Precision Measurements at the LHC

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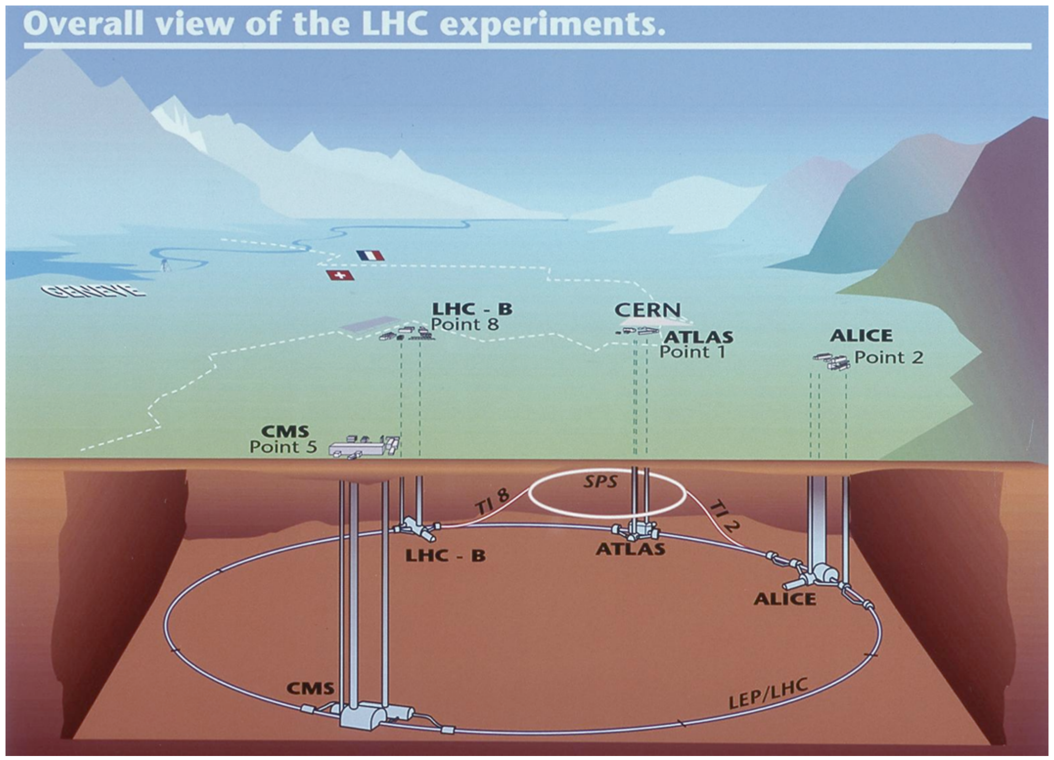
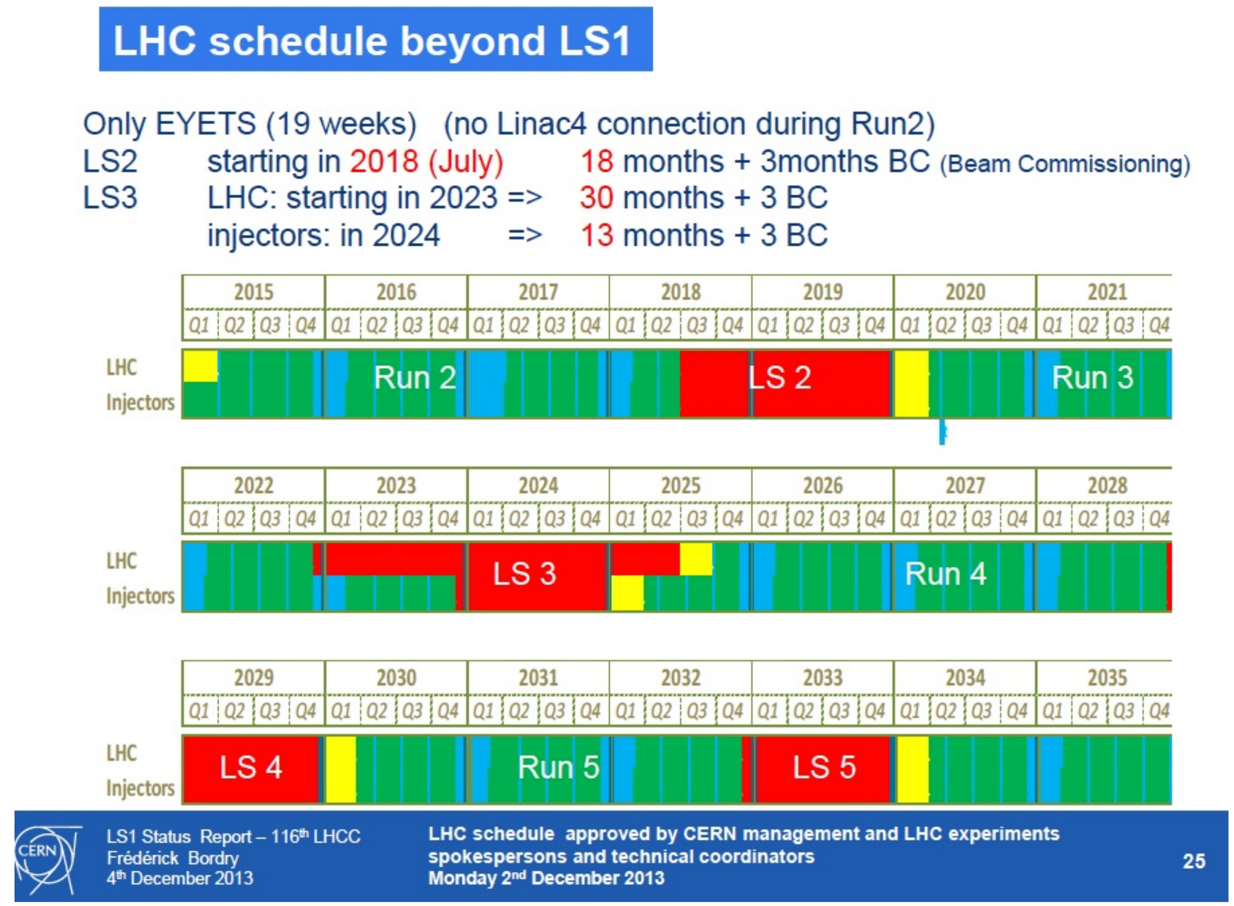
Future of Large Hadron Collider

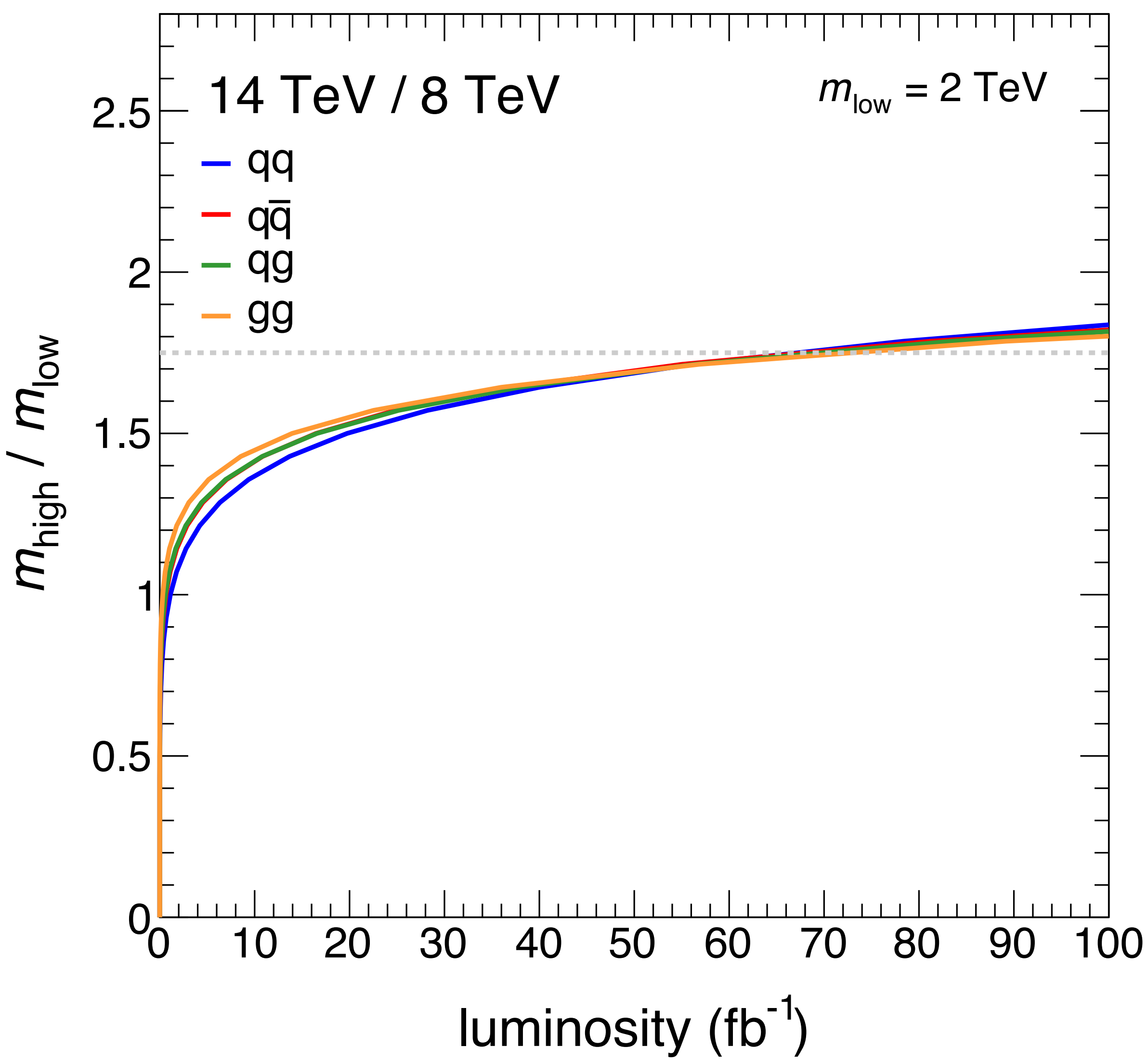




- Will continue and improve in the next two decades
  - E_{cm} = 13-14 TeV.
  - 95+% more data.

As data accumulates

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



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

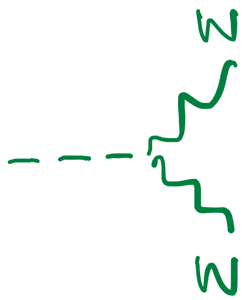
Reached "slow" phase after Moriond 2017

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

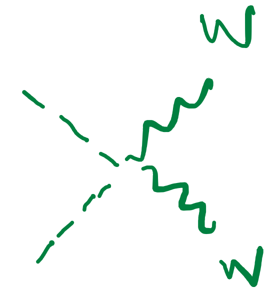
In addition to waiting patiently...

Higgs measurements

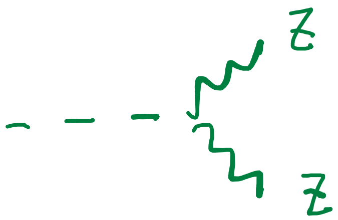
SM Higgs couplings



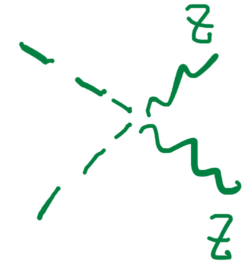
$$i\frac{g^2 v}{2}\eta_{\mu\nu} = 2i\frac{m_W^2}{v}\eta_{\mu\nu}$$



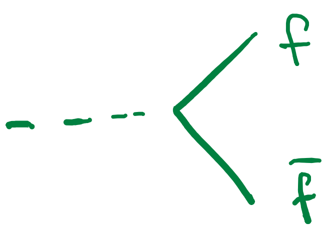
$$i\frac{g^2}{4}2\eta_{\mu\nu} = 2i\frac{m_W^2}{v^2}\eta_{\mu\nu}$$



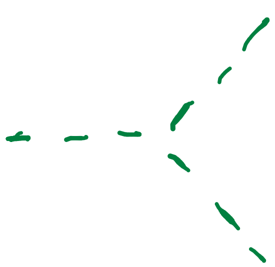
$$i\frac{(g^2+g'^2)}{4}\eta_{\mu\nu} = 2i\frac{m_Z^2}{v}$$



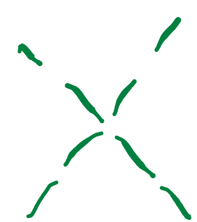
$$\frac{i(g^2+g'^2)}{8}4\eta_{\mu\nu}$$



$$-i\frac{y_f}{\sqrt{2}} = -i\frac{m_f}{v}$$



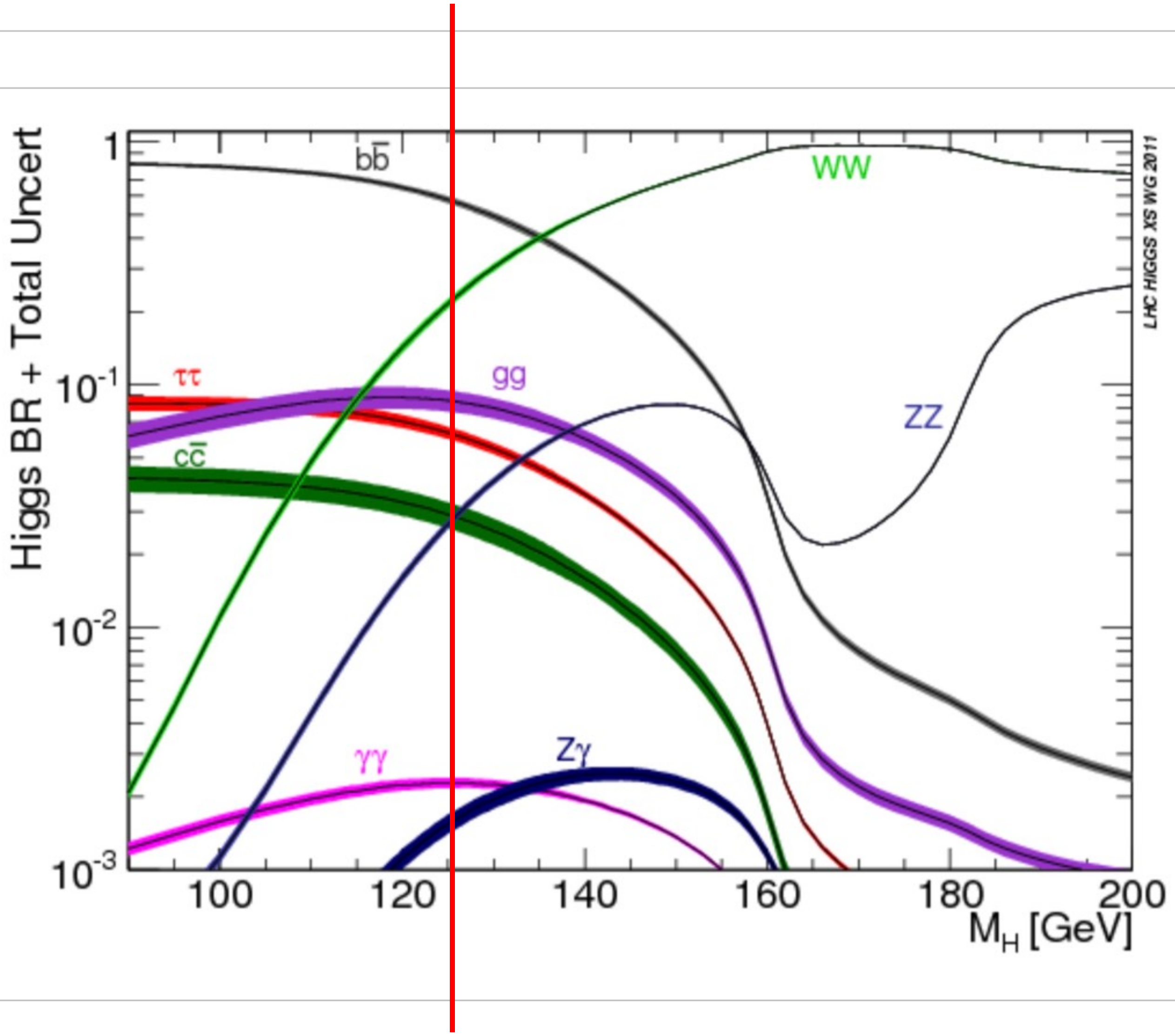
$$-i\lambda v\,3! = -3i\frac{m_h^2}{v}$$

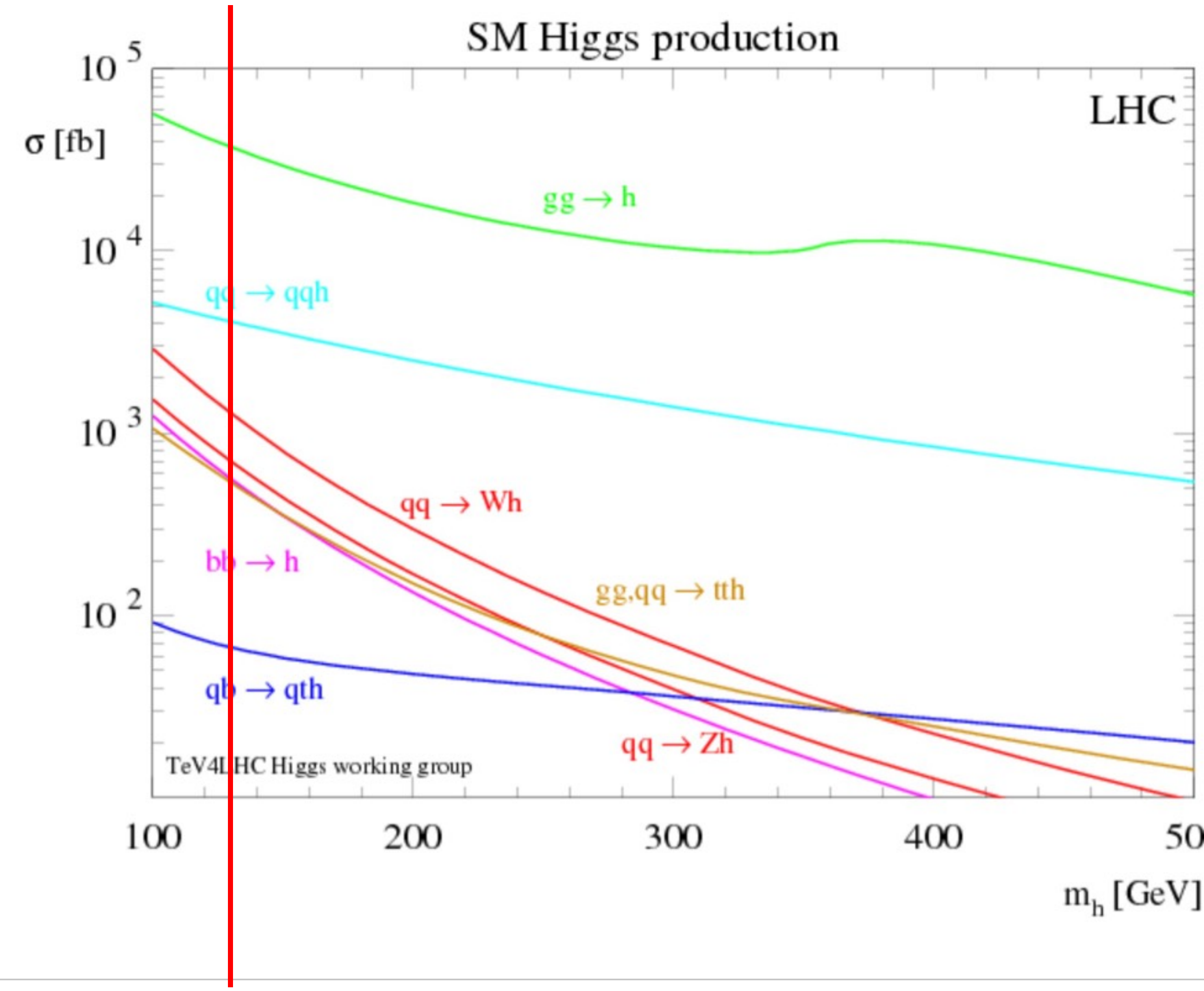


$$-i\frac{\lambda}{4}4! = -i\,3\frac{m_h^2}{v^2}$$

$$V(h) = -\mu^2 h^\dagger h + \lambda(h^\dagger h)^2$$

$$v^2 = \frac{\mu^3}{\lambda}, \quad m_h^2 = 2\lambda v^2$$


Higgs BR + Total Uncert
LHC HIGGS XS WG 2011
$b\bar{b}$
WW
ZZ
$\tau\tau$
gg
$c\bar{c}$
$\gamma\gamma$
$Z\gamma$
1
10^{-1}
10^{-2}
10^{-3}
100
120
140
160
180
200
M_H [GeV]


SM Higgs production
LHC
σ [fb]
$gg \to h$
$qq \to qqh$
$qq \to Wh$
$b\bar{b} \to h$
$gg,qq \to t\bar{t}h$
$qb \to qth$
$qq \to Zh$
TeV4LHC Higgs working group
10^5
10^4
10^3
10^2
100
200
300
400
500
m_h [GeV]

Measurement of Higgs coupling

Rate for Higgs production the decay to final state j

$$R_j = \sigma_{prod} \times BR_j = \sigma_{prod} \times \frac{\Gamma_j}{\Gamma_{tot}}$$

Parameterizing Higgs coupling to state i g_i

$$\kappa_i = \frac{g_{i\,exp}}{g_{i\,SM}}$$

Typically, we can consider

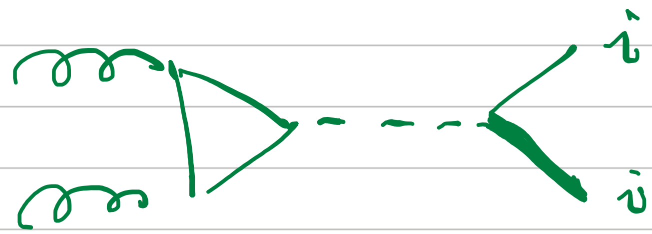
g_W, g_Z, g_t, g_b, g_c, g_τ, g_γ, g_g, $g_{Z\gamma}$

g_{3h}, ...

