The scalar sector of the SM and beyond

HEP-EPS 2013

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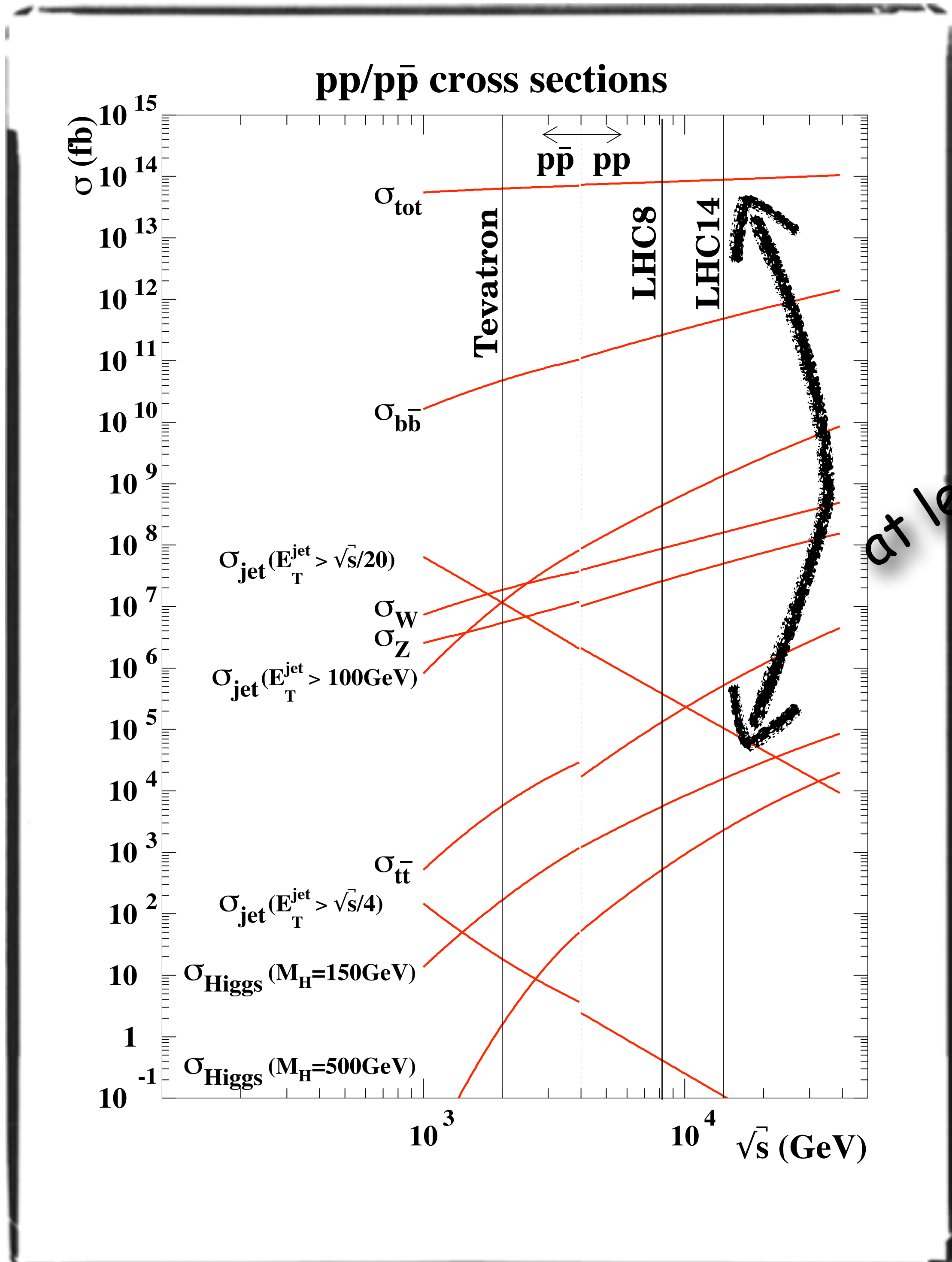
We are living a privileged moment in the history of HEP

SM Higgs @ LHC

The production of a Higgs is wiped out by QCD background



at least 10 orders of magnitude

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

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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 copies of) John Ellis' office

Now what?

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

the words of a string theorist

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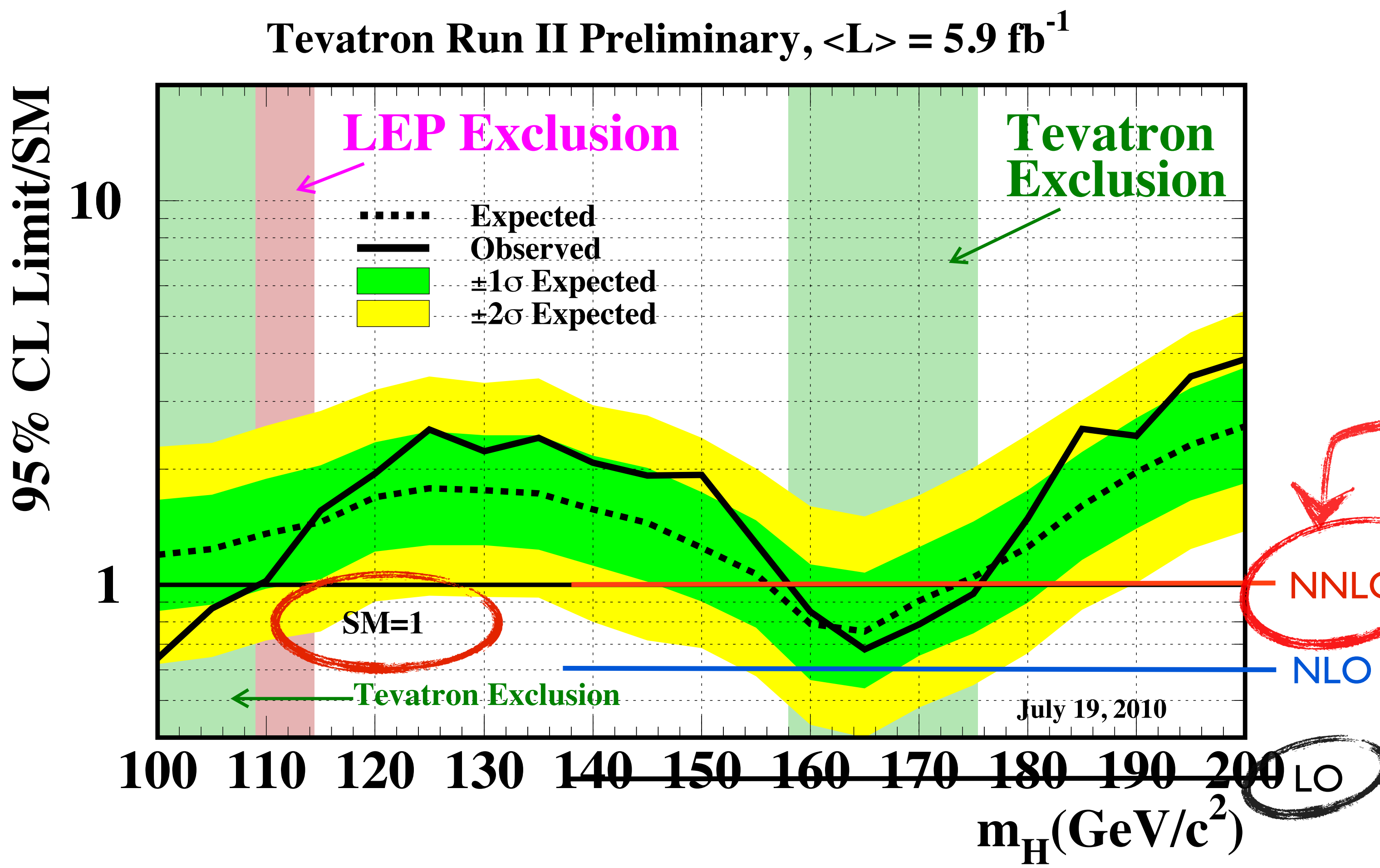
Why did it work better than expected?



- 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

K-factor ≈ 1.25

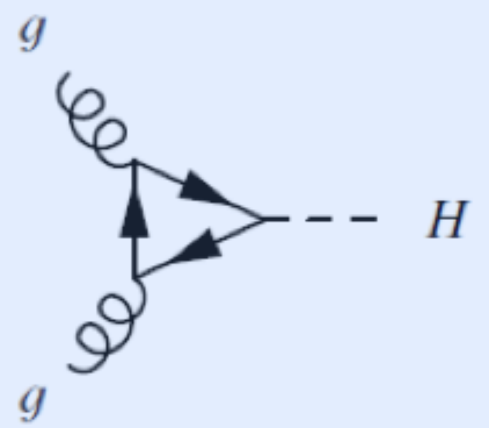
K-factor ≈ 2

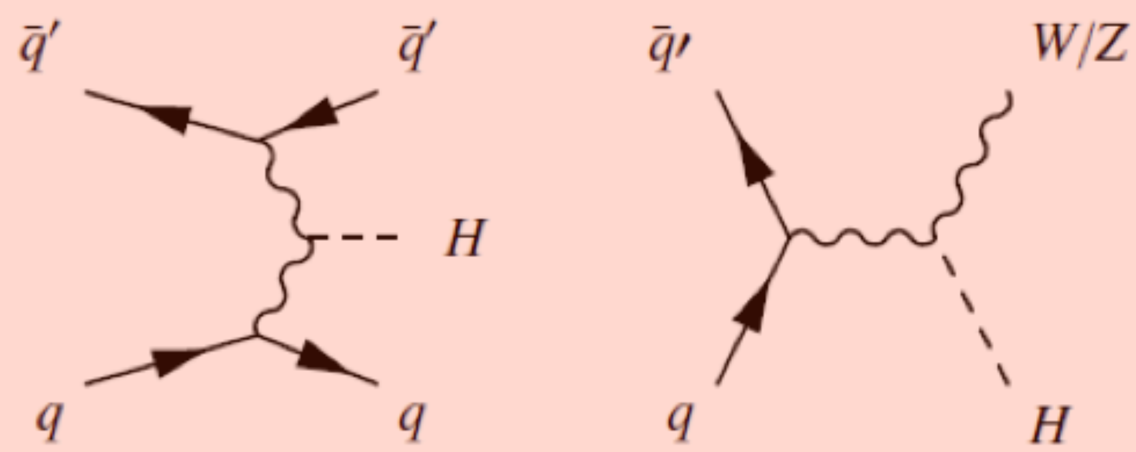
R. Harlander, talk @ LHCP'13

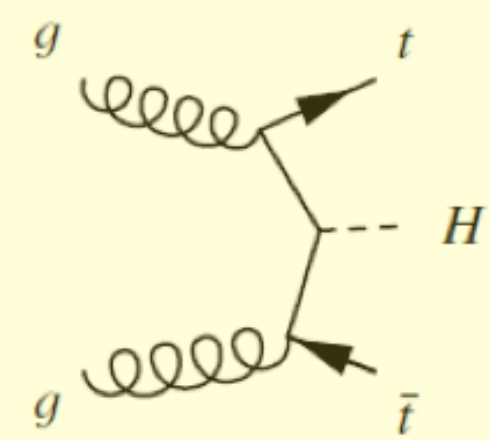
SM Precision Higgs Physics

SM Higgs computations: State of the art

e.g. LHCHXSWG YR1 & YR2 & YR3







~TODAY~

N^2LO+N^2LL QCD

NLO EW

N^2LO QCD

NLO EW

NLO QCD

~TOMORROW~

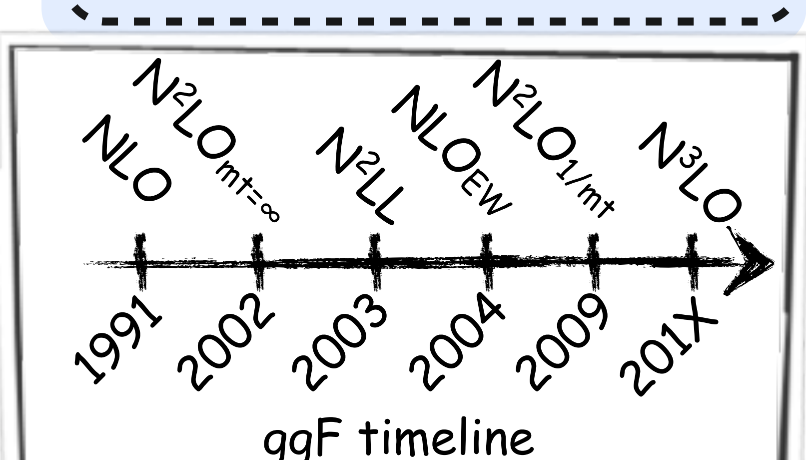
inclusive	Higgs p_T
N^3LO QCD	NLO QCD
$(m_t=\infty)$	w/ finite m_t, m_b
	(3 scale pb!)

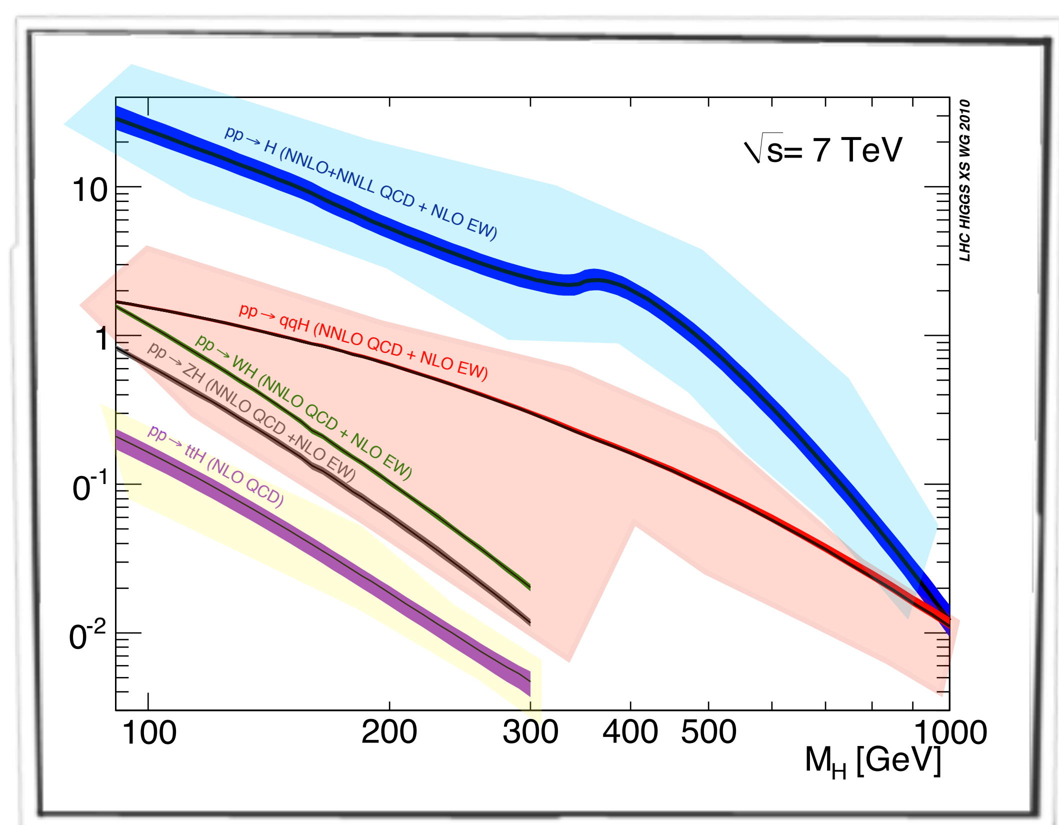
see also De Florian's talk

NLO results in MC

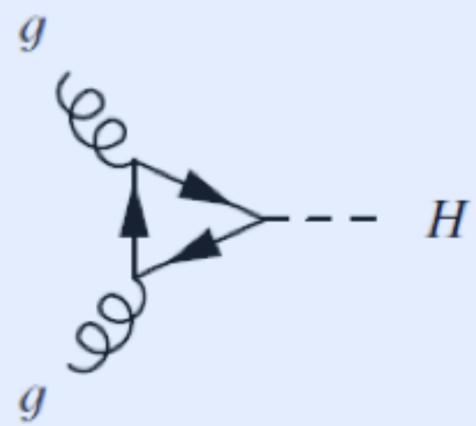
POWHEG, aMC@NLO

+ N^2LO PDF sets





The ggH Frontiers



~TODAY~

N^{2}LO+N^{2}LL QCD

NLO EW

~TOMORROW~

inclusive	Higgs p_T
N^{3}LO QCD	NLO QCD
($m_t=\infty$)	w/ finite m_t,m_b
	(3 scale pb!)

2 → 2 @ 2-loop

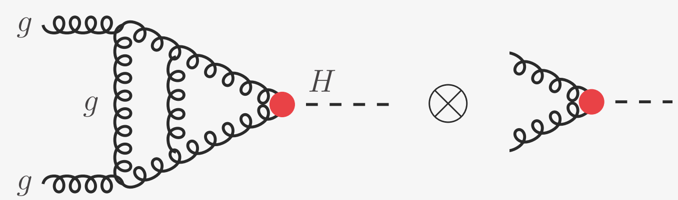
similar to ttbar @ N^{2}LO

recently achieved by Czakon/Mitov

2 → 1 @ 3-loop

Inclusive XS

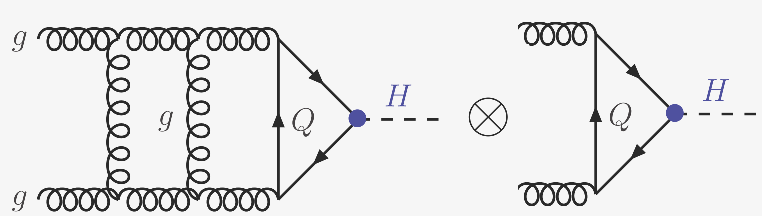
N^{2}LO$_\infty$ α_s^4 2-loop



g_s^6 $\otimes$ g_s^2

Harlander, Kilgore '02 Anastasiou, Melnikov '02

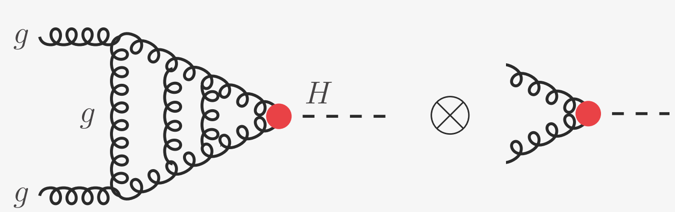
N^{2}LO$_{mt}$ α_s^4 3-loop



g_s^6 $\otimes$ g_s^2

first corrections in 1/mt: Harlander et al '09

N^{3}LO$_\infty$ α_s^5 3-loop

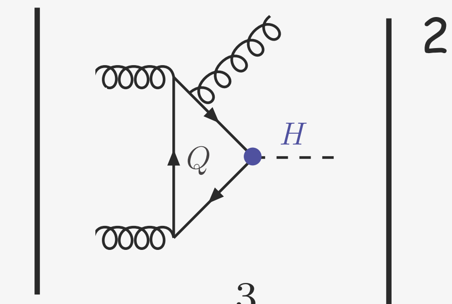


g_s^8 $\otimes$ g_s^2

first steps: Baikov, Chetyrkin '06 Ball et al '13

Higgs p_T

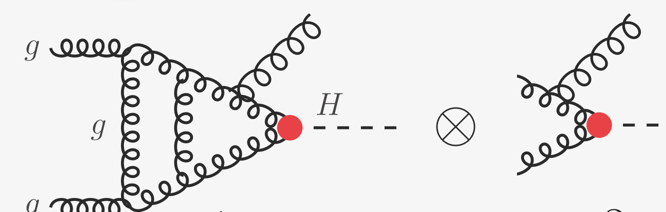
LO$_{mt}$ α_s^3 1-loop



g_s^3

Baur, Glover '90

N^{2}LO$_\infty$ α_s^5 2-loop



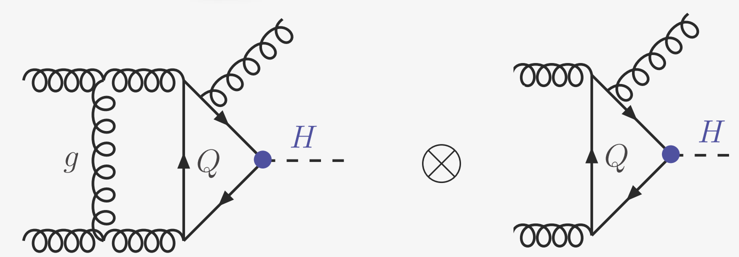
g_s^7 $\otimes$ g_s^3

Boughezal et al '13

~TODAY~

~TOMORROW~

NLO$_{mt}$ α_s^4 2-loop



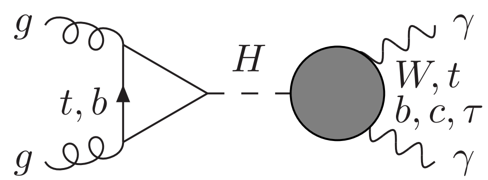
g_s^5 $\otimes$ g_s^3

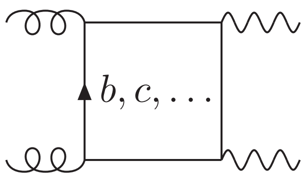
first corrections in 1/mt: Harlander et al '12

Signal/Background Interference

Naively small since the width is small (Γ_H=4MeV, Γ_H/m_H =3x10^{-5}) for a light Higgs

but S: gg➤h➤$\gamma\gamma$ = 2-loop versus B: gg➤$\gamma\gamma$ = 1-loop





Dicus, Willenbrock '88

Dixon, Siu '03

could have expected x10% corrections in the rate

but malicious/accidental cancelation ➤ 2-3% effect

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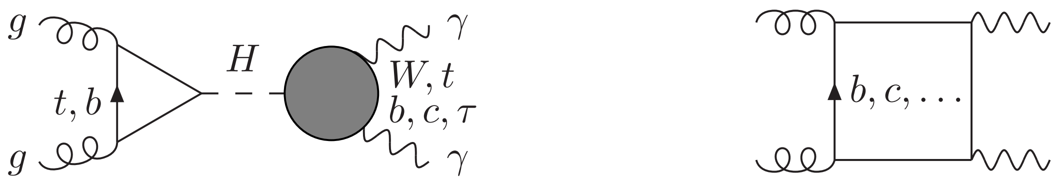

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Residual effect: downward shift of $M_{\gamma\gamma}$ mass peak

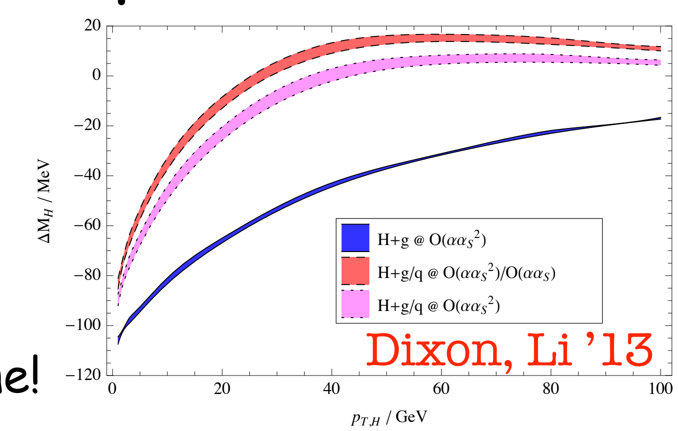
$\Delta M_{\gamma\gamma}$ =-120 MeV @ LO S. Martin '12

$\Delta M_{\gamma\gamma}$ =-70 MeV @ NLO Dixon, Li '13

(large K-factor of signal)

$\Delta M_{\gamma\gamma}$ has a strong dependence on Higgs pT

can be measured in $\gamma\gamma$ channel alone!



