Search for Multi-Higgs Final States@Hadron Colliders

The measurement Higgs Self-Couplings

Qi-Shu Yan (UCAS, Beijing)

Program on High Energy Physcis
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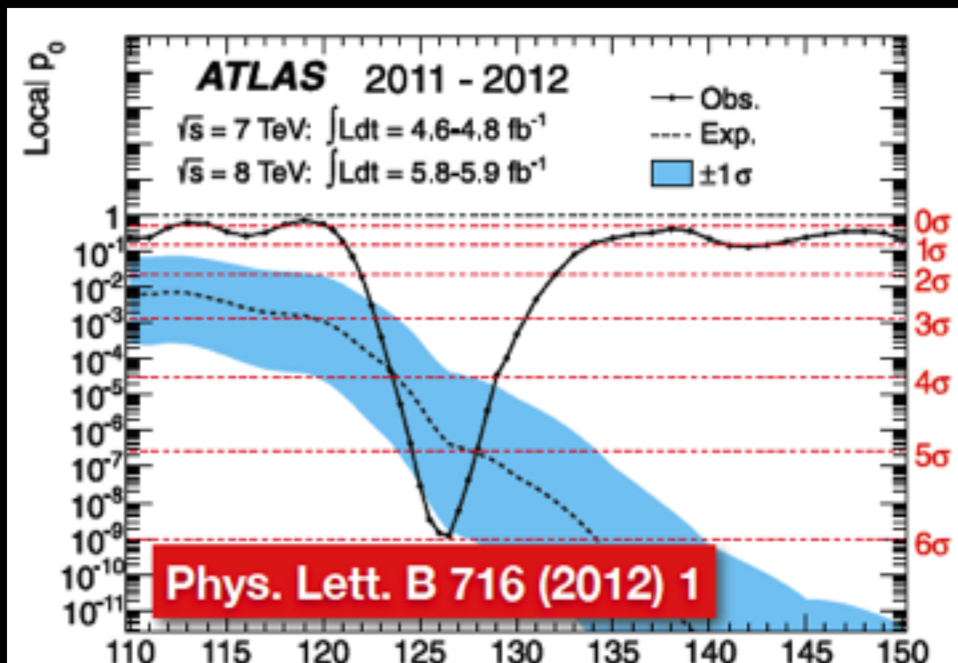
Outline

- Introduction
- Analysis1: the trilinear coupling λ_3 $\boxed{3\ell 2j + \not{E}\ \mathbf{mode}}$
- Analysis2: the quartic coupling λ_4 $\boxed{4b2\gamma}$
- Conclusion

Based on:
Q.Li, Z. Li, QY, X.R. Zhao, PRD92(2015)1,014015, arXiv:1503.07611
C.Y. Chen,QY, X.R. Zhao, Z.J. Zhao, Y.M. Zhong, PRD93 (2016)1, 013007, arXiv:1510.04013

Introduction



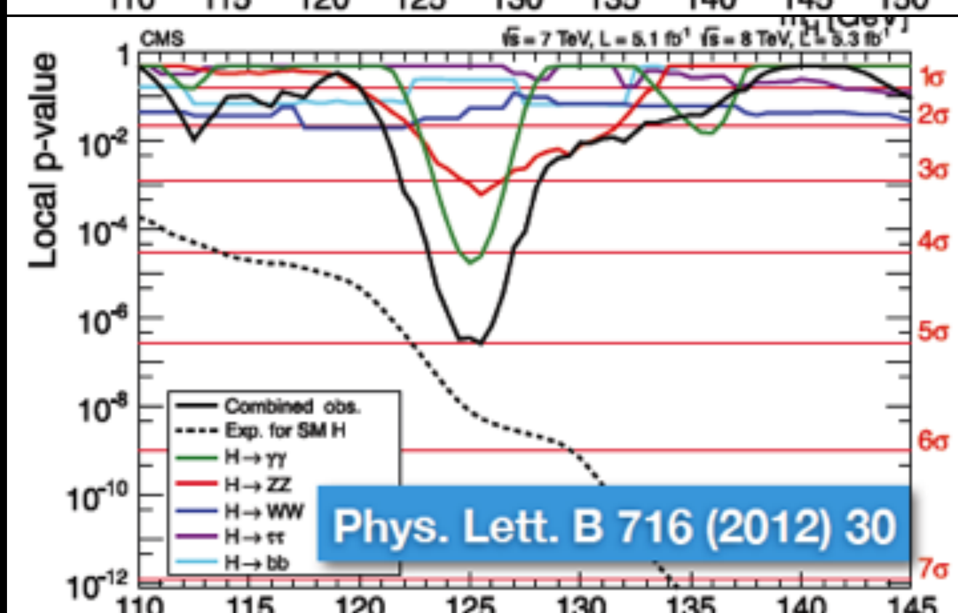


Photo: A. Mahmoud

François Englert

Prize share: 1/2

Photo: A. Mahmoud

Peter W. Higgs

Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Introduction

$$V(\phi) = -\mu^2 \phi^\dagger \phi + \frac{\lambda}{4}(\phi^\dagger \phi)^2 \, ,$$

$$V(\phi_0, S) = \lambda \left(\phi_0^2 - \frac{v_{EW}^2}{2} \right)^2 + \frac{a_1}{2} \left(\phi_0^2 - \frac{v_{EW}^2}{2} \right) S + \frac{a_2}{2} \left(\phi_0^2 + \frac{v_{EW}^2}{2} \right) S^2 + \frac{1}{4} \left(2b_2 + a_2 v_{EW}^2 \right) S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4,$$

$$\begin{aligned} V(\phi_1, \phi_2) = {} & m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 + (m_{12}^2 \phi_1^\dagger \phi_2 + h.c.) \\ & + \frac{\lambda_1}{4} (\phi_1^\dagger \phi_1)^2 + \frac{\lambda_2}{4} (\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) + \lambda_4 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) \\ & + \frac{1}{2} \left[\frac{1}{2} \lambda_5 (\phi_1^\dagger \phi_2)(\phi_1^\dagger \phi_2) + \lambda_6 (\phi_1^\dagger \phi_1)(\phi_1^\dagger \phi_2) + \lambda_7 (\phi_2^\dagger \phi_2)(\phi_1^\dagger \phi_2) + h.c. \right] \, , \end{aligned}$$

Unsolved questions of the SM: Shape of Higgs potential, the matter-antimatter asymmetry, EW baryogensis, CP violation in Higgs potential, …

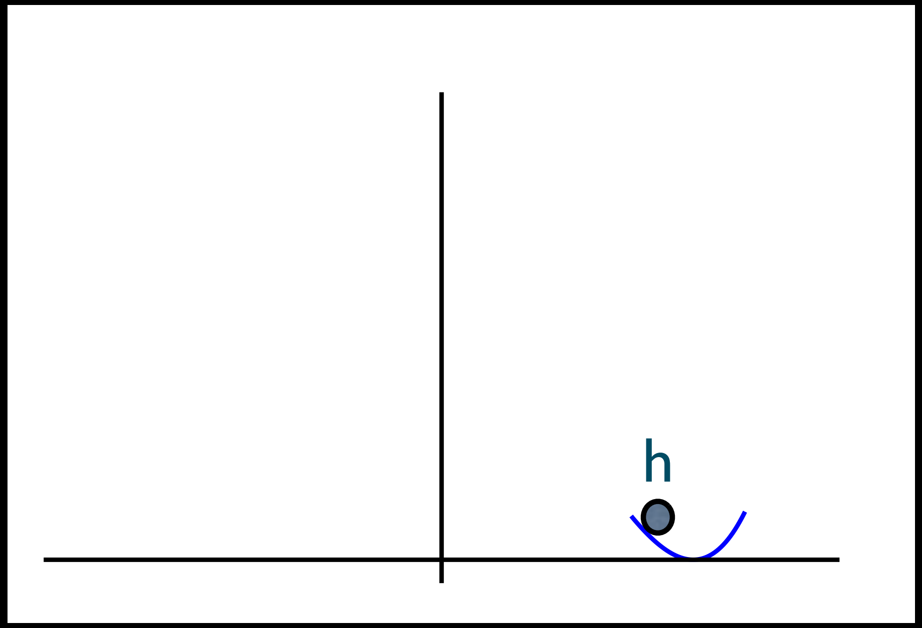
Introduction

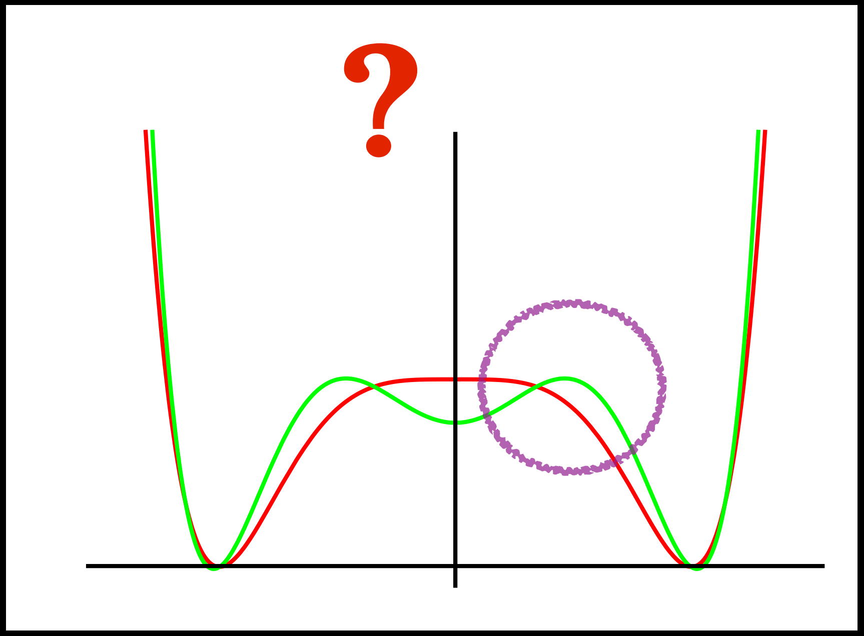
- 1) Understanding the nature of Higgs boson, composite of fundamental
- 2) Detecting the EWSB mechanisms and model discriminating
- 3) Probe EW baryogensis scenario, the EW phase transition, CP sources from Higgs Potential, …
- 4) Probe new physics …

Higgs self-couplings encode the forces causing vev. Measuring them can address big scientific issues.

See Chris Quigg's talk on Jan/18/2016

Introduction





A big question: the shape of Higgs potential is crucial for the strong first order electroweak phase transition, which is badly needed in the EW Baryogenesis scenarios.

