Precision measurement at the LHC

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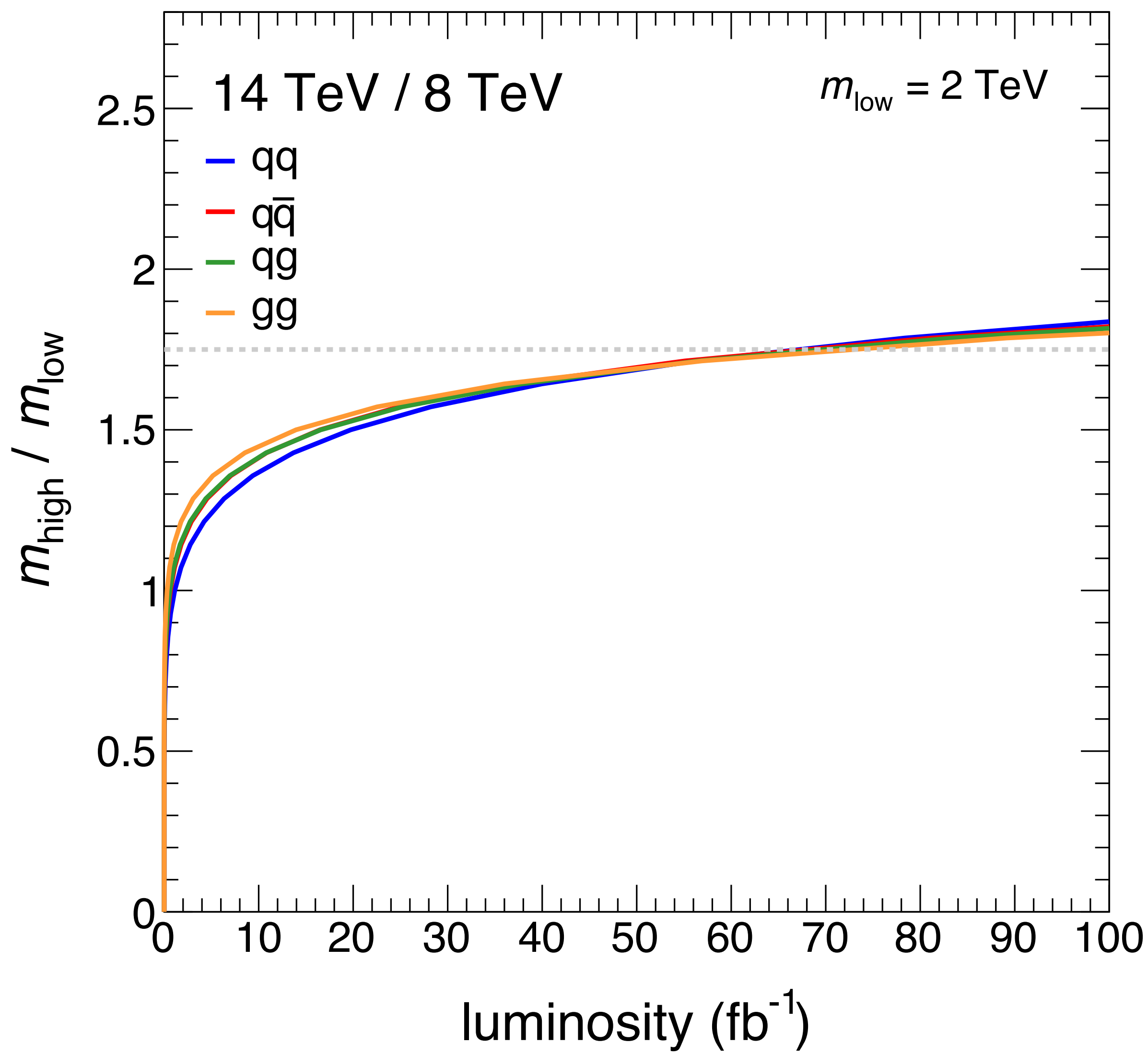
Why we do precision measurement at the LHC?

