HH Studies at 100 TeV

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Outline

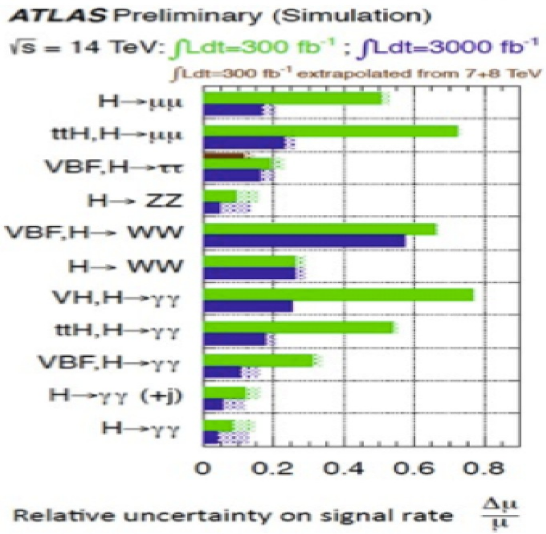
- Introduction
- What we learn from HL-LHC studies
- Prospects for 100 TeV
- Implications of BSM
- Conclusion

Documentation:

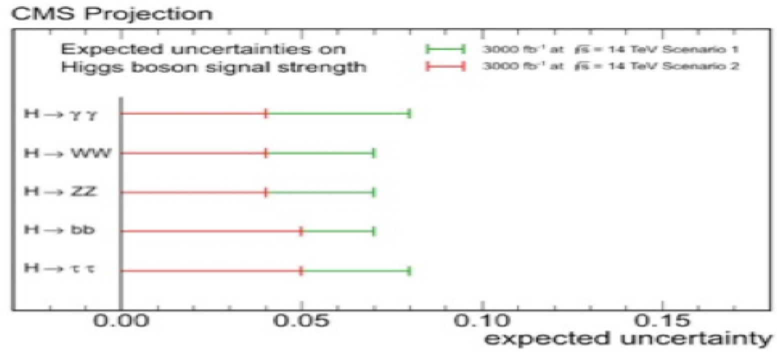
- In preparation and based on talk given at HKUST in Jan. 2015

Introduction

- LHC/HL-LHC will provide unprecedented and unparalleled physics opportunities for testing the validity of SM and search for BSM.
- Determine the Higgs coupling to a few % level
- Sensitive to new physics: $\Delta \frac{g}{g_{SM}} < 5\% \left(\frac{1TeV}{\Lambda} \right)^2$
- But very likely, we need FCC to explore BSM at the energy frontier.



Based on parametric simulation

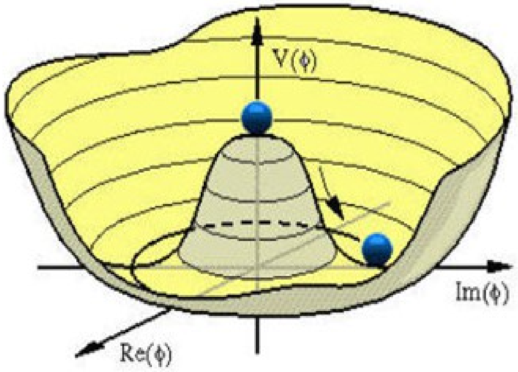


$L (fb^{-1})$	$H \rightarrow \gamma\gamma$	$H \rightarrow WW$	$H \rightarrow ZZ$	$H \rightarrow bb$	$H \rightarrow \tau\tau$	$H \rightarrow Z\gamma$	$H \rightarrow inv.$
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[6, 17]

Assumptions on systematic uncertainties
Scenario 1: no change
Scenario 2: Δ theory / 2, rest ∝ $1/\sqrt{L}$

Extrapolated from 2011/12 results

Probing the Higgs Potential



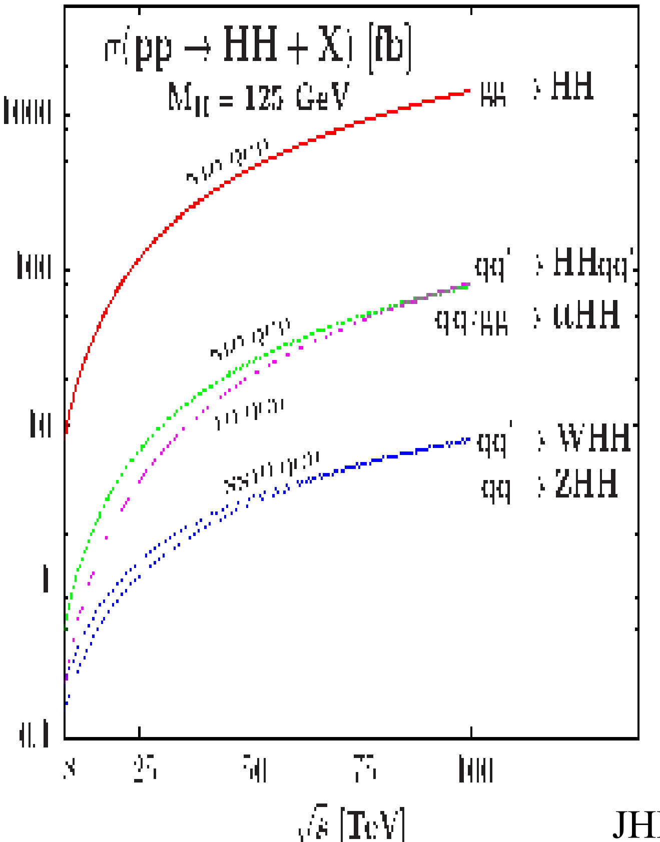
- From the scalar potential before EWSB:
  - $V(\Phi)=-\mu^2|\Phi|^2 +\lambda|\Phi|^4$
- $V(\Phi)$ after EWSB with $M_h^2 = 2\mu^2$, $v^2 = \mu^2/\lambda$
  - $\Phi=(0,(v+h)/\sqrt{2})$
  - $V(h)=1/2M_h^2h^2 +1/2M_h^2/v\, h^3 +1/8M_h^2/v^2h^4$ + Const
- Trilinear and Quartic Higgs coupling:
  - $\lambda_{hhh}=3M_h^2/v$
  - $\lambda_{hhhh}=3M_h^2/v^2$
- Within SM, everything known: λ_{hhh}~0.13.

