Implications on Possible New Physics

from direct and indirect measurements

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European Strategy
for Particle Physics

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CERN

Back to the Future

Picture courtesy of R. Rattazzi

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We are only a few years behind schedule!

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☑ what are its quantum numbers: J^{PC}? SU(2)xU(1) charges?

☑ what screens the quantum corrections to its mass?

☑ is it an elementary scalar or a composite bound state?

☑ is it alone or part of an extended sector?

☑ is it a portal to SM-neutral new physics?

Outline

① Higgs sector

- Theory implications
- Higgs quantum numbers
- Higgs couplings

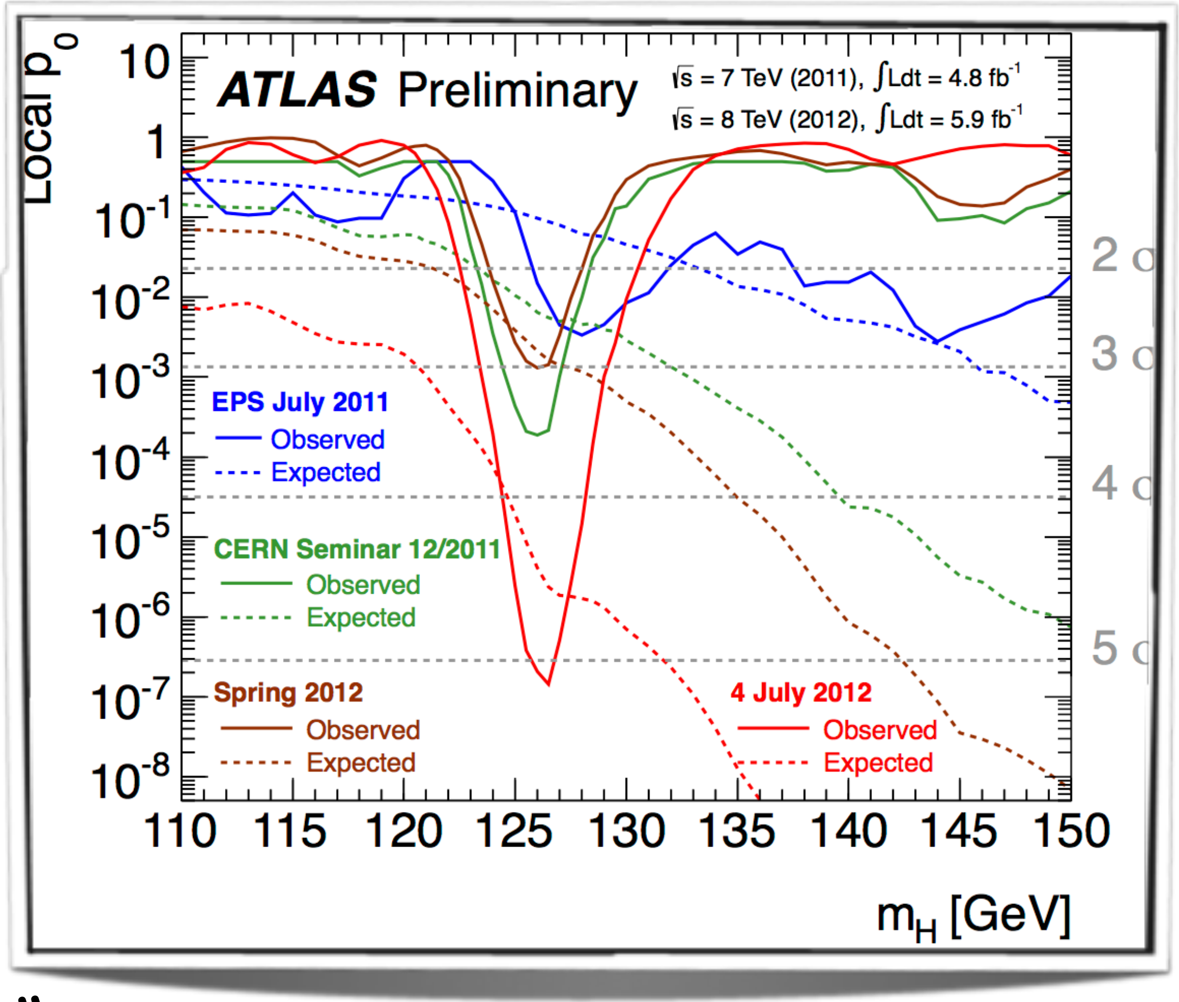
② Direct searches

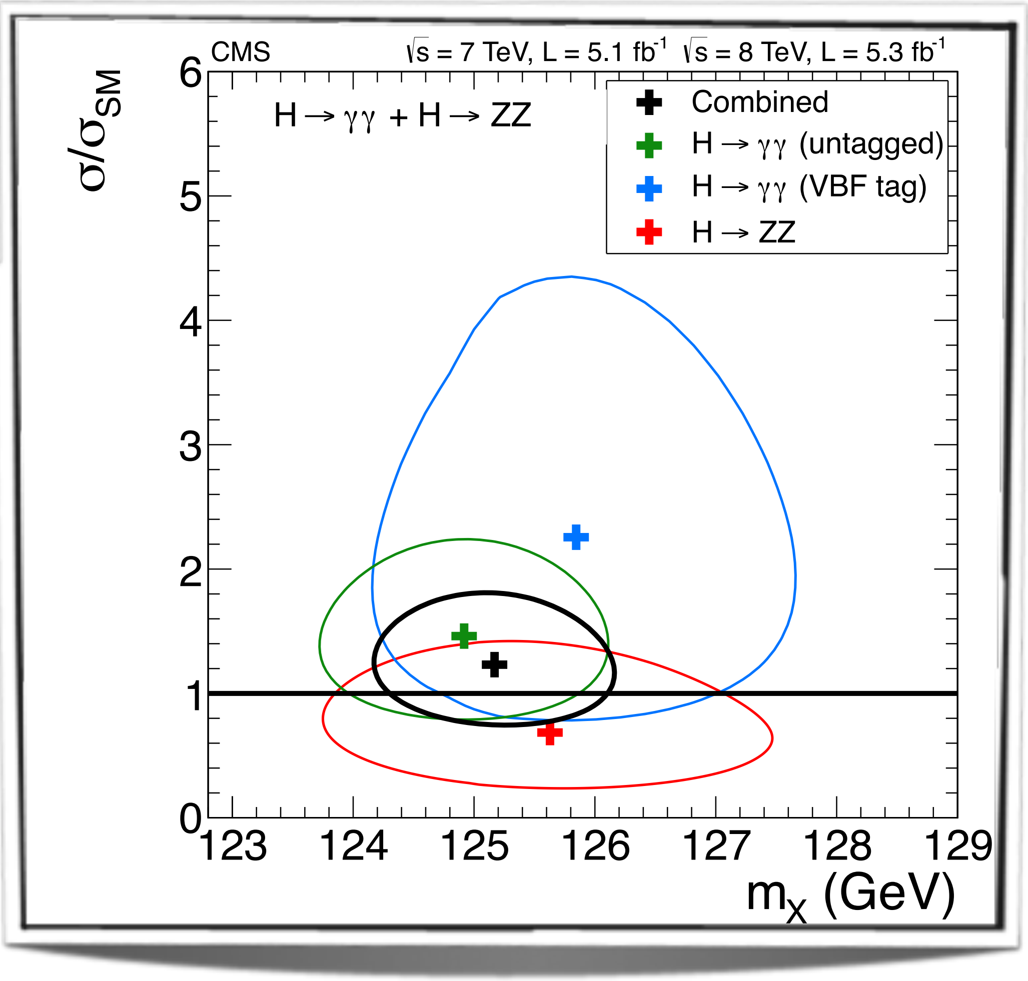
- SUSY
- Exotics

Disclaimer:
I won't have time to cover many interesting things
(top, xdim, blackholes...).

Where are we?

A new particle has been discovered!





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Where are we? What's next?

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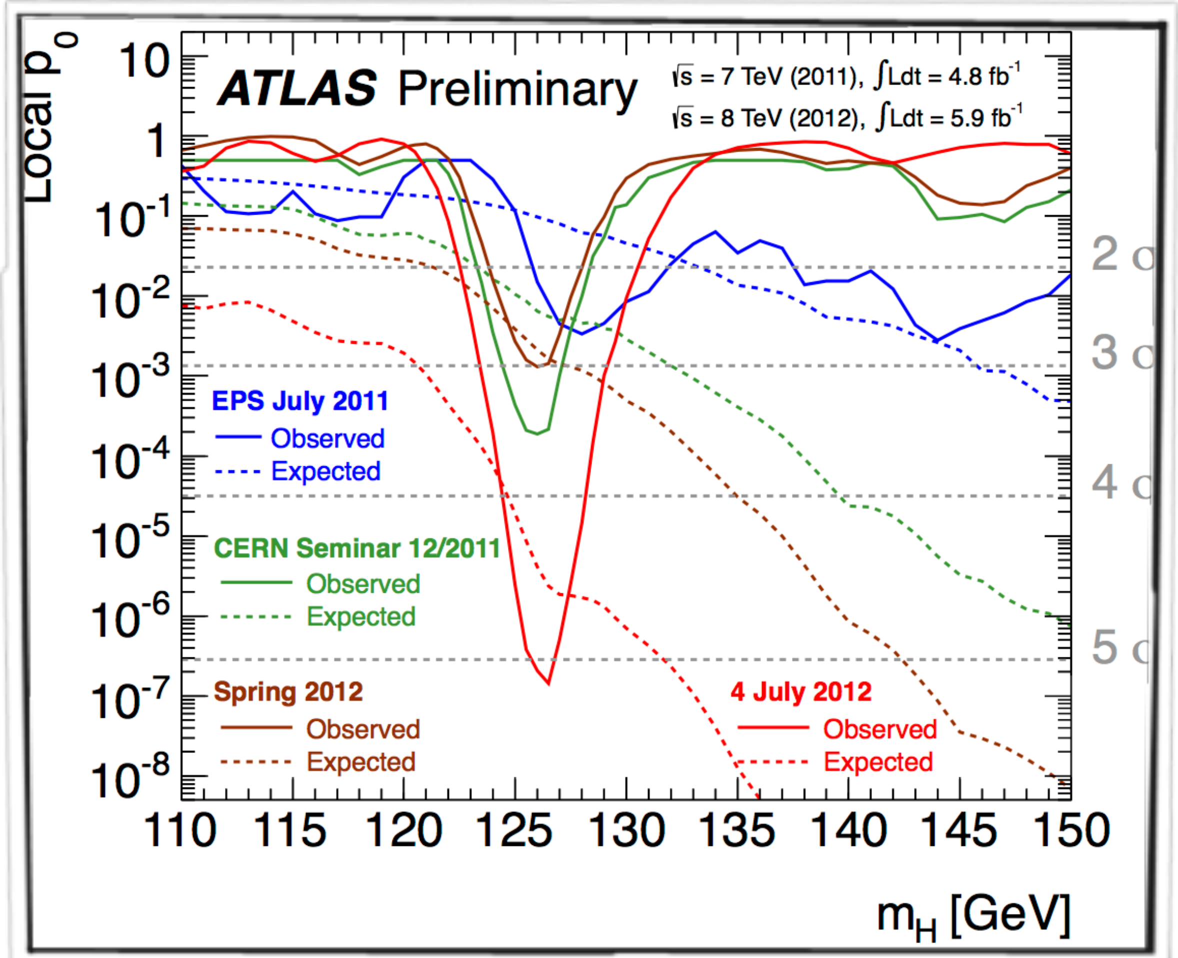

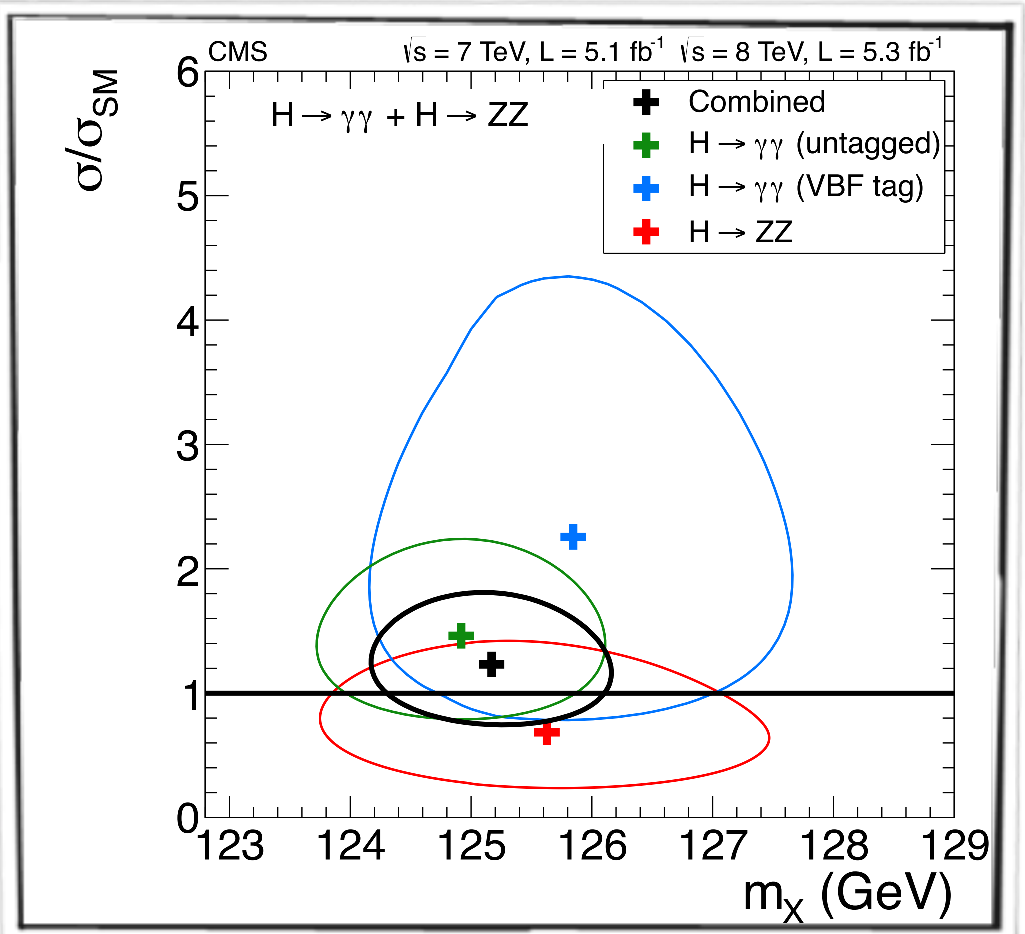

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This discovery raises some questions:

Deviations from SM?

What are the implications for the search of New Physics?

Theory speculations/implications

Many of my theory colleagues also started wild speculations/extrapolations

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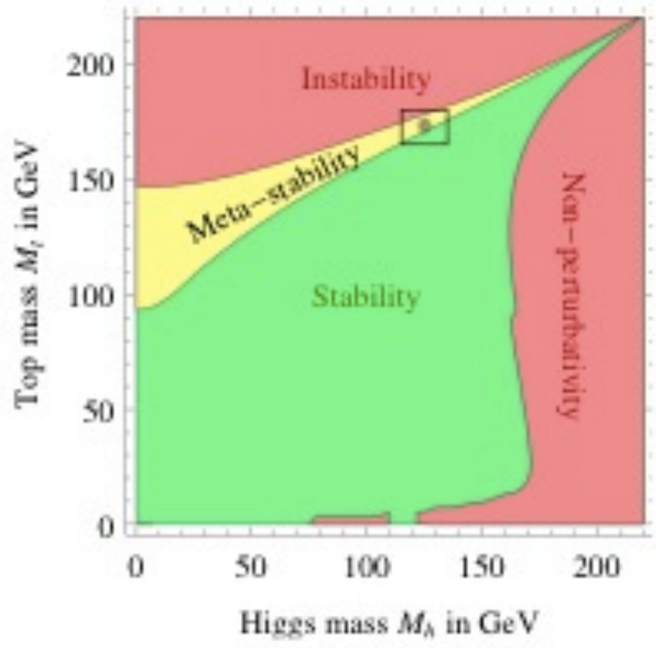
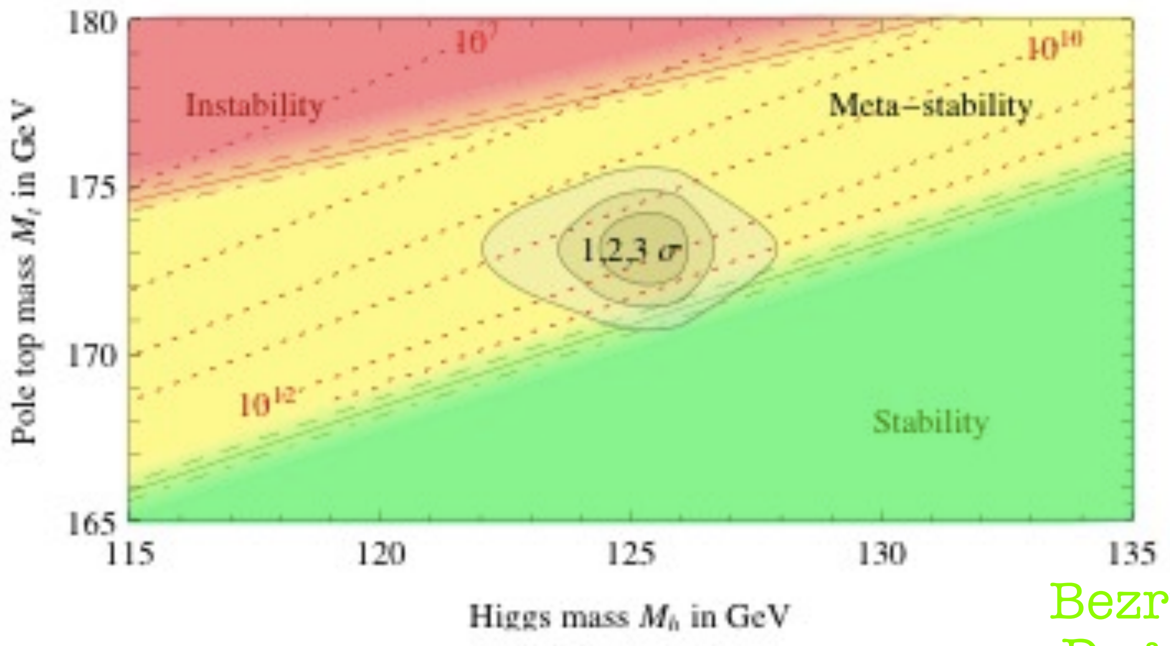
the SM vacuum is stable/metastable

and the validity of the SM can be extended up to the Planck scale!





Bezrukov et al ’12
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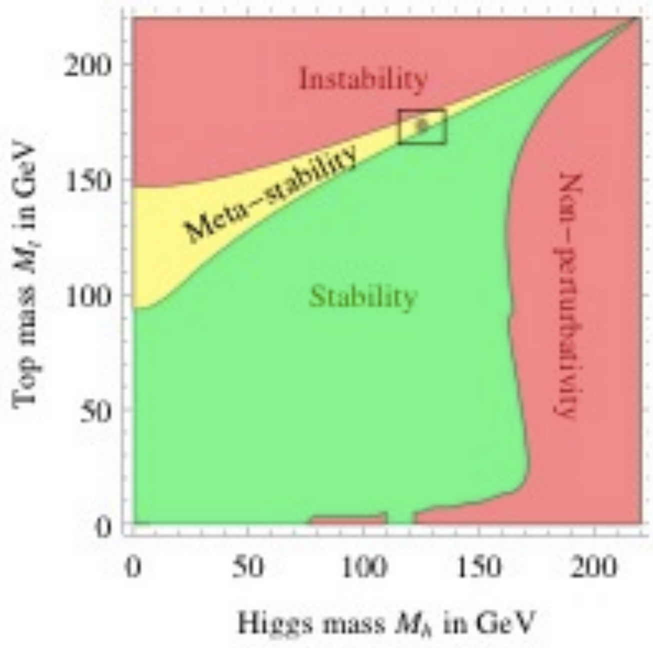

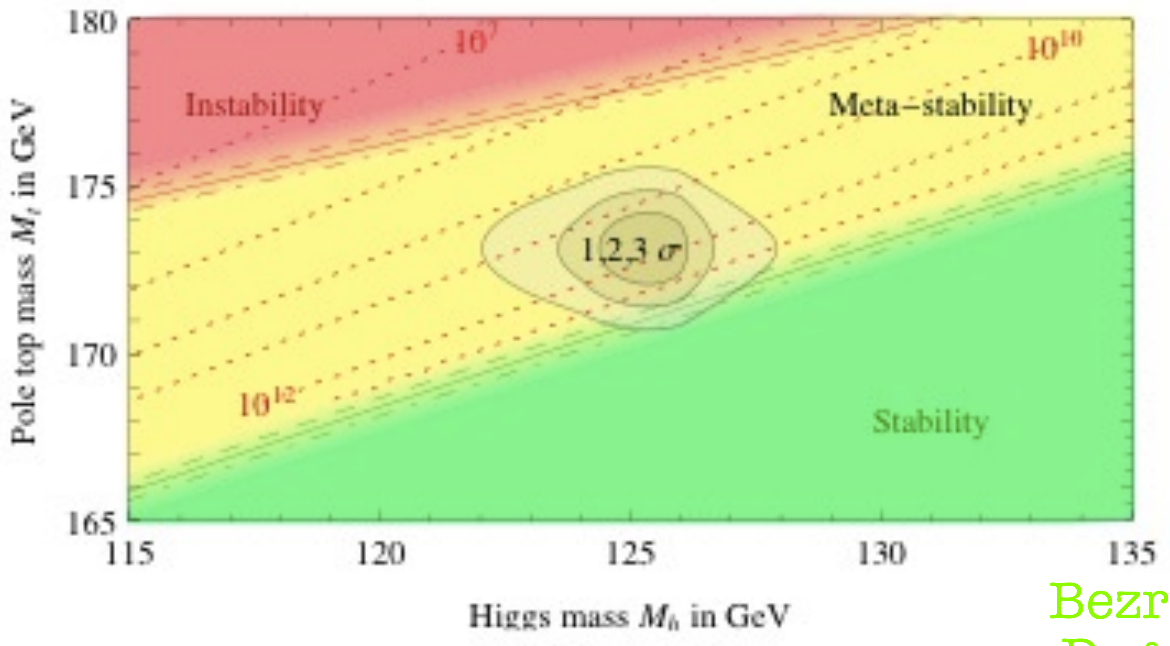

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- ☑ if $m_H > M_{\text{stability}}$, the Higgs could serve as an inflaton
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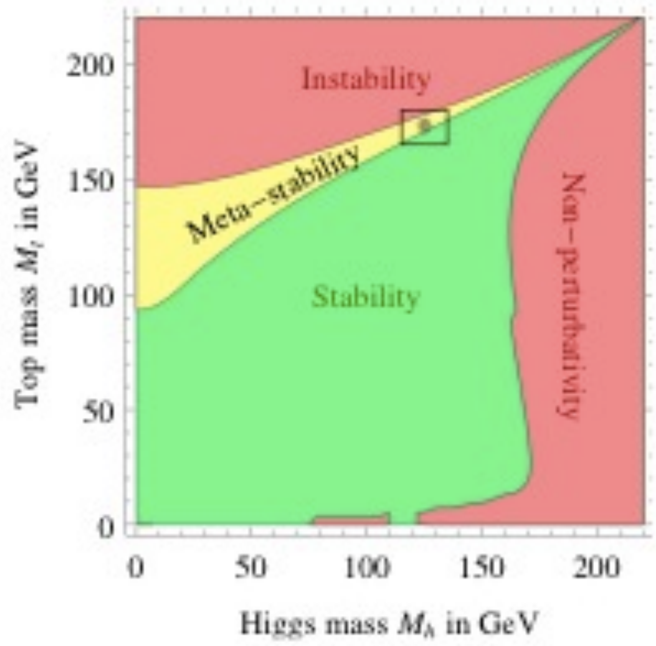

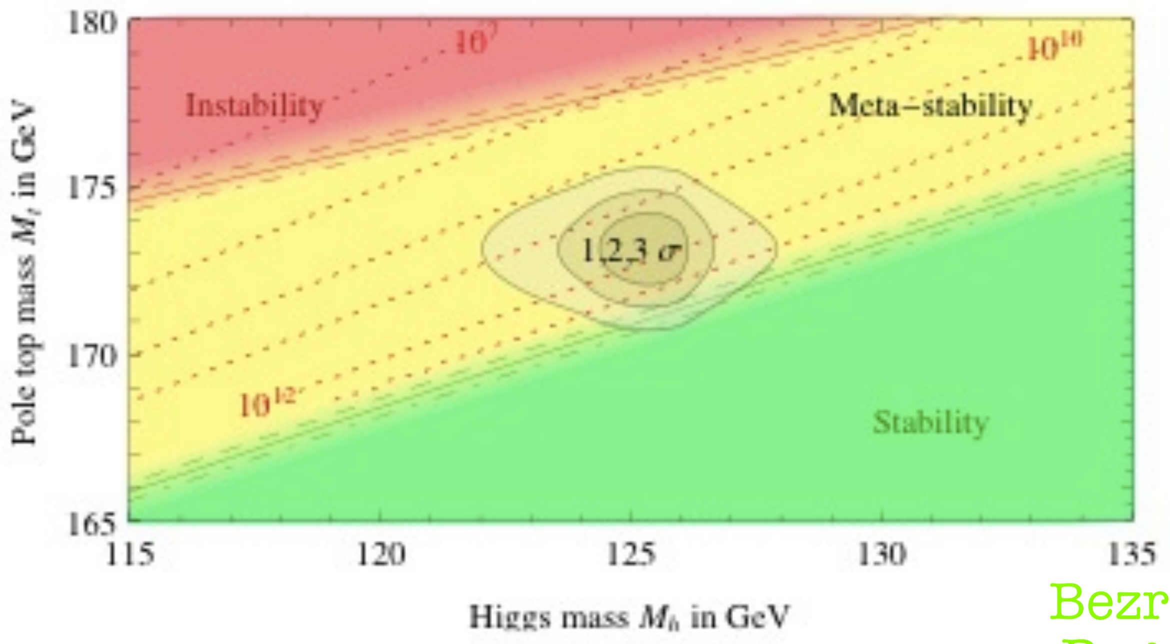

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need precise Higgs&top mass/couplings (and α_s) measurements (ILC, μ coll.)

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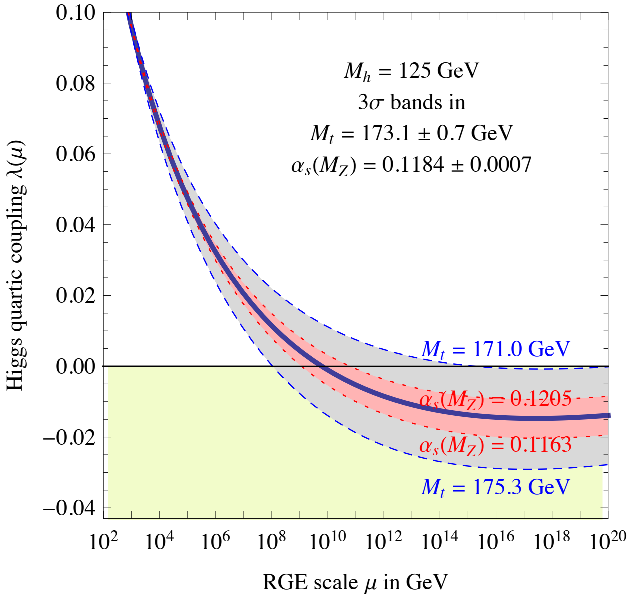

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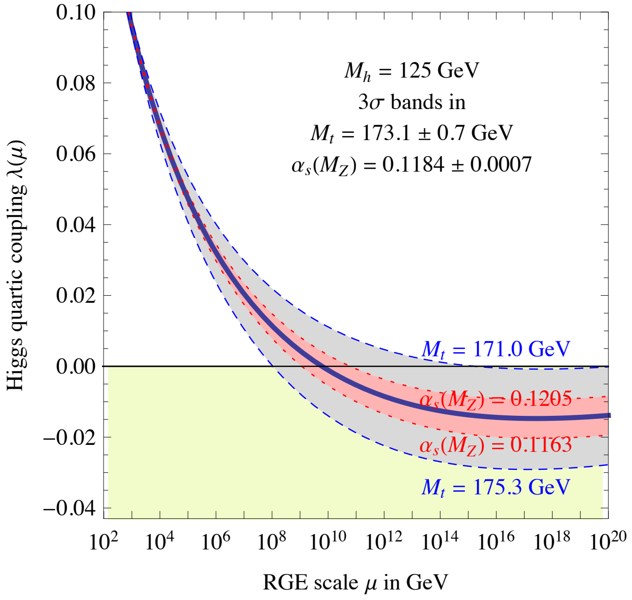

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absence of new energy scale between the Fermi and the Planck scale?

