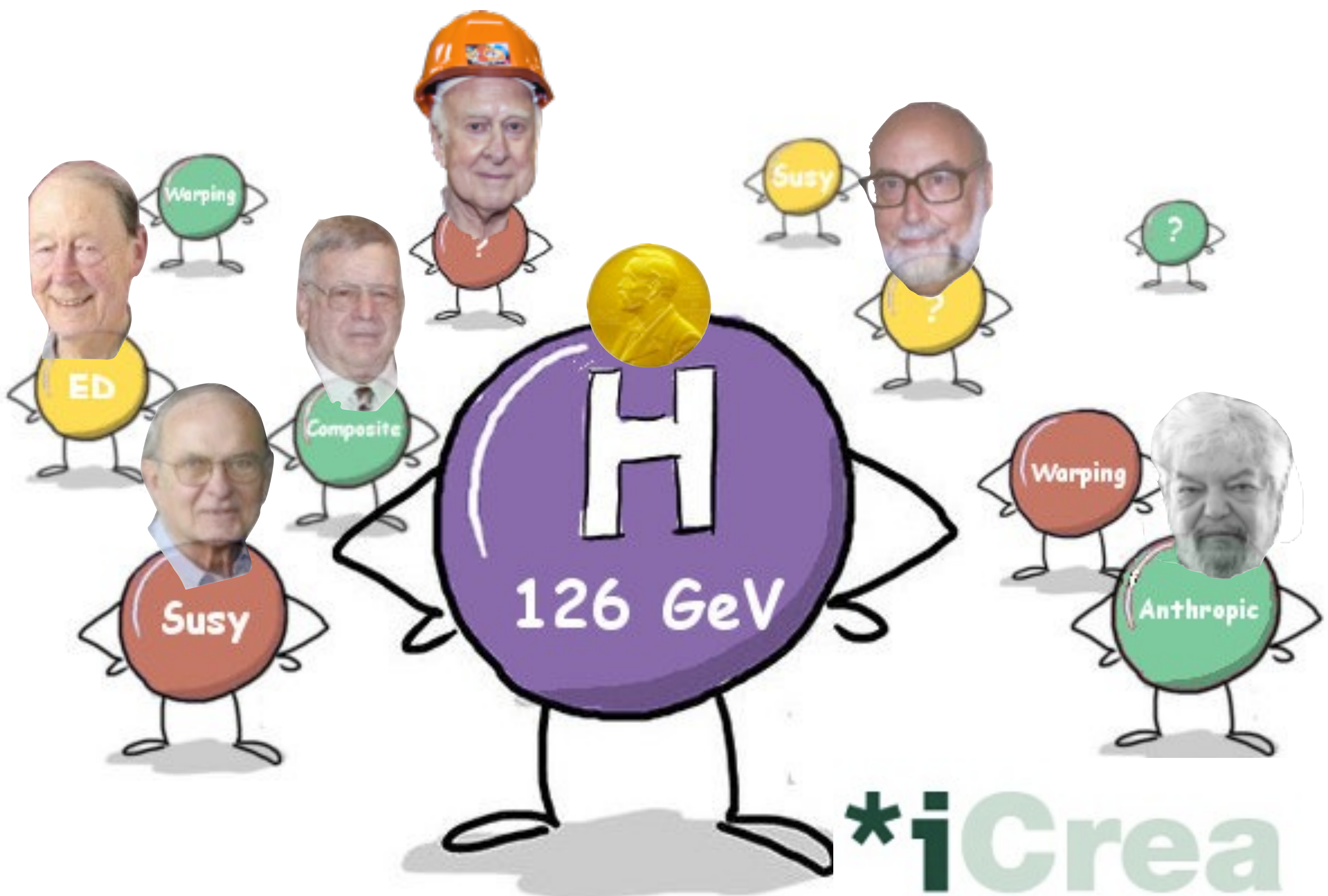
After the Discovery: Challenges and Open Questions in Higgs Physics



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Universität Wien,
October 31, 2013

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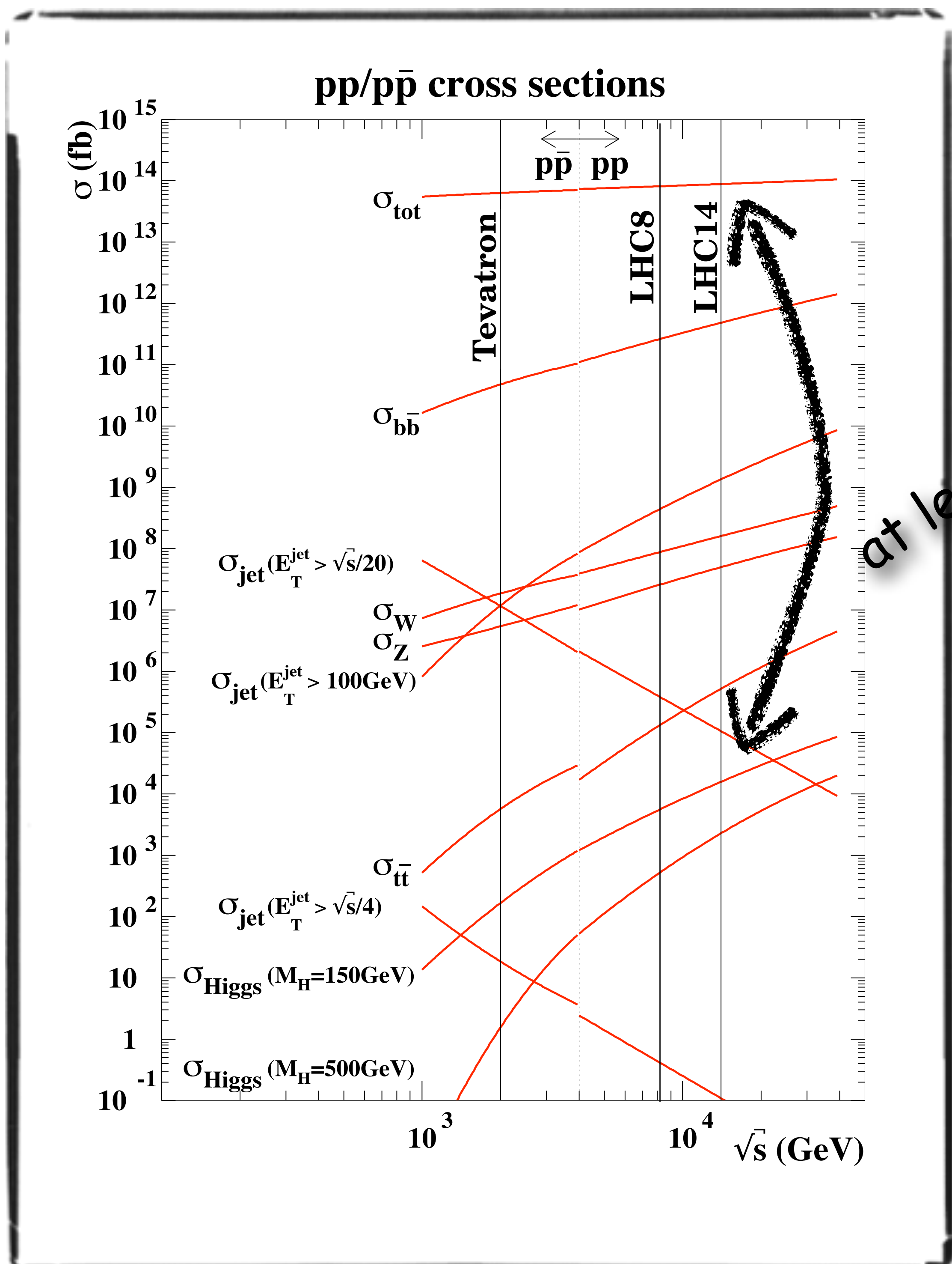
We are living a privileged moment in the history of HEP

(picture: courtesy of A. Hoecker]

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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... like finding the paper you are looking for in (10^8 copies of) John Ellis' office

1

The importance of being Higgs

... or "why the Higgs boson is not just yet another particle?"

Why was the LHC built?

symmetry breaking: new phase with more degrees of freedom

massive $W^{\pm}$, Z: 3 physical polarizations=eaten Goldstone bosons $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V}$

$\Rightarrow$ UV behavior of these Goldstone's? $\Leftarrow$

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$$\Sigma = e^{i\sigma^a \pi^a / v}$$

Goldstone of $SU(2)_L \times SU(2)_R / SU(2)_V$

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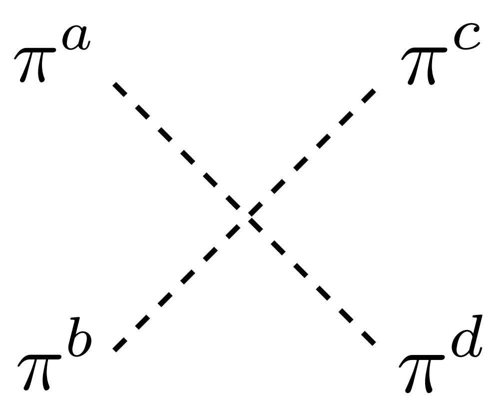
$$\boxed{\mathcal{L}_{\rm mass} = \frac{1}{2}(\partial_\mu \pi^a)^2 - \frac{1}{6v^2}\left((\pi^a \partial_\mu \pi^a)^2 - (\pi^a)^2 (\partial_\mu \pi^a)^2\right) + \ldots}$$

contact interaction growing with energy



$$\mathcal{A}\left(\pi^a \pi^b \to \pi^c \pi^d\right) = \mathcal{A}(s,t,u)\delta^{ab}\delta^{cd} + \mathcal{A}(t,s,u)\delta^{ac}\delta^{bd} + \mathcal{A}(u,t,s)\delta^{ad}\delta^{bc}$$

$$\mathcal{A}(s,t,u) = \frac{s}{v^2}$$ Weinberg's LET

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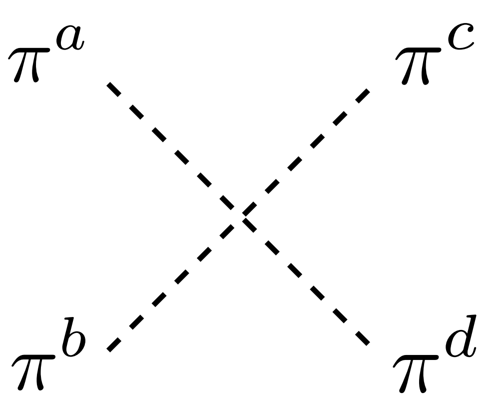

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the behavior of this amplitude is not consistent above $4\pi v$ (≈1÷3TeV)

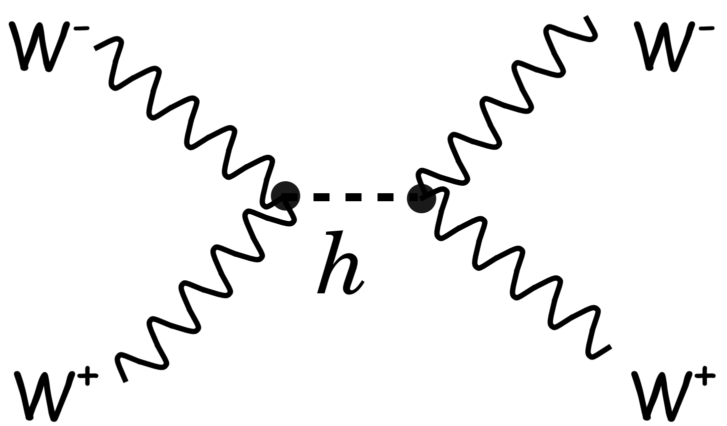
Lee, Quigg & Thacker '77

What is the SM Higgs?

A single scalar degree of freedom neutral under $SU(2)_L \times SU(2)_R / SU(2)_V$

$$\mathcal{L}_{\mathrm{EWSB}} = \frac{v^2}{4} \mathrm{Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right) \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - \lambda \bar{\psi}_L \Sigma \psi_R \left(1 + c\frac{h}{v}\right)$$

'a', 'b' and 'c' are arbitrary free couplings



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

growth cancelled for
a = 1
restoration of
perturbative unitarity

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

$$\Sigma = e^{i\sigma^a \pi^a / v}$$

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$$D_\mu \Sigma \approx W_\mu$$

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For a=1: perturbative unitarity in elastic channels $WW \to WW$

For $b = a^2$: perturbative unitarity in inelastic channels $WW \to hh$

Cornwall, Levin, Tiktopoulos '73

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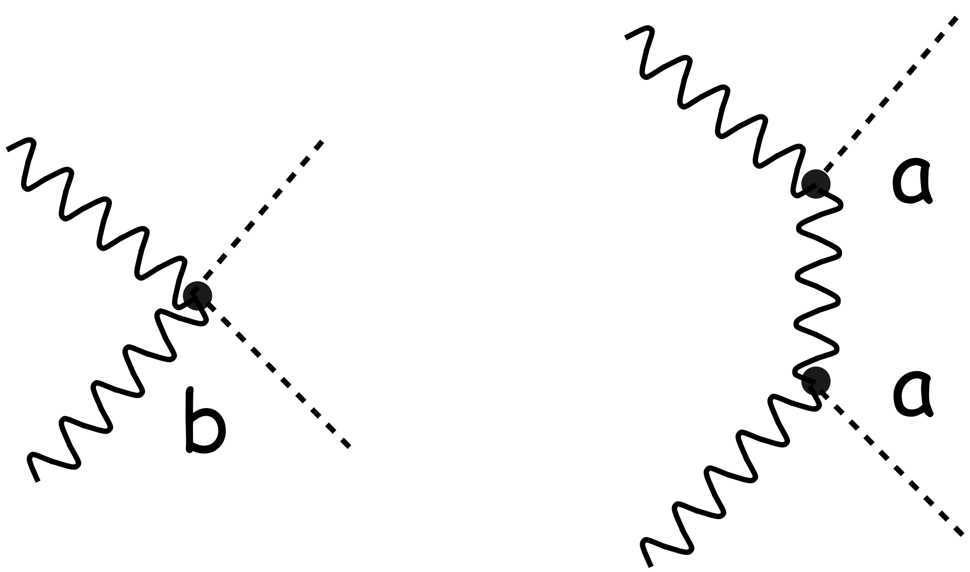

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For b = a^2: perturbative unitarity in inelastic channels WW $\to$ hh

