Composite Higgs Model parameter determination at the FCC-ee

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Based on:

DC, Redi,Tesi, JHEP 1204 (2012) 042

Barducci et al, JHEP 1304 (2013) 152; JHEP 1508 (2015) 127; JHEP 1607 (2016) 068

Janot, JHEP 1504 (2015) 182

DC, Janot, Moretti in preparation

FCC hh ee he 2nd FCC Physics Workshop

15-19 January 2018

CERN

Outline

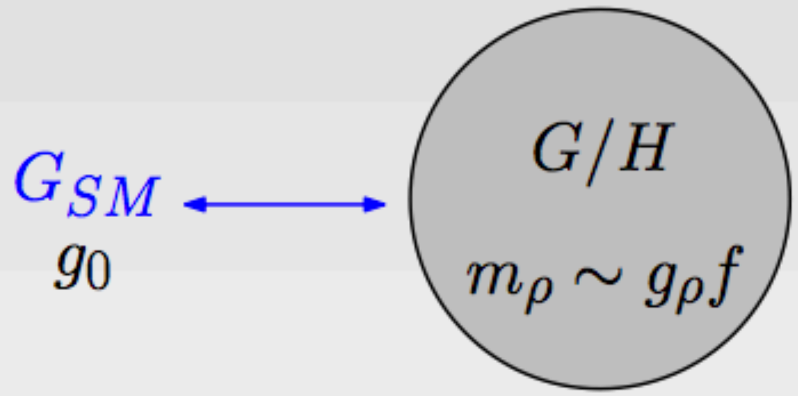
☑ We assess the scope of a Future Circular Collider operating in e+e- mode (FCC-ee) in determining the fundamental ingredients of Composite Higgs Models:

- Higgs coupling deviations
- New spin-1 resonances
- EW top-quark coupling deviations and modification of their L/R structure
- Partial compositeness of the quark-top (indirect evidence of heavy partners)

☑ We realise this program by using the 4-Dimensional Composite Higgs Model (4DCHM) as a realistic implementation of EWSB by a composite pseudo-Nambu Goldstone Boson (pNGB) Higgs emerging from SO(5)→SO(4)

☑ We establish the sensitivity of the FCC-ee to the parameter space of the model, still allowed after the foreseen direct and indirect bounds set by HL-LHC, via the processes $e^+e^- \to \mu^+\mu^-$, for several c.o.m. energies and $e^+e^- \to t\bar{t}$ at $\sqrt{s}$=365GeV

Higgs as a Composite Pseudo Goldstone Boson



Kaplan, Georgi '80s

f = scale of the breaking G →H

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?

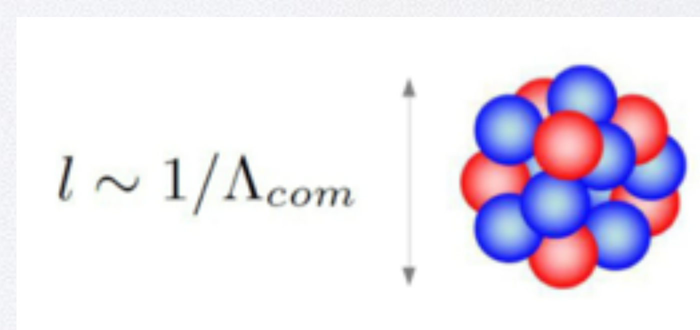
- G is only an approximate global symmetry $g_0 \;\rightarrow\; V(h)$
- EWSB as in the SM

small tuning f ~TeV

- And the hierarchy problem?

no Higgs mass term at tree level

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



Explicit Models in 4D

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

Linear elementary-composite couplings (partial compositeness)

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

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

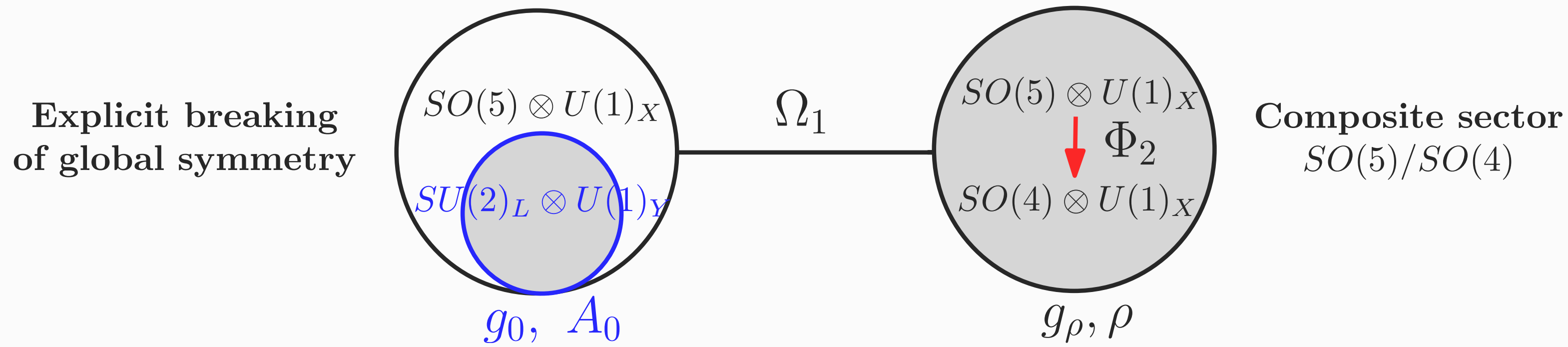
$m_W = 80\,\mathrm{GeV}$

0

} v

4DCHM = minimal 4D realisation of MCHM5

(DC,Redi,Tesi 2012) (Agashe,Contino,Pomarol 2004)



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

$$\Omega_i = e^{i\frac{f}{f_i^2}\Pi} \qquad \Pi = \sqrt{2} h^{\hat{a}} T^{\hat{a}} \qquad \mathbf{\Phi}_2 \equiv \Omega_2 \varphi_0 \ , \ \varphi_0^i = \delta_5^i \ , \qquad \sum_{n=1}^{2} \frac{1}{f_n^2} = \frac{1}{f^2}$$

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

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

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

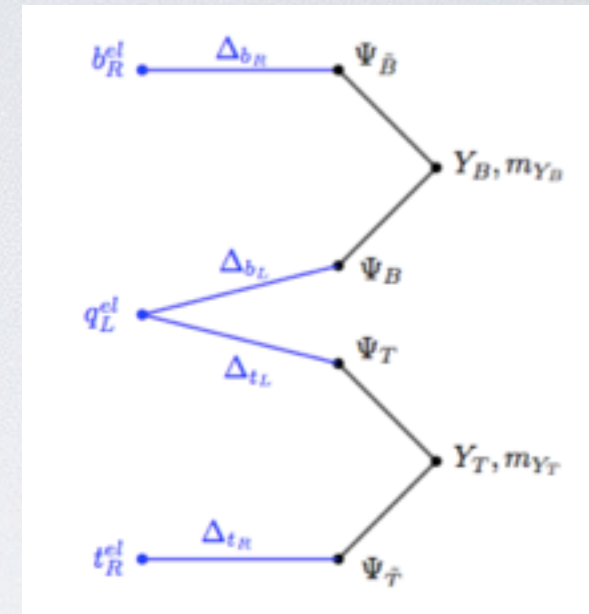
spin-1 resonances = gauge fields of SO(5) x U(1)

5 Z' + 3 W' (get mass by the SSB mechanism)

4 GB's (3 eaten by W,Z + 1 Higgs)

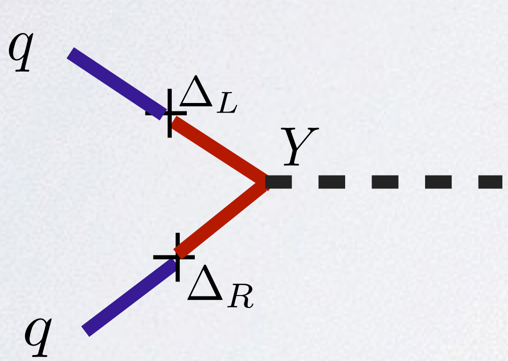
Partners of the third generation quarks

In the 4DCHM we include four 5-plets of extra fermions $\Psi_{T,\tilde{T}/B,\tilde{B}}$ to get an UV finite potential



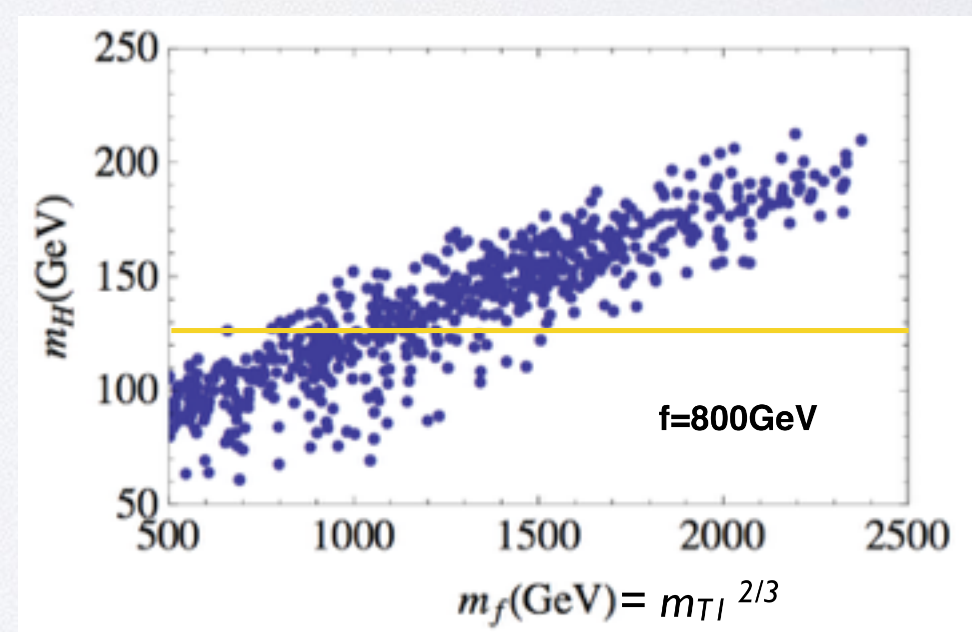
$$
\begin{aligned}
\mathcal{L}^{\mathrm{CHM}_5} = \mathcal{L}^{el}_{fermions} \\
&+ \Delta\, \bar{q}^{el}_L \Omega_1 \Psi_T + \Delta\, \bar{t}^{el}_R \Omega_1 \Psi_{\tilde{T}} + h.c. \\
&+ \bar{\Psi}_T (i \not{D}^\rho - m_T) \Psi_T + \bar{\Psi}_{\tilde{T}} (i \not{D}^\rho - m_{\tilde{T}}) \Psi_{\tilde{T}} \\
&- Y_T \bar{\Psi}_{T,L} \Phi_2^T \Phi_2 \Psi_{\tilde{T},R} - m_{Y_T} \bar{\Psi}_{T,L} \Psi_{\tilde{T},R} + h.c. \\
&+ (T \to B),
\end{aligned}
$$

Linear elementary-composite couplings (partial compositeness)



$$m_t \sim \frac{v}{\sqrt{2}} \frac{\Delta_{t_L}}{m_T} \frac{\Delta_{t_R}}{m_{\tilde{T}}} \frac{Y_T}{f}$$

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

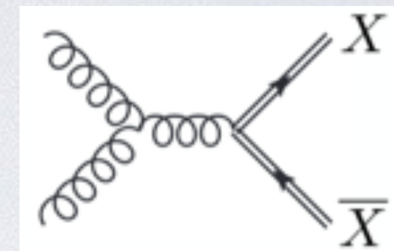


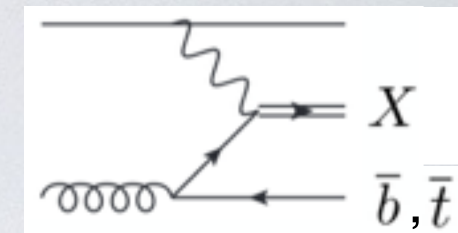
Extra-fermions of the model:
$T^{2/3}$ (#8) $B^{-1/3}$ (#8) $X^{5/3}$ (#2) $Y^{-4/3}$ (#2)
with masses in the TeV range

De Curtis, Redi, Tesi, JHEP 1204(2012)042

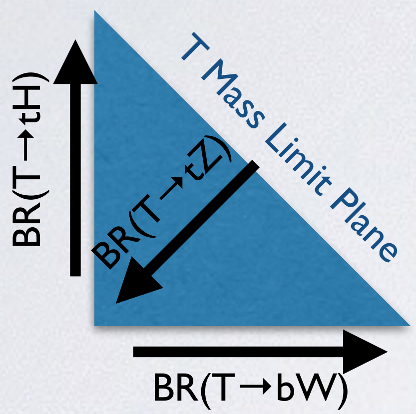
Lower bounds on the partners of the 3rd generation quarks by direct searches

Bounds from multiple topology searches: pair production (model independent) and associated single production (depends on the couplings)

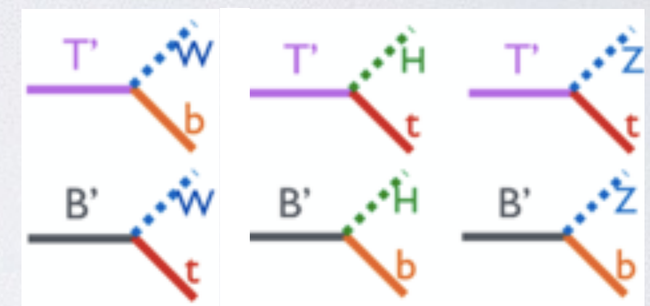


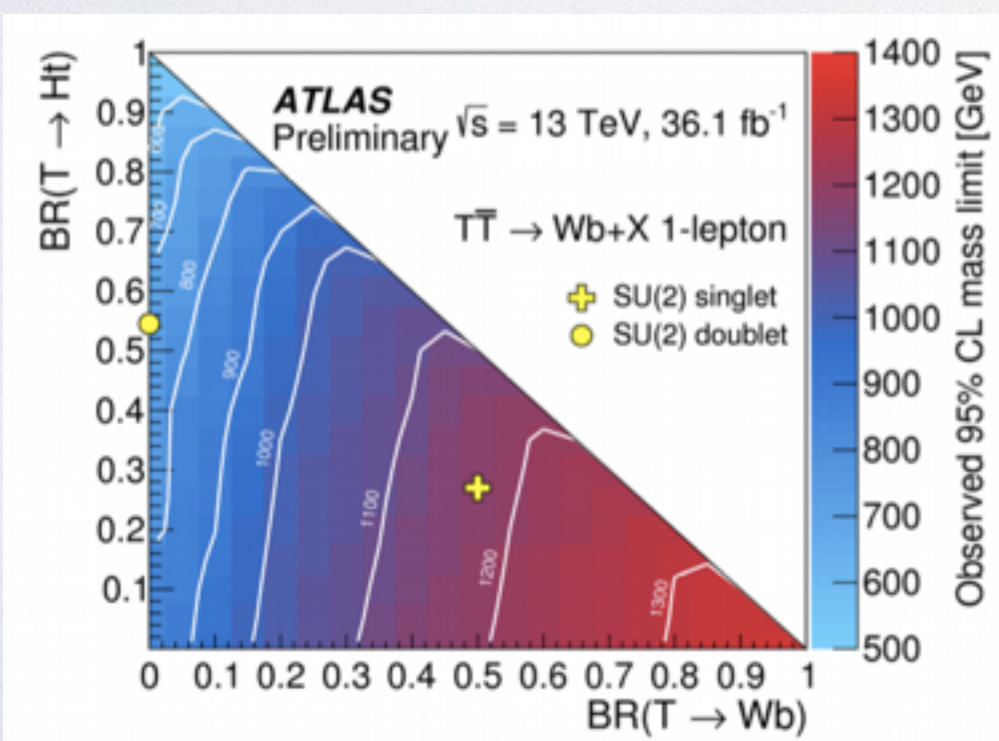


Pair production searches set σ x BR limits depending on the extra-fermion mass



In BSM scenarios one deals with multiple heavy extra quarks with generic decay channels





ATLAS-CONF-2016-14

- Significantly improved limits (Run1)
  - $m_{T/Y}$(Wb=100%) > 1350 (782) GeV
  - m_T (singlet) > 1170 GeV
  - $m_{B/X}$ (Wt=100%) > 1250 GeV
  - m_B(singlet) > 1180 GeV
- With 300/3000 fb-1 and augmented search techniques, expect to probe around 1.5 TeV with both single (depends on couplings) production searches

