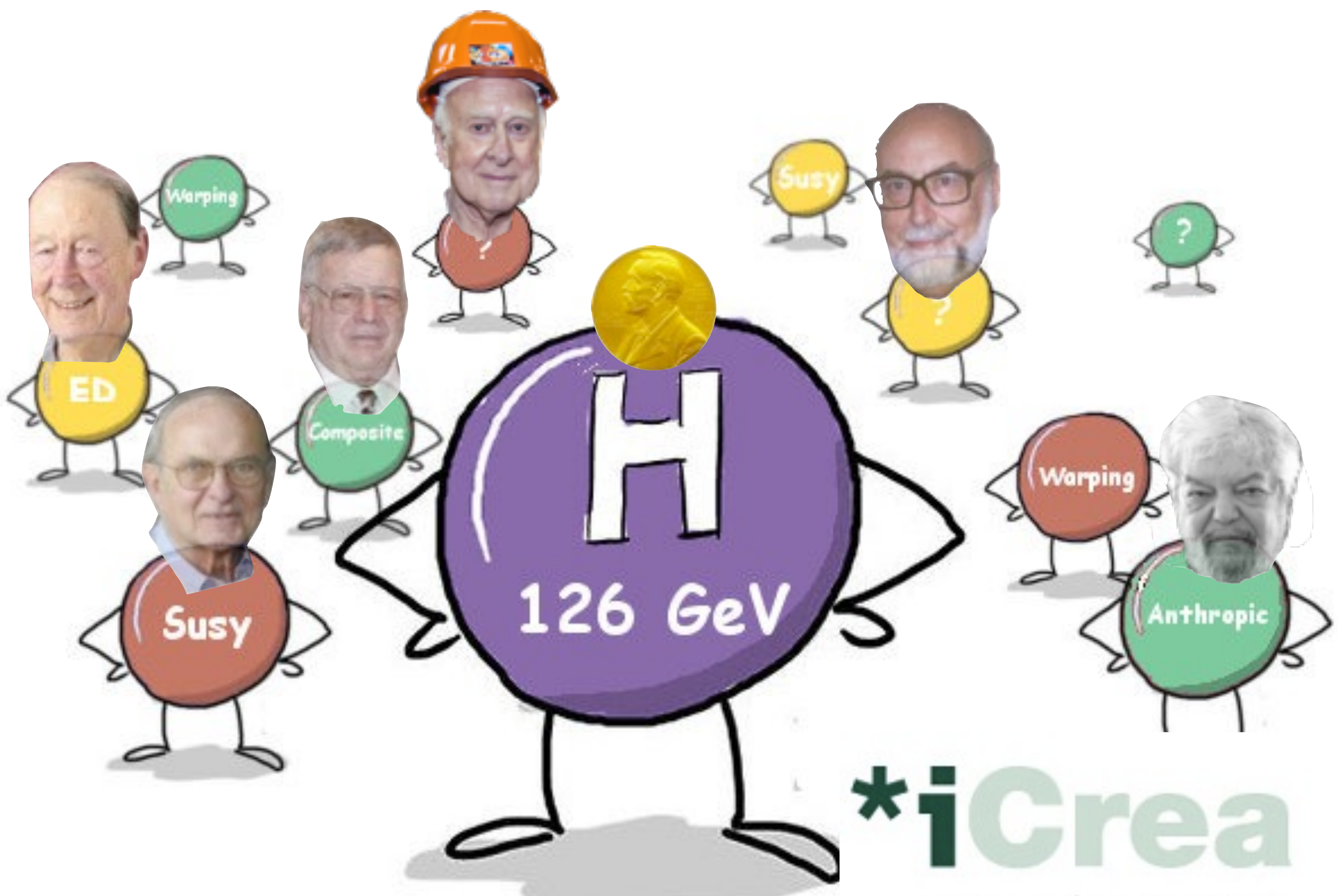
Resolving
Higgs coupling puzzles



IFT, UAM

September 25, 2013

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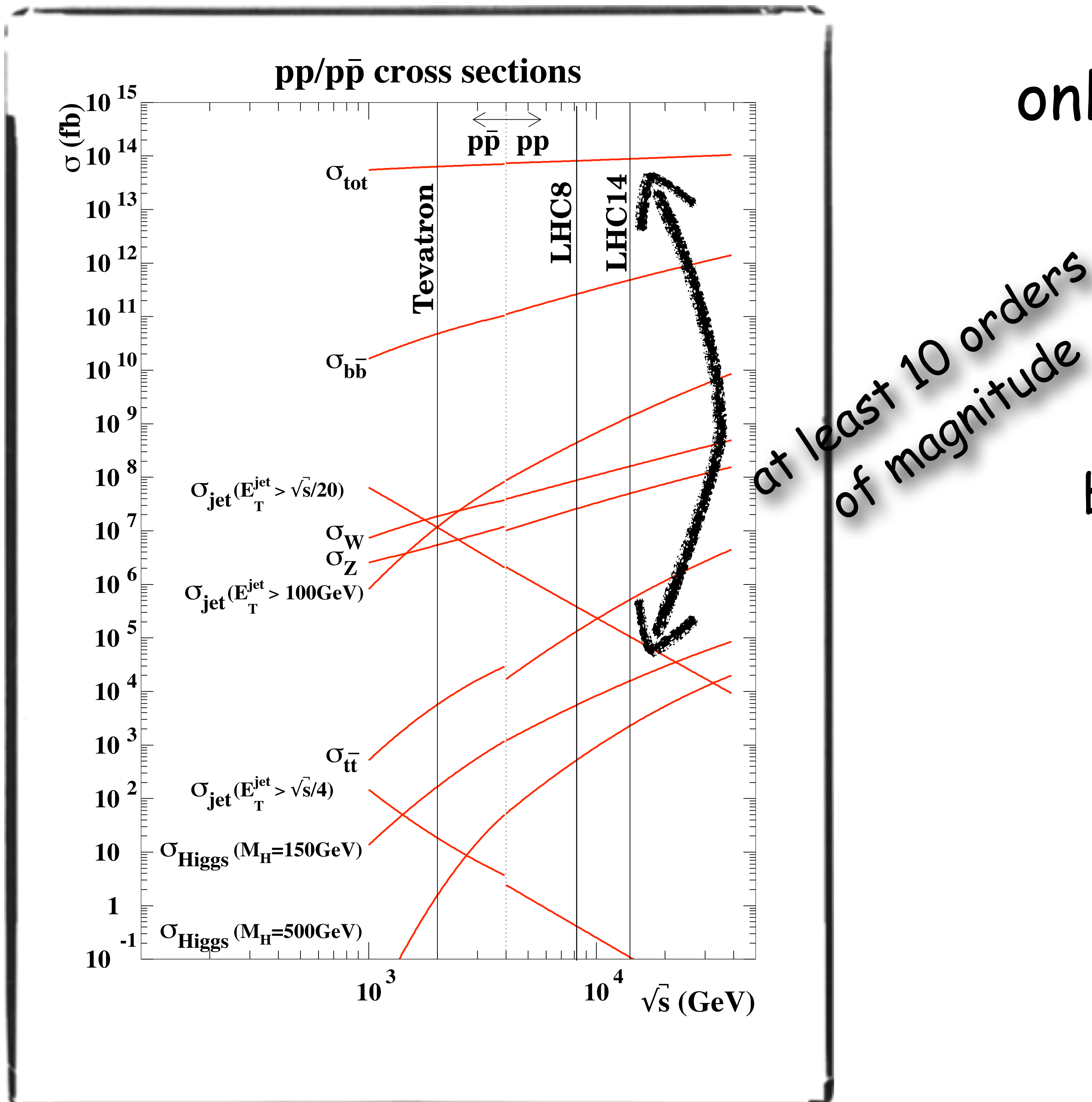
*iCrea
INSTITUCIÓ CATALANA DE
RECERCA I ESTUDIS AVANÇATS

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

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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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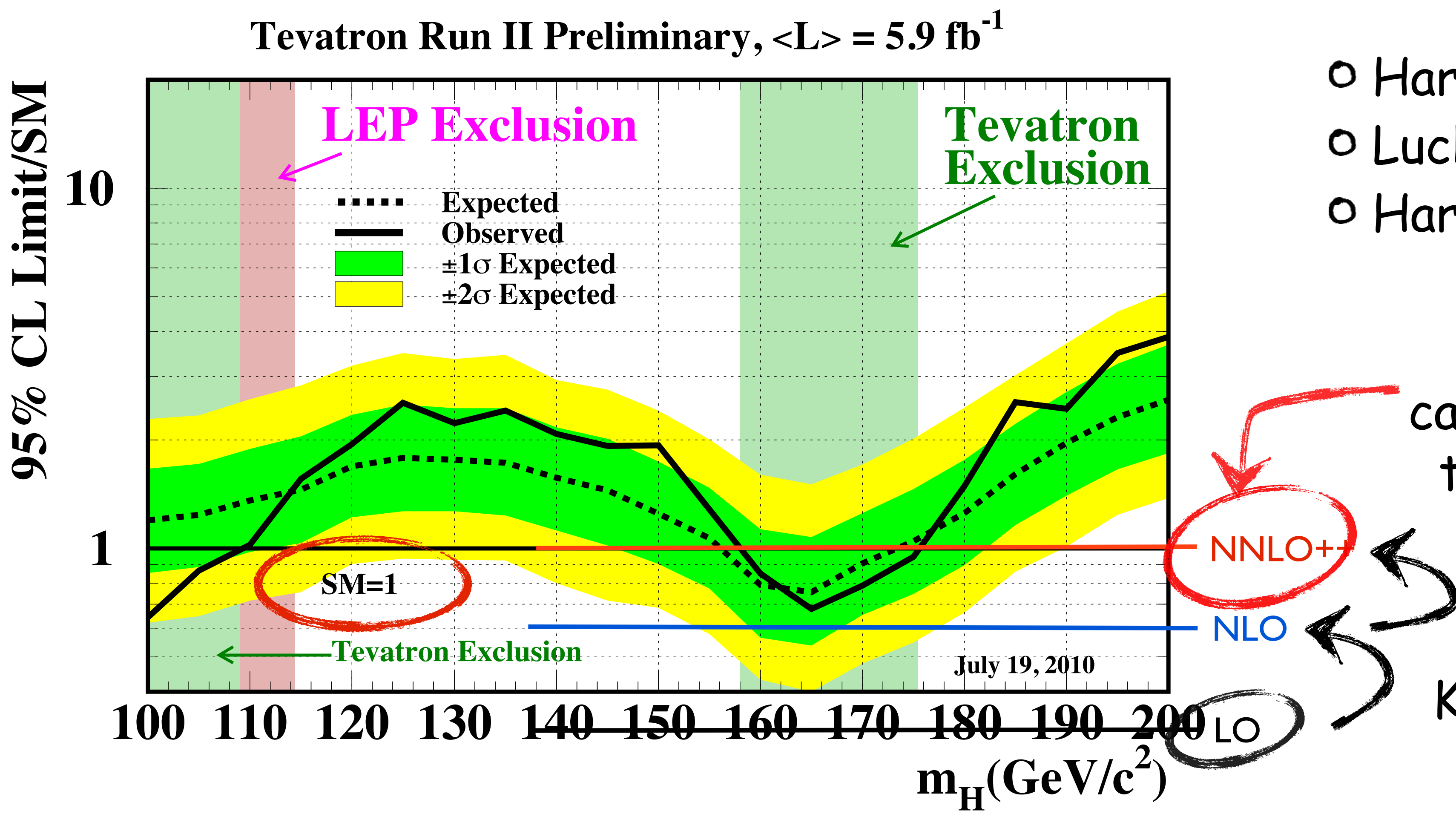
Why did it work better than expected?



