Composite Higgs Phenomenology at the LHC and Future Colliders

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Based on:
DC, Redi,Tesi, JHEP 1204,042 (2012); Barducci et al, JHEP 1304, 152 (2013);
Barducci et al, JHEP 1309,047 (2013); Barducci, DC, Moretti, Pruna, JHEP 1402,005 (2014);
Barducci, DC, Moretti, Pruna, in preparation (2015)

HPNP2015 The 2nd Toyama International Workshop on "Higgs as a Probe of New Physics 2015"

11.–15. February 2015, University of Toyama, Japan

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

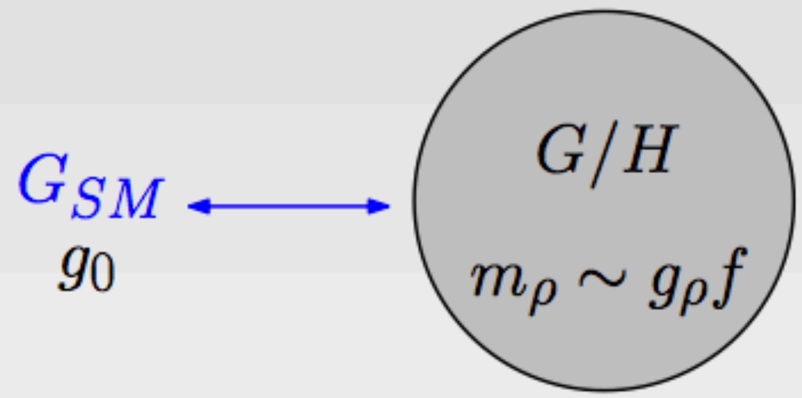
- ☑ Extra spin-1 and spin-1/2 resonances are naturally present in CHMs

- ☑ Minimal effective description: the 4-Dimensional Composite Higgs Model (4DCHM)

- ☑ Signatures at the LHC: scalar sector, extra resonances

- ☑ Phenomenology at future e+e- colliders: great potential on Higgs and top couplings (test of partial compositeness)

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

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

Composite Higgs Model

From now on, composite=pseudo-Goldstone

How to construct a *complete* Composite Higgs Model?

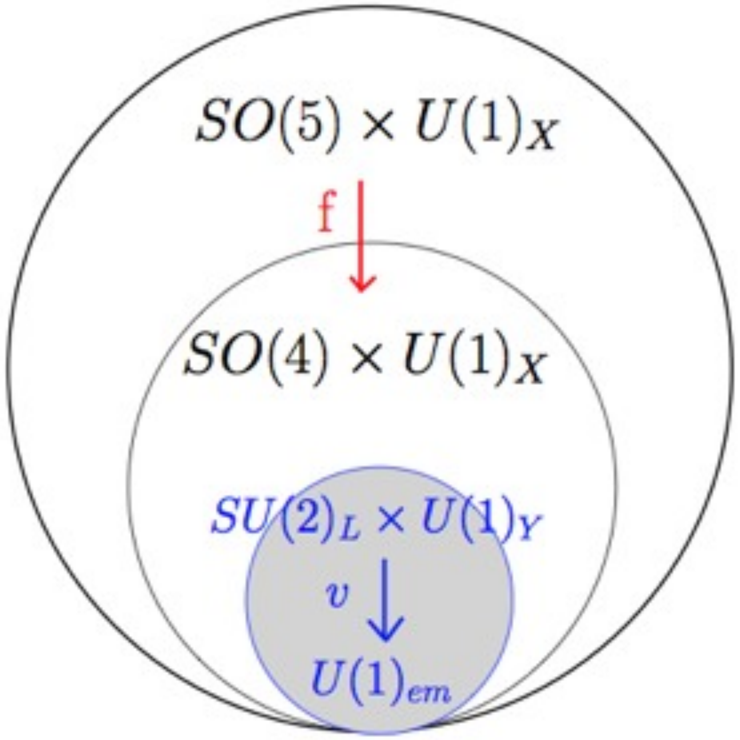
- $G/H \supset \mathbf{4}$, $G_{SM} \subset H$
- Computable Higgs mass: finite 1-loop effective potential
- Need for composite resonances!
- Not too large tuning $\quad \xi = \frac{v^2}{f^2}, \quad v = 246 \text{ GeV}, \quad f \sim 1 \text{ TeV}$

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
$(m_h \ll m_\rho)$



Explicit Models in 4D

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

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

4DCHM = Minimal 4D realization of MCHM5

DC, Redi, Tesi '11 — Agashe, Contino, Pomarol '04

Strong sector: resonances + Higgs bound state

Extra particle content:
- Spin 1 resonances → $5\ Z', 3\ W'$
- Spin 1/2 resonances →

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

minimum for UV finite Higgs potential

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

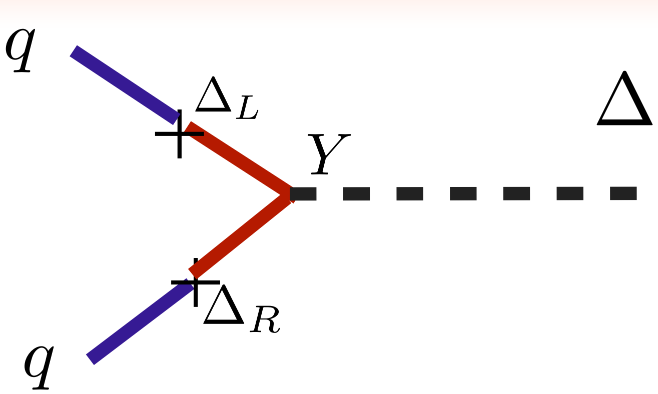
g_ρ= strong coupling

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

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

0 } v

Linear elementary-composite couplings (partial compositeness)



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

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

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

SM hierarchies are generated by the mixings:
light quarks elementary, b and t partially composite

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

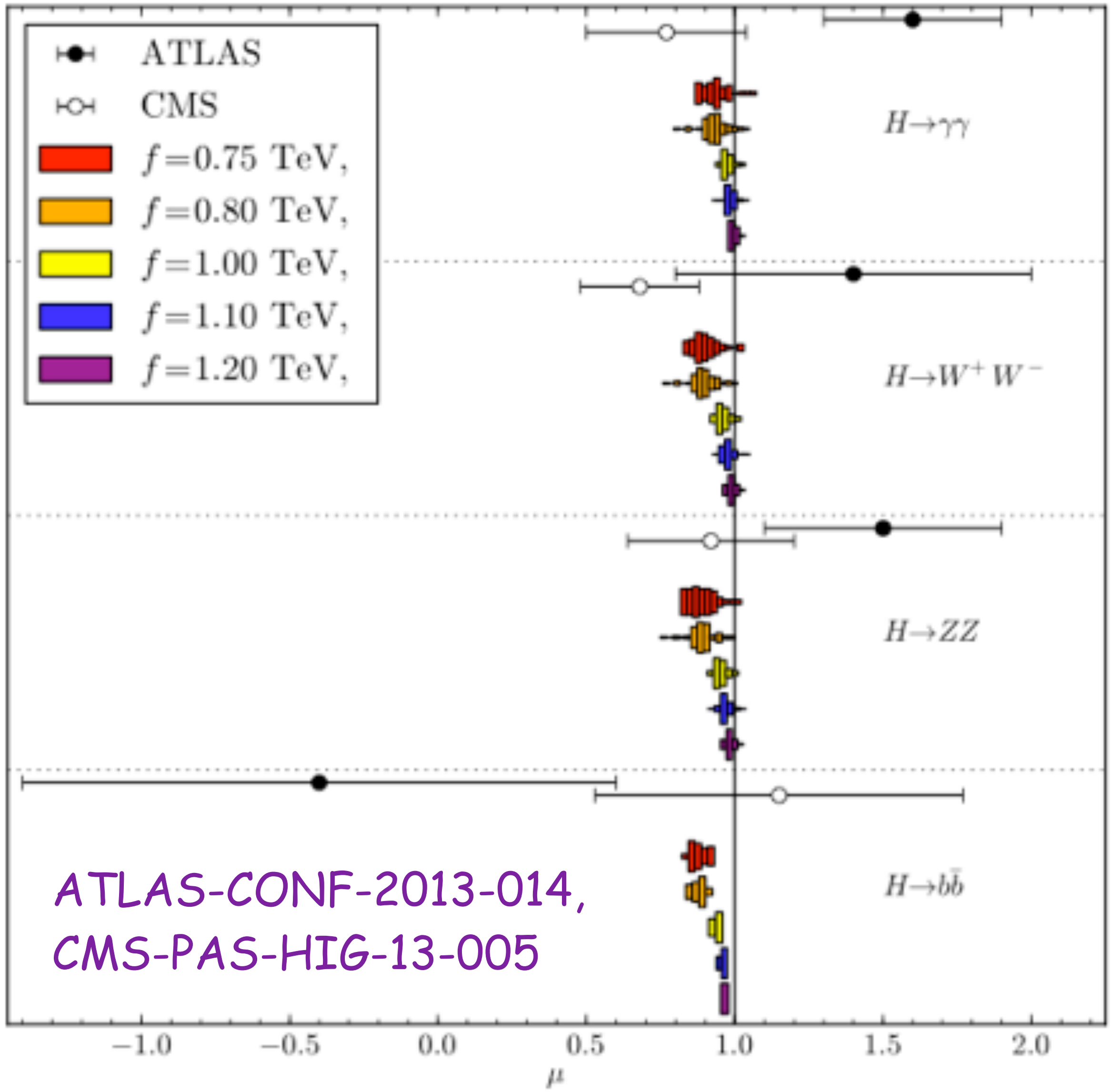
LanHEP: package for the automated generation of Feynman rules
Semenov, arXiv:1005.1909
CalcHEP: package for automated calculations of physical observables
Belyaev et al, Comput. Phys. Commun. 184 (2013) 1729
HEPMDB: model available at https://hepmdb.soton.ac.uk

- 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 compositeness spirit)

- Benchmark points: $.75 < f(\text{TeV}) < 1.5$ and $1.5 < g_\rho < 3$
  $m_\rho \simeq f g_\rho \geq 2 \text{ TeV}$ (EWPT)

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

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



- Higgs couplings to SM states are modified due to mixing
- 15~20% reduction of Higgs total width due to Hbb coupling modification
- For production and decay channels **heavy bosonic and fermionic states can play a role via loops** but NGB symmetry protects the couplings **No large deviations.**

performing χ^2- the 4DCHM can fit as well as the SM

points compliant with bounds from
$t', \; b', \; T_{5/3}$ direct searches

Drell-Yan signals from the 4DCHM at the LHC

Barducci, Belyaev, DC, Moretti, Pruna, 1210.2927

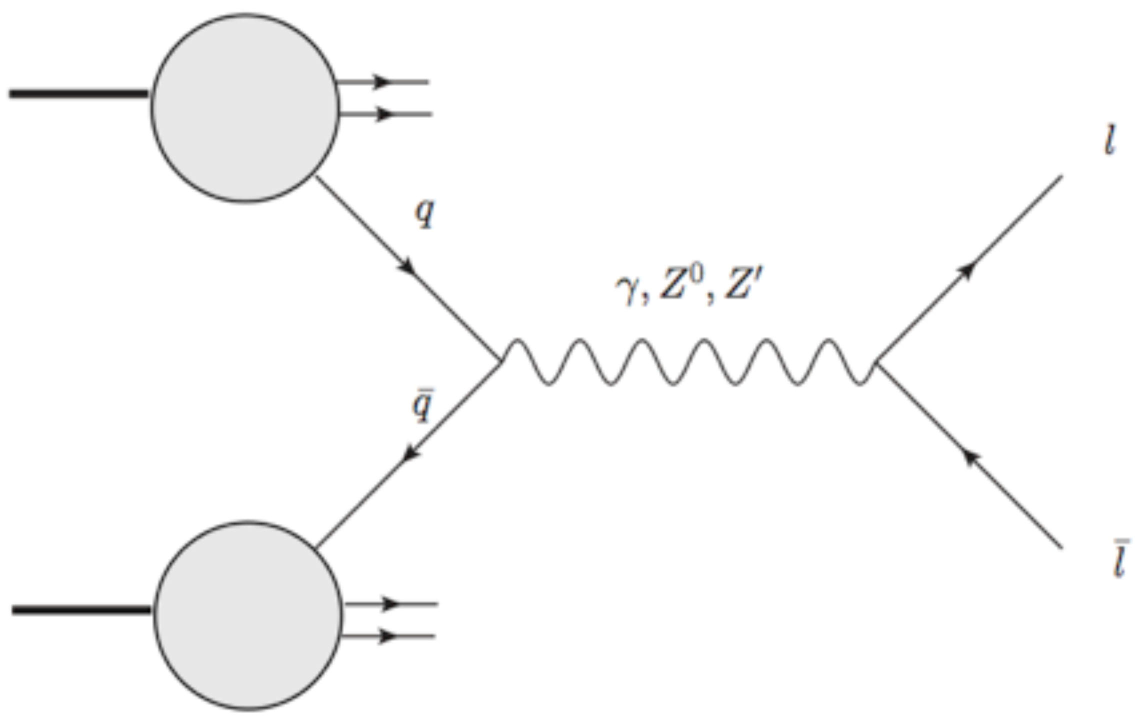
Quarks can annihilate also in Z' (and W')

tree-level processes

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

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

$l = e, \mu$



Z' (W') could be discovered as peak in the di-lepton invariant mass (missing-energy invariant mass) spectrum $Z' = Z_2, Z_3, Z_5 \quad W' = W_2, W_3$