M. Narain talk, LFC17 ECT* Sept.2017

Bounds on Higgs compositeness
from Higgs coupling measurements and EWPO Fit

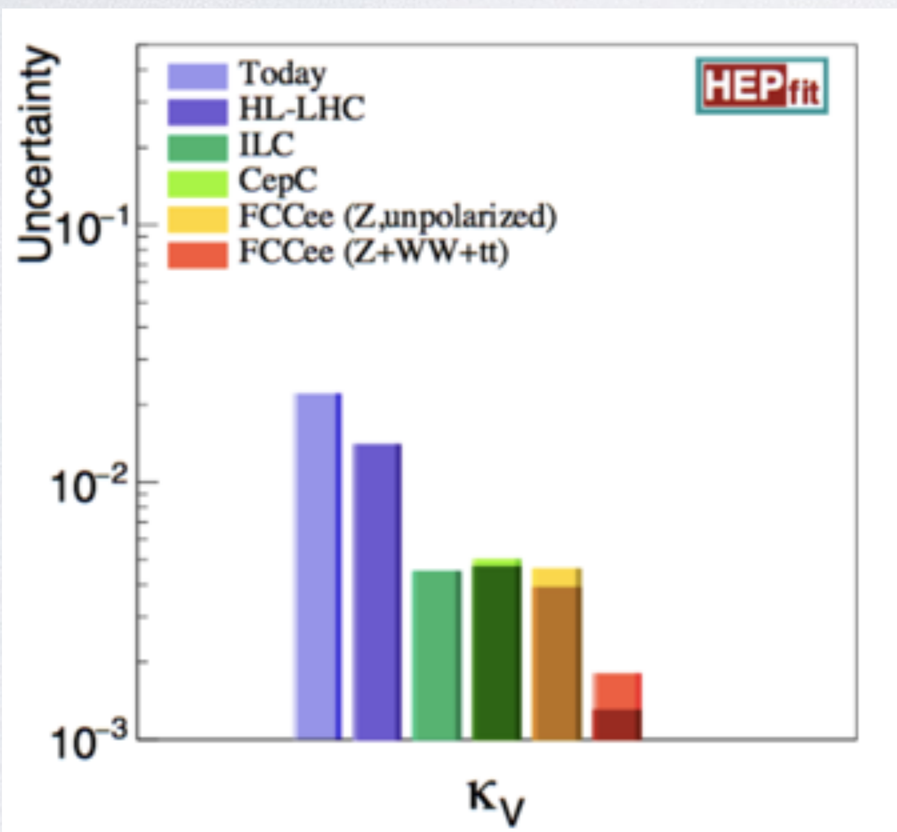
CMS Projection for precision of Higgs coupling measurement

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ
300	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]
3000	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]

factor 2-3 improvement from HL-LHC

The sensitivity increases with the EWPO fit

see Piccinini talk



light shaded areas consider the effects of theoretical uncertainty

J.De Blas et al.1611.05354

In Composite Higgs Models the Higgs couplings are modified

Ex. in SO(5)/SO(4) $\quad \dfrac{g_{HZZ}}{g_{HZZ}^{SM}} \sim \sqrt{1-\xi}$

$\xi < 0.03$ after HL-LHC
$\xi < 0.008$ after ILC/CepC
$\xi < 0.002$ after FCC-ee

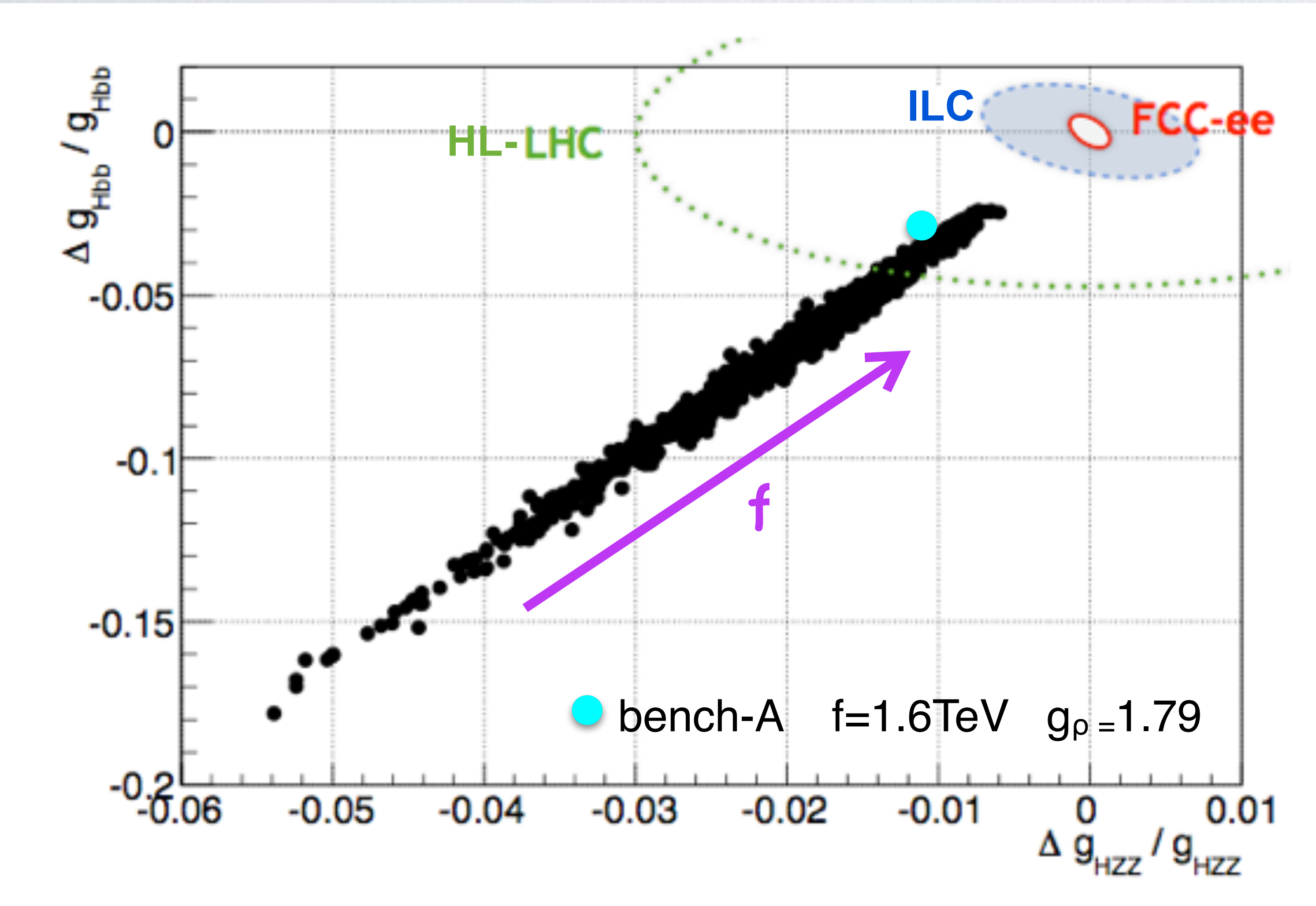
$$\xi = \frac{v^2}{f^2}$$

f > 5-6 TeV

4DCHM : Higgs coupling deviations

Deviations expected for HZZ and Hbb couplings in the 4DCHM compared with the relative precision expected at HL-LHC, ILC, FCC-ee

Barducci et al. JHEP 1309(2013)047
Janot PoS EPS HEP2015,333 (2015)



f = compositeness scale

$0.75 \leq f\ (\text{TeV}) \leq 1.6$

g_ρ = strong coupling

$1.5 \leq g_\rho \leq 3$

scan over the 4DCHM fermion parameters

$$\frac{g_{HZZ}}{g^{SM}_{HZZ}} \sim \sqrt{1-\xi}$$

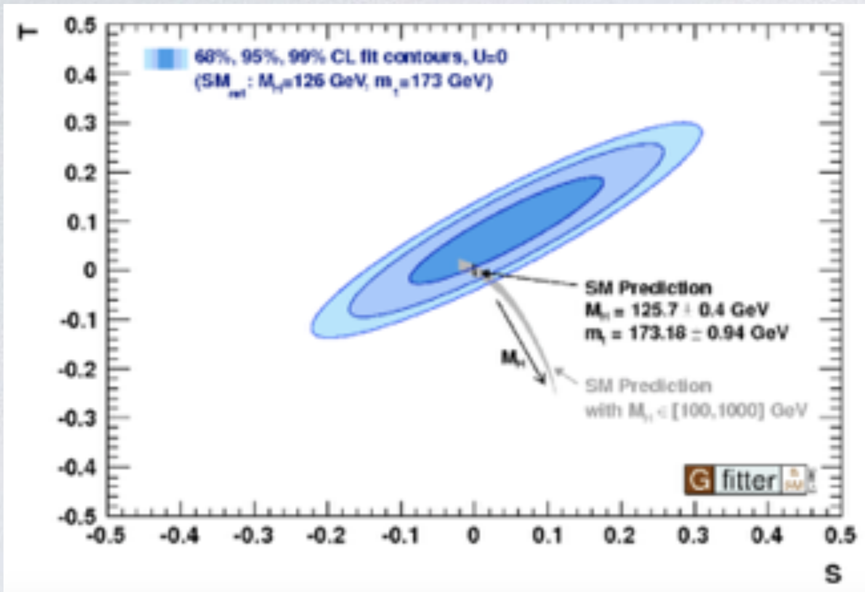
$$\frac{g_{Hbb}}{g^{SM}_{Hbb}} \sim \frac{1-2\xi}{\sqrt{1-\xi}} \qquad \xi = \frac{v^2}{f^2}$$

4DCHM black points: $M_{Z'} \sim f g_\rho > 2$ TeV and M_T >800GeV, $M_{5/3}$ >900GeV

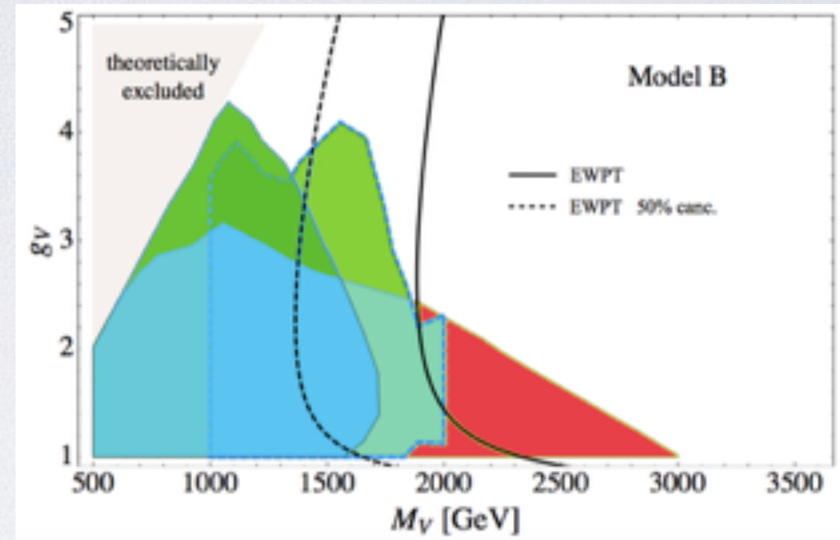
FCC-ee will be able to discover bench-A with a 10σ significance!!

Bounds from the Oblique Parameters S,T,W,Y

see Panico talk

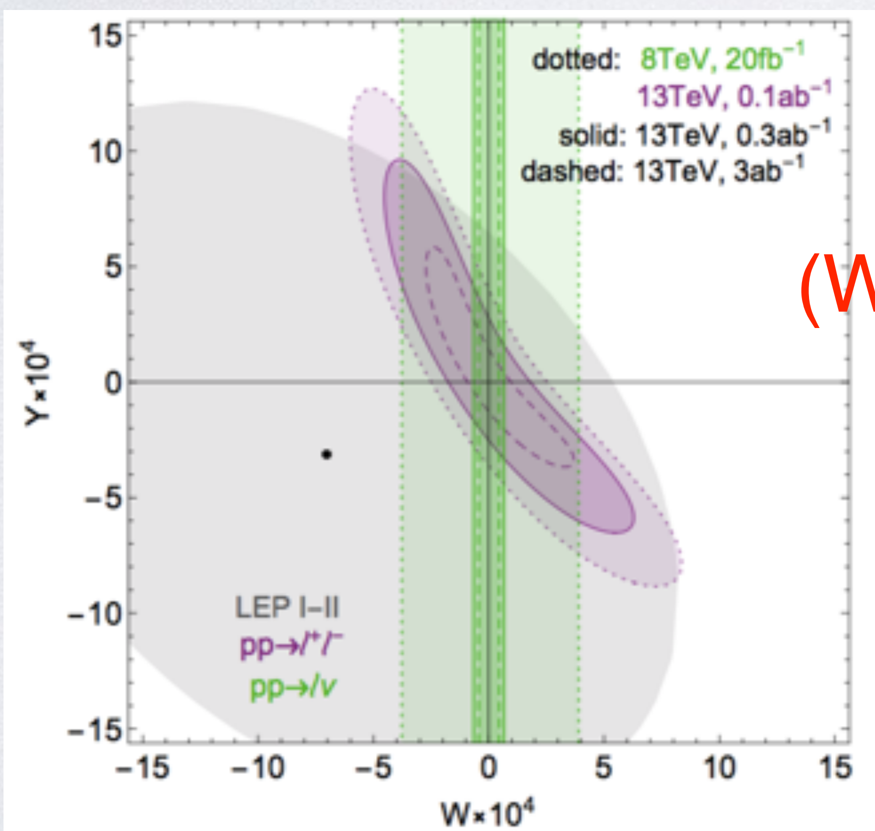


(S,T)



M_V > 2TeV

Pappadopulo et al.JHEP09(2014)060



HL-LHC bounds: $|W| < 0.045 \times 10^{-3}\,, \ |Y| < 0.08 \times 10^{-3}$

Farina et al. Phys.Lett.B772(2017)210

(W,Y)

WARNING

Attention should be paid in translating the bounds on the “tail" parameters W,Y to (M_V,g_V) plane

The tails can reserve surprises (depletion of events)

