The 4D Composite Higgs Model at the LHC

Stefania De Curtis

Based on: Redi, Tesi, DC, JHEP 1204(2012)042;
Barducci, Belyaev, Brown, Moretti, Pruna, DC, 1210.2927 and 1302.2371

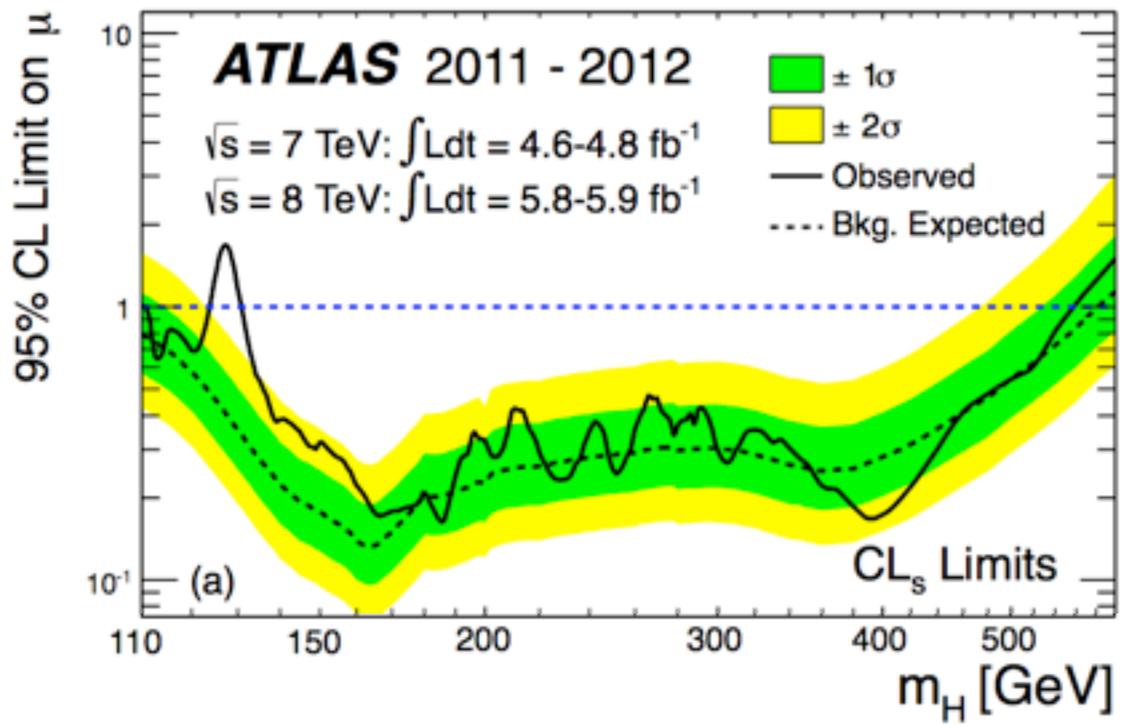
Strongly interacting dynamics beyond the Standard Model and the Higgs boson

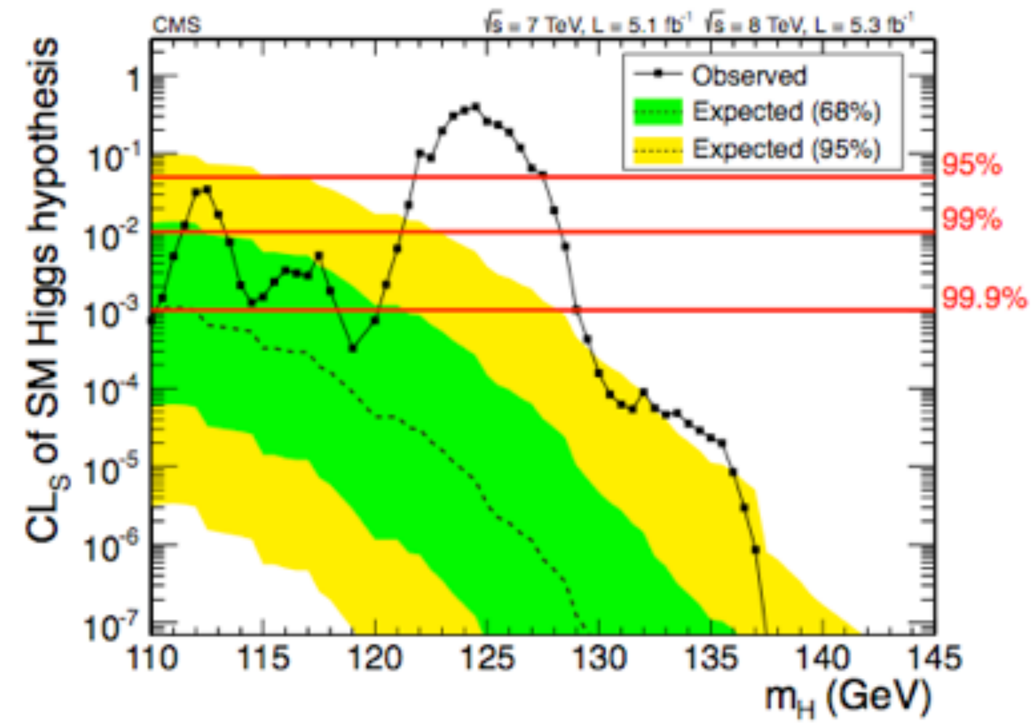
24-26 April 2013
Higgs Centre for Theoretical Physics
University of Edinburgh

Outline

- A 125 GeV Higgs-like signal observed at the LHC, is it the "fundamental" Standard Model Higgs ?
- From a theoretical point of view the SM is unsatisfactory. Explore BSM solutions to the hierarchy problem: Higgs as Nambu-Goldstone boson
- Minimal effective description: the 4-Dimensional Composite Higgs Model (4DCHM)
- Signatures at the LHC: scalar sector, extra resonances

July 31, 2012 Phys. Lett. B716

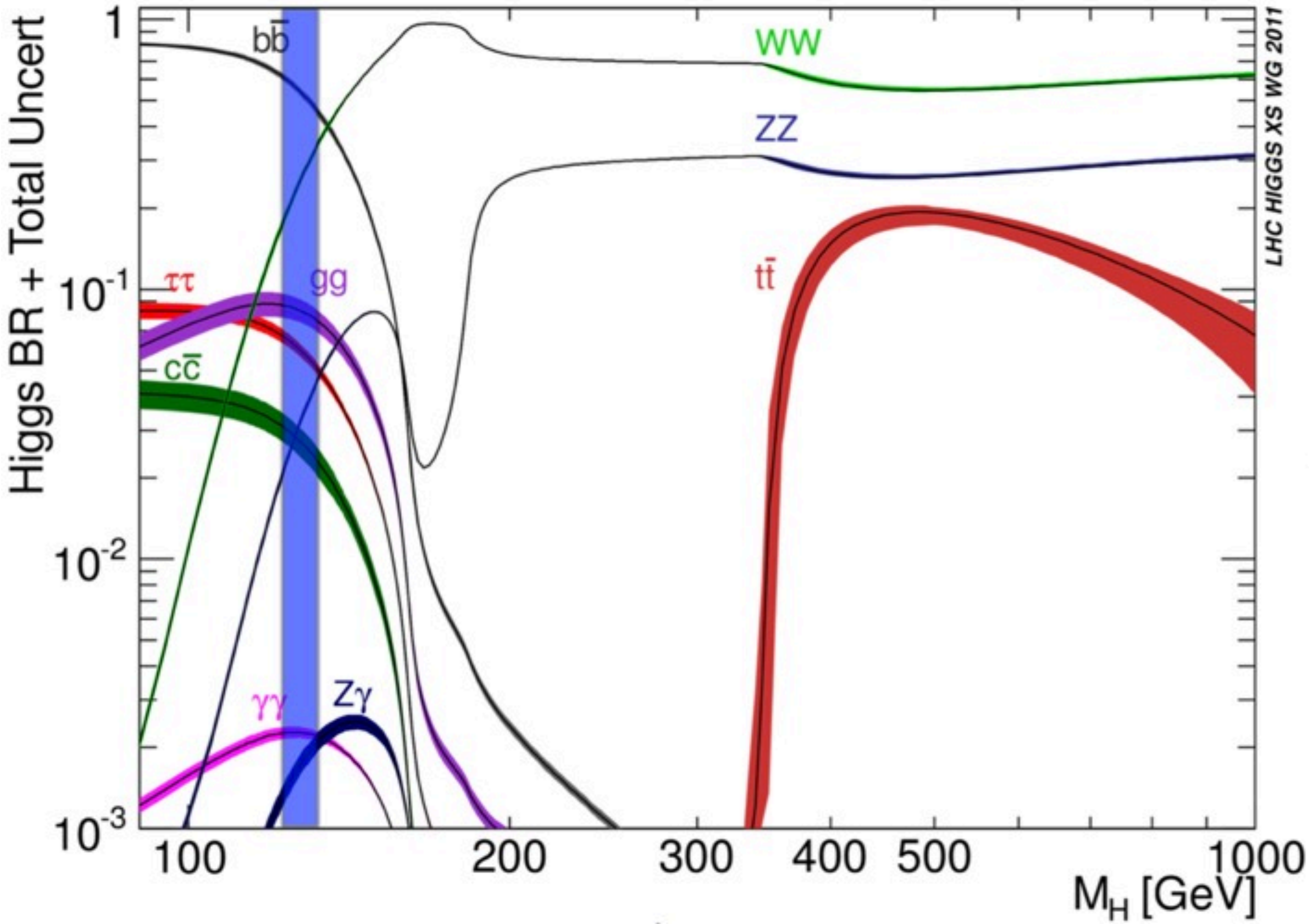




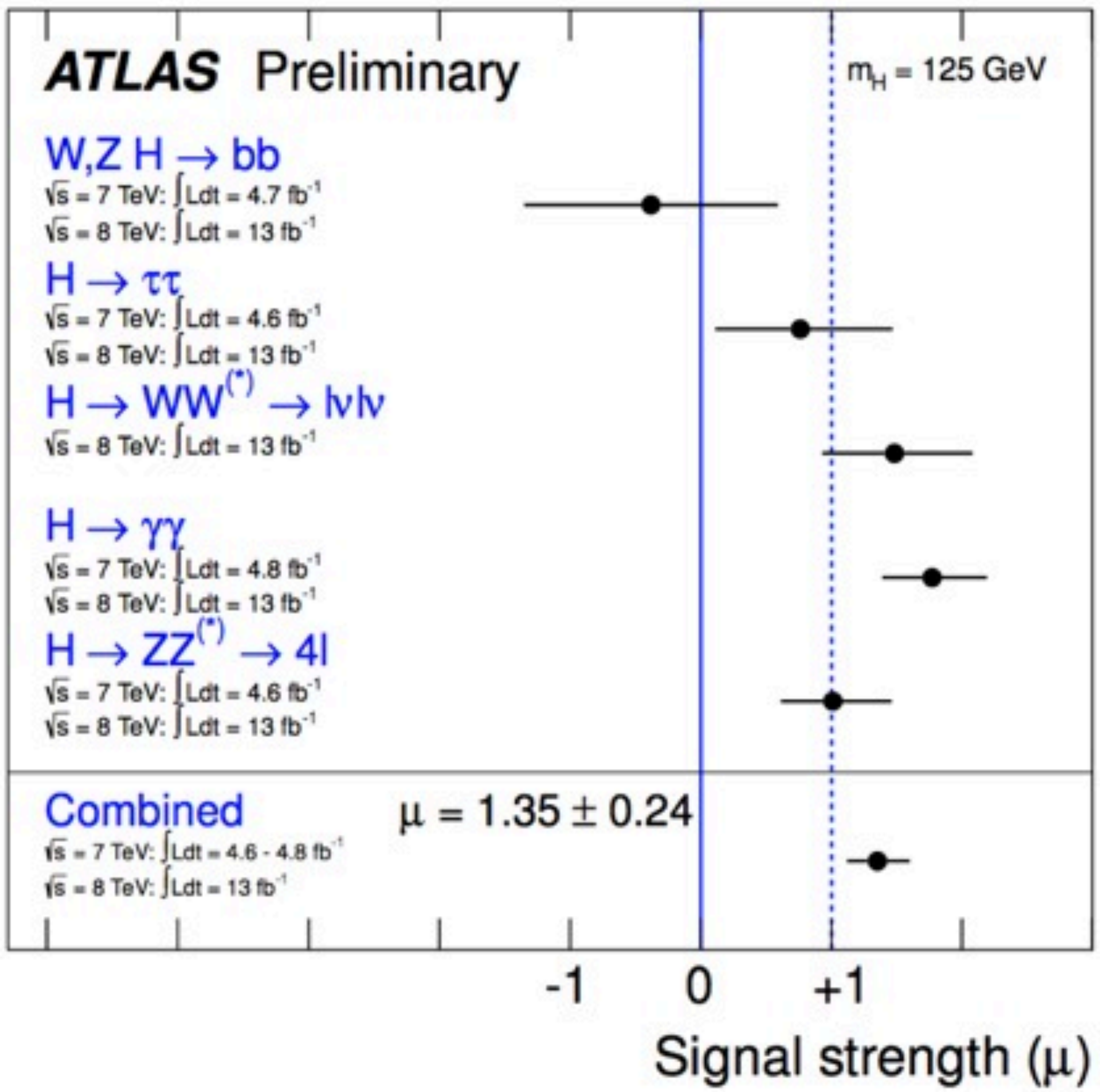
$$m_h \approx 125\,\mathrm{GeV}$$

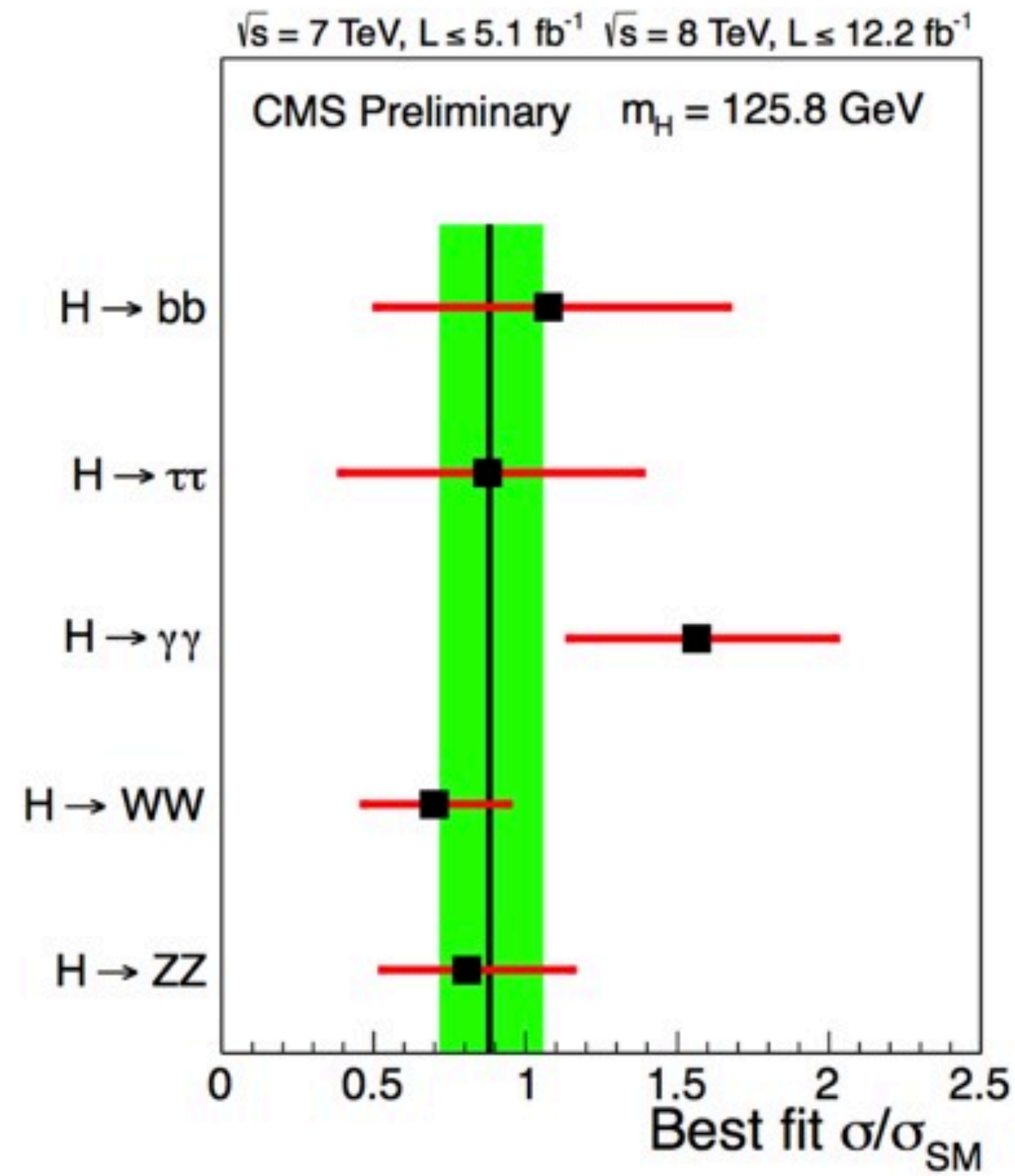
What is the nature of the Higgs particle?

Standard Model Higgs Branching Ratios



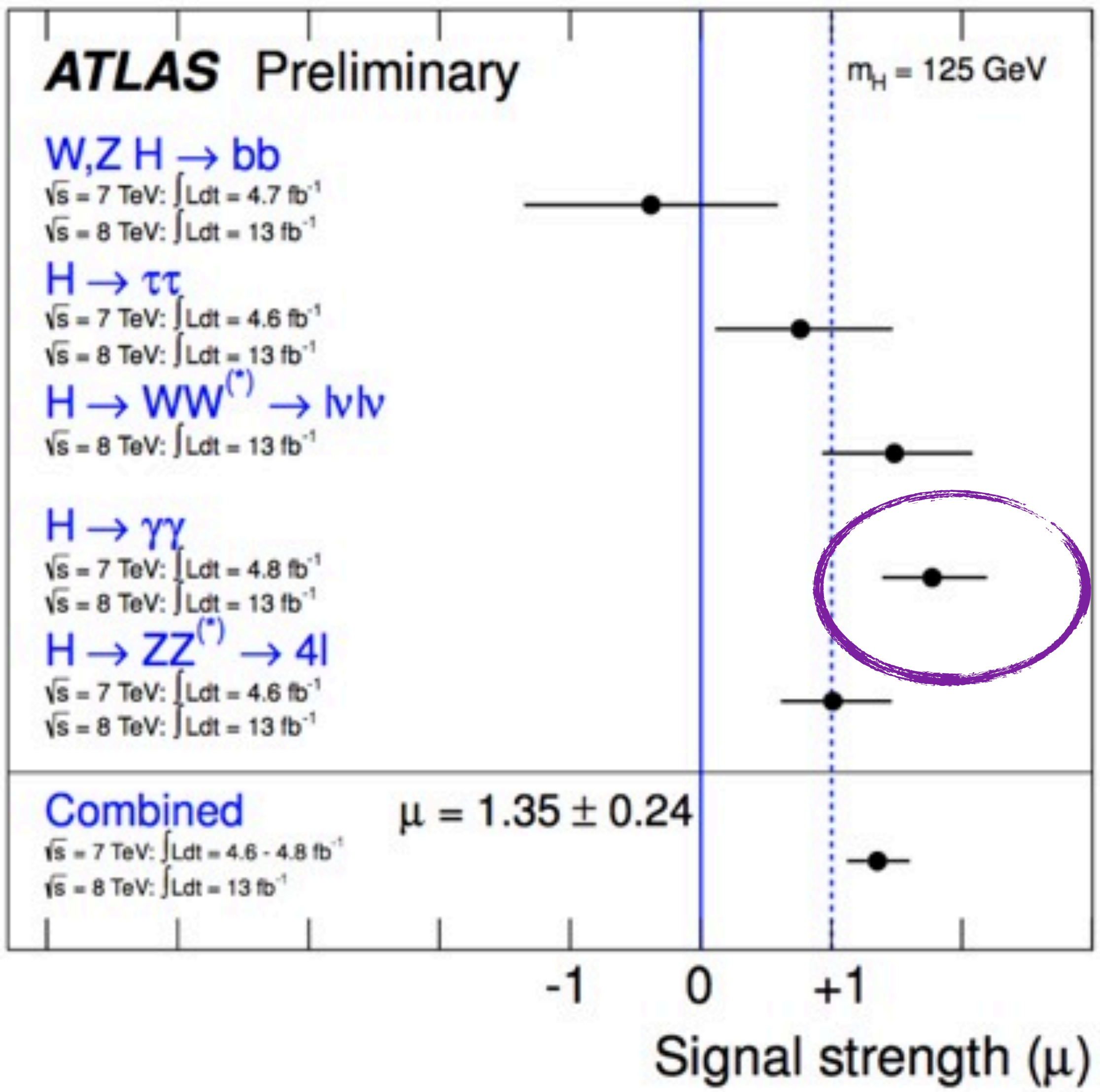
with a mass of 125 GeV many decay channels accessible