Anthropic vs. natural EWSB...

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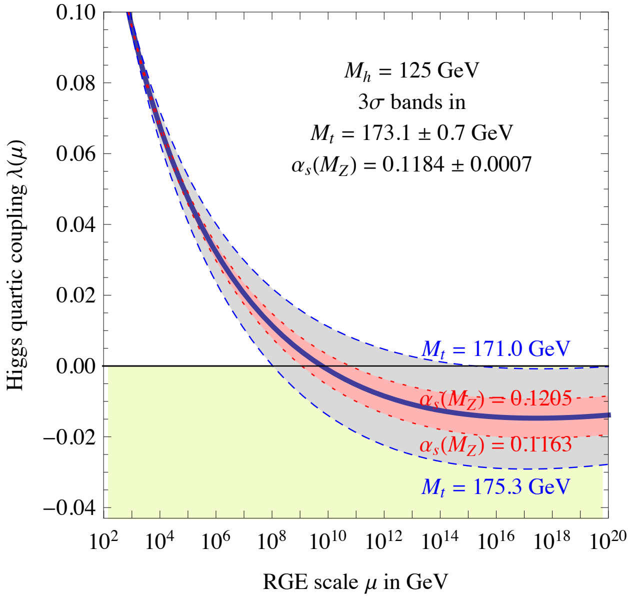

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But these implications are based on the assumption that the 126 GeV particle observed is the SM Higgs and that the Dark Matter sector is decoupled from the weak sector.
Let us stay closer to the TeV scale and try to understand the implications of the Higgs discovery (?) for LHC/ILC/CLIC/...

Higgs' J^{PC}

Have we observed a scalar?

Spin $\leftrightarrows$ angular distribution of final decay products

- ☑ spin-1: forbidden by Landau-Yang's theorem (ie Bose symmetry)
- ☑ $gg \to X \to \gamma\gamma$ and $q\bar{q} \to X \to \gamma\gamma$ e.g., Gao et al '10
  - ❖ spin-0: flat in cos θ*
  - ❖ spin-2: quartic in cos θ*: $\frac{d\sigma}{d\Omega} \propto \frac{1}{4} + \frac{3}{2}\cos^2\theta + \frac{1}{4}\cos^4\theta$
- ☑ $gg \to X \to ZZ^\star \to 4l$ Choi et al '02 De Rujula et al. '10
- ☑ $gg \to X \to WW^\star \to 2l2\nu$ Ellis, Hwang '12

Parity $\leftrightarrows$ angular distribution of final decay products

- ☑ CP-odd: couplings to W and W are loop-induced only! Hard to explain data.
- ☑ angular distribution of leptons in $gg \to X \to ZZ^\star \to 4l$
- ☑ angular distribution of jets produced in VBF Plehn et al '01
- ☑ spin correlations in $X \to \tau\tau$ Berge et al '08

Can be solved at LHC$_8$ (may be), LHC$_{14}$ (for sure)

too academic questions? Sensitivity to degree admixture of admixture even/odd?

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Contino, Grojean, Moretti, Piccinini, Rattazzi '10

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$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2} m_h^2 h^2 - \frac{d_3}{6}\left(\frac{3m_h^2}{v}\right) h^3 - \frac{d_4}{24}\left(\frac{3m_h^2}{v^2}\right) h^4 \ldots$$

$$- \left(m_W^2\, W_\mu W_\mu + \frac{1}{2} m_Z^2\, Z_\mu Z_\mu\right)\left(1 + 2a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \ldots\right)$$

$$- \sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar{\psi}^{(i)} \psi^{(i)} \left(1 + c_\psi \frac{h}{v} + c_{2\psi} \frac{h^2}{v^2} + \ldots\right)$$

$$+ \frac{g^2}{16\pi^2}\left(c_{WW}\, W^+_{\mu\nu} W^-_{\mu\nu} + c_{ZZ}\, Z^2_{\mu\nu} + c_{Z\gamma}\, Z_{\mu\nu}\gamma_{\mu\nu}\right)\frac{h}{v} + \ldots$$

$$+ \frac{g^2}{16\pi^2}\left[\gamma^2_{\mu\nu}\left(c_{\gamma\gamma}\frac{h}{v} + \ldots\right) + G^2_{\mu\nu}\left(c_{gg}\frac{h}{v} + c_{2gg}\frac{h^2}{v^2} \ldots\right)\right]$$

$$+ \frac{g^2}{16\pi^2}\left[\frac{c_{hhgg}}{\Lambda^2} G^2_{\mu\nu}\frac{(\partial_\rho h)^2}{v^2} + \frac{c'_{hhgg}}{\Lambda^2} G_{\mu\rho}G_{\rho\nu}\frac{\partial_\mu h \partial_\nu h}{v^2} + \ldots\right]$$

$$+ \ldots$$

Contino, Grojean, Moretti, Piccinini, Rattazzi ’10

SM

$$a = b = c = d_3 = d_4 = 1$$

$$c_{2\psi} = c_{WW} = c_{ZZ} = c_{Z\gamma} = c_{\gamma\gamma} = \ldots = 0$$

A few (reasonable) assumptions:

☑ spin-0 & CP-even

↖ $\gamma\gamma$ ↖ WW & ZZ

☑ custodial symmetry

↖ EWPD

☑ no Higgs FCNC

(generalization of Glashow-Weinberg th.)

↖ Flavor

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$$+ \dots$$

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

still large parameter space

$\Downarrow$ $\Downarrow$ $\Downarrow$

4 operators @ O(p^2): c$_V$, c$_t$, c$_b$, c$_T$

2 operators @ O(p^4): c$_g$ c$_\gamma$

(contribute to the same order as O(p^2) to gg→h and h→$\gamma\gamma$)

$a = b = d_3 = d_4 = 1$

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still large parameter space

⇓ ⇓ ⇓

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⇙ ⇙ ⇙

$$+\frac{g^2}{16\pi^2}\left(c_{WW}\, W^+_{\mu\nu}W^-_{\mu\nu} + c_{ZZ}\, Z^2_{\mu\nu} + c_{Z\gamma}\, Z_{\mu\nu}\gamma_{\mu\nu}\right)\frac{h}{v} + \ldots$$

Not enough data/sensitivity to determine all these parameters

⇓ ⇓ ⇓

But we can put some of the SM structures under probation

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

☑ spin-0 & CP-even

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The perturbative unitarity conundrum

the Higgs plays a crucial in the UV behavior of massive state scattering

$$\mathcal{L}_{\mathrm{EWSB}} = -m_V^2 V_\mu V^\mu \left(1 + 2a\frac{h}{v}\right) - m_\psi \bar{\psi}\psi \left(1 + c\frac{h}{v}\right)$$

'a' and 'c' are arbitrary free couplings

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

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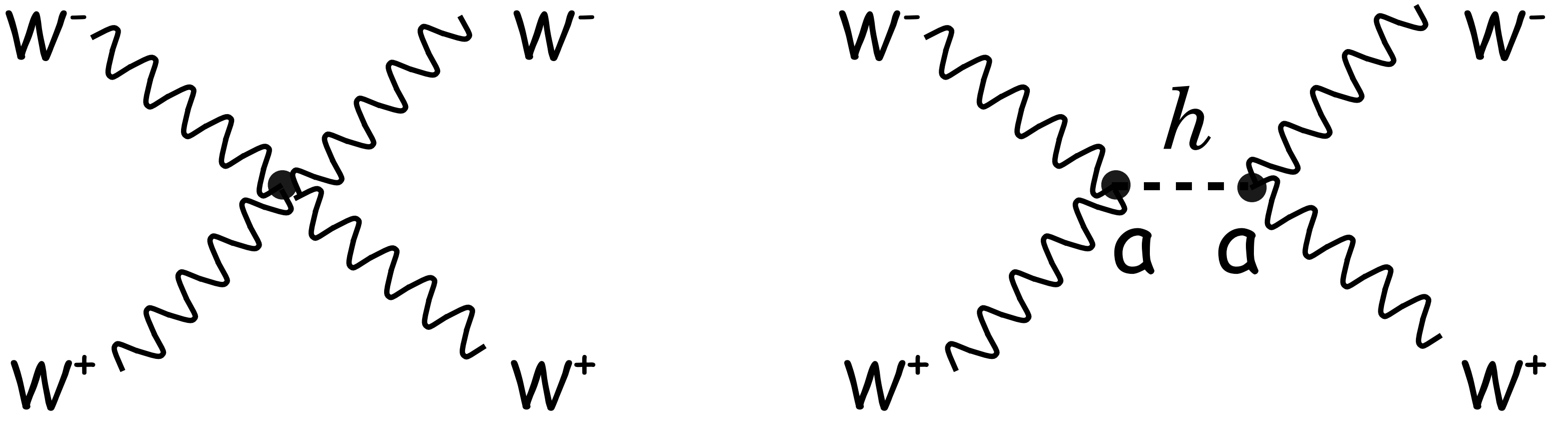

$$\mathcal{A} = \frac{1}{v^2}\left(s - \frac{a^2 s^2}{s - m_h^2}\right)$$

For a=1: perturbative unitarity in elastic channels WW → WW

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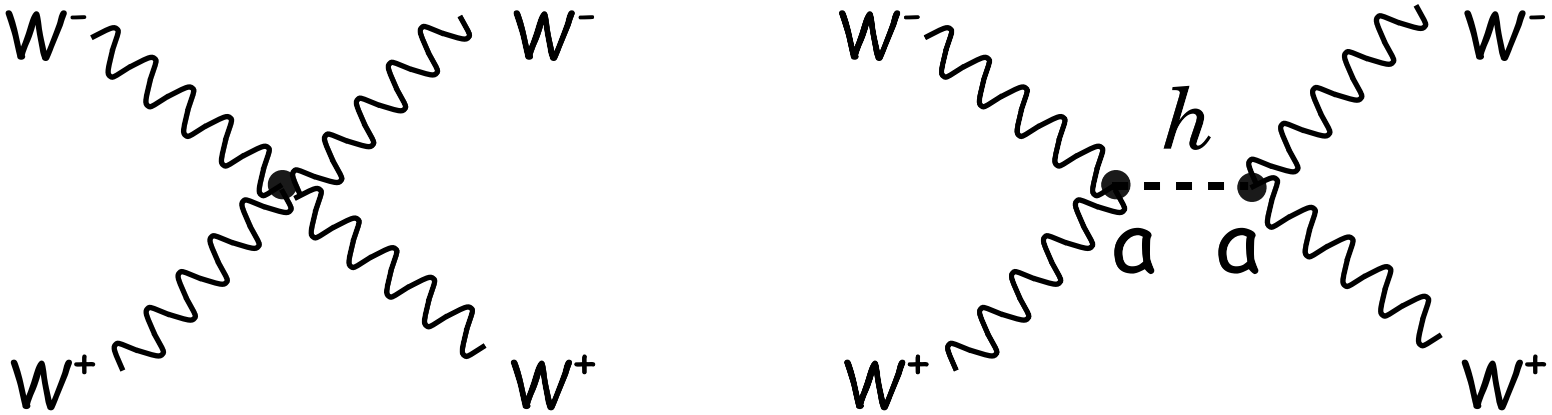

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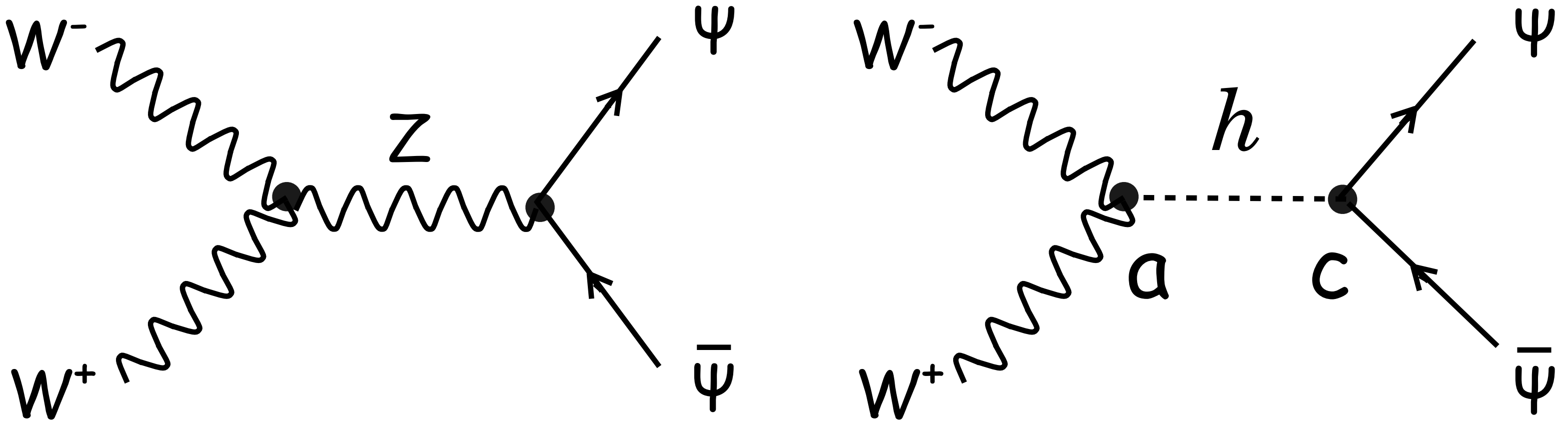

$$\mathcal{A} = \frac{m_\psi \sqrt{s}}{v^2}\left(1 - \frac{ac\, s}{s - m_h^2}\right)$$

For ac=1: perturbative unitarity in inelastic WW → $\psi\ \psi$

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

The perturbative unitarity conundrum

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$$\mathcal{L}_{\mathrm{EWSB}} = -m_V^2 V_\mu V^\mu \left(1 + 2a\frac{h}{v}\right) - m_\psi \bar{\psi}\psi \left(1 + c\frac{h}{v}\right)$$

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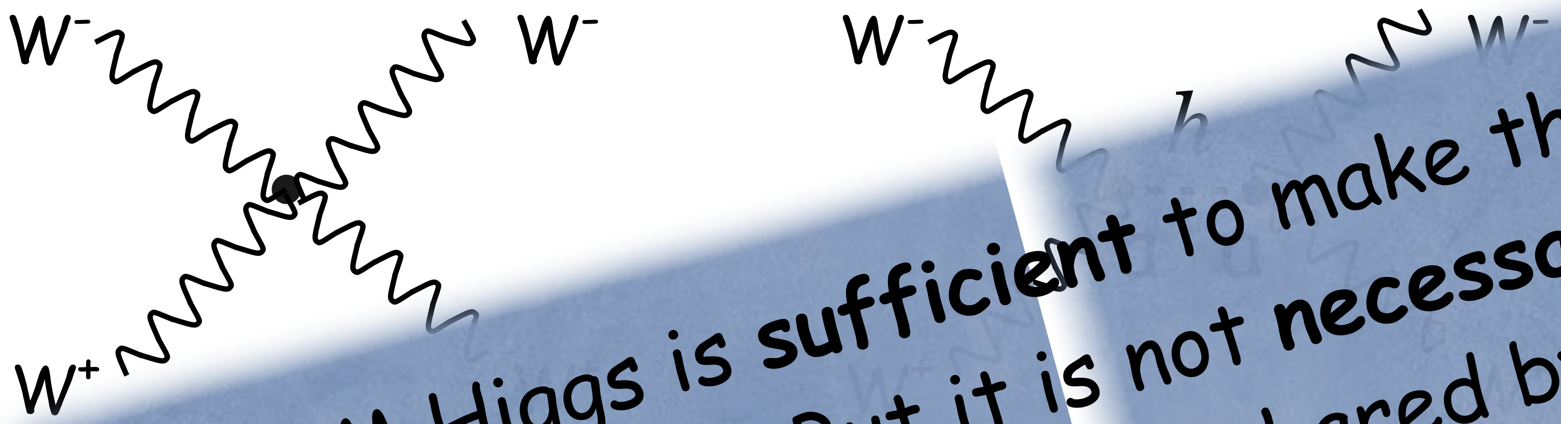


$$\mathcal{A} = \frac{1}{v^2}\left(s - \frac{a^2 s^2}{s - m_h^2}\right)$$

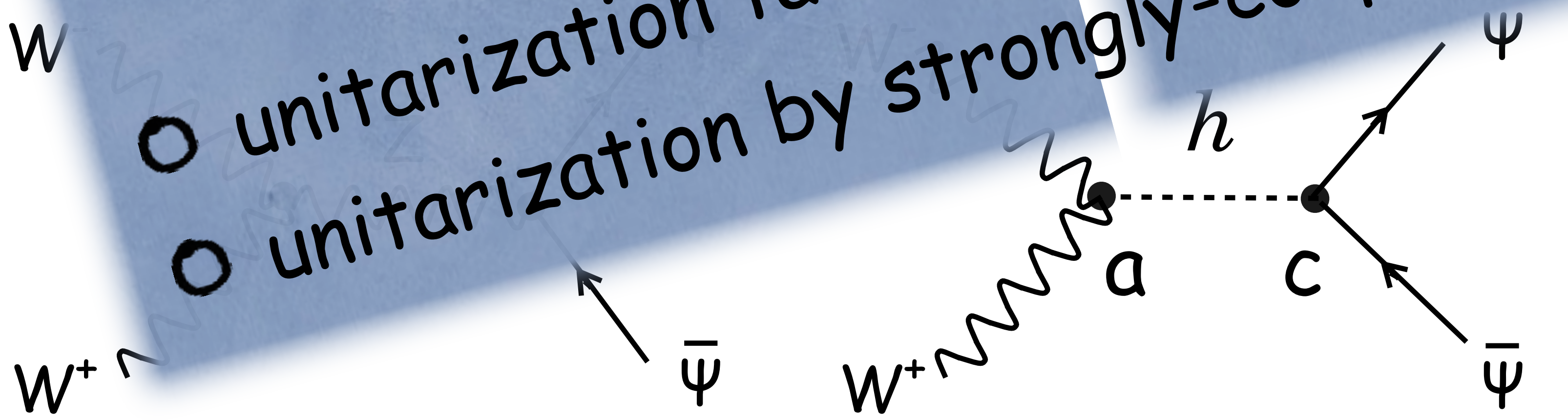
For a=1: perturbative unitarity in elastic channels WW → WW

The SM Higgs is **sufficient** to make the theory consistent

But it is not **necessary**:

○ unitarization task can be shared by several states

○ unitarization by strongly-coupled heavy resonances



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Cornwall, Levin, Tiktopoulos '73

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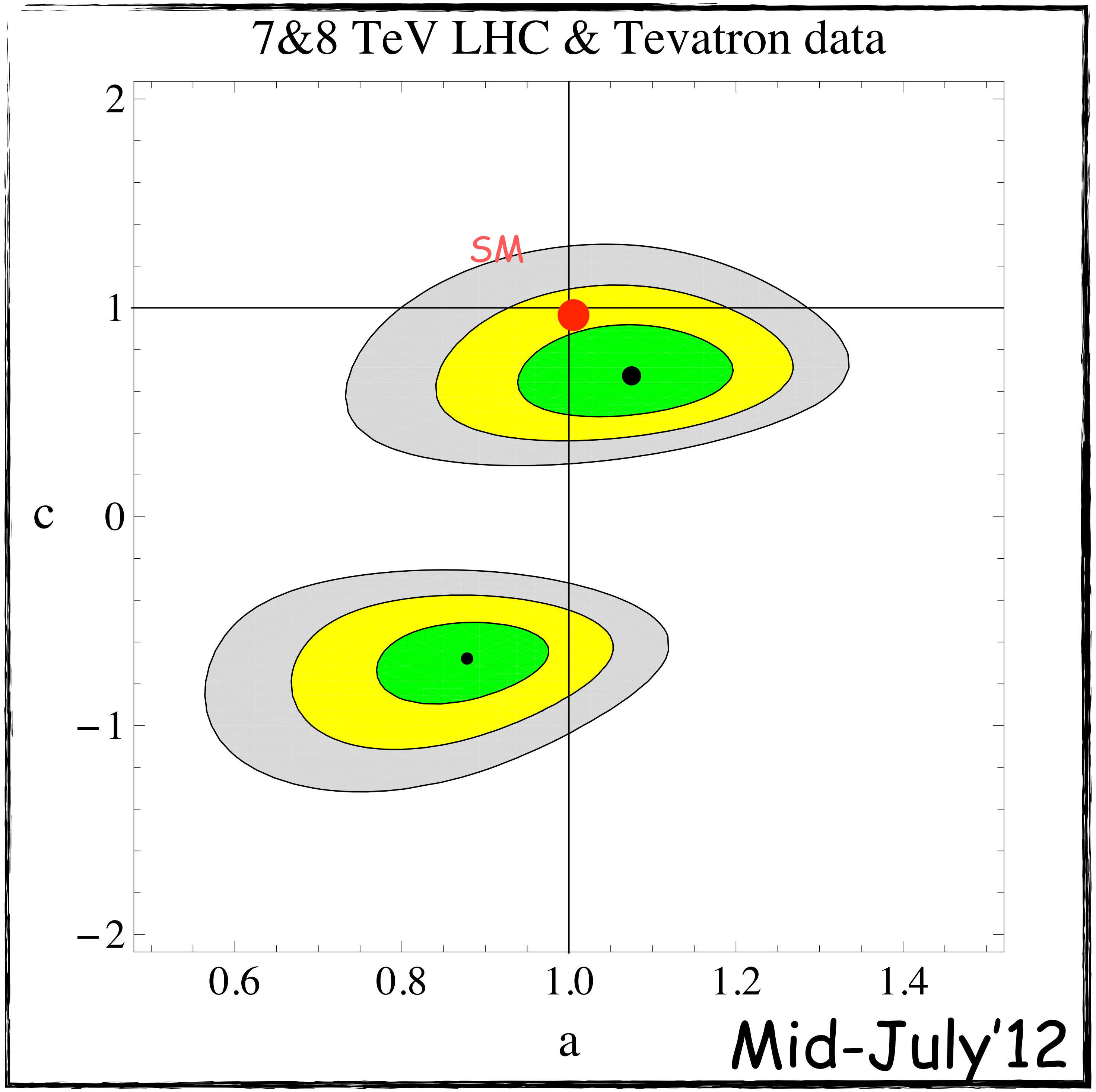
Unitarity: χ^2 fit to the “125” excess

Espinosa, Grojean, Muhlleitner, Trott ’12



note: a fermiophobic Higgs ($c=0$) is disfavored by data (mostly VBF channels) at 97%CL

for similar analyses, see also

Giardino, Kannike, Raidal, Strumia ’12
Carni, Falkowski, Kuflik, Volansky, Zupan ’12
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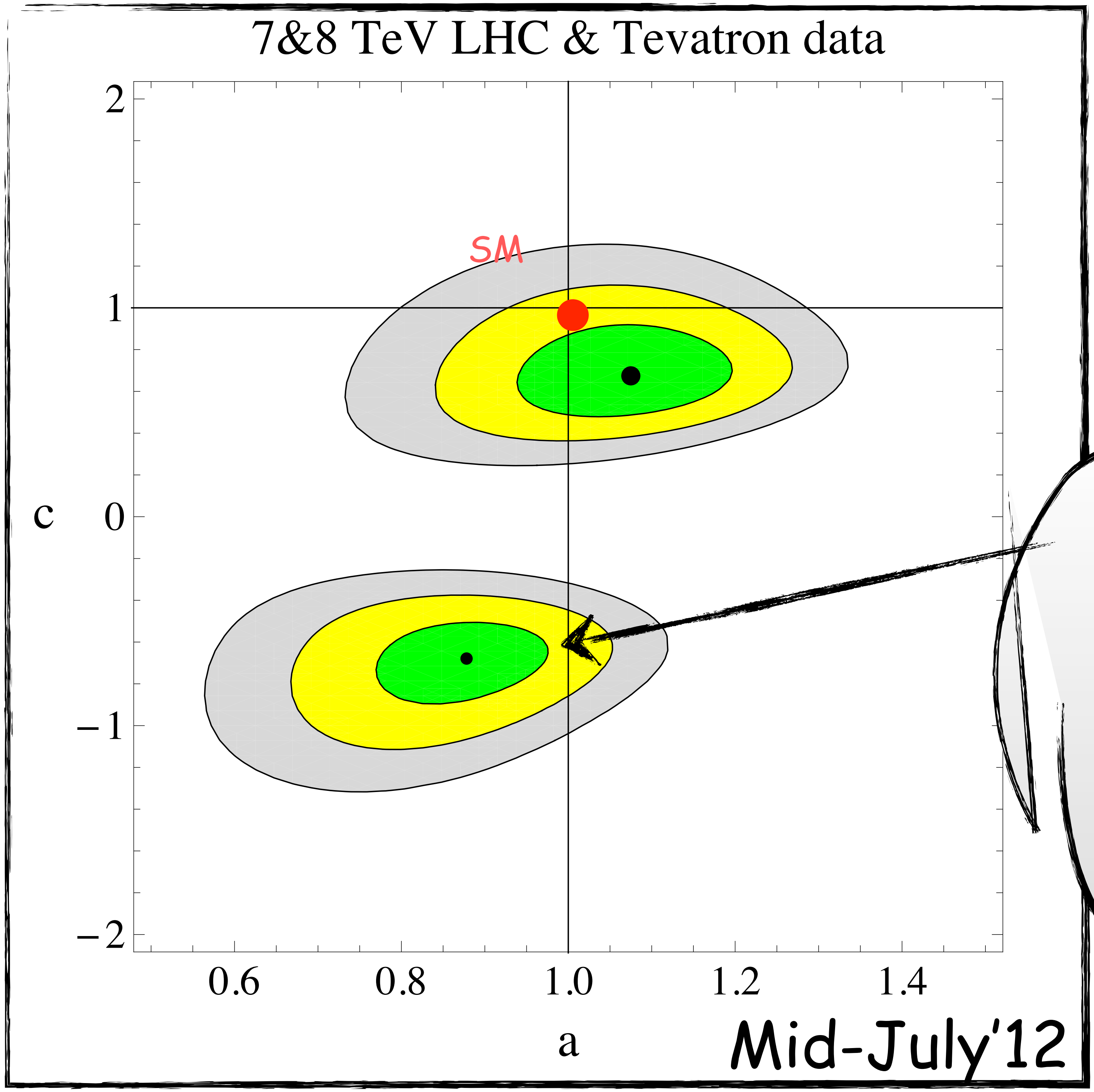

Mid-July’12

note: a fermiophobic Higgs (c=0) is disfavored by data (mostly VBF channels) at 97%CL

