Composite Higgs Models at e+e- Colliders

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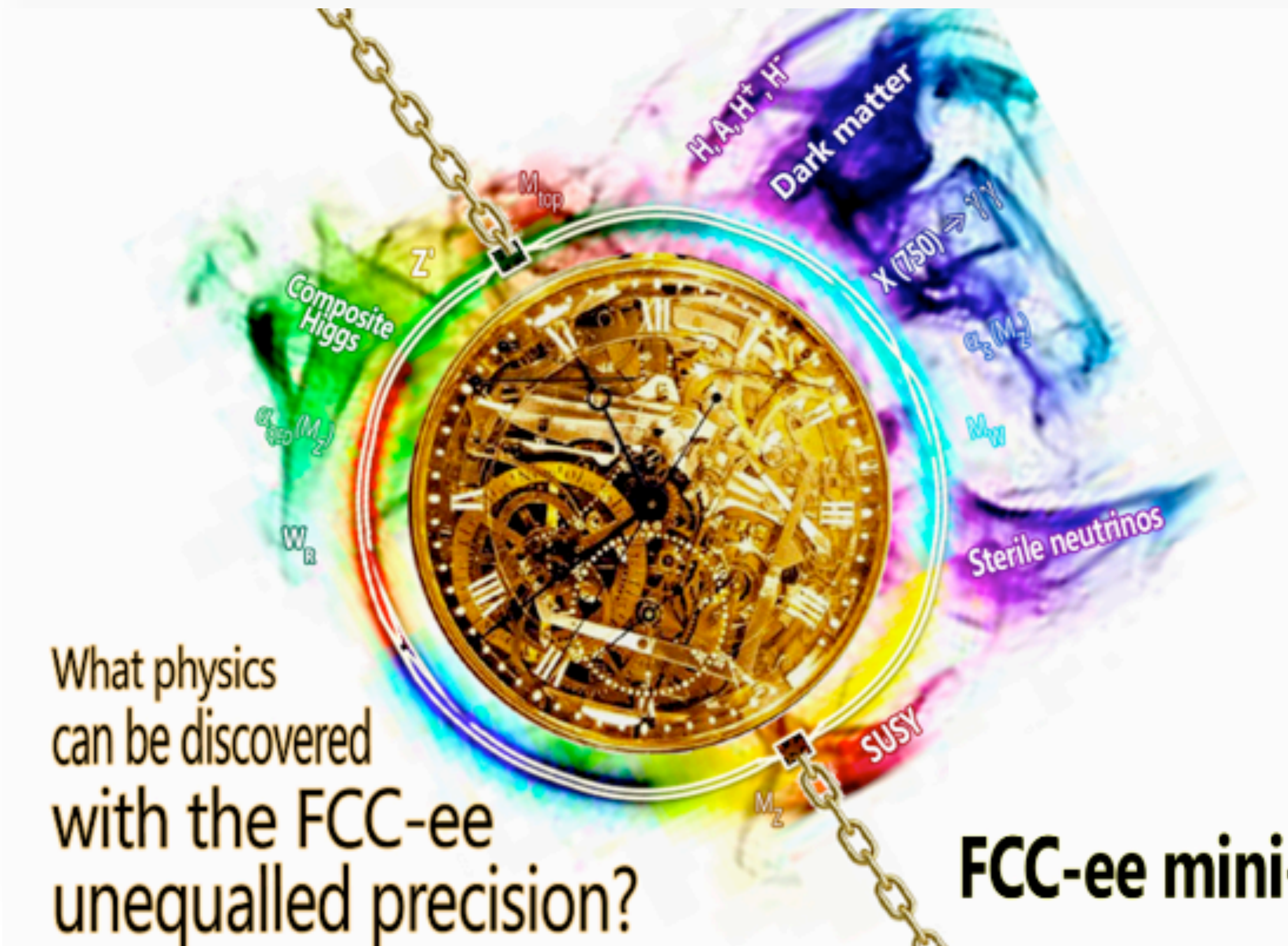


Based on:
DC, Redi,Tesi, JHEP 1204 (2012) 042;
Barducci et al, JHEP 1304 (2013) 152;
JHEP 1309 (2013) 047; JHEP 1402 (2014) 005; JHEP 1508 (2015) 127;
DC, Janot, Moretti in preparation

2-3 Feb 2016

FCC-ee mini-workshop: Physics behind precision

- ☑ The Higgs at 125 GeV opened up the stage of particle property determination and made the **physics case for future accelerators** stronger than ever

- ☑ Theoretical arguments supporting the importance of **sub-percent Higgs coupling precision** continue to grow, especially to find hints for non-SM Higgs **(how can we decide if it is the elementary SM Higgs or a composite state from a strong dynamics?)**

- ☑ An **e+e- collider** could help in detecting **deviations in the cross sections for single, double Higgs production**, but it will also have a **great potential on top physics**: mass, width and precise coupling determination, very important for NP (for ex. indirect probe of partial compositeness)

- ☑ The study of top quark is often considered a part of precision QCD (top quark mass, width, $t\bar{t}$ threshold scan) but also .... **precise measurements of top properties and interactions provide sensitivities to New Physics** ⟶ Couplings to photon/Z-boson, top Yukawa coupling

TOP physics is an important sector of EWSB studies complementary to HIGGS measurements

What is the nature of the top quark?

Is it a heavy quark or an ordinary quark? M.Peskin LCWS15

Does composite Higgs imply composite top?

Indirect hints of compositeness at e+e- colliders

QUESTION: To which level of precision do we need to measure the Higgs and top couplings to probe the dynamics behind the EW symmetry breaking mechanism? Try to answer within a Composite PNGB Higgs Scenario

- ☑ Higgs as a PNGB provides an elegant solution for naturalness
- ☑ **Extra spin-1 and spin-1/2 resonances are naturally present in CHMs**
  Minimal effective calculable description: the 4D Composite Higgs Model (4DCHM)
- ☑ The top quark is described as a **(partially) composite** state

☑ The very accurate measurements at an e+e- collider of the top quark form factors will improve the precision of our knowledge over what will be possible at the HL-LHC

Why is it important to do this?

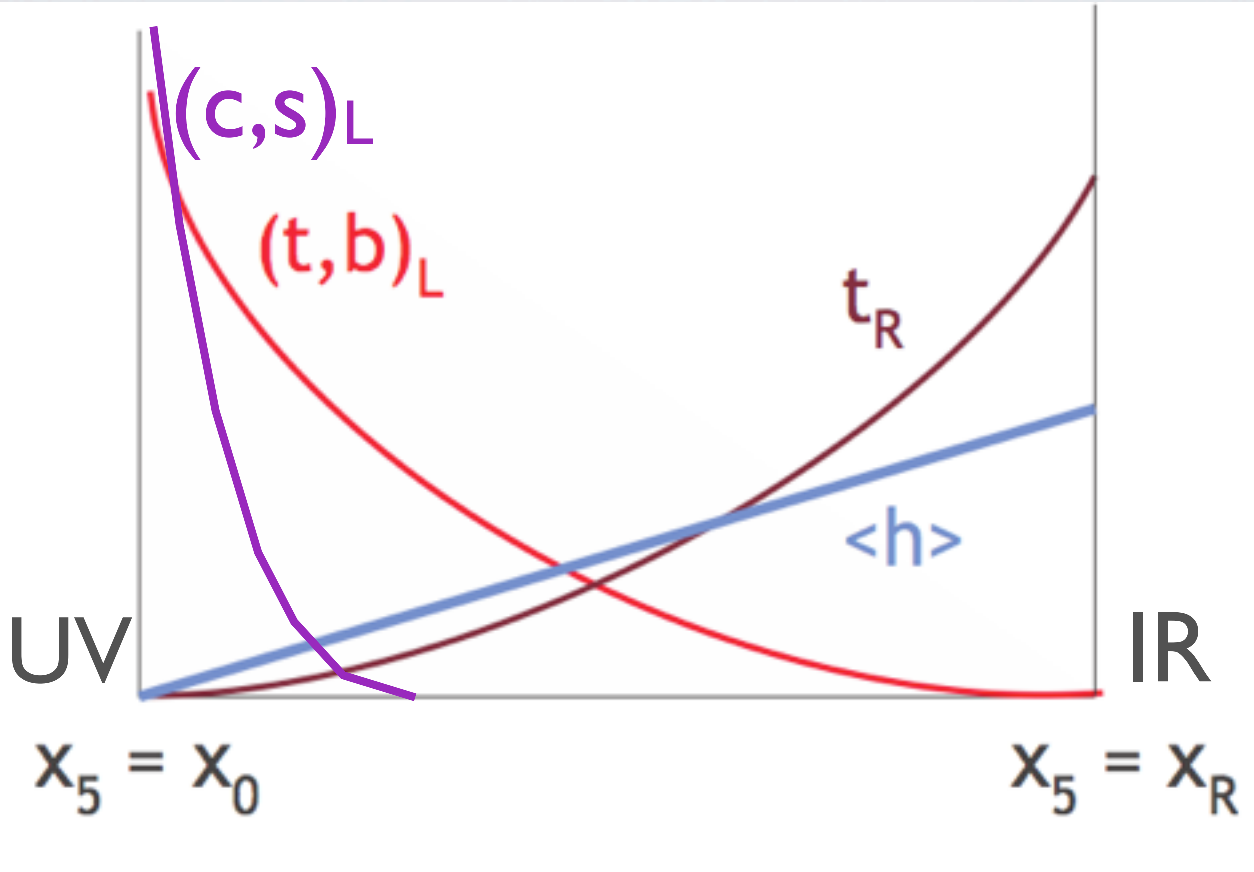
☑ The top quark is the **heaviest particle of the SM** and its coupling to the Higgs is the largest of any particle. In the SM there is no explanation for it as there is no explanation for EWSB (it is put in by hand!)

Can we find an explanation outside the SM?

☑ The idea that remains attractive is that the Higgs boson is composite.
New interactions at the TeV scale bind the Higgs constituents and are responsible for EWSB. This is compatible with a Higgs **light** and **weakly coupled** if the Higgs is a pseudo Nambu-Goldstone Boson

☑ Compositeness of the Higgs can bring compositeness of the top quark and the prediction of new particles: vector-like tops T (needed to give a finite and calculable theory of the Higgs mass), new vector resonances Z',W' (contributing to the EW top axial and vector-axial coupling modification)

A way to understand this scenario is to model the new strong interactions by a warped 5th dimension (Randall-Sundrum construction)

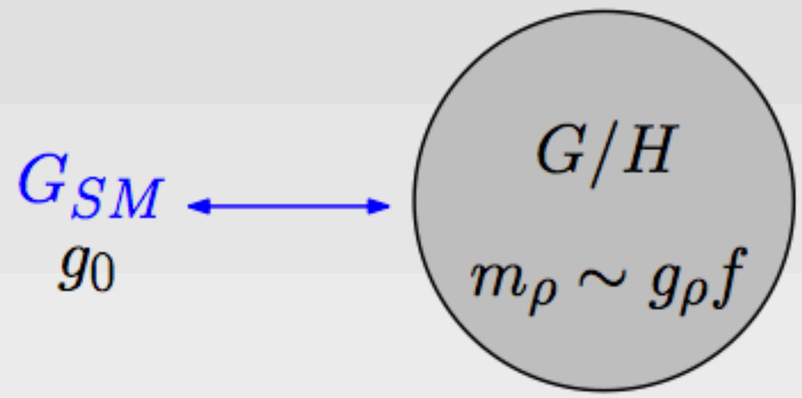


M. Peskin LCWS15

the Higgs is localized near the IR brane, the $(t,b)_L$ doublet must be elementary to satisfy EWPT ($\Gamma(Z \to bb)$). Then t_R **must be highly composite** to provide good overlap with the Higgs vev in the 5th dimension

To test this idea it is crucial to measure the L/R structure of the top EW couplings

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?

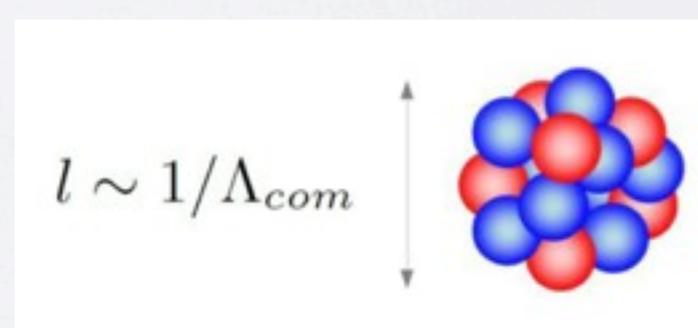
- G is only an approximate global symmetry $g_0 \rightarrow V(h)$
- EWSB as in the SM

small tuning f ~TeV

- And the hierarchy problem?

no Higgs mass term at tree level

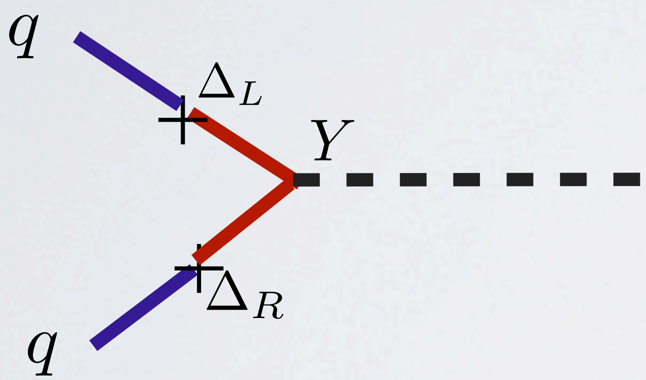
$$\rightarrow \delta m_h^2 \sim \frac{g_0^2}{16\pi^2}\Lambda_{com}^2$$



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)



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

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

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

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

top Yukawa coupling generated by the elementary-composite couplings

Higgs Coupling Summary

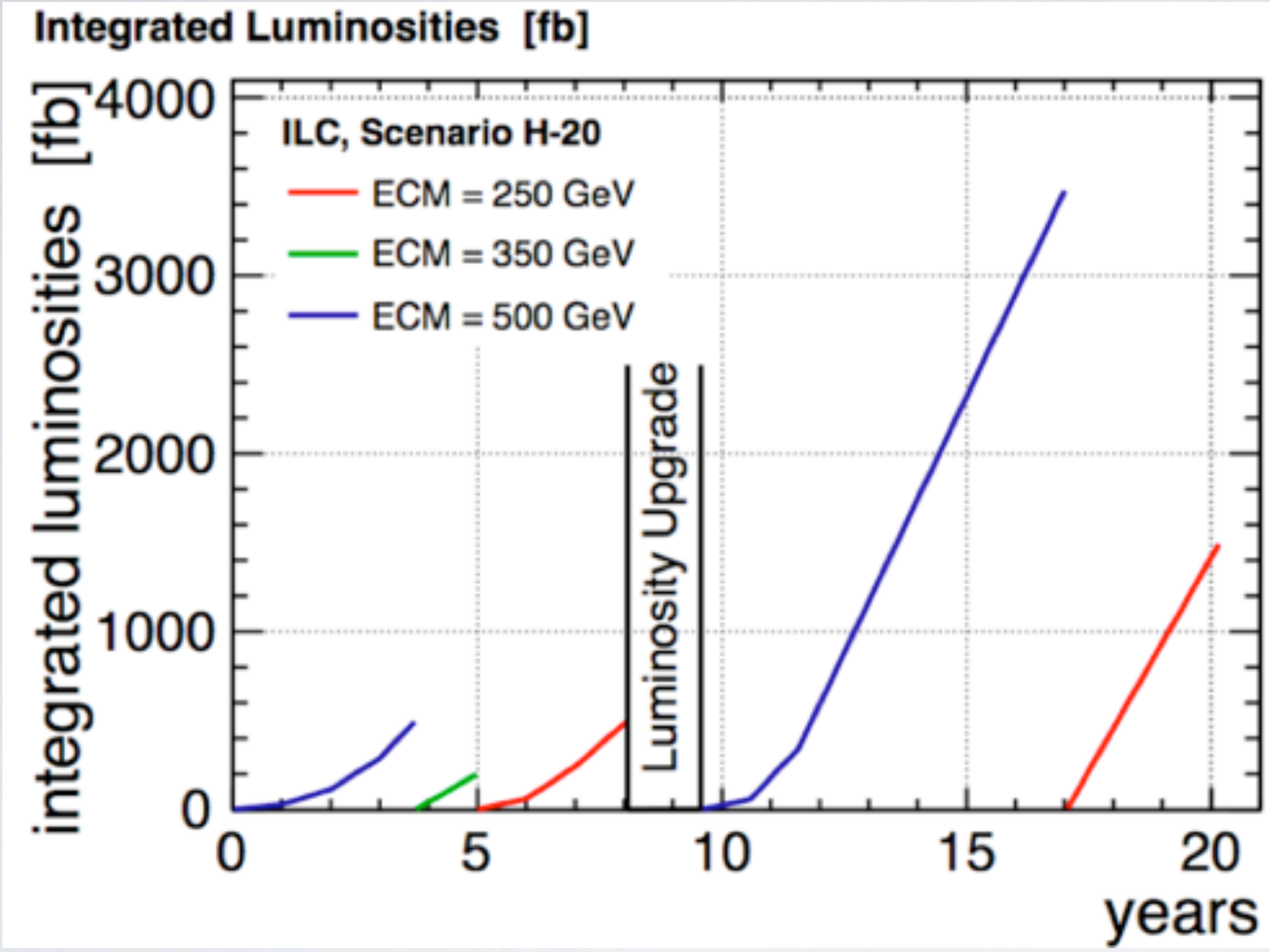
M. Klute LCWS2015

Uncertainties	HL-LHC*	μ-	CLIC	ILC**	CEPC	FCC-ee
m_H [MeV]	40	0.06	40	30	5.5	8
Γ_H [MeV]	-	0.17	0.16	0.16	0.12	0.04
g_{HZZ} [%]	2.0	-	1.0	0.6	0.25	0.15
g_{HWW} [%]	2.0	2.2	1.0	0.8	1.2	0.2
g_{Hbb} [%]	4.0	2.3	1.0	1.5	1.3	0.4
$g_{H\tau\tau}$ [%]	2.0	5	2.0	1.9	1.4	0.5
$g_{H\gamma\gamma}$ [%]	2.0	10	6.0	7.8	4.7	1.5
g_{Hcc} [%]	-	-	2.0	2.7	1.7	0.7
g_{Hgg} [%]	3.0	-	2.0	2.3	1.5	0.8
g_{Htt} [%]	4.0	-	4.5	18	-	-
$g_{H\mu\mu}$ [%]	4.0	2.1	8.0	20	8.6	6.2
g_{HHH} [%]	30	-	24	-	-	-

* Estimate for two HL-LHC experiments
** ILC lumi upgrade improves precision by factor 2

For ~10y operation. Lots of "!,*,?"
Every number comes with her own story.