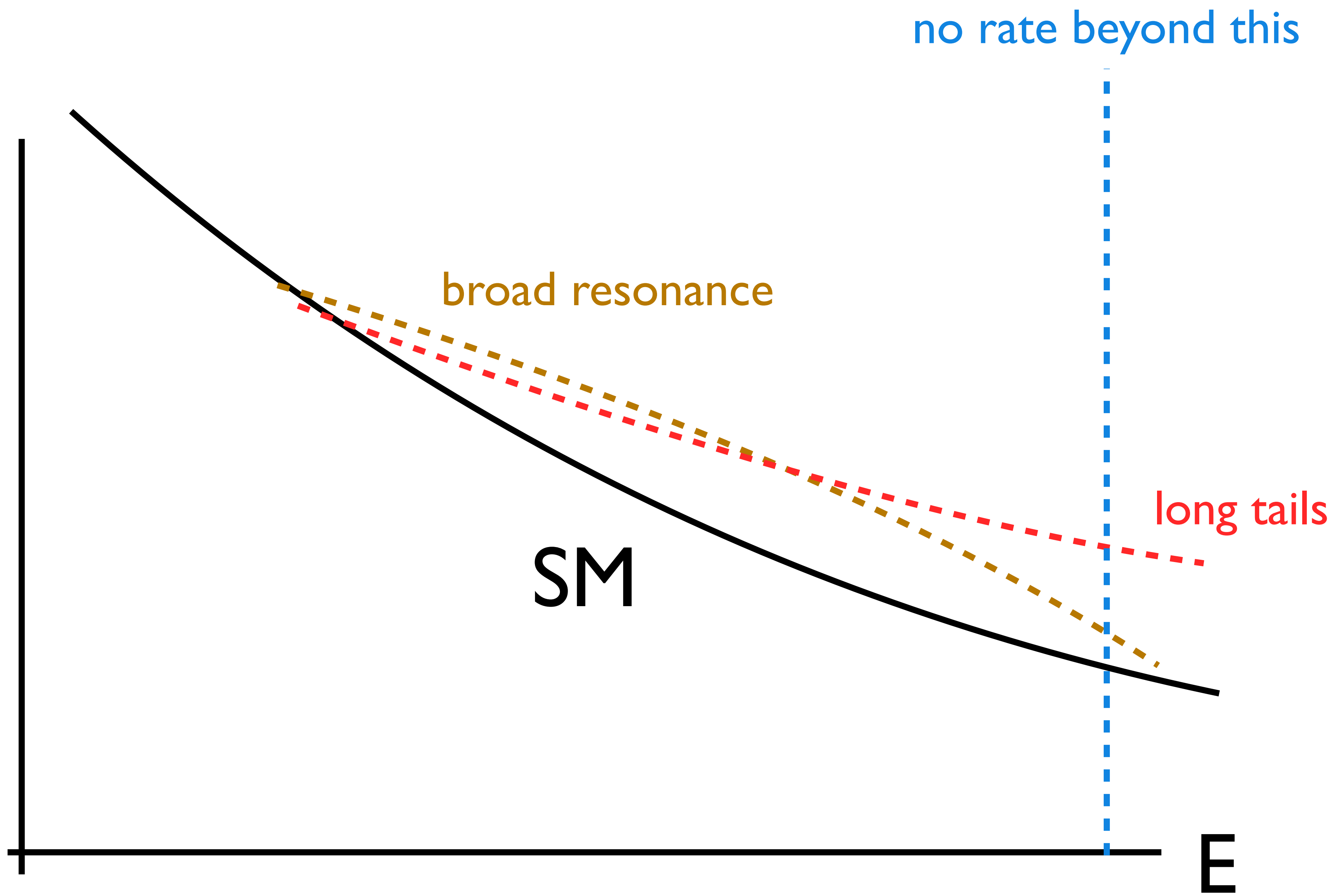
Naive scaling of the reach assuming the same number of signal events:



From Lian-Tao

We have reached the slow phase for the resonance searches!

Why we do precision measurement at the LHC?



From Lian-Tao

New physics may only show its tails at the LHC!

Why we do precision measurement at the LHC?

Compared with LEP, we have more energy and

Energy helps precision!

To reach the mass scale $\Lambda \sim 2$ TeV:

$$\text{LEP}: \quad \frac{\delta\sigma}{\sigma_{SM}} \sim \frac{m_Z^2}{\Lambda^2} \sim 2.1 \times 10^{-3}$$

$$\text{LHC}: \quad \frac{\delta\sigma}{\sigma_{SM}} \sim \frac{E_c^2}{\Lambda^2} \sim 0.25, \qquad E_c \sim 1\,\text{TeV}$$

The high energy at the LHC overcome its low statistics (mainly due to systematics and reducible backgrounds)

See also Farina, Ruderman, Panico, Pappadopulo, Torre, Wulzer

Which energy bin has the most sensitivity?

$$n_\sigma = \sqrt{n_b + (\Delta \times n_b)^2}, \qquad n_s = n_b \left(\frac{E_c}{\Lambda}\right)^p$$

The 1-sigma reach on Λ :

$$n_s = n_\sigma \Rightarrow \Lambda = E_c \times n_b^{\frac{1}{2p}}$$

$$n_b(E_c) = \delta E_c \times \frac{dL_{f\bar{f}}}{dE_c} \times \hat{\sigma}_{f\bar{f}}^{SM}(E_c^2)$$

$$\hat{\sigma}_{f\bar{f}}^{SM}(E_c^2) \sim \frac{1}{E_c^2}, \qquad \frac{dL_{f\bar{f}}}{dE_c} \sim \frac{1}{E_c^{n_L}}$$

Then, we have:

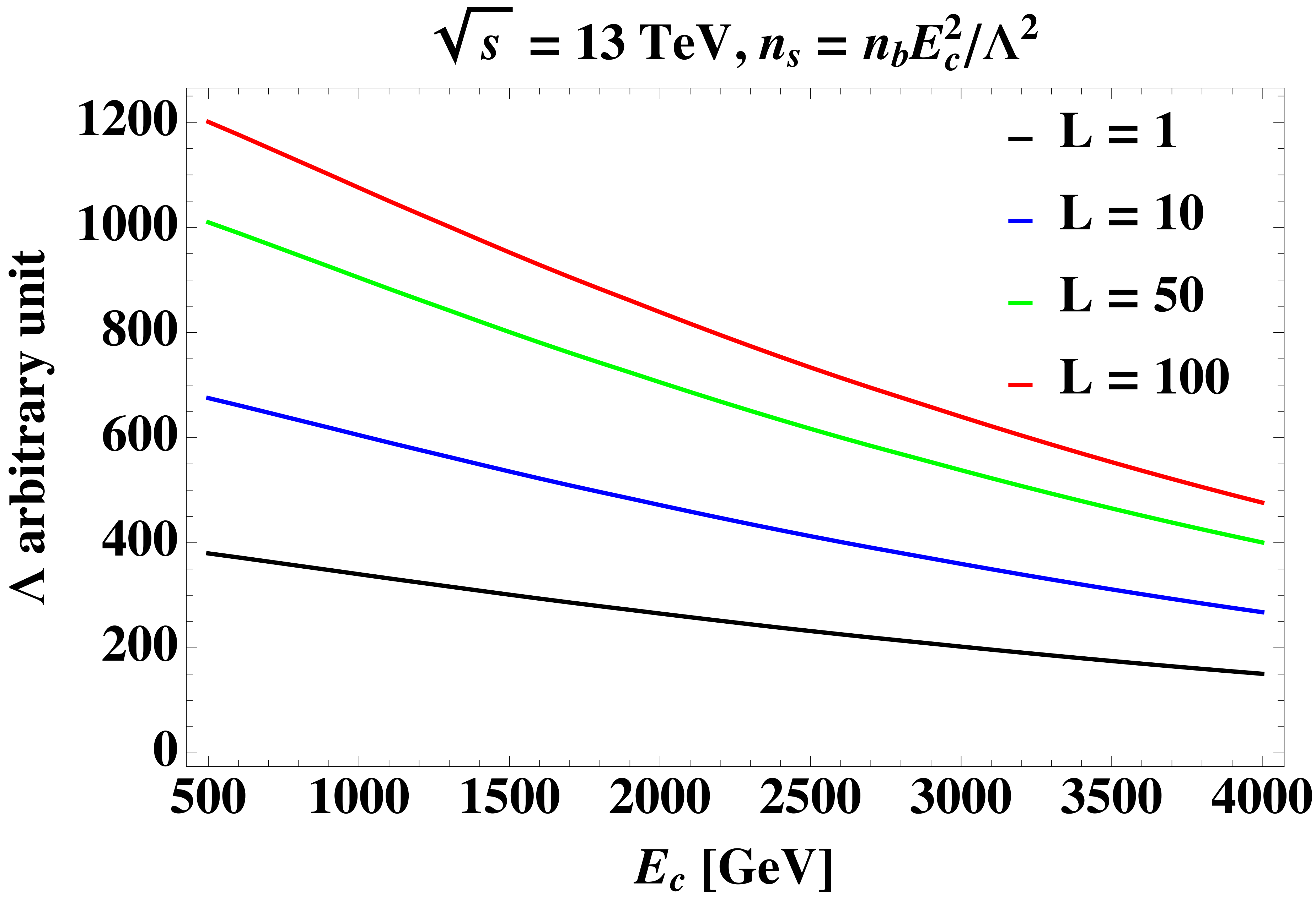
$$\Lambda \sim E_c^{1-\frac{n_L+2}{2p}}$$

Which energy bin has the most sensitivity?

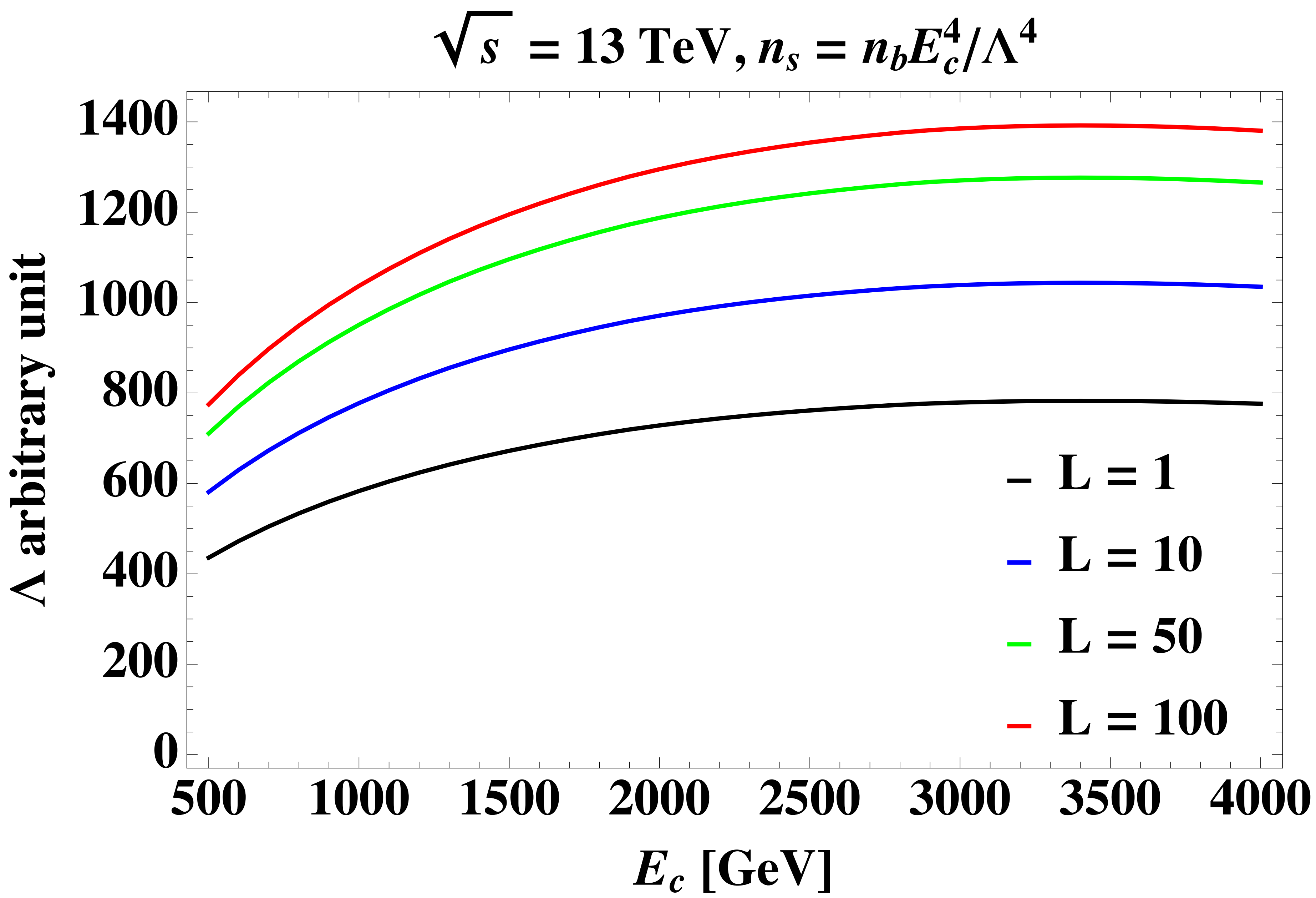
$$\Lambda \sim E_c^{1-\frac{n_L+2}{2p}}, \qquad n_L \sim 4-5$$

- For dimension-six, p = 2, the low energy bin has the sensitivity.
- For dimension-eight, p = 4, the highest bin has the sensitivity.
- But the systematic will change the whole picture! It crucially depends on the exact number of events and thus process-dependent!