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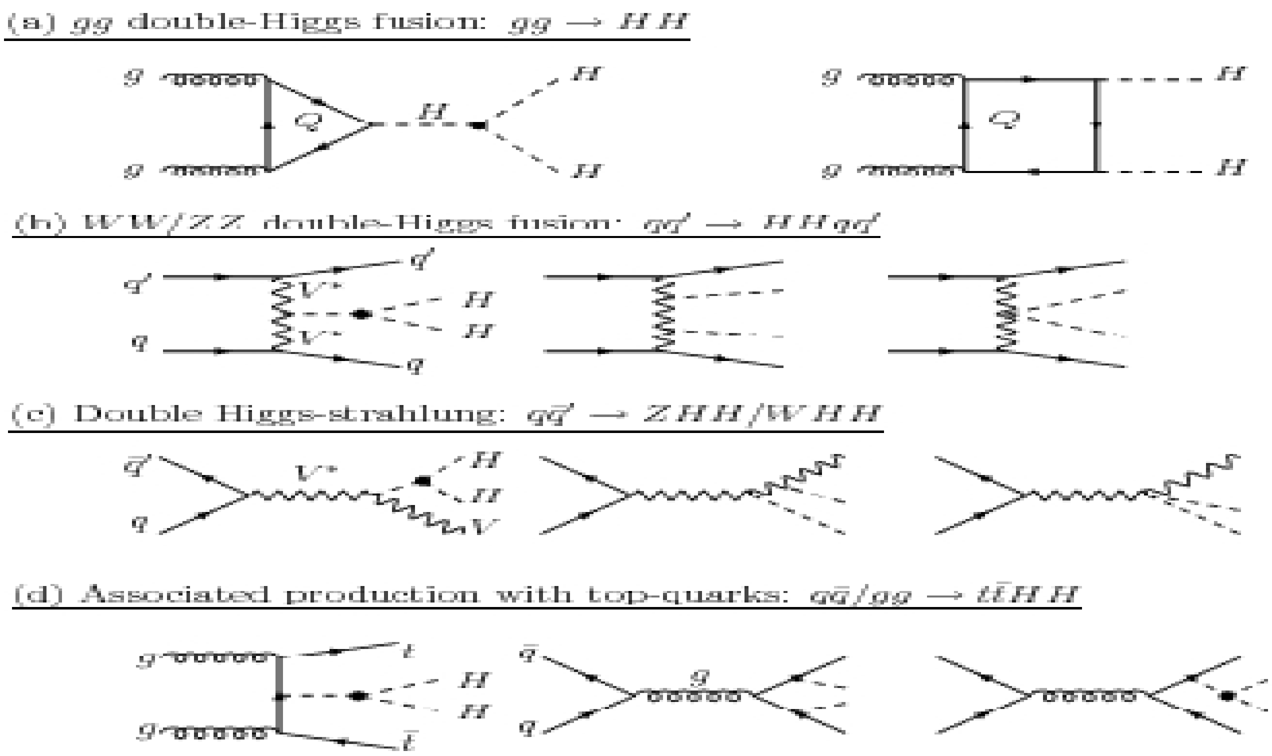
	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

$R=\sigma(E)/\sigma(14\text{TeV})$

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)

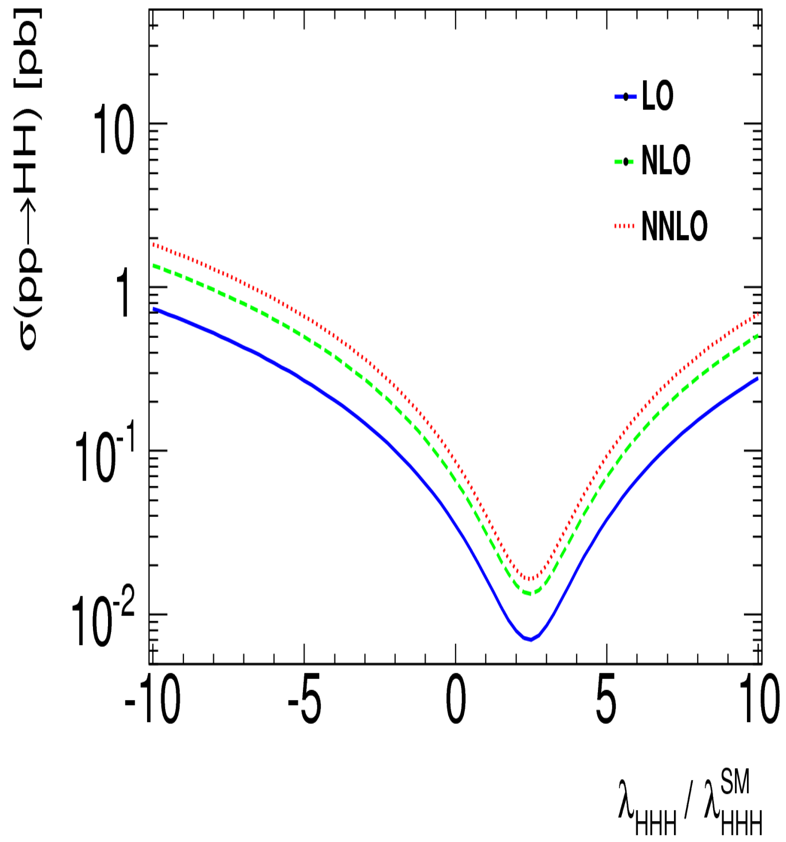
– due to the destructive interference ruled by yt and λ

