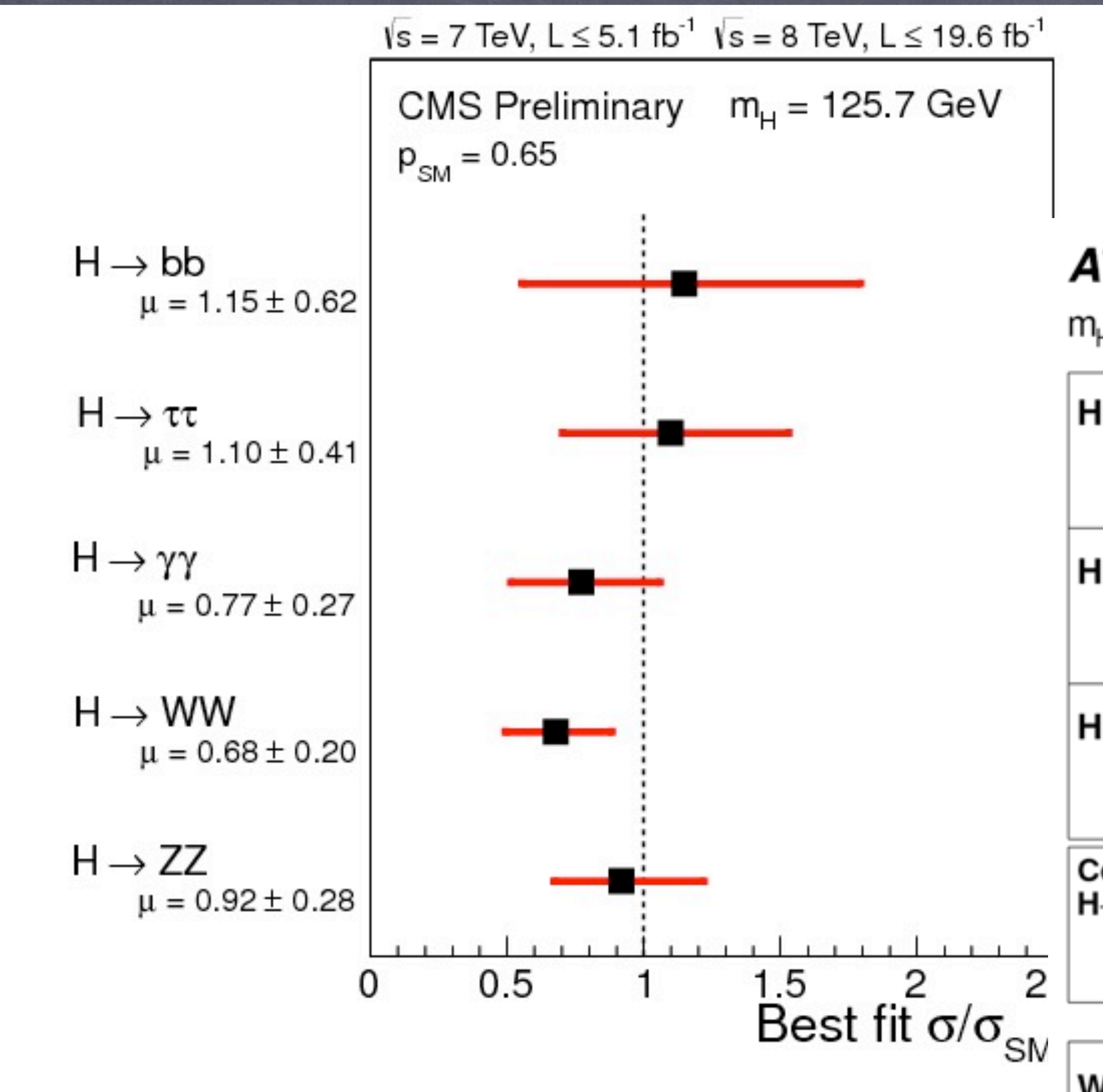
What the Higgs has to say about New Physics

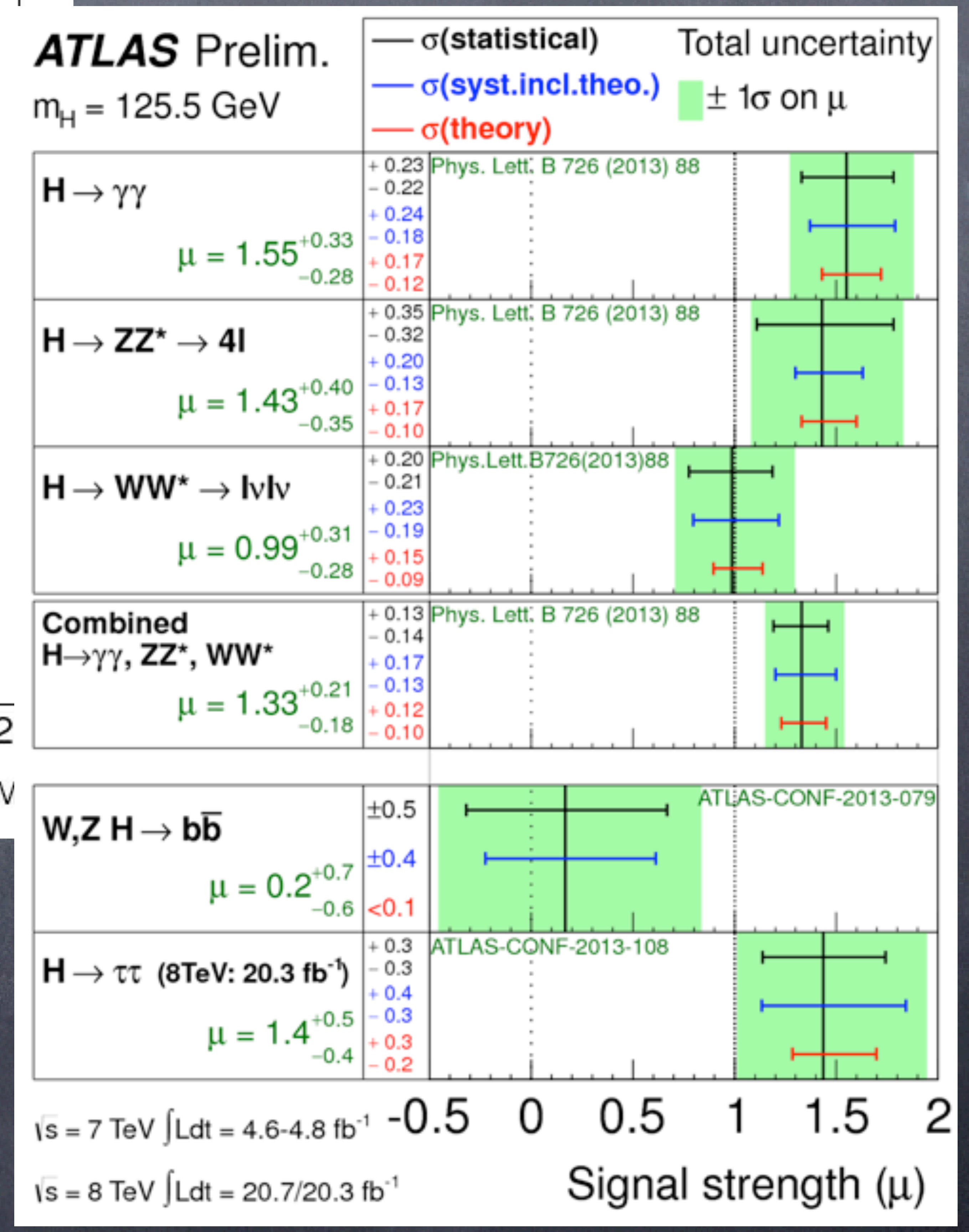
Veronica Sanz
Sussex

Christmas Workshop, IFT

Power to the data*

*Quoting Concha and friends


√s = 7 TeV, L ≤ 5.1 fb-1 √s = 8 TeV, L ≤ 19.6 fb-1
CMS Preliminary
mH = 125.7 GeV
pSM = 0.65
H → bb
μ = 1.15 ± 0.62
H → ττ
μ = 1.10 ± 0.41
H → γγ
μ = 0.77 ± 0.27
H → WW
μ = 0.68 ± 0.20
H → ZZ
μ = 0.92 ± 0.28
0
0.5
1
1.5
2
2
Best fit σ/σSM


ATLAS Prelim.
mH = 125.5 GeV
σ(statistical)
σ(syst.incl.theo.)
σ(theory)
Total uncertainty
± 1σ on μ
H → γγ
μ = 1.55 +0.33 −0.28
+ 0.23 − 0.22
+ 0.24 − 0.18
+ 0.17 − 0.12
Phys. Lett. B 726 (2013) 88
H → ZZ* → 4l
μ = 1.43 +0.40 −0.35
+ 0.35 − 0.32
+ 0.20 − 0.13
+ 0.17 − 0.10
Phys. Lett. B 726 (2013) 88
H → WW* → lνlν
μ = 0.99 +0.31 −0.28
+ 0.20 − 0.21
+ 0.23 − 0.19
+ 0.15 − 0.09
Phys.Lett.B726(2013)88
Combined
H→γγ, ZZ*, WW*
μ = 1.33 +0.21 −0.18
+ 0.13 − 0.14
+ 0.17 − 0.13
+ 0.12 − 0.10
Phys. Lett. B 726 (2013) 88
W,Z H → bb̄
μ = 0.2 +0.7 −0.6
±0.5
±0.4
<0.1
ATLAS-CONF-2013-079
H → ττ (8TeV: 20.3 fb-1)
μ = 1.4 +0.5 −0.4
+ 0.3 − 0.3
+ 0.4 − 0.3
+ 0.3 − 0.2
ATLAS-CONF-2013-108
√s = 7 TeV ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV ∫Ldt = 20.7/20.3 fb-1
-0.5
0
0.5
1
1.5
2
Signal strength (μ)

Couplings

Each channel isn't that well measured

BUT

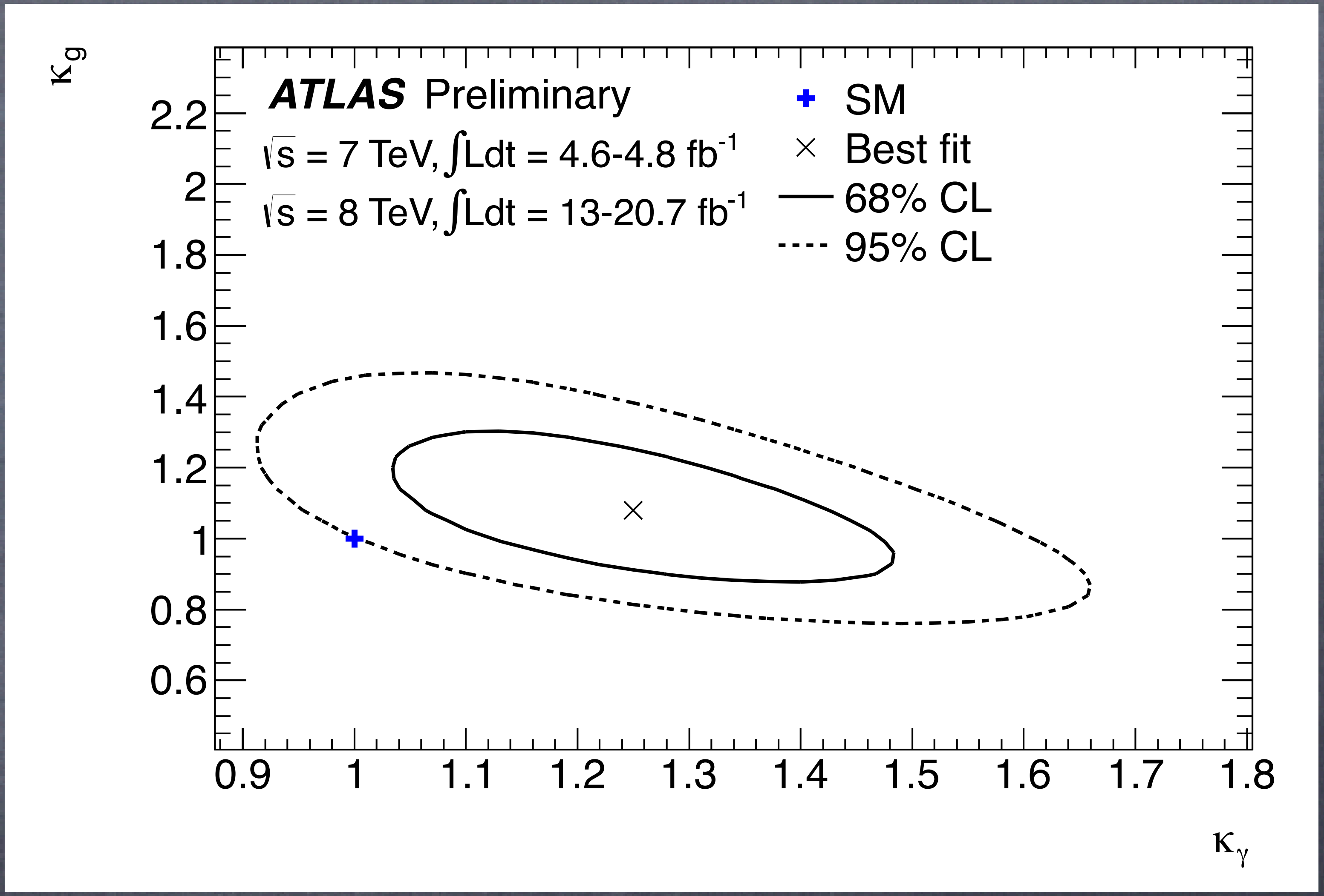
powerful information

assume a scenario and fit

Looking for particles in the loops

$$\kappa_g^2 = \frac{\sigma_{prod}(gg \to h)}{\sigma_{prod}(gg \to h)_{SM}}$$

$$\kappa_\gamma^2 = \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{SM}}$$



From data to ideas

Light SM-like Higgs is a reality

stabilization of the electroweak scale

use of symmetries
SUSY and Goldstone (shift)

examples of
weak and strong coupling

Higgs data
and its stabilization mechanism

Supersymmetry

SUSY Higgs

chiral multiplet with a fermion, Higgsino

$$\Phi = (H, \tilde{H})$$

chiral symmetry
inherited by the Higgs

e.g. Giudice, Rattazzi 97

$$m_h^2 = m_Z^2 \cos^2(2\beta) + (\text{loop}) m_{\tilde{t}}^2 \log(m_{\tilde{t}_2}/m_{\tilde{t}_1})$$

SUSY Higgs and the third generation

Light stops couple to the Higgs and affect its production and decay modes

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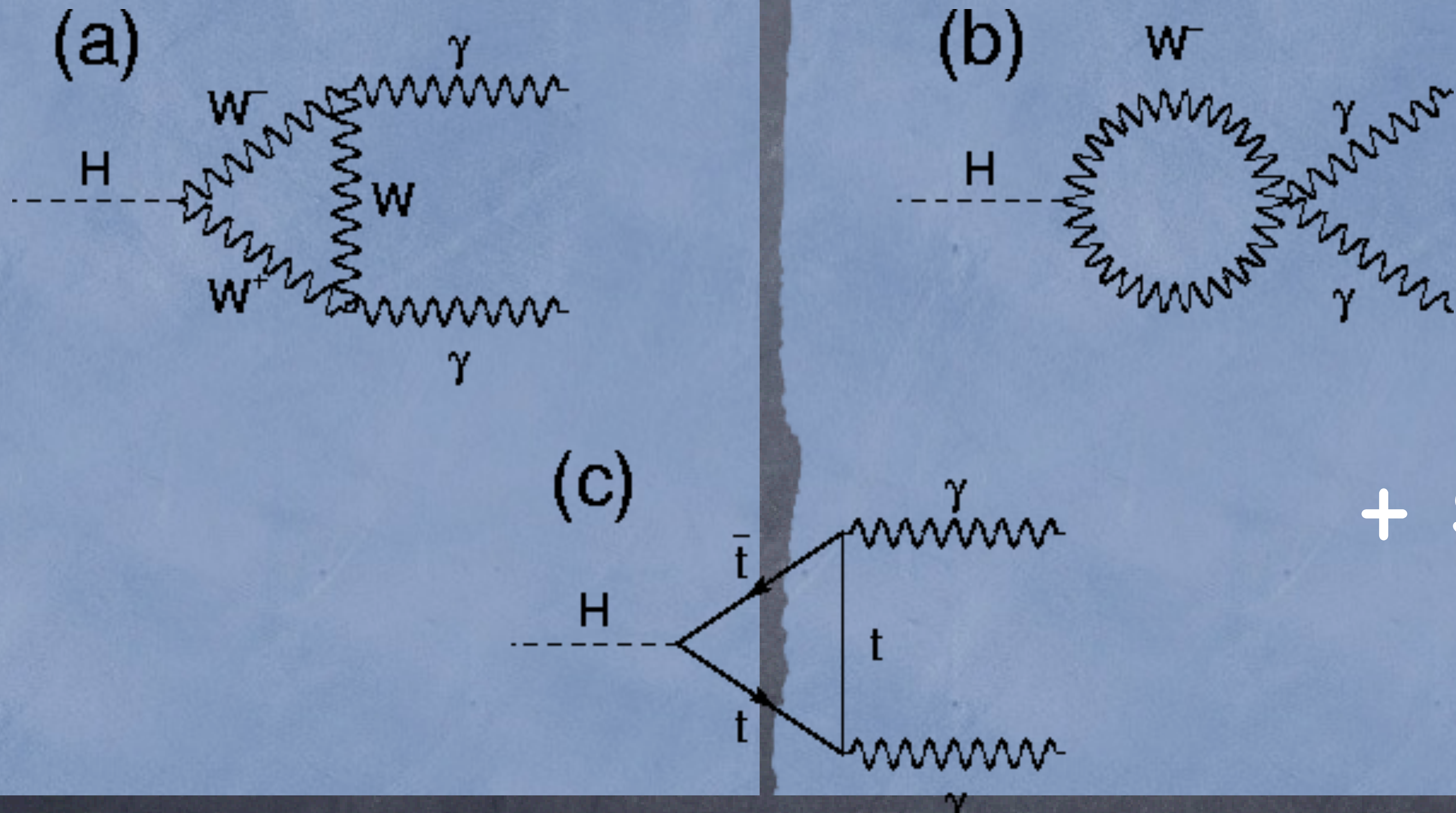
SM contributions

