Physics beyond the Standard Model

after the 125 GeV Higgs discovery

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Christophe Grojean

ICREA@IFAE/Barcelona

(christophe.grojean@cern.ch)

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RECERCA I ESTUDIS AVANÇATS

Where are we?

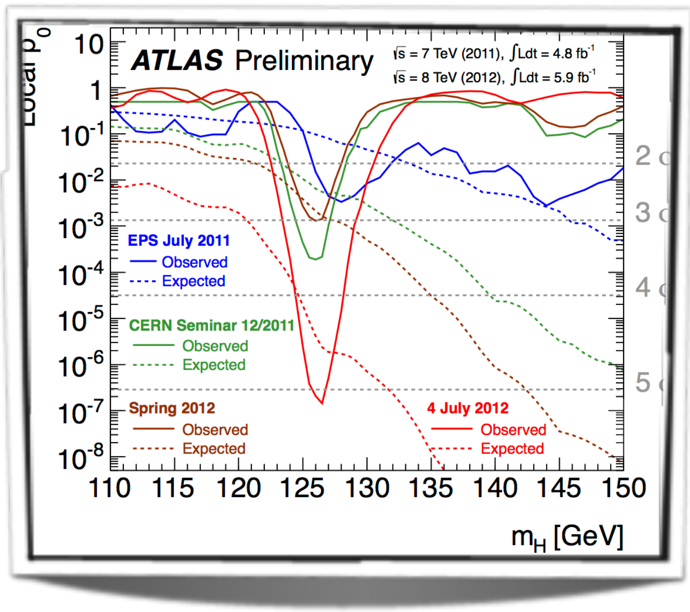
we are living a privileged moment in the history of HEP

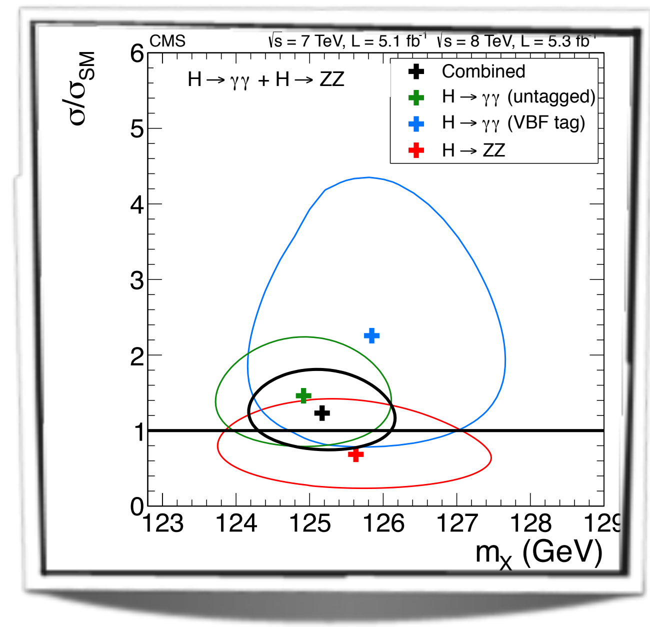
"We have found a new particle" CMS

Where are we? What's next?

we are living a privileged moment in the history of HEP

"We have found a new particle" CMS





"this discovery came at half the LHC design energy, much more severe pileup, and one-third of the integrated luminosity that was originally judged necessary" ATLAS

Higgs is the most exotic particle of the "SM"

its discovery has profound implications

- Spin 0? Against naturalness: small mass only if protected by symmetry
- Couplings not dictated by gauge symmetry? Against gauge principle (elegance, predictivity, robustness, variety) which used to rule the world (gravity, QCD, QED, weak interactions)
- Triumph of QM+SR that predict (anti)particles of spin 0, 1/2, 1, (3/2 ?), 2

Now what? What's next?

" With great power comes great responsibility "

Voltaire & Spider-Man

which, in particle physics, really means

" With great discoveries come great measurements "

BSMers desperately looking for anomalies
(true credit: F. Maltoni
actually, first google hit gives a link to an article of
the Guardian on... the Higgs boson!)

1

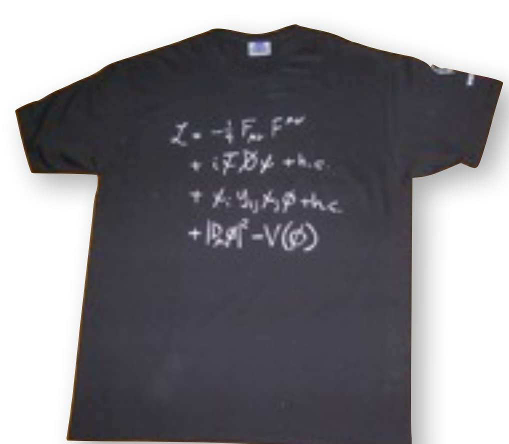
Higgs properties

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

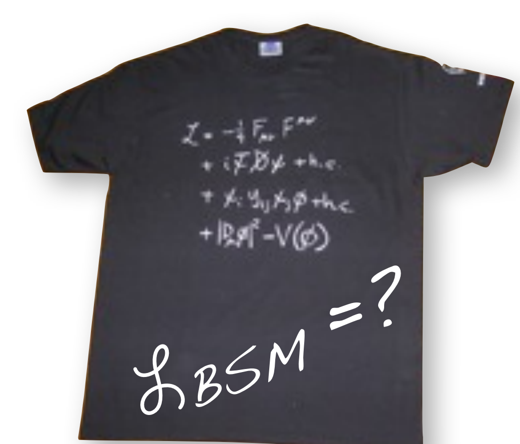
2

Higgs couplings



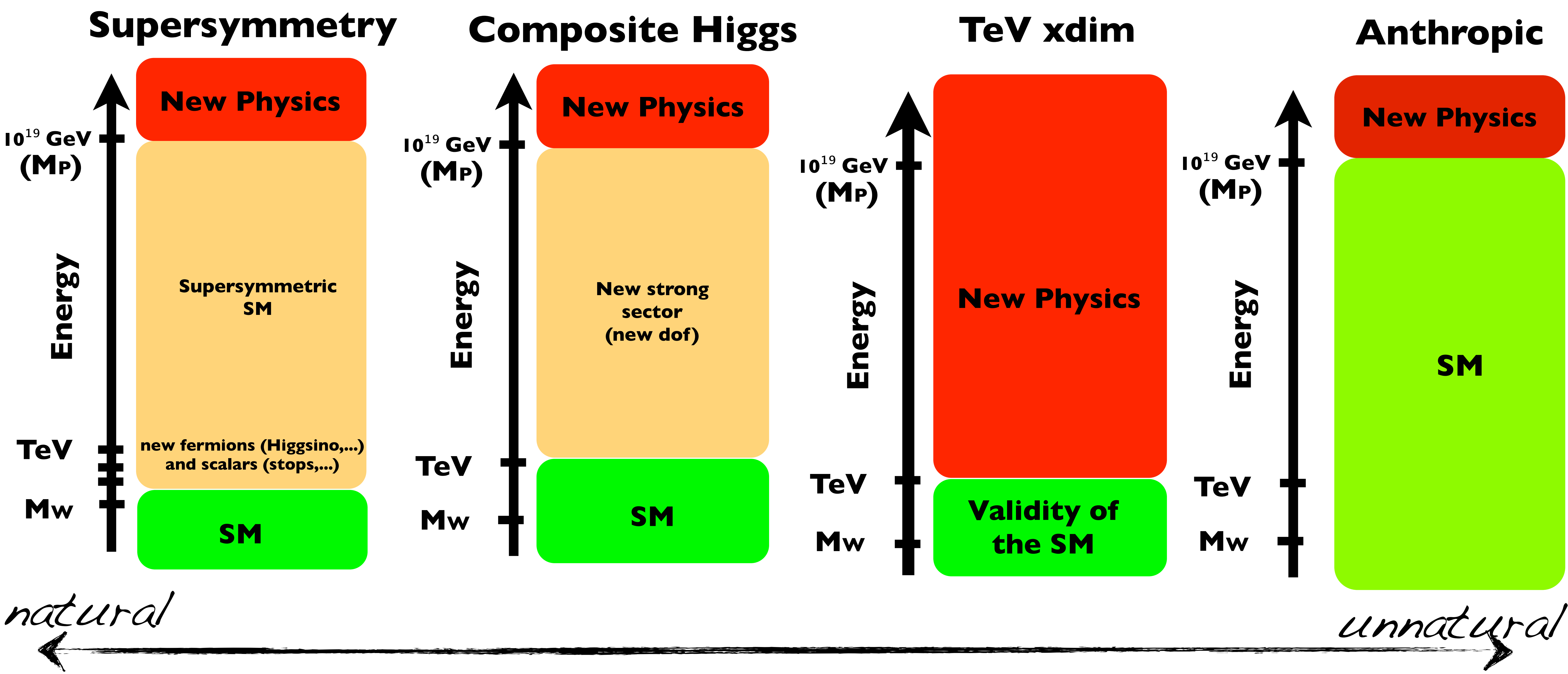
3

BSM implications



Which New Physics?

A. Pomarol, lecture @ CERN, '13



still plausible
but may be not in their
minimal/simplest incarnations

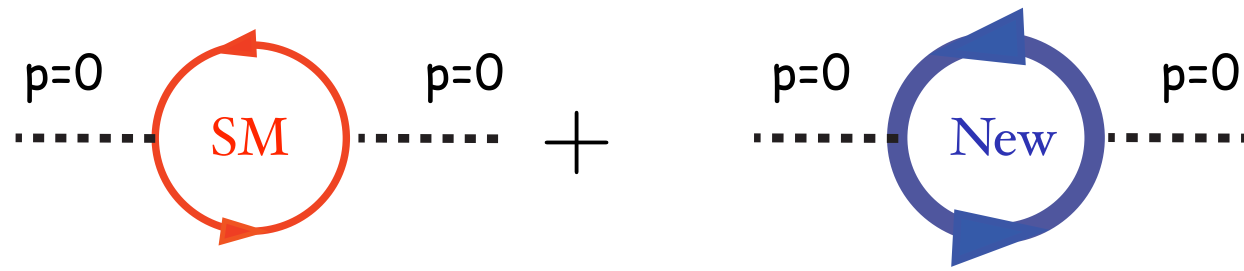
unlikely

Will we
ever
know?

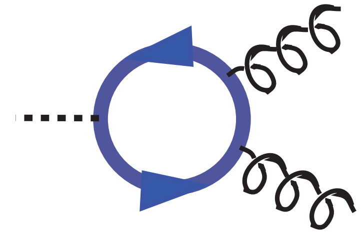
(can the Nature be unnatural?)

Higgs couplings = test of Naturalness?

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

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

generically



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

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

$$\frac{g_*^2}{16\pi^2}\frac{1}{m_*^2}\left(\partial_\mu |H|^2\right)^2$$

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

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

nice to be able to measure Γ

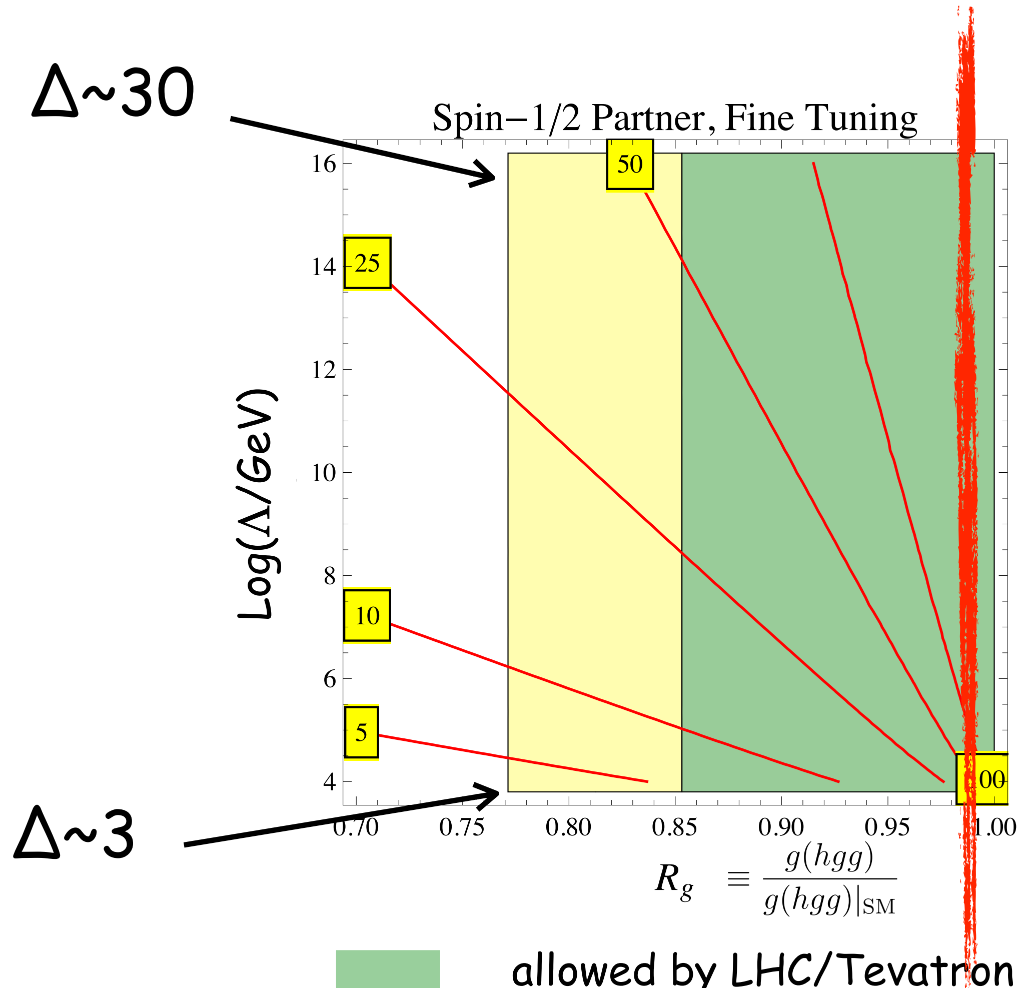
Generically, natural scenarios come with deviations of the Higgs coupling

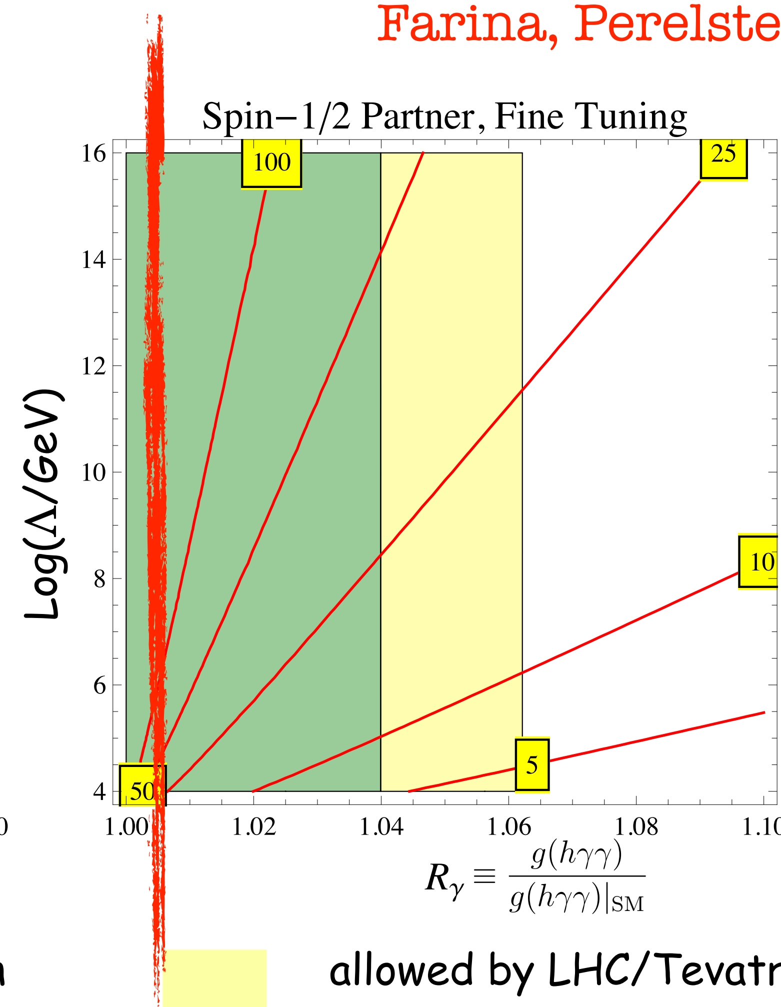
Higgs couplings = test of Naturalness?

simple toy model: a single spin-$\frac{1}{2}$ top partner

deviations in the couplings ⇔ amount of fine-tuning $\Delta = \delta m_H^2 / m_H^2$

Farina, Perelstein, Rey-Le Noisier, '13





allowed by LHC/Tevatron at 68%CL

allowed by LHC/Tevatron at 95%CL

Λ cutoff scale of log. divergences to the Higgs mass

High scale models ($\Lambda \sim 10^{16}$GeV) come with a generic fine-tuning O(1/30)

increasing the couplings measurement to 1% precision will raise the fine-tuning to O(1/400)

Higgs couplings = test of Naturalness?