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

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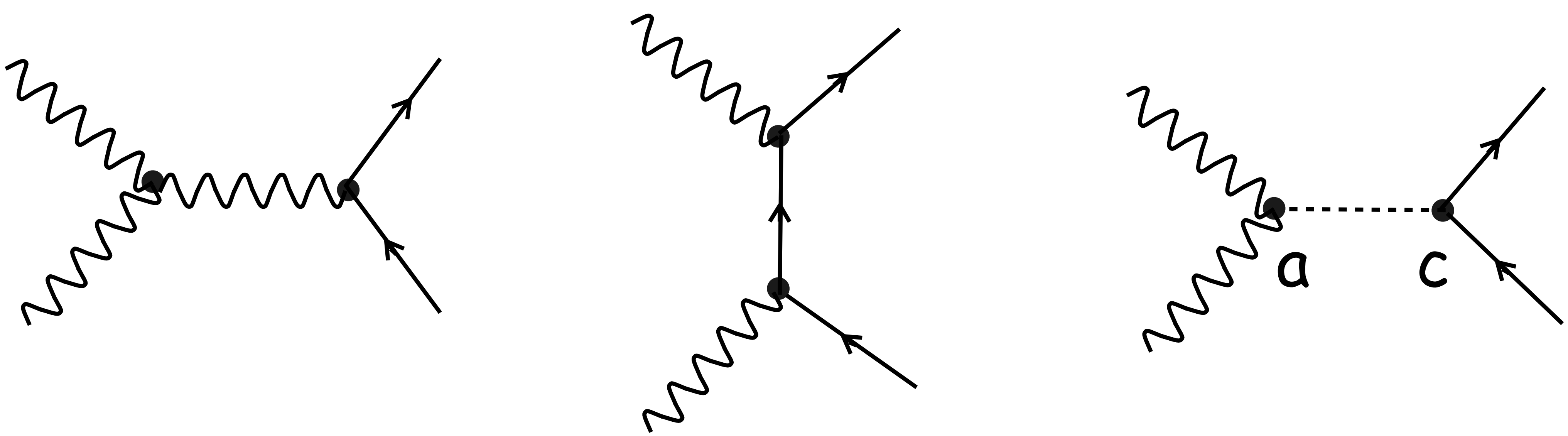

What is the SM Higgs?

A single scalar degree of freedom neutral under $SU(2)_L \times SU(2)_R / SU(2)_V$

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4} \mathrm{Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right) \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - \lambda \bar{\psi}_L \Sigma \psi_R \left(1 + c\frac{h}{v}\right)$$

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For a=1: perturbative unitarity in elastic channels WW $\to$ WW

For b = a^2: perturbative unitarity in inelastic channels WW $\to$ hh

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

'a=1', 'b=1' & 'c=1' define the SM Higgs

Higgs properties depend on a single unknown parameter (m_H)

$\mathcal{L}_{\rm EWSB}$ can be rewritten as $D_\mu H^\dagger D_\mu H$

$$H = \frac{1}{\sqrt{2}} e^{i\sigma^a \pi^a / v} \begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

h and π^a (ie W_L andZ_L) combine to form a linear representation of $SU(2)_L \times U(1)_Y$

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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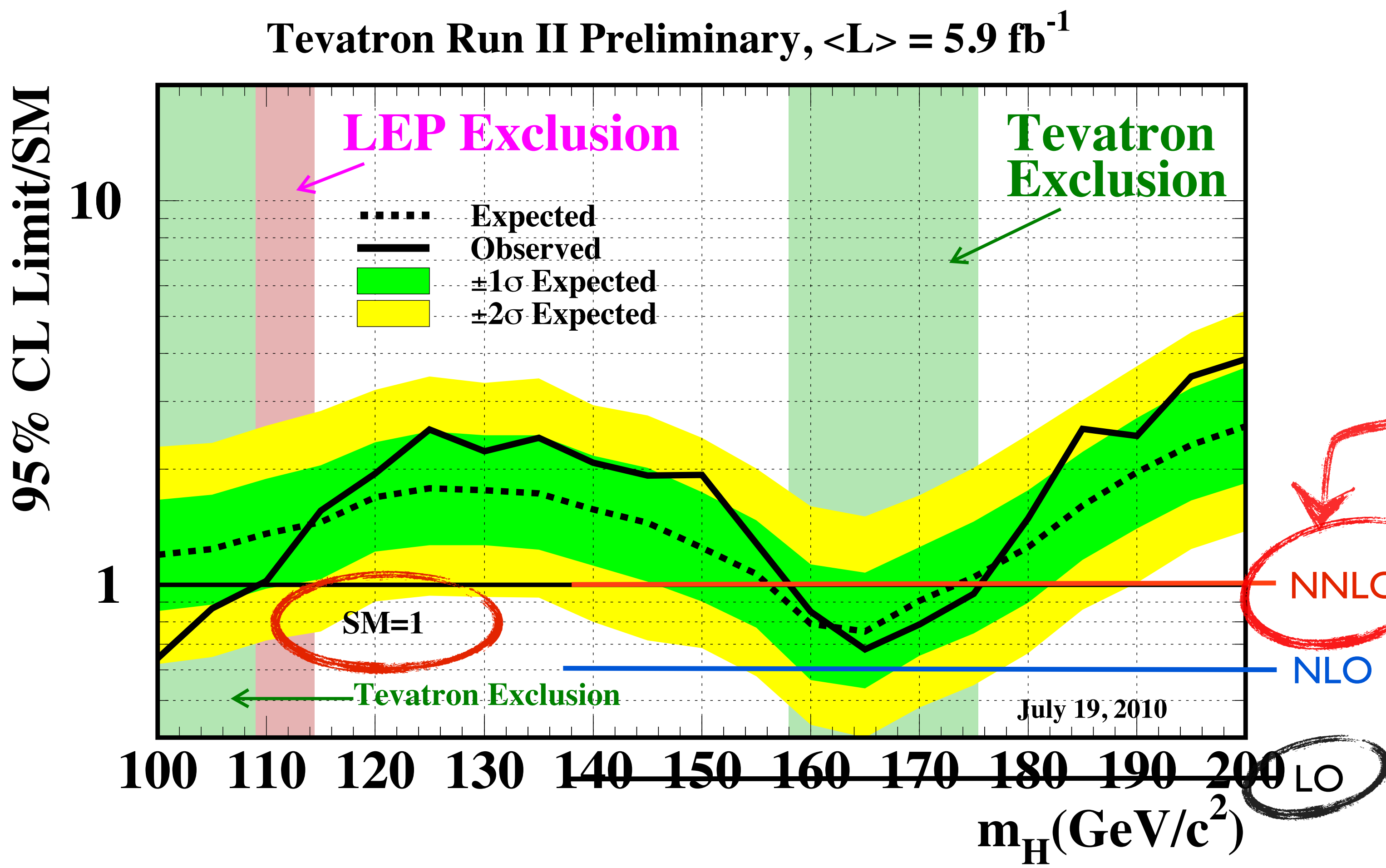
Why did it work better than expected?



- 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

What's next?

"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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Great success...

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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:

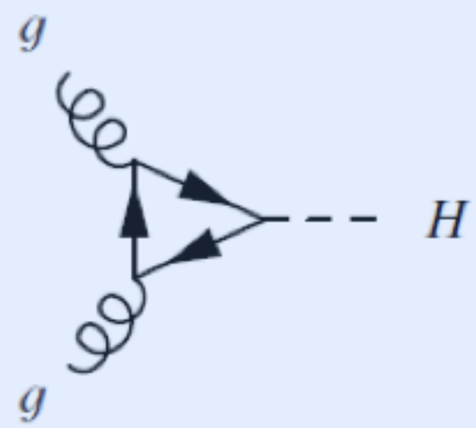
exploration/discovery era or consolidation/measurement era?

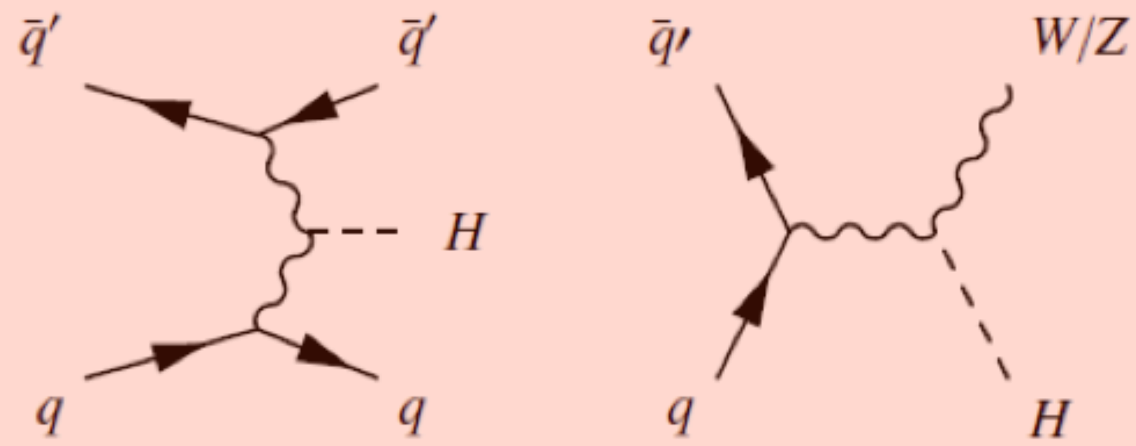
2

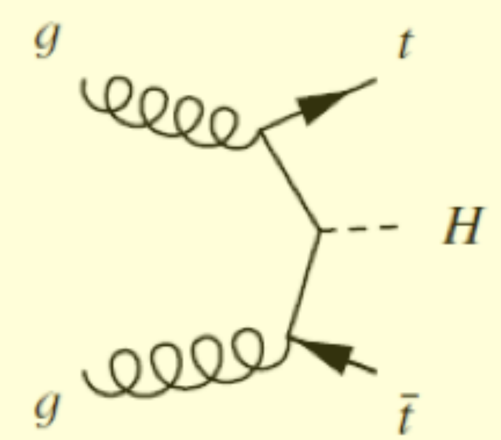
SM Precision Higgs Physics

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

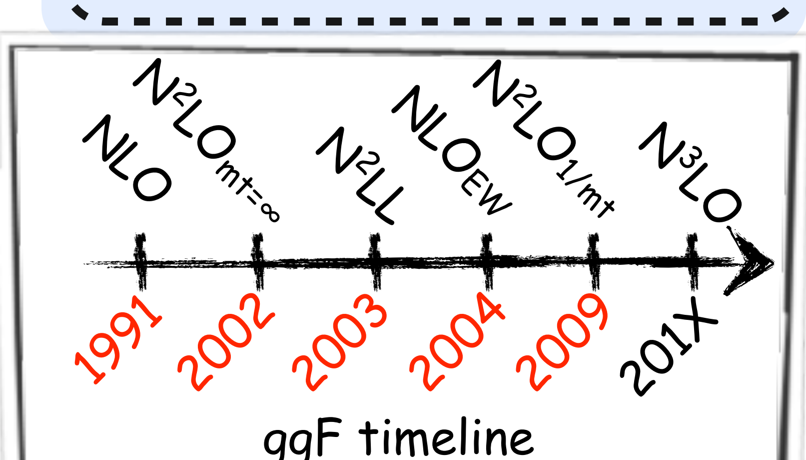
NLO QCD

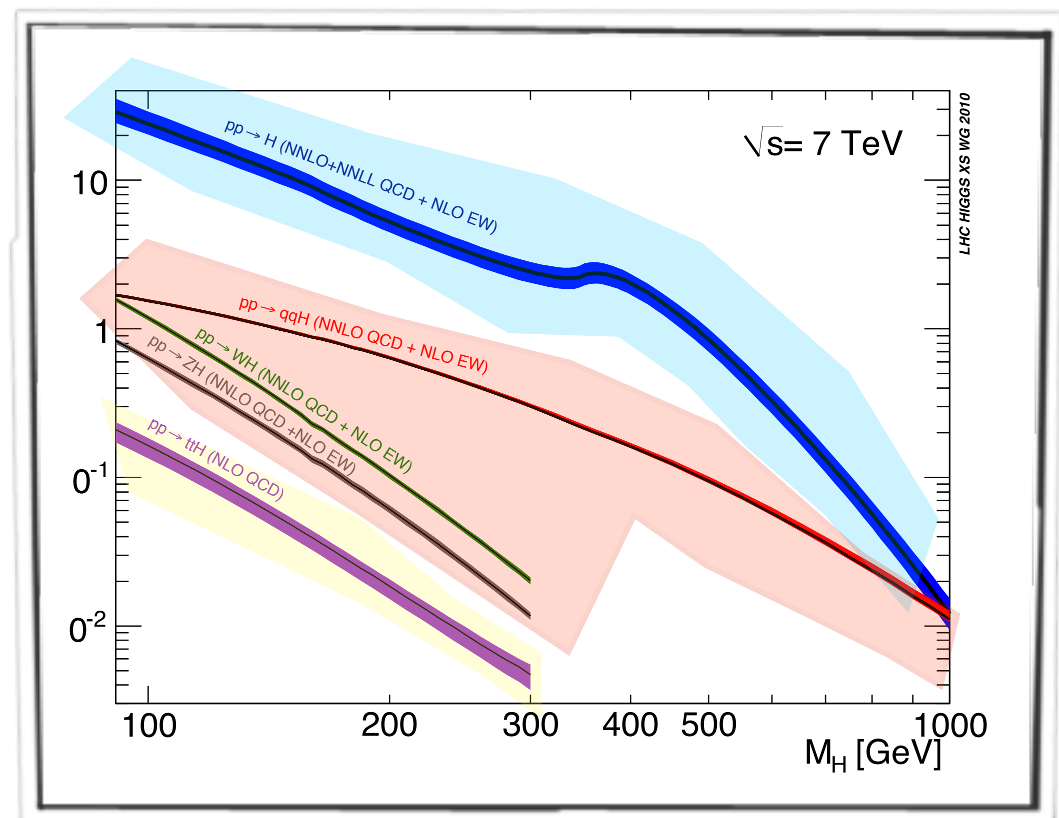
~TOMORROW~

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

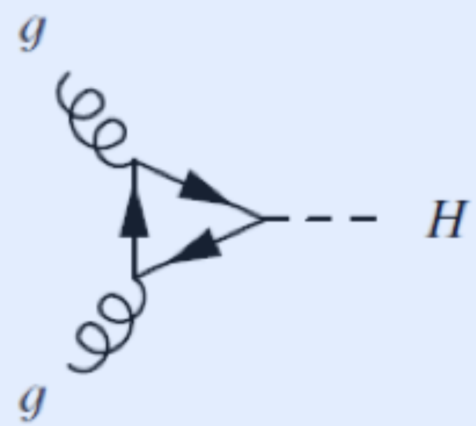
NLO results in MC
POWHEG, aMC@NLO

+ N^2LO PDF sets





The ggH Frontiers



~TODAY~

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

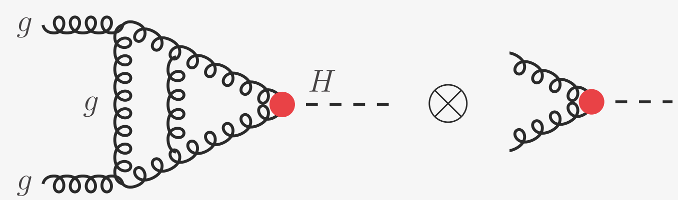
~TOMORROW~

inclusive	Higgs p_T
N^{3}LO QCD ($m_t=\infty$)	NLO QCD 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

