Composite Higgs phenomenology at the LHC and Future Colliders

Stefania De Curtis

INFN and Dept. of Physics and Astronomy, Florence University, Italy

Based on: DC, Redi,Tesi, JHEP 1204,042 (2012); Barducci et al, JHEP 1304, 152 (2013); Barducci et al, JHEP 1309,047 (2013); DC, Redi, Vigiani, JHEP 1406,071 (2014); Barducci, DC, Moretti, Pruna, JHEP 1402,005 (2014)

574. Wilhelm und Else Hereaus Seminar
STRONG INTERACTIONS IN THE LHC ERA
Physikzentrum Bad Honnef, Germany, Nov. 12-14, 2014

Outline

- ☑ The 125 GeV Higgs-like signal observed at the LHC could not be the "fundamental" Standard Model Higgs
- ☑ From a theoretical point of view the SM is unsatisfactory. Explore BSM solutions: Higgs as Nambu-Goldstone boson provides an elegant solution for naturalness
- ☑ Minimal effective description: the 4-Dimensional Composite Higgs Model (4DCHM) and generalizations
- ☑ Signatures at the LHC: scalar sector, extra resonances
- ☑ Phenomenology at future e+e- colliders

Why Beyond the Standard Model ?

Is Naturalness a good guideline?

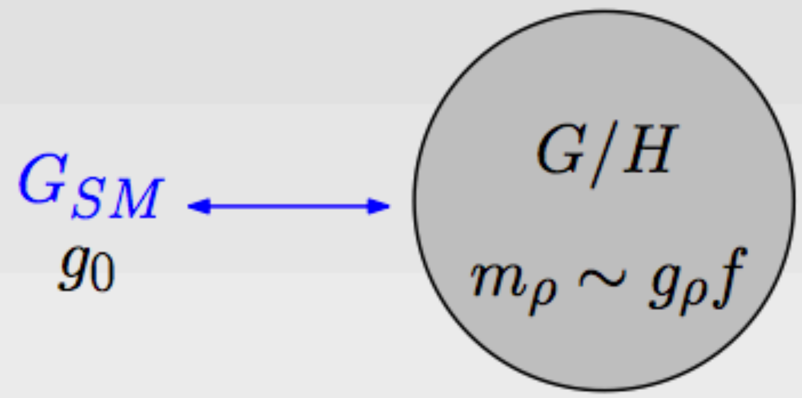
$\sim \Lambda^2 H^\dagger H$

In the SM, Higgs is not naturally light.

New paradigms...

- Supersymmetry
- Strong dynamics near the TeV scale
  - Technicolor
  - Extra Dimension
  - Higgsless
  - Composite Higgs Models

Higgs as a Composite Pseudo Goldstone Boson



Kaplan, Georgi '80s

The basic idea

- Higgs as Goldstone Boson of G/H in a **strong** sector
- An idea already realized for pions in QCD

How to get an Higgs mass?

- G is only an approximate global symmetry $g_0 \;\rightarrow\; V(h)$
- EWSB as in the SM
- And the hierarchy problem?

no Higgs mass term at tree level

$$\rightarrow \delta m_h^2 \sim \frac{g_0^2}{16\pi^2}\Lambda_{com}^2$$

Characteristics of a Composite Higgs

It is not a true (SM-like) Higgs...

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 + V(h) + \frac{v^2}{4}\mathrm{Tr}\left[(D_\mu\Sigma)^\dagger(D^\mu\Sigma)\right]\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right)$$

$$- \frac{v}{\sqrt{2}}\sum_{i,j}\left(\bar{u}_L^i \bar{d}_L^i\right)\Sigma\begin{pmatrix}\lambda_{ij}^u u_R^j \\ \lambda_{ij}^d d_R^j\end{pmatrix}\left(1 + c\frac{h}{v} + \cdots\right) + \mathcal{L}_{SM,\not h}$$

$$\Sigma = e^{i\frac{\sigma^a\chi^a}{v}}$$

- SM Higgs for a $a = b = c = 1$
- GB Higgs $a = \sqrt{1 - v^2/f^2},\ b = 1 - 2\ v^2/f^2$ SM limit $f \to \infty$
- Composite Higgs only partly unitarizes WW scattering $A(s,t,u) \sim \frac{s+t}{f^2}$
- Technicolor limit $f = v$

Composite Higgs Model

From now on, composite=pseudo-Goldstone

How to construct a *complete* Composite Higgs Model?

- $G/H \supset \mathbf{4}$, $G_{SM} \subset H$
- Computable Higgs mass: finite 1-loop effective potential
- Need for composite resonances!
- Not too large tuning $\quad \xi = \frac{v^2}{f^2}, \quad v = 246\ \text{GeV}, \quad f \sim 1\ \text{TeV}$

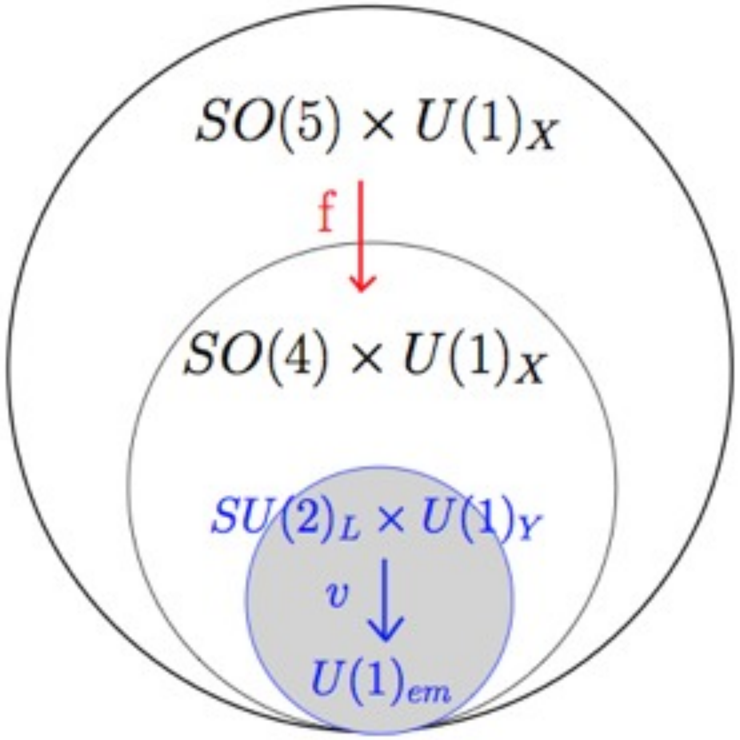
MINIMAL MODEL with $SU(2)_C$

Agashe, Contino, Pomarol (hep-ph/0412089)

$$\frac{SO(5)}{SU(2)_L \times SU(2)_R} \quad \rightarrow \quad \text{GB: } (\mathbf{2}, \mathbf{2})$$

Higgs = pseudo-GB

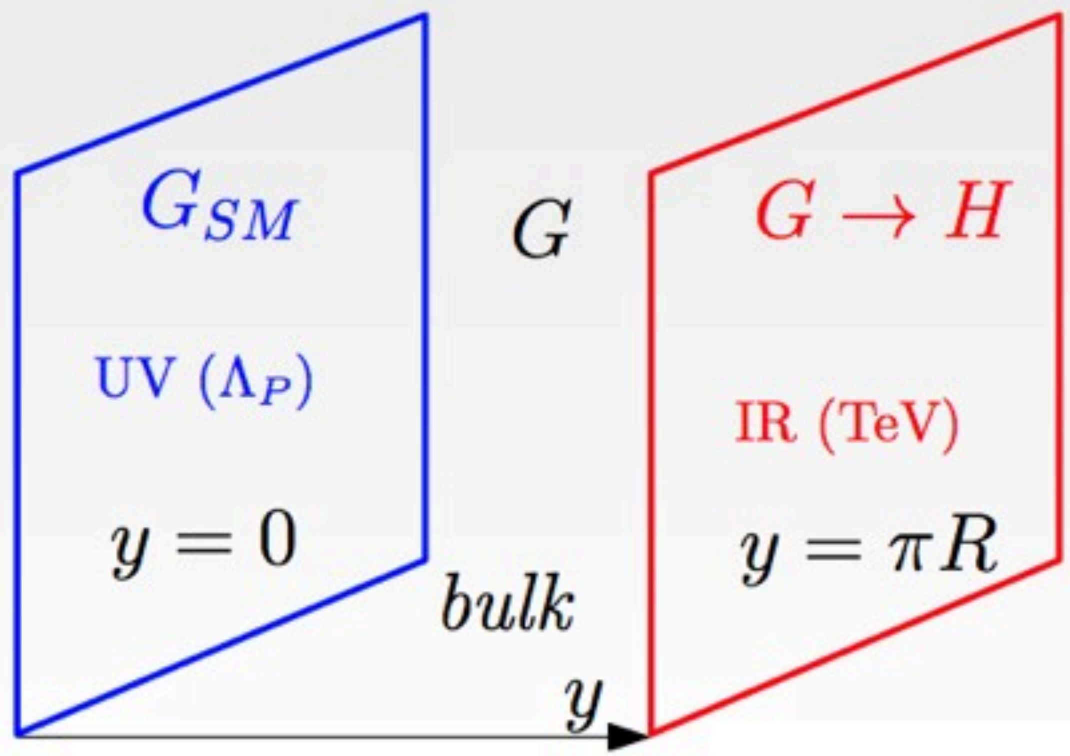
$(m_h \ll m_\rho)$



Composite Higgs Model in 5D

- Composite physics realized by Randall-Sundrum scenario
- H is the fifth component (A_5) of extradim. gauge field

$$\partial_y A_\mu|_{UV} = 0$$



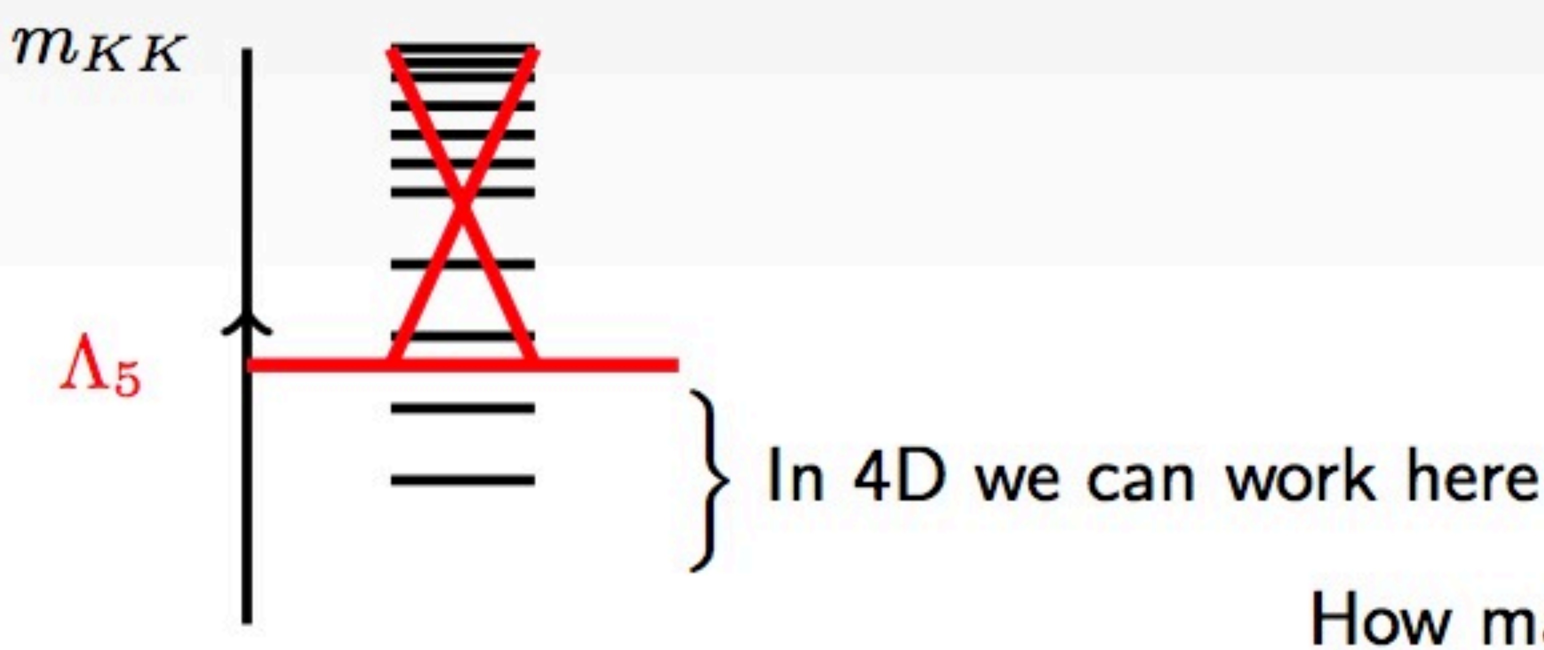
$$A_\mu^{\hat{a}}|_{IR} = 0$$
$$\partial_y A_\mu^{a}|_{IR} = 0$$
$$ds^2 = e^{-2ky}dx^2 - dy^2$$

- Symmetry breaking via boundary conditions
- $\#$ resonances $= \infty$
- Compositness degree $\sim$ localization towards IR

Composite Higgs Model in 4D

- Only few resonances below the 5D cut-off, $\Lambda_5 \sim 16\pi^2/g_5^2$
- 4D models can be more general
- Composite physics largely indipendent of 5D bulk
- Only the first resonance "observable" at LHC

Very roughly



How many resonances?
Just 1!

Explicit Models in 4D

Elementary Sector		Strong Sector
$A_\mu, \psi \in SU(2) \times U(1)_Y$	$\longleftrightarrow$ $\mathcal{L}_{\rm mix} = g_0 A_\mu J^\mu_\rho + \Delta \bar{\psi} \Psi$	$\rho_\mu, \Psi \in G_{\rm strong}$
$g_0 < 1$		$m_\rho,\ 1 < g_\rho < 4\pi$

4D Effective descriptions:

- Simplified model (two sectors without GB) Contino, Kramer, Son, Sundrum '07
- General low-energy effective description of a GB Higgs (CCWZ) Giudice, Grojean, Pomarol, Rattazzi '07
- Add the lightest composite resonance Contino et al. 1109.1570; De Simone et al. 1211.5663; Grojean et al.1306.4655

Discrete models: Panico, Wulzer 1106.2719; DC, Redi,Tesi 1110.1613

- Deconstruction of a 5D model
- Description of the composite degrees of freedom accessible at the LHC
- Calculability

How to break G/H and add spin-1 resonances

Consider the σ-models Ω_1 and Ω_2 $(\Phi_2 = \Omega_2 \phi_0)$ respectively,

$$\frac{G_L \times G_R}{G_{L+R}} \quad \text{and} \quad \frac{G}{H}$$

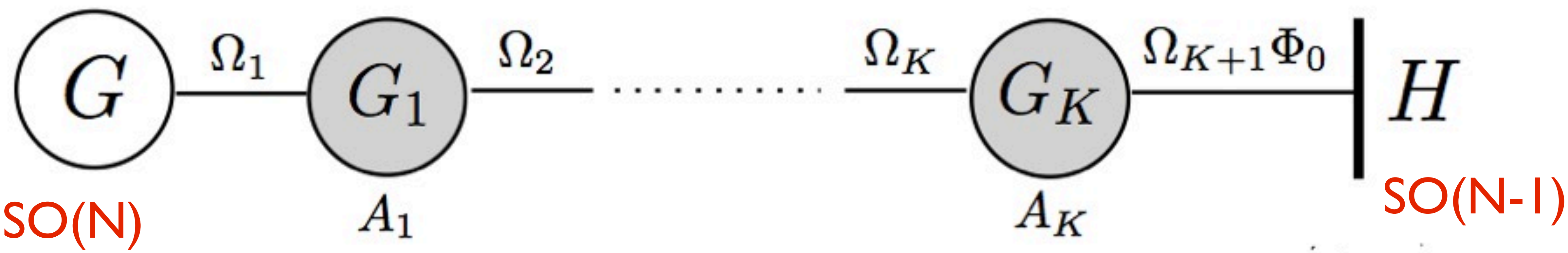
...and *gauge* G_R x G.

$$\mathcal{L} = \frac{f_1^2}{4} \mathrm{Tr} \left| D_\mu \Omega_1 \right|^2 + \frac{f_2^2}{2} (D_\mu \Phi_2)^T D^\mu \Phi_2 - \frac{1}{4 g_\rho^2} \rho^A_{\mu\nu} \rho^{A\mu\nu}$$

$$D_\mu \Omega_1 = \partial_\mu \Omega_1 - i A_\mu \Omega_1 + i \Omega_1 \rho_\mu, \qquad \Omega_n = e^{i \frac{f}{f_n^2} h^{\hat{a}} T^{\hat{a}}}$$
$$D_\mu \Phi_2 = \partial_\mu \Phi_2 - i \rho_\mu \Phi_2$$

- Resonances in H and G/H (as vector/axial QCD mesons)
- G_L non-linear global symmetry, H unbroken one. GB field $\Phi = \Omega_1 \Phi_2$
- Kinetic terms for $A_\mu \in G_{SM}$ fix the model

K copies $\longrightarrow$ moose model



$$\Omega_i \to g_{i-1}\,\Omega_i\,g_i^\dagger\,, \quad \Omega_{K+1} \to g_K\,\Omega_{K+1}\,h^\dagger$$

$$\text{GBs}: \quad U(\Pi) = \Omega_1 \ldots \Omega_{K+1}$$

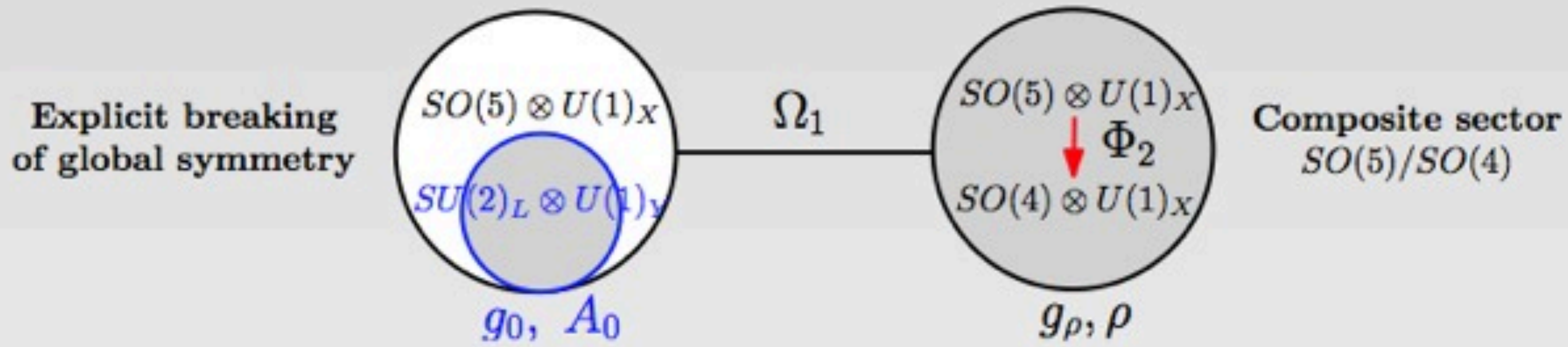
K massive spin-1 resonances $\quad + \quad$ $SO(N)/SO(N-1)$ GBs

nearest neighbour interactions : $\quad K \to \infty \quad \Rightarrow \quad$ 5D theory

4DCHM = Minimal 4D realization of MCHM5

DC, Redi, Tesi '11

Agashe, Contino, Pomarol '04



$$\mathcal{L}_{\rm ele} = -\frac{1}{4}A^a_{\mu\nu}A^a_{\mu\nu} - \frac{1}{4}B_{\mu\nu}B_{\mu\nu}$$

$$\mathcal{L}_{\rm comp} = -\frac{1}{4}\rho^A_{\mu\nu}\rho^A_{\mu\nu} + \frac{1}{2}m^2_\rho \rho^a_\mu \rho^a_\mu + \frac{1}{2}m^2_{a_1}\rho^{\hat a}_\mu \rho^{\hat a}_\mu + |\partial_\mu H - i g_\rho \rho_\mu H|^2 + \text{nl terms...}$$

$$\mathcal{L}_{\rm mix} = \frac{1}{2}m^2_\rho \frac{g_0^2}{g_\rho^2}A^2_\mu - m^2_\rho \frac{g_0}{g_\rho}A_\mu \rho_\mu + (\partial^\mu H^\dagger A_\mu H)\ \text{nl terms...}$$

- Non linear structure ↔ GB Higgs
- GB decay constant

$$f^2 = \frac{f_1^2 f_2^2}{f_1^2 + f_2^2}$$

- Composite spectrum

$$SO(4) \to m^2_\rho = \frac{g^2_\rho f_1^2}{2}, \qquad \frac{SO(5)}{SO(4)} \to m^2_{a_1} = \frac{g^2_\rho (f_1^2 + f_2^2)}{2}$$

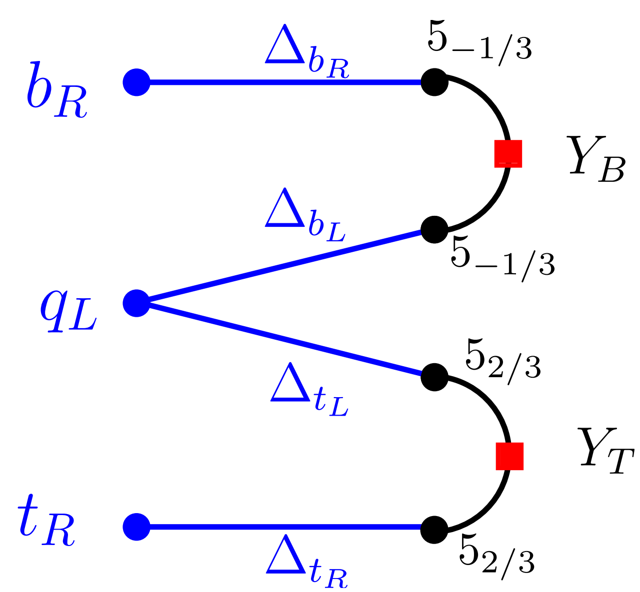
Fermion sector: which representation?