ILC running scenario (H-20) up to 500GeV and 20 years of running



ILC running scenario H-20

	first phase	after lumi upgrade	total
250 GeV	500 fb^{-1}	1500 fb^{-1}	2 ab^{-1}
350 GeV	200 fb^{-1}		0.2 ab^{-1}
500 GeV	500 fb^{-1}	3500 fb^{-1}	4 ab^{-1}
time	8.1 years	10.6 years	20.2 years*

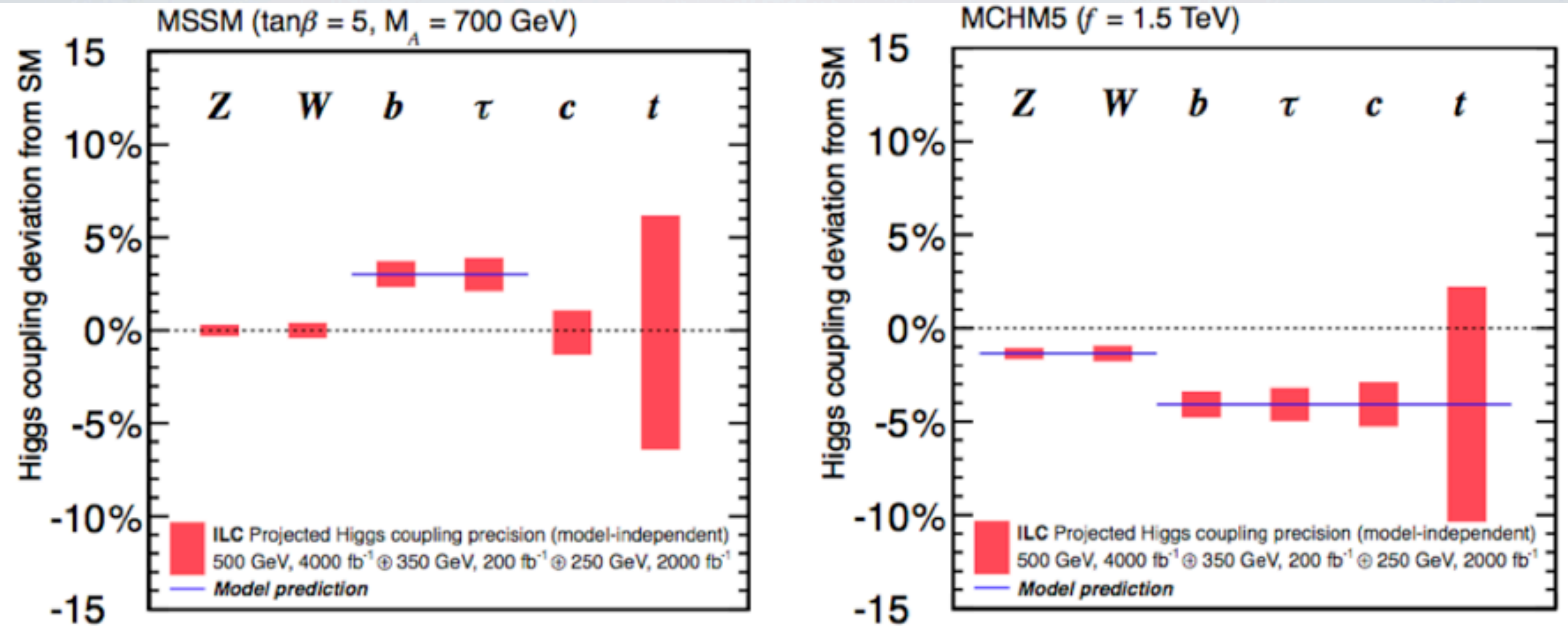
FCC-ee

$\sqrt{s}$ (GeV)	90	160	240	350	350+
$\mathscr{L}$ (ab^{-1}/year)	86.0	15.2	3.5	1.0	1.0
Events/year	3.6×10^{12}	6.1×10^{7}	7.0×10^{5}	4.2×10^{5}	2.5×10^{4}
Event type	Z	WW	HZ	$t\bar{t}$	WW → H
Years	0.3 (2.5)	1	3	0.5	3

The FCC-ee core programme can be completed in about 8 to 10 years

Power of ILC to distinguish different NP models through Higgs measurements

LCC Physics WG 1506.05992



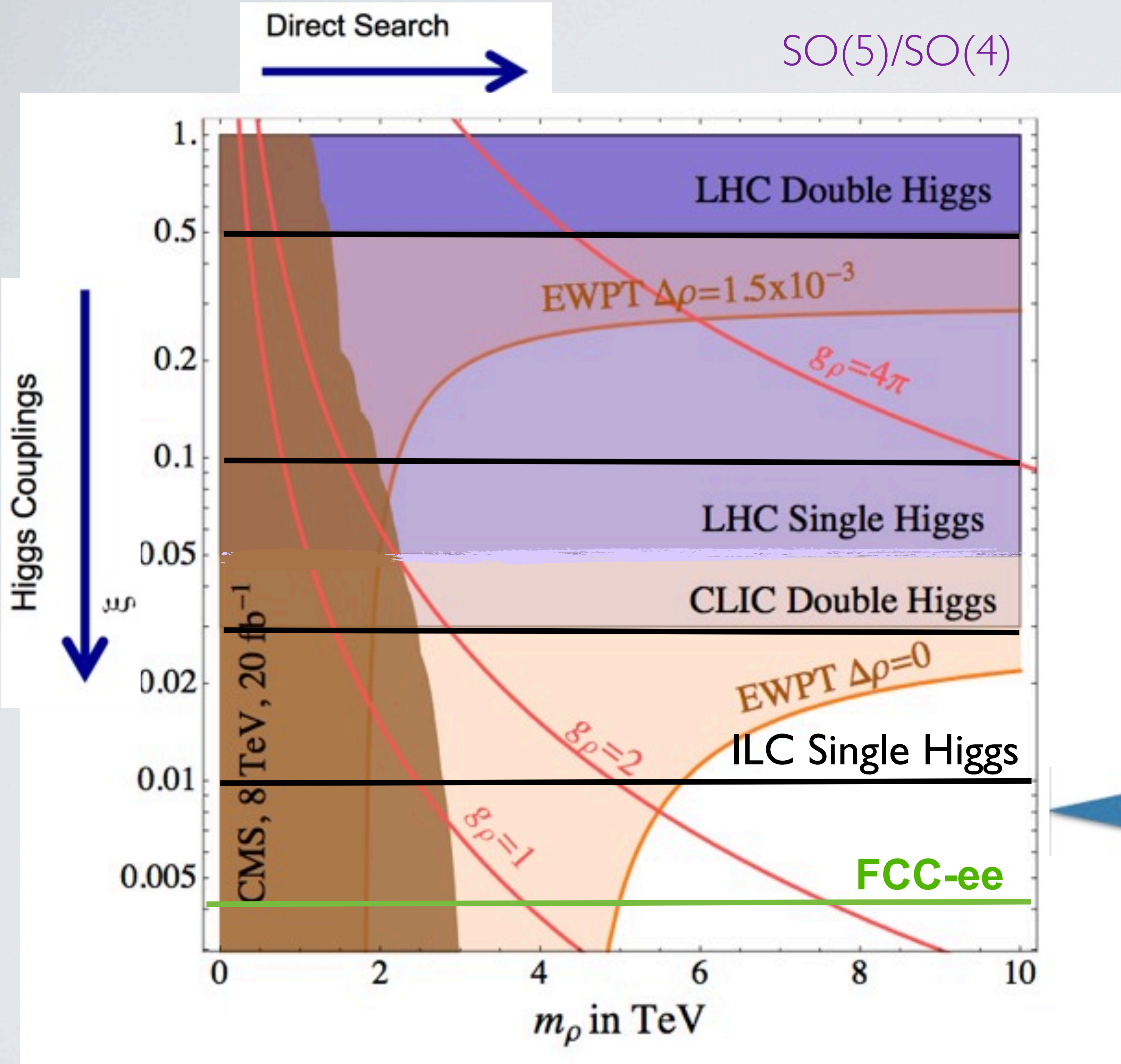
Higgs coupling modifications in a SUSY and Composite Higgs representative models. The error bars indicate the 1σ uncertainties expected from a model independent fit to the full ILC data set (H-20)

General parametrization of the GB Higgs couplings: low-energy effective Lagrangian

Giudice, Grojean, Pomarol, Rattazzi 0703114

Contino et al. 1309.7038

SO(5)/SO(4)



Expected sensitivities at:

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

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

ILC 250GeV 250fb^{-1}

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

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

$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \sqrt{1-\xi} \qquad \xi = \frac{v^2}{f^2}$$

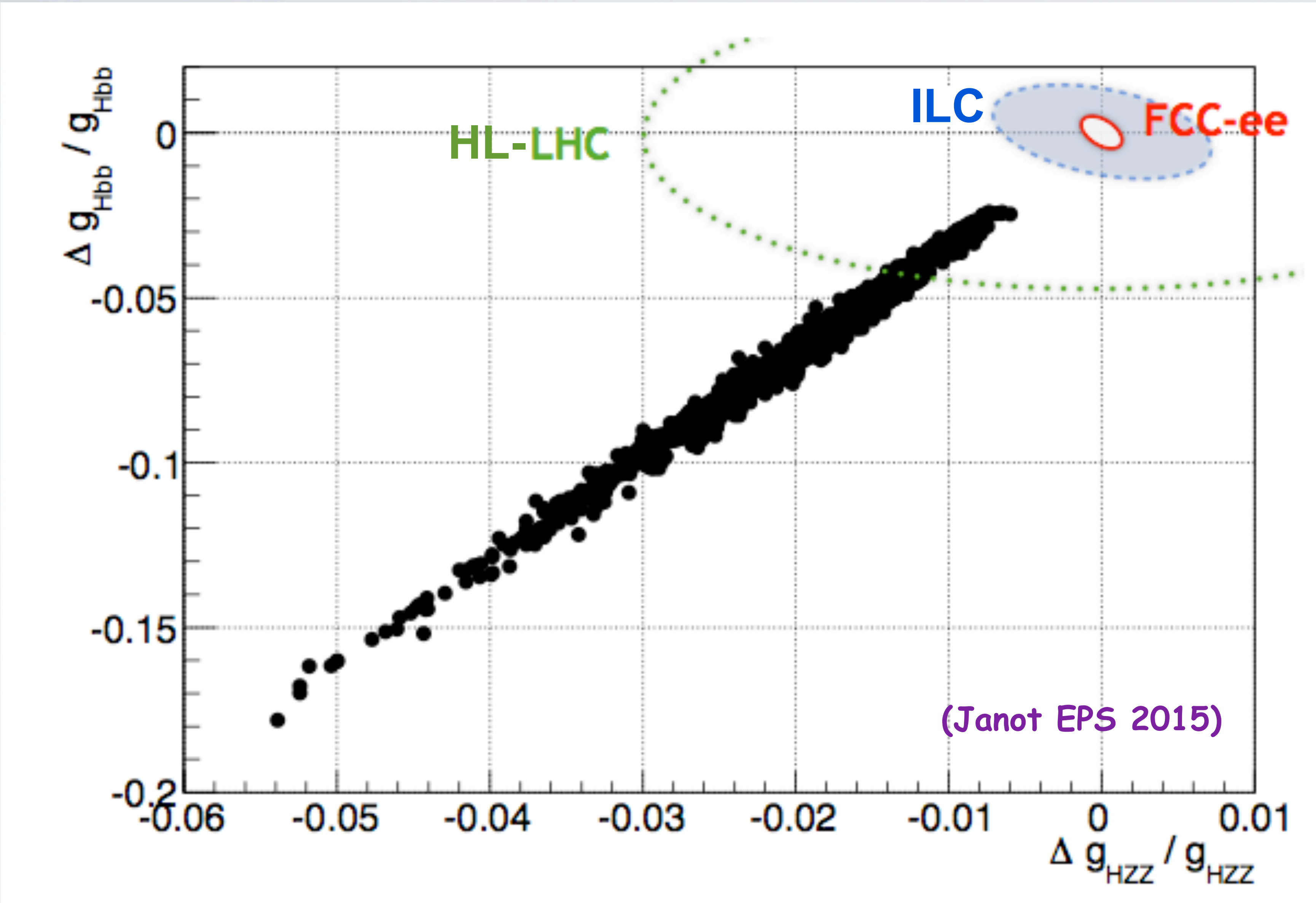
ILC (250+500 LumiUP)

$$\frac{\Delta g_{hVV}}{g_{hVV}} = 0.4\%$$

(K.Fujii LCWS15)

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!

4DCHM : deconstruction of the minimal SO(5)/SO(4) 5D model, truncated to describe the composite degrees of freedom accessible to the LHC (DC,Redi,Tesi 1110.1613)



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

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

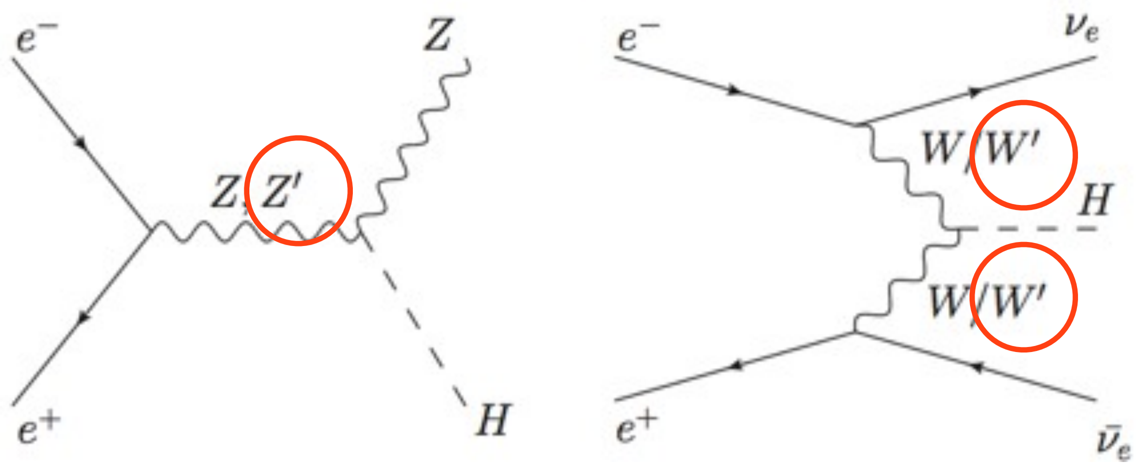
(CMS PAS B2G-15-006)