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

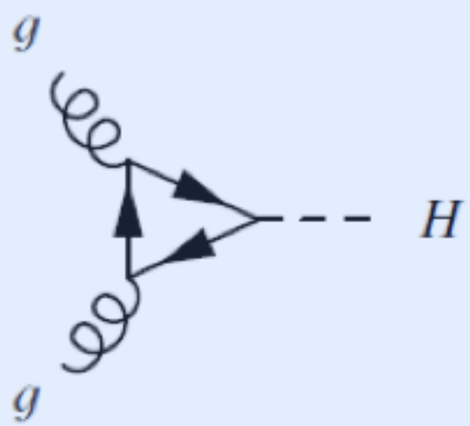
higher precision in theory calculation makes it easier to find the Higgs than initially thought

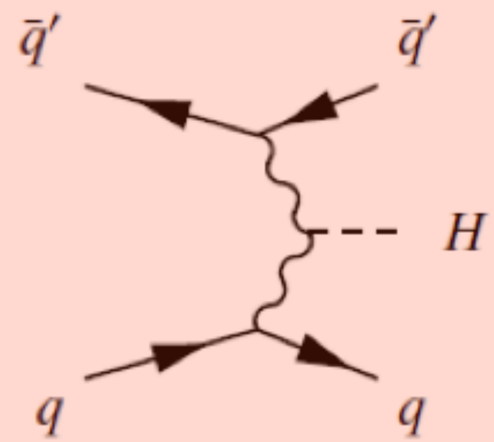
R. Harlander, talk @ LHCP'13

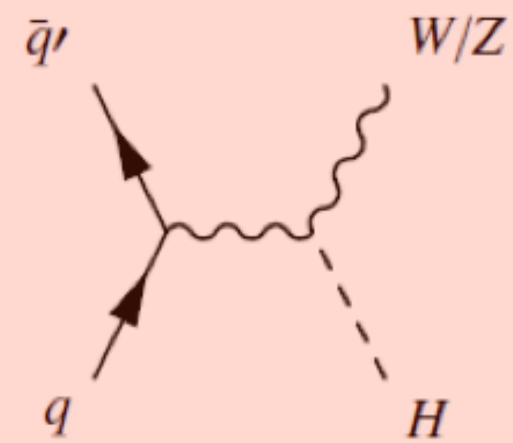
SM Precision Higgs Physics

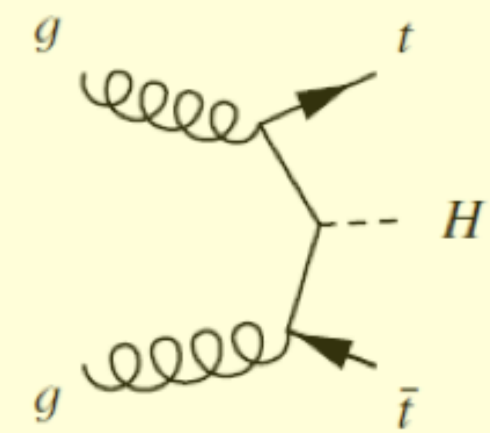
SM Higgs computations: State of the art

e.g. LHCHXSWG YR1 & YR2 & YR3







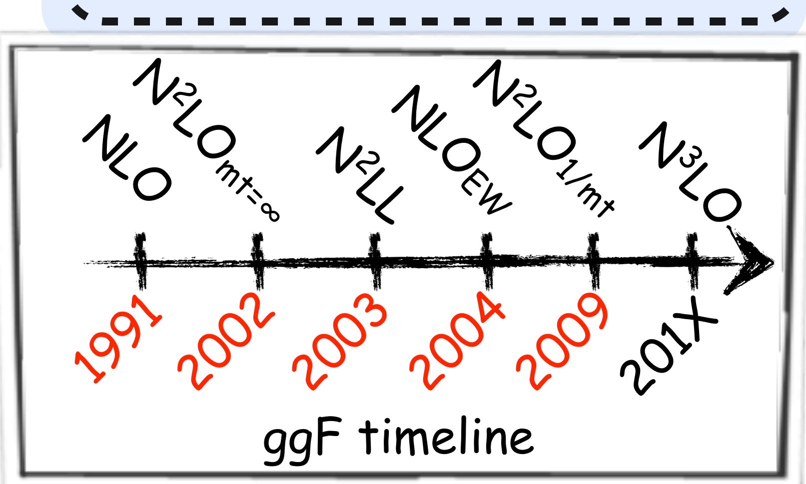


~TODAY~

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

~TOMORROW~

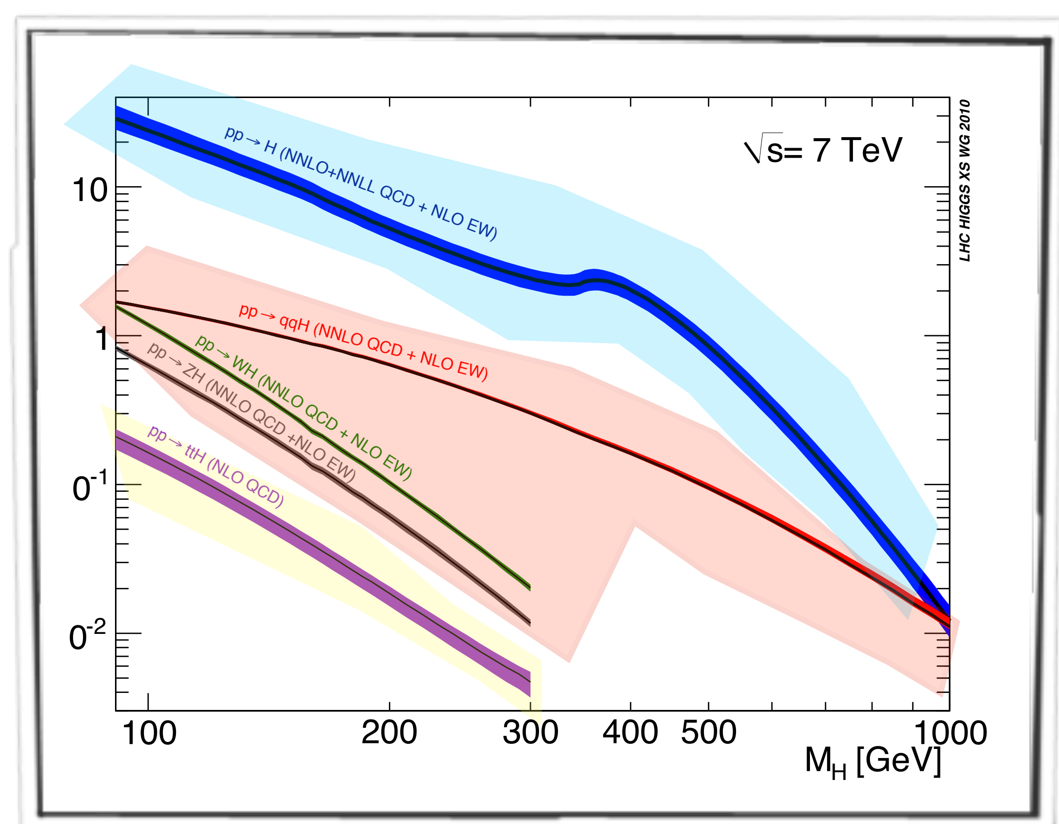
inclusive	Higgs p_T
N^3LO QCD ($m_t=\infty$)	NLO QCD w/ finite m_t,m_b (3 scale pb!)



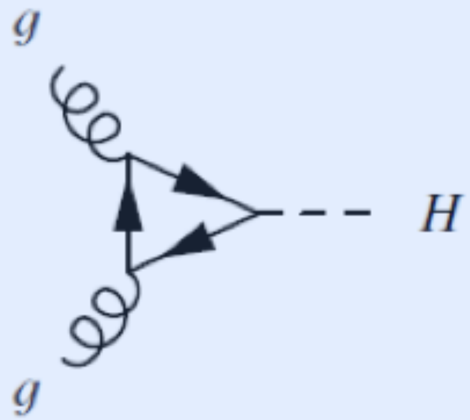
NLO results in MC

POWHEG, aMC@NLO

+ N^2LO PDF sets



The ggH Frontiers



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N²LO+N²LL QCD

NLO EW

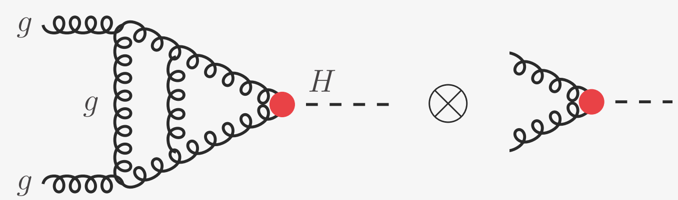
~TOMORROW~

inclusive	Higgs p_T
N³LO QCD ($m_t=\infty$)	NLO QCD w/ finite m_t,m_b (3 scale pb!)

