Strongly coupled new physics and Precision measurements at the LHC

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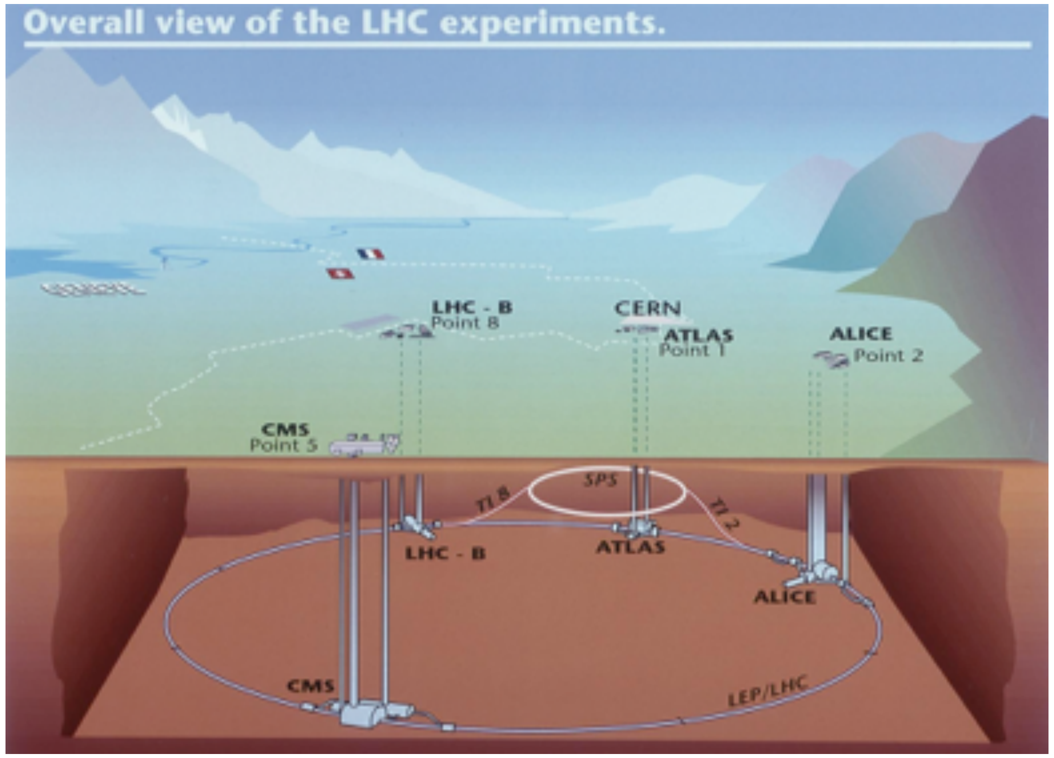
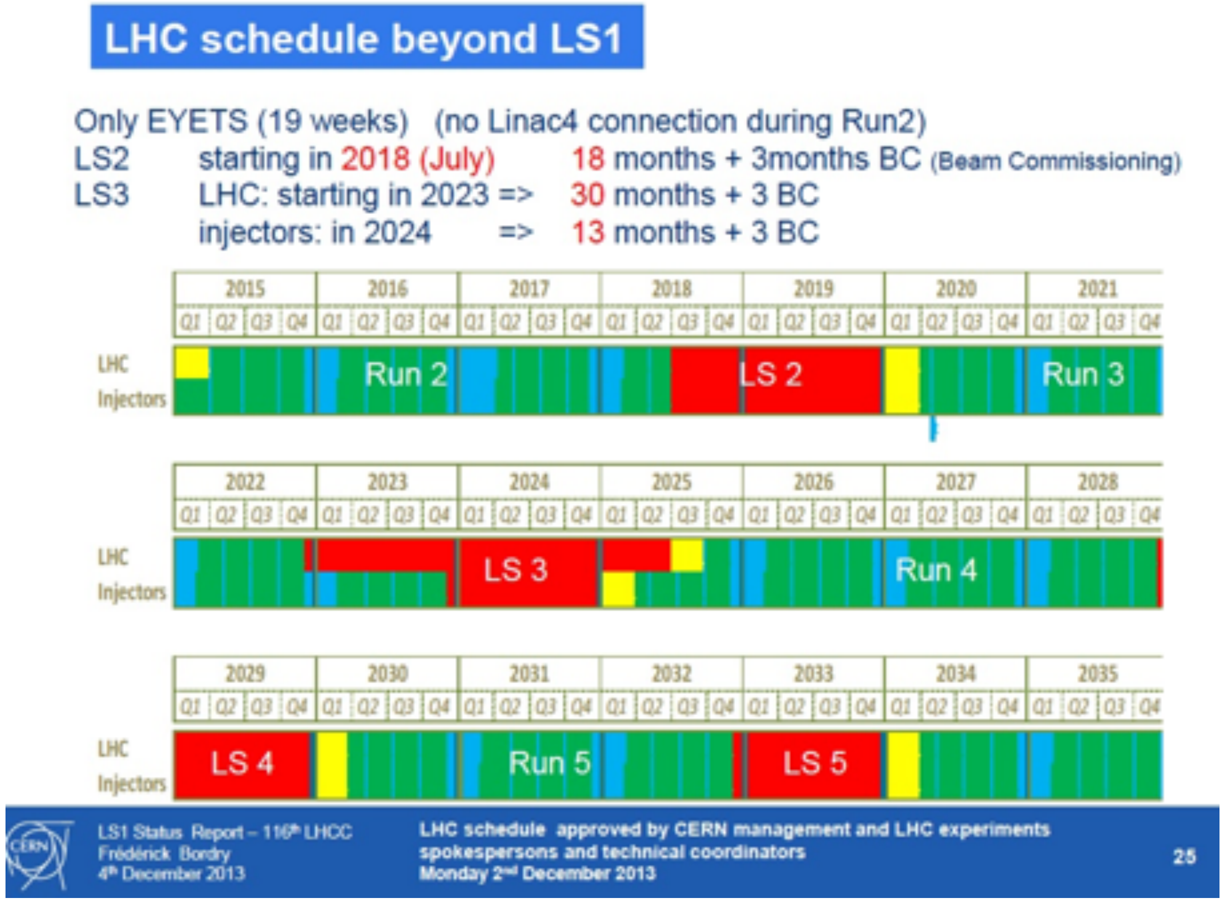
Work in collaboration with Da Liu and Andrea Tesi

2017 CERN-CKC workshop. Jeju island, Korea. June 2. 2017

Future of Large Hadron Collider





LHC schedule beyond LS1

Only EYETS (19 weeks) (no Linac4 connection during Run2)
LS2 starting in 2018 (July) 18 months + 3months BC (Beam Commissioning)
LS3 LHC: starting in 2023 => 30 months + 3 BC
injectors: in 2024 => 13 months + 3 BC

LS1 Status Report – 116th LHCC
Frédérick Bordry
4th December 2013

LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators
Monday 2nd December 2013

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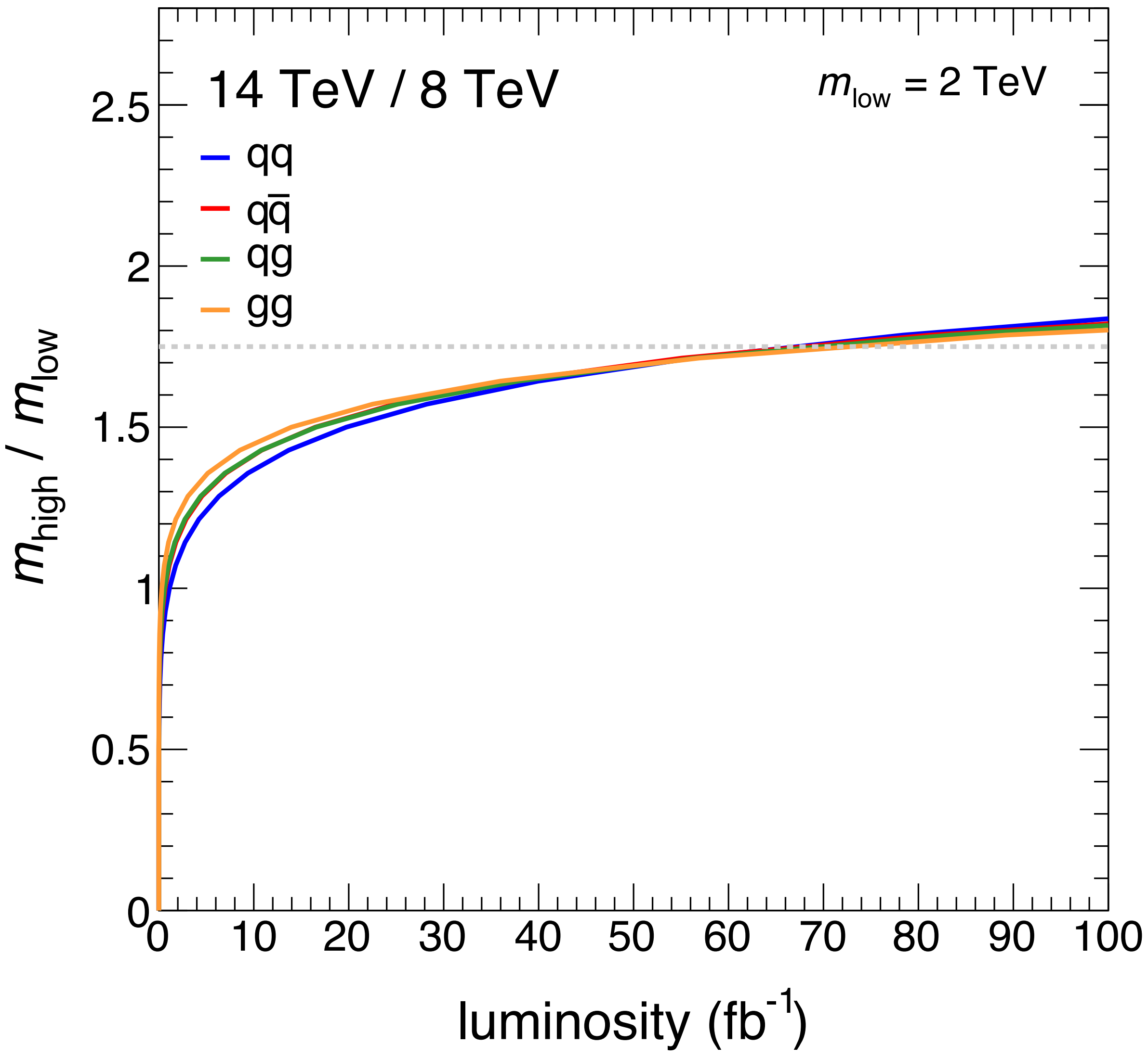
- Will continue and improve in the next two decades
  - E_{cm} = 13-14 TeV.
  - 95+% more data.