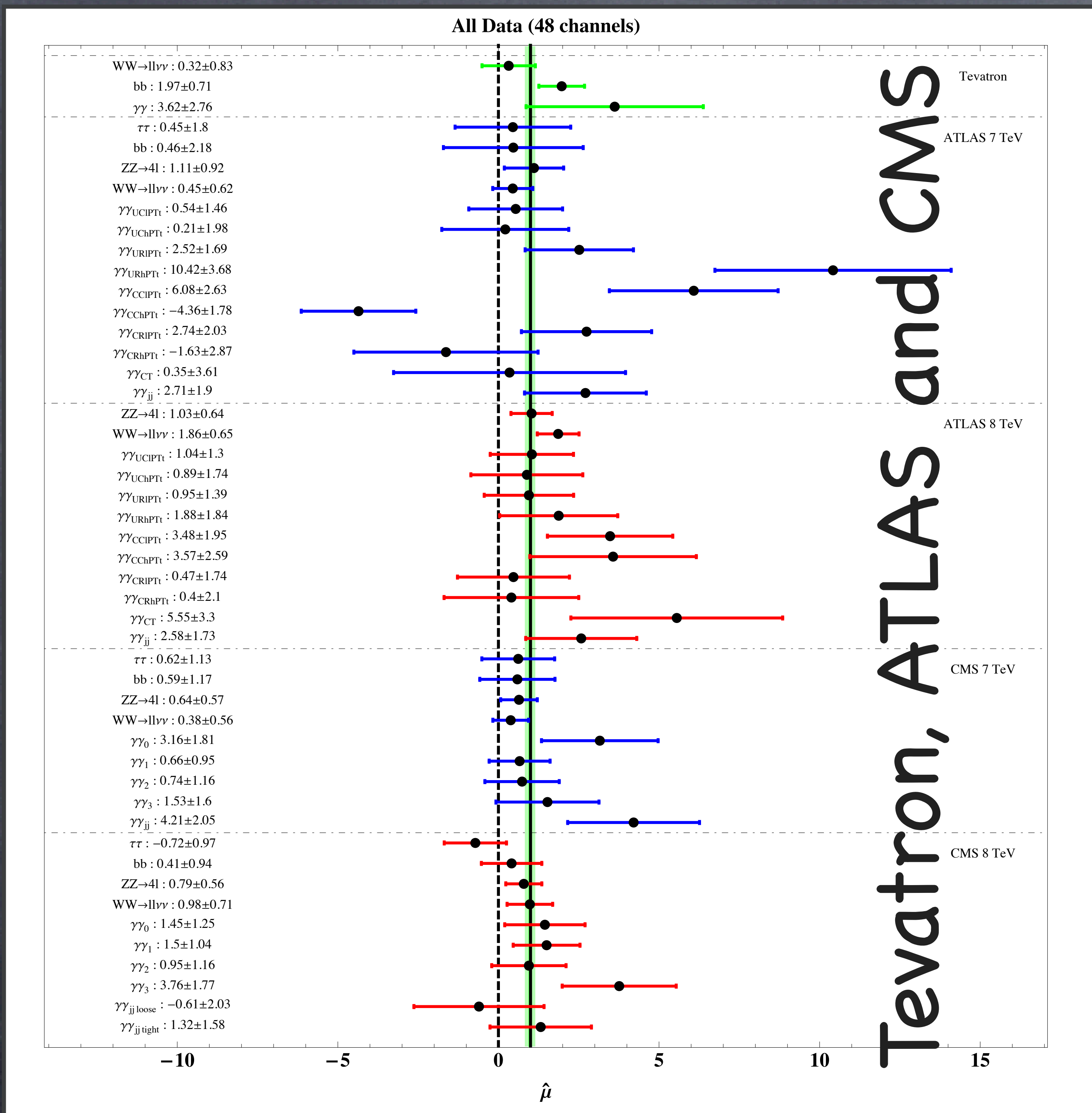


+ stops running in the loop

$$F_\gamma^{SM}(m_t, W, m_b \cdots) = F_1(\tau_W) + \sum_{i=t,b\cdots} N_c\, Q_i^2\, F_{1/2}(\tau_i)\left(1 - \frac{\alpha_s}{\pi}\right) \approx 1/(0.155 - 0.002\, i)$$

Fit to Higgs properties in BSM

Espinosa, Grojean, VS, Trott, 2012



Fit to Higgs properties in BSM

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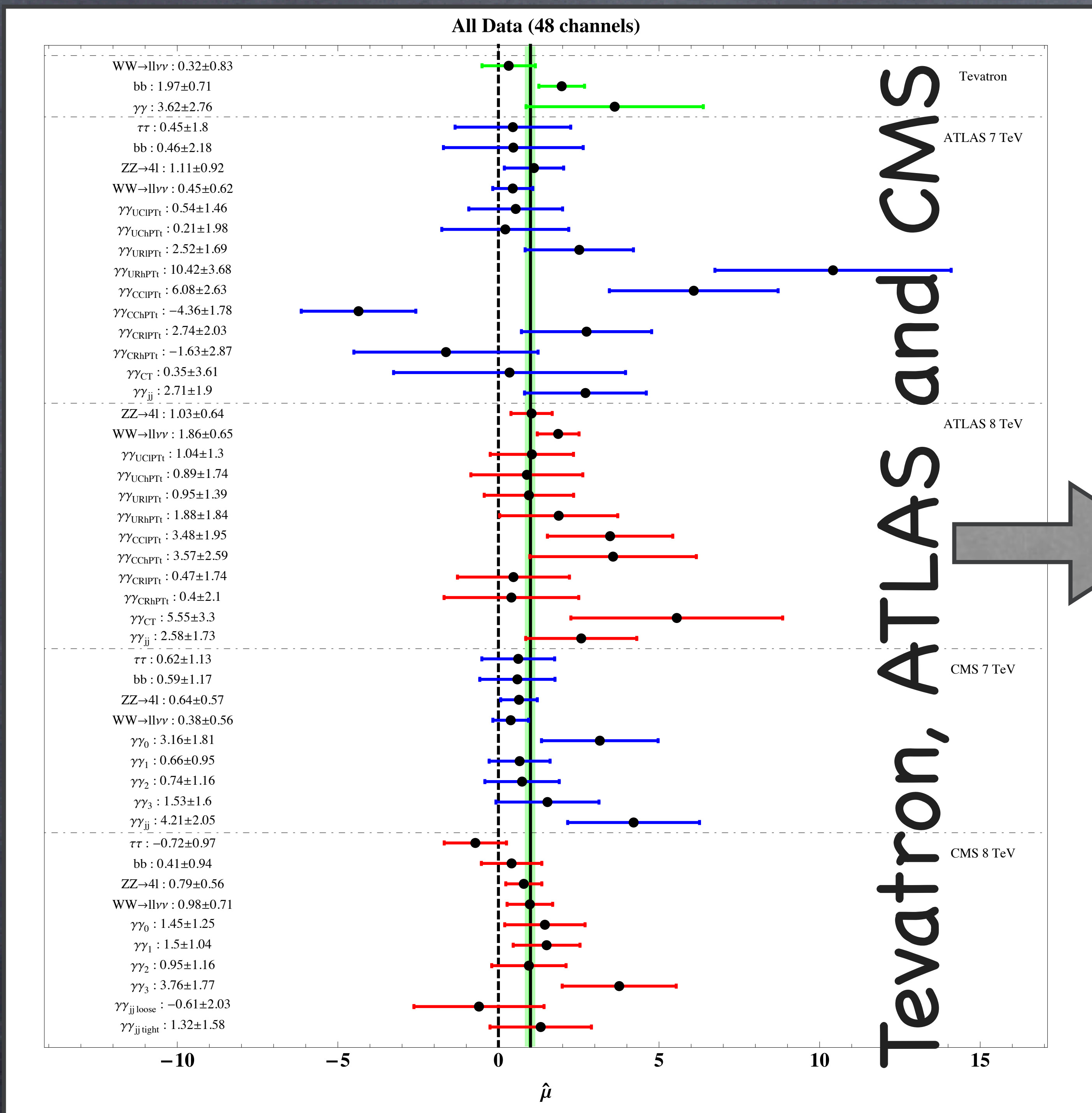
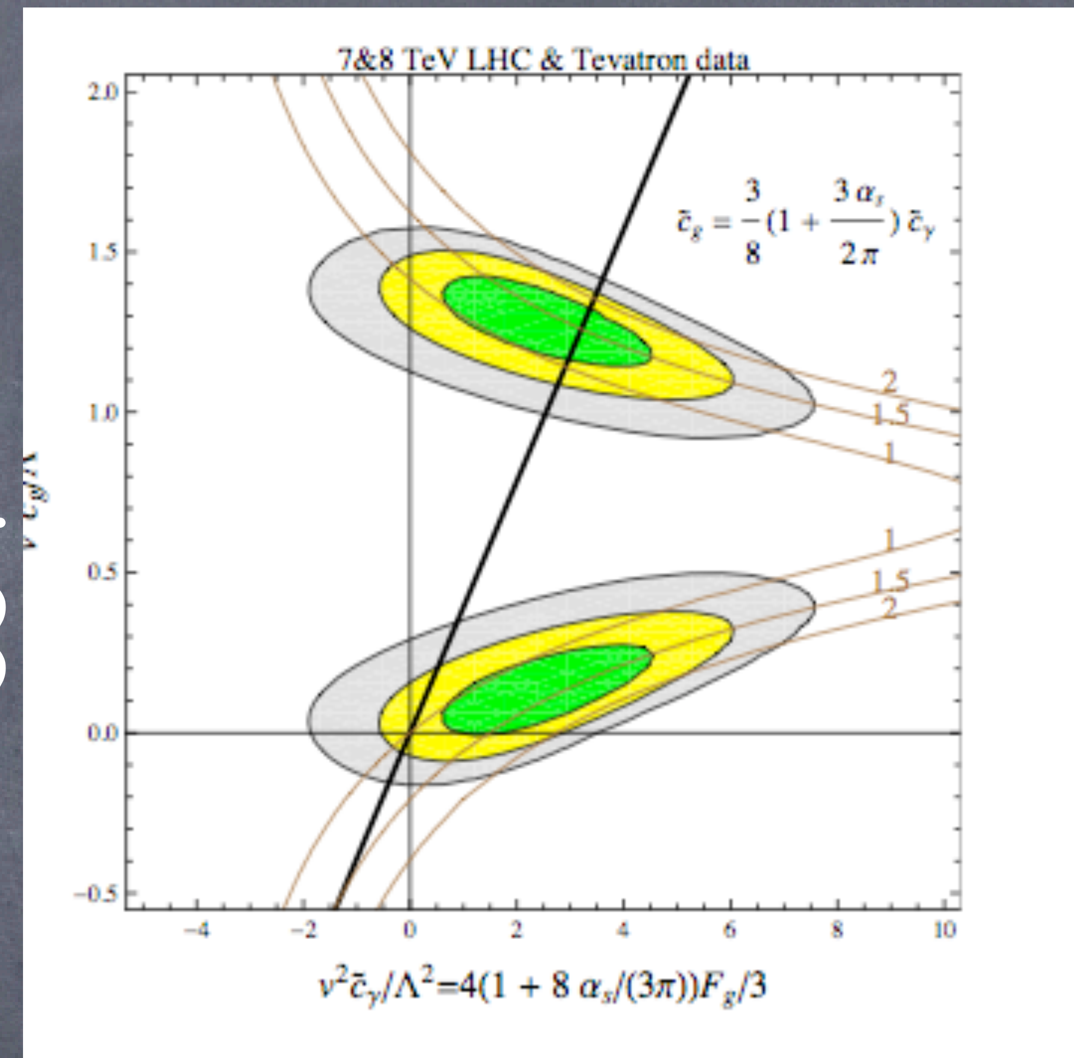


