Linear Collider Physics Outlook

(after LHC8)

ECFA LC2013

DESY, May 31, 2013

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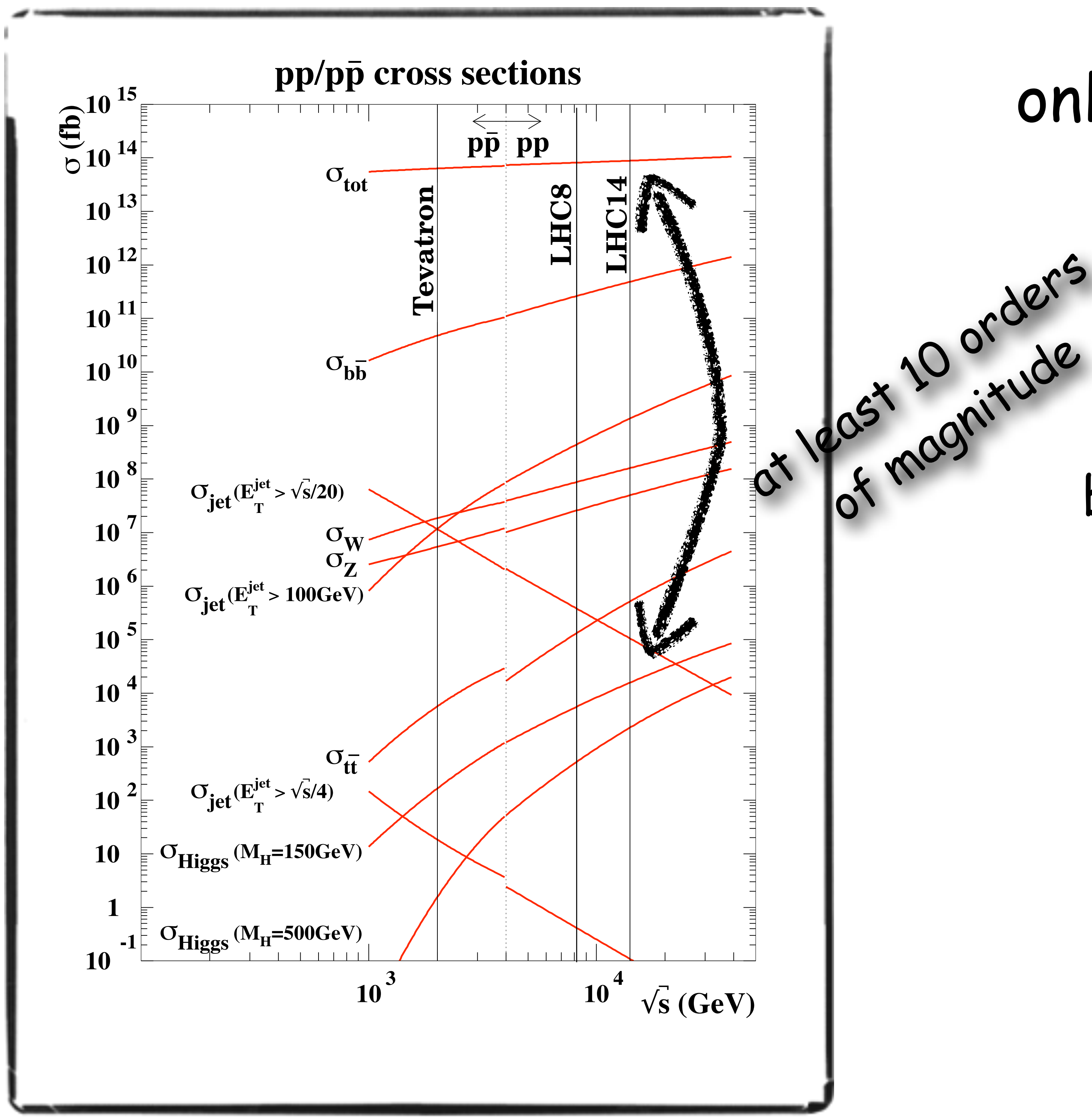
We are living a privileged moment in the history of HEP

(picture: courtesy of A. Hoecker]

SM Higgs @ LHC

The production of a Higgs is wiped out by QCD background



only 1 out of 100 billions events are "interesting"

(for comparison, Shakespeare's 43 works contain only 884,429 words in total)

furthermore many of the background events furiously look like signal events

SM Higgs @ LHC

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furthermore many of the background events furiously look like signal events

... like finding the paper you are looking for in 10^8 John Ellis' offices

Where are we?

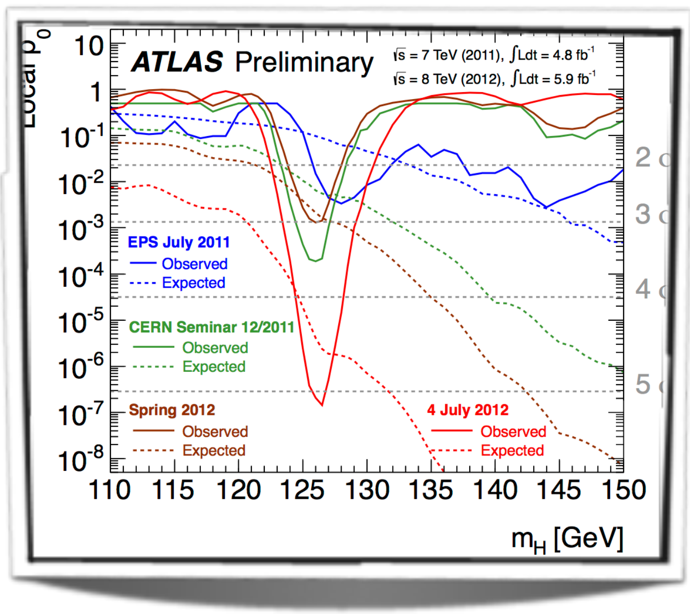
we are living a privileged moment in the history of HEP

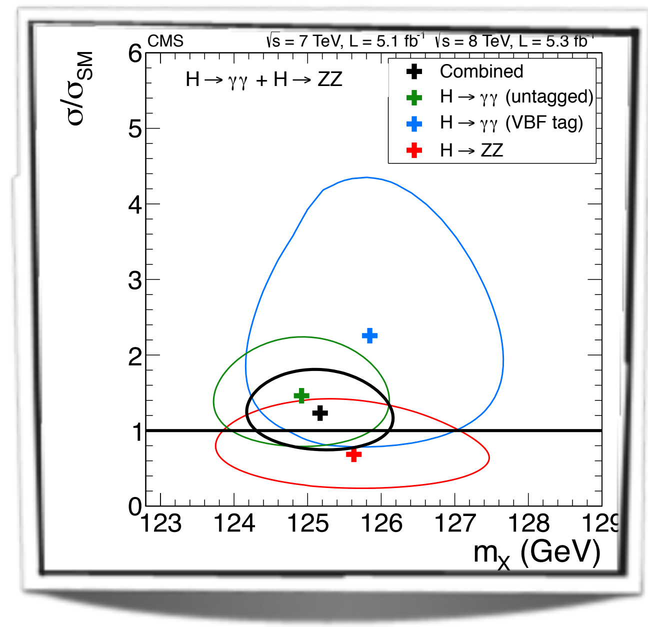
"We have found a new particle" CMS

Where are we? What's next?

we are living a privileged moment in the history of HEP

"We have found a new particle" CMS





"this discovery came at half the LHC design energy, much more severe pileup, and one-third of the integrated luminosity that was originally judged necessary" ATLAS

Higgs is the most exotic particle of the SM

its discovery has profound implications

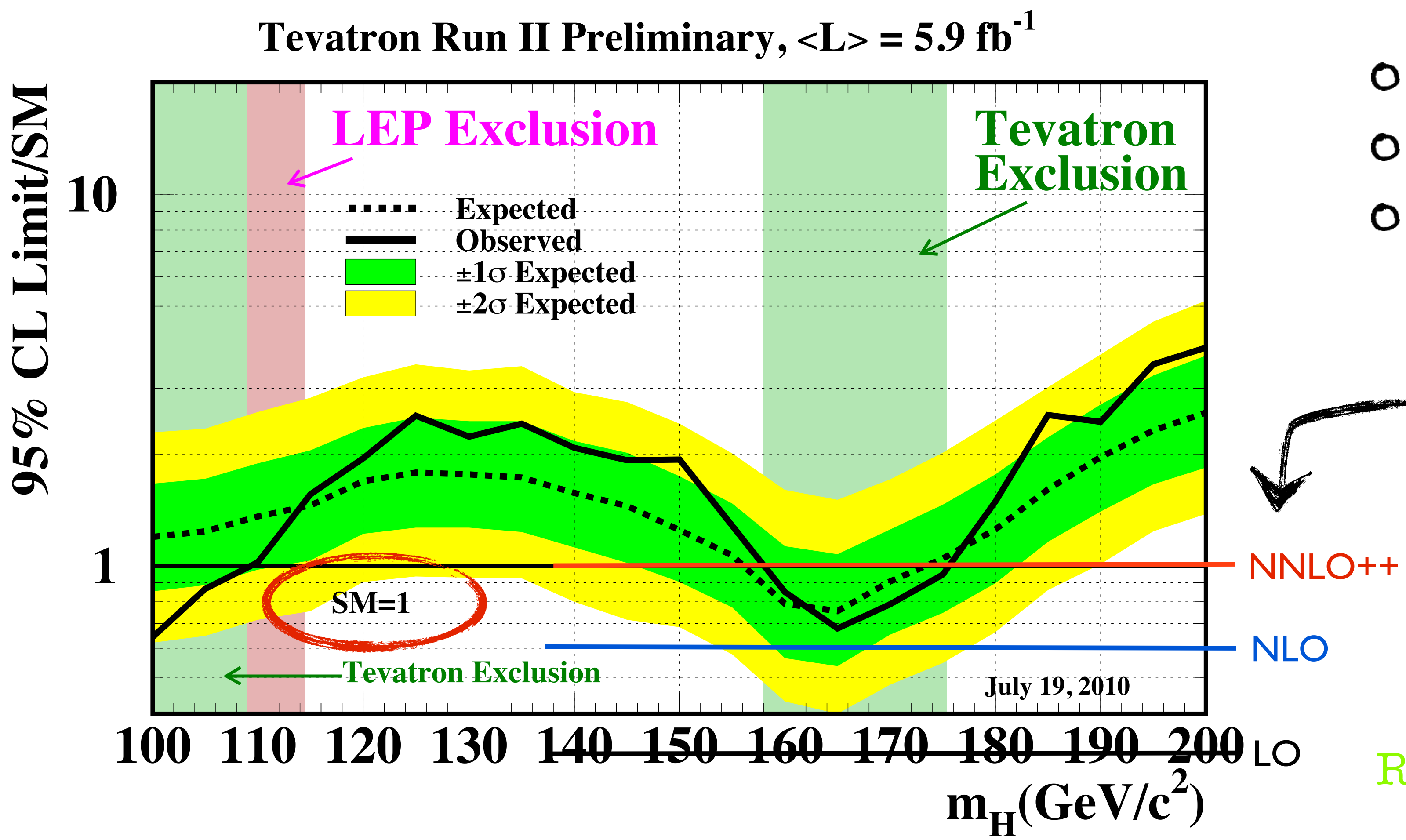
- Spin 0? Against naturalness: small mass only if protected by symmetry
- Couplings not dictated by gauge symmetry? Against gauge principle (elegance, predictivity, robustness, variety) which used to rule the world (gravity, QCD, QED, weak interactions)
- Triumph of QM+SR that predict (anti)particles of spin 0, 1/2, 1, (3/2 ?), 2

Now what?

“The experiment worked better than expected and the analysis uncovered a very difficult to find signal”

the words of a string theorist

Why did it work better than expected?



- Hard work from experimentalists
- Luck with a positive fluctuation
- Hard work from the theorists too

higher precision in theory calculation makes it easier to find the Higgs than initially thought

R. Harlander, talk @ LHCP’13

Now what?

"The experiment worked better than expected and the analysis uncovered a very difficult to find signal"

the words of a string theorist

but the experimentalists haven't found what the theorists told them they will find in addition to the Higgs boson:
no susy, no BH, no extra dimensions, nothing ...

Have the theorists been lying for so many years?

Have the exp's been too naive to believe the th's?

Why should you listen to the rest of this talk?

What does come with the Higgs?

We know that the Higgs is not the end of the story

- dark matter
- matter antimatter asymmetry
- hierarchy/naturalness problem
- ...

All these point towards an extended EW/Higgs sector

but so far this extension has been very elusive

- Direct searches @ LHC: M_{new} >~ O(500 GeV) unless reduced couplings to fermions/gluons
- EW precision data: M_{new} >~ O(TeV) unless some selection rules (eg R-parity)
- Flavor data: M_{new} >~ O(1000 TeV) unless some protection (eg MVF...)
- ...

HEP future:

exploration/discovery era or consolidation/measurement era?

let's use what we have at our disposal (the Higgs) to explore BSM sector

and see which machine can help us

Now what? What's next?

" With great power comes great responsibility "

Voltaire & Spider-Man

which, in particle physics, really means

" With great discoveries come great measurements "

BSMers desperately looking for anomalies
(true credit: F. Maltoni
actually, first google hit gives a link to an article of the Guardian on... the Higgs boson!)