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

The Double Higgs Production

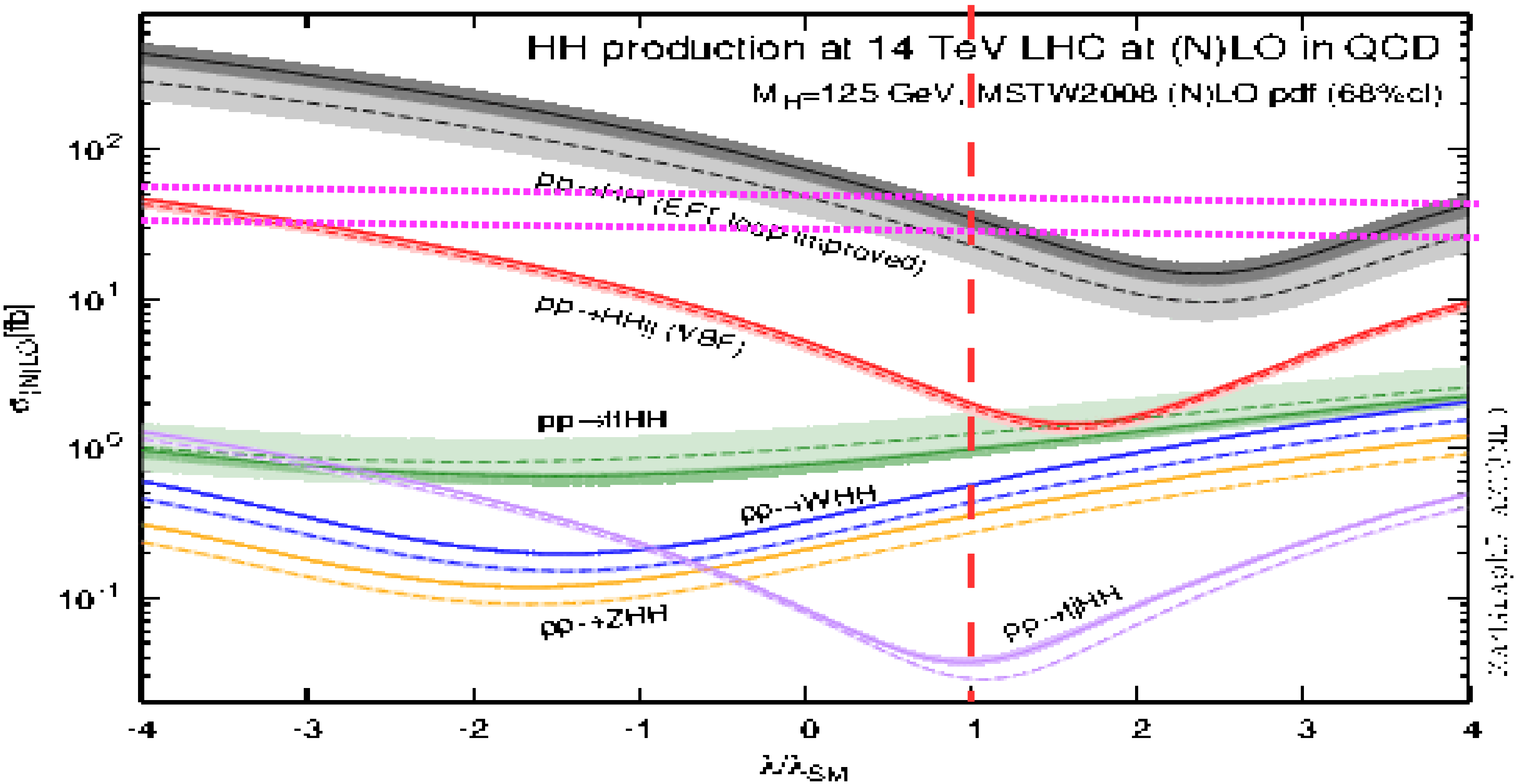
- The ggHH cross section and uncertainties at NNLO are available (Florian et al PRL 111 (2013) 201801)

$E_{c.m.}$	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

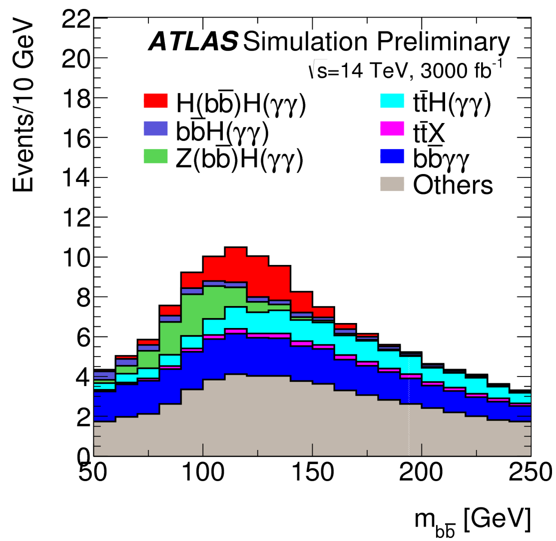
- The HH production cross section at 14 TeV is small, 40 fb.
- Selection of HH final states has been studied:
  - HH→bbγγ: clean but small rate, seems best
  - Other channels suffered either too small rate or huge background from ttbar or Z+jets, but work is on going.
  - Have to combine all possible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

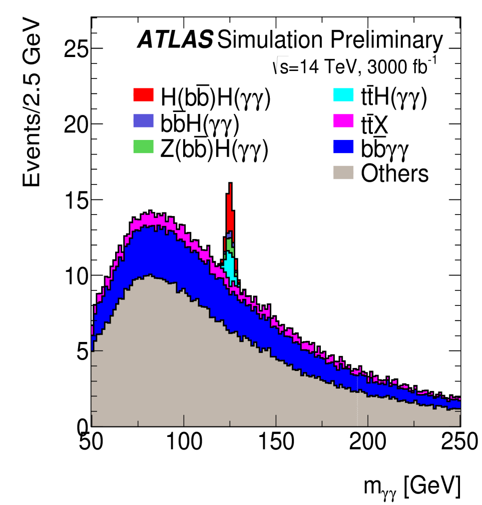
Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b} + b\bar{b}$	33%	40,000
$b\bar{b} + W^+W^-$	25%	31,000
$b\bar{b} + \tau^+\tau^-$	7.3%	8,900
$ZZ + b\bar{b}$	3.1%	3,800
$W^+W^- + \tau^+\tau^-$	2.7%	3,300
$ZZ + W^+W^-$	1.1%	1,300
$\gamma\gamma + b\bar{b}$	0.26%	320
$\gamma\gamma + \gamma\gamma$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

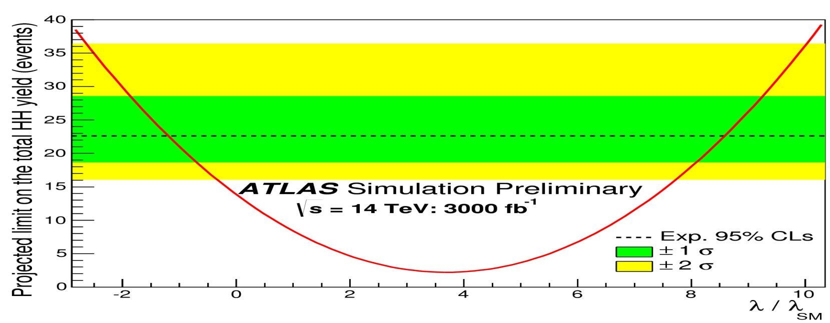
HH→bbγγ at HL-LHC

- ATLAS and CMS updated the HH→bbγγ 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
$t\bar{t}(\geq 1\text{ lepton})$	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



