Precision measurements at the LHC

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Work in collaboration with Da Liu and Andrea Tesi

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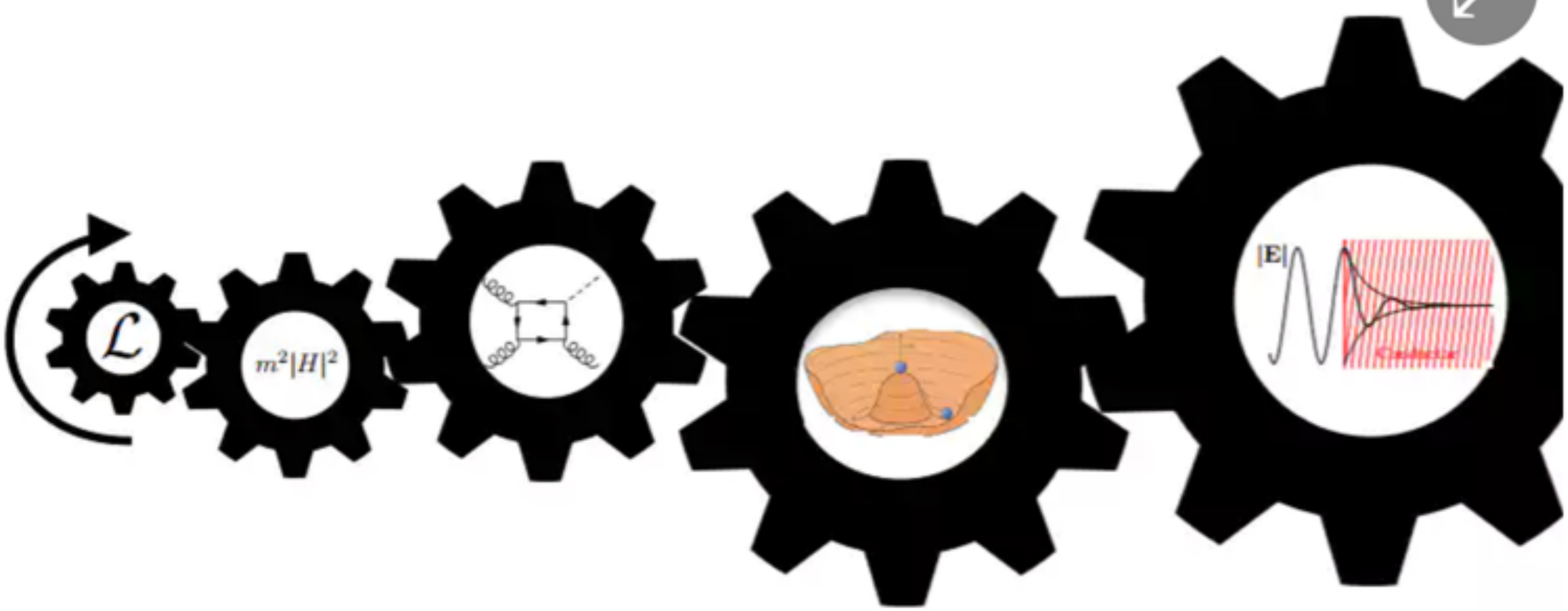
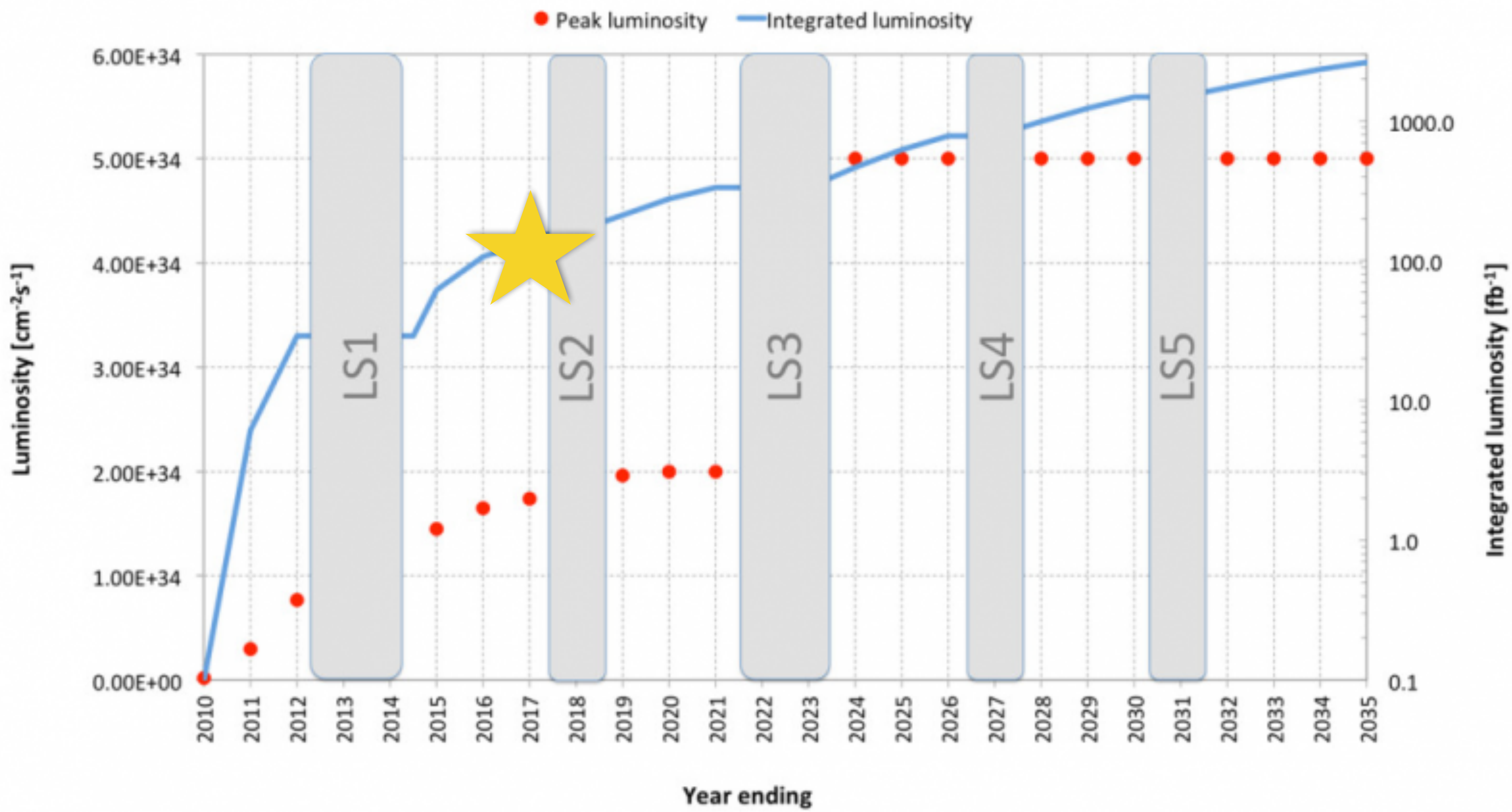
Status of new physics searches

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



Peak luminosity
Integrated luminosity
Luminosity [cm-2s-1]
Integrated luminosity [fb-1]
Year ending
6.00E+34
5.00E+34
4.00E+34
3.00E+34
2.00E+34
1.00E+34
0.00E+00
1000.0
100.0
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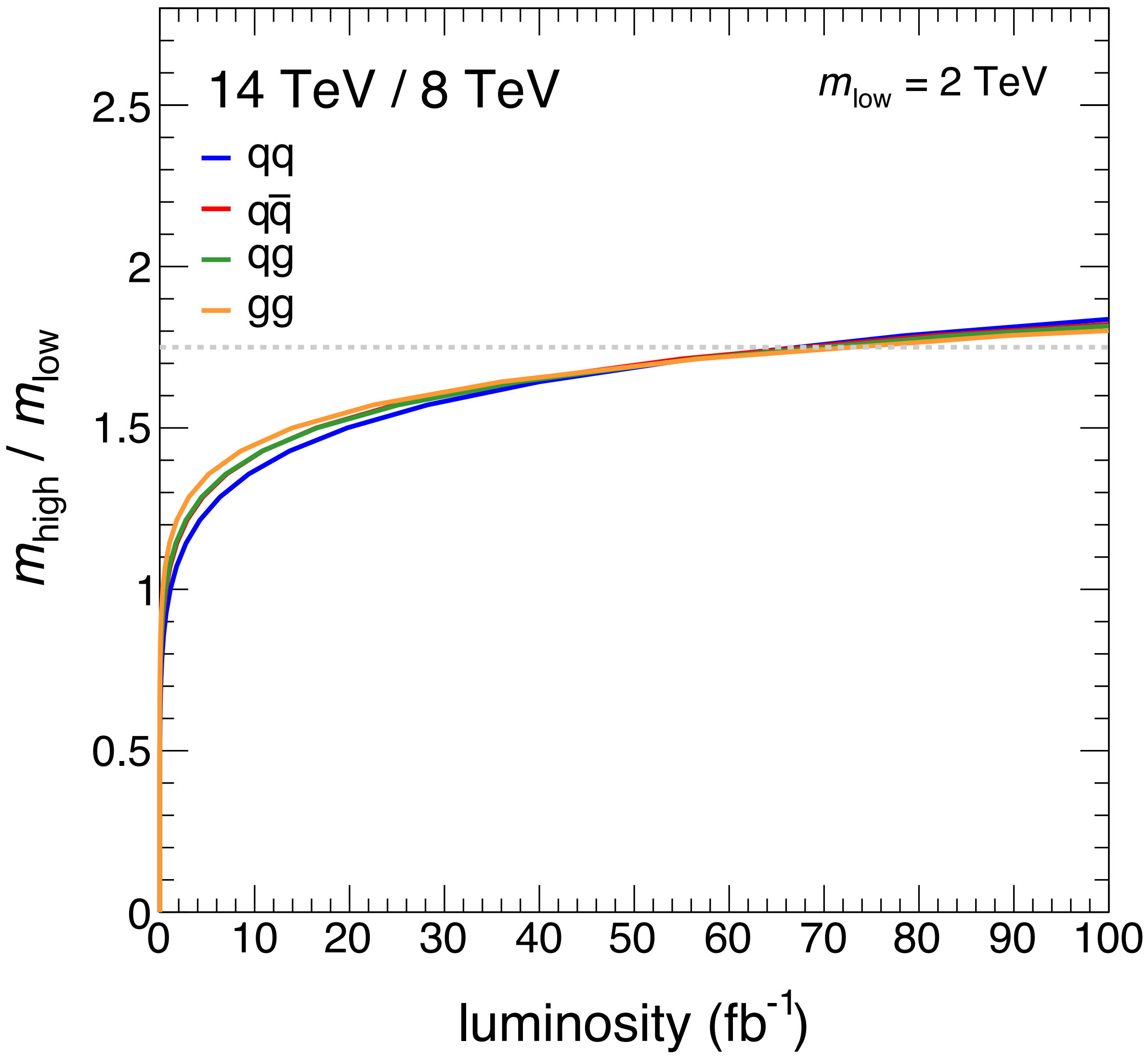
As data accumulates

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

- For example:
  - Current gluino limit is about 2 TeV
  - With about 100 times more data, the sensitivity on gluing production cross section improve by a factor of 10 (r.f. $S/B^{1/2}$)
  - Now, the production cross section is proportional to about $(M_{gluino})^{-7}$
  - A factor 10 in cross section ≈ 30-40% on M_{gluino} .
  - So, 20 years later, we can reach to about 2.8 or 3 TeV.

LHC will press on the "standard" searches for SUSY, extraD, composite... with slower progresses

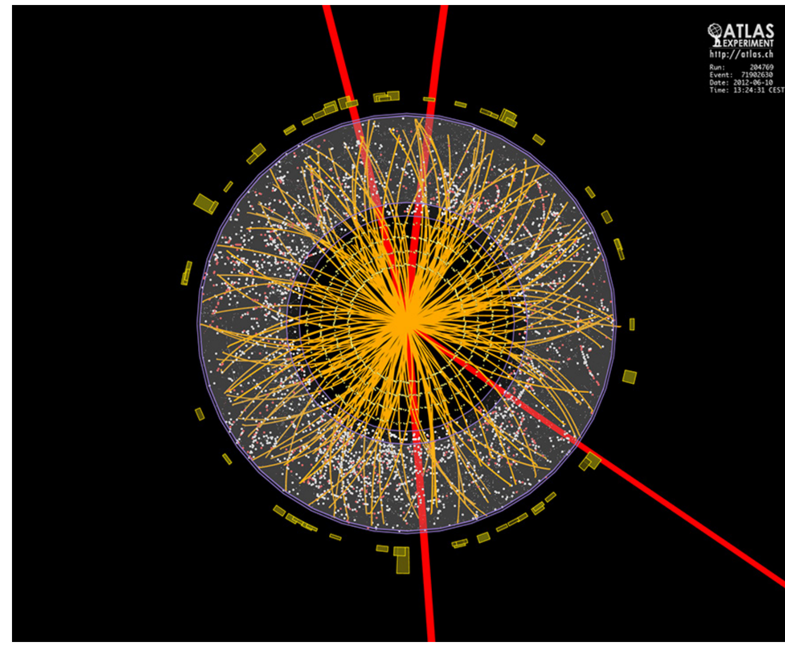
In the meantime
LHC enters precision era

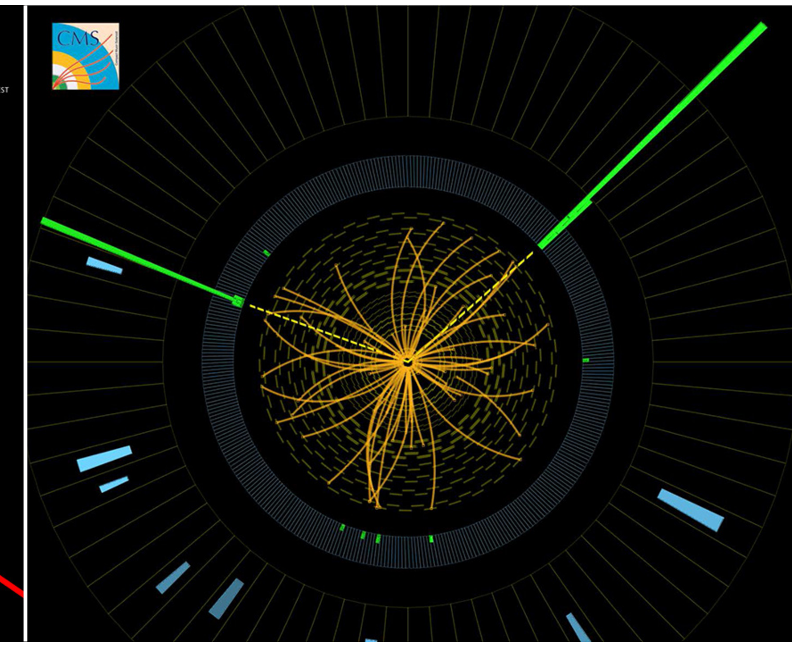
This will be done with 95+% more LHC data.