Which energy bin has the most sensitivity?



Which energy bin has the most sensitivity?



Effective Operators

The model-independent way to capture the new physics effects below the cut-off:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{i\in 6} \frac{c_i}{\Lambda^2}\mathcal{O}_i + + \sum_{i\in 8} \frac{c_i}{\Lambda^4}\mathcal{O}_i$$

We are focusing on the following dimension-six operators:

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}, \qquad \mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}, \qquad \mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\nu}_{\mu} W^{b}_{\nu\rho} W^{c\rho\mu}, \qquad \mathcal{O}_T = \frac{g^2}{2}(H^\dagger \overleftrightarrow{D}^\mu H)(H^\dagger \overleftrightarrow{D}_\mu)H$$

$$\mathcal{O}^u_R = ig^2\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \bar{u}_R \gamma^\mu u_R, \qquad \mathcal{O}^d_R = ig^2\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \bar{d}_R \gamma^\mu d_R$$

$$\mathcal{O}^q_L = ig^2\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \bar{Q}_L \gamma^\mu Q_L, \qquad \mathcal{O}^{(3)q}_L = ig^2\left(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right) \bar{Q}_L \sigma^a \gamma^\mu Q_L$$

An example: $\mathcal{O}_W$

$$\frac{c_W \mathcal{O}_W}{\Lambda^2} = \frac{igc_W}{2\Lambda^2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$

LEP:

$$\mathcal{L} = -\frac{\tan\theta_W}{2}\hat{S} W^{(3)}_{\mu\nu} B^{\mu\nu}$$

$$\hat{S} = c_W \frac{m_W^2}{\Lambda^2} \Rightarrow \Lambda > 2.5\,\mathrm{TeV}@95\%, \qquad c_W = 1$$

LHC:

$$W_L^+ W_L^-, W_L^\pm Z_L, W_L^\pm h, Z_L h : \frac{\delta\sigma}{\sigma_{SM}} \sim c_W \frac{E_c^2}{\Lambda^2}$$

Energy growing behaviour!

- Unfortunately, the SM WW, WZ processes are dominated by the transverse modes:

$$\sigma_{SM}^{total}/\sigma_{SM}^{LL} \sim 15-50$$

see Pomarol (Aspen 2017)

Polarization tagging is essential to obtain bound!

- For W(Z)h(bb), the reducible backgrounds are the problem:

$$\text{LHC @ 8 TeV}: \qquad \sigma_{b}^{red}/\sigma_{SM}^{Wh} \sim 200-10$$

None of them are easy! Here we are going to give some benchmarks!

Bounds on $\mathcal{O}_W$ at the LEP and the HL-LHC

Λ[TeV] @95%	$\mathcal{O}_W, \Delta = 0$
LEP	2.5
$WV(\ell + jets)$ [0.5,1.0] TeV	(5.2,2.5,2.1)
$WV(\ell + jets)$ [1.0,1.5] TeV	(4.8,2.2,1.9)
$Zh(\nu\nu bb)$[0.5,1.0] TeV	(3.4,2.4,1.9)
$Zh(\nu\nu bb)$[1.0,1.5] TeV	(3.2,2.3,1.8)
$W^{\pm}h(\ell bb)$ [0.5,1.0] TeV	(4.3,3.0,2.4)
$W^{\pm}h(\ell bb)$ [1.0,1.5] TeV	(4.0,2.9,2.3)
$W^{\pm}h(\ell + \ell\nu\ell\nu)$ [0.5,1.0] TeV	2.4
$W^{\pm}h(\ell + \ell\nu\ell\nu)$ [1.0,1.5] TeV	2.3