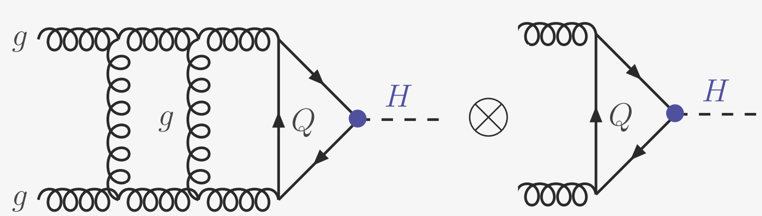
N^{2}LO$_\infty$ α_s^4 2-loop



g_s^6 g_s^2

Harlander, Kilgore '02 Anastasiou, Melnikov '02

N^{2}LO$_{mt}$ α_s^4 3-loop



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

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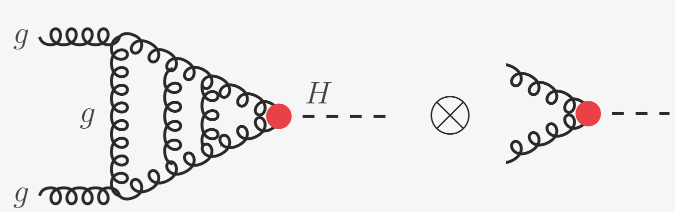
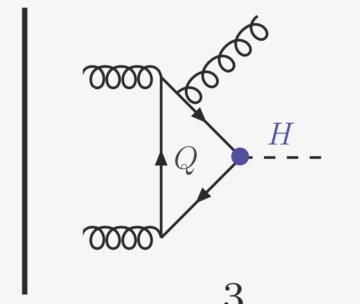


g_s^8 g_s^2

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

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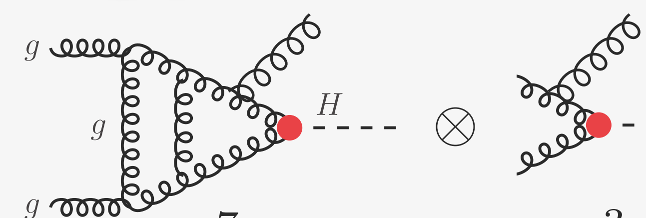

g_s^7 g_s^3

Boughezal et al '13

~TODAY~

~TOMORROW~

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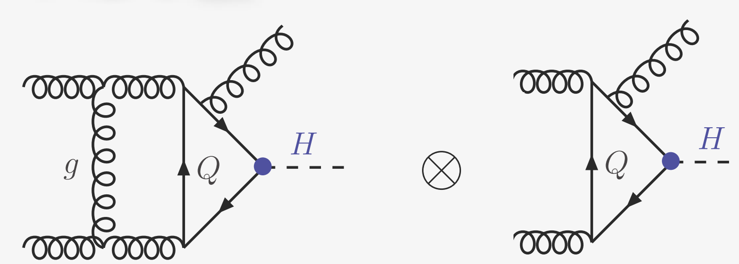


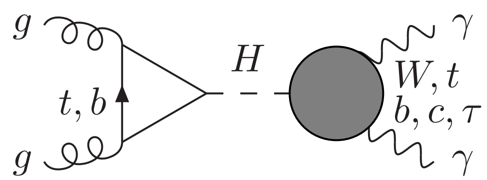
g_s^5 g_s^3

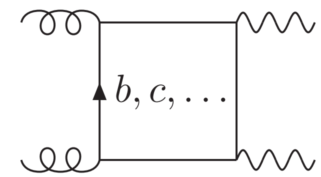
first corrections in 1/mt: Harlander et al '12

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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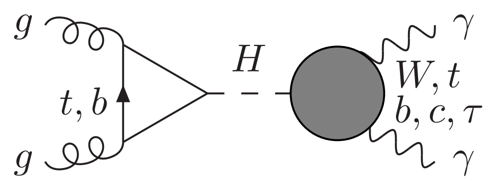

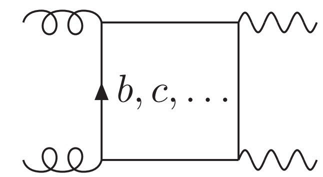

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Residual effect: downward shift of $M_{\gamma\gamma}$ mass peak

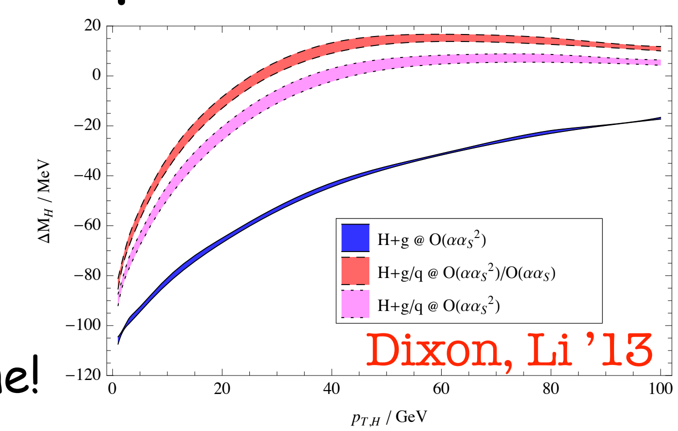
$\Delta M_{\gamma\gamma}$ =-120 MeV @ LO S. Martin '12

$\Delta M_{\gamma\gamma}$ =-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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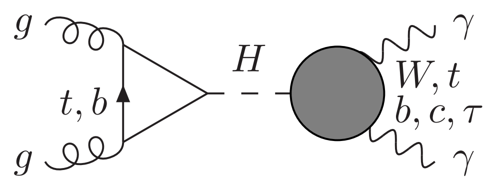

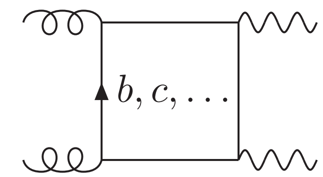

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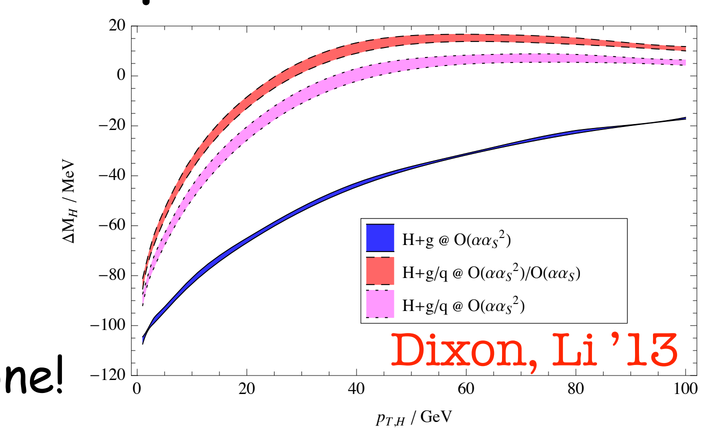

Access to the Higgs width @ LHC?

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? What's next?

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" *With great power comes great responsibility* "

Voltaire & Spider-Man

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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

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1

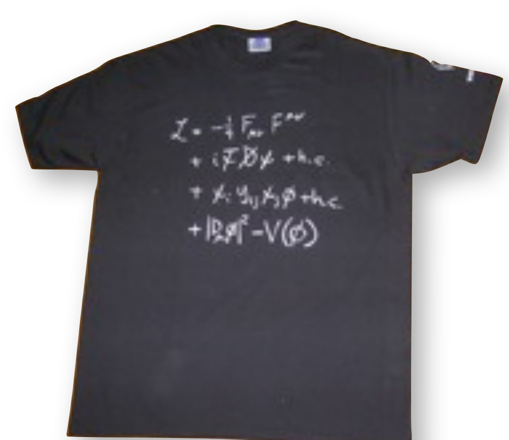
Higgs properties

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

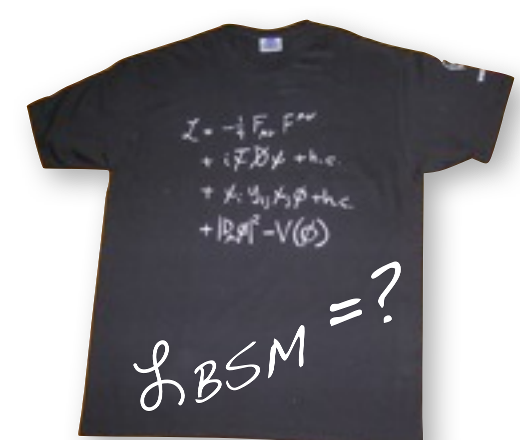
2

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

already bounded by flavor physics

bosonic sector — irrelevant operators (dim-6) only

- ➤ edm's
- ➤ Higgs signal strengths
- ➤ Higgs kinematical distribution

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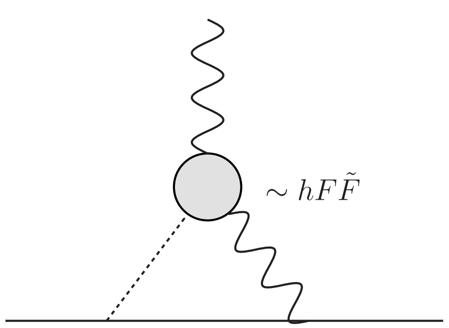
➤ edm's
➤ Higgs signal strengths
➤ Higgs kinematical distribution

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.

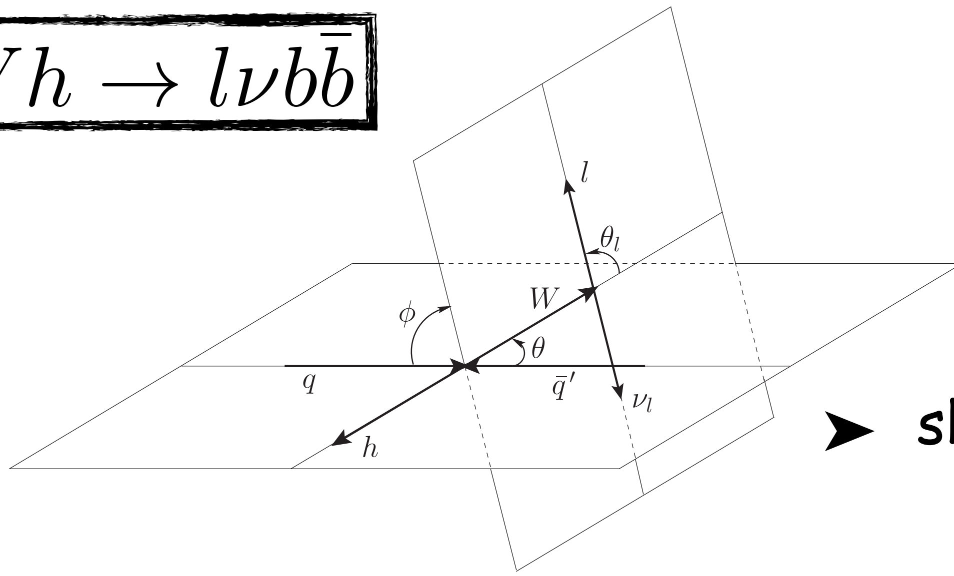
CP-odd observables

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 '13

➤ should allow one to constrain the third CP direction

➤ no estimate of the sensitivity yet ➤

Elias-Miro et al '13

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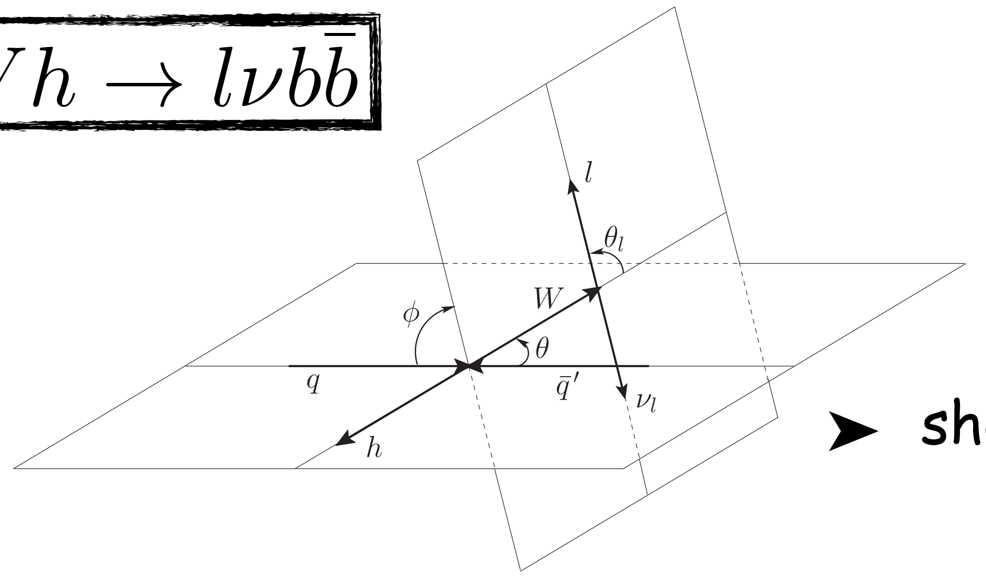