A phenomenolgical choice (protecting $Zb\bar{b}$) — Agashe, Contino, da Rold, Pomarol '06

$$\mathbf{5}_{2/3} = \underbrace{\mathbf{2}_{1/6}}_{q_L} \oplus \mathbf{2}_{7/6} \oplus \underbrace{\mathbf{1}_{2/3}}_{u_R}, \quad \mathbf{5}_{-1/3} = \mathbf{2}_{5/6} \oplus \underbrace{\mathbf{2}_{1/6}}_{q_L} \oplus \underbrace{\mathbf{1}_{-1/3}}_{d_R}, \quad Y = T_{3R} + X$$

4DCHM: four extra fermions in 5 reps of SO(5) -- minimum for UV finite effective potential

Explicit breaking of global symmetry



Composite sector
$SO(5)/SO(4)$

Extra fermions:
- 8 t', 8 b' $Q_{em} = 2/3, -1/3$
- $2\tilde{T}$, $2\tilde{B}$ $Q_{em} = 5/3, -4/3$

$$\mathcal{L}_{\rm 4DCHM} = \mathcal{L}^{el}_{fermions}$$
$$+ \Delta_{t_L} \bar{q}^{el}_L \Omega_1 \Psi_T + \Delta_{t_R} \bar{t}^{el}_R \Omega_1 \Psi_{\tilde{T}} + h.c.$$
$$+ \bar{\Psi}_T (i \not{D}^\rho - m_T)\Psi_T + \bar{\Psi}_{\tilde{T}} (i \not{D}^\rho - m_{\tilde{T}})\Psi_{\tilde{T}}$$
$$- Y_T \bar{\Psi}_{T,L} \Phi_2^T \Phi_2 \Psi_{\tilde{T},R} - m_{Y_T} \bar{\Psi}_{T,L} \Psi_{\tilde{T},R} + h.c.$$
$$+ (T \to B)$$

→ Explicit SO(5) breaking

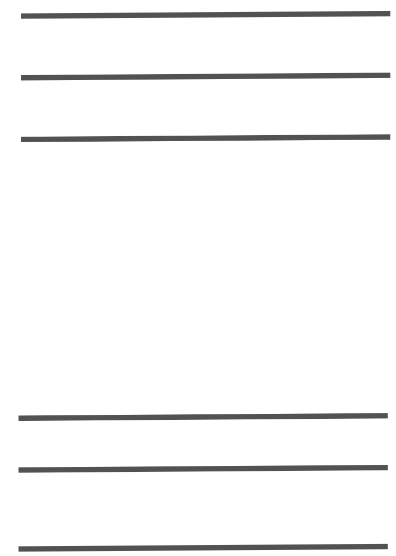
→ Composite physics SO(5)/SO(4)

Partial compositeness: 3rd generation quarks only

Strong sector: resonances + Higgs bound state

Extra particle content:
- Spin 1 resonances
- Spin 1/2 resonances

Spectrum:

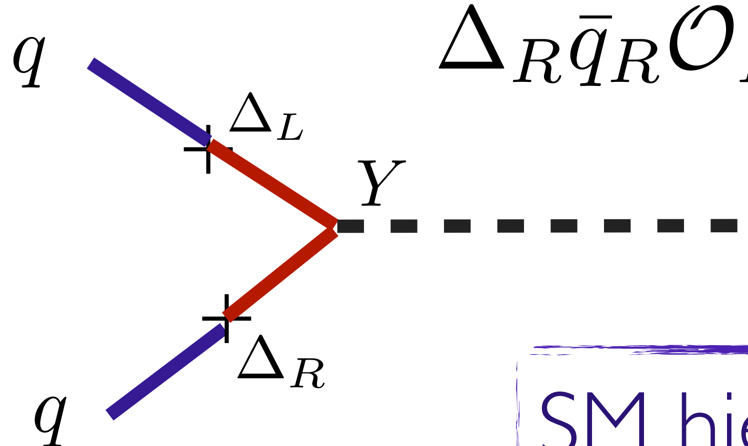


$m_\rho = g_\rho f$ } f

$m_h = 125\,\mathrm{GeV}$
$m_W = 80\,\mathrm{GeV}$ } v
0

$g_\rho =$ strong coupling

Linear elementary-composite couplings (partial compositeness)



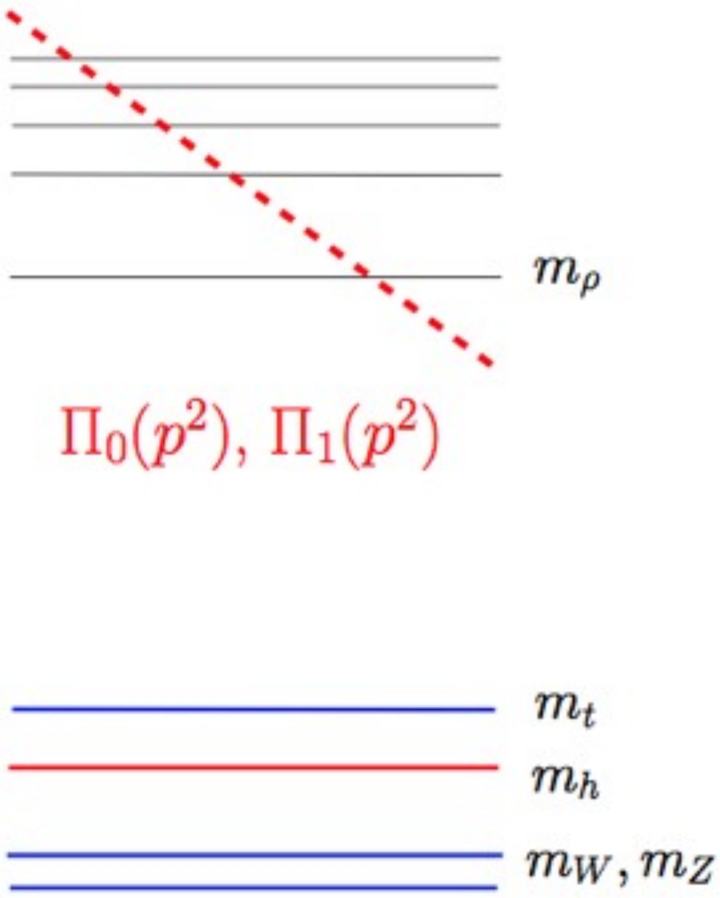
$$\Delta_R \bar{q}_R \mathcal{O}_L + \Delta_L \bar{q}_L \mathcal{O}_R + Y \bar{\mathcal{O}}_L H \mathcal{O}_R$$

$$y_{SM} = \epsilon_L \cdot Y \cdot \epsilon_R \qquad \epsilon = \frac{\Delta}{m_Q}$$

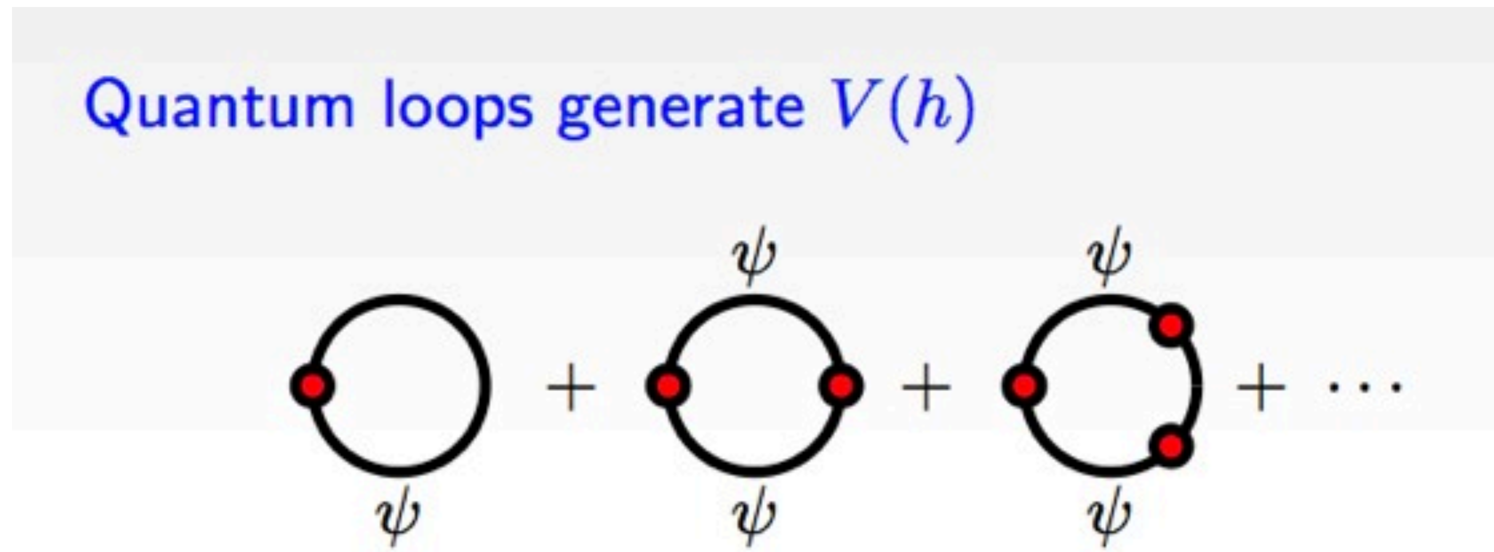
SM hierarchies are generated by the mixings:
light quarks elementary, top strongly composite

$$m_t \sim \frac{v}{\sqrt{2}} \frac{\Delta_{t_L}}{m_\psi} \frac{\Delta_{t_R}}{m_\chi} \frac{Y_T}{f}$$

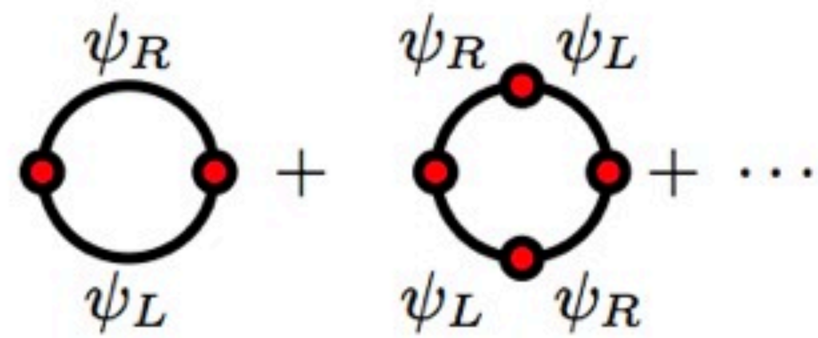
And the Higgs mass?



Integrate out the composite sector and get a low-energy Lagrangian with form-factors Agashe, Contino, Pomarol '04



Contribution from the gauge loops subleading



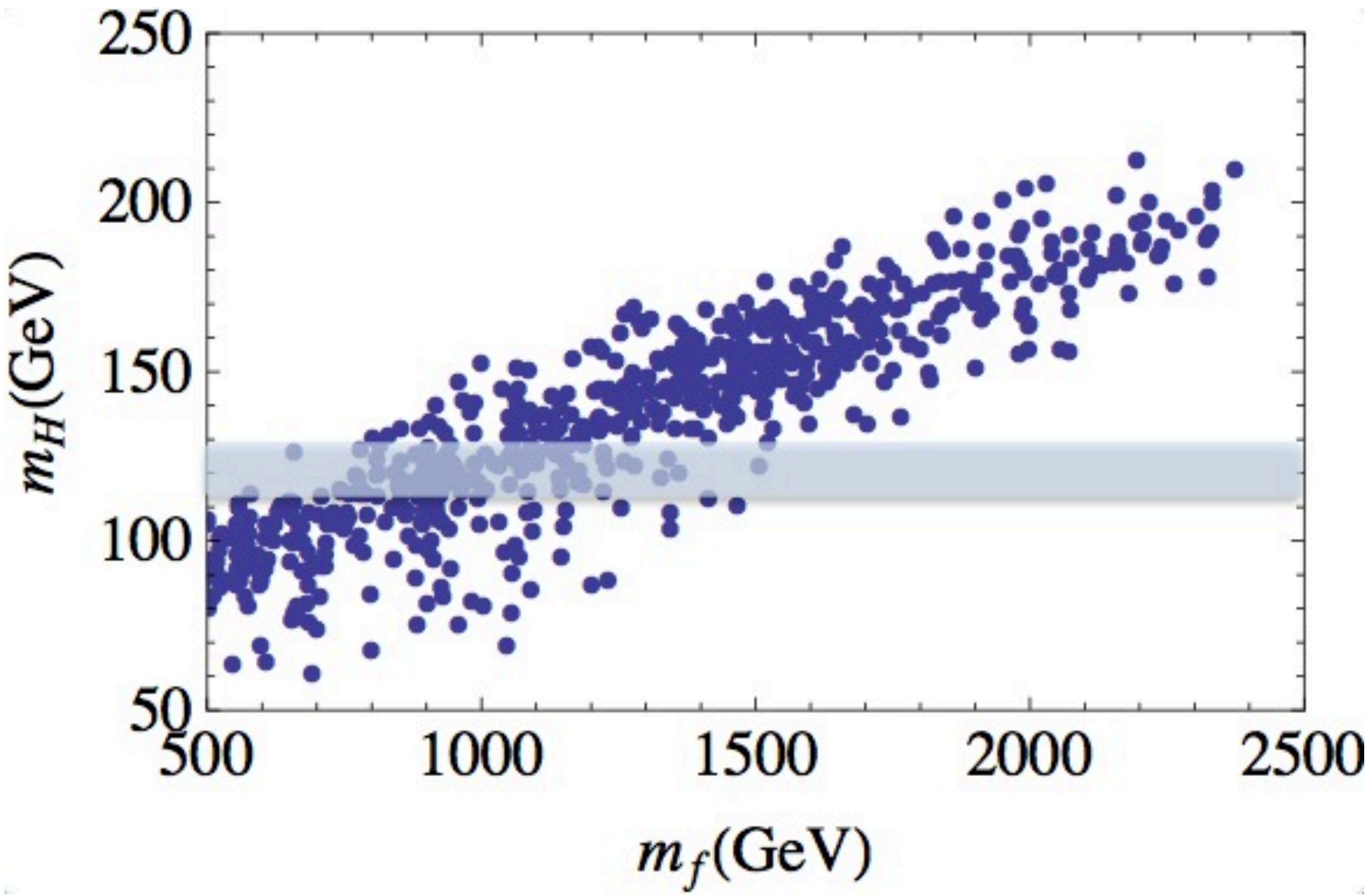
Is the potential finite? Yes !
Coset resonances are crucial for the finitness

$$m_H \sim 0.3\, y_t \frac{m}{f} v$$

Correlation with the lightest extra fermion mass

DC, Redi, Tesi '11

$$f = 800 \text{ GeV}, \ \xi \sim 0.1$$



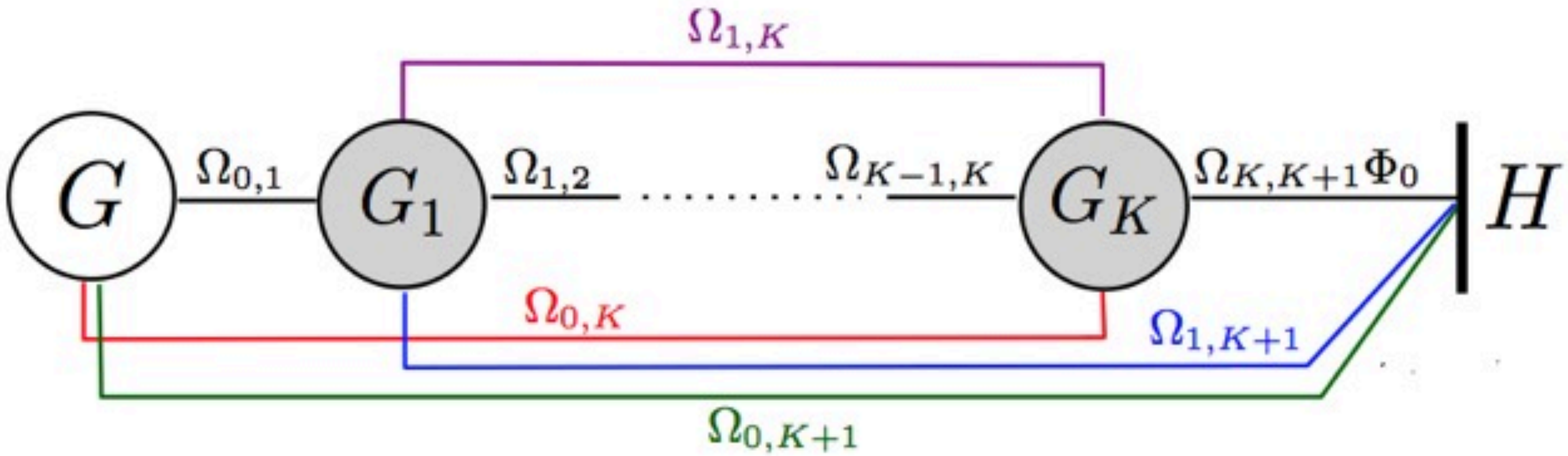
125 GeV Higgs wants light (in the TeV region) fermionic partners

The non-discovery of light extra fermions at LHC run2 requires a largest fine-tuning

Non minimal terms allowed by the symmetry

Add non nearest neighbour interactions (also considered in low energy QCD)

DC, Redi, Vigiani '14



link fields: $\Omega_{i,j} \equiv \prod_{k=i+1}^{j} \Omega_k$

$$\Omega_{i,j} \to g_i \Omega_{i,j} g_j^\dagger$$

$$\Omega_{i,K+1} \to g_i \Omega_{i,K+1} h^\dagger(\Pi, g_i)$$

The model reproduces the most general effective lagrangian up to two derivatives for a $SO(N)/SO(N-1)$ CHM

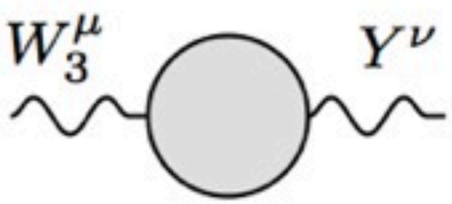
equivalent to CCWZ formulation (Marzocca, Serone, Shu (hep-ph/1205.0770))

▶ Interpolate between discrete models and low energy effective models

calculability generality

S parameter

Tree level contribution due to spin-1 resonances (see Grojean, Matsedonskyi, Panico hep-ph/1306.4655 for other contributions)



$$\Delta S = 4\pi v^2 \frac{d \ \log \Pi_1}{dp^2}\Big|_{p^2=0}$$

from non-minimal terms

$$\Delta S = 4\pi v^2 \sum_{i=1}^{K} \left(\frac{1}{m_{\rho_i}^2} + \frac{1}{m_{a_i}^2} \right) + 4\pi v^2 \frac{d \log \mathcal{N}}{dp^2}\Big|_{p^2=0}$$

nearest neighbour interactions $\longrightarrow$ $\Delta S \gtrsim \frac{4\pi v^2}{m_\rho^2}$ (~ ED theories Barbieri, Pomarol, Rattazzi hep-ph/0310285)

