Discovery Potential of Higgs boson pair production via fully leptonic modes at a 100 TeV collider

Qi-Shu Yan (UCAS, Beijing)

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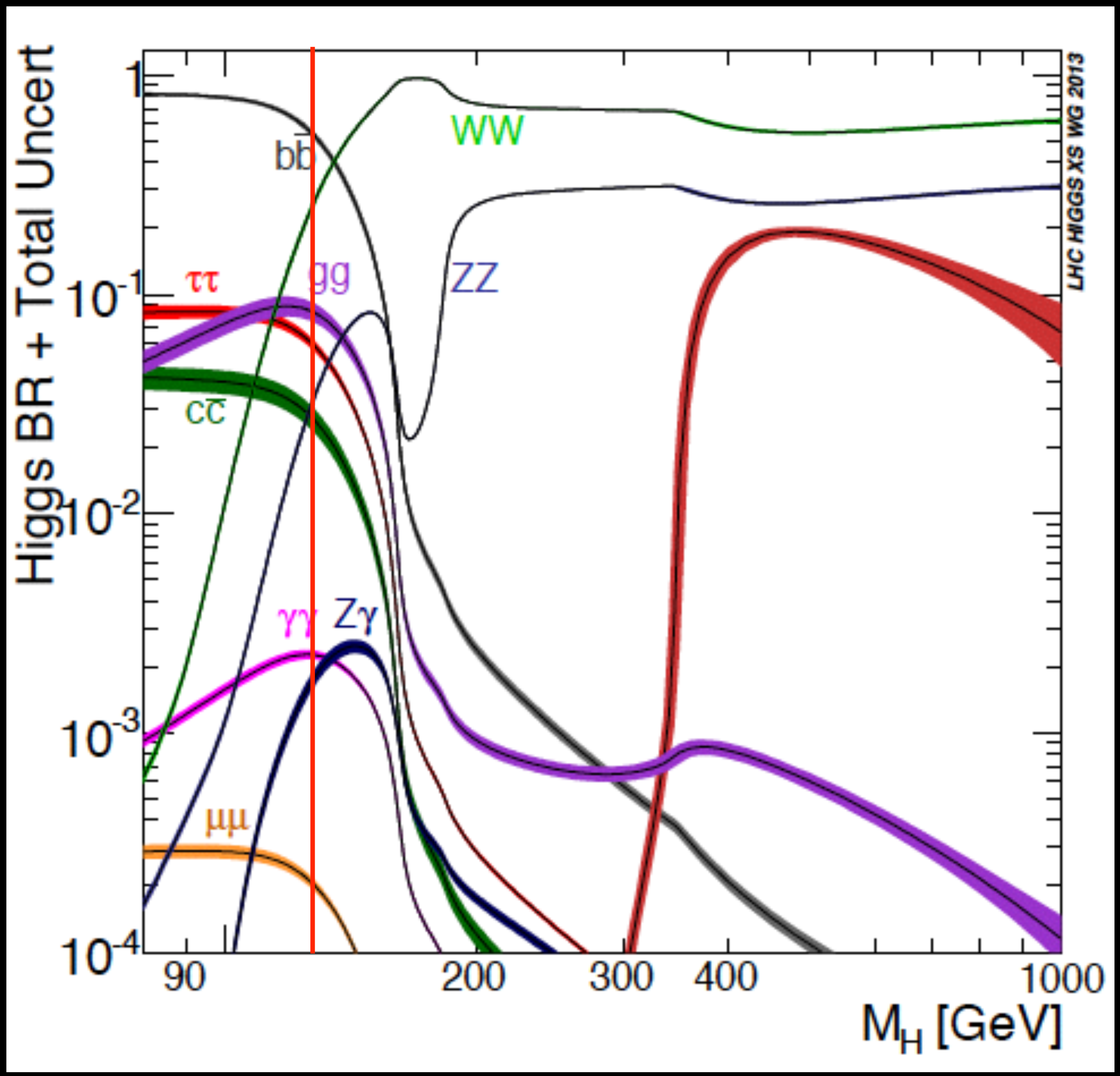
Outline

- Introduction
- Setup for MC
- Our Analysis
- Conclusions

Mainly based on:
X.R. Zhao, Q.Li, Z. Li, QY, arXiv:1604.04329

Higgs Properties



Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.28×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.64×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.15×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.32×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.77×10^{-1}	$^{+3.2\%}_{-3.3\%}$
$H \to Z\gamma$	1.54×10^{-3}	$^{+9.0\%}_{-8.9\%}$
$H \to \mu^+\mu^-$	2.19×10^{-4}	$^{+6.0\%}_{-5.9\%}$

The ee collision of CEPC can measure gauge and Yukawa couplings precisely.

The pp collision of CEPC/SPPC can measure self-couplings directly.

Higgs Working Group, 1307.1347

Introduction

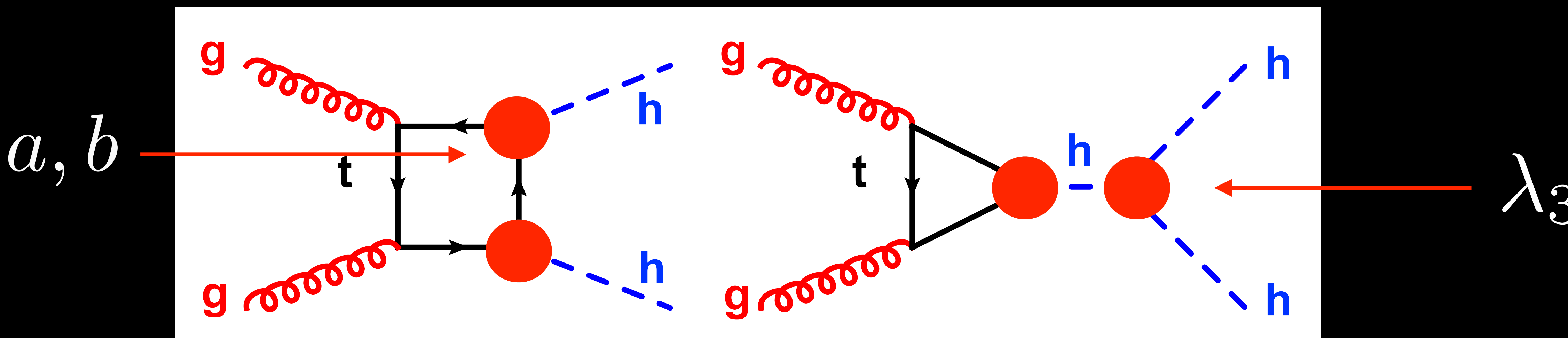
- 1) Detecting the EW symmetry breaking mechanisms
- 2) Probe the EW phase transition, EW baryogensis scenarios, CP sources in Higgs Potential, …

$H \to hh$

- 3) Probe new physics (new Higgs bosons?) …

Measuring Higgs self-couplings at pp collision of SPPC could be a key to probe those unsolved questions!

Higgs Pair production at hadron colliders



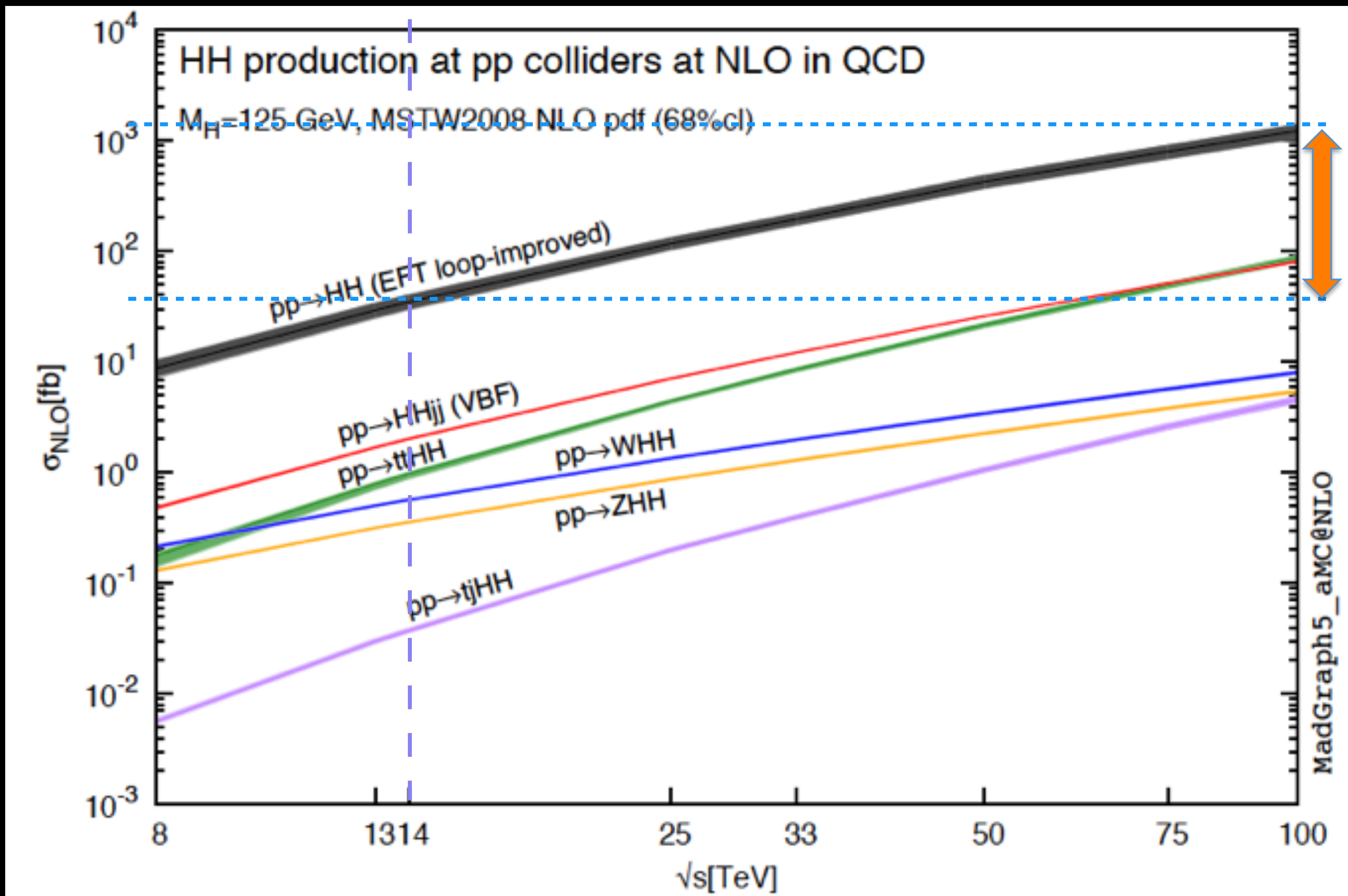
$$\mathcal{L}_1 = Y_t \left(a\, \bar{t}t + i\, b\, \bar{t}\gamma_5 t\right) h + \lambda_3\, \lambda_{SM}\, v\, h\, h\, h + \cdots\ ,$$

$$\sigma(gg \to hh) = G_1\, a^4 + G_2\, b^4 + G_3\, a^2\, b^2 + (G_4\, a^3 + G_5\, a\, b^2)\, \lambda_3 + (G_6\, a^2 + G_7\, b^2)\, \lambda_3^2$$

