Prospects of exotics searches at the LHC

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Work in collaboration with Da Liu and Andrea Tesi

Planck 2017. May 27, Warsaw

Strongly coupled new physics and Precision measurements at the LHC

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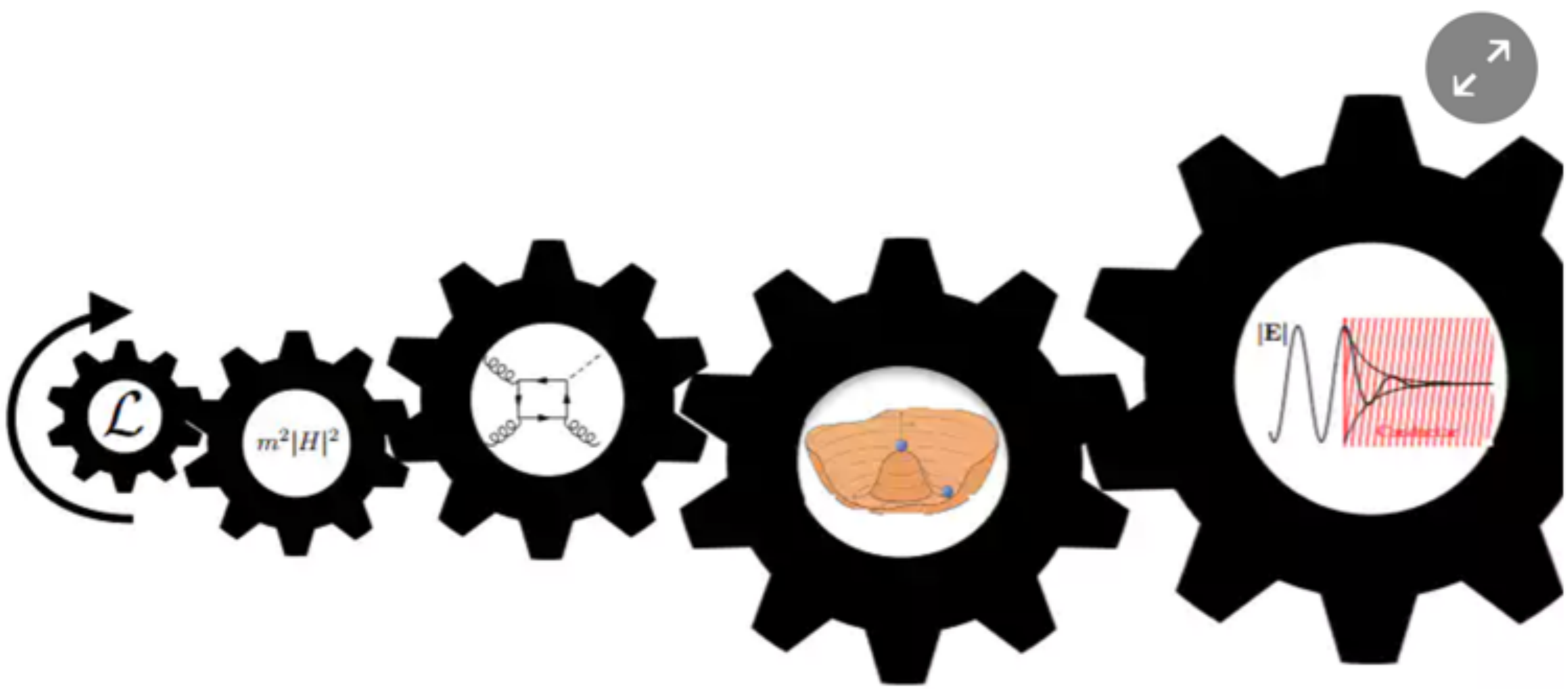
Status of new physics searches

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

Status of BSM

- Is X (X≈SUSY) dead?
  - No. It can always be a little heavier.
  - Concrete. Still addresses a lot of questions.
  - Can't just abandon the lamppost. Should keep going with the "standard" searches.

Status of BSM

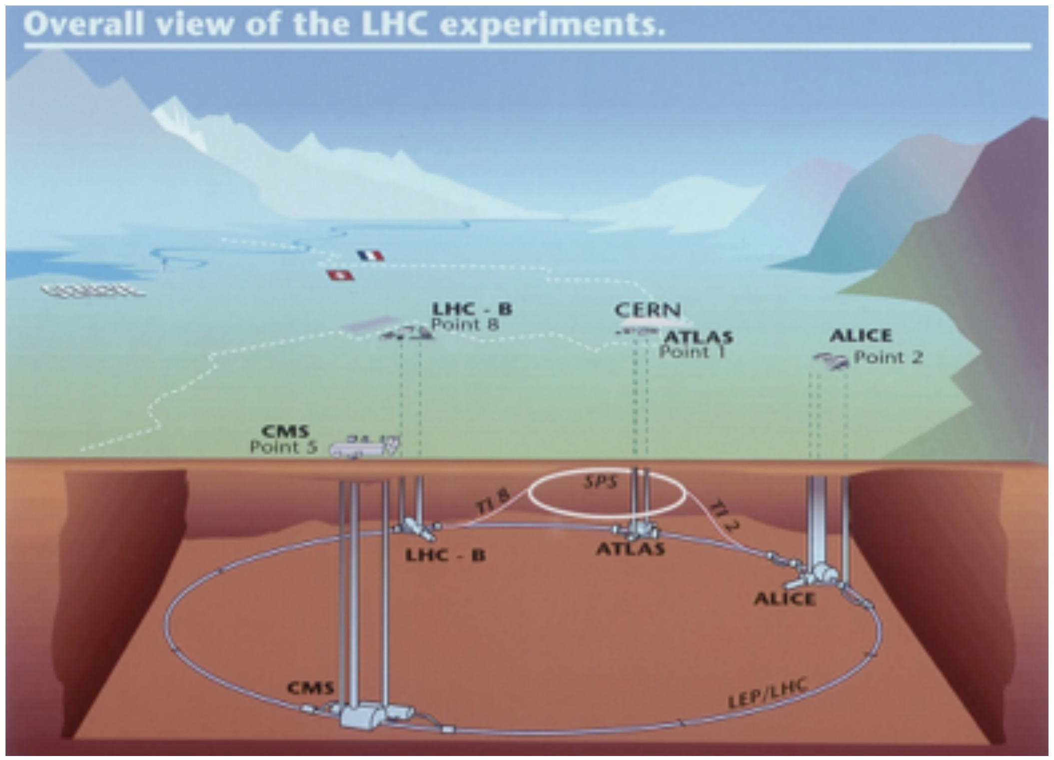
If you know of a better hole, go to it

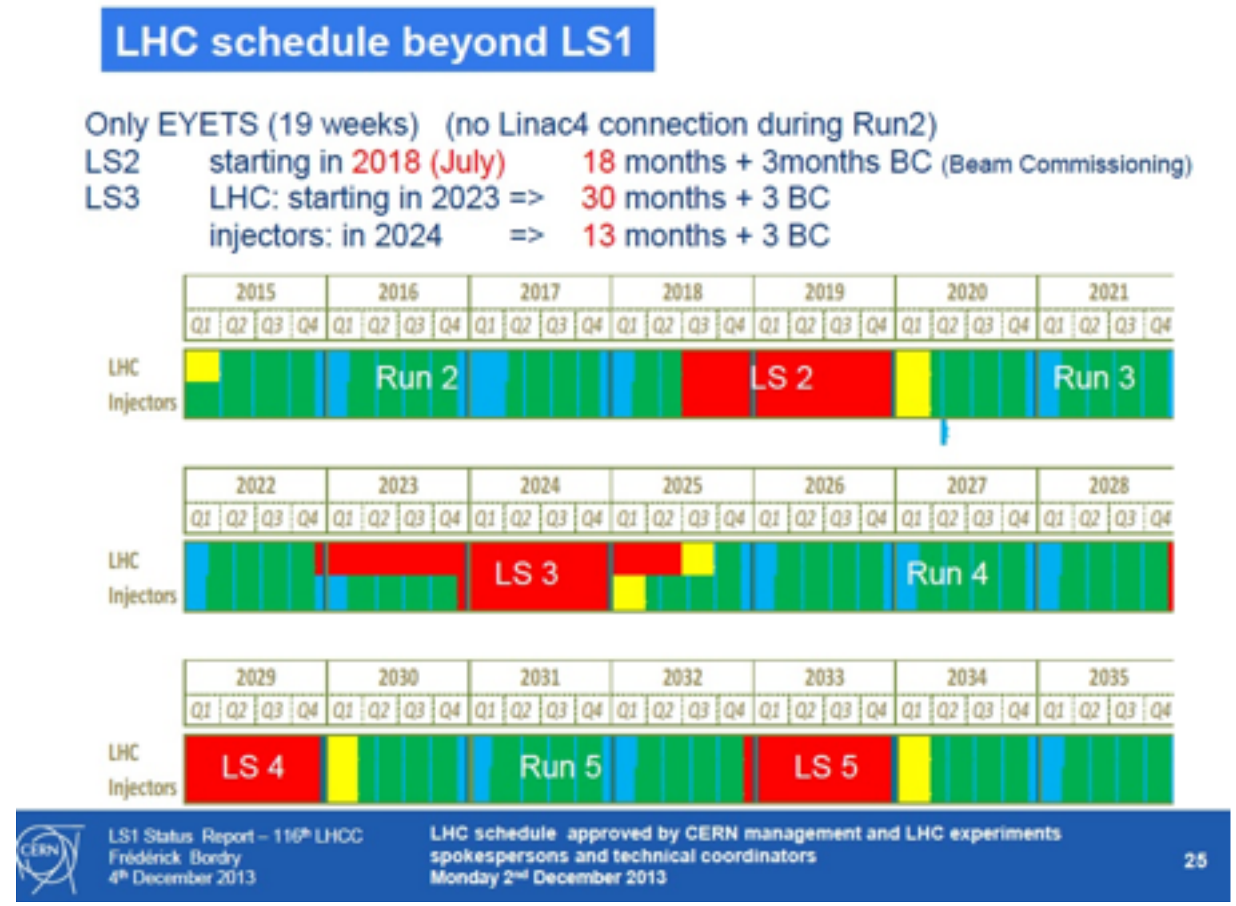
John Ellis on SUSY.