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

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

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

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

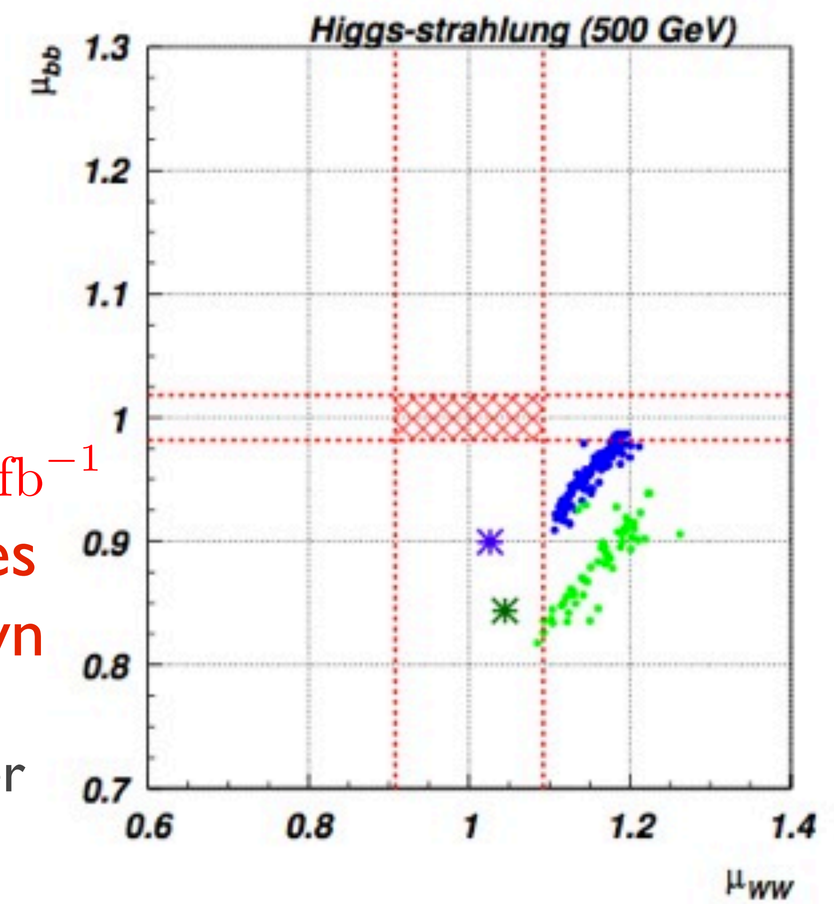
$\sqrt{s} = 500\ \text{GeV}, \mathcal{L} = 500\text{fb}^{-1}$

expected accuracies for the μ_i are shown

ILC TDR 1306.6352

ILC Higgs White Paper 1310.0763

Snowmass 1310.8361



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

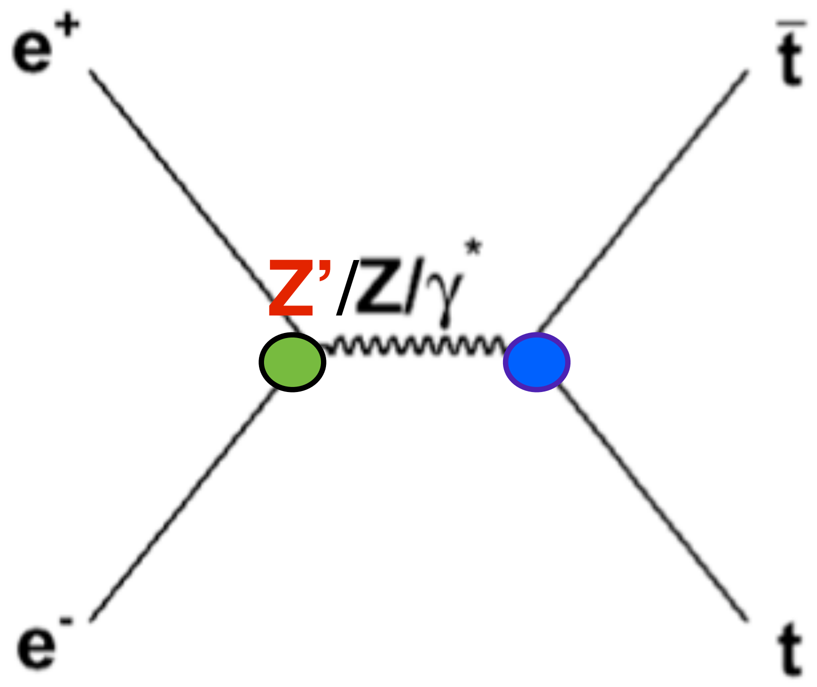
$f = 1000\ GeV,\ g_\rho = 2$

* rescaling the couplings

naively rescaling the Higgs couplings could be inaccurate as it fails to account for significative interference effects, sizeable at $\sqrt{s} = 500\text{GeV}$

To be updated

Top quark precision physics at an e+e- collider



The CHM 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 $M_{Z'}$

$e^+e^- \to$ tt production is one of the most prominent 6f process, **strong sensitivity also to new particles.** Asymmetries O(1)

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}

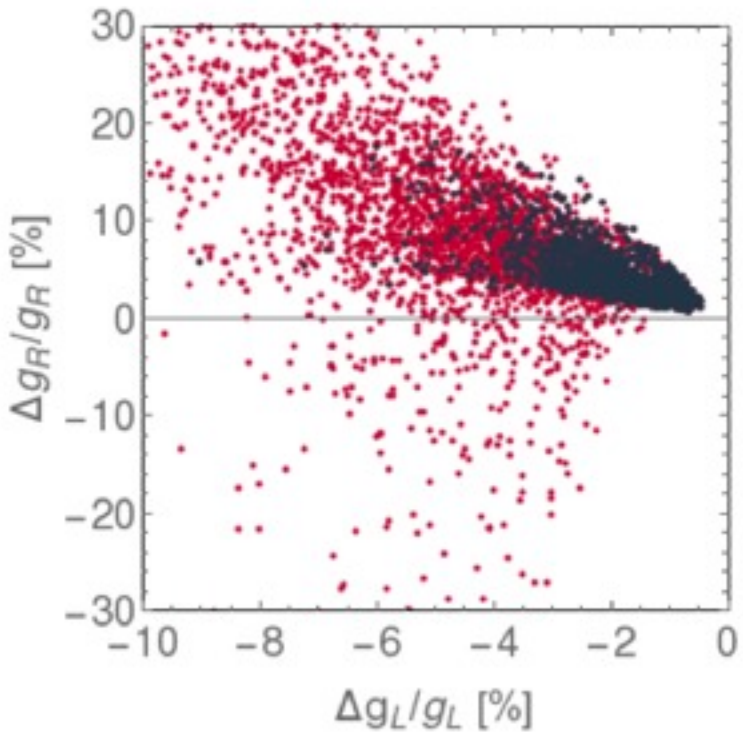
Born approximation - QCD and EW corrections not included
ISR and beamstrhalung included but not important when considering $\mathcal{O}/\mathcal{O}_{\rm SM}$

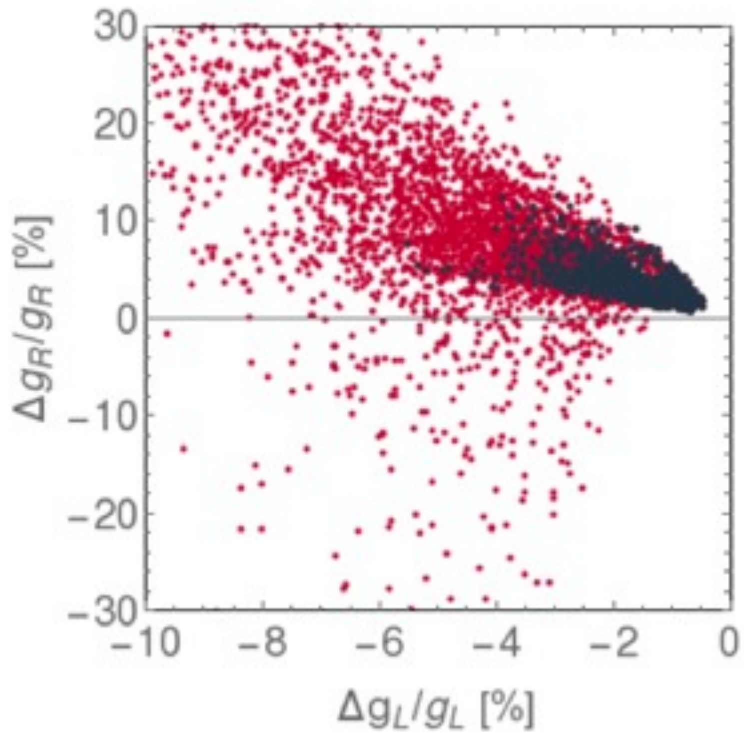
Top-quark EW coupling modification in the 4DCHM

$$\Gamma_\mu^{t\bar{t}X}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(F_{1V}^X(k^2) + \gamma_5 F_{1A}^X(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^X(k^2) + \gamma_5 F_{2A}^X(k^2)\right)\right\}$$

$X = \gamma, Z$

in the SM, tree level, all $F_2 = 0$ and $F_{1V}^{\gamma,SM} = \frac{2}{3},\ F_{1A}^{\gamma,SM} = 0,\ F_{1V}^{Z,SM} = \frac{1}{4s_w c_w}\left(1 - \frac{8}{3}s_w^2\right),\ F_{1A}^{Z,SM} = -\frac{1}{4s_w c_w},$





$g_L = e(F_{1A}^Z - F_{1V}^Z)$

$g_R = e(F_{1A}^Z + F_{1V}^Z)$

$\Delta g/g[\%] = (g - g^{SM})/g$

Barducci,DC,Moretti,Pruna, 1504.05407

$1.5 < g_\rho < 3,\ 0.75 < f(\text{TeV}) < 1.5$ and scan over 4DCHM fermion parameters

black points: $M_{Z'} \sim f g_\rho > 2$ TeV and $M_{t',b',X} > 0.8$ TeV(left), 1 TeV(right)

compliant with direct search limits and EWPT bounds (S,T, Zb_Lb_L)

(Grojean, Matsedonskyi, Panico 1306.4655)

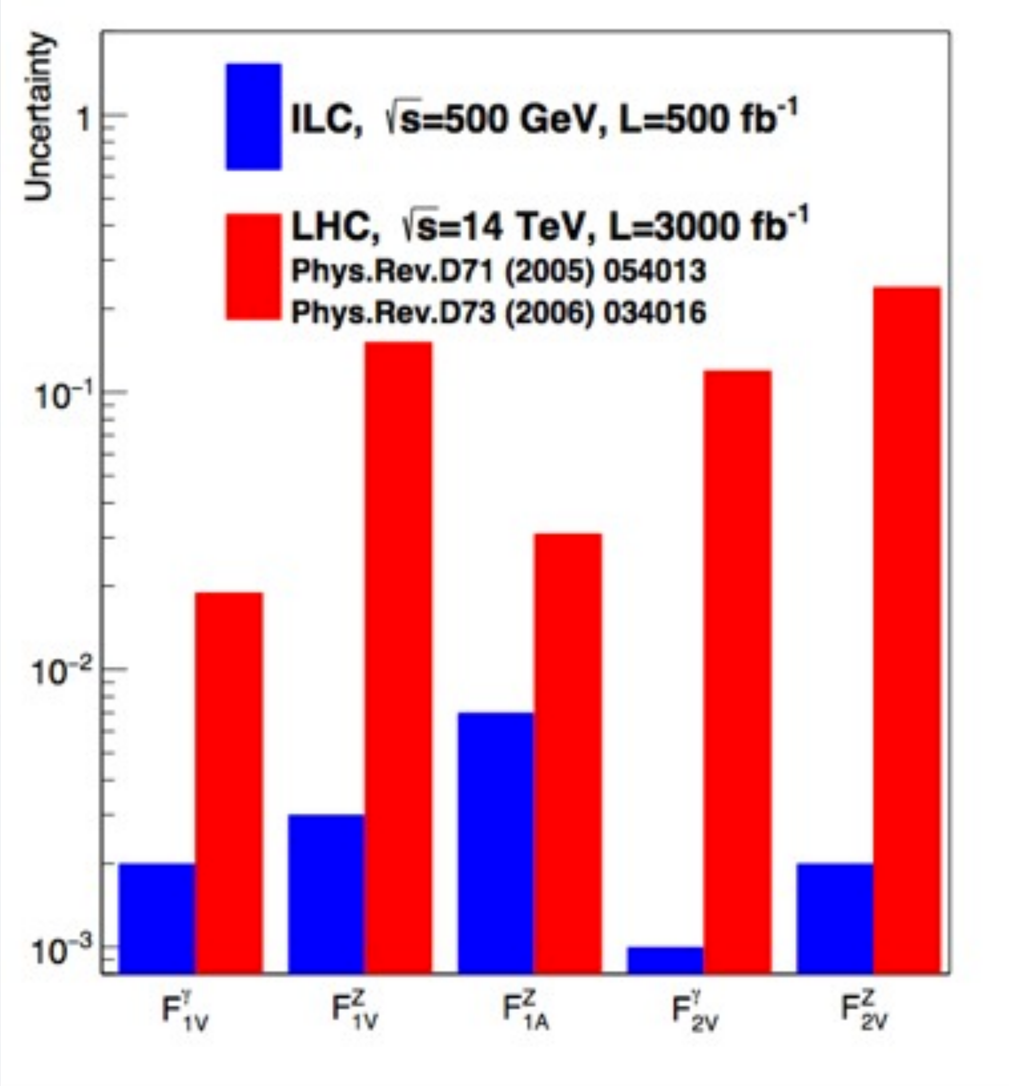
max deviation on the left/right couplings -8/+20%

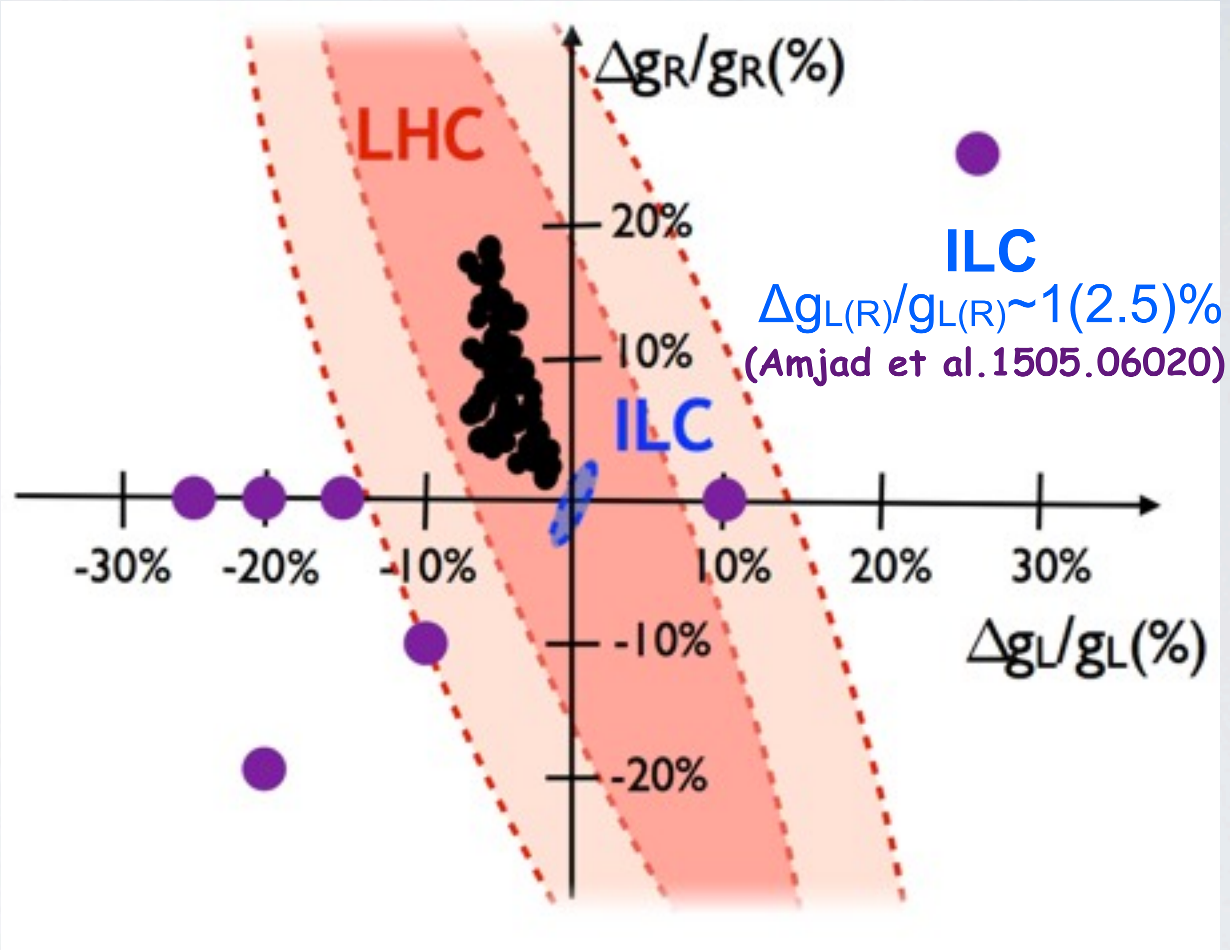
Top-quark EW coupling determination

Various BSM models predict large deviations in the top EW couplings

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

(based on Richard 1403.2893) Barducci, et al 1504.05407





sensitivities:

LHC ~ 10%, HL-LHC ~ 5%

ILC(500) < 1% with polarized beams

(ILC-TDR 1306.6352; Amjad et al. 1505.06020)

x-section and A_{FB} for $P(e^-)$=+/-80%, $P(e^+)$=+/-30%

Polarization needed to disentangle Z and γ form factors

Assumptions: $(\delta\sigma/\sigma)_{stat} \sim 0.5\%$; $(\delta A_{FB}/A_{FB})_{stat} \sim 1.8\%$

QCD corrections are under control.

Large EW one-loop corrections - further work is needed.