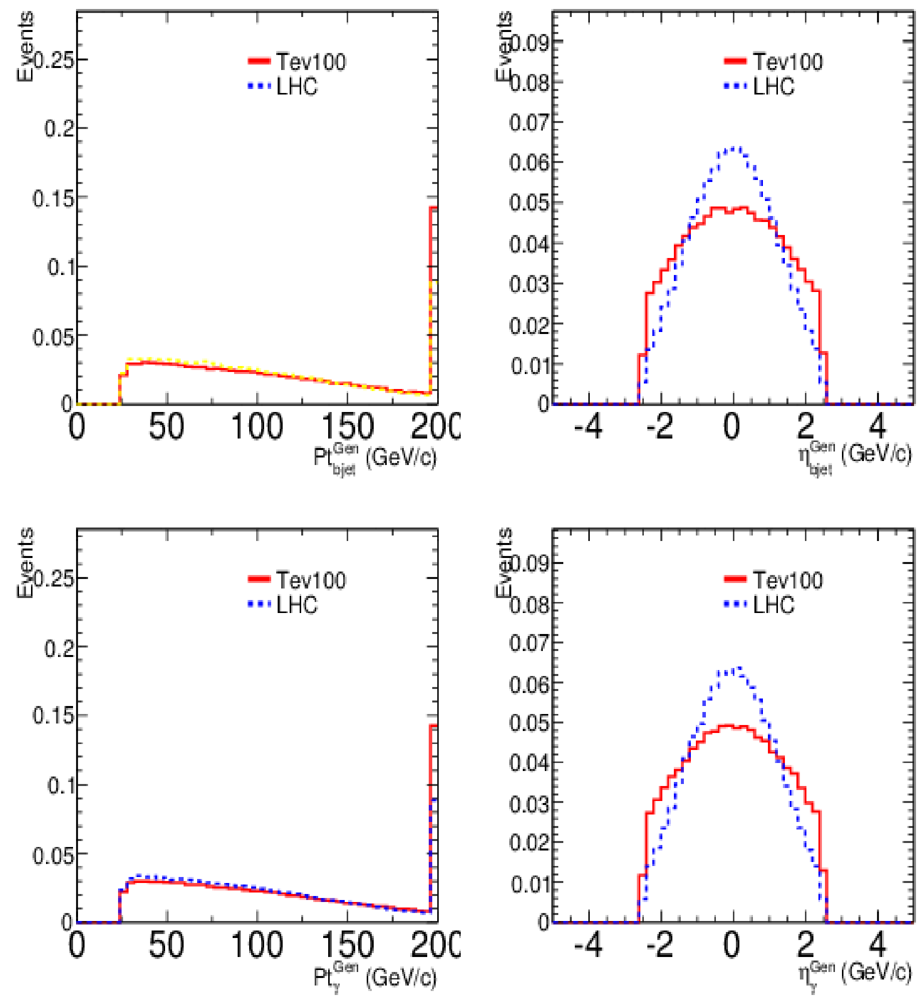




14 TeV vs 100 TeV

- 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



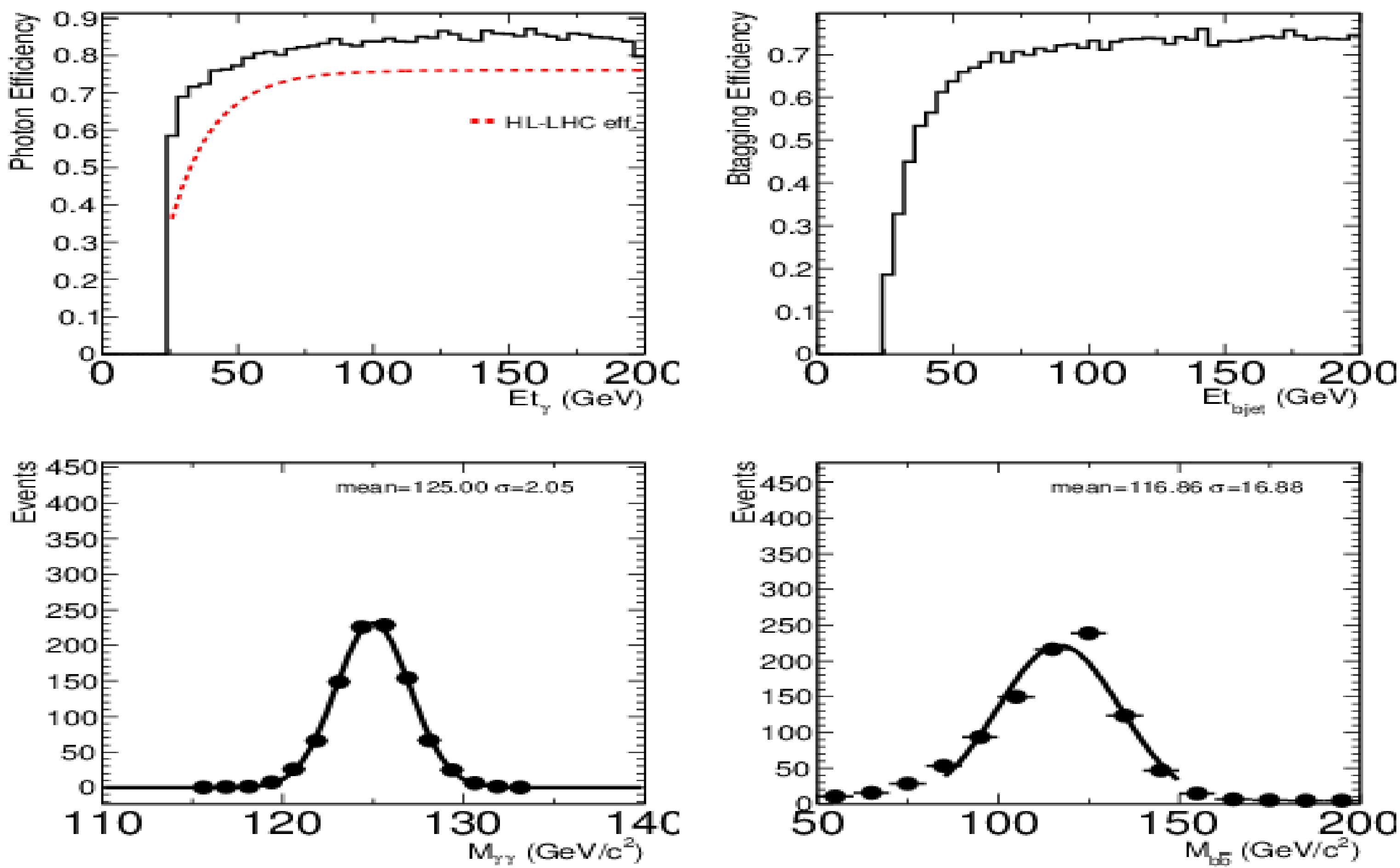
Fast Simulation Setup

- 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+-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