I probably disagree with him on the exact location and size of the "better hole"

But I share the general sentiment.

Future of Large Hadron Collider

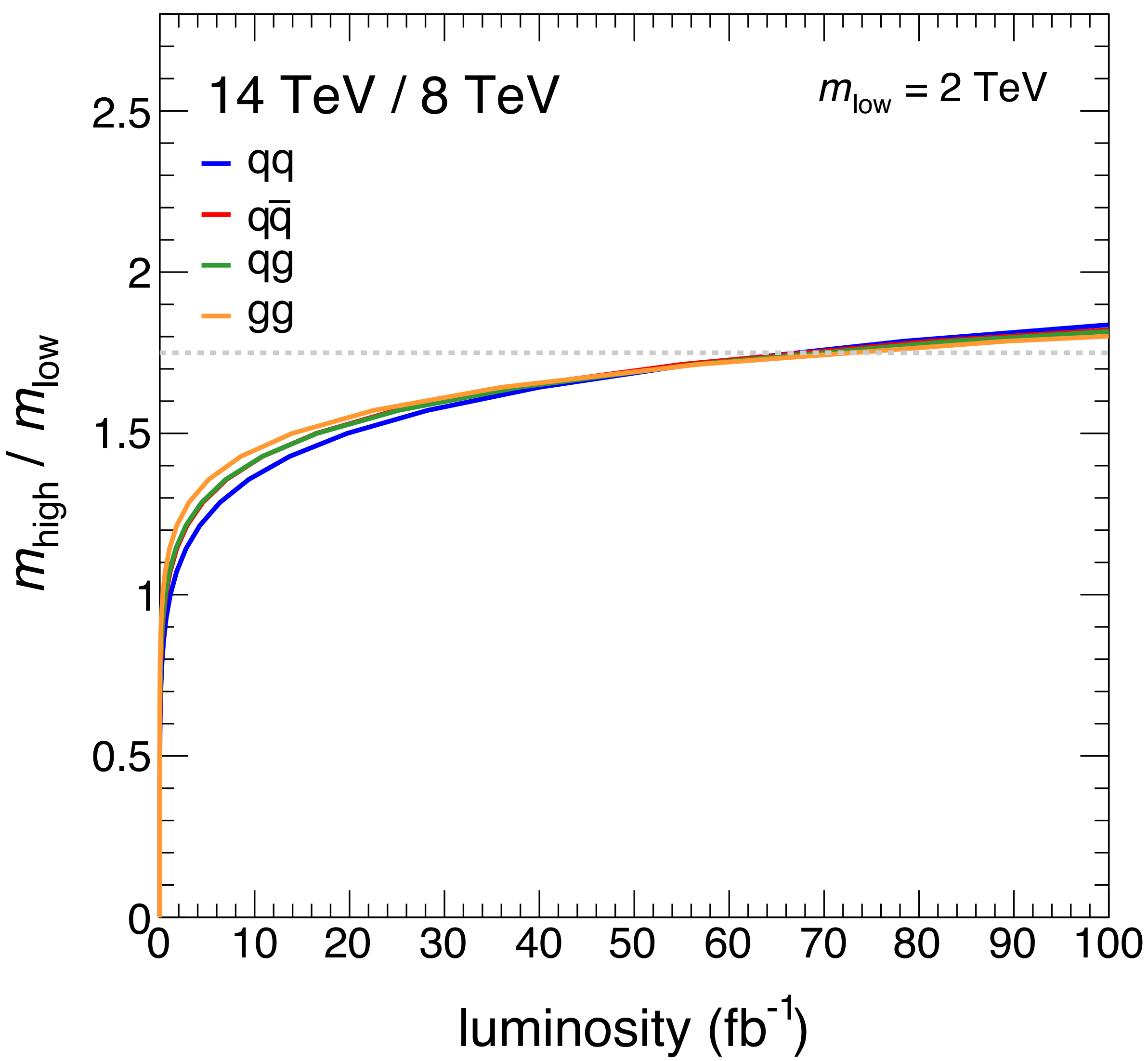




– Will continue and improve in the next two decades
  - E_{cm} = 13-14 TeV.
  - 95+% more data.

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

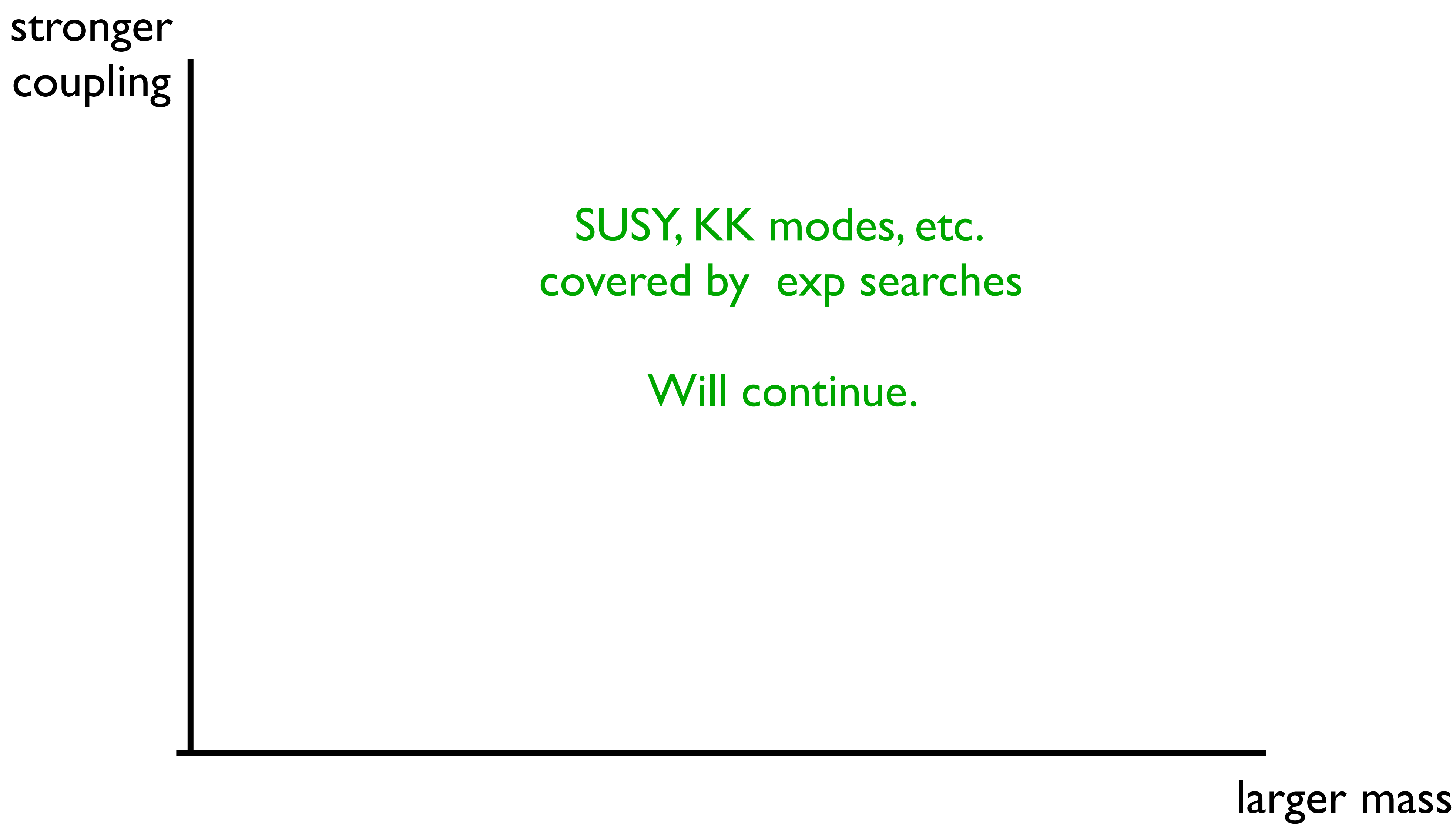
LHC will press on to search for SUSY, extraD, composite... with slower progresses

Instead of just waiting...