1

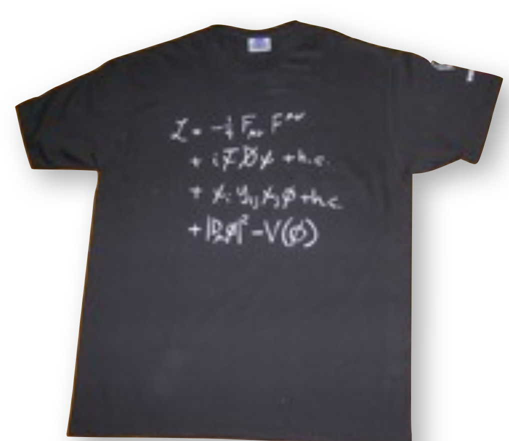
Higgs properties

J^{PC}

Important & nice to see progresses but "this question carries a similar potential for surprise as a football game between Brazil and Tonga" Resonaances

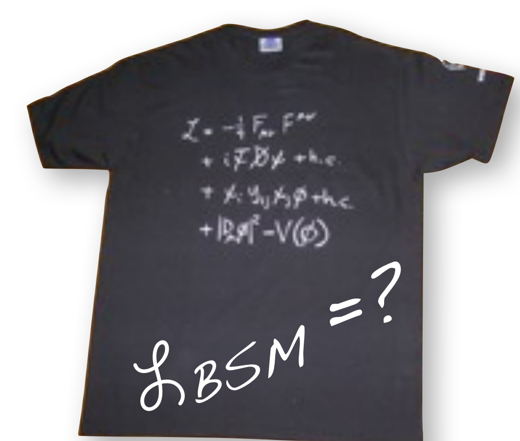
2

Higgs couplings



3

BSM implications



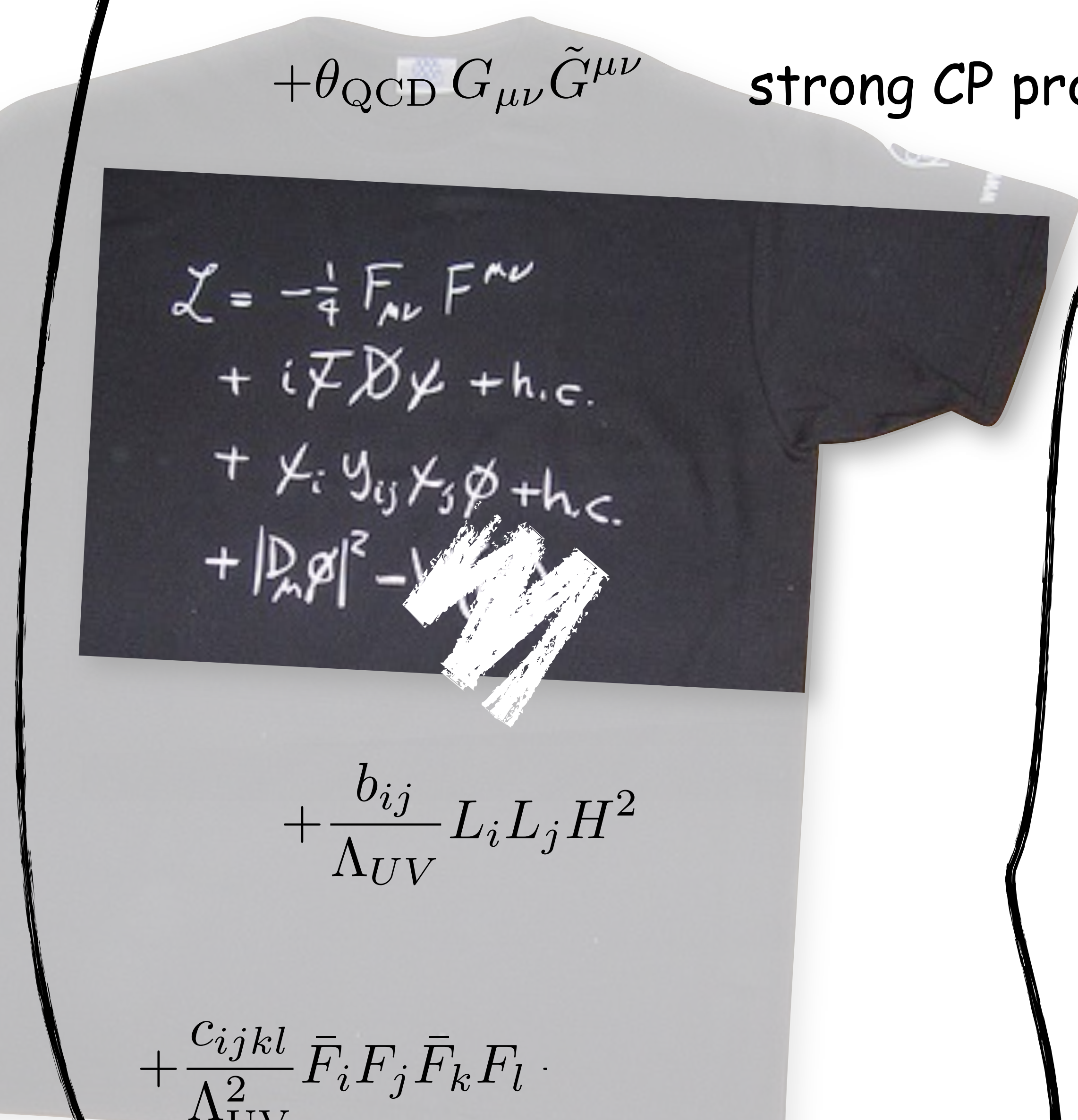
SM & New Physics

$\Lambda_{\rm UV}^4 \sqrt{g}$ cosmological constant — D=0

$+\Lambda_{\rm UV}^2 |H|^2$ Higgs mass — D=2

$+\theta_{\rm QCD}\, G_{\mu\nu}\tilde{G}^{\mu\nu}$ strong CP problem — D=4

3 problems imposed to us by data:
whatever the scale of NP is, some special structure is needed to avoid these pbs



D=4 Lagrangian describes perfectly the data but... it is not enough

$$+\frac{b_{ij}}{\Lambda_{UV}} L_i L_j H^2$$

D=5 operators are needed to generate neutrino masses $\Lambda_{\rm UV} \sim 10^{14\div 18}$ GeV?

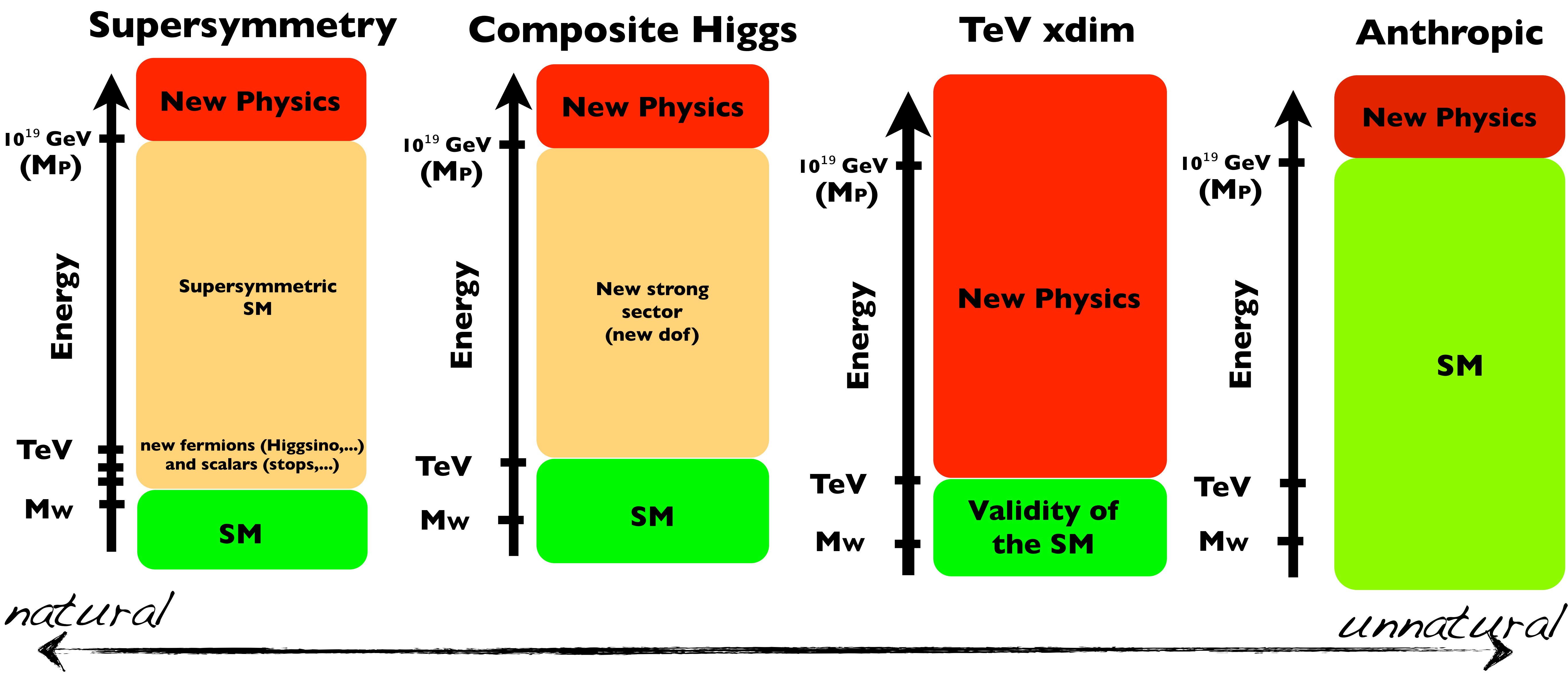
$$+\frac{c_{ijkl}}{\Lambda_{\rm UV}^2} \bar{F}_i F_j \bar{F}_k F_l$$

$+\ldots$ (59 independent structures)

D=6 operators capture the leading effects of New Physics

Which New Physics?

A. Pomarol, lecture @ CERN, '13



still plausible
but may be not in their
minimal/simplest incarnations

unlikely

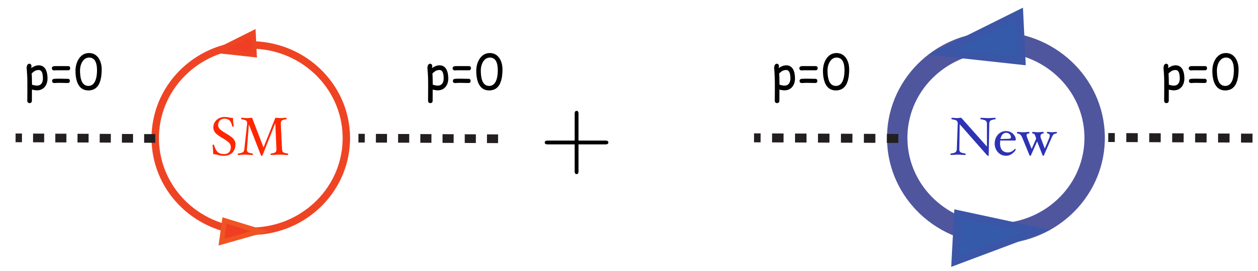
Will we
ever
know?

(can the Nature be unnatural?)

Higgs couplings = test of Naturalness?

$$-(125\ \mathrm{GeV})^2\left(\frac{\Lambda}{600\ \mathrm{GeV}}\right)^2 \qquad\qquad \frac{g_*^2}{16\pi^2}\Lambda^2$$

$\delta m_H^2 =$



$\sim m_H^2$

$$\frac{g_s^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 G_{\mu\nu}^2 \qquad \frac{e^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 F_{\mu\nu}^2 \qquad \frac{g_*^2}{16\pi^2}\frac{1}{m_*^2}\left(\partial_\mu |H|^2\right)^2$$

$$\frac{\Delta BR(h\to\gamma\gamma, Z\gamma, gg)}{\mathrm{SM}} \sim \frac{g_*^2 v^2}{m_*^2}$$

$$BR(h\to ii) = BR_{\mathrm{SM}}$$

$$\Gamma = \left(1 - \frac{g_*^2 v^2}{16\pi^2 m_*^2}\right)\Gamma_{\mathrm{SM}}$$

nice to be able to measure Γ @ ILC

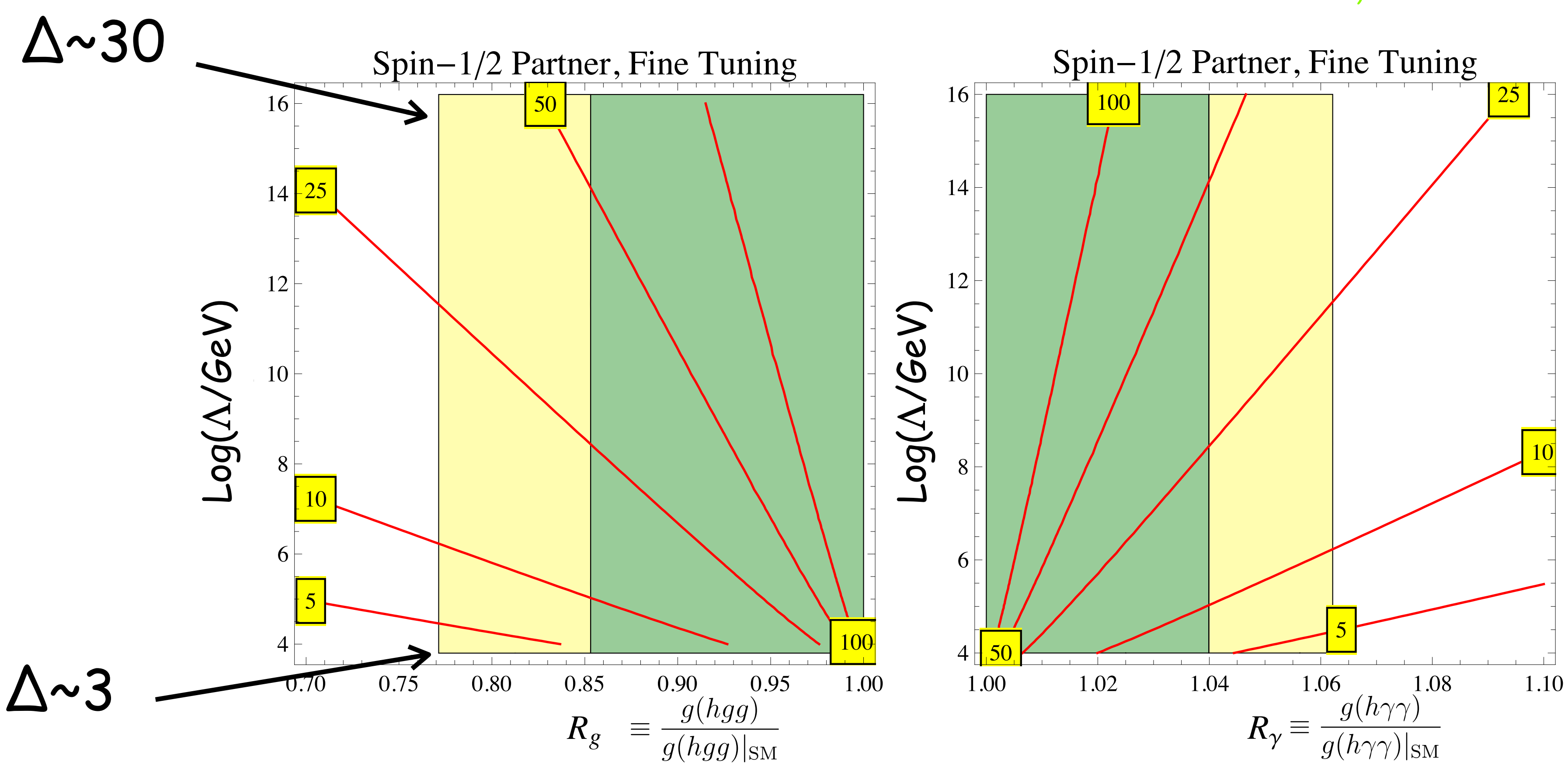
Generically, natural scenarios come with deviations of the Higgs coupling

Higgs couplings = test of Naturalness?

simple toy model: a single spin-$\frac{1}{2}$ top partner

deviation in the couplings ⇔ amount of fine-tuning $\Delta = \delta m_H^2/m_H^2$

Farina, Perelstein, Rey-Le Noisier, '13



allowed by LHC/Tevatron at 68%CL

allowed by LHC/Tevatron at 95%CL

Λ cutoff scale of log. divergences to the Higgs mass

Higgs scale models ($\Lambda \sim 10^{16}$GeV) come with a generic fine-tuning O(1/30)

increasing the couplings measurement to 1% precision will raise the fine-tuning to O(1/400)

Higgs couplings = test of Naturalness?