This talk:
targets and challenges

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

Measuring Higgs after the discovery

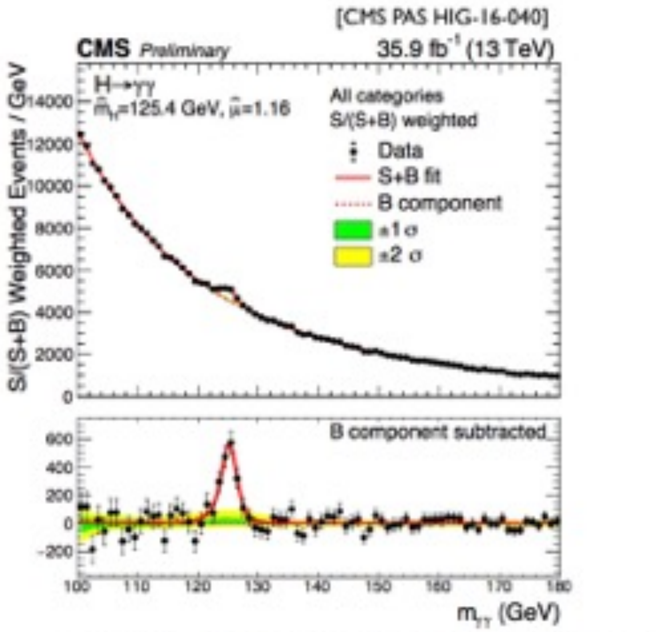




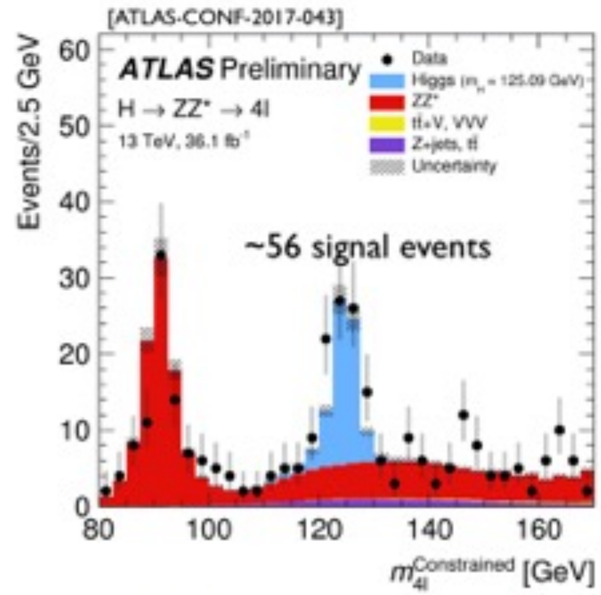
We have made significant progresses.

There is still a long way to go to understand the Higgs.
LHC can't finish the job, but it can do a lot.

Behaving like a Higgs boson

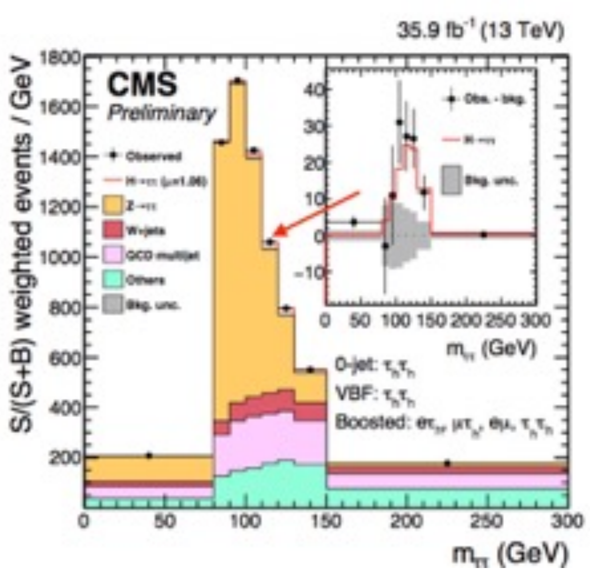


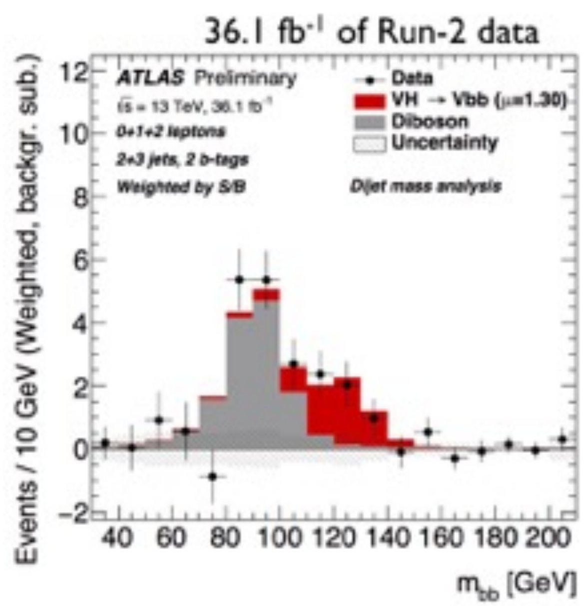
$\mu = 1.16^{+0.15}_{-0.14} = 1.16^{+0.11}_{-0.10}(\mathrm{stat})^{+0.09}_{-0.08}(\mathrm{exp})^{+0.06}_{-0.05}(\mathrm{theo})$



$\mu = 1.28^{+0.18}_{-0.17}(\mathrm{stat.})^{+0.08}_{-0.06}(\mathrm{exp.})^{+0.08}_{-0.06}(\mathrm{th.})$

Higgs gauge boson coupling well established.

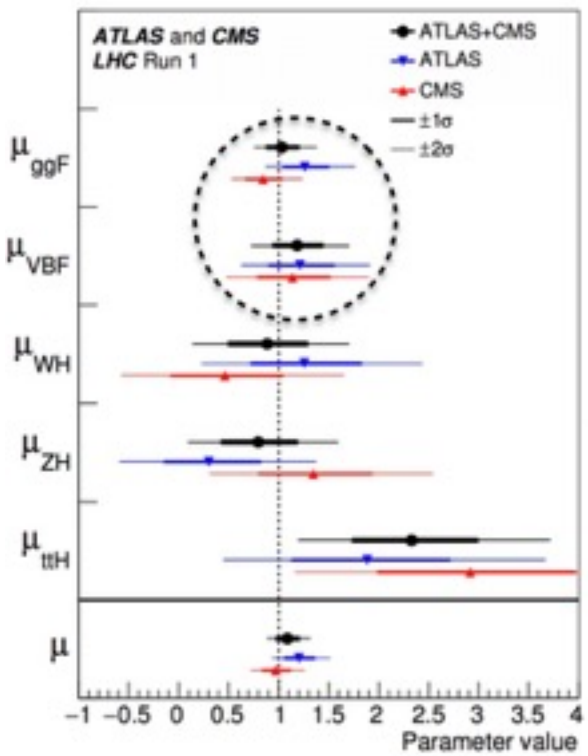


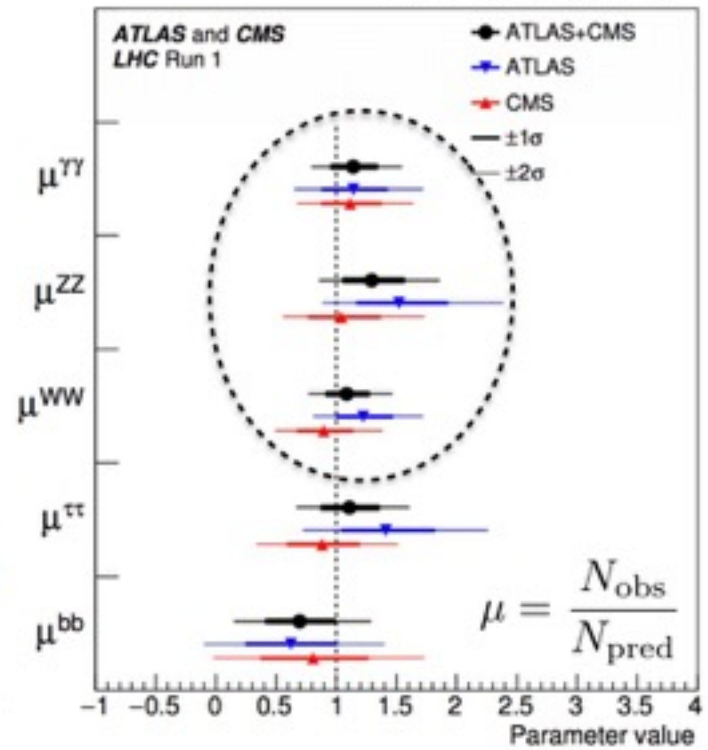


Started to see Higgs fermion coupling as well.

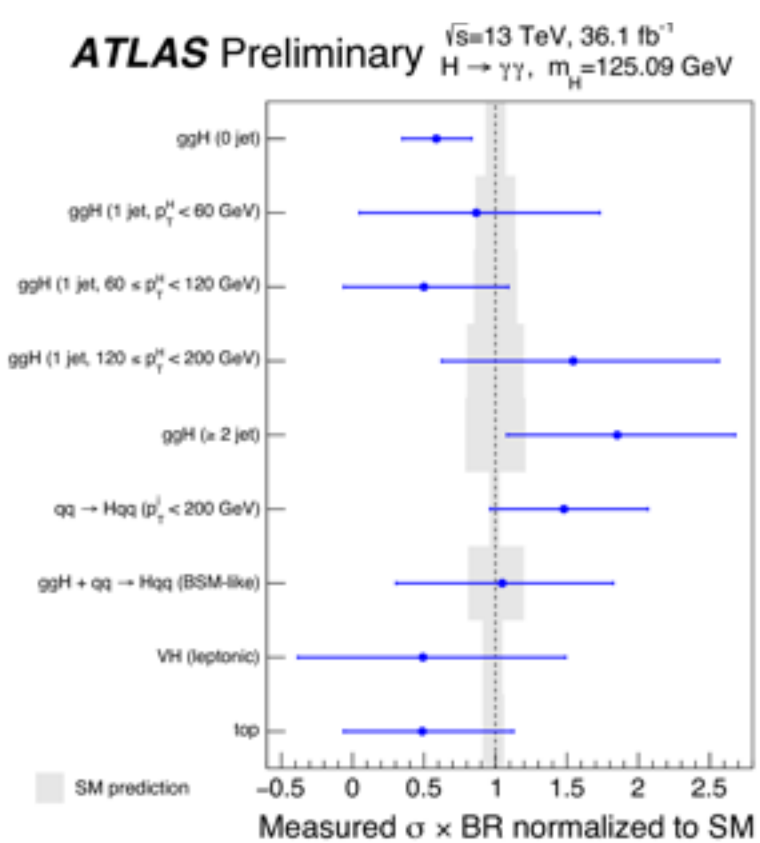
Roughly agree with Standard Model

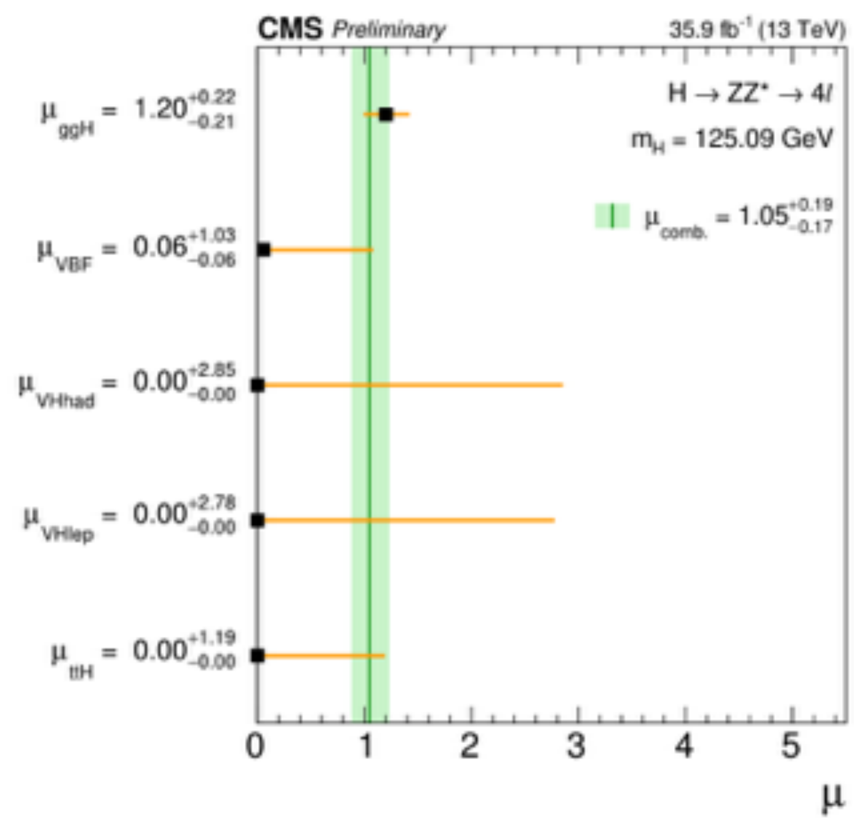
[JHEP 08 (2016) 045]





Agree to about 10-20%





Not entirely surprising

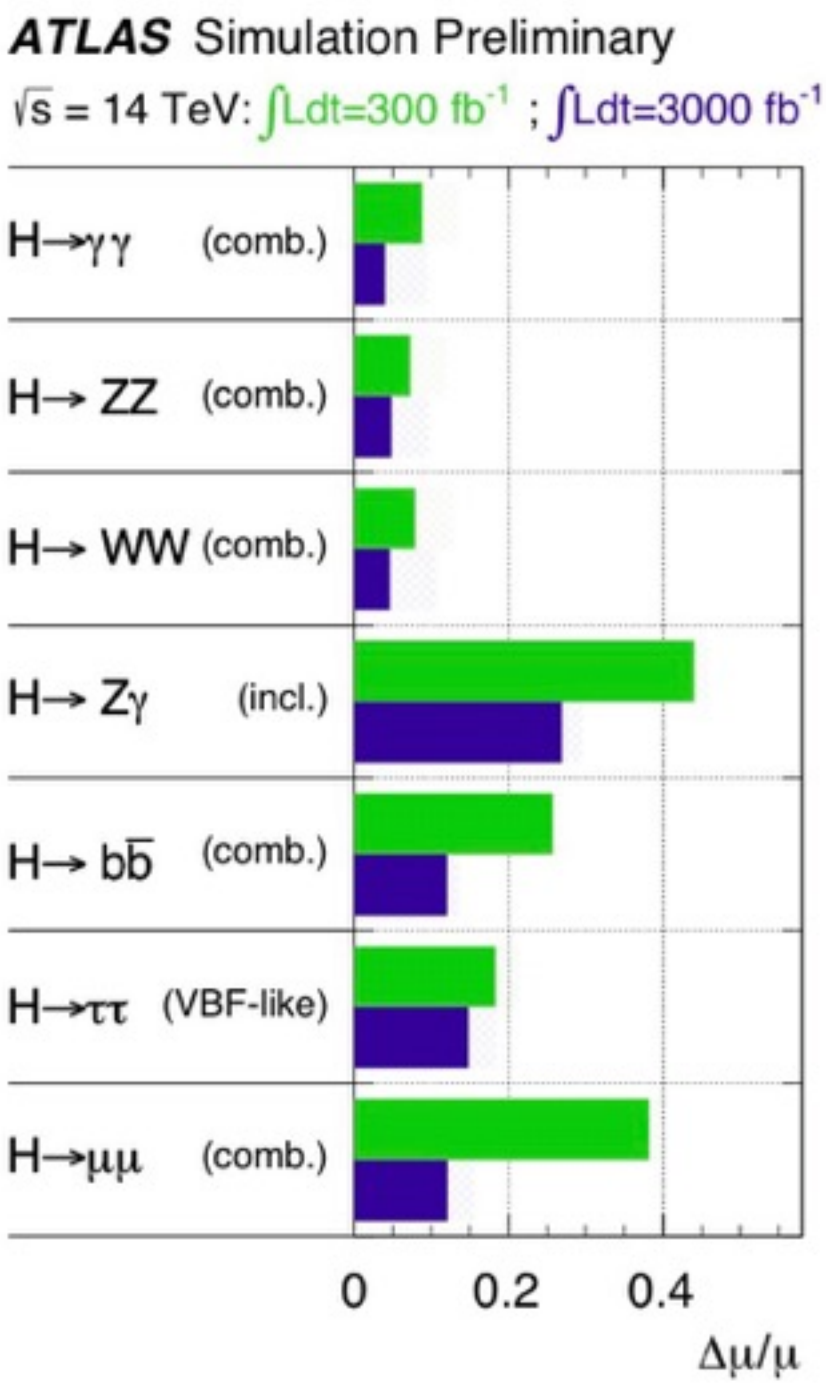
- In general, deviation induced by new physics is of the form