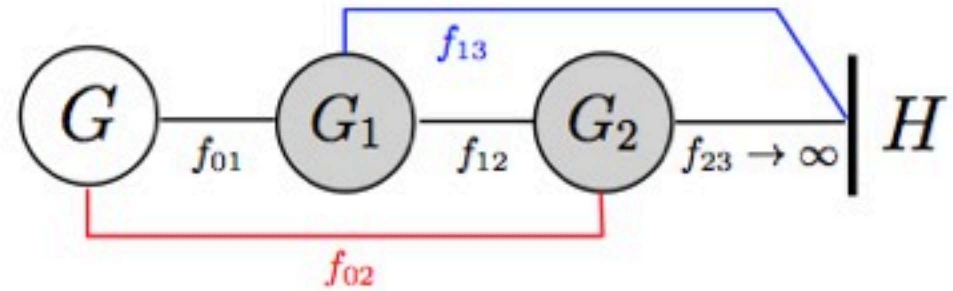
non nearest neighbour interactions $\longrightarrow$ $\mathcal{N}(p^2)$

$$f_{0K+1} : \quad \Delta S = 4\pi v^2 \sum_{i=1}^{N} \left(\frac{1}{m_{\rho_i}^2} + \frac{1}{m_{a_i}^2} \right) \frac{f^2 - f_{0K+1}^2}{f^2}$$

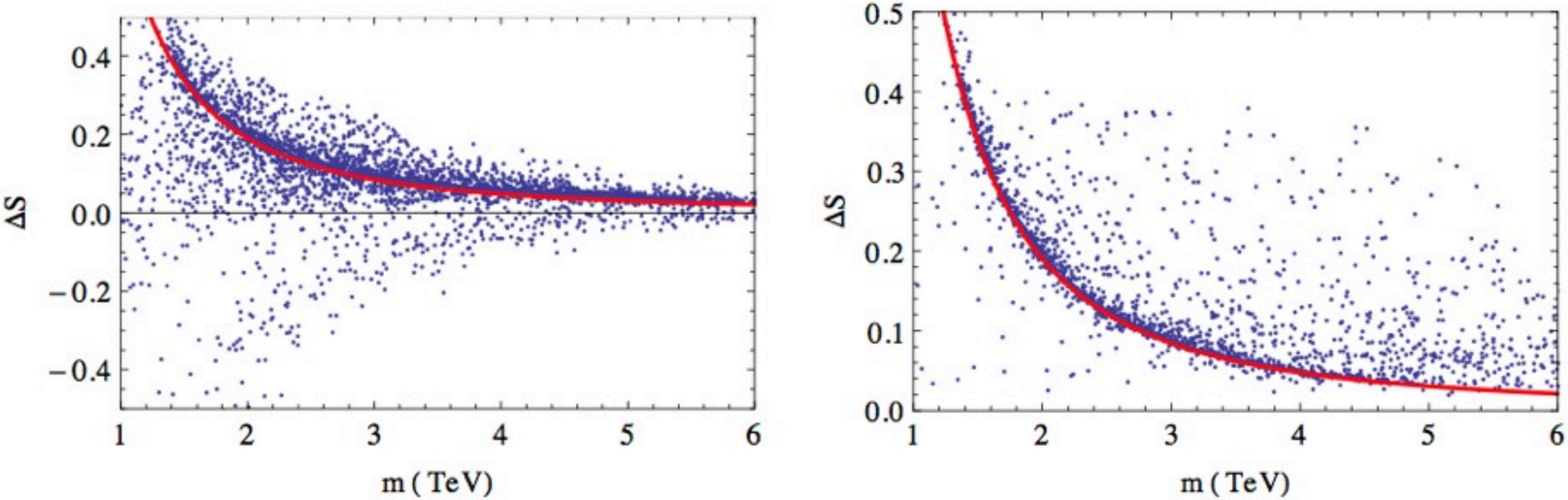
smaller contribution to S but the potential depends quadratically on the cut-off

Simple model: ρ_1, ρ_2, a_1

$V(h) \sim \log\Lambda$



$f_{02} \neq 0,\ f = 1\,\text{TeV}$ $\qquad$ $f_{13} \neq 0,\ f = 1\,\text{TeV}$



$$\Delta S < \frac{4\pi v^2}{m_\rho^2}$$

non minimal terms can lower the tree level contribution to the S parameter

If only minimal terms are considered the bound is $m_\rho \geq 2\ \text{TeV}$

Phenomenology of the 4DCHM at the LHC and future e^+e^- colliders

Implementation of the 4DCHM

- Calculable 4D description: good framework to study general CHM features
- The particle spectrum is quite large and also the parameter space

  - SM leptons: e, μ, τ, and ν_e, ν_μ, ν_τ
  - SM quarks; u, d, c, s, t, b
  - SM gauge bosons: $\gamma, Z^0, W^\pm, g$
  - 5 extra neutral gauge bosons: $Z'_{i=1,\ldots,5}$
  - 3 extra charged gauge bosons: $W'^{\pm}_{i=1,2,3}$
  - 8 extra charged 2/3 fermions: $t'_{i=1,\ldots,8}$
  - 8 extra charged -1/3 fermions: $b'_{i=1,\ldots,8}$
  - 2 charged 5/3 fermions: $T'_{i=1,2}$
  - 2 charged -4/3 fermions: $B'_{i=1,2}$
  - 1 Higgs boson

4DCHM implemented in numerical tools

- Scan over model parameters with Mathematica program constrained by $\alpha, M_Z, G_F, Z_{b\bar{b}}$ coupling, and by top, bottom, Higgs masses:

$$165 < m_t(GeV) < 175, \; 2 < m_b(GeV) < 6, \; 124 < m_H(GeV) < 126$$

output automatically read by LanHEP/CalcHEP

Automated implementation

LanHEP: package for the automated generation of Feynman rules
Semenov, arXiv:1005.1909
CalcHEP: package for automated calculations of physical observables
Belyaev et al, Comput. Phys. Commun. 184 (2013) 1729
HEPMDB: model available at https://hepmdb.soton.ac.uk

- Fermion parameter range for the scan:
  - $500 \text{ GeV} \leq m_*, \Delta_{t_L}, \Delta_{t_R}, Y_T, m_{Y_T}, Y_B, m_{Y_B} \leq 5000 \text{ GeV}$
  - $50 \text{ Gev} \leq \Delta_{b_L}, \Delta_{b_R} \leq 500 \text{ GeV}$ (partial compositness spirit)

- Benchmark points: $750 < f(\text{GeV}) < 1200$ and choosing g_ρ to get
  $m_\rho \simeq f g_\rho \geq 2 \text{ TeV}$ (EWPT)

Drell-Yan signals from the 4DCHM at the LHC

Barducci, Belyaev, DC, Moretti, Pruna, 1210.2927

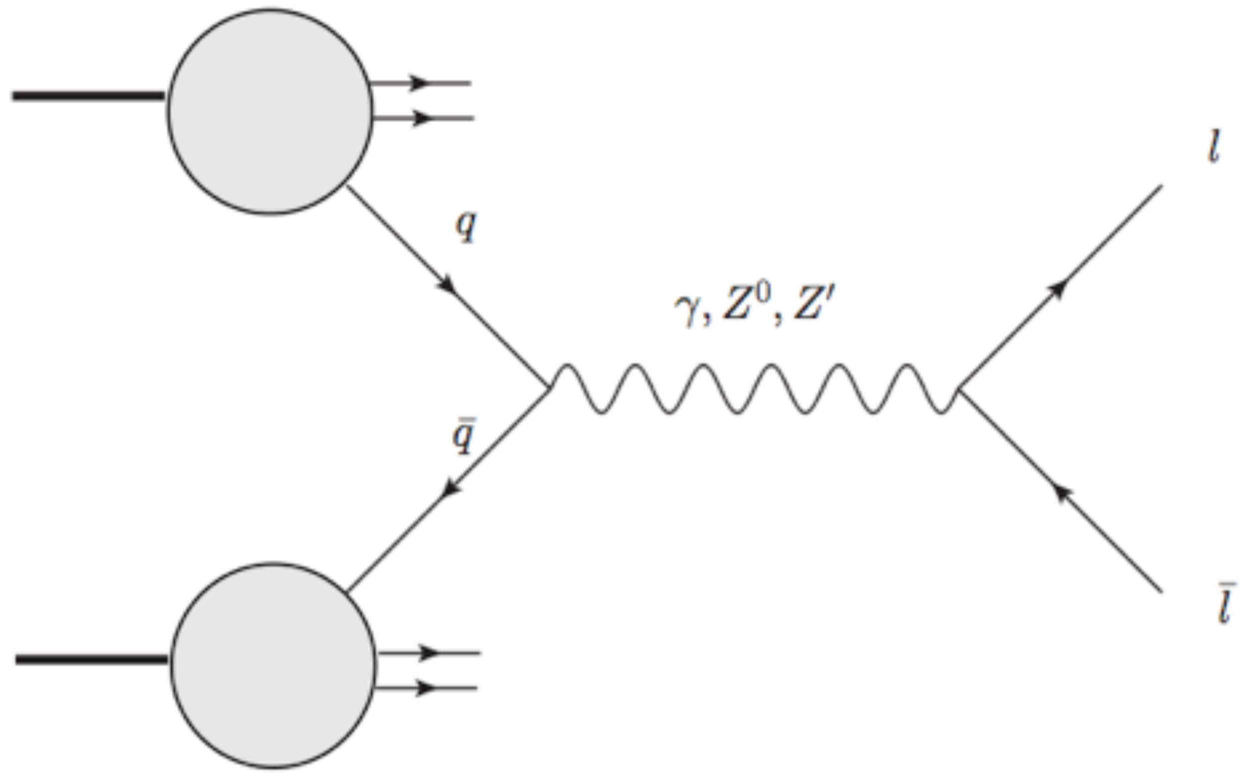
Quarks can annihilate also in Z' (and W')

tree-level processes

$$pp \to l^+ l^- \quad (NC)$$

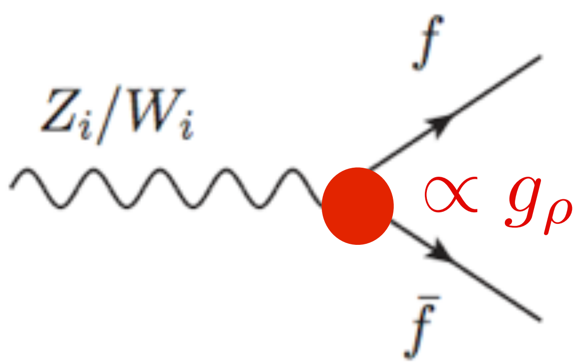
$$pp \to l^+ \nu_l + c.c \quad (CC)$$

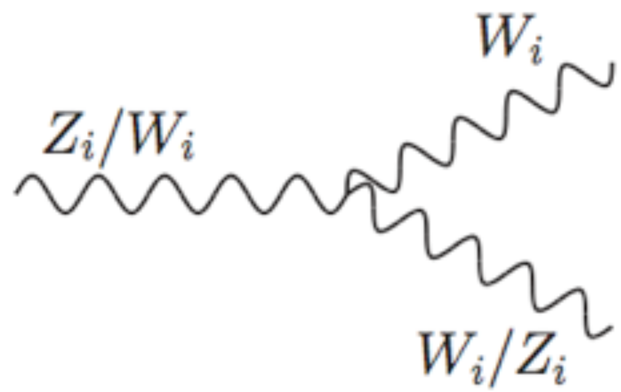
$$l = e, \mu$$

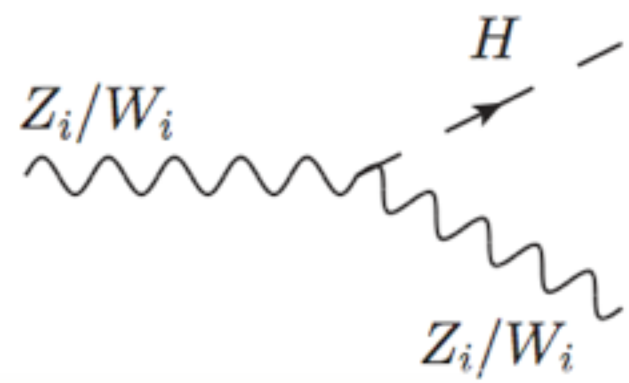


- DY allow us to investigate new gauge boson resonances
- Z' may be discovered as a peak in the dilepton invariant mass spectrum $Z' = Z_2, Z_3, Z_5$
- W' may be discovered as a peak in the dilepton missing-energy transverse mass spectrum $W' = W_2, W_3$

Widths of Z' and W'





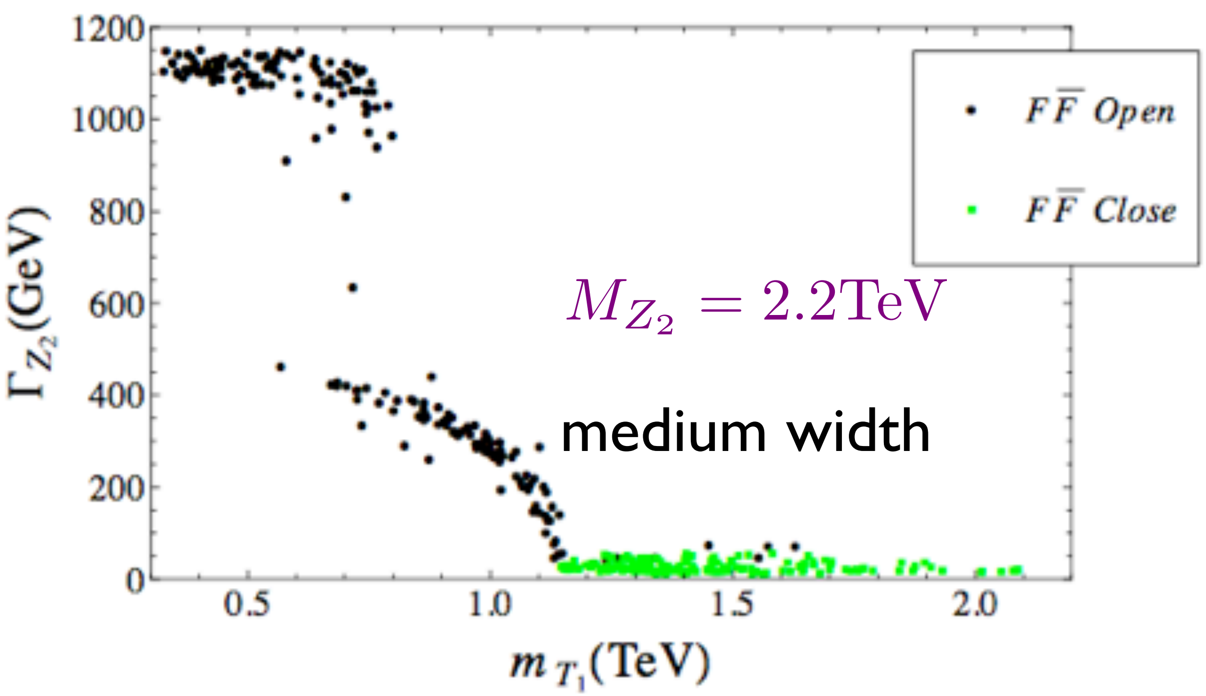


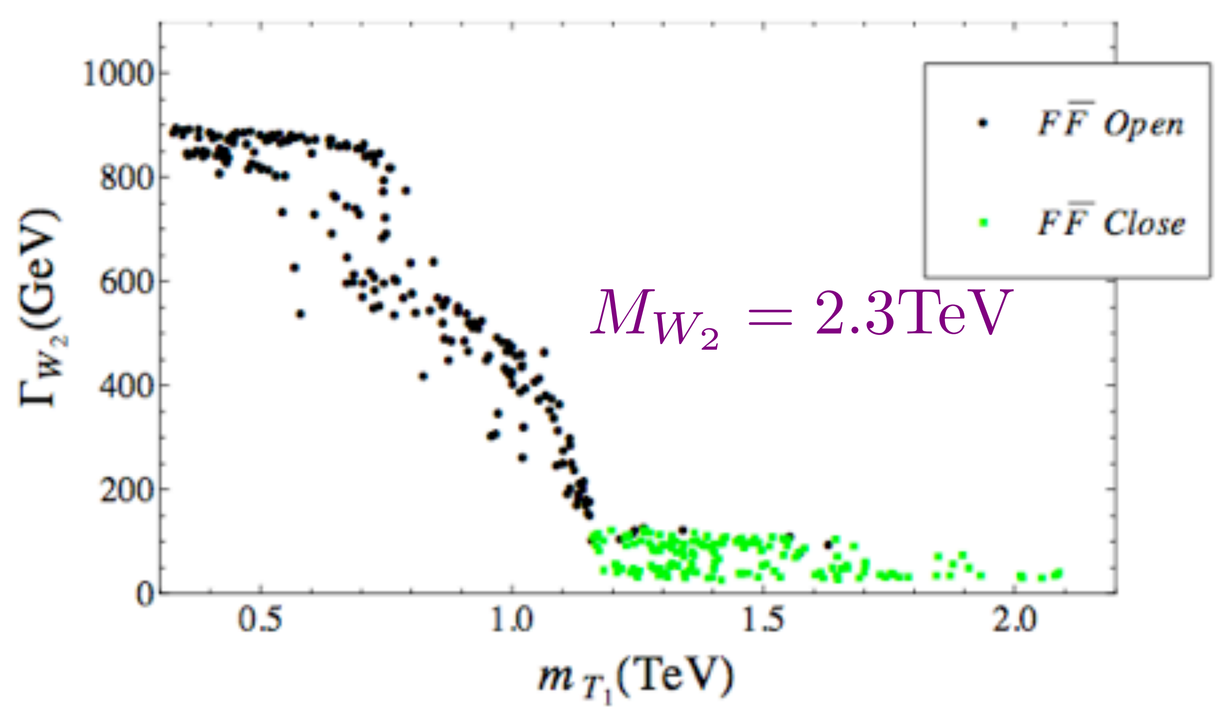
large number of fermions strongly coupled to W'and Z'

Two possible extreme situations

- $M_{Z'/W'} < 2m_{t'/b'} \rightarrow$ Small width $(< 100 GeV)$
- $M_{Z'/W'} > 2m_{t'/b'} \rightarrow$ Large width $(\Gamma_{Z_i/W_i} \simeq mass/2)$