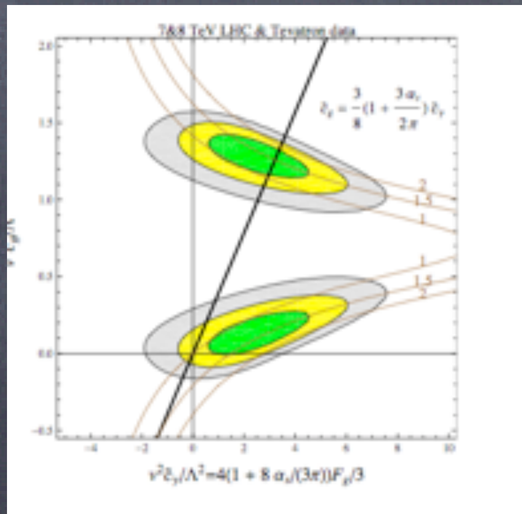
Tevatron, ATLAS and CMS

effect on gg production

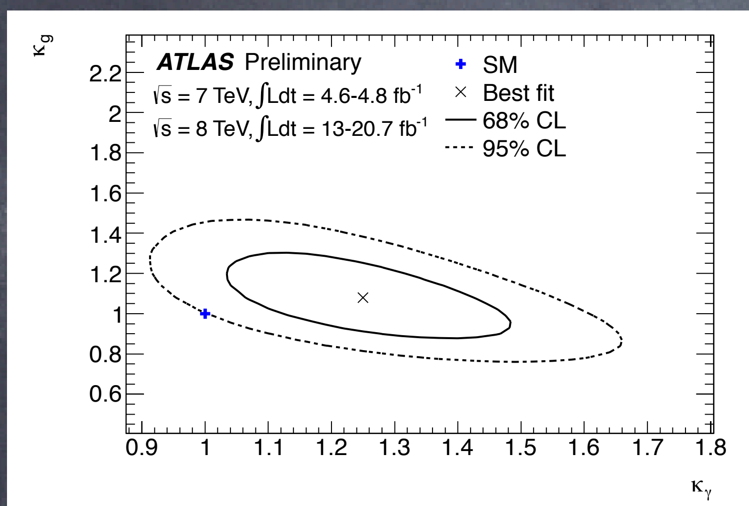


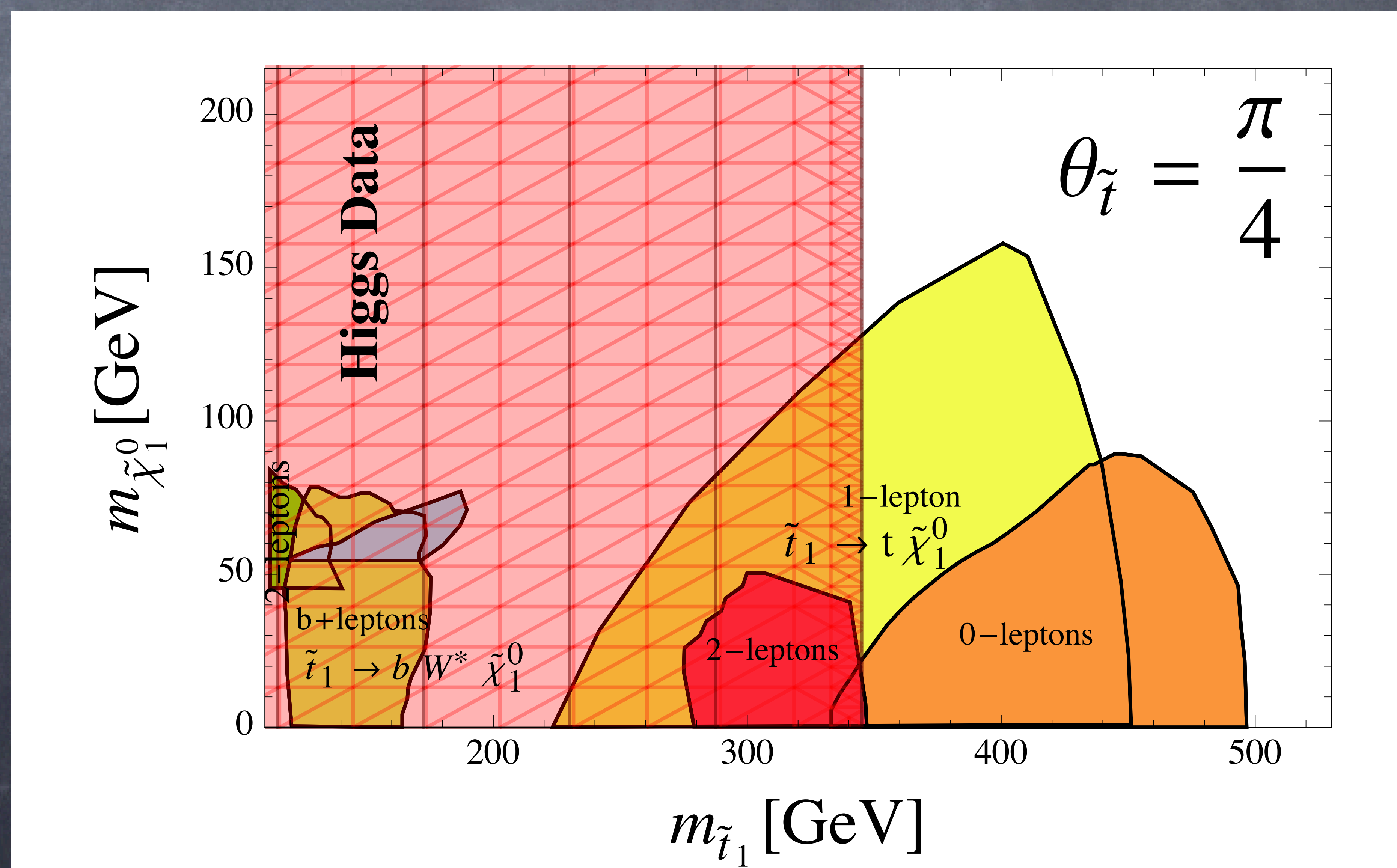
effect on diphoton

green, yellow, gray= 1,2 and 3 sigma



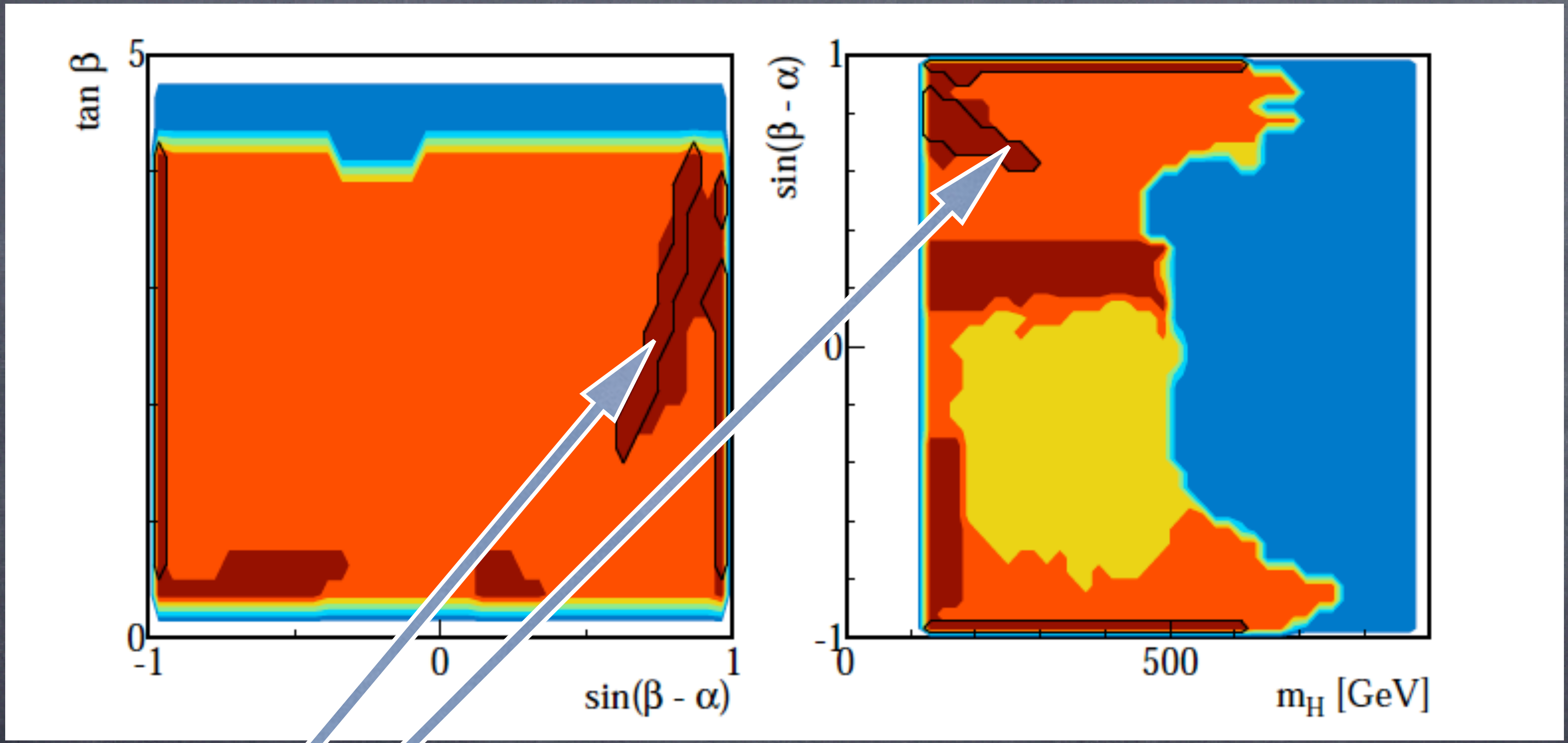
+ mW + btosgamma → Stops





95% CL exclusion

In SUSY, parameter space of 2HDM



Allowed regions

Coleppa 1305.0002

Composite Higss

Another option

Higgs as a pseudo-Goldstone boson

Composite Higgs

scalar doublet, CP even

Another option

Higgs as a pseudo-Goldstone boson

Composite Higgs

scalar doublet, CP even

rho, a1, f2...

scale symmetry

breaking: f

$$\xi = v^2/f^2$$

EW scale: v

pions

Another option

Higgs as a pseudo-Goldstone boson

Composite Higgs

scalar doublet, CP even

rho, a1, f2...
scale symmetry
breaking: f

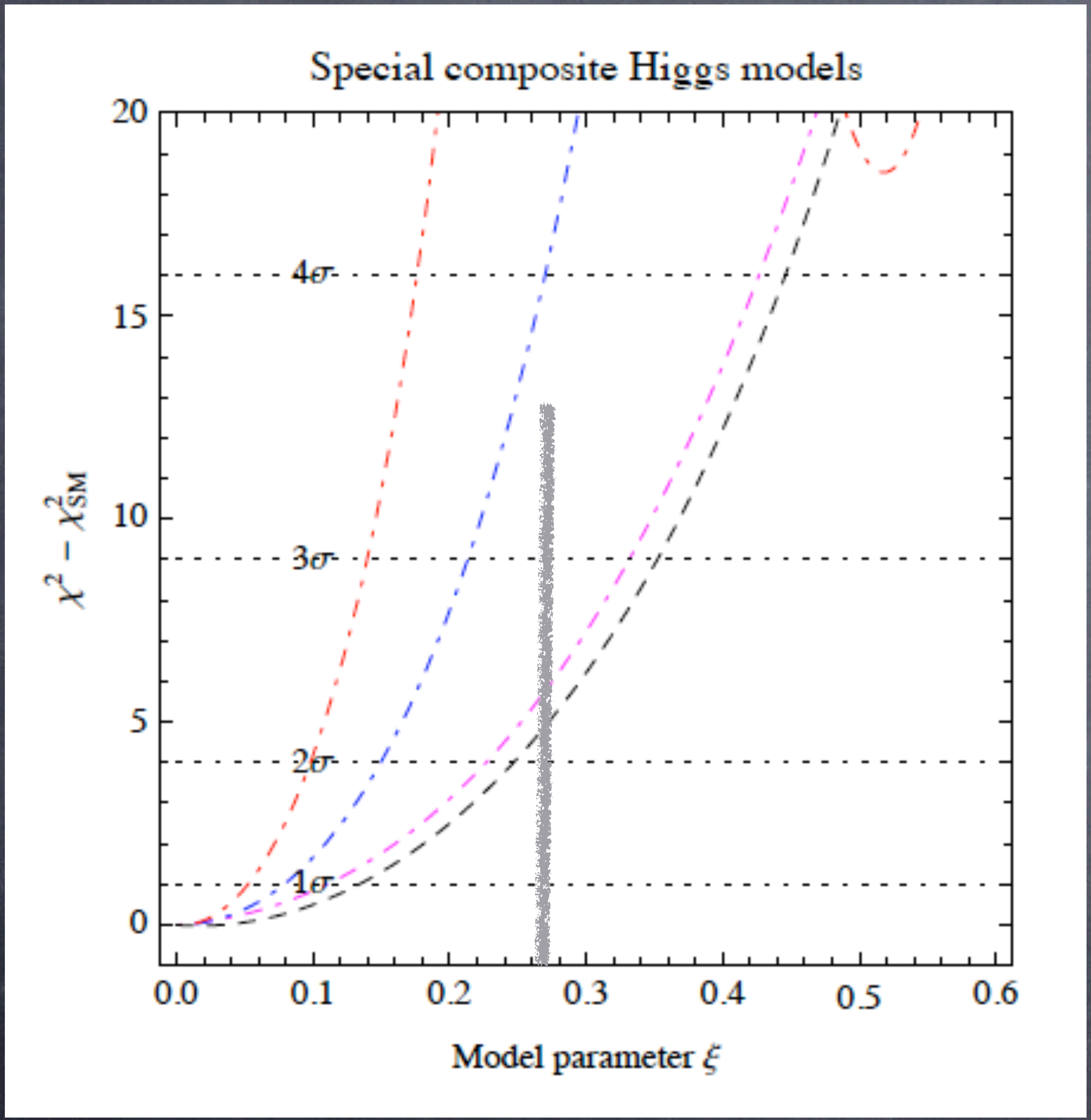
$$\xi = v^2/f^2$$

EW scale: v
pions

screening UV,
stabilization EW scale

buys you time until
hitting the resonance scale

The composite Higgs doesn't have the same couplings as the SM higgs



Strumia et al. 2013

Higgs data
no unnaturalness

$$f \gtrsim 500 \text{ GeV}$$

This is (was) not mainstream, why?

original idea
Georgi et al, 82

strong coupling

but

the main hurdle is generating a potential

(mass, quartic...)

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Georgi et al, 82

strong coupling
but
the main hurdle is generating a potential
(mass, quartic...)

$$\underline{m}^2 \propto \underline{\lambda} v^2$$

protected
same suppression

expect $v \sim f$

But this is a symmetry argument
in explicit models one can search for mechanisms

explicit models dealing strong coupling?
Holographic pseudoGB
(extra-dimensions)
and partial compositeness

Pomarol et al. 04
Contino et al. 07

A lot of model building after that...

Higgs mass
top-partner contribution

$$m_h^2 \sim \frac{N_c y_t^2}{16\pi^2} \frac{v^2}{f^2} m_T^2$$

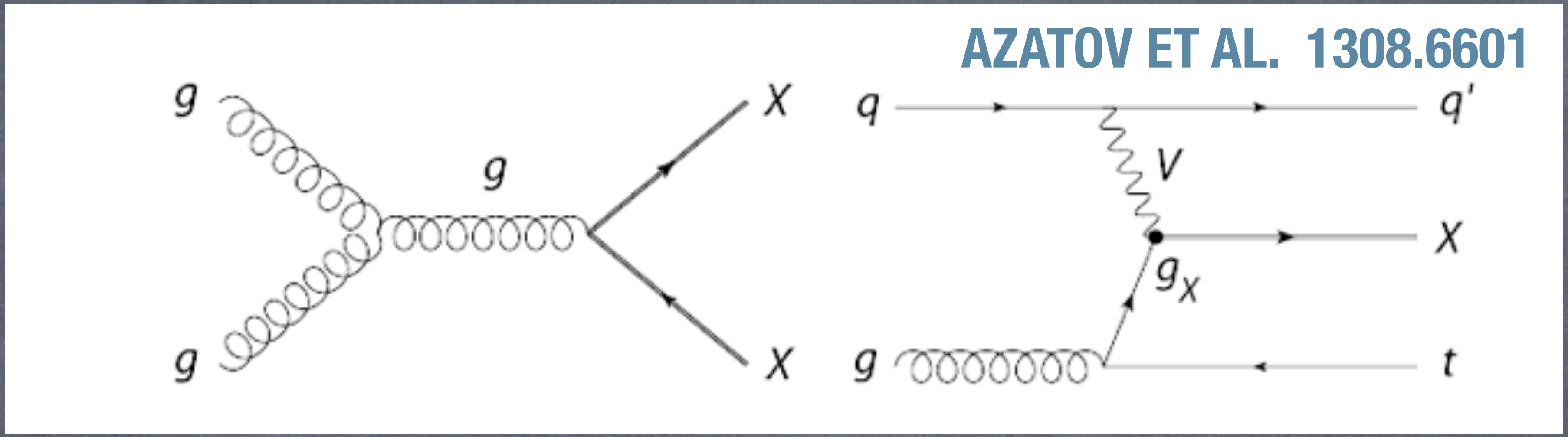
One could still push

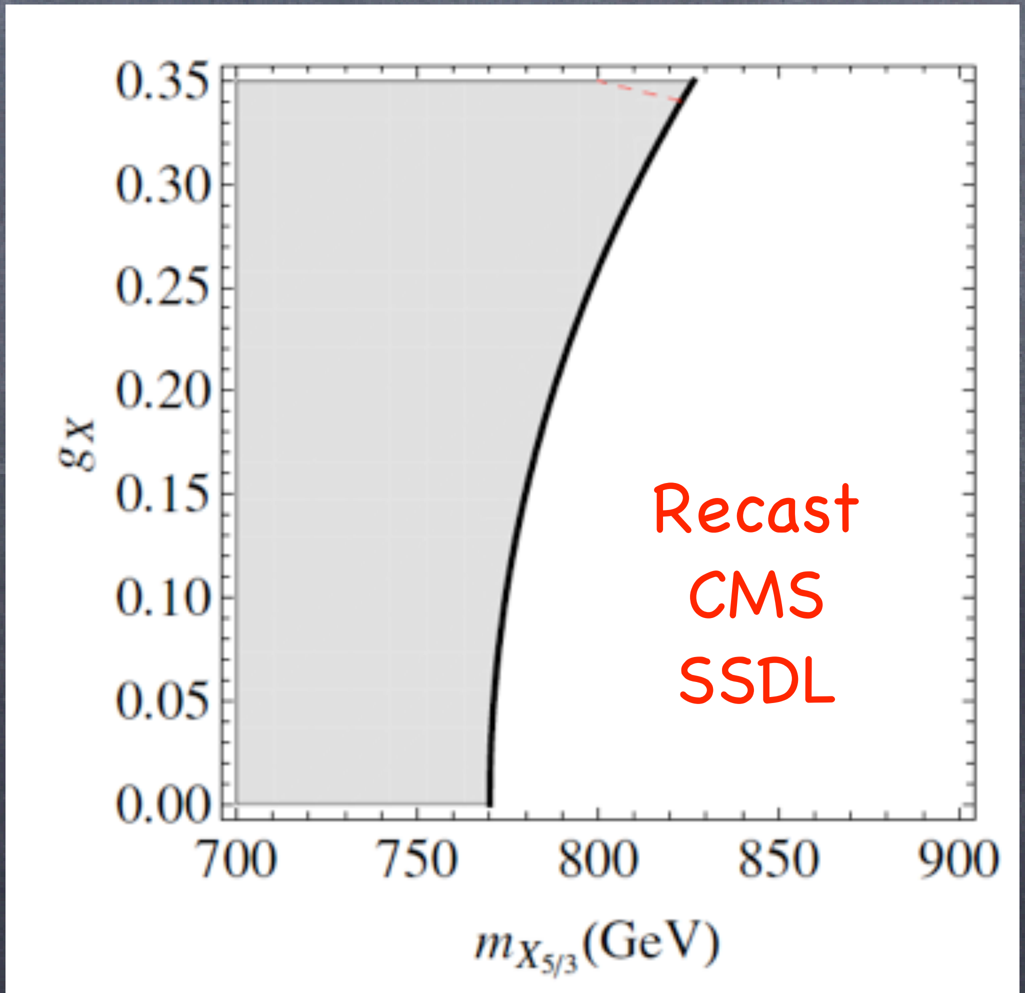
$$f \sim TeV$$

but

$$m_T \lesssim TeV$$

$$m_T \lesssim TeV$$





Higgs Effective Lagrangian
The LEP mentality

Now, let's be agnostic

how can we use Higgs data to constrain NP in a "model-independent" way?