MSSM: more complicated situation: 2 stops w/ mixing

$$\frac{\sigma(gg \to h)}{\mathrm{SM}} \approx (1 - 0.7\, F_{\tilde{t}})^2 \qquad \frac{\Gamma(h \to \gamma\gamma)}{\mathrm{SM}} \approx (1 + 0.2\, F_{\tilde{t}})^2$$

$$F_{\tilde{t}} = -\frac{1}{3}\left[\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{1}{4}\sin^2(2\,\theta_t)\,\frac{\delta m^4}{m_{\tilde{t}_1}^2\, m_{\tilde{t}_2}^2}\right].$$

Small mixing: → $\Gamma(gg \to h)$ enhanced, $\Gamma(h \to \gamma\gamma)$ suppressed

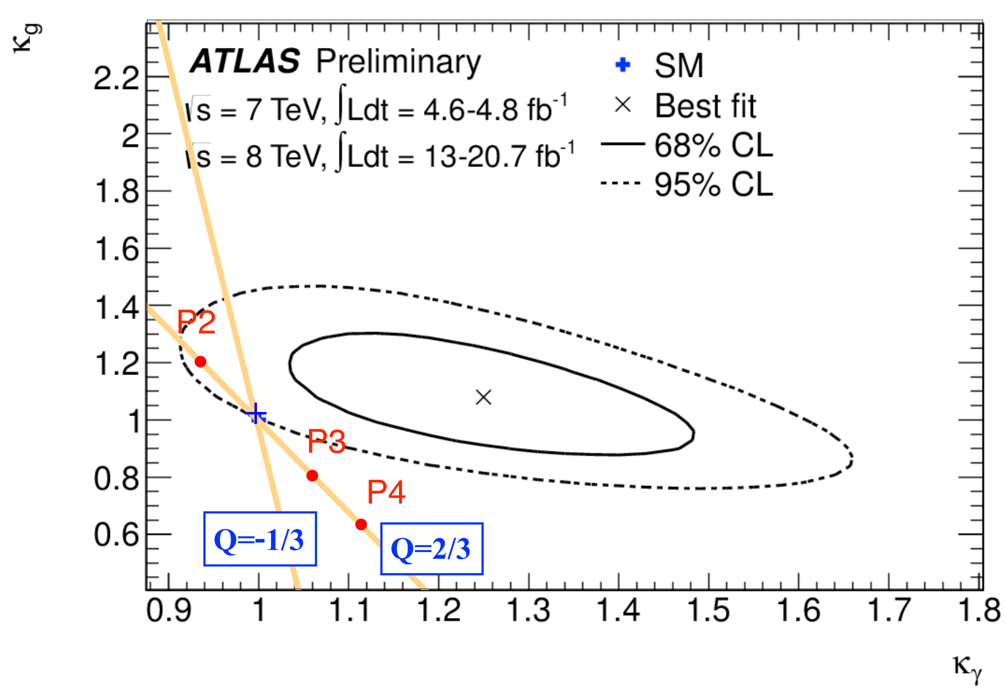
Large mixing: → $\Gamma(gg \to h)$ suppressed, $\Gamma(h \to \gamma\gamma)$ enhanced

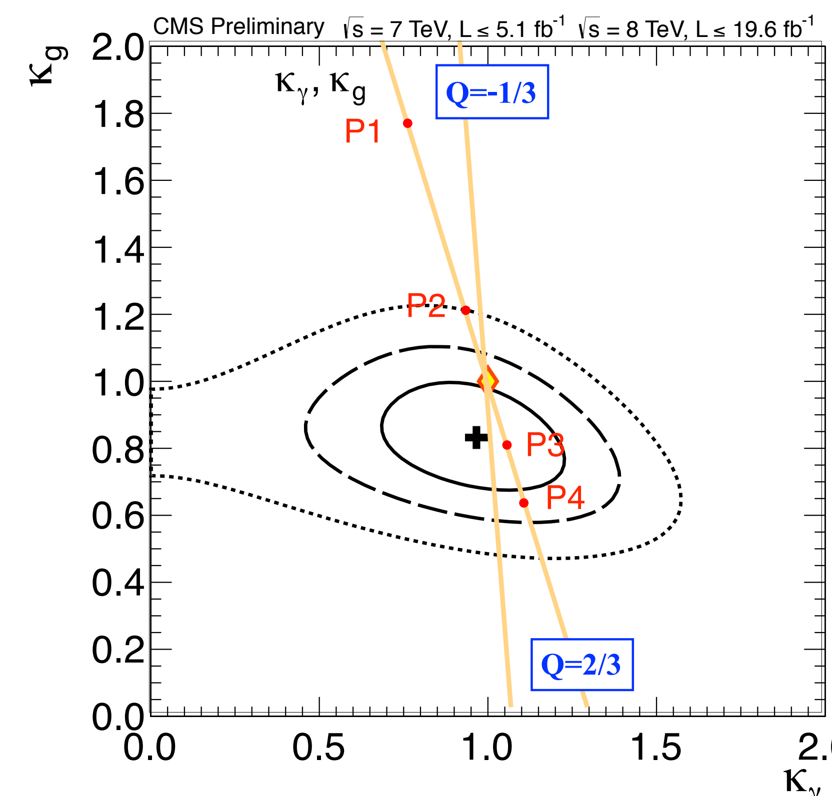
P1: $m_{\tilde{t}_1} = 100\,\mathrm{GeV},\ m_{\tilde{t}_2} = 300\,\mathrm{GeV},\ \theta_t = 0$

P2: $m_{\tilde{t}_1} = 200\,\mathrm{GeV},\ m_{\tilde{t}_2} = 500\,\mathrm{GeV},\ \theta_t = 0$

P3: $m_{\tilde{t}_1} = 400\,\mathrm{GeV},\ m_{\tilde{t}_2} = 1000\,\mathrm{GeV},\ \theta_t = \pi/4$

P4: $m_{\tilde{t}_1} = 500\,\mathrm{GeV},\ m_{\tilde{t}_2} = 1500\,\mathrm{GeV},\ \theta_t = \pi/4$





no direct measure of fine-tuning but Higgs couplings can teach us about stops which are the key players in naturalness

Direct vs. indirect search for top partners

If no beyond Standard Model physics is seen at the LHC:

How large can deviations from the Standard Model Higgs couplings be?

Gupta, Rzehak, Wells '12

see Rzehak's talk

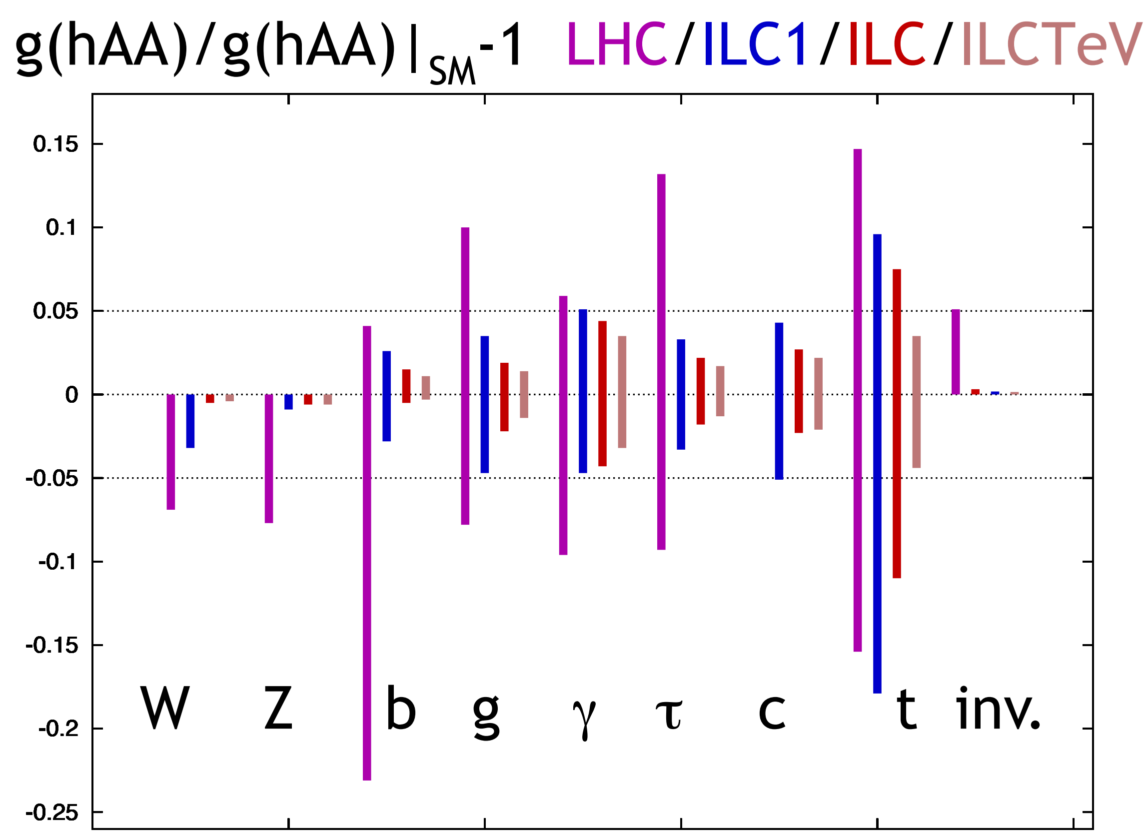
⇒ How well do we need to know these couplings?

maximal deviations from the SM Higgs couplings

	$\lvert\Delta hVV\rvert$	$\lvert\Delta h\bar{t}t\rvert$	$\lvert\Delta h\bar{b}b\rvert$	$\lvert\Delta hhh\rvert$
Mixed-in Singlet	6%	6%	6%	18%
Composite Higgs	8%	tens of %	tens of %	tens of %
MSSM	$< 1\%$	3%	10%, 100%	2%, 15%

$\tan\beta > 20$ no superpartners → 10%, 2%; all other cases → 100%, 15%

Peskin '12



Precision Higgs physics can capture New Physics that LHC has missed!

Precision Higgs Physics

Chiral Lagrangian for a light Higgs-like scalar

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

$$- \left(m_W^2 W_\mu W^\mu + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right)\left(1 + 2c_V \frac{h}{v} + b_V \frac{h^2}{v^2} + \ldots\right)$$

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

O(p²)

$$+ \frac{\alpha_{em}}{8\pi}\left(2\, c_{WW}\, W^+_{\mu\nu} W^{-\,\mu\nu} + c_{ZZ}\, Z_{\mu\nu} Z^{\mu\nu} + 2\, c_{Z\gamma}\, Z_{\mu\nu}\gamma^{\mu\nu} + c_{\gamma\gamma}\, \gamma_{\mu\nu}\gamma^{\mu\nu}\right)\frac{h}{v}$$

$$+ \frac{\alpha_s}{8\pi} c_{gg} G^a_{\mu\nu} G^{a\,\mu\nu} \frac{h}{v}$$

$$+ c_W \left(W^-_\nu D_\mu W^{+\,\mu\nu} + W^+_\nu D_\mu W^{-\,\mu\nu}\right)\frac{h}{v} + c_Z Z_\nu \partial_\mu Z^{\mu\nu} \frac{h}{v}$$

$$+ \left(\frac{c_W}{\sin\theta_W \cos\theta_W} - \frac{c_Z}{\tan\theta_W}\right) Z_\nu \partial_\mu \gamma^{\mu\nu} \frac{h}{v}$$

O(p⁴)

$$+ \mathcal{O}\left(p^6\right)$$

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

Chiral Lagrangian for a light Higgs-like scalar

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$$- \left(m_W^2\, W_\mu W^\mu + \frac{1}{2}m_Z^2\, Z_\mu Z^\mu\right)\left(1 \ldots\right.$$

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

$$+\frac{\alpha_{em}}{8\pi}\left(2\, c_{WW}\, W^+_{\mu\nu}W^{-\,\mu\nu} + c_{ZZ}\, Z_{\mu\nu}Z^{\mu\nu} + 2\, c_{Z\gamma}\, Z_{\mu\nu}\gamma^{\mu\nu} + c_{\gamma\gamma}\, \gamma_{\mu\nu}\gamma^{\mu\nu}\right)\frac{h}{v}$$

still large LO parameter space

⇓ ⇓ ⇓

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 $gg \to h$ and $h \to \gamma\gamma$)

Not enough data/sensitivity to determine all these parameters

⇓ ⇓ ⇓

But we can put some of the SM structures under probation

assumptions:

- ☑ spin-0 & CP-even
  - ↖ $\gamma\gamma$ ↖ WW & ZZ
- ☑ custodial symmetry
  - ↖ EWPD
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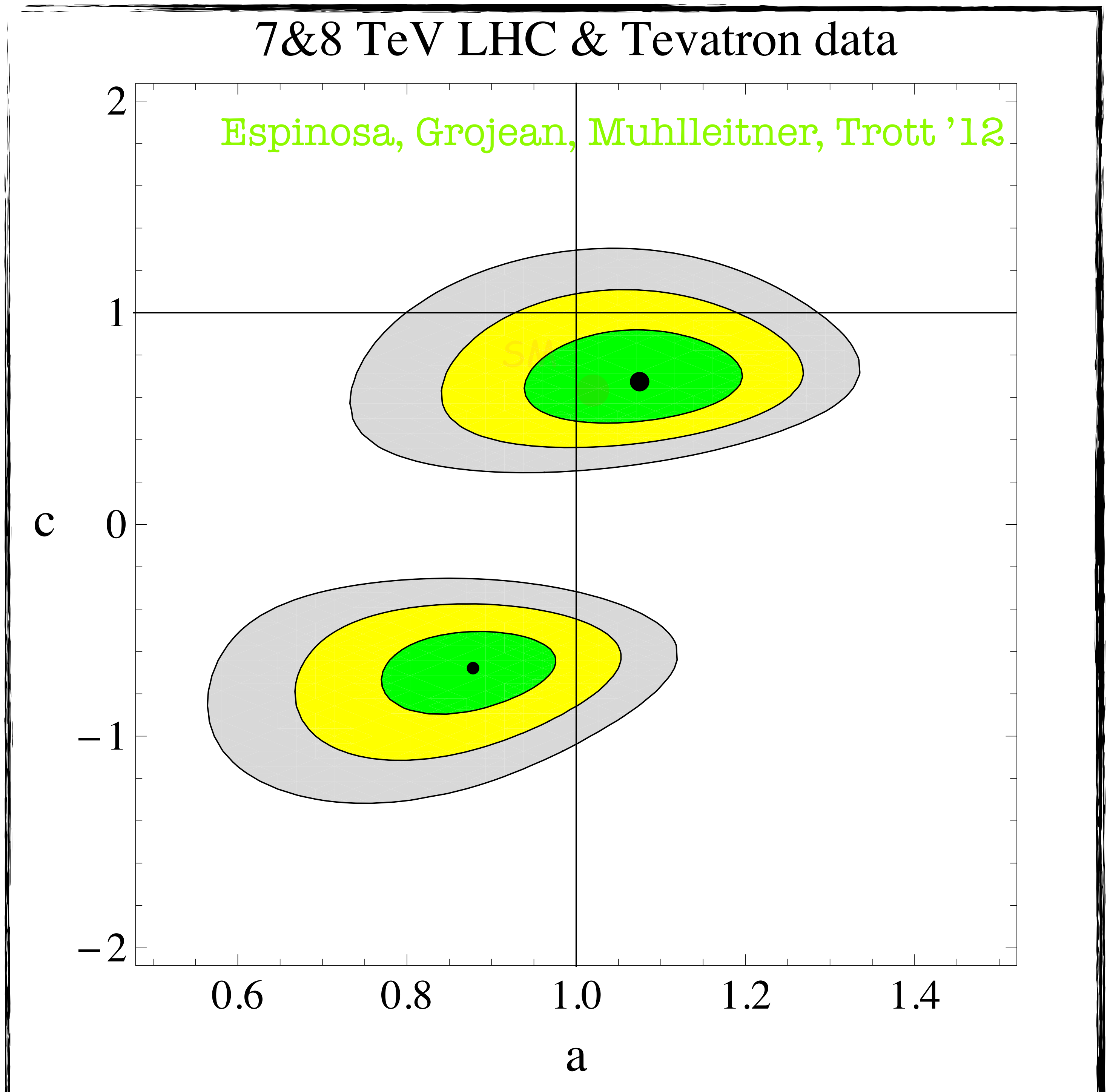
  - ↖ Flavor