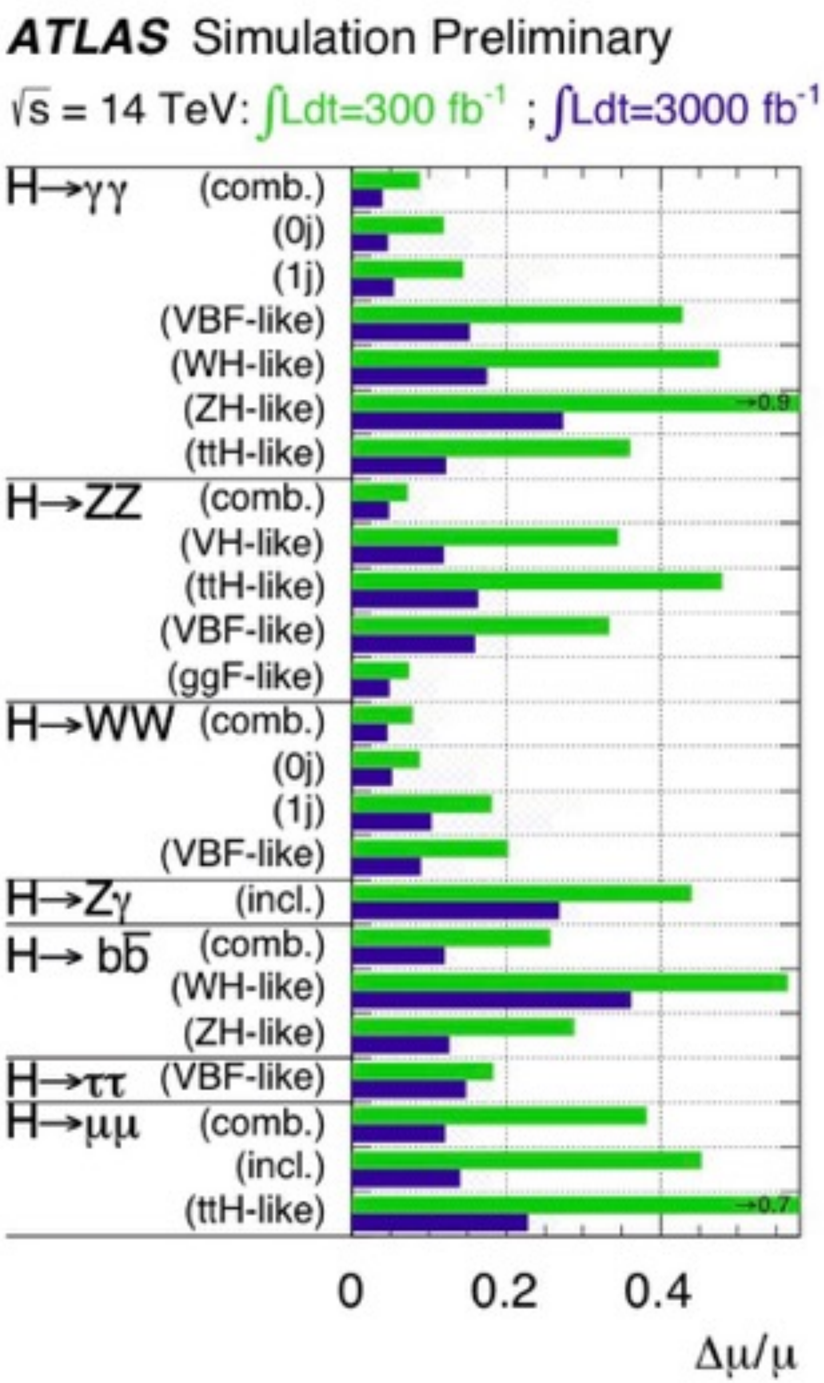
$$\delta \simeq c \frac{v^2}{M_{\rm NP}^2}$$

M_{NP} : mass of new physics
c: $O(1)$ coefficient

  - Current LHC precision: 10%
    $\Rightarrow$ sensitive to M_{NP} < 500-700 GeV
  - At the same time, direct searches constrain new physics below TeV already.
  - Unlikely to see O(1) deviation.

LHC entering precision measurement stage



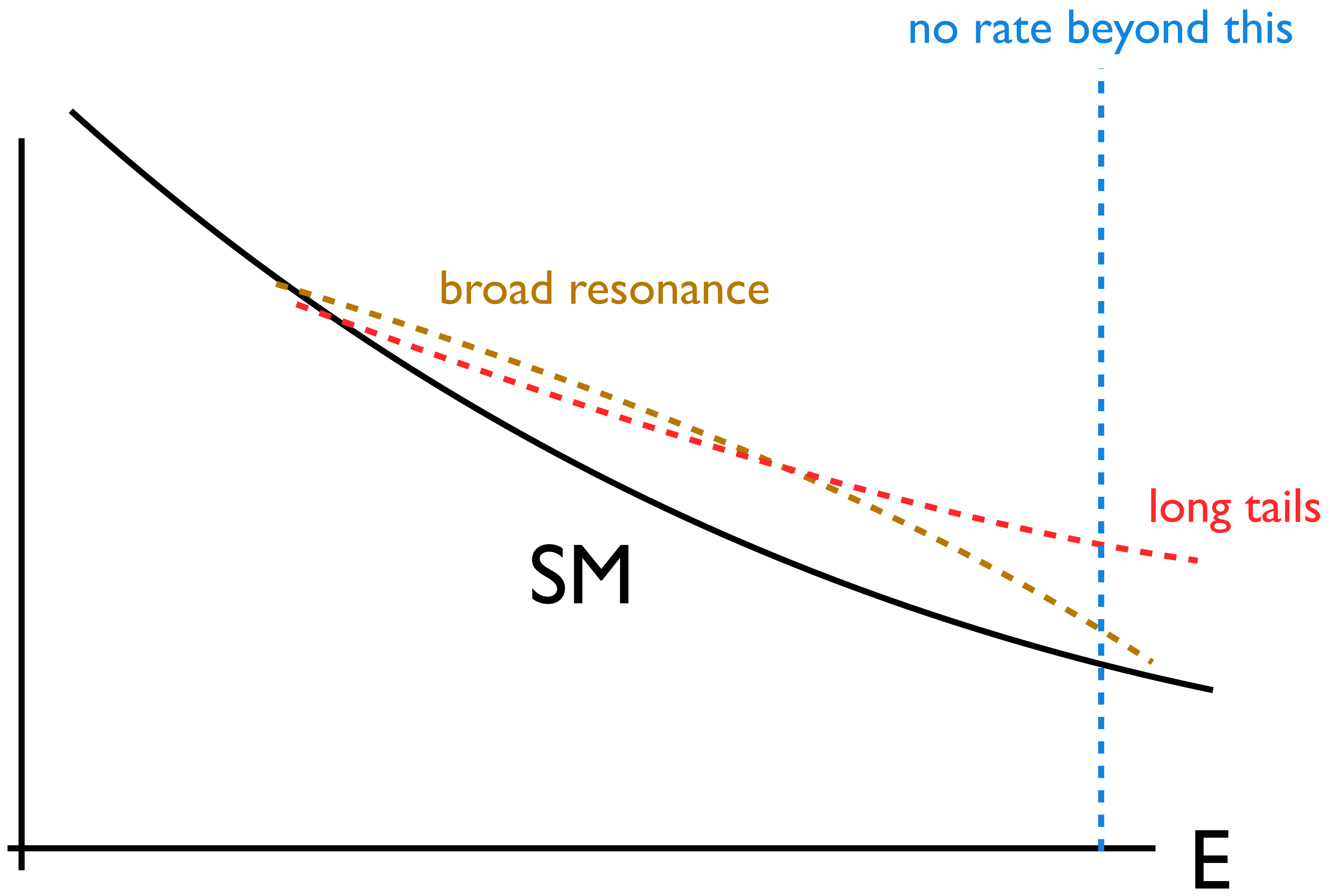


➡ 4-5% on Higgs coupling, reach TeV new physics

Another 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



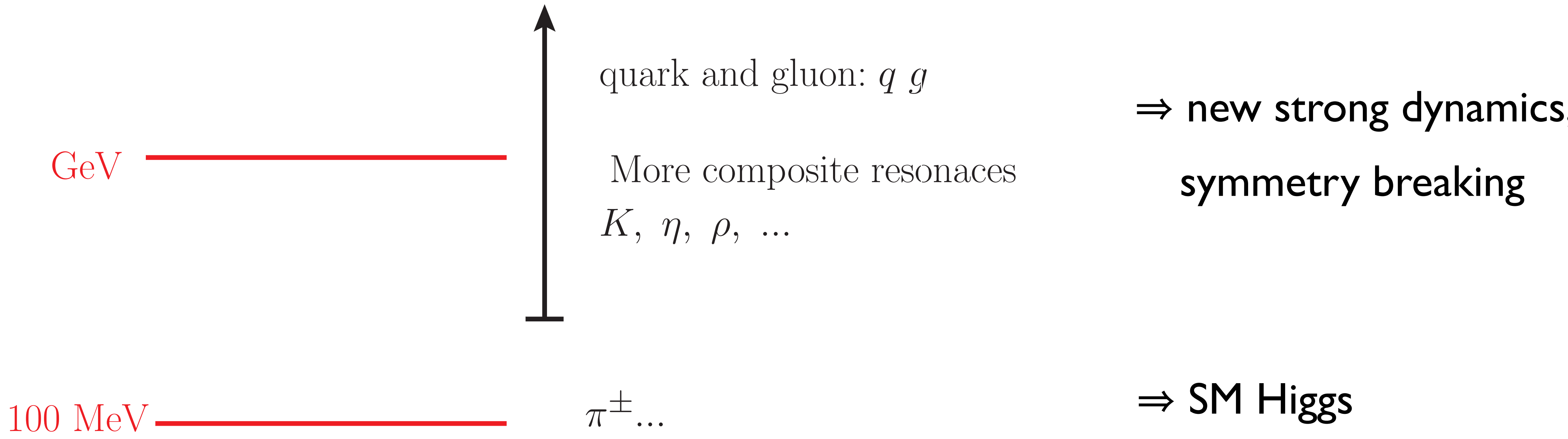
- Example: strongly coupled heavy new physics

e.g. Liu, Pomarol, Rattazzi, Riva

My focus here:

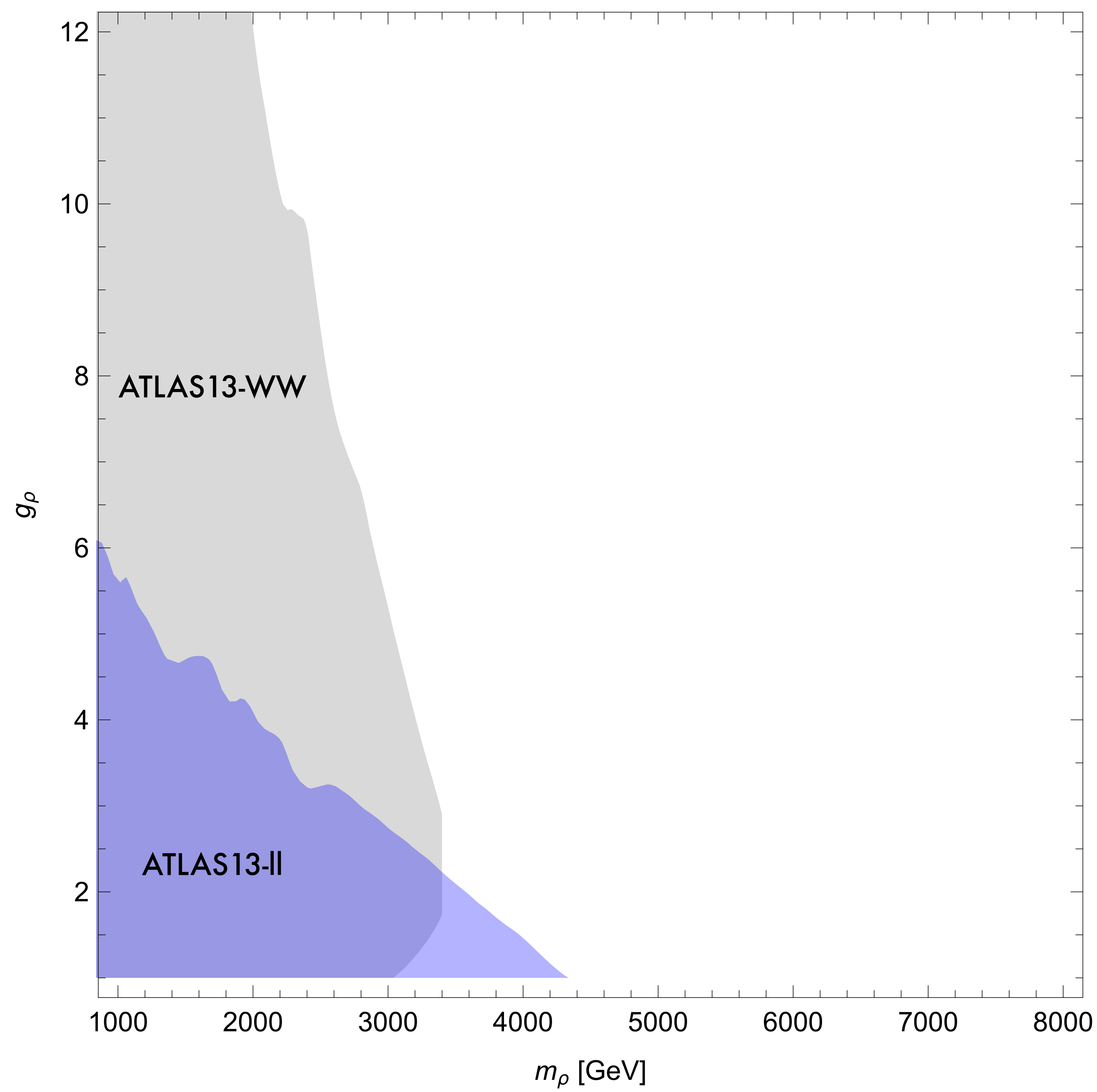
- The question of electroweak symmetry breaking has hinted that there should be NP not too far away from the weak scale.
  - Naturalness, etc.
  - Some of these need strong dynamics
- Final states with W/Z/h/top. "Precision measurement"
- I will focus here on di-boson.