As data accumulates

Run 1 limit   2 TeV, e.g. pair of 1 TeV gluino.



Rapid gain initial 10s fb^{-1}, slow improvements afterwards.

Reached “slow” phase after Moriond 2017

LHC will press on the “standard” searches for SUSY, extraD, composite… with slower progresses

In addition to waiting patiently…

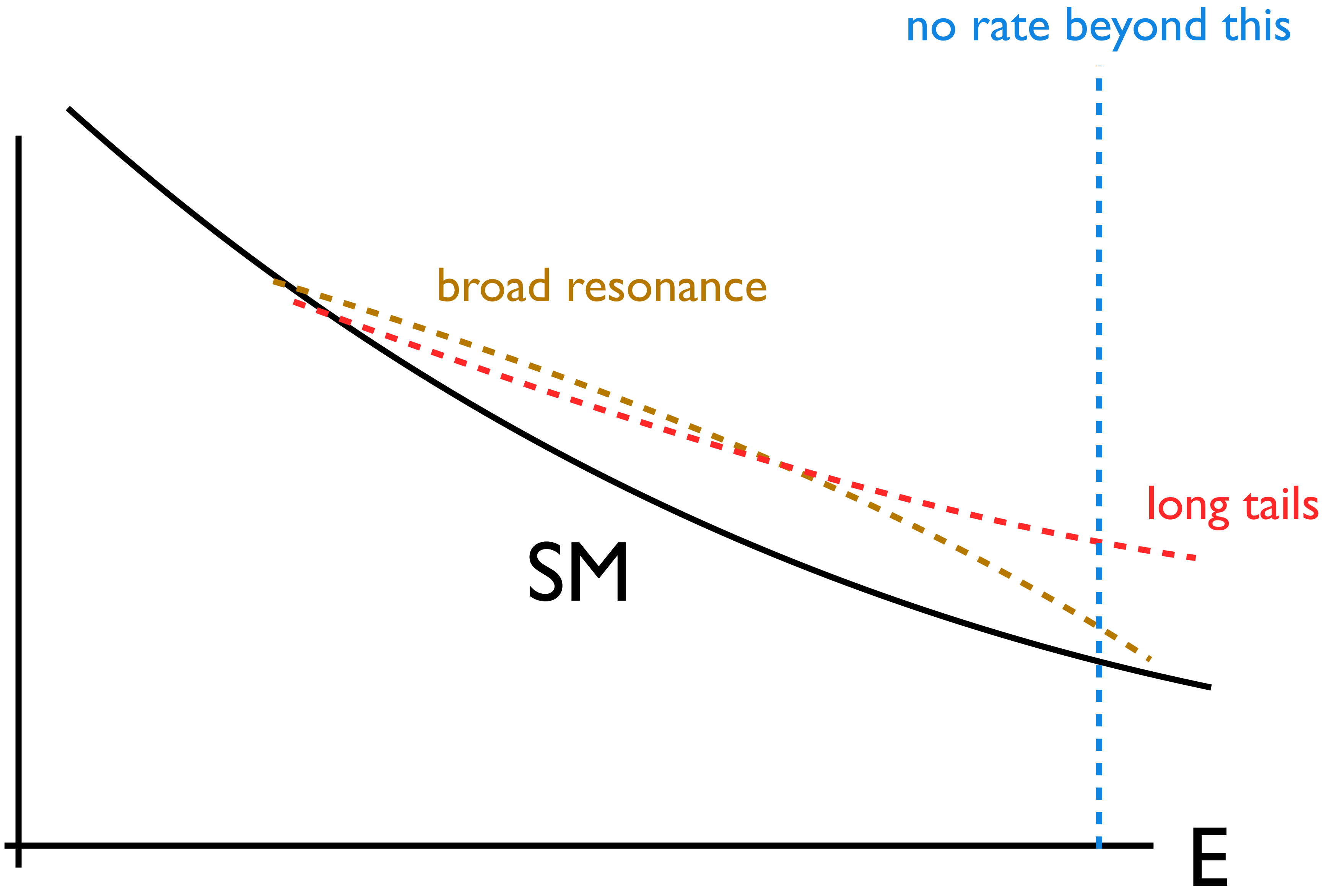
Do more with (95+% more) LHC data.

On-going work. Preliminary results.
With Da Liu and Andrea Tesi.

A direction with potential

- Difficult channels that:
  - Not rate limited, but small S/B
  - Limited by reducible backgrounds, systematics.
  - More data and more time (improving techniques) can help.

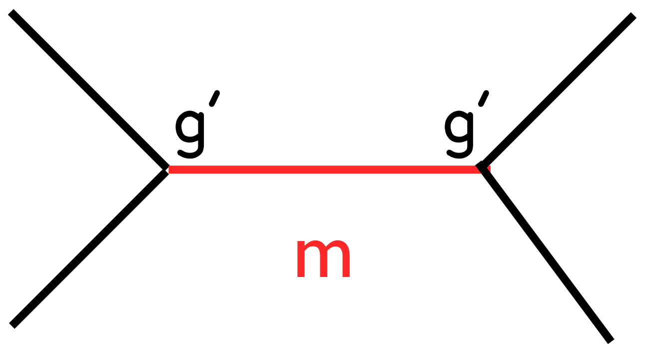
Shapes of signals



- Strongly coupled heavy new physics

e.g. Liu, Pomarol, Rattazzi, Riva

Strong coupling



m > kinematical limit. Integrate out

$$\frac{g'^2}{m^2}\mathcal{O}^{(6)}$$

Best channels are usually di-lepton, di-jet and so on.
Well studied

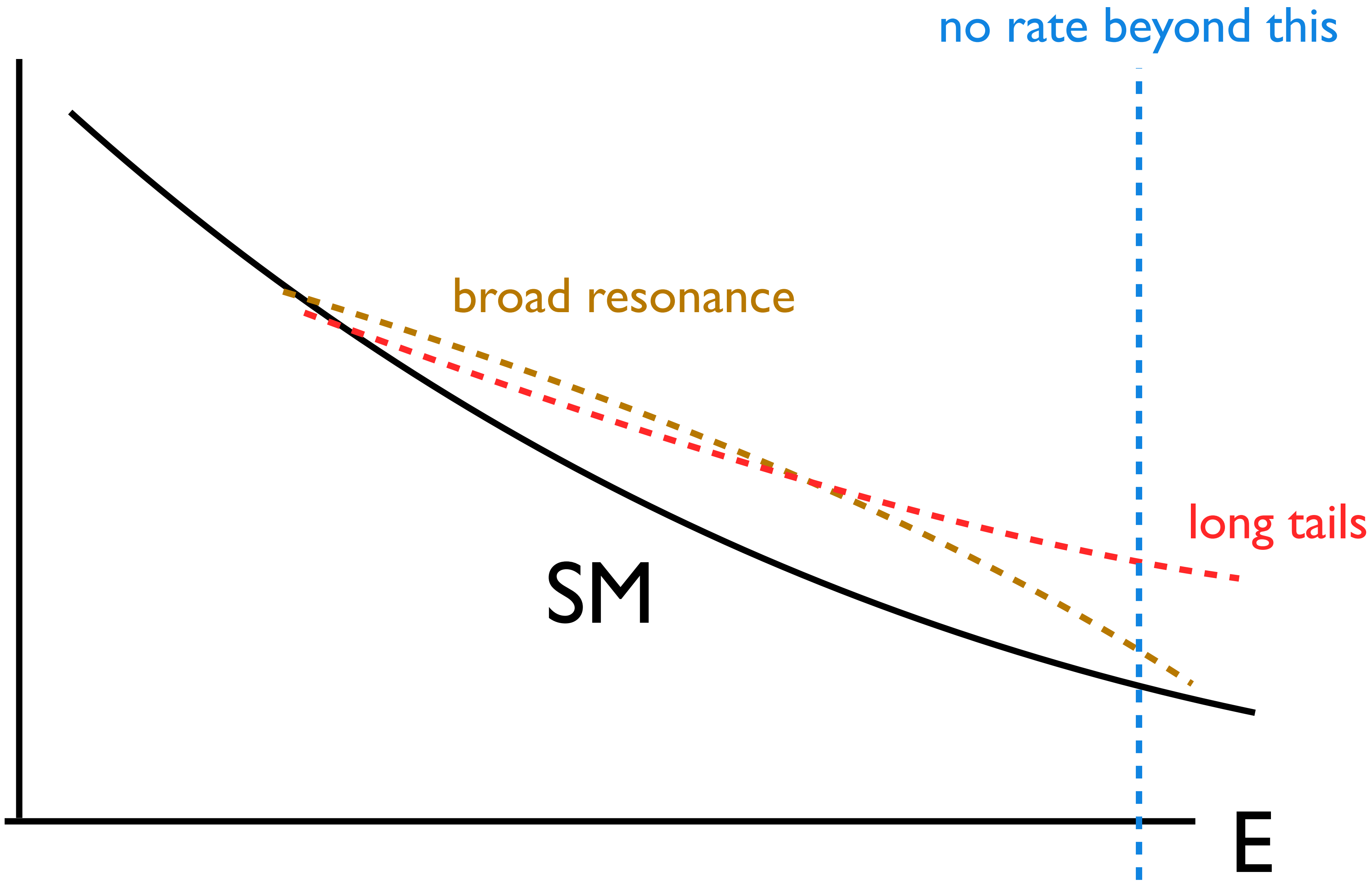
Another recent example of using di-lepton and potentially di-jet

Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer

My focus here:

- The question of electroweak symmetry breaking has hinted that there should be NP not too far away from the weak scale.
  - Naturalness, etc.
  - Some of these need strong dynamics
- Final states with W/Z/h/top. “Precision measurement”

Broad features with di-boson, tops etc.



- Closely related to electroweak symmetry breaking
- Difficult. More data can help a lot.

Operators.

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

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

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

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

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

dim 6

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

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

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

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

dim 8

Observables.

Observable	$\delta\sigma/\sigma_{\rm SM}$	Observable	$\delta\sigma/\sigma_{\rm SM}$
$\hat{S}$	$(c_W + c_B)\frac{m_W^2}{\Lambda^2}$	$\hat{T}$	$4c_T\frac{m_W^2}{\Lambda^2}$
$W_L^+W_L^-$	$\left[(c_W + c_{HW})T_f^3 + (c_B + c_{HB})Y_f t_w^2\right]\frac{E_c^2}{\Lambda^2}, c_f\frac{E_c^2}{\Lambda^2}, c_{TH}\frac{E_c^4}{\Lambda^4}, c_{TH}^{(3)}\frac{E_c^4}{\Lambda^4}$	$W_T^+W_T^-$	$c_{3W}\frac{m_W^2}{\Lambda^2} + c_{3W}^2\frac{E_c^4}{\Lambda^4}, c_{TWW}\frac{E_c^4}{\Lambda^4}$
$W_L^\pm Z_L$	$\left(c_W + c_{HW} - 4c_L^{(3)q}\right)\frac{E_c^2}{\Lambda^2}, c_{TH}^{(3)}\frac{E_c^4}{\Lambda^4}$	$W_T^+Z_T(\gamma)$	$c_{3W}\frac{m_W^2}{\Lambda^2} + c_{3W}^2\frac{E_c^4}{\Lambda^4}, c_{TWB}\frac{E_c^4}{\Lambda^4}$
$W_L^\pm h$	$\left(c_W + c_{HW} - 4c_L^{(3)q}\right)\frac{E_c^2}{\Lambda^2}, c_{TH}^{(3)}\frac{E_c^4}{\Lambda^4}$	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 WW/Wh, and Higgs measurement all relevant.
  - Sensitive to different combination of the operators.
- O_{HW} and O_{HB} contribute to $h \to Z\gamma$.
- LEP limit on O_T dominant. LHC probably can't improve.

Precision measurement at the LHC possible?

LEP precision tests probe NP about 2 TeV

$$\frac{\delta\sigma}{\sigma_{\rm SM}} \sim \frac{m_W^2}{\Lambda^2} \sim 2\times 10^{-3}$$

At LHC

Signal-SM interference

$$\frac{\delta\sigma}{\sigma_{\rm SM}} \sim \frac{E^2}{\Lambda^2} \sim 0.25$$

Without interference

$$\frac{\delta\sigma}{\sigma_{\rm SM}} \sim \frac{E^4}{\Lambda^4} \sim 0.05$$

LHC has potential.

Both interference and energy growing behavior crucial

Helicity structure at LHC

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

(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	$\frac{E^2}{\Lambda^2}$	$\frac{E^4}{\Lambda^4} \frac{m_W^2}{E^2}$

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$(0, \pm), (\pm, 0)$	$\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2} \frac{m_W}{E}$	$\frac{E^2}{\Lambda^2} \frac{m_W}{E}$	$\frac{E^2}{\Lambda^2} \frac{m_W}{E}$	$\frac{E^2}{\Lambda^2} \frac{m_W}{E}$	$\frac{m_W^2}{\Lambda^2} \frac{m_W}{E}$	$\frac{E^4}{\Lambda^4} \frac{m_W}{E}$
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$(0,0)$	1	$\boxed{\frac{E^2}{\Lambda^2}}$	$\boxed{\frac{E^2}{\Lambda^2}}$	$\boxed{\frac{E^2}{\Lambda^2}}$	$\boxed{\frac{E^2}{\Lambda^2}}$	0	$\frac{E^4}{\Lambda^4}\frac{m_W^2}{E^2}$
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▢ growing with energy

Helicity structure at LHC

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$(0,\pm),(\pm,0)$	$\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^4}{\Lambda^4}\frac{m_W}{E}$
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$(0,\pm),(\pm,0)$	$\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{m_W^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^4}{\Lambda^4}\frac{m_W}{E}$
$(\pm,\pm)$	$\frac{m_W^2}{E^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	0	0	$\frac{m_W^2}{\Lambda^2}$	$\frac{E^4}{\Lambda^4}\frac{m_W^2}{E^2}$

🟦 growing with energy

🟩 SM piece is small. Interference does not grow with E.

Helicity structure at LHC

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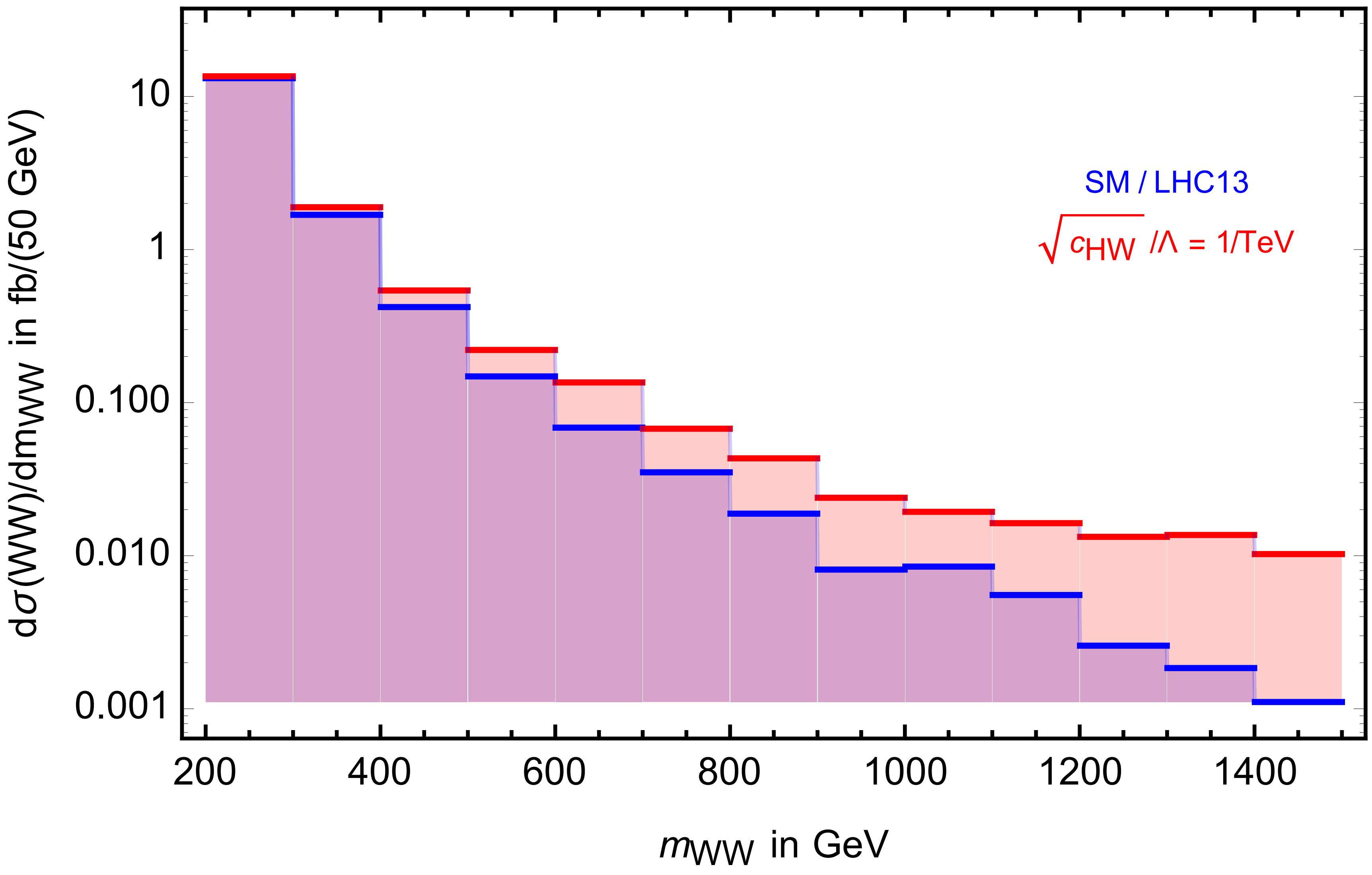
$(0, \pm), (\pm, 0)$	$\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{m_W^2}{\Lambda^2}\frac{m_W}{E}$	$\frac{E^4}{\Lambda^4}\frac{m_W}{E}$
$(\pm, \pm)$	$\frac{m_W^2}{E^2}$	$\frac{m_W^2}{\Lambda^2}$	$\frac{m_W^2}{\Lambda^2}$	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.

