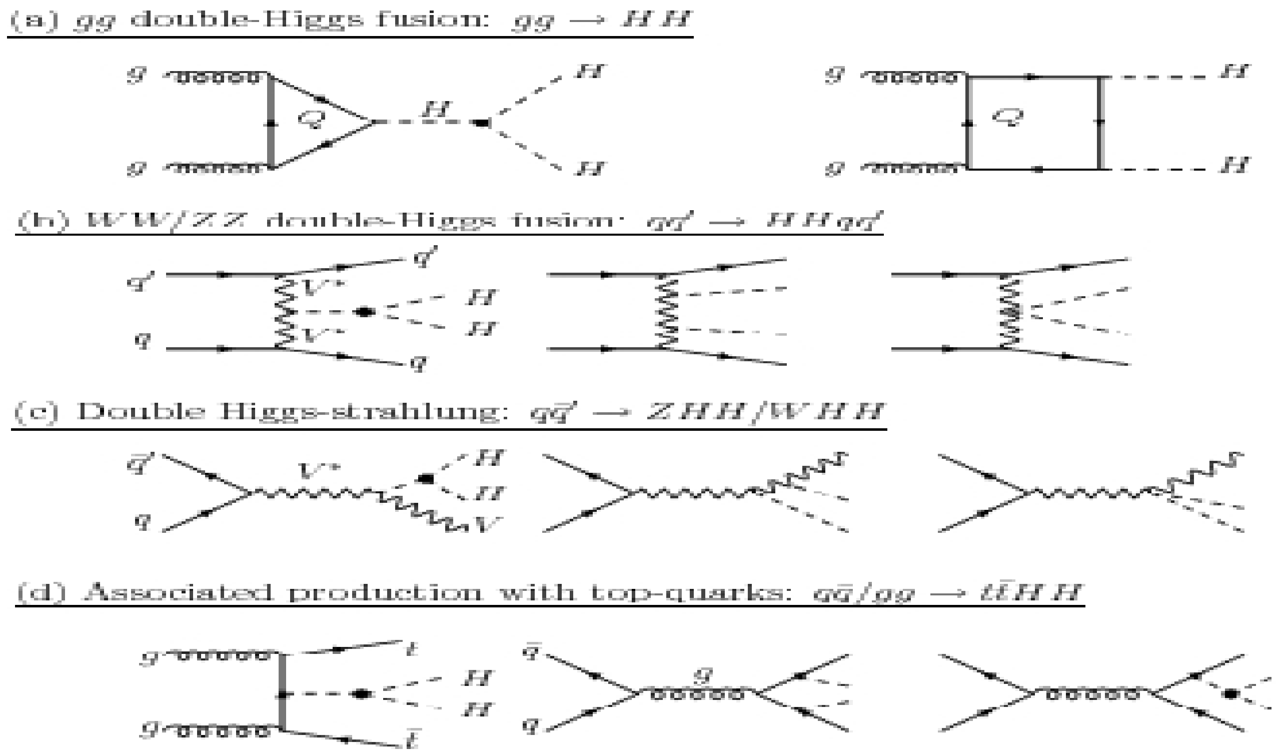
	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	500	1600‡	500+1000	1600+2500‡	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%

- Combination of colliders:

LHC +ILC	HL-LHC							
	+ILC-up	+(TLEP)			+ILC-up		+CLIC	
		+CLIC	+HE-LHC	+VLHC	+HE-LHC	+VLHC	+HE-LHC	+VLHC
21%	12.6%	15.2/9.8%	18.6%	7.9%	10.9%	6.8%	12.5/8.9%	7.2/6.2%

The Double Higgs Production

- The main di-Higgs production channels at pp collider:



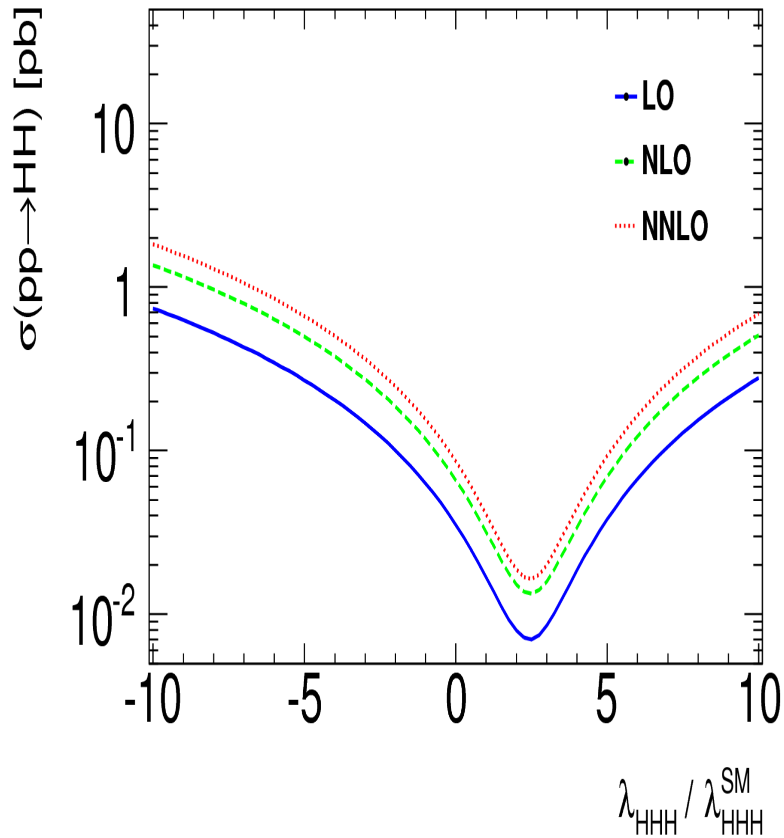
- gg→HH dominant production, but small only ~1/1000 of σ(gg→H)
  - due to the destructive interference ruled by yt and λ

- Other hh production channels have about 10% of total σ(gg→HH)

The Double Higgs Production

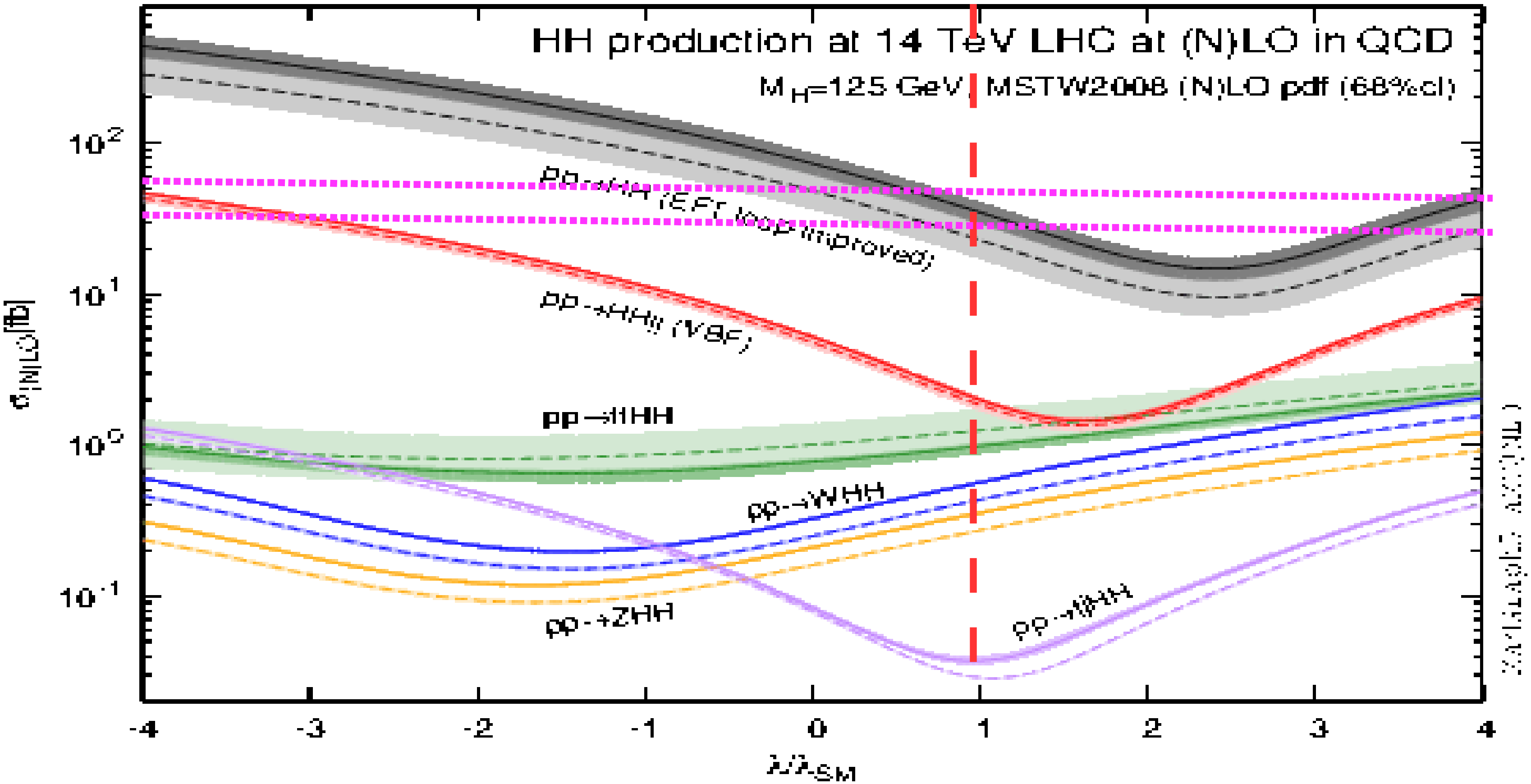
- The ggHH cross section and uncertainties at NNLO are available (Florian et al PRL 111 (2013) 201801)