Warm up: Composite Higgs



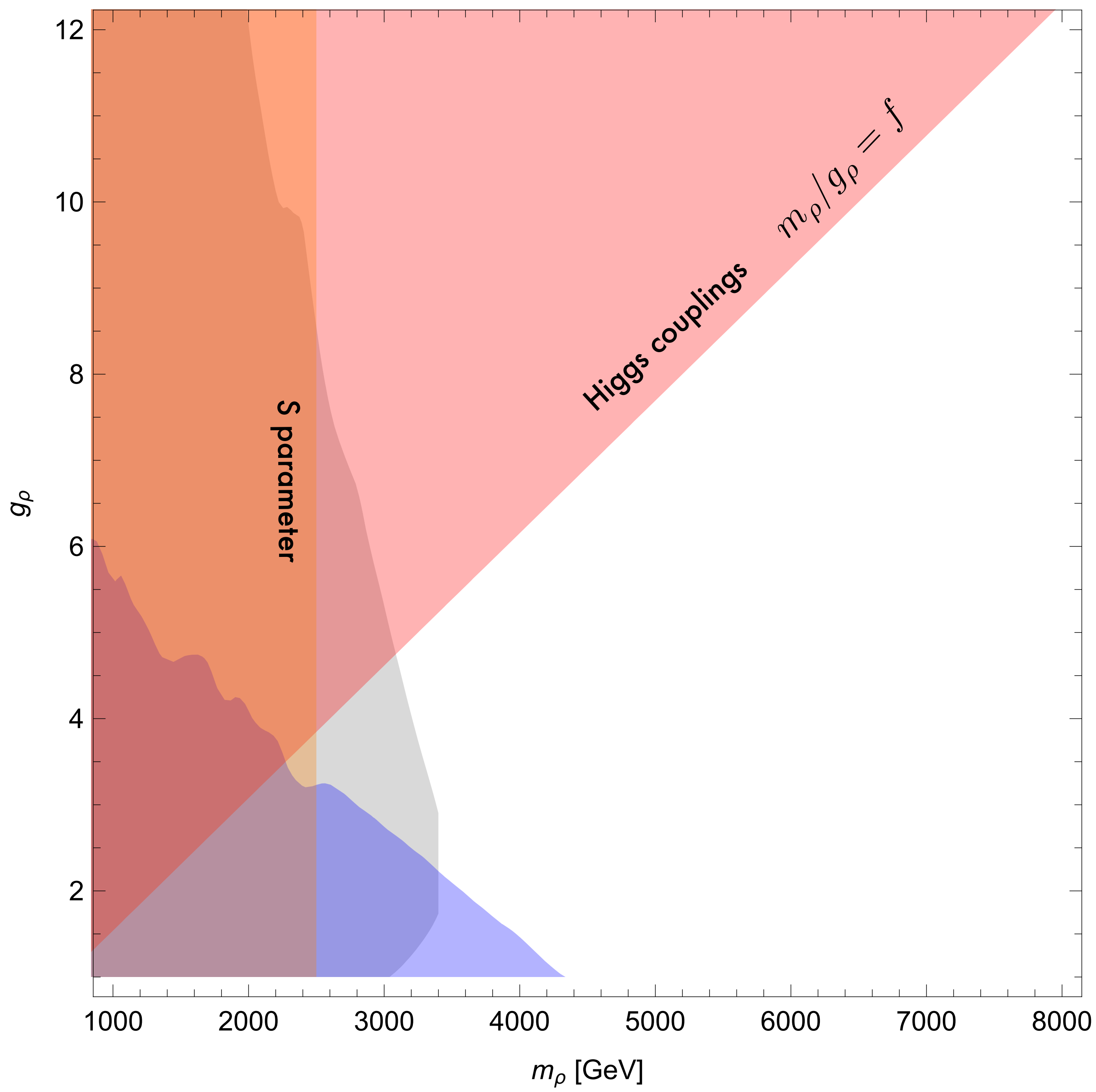
- Construct a new strong dynamics in which the pion-like states will be the SM Higgs.
- Nature may be more interesting, but it could also just repeat itself.

Spin-1 resonances



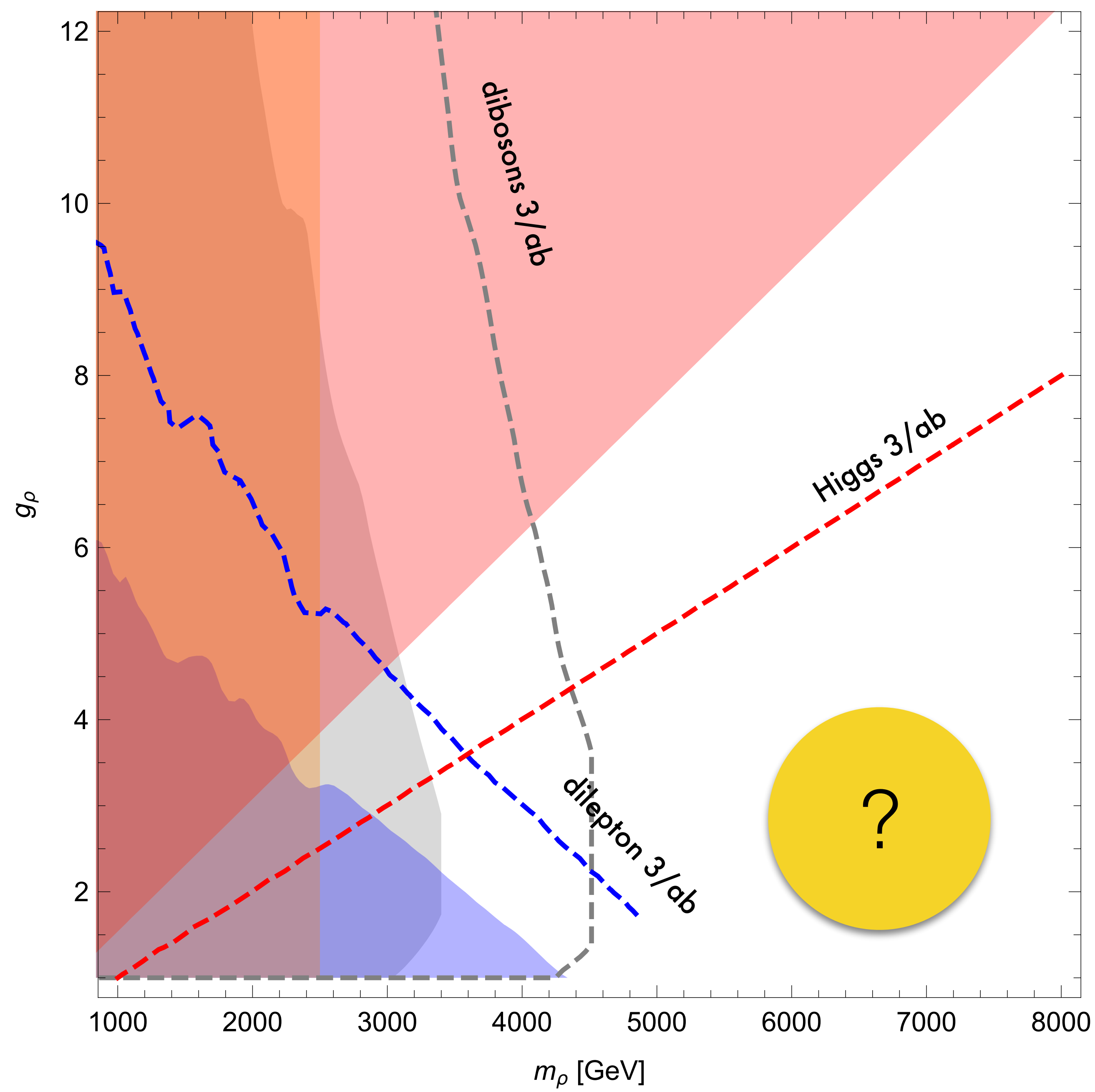
Neutral spin-1 resonance typical of composite Higgs models

Spin-1 resonances



Indirect constraints are also present

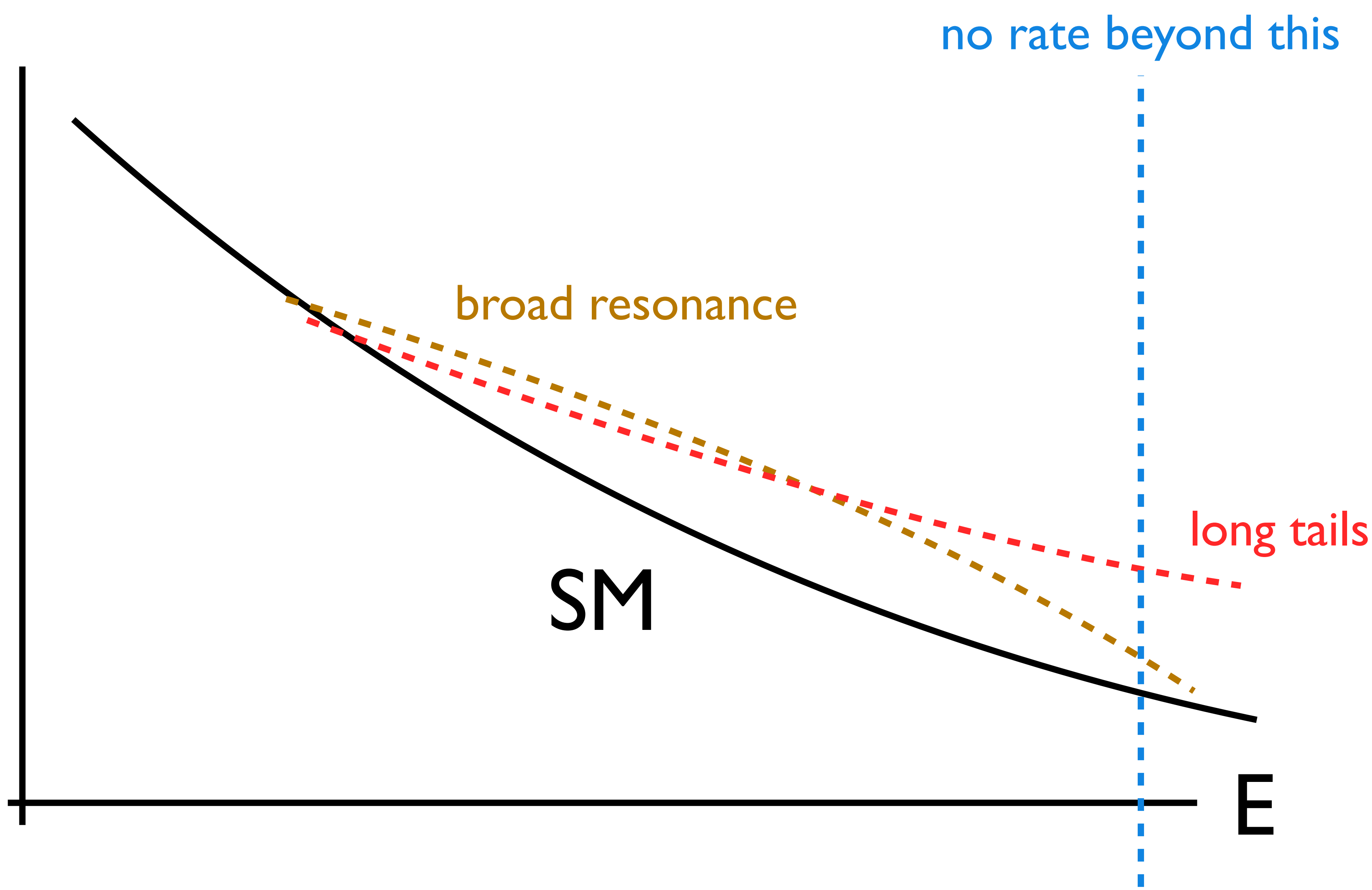
Spin-1 resonances



Projected sensitivity, a large portion of the space will be covered

can we expect further improvements?

Broad features with di-boson, tops etc.



- Challenging. Current LHC sensitivity and performance not good enough.
- Will focus on setting performance benchmarks or goals for the LHC.

Operators: d=6

name	structure	coefficient (power counting)
$\mathcal{O}_H$	$\frac{1}{2}\left(\partial_\mu \lvert H\rvert^2\right)^2$	c_H/f^2
$\mathcal{O}_y$	$y\bar{Q}_L H u_R \lvert H\rvert^2$	c_y/f^2
$\mathcal{O}_W$	$ig\left(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$	c_W/m_*^2
$\mathcal{O}_B$	$ig'\left(H^\dagger \overleftrightarrow{D}^\mu H\right) D^\nu B_{\mu\nu}$	c_B/m_*^2
$\mathcal{O}_{HW}$	$ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu}$	$c_{HW}/m_*^2 \times (g_*/4\pi)^2$
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O_L^q	$ig^2\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\bar{Q}_L\gamma^\mu Q_L$	$c_q/m_*^2 \times \epsilon_q^2$
$O_L^{q,3}$	$ig^2\left(H^\dagger\sigma^a \overleftrightarrow{D}_\mu H\right)\bar{Q}_L\sigma^a\gamma^\mu Q_L$	$c_{q,3}/m_*^2 \times \epsilon_q^2$
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O_R^u	$ig^2\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\bar{d}_R\gamma^\mu d_R$	$c_d/m_*^2 \times \epsilon_d^2$
O_T	$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	c_T/f^2
$\mathcal{O}_6$	$\lvert H\rvert^6$	λ_3/f^2

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O_R^u	$ig^2(H^\dagger \overleftrightarrow{D}_\mu H)\bar{d}_R\gamma^\mu d_R$	$c_d/m_*^2 \times \epsilon_d^2$
O_T	$(H^\dagger \overleftrightarrow{D}_\mu H)^2$	c_T/f^2
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Only constrained by inclusive Higgs measurement

Operators: d=6

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Di-boson production

Operators: d=6

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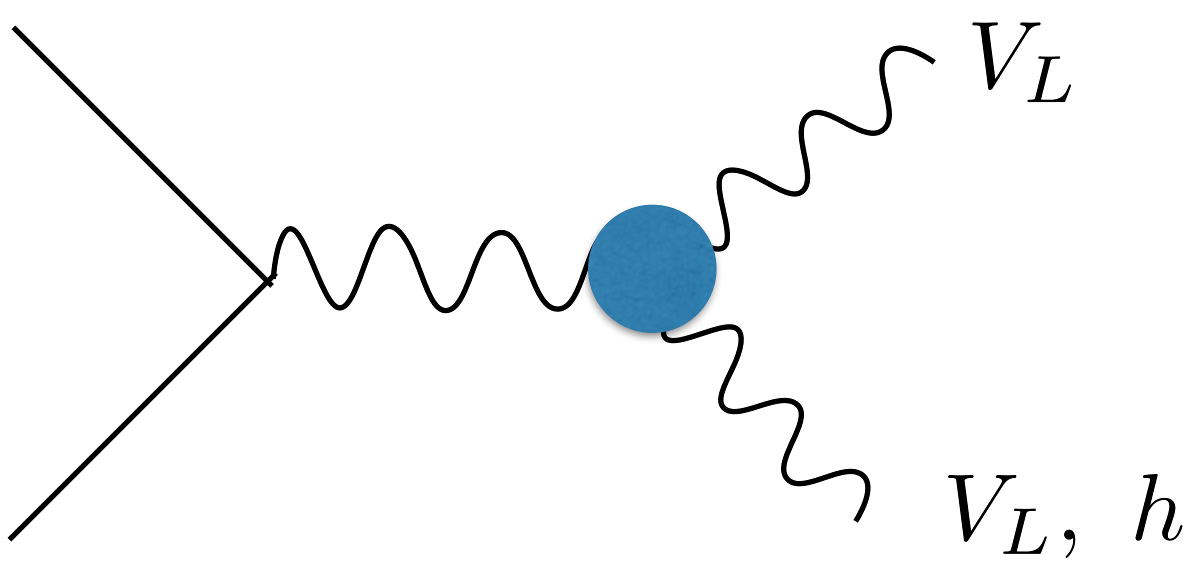
LEP constraint.