“disfermiophilia”

the current data prefers “negative” coupling to fermions

≈

positive interference between top and W in $\gamma\gamma$ channel

for similar analyses, see also

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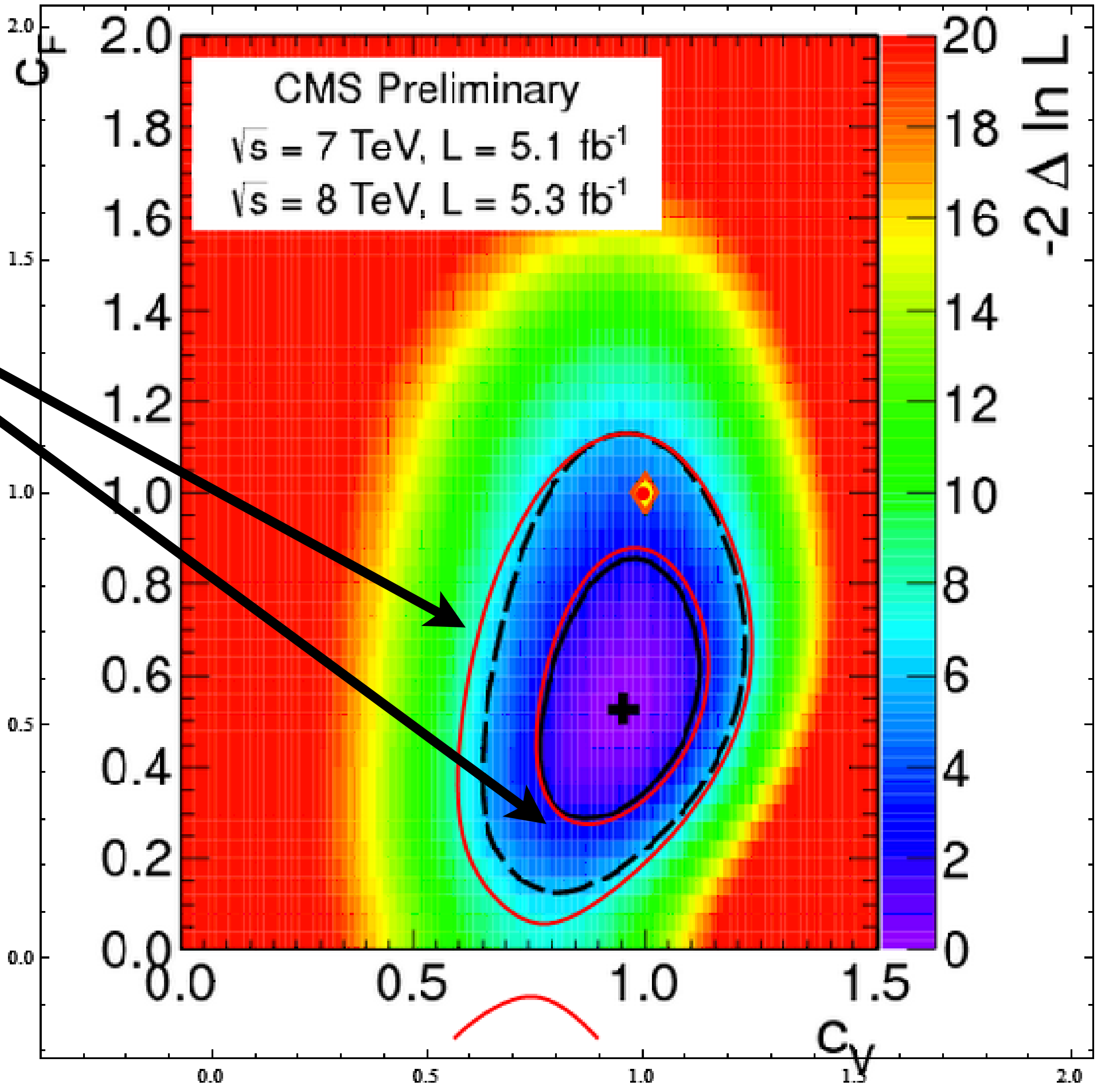
Unitarity: simplified vs. “official” fit

CMS imposed a prior c > 0
(it doesn’t affect χ^2, but it modifies $\Delta\chi^2$)

Our contours



good agreement
despite
crude approximations

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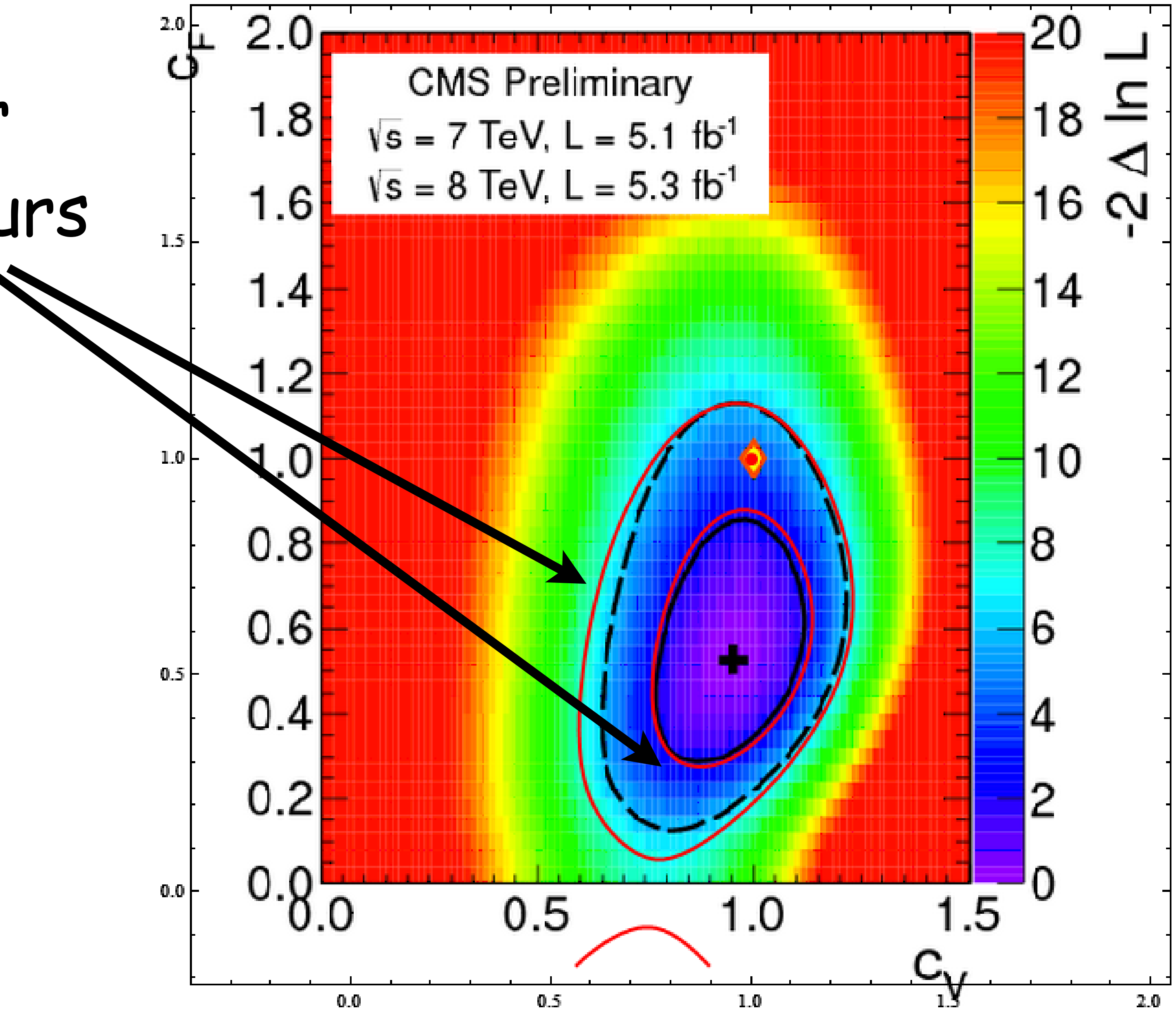

good agreement
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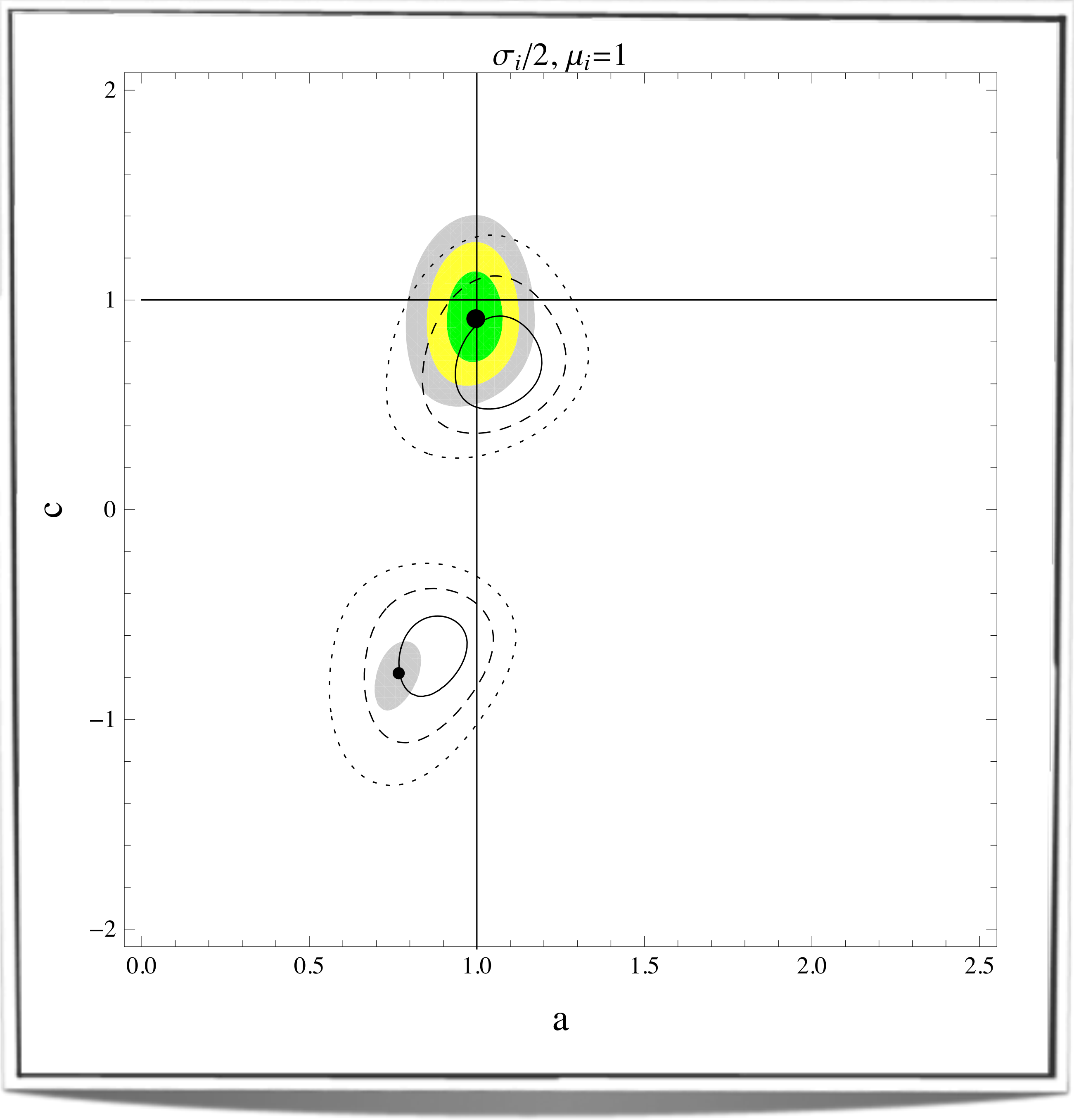
- ☑ Gaussian approximations
- ☑ no correlation among various channels
- ☑ naive combination of rescaled channels
- ☑ forgetting many nuisance parameters

Unitarity: looking to the future



Tevatron and LHC 7TeV data unchanged

LHC 8TeV, $\mu_i = 1$, but $\sigma_i = \sigma_i^{(ICHEP)}/2$

☑ Current sensitivity:

20% on C_V and 30% on C_F

☑ 300/fb @ 14TeV sensitivity:

5% on C_V and 10% on C_F

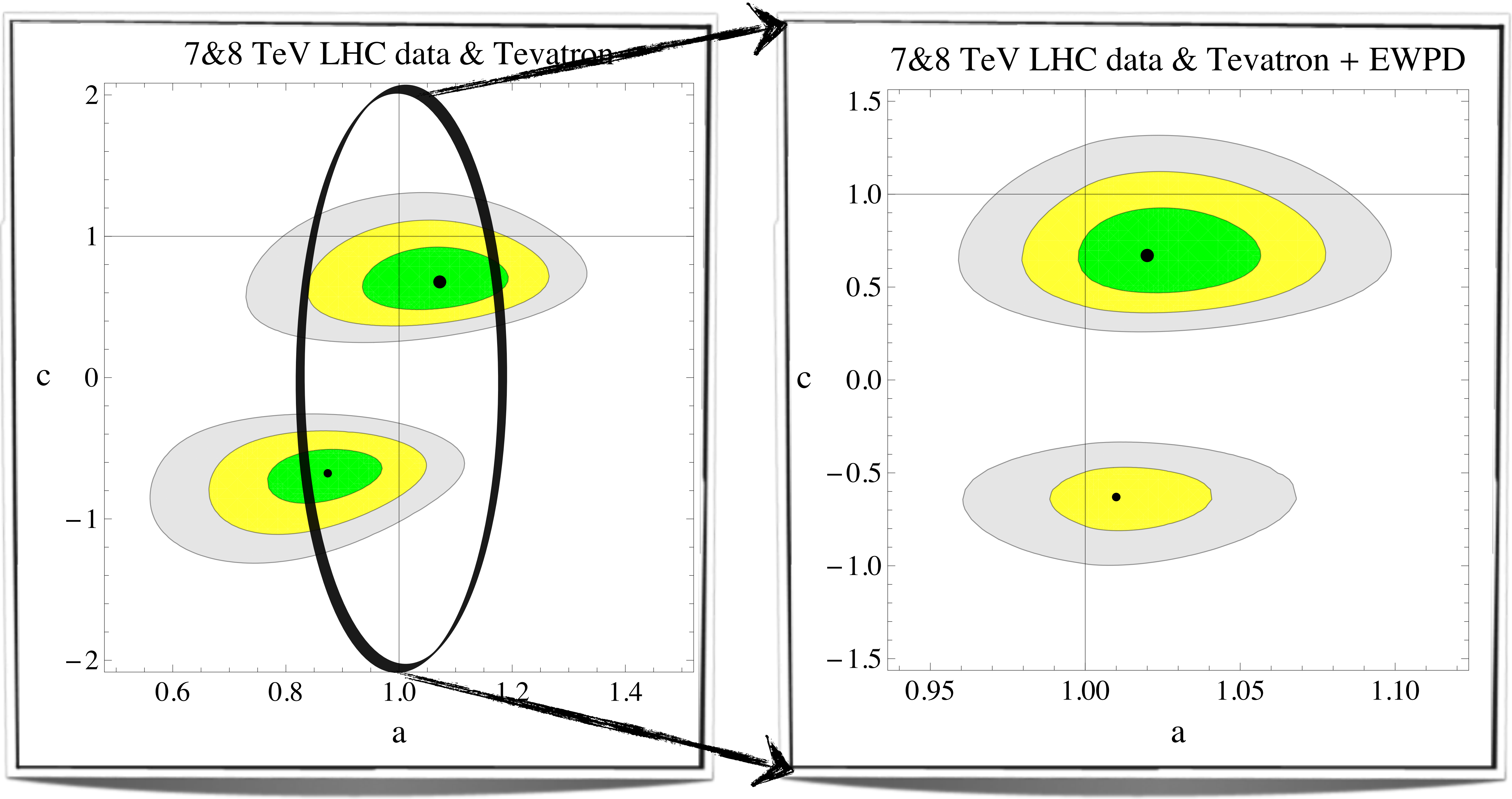
☑ 3/ab @ 14TeV sensivity:

3% on C_V and 5% on C_F

LHC2TSP WG1

Unitarity: LHC meets LEP

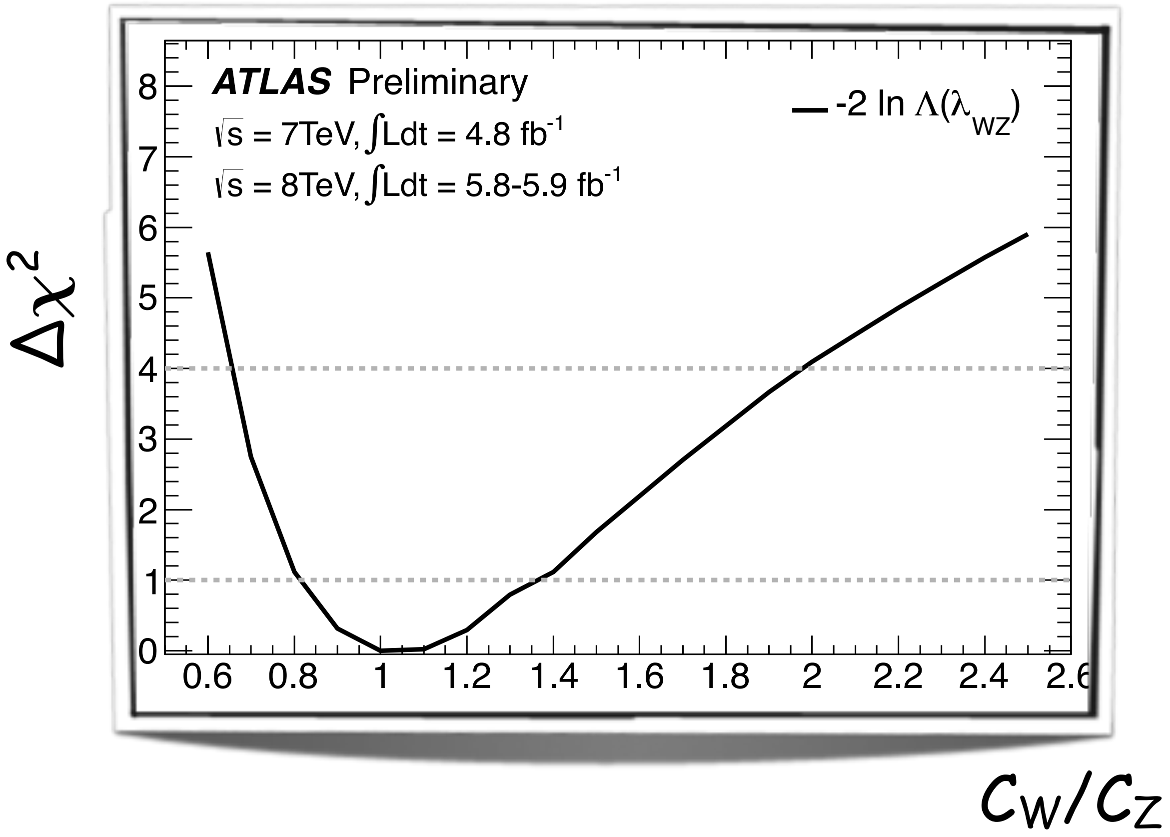
Espinosa, Grojean, Muhlleitner, Trott '12

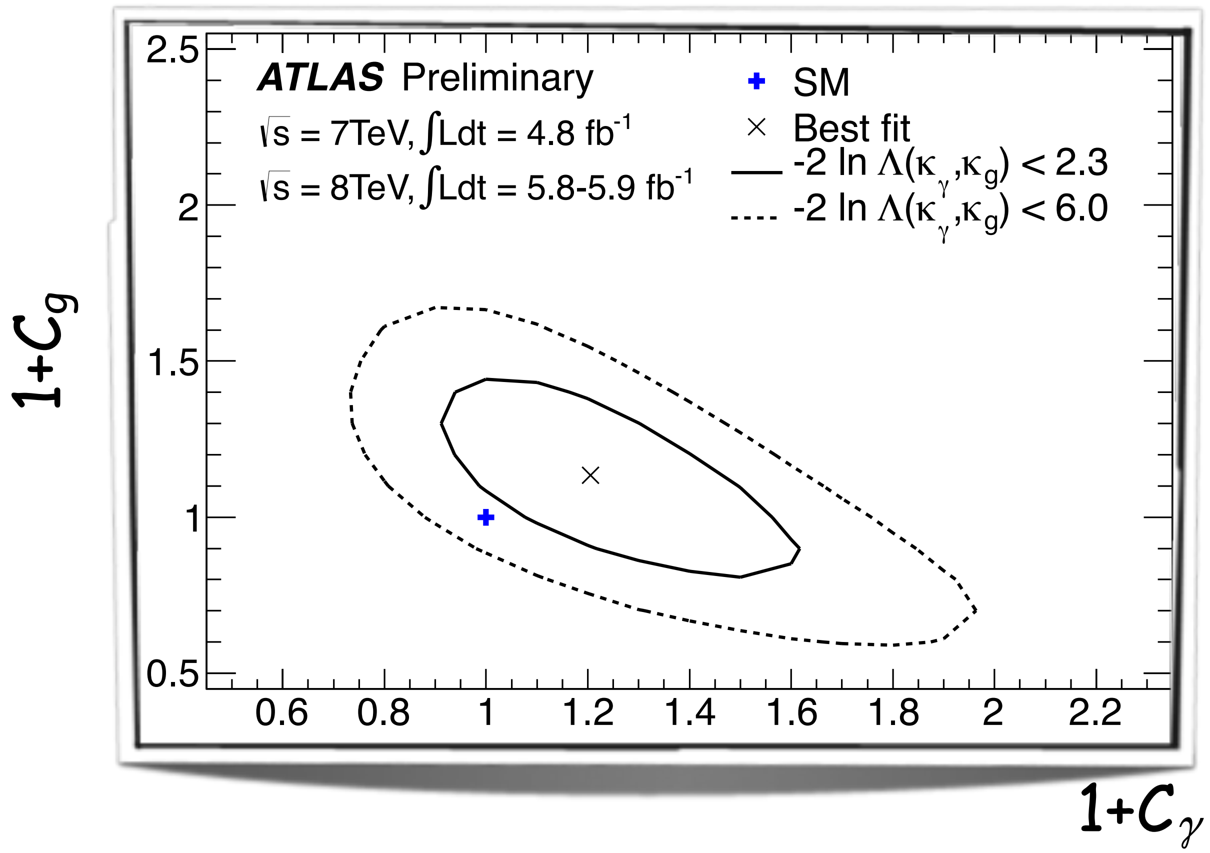


EW data prefer value of 'a' close to 1

Other tests of the SM structure

- custodial symmetry: $C_W=C_Z$?
- probing the weak isospin symmetry: $C_u=C_d$?
- quark and lepton symmetry: $C_q=C_l$?
- new non-SM particle contribution: BR_{inv}? $C_g=C_\gamma=0$?





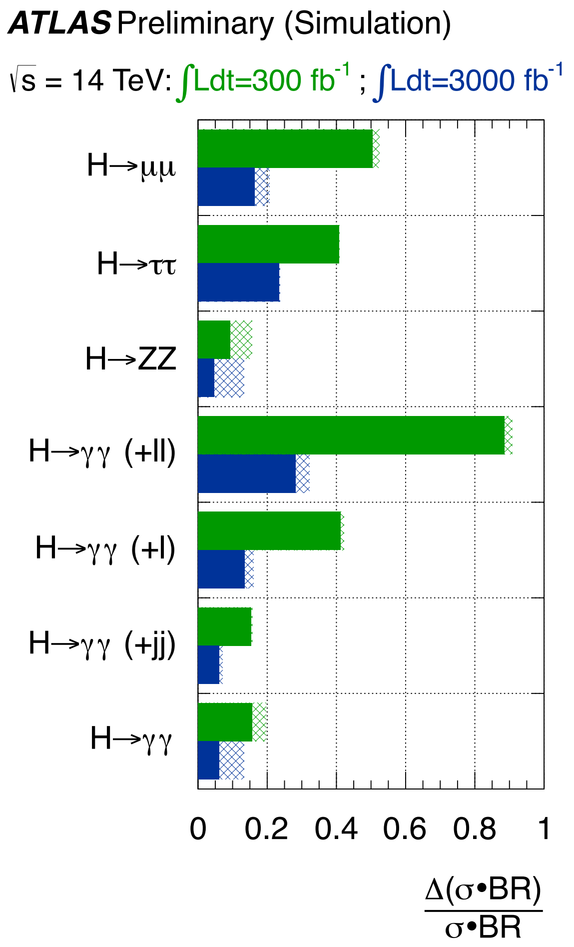
ATLAS-CONF-2012-127

Some tensions

but no statistically significant deviations from the SM structure

Higgs couplings measurements

$\text{LHC}_{300/\text{fb}}$, HL-LHC, ILC, CLIC
will measure Higgs couplings with good/excellent precision



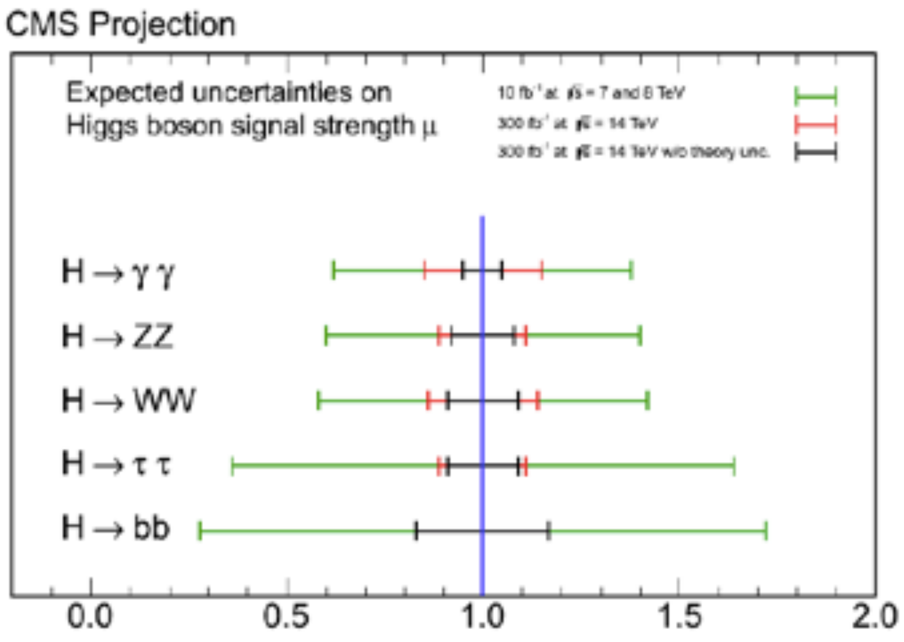
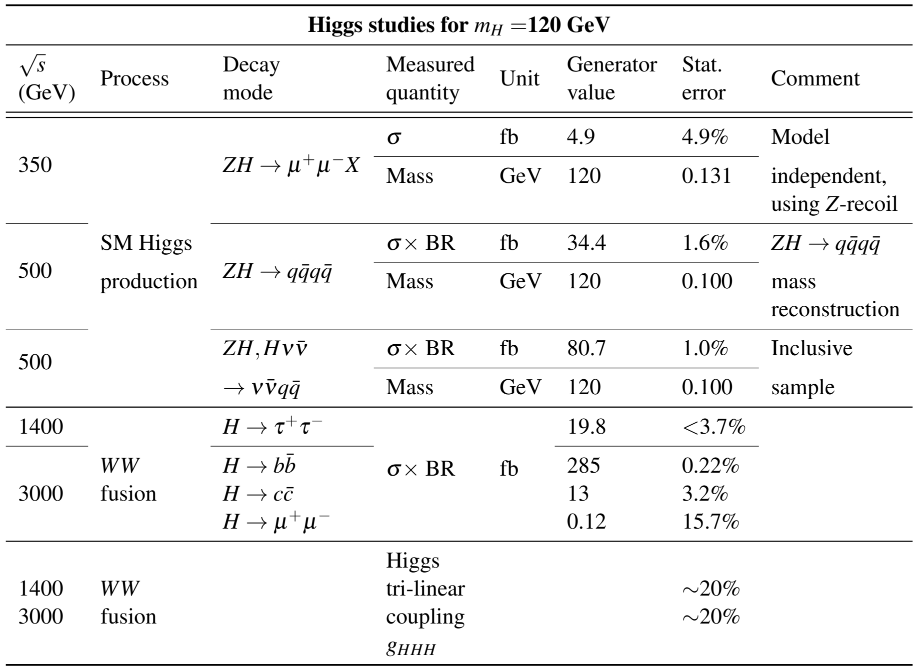


Table 5: Summary of results obtained in the Higgs studies for m_H =120 GeV. All analyses at centre-of-mass energies of 350 GeV and 500 GeV assume an integrated luminosity of 500 fb^{-1}, while the analyses at 1.4 TeV (3 TeV) assume 1.5 ab^{-1}(2 ab^{-1}).