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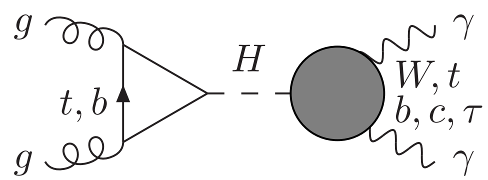

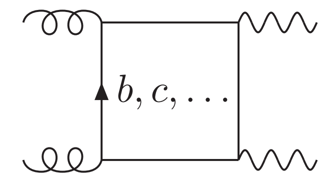

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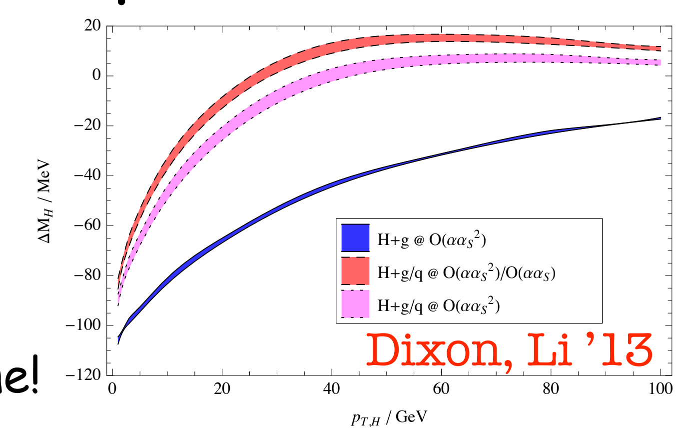

Access to the Higgs width @ LHC?

often said, it is impossible to measure the Higgs width at the LHC. Not quite true.
it can be done either via the measure the mass shift or via the rate

Zero Width Approx.

$$\mu = \frac{\kappa_g^2 \kappa_\gamma^2}{\kappa_H^2}$$

ratios of κ only

no direct access to the width itself

(upper bound if κ_V < 1 is assumed
e.g. Dobrescu, Lykken '12)

Narrow Width Approx.

different width dependence $\mu = \frac{\kappa_g^2 \kappa_\gamma^2}{\kappa_H^2} + I \frac{\kappa_g \kappa_\gamma \kappa_H^2}{\kappa_H^2}$

Γ_H can be fitted w/o assumption

$I \approx -1.6\%$

Now what?

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

the words of a string theorist

Great success...

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

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Have the theorists been lying for so many years?

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

HEP future:

exploration/discovery era or consolidation/measurement era?

Now what? What's next?

Now what? What's next?

" With great power comes great responsibility "

Voltaire & Spider-Man

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)

The Higgs has access to EW coupled New Physics

which is less constrained by direct searches than strongly coupled NP

Now what? What's next?

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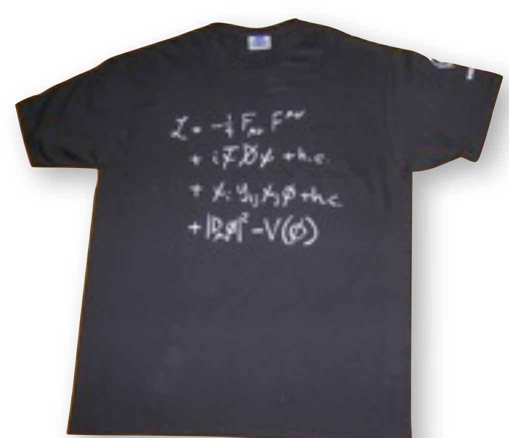
The Higgs has access to EW coupled New Physics
which is less constrained by direct searches than strongly coupled NP

1 Higgs properties

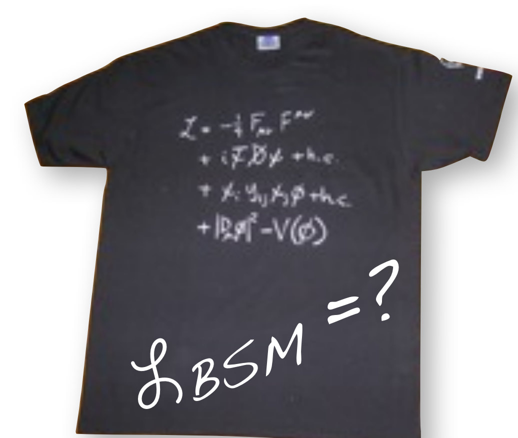
J^{PC}

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



The relevant (and difficult) CP question about the Higgs

A 0^+ Higgs can have CP violating couplings

fermionic sector — marginal operators (dim-4) ➤ phase of V_{CKM} matrix

bosonic sector — irrelevant operators (dim-6) only
- ➤ edm's
- ➤ Higgs signal strengths
- ➤ Higgs kinematical distribution

The relevant (and difficult) CP question about the Higgs

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➤ edm's
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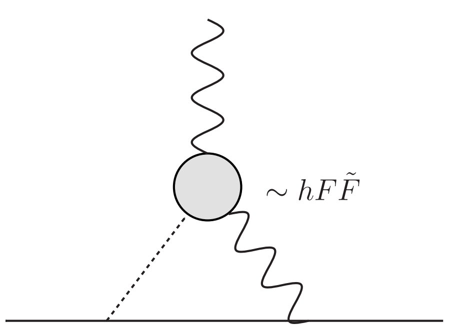
➤ Higgs kinematical distribution

Among the 59 irrelevant directions, 3 of them induce $\cancel{CP}$ Higgs couplings in the EW bosonic sector

$$\boxed{H^\dagger H B_{\mu\nu}\tilde{B}^{\mu\nu} \qquad (D^\mu H)^\dagger \sigma^i (D^\nu H)\tilde{W}^i_{\mu\nu} \qquad (D^\mu H)^\dagger (D^\nu H)\tilde{B}_{\mu\nu}}$$

γ operator:
already severely constrained
by e and q EDMs
McKeen, Pospelov, Ritz '12



Z operator(s):
studied in the kinematical distributions
for h → ZZ → 4l

see the f_{a3} CMS study

Higgs rates?
poor constraints
since no interference with SM
effects ≈ dim-8 CP-even operators

➤ ➤ ➤

need to look for CP-odd observables
that are linear in the $\cancel{CP}$ Wilson coeffs.

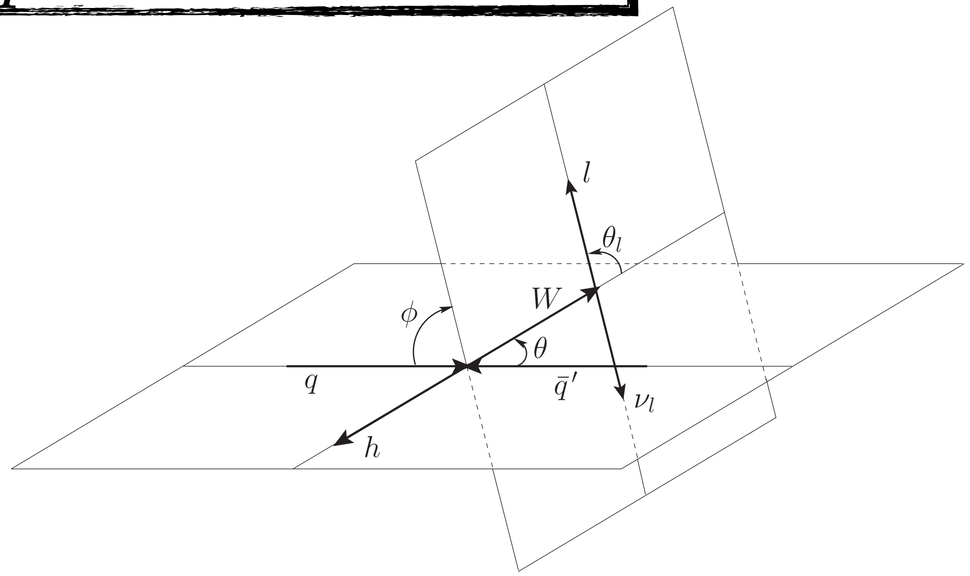
CP-odd observables

The $\not{C}\!P$ operators with W and Z are best studied in the VH channels

where the Higgs can be boosted (the derivatives in the operators don't hurt)

Godbole et al '13

$$\boxed{q\bar{q}' \to Wh \to l\nu b\bar{b}}$$



the asymmetry in the variable

$$\vec{l} \cdot (\vec{h} \times \vec{q})$$

is linear in $\not{C}\!P$ coefficient

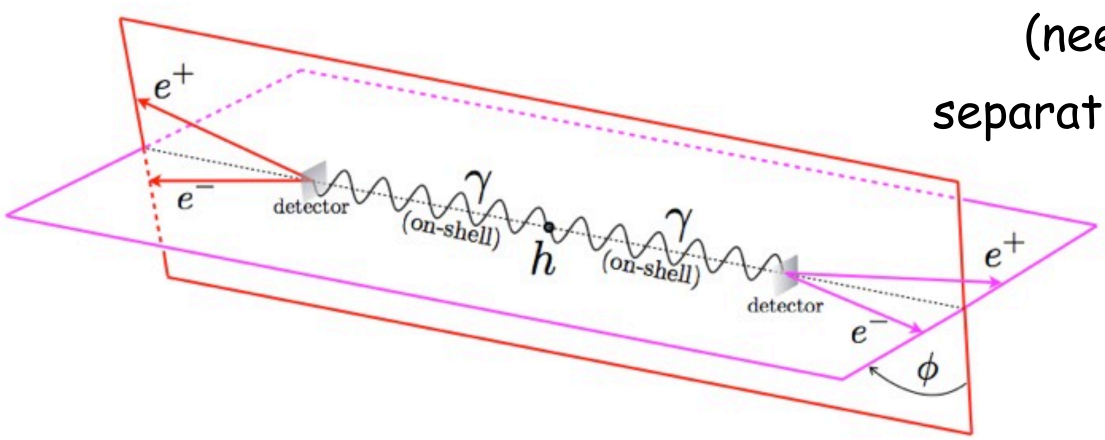
Delaunay et al 'in progress

➤ should allow one to constraint the third CP direction

Another CP-odd observable can be constructed in h➛γγ channel

the $\not{C}\!P$ operator impacts the correlation between the photon polarizations that can be tracked back to the correlation between the converted e⁻

e.g. talk by J. Zupan at KITP '13



challenging

(need to reconstruct the separation angles between the e)

but interesting

Towards BSM 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)

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

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

Contino, Grojean, Moretti, Piccinini, Rattazzi '10 + many others refs.

Chiral Lagrangian for a light Higgs-like scalar

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

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

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

still large LO parameter space

⇓ ⇓ ⇓

4 operators @ O(p²): cV, ct, cb, cT

2 operators @ O(p⁴): cg cγ

(contribute to the same order as O(p²) to gg→h and h→γγ)

O(p²)

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

Not enough data/sensitivity to determine all these parameters

⇓ ⇓ ⇓

But we can put some of the SM structures under probation

O(p⁴)

assumptions:

☑ spin-0 & CP-even

↖ $\gamma\gamma$ ↖ WW & ZZ

☑ custodial symmetry

↖ EWPD

☑ no Higgs FCNC

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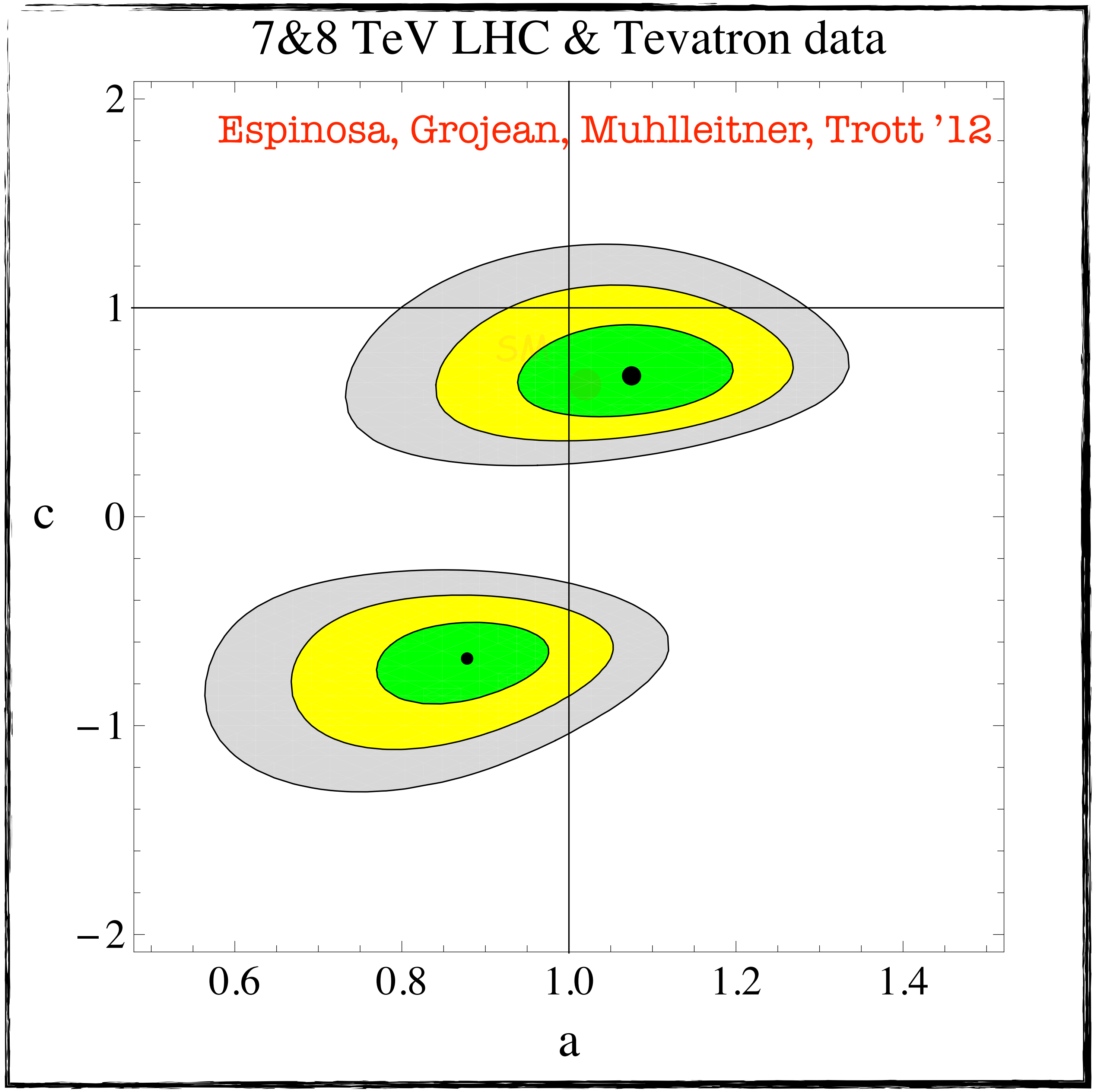
Higgs coupling fits: test of unitarity



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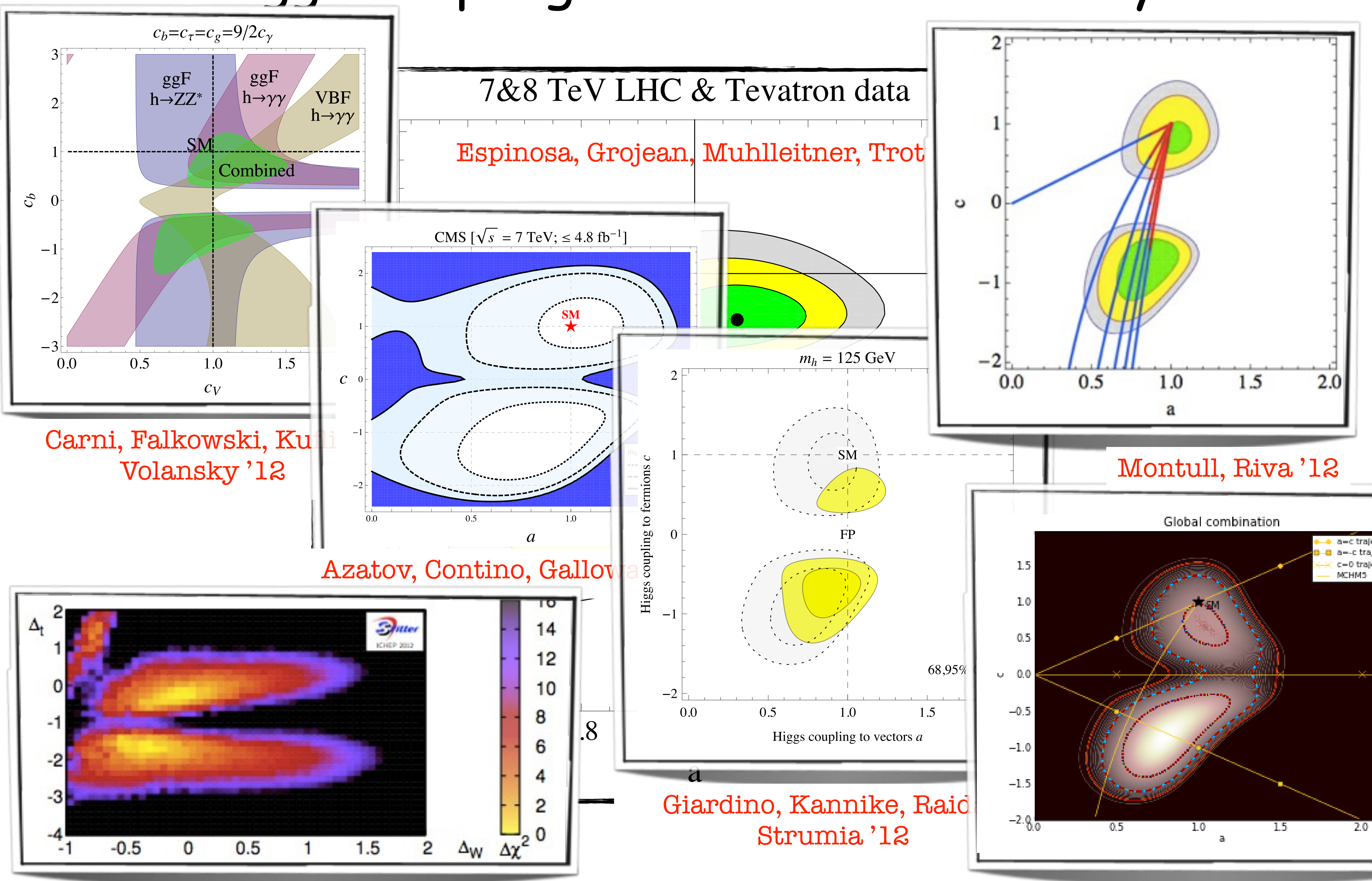