e.g. S-parameter: $$\frac{m_*}{\sqrt{c_W + c_B}} > 2.5 \text{ TeV}$$

Diboson production at the LHC

$$q\bar{q} \to VV, \quad V = W, Z, h.$$

Test of Higgs physics at high scale



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:

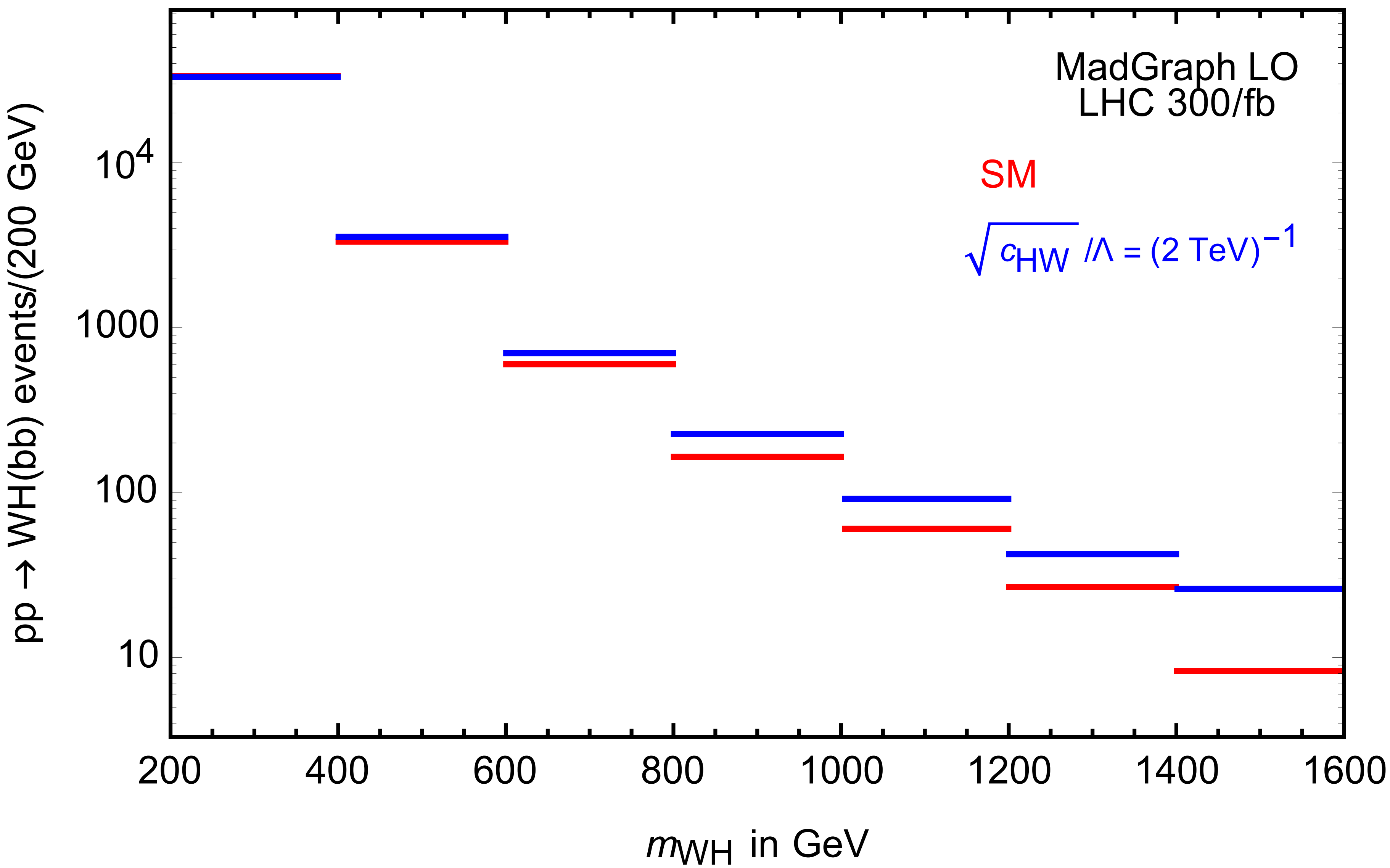
$$\mathcal{L} = -\frac{\tan\theta_W}{2}\hat{S} W^{(3)}_{\mu\nu} B^{\mu\nu}$$

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

LHC longitudinal mode:

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

Energy growing behavior



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

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

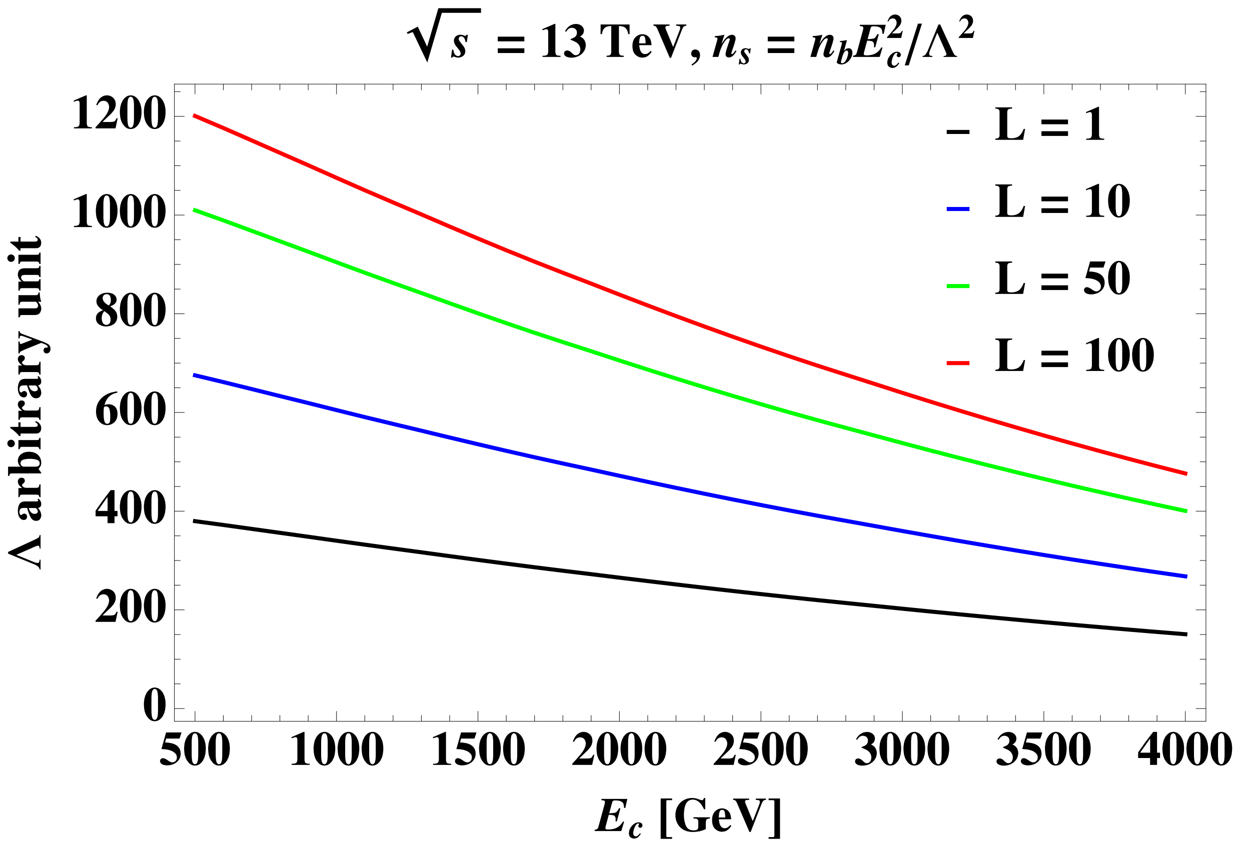
n: 5-8 falling parton luminosity

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

$\mathcal{L}$ = integrated luminosity

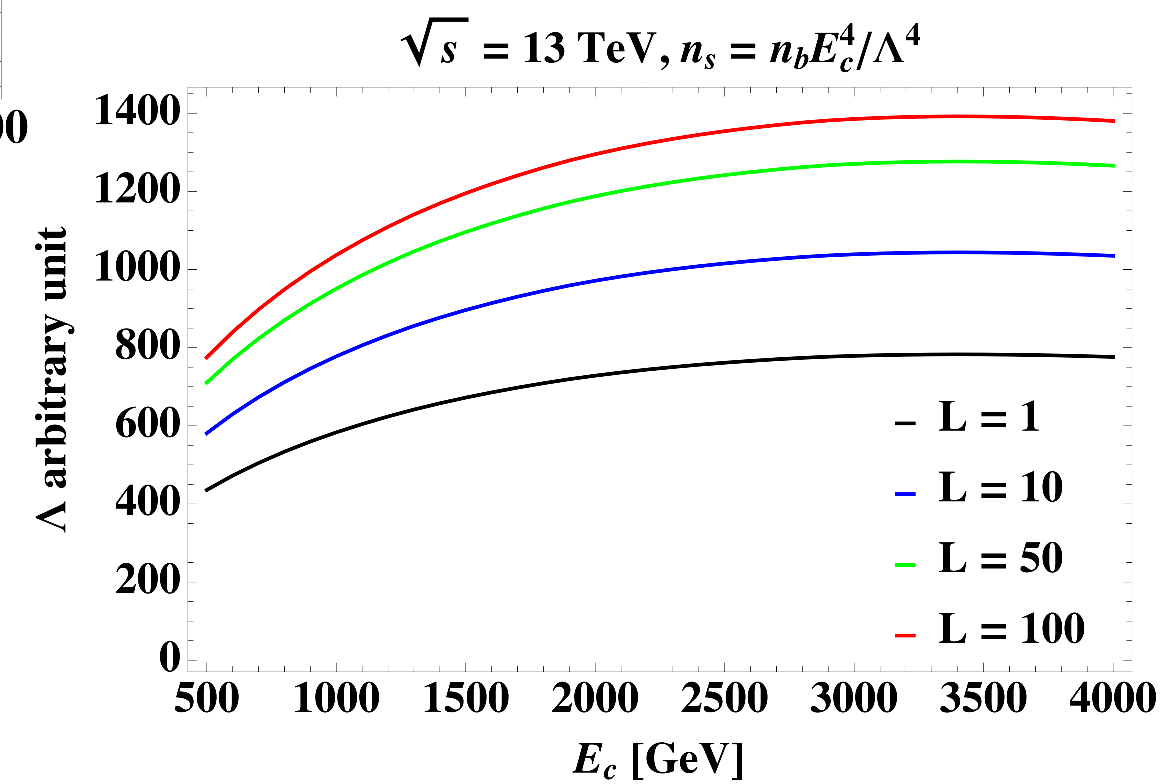
- For small d, lower E with higher reach. (e.g. dim 6, d=2)
  - Limited by systematics.
- Interference important. Otherwise, signal proportional to (operator)^2, effect further suppressed by $(E/\Lambda)^d$.

Ideal case.



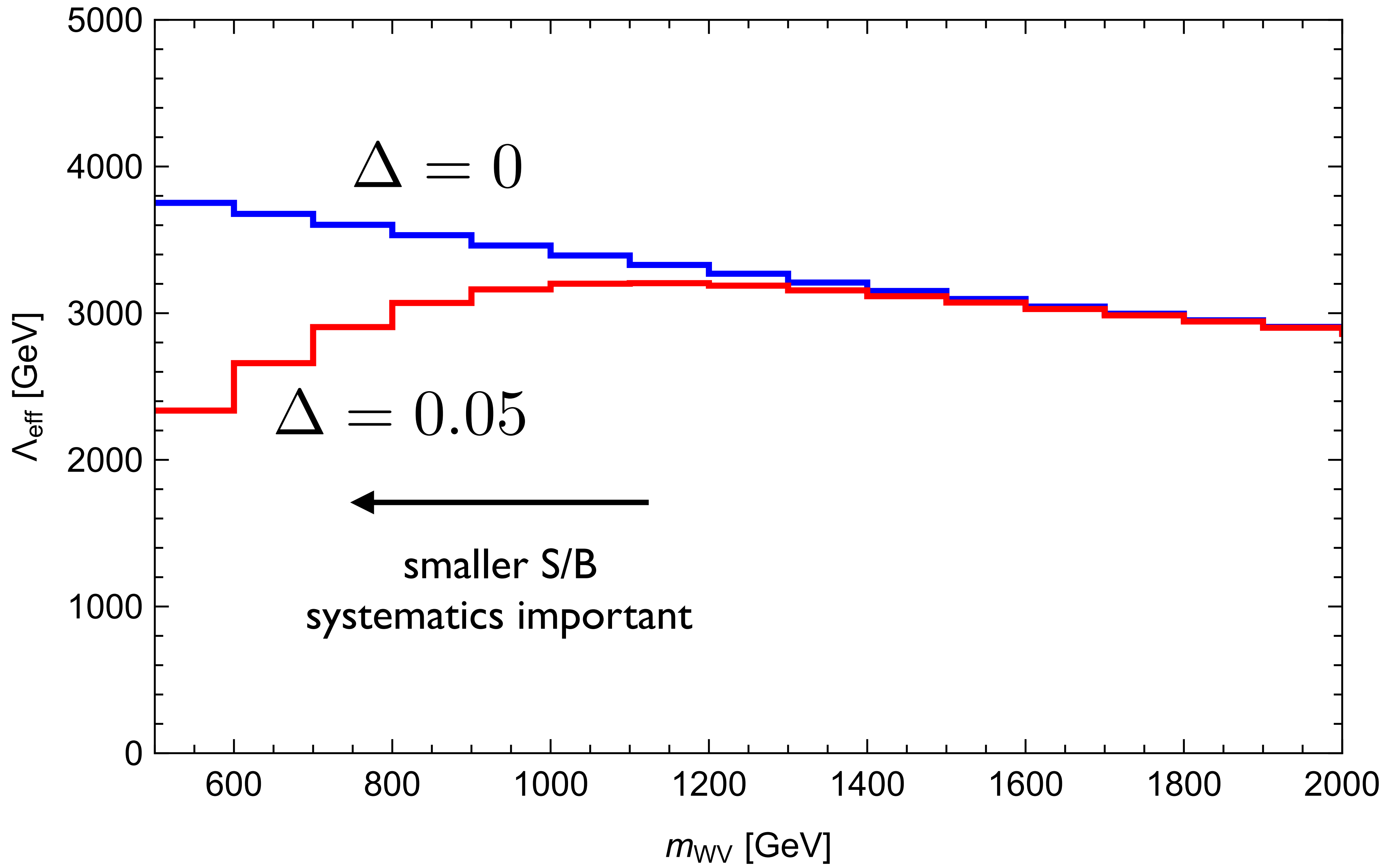
dim 6, with interference
Stronger limit at lower energy