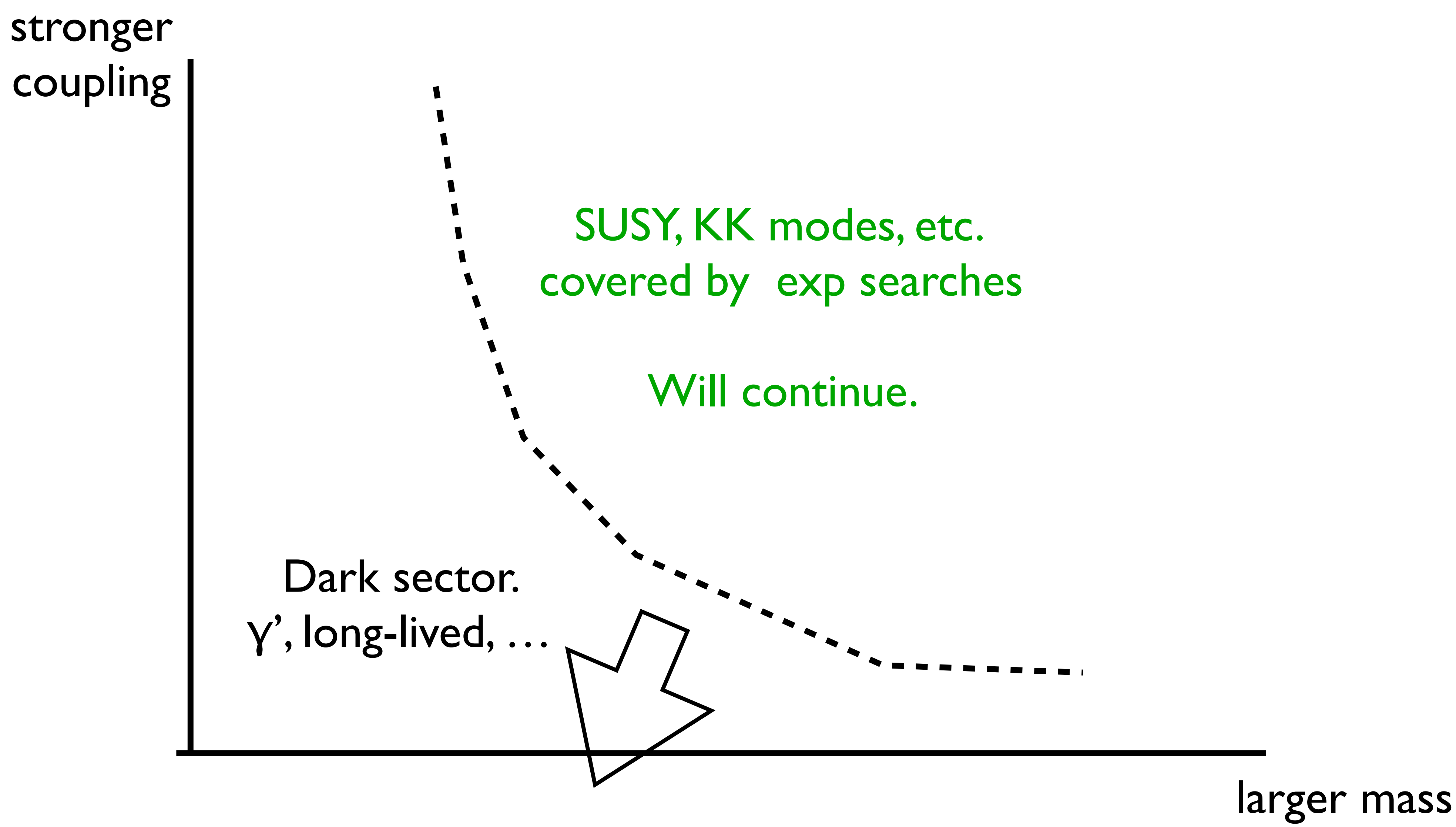
Do more with (95+% more) LHC data.

On-going work. Rough estimates.
Goal is to point out promising directions rather than making precise projection.

Pushing boundary

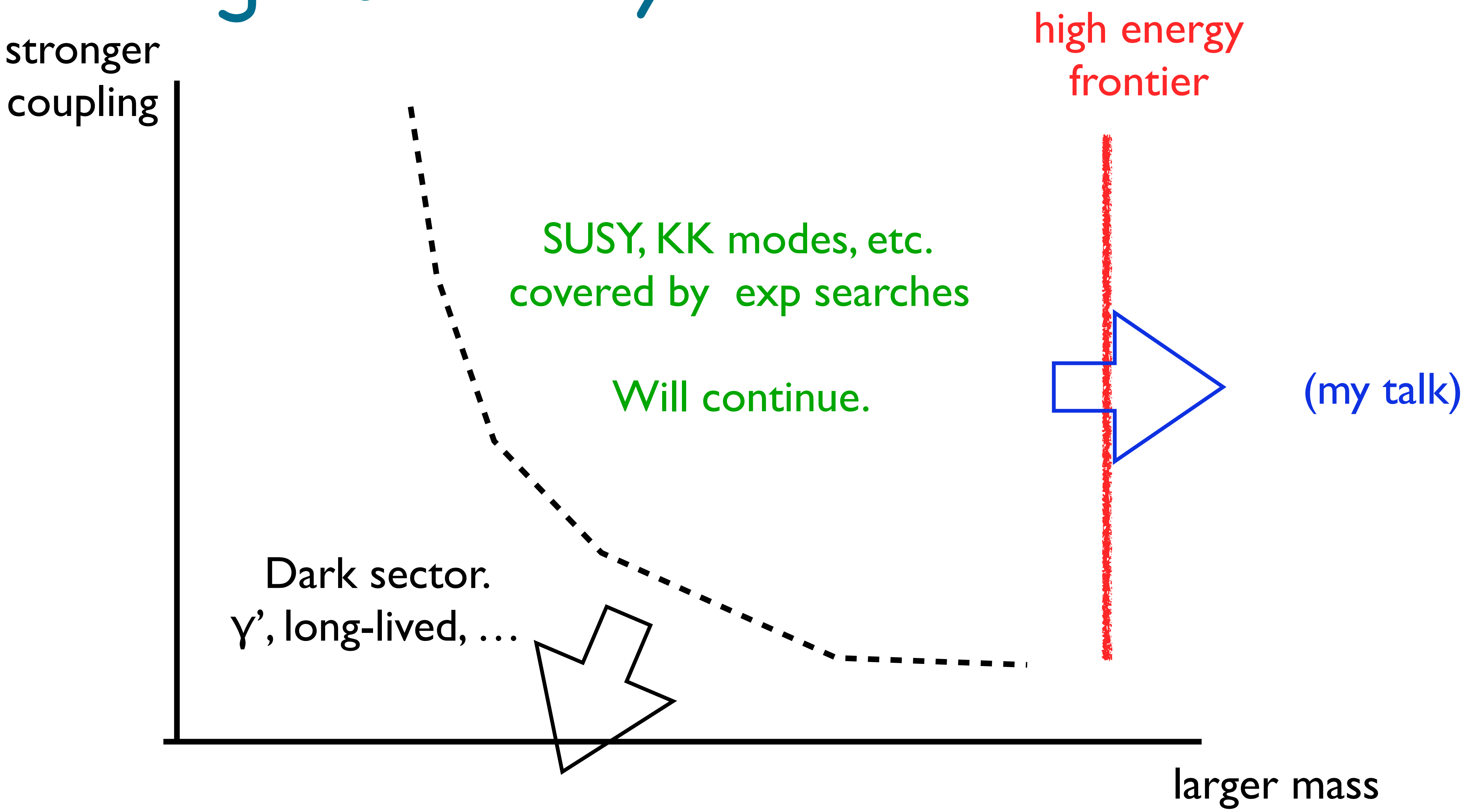


Pushing boundary



Very important to search.
In the spirit of leaving no
stone unturned

Pushing boundary



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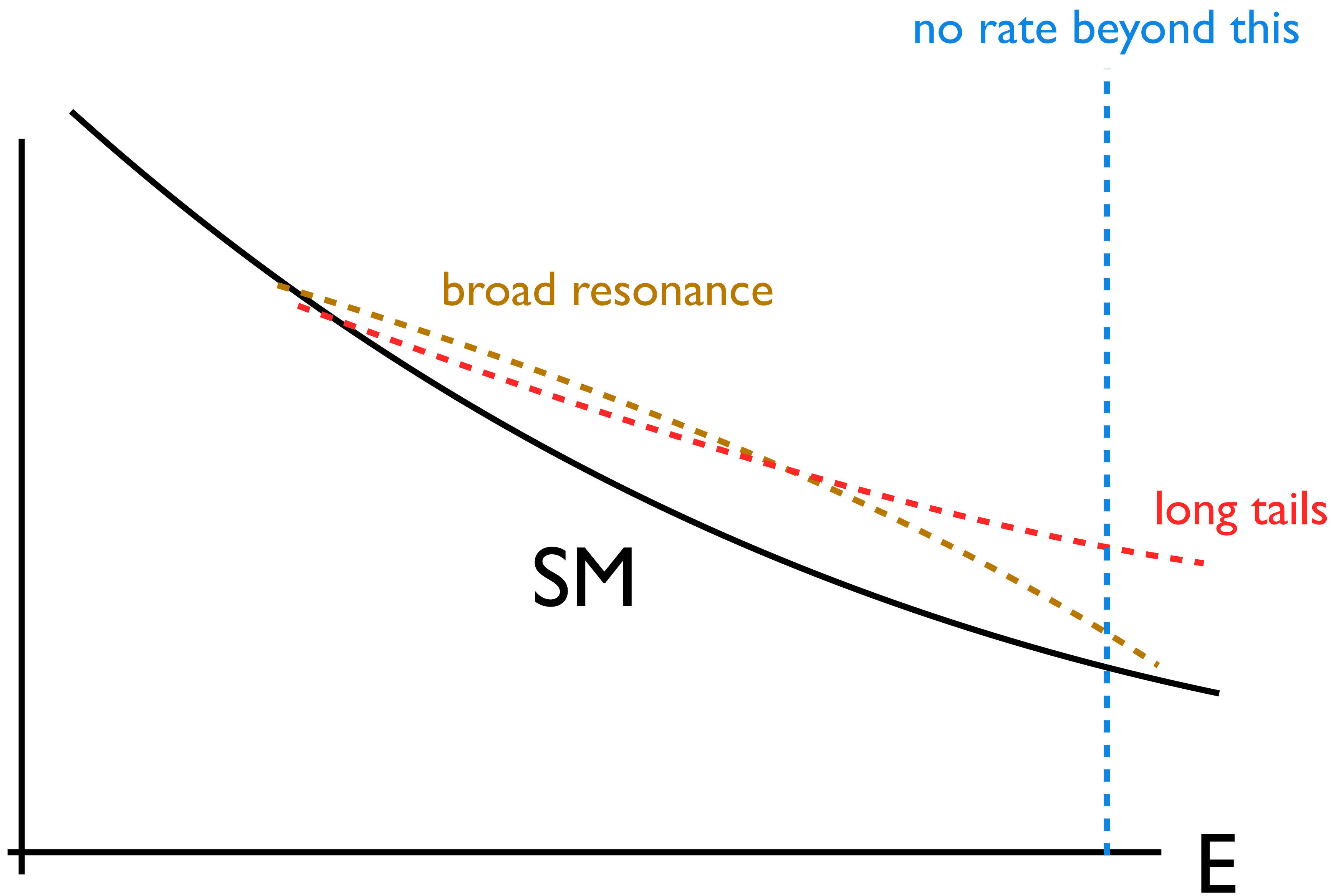
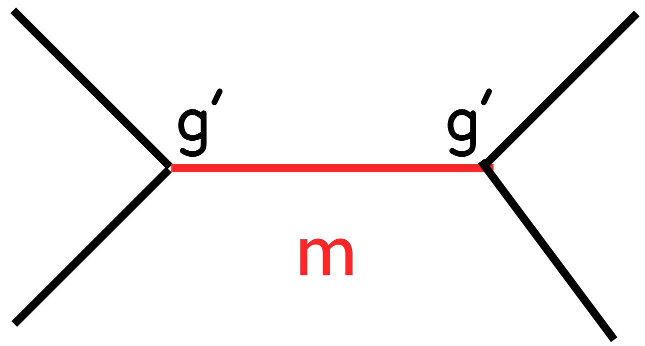
Shapes of signals