$E_{c.m.}$	8 TeV	14 TeV	33 TeV	100 TeV
σ_{NNLO}	9.76 fb	40.2 fb	243 fb	1638 fb
Scale [%]	$+9.0-9.8$	$+8.0-8.7$	$+7.0-7.4$	$+5.9-5.8$
PDF [%]	$+6.0-6.1$	$+4.0-4.0$	$+2.5-2.6$	$+2.3-2.6$
PDF + α_S [%]	$+9.3-8.8$	$+7.2-7.1$	$+6.0-6.0$	$+5.8-6.0$



Triple Higgs coupling sensitivity

- Higgs self-coupling depends on processes; VBF is most sensitive, but small
- Some degeneracies likely to be resolved using kinematic and other processes: HHj, VBF, ttHH, VHH.



Higgs Pair Production at HL-LHC

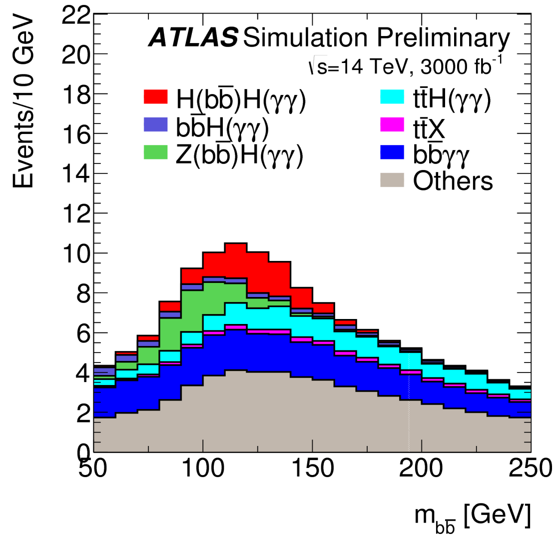
- The HH production cross section at 14 TeV is small, 40 fb.
- Selection of HH final states has been studied:
  - HH→bbγγ: clean but small rate, seems best
  - Other channels suffered either too small rate or huge background from ttbar or Z+jets, but work is on going.
  - Have to combine all possible channels to improve the sensitivity

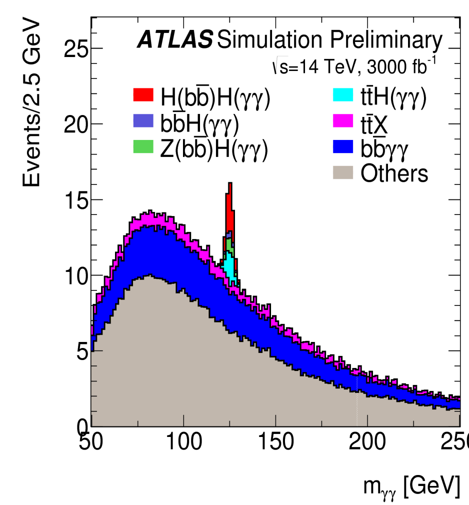
Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b} + b\bar{b}$	33%	40,000
$b\bar{b} + W^+W^-$	25%	31,000
$b\bar{b} + \tau^+\tau^-$	7.3%	8,900
$ZZ + b\bar{b}$	3.1%	3,800
$W^+W^- + \tau^+\tau^-$	2.7%	3,300
$ZZ + W^+W^-$	1.1%	1,300
$\gamma\gamma + b\bar{b}$	0.26%	320
$\gamma\gamma + \gamma\gamma$	0.0010%	1.2

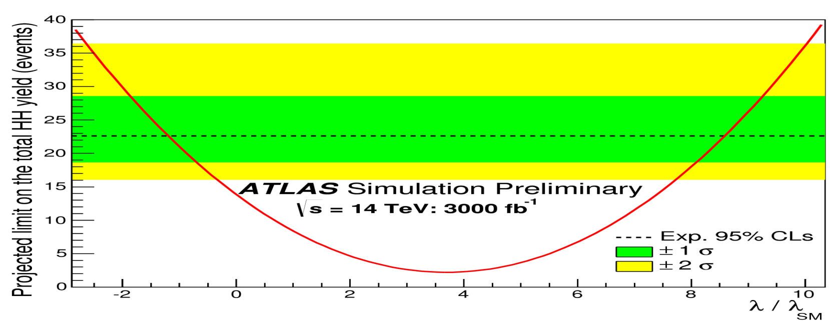
$HH \rightarrow bb\gamma\gamma$ at HL-LHC

- ATLAS and CMS updated the $HH \rightarrow bb\gamma\gamma$ at HL-LHC with 3000 fb-1
- Obtained significance is1.3 σ for ATLAS and 2σ for CMS (ATL-PHYS-PUB-2014-019)
- ATLAS set limit on trilinear Higgs coupling $-1.3<\lambda/\lambda_{SM}<8.7$ @ 95% CL.

Expected yields (3000 fb^{-1}) Samples	Total	Barrel	End-cap
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=1)$	8.4±0.1	6.7±0.1	1.8±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=0)$	13.7±0.2	10.7±0.2	3.1±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=2)$	4.6±0.1	3.7±0.1	0.9±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=10)$	36.2±0.8	27.9±0.7	8.2±0.4
$b\bar{b}\gamma\gamma$	9.7±1.5	5.2±1.1	4.5±1.0
$c\bar{c}\gamma\gamma$	7.0±1.2	4.1±0.9	2.9±0.8
$b\bar{b}\gamma j$	8.4±0.4	4.3±0.2	4.1±0.2
$b\bar{b}jj$	1.3±0.2	0.9±0.1	0.4±0.1
$jj\gamma\gamma$	7.4±1.8	5.2±1.5	2.2±1.0
$t\bar{t}(\geq 1$ lepton$)$	0.2±0.1	0.1±0.1	0.1±0.1
$t\bar{t}\gamma$	3.2±2.2	1.6±1.6	1.6±1.6
$t\bar{t}H(\gamma\gamma)$	6.1±0.5	4.9±0.4	1.2±0.2
$Z(b\bar{b})H(\gamma\gamma)$	2.7±0.1	1.9±0.1	0.8±0.1
$b\bar{b}H(\gamma\gamma)$	1.2±0.1	1.0±0.1	0.3±0.1
Total Background	47.1±3.5	29.1±2.7	18.0±2.3
$S/\sqrt{B}(\lambda/\lambda_{SM}=1)$	1.2	1.2	0.4