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



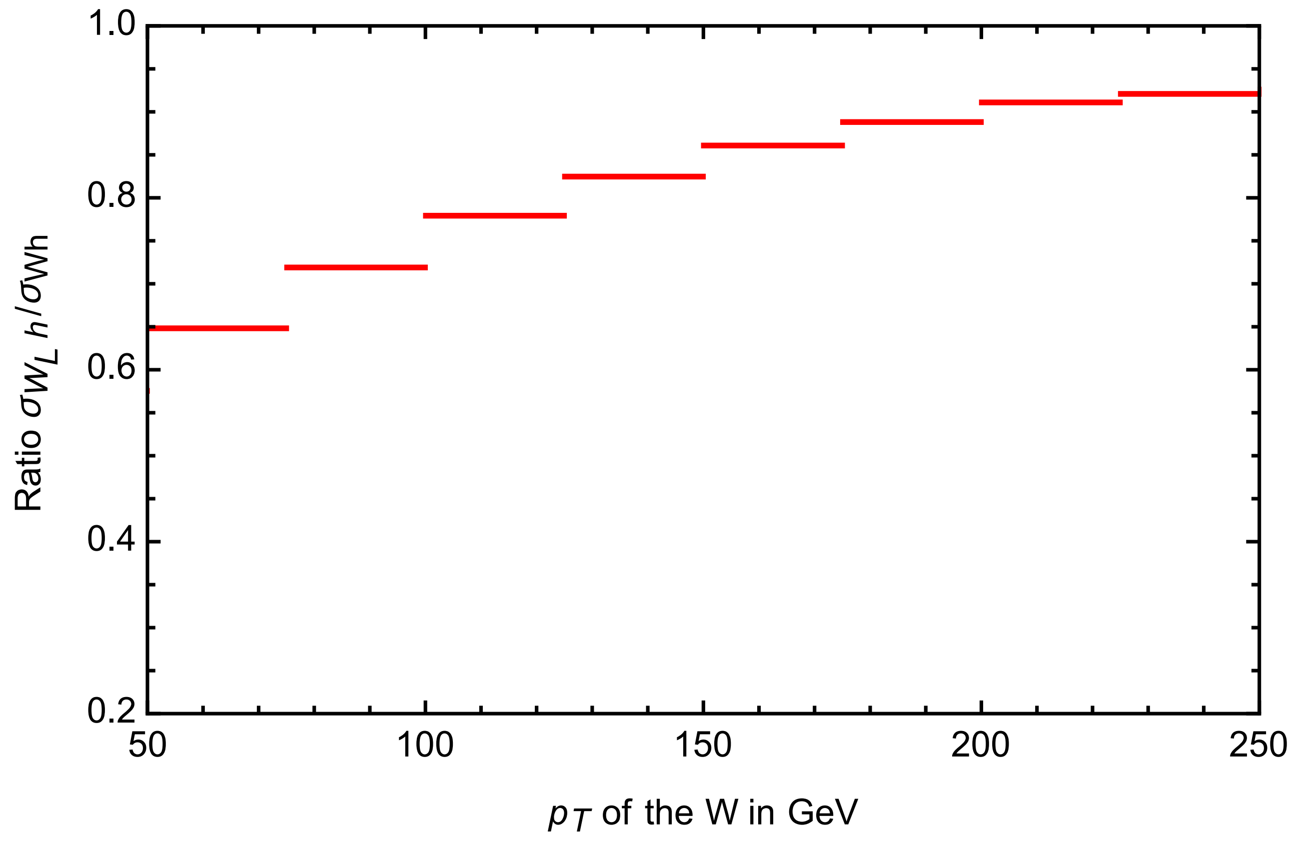
dim 8 with interference
or dim 6 without interference

The role of systematics



Wh(bb) channel

Useful. Can be done "inclusively", no need to keep track of polarization of W



Signal:

$$\frac{\delta\sigma_{W_L h}}{\sigma_{\rm SM}} = \frac{\hat{s}}{\Lambda^2}\left(c_W + c_{HW} - 4c_L^{(3)}\right)$$

Wh(bb) channel

However, current searches not sensitive

Table 13: The fitted Higgs boson signal and background yields for each signal region category in each channel after the full selection of the multivariate analysis. The yields are normalised by the results of the global likelihood fit. All systematic uncertainties are included in the indicated uncertainties. An entry of "-" indicates that a specific background component is missing in a certain region, or that no simulated events are left after the analysis selection.

Signal regions	0-lepton		1-lepton		2-lepton			
	$p_T^V > 150$ GeV, 2-tag		$p_T^V > 150$ GeV, 2-tag		75 GeV $< p_T^V <$ 150 GeV, 2-tag		$p_T^V > 150$ GeV, 2-tag	
Sample	2-jet	3-jet	2-jet	3-jet	2-jet	≥3-jet	2-jet	≥3-jet
$Z+ll$	9.0 ± 5.1	15.5 ± 8.1	< 1	–	9.2 ± 5.4	35 ± 19	1.9 ± 1.1	16.4 ± 9.3
$Z+cl$	21.4 ± 7.7	42 ± 14	2.2 ± 0.1	4.2 ± 0.1	25.3 ± 9.5	105 ± 39	5.3 ± 1.9	46 ± 17
Z+HF	2198 ± 84	3270 ± 170	86.5 ± 6.1	186 ± 13	3449 ± 79	8270 ± 150	651 ± 20	3052 ± 66
$W+ll$	9.8 ± 5.6	17.9 ± 9.9	22 ± 10	47 ± 22	< 1	< 1	< 1	< 1
$W+cl$	19.9 ± 8.8	41 ± 18	70 ± 27	138 ± 53	< 1	< 1	< 1	< 1
W+HF	460 ± 51	1120 ± 120	1280 ± 160	3140 ± 420	3.0 ± 0.4	5.9 ± 0.7	< 1	2.2 ± 0.2
Single top-quark	145 ± 22	536 ± 98	830 ± 120	3700 ± 670	53 ± 16	134 ± 46	5.9 ± 1.9	30 ± 10
$t\bar{t}$	463 ± 42	3390 ± 200	2650 ± 170	20640 ± 680	1453 ± 46	4904 ± 91	49.6 ± 2.9	430 ± 22
Diboson	116 ± 26	119 ± 36	79 ± 23	135 ± 47	73 ± 19	149 ± 32	24.4 ± 6.2	87 ± 19
Multi-jet e sub-ch.	–	–	102 ± 66	27 ± 68	–	–	–	–
Multi-jet μ sub-ch.	–	–	133 ± 99	90 ± 130	–	–	–	–
Total bkg.	3443 ± 57	8560 ± 91	5255 ± 80	28110 ± 170	5065 ± 66	13600 ± 110	738 ± 19	3664 ± 56
Signal (fit)	58 ± 17	60 ± 19	63 ± 19	65 ± 21	25.6 ± 7.8	46 ± 15	13.6 ± 4.1	35 ± 11
Data	3520	8634	5307	28168	5113	13640	724	3708

WH(bb) – ATLAS-CONF-2017-041

$$S_{\mathrm{SM}}/B \approx 10^{-2}$$

Wh(bb) channel

Potential to improve!

Jet definition	σ_S/fb	σ_B/fb	$S/\sqrt{B \cdot \text{fb}}$
C/A, $R = 1.2$, MD-F	0.57	0.51	0.80
$K_\perp$, $R = 1.0$, y_{cut}	0.19	0.74	0.22
SISCone, $R = 0.8$	0.49	1.33	0.42

TABLE I: Cross section for signal and the Z+jets background in the leptonic Z channel for $200 < p_{TZ}/\text{GeV} < 600$ and $110 < m_J/\text{GeV} < 125$, with perfect b-tagging; shown for our jet definition, and other standard ones at near optimal R values.

Butterworth, Davison,Rubin, Salam, '08

– O(1) S/B is not completely out of the question.

Reach projection

Crude parameterization of significance

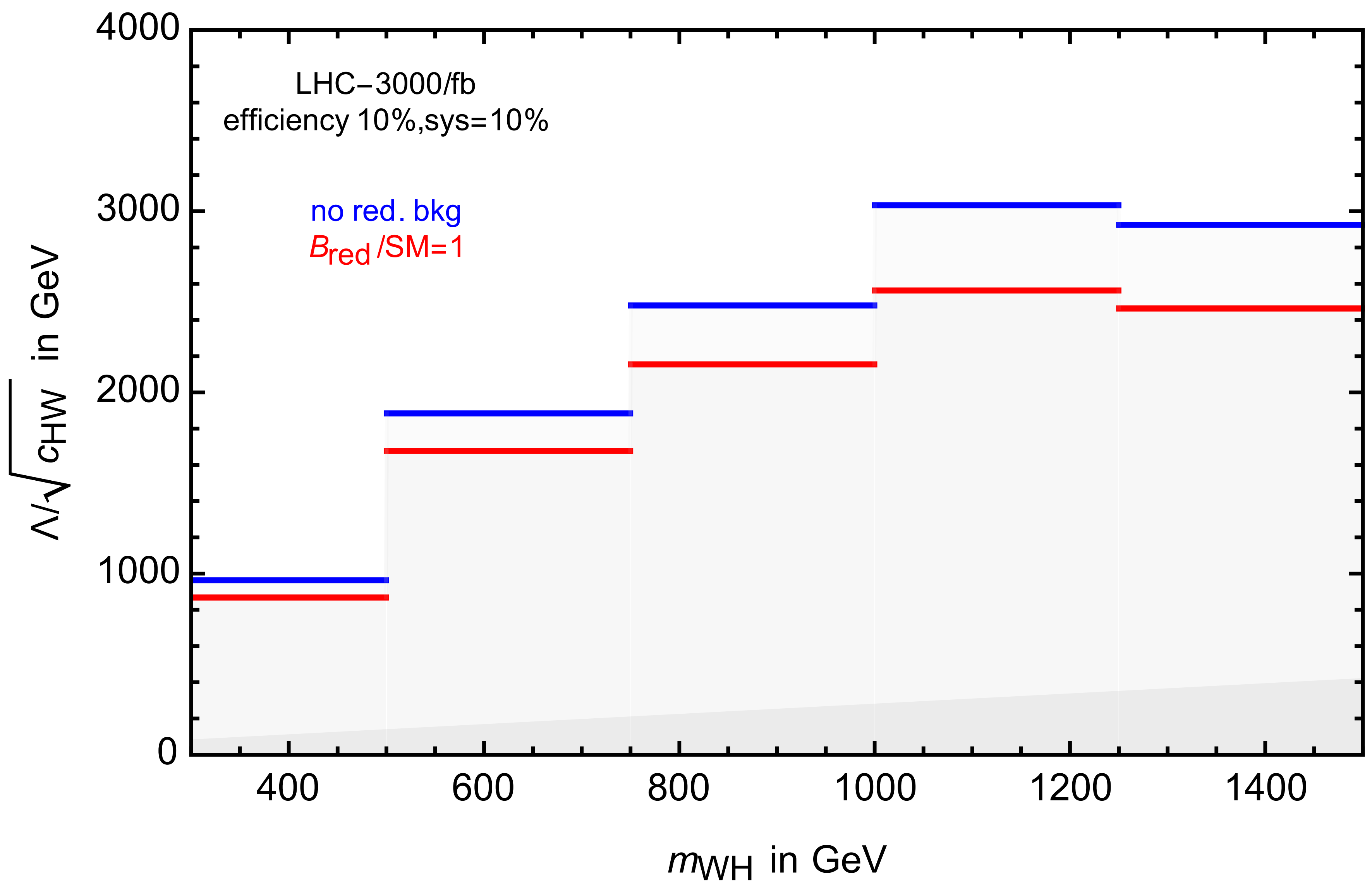
$$\frac{S^{h_1}}{\sqrt{B}} = \frac{\epsilon_{\rm sig}[\epsilon_{h_1}(\mathcal{M}^{h_1}_{\rm sig} + \mathcal{M}^{h_1}_{\rm SM})^2 + \sum_{h\neq h_1} \epsilon_h(\mathcal{M}^h_{\rm sig} + \mathcal{M}^h_{\rm SM})^2] \times \mathcal{L}}{\sqrt{[\epsilon_{h_1}\sigma^{h_1}_{\rm SM} + \sum_{h\neq h_1} \epsilon_h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

ϵ_{sig} signal efficiency or acceptance

ϵ_h (mis)tag probability of polarization h

Δ: systematical error

Wh(bb) at the LHC (benchmark)



Limit on signal in a given energy bin

comparable limits from h(jjlv), backgrounds are all EW, larger efficiency expected

WW, WZ. 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	$\frac{E^2}{\Lambda^2}$	$\frac{E^4}{\Lambda^4}\frac{m_W^2}{E^2}$

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

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

growing with energy

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

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

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

growing with energy

(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.

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

Potential difficulties

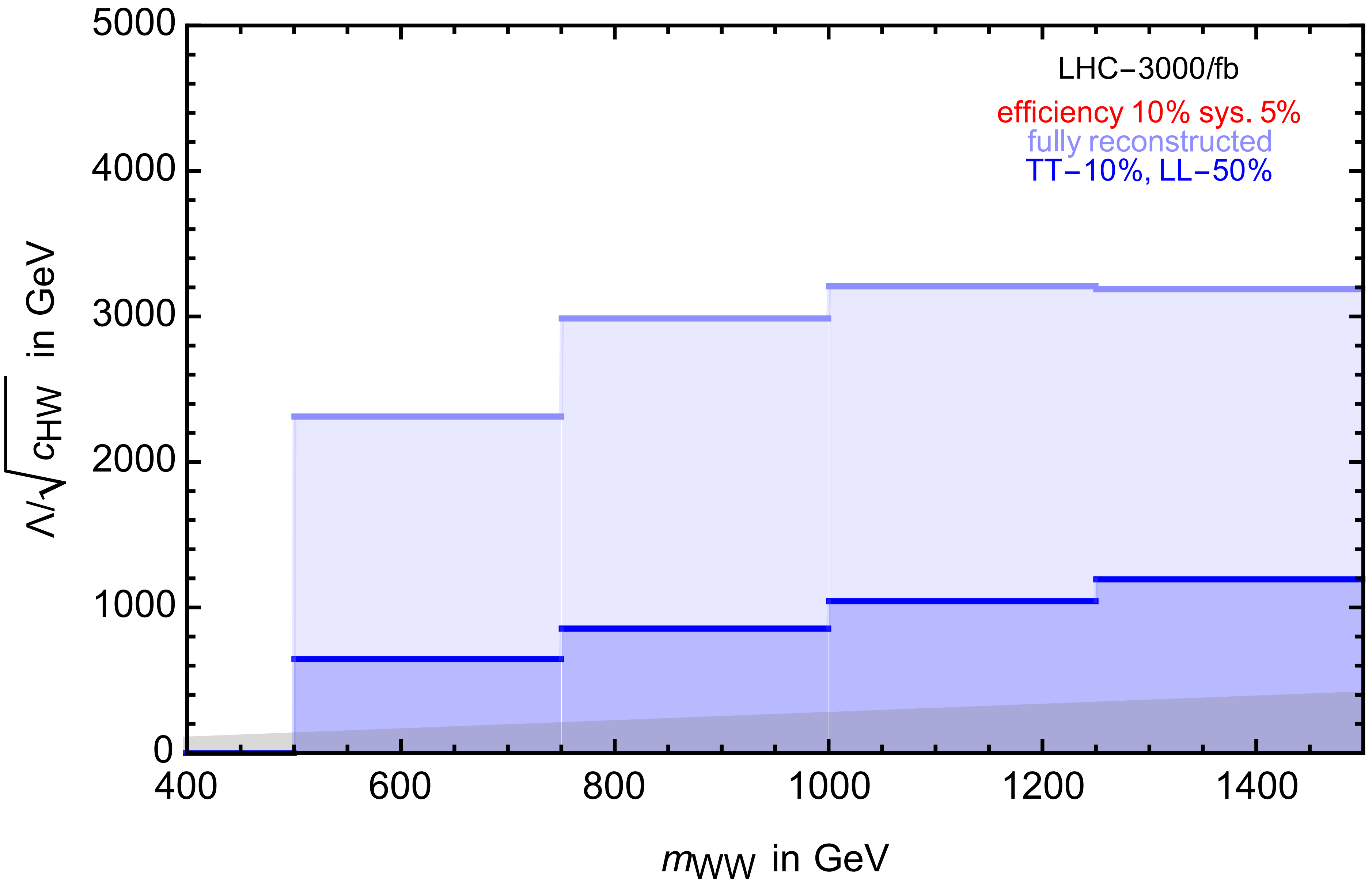
SM WW, WZ processes are dominated by transverse modes

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

Polarization tagging of W/Z crucial

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).

