Recent progress in Higgs analyses

Veronica Sanz (Sussex)
DESY

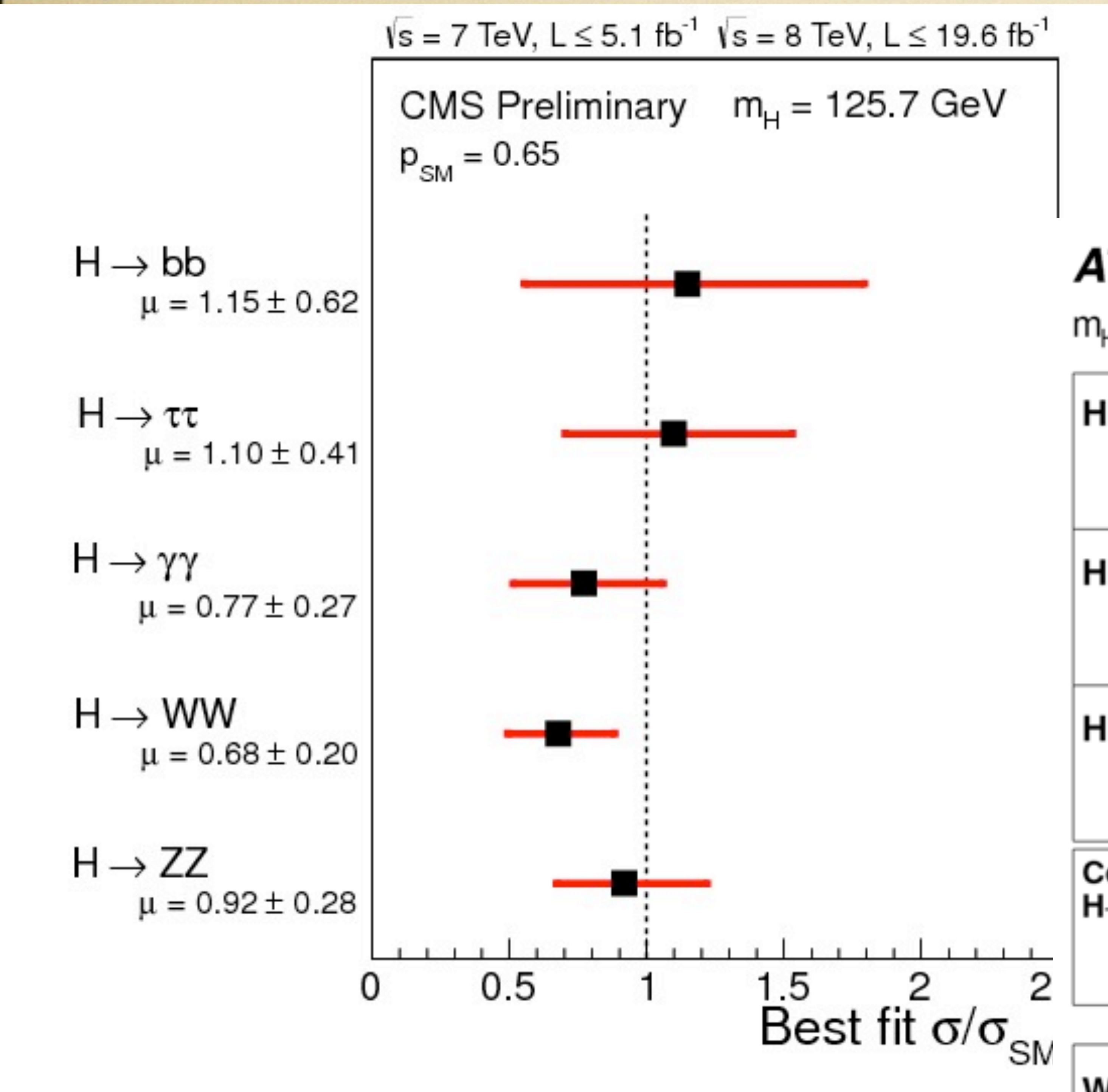
Outline

- Power to the data
- From data to ideas: Supersymmetry and Composite Higgs
- Higgs Effective Theory

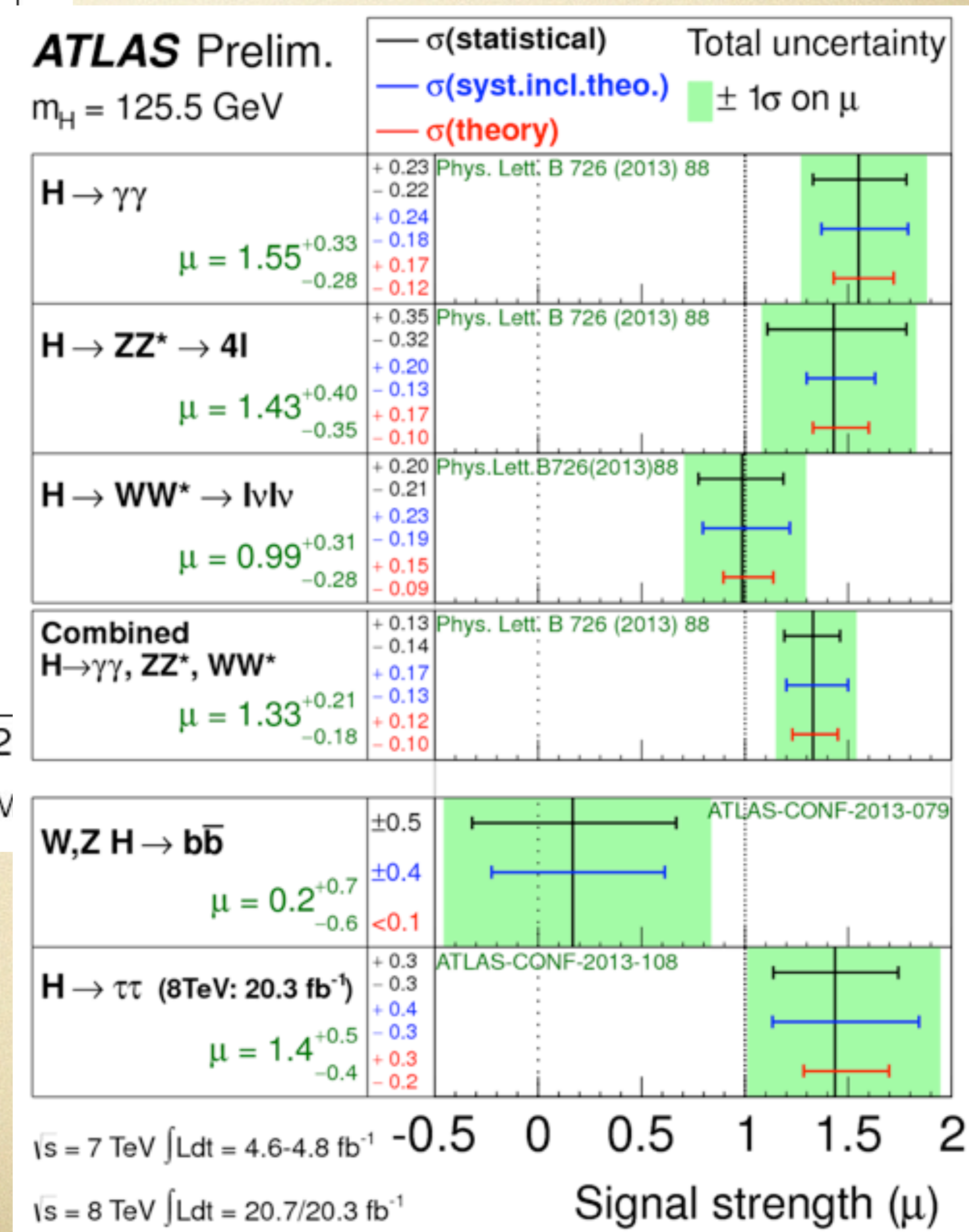
disclaimer

not an exhaustive review

Power to the data



√s = 7 TeV, L ≤ 5.1 fb-1 √s = 8 TeV, L ≤ 19.6 fb-1
CMS Preliminary m_H = 125.7 GeV
p_SM = 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
Best fit σ/σ_SM



ATLAS Prelim.
m_H = 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
Phys. Lett. B 726 (2013) 88
H → ZZ* → 4l
μ = 1.43 +0.40 −0.35
H → WW* → lνlν
μ = 0.99 +0.31 −0.28
Combined
H→γγ, ZZ*, WW*
μ = 1.33 +0.21 −0.18
W,Z H → bb̄
μ = 0.2 +0.7 −0.6
ATLAS-CONF-2013-079
H → ττ (8TeV: 20.3 fb-1)
μ = 1.4 +0.5 −0.4
ATLAS-CONF-2013-108
√s = 7 TeV ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV ∫Ldt = 20.7/20.3 fb-1
Signal strength (μ)

Couplings

Each channel is not that well measured

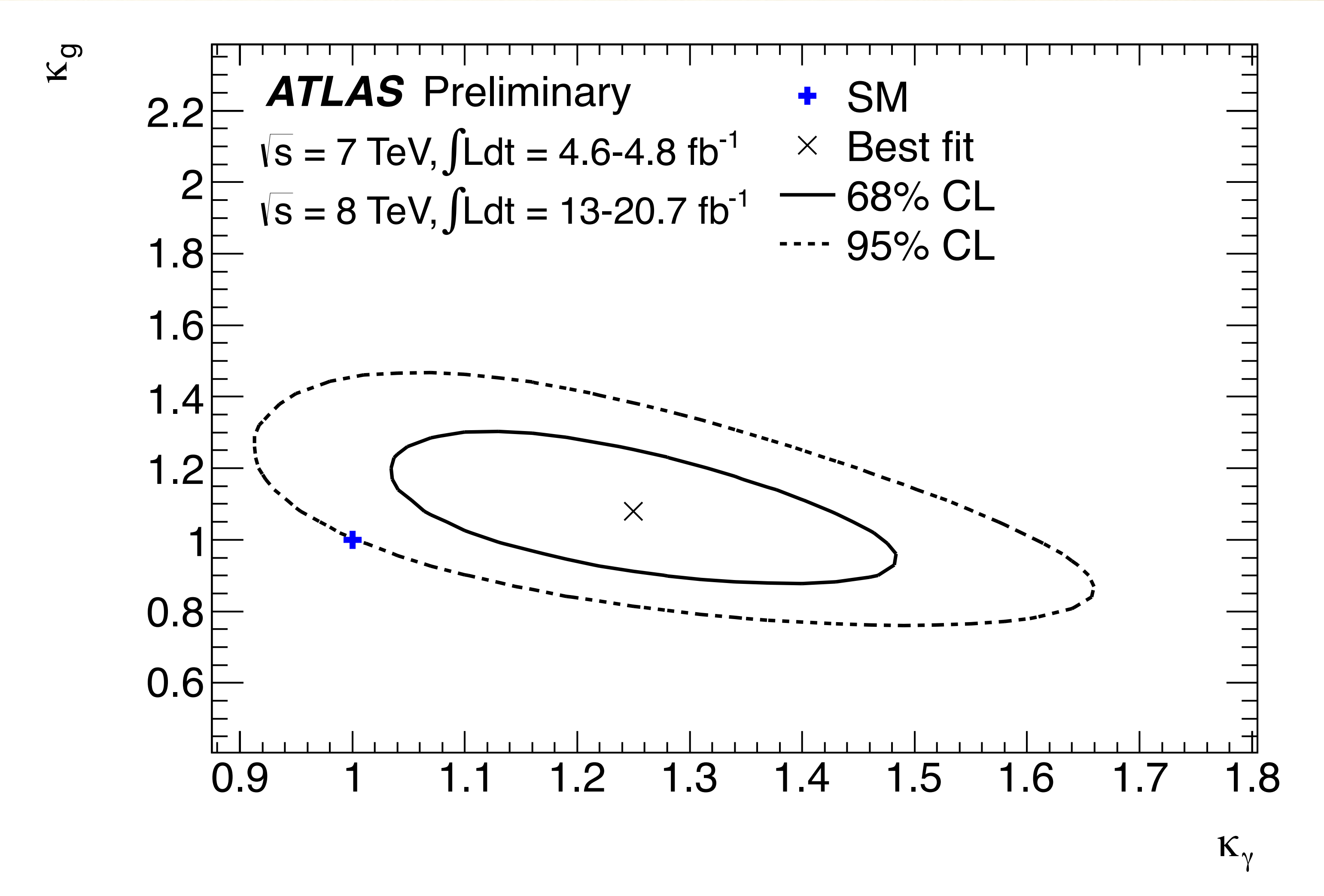
BUT

powerful information
assume 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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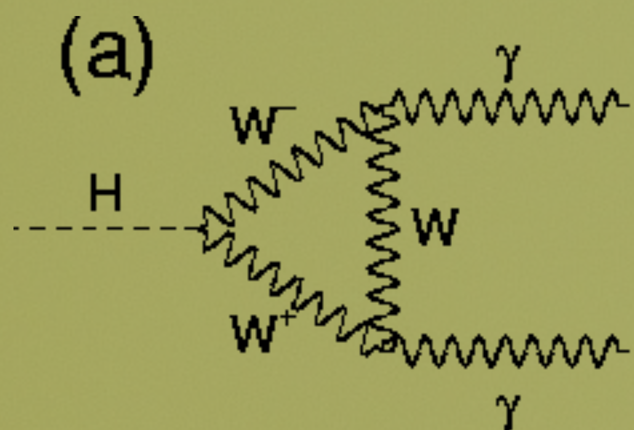
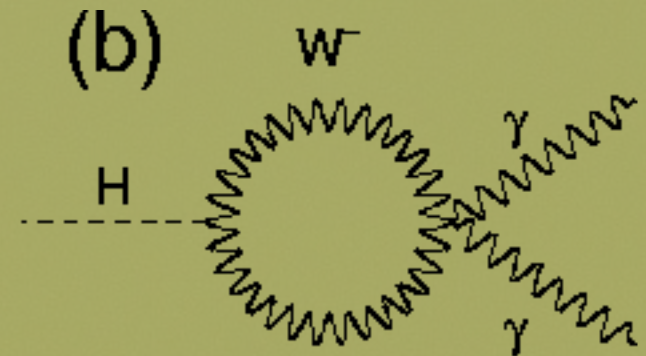
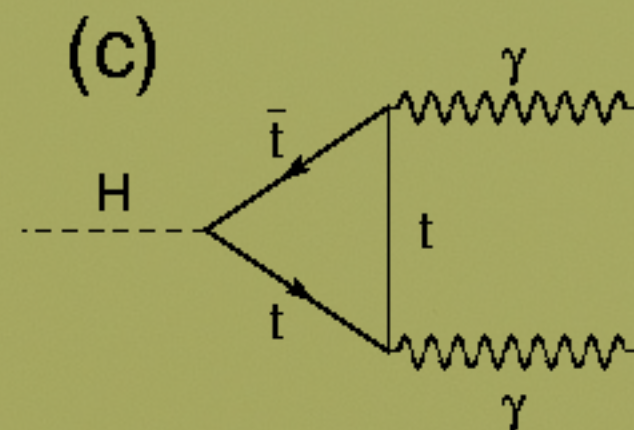
SM contributions