Carni, Falkowski, Kuflik, Volansky '12

Espinosa, Grojean, Muhlleitner, Trott

Azatov, Contino, Galloway

Montull, Riva '12

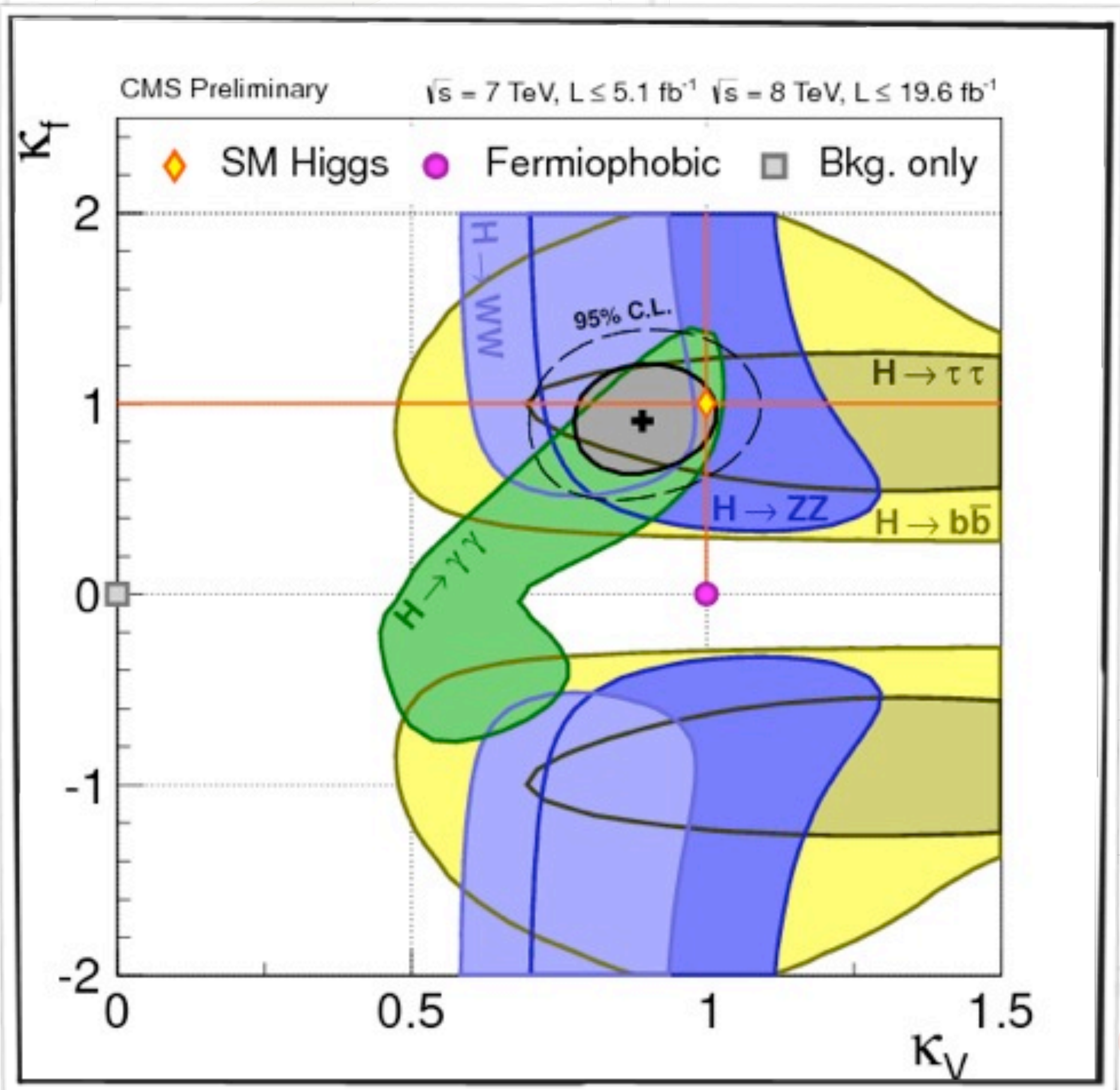
Giardino, Kannike, Raidal, Strumia '12

Plehn, Rauch '12

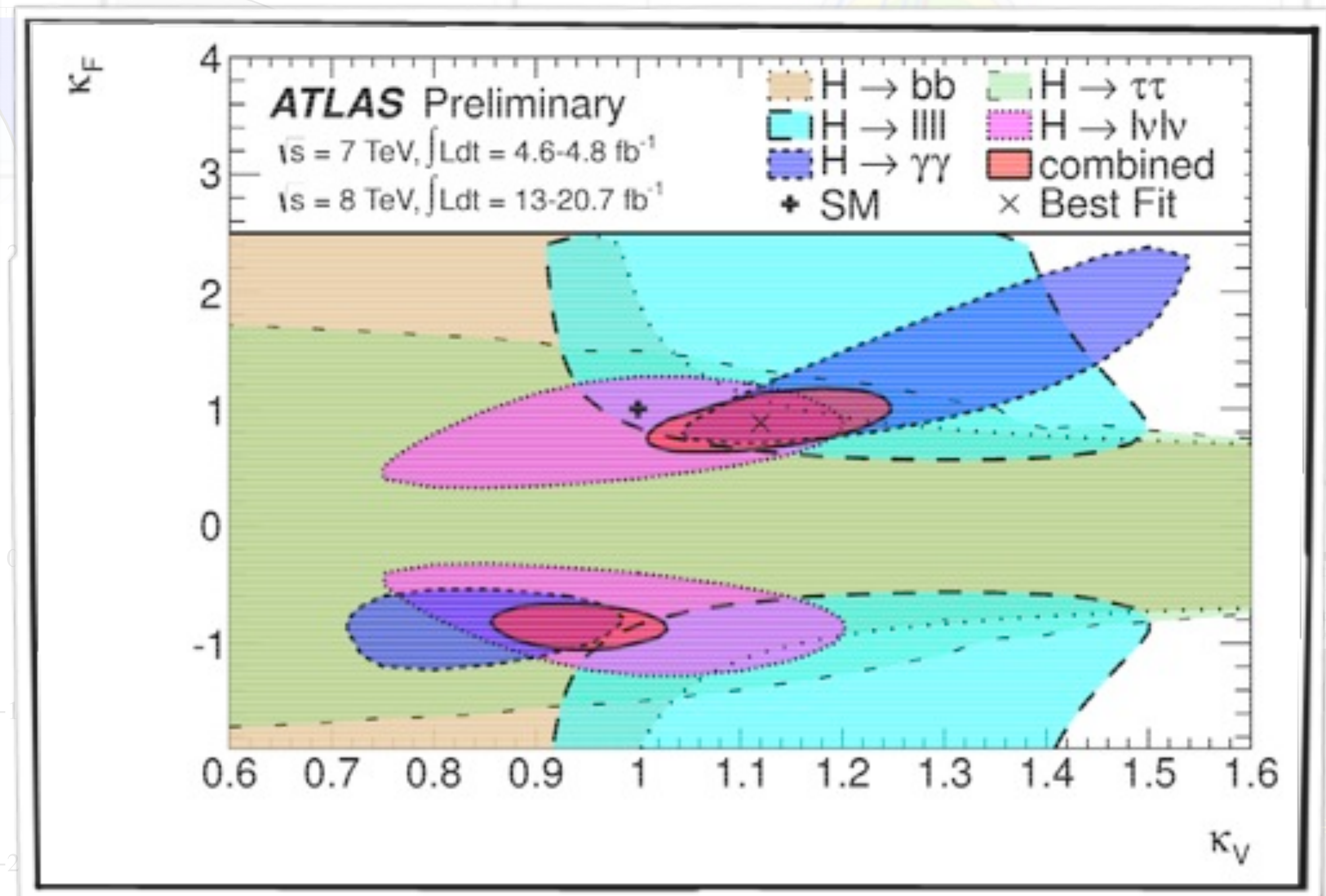
Ellis, You '12

Higgs coupling fits: test of unitarity

don't leave it in the hands of theorists!



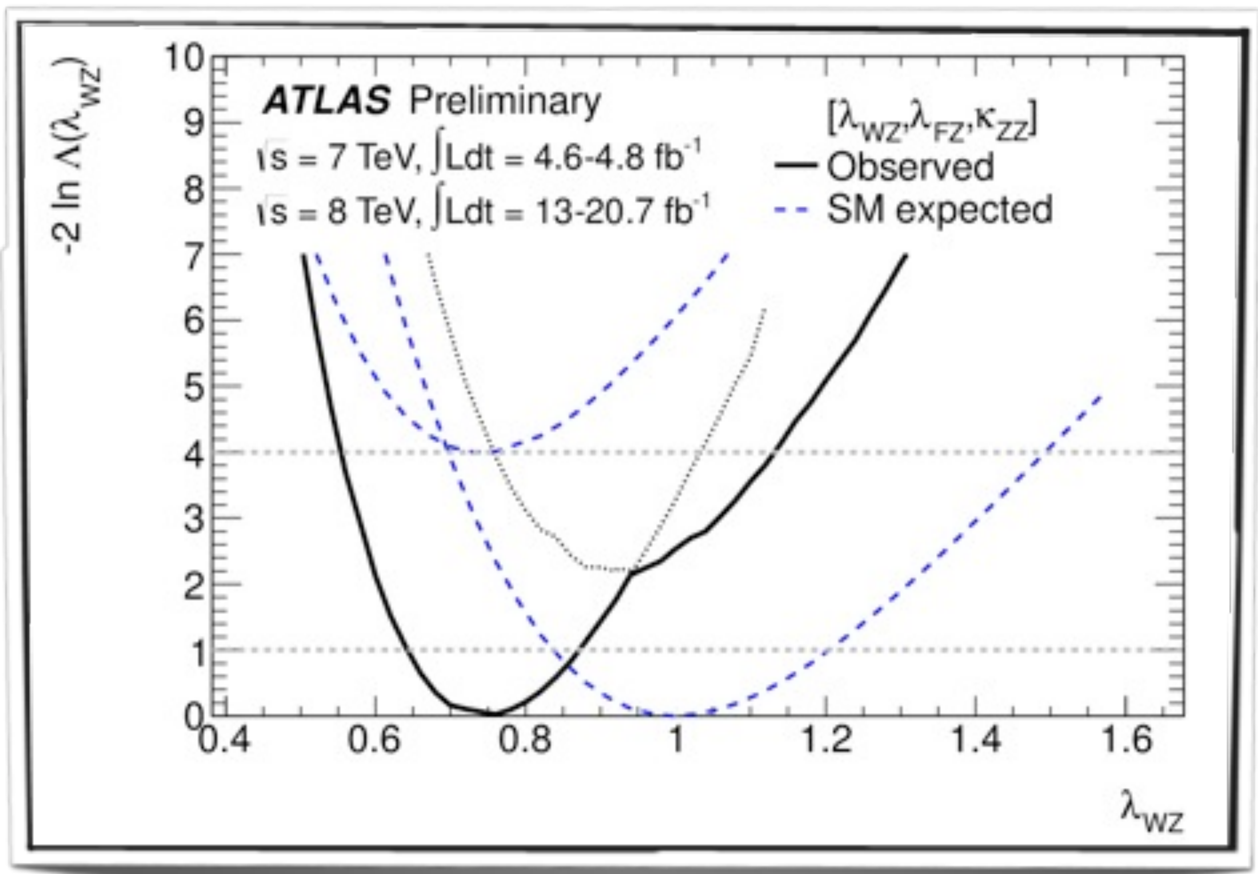
CMS

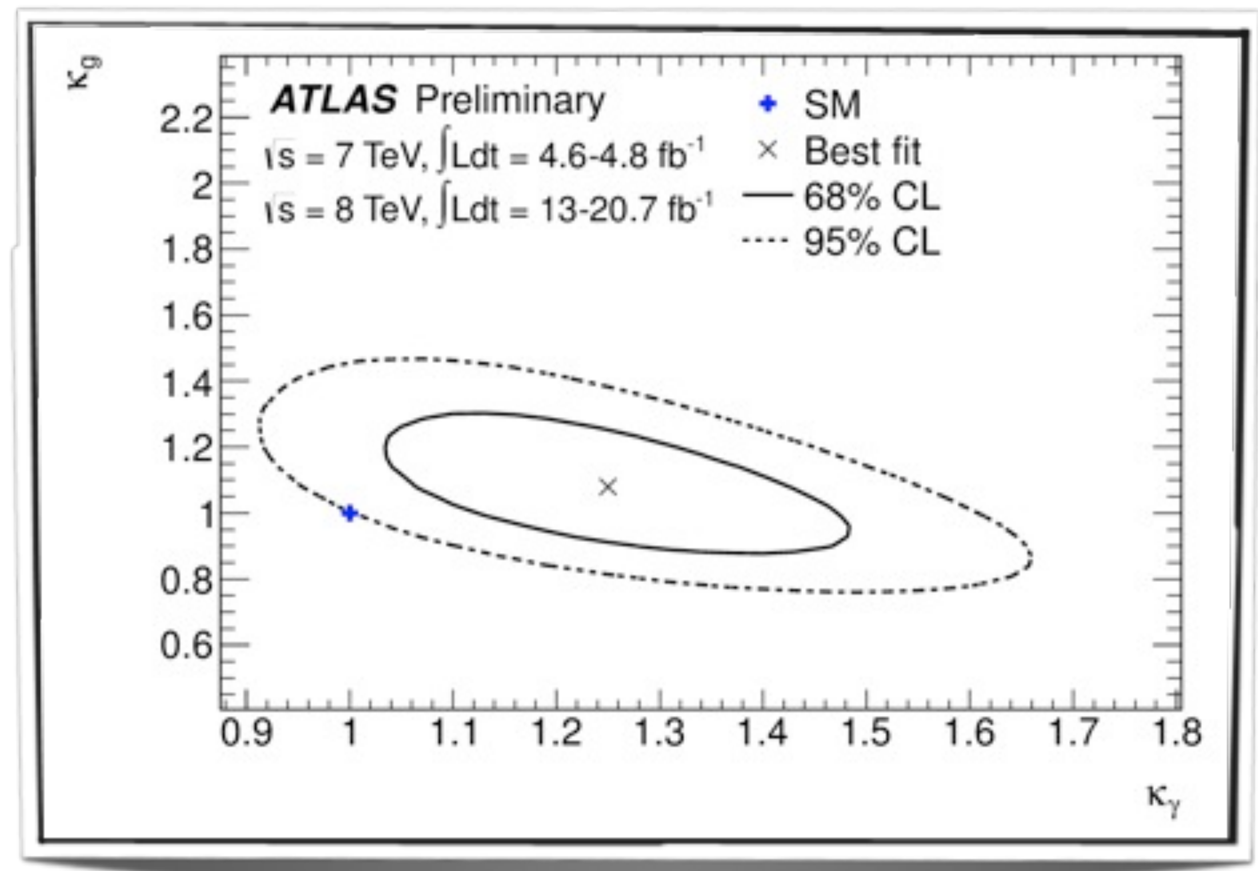


ATLAS

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-2013-034

Some tensions

but no statistically significant deviations from the SM structure

Beyond current channels

the LHC measurements are plagued with several degeneracies

inability to resolve the top loops

- the bearable lightness of the Higgs: rich spectroscopy w/ multiple decays channels
- the unbearable lightness: loops saturate and don't reveal the physics @ energy physics (*)

(*) unless it doesn't decouple (e.g. 4th generation)

m_H(GeV)	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t\to\infty)}$	$\frac{\sigma_{NLO}(m_t,m_b)}{\sigma_{NLO}(m_t\to\infty)}$
125	1.061	0.988
150	1.093	1.028
200	1.185	1.134

e.g. Grazzini, Sargsyan '13

the inclusive rate doesn't "see" the finite mass of the top

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the inclusive rate
doesn't "see" the finite mass of the top

(*) unless it doesn't decouple
(e.g. 4th generation)

$\Rightarrow$ cannot disentangle
- long distance physics (modified top coupling)
- short distance physics (new particles running in the loop) $\Leftarrow$

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

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

fermionic top-partners in composite Higgs models exactly lead to $\Delta c_t = \Delta c_g = \frac{9}{4}\Delta c_\gamma$.

Beyond current channels

the LHC measurements are plagued with several degeneracies

inability to resolve the top loops

- the bearable lightness of the Higgs: rich spectroscopy w/ multiple decays channels
- the unbearable lightness: loops saturate and don't reveal the physics @ energy physics [(*)]

$m_H(\mathrm{GeV})$	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t\to\infty)}$	$\frac{\sigma_{NLO}(m_t,m_b)}{\sigma_{NLO}(m_t\to\infty)}$
125	1.061	0.988
150	1.093	1.028
200	1.185	1.134

e.g. Grazzini, Sargsyan '13

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fermionic top-partners in composite Higgs models exactly lead to $\Delta c_t = \Delta c_g = \frac{9}{4}\Delta c_\gamma$.

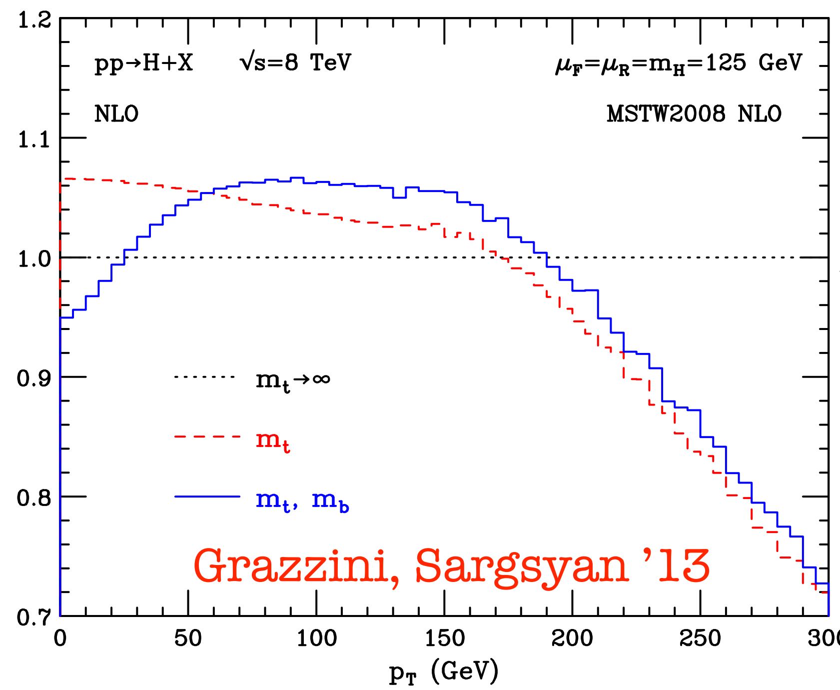
having access to $ht\bar{t}$ final state will resolve this degeneracy
but notoriously difficult channel
14%-4% @ LHC^{14}_{300}-LHC^{14}_{3000} vs 10%-4% @ ILC^{500}_{500}-$\mathrm{ILC}^{1000}_{1000}$

Beyond current channels

cut open the top loops

high $p_T \approx$ Higgs off-shell
we "see" the details of the particles
running inside the loops

Baur, Glover '90
Langenegger, Spira, Starodumov, Trueb '06



Note: LO only
NLO_{m_t} is not known
$1/m_t$ corrections known $O(\alpha_s^4)$
few % up to p_T~150 GeV

Harlander et al '12

the high p_T tail
is tens' % sensitive
to the mass of top

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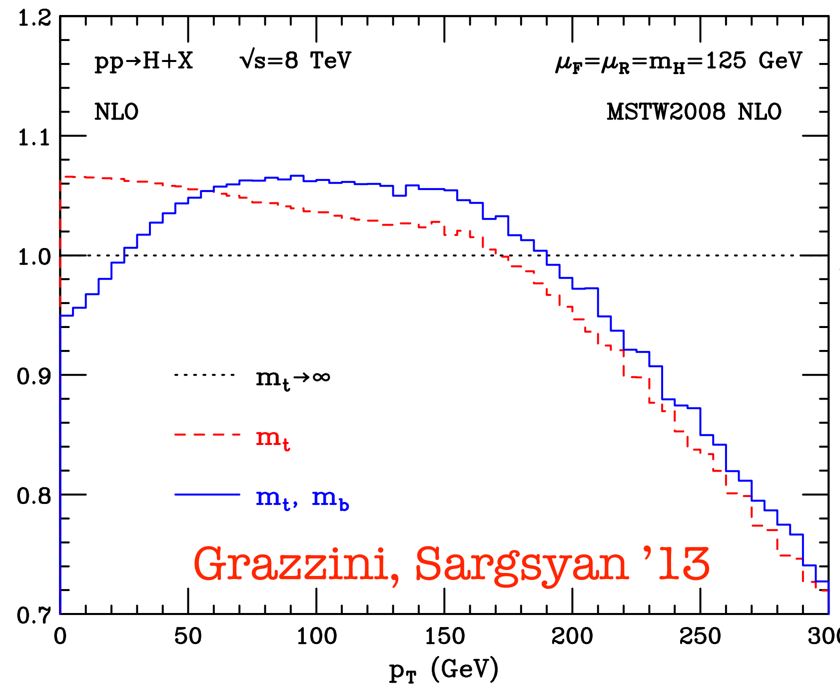