Systematics must be controlled to 1% level

Top-quark EW coupling determination @ the ILC

$$\Gamma_\mu^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left\{\gamma_\mu\left(F_{1V}^X(k^2)+\gamma_5 F_{1A}^X(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^X(k^2)+\gamma_5 F_{2A}^X(k^2)\right)\right\}$$

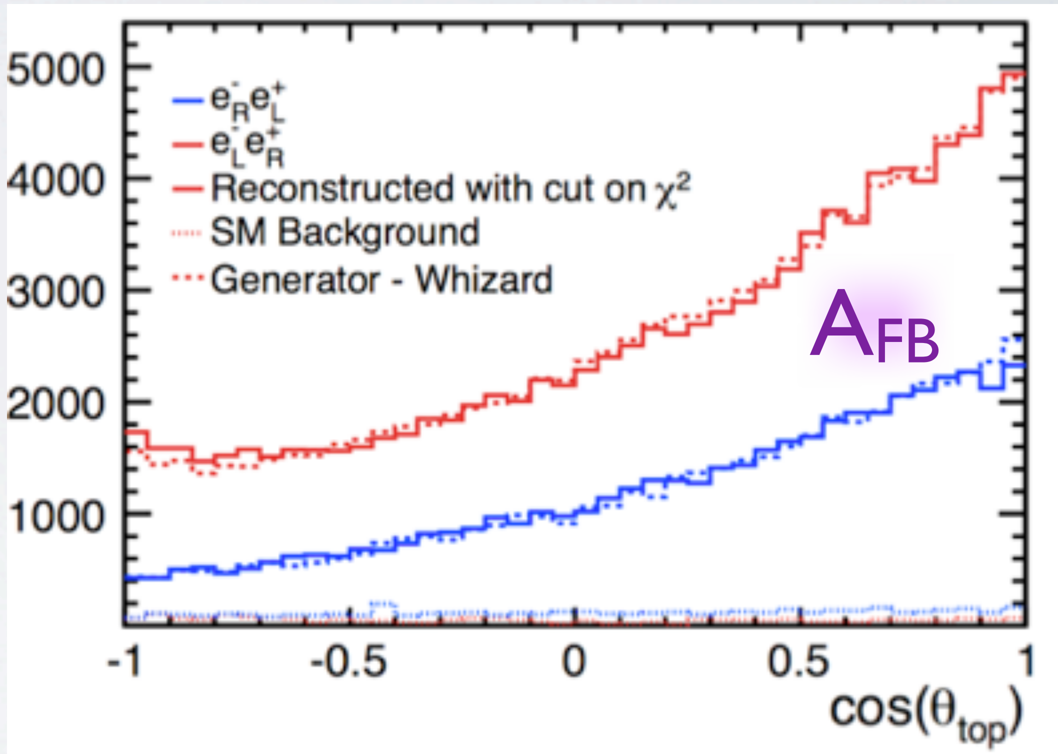
extraction of different γ and Z couplings/form factors at ILC rely on $\sqrt{s}$ above threshold and e+e- polarized beams

Amjad et al. 1505.06020

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

$\mathcal{P}_{e^-}, \mathcal{P}_{e^+}$	$(\delta\sigma/\sigma)_{stat.}$ [%]	$(\delta A^t_{FB}/A^t_{FB})_{stat.}$ [%]
$-0.8, +0.3$	0.47	1.8
$+0.8, -0.3$	0.63	1.3

Quantity	g_L^γ	g_R^γ	g_L^Z	g_R^Z	
SM Value at tree level	2/3	2/3	0.824	-0.364	
Standard deviation	0.005	0.005	0.008	0.009	
Relative precision [%]	0.8	0.8	1.0	2.5	
Full Data Set [%]	0.6	0.6	0.6	1.0	(LCWS15)

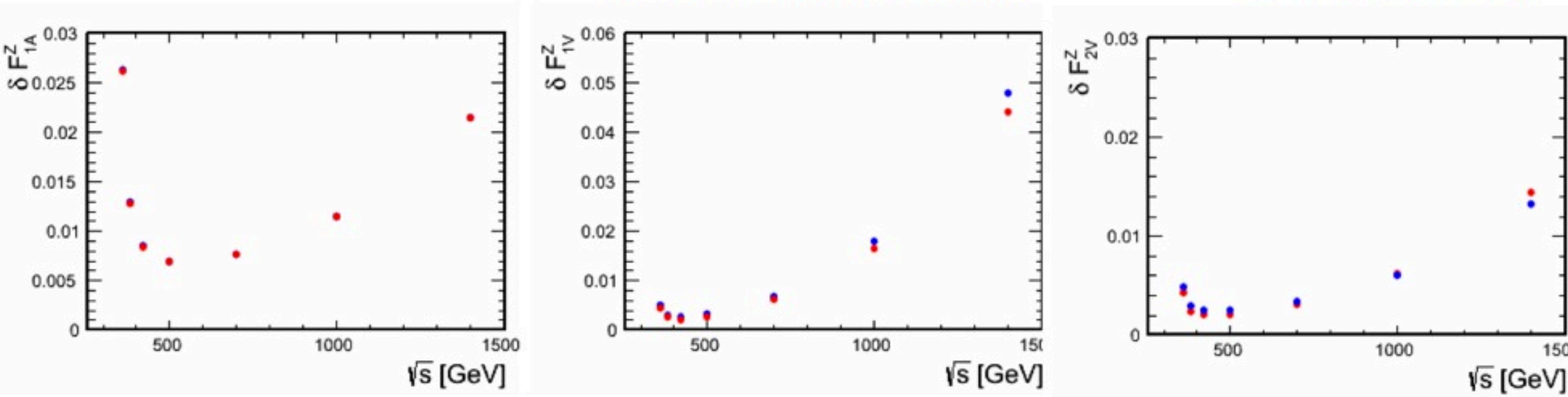


Top-quark EW coupling determination @ the ILC sensitivity vs. $\sqrt{s}$

(M.Vos talk)

stat. dominated uncertainty:
$\delta\sigma/\sigma \sim 1/\sqrt{N}$ $\delta A_{FB} = (1 - A^2_{FB}) \times \delta\sigma/\sigma$
Integrated luminosity: 2 x 250/fb

Nominal beam polarization (e^- 80%, e^+ 30%)
Electron polarization only



- F_{1V}: shallow minimum → *optimal around 400 GeV*
- F_{1A}, A_{FB} degraded strongly close to threshold → *500 GeV*
- F_{2V}: impact of new physics grows strongly with energy → 1-3 TeV

Truly optimal: comprehensive program at several energies

Top-quark EW coupling determination at the FCC-ee

the lack of initial polarization is compensated by the presence of substantial final state polarization and by a larger integrated luminosity

- At FCC-ee, the final state top quarks are produced with non-zero polarization (ttZ)
  - The top polarization (and the total rate) depend on the ttZ/γ couplings
  - The top polarization is maximally transferred to the top decay products $t \to Wb$
    - ➡ Affect the energy and angular distributions of these decay product

      Similar to τ polarization in $Z \to \tau^+\tau^-$ events at LEP

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

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 360 GeV and 2.6/ab (3years)

(Janot 1503.01325, HEP-EPS 2015)

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

Lepton energy and angular distributions

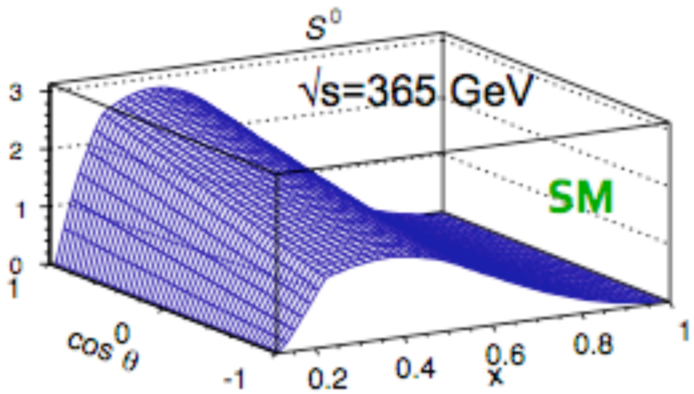
- **Parameterization of the ttV vertex (V = Z, γ)**

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

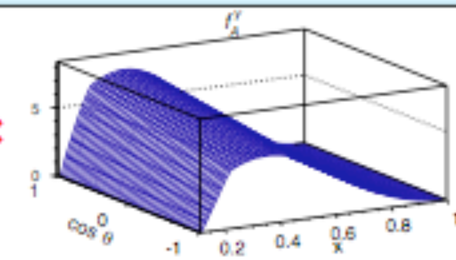
$$\frac{d^2\sigma}{dx\,d\cos\theta} =$$



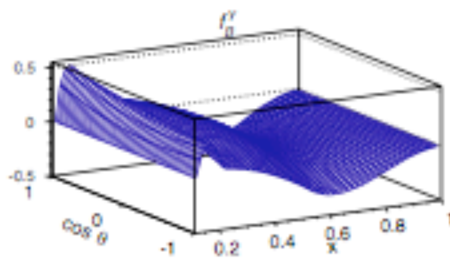
$\delta A_V = \delta B_V = \delta C_V = \delta D_V = 0$

+

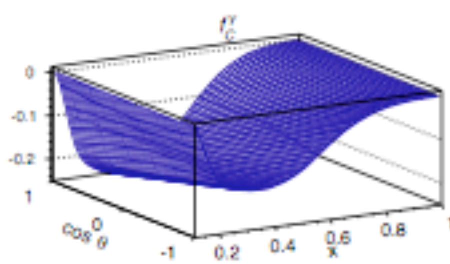
δA_γ ×



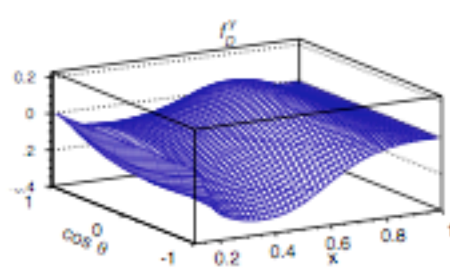
δB_γ ×



δC_γ ×

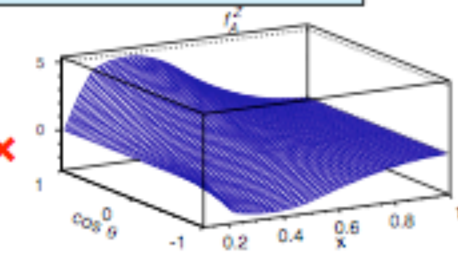


δD_γ ×

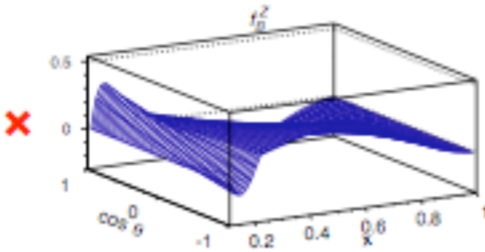


+

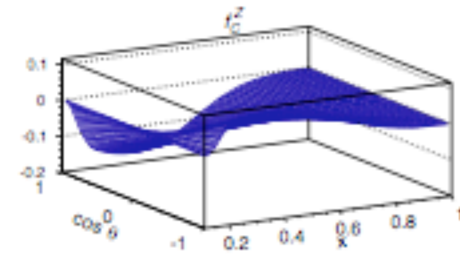
δA_Z ×



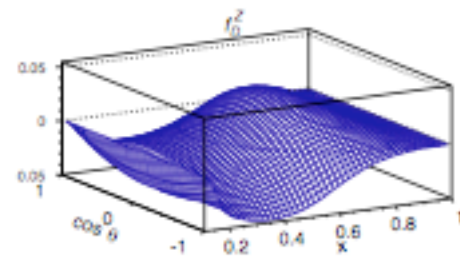
δB_Z ×



δC_Z ×



δD_Z ×



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%

Optimal-Observable statistical analysis

The 8 form factors can be determined simultaneously if the 9 distribution functions are linearly independent

Only the 6 CP-conserving form factors are considered $F_{1V}^{\gamma Z}$, $F_{1A}^{\gamma Z}$, $F_{2V}^{\gamma Z}$

The elements of the covariance matrix (the statistical uncertainties) are derived from a likelihood fit to the lepton angular/energy distributions and the total event rate

Absolute statistical uncertainties on the form factors expected at FCC-ee from angular and energy distributions of leptons or b-jets

(Courtesy Patrick Janot, HEP-EPS 2015)

	$gA_{\gamma,Z} = 2e(F_{1V}^{\gamma,Z} + F_{2V}^{\gamma,Z})$		$gB_{\gamma,Z} = 2eF_{1A}^{\gamma,Z}$		$gC_{\gamma,Z} = 2eF_{2V}^{\gamma,Z}$	
Coupling	$\sigma(F_{1V}^{\gamma})$	$\sigma(F_{1V}^{Z})$	$\sigma(F_{1A}^{\gamma})$	$\sigma(F_{1A}^{Z})$	$\sigma(F_{2V}^{\gamma})$	$\sigma(F_{2V}^{Z})$
Leptons	1.1×10^{-3}	2.8×10^{-3}	1.2×10^{-2}	2.3×10^{-2}	0.8×10^{-3}	2.2×10^{-3}
b jets	1.2×10^{-3}	5.7×10^{-3}	1.5×10^{-2}	1.1×10^{-2}	1.2×10^{-3}	5.7×10^{-3}

A full simulation study is needed to confirm b-jets numbers

- Very conservative lepton ID efficiencies and angular / momentum resolutions were used

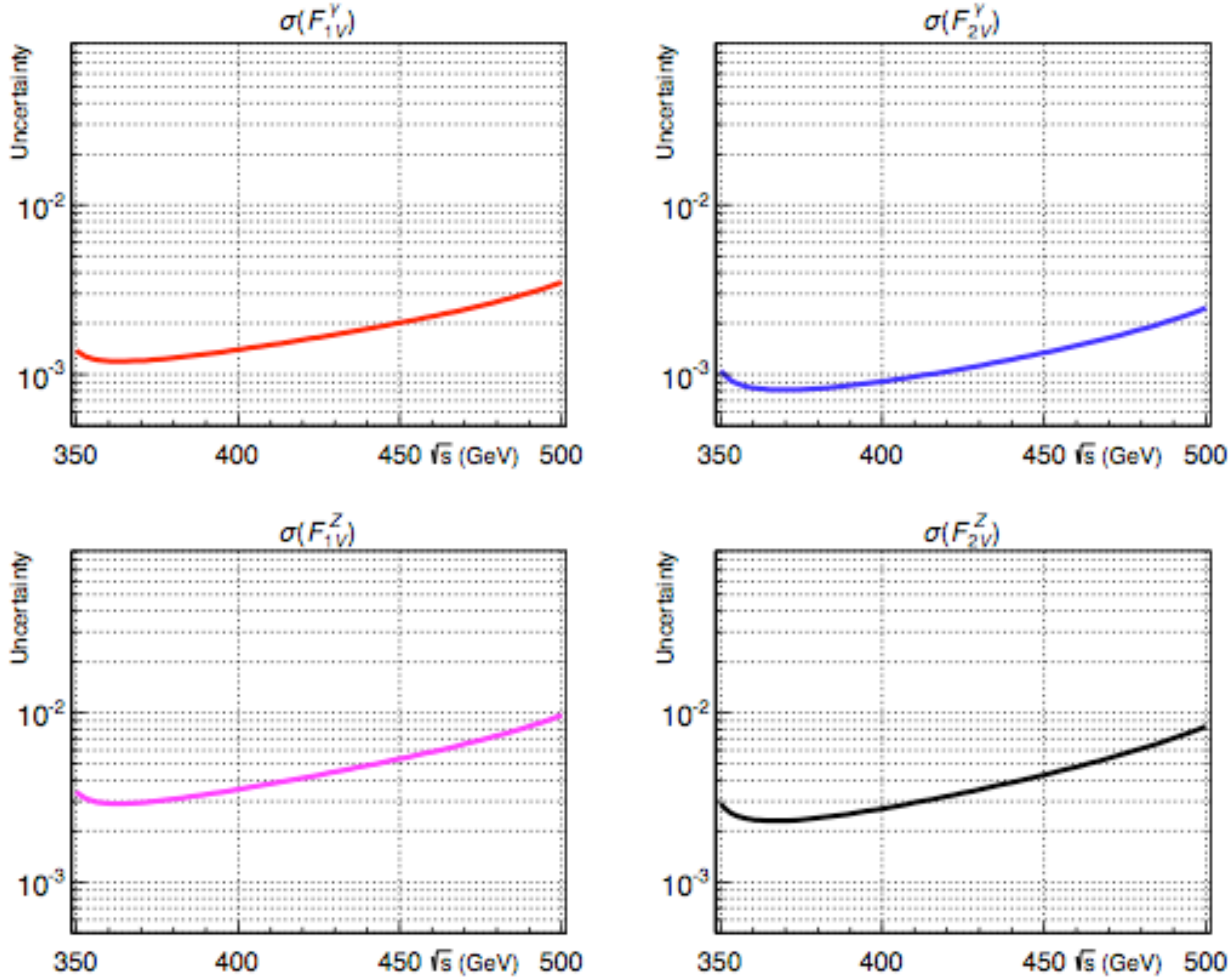
For details see Janot 1503:01325)

The dominant systematic uncertainty is of theoretical nature. The derived statistical uncertainties on the form-factors are reliable if σ^{TOT}th.uncert. ~ 2% ... a challenge at the production threshold

(Courtesy Patrick Janot, HEP-EPS 2015)

What about larger $\sqrt{s}$?