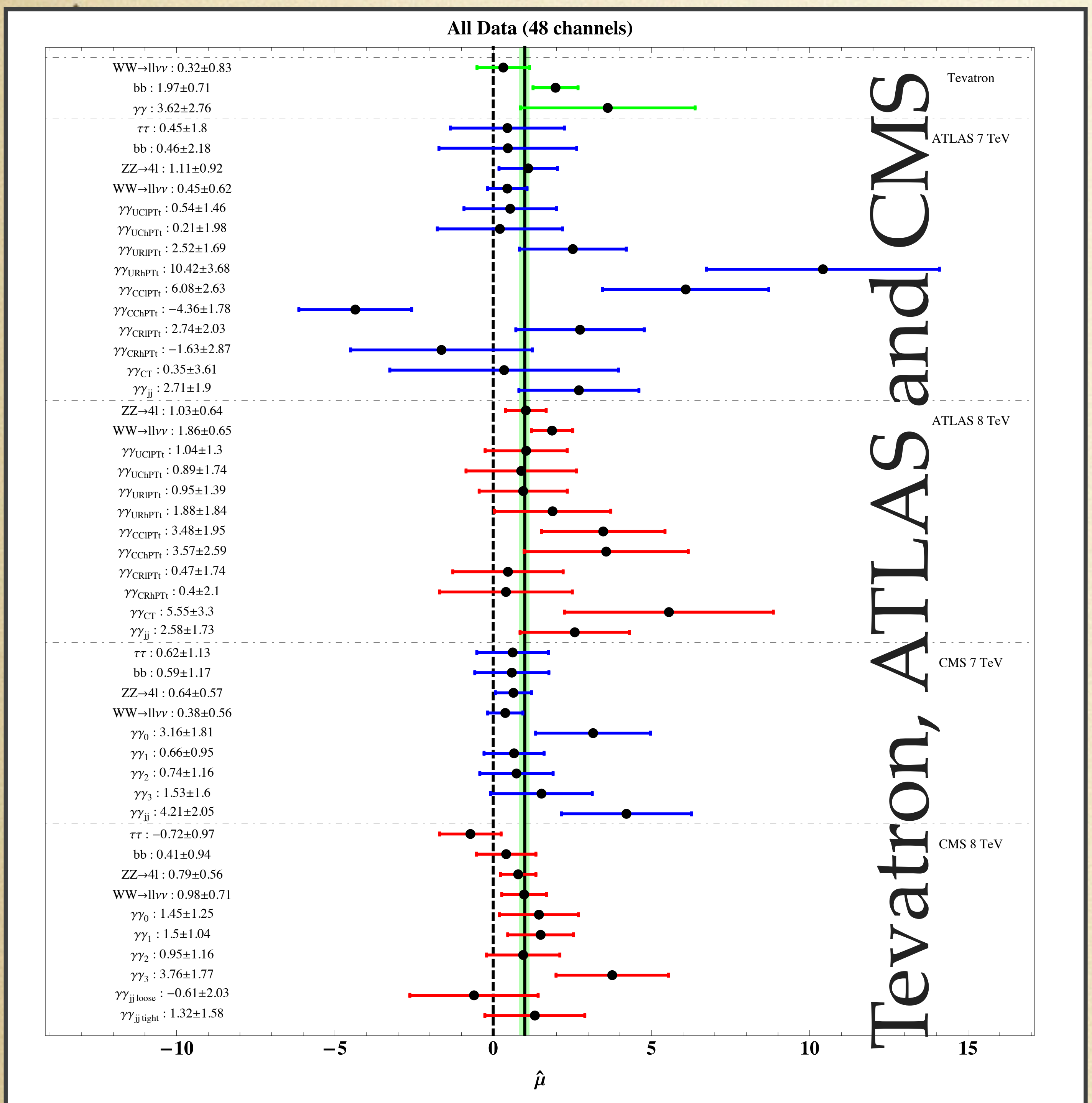


+ stops running in the loop

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

Fit to Higgs properties in BSM

example fromEspinosa, Grojean, VS, Trott, 2012



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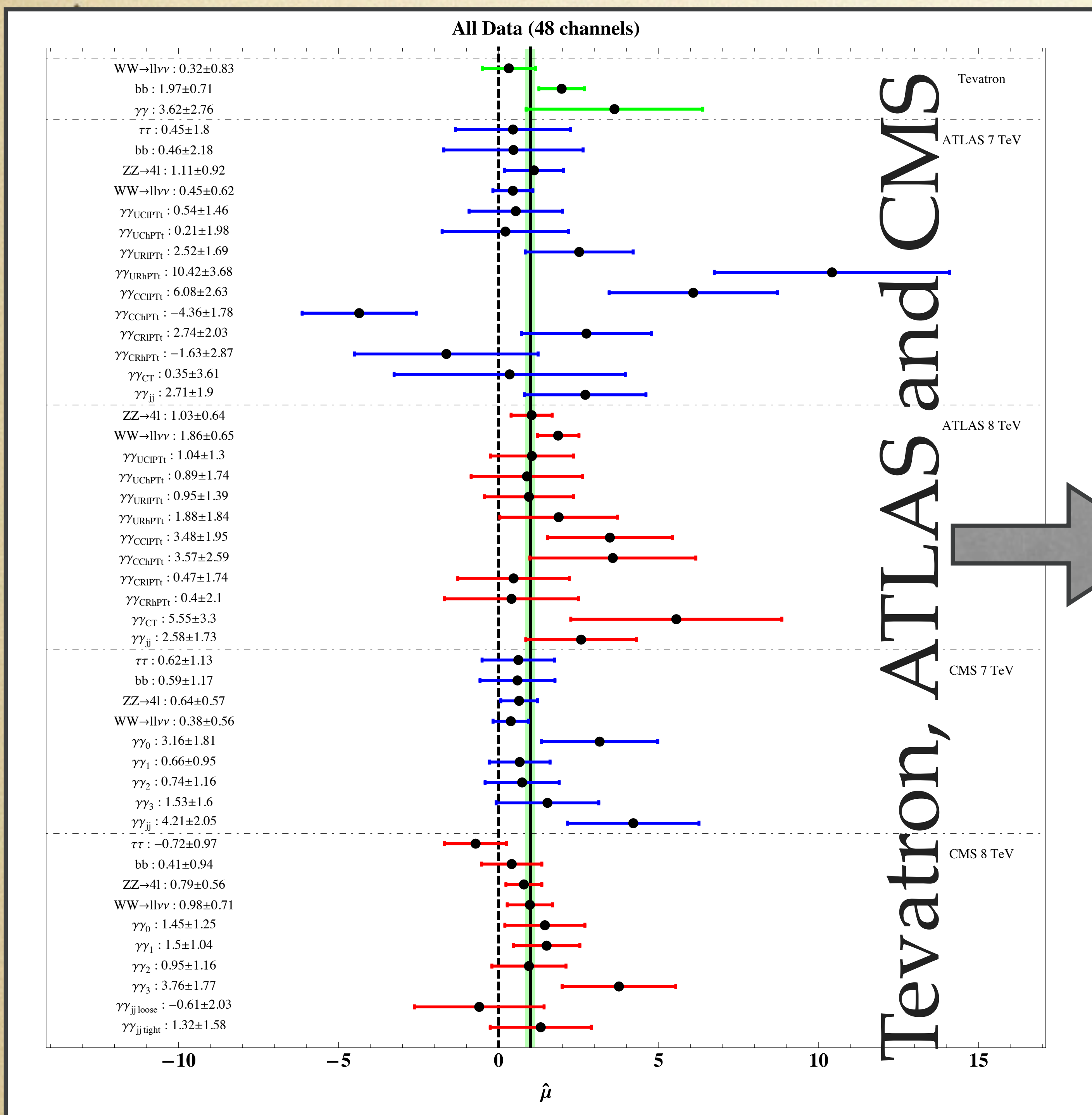
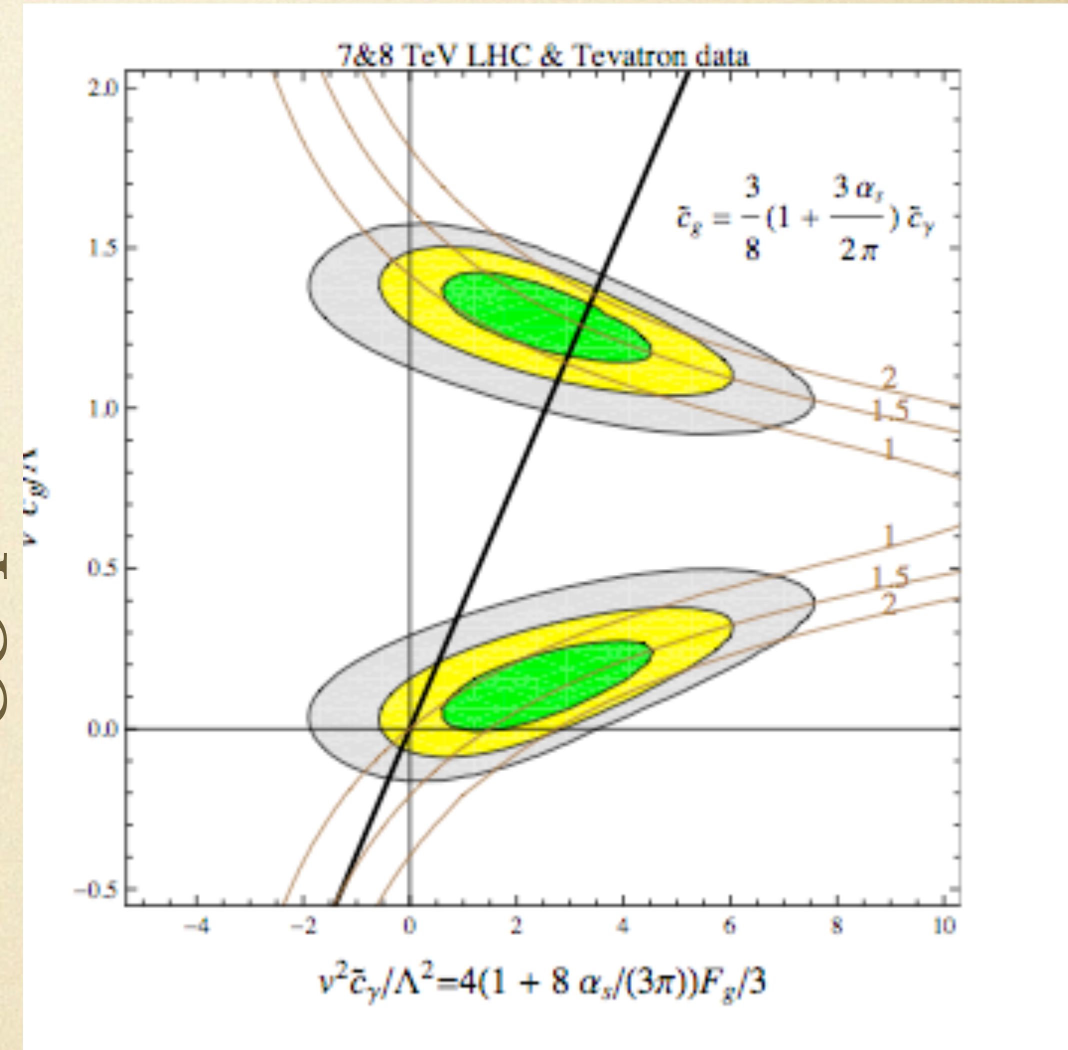