CEPC Pre-CDR report
M. Trodden, Rev.Mod.Phys.71(1999)1463
D.E. Morrissey, M.J. Musolf, NJP14(2012)125003
N.Arkani-Hamed, T.Han, M.Mangano, L.T.Wang, 1511.06495

Introduction

$$\Delta L = -\frac{1}{2}m_H^2 H^2 - \lambda_3 \lambda_{SM} v H^3 - \frac{1}{4}\lambda_4 \lambda_{SM} H^4 + \cdots ,$$

$$\lambda_3 = \lambda_4 = 1, \text{ for the SM case}$$

The mass of Higgs is measured by the LHC run 1, Higgs' couplings to VB and matters @CEPC/FCC/ILC

Higgs self-couplings measmt. is the prime target of future LHC runs and future colliders

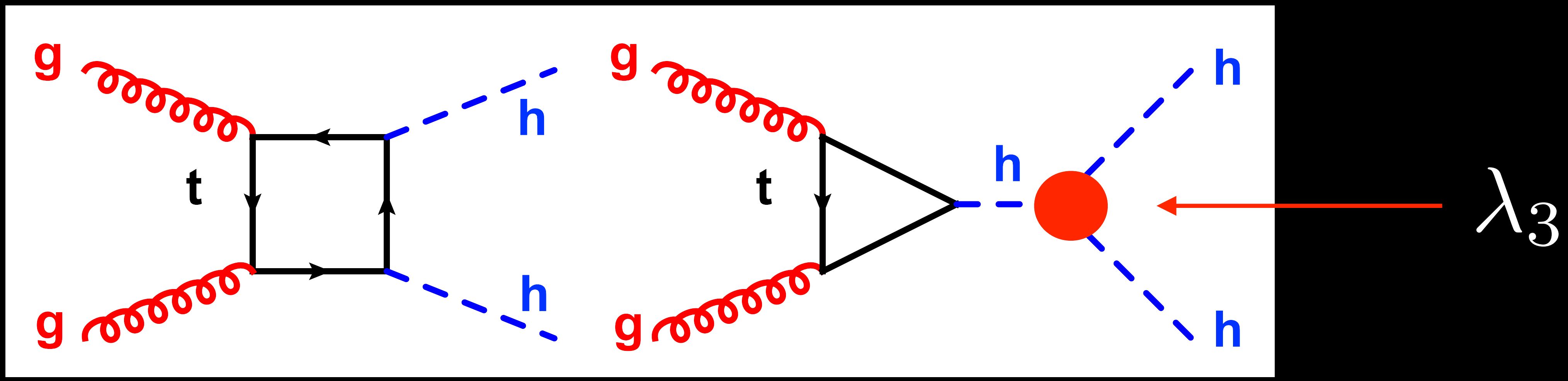
$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2 + \frac{\kappa(\phi^\dagger \phi)^3}{\Lambda^2}$$

X.Zhang, PRD47(1993)3065

F.P. Huang, P.H. Gu, P.F. Yin, Z.H. Yu, X. Zhang, 1511.03969

P. Huang, A. Joglekar, B. Li, C.E.M. Wagner, 1512.00068

Analysis1: trilinear coupling



The dominant channel of Higgs pair production @LHC due to the large gluon fluxes.

$$\sigma(pp \to hh, 14\ \mathrm{TeV}) = 34.5 - 23.1\,\lambda_3 + 4.82\,\lambda_3^2$$

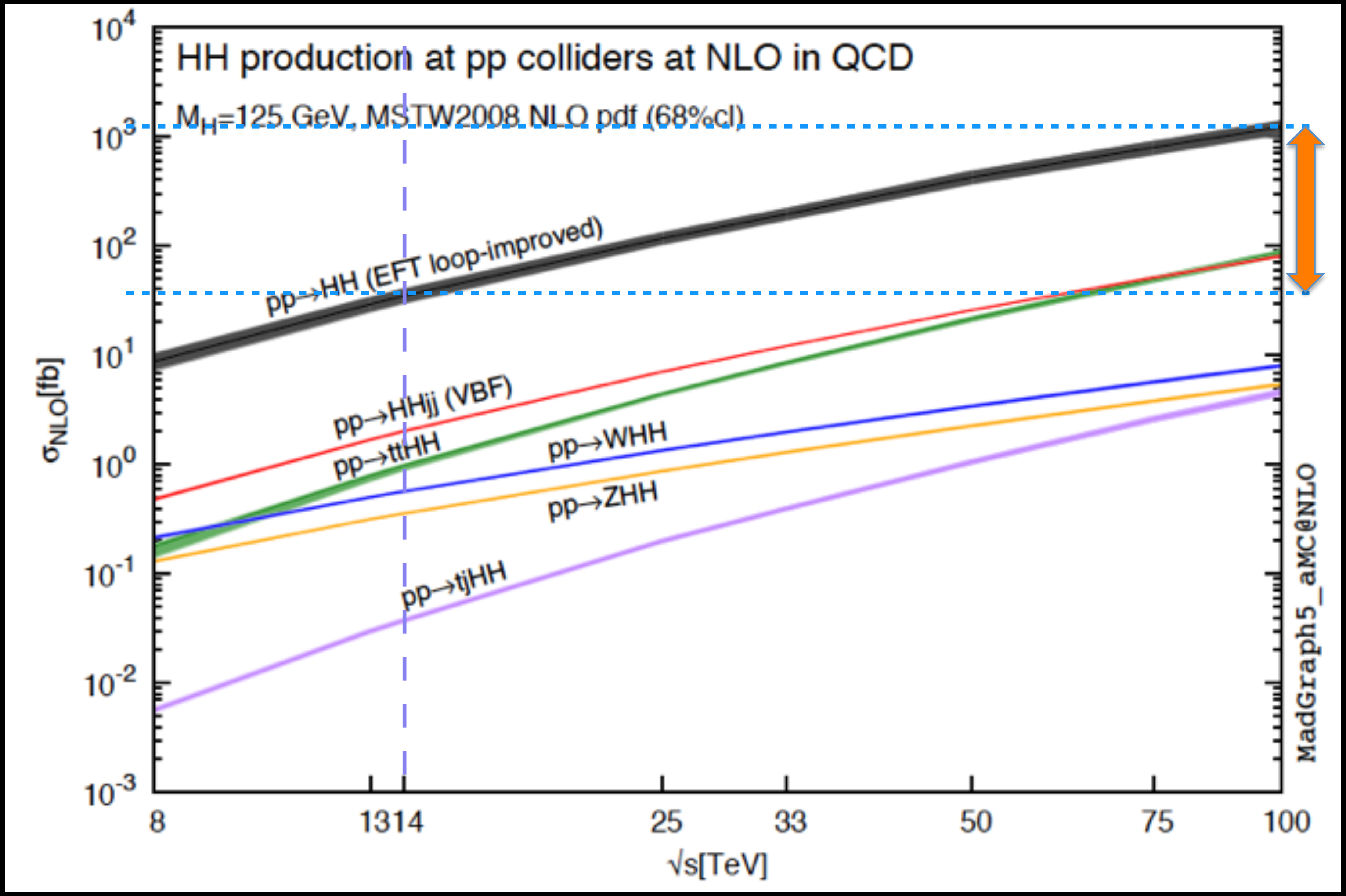
With K=1.8, ~ 40fb @ LHC14TeV

O.J.P. Eboli, G.C. Marques, S.F. Novaes and A.A. Natale, Phys.Lett.B197, 269 (1987)

D.A. Dicus, K.J. Kallianpur and S.S.D. Willenbrock, Phys. Lett. B 200, 187 (1988)

C.S. Li, H.T. Li, D.Y. Shao, Chin. Sci. Bull.59, 2709(2014)

Analysis1: trilinear coupling



At a 100 TeV collider, the cross section be enhanced by a factor 40 or so

$$\sigma(pp \to hh, 100\ \text{TeV}) = 1710 - 1030\,\lambda_3 + 197\,\lambda_3^2$$

K=1.6, ~ 1600fb @ 100TeV

R.Frederix, S.Frixione, V.Hirschi, F.Maltoni, O.Mattelaer, P.Torrielli, E.Vryonidou and M.Zaro,Phys.Lett.B732,142 (2014)

Analysis1: trilinear coupling

Mode	Authors	Ref.	sig. (Assumed L.)
$b\bar{b}W^+W^-$	Andreas, Li-Lin, Jose	1209.1489	$2.4(600\ fb^{-1})$
$b\bar{b}\gamma\gamma$	Vernon, Lisa, Jakson, Gabe	1311.2931	$\Delta\lambda_3/\lambda_3 = 0.40\ (3\ ab^{-1}\ )$
$b\bar{b}\tau^+\tau^-\&b\bar{b}b\bar{b}+ISR$	Dolan, Englert, Spannowsky	1206.5001	$1.5\ (1\ ab^{-1})$
$b\bar{b}\gamma\gamma$	ATLAS	ATL-PHYS-PUB-2014-019	$1.2\ (3\ \mathrm{ab}^{-1})$

Modes proposed in literatures from pheno. side
More realistic issues from experimental side

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
$bb\gamma\gamma$	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

Two Lessons:

1. Faked b
2. Faked photon

ATL-PHYS-PUB-2014-019

Guido Tonelli's talk on Jan/18/2016

Analysis1: trilinear coupling

Mode	Authors	Ref.	sig. (Assumed L.)
$b\bar{b}W^+W^-$	Andreas, Li-Lin, Jose	1209.1489	$2.4(600\ fb^{-1})$
$b\bar{b}\gamma\gamma$	Vernon, Lisa, Jakson, Gabe	1311.2931	$\Delta\lambda_3/\lambda_3 = 0.40\ (3\ ab^{-1}\ )$
$b\bar{b}\tau^+\tau^-\&b\bar{b}b\bar{b}+ISR$	Dolan, Englert, Spannowsky	1206.5001	$1.5\ (1\ ab^{-1})$
$b\bar{b}\gamma\gamma$	ATLAS	ATL-PHYS-PUB-2014-019	1.2 (3 ab^{-1})

To overcome the faked b and faked photon issues@LHC

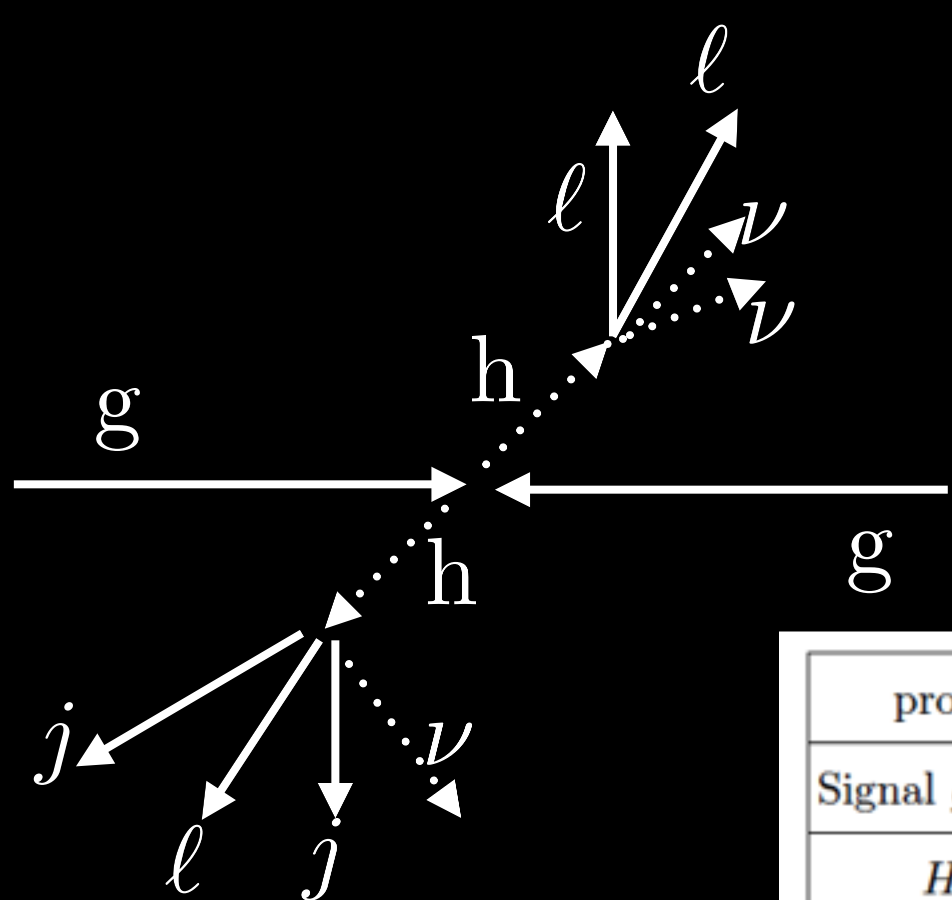
We propose to look at the mode:

$$hh \to WW^*WW^* \to 3\ell + 2j + \text{missing energy}$$

To suppress the huge background from ZW, only same flavour same charge lepton final states are considered.