Assume NP is heavy

Higgs anomalous couplings

Effective theory approach:
ex. operators involving the HVV vertices

$$\mathcal{L}_{eff} = \sum_i \frac{f_i}{\Lambda^2}\mathcal{O}_i$$

$$\epsilon_i = f_i \frac{v^2}{\Lambda^2}$$

a set of operators

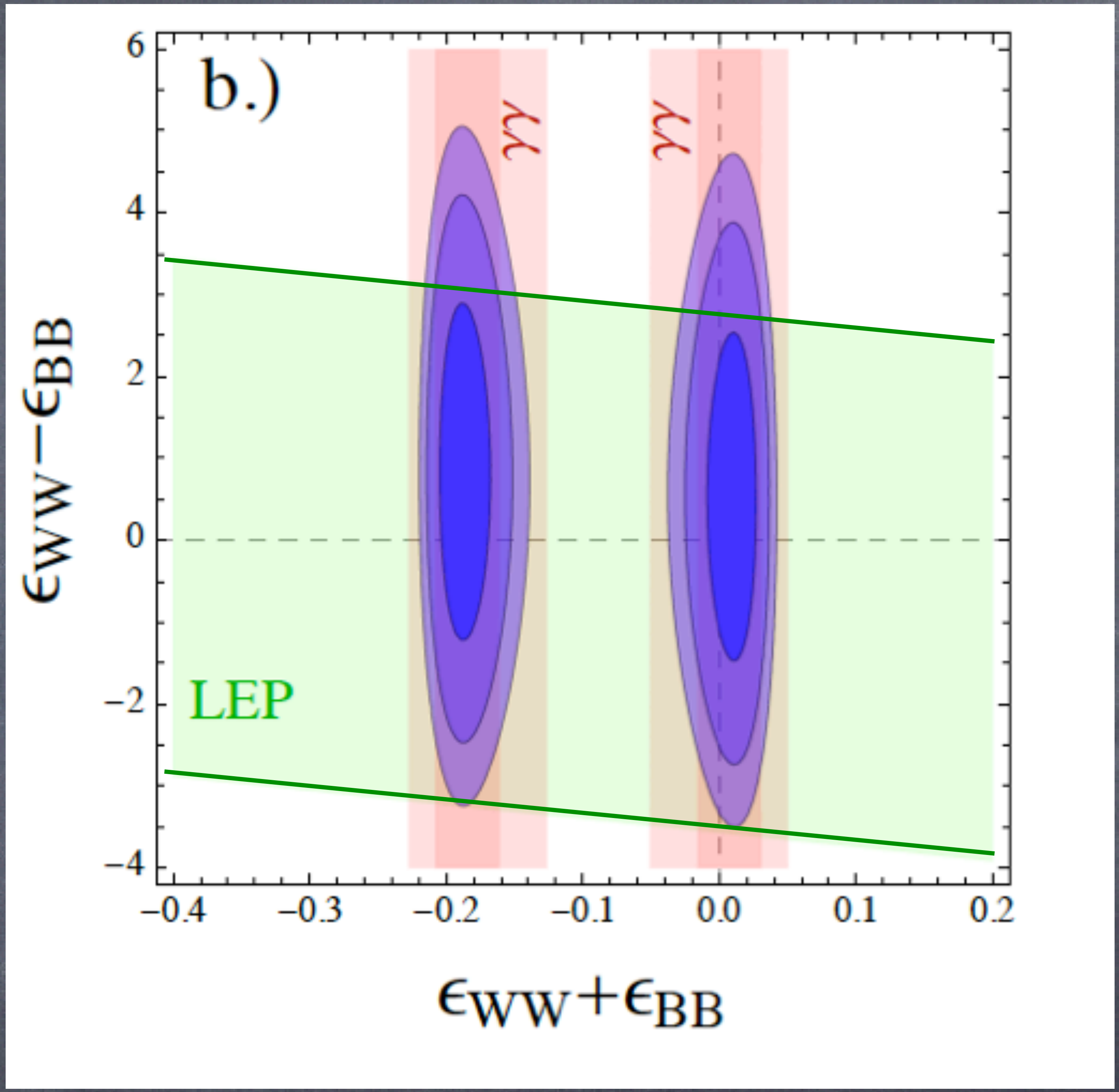
$$\mathcal{O}_W = (D_\mu \Phi)^\dagger \widehat{W}^{\mu\nu}(D_\nu \Phi)$$
$$\mathcal{O}_B = (D_\mu \Phi)^\dagger (D_\nu \Phi)\ \widehat{B}^{\mu\nu}$$
$$\mathcal{O}_{WW} = \Phi^\dagger \widehat{W}^{\mu\nu}\widehat{W}_{\mu\nu}\Phi$$
$$\mathcal{O}_{BB} = (\Phi^\dagger \Phi)\ \widehat{B}^{\mu\nu}\widehat{B}_{\mu\nu}$$

operators contributing to tree S,T:
set them to zero? running

Grojean et al. 2013
Pomarol et al. 2013
most recent
1312.2928 & 1312.2014

$$\mathcal{O}_W = (D_\mu\Phi)^\dagger \widehat{W}^{\mu\nu}(D_\nu\Phi)$$
$$\mathcal{O}_B = (D_\mu\Phi)^\dagger(D_\nu\Phi)\ \widehat{B}^{\mu\nu}$$
$$\mathcal{O}_{WW} = \Phi^\dagger \widehat{W}^{\mu\nu}\widehat{W}_{\mu\nu}\Phi$$
$$\mathcal{O}_{BB} = (\Phi^\dagger\Phi)\ \widehat{B}^{\mu\nu}\widehat{B}_{\mu\nu}$$

eWW and eBB uses mostly h->aa

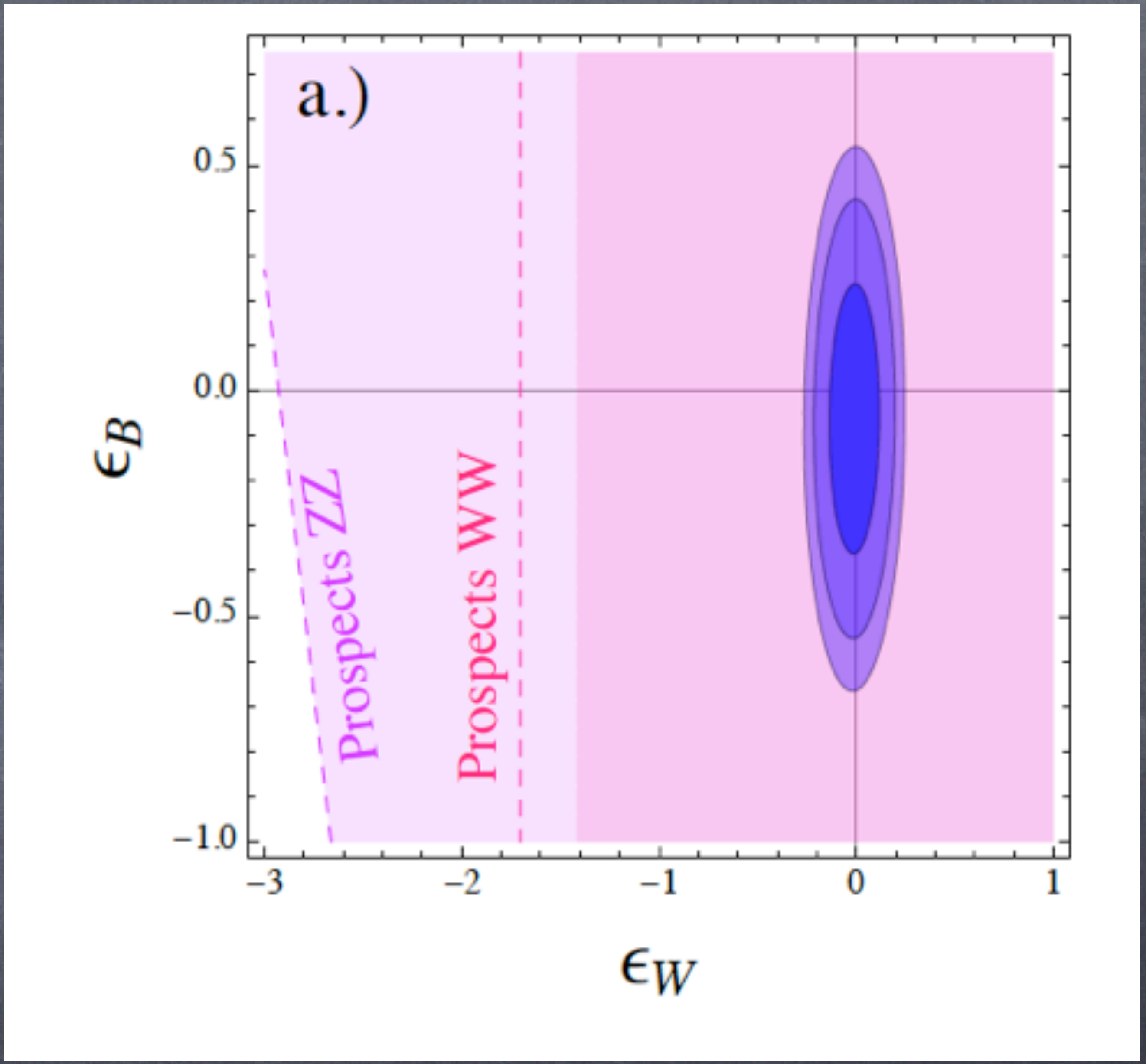


LHC data surpasses PEWT

Masso and VS
PRD 2012

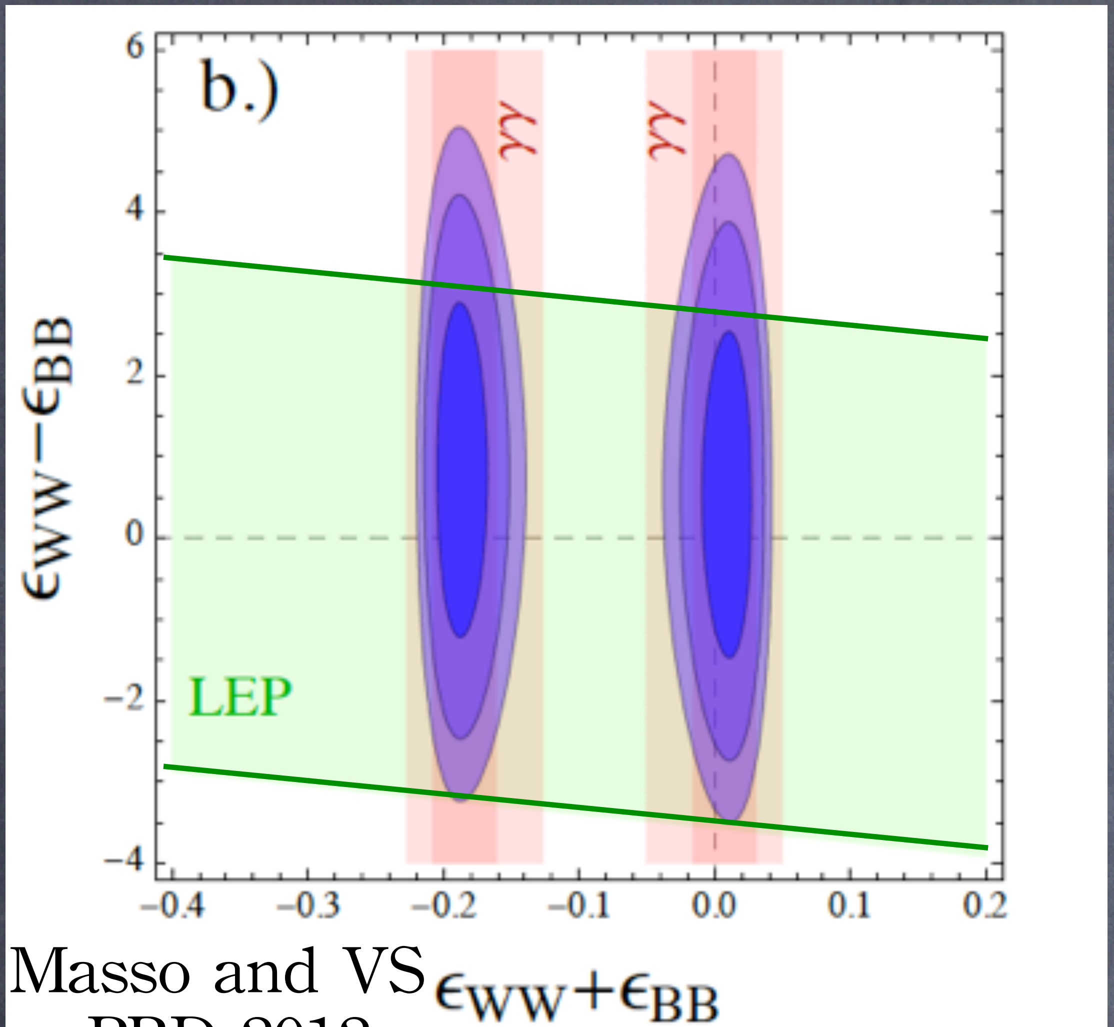
$$\mathcal{O}_W = (D_\mu \Phi)^\dagger \widehat{W}^{\mu\nu} (D_\nu \Phi)$$
$$\mathcal{O}_B = (D_\mu \Phi)^\dagger (D_\nu \Phi)\ \widehat{B}^{\mu\nu}$$
$$\mathcal{O}_{WW} = \Phi^\dagger \widehat{W}^{\mu\nu} \widehat{W}_{\mu\nu} \Phi$$
$$\mathcal{O}_{BB} = (\Phi^\dagger \Phi)\ \widehat{B}^{\mu\nu} \widehat{B}_{\mu\nu}$$

But when it comes to eW and eB, data h->WW,ZZ



More ideas? differential information?

Is the LEP/LHC comparison fair?

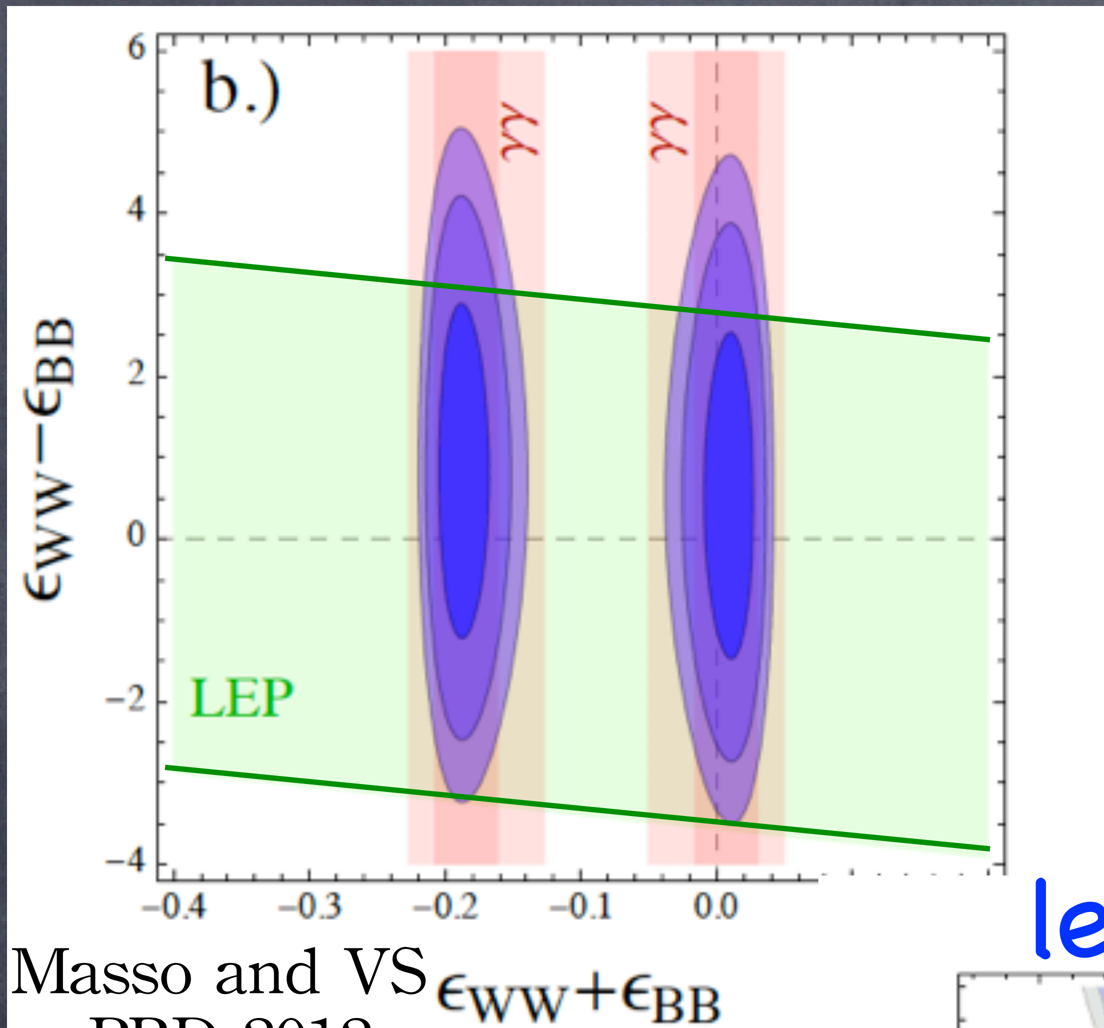


Masso and VS
PRD 2012

Not clear

Dawson et al 1311.3107

Is the LEP/LHC comparison fair?