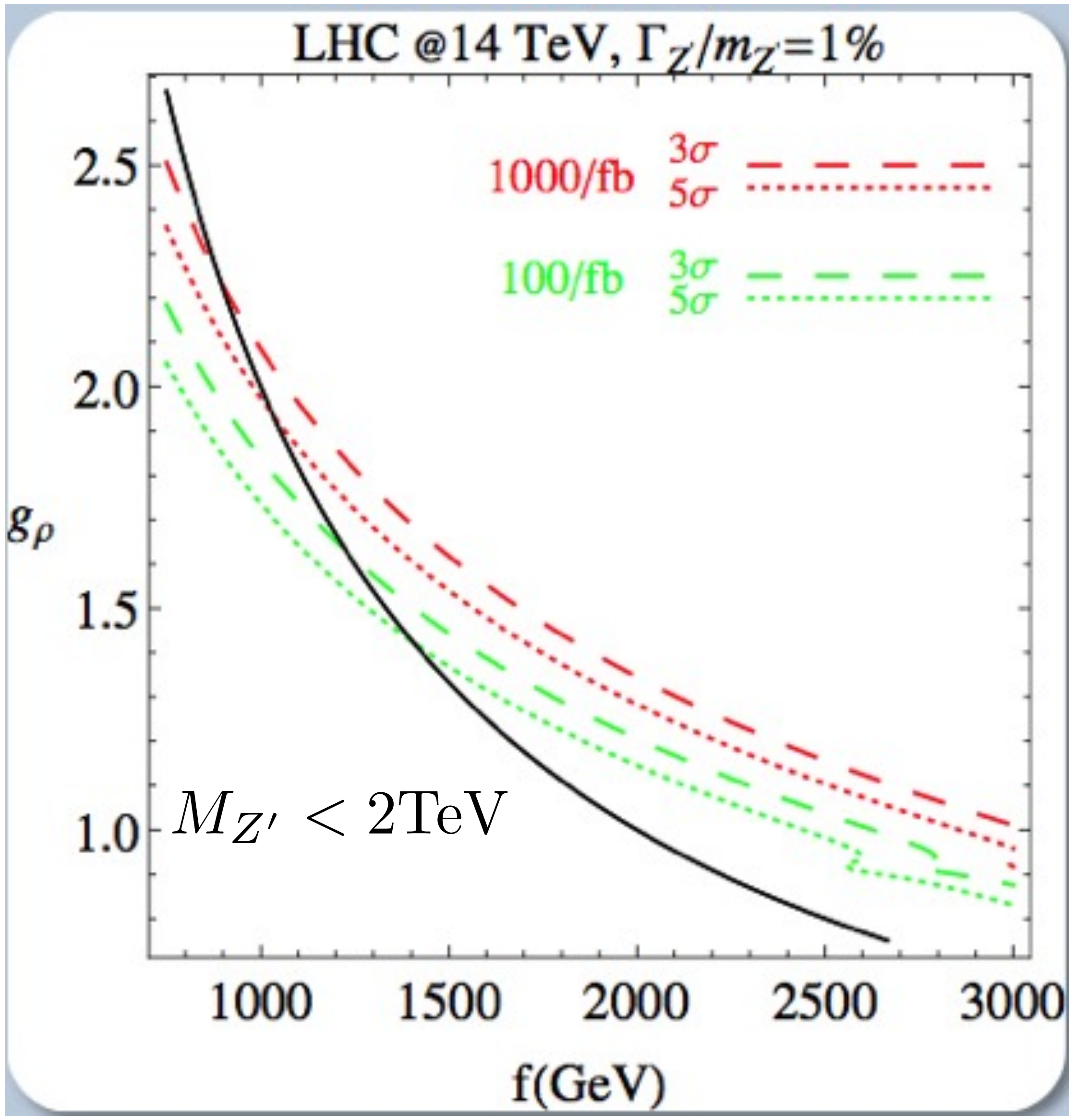
- Bounds on the mass of new Z' and W' **crucially depend on their widths** (large width if the threshold for the decay into $T\bar{T}$ is reached)

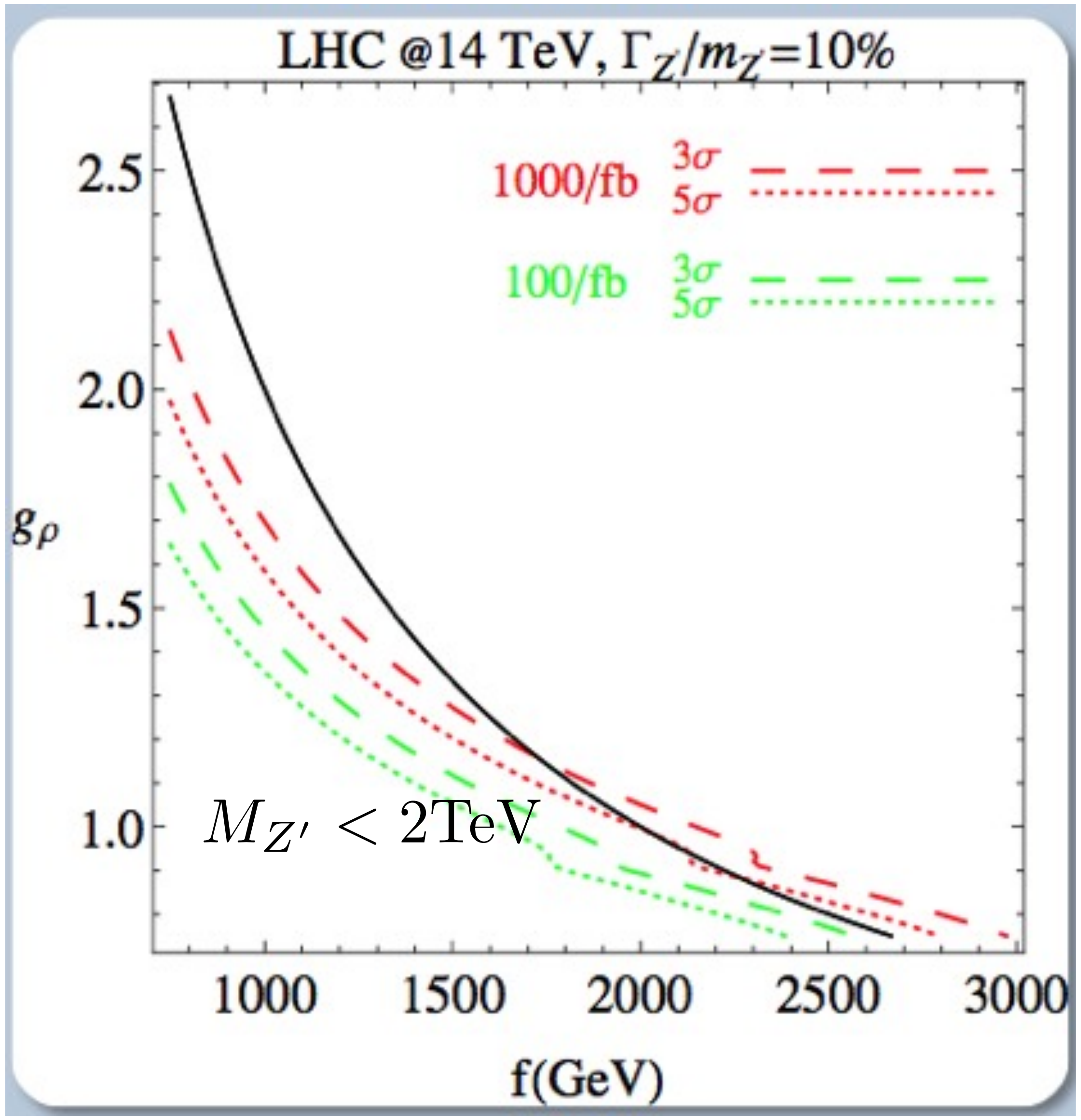
- The analysis of the Z' and W' line shapes could reveal the presence (or not) of light extra fermions

Calculating significance, neutral channel - 14 TeV LHC

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

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





$\Gamma_{Z'}/M_{Z'} = 1\%$ $\Gamma_{Z'}/M_{Z'} = 10\%$

small width is mandatory for Z’ detection in DY processes

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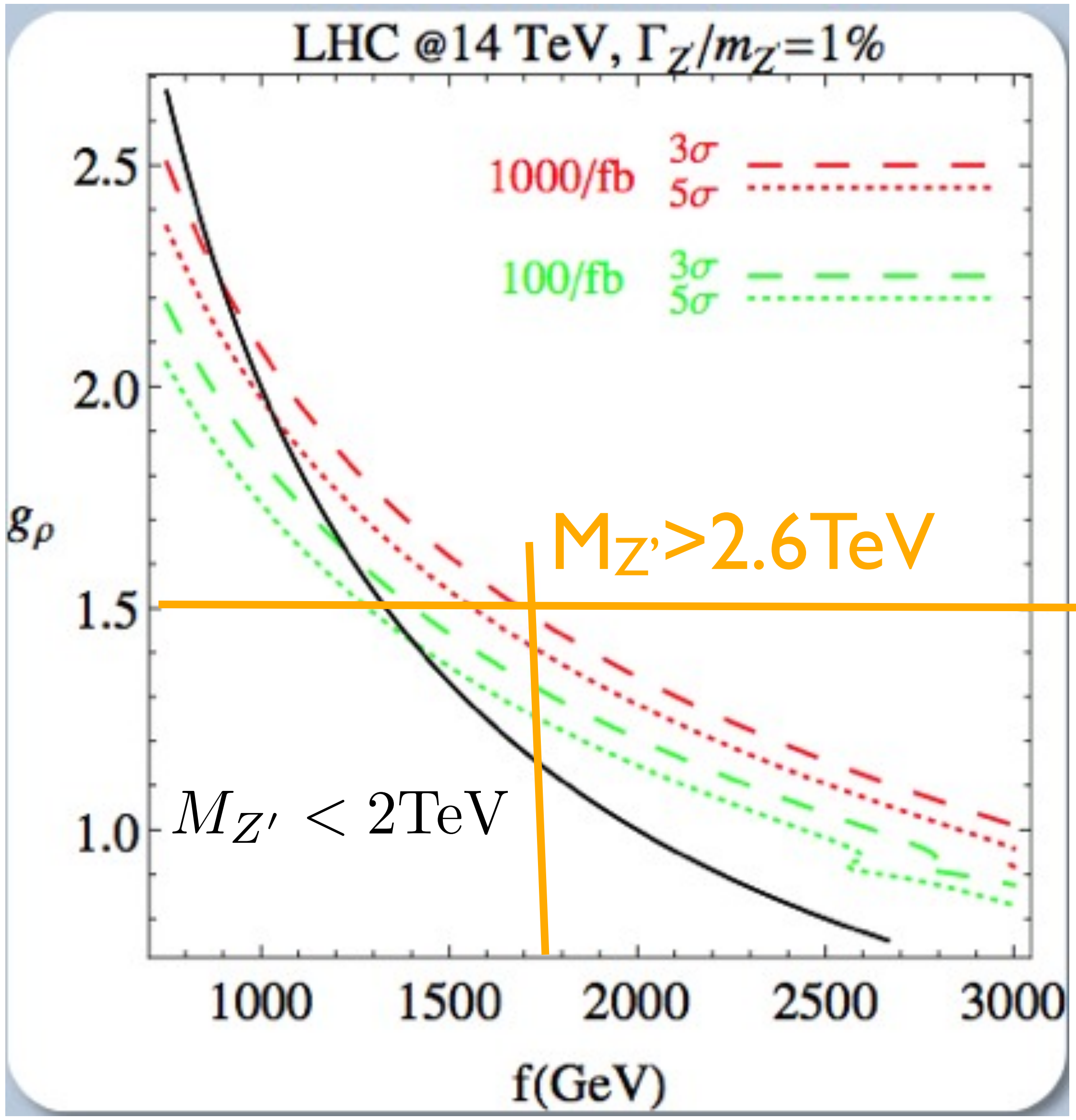
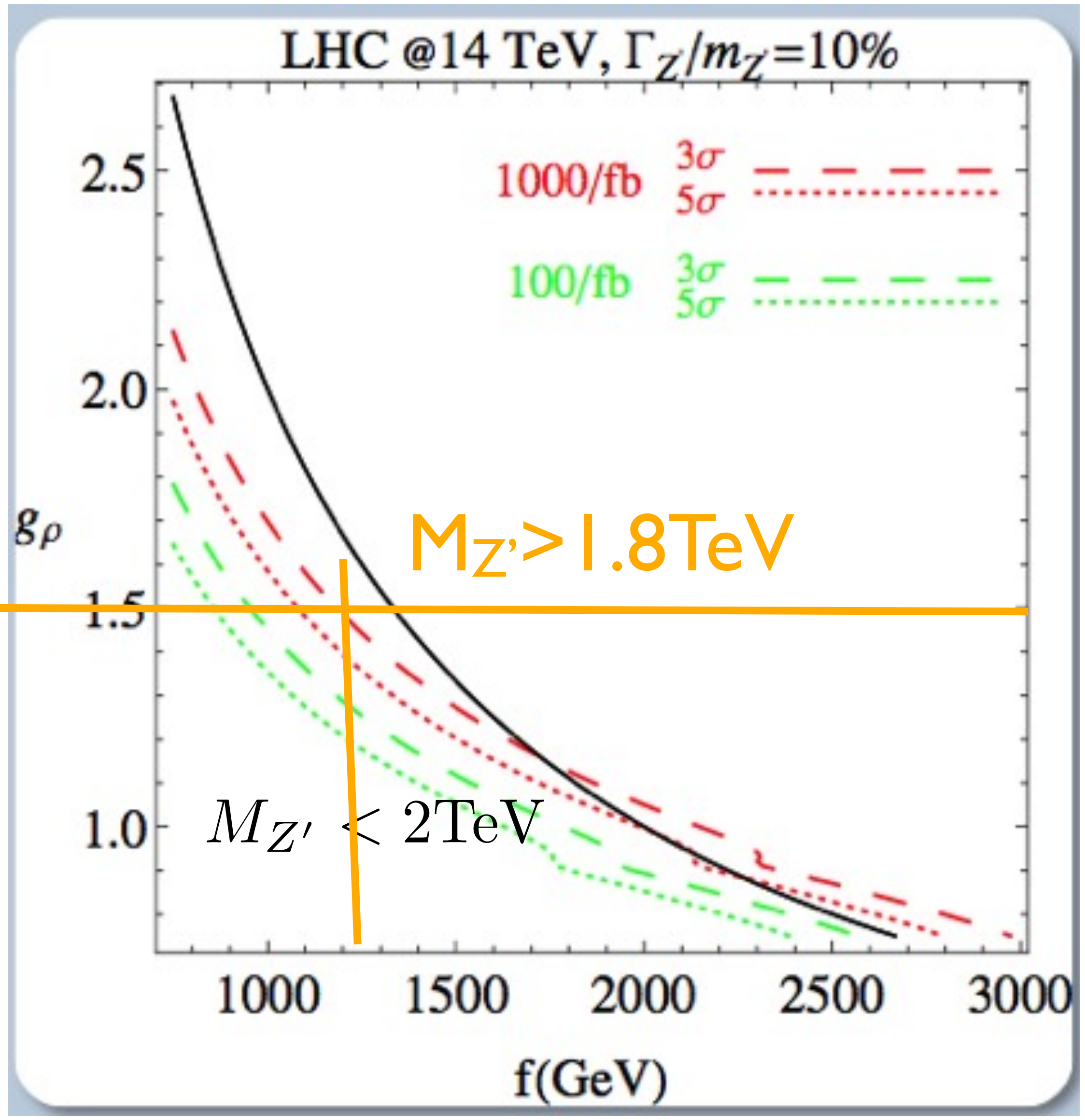