Including possible exotic decays, we at least can add

Γ_{exo} or Γ_{tot}.

Typical processes for Higgs coupling measurements



$i = Z, W, b, \tau, \gamma \ldots$

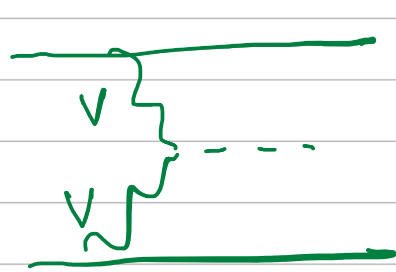
define

$$\mu_{gi} = \frac{\sigma(gg \to h \to i)}{\sigma_{SM}(gg \to h)}$$

$$\mu_{gi} \propto k_g^2 \, k_i^2$$

$V = W, Z$

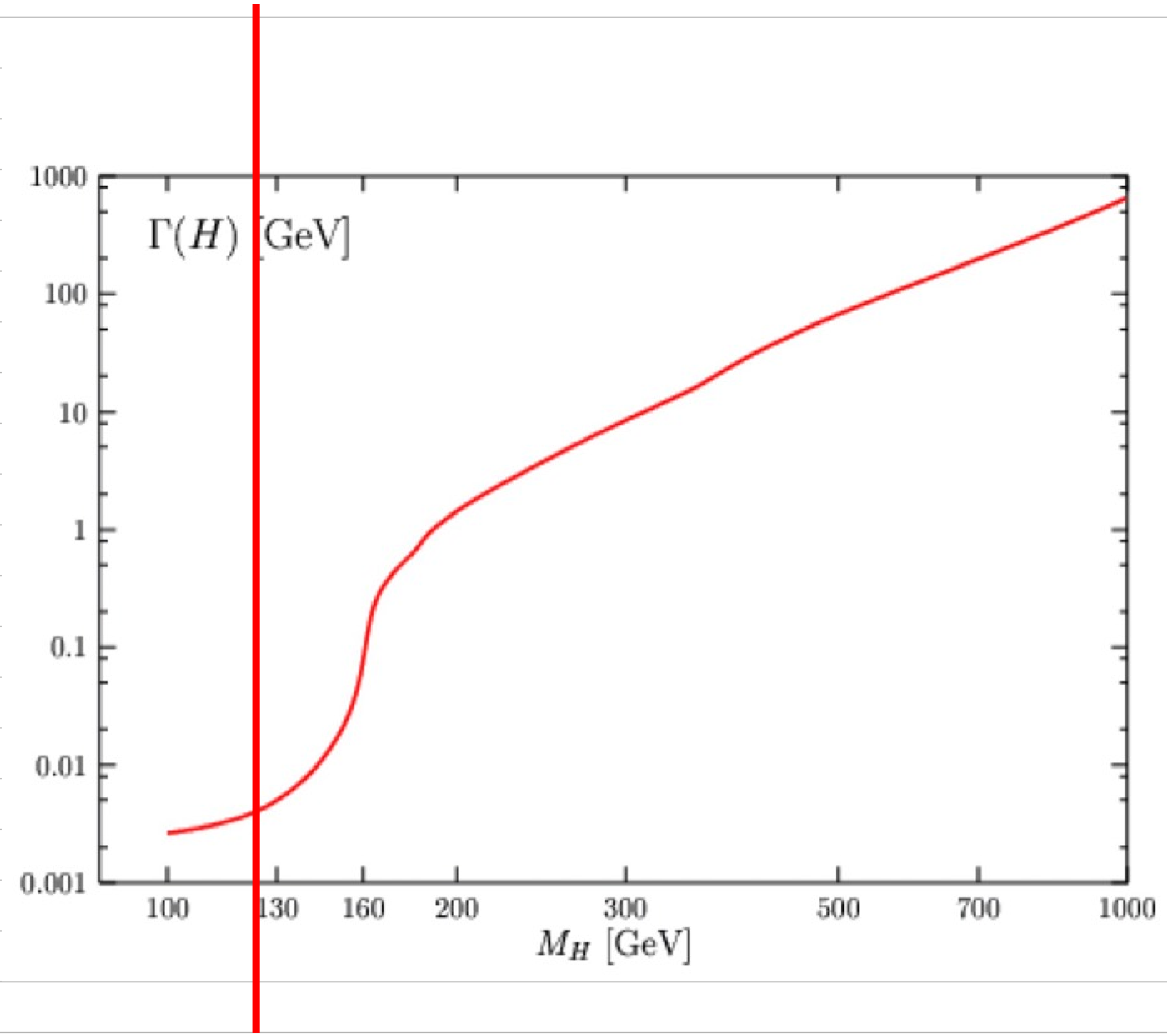
$$\mu_{Vi} = \frac{\sigma(q\bar{q} \to Vh \, (h \to i))}{\sigma_{SM}(q\bar{q} \to Vh)} \propto k_V^2 \, k_i^2$$



VV: WW, ZZ, $Z\gamma$

In order to measure couplings, knowing Γ_{tot} is necessary (or we have to make assumptions about it)

Higgs width measurement.



Higgs width a few MeV. ≪ resolution

Width measurement

$$\hat{\sigma}(gg \to h \to ZZ) \sim \int d\hat{s} \frac{|A(gg \to H \to ZZ)|^2}{(\hat{s} - m_h^2)^2 + \Gamma_{tot}^2 m_h^2}$$

$$|A(gg \to h \to ZZ)| = \kappa_g^2 \kappa_Z^2 \cdot f(\hat{s})$$

Off shell above threshold, $\hat{s} > m_h^2$

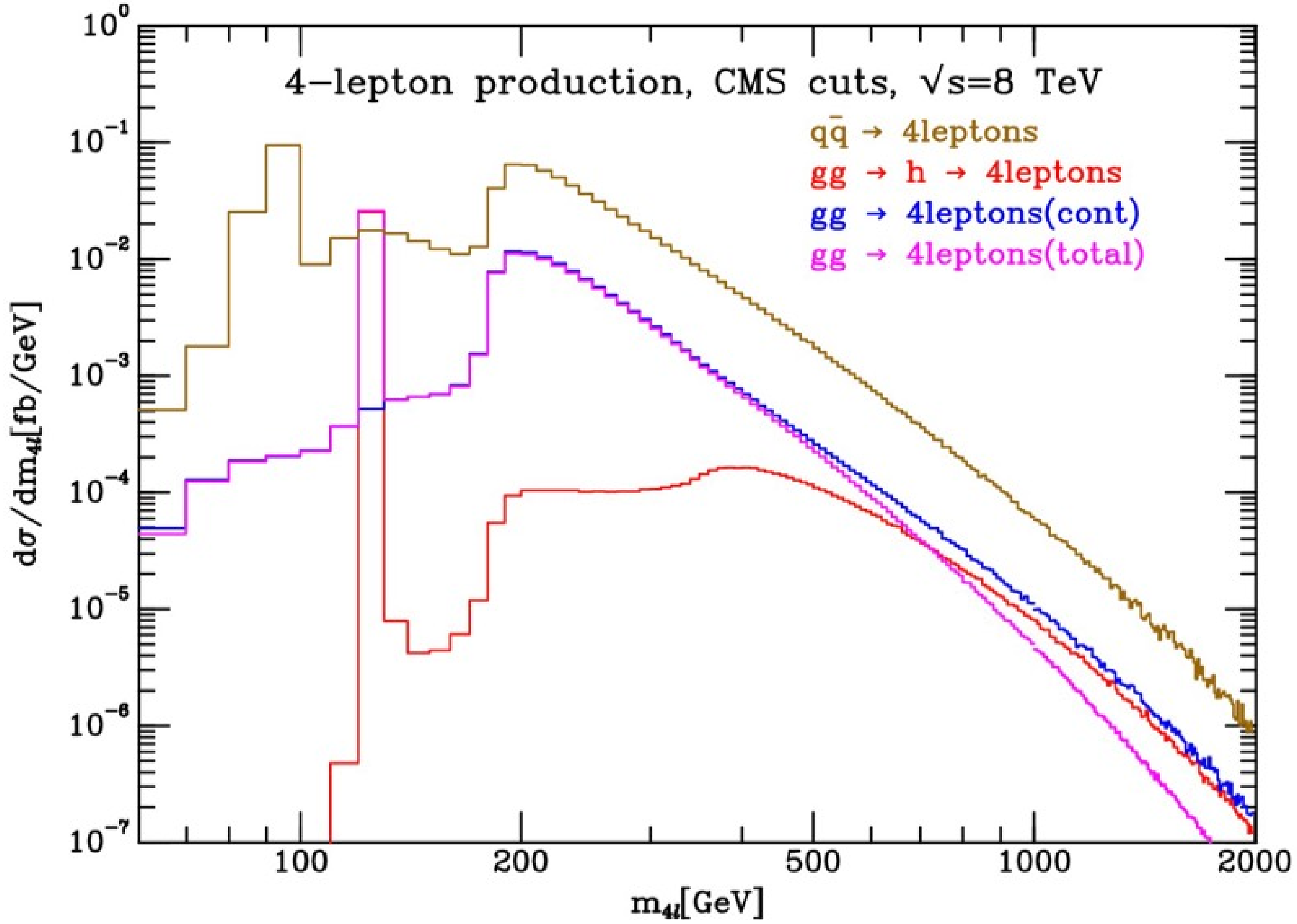
$$\hat{\sigma}^{\text{off-shell}} \sim \int d s \frac{\kappa_g^2 \kappa_s^2 f(\hat{s})}{\hat{s}}$$ $f(\hat{s})$ known function

On-shell

Narrow width approximation $\dfrac{1}{(\hat{s}^2 - m_h^2)^2 + m_h^2 \Gamma_{tot}^2} \to \dfrac{\pi}{m_h \Gamma_{tot}} \delta(\hat{s} - m_h^2)$

$$\hat{\sigma}^{\text{on-shell}} \sim \frac{\kappa_g^2 \kappa_Z^2 f(\hat{s} = m_h^2)}{m_h \Gamma_{tot}}$$

$$\Gamma_{tot} \sim \frac{\sigma^{\text{off-shell}}}{\sigma^{\text{on-shell}}}.$$



Current limit $\Gamma_{tot} < 4\text{-}5\ \Gamma_{SM}$

For example: extraction of κ_g

Assume (no model indep. determination possible)

$$\Gamma_{tot} = \Gamma_V + \Gamma_{bb}$$

- No exotic modes.
- Only included dominant channel for simplicity

$$\kappa_g^2 = (\mu_{gV} + \mu_{gb}) = \Big(\mu_{gV} + \underbrace{\frac{\mu_{Vb}}{\mu_{V\gamma}}}\mu_{g\gamma}\Big)$$

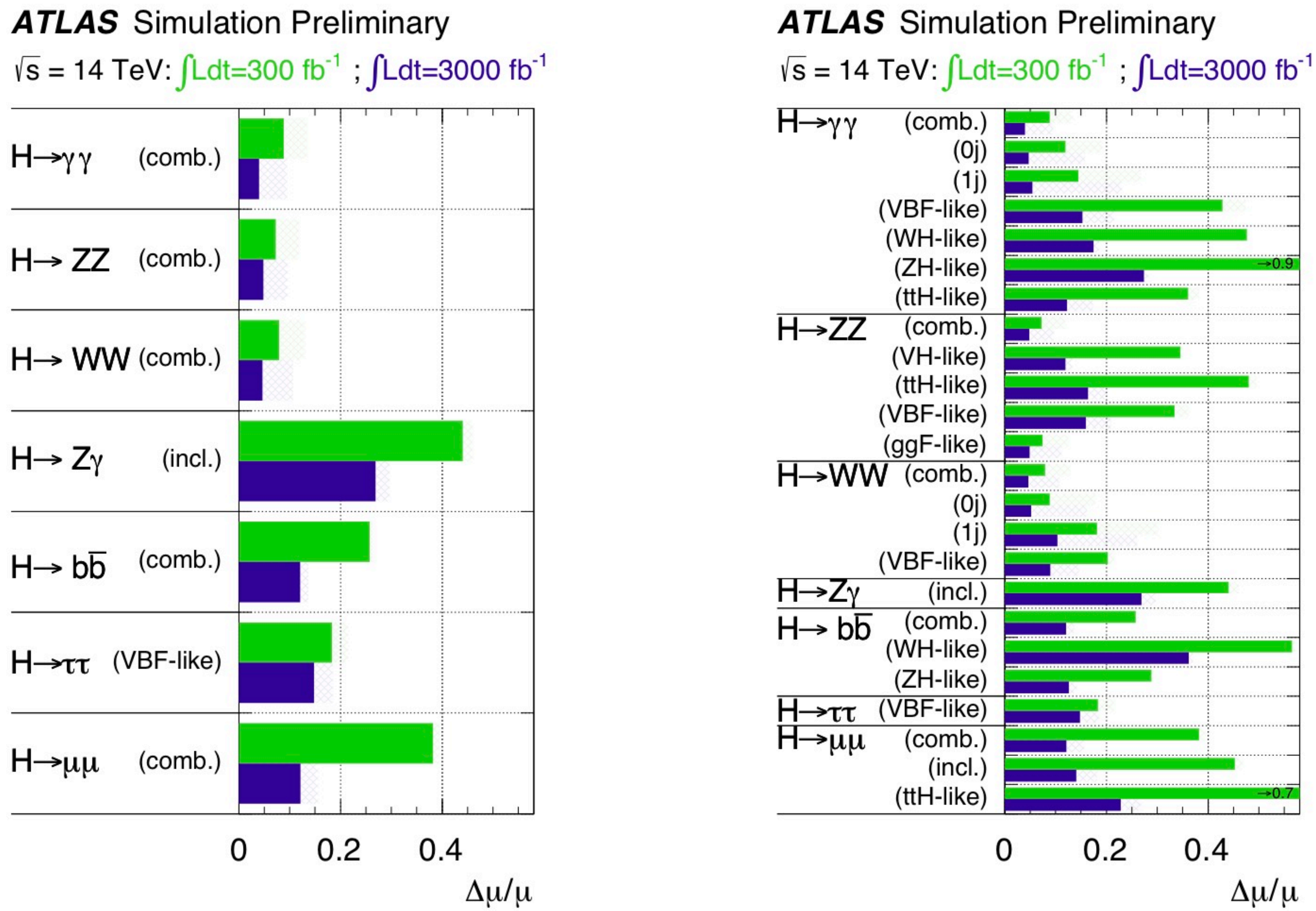
many systematics cancel in this ration

errors: at $3\,ab^{-1}$

$\mu_{gV} \sim 7\%$, $\mu_{g\gamma} \sim 5\%$

$\delta\kappa_g \sim .8\%$

All channels combined $\sim 5\%$



~5% at best

systematics limited.

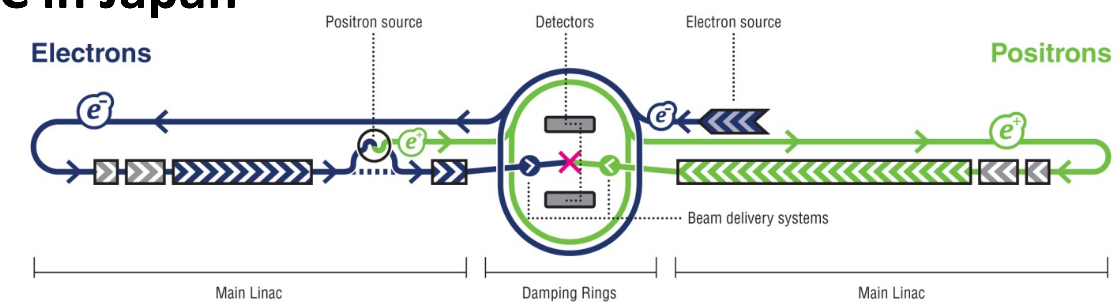
Figure 1: Relative uncertainty on the signal strength μ for all Higgs final states considered in this note in the different experimental categories used in the combination, assuming a SM Higgs boson with a mass of 125 GeV expected with 300 fb^{-1} and 3000 fb^{-1}of 14 TeV LHC data. The uncertainty pertains to the number of events passing the experimental selection, not to the particular Higgs boson process targeted. The hashed areas indicate the increase of the estimated error due to current theory systematic uncertainties. The abbreviation "(comb.)" indicates that the precision on μ is obtained from the combination of the measurements from the different experimental sub-categories for the same final state, while "(incl.)" indicates that the measurement from the inclusive analysis was used. The left side shows only the combined signal strength in the considered final states, while the right side also shows the signal strength in the main experimental sub-categories within each final state.