Higgs studies for m_H =120 GeV

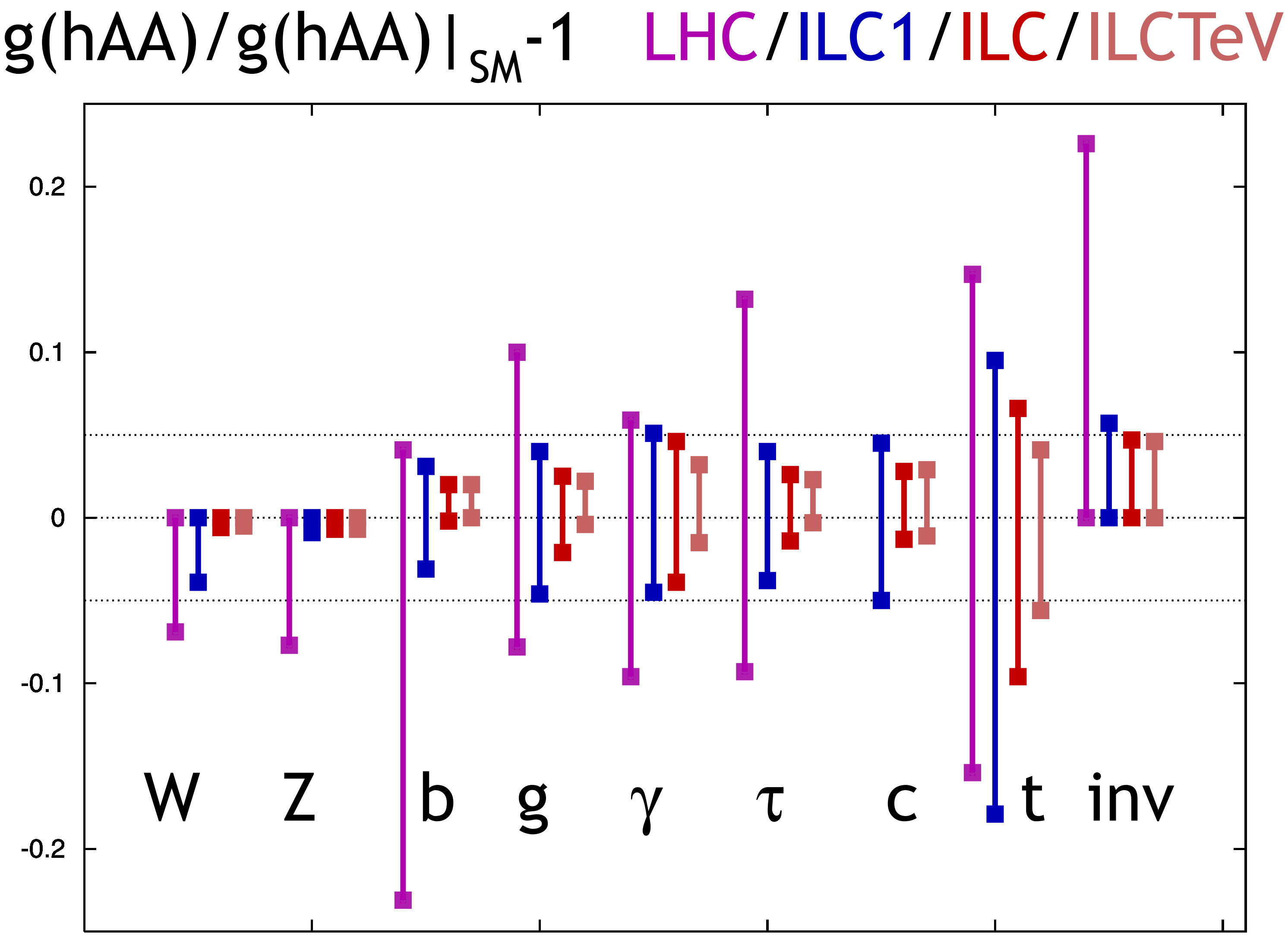
$\sqrt{s}$ (GeV)	Process	Decay mode	Measured quantity	Unit	Generator value	Stat. error	Comment
350	SM Higgs production	$ZH \to \mu^+\mu^- X$	σ	fb	4.9	4.9%	Model independent, using Z-recoil
			Mass	GeV	120	0.131	
500		$ZH \to q\bar{q}q\bar{q}$	$\sigma\times$ BR	fb	34.4	1.6%	$ZH \to q\bar{q}q\bar{q}$ mass reconstruction
			Mass	GeV	120	0.100	
500		$ZH, H\nu\bar{\nu} \to \nu\bar{\nu}q\bar{q}$	$\sigma\times$ BR	fb	80.7	1.0%	Inclusive sample
			Mass	GeV	120	0.100	
1400	*WW* fusion	$H \to \tau^+\tau^-$	$\sigma\times$ BR	fb	19.8	<3.7%	
3000		$H \to b\bar{b}$			285	0.22%	
		$H \to c\bar{c}$			13	3.2%	
		$H \to \mu^+\mu^-$			0.12	15.7%	
1400	*WW* fusion		Higgs tri-linear coupling g_{HHH}			~20%	
3000						~20%	

5-10% @ $\text{LHC}^{14\text{TeV}}_{300/\text{fb}}$

1-5% @ ILC/CLIC

direct acces to Γ_{inv}

Higgs couplings measurements



$g(hAA)/g(hAA)|_{SM}-1$ LHC/ILC1/ILC/ILCTeV

Peskin'12

Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 σ confidence intervals for LHC at 14 TeV with 300 fb^{-1}, for ILC at 250 GeV and 250 fb^{-1} ('ILC1'), for the full ILC program up to 500 GeV with 500 fb^{-1} ('ILC'), and for a program with 1000 fb^{-1} for an upgraded ILC at 1 TeV ('ILCTeV'). The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

5-10% @ LHC$^{14TeV}_{300/fb}$

1-5% @ ILC/CLIC

Which Higgs couplings?

lot of study on SM-like Higgs couplings

but should also access the prospects for non-SM couplings

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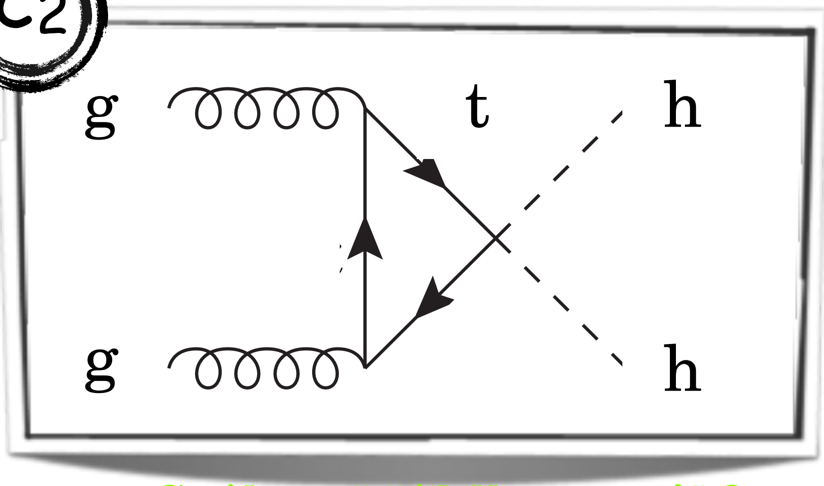
c_2



Grôber, Mühlleitner '10
Contino et al '12
Gillioz et al '12

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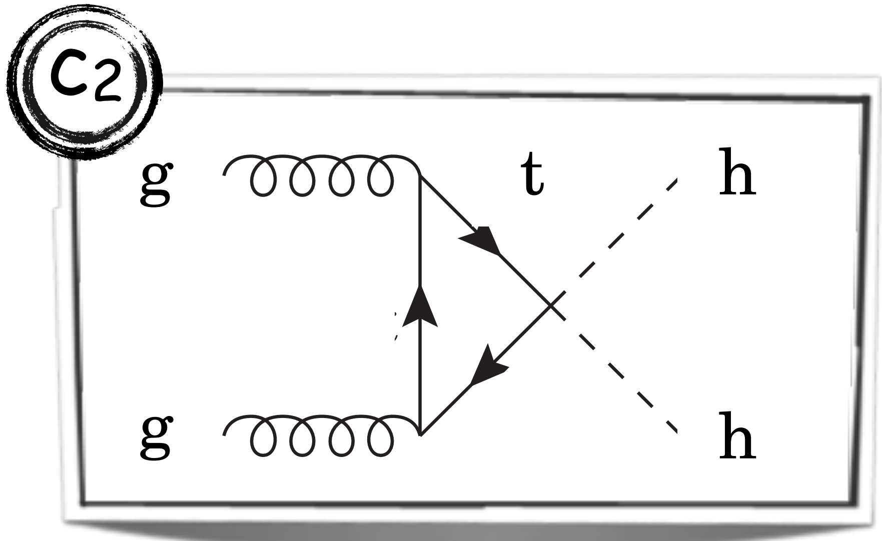

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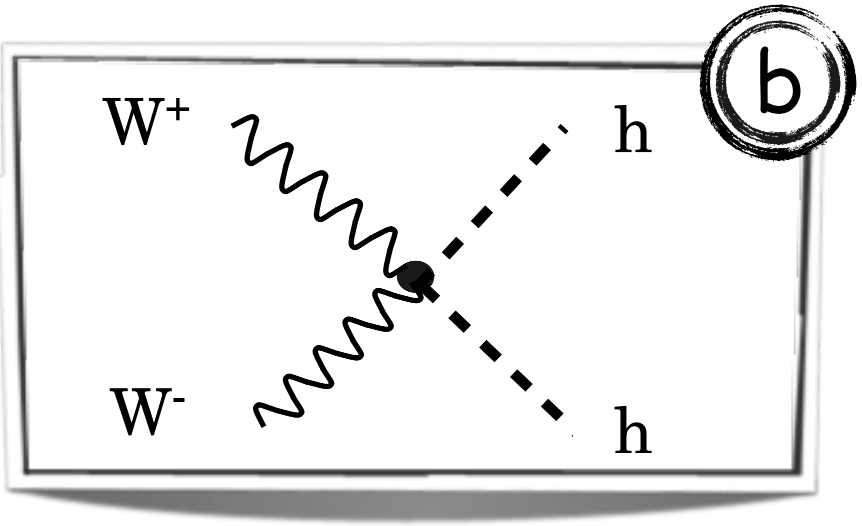

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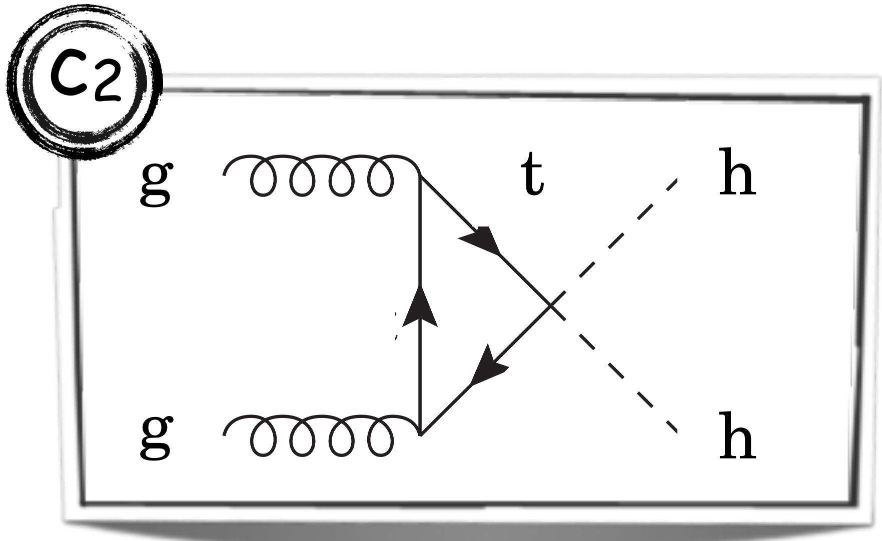

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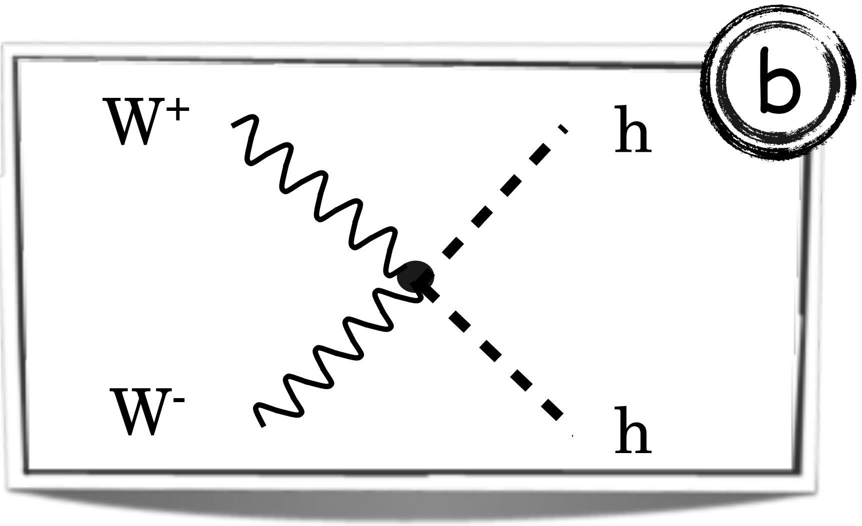

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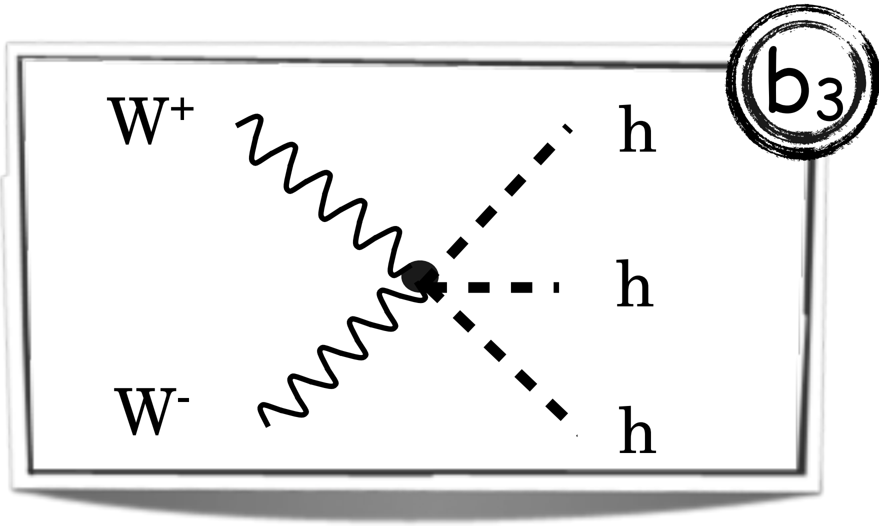

Contino, Grojean, Pappadopoulo,
Rattazzi, Thamm 'to appear

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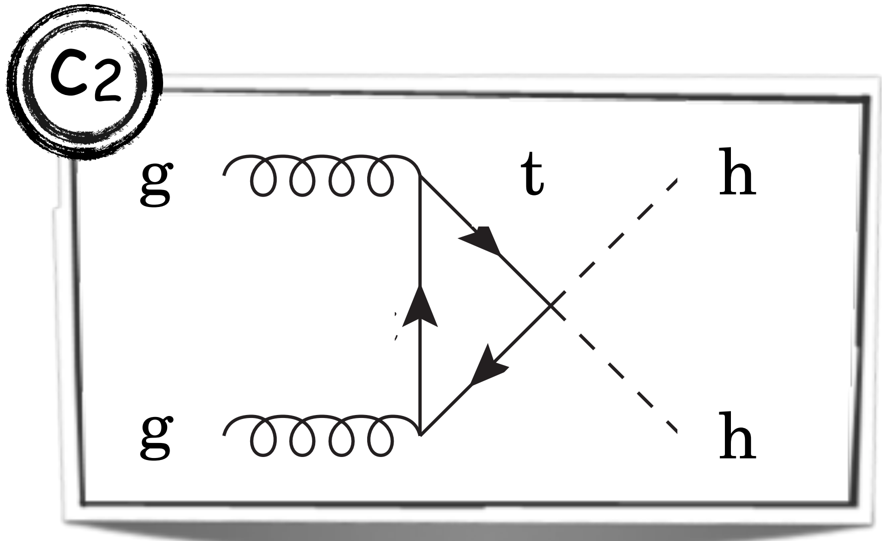

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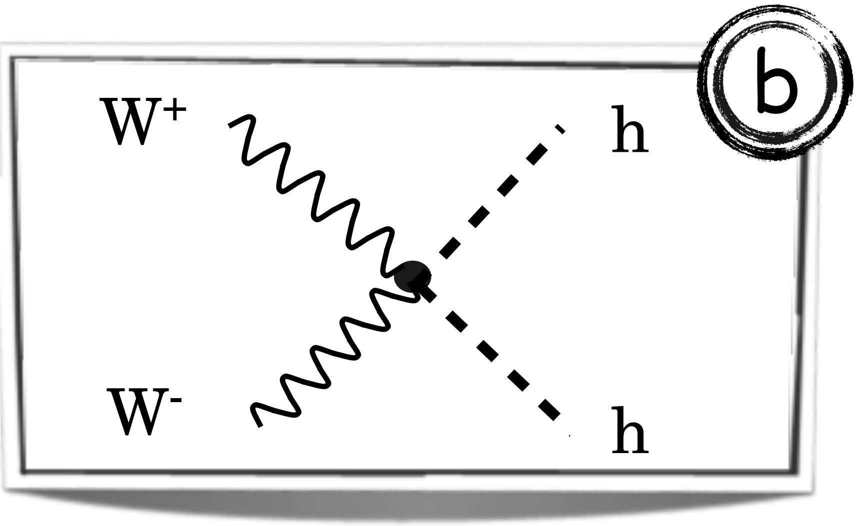

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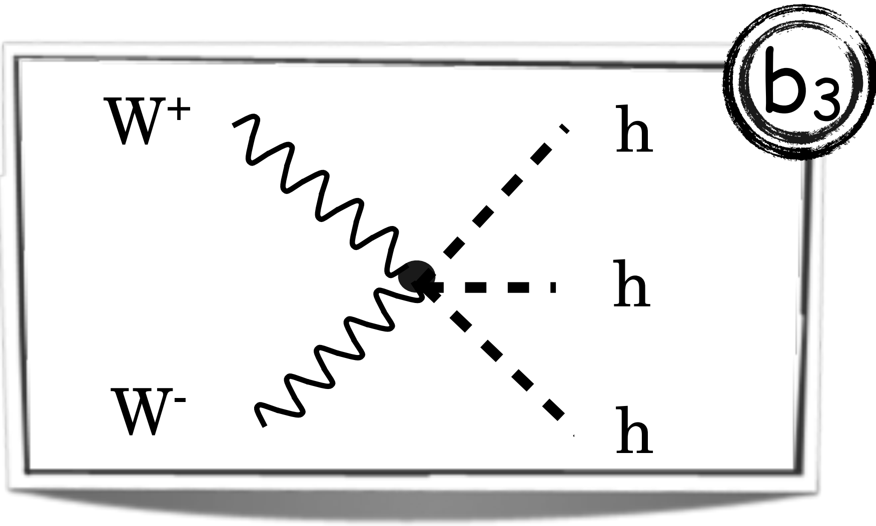

Contino, Grojean, Pappadopoulo,
Rattazzi, Thamm 'to appear

tests of Higgs non-linearities, can answer crucial questions:

- ☑ is the Higgs composite or elementary?
- ☑ is the EW sym. breaking sector strongly coupled?
- ☑ is the Higgs a doublet or a singlet (eg a dilaton): $b-1 = 2(a^2-1)$?
- ☑ is the Higgs a doublet or a singlet (eg a dilaton): $3b_3 = 4a(b-a^2)$?

require a new facility beyond current LHC

Which Higgs couplings?

often said that measurement of h^3 is a crucial to establish the Higgs mechanism

... beautiful dedicated studies HH→bbWW, bb$\gamma\gamma$

30% sensitivity @ HL-LHC, 20% @ ILC, 20% @CLIC

(possible improvement but using additional jet radiation)

Dolan, Englert, Spannowsky '12

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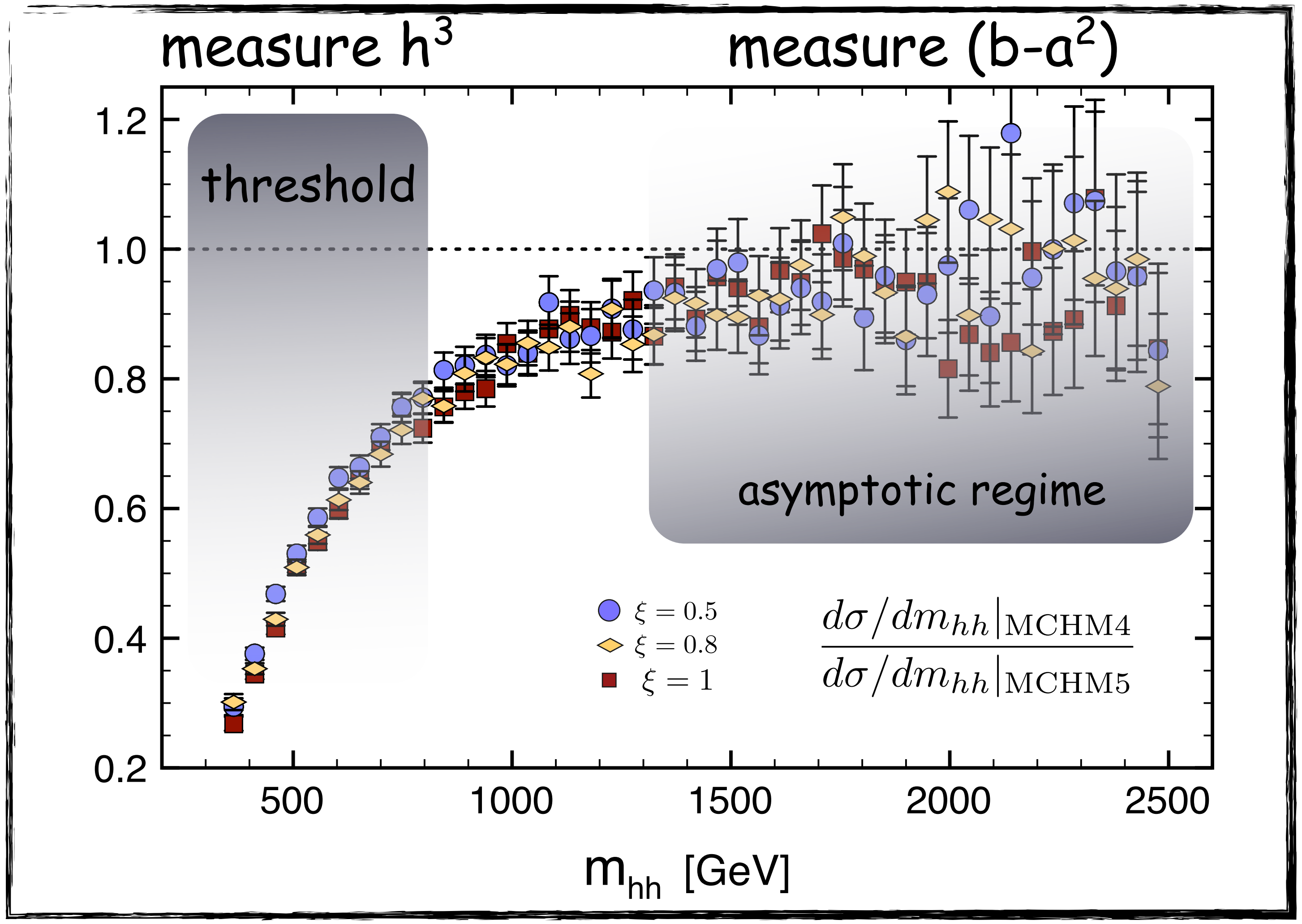
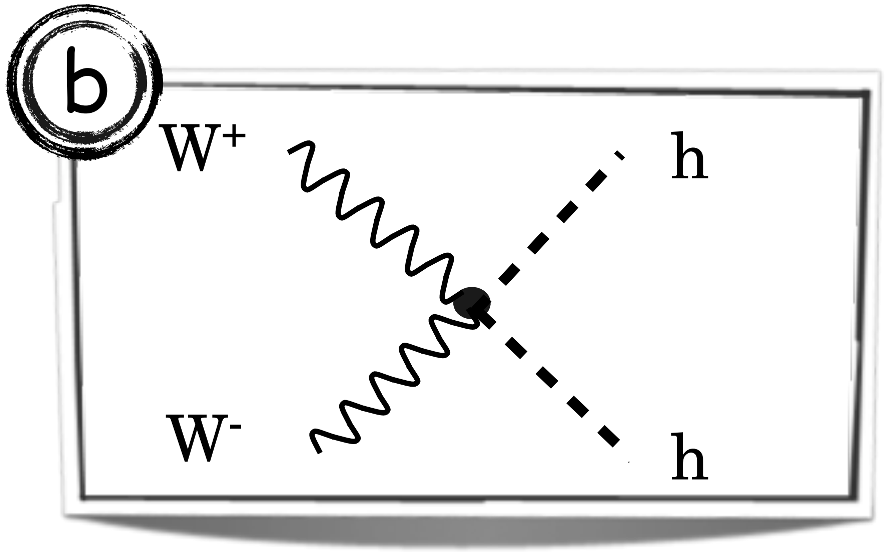
hh invariant mass distribution





non-standard "b" coupling could also modify the sensitivity on h^3

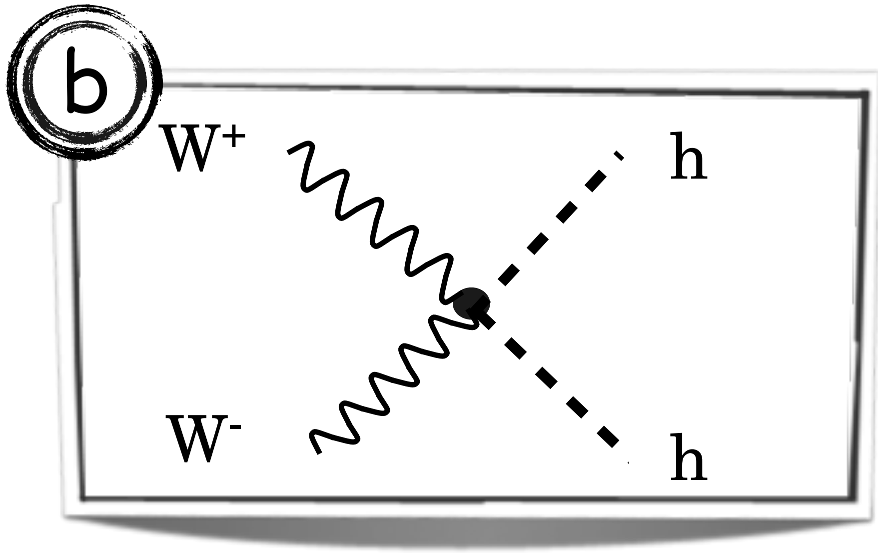
two models with
same asymptotic regime but
different higgs-self-coupling

Which Higgs couplings?

'b' is a high energy quantity:

question to address is very different than measurement of h^3.

Need LHC results to know which question to ask!