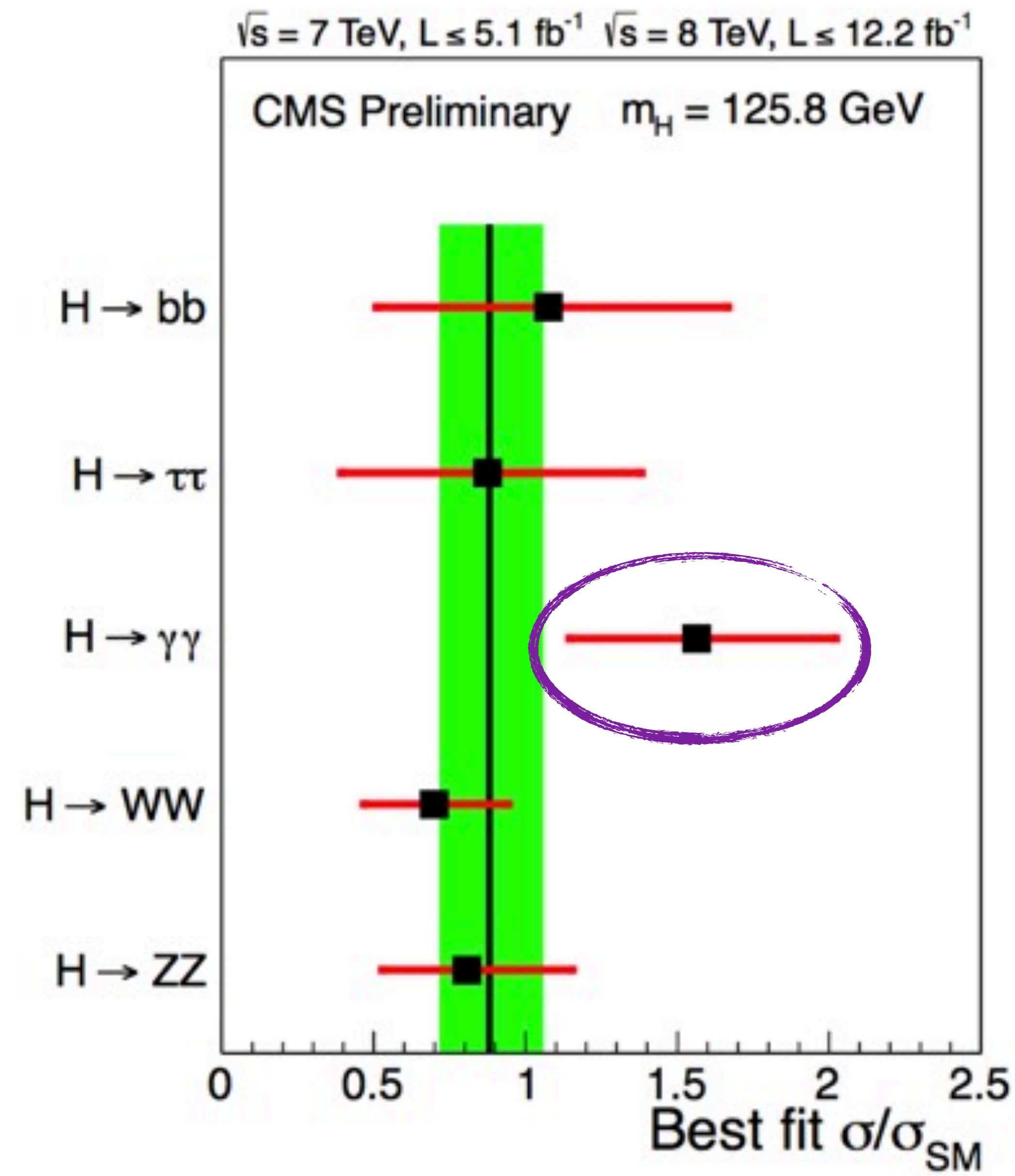




Moriond 2013

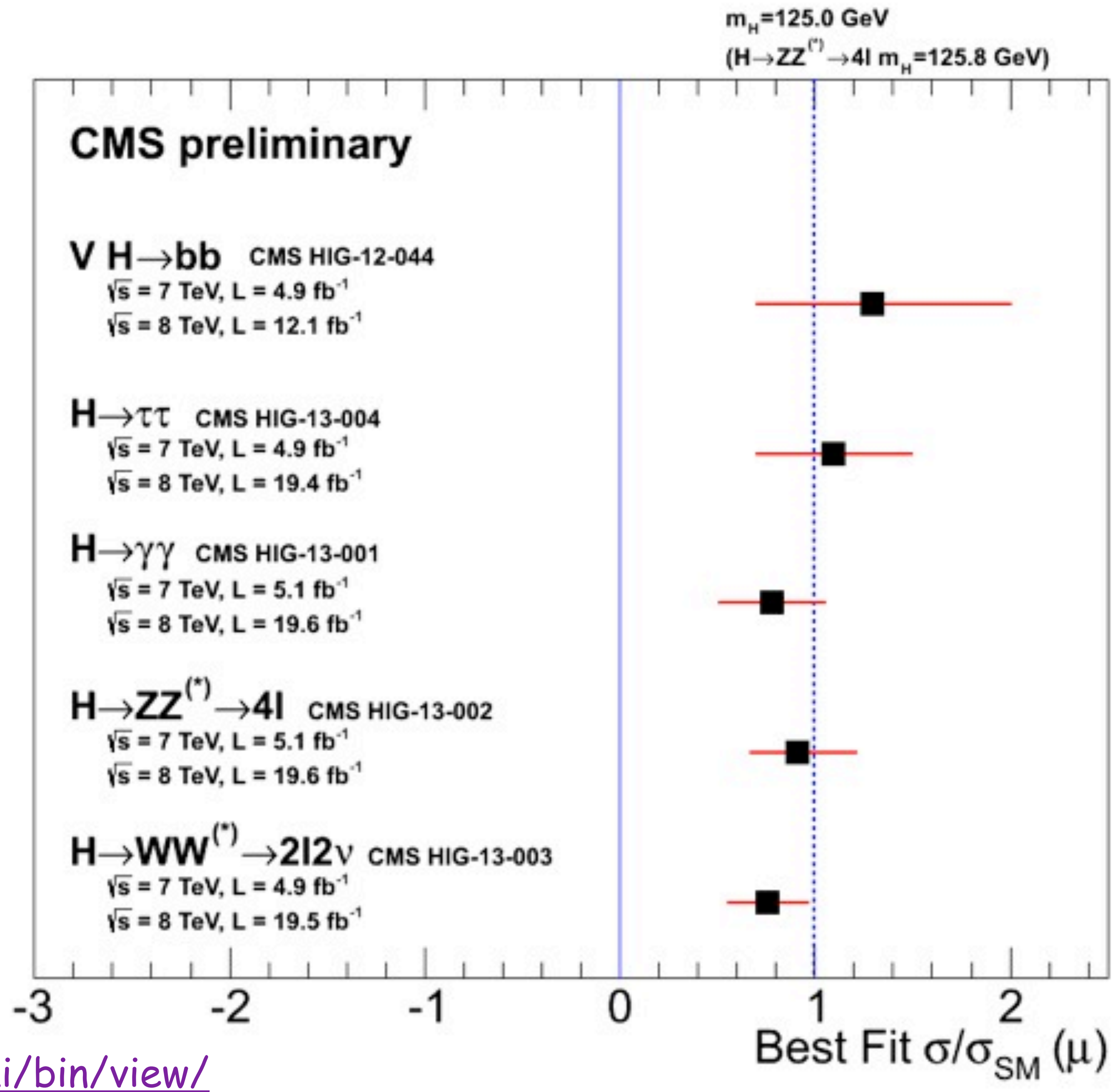
Interesting news: there could be hints of inconsistency with the SM predictions, for example in the $\gamma\gamma$ channel





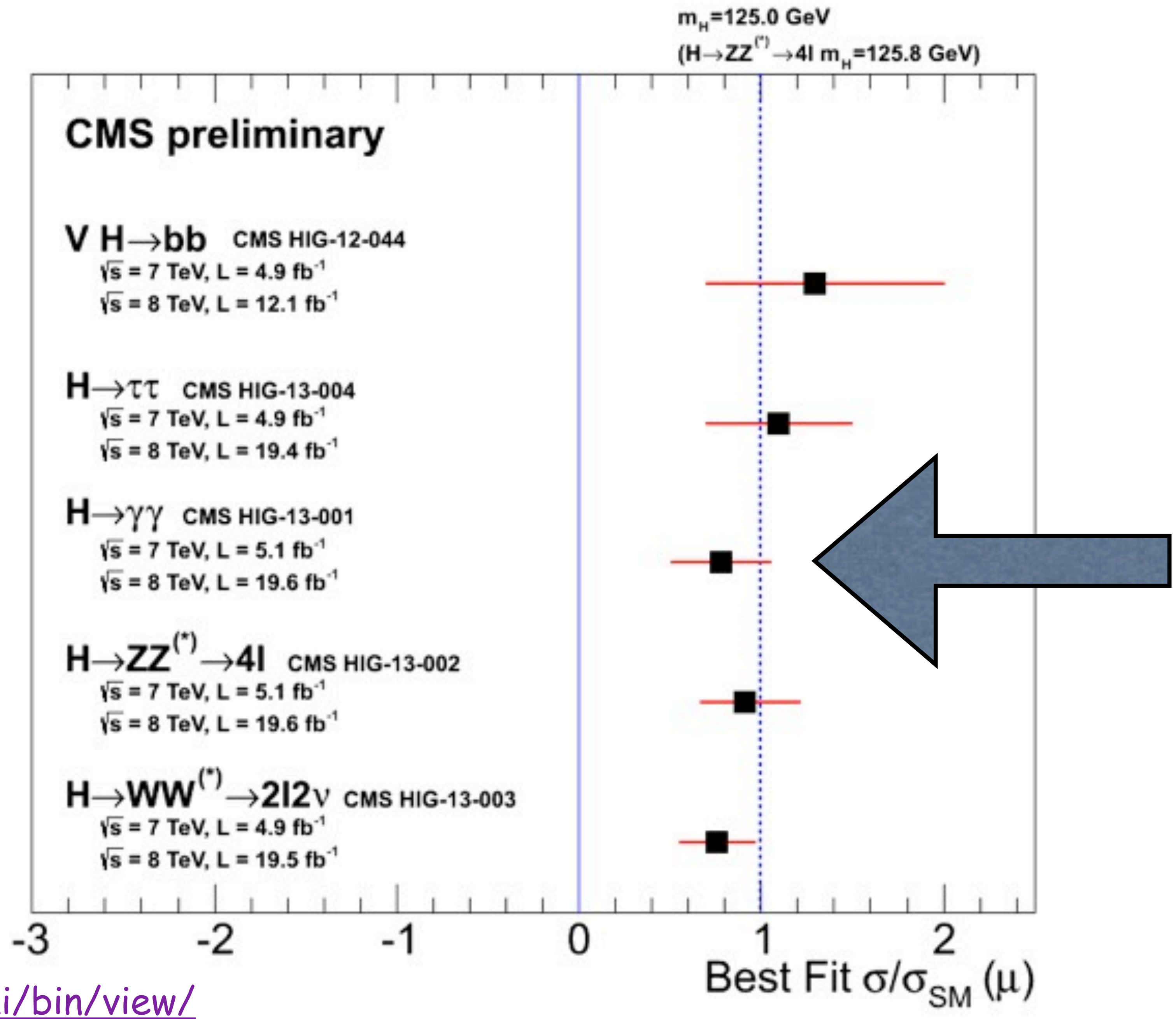
Moriond 2013

BUT recent CMS results with full 7+8 TeV dataset (preliminary) seems to point in the opposite direction!



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

BUT recent CMS results with full 7+8 TeV dataset (preliminary) seems to point in the opposite direction!



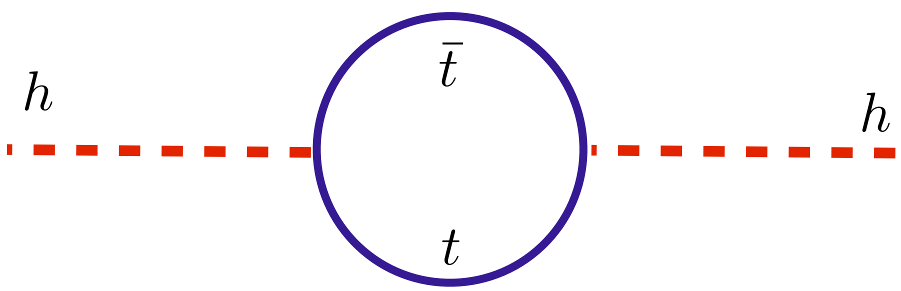
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

extraordinary agreement with the SM predictions

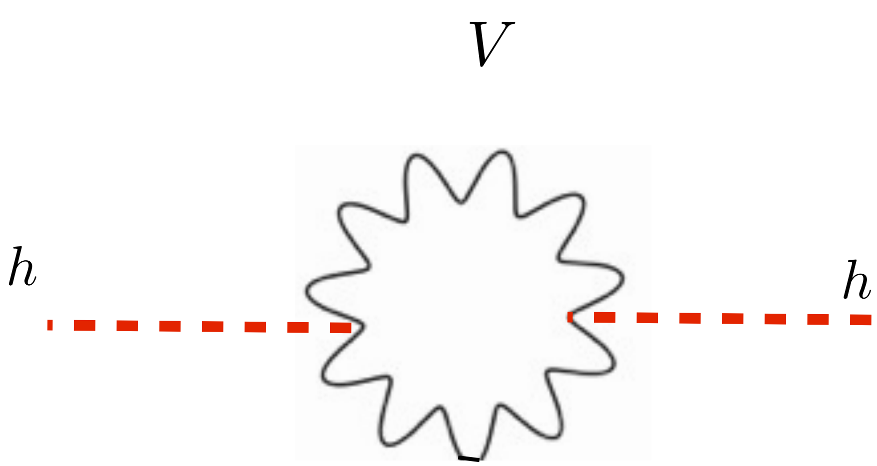
Even with the discovery of a Higgs-like particle we know that the SM cannot be the end of the story

Hierarchy Problem

Perturbatively:



$$\delta m_h^2 = -\frac{3\lambda_t^2}{8\pi^2}\Lambda_t^2 \longrightarrow \Lambda_t \sim 3\, m_h$$

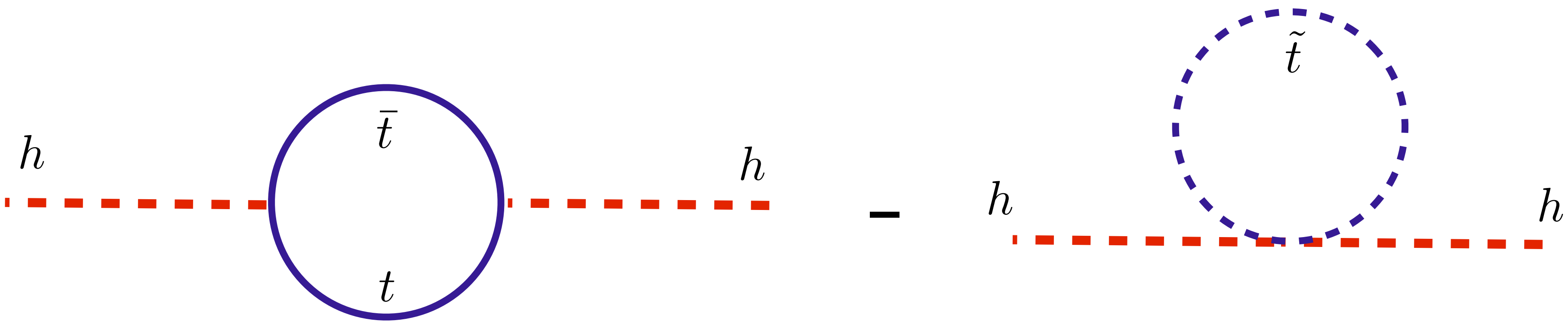


$$\delta m_h^2 = \frac{9g^2 + 3g'^2}{32\pi^2}\Lambda_g^2 \longrightarrow \Lambda_g \sim 9\, m_h$$

If the theory is natural new physics beyond SM must exist at the TEV scale.

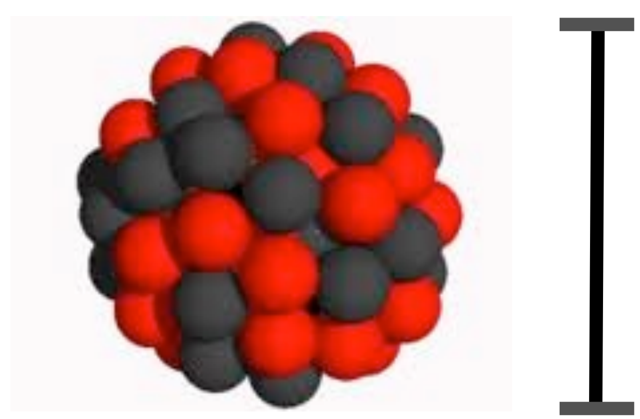
Two paradigms:

- Weak Coupling:
  Supersymmetry



$\sim 100\,\mathrm{GeV}$

- Strong Coupling:
  Technicolor, Composite Higgs, Higgsless, Extra-dimensions ...

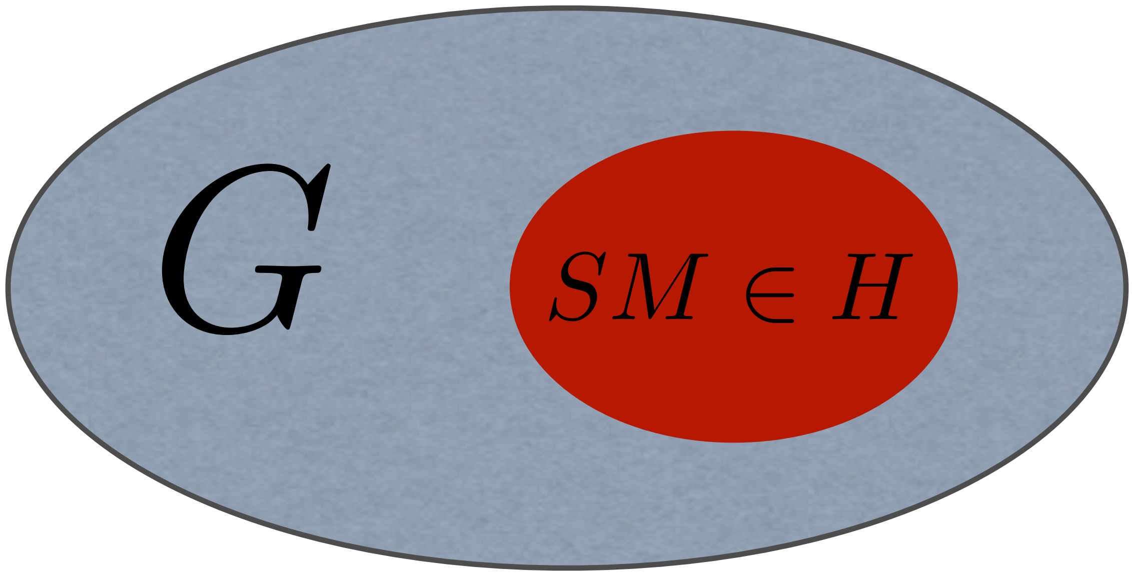


$$\sim \frac{1}{\mathrm{TeV}}$$

HIGGS PNGB

The Higgs scalar could be a NGB

Georgi, Kaplan (1984)



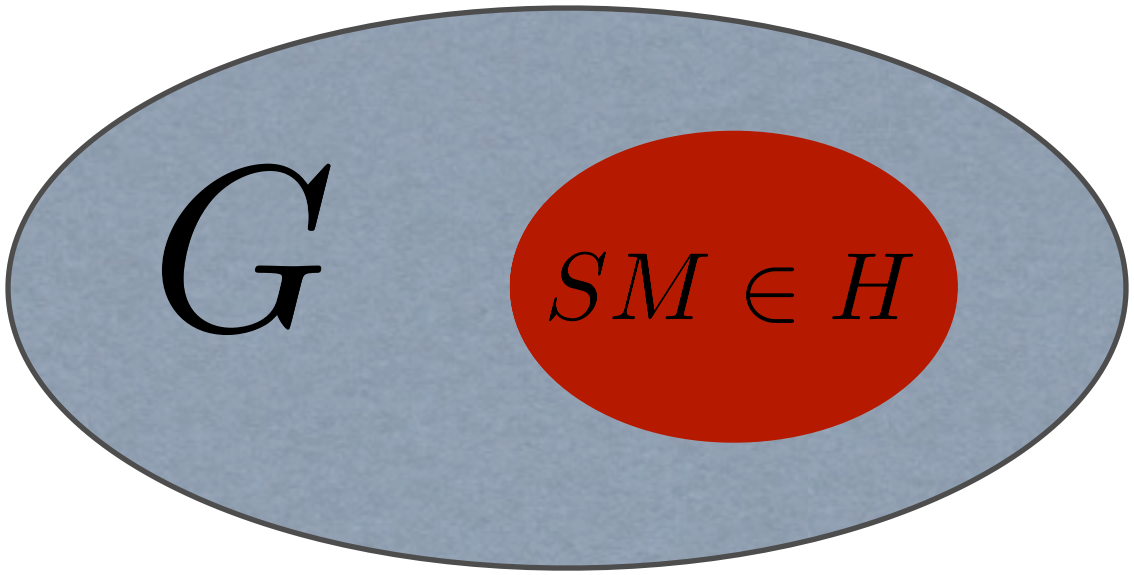
$$\mathrm{NGB} = \frac{G}{H}$$

$$U = e^{i\frac{\pi^{\hat{a}} T^{\hat{a}}}{f}}$$

Low energy Lagrangian $\mathcal{L} = f^2 D^{\hat{a}}_{\mu} D^{\hat{a}\mu} + \dots$

The Higgs scalar could be a NGB

Georgi, Kaplan (1984)



$$\text{NGB} = \frac{G}{H}$$

$$U = e^{i\frac{\pi^{\hat{a}}T^{\hat{a}}}{f}}$$

Low energy Lagrangian $\quad \mathcal{L} = f^2 D^{\hat{a}}_{\mu} D^{\hat{a}\mu} + \ldots$

Ex:

$$\frac{SO(5)}{SU(2)_L \otimes SU(2)_R} \longrightarrow GB = (2, 2)$$

Agashe,Contino,Pomarol (2004)

minimum number to be identified with the SM Higgs doublet

If the symmetry is exact the Higgs is massless

Higgs cannot be exact NGB
the shift symmetry $h \to h + c$ must be broken

G symmetry broken explicitly in SM

Similar to QCD: $U(2)_L \times U(2)_R \longrightarrow U(1)_{em} \times U(1)$

Higgs cannot be exact NGB
the shift symmetry $h \to h + c$ must be broken

G symmetry broken explicitly in SM

Similar to QCD: $U(2)_L \times U(2)_R \longrightarrow U(1)_{em} \times U(1)$

Higgs potential generated by radiative corrections
(a la Coleman-Weinberg) $\longrightarrow < h > \sim v$

Higgs is naturally light - relieves hierarchy problem

Higgs cannot be exact NGB
the shift symmetry $h \to h + c$ must be broken

G symmetry broken explicitly in SM

Similar to QCD: $U(2)_L \times U(2)_R \longrightarrow U(1)_{em} \times U(1)$

Higgs potential generated by radiative corrections
(a la Coleman-Weinberg) $\longrightarrow$ $< h > \sim v$