Nr.	Coupling	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
1	κ	4.2%	3.0%	2.4%	3.2%	2.2%	1.7%
2	$\kappa_V = \kappa_Z = \kappa_W$	4.3%	3.0%	2.5%	3.3%	2.2%	1.7%
	$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$	8.8%	7.5%	7.1%	5.1%	3.8%	3.2%
3	κ_Z	4.7%	3.7%	3.3%	3.3%	2.3%	1.9%
	κ_W	4.9%	3.6%	3.1%	3.6%	2.4%	1.8%
	κ_F	9.3%	7.9%	7.3%	5.4%	4.0%	3.4%
4	κ_V	5.9%	5.4%	5.3%	3.7%	3.2%	3.0%
	κ_u	8.9%	7.7%	7.2%	5.4%	4.0%	3.4%
	κ_d	12%	12%	12%	6.7%	6.2%	6.1%
5	κ_V	4.3%	3.1%	2.5%	3.3%	2.2%	1.7%
	κ_q	11%	8.7%	7.8%	6.6%	4.5%	3.6%
	κ_l	10%	9.6%	9.3%	6.0%	5.3%	5.1%
6	κ_V	4.3%	3.1%	2.5%	3.3%	2.2%	1.7%
	κ_q	11%	9.0%	8.1%	6.7%	4.7%	3.8%
	κ_τ	12%	11%	11%	9.2%	8.4%	8.1%
	κ_μ	20%	20%	19%	6.9%	6.3%	6.1%
7	κ_Z	8.1%	7.9%	7.8%	4.3%	3.9%	3.8%
	κ_W	8.5%	8.2%	8.1%	4.8%	4.1%	3.9%
	κ_t	14%	12%	11%	8.2%	6.1%	5.3%
	κ_b	23%	22%	22%	12%	11%	10%
	κ_τ	14%	13%	13%	9.8%	9.0%	8.7%
	κ_μ	21%	21%	21%	7.3%	7.1%	7.0%
8	κ_Z	8.1%	7.9%	7.9%	4.4%	4.0%	3.8%
	κ_W	9.0%	8.7%	8.6%	5.1%	4.5%	4.2%
	κ_t	22%	21%	20%	11%	8.5%	7.6%
	κ_b	23%	22%	22%	12%	11%	10%
	κ_τ	14%	14%	13%	9.7%	9.0%	8.8%
	κ_μ	21%	21%	21%	7.5%	7.2%	7.1%
	κ_g	14%	12%	11%	9.1%	6.5%	5.3%
	κ_γ	9.3%	9.0%	8.9%	4.9%	4.3%	4.1%
	$\kappa_{Z\gamma}$	24%	24%	24%	14%	14%	14%

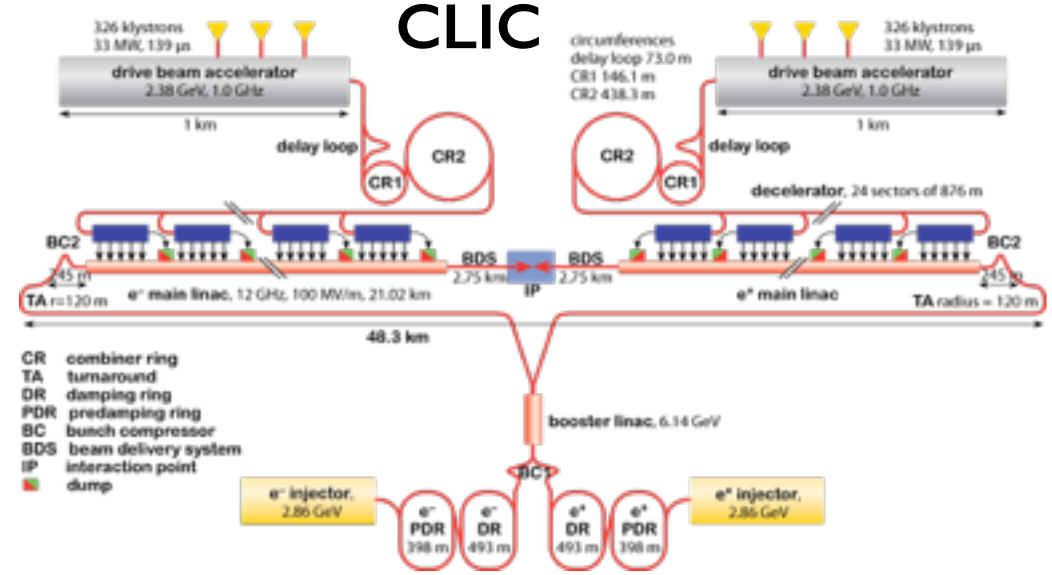
Table 3: Expected precision on Higgs coupling scale factors with 300 or 3000 fb^{-1} of $\sqrt{s} = 14$ TeV data for selected parametrizations, assuming no decay modes beyond those in the SM. With SM decay modes only, the Higgs total width can still differ from the SM value if any of its couplings to SM particles differ from the expected values. The coupling scale factor $\boldsymbol{\kappa}$ represents all SM particles, $\boldsymbol{\kappa_V}$ represents the gauge bosons W and Z, $\boldsymbol{\kappa_F}$ represents all fermions, $\boldsymbol{\kappa_u}$ represents all up-type fermions, $\boldsymbol{\kappa_d}$ represents all down-type fermions, $\boldsymbol{\kappa_q}$ represents all quarks, and $\boldsymbol{\kappa_l}$ represents all leptons. The results are reported for 3 different assumptions on the theory uncertainties: the current size, half of the current size, and no theory uncertainties.

Beyond the LHC, future facilities

ILC in Japan



CLIC

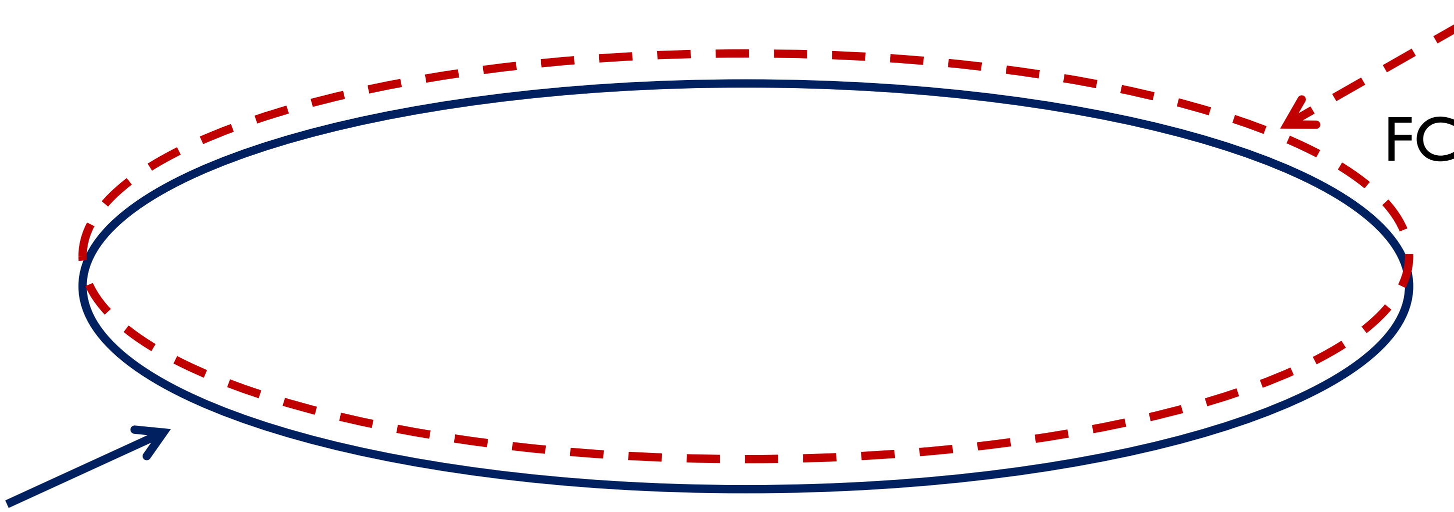


Circular. "Scale up" LEP+LHC

~100 TeV

pp collider

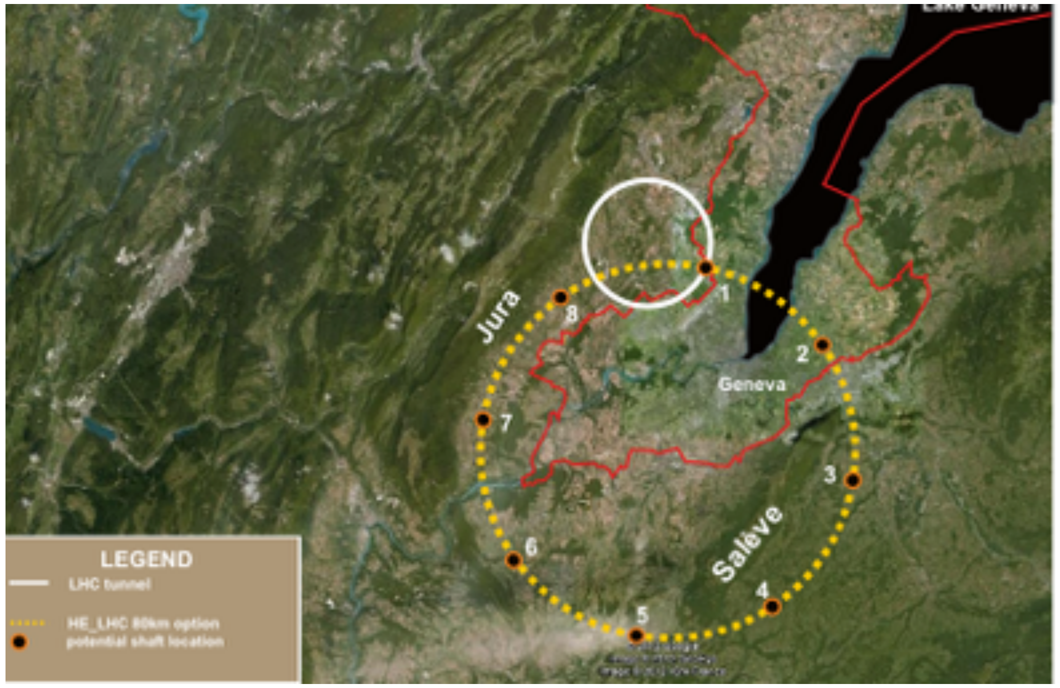
FCC-hh (CERN), SppC(China)



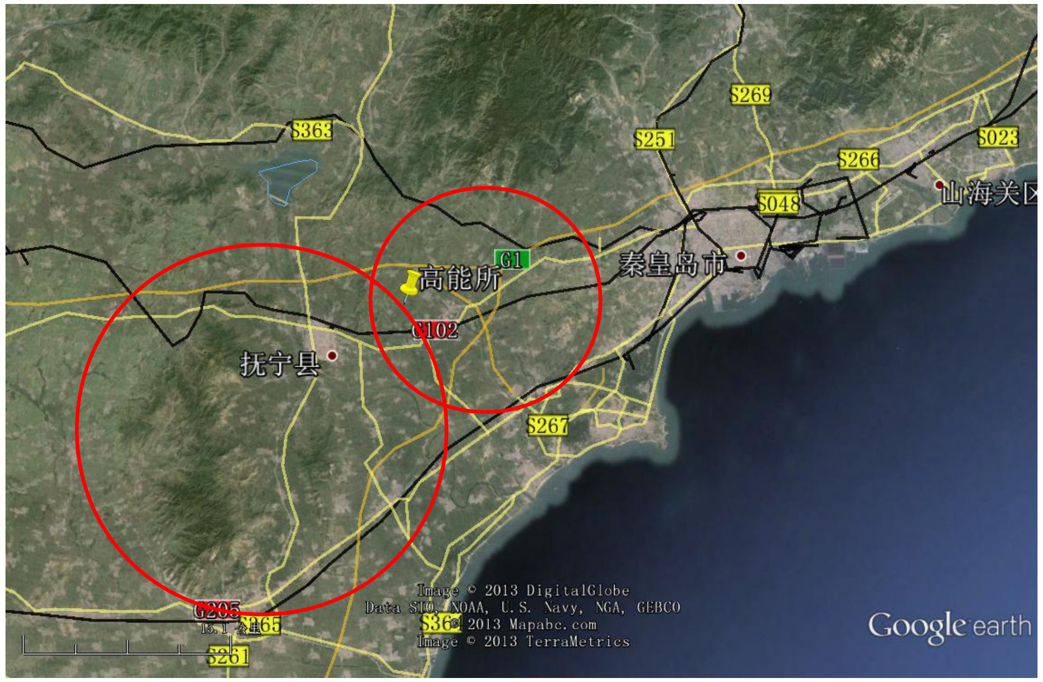
250 GeV **e^-e^+ Higgs Factory**

FCC-ee (CERN), CEPC(China)

Future circular colliders



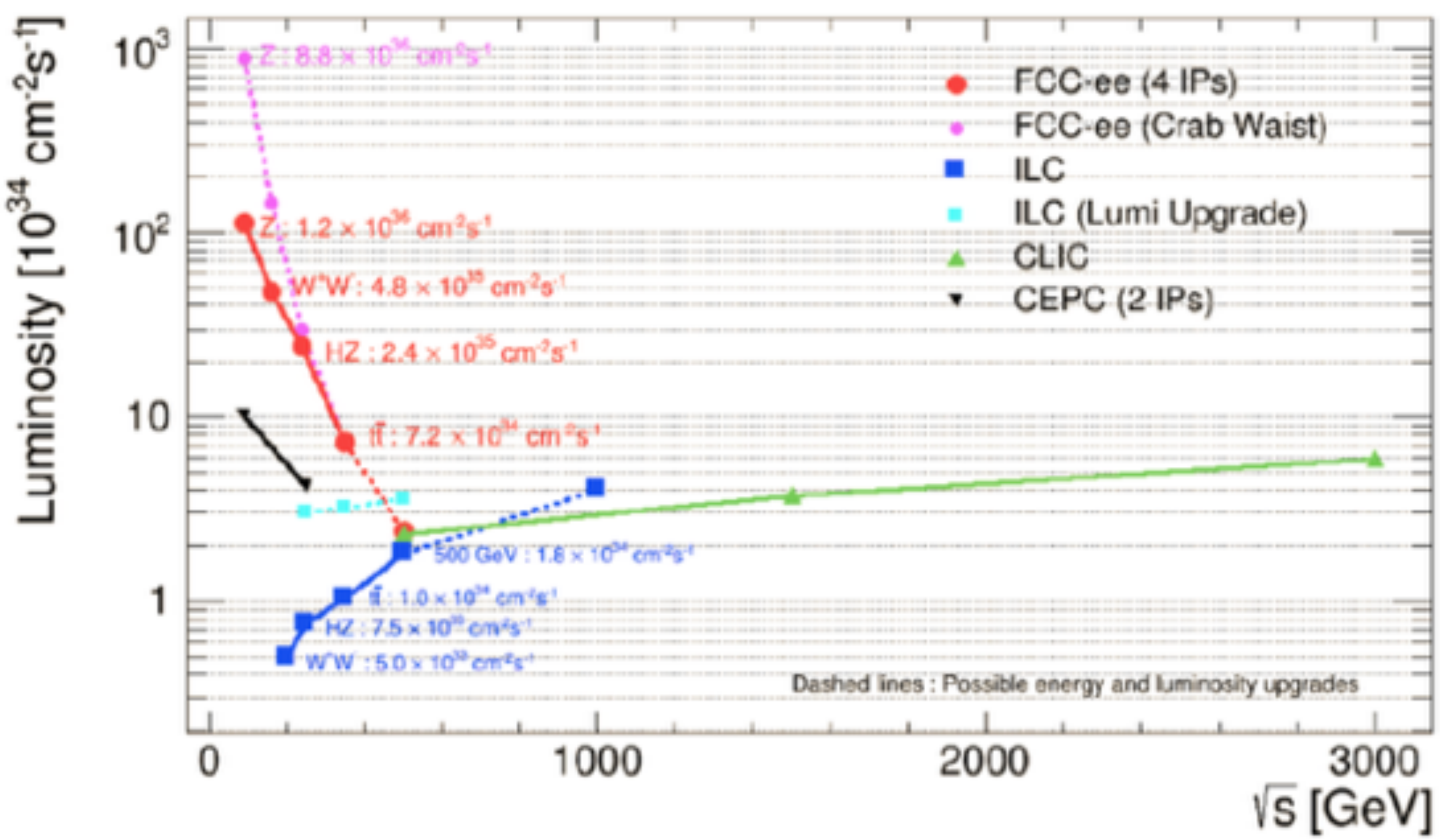
CERN
Higgs factory: FCC-ee
pp Collider: FCC-hh



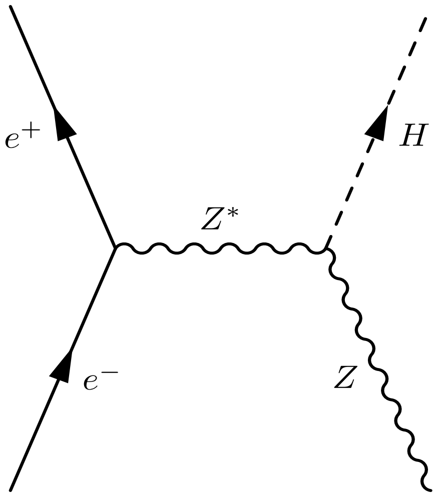
China.
Higgs factory: CEPC
pp Collider: SppC

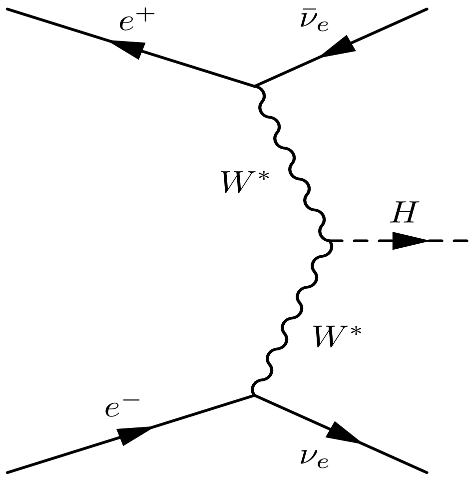
Higgs factories

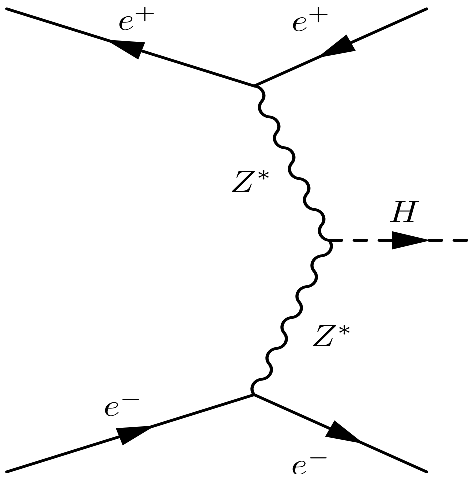
- FCC-ee, CEPC, ILC, CLIC.
- Physics case relatively independent of the outcome of the LHC.
  - Reach further than the LHC.
  - Address questions that LHC can't answer.