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

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

Higgs Pair Production



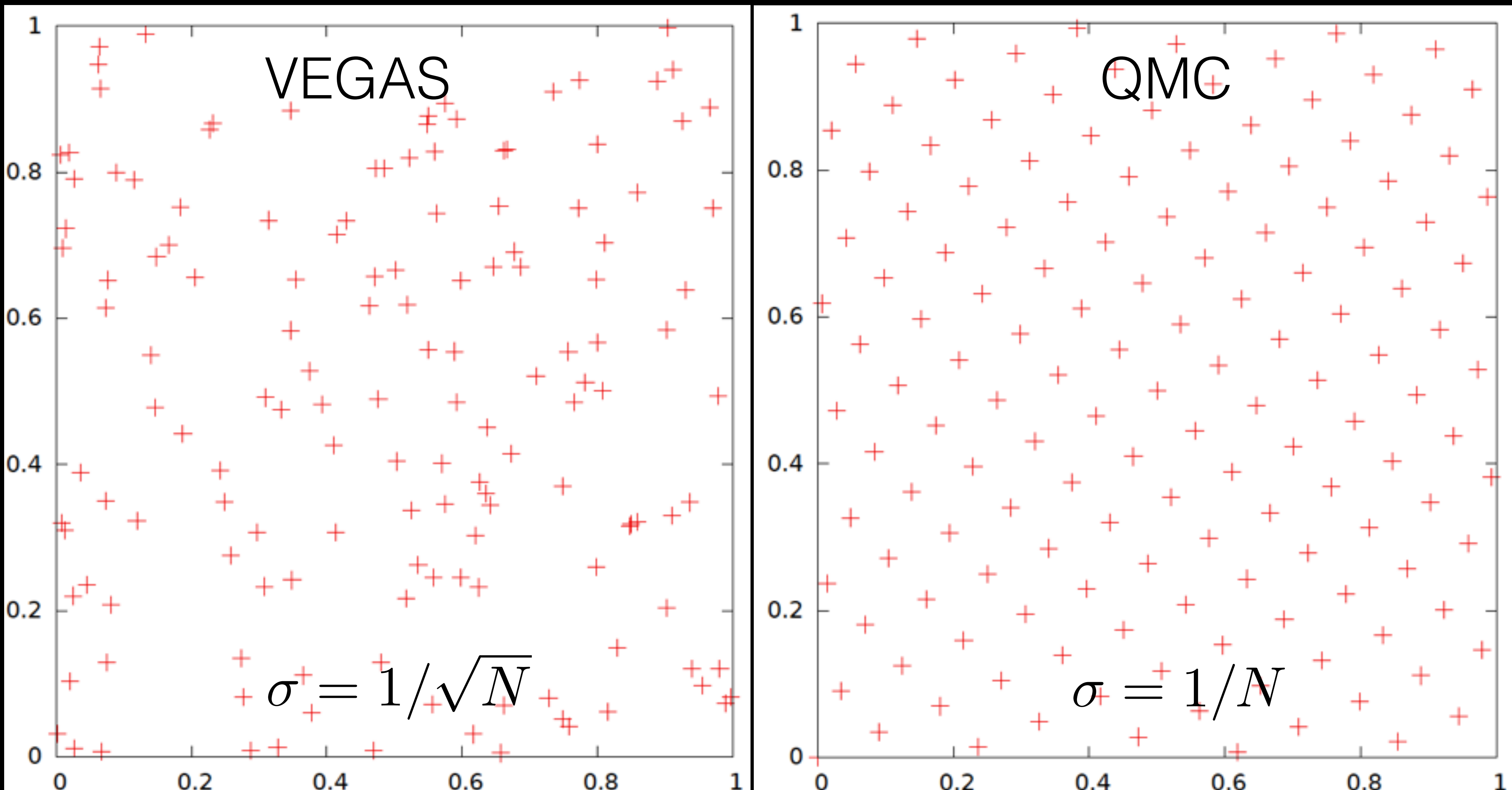
At a 100 TeV collider, the cross section of Higgs pair production in the SM be enhanced by a factor 40 or so

R.Frederix, S.Frixione, V.Hirschi, F.Maltoni, O.Mattelaer, P.Torrielli, E.Vryonidou and M.Zaro,Phys.Lett.B732,142 (2014)
Q.H. Cao, Y. Liu, B. Yan, 1511.03311

Setup4MC simulation

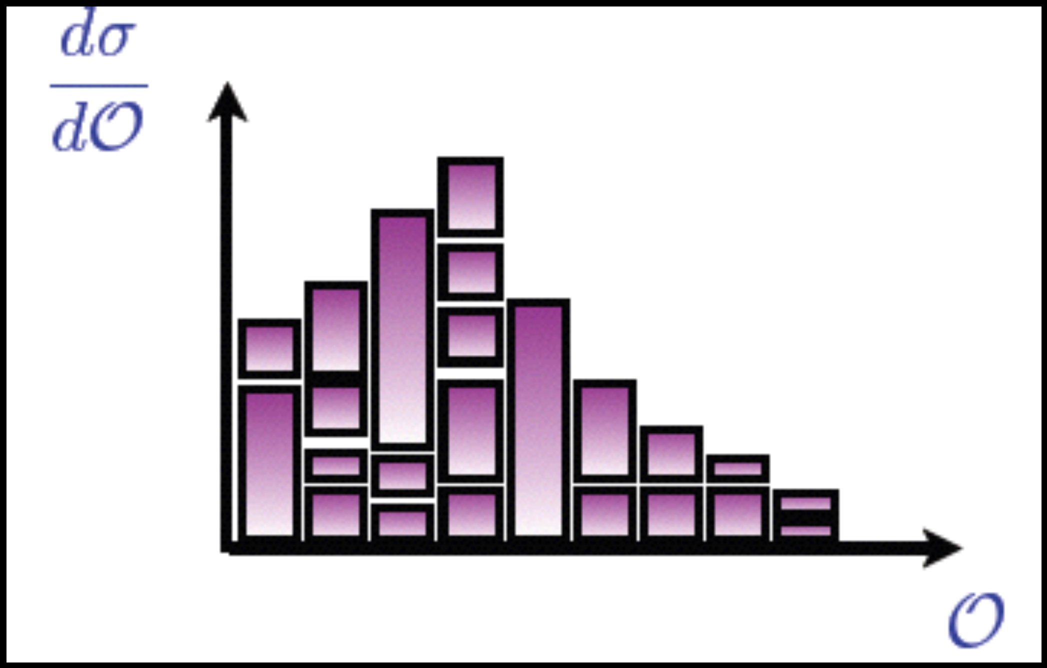
- PDF: **NNPDF2.3**
- Matrix Elements: **MadLoop**
- Phase Space Integration: **QMC**
- Parton Shower: **Pythia**
- Detector Simulation: **Delphes3.0**
- Analaysis: **ROOT and TMVA**