U.Baur, T.Plehn and D.L.Rainwater, Phys.Rev.D68,033001(2003)

Analysis1: trilinear Coupling



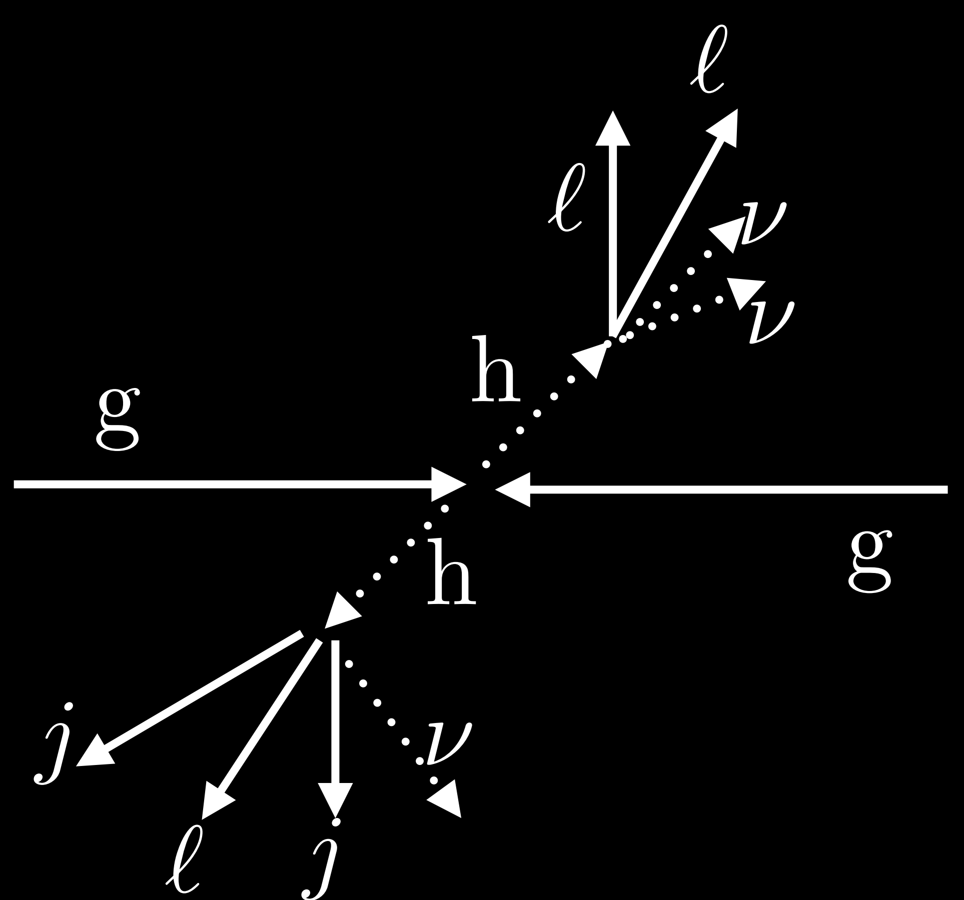
$n(\ell) = 3$, $P_t(\ell_1) > 30$ GeV,
$P_t(\ell_2) > 10$ GeV, $P_t(\ell_3) > 5$ GeV
$\eta(\ell_i) < 2.5$
Veto tagged b events
MET > 20 GeV

$e^{\pm}e^{\pm}\mu^{\mp}$ and $\mu^{\pm}\mu^{\pm}e^{\mp}$

Four patterns are considered

processes	$\sigma^{\mathrm{LO}} \times$ branching fraction (fb)	K factors	No. Events after preselection cuts
Signal $gg \to HH$	3.0×10^{-2}	1.8 [12]	16.3
$HW^{\pm}$	1.2	1.2 [76]	119.4
WWW	1.4	1.8 [77]	363.9
$t\bar{t}W^{\pm}$	4.6	1.3 [78]	451.4
$t\bar{t}H$	2.1	1.2 [79]	101.3
$ZW, \gamma W$	233	1.8 [80]	~ 0
S/B	0.02		
$S/\sqrt{B}$	0.53		

Analysis1: trilinear Coupling



To suppress background, finding the correct combination is crucial!

$e^-e^-\mu^+$, $e^+e^+\mu^-$, $\mu^+\mu^+e^-$, and $\mu^-\mu^-e^+$

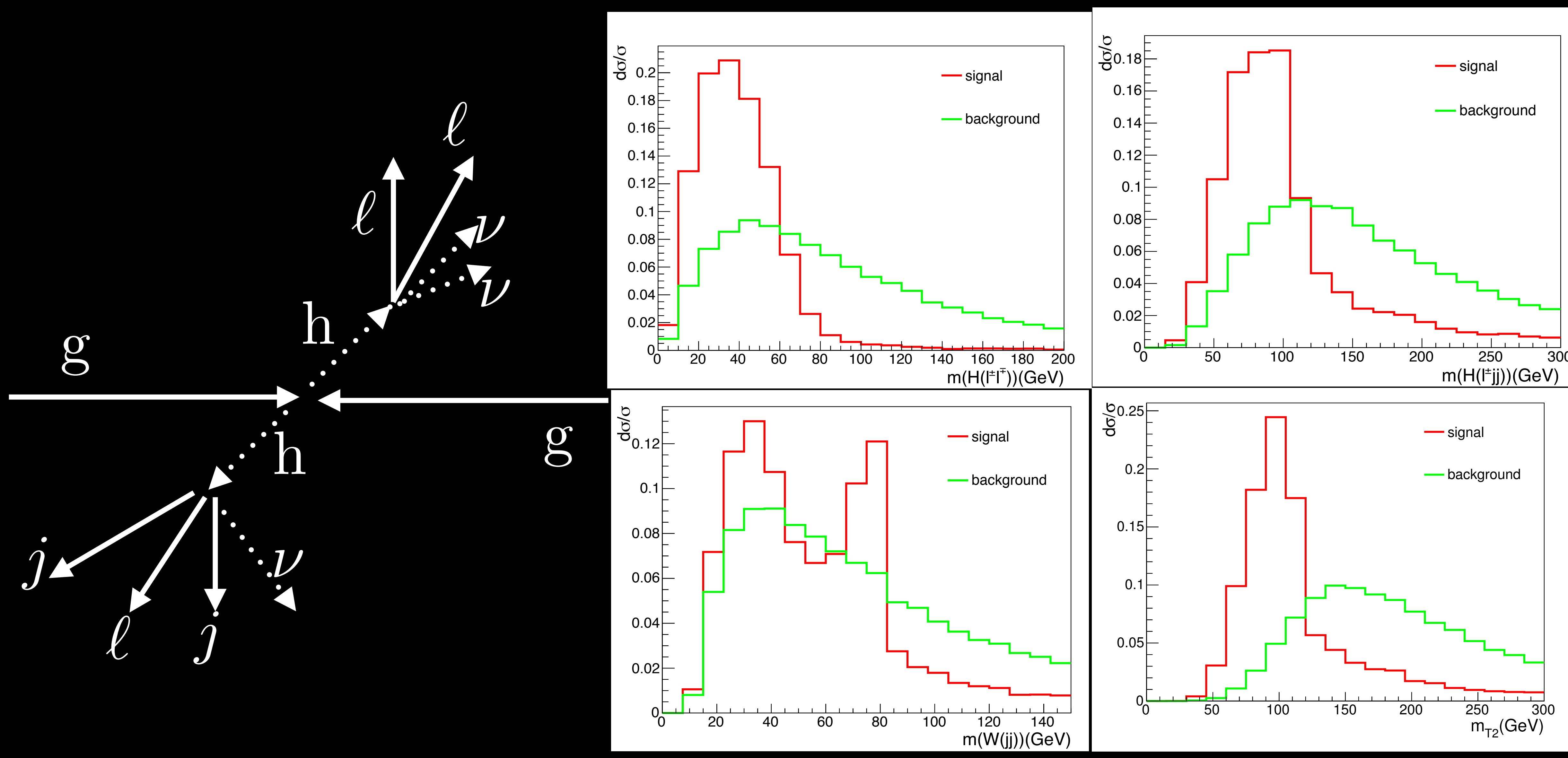
Two Combinations are possible?

$(H(\ell_1^\pm\ell_3^\mp),\ H(\ell_2^\pm jj))$ or $(H(\ell_2^\pm\ell_3^\mp), H(\ell_1^\pm jj))$

Methods	The percentage of correctness (%)
$\lvert m_{H(ll)} - m_{H(ljj)}\rvert$	68.9
$\Delta R(l^\pm, l^\mp)$	85.0
$\Delta R(l^\pm, W_{jj})$	89.9
$P_t[H(ll)] + P_t[H(ljj)]$	90.3
$\Delta_R(H(ll), H(ljj))$	92.0
$m_{H(ll)} + m_{H(ljj)}$	95.4

Q. Li, Z. Li, QY, X.R. Zhao, PRD92(2015)1,014015, arXiv:1503.07611

Analysis1: trilinear Coupling



Reconstructed visible Higgs masses + mT2 variable fully utilises the kinematics of pair production

C.G.Lester, D.J.Summers, Phys.Lett.B463, 99 (1999)

Q. Li, Z. Li, QY, X.R. Zhao, PRD92(2015)1,014015, arXiv:1503.07611

Analysis1:trilinear Coupling

14TeV, 3000fb^{-1}

	after preselection	Cut	MLP	BDT
Signal	13.7	6.2	5.7	3.8
Background	913.5	36.8	21.7	6.2
S/B	1.5×10^{-2}	0.17	0.26	0.62
$S/\sqrt{B}$	0.45	1.0	1.2	1.5

100TeV, 3000fb^{-1}

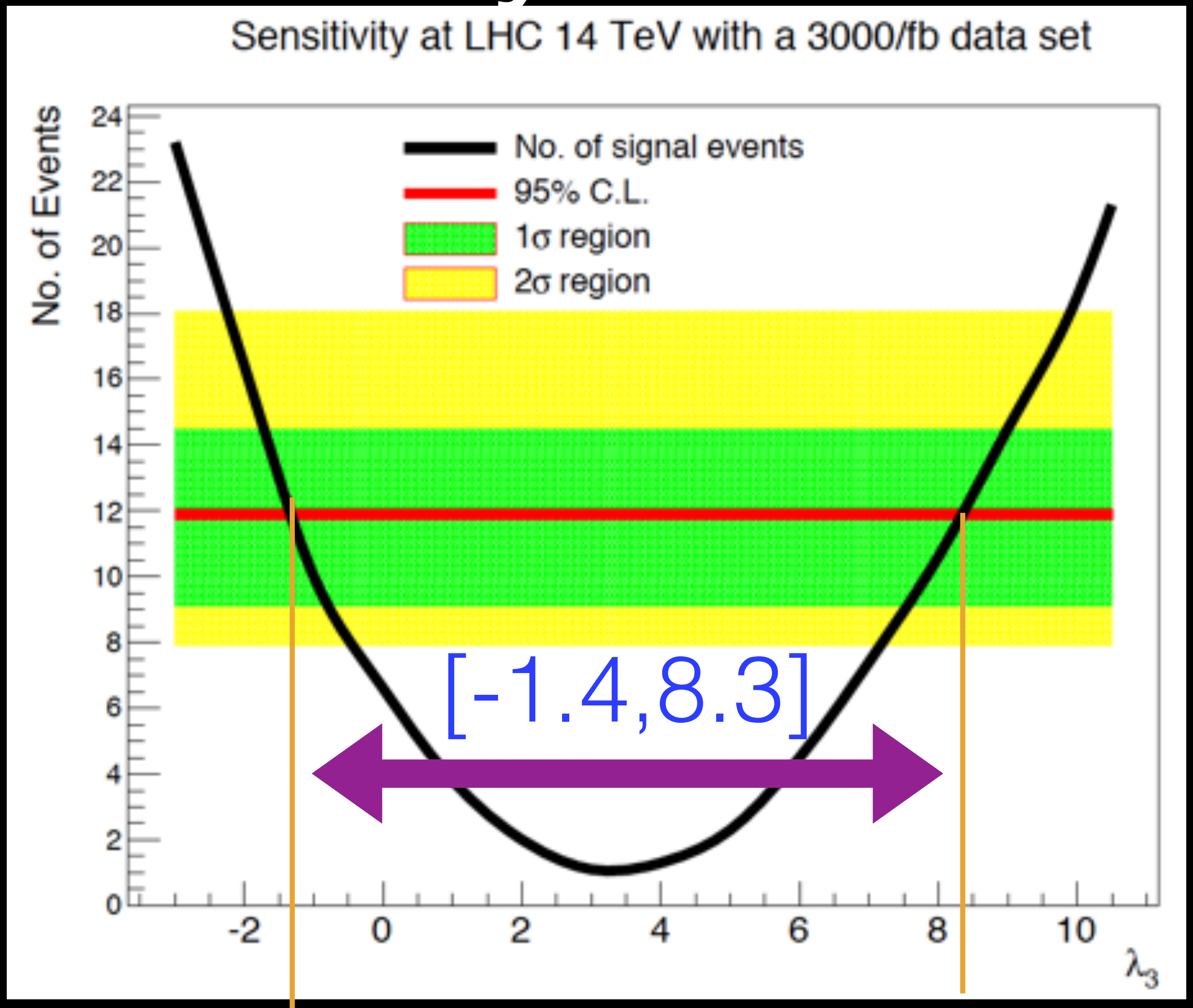
	after preselection	Cut	MLP	BDT
Signal	416.8	160.0	80.4	104.0
Background	14801.8	523.6	107.3	67.1
S/B	2.8×10^{-2}	0.31	0.75	1.5
$S/\sqrt{B}$	3.43	7.0	7.8	12.7

