Probing Anomalous Heavy Neutral Higgs Boson at the LHC via

VV Scattering & VH Associated Production

Hong-Yu Ren & Ling-Hao Xia

on behalf of **Prof. Yu-Ping Kuang**

(*Center for High Energy Physics, Tsinghua University*)

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Contents

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Background

The discovery of the ~125GeV Higgs Boson is a triumph, but seemingly **not the end**…

Searching for new physics (**NP**) beyond SM is the most important goal of the future particle physics

Theoretical Clues:

the Triviality Problem, UnNaturalness, the Dark Matter…

We study the **NP** containing more than one Higgs Bosons

In many new physics models (2HDM, MSSM, LRSM, etc),

- **the lightest Higgs boson:** a SM-like Higgs boson
- **other heavy Higgs bosons:** usually with mass ~TeV, maybe within the searching ability of LHC

However, searching for heavy Higgs boson model by model is not an efficient way

So we choose a model-independent way, using the dim-6 effective Lagrangian to describe the anomalous Higgs interaction

Anomalous Couplings of the Heavy Neutral Higgs Bosons

Our goal is to search for the Non-Standard Model (**NS**) heavy neutral Higgs boson at the 14TeV LHC

Let $\phi_1,\ \phi_2, ...$ be original Higgs field with the potential $V(\phi_1,\ \phi_2,\ ...)$, which causes mixing between the Higgs fields.

Let $\phi_h,\ \phi_H$ be the lightest Higgs and a heavier neutral Higgs fields with Higgs bosons $h,\ H$

The mixing generates the VEVs v_h, v_H, and the effective Higgs-Gauge coupling constant g_h, g_H .

The ~125GeV Higgs boson *h*

- treated as a SM-like Higgs with negligible anomalous couplings

A heavy neutral Higgs boson *H*

- with not so small gauge interaction
- **model-independent** formulation of its **gauge and Yukawa** couplings based on effective Lagrangian

Anomalous Couplings of the Heavy Neutral Higgs Bosons : Dim-4

Yukawa Couplings

Multi-Higgs-fermion couplings are irrelevant to our study. So up to dim-6, there is no new coupling form other than the Yukawa couplings

$$h f\bar{f}: \qquad \frac{y_f^h}{\sqrt{2}}\bar{\psi}_f\phi_h\psi_f \sim \frac{y_f^{\rm SM}}{\sqrt{2}}\bar{\psi}_f\phi_h\psi_f$$

$$H f\bar{f}: \qquad \frac{y_f^H}{\sqrt{2}}\bar{\psi}_f\phi_H\psi_f = C_f\frac{y_f^{\rm SM}}{\sqrt{2}}\bar{\psi}_f\phi_H\psi_f$$

- C_t is most relevant since it concerns the *H-g-g* and *H-t-t* couplings, but has no clear experimental constraints
- **Type-I** $C_t \sim 1$
- **Type-II** $C_t < 1$
- **Constraint**

$$M_f = \frac{1}{\sqrt{2}}y_f^{\rm SM} = \frac{1}{\sqrt{2}}(y_f^h v_h + y_f^H v_H + \cdots)$$

Gauge Couplings

The dim-4 Higgs-gauge couplings of h and H have the similar forms

$$\mathcal{L}^{(4)}_{H_{\rm SM}VV} \propto g^2 v H_{\rm SM}V_\mu V^\mu$$

$$\mathcal{L}^{(4)}_{hVV} \propto g_h^2 v_h hV_\mu V^\mu = \rho_h g^2 v hV_\mu V^\mu \qquad \rho_h = \frac{g_h^2 v_h}{g^2 v}$$

$$\mathcal{L}^{(4)}_{HVV} \propto g_H^2 v_H HV_\mu V^\mu = \rho_H g^2 v HV_\mu V^\mu \qquad \rho_H = \frac{g_H^2 v_H}{g^2 v}$$

- The anomalous form differs from the SM form only by **an extra factor** ρ_h (ρ_H)
- **Constraint**

$$M_W^2 = \frac{1}{4}g^2 v(\rho_h v_h + \rho_H v_H + \cdots)$$

Anomalous Couplings of the Heavy Neutral Higgs Bosons : Dim-6

Gauge Couplings

momentum-dependent, **sensitive to high energies**

$$\mathcal{L}^{(6)}_{HVV} = \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n$$

$$\mathcal{O}_{WW} = \Phi_H^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi_H,$$
$$\mathcal{O}_{BB} = \Phi_H^\dagger \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi_H,$$
$$\mathcal{O}_{W} = (D_\mu\Phi_H)^\dagger \hat{W}^{\mu\nu}(D_\nu\Phi_H),$$
$$\mathcal{O}_{B} = (D_\mu\Phi_H)^\dagger \hat{B}^{\mu\nu}(D_\nu\Phi_H)$$

The relevant dim-6 effective Lagrangian expressed in weak boson field and H

$$\begin{aligned}\mathcal{L}^H_{eff} &= g_{H\gamma\gamma} H A_{\mu\nu}A^{\mu\nu} \\ &+ g^{(1)}_{HZ\gamma} A_{\mu\nu} Z^\mu \partial^\nu H + g^{(2)}_{HZ\gamma} H A_{\mu\nu} Z^{\mu\nu} \\ &+ g^{(1)}_{HZZ} Z_{\mu\nu} Z^\mu \partial^\nu H + g^{(2)}_{HZZ} H Z_{\mu\nu} Z^{\mu\nu} \\ &+ g^{(1)}_{HWW} (W^+_{\mu\nu} W^{-\mu}\partial^\nu H + \mathrm{H.c.}) + g^{(2)}_{HWW} H W^+_{\mu\nu} W^{-\mu\nu}\end{aligned}$$

$$g_{H\gamma\gamma} = -\kappa\frac{s^2(f_{BB}+f_{WW})}{2\Lambda^2},$$
$$g^{(1)}_{HZ\gamma} = \kappa\frac{s(f_W - f_B)}{2c\Lambda^2}, \quad g^{(2)}_{HZ\gamma} = \kappa\frac{s[s^2 f_{BB} - c^2 f_{WW}]}{c\Lambda^2},$$
$$g^{(1)}_{HZZ} = \kappa\frac{c^2 f_W + s^2 f_B}{2c^2\Lambda^2}, \quad g^{(2)}_{HZZ} = -\kappa\frac{s^4 f_{BB} + c^4 f_{WW}}{2c^2\Lambda^2},$$
$$g^{(1)}_{HWW} = \kappa\frac{f_W}{2\Lambda^2}, \quad g^{(2)}_{HWW} = -\kappa\frac{f_{WW}}{\Lambda^2},$$

$$\kappa = \rho_H g M_W$$

Constraints on the Anomalous Coupling Constants : by Unitarity

The momentum-dependence of the anomalous couplings may violate the unitarity of the LO S-matrix at high energies.

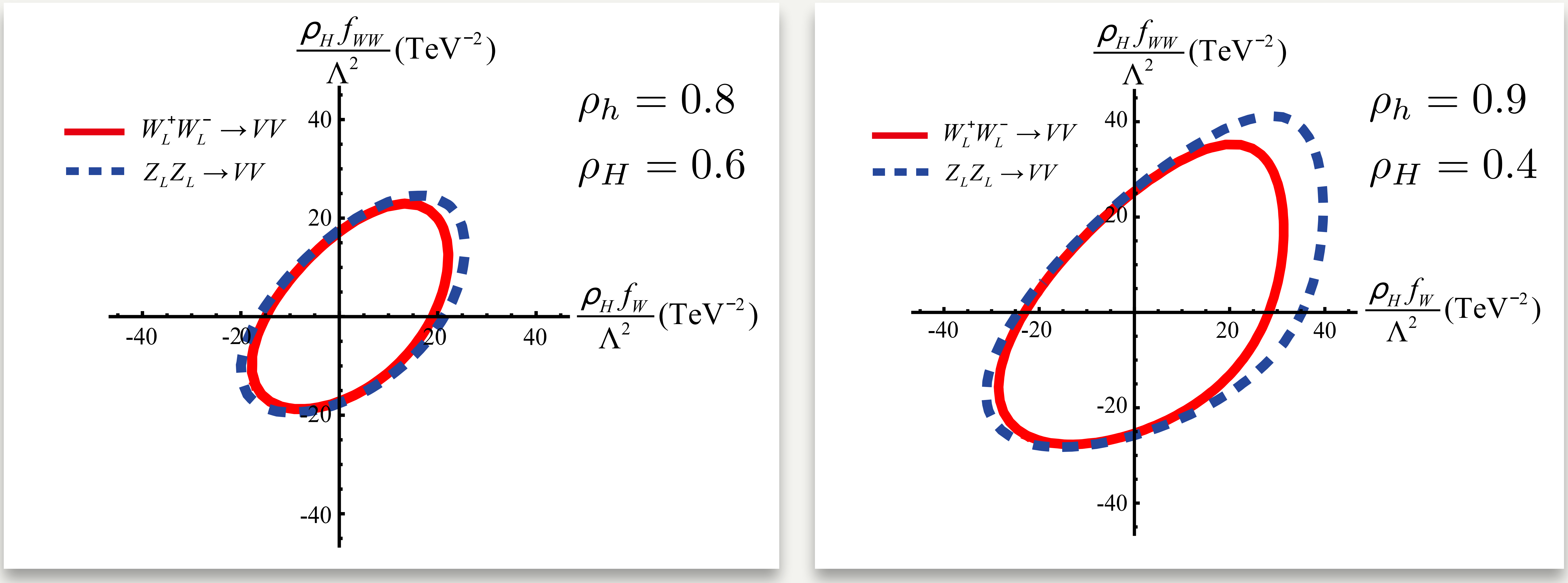
$$|S^\dagger S| = |1 - iT|^2 = 1 \Rightarrow (\mathrm{Re}\langle a|T|a\rangle)^2 + \sum_{|b\rangle \neq |a\rangle} |\langle b|T|a\rangle|^2 \leq 1$$

$$i\mathcal{M}(\lambda_i\lambda_i \to \lambda_f\lambda_f) = 16\pi \sum_J (J + \frac{1}{2})\langle\lambda_f\lambda_f|iT^J|\lambda_i\lambda_i\rangle P_J(\cos\theta)$$

Needing to be recalculated because there are two Higgs bosons in our theory

Expand the LO amplitude by partial wave, and the S-wave results are shown:

Longitudinal W bosons scattering gives the most strict constraints



$E_{\mathrm{CM}} = 3\mathrm{TeV}$

Constraints on the Anomalous Coupling Constants : by Experiments

$H\gamma\gamma$ & $HZ\gamma$

Sensitive to dim-6 anomalous couplings, and the results of the experiments show no trend to be distinguished from SM

$H \to \gamma\gamma$ ⇨ $f_{BB} \approx -f_{WW}$

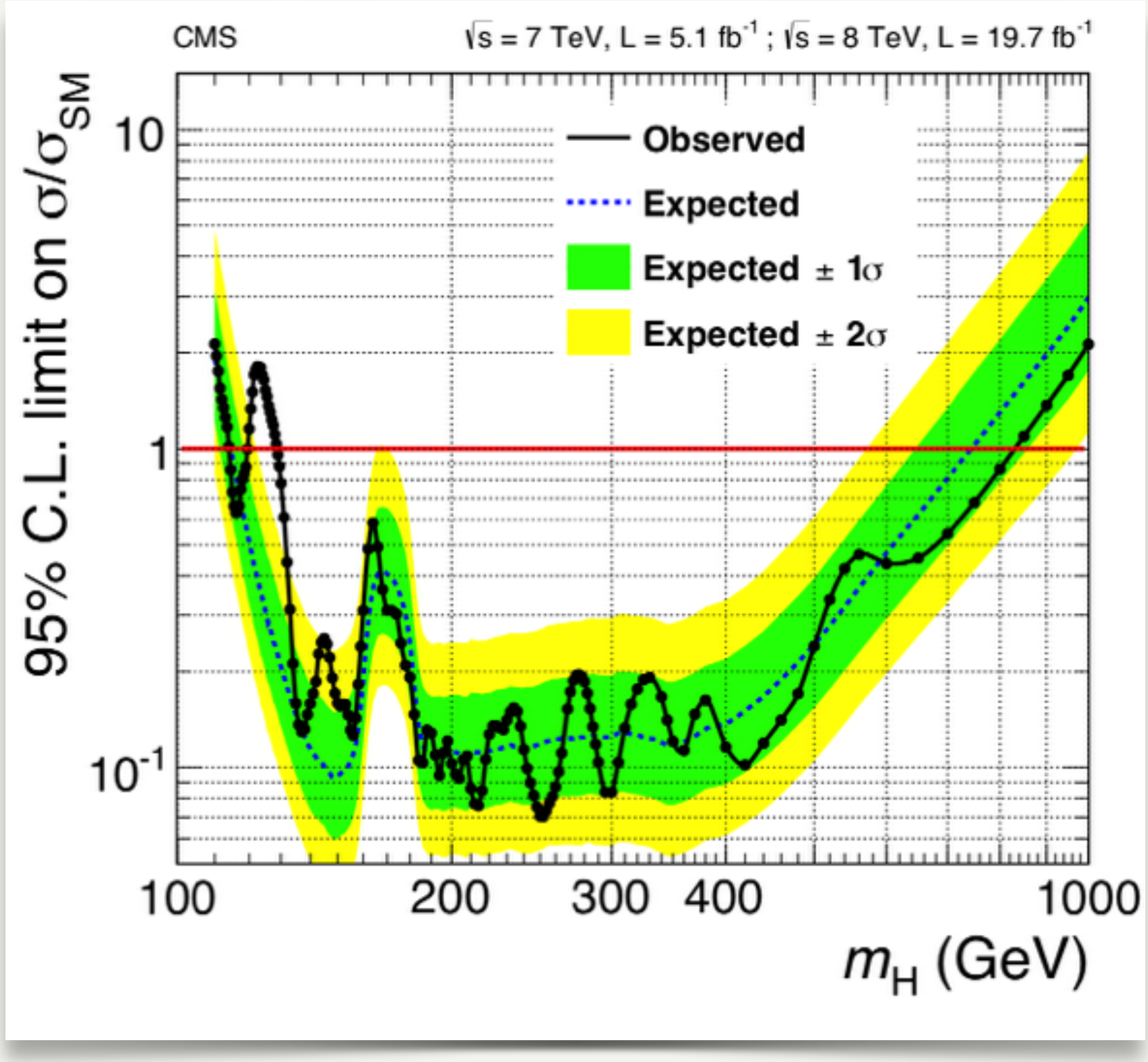
$H \to Z\gamma$ ⇨ $f_B \approx f_W - 4f_{WW}$