MSSM: more complicated situation: 2 (spin-0) stops w/ mixing

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

$$F_{\tilde t} = -\frac{1}{3}\left[\frac{m_t^2}{m_{\tilde t_1}^2}+\frac{m_t^2}{m_{\tilde t_2}^2}-\frac{1}{4}\,\sin^2(2\,\theta_t)\,\frac{\delta m^4}{m_{\tilde t_1}^2\,m_{\tilde t_2}^2}\right].$$

Small mixing: $F_{\tilde t} < 0$ → $\Gamma(gg\to h)$ enhanced, $\Gamma(h\to\gamma\gamma)$ suppressed

Large mixing: $F_{\tilde t} > 0$ → $\Gamma(gg\to h)$ suppressed, $\Gamma(h\to\gamma\gamma)$ enhanced

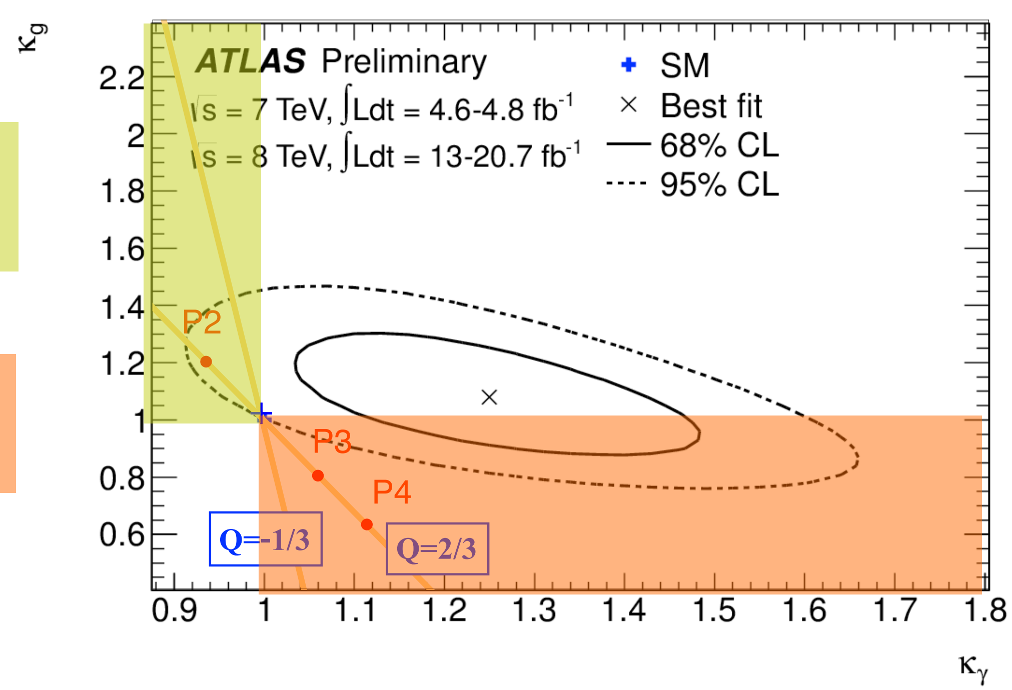
P1: $m_{\tilde t_1}=100\,\text{GeV},\ m_{\tilde t_2}=300\,\text{GeV},\ \theta_t=0$

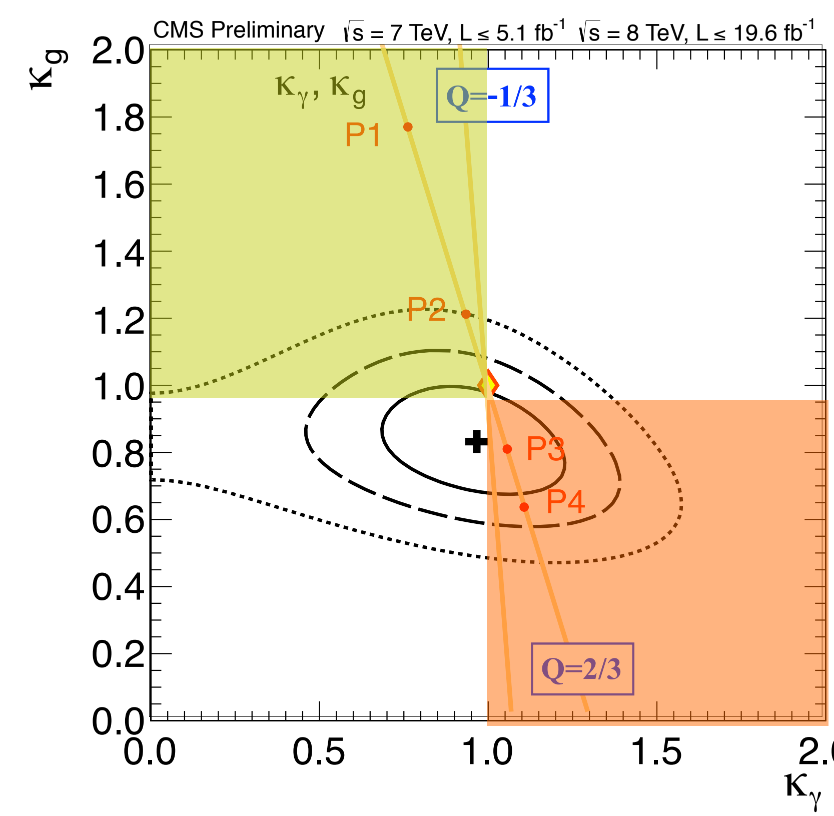
P2: $m_{\tilde t_1}=200\,\text{GeV},\ m_{\tilde t_2}=500\,\text{GeV},\ \theta_t=0$

P3: $m_{\tilde t_1}=400\,\text{GeV},\ m_{\tilde t_2}=1000\,\text{GeV},\ \theta_t=\pi/4$

P4: $m_{\tilde t_1}=500\,\text{GeV},\ m_{\tilde t_2}=1500\,\text{GeV},\ \theta_t=\pi/4$

Contino, Genova '13





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

Higgs couplings = test of Naturalness?

$$\frac{\Delta g}{g_{SM}} \approx \frac{g_*^2 v^2}{m_*^2} \approx ?$$

to which level of precision do we need to measure the Higgs couplings
to probe the naturalness of the theory?

Models where the Higgs mass is UV insensitive

$$m_H^2 \sim \frac{N_c y_t^2}{16\pi^2} m_*^2 \quad \Rightarrow \quad \frac{\Delta g}{g_{SM}} \sim \frac{N_c g*^2}{16\pi^2}$$

~ 1 for strongly coupled models

~ 1% for weakly coupled models

Models where the Higgs mass has a UV logarithmic insensitivity

e.g. high scale susy breaking

$$m_H^2 \sim \frac{N_c y_t^2}{16\pi^2} m_*^2 \log(\Lambda/m_*) \quad \Rightarrow \quad \frac{\Delta g}{g_{SM}} \sim \frac{N_c g*^2}{16\pi^2} \log(\Lambda/m_*)$$

~ 1

O(1%) precision Higgs physics could be as important as direct searches for new physics
to probe the naturalness of EWSB

Weakly coupled models

Higgs & SUSY/MSSM

no new super-particles ⋯▸ decoupling limit?

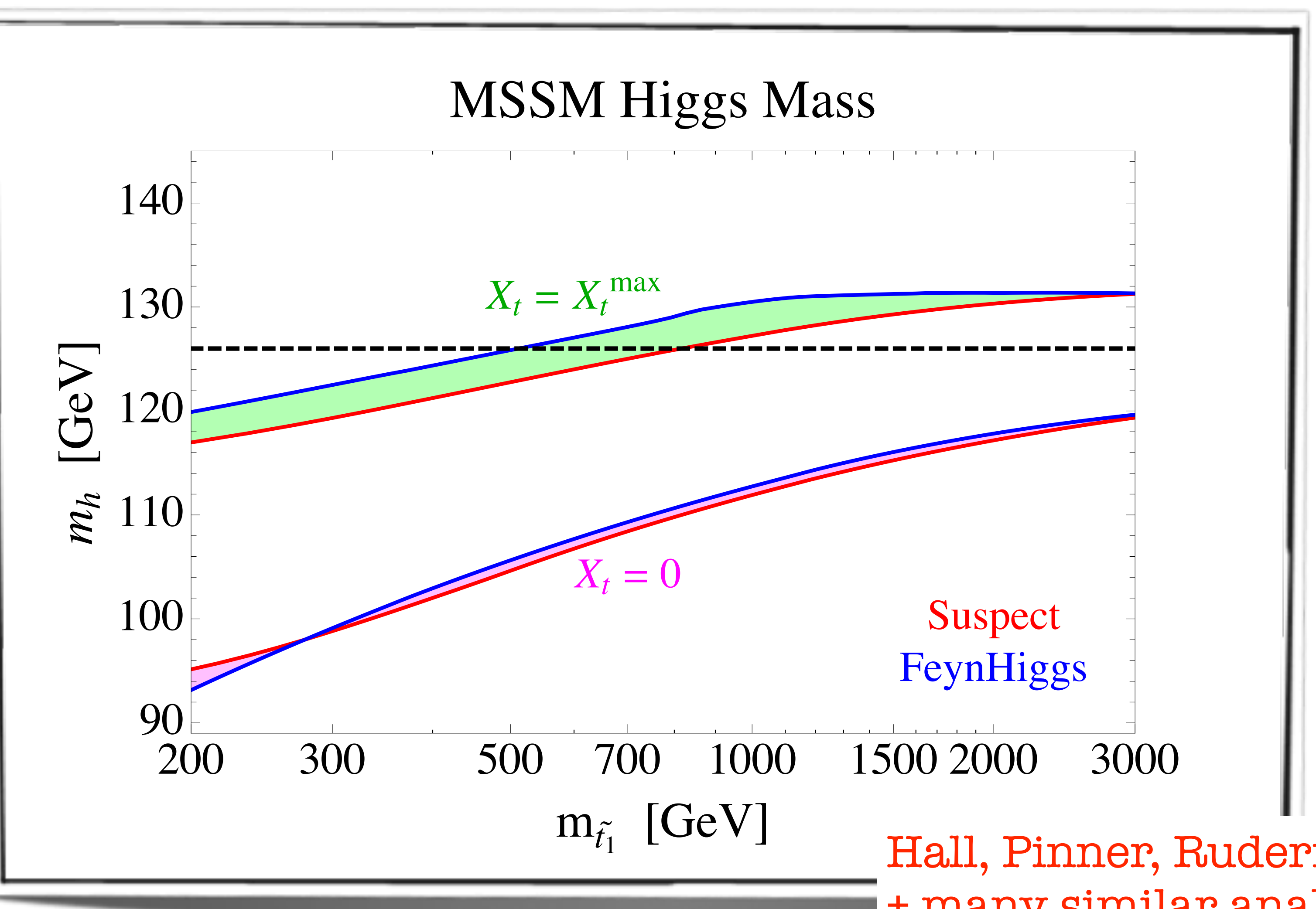
high Higgs mass
implies
susy is badly broken

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

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

$(\gtrsim 87\mathrm{GeV})^2$

substantial loop contribution
from stops



Hall, Pinner, Ruderman '11
+ many similar analyses

large mixing
heavy stops

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

⇓ ⇓

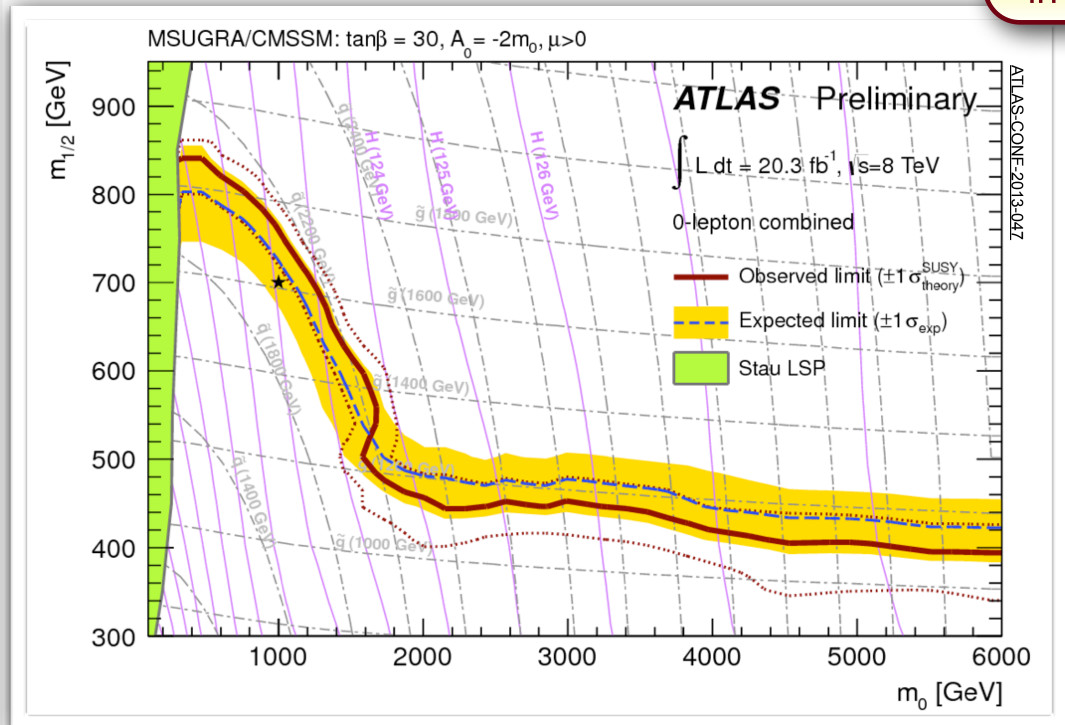
irreducible
fine-tuning ~ O(1%)

Cornering SUSY parameter space

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

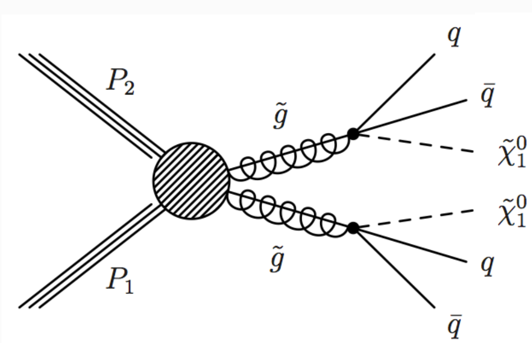
here: example of scenario compatible with a low-mass Higgs as recently discovered

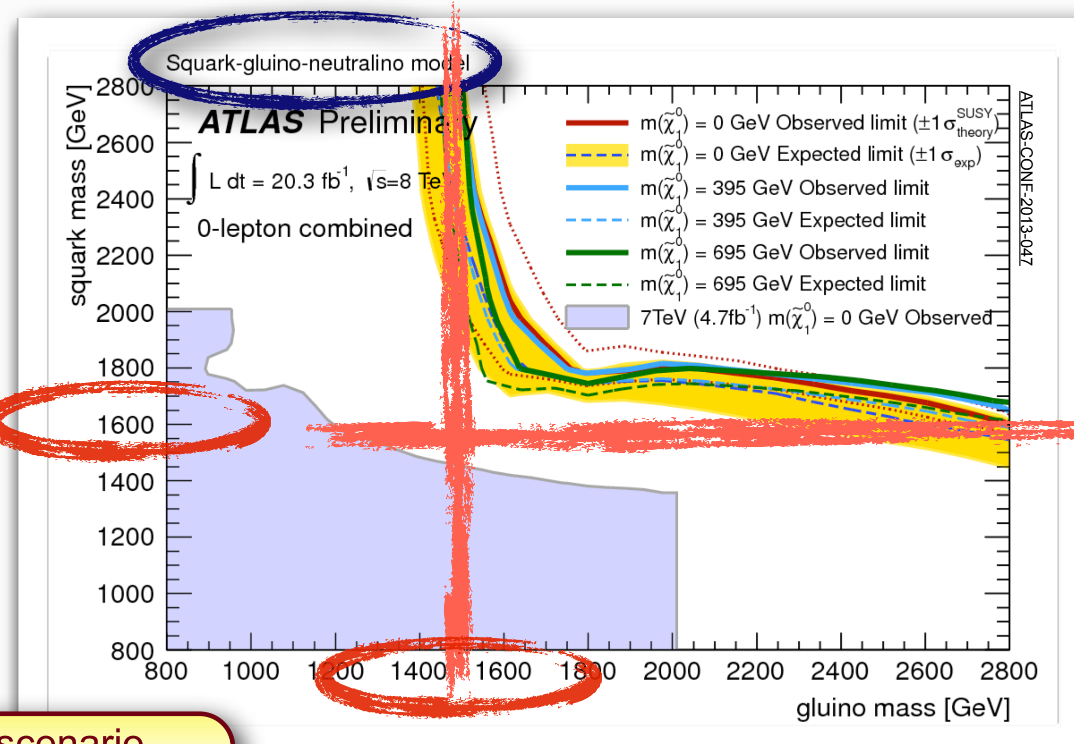
Dissertori, ECFA '13



- eg. for m(squark) = m(gluino), exclude below ~1800 GeV
- these searches typically target large M_{eff} and large difference m(SUSY) - m(LSP)
- the very inclusive searches keep sensitivity even for m(LSP) up to several hundreds of GeV (at some stage trigger-constrained)

- recently also targeting more compressed spectra and higher jet multiplicities





in the context of a simplified MSSM scenario

These bounds are not "robust" and don't exclude weak scale SUSY but call for non-minimal models

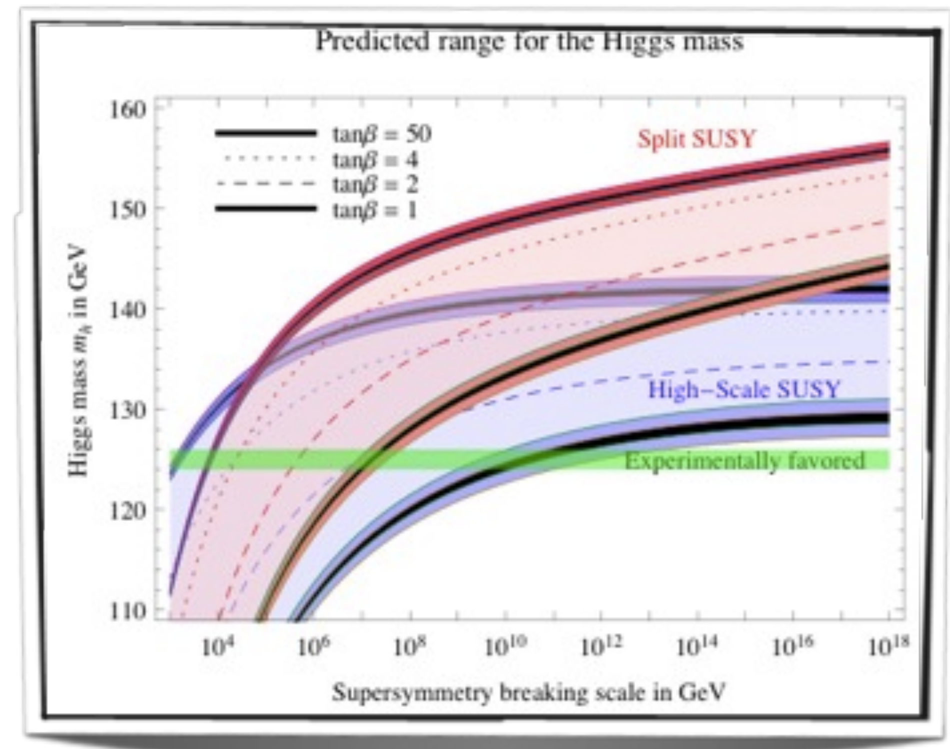
Saving SUSY

SUSY is Natural
but not plain vanilla

- ~~CMSSM~~
- pMSSM
- NMSSM
- Hide SUSY
  - reduce production (eg. split families) Mahbubani et al
  - reduce MET (e.g. ~~R-parity~~, compressed spectrum) Csaki et al

Should be priority #1

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



Giudice, Strumia '11

unification etc... → Split SUSY:
susy scalars @ m_{susy}, susy fermions @ m_Z

string etc... → high scale SUSY:
susy scalars & susy fermions @ m_{susy}

Strongly coupled models

Composite Higgs Models

Higgs anomalous couplings ➲ strong scatterings ➲

resonances production ➲

What is the SM Higgs?

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

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

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

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 and Z_L) combine to form a linear representation of $SU(2)_L \times U(1)_Y$

The New Physics Mass Gap

One solution to the hierarchy pb:

Higgs transforms non-linearly under some global symmetry

Higgs=Pseudo-Goldstone boson (PGB)

SM: $SO(4)/SO(3)$ — $W^{\pm}_L$ & Z_L ⇒ BSM: G/H — $W^{\pm}_L$ & Z_L & h

Examples:

$SO(5)/SO(4)$: 4 PGBs=$W^{\pm}_L$, Z_L, h ← Minimal Composite Higgs Model

Agashe, Contino, Pomarol '04

$SO(6)/SO(5)$: 5 PGBs=H, a ← Next MCHM

Gripaios, Pomarol, Riva, Serra '09

$SU(4)/Sp(4,\mathbb{C})$: 5 PGBs=H, s

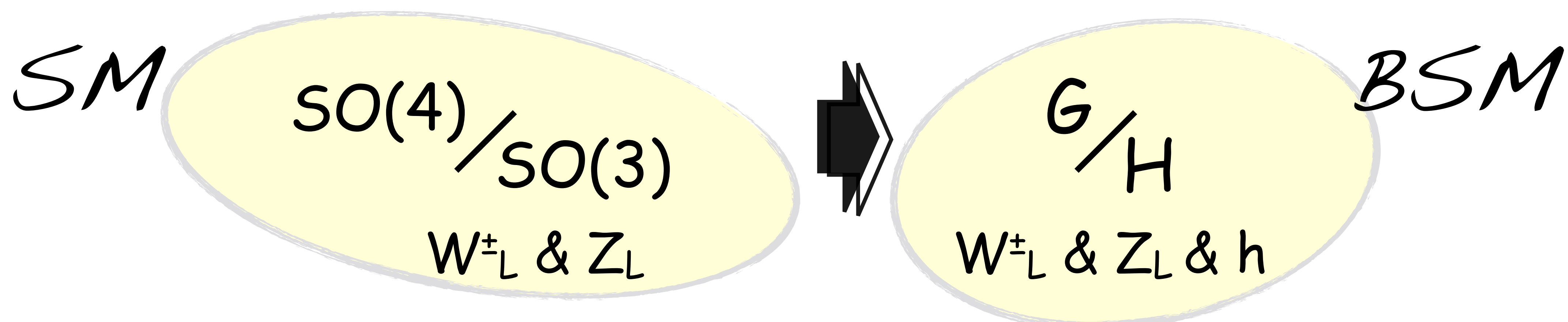
$SO(6)/SO(4)\times SO(2)$: 8 PGBs=H_1+H_2 ← Minimal Composite Two Higgs Doublets

Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11

Higgs as a PGB: a natural extension of SM

One solution to the hierarchy pb:
Higgs transforms non-linearly under some global symmetry

Higgs=Pseudo-Goldstone boson (PGB)



How can we tell the difference with the SM Higgs?