2 → 2 @ 2-loop
similar to ttbar @ N²LO
recently achieved by Czakon/Mitov
2 → 1 @ 3-loop

Inclusive XS

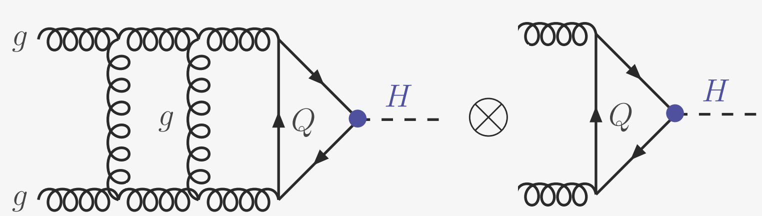
N²LO∞ α_s^4 2-loop



g_s^6 g_s^2

Harlander, Kilgore '02 Anastasiou, Melnikov '02

N²LOmt α_s^4 3-loop



g_s^6 g_s^2

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

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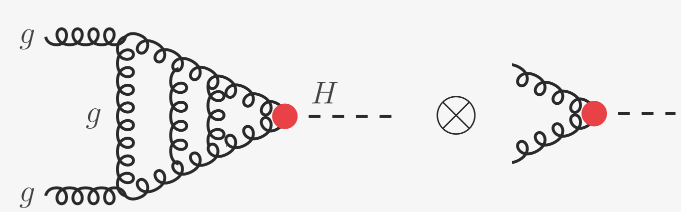
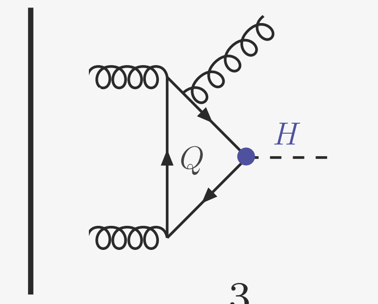


g_s^8 g_s^2

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

Higgs p_T

LOmt α_s^3 1-loop



g_s^3 Baur, Glover '90

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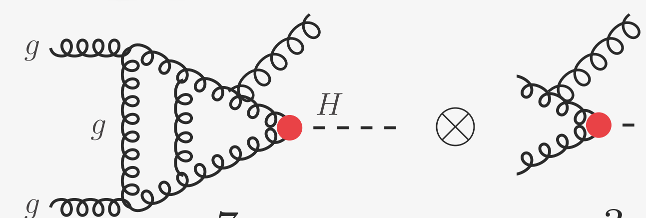

g_s^7 g_s^3

Boughezal et al '13

~TODAY~

~TOMORROW~

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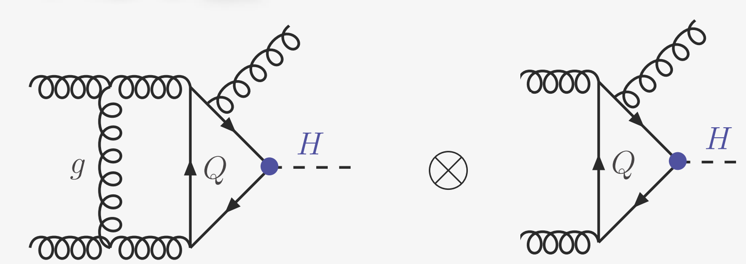


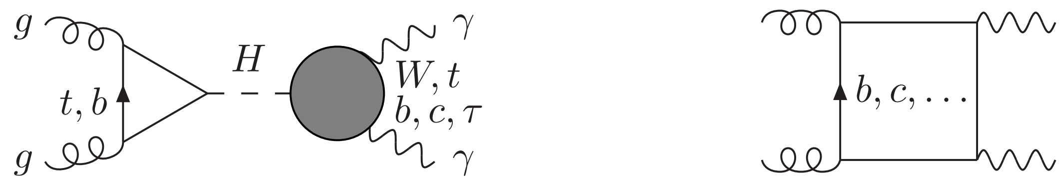
g_s^5 g_s^3

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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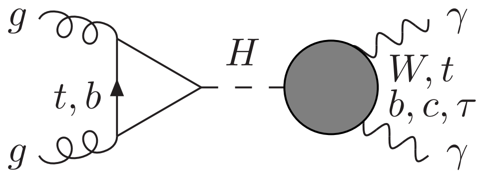

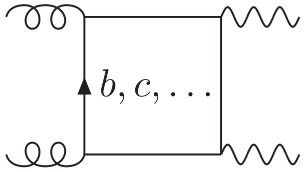

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Residual effect: downward shift of $M_{\gamma\gamma}$ mass peak

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

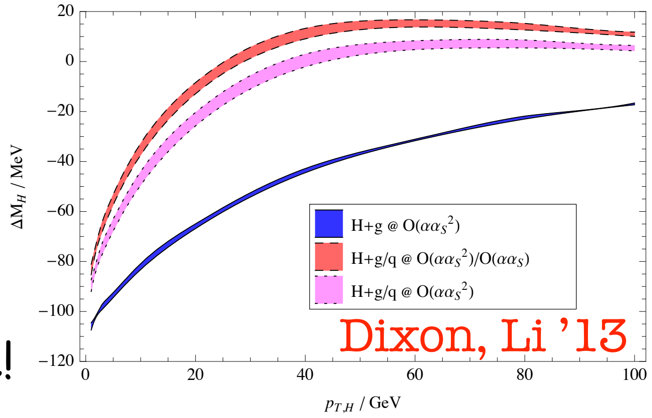
$\Delta M_{\gamma\gamma}$ =-70 MeV @ NLO Dixon, Li '13

(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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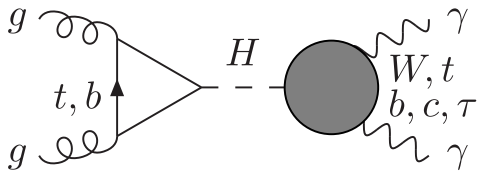

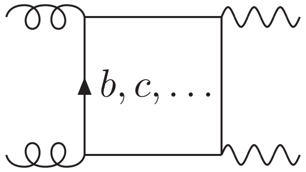

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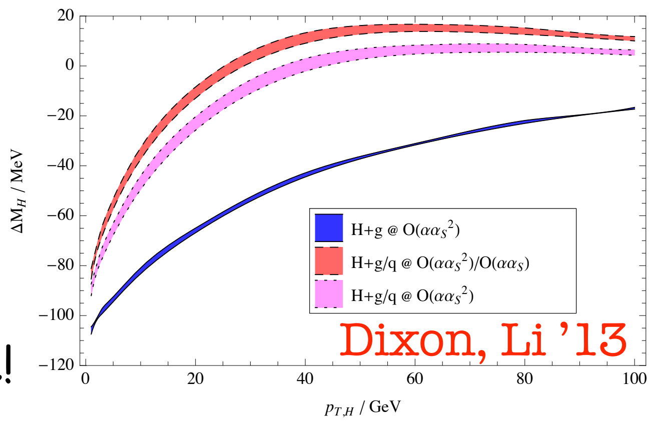

Access to the Higgs width @ LHC?

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?

"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?

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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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which is less constrained by direct searches than strongly coupled NP

1

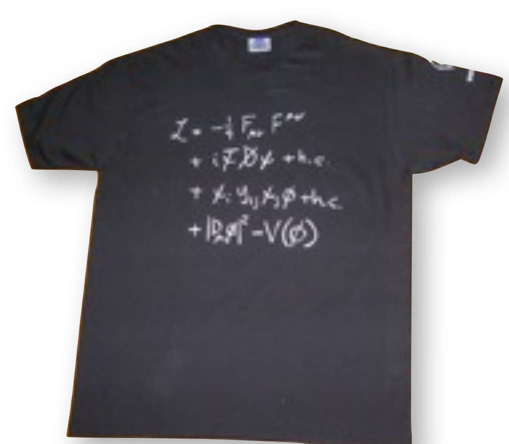
Higgs properties

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

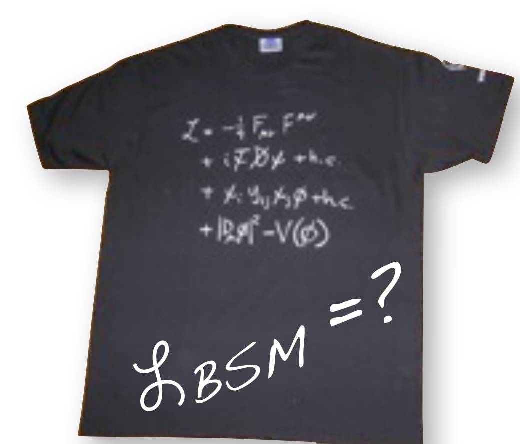
2

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

already bounded by flavor physics

bosonic sector — irrelevant operators (dim-6) only

➤ edm's

➤ Higgs signal strengths

➤ Higgs kinematical distribution

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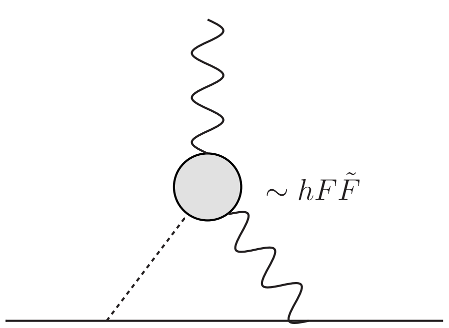
Among the 59 irrelevant directions, 3 of them induce $\not{CP}$ Higgs couplings in the EW bosonic sector

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

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

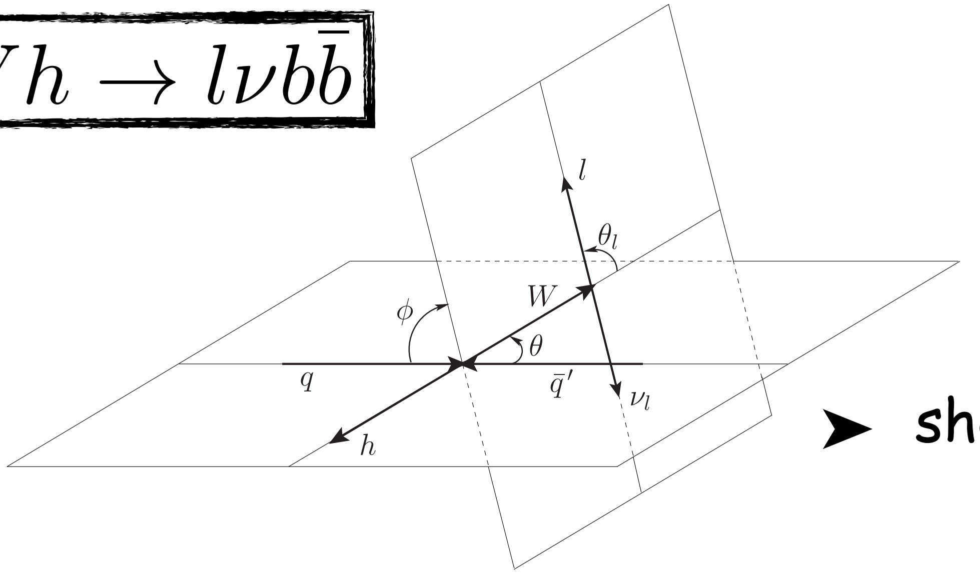
need to look for CP-odd observables
that are linear in the $\not{CP}$ Wilson coeffs.