Higgs is naturally light - relieves hierarchy problem

Deviations from SM: $\mathcal{O}\left(\frac{v^2}{f^2}\right)$

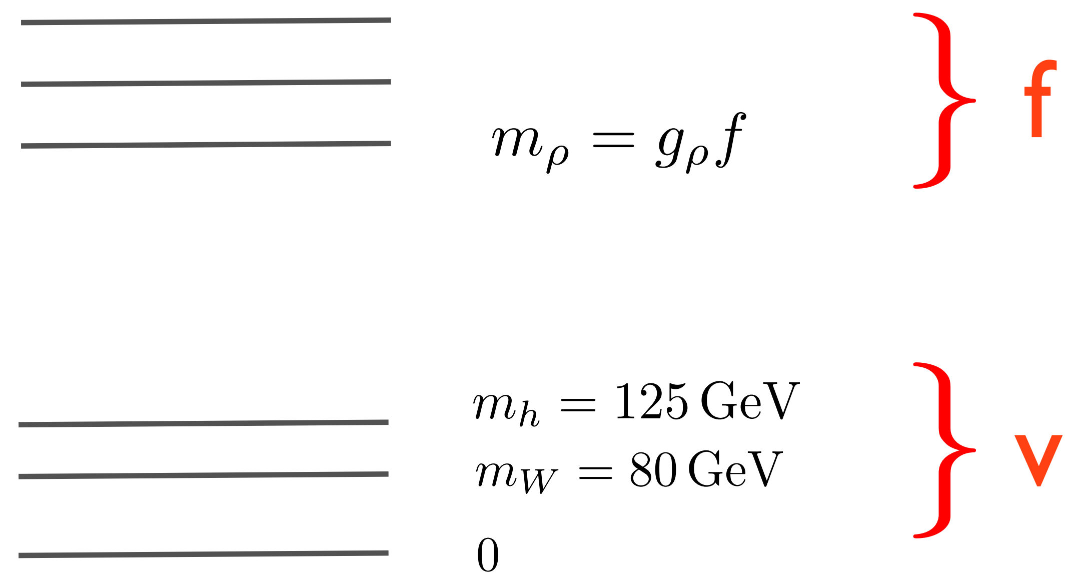
$\mathrm{TUNING} \propto \frac{f^2}{v^2}$ Small Tuning $\longrightarrow$ $f < TeV$

Strong sector: resonances + Higgs bound state

Extra particle content:

- Spin 1 resonances
- Spin 1/2 resonances

Spectrum:



$g_\rho =$ strong coupling

Strong sector: resonances + Higgs bound state

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

Spectrum:

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

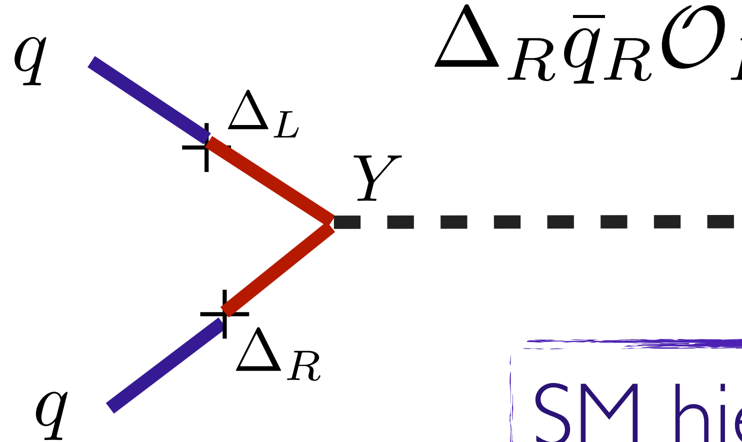
$g_\rho =$ strong coupling

$m_h = 125\,\mathrm{GeV}$

$m_W = 80\,\mathrm{GeV}$ } v

0

Linear elementary-composite couplings (partial compositeness)

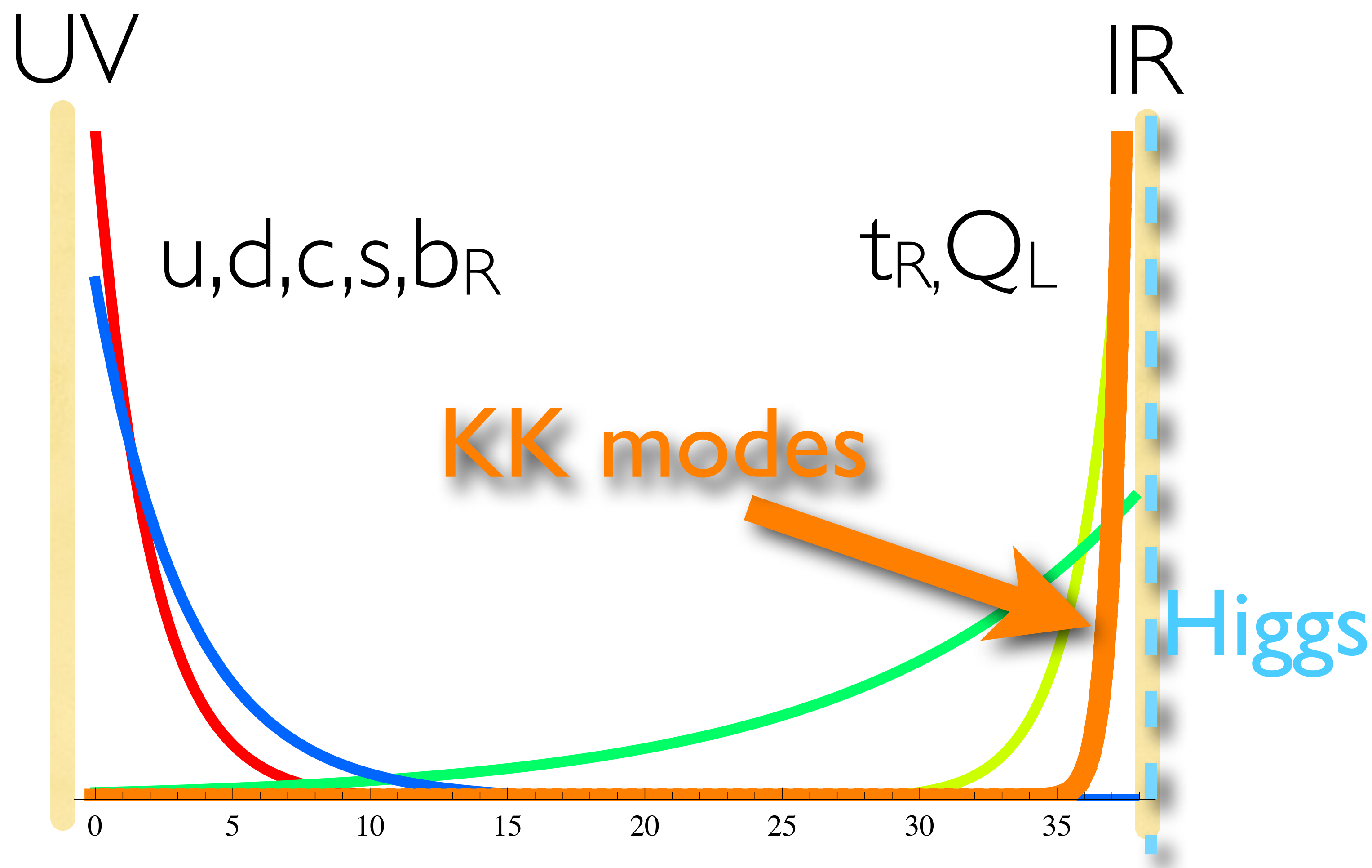


$$\Delta_R \bar{q}_R \mathcal{O}_L + \Delta_L \bar{q}_L \mathcal{O}_R + Y \bar{\mathcal{O}}_L H \mathcal{O}_R$$

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

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

MODELS



- **5D Models**

Randall, Sundrum (1999)

$$ds^2 = e^{-2kry}(-dt^2 + dx^2) + dy^2$$

Simplest description of **Higgs as PNGB** with symmetry pattern $SO(5) \to SO(4)$ is the MCHM5 by Agashe, Contino, Pomarol

Through AdS/CFT correspondence **5D models are dual to 4D strongly coupled theories**. Relevant physics dominated by the lowest modes

- **4D Models**

Low energy Lagrangian determined by the symmetries: CCWZ procedure

$$U(\Pi) = e^{\frac{i\Pi^{\widehat{a}}T^{\widehat{a}}}{f}} \qquad U^\dagger \partial_\mu U = iE^a_\mu T^a + iD^{\widehat{a}}_\mu T^{\widehat{a}}$$

An effective Lagrangian for $G \to H$ can be built similar to QCD

$$\mathcal{L} = \frac{f^2}{4} D^{\hat{a}}_\mu D^{\mu\hat{a}}$$

To introduce **resonances** start from G/H and consider another sigma-model

$$\frac{G_L \otimes G_R}{G_{L+R}} \qquad \Omega \to g_L \Omega g_R^\dagger$$

and gauge $diag(G_R \otimes G)$

- **4D Models**

Low energy Lagrangian determined by the symmetries: CCWZ procedure

$$U(\Pi) = e^{\frac{i\Pi^{\hat{a}}T^{\hat{a}}}{f}} \qquad U^\dagger \partial_\mu U = iE^a_\mu T^a + iD^{\hat{a}}_\mu T^{\hat{a}}$$

An effective Lagrangian for $G \to H$ can be built similar to QCD

$$\mathcal{L} = \frac{f^2}{4} D^{\hat{a}}_\mu D^{\mu\hat{a}}$$

To introduce **resonances** start from G/H and consider another sigma-model

$\frac{G_L \otimes G_R}{G_{L+R}}$ $\quad \Omega \to g_L \Omega g_R^\dagger$ $\quad$ and gauge $diag(G_R \otimes G)$

$$\mathcal{L}_{2-site} = \frac{f_1^2}{4} \mathrm{Tr}\,|D_\mu \Omega|^2 + \frac{f_2^2}{2} \mathcal{D}^{\hat{a}}_\mu \mathcal{D}^{\mu\hat{a}} - \frac{1}{4g_\rho^2} \rho^A_{\mu\nu} \rho^{A\mu\nu}$$

$$D_\mu \Omega = \partial_\mu \Omega - iA_\mu \Omega + i\Omega \rho_\mu$$

- **4D Models**

Low energy Lagrangian determined by the symmetries: CCWZ procedure

$$U(\Pi) = e^{\frac{i\Pi^{\hat{a}}T^{\hat{a}}}{f}} \qquad U^\dagger \partial_\mu U = iE^a_\mu T^a + iD^{\hat{a}}_\mu T^{\hat{a}}$$

An effective Lagrangian for $G \to H$ can be built similar to QCD

$$\mathcal{L} = \frac{f^2}{4} D^{\hat{a}}_\mu D^{\mu\hat{a}}$$

To introduce **resonances** start from G/H and consider another sigma-model

$$\frac{G_L \otimes G_R}{G_{L+R}} \qquad \Omega \to g_L \Omega g_R^\dagger$$

and gauge $diag(G_R \otimes G)$

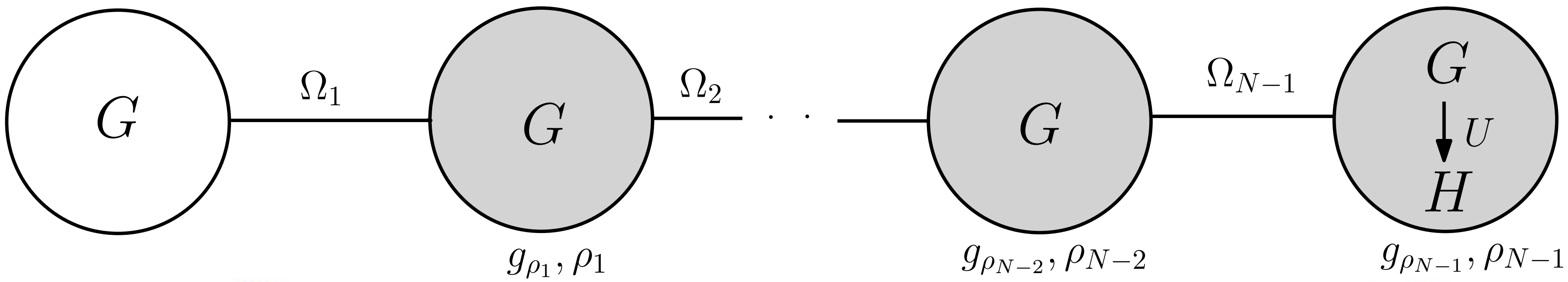
$$\mathcal{L}_{2-site} = \frac{f_1^2}{4} \mathrm{Tr}\, |D_\mu \Omega|^2 + \frac{f_2^2}{2} \mathcal{D}^{\hat{a}}_\mu \mathcal{D}^{\mu\hat{a}} - \frac{1}{4g_\rho^2} \rho^A_{\mu\nu} \rho^{A\mu\nu}$$

$$D_\mu \Omega = \partial_\mu \Omega - iA_\mu \Omega + i\Omega \rho_\mu$$

G_L gauge fields, external sources for the composite sector

new spin-1 resonances $\rho_\mu \in Adj[G]$

More resonances can be added:

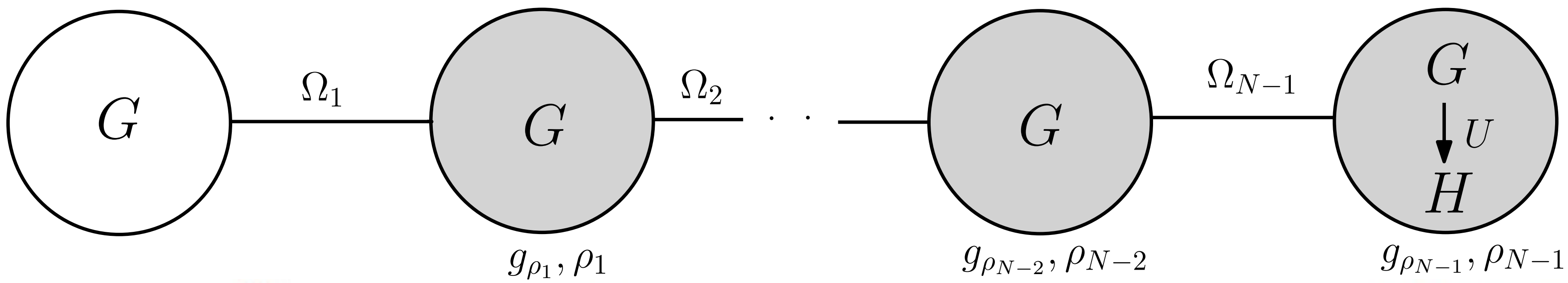


$$\rho_i^\mu \in Adj[G_i]$$

$$U' \equiv \Big(\prod_{i=1}^{N} \Omega_i\Big) U \qquad \sum_{i=1}^{N+1} \frac{1}{f_i^2} = \frac{1}{f^2} \qquad U'(\Pi) = e^{\,if(\sum_{i=1}^{N+1} \frac{1}{f_i^2})\Pi} = e^{\,i\Pi/f}$$

nearest neighbor interactions reproduce extra-dim

More resonances can be added:

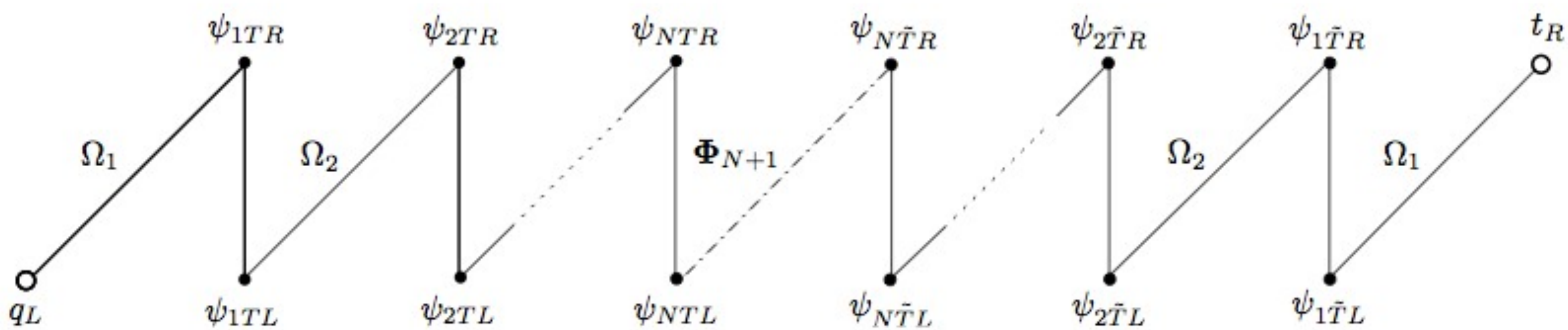


$\rho_i^\mu \in Adj[G_i]$

$$U' \equiv \left(\prod_{i=1}^{N} \Omega_i\right) U \qquad \sum_{i=1}^{N+1} \frac{1}{f_i^2} = \frac{1}{f^2} \qquad U'(\Pi) = e^{\,i f\left(\sum_{i=1}^{N+1} \frac{1}{f_i^2}\right)\Pi} = e^{\,i\Pi/f}$$

nearest neighbor interactions reproduce extra-dim

Analogous construction for fermions, realizing partial compositeness

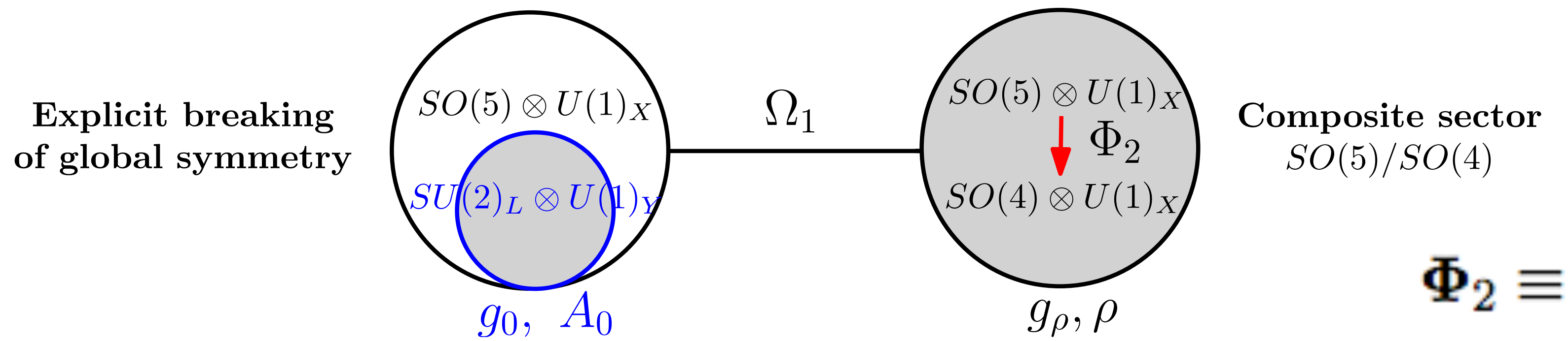


Two fermionic multiplets for each site (here only top)

Elementary-composite states talk through linear couplings

Minimal SO(5)/SO(4) model in 4D

Redi, Tesi, DC, (2011)



$$\mathbf{\Phi}_2 \equiv \Omega_2 \boldsymbol{\varphi}_0 \ , \ \varphi_0^i = \delta_5^i \ ,$$

Composite spin-1 Lagrangian:

$$\Omega_1 = \frac{SO(5)_L \times SO(5)_R}{SO(5)_{L+R}} \qquad \mathbf{\Phi_2} = \frac{SO(5)}{SO(4)}$$

$$\mathcal{L} = \frac{f_1^2}{4} tr[(D_\mu \Omega_1)^\dagger D^\mu \Omega_1] + \frac{f_2^2}{2} (D_\mu \mathbf{\Phi}_2)^T (D^\mu \mathbf{\Phi}_2) - \frac{1}{4g_\rho^2} tr[\rho^{\mu\nu}\rho_{\mu\nu}]$$

$$D_\mu \Omega_1 = \partial_\mu \Omega_1 - i A_\mu \Omega_1 + i \Omega_1 \rho_\mu$$

$$D_\mu \mathbf{\Phi}_2 = \partial_\mu \mathbf{\Phi}_2 - i \rho_\mu \mathbf{\Phi}_2.$$

$$\Omega_i = e^{i \frac{f}{f_i^2} \Pi}$$
$$\Pi = \sqrt{2} h^{\hat{a}} T^{\hat{a}}$$

spin-1 resonances = gauge fields of SO(5) x U(1)

Composite gauge boson spectrum (5 neutral Z'+ 3 charged W'):

$$m_\rho^2 = \frac{g_\rho^2 f_1^2}{2}$$

$$m_{a_1}^2 = \frac{g_\rho^2 (f_1^2 + f_2^2)}{2}$$

$$m_{\rho_X}^2 = \frac{g_{\rho_X}^2 f_1^2}{2}$$

Composite gauge boson spectrum (5 neutral Z'+ 3 charged W'):

$$m_\rho^2 = \frac{g_\rho^2 f_1^2}{2}$$
$$m_{a_1}^2 = \frac{g_\rho^2 (f_1^2+f_2^2)}{2}$$
$$m_{\rho_X}^2 = \frac{g_{\rho_X}^2 f_1^2}{2}$$

SM fields are introduced adding kinetic terms for the sources

$$\mathcal{L}^{el}_{gauge} = -\frac{1}{4g_0^2} F^a_{\mu\nu} F^a_{\mu\nu} - \frac{1}{4g_{0Y}^2} Y_{\mu\nu} Y^{\mu\nu}$$

$\gamma, W^{\pm}, Z$
massless before EWSB

Composite gauge boson spectrum (5 neutral Z'+ 3 charged W'):

$$m_\rho^2 = \frac{g_\rho^2 f_1^2}{2}$$

$$m_{a_1}^2 = \frac{g_\rho^2 (f_1^2 + f_2^2)}{2}$$

$$m_{\rho_X}^2 = \frac{g_{\rho_X}^2 f_1^2}{2}$$

SM fields are introduced adding kinetic terms for the sources

$$\mathcal{L}_{gauge}^{el} = -\frac{1}{4g_0^2} F_{\mu\nu}^a F_{\mu\nu}^a - \frac{1}{4g_{0Y}^2} Y_{\mu\nu} Y^{\mu\nu}$$

$\gamma, W^\pm, Z$ massless before EWSB

Physical parameters:

$$\frac{1}{g^2} = \frac{1}{g_0^2} + \frac{1}{g_\rho^2}$$

$$\frac{1}{g'^2} = \frac{1}{g_{0Y}^2} + \frac{1}{g_\rho^2} + \frac{1}{g_{\rho_X}^2}$$