$\Gamma_{Z'}/M_{Z'} = 1\%$ $\Gamma_{Z'}/M_{Z'} = 10\%$

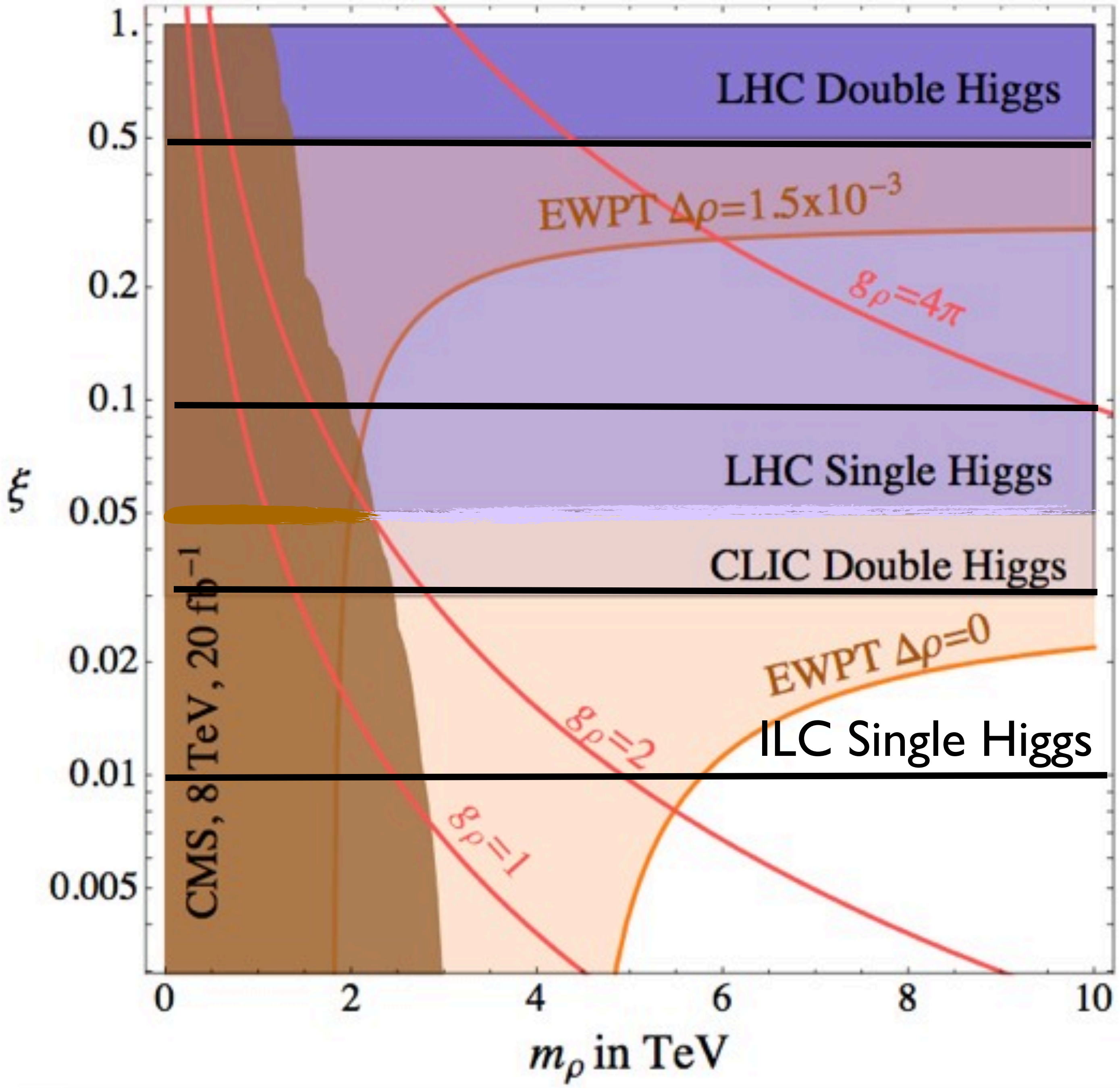
small width is mandatory for Z' detection in DY processes if the LHC will not measure deviations from the SM in single Higgs production larger than 10% and does not discover any new particle with a clear role ....

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 environment for precision measurements) could help in detecting deviations in the cross sections for single, double Higgs production, top pair production ..... ⟶ (indirect) probe of compositeness 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 $300 fb^{-1}$

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

ILC 250GeV 250fb^{-1}

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

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

EWPT mainly from deviations on g_{hVV}

(see Fujii talk)

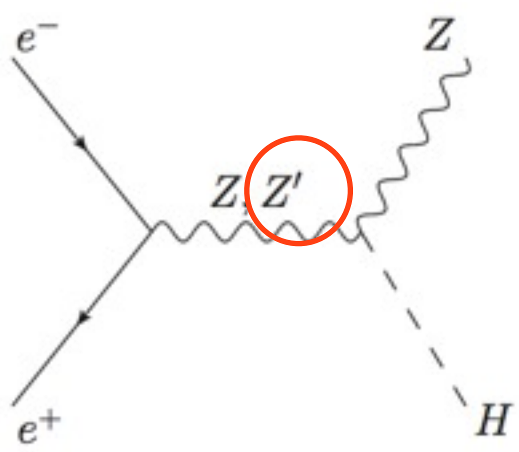
To the sensitivity on $\xi = v^2/f^2$ it corresponds a reach on the compositeness scale $\Lambda = 4\pi f$ (Ex. Λ =30-40 TeV @ILC)

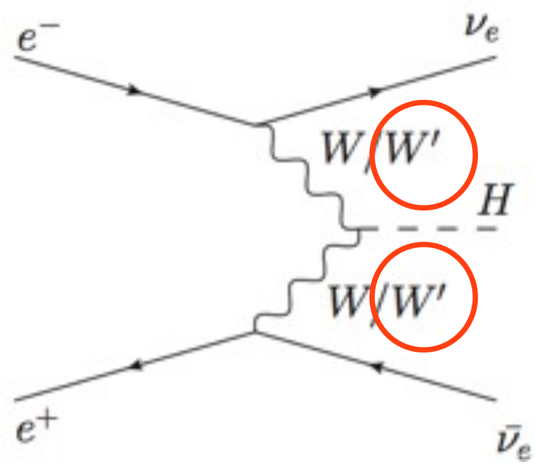
but the model details often matter!

Use the 4DCHM to test the potential of the proposed e^+e^- colliders in detecting PNGB Higgs models

(Barducci,DC,Moretti,Pruna,1311.3305)

Single Composite Higgs Boson produced via HS and VBF





Extra Gauge bosons Z' and W' can be exchanged

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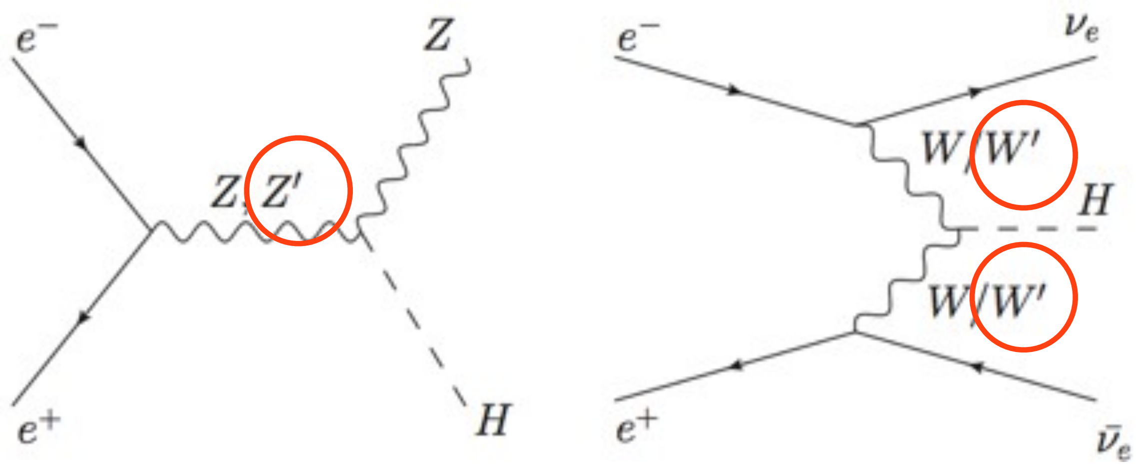


Extra Gauge bosons Z' and W' can be exchanged

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

$$i = b\bar{b},\ W^+W^-$$

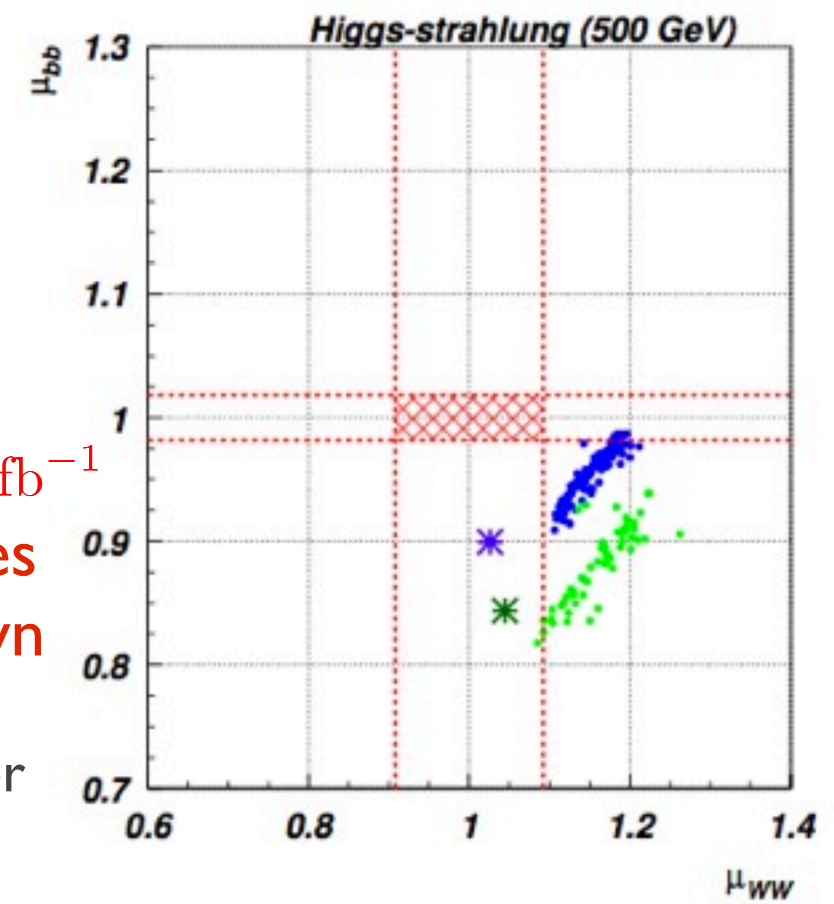
$\sqrt{s} = 500$ GeV, $\mathcal{L} = 500 {\rm fb}^{-1}$

expected accuracies for the μ_i are shown

ILC TDR 1306.6352

ILC Higgs White Paper 1310.0763

Snowmass 1310.8361



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

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

* = decoupl. limit

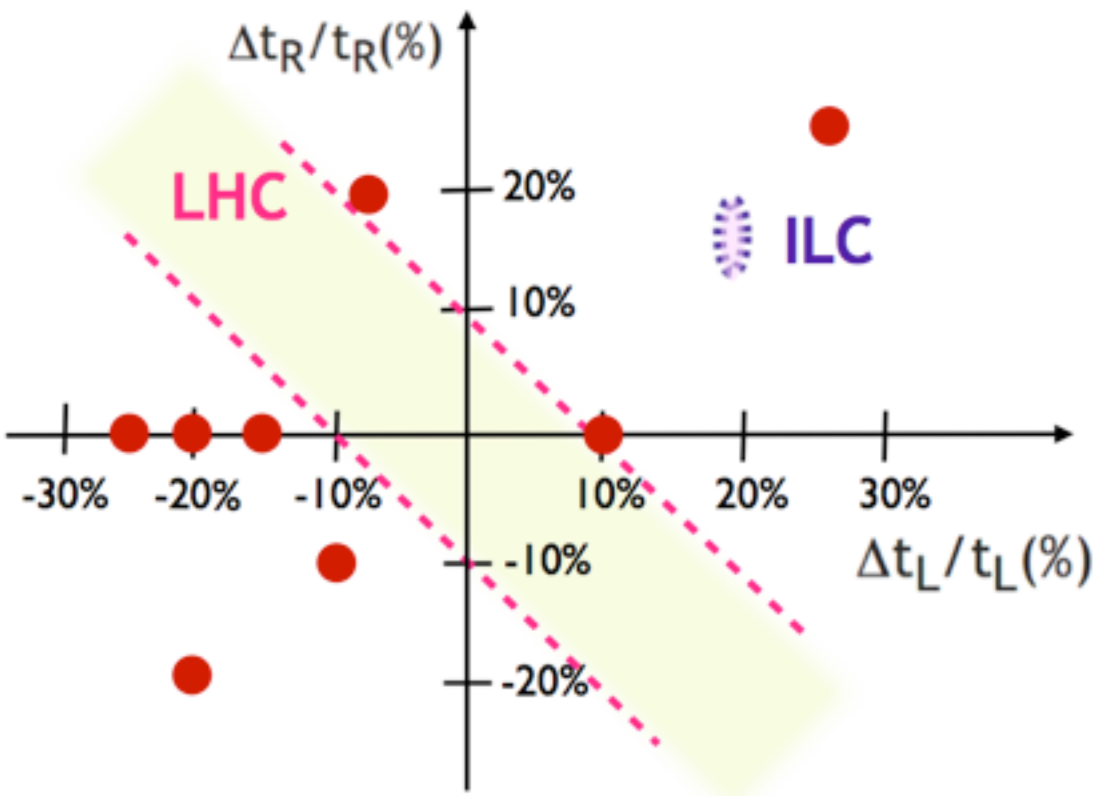
the decoupling limit could be inaccurate as it fails to account for significative interference effects