CP-odd observables

The ~~CP~~ 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

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



the asymmetry in the variable

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

is linear in ~~CP~~ 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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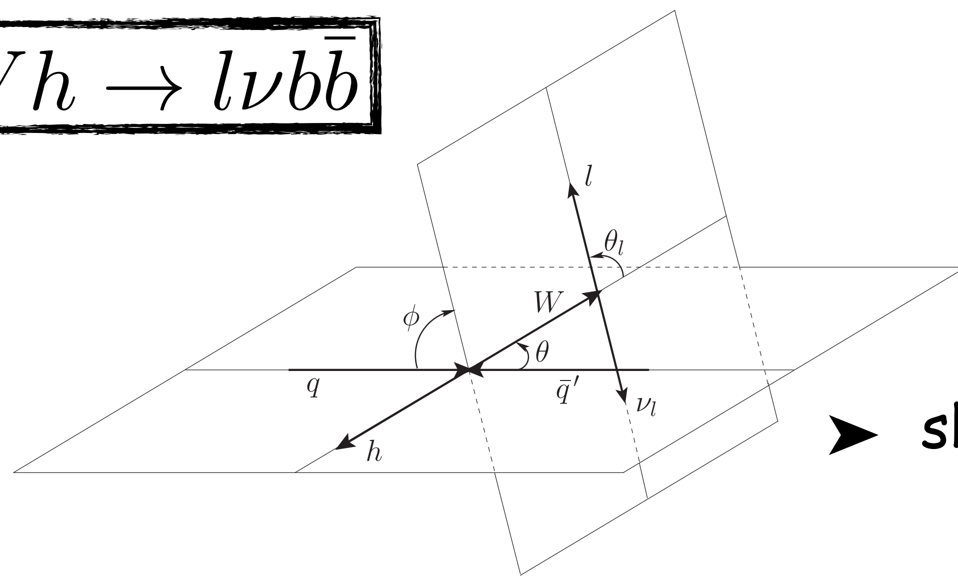

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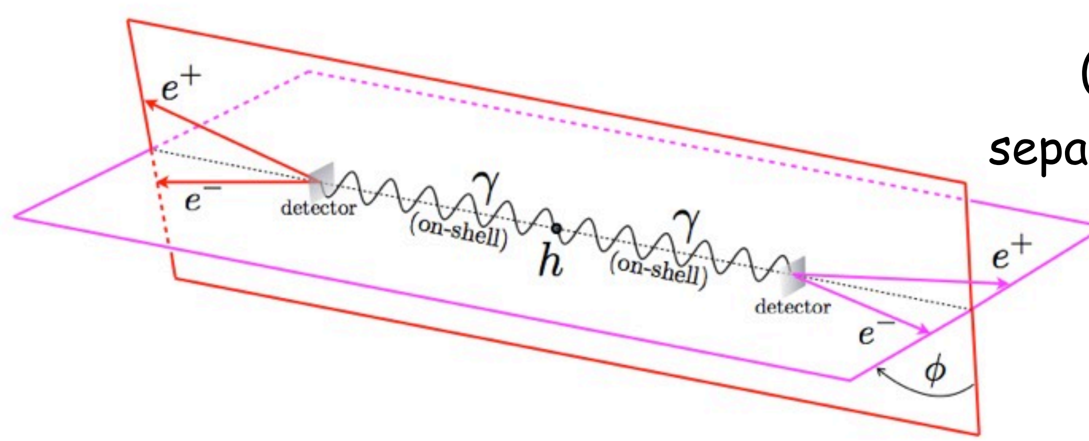
Another CP-odd observable can be constructed in h➛$\gamma\gamma$ channel

the $\not{CP}$ 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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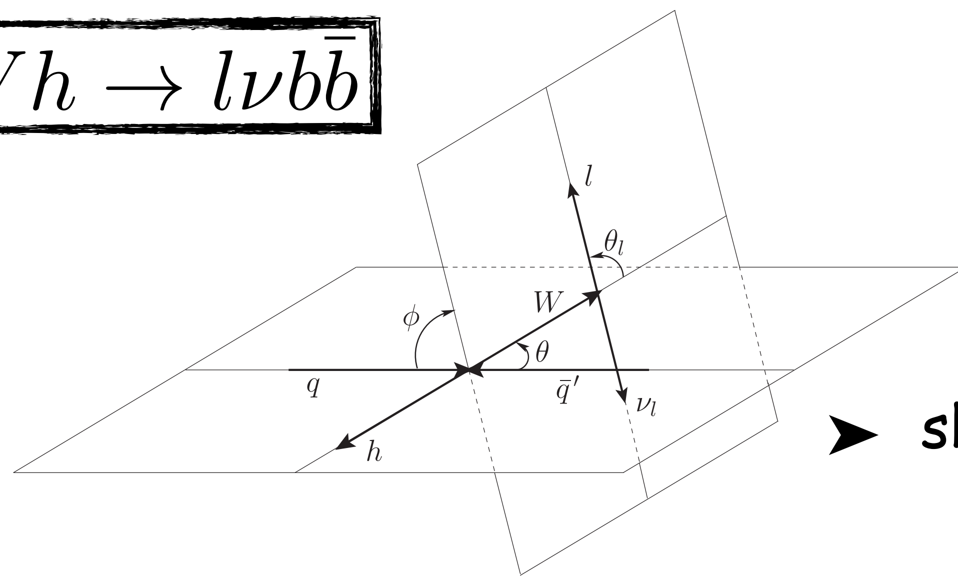

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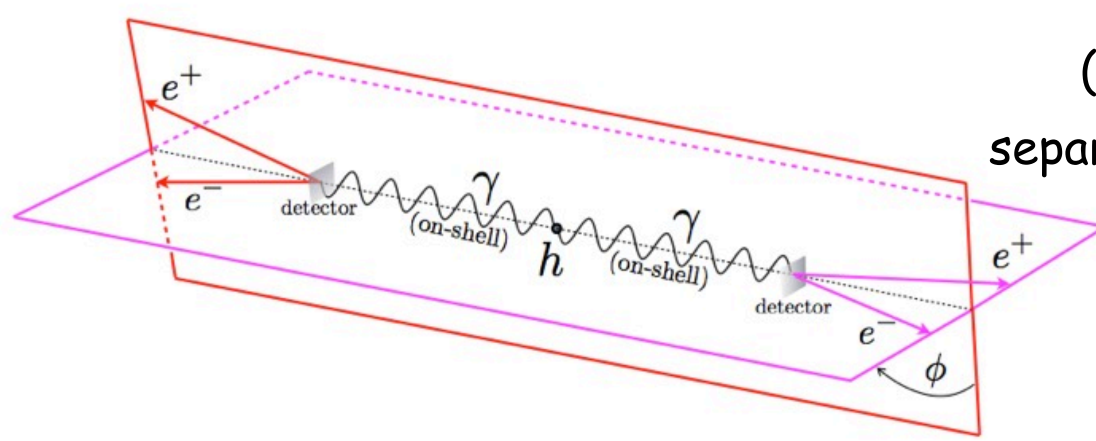

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Do we need Higgs data?

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

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.

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

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

$O(p^2)$

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

$O(p^4)$

still large LO parameter space

⇓ ⇓ ⇓

4 operators @ $O(p^2)$: c_V, c_t, c_b, c_τ

2 operators @ $O(p^4)$: c_g c_γ

(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:

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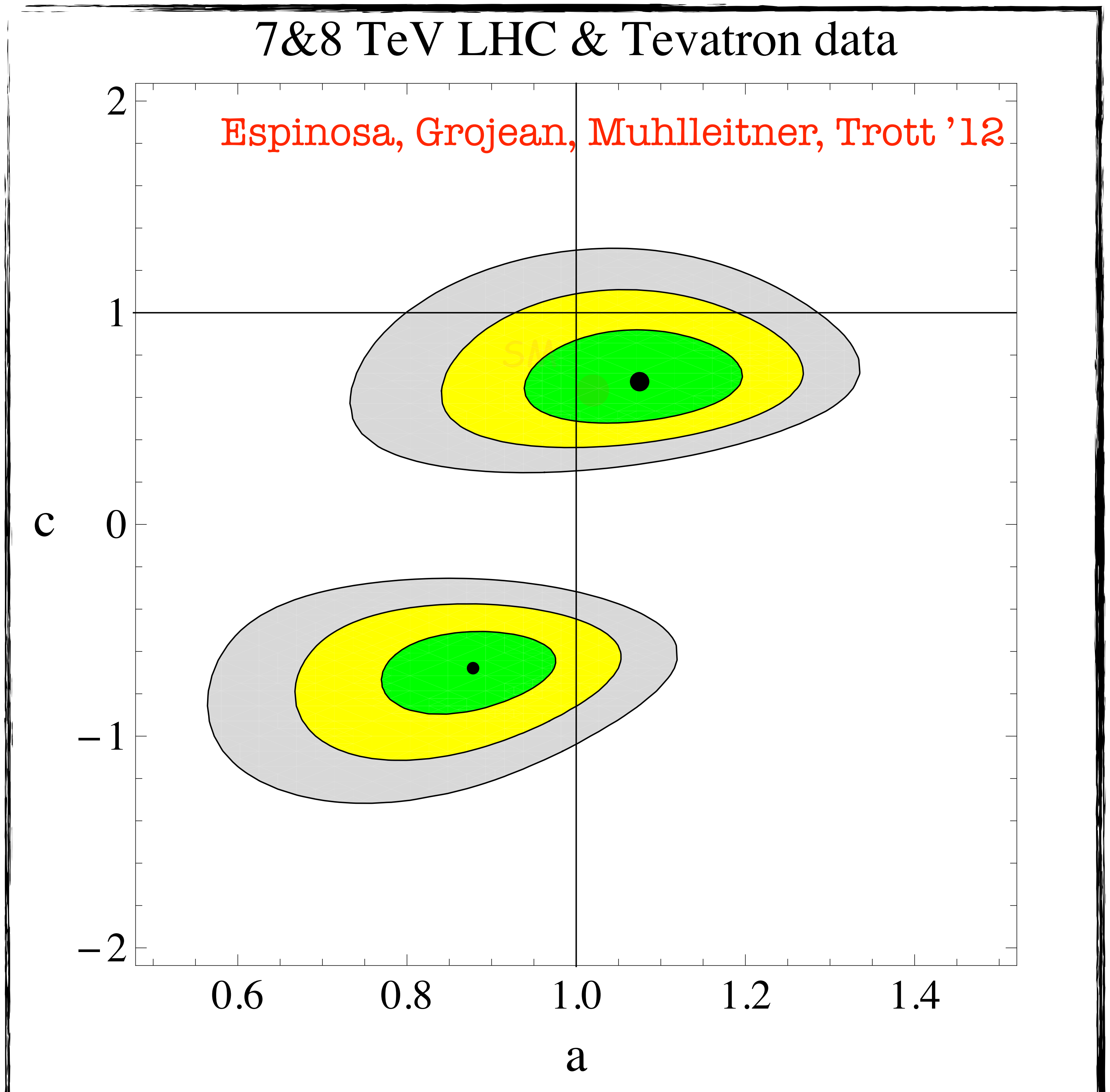
Higgs coupling fits: test of unitarity