Masso and VS
PRD 2012

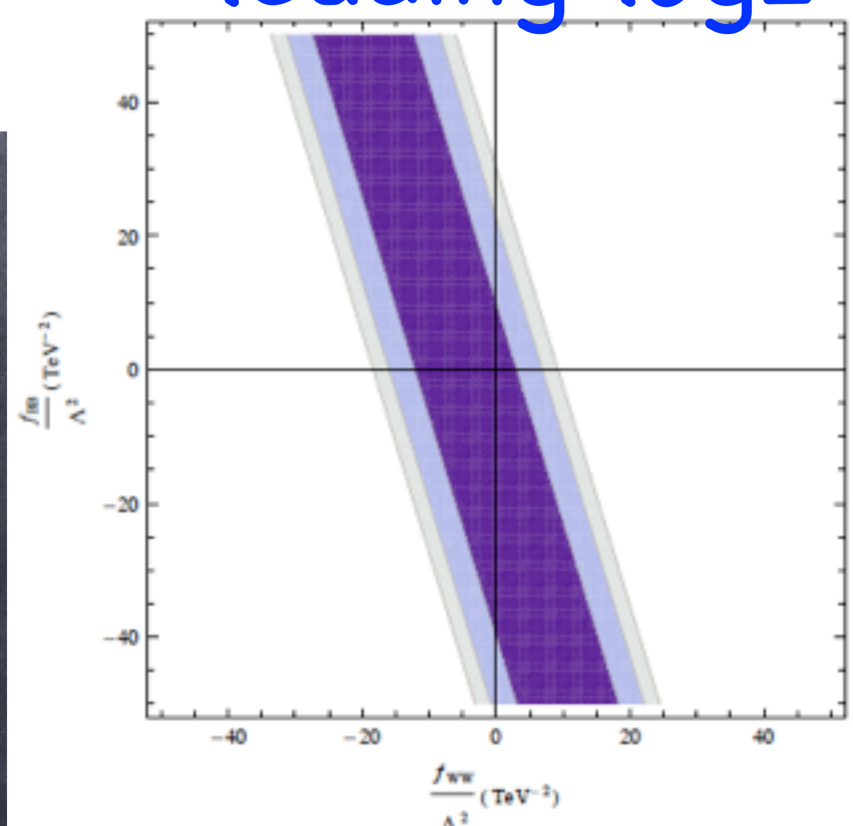
Not clear

Dawson et al 1311.3107

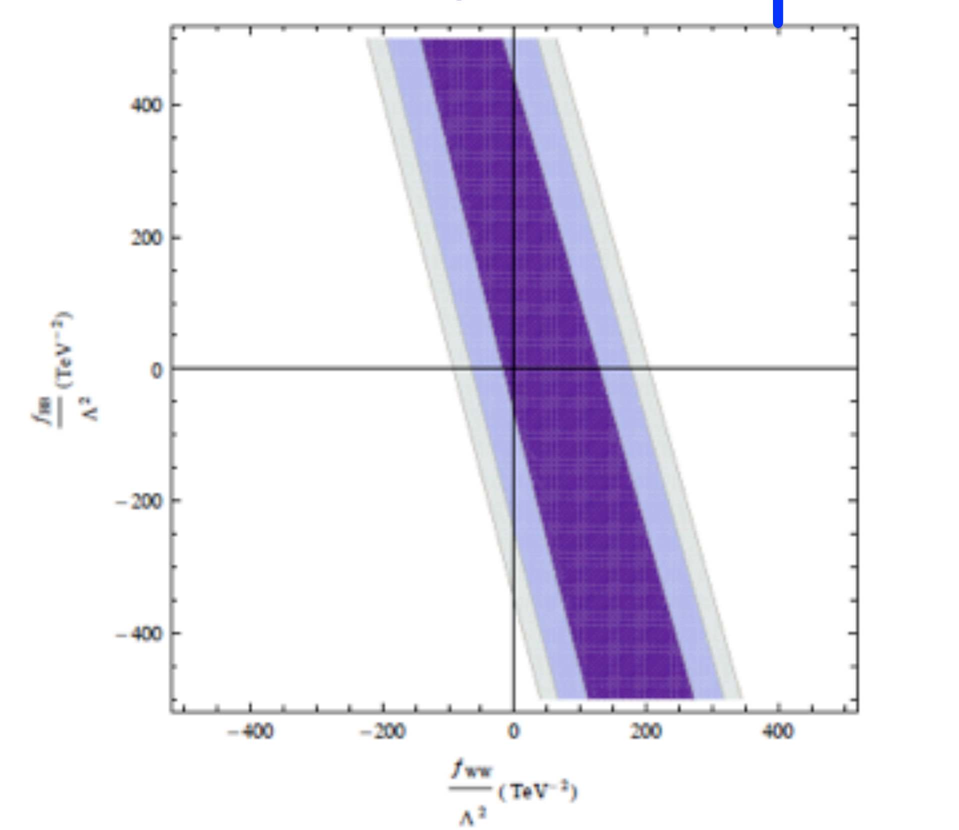
dim6 operators at loop level to S,T,U

renormalization scheme dependence, gauge invariance

leading logL



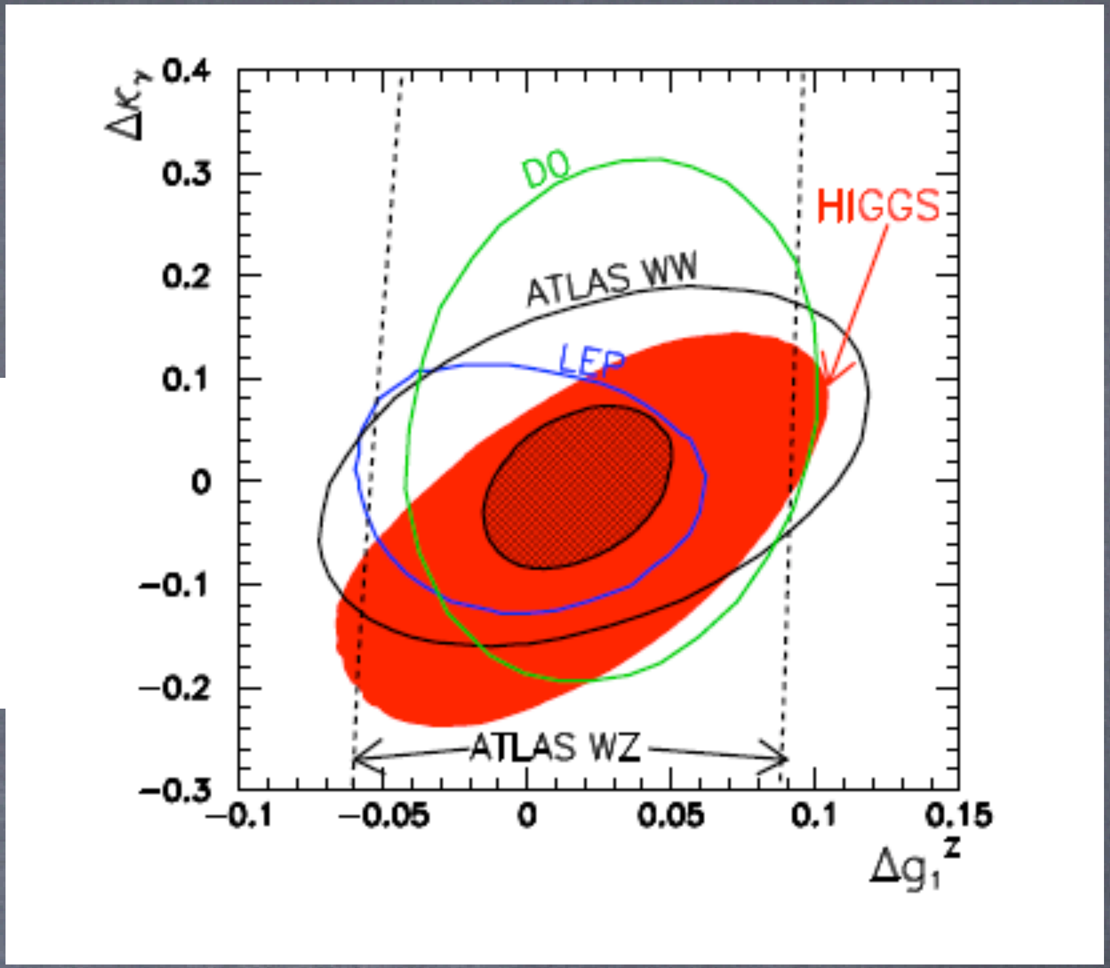
Ren Sch dep



oblique parameter constraints MUCH weaker than thought before

Correlate HVV with VVV

$$\mathcal{L}_{WWV} = -ig_{WWV}\Big\{g_1^V\left(W^+_{\mu\nu}W^{-\,\mu}V^\nu - W^+_\mu V_\nu W^{-\,\mu\nu}\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2}W^+_{\mu\nu}W^{-\,\nu\rho}V_\rho{}^\mu\Big\}\,, \quad (4)$$



Corbett et al PRL 111 (2013)

Linear vs non-linear realization

Correlations depend on realization

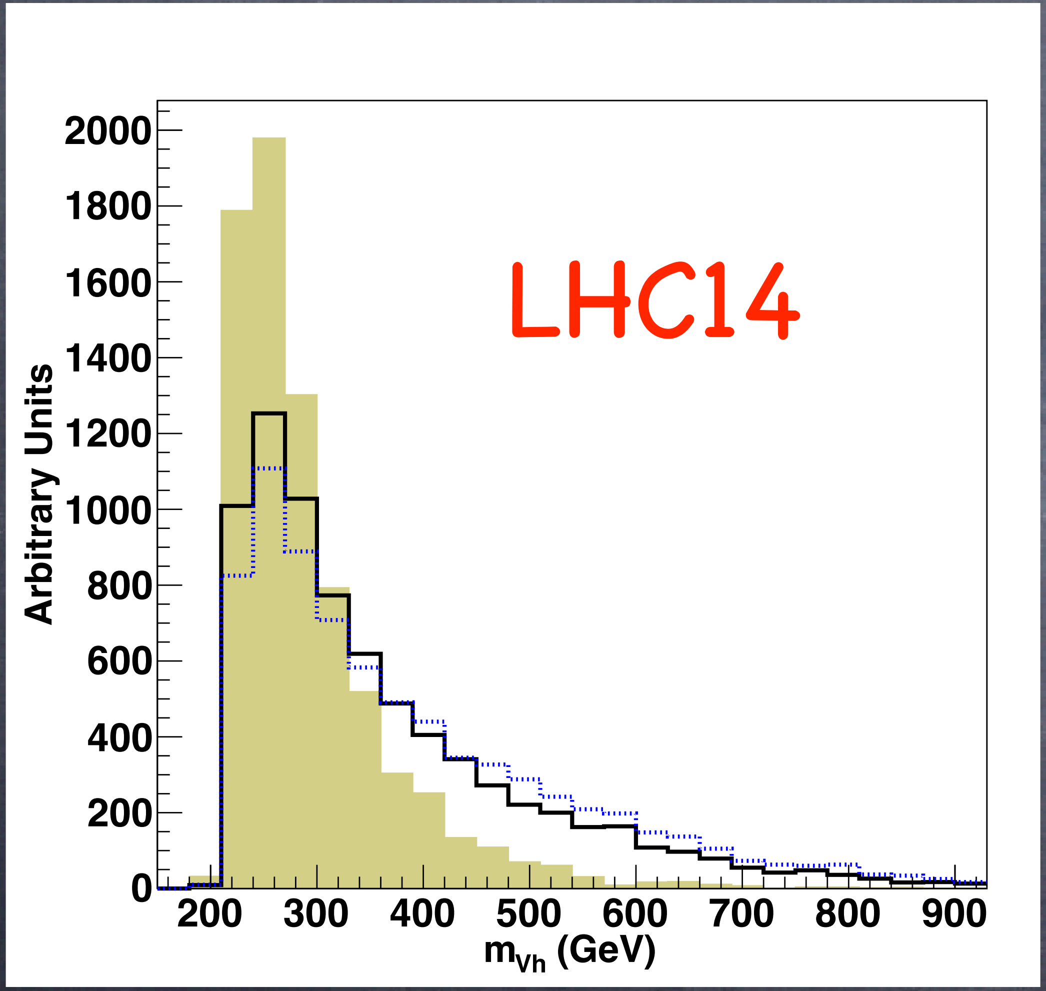
dim8 in linear realization may be sizeable in the non-linear expansion

Brivio et al 1311.1823

From total rates to differential information

New Physics
different Lorentz structure
boosted topologies & COM dependence

New Physics
different Lorentz structure
boosted topologies & COM dependence



Alloul, Fuks, VS. 1310.5150

Invariant mass in associated production w/ HEFT

not enough data yet for this, but instead

ratios of COM

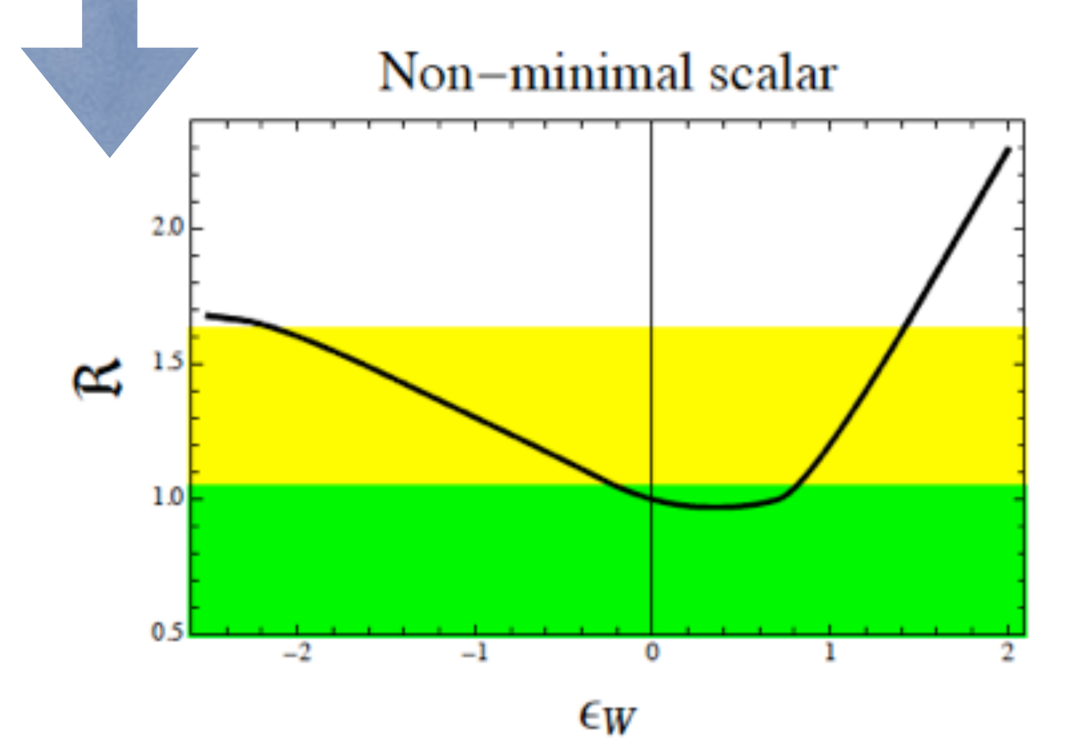
Energy dependence in associated production

Ellis, VS, You. 2013

pp -> V* -> V h

double ratio

$$\mathcal{R}_{\rm data} \equiv \left(\frac{\sigma^{\rm data}_{\rm CMS\ LHC\ 8}}{\sigma^{\rm data}_{\rm TeVatron}} \right) \Big/ \left(\frac{\sigma^{0+}_{\rm LHC\ 8}}{\sigma^{0+}_{\rm TeVatron}} \right) = \frac{\sigma^{0+}_{\rm TeVatron}}{\sigma^{\rm data}_{\rm TeVatron}} \frac{\sigma^{\rm data}_{\rm CMS\ LHC\ 8}}{\sigma^{0+}_{\rm LHC\ 8}} = \frac{\mu_{\rm LHC\ 8}}{\mu_{\rm TeVatron}} = 0.47 \pm 0.58\,. \tag{16}$$