Tevatron, ATLAS and CMS

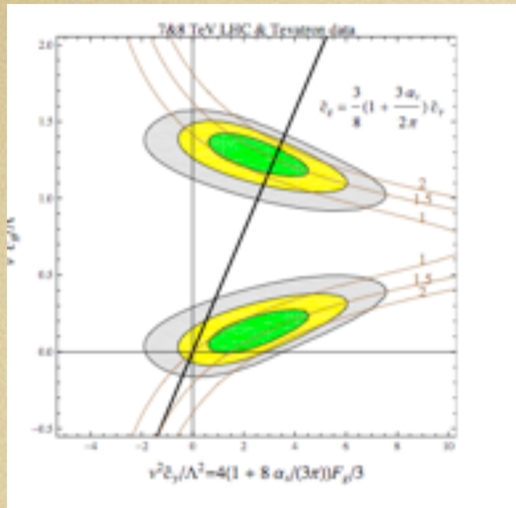
effect on gg production



effect on diphoton

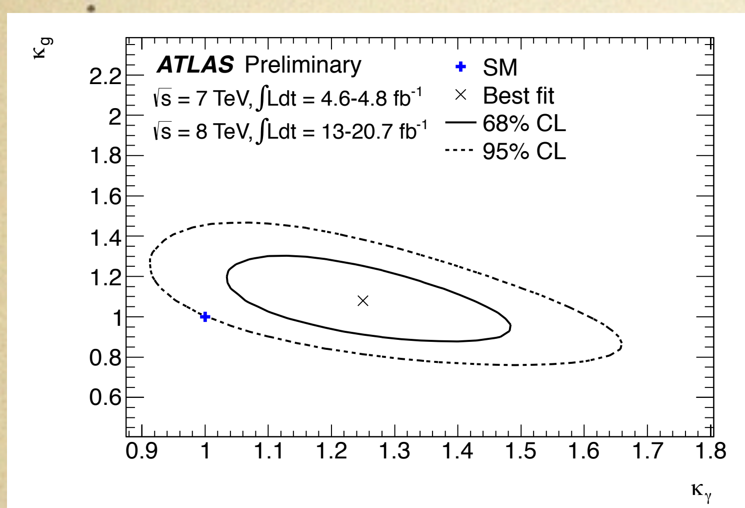
green, yellow, gray=
1,2 and 3 sigma

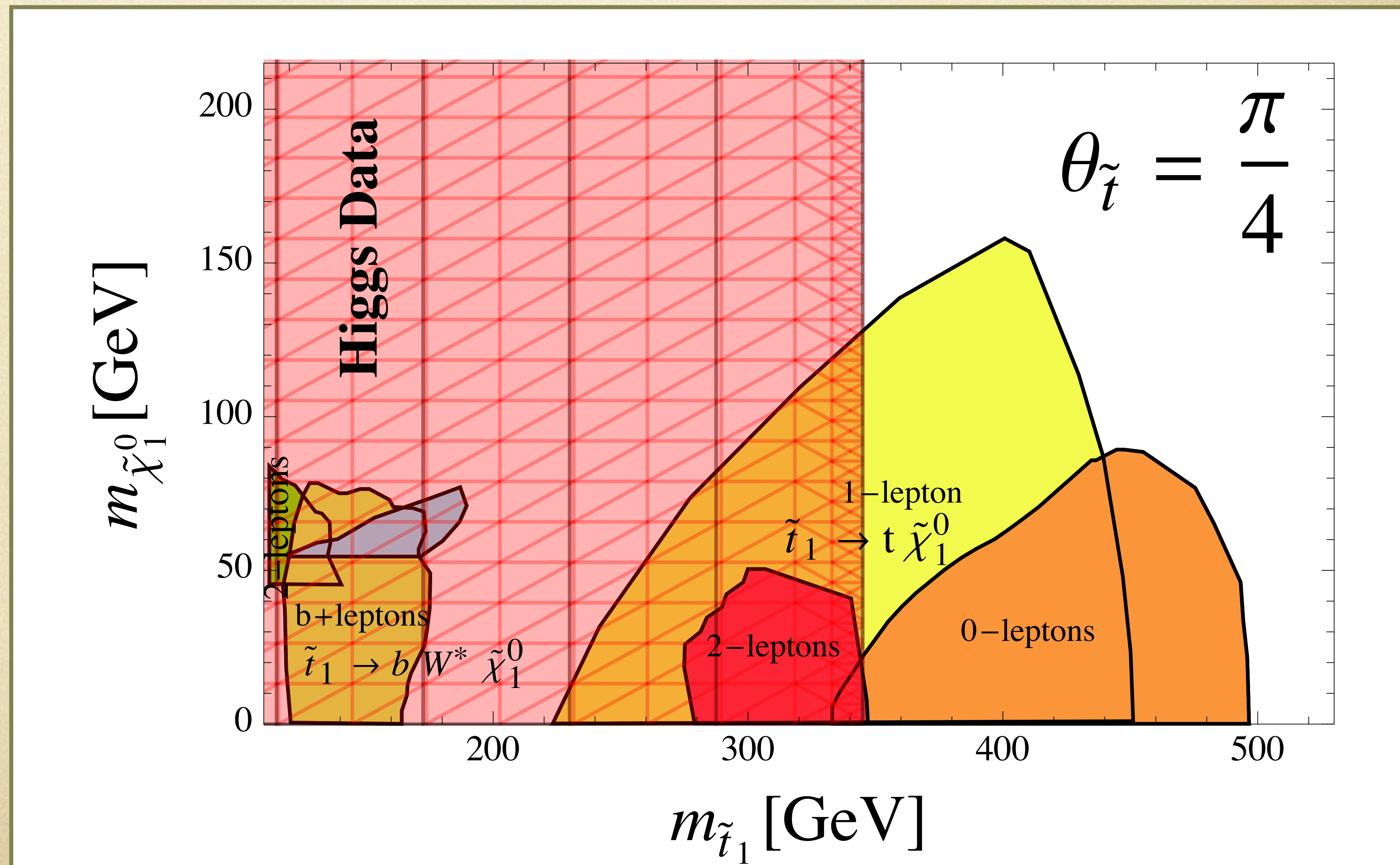
the quality of the fit as good as SM



+ mW + btosgamma

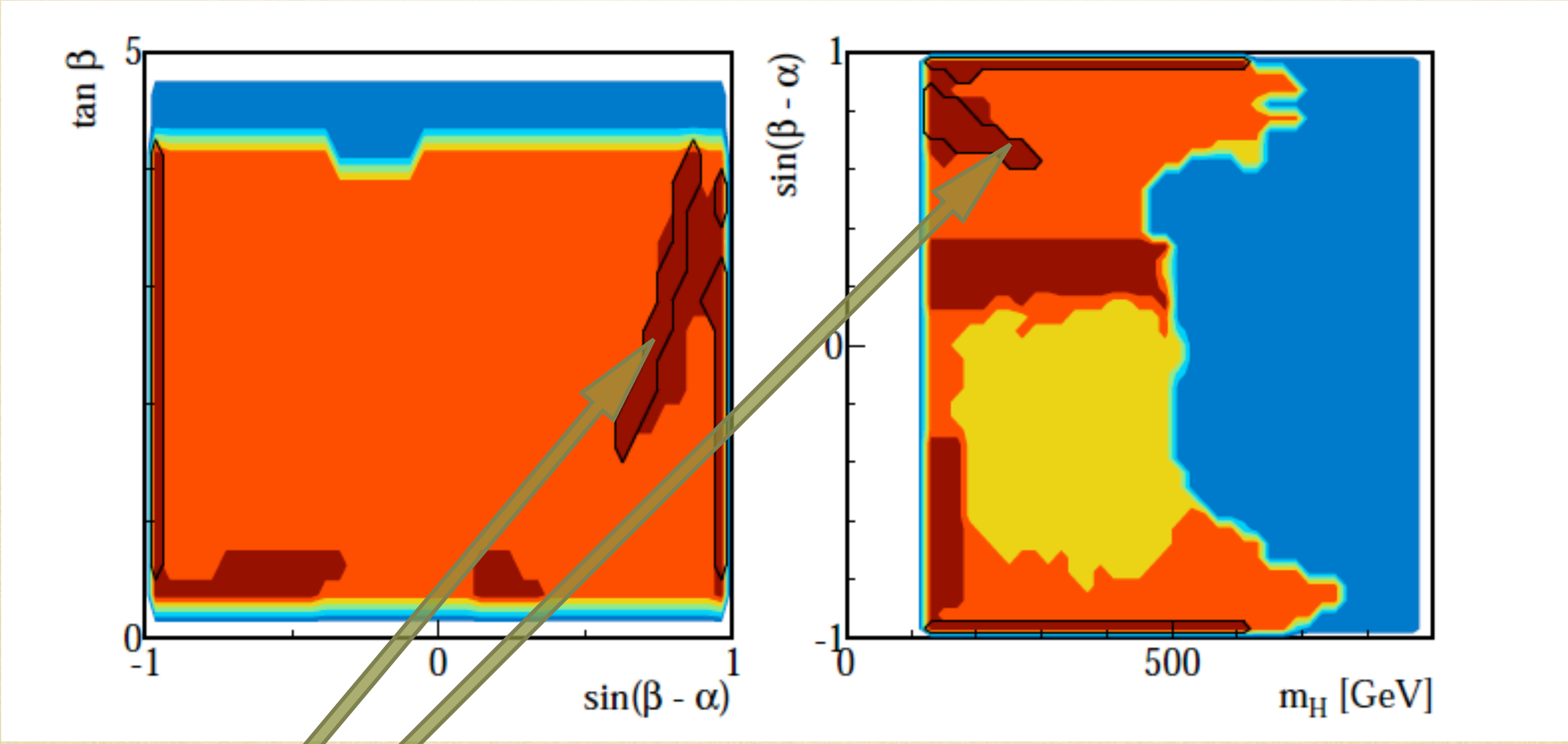
Stops





95% CL exclusion

In SUSY, parameter space of 2HDM



Allowed regions

Coleppa 1305.0002

Composite Higgs

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

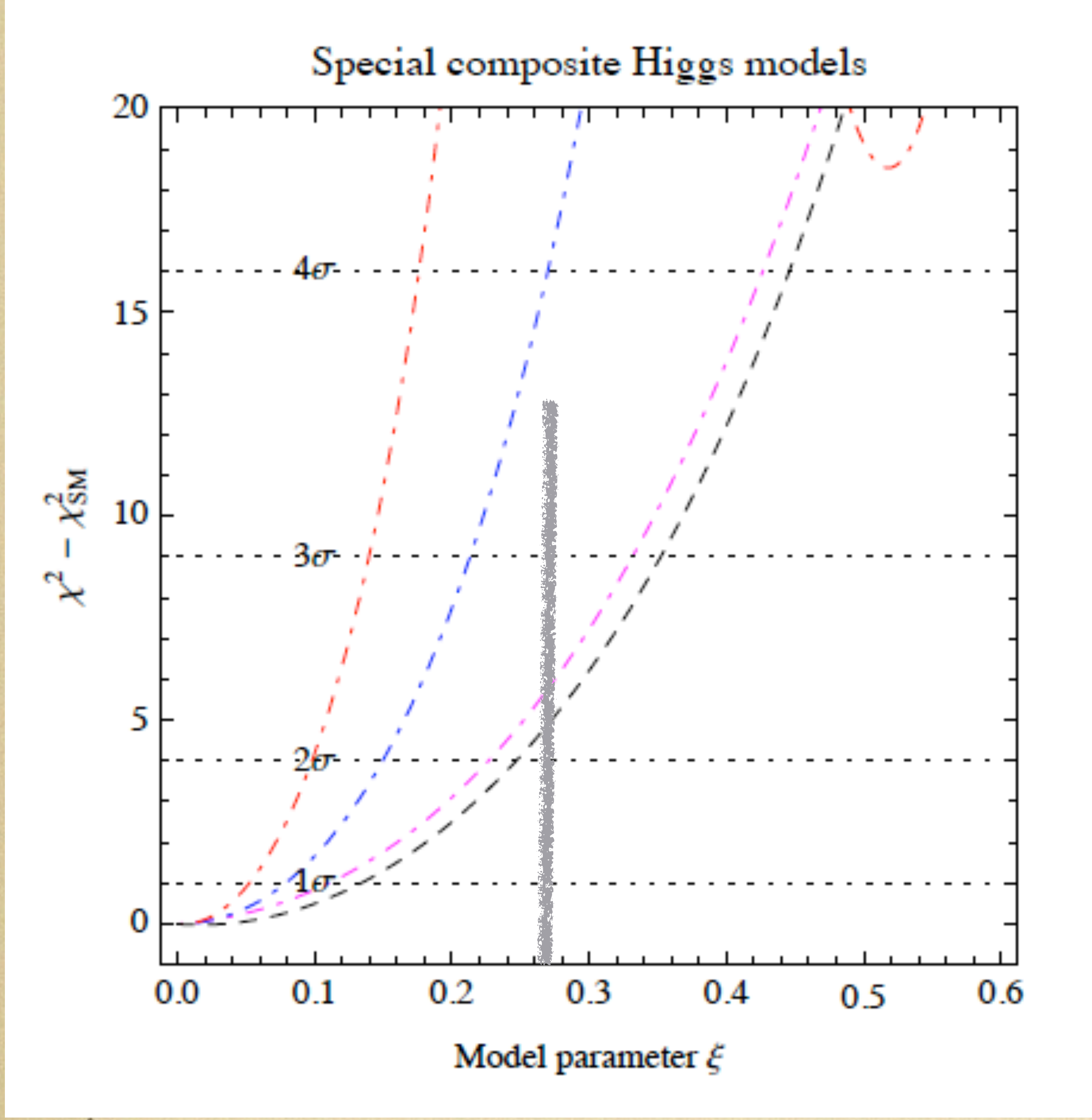
$$\xi = v^2/f^2$$

EW scale: v
pions

screening UV,
stabilization EW scale

buys 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

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$$m^2 \propto \lambda v^2$$

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

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

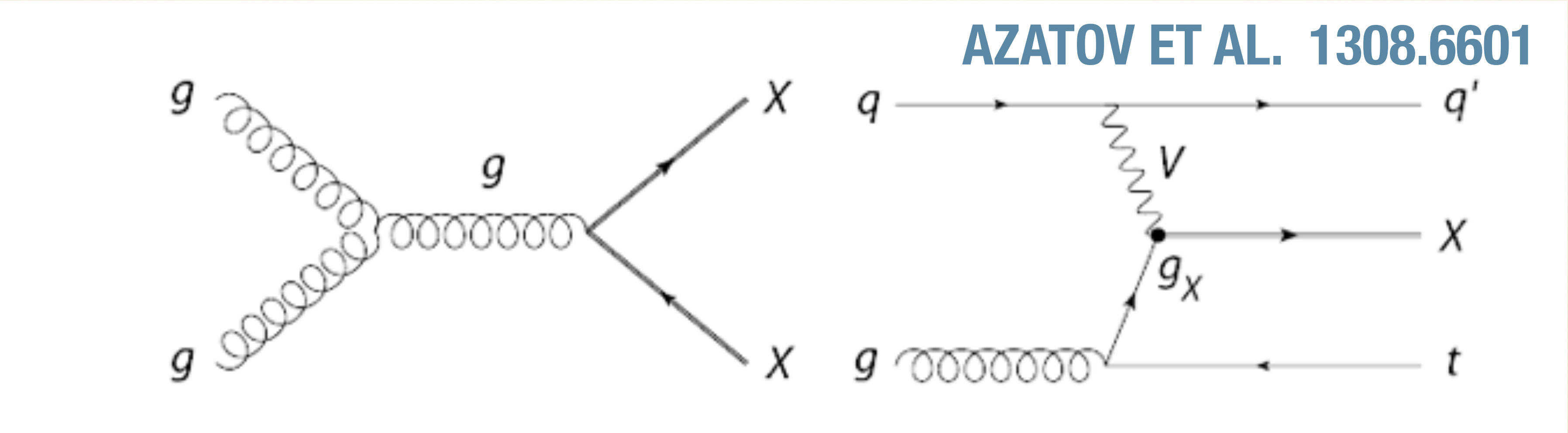
One could still push

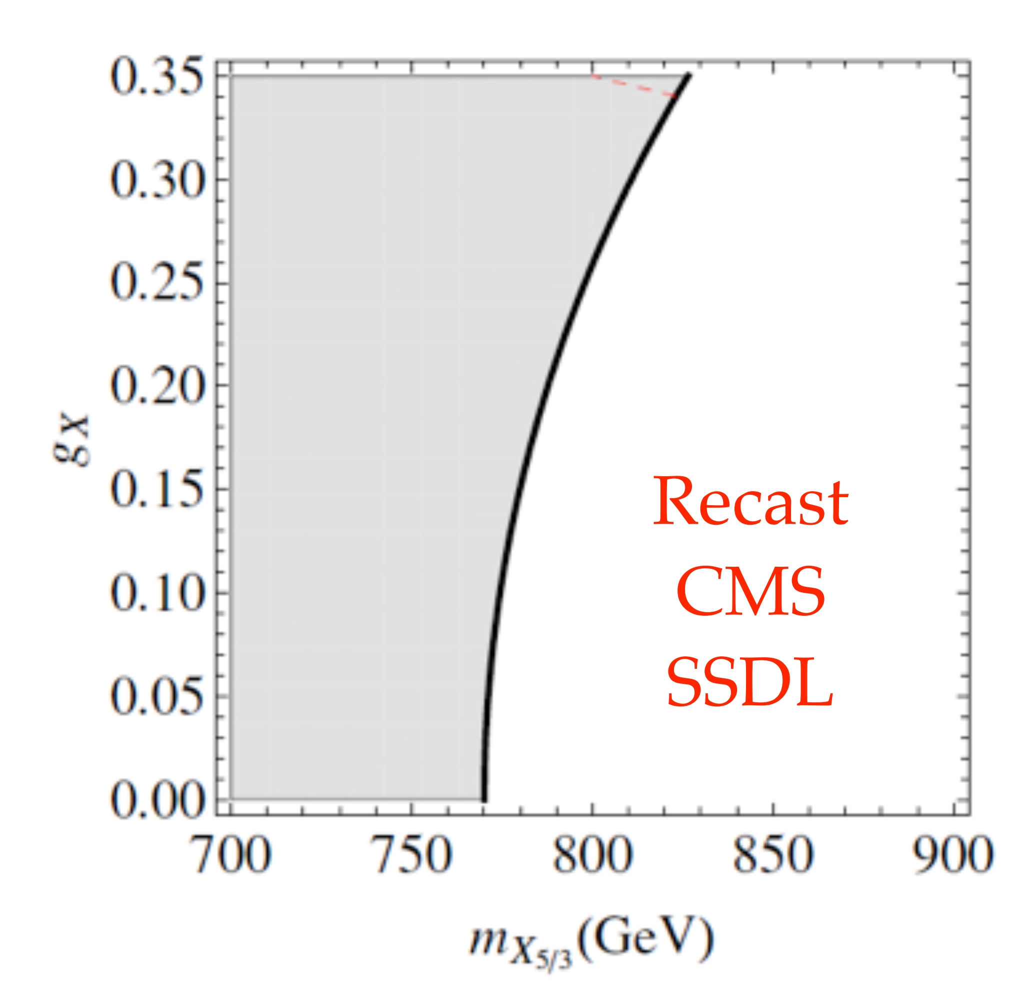
$$f \sim TeV$$

but

$$m_T \lesssim TeV$$

$m_T \lesssim TeV$





Higgs Effective Theory

Shouldn't we focus on discovery searches?

New Physics could be heavy
as compared with the channel we look at

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EFT: expansion in higher-dimensional operators (HDOs)

Buchmuller and Wyler. NPB (86)

Advantages of EFT

model independent

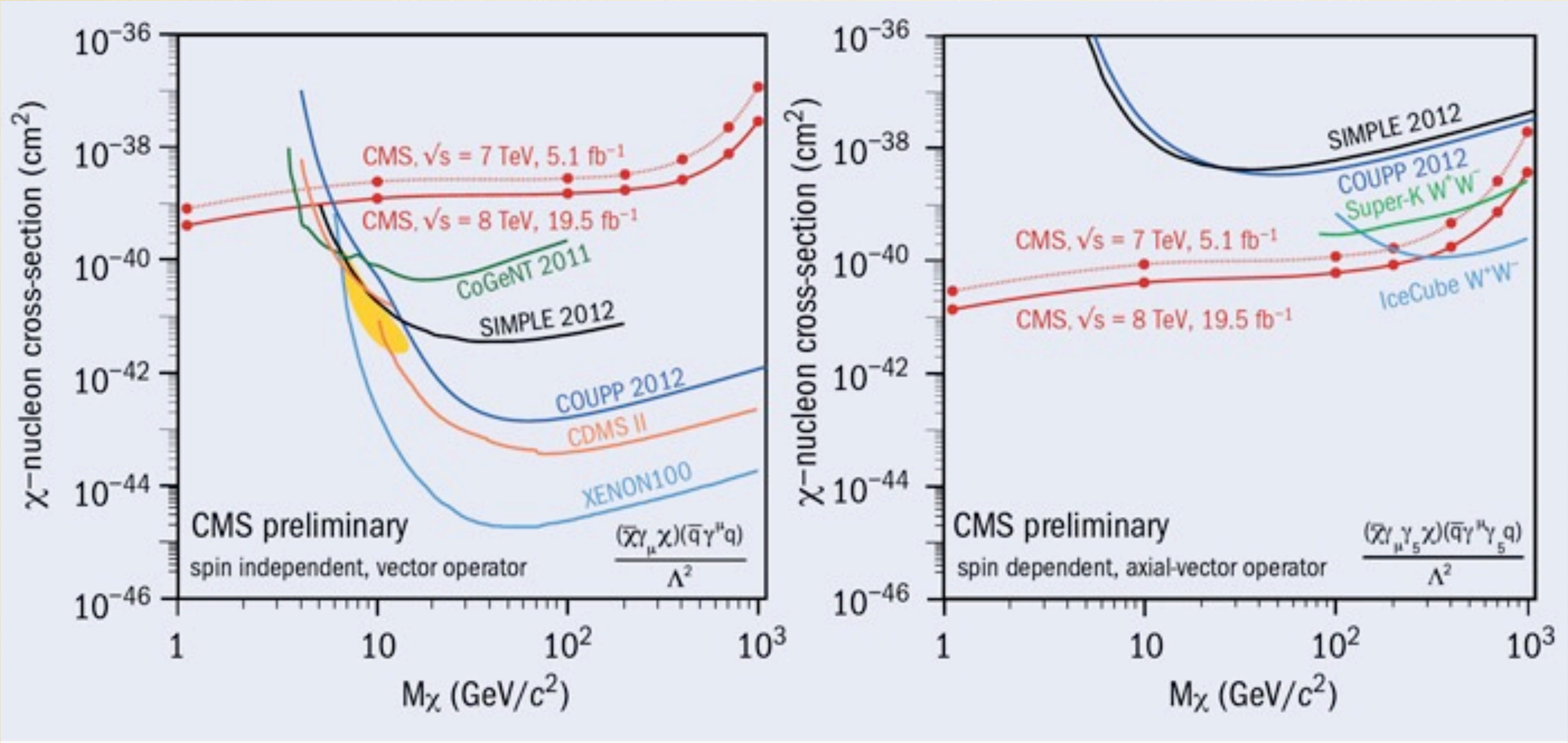
Systematic studies

One operator, corrs.