- Evolution of the absolute resolutions expected at FCC-ee as a function of $\sqrt{s}$:

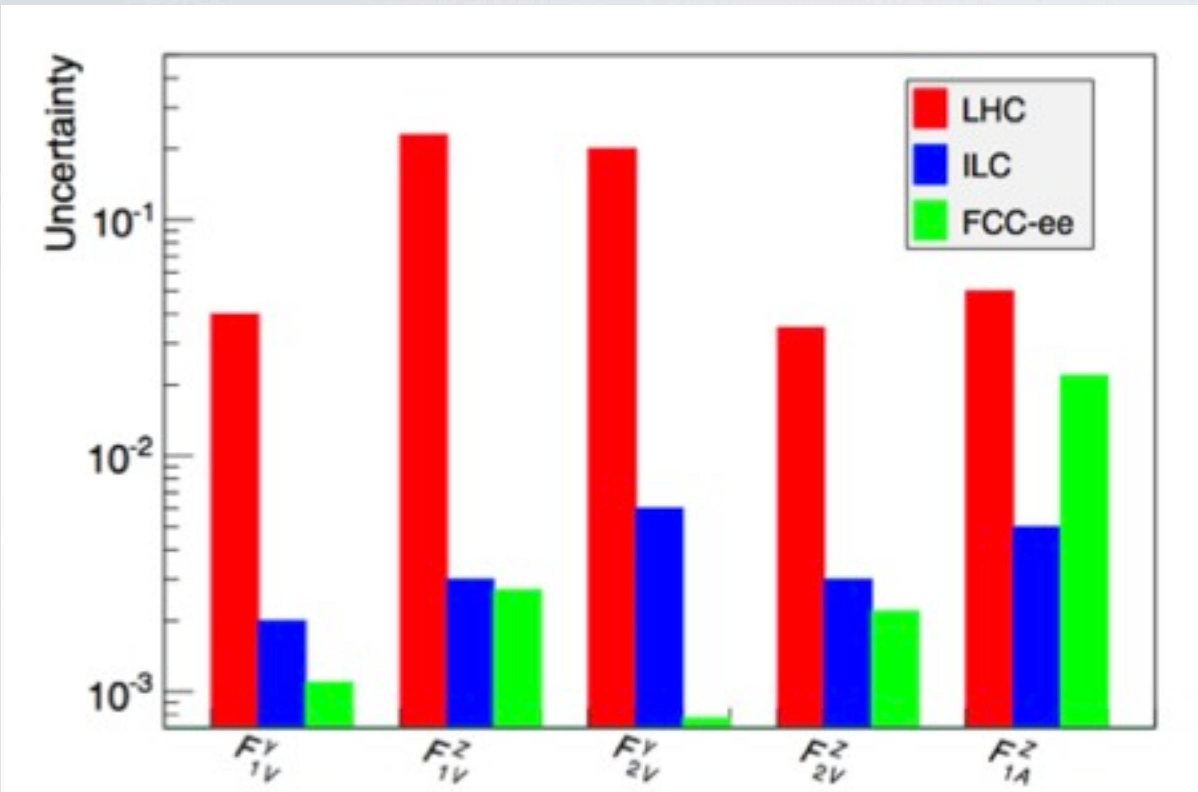


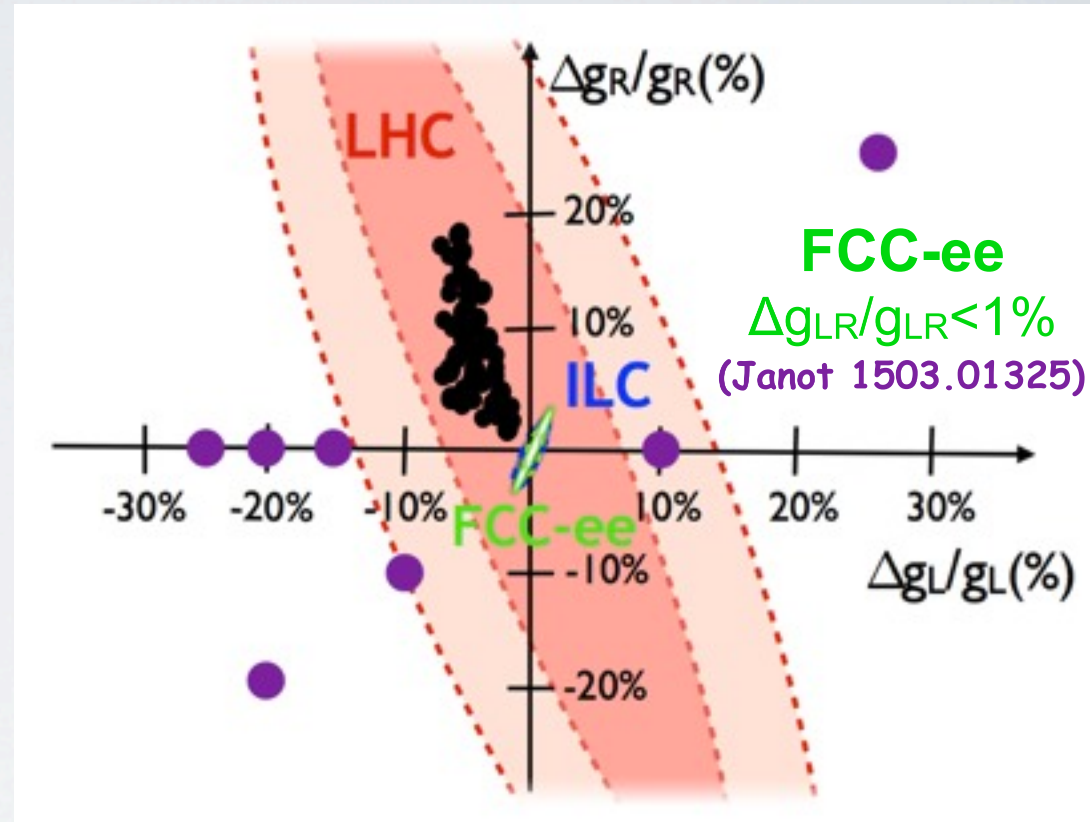
Optimum is at $\sqrt{s}$ ~ 365 GeV except for F_{1A}^{Z}

The sensitivity on F^{Z}_{1A} can be reduced by a factor 2 by increasing the c.o.m. energy to 420 GeV

Top-quark EW coupling determination at the FCC-ee

Optimal-observable analysis of lepton angular and energy distributions from top-quark pair production with semi-leptonic decays at FCC-ee with 360 GeV and 2.6 ab^{-1}





LHC (14 TeV, 300 fb^{-1})
ILC(500GeV, 500 fb^{-1}) with polarized beams
(ILC-TDR 1306.6352; Amjad et al. 1505.06020)
FCC-ee (360GeV, 2.6 ab^{-1}) from lepton angular and energy distributions
(Janot 1503.01325)

continuous(dashed): from angular and energy distributions of leptons (b-quarks)
(Janot, EPS HEP 2015, WhatNext White paper of CSN1)

total x-section predicted with a 2% precision
warning: large QCD corr. near threshold , possible underestimation of x-section error

Impact of the $\sigma^{TOT}_{th.uncertainty}$ on the top-quark EW coupling determination at CLIC@380GeV

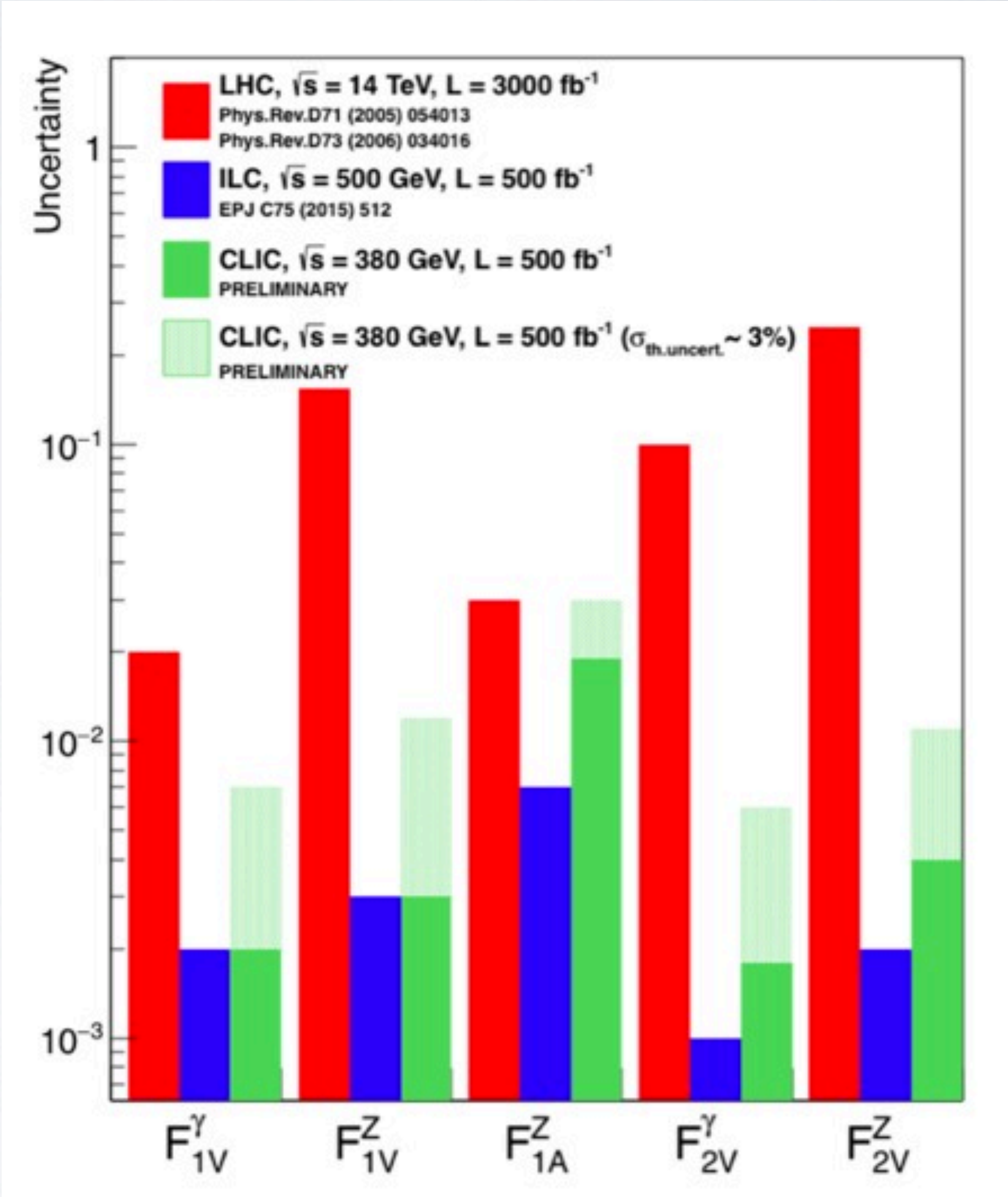
(M.Vos talk)

CLIC@380GeV L=500fb^{-1}

$$\mathcal{P}_{e^-} = \pm 0.8; \mathcal{P}_{e^+} = 0$$

CLIC: similar precision to ILC except for the coupling F_{1A}^{Z} that suffers the large statistical error of A_{FB} ~5%

Conservative scenario for CLIC: NNNL calculations at threshold predict a 3% theory uncertainty

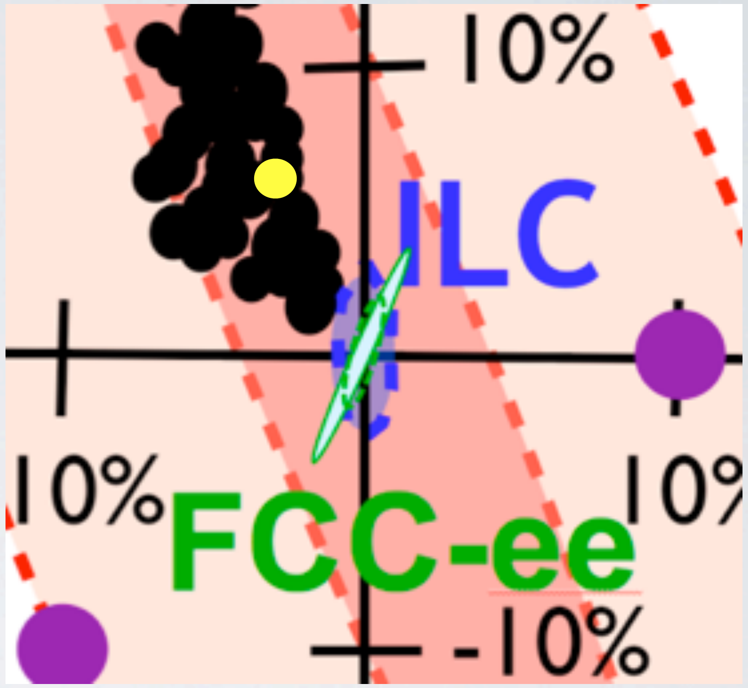


Top-quark EW coupling determination at the FCC-ee for a 4DCHM benchmark point

f =1.3TeV, g_ρ =1.5, m_Q=1.47TeV

$$M_{Z'_{2,3,5}} = 2122, 2214, 2831\ GeV$$

$$\Gamma_{Z'_{2,3,5}} = 452, 319, 91\ GeV$$



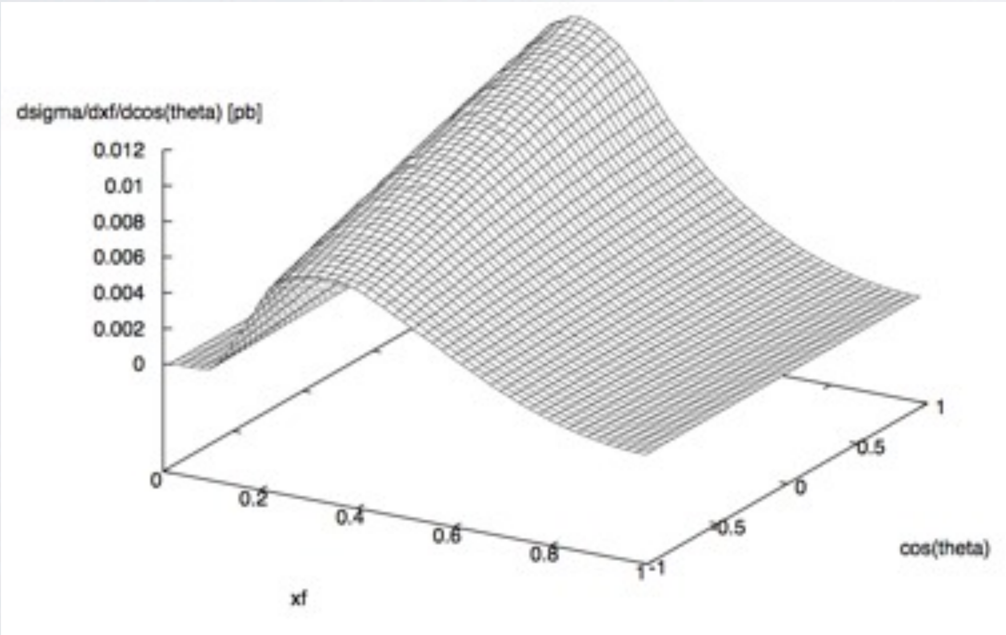
top EW couplings deviations

$\Delta g^{\gamma}_{L} = \Delta g^{\gamma}_{R} = 0$
$\Delta g^{Z}_{L} = -0.007135$
$\Delta g^{Z}_{R} = -0.007076$

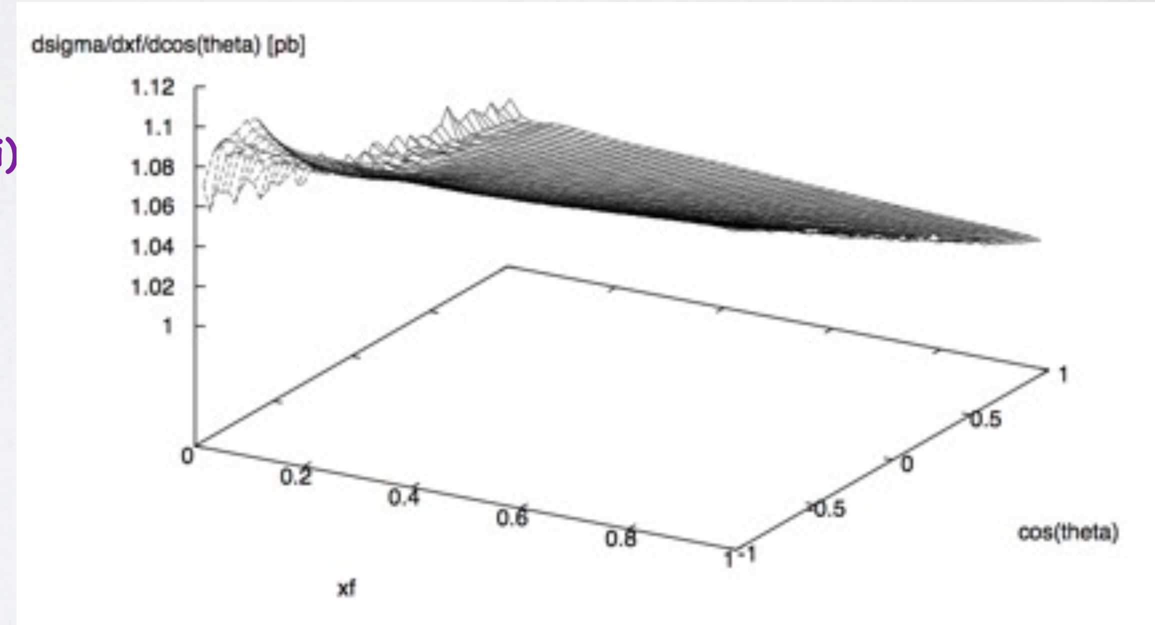
→

$\Delta g^{Z}_{L}/g^{Z}_{L}(\%) = -2.8$
$\Delta g^{Z}_{R}/g^{Z}_{R}(\%) = 6.2$

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



(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

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

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

(P.Janot)

☑ Fit of F_{1V}^{γ} , F_{1A}^{γ} , F_{1V}^{Z} , F_{1A}^{Z} (by fixing all the F_2=0, SM value)

			marginalised	(individual) uncertainties
ΔF_1V^gamma	=	0.0185480416488	+/- 0.00109231135117	(0.000601304139852)
ΔF_1V^Z	=	-0.0194162236349	+/- 0.00263630696037	(0.0016046847253)
ΔF_1A^gamma	=	-0.00216258019151	+/- 0.00693281220269	(0.00615422547088)
ΔF_1A^Z	=	0.0153732528192	+/- 0.0135796307785	(0.00759866410111)

ΔF_{1V}^{γ} is more than **16σ from 0** !
ΔF_{1V}^{Z} is more than **7σ from 0**
ΔF_{1A}^{γ},ΔF_{1A}^{Z} are ~ compatible with 0

The FCC-ee run at its highest energy (365-370 GeV) would therefore either discover (with a 16σ significance) or firmly exclude this 4DCHM benchmark