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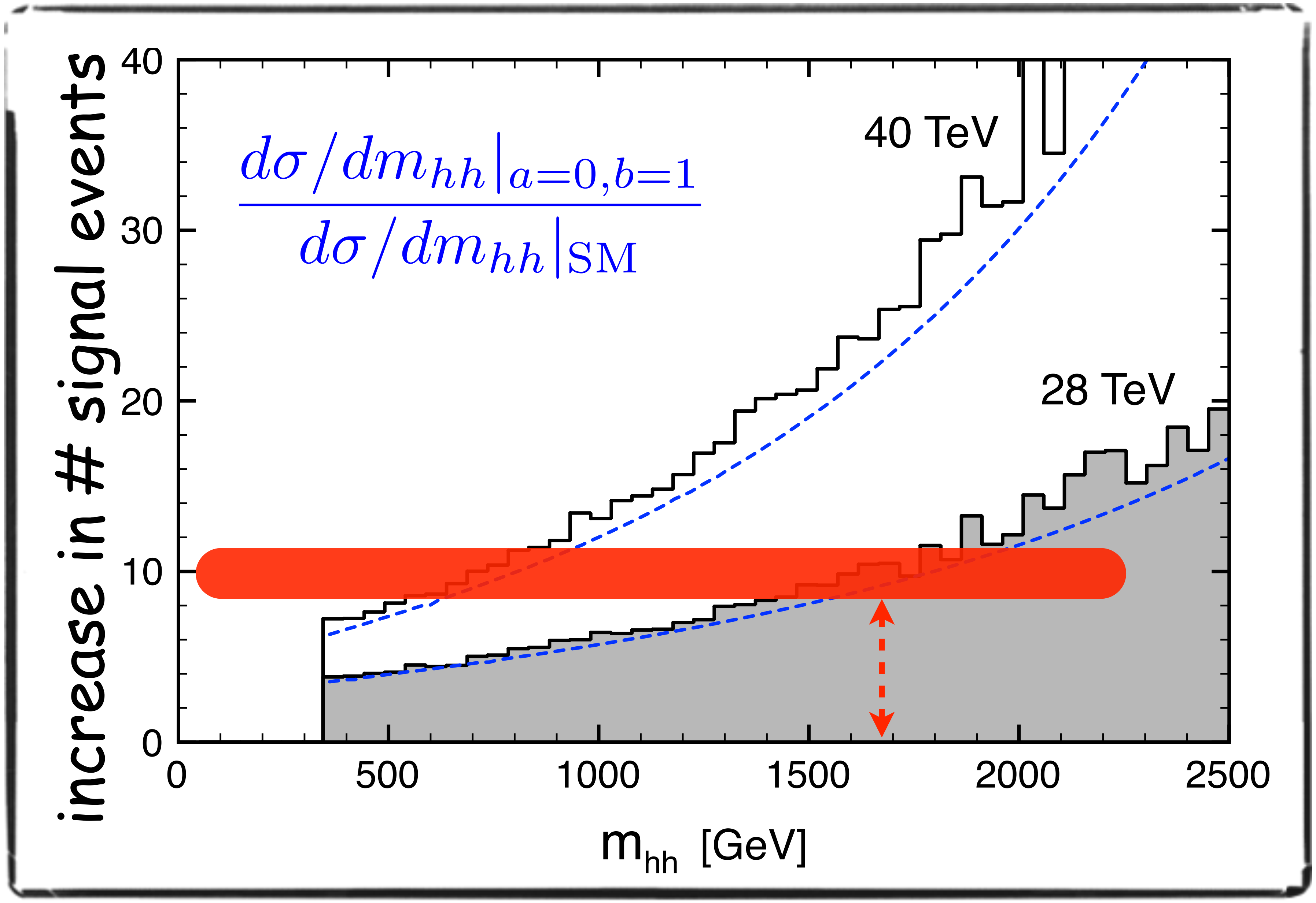
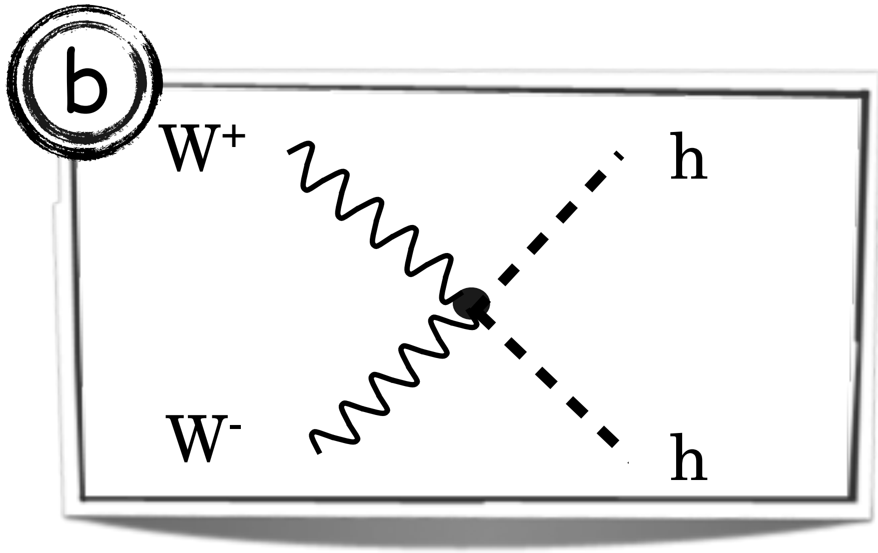




HL-LHC vs. HE-VLHC

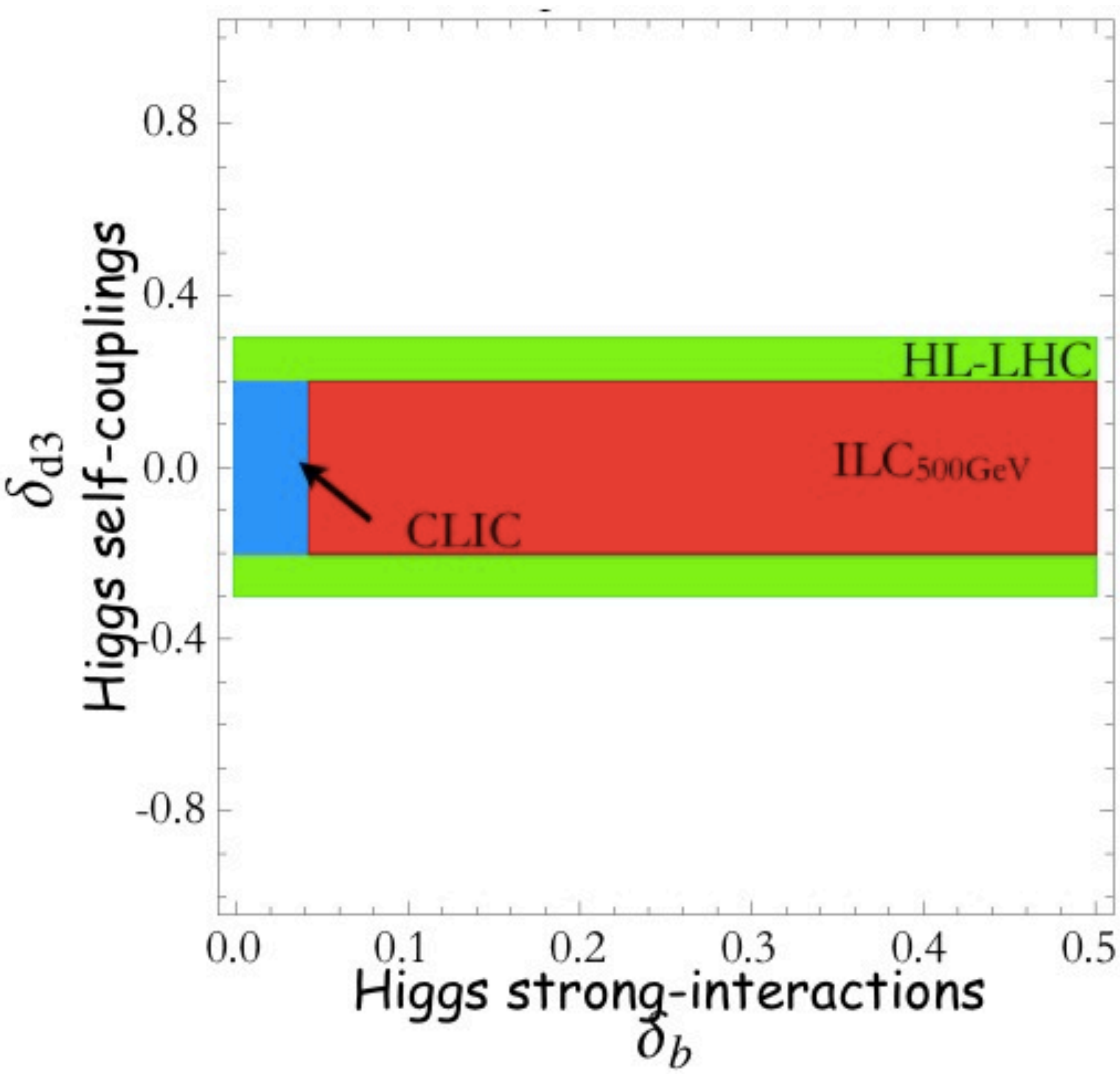
10 x lum ≈ 10 x events

2 x √s = 10 x events
iif m_{hh} > 1.6TeV

Which Higgs couplings?

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm 'in progress

$$\mathcal{L}_{\mathrm{EWSB}} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}\right) \qquad V(h) = \frac{1}{2}m_h^2h^2 + d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3$$



- HL-LHC has limited sensitivity on d_3 and b
- ILC has a some sensitivity on d_3 but none on b
- CLIC can probe both d_3 and b

Resolving sign ambiguities with ILC

LHC is totally insensitive to the relative sign
in the Higgs couplings to W and Z
Yet this sign is physical and enters in process with interference

Farina, Grojean, Salvioni '12

Resolving sign ambiguities with ILC

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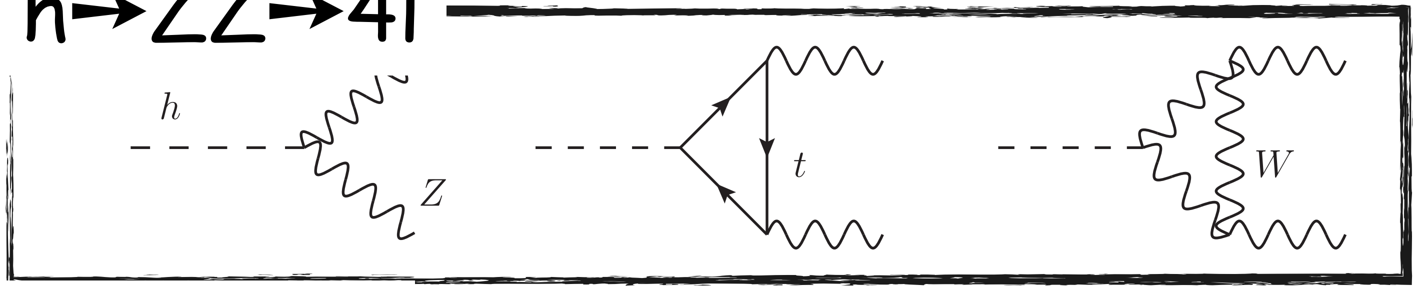
Farina, Grojean, Salvioni '12

discriminating power

ILC sensitivity
($\sqrt{s}$=800GeV and 1ab^{-1})

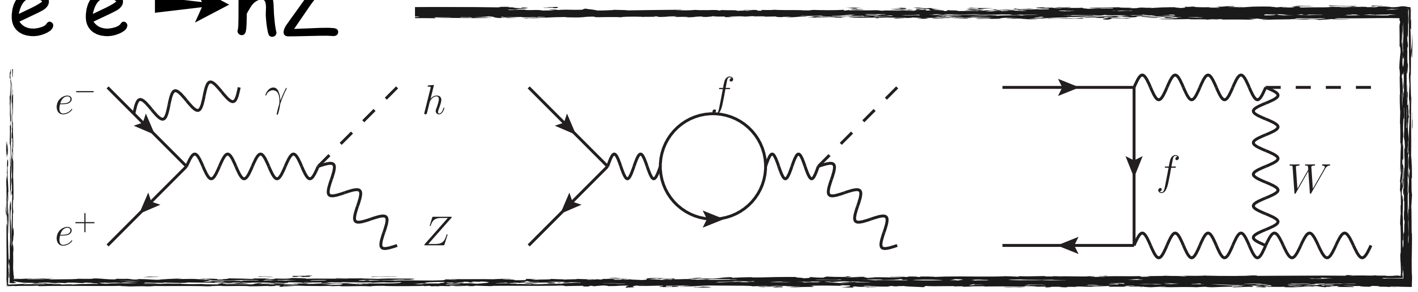
h→ZZ→4l



$$\Delta = \left|\frac{\Gamma_Z^+ - \Gamma_Z^-}{\Gamma_Z^+ + \Gamma_Z^-}\right| = \delta \approx 1\%$$

≈1% ☠

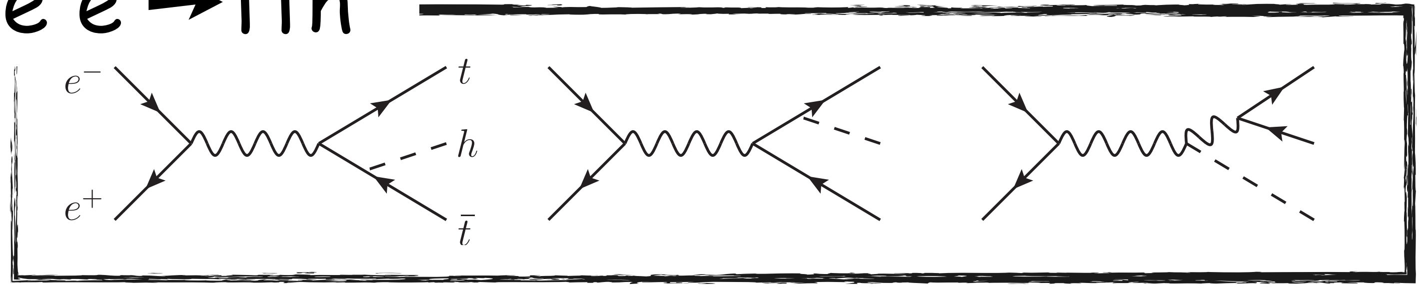
e⁺e⁻→hZ



$$\Delta = \left|\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}\right| \approx 15\%$$

≈5% ☺

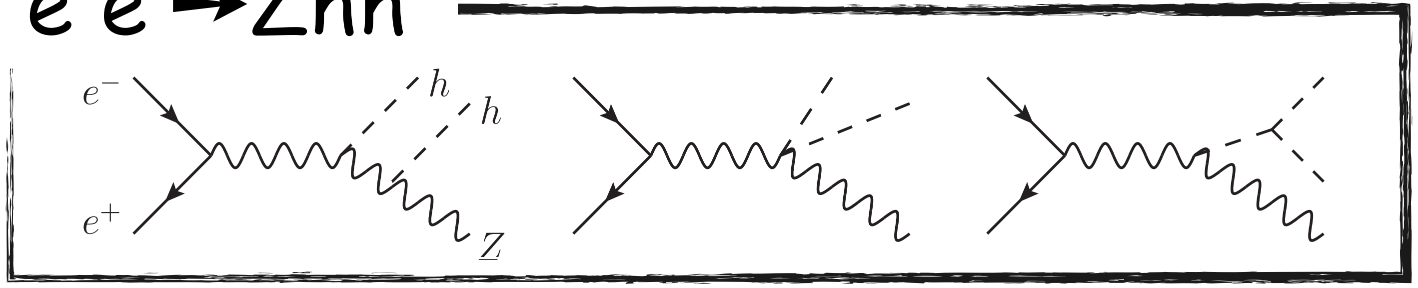
e⁺e⁻→tth



$$\Delta = \left|\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}\right| \lesssim 4\%$$

≈10% ☠

e⁺e⁻→Zhh



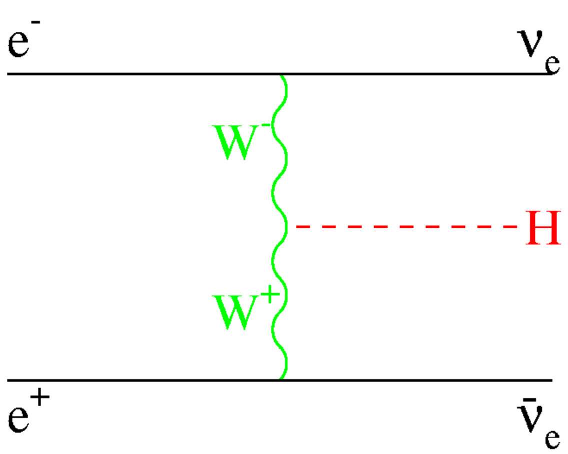
$$\Delta = \left|\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}\right| \approx 50\%$$

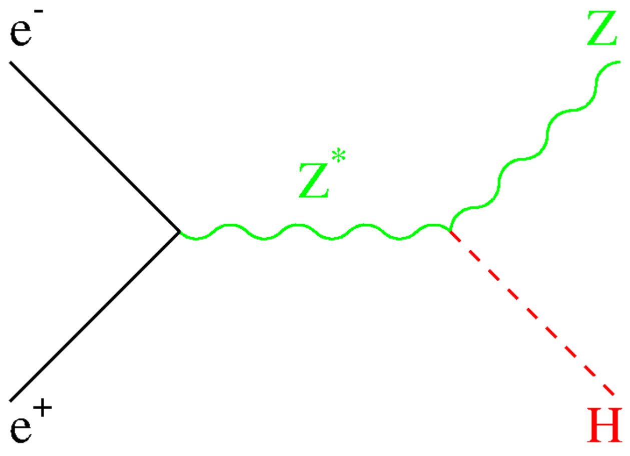
≈10% ☺
but can also be affected by deviations in h^3

Resolving sign ambiguities with LEP3

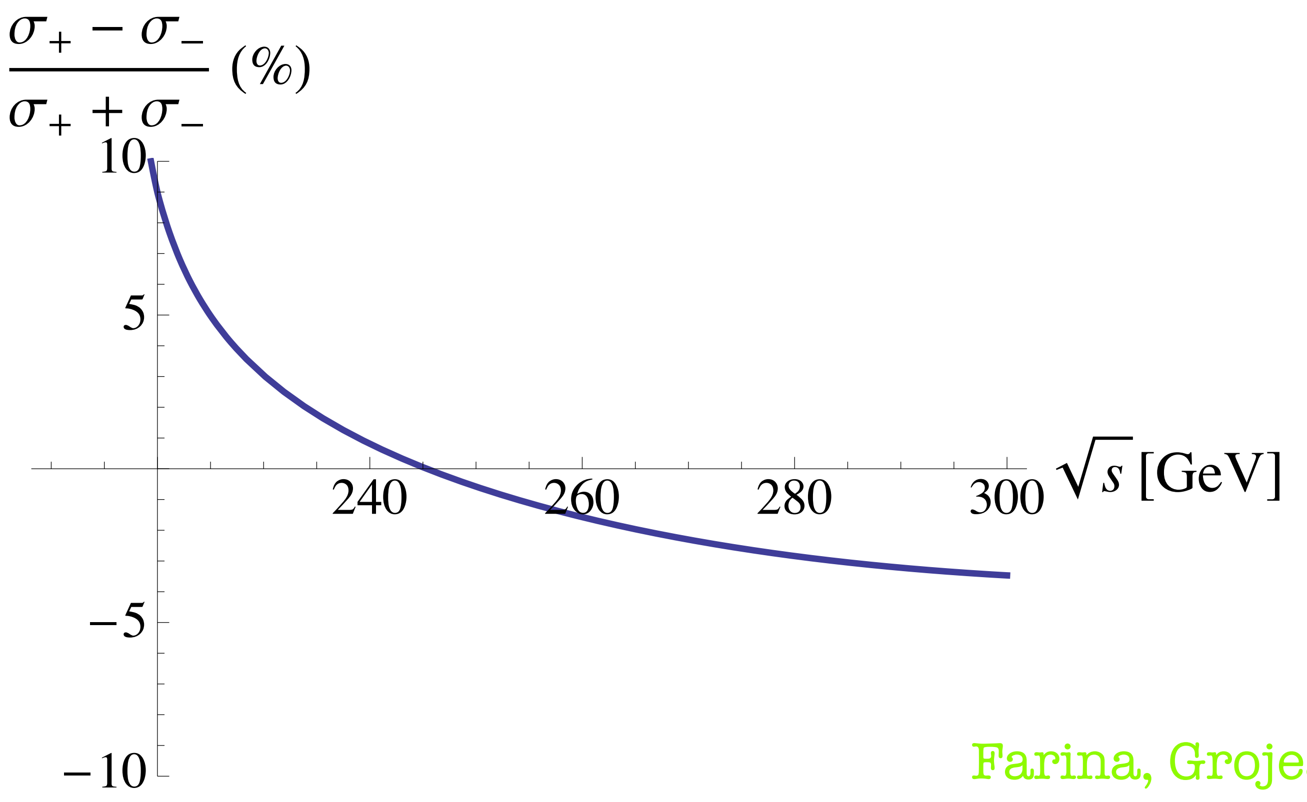
negative interference in SM

positive interference if the relative sign is flipped





relative increase
SM/opposite sign



LEP3 exp. sensitivity O(2-3%)

Farina, Grojean, Schmitt

BSM interpretation of deviations in Higgs couplings

New interactions
composite Higgs

New particles
e.g. a second Higgs

BSM interpretation of deviations in Higgs couplings

New interactions
composite Higgs

New particles
e.g. a second Higgs

- deviation δ_h
- no new state up to M

$$g_\rho > \sqrt{\delta_h}(M/v)$$

$g_\rho \sim 4$ $\quad \delta_h \sim 10\% \Rrightarrow M \sim 3\text{TeV}$
$\quad \delta_h \sim 1\% \Rrightarrow M \sim 10\text{TeV}$

(similar, but indirect, to an enhancement δ_h in WW scattering)

BSM interpretation of deviations in Higgs couplings

New interactions composite Higgs

- deviation δ_h
- no new state up to M

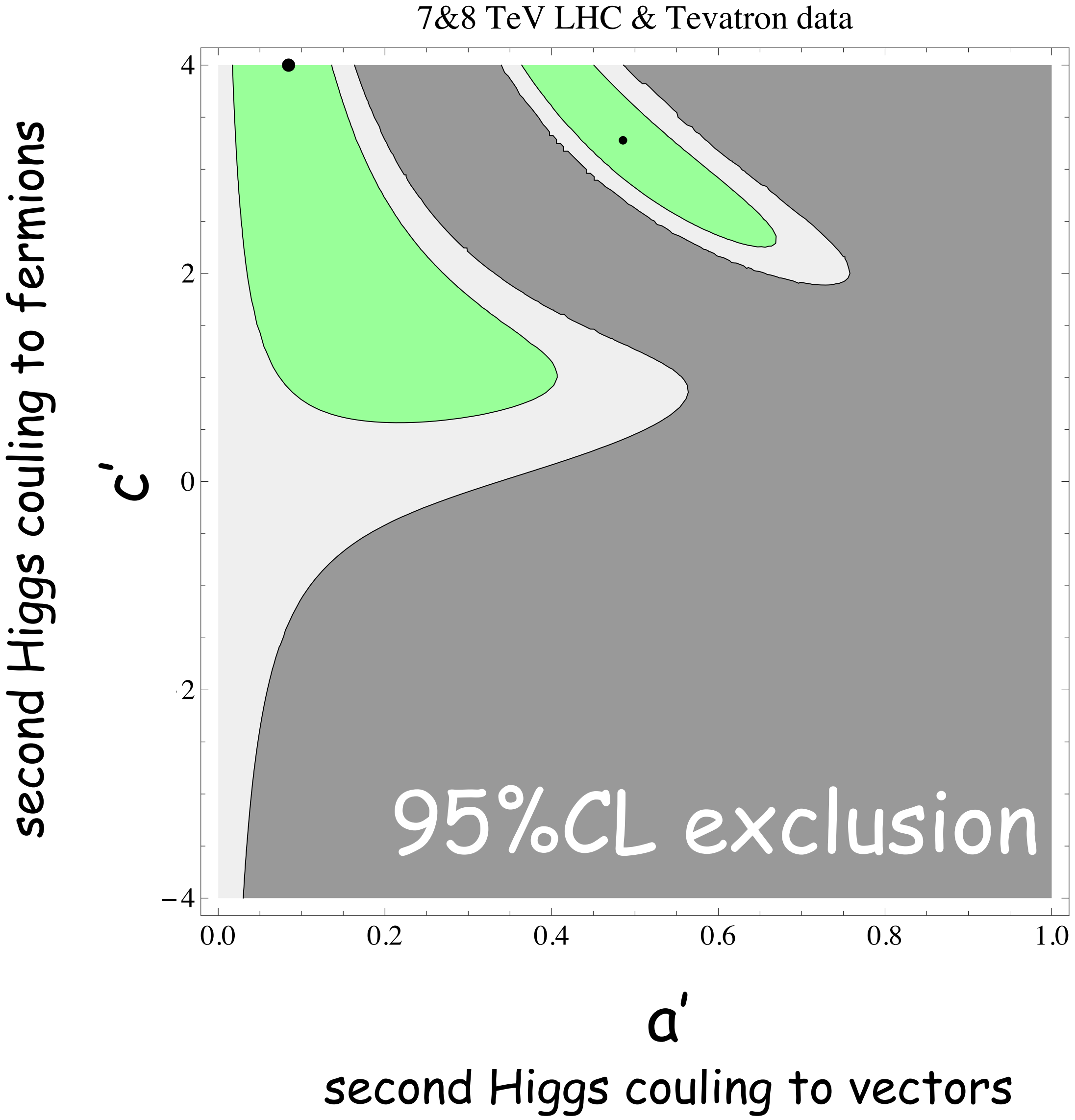
$$g_\rho > \sqrt{\delta_h}(M/v)$$

g_ρ~4 δ_h~10% ⇛ M~3TeV

δ_h~1% ⇛ M~10TeV

(similar, but indirect, to an enhancement δ_h in WW scattering)

New particles e.g. a second Higgs



Exotic Higgs(es)

Many production and decay modes have been studied...

- ☑ Fermiophobic Higgs
- ☑ Charged Higgs
- ☑ Doubly charged Higgs
- ☑ Higgs decaying to long lived particles
- ☑ Higgs decaying to light pseudo-scalar particles
- ☑ Higgs flavor changing decays
- ☑...

... so far only the searches for the SM Higgs have successfully observed a clear signal

LHC2TSP WG1

Triple gauge boson couplings @ LC

$$\mathcal{L}_V = -ig\cos\theta_W g_1^Z Z^\mu \left(W^{+\nu}W^-_{\mu\nu} - W^{-\nu}W^+_{\mu\nu}\right) - ig\left(\cos\theta_W \kappa_Z Z^{\mu\nu} + \sin\theta_W \kappa_\gamma F^{\mu\nu}\right) W^+_\mu W^-_\nu$$

TGC are generated by heavy resonances

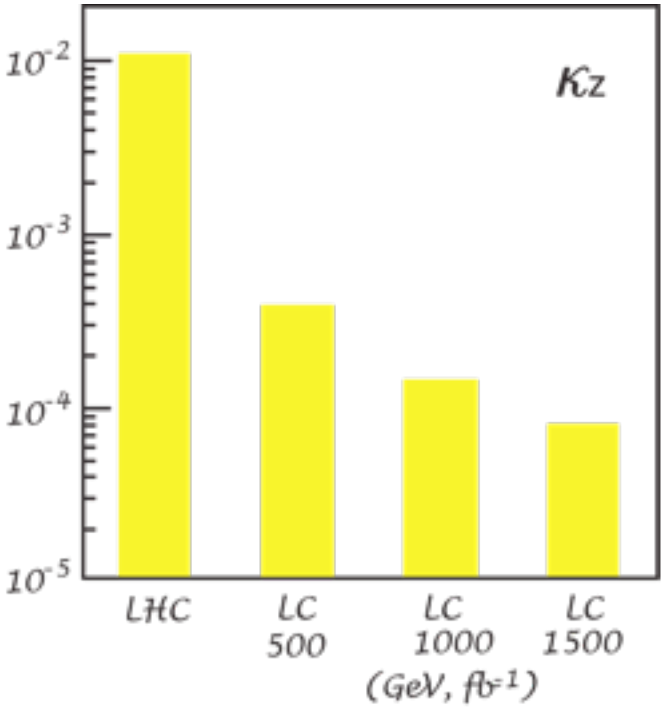
$$g_1^Z = \frac{m_Z^2}{m_\rho^2} c_W \qquad \kappa_\gamma = \frac{m_W^2}{m_\rho^2}\left(\frac{g_\rho}{4\pi}\right)^2 (c_{HW} + c_{HB}) \qquad \kappa_Z = g_1^Z - \kappa_\gamma \tan^2\theta_W$$

@ LHC$_{100/fb}$ $g_1^Z \sim 1\%$ $\kappa_\gamma \sim \kappa_Z \sim 5\%$

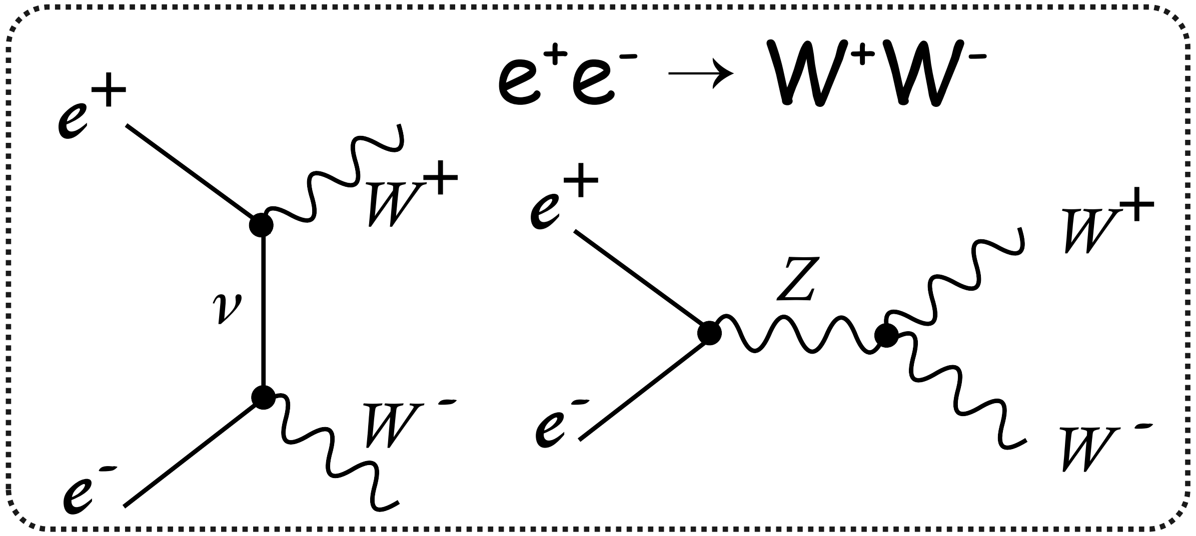
sensitive to resonance
up to m$_\rho$~800 GeV

not competitive with the measure of S at LEPII

@ ILC



$e^+e^- \rightarrow W^+W^-$



0.1‰ accuracy $\Rightarrow$ sensitive to resonance
up to m$_\rho$~8TeV

T. Abe et al, Snowmass '01

Probing strong WW scattering

Without a Higgs, $V_L V_L$ scattering amplitudes are growing with E^2
can this growth be seen?