- Five parameters left :

$C_t, \ \rho_h, \ \rho_H, \ f_W, \ f_{WW}$

The experimental constraints are derived from the 95% CL upper limits on $\mu = \sigma/\sigma_{\rm exp}$

$$\sigma = \sigma(pp \to H + \cdots)\frac{\Gamma(H \to X)}{\Gamma(H \to ZZ) + \Gamma(H \to WW) + \cdots}$$



- The strongest constraint on a SM Higgs boson is the CMS result obtained from the channel $H \to ZZ \to 4l$
- Other channels are also taken into consideration

$M_H = 400\text{GeV}, \ 500\text{GeV}, \ 800\text{GeV}$ are taken as examples to do the analysis

Constraints on the Anomalous Coupling Constants : by Experiments

	Type-I	Type-II
M_H= 400GeV	Hardly avoid being excluded	Figure (a)
M_H= 500GeV	Figure (b)	Figure (c)
M_H= 800GeV	Almost all values of f_W and f_{WW} are available to make the heavy neutral Higgs boson not excluded by the exclusion bound	

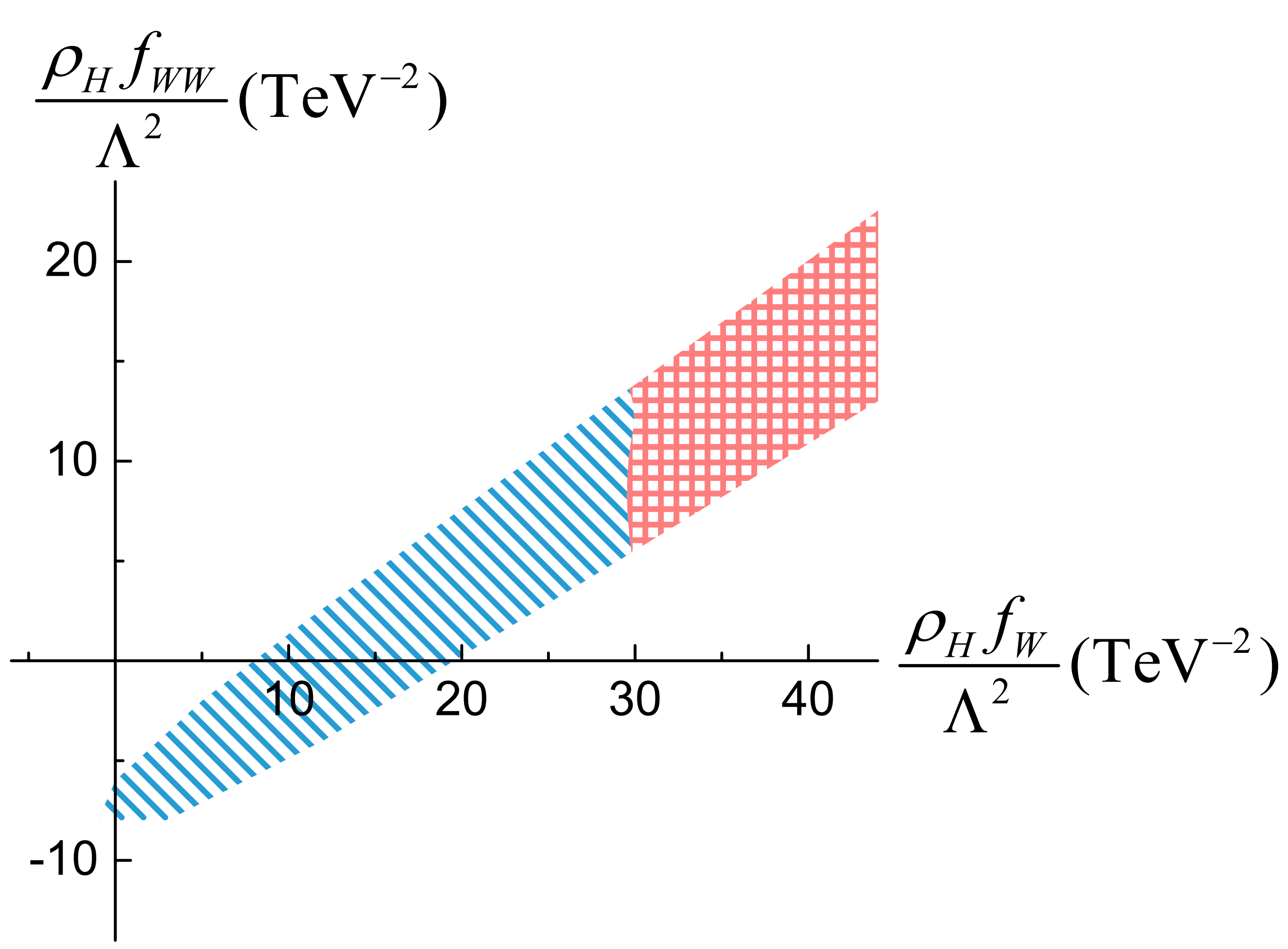


Figure (a) **400II**

$C_t = 0.5,\ \rho_h = 0.9,\ \rho_H = 0.4$

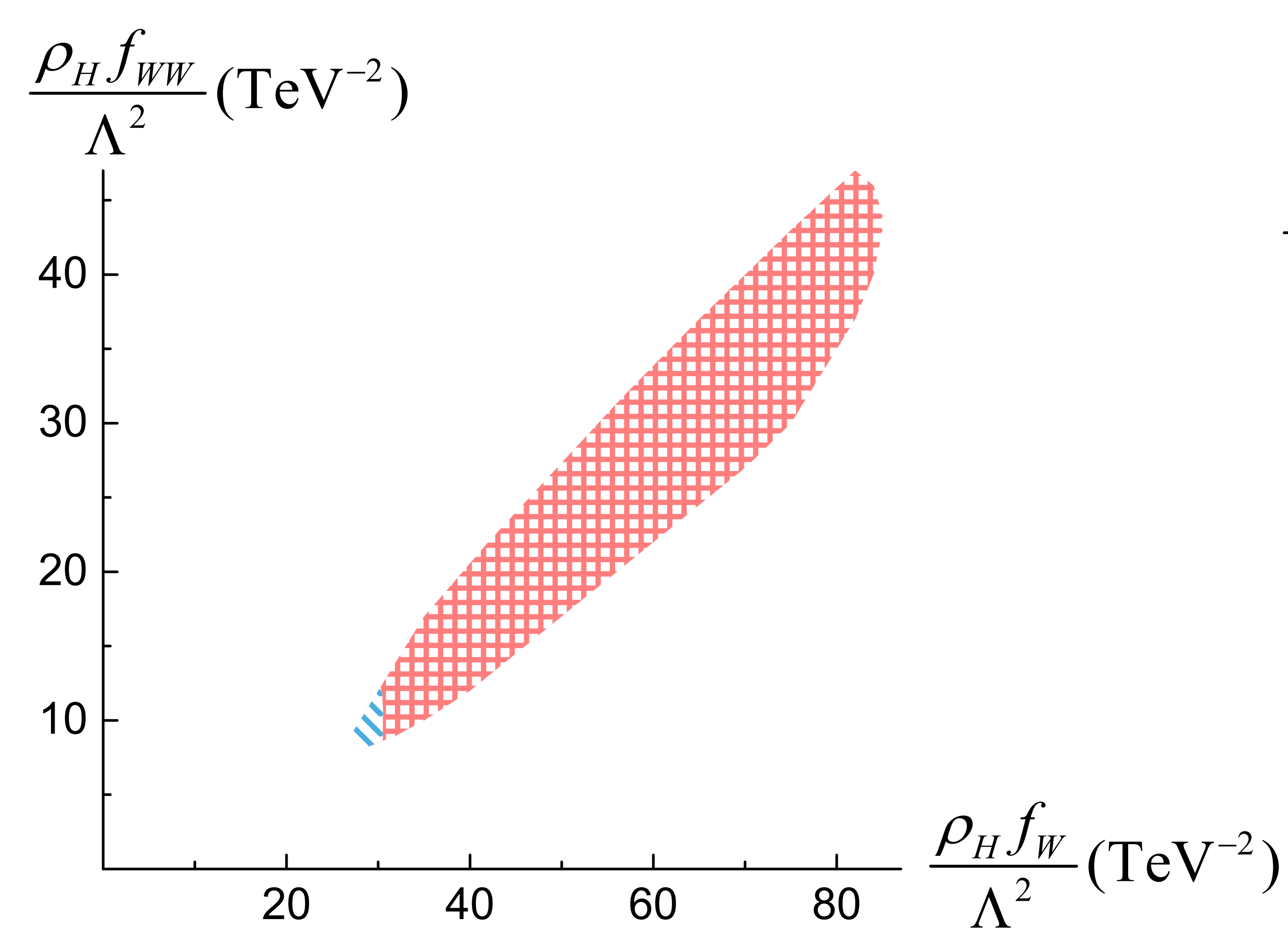


Figure (b) **500I**

$C_t = 1,\ \rho_h = 0.9,\ \rho_H = 0.4$

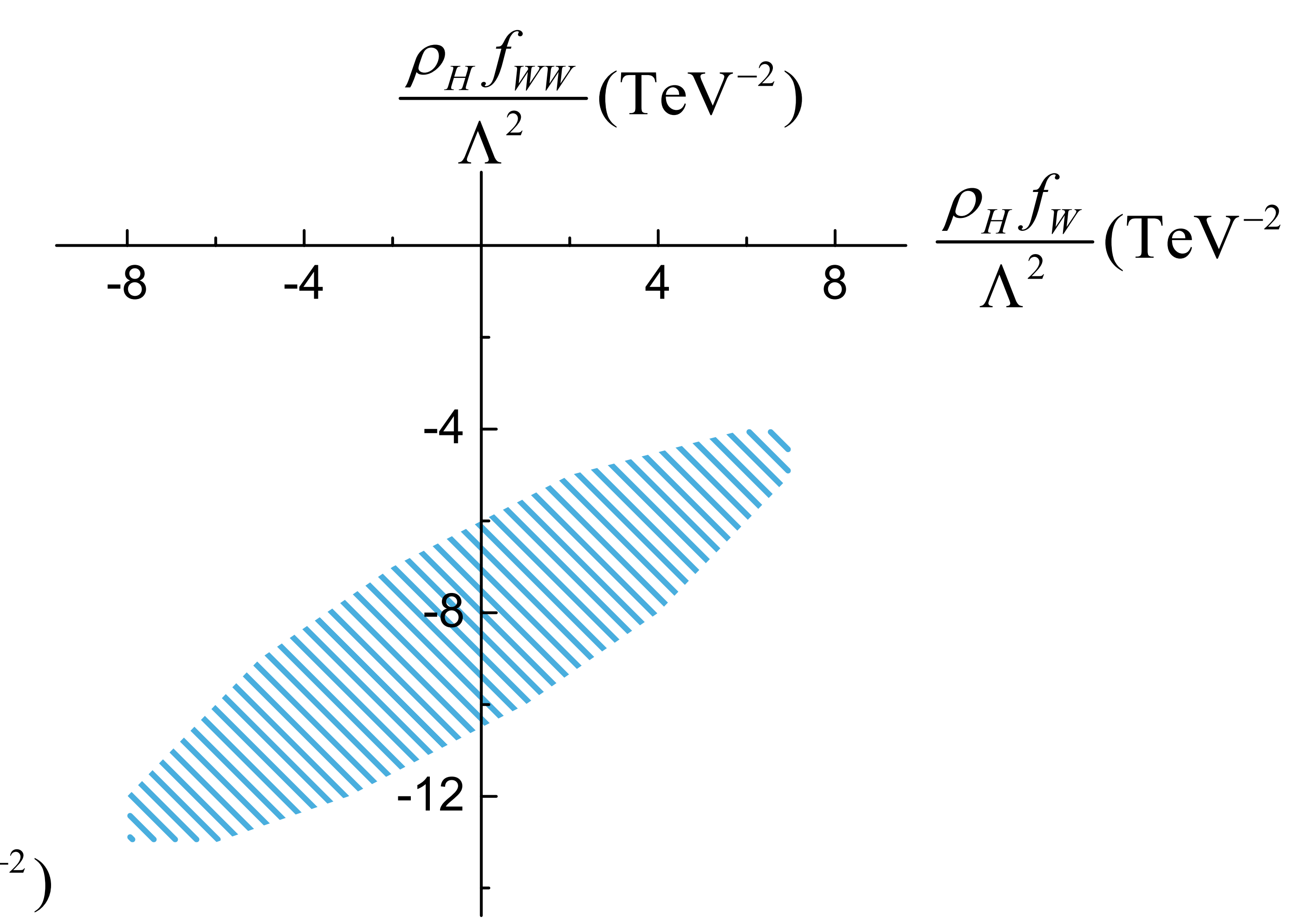


Figure (c) **500II**

$C_t = 0.6,\ \rho_h = 0.8,\ \rho_H = 0.6$

Probing Heavy Neutral Higgs Boson

Parameters and Statistacal method

As the Type-I 400GeV heavy Higgs can hardly avoid being excluded, so we take the five set of parameters as below to do simulation, according to the former analysis:

	M_H	C_t	ρ_h	ρ_H	$\rho_H f_W/\Lambda^2(\mathrm{TeV}^{-2})$	$\rho_H f_{WW}/\Lambda^2(\mathrm{TeV}^{-2})$
400II	400	0.5	0.9	0.4	14	0
500I	500	1	0.9	0.4	30	10
500II	500	0.6	0.8	0.6	6	-5
800I	800	1	0.8	0.6	6	-5
800II	800	0.2	0.9	0.25	6	-5

We take Poisson Distribution to determine the statistic significance σ_{stat} as below.

- ✓ **Signal and Background Cross Sections:**

  $\sigma_B \equiv \sigma(C_t = 1, \rho_h = 1, \rho_H = 0, f_W = 0, f_{WW} = 0)$, and $\sigma_S \equiv \sigma - \sigma_B$

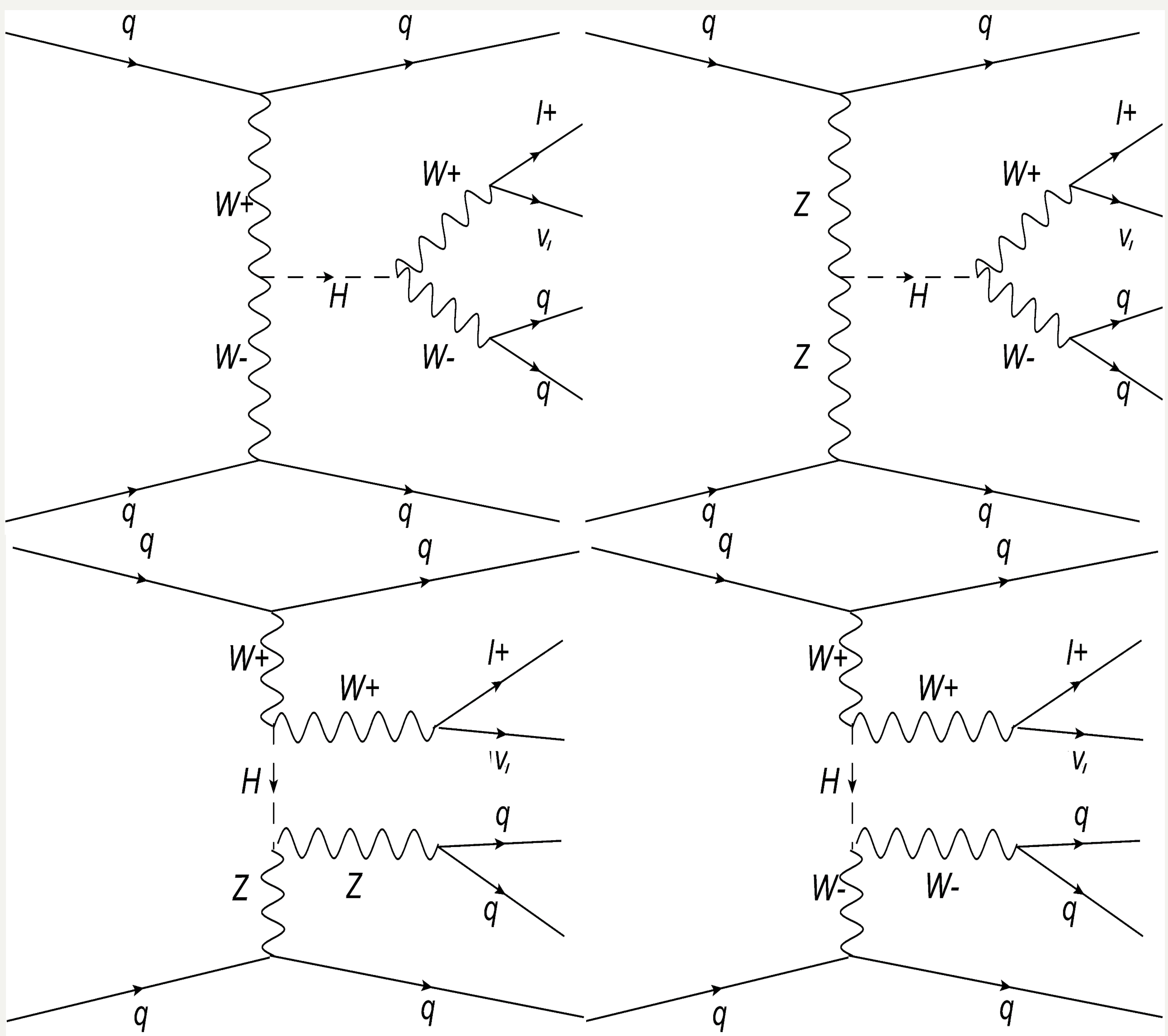
- ✓ **Statistical Significance Using Poisson Distribution:**

  $P_B = \sum_N e^{-N_B} \frac{N_B^N}{N!}$, with $N = N_S + N_B, N_S + N_B + 1, \cdots, \infty$

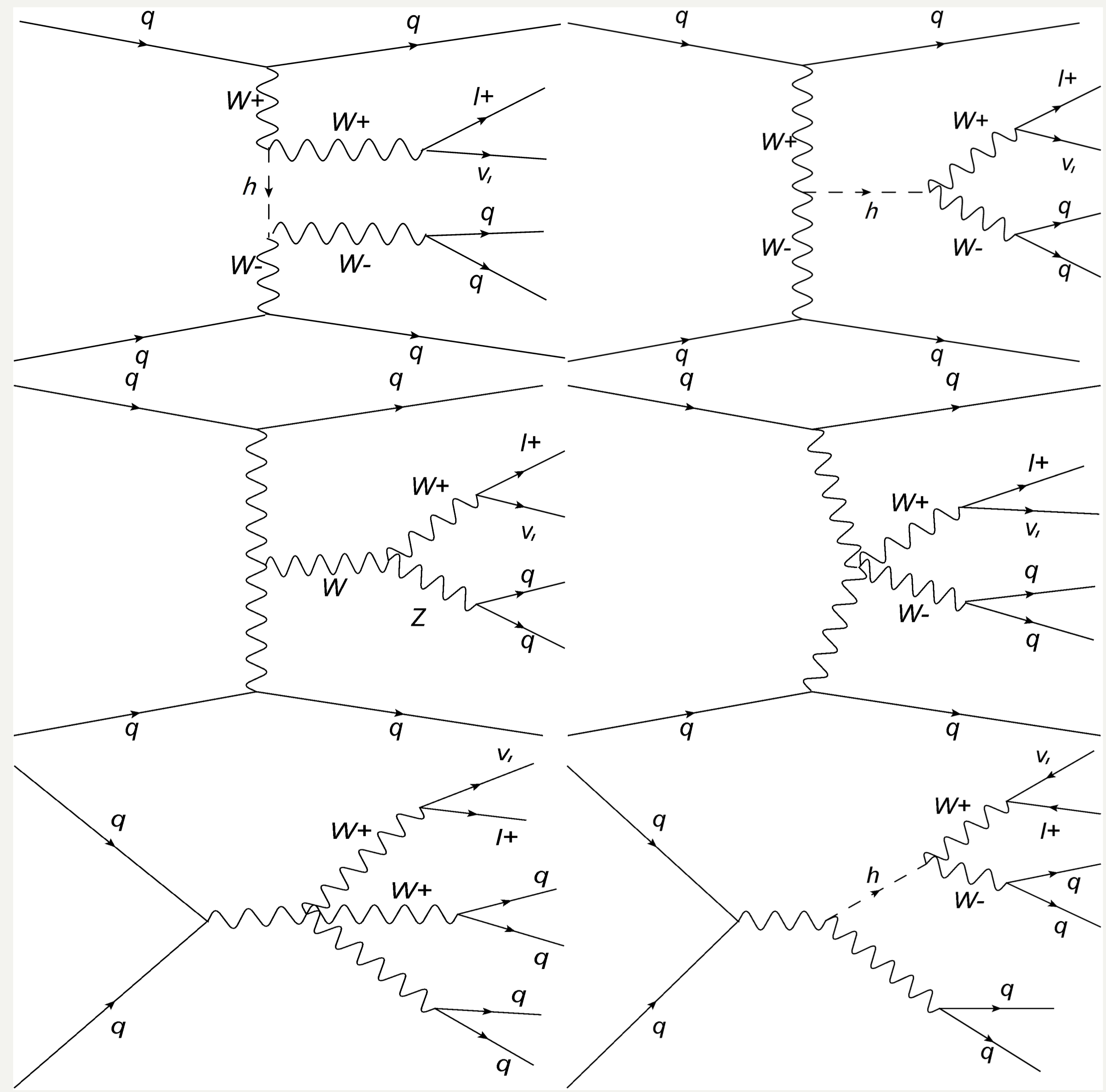
- ✓ **When N_B is sufficiently large, we can approximate σ_{stat} by:** $\boldsymbol{\sigma_{stat} = \frac{N_S}{\sqrt{N_B}}}$

Probing Heavy Neutral Higgs Boson via Weak-Boson Scattering: Signal & IB

Signal processes:
Weak-boson scattering with a s/t-channel heavy Higgs. A *W*+ decays leptonicly and the other weak boson decays to quarks in the final state.

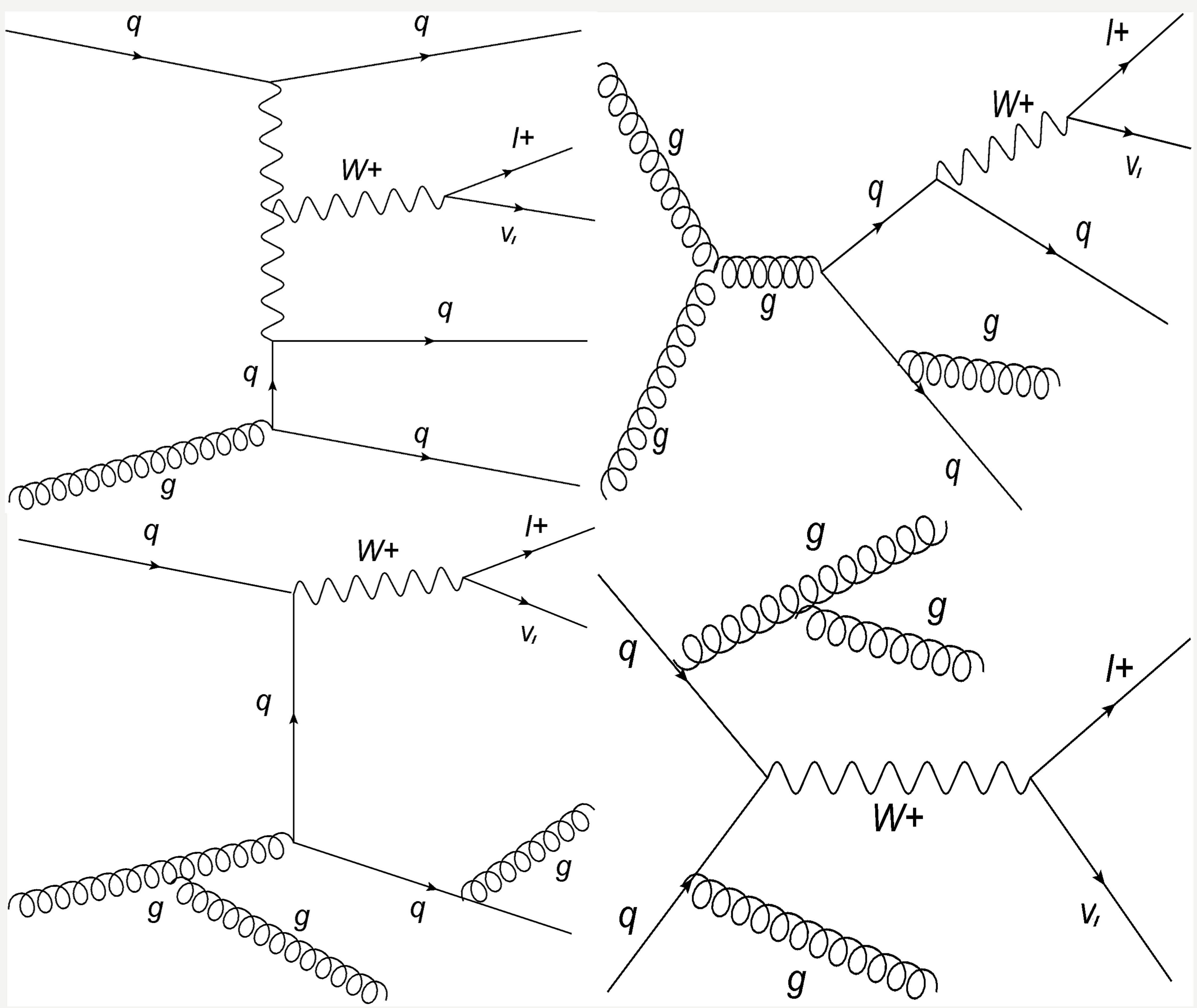


Typical irreducible background:
calculated together with signal processes.