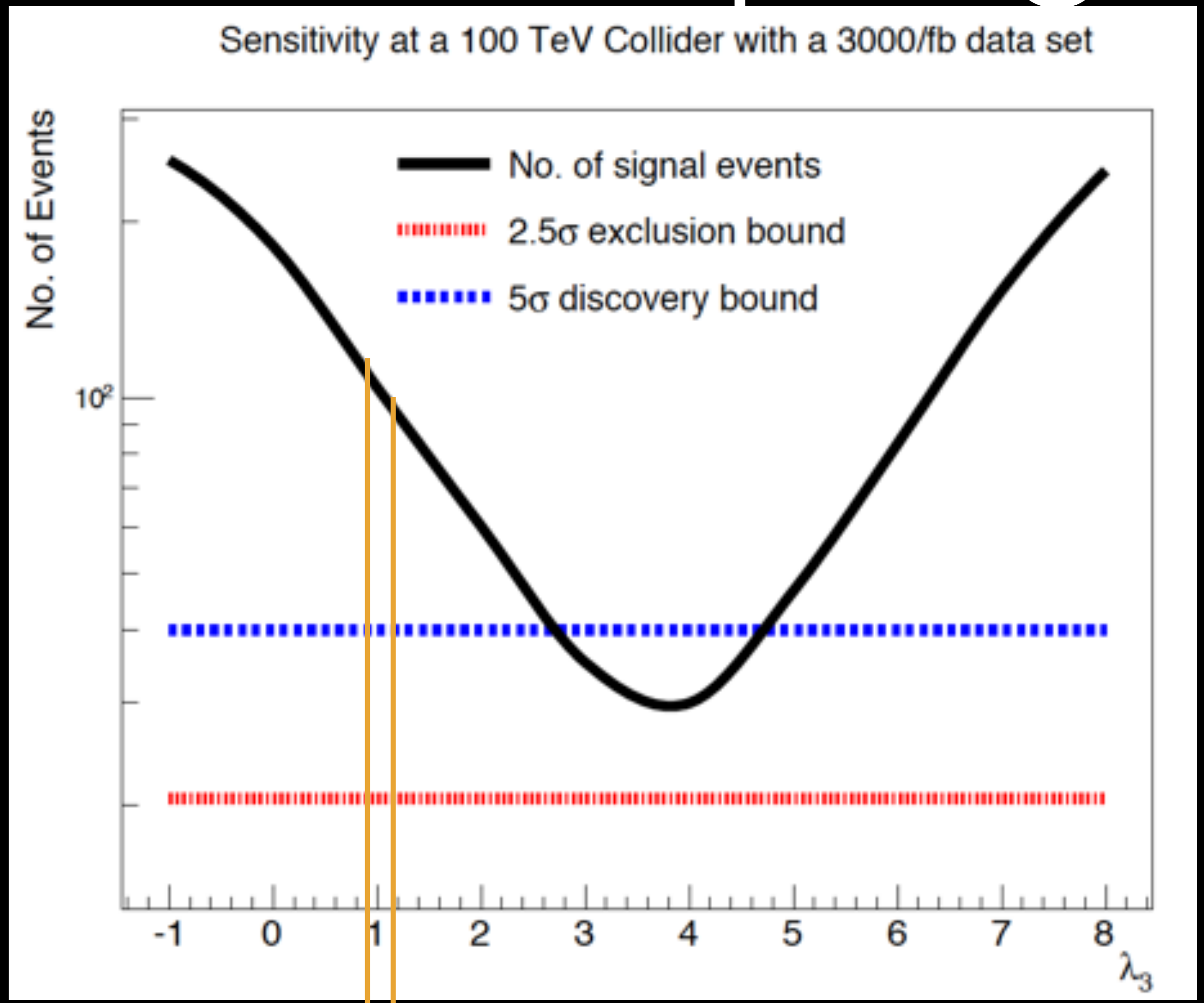
The Cut-based method:

$M_h(\ell\ell) < 55$ GeV, $M_h(\ell jj) < 110$ GeV, $M_{T2} < 100$ GeV

Q. Li, Z. Li, QY, X.R. Zhao, PRD92(2015)1,014015, arXiv:1503.07611

Analysis1: trilinear Coupling

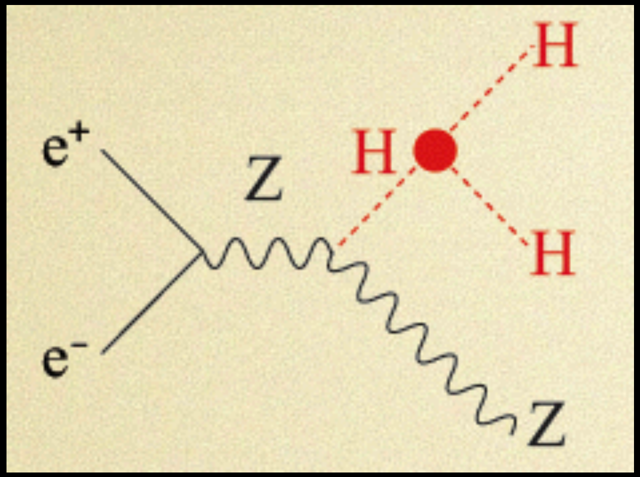


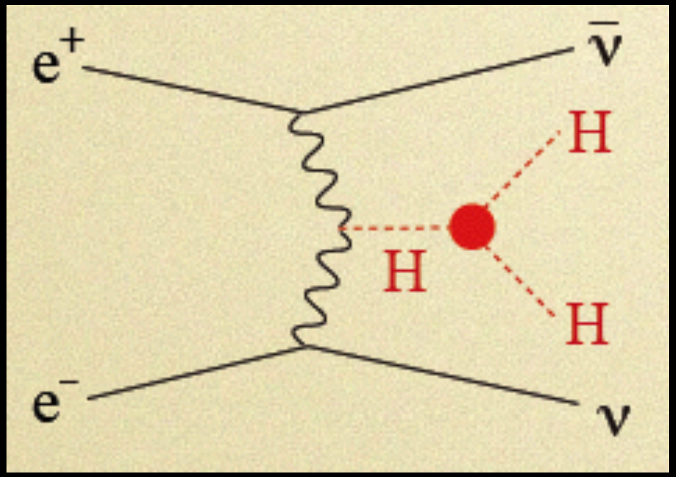


By using the invariant mass of three leptons in the final state, we can determine trilinear coupling to [0.9,1.2] at a 100 TeV collider with an integrated luminosity 30/ab.