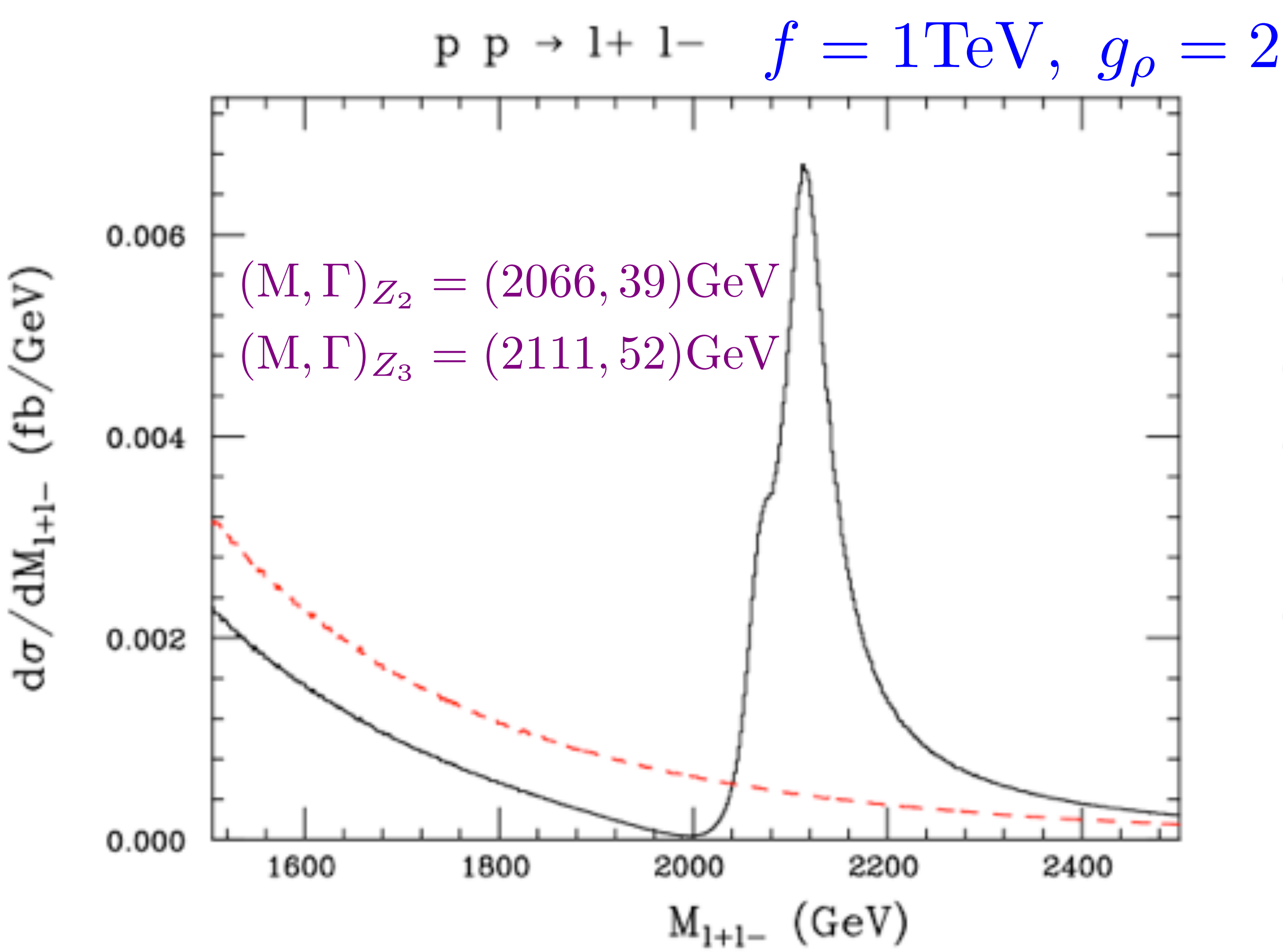
mandatory for leptonic DY processes

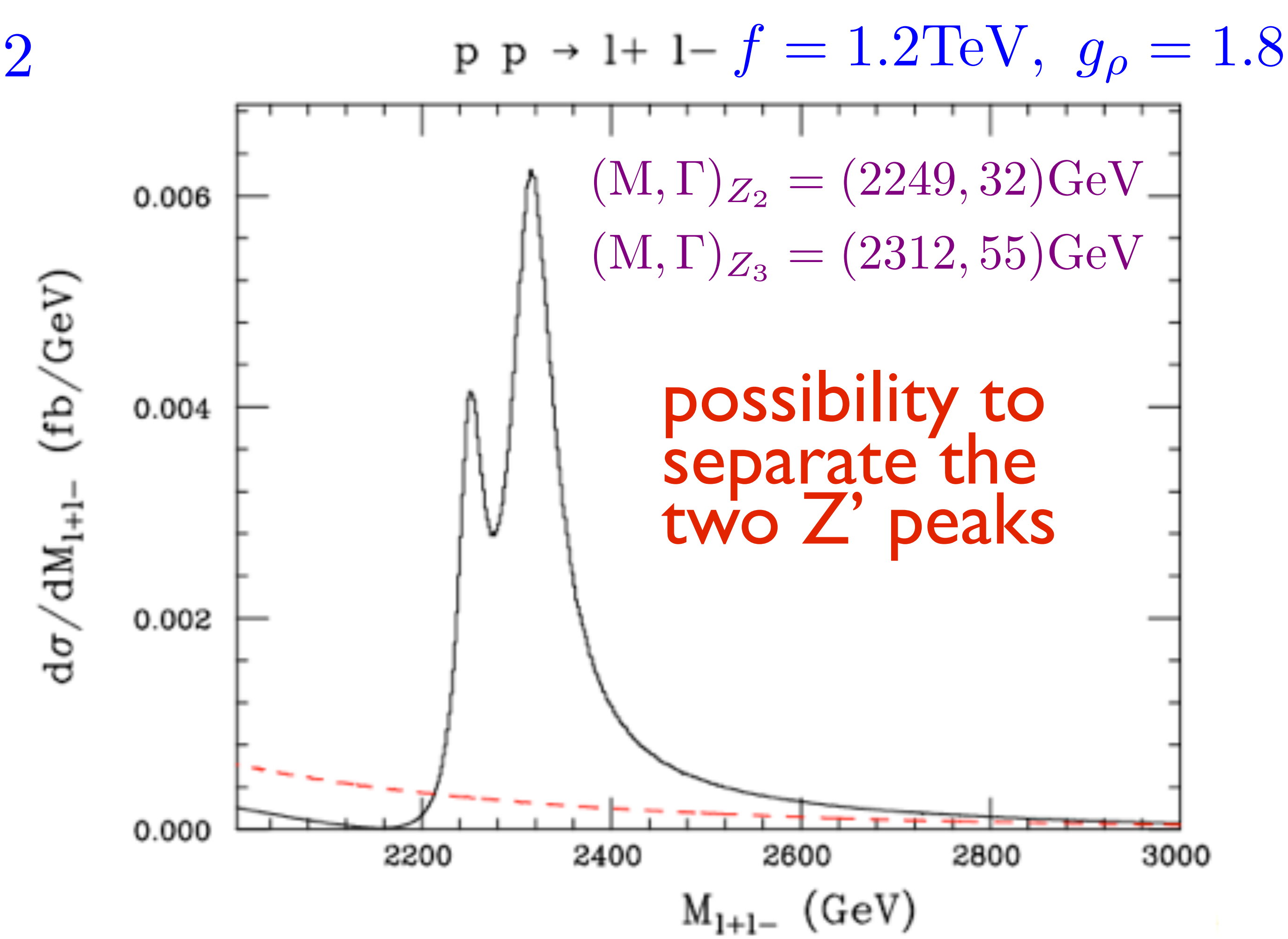




Exploring the line-shape at LHC14 - Neutral Channel

- The LanHEP/CalcHEP/Mathematica implementation give us a powerful tool for an automatized analysis of the 4DCHM





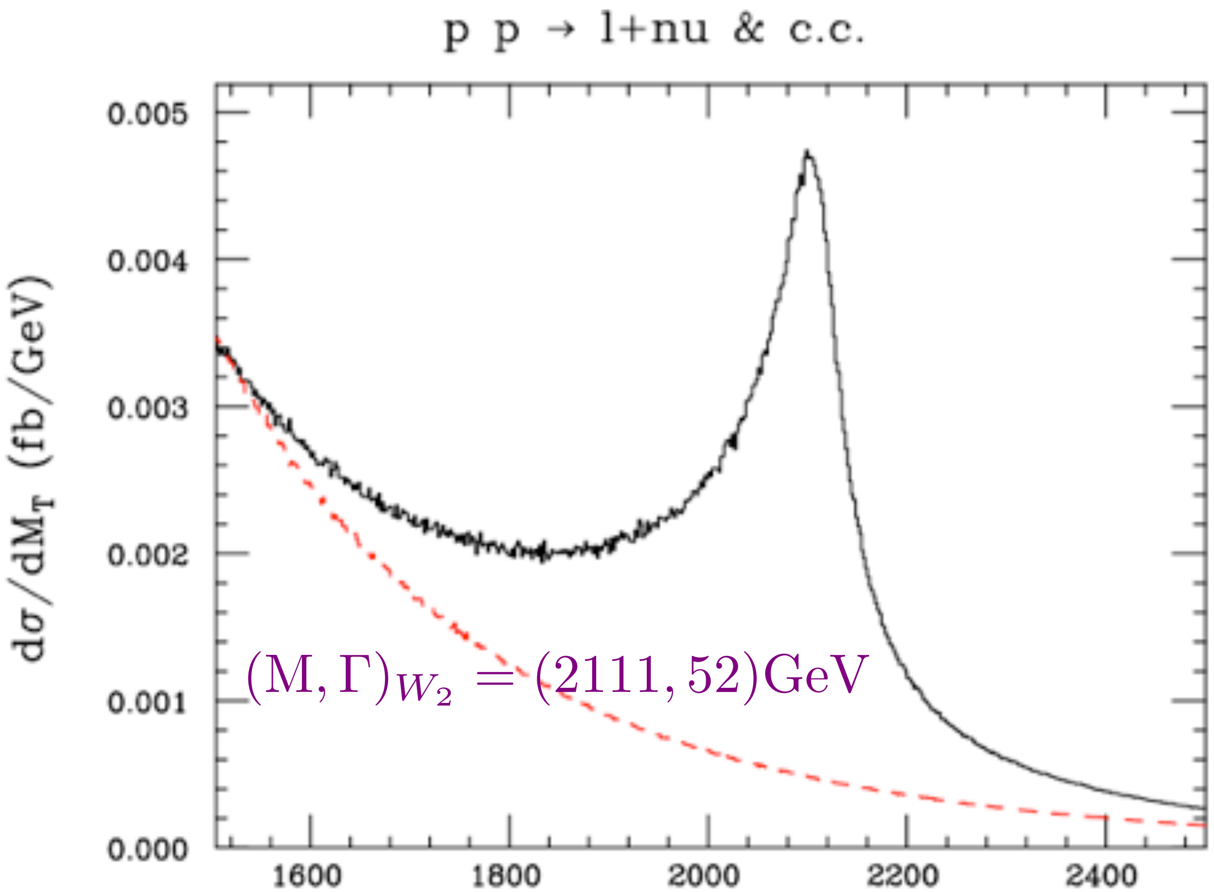
Differential distributions in the invariant mass M_{l+l-} for NC DY

cuts :

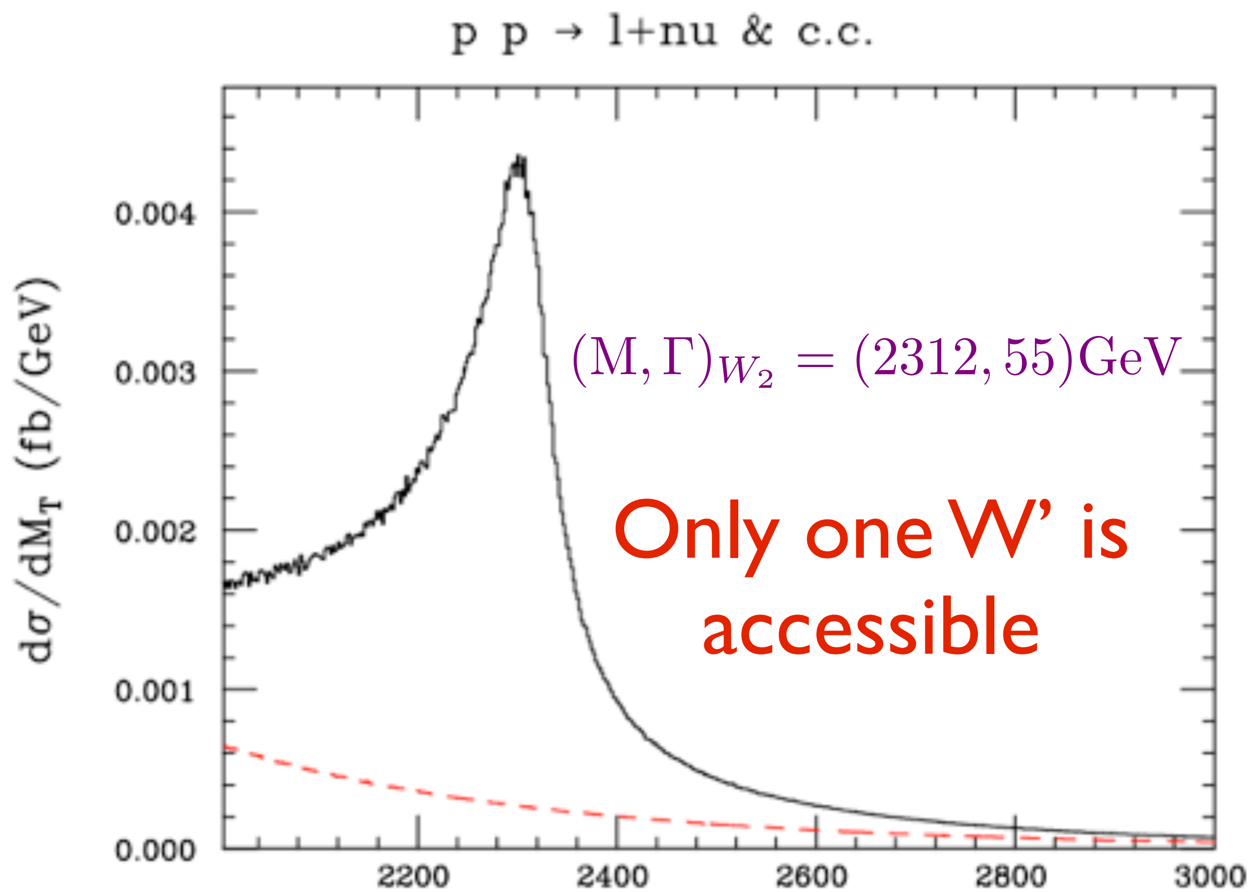
$$p_l^T > 20 \text{ GeV}$$
$$|\eta_l| < 2.5$$
$$M_{l^+l^-} > 2 \text{ TeV}$$

The heaviest Z_5 is inaccessible

Exploring the line-shape at LHC14 - Charged Channel



$f = 1\text{TeV}, \;\; g_\rho = 2$



$f = 1.2\text{TeV}, \;\; g_\rho = 1.8$

Differential distributions in the transverse mass M_T for CC DY

cuts :
$p_l^T > 20$ GeV
$|\eta_l| < 2.5$
$M_T > 2$ TeV

Mass correlation in the 4DCHM:

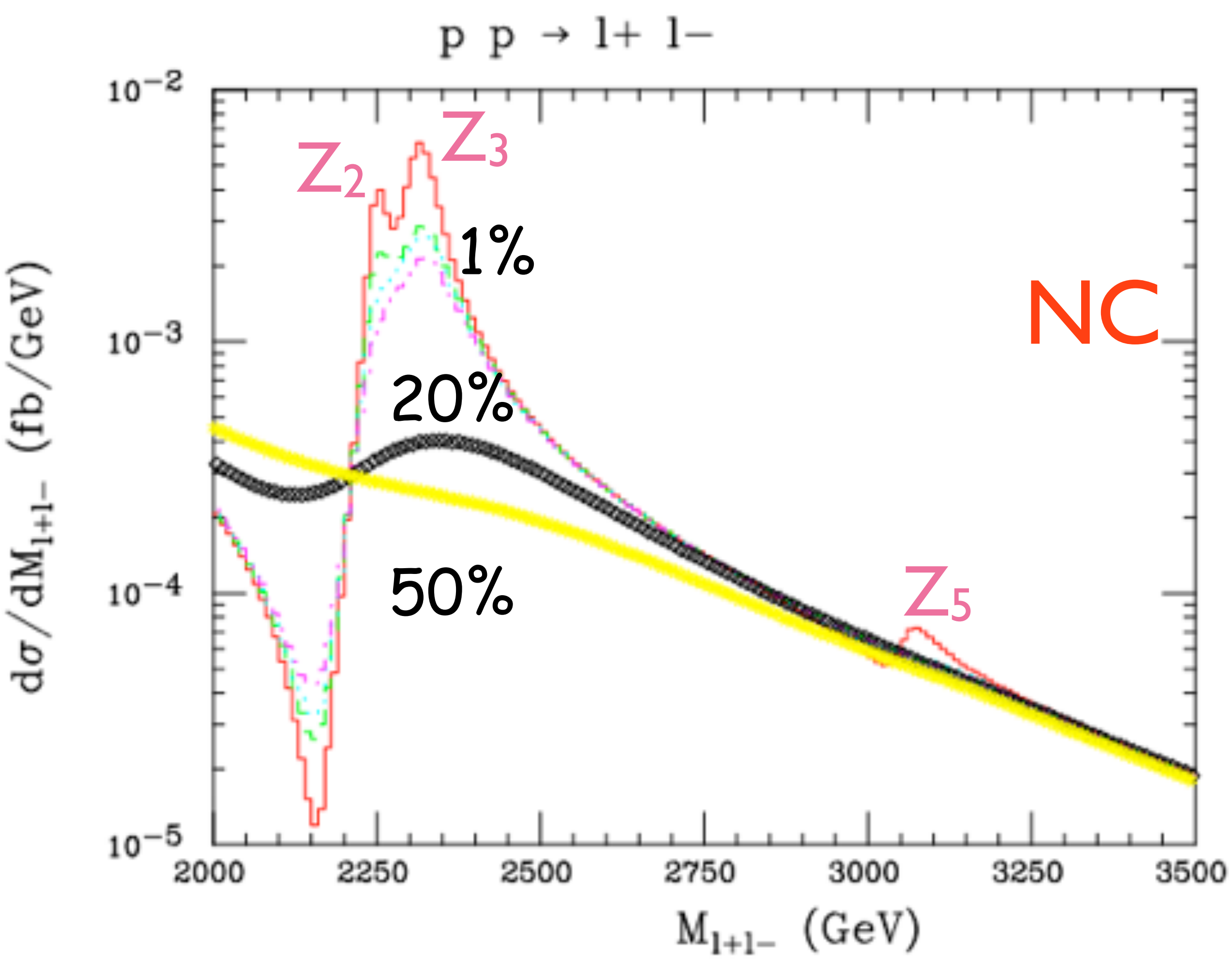
$$M_{W_2}^2 \simeq \frac{f^2 g_*^2}{c_\theta^2}\left(1 - \frac{s_\theta^2 c_\theta^4}{2c_{2\theta}}\xi^2\right)$$

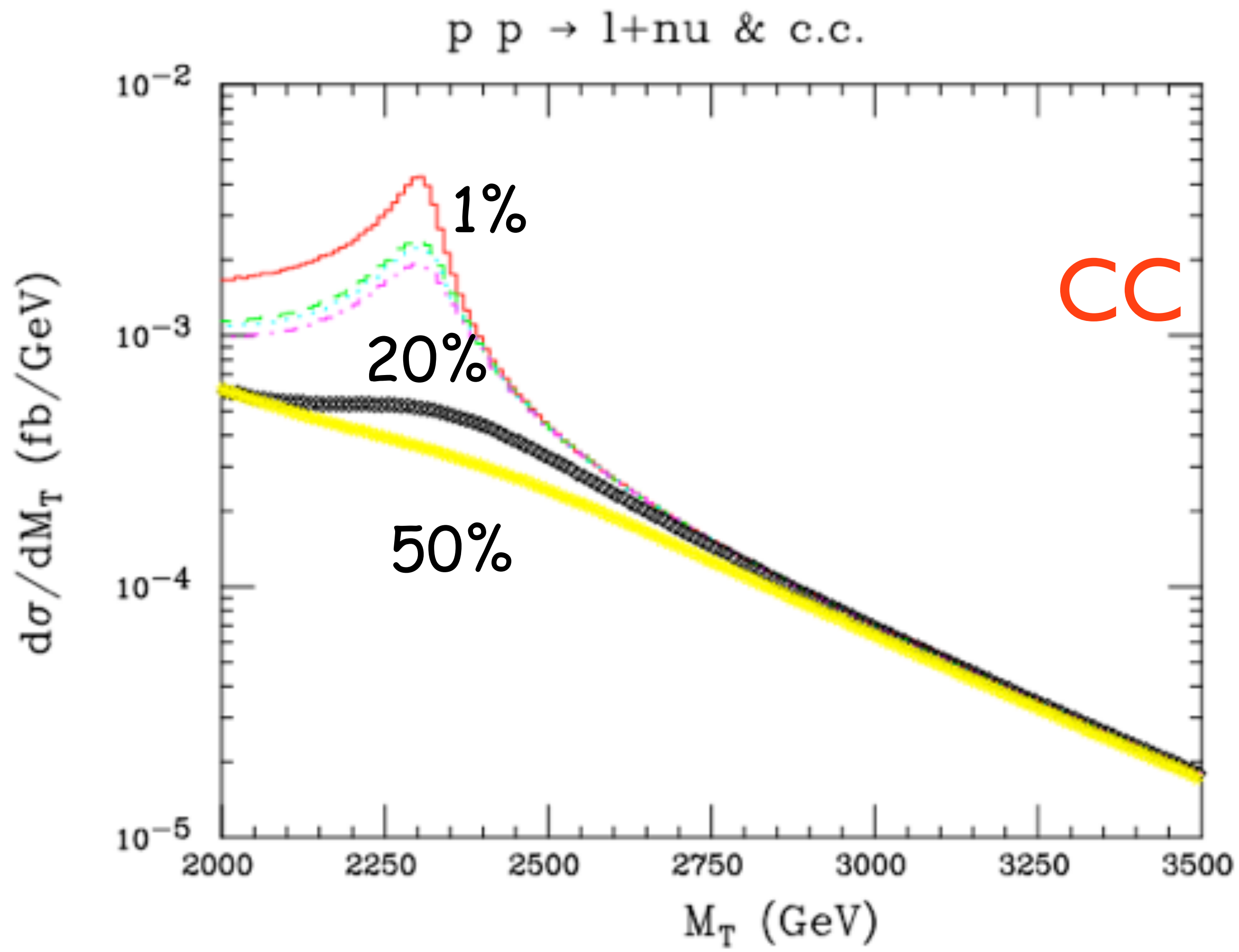
$$M_{Z_3}^2 \simeq \frac{f^2 g_*^2}{c_\theta^2}\left(1 - \frac{s_\theta^2 c_\theta^4}{4c_{2\theta}}\xi^2\right)$$