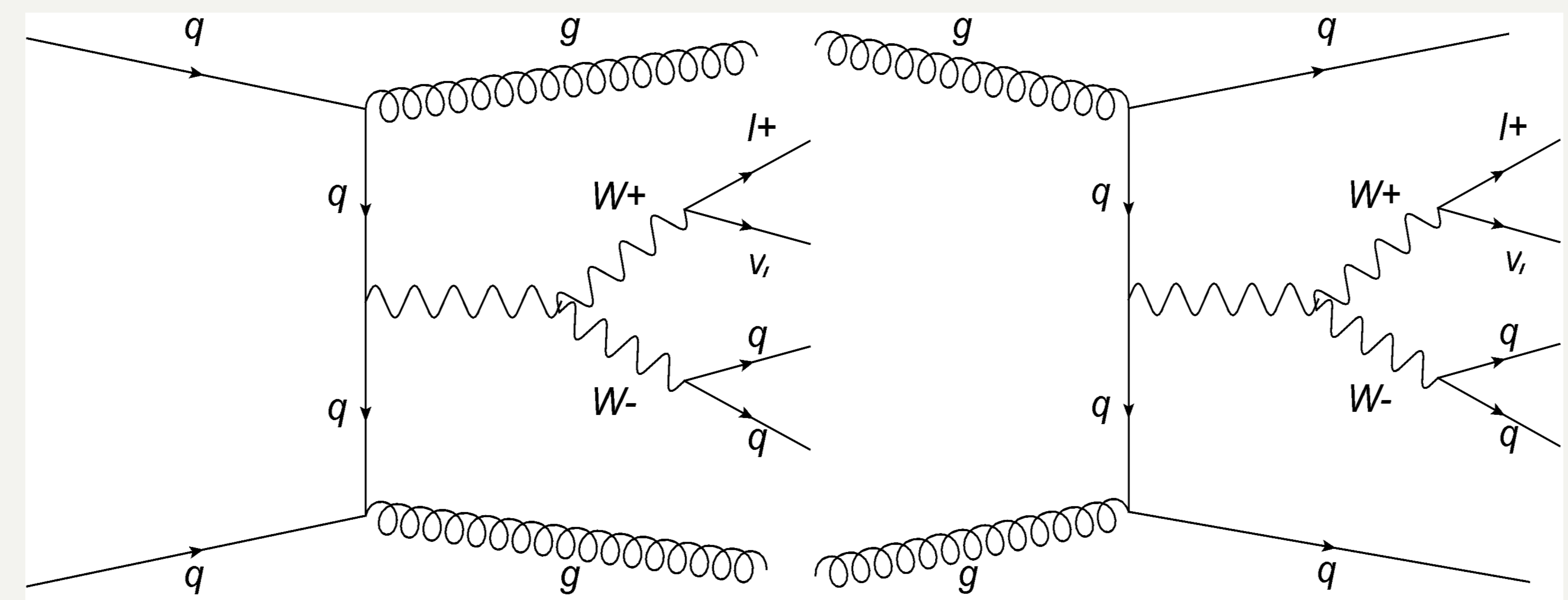


Probing Heavy Neutral Higgs Boson via Weak-Boson Scattering: RBs

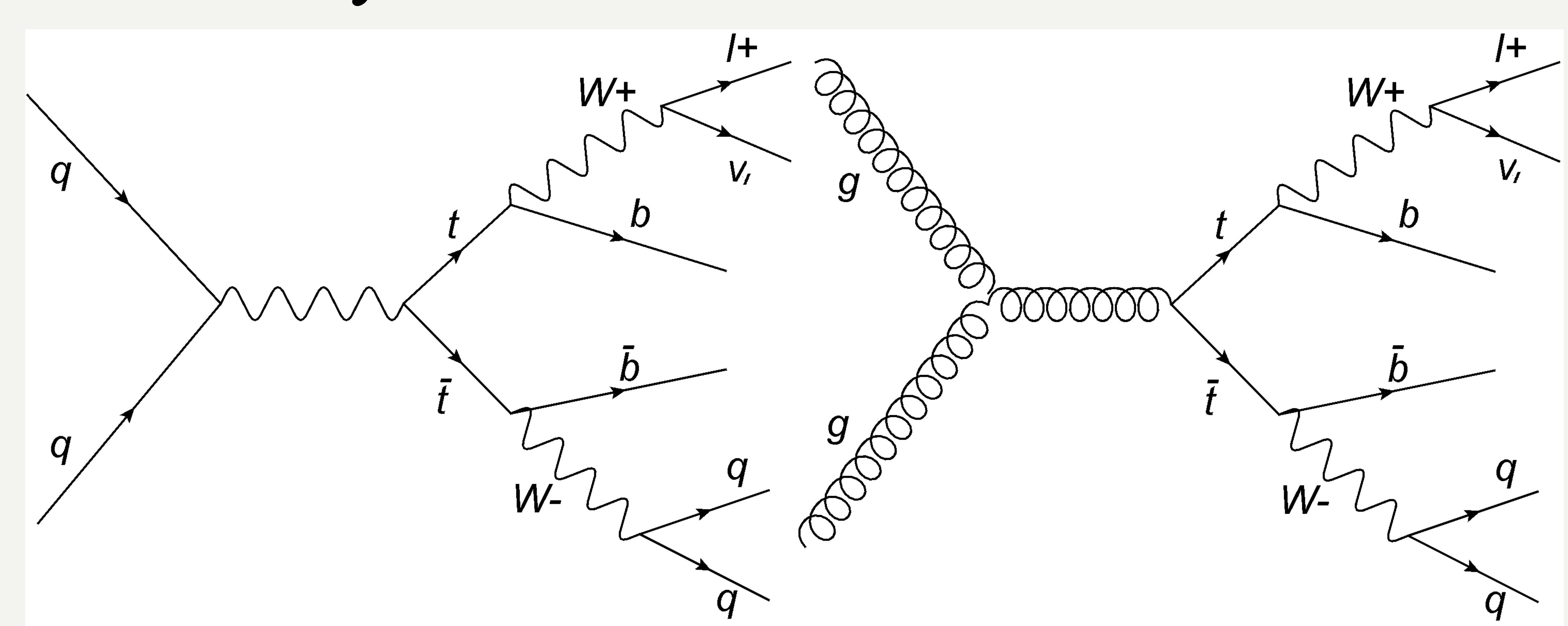
Typical *W+jjj* background:
match partons with jets up to the multiplicity of 3.



Typical QCD *WV+jj* background:
a *W+* decays leptonicly and a *V* decays to a fat jet



Typical Top quark background:
a top decays leptonicly and the other decays hadronicly



Probing Heavy Neutral Higgs Boson via Weak-Boson Scattering: MC & Cuts

Detector acceptance:

$|\eta| \leq 5$ and $p_T \geq 20$GeV for jets
$|\eta| \leq 2.5$ and $p_T \geq 10$GeV for electrons
$|\eta| \leq 2.4$ and $p_T \geq 10$GeV for muons

Jet algorithm:

anti-*kT* with *R=0.7*

Cut 1: lepton number cut

$N(l^+) = 1, N(l^-) = 0$ **and** $|\eta(l^+)| < 2$

Cut 2: p_T cut

$p_T(leptons) > 150GeV$

Cut 3: forward jet cut

$p_T(j^f) > 35GeV$ **and** $E(j^f) > 300GeV$

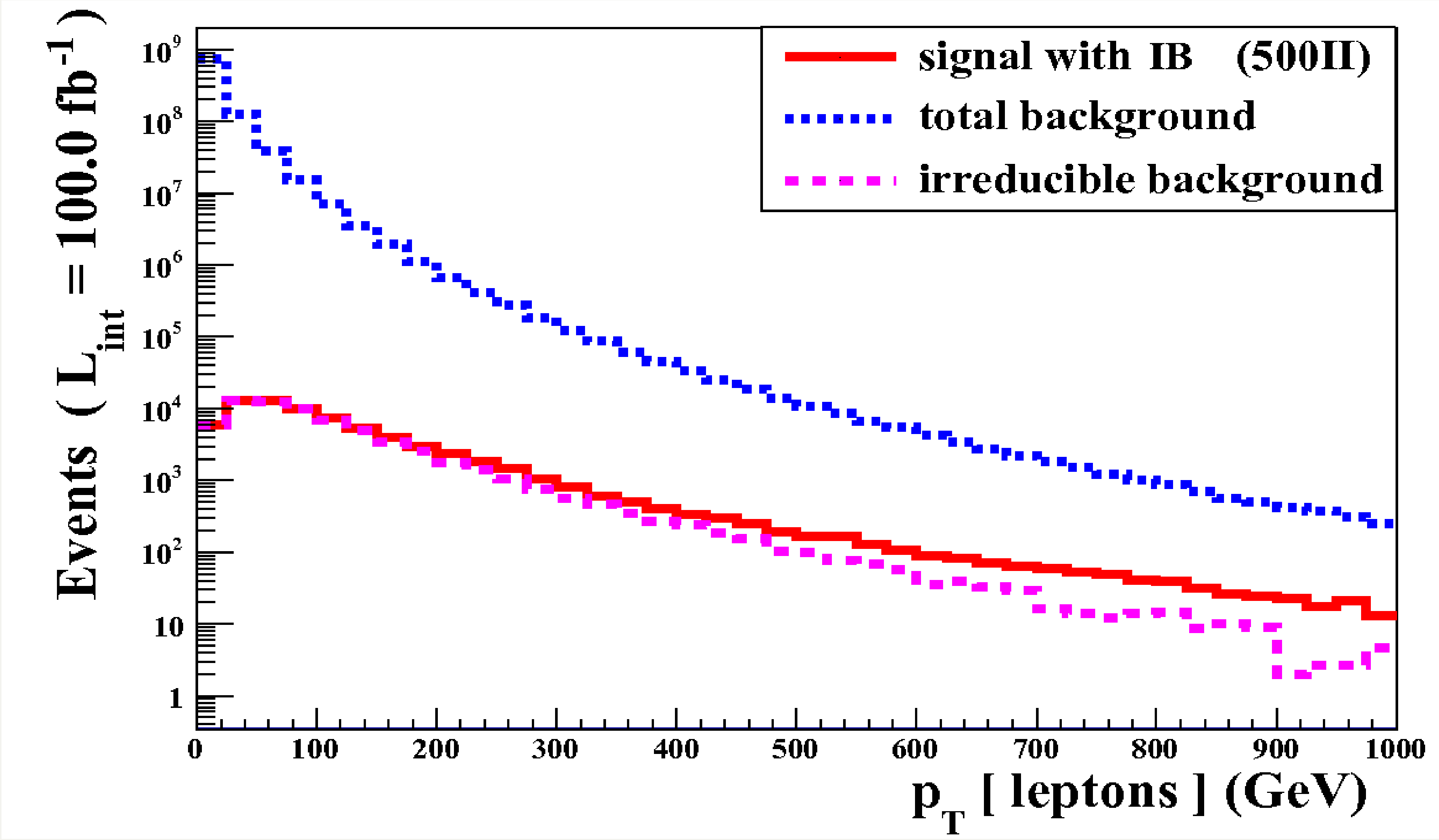
$2 < |\eta(j^f)| < 5$ **and** $\eta(j_1^f)\,\eta(j_2^f) < 0$