Two scale dynamics:

✗ f=scale of strong dynamics=compositeness scale of the Higgs

✗ v=246GeV radiatively generated

f~v: Technicolor --- f>>v: SM

Composite Higgs vs. Technicolor?

Two different models of strong interactions

technicolor	strong sector with a single scale	$f \sim v$
composite Higgs	strong sector with two scales	$f \gg v$

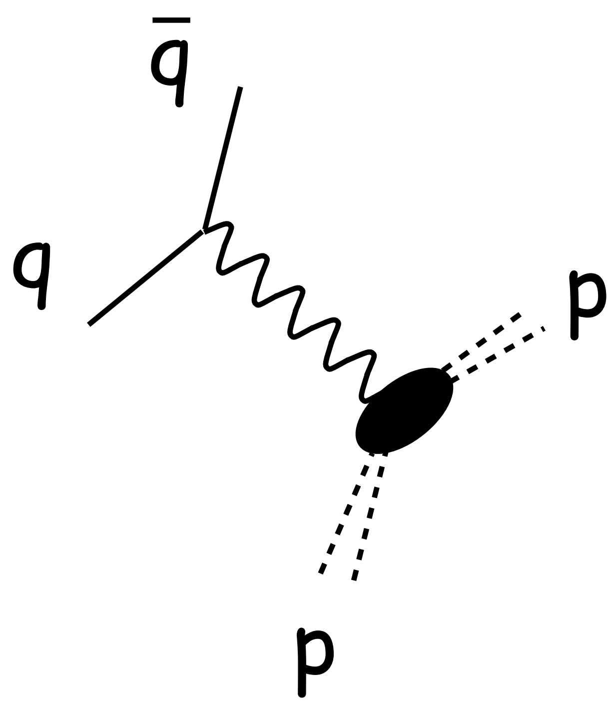
- ☑ mass gap is welcome and allows to pass EW precision constraints
- ☑ EW scale is radiatively generated by SM interactions

f	scale of strong interactions
g_ρ	coupling of the strong sector
$m_\rho \approx g_\rho f$	mass scale of resonances of strong sector

How to probe the composite nature of the Higgs?

1. Anomalous Higgs couplings

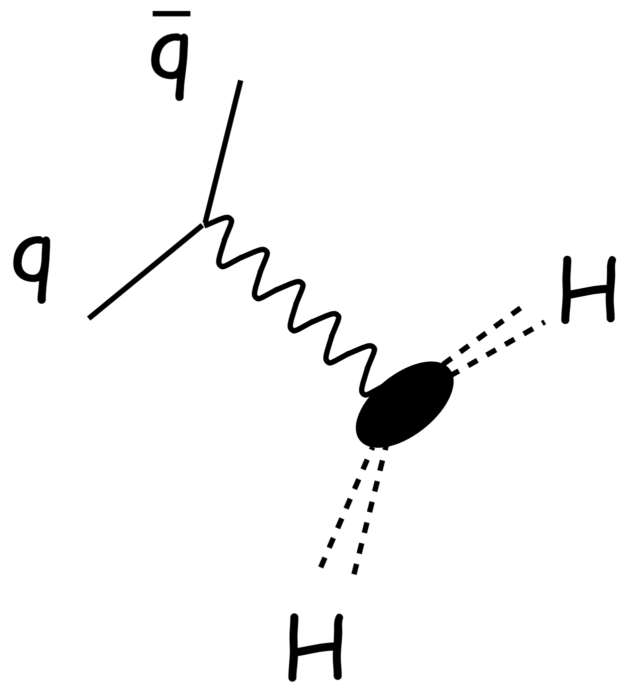
How to probe the compositeness of the Higgs?



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{16 m_H^2 \sin^4 \theta/2} \frac{E'}{E^3} \left(2\tilde{K}_1 q^2 \sin^2 \theta/2 + \tilde{K}_2 \cos^2 \theta/2 \right)$$

Rosenbluth-type cross-section

How to probe the compositeness of the Higgs?



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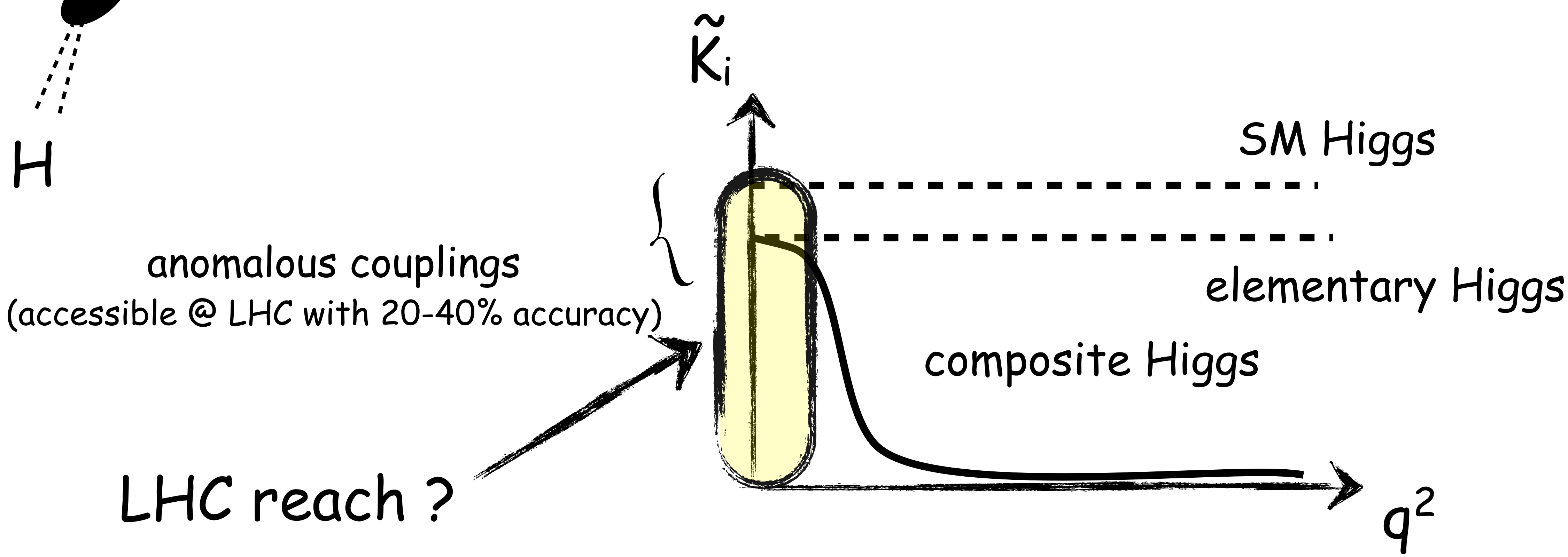
Rosenbluth-type cross-section



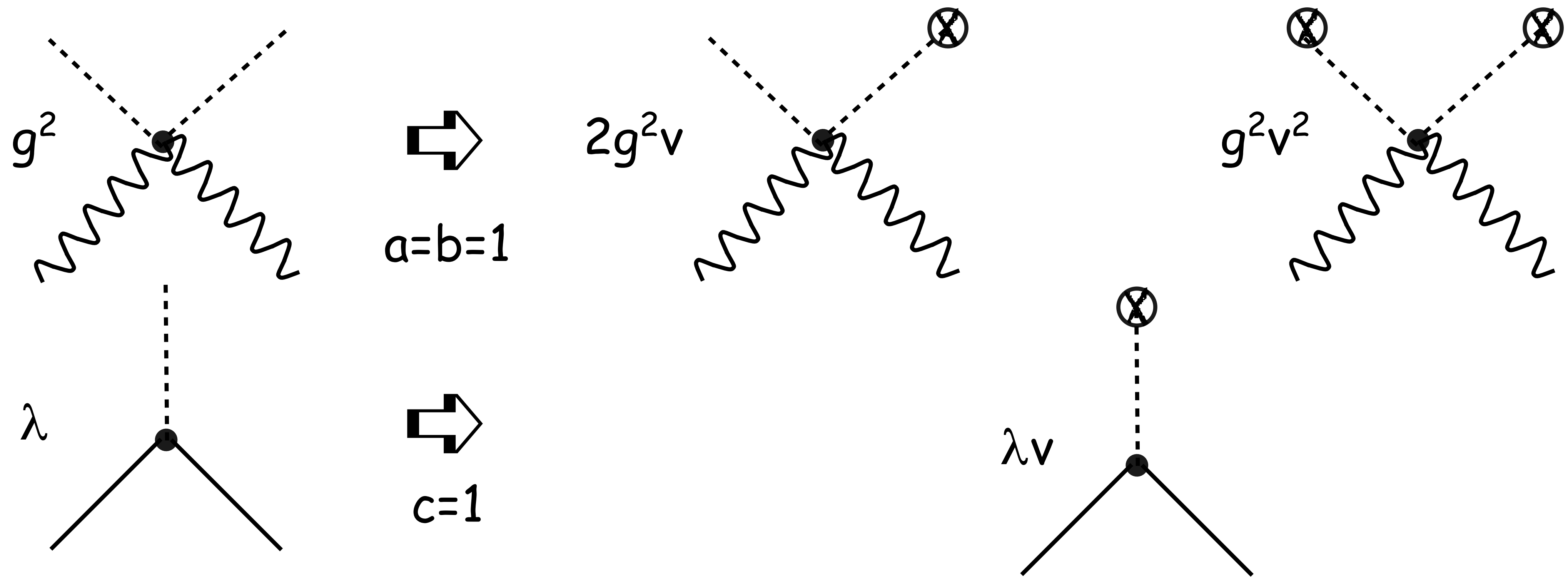
Need to develop tools to understand the physics of a composite Higgs

- use effective theory approach
- rely on symmetries of the problem

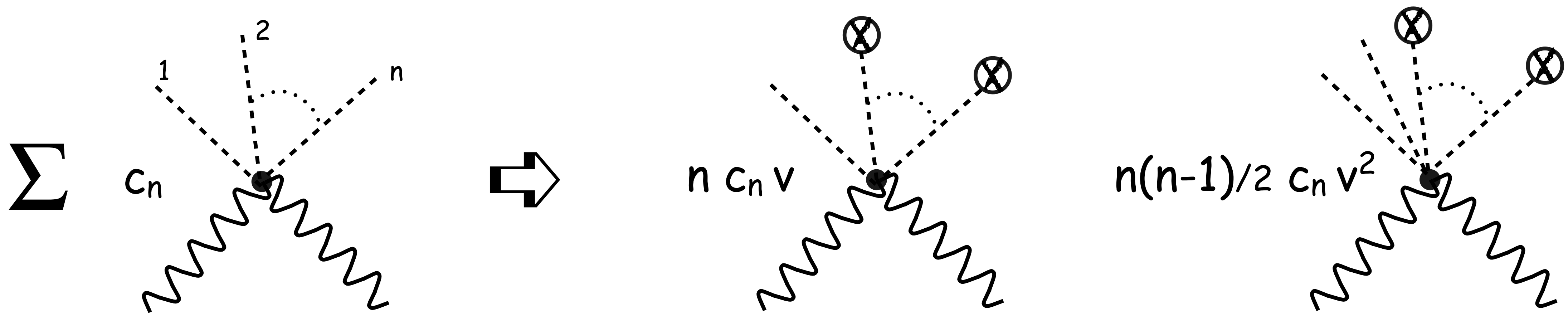
} identify interesting processes

Non-linear Higgs

the SM connection between masses and Higgs couplings



is lost in the presence of non-renormalisable higgs interactions



Minimal Composite Higgs Examples

The SILH Lagrangian is an expansion for small v/f
5D MCHM give a completion for large v/f

$$m_W^2 = \frac{1}{4} g^2 f^2 \sin^2 v/f \Rrightarrow g_{hWW} = \sqrt{1-\xi}\, g_{hWW}^{\rm SM} \Rrightarrow \begin{cases} a = \sqrt{1-\xi} \\ b = 1-2\xi \end{cases}$$

MCHM4

Fermions embedded in spinorial of SO(5)

$$m_f = M \sin v/f$$

$$\Downarrow$$

$$g_{hff} = \sqrt{1-\xi}\, g_{hff}^{\rm SM}$$

$$\Downarrow$$

$$c = \sqrt{1-\xi}$$

universal shift of the couplings
no modifications of BRs

MCHM5

Fermions embedded in 5+10 of SO(5)

$$m_f = M \sin 2v/f$$

$$\Downarrow$$

$$g_{hff} = \frac{1-2\xi}{\sqrt{1-\xi}}\, g_{hff}^{\rm SM}$$

$$\Downarrow$$

$$c = \frac{1-2\xi}{\sqrt{1-\xi}}$$

BRs now depends on v/f

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

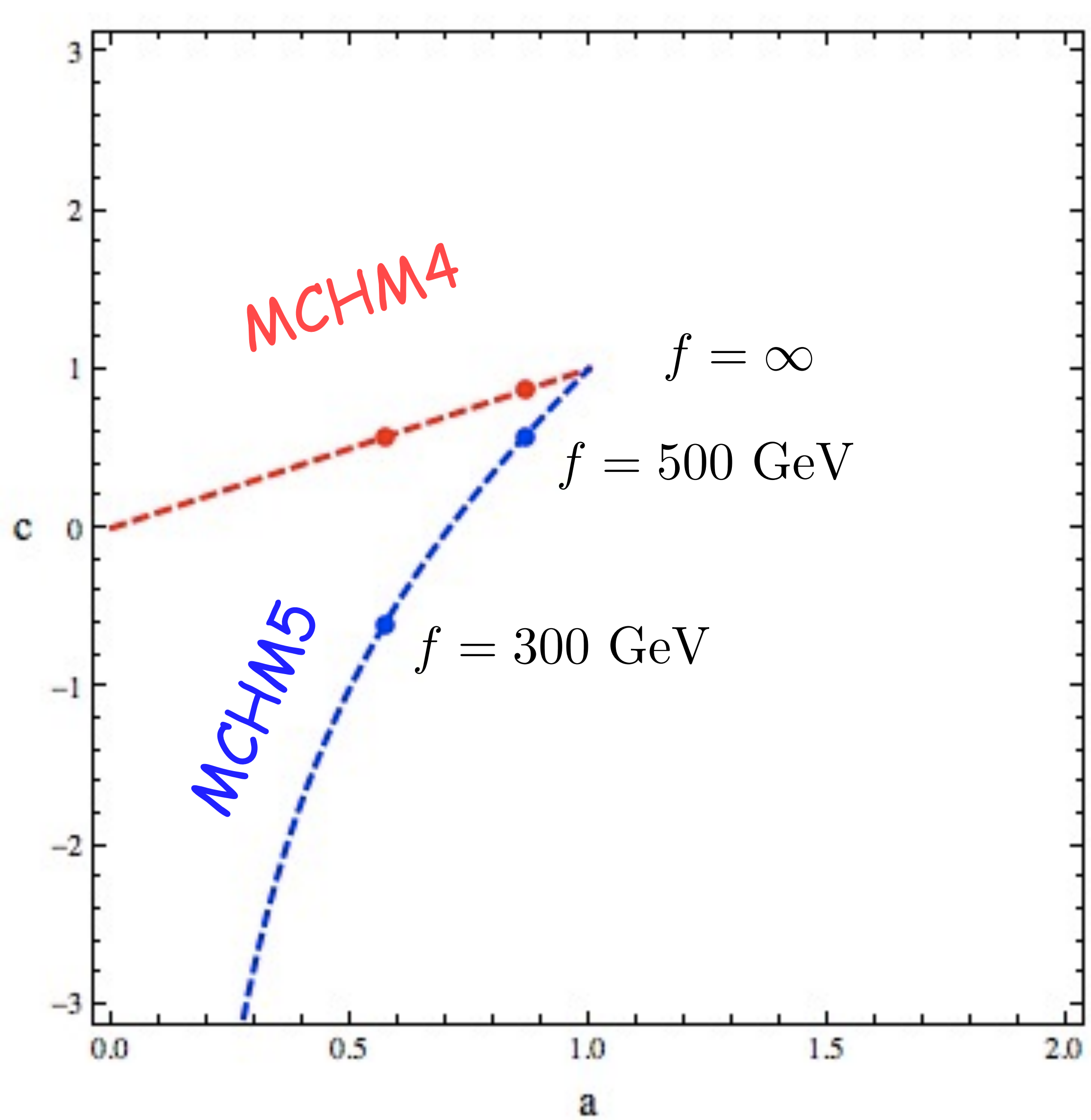
Higgs Fits

MCHM5

$$a = \sqrt{1-\xi} \quad b = 1-2\xi \quad c = \frac{1-2\xi}{\sqrt{1-\xi}}$$

MCHM4

$$a = \sqrt{1-\xi} \quad b = 1-2\xi \quad c = \sqrt{1-\xi}$$



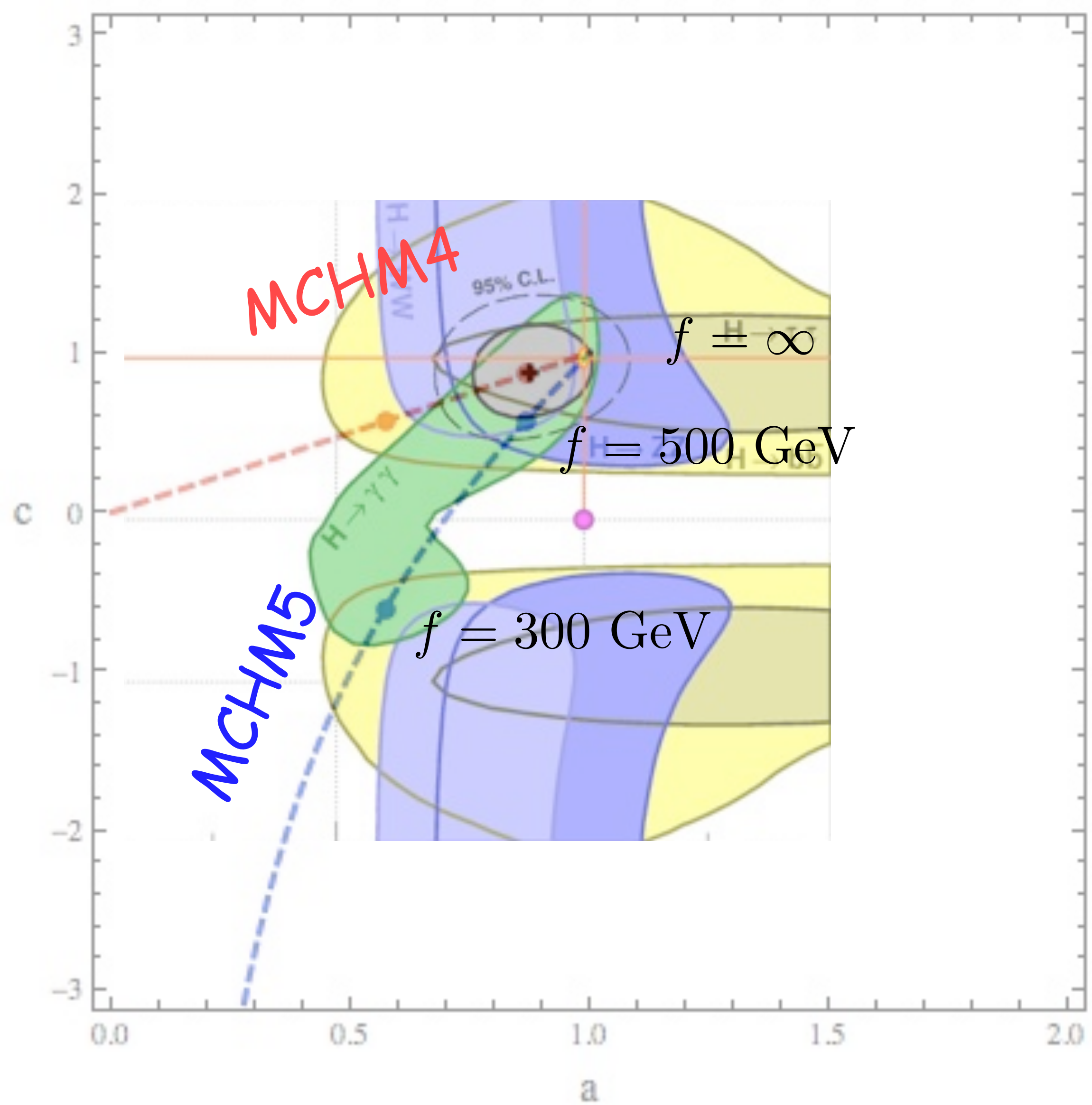
Higgs Fits

MCHM5

$$a = \sqrt{1-\xi} \quad b = 1-2\xi \quad c = \frac{1-2\xi}{\sqrt{1-\xi}}$$

MCHM4

$$a = \sqrt{1-\xi} \quad b = 1-2\xi \quad c = \sqrt{1-\xi}$$



Conclusions?