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

Higgs coupling fits: test of unitarity



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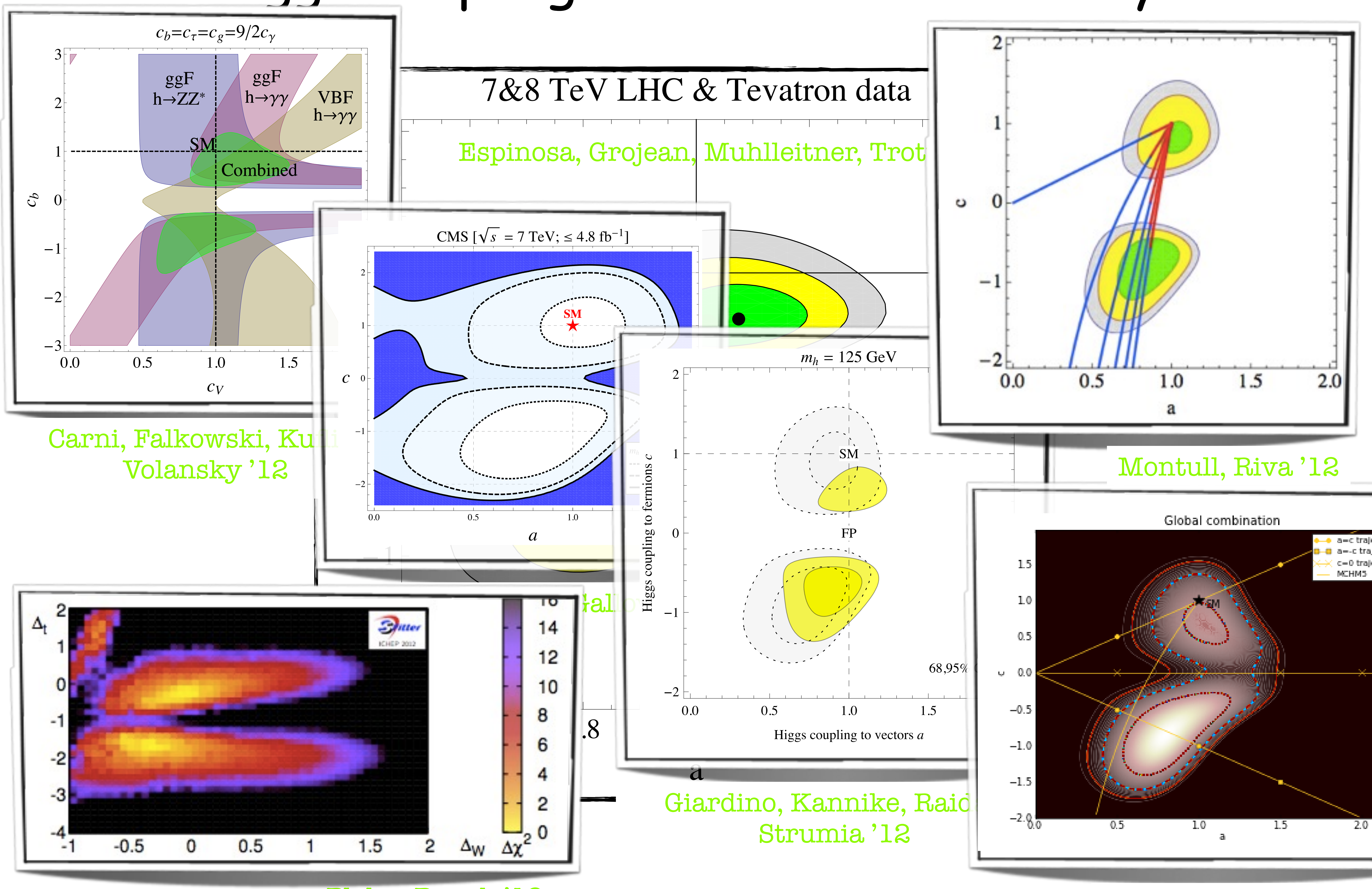


Carni, Falkowski, Ku
Volansky '12

Espinosa, Grojean, Muhlleitner, Trot

Montull, Riva '12

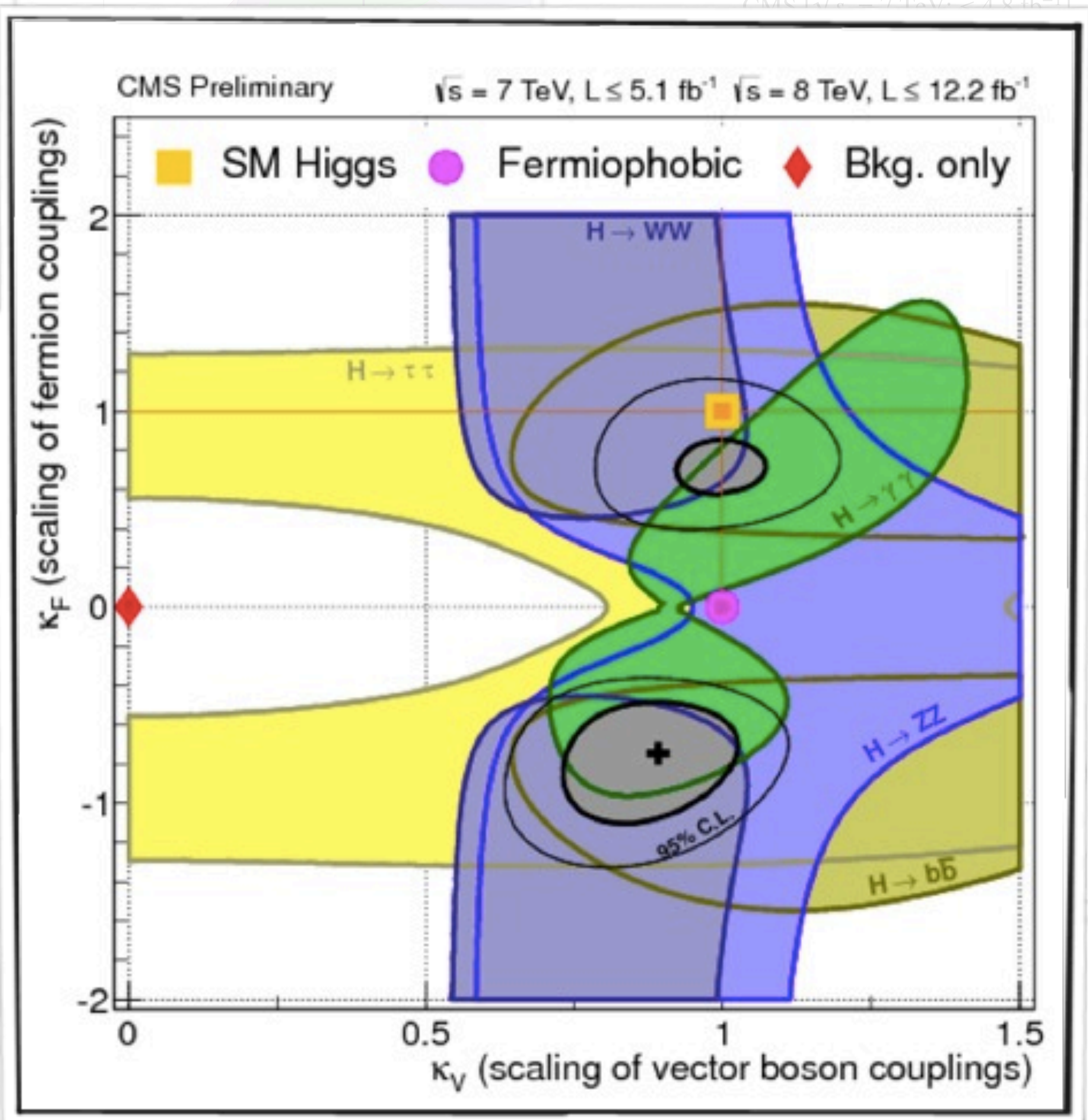
Giardino, Kannike, Raid
Strumia '12

Plehn, Rauch '12

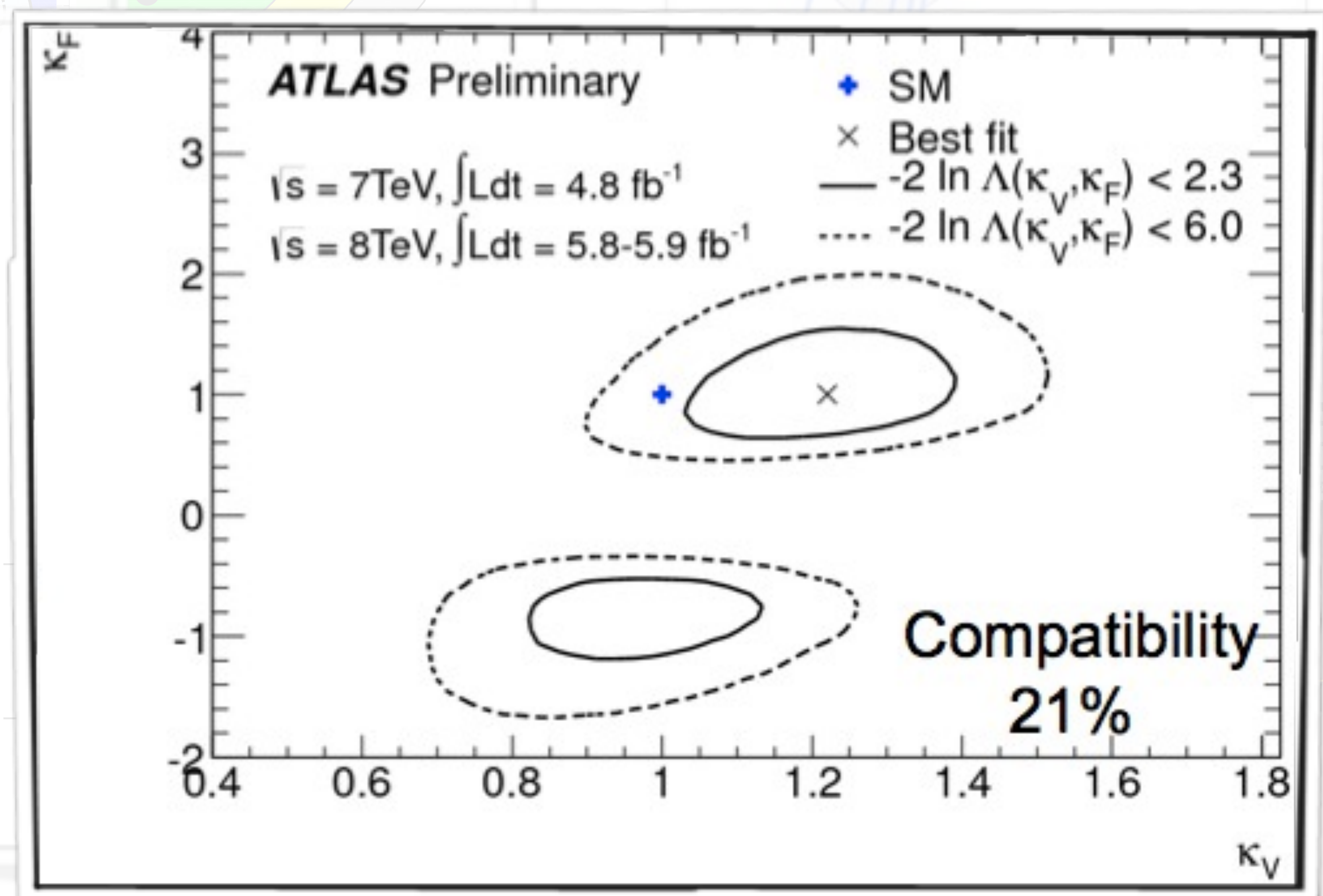
Ellis, You '12

Higgs coupling fits: test of unitarity

don't leave it in the hands of theorists!