Top quark precision physics at an e+e- collider

Various BSM models predict large deviations in the top EW couplings.

Ex. Zt_Lt_L, Zt_Rt_R ● = different BSM scenarios (left) 4DCHM (right)

Richard 1403.2893; Grojean, LCWS14 talk



sensitivities: LHC ~ 10%

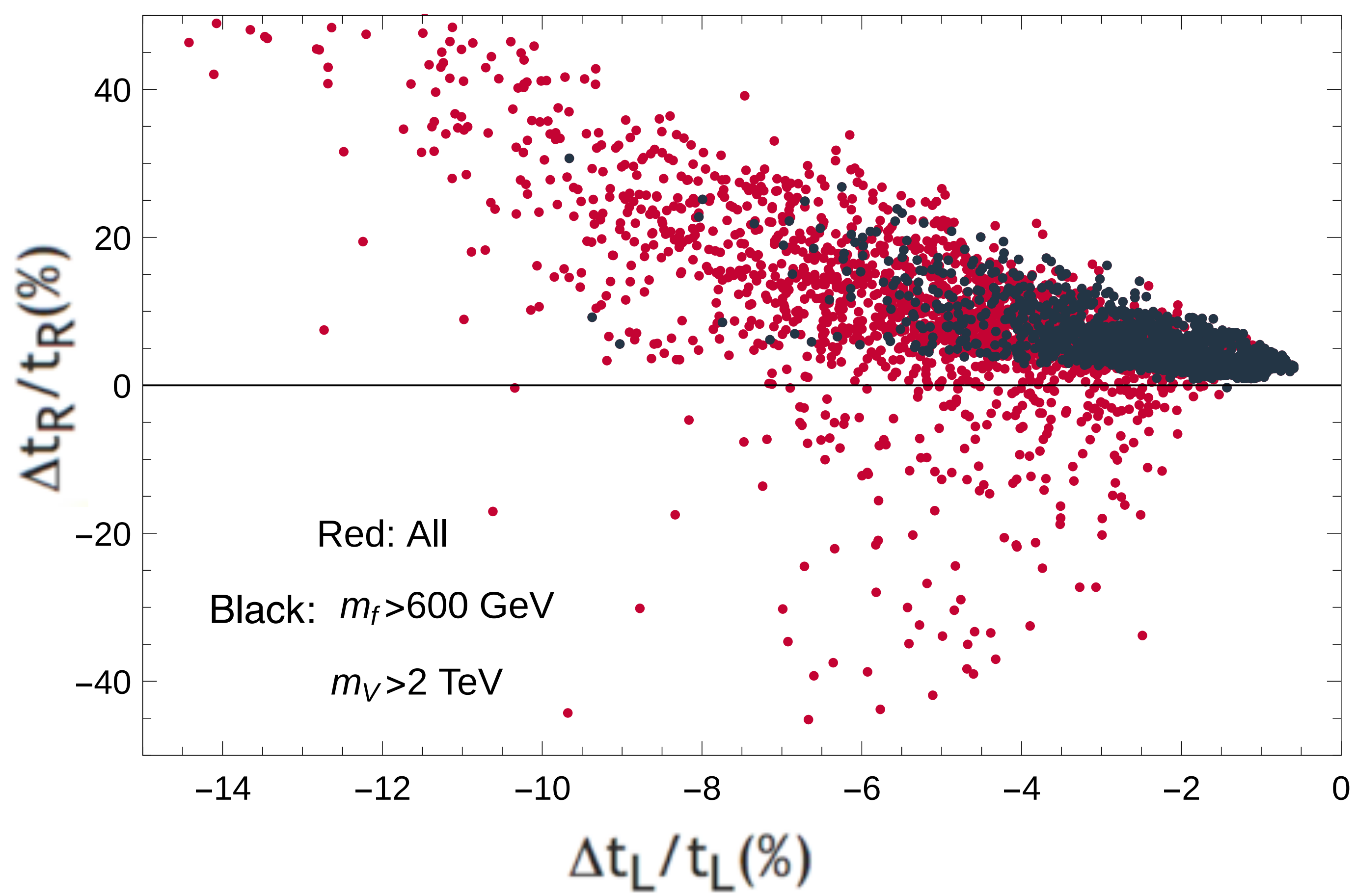
HL-LHC ~ 4%

ILC(500) < 1% with polarized beams

(ILC-TDR 1306.6352)

Barducci, DC, Moretti, Pruna, in preparation

$$1.5 < g_\rho < 3,\ \ 0.75 < f(\mathrm{TeV}) < 1.5$$



scan over 4DCHM fermion parameters
max deviation on the left/right couplings -10/+20%

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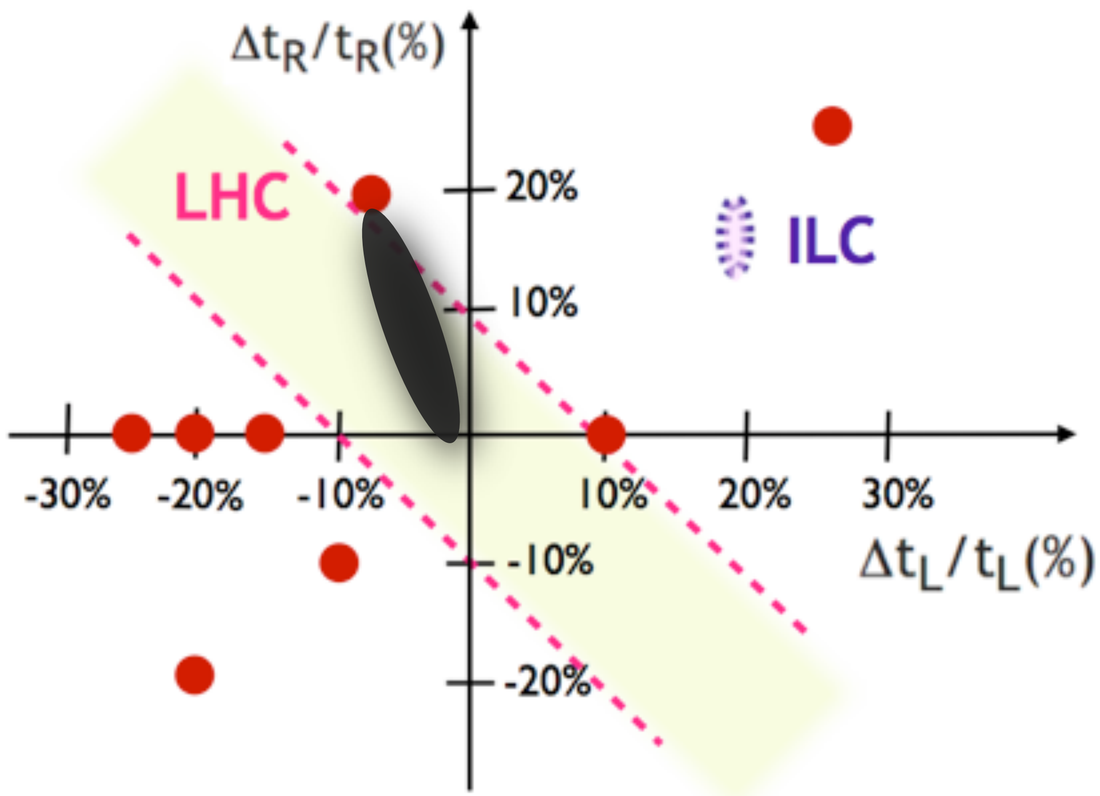

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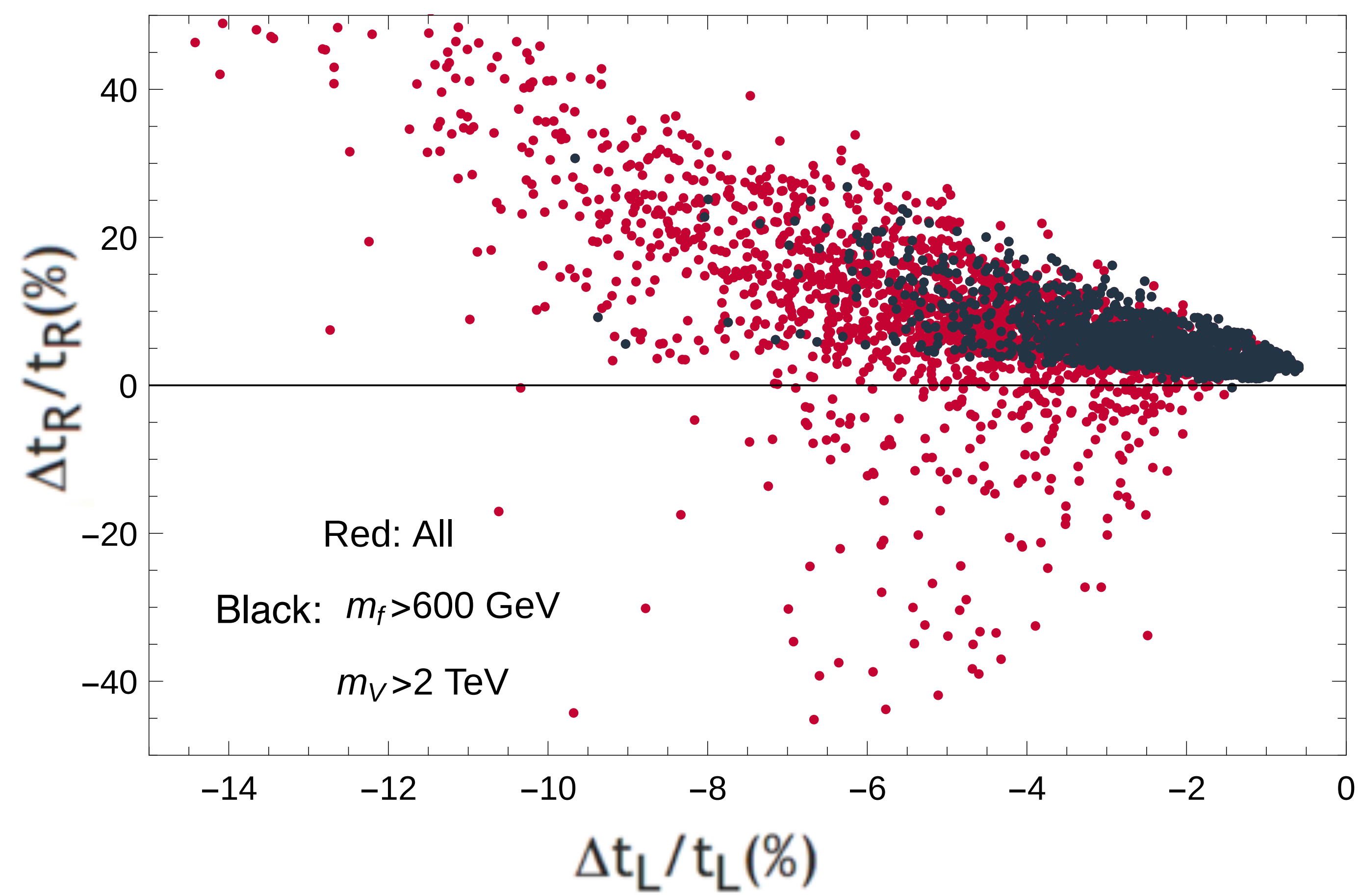