best fit point
=
MCHM4 with f=500GeV?
but pb with EWPT!

f >≈ 500GeV

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

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

Goldstone sym. (PGB Higgs)

Anomalous Higgs Couplings

Giudice, Grojean, Pomarol, Rattazzi '07

$$\mathcal{L} \supset \frac{c_H}{2f^2}\partial^\mu\left(|H|^2\right)\partial_\mu\left(|H|^2\right) \qquad c_H \sim \mathcal{O}(1)$$

$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \Longrightarrow \mathcal{L} = \frac{1}{2}\left(1 + c_H\frac{v^2}{f^2}\right)(\partial^\mu h)^2 + \ldots$$

Modified Higgs propagator ~ Higgs couplings rescaled by $\frac{1}{\sqrt{1+c_H\frac{v^2}{f^2}}} \sim 1 - c_H\frac{v^2}{2f^2} \equiv 1 - \xi/2$

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

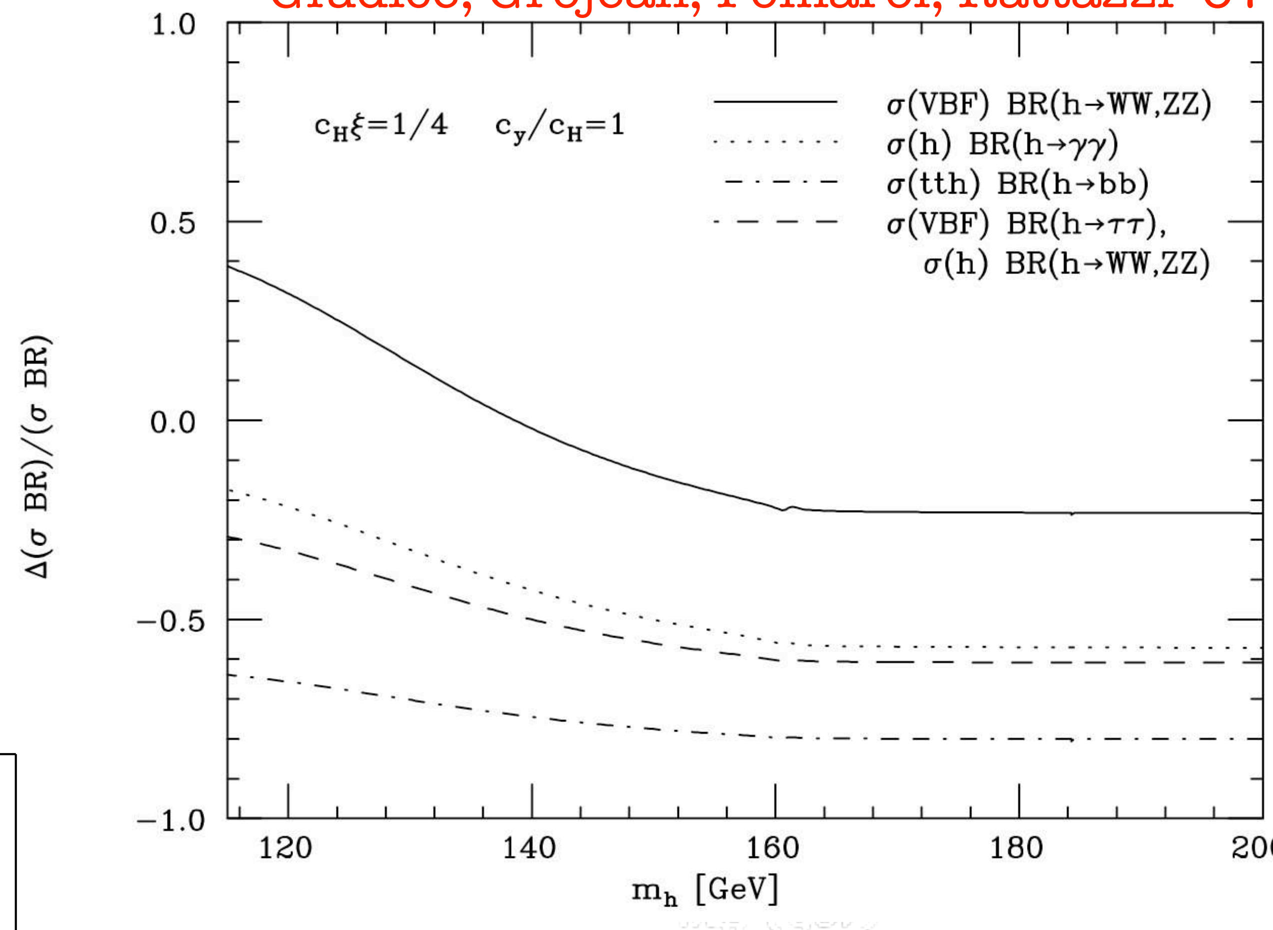
a = 1-ξ/2 b = 1-2ξ c = 1-ξ/2

Higgs anomalous couplings @ LHC

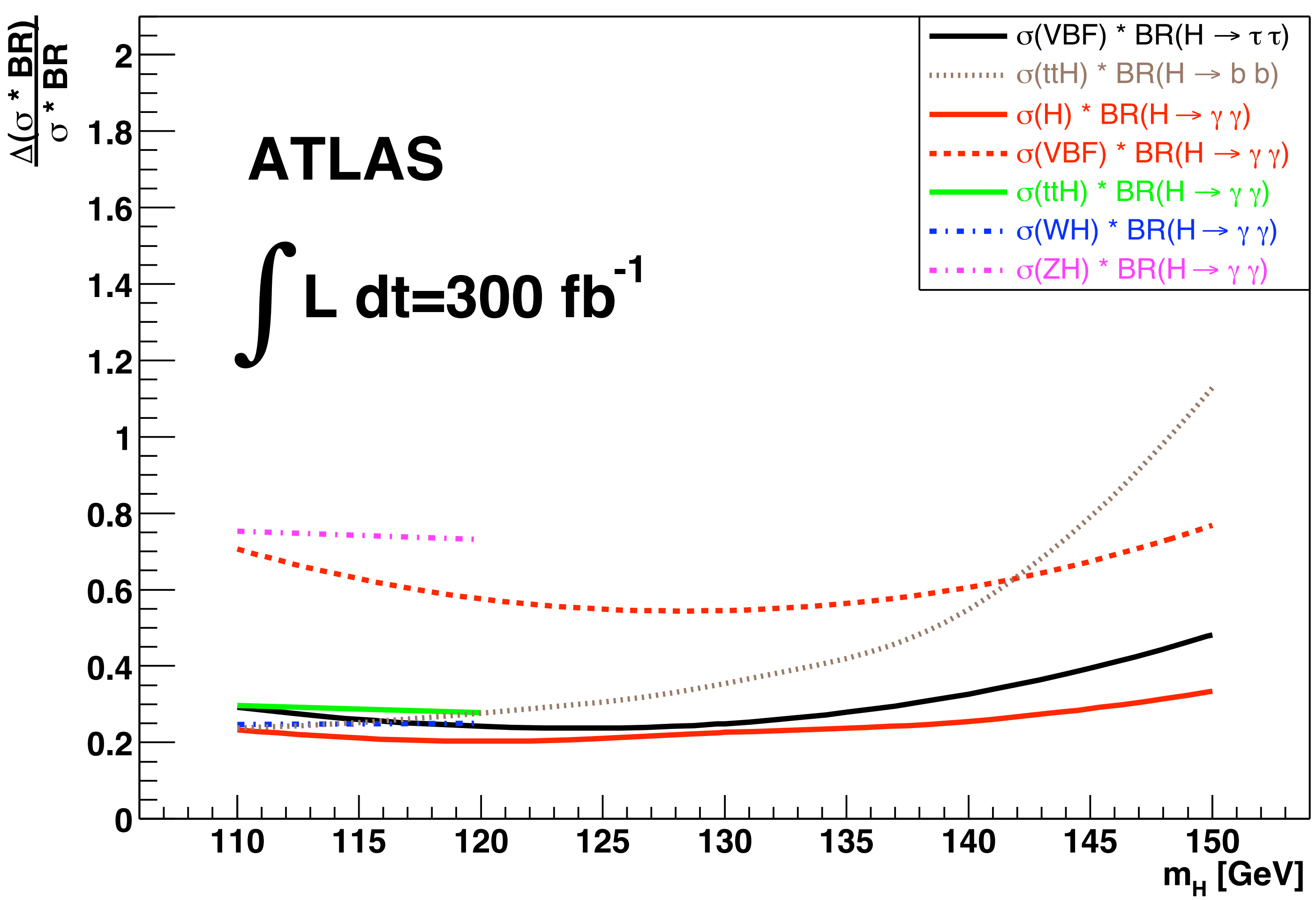
$$\Gamma\left(h \to f\bar{f}\right)_{\rm SILH} = \Gamma\left(h \to f\bar{f}\right)_{\rm SM}\left[1 - \frac{v^2}{f^2}\left(2c_y + c_H\right)\right]$$

$$\Gamma\left(h \to gg\right)_{\rm SILH} = \Gamma\left(h \to gg\right)_{\rm SM}\left[1 - \frac{v^2}{f^2}\left(2c_y + c_H\right)\right]$$

Giudice, Grojean, Pomarol, Rattazzi '07



observable @ LHC?



Duhrssen '03

LHC can measure

$$c_H\frac{v^2}{f^2},\ c_y\frac{v^2}{f^2}$$

up to 0.2-0.4

i.e. $4\pi f \sim 5-7\ \text{TeV}$

(ILC/CLIC could go to few %, ie, test composite Higgs up to 4πf ~ 30/60 TeV)

EWPT constraints

$$\hat{T} = c_T \frac{v^2}{f^2} \Longrightarrow |c_T \frac{v^2}{f^2}| < 2 \times 10^{-3}$$

removed by custodial symmetry

$$\hat{S} = (c_W + c_B) \frac{m_W^2}{m_\rho^2} \Longrightarrow m_\rho \geq (c_W + c_B)^{1/2}\, 2.5\,\text{TeV}$$

There are also some 1-loop IR effects

Barbieri, Bellazzini, Rychkov, Varagnolo '07

$$\hat{S}, \hat{T} = a \log m_h + b$$

modified Higgs couplings to matter

$$\Downarrow$$

$$\hat{S}, \hat{T} = a\left((1 - c_H \xi) \log m_h + c_H \xi \log \Lambda\right) + b$$

effective Higgs mass

$$m_h^{\text{eff}} = m_h \left(\frac{\Lambda}{m_h}\right)^{c_H v^2/f^2} > m_h$$

LEPII, for m_h~115 GeV: $c_H v^2/f^2 < 1/3 \div 1/2$

IR effects can be cancelled by heavy fermions (model dependent)

Flavor Constraints

$$\left(1+\frac{c_{ij}|H|^2}{f^2}\right) y_{ij}\bar{f}_{Li}Hf_{Rj} = \left(1+\frac{c_{ij}v^2}{2f^2}\right)\frac{y_{ij}v}{\sqrt{2}}\bar{f}_{Li}f_{Rj}$$

$$\left(1+\frac{3c_{ij}v^2}{2f^2}\right)\frac{y_{ij}v}{\sqrt{2}}h\bar{f}_{Li}f_{Rj}$$

mass terms

Higgs fermion interactions

mass and interaction matrices are not diagonalizable simultaneously if c_{ij} are arbitrary

$\Rrightarrow$ FCNC

SILH: c_y is flavor universal

$\Rrightarrow$ Minimal flavor violation built in

How to probe the composite nature of the Higgs?

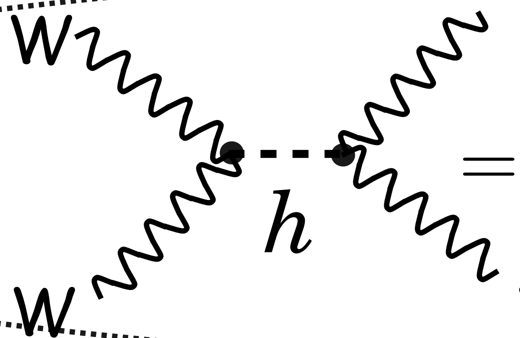
2. Probing strong scatterings

How to probe the strong dynamics?

pair production of light states beloging to the strong sector

Giudice, Grojean, Pomarol, Rattazzi '07

- strong WW scattering



$$= -(1-\xi)g^2 \frac{E^2}{M_W^2}$$

no exact cancellation of the growing amplitudes

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

large $\mathcal{L}_{int}$ needed

not competitive with the measurement of 'a' via anomalous couplings

- strong double Higgs production

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

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

access to a new interaction, 'b'

distinction between 'active' (higgs) and 'passive' (dilaton) scalar in EWSB dynamics

Scale of Strong WW scattering?

$$\mathcal{A}_{TT\to TT} \sim g^2 f(t/s)$$

f is a rational fct
expected O(1) for t~-s/2

$$\mathcal{A}_{LL\to LL} \sim \frac{s}{v^2}$$

onset of strong scattering at the weak scale

hard cross-section
(t~-s/2)

$$\left.\frac{d\sigma_{LL\to LL}/dt}{d\sigma_{TT\to TT}/dt}\right|_{t\sim -s/2} = N_h \frac{s^2}{M_W^4}$$

'inclusive' cross-section
$(-s + Q^2_{\rm min} < t < -Q^2_{\rm min})$

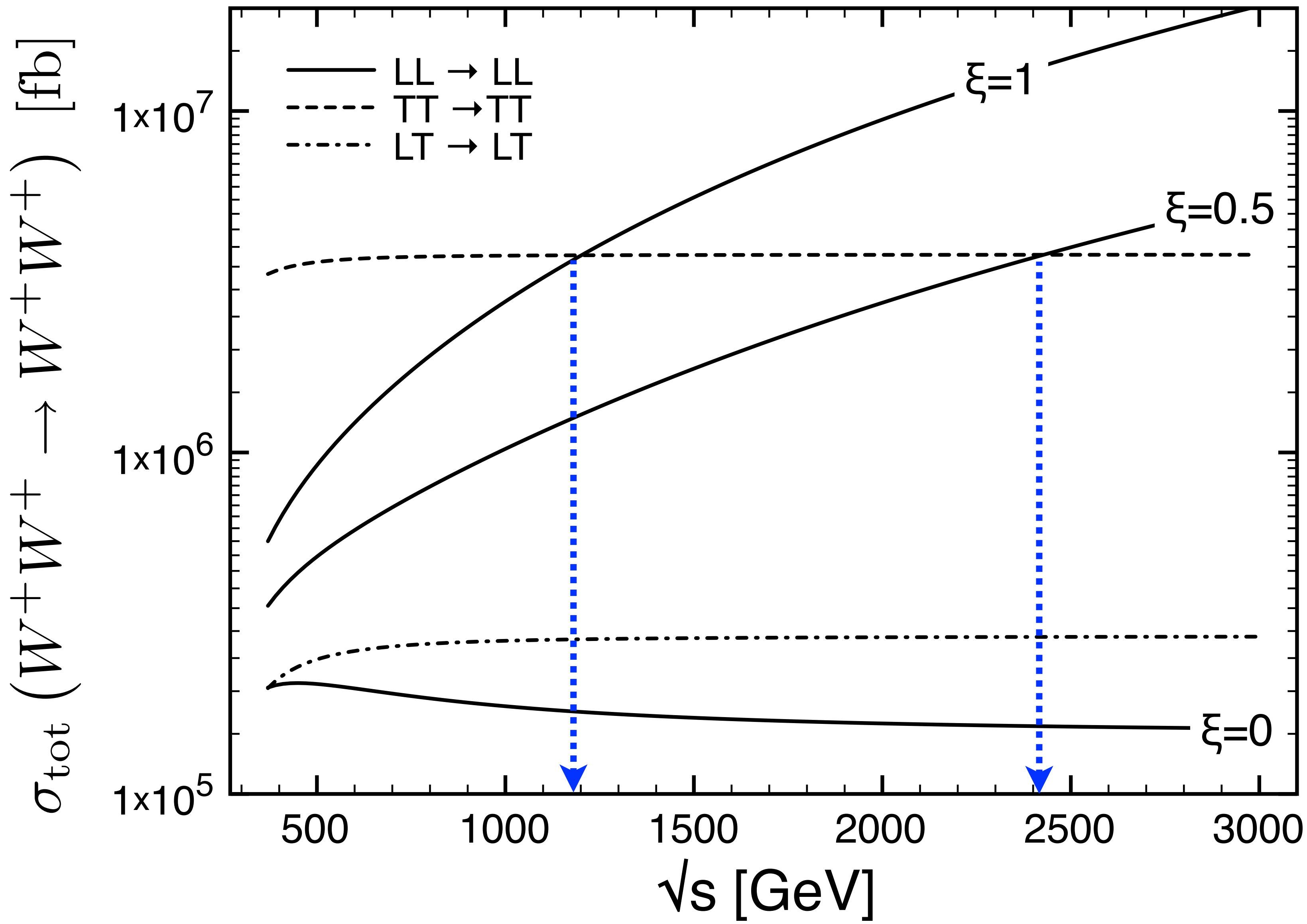
$$\frac{\sigma_{LL\to LL}(Q_{\rm min})}{\sigma_{TT\to TT}(Q_{\rm min})} = N_s \frac{s\, Q^2_{\rm min}}{M_W^4}$$

NDA estimates

$$N_h \sim 1 \qquad N_s \sim 1$$

Total cross sections

disentangling L from T polarization is hard



The onset of strong scattering is delayed to larger energies due to the dominance of TT → TT background

The dominance of T background will be further enhanced by the pdfs since the luminosity of W_T inside the proton is $\log(E/M_W)$ enhanced

Coulomb enhancement (SM)

$W^+W^+ \to W^+W^+$

the total cross section is dominated by the poles
in the exchange of γ and Z in the t- and u-channels