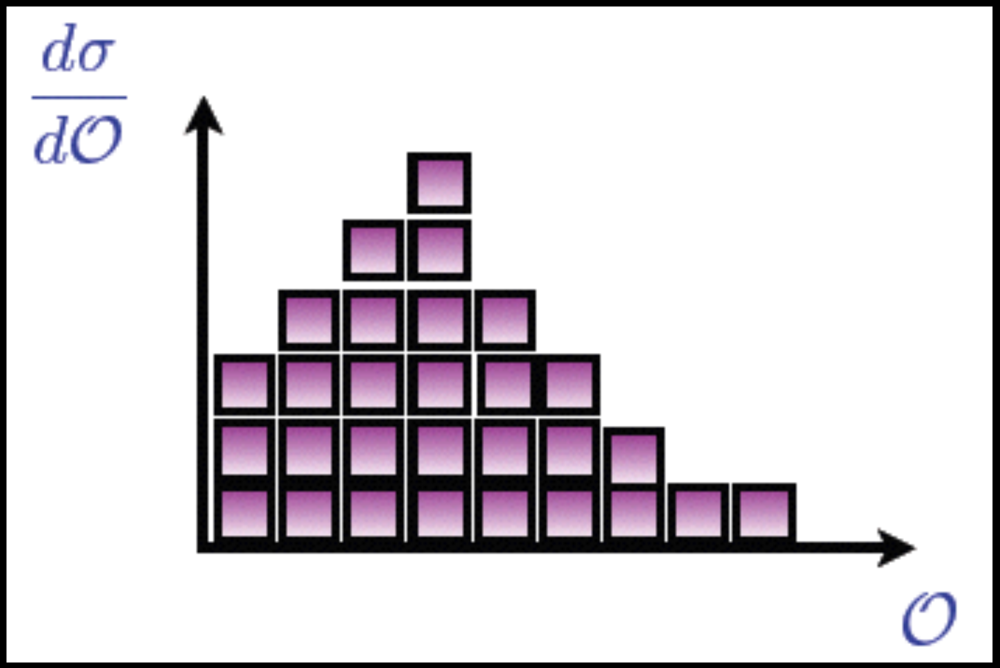
Setup4MC simulation



Why QMC? Faster convergence to determine differential cross section

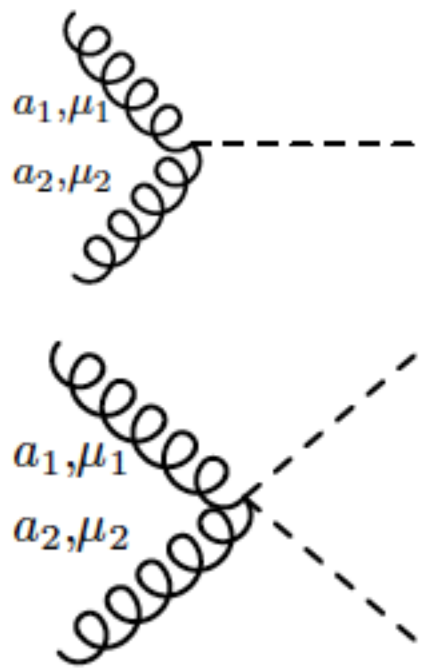
Setup4MC simulation





QMC :
phase space integration and
unweighted event generation

	VEGAS	QMC-based
integration result(fb)	19.0 ± 0.2	19.269 ± 0.003
reweighting efficiency	36.6%	75.8%



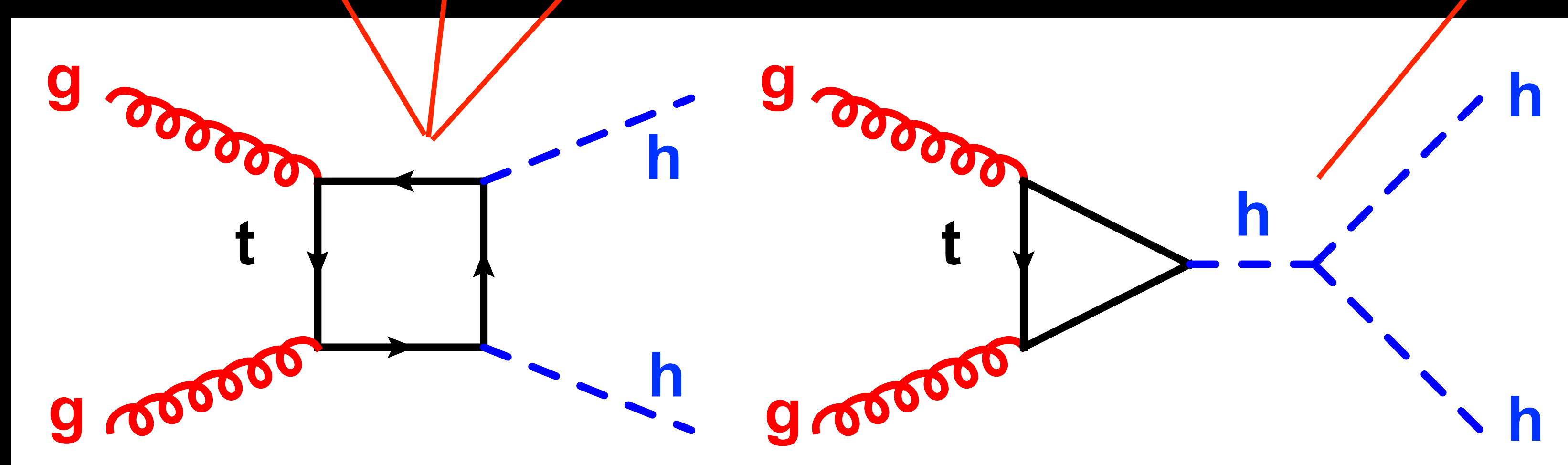
$$= -i\frac{\sqrt{2}g_s^2 m_t a Y_t \delta_{a_1 a_2} g_{\mu_1 \mu_2}}{16\pi^2}$$

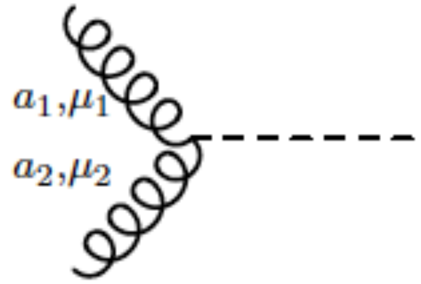
$$= -i\frac{g_s^2 Y_t^2 \delta_{a_1 a_2} g_{\mu_1 \mu_2}}{16\pi^2}(a^2 + b^2)$$

$$\mathcal{L}_1 = Y_t\,(a\,\bar{t}t + i\,b\,\bar{t}\gamma_5 t)\,h + \lambda_3\,\lambda_{SM}\,v\,h\,h\,h + \cdots\,,$$

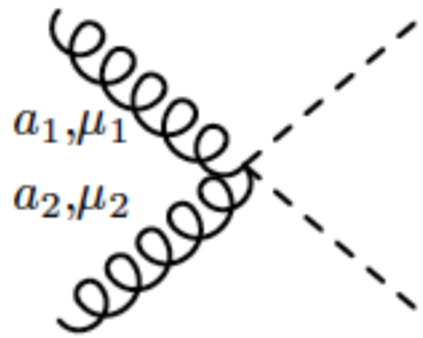
Except tree-level vertices, new R2 terms must be added, as required by the OPP method.

$$\sigma(gg \to hh) = G_1\,a^4 + G_2\,b^4 + G_3\,a^2\,b^2 + (G_4\,a^3 + G_5\,a\,b^2)\,\lambda_3 + (G_6\,a^2 + G_7\,b^2)\,\lambda_3^2$$





$$= -i\frac{\sqrt{2}g_s^2 m_t a Y_t \delta_{a_1 a_2} g_{\mu_1\mu_2}}{16\pi^2}$$



$$= -i\frac{g_s^2 Y_t^2 \delta_{a_1 a_2} g_{\mu_1\mu_2}}{16\pi^2}(a^2+b^2)$$

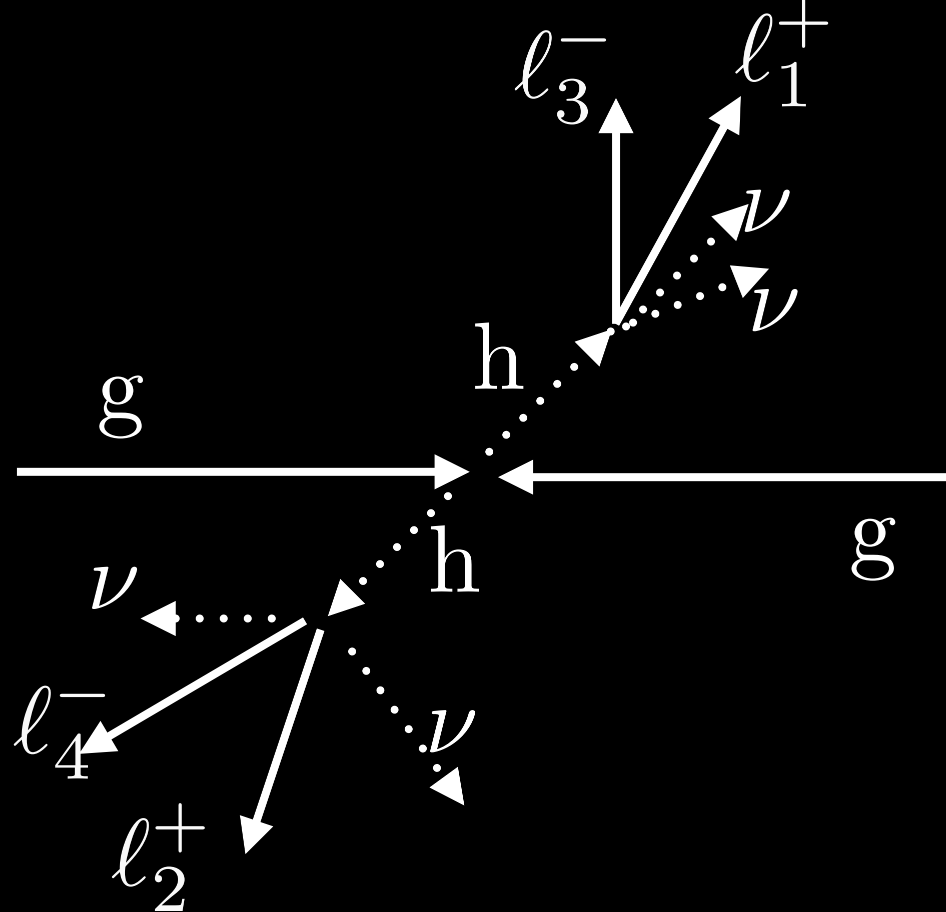
$$\mathcal{L}_1 = Y_t\,(a\,\bar{t}t + i\,b\,\bar{t}\gamma_5 t)\,h + \lambda_3\,\lambda_{SM}\,v\,h\,h\,h + \cdots,$$

Except tree-level vertices, new R2 terms must be added, as required by the OPP method.

$$\sigma(gg\to hh) = G_1\,a^4 + G_2\,b^4 + G_3\,a^2\,b^2 + (G_4\,a^3 + G_5\,a\,b^2)\,\lambda_3 + (G_6\,a^2 + G_7\,b^2)\,\lambda_3^2$$

	G_1 (fb)	G_2 (fb)	G_3 (fb)	G_4 (fb)	G_5 (fb)	G_6 (fb)	G_7 (fb)
14 TeV	34.5	3.37	268	−23.1	−119	4.82	15.1
33 TeV	227	23.1	1.67×10^3	−143	−723	28.7	89.0
R^{33}	6.6	6.8	6.2	6.2	6.2	5.9	5.9
100 TeV	1.71×10^3	186	1.20×10^4	-1.03×10^3	-5.09×10^3	199	610
R^{100}	49.6	55.2	44.9	44.6	42.8	41.2	40.4

$$gg \to hh \to w^+w^-w^+w^- \to 4\ell + \text{MET}$$



The topology of our signal
2 W bosons are on-shell
and 2 W bosons are off-shell

Production rates of Signal and Background

	$\sigma \times Br$ (fb)	Expected number of events at $3000\,\mathrm{fb}^{-1}$	Number of events generated	K-factors
HH	0.18	5.7×10^2	500,000	1.6
ZZ	4.8×10^2	1.4×10^6	-	-
Z h	5.56	1.67×10^4	500,000	0.97
ZW^+W^-	6.34	1.90×10^4	500,000	2.8
$Zt\bar{t}$	1.97×10^2	5.91×10^5	5,000,000	1.1
$t\bar{t}$ h	1.41×10^1	4.22×10^4	1,000,000	1.2
$t\bar{t}t\bar{t}$	5.48	1.65×10^4	400,000	1.3
$t\bar{t}W^+W^-$	1.78	5.35×10^3	200,000	1.3
hW^+W^-	6.02×10^{-2}	1.81×10^2	50,000	1.4
$W^+W^-W^+W^-$	2.74×10^{-2}	8.23×10^1	10,000	2.8

TABLE II. The expected number of events with 3 ab^{-1} integrated luminosity at $\sqrt{s} = 100$ TeV and the generated events for all processes are displayed.