Cut 4: fat jet cut

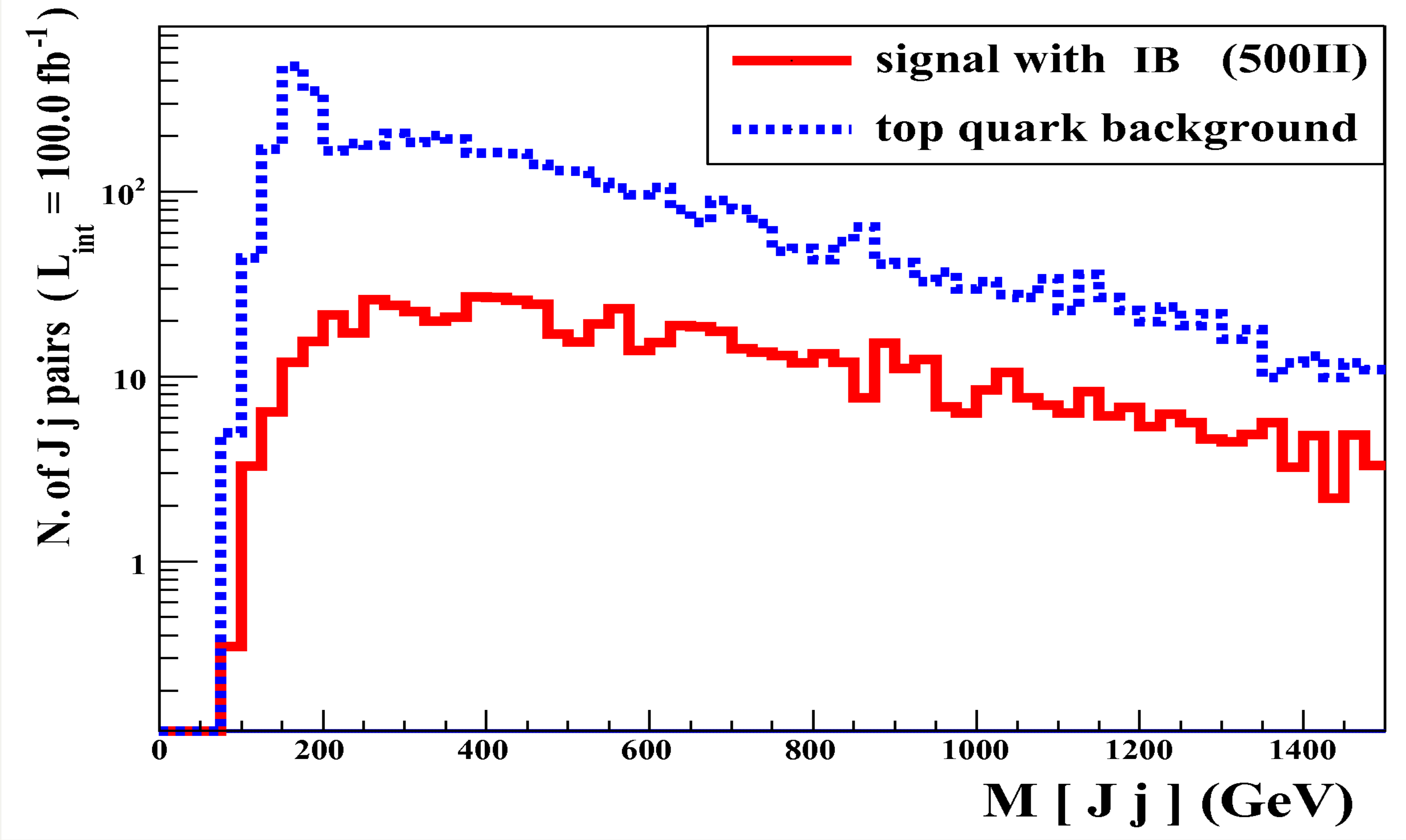
$70GeV < M(J) < 100GeV$ **and** $|\eta_J| < 2$

Cut 5: top quark veto

Reject events with *130GeV<M(J,j)<240GeV*



Plot after cut 1 for *pT* of leptons



Plot after cut 4 for invariant mass of the fat jet and any other jet

Probing Heavy Neutral Higgs Boson via Weak-Boson Scattering: Result

σ_{stat}	$L_{int}(fb^{-1})$ needed by a required significance				
	400I	**500I**	**500II**	**800I**	**800II**
1σ	32	34	3.9	12	5.7
3σ	288	307	35	110	52
3σ	800	852	96	306	143

- **500II and 800II:**

  hopeful to be discovered (at the 5σ level) in the first few years run of the 14 TeV LHC

- **800I:**

  can be discovered (at the 5σ level) for an integrated luminosity of 300fb^{-1} at the 14TeV LHC

- **400I and 500I:**

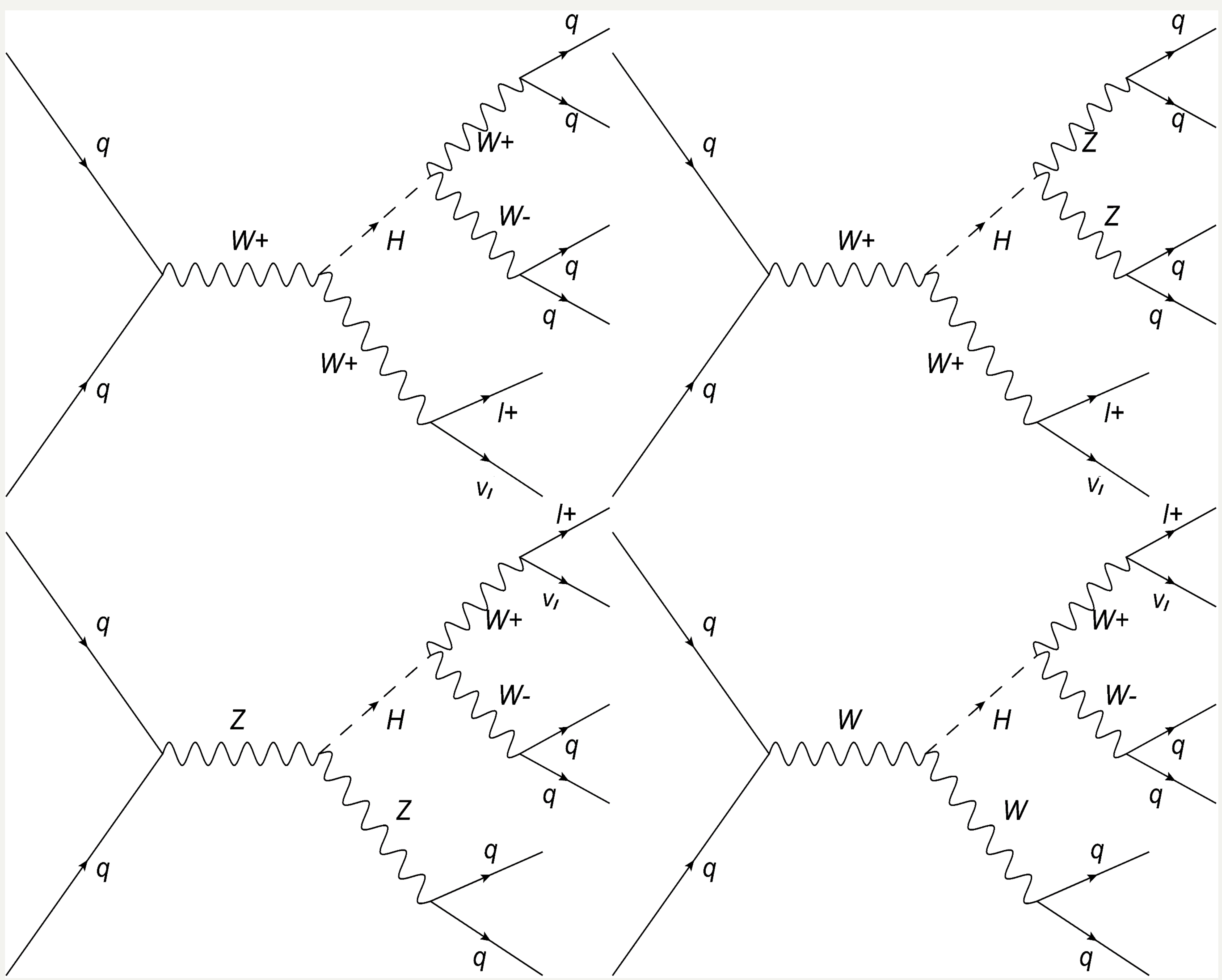
  can have evidences (at the 3σ level) for an integrated luminosity of 300fb^{-1} at the 14TeV LHC

Note:

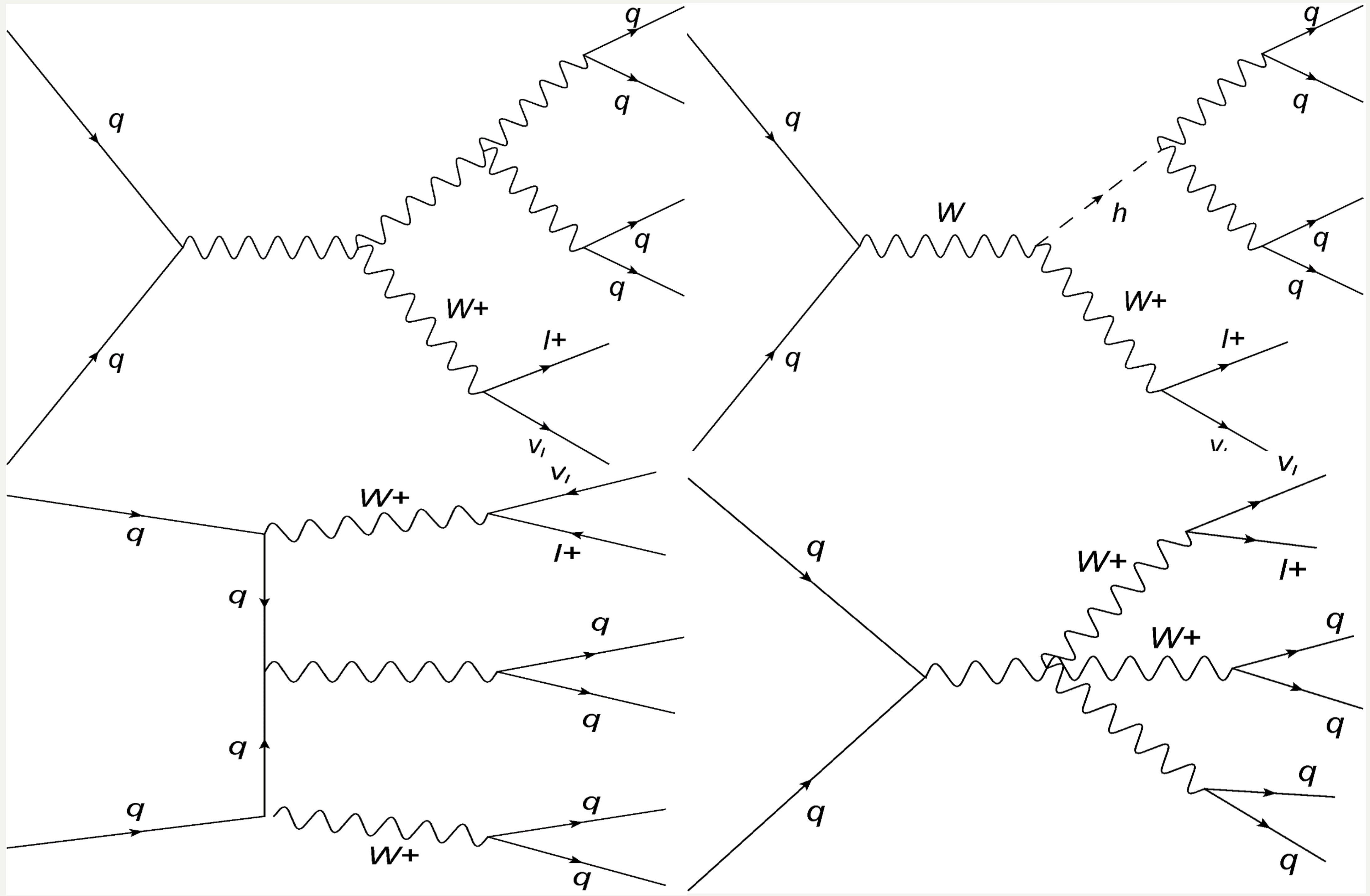
Since there is a missing neutrino in the final state, we have to search transverse mass distribution to measure the heavy Higgs mass. Unfortunately, a steep descent M_H can not be clearly seen.

Probing Heavy Neutral Higgs Boson via VH Associated Production: Signal, IB & RBs

Signal processes:
associated heavy Higgs production with the Higgs decays to weak bosons. The $W+$ decays leptonicly and the other two weak bosons decay to quarks.



Typical irreducible background:
calculated together with signal processes.



Reducible backgrounds:

- ✓ W + n-jet processes with $n \leq 3$
- ✓ $W + V$ + n-jet processes with $n \leq 2$
- ✓ Top-quark background

The diagrams are about the same with weak boson scattering.