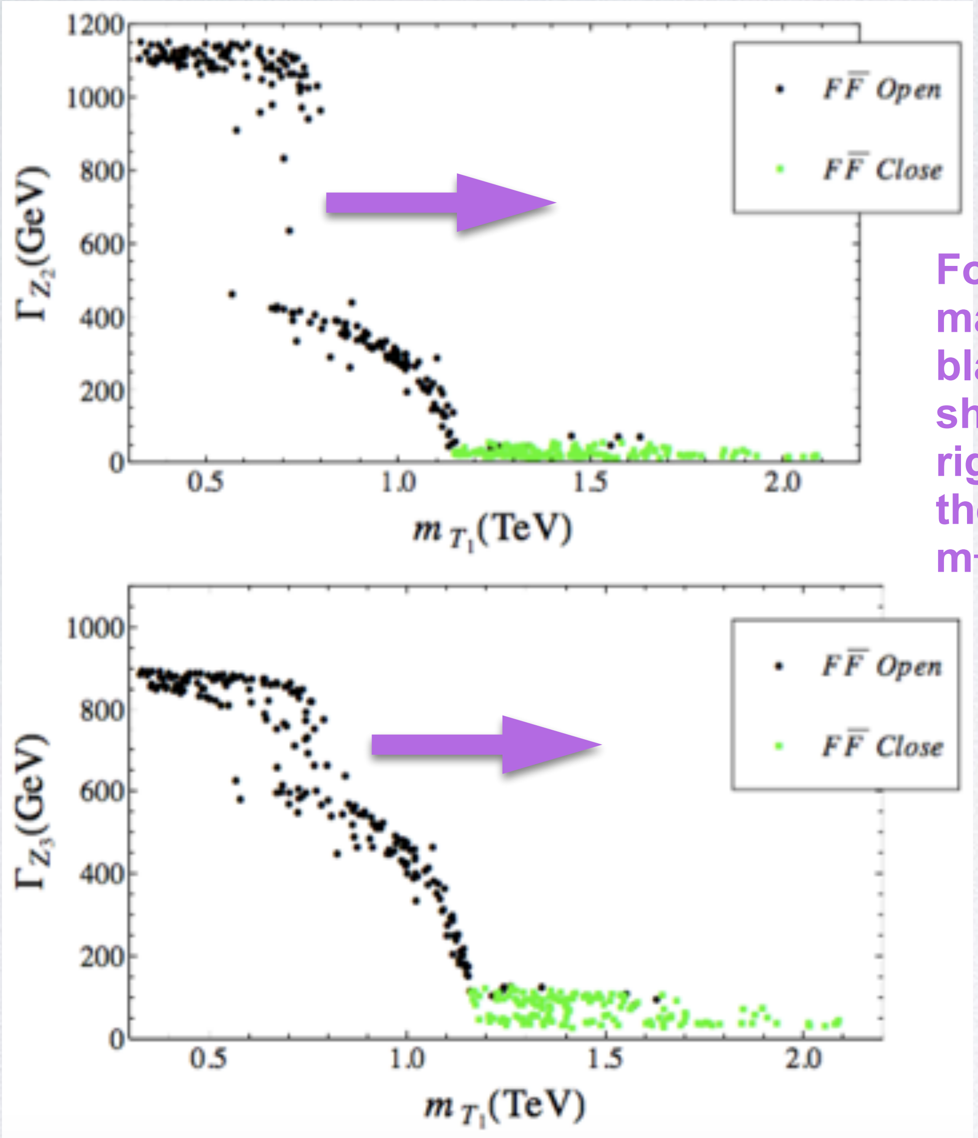
(Accomando et al.JHEP1607(2016)068, Alioli at al.1712.02347)

model independent analyses can fail

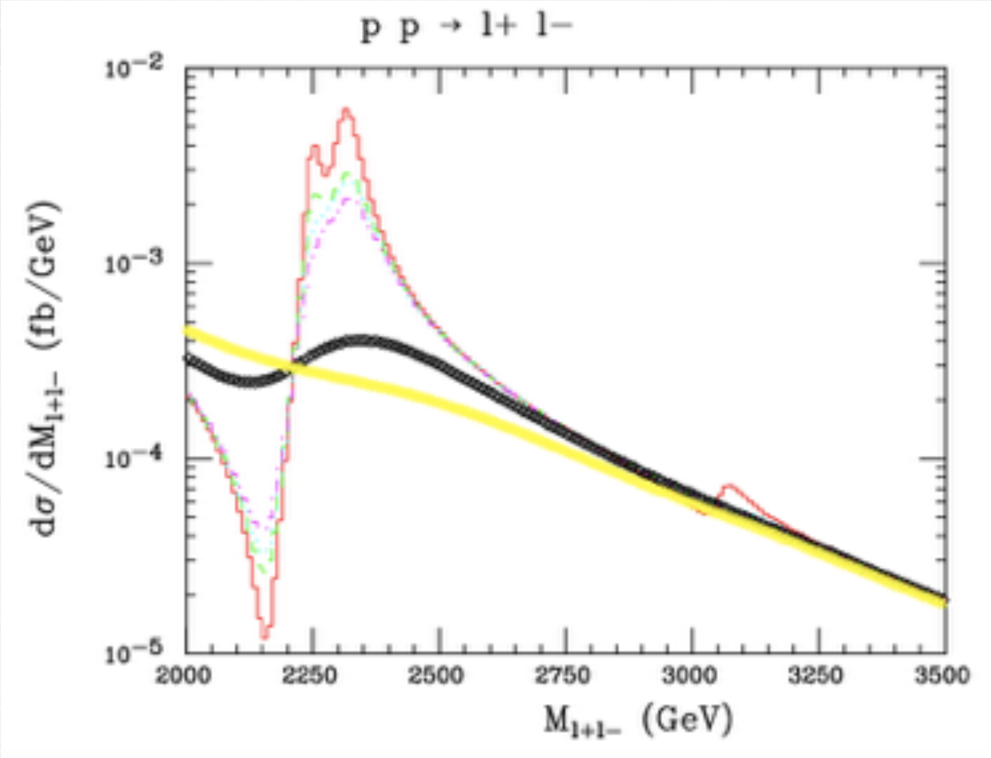
Calculating significance, neutral channel DY at the LHC

Three ingredients to be taken into account:

- ☑ finite widths of the new massive vectors (large width if $Z' \to \bar{T}T$)
- ☑ multi-Z' signal, typical of CHMs
- ☑ interference effects



For larger Z' masses the black points shift to the right up to the threshold $m_T = m_{Z'}/2$



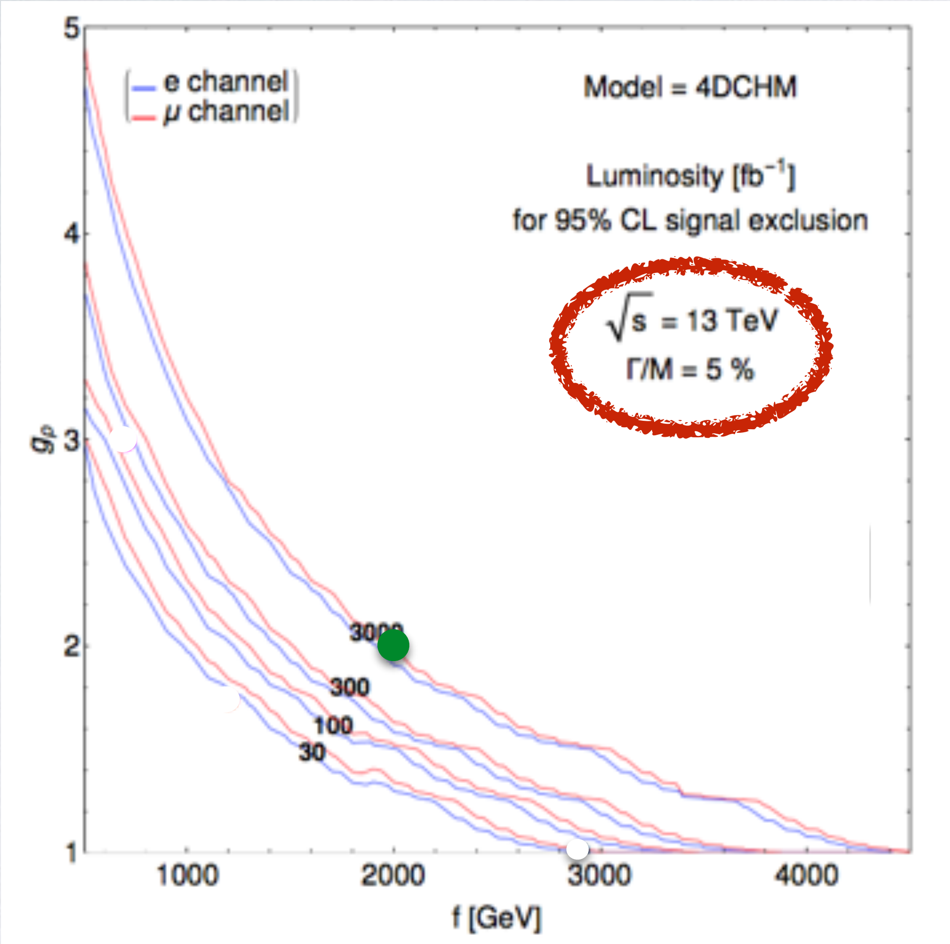
Differential distribution in the lepton invariant mass for 6 different choices of the Z's widths: Γ/M ~ 2% (red); 3%(green, cyan); 4% (magenta) ; 20% (black); **> 40% (yellow)**

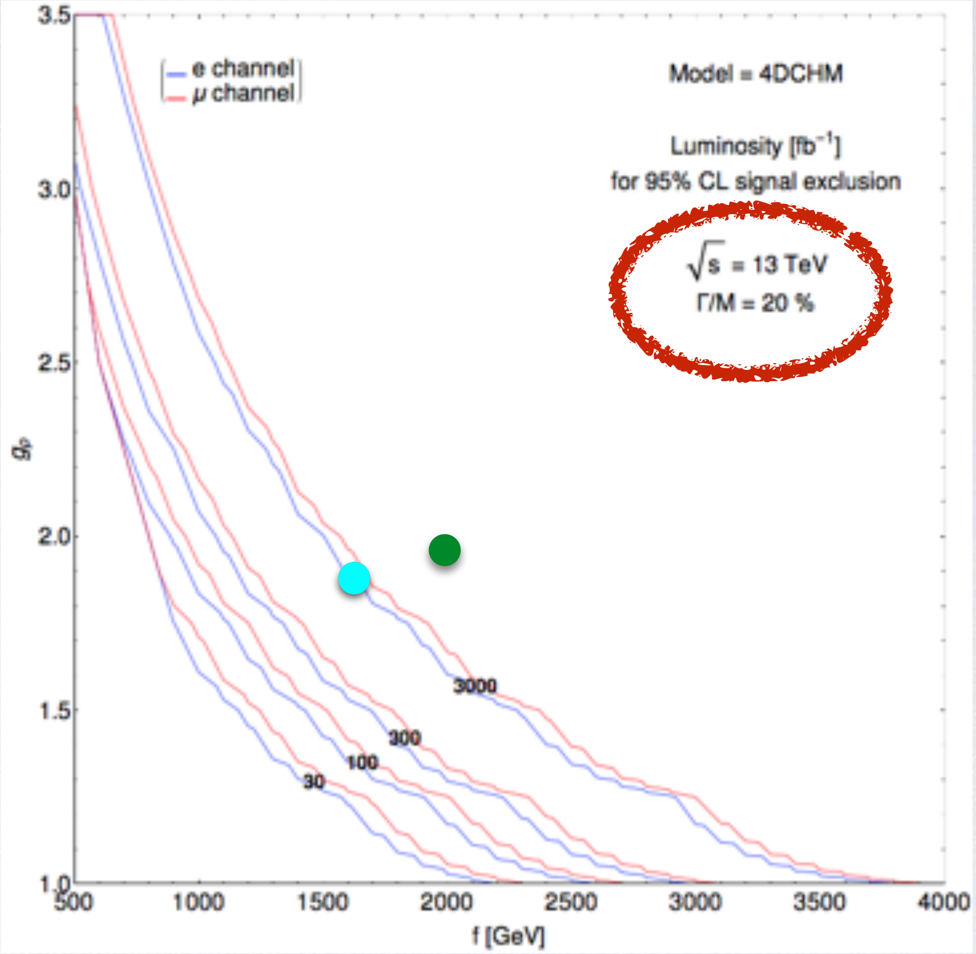
f=1200 GeV g*= 1.8
MZ2=2249GeV MZ3=2312GeV

Notice the very pronounced dip before the peaks due to the interference (much more pronounced for multi-Z')

Barducci et al.JHEP 1304(2013)152

Calculating significance, neutral channel DY at the LHC-13TeV





Projected 95%CL exclusion limits for the 4DCHM with Γ/M=5% and Γ/M=20% for electron/muon channel and different integrated luminosity values

Accomando et al.JHEP1607(1016)068

Events within the crossing point (where the signal intersects the SM expectation) and $M_{Z3}+3\Gamma_{Z3}$
(model dependent optimization)

Ex. g_ρ =2 and f=2TeV is at the border of the exclusion limit for HL-LHC if Γ/M=5% but it is still allowed if Γ/M=20%

Analysis at the FCC-ee is based on bench-A

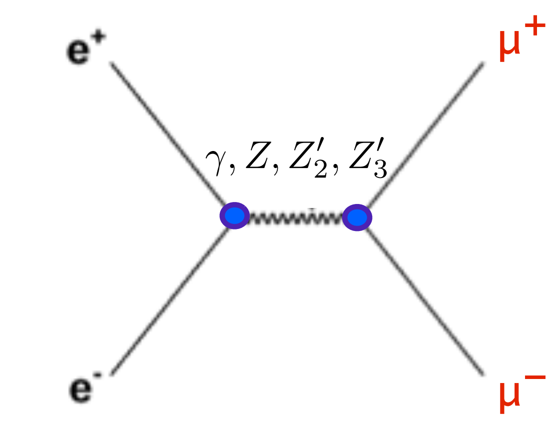
High-precision at low energy
Can new physics be hiding in tails?

$e^+e^- \to \mu^+\mu^-$ at FCC-ee

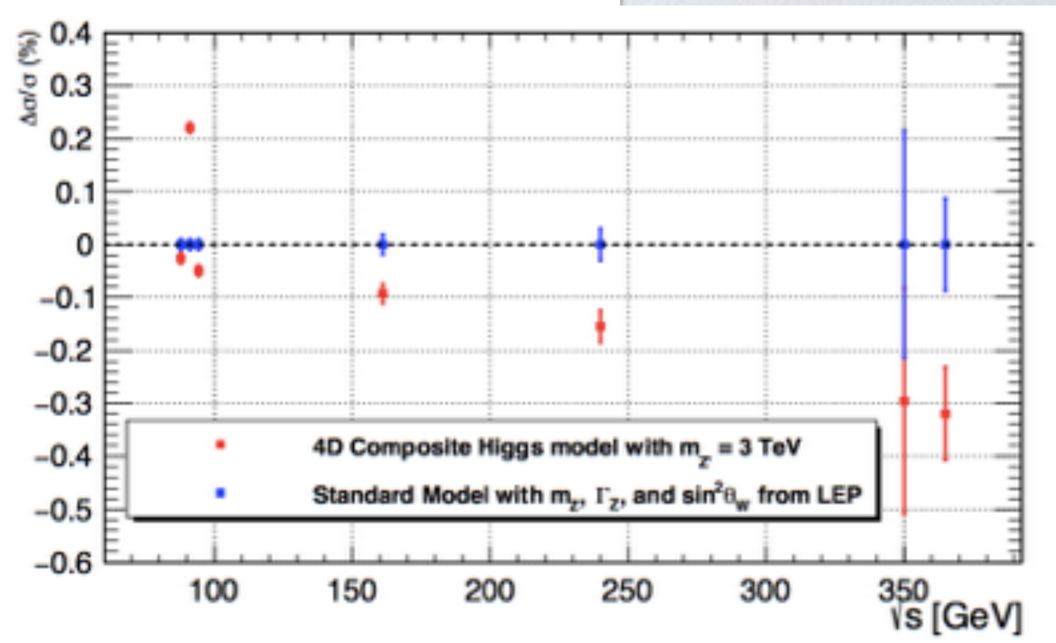
DC,Moretti,Janot in preparation

Analysis based on **cross sections** and **A_{FB}** at **87.9, 91.2, 94.3, 161, 240, 350**, and **365 GeV** c.o.m energies with the FCC-ee design luminosities at each energy point:

- 150 ab-1 at and around the Z pole
- 10 ab^{-1} at the WW threshold
- 5 ab^{-1} at the HZ maximum
- 0.2 ab^{-1} at the ttbar threshold
- 1.5 ab^{-1} at 365 GeV



- Zee coupling modification
- Z' propagator effects



The uncertainties included are:

- statistical
- theory systematics: 10^{-4} for the luminosity determination (Bhabha cross section), and 5×10^{-5} for A_{FB}
- beam energy determination: precision of 100 keV at the Z pole and the WW threshold, and of 5 MeV above

1000 "gedanken experiments" produced, with cross section and A_{FB} smeared according to their uncertainties. **The measured values are fitted to the 4DCHM parameters**

The fitted parameters are:
- f = the compositeness scale
- θ, ψ = mixing angles of Z_2 and Z_3
- M_Z, Γ_Z

All the other parameters follow from the model constraints, ex.