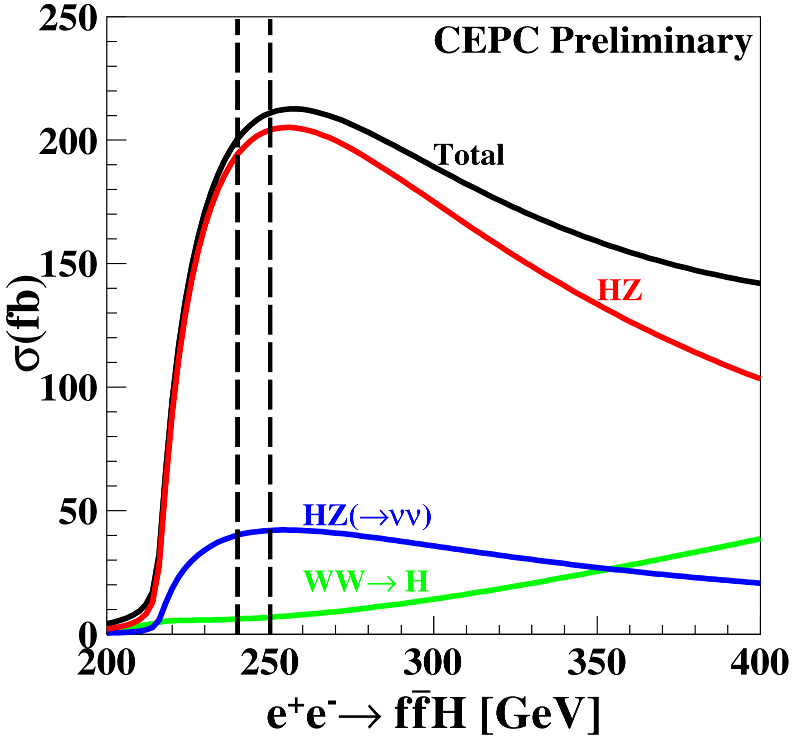


Higgs factory processes



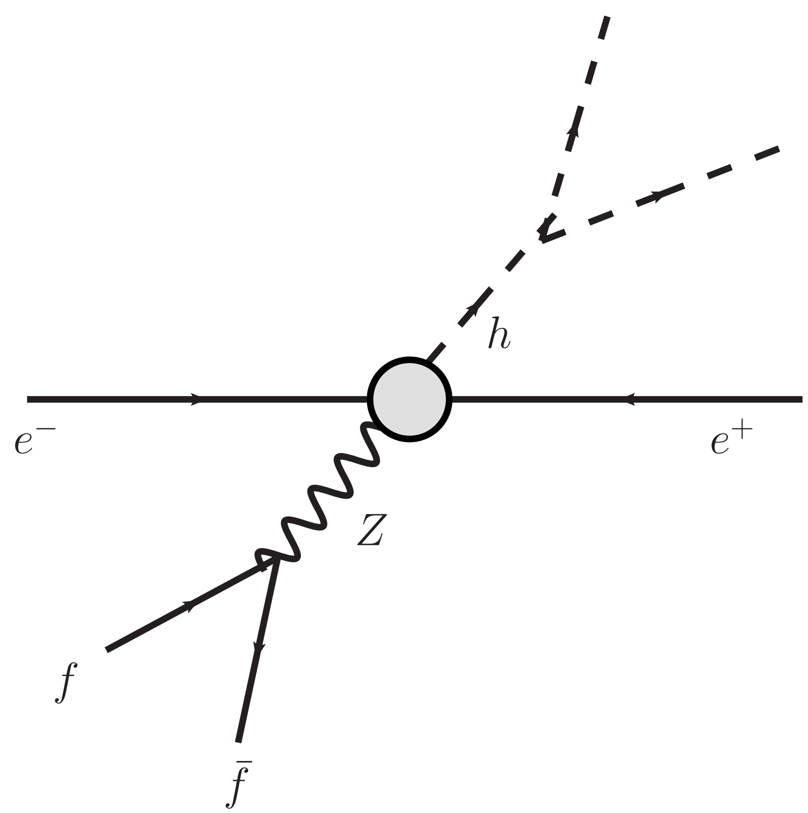


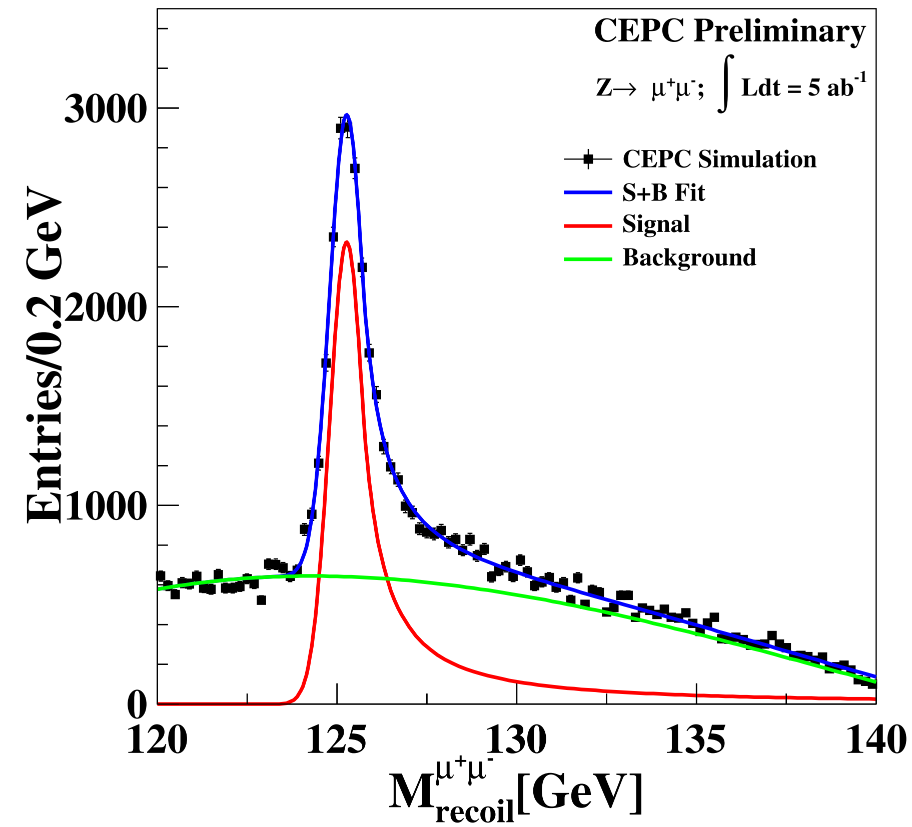




Process	Cross section	Nevents in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\nu H$	6.72	3.36×10^4
$e^+e^- \to eeH$	0.63	3.15×10^3
Total	219	1.10×10^6

Zh cross section



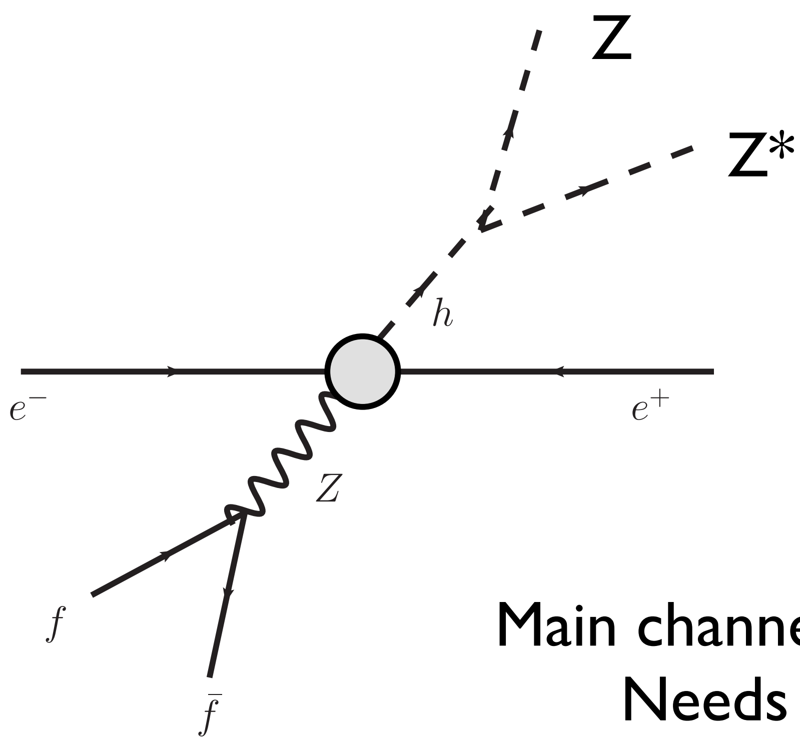


$$M^2_{\rm recoil} = (\sqrt{s} - E_{ff})^2 - p^2_{ff} = s - 2E_{ff}\sqrt{s} + m^2_{ff}$$

Can use recoil mass to identify Zh process, independent of Higgs decay

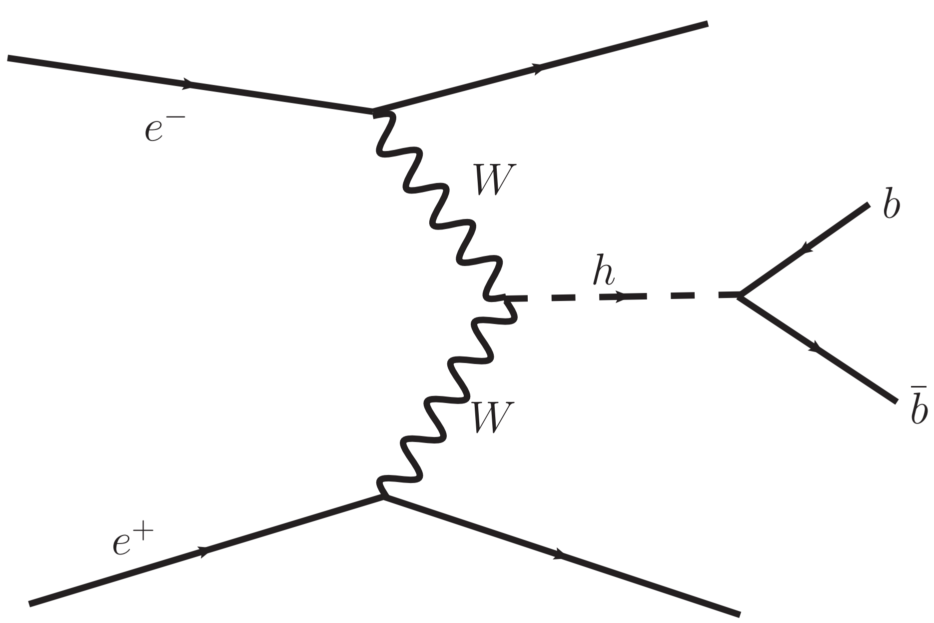
⇒ inclusive measurement of Zh cross section

Higgs width. Unique capability of lepton colliders.



$$\Gamma_H \propto \frac{\Gamma(H \to ZZ^*)}{\mathrm{BR}(H \to ZZ^*)} \propto \frac{\sigma(ZH)}{\mathrm{BR}(H \to ZZ^*)}$$

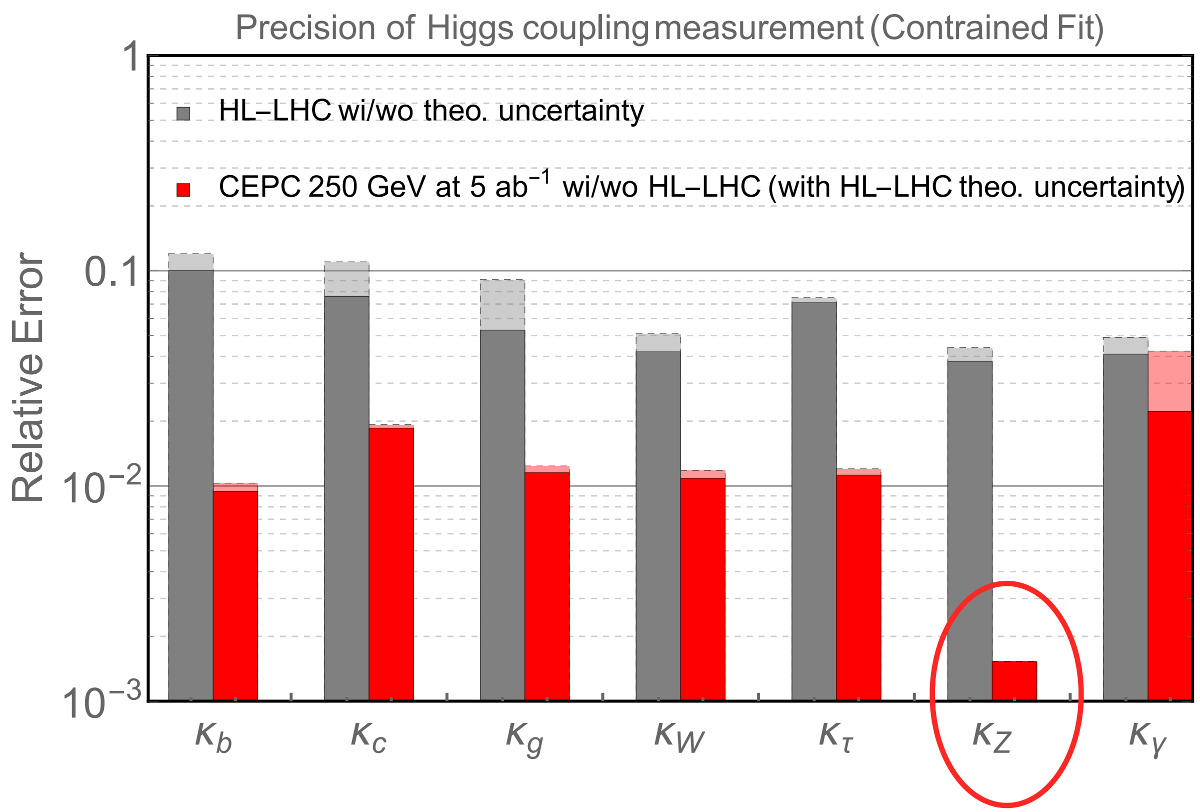
Main channel at 250 GeV.
Needs statistics



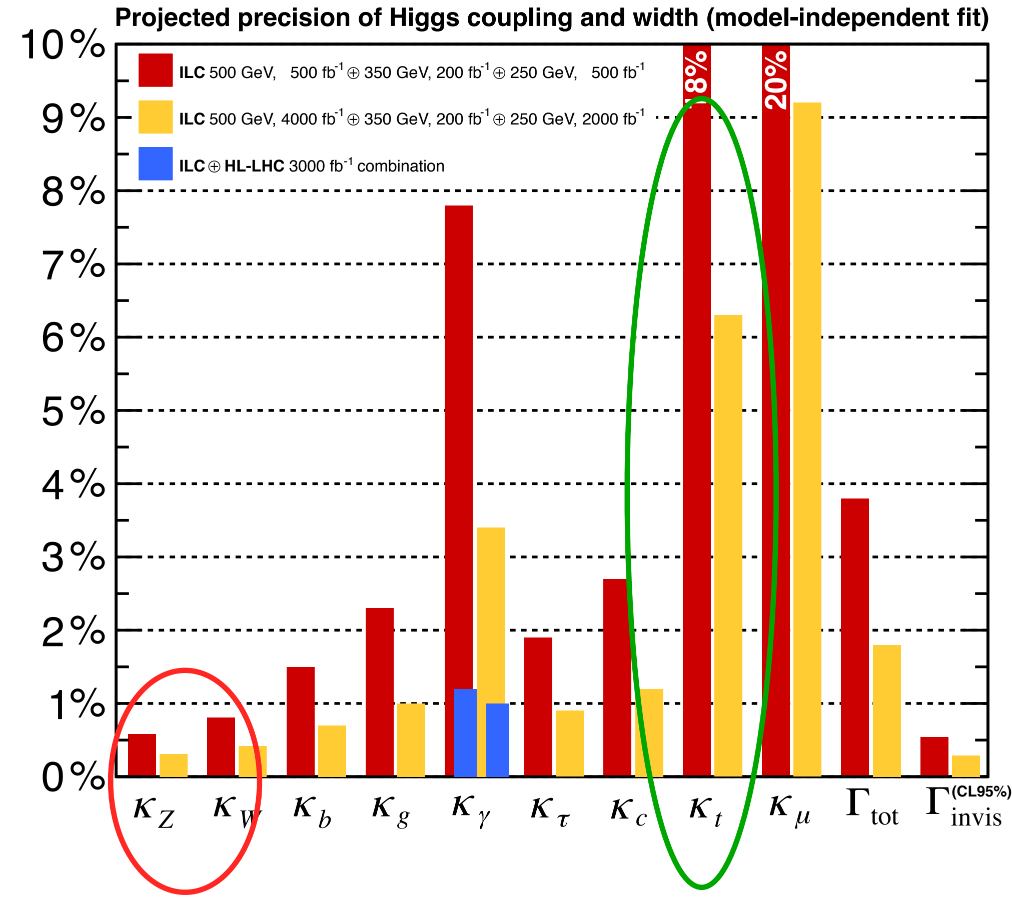
$$\Gamma_H \propto \frac{\Gamma(H \to bb)}{\mathrm{BR}(H \to bb)} \propto \frac{\sigma(\nu\nu H \to \nu\nu bb)}{\mathrm{BR}(H \to bb) \cdot \mathrm{BR}(H \to WW^*)}$$

Needs to go beyond 250.

Higgs factories



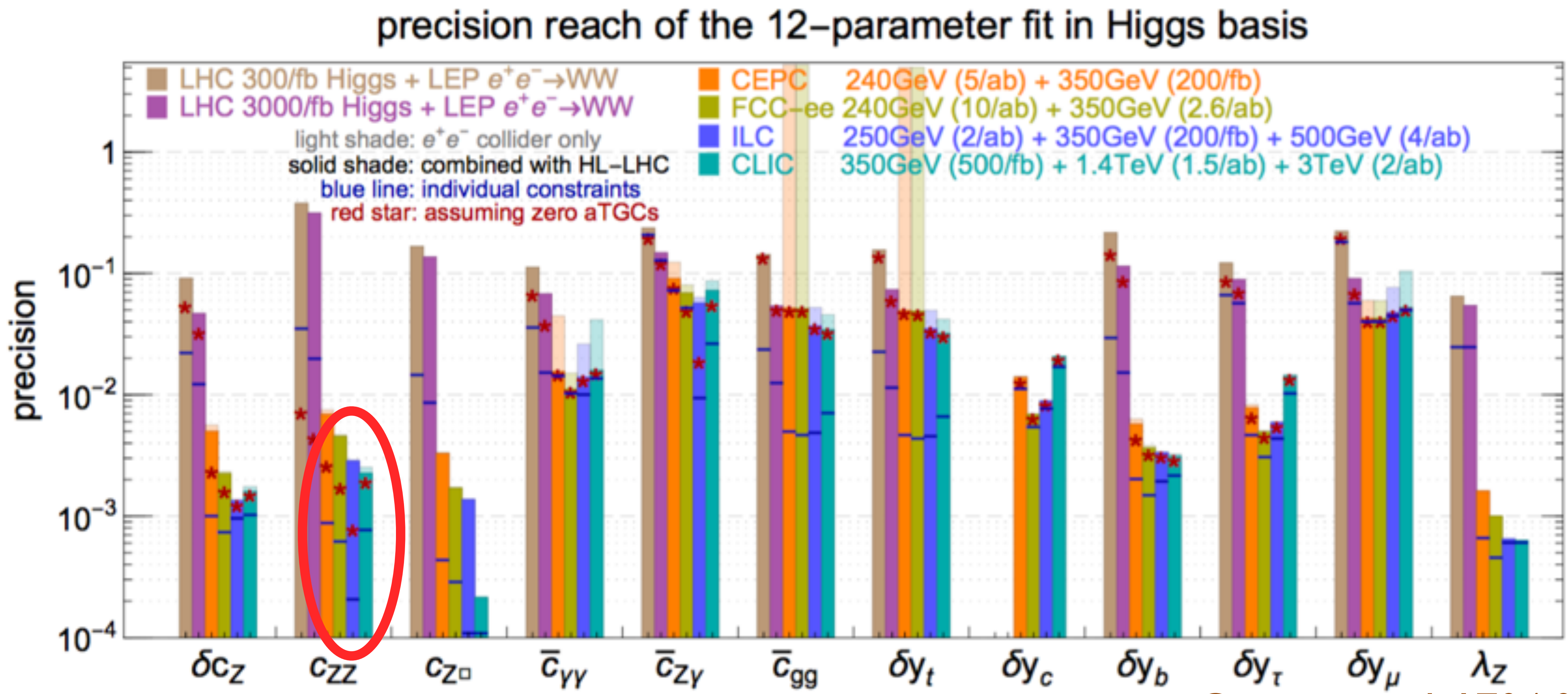
$$\kappa_X = \frac{\text{Measured Higgs-X coupling}}{\text{Standard Model Higgs-X coupling}}$$



Highlights:

HZ coupling to sub-percent level.
Many couplings to percent level.
Model independent measurement of total width.
Sensitive to the triple Higgs coupling: 20-30%

Lepton colliders and precision measurements



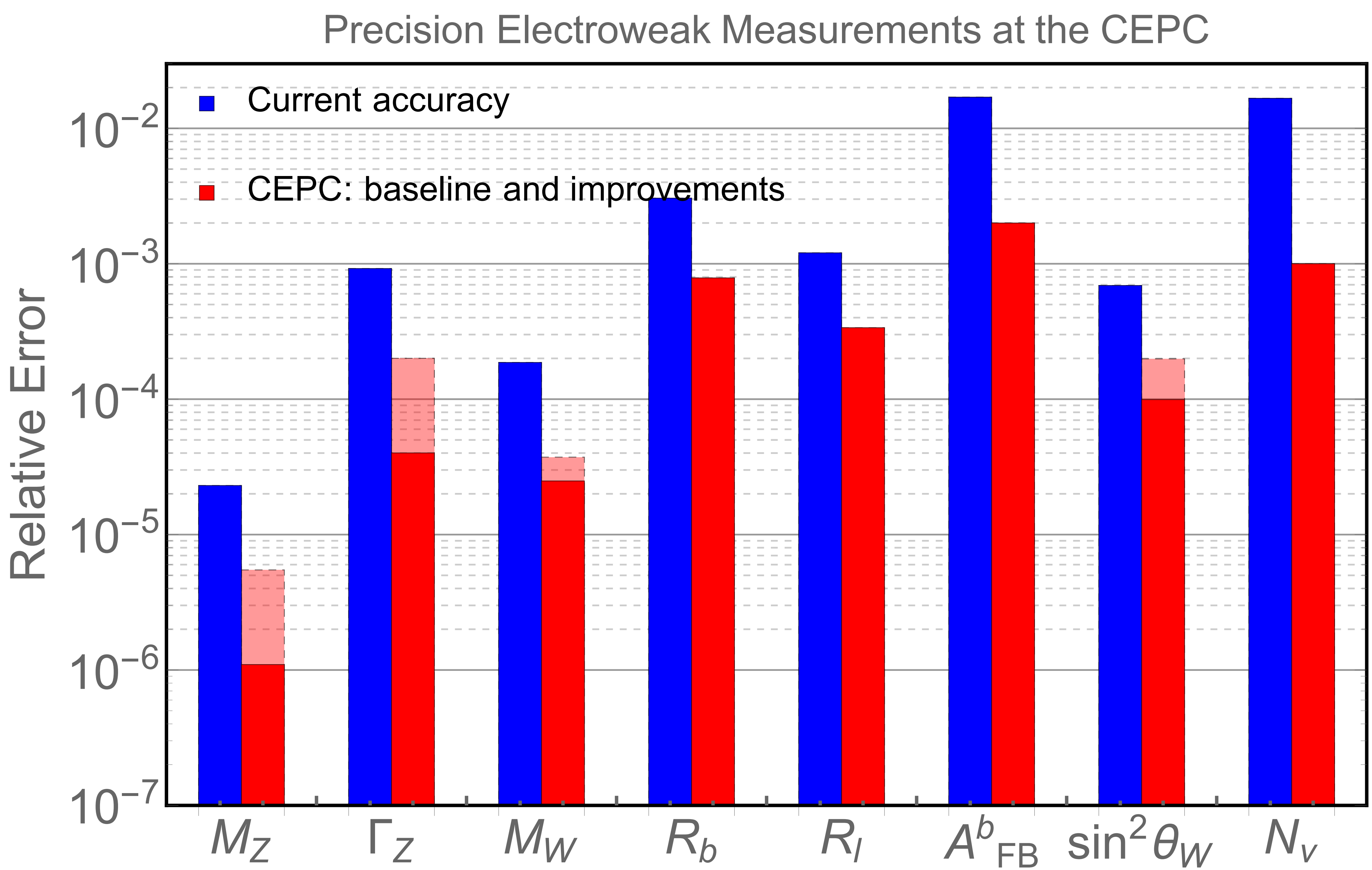
Grojean et al. 1704.02333

New physics with mass M_{NP} can affect Higgs coupling as

$$\delta \sim \frac{m_W^2}{M_{\rm NP}^2}$$

Sub percent precision, reach to new physics at multi-TeV scale.
Far beyond the reach of LHC.