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Harlander et al '12

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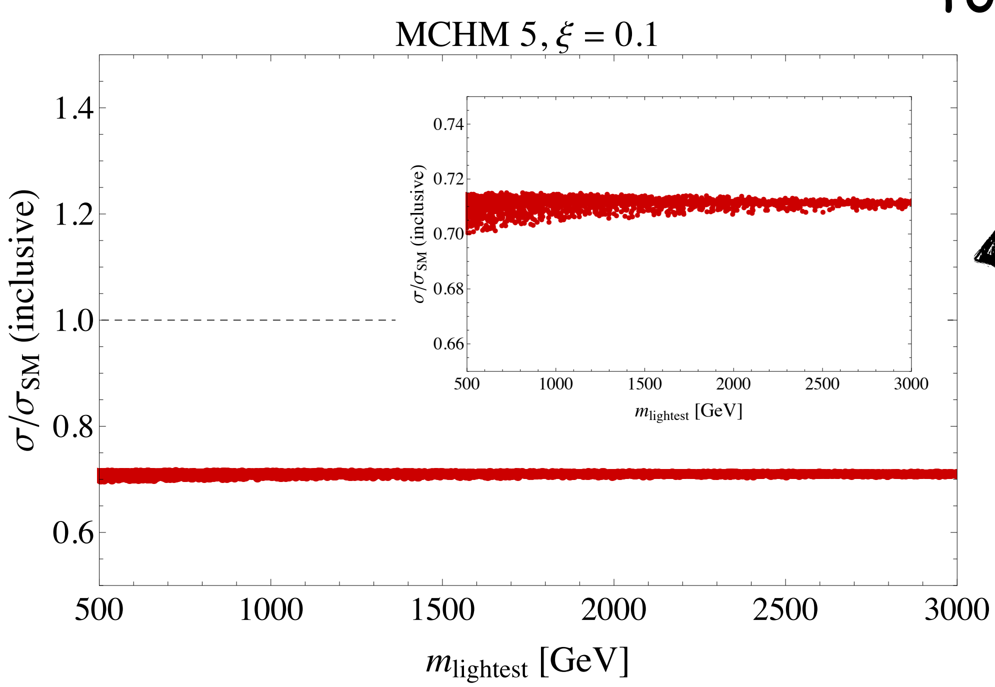
to the mass of top

Composite Higgs Model

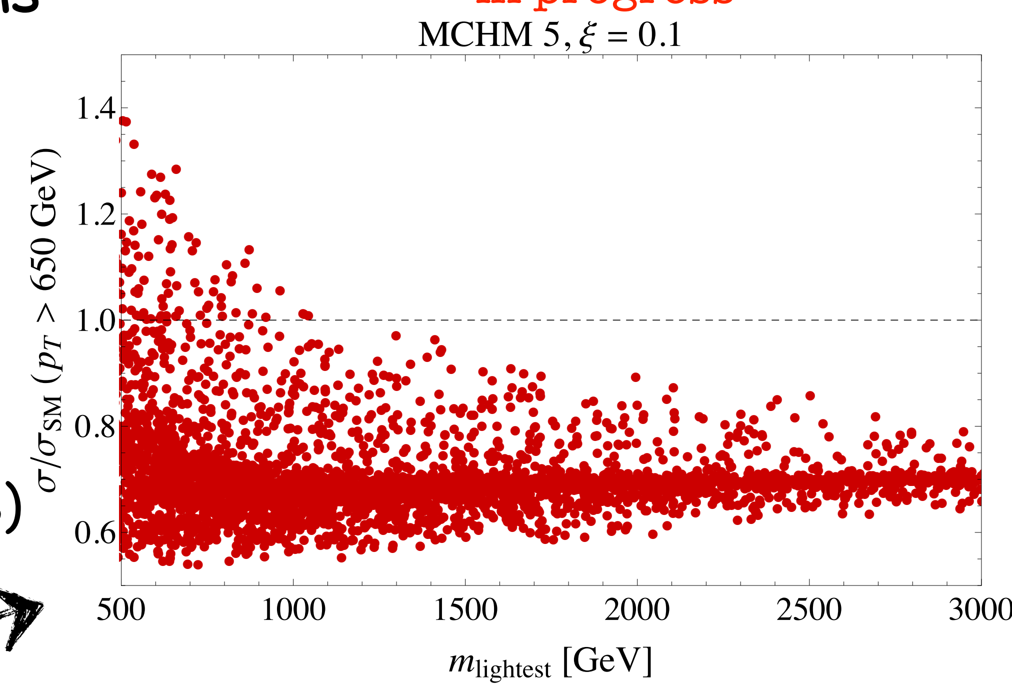
top partners contributions

Grojean, Salvioni, Schlaffer, Weiler
' in progress



inclusive rate: O(%)

with high-p_T cut: O(x10'%)



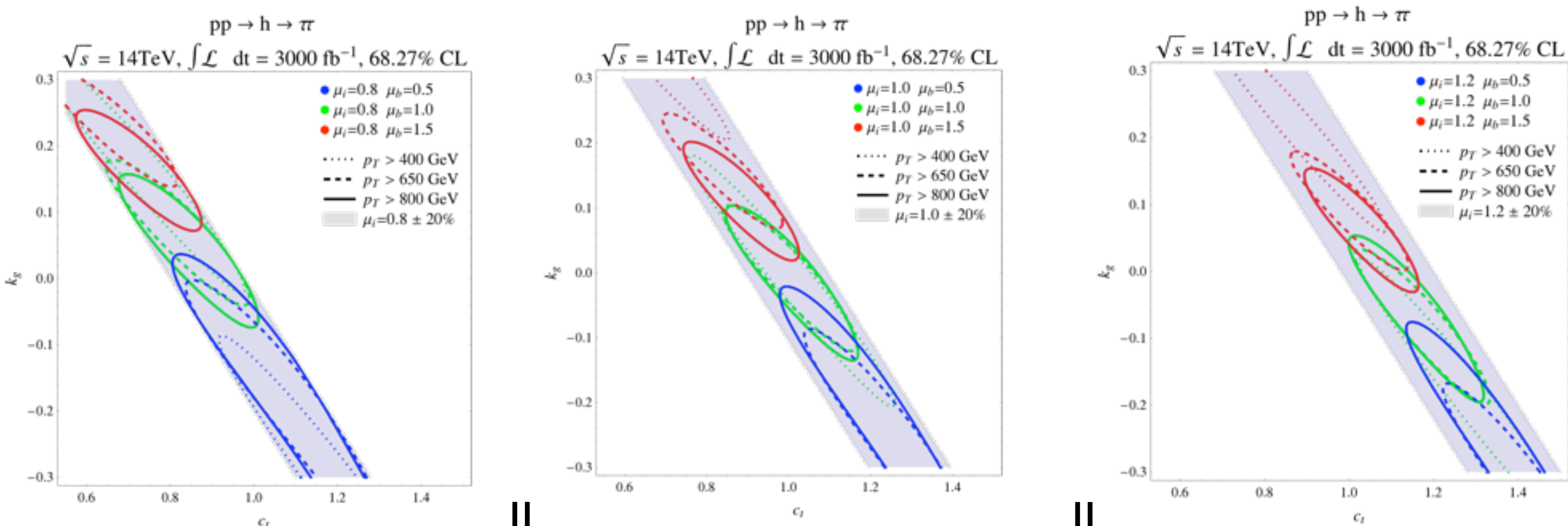
high p_T tail "sees" the top partners that are missed by the inclusive rate

Beyond current channels

cut open the top loops

Grojean, Salvioni, Schlaffer, Weiler
' in progress

high p_T tail discriminates short and long distance physics contribution to $gg \to h$



$\Downarrow$ $\Downarrow$

Competitive/complementary to htt channel to measure the top-Higgs coupling

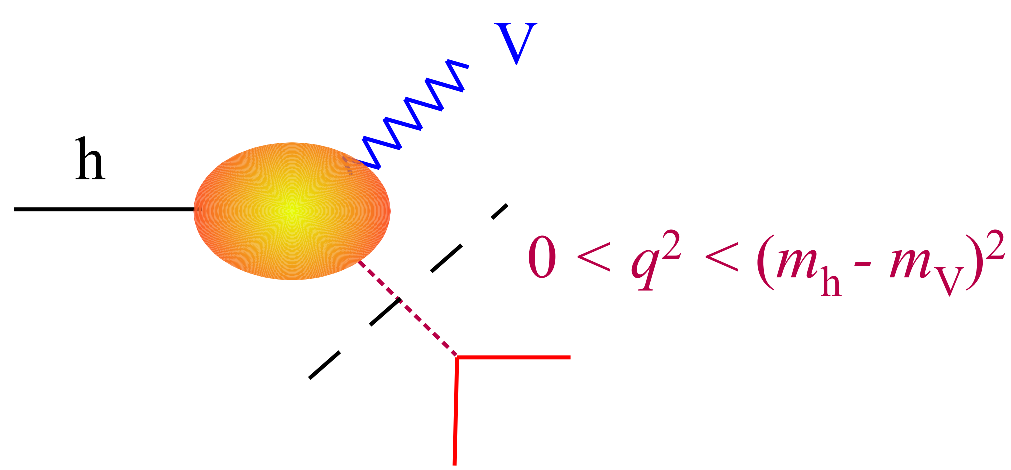
Are the NLO_m QCD corrections (not known) going to destroy all the sensitivity?
Frontier priority: N^3LO_∞ for inclusive xs or NLO_{mt} for pT spectrum?

Staying differential

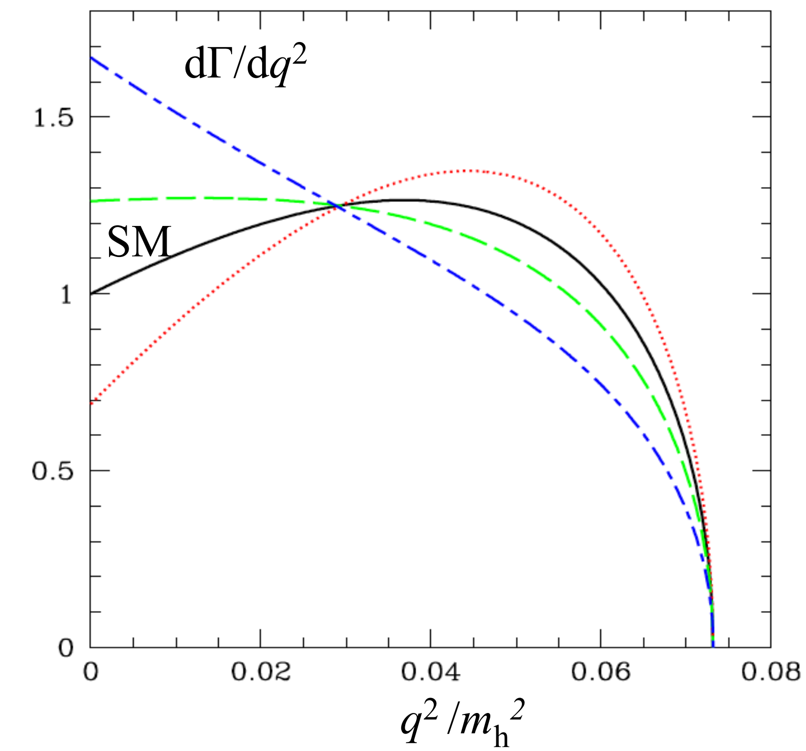
Isidori, Manohar, Trott '13
Isidori, Trott '13

Another benefit of the lightness of the Higgs:

h→VV* = h→Vff, the offshellness of the fermion pair gives access to additional dynamics



possible modifications of the shape leading to the same rate



- the decays h→VV*→Vff probe the low q2 dependence of the form factors
- the associate production ff→Vh probe the high q2 dependence of the form factors

- particularly relevant if ∃ light degrees of freedom/pole that can mediate the decay V*→ff
- for a Higgs doublet with decoupling new physics, the distribution gives access to derivate ops

$$(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} \qquad\qquad (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

which are, however, are already constrained by EW data and Higgs rates (in particular h→Zγ)

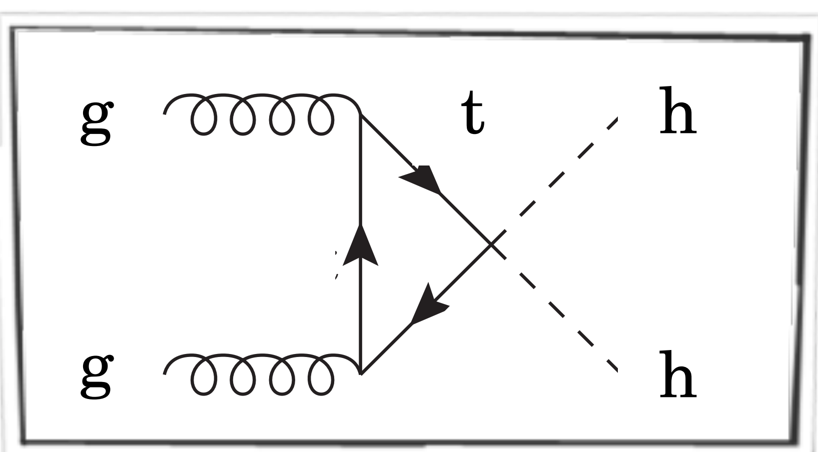
- the effects can be larger if SU(2)xU(1) is non-linearly realized (not so likely given the current Higgs data)

Beyond linear couplings

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

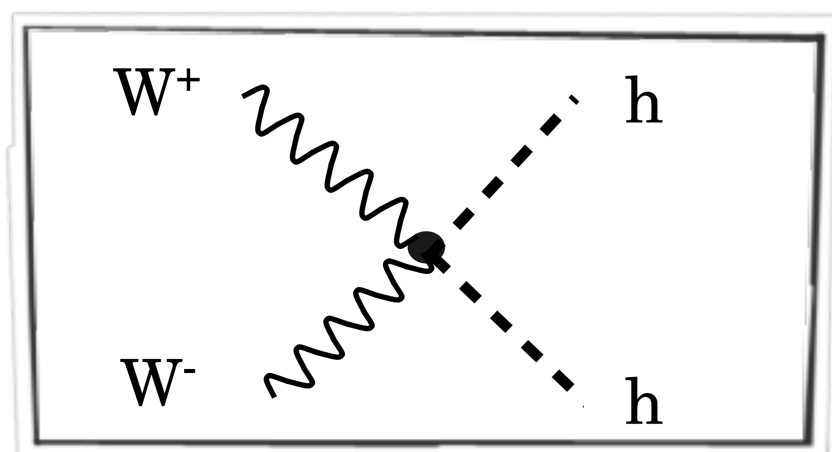
not an easy question at the LHC since we need multi-Higgs couplings



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

see also Contino's talk

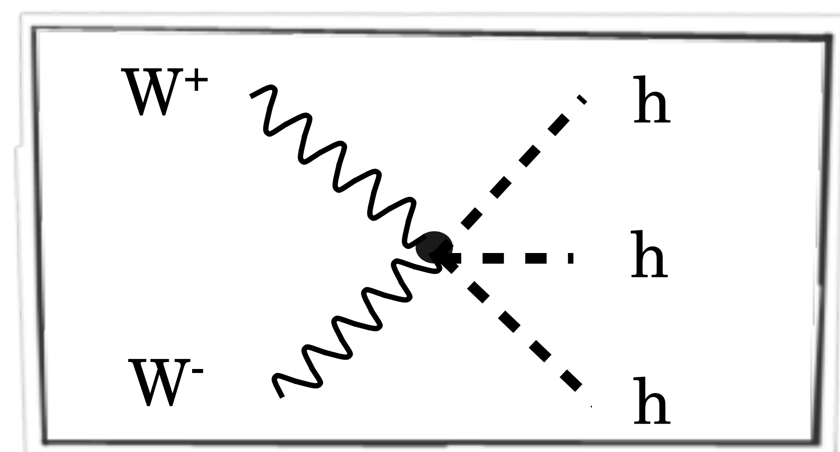
$\sigma^{SM}_{14\text{TeV}} \approx 20\,\text{fb}$



Contino, Grojean,
Moretti, Piccinini, Rattazzi '10

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

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



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

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

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

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

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 %

$h \to \mu\mu$ (together with $h \to \tau\tau$):

provides an insight into lepton mass generation

$h \to cc$:

provides an insight into 2nd gen. mass generation

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2

Look for SM forbidden LF violating decays $h \to \mu\tau$ and $h \to e\tau$

Blankenburg, Ellis, Isidori '12

- not currently strongly constrained: BR<10%
- ATLAS and CMS have in principle the sensitivity to set bounds O(1%)
- but ILC/CLIC can certainly do much better

Harnik et al '12

Davidson, Verdier '12

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Harnik et al '12

Davidson, Verdier '12

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
$h \to W/Z+P$
can be a good probe of NP

Back to loop computations

There is a tremendous effort in computing radiative corrections in SM Higgs physics
it is now time to bring BSM Higgs computations to higher accuracy
at least to test/measure possible deviations

A lot has been done with the MSSM and contributed to explore the parameter space

Need to think in a model-independent way

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c_i}{\Lambda^2}\mathcal{O}_i^{6D} + \ldots$$

$\mathcal{L} \underset{c_i \to 0}{\to} \mathcal{L}_{\rm SM}$ but $\sigma \times \mathrm{BR}_{\mathcal{L}} \underset{c_i \to 0}{\not\to} \sigma \times \mathrm{BR}_{\mathcal{L}_{\rm SM}}$

available to LO only

available to N...NLO

New frontier in Higgs precision physics:
computing radiative corrections in the effective Lagrangian

For a discussion, see e.g. Contino, Ghezzi, Grojean, Muhlleitner, Spira '13
Passarino '12

RG-improved Higgs physics

Grojean, Jenkins, Manohar, Trott '13 Elias-Miro, Espinosa, Masso, Pomarol '13

Integrating-out heavy degrees of freedom gives Wilson coefficients @ NP scale

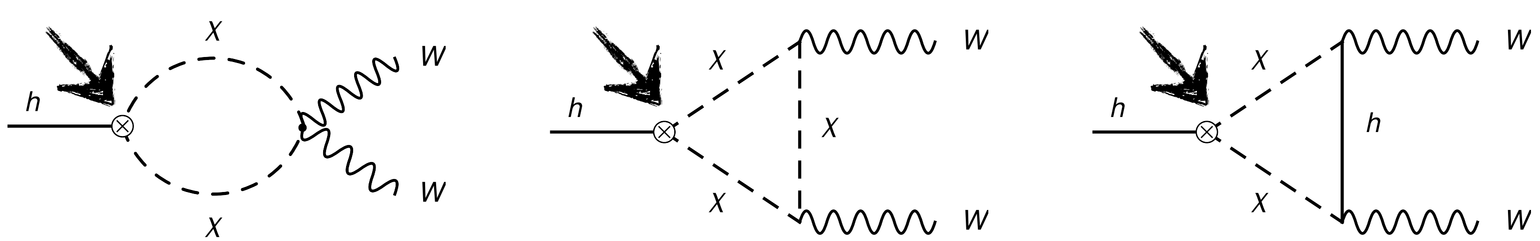
Higgs physics is done around the weak scale

RG effects can give important effects

$$\bar{c}_i(\mu) \simeq \left(\delta_{ij} + \gamma_{ij}^{(0)} \frac{\alpha}{8\pi} \log\left(\frac{\mu^2}{M^2}\right)\right) \bar{c}_j(M)$$

anomalous dimensions

operator that induces universal shift of couplings $(\partial_\mu |H|^2)^2$



$$\mu \frac{d}{d\mu} \begin{pmatrix} c_H \\ c_W + c_B \\ c_{HW} + c_{HB} \end{pmatrix} = \frac{\alpha}{4\pi} \gamma \begin{pmatrix} c_H \\ c_W + c_B \\ c_{HW} + c_{HB} \end{pmatrix} \qquad \gamma_{ij}^{(0)} = \begin{pmatrix} 0 & 0 & 0 \\ -1/6 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

RG-improved Higgs physics

Grojean, Jenkins, Manohar, Trott '13

Elias-Miro, Espinosa, Masso, Pomarol '13

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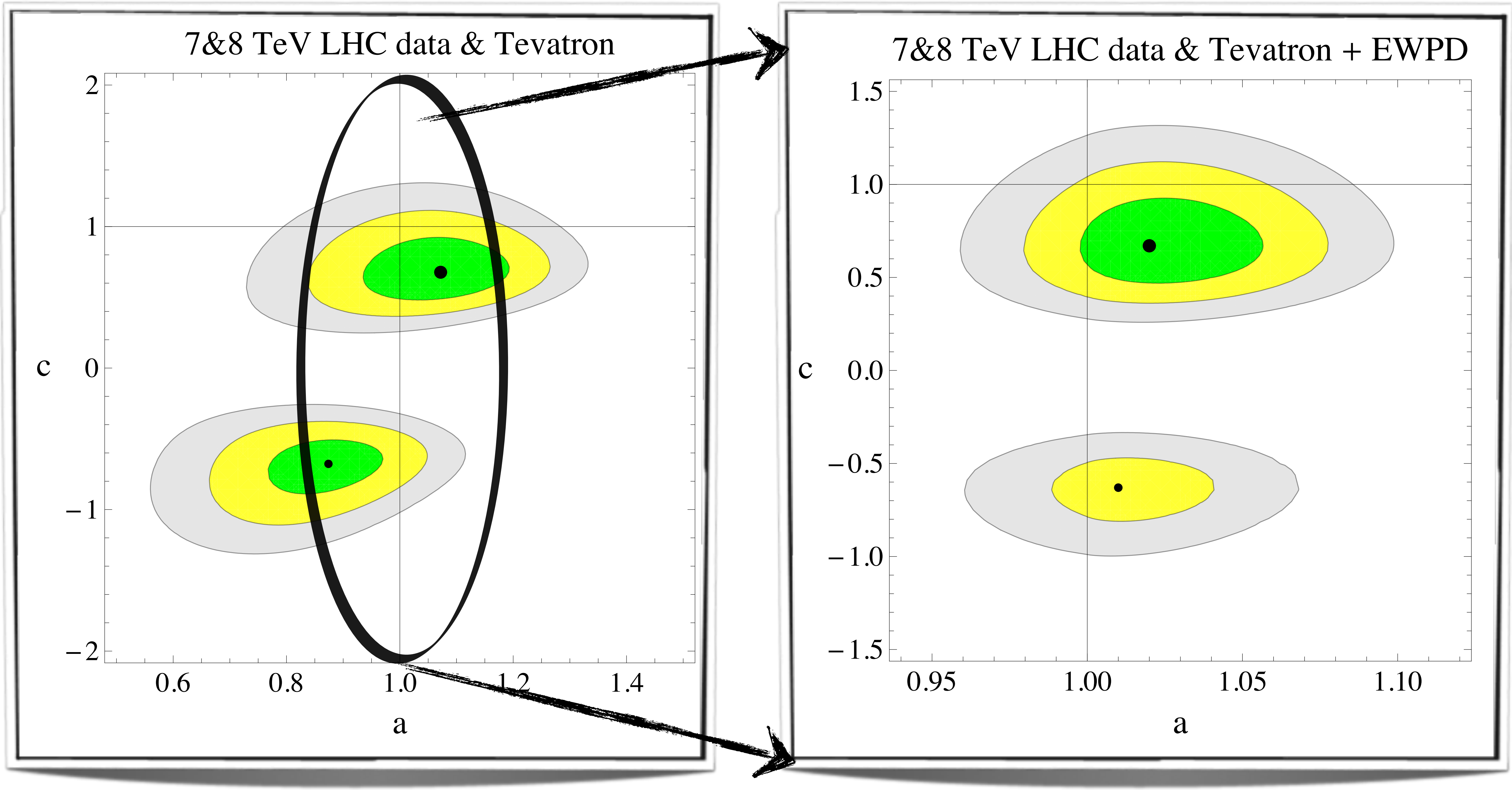
anomalous dimensions

$$\bar{c}_{W+B}(\mu) = \underbrace{\bar{c}_{W+B}(M)}_{\frac{m_W^2}{M^2}} + \# \frac{g^2}{16\pi^2} \underbrace{\log\left(\frac{\mu^2}{M^2}\right) \bar{c}_H(M)}_{\frac{g^2}{16\pi^2}\frac{v^2}{f^2} = \frac{g_*^2}{16\pi^2}\frac{m_W^2}{M^2} \times \text{Log}}$$

RG-Higgs physics: Don't forget LEP!