Translation to thy

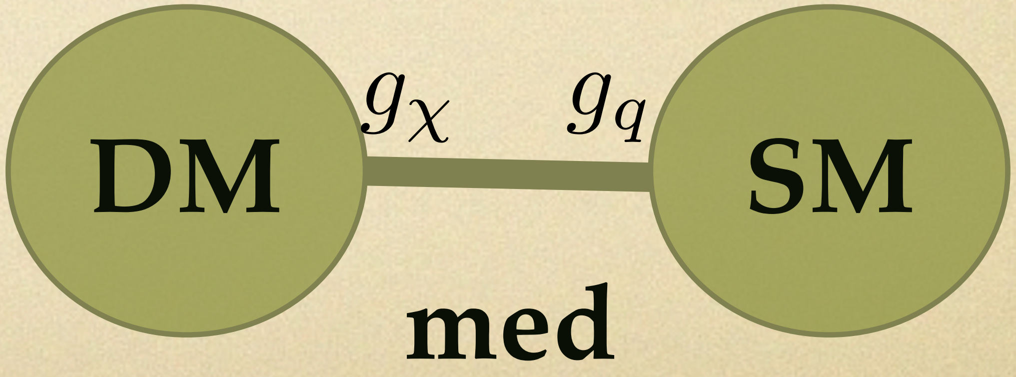
Beware of abusing the HDO framework

ex. Monojet searches as DM searches



HDO for DM

$$\frac{1}{\Lambda^2}\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$$



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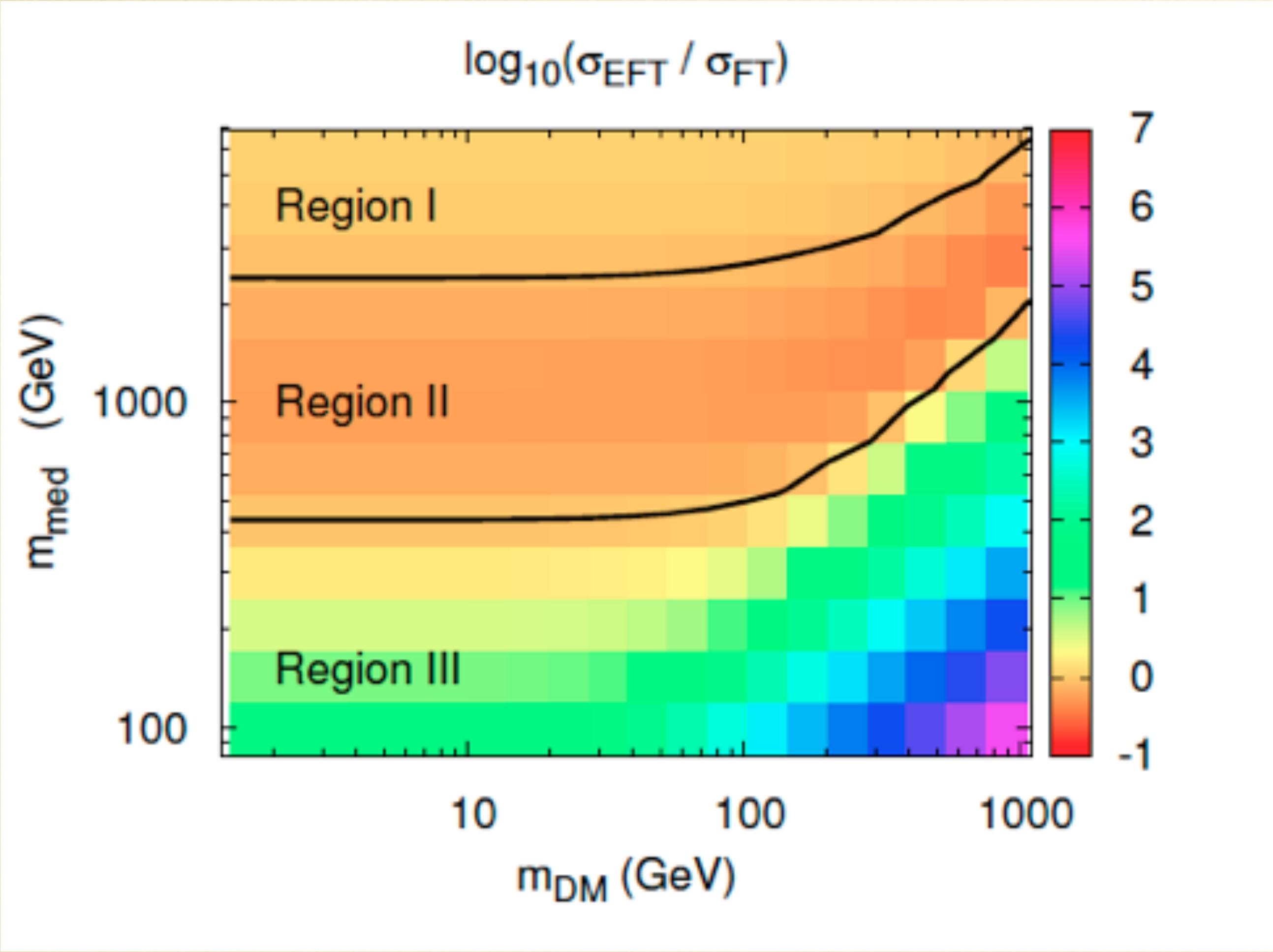
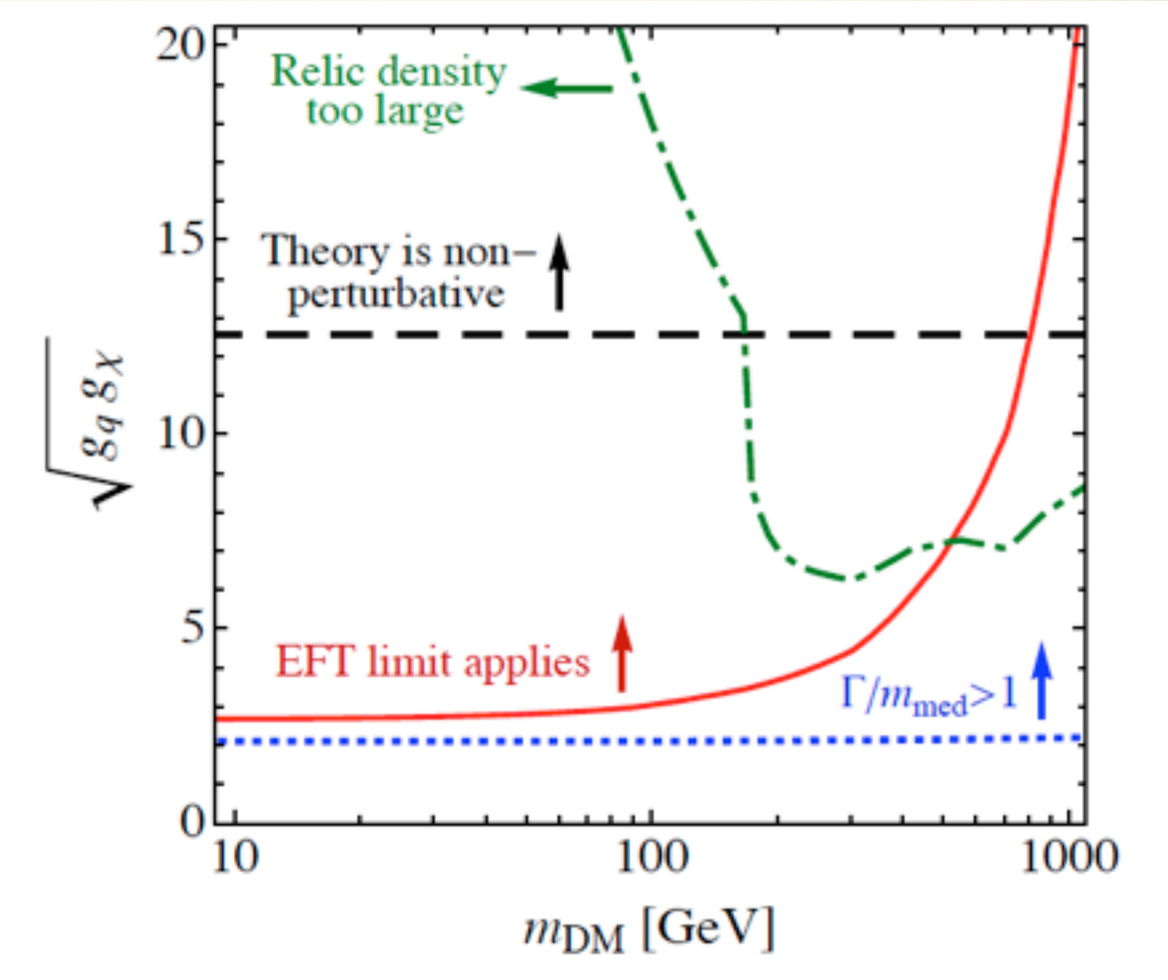




Buchmueller, Dolan and McCabe. 1308.6799

Limits valid to 20% if

$$m_{med} > \ 2.5 \text{ TeV}$$

$$\sqrt{g_\chi g_q} > 3 \qquad\qquad \Gamma/m_{med} > 1$$

Expansion may (non-trivially) *fail*

Some operators could have large coefficients

ex. $\frac{c_6}{\Lambda^2}(D^\mu\Phi^\dagger)\hat{W}_{\mu\nu}(D^\nu\Phi)$ could be loop-ind

$\frac{c_8}{\Lambda^4}(D^\rho\Phi^\dagger)(D_\rho\Phi)\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}$ could dominate

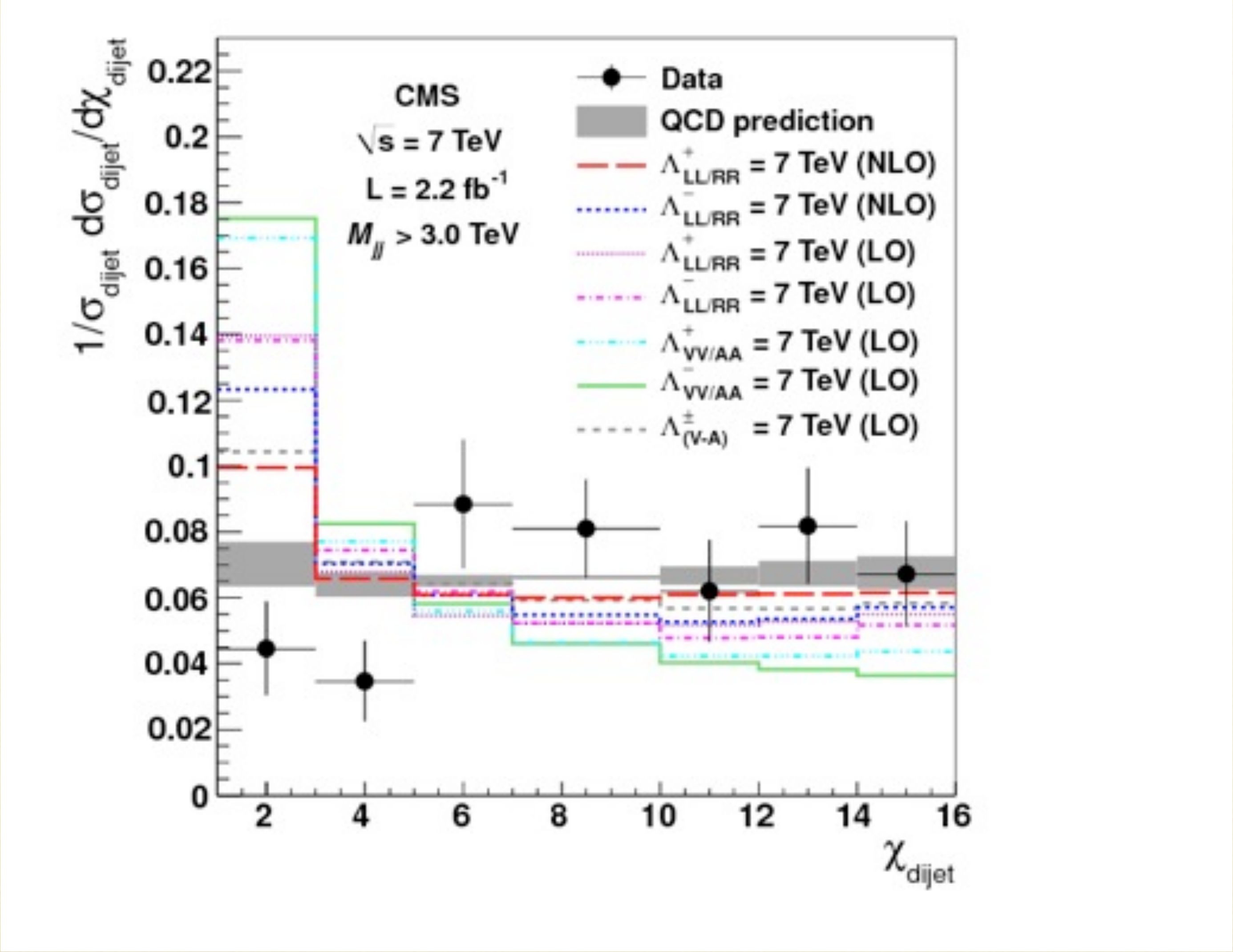
specially dangerous when

$$\Lambda \sim m_W \text{ and high-}p_T$$

How do we look for HDOs?

HDOs affect momentum dependence: angular, pT and inv mass distributions

Usual searches,



ex. dijet searches

Dijet angular distribution

HDOs affect momentum dependence: angular, pT and inv mass distributions

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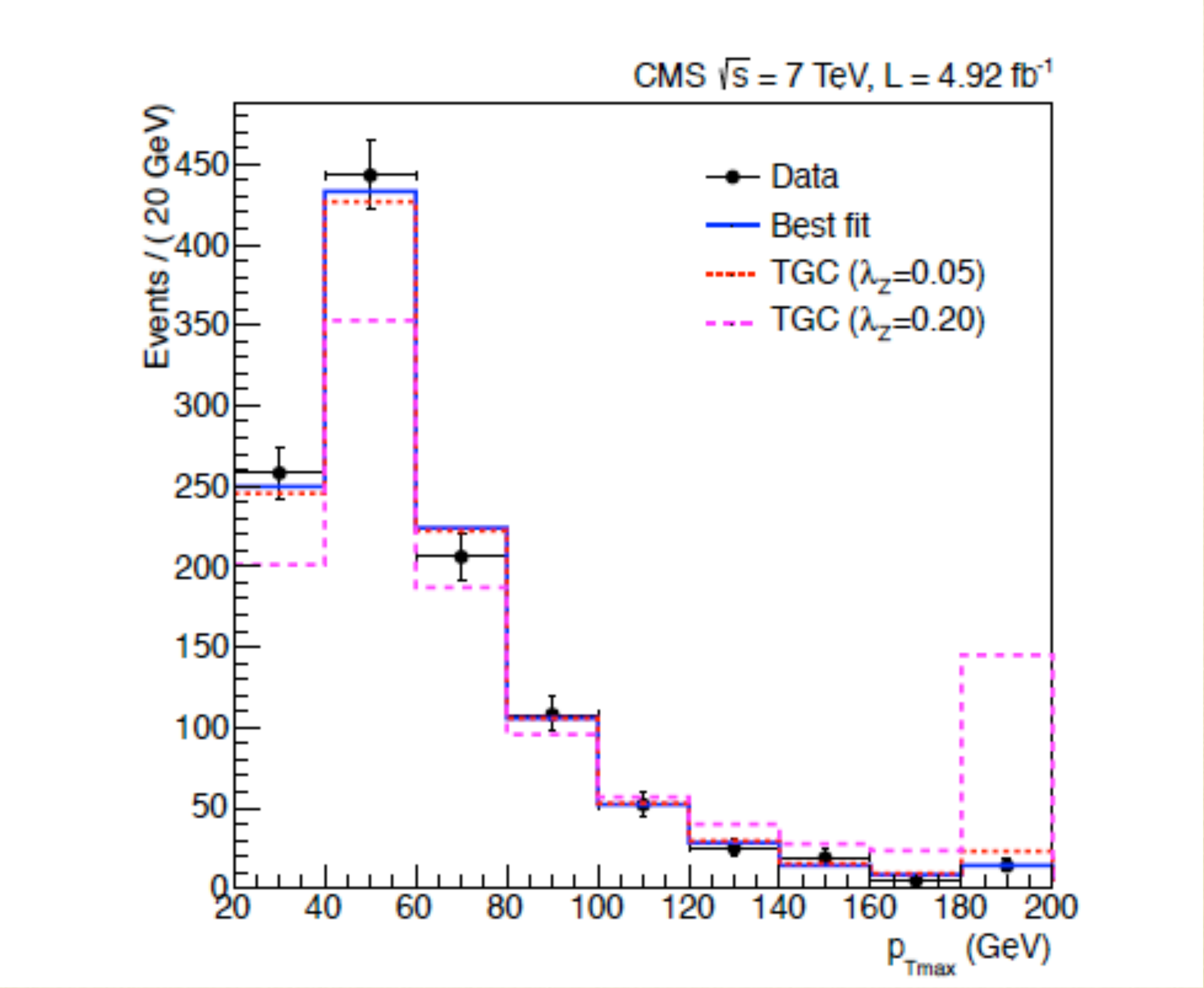

ex. TGCs

leading lepton pT

And what about the Higgs?