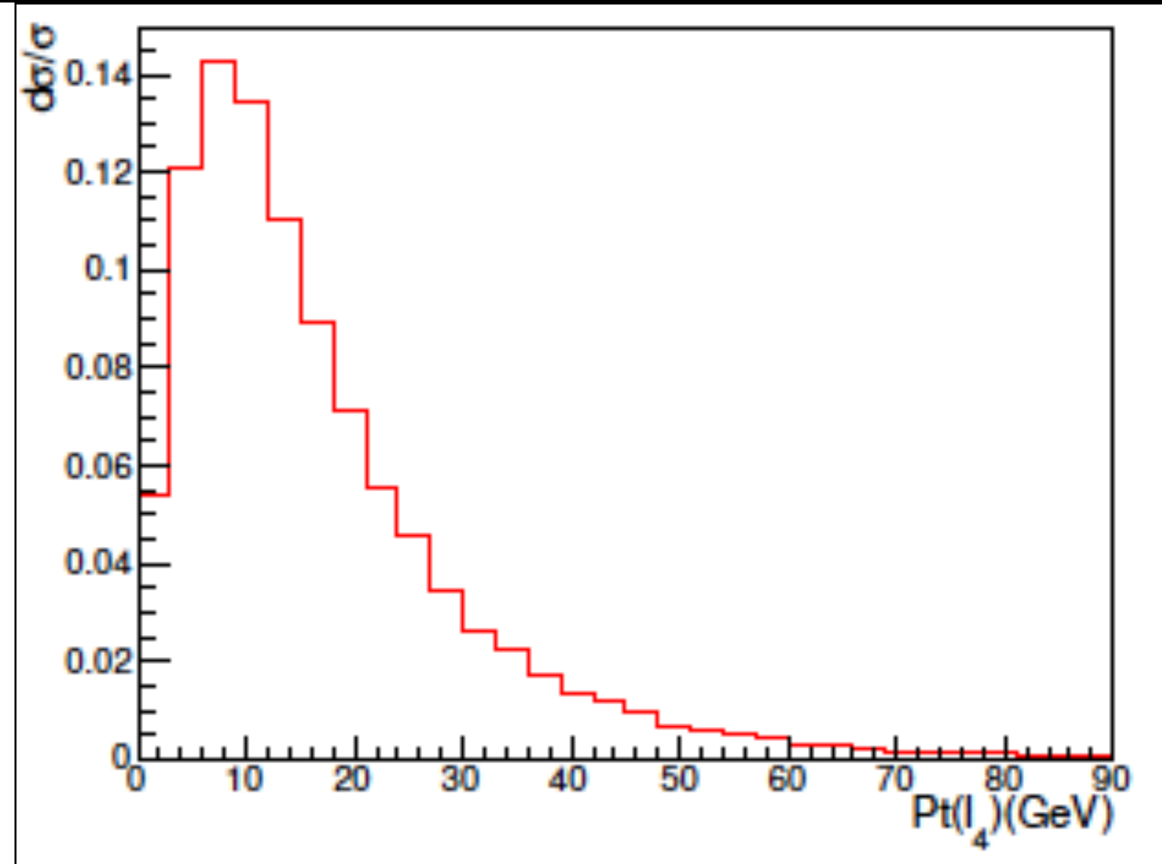
Same-signed leptons final state are chosen to suppress the ZZ background

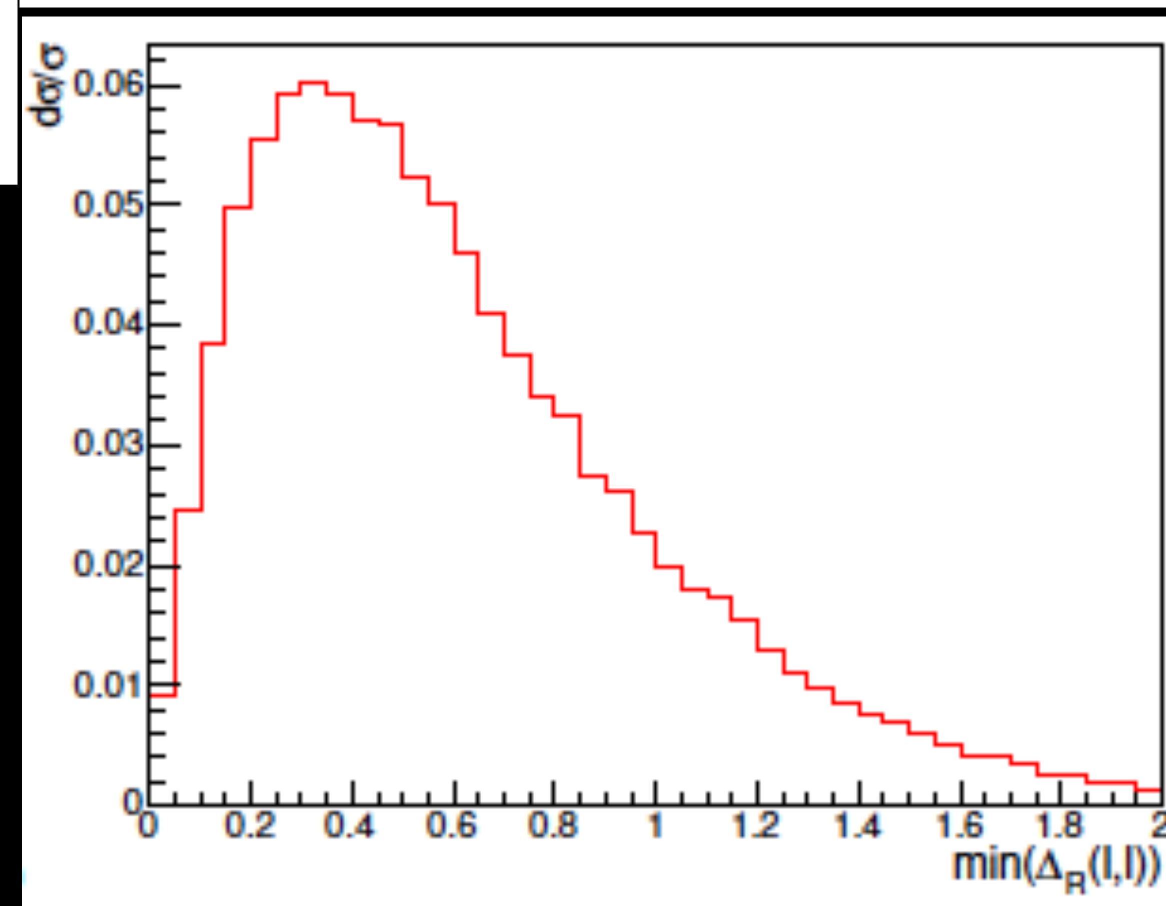
processes	Labels in Figs.	Cross section in fb	M1 $\ell^+\ell^-\ell^+\ell^-$	M2 $e^+e^-\mu^+\mu^-$	M3 $\ell^+\ell^-\ell^\pm\ell'^\mp$	M4 $\ell^+\ell'^-\ell^+\ell'^-$
hh	signal	0.29	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{1}{8}$
Zh, ZW^+W^-, $Zt\bar{t}$	$Z+$	5.40,17.8,217	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{2}$	0
$t\bar{t}h$, $t\bar{t}t\bar{t}$, $t\bar{t}W^+W^-$	$t\bar{t}+$	16.9,7.12,2.3	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{1}{8}$
hW^+W^-, $W^+W^-W^+W^-$	EW	8.4×10^{-2}, 7.7×10^{-2}	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{1}{8}$
ZZ		485	$\frac{1}{2}$	$\frac{1}{2}$	0	0

TABLE III. The cross sections of four leptonic mode at a 100 TeV collider for different processes are tabulated, where $\ell = e, \mu$. Fraction of four modes in all the final states are shown.

Preselection Cuts	Description
1	$n_\ell = 4$ $P_t(\ell_1) > 30$ GeV, $P_t(\ell_2) > 15$ GeV $P_t(\ell_3) > 10$ GeV, $P_t(\ell_4) > 8$ GeV. $\lvert \eta^{max}(\ell_i) \rvert < 4$ $\Delta R^{min}(\ell, \ell) > 0.15$
2	b jet veto
3	low energy hadron veto and Z mass veto

TABLE IV. The preselection cuts in our analysis are tabulated.