- Need large SM piece to interfere with. Longitudinal (0,0) most promising.

Growing with energy



Sensitivity to tails. Ideal case.

"tail" parameterized by $\frac{\mathcal{O}}{\Lambda^d}$

$\Lambda \approx m_*$

$$\sigma_{\rm signal} \propto \frac{1}{E^n}\left(\frac{E}{\Lambda}\right)^d \qquad \sigma_{\rm SM} \propto \frac{1}{E^n}$$

E: energy bin of the measurement

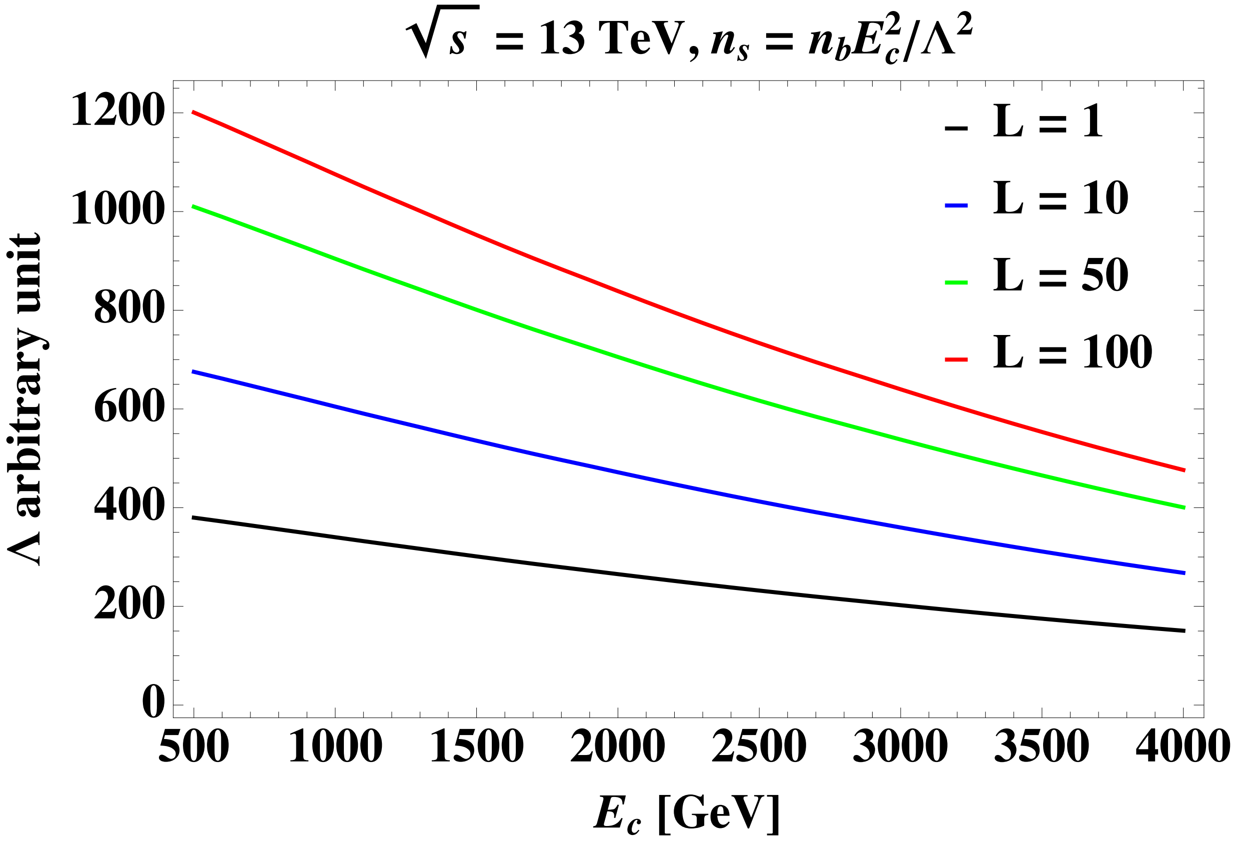
n: 5-8 falling parton luminosity

$$\frac{S}{\sqrt{B}} \sim \sqrt{\frac{\mathcal{L}}{E^n}}\left(\frac{E}{\Lambda}\right)^d$$

$\mathcal{L}$ = integrated luminosity

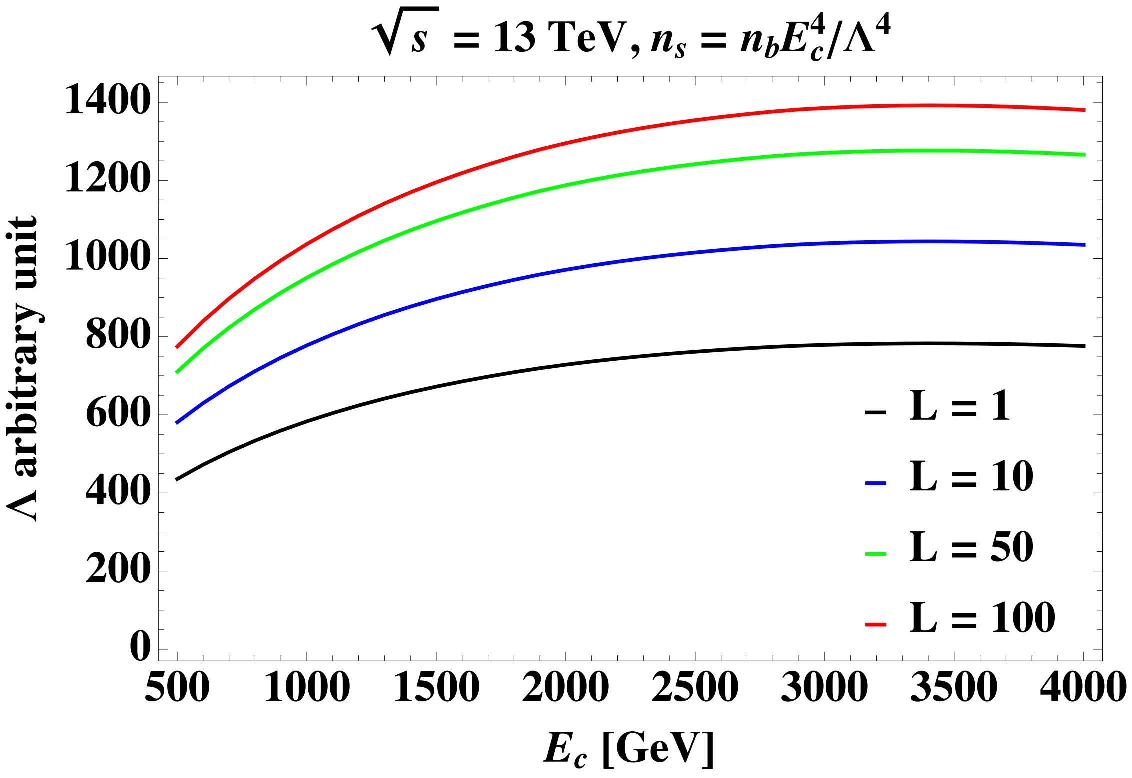
- For small d, lower E with higher reach. (e.g. dim 6, d=2)
  - Limited by systematics.
- Interference important. Otherwise, signal proportional to $(\text{operator})^2$, effect further suppressed by $(E/\Lambda)^d$.

Ideal case.