Effective operator

This 'differential' information is more stringent than a global fit to LHC8 data

With more data
one can start asking more questions

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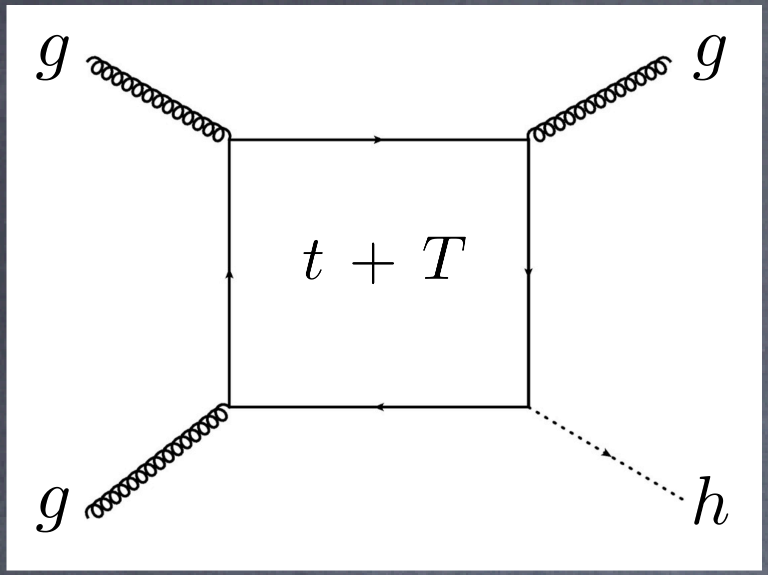
Composite Higgs and Little Higgs
top-partners affect the loops
BUT
low-energy cancellation

No information on top-partners
from Higgs couplings

Higher order corrections evade the cancellation

Banfi, Martin, VS. 2013



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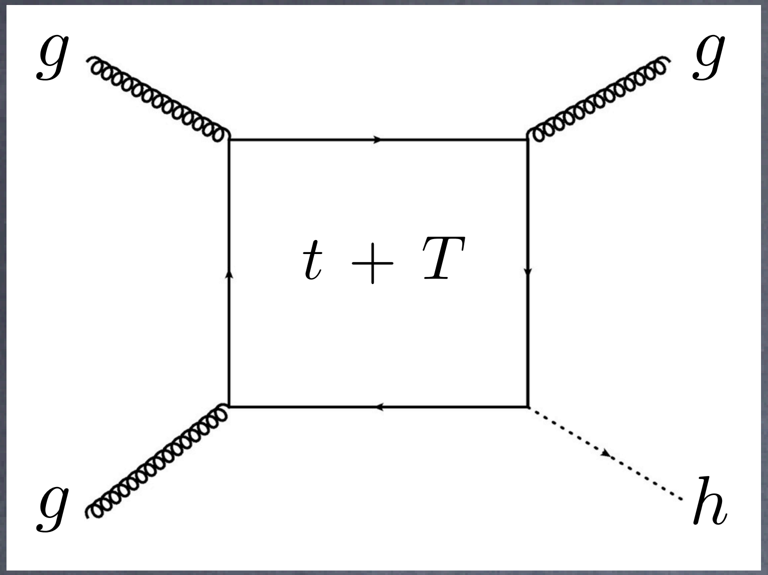

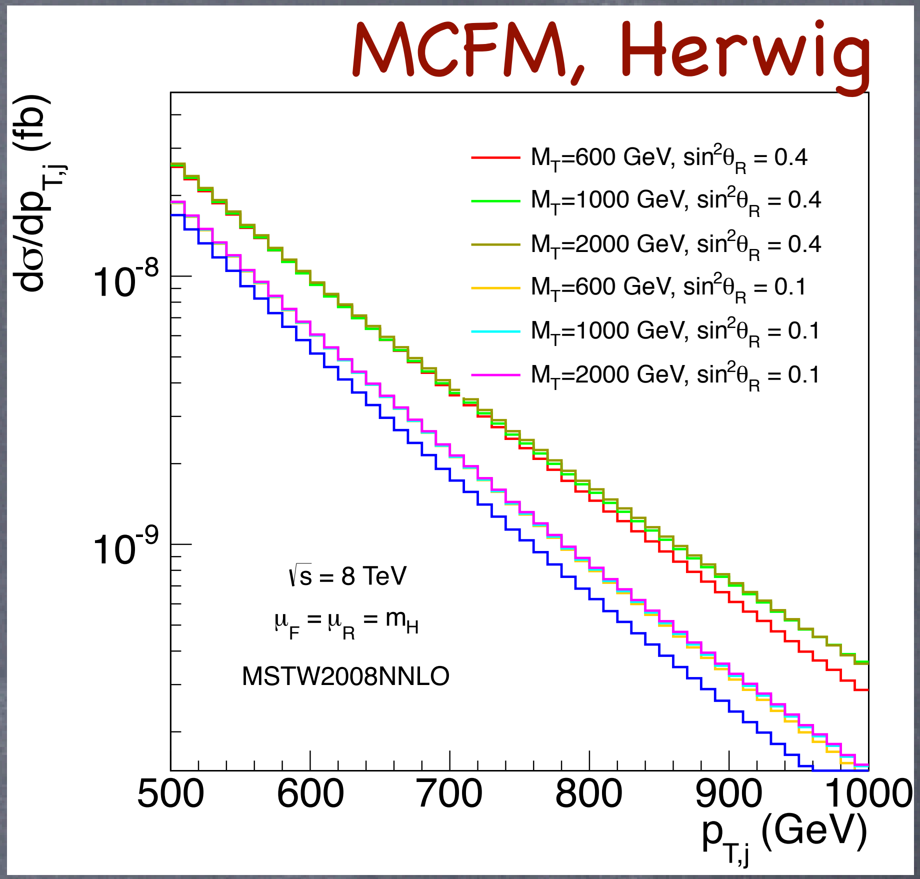

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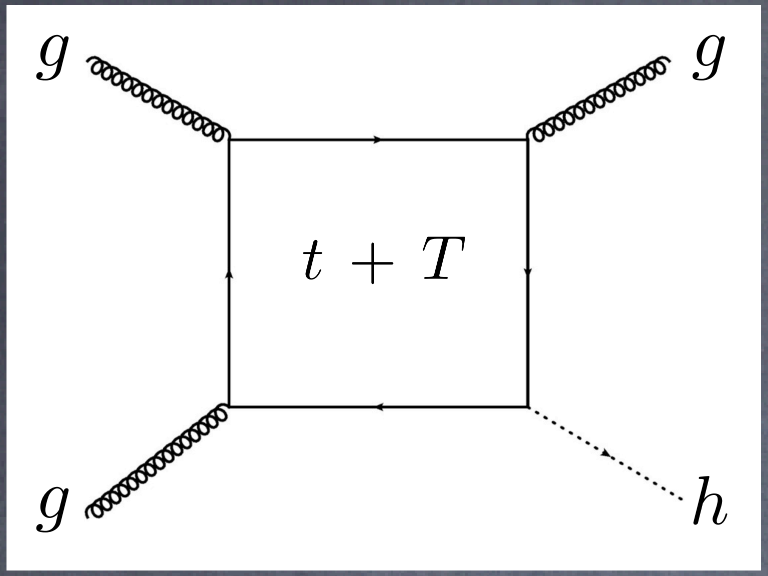
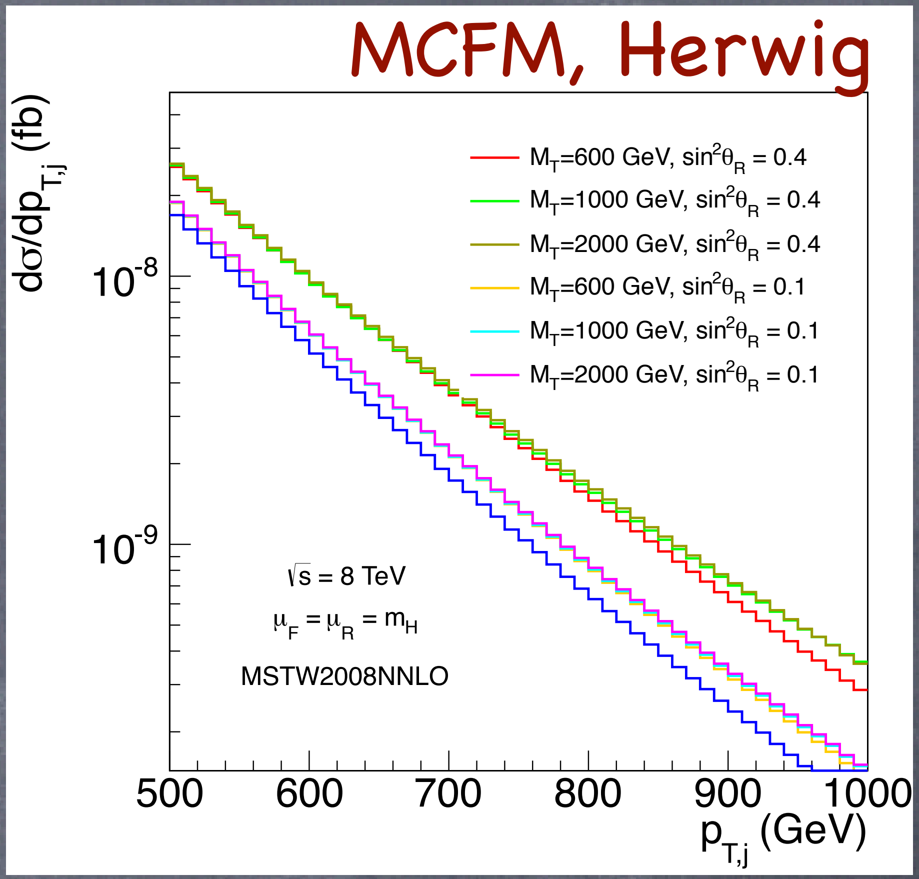
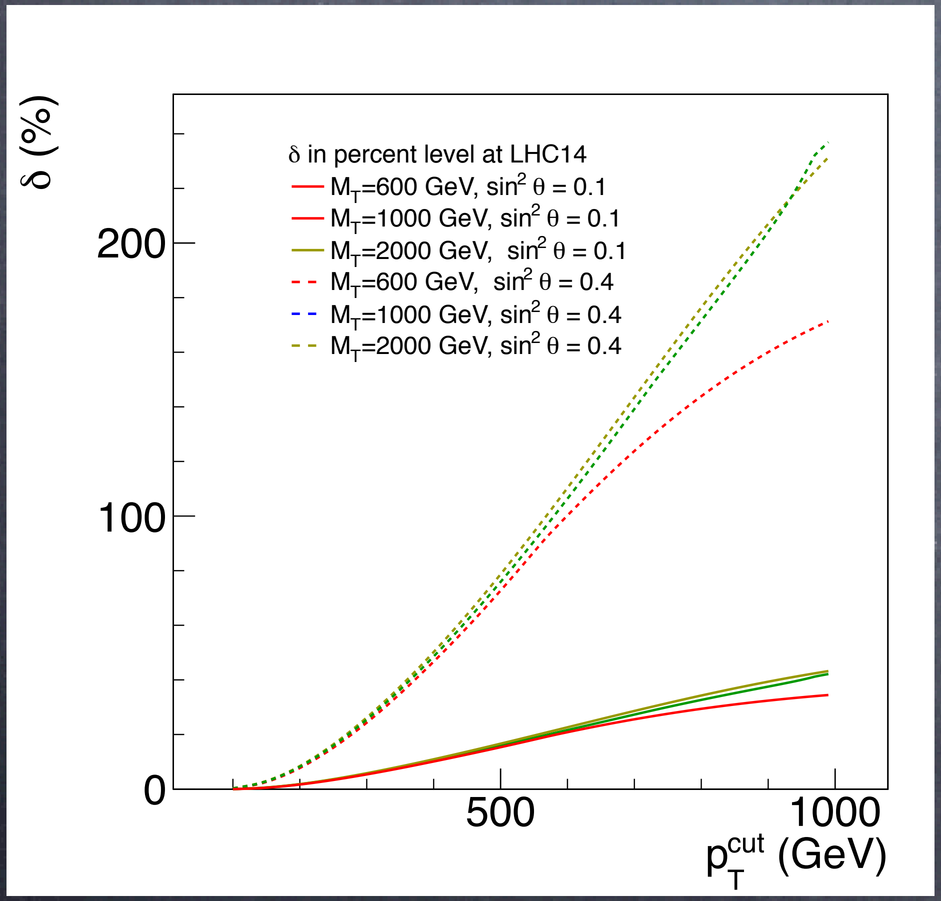