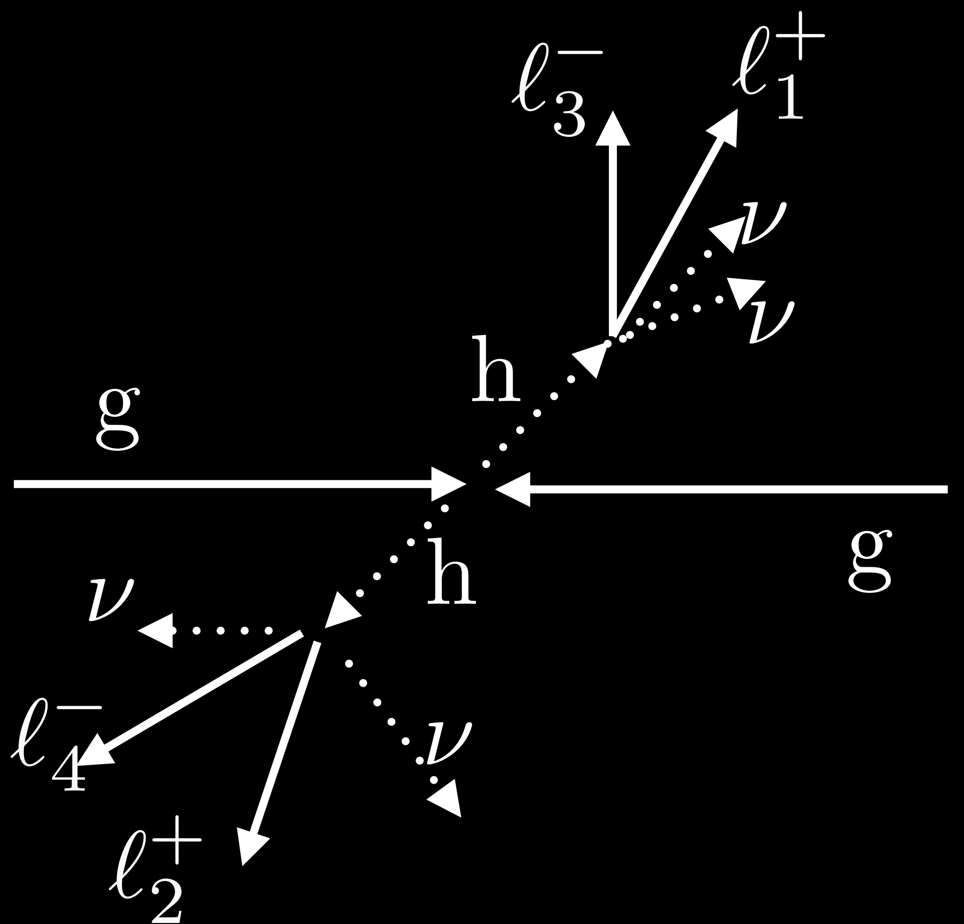
Hadronic level analysis in the SM:
Two leptons from a Higgs boson might fly closely due to 1) moderately boosted Higgs, 2) spin correlation between them.

Assumed integrated luminosity 3000/fb of a 100 TeV collision

Processes	Pre-Sel. Cuts	$n_j \leq 2$	$M_{T2} < 115\,\text{GeV}$	$m(h^{vis}) < 60\,\text{GeV}$	$\Delta m > 50\,\text{GeV}$	BDT
hh	172	150	124	91.2	68.8	99.8
Z h	243	238	197	66.6	23.4	27.4
ZW^+W^-	1.60×10^3	1.54×10^3	444	173	91.4	111.7
$Zt\bar{t}$	2.55×10^3	1.45×10^3	542	222	117	89.7
$t\bar{t}h$	446	245	128	68.0	31.1	29.5
$t\bar{t}t\bar{t}$	254	24.4	3.96	1.44	1.04	3.63
$t\bar{t}W^+W^-$	151	71.2	12.5	4.16	2.48	4.30
hW^+W^-	44.5	42.7	20.3	10.3	4.94	6.11
$W^+W^-W^+W^-$	50.9	47.3	5.67	1.98	1.20	1.98
S/B	3.2×10^{-2}	4.1×10^{-2}	0.10	0.17	0.25	0.38
$S/\sqrt{B}$	2.35	2.48	3.37	3.90	4.20	6.1

Cut efficiency are demonstrated for M3 mode

A Partial Reconstruction Method

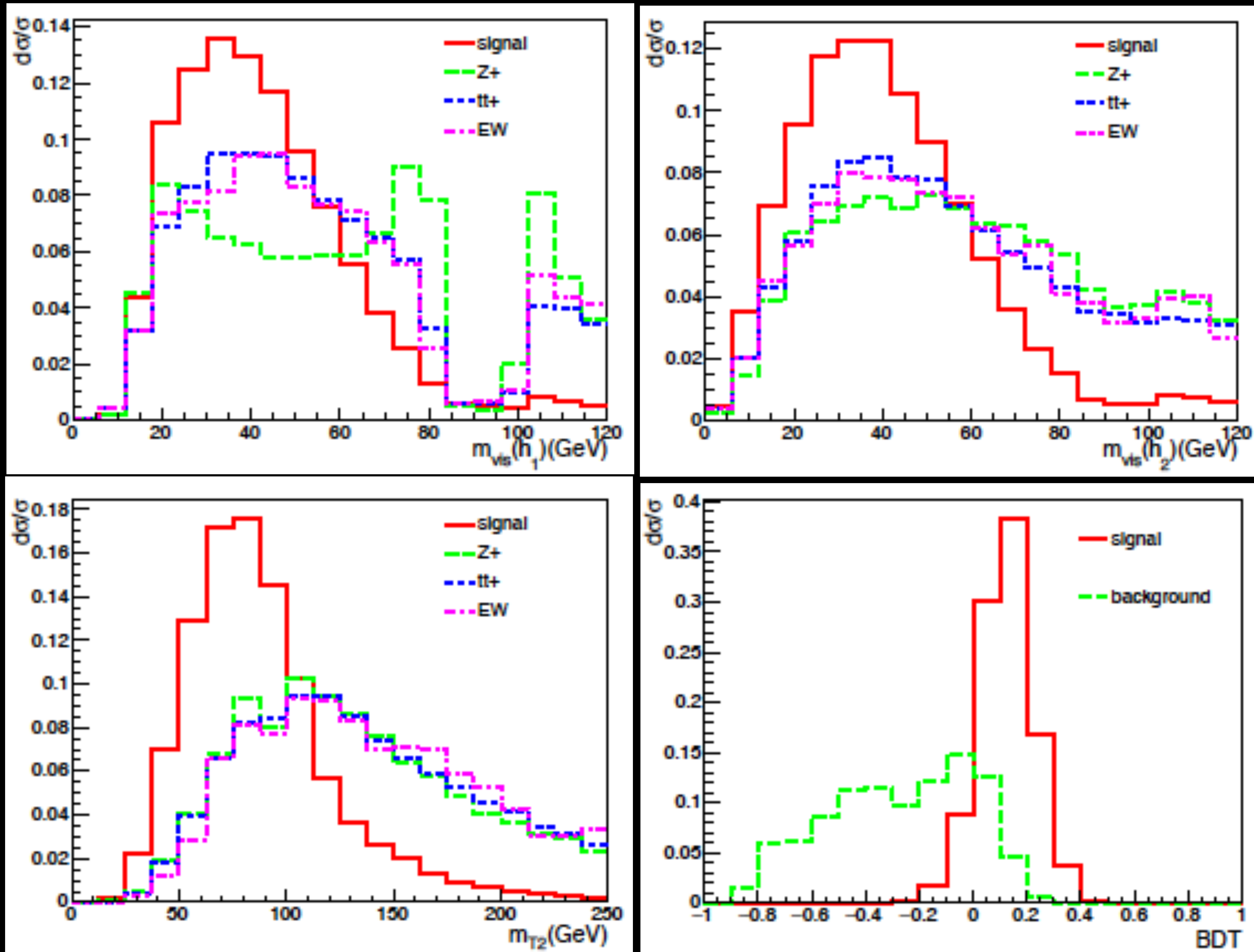


- For M3 and M4 modes,there are only two possible combinations.
- We pick the combination which yields the smaller $m_{\ell_1\ell_2} + m_{\ell_3\ell_4}$

This reconstruction method can find the correct combination up to 95%.

To suppress SM background, finding the correct combination is crucial!