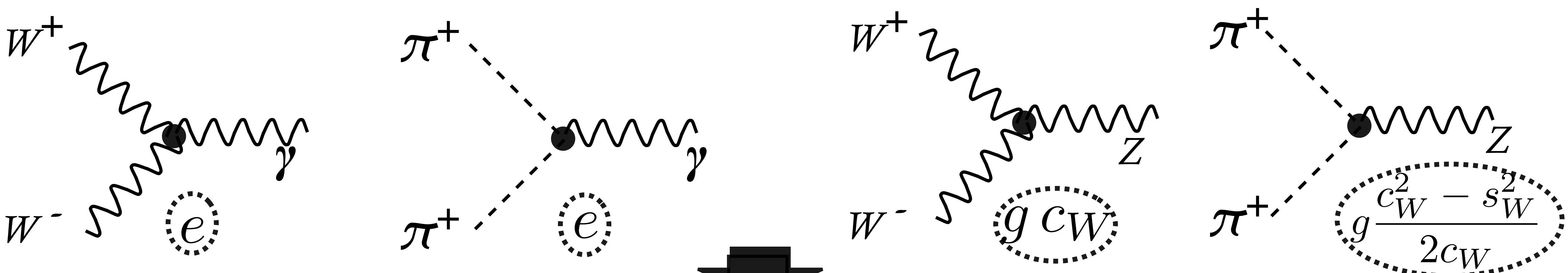
$$\mathcal{A} = \frac{a^t_\gamma\, s}{t} + \frac{a^t_Z\, s}{t - M_Z^2} + \frac{a^u_\gamma\, s}{u} + \frac{a^u_Z\, s}{u - M_Z^2} + \ldots \Rightarrow \sigma \sim \frac{1}{16\pi}\left(\frac{{a^t_\gamma}^2 + {a^u_\gamma}^2}{M_\gamma^2} + \frac{{a^t_Z}^2 + {a^u_Z}^2}{M_\gamma^2 + M_Z^2}\right)$$

M_γ = regulateur of Coulomb singularity=off-shellness of W ~ M_W

eïkonal limit

$a_\gamma = 2 \cdot (\text{electric charge of } W^+)^2$
universal for T and L

$a_Z = 2 \cdot (\text{“SU(2) charge” of } W^+)^2$
different for T and L



SM $\quad \dfrac{\sigma_{TT\to TT}}{\sigma_{LL\to LL}} \sim 20$ (for $M_\gamma \sim M_Z$)

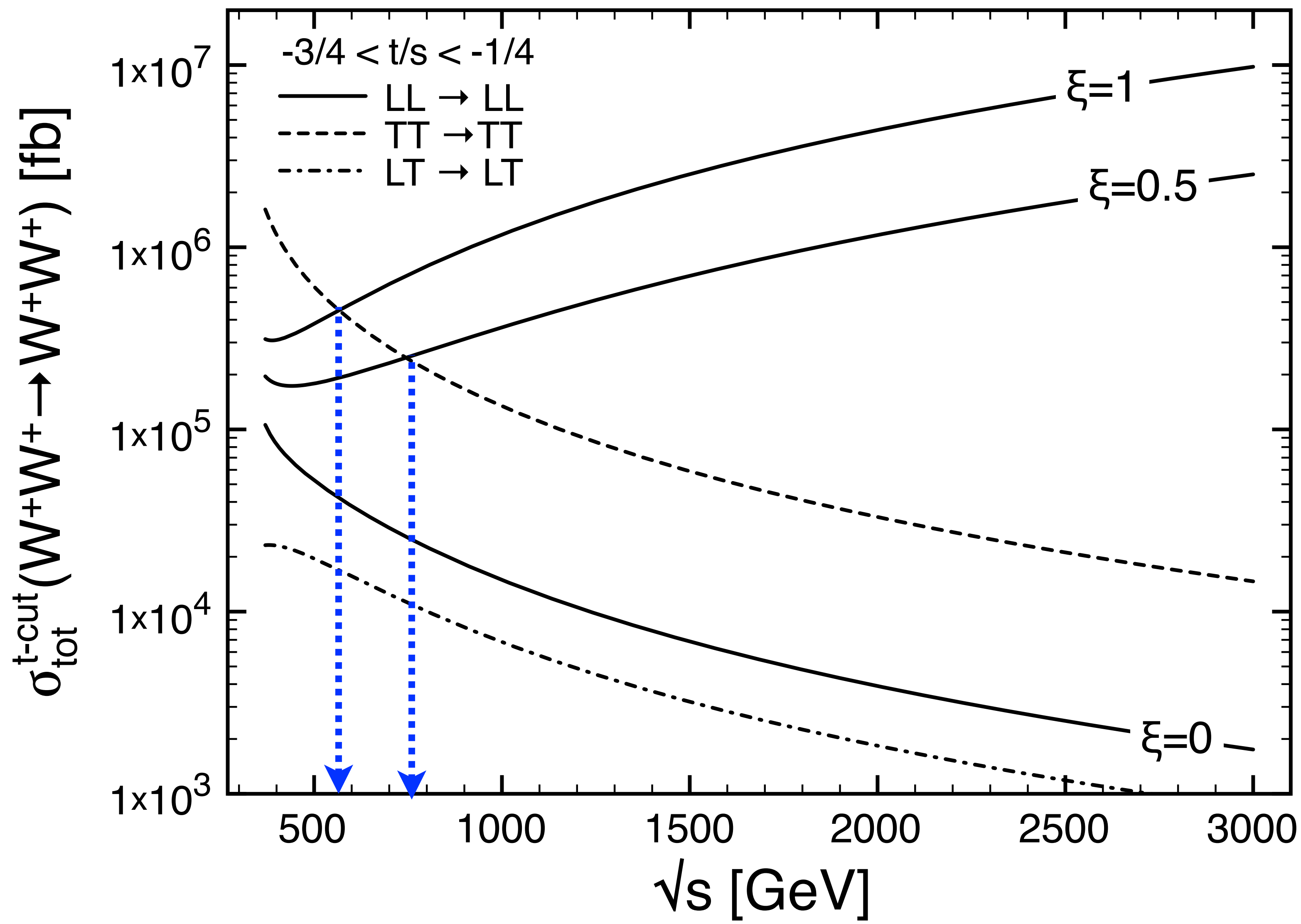
$N_s \sim 1/500$

$\Rrightarrow$ T-dominance is the result of multiplicity and larger SU(2) charges $\Lleftarrow$

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

Hard scattering (central region)

we need to look at the central region, i.e. large scattering angle, to be sensitive to strong EWSB

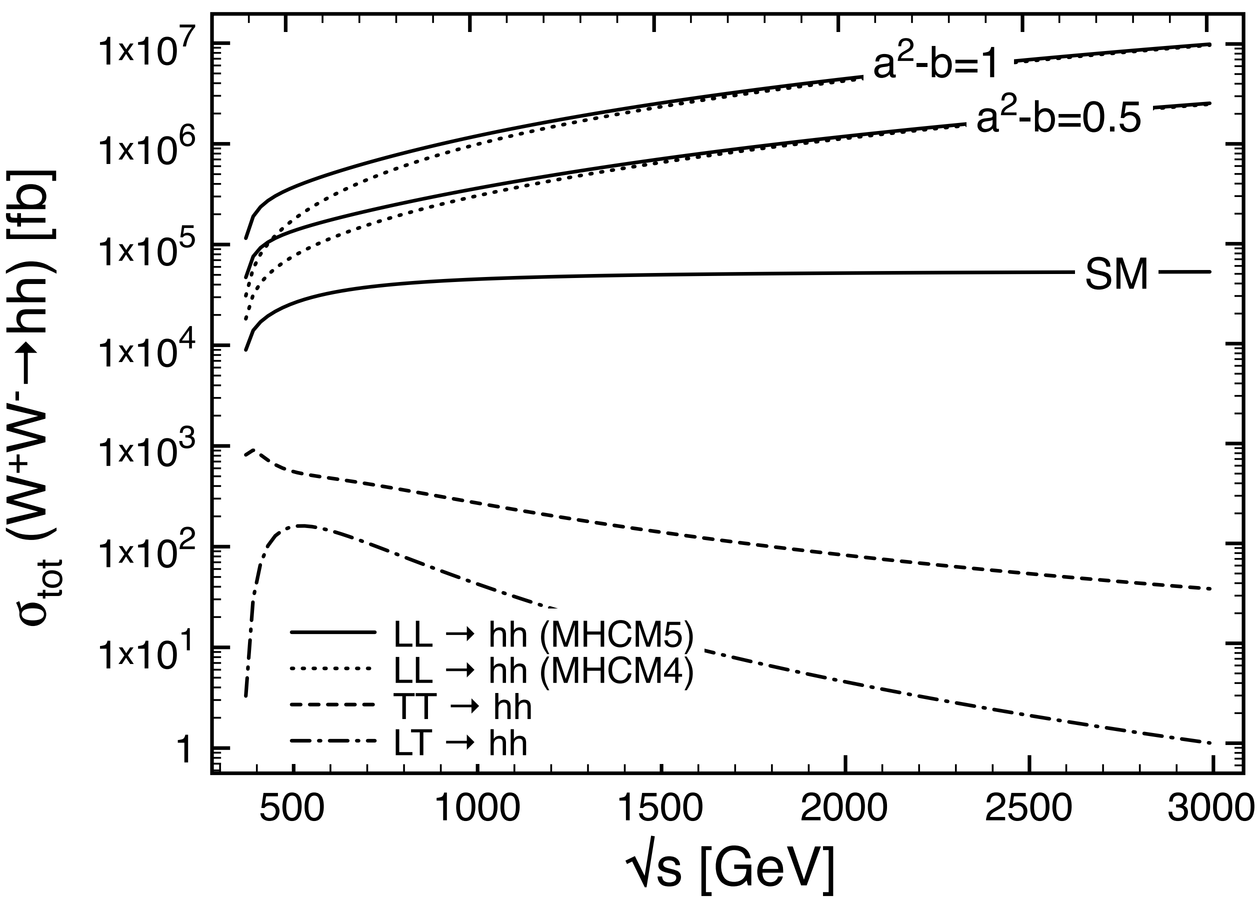


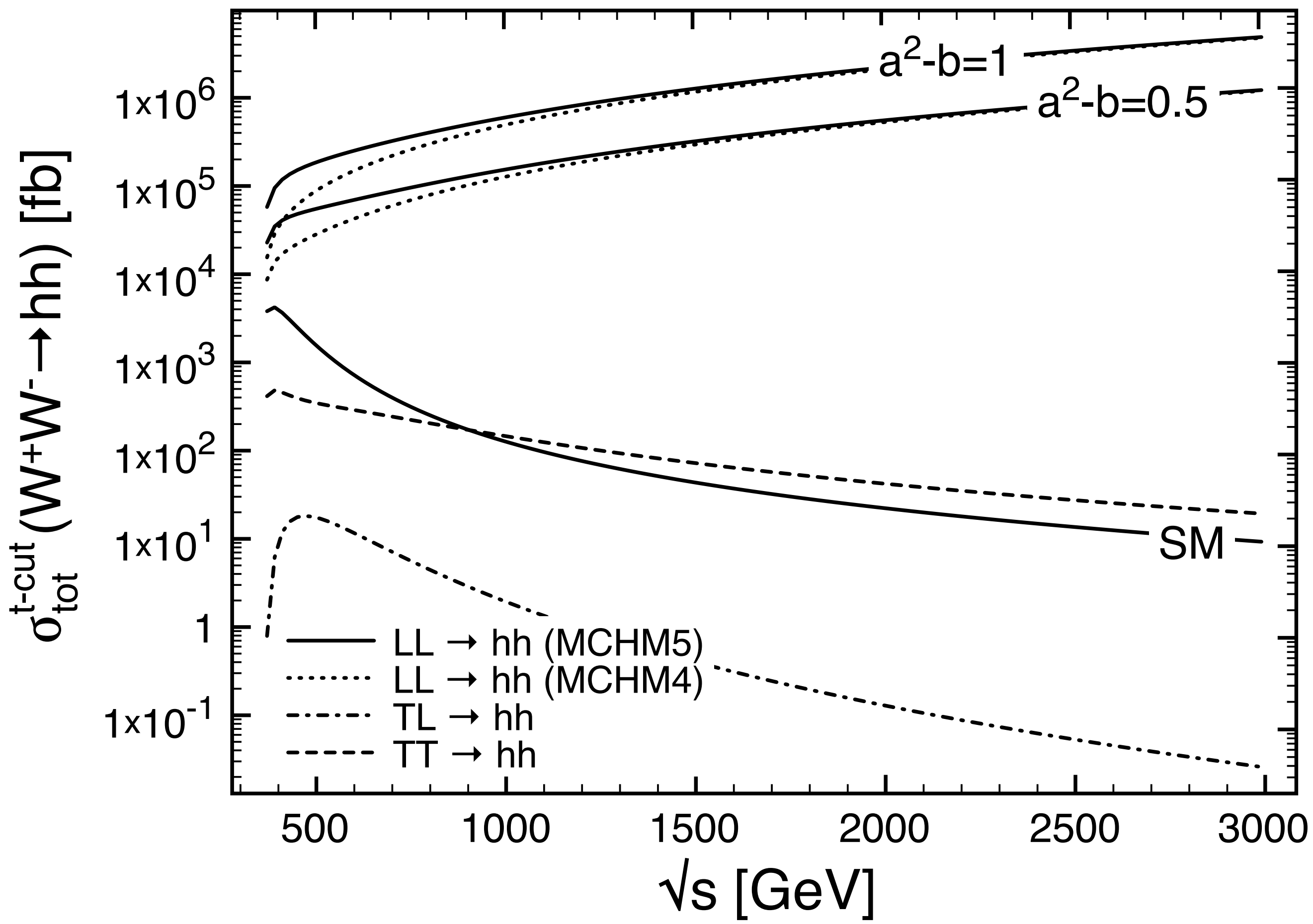
$$\frac{\sigma^{\rm hard}_{LL\to LL}}{\sigma^{\rm hard}_{TT\to TT}} \simeq \left(\frac{\sqrt{s}}{7.4 M_W}\right)^4 \xi^2$$

$$N_h = 1/2304$$

- hard cross-section = faster growth with energy
- onset of strong scattering still at high scale

EW bckg for WW → hh

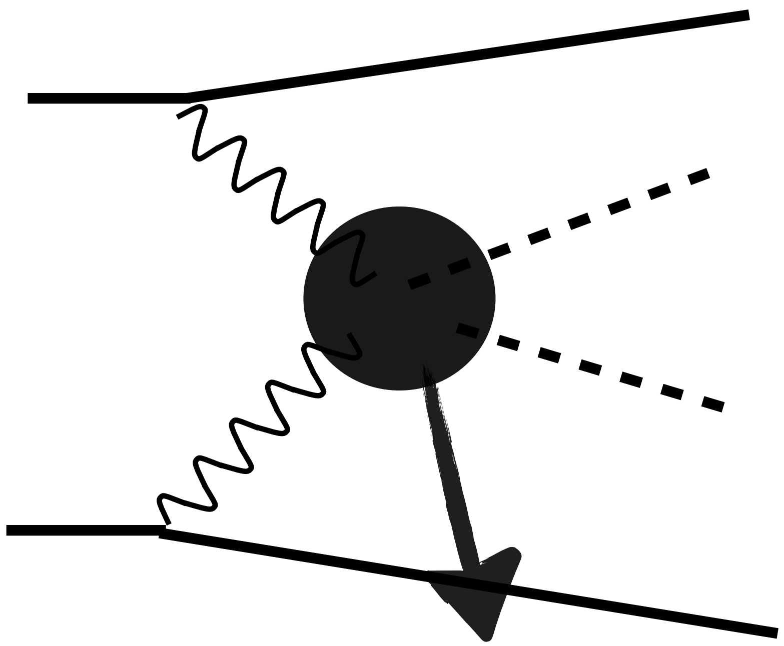




$$\frac{d\sigma^{LL\to hh}/dt}{d\sigma^{TT\to hh}/dt} = \frac{1}{8}\frac{\xi^2}{\xi^2+(1-\xi)^2}\left(\frac{\sqrt{s}}{M_W}\right)^4$$

no T polarization pollution,
neither in the total cross section,
nor in the central region

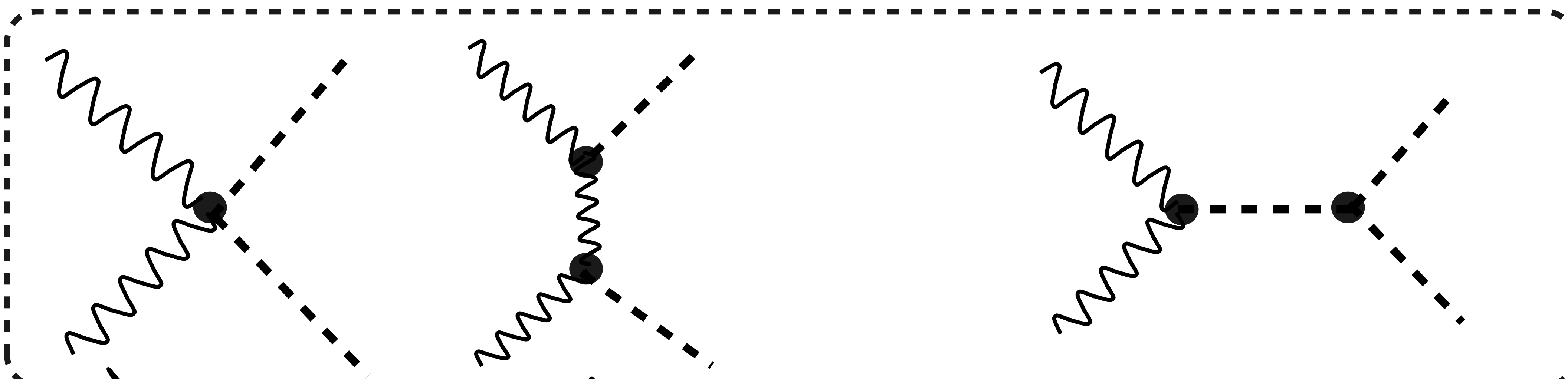
Double Higgs production (VBF)



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

$$V(h) = \frac{1}{2}m_h^2 h^2 + d_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 + d_4 \frac{1}{24}\left(\frac{3m_h^2}{v^2}\right) h^4 + \ldots$$

SM: $a=b=d_3=d_4=1$



$$\underset{m_{hh}^2 \gg m_W^2}{\mathcal{A} \sim} \left(b - a^2\right)\frac{4m_{hh}^2}{v^2}$$

asymptotic behavior
sensitive to strong interaction

$$\underset{m_{hh}^2 \sim 4m_h^2}{\mathcal{A} \sim} \mathrm{cst.} + 3ad_3 \frac{m_h^2}{v^2}$$

threshold effect
anomalous coupling'