Espinosa, Grojean, Muhlleitner, Trott '12



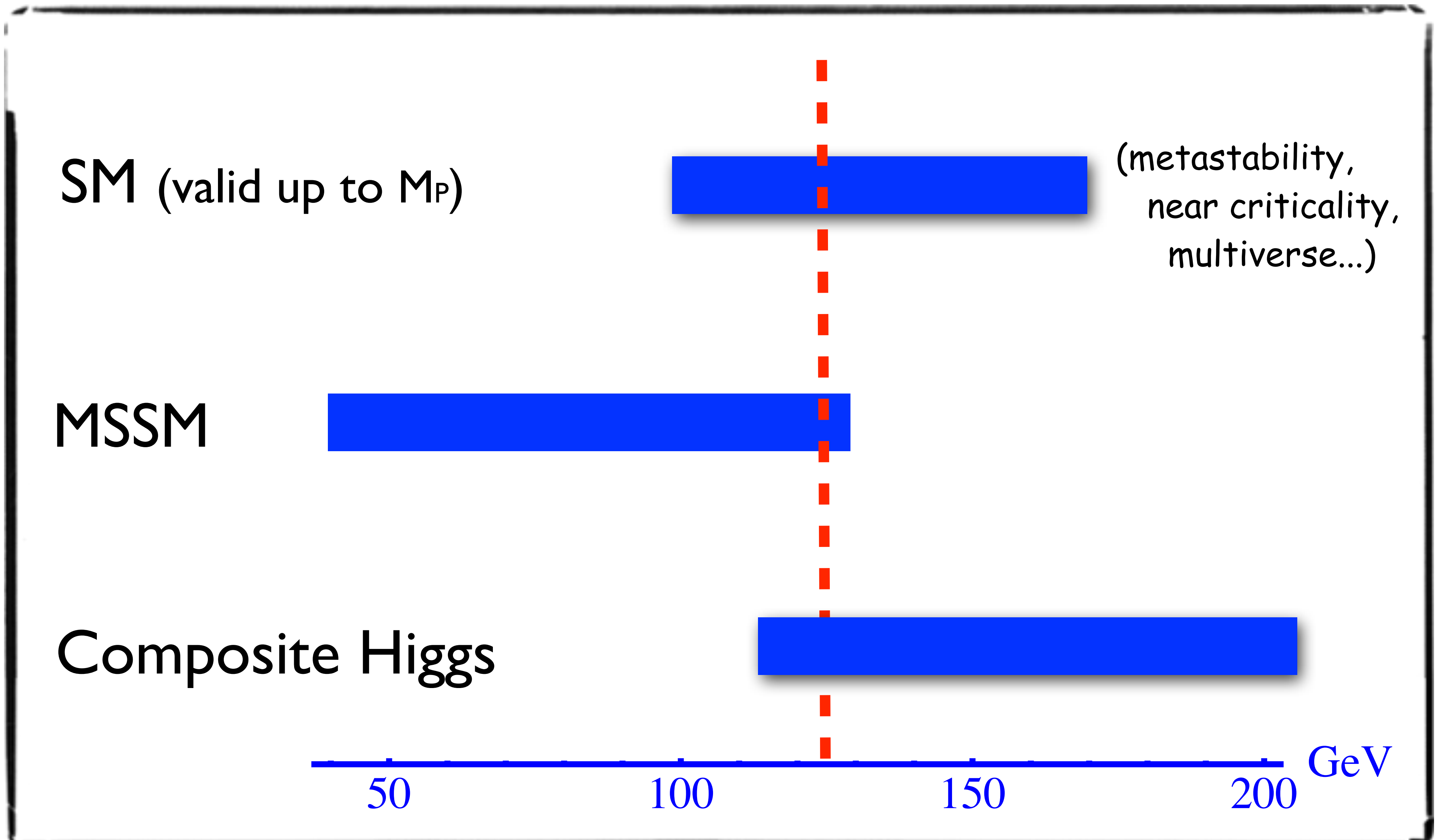
EW data prefer value of 'a' close to 1

by running, a shift of the coupling induced oblique corrections
that are already highly constrained by LEP data

for other more complete studies along this line, see
Eboli et al '12
Falkowski, Riva, Urbano '13
Elias-Miro, Espinosa, Masso, Pomarol ' to appear

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

Conclusions: Executive Summary

The LHC leaves us with the deepest mathematical pb:

Dissertori, ECFA '13

$$\infty \cdot 0 = ?$$

number of already performed BSM searches

number of significant/ interesting/exciting deviations from SM predictions

general state of (our) mind (?)

Understanding the scalar sector of the SM
will help us grasping what lays beyond the SM

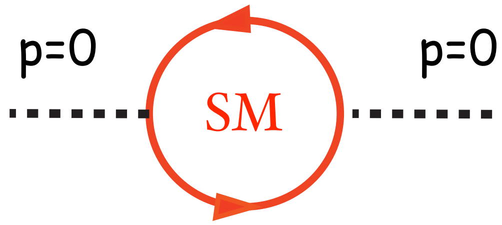
EXTRA SLIDES

see also Giudice's talk

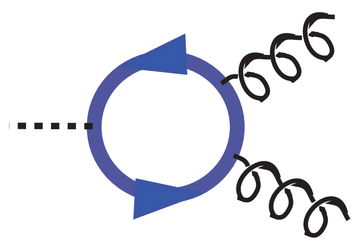
Higgs couplings and Naturalness

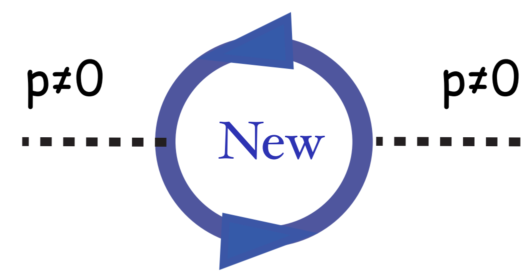
Higgs couplings = test of Naturalness?

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

$\delta m_H^2 =$  $+$  $\sim m_H^2$

generically





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

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

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

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

nice to be able to measure Γ

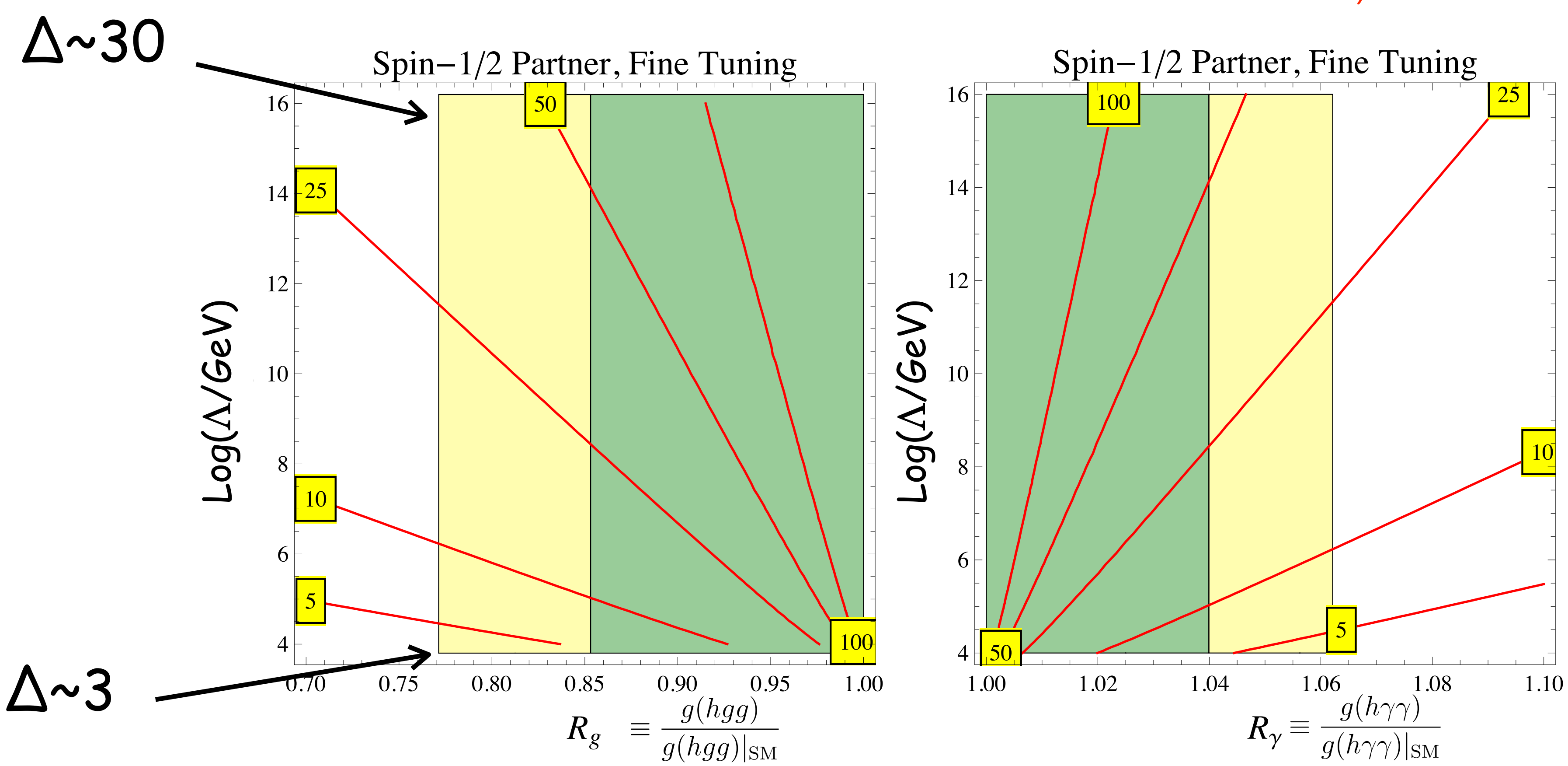
Generically, natural scenarios come with deviations of the Higgs coupling

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 (spin-0) stops w/ mixing

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

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

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

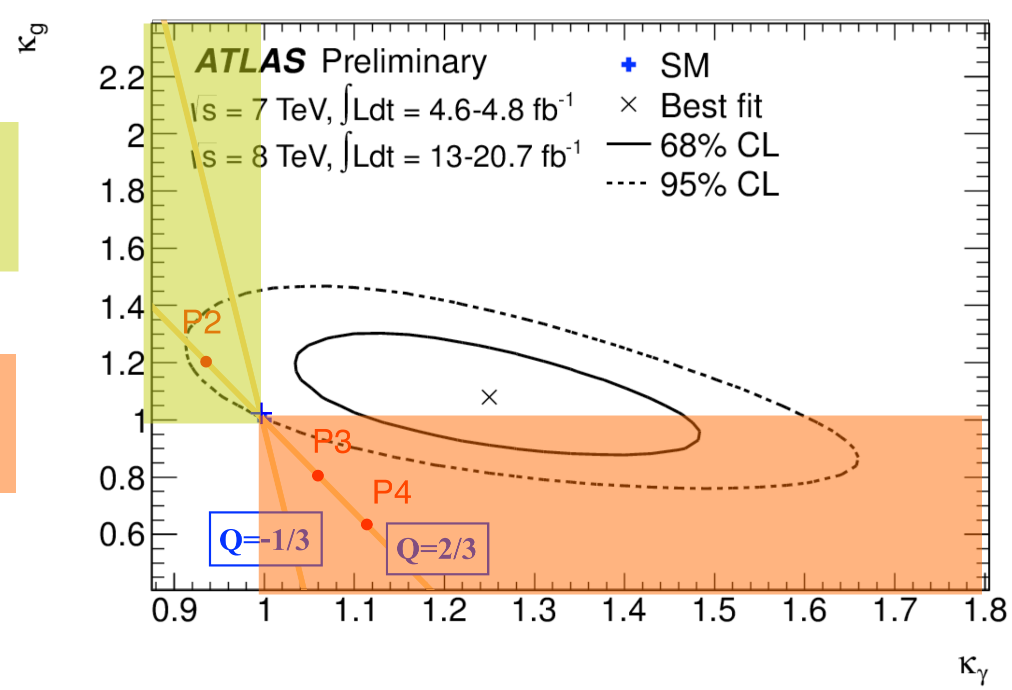
P1: $m_{\tilde{t}_1} = 100\,\text{GeV},\ m_{\tilde{t}_2} = 300\,\text{GeV},\ \theta_t = 0$

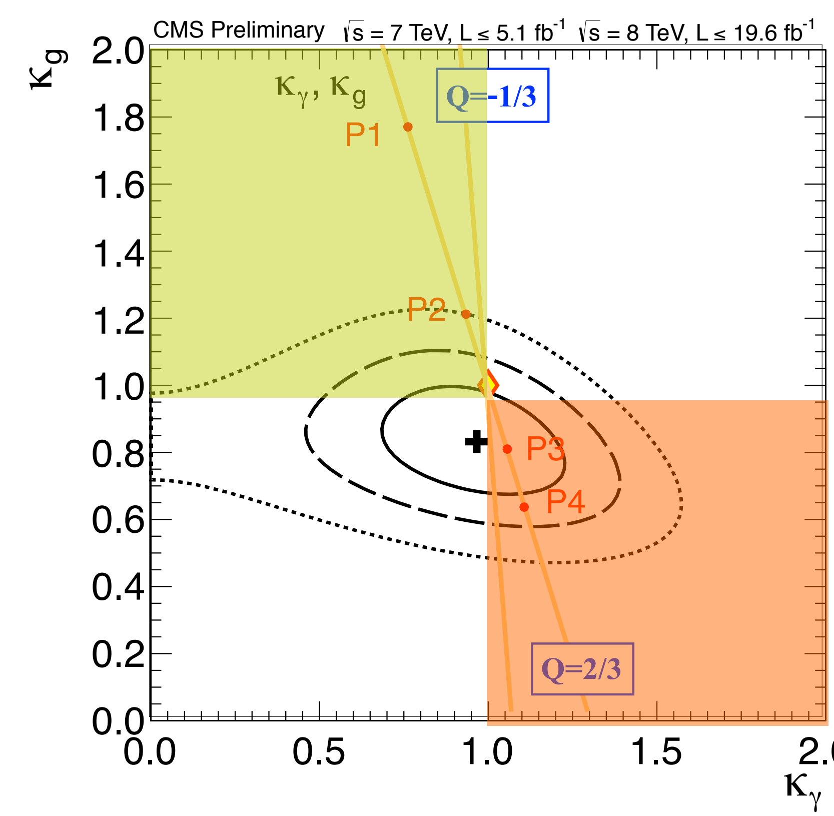
P2: $m_{\tilde{t}_1} = 200\,\text{GeV},\ m_{\tilde{t}_2} = 500\,\text{GeV},\ \theta_t = 0$

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

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

Contino, Genova '13





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

EXTRA SLIDES

Weakly coupled models

Higgs & SUSY/MSSM

no new super-particles ⇢ decoupling limit?

high Higgs mass
implies
susy is badly broken

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

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

$(\geq 87\text{GeV})^2$

substantial loop contribution
from stops

Higgs & SUSY/MSSM

no new super-particles ⋯→ decoupling limit?

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(125 GeV)²

(≳ 87GeV)²

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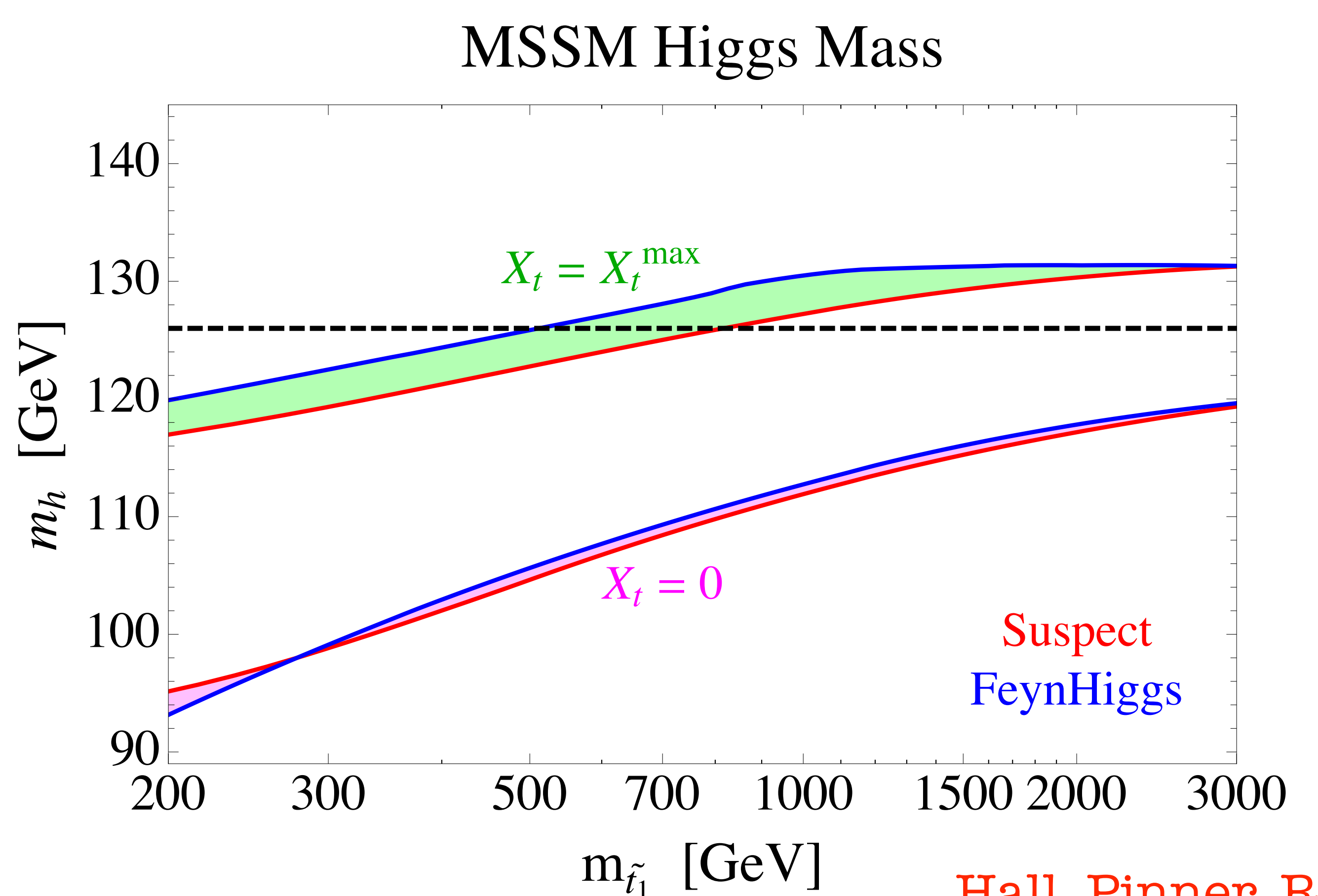