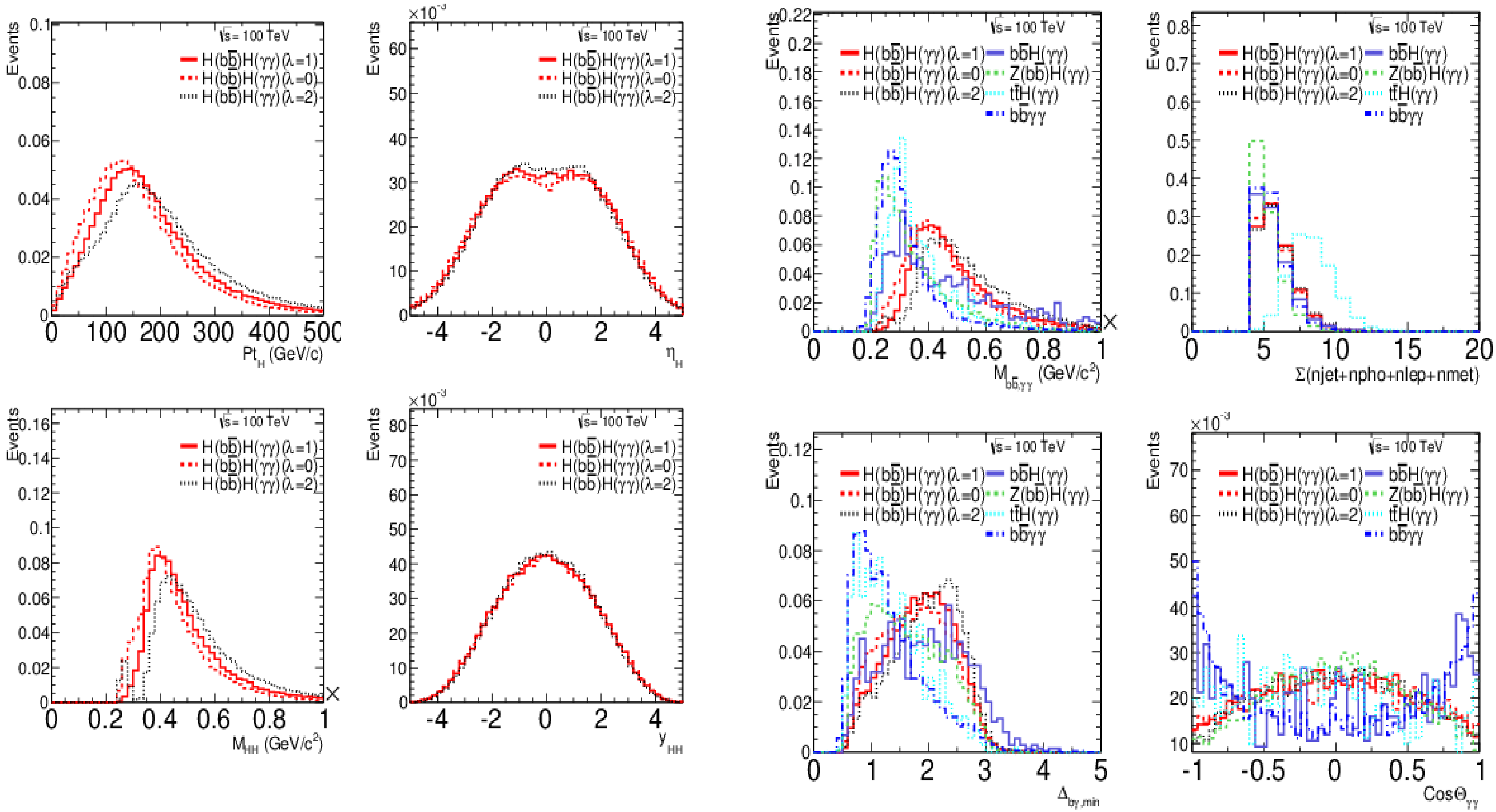
•Photon, btag efficiency and mass distributions

•Mγγ, Mbb are similar to LHC; Photon eff is higher than what used in HL-LHC.



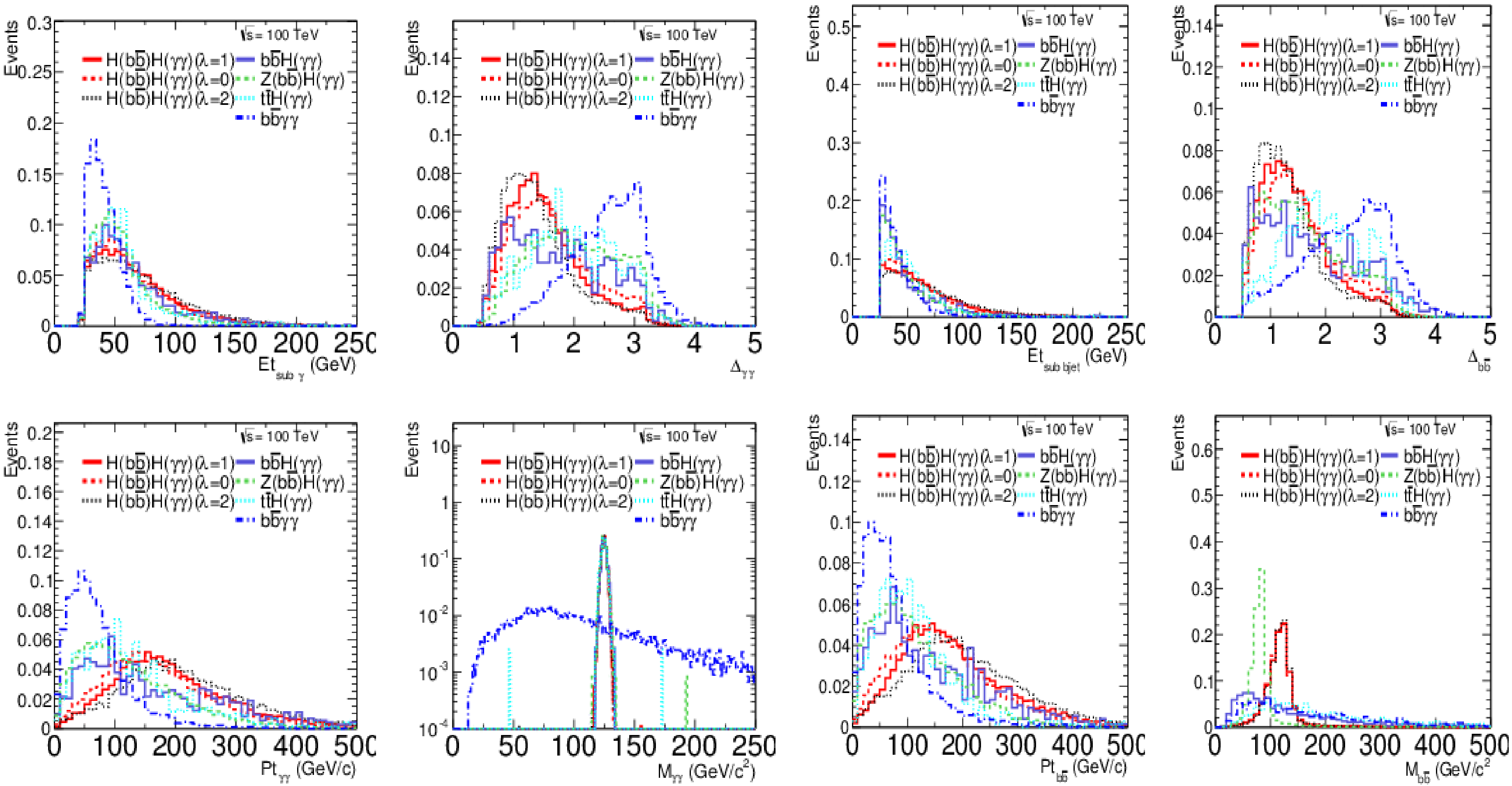
HH→bbγγ Kinematics

- 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|<2.5
  - Require 2 photons with Pt>35 GeV, |eta|<2.5
  - 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