- Not rate limited, but small S/B, systematics...
- Strongly coupled heavy new physics

e.g. Liu, Pomarol, Rattazzi, Riva

Naive 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

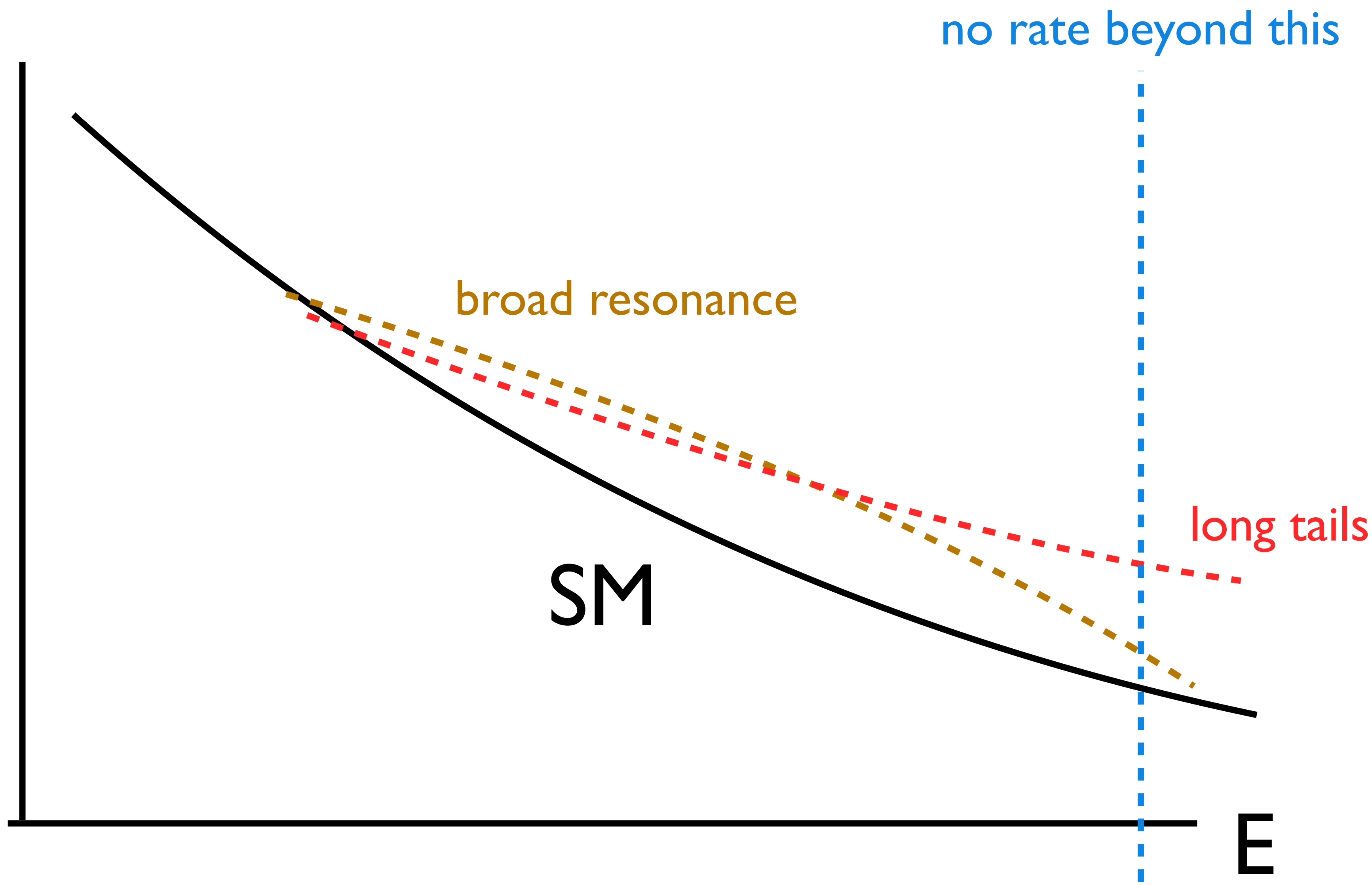
For example, Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer

With more motivation:

- 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”

For example, talks of Franceschini and Miro at this conference

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

Precision measurement at the LHC possible?

LEP precision tests probe 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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$(\pm, \mp)$	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.
- Need large SM piece to interfere with. Longitudinal (0,0) most promising.

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

growing with energy

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

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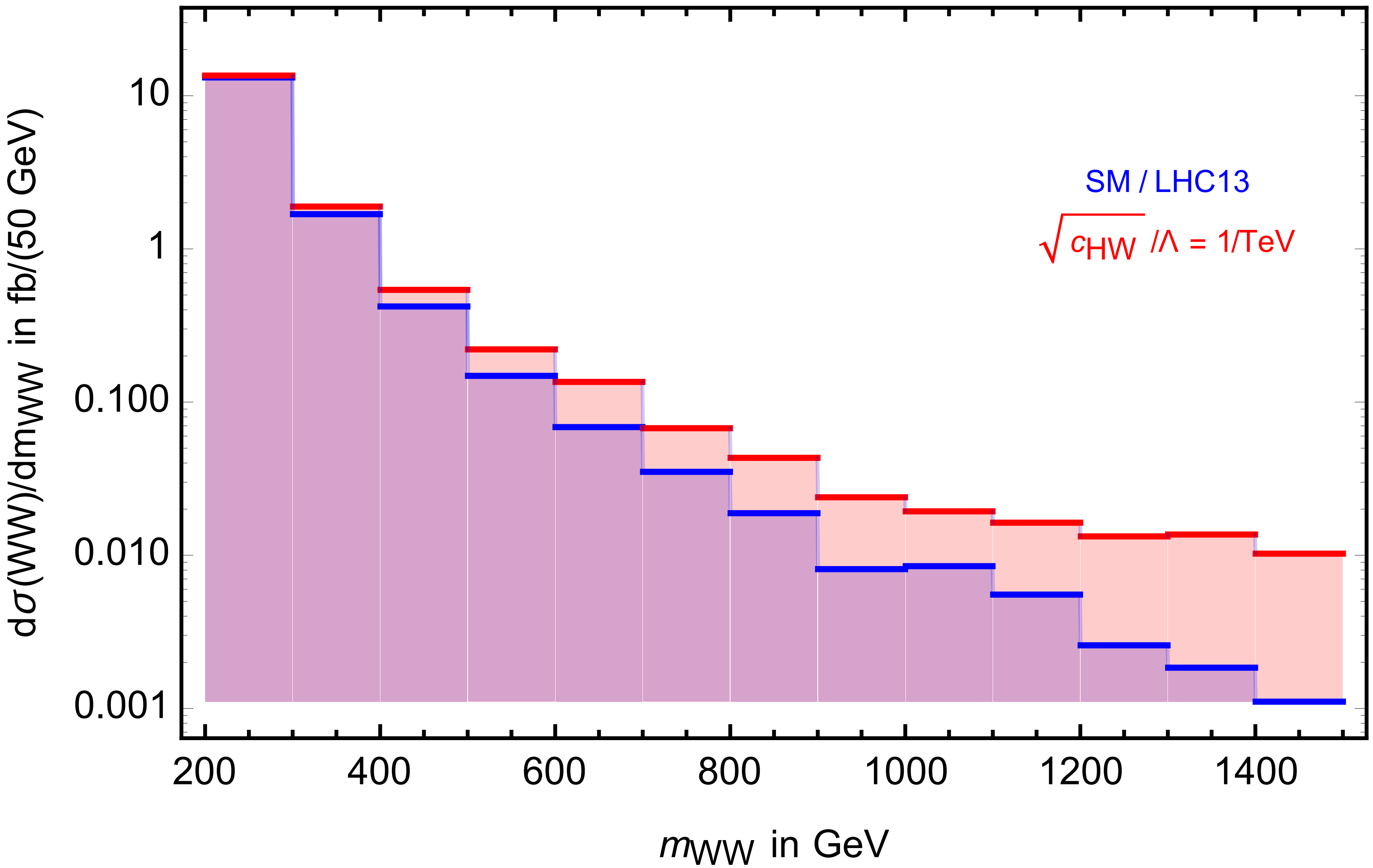
Growing with energy



Observables.