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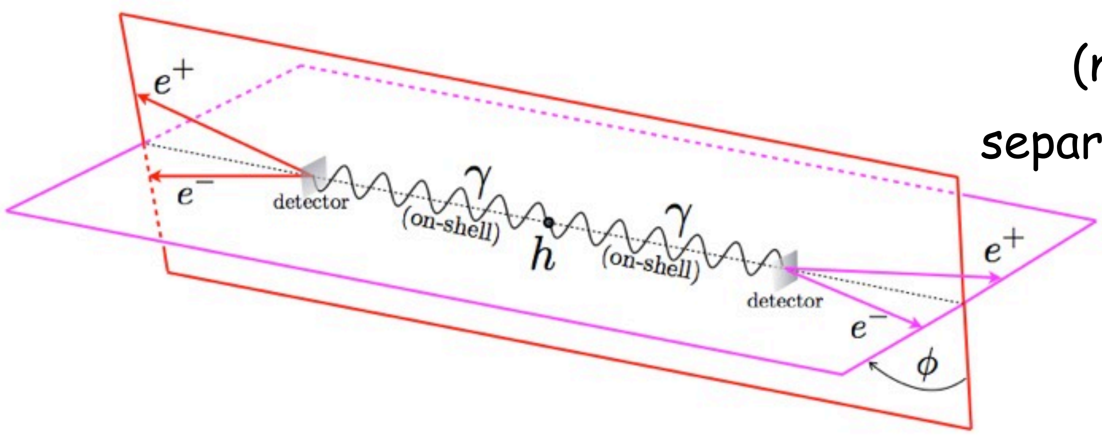
Another CP-odd observable can be constructed in h➝$\gamma\gamma$ channel

the $\cancel{CP}$ 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

Elias-Miro et al '13

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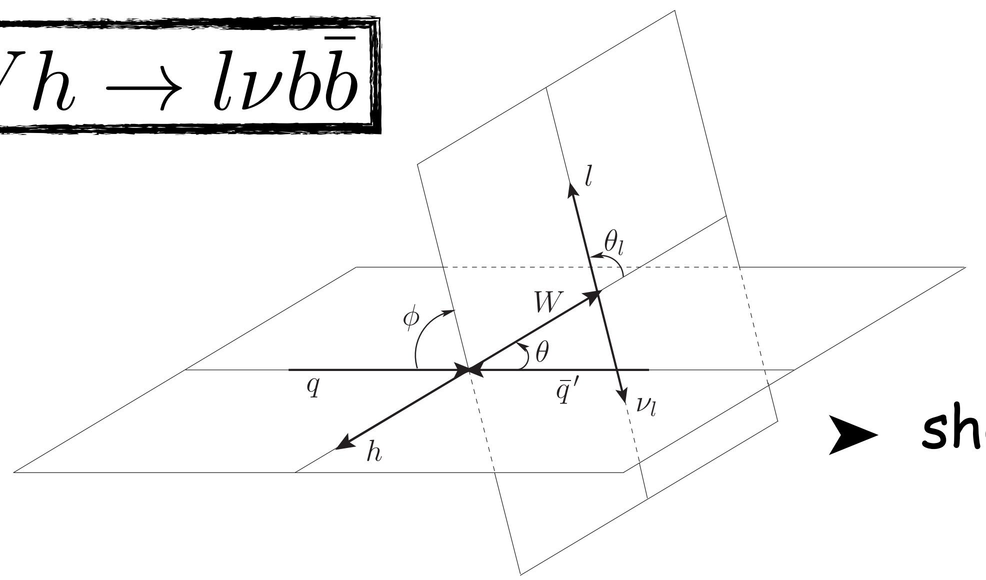

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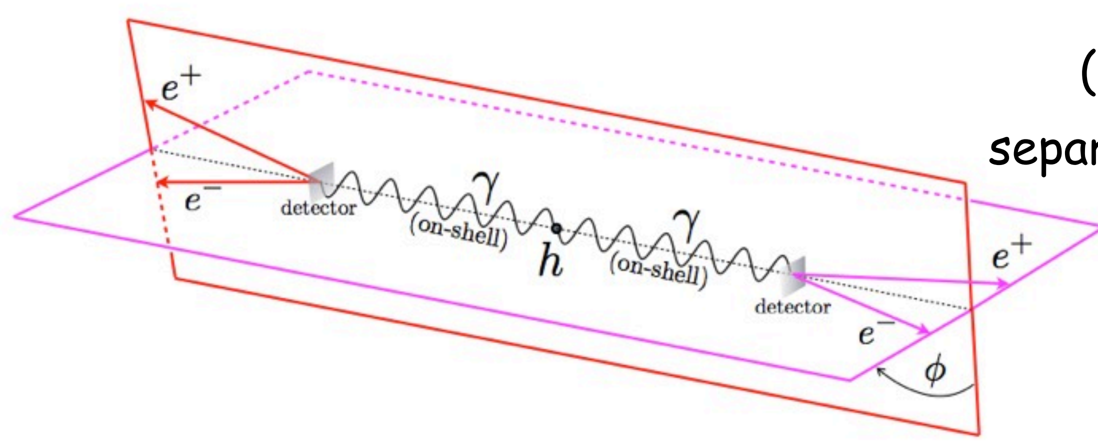

challenging

(need to reconstruct the separation angles between the e)

but interesting

Do we need Higgs data?

The $\not{CP}$ Higgs couplings are generated by operators that also induce TGC that are already tested at the % level by LEP data and the constraints can certainly be improved at the LHC

Elias-Miro et al '13

3

Towards BSM Precision Higgs Physics

Chiral Lagrangian for a light Higgs-like scalar

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

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

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

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

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

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

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

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

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

still large LO parameter space

⇓ ⇓ ⇓

4 operators @ O(p²): c_V, c_t, c_b, c_τ

2 operators @ O(p⁴): c_g c_γ

(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

↖ γγ ↖ WW & ZZ

☑ custodial symmetry

↖ EWPD

☑ no Higgs FCNC

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Higgs power counting

Giudice, Grojean, Pomarol, Rattazzi '07

- extra Higgs leg: H/f
- extra derivative: ∂/m_ρ

- **Genuine strong operators** (sensitive to the scale f)

$$\frac{c_H}{2f^2}\left(\partial^\mu |H|^2\right)^2 \qquad \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)^2 \qquad \frac{c_y y_f}{f^2}|H|^2 \bar{f}_L H f_R + \text{h.c.} \qquad \frac{c_6 \lambda}{f^2}|H|^6$$

custodial breaking

- **Form factor operators** (sensitive to the scale $m_\rho = g_\rho f$) (g_{SM} factors in V)

$$\frac{ic_W}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i \qquad \frac{ic_B}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$

$$\frac{ic_{HW}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} \qquad \frac{ic_{HB}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

$$\frac{c_\gamma}{m_\rho^2}\frac{g_\rho^2}{16\pi^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} \qquad \frac{c_g}{m_\rho^2}\frac{g_\rho^2}{16\pi^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$

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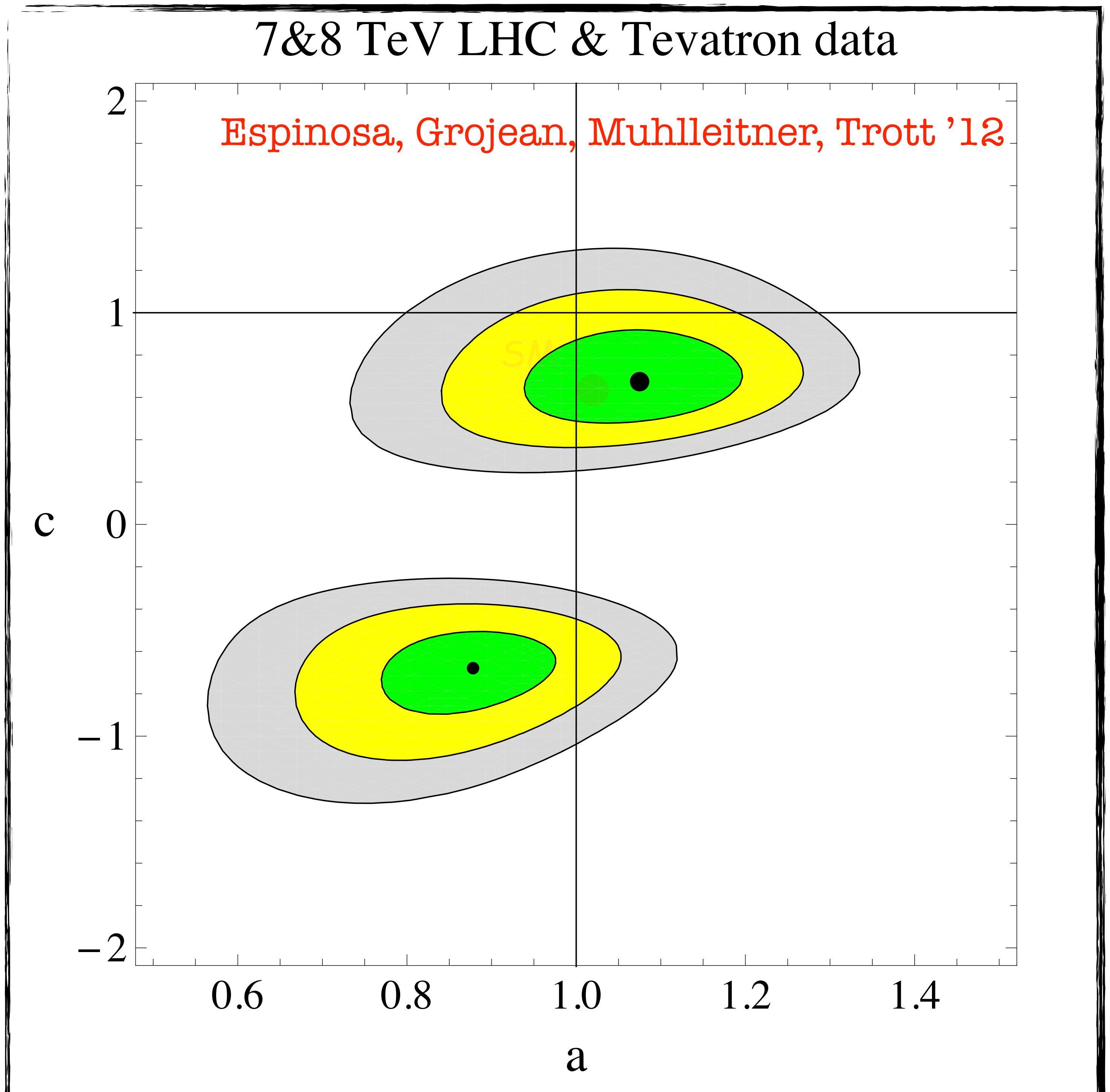
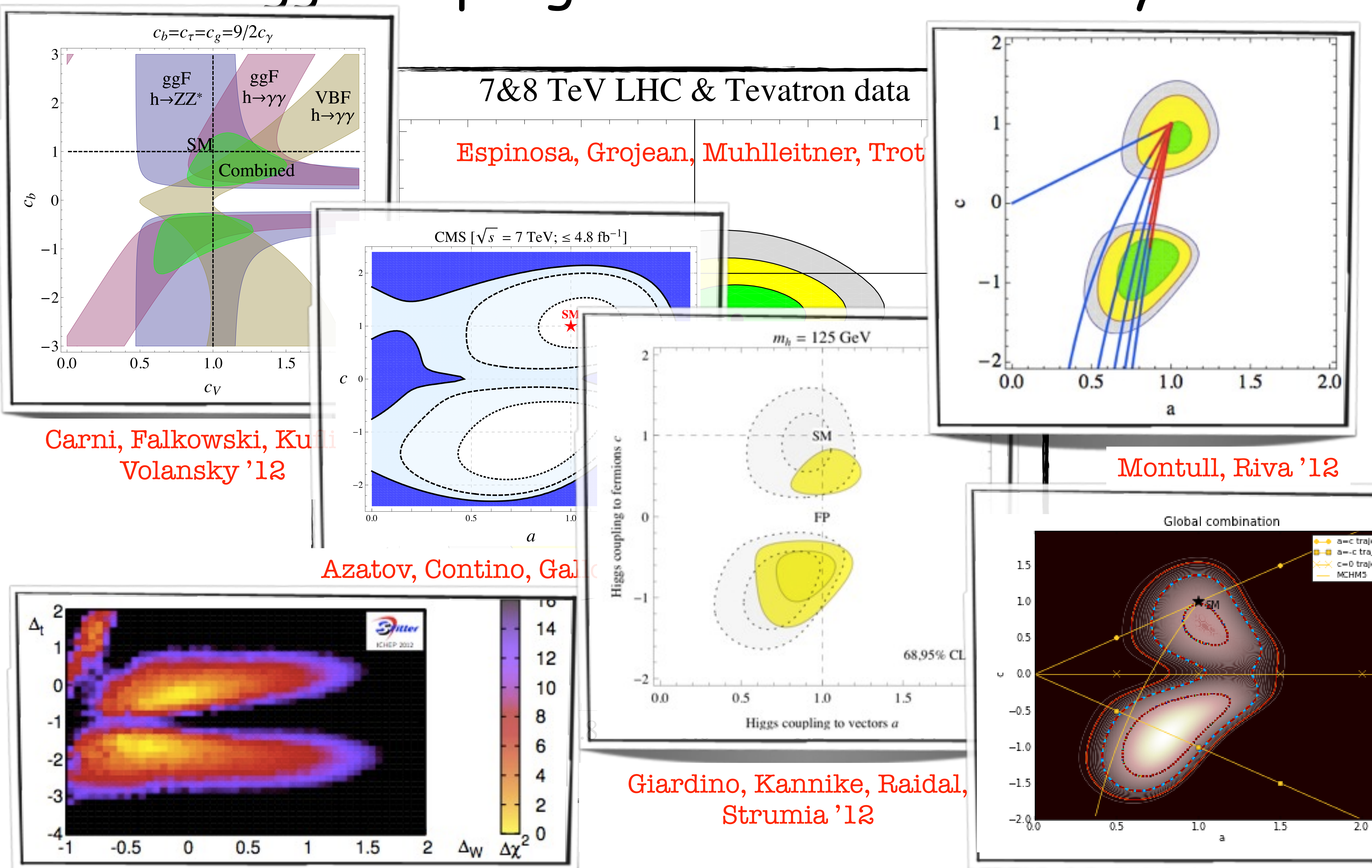
Goldstone sym. (PGB Higgs)