Possibility to improve searches for Z'(or W') if a W'(or Z') is discovered

The role of extra-fermions

Z' and W' line shapes in relation with masses of heavy fermions: take the **same masses** and **increase the widths** $\Gamma/M \sim 1\%,\ 20\%,\ 50\%$



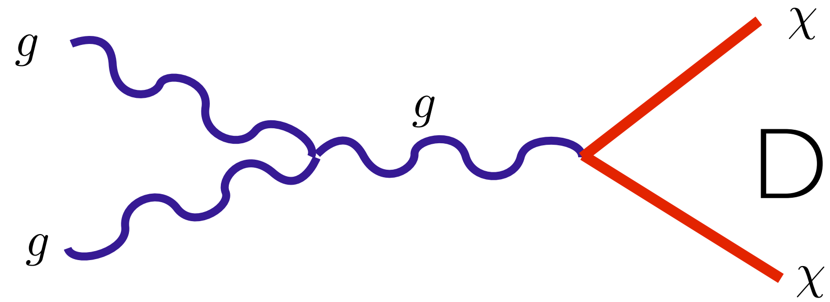


- **Bounds on the mass of new Z' and W'** from direct searches in leptonic DY processes **crucially depend on their widths**
- The analysis of the **Z' and W' line shapes would reveal the presence (or not) of light extra fermions**

Spin-1/2 : composite fermions could be light + exotic

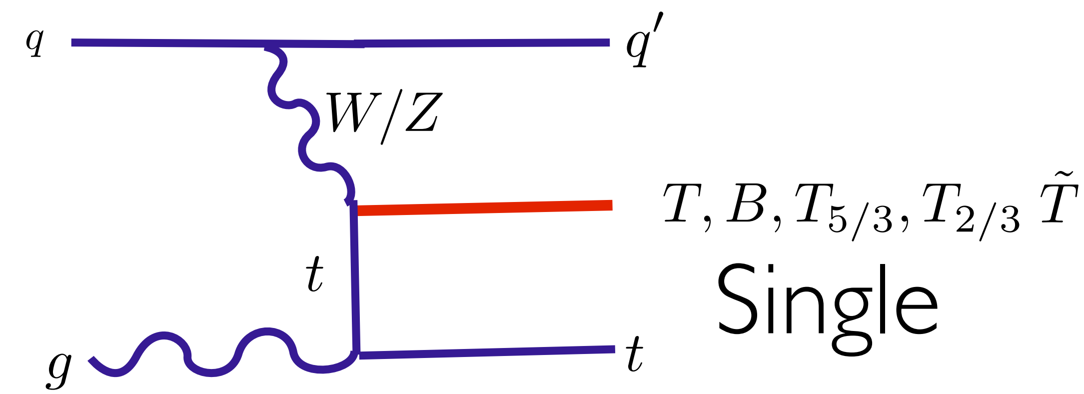
- Production:

Contino, Servant (2008)

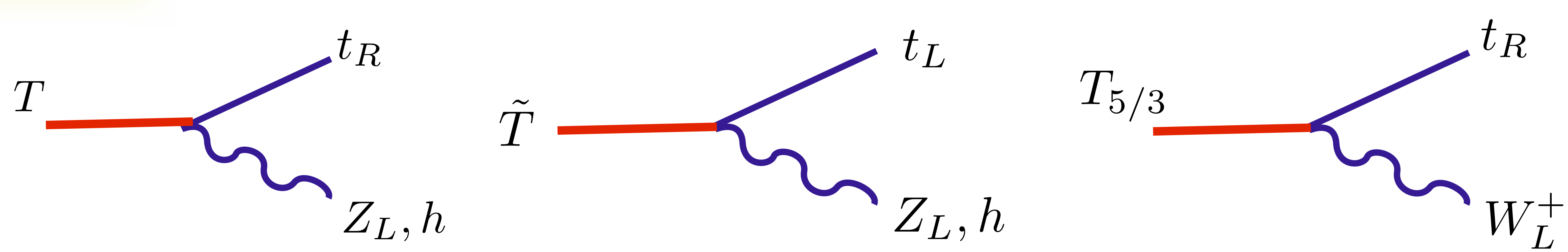


Double

Mrazek,Wulzer (2009); Aguilar-Saveedra(2009)



- Decays: Multi-lepton signatures



De Simone et al. 1211.5663; Matsedonskyi et al. 1204.633, 1409.0100

Bounds from direct searches at LHC (pair production) which assume 100% BR of t' in Wb or Zt , and 100% BR of b' in Wt or Zb rescaled to take into account the BR's in the 4DCHM, give $M_{T_1}, M_{B_1} > 600\ \mathrm{GeV}$

Work in progress: implement the direct search results on the 4DCHM extra-fermions Barducci et al. 1405.0737

The 4DCHM and the 125 GeV Higgs-like signals at the LHC

- Higgs couplings to SM states are modified due to mixing

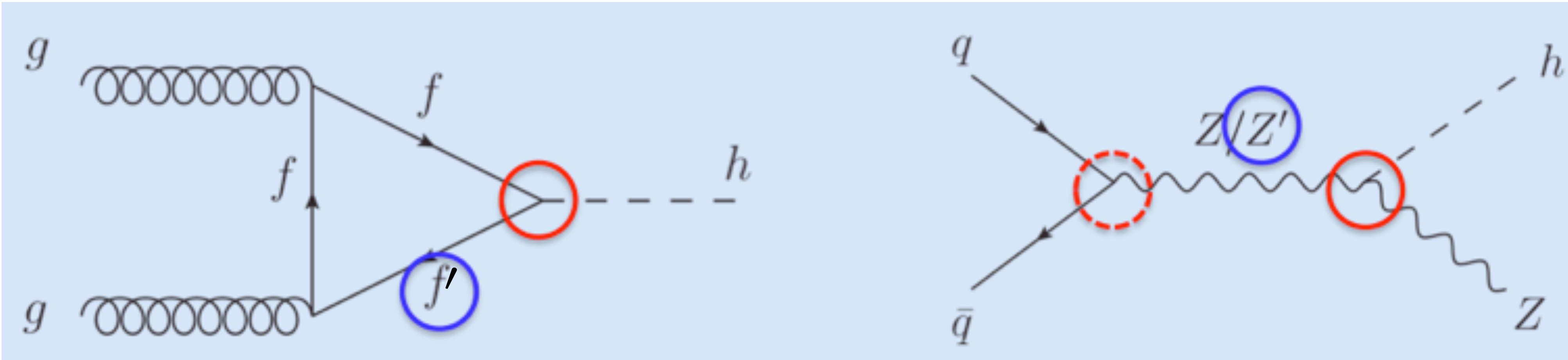
$$g_{HVV} = g_{HVV}^{\rm SM}\sqrt{1-\xi};\; g_{Hff} = g_{Hff}^{\rm SM}\frac{(1-2\xi)}{\sqrt{1-\xi}}$$

- For production and decay channels exploited in the LHC searches **heavy bosonic and fermionic states can play a role via loops**

- In the literature use effective schemes to study the **residual effect of the (decoupled) composite sector** on the SM one.
NGB symmetry protects the couplings. **No large deviations expected**

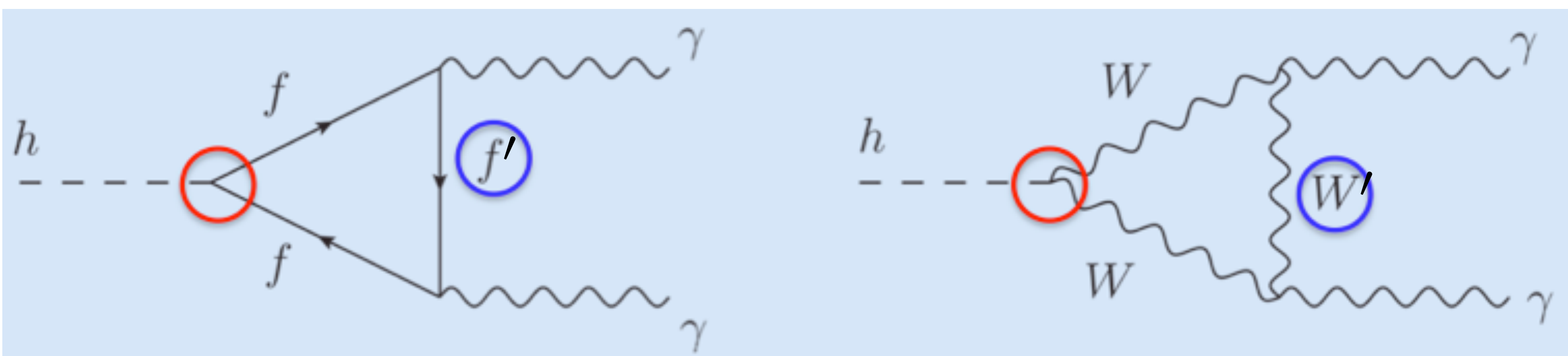
- The 4DCHM is a completely calculable framework. Let's use it to test the PNGB hypothesis against the experimental data

Modification of the production rates



ex: gluon fusion and Higgs-strahlung, extra particles can be exchanged

Modification of the decay rates



ex: gamma gamma decay, extra particles can be exchanged

The 4DCHM and the 125 GeV Higgs-like signals at the LHC

- Define the R or μ parameters, i.e. the observed events over the SM
    - Introduce reduced couplings à la LHC HXSWG (A. Denner et al (arXiv:1209.0040))
    - We can cast R's in terms of κ's

$$R_{YY}^{Y'Y'} = \frac{\kappa_{Y'}^2 \kappa_Y^2}{\kappa_H^2}$$

$$Y, Y' = b/\tau/g/\gamma/V$$

$$\kappa_{b/\tau/g/\gamma/V}^2 = \frac{\Gamma(H \to b\bar{b}/\tau^+\tau^-/gg/\gamma\gamma/VV)|_{\text{4DCHM}}}{\Gamma(H \to b\bar{b}/\tau^+\tau^-/gg/\gamma\gamma/VV)|_{\text{SM}}}$$

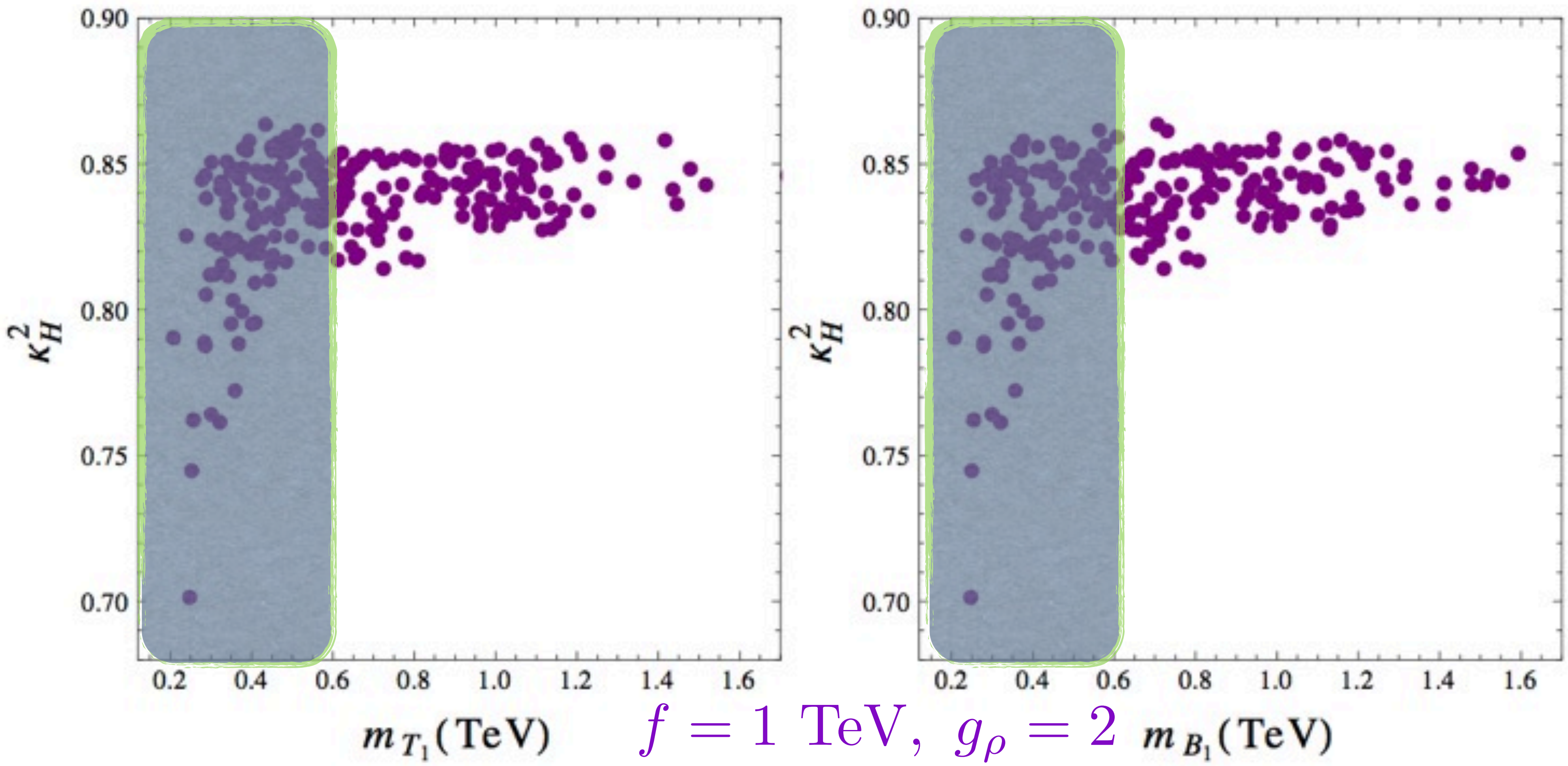
$$\kappa_H^2 = \frac{\Gamma_{\text{tot}}(H)|_{\text{4DCHM}}}{\Gamma_{\text{tot}}(H)|_{\text{SM}}}.$$

Higgs width

κ_H smaller: $b - b'$ mixing, all Higgs rates rise

- ~15-20% reduction in the 4DCHM **mainly due to the modification of the Hbb coupling** but also **loop effects** especially for low extra-fermion masses

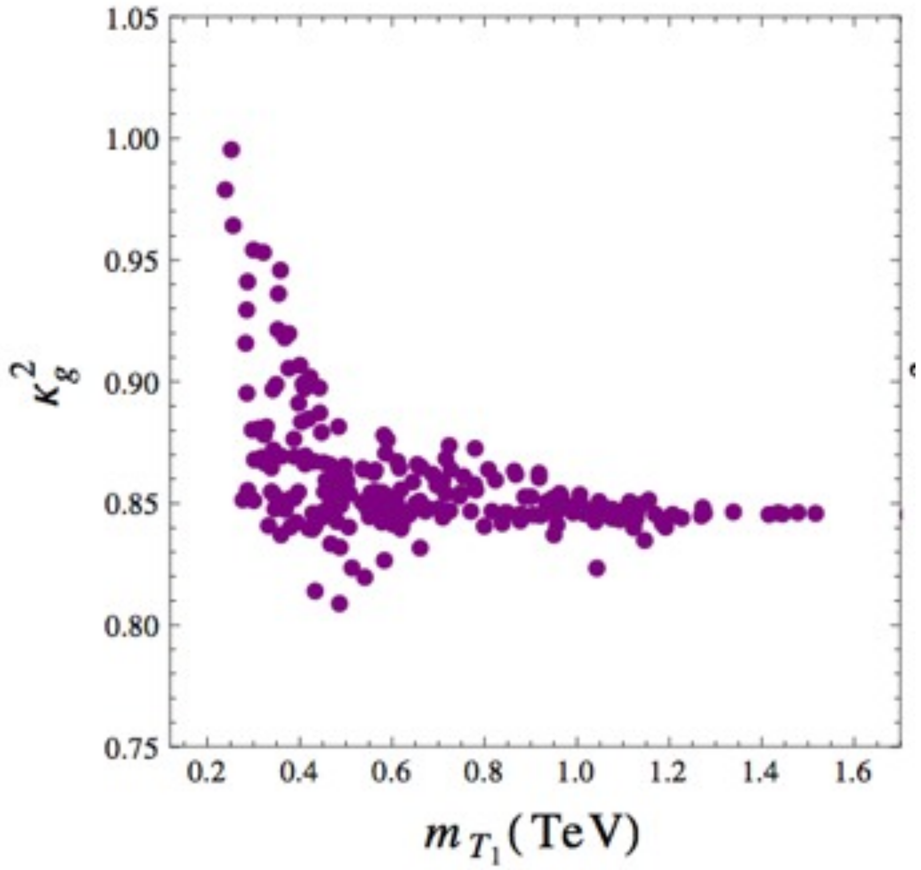
direct searches exclusion: $M_{T_1}, M_{B_1} > 600\ GeV$



$f = 1$ TeV, $g_\rho = 2$

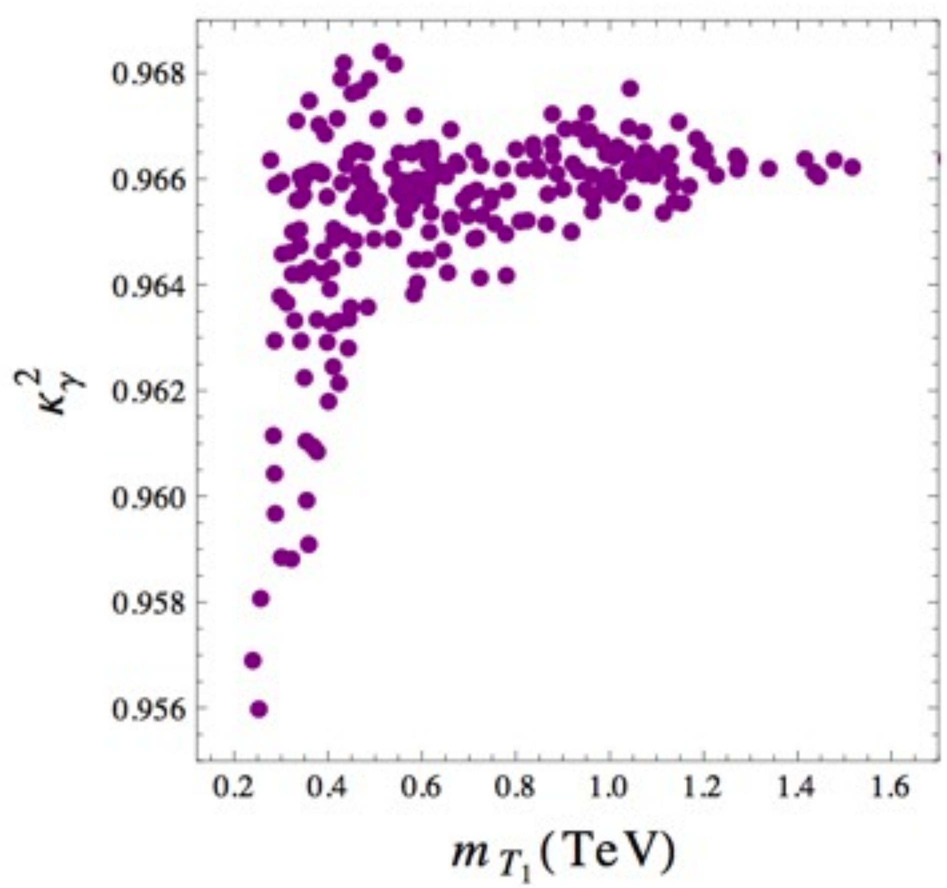
in agreement with $c^2 = \dfrac{(1-2\xi)^2}{1-\xi}$