$L = 3\,\mathrm{ab}^{-1}$

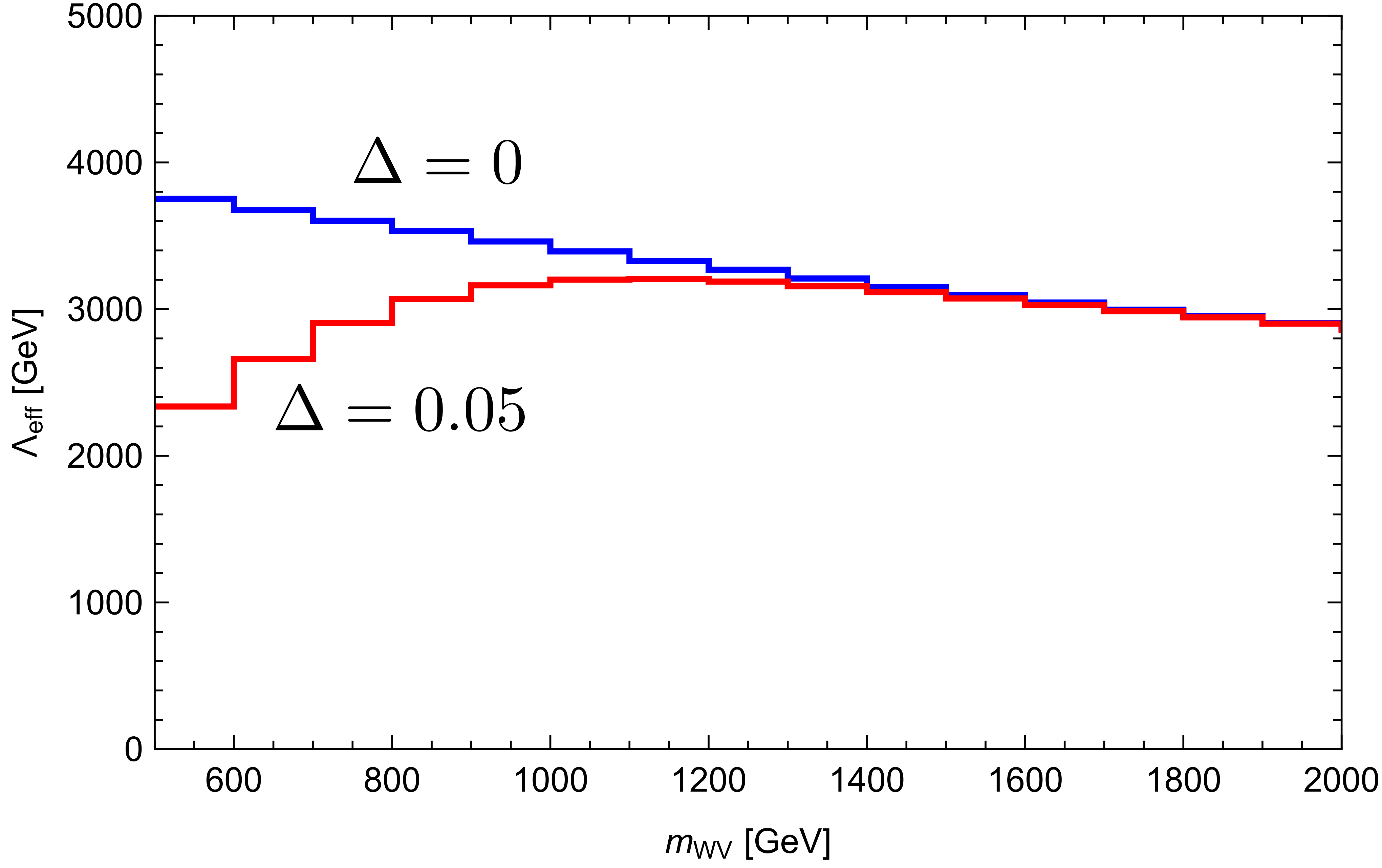
The selection efficiency $\epsilon = 10\%$ for semi-leptonic channels

The selection efficiency $\epsilon = 50\%$ for fully leptonic channels

(blue box) $(\epsilon_{LL} = 1.0 \&\& \epsilon_{TT} = 0, \epsilon_{LL} = 0.5 \&\& \epsilon_{TT} = 0.05, \epsilon_{LL} = 0.5 \&\& \epsilon_{TT} = 0.1)$

(red box) reducible background is (0, 3, 10) times irreducible background

The role of systematics



Another example: $\mathcal{O}_L^{(3)q}$
Flavour-universal effects

$$\mathcal{O}_L^{(3)q} = ig^2 \left(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H \right) \bar{Q}_L \sigma^a \gamma^\mu Q_L$$

LEP:

$$\delta g_{ZbbL} = -c_L^{(3)q} \frac{2g}{\cos\theta_w} \frac{m_W^2}{\Lambda^2} \Rightarrow \Lambda > 2.2\,\mathrm{TeV}@95\%, \qquad c_L^{(3)q} = 1$$

LHC:

$$W_L^+ W_L^-, W_L^\pm Z_L, W_L^\pm h, Z_L h : \frac{\delta\sigma}{\sigma_{SM}} \sim c_L^{(3)q} \frac{E_c^2}{\Lambda^2}$$

Bounds on $\mathcal{O}_L^{(3)q}$ at the LEP and the HL-LHC

Λ[TeV] @95%	$\mathcal{O}_L^{(3)q}, \Delta = 0$
LEP	2.2
$WV(\ell + jets)$ [0.5,1.0] TeV	(3.0,2.1,1.9)
$WV(\ell + jets)$ [1.0,1.5] TeV	(3.8,2.6,2.4)
$Zh(\nu\nu bb)$ [0.5,1.0] TeV	(6.8,4.9,3.8)
$Zh(\nu\nu bb)$ [1.0,1.5] TeV	(6.3,4.6,3.7)
$W^{\pm}h(\ell bb)$ [0.5,1.0] TeV	(8.4,5.9,4.6)
$W^{\pm}h(\ell bb)$ [1.0,1.5] TeV	(7.5,5.2,3.8)
$W^{\pm}h(\ell + \ell\nu\ell\nu)$ [0.5,1.0] TeV	4.6
$W^{\pm}h(\ell + \ell\nu\ell\nu)$ [1.0,1.5] TeV	3.8