X.R. Zhao, Q. Li, Z. Li, QY, arXiv:1604.04329



Visible Higgs boson masses and mT2 variable in M3 mode

Assumed integrated luminosity 3000/fb of a 100 TeV collision

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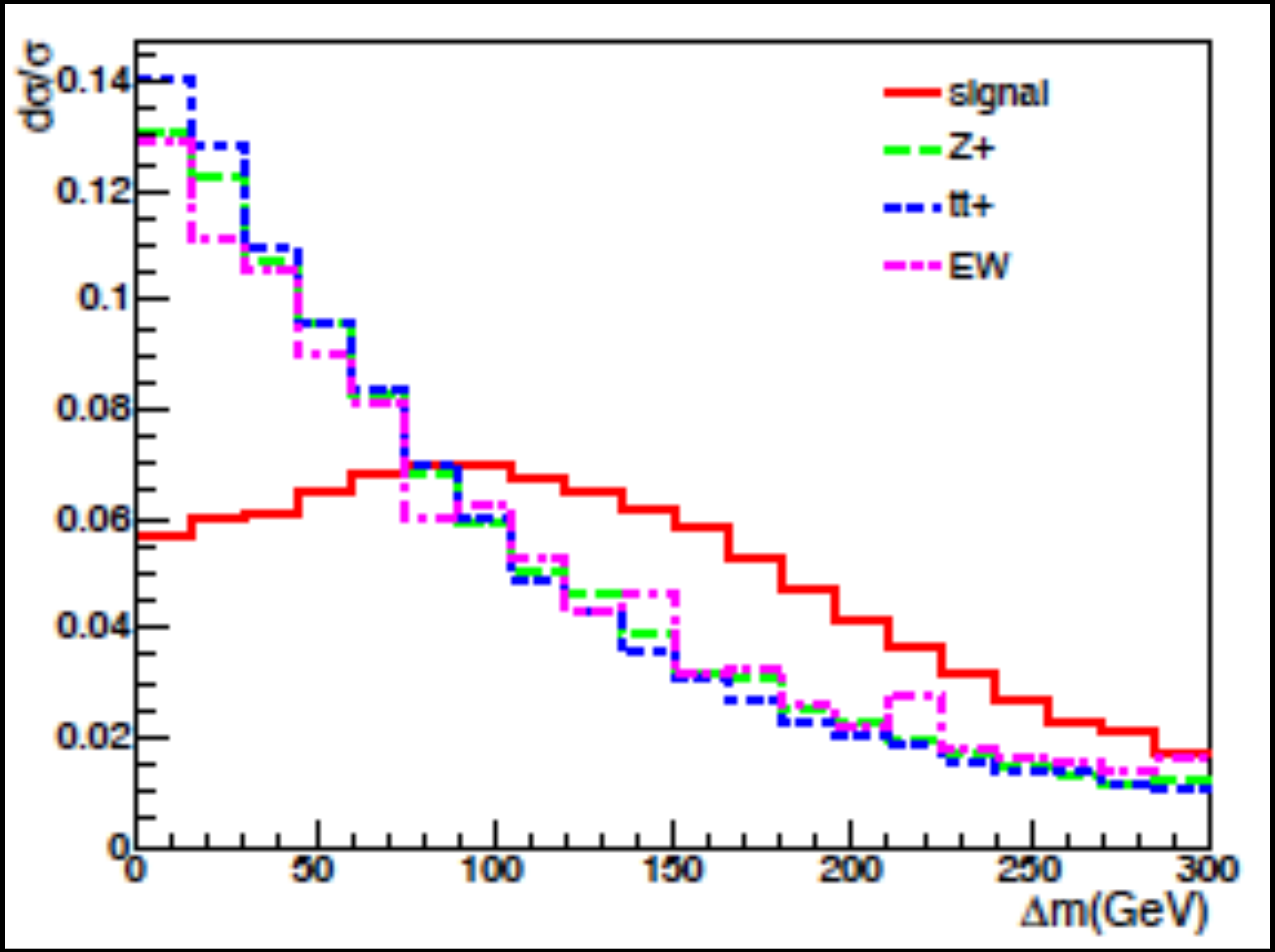
S/B	3.2×10^{-2}	4.1×10^{-2}	0.10	0.17	0.25	0.38
$S/\sqrt{B}$	2.35	2.48	3.37	3.90	4.20	6.1

Cut efficiency are demonstrated for M3 mode



A new variable is found useful.

$$m_1 = m_{\ell_1\ell_3} + m_{\ell_2\ell_4}$$
$$m_2 = m_{\ell_1\ell_4} + m_{\ell_2\ell_3}$$
$$\Delta m = |m_1 - m_2|$$

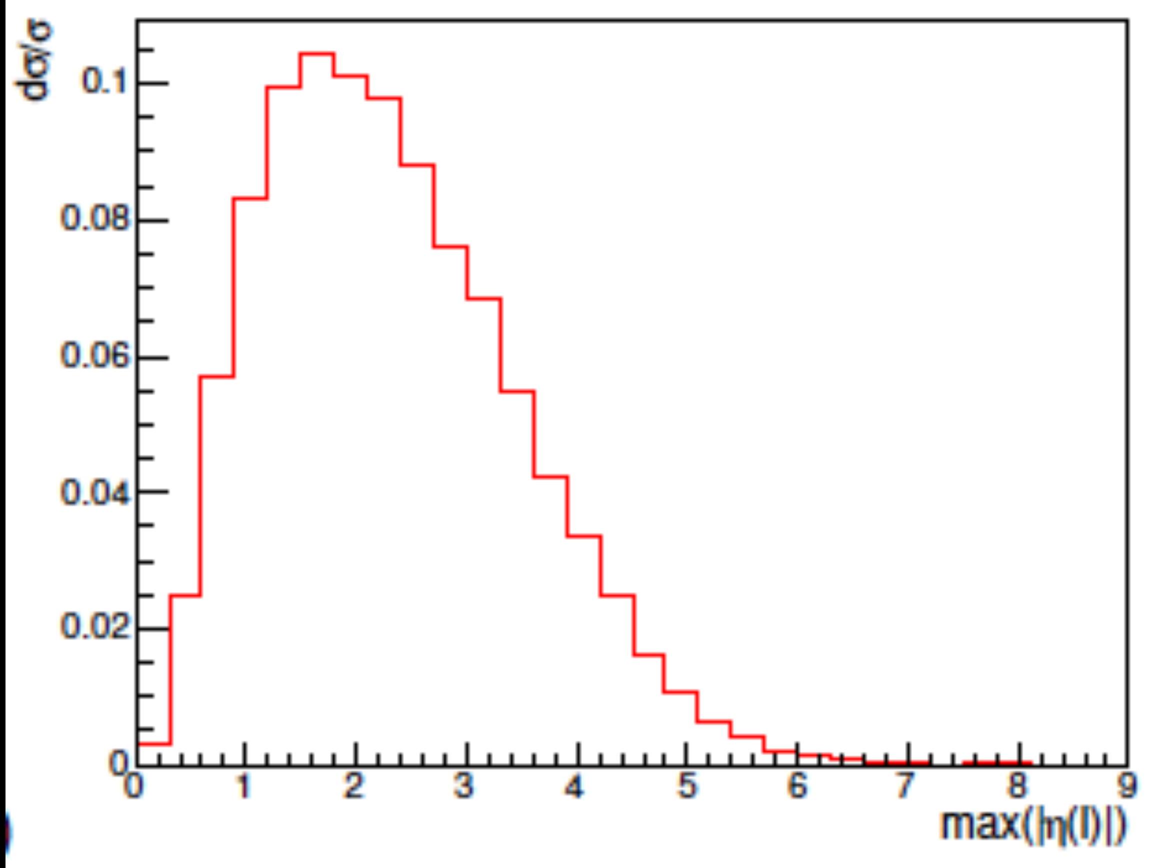
Assumed integrated luminosity 3000/fb of 100 TeV collision

Processes	Pre-Sel. Cuts	$n_j \leq 2$	$M_{T2} < 110\,\mathrm{GeV}$	$m(h_1{}^{vis}) < 60\,\mathrm{GeV}$	$\Delta m > 50\,\mathrm{GeV}$	BDT
hh	55.2	48.5	40.5	36.3	28.8	43.9
$t\bar{t}h$	147.1	80.5	44.4	27.1	13.7	14.3
$t\bar{t}t\bar{t}$	77.4	7.93	1.27	5.13×10^{-1}	3.59×10^{-1}	1.24
$t\bar{t}W^+W^-$	47.1	22.6	4.21	1.94	1.21	1.94
hW^+W^-	15.1	14.5	7.41	4.36	2.11	4.46
$W^+W^-W^+W^-$	15.9	15.0	2.37	1.08	6.22×10^{-1}	1.86
S/B	0.18	0.35	0.68	1.04	1.6	1.9
$S/\sqrt{B}$	3.17	4.09	5.24	6.13	6.79	9.2

Cut efficiency are demonstrated for M4 mode

The sensitivity of M4 mode could be better than M3 mode.

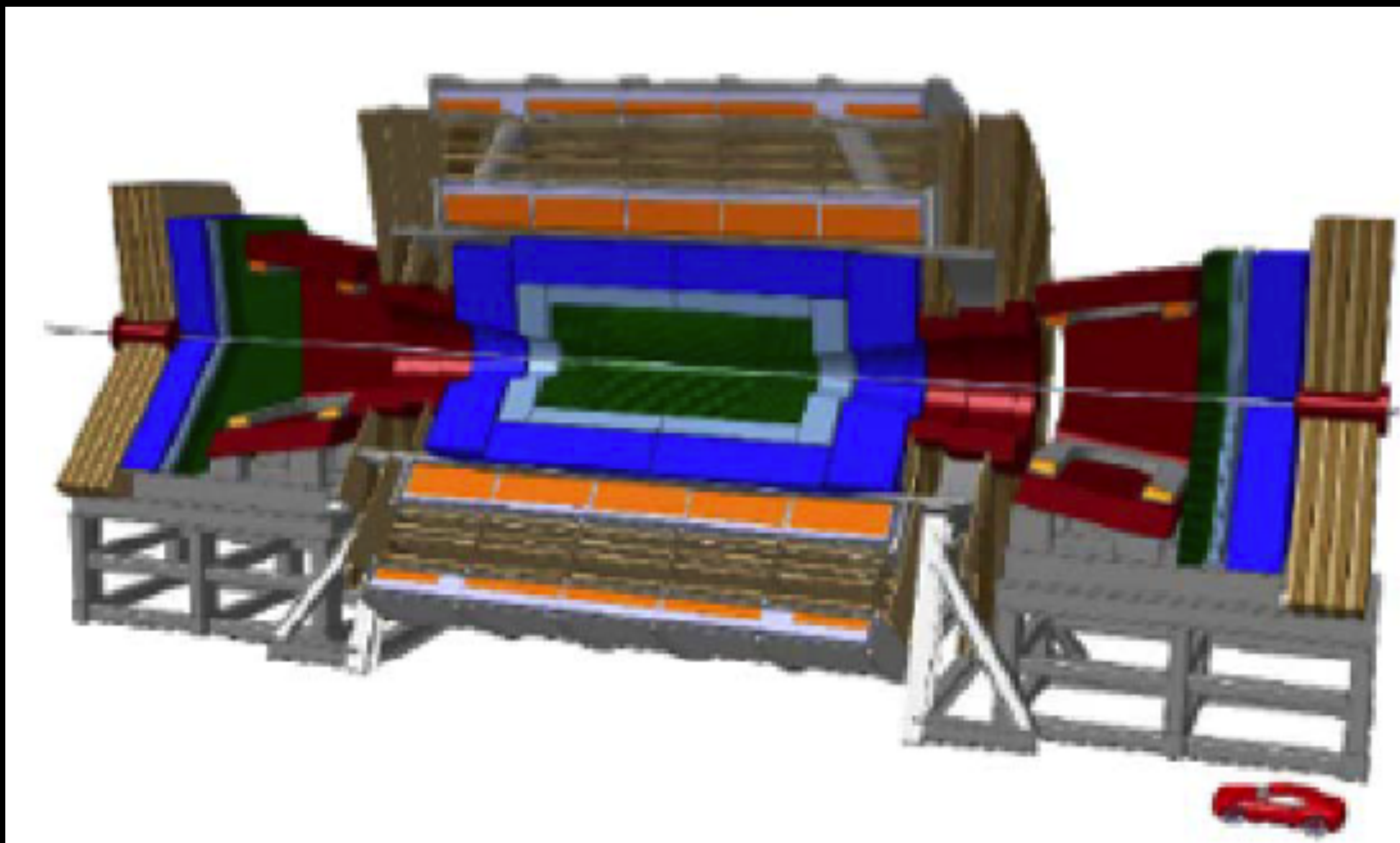
How detector effect can change our hadronic analysis?