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

- 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.

Sensitivity to tails. Ideal case.

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

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

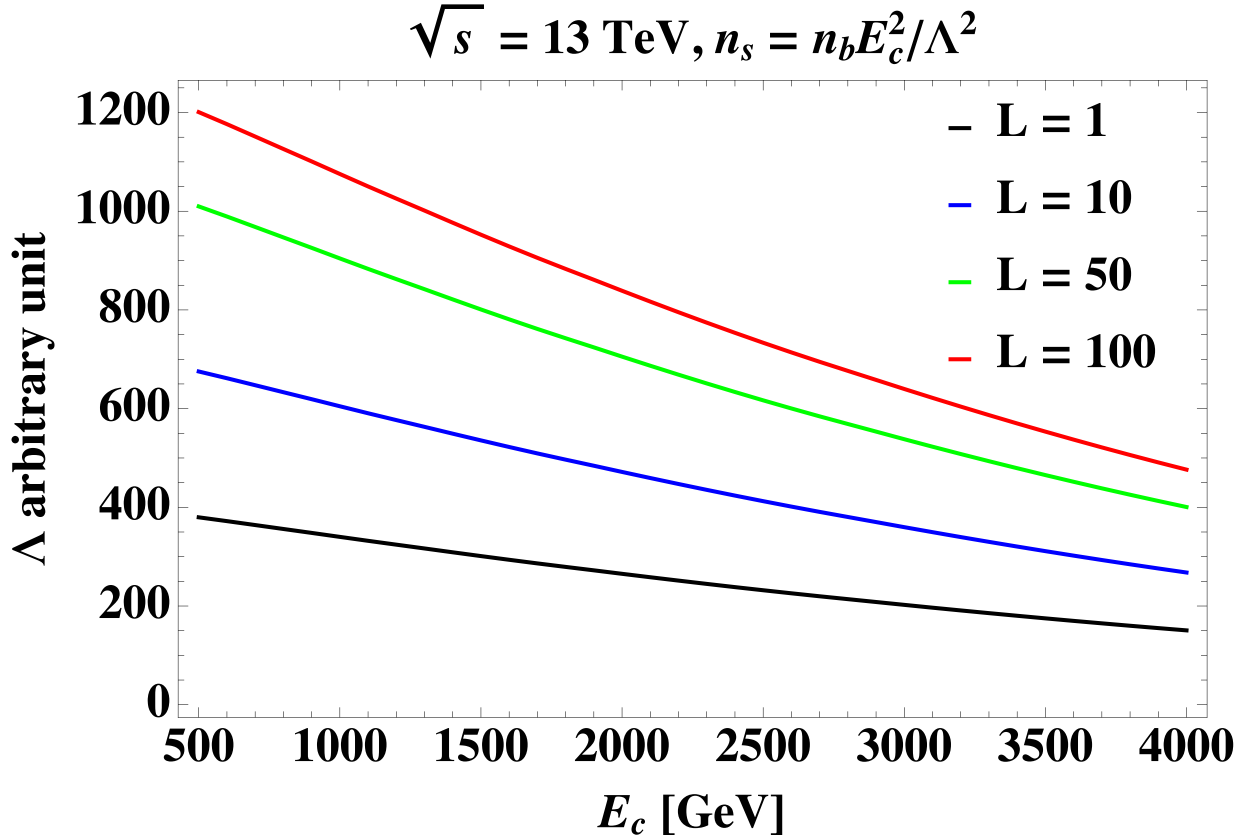
E: energy bin of the measurement

n: 5-8 falling parton luminosity

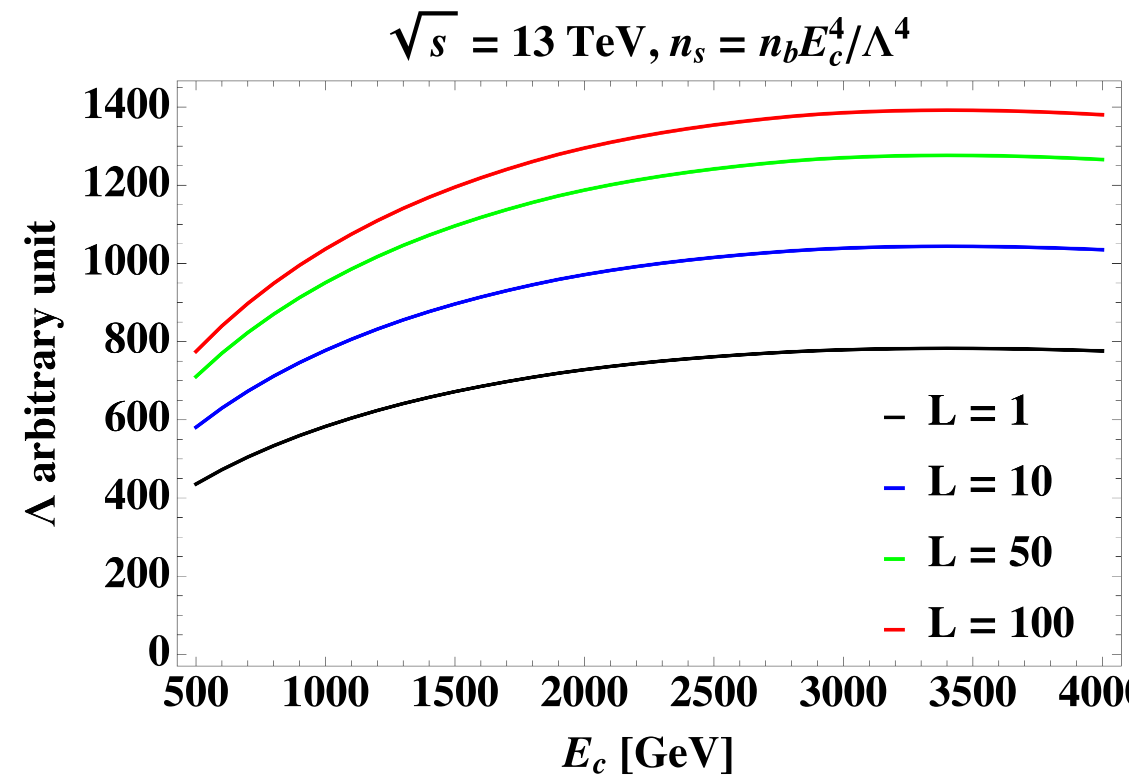
$$\frac{S}{\sqrt{B}} \sim \sqrt{\frac{\mathcal{L}}{E^n}}\left(\frac{E}{\Lambda}\right)^d$$

$\mathcal{L}$ = 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 (operator)^2, effect further suppressed by $(E/\Lambda)^d$.

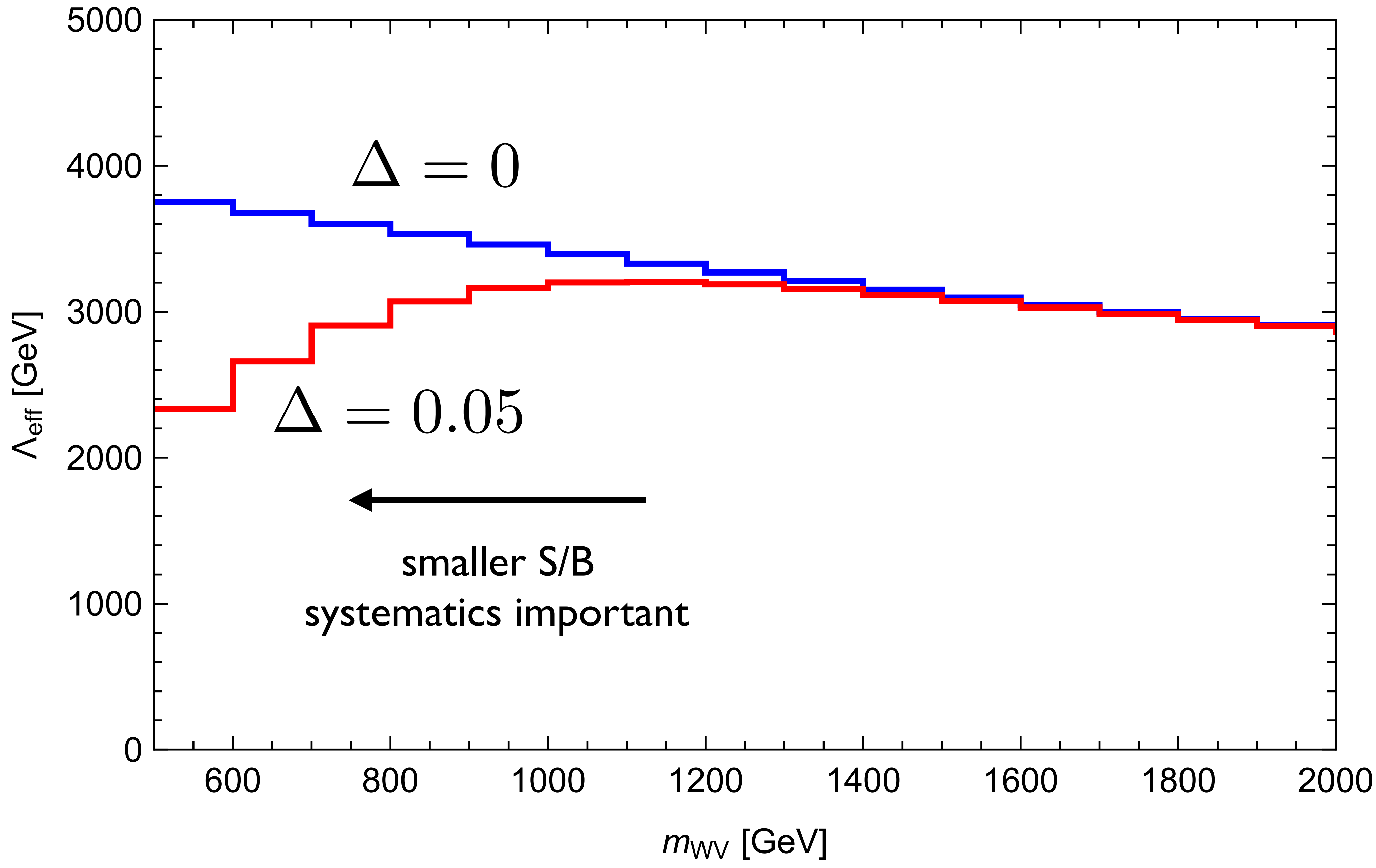


dim 6, with interference



dim 8 with interference
or dim 6 without interference

The role of systematics



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

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

LEP precision test:

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

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

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

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).