Probing Heavy Neutral Higgs Boson via VH Associated Production: MC & cuts

Detector acceptance:

$|\eta| \leq 5$ and $p_T \geq 20$GeV for jets
$|\eta| \leq 2.5$ and $p_T \geq 10$GeV for electrons
$|\eta| \leq 2.4$ and $p_T \geq 10$GeV for muons

Jet algrithm:

anti-kT with R=0.7
J_1/J_2 **denotes the jet with the 1st/2nd largest** p_T

Cut 1: lepton p_T cut

$N(l^+) = 1, N(l^-) = 0$, $p_T(leptons) > 400GeV$

Cut 2: fat jet cut

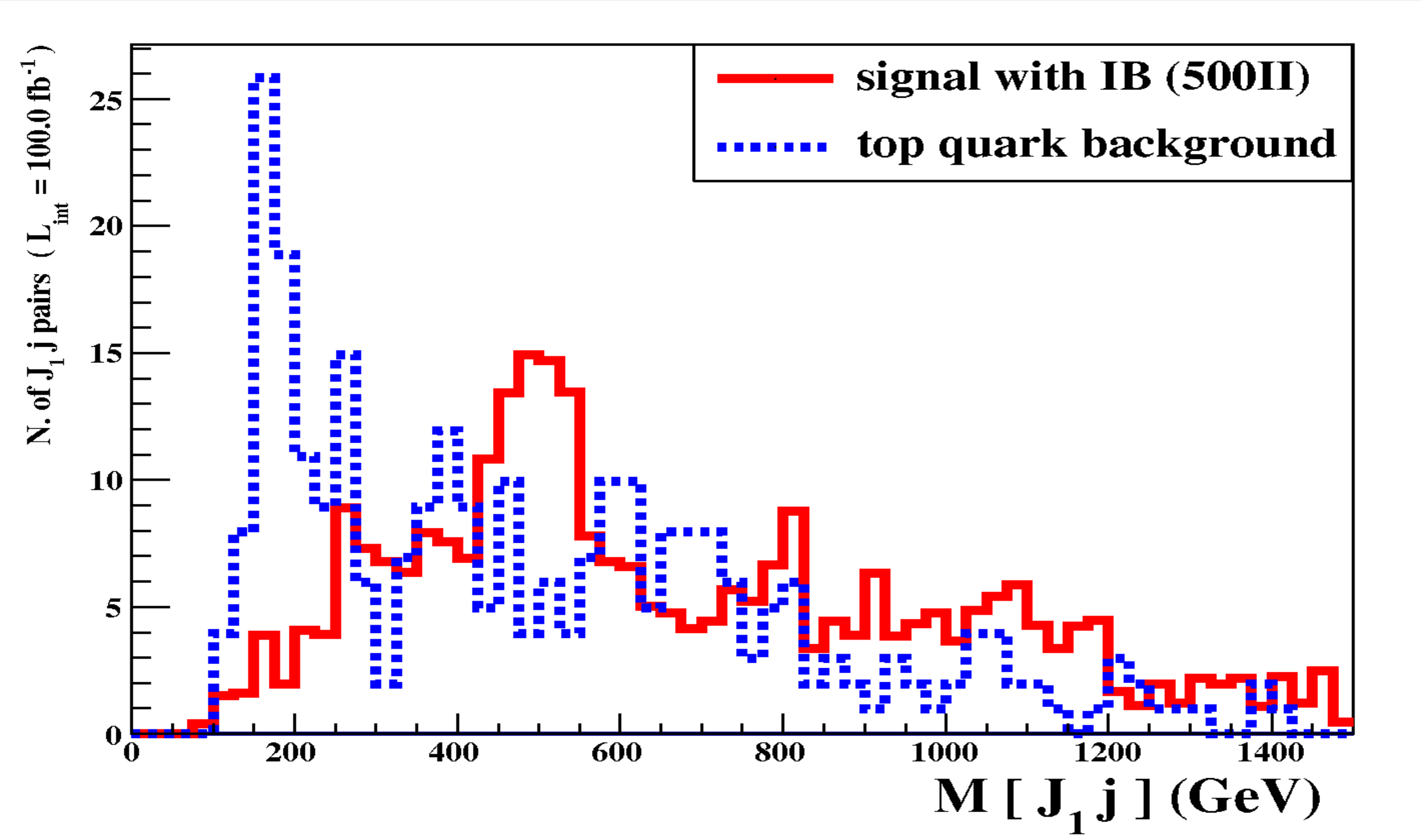
$70GeV < M(J_1) < 100GeV$
$70GeV < M(J_2) < 100GeV$

Cut 3: top quark veto

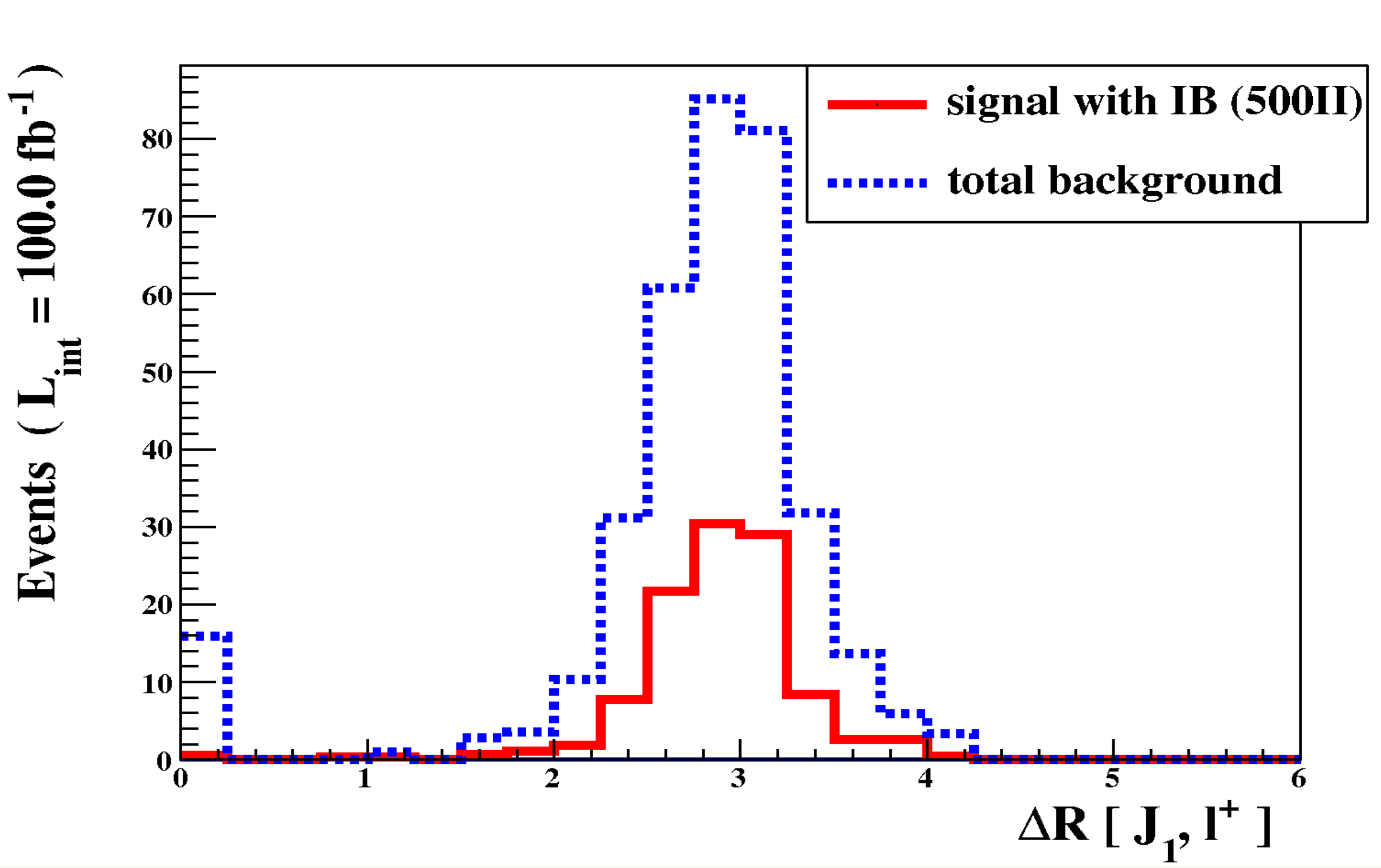
Reject events with $130GeV < M(J_1, j) < 240GeV$

Cut 4: ΔR cut

$\Delta R(J_1, l^+) > 2.5$ **and** $\Delta R(J_2, l^+) > 0.7$



Plot after cut 2 for invariant mass of the fat jet and any other jet



Plot after cut 3 for $\Delta R(J_1, l^+)$

Probing Heavy Neutral Higgs Boson via VH Associated Production: Cut efficiencies

Cut efficiencies for VH associated production are show below (in fb)

	data	Initial	Cut 1	Cut 2	Cut 3	Cut 4
σ_{S+IB}	400II	2085	46.9	2.78	2.32	2.04
	500I	2009	25.7	1.21	1.08	0.92
	500II	2037	54.4	4.36	3.79	3.11
	800II	1996	25.3	1.41	1.24	1.11
	800I	1917	18.6	0.63	0.53	0.43
σ_B	IB	1925	13.1	0.21	0.13	0.06
	w+njets	31500000	1422	2.91	2.15	1.39
	tt	92000	65.9	0.72	0.15	0.06
	wvjj	7600	47.9	0.34	0.25	0.18

Probing Heavy Neutral Higgs Boson via VH Associated Production: Result

The result for associated VH production

σ_{stat}	$L_{int}(fb^{-1})$ needed by a required significance				
	400I	**500I**	**500II**	**800I**	**800II**
1σ	0.43	0.18	2.3	13	1.6
3σ	3.9	1.6	21	115	14
3σ	10.8	4.5	57	319	39

- **400I 500I 500II 800II:**

  hopeful to be discovered (at the 5σ level) in the first few years run of the 14 TeV LHC

- **800I:**

  can be discovered (at the 5σ level) for an integrated luminosity of $300fb^{-1}$ at the 14TeV LHC

Probing Heavy Neutral Higgs Boson

Comparison of the two detecting methods

For associated VH production

σ_{stat}	$L_{int}(fb^{-1})$ needed by a required significance				
	400I	500I	500II	800I	800II
1σ	0.43	0.18	2.3	13	1.6
3σ	3.9	1.6	21	115	14
3σ	10.8	4.5	57	319	39

For weak boson scattering

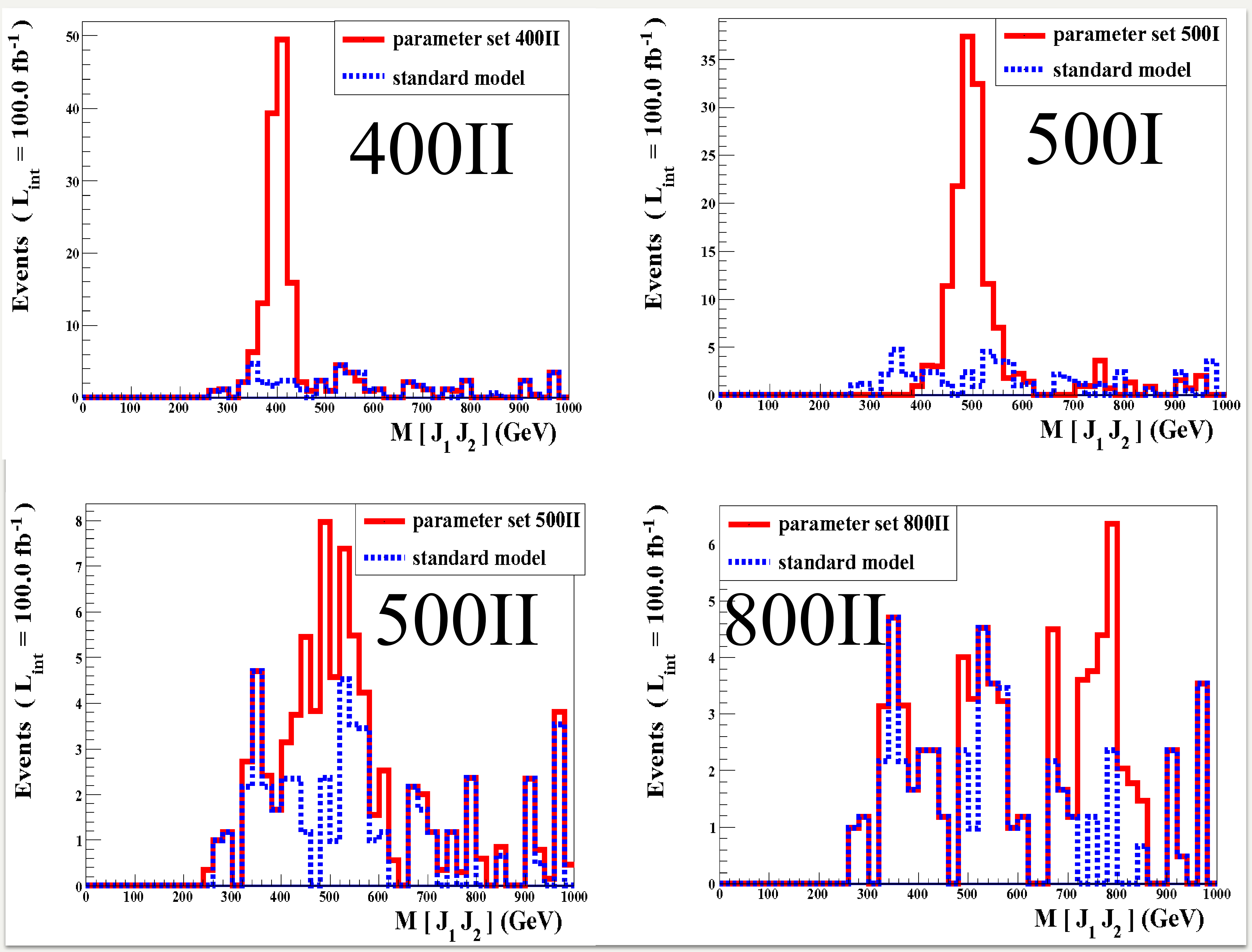
σ_{stat}	$L_{int}(fb^{-1})$ needed by a required significance				
	400I	500I	500II	800I	800II
1σ	32	34	3.9	12	5.7
3σ	288	307	35	110	52
3σ	800	852	96	306	143

Determining the parameters

Measuring the mass of heavy Higgs

If H is there, how can we find its mass?