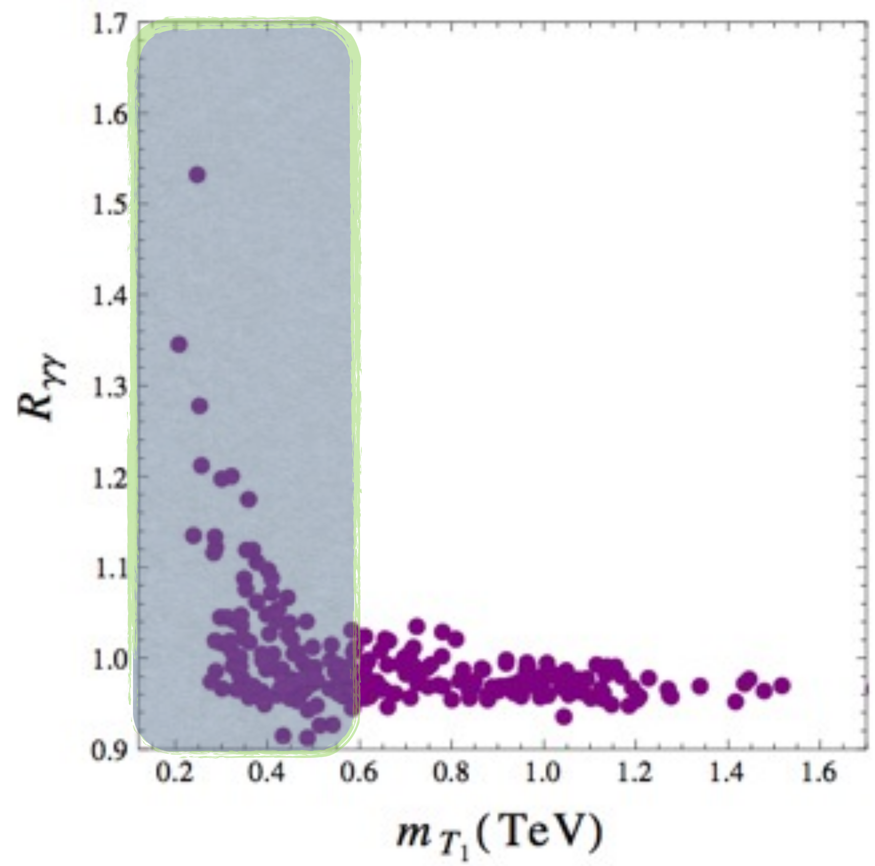
$$\xi = \frac{v^2}{f^2}$$



$$R_{\gamma\gamma} = \frac{k_g^2 k_\gamma^2}{k_H^2}$$

- t-t' mixing in κ_g^2
- t' and b' loops constructively interfere with the t loops in κ_g^2 and destructively with the leading W loop in κ_γ^2 (typical of PNGB nature of the Higgs)





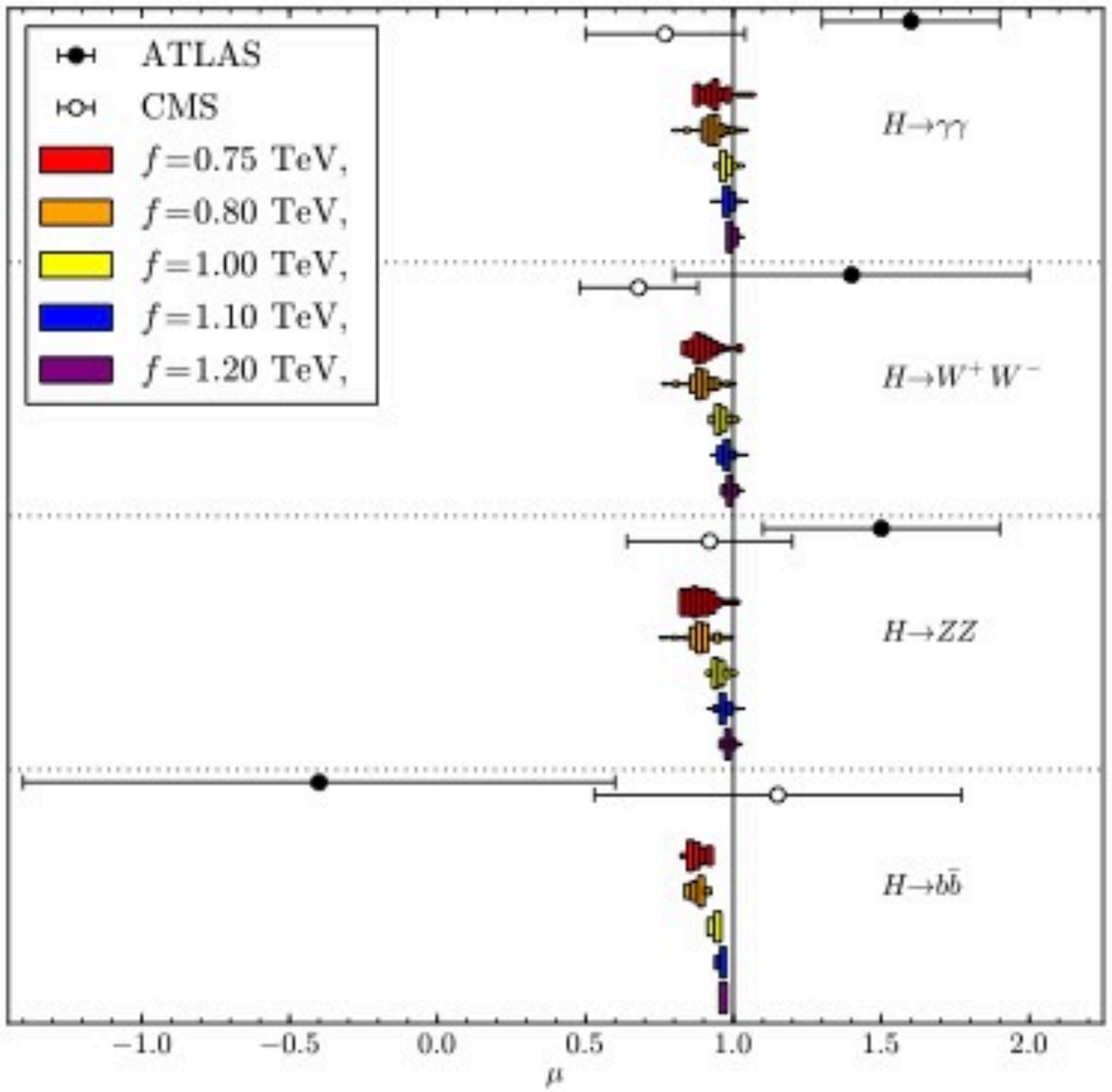
These contrasting effects lead to:

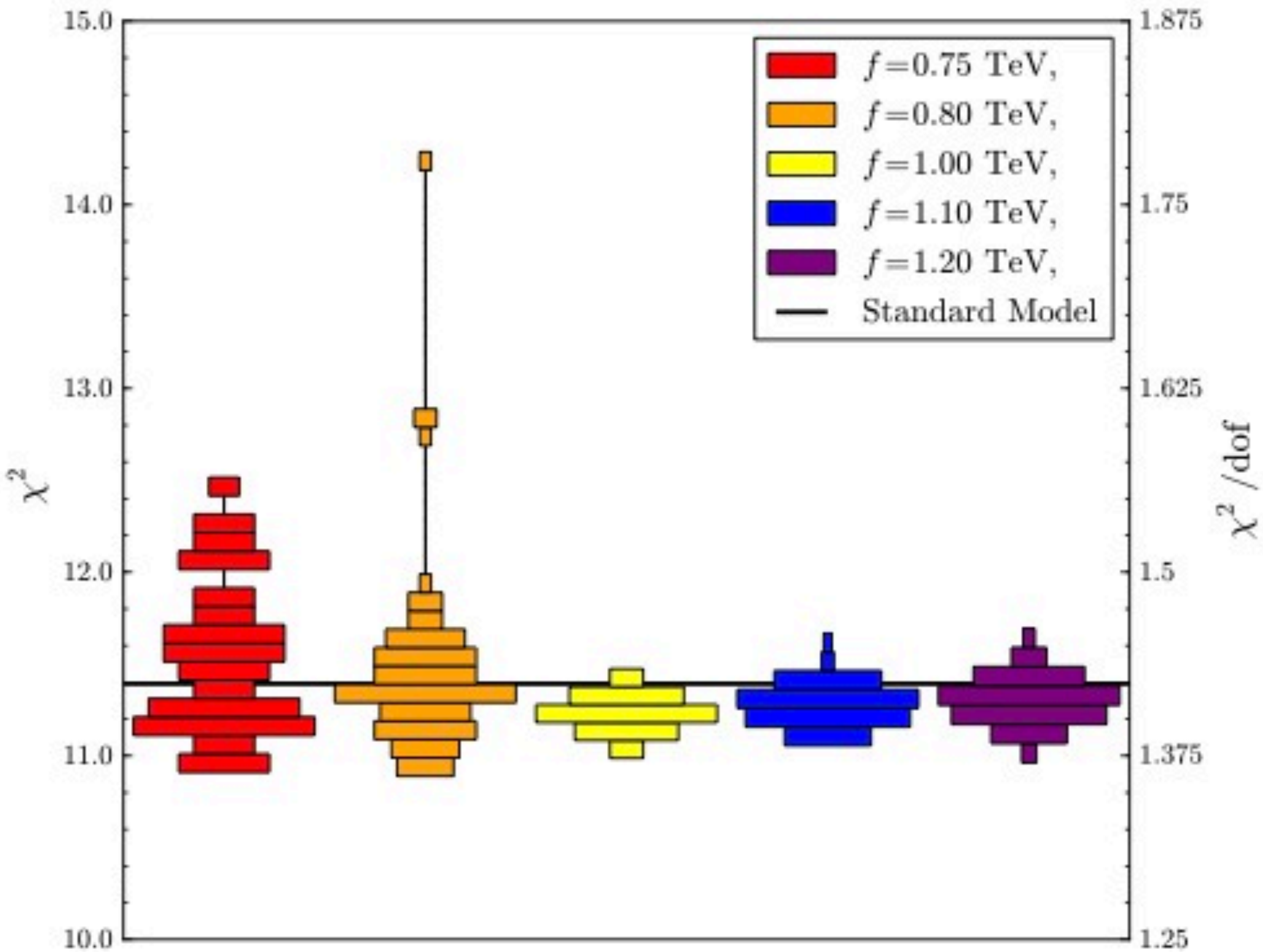
$$R_{\gamma\gamma} \sim 1$$

$$f = 1 \text{ TeV}, \; g_\rho = 2$$

Compare 4DCHM to LHC data

Barducci,Belyaev,Brown,DC,
Moretti,Pruna,1302.2371





Points compliant with t', b', $T_{5/3}$ direct searches

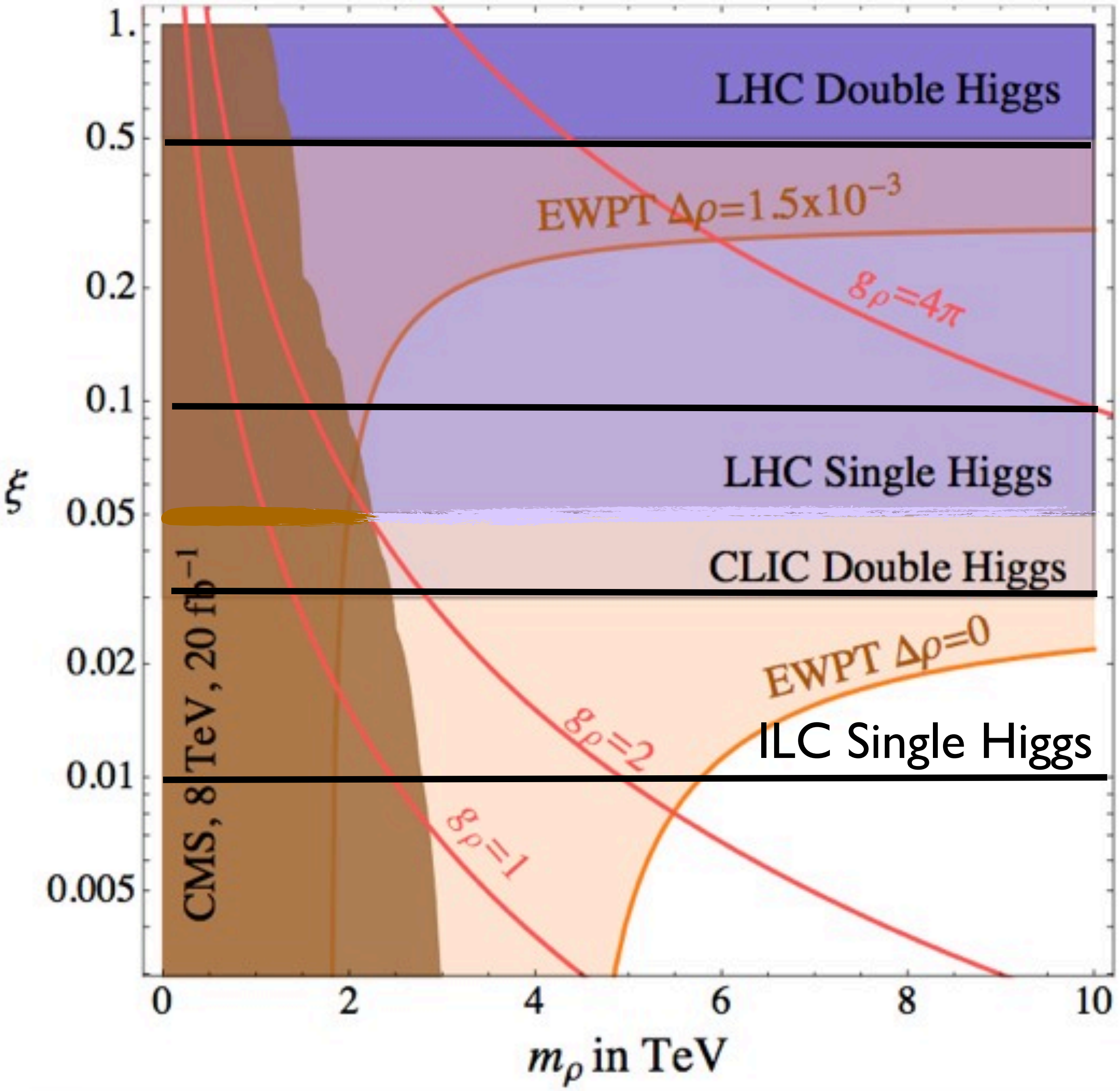
performing χ^2- the 4DCHM can fit as well as the SM if LHC will not measure deviations from the SM in single Higgs production larger than 10% and does not discover any new particle with a clear role ....

How can we decide if the Higgs is the elementary SM Higgs or is it a composite state of a strong dynamics or it emerges as a PNGB from an underlying broken symmetry?

an electron-positron collider (cleaner enviroment, precision measurements, large number of Higgs bosons produced) could help in detecting deviations in the cross sections for single, double Higgs production or in the detection of the triple Higgs final state ⟶ (indirect) probe of compositness and PNGB schemes

Use a general parametrization of the Higgs couplings by means of an effective Lagrangian

Contino,Grojean, Pappadopulo, Rattazzi,Thamm 1309.7038



Expected sensitivities at:

LHC 14TeV $300fb^{-1}$

CLIC 3TeV $1ab^{-1}$

ILC 250GeV 250fb^{-1}

+500GeV $500fb^{-1}$

(68% error on the x-section value w.r. to SM)

EWPT mainly from deviations on g_{hVV}

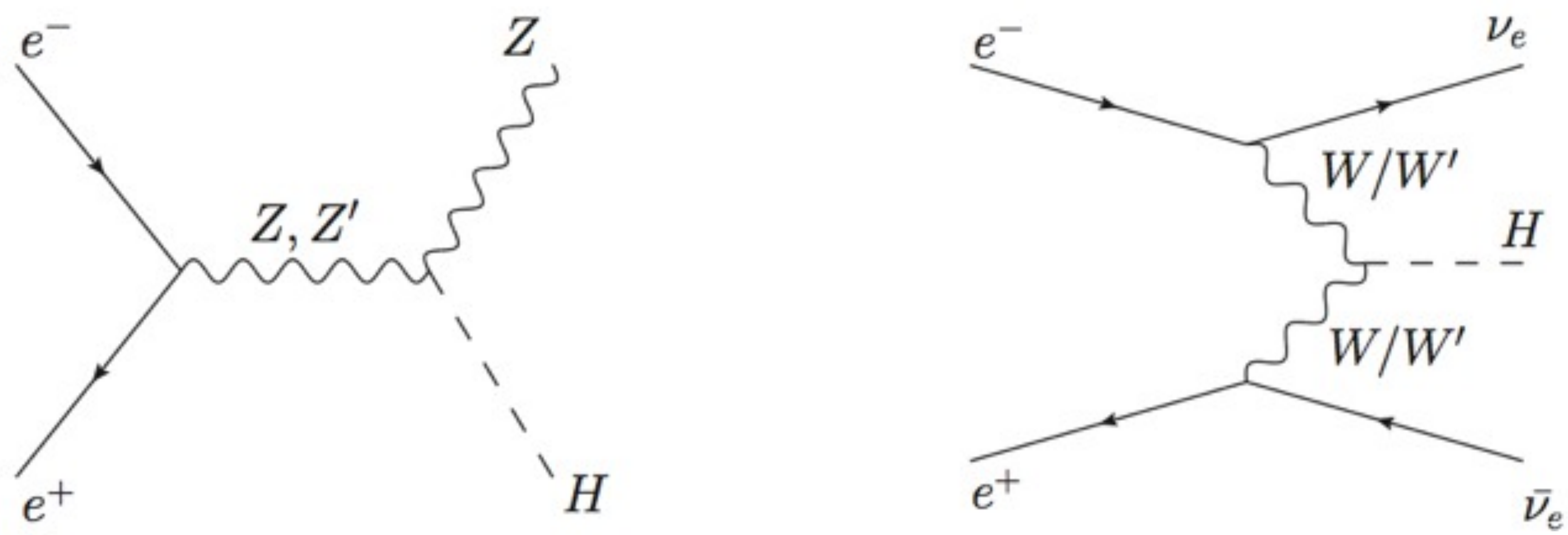
To the sensitivity on $\xi = v^2/f^2$ it corresponds a reach on the compositness scale $\Lambda = 4\pi f$ (Ex. Λ=30-40 TeV @ILC)

but the model details often matter!

Use the 4DCHM to test the potential of the proposed e^+e^- colliders in detecting PNGB Higgs models (Barducci,DC,Moretti,Pruna,1311.3305)

ILC as an example with $(\sqrt{s}(\text{GeV}), L(fb^{-1})$=(250,250), (500,500),(1000,1000)

Single Composite Higgs Boson produced via HS and VBF

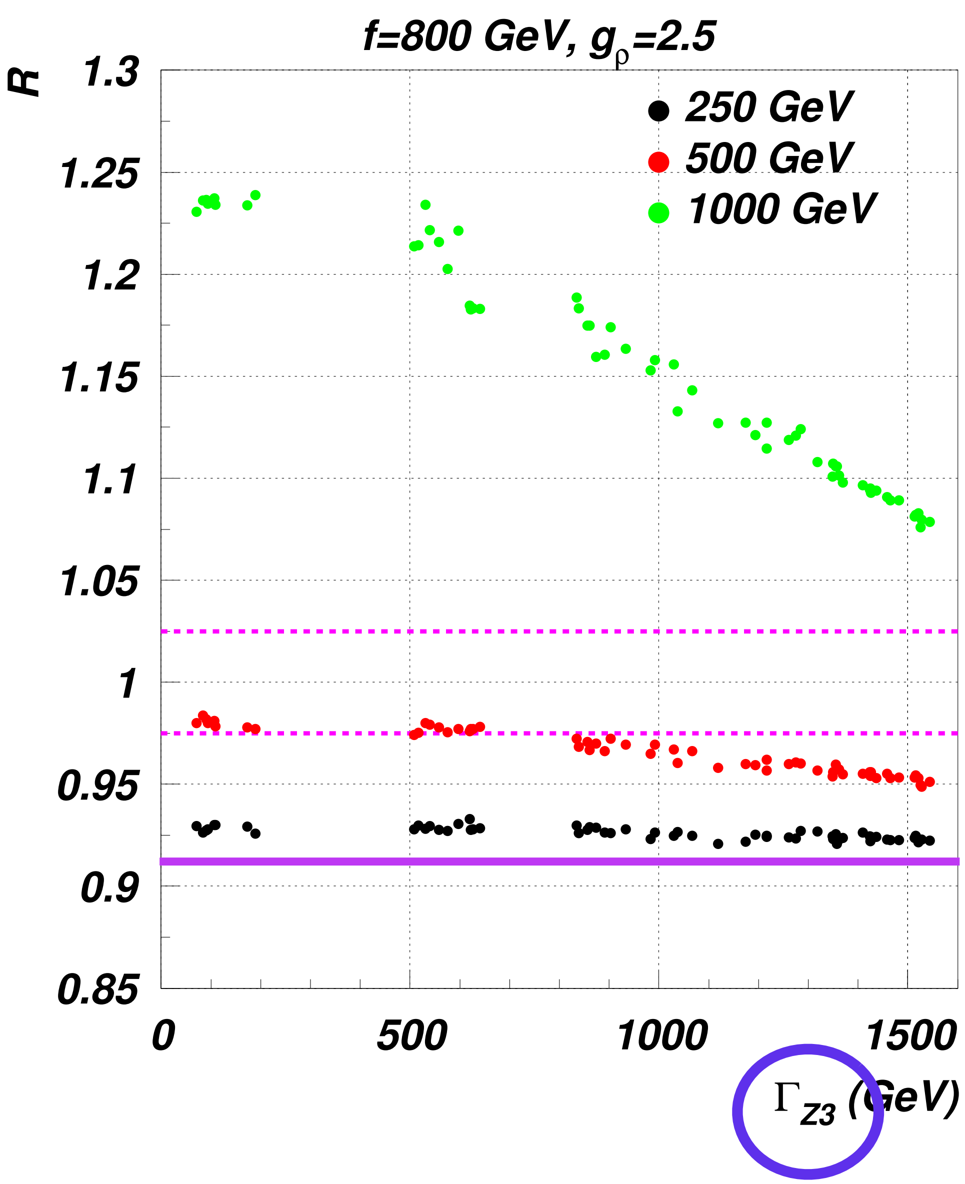


Extra Gauge bosons W' and Z' can be exchanged

We have performed parameter scans for various benchmark points of the 4DCHM with $M_{Z',W'} \sim 2$ TeV