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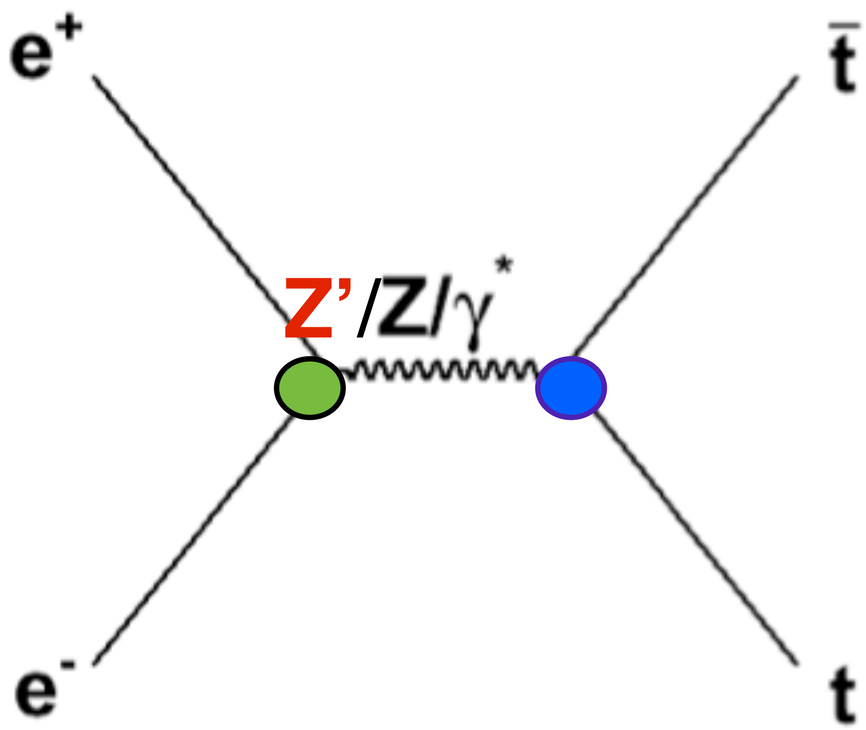
Top pair production within the 4DCHM

$\sqrt{s} = 370, 500, 1000$ GeV



The modifications of the process arise via 3 effects:

- ☑ modification of the Zee coupling (negligible)
- ☑ modification of the Ztt coupling from: mixing between top and extra fermions (partial compositeness), mixing between Z and Z's
- ☑ the s-channel exchange of the new Z's (interference) - commonly neglected BUT can be very important also for large $M_{Z'}$

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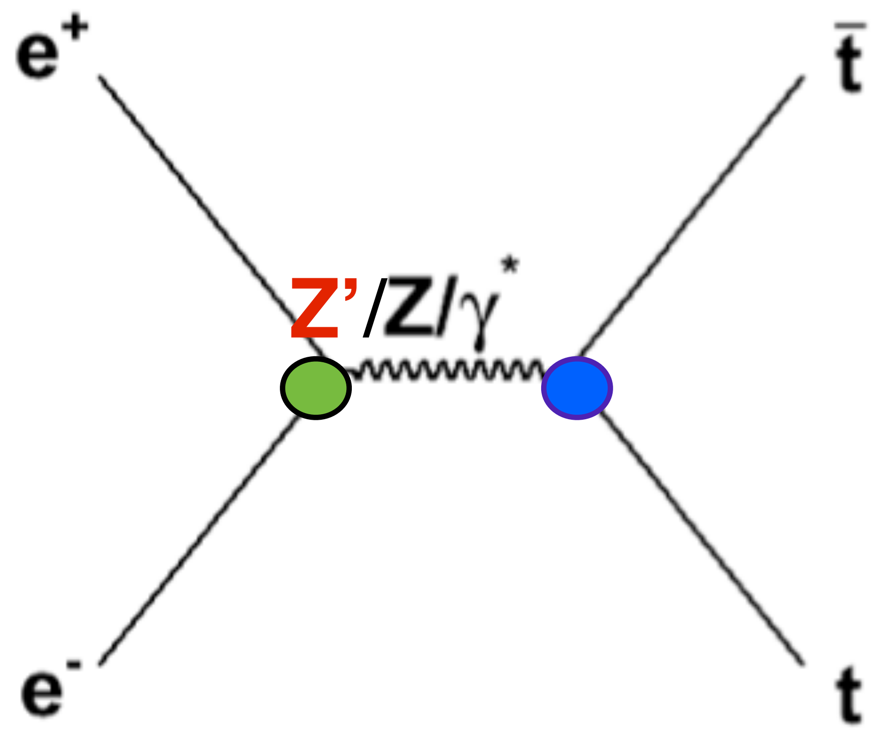

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Observables:
- Total cross-section $\sigma(e^+e^- \to t\bar{t})$
- Forward-Backward Asymmetry A_{FB}
- Single and Double Spin Asymmetries A_L , A_{LL}

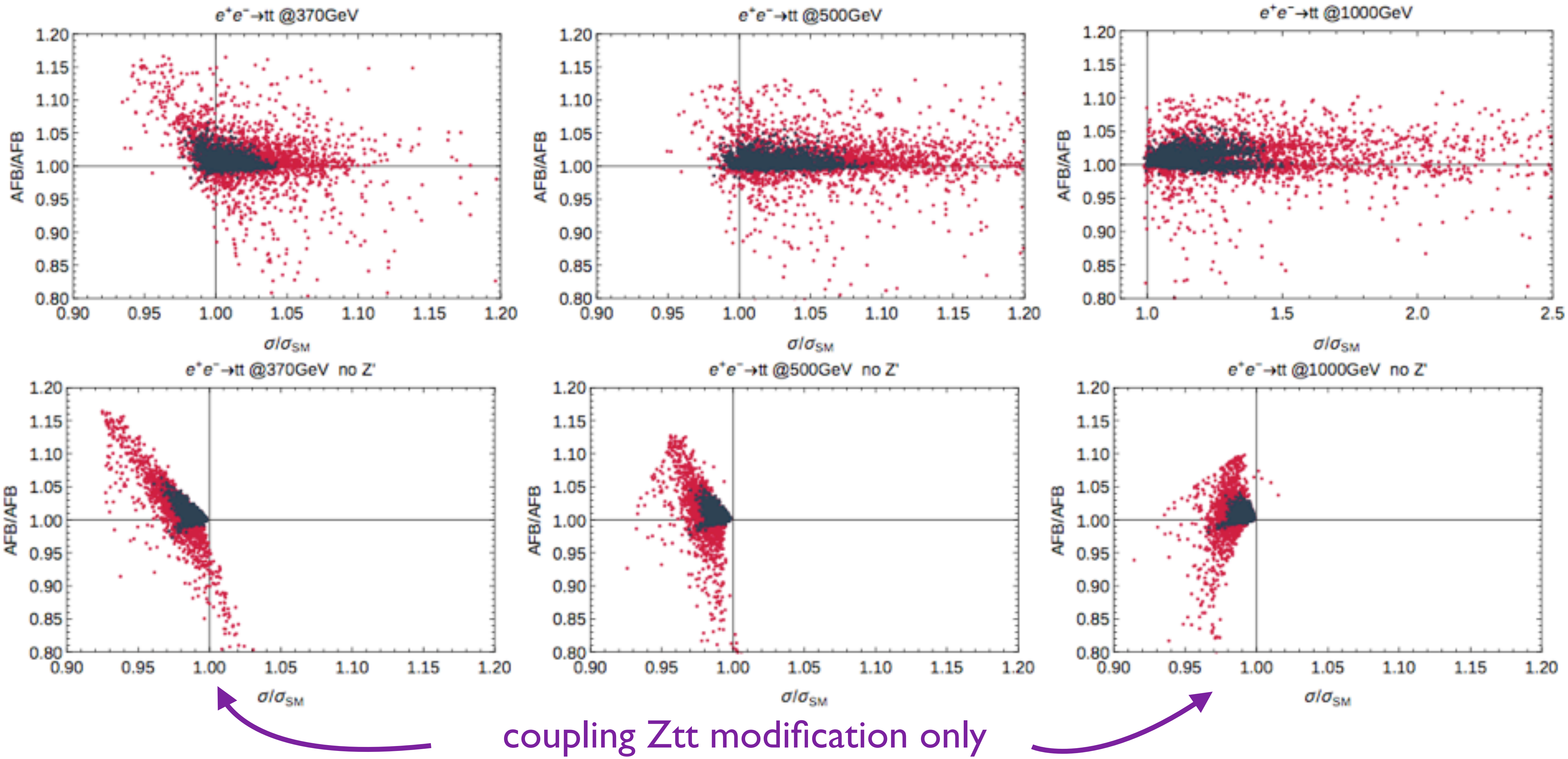
(leptons from top (antitop) semi-leptonic decays are used as spin analyzers)

Born approximation - QCD and EW corrections and EW not included

ISR and beamstrhalung included but not important when considering $\mathcal{O}/\mathcal{O}_{\rm SM}$

With or without Z' exchanges @ 370, 500, 1000 GeV

red: all points f=0.75-1.5, g_s=1.5-3, black: M_T>600GeV $M_{Z'}$>2TeV



coupling Ztt modification only

Interference of the Z' with the SM plays a crucial role

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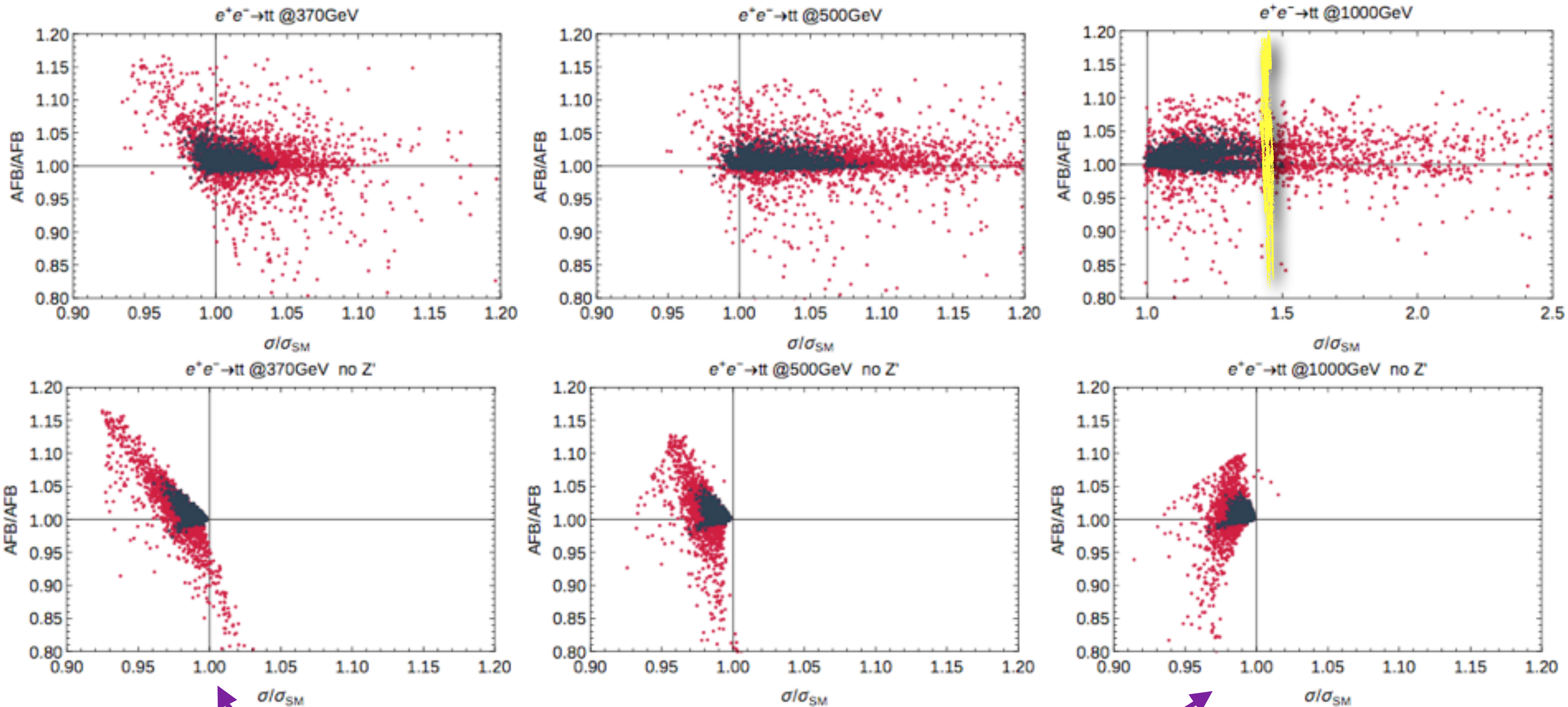
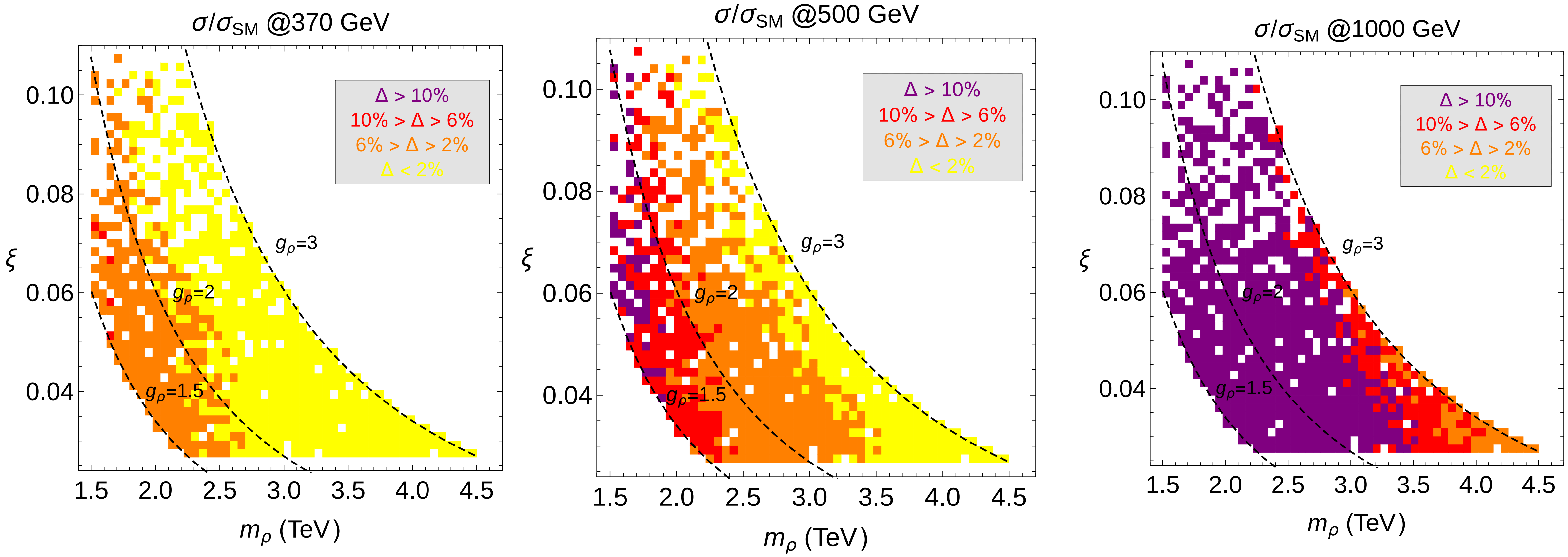


coupling Ztt modification only

Interference of the Z' with the SM plays a crucial role

up to 40% deviation in the x-sect @ 1000 GeV !