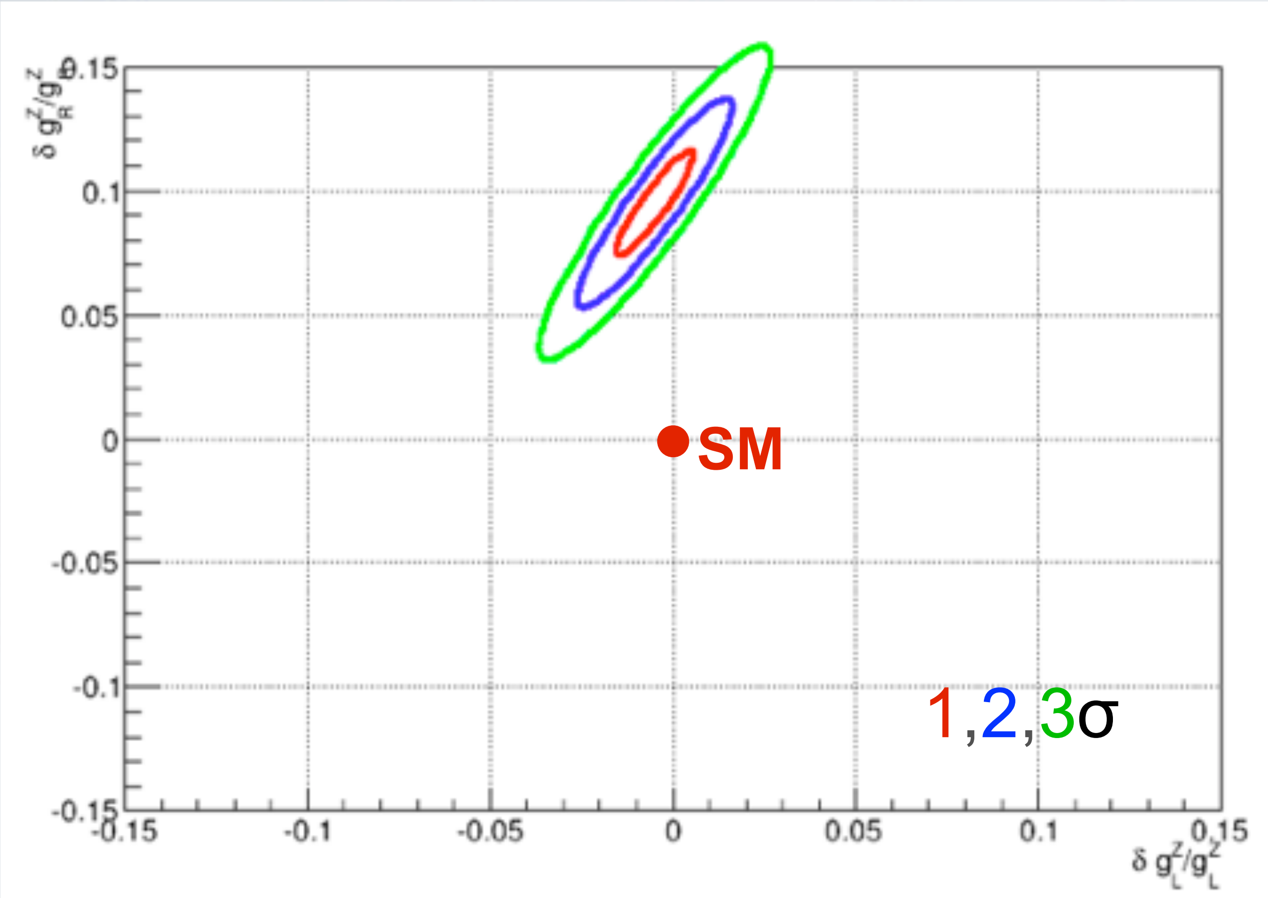
From the 4 form factor, one can fit the 4 top EW couplings:

ΔgL^Z	=	-0.0012624169474	+/- 0.00487850785471	(0.00104558106096)
ΔgR^Z	=	-0.0108633121625	+/- 0.0036810341515	(0.000926199117364)
ΔgL^gamma	=	0.00511647521638	+/- 0.00230761104835	(0.000372703605519)
ΔgR^gamma	=	0.00646706449509	+/- 0.00206387449922	(0.000374782280697)

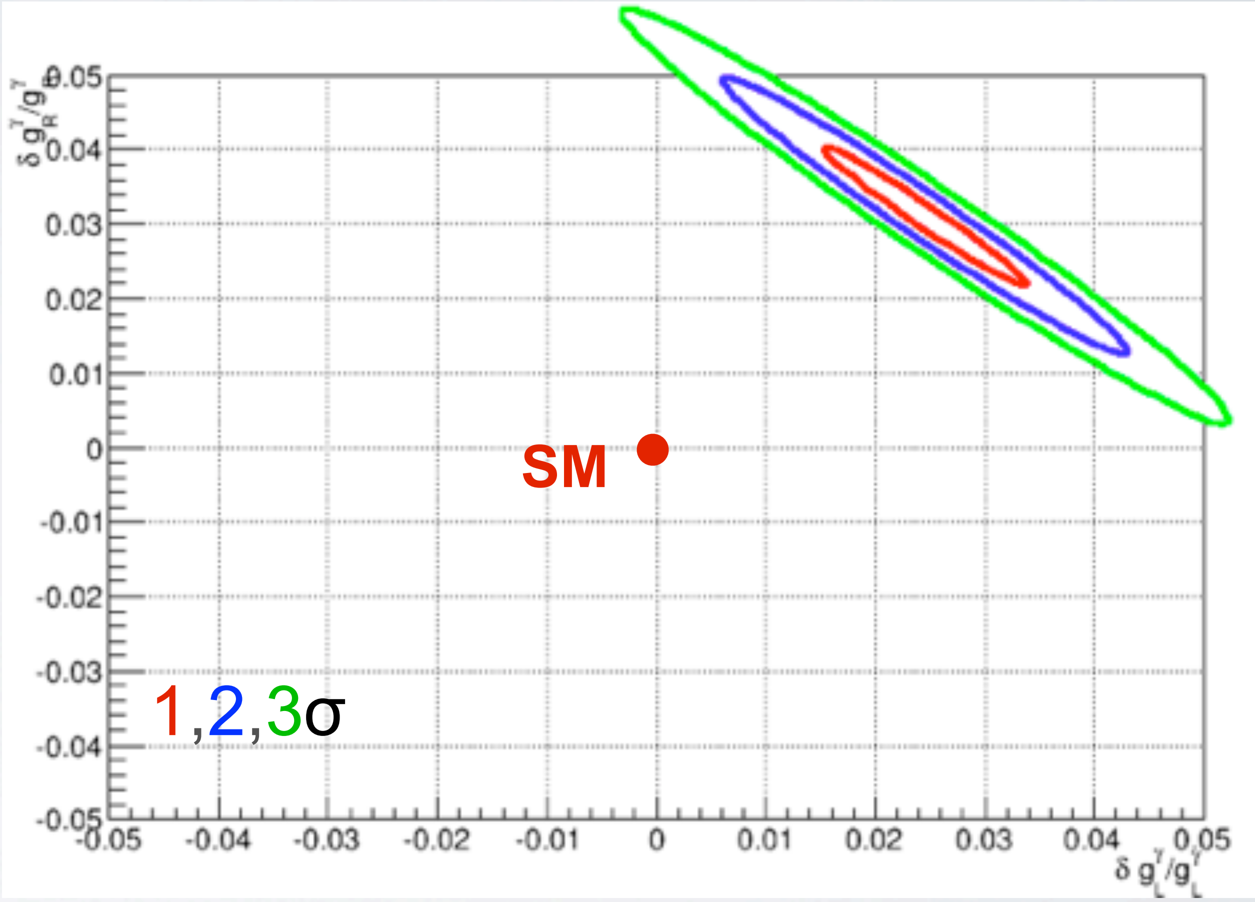
Top-quark EW coupling determination at the FCC-ee for a 4DCHM benchmark point

(P.Janot)

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



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



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 distribution obtained by removing the Z's

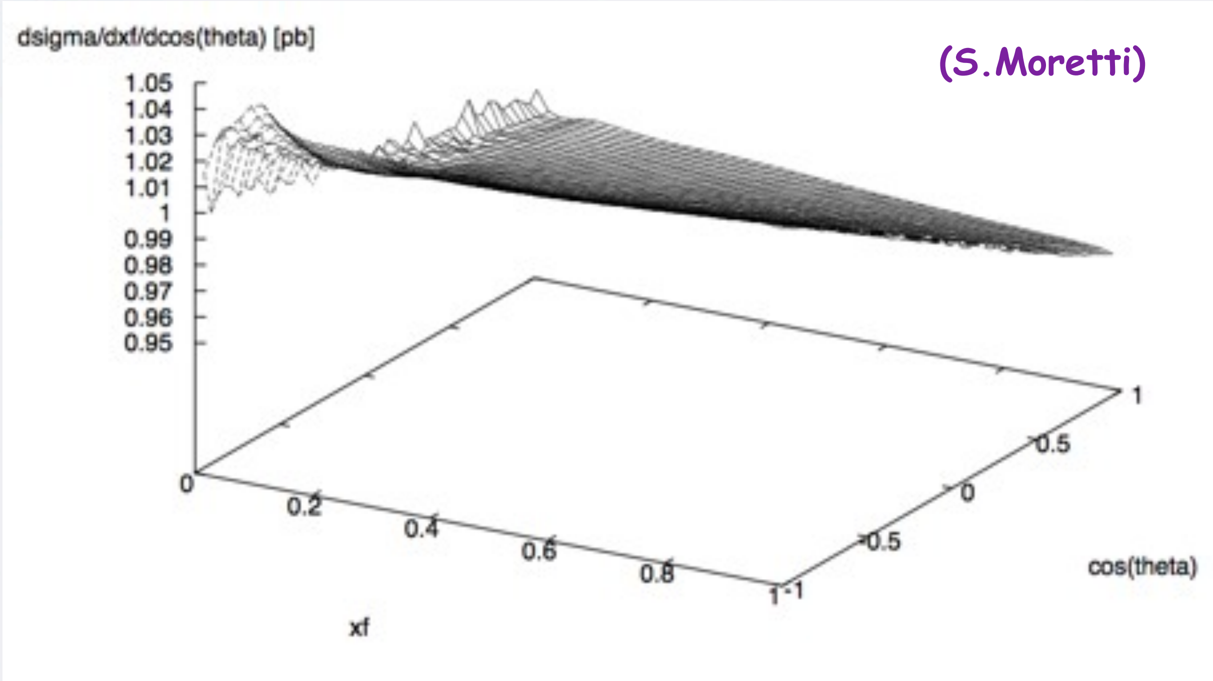
☑ Fit of F_{1V}^{γ} , F_{1A}^{γ} , F_{1V}^{Z} , F_{1A}^{Z} (by fixing all the F_2=0, SM value)

ΔF_1V^gamma	=	-0.000336442749397	+/-	0.00106286209443	(0.000585199541763)
ΔF_1V^Z	=	-0.0227066478739	+/-	0.00256578095206	(0.00156229735908)
ΔF_1A^gamma	=	-0.0014546945567	+/-	0.00673523092641	(0.00599158504968)
ΔF_1A^Z	=	-0.000241121447871	+/-	0.0132168841241	(0.00739682088364)

ΔF_{1V}^{Z} is ~ **9σ from 0**

ΔF_{1V}^{γ} , ΔF_{1V}^{Z}, ΔF_{1V}^{Z} are compatible with 0

$$e^+e^- \to \gamma, Z \to t\bar{t} \to b\bar{b}W^+W^- \to b\bar{b}l^+l^-\nu\bar{\nu}$$



$$\frac{d^2\sigma^{noZ'}_{4DCHM}}{dxd\cos\theta} \quad \frac{d^2\sigma^{noZ'}_{SM}}{dxd\cos\theta}$$

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

(P.Janot)

Four parameter fit for the EW couplings:

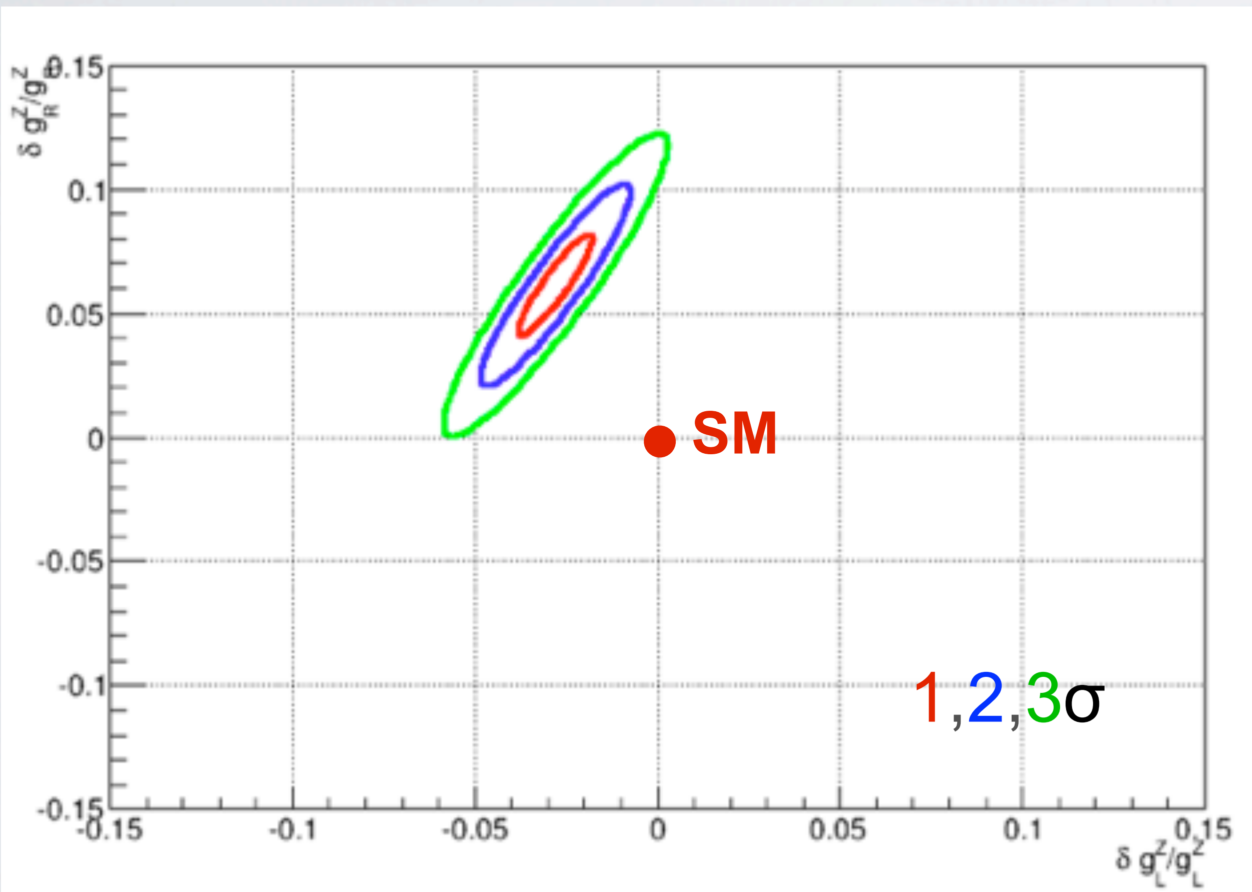
ΔgL^Z = -0.00716561621999 +/- 0.00474857910749 (0.00101814006264)
ΔgR^Z = -0.00701503925374 +/- 0.00358297962061 (0.000901572343573)
ΔgL^gamma = -0.000559301118803 +/- 0.00224477497389 (0.000362731021188)
ΔgR^gamma = 0.000349186626273 +/- 0.00200793560493 (0.00036473746555)

compare with the model values

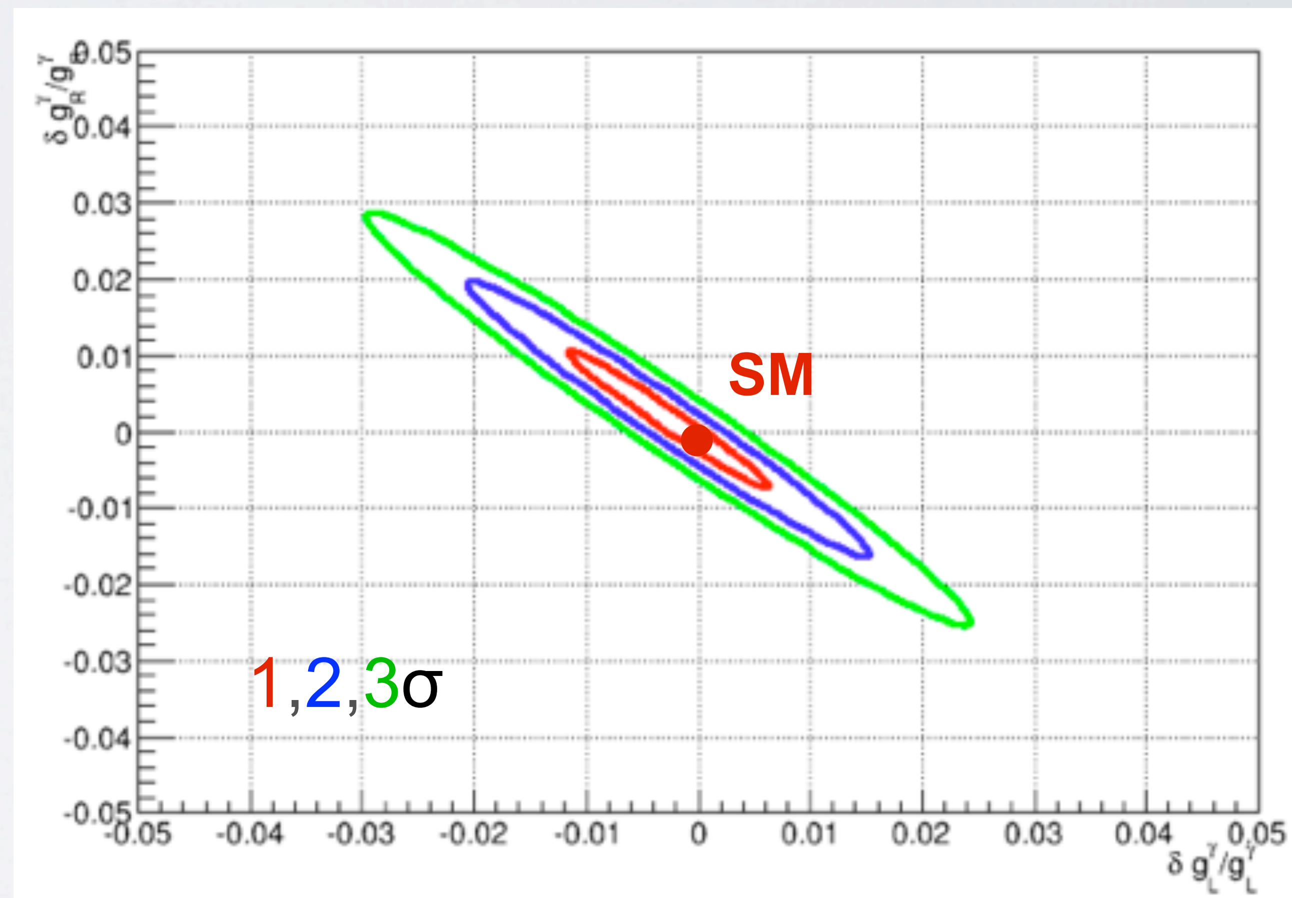
$\Delta g^Z{}_L$=-0.007135
$\Delta g^Z{}_R$=-0.007076
$\Delta g^\gamma{}_L=\Delta g^\gamma{}_R$=0

!!