Limit projection

Crude parameterization of significance

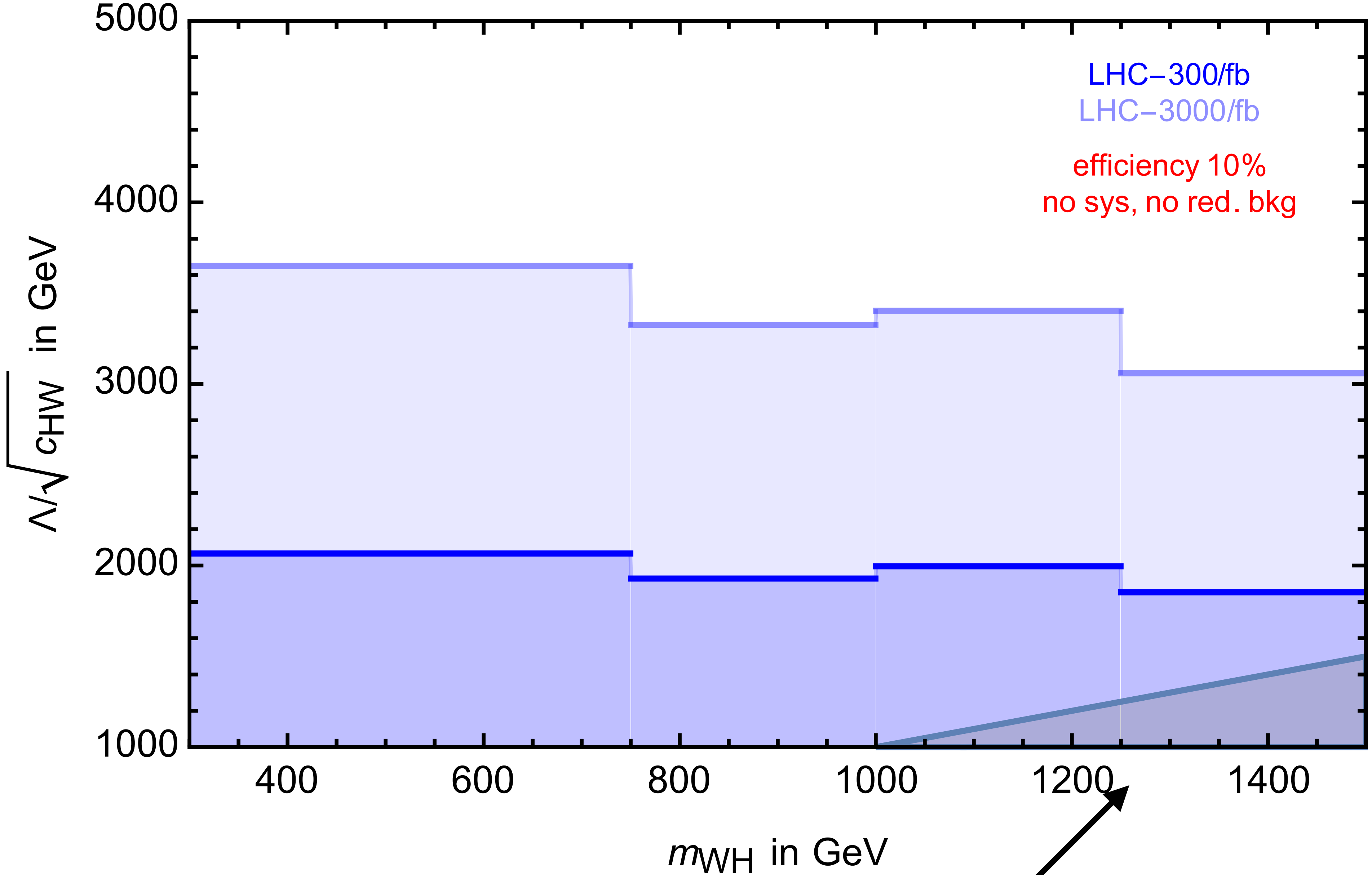
$$\frac{S^{h_1}}{\sqrt{B}} = \frac{\epsilon_{\rm sig}[\epsilon_{h_1}(\mathcal{M}^{h_1}_{\rm sig} + \mathcal{M}^{h_1}_{\rm SM})^2 + \sum_{h\neq h_1} \epsilon_h(\mathcal{M}^{h}_{\rm sig} + \mathcal{M}^{h}_{\rm SM})^2] \times \mathcal{L}}{\sqrt{[\epsilon_{h_1}\sigma^{h_1}_{\rm SM} + \sum_{h\neq h_1} \epsilon_h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