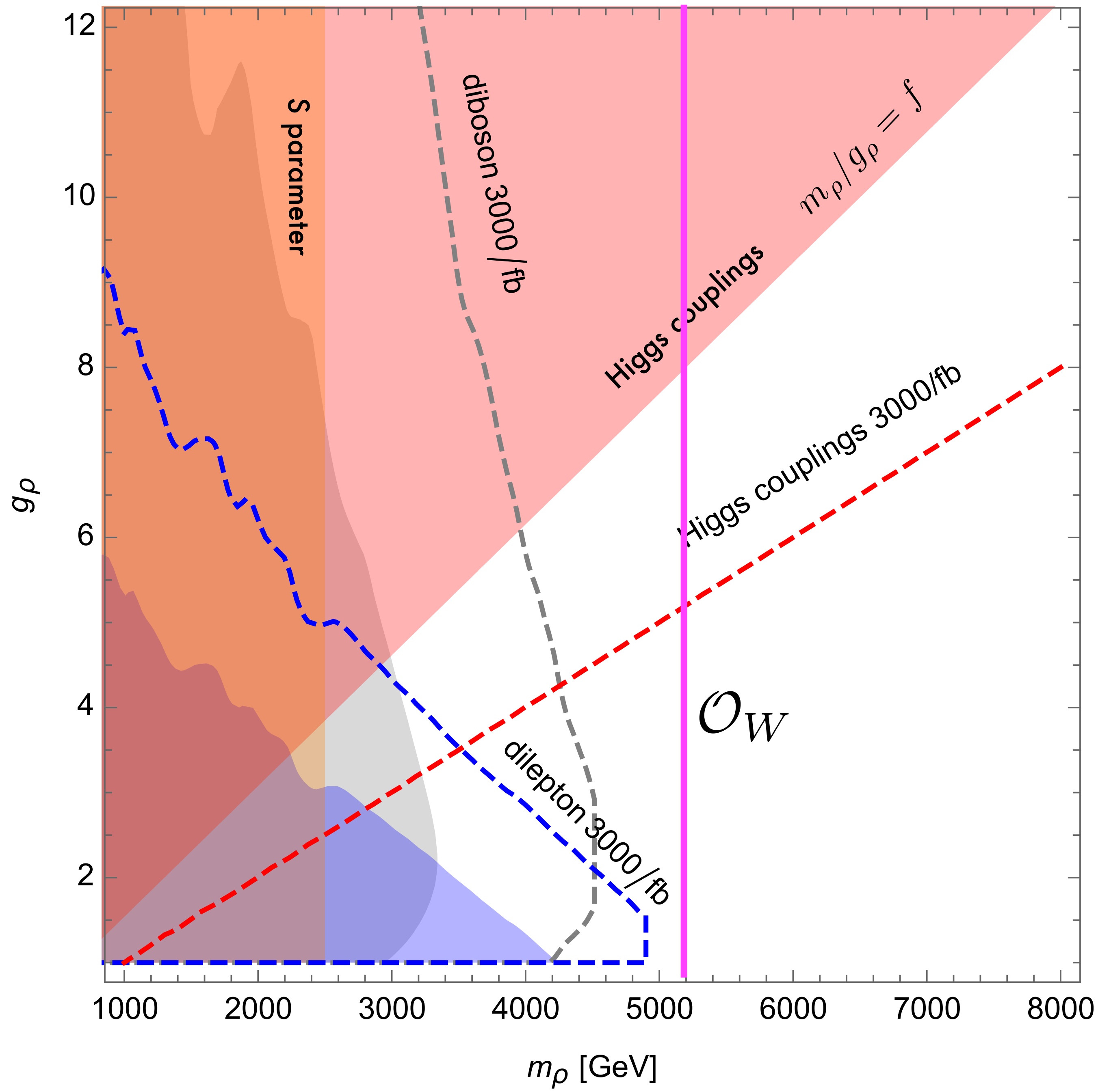
$L = 3\,\mathrm{ab}^{-1}$

The selection efficiency $\epsilon = 10\%$ for semi-leptonic channels
The selection efficiency $\epsilon = 50\%$ for fully leptonic channels

Blue box: $(\epsilon_{LL} = 1.0 \&\& \epsilon_{TT} = 0, \epsilon_{LL} = 0.5 \&\& \epsilon_{TT} = 0.05, \epsilon_{LL} = 0.5 \&\& \epsilon_{TT} = 0.1)$

Red box: reducible background is (0, 3, 10) times irreducible background

Compare with direct searches



Shaded areas:
Present bounds

Dimension-8

- Gives rise to unique signals.
  - ZZ, $\gamma\gamma$.

- Can interfere with the SM in some cases where dim-6 do not.
  - e.g. $W_T W_T$, $W_T Z_T$. SM rate about 20 times $W_L W_L$.
  - Dim-6 interference with SM suppressed. Dim-8 interfere with SM. Equally important.

$$
{}_8\mathcal{O}_{TWW} = g^2 \mathcal{T}_f^{\mu\nu} W^a_{\mu\rho} W^{a\,\rho}_{\nu} \qquad {}_8\mathcal{O}_{TBB} = g'^2 \mathcal{T}_f^{\mu\nu} B_{\mu\rho} B^{\rho}_{\nu}
$$

$$
{}_8\mathcal{O}_{TWB} = g g' \mathcal{T}_f^{a\,\mu\nu} W^a_{\mu\rho} B^{\rho}_{\nu}, \qquad {}_8\mathcal{O}_{TH} = g^2 \mathcal{T}_f^{\mu\nu} D_\mu H^\dagger D_\nu H
$$

$$
{}_8\mathcal{O}^{(3)}_{TH} = g^2 \mathcal{T}_f^{a\,\mu\nu} D_\mu H^\dagger \sigma^a D_\nu H
$$

$$
\mathcal{T}_f^{\mu\nu} = \frac{i}{4} \bar{\psi} (\gamma^\mu \overleftrightarrow{D}^\nu + \gamma^\nu \overleftrightarrow{D}^\mu) \psi \qquad \mathcal{T}_f^{a,\,\mu\nu} = \frac{i}{4} \bar{\psi} (\gamma^\mu \overleftrightarrow{D}^\nu + \gamma^\nu \overleftrightarrow{D}^\mu) \sigma^a \psi
$$