Q. Li, Z. Li, QY, X.R. Zhao, PRD92(2015)1,014015, arXiv:1503.07611

Analysis1: trilinear coupling

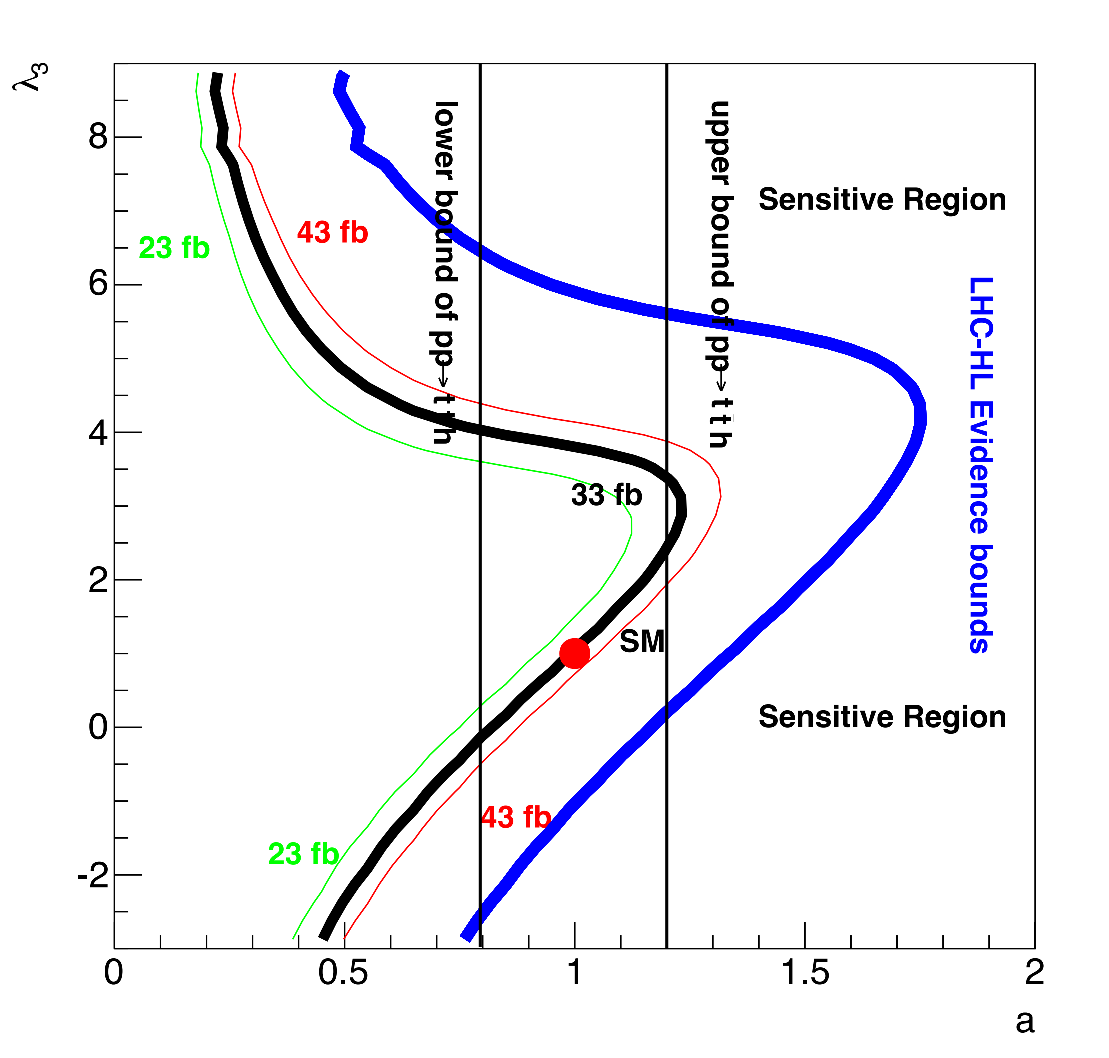


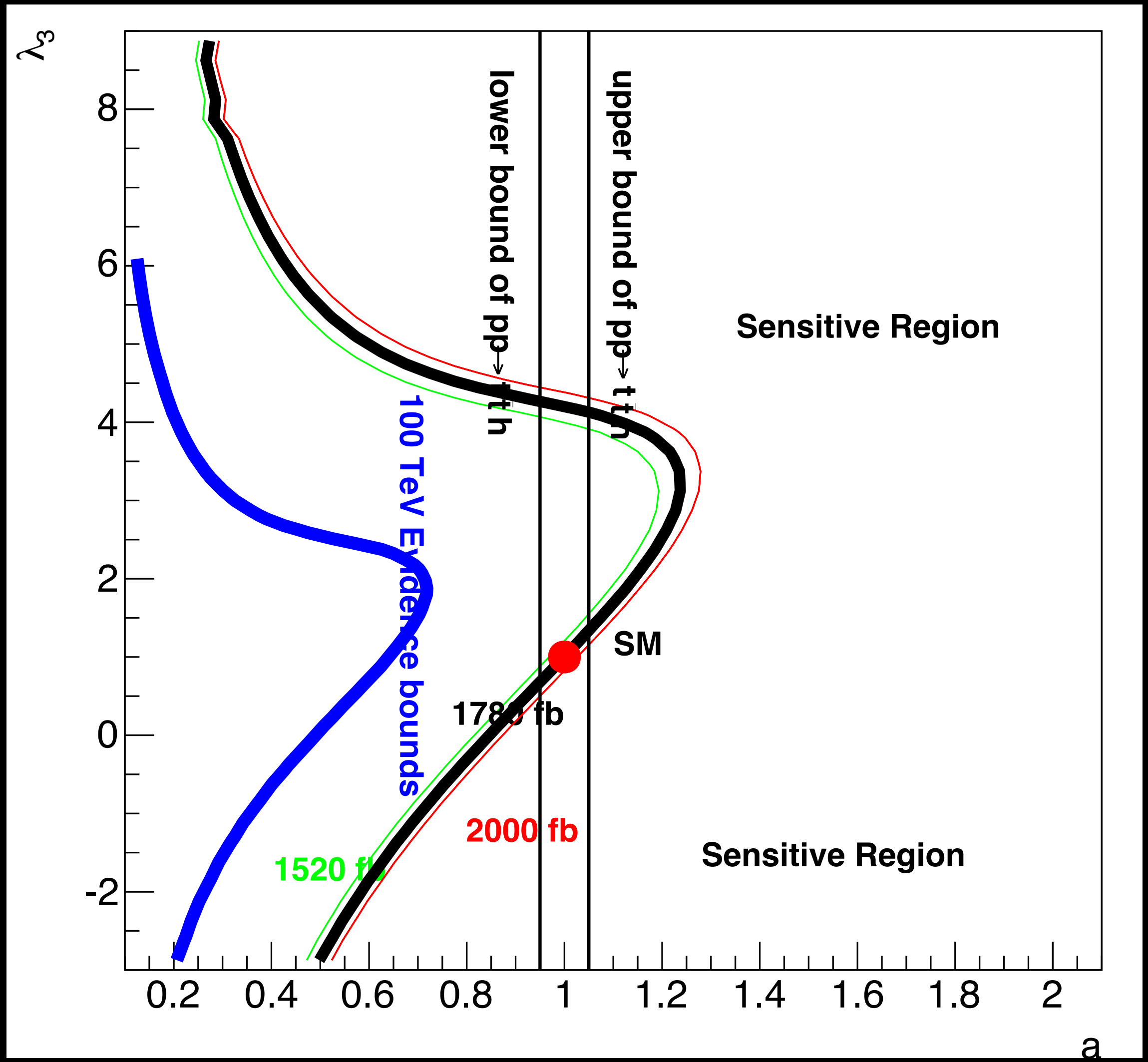


ILC(1TeV,4/ab) can measure trilinear Higgs Coupling
up to 10 percent

J. Tian, LC-REP-2013-003
T. Barklow, J. Brau, K. Fujii, J. Gao, J. List, N. Walker, K. Yokoya, arXiv: 1506.07830

Analysis1: trilinear Coupling



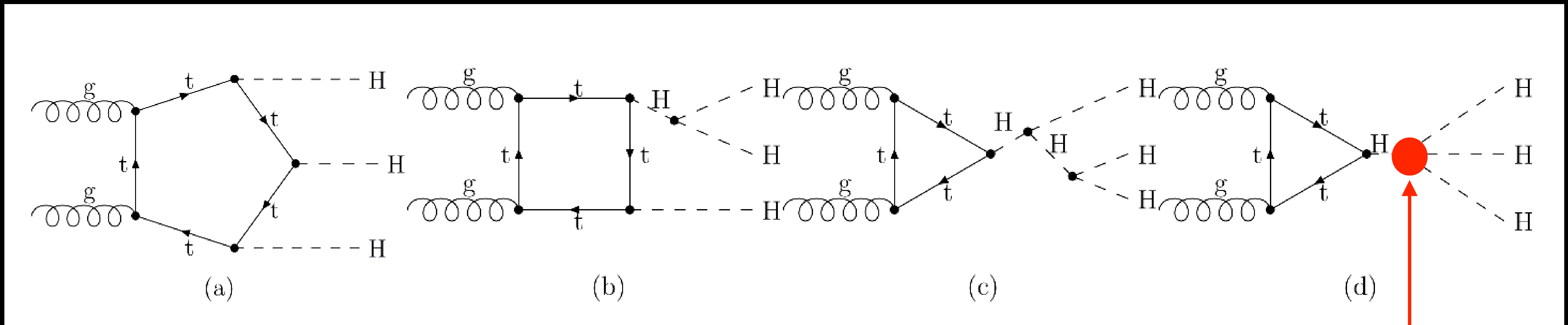


$$\Delta\mathcal{L} = Y_t\,(a\,\bar{t}t + i\,b\,\bar{t}\gamma_5 t)\,h + \lambda_3\,\lambda_{SM}\,v\,h\,h\,h + \cdots$$

Ratio of $\sigma(t\bar{t}Z)/\sigma(t\bar{t}h)$

J.F. Gunion, B. Grzadkowski, X.G. He, PRL77(1996)5172
M.Mangano, T. Plehn, P. Reimitz, T. Schell, H.S. Shao, 1507.08169
Q. Li, Z. Li, Y. Song, QY, X.R. Zhao, in preparation

Analysis2: Quartic Coupling



E_{CM}	14 TeV	33 TeV	100 TeV
$\sigma(gg \to hhh)$	4.1×10^{-2} fb	0.33 fb	3.2 fb

Only accessible at a 100 TeV collider!

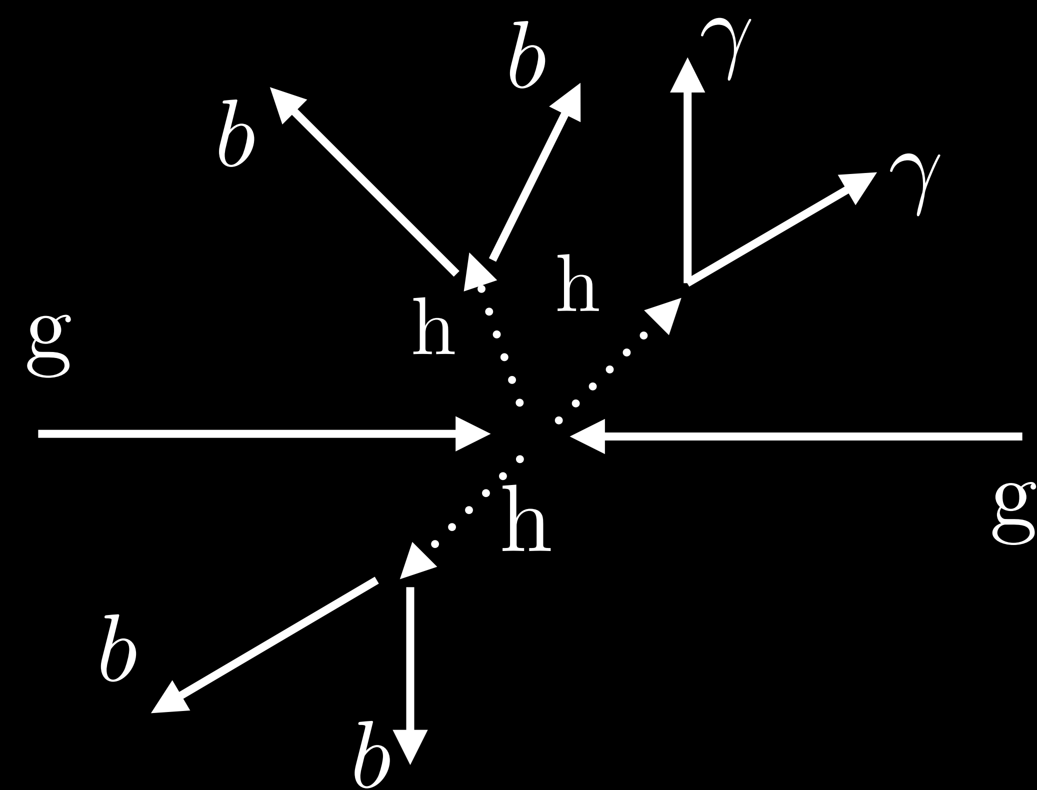
E_{CM}	500 GeV	1 TeV	3 TeV
$\sigma(e^+e^- \to Zhhh)$	3.3×10^{-3} ab	4.1×10^{-1} ab	1.5×10^{-1} ab

Cross section @LC is tiny.

C.Y. Chen,QY, X.R. Zhao, Z.J. Zhao, Y.M. Zhong, PRD93 (2016)1, 013007

Analysis2: Quartic Coupling

Decay Channel	Branching Ratio
$HHH \to b\bar{b}b\bar{b}W^+W^-$	22.34%
$HHH \to b\bar{b}b\bar{b}b\bar{b}$	20.30%
$HHH \to b\bar{b}W^+W^-W^+W^-$	8.20%
$HHH \to b\bar{b}b\bar{b}\tau^+\tau^-$	7.16%
$HHH \to b\bar{b}b\bar{b}gg$	6.54%
$HHH \to b\bar{b}b\bar{b}ZZ$	2.69%
$HHH \to W^+W^-W^+W^-W^+W^-$	1.00%
$HHH \to W^+W^-W^+W^-\tau^+\tau^-$	0.96%
$HHH \to W^+W^-W^+W^-gg$	0.88%
$HHH \to W^+W^-W^+W^-ZZ$	0.36%
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	0.29%



Selection Cuts:

1) $N_b \geq 2,\ P_t(b) > 30$ GeV
2) $n_\gamma = 2, P_t(\gamma) > 30$ GeV
3) $P_t(j_1) \geq 30$ GeV
4) $n_j = 2\&3$

C.Y. Chen, QY, X.R. Zhao, Z.J. Zhao, Y.M. Zhong, PRD93 (2016)1, 013007

Analysis2: Quartic Coupling

	$\sigma \times BR$ (fb)	K factors	Events after preselection cuts
Signal	9.5×10^{-3}	2.0	50
$b\bar{b}jj\gamma\gamma$	1.9×10^{2}	1.0	2.3×10^{5}
$H(\gamma\gamma)t\bar{t}$	77	1.2	2.2×10^{4}
S/B	1.9×10^{-4}		
$S/\sqrt{S+B}$	9.8×10^{-2}		

After top veto and Higgs boson reconstruction, it is still difficult (30/ab)

	Signal	$b\bar{b}jj\gamma\gamma$	$Ht\bar{t}$
preselection	50	2.3×10^{5}	2.2×10^{4}
$\chi^2_{H,min} < 6.1$	26	4.6×10^{4}	9.9×10^{3}
$\lvert m_H^{rec} - 126\ \text{GeV}\rvert < 5.1\ \text{GeV}$	20	1.7×10^{4}	7.0×10^{3}
S/B	8.3×10^{-4}		
$S/\sqrt{S+B}$	0.13		

Analysis2: Quartic Coupling

	Cuts based method	BDT> 0.02	MLP> 0.51
Signal	20	34	49
Background	2.4×10^4	2.8×10^4	9.9×10^4
S/B	8.3×10^{-4}	1.2×10^{-3}	5.0×10^{-4}
$S/\sqrt{S+B}$	0.13	0.20	0.16

MVA can improve and optimise signal/background discrimination, but…

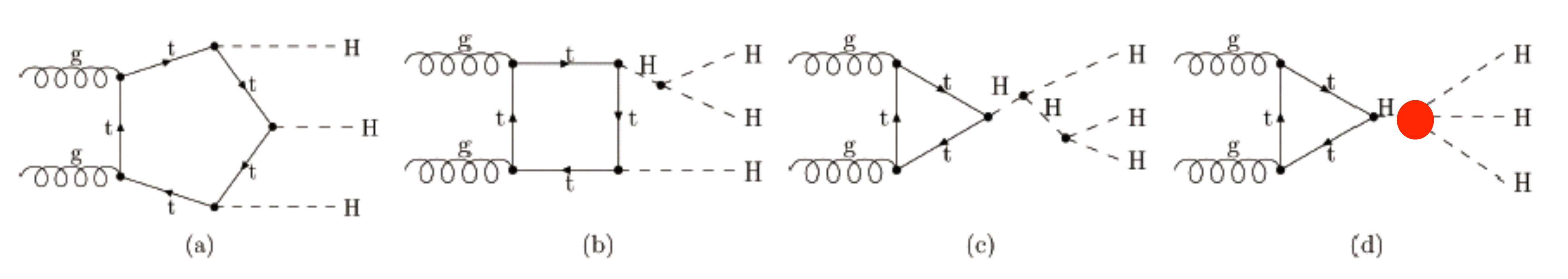
Integrated Luminosity (ab^{-1})	30	300	3000	1.83×10^4
$S/\sqrt{S+B}$	0.2	0.6	2.0	5.0

To discover the signal in the SM is challenging if only 20-30/ab for FCC/SPPC. Maybe other modes?