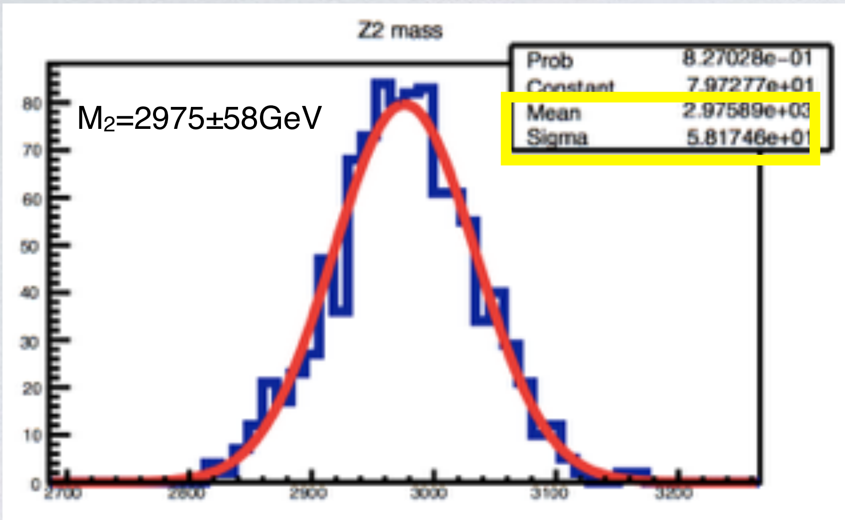
$$M_{Z_2}^2 \simeq \frac{f^2 g_*^2}{c_\psi^2}\left(1 - \frac{s_\psi^2 c_\psi^4}{4c_{2\psi}}\xi\right)$$

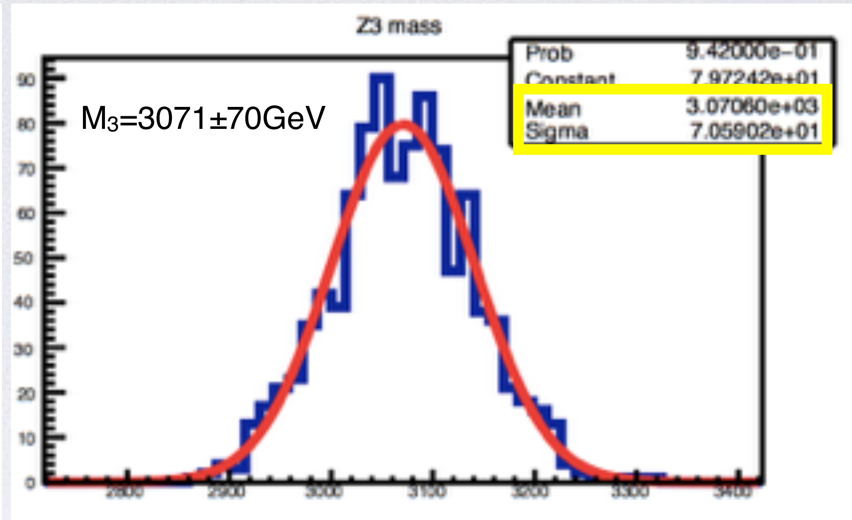
$$M_Z^2 \simeq \frac{f^2}{4} g_*^2\left(s_\theta^2 + \frac{s_\psi^2}{2}\right)\xi$$

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

$e^+e^- \to \mu^+\mu^-$ FCC-ee - fit to 4DCHM - bench-A

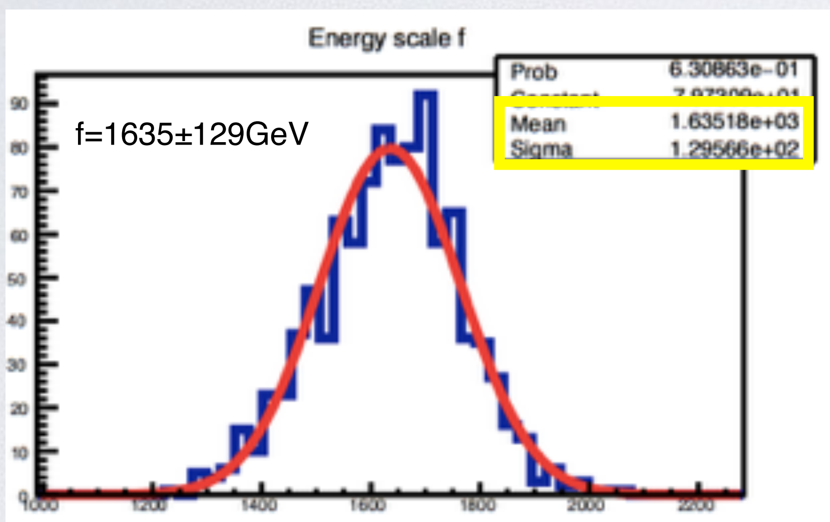
(P.Janot)

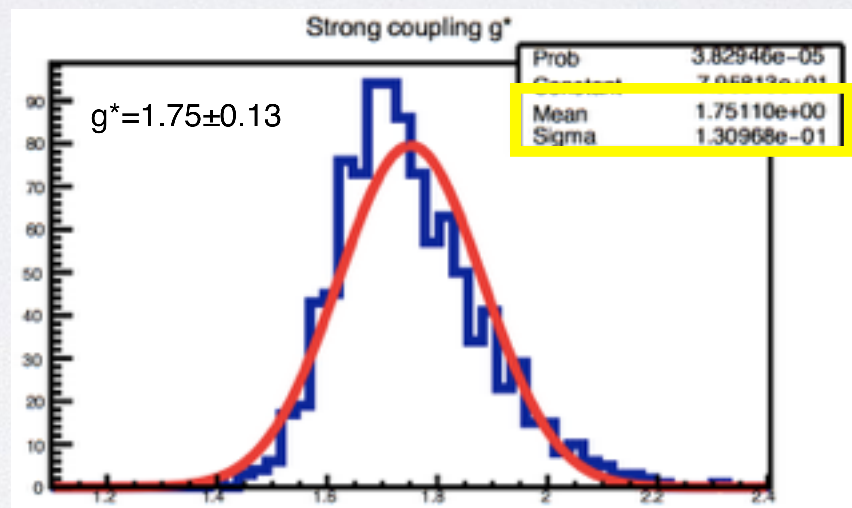




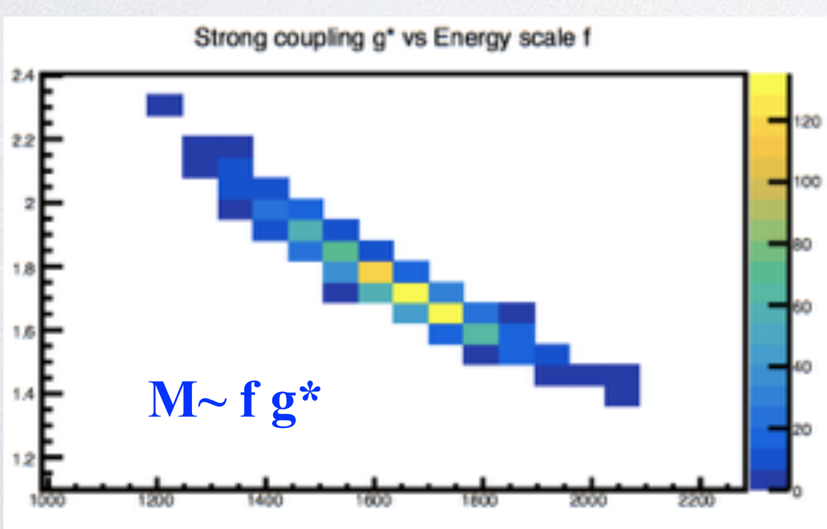
M_{Z2}=2980.1GeV
M_{Z3}=3066.5GeV

The plots show the total uncertainty on each of the parameters, not fixing the other parameters to their central value

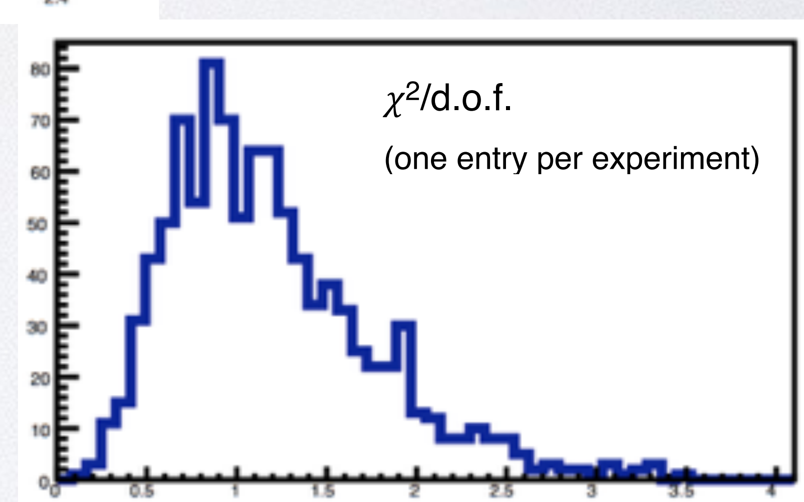




f=1600.2 GeV
g*=1.787

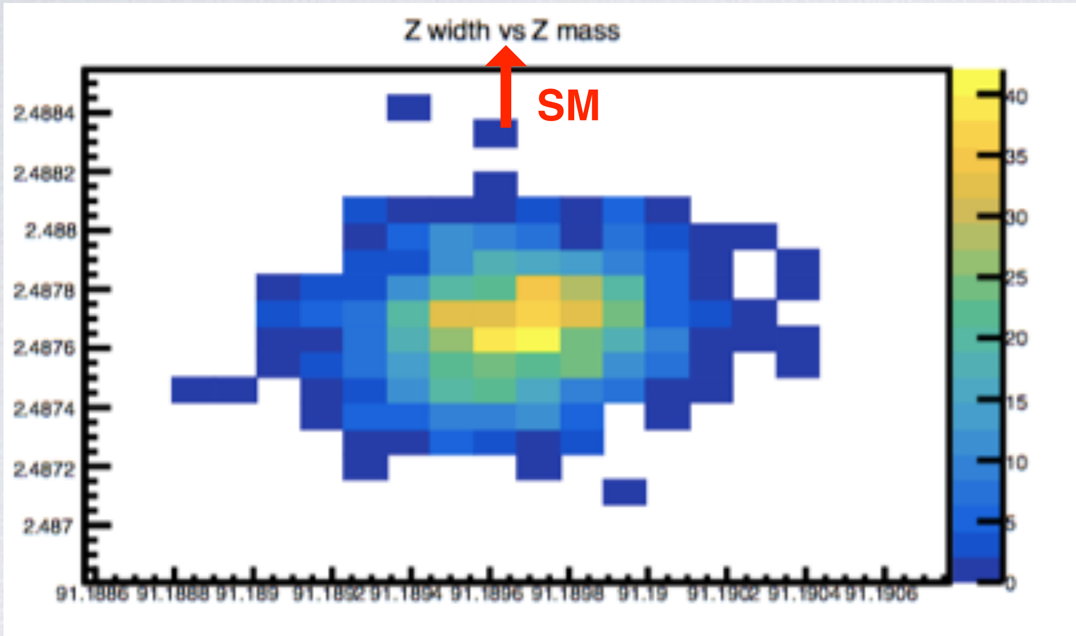


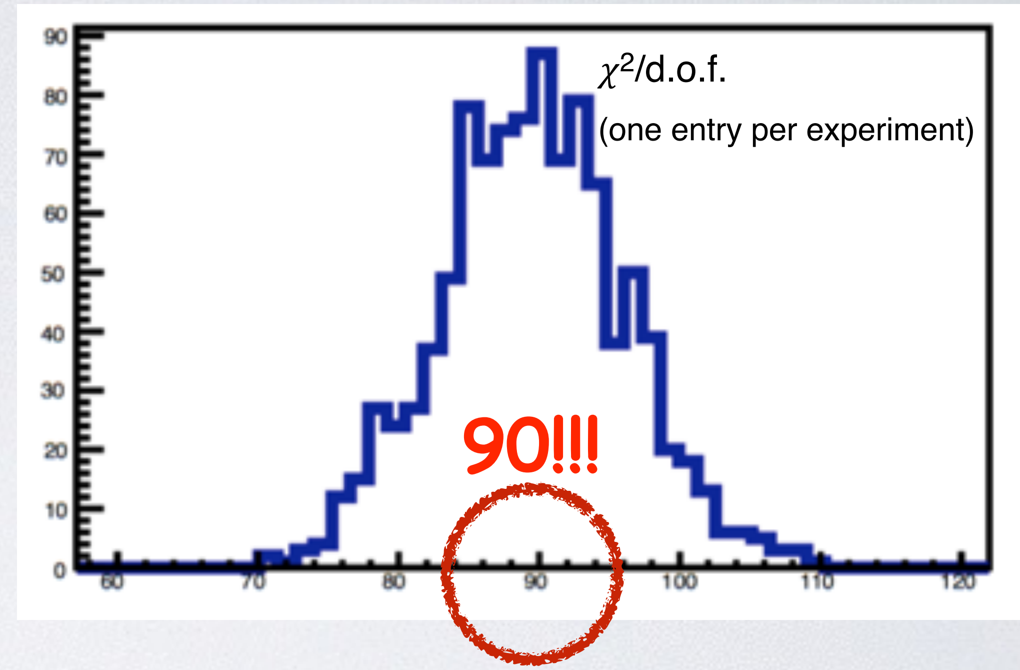
Strong correlation between f and g* : at the leading order the deviations depend on (f g*)



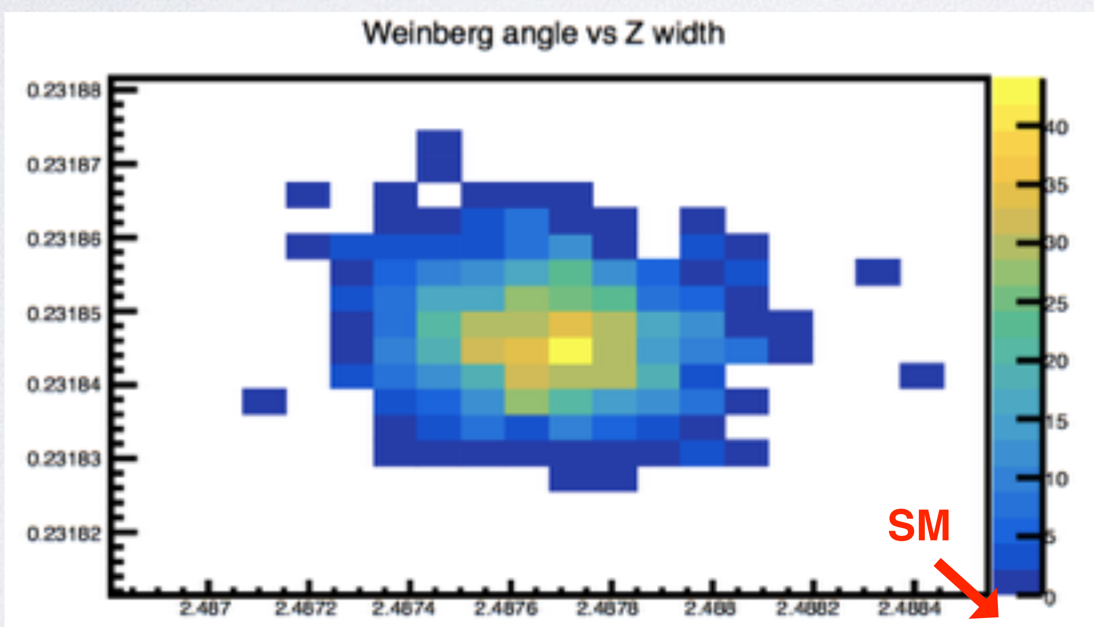
VERY GOOD QUALITY of THE FIT

$e^+e^- \rightarrow \mu^+\mu^-$ - 4DCHM fit to SM with FCC-ee statistics





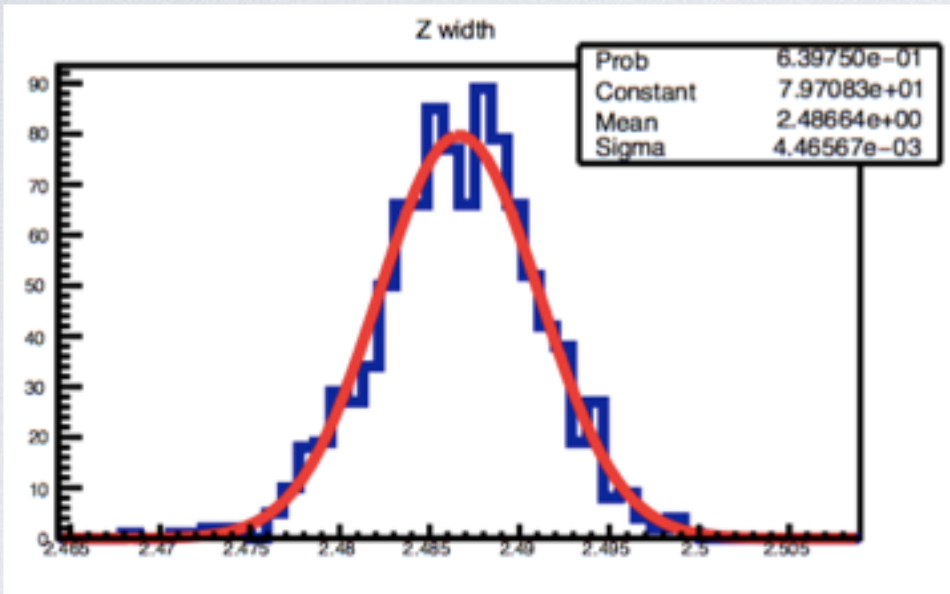
The χ^2/d.o.f. is 90, meaning that the muon data would deviate from the SM by **almost 10 sigma** at the FCC-ee.