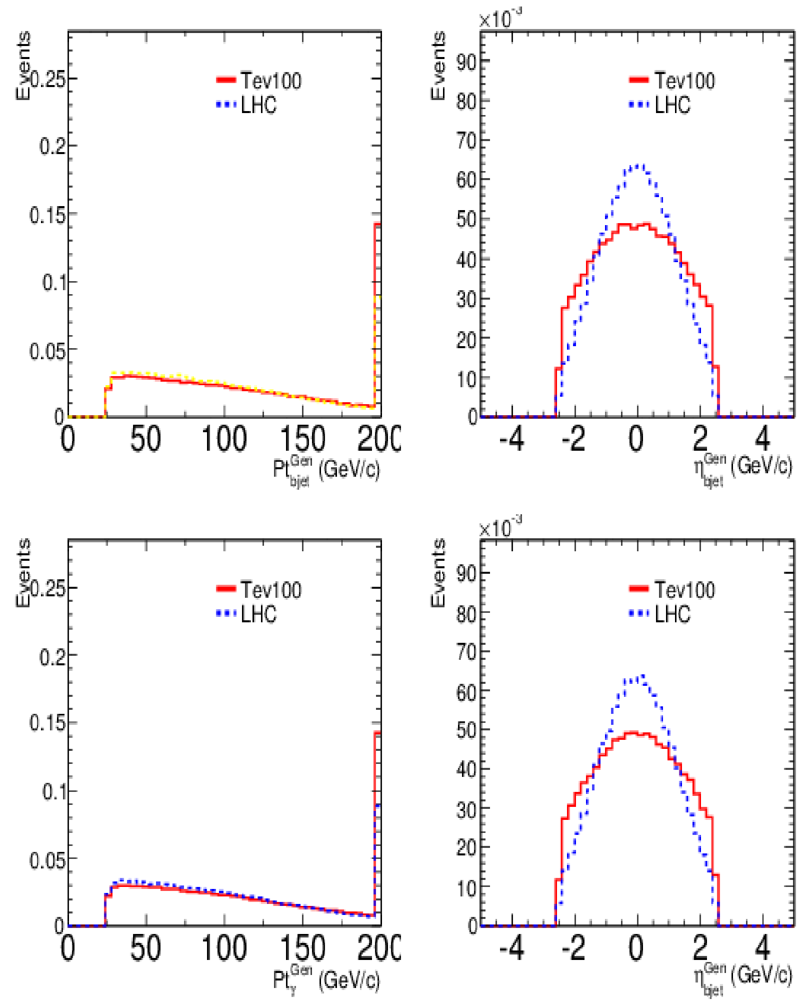




14 TeV vs 100 TeV

- The Kinematic of products of gg→HH are very similar.
- Signal and background should scale well with its ratio of cross section.

Br*σ(pb)	14TeV	100 TeV	R
hh->bbγγ	0.000105	0.0035	34
bbγγ	0.49	8.4	17
bbjγ	480	8960	19
jjγγ	14.5	164.2	11
zh	0.00011	0.00087	8
bbh	0.00223	0.0505	23
tth	0.00068	0.0373	55

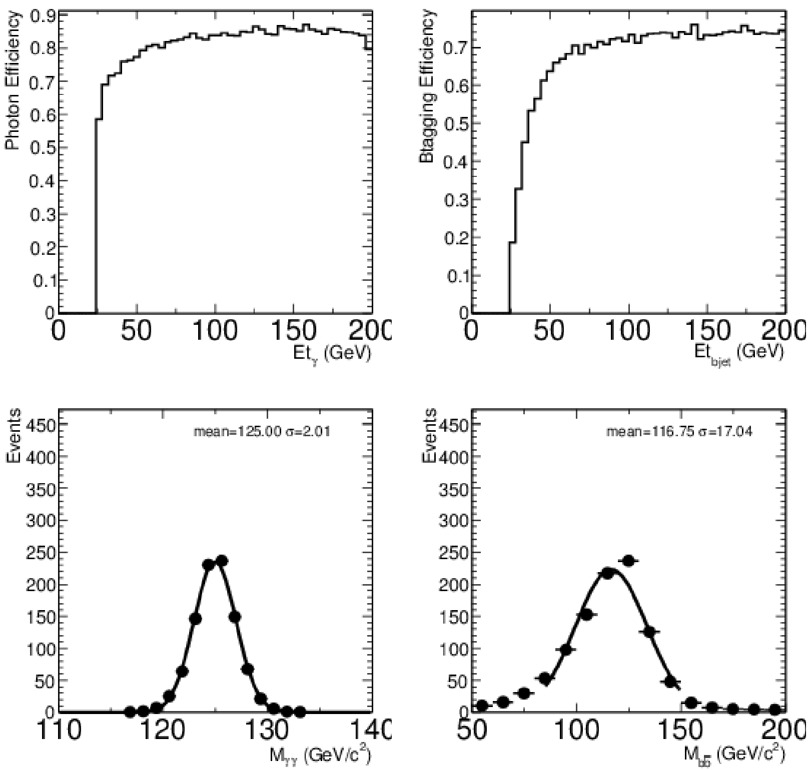


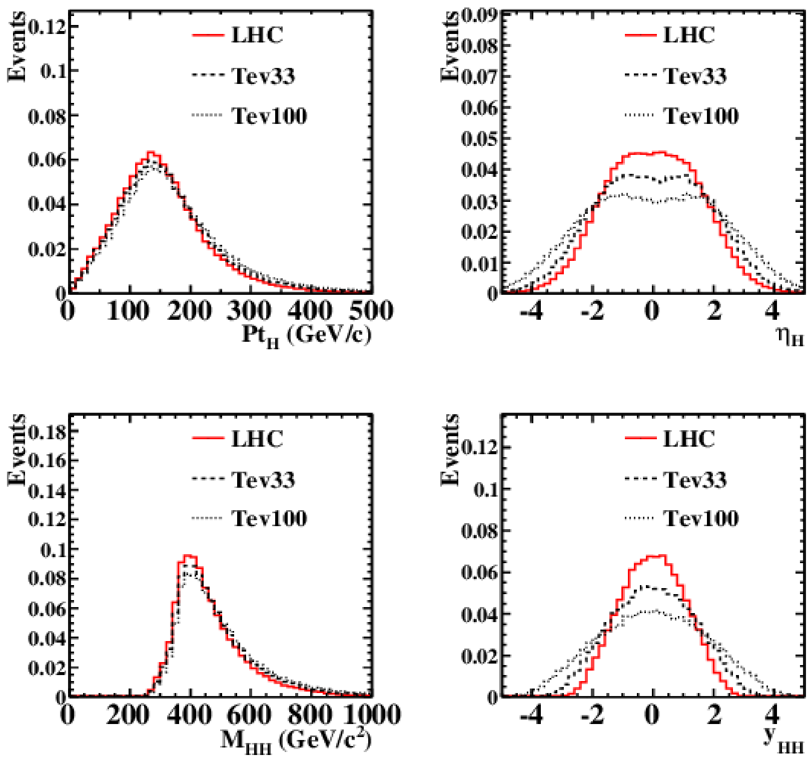
Fast Simulation Setup

- Focus on HH→bbγγ channel as baseline.
- Signal: Madgraph V1.5.14+pythia6.2
- Background: MadGraph5.14 with MLM matching up to 1 partons
- Simulated with Delphes V3.1.2 with ATLAS responses
  - Ecal smeared with: $\sigma_{ET}/E_T = 0.20/\sqrt{E_T} \oplus 0.17\%$
  - Use the anti-kT for jets with a radius of 0.5
  - btag eff. at 75% for b, 18.8% for c and 1% for mistag, up $|\eta|<2.5$
  - Including faking photon contributions:
    - Fake rate =0.0093exp(-Et(GeV)/27) from ATLAS
    - Fake photon Et scaled from Jet Et by 75% with σ=0.12
- For future studies, we should converge the expected detector performances.
  - Tracking coverage, lepton ID efficiency, and fakes
  - Jet resolutions, missing Et resolution, and pile-up rejections.