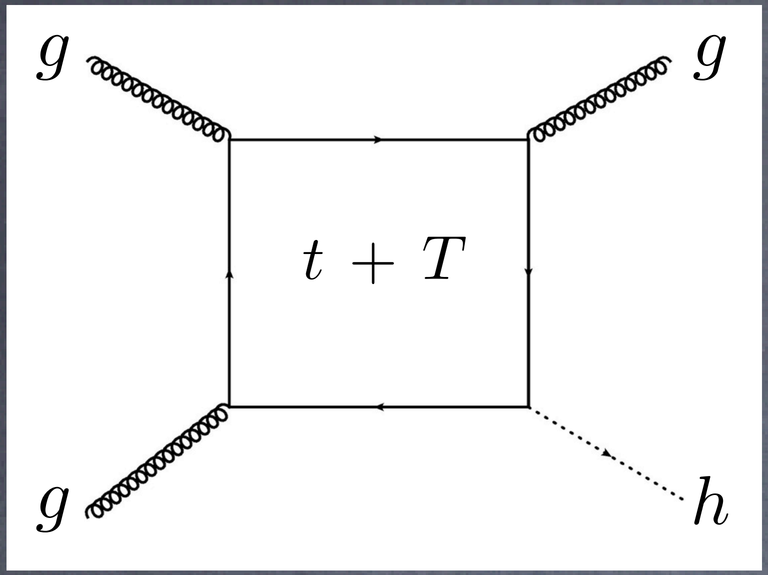


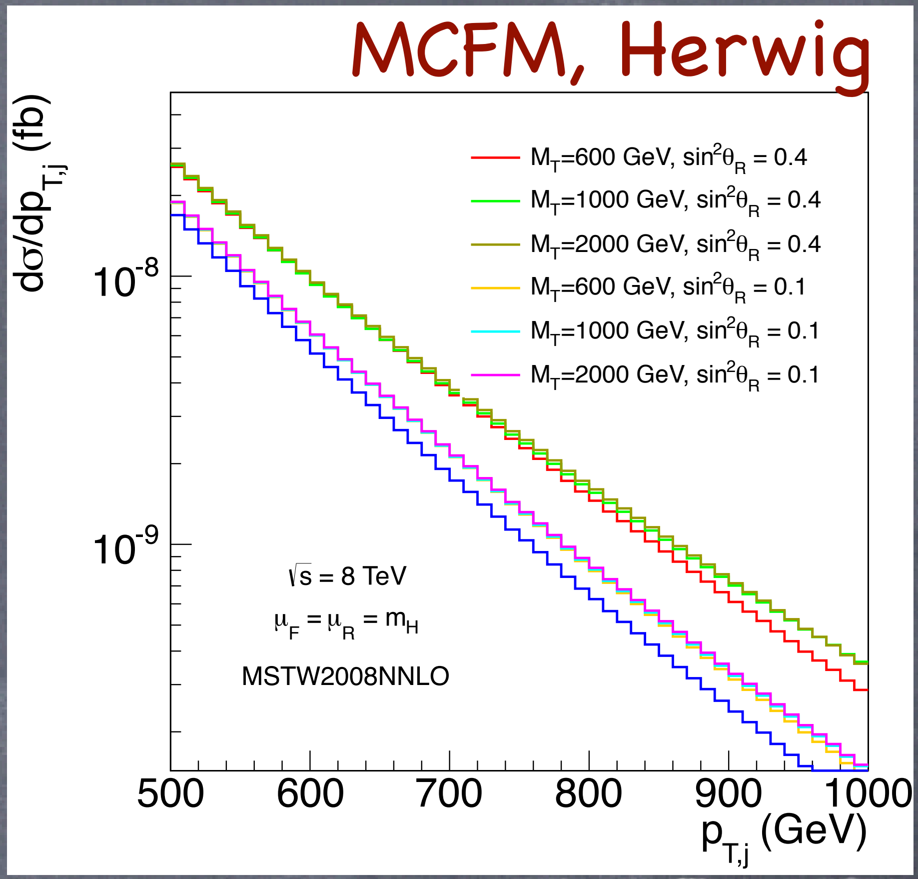


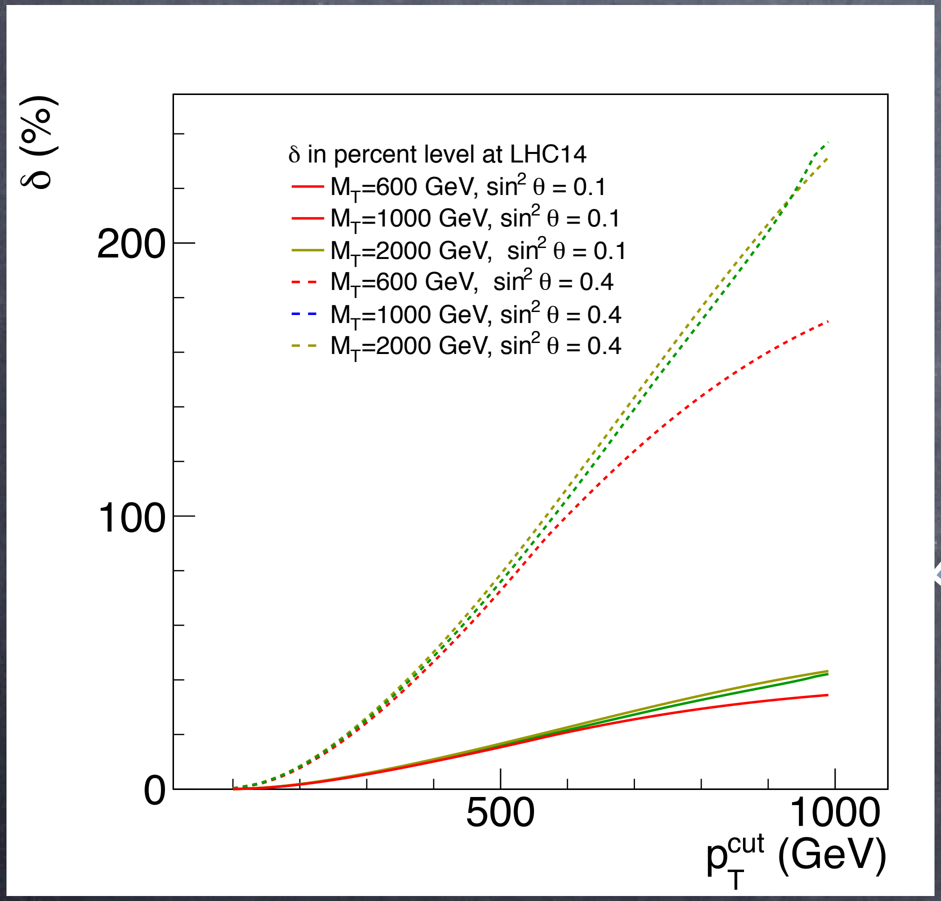
limited by lack of NLO computations

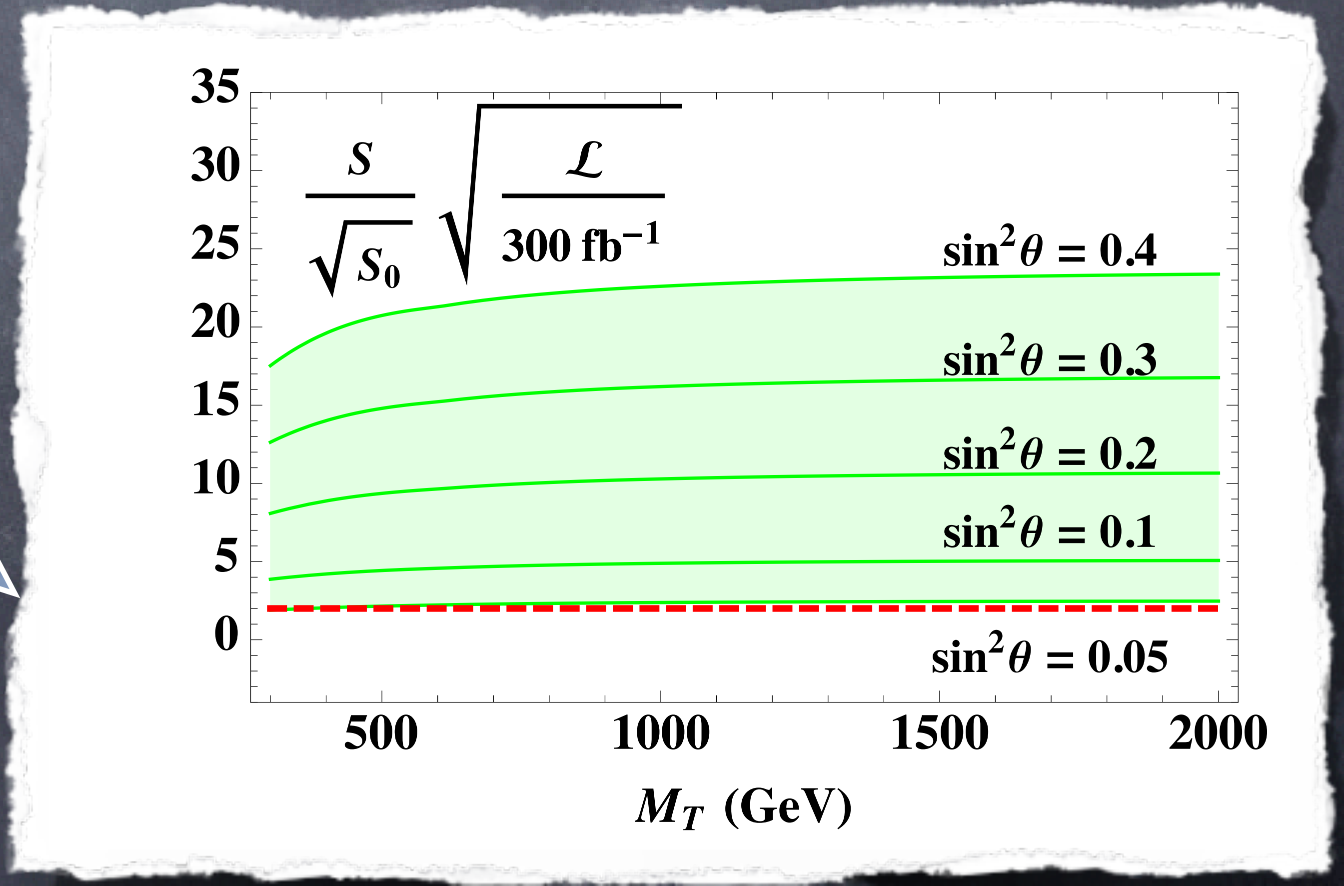
Higher order corrections evade the cancellation

Banfi, Martin, VS. 2013







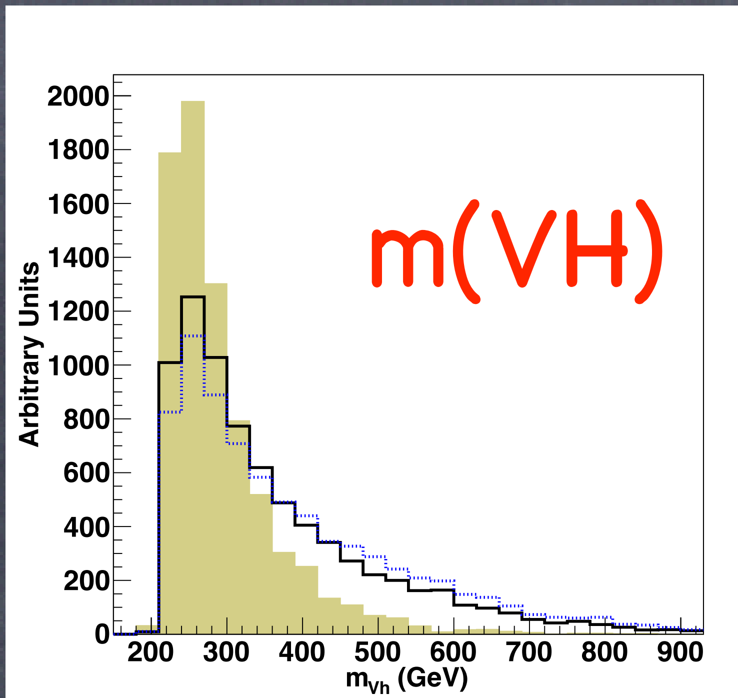


limited by lack of NLO computations

Pushing to QCD NLO

w/Campbell, Williams. In prep

So far, Higgs anomalous couplings is is LO, but



Alloul, Fuks, VS. 1310.5150

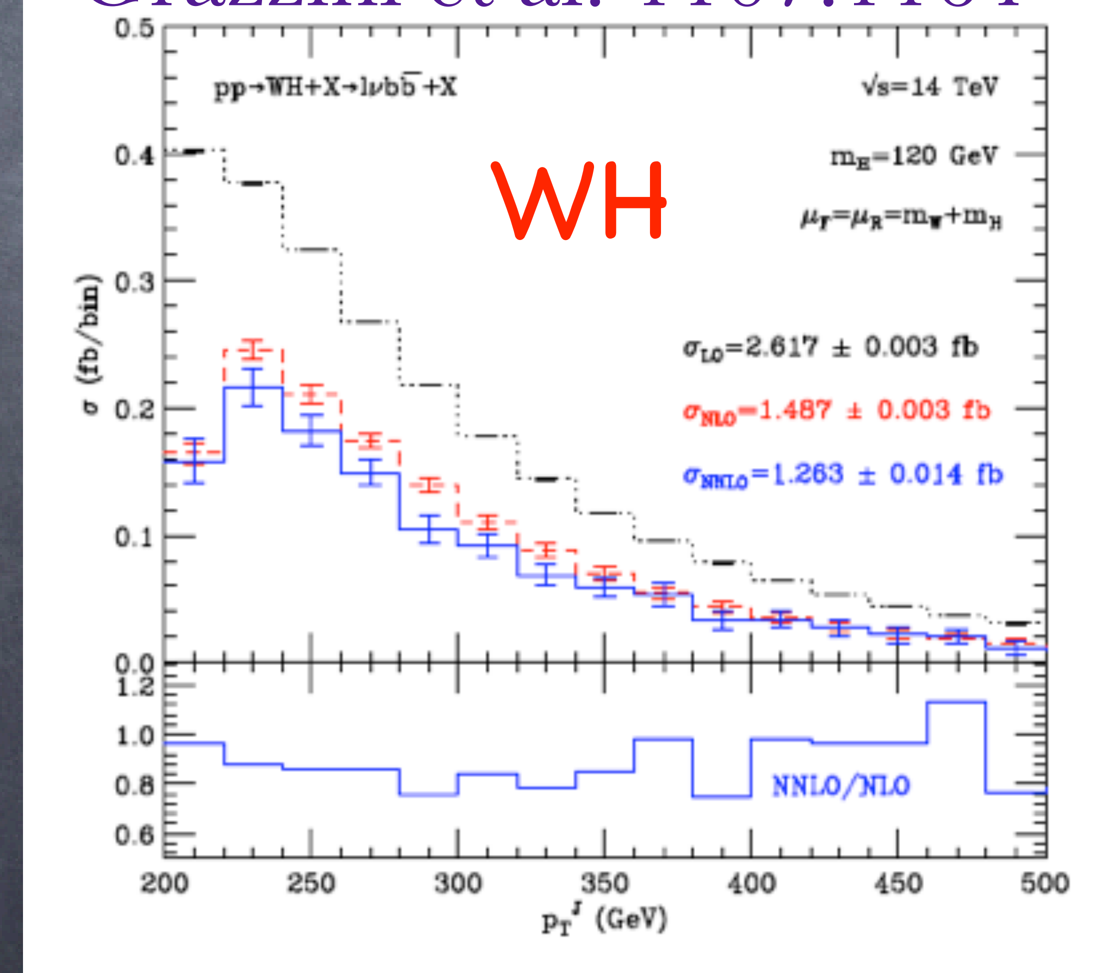
Anomalous couplings-> tails of distributions

need higher precision to beat QCD/EW corrs

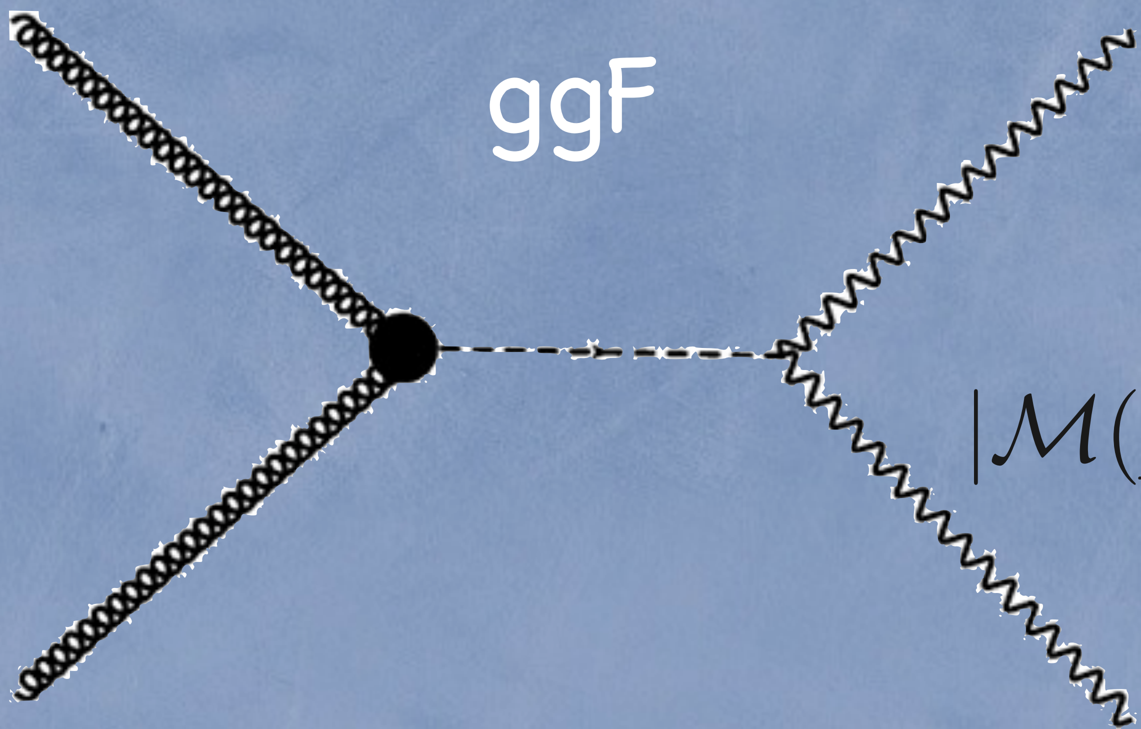
SM state of the art

Need NLO for anomalous couplings: different Lorentz structure, not just a K factor

Grazzini et al. 1107.1164



QCD NLO corrections in ggF, VBF and AP can be handled as follows



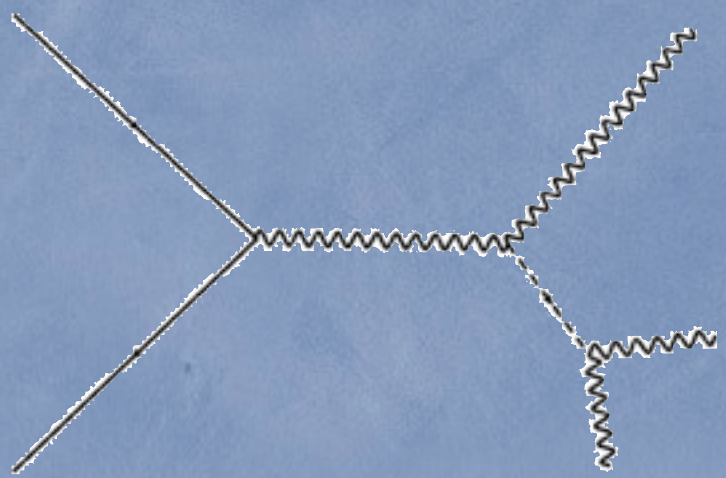
$$|\mathcal{M}(p_1 + p_2 \to H(\to V^* V^{(*)}) + X)|^2$$

$$= |\mathcal{M}(p_1 + p_2 \to H + X)|^2 \mathcal{P}_H(s_{VV})^2 |\mathcal{M}(H \to V^* V^{(*)})|^2$$

NLO is obtained by re-weighting H+jets results by

$$\mathcal{R}(\Lambda) = \frac{|\mathcal{M}^{\Lambda}(H \to f)|^2}{|\mathcal{M}^{SM}(H \to f)|^2}$$

same goes for associated production



$$= \mathcal{J}^\mu(p_1, p_2, X)\mathcal{P}_{\mu\nu}(V)J^\nu(V, H)$$

$$\mathcal{A}_\Lambda^{NLO}(p_1 + p_2 \to V(\to H + V) + X) = \mathcal{J}^\mu_{NLO}(p_1, p_2, X)\mathcal{P}_{\mu\nu}(V)J^\nu_\Lambda(V, H)$$

and vector boson fusion

soon w/ Campbell and Williams
public MCFM+POWHEG implementation
of Higgs anomalous couplings at QCD NLO