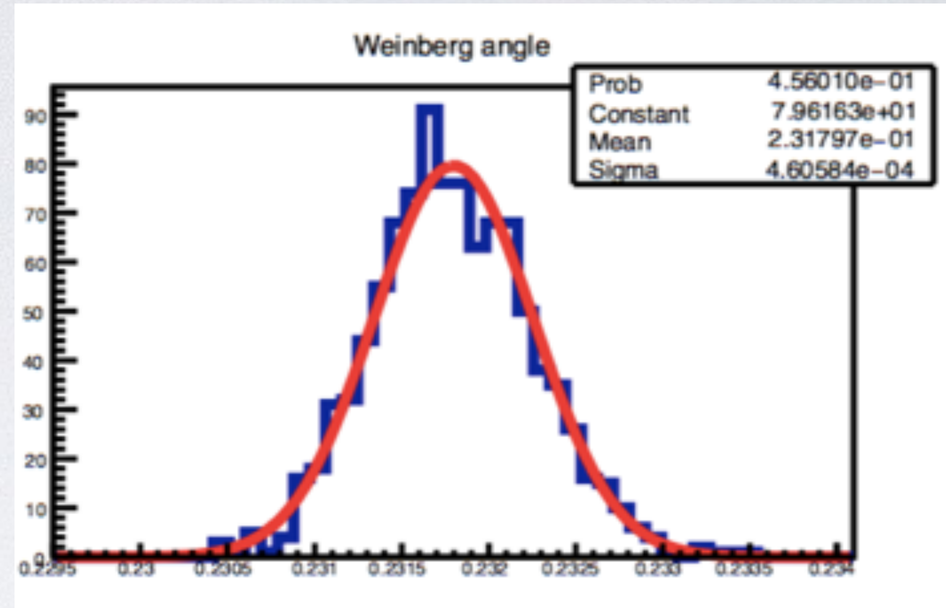


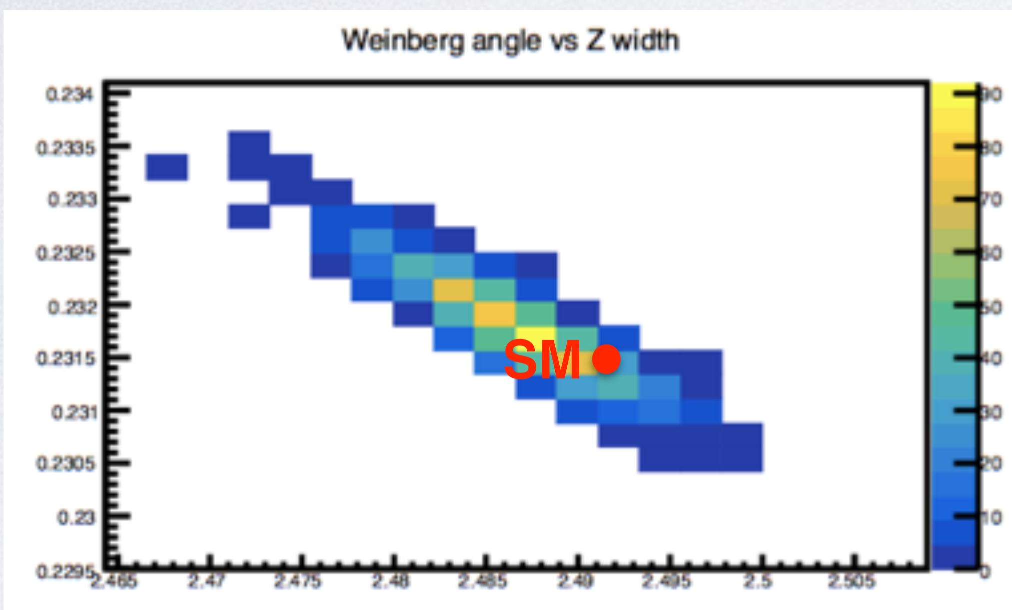
the coloured areas in the 2D plots are roughly the 3-sigma ellipses (1000 experiments generated)

The SM values lie very far outside the 3-sigma ellipses

$e^+e^- \to \mu^+\mu^-$ - 4DCHM fit to SM with LEP statistics -

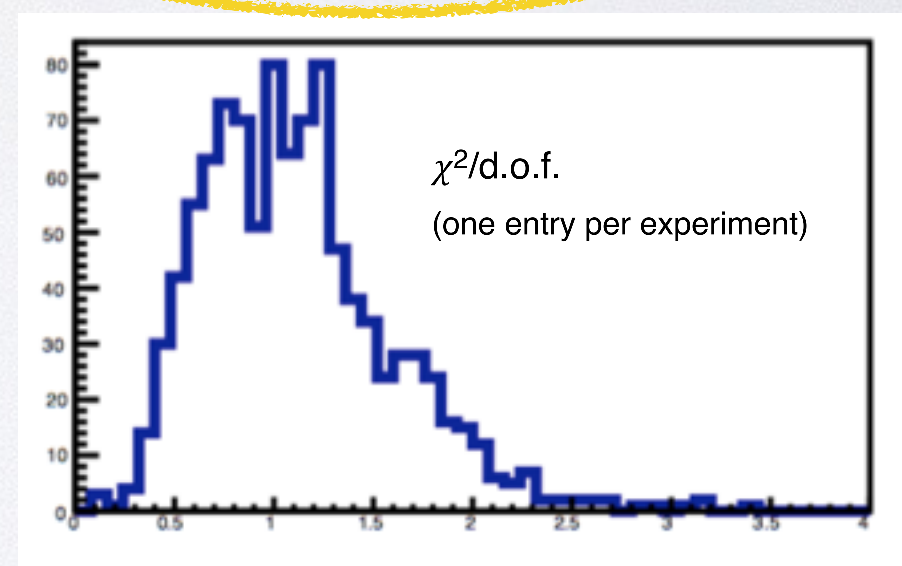






The χ^2/d.o.f. is around 1 meaning that bench-A passed the LEP scrutiny

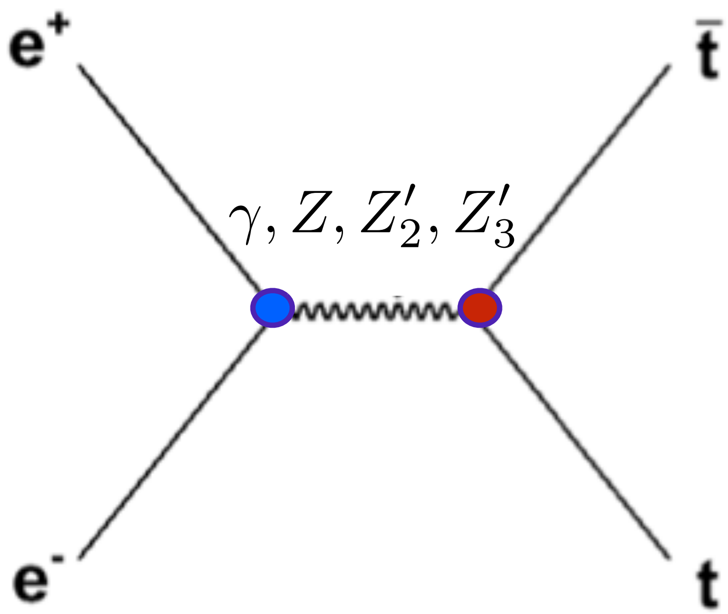
The SM values lie close to the border of the 1-sigma ellipse



the coloured areas in the 2D plots are roughly the 3-sigma ellipses (1000 experiments generated)

VERY GOOD QUALITY of THE FIT

4DCHM parameter determination using $\sigma(e^+e^- \to t\bar{t})$



By using the muon observables we were able to extract f, θ, ψ, g^* from which we get (lepton universality):

- ☑ modification of the Zee couplings and the Z'ee ones
- ☑ the masses M_{Z2} and M_{Z3} (their widths do not play any role at the FCC-ee energies)

Can we have some hint of the "partial compositeness" paradigm generally invoked in CHMs?

Use the double differential cross-section for top-pair production close to the threshold

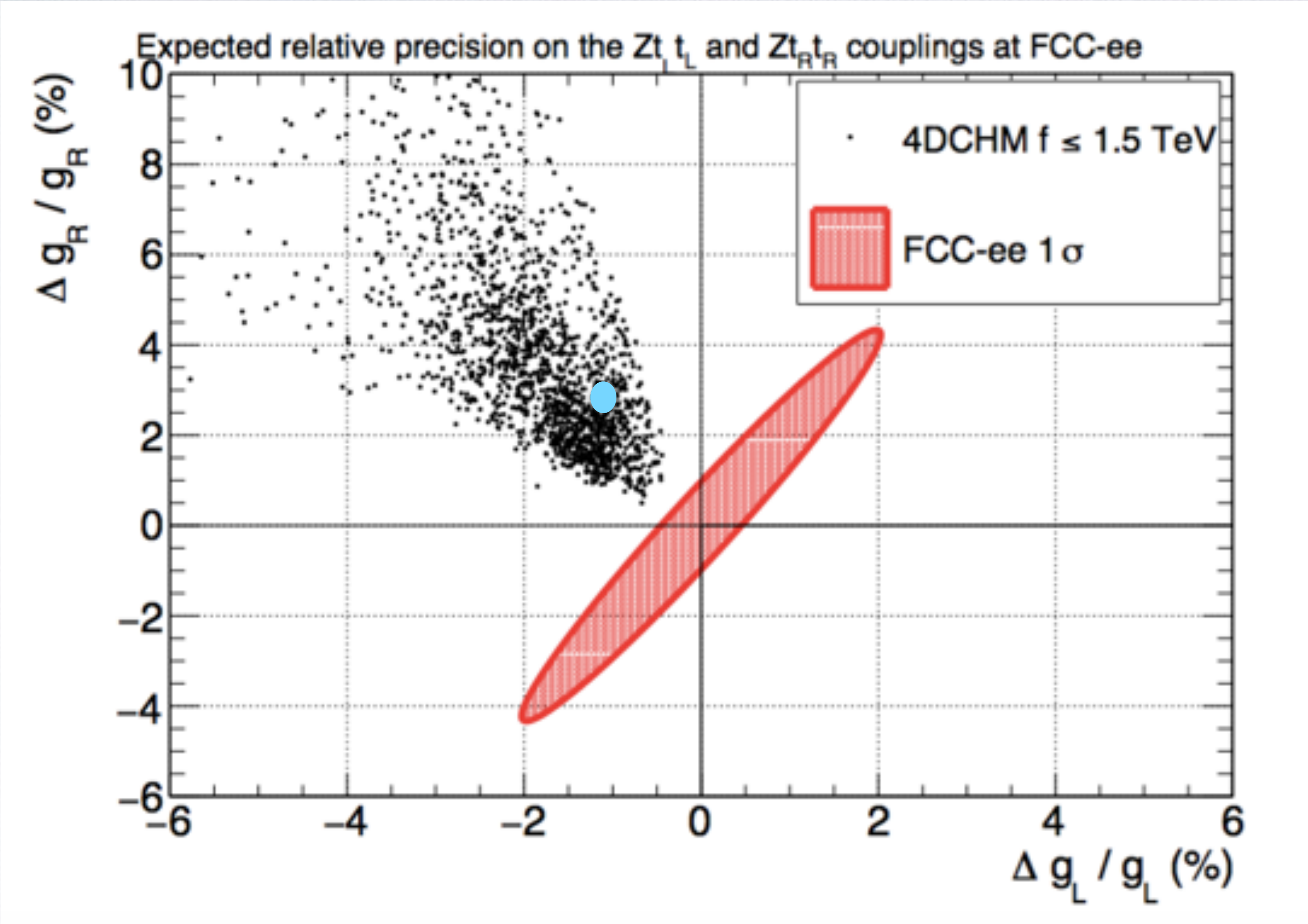
The modifications of the process now arise via 3 effects:

- ☑ modification of the Zee coupling (known from $\mu^+\mu^-$)
- ☑ the s-channel exchange of the Z's (interference)
- ☑ modification of the Ztt coupling from: mixing between Z and Z's + mixing between top and extra fermions (partial compositeness)

Top-quark EW coupling determination at the FCC-ee

Various BSM models predict large deviations in the top EW couplings

Ex. Zt_Lt_L, Zt_Rt_R 4DCHM (●) (Barducci, et al 1504.05407)



$$g_{R,L} = e(F_{1A}^Z \pm F_{1V}^Z)$$

f = compositeness scale

0.75 ≤ f (TeV) ≤ 1.5

g_ρ = strong coupling

1.5 ≤ g_ρ ≤ 3

scan over the 4DCHM fermion parameters M_T>900GeV

● bench-A ($M_{Z'}$~3TeV, M_T~1.4TeV

Expected relative precision on the top EW couplings by using a fully simulated e+e- collisions at 365 GeV for an integrated luminosity of 1.6 ab^{-1} corresponding to ~4 years of running

(Foppiani 1703.01626)

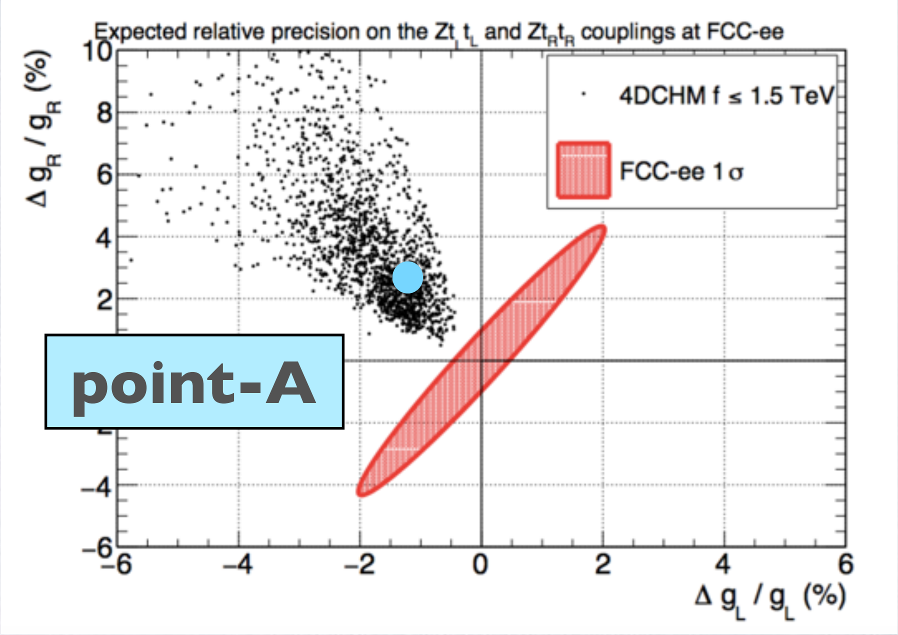
In agreement with the optimal-observable analysis of the lepton angular and energy distributions from top-pair production with semi-leptonic decays

Janot, JHEP 1504 (2015) 182;
PoS EPSHEP 2015,333 (2015)