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



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



15σ ellipse passes via the (0,0) point !

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

Comments and outlook

We have shown with a concrete example how, with the high precision in the EW top-coupling determination of the FCC-ee, a benchmark point of the 4DCHM can be discovered or excluded with a very high statistical significance.
We expect it holds true for almost all the black points corresponding to "natural" choices of the CHM parameters

VERY IMPORTANT RESULT: the effective couplings extracted are affected by the dynamics of the Z's exchanges

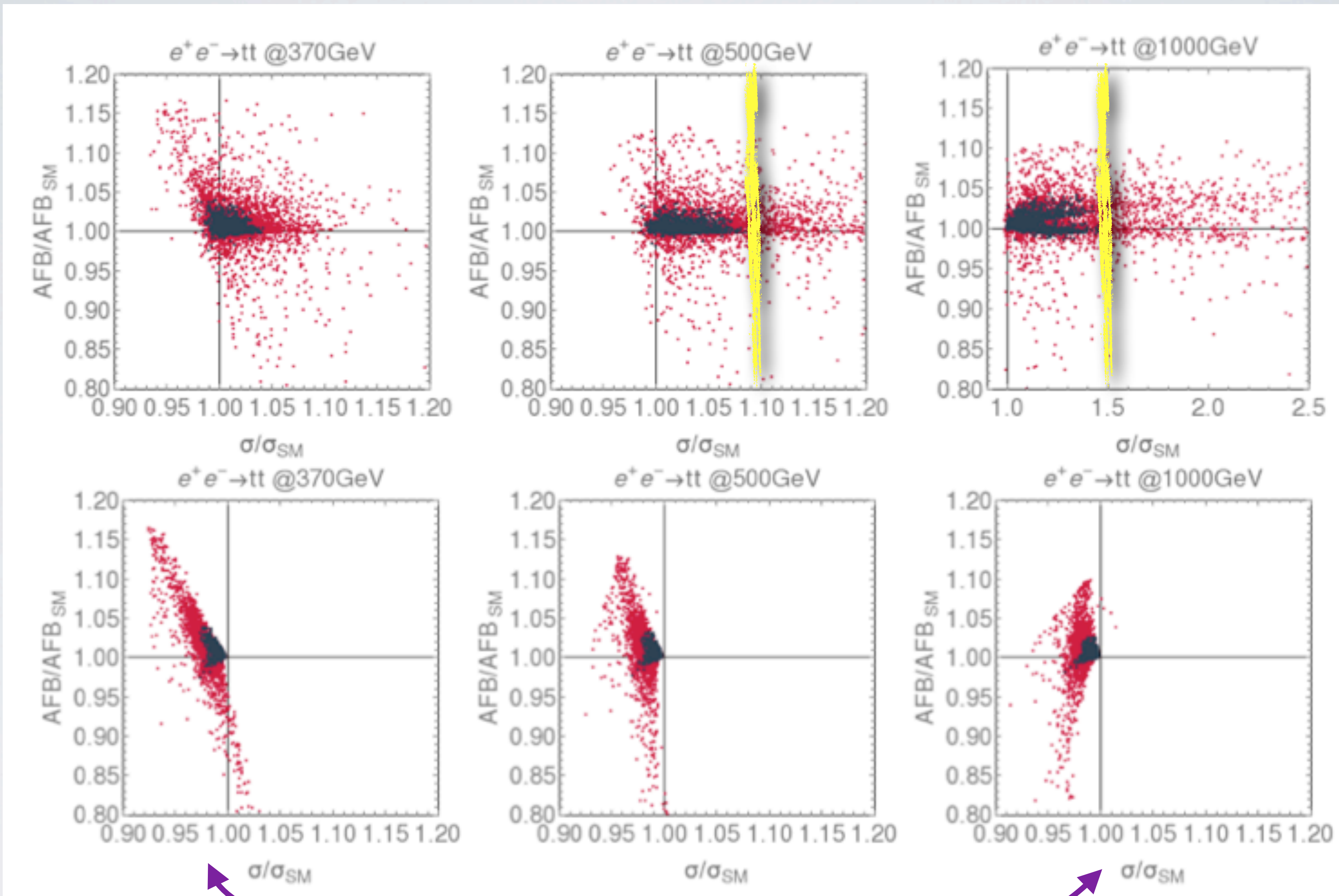
In particular deviations in the left and right top couplings to the photon (which are not expected) give clear indication of interference effects of the Z's with the photon itself. They give an indirect evidence of the new spin-1 resonance(s)

By inspecting the role of the Z's in the theoretical expression of the differential x-section within the 4DCHM (as a representative of CHMs), we will find the relation between the top effective coupling to photon modification, and the physical properties of the Z'(s): mass, width, couplings.

The optimal-observable statistical analysis offers a unique possibility to disentangle the effects of coupling modifications (always taken into account in NP searches) from Z's interference effects (often neglected), important also for c.o.m. energies $\ll M_{Z'}$

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>800GeV $M_{Z'}$>2TeV



coupling Ztt modification only

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

up to 10(50)% deviation in the x-sect @ 500(1000) GeV !

SUMMARY

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

- ☑ Top and Higgs are a golden couple: the effects of new TeV interactions are manifest in the properties of both

- ☑ Hadron collider physics is not yet sensitive to these effects

- ☑ Hopefully, the high precision of e+e- colliders could discover imprints of compositeness or other NP source.

BACKUP SLIDES

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 $\xi = \frac{v^2}{f^2}, \quad v = 246 \text{ GeV}, \quad f \sim 1 \text{ TeV}$

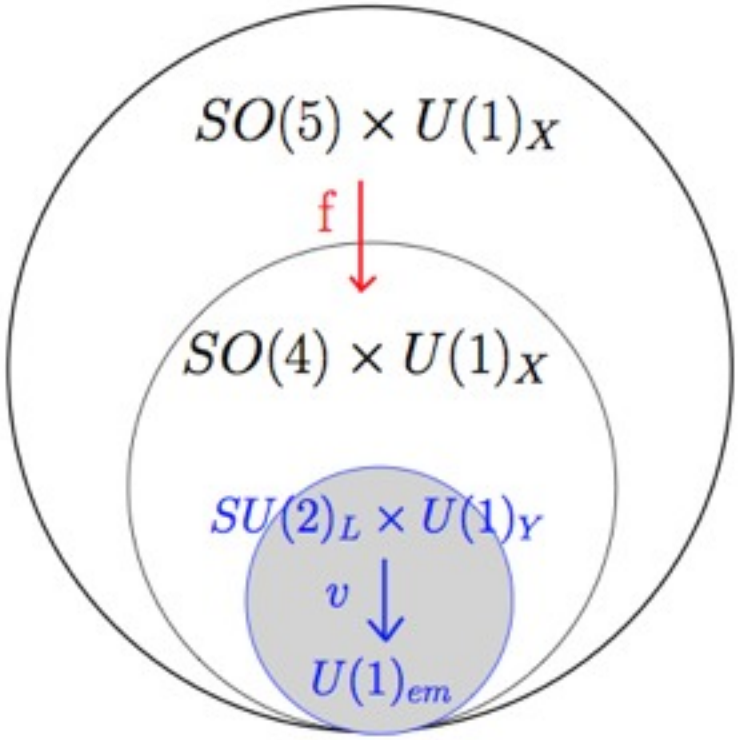
MINIMAL MODEL with $SU(2)_C$

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

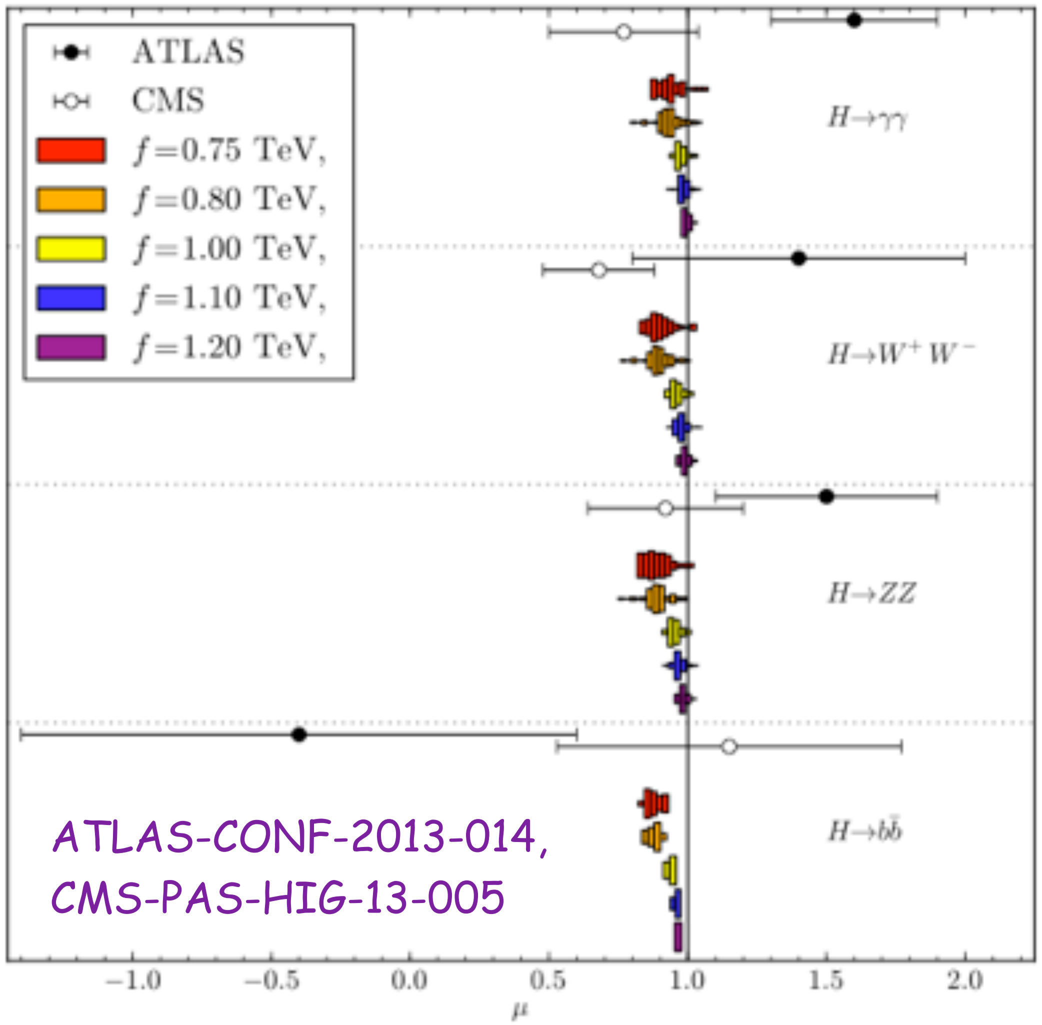
$(m_h \ll m_\rho)$



4DCHM : deconstruction of the minimal SO(5)/SO(4) 5D model, truncated to describe the composite degrees of freedom accessible to the LHC (DC,Redi,Tesi 1110.1613)

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

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



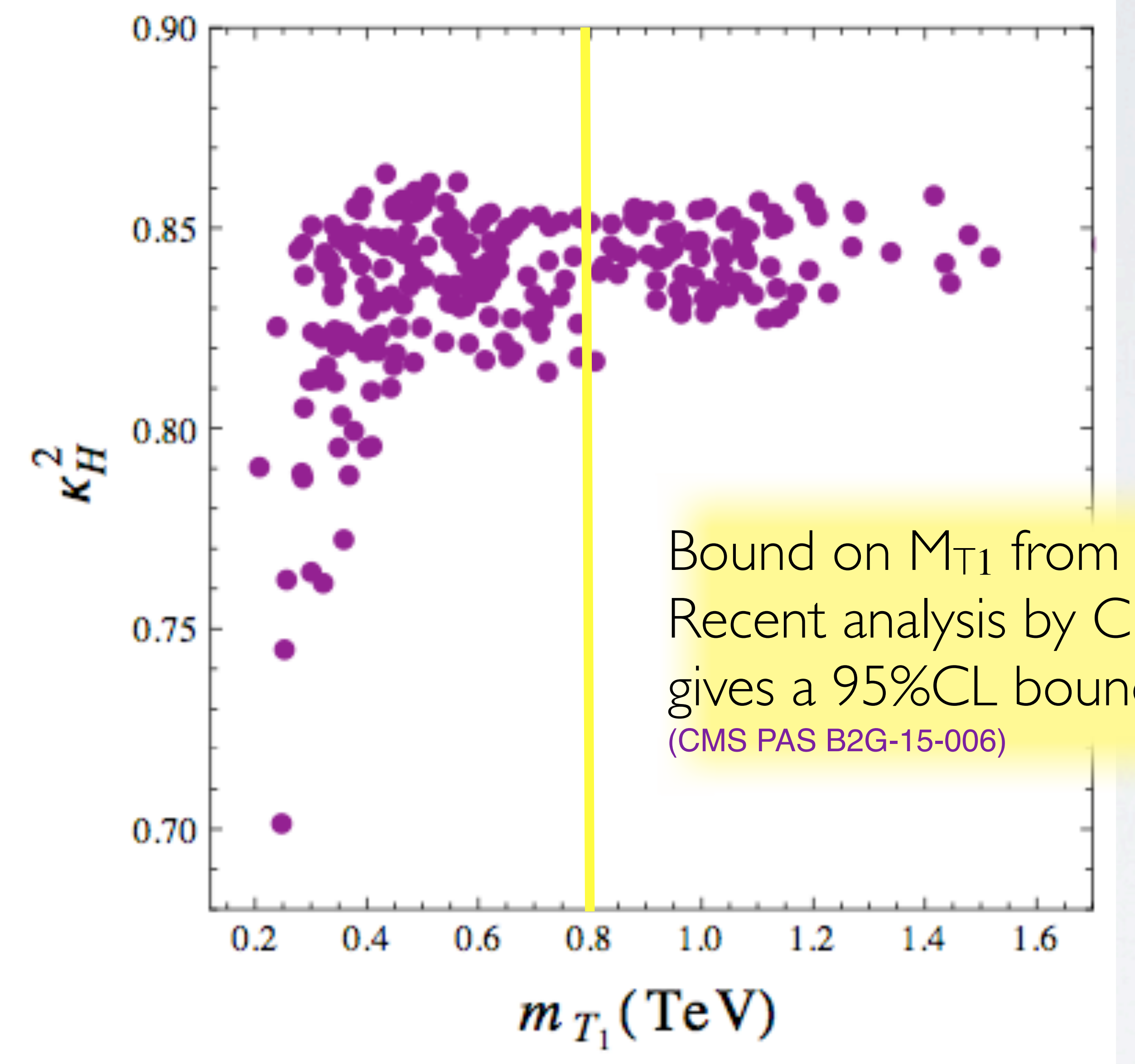
- Higgs couplings to SM states are modified due to mixing
- ~15% reduction of Higgs total width due to Hbb coupling modification
- For production and decay channels **heavy bosonic and fermionic states can play a role via loops** but NGB symmetry protects the couplings **No large deviations.**

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

points compliant with bounds from direct T_1,B_1,$T_{5/3}$ searches

Reduction of the Higgs total width in CHMs due to Hbb coupling modification (partial compositeness)

4DCHM for the benchmark point $f = 1$ TeV and $g_* = 2$.