Beautiful dedicated studies based on higgsless EW chiral Lagrangian

$$\begin{aligned}\mathcal{L}_4 &= \ell_4(\frac{v}{\Lambda})^2[\mathrm{Tr}(\mathcal{V}_\mu \mathcal{V}_\nu)]^2 \\ \mathcal{L}_5 &= \ell_5(\frac{v}{\Lambda})^2[\mathrm{Tr}(\mathcal{V}_\mu \mathcal{V}^\mu)]^2\end{aligned}$$

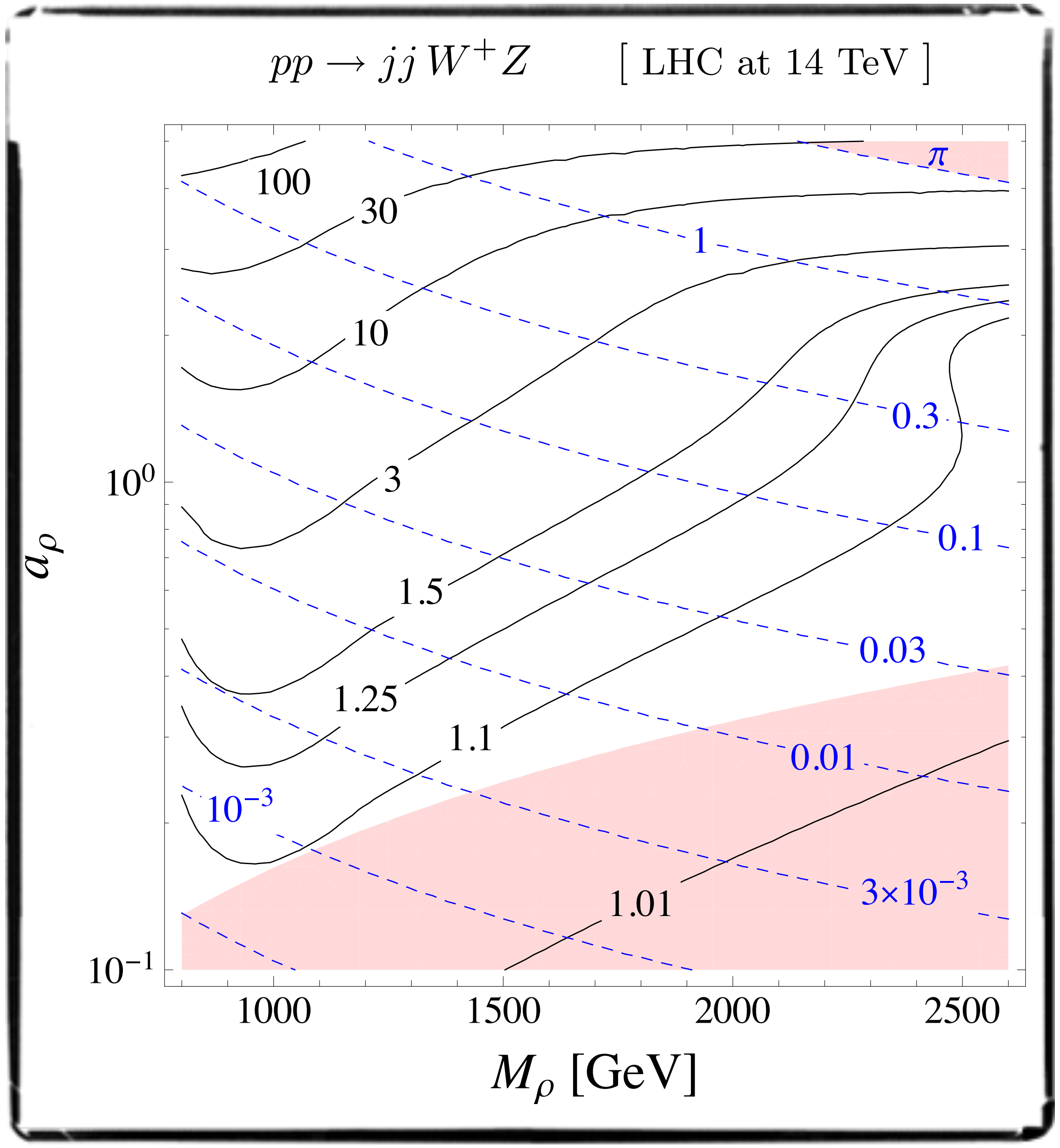
$$\mathcal{V}_\mu \equiv (D_\mu U)U^\dagger$$

HL-LHC sensitivity in the “interesting” region, ie compatible with EW data

but we need to rethink this question since we have a “Higgs” which certainly partially cancels the growth of the scattering amplitudes, making the observation more difficult

Resonances Effects in WW Scattering

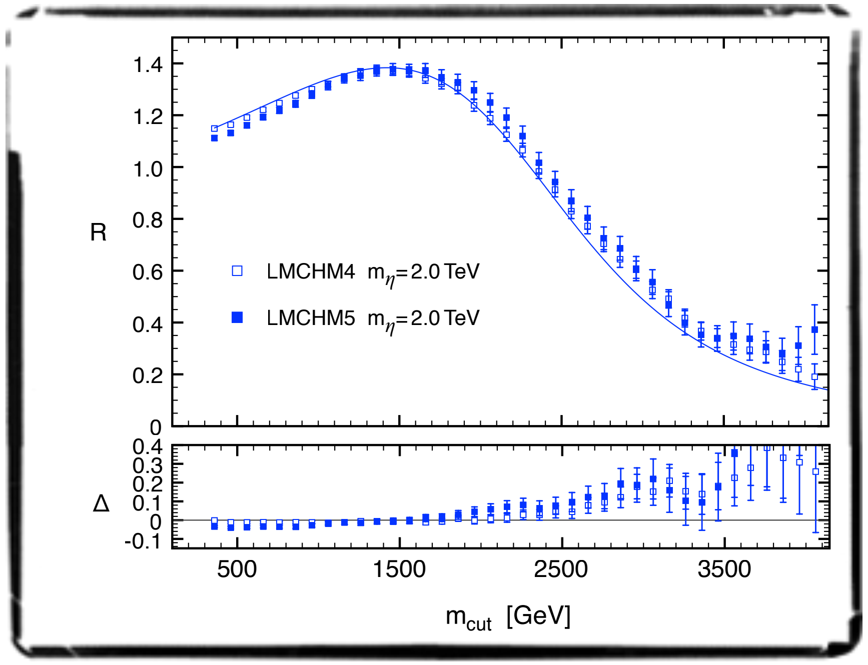
Contino, Marzocca, Pappadopulo, Rattazzi '11



$\xi = 0.5$

$m_{\text{cut}} = 800\,\text{GeV}$

$R = \frac{\sigma(\rho_L)}{\sigma(\text{LET})}$ $\frac{\Gamma_{\rho_L}}{m_{\rho_L}}$



channel complementary
to pin down the nature of the resonance

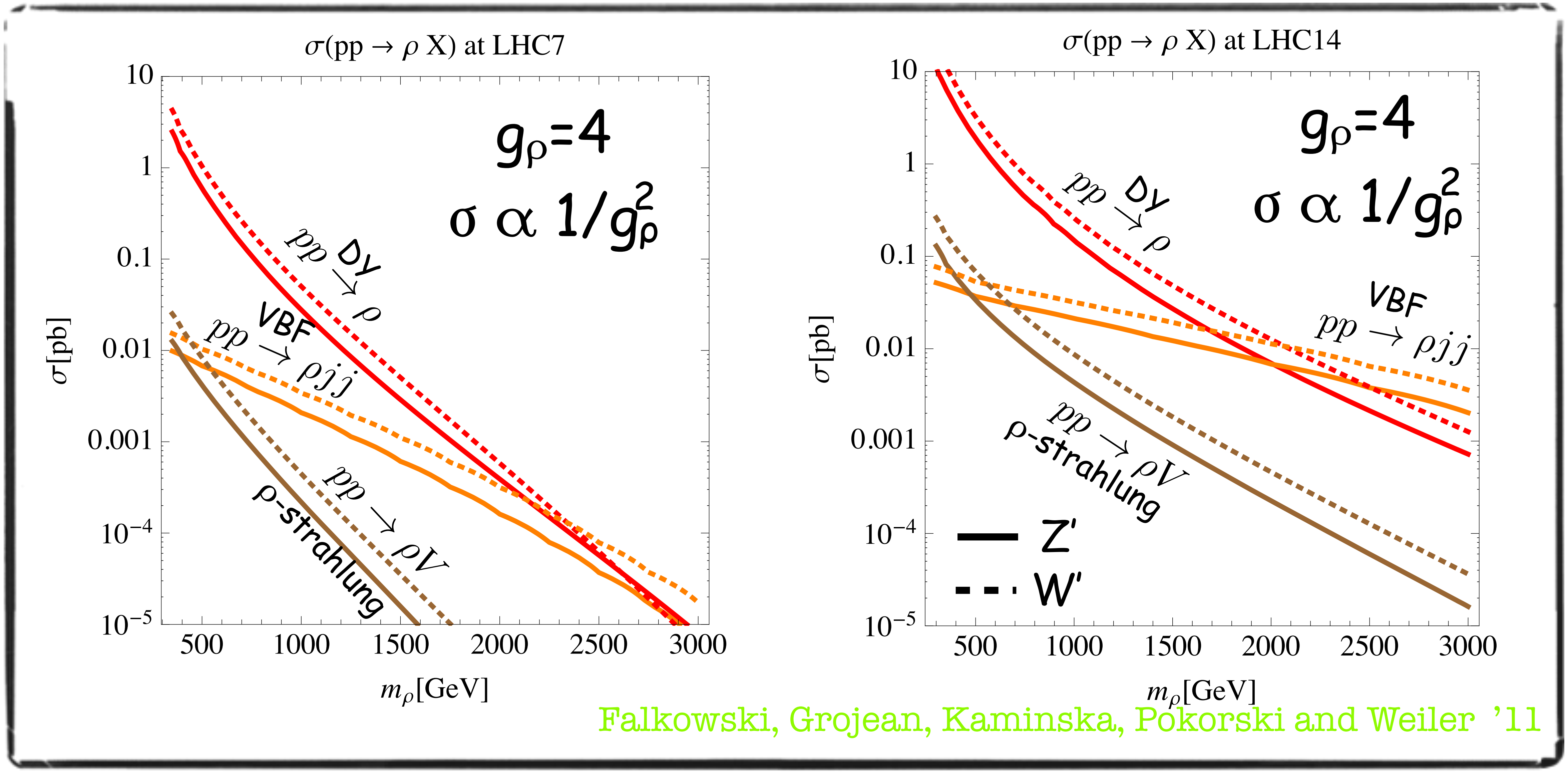
		W^+W^-	W^+Z	W^+W^+	hh
ρ	(1,3)	↑	↑	↓	↓
η	(1,1)	↑	↓	↓	↑
Δ	(3,3)	↑	↑	↑	↑

Difficult measurements: Precision physics

- ☑ @ high energy
- ☑ need performant forward tagging efficiencies
- ☑ fight large pile-up...

Resonance Searches: di-boson final states

Observing a tower of resonances would a direct evidence of the strong interactions
However, in the best configuration, LHC will have access to a few ones only



Falkowski, Grojean, Kaminska, Pokorski and Weiler '11

VBF vs. DY:

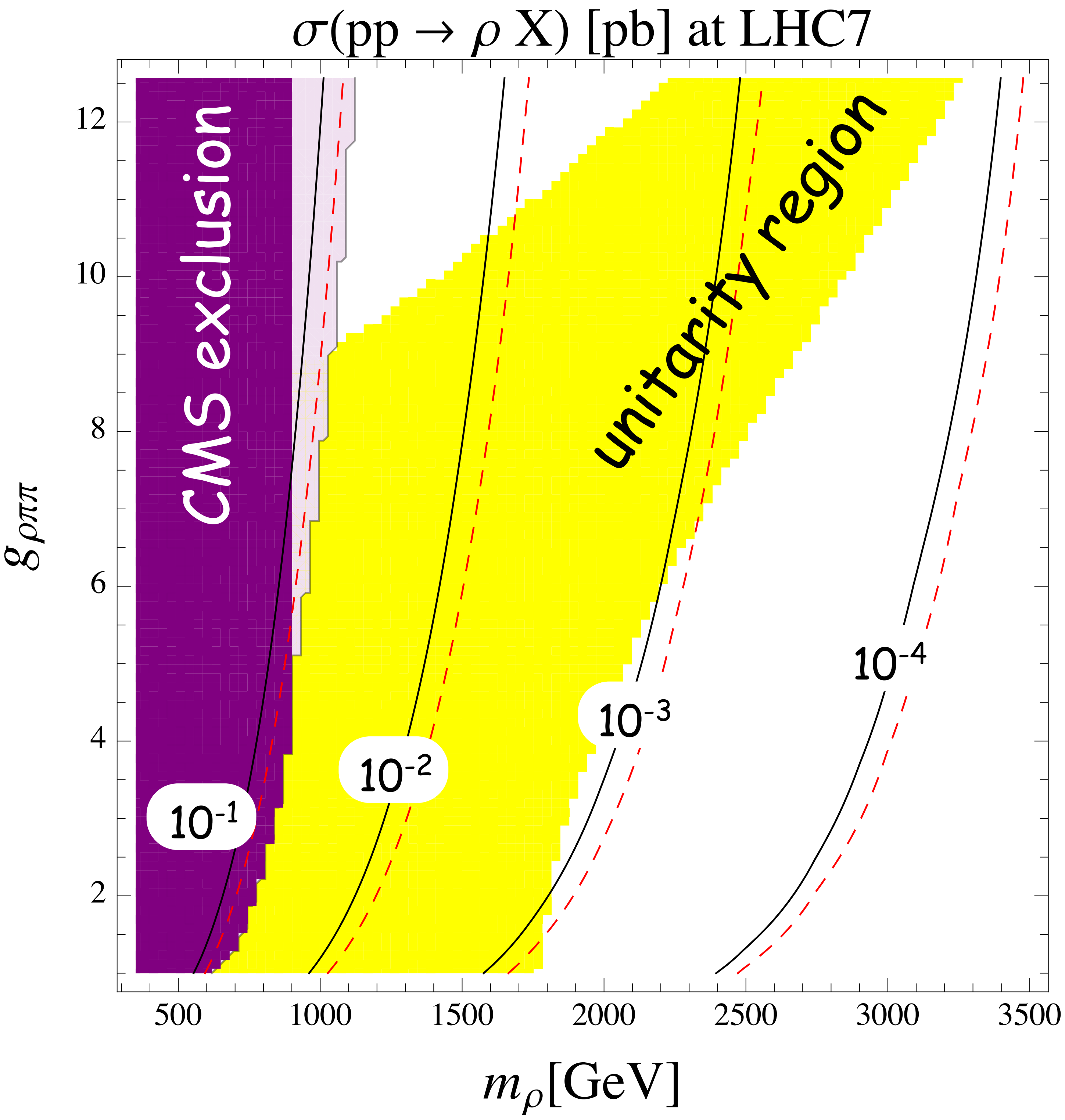
- 3-body final state
- qq initiated process ⇨ PDFs become more dominant at large x

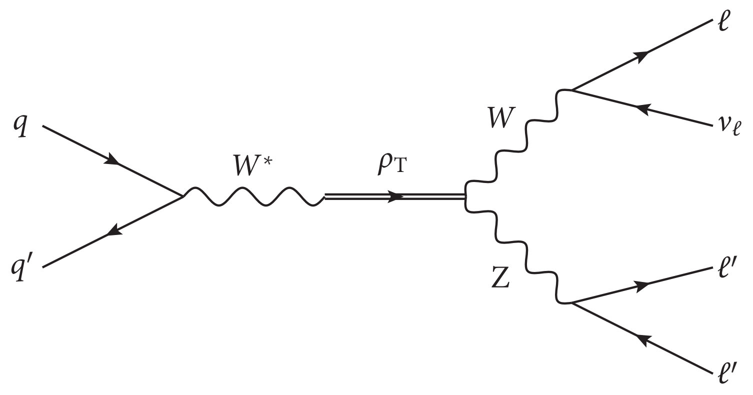
(NB: DY can be enhanced by larger direct couplings of resonances to light quarks but severe dijet constraints)

Resonance Searches

Falkowski, Grojean, Kaminska, Pokorski and Weiler ’11

higgsless setup





- Current best limits from the 1fb^{-1} CMS search for WZ resonances

CSM-PAS-EXO-11-041

- D0 search for WW and WZ resonances gives weaker bounds

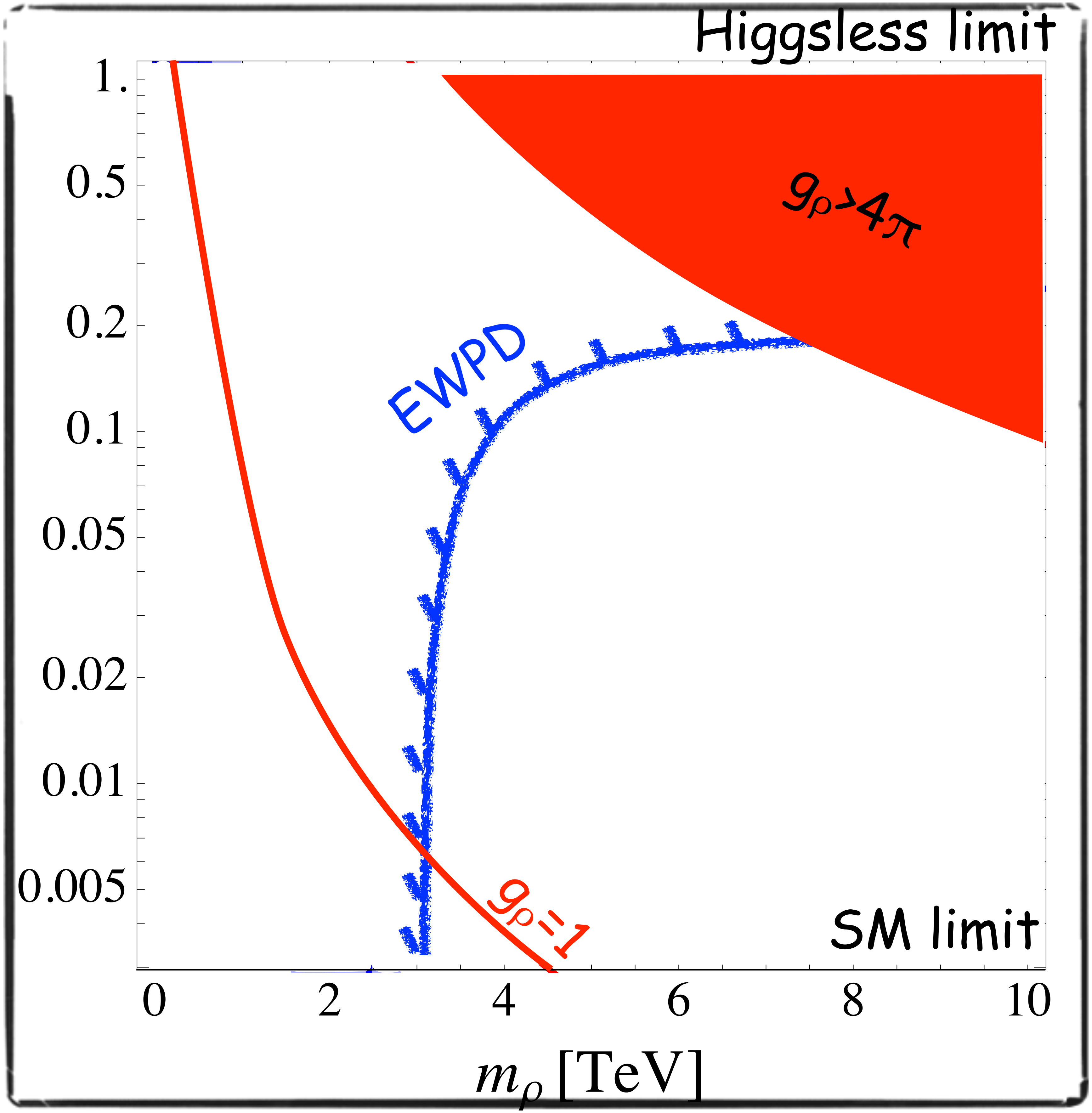
Abazov et al, ’10

- LHC limits on leptonic Z’ and W’ resonances are not competitive because of the small leptonic branching fraction

Resonance Searches vs Indirect Probes

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm ‘in progress

$$\left(\frac{\text{weak scale}}{\text{strong scale}}\right)^2 = \xi$$



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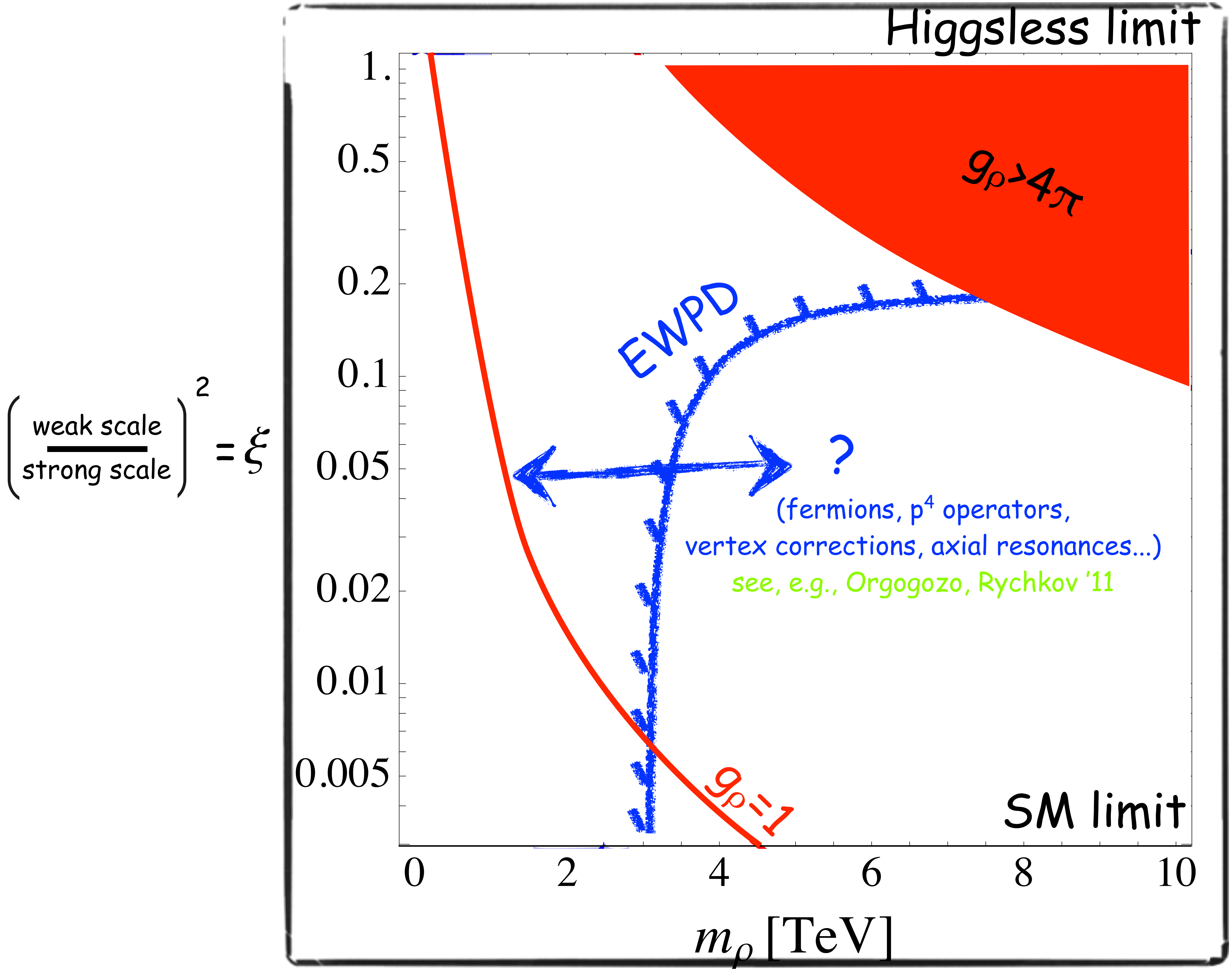

Resonance Searches vs Indirect Probes

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Strong WW scattering

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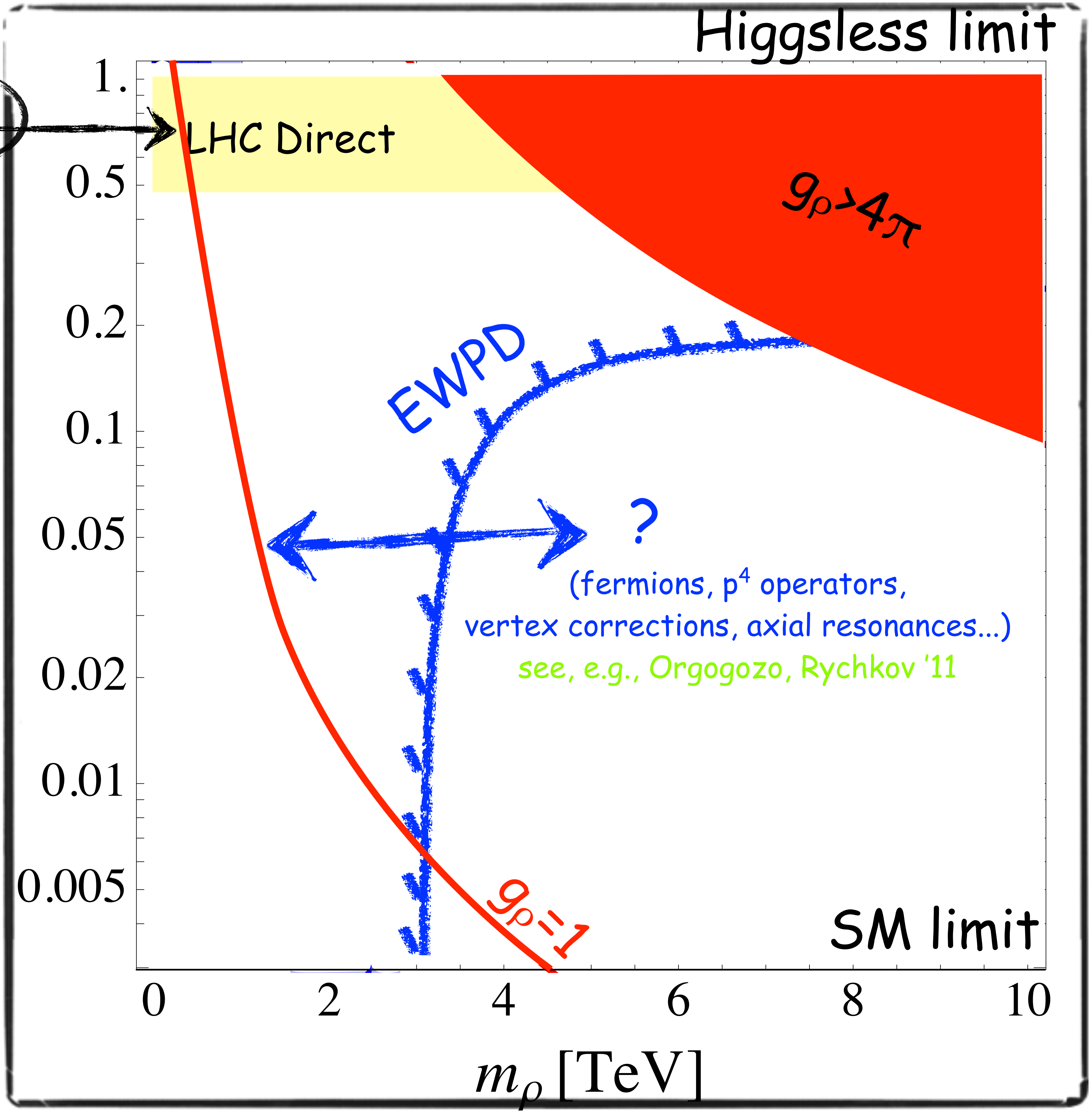