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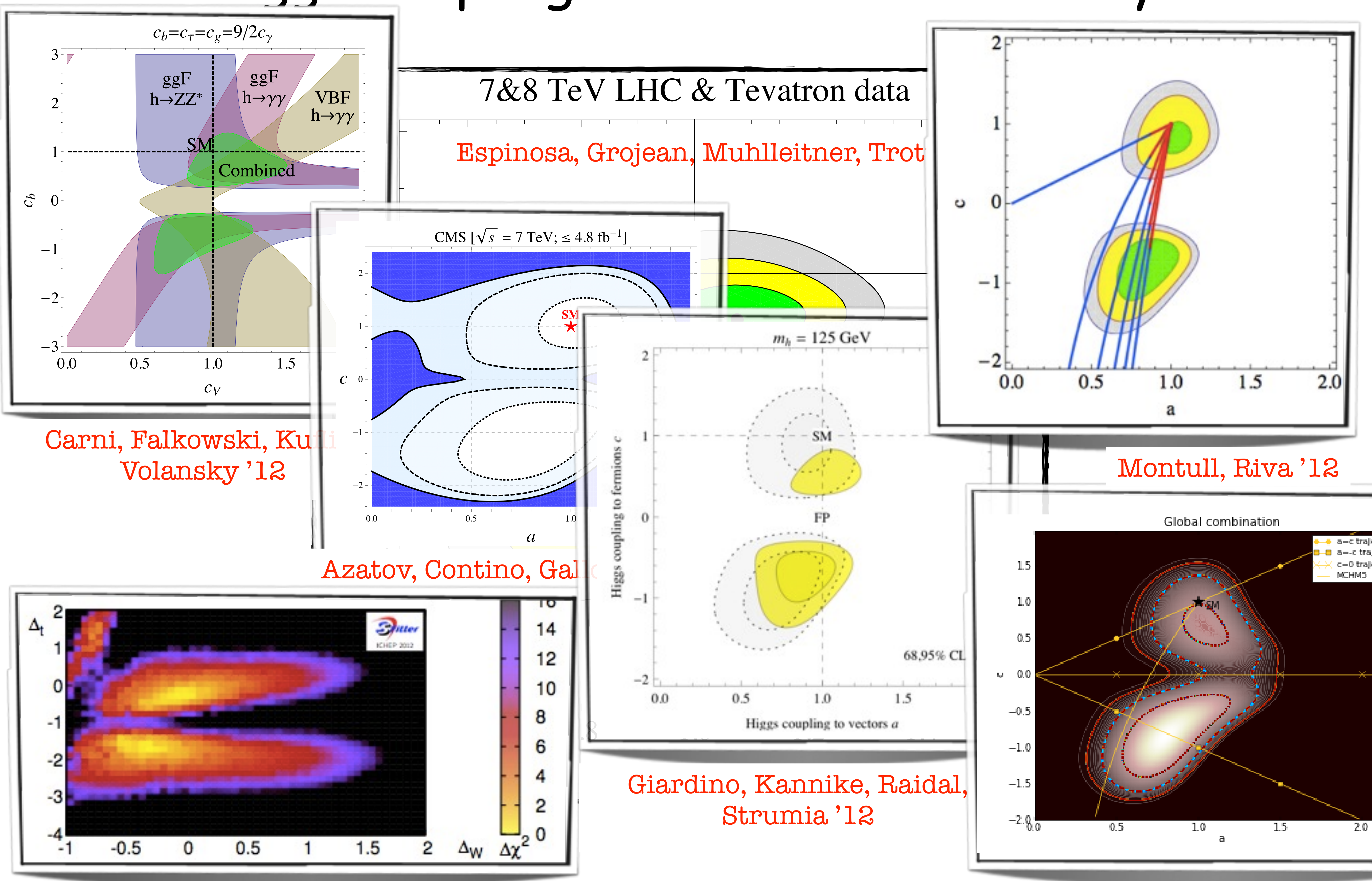


Carni, Falkowski, Ku... Volansky '12

Espinosa, Grojean, Muhlleitner, Trot...

Azatov, Contino, Gal...

Montull, Riva '12

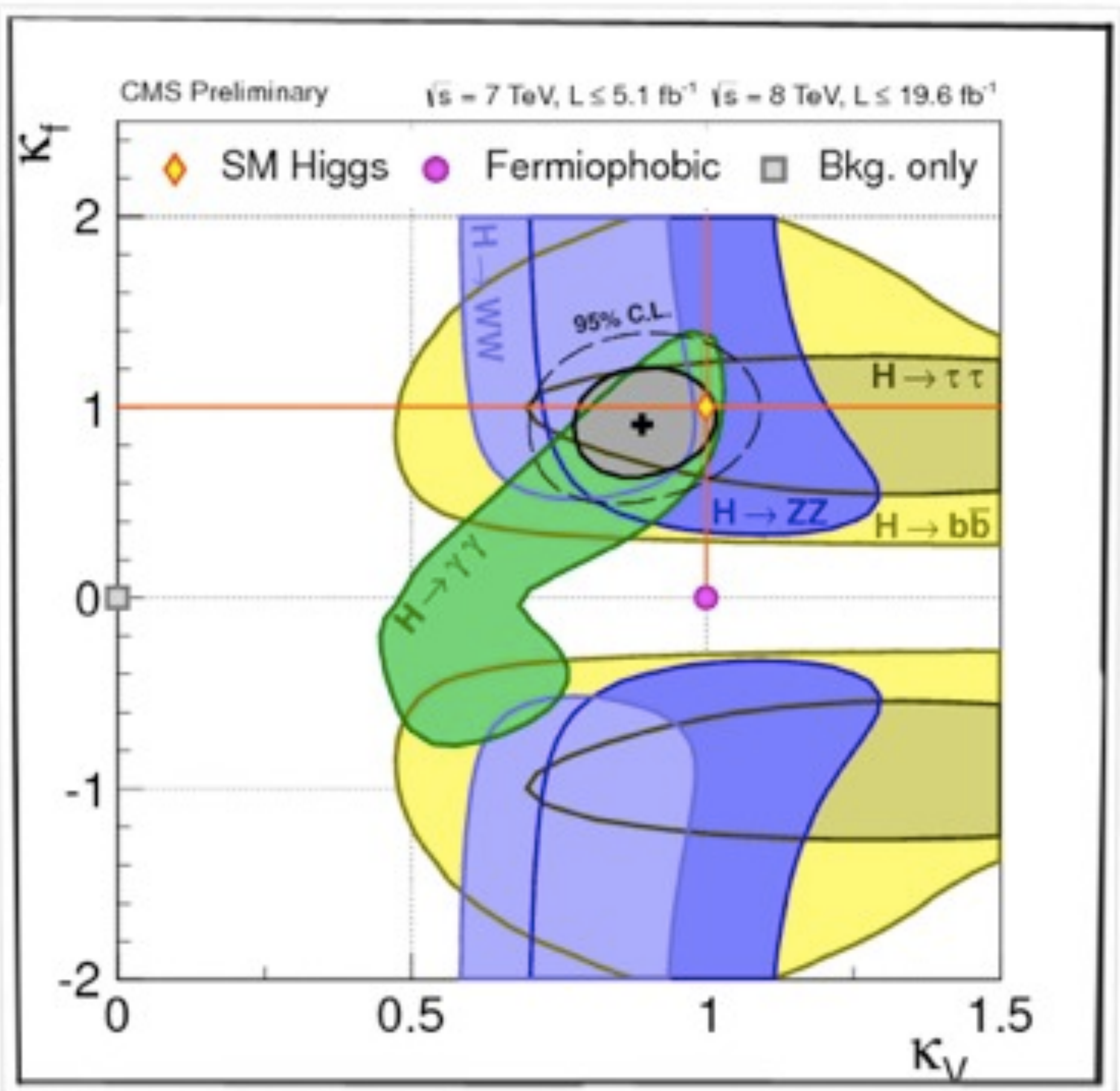
Giardino, Kannike, Raidal, Strumia '12

Plehn, Rauch '12

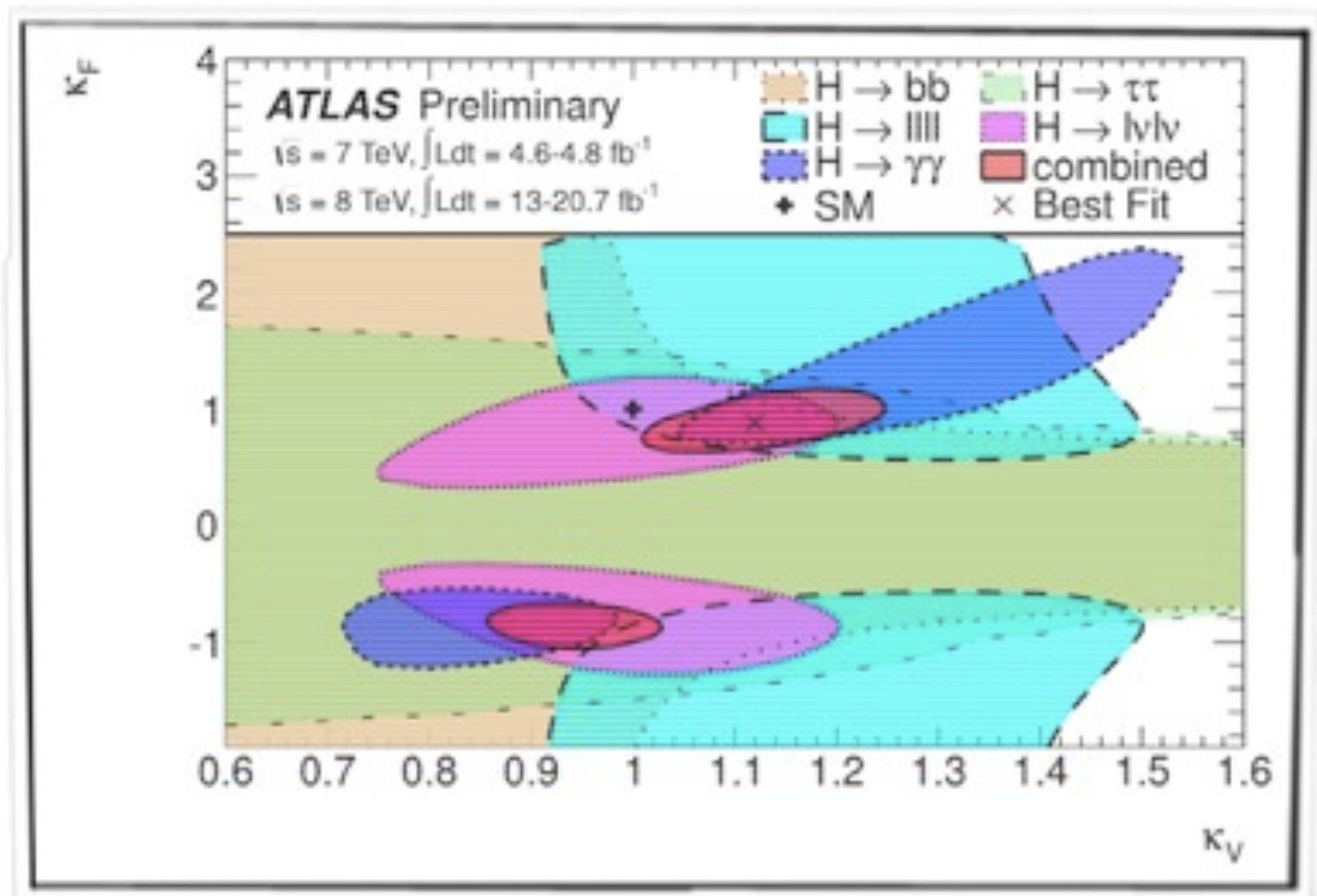
Ellis, You '12

Higgs coupling fits: test of unitarity

don't leave it in the hands of theorists!