Detector responses and kinematics

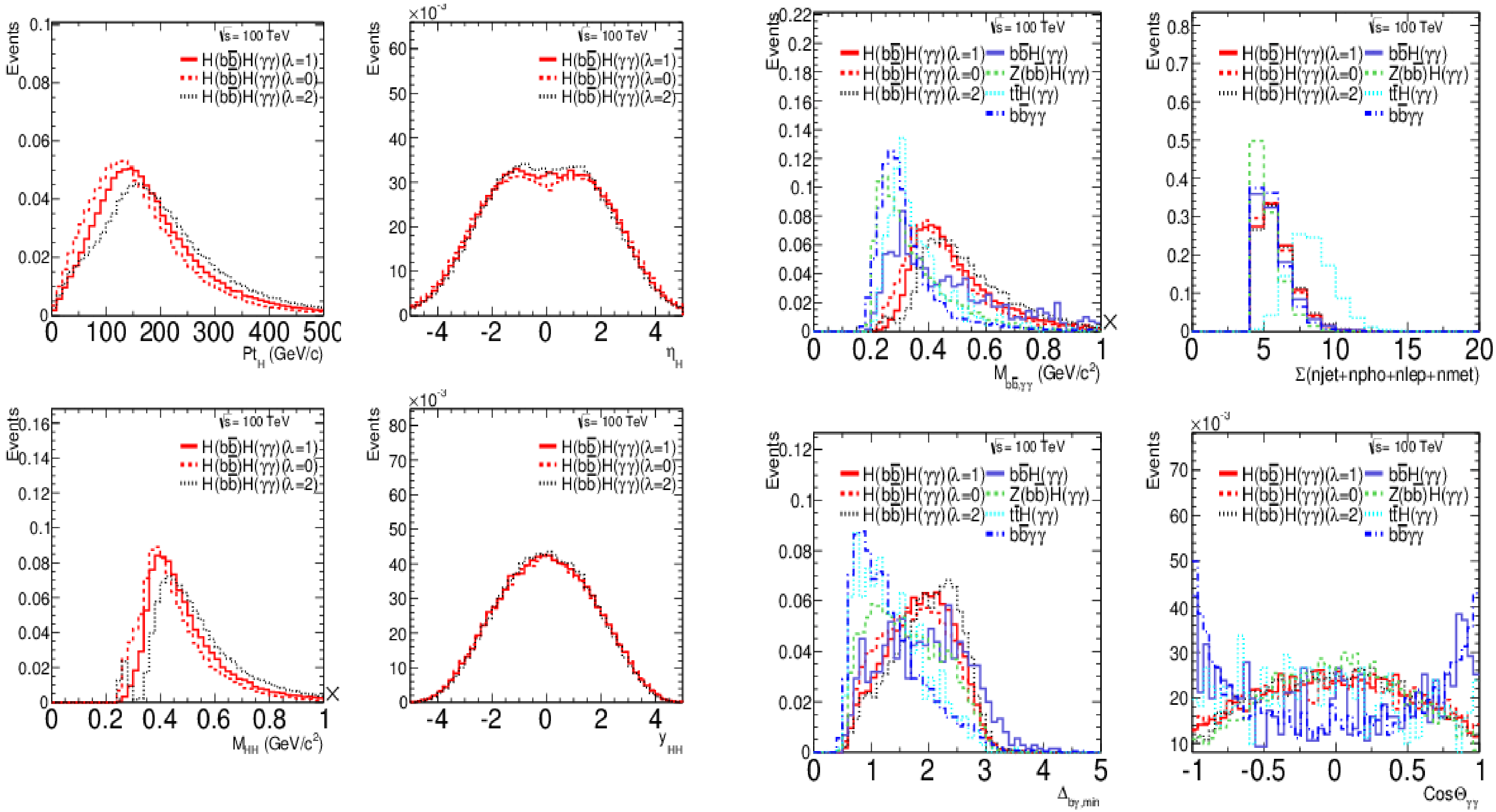
- Photon, btag efficiency and mass distributions
- Mγγ and Mbb are similar to LHC; Photon ID eff is better(0.76-2*exp(-Et(GeV)/16.1))
- Higgs kinematic at Tev100 are very similar to LHC, bit extending to large eta





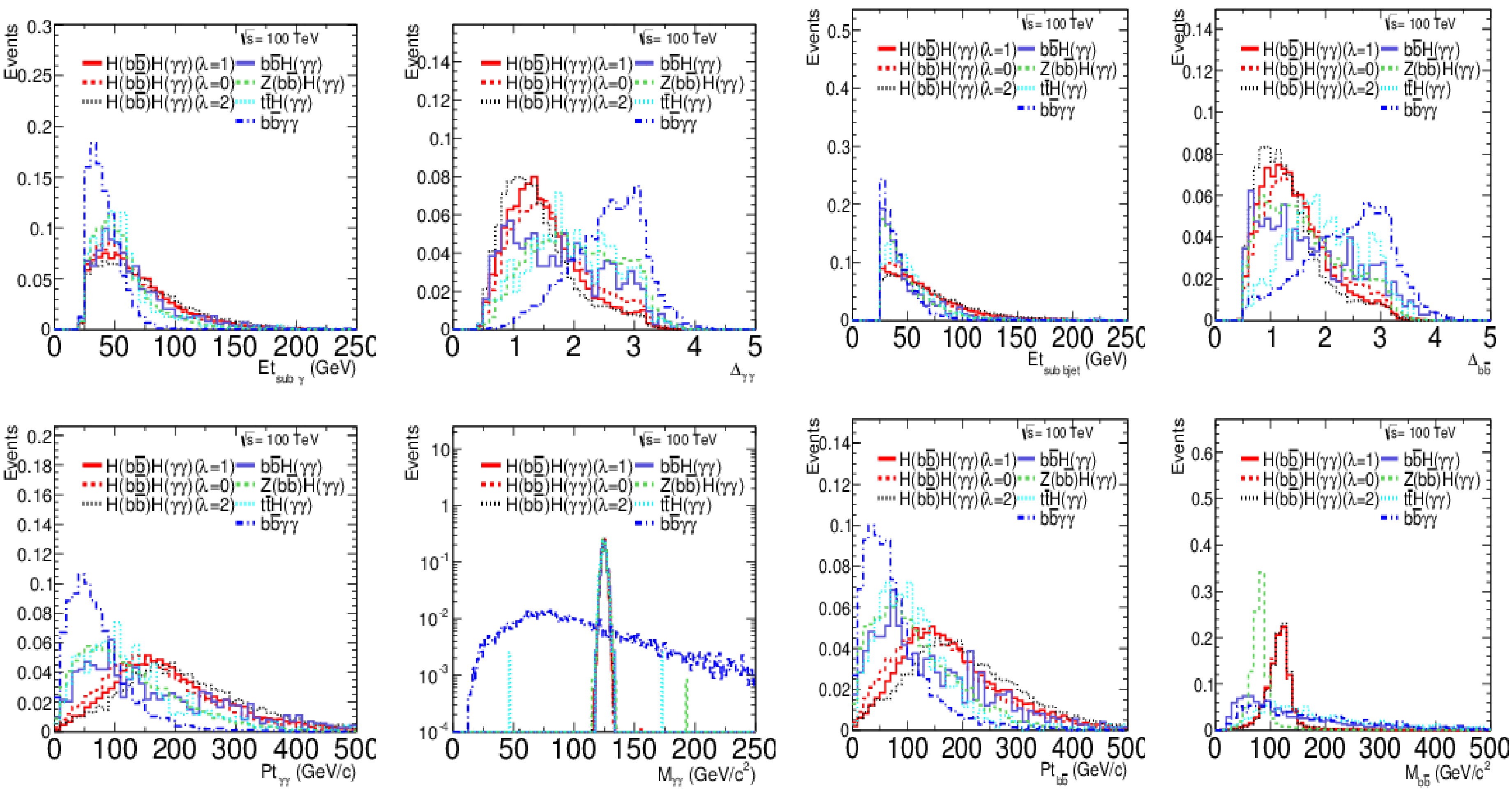
HH→bbγγ Kinematics

- Comparing HH kinematic with background distributions.



H→γγ, H→bb

•Comparing H→γγ, H→bb with background distributions. .