Higgs coupling fits: test of unitarity



Higgs coupling fits: test of unitarity



Espinosa, Grojean, Muhlleitner, Trot

Carni, Falkowski, Ku
Volansky ’12

Montull, Riva ’12

Azatov, Contino, Gal

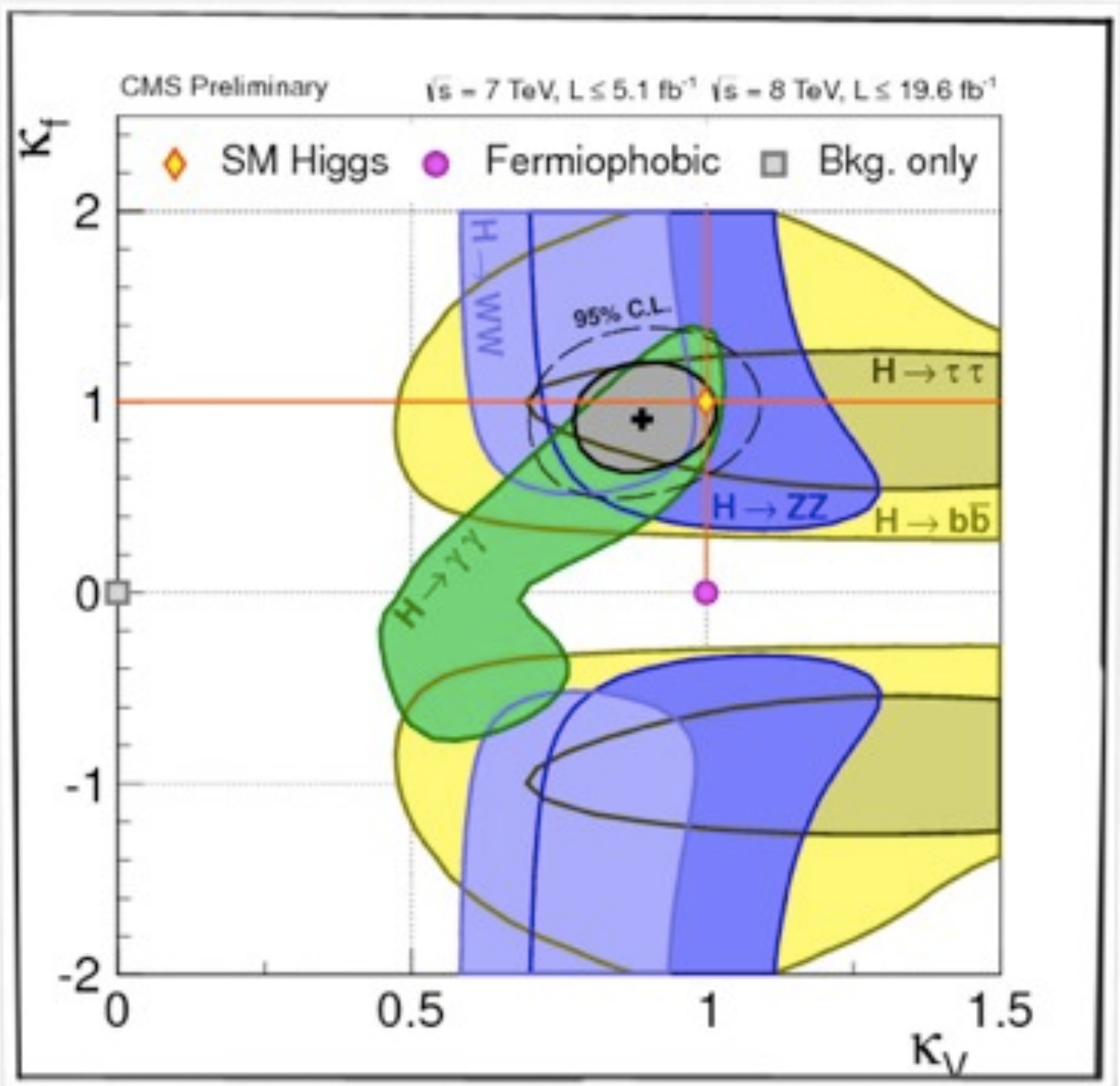
Giardino, Kannike, Raidal,
Strumia ’12

Plehn, Rauch ’12

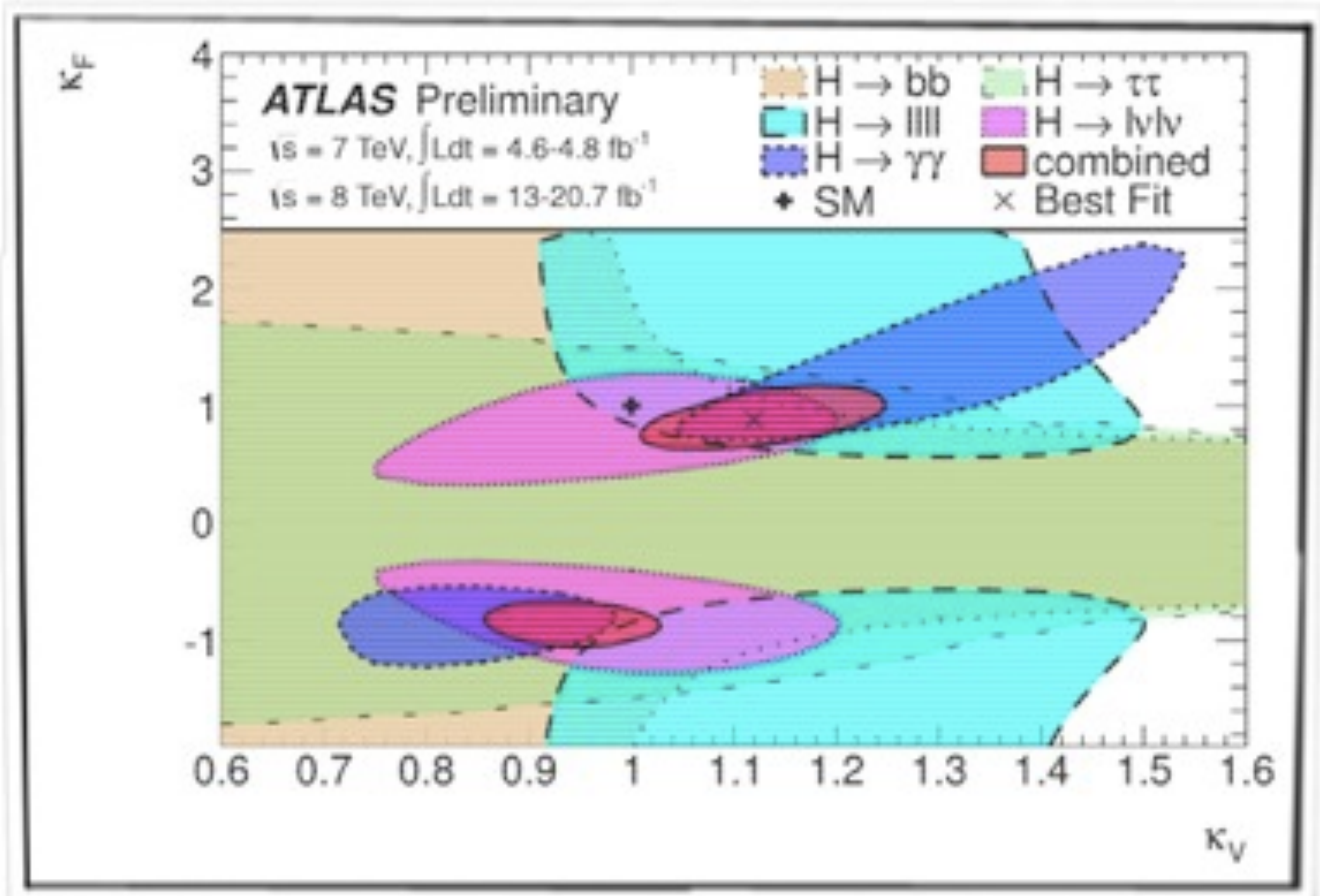
Ellis, You ’12

s coupling fits: test of unitarity

don't leave it in the hands of theorists!



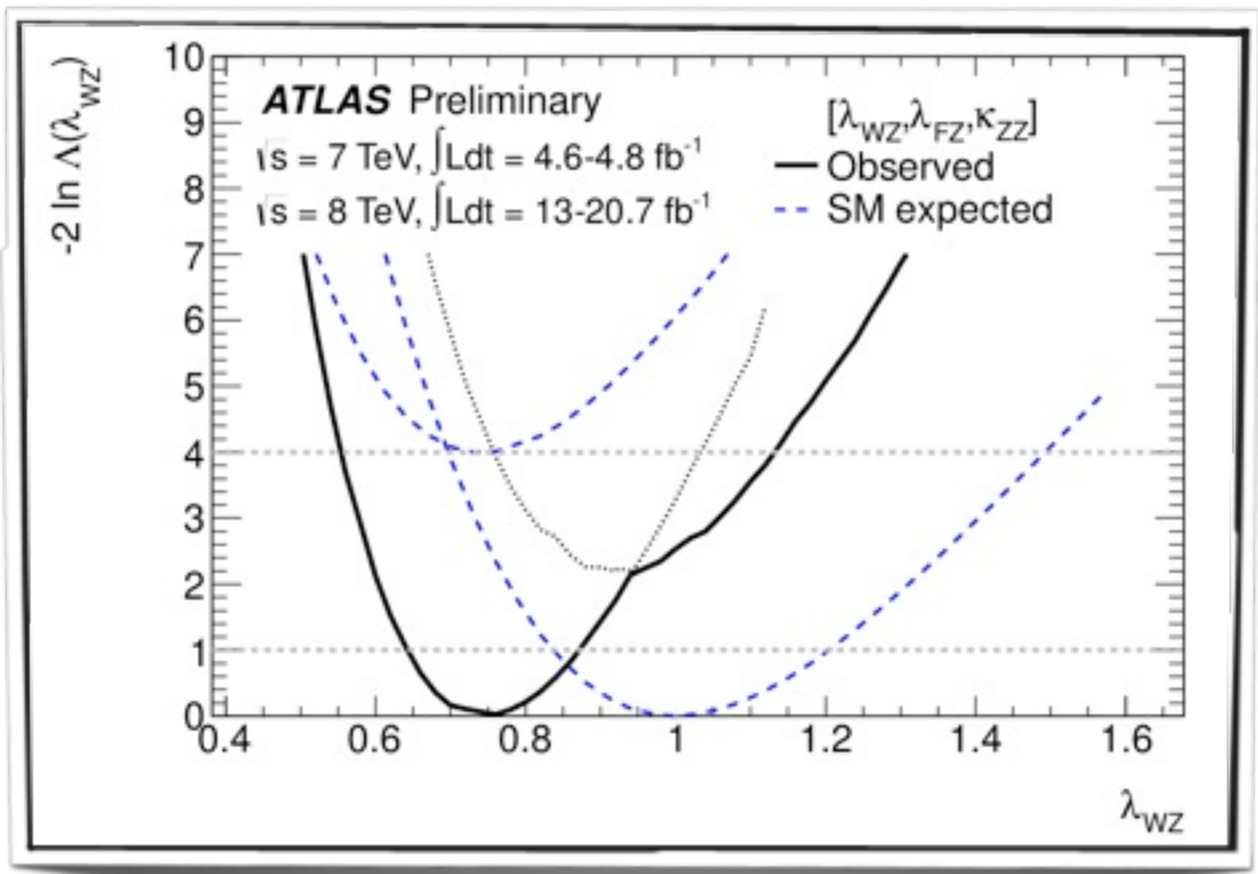
CMS

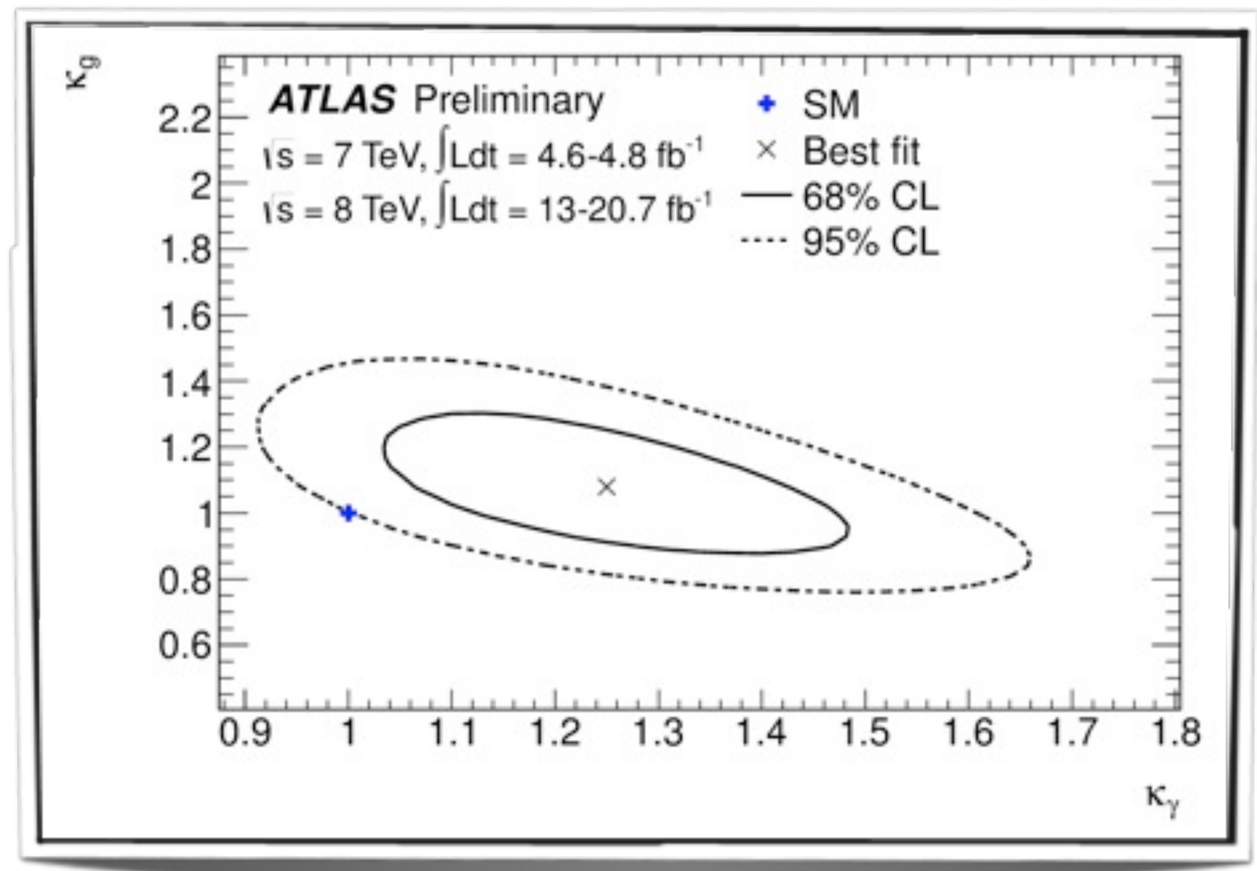


ATLAS

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

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 $\sigma \times \mathrm{BR}_{\mathcal{L}} \underset{c_i \to 0}{\cancel{\to}} \sigma \times \mathrm{BR}_{\mathcal{L}_{\rm SM}}$