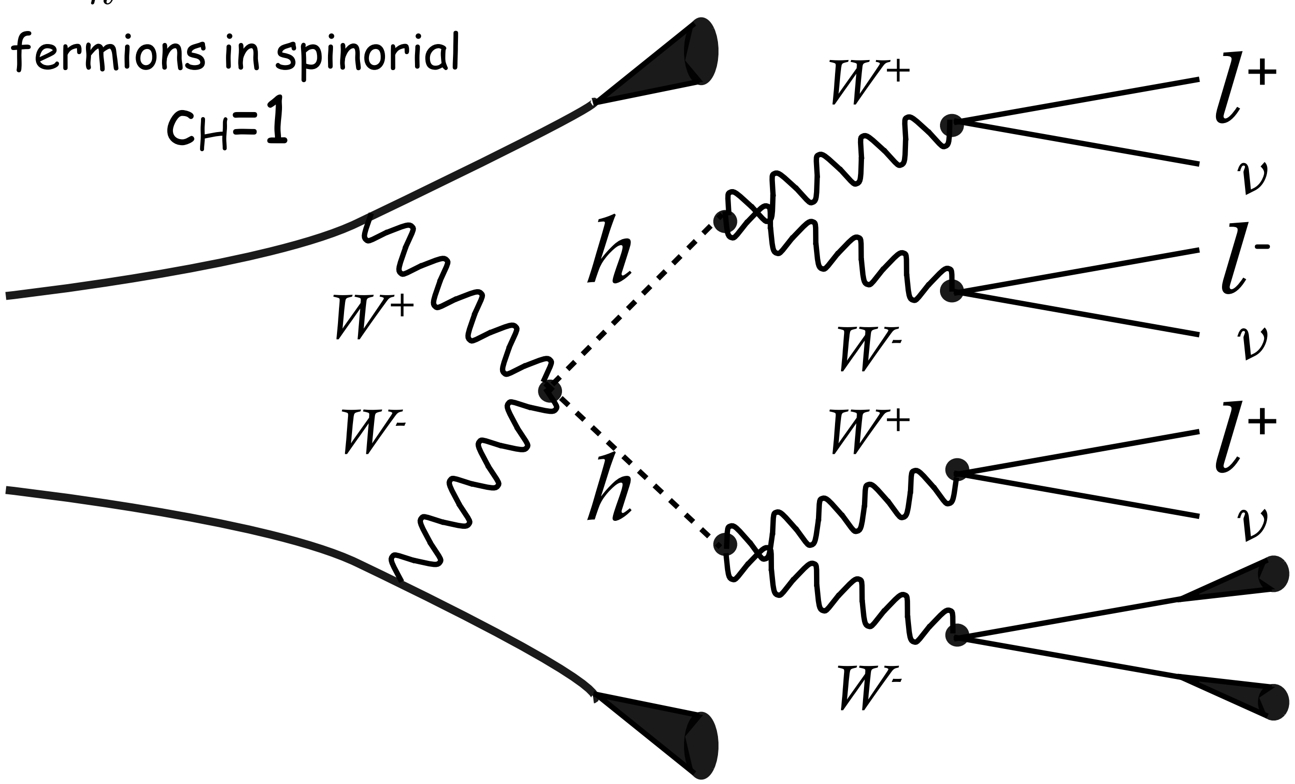
Strong Higgs production: (3L+jets) analysis

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

strong boson scattering ⇔ strong Higgs production

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

$m_h = 180$ GeV
fermions in spinorial
c_H=1



acceptance cuts

jets	leptons
$p_T \geq 30$ GeV	$p_T \geq 20$ GeV
$\delta R_{jj} > 0.7$	$\delta R_{lj(ll)} > 0.4(0.2)$
$\|\eta_j\| \leq 5$	$\|\eta_j\| \leq 2.4$

Dominant backgrounds: Wll4j, $t\bar{t}$W2j, $t\bar{t}$2W(j), 3W4j...

forward jet-tag, back-to-back lepton, central jet-veto

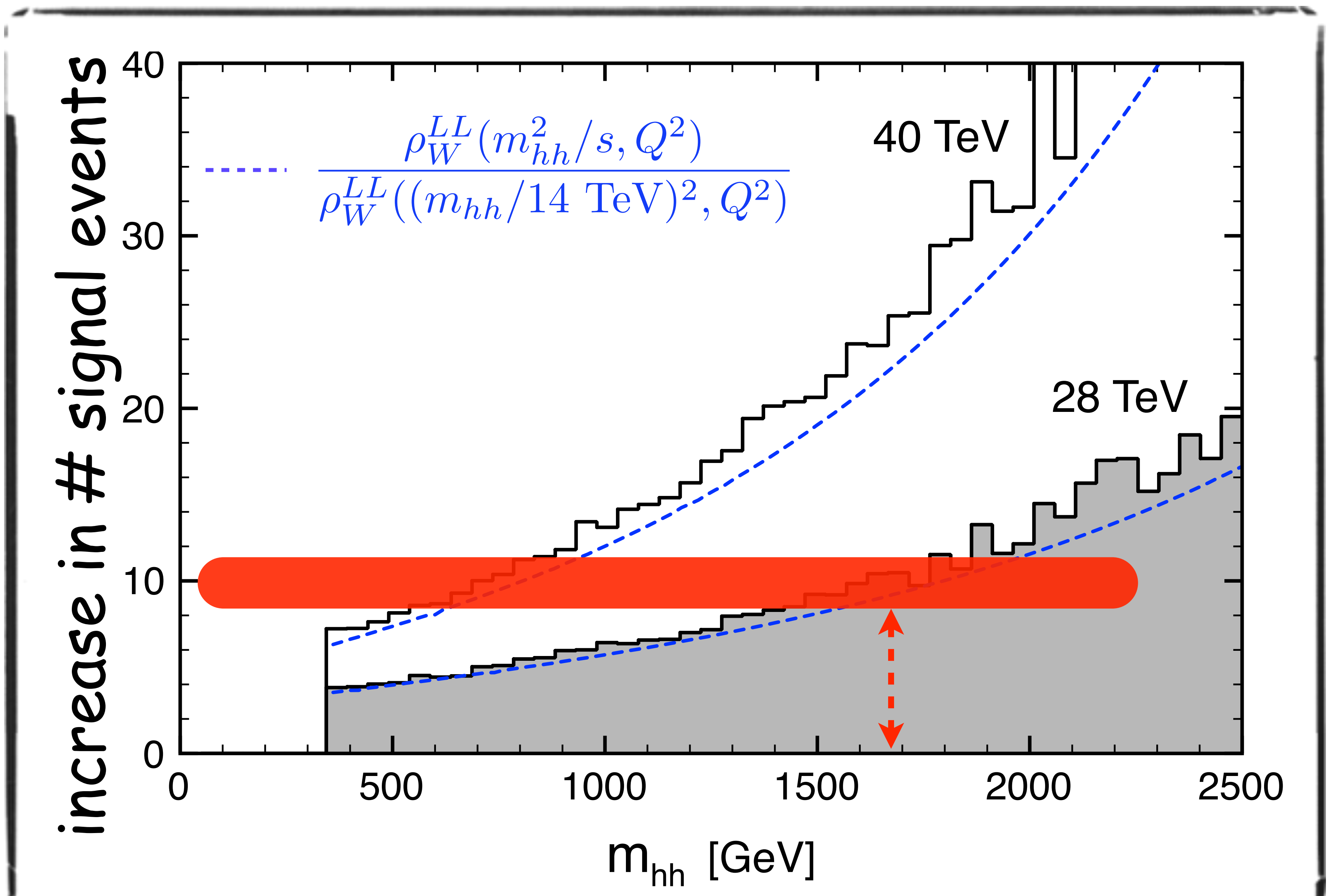
v/f	1	$\sqrt{0.8}$	$\sqrt{0.5}$
significance @ 300 fb^{-1}	4.0	2.9	1.3
luminisity for 5σ (fb^{-1})	450	850	3500

⇚good motivation to HL-LHC

Dependence on Collider Energy

$$\sigma = \hat{\sigma}(s_0) \times \int_{s_0} \frac{d\hat{s}}{\hat{s}} \frac{\hat{\sigma}(\hat{s})}{\hat{\sigma}(s_0)} \rho(\hat{s}/s)$$

increase collider energy $\sqrt{s}$ = sensitive to PDFs at smaller x
bigger cross-sections



HL-LHC vs. HE-LHC

10 x lum ≈ 10 x events

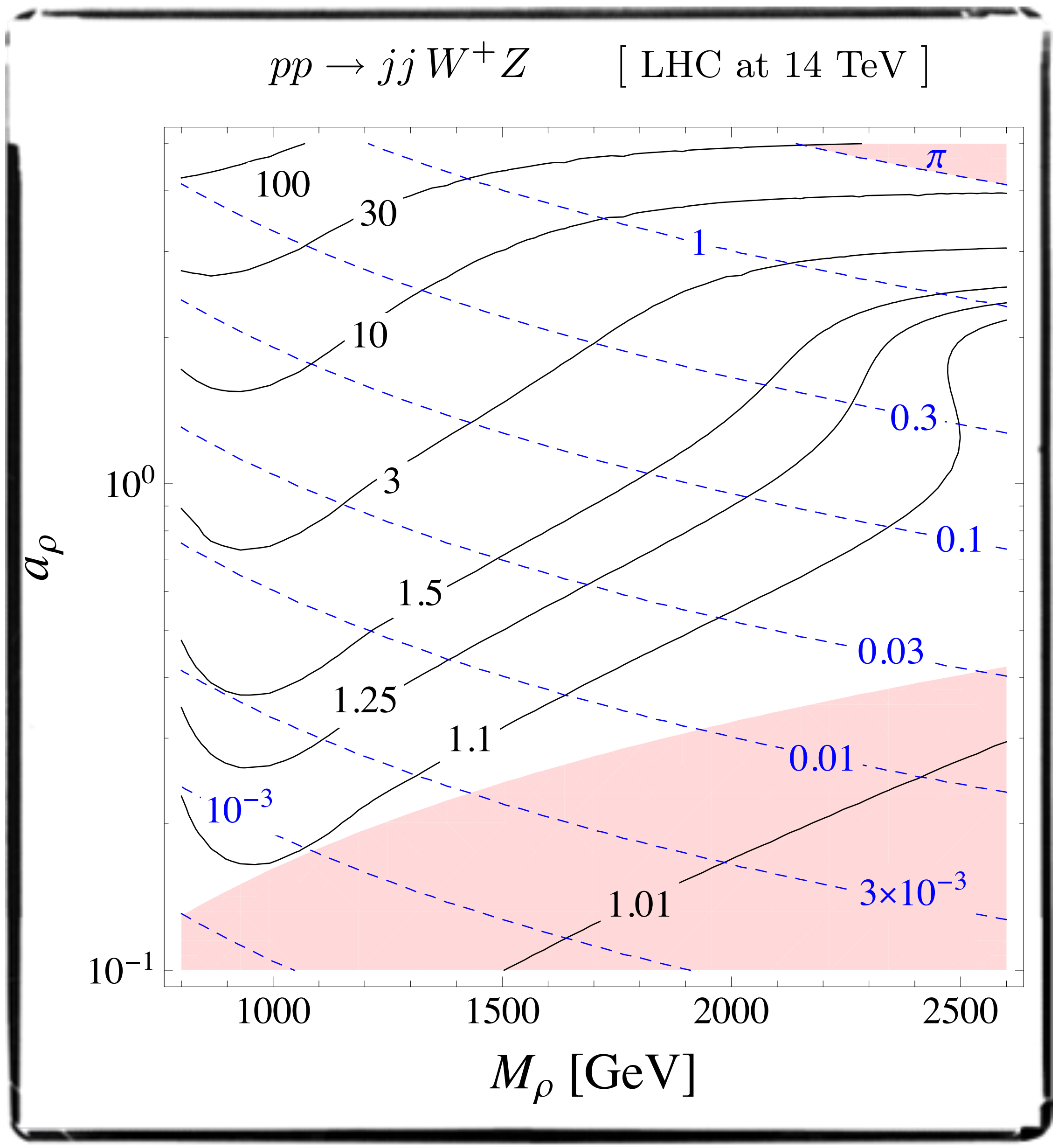
2 x $\sqrt{s}$ = 10 x events
iif m_{hh}>1.6TeV

How to probe the composite nature of the Higgs?

3. Strong sector resonances

Resonances Effects in WW Scattering

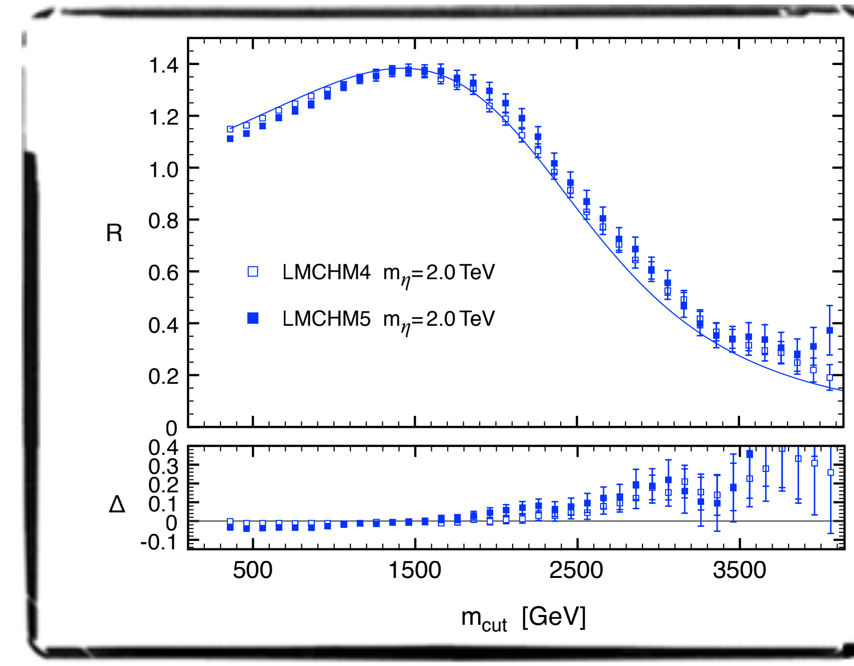
Contino, Marzocca, Pappadopulo, Rattazzi '11



$\xi = 0.5$

$m_{\rm cut} = 800\,\text{GeV}$

$R = \dfrac{\sigma(\rho_L)}{\sigma(\text{LET})}$ $\dfrac{\Gamma_{\rho_L}}{m_{\rho_L}}$



channel complementary
to pin down the nature of the resonance

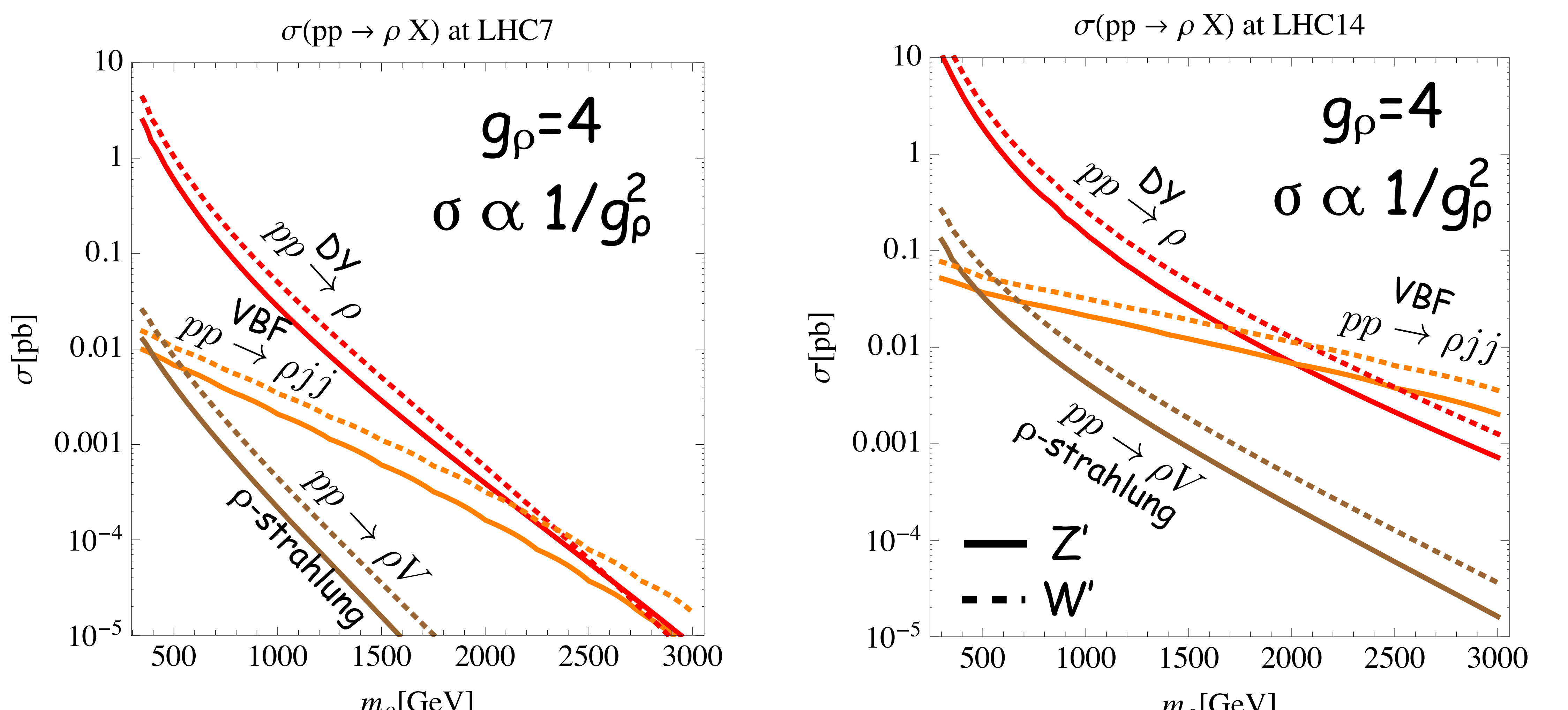
		W^+W^-	W^+Z	W^+W^+	hh
ρ	(1,3)	↑	↑	↓	↓
η	(1,1)	↑	↓	↓	↑
Δ	(3,3)	↑	↑	↑	↑

Difficult measurements: Precision physics

- ☑ @ high energy
- ☑ need performant forward tagging efficiencies
- ☑ fight large pile-up...