Bounds on the composite scale and coupling from $\sigma(e^+e^- \to t\bar{t})$



$$\xi = \frac{v^2}{f^2}, \quad m_\rho = f g_\rho, \quad \Delta = \frac{\sigma - \sigma_{SM}}{\sigma_{SM}}$$

Points correspond to f=0.75-1.5, g_s=1.5-3, M_T>600GeV. For each point we have selected the configuration corresponding to the maximal deviation

sensitivity up to $M_{Z'}$ ~ 3.5 TeV @ 500GeV

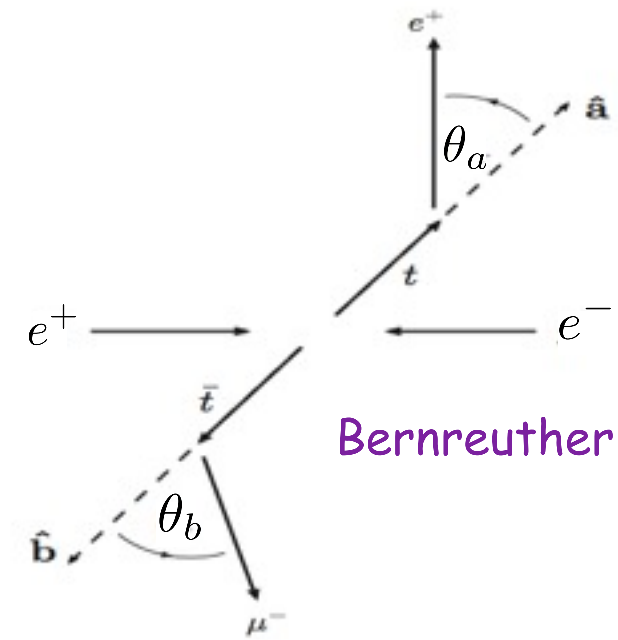
Single Spin Asymmetry A_L

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_a d\cos\theta_b} = \frac{1}{4}[1 + B_1\cos\theta_a + B_2\cos\theta_b - C\cos\theta_a\cos\theta_b]$$

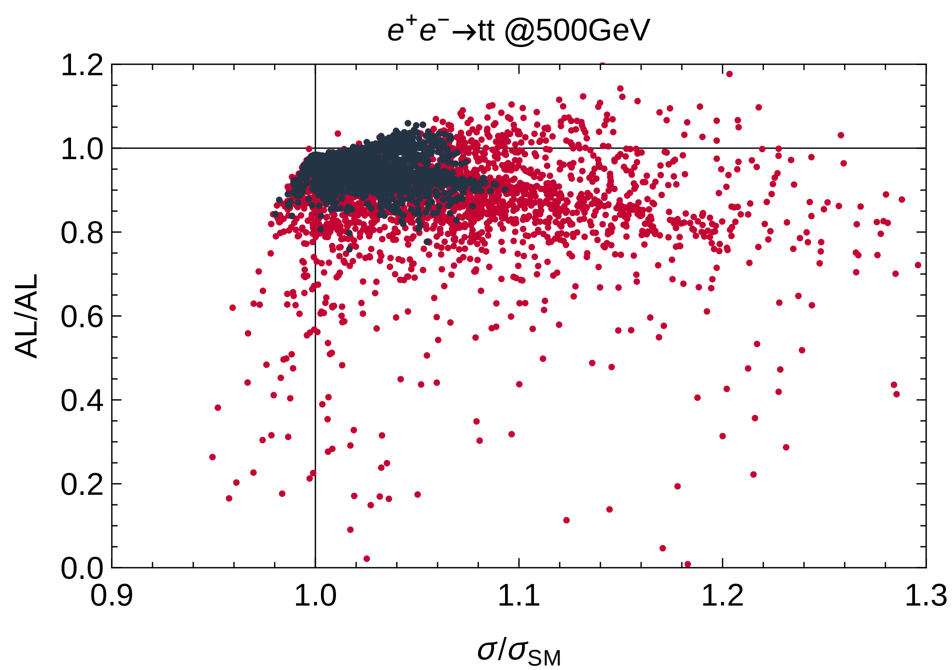
$$B_1 \sim A_L(t),\ B_2 \sim A_L(\bar{t}),\ C \sim A_{LL}$$

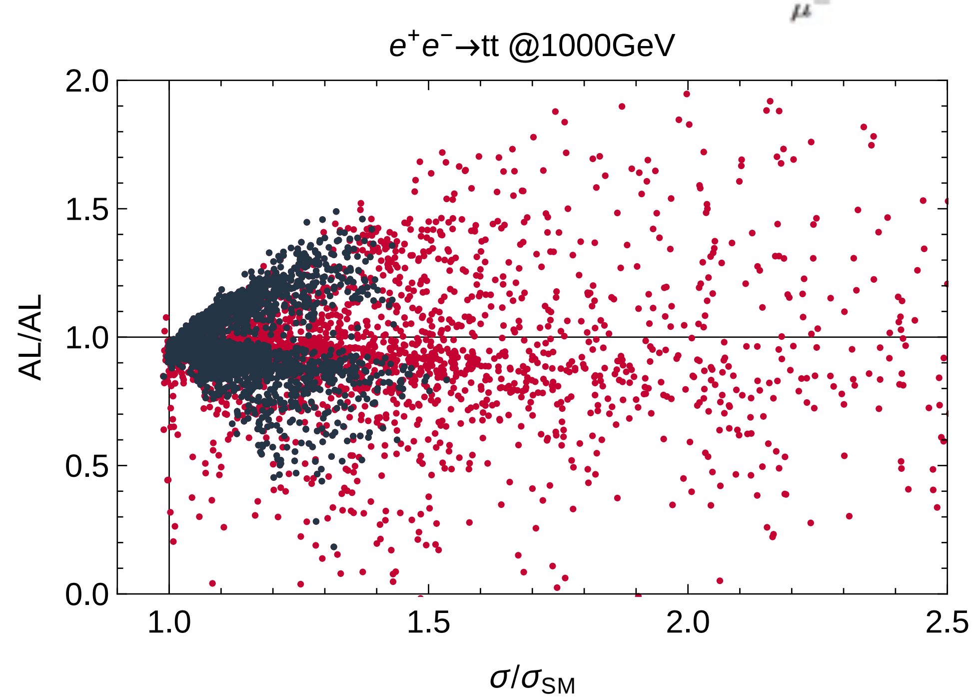
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_a} = \frac{1}{2}[1 + A_L\cos\theta_a]$$

helicity angle distribution



Bernreuther 0805.1333





large deviations of both signs @ 1000GeV mainly due to the SM-Z's interference

A_L is unique in offering the chance to separate Z_2 and Z_3 as they contribute in opposite directions (beam polarization could help)

Conclusions

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

- ☑ Realistic scenarios can be built and analyzed with the full spectrum: the 4DCHM embeds the main characteristics of composite Higgs models with partial compositeness

- ☑ If nothing is seen, or, better, if the LHC gives some evidence, e^+e^- machines will have a great potential in testing composite Higgs scenarios: precise measurements of the Higgs and top couplings

- ☑ Warning: interference effects of the new resonances could be crucial and must be taken into account to extract the sensitivities to CHMs

BACKUP SLIDES

4DCHM = Minimal 4D realization of MCHM5

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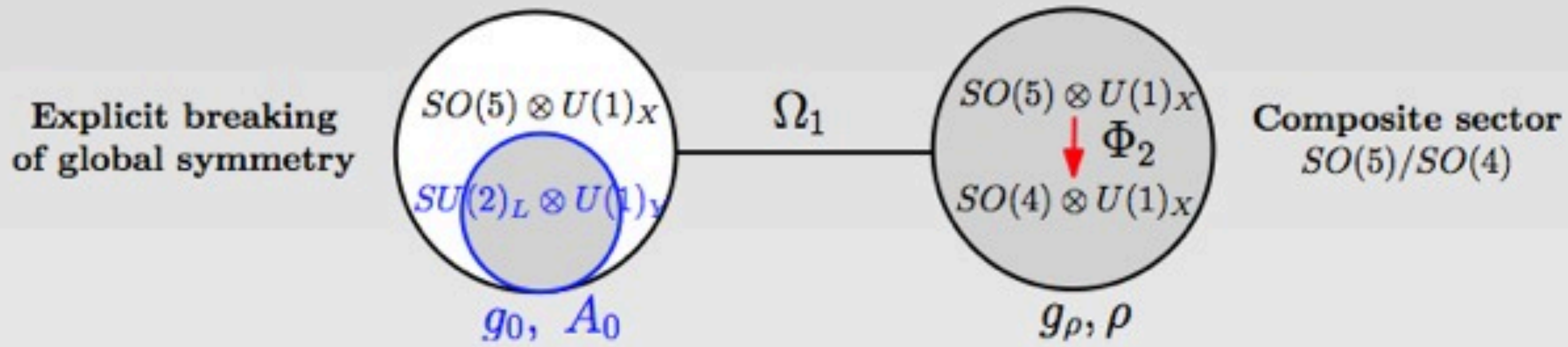


$$\mathcal{L}_{\rm ele} = -\frac{1}{4}A^a_{\mu\nu}A^a_{\mu\nu} - \frac{1}{4}B_{\mu\nu}B_{\mu\nu}$$

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

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

- 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

$$SO(4) \rightarrow m_\rho^2 = \frac{g_\rho^2 f_1^2}{2}, \qquad \frac{SO(5)}{SO(4)} \rightarrow m_{a_1}^2 = \frac{g_\rho^2(f_1^2 + f_2^2)}{2}$$

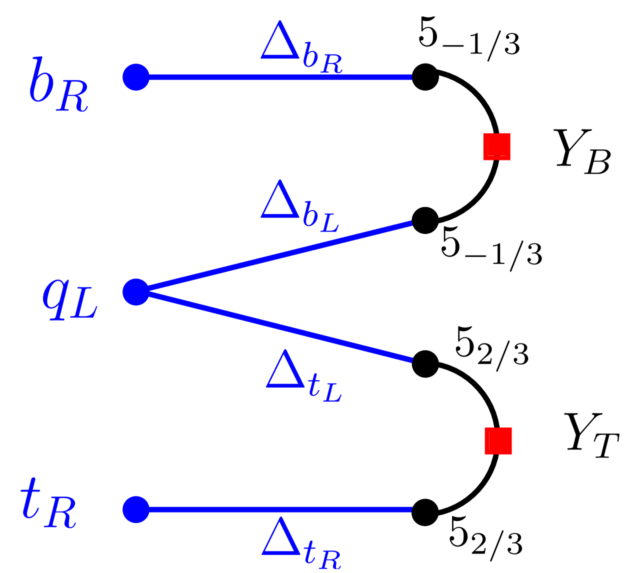
Fermion sector: which representation?