Inclusive HS production cross-section is affected by Z's

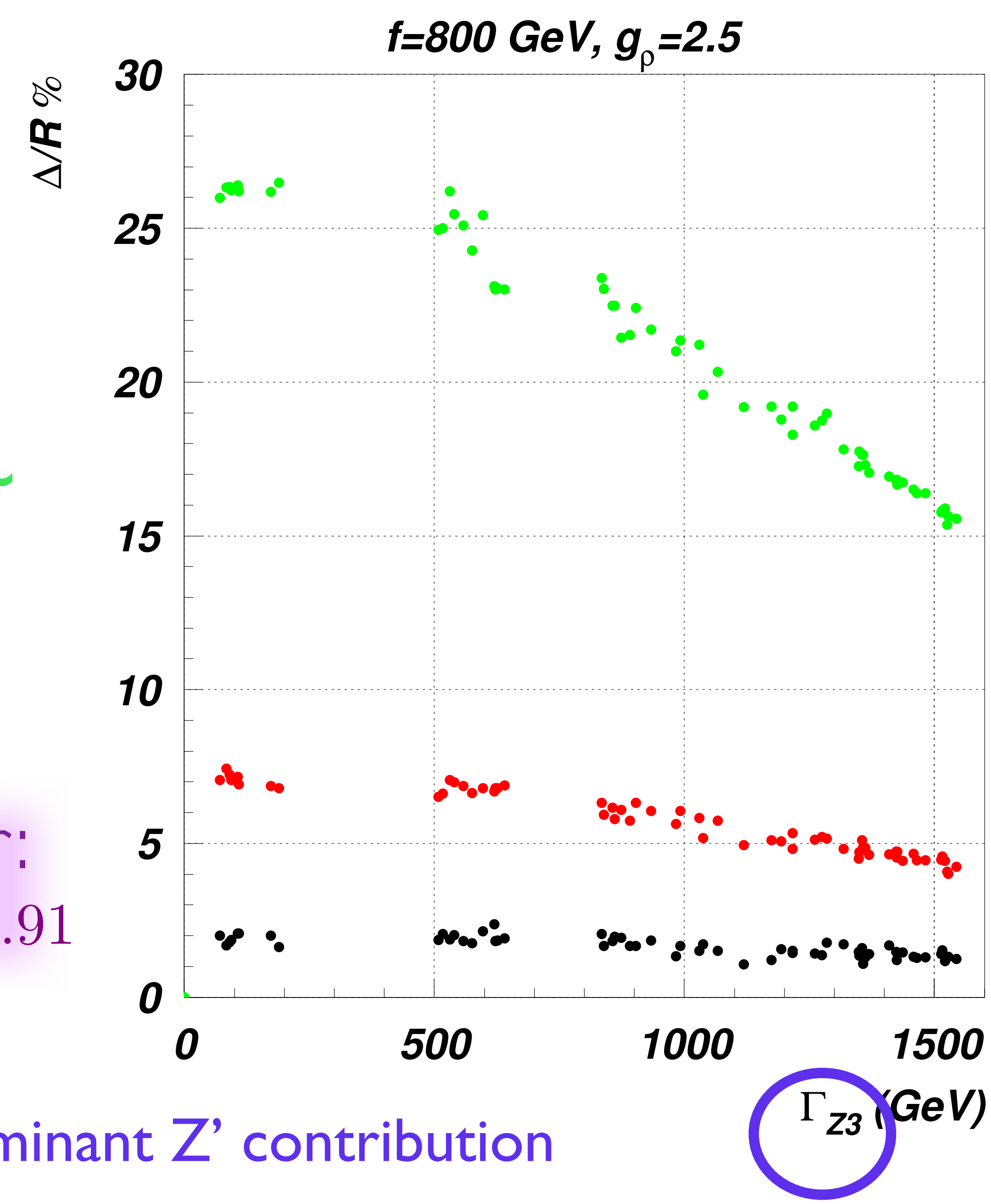
define: $R = \frac{\sigma(ZH)_{4DCHM}}{\sigma(ZH)_{SM}}$, $\Delta = R - \kappa^2_{HZZ}$, $\kappa_{HZZ} = \frac{g^{4DCHM}_{HZZ}}{g^{SM}_{HZZ}}$



$\xi = 0.1$

interference ~ $1/\Gamma_{Z_3}$

rescaling factor: $k^2_{HZZ} \sim (1-\xi) \sim 0.91$



Width of the dominant Z' contribution

deviations from the SM up to 25% for 1 TeV machine
the Z-Z' interference is very important

125 GeV Higgs boson produced via HS at a e+e- collider

$$\mu_i = \frac{\sigma(e^+e^- \to HX)_{\mathrm{4DCHM}} \mathrm{BR}(H \to i)_{\mathrm{4DCHM}}}{\sigma(e^+e^- \to HX)_{\mathrm{SM}} \mathrm{BR}(H \to i)_{\mathrm{SM}}}$$

$f = 800\ GeV,\ g_\rho = 2.5$
$f = 1000\ GeV,\ g_\rho = 2$

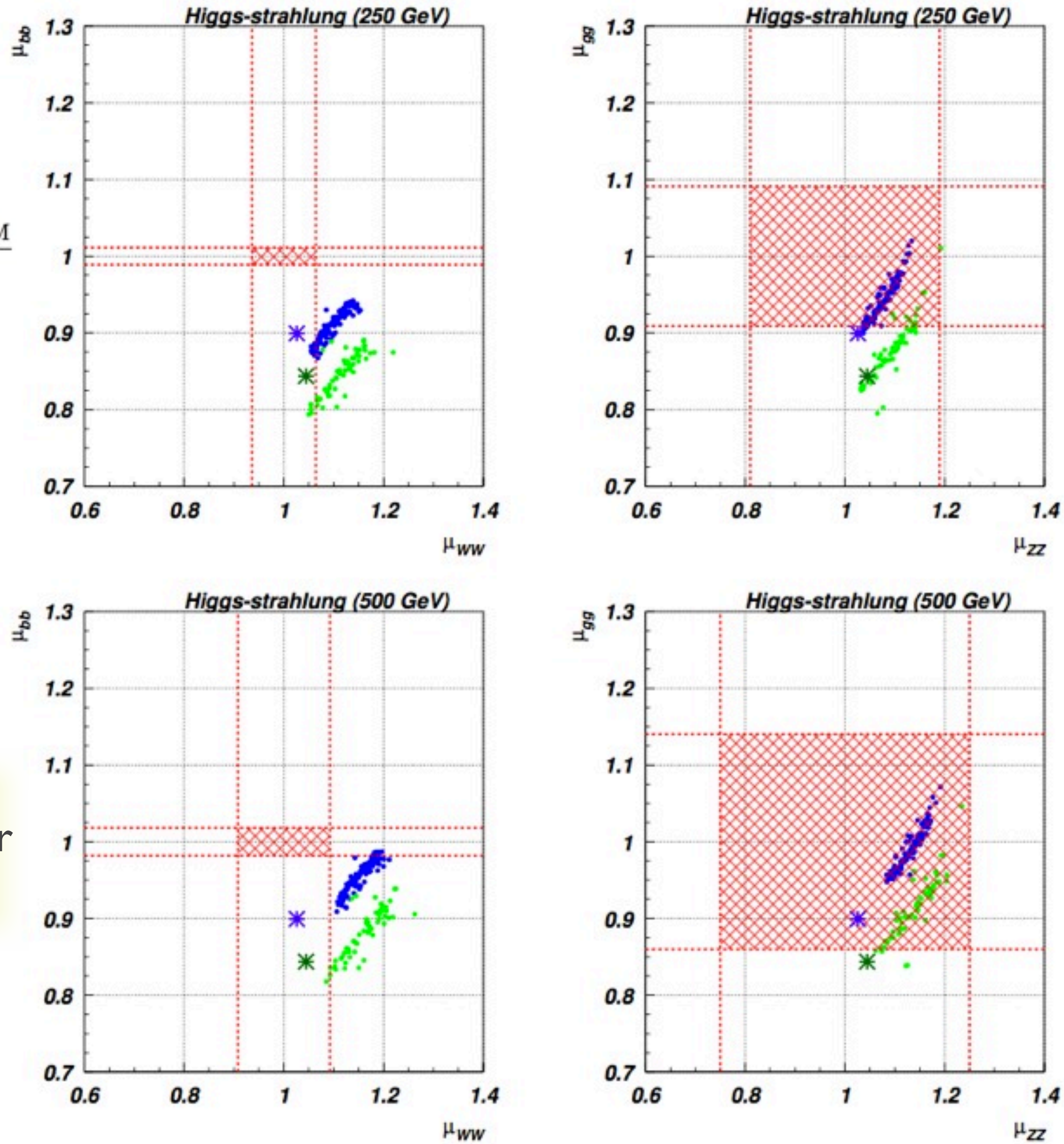
* = decoupl. limit

expected accuracies for the μ_i are shown

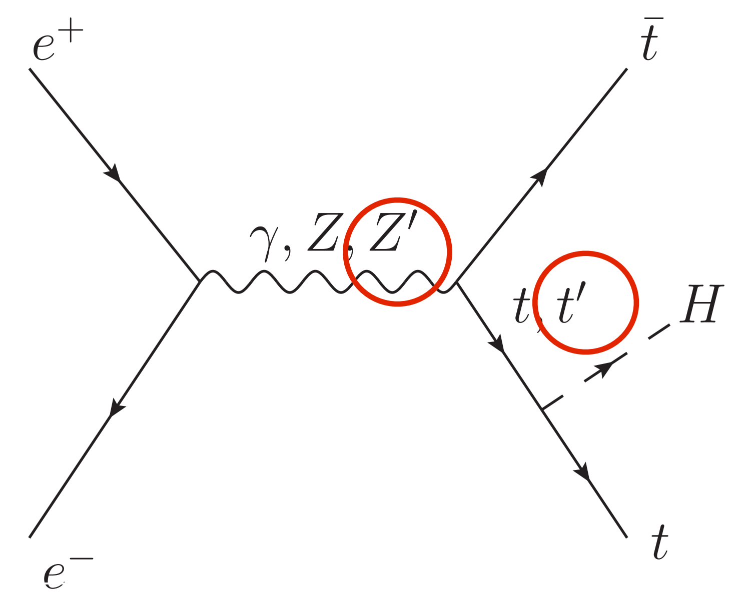
ILC TDR 1306.6352
ILC Higgs White Paper 1310.0763

the decoupling limit could be inaccurate as it fails to account for significative interference effects

Effects still present for VBF production but smaller due to the different topologies of the Feynman diagrams

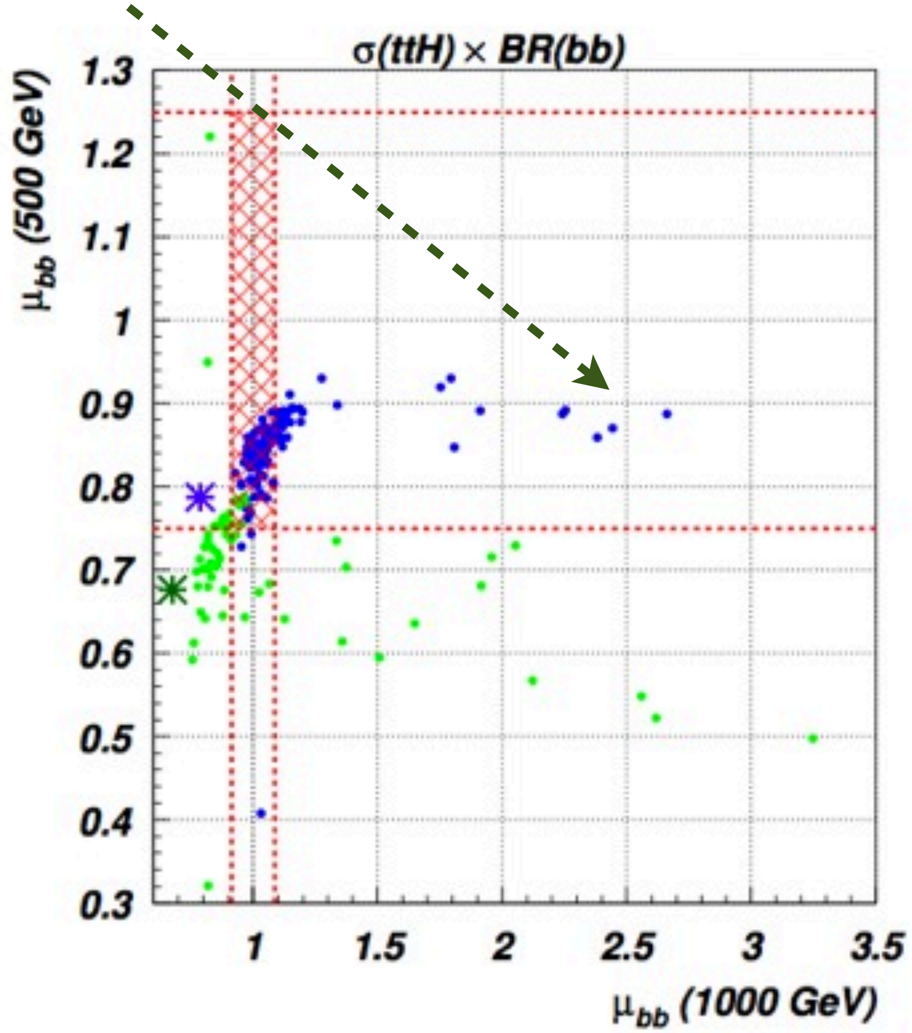


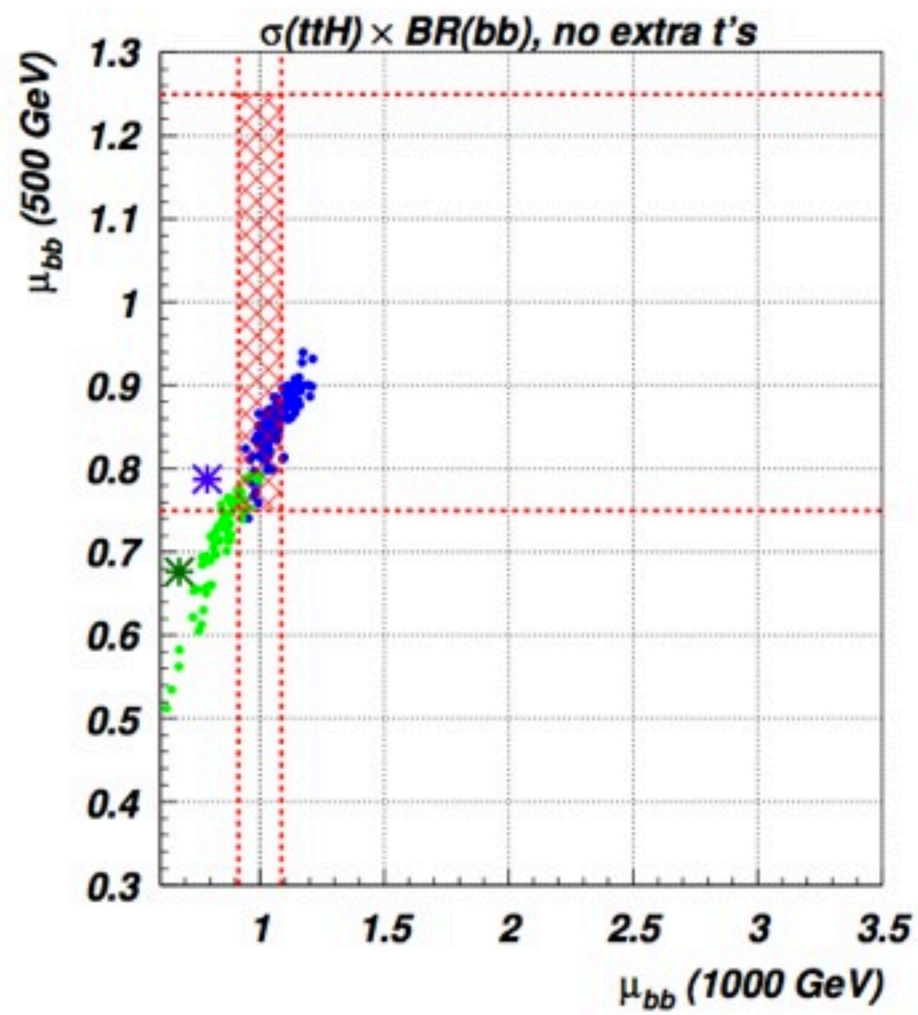
The top Yukawa coupling from $e^+e^- \to t\bar{t}H$



exchange of a t' resonant with the Ht pair production

scan for $m_{t'} > 600\ GeV$





$f = 800\ GeV,\ g_\rho = 2.5$

$f = 1000\ GeV,\ g_\rho = 2$

expected accuracies for the μ_i are shown

* = decoupl. limit

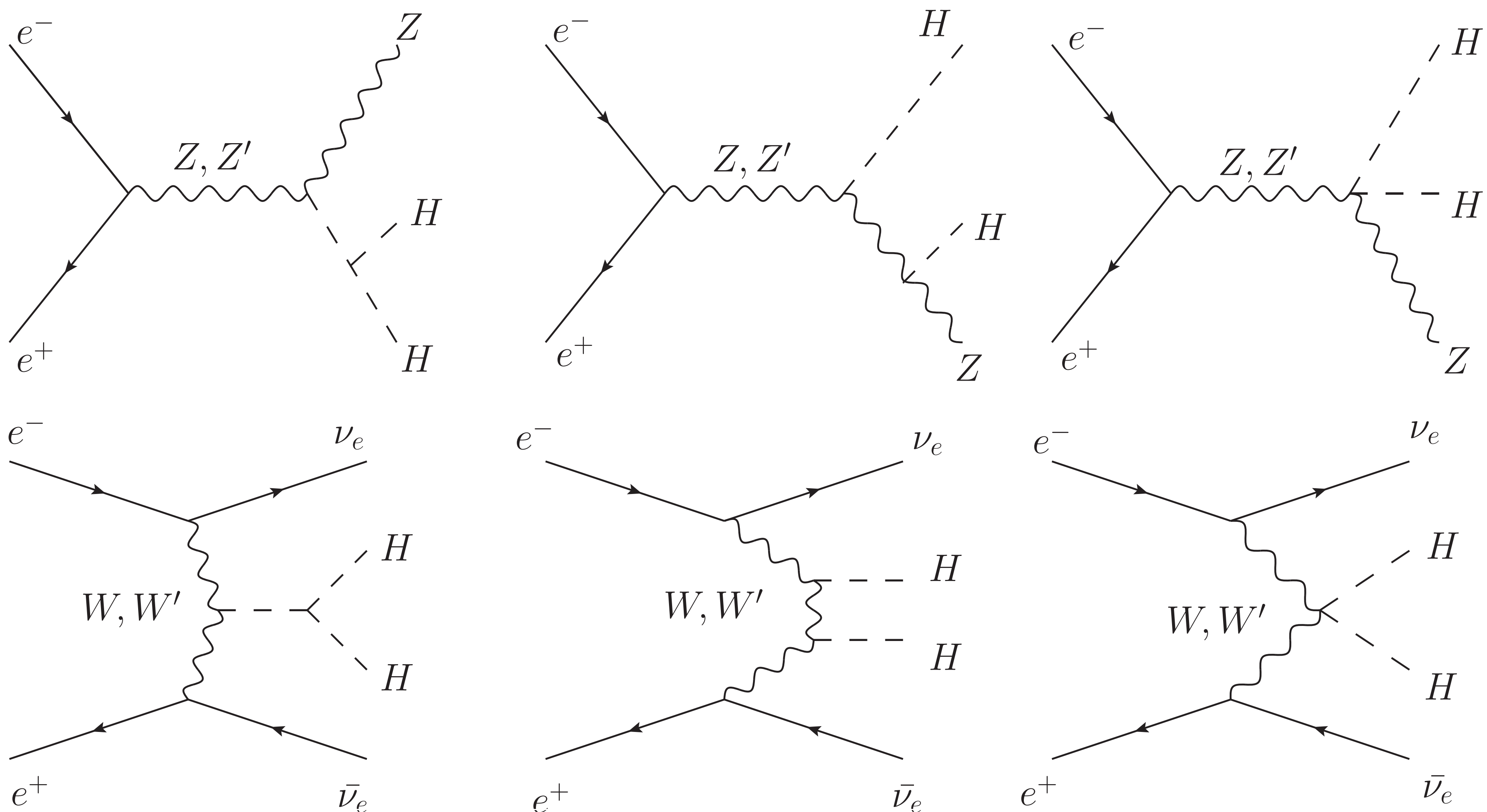
only $b\bar{b}$ decay mode considered

The triple Higgs self-coupling

In the 4DCHM the Higgs potential is UV finite $\longrightarrow \quad v,\ m_H$

at the leading order:

$$\lambda = \frac{3m_H^2}{v}\frac{1-2\frac{v^2}{f^2}}{\sqrt{1-\frac{v^2}{f^2}}} = \lambda_{\rm SM}\frac{1-2\xi}{\sqrt{1-\xi}}$$



double Higgs production via HS and via VBF double Higgs production via HS : $ZHH \to Zb\bar{b}b\bar{b}$

double Higgs production via VBF : $\nu\bar{\nu}HH \to \nu\bar{\nu}b\bar{b}b\bar{b}$