Hall, Pinner, Ruderman '11
+ many similar analyses

large mixing
heavy stops

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

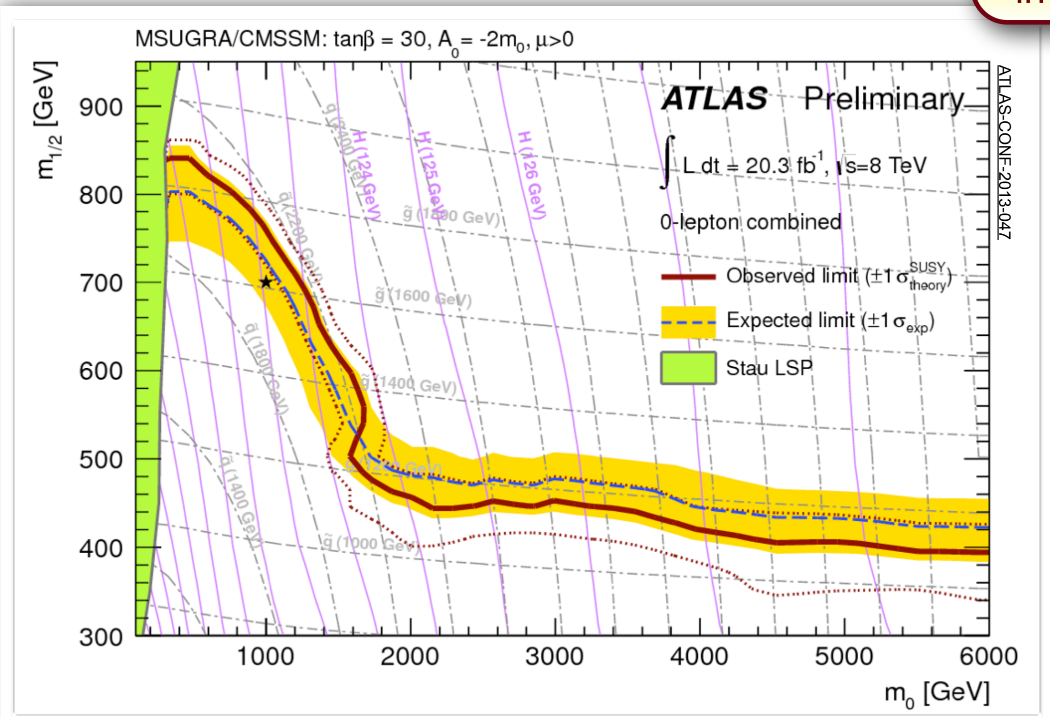
$\Downarrow$ $\Downarrow$

irreducible
fine-tuning ~ O(1%)

Cornering SUSY parameter space

see
Dissertori @ ECFA '13

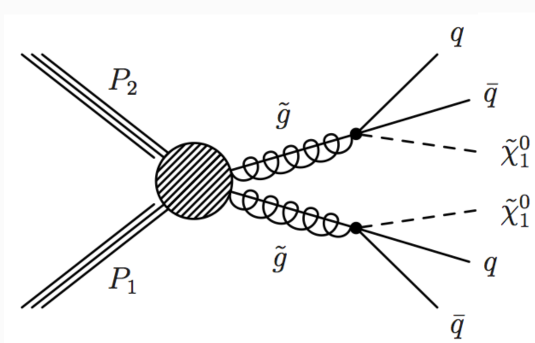
in the context of a concrete model, here MSUGRA/cMSSM

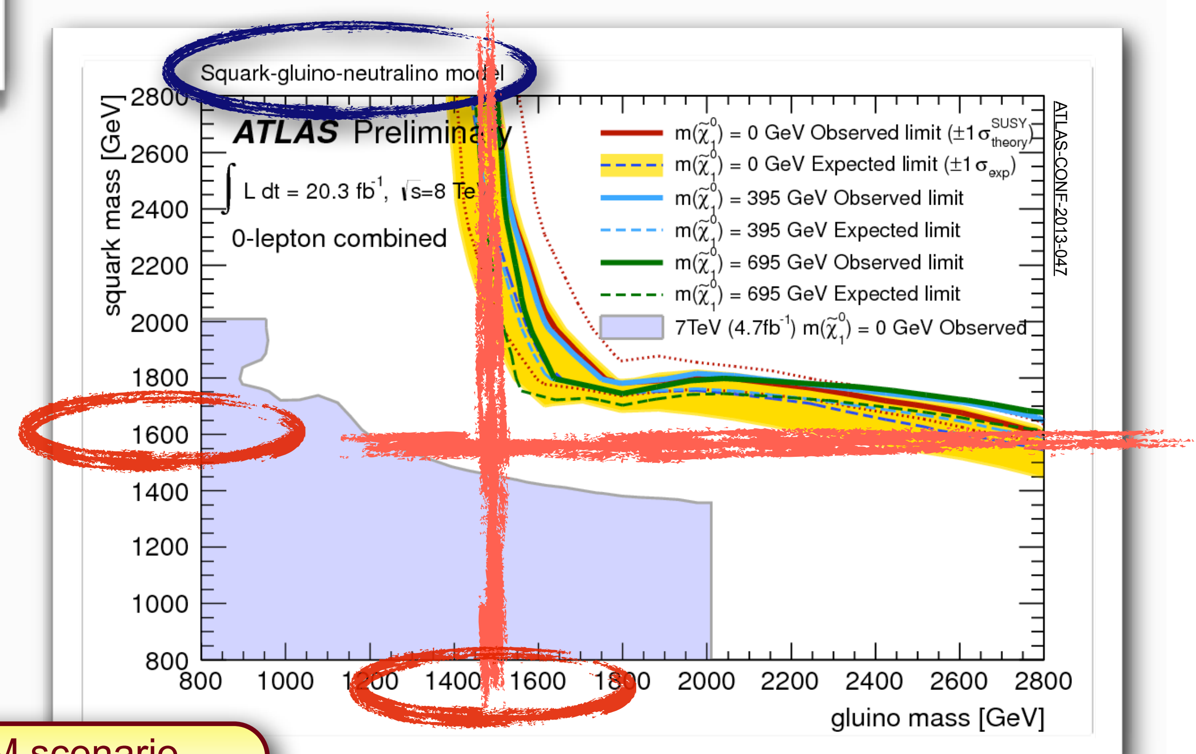


here: example of scenario compatible with a low-mass Higgs as recently discovered

- **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)

- 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

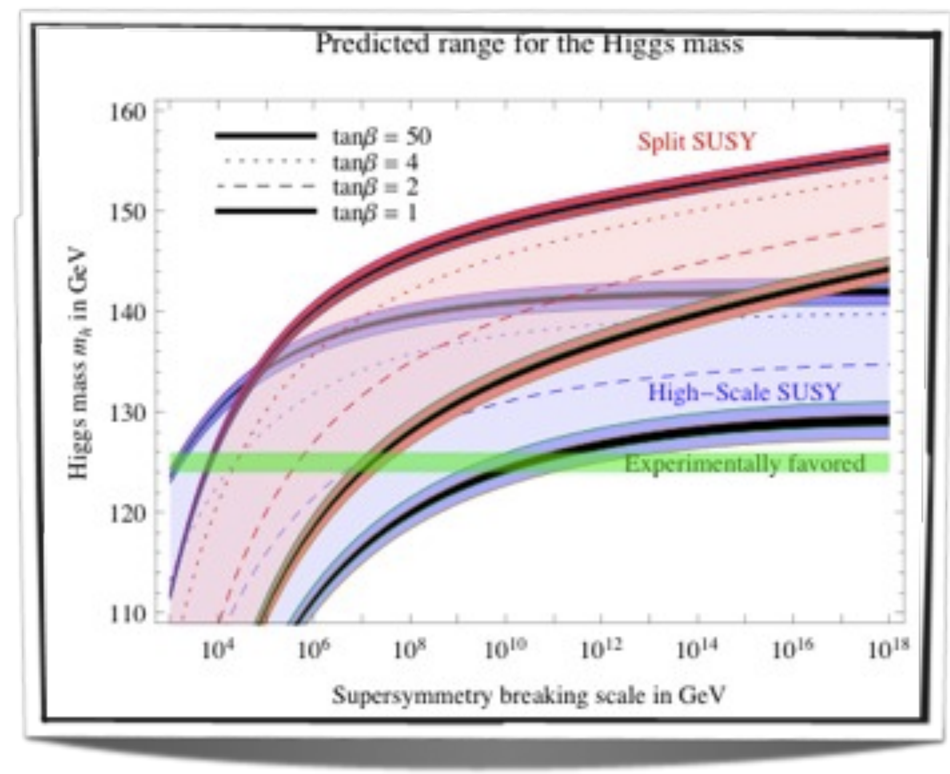
SUSY is Natural
but not plain vanilla

heavy stops,
large stop mixing,
extended Higgs sector

- ~~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

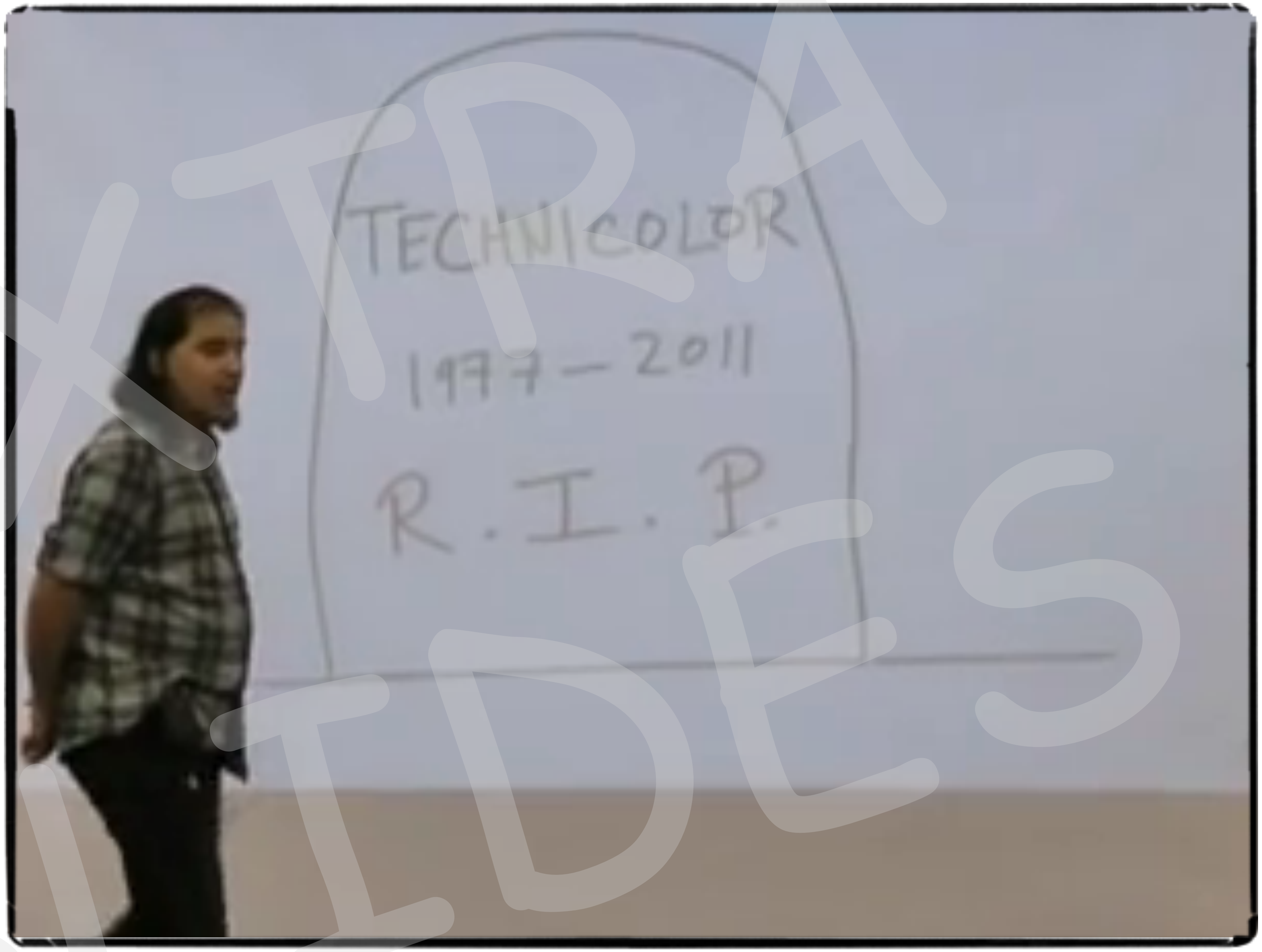
SUSY solves the big hierarchy
(or not even that)
but not the little hierarchy



unification etc...

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

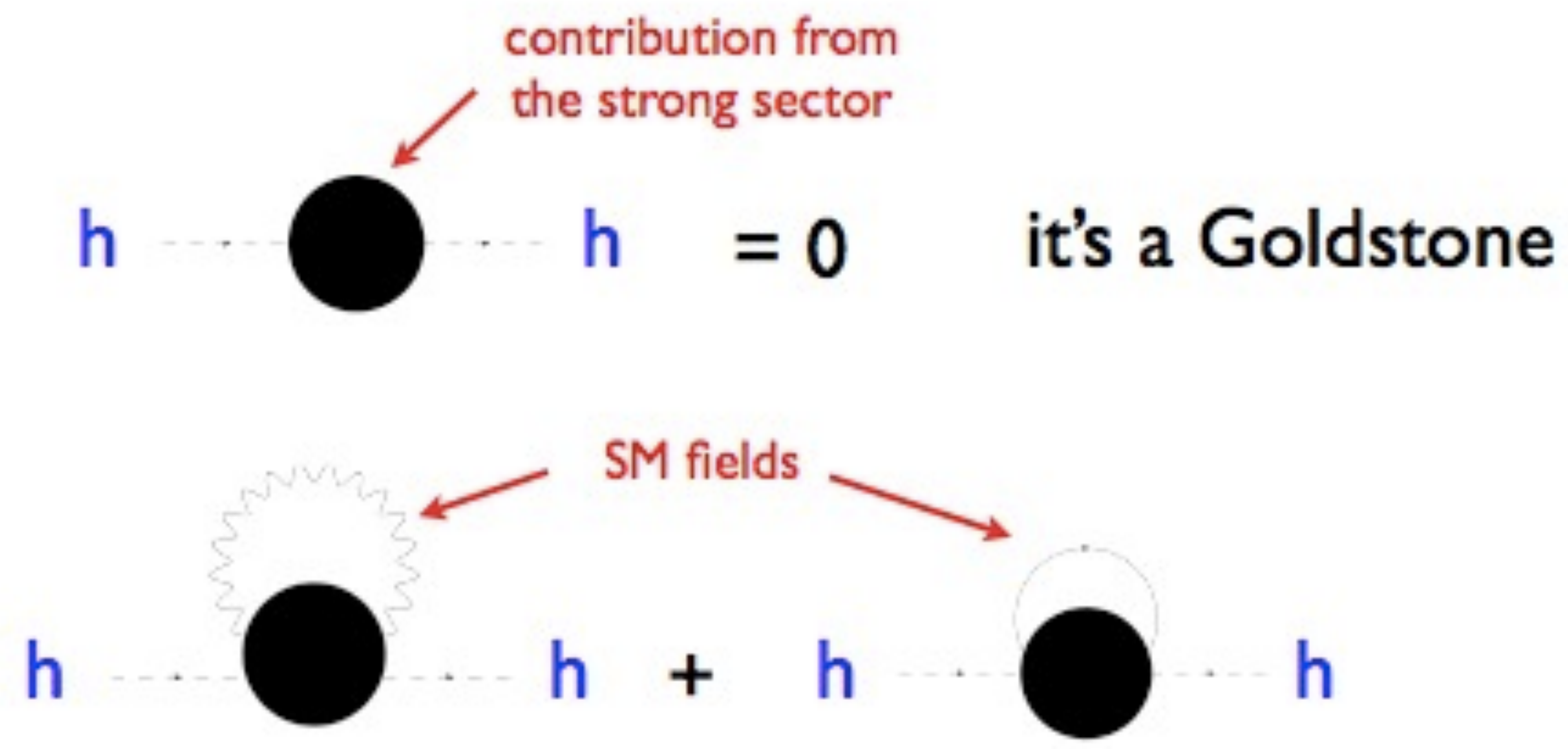
string etc...



Strongly coupled models

Light composite Higgs from "light" resonances

The interactions between the strong sector and the SM generate a potential for the Higgs



Impossible to compute the details of the potential from first principles
but using general properties on the asymptotic behavior of correlators
(saturation of Weinberg sum rules with the first few lightest resonances)
it is possible to estimate the Higgs mass

Pomarol, Riva '12

Marzocca, Serone, Shu '12

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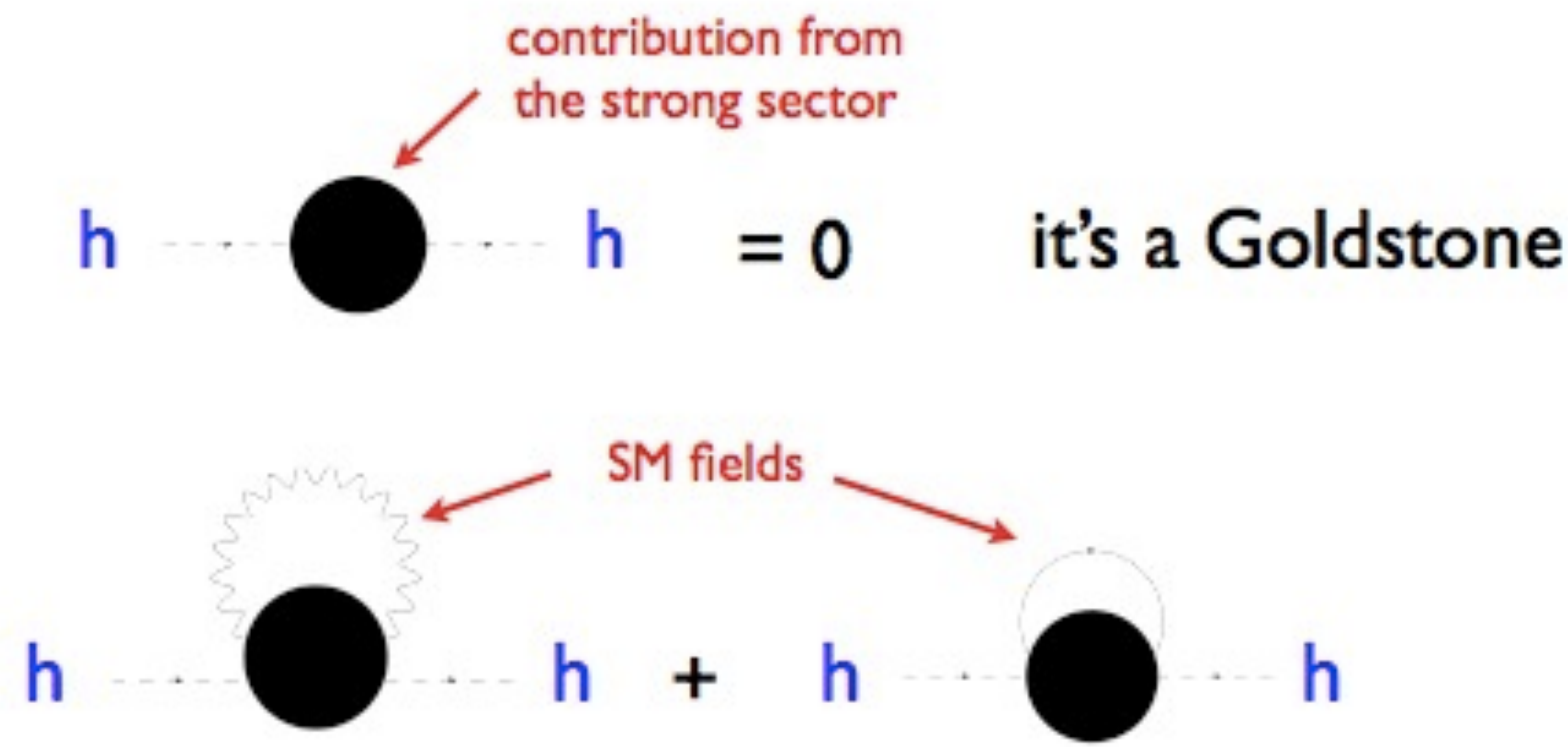

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(saturation of Weinberg sum rules with the first few lightest resonances)
it is possible to estimate the Higgs mass

Pomarol, Riva '12

Marzocca, Serone, Shu '12

$$m_h^2 \approx \frac{3}{\pi^2}\frac{m_t^2 m_Q^2}{f_{G/H}^2}$$

$\Rightarrow$

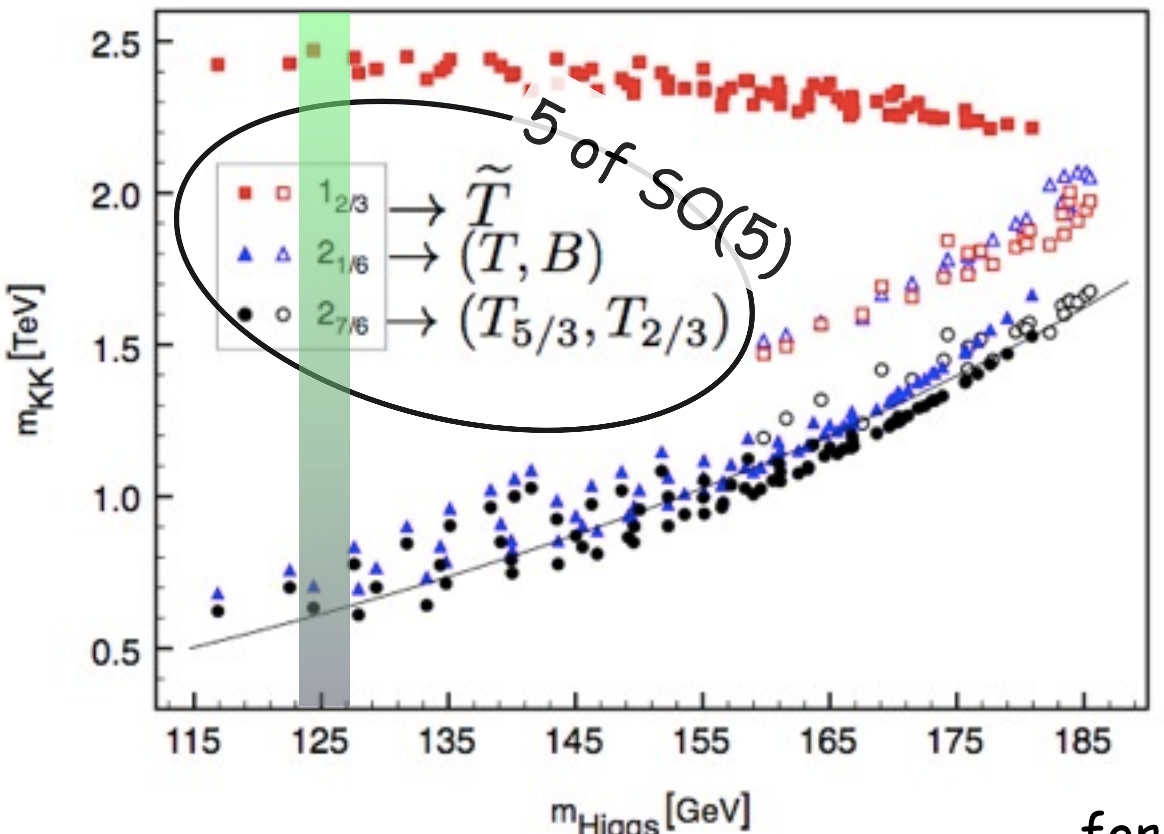
$$m_Q \lesssim 700\ \mathrm{GeV}\left(\frac{m_h}{125\ \mathrm{GeV}}\right)\left(\frac{160\ \mathrm{GeV}}{m_t}\right)\left(\frac{f}{500\ \mathrm{GeV}}\right)$$

fermionic resonances below ~ 1 TeV
vector resonances ~ few TeV (EW precision constraints)
~ for a natural (<20% fine-tuning) set-up ~