Mixing elementary-composite

$$m_{\rho_{aL}} = \frac{m_\rho}{\cos\theta_L}, \quad \tan\theta_L = \frac{g_0}{g_\rho}$$

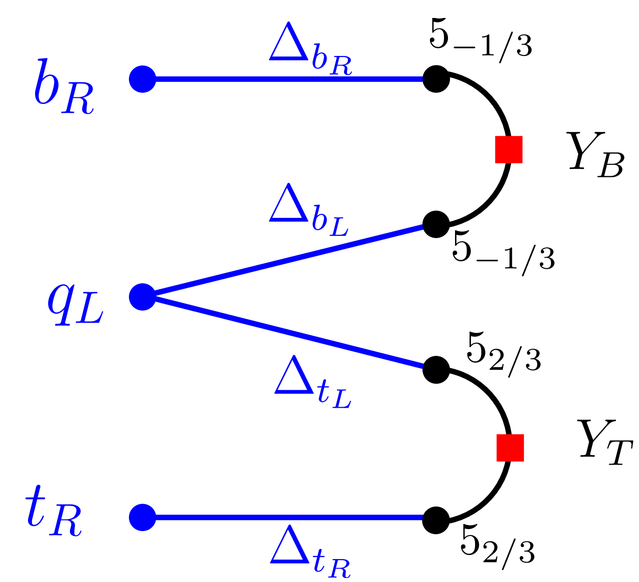
Each SM fermion couples to Dirac fermion in a rep of SO(5)

Partial compositeness only with the quark 3rd generation

Light generations are elementary, t&b partially composite

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

Explicit breaking of global symmetry



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

Extra fermions:

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

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

→ Explicit SO(5) breaking (for the line $+ \bar{\Psi}_T (i \not{D}^{\rho} - m_T)\Psi_T + \dots$)

→ Composite physics SO(5)/SO(4) (for the line $- Y_T \bar{\Psi}_{T,L} \Phi_2^T \Phi_2 \Psi_{\tilde{T},R} - \dots$)

$\Delta_{t_{L,R}}, \ \Delta_{b_{L,R}}, \ g_0, g_{0Y}$ break NGB symmetry

Low energy effective action in terms of **form factors** by integrating out the heavy states

$$\mathcal{L}_{\text{eff}}^{gauge} = \frac{1}{2} P_{\mu\nu}^T \Big[\left(\Pi_0(p^2) + \frac{s_h^2}{4} \Pi_1(p^2) \right) A_{aL}^\mu A_{aL}^\nu + \left(\Pi_Y(p^2) + \frac{s_h^2}{4} \Pi_1(p^2) \right) Y^\mu Y^\nu + 2 s_h^2\, \Pi_1(p^2)\ \widehat{H}^\dagger T_L^a Y \widehat{H}\ A_\mu^{aL} Y_\nu \Big]$$

from m_W^2 and $\Pi_1(0) = f^2$ ⇨ $v^2 = f^2 \sin^2 \dfrac{\langle h \rangle}{f}$

GB's described by $\Omega_1 \Omega_2 \varphi_0 = e^{\,i\Pi/f} \varphi_0 = \frac{1}{h} \sin\frac{h}{f} \left(h_1, h_2, h_3, h_4, h \cot\frac{h}{f} \right)$

$$s_h = \sin\frac{h}{f} \qquad H = \begin{pmatrix} h_2 + i h_1 \\ h_4 - i h_3 \end{pmatrix} \qquad \hat{H} = \frac{1}{h} \begin{pmatrix} h_2 + i h_1 \\ h_4 - i h_3 \end{pmatrix}$$

analogously with fermions (here only top):

Contino, Da Rold, Pomarol (2006)

$$\mathcal{L}_{\rm eff}^{ferm} = \bar{q}_L \not{p} \left(\Pi_0^q(p^2) + \frac{1}{2} s_h^2 \Pi_1^q(p^2) \hat{H}_c \hat{H}_c^\dagger\right) q_L + \bar{t}_R \not{p} \left(\Pi_0^t(p^2) + \frac{1}{2} s_h^2 \Pi_1^t(p^2)\right) t_R + \frac{s_h c_h}{\sqrt{2}} M_1^t(p^2)\, \bar{q}_L \hat{H}_c t_R + \text{h.c.}$$

from which we derive:

top Yukawa coupling

$$m_t \simeq \frac{1}{\sqrt{2}} \frac{\Delta_{tL}}{m_T} \frac{\Delta_{tR}}{m_{\tilde{T}}} \frac{Y_T}{f} v \equiv \frac{1}{\sqrt{2}} y_t\, v$$

analogously with fermions (here only top):

Contino, Da Rold, Pomarol (2006)

$$\mathcal{L}_{\rm eff}^{ferm} = \bar{q}_L \not{p} \left(\Pi_0^q(p^2) + \frac{1}{2} s_h^2 \Pi_1^q(p^2) \hat{H}_c \hat{H}_c^\dagger \right) q_L + \bar{t}_R \not{p} \left(\Pi_0^t(p^2) + \frac{1}{2} s_h^2 \Pi_1^t(p^2) \right) t_R$$
$$+ \frac{s_h c_h}{\sqrt{2}} M_1^t(p^2)\, \bar{q}_L \hat{H}_c t_R + \text{h.c.}$$

from which we derive:

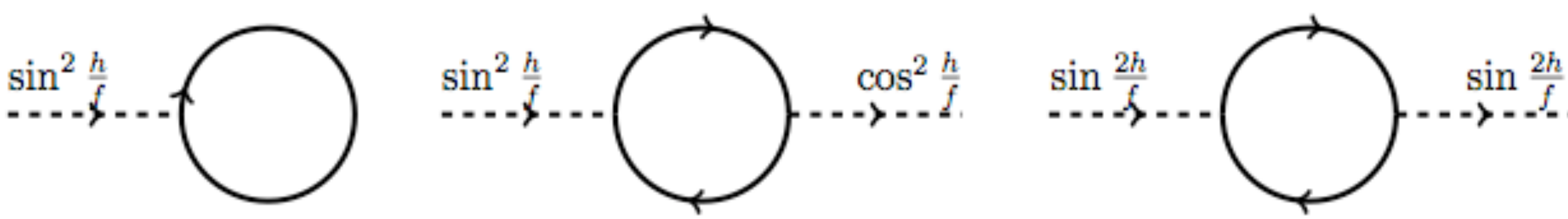
top Yukawa coupling

$$m_t \simeq \frac{1}{\sqrt{2}} \frac{\Delta_{tL}}{m_T} \frac{\Delta_{tR}}{m_{\tilde{T}}} \frac{Y_T}{f} v \equiv \frac{1}{\sqrt{2}} y_t\, v$$

Coleman-Weinberg effective potential generated at 1-loop

$$V(h)_{gauge} = \frac{9}{2} \int \frac{d^4p}{(2\pi)^4} \ln \left[1 + \frac{1}{4} \frac{\Pi_1(p^2)}{\Pi_0(p^2)} \sin^2 \frac{h}{f} \right] \approx \int \frac{d^4p}{(2\pi)^4} \frac{9\Pi_1}{8\Pi_0} \sin^2 \frac{h}{f}$$

$$V(h)_{fermions} \approx -N_c \int \frac{d^4p}{(2\pi)^4} \left[\frac{\Pi_1^{q_1}}{\Pi_0^q} + \frac{\Pi_1^u}{\Pi_0^u} \right] \sin^2 \frac{h}{f} + N_c \int \frac{d^4p}{(2\pi)^4} \left[\frac{(M_1^u)^2}{p^2 \Pi_0^q \Pi_0^u} \right] \sin^2 \frac{h}{f} \cos^2 \frac{h}{f}$$



$$V(h) \approx \alpha\, s_h^2 - \beta\, s_h^2 c_h^2$$ → **UV finite in the 4DCHM**

EWSB → $\langle s_h \rangle = \frac{v}{f} = \sqrt{\frac{\beta - \alpha}{2\beta}} \neq 0$

top Yukawa coupling

$$m_H^2 \simeq \frac{8\beta v^2}{f^4} \sim y_t\, m_T \frac{v}{f}$$

lightest extra-fermion

$$V(h) \approx \alpha\, s_h^2 - \beta\, s_h^2 c_h^2$$ → UV finite in the 4DCHM

EWSB → $\langle s_h \rangle = \frac{v}{f} = \sqrt{\frac{\beta-\alpha}{2\beta}} \neq 0$

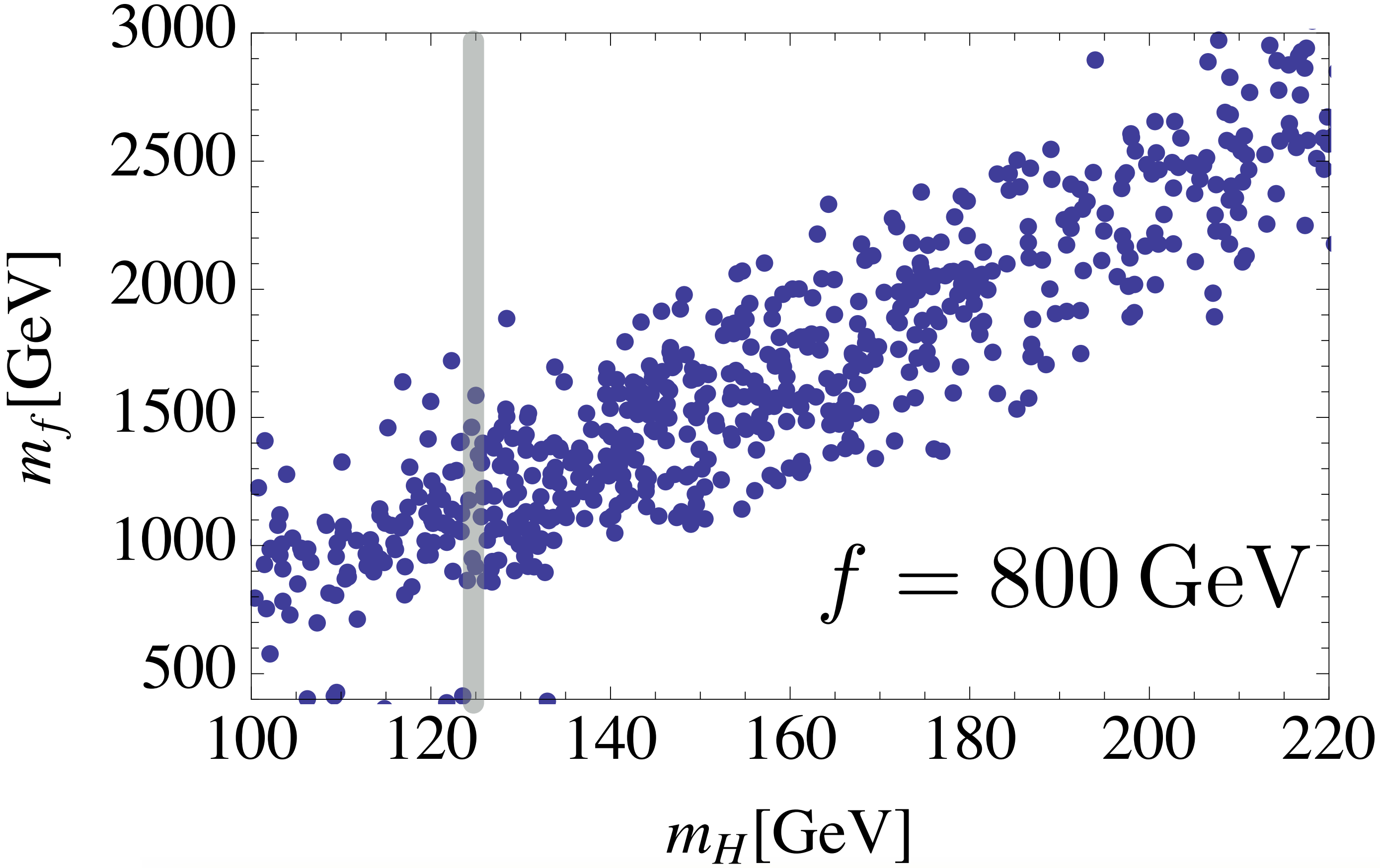
$$m_H^2 \simeq \frac{8\beta v^2}{f^4} \sim y_t\, m_T \frac{v}{f}$$

top Yukawa coupling

lightest extra-fermion

- **4DCHM**

General scan: Redi, Tesi, DC (2011) Redi, Tesi (2012)



Tuning

$$\Delta \sim \frac{f^2}{v^2} \sim 10$$

Panico, Redi, Tesi, Wulzer (2012)

New fermions should be seen in the near future!

SIGNATURES

Implementation of the 4DCHM

- Calculable 4D description: good framework to study general CHM features
- LHC will at best produce the lightest resonances ⟶ 4DCHM is a simplified model useful for LHC signatures
- The particle spectrum is quite large and also the number of parameters

Leptons: $e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$	Quarks: $T_{1,8}, B_{1,8}, \tilde{T}_{1,2}, \tilde{B}_{1,2}$
Quarks: u, d, c, s, t, b	Gauge Bosons: $Z'_{1,5}, W'_{1,3}$
Gauge Bosons: $\gamma, Z^0, W^\pm$	
Higgs Boson: H	
Gluons: g	

Gauge parameters: f, g_*

Fermionic parameters: $m_*, \Delta_{t_L}, \Delta_{t_R}, \Delta_{b_L}, \Delta_{b_R}, Y_B, Y_T, m_{Y_T}, m_{Y_B}$

- We have taken $g_\rho = g_{\rho X} = g_*$, $m_T = m_{\tilde{T}} = m_*$

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

- LanHEP and CalcHEP: Packages for automatic generation of Feynman rules and for calculation of physical observables **(Semenov 1005.1909, Belyaev et al 1207.6082)**

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

- Benchmark points: $750 < f(\text{GeV}) < 1200$ and choosing g_* to get

$$M_{Z'} \simeq f g_* > 2\text{TeV} \qquad \text{(EWPT)}$$

Bounds on extra-fermions

- Limits on T_1 and B_1 masses from direct searches at LHC (pair production) rescaled to take into account the BR's in the 4DCHM

From CMS analysis with 7 TeV dataset which assume 100% BR of t' in Wb or Zt , and 100% BR of b' in Wt or Zb, we get: $m_{T_1},\ m_{B_1} > 400\mathrm{GeV}$

(see also Matsedonskyi, Panico, Wulzer (2013))

New ATLAS analysis with 8 TeV dataset **could improve** these bounds

(ATLAS-CONF-2013.018)

Bounds on extra-fermions

- Limits on T_1 and B_1 masses from direct searches at LHC (pair production) rescaled to take into account the BR's in the 4DCHM

From CMS analysis with 7 TeV dataset which assume 100% BR of t' in Wb or Zt , and 100% BR of b' in Wt or Zb, we get: $m_{T_1},\ m_{B_1} > 400\mathrm{GeV}$
(see also Matsedonskyi, Panico, Wulzer (2013))

New ATLAS analysis with 8 TeV dataset **could improve** these bounds
(ATLAS-CONF-2013.018)

- **Limits on the mass of the exotic** $\tilde{T}_1$ are also enforced (ATLAS-CONF-2012.130)

Notice that in the 4DCHM there are regions where the $\tilde{T}_1$ is not the lightest heavy fermion $(\tilde{T}_1 = T_{5/3})$

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

- Higgs couplings to SM states are modified due to mixing

- 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

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

$$R_{YY} = \frac{\sigma(pp \to HX)|_{\rm 4DCHM} \times {\rm BR}(H \to YY)|_{\rm 4DCHM}}{\sigma(pp \to HX)|_{\rm SM} \times {\rm BR}(H \to YY)|_{\rm SM}}$$

$$YY = \gamma\gamma, b\bar{b}, WW, ZZ$$

- Relevant production processes:

$gg \to H$ gluon fusion, $q\bar{q}' \to VH$ Higgs-strahlung

$V = W, Z$

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

$$R_{YY} = \frac{\sigma(pp \to HX)|_{\rm 4DCHM} \times {\rm BR}(H \to YY)|_{\rm 4DCHM}}{\sigma(pp \to HX)|_{\rm SM} \times {\rm BR}(H \to YY)|_{\rm SM}}$$

$$YY = \gamma\gamma, b\bar{b}, WW, ZZ$$

- Relevant production processes:

$gg \to H$ gluon fusion, $q\bar{q}' \to VH$ Higgs-strahlung

$V = W, Z$

- At leading order ⟶ trade a cross section for a width:

$$R_{YY}^{Y'Y'} = \frac{\Gamma(H \to Y'Y')|_{\rm 4DCHM} \times \Gamma(H \to YY)|_{\rm 4DCHM}}{\Gamma(H \to Y'Y')|_{\rm SM} \times \Gamma(H \to YY)|_{\rm SM}} \frac{\Gamma_{\rm tot}(H)|_{\rm SM}}{\Gamma_{\rm tot}(H)|_{\rm 4DCHM}}$$

$Y'Y'$ denote incoming particles for the Higgs production

- cast R s in terms of κ s

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

for $YY = \gamma\gamma, WW, ZZ$ take $Y'Y' = gg$

for $YY = b\bar{b}$ take $Y'Y' = VV$

- introduce reduced couplings

LHC HXSWG, 1209.0040

$$\kappa_{b,g,\gamma,V}^2 = \frac{\Gamma(H \to b\bar{b}, gg, \gamma\gamma, VV)|_{\rm 4DCHM}}{\Gamma(H \to b\bar{b}, gg, \gamma\gamma, VV)|_{\rm SM}}$$

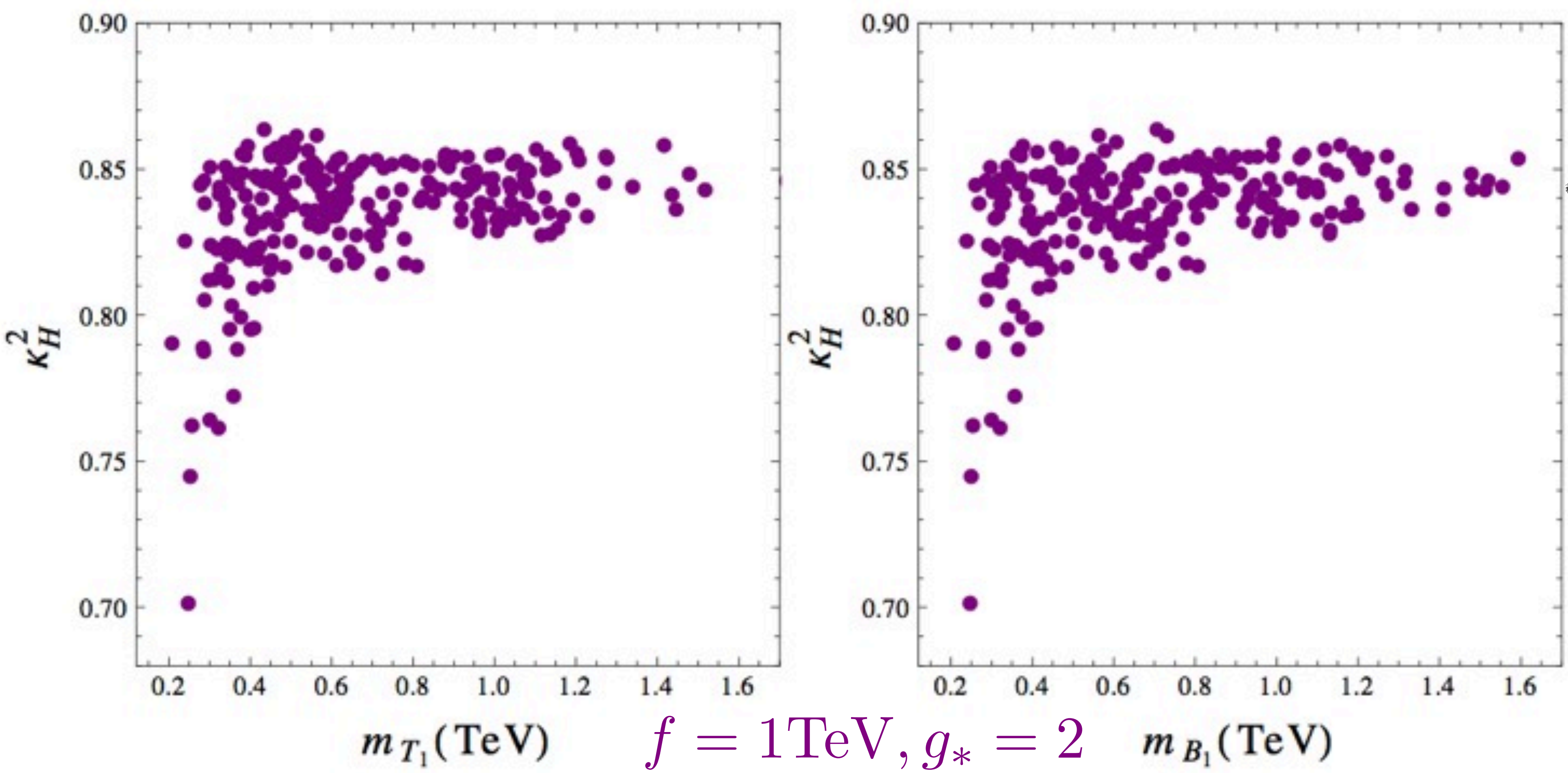
$VV \to WW, ZZ$

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

- LHC exps perform fits to the κ s to test BSM physics with the assumption $\kappa_H^2 = 1$ not valid in the 4DCHM

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

- The total width is dominated by the bb decay channel
- ~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