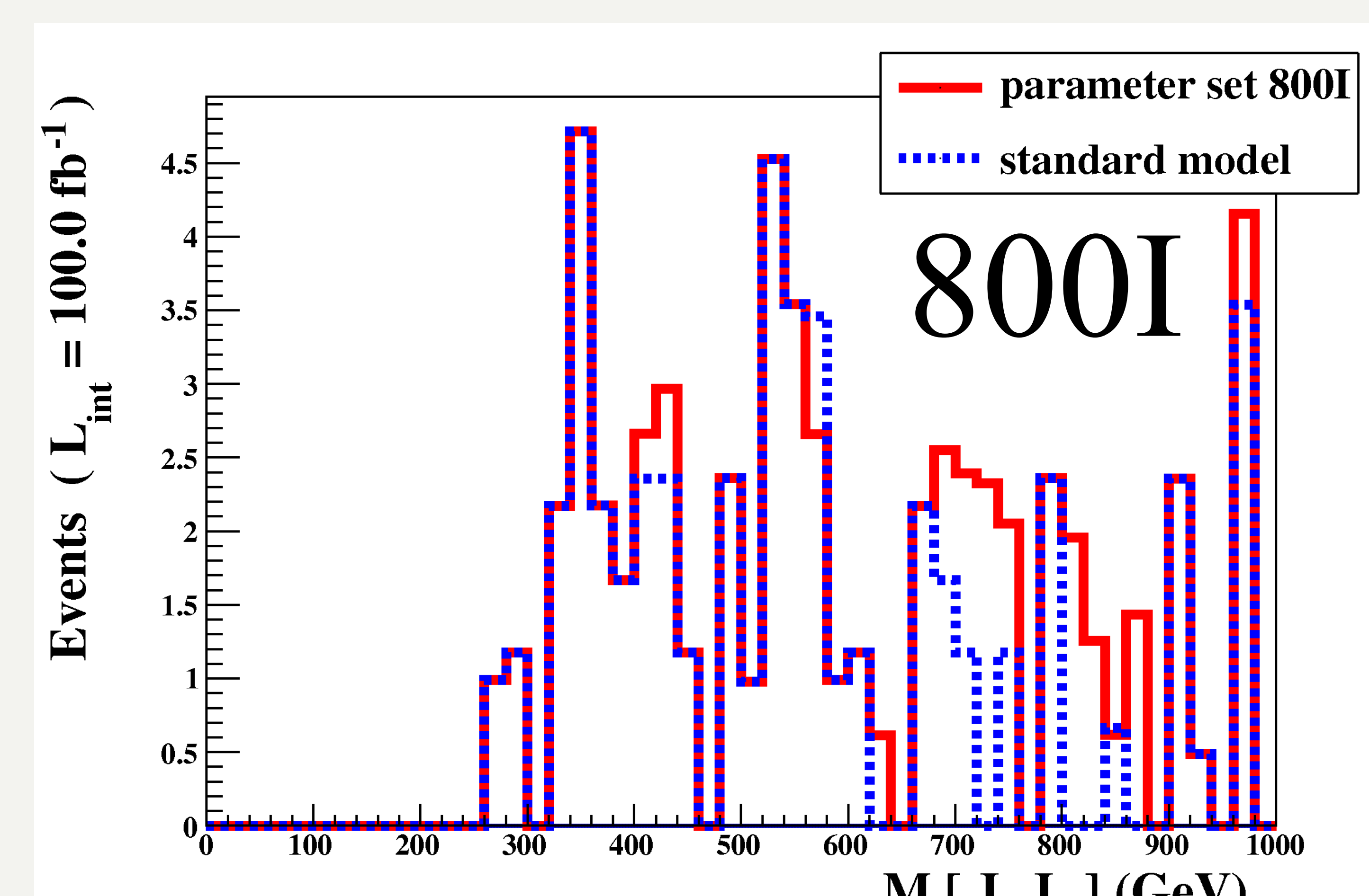
- ✓ **Weak boson scattering: No!** There is missing energy and M_T does not has a significant signature.
- ✓ **VH associated production: Yes!** But just in the case H decays to two fat jets and the width of H should not be too large.

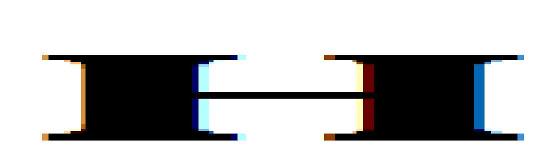


We apply a cut in addition:

$$\Delta R(J_2, l^+) > 2.5$$

Then both J_1 and J_2 will mainly come from the decay of H.



 is too fat!

Determining the parameters

Measuring the Anomalous Coupling Constants

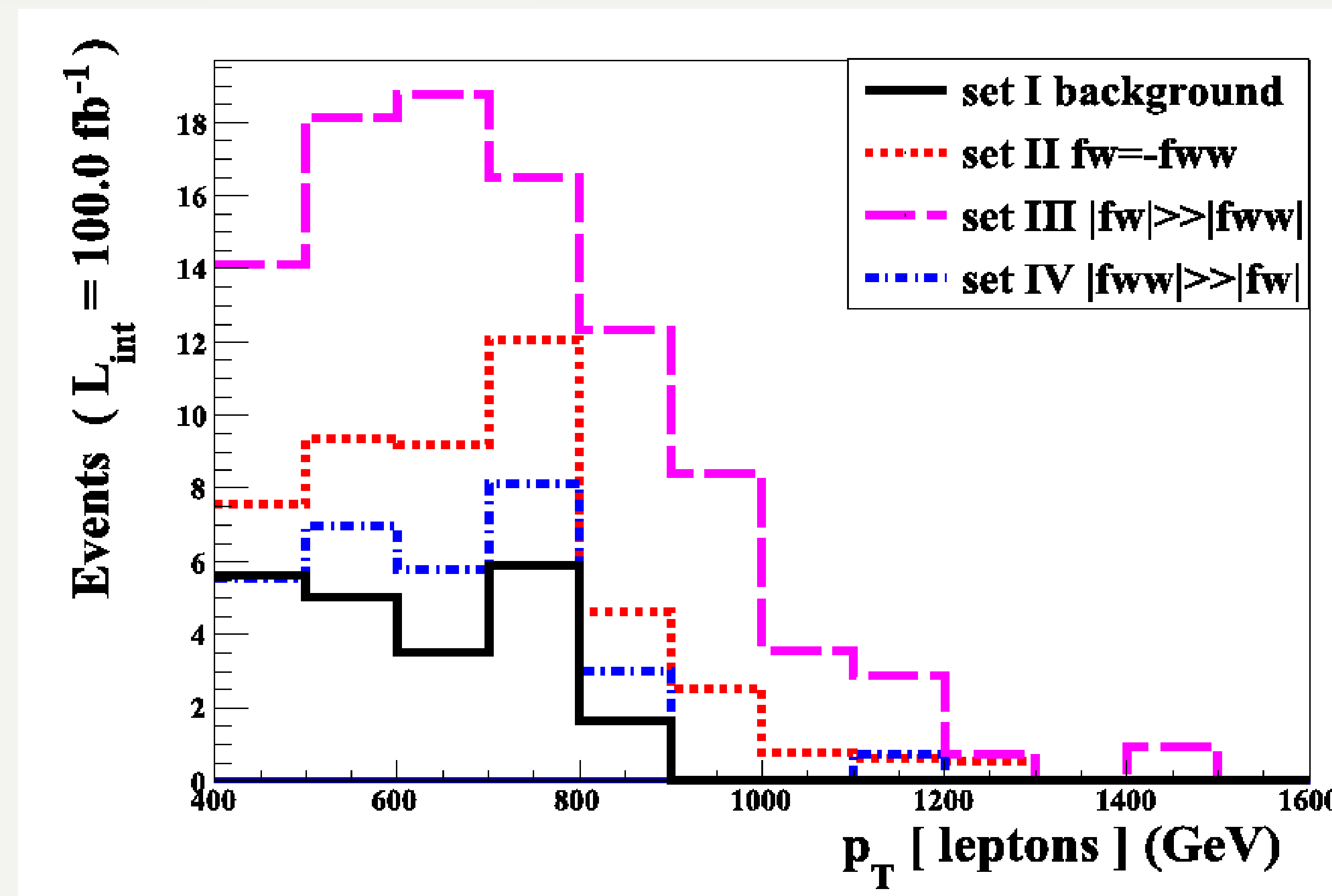
If we can measure the anomalous coupling constants f_W and f_{WW}, it will serve as **a new high energy criterion for new physics models**: Surviving physics models must predict f_W and f_{WW} consistent with the measured values.

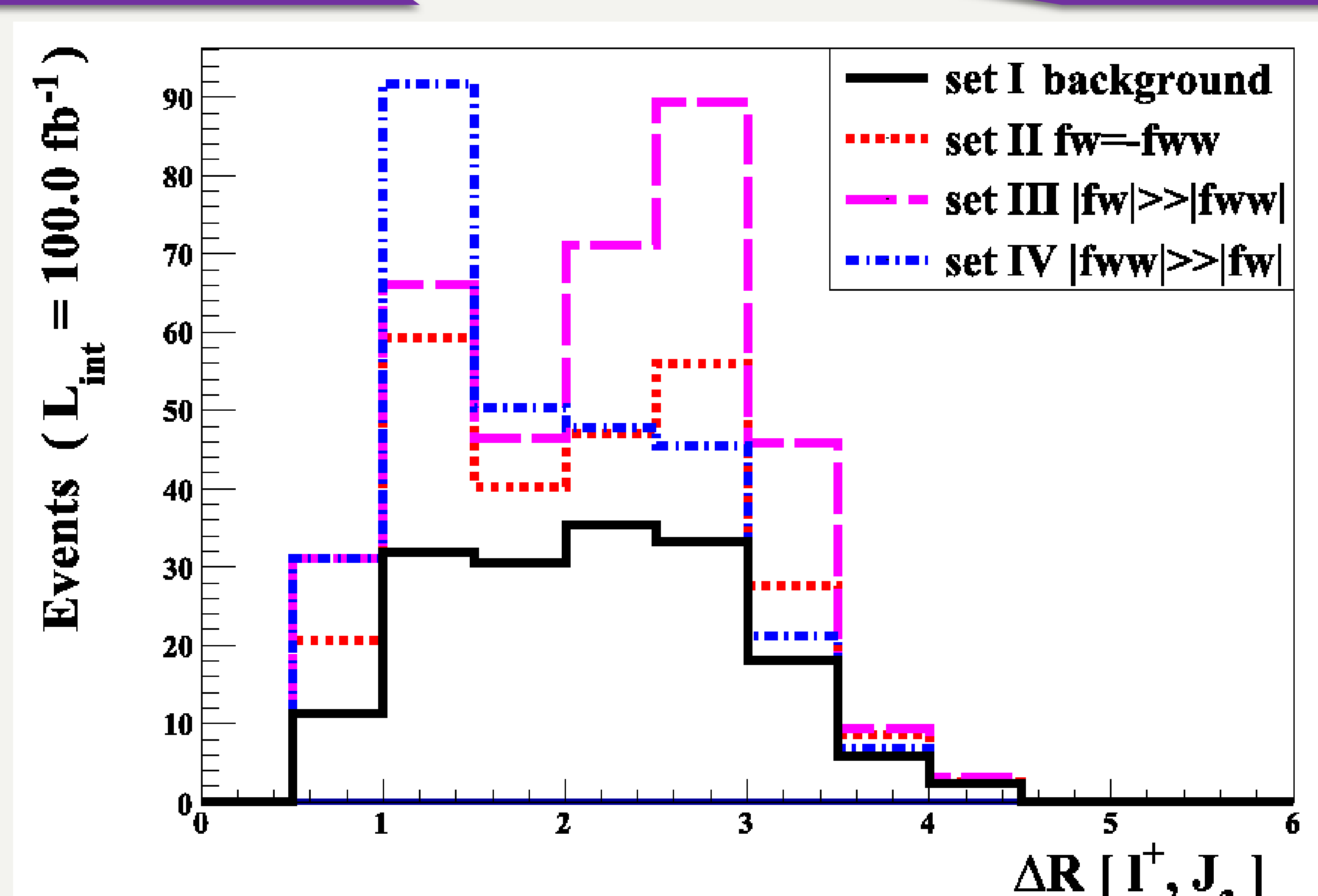
Plotted after we observe the resonance peak and select the events in the resonance peak.