Higgs anomalous couplings

HDOs generate HVV interactions with more derivatives

$$-\frac{1}{4} h\, g^{(1)}_{hVV} V_{\mu\nu} V^{\mu\nu}$$

$$-h\, g^{(2)}_{hVV} V_{\nu} \partial_{\mu} V^{\mu\nu}$$

$$-\frac{1}{4} h\, \tilde{g}_{hVV} V_{\mu\nu} \tilde{V}^{\mu\nu}$$

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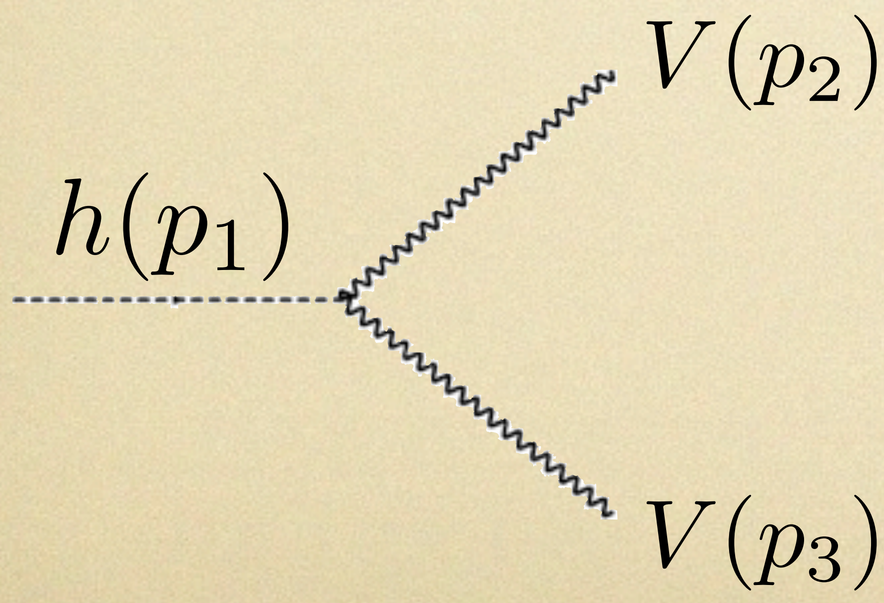
ex. Feynman rule if mh>2mV



$$i\eta_{\mu\nu} \left(g^{(1)}_{hVV} \left(\frac{\hat{s}}{2} - m_V^2 \right) + 2 g^{(2)}_{hVV} m_V^2 \right)$$

$$-i g^{(1)}_{hVV} p_3^{\mu} p_2^{\nu}$$

$$-i \tilde{g}_{hVV} \epsilon^{\mu\nu\alpha\beta} p_{2,\alpha} p_{3,\beta}$$

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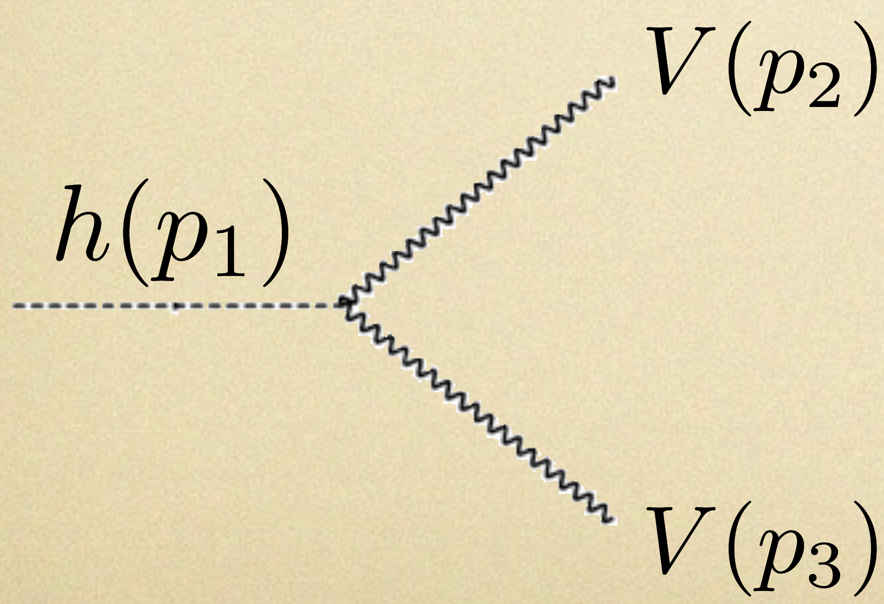

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total rates, COM, angular, inv mass and pT distributions

Framework for EFT studies

Higgs BRs

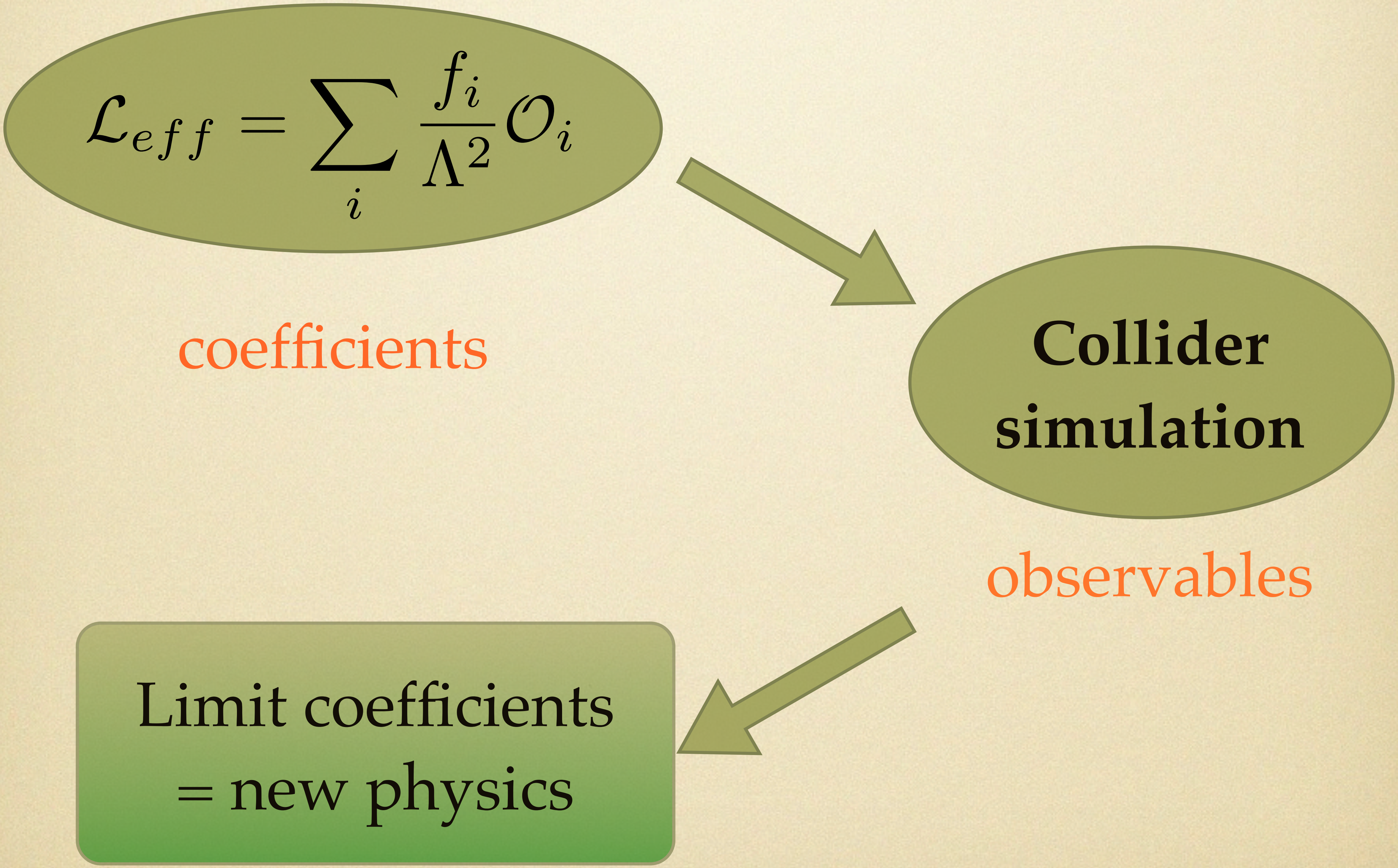
eHDECAY

Contino, Ghezzi, Grojean, Muhlleitner and Spira.
1303.3876

Production rates and kinematic distributions

depend on cuts
need radiation and detector effects
Simulation tools

We need a framework



A couple of tools

1. Feynrules HDOs involving Higgs and TGCs

Alloul, Fuks, VS. 1310.5150

links to CalcHEP, LoopTools, Madgraph...

HDOs->Madgraph-> Pythia... -> FastSim / FullSim

2.QCD NLO HDOs involving Higgs and TGCs

VS and Williams. In prep.

MCFM and POWHEG

Pythia, Herwig... -> FastSim / FullSim

Before we move onto Higgs physics

Reviewing LEP constraints

Is LEP the ultimate fit?

LEP TGCs and EWPTs
provide useful information of Higgs physics

Does LEP obviate LHC measurements?

LEP fit to WW observables (TGCs)

Falkowski, Fichet, Mohan, Riva, VS.
Les Houches proceedings. 1405.1617

Total cross section and diff distributions from
ALEPH, DELPHI, L3, OPAL, LEP Electroweak Collaboration.
Phys.Rept. 532

SM NLO from RACOONWW

$$c_{WB} = -0.01 \pm 0.03, \qquad c_W = 1.18 \pm 0.56, \qquad c_{3W} = -0.30 \pm 0.16,$$

the fit leads to no meaningful limits, strong sensitivity to quadratic terms (= higher-orders)

to compare with setting by hand c3W=0

$$c_{WB} = 0.03 \pm 0.02, \qquad c_W = 0.18 \pm 0.07,$$

Consequences:

1. TGCs at the LHC are terribly important

2. LEP TGCs do not constrain Higgs operators to the extent it was thought before by, e.g.

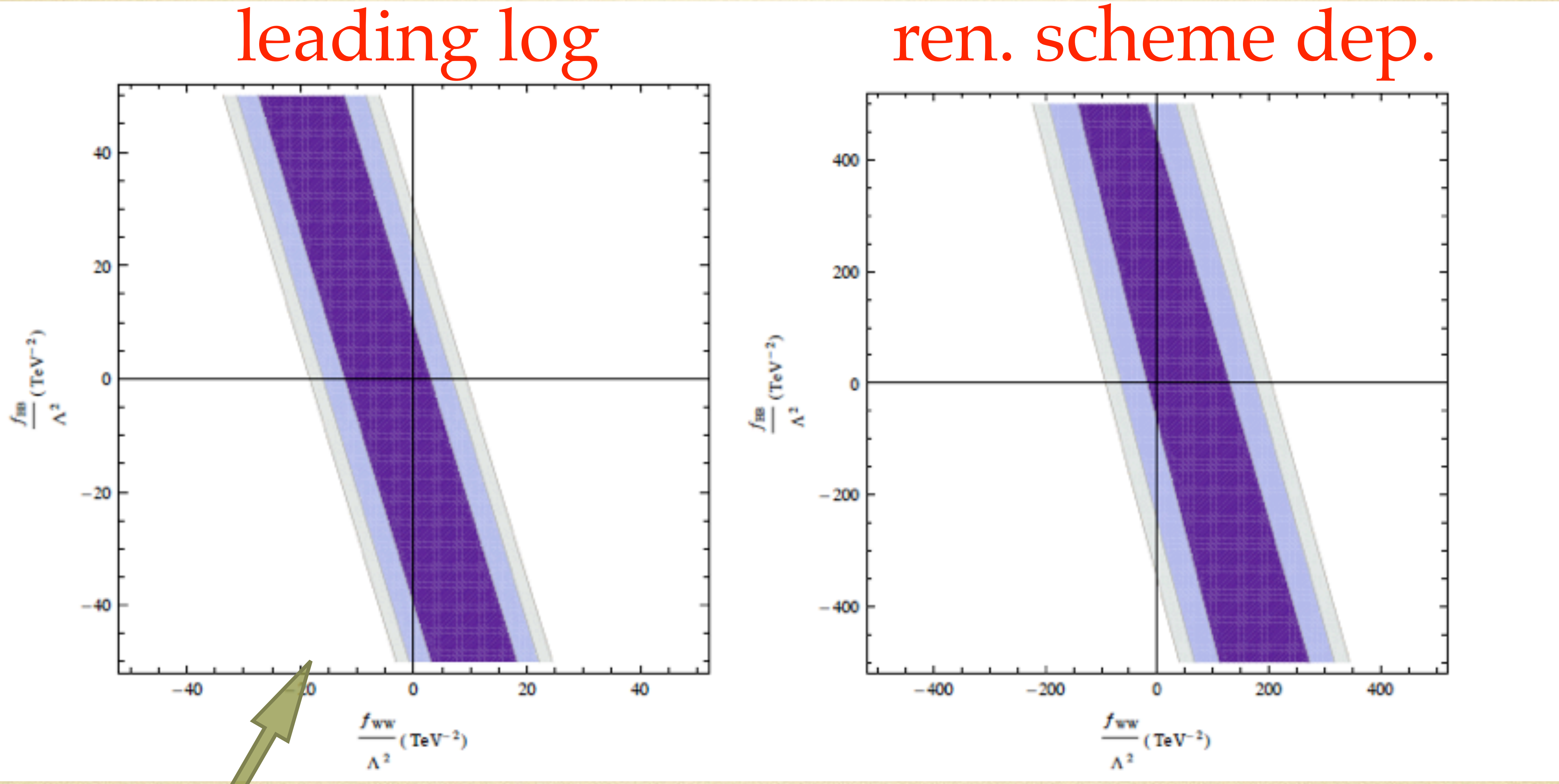
Pomarol and Riva. 1308.2803

Corbett et al. 1211.4580

Higgs data truly complementary to TGCs

Same goes for EWPTs

renormalization/matching is important



results of
Masso, VS. 1211.1320

Cheng, Dawson, Zhang. 1311.3107

operators at loop-order in STU

Higgs data is complementary to EWPT and TGCs

Complete analysis of dim-6 Higgs

Ellis, VS and You.
1404.3667

Number of independent operators in Higgs physics

In the SILH basis

$$\bar{c}_i \equiv \left\{\bar{c}_H, \bar{c}_{t,b,\tau}, \bar{c}_W, \bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_\gamma, \bar{c}_g\right\}.$$

(cB has been eliminated using S)

Other operators affect TGCs and EWPTs but not Higgs

$$\begin{aligned}
\mathcal{L} \supset\ & \frac{\bar{c}_H}{2v^2}\partial^\mu\left[\Phi^\dagger\Phi\right]\partial_\mu\left[\Phi^\dagger\Phi\right] + \frac{g'^2\ \bar{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\ \bar{c}_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G_a^{\mu\nu} \\
+\ & \frac{2ig\ \bar{c}_{HW}}{m_W^2}\left[D^\mu\Phi^\dagger T_{2k}D^\nu\Phi\right]W^k_{\mu\nu} + \frac{ig'\ \bar{c}_{HB}}{m_W^2}\left[D^\mu\Phi^\dagger D^\nu\Phi\right]B_{\mu\nu} \\
+\ & \frac{ig\ \bar{c}_W}{m_W^2}\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi\right]D^\nu W^k_{\mu\nu} + \frac{ig'\ \bar{c}_B}{2m_W^2}\left[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi\right]\partial^\nu B_{\mu\nu} \\
+\ & \frac{\bar{c}_t}{v^2}y_t\Phi^\dagger\Phi\ \Phi^\dagger\cdot\bar{Q}_L t_R + \frac{\bar{c}_b}{v^2}y_b\Phi^\dagger\Phi\ \Phi\cdot\bar{Q}_L b_R + \frac{\bar{c}_\tau}{v^2}y_\tau\ \Phi^\dagger\Phi\ \Phi\cdot\bar{L}_L\tau_R\,.
\end{aligned}$$