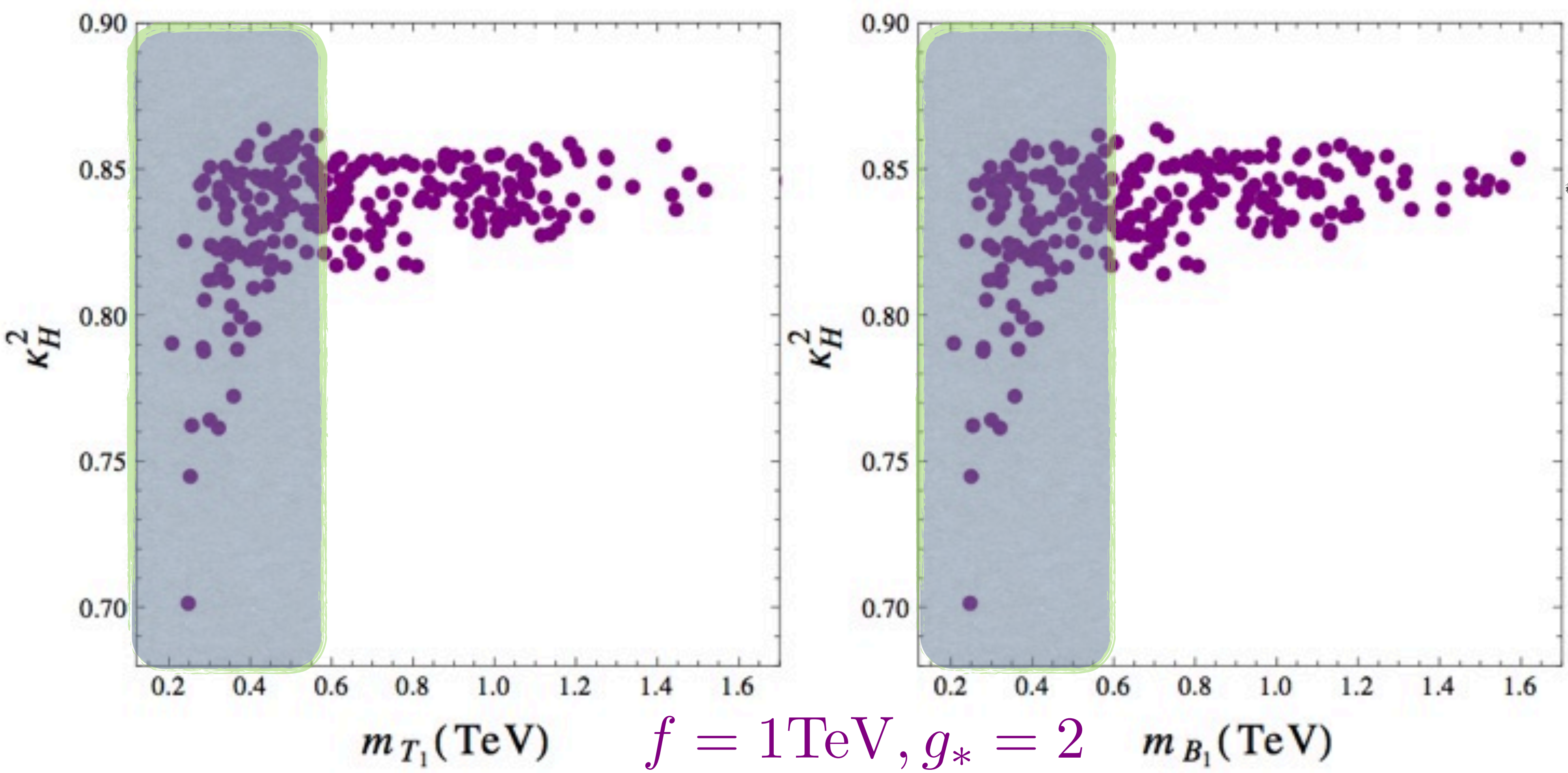
in agreement with $c^2 = \frac{(1-2\xi)^2}{1-\xi}$

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

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

- The total width is dominated by the bb decay channel
- ~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

Look at direct search exclusion



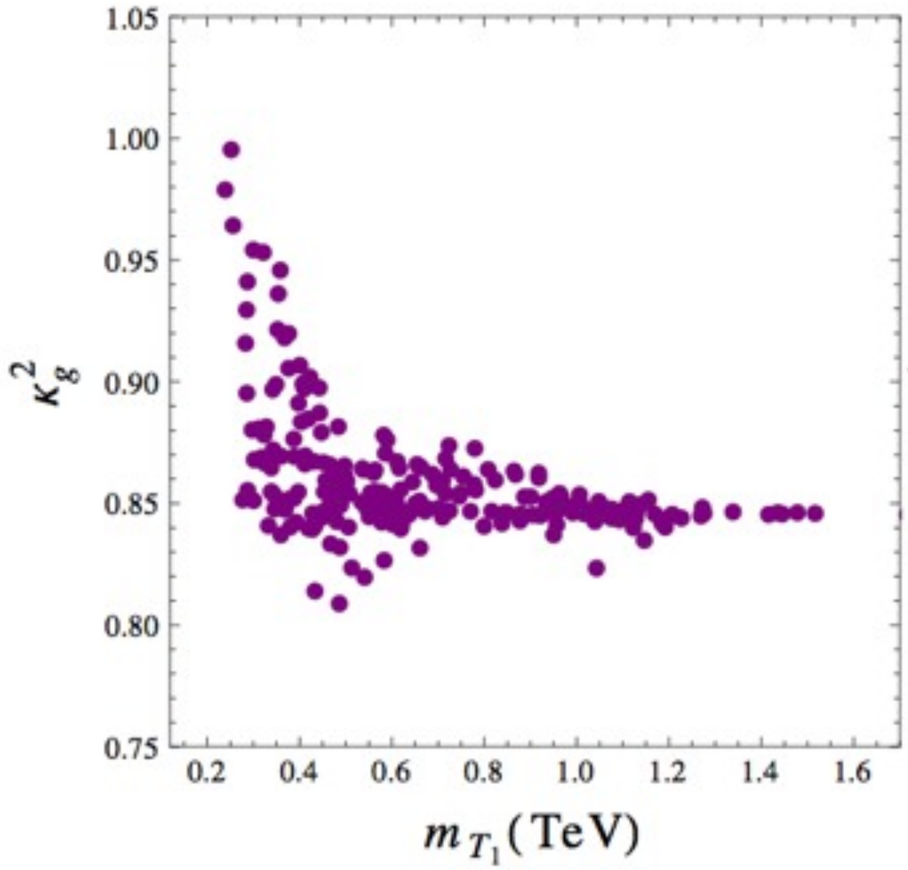
in agreement with $c^2 = \dfrac{(1-2\xi)^2}{1-\xi}$

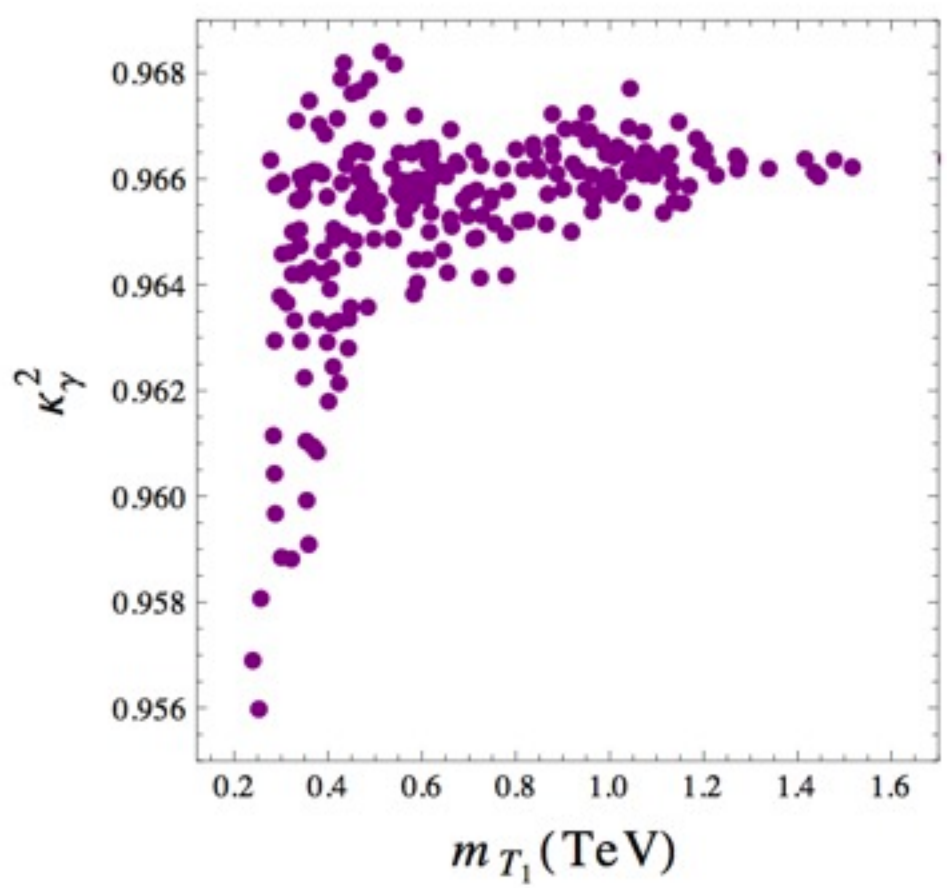
$$\xi = \frac{v^2}{f^2}$$

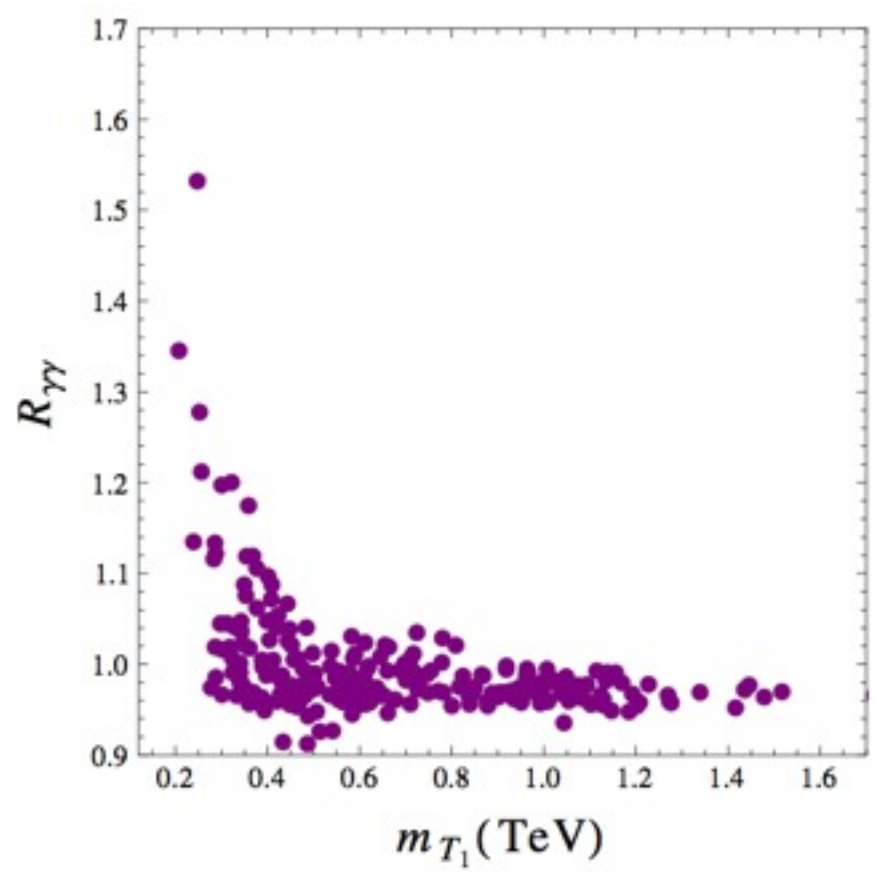
Unfolding the contributions to:

$$R_{\gamma\gamma} = \frac{\kappa_g^2 \kappa_\gamma^2}{\kappa_H^2}$$

- 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



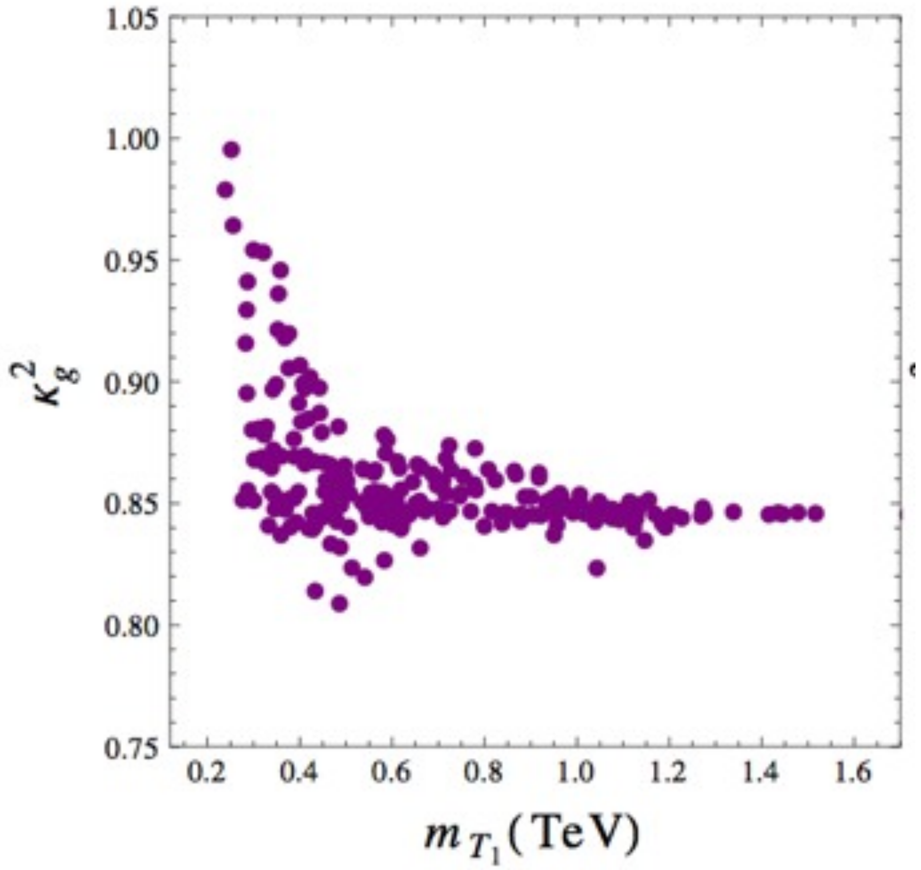




These contrasting effects lead to:

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

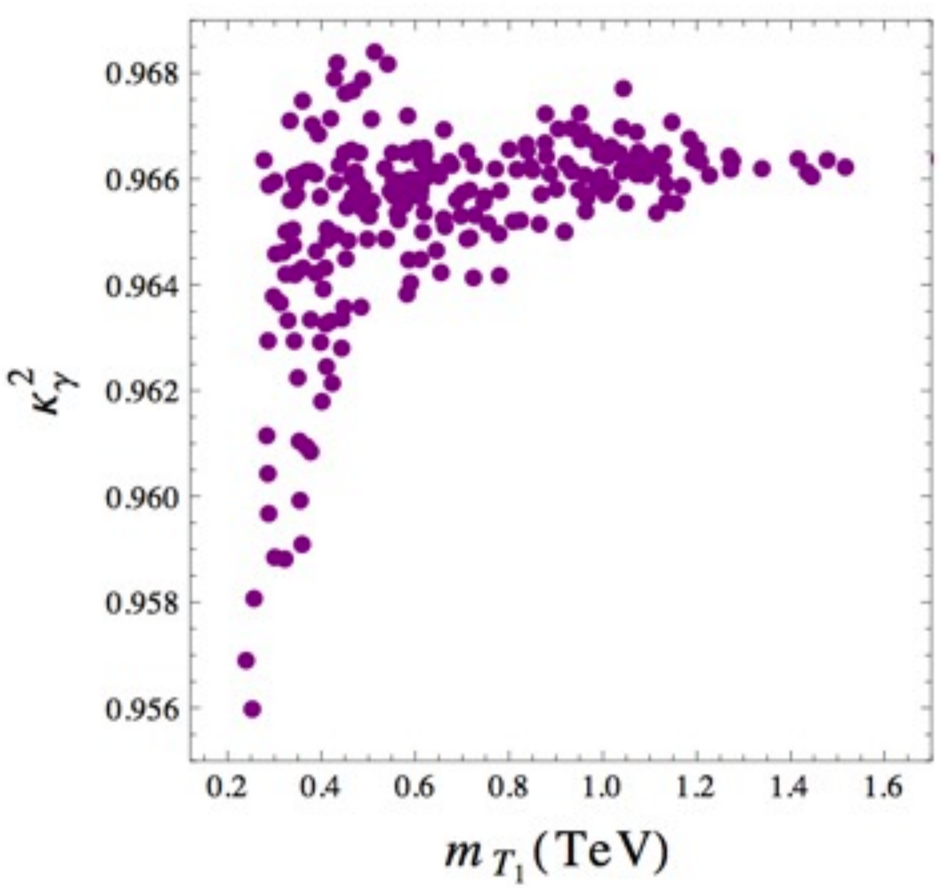
$$f = 1\mathrm{TeV}, g_* = 2$$

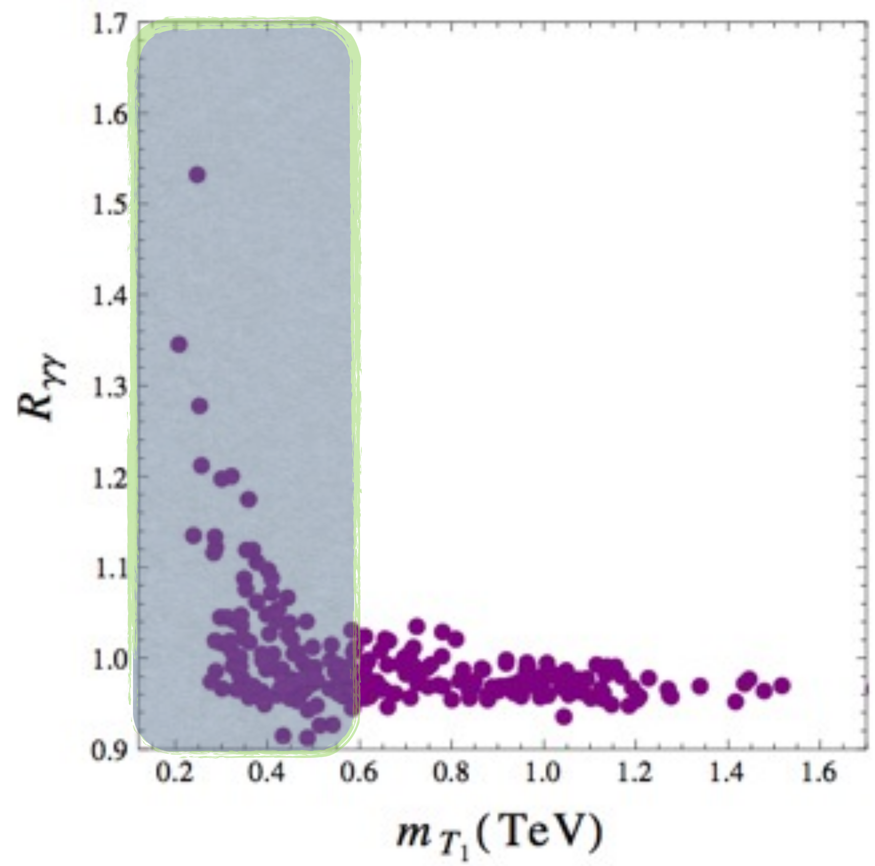


Unfolding the contributions to:

$$R_{\gamma\gamma} = \frac{\kappa_g^2 \kappa_\gamma^2}{\kappa_H^2}$$

- 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





These contrasting effects lead to:

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

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

LHC measurements from ATLAS and CMS

	ATLAS	CMS
$R_{\gamma\gamma}$	1.8 ± 0.4	$1.564^{+0.460}_{-0.419}$
R_{ZZ}	1.0 ± 0.4	$0.807^{+0.349}_{-0.280}$
R_{WW}	1.5 ± 0.6	$0.699^{+0.245}_{-0.232}$
R_{bb}	-0.4 ± 1.0	$1.075^{+0.593}_{-0.566}$

pre-Moriond

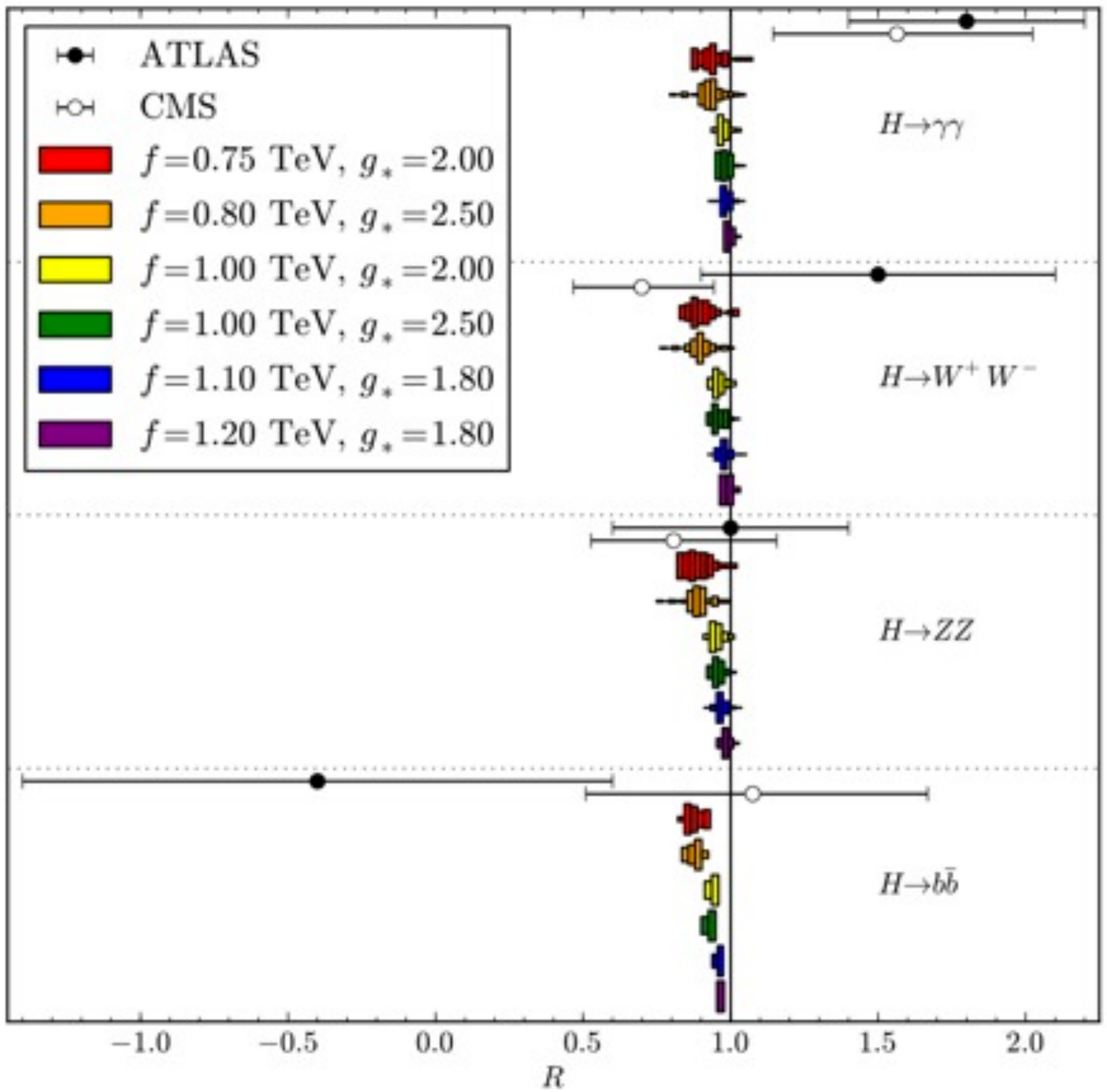
ATLAS-CONF-2012-170
https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12045TWiki