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

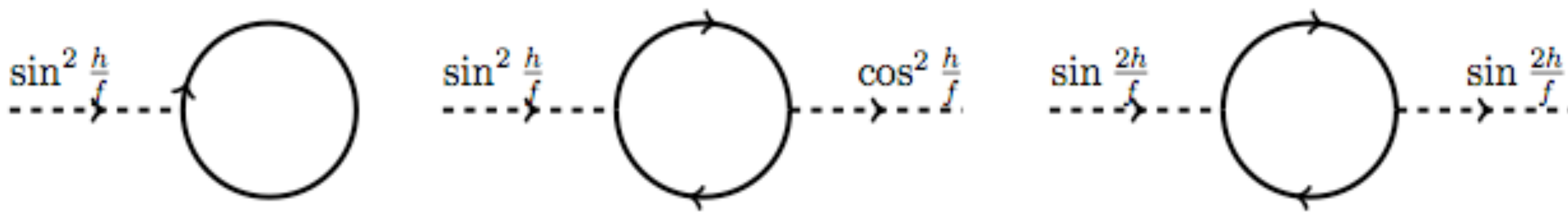
Partial compositeness: 3rd generation quarks only top Yukawa coupling

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

Coleman-Weinberg effective potential generated at 1-loop

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

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

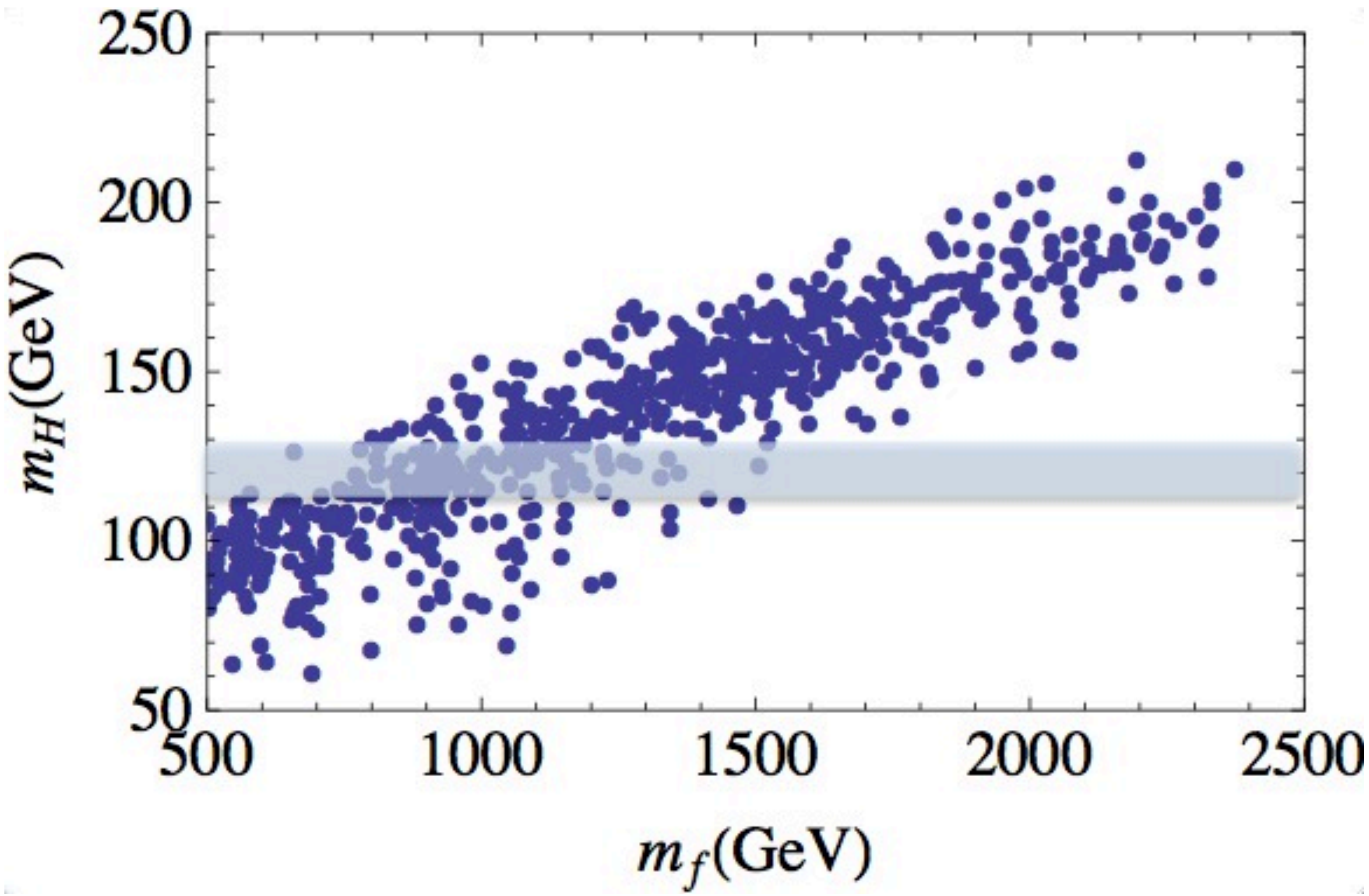


UV finite in the 4DCHM

Correlation with the lightest extra fermion mass

DC, Redi, Tesi '11

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



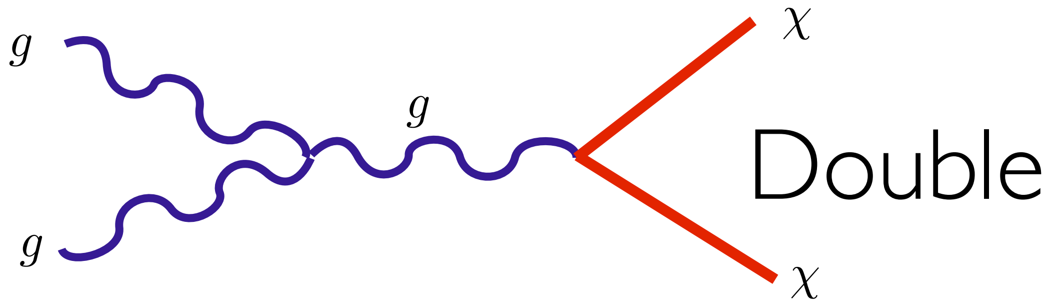
125 GeV Higgs wants light (in the TeV region) fermionic partners

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

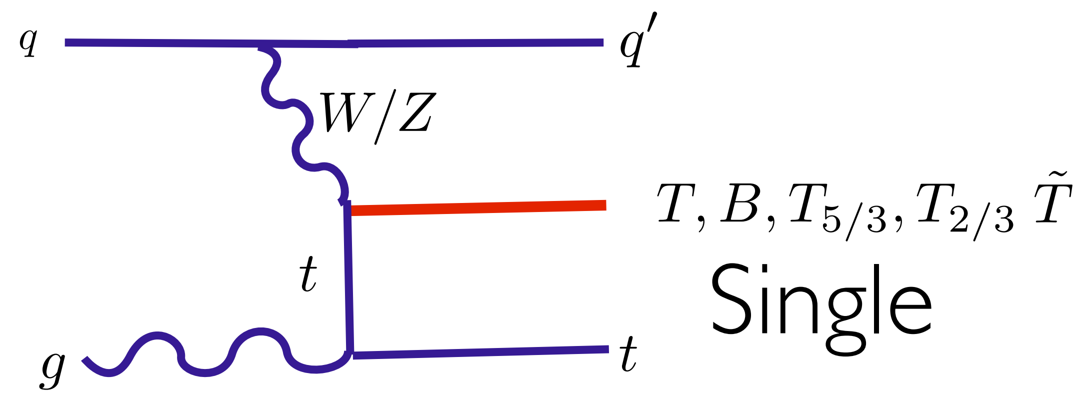
Spin-1/2 : composite fermions could be light + exotic

- Production:

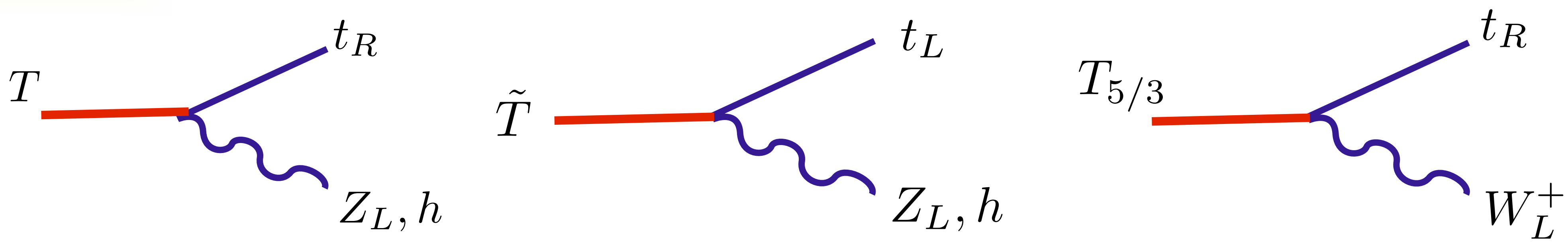
Contino, Servant (2008)



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



- Decays: Multi-lepton signatures

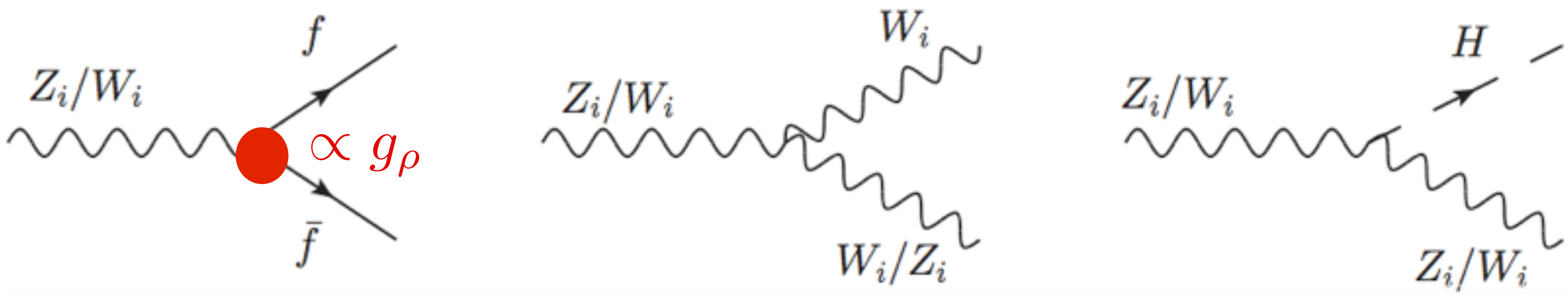


De Simone et al. 1211.5663; Matsedonskyi et al. 1204.633, 1409.0100

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

Widths of Z' and W'

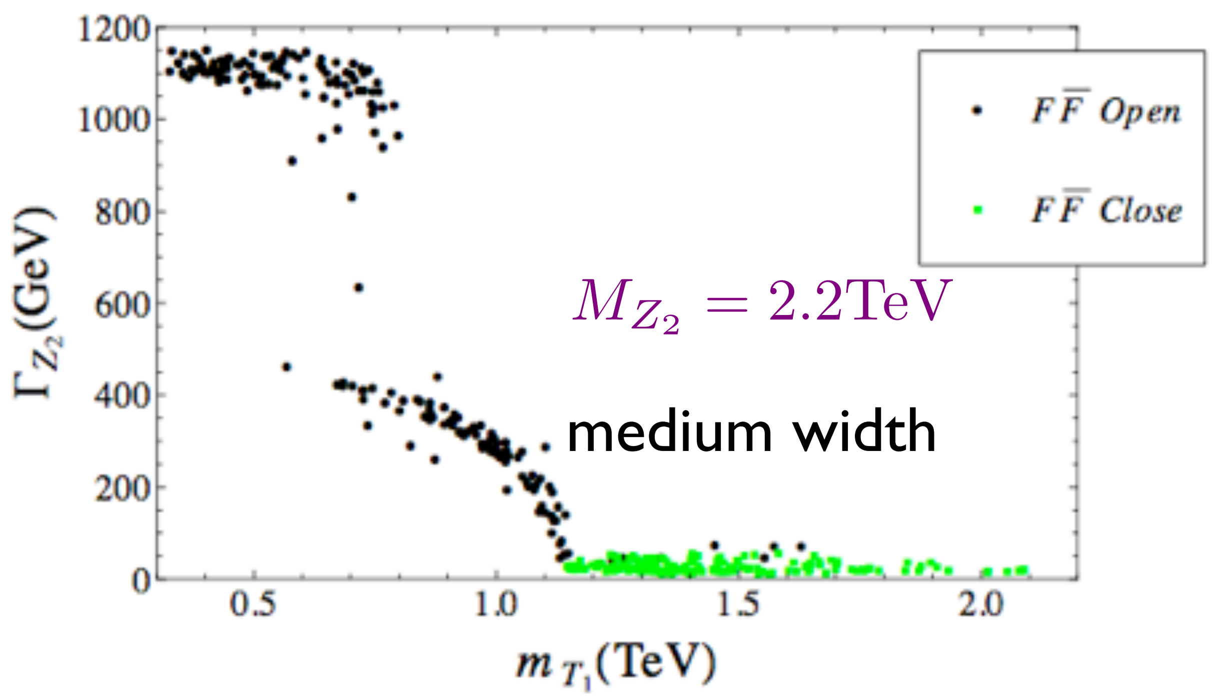


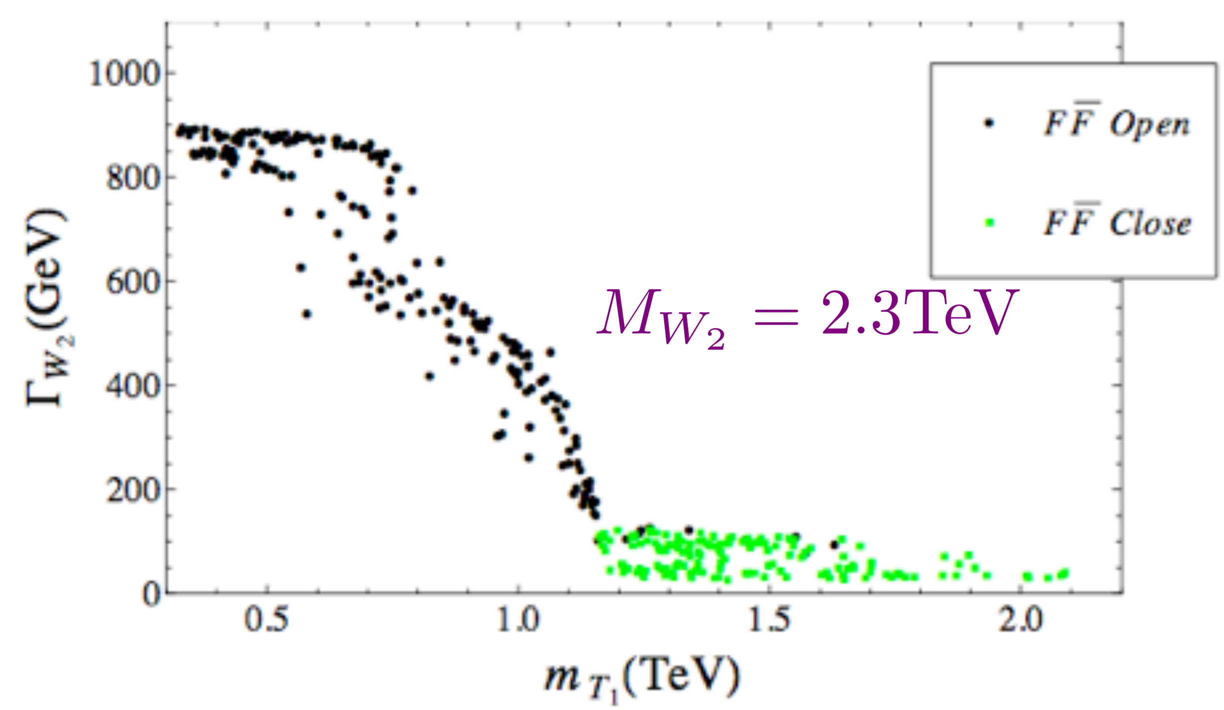
large number of fermions strongly coupled to W'and Z'