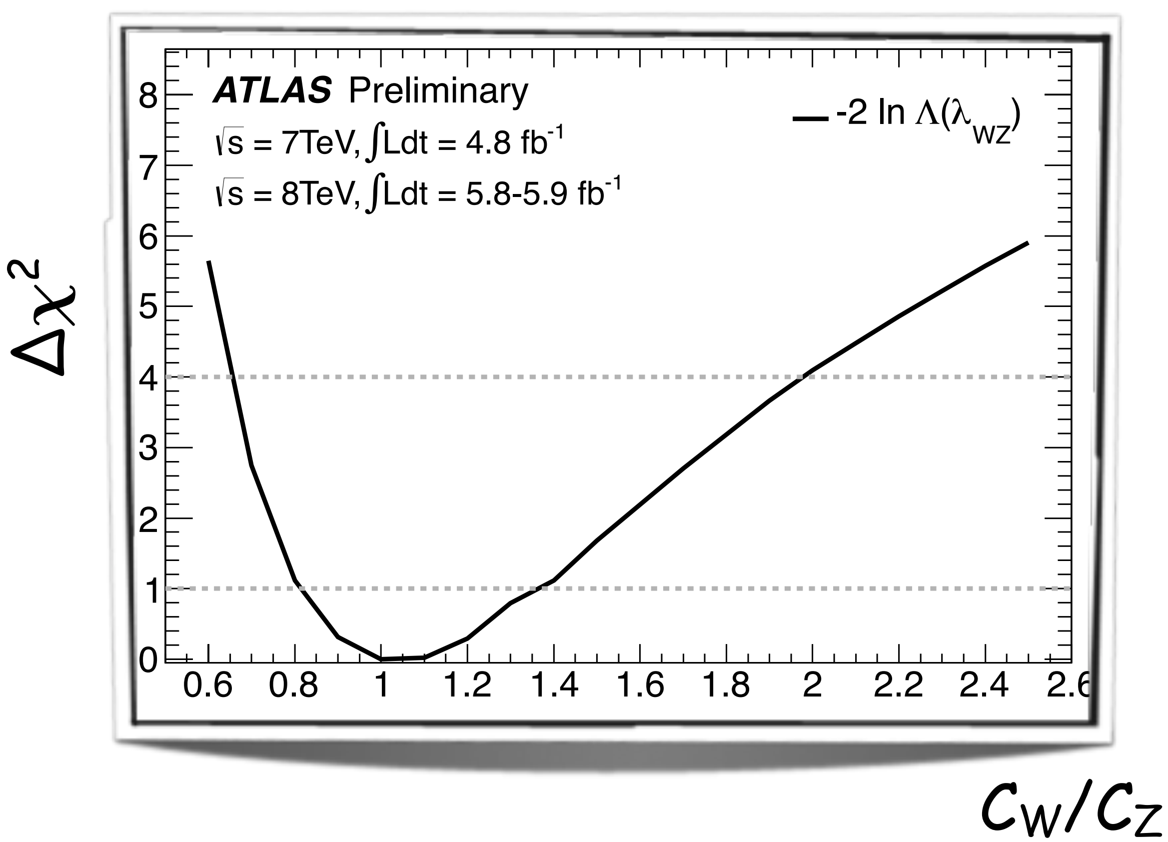
CMS

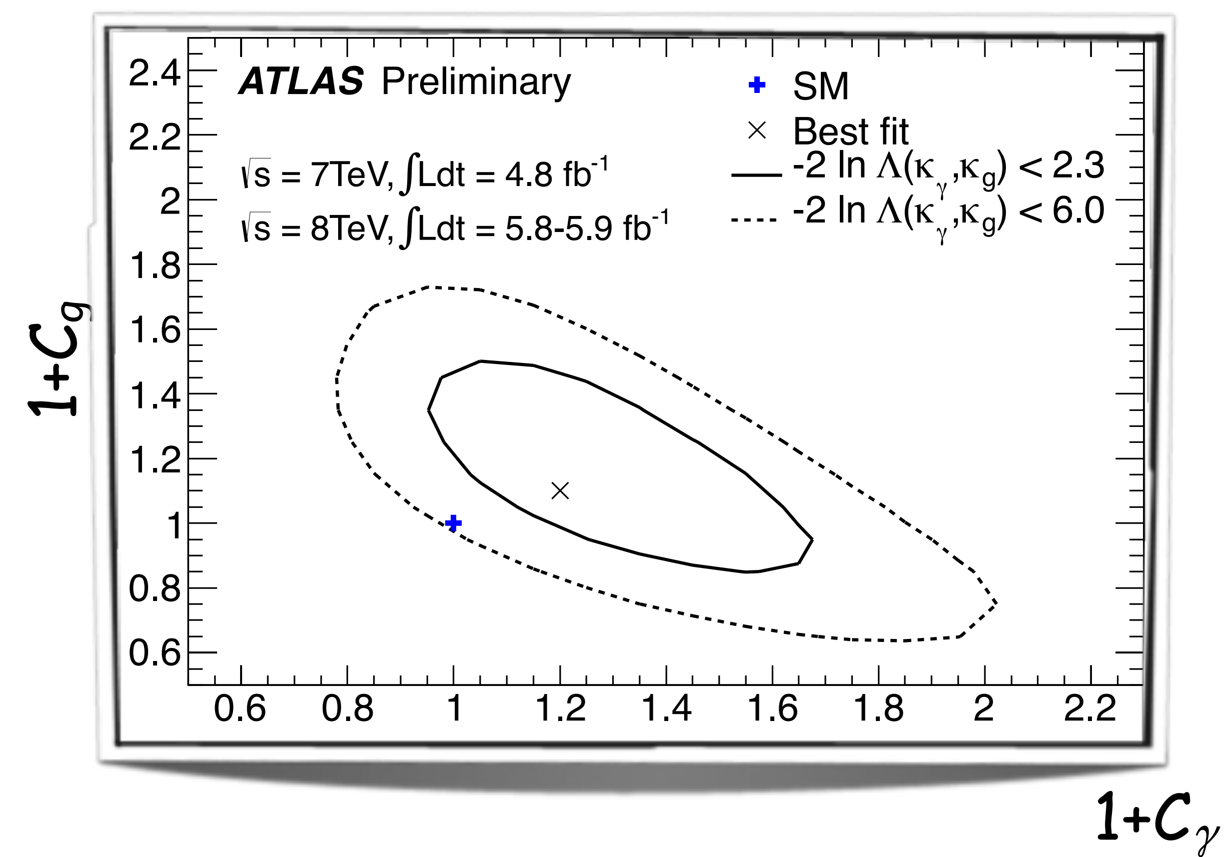


ATLAS

χ^2 fit: other tests of the SM structures

- 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: the need to go beyond current channels

the LHC measurements are plagued with several degeneracies

- inability to resolve the top loops

$$\mathcal{L} = \frac{\alpha_s c_g}{12\pi}|H|^2 G^{a\,2}_{\mu\nu} + \frac{\alpha c_\gamma}{2\pi}|H|^2 F_{\mu\nu} + y_t c_t \bar{q}_L \tilde{H} t_R |H|^2$$

$$\frac{\sigma(gg \to h)}{\mathrm{SM}} = (1 + (c_g - c_t)v^2)^2 \qquad \frac{\Gamma(h \to \gamma\gamma)}{\mathrm{SM}} = (1 + (c_\gamma - 4c_t/9)v^2)^2$$

cannot separate modified Yukawa from contact operators
having access to htt final state will resolve this degeneracy
fermionic top-partners in composite Higgs models exactly lead to $\Delta c_t = \Delta c_g = \frac{9}{4}\Delta c_\gamma$.

14%-4% @ LHC^{14}_{300}-LHC^{14}_{3000} vs 10%-4% @ ILC^{500}_{500}-$\mathrm{ILC}^{1000}_{1000}$

- inability to measure the total width

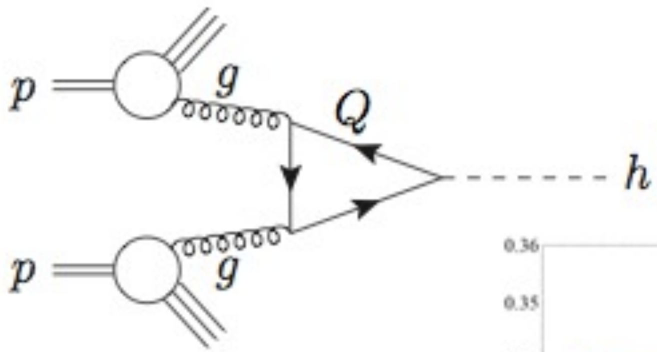
$$\mathcal{L} = \frac{c_H}{2}\left(\partial|H|^2\right)^2 \qquad \Gamma = (1 - c_H v^2/2)^2\, \Gamma_{\mathrm{SM}} + \Gamma_{\mathrm{inv.}}$$

cannot separate universal coupling rescaling from undetected width (portal to DM?)

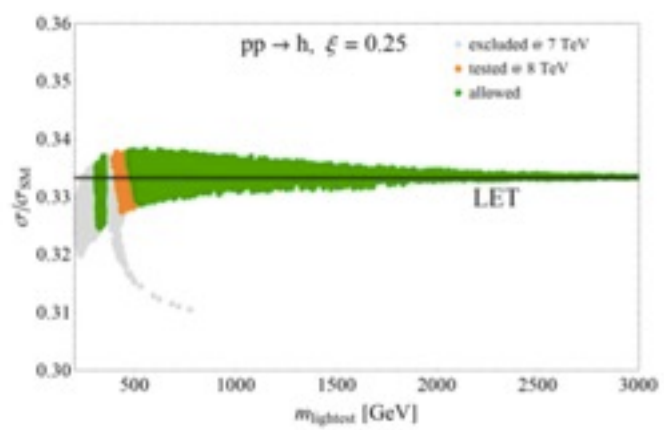
ILC^{500}_{500} can measure the Higgs width to 6% accuracy (BRinv up to 1%)

Top partners & Composite Higgs physics

~ current single higgs processes are insensitive to top partners ~



$\sigma^{SM}_{14\mathrm{TeV}} \approx 50$ pb



two competing effects that cancel:

- ☑ T's run in the loops
- ☑ T's modify top Yukawa coupling

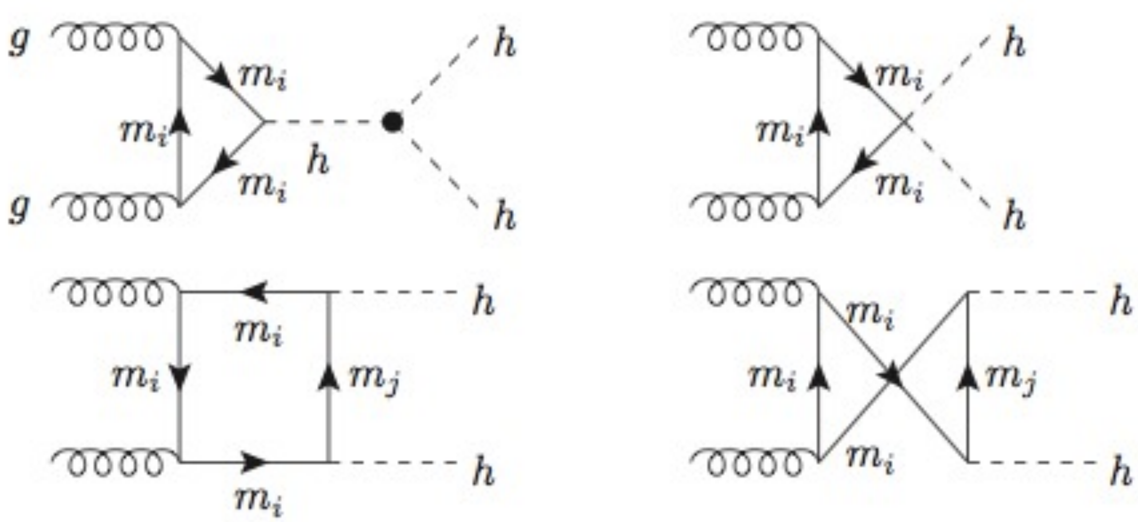
Falkowski '07

Azatov, Galloway '11

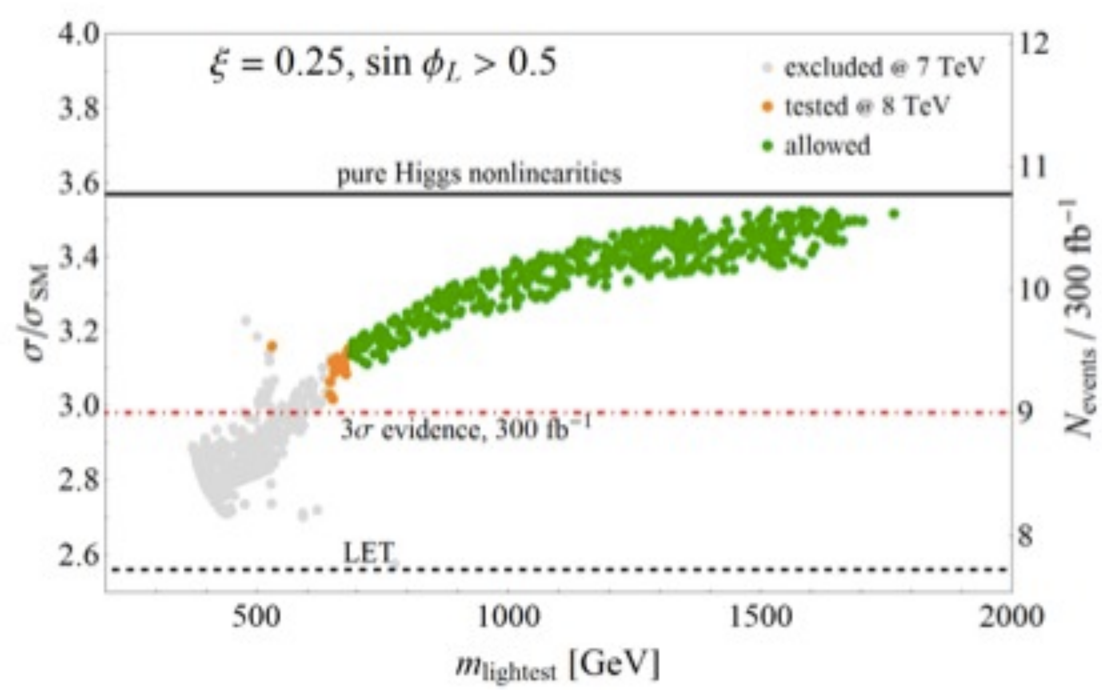
Delaunay, Grojean, Perez, '13

~ sensitivity in double Higgs production ~

Gillioz, Grober, Grojean, Muhlleitner, Salvioni '12



$\sigma^{SM}_{14\mathrm{TeV}} = 17.9$fb



The 2 questions about the Nature of the Higgs

1. Is the Higgs elementary or composite?

single Higgs production

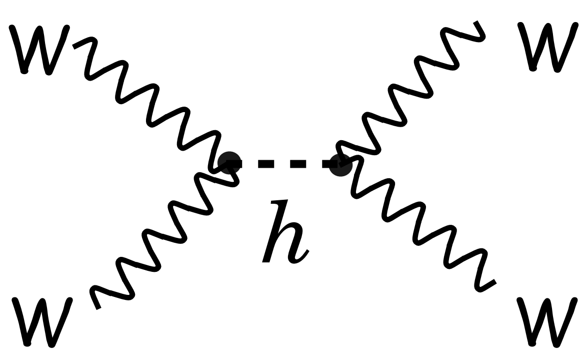
deviations in Higgs couplings can be due either to
1. weakly coupled light states
2. strongly coupled heavy states

$$\frac{\delta g_h}{g_h} \sim \frac{g_*^2}{g_{SM}^2}\frac{m_W^2}{M^2}$$

observing deviations of order δ_h and no new states up to M
would be an indication of Higgs compositeness

$$g_* > \sqrt{\delta_h}\ M/v$$

WW scattering



$$\mathcal{A} \sim \delta_h \frac{s}{v^2} \equiv g_*^2(E)$$

an excess δ_{hh} @ energy E
also gives a lower bound on g*

$$g_*(E) > \sqrt{\delta_{hh}}\ E/v$$

would be a direct evidence of Higgs compositeness

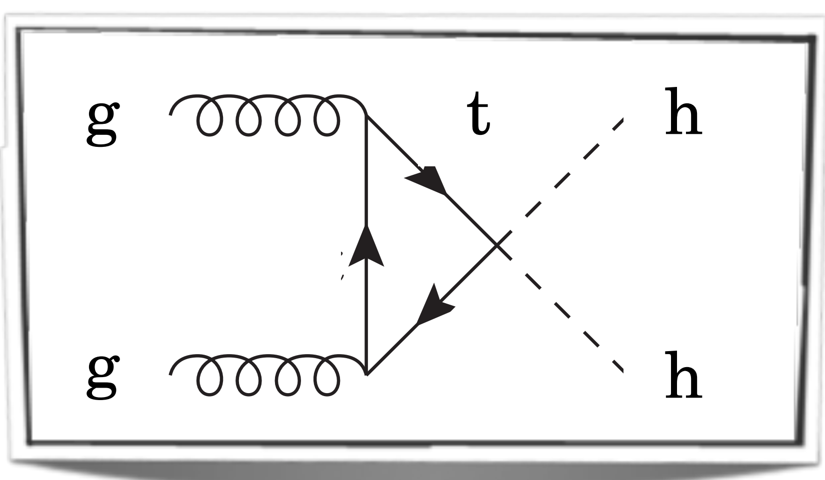
The 2 questions about the Nature of the Higgs

2. Is the Higgs part of an SU(2) doublet? Does New Physics flow towards the SM in the IR?

production and decay rates in agreement with SM is a good hint
but can never exclude a malicious conspiracy
and the SU(2)xU(1) quantum # of the Higgs cannot be measured in single higgs processes

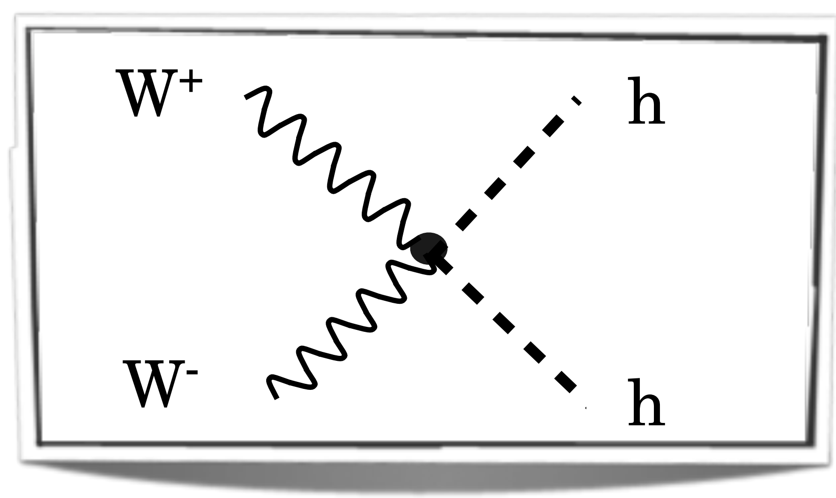
Higgs doublet?