ϵ_{sig} signal efficiency or acceptance

ϵ_h (mis)tag probability of polarization h

Δ: systematical error

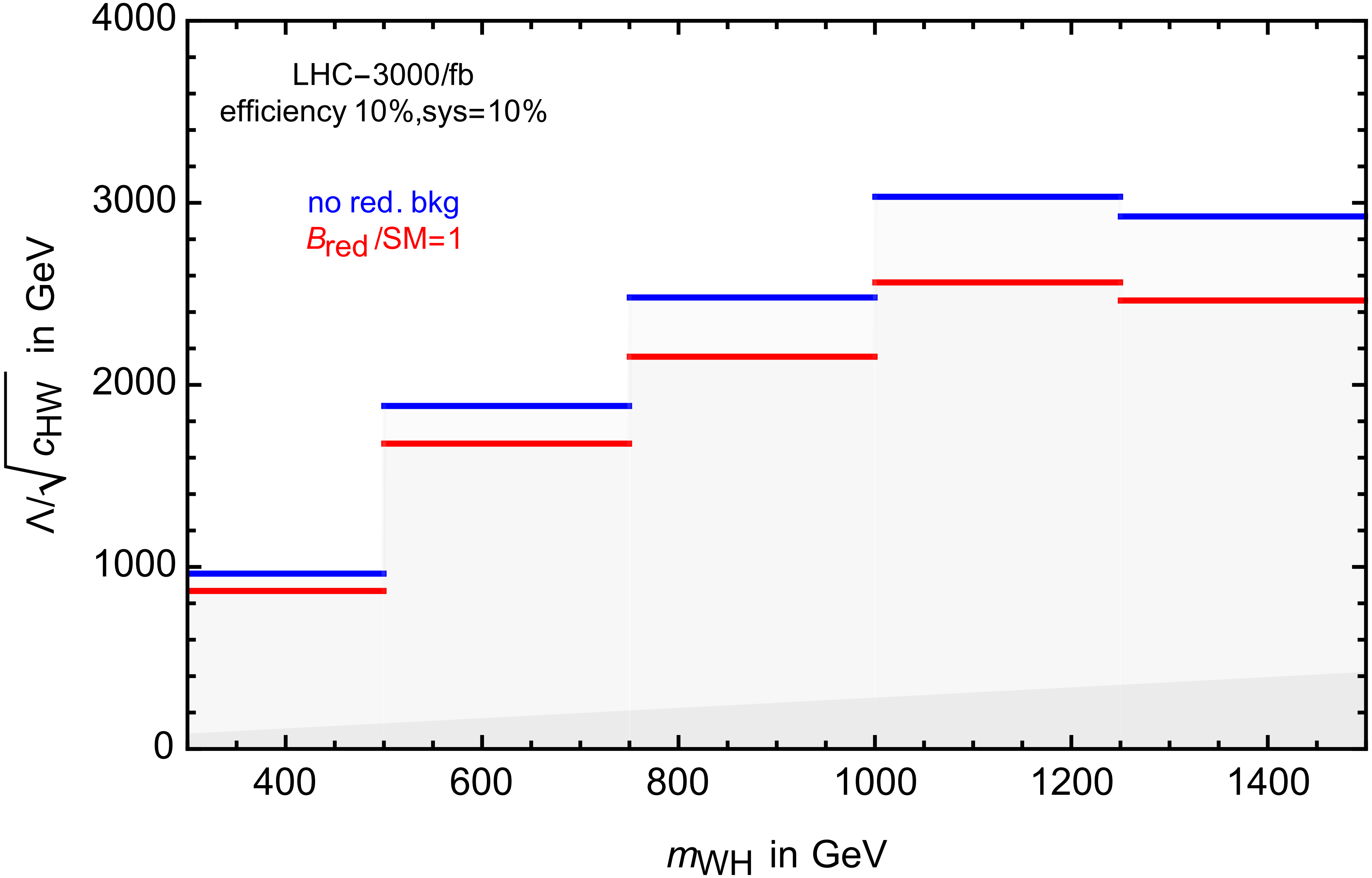
Wh channel



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

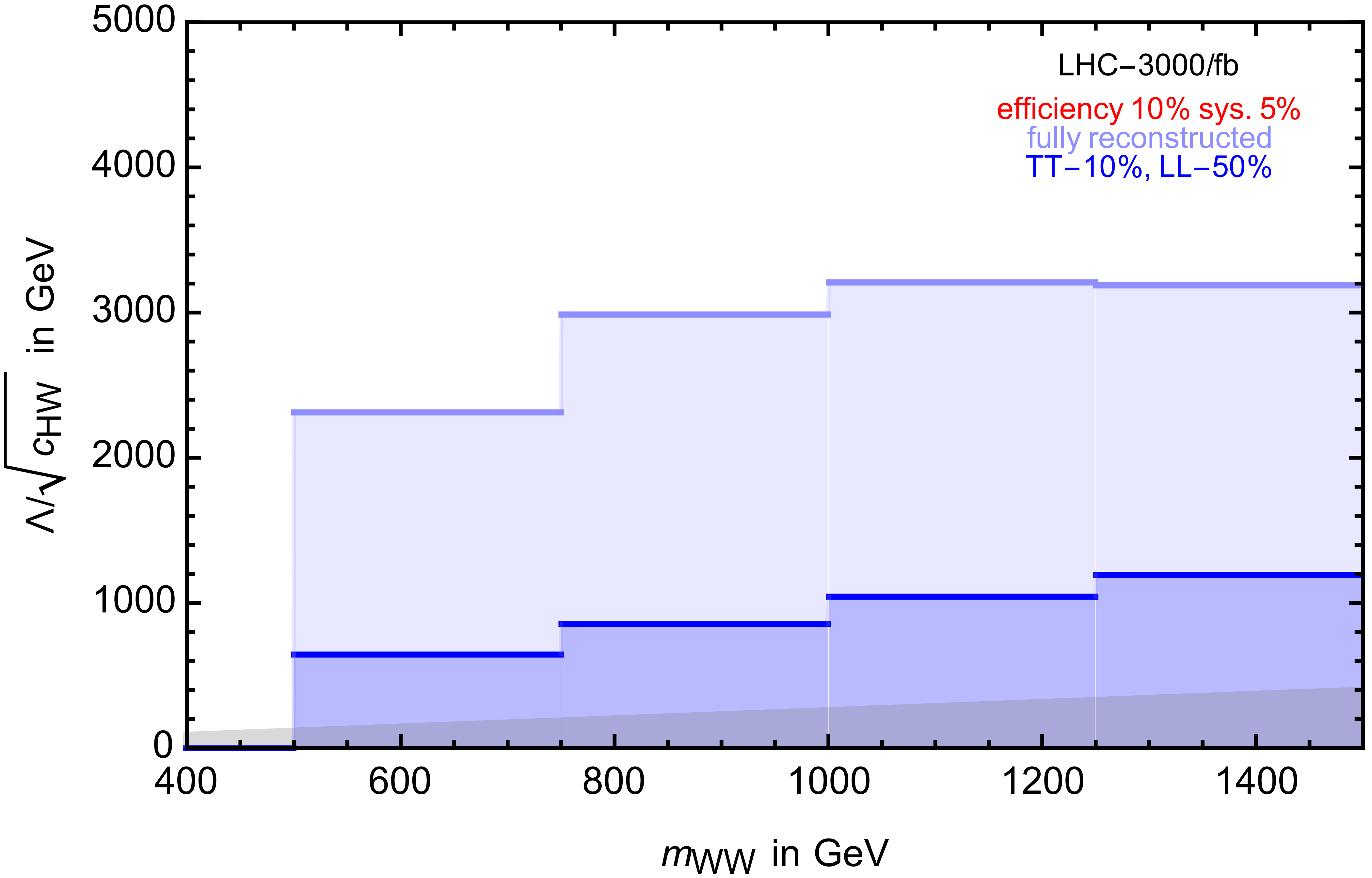
EFT not valid

Wh channel



With assumptions about systematics and background.

WW, semileptonic channel



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

LHC benchmarks

Λ[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
$WV(\ell + jets)$	4.8(1.9)	1.5(0.71)	4.8(1.9)	1.5(0.71)	1.2
$W^{\pm}h(\ell bb)$	(4.0,2.9,2.3)		(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

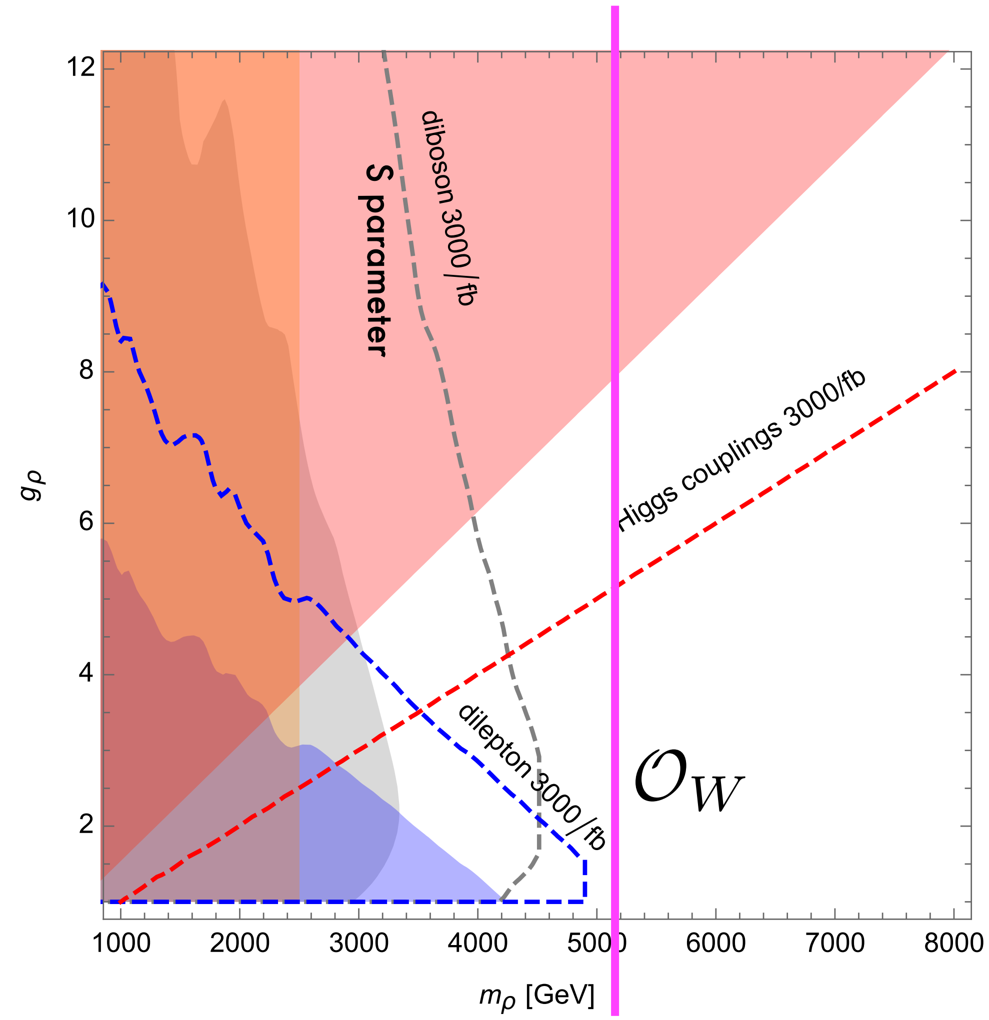
tagging eff 50%, mis-tagging rate 10%, no systematics

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.