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





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

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

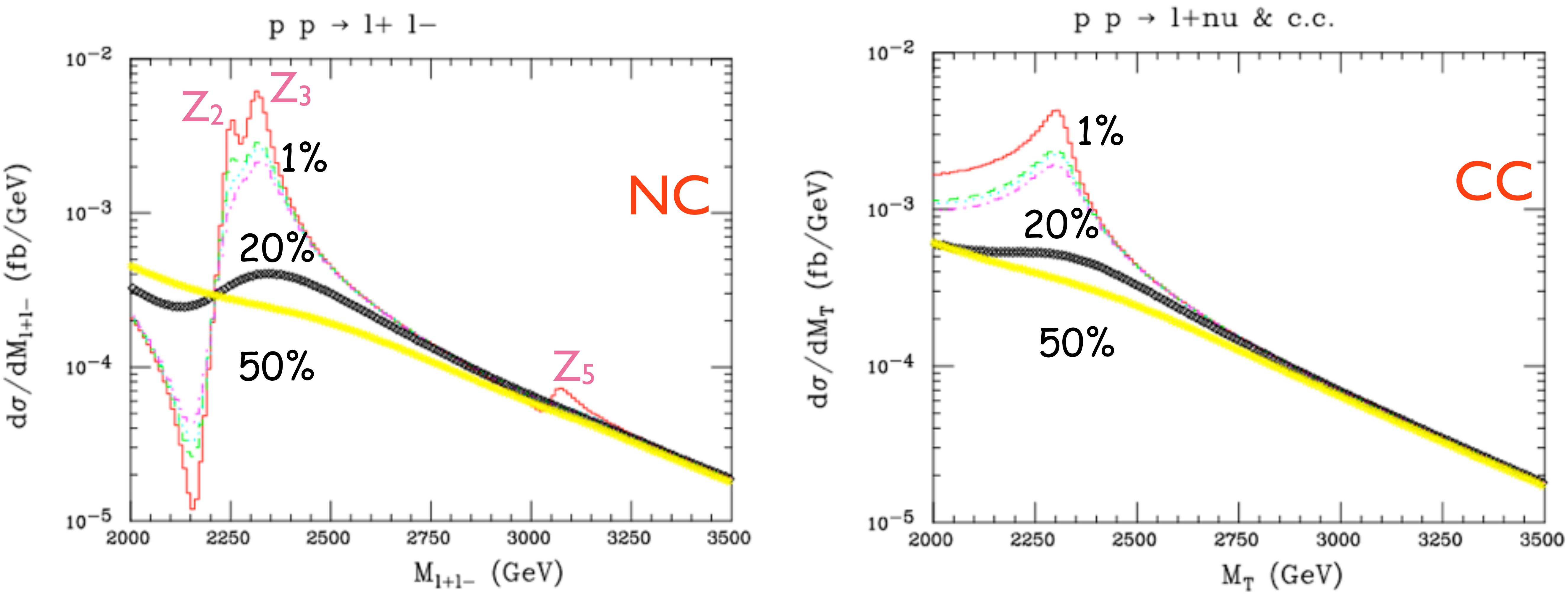
mandatory for leptonic DY processes

Analogous for the W'

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

The role of extra-fermions

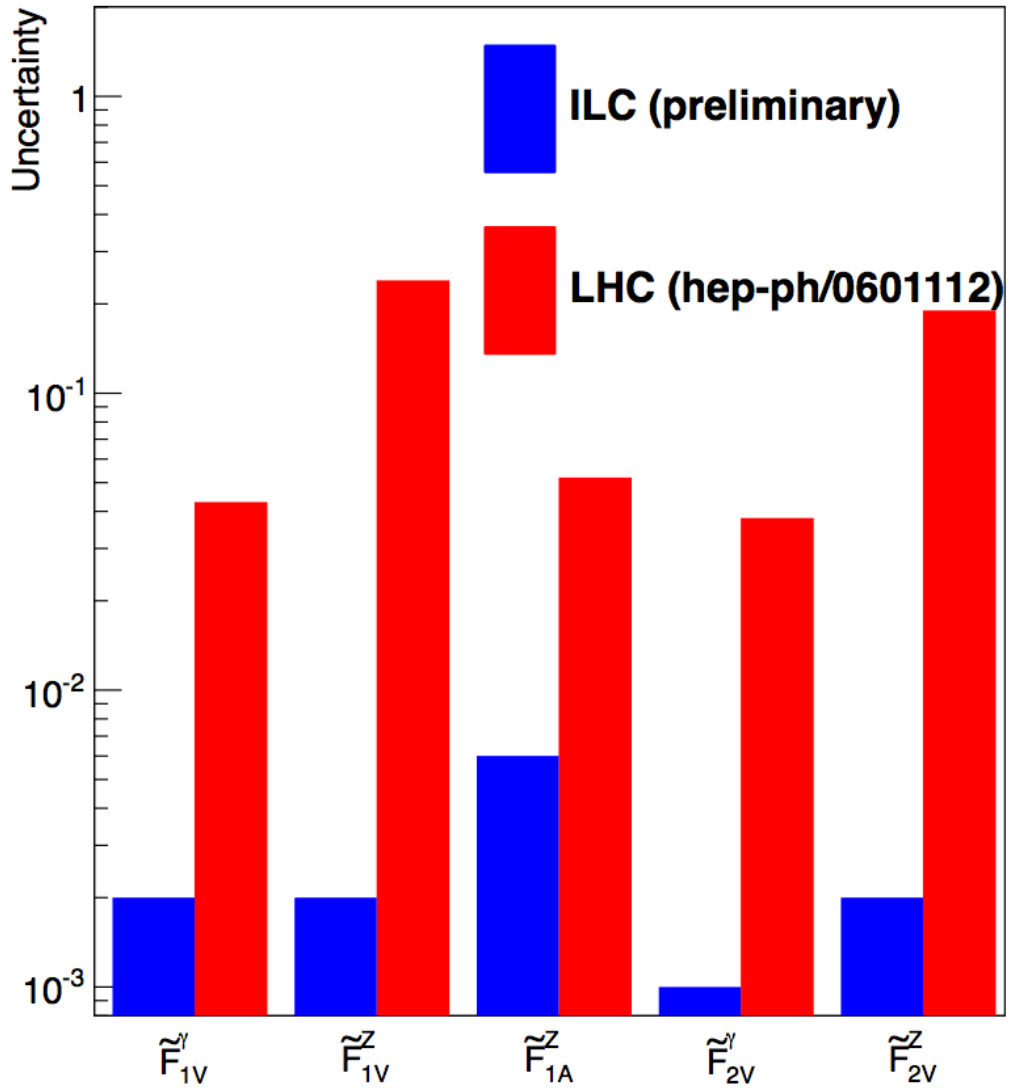
Z' and W' line shapes in relation with masses of heavy fermions: take the **same masses** and **increase the widths** $\Gamma/M \sim 1\%,\ 20\%,\ 50\%$



- **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**

Top quark couplings to Z and γ

$$\Gamma_{\mu}^{ttX}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu \left(\widetilde{F}_{1V}^X(k^2) + \gamma_5 \widetilde{F}_{1A}^X(k^2)\right) + \frac{(q-\bar{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^X(k^2) + \gamma_5 \widetilde{F}_{2A}^X(k^2)\right)\right\}$$



Statistical precision for CP conserving form factors expected at the LHC (300 fb^{-1}) and ILC 500 (500 fb^{-1}) with P=+/-0.8; P'=-/+0.3

(Amjad et al. 1307.8102)

$$\delta\sigma \sim 0.5\%(\mathrm{stat+lumi})$$
$$\delta A_{FB} \sim 2\%(\mathrm{stat+lumi})$$

Determination of the left and right couplings of the top to the Z to better than 1% - mandatory to distinguish among BSM models

Observables:

☑ Total cross-section $\sigma(e^+e^- \to t\bar{t})$

☑ Forward-Backward Asymmetry $A_{FB} = \frac{N(\cos\theta^* > 0) - N(\cos\theta^* < 0)}{N(\cos\theta^* > 0) - N(\cos\theta^* < 0)}$

☑ Double and Single Spin Asymmetries

$$A_{LL} = \frac{N(+,+) + N(-,-) - N(+,-) - N(-,+)}{N_{tot}}$$

$$A_L = \frac{N(-,-) + N(-,+) - N(+,+) - N(+,-)}{N_{tot}}$$

θ^* is the polar angle in the $t\bar{t}$ rest frame or the c.o.m. e+e- system
N(+,-) is the number of events with +1 (-1) helicity for top (antitop)

- Asymmetries are extracted as coefficients in the angular distribution of the top (antitop) decay products: ex. A_L and A_{LL} are related to the helicity angle distribution (see M.Vos talk)

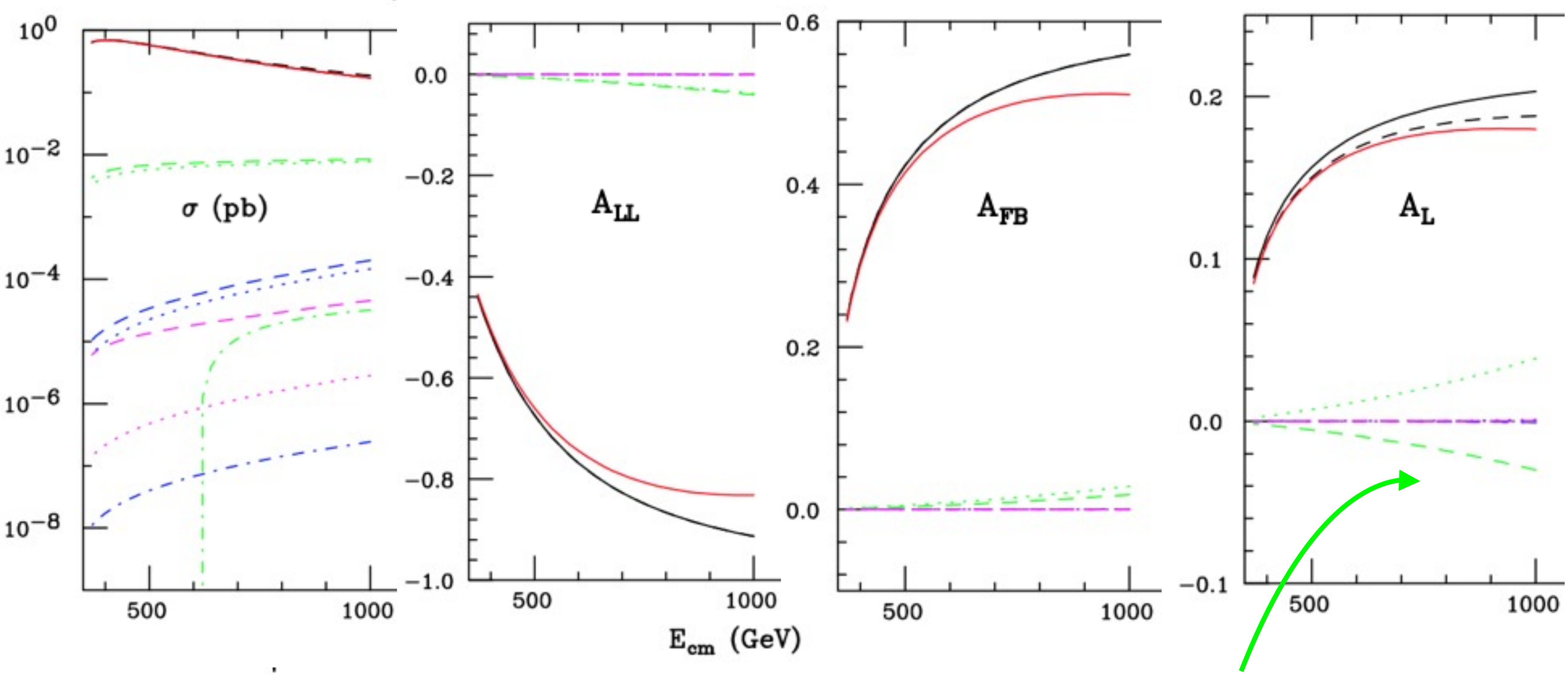
- Spin asymmetries or top polarization asymmetries focus on the helicity structure of the final state fermions (leptons from top (antitop) semi-leptonic decays are used as spin analyzers)

- A_L is sensitive to the relative sign of vector and axial couplings of Z and Z' to $t\bar{t}$

We define observables over the entire invariant mass spectrum of the tt system
The code used for our study is based on helicity amplitudes, defined through HELAS subroutines

Disentangling the effects

4DCHM: $M_\rho = f g_\rho = 3\text{TeV},\ \Gamma_{Z'}/M_{Z'} = 0.03$



solid: |SM|^2

dashed: |4DCHM|^2

solid: |SM'|^2 without Z's

dashed: Int(SM,Z2)

dotted: Int(SM,Z3)

the two Z' interference contributions are opposite sign for A_L and same sign for sigma, A_{LL}, A_{FB}

A_L is unique in offering the chance to separate Z_2 and Z_3 as they contribute in opposite directions