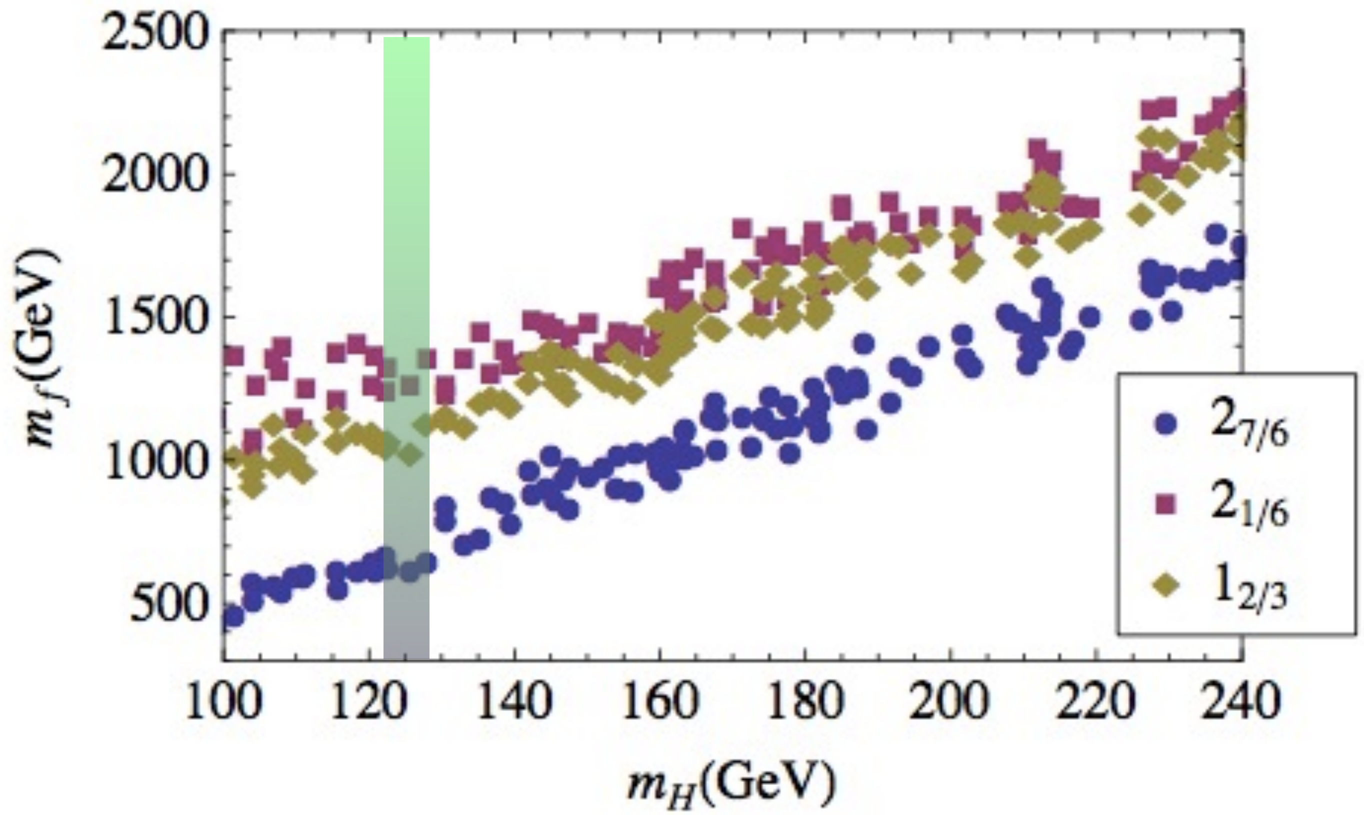
Light composite Higgs from "light" resonances

true spectrum in explicit realizations

Contino, Da Rold, Pomarol '06



De Curtis, Redi, Tesi '11



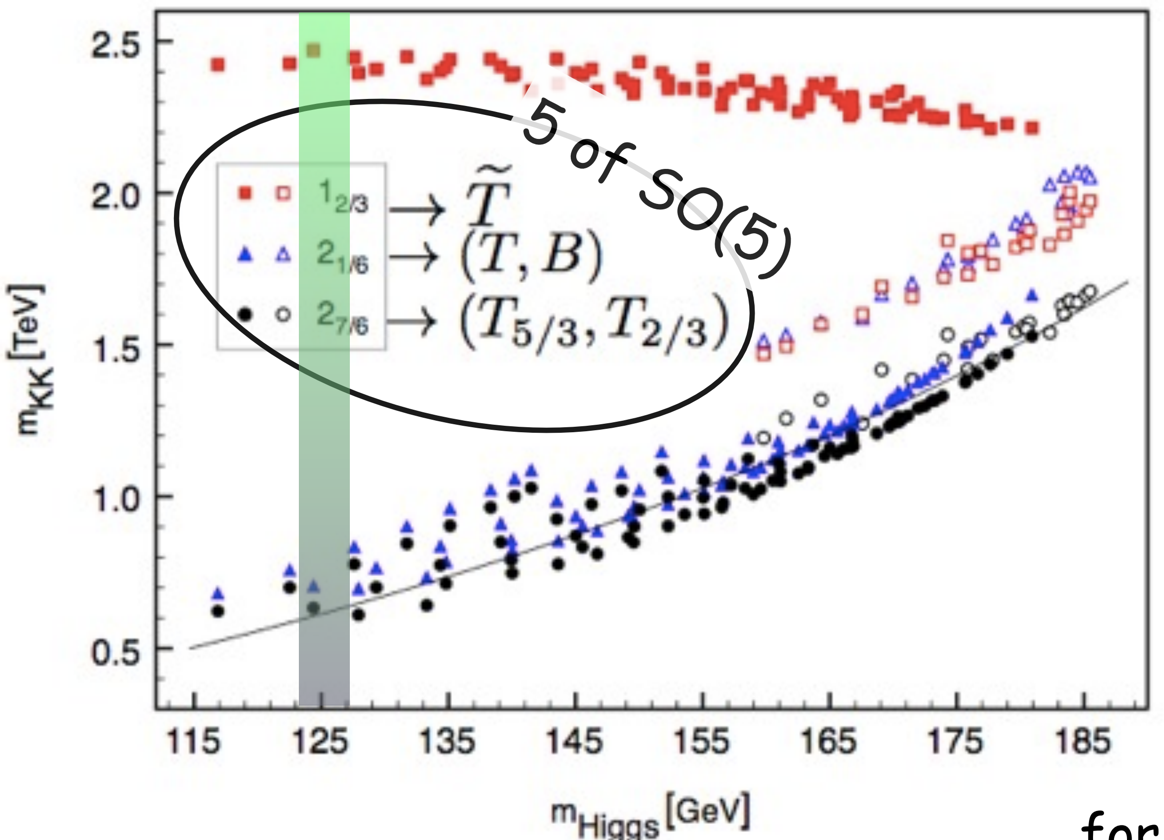
for similar results, see also

Matsedonskyi, Panico, Wulzer '12 & Marzocca, Serone, Shu '12

Light composite Higgs from "light" resonances

true spectrum in explicit realizations

Contino, Da Rold, Pomarol '06



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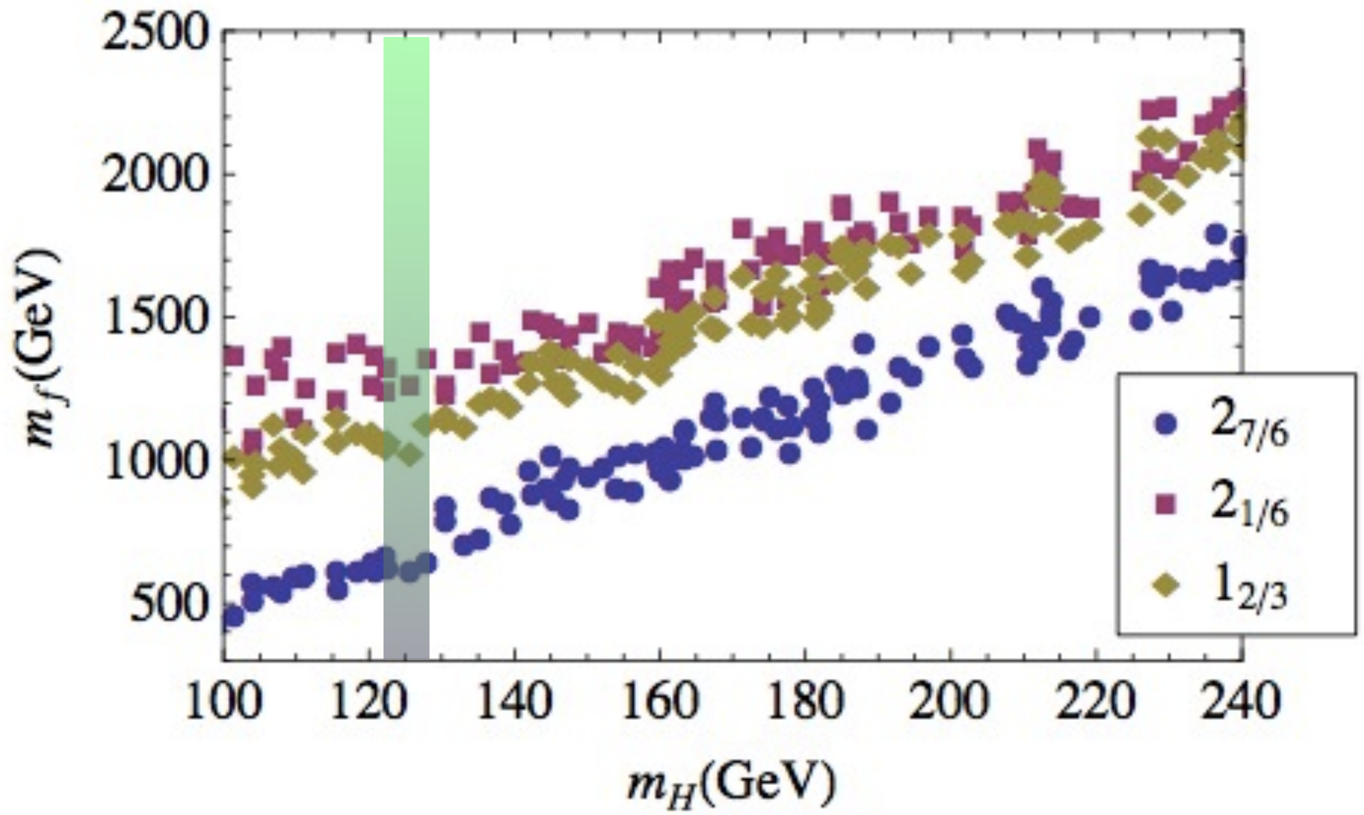


for similar results, see also

Matsedonskyi, Panico, Wulzer '12 & Marzocca, Serone, Shu '12

Nice AdS/CFT interpretation

$$\mathrm{Dim}[\mathcal{O}_\Psi] = \frac{3}{2} + |M_\Psi + \frac{1}{2}|$$

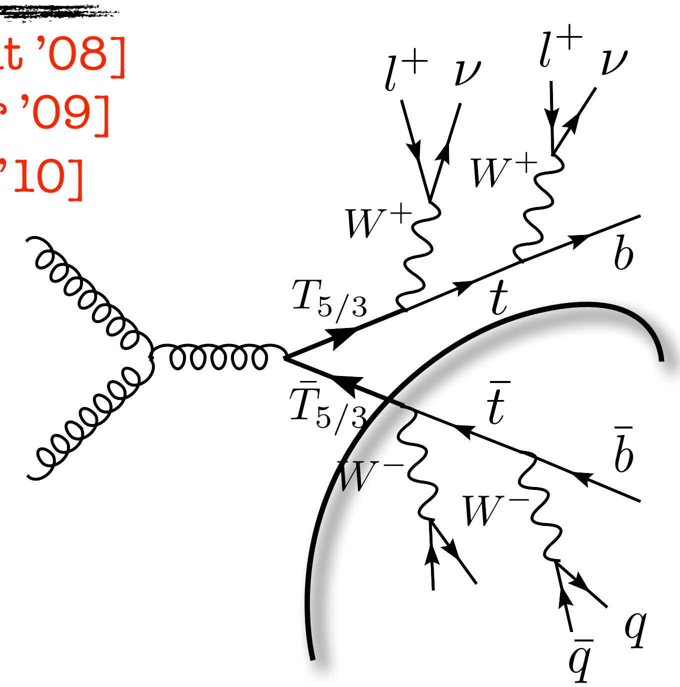
$$M_\Psi = 1/2 \leftrightarrow \dim[\mathcal{O}_\Psi] = 3/2 \leftrightarrow \text{light free field decoupled from CFT}$$

Rich phenomenology of the top partners

Search in same-sign di-lepton events

[Contino, Servant '08]
[Mrazek, Wulzer '09]
[Dissertori et al '10]

- *tt+jets* is not a background [except for charge mis-ID and fake e⁻]
- the resonant (*tW*) invariant mass can be reconstructed

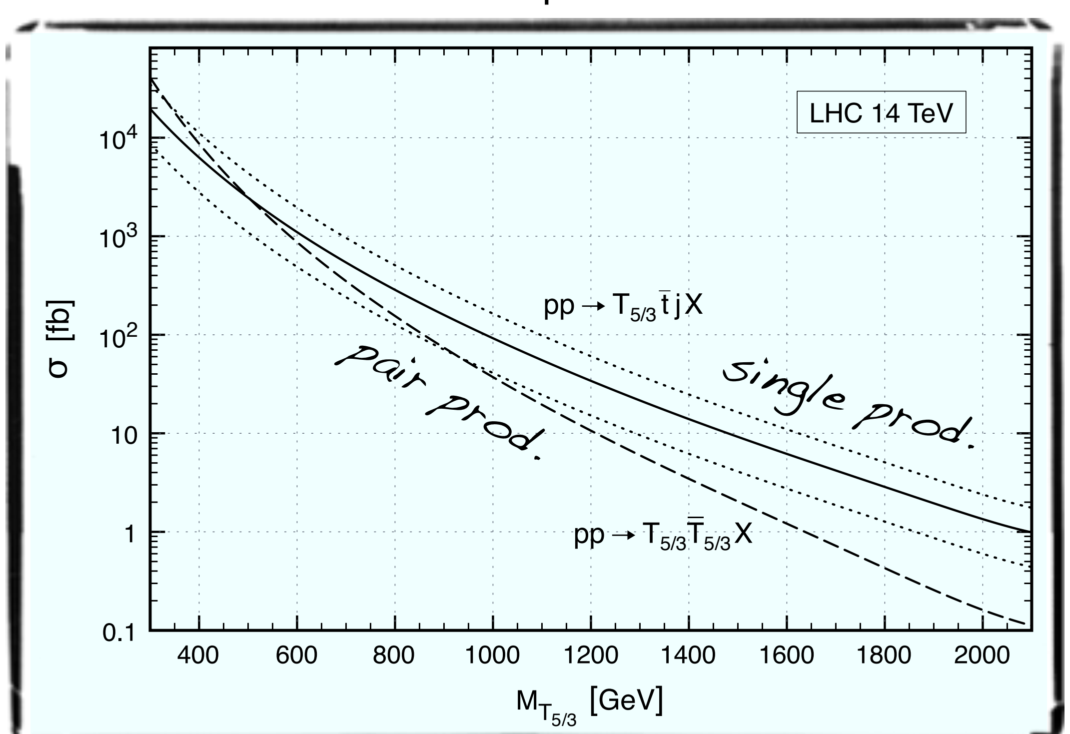


discovery potential (LHC$_{14\text{TeV}}$)

$M_{5/3}$=500 GeV (σxBR≈100/fb) → 56 pb^{-1}

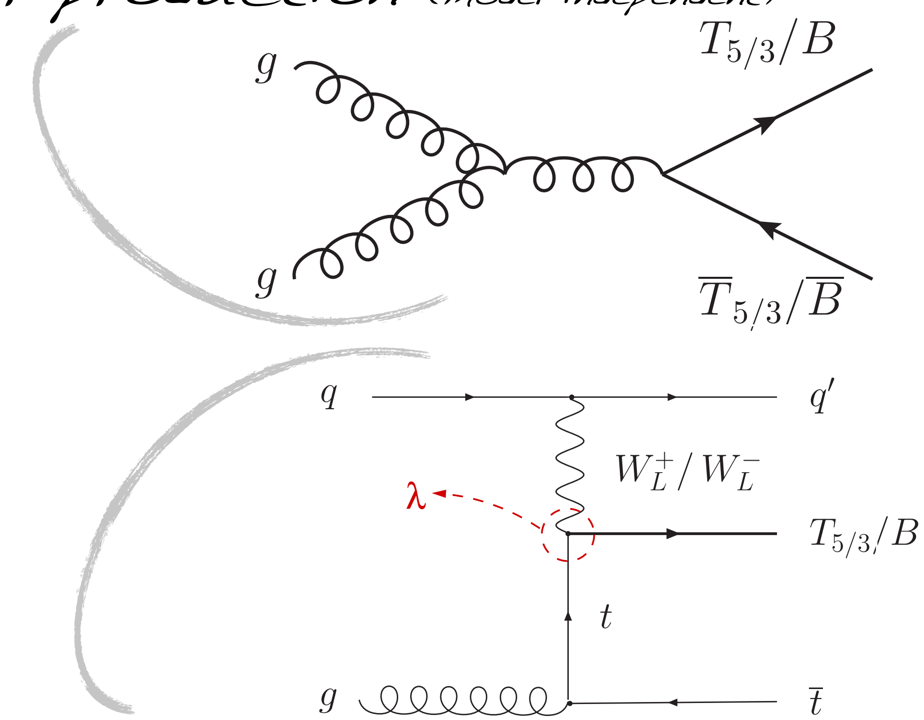
$M_{5/3}$=1 TeV (σxBR≈2/fb) → 15 fb^{-1}

Dissertori, Furlan, Moortgat, Nef '09]
4



[Contino, Servant '08]

Pair production (model independent)



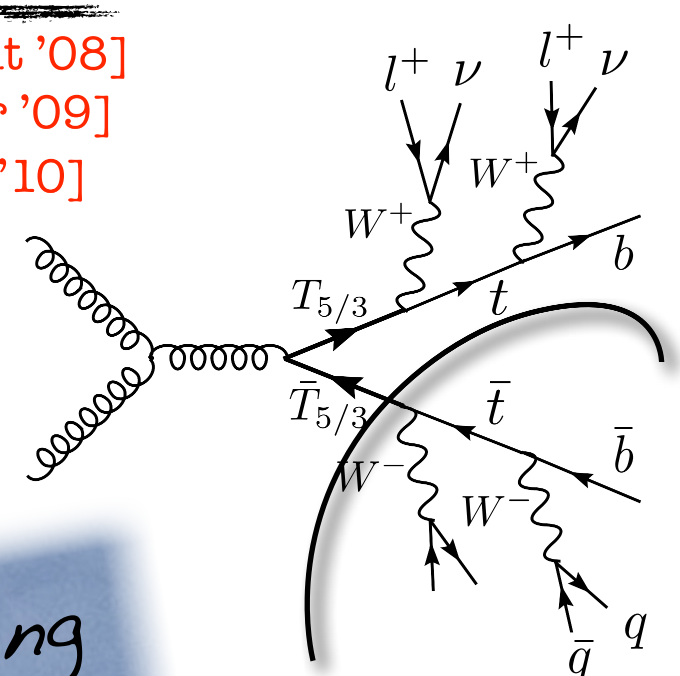
Single production (model dependent)

Rich phenomenology of the top partners

Search in same-sign di-lepton events

[Contino, Servant '08]
[Mrazek, Wulzer '09]
[Dissertori et al '10]

- *$t\bar{t}$+jets* is not a background [except for charge mis-ID and fake e⁻]
- the resonant (tW) invariant mass can be reconstructed