Global fit to signal strengths and kinematic distributions

<u>Conclusions of the analysis</u>

1. Breaking of blind directions requires information on associated production (AP)

2. Kinematic distributions in AP is as sensitive (or more) than total rates

Global fit to signal strengths
and kinematic distributions

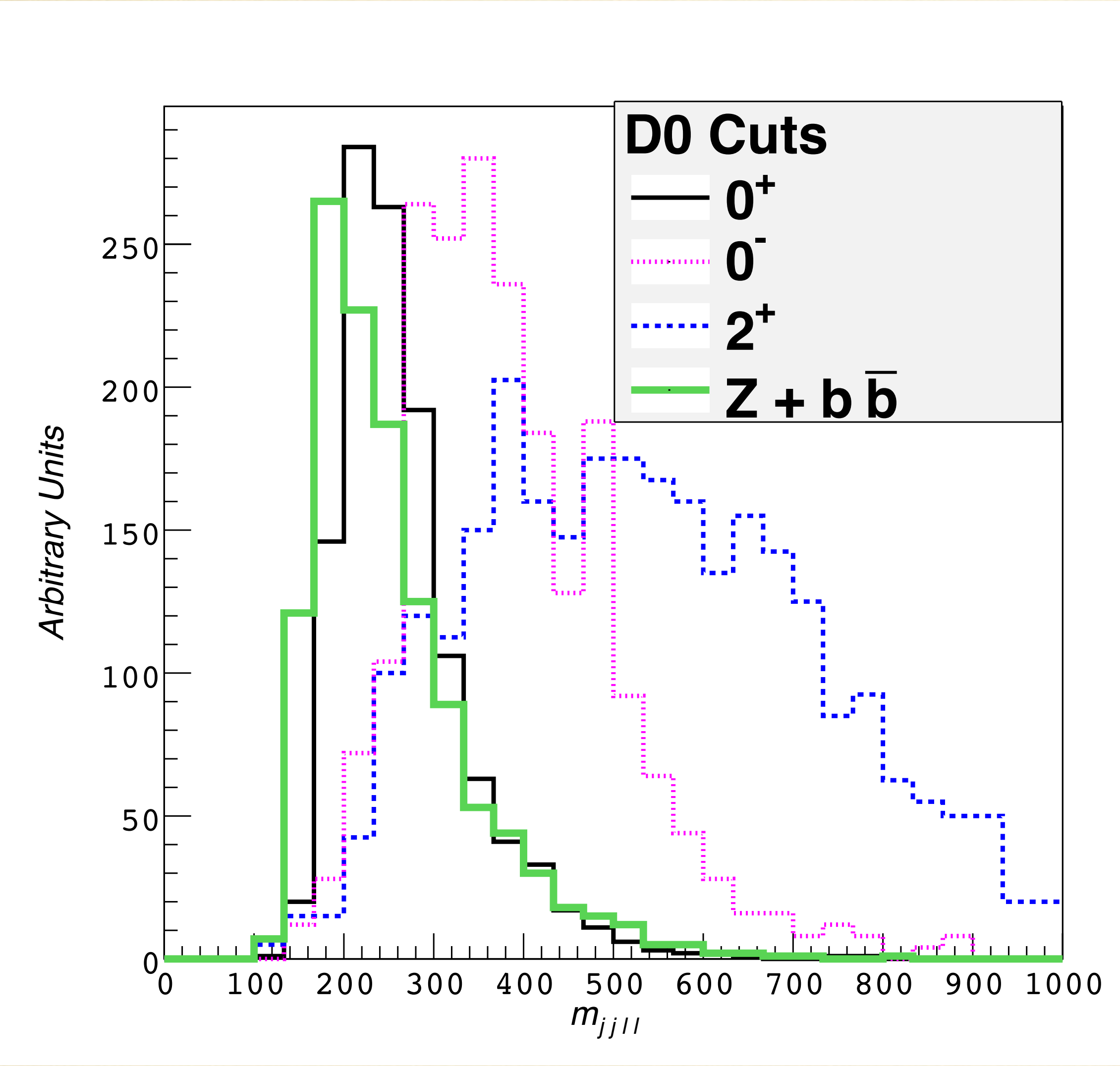
Conclusions of the analysis

1. Breaking of blind directions requires information on associated production (AP)

2. Kinematic distributions in AP is as sensitive (or more) than total rates

Kinematics of associated production

AP is very sensitive to the Lorentz structure of the vertex



Ellis, Hwang, VS, You. 1208.6002

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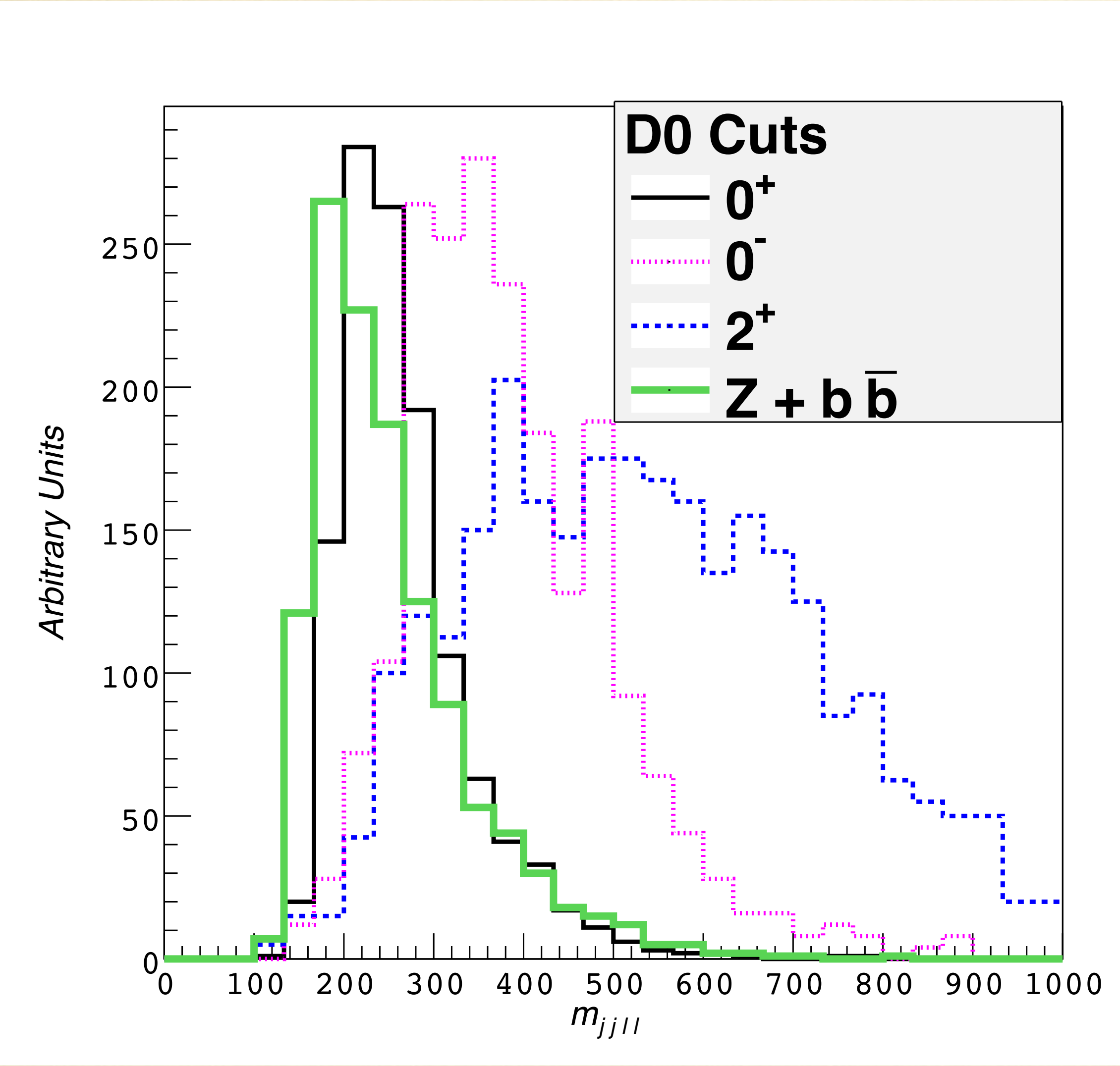
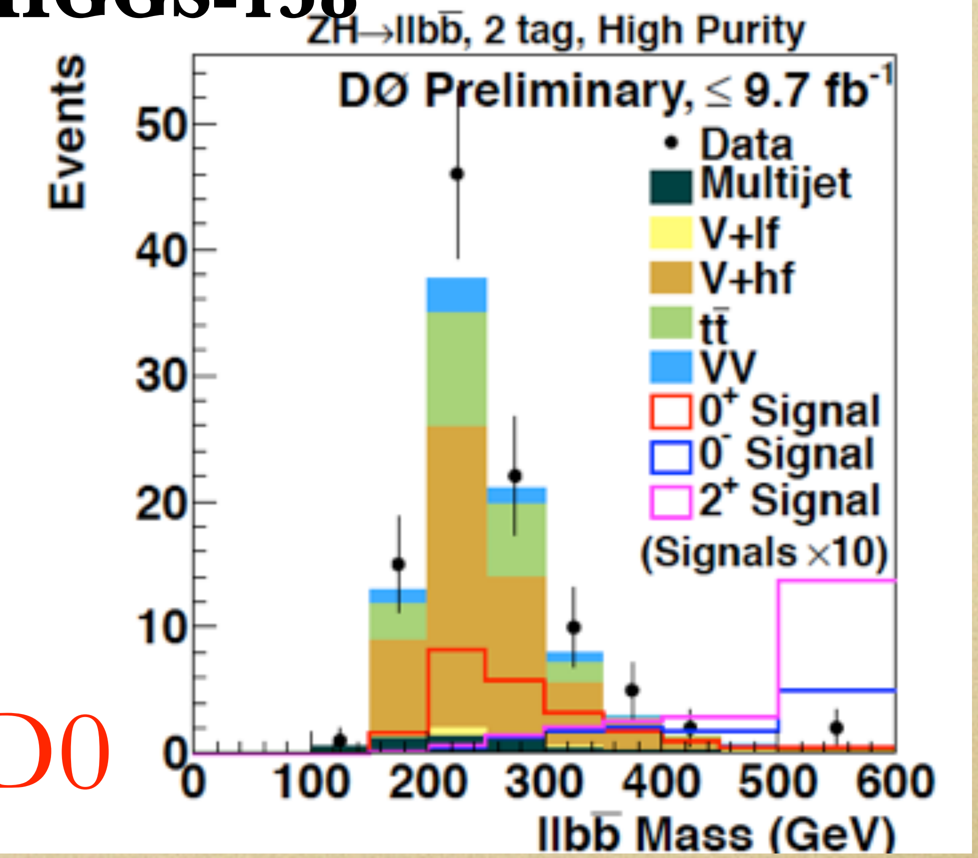