WW, semileptonic channel



$$\mathcal{M}_f^{00} = -\frac{\sin\theta}{2}\left\{T_f^3 g^2 + Y_f g'^2 + \frac{s}{\Lambda^2}\left[(c_W + c_{HW})T_f^3 g^2 + (c_B + c_{HB})Y_f g'^2 + \delta_f c_f\right]\right\}$$

LHC benchmarks

Λ[TeV]	$\mathcal{O}_W$	$\mathcal{O}_B$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$
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

ideal case, perfect pol tagging, no systematics

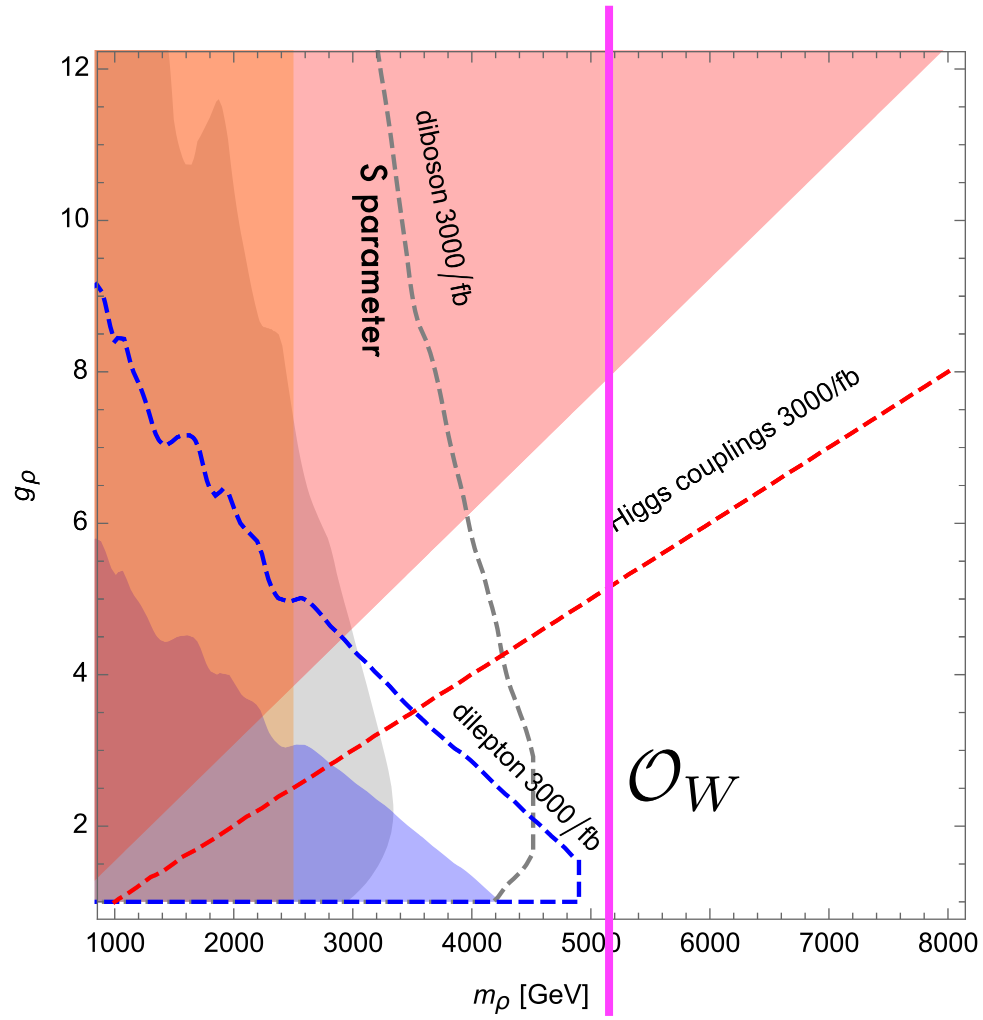
tagging eff 50%, mis-tagging rate 5%, no systematics

tagging eff 50%, mis-tagging 10%

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

– 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.

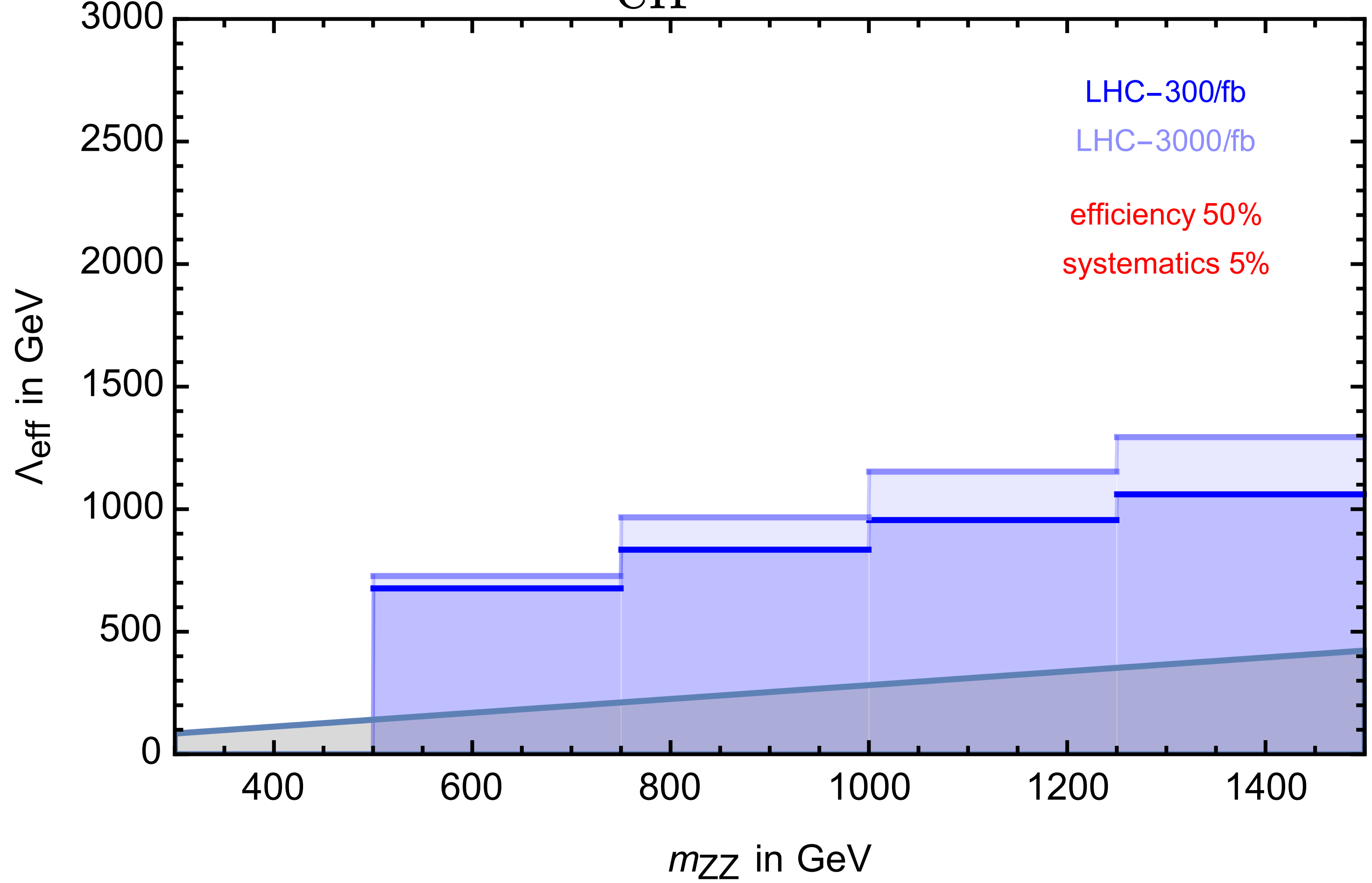
Dimension-8

- 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	$\frac{E^4}{\Lambda^4}$

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



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

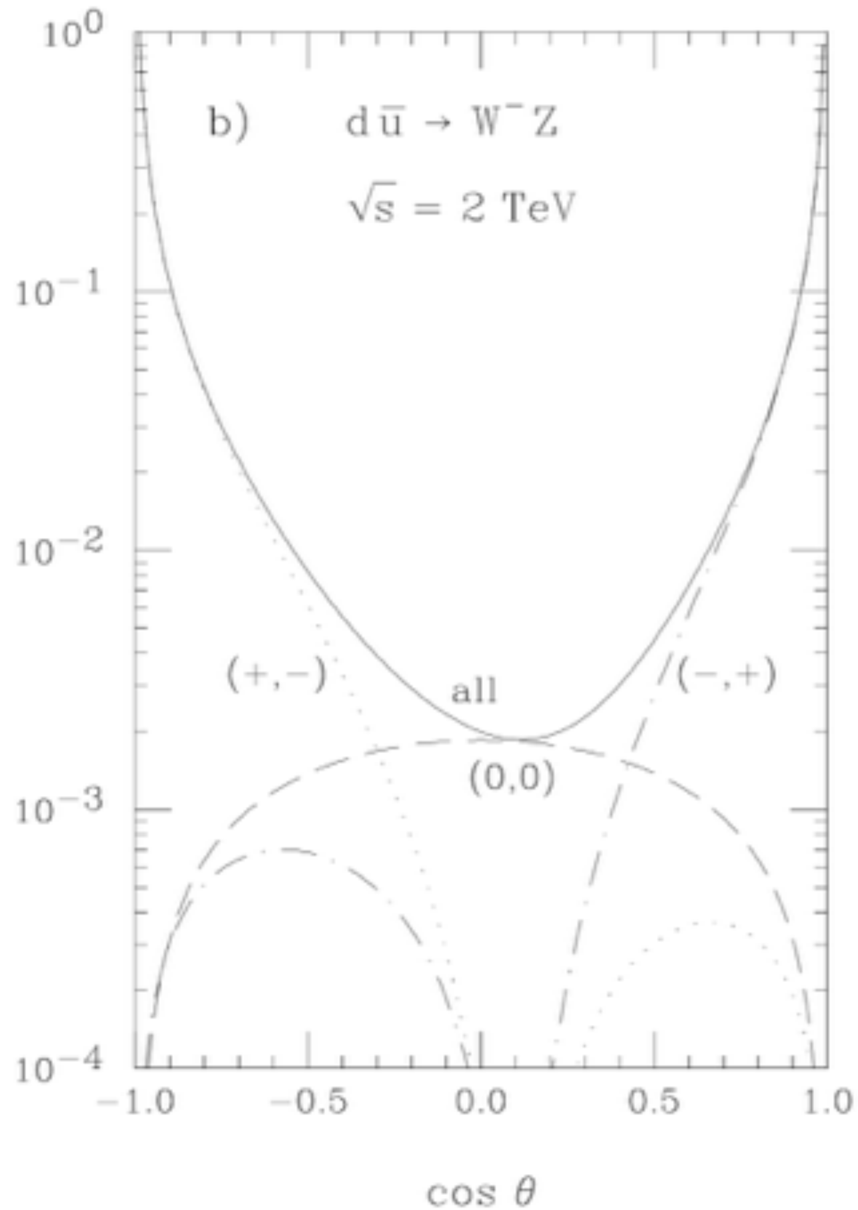
Conclusion

- LHC is pursuing a comprehensive program which covers the ground pretty well. After Moriond 2017, slow gain with 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

Using kinematics instead of tagging

Need to separate longitudinal versus transverse (non EW bkg are small)



Baur, Han, Ohnemus '95

see Franceschini at Planck17

difficult to reconstruct the scattering angle in parton frame,

Under investigation

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

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

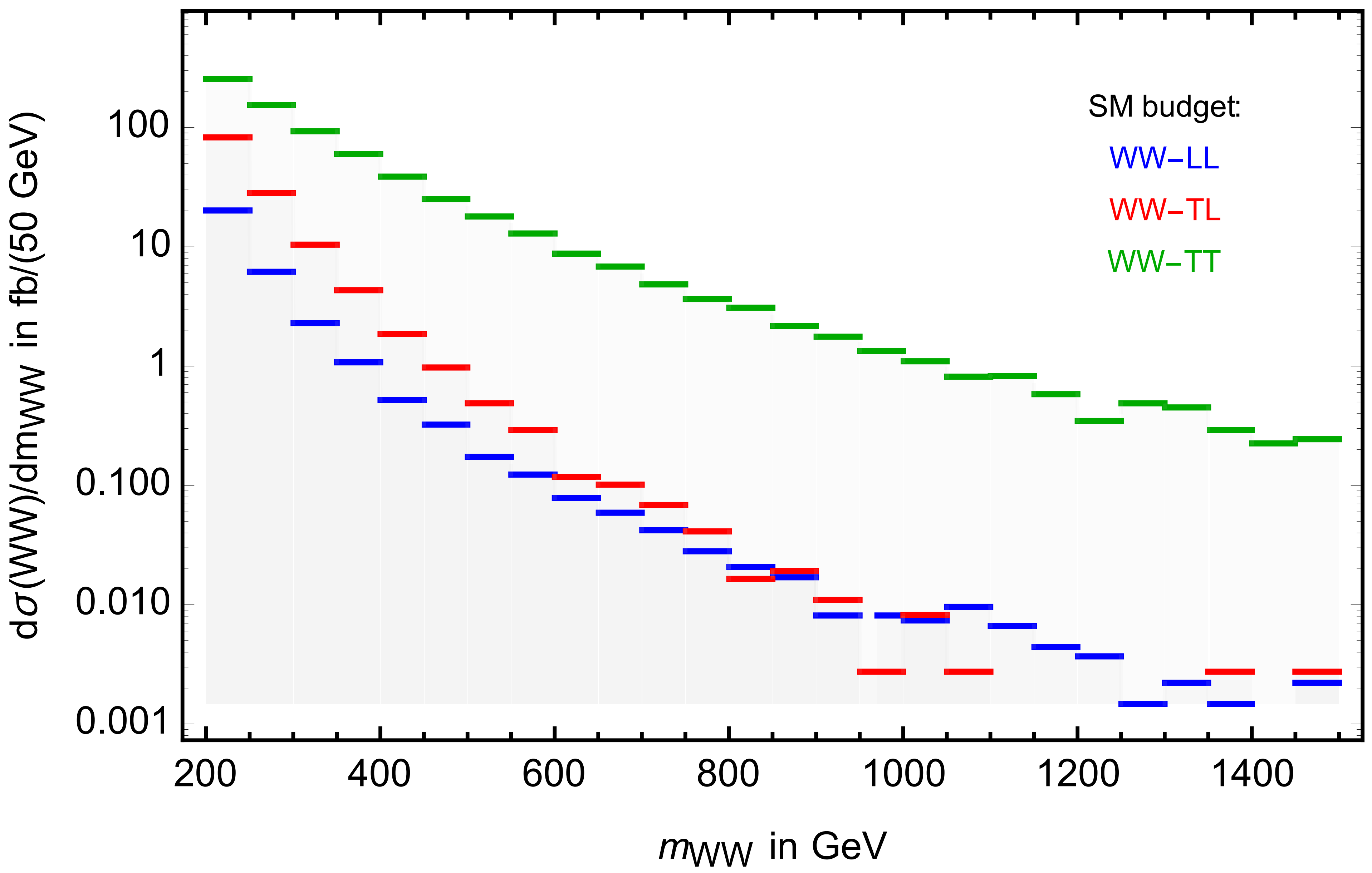
The selection efficiency $\epsilon = 10\%$ for semi-leptonic channels

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

WW, semileptonic channel



Typical resonances

resonance mass	m_*
generic relation	$m_* = g_* f$
coupling to 'composite' particles	g_* Higgs, W/Z goldstones, top
coupling to 'elementary' particles	$g_{\rm SM}\dfrac{g_{\rm SM}}{g_*}$ light quarks, leptons, transverse W/Z

Modulo tunings, the program here is to explore
m* vs. g* parameter space

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	$\left[(c_W + c_{HW})T_f^3 - (c_B + c_{HB})Y_f t_w^2\right]\frac{E_c^2}{\Lambda^2}, c_f\frac{E_c^2}{\Lambda^2}$
$Z_T Z_T$	$(c_{TWW} + t_w^2 c_{TBB} - 2T_f^3 t_w^2 c_{TWB})\frac{E_c^4}{\Lambda^4}$	$\gamma\gamma$	$(c_{TWW} + t_w^2 c_{TBB} + 2T_f^3 t_w^2 c_{TWB})\frac{E_c^4}{\Lambda^4}$
$h \to Z\gamma$	$(c_{HW} - c_{HB})\frac{(4\pi v)^2}{\Lambda^2}$	$h \to W^+W^-$	$(c_W + c_{HW})\frac{m_W^2}{\Lambda^2}$

- 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.