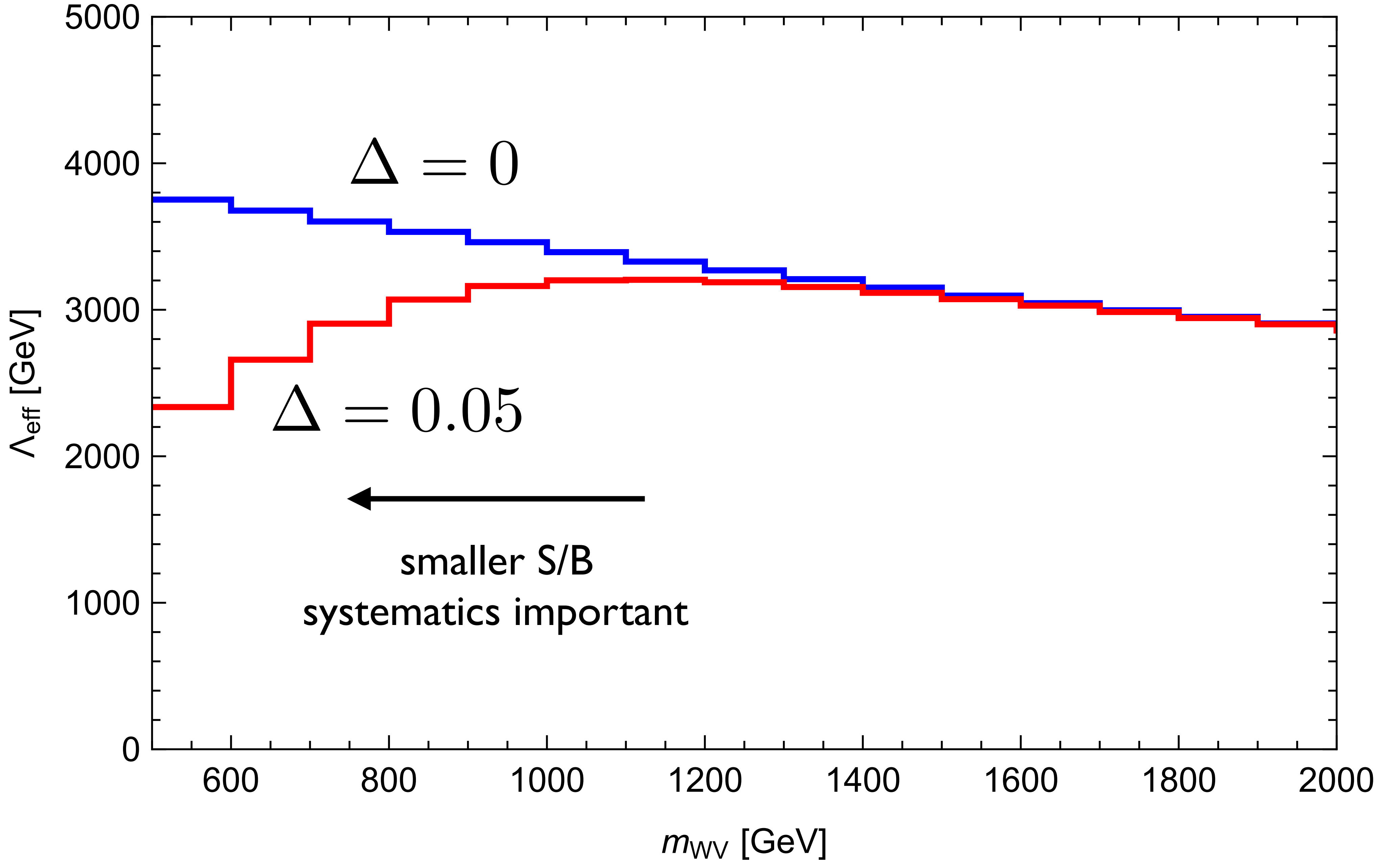
dim 6, with interference
Stronger limit at lower energy

E_c = partonic c.o.m. energy
= diboson invariant mass



dim 8 with interference
or dim 6 without interference

The role of systematics



smaller S/B
systematics important

An example: $\mathcal{O}_W$ LHC contribution same as $\mathcal{O}_{HW}$

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

LEP precision test:

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

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

LHC longitudinal mode:

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

Potential difficulties

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SM WW, WZ processes are dominated by transverse modes

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

Polarization tagging of W/Z crucial

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Polarization tagging of W/Z crucial

Wh/Zh(bb) channels have large reducible background

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

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

Polarization tagging of W/Z crucial

Wh/Zh(bb) channels have large reducible background

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

Difficult measurement. Large improvement needed.
Much more data and 20 years can help!
Instead of making projections based on current performance, we will give several targets (goals).

Reach projection

Crude parameterization of significance

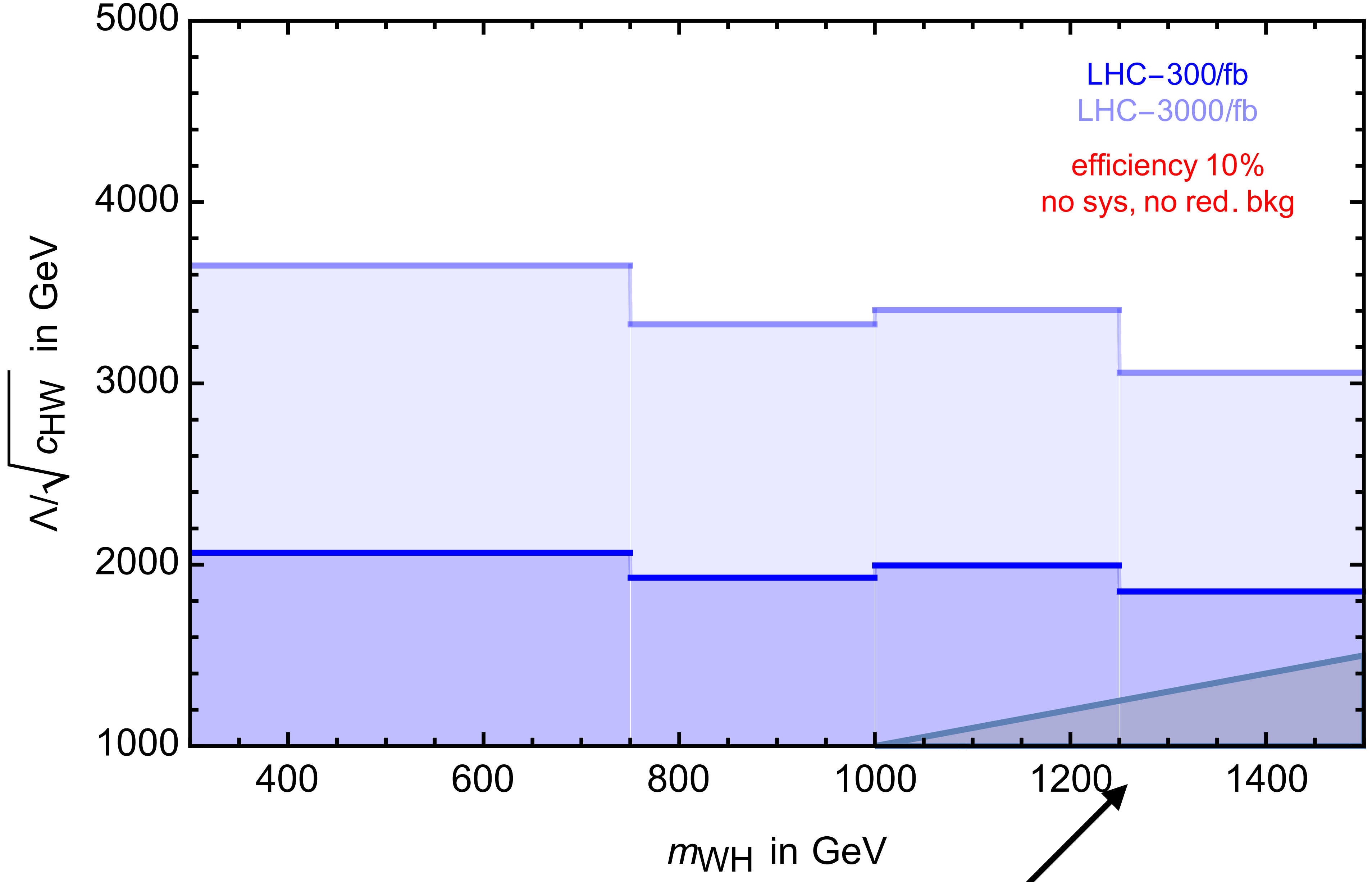
$$\frac{S^{h_1}}{\sqrt{B}} = \frac{\epsilon_{\rm sig}[\epsilon_{h_1}(\mathcal{M}^{h_1}_{\rm sig} + \mathcal{M}^{h_1}_{\rm SM})^2 + \sum_{h\neq h_1} \epsilon_h(\mathcal{M}^{h}_{\rm sig} + \mathcal{M}^{h}_{\rm SM})^2] \times \mathcal{L}}{\sqrt{[\epsilon_{h_1}\sigma^{h_1}_{\rm SM} + \sum_{h\neq h_1} \epsilon_h \sigma^h_{\rm SM}]\mathcal{L} + (\Delta \times n_{\rm SM})^2}}$$