Ellis, Hwang, VS, You. 1208.6002

Test JCP of the Higgs

$$m_{Vh}$$

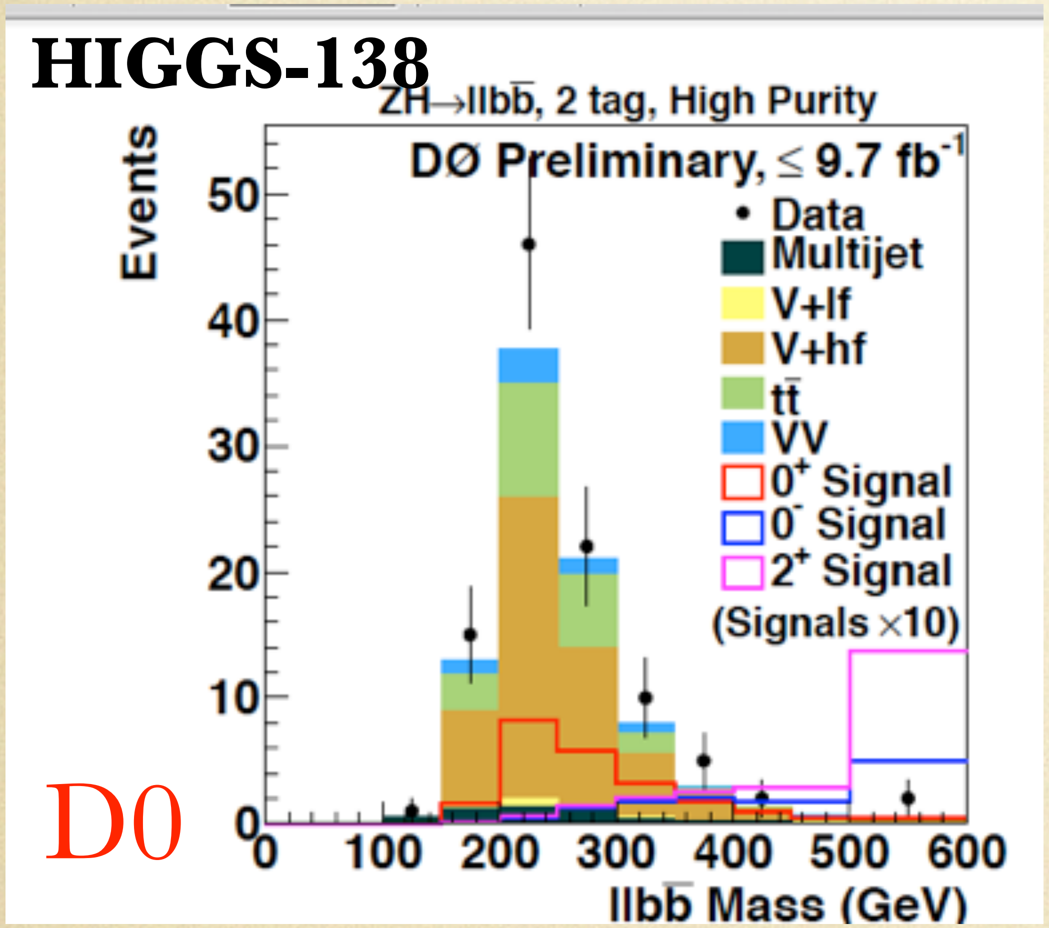
HIGGS-138

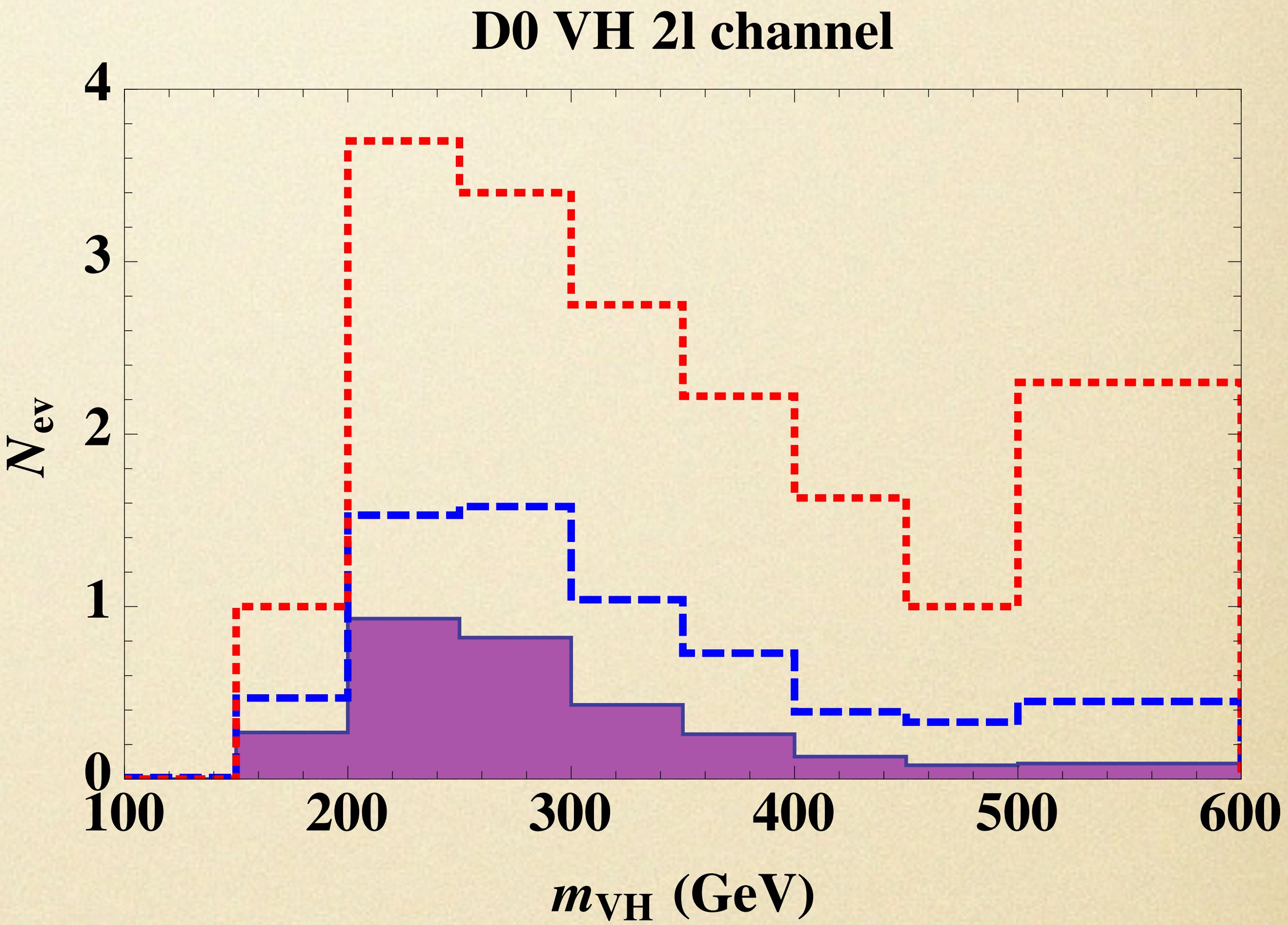


D0

Kinematics of associated production

Higgs' HDOs also have a different Lorentz structure



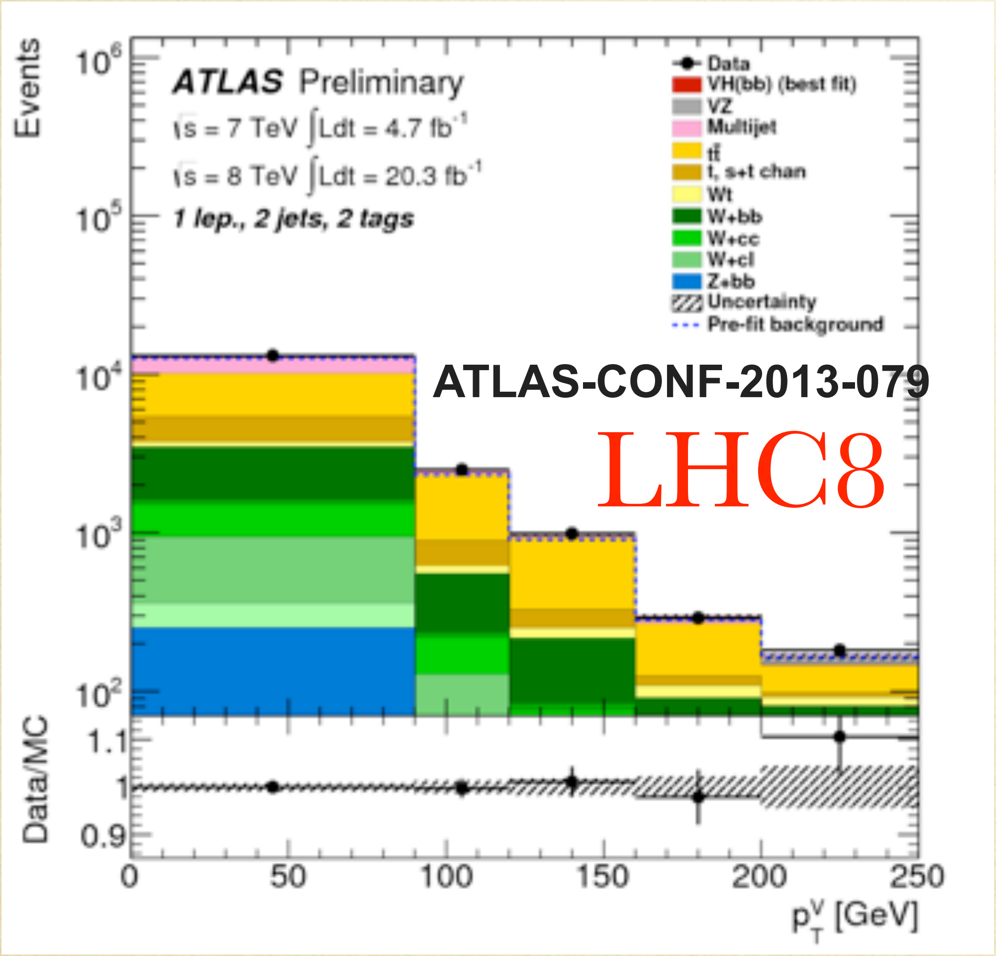


Feynrules -> MG5-> pythia->Delphes3
validate SM/BGs => expectation for HDOs

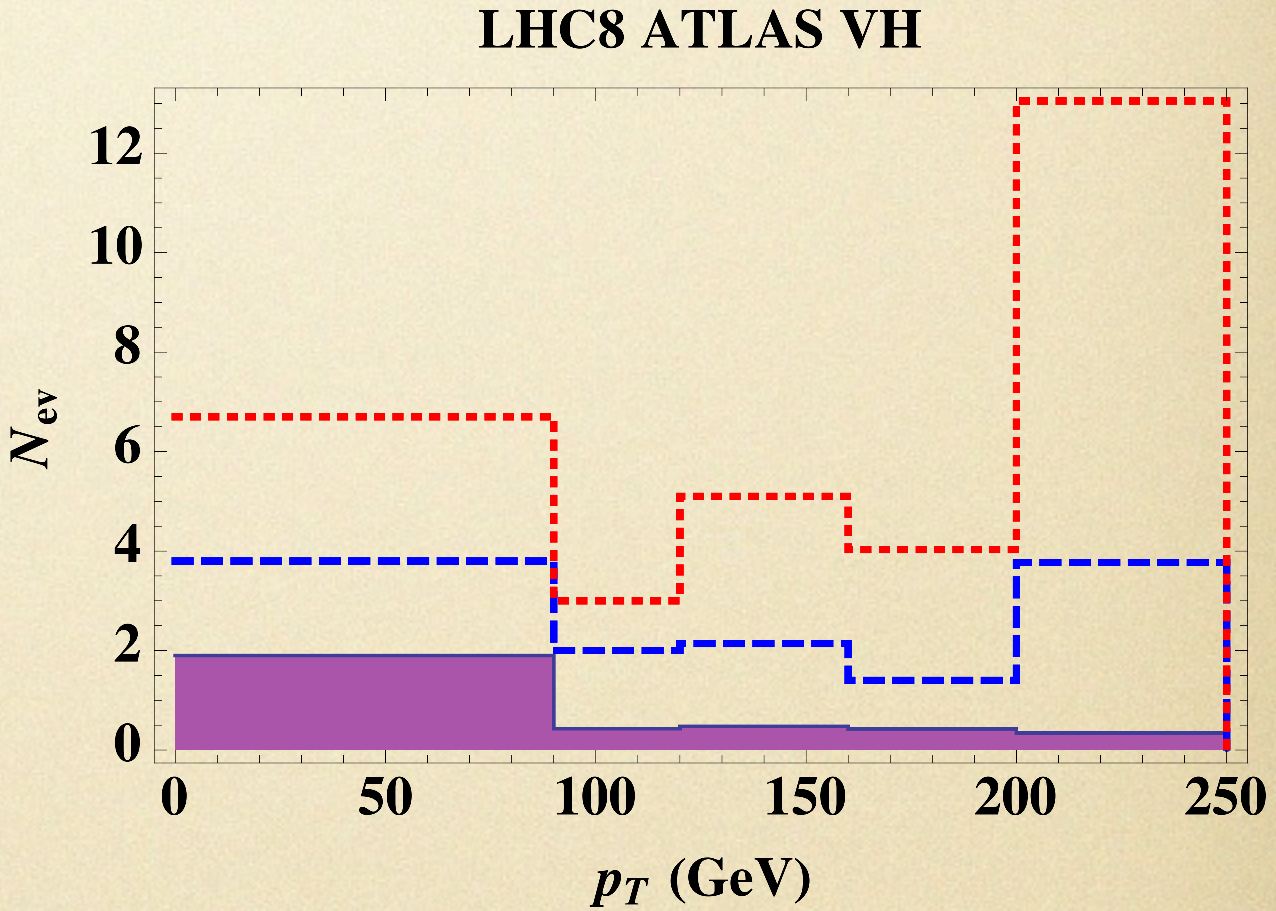
Last bin constraint better than D0 signal strength

Kinematics of associated production

LHC data should be even better



only p_T^V available



Feynrules -> MG5-> pythia->Delphes3

verified for SM/BGs => expectation for HDOs

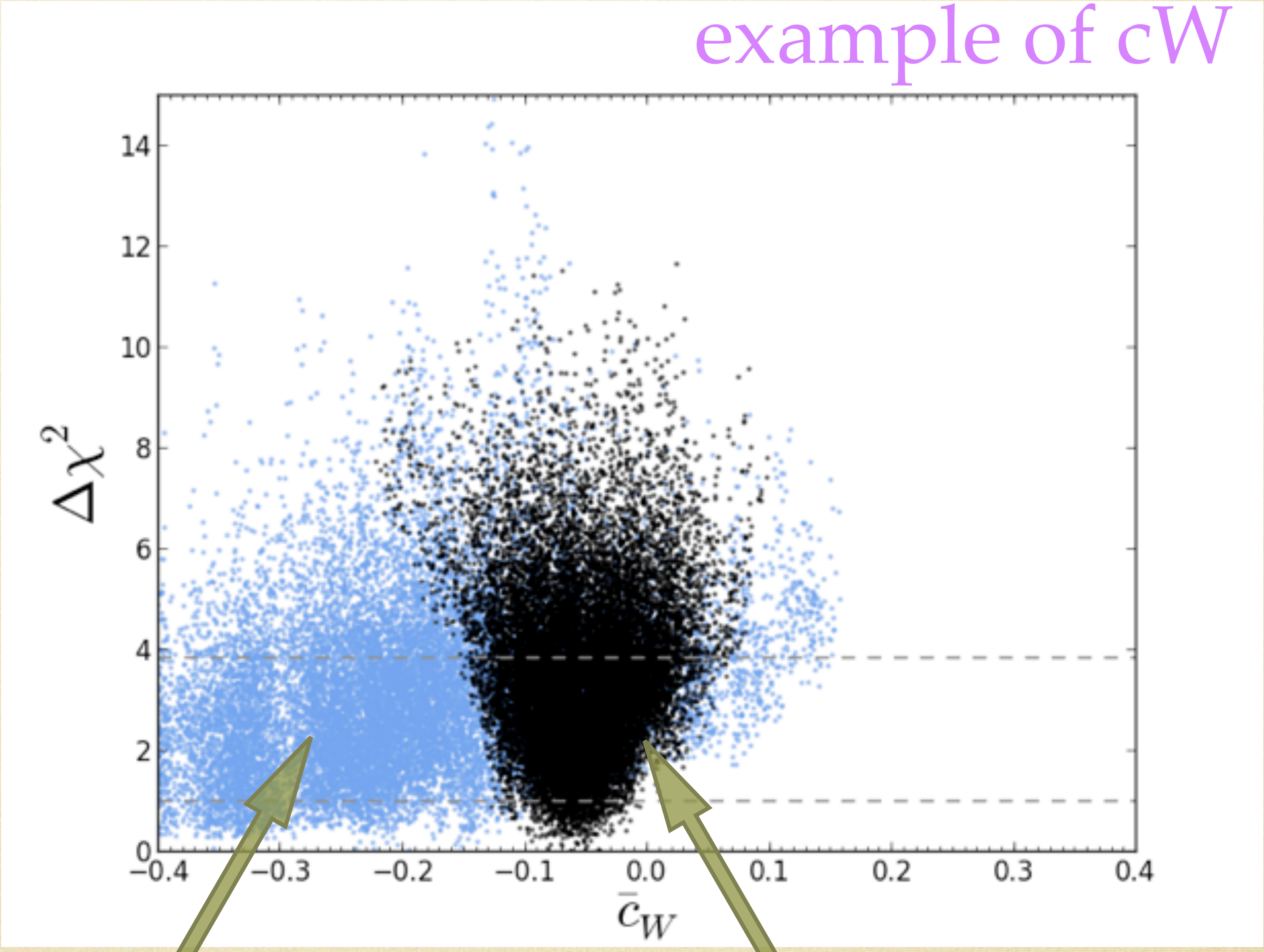
Global fit to signal strengths and kinematic distributions

Conclusions of the analysis

1. Breaking of blind directions requires information on associated production (AP)

2. Kinematic distributions in AP is as sensitive (or more) than total rates

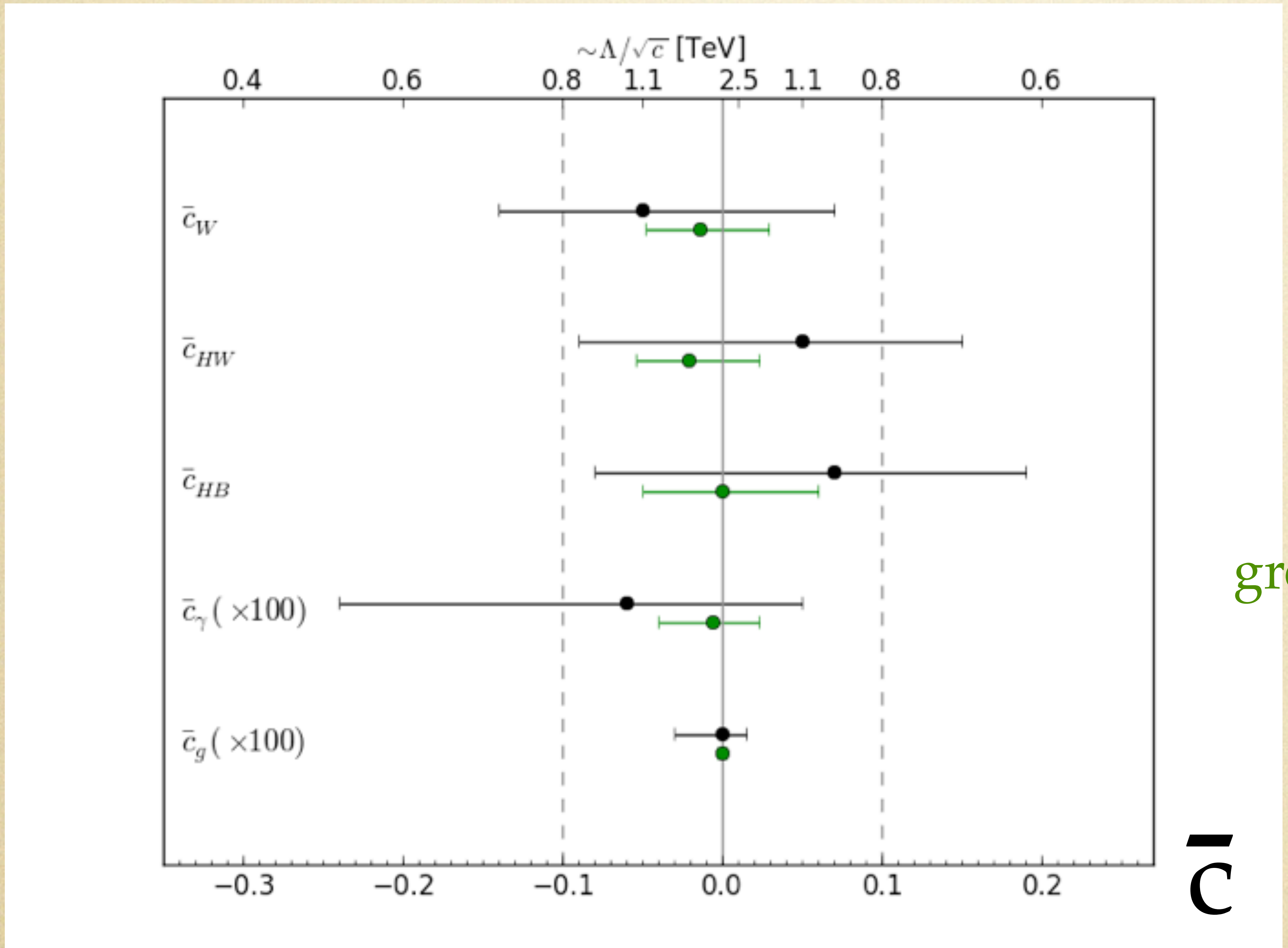
Global fit to 8 parameters



without AP

with AP

In summary



black global fit

green one-by-one fit

ct,cd,cH: no meaningful constraints

Conclusions

Higgs is here, SM-like scalar
this is just the beginning

SUSY and Composite Higgs are in good health
direct/indirect complementarity using Higgs data

Absence of hints in direct searches
EFT approach to Higgs physics

SM precision crucial: excess as genuine new physics

LEP constraints not as powerful as expected
Higgs physics is complementary

Complete global fit to Higgs physics
can use differential information

Framework for HDO studies

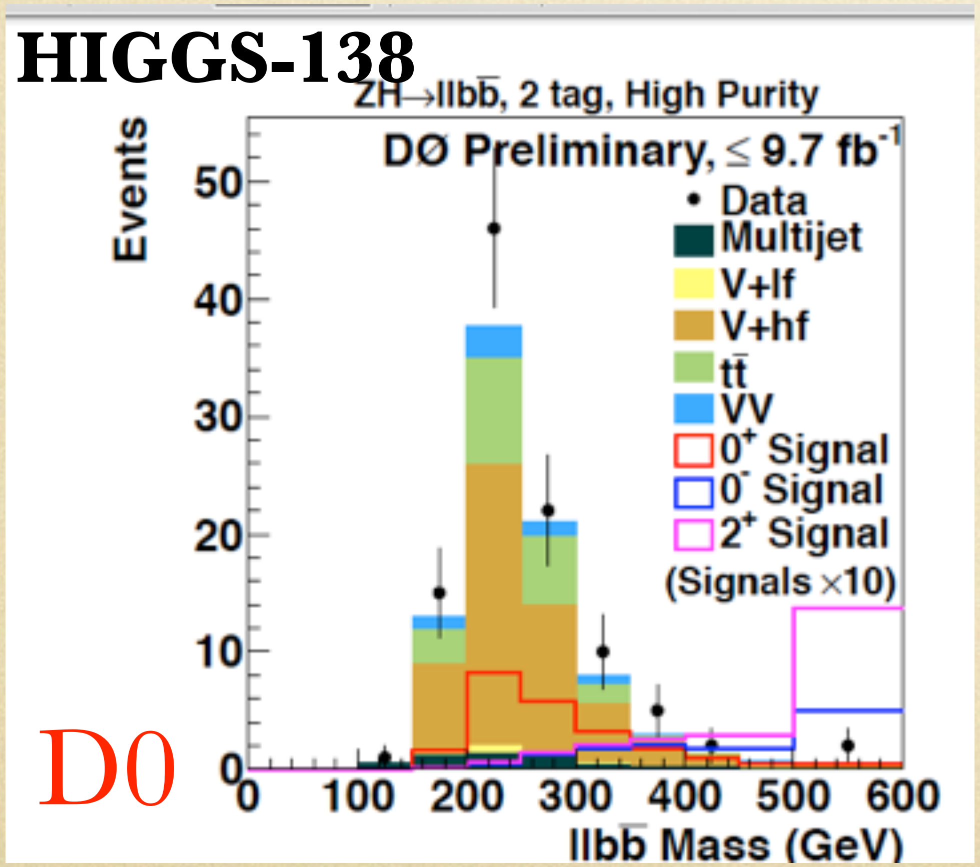
Feynrules HDOs involving Higgs and TGCs

Alloul, Fuks, VS. 1310.5150

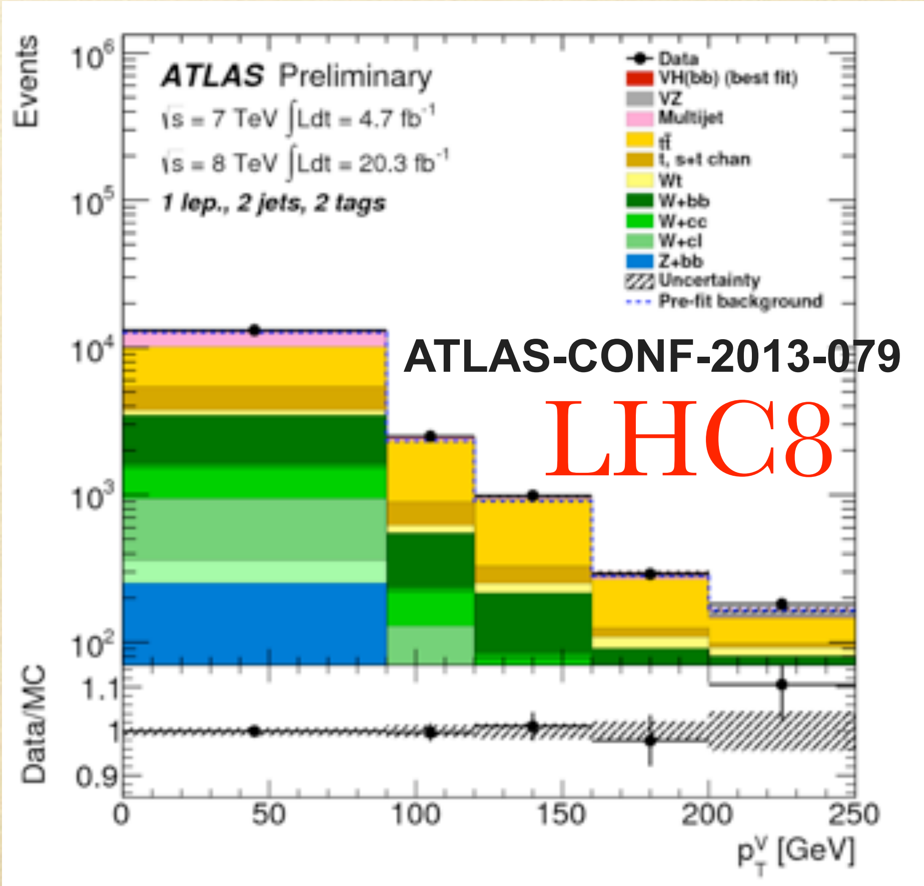
links to CalcHEP, LoopTools, Madgraph...