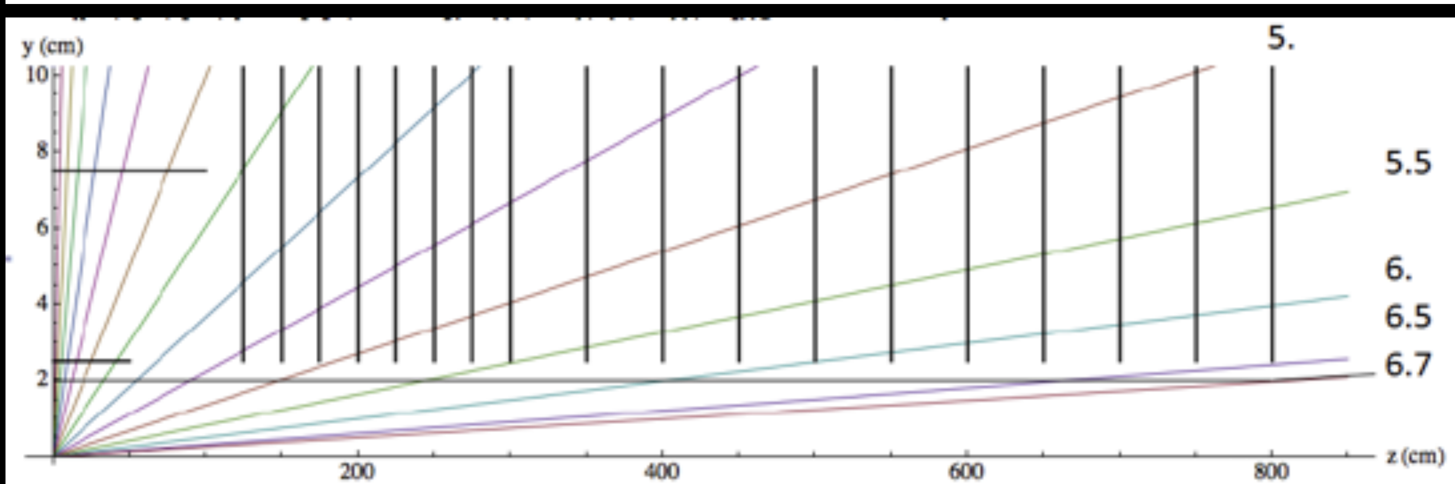


Eta Coverage	Signal Acceptance Efficiency
$\lvert\eta\rvert < 2$	50%
$\lvert\eta\rvert < 3$	73%
$\lvert\eta\rvert < 4$	91%
$\lvert\eta\rvert < 5$	98%
$\lvert\eta\rvert < 6$	≈100%

Lepton acceptance efficiency is shown.

FCC baseline detector
from Albert De Roeck's talk





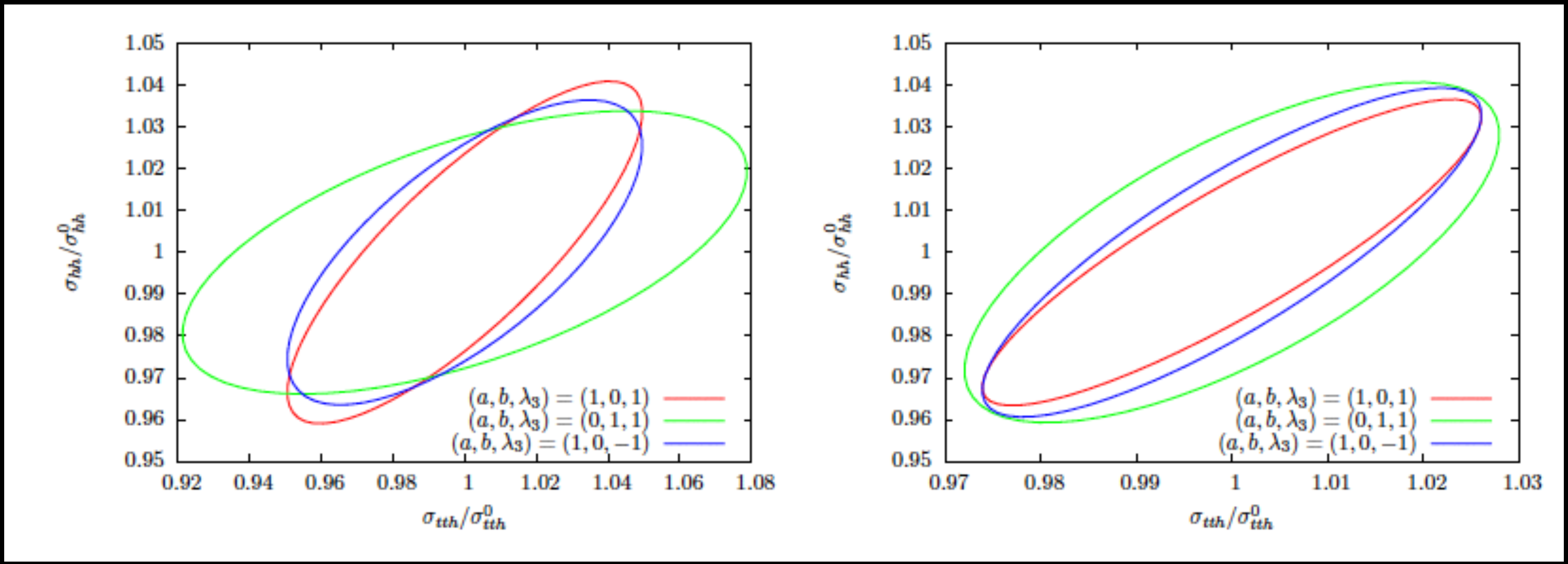
FCC detector baseline design: forward dipoles to cover large eta regions, a better tracker resolution, …

	$\eta^{max}(\ell)$	$\eta^{max}(b)$	$\Delta R(\ell)$	$P_{t,min}(j)$ GeV	$P_{t,min}(\ell)$ GeV
ATLAS-like	2.5	2.5	0.5	20	10
A1	4.0	2.5	0.5	20	10
A2	4.0	4.0	0.5	20	10
A3	4.0	4.0	0.3	20	10
FCC	6.0	6.0	0.3	40	20
F1	6.0	6.0	0.3	20	20
F2	6.0	6.0	0.3	20	10

Seven detector setups are considered

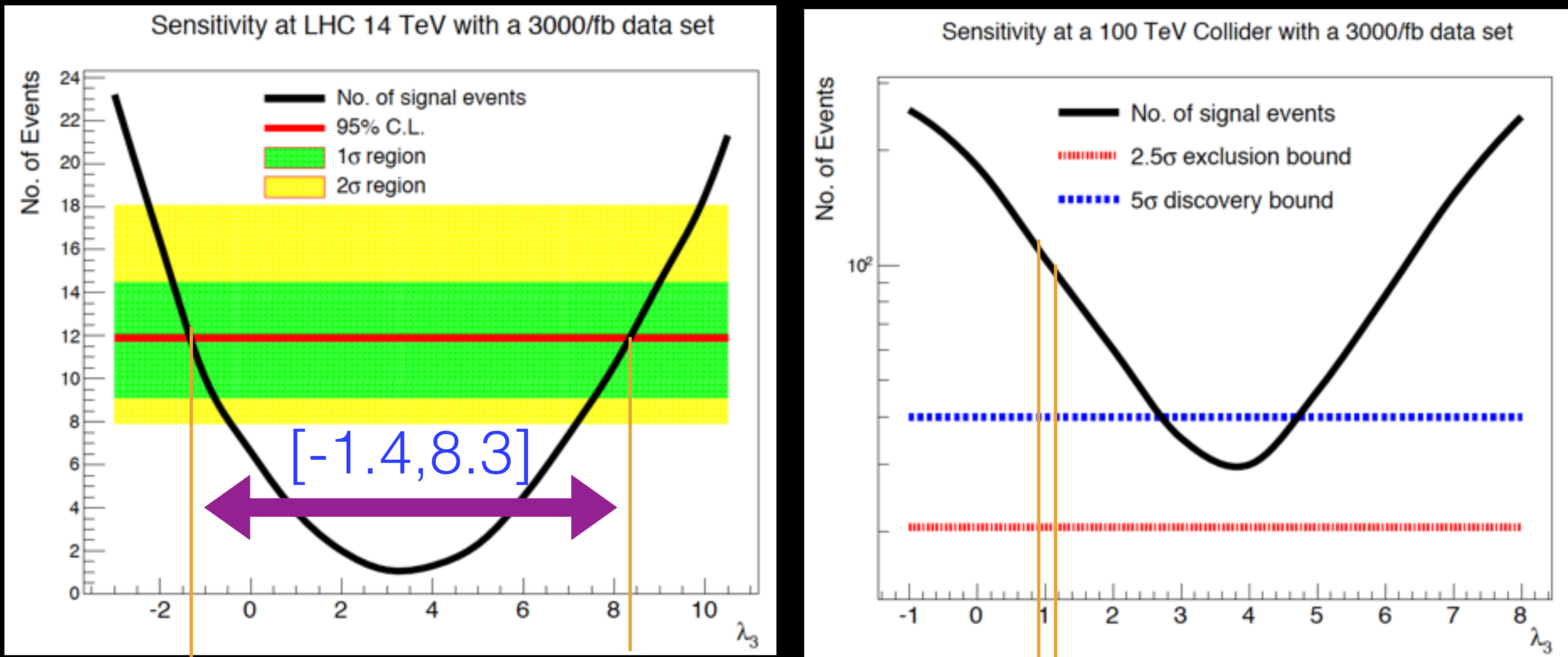
	M3			M4		
	S	B	$S/\sqrt{B}$	S	B	$S/\sqrt{B}$
Hadronic Analysis	99.8	274.3	6.1	43.9	23.8	9.2
ATLAS-like	13.2	62.4	1.7	6.3	8.5	2.2
A1	18.6	108.3	1.8	8.7	13.4	2.4
A2	18.3	93.3	1.9	8.7	11.6	2.6
A3	35.8	156.2	2.9	16.7	18.9	3.8
FCC	18.6	82.6	2.0	8.0	13.6	2.2
F1	18.3	57.5	2.4	8.1	8.0	2.9
F2	38.2	177.5	2.9	17.5	19.1	4.0