Potential difficulties

SM WW, WZ processes are dominated by transverse modes

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

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 on W,Y at LHC3000

$$W \sim \frac{m_W^2}{\Lambda^2} \longleftarrow \frac{1}{\Lambda^2}(D^\mu W^a_{\mu\nu})^2$$

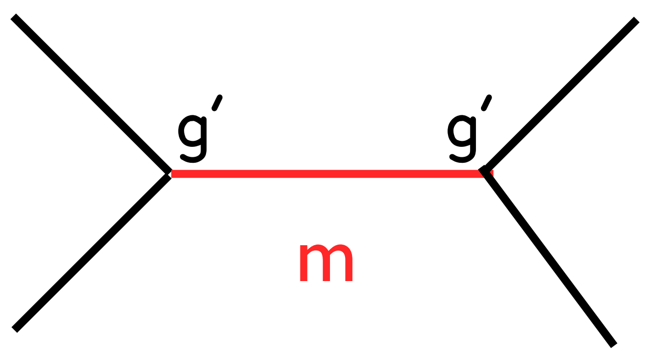
Farina et al $\Lambda \gtrsim 19\ \mathrm{TeV}$ LHC 3/ab

systematics 5%

Comparing with di-boson

$$\Lambda \gtrsim 4\ \mathrm{TeV}\sqrt{c_{\mathrm{diboson}}}\ , \quad c_{\mathrm{diboson}} = 1, \frac{g_*}{g}$$

Generic signal



m > kinematical limit. Integrate out $$\frac{g'^2}{m^2}\mathcal{O}^{(6)}$$

Best channels are usually di-lepton, di-jet and so on.
Can also be broad resonances
Well studied

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

Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer

Two directions (more tuning, simpler)

Higgs coupling: $\delta \simeq \frac{v^2}{f^2} \to f > 700\text{GeV}$ $\qquad V_h(v/f)$

Higgs mass: $m_h^2 \simeq b \frac{3y_t^2 v^2}{2\pi^2} \left(\frac{m_*}{f}\right)^2 \sim b \cdot (125 \text{ GeV})^2 \frac{g_*^2}{4}$

Fix f, increase g_* (hence increase $m_* = g_* f$)
Fix tuning for v/f, increase tuning of m_h .
Better for electroweak precision, $S \approx m_W^2 / m_*^2$; FCNC…
Heavier and broader resonances.
Deviation in Higgs coupling unchanged

Fix ratio $m_* / f \approx g_*$, increase m_* and f.
Fix tuning for Higgs mass. Increase tuning of v/f.
Better for electroweak precision, FCNC…
Heavier resonances. Less deviation in Higgs coupling.

Two fine tunings of composite Higgs

Λ, or m_ρ, or m_* $\approx$ $g_* f$ (or $g_\rho f$)

f, similar to f_π

v, $m_h \approx$ 100 GeV

1. Generates Higgs potential with EWSB $V_h(v/f)$ expect $v \approx f$

However, Higgs coupling deviation: $\delta \simeq \frac{v^2}{f^2} \to f > 700\text{GeV}$

2. Higgs mass: $m_h^2 \simeq b \frac{3y_t^2 v^2}{2\pi^2} \left(\frac{m_*}{f}\right)^2 \sim b \cdot (125\ \text{GeV})^2 \frac{g_*^2}{4}$

light Higgs needs small b and/or small m_*

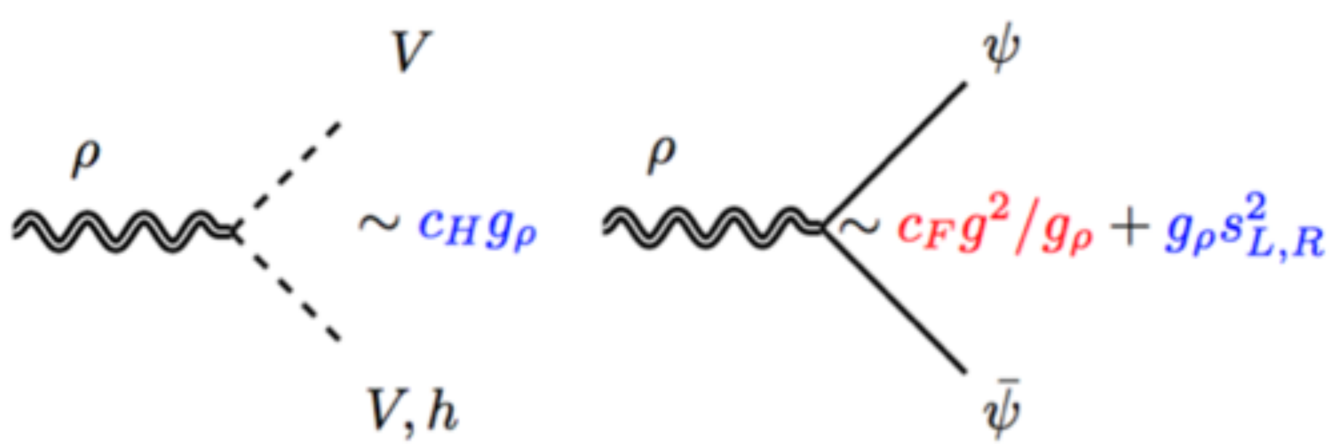
New vector resonances

see also Pappadopulo Thamm Torre Wulzer

Weakly coupled to elementary particles / strongly coupled to Higgs

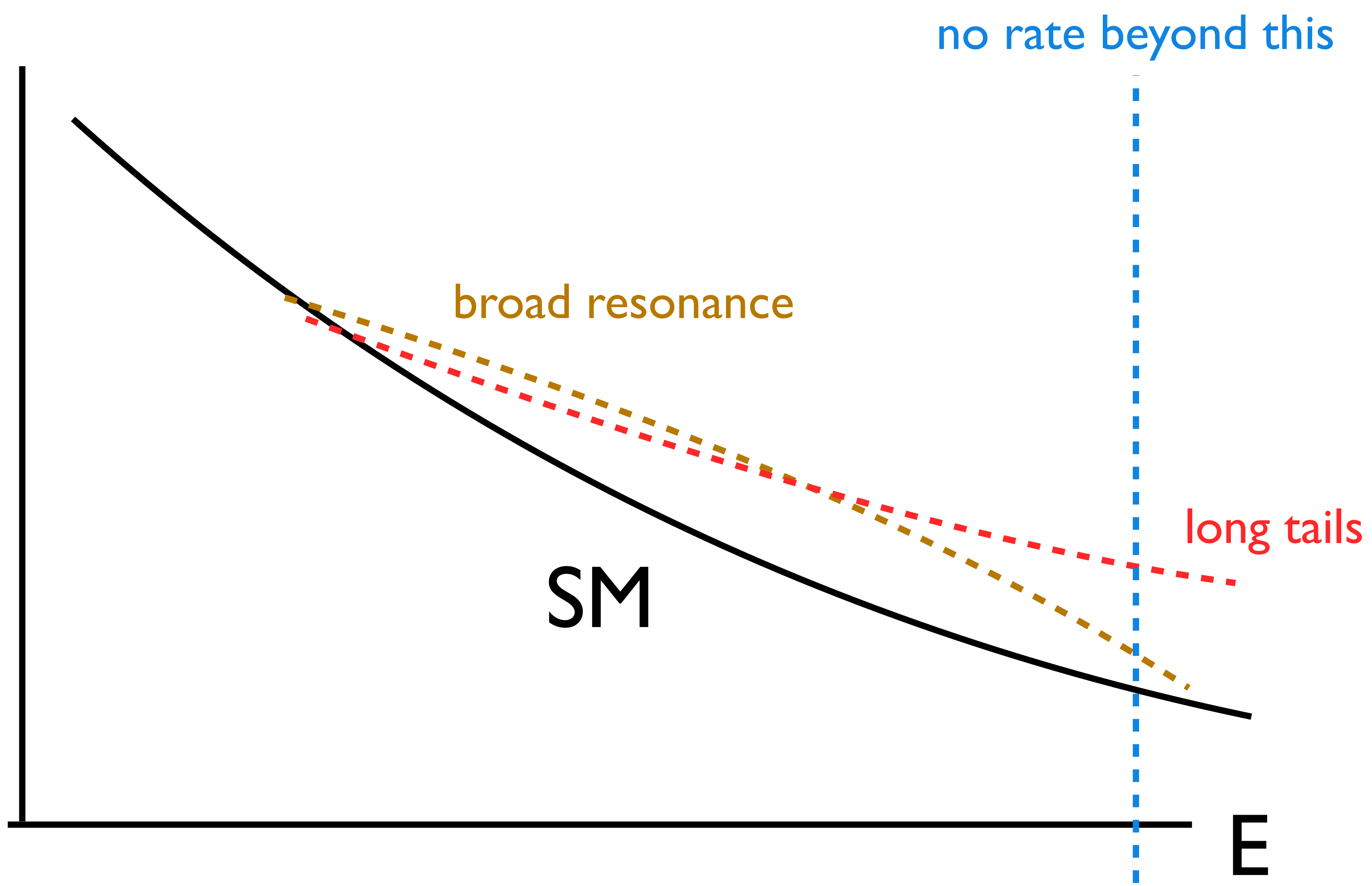
$$-\frac{1}{4}(D_\mu \rho_\nu)^2 + \frac{m_*^2}{2}\rho_\mu^2 + i g_* c_H\, \rho_\mu^a J_H^{\mu a} + \frac{g^2}{g_*} c_3 \rho_\mu^a J_3^{\mu a} + \frac{g^2}{g_*} c_f \rho_\mu^a J_f^{\mu a}$$

Strongly coupled to dibosons, weakly coupled to dileptons



Production rates scales like $\sigma(\rho) \sim \dfrac{g^4}{g_*^2}$

Broad features with di-boson, tops etc.



- Focusing on the "tail" case in the following.

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

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

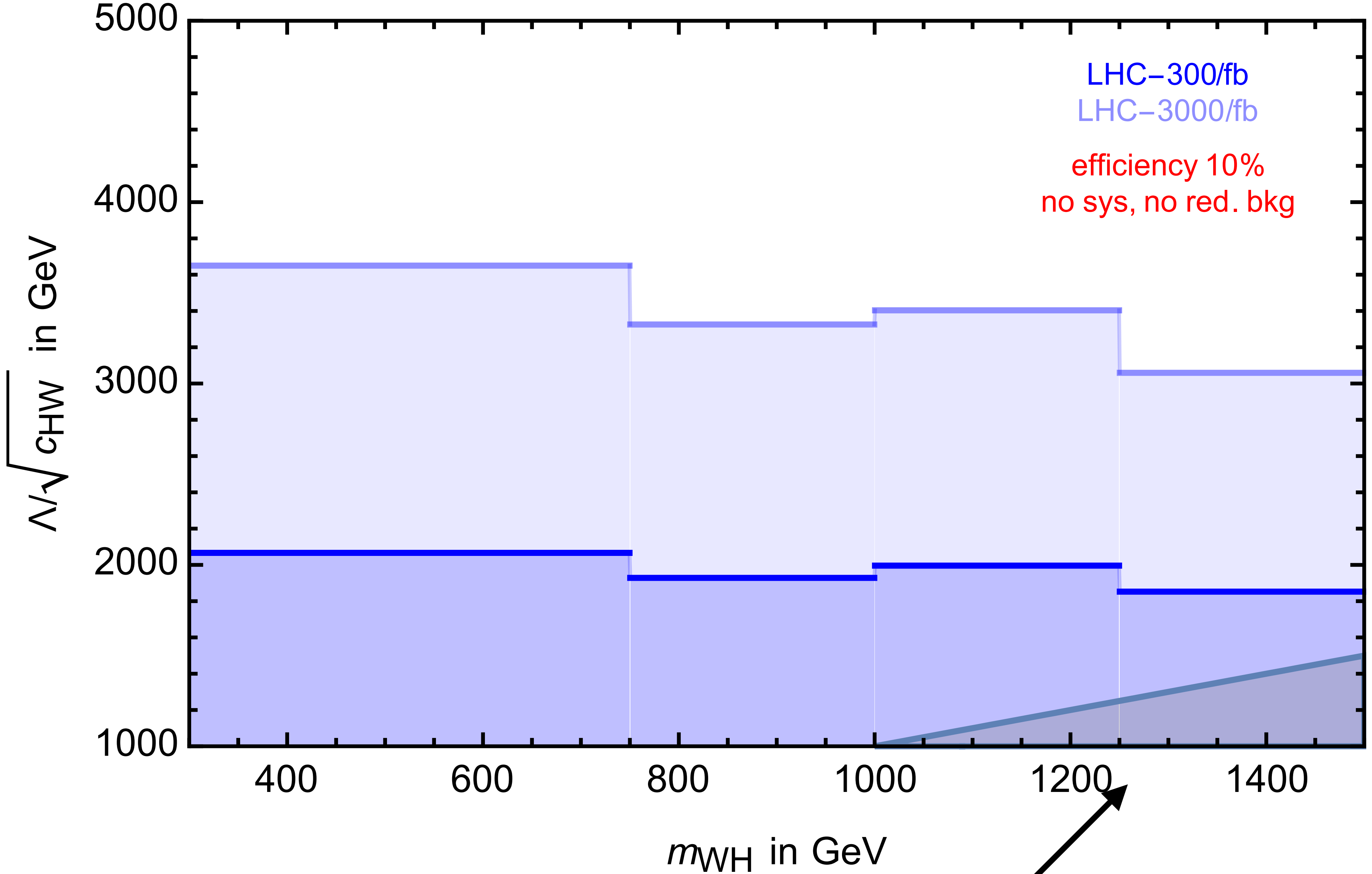
$$_8\mathcal{O}_{TWB} = gg' \mathcal{T}^{a\,\mu\nu}_f W^a_{\mu\rho} B^\rho_\nu, \qquad _8\mathcal{O}_{TH} = g^2 \mathcal{T}^{\mu\nu}_f D_\mu H^\dagger D_\nu H$$

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

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

dim 8

Wh channel



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

EFT not valid