	ATLAS	CMS
$R_{\gamma\gamma}$	1.6 ± 0.3	$0.78^{+0.28}_{-0.26}$
R_{ZZ}	1.5 ± 0.4	$0.91^{+0.30}_{-0.24}$
R_{WW}	1.4 ± 0.6	$0.76^{+0.21}_{-0.21}$

post-Moriond

ATLAS-CONF-2013-014
https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13001(2,3)TWiki

- Compare 4DCHM for all (f, g_*) benchmarks to data
- Points compliant with t', b', $T_{5/3}$ direct searches



Pre-Moriond

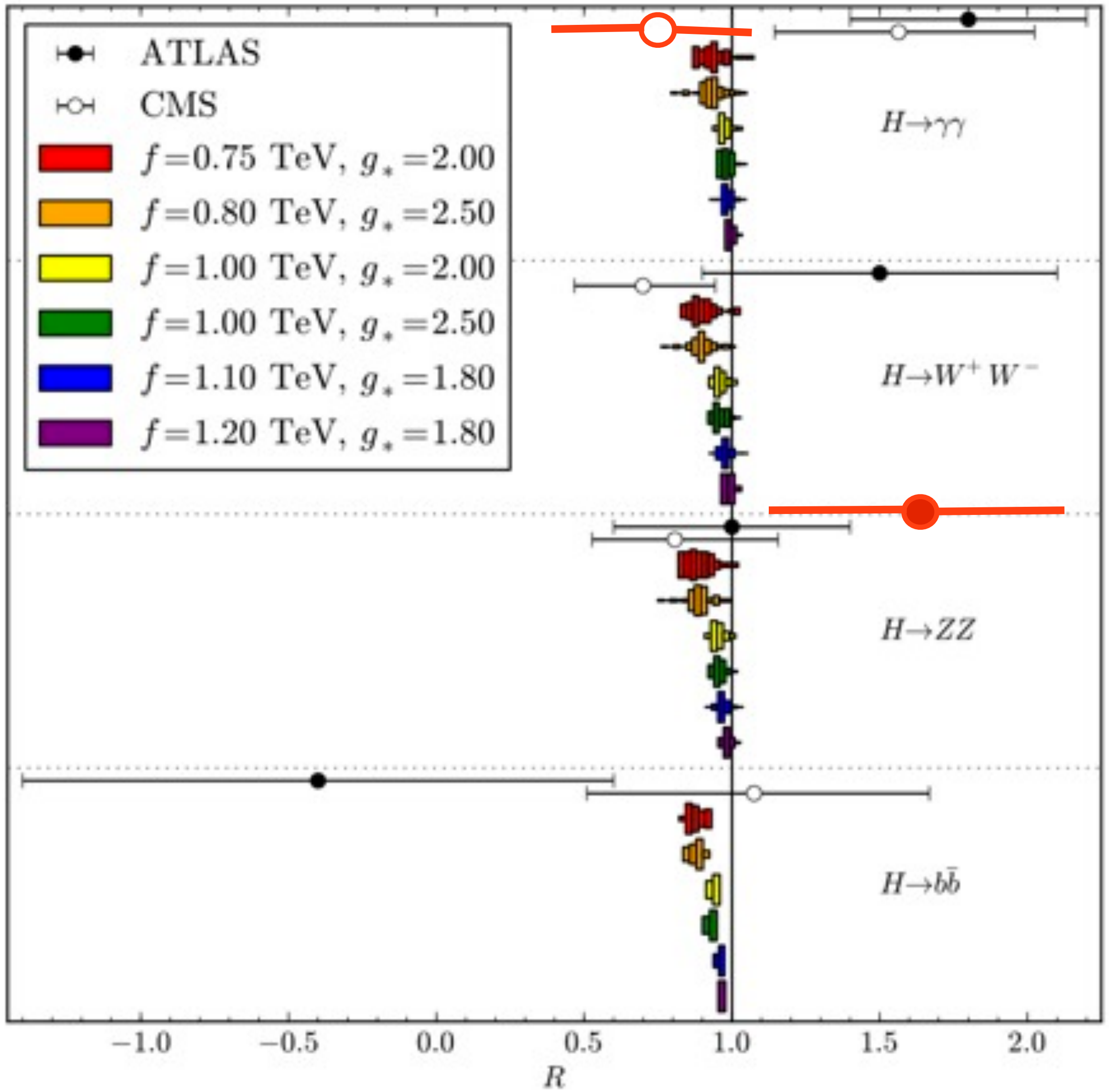
Barducci,Belyaev,Brown,DC,Moretti,Pruna,1302.2371

for each benchmark the results are shown as a series of normalized histograms - **they vary very little!**

as the scale f is increased the model gets more constrained

also shown the CMS&ATLAS exp. measurements with 68%CL error bars

- Compare 4DCHM for all (f, g_*) benchmarks to data
- Points compliant with t', b', $T_{5/3}$ direct searches



for each benchmark the results are shown as a series of normalized histograms - **they vary very little!**

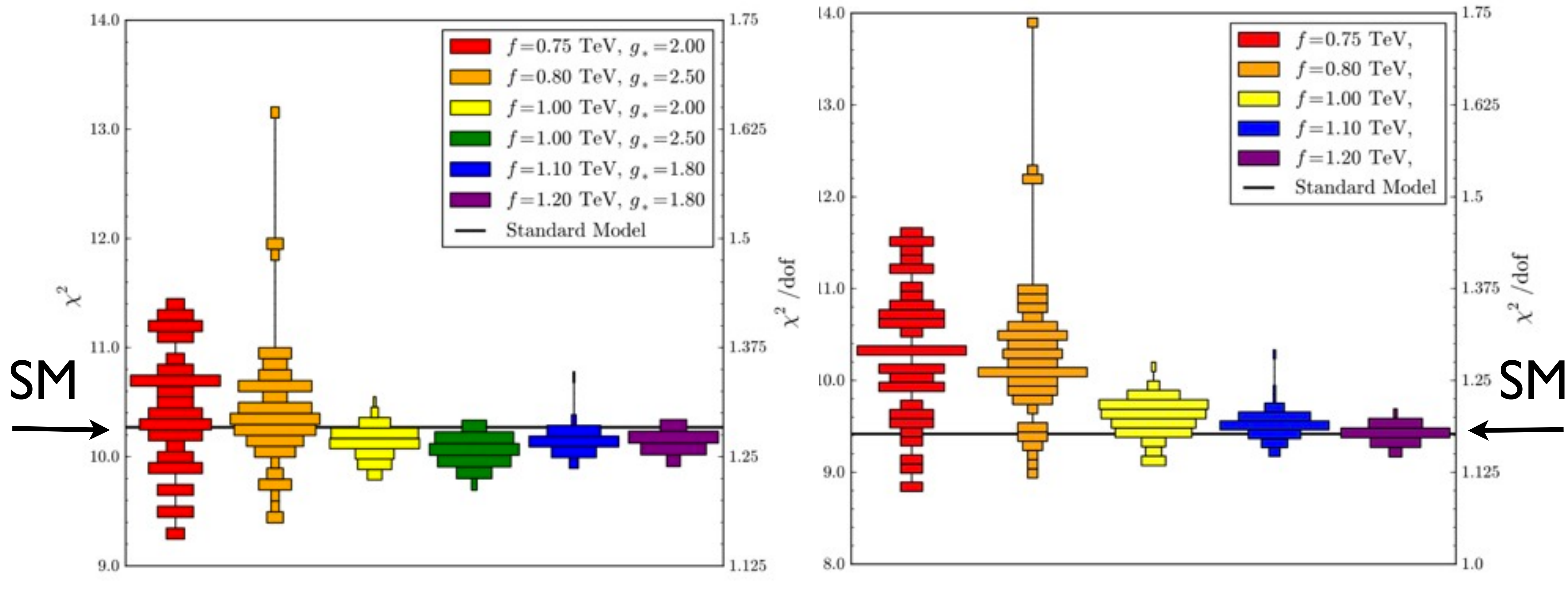
as the scale f is increased the model gets more constrained

also shown the CMS&ATLAS exp. measurements with 68%CL error bars

Pre-Moriond Post-Moriond

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

- performing χ^2: the 4DCHM can fit as well as the SM
- only points compliant with direct searches are shown



Pre-Moriond

Post-Moriond

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

Drell-Yan signals from 4DCHM at the LHC

Barducci,Belyaev,DC,Moretti,Pruna, 1210.2927

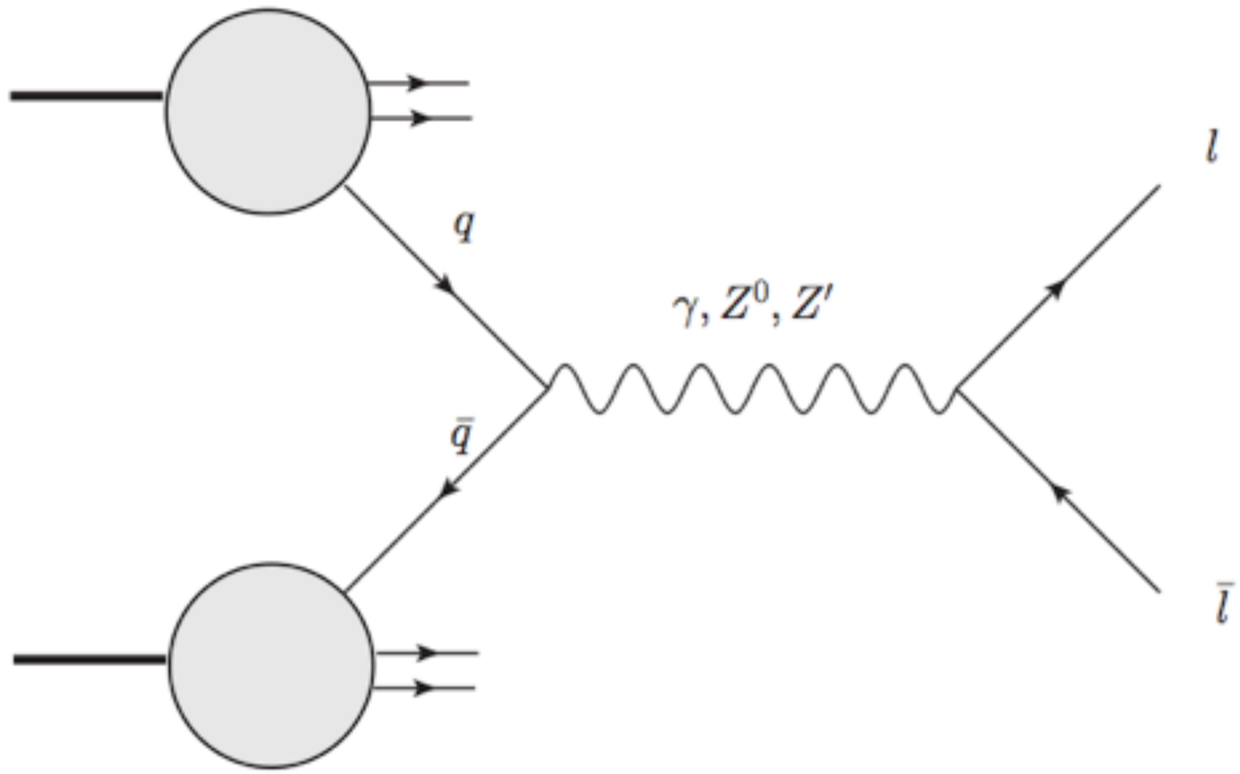
Quarks can annihilate also in Z' (and W')

tree-level processes

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

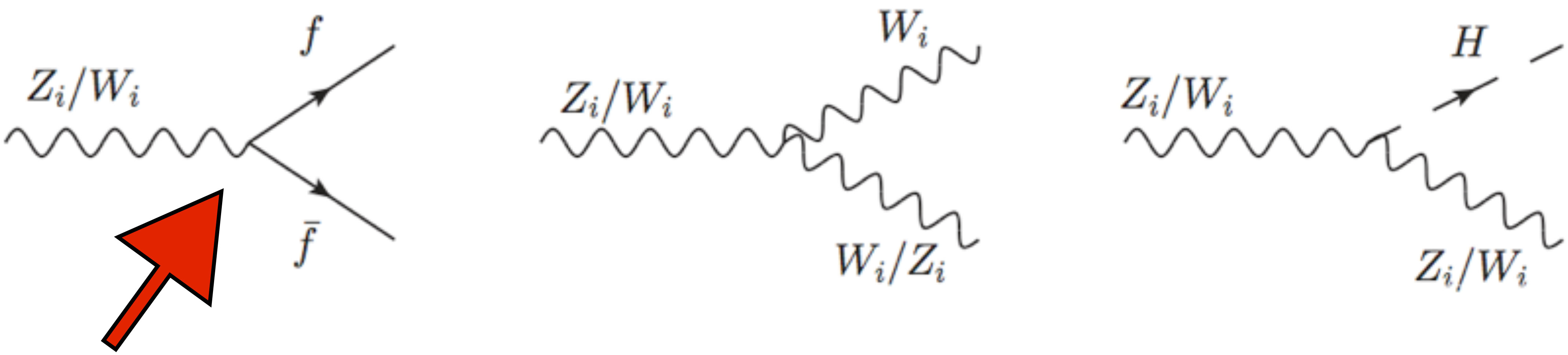
$pp \to l^+ \nu_l + c.c$ (CC)

$l = e, \mu$



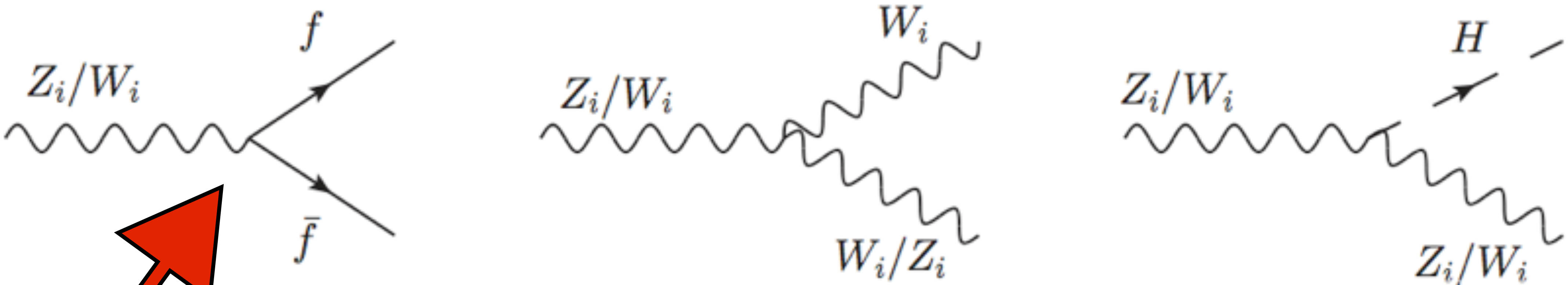
- DY allow us to investigate new gauge boson resonances
- Z' may be discovered as a peak in the dilepton invariant mass spectrum $Z' = Z_2, Z_3, Z_5$
- W' may be discovered as a peak in the dilepton missing-energy transverse mass spectrum $W' = W_2, W_3$

Widths of Z' and W'



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

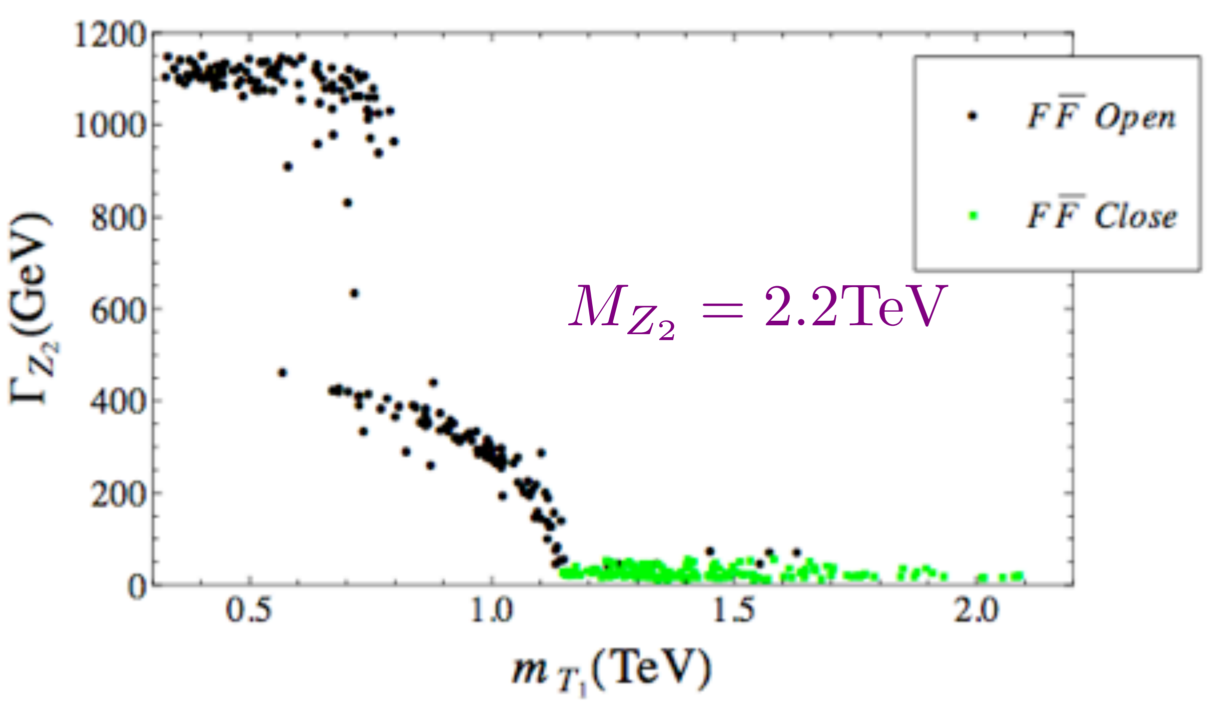
Widths of Z' and W'

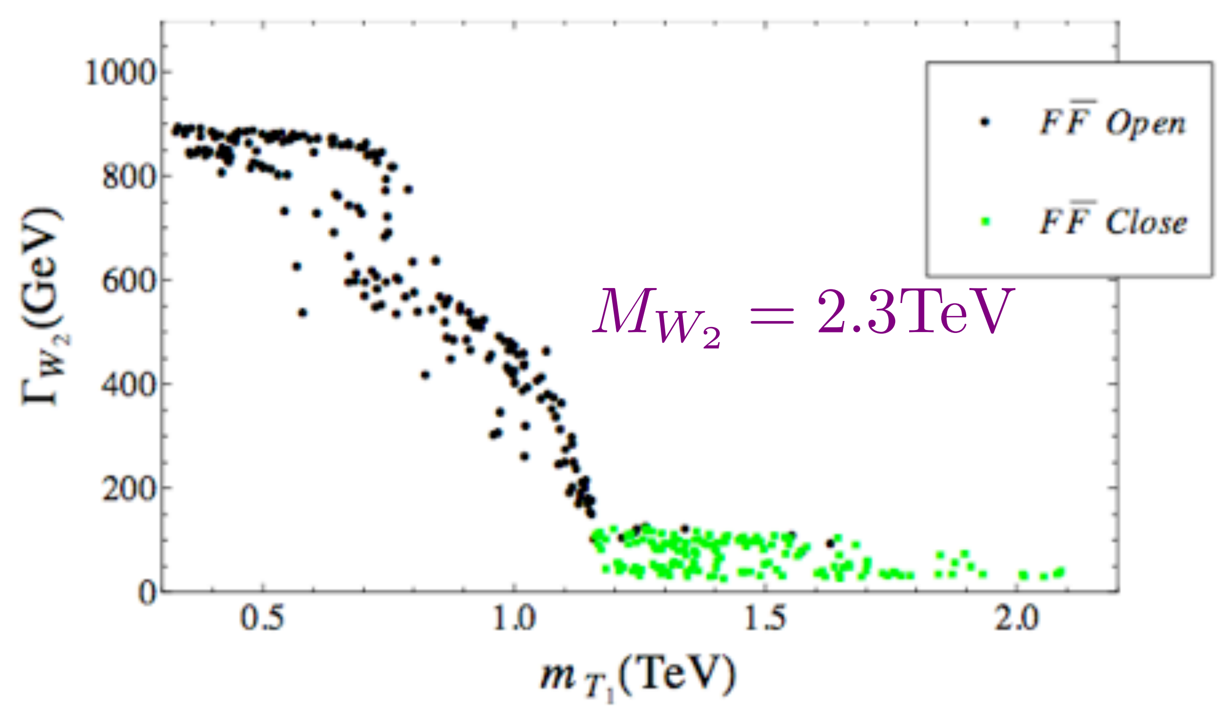


large number of fermions strongly coupled to W'and Z'