Summary about the Observables

Observable	$\delta\sigma/\sigma_{\rm SM}$	Observable	$\delta\sigma/\sigma_{\rm SM}$
$\hat{S}$	$(c_W + c_B)\frac{m_W^2}{\Lambda^2}$	$\hat{T}$	$4c_T\frac{m_W^2}{\Lambda^2}$
$W_L^+W_L^-$	$\left[(c_W + c_{HW})T_f^3 + (c_B + c_{HB})Y_f t_w^2\right]\frac{E_c^2}{\Lambda^2}, c_f\frac{E_c^2}{\Lambda^2}, c_{TH}\frac{E_c^4}{\Lambda^4}, c_{TH}^{(3)}\frac{E_c^4}{\Lambda^4}$	$W_T^+W_T^-$	$c_{3W}\frac{m_W^2}{\Lambda^2} + c_{3W}^2\frac{E_c^4}{\Lambda^4}, c_{TWW}\frac{E_c^4}{\Lambda^4}$
$W_L^{\pm}Z_L$	$\left(c_W + c_{HW} + 4c_L^{(3)q}\right)\frac{E_c^2}{\Lambda^2}, c_{TH}^{(3)}\frac{E_c^4}{\Lambda^4}$	$W_T^{\pm}Z_T(\gamma)$	$c_{3W}\frac{m_W^2}{\Lambda^2} + c_{3W}^2\frac{E_c^4}{\Lambda^4}, c_{TWB}\frac{E_c^4}{\Lambda^4}$
$W_L^{\pm}h$	$\left(c_W + c_{HW} + 4c_L^{(3)q}\right)\frac{E_c^2}{\Lambda^2}, c_{TH}^{(3)}\frac{E_c^4}{\Lambda^4}$	Zh	$\left[(c_W + c_{HW})T_f^3 - (c_B + c_{HB})Y_f t_w^2\right]\frac{E_c^2}{\Lambda^2}, c_f\frac{E_c^2}{\Lambda^2}$
Z_TZ_T	$(c_{TWW} + t_w^2 c_{TBB} - 2T_f^3 t_w^2 c_{TWB})\frac{E_c^4}{\Lambda^4}$	$\gamma\gamma$	$(c_{TWW} + t_w^2 c_{TBB} + 2T_f^3 t_w^2 c_{TWB})\frac{E_c^4}{\Lambda^4}$
$h \to Z\gamma$	$(c_{HW} - c_{HB})\frac{(4\pi v)^2}{\Lambda^2}$	$h \to W^+W^-$	$(c_W + c_{HW})\frac{m_W^2}{\Lambda^2}$

- LEP precision EW, high energy non-resonant WV/Vh, and Higgs measurement all relevant.
  - Sensitive to different combination of the operators.
- O_{HW} and O_{HB} contribute to $h \to Z\gamma$, expect to be relatively small in the minimal coupled theory.
- LEP limit on O_T dominant. LHC probably can't improve.

Summary about the Bounds at the LEP and the HL-LHC

$$L = 3\,\mathrm{ab}^{-1}$$

Λ[TeV] @95%	$\mathcal{O}_W$	$\mathcal{O}_B$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$
LEP	2.5	2.5	0.3	0.3
$WV(\ell + jets)$ [0.5,1.0] TeV	(5.2,2.5,2.1)	(1.5,0.77,0.67)	(5.2,2.5,2.1)	(1.5,0.77,0.67)
$WV(\ell + jets)$ [1.0,1.5] TeV	(4.8,2.2,1.9)	(1.5,0.79,0.71)	(4.8,2.2,1.9)	(1.5,0.79,0.71)
$Zh(\nu\nu bb)$[0.5,1.0] TeV	(3.4,2.4,1.9)	(1.2,0.90,0.74)	(3.4,2.4,1.9)	(1.2,0.90,0.74)
$Zh(\nu\nu bb)$[1.0,1.5] TeV	(3.2,2.3,1.8)	(1.3,0.98,0.83)	(3.2,2.3,1.8)	(1.3,0.98,0.83)
$W^{\pm}h(\ell bb)$ [0.5,1.0] TeV	(4.3,3.0,2.4)		(4.3,3.0,2.4)	
$W^{\pm}h(\ell bb)$ [1.0,1.5] TeV	(4.0,2.9,2.3)		(4.0,2.9,2.3)	
$W^{\pm}h(\ell + \ell\nu\ell\nu)$ [0.5,1.0] TeV	2.4		2.4	
$W^{\pm}h(\ell + \ell\nu\ell\nu)$ [1.0,1.5] TeV	2.3		2.3	
$h \to Z\gamma$			1.7	1.7

The selection efficiency $\epsilon = 10\%$ for semi-leptonic channels

The selection efficiency $\epsilon = 50\%$ for fully leptonic channels

$(\epsilon_{LL} = 1.0 \&\& \epsilon_{TT} = 0, \epsilon_{LL} = 0.5 \&\& \epsilon_{TT} = 0.05, \epsilon_{LL} = 0.5 \&\& \epsilon_{TT} = 0.1)$

reducible background is (0, 3,10) times irreducible background

Summary about the Bounds at the LEP and the HL-LHC

$$L = 3\,\mathrm{ab}^{-1}$$

Λ[TeV] @95%	$\mathcal{O}_L^q$	$\mathcal{O}_L^{(3)q}$	$\mathcal{O}_R^u$	$\mathcal{O}_R^d$
LEP	3.2	2.2	2.5	0.98
$WV(\ell + jets)$ [0.5,1.0] TeV	(4.5,2.4,2.1)	(3.0,2.1,1.9)	(3.9,2.1,1.9)	(1.6,1.2,1.2)
$WV(\ell + jets)$ [1.0,1.5] TeV	(4.7,2.6,2.3)	(3.8,2.6,2.4)	(4.0,2.2,2.0)	(2.2,1.6,1.5)
$Zh(\nu\nu bb)$ [0.5,1.0] TeV	(2.0,1.8,1.6)	(6.8,4.9,3.8)	(3.7, 2.8,2.3)	(1.6,1.4,1.3)
$Zh(\nu\nu bb)$ [1.0,1.5] TeV	(2.7,2.4,2.2)	(6.3,4.6,3.7)	(3.9,3.0,2.5)	(2.2,1.9,1.7)
$W^{\pm}h(\ell bb)$ [0.5,1.0] TeV		(8.4,5.9,4.6)		
$W^{\pm}h(\ell bb)$ [1.0,1.5] TeV		(7.5,5.2,3.8)		
$W^{\pm}h(\ell + \ell\nu\ell\nu)$ [0.5,1.0] TeV		4.6		
$W^{\pm}h(\ell + \ell\nu\ell\nu)$ [1.0,1.5] TeV		3.8		