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

Bound on M_{T1} from direct search is ~800GeV
Recent analysis by CMS for 2.2 fb^{-1} at 13 TeV gives a 95%CL bound $M_{5/3} > 900$ GeV
(CMS PAS B2G-15-006)

T_1 is the lightest $T_{2/3}$

15% deviation for natural choices of f and g* (smaller for larger f)

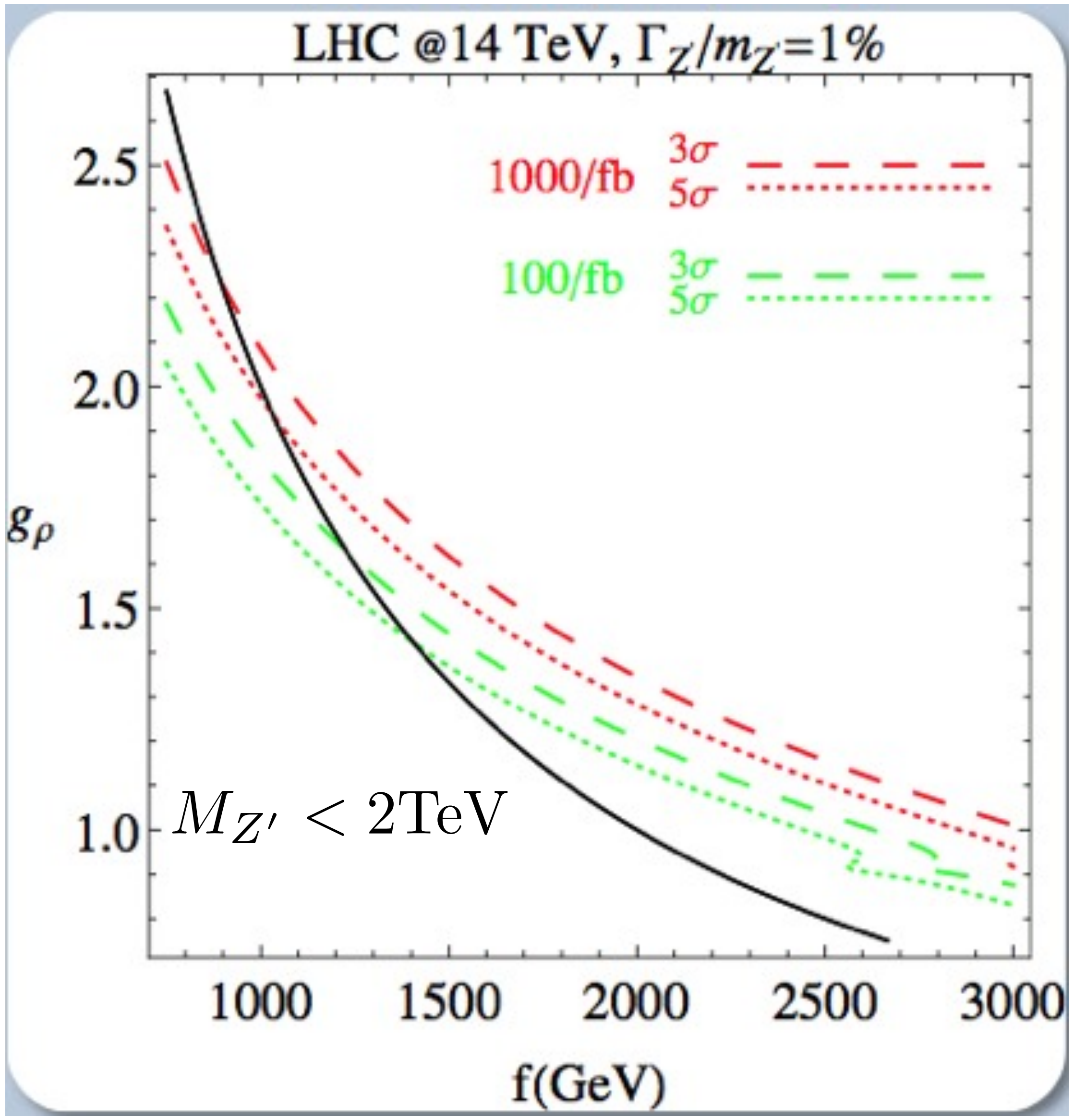
result depends on the extra-fermion setup but it is common to CHM with partial compositeness

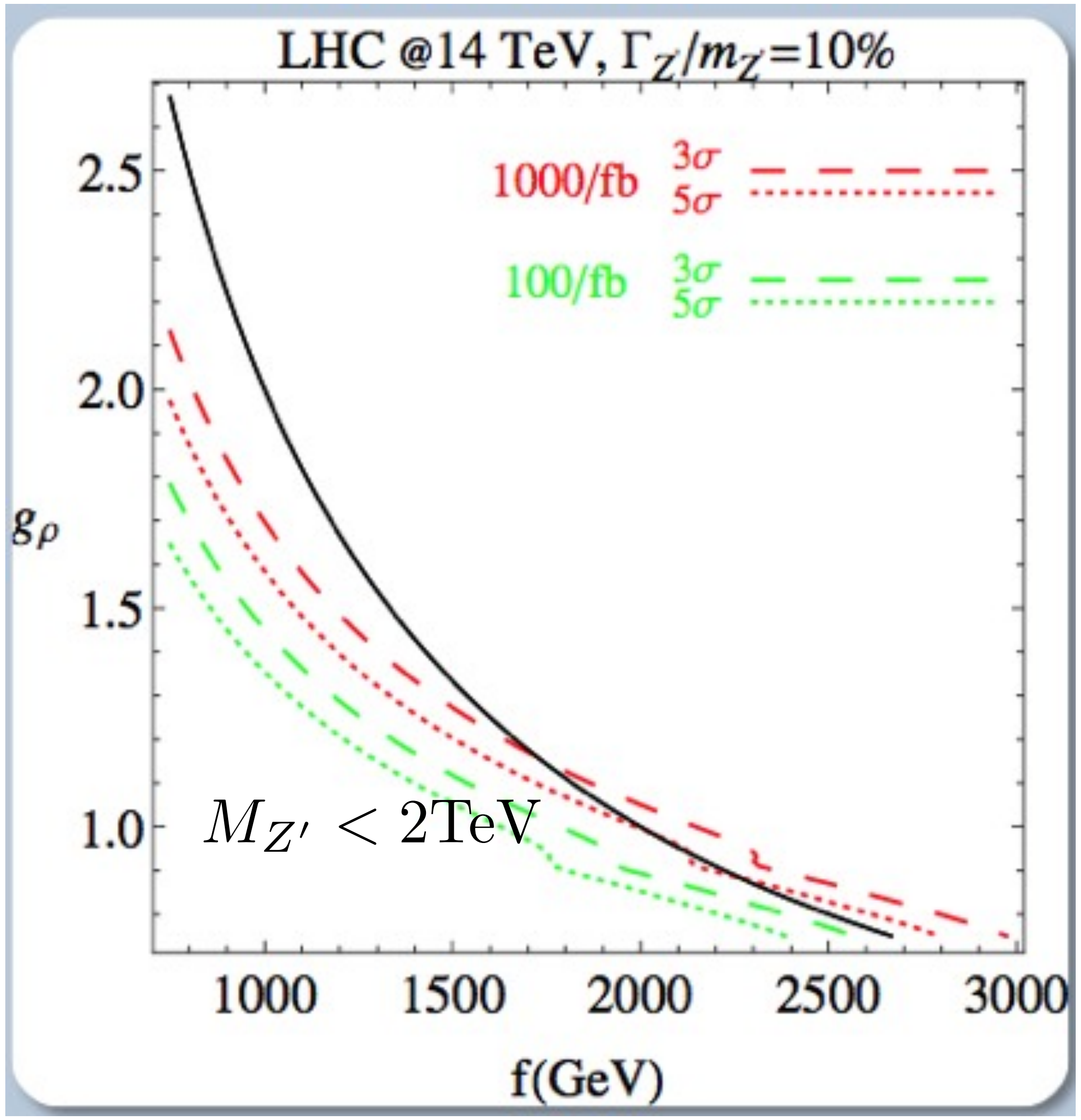
FCC-ee will measure Γ_H to better than 1% !!

Calculating significance, neutral channel - 14 TeV LHC

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

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





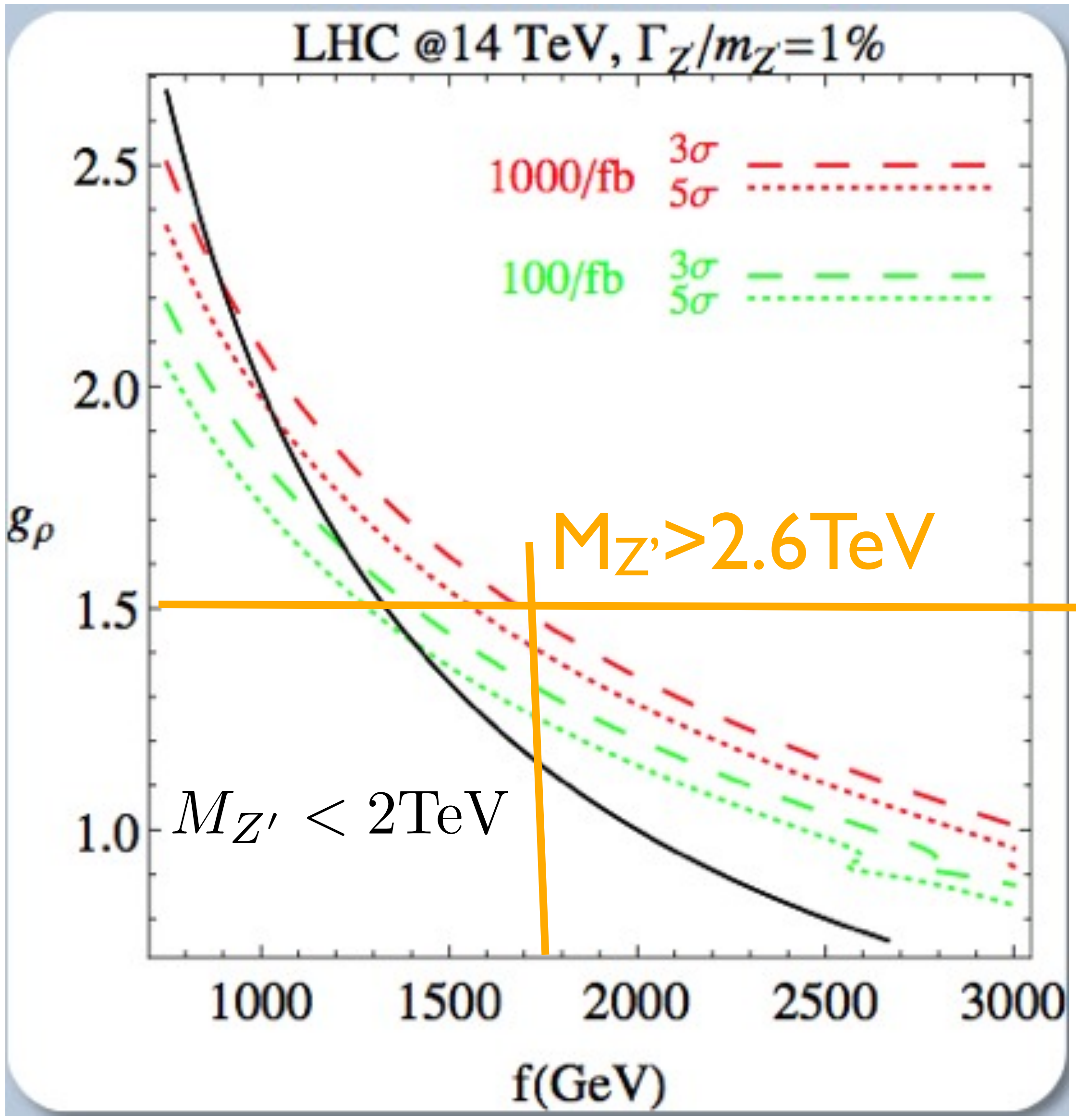
$\Gamma_{Z'}/M_{Z'} = 1\%$ $\Gamma_{Z'}/M_{Z'} = 10\%$

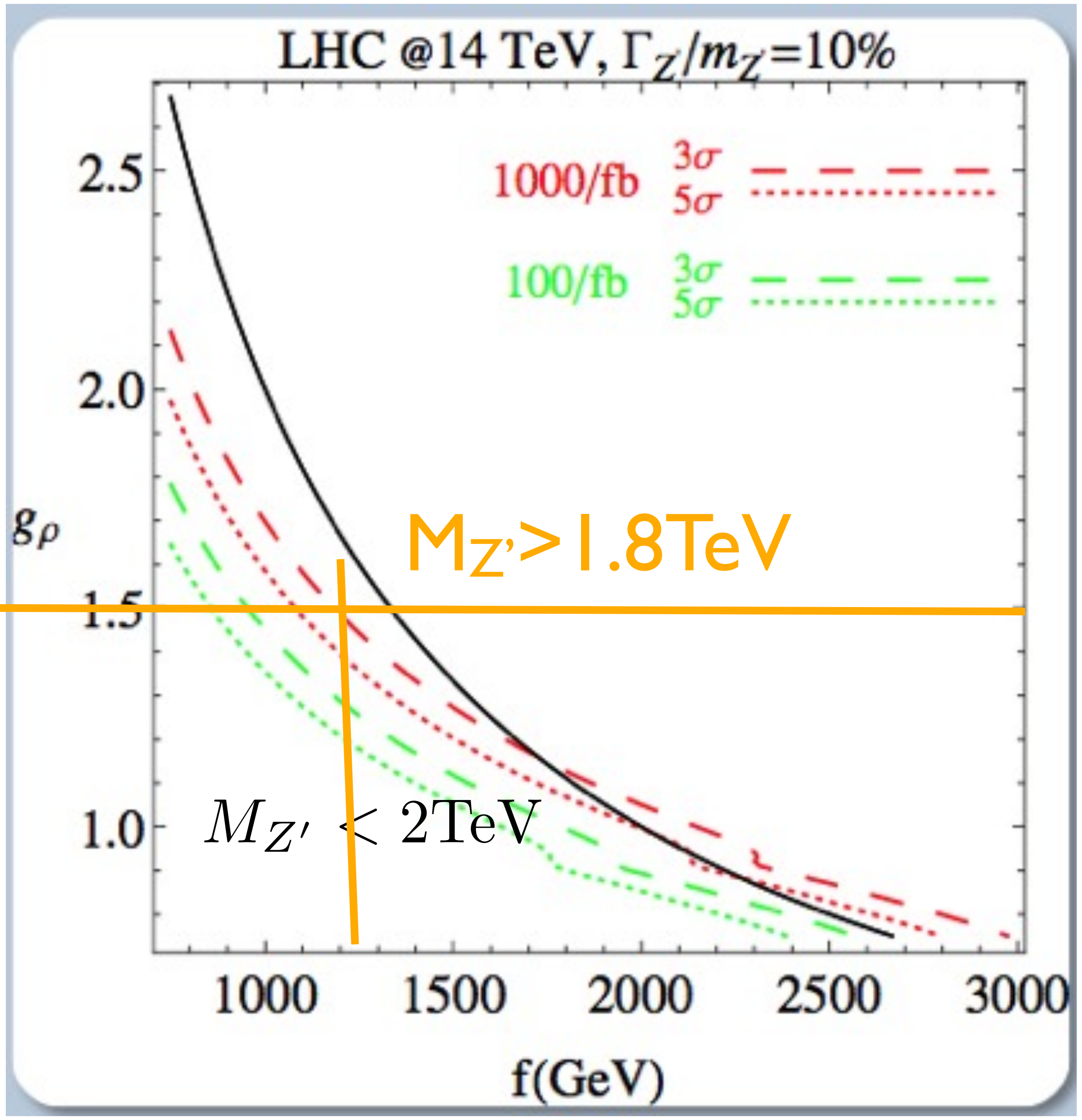
small width is mandatory for Z' detection in DY processes

Calculating significance, neutral channel - 14 TeV LHC

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

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

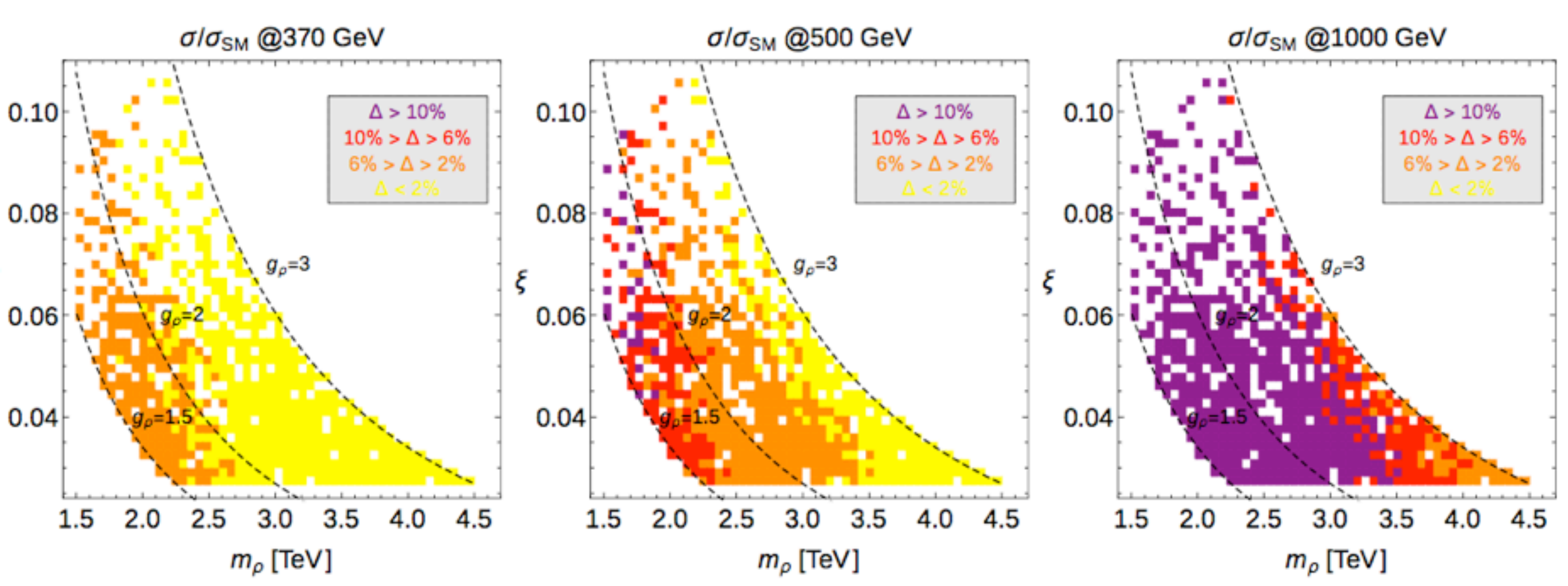




$\Gamma_{Z'}/M_{Z'} = 1\%$ $\qquad \Gamma_{Z'}/M_{Z'} = 10\%$

small width is mandatory for Z' detection in DY processes

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



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

Barducci, et al 1504.05407

Points correspond to f=0.75-1.5, g_s=1.5-3, M_T>800GeV. For each point we have selected the configuration corresponding to the maximal deviation

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

Note: HL-LHC expectation ~ 6 TeV (NWA and neglecting interference with γ and Z) can be very optimistic in realistic cases (work in progress)