Top-quark EW coupling determination at the FCC-ee for a 4DCHM benchmark point

f =1.6TeV, g_ρ =1.8, m*=2.6TeV

M_{Z2}=2980.1GeV **M_{Z3}=3066.5GeV**
Γ/M=20%



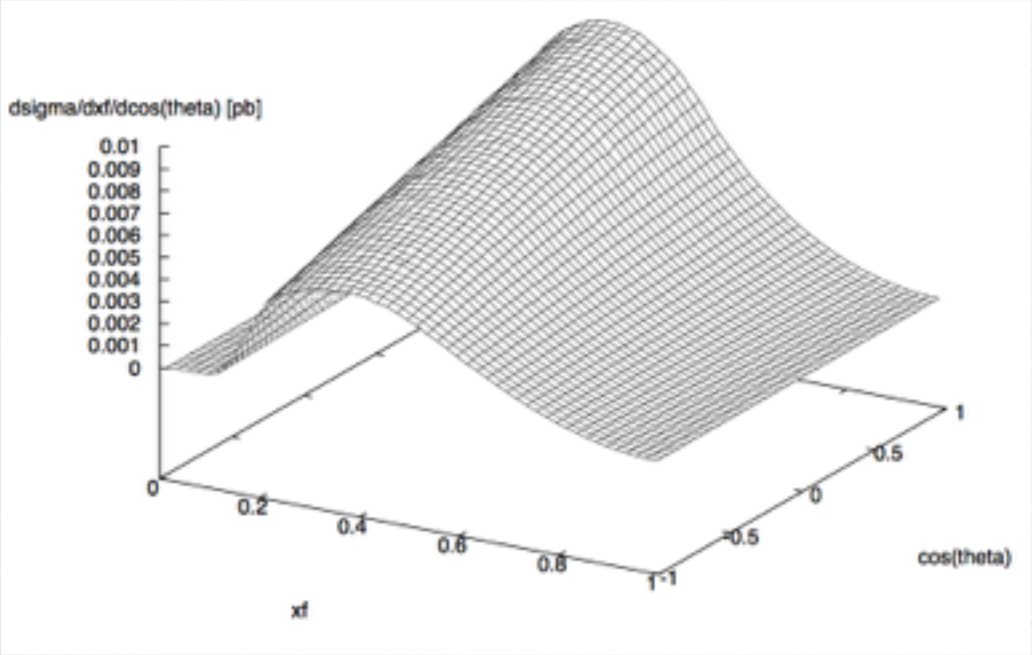
top EW coupling deviations

$\Delta g^{\gamma}_L = \Delta g^{\gamma}_R = 0$
$\Delta g^Z_L = -0.0022$
$\Delta g^Z_R = -0.0027$

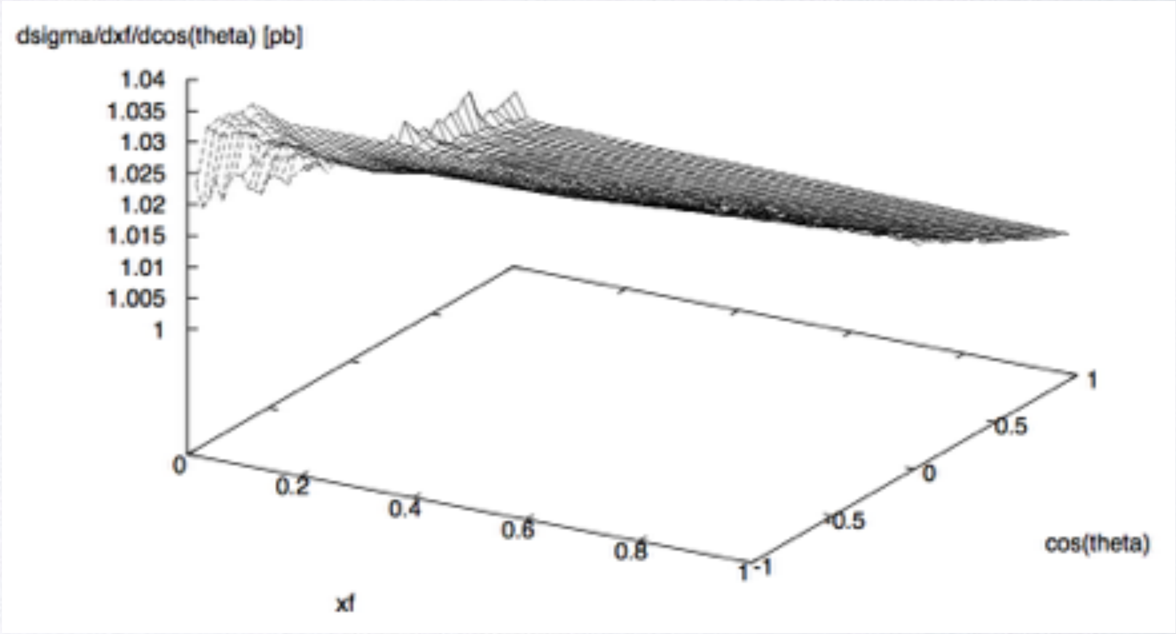
→

$\Delta g^Z_L / g^Z_L (\%) = -0.9$
$\Delta g^Z_R / g^Z_R (\%) = 2.4$

$$e^+e^- \to \gamma, Z, Z' \to t\bar{t} \to b\bar{b}W^+W^- \to b\bar{b}l^+l^-\nu\bar{\nu}$$



(S.Moretti)



$$\frac{d^2\sigma_{\rm SM}}{dx d\cos\theta}$$

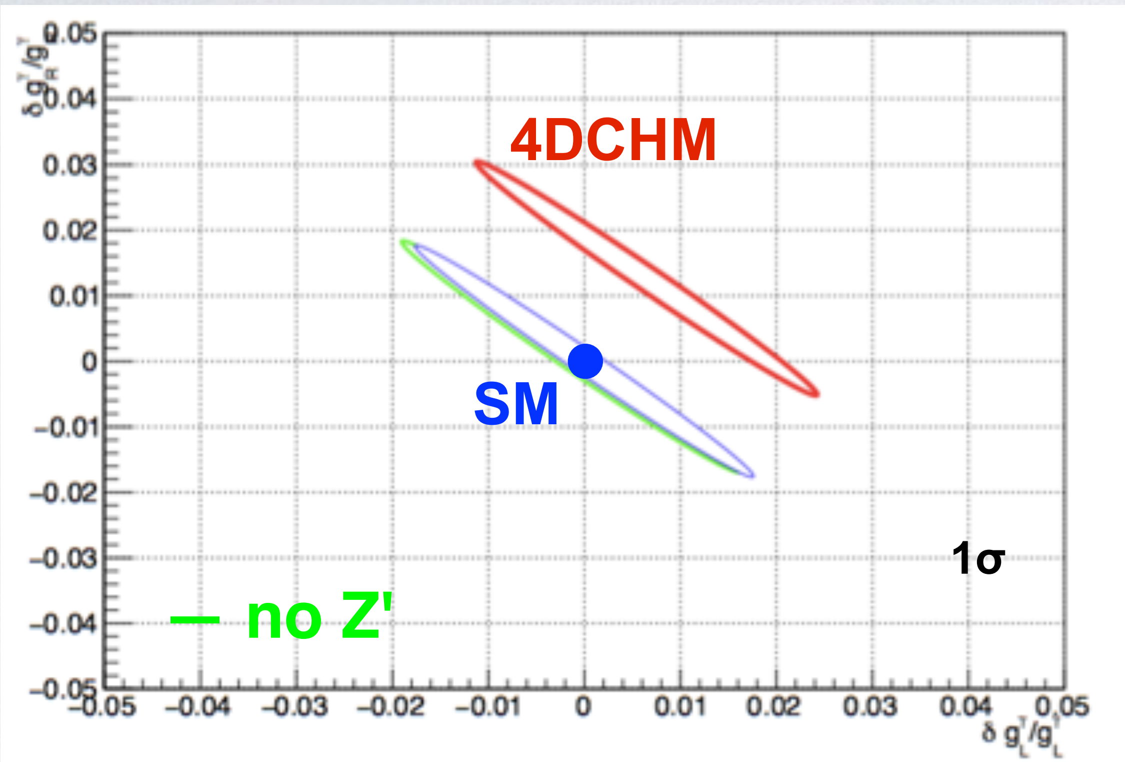
x = reduced lepton energy
θ = lepton polar angle in the tt pair rest frame

$$\frac{d^2\sigma_{\rm 4DCHM}}{dx d\cos\theta} \Big/ \frac{d^2\sigma_{\rm SM}}{dx d\cos\theta}$$

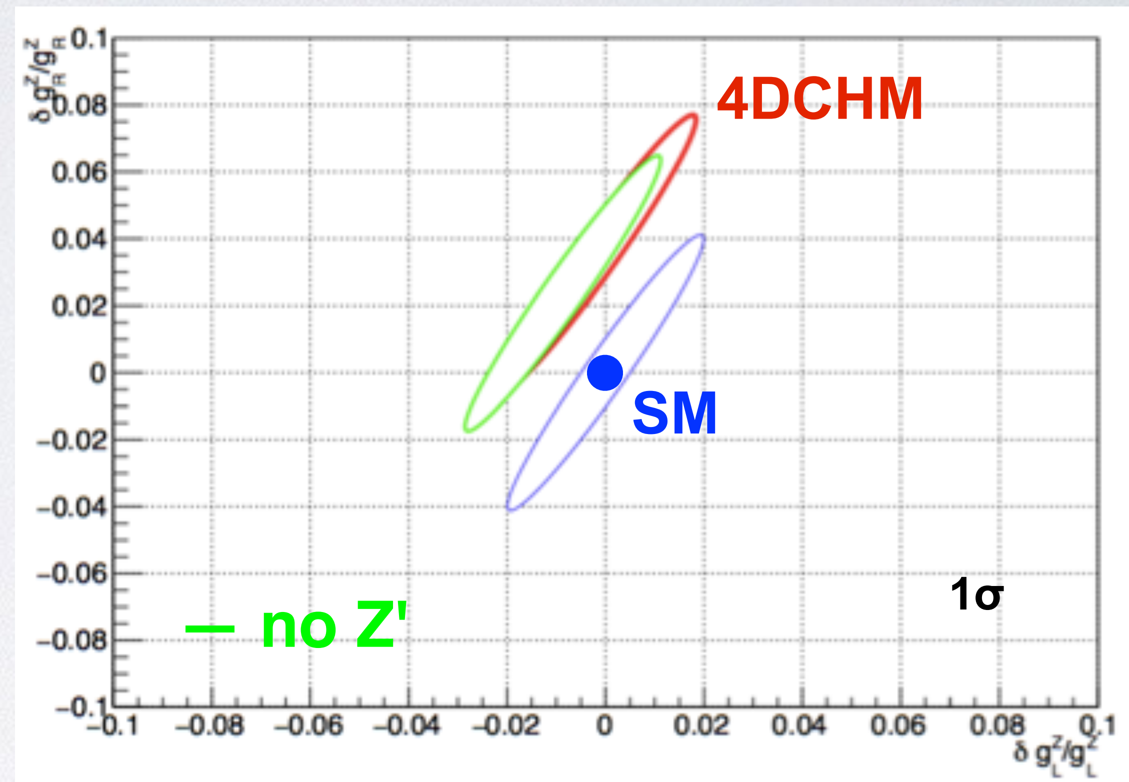
Top-quark EW coupling determination at the FCC-ee for the 4DCHM point-A

(P.Janot)

$(\Delta g_L^{\gamma}/g_L^{\gamma}\ ,\ \Delta g_R^{\gamma}/g_R^{\gamma})$



$(\Delta g_L^{Z}/g_L^{Z}\ ,\ \Delta g_R^{Z}/g_R^{Z})$

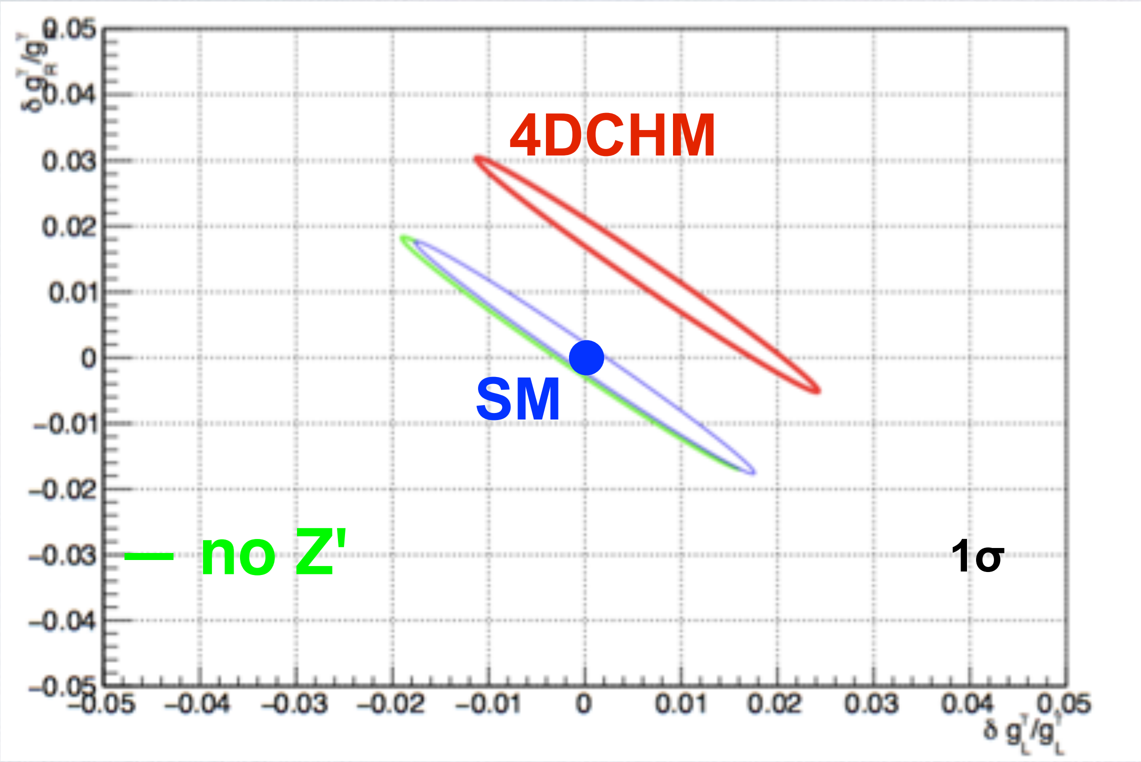


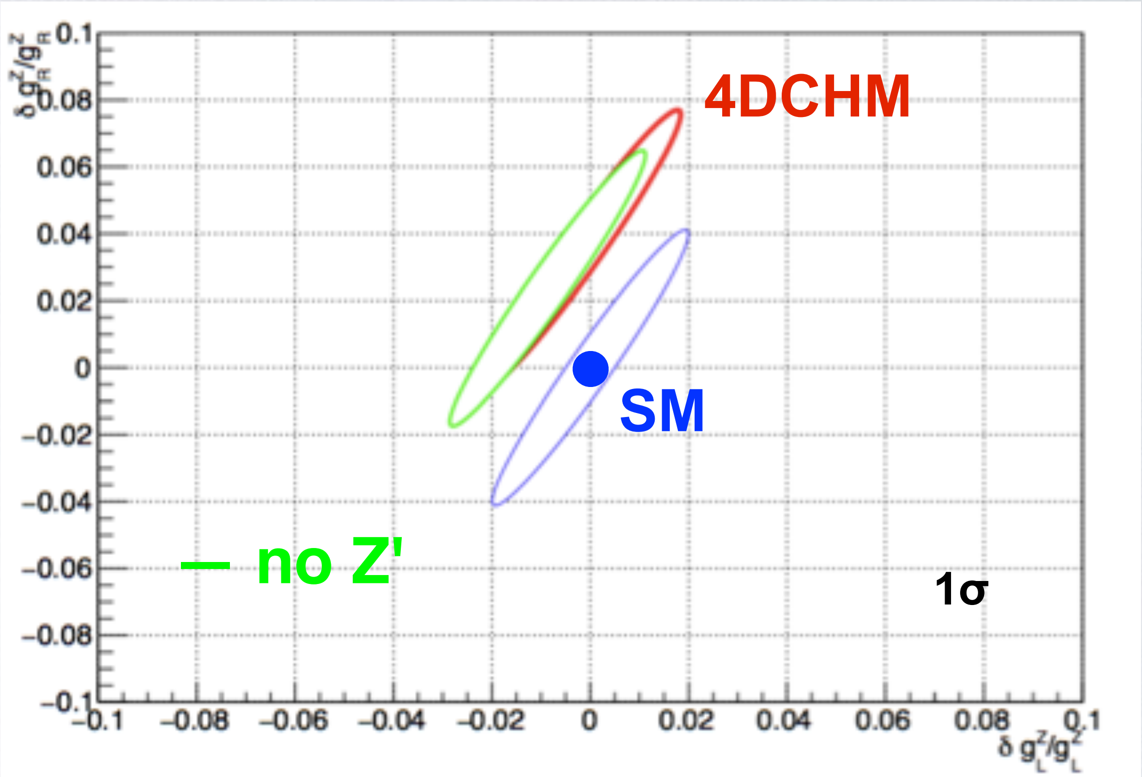
Notice that the 4DCHM predicts no deviations of the top-quark couplings to the photon from the SM model ones due to the $U(1)_{em}$ invariance

The deviations here extracted are also due to the Z' exchanges (effective couplings)

Check: use the distributions obtained by removing the Z's

— green ellipses





Four parameter fit for the EW couplings:

ΔgL^gam = -0.0003 +/- 0.0005
ΔgR^gam = -0.0001 +/- 0.0005
ΔgL^Z = -0.0022 +/- 0.0013
ΔgR^Z = -0.0027 +/- 0.0012

compare with point-A values

$\Delta g^{\gamma}_{L} = \Delta g^{\gamma}_{R} = 0$

$\Delta g^{Z}_{L} = -0.0022$

$\Delta g^{Z}_{R} = -0.0027$

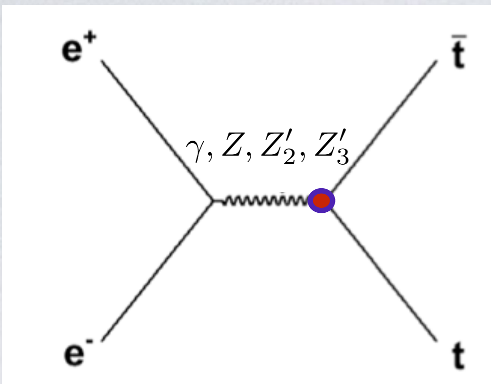
!!