not an easy question at the LHC since we need multi-Higgs couplings



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

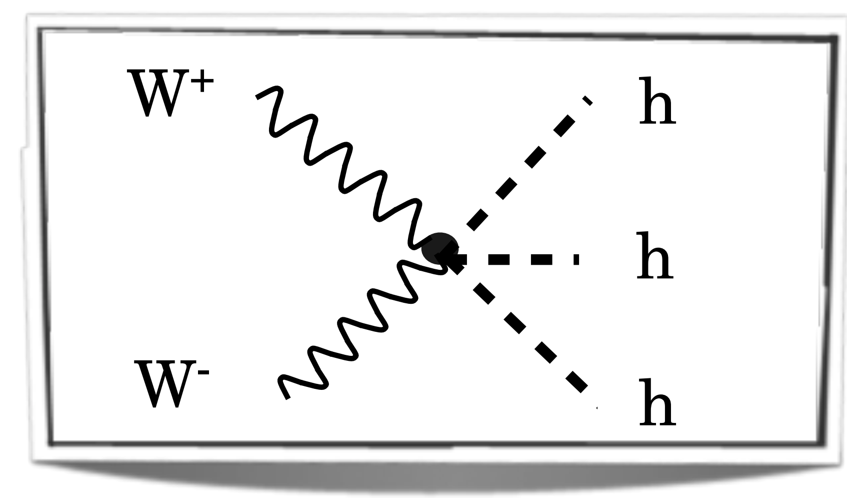
$$\sigma^{SM}_{14\mathrm{TeV}} \approx 20\,\mathrm{fb}$$



Contino, Grojean,
Moretti, Piccinini, Rattazzi '10

$b_V - 1 = 2(c_V^2-1) + O(c_V^2-1)^2$

$$\sigma^{SM}_{14\mathrm{TeV}} \approx 0.5\,\mathrm{fb}$$



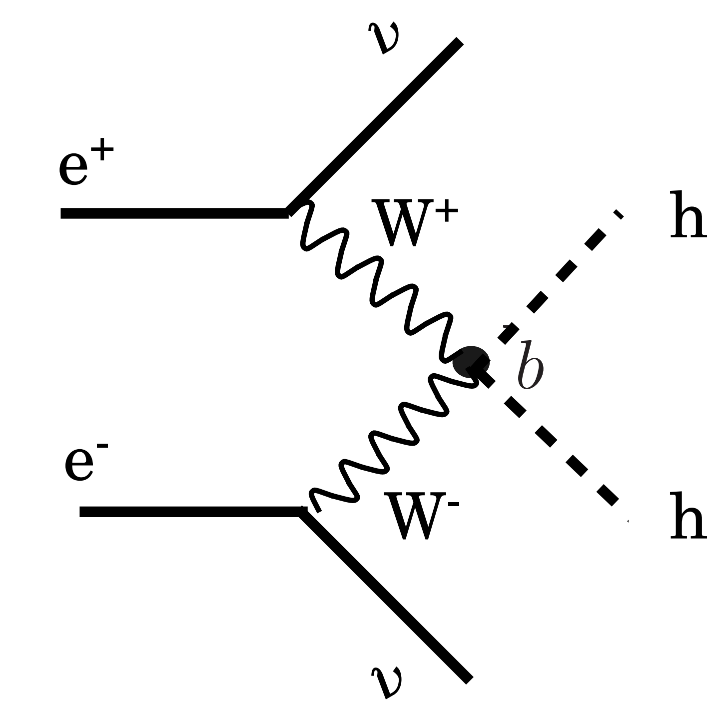
Contino, Grojean, Pappadopoulo,
Rattazzi, Thamm 'to appear

$3b_{3V} = 4\, c_V(b_V - c_V^2) + O(c_V^2-1)^2$

$$\sigma^{SM}_{14\mathrm{TeV}} < 1\,\mathrm{ab}$$

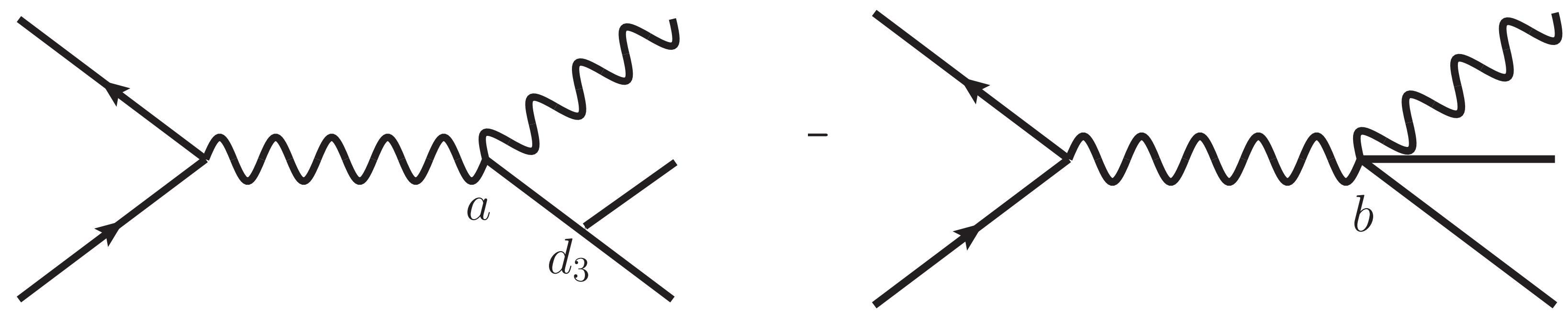
(single Higgs production by gluon fusion: $\sigma^{SM}_{14\mathrm{TeV}} \approx 50\,\mathrm{pb}$)

Double Higgs production



$\sigma^{\rm SM}_{3\ \rm TeV} \sim 1\ \rm fb$ $\sigma^{\rm SM}_{500\ \rm GeV} \sim 0.01\ \rm fb$

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



Higgs self-coupling:
difficult measurement
won't teach us much about NP

double Higgsstrahlung
maximal at √s=500GeV

$\rm ILC^{500}_{1000}$ can measure the linear Higgs couplings with % accuracy but limited on quad. coup.

$\rm CLIC^{3TeV}_{1000}$ can measure the quadratic Higgs couplings with % accuracy

Higgs is a doublet		Higgs is a Goldstone boson	
$b_V - 1 = 2(c_V^2-1) + O(c_V^2-1)^2$	(*)	$b_V - 1 = 2(c_V^2-1)$	(**)

Given the % precision on 'c_V' and 'b_V', if we see some deviations, what can we conclude

- 1% deviations: we can tell if (*) is fulfilled, hence tell if h is part of a doublet (for instance for a dilaton $b_V - 1 = (c_V^2-1)$)
- 10% deviations: we can distinguish (*) from (**) and tell if h is a Goldstone or not

Higgs rare decays

1

ILC TDR, '13

Mode	LHC	ILC(250)	ILC500	ILC(1000)
WW	4.1 %	1.9 %	0.24 %	0.17 %
ZZ	4.5 %	0.44 %	0.30 %	0.27 %
$b\bar{b}$	13.6 %	2.7 %	0.94 %	0.69 %
gg	8.9 %	4.0 %	2.0 %	1.4 %
$\gamma\gamma$	7.8 %	4.9 %	4.3 %	3.3 %
$\tau^+\tau^-$	11.4 %	3.3 %	1.9 %	1.4 %
$c\bar{c}$	–	4.7 %	2.5 %	2.1 %
$t\bar{t}$	15.6 %	14.2 %	9.3 %	3.7 %
$\mu^+\mu^-$	–	–	–	16 %
self	–	–	104%	26 %
BR(invis.)	$<$ 9%	$<$ 0.44 %	$<$ 0.30 %	$<$ 0.26 %
$\Gamma_T(h)$	20.3%	4.8 %	1.6 %	1.2 %

h → μμ (together with h → ττ):

provides an insight into lepton mass generation

h → cc:

provides an insight into 2nd gen. mass generation

2

Look for SM forbidden LF violating decays h → μτ and h → eτ

- not currently strongly constrained: BR<10% Blankenburg, Ellis, Isidori '12
- ATLAS and CMS have in principle the sensitivity to set bounds O(1%) Harnik et al '12, Davidson, Verdier '12
- but ILC/CLIC can certainly do much better

3

Isidori et al '13

VP mode	$\mathcal{B}^{\rm SM}$	VP^* mode	$\mathcal{B}^{\rm SM}$
$W^-\pi^+$	0.6×10^{-5}	$W^-\rho^+$	0.8×10^{-5}
W^-K^+	0.4×10^{-6}	$Z^0\phi$	0.4×10^{-5}
$Z^0\pi^0$	0.3×10^{-5}	$Z^0\rho^0$	0.4×10^{-5}
$W^-D_s^+$	2.1×10^{-5}	$W^-D_s^{*+}$	3.5×10^{-5}
W^-D^+	0.7×10^{-6}	W^-D^{*+}	1.2×10^{-6}
$Z^0\eta_c$	1.4×10^{-5}	Z^0J/ψ	1.4×10^{-5}

rare semi-hadronic decays of the type

h → W/Z+P

can be a good probe of NP

⇓ ⇓

we need to estimate ILC/CLIC sensitivities

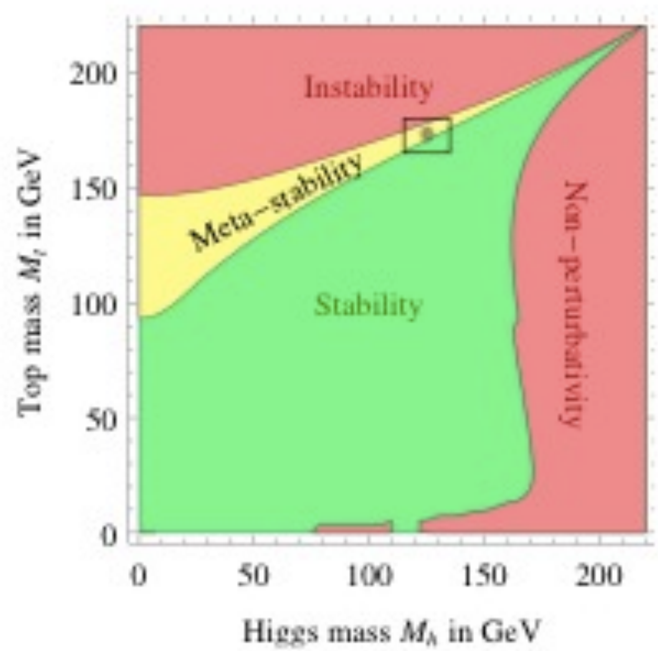
Early Universe Implications

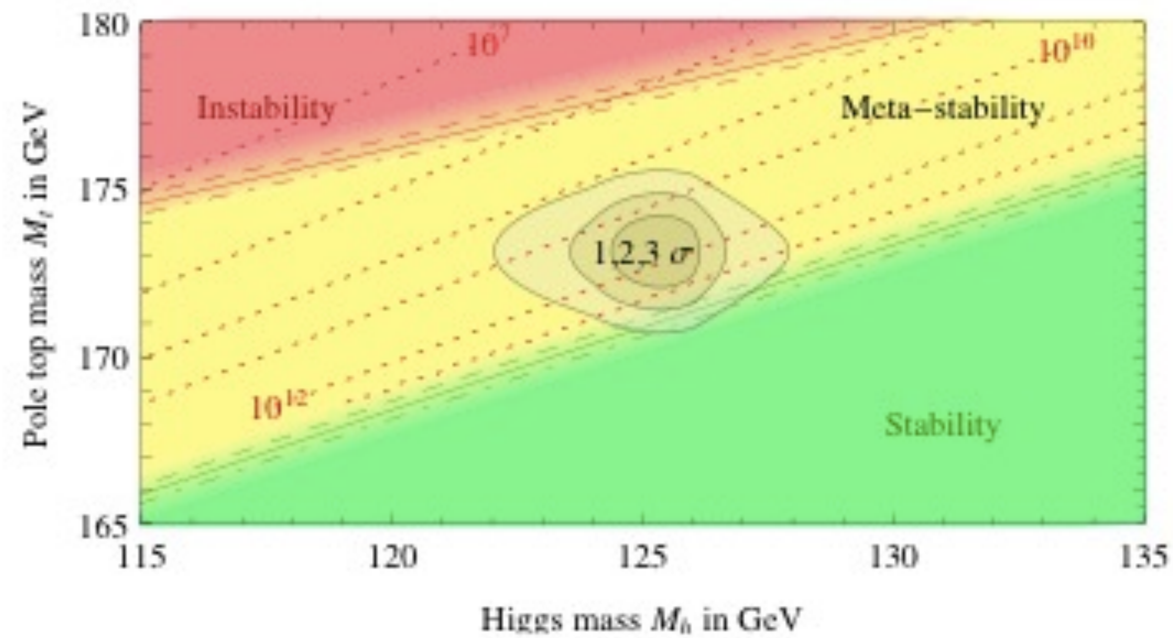
The fate of the EW vacuum

Many of my theory colleagues also started wild speculations/extrapolations

the SM vacuum is stable/metastable

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





Bezrukov et al ’12
Degrassi et al ’12

It is almost certain (>4σ) that $m_H > M_{mestability}$ and totally certain that $m_H < M^{h^3}_{Landau}$

(even though this certainty might by questioned by threshold effects at the Planck scale Holthausen, Lim and Lindner ’12)

Not totally clear yet if m_H is above $M_{stability}$, but rather important question since

- ☑ if $m_H > M_{stability}$, the Higgs could serve as an inflaton
- ☑ if $m_H = M_{stability}$ the SM is asymptotically safe, ie consistent up to arbitrary high energy

Bezrukov et al ’12

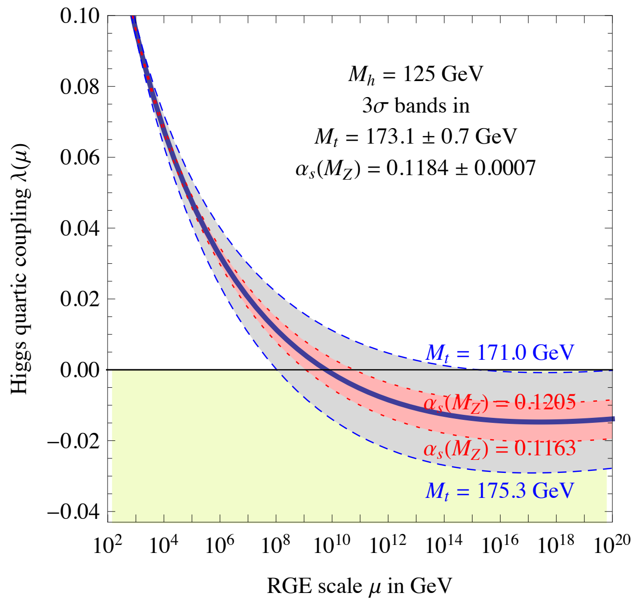
need precise Higgs&top mass/couplings (and α_s) measurements (ILC, μ coll.)

and better understanding of pole vs MS top mass Alekhin, Djouadi, Moch ’12

ILC: m_{top} with 100 MeV accuracy (efficency of final b=90% & particle flow jet E reconstruction: 4%)

From the EW scale to M_{Pl}... and return

Many of my theory colleagues started wild speculations/extrapolations



$$\lambda(M_{Pl}) = -0.0144 + 0.0028\left(\frac{M_h}{\text{GeV}} - 125\right) \pm 0.0047_{M_t} \pm 0.0018_{\alpha_s} \pm 0.0028_{\text{th}}$$

Degrassi et al '12

is the Higgs potential vanishing potential at M_{Pl}?