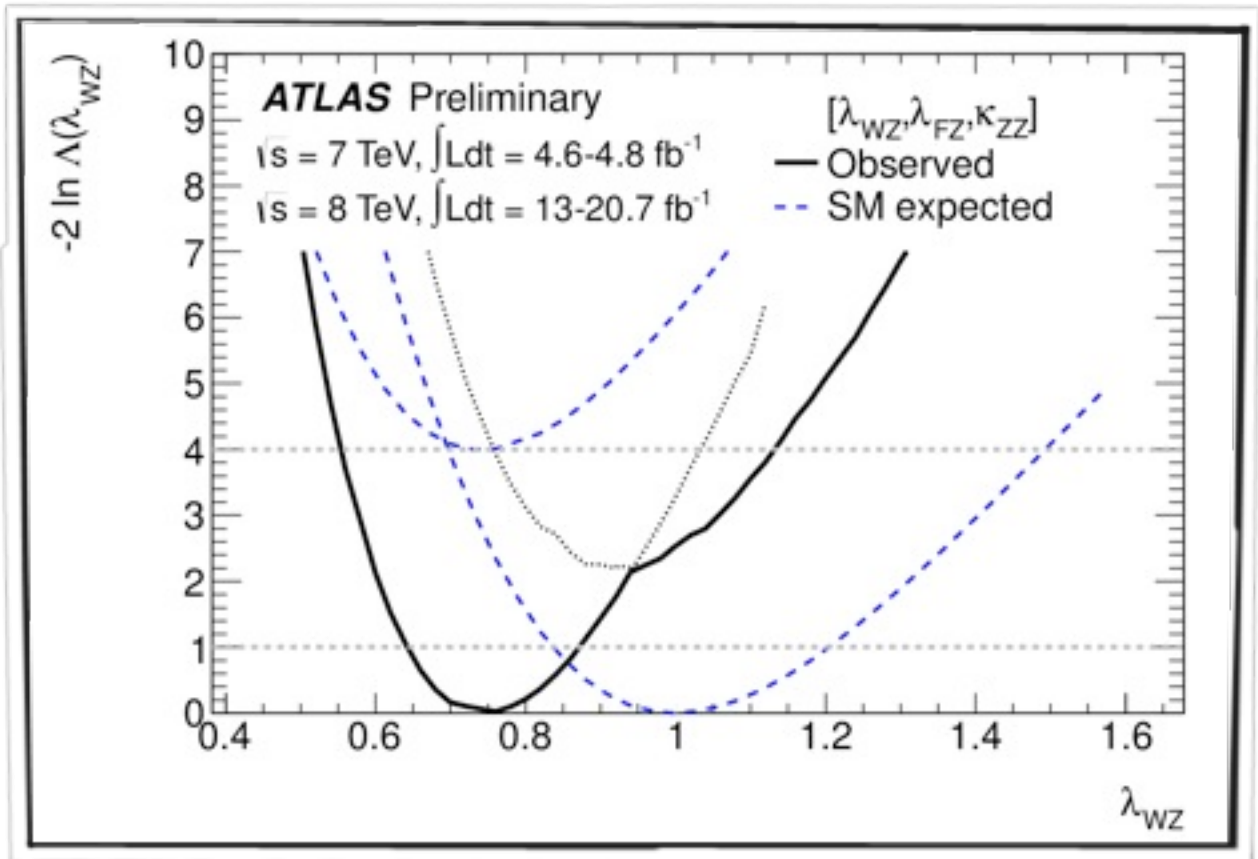
CMS

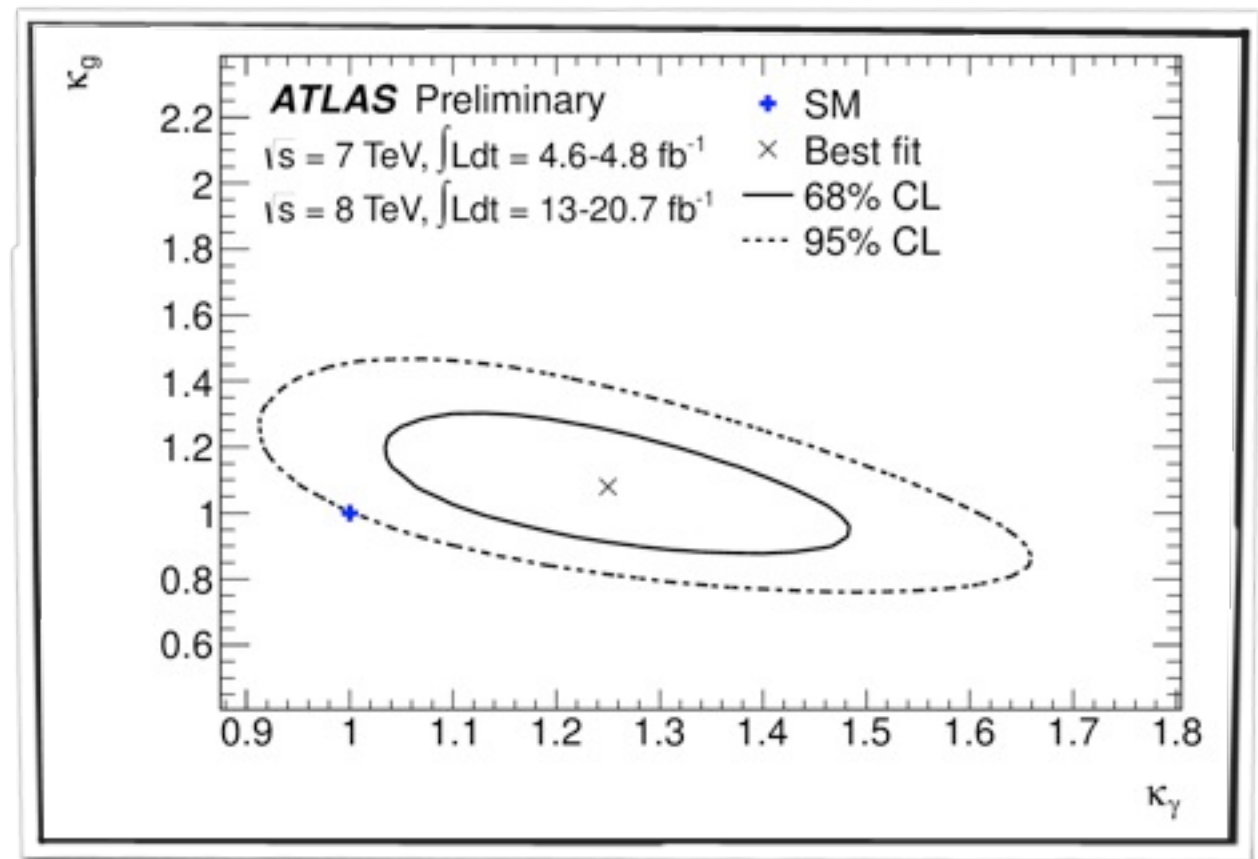


ATLAS

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 (*)

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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⇛ cannot disentangle
- long distance physics (modified top coupling)
- short distance physics (new particles running in the loop)

⇚

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

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

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

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

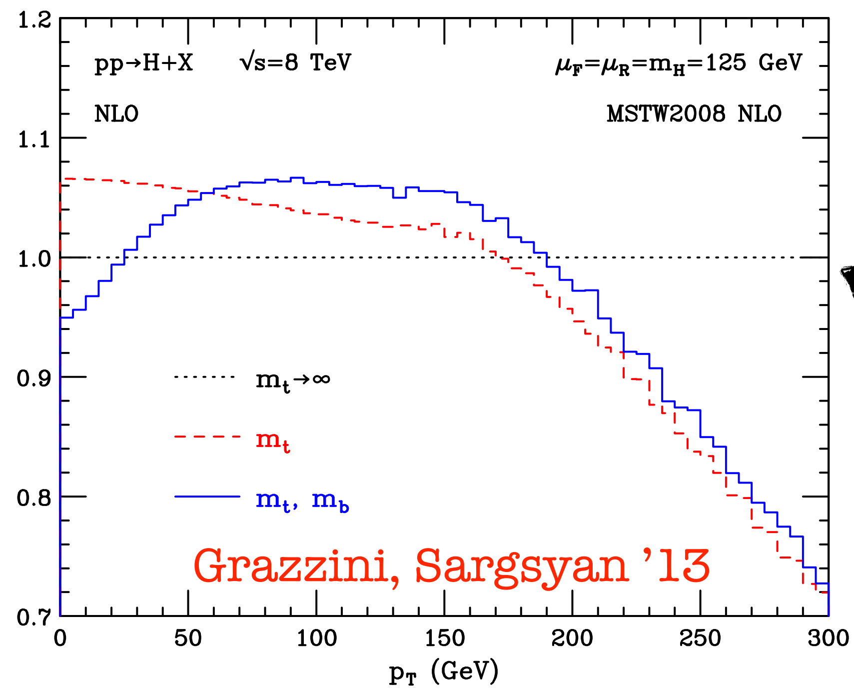
having access to htt̄ final state will resolve this degeneracy
but notoriously difficult channel
14%-4% @ LHC^{14}_{300}-LHC^{14}_{3000} vs 10%-4% @ ILC^{500}_{500}-ILC^{1000}_{1000}