The top EW coupling 4DCHM deviations are reproduced by the fit

The photon couplings are not modified

Z' dependence of the top-quark EW coupling corrections (determination at the FCC-ee for the 4DCHM point-A)

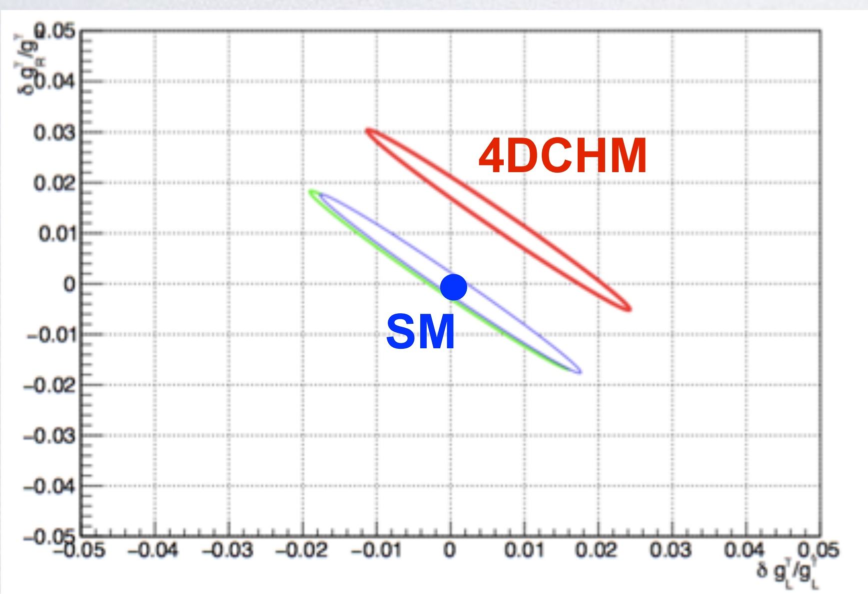
Both Z'_2 and Z'_3 are active in the top pair production



At the FCC-ee with $\sqrt{s}$=365 GeV$\ll M_{Z'}$ the Z'-exchanges result in an effective modification of the EW top couplings

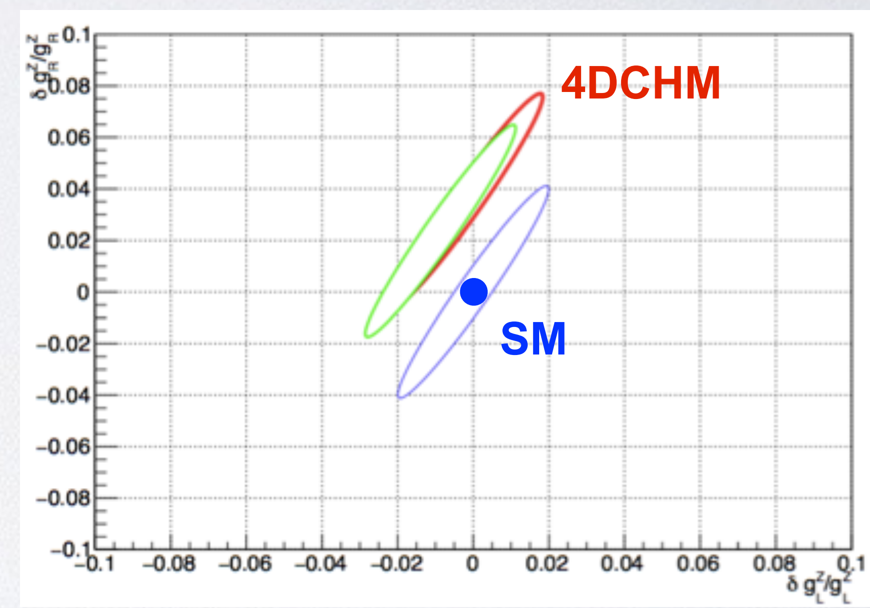
$$\Delta g^{\mathrm{eff}} = \Delta g + \sum_{i=2,3} g'_i \frac{s}{m_i^2} A(g^e, g'^e, s)$$

where g' are the Z'tt couplings and g'^e the Z'ee



← Δg^γ =0 and the deviation comes from the interference of Z_2 and Z_3 which sum in the same direction

$\Delta g^Z \neq 0$ and the Z_2 contribution almost cancel the Z_3 one →



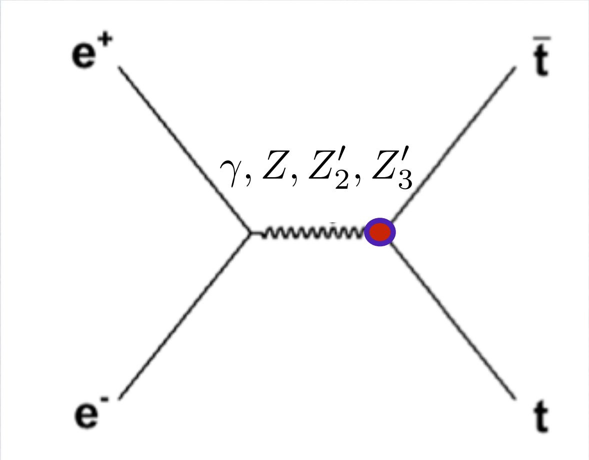
full 4DCHM (red ellipses)

ΔgL^gam = 0.0013 +/- 0.0005
ΔgR^gam = 0.0026 +/- 0.0005
ΔgL^Z = -0.0004 +/- 0.0013
ΔgR^Z = -0. 0041 +/- 0.0012

8σ away from the SM
(global significance of the 4-parameter fit)

Z'tt coupling determination at the FCC-ee for the 4DCHM point-A

By using the expression for the effective modification of the EW top couplings



$$\Delta g^{\gamma\text{eff}}_{L,R} = \sum_{i=2,3} g'_{iL,R} \frac{s}{M^2_{Z_i}} A^{\gamma}_i(g^e, g'^e, s)$$

$$\Delta g^{Z\text{eff}}_{L,R} = \Delta g^{Z}_{L,R} + \sum_{i=2,3} g'_{iL,R} \frac{s}{M^2_{Z_i}} A^{Z}_i(g^e, g'^e, s)$$

and the results of the fit to the muon observables for the g^e , g'^e and M_{Z2}, M_{Z3} we can extract the Z’tt couplings

In particular we can fit the parameters $K_{L,R}$ proportional to the linear mixing $\Delta t_{L,R}$ between the top-quark and the heavy top-partners

work in progress

$$K_L = \tilde{\Delta}^2_{t_L}(1 + \tilde{M}^2_{Y_T}), \qquad K_R = \tilde{\Delta}^2_{t_R}(1 + (\tilde{M}_{Y_T} + \tilde{Y}_T)^2)$$

The FCC-ee can provide an indirect evidence of the quark-top partial compositeness

Conclusions

- Future e+e- machines will have a great potential for BSM indirect evidence

- The FCC-ee could find clear hints of compositeness both from coupling deviations and from the imprints of new particles

- The very-high precision in muon observables at different energies will make ievident the presence of new Z'(s) (not excluded by the HL-LHC) at a **10σ-level** and also allows a model-dependent parameter determination for **f, g*, mixing Z-Z' angles**

- The EW top-coupling determination of the FCC-ee allows to disentangle the effects of coupling modifications (always taken into account in NP searches) from Z's interference effect

- By using the expressions for the EW top effective couplings and the physical properties of the Z'(s) we will have the access to the elementary-composite mixing in the top sector (partial-compositeness)

New Physics could have escaped the LHC scrutiny and manifest indirectly at very-high precision, low-energy experiments

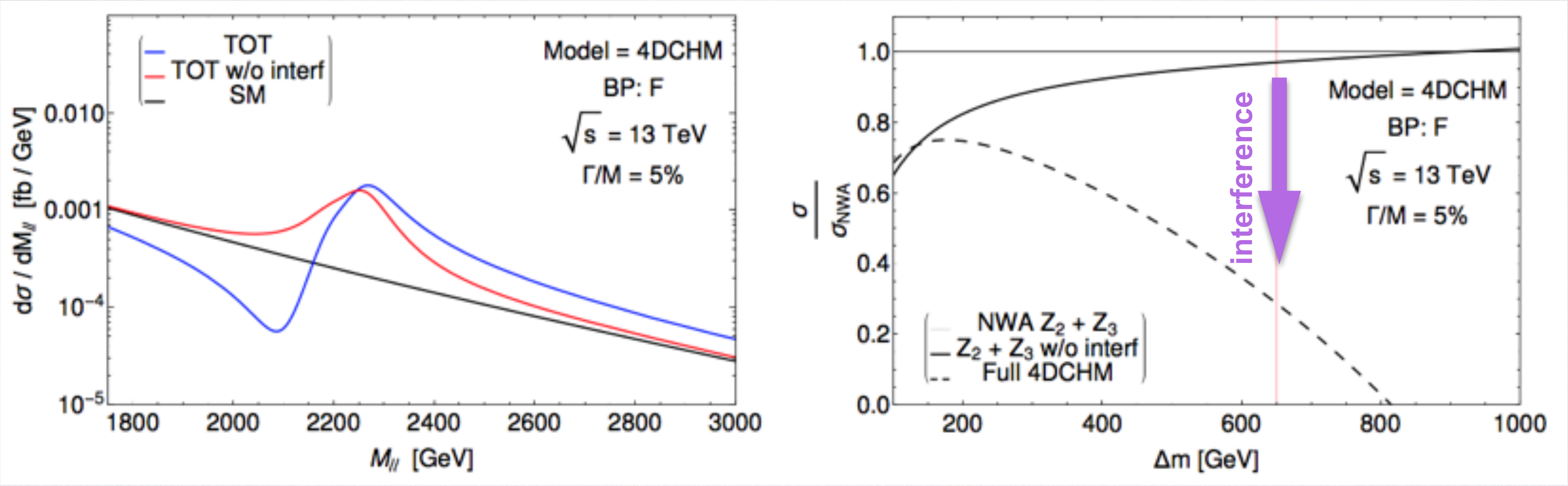
BACKUP SLIDES

Calculating significance, neutral channel DY at the LHC

Three ingredients to be taken into account:

- ☑ finite widths of the new massive vectors (large width if $Z' \to \bar{T}T$)
- ☑ multi-Z' signal, typical of CHMs
- ☑ interference effects

Accomando et al.JHEP1607(1016)068



Differential distribution in the lepton invariant mass for the double-resonant scenario

$\frac{\sigma_{\rm 4DCHM}}{\sigma_{\rm NWA(Z_2+Z_3)}}$ - - - - - - $\frac{\sigma_{\rm FW(Z_2+Z_3)}}{\sigma_{\rm NWA(Z_2+Z_3)}}$ ———

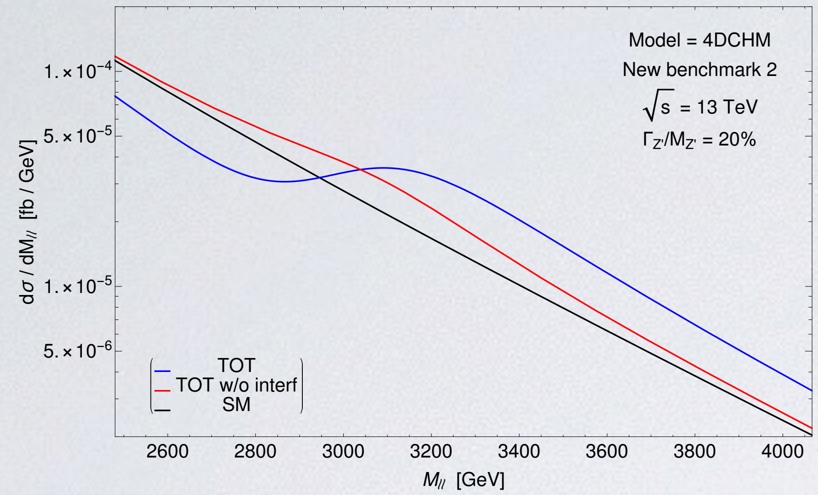
f=1200GeV g*= 1.75
M_{Z2}= 2192GeV M_{Z3}=2258GeV

Δm = invariant mass window around the Z_3 pole mass

One should avoid using the NWA (and also the FWA) to derive limits on the mass of new resonances. INTERFERENCE EFFECTS are UNAVOIDABLE even for a single resonance scenario

Because of the dip (due to the interference) the choice of the integration window is very crucial: the bump signal could be washed out !

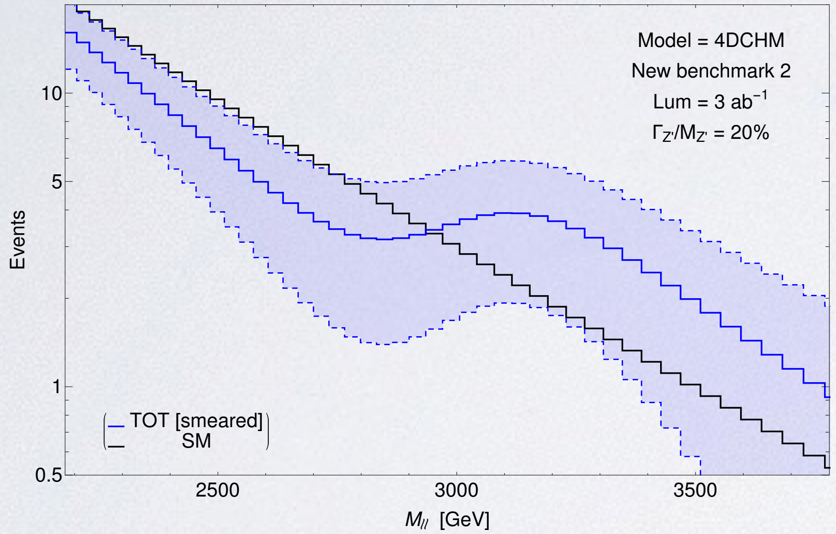
bench-A DY @ LHC 3000 fb-1



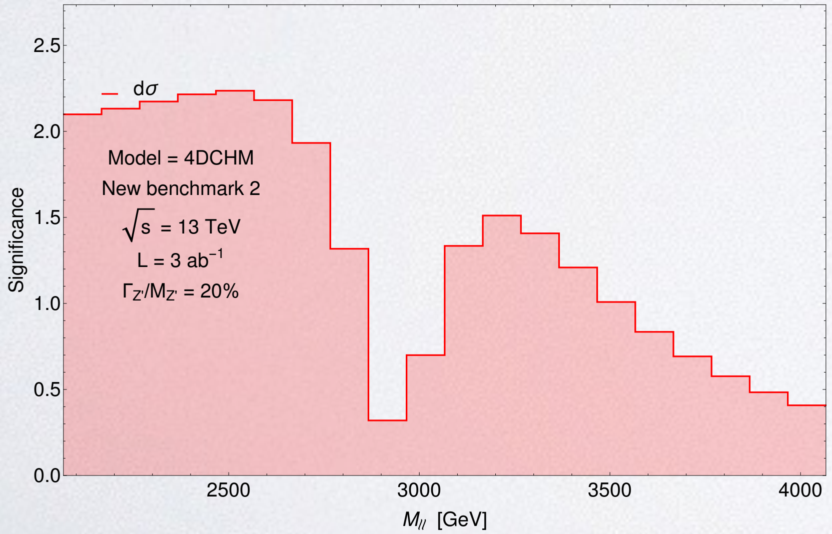
f=1600GeV g^*=1.8 ξ= 0.024

M_{Z2}=2.98TeV M_{Z3}=3.07GeV M_B=1.40TeV Γ/M=20%

1. The two resonances are nearly degenerate and quite large width: the interference effects are very important Both interference and FW affect the "on-shell" part of the differential cross-section



2. Smearing by convoluting the signal with a Gaussian distribution (width= 1.2% of M_{ll} according to CMS detector resolution for electron pairs)



3. Even considering an appropriate integration range (starting from the crossing point) the significance under the peak is 1.5 at most
One could consider the depletion of events before the peak as positive significance (this is currently under study by the experimental collaborations)

J.Fiaschi private communication

Top-quark EW coupling determination at the FCC-ee

At the FCC-ee the final state top-quarks are produced with non-zero polarization which depends on the ttZ/ttγ couplings

the top polarization is maximally transferred to the top decay products

$$t\bar{t} \to (bW^+)(\bar{b}W^-) \to (bqq')(\bar{b}l\nu)$$

Optimal-observable analysis of lepton angular and energy distributions from top-quark pair production with semi-leptonic decays is used to predict the sensitivity to the EW top-quark couplings at FCC-ee with 365 GeV and 1.6/ab (3years)

Parameterization of the ttV vertex (V = Z, γ) (Grzadkowski, Hioki 0004223, Janot 1503.01325, HEP-EPS 2015)

$$\Gamma^{\mu}_{vt\bar{t}} = \frac{g}{2}\,\bar{u}(p_t)\left[\gamma^{\mu}\{A_v + \delta A_v - (B_v + \delta B_v)\gamma_5\} + \frac{(p_t - p_{\bar{t}})^{\mu}}{2m_t}(\delta C_v - \delta D_v\gamma_5)\right]v(p_{\bar{t}})$$

$$\frac{d^2\sigma}{dx\,d\cos\theta} \sim \frac{3\pi\beta\alpha^2(s)}{2s}B_l\Big[\underbrace{S^0(x,\theta)}_{\text{SM}} + \sum_{i=1}^{8}\delta_i f^i(x,\cos\theta)\Big] \qquad \delta_i = \delta(A,B,C,D)_V \qquad f_i = f^V_{A,B,C,D}(x,\cos\theta)$$

V = Z, γ

θ = lepton polar angle
x = reduced lepton energy

B_l = fraction of tt events with at least one semi-leptonic top decay (l=e,μ) ~44%

The 8 form factors can be determined simultaneously if the 9 distribution functions S^0 and f_i are linearly indep.