I. Hinchliffe, A. Kotwal, M.L. Mangano, C. Quigg and L.T. Wang, Int. J. Mod. Phys. A30, no.23, 1544002 (2015) [arXiv:1504.06108 [hep-ph]].

C.Y. Chen,QY, X.R. Zhao, Z.J. Zhao, Y.M. Zhong, PRD93 (2016)1, 013007

Analysis2: Quartic Coupling



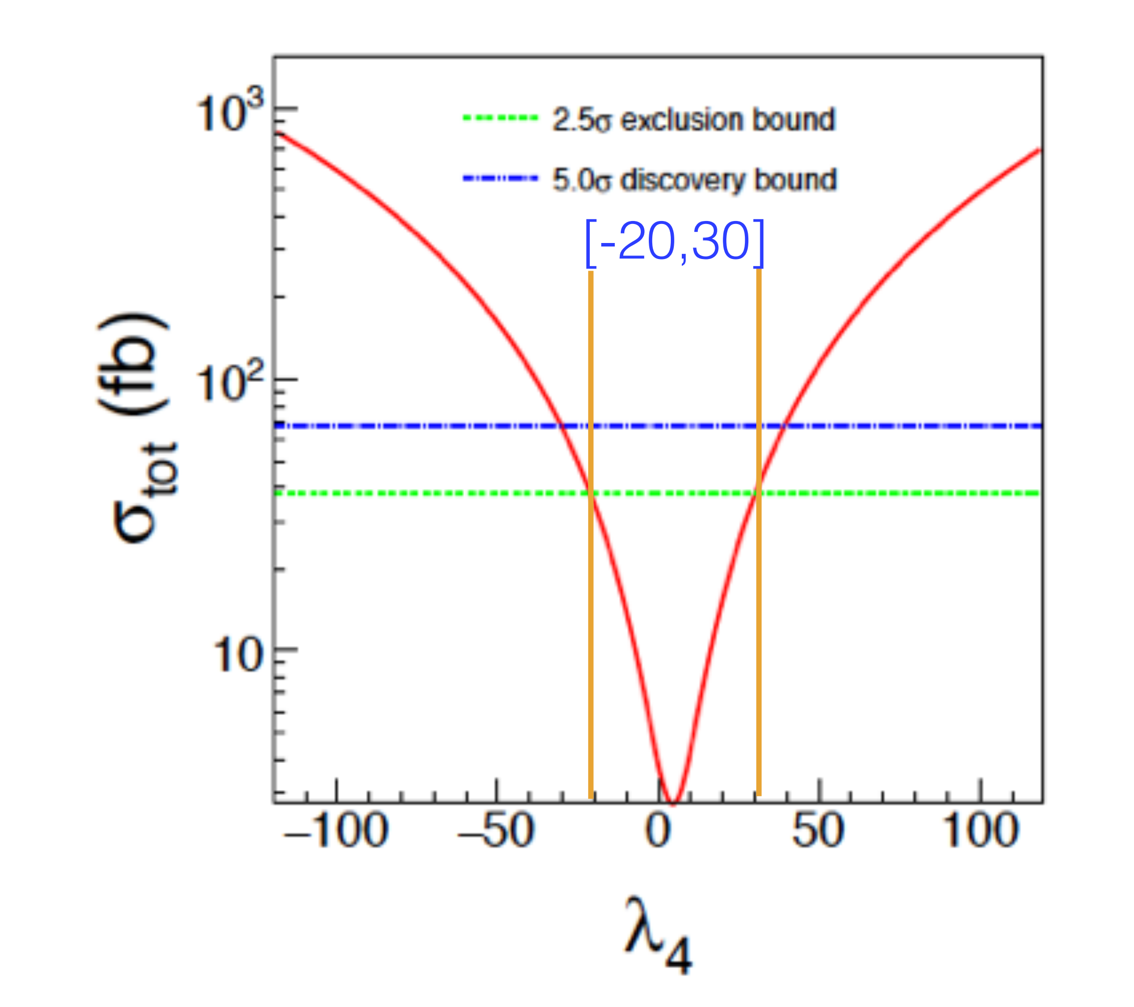
$$\sigma(\lambda_3,\lambda_4) = A\lambda_4^2 + \underline{\left(B\lambda_3^2 + C\lambda_3 + D\right)\lambda_4} + E\lambda_3^4 + F\lambda_3^3 + G\lambda_3^2 + H\lambda_3 + I\,,$$

A	B	C	D	E	F	G	H	I
5.28×10^{-2}	0.14	-0.76	0.15	2.28×10^{-2}	-5.36×10^{-2}	3.11	-14.57	15.36

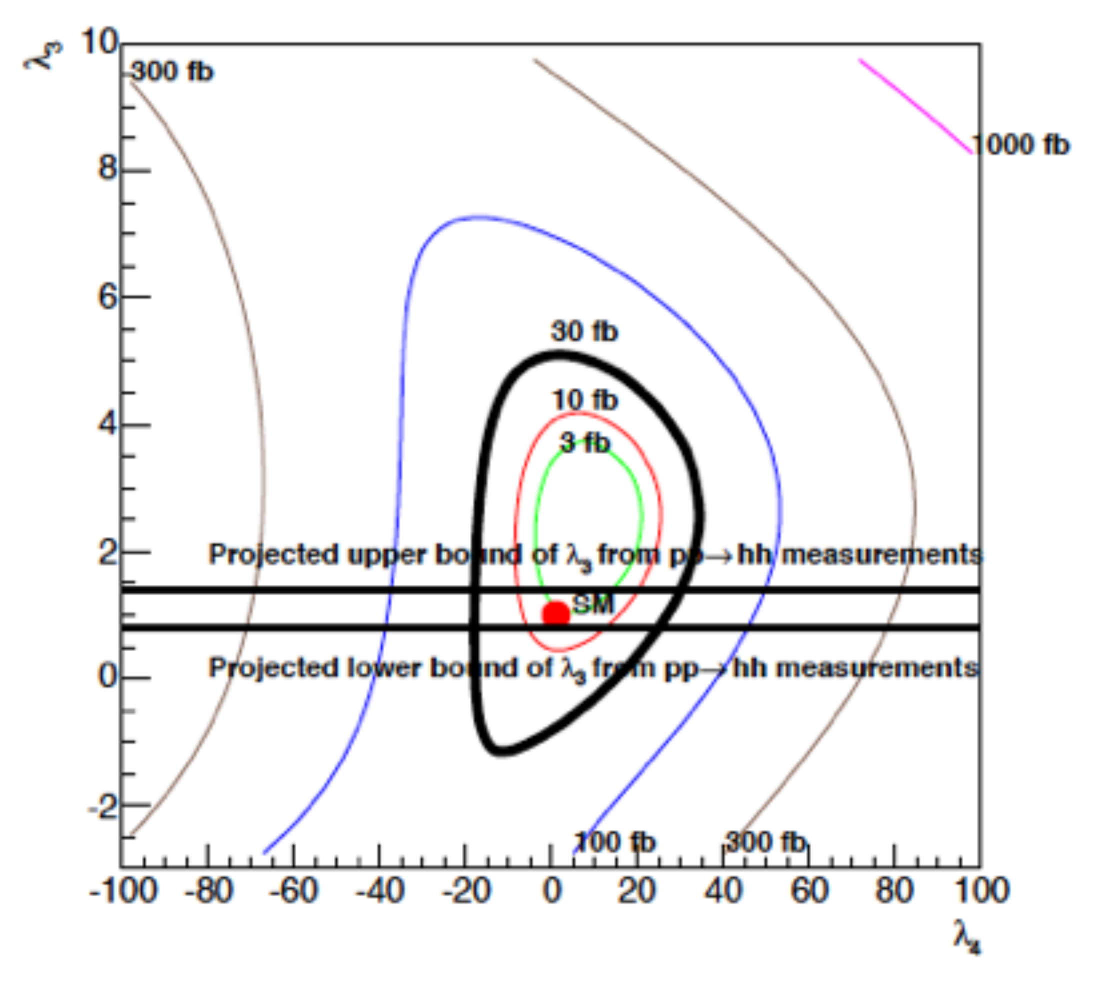
Directly detecting quartic couplings is difficult at least for 4b2gamma mode.

C.Y. Chen, QY, X.R. Zhao, Z.J. Zhao, Y.M. Zhong, PRD93 (2016)1, 013007

Analysis2: Quartic Coupling



(a)The fitted cross section when λ_3 is fixed



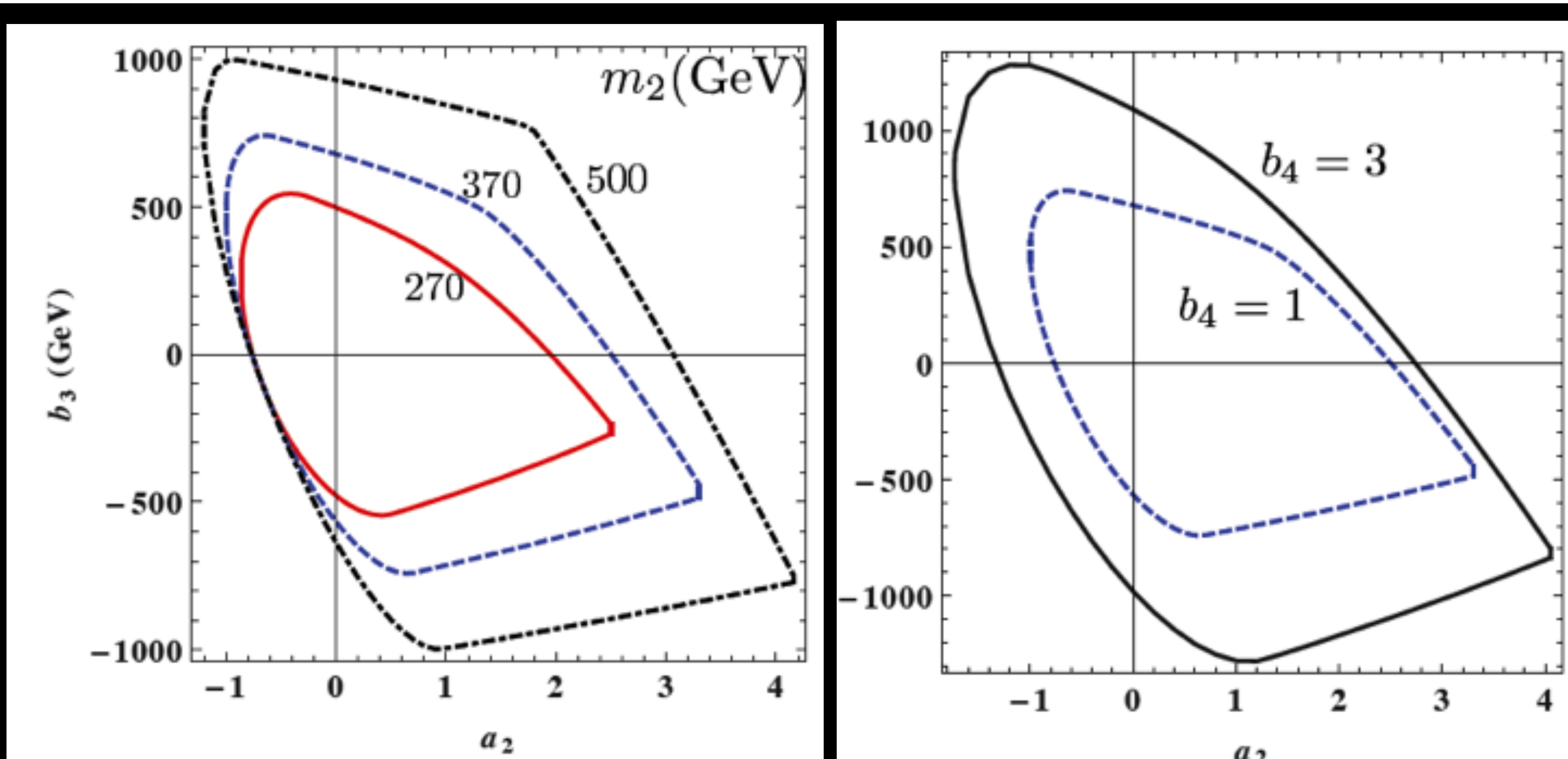
(b)The feasibility of λ_3 and λ_4

Trilinear and quartic couplings are correlated.