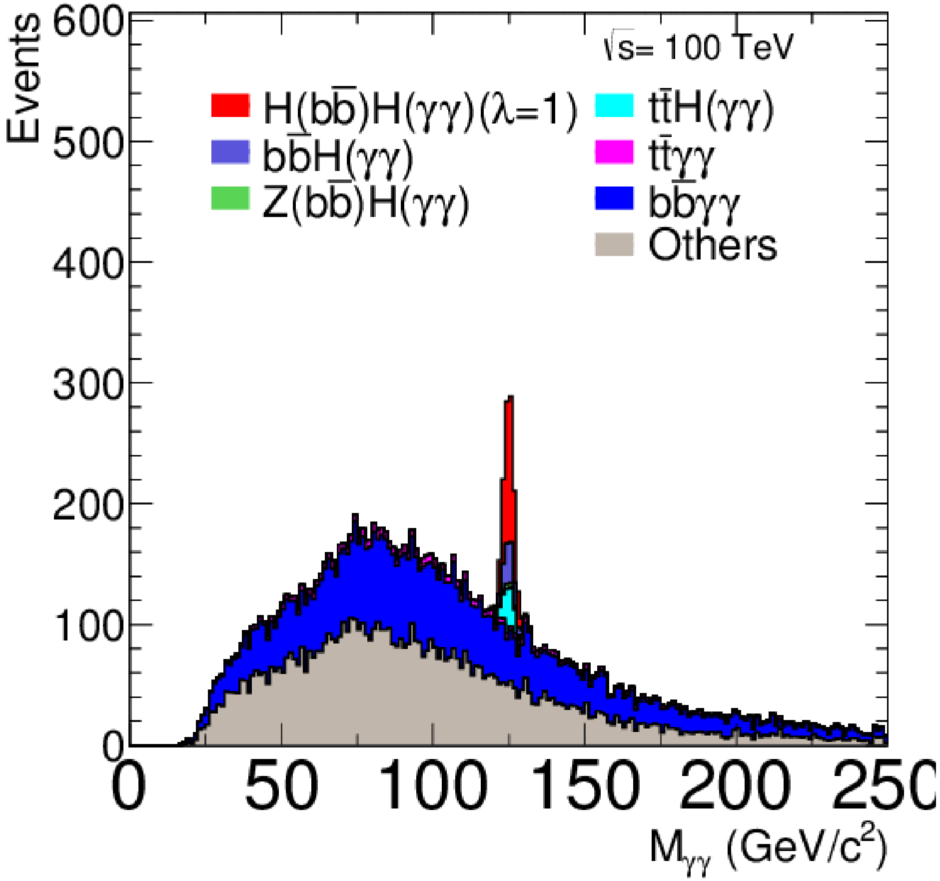
- bbγγ seems still dominant and can be further reduced with MVA.
- Expected S/√B~16.5 for Tev100 with 3 fb^{-1}.
- Comparison with recent studies: 1412.7154 reported S/√B=8.4 using conservative eff. while 1502.00539 reports S/√B=15.2 using comparab eff.

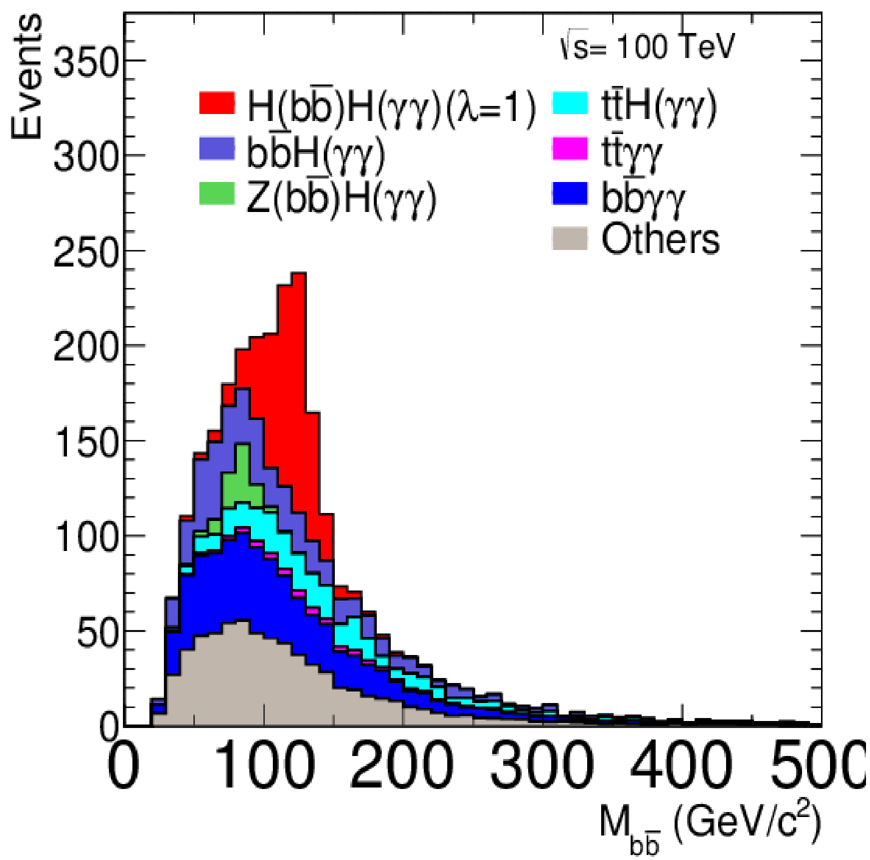
Samples	$\sigma \cdot BR$ (fb)	Generated Evt	Selected Evt	Acc.	Expected (Statistic)
$H(b\bar{b})H(\gamma\gamma)(\lambda=1)$	3.53	100000	3955	0.040	418.8±6.6
$H(b\bar{b})H(\gamma\gamma)(\lambda=0)$	6.88	100000	3322	0.03322	685.7±11.9
$H(b\bar{b})H(\gamma\gamma)(\lambda=2)$	1.76	100000	4566	0.04566	241.1±3.6
$b\bar{b}H(\gamma\gamma)$	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