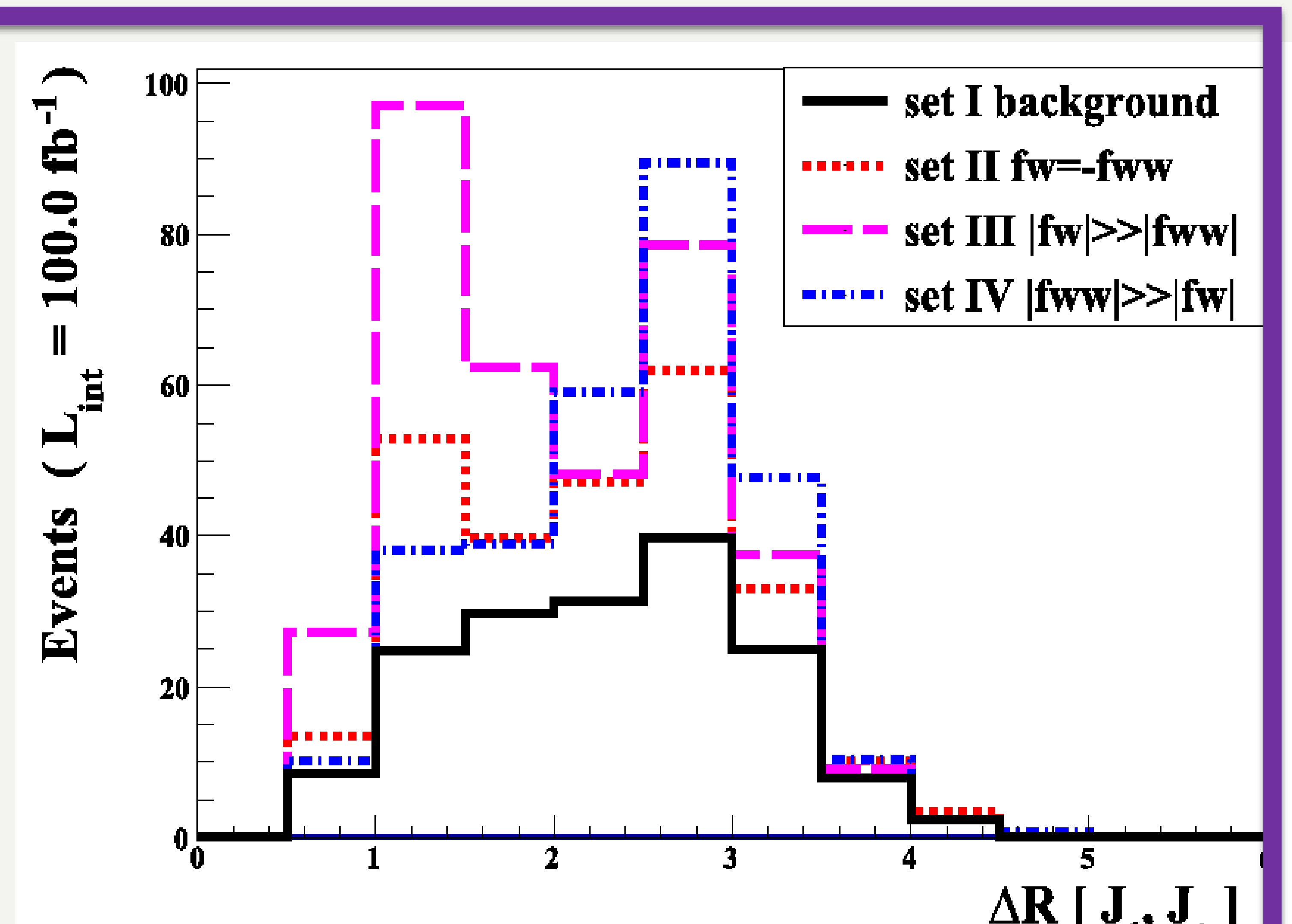
Now we try to distinguish the four parameter sets of f_W and f_{WW} listed here.

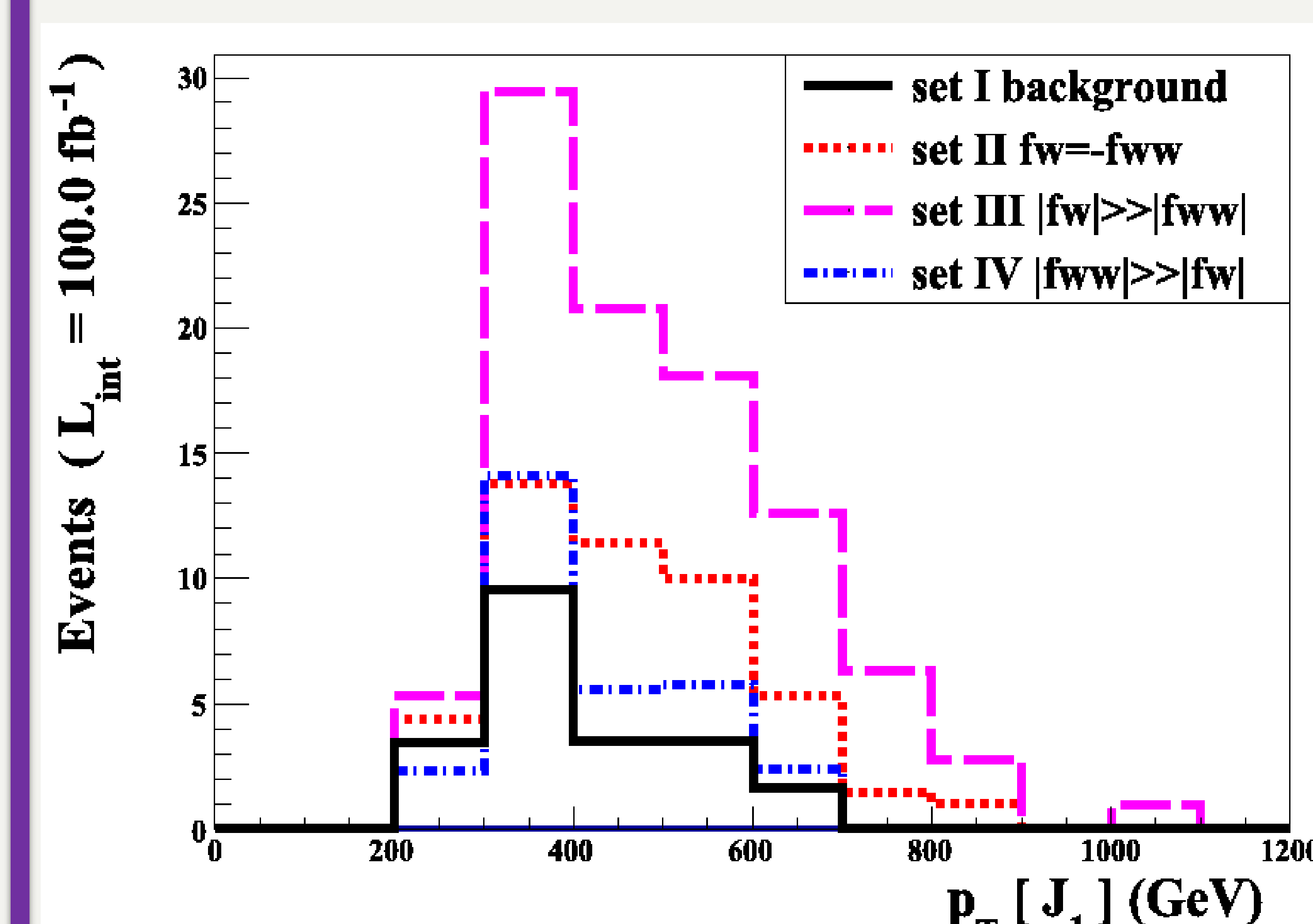
set	M_H	C_t	ρ_h	ρ_H	f_W	f_{WW}
I	500	1	0.8	0	0	0
II	500	0.6	0.8	0.6	6	-6
III	500	0.6	0.8	0.6	12	0
IV	500	0.6	0.8	0.6	0	12

Plotted just after cut 4, before we know the mass of H









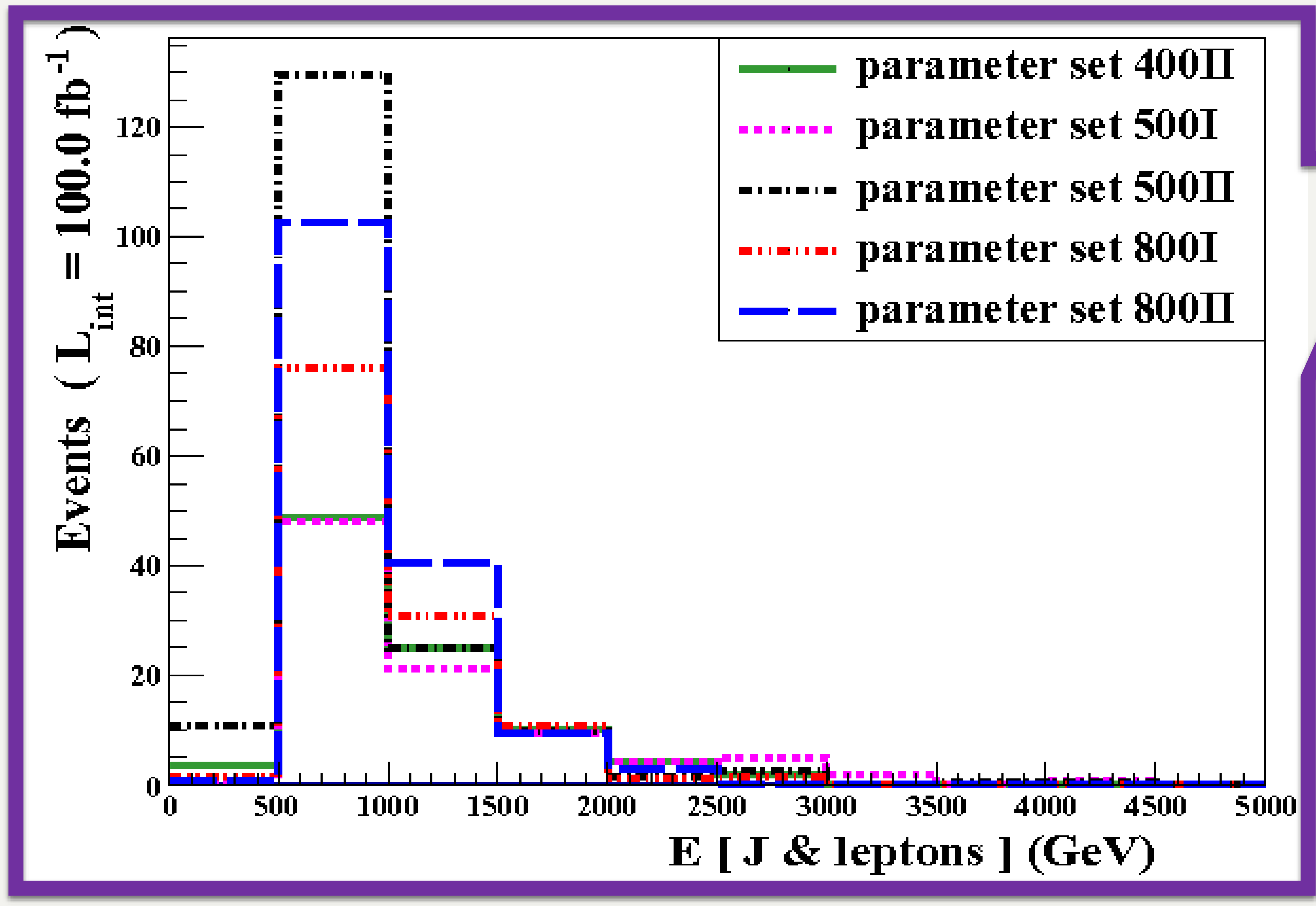
Summary

- To search for new physics beyond SM, we suggest to search for **heavy neutral Higgs bosons** which are generally contained in new physics models.
- We identify the lightest mass eigenstate h as the recently discovered ~125GeV Higgs, and study model independently the properties of the fermion and gauge couplings of both h and a heavier neutral Higgs boson H, based on the effective Lagrangian up to dim-6 operators.
- We estimate the constraints of the anomalous couplings constants according to the unitarity requirement and the 95%CL upper limits of LHC experiments.
- We propose VV scattering and associated VH production as two processes to detect H, both of which are semi-leptonic. We gave the Monte Carlo results and found that the **associated VH production is more sensitive**.
- For VH associated production, we can determine Higgs mass through the resonance peak of $M(J_1, J_2)$ for parameter set 400I, 500I, 500II and 800II.
- Finally We constructed four observables to measure the anomalous coupling constants and proposed a new high energy criterion for new physics models.

Thanks for your attention!

Checking the unitary

The plot for center of mass energy distribution



Weak boson scattering:
The center of mass energy for the two weak bosons

VH production:
The energy for events in which H decays to a fat jet and two leptons.

VH production:
The energy for events in which H decays to two fat jets.