(fermions, p^4 operators, vertex corrections, axial resonances...)

see, e.g., Orgogozo, Rychkov '11

Resonance Searches vs Indirect Probes

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm 'in progress

Strong WW scattering

Anomalous Higgs couplings

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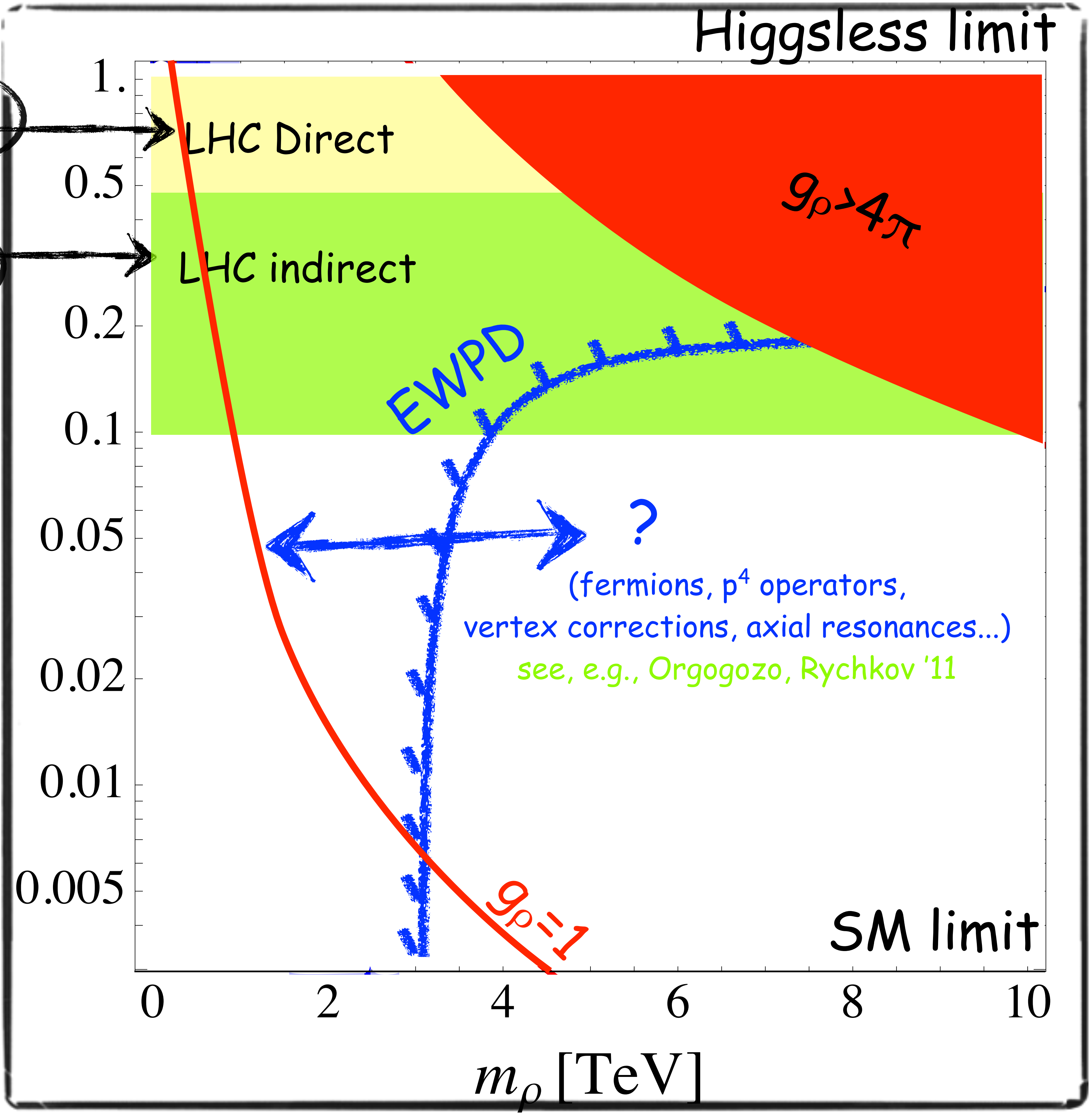

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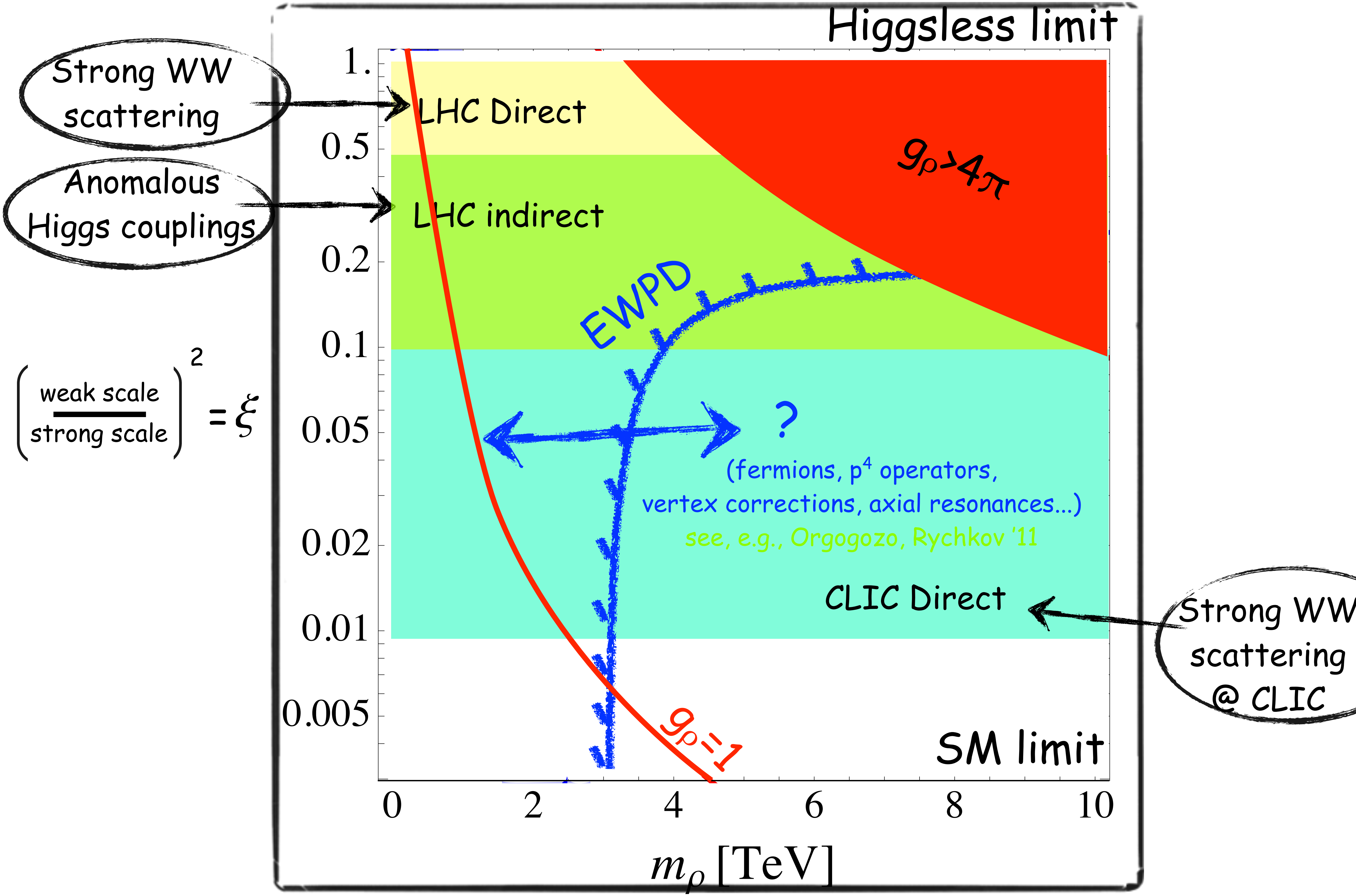

Strong WW scattering

Anomalous Higgs couplings

$$\left(\frac{\text{weak scale}}{\text{strong scale}}\right)^2 = \xi$$

Strong WW scattering @ CLIC

Resonance Searches vs Indirect Probes

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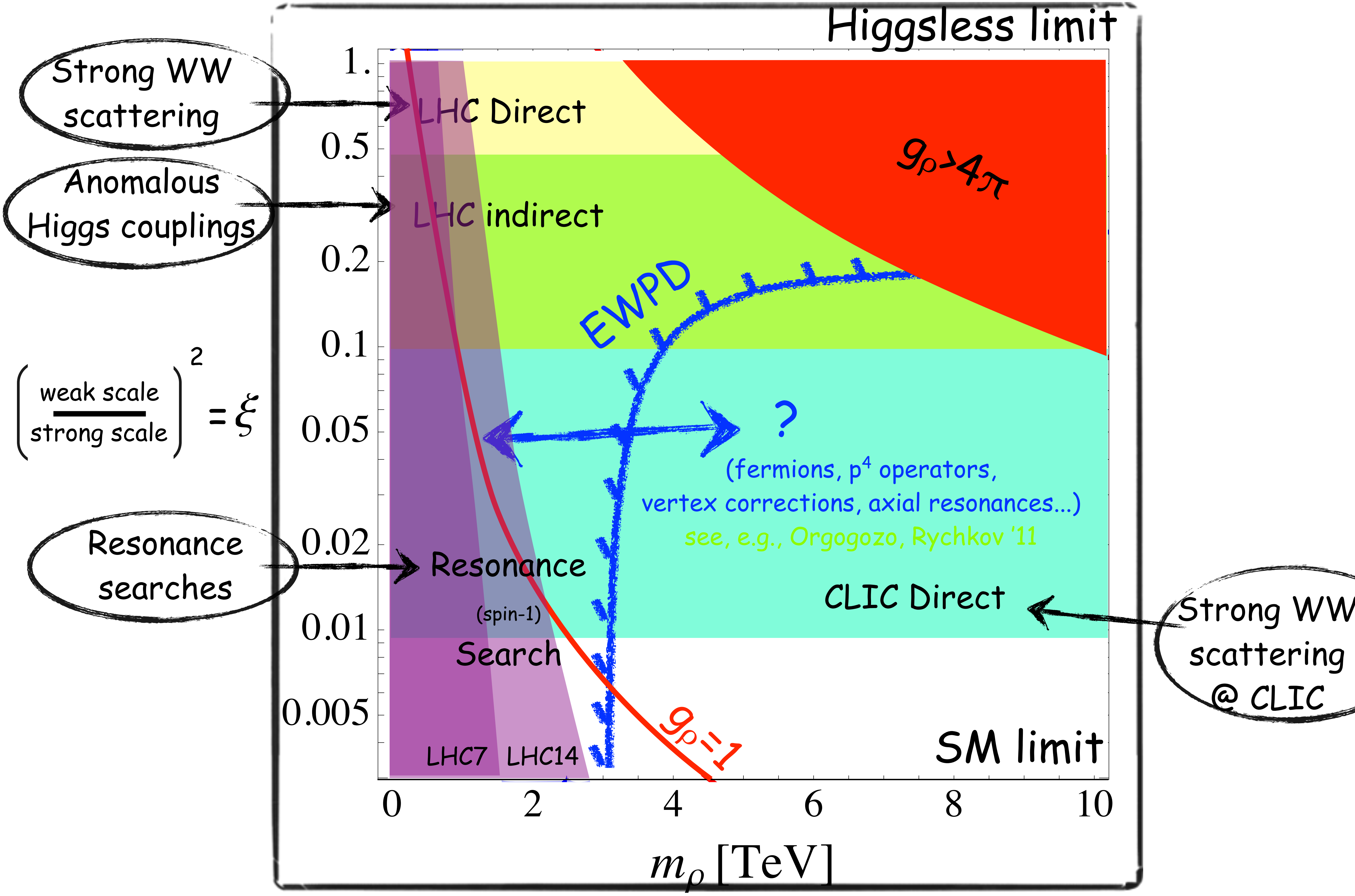

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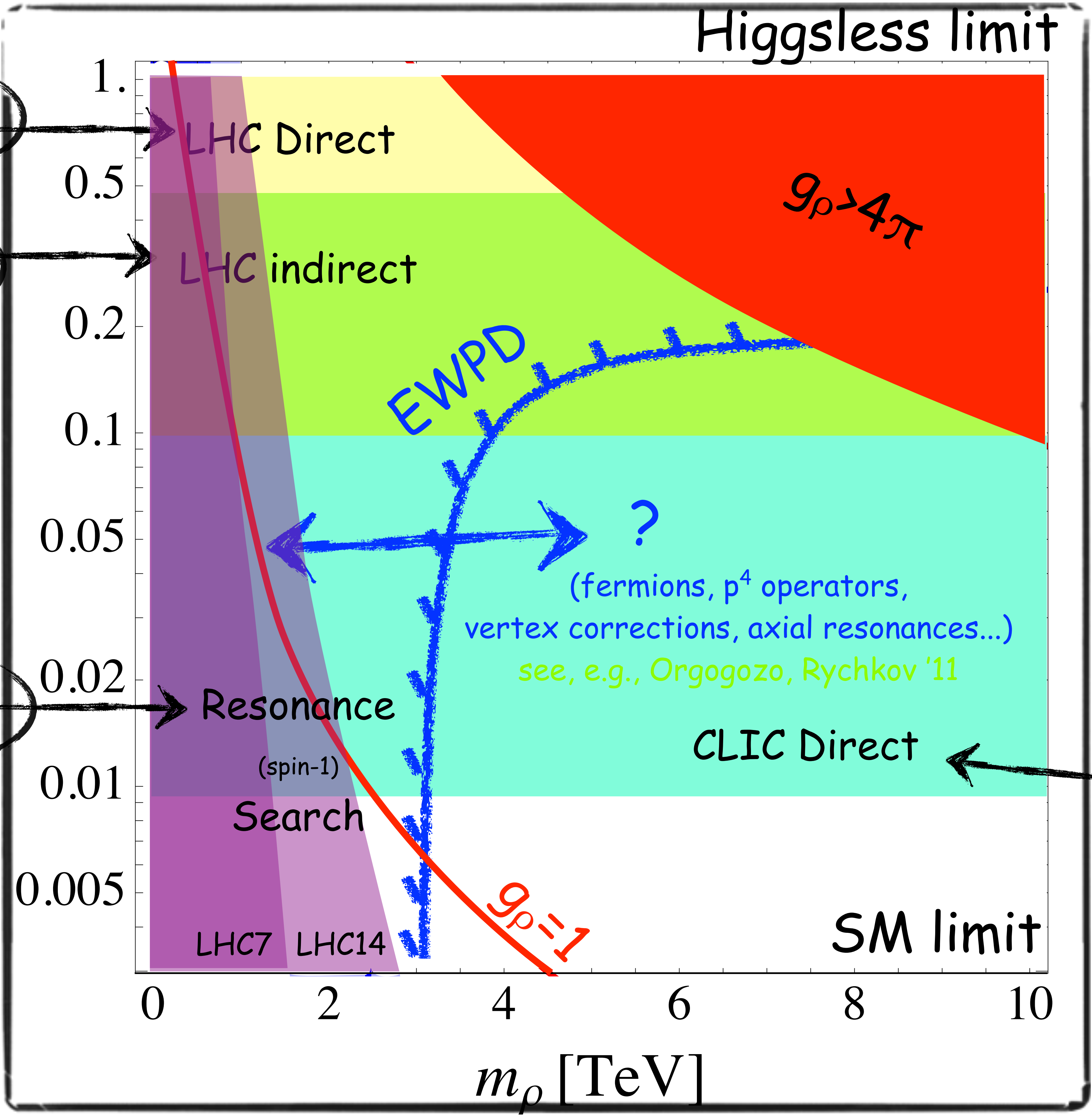

Strong WW scattering

Anomalous Higgs couplings

$$\left(\frac{\text{weak scale}}{\text{strong scale}}\right)^2 = \xi$$

Resonance searches

Strong WW scattering @ CLIC

NB:
the lower the scale of strong interaction, the more difficult to see resonances
(broader resonances & weaker couplings to light SM quarks)

Outline

① Higgs sector

- Theory implications
- Higgs quantum numbers
- Higgs couplings

② Direct searches

- SUSY
- Exotics

Disclaimer:
I won't have time to cover many interesting things
(top, xdim, blackholes...).

Higgs & SUSY/MSSM

no new super-particles ⇢ decoupling limit?

$$m_h^2 \;=\; M_Z^2 \cos^2 2\beta + \delta_t^2$$

Higgs & SUSY/MSSM

no new super-particles ⇢ decoupling limit?

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$\swarrow$

(125 GeV)^2

Higgs & SUSY/MSSM

no new super-particles ⇢ decoupling limit?

$$m_h^2 = M_Z^2 \cos^2 2\beta + \delta_t^2$$

(125 GeV)^2

($\geq$ 87GeV)^2

substantial loop contribution
from stops

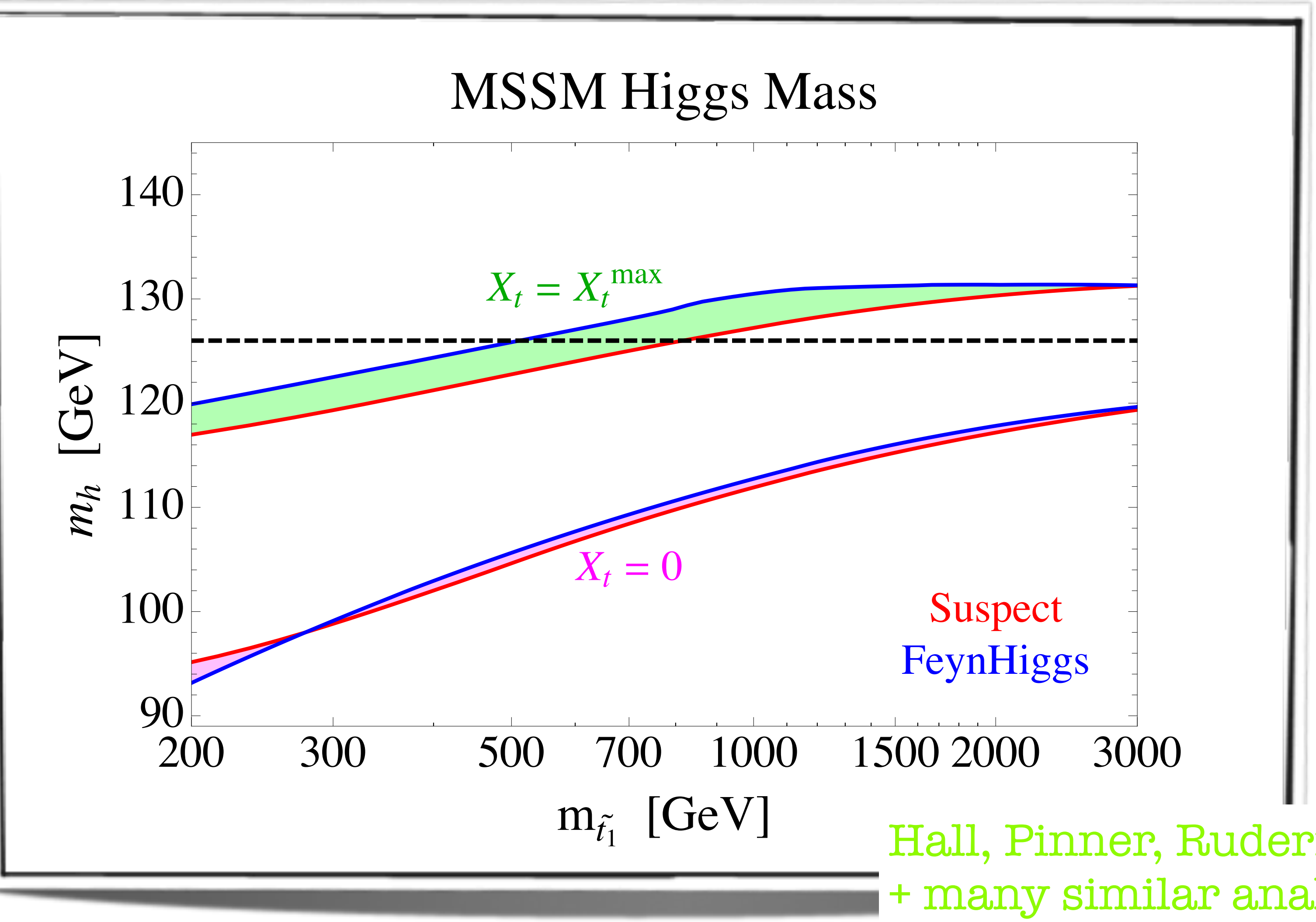
Higgs & SUSY/MSSM

no new super-particles ⇢ decoupling limit?

$$m_h^2 = M_Z^2 \cos^2 2\beta + \delta_t^2$$

$(125\ \text{GeV})^2$ $(\gtrsim 87\text{GeV})^2$

substantial loop contribution
from stops



Hall, Pinner, Ruderman '11
+ many similar analysse

large mixing
heavy stops

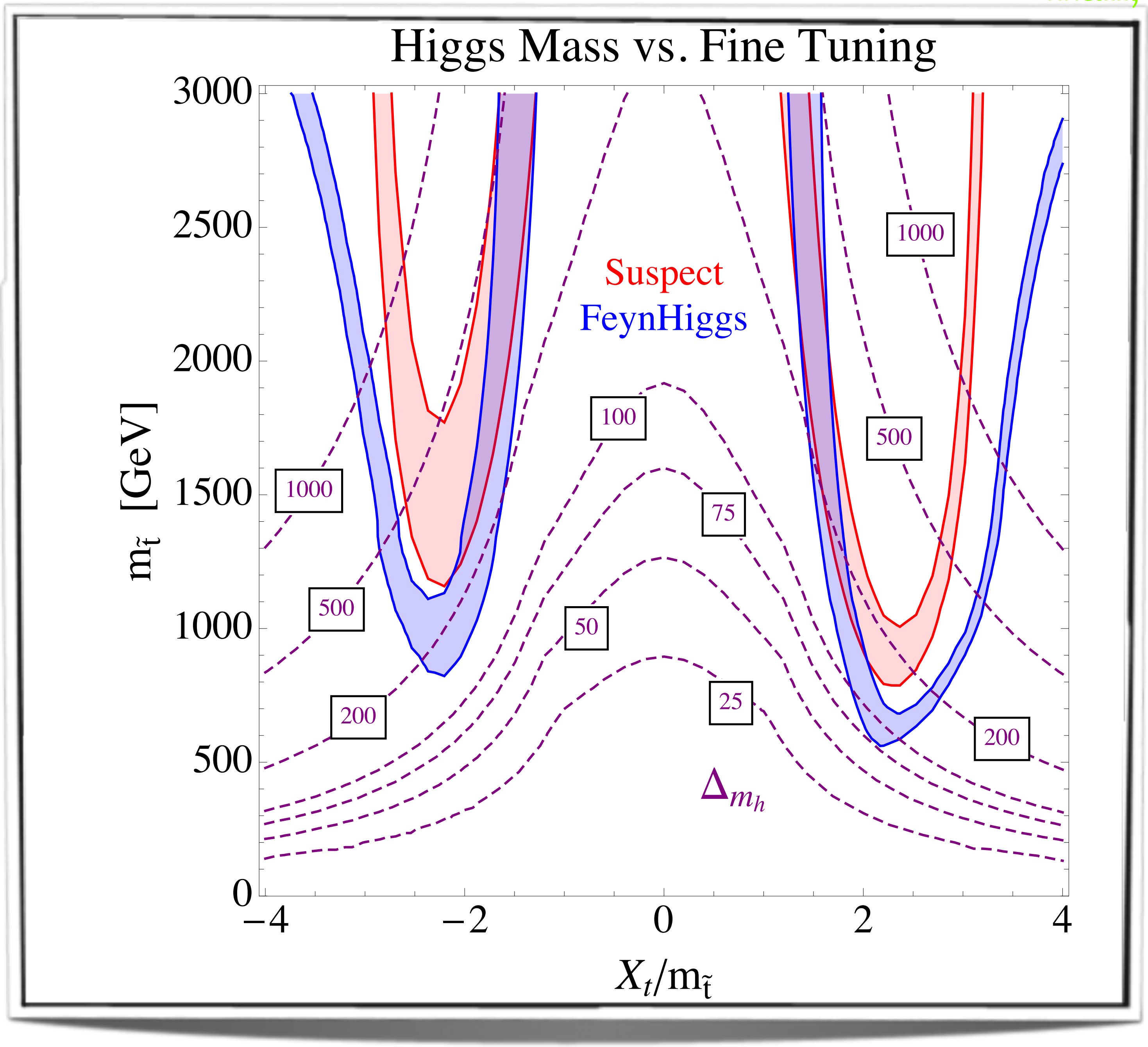
$$\sqrt{m_{Q_3} m_{u_3}} \gtrsim 700\ \text{GeV}$$

$\Downarrow$ $\Downarrow$

irreducible
fine-tuning ~ O(1%)

MSSM fine-tuning

Hall, Pinner, Ruderman '11



maximal mixing requires engineering

$$m_{\tilde{t}}^2(M_Z) \simeq 5.0 M_3^2(M_G) + 0.6 m_{\tilde{t}}^2(M_G)$$
$$A_t(M_Z) \simeq -2.3 M_3(M_G) + 0.2 A_t(M_G)$$

⇢ generically $|A_t/m_{\tilde{t}}| \leq 1$

Fermisek, Kim '06

Natural SUSY

SUSY fine-tuning troubles originate from

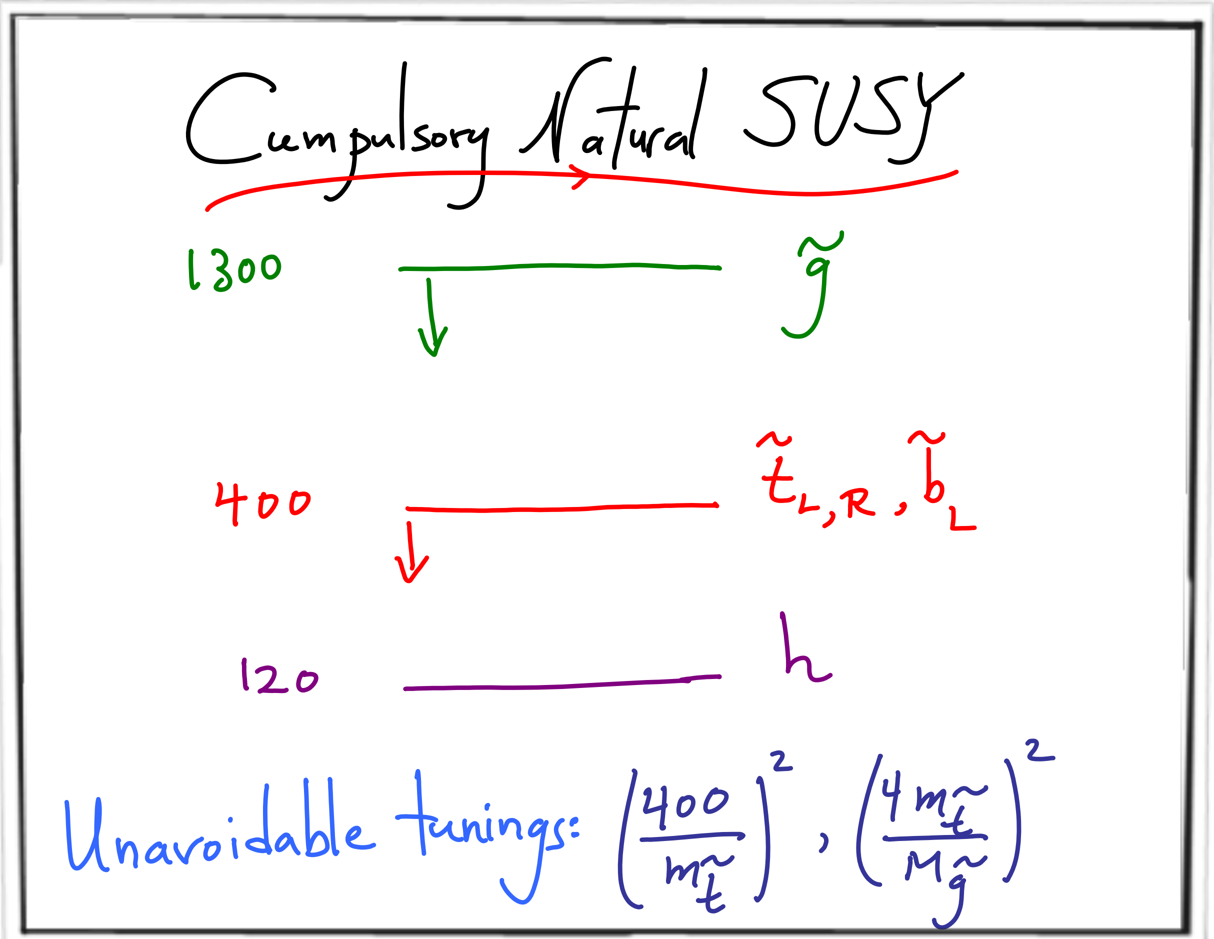
LHC2TSP WG2

$$-\frac{m_Z^2}{2} = |\mu|^2 + m_{H_u}^2$$

light higgsinos

light stops (1-loop)
light gluinos (2-loops)