Resonance Searches: di-boson final states

Observing a tower of resonances would a direct evidence of the strong interactions
However, in the best configuration, LHC will have access to a few ones only



Falkowski, Grojean, Kaminska, Pokorski and Weiler '11

VBF vs. DY:
- 3-body final state
- qq initiated process ⇨ PDFs become more dominant at large x

(NB: DY can be enhanced by larger direct couplings of resonances to light quarks but severe dijet constraints)

Resonance Decays

Dominant decays into longitudinal SM gauge bosons

$$\Gamma(\rho^0 \to W^+W^-) \approx \Gamma(\rho^\pm \to ZW^\pm) \approx \frac{m_\rho g_{\rho\pi\pi}^2}{48\pi} = \frac{m_\rho^5}{192\pi g_\rho^2 v^4}$$

corrections 30%-10% from transverse SM gauge bosons

Suppressed decays to SM quarks and leptons

$$\mathrm{Br}(\rho^\pm \to e^\pm \nu) \approx 2\mathrm{Br}(\rho^0 \to e^+e^-) \approx \frac{16 m_W^4}{m_\rho^4}$$

$\Downarrow$ $\Downarrow$ $\Downarrow$

searches in WW, WZ channels in DY processes

Resonance Searches vs Indirect Probes

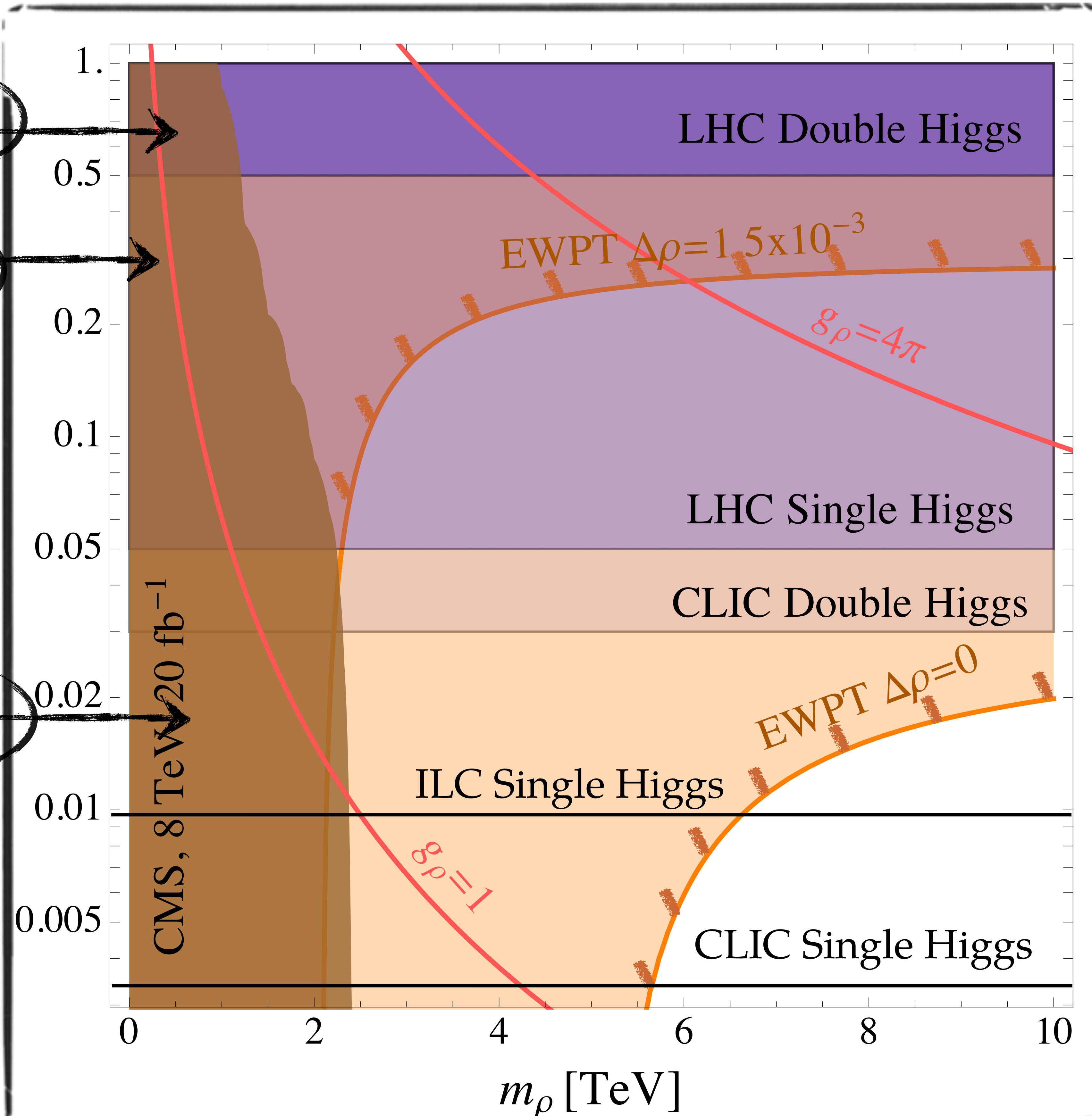
Contino, Grojean, Pappadopoulo, Rattazzi, Thamm '13

Strong WW scattering

Anomalous Higgs couplings

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

Resonance searches



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

Resonance Searches vs Indirect Probes

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm '13

Strong WW

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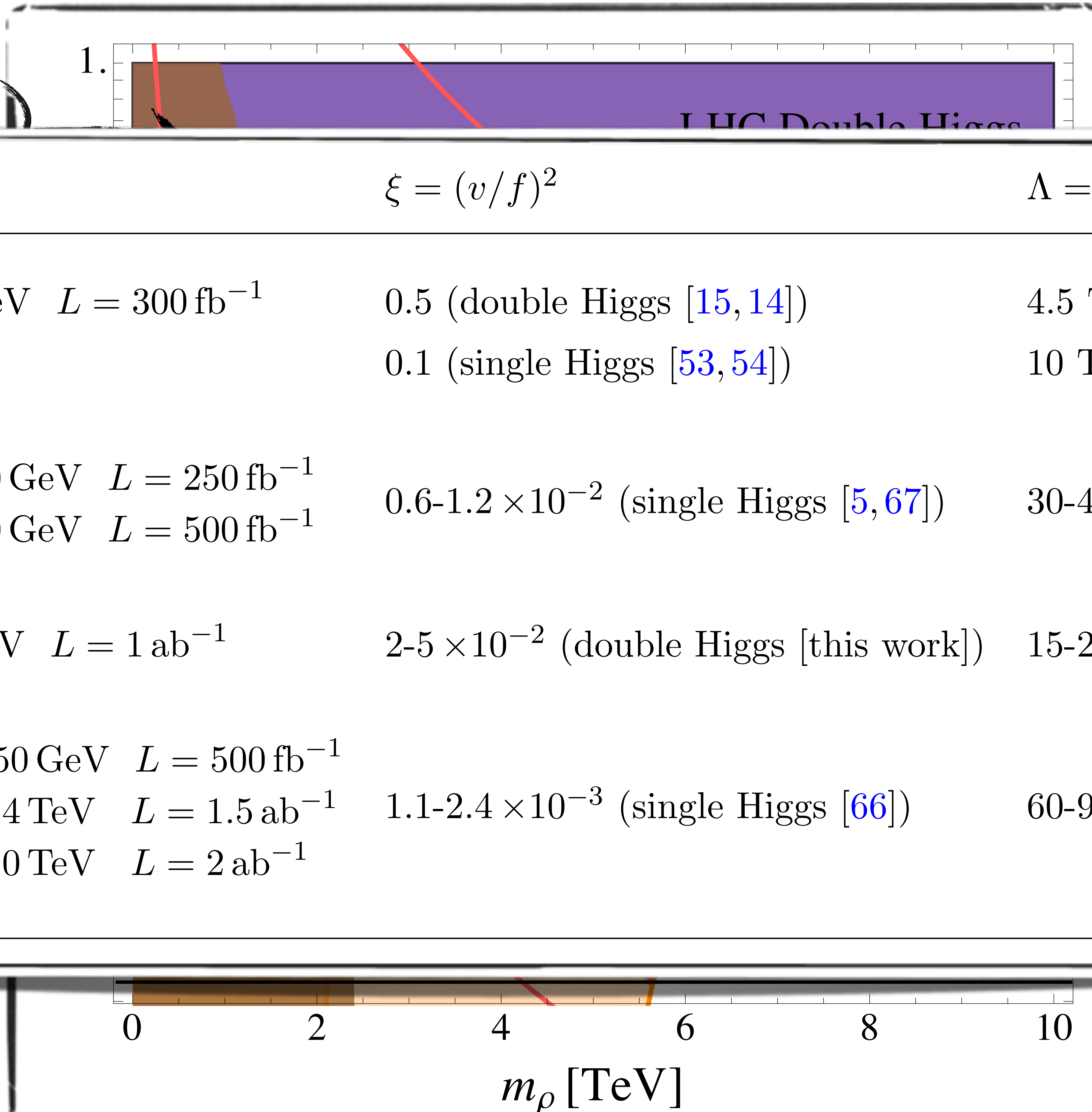
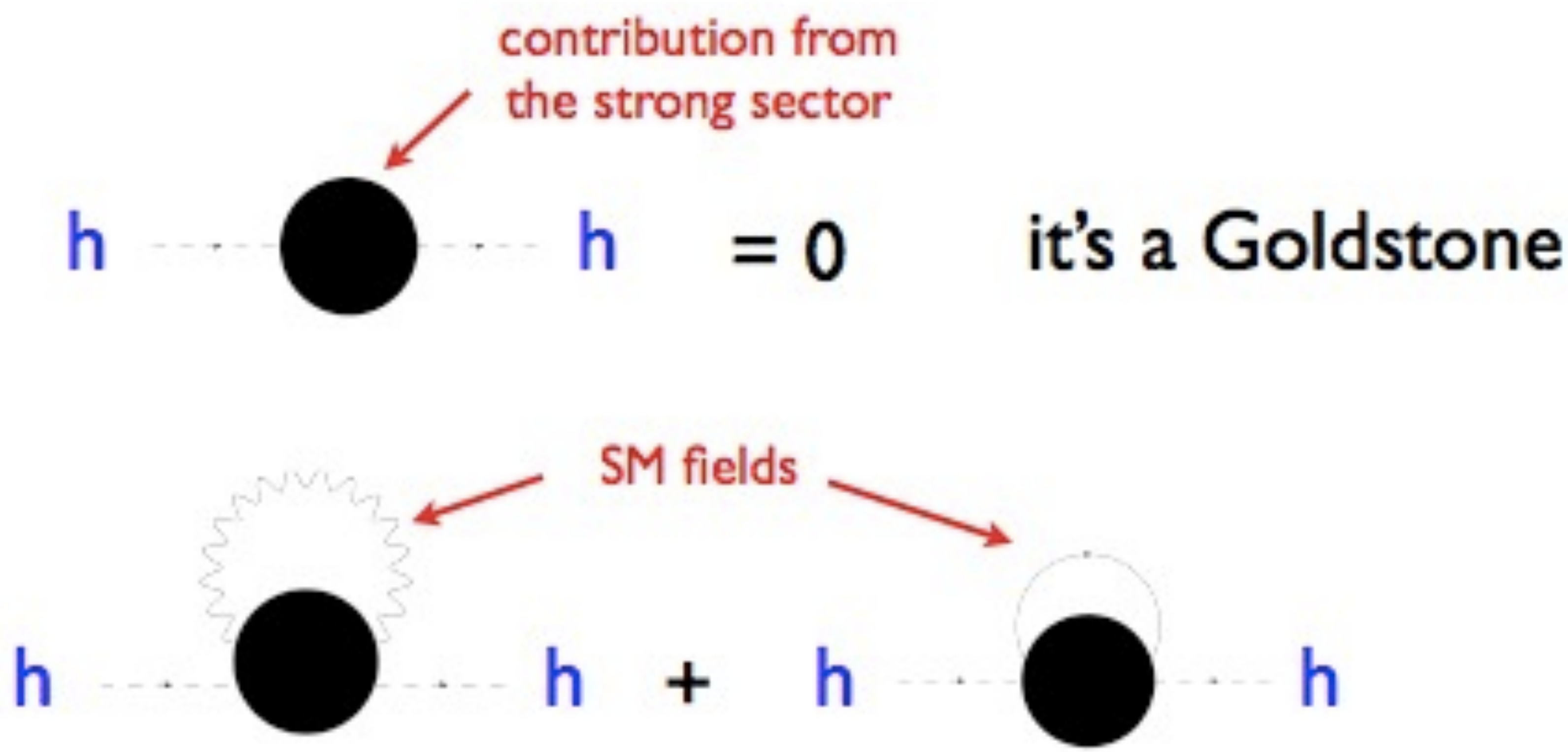
resonances
(broader resonances & weaker couplings to light SM quarks)



	$\xi = (v/f)^2$	$\Lambda = 4\pi f$
LHC 14 TeV $L = 300\,\text{fb}^{-1}$	0.5 (double Higgs [15, 14])	4.5 TeV
	0.1 (single Higgs [53, 54])	10 TeV
ILC 250 GeV $L = 250\,\text{fb}^{-1}$ + 500 GeV $L = 500\,\text{fb}^{-1}$	0.6-1.2 $\times 10^{-2}$ (single Higgs [5, 67])	30-40 TeV
CLIC 3 TeV $L = 1\,\text{ab}^{-1}$	2-5 $\times 10^{-2}$ (double Higgs [this work])	15-20 TeV
CLIC 350 GeV $L = 500\,\text{fb}^{-1}$ + 1.4 TeV $L = 1.5\,\text{ab}^{-1}$ + 3.0 TeV $L = 2\,\text{ab}^{-1}$	1.1-2.4 $\times 10^{-3}$ (single Higgs [66])	60-90 TeV

Light composite Higgs from "light" resonances

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



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

Pomarol, Riva '12

Marzocca, Serone, Shu '12

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

⇒

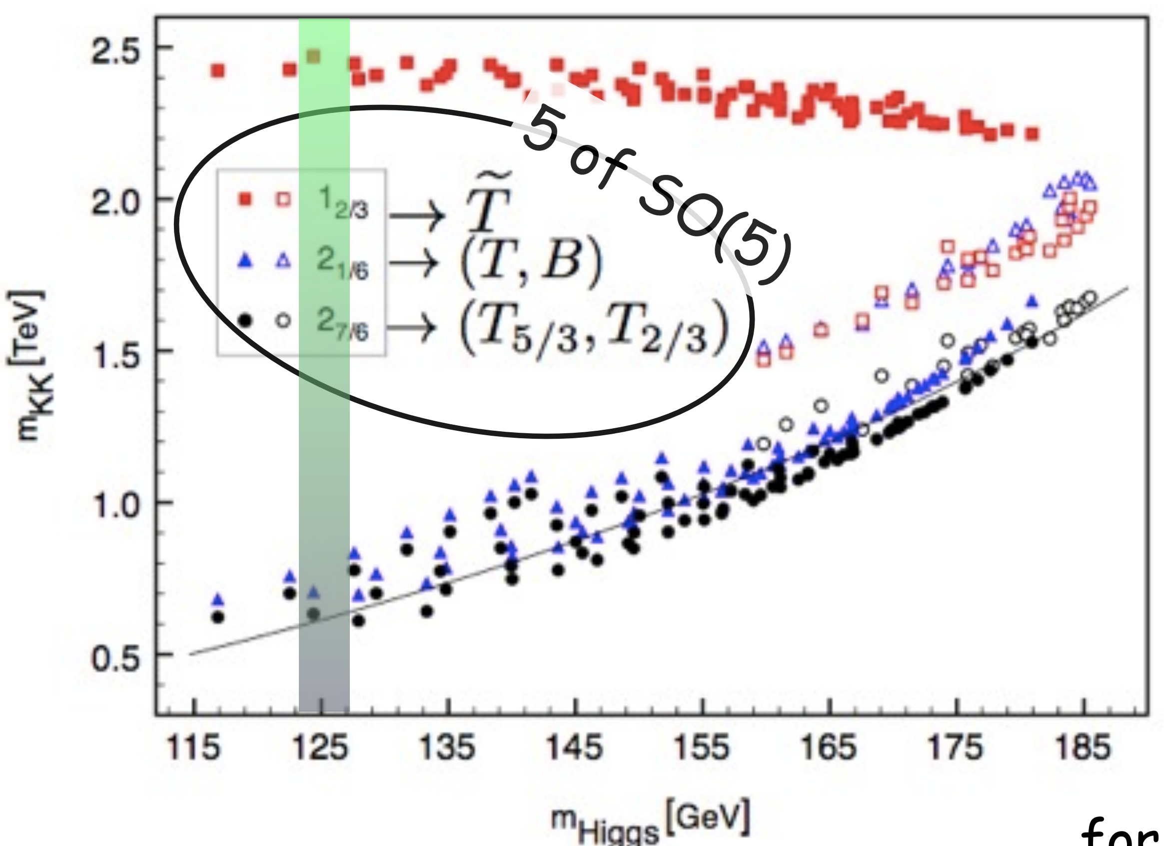
$$m_Q \lesssim 700\text{ GeV}\left(\frac{m_h}{125\text{ GeV}}\right)\left(\frac{160\text{ GeV}}{m_t}\right)\left(\frac{f}{500\text{ GeV}}\right)$$

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

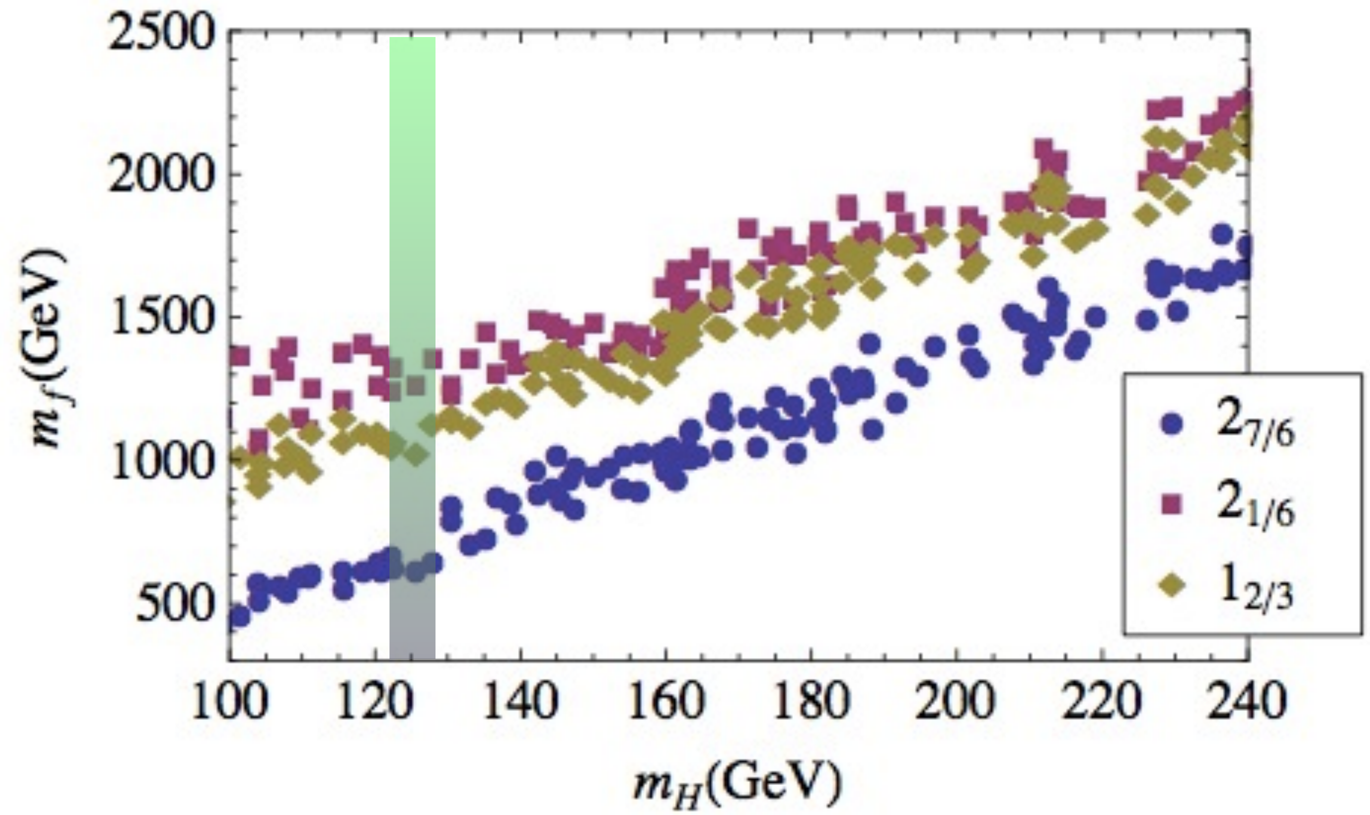
Light composite Higgs from "light" resonances

true spectrum in explicit realizations

Contino, Da Rold, Pomarol '06



De Curtis, Redi, Tesi '11



for similar results, see also

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

Nice AdS/CFT interpretation

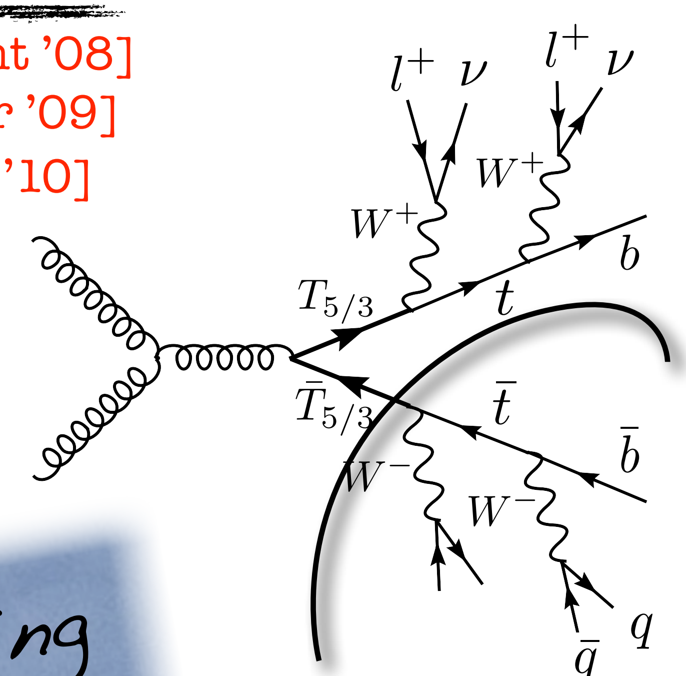
$$\text{Dim}[\mathcal{O}_\Psi] = \frac{3}{2} + |M_\Psi + \frac{1}{2}|$$