Beyond current 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
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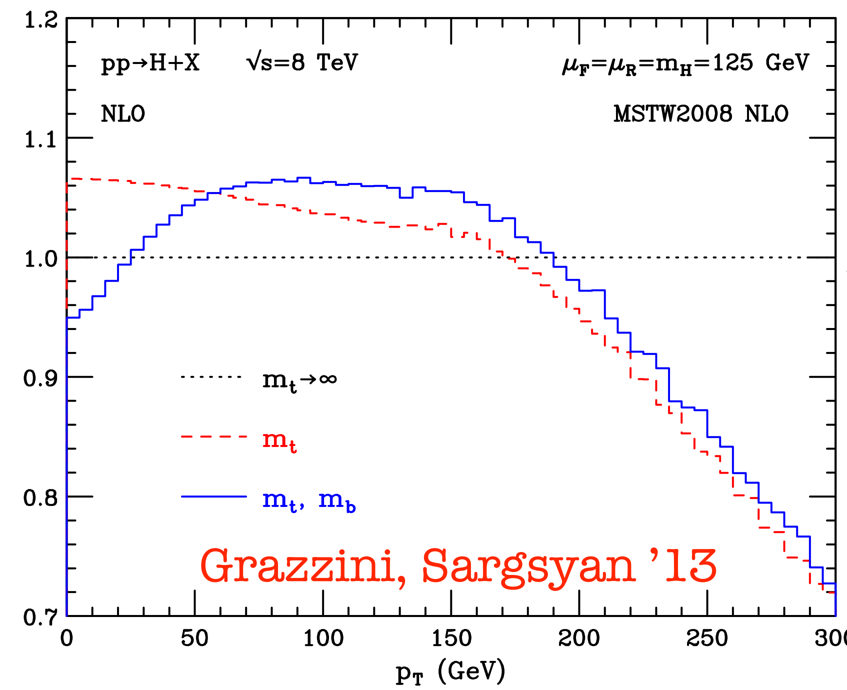


Note: LO only
NLO_{mt} is not known
$1/m_t$ corrections known $O(\alpha_s^4)$
few % up to p_T~150 GeV

Harlander et al '12

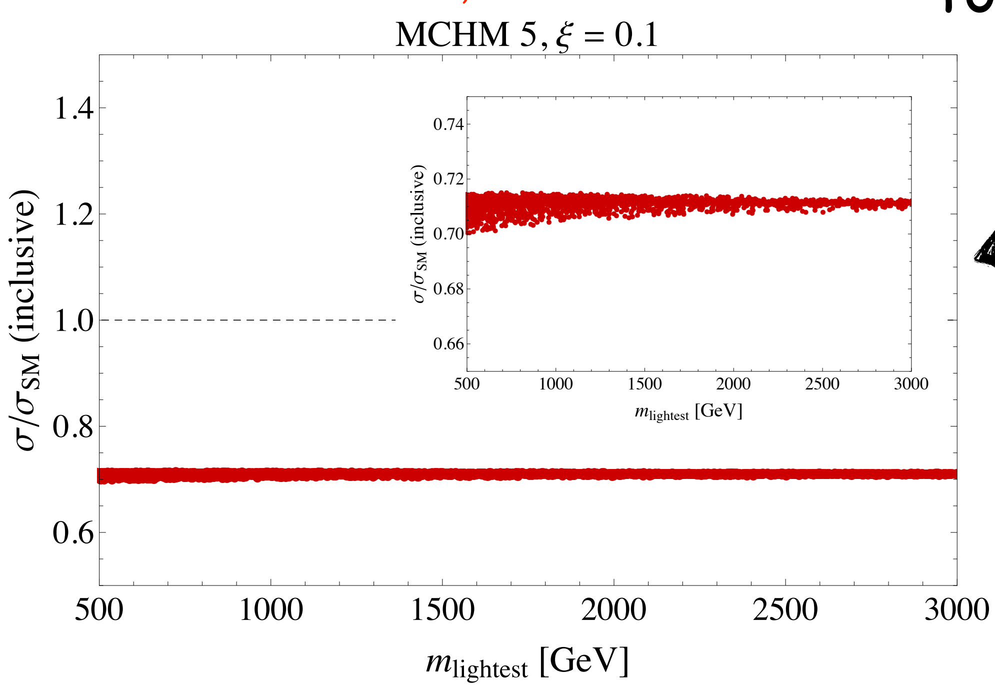
the high p_T tail is tens' % sensitive to the mass of top

Composite Higgs Model

top partners contributions

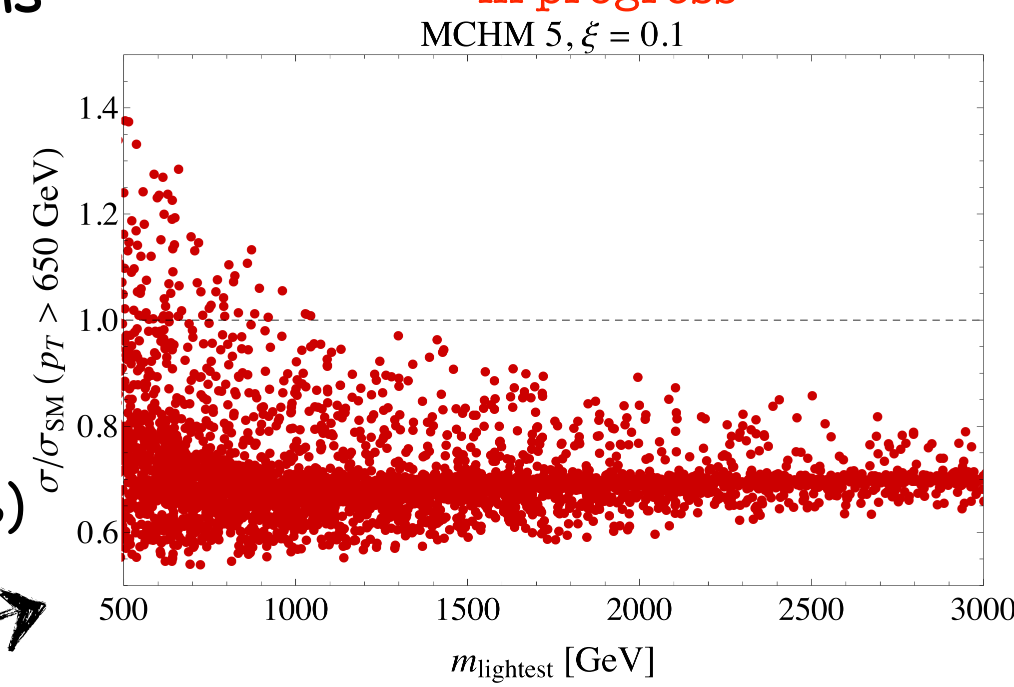
see also Banfi, Martin, Sanz '13
see also Azatov, Paul '13

Grojean, Salvioni, Schlaffer, Weiler ' in progress



inclusive rate: O(%)

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



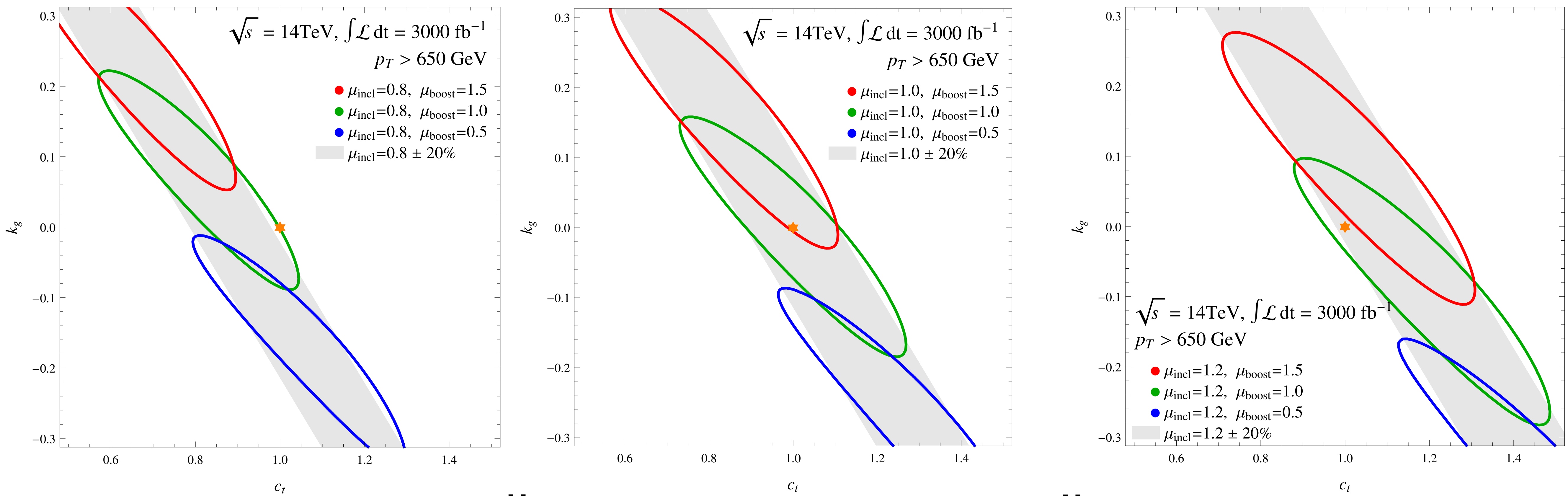
high p_T tail "sees" the top partners that are missed by the inclusive rate

Beyond current channels

cut open the top loops

Grojean, Salvioni, Schlaffer, Weiler
' in progress
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?

Boosted Higgs

QCD corrections?

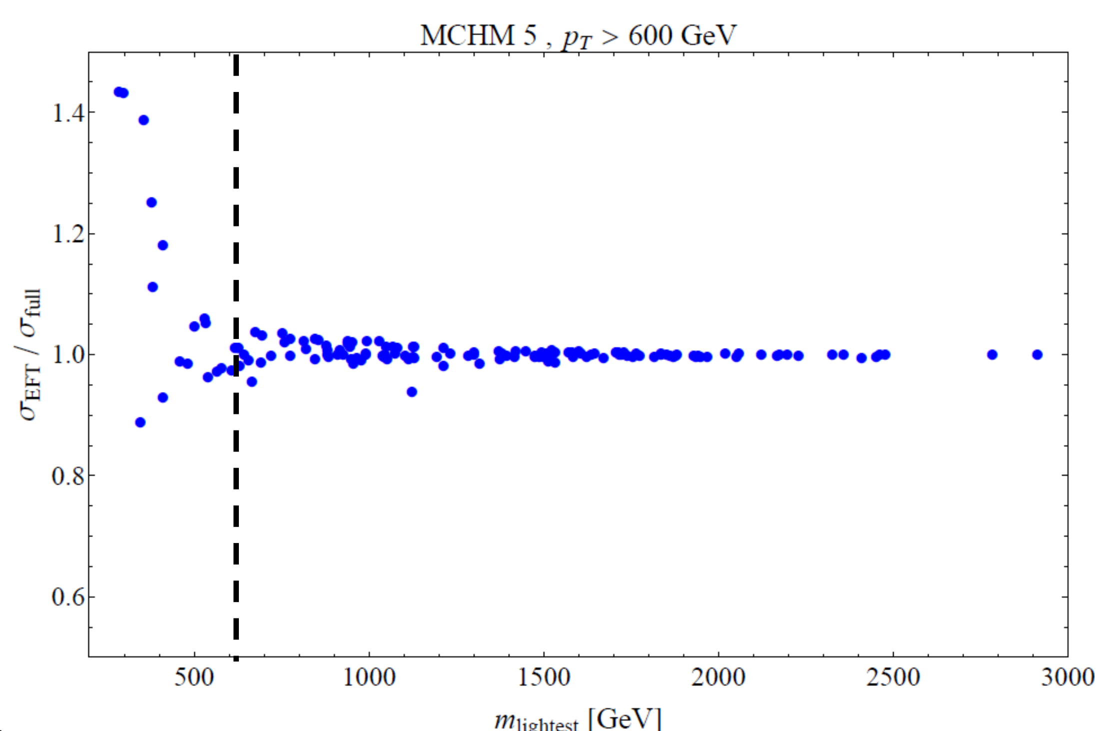
pT distribution with full quark mass dependence known at LO order.
K-factor are known to be large. However, most of the QCD corrections drop out in xs ratios:

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

- ☑ 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%

Boosted SUSY Higgs

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

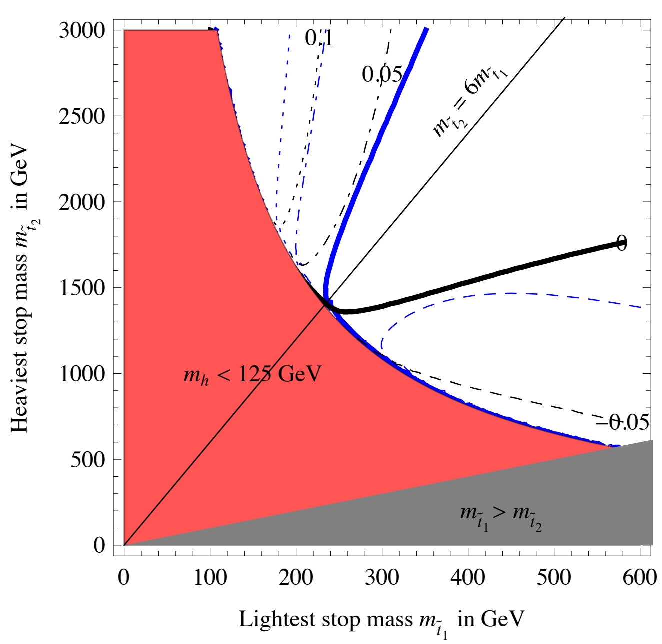
$$\frac{\Gamma(h \leftrightarrow gg)}{\Gamma(h \leftrightarrow gg)_{\rm SM}} = (1+\Delta_t)^2 \,, \qquad \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\rm SM}} = (1-0.28\Delta_t)^2$$

$$\Delta_t \approx \frac{m_t^2}{4}\left(\frac{1}{m_{\tilde{t}_1}^2} + \frac{1}{m_{\tilde{t}_2}^2} - \frac{X_t^2}{m_S^2}\right)$$

... 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)

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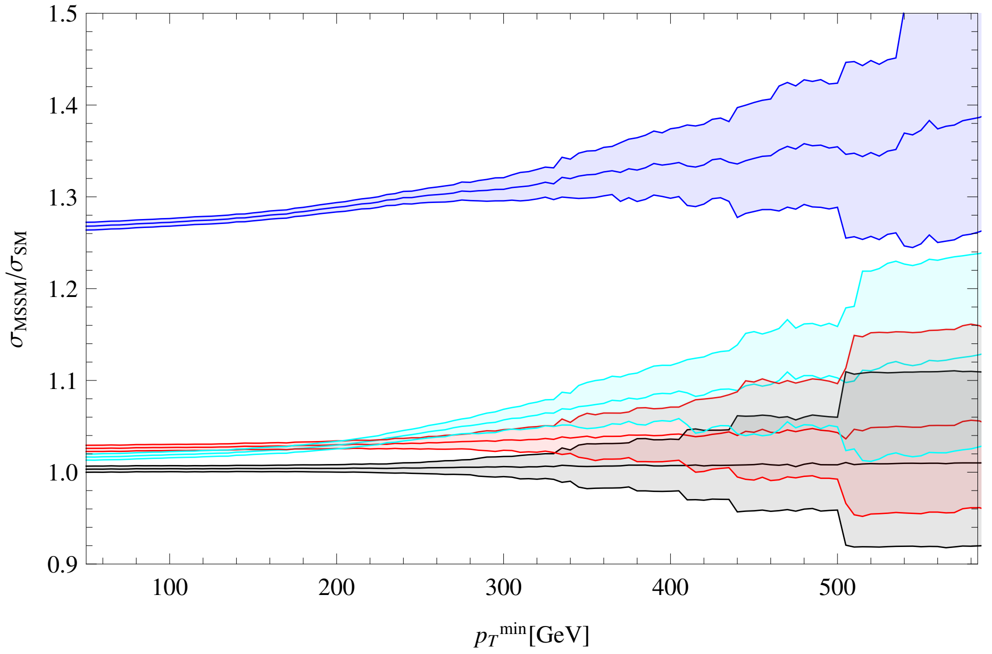


P1: mt1=395, mt2=2412, At=2420, Δt=0.002

P2: mt1=192, mt2=1224, At=1220, Δt=0.01

P3: mt1=259, mt2=1212, At=0, Δt=0.12

P4: mt1=226, mt2=484, At=532, Δt=0.015

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

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

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

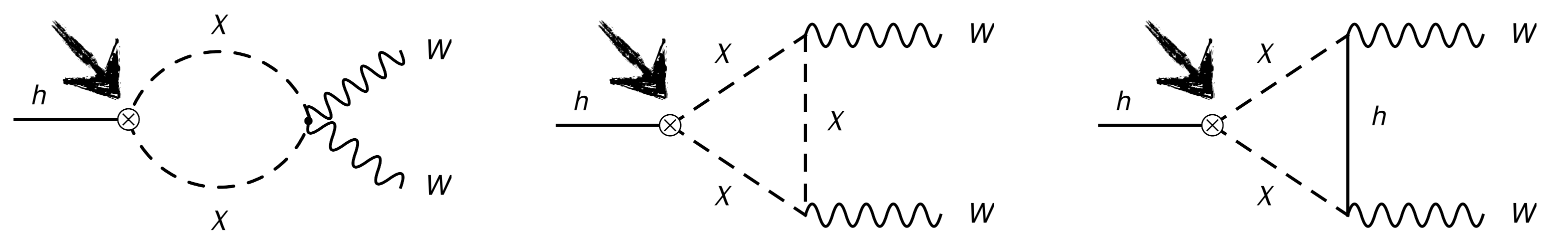
Grojean, Jenkins, Manohar, Trott '13   Elias-Miro, Espinosa, Masso, Pomarol '13

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 $(\partial_\mu |H|^2)^2$



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

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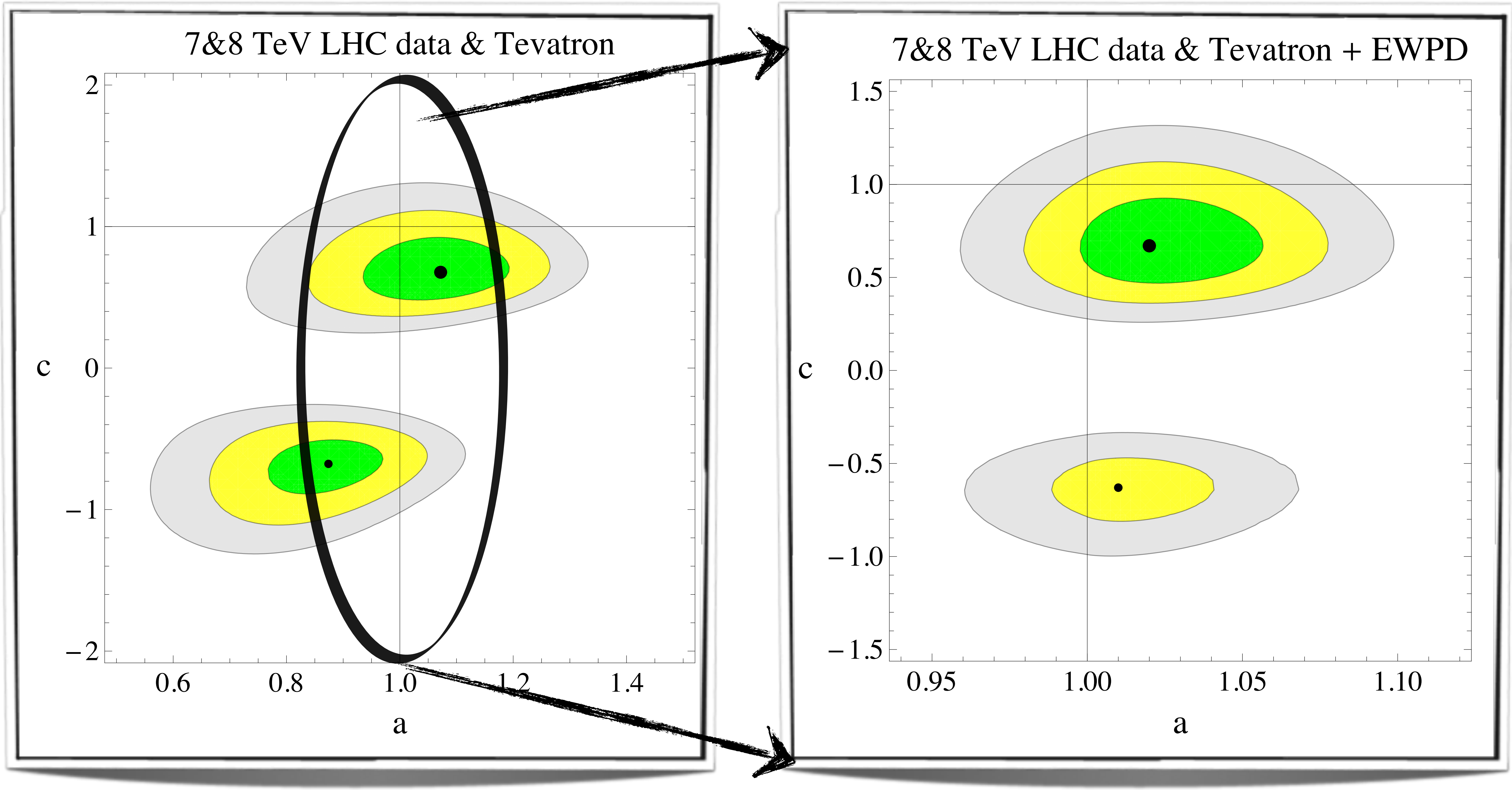
↑ anomalous dimensions

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

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 '13

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

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- 0: number of significant/ interesting/exciting deviations from SM predictions
- ?126?: general state of (our) mind (?)

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