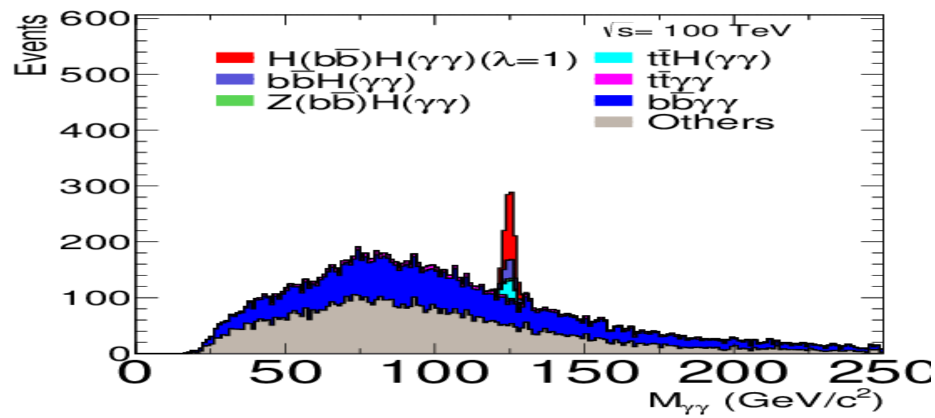
Events Selections

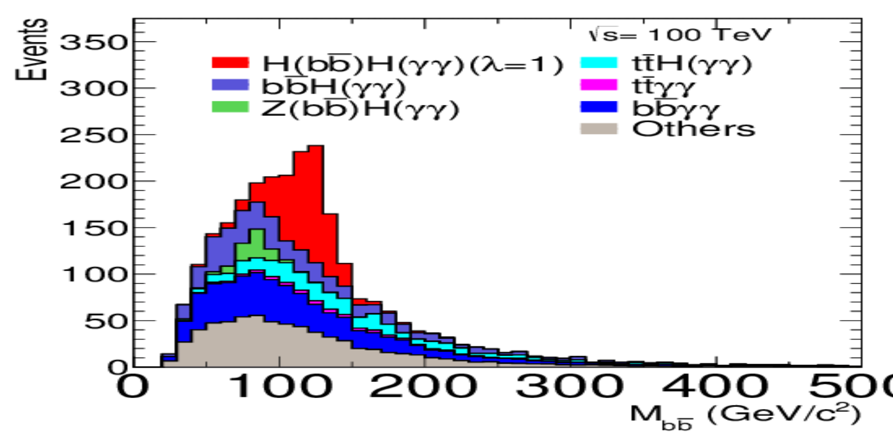
- Selecting bjet and photon:
  - Require 2 bjets with Et>35 GeV, |eta|<2.0
  - Require 2 photons with Pt>35 GeV, |eta|<2.0
  - bjet tag via truth matching of b-quark within cone of 0.4
- Mass and Angular cuts:
  - Tighten $|M_{\gamma\gamma}-125|<3$ GeV from 5 Gev used for snowmass.
  - $|M_{bb}-110|<25$ GeV
  - $\Delta R_{\gamma\gamma}<2.0$; $\Delta R_{bb}<2.0$
  - H decay angle $|\cos\theta_H|<0.8$ in the rest frame of HH
- Kinematic cuts:
  - $Pt_{\gamma\gamma}>100$ GeV, $Pt_{bb}>100$ GeV
  - $M_{bb\gamma\gamma}>300$ GeV
  - Requiring Sum of (njet+npho+nlep+nmet)<7

Results

- bbγγ seems still dominant and can be further reduced with MVA.
- Expected $S/\sqrt{B}$~16.5 for Tev100 with 3 fb^{-1}.
- Recent studies from 1412.7154: reported 8.4 significance with difference eff.

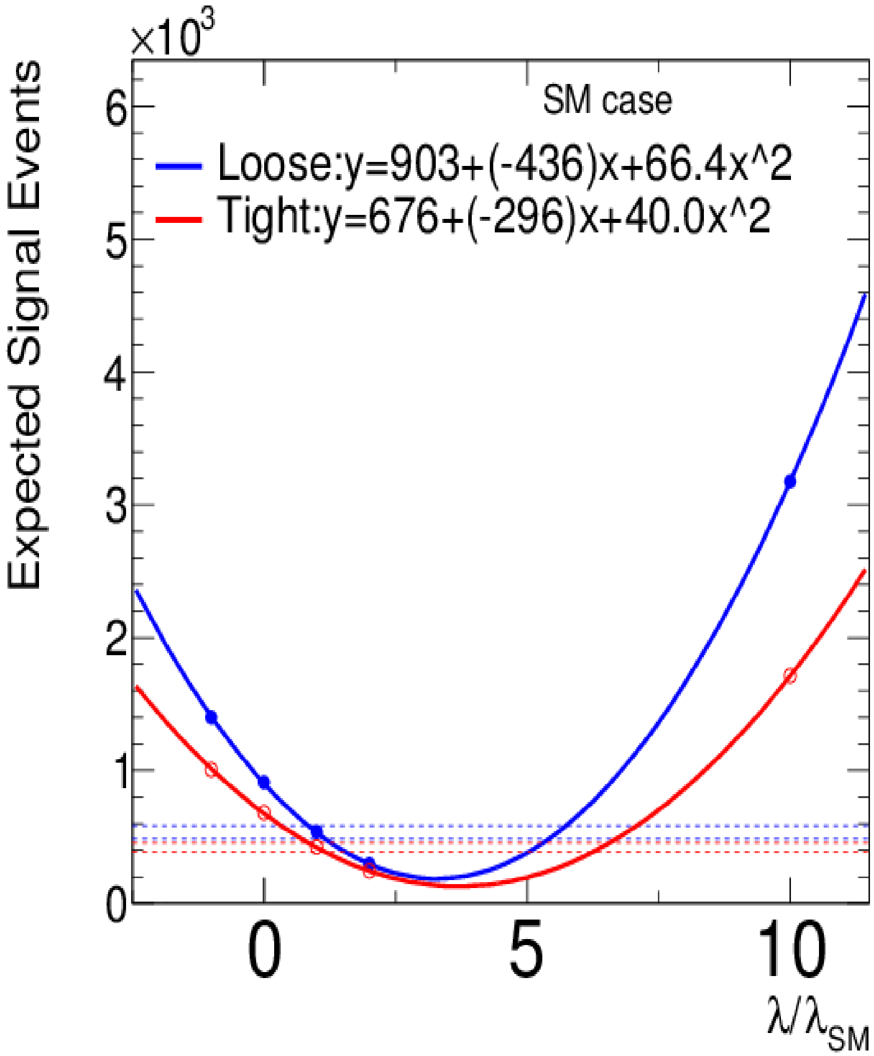
Samples	$\sigma \cdot BR$ (fb)	Generated Evt	Selected Evt	Acc.	Expected (Statistic)
$H(b\bar{b})H(\gamma\gamma)(\lambda=1)$	3.53	100000	3955	0.040	418.8±6.6
$H(b\bar{b})H(\gamma\gamma)(\lambda=0)$	6.88	100000	3322	0.03322	685.7±11.9
$H(b\bar{b})H(\gamma\gamma)(\lambda=2)$	1.76	100000	4566	0.04566	241.1±3.6
$b\bar{b}H(\gamma\gamma)$	50.49	99611	78	0.00078	118.6±13.4
$Z(b\bar{b})H(\gamma\gamma)$	0.8756	68585	378	0.0055	14.5±0.7
$t\bar{t}H(\gamma\gamma)$	37.26	63904	67	0.0010	117.2±14.3
$t\bar{t}\gamma\gamma$	335.8	150654	1	6.6e-06	6.75±6.7
$t\bar{t}\gamma$	108400	285787	0.013	4.7e-08	15.2±3.2
$b\bar{b}\gamma\gamma$	5037	763962	11	1.4e-05	217.6±65.6
$b\bar{b}j\gamma$	8960000	1119406	0.0051	4.6e-09	123.6±31.9
$jj\gamma\gamma$	164200	813797	0.056	6.9e-08	33.9±3.8
Total background	-	-	-	-	647.3±76.0
$S/\sqrt{B}$	-	-	-	-	16.5