	ZHH @ 500 GeV	$\nu\bar{\nu}HH$ @ 1000 GeV
$b\bar{b}$	0.64	0.38

ILC TDR 1306.6352

$f = 800\ GeV,\ g_\rho = 2.5$

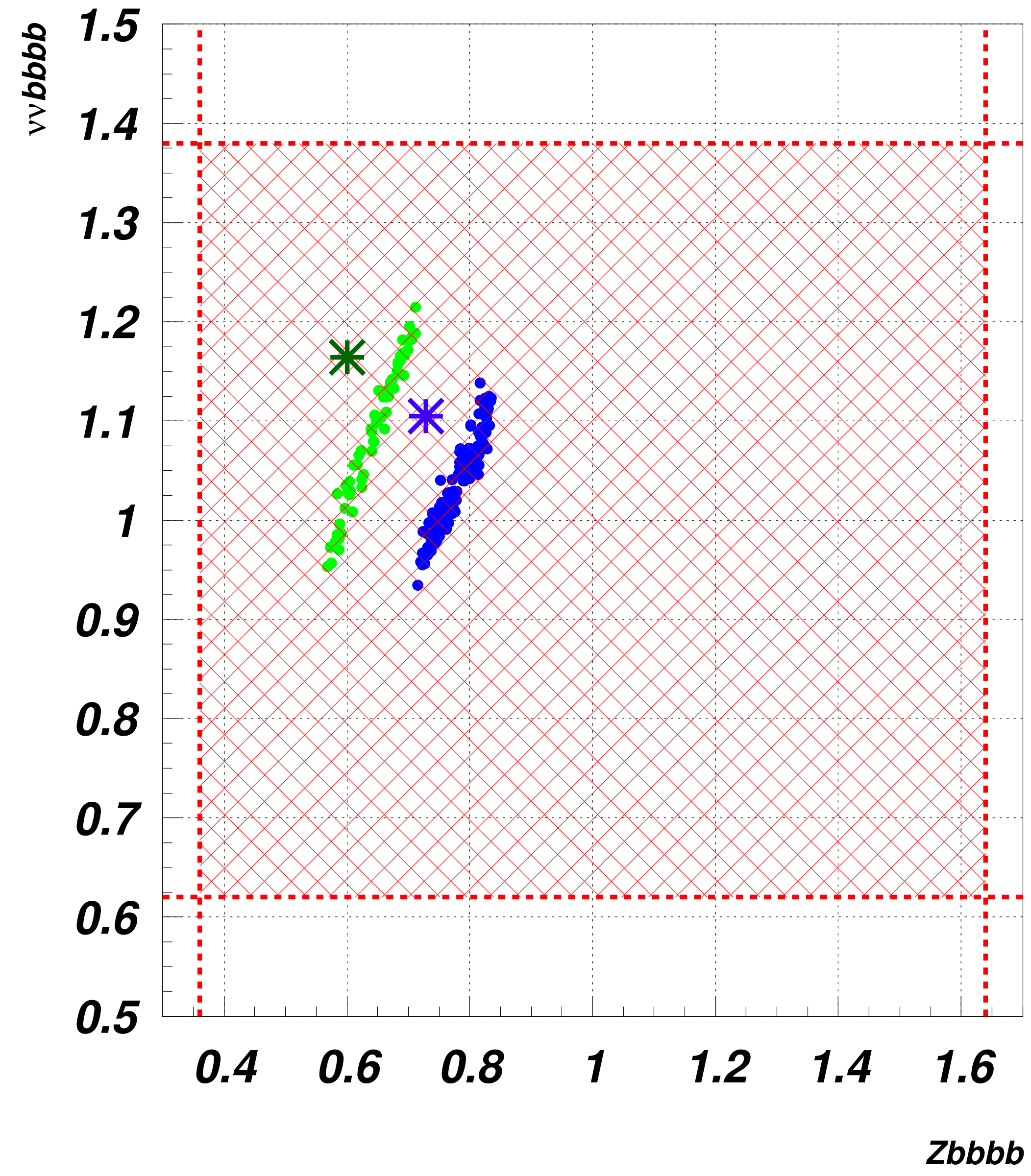
$f = 1000\ GeV,\ g_\rho = 2$

* = decoupl. limit

sizable deviations in λ are possible from variation of production and/or decay rates at the level of several 10%

expected accuracies for the μ_i are shown

to be reduced by a factor 2 at least (ILC LumUP)



Conclusions

☑ Higgs as a Nambu-Goldstone Boson is a compelling possibility for stabilising the EW scale

☑ Realistic scenarios can be built and analysed with the full spectrum

☑ The 4DCHM embeds the main characteristics of composite Higgs models with partial compositness

☑ New spin-1 resonances manifest themselves (mainly) in DY channels and could be accessible at LHC run2

☑ The 4DCHM fits the current LHC data pointing to the discovery of a 125 GeV Higgs boson

☑ Other possible signatures: extra fermions (in the mass region accessible to LHC run2)

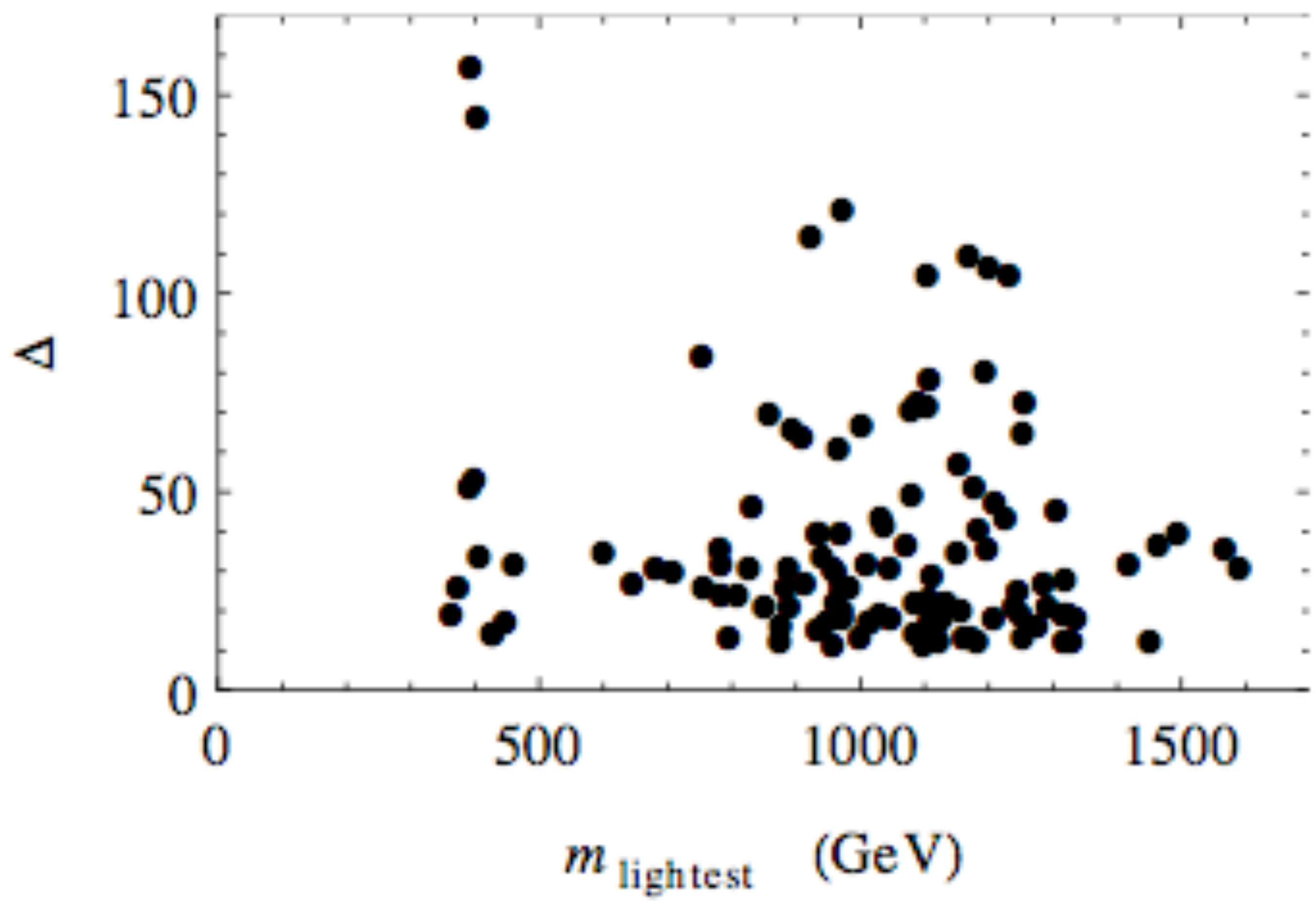
☑ If nothing is seen, future e^+e^- machines will have a great potential in testing the salient features of composite Higgs models in particular for PNGB Higgs

BACKUP SLIDES

Tuning:

Panico, MR, Tesi, Wulzer '12

$$\Delta = \mathrm{Max_i} \left| \frac{\partial \log m_Z}{\partial \log x_i} \right|$$



$$f = 800\,\mathrm{GeV}$$

$$\Delta_{avg} \sim 30$$

Low energy effective action

A useful tool: integrating out resonances.

$$\mathcal{L} = \frac{P^T_{\mu\nu}}{2}\Big[\Big(\Pi_0(p) + \frac{s_h^2}{4}\,\Pi_1(p)\Big)\,A^a_\mu A^a_\nu + \Big(\Pi_B(p) + \frac{s_h^2}{4}\,\Pi_1(p)\Big)\,B_\mu B_\nu$$
$$+\, 2s_h^2\,\Pi_1(p)\;\widehat{H}^\dagger T^a_L Y \widehat{H}\; A^a_\mu B_\nu\Big], \qquad s_h^2 = \sin^2\frac{h}{f}$$

- $\Pi_i(p)$ form factors of the composite sector
- EW scale

$$\frac{v}{f} = \sin\frac{\langle h\rangle}{f}$$

- SM couplings

$$\frac{1}{g^2} = -\Pi_0'(0) = \frac{1}{g_0^2} + \frac{1}{g_\rho^2}$$
$$\frac{1}{g'^2} = -\Pi_B'(0) = \frac{1}{g_{0Y}^2} + \frac{1}{g_\rho^2} + \frac{1}{g_{\rho X}^2}$$

$\log \Lambda^2$-contributions to S and T

Reduced coupling to WW.

$$S = \frac{1}{12\pi}(1 - a^2)\log\left(\frac{\Lambda^2}{m_H^2}\right)$$

$$T = -\frac{3}{16\pi c_W^2}(1 - a^2)\log\left(\frac{\Lambda^2}{m_H^2}\right)$$

In other words

$$m_H \to m_H^{\text{eff}} = m_H\left(\frac{\Lambda}{m_H}\right)^{1-a^2}$$

Z' and W' decay channels

Z' main branching ratios

SMALL WIDTH	LARGE WIDTH
• $t\bar{t}$ $\mathcal{O}(60\%)$	• $t'\bar{t}'$,$b'\bar{b}'$$\mathcal{O}(30\%)$
• W^+W^-, Z^0H, $b\bar{b}$ $\mathcal{O}(10\%)$	• $T'\bar{T}'$,$B'\bar{B}'$ $\mathcal{O}(10\%)$
• leptons an light quarks $\mathcal{O}(1\%)$	• $t\bar{t}$, $b\bar{b}$ $\mathcal{O}(1\%)$
• $t\bar{t}'$ and $b\bar{b}' \lesssim 0.5\%$	

mandatory for leptonic DY processes

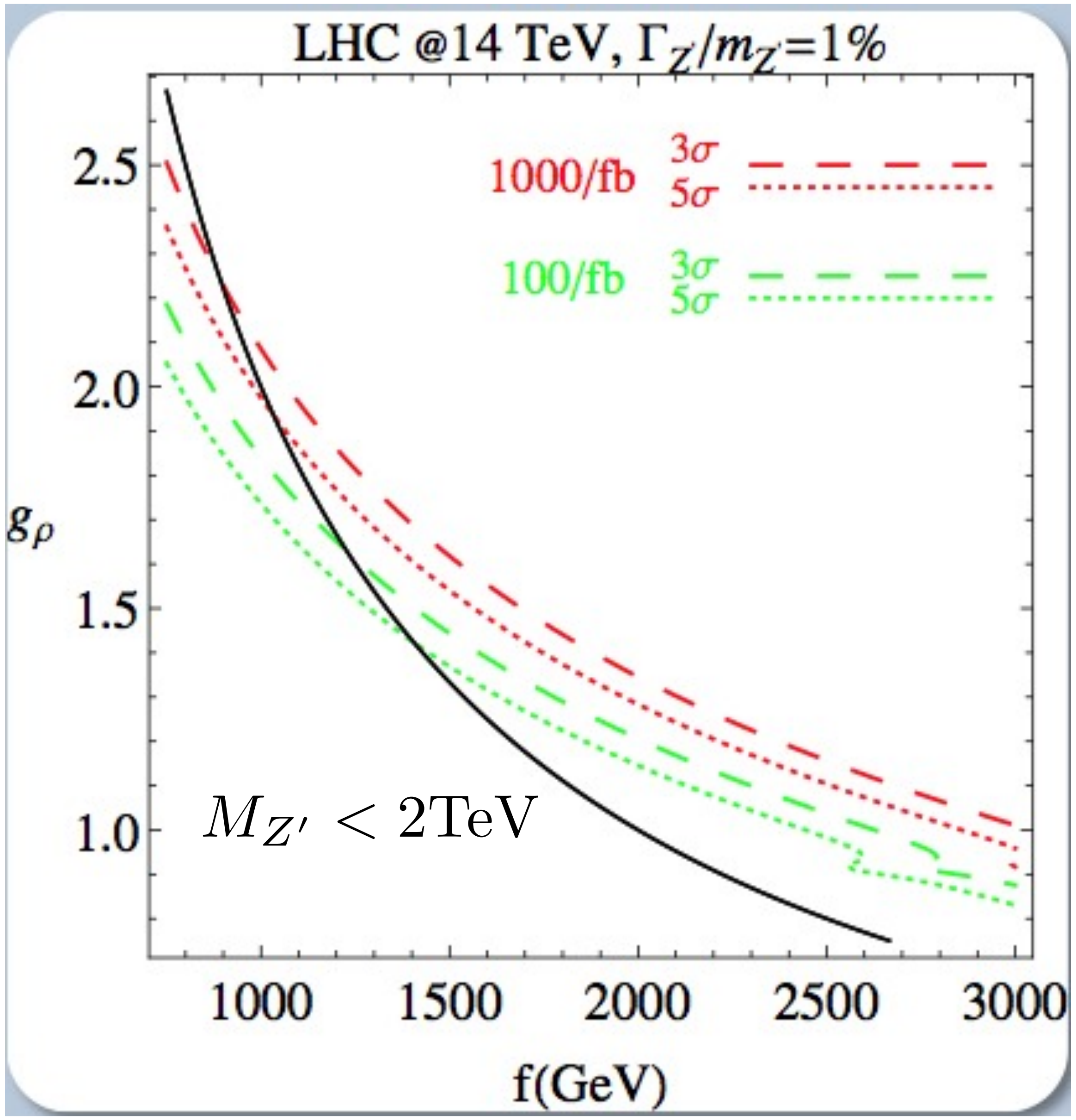
Analogous for the W'

The Z' and W' decay widths affect LHC Drell-Yan signatures

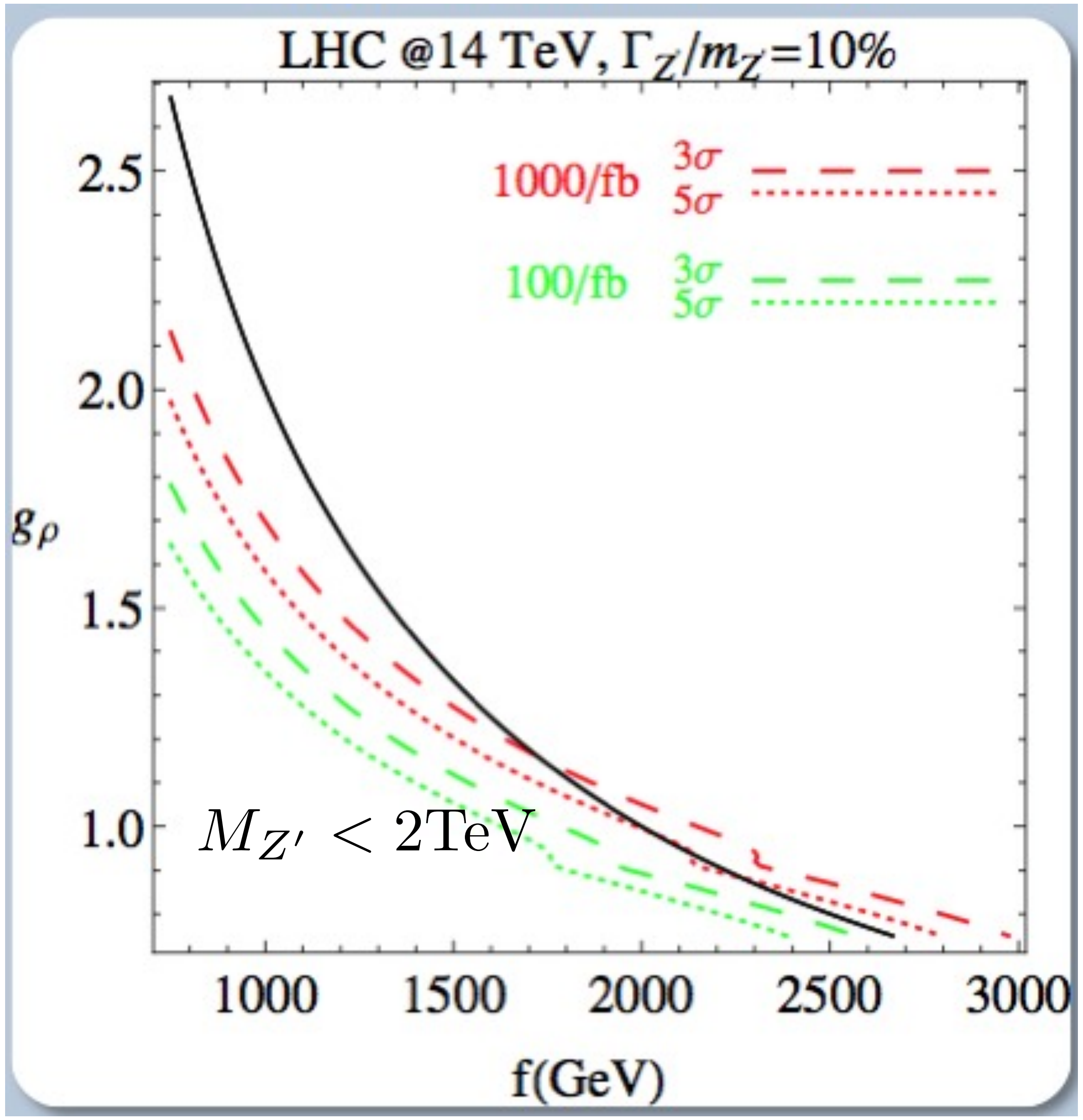
Calculating significance, neutral channel - 14 TeV LHC

$S/\sqrt{B}\ \sqrt{\mathcal{L}}$ $\mathcal{L} = 100/1000\ \mathrm{fb}^{-1}$

$$M_{Z'} = f g_\rho$$



$\Gamma_{Z'}/M_{Z'} = 1\%$



$\Gamma_{Z'}/M_{Z'} = 10\%$