Froggatt, Nielsen, Takanishi '01
Arkani-Hamed et al '08
Shaposhnikov, Wetterich '09

EWSB determined by Planck physics? M_{Pl} calculable from weak scale non-gravitational quantities?
absence of new energy scale between the Fermi and the Planck scale?
Anthropic vs. natural EWSB...

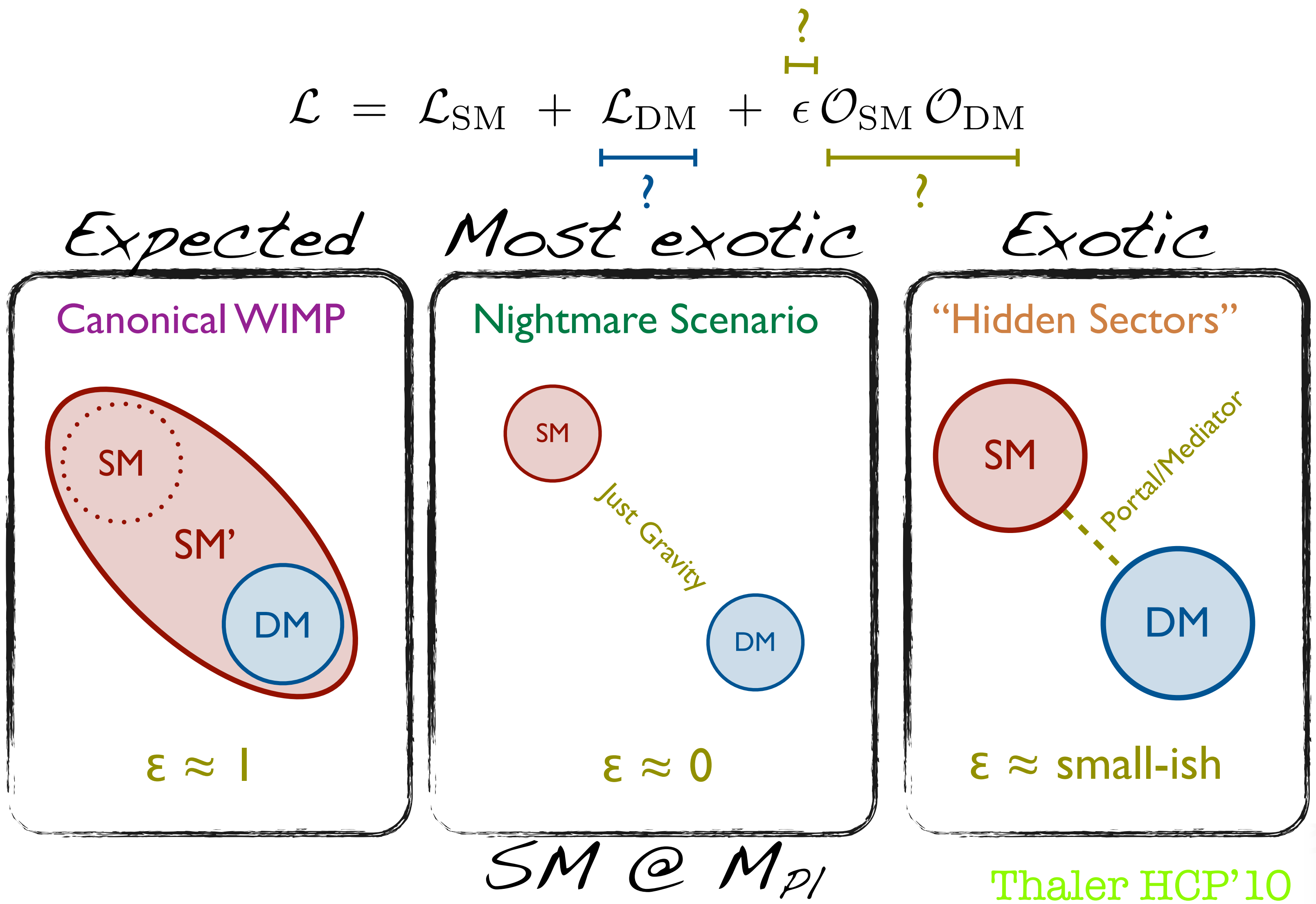
But these implications are based on the assumptions
(1) that the 126 GeV particle observed is *exactly* the SM Higgs
(2) that the Dark Matter sector is decoupled from the weak sector

From the EW scale to M_{Pl}... and return

Many of my theory colleagues started wild speculations/extrapolations

SM/DM Couplings

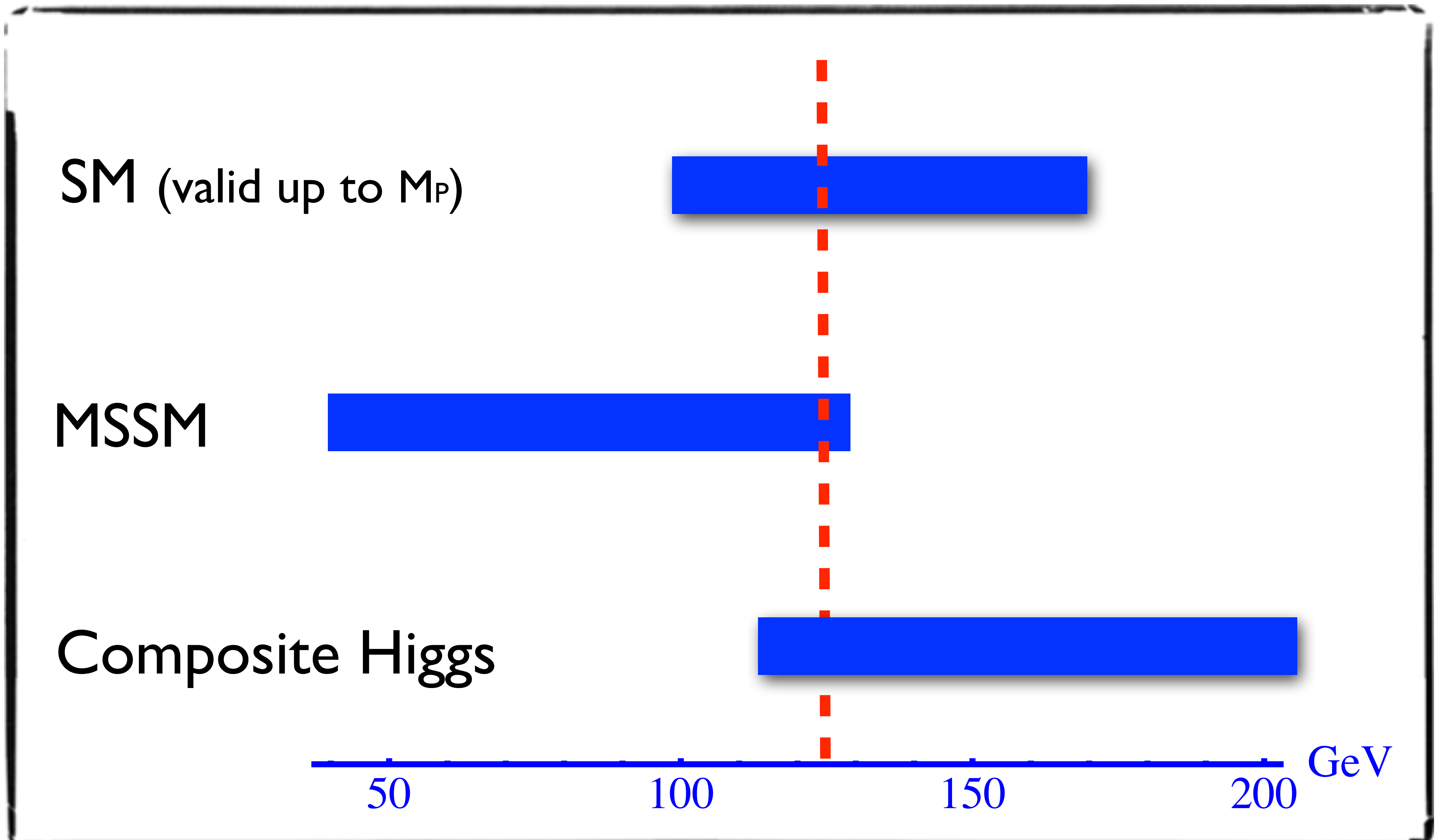
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \epsilon\, \mathcal{O}_{\rm SM}\, \mathcal{O}_{\rm DM}$$



Thaler HCP'10

125 GeV Higgs = Exotic BSM?

the value of the Higgs mass
together with the absence of any additional new physics so far
restrict any BSM model to exotic corners of its parameter space



Pomarol ICHEP'12

disclaimer
the notion of "exotic" has to be understood on a statistical basis, ie it depends on our culture (=what we are used to)
and there will always be someone to claim that his/her model is the most natural one

Weakly coupled models

Higgs & SUSY/MSSM

no new super-particles ⋯→ decoupling limit?

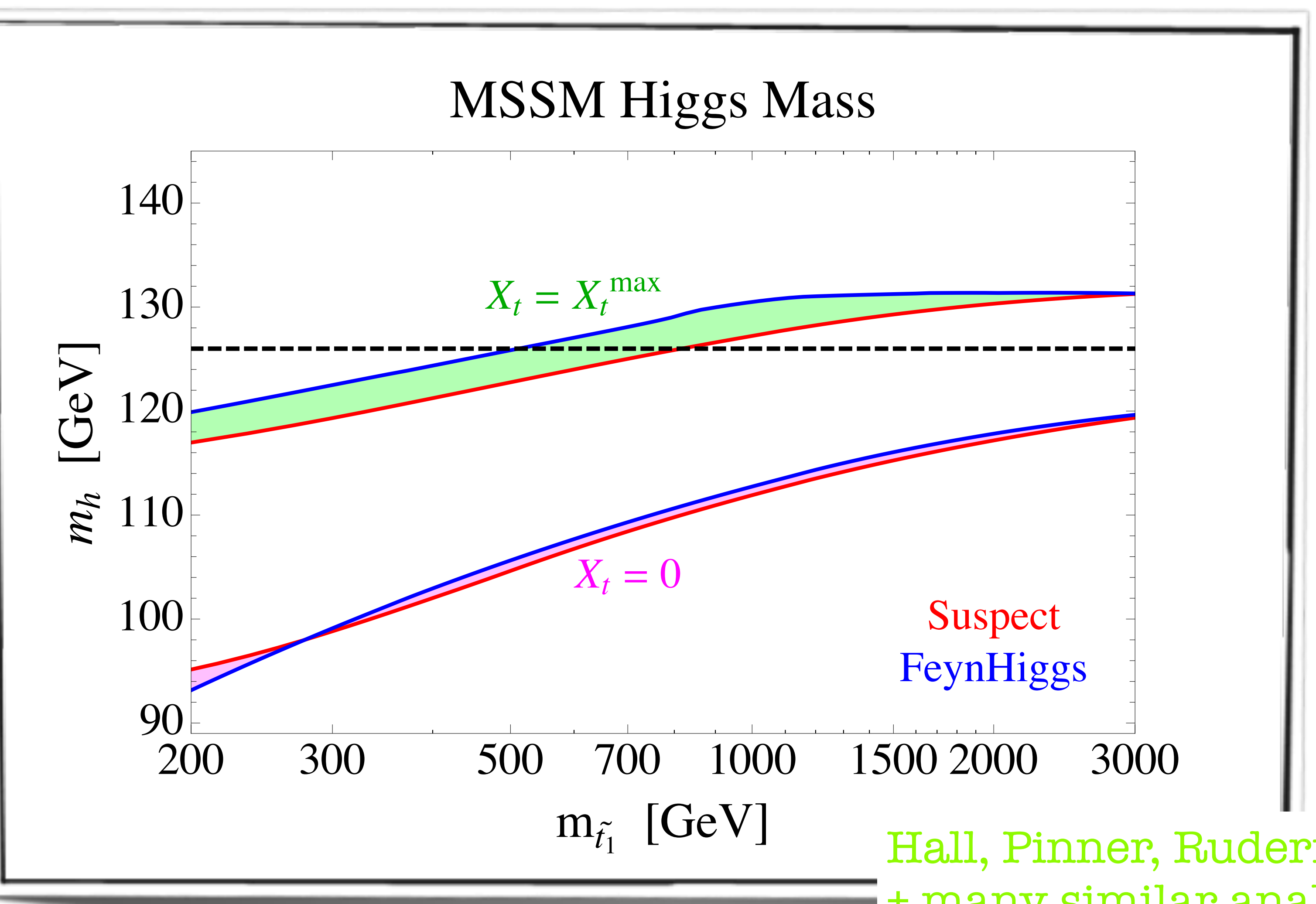
high Higgs mass
implies
susy is badly broken

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

(125 GeV)²

(≳ 87GeV)²

substantial loop contribution
from stops



Hall, Pinner, Ruderman '11
+ many similar analyses

large mixing
heavy stops

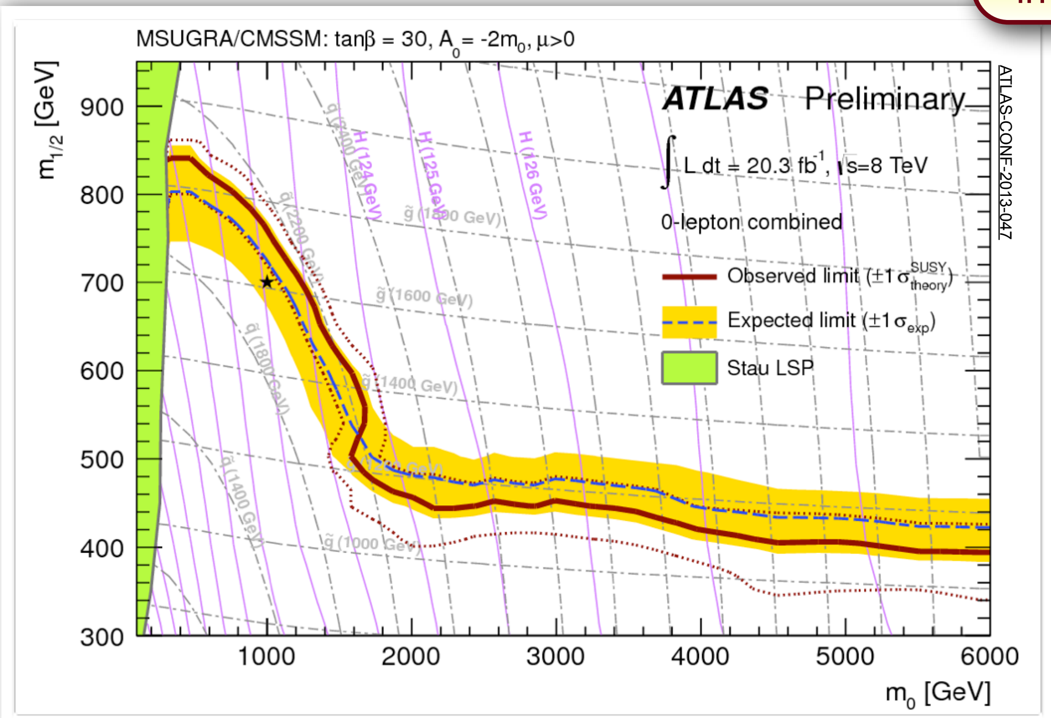
$$\sqrt{m_{Q_3} m_{u_3}} \gtrsim 700 \text{ GeV}$$

⇓ ⇓

irreducible
fine-tuning ~ O(1%)