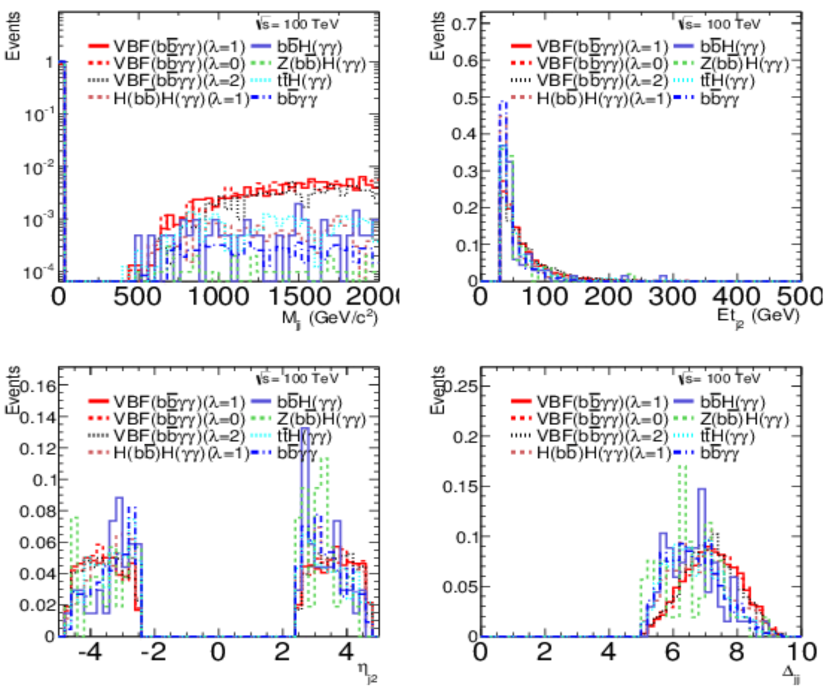
Higgs Self-Coupling Measurement

- Once gg→HH→bbγγ established, we estimated dλ with slop of dσ/σ/dλ
- Expected precision with dσ/σ/dλ=-0.51
  - dλ = dσ/σ/(dσ/σ/dλ)=15%.
- Loose cuts with dσ/σ/dλ=-0.57 :
  - Having more BKG, dλ=16.6%
- Sensitivity seems not depend on cuts.
- This is based on 3 ab^{-1} data. In order to achieve 5% precision, we need more data ~30 ab^{-1} at Tev100.
- Studying HHj, VBF and ttHH production processes, which are useful to break the degeneracy of Higgs self-coupling.

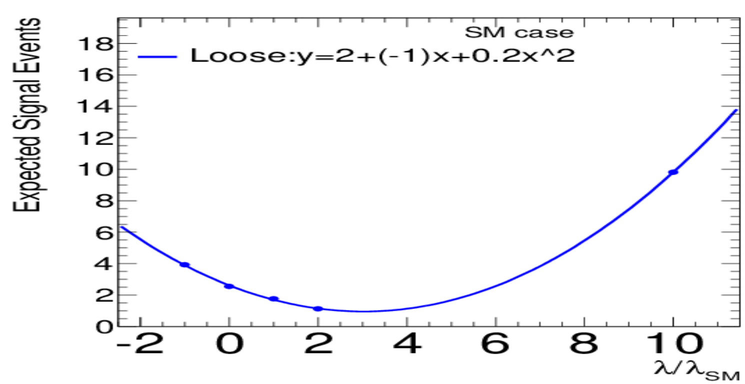


VBF→HH→bbγγ at 100 TeV

- Cross section for VV→HH→bbγγ is much smaller than gg→HH production.
- First look by selecting:
  - Two forwarded jets: Et>15 GeV; |η|>2.5; dη>3.0; mjj>400 GeV
  - Using the same selections for Higgs decay: H→bb and H→γγ
  - Signal rate seems small, other decay channels that may be useful.



Samples	$\sigma \cdot BR$ (fb)	Generated Evt	Selected Evt	Acc.	Expected (Statistic)
$VBF(bb\gamma\gamma)(\lambda=1)$	0.0823	100000	715	0.0072	1.77±0.066
$VBF(bb\gamma\gamma)(\lambda=0)$	0.175	100000	485	0.0048	2.55±0.12
$VBF(b\bar{b}\gamma\gamma)(\lambda=2)$	0.0801	100000	468	0.0047	1.12±0.052
$H(b\bar{b})H(\gamma\gamma)(\lambda=1)$	3.53	100000	19	0.00019	2.01±0.46
$Z(bb)H(\gamma\gamma)jj$	0.18	2779	4	0.0014	0.78±0.39
$t\bar{t}H(\gamma\gamma)$	37.26	63904	4	6.26e-05	7.00±3.50
$t\bar{t}\gamma$	108400	285787	0.0015	5.14e-09	1.67±1.18
$jj\gamma\gamma$	164200	813797	0.0002	2.46e-10	0.12±0.086
Total background	-	-	-	-	11.57871±3.742603
$S/\sqrt{B}$	-	-	-	-	0.5187966



TTHH→ttbbbb at 100 TeV

- T. Liu et al have looked ttHH→ttbbbb channel (arXiv:1410.1855v2)
- Constructing bb mass out of 6 bjets:
  - Pairing bjets by minimizing $\chi^2 = \sqrt{(((m_{bb}-m_H)/dm)^2+((m_{bb}-m_H)/dm)^2)}$
  - Selecting isolated lepton Et>20, |eta|<2.5
  - Anti-Kt algorithm: Et>20, |eta|<4.5, njet<7

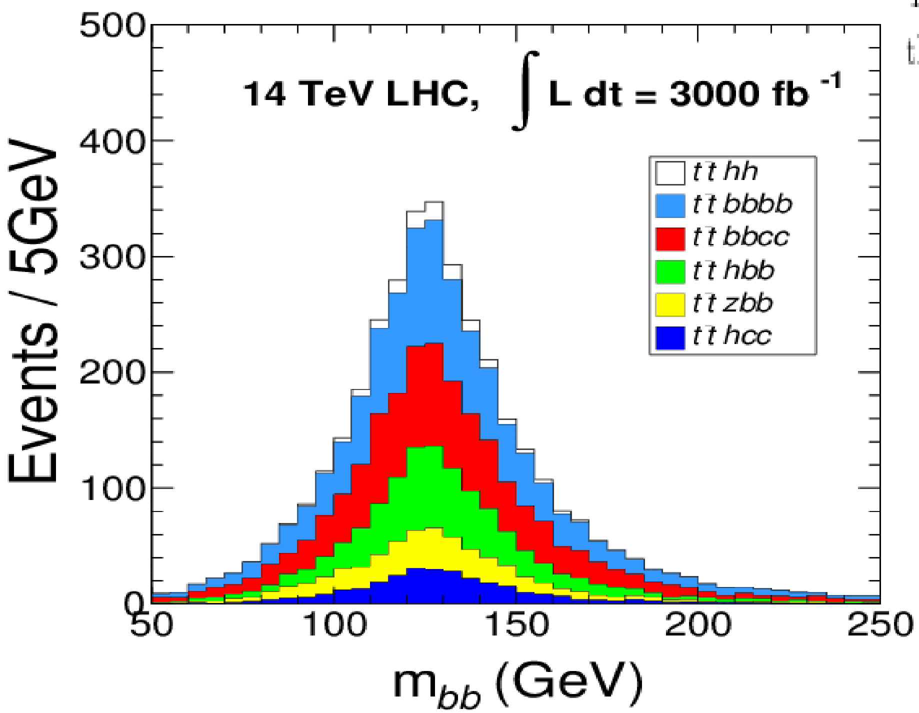


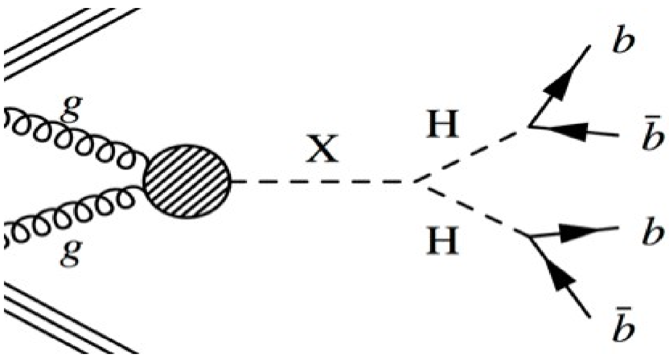
Table 1: Cut flows of searching for $pp \to t\bar{t}hh \to t\bar{t}b\bar{b}b\bar{b}$ at the 100 TeV pp -collider via the semi-leptonic top-pair channel. The unit used in the table is attobarn.