Compare with direct searches



Shaded areas:
current bounds

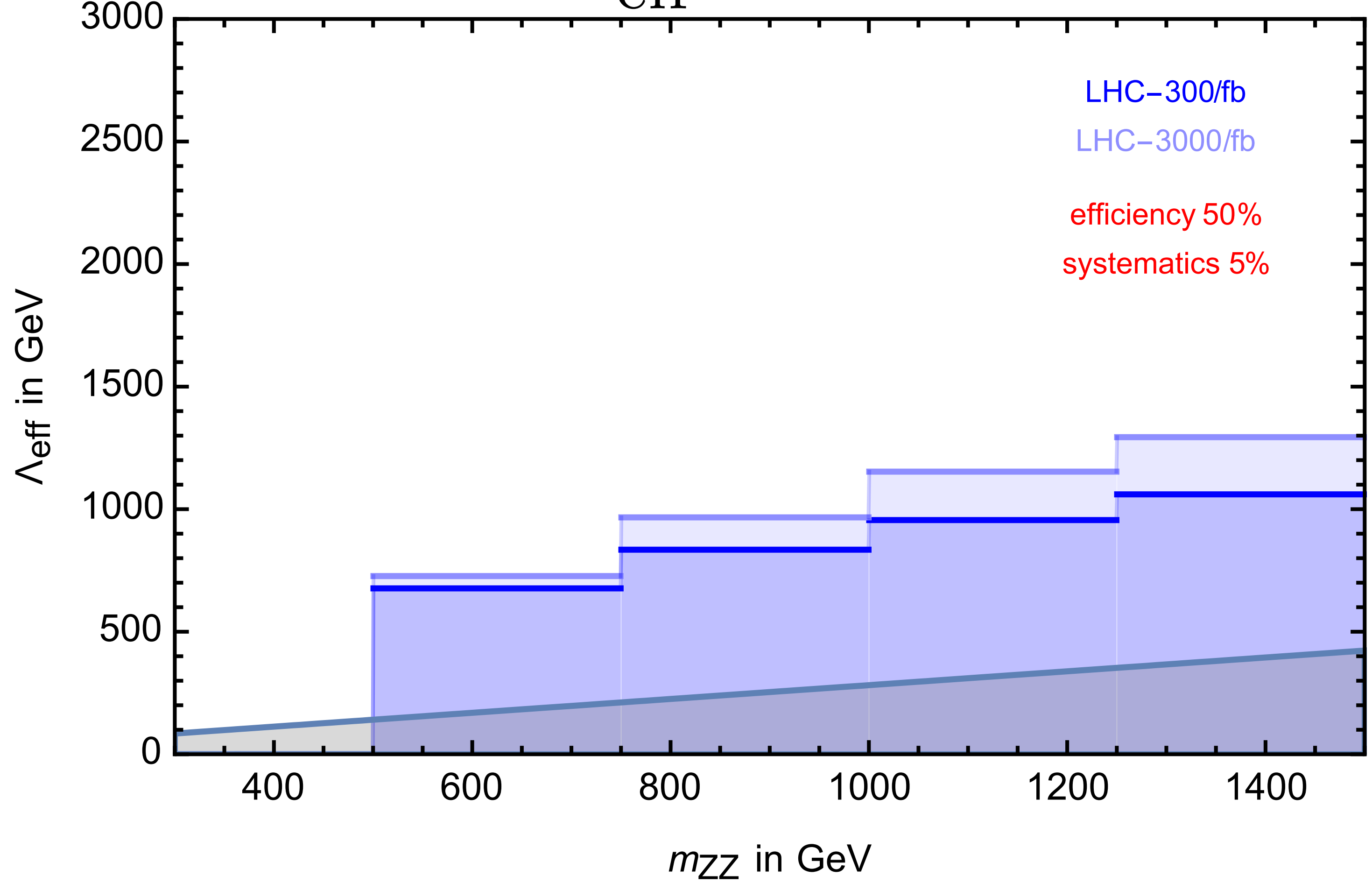
Most optimistic case can be competitive with direct narrow resonance searches.

More importantly, 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.

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



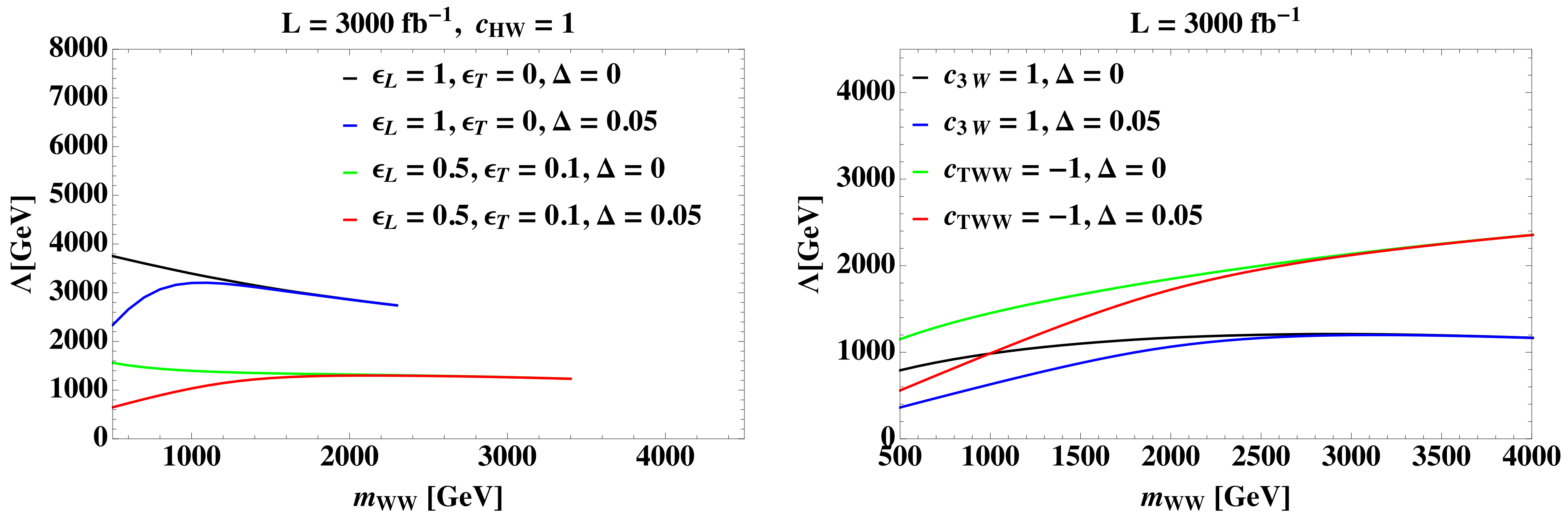
Λ[TeV]	$\mathcal{O}_{TWW}$	$\mathcal{O}_{TWB}$	$\mathcal{O}_{TH}$	$\mathcal{O}_{TH}^{(3)}$
$WV(\ell + jets)$	0.90	0.90	1.1(0.83)	0.83(0.65)
$W^{\pm}h(\ell bb)$				(0.86,0.79,0.76)
$W^{\pm}h(\ell + \ell\nu\ell\nu)$				0.67

Conclusion

- LHC is pursuing a comprehensive program which covers the ground pretty well. After Moriond 2017 slow gain with lumi.
- Long term prospect at LHC: focusing on broad features. Di-boson, ttbar, etc.
- Non-resonant, broad features. Difficult. But a lot data can make a significant difference here!
- Even without a discovery, this can have lasting impact on future directions (similar to LEP electroweak program).

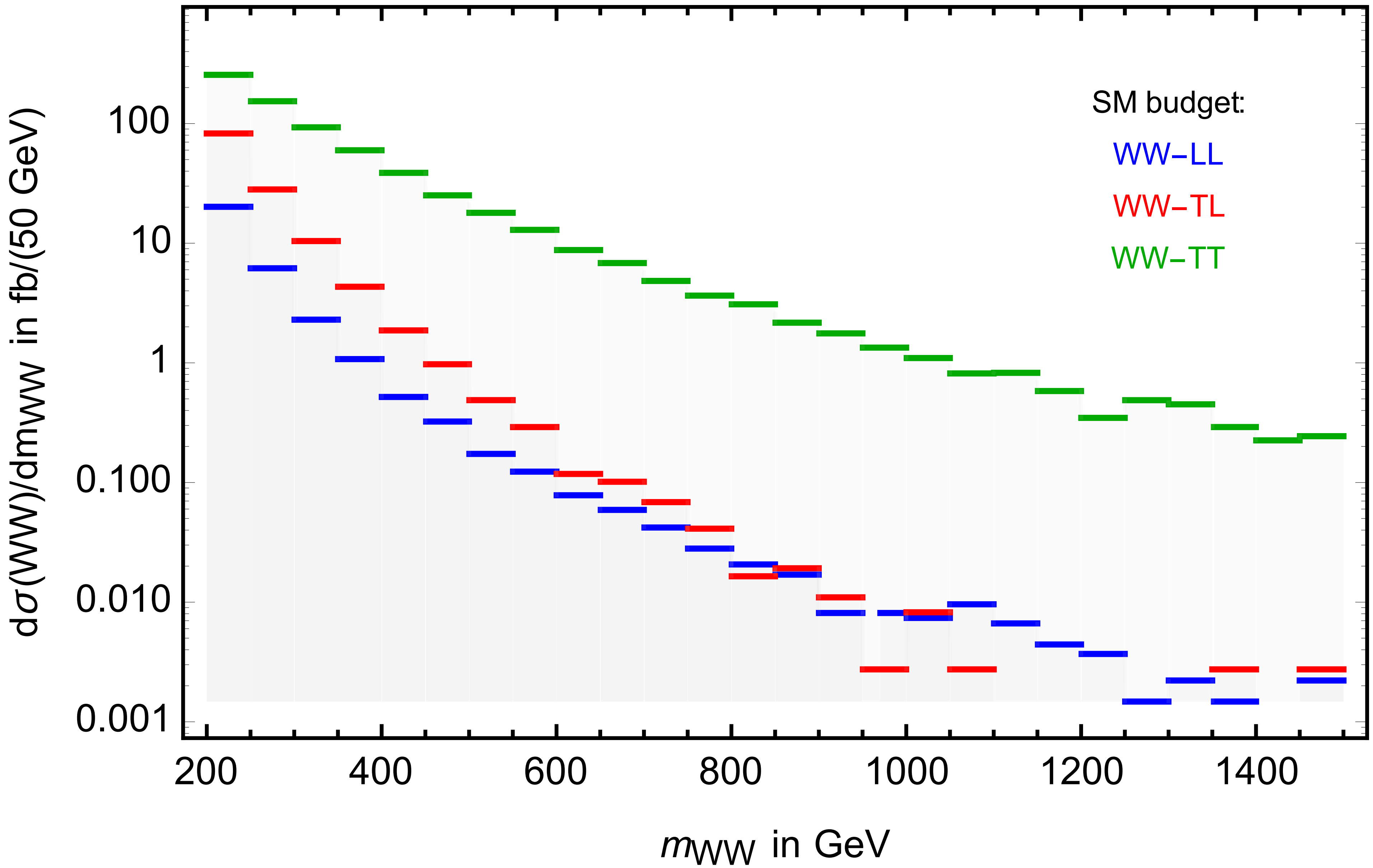
extra

c_W



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

obstruction to longitudinal WW: large irreducible bkg



largest irreducible TT background at large energies