$\epsilon_{\rm sig}$ signal efficiency or acceptance

$\epsilon_{\rm h}$ (mis)tag probability of polarization h

Δ: systematical error

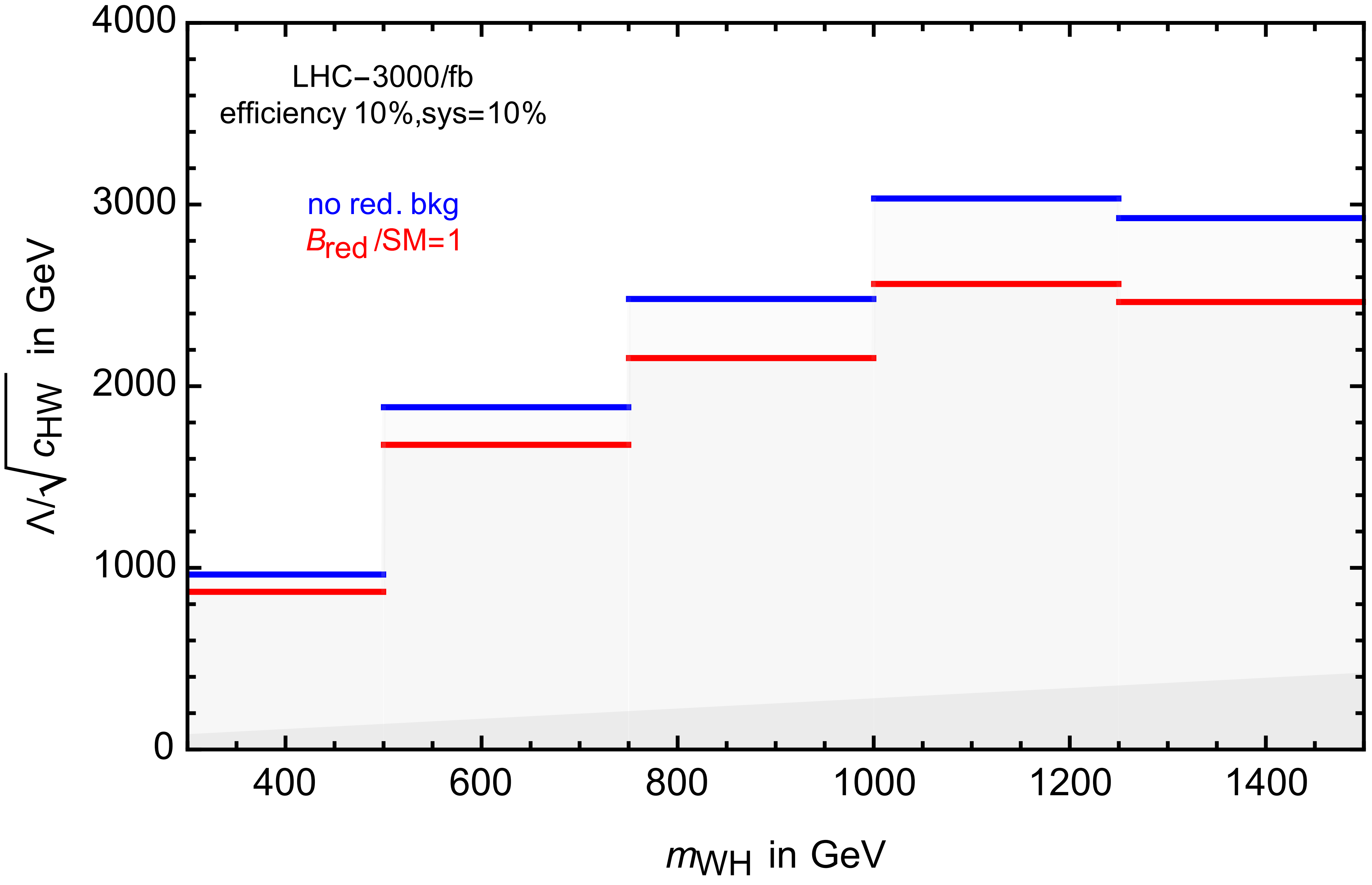
Wh channel



gray area: $m_{Wh} > \frac{\Lambda}{\sqrt{c}}$

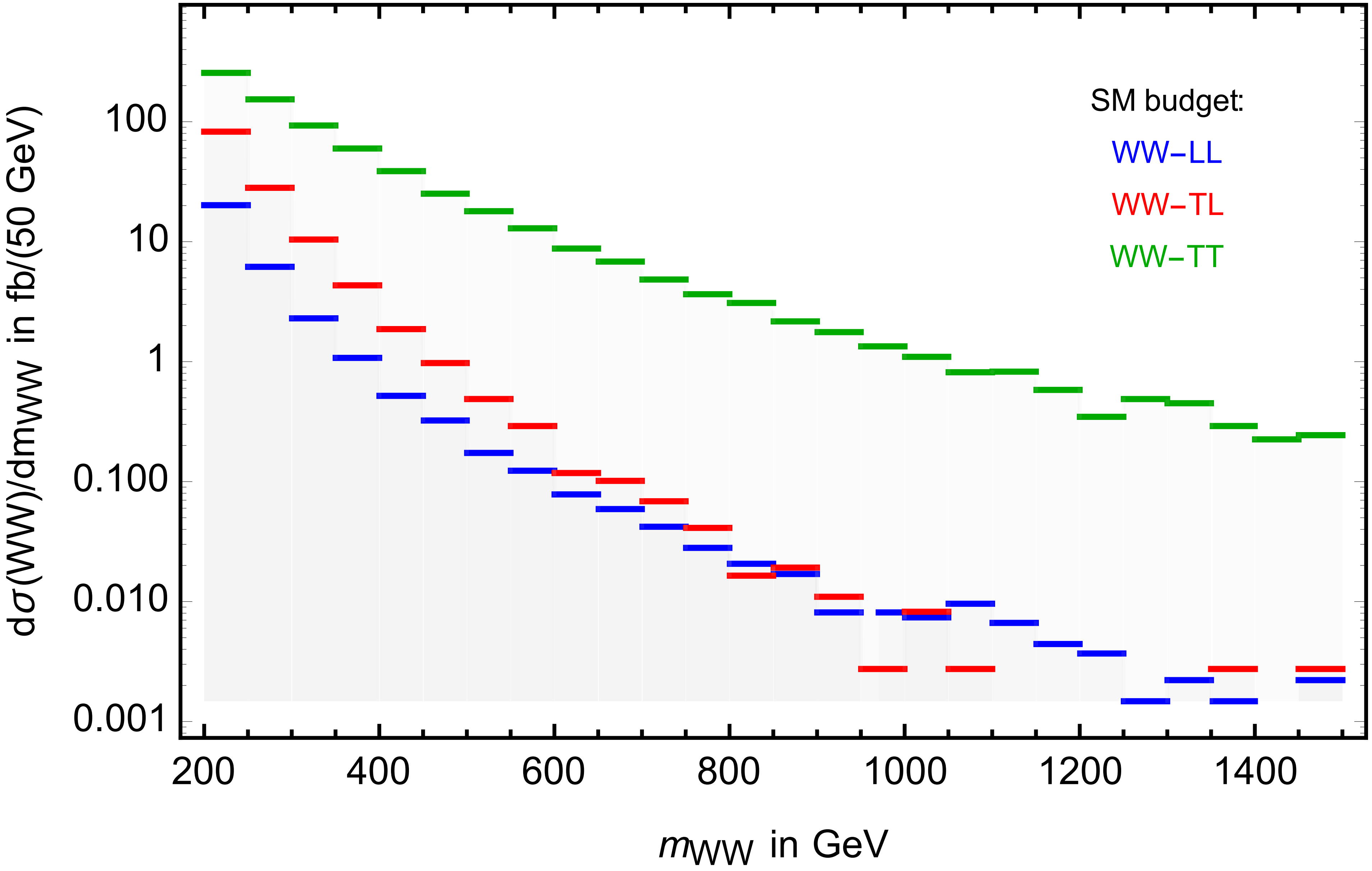
EFT not valid

Wh channel

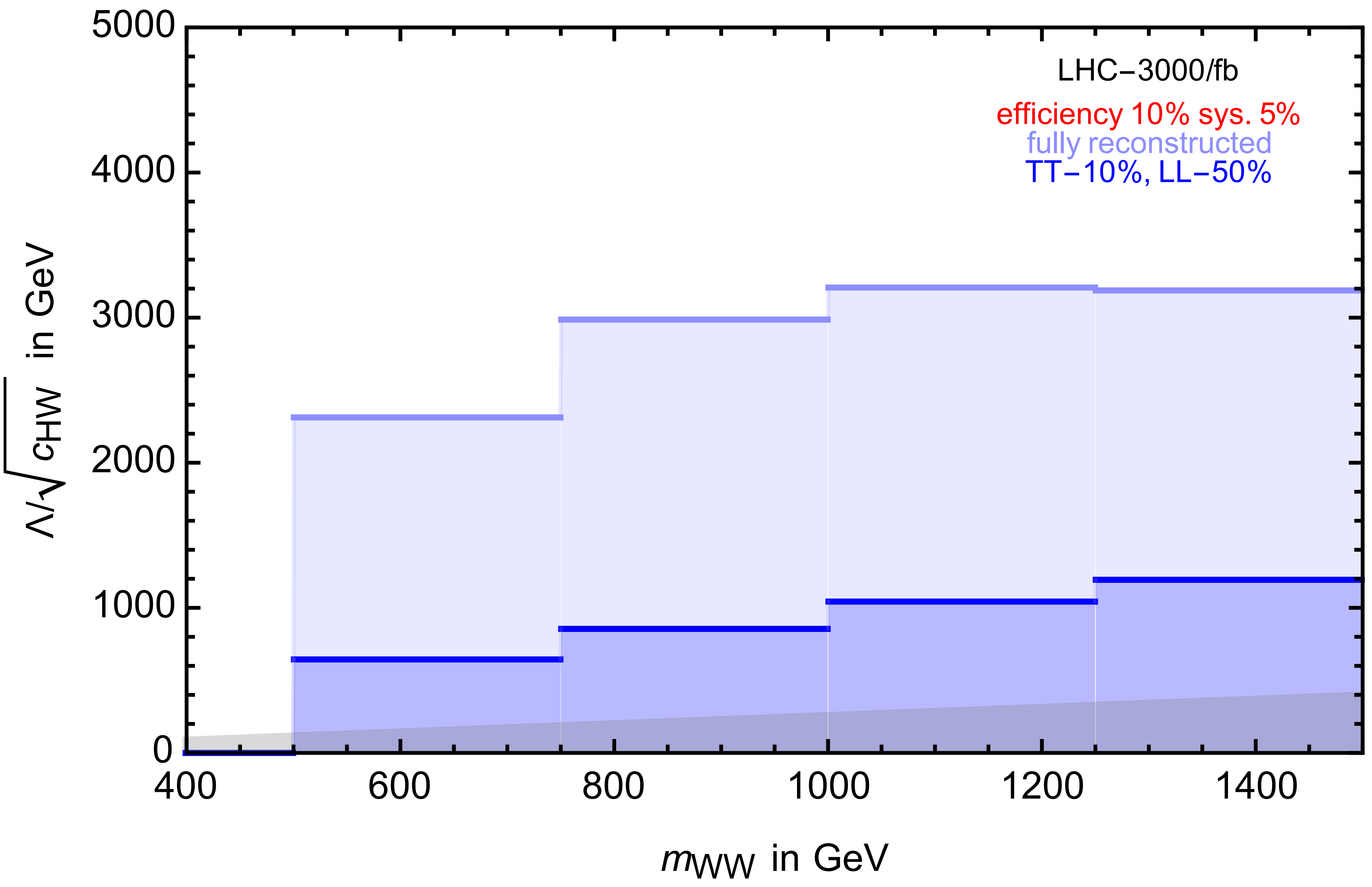


With assumptions about systematics and background.