C.Y. Chen,QY, X.R. Zhao, Z.J. Zhao, Y.M. Zhong, PRD93 (2016)1, 013007

Benchmark study4NP

$$V(\phi_0, S) = \lambda \left(\phi_0^2 - \frac{v_{EW}^2}{2}\right)^2 + \frac{a_1}{2}\left(\phi_0^2 - \frac{v_{EW}^2}{2}\right) S + \frac{a_2}{2}\left(\phi_0^2 + \frac{v_{EW}^2}{2}\right) S^2 + \frac{1}{4}\left(2b_2 + a_2 v_{EW}^2\right) S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4,$$

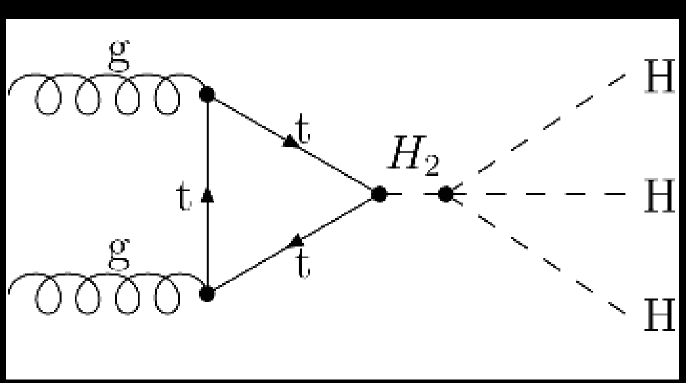


Experimental Constraints from all Higgs measurements, theoretical constraints: unitarity, vacuum stability, …

Benchmark study4NP

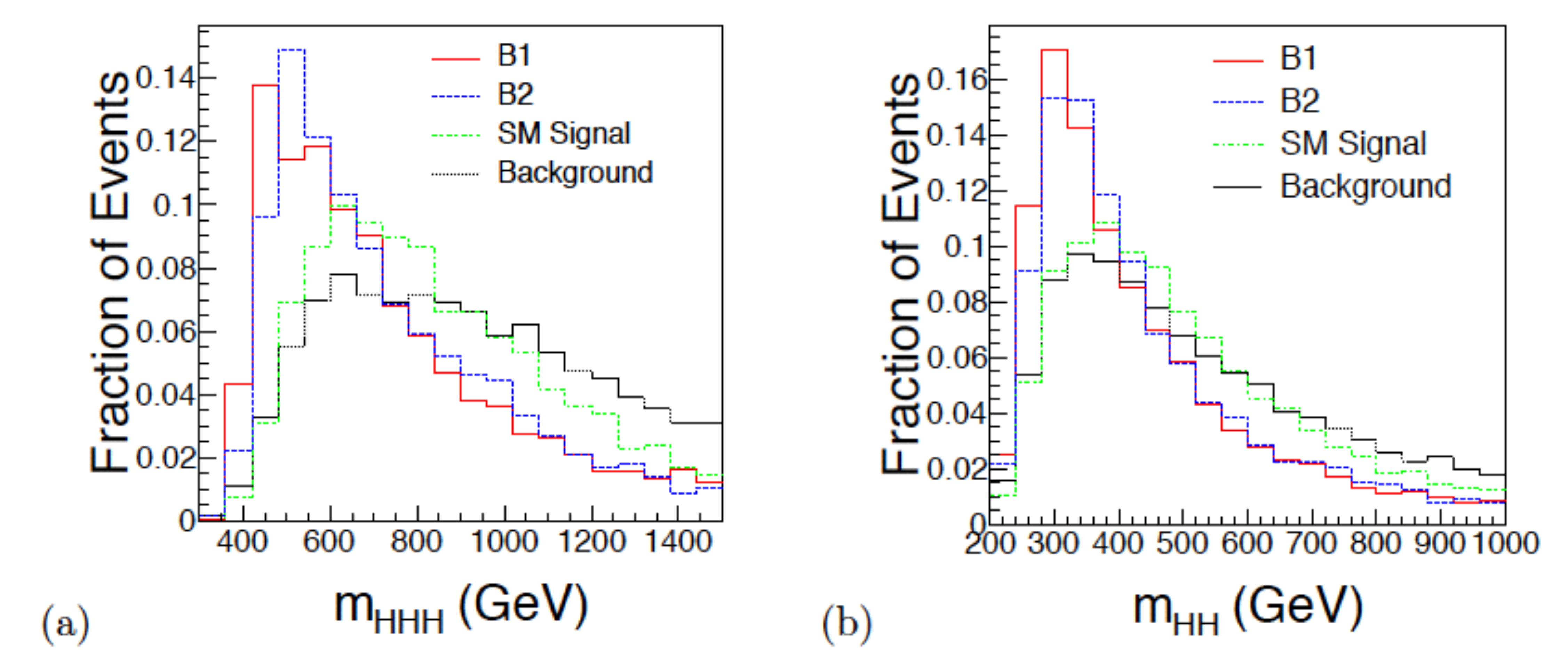
	B1	B2	B3
m_{H_2} (GeV)	460	500	490
θ	0.354	0.354	0.354
a_2	3.29	3.48	3.43
b_3 (GeV)	-706	-612	-637
b_4	8.38	8.38	8.38

	B1	B2	B3
$\Gamma_{\rm tot}(H_2)$ (GeV)	5.6	7.5	7.0
$BR(H_2 \to W^+W^-)$	0.57	0.56	0.57
$BR(H_2 \to ZZ)$	0.27	0.27	0.27
$BR(H_2 \to t\bar{t})$	0.15	0.16	0.16
$BR(H_2 \to b\bar{b})$	3.4×10^{-4}	2.8×10^{-4}	2.9×10^{-4}
$BR(H_2 \to HH)$	5.3×10^{-7}	8.8×10^{-7}	1.5×10^{-7}
$BR(H_2 \to HHH)$	1.0×10^{-3}	1.4×10^{-3}	1.3×10^{-3}
$\sigma(gg \to H_2)$ @ 14 TeV (fb)	3.2×10^2	2.3×10^2	2.5×10^2
$\sigma(gg \to HHH)$ @ 14 TeV (fb)	0.70	0.69	0.71
$\sigma(gg \to H_2)$ @ 100 TeV (fb)	1.4×10^4	1.1×10^4	1.2×10^4
$\sigma(gg \to HHH)$ @ 100 TeV (fb)	37	38	39



Production rate is enhanced!

Benchmark study4NP



	SM(BDT> 0.02)	B1(BDT> −0.02)	B2(BDT> −0.02)	B3(BDT> −0.03)
Signal	34	3.7×10^2	4.4×10^2	4.6×10^2
Background	2.8×10^4	3.0×10^4	3.1×10^4	4.0×10^4
S/B	1.2×10^{-3}	1.2×10^{-2}	1.4×10^{-2}	1.1×10^{-2}
$S/\sqrt{S+B}$	0.20	2.1	2.5	2.3

Conclusions

- Multi-Higgs final states are important to address big questions
- HL-LHC can reveal trilinear coupling to some degree by using 3lepton+2j+MET mode
- a 100 TeV future collider can be of great help to determine trilinear coupling
- More works should be done in order to know which mode is best to probe quartic coupling

MC4BSM 2016 Beijing

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July 20-24 2016, UCAS-Huairou, China

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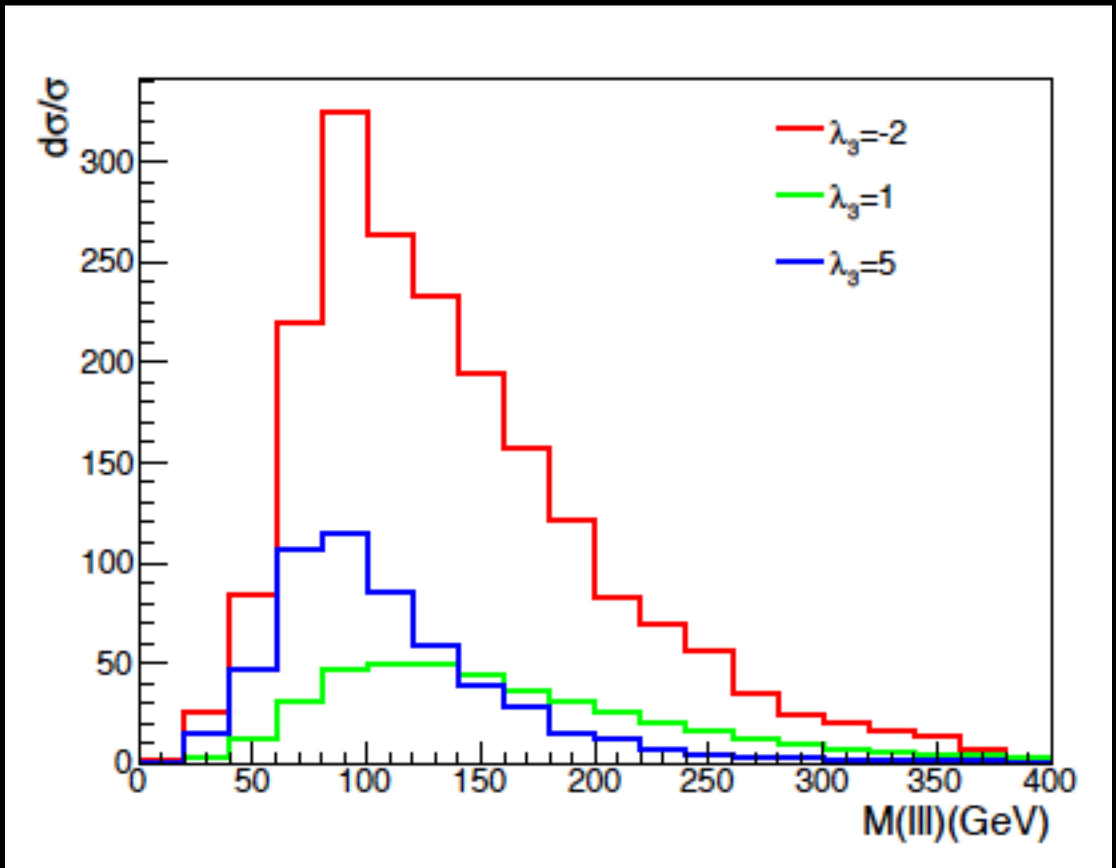
MC4BSM is a series of workshops aiming to gather theorists andexperimentalists interested in developing Monte Carlo tools to simulate collidersignatures of Beyond the Standard Model Physics,and to use such tools inphenomenological studies and in searchesfor new physics at energy frontiercolliders. Since 2006, nine workshop have been held in this series, hosted inUSA, Switzerland, Denmark, Germany, and Korea.