$\frac{(bb\gamma\gamma)}{(jj\gamma\gamma)}$ =6.4

Mbb and Mγγ

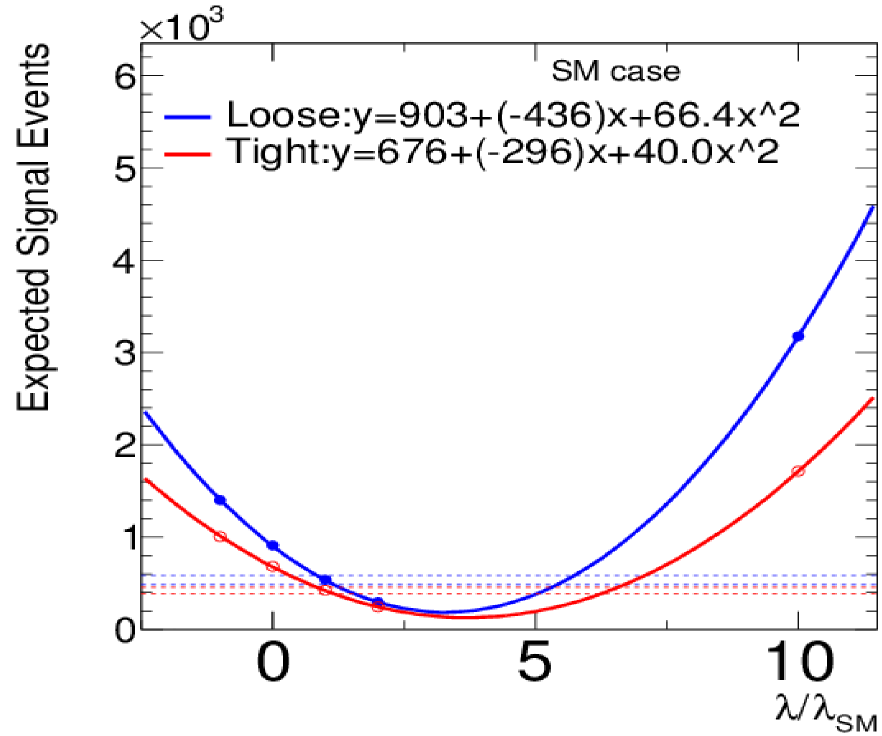
•Mbb vs Mγγ when one of them consistent with Higgs mass.

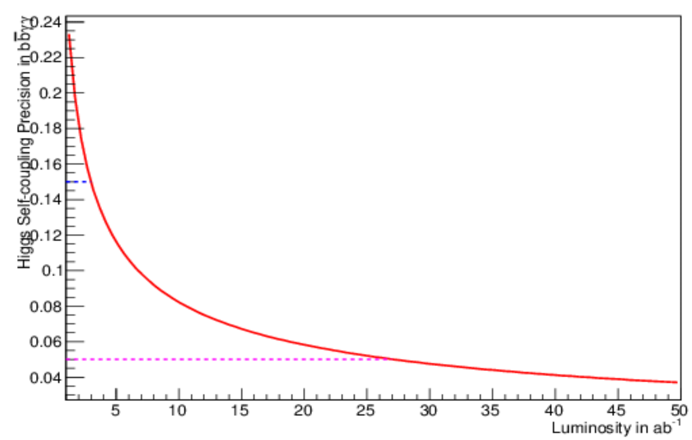




Higgs Self-Coupling Measurement

- Once gg→HH→bbγγ established, we measure dλ using slop of dσ/dλ
- Expected precision with dσ/dλ=-0.51
  - dλ = dσ/(dσ/dλ)=15% for 3ab^{-1}
- Loose cuts is more sensitive to slop, but more bkg gives slight worse results: dσ/dλ=-0.57 →dλ=16.6%
- For 5% precision, we need ~27 ab^{-1} at Tev100 and the projection
- Studying HHj, VBF and ttHH production processes, which are useful to break the degeneracy of Higgs self-coupling.





VBF→HH→bbγγ at 100 TeV

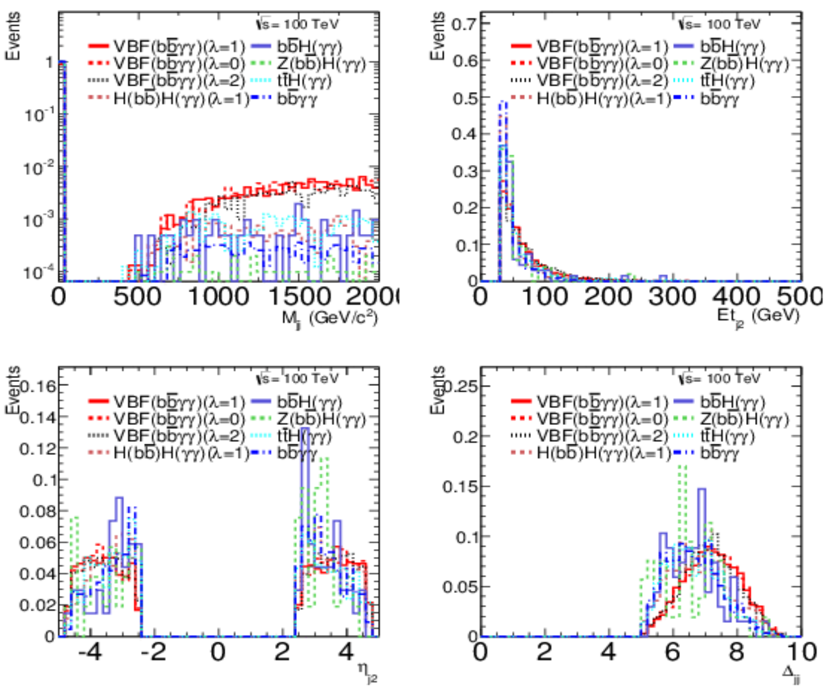
•Cross section for VV→HH→bbγγ is much smaller than gg→HH production.

•First look by selecting:

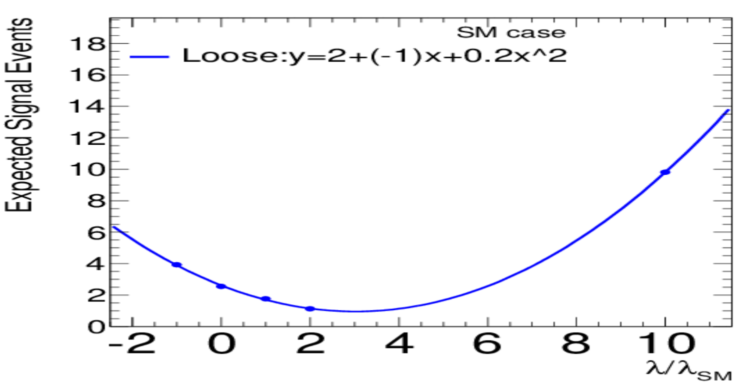
–Two forwarded jets: Et>15 GeV; |η|>2.5; dη>3.0; mjj>400 GeV

–Using the same selections for Higgs decay: H→bb and H→γγ

–Signal rate seems small, other decay channels that may be more useful.