The selection efficiency $\epsilon = 10\%$ for semi-leptonic channels
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(blue box) $(\epsilon_{LL} = 1.0\&\&\epsilon_{TT} = 0, \epsilon_{LL} = 0.5\&\&\epsilon_{TT} = 0.05, \epsilon_{LL} = 0.5\&\&\epsilon_{TT} = 0.1)$

(red box) reducible background is (0, 3, 10) times irreducible background

Summary about the Bounds at the LEP and the HL-LHC $L = 3\,\mathrm{ab}^{-1}$

Λ[TeV]	$\mathcal{O}_{3W}$	$\mathcal{O}_{TWW}$	$\mathcal{O}_{TWB}$	$\mathcal{O}_{TH}$	$\mathcal{O}_{TH}^{(3)}$
LEP	0.4				
$WV(\ell + jets)$	1.2	0.90	0.90	(1.1,0.87,0.83)	(0.83,0.67,0.65)
$W^{\pm}h(\ell bb)$					(0.86,0.79,0.76)
$W^{\pm}h(\ell + \ell\nu\ell\nu)$					0.74
$ZZ(4\ell)$		1.4	0.71		
$ZZ(2\ell 2j)$		1.6	0.76		
$W^{\pm}\gamma(\ell + \gamma)$	1.3		1.4		
$Z\gamma(\ell\ell + \gamma)$		1.5	1.1		
$Z\gamma(\nu\nu + \gamma)$		1.4	1.0		
$\gamma\gamma$		2.0	1.6		

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Red box: reducible background is (0, 3, 10) times irreducible background

Conclusion

- New physics may only show its tail at the LHC, it is important to do the precision measurement.
- The EFT is a convenient and model-independent way to capture the effects.
- With high energy at hand, LHC can beat LEP precision.
- Non-resonant, broad features. Difficult. But a lot data can make a significant difference here!

Helicity structure

$$f_L \bar{f}_R \to W^+ W^-$$

(h_{W^+}, h_{W^-})	SM	$\mathcal{O}_W$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_B$	$\mathcal{O}_{3W}$	$\mathcal{O}_{TWW}$
$(\pm, \mp)$	1	0	0	0	0	0	$\frac{E^4}{\Lambda^4}$
$(0, 0)$	1	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	0	$\frac{E^4}{\Lambda^4}\frac{m_W^2}{E^2}$
$(0, \pm), (\pm, 0)$	$\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^4}{\Lambda^4}\frac{m_W}{E}$
$(\pm, \pm)$	$\frac{m_W^2}{E^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	0	0	$\frac{E^2}{\Lambda^2}$	$\frac{E^4}{\Lambda^4}\frac{m_W^2}{E^2}$

$$f_R \bar{f}_L \to W^+ W^-$$

(h_{W^+}, h_{W^-})	SM	$\mathcal{O}_W$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_B$	$\mathcal{O}_{3W}$	$\mathcal{O}_{TWW}$
$(\pm, \mp)$	0	0	0	0	0	0	$\frac{E^4}{\Lambda^4}$
$(0, 0)$	1	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	$\frac{E^2}{\Lambda^2}$	0	$\frac{E^4}{\Lambda^4}\frac{m_W^2}{E^2}$
$(0, \pm), (\pm, 0)$	$\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{m_W^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^4}{\Lambda^4}\frac{m_W}{E}$
$(\pm, \pm)$	$\frac{m_W^2}{E^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	0	0	$\frac{m_W^2}{\Lambda^2}$	$\frac{E^4}{\Lambda^4}\frac{m_W^2}{E^2}$

- Whether interference or not depends on polarization of WW. Polarization differentiation can be crucial.

SM di-boson rates

	WZ		WW		Wh		Zh	
Polarizations	8 TeV	13 TeV	8 TeV	13 TeV	8 TeV	13 TeV	8 TeV	13 TeV
σ_{LL}	0.78 pb	1.5 pb	2.0 pb	3.7 pb	0.28 pb	0.58 pb	0.12 pb	0.29 pb
σ_{LT+TL}	2.3 pb	4.4 pb	7.5 pb	12.6 pb	0.25 pb	0.50 pb	0.14 pb	0.28 pb
σ_{TT}	9.3 pb	18.2 pb	24.4 pb	47.0 pb	–	–	–	–

	ZZ		$W\gamma$		$Z\gamma$		$\gamma\gamma$	
Polarizations	8 TeV	13 TeV	8 TeV	13 TeV	8 TeV	13 TeV	8 TeV	13 TeV
σ_{LL}	0.28 pb	0.52 pb	–	–	–	–	–	–
σ_{LT+TL}	1.1 pb	2.0 pb	9.9 pb	15.6 pb	11.5 pb	17.6 pb	–	–
σ_{TT}	3.2 pb	6.3 pb	47.8 pb	79.5 pb	32.8 pb	52.9 pb	117 pb	160 pb

From MadGraph LO