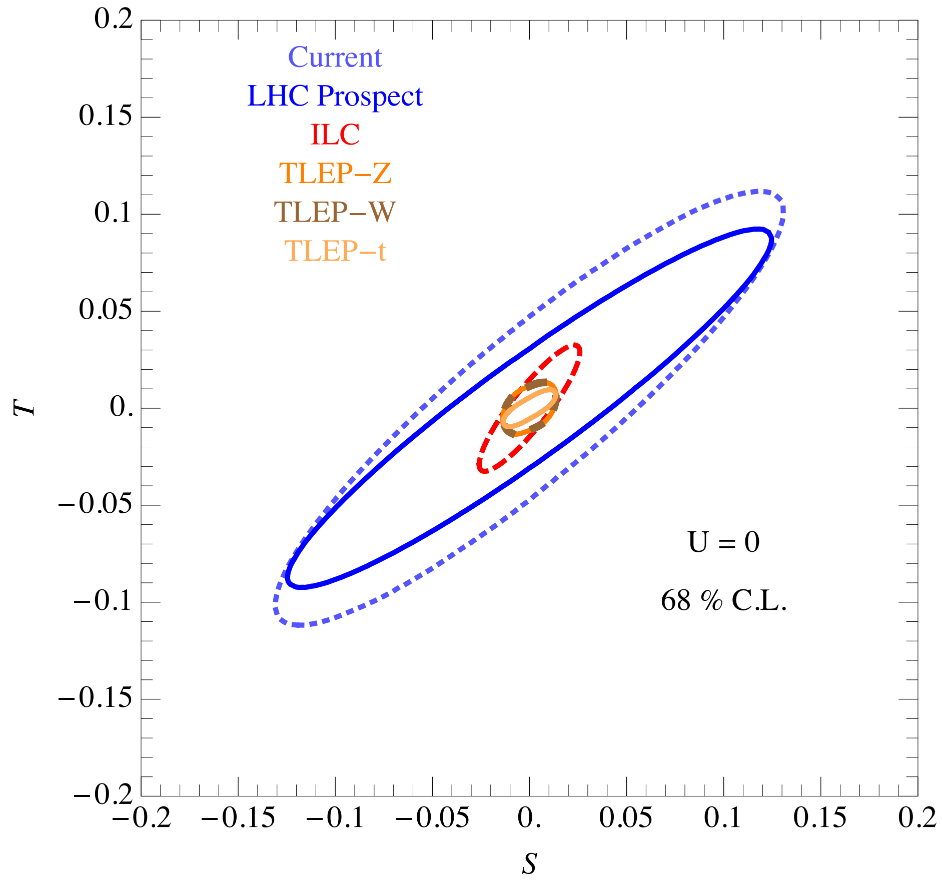
Big advance in electroweak precision

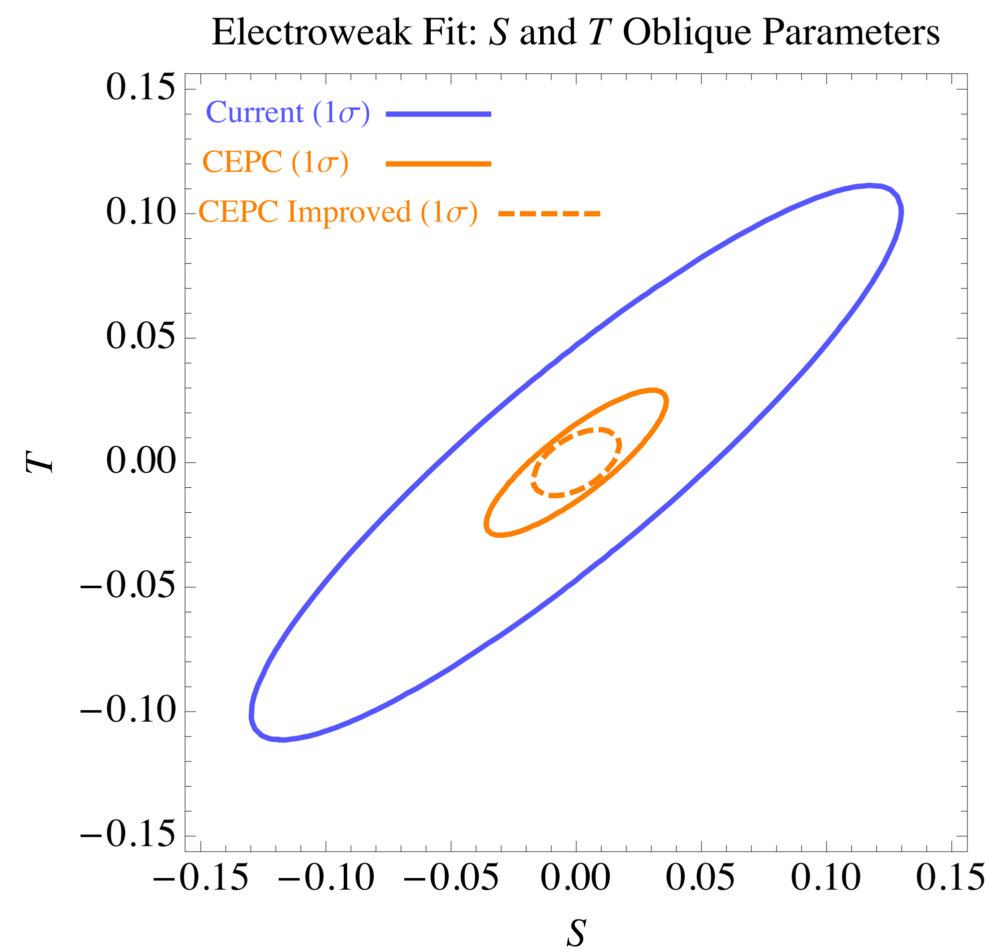


Large improvements across the board

Electroweak precision at CEPC

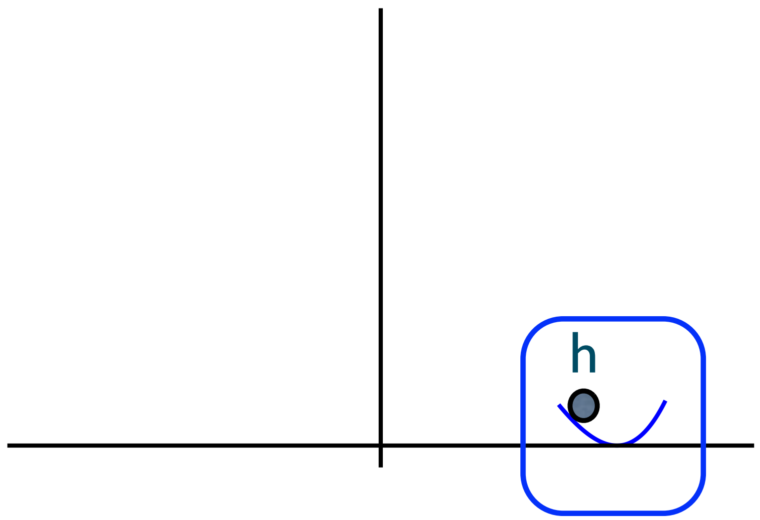
- A big step beyond the current precision.



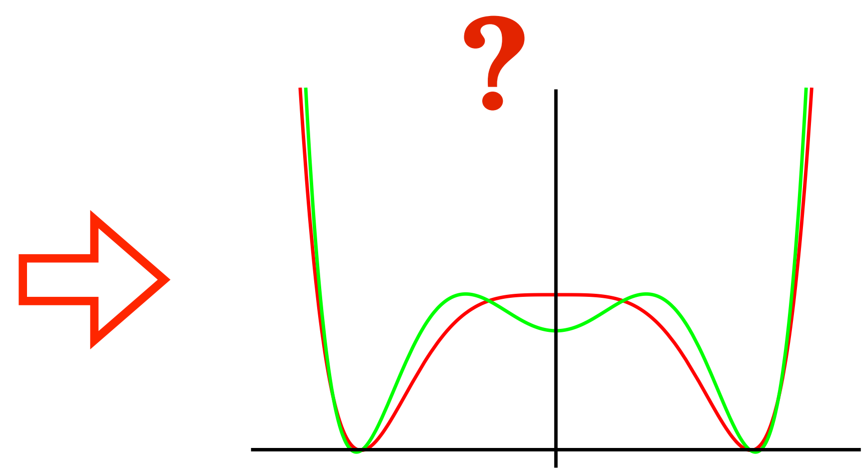


J. Fan, M. Reece, LT Wang, 1411.1054

Not even sure about "Mexican hat".



What we know now

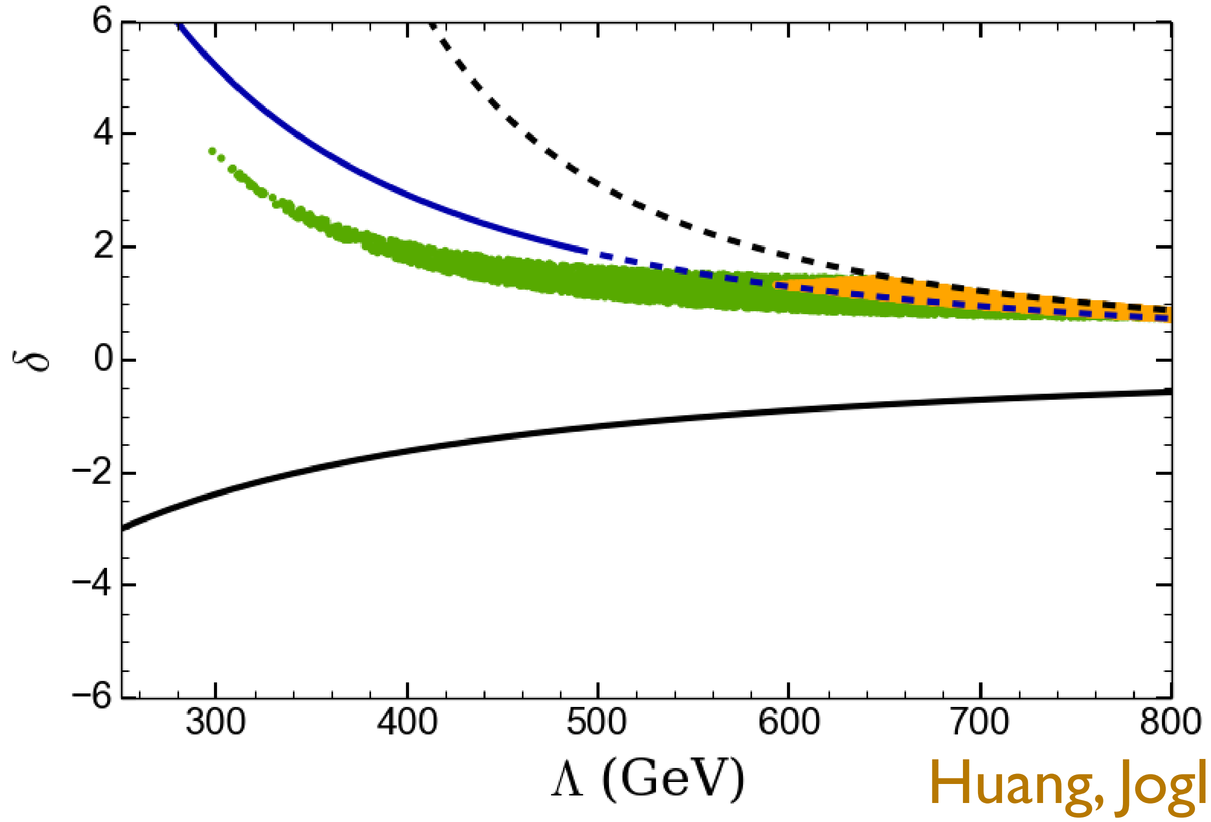


$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4}h^4 \quad \text{or} \quad V(h) = \frac{1}{2}\mu^2 h^2 - \frac{\lambda}{4}h^4 + \frac{1}{\Lambda^2}h^6$$

Is the EW phase transition first order?

LHC can not distinguish these definitively.

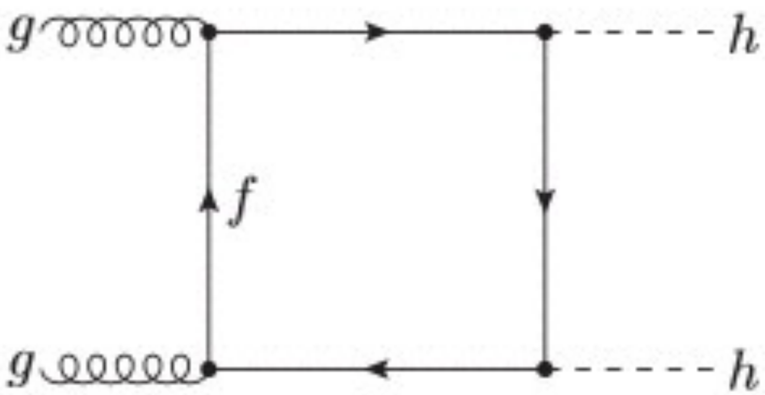
1st order phase transition
⇒ large modification of trilinear coupling

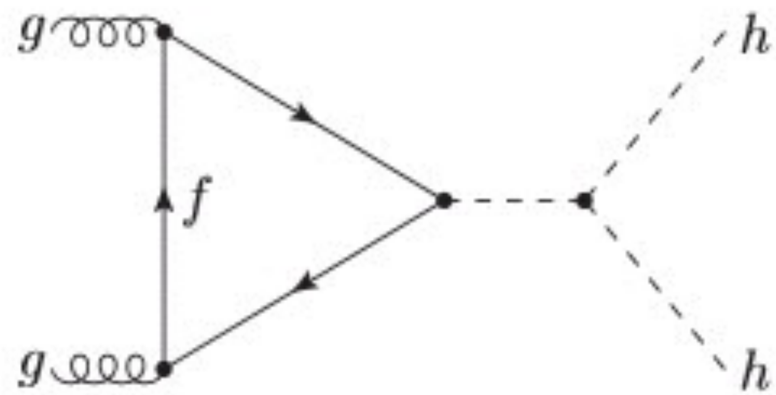


Huang, Joglekar, Li, Wagner, 1512.00068

$$V(h) = \frac{m^2}{2}h^2 + \lambda h^4 + \frac{1}{\Lambda^2}h^6 + \ldots$$

Measuring triple Higgs





f = top, …   Many possible final state. Very difficult channel.

LHC at 3 ab^{-1} ≈ 100% .

Triple Higgs coupling at 100 TeV pp collider 30 ab^{-1}
Some preliminary studies, incomplete not fully realistic.