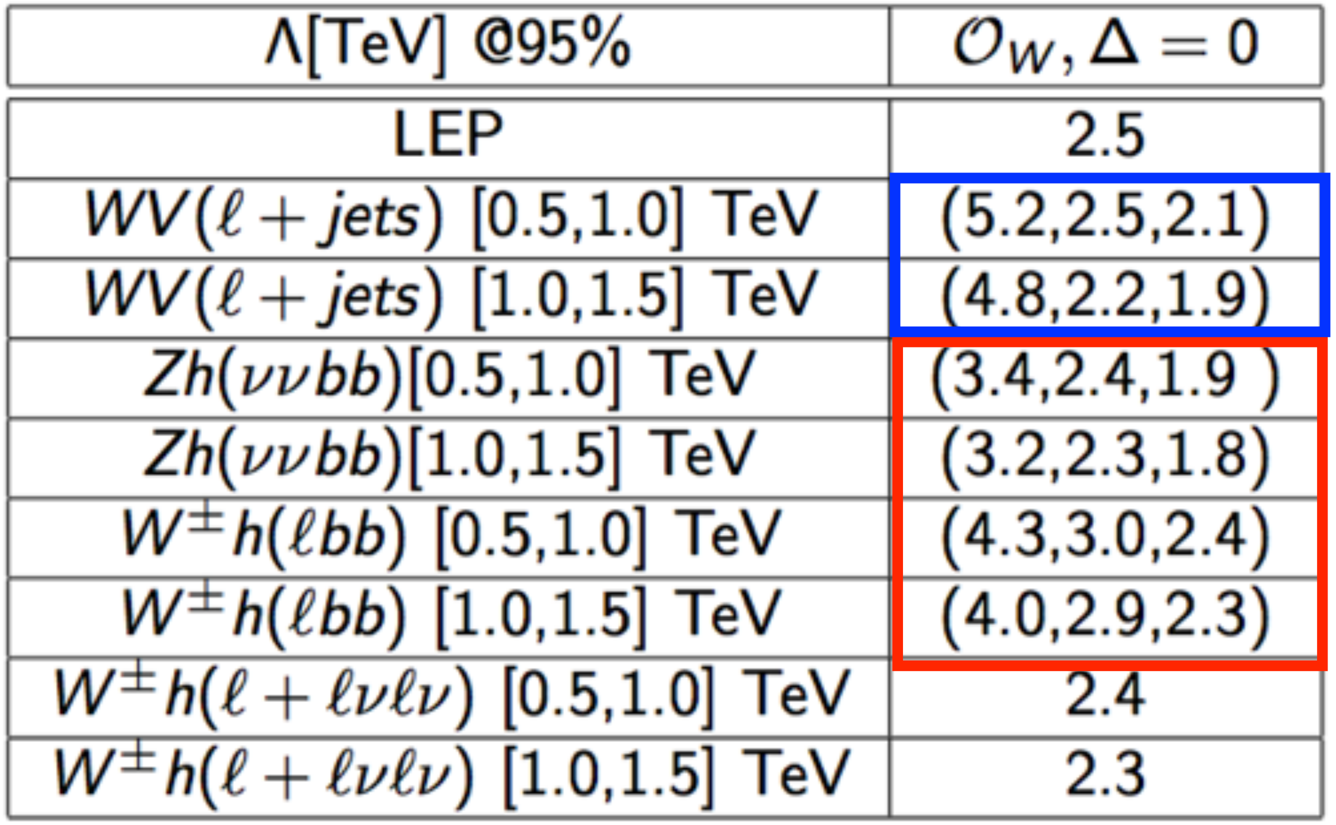
WW, semileptonic channel



WW, semileptonic channel



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

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

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

LHC benchmarks

$\Lambda[\mathrm{TeV}]$	$\mathcal{O}_W$	$\mathcal{O}_B$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_{3W}$
LEP	2.5	2.5	0.3	0.3	0.4
$WV(\ell + jets)$	$\boxed{4.8}(\boxed{1.9})$	$\boxed{1.5}(\boxed{0.71})$	$\boxed{4.8}(\boxed{1.9})$	$\boxed{1.5}(\boxed{0.71})$	$\boxed{1.2}$
$W^{\pm}h(\ell bb)$	$(\boxed{4.0,2.9,2.3})$		$(\boxed{4.0,2.9,2.3})$		
$W^{\pm}h(\ell + \ell\nu\ell\nu)$	1.6		1.6		
$h \to Z\gamma$			1.7	1.7	

☐ ideal case, perfect pol tagging, no systematics

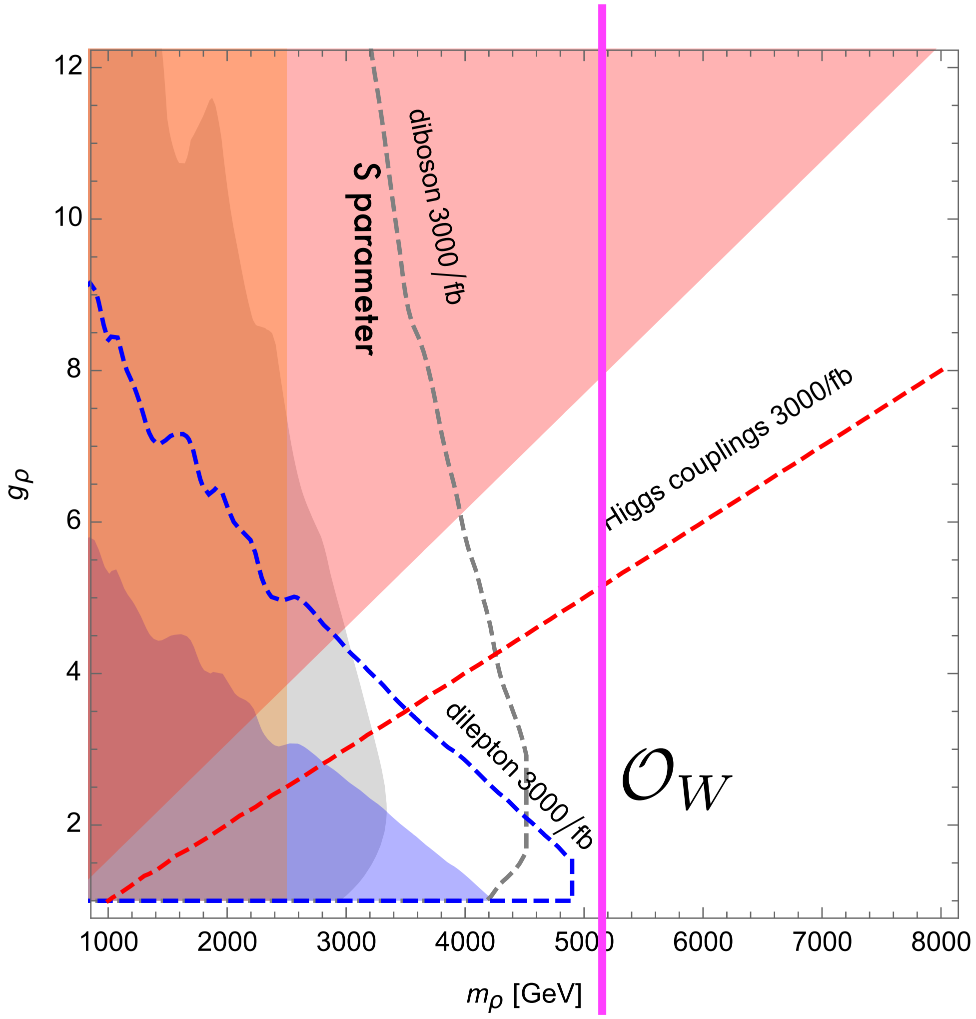
☐ tagging eff 50%, mis-tagging rate 10%, no systematics

☐ reducible bkg 0, 3, 10 times of the irreducible rate

☐ interference effect not important.

- Can beat LEP precision if some of these benchmarks can be reached.

Direct searches of composite resonance



Shaded areas:
current bounds

Most optimistic case can be competitive with direct narrow resonance searches.

The resonance may be broad, not covered by direct searches.

Dimension-8

- Less sensitive. But can be leading effect in certain NP scenarios.