Cornering SUSY parameter space

in the context of a concrete model, here MSUGRA/cMSSM

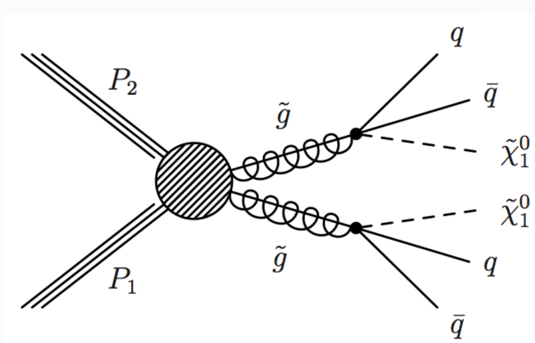


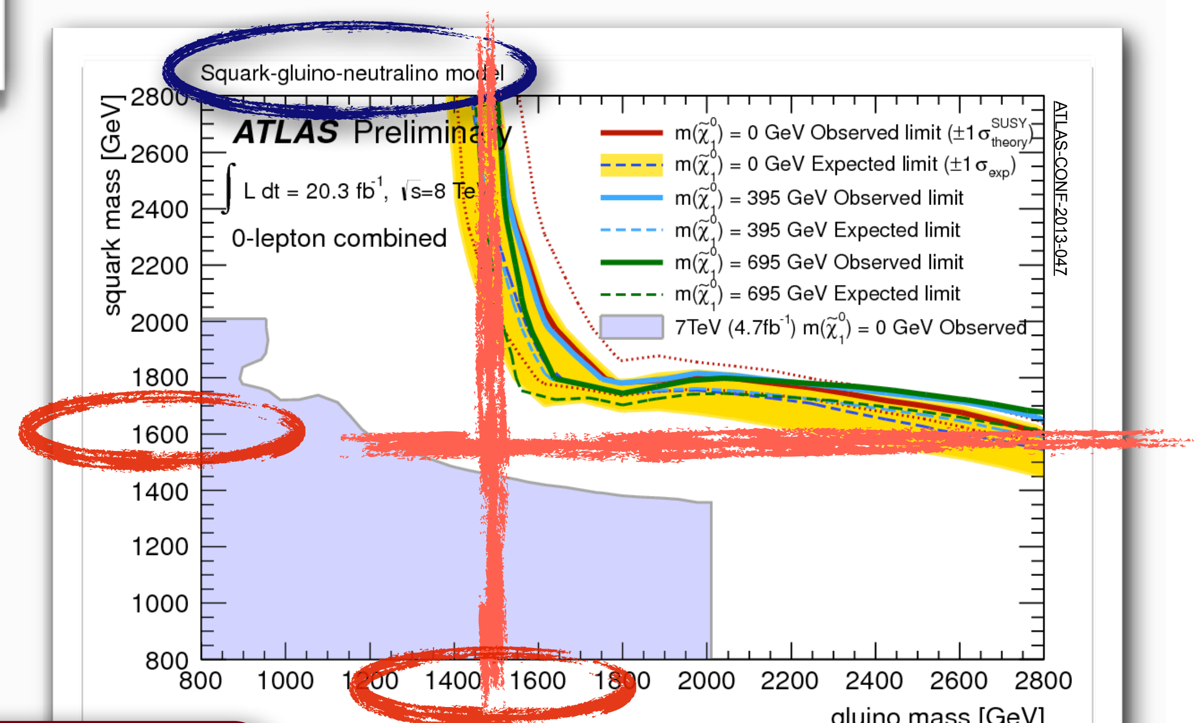
here: example of scenario compatible with a low-mass Higgs as recently discovered

- **eg. for m(squark) = m(gluino), exclude below ~1800 GeV**
- these searches typically target large M_{eff} and large difference m(SUSY) - m(LSP)
- the very inclusive searches keep sensitivity even for m(LSP) up to several hundreds of GeV (at some stage trigger-constrained)

see Dissertori's talk

- recently also targeting more compressed spectra and higher jet multiplicities





in the context of a simplified MSSM scenario

These bounds are not "robust" and don't exclude weak scale SUSY but call for non-minimal models

Saving SUSY

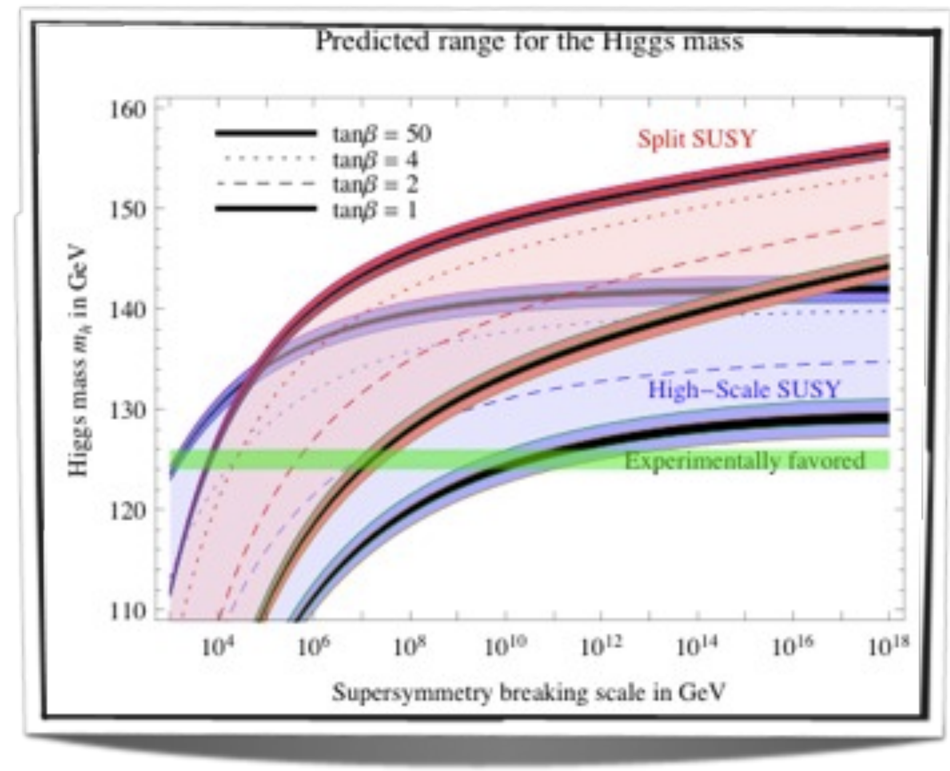
SUSY is Natural but not plain vanilla

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

Should be priority #1

ILC can complement LHC

SUSY solves the big hierarchy (or not even that) but not the little hierarchy



unification etc... →

- Split SUSY: Giudice, Strumia '11
  susy scalars @ m_{susy}, susy fermions @ m_Z

string etc... →

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

Searching SUSY @ ILC

1

A. Pomarol, lecture @ CERN, '13

SUSY is natural but not minimal

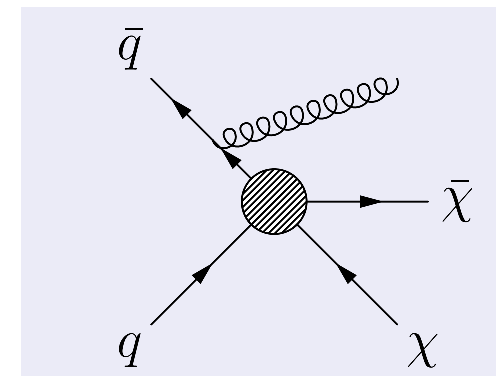
Stops and **Higgsinos** are the lightest sparticles:

$$\mu^2 + m_{H_u}^2 = -\frac{m_h^2}{2} \approx -(88\ \text{GeV})^2$$

$$\delta m_{H_u}^2 = -\frac{3y_t^2}{8\pi^2}\left(m_{Q_3}^2 + m_{u_3}^2 + |A_t|^2\right)\ln\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$$

➥ Stop mass ~ 500 GeV
Higgisinos mass ~ 100 GeV

Pair produced Higgsinos are difficult to observe
(low $\not{E}_T$ soft non-isolated leptons)!
monojet/monophoton + $\not{E}_T$ searches



LEP1 bound (100GeV) still holds

Good prospects @ ILC
(see benchmarks of ILC TDR)

2 ILC has also immense capabilities with EW gauginos

3 ILC can also help identifying SUSY thanks to its unique capability to determine the spin of the particles

Conclusions: Higgs = Person of year 2012?

as of 06/12/12

TIME
Person of the Year

Magazine | Video | LIFE | Person of the Year

NEWSFEED | U.S. | POLITICS | WORLD | BUSINESS | TECH | HEALTH | SCIENCE | ENTERTAINMENT | STYLE

2012 2011 2010 2009 2008

Who Should Be TIME's Person of the Year 2012?

As always, TIME's editors will choose the Person of the Year, but that doesn't mean readers shouldn't have their say. Cast your vote for the person you think most influenced the news this year for better or worse. Voting closes at 11:59 p.m. on Dec. 12, and the winner will be announced on Dec. 14.

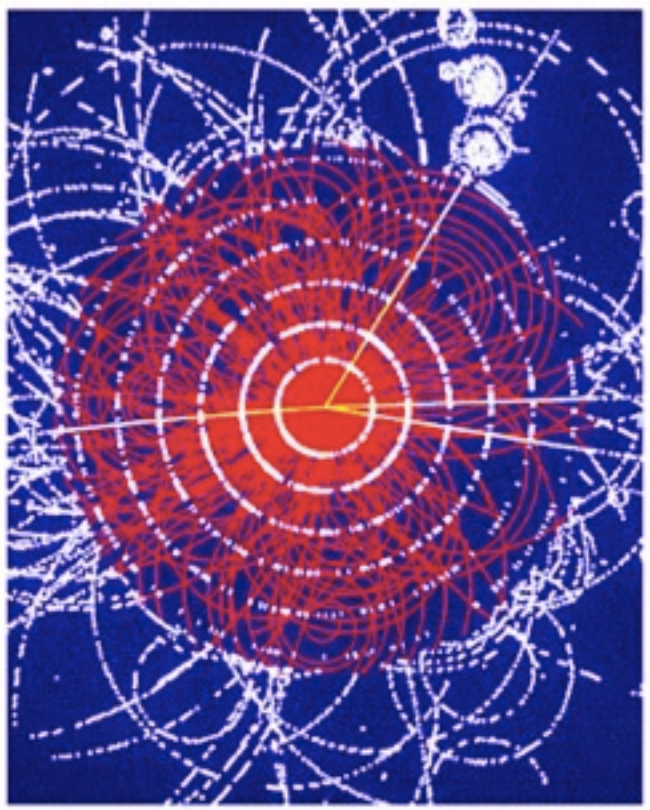
Like 1.5k | Tweet 536 | +1 20 | Share 7

THE CANDIDATES

The Higgs Boson

18 of 40

By Jeffrey Kluger | Monday, Nov. 26, 2012



SSPL/GETTY IMAGES

Simulation of a Higgs-Boson decaying into four muons, CERN.

What do you think?

Should The Higgs Boson be TIME's Person of the Year 2012?

Definitely | No Way

VOTE

Take a moment to thank this little particle for all the work it does, because without it, you'd be just inchoate energy without so much as a bit of mass. What's more, the same would be true for the entire universe. It was in the 1960s that Scottish physicist Peter Higgs first posited the existence of a particle that causes energy to make the jump to matter. But it was not until last summer that a team of researchers at Europe's Large Hadron Collider — Rolf Heuer, Joseph Incandela and Fabiola Gianotti — at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The Higgs — as particles do — immediately decayed to more-fundamental particles, but the scientists would surely be happy to collect any honors or awards in its stead.

Photos: Step inside the Large Hadron Collider.

WHO SHOU
YEAR 2012

The Candidates
Video
Poll Results

PAST PERS

2011: The

2009: Ben

Most Read

1 Who S
2 LIFE B the Fa
3 Nativ
4 The $7 Coffee

Name	Definitely	No Way
Kim Jong Un	4,295,657	129,581
Jon Stewart	924,111	58,864
Undocumented Immigrants	667,023	74,312
Aung San Suu Kyi and Thein Sein	563,922	53,253
Gabby Douglas	533,606	74,583
Stephen Colbert	526,534	66,301
Chris Christie	521,277	87,263
Hillary Clinton	506,973	84,007
Ai Weiwei	480,147	72,596
Mohamed Morsi	427,956	1,023,857
Roger Goodell	397,952	93,874
Sheldon Adelson	388,787	151,562
Malala Yousafzai	297,535	46,968
E.L. James	272,248	99,274
Bashar Assad	264,088	156,161
The Mars Rover	95,701	58,080
Psy	95,600	94,624
Barack Obama	84,161	96,045
Felix Baumgartner	73,234	78,747
The Higgs Boson Particle	68,927	54,589
Pussy Riot	53,194	77,026
Bill Clinton	45,108	80,799
Sandra Fluke	39,730	79,275
Michael Phelps	39,616	87,722
Mitt Romney	29,[illegible]24	116,700
Joe Biden	27,61[illegible]	96,187
John Roberts	23,240	74,646
Mo Farah	20,577	75,041
Benjamin Netanyahu	20,450	125,499
Marissa Mayer	19,636	83,571
Michael Bloomberg	19,509	93,629
Paul Ryan	16,662	103,846
Jay-Z	13,558	105,935
Tim Cook	12,406	95,050
Mario Draghi	12,303	80,305
Xi Jinping	10,092	77,441
Bo Xilai	8,015	93,314
Karl Rove	5,336	103,841

??

20/40

[slide stolen from A. David talk@LHCHXSWG CERN '12]

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as of 06/12/12

TIME
Person of the Year

Magazine | Video | LIFE | Person of the Year

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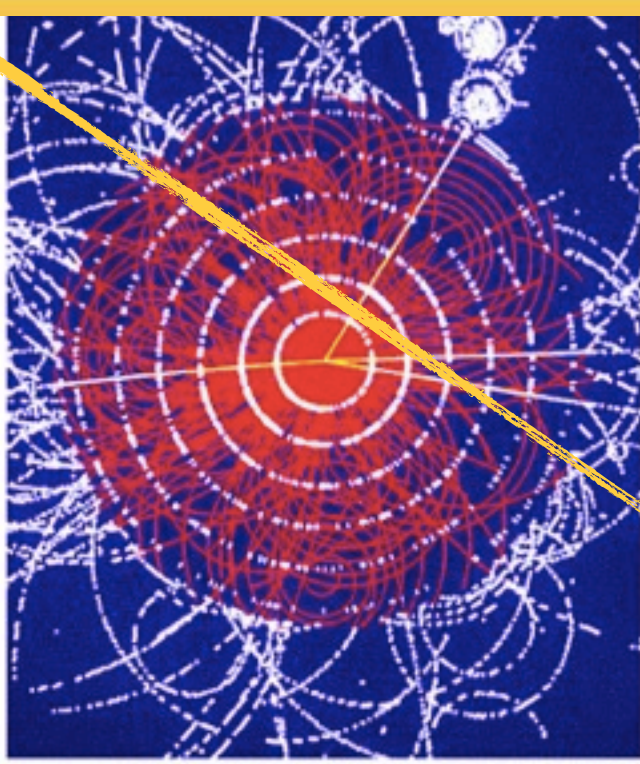

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20/40

[slide stolen from A. David talk@LHCHXSWG CERN '12]

Conclusions: Higgs = Person of year 2012?

Conclusions: Higgs = Person of year 2013?

A Nobel prize? A Milner prize?

An approved ILC?

we'll see in the fall, but we can already celebrate...

2013 Prince of Asturias Award for Technical and Scientific Research

...better than nothing!