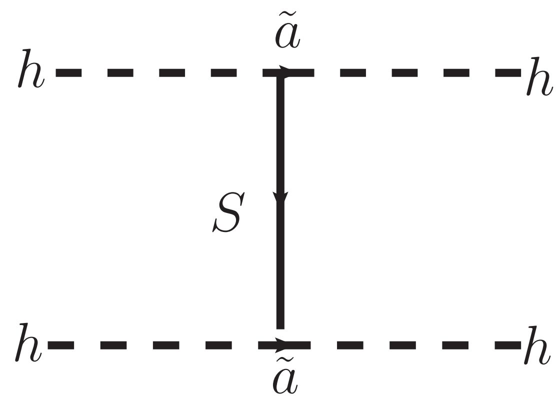
$$\frac{\lambda}{\lambda_{\rm SM}} \in \begin{cases} [0.891, 1.115] & \text{no background syst.} \\ [0.882, 1.126] & 25\%\ hh, 25\%\ hh + \text{jet} \\ [0.881, 1.128] & 25\%\ hh, 50\%\ hh + \text{jet} \end{cases}$$

Barr, Dolan, Englert, de Lima, Spannowsky

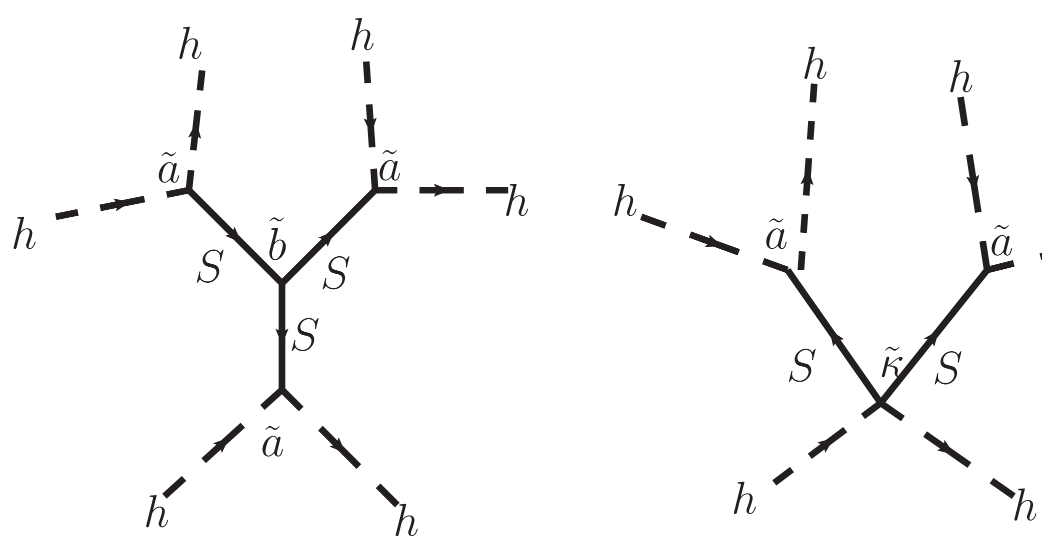
ILC 500: 27%
ILC ultimate, 1 TeV 5 ab-1: 10%

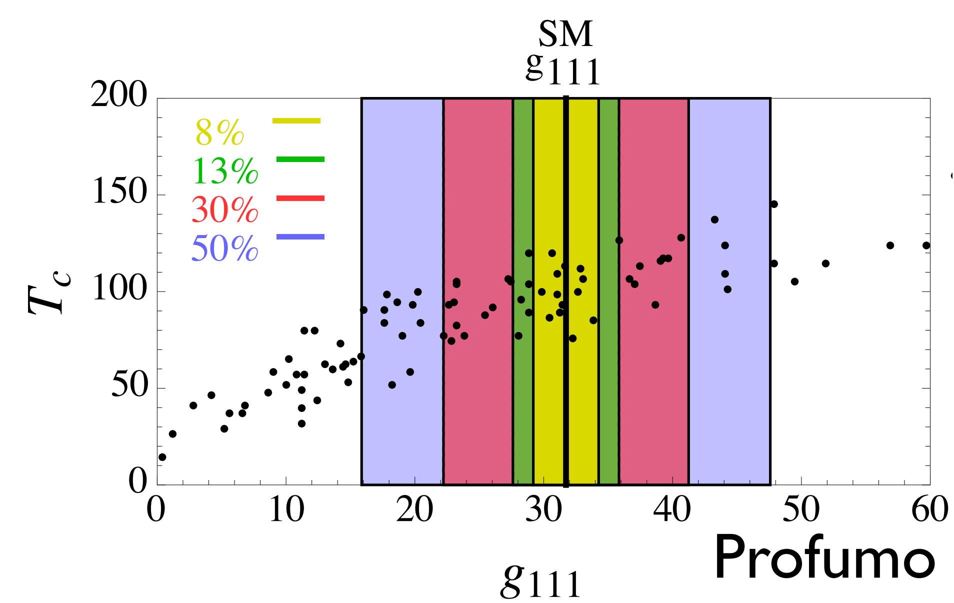
Simple example: Generic singlet model

$$m^2 h^\dagger h + \tilde{\lambda}(h^\dagger h)^2 + m_S^2 S^2 + \tilde{a} S h^\dagger h + \tilde{b} S^3 + \tilde{\kappa} S^2 h^\dagger h + \tilde{h} S^4$$



shift in h-Z coupling > %
Higgs factory important

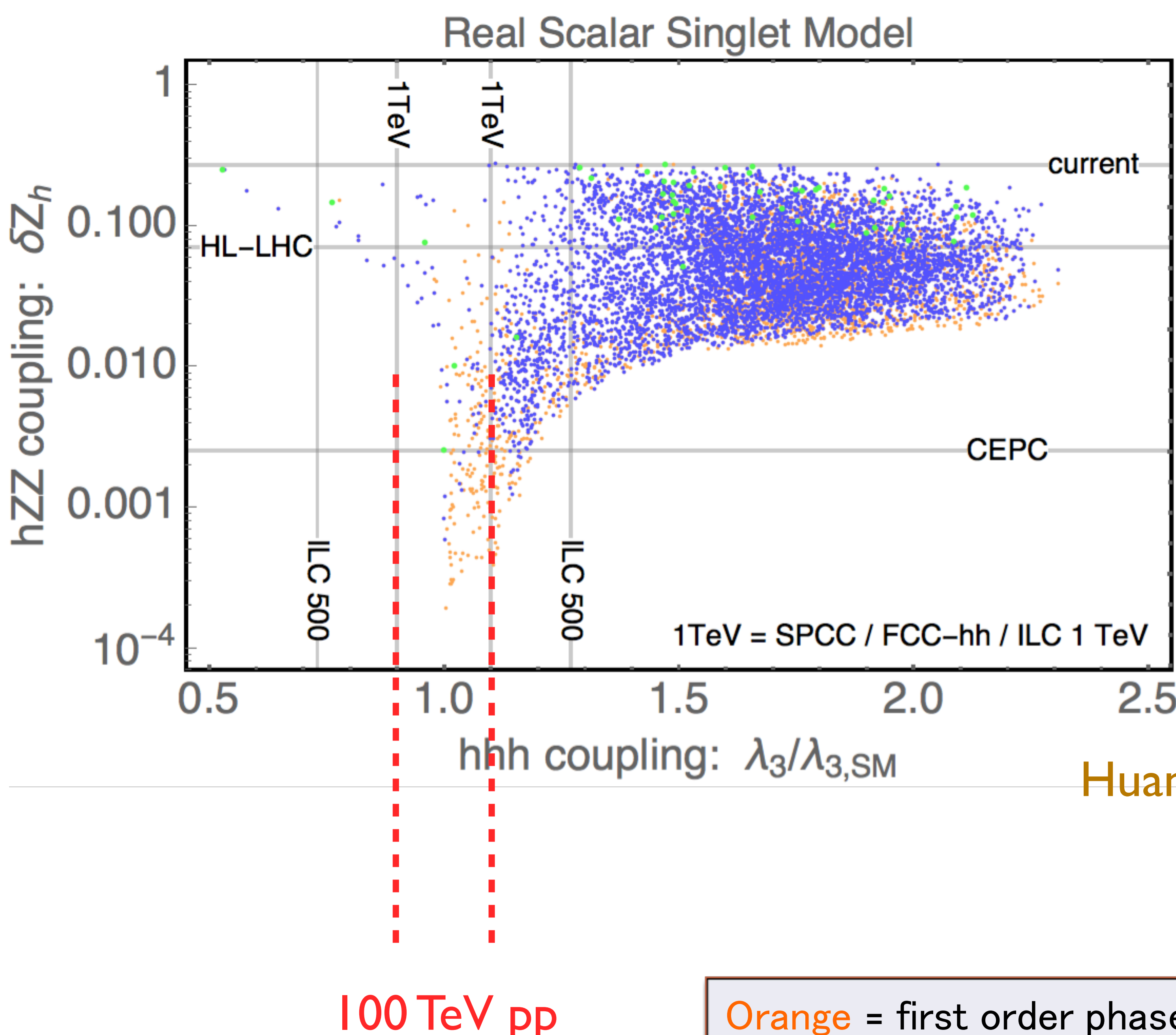




Profumo et al

O(1) devidation in triple Higgs coupling

Also considering Higgs factories



Huang, Long, LTW, in progress

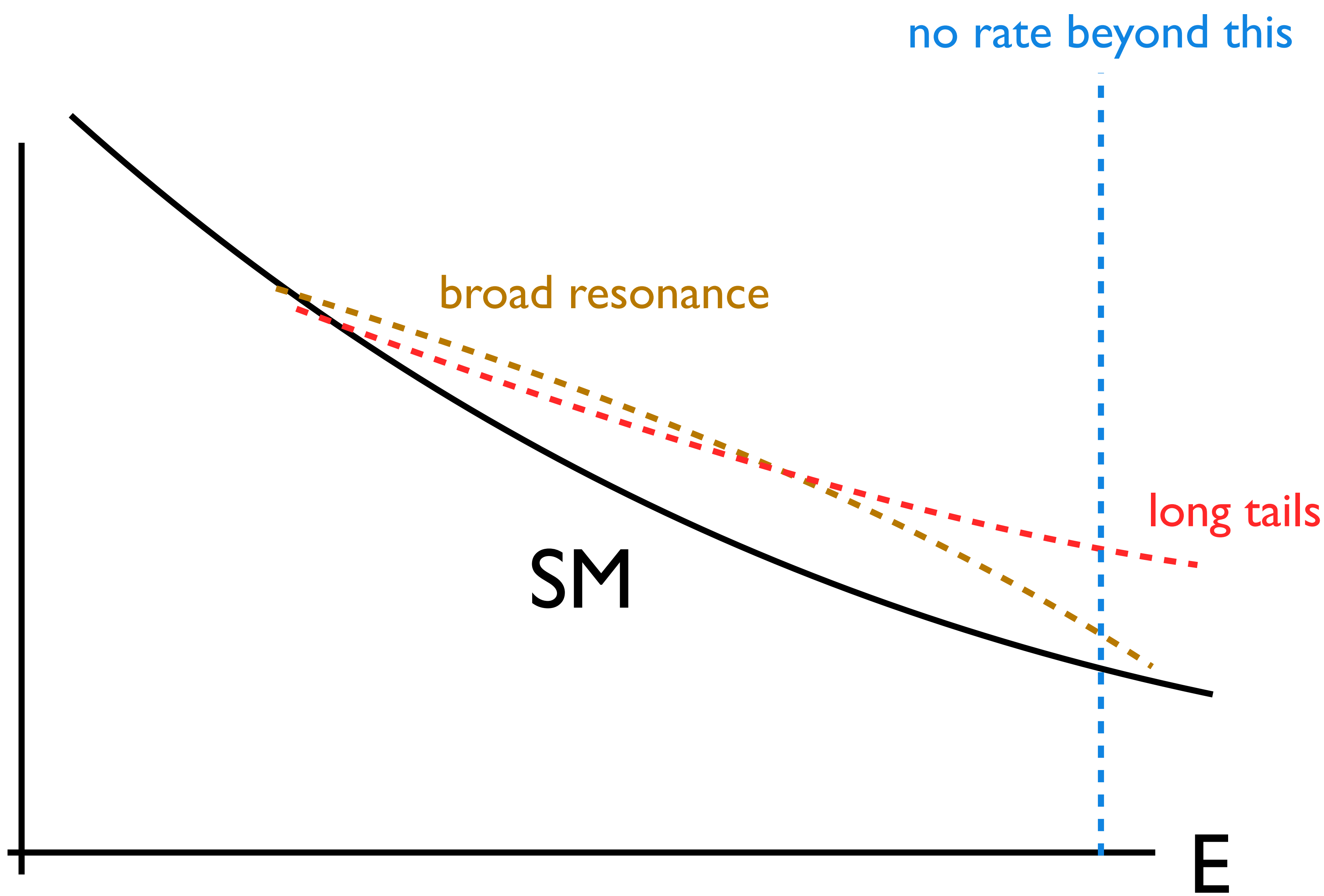
Orange = first order phase transition, $v(T_c)/T_c > 0$
Blue = "strongly" first order phase transition, $v(T_c)/T_c > 1.3$
Green = very strongly 1PT, could detect GWs at eLISA

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

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.

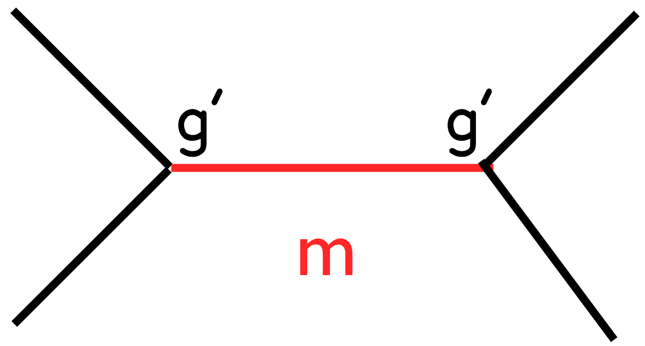
Shapes of signals



- 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

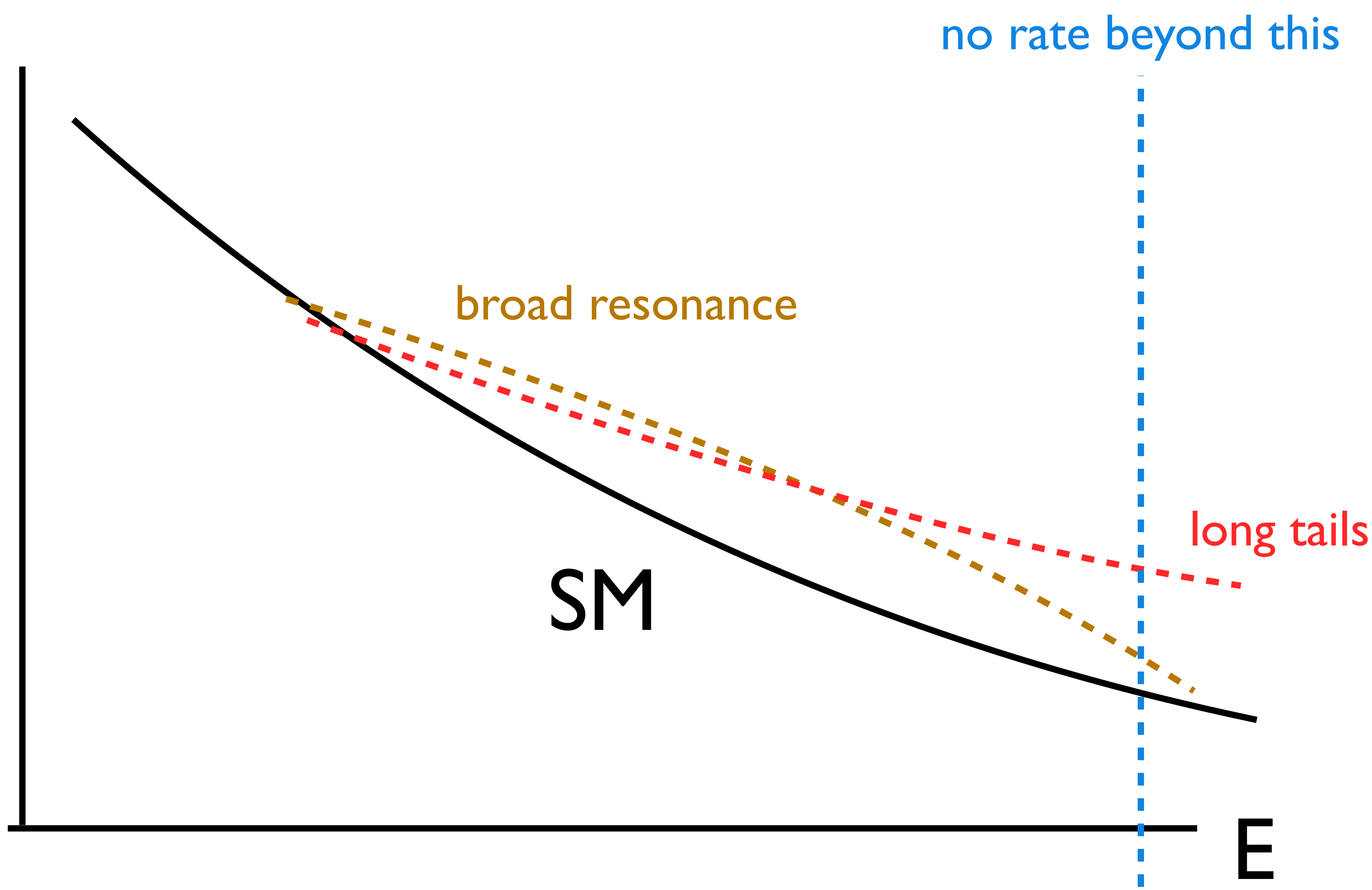
Another recent example of using di-lepton and potentially di-jet