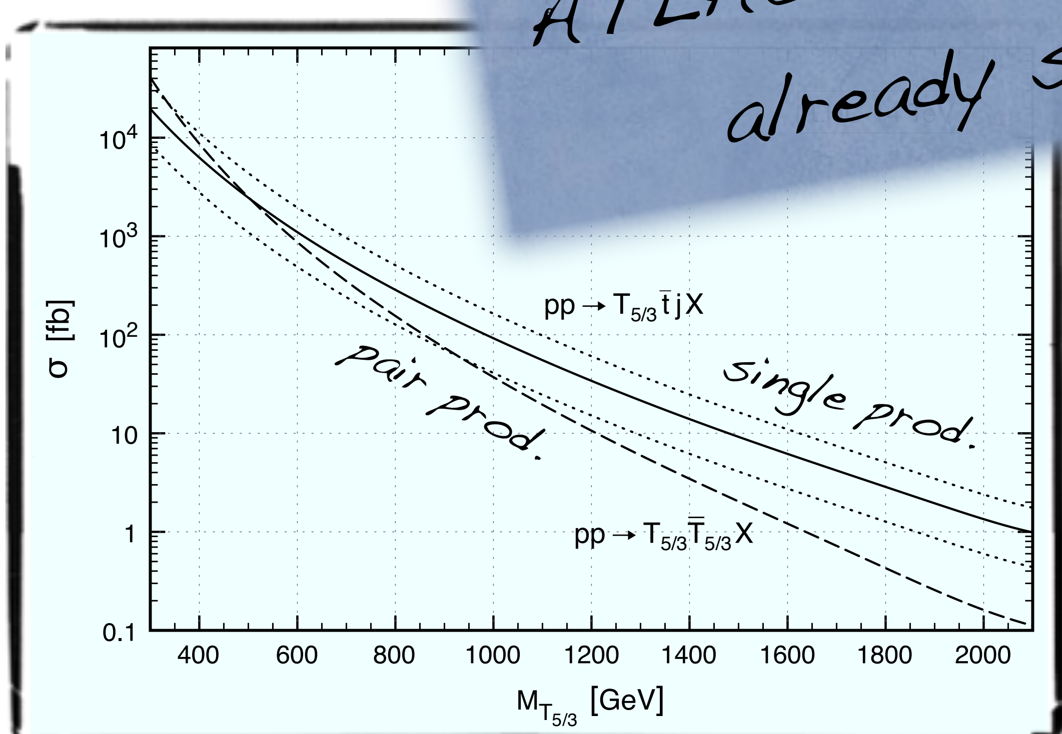


discovery potential (LHC14TeV)

$M_{5/3}$=500 GeV (σxBR≈100/fb) → 56 pb^{-1}

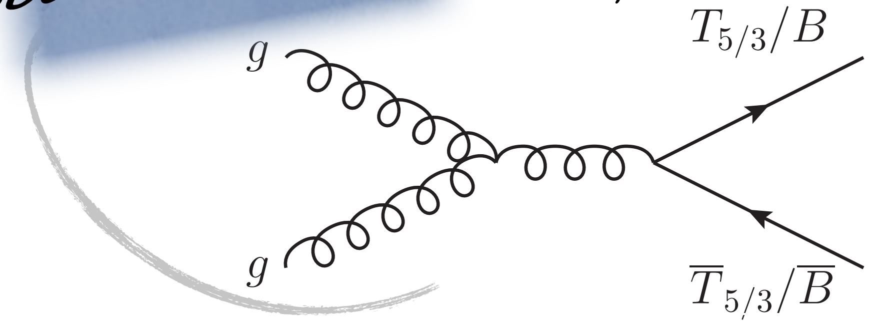
$M_{5/3}$=1 TeV (σxBR≈2/fb) → 15 fb^{-1}

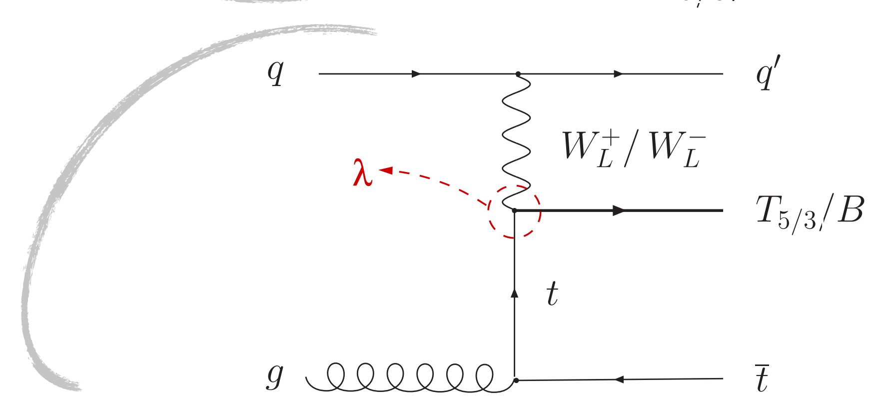
ATLAS & CMS searches ongoing
already stringent bounds



[Contino, Servant '08]

(model independent)



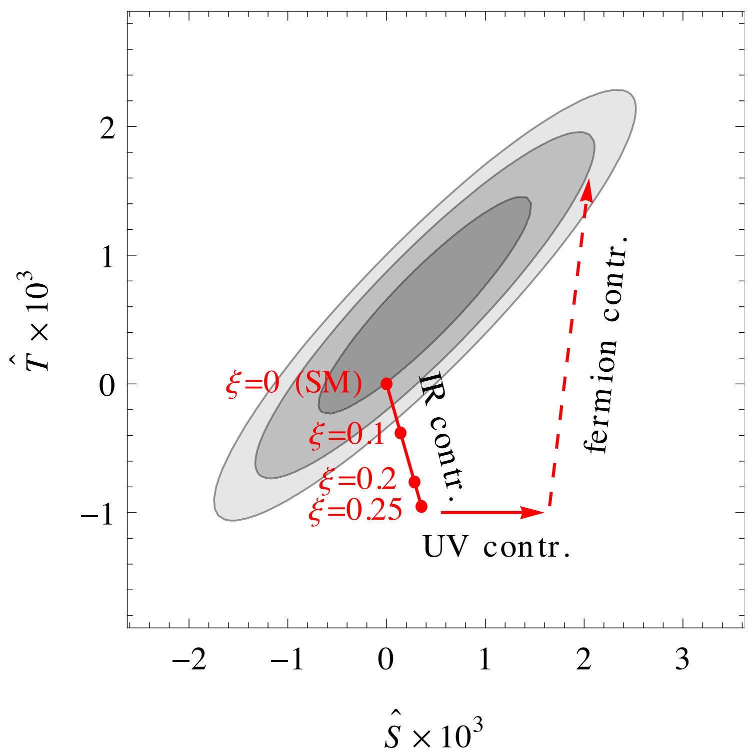


Single production (model dependent)

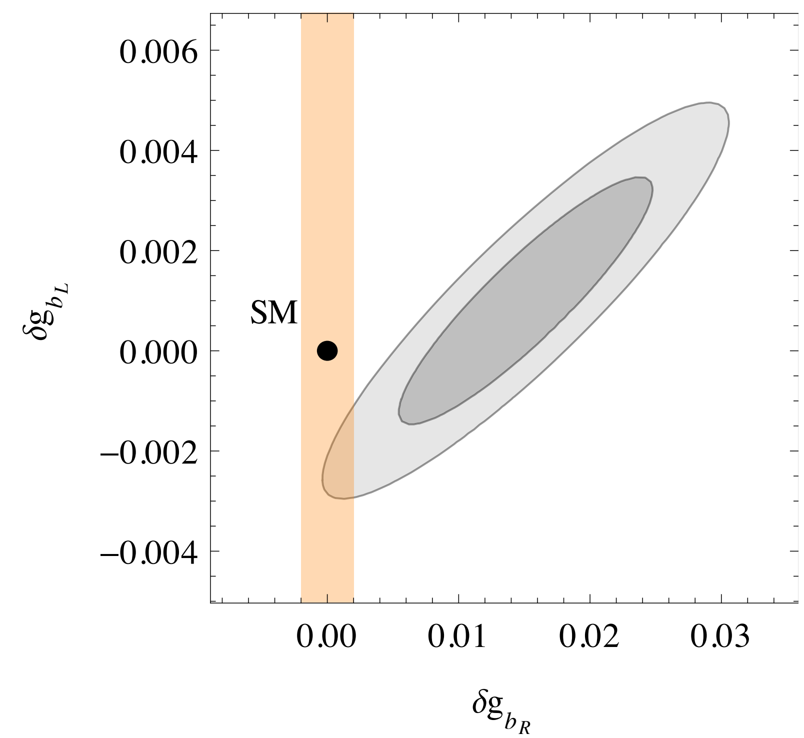
Top partners & EWPT

Grojean, Matsedonskyi, Panico '13

Oblique parameters



Zb_Lb_L



tree-level contribution

$$\Delta\widehat{S} \simeq \frac{g^2}{g_*^2}\xi \simeq \frac{m_w^2}{m_*^2}$$

Higgs loop

$$\Delta\widehat{S} = \frac{g^2}{192\pi^2}\xi \log\left(\frac{m_*^2}{m_h^2}\right) \simeq 1.4\cdot 10^{-3}\,\xi \qquad \Delta\widehat{T} = -\frac{3g'^2}{64\pi^2}\xi \log\left(\frac{m_*^2}{m_h^2}\right) \simeq -3.8\cdot 10^{-3}\,\xi$$

fermion loop

$$\Delta\widehat{S}^{div}_{ferm} = \frac{g^2}{8\pi^2}(1-2c^2)\,\xi \log\left(\frac{m_*^2}{m_4^2}\right) \qquad \Delta\widehat{T} \simeq \frac{N_c}{16\pi^2}y_t^2\,\xi \simeq 2\cdot 10^{-2}\,\xi$$

tree-level contribution

$$\frac{\delta g_{b_L}}{g_{b_L}^{SM}} \sim \frac{y_L^2 f^2}{m^2}\frac{m_z^2}{m_*^2} \simeq 8\cdot 10^{-4}\,\frac{f}{m}\left(\frac{4\pi}{g_*}\right)^2\xi$$

fermion loop

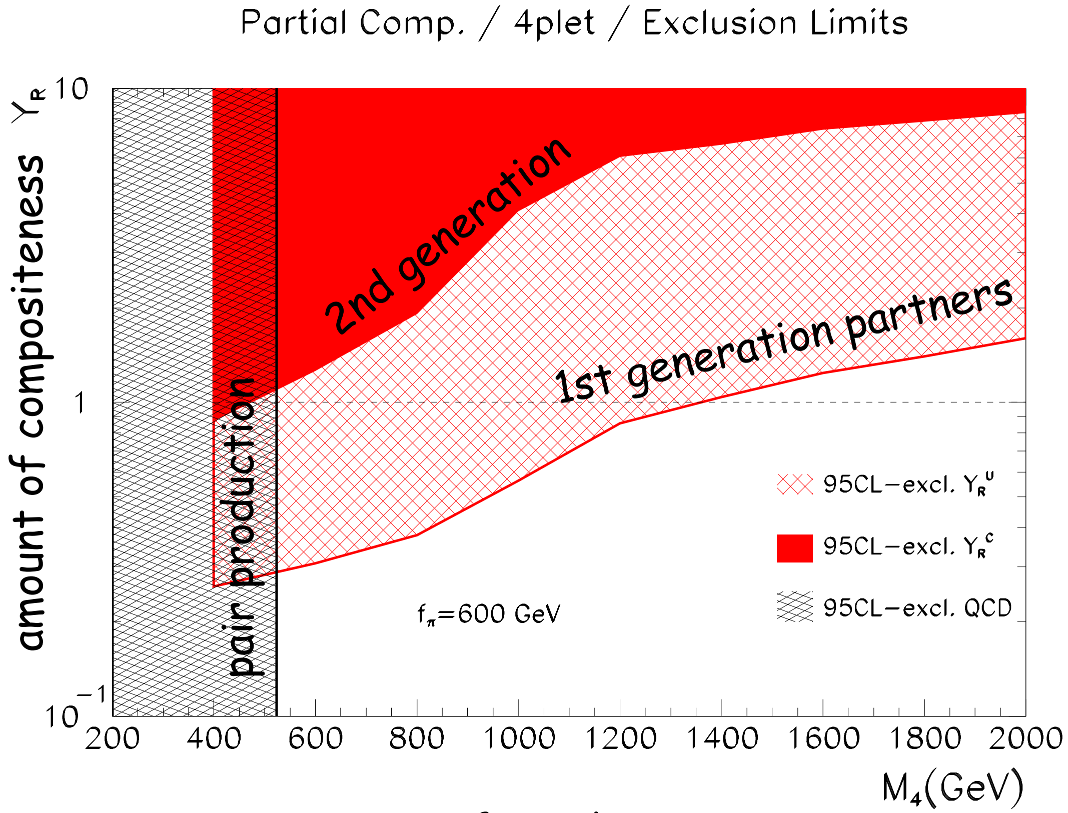
$$\frac{\delta g_{b_L}}{g_{b_L}^{SM}} \simeq \frac{y_t^2}{16\pi^2}\xi \log\left(\frac{m_*^2}{m_4^2}\right) \simeq 2\cdot 10^{-2}\,\xi$$

ξ<0.1 ⇨ we might have to wait LHC-HL to see any new physics in Higgs data

BSM Higgs precision era

Light quark compositeness pheno

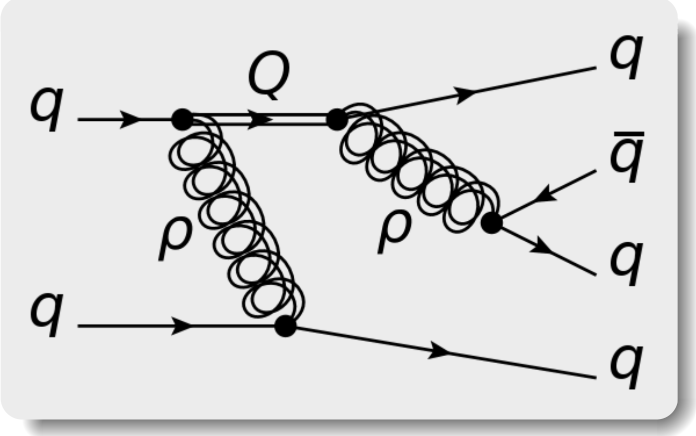
Redi, Sanz, de Vries, Weiler '13
Delaunay et al '13



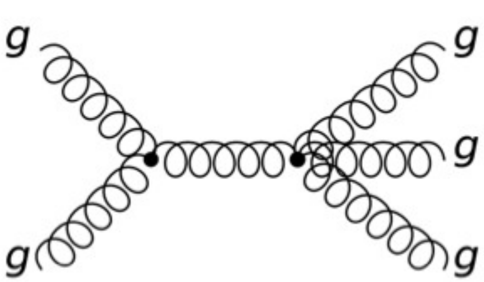
mass of quark partners

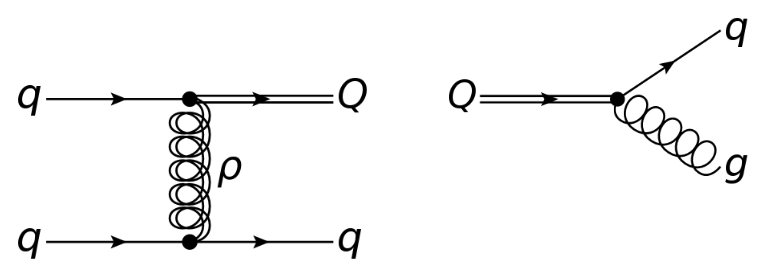
- ☑ LHC searches already put interesting bounds on light quark partners
- ☑ dedicated searches can significantly improve them

4 jet searches



3 jet searches





QCD vs. Composite Partners

Cut-flow	$m_Q = 600$ GeV		$m_Q = 1200$ GeV	
	signal	QCD	signal	QCD
p_T leading jet > 450 GeV	0.51	0.0067	0.90	0.0067
$H_T > m_Q$	0.51	0.0067	0.80	0.0015
$\|m_{jj} - m_Q\| <$ (30, 50) GeV	0.15	0.00037	0.11	2.5×10^{-5}
$\Delta\phi_{jj} > 1.5$	0.045	9.9×10^{-5}	0.060	2.1×10^{-7}

Cornering Higgs compositeness

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

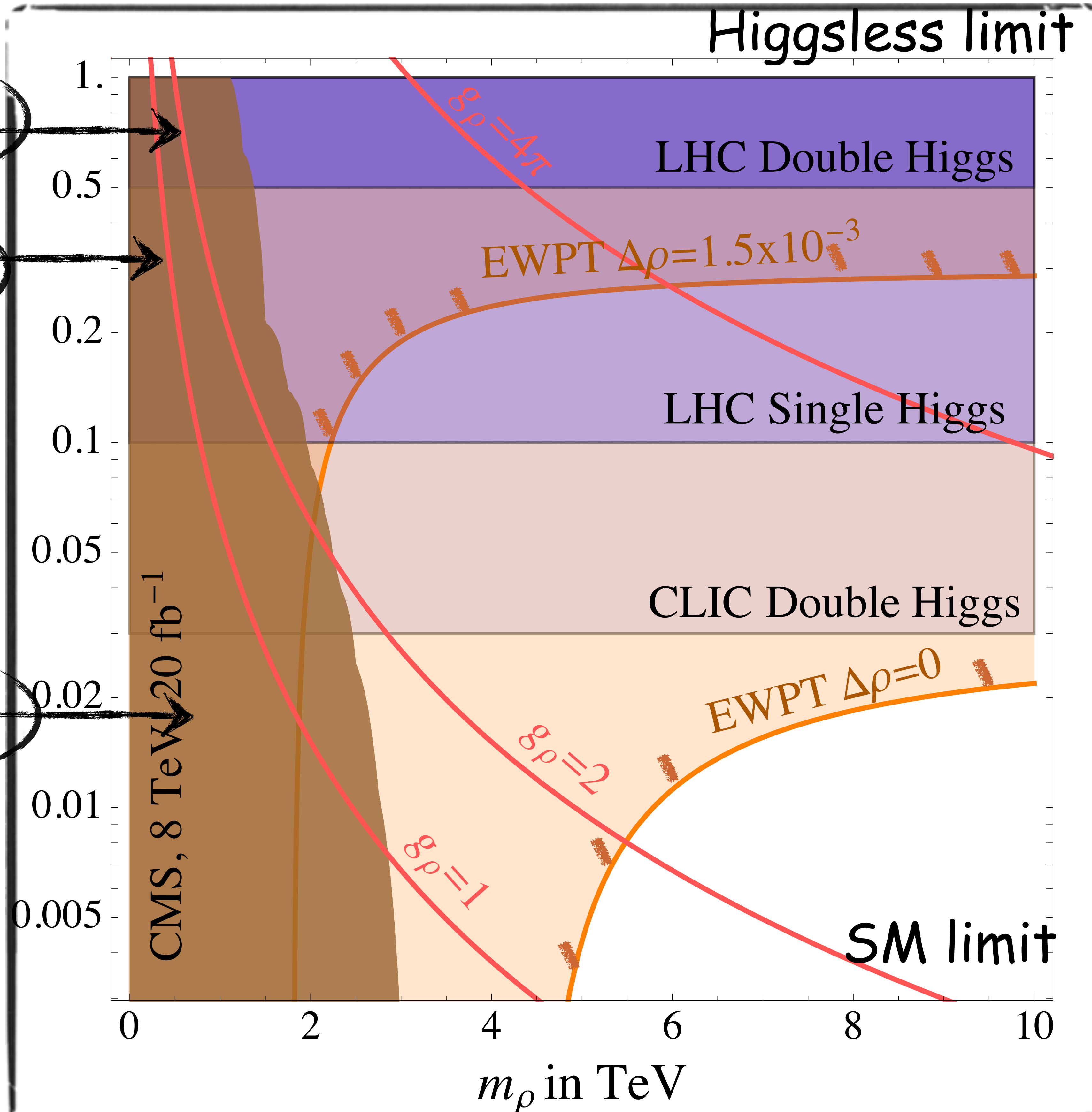
Strong WW scattering

Anomalous Higgs couplings

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

Resonance searches

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



Cornering Higgs compositeness

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

	$\xi = (v/f)^2$	Λ
LHC $L = 300\,\mathrm{fb}^{-1}$	0.5 (double Higgs [1,2])	4.5 TeV
	0.1 (single Higgs [3,4])	10 TeV
ILC 500 GeV $L = 1\,\mathrm{ab}^{-1}$	5×10^{-3} (single Higgs [5])	45 TeV
CLIC 3 TeV $L = 1\,\mathrm{ab}^{-1}$	5×10^{-2} (double Higgs [6])	15-20 TeV
	2×10^{-3} (single + double Higgs [5])	70 TeV

References

[1] G. F. Giudice, C. Grojean, A. Pomarol and R. Rattazzi, JHEP **0706** (2007) 045 [arXiv:hep-ph/0703164].

[2] R. Contino, C. Grojean, M. Moretti, F. Piccinini and R. Rattazzi, JHEP **1005** (2010) 089 [arXiv:1002.1011 [hep-ph]].

[3] **CMS** Collaboration, 2012, CMS NOTE-2012/006.

[4] **ATLAS** Collaboration, 2012, ATL-PHYS-PUB-2012-004.

[5] V. Barger, T. Han, P. Langacker, B. McElrath and P. Zerwas, Phys. Rev. D **67** (2003) 115001 [arXiv:hep-ph/0301097].

[6] R. Contino, C. Grojean, D. Pappadopulo, R. Rattazzi and A. Thamm, work in progress.