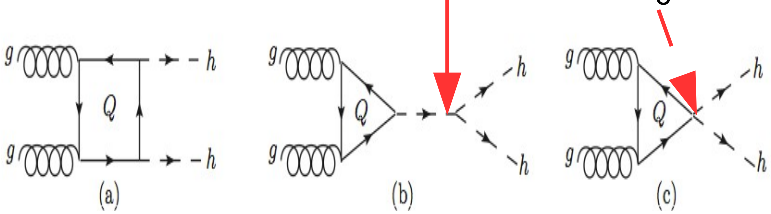
Samples	$\sigma \cdot BR$ (fb)	Generated Evt	Selected Evt	Acc.	Expected (Statistic)
$VBF(b\bar{b}\gamma\gamma)(\lambda=1)$	0.0823	100000	715	0.0072	1.77±0.066
$VBF(b\bar{b}\gamma\gamma)(\lambda=0)$	0.175	100000	485	0.0048	2.55±0.12
$VBF(b\bar{b}\gamma\gamma)(\lambda=2)$	0.0801	100000	468	0.0047	1.12±0.052
$H(b\bar{b})H(\gamma\gamma)(\lambda=1)$	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

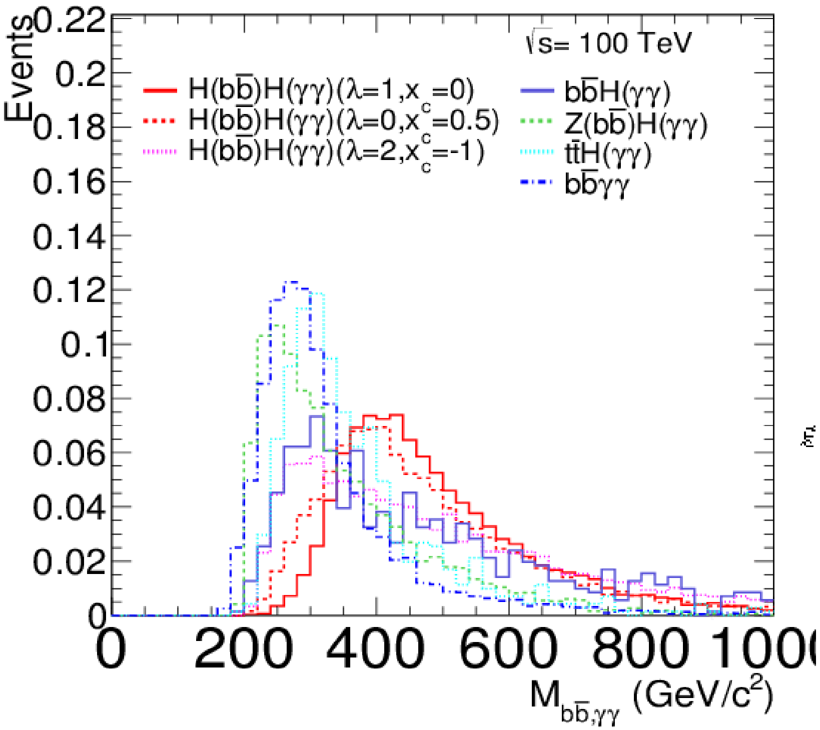


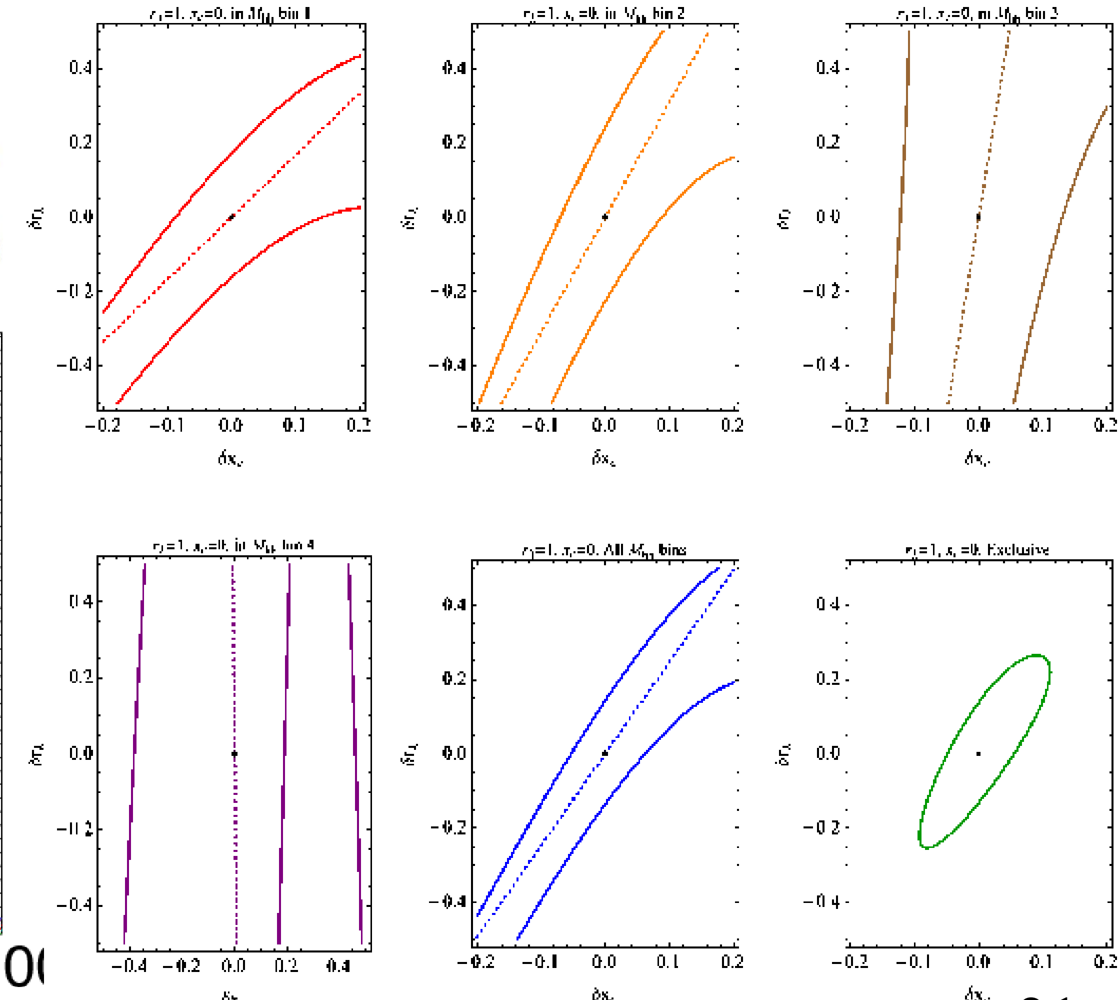
Probing Modified Higgs Self-Coupling via Dim=6 Operators

- Di-Higgs production and kinematics can be enhanced by new physics, which characterized by dim=6 operators ($O_{\Phi,2}$ and $O_{\Phi,3}$) as λ and x_c .

- In SM expected: λ=1 and x_c=0







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 3 ab^{-1} and 5% with ~30 ab^{-1} for SM case.
- On-going work:
    - Optimizing and including other processes and decays.
    - Quantify the impact of BSM effects using Dim=6 operators.