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

Rich phenomenology of the top partners

Search in same-sign di-lepton events

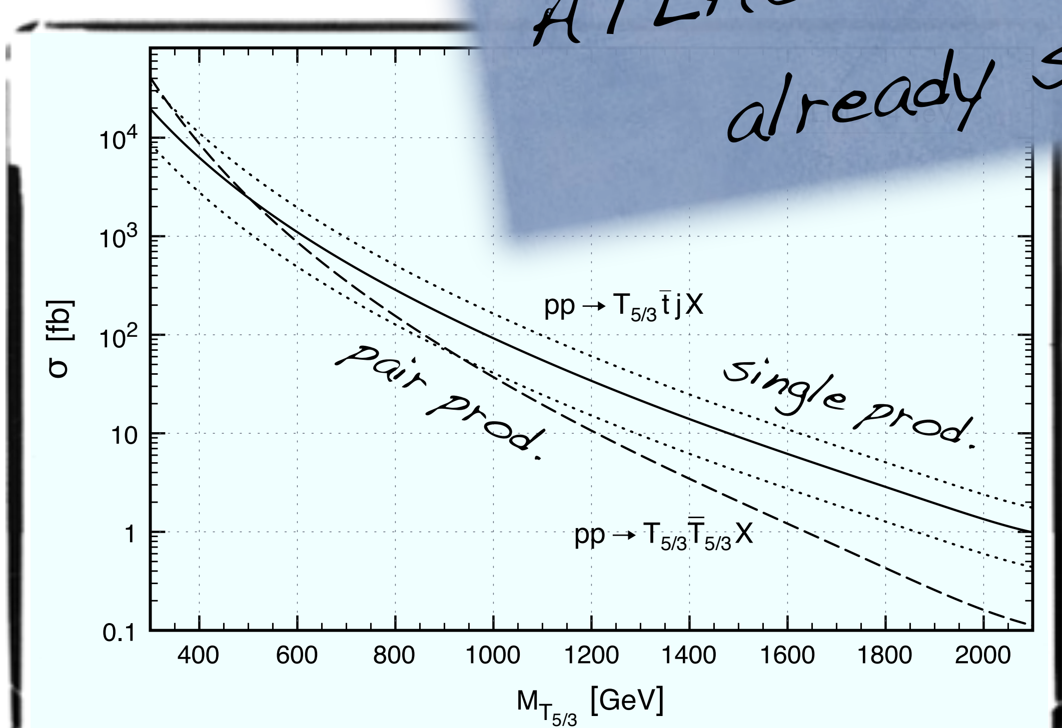
[Contino, Servant '08]
[Mrazek, Wulzer '09]
[Dissertori et al '10]



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

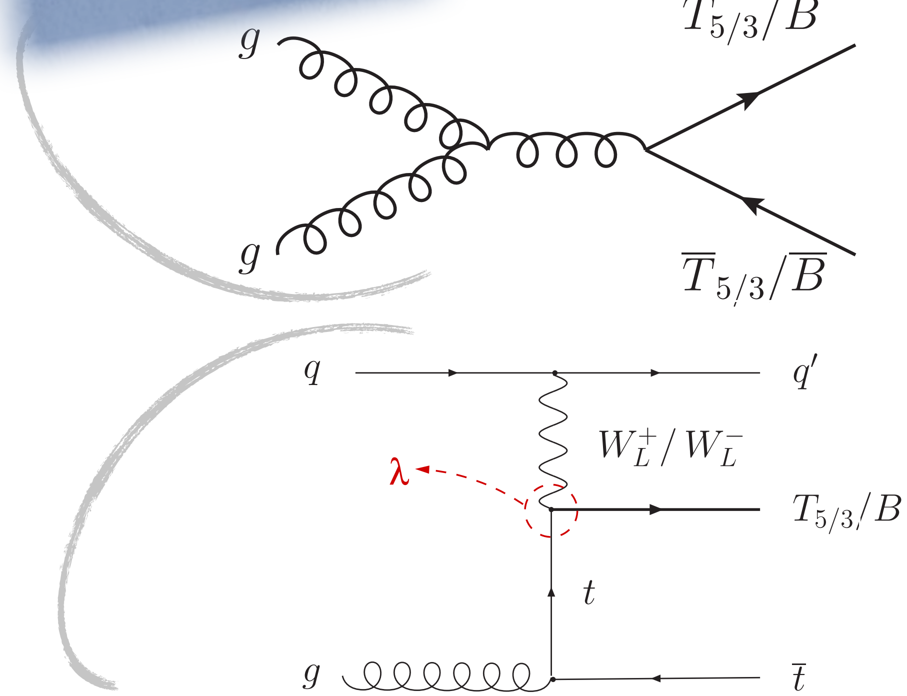
discovery potential (LHC$_{14TeV}$)
$M_{5/3}$=500 GeV (σxBR≈100/fb) → 56 pb^{-1}
$M_{5/3}$=1 TeV (σxBR≈2/fb) → 15 fb^{-1}

ATLAS & CMS searches ongoing
already stringent bounds



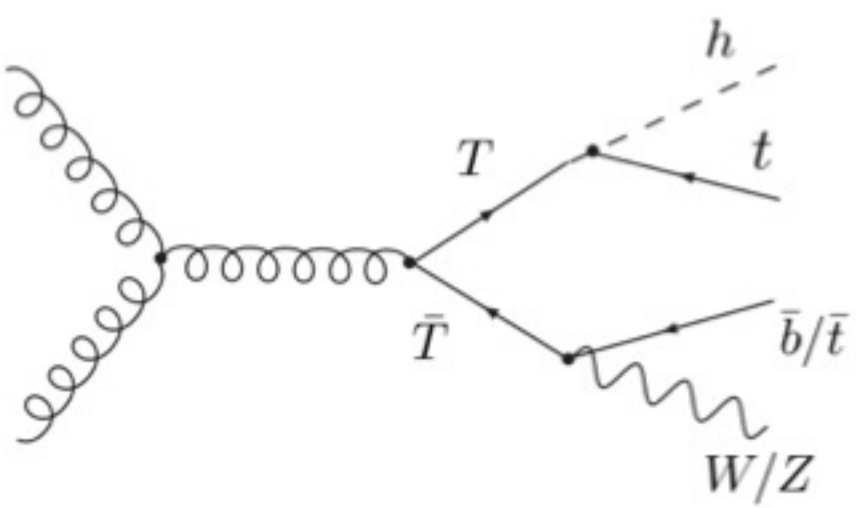
[Contino, Servant '08]

(model independent)



Single production (model dependent)

Rich phenomenology of the top partners



l± + 4b final state

Aguilar-Saavedra '09

$T\bar{T} \to HtW^-\bar{b} \to HW^+bW^-\bar{b}$ $\quad H \to b\bar{b}, WW \to \ell\nu q\bar{q}'$,

$T\bar{T} \to HtV\bar{t} \to HW^+bVW^-\bar{b}$ $\quad H \to b\bar{b}, WW \to \ell\nu q\bar{q}', V \to q\bar{q}/\nu\bar{\nu}$

l± + 6b final state

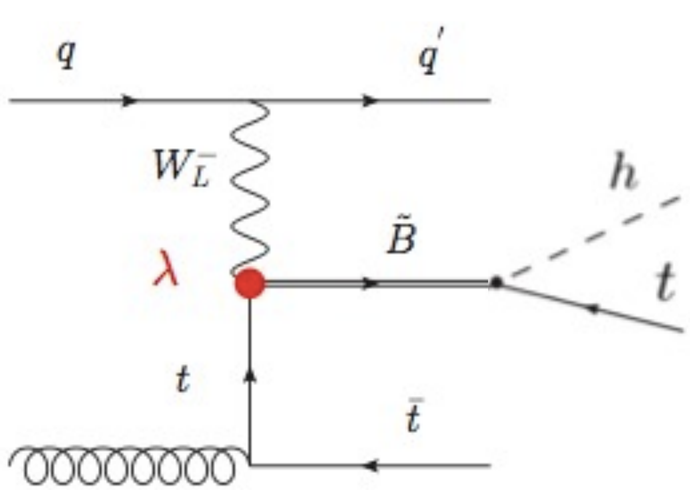
Aguilar-Saavedra '09

$T\bar{T} \to HtH\bar{t} \to HW^+b\,HW^-\bar{b}$ $\quad H \to b\bar{b}, WW \to \ell\nu q\bar{q}'$

$\gamma\gamma$ final state

Azatov et al '12

$thbW/thtZ/thth,\ h \to \gamma\gamma$



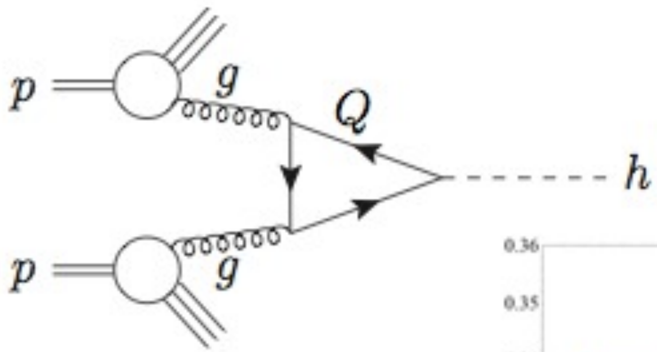
l± + 4b final state

Vignaroli '12

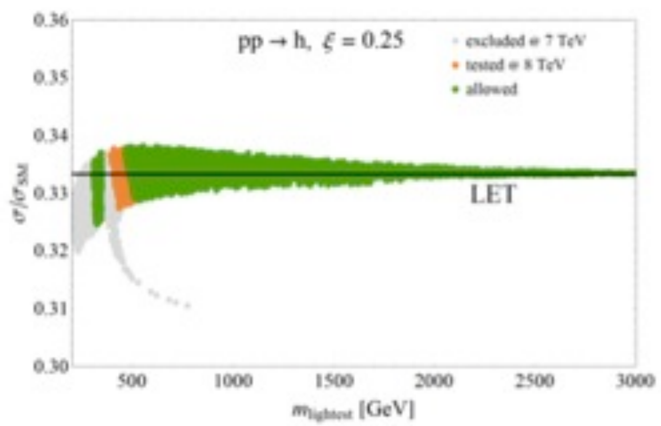
$pp \to (\tilde{B} \to (h \to bb)b)t + X$

Top partners & Higgs physics

~ current single higgs processes are insensitive to top partners ~



$\sigma^{SM}_{14\text{TeV}} \approx 50$ pb



two competing effects that cancel:

- ☑ T's run in the loops
- ☑ T's modify top Yukawa coupling

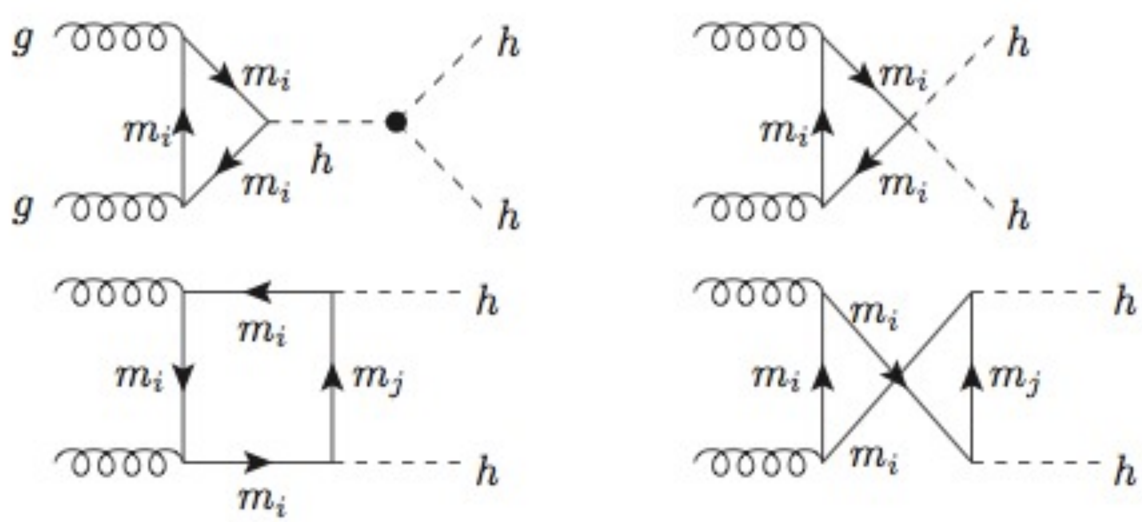
Falkowski '07

Azatov, Galloway '11

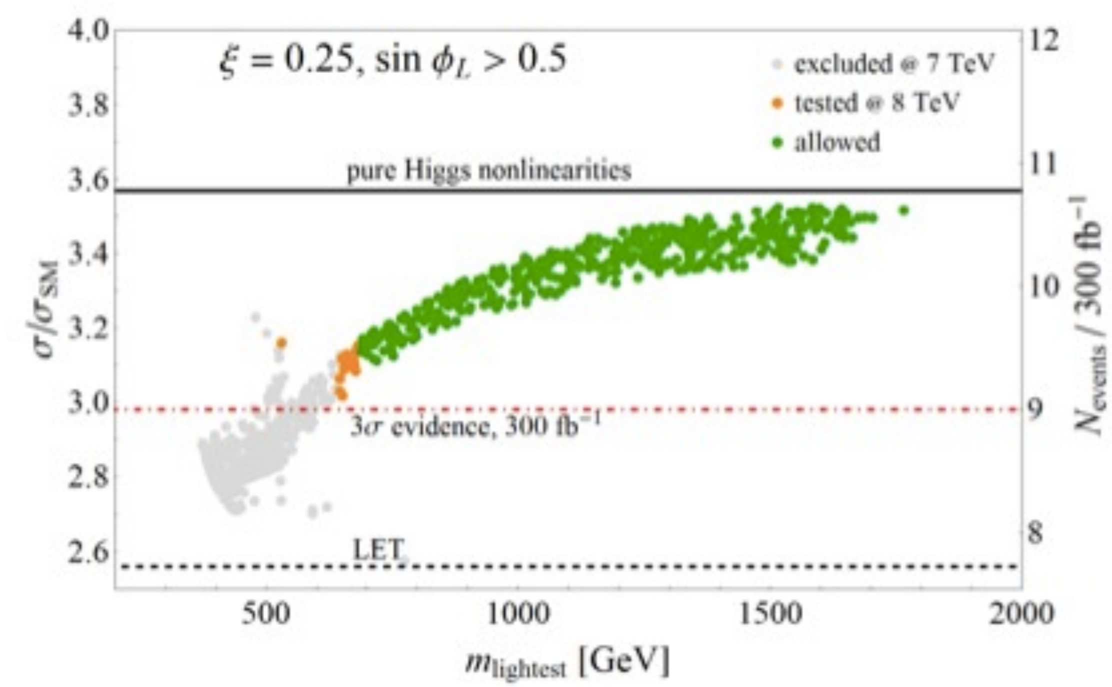
Delaunay, Grojean, Perez, '13

~ sensitivity in double Higgs production ~

Gillioz, Grober, Grojean, Muhlleitner, Salvioni '12



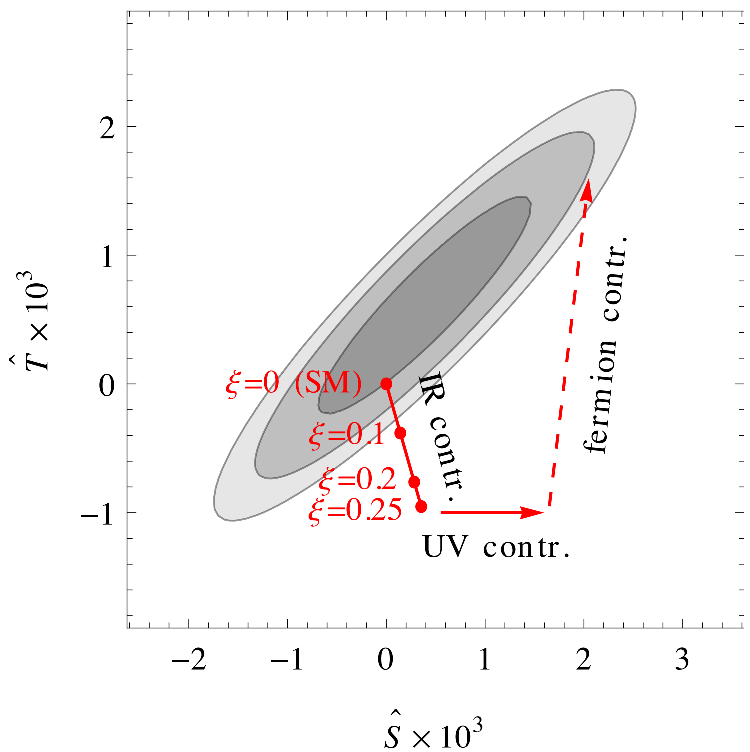
$\sigma^{SM}_{14\text{TeV}} = 17.9\text{fb}$



Top partners & EWPT

Grojean, Matsedonskyi, Panico '13

Oblique parameters



tree-level contribution

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

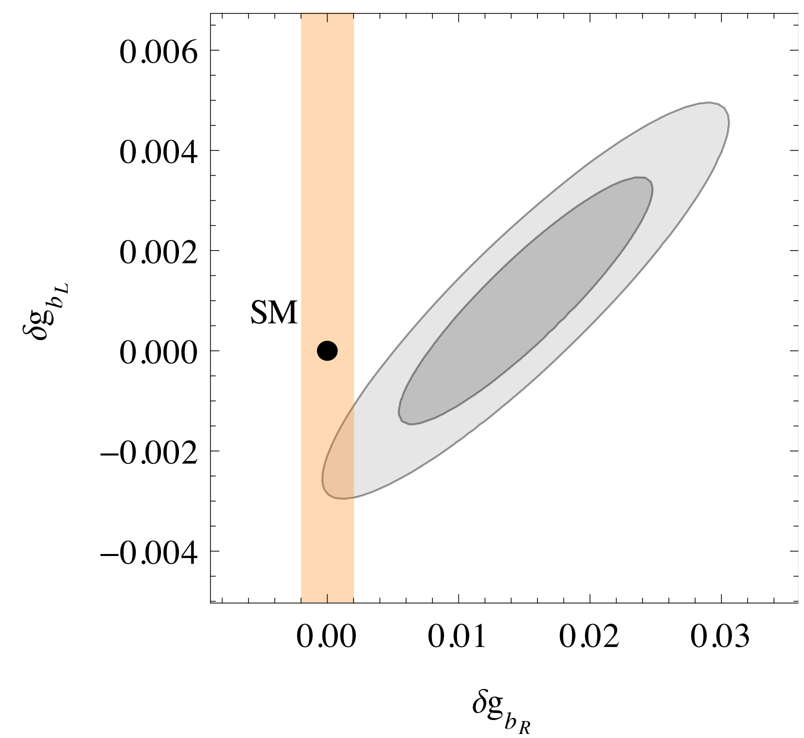
Higgs loop

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

fermion loop

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

Zb_Lb_L



tree-level contribution

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

fermion loop

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

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

BSM Higgs precision era