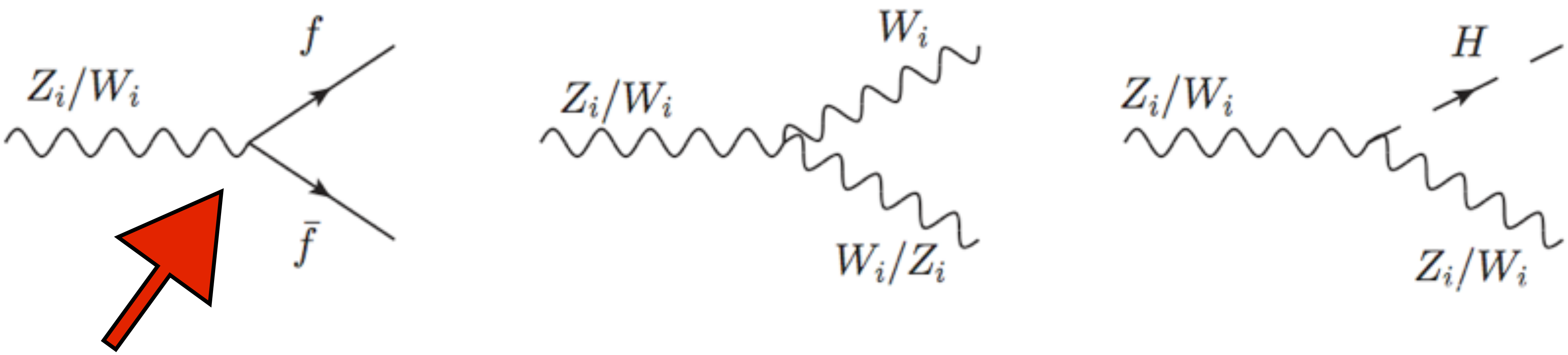
Two possible extreme situations

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





Widths of Z' and W'

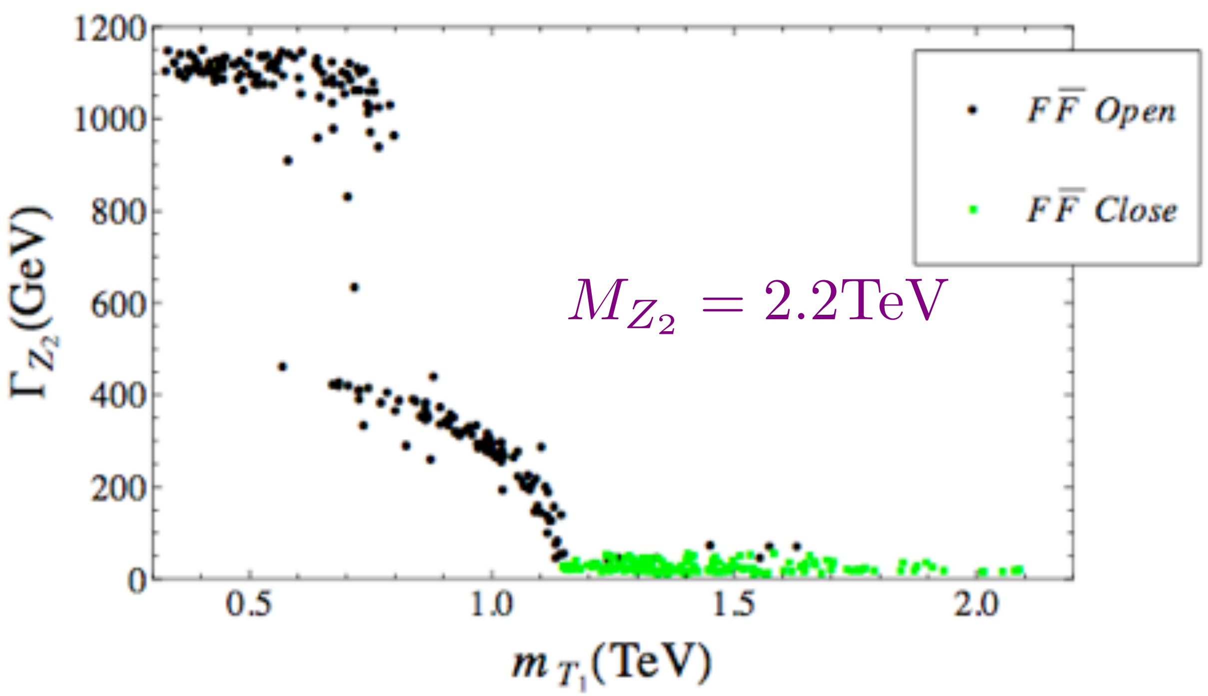


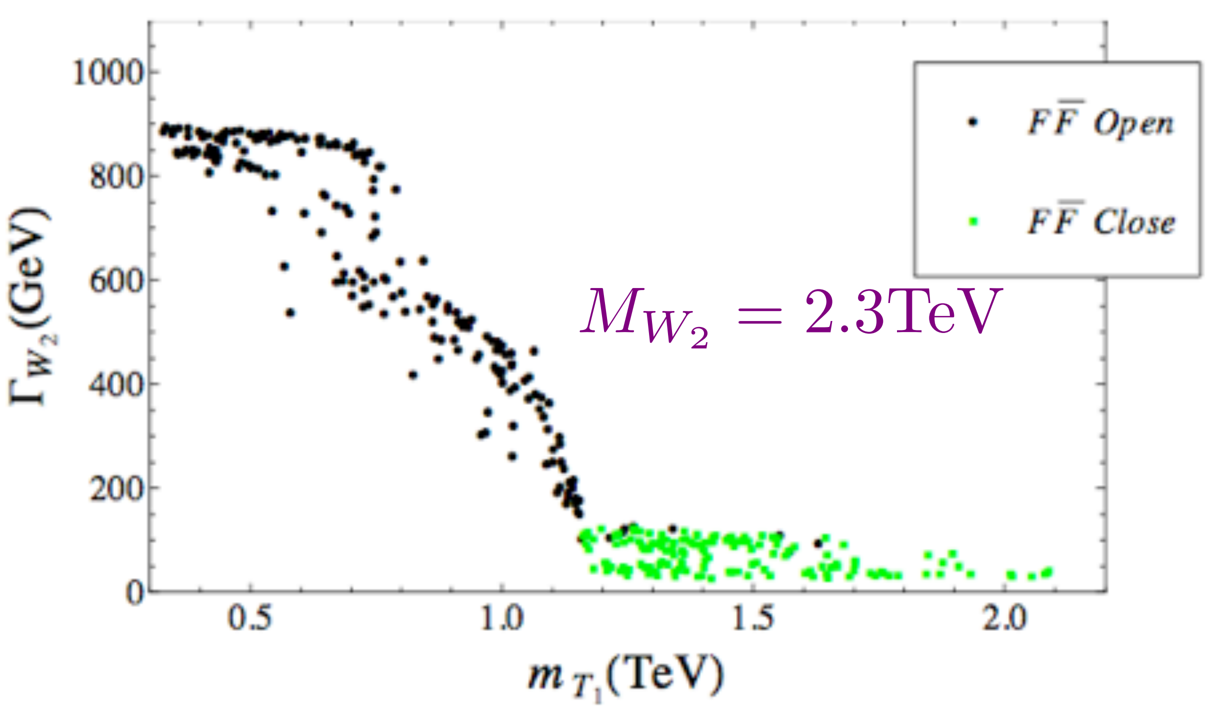
large number of fermions strongly coupled to W'and Z'

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

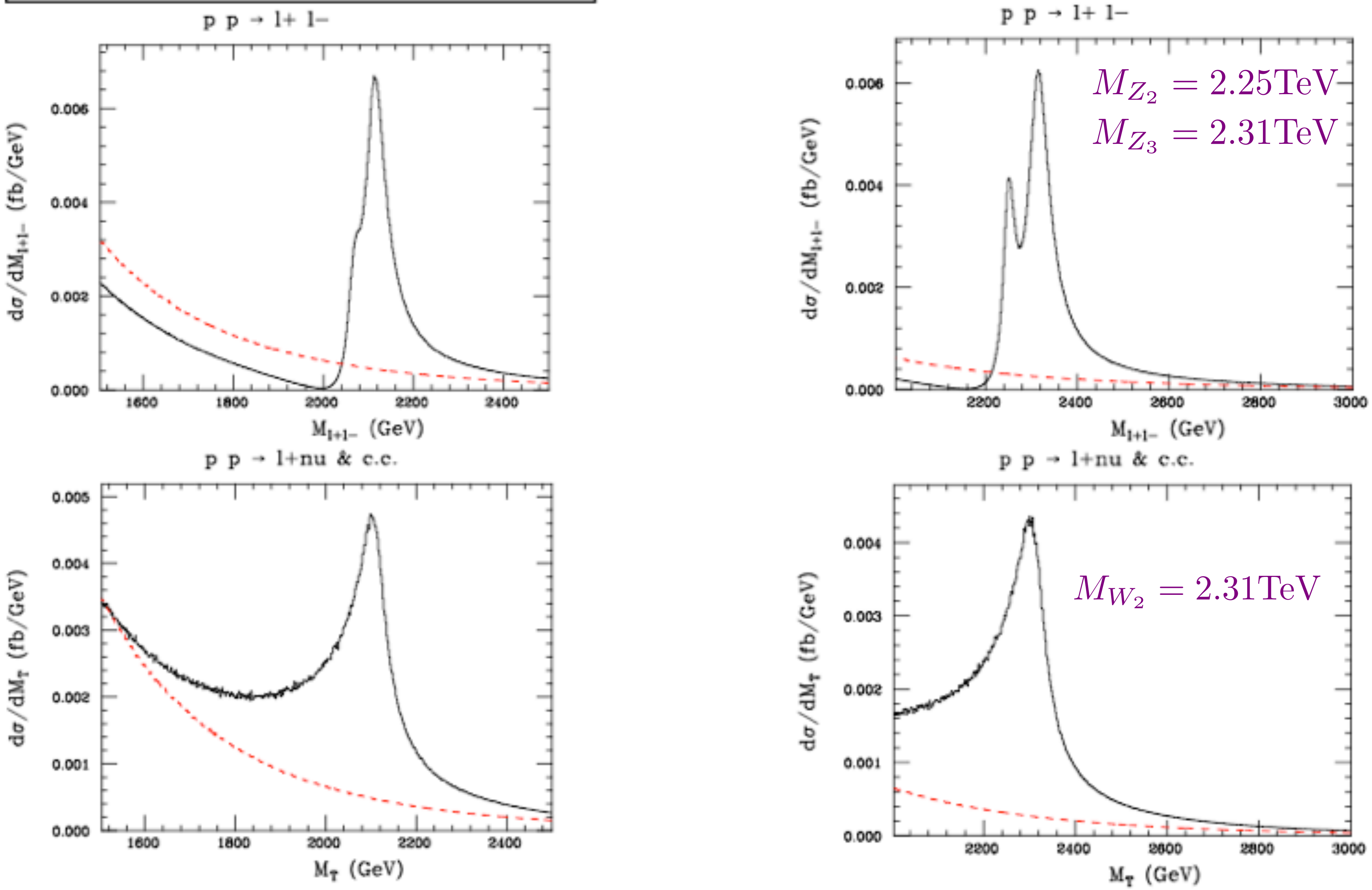




- The LanHEP/CalcHEP/Mathematica implementation give us a powerful tool for an automatized analysis of the 4DCHM

Invariant/Transverse mass distributions

$f = 1\ TeV\ g_* = 2\ TeV$ | $f = 1.2\ TeV\ g_* = 1.8\ TeV$

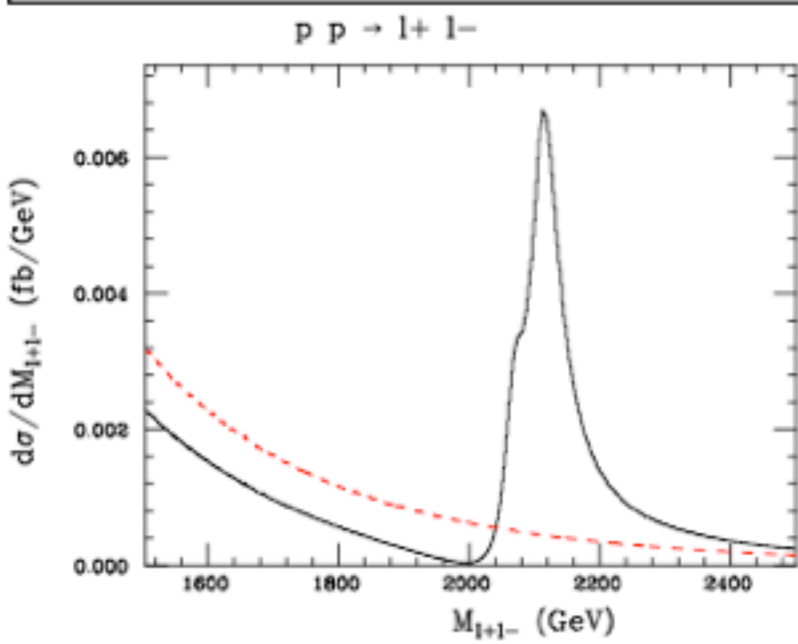


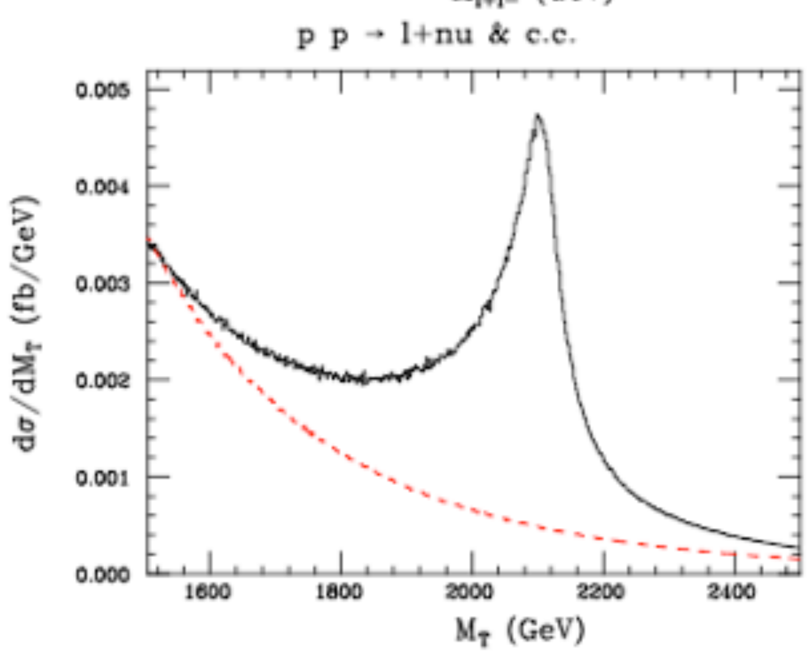
Heavier resonances inaccessible at the 14 TeV LHC even with 300 fb-1

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

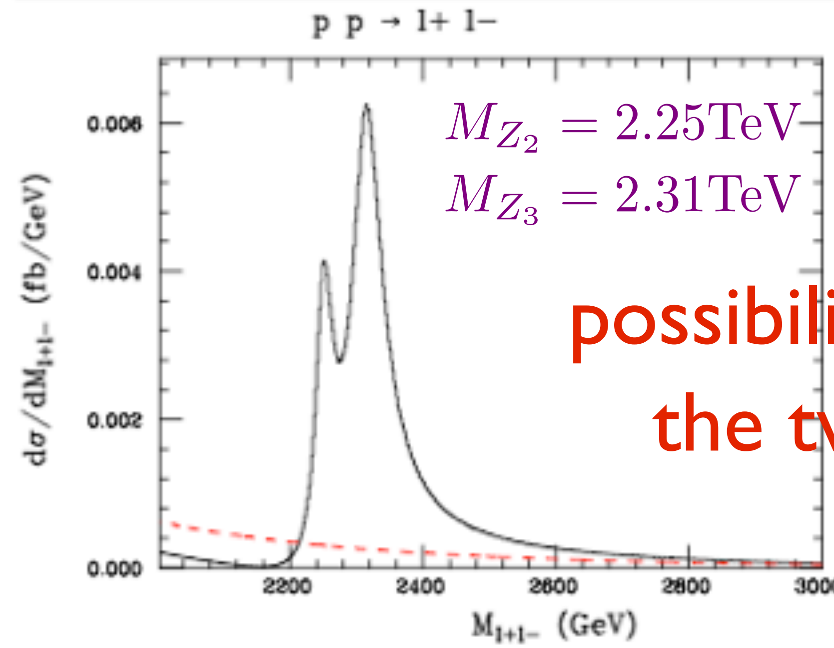
Invariant/Transverse mass distributions

$f = 1\ TeV\ g_* = 2\ TeV$

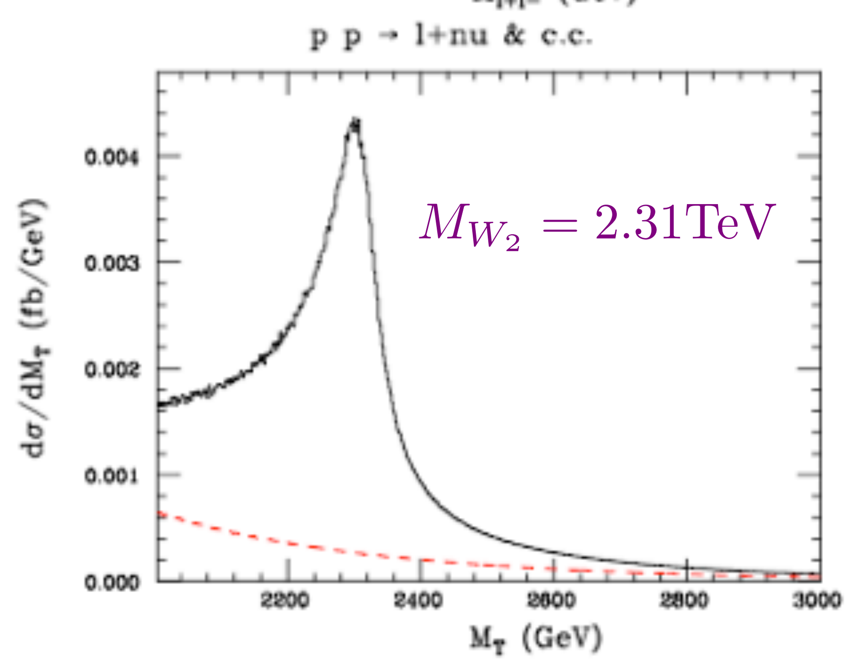




$f = 1.2\ TeV\ g_* = 1.8\ TeV$



possibility to separate the two Z' peaks



Heavier resonances inaccessible at the 14 TeV LHC even with 300 fb-1

• **Mass correlation in the 4DCHM**

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

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

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

• **Complementarity** between **cross sections** and **AFB distributions** (limited to lightest resonances: Z_2, Z_3, W_2)

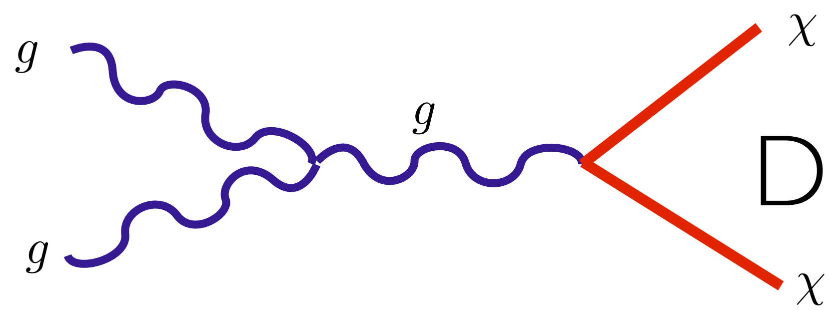
• Analyzed the features of the **Z' and W' line shapes** in relation with masses of heavy fermions

• **Only 14 TeV stage** of LHC has the potential to probe the model assuming standard and Super-LHC luminosities

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

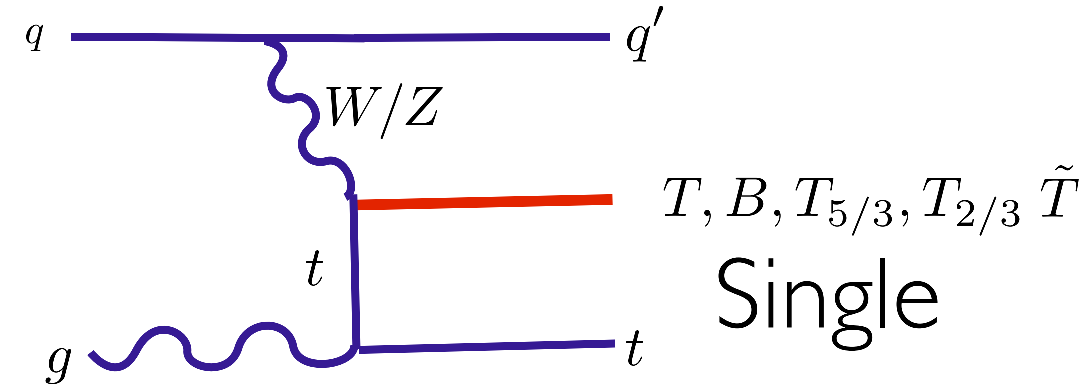
- Production:

Contino, Servant (2008)



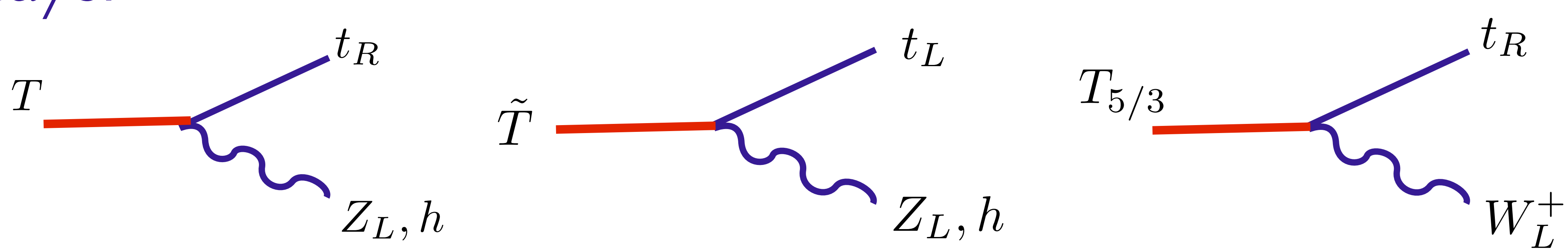
Double

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



Single

- Decays:



Multi-lepton signatures

Work in progress: implement the direct search results on the 4DCHM extra-fermions and translate into bounds on the model parameter space

CONCLUSIONS

- The Higgs as Nambu-Goldstone boson is a compelling possibility for stabilizing the electro-weak scale

- Realistic scenarios can be build and the relevant features of CHMs can be reproduced from a 4D point of view. First resonance is sufficient for theory & LHC