6-parameter fit (CP-conserving only)

(see also N.Foppiani talk) (Courtesy Patrick Janot, HEP-EPS 2015)

Lepton energy and angular distributions

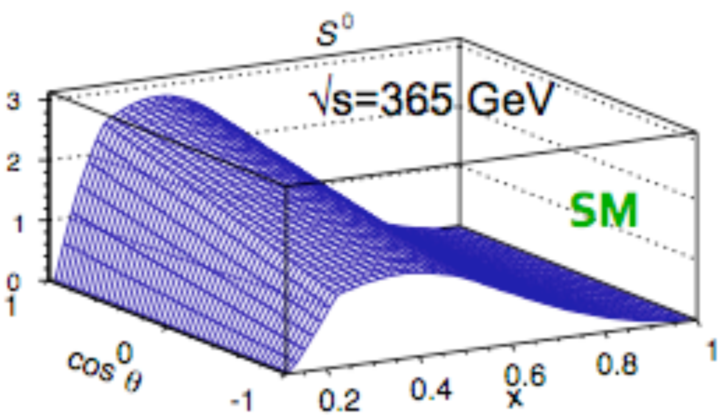
- **Parameterization of the ttV vertex (V = Z, γ)**

B. Grzadkowski, Z. Hioki, hep-ph/0004223

$$\Gamma^{\mu}_{vt\bar{t}} = \frac{g}{2}\,\bar{u}(p_t)\left[\gamma^{\mu}\{A_v + \delta A_v - (B_v + \delta B_v)\gamma_5\} + \frac{(p_t - p_{\bar{t}})^{\mu}}{2m_t}(\delta C_v - \delta D_v \gamma_5)\right]v(p_{\bar{t}})$$

θ = lepton polar angle

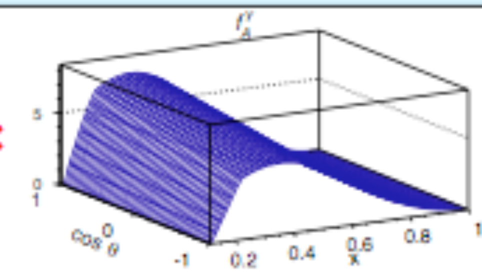
$$\frac{d^2\sigma}{dx\,d\cos\theta} =$$



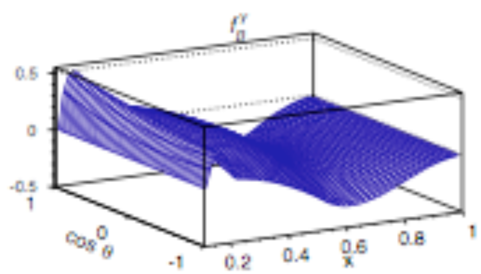
$\delta A_V = \delta B_V = \delta C_V = \delta D_V = 0$

+

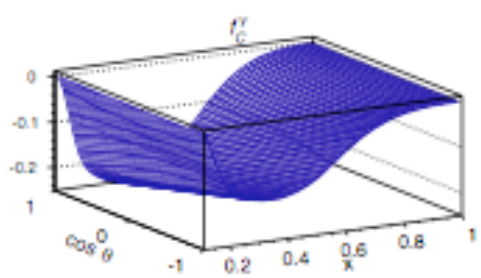
$\delta A_\gamma \times$



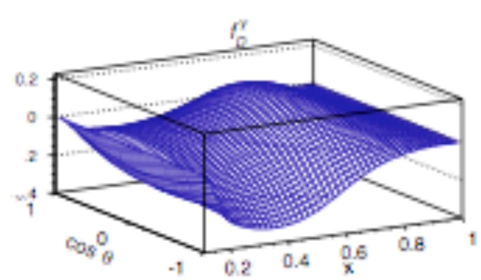
$\delta B_\gamma \times$



$\delta C_\gamma \times$

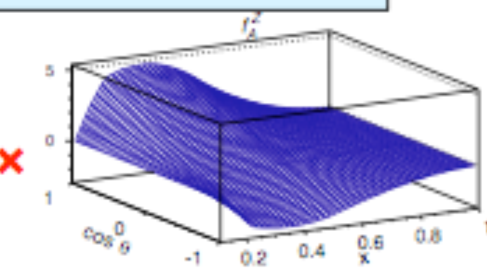


$\delta D_\gamma \times$

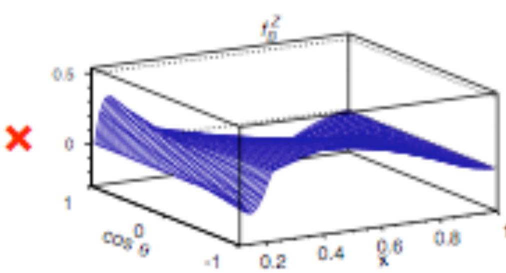


+

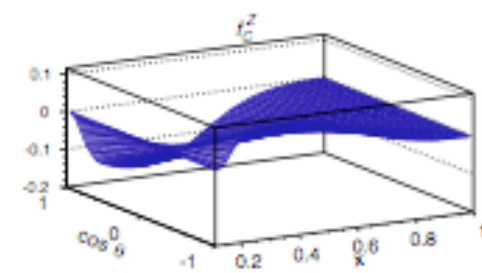
$\delta A_Z \times$



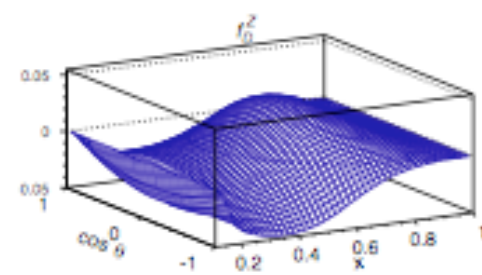
$\delta B_Z \times$



$\delta C_Z \times$



$\delta D_Z \times$



x = reduced lepton energy

$$x_f \equiv \frac{2E_f}{m_t}\sqrt{\frac{1-\beta}{1+\beta}} \qquad \beta\left(\equiv\sqrt{1-4m_t^2/s}\right)$$

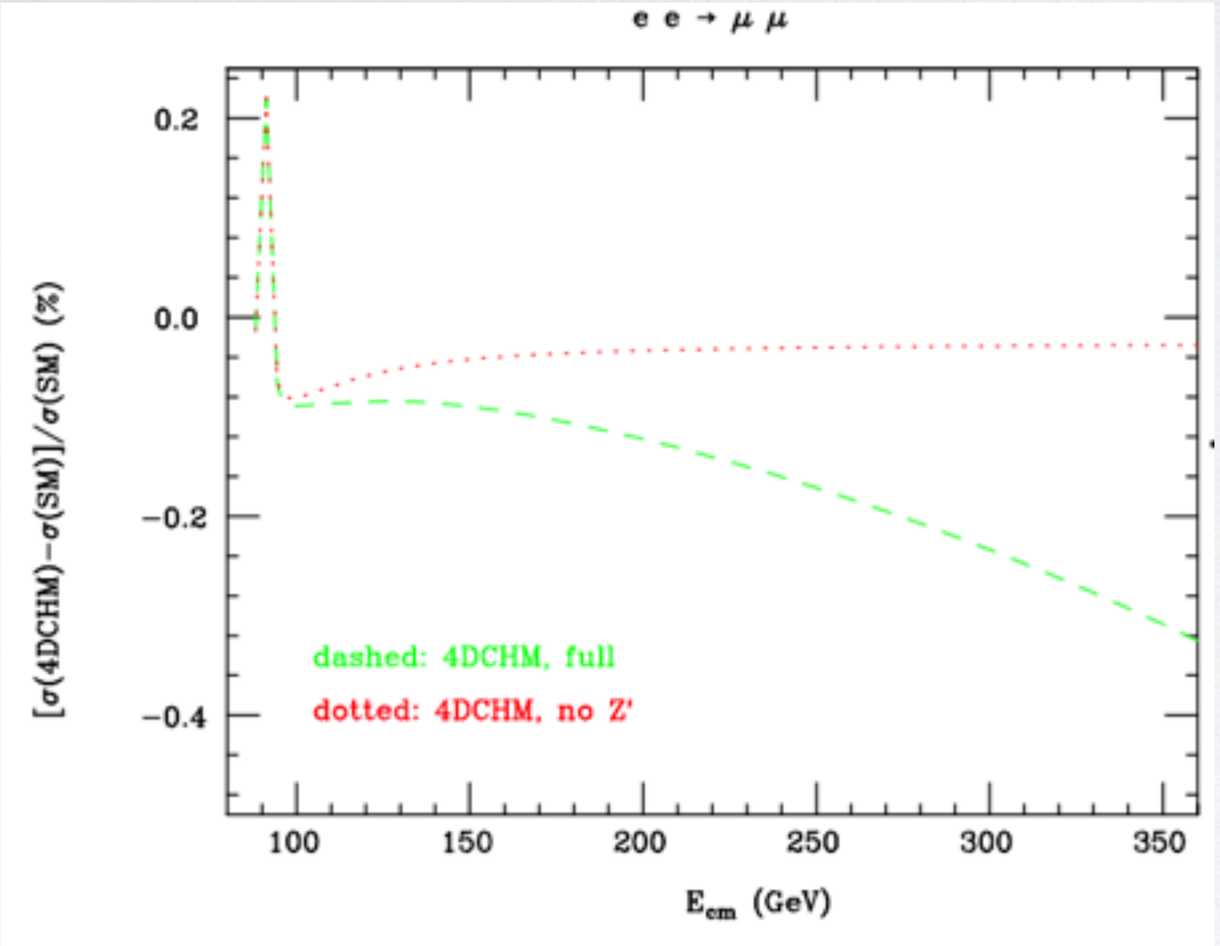
$$\frac{d^2\sigma}{dx\,d\cos\theta} \sim \frac{3\pi\beta\alpha^2(s)}{2s}B_l\left[S^0(x,\theta) + \sum_{i=1}^{8}\delta_i f^i(x,\cos\theta)\right] \qquad \delta_i = \delta(A,B,C,D)_V \qquad f_i = f^V_{A,B,C,D}(x,\cos\theta)$$

B_l = fraction of tt events with at least one semi-leptonic top decay (l=e,μ) ~44%

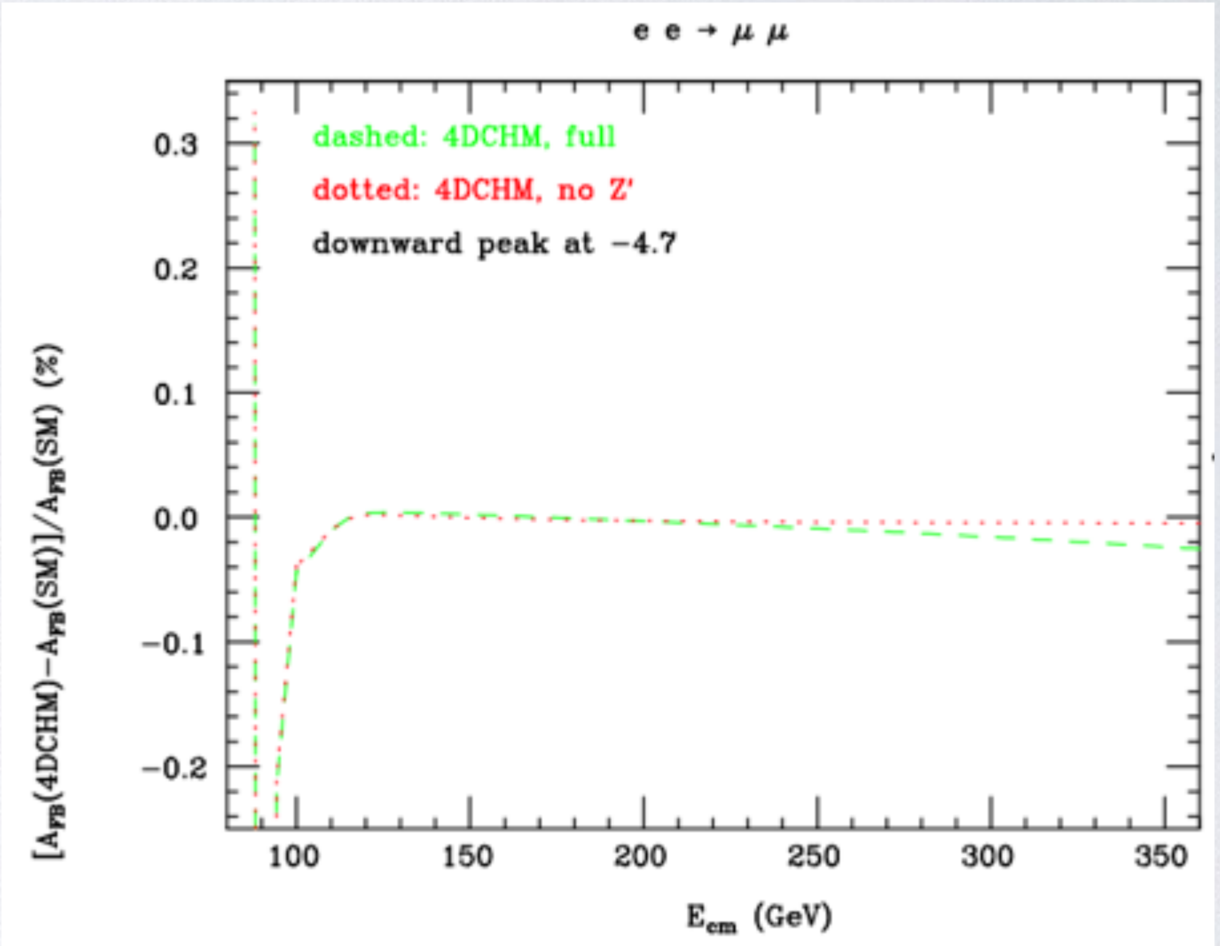
4DHM bench-A $e^+e^- \to \mu^+\mu^-$

f=1600.2 GeV g^*=1.787 ξ= 0.024 M_{Z2}=2980.1GeV M_{Z3}=3066.5GeV Γ/M=20%

cross-section



forward-backward asymmetry



Energy dependence of the 4DCHM corrections with and without the Z_2 and Z_3 propagator contributions