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

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

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

growing with energy

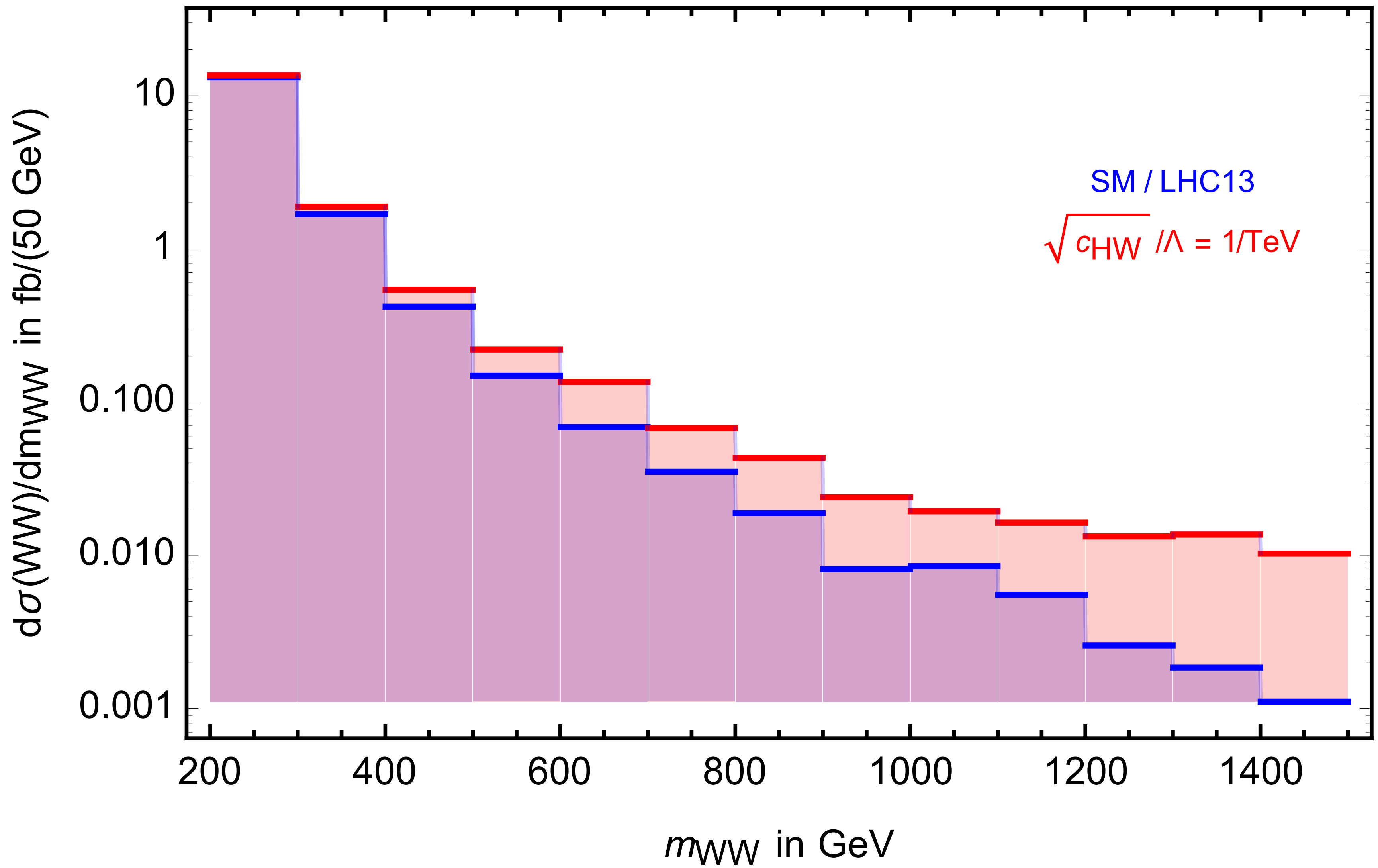
$$f_R \bar{f}_L \to W^+ W^-$$

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

$\Lambda \approx m_*$

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

E: energy bin of the measurement

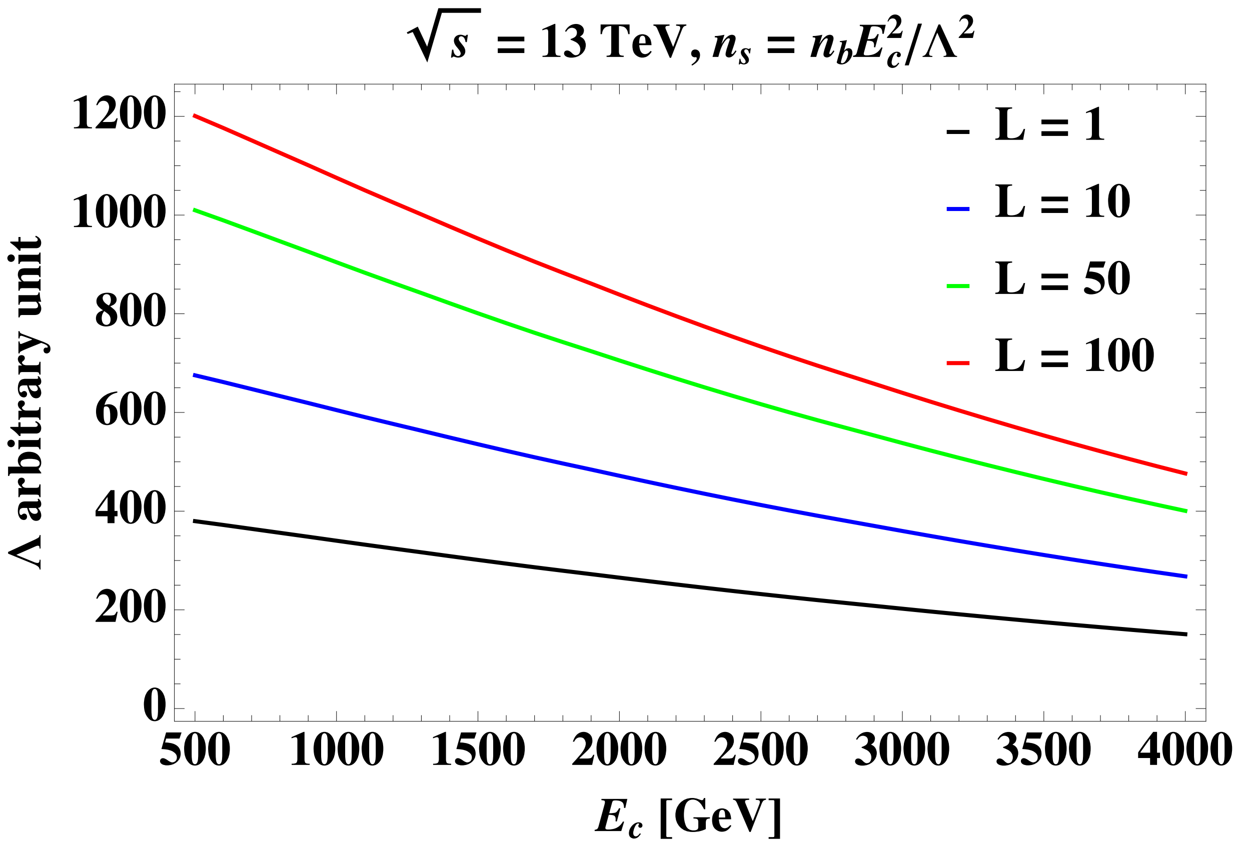
n: 5-8 falling parton luminosity

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

$\mathcal{L}$ = integrated luminosity

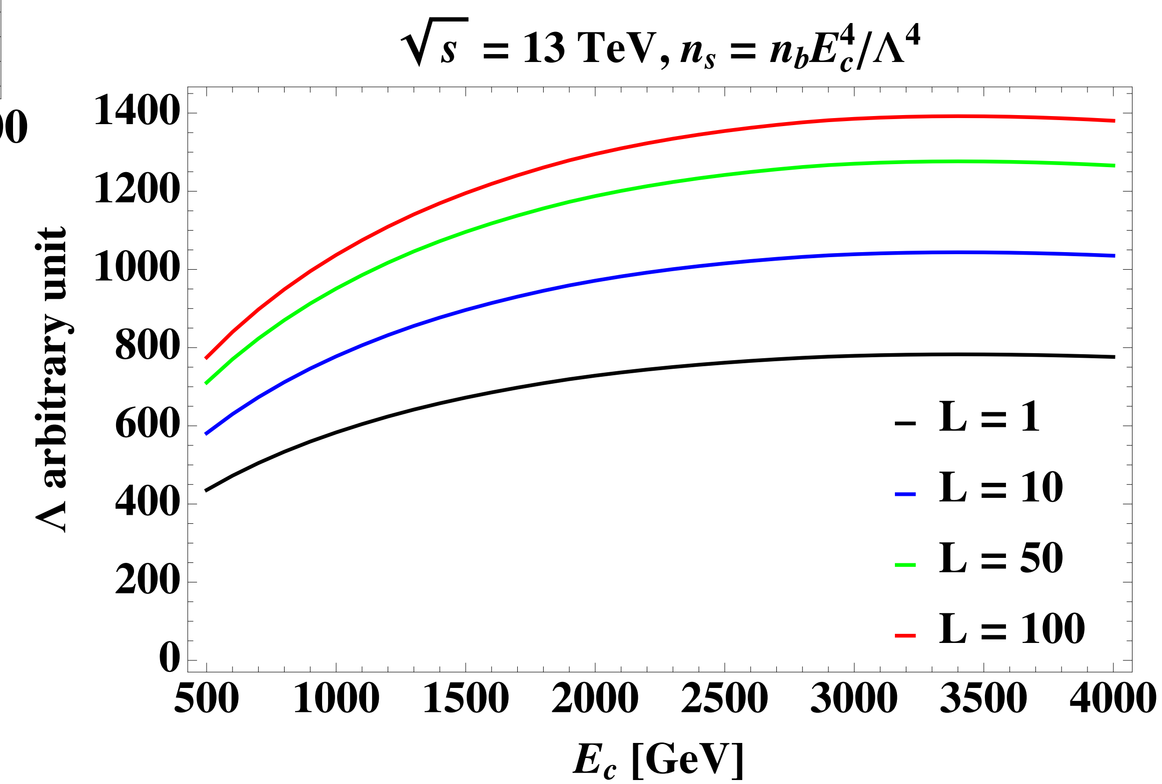
- For small d, lower E with higher reach. (e.g. dim 6, d=2)
  - Limited by systematics.
- Interference important. Otherwise, signal proportional to (operator)^2, effect further suppressed by $(E/\Lambda)^d$.

Ideal case.



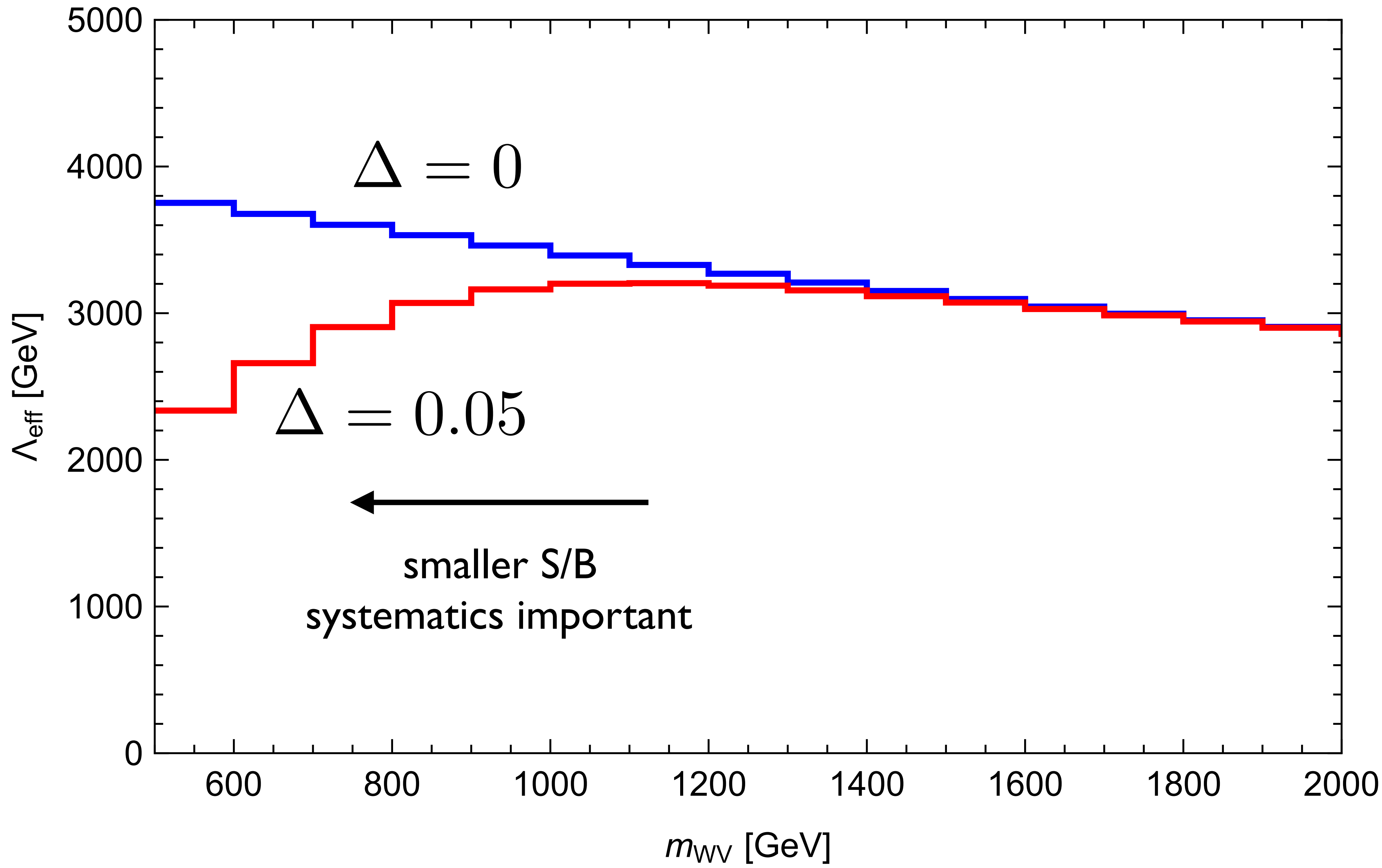
dim 6, with interference
Stronger limit at lower energy

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



dim 8 with interference
or dim 6 without interference

The role of systematics



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

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).

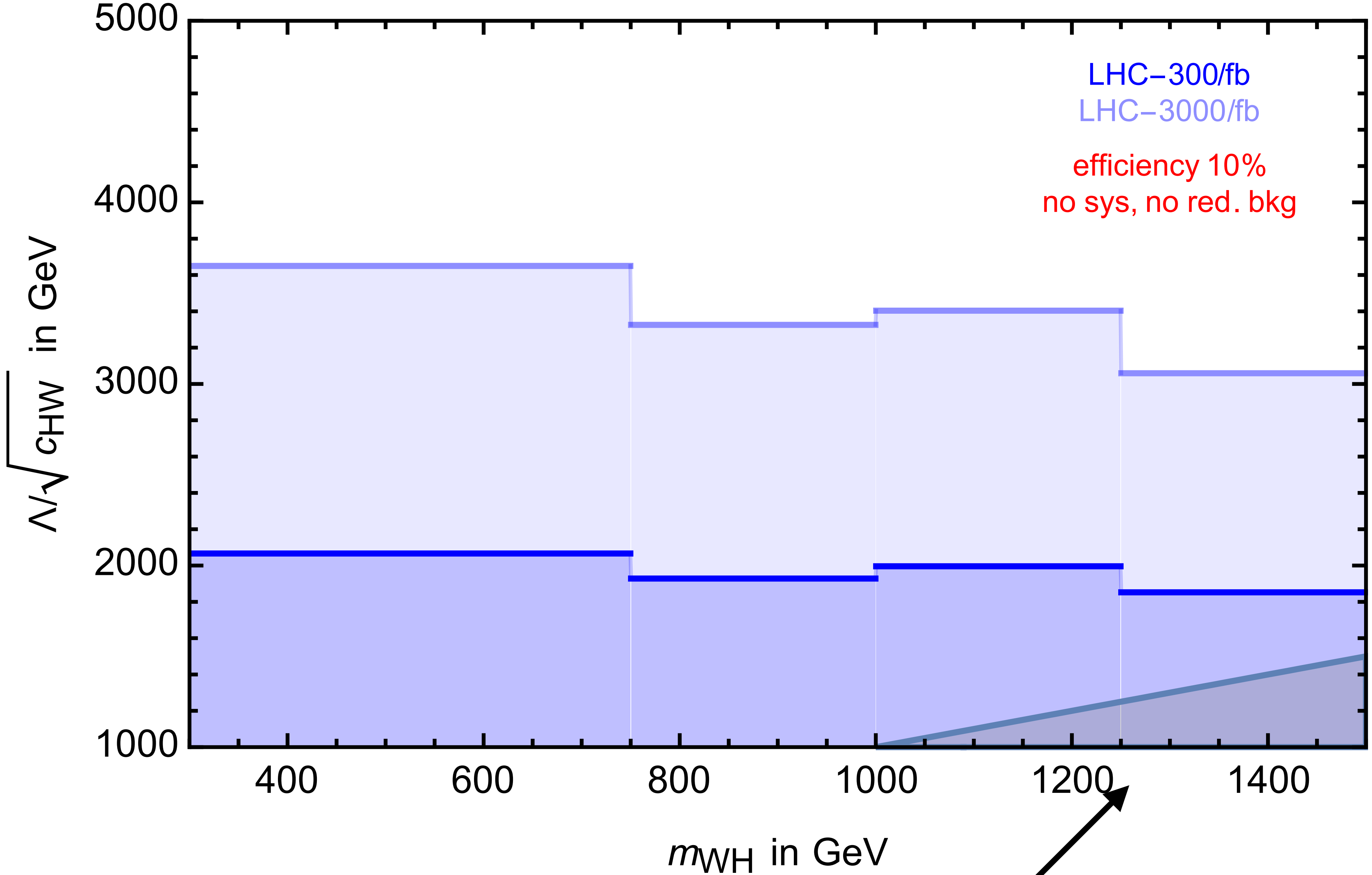
Reach projection

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
ϵ_h (mis)tag probability of polarization h
Δ: systematical error