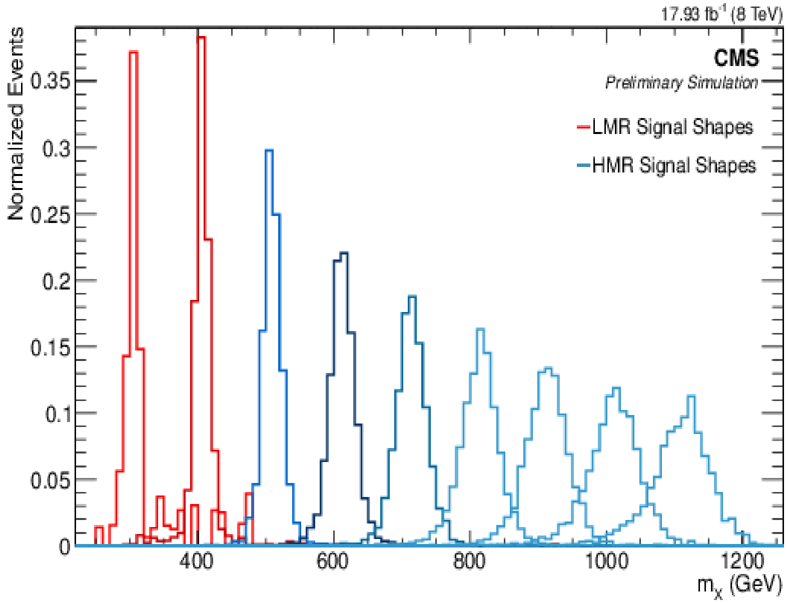
$\sqrt{s}$ = 100 TeV	$t\bar{t}hh$	$t\bar{t}b\bar{b}b\bar{b}$	$t\bar{t}b\bar{b}c\bar{c}$	$t\bar{t}hb\bar{b}$	$t\bar{t}Zb\bar{b}$	$t\bar{t}hc\bar{c}$
Preselection	830.5	72678.7	13322.6	10231.8	3252.0	1995.7
Di-Higgs rec.	608.4	31679.7	6285.2	5689.9	1504.0	1193.3
Top rec.	240.1	10384.4	2189.1	2208.6	428.0	384.9

- Significance: 3.3σ
- Slop: d(σ/σ)/(λ/λsm)=0.3
- Higgs self coupling: 70% with $3ab^{-1}$, or 20% with 30 ab^{-1}.

HH Production in BSM

- Production cross section significant enhanced in many BSM models.
- HH resonant production (KK-gravitons, 2HDM, NMSSM...)
  - Possibly enhanced large cross section
  - Could cut on Mx mass to reduce the contribution
  - ATLAS and CMS have carried such searches at Run1

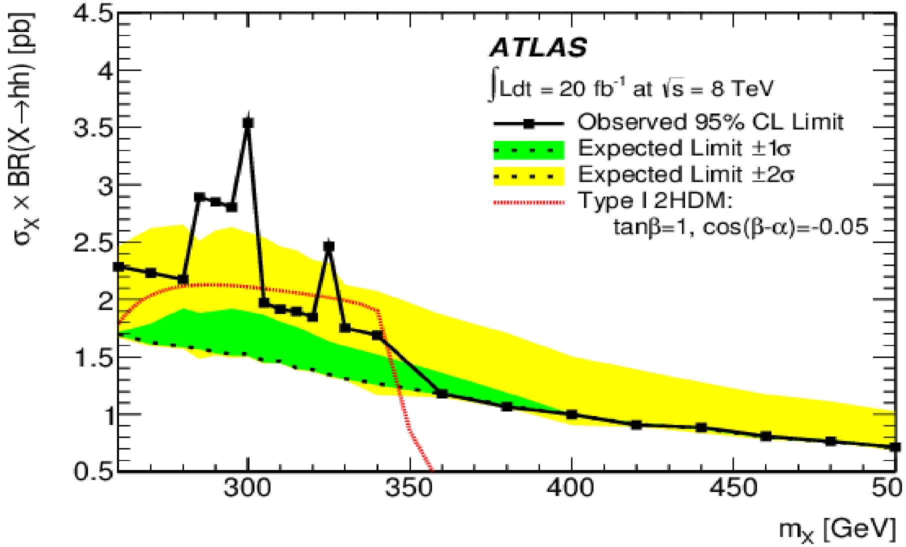


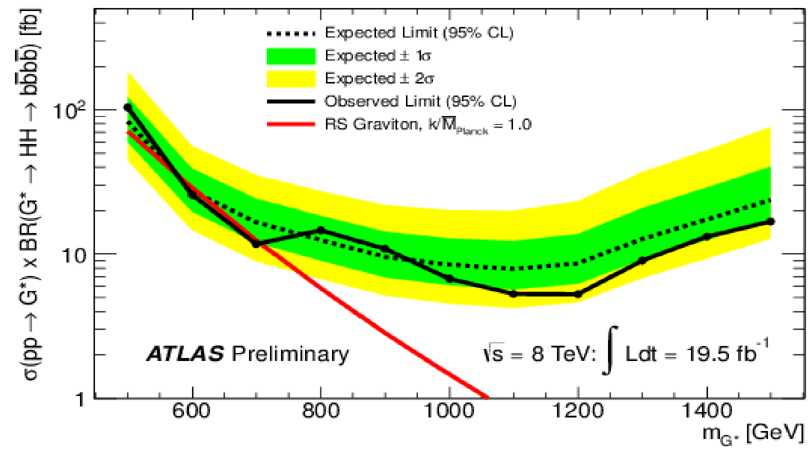


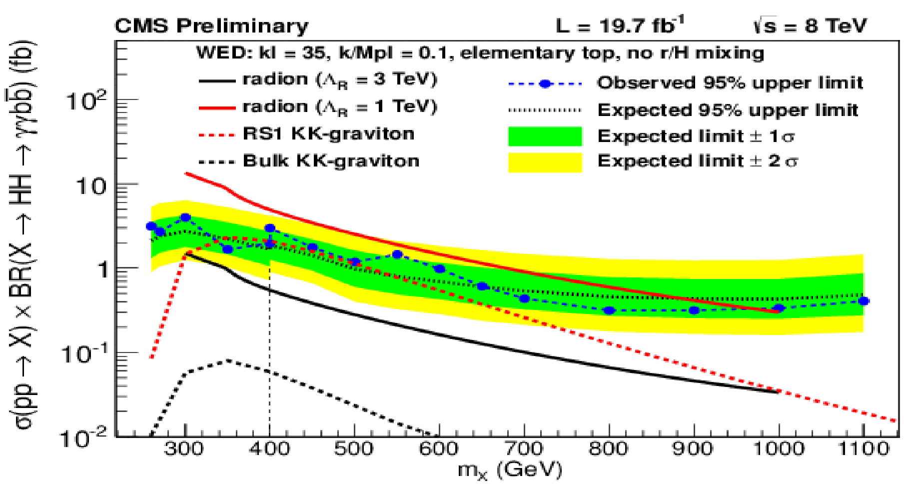
- HH no-resonant enhancement
  - Composite Higgs/Little Higgs
  - Can modify coupling and kinematics

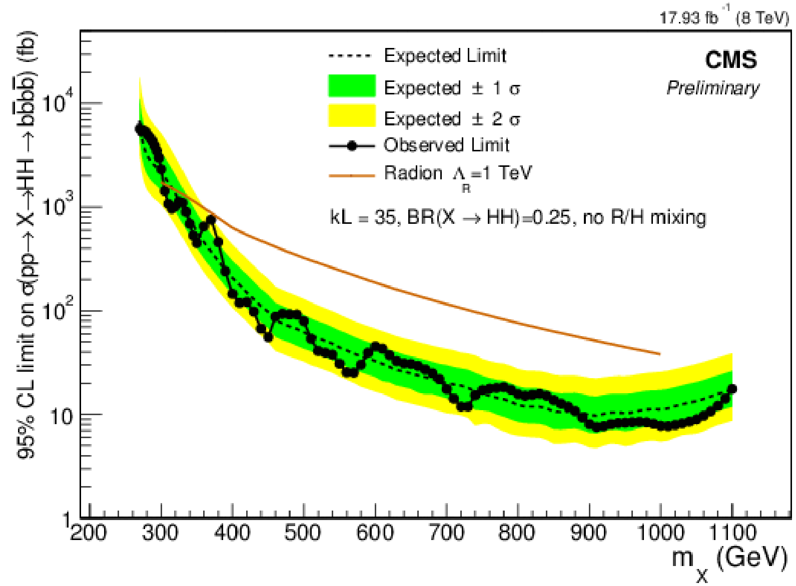
Searches for HH→bbbb, bbγγ at Run1

- ATLAS: HH→bbγγ (arXiv:1406.5053) and HH→bbbb (ATLAS-CONF-2014-005)
- CMS: HH→bbγγ (CMS-PAS-HIG-13-032) and HH→bbbb (CMS-PAS-HIG-14-013)