- 4DCHM is a simple and calculable framework encoding all the relevant ingredients. Implemented in numerical tools

- 4DCHM can fit the LHC data pointing to the discovery of a 125-Higgs as well as the SM

- New resonances must be present nearby with a specific pattern. Light Higgs requires light fermionic partners

Let's wait for LHC14

BACKUP SLIDES

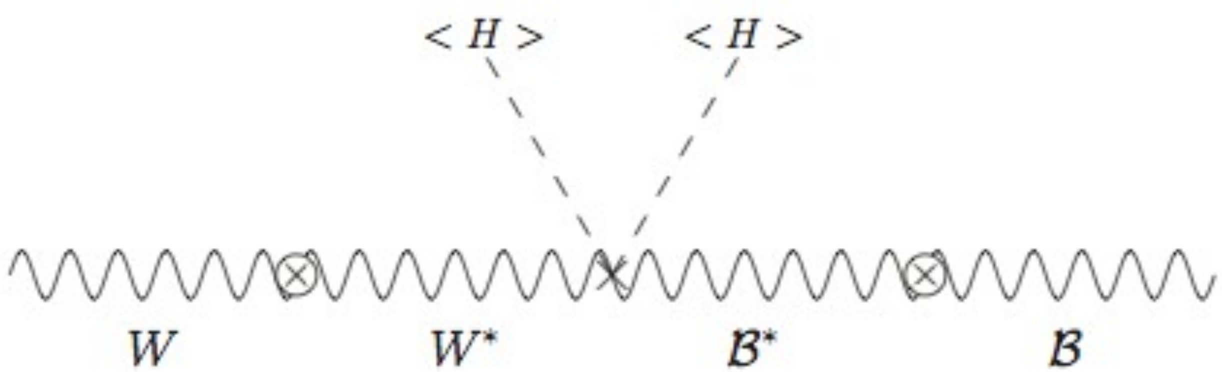
Electro-Weak Precision Tests

Typical modifications

$$\delta g_{SM} = \kappa \frac{v^2}{m_\rho^2}$$

Tree-level:

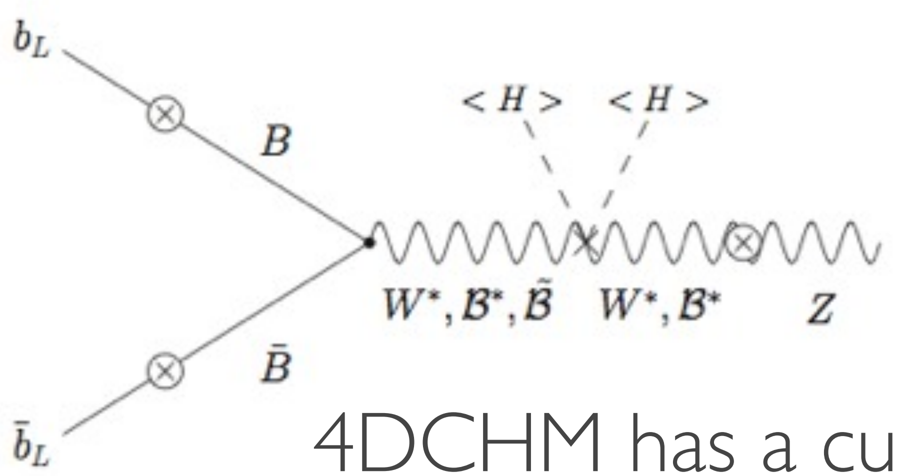
S-parameter: $\frac{S}{16\pi v^2} \left(H^\dagger \tau^a H\right) W^a_{\mu\nu} B^{\mu\nu}$



$$S \sim 4\pi v^2 \left(\frac{1}{m_\rho^2} + \frac{1}{m_{a_1}^2}\right)$$

$$S < 0.3 \longrightarrow m_\rho > 2-3\,\text{TeV}$$

Third generation Z-couplings:



$$\frac{\delta g_L}{g_L} \sim \epsilon_L^2 \frac{v^2}{m_\rho^2} \qquad \left.\frac{\delta g_{Lb}}{g_{Lb}}\right|_{max} \sim 10^{-3}$$

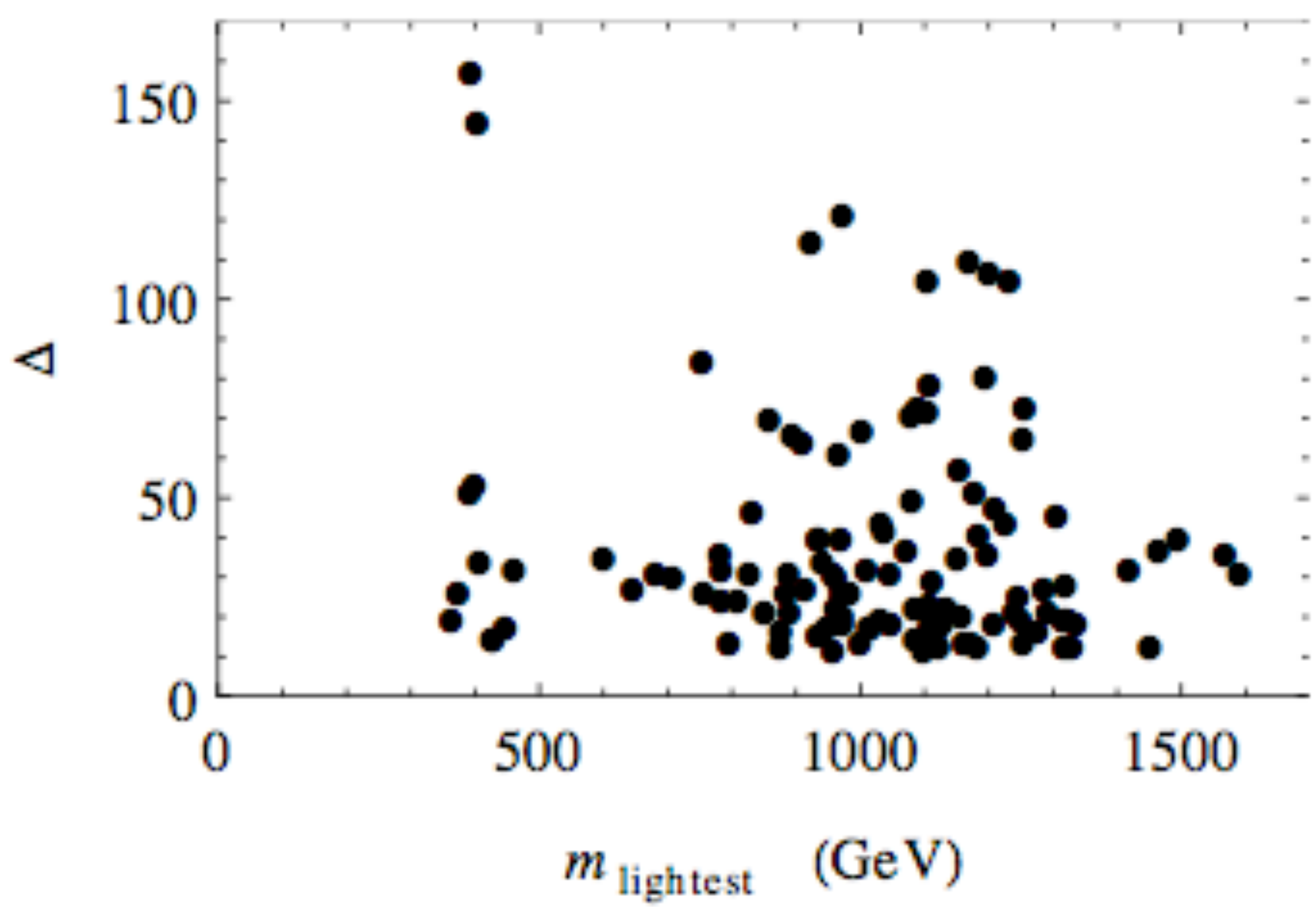
4DCHM has a custodial symmetry preventing large corrections

Possible problems with T-parameter at 1-loop

Tuning:

Panico, MR, Tesi, Wulzer '12

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

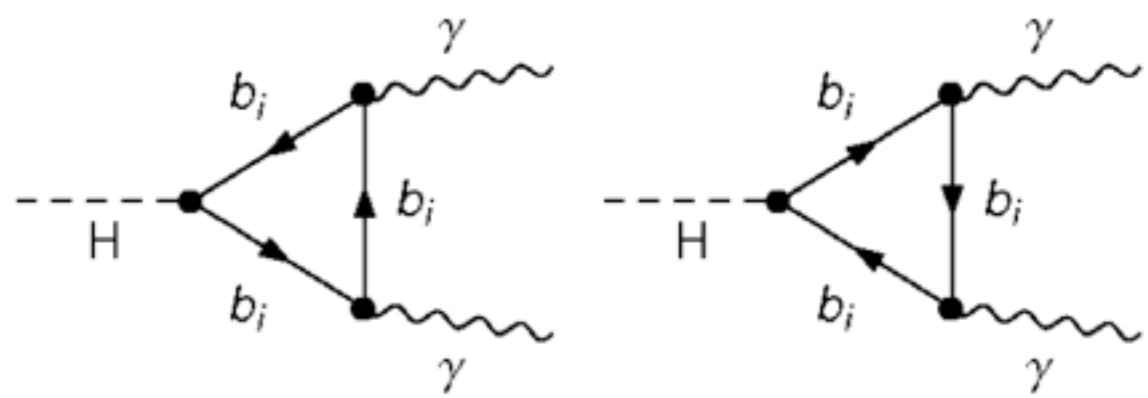


$$f = 800\,\mathrm{GeV}$$

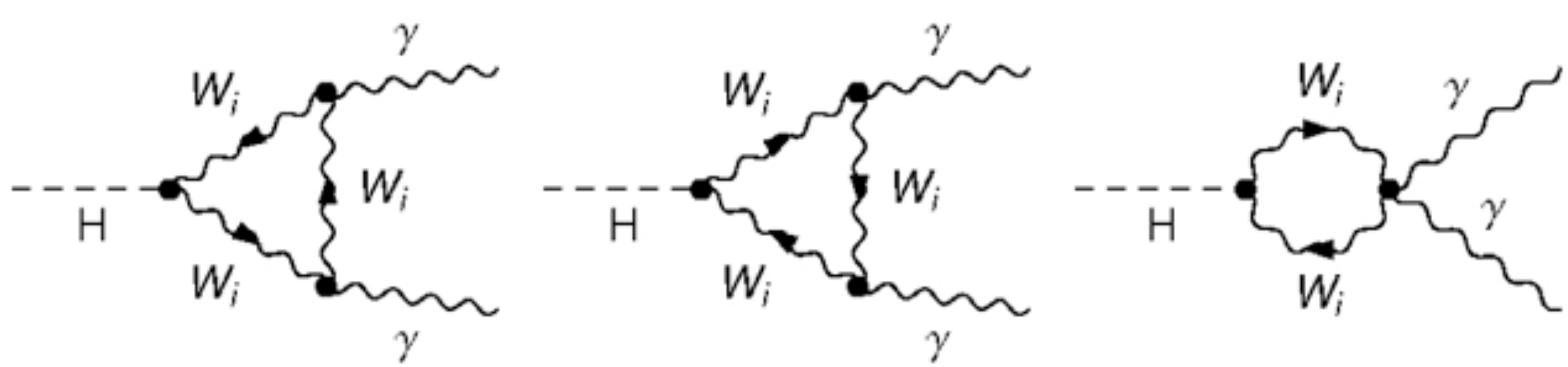
$$\Delta_{avg} \sim 30$$

$H \to \gamma\gamma$

- Loop Diagrams involving extra fermions and gauge bosons



$H \to \gamma\gamma$ induced by fermionic loop

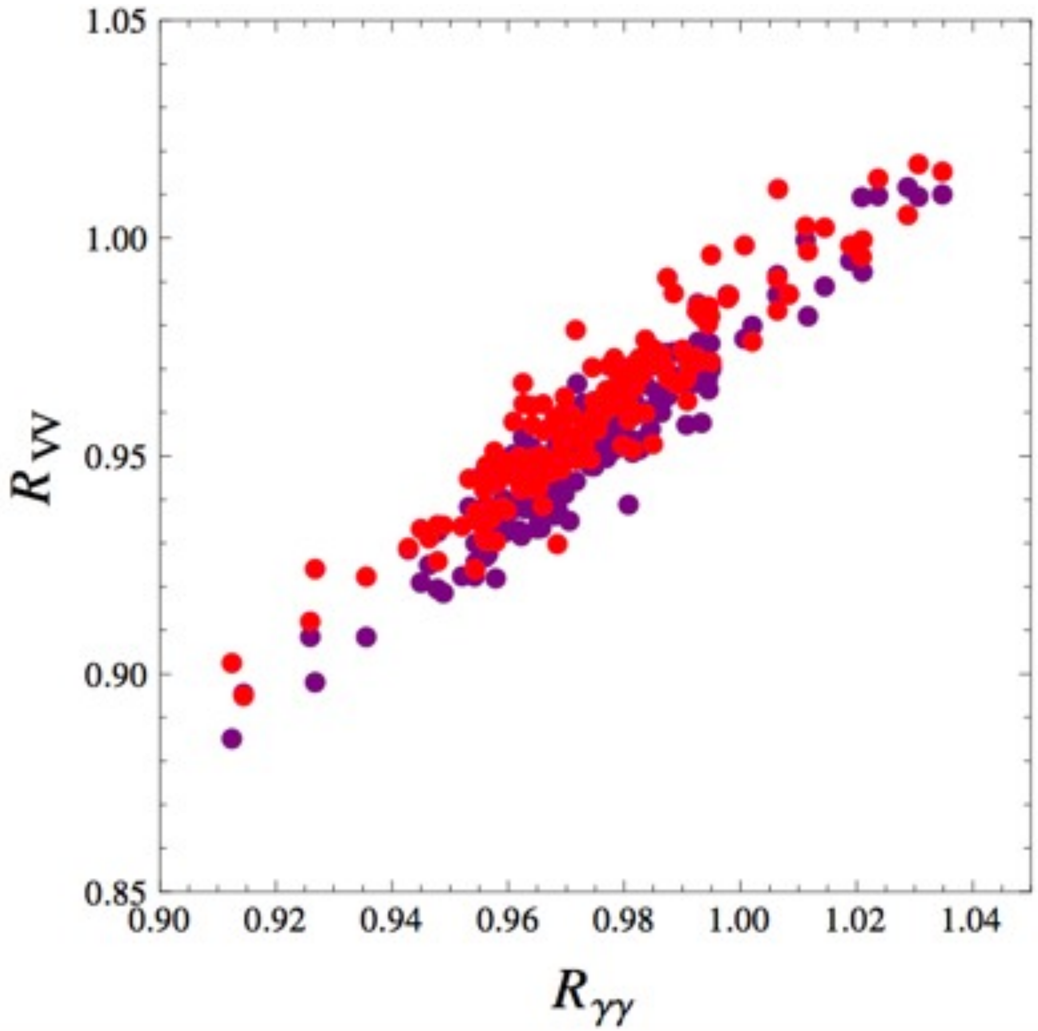


$H \to \gamma\gamma$ induced by charged vector loop

NGB symmetry protects the couplings, no large deviations expected

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

- the production mode is gg fusion
- all points compliant with direct searches for t', b' and $T_{5/3}$



VV=WW, ZZ

consider (as CMS/ATLAS)

$ZZ^* \to 4l,\ WW^* \to 2l2\nu$

with BR's in 4DCHM

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

Points prefer to stay below 1 (some points above).
Strong correlation suggests common cause for effect

Z' and W' decay channels

Z' main branching ratios

SMALL WIDTH

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

LARGE WIDTH

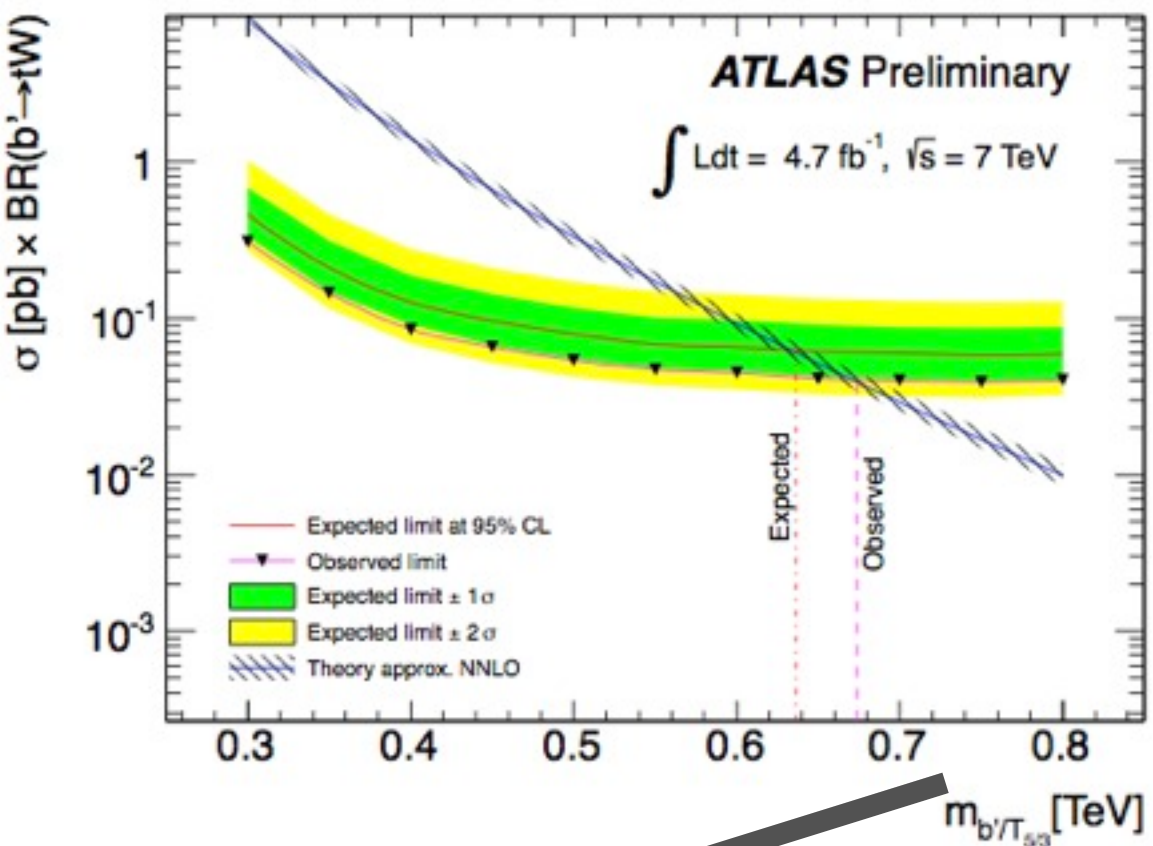
- $t'\bar{t}', b'\bar{b}' \mathcal{O}(30\%)$
- $T'\bar{T}', B'\bar{B}'$ $\mathcal{O}(10\%)$
- $t\bar{t}, b\bar{b}$ $\mathcal{O}(1\%)$

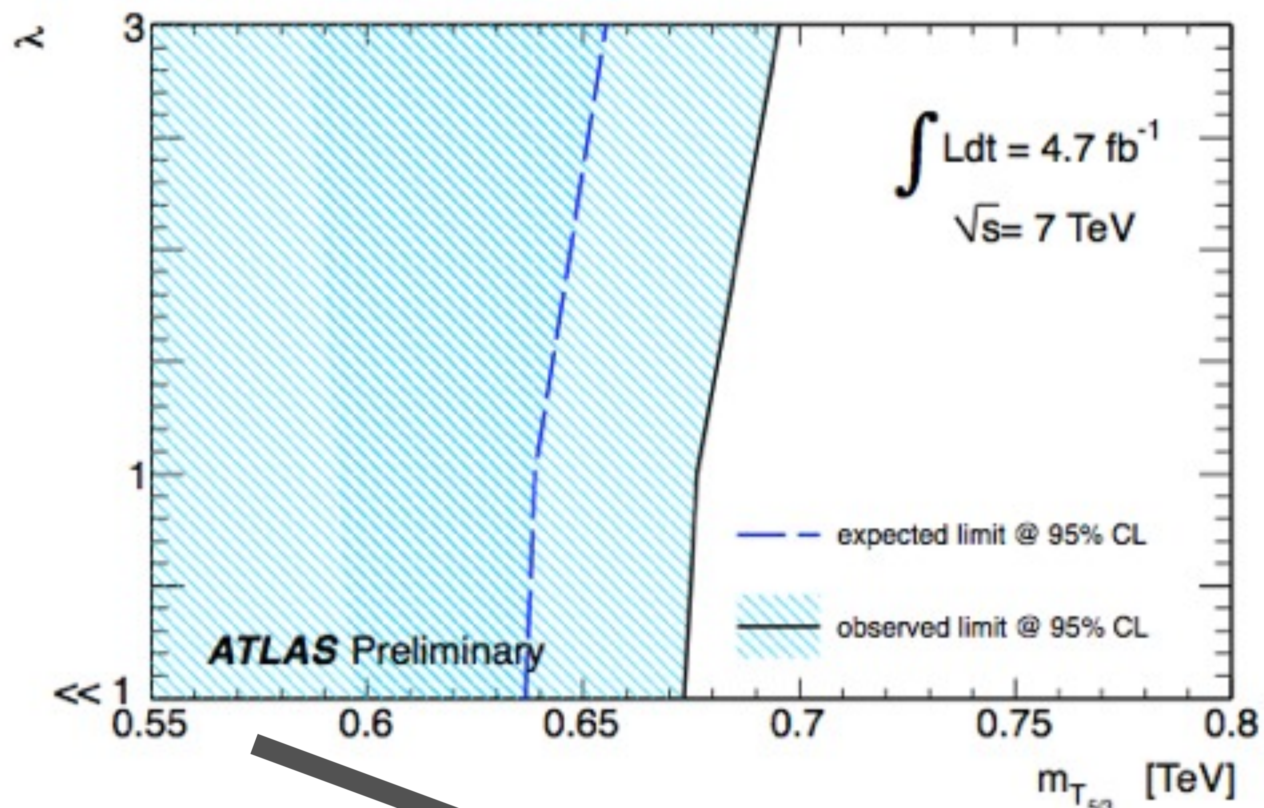
Analogous for the W'

mandatory for leptonic DY processes

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

ATLAS-CONF-2012-130





double production

double+single production