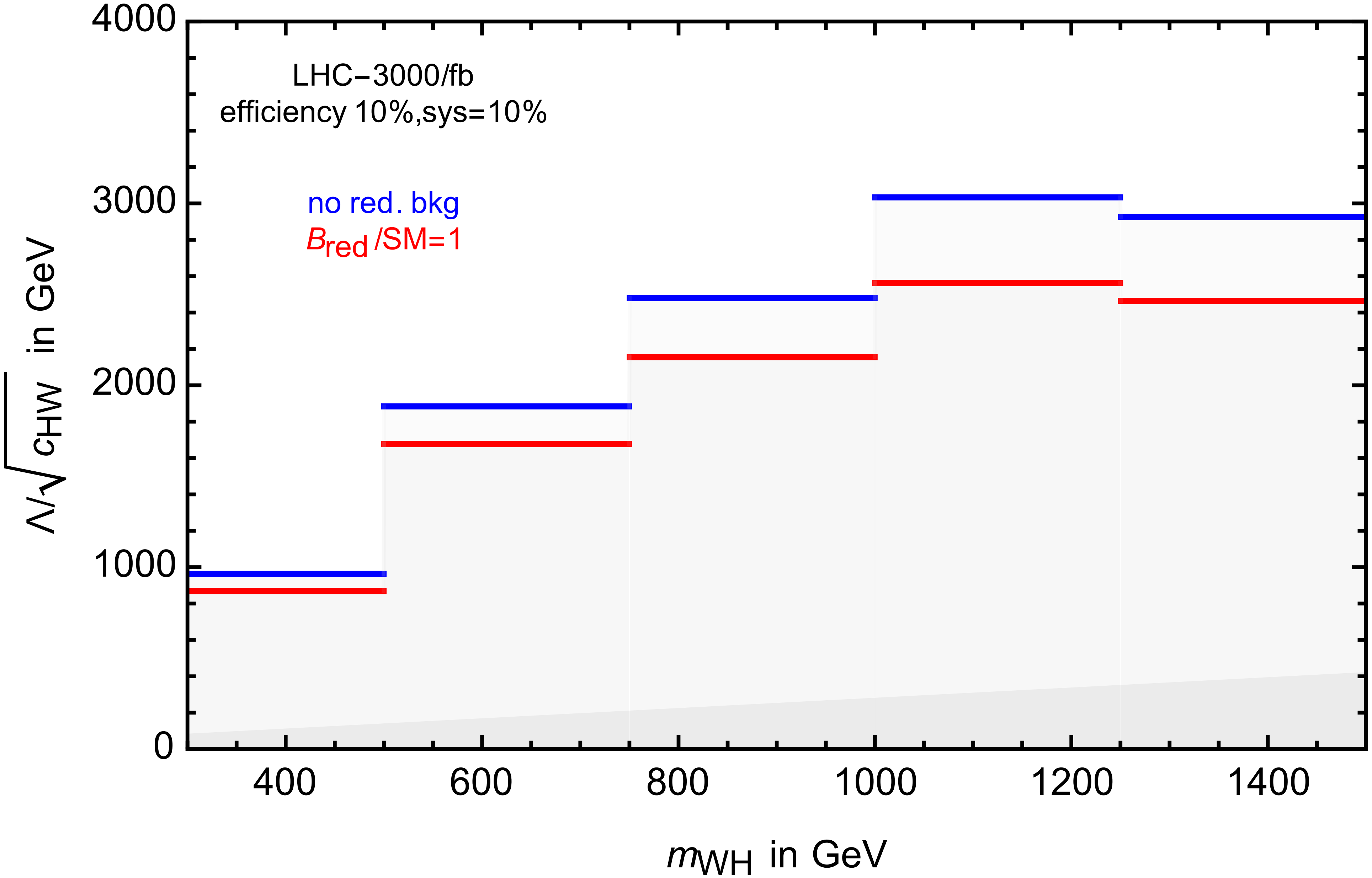
Wh channel



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

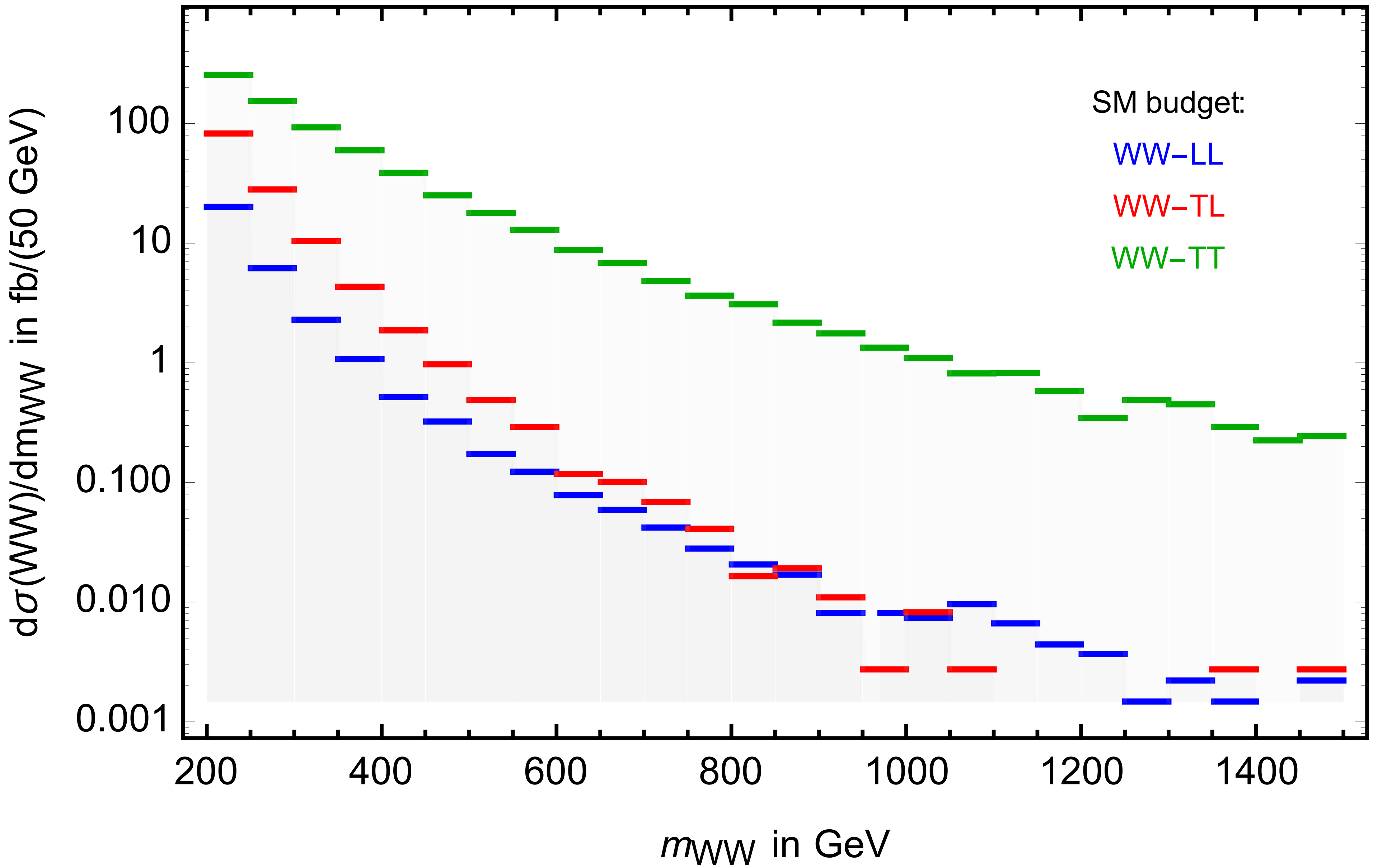
EFT not valid

Wh channel

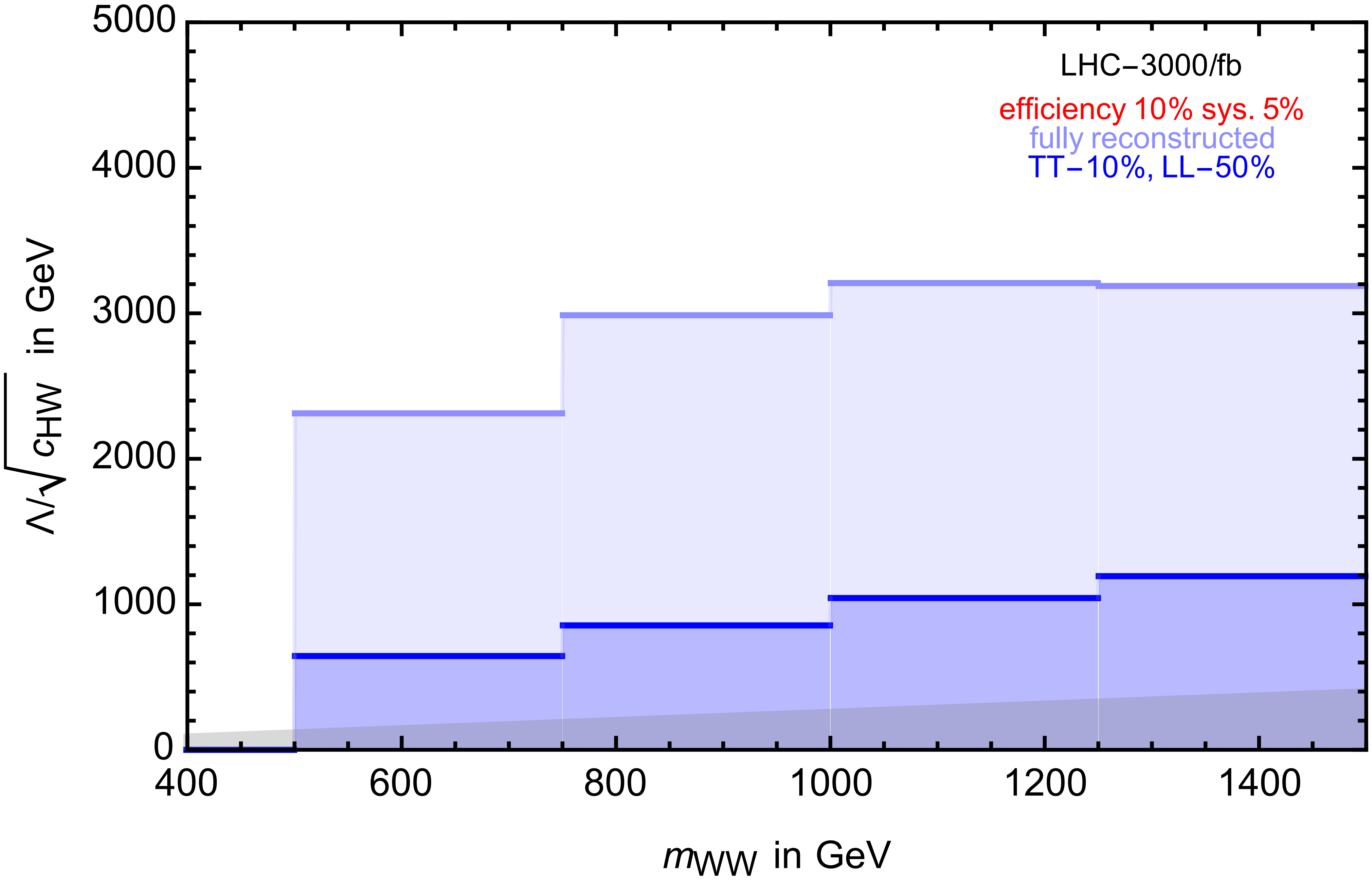


With assumptions about systematics and background.

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

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

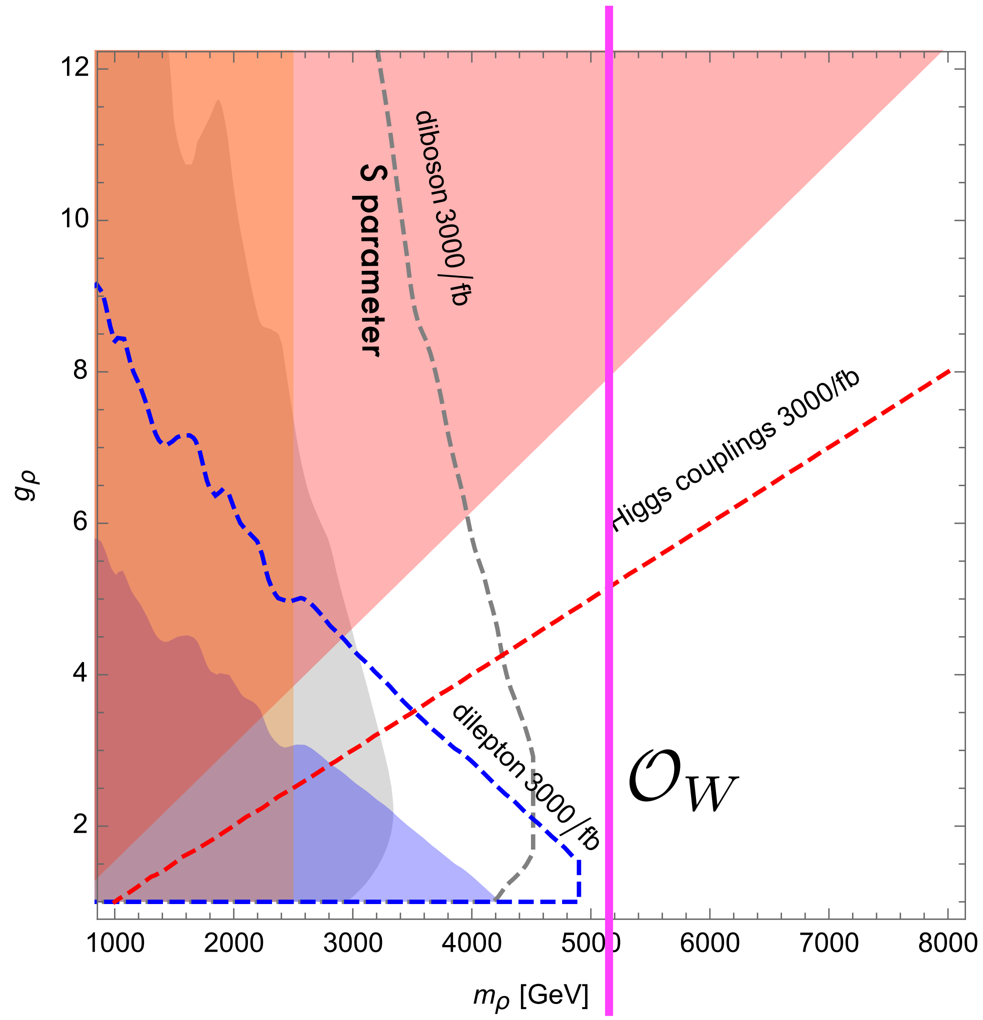
tagging eff 50%, mis-tagging rate 10%, no systematics

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.

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.

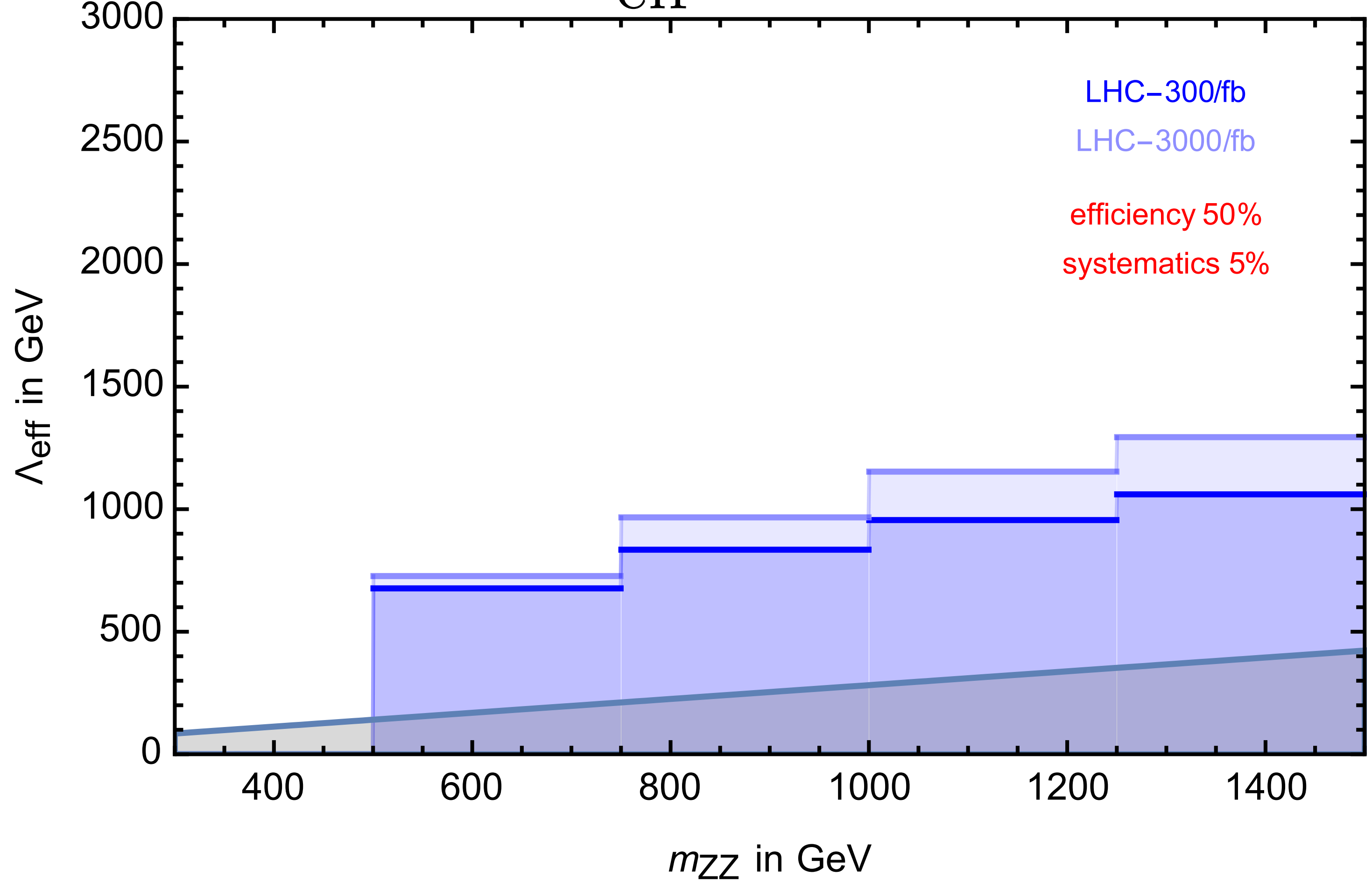
- Gives rise to unique signals.
  - ZZ, γγ, hh.

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

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



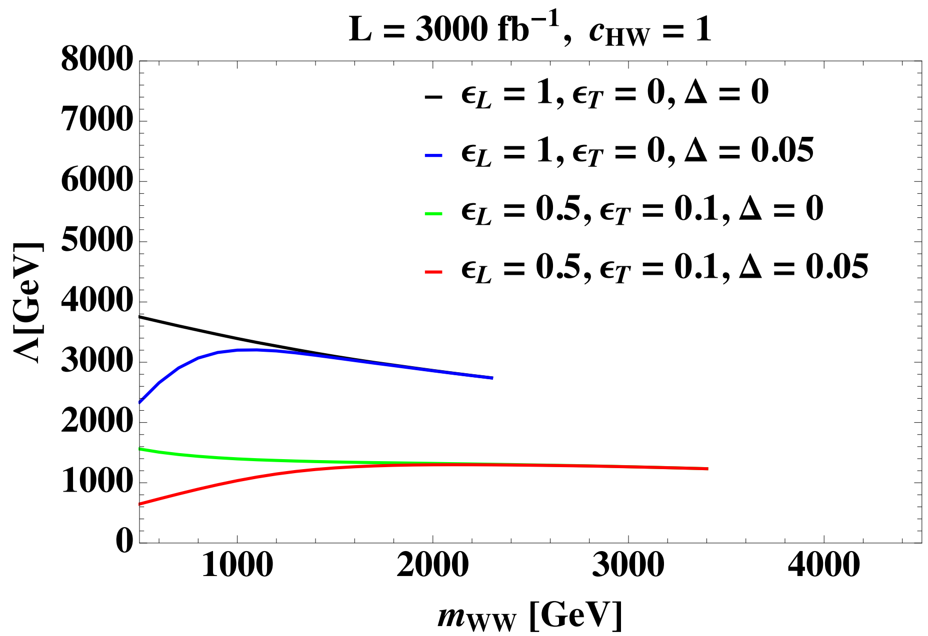
Λ[TeV]	$\mathcal{O}_{TWW}$	$\mathcal{O}_{TWB}$	$\mathcal{O}_{TH}$	$\mathcal{O}_{TH}^{(3)}$
$WV(\ell + jets)$	0.90	0.90	1.1(0.83)	0.83(0.65)
$W^{\pm}h(\ell bb)$				(0.86,0.79,0.76)
$W^{\pm}h(\ell + \ell\nu\ell\nu)$				0.67

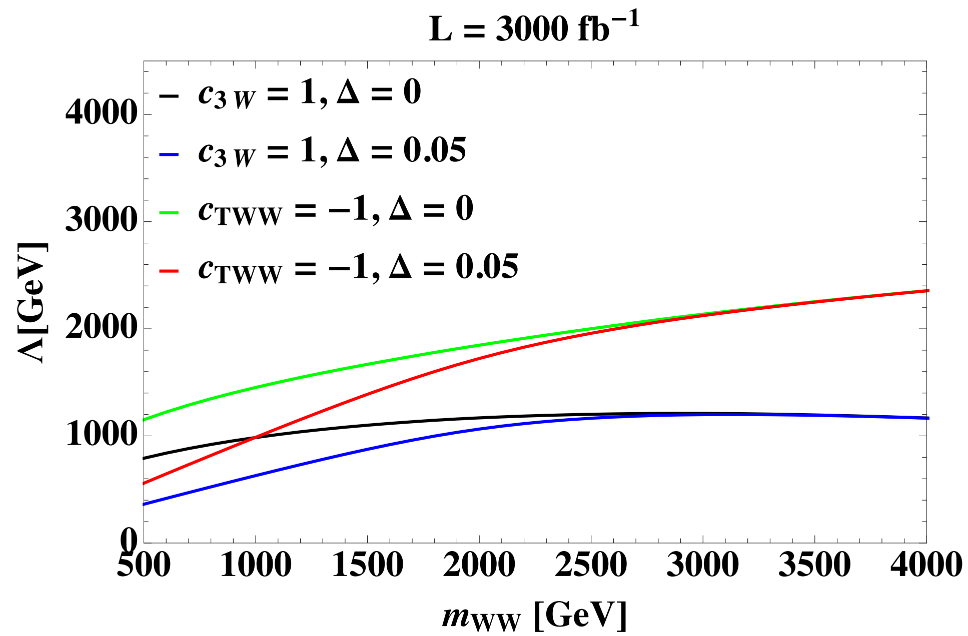
Conclusion

- 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

c_W



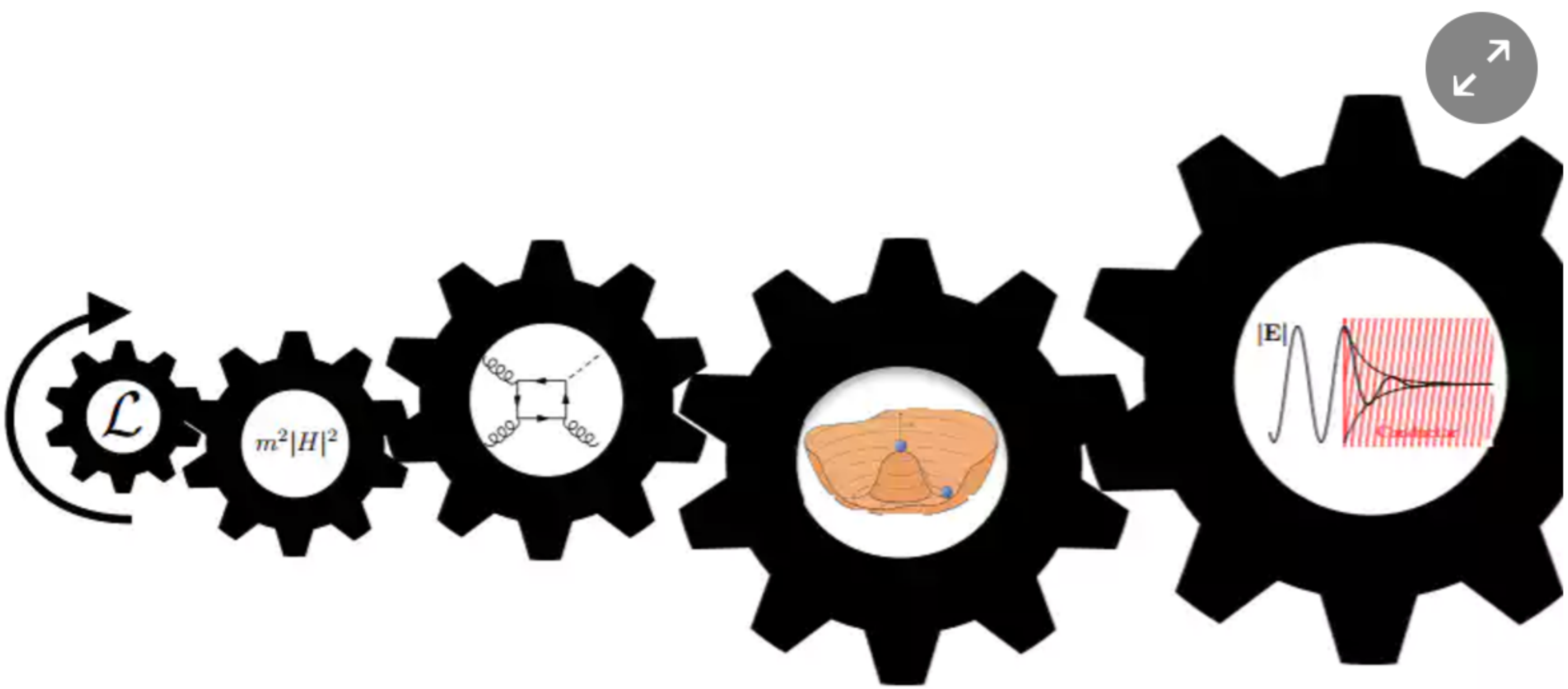


$$\mathcal{M}_f^{00} \to -\frac{\sin\theta}{2}\left\{T_f^3 g^2 + Y_f g'^2 + \frac{s}{\Lambda^2}\left[(c_W + c_{HW})T_f^3 g^2 + (c_B + c_{HB})Y_f g'^2\right]\right\} - c_{TH}\frac{g^2}{16}\frac{s^2}{\Lambda^4}\sin 2\theta$$
$$- g^2 \sin\theta \frac{s}{\Lambda^2}\left[\delta_f^{u_R} c_R^u + \delta_f^{d_R}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

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



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