Effects of detector can decrease the significance of hadron level analysis by at least a factor 2. Including soft leptons in the analysis can increase the sensitivity by a factor 2 or so.



PDF uncertainty is less than 10%

Cubic Coupling@HC

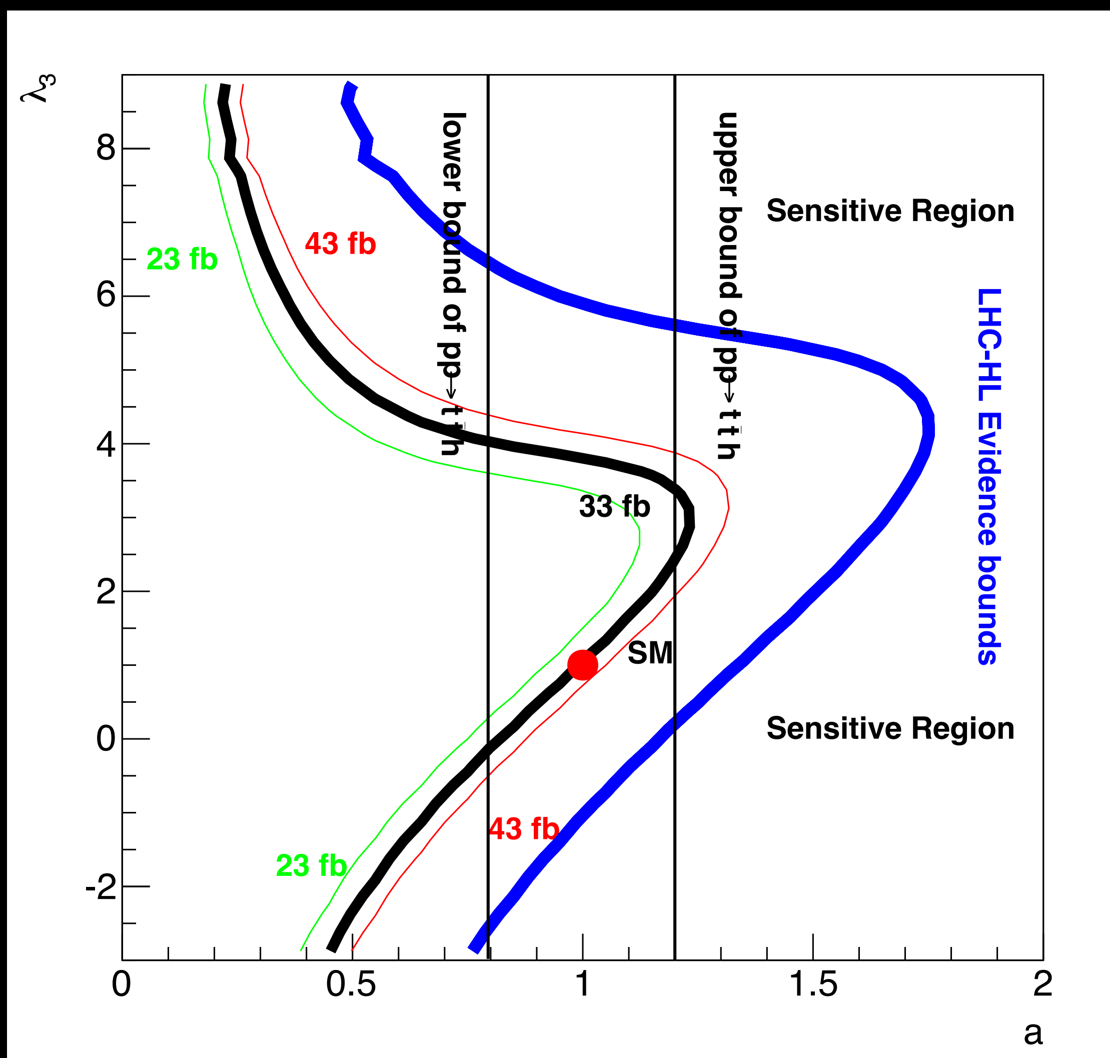


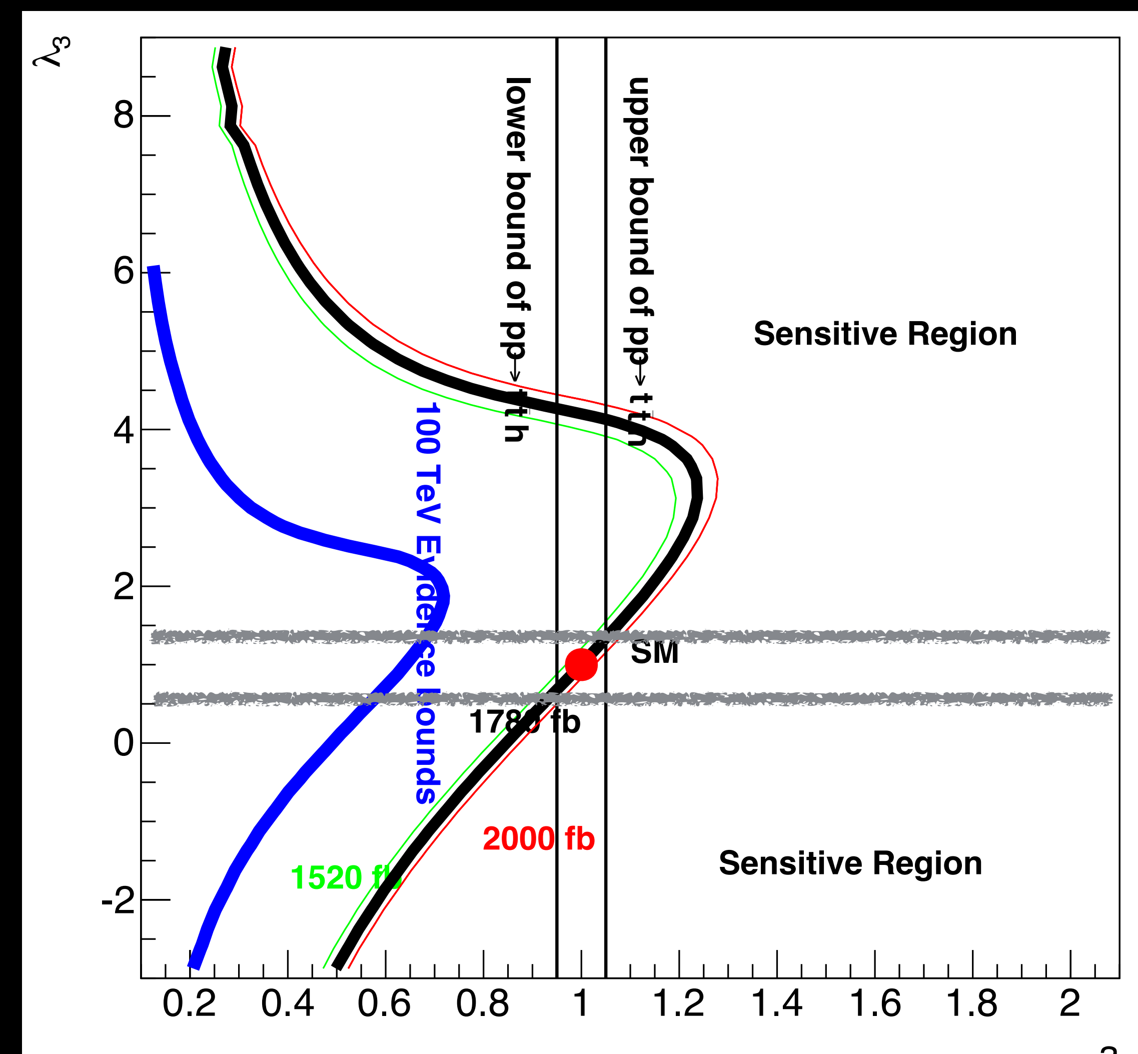
By using the invariant mass of three leptons in the final state, we can determine trilinear coupling to [0.9,1.2] at a 100 TeV collider with an integrated luminosity 30/ab.

$$gg \to hh \to W^*WW^*W \to 3l2j + \mathrm{MissE}$$

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

Correlation between Higgs pair production and tth measurement





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, QY, X.R. Zhao, PRD92(2015)1,014015, arXiv:1503.07611
X.R. Zhao, Q. Li, Z. Li, QY, 1604.04329

Conclusions

- Multi-Higgs final states are important to reveal the nature of Higgs boson and related issues
- A 100 TeV future collider can be of great help to measure Higgs self-coupling and address these issues
- The fully leptonic modes are doable at a 100 TeV collider
- Detector setup can affect the sensitivity by a factor of 2 or 4.