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

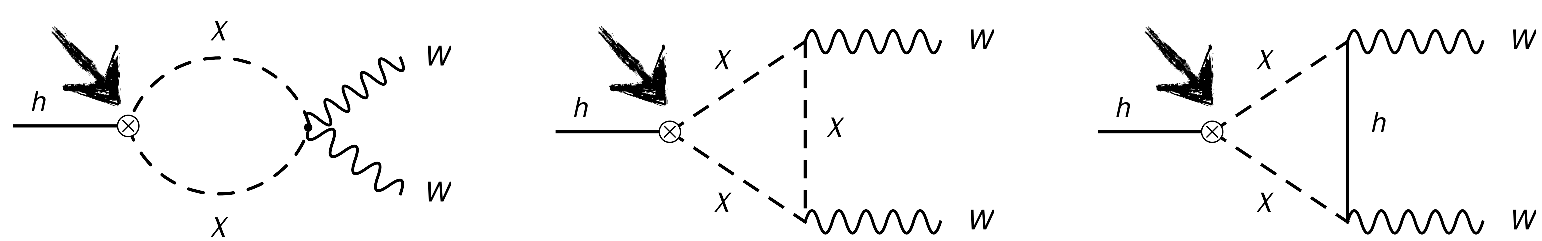
Integrating-out heavy degrees of freedom gives Wilson coefficients @ NP scale

Higgs physics is done around the weak scale

RG effects can give important effects

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

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



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

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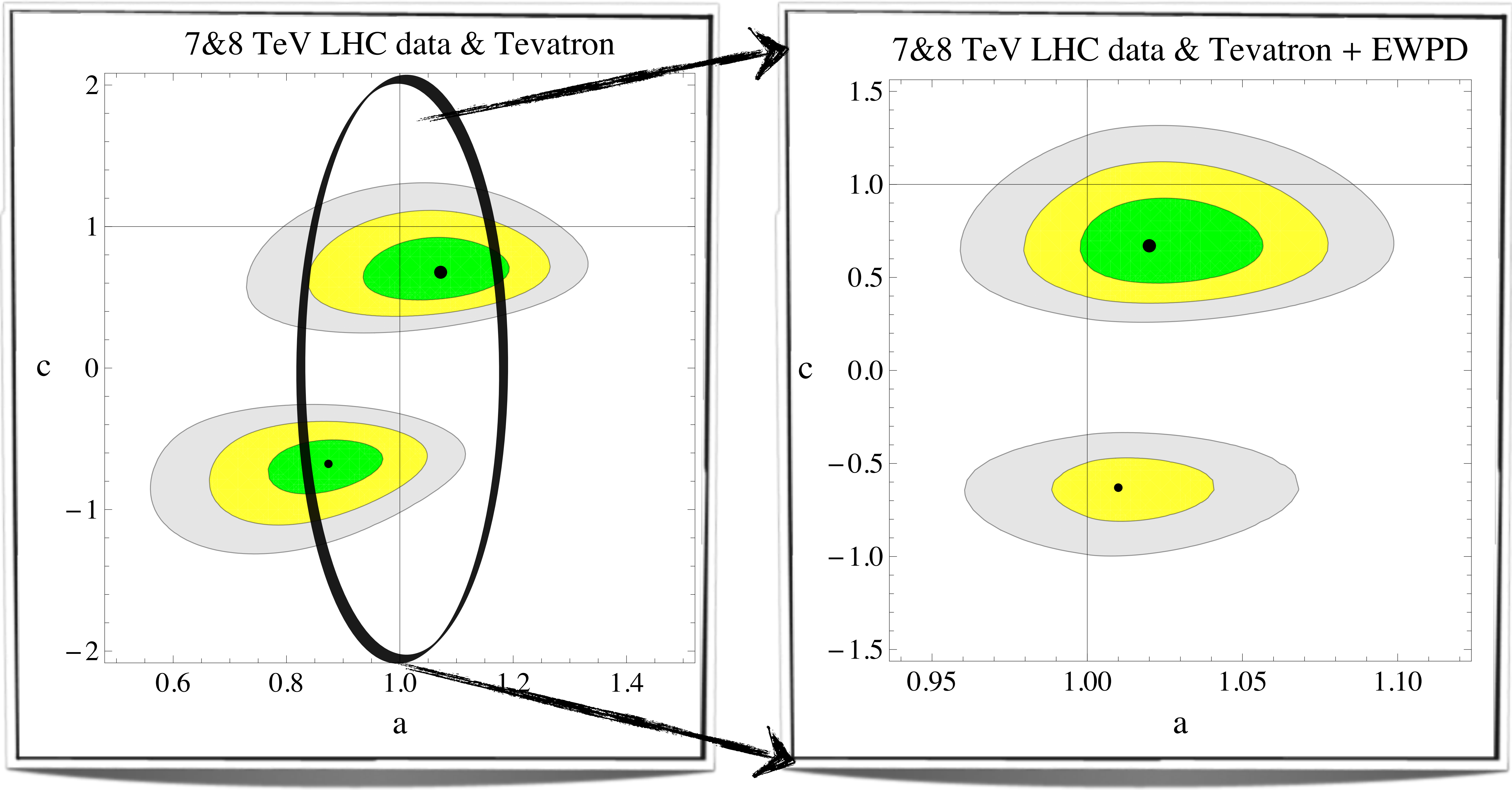
anomalous dimensions

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

Barbieri et al '07

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 '13

4

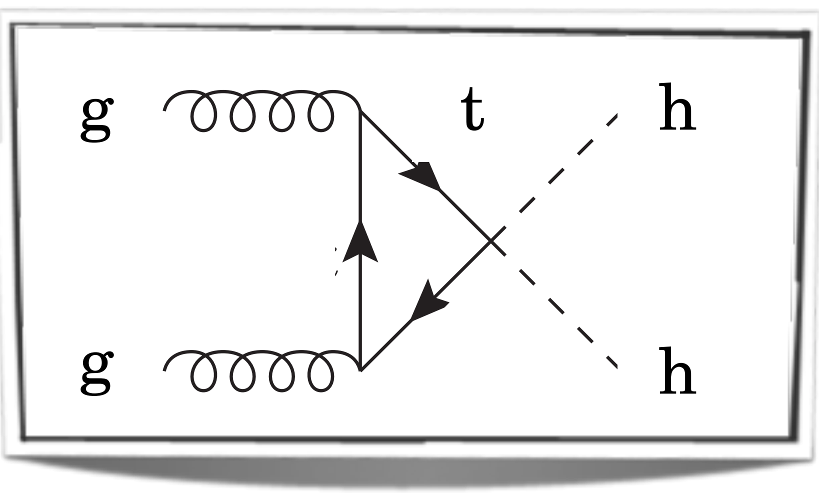
Beyond current channels

1.) Beyond linear Higgs couplings

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

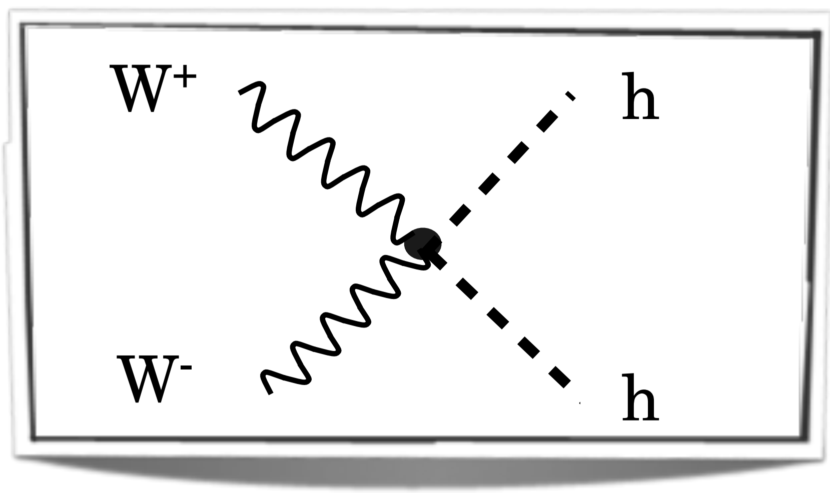
production and decay rates in agreement with SM is a good hint
but can never exclude a malicious conspiracy
and the SU(2)xU(1) quantum # of the Higgs cannot be measured in single higgs processes

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



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

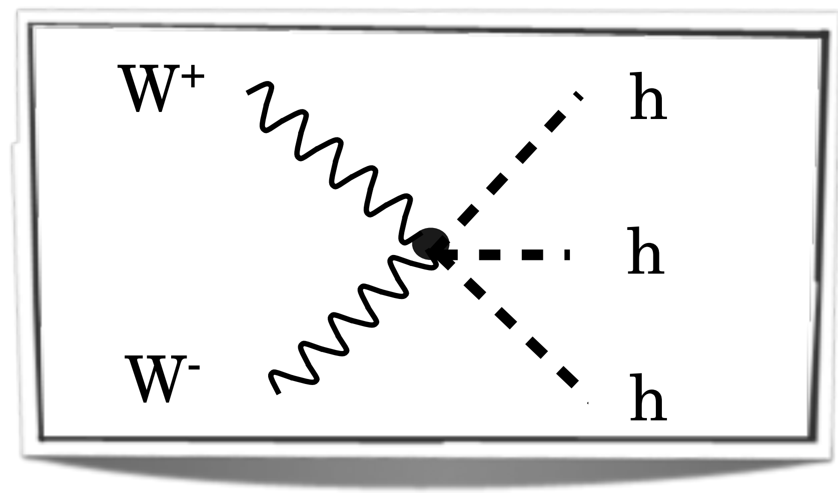
$$\sigma^{SM}_{14\mathrm{TeV}} \approx 20\,\mathrm{fb}$$



Contino, Grojean,
Moretti, Piccinini, Rattazzi '10

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

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



Contino, Grojean, Pappadopoulo,
Rattazzi, Thamm '13

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

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

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

1.) Beyond linear Higgs couplings

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm '13

$$\mathcal{A}\left(W_L^a W_L^b \to W_L^c W_L^d\right) = \mathcal{A}(s,t,u)\delta^{ab}\delta^{cd} + \mathcal{A}(t,s,u)\delta^{ac}\delta^{bd} + \mathcal{A}(u,t,s)\delta^{ad}\delta^{bc} \qquad \mathcal{A} = \left(1-a^2\right)\frac{s}{v^2}$$

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to hh\right) = \left(W_L^+ W_L^- \to hh\right) = \left(b-a^2\right)\frac{s}{v^2}$$

if the Higgs is part of a doublet and custodial symmetry is at work

$$1-a^2 \simeq -(b-a^2)$$

a single operator of dimension-6 controls these 2 processes: $\frac{c_H}{2f^2}\left(\partial^\mu |H|^2\right)^2$

$$\boxed{\Delta b = 2\Delta a^2\left(1+O(\Delta a^2)\right)}$$

$$\Delta b \equiv 1-b$$
$$\Delta a^2 \equiv 1-a^2$$

a dimension-8 operator controls the deviations to this universal relation

$$O'_H = \frac{c'_H}{2f^4}|H|^2\partial_\mu|H|^2\partial^\mu|H|^2$$

$$a = 1 - \frac{c_H}{2}\frac{v^2}{f^2} + \left(\frac{3c_H^2}{8} - \frac{c'_H}{4}\right)\frac{v^4}{f^4}$$

$$b = 1 - 2c_H\frac{v^2}{f^2} + \left(3c_H^2 - \frac{3c'_H}{2}\right)\frac{v^4}{f^4}$$

if the Higgs is a Goldstone

then non-linear symmetry relates operators of different dimensions

1.)