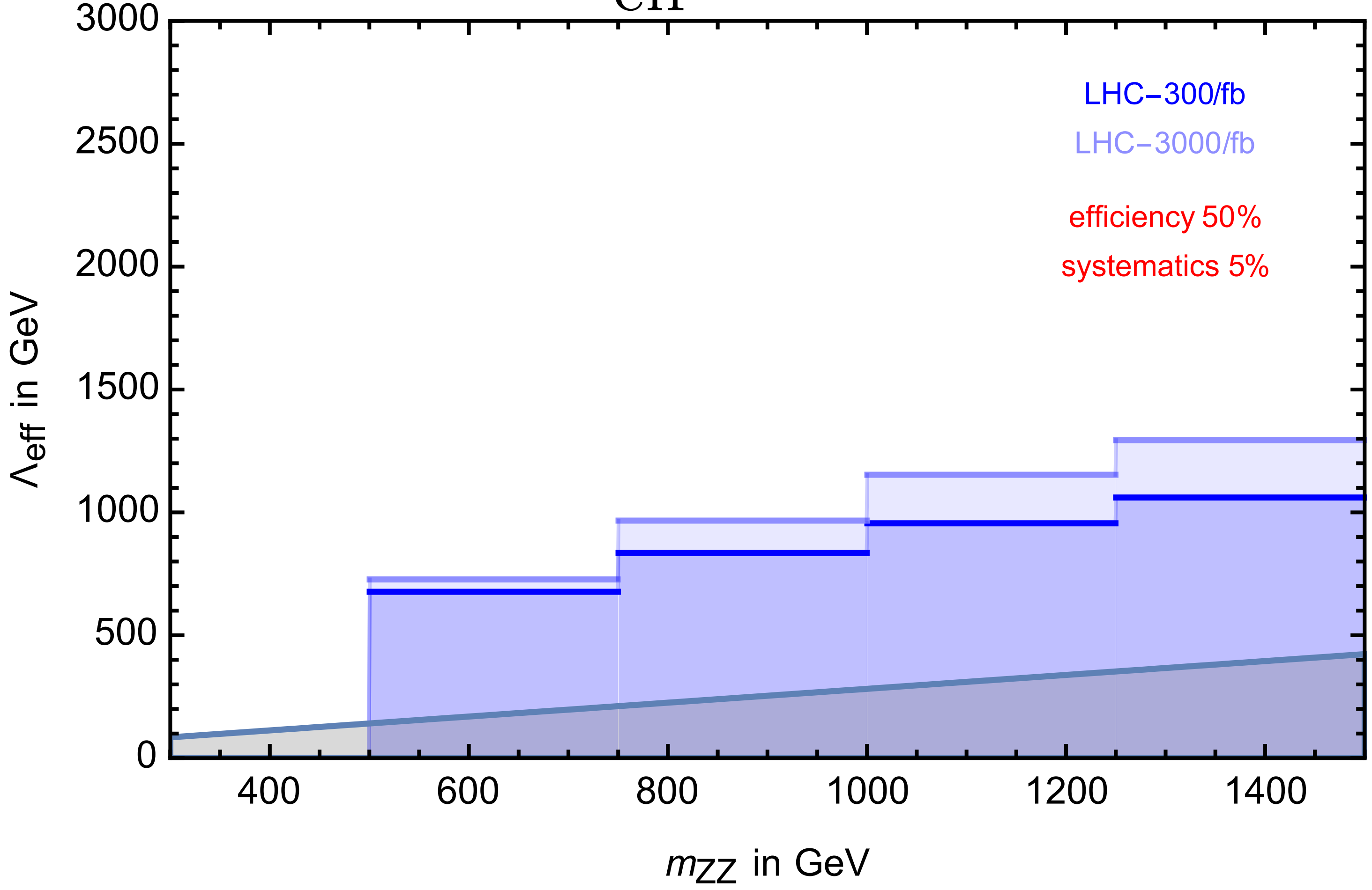
- Gives rise to unique signals.
  - ZZ, $\gamma\gamma$, hh.

- Can interfere with the SM in some cases where dim-6 do not.
  - e.g. W_T W_T . SM rate about 10 times $W_L W_L$.
  - Dim-6 interference with SM suppressed. Dim-8 interfere with SM. Equally important.

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

(h_{W^+}, h_{W^-})	SM	$\mathcal{O}_W$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_{3W}$	$\mathcal{O}_8$
$(\pm, \mp)$	1	0	0	0	0	$\frac{E^4}{\Lambda^4}$

$$\frac{g^2}{\Lambda_{\text{eff}}^4} T_f^{\mu\nu} W^a_{\mu\rho} W^{a\ \rho}_{\nu}$$



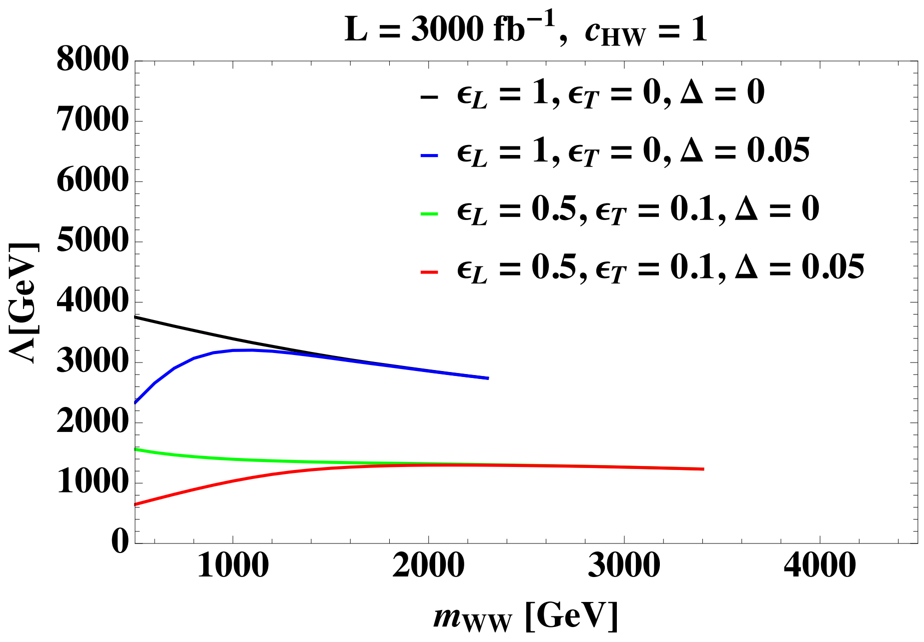
Λ[TeV]	$\mathcal{O}_{TWW}$	$\mathcal{O}_{TWB}$	$\mathcal{O}_{TH}$	$\mathcal{O}^{(3)}_{TH}$
$WV(\ell + jets)$	0.90	0.90	1.1(0.83)	0.83(0.65)
$W^{\pm}h(\ell bb)$				(0.86,0.79,0.76)
$W^{\pm}h(\ell + \ell\nu\ell\nu)$				0.67

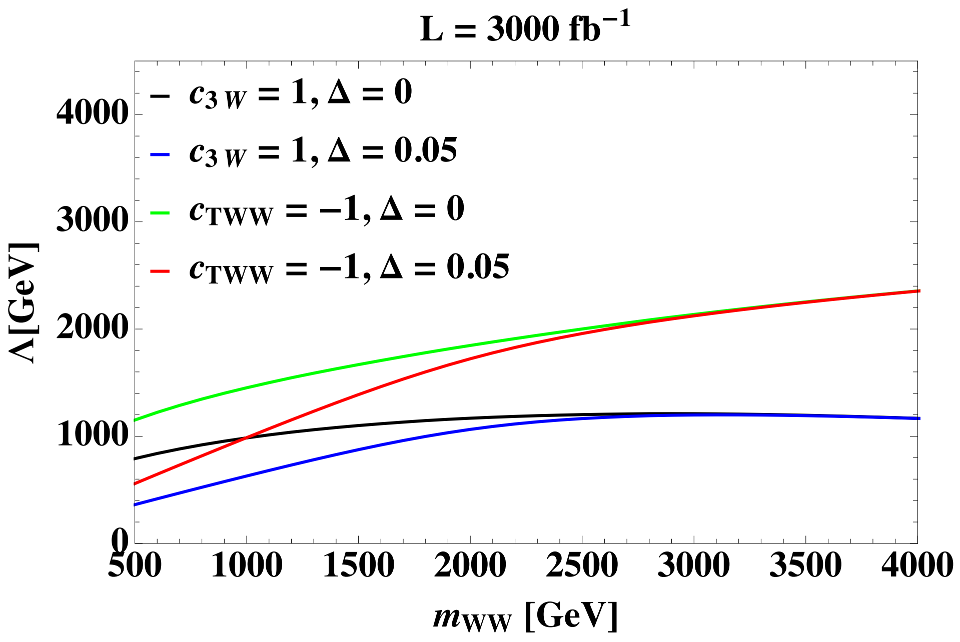
Conclusion

- LHC is pursuing a comprehensive program which covers the ground pretty well. After Moriond 2017, slow gain with luminosity.
- A promising long term prospect at LHC: focusing on non-resonant broad features. Di-boson, ttbar, etc.
- Difficult. But a lot data can make a significant difference here!
- May find other things, such as broad resonance, along the way.
- Even without a discovery, this can have lasting impact on future directions (similar to LEP electroweak program).

extra

c_W





$$\mathcal{M}_f^{00} \to -\frac{\sin\theta}{2}\left\{T_f^3 g^2 + Y_f g'^2 + \frac{s}{\Lambda^2}\left[(c_W + c_{HW})T_f^3 g^2 + (c_B + c_{HB})Y_f g'^2\right]\right\} - c_{TH}\frac{g^2}{16}\frac{s^2}{\Lambda^4}\sin 2\theta$$
$$- g^2 \sin\theta \frac{s}{\Lambda^2}\left[\delta_f^{u_R} c_R^u + \delta_f^{d_R} c_R^d + \delta_f^{u_L}(c_L^q + c_L^{(3)q}) + +\delta_f^{d_L}(c_L^q - c_L^{(3)q})\right]$$

Status of new physics searches

From gravity to the Higgs we're still waiting for new physics

Annual physics jamboree Rencontres de Moriond has a history of revealing exciting results from colliders, and this year new theories and evidence abound

Guardian