ATLAS



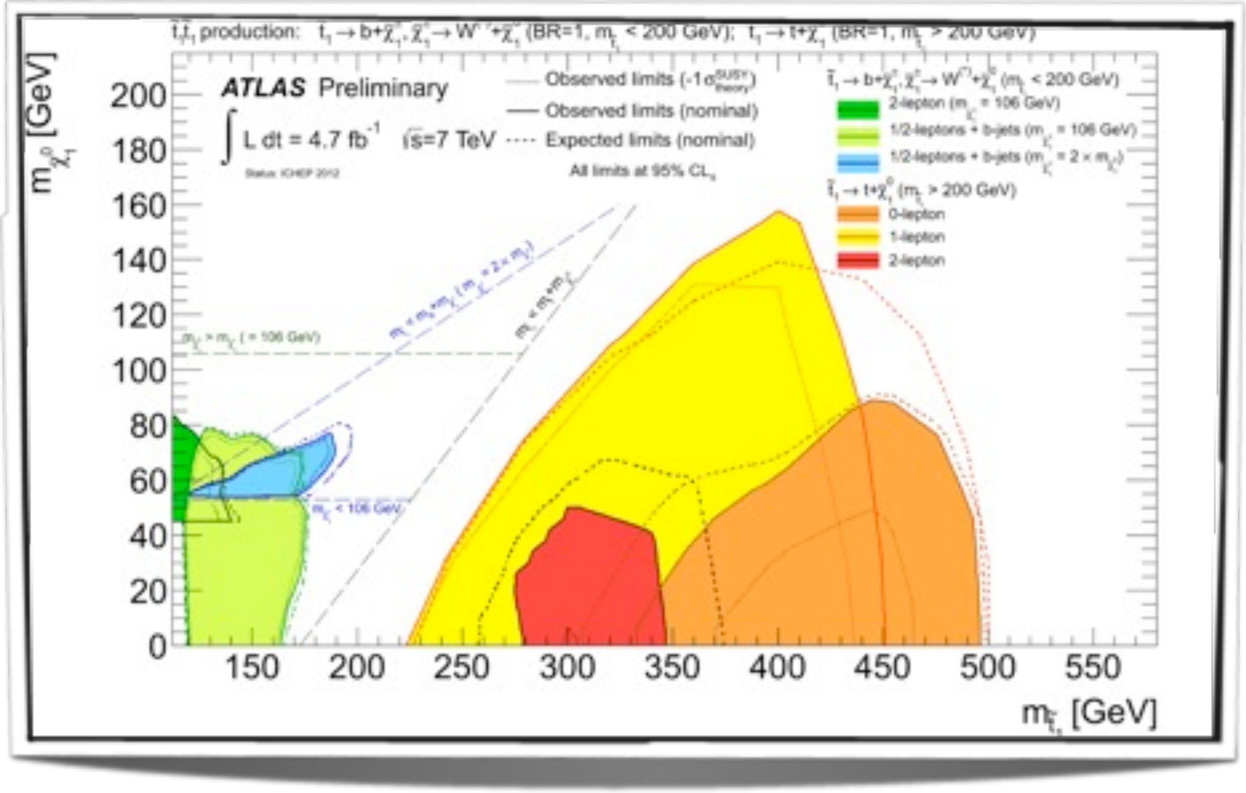
Cumpulsory Natural SUSY

1300 $\tilde{g}$

400 $\tilde{t}_{L,R}$, $\tilde{b}_L$

120 h

Unavoidable tunings: $\left(\frac{400}{m_{\tilde{t}}}\right)^2$, $\left(\frac{4 m_{\tilde{t}}}{M_{\tilde{g}}}\right)^2$



Arkani-Hamed @ SavasFest

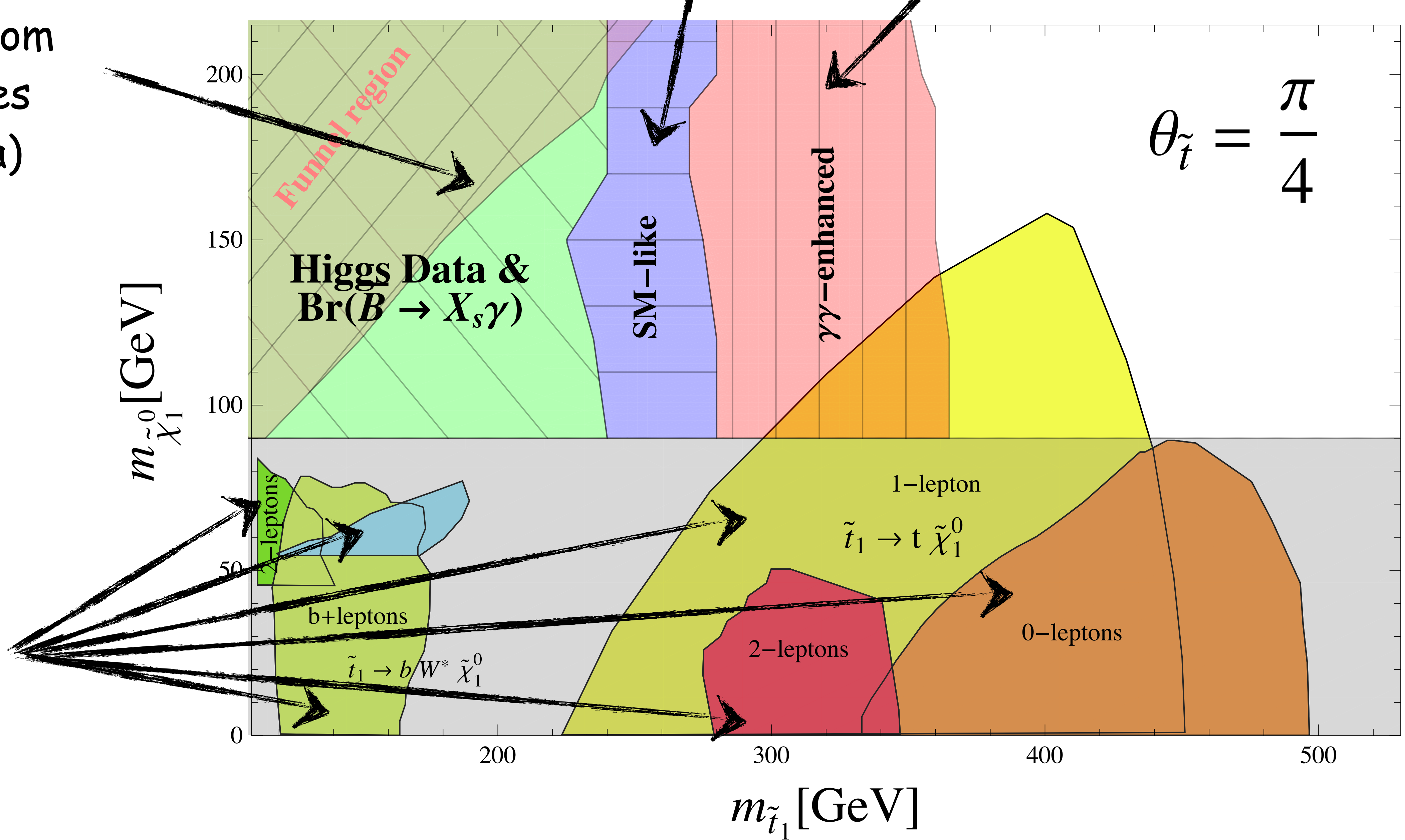
new Goldwin's law: every HEP review talk has to show a slide by Nima

Stop mass constraints from Higgs global fit

Espinosa, Grojean, Sanz, Trott ’12

BR($B_s \to X_s\gamma$) prefers degenerate stops ⊃ kills the low stop mass region

then Higgs data put a lower bound of the stop mass



prospects
μ_i=1, σ_i=σ^{ICHEP}/2

prospects
μ_i=μ^{ICHEP}, σ_i=σ^{ICHEP}/2

lower bound from
Higgs searches
(current data)

direct searches

Saving SUSY

Saving SUSY

SUSY is Natural
but not plain vanilla

Saving SUSY

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but not plain vanilla

- ~~CMSSM~~
- pMSSM
- NMSSM
- Hide SUSY
  - reduce production (eg. split families)
  - reduce MET (e.g. ~~R-parity~~, compressed spectrum)

Saving SUSY

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is the SM minimal?
why susy should be minimal?

Saving SUSY

SUSY is Natural
but not plain vanilla

SUSY solves the big hierarchy
but not the little hierarchy

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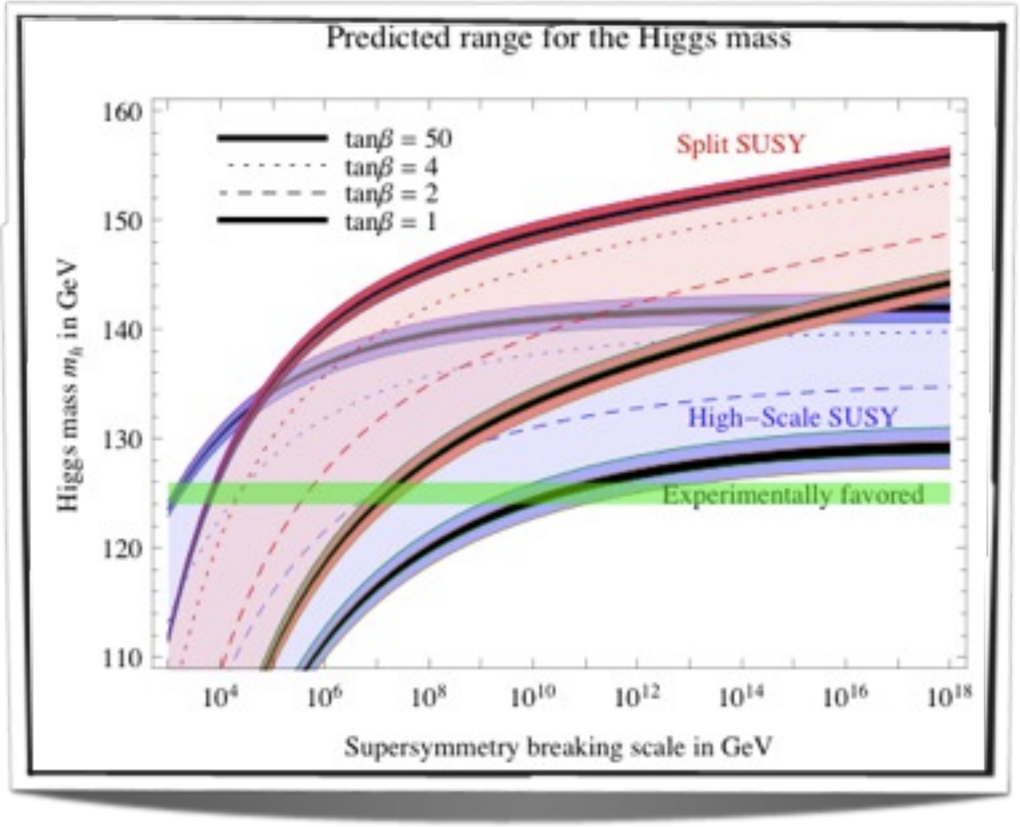


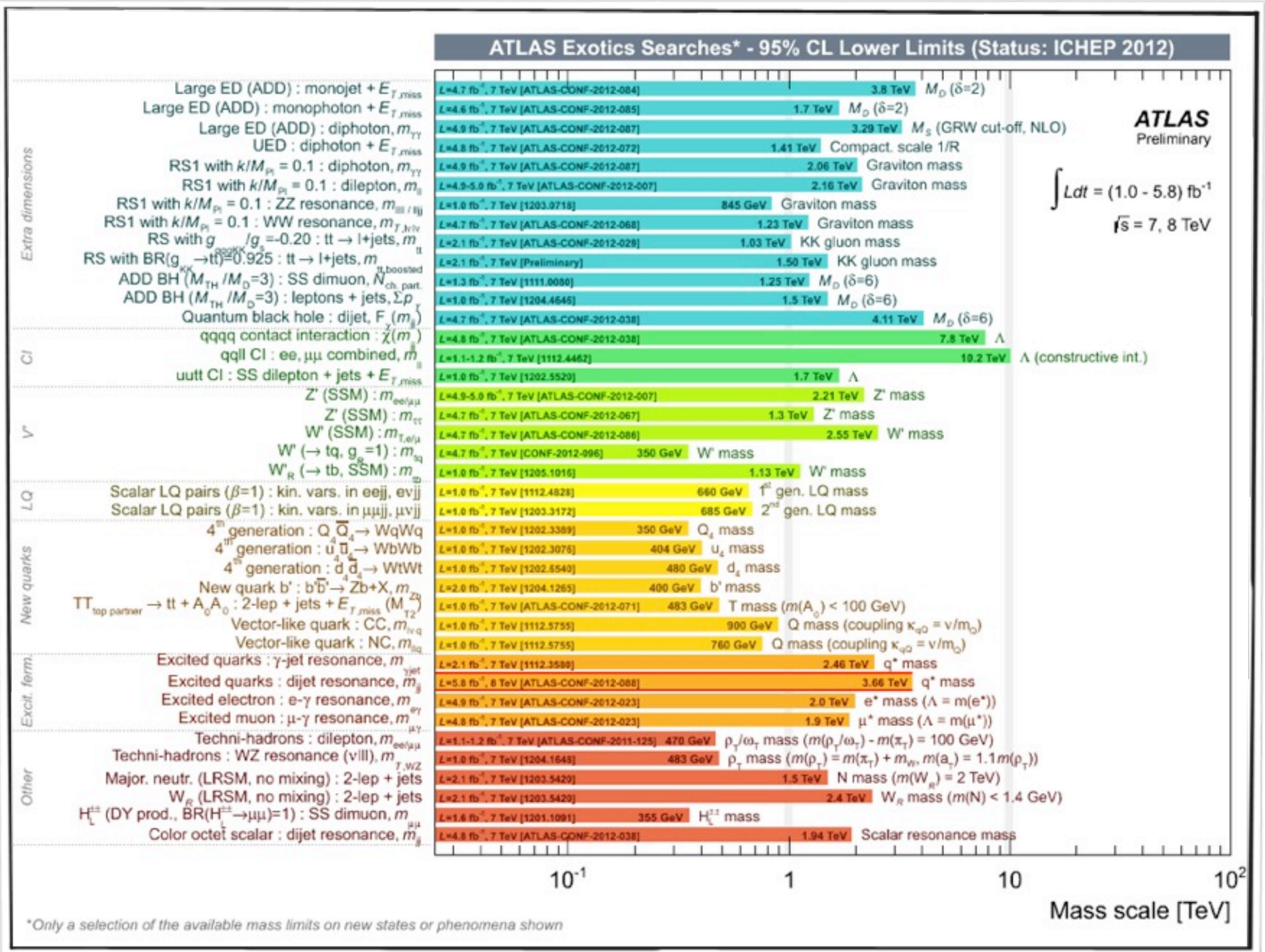
Giudice, Strumia '11

unification etc...

string etc...

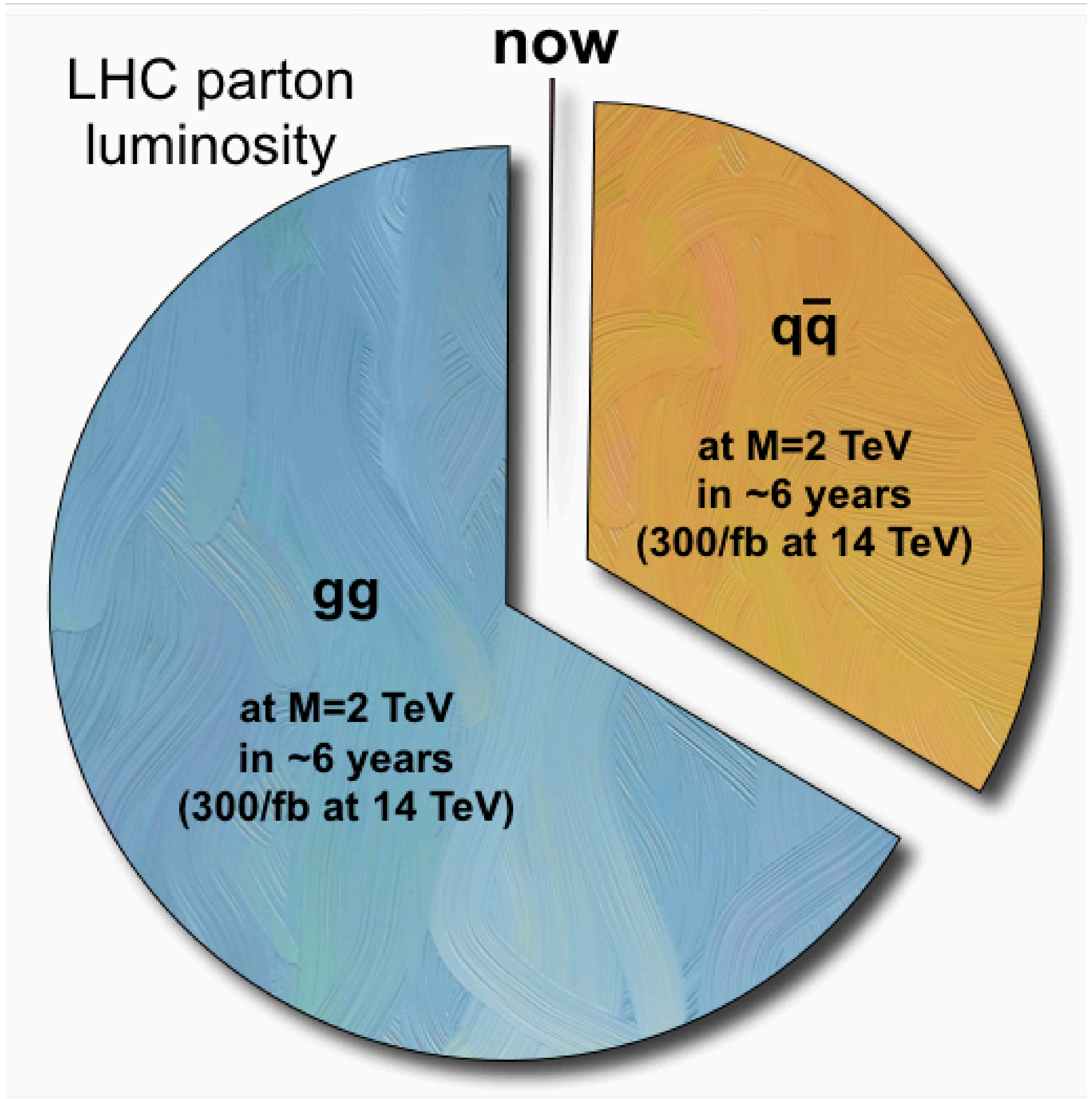
- Split SUSY:
  susy scalars @ m_{susy}, susy fermions @ m_Z
- high scale SUSY:
  susy scalars & susy fermions @ m_{susy}

Exotics


ATLAS Exotics Searches* - 95% CL Lower Limits (Status: ICHEP 2012)
ATLAS
Preliminary
$\int L dt = (1.0 - 5.8)\ \mathrm{fb}^{-1}$
$\sqrt{s} = 7, 8$ TeV
Extra dimensions
Large ED (ADD) : monojet + $E_{T,miss}$
L=4.7 fb^{-1}, 7 TeV [ATLAS-CONF-2012-084] 3.8 TeV M_D (δ=2)
Large ED (ADD) : monophoton + $E_{T,miss}$
L=4.6 fb^{-1}, 7 TeV [ATLAS-CONF-2012-085] 1.7 TeV M_D (δ=2)
Large ED (ADD) : diphoton, $m_{\gamma\gamma}$
L=4.9 fb^{-1}, 7 TeV [ATLAS-CONF-2012-087] 3.29 TeV M_S (GRW cut-off, NLO)
UED : diphoton + $E_{T,miss}$
L=4.8 fb^{-1}, 7 TeV [ATLAS-CONF-2012-072] 1.41 TeV Compact. scale 1/R
RS1 with k/M_{Pl} = 0.1 : diphoton, $m_{\gamma\gamma}$
L=4.9 fb^{-1}, 7 TeV [ATLAS-CONF-2012-087] 2.06 TeV Graviton mass
RS1 with k/M_{Pl} = 0.1 : dilepton, m_{ll}
L=4.9-5.0 fb^{-1}, 7 TeV [ATLAS-CONF-2012-007] 2.16 TeV Graviton mass
RS1 with k/M_{Pl} = 0.1 : ZZ resonance, $m_{llll / lljj}$
L=1.0 fb^{-1}, 7 TeV [1203.0718] 845 GeV Graviton mass
RS1 with k/M_{Pl} = 0.1 : WW resonance, $m_{T,l\nu l\nu}$
L=4.7 fb^{-1}, 7 TeV [ATLAS-CONF-2012-068] 1.23 TeV Graviton mass
RS with g_{qqKK}/g_s=-0.20 : tt → l+jets, m_{tt}
L=2.1 fb^{-1}, 7 TeV [ATLAS-CONF-2012-029] 1.03 TeV KK gluon mass
RS with BR(g_{KK}→tt)=0.925 : tt → l+jets, $m_{tt,boosted}$
L=2.1 fb^{-1}, 7 TeV [Preliminary] 1.50 TeV KK gluon mass
ADD BH (M_{TH}/M_D=3) : SS dimuon, $N_{ch. part.}$
L=1.3 fb^{-1}, 7 TeV [1111.0080] 1.25 TeV M_D (δ=6)
ADD BH (M_{TH}/M_D=3) : leptons + jets, Σp_T
L=1.0 fb^{-1}, 7 TeV [1204.4646] 1.5 TeV M_D (δ=6)
Quantum black hole : dijet, $F_\chi(m_{jj})$
L=4.7 fb^{-1}, 7 TeV [ATLAS-CONF-2012-038] 4.11 TeV M_D (δ=6)
CI
qqqq contact interaction : $\chi(m_{jj})$
L=4.8 fb^{-1}, 7 TeV [ATLAS-CONF-2012-038] 7.8 TeV Λ
qqll CI : ee, μμ combined, m_{ll}
L=1.1-1.2 fb^{-1}, 7 TeV [1112.4462] 10.2 TeV Λ (constructive int.)
uutt CI : SS dilepton + jets + $E_{T,miss}$
L=1.0 fb^{-1}, 7 TeV [1202.5520] 1.7 TeV Λ
V'
Z' (SSM) : $m_{ee/\mu\mu}$
L=4.9-5.0 fb^{-1}, 7 TeV [ATLAS-CONF-2012-007] 2.21 TeV Z' mass
Z' (SSM) : $m_{\tau\tau}$
L=4.7 fb^{-1}, 7 TeV [ATLAS-CONF-2012-067] 1.3 TeV Z' mass
W' (SSM) : $m_{T,e/\mu}$
L=4.7 fb^{-1}, 7 TeV [ATLAS-CONF-2012-086] 2.55 TeV W' mass
W' (→ tq, g_R=1) : m_{tq}
L=4.7 fb^{-1}, 7 TeV [CONF-2012-096] 350 GeV W' mass
W'_R (→ tb, SSM) : m_{tb}
L=1.0 fb^{-1}, 7 TeV [1205.1016] 1.13 TeV W' mass
LQ
Scalar LQ pairs (β=1) : kin. vars. in eejj, eνjj
L=1.0 fb^{-1}, 7 TeV [1112.4828] 660 GeV 1st gen. LQ mass
Scalar LQ pairs (β=1) : kin. vars. in μμjj, μνjj
L=1.0 fb^{-1}, 7 TeV [1203.3172] 685 GeV 2nd gen. LQ mass
New quarks
4th generation : $Q_4\bar{Q}_4$→ WqWq
L=1.0 fb^{-1}, 7 TeV [1202.3389] 350 GeV Q_4 mass
4th generation : $u_4\bar{u}_4$→ WbWb
L=1.0 fb^{-1}, 7 TeV [1202.3076] 404 GeV u_4 mass
4th generation : $d_4\bar{d}_4$→ WtWt
L=1.0 fb^{-1}, 7 TeV [1202.5540] 480 GeV d_4 mass
New quark b' : $b'\bar{b}'$→ Zb+X, m_{Zb}
L=2.0 fb^{-1}, 7 TeV [1204.1265] 400 GeV b' mass
$TT_{top\ partner}$ → tt + A_0A_0 : 2-lep + jets + $E_{T,miss}$ (M_{T2})
L=1.0 fb^{-1}, 7 TeV [ATLAS-CONF-2012-071] 483 GeV T mass ($m(A_0)$ < 100 GeV)
Vector-like quark : CC, $m_{l\nu q}$
L=1.0 fb^{-1}, 7 TeV [1112.5755] 900 GeV Q mass (coupling $\kappa_{qQ} = v/m_Q$)
Vector-like quark : NC, m_{llq}
L=1.0 fb^{-1}, 7 TeV [1112.5755] 760 GeV Q mass (coupling $\kappa_{qQ} = v/m_Q$)
Excit. ferm.
Excited quarks : γ-jet resonance, $m_{\gamma jet}$
L=2.1 fb^{-1}, 7 TeV [1112.3580] 2.46 TeV q* mass
Excited quarks : dijet resonance, m_{jj}
L=5.8 fb^{-1}, 8 TeV [ATLAS-CONF-2012-088] 3.66 TeV q* mass
Excited electron : e-γ resonance, $m_{e\gamma}$
L=4.9 fb^{-1}, 7 TeV [ATLAS-CONF-2012-023] 2.0 TeV e* mass (Λ = m(e*))
Excited muon : μ-γ resonance, $m_{\mu\gamma}$
L=4.8 fb^{-1}, 7 TeV [ATLAS-CONF-2012-023] 1.9 TeV μ* mass (Λ = m(μ*))
Other
Techni-hadrons : dilepton, $m_{ee/\mu\mu}$
L=1.1-1.2 fb^{-1}, 7 TeV [ATLAS-CONF-2011-125] 470 GeV ρ_T/ω_T mass ($m(\rho_T/\omega_T) - m(\pi_T)$ = 100 GeV)
Techni-hadrons : WZ resonance (νlll), $m_{T,WZ}$
L=1.0 fb^{-1}, 7 TeV [1204.1648] 483 GeV ρ_T mass ($m(\rho_T) = m(\pi_T) + m_W$, $m(a_T) = 1.1 m(\rho_T)$)
Major. neutr. (LRSM, no mixing) : 2-lep + jets
L=2.1 fb^{-1}, 7 TeV [1203.5420] 1.5 TeV N mass ($m(W_R)$ = 2 TeV)
W_R (LRSM, no mixing) : 2-lep + jets
L=2.1 fb^{-1}, 7 TeV [1203.5420] 2.4 TeV W_R mass ($m(N)$ < 1.4 GeV)
$H_L^{\pm\pm}$ (DY prod., BR($H_L^{\pm\pm}$→μμ)=1) : SS dimuon, $m_{\mu\mu}$
L=1.6 fb^{-1}, 7 TeV [1201.1091] 355 GeV $H_L^{\pm\pm}$ mass
Color octet scalar : dijet resonance, m_{jj}
L=4.8 fb^{-1}, 7 TeV [ATLAS-CONF-2012-038] 1.94 TeV Scalar resonance mass
10^{-1}
1
10
10^2
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena shown

Exotic Exotics

if you are depressed by the absence of observation of new physics, always remember Günter's plot



G. Dissertori '12

Conclusions

A lot of take-home messages

(will be expensive if you are traveling with Easyjet!)

A new particle has been discovered and it is likely to play a key role in our understanding of the fundamental laws of Nature

but we should remember that the SM doesn't explain the EW scale

is the EW scale "natural" or fine-tuned?

is the Dark Matter linked to the EW physics?

are neutrino masses indicating a new (high) scale?

will the fundamental interactions unify?

we have to make sure that the next exp. facilities can answer these questions without (too much) theoretical prejudice