Beyond linear Higgs couplings

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm '13

Scenario 1: 10% deviations are observed

$\Delta a^2 \sim \Delta b \sim 10\%$

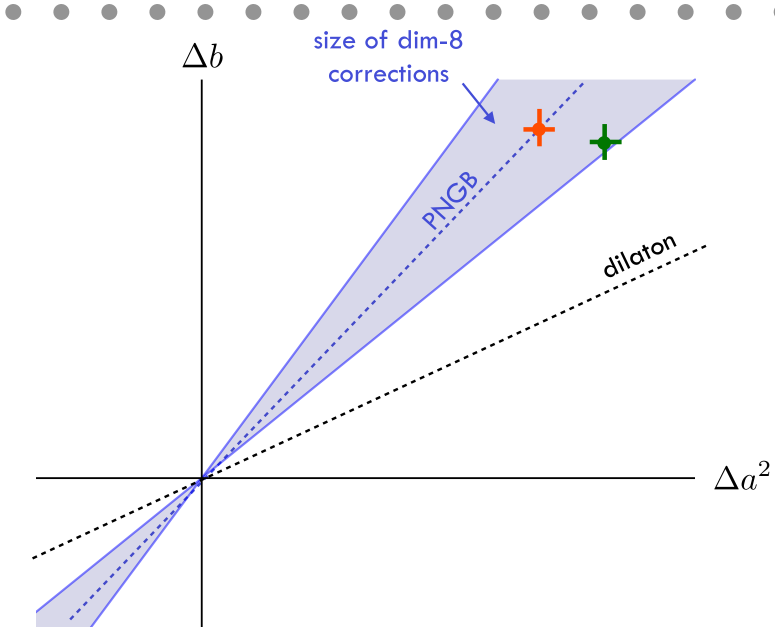
Exp. precision $\sim 1\%$

Test dim-8 operators

the corrections to the universal relation between 'a' and 'b' are O(1%)

1. PNGB (and specific coset) proved

2. SILH proved, PNGB disproved



can distinguish a PNGB from a non PNGB resonance

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Beyond linear Higgs couplings

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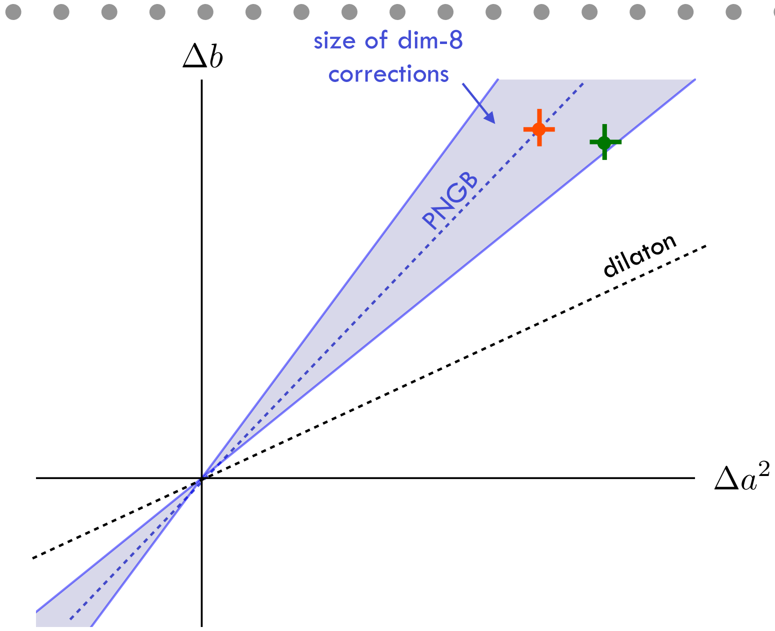


can distinguish a PNGB from a non PNGB resonance

Scenario 2: 1% deviations are observed

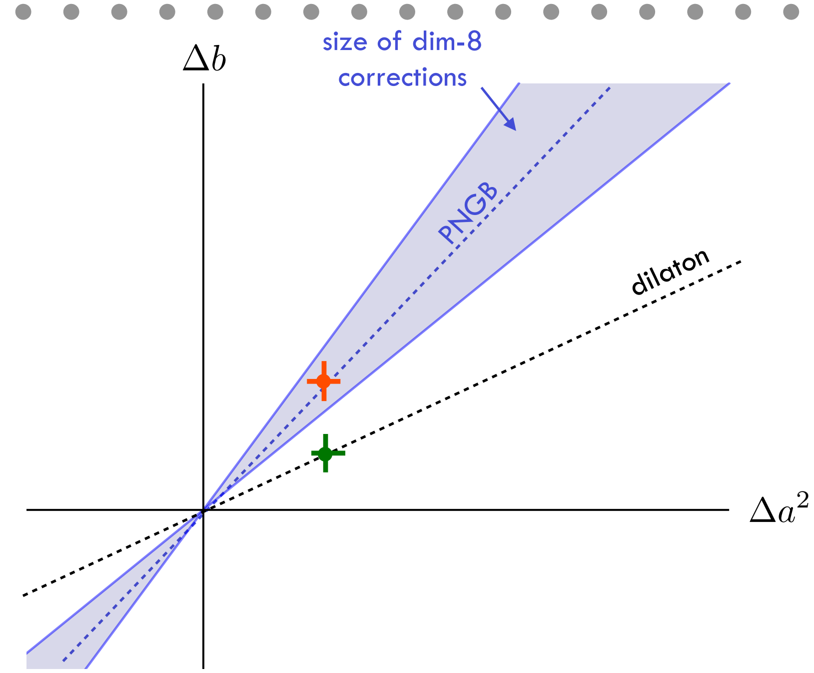
$\Delta a^2 \sim \Delta b \sim 1\%$

Exp. precision $\sim 1\%$

the corrections to the universal relation are beyond any future sensitivity

1. SILH proved

2. SILH (i.e. Higgs doublet) disproved



can distinguish a doublet from a non-doublet resonance

2.) Beyond inclusive channels

the LHC measurements are plagued with several degeneracies

ex: 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(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

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

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200	1.185	1.134

e.g. Grazzini, Sargsyan '13

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

$\Rightarrow$ 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 $\Delta c_t = \Delta c_g = \frac{9}{4}\Delta c_\gamma$.

2.) Beyond inclusive channels

the LHC measurements are plagued with several degeneracies

ex: 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(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

(*) 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)

$\Leftarrow$

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

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

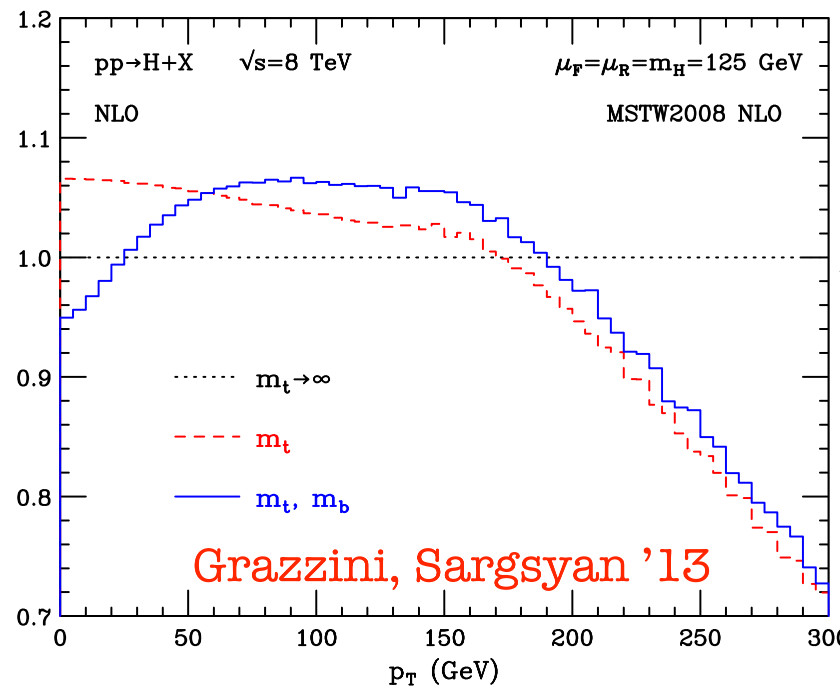
having access to $ht\bar{t}$ final state will resolve this degeneracy
but notoriously difficult channel
14%-4% @ LHC^{14}_{300}-LHC^{14}_{3000} vs 10%-4% @ ILC^{500}_{500}-ILC^{1000}_{1000}

2.) Beyond inclusive channels

cut open the top loops

high p_T ≈ 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

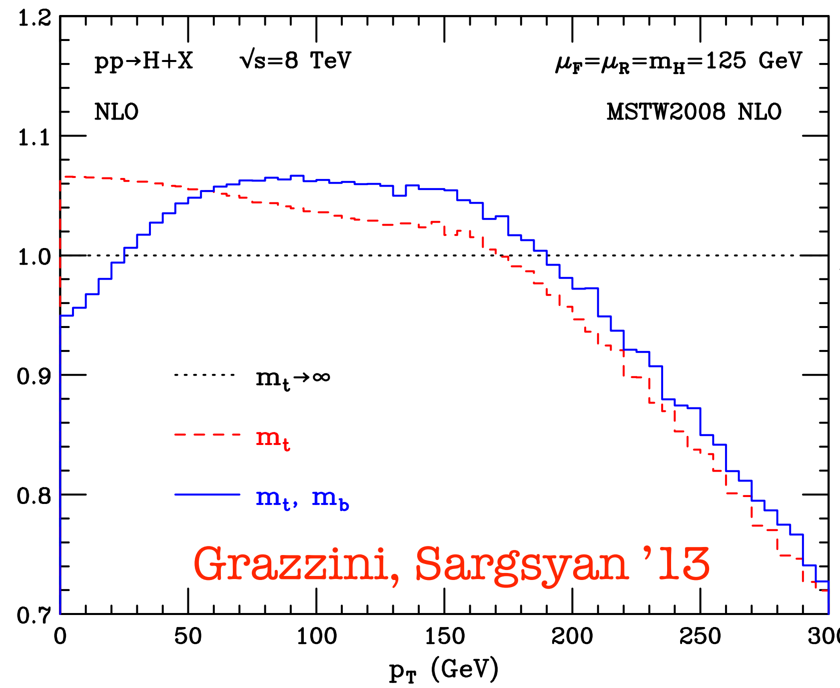
the high p_T tail
is tens' % sensitive
to the mass of top

2.) Beyond inclusive 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_{mt} is not known
$1/m_t$ corrections known $O(\alpha_s^4)$
few % up to p_T~150 GeV

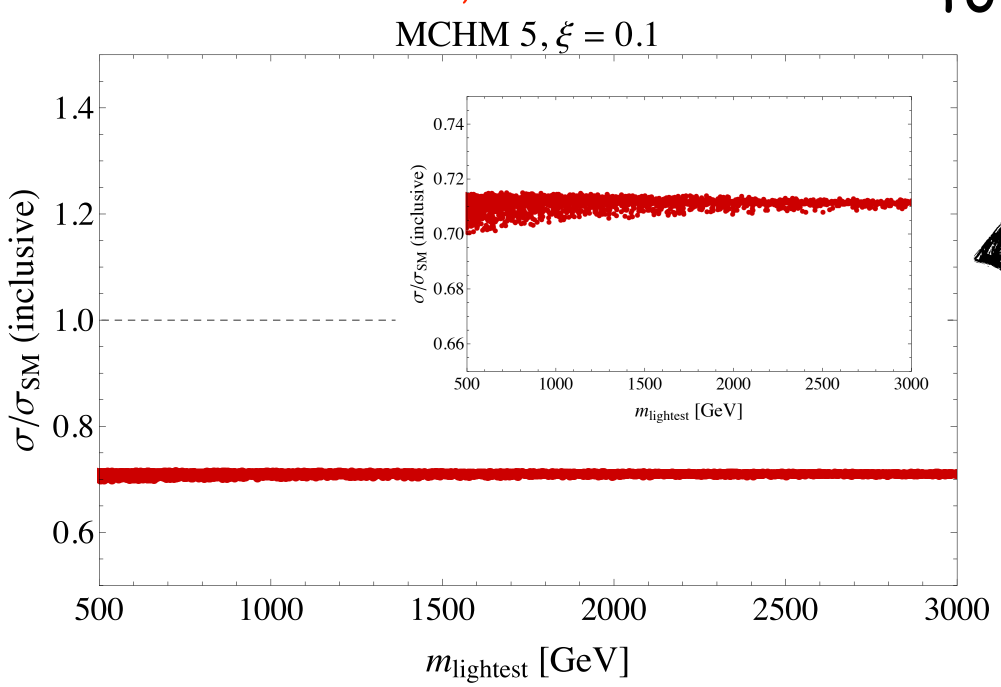
Harlander et al '12

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

Composite Higgs Model

top partners contributions

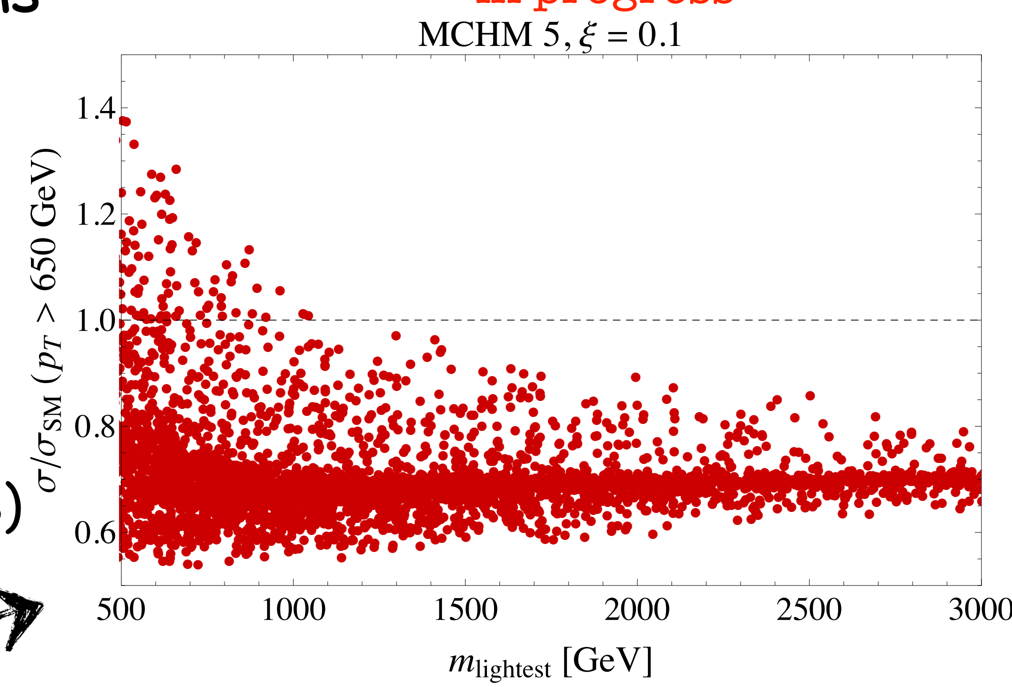
see also Banfi, Martin, Sanz '13
see also Azatov, Paul '13



inclusive rate: O(%)

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

Grojean, Salvioni, Schlaffer, Weiler
' in progress



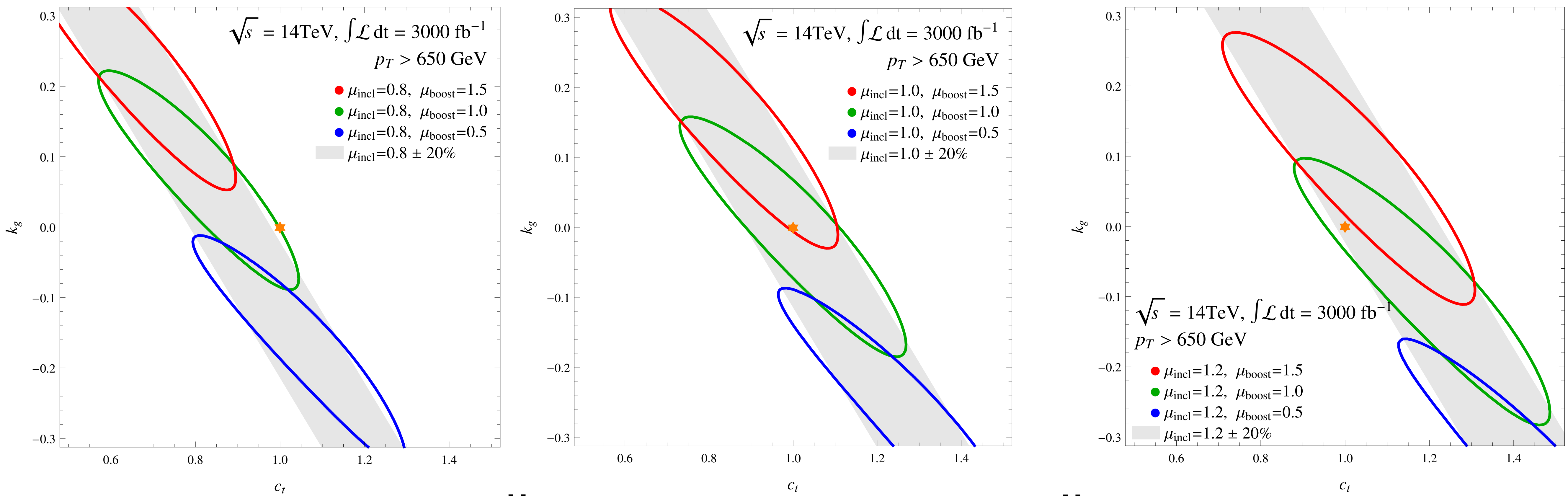
high p_T tail "sees" the top partners that are missed by the inclusive rate

2.) Beyond inclusive channels

cut open the top loops

Grojean, Salvioni, Schlaffer, Weiler
' in progress
see also Azatov, Paul '13

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?