http://indico.ihep.ac.cn/event/5301/

Contact: Qiang Li qliphy0@pku.edu.cn
Qi-Shu Yan yanqishu@ucas.ac.cn

Backup

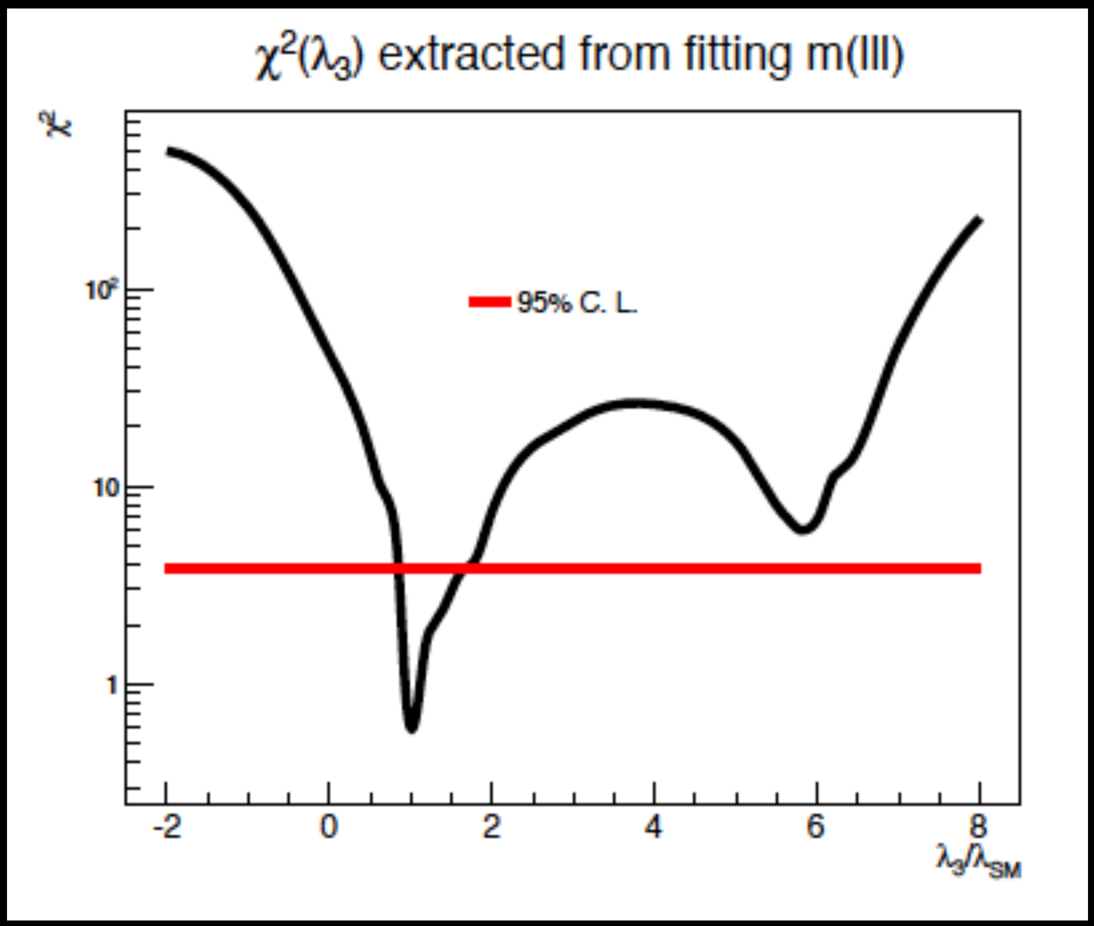


$$\chi^2(\lambda_3) = \sum_{i=1}^{n_D} \frac{(N_i - f N_i^0)^2}{f N_i^0} + (n_D - 1)$$

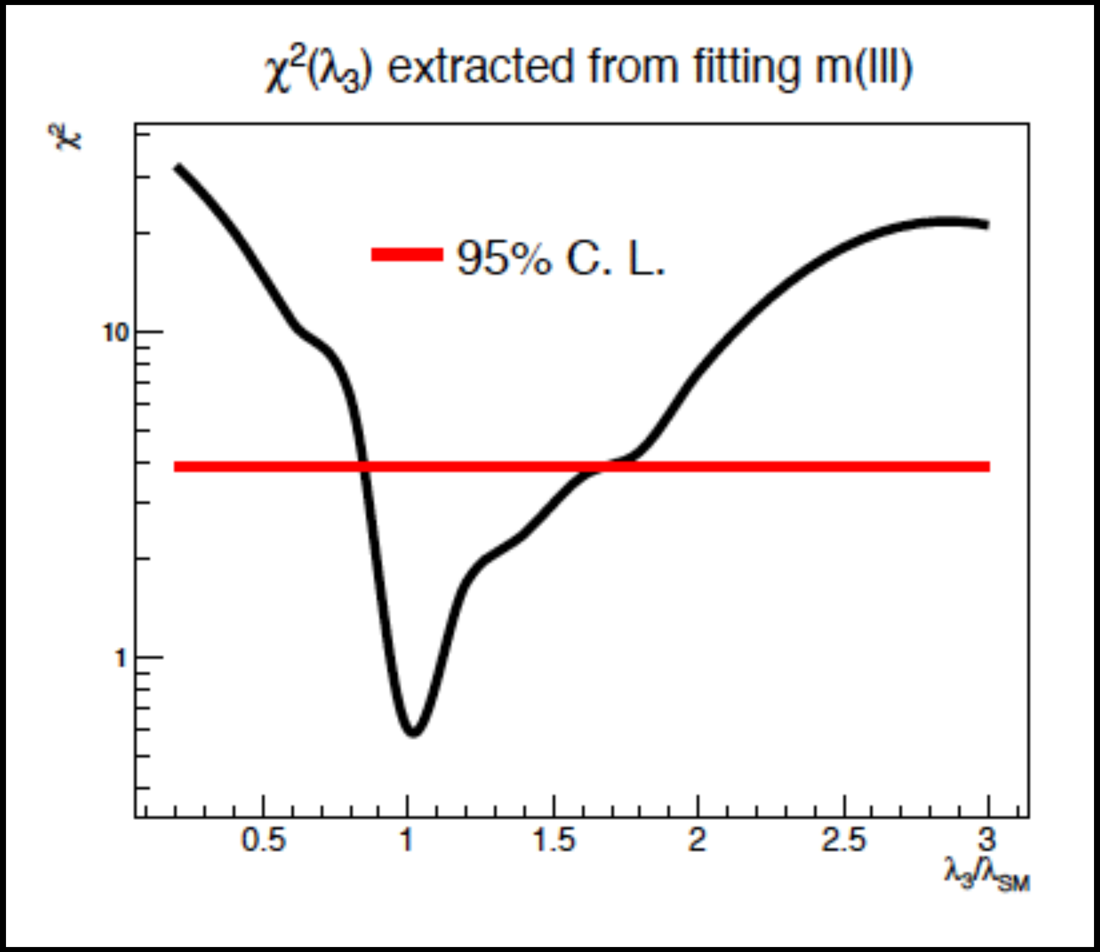
$$f = \begin{cases} (1+\Delta N)^{-1} & \text{for } \bar{f} < (1+\Delta N)^{-1}, \\ \bar{f} & \text{for } (1+\Delta N)^{-1} < \bar{f} < 1 + \Delta N \\ 1 + \Delta f & \text{for } \bar{f} > 1 + \Delta N\,, \end{cases}$$

$$\bar{f}^2 = \sum_{i=1}^{n_D} \frac{N_i^2}{N_i^0} / (\sum_{i=1}^{n_D} N_i^0)$$

Backup



$\chi^2(\lambda_3)$ extracted from fitting m(lll)
χ^2
95% C. L.
10²
10
1
-2
0
2
4
6
8
λ_3/λ_{SM}



$\chi^2(\lambda_3)$ extracted from fitting m(lll)
χ^2
95% C. L.
10
1
0.5
1
1.5
2
2.5
3
λ_3/λ_{SM}

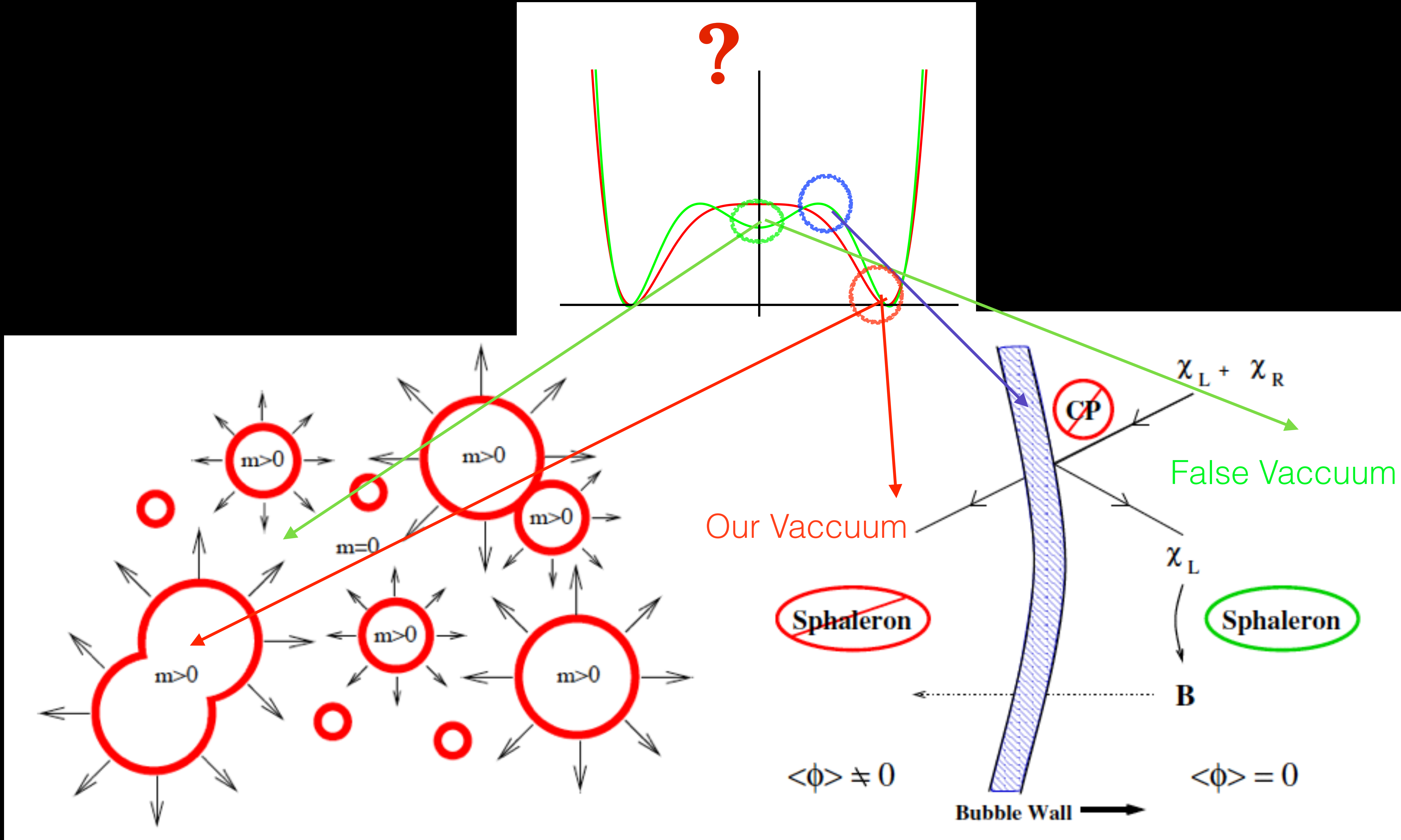


Fig. 11. Bubble nucleation during a first-order EWPT.

The bubble wall needs the little bump in potential shape

J.M. Cline, hep-ph/0609145
D.E. Morrissey, M.J. Musolf, NJP14(2012)125003