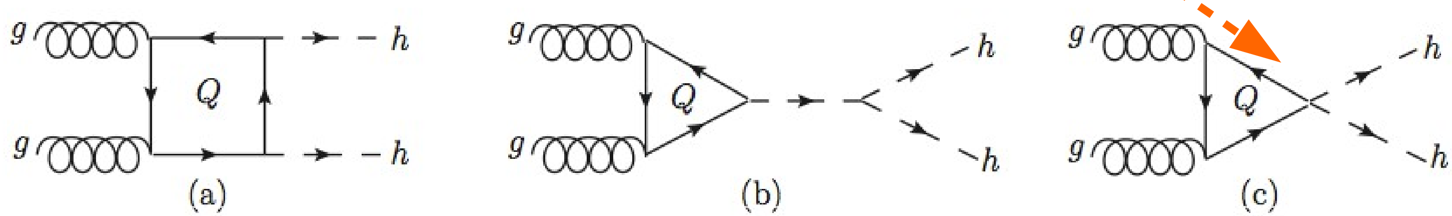






Non-resonant HH enhancement

- Interferences between SM and BSM diagrams could make σ degenerate in parameter space.(arXiv:1405.7040V1)



$$\frac{d\hat{\sigma}(gg \to hh)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{512(2\pi)^3} \left[\left| \left(c_{tri} \frac{3m_h^2}{\hat{s} - m_h^2} + c_{nl} \right) F_\triangle + c_{box} F_\Box \right|^2 + |c_{box} G_\Box|^2 \right]$$

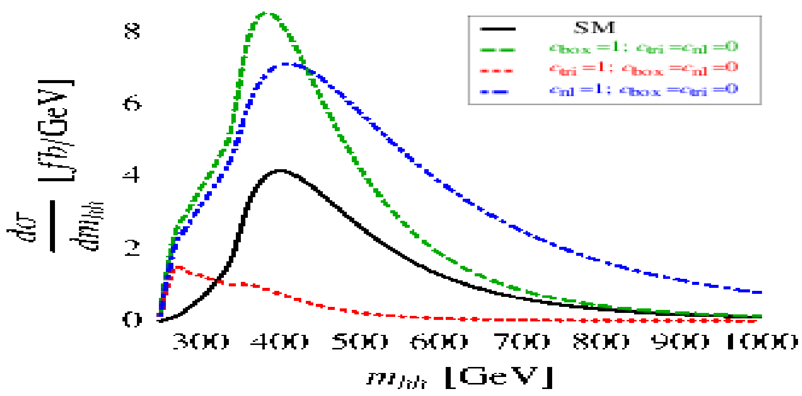
$$c_{box}^{(\mathrm{SM})} = 1 \,, \qquad c_{tri}^{(\mathrm{SM})} = 1 \,, \qquad c_{nl}^{(\mathrm{SM})} = 0$$

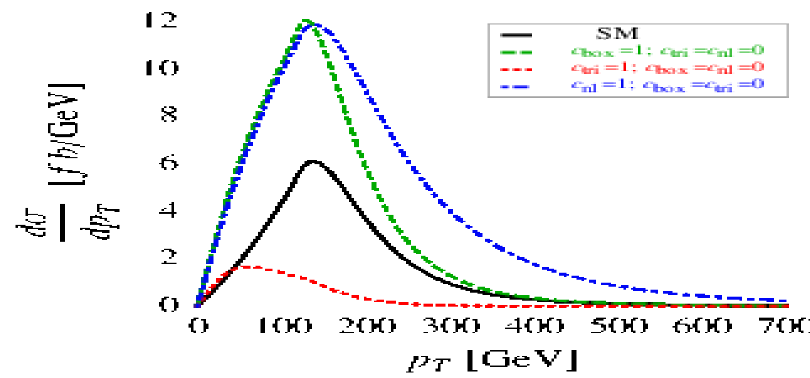
- Total cross section is expressed as

$$\sigma(gg \to hh) = \sigma^{SM}(gg \to hh)[1.849\ c_{box}^2 + 0.201\ c_{tri}^2 + 2.684\ c_{nl}^2$$
$$-1.050\ c_{box}c_{tri} - 3.974\ c_{box}c_{nl} + 1.215\ c_{tri}c_{nl}].$$

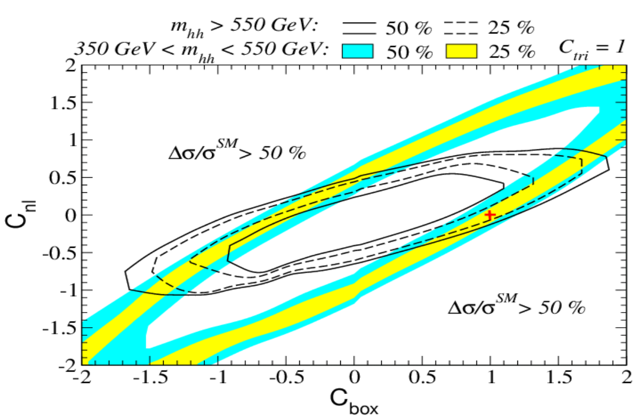
Constrain Couplings with Kinematic distributions

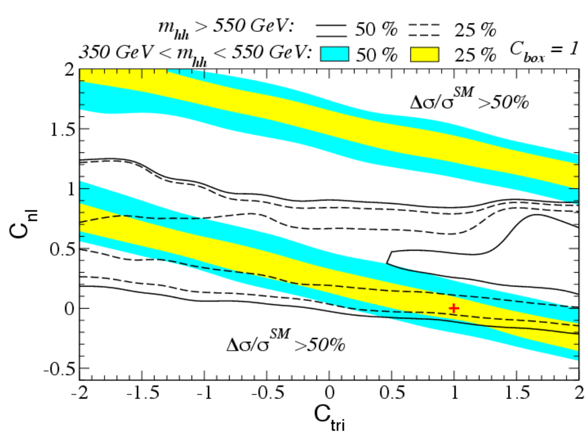
• Kinematic distributions can help to constrain the parameters

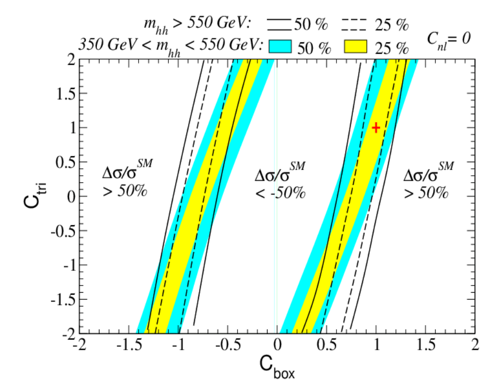




• Separating two mhh bins allows for a significant improvement in constrain coupling over cross section measurement alone.







Conclusions

- Measuring Higgs self-coupling crucial to understand Higgs potential & EWSB.
- The challenge is to identify the tiny signal out of huge background.
- Projected $HH \rightarrow bb\gamma\gamma$ significance is about 1.2-2.0σ at HL-LHC with 3000 fb^{-1}. Lots of work still needed to understand the actual HL-LHC sensitivity and likely improve with run2, phase 2 upgrades.
- Measuring $HH \rightarrow bb\gamma\gamma$ seems feasible at FCC 100 TeV hadron colliders with significant increased production cross section.
- The statistic accuracy of Higgs self-coupling is about 15% with 3000 fb^{-1} and 5% with more data 30 ab^{-1}.
- Although we do not know where the new physics is, the FCC collider will measure the Higgs potential precisely.