2.)

Boosted Higgs

QCD corrections?

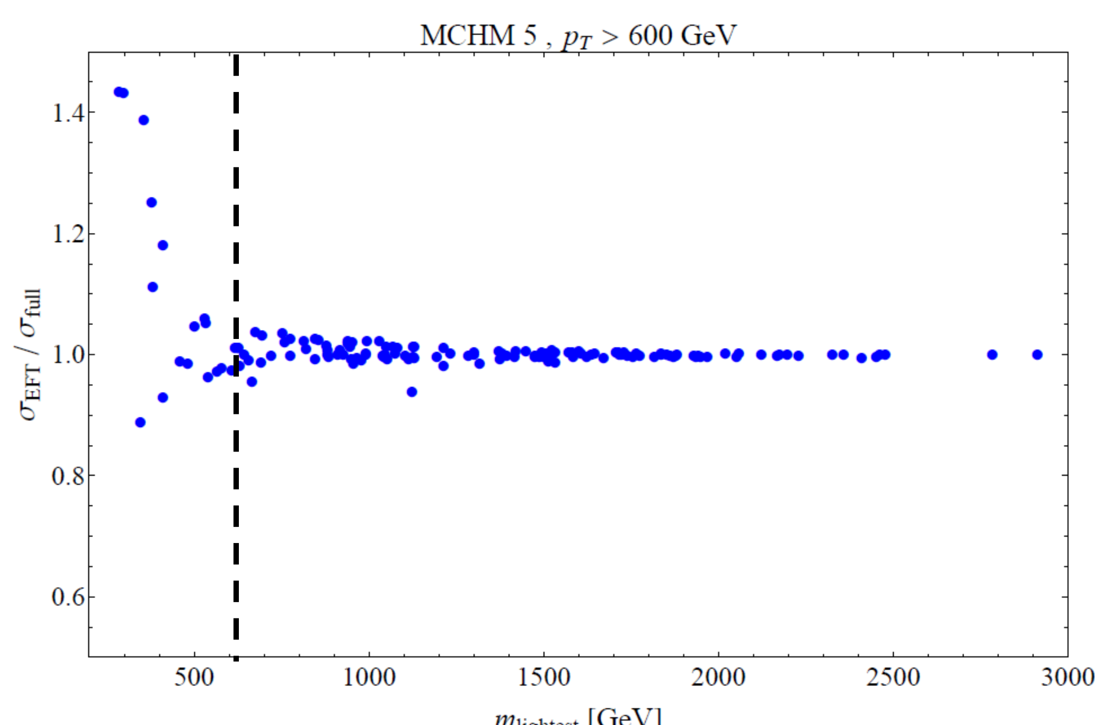
pT distribution with full quark mass dependence known at LO order.
K-factor are known to be large. However, most of the QCD corrections drop out in xs ratios:

$$\sigma(p_T > 650\ \mathrm{GeV})/\sigma(p_T > 200\ \mathrm{GeV})$$

- ☑ scale variation around few % corrections only
- ☑ LO→NLO in $m_t=\infty$ limit (MCFM): less than 10% corrections

Validity of EFT approach?

we rely on an EFT approach to describe the effects of heavy resonances
but we impose a large pT cut potentially close to the cutoff



☑ for masses above pTmin, the effective theory is accurate within < 10%

2.)

Boosted SUSY Higgs

natural susy calls for light stop(s) that can affect the Higgs physics

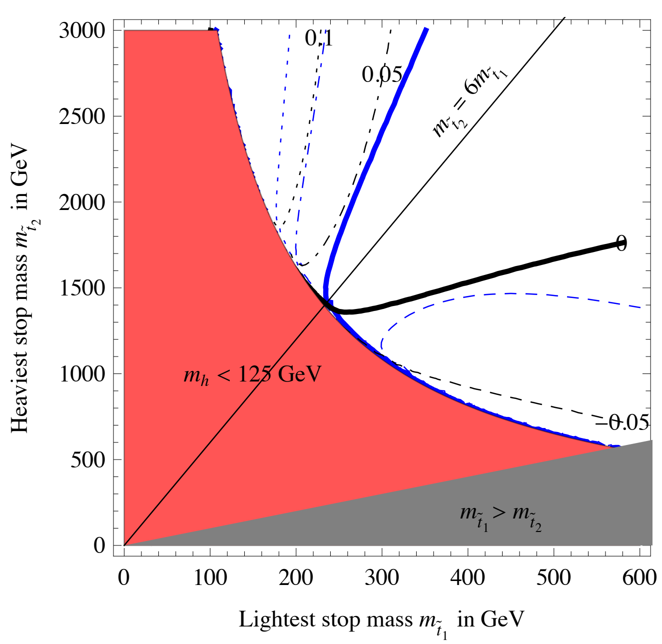
$$\frac{\Gamma(h \leftrightarrow gg)}{\Gamma(h \leftrightarrow gg)_{\rm SM}} = (1+\Delta_t)^2 \ , \qquad \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\rm SM}} = (1-0.28\Delta_t)^2$$

$$\Delta_t \approx \frac{m_t^2}{4}\left(\frac{1}{m_{\tilde t_1}^2} + \frac{1}{m_{\tilde t_2}^2} - \frac{X_t^2}{m_S^2}\right)$$

... or not if $\Delta_t \approx 0$, e.g. light stop window in the MSSM

(stop right ~200-400GeV ~ neutralino w/ gluino < 1.5 TeV)

Delgado et al '12



- ✦ Higgs rates
- ✦ flavor constraints (ε_K, $B \to X_s + \gamma$)
- ✦ RG evolution
- ✦ DM

difficult direct search (trigger on stop+extra jet)

2.)

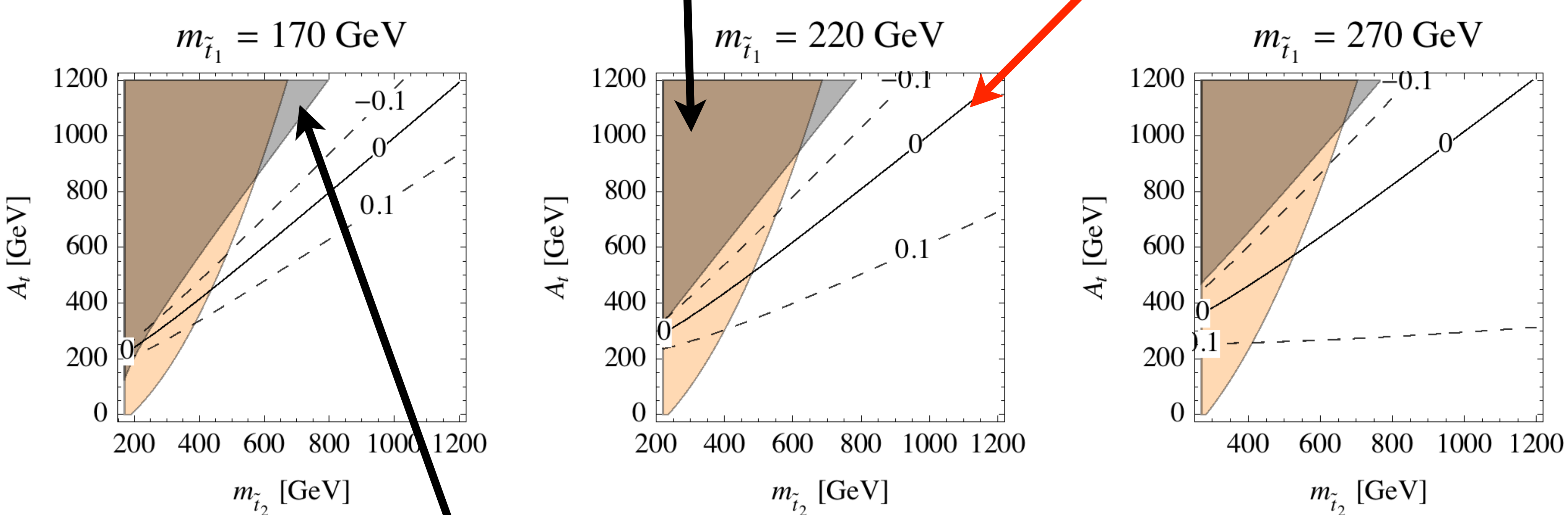
The light stop flat direction

flat direction

$\Delta_t \approx 0$

Real soft masses

$m_Q, m_U \in \mathbb{R}$



Charge-color breaking vacua

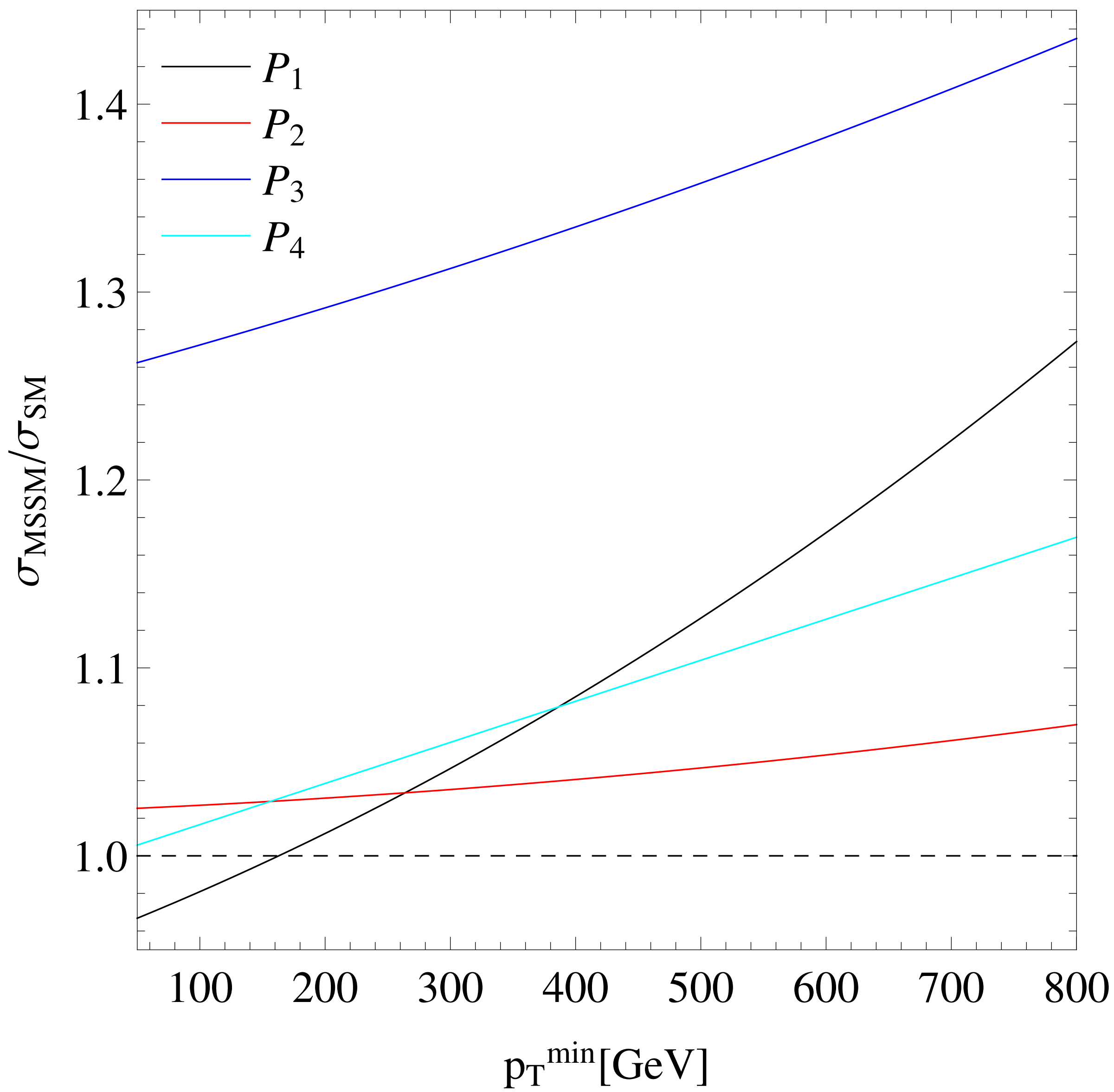
$$A_t^2 + 3\mu^2 < a \cdot \left(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2\right) \qquad h A_t \tilde{t}_L \tilde{t}_R^*$$

2.)

Boosted SUSY Higgs

Grojean, Salvioni, Schlaffer, Weiler ‘ in progress

Point	$m_{\tilde{t}_1}$ [GeV]	$m_{\tilde{t}_2}$ [GeV]	A_t [GeV]	Δ_t
P_1	171	440	490	0.0026
P_2	192	1224	1220	0.013
P_3	259	1212	0	0.12
P_4	226	484	532	0.015



~10% sensitivity on boosted h+j can close out the light stop window

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

Beyond the Higgs

Beyond the Higgs

"Higgs = emergency tire of the SM"

Altarelli @ Blois'10

[picture courtesy to Andreas Weiler]