simulations: HDOs->Madgraph-> Pythia... -> FastSim/FullSim

ex. Higgs in associated production



m_{Vh}



p_T^V

Framework for HDO studies

Feynrules HDOs involving Higgs and TGCs

Alloul, Fuks, VS. 1310.5150

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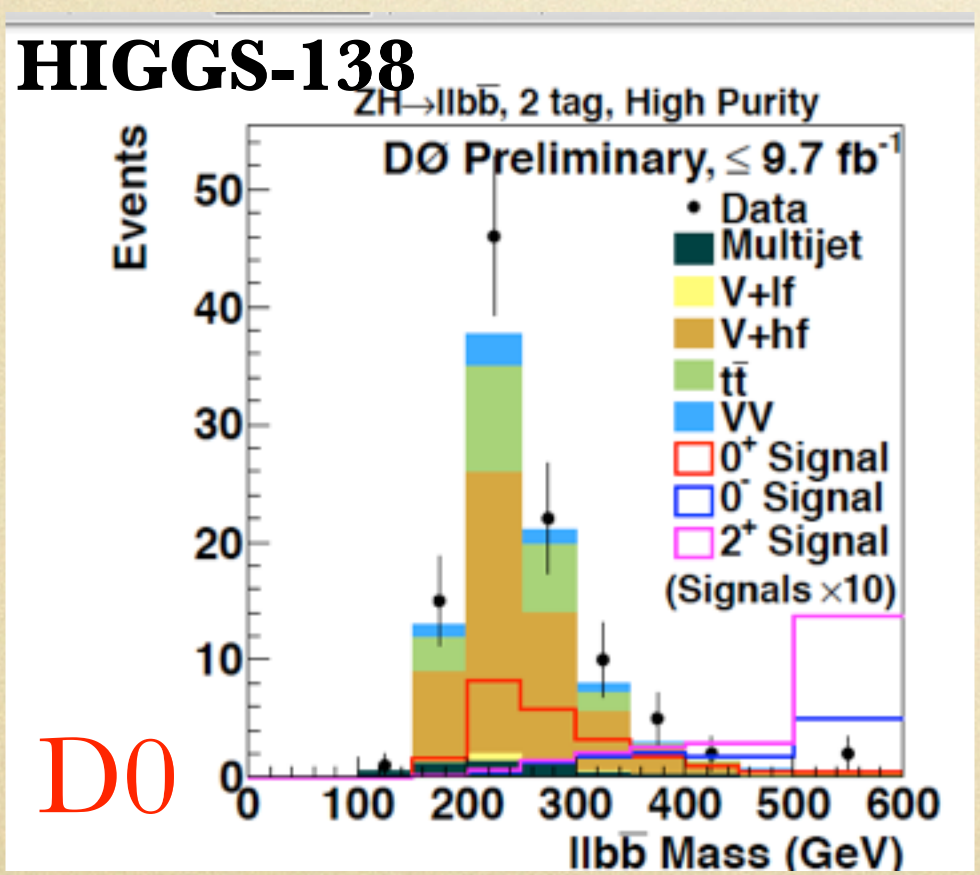
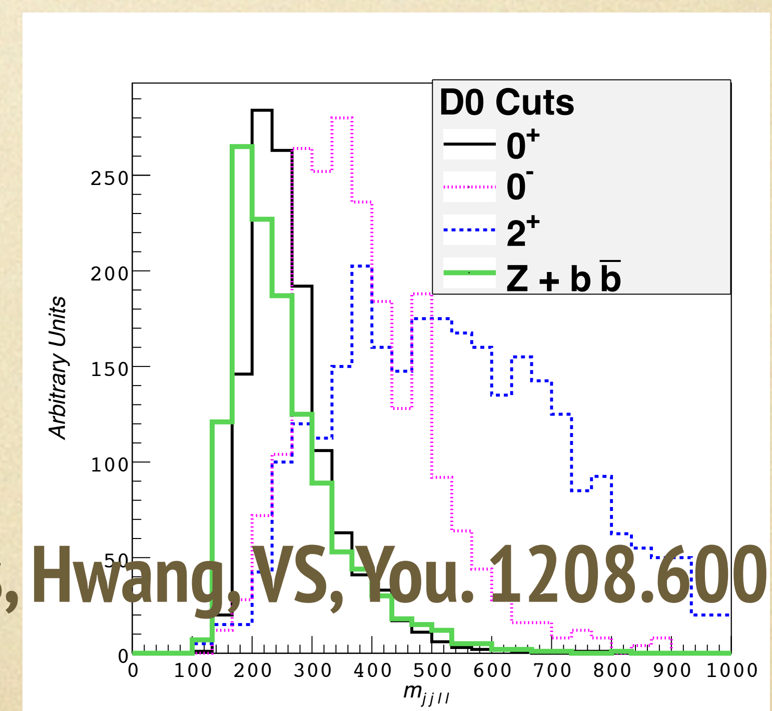
ex. Higgs in associated production



m_{Vh}

Test other JCP



Ellis, Hwang, VS, You. 1208.6002

Three CP-conserving operators affect TGCs

$$\mathcal{L}_{\rm TGC}^{D=6} = \frac{c_{WB}\, g_L g_Y}{m_W^2} B_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H + \frac{i c_W\, g_L}{2 m_W^2} \left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H \right) (D^\nu W_{\mu\nu})^i + \frac{c_{3W}\, g_L^3}{m_W^2} \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$$
$$+ \tilde{c}_{WB} \frac{g_L g_Y}{m_W^2} \tilde{B}_{\mu\nu} W^i_{\mu\nu} H^\dagger \sigma^i H + \frac{\tilde{c}_{3W}\, g_L^3}{m_W^2} \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} \tilde{W}^k_{\rho\mu}. \quad (8)$$

$$\mathcal{L}_{\rm TGC}^{+} = i(1+\delta g_1^V) \left(W^+_{\mu\nu} W^-_\mu - W^-_{\mu\nu} W^+_\mu \right) V_\nu + i(1+\delta\kappa_V)\, V_{\mu\nu}\, W^+_\mu W^-_\nu$$
$$+ i \frac{\lambda_V}{m_W^2} W^+_{\mu\nu} W^-_{\nu\rho} V_{\rho\mu} - g_5^V \epsilon_{\mu\nu\rho\sigma} \left(W^+_\mu \partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu \right) V_\sigma,$$

dim-6 and TGCs

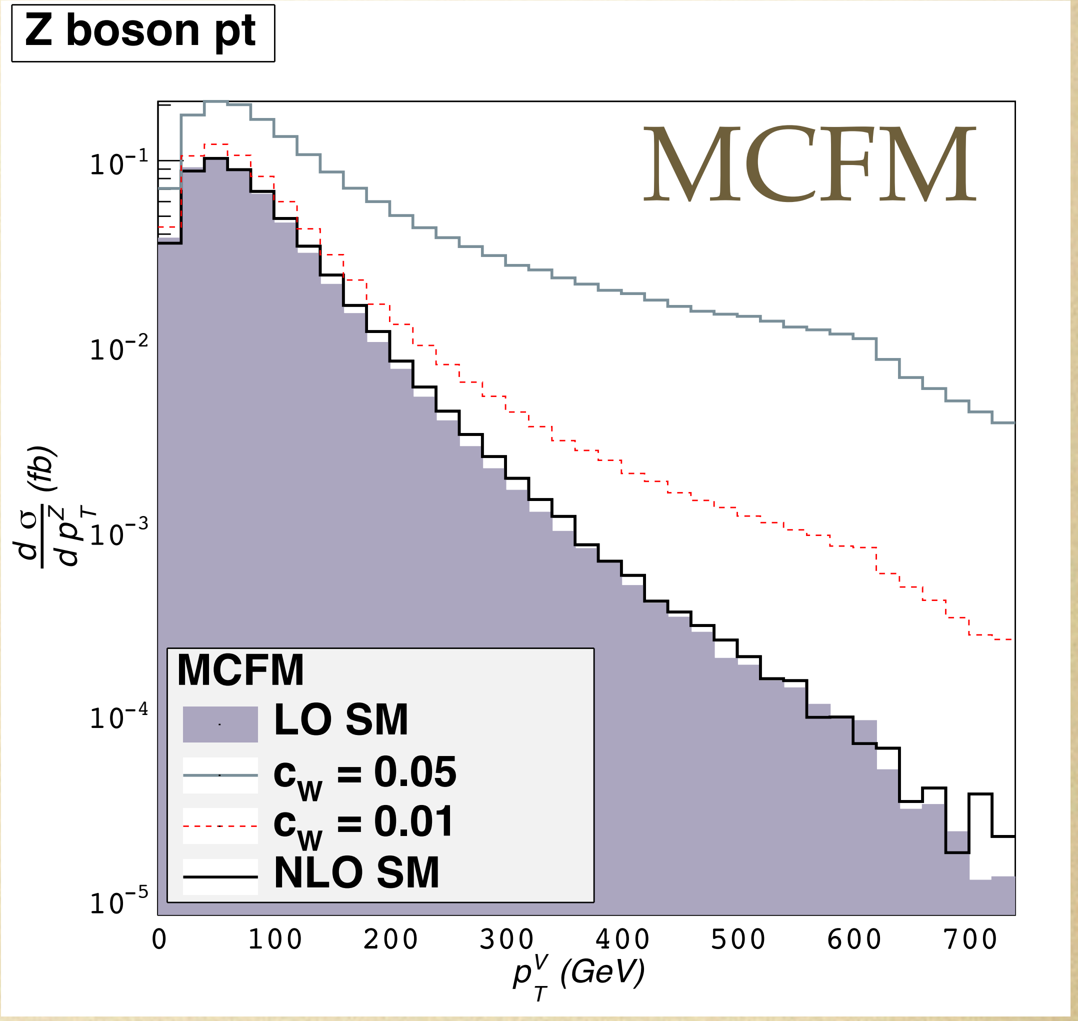
$$\begin{aligned}
\delta\kappa_\gamma &= 4 c_{WB}, \\
\delta\kappa_Z &= -4 \frac{g_Y^2}{g_L^2} c_{WB} - \frac{g_L^2 + g_Y^2}{2 g_L^2} \\
\delta g_Z &= -\frac{g_L^2 + g_Y^2}{2 g_L^2} c_W, \\
\lambda_\gamma = \lambda_Z &= -6 g_L^2 c_{3W}, \\
\tilde{\kappa}_\gamma &= 4 \tilde{c}_{WB}, \\
\tilde{\kappa}_Z &= -4 \frac{g_Y^2}{g_L^2} \tilde{c}_{WB}, \\
\tilde{\lambda}_\gamma = \tilde{\lambda}_Z &= -6 g_L^2 \tilde{c}_{3W},
\end{aligned}$$

cW and cWB
affect Higgs physics
and S-parameter,
but more independent
operators involved

Kinematics of associated production

comment 1:
pTV is more sensitive than mVH to QCD NLO
but effect not yet at the level of operator values we can bound

comment 2:
Sensitivity to quadratic orders in c's (dim-8) is less than current errors.



VS and Williams. In prep.

Boring and necessary details

Bottom-up approach:
operators w/ SM particles and symmetries,
plus the newcomer, the Higgs

Boring and necessary details

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Realization of EWSB

A

Linear or non-linear

Boring and necessary details

Bottom-up approach:
operators w/ SM particles and symmetries,
plus the newcomer, the Higgs

A

Realization of EWSB

Linear or non-linear

B

And the Higgs could be

Weak doublet or singlet

Once this choice is made, expand...

$$\frac{1}{\Lambda^2}$$ Integrating out new physics

$$\frac{v^2}{f^2}$$ Non-linearity $U = e^{i\Pi(h)/f}$

...order-by-order

For example, some operators
Higgs-massive vector bosons

ex.

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

$$\mathcal{O}_W = (D_\mu\Phi)^\dagger \widehat{W}^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_B = (D_\mu\Phi)^\dagger(D_\nu\Phi)\ \widehat{B}^{\mu\nu}$$

$$\mathcal{O}_{WW} = \Phi^\dagger \widehat{W}^{\mu\nu}\widehat{W}_{\mu\nu}\Phi$$

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C

UV theory: tree-level or loop
may need a model bias

ex. SILH

$$\frac{2igc_{HW}}{m_W^2}(D^\mu\Phi^\dagger)\hat{W}_{\mu\nu}(D^\nu\Phi)$$

Giudice, Grojean, Pomarol, Rattazzi. 0703164 redundancies trade off operators using EOM

D Choice of basis

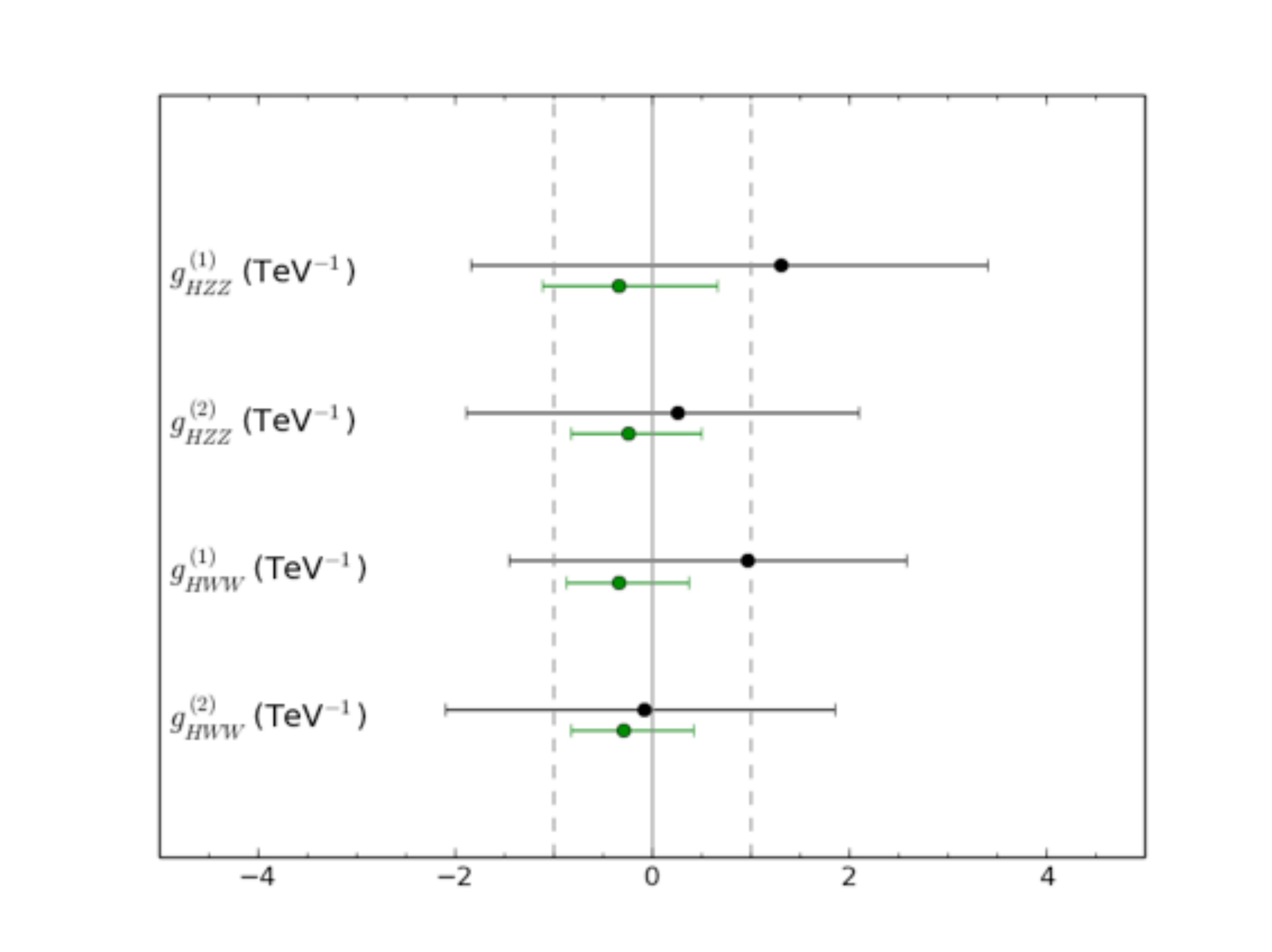
And, **finally**

Observables as a function of HDOs coefficients

In summary

In terms of Higgs' anomalous couplings

$$\mathcal{L} \supset - \frac{1}{4} g^{(1)}_{HZZ} Z_{\mu\nu} Z^{\mu\nu} h - g^{(2)}_{HZZ} Z_\nu \partial_\mu Z^{\mu\nu} h$$
$$- \frac{1}{2} g^{(1)}_{HWW} W^{\mu\nu} W^\dagger_{\mu\nu} h - \left[g^{(2)}_{HWW} W^\nu \partial^\mu W^\dagger_{\mu\nu} h + \text{h.c.} \right],$$



black global fit
green one-by-one fit