Into the future

Higgs factories

1. HL-LHC

2. A linear collider

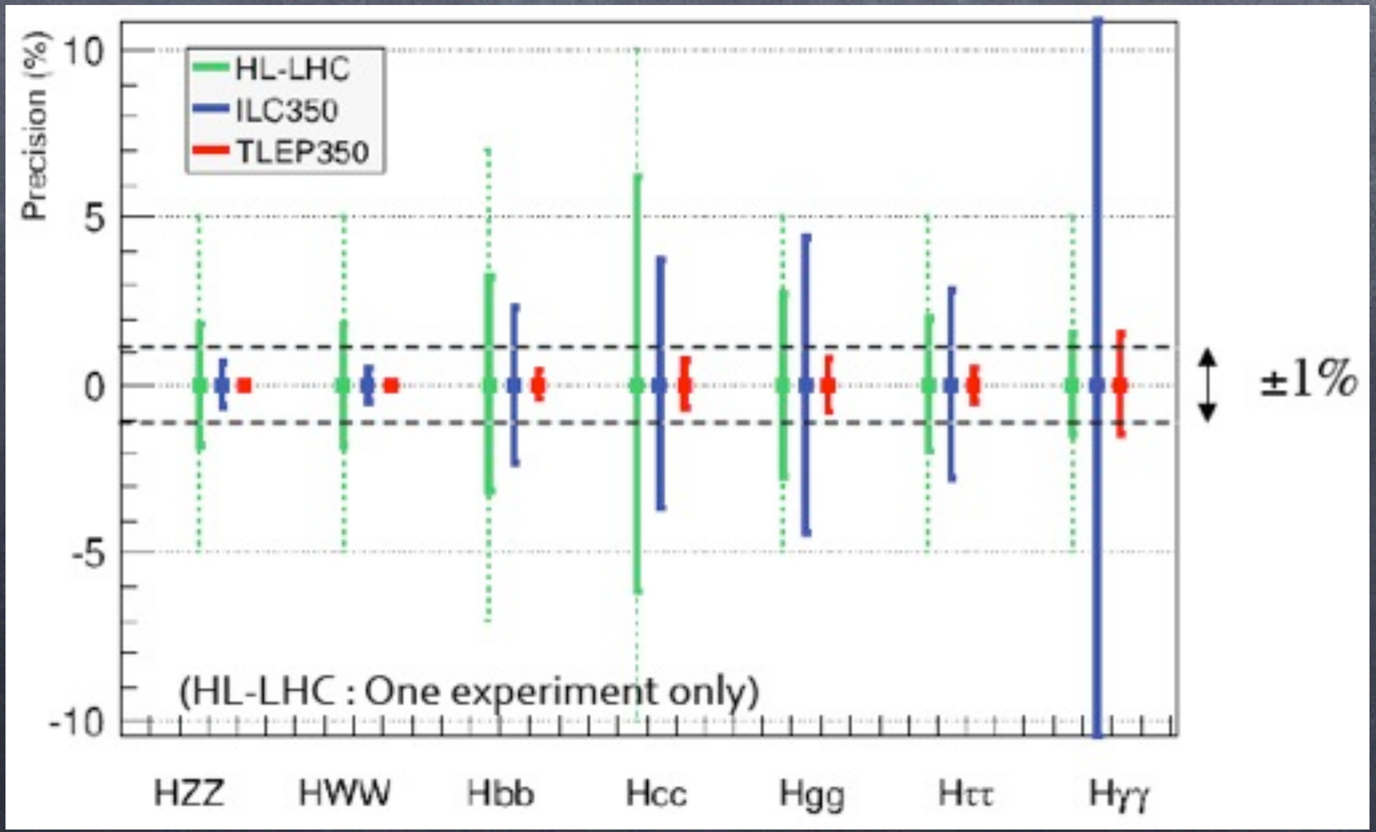
ILC up to 500 GeV

CLIC up to 3 TeV

4. A circular e+e- collider: LEP3, TLEP

(host of 100 TeV of VHE collider)

5. A muon collider



Conclusions

Higgs, scalar particle and quite SM-like

this is just the beginning

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most powerful constraints by

fit rates and

differential distributions -> precision

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SUSY, composite and little Higgs and Eff L
direct/indirect (Higgs)
Higgs data at the level of PEWT for some variables

Conclusions

Higgs, scalar particle and quite SM-like

this is just the beginning

most powerful constraints by

fit rates and

differential distributions -> precision

SUSY, composite and little Higgs and Eff L

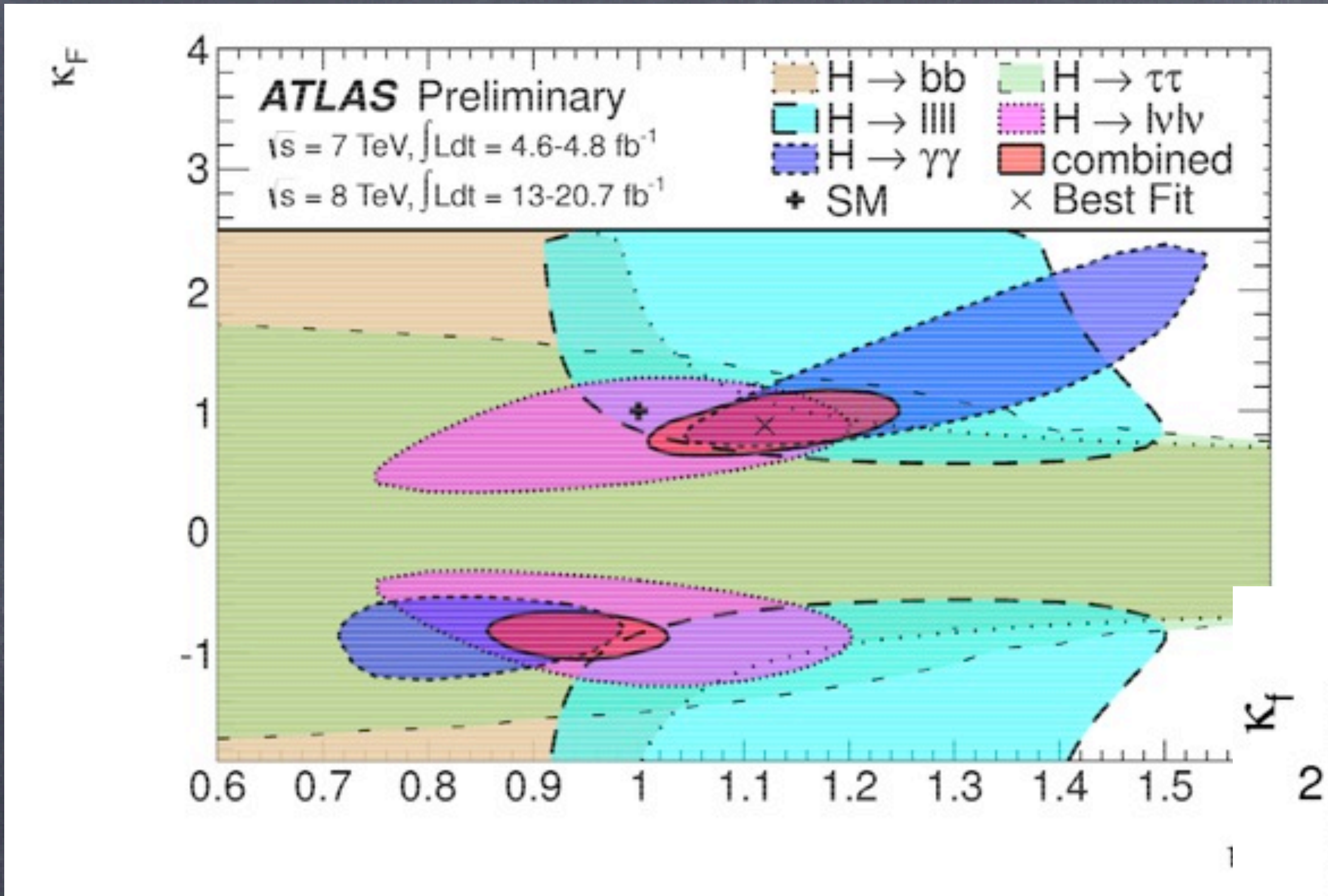
direct/indirect (Higgs)

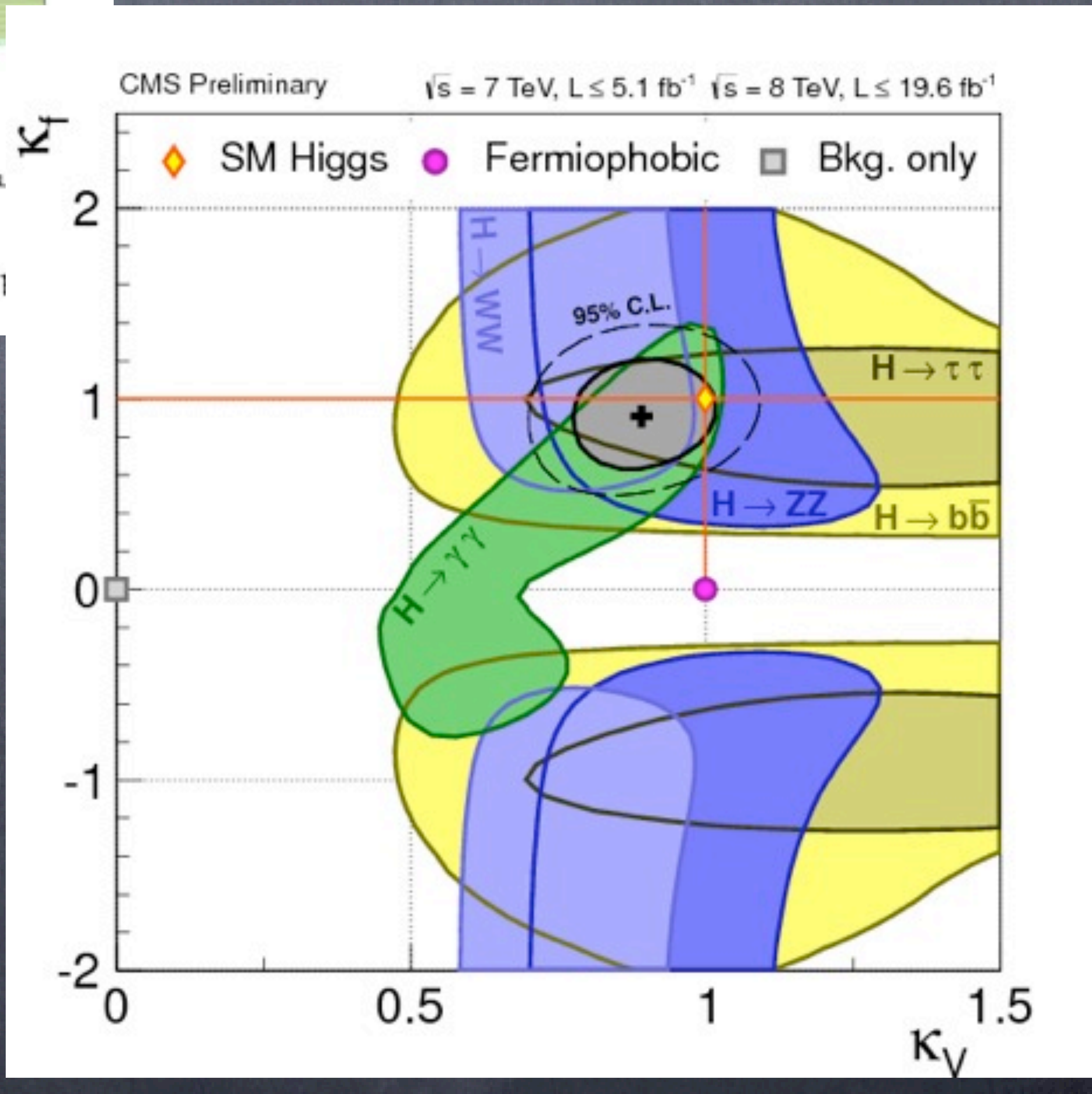
Higgs data at the level of PEWT for some variables

What now?

a lot of the theory space cleared out

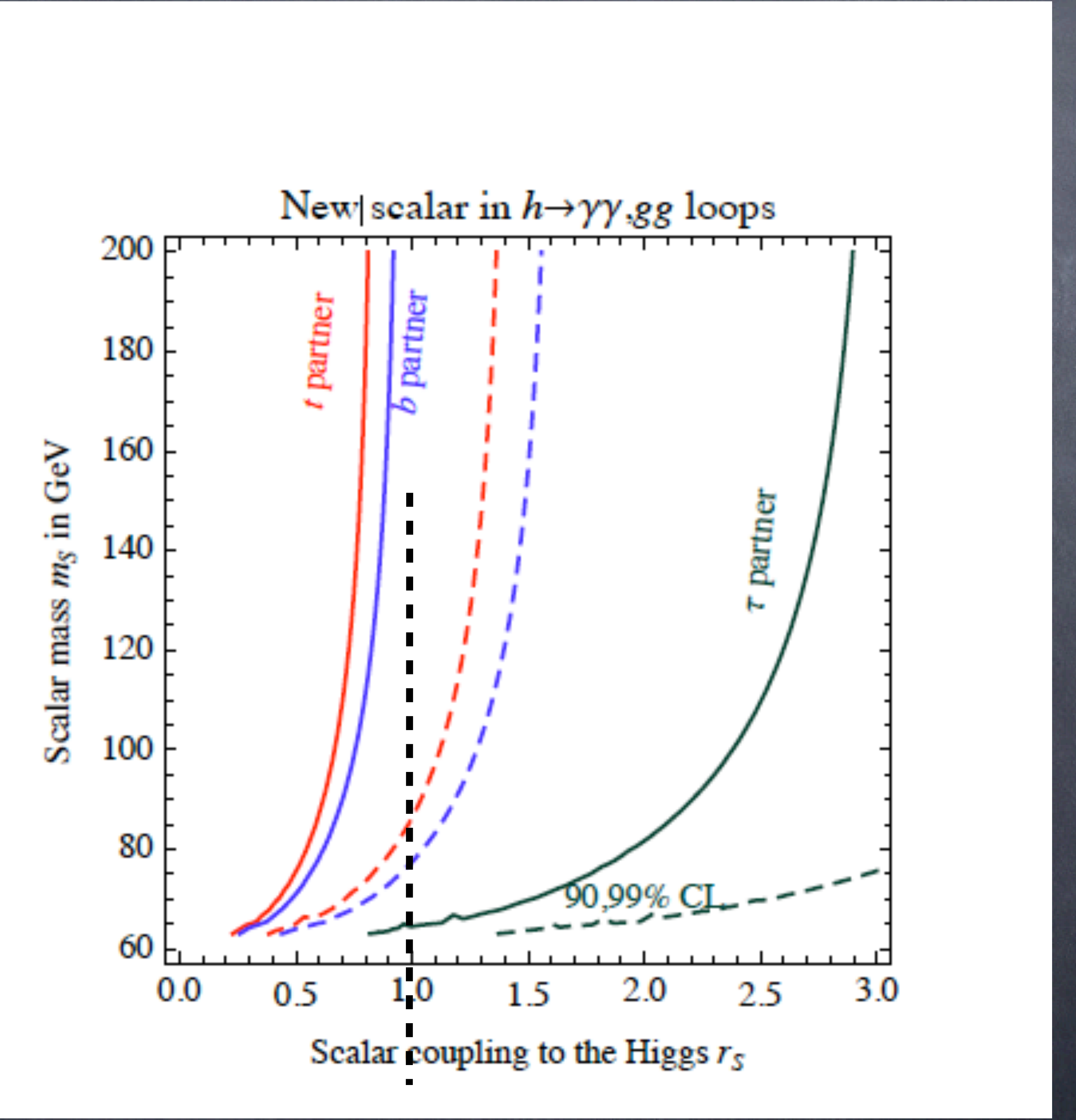
data -> new ideas in model building


ATLAS Preliminary
√s = 7 TeV, ∫Ldt = 4.6-4.8 fb⁻¹
√s = 8 TeV, ∫Ldt = 13-20.7 fb⁻¹
H → bb
H → llll
H → γγ
SM
H → ττ
H → lνlν
combined
× Best Fit
κF


CMS Preliminary
√s = 7 TeV, L ≤ 5.1 fb⁻¹ √s = 8 TeV, L ≤ 19.6 fb⁻¹
SM Higgs
Fermiophobic
Bkg. only
95% C.L.
H → ττ
H → ZZ
H → bb̄
H → γγ
H → WW
κf
κV

Example

$$r_s \, \frac{2m_s^2}{v} \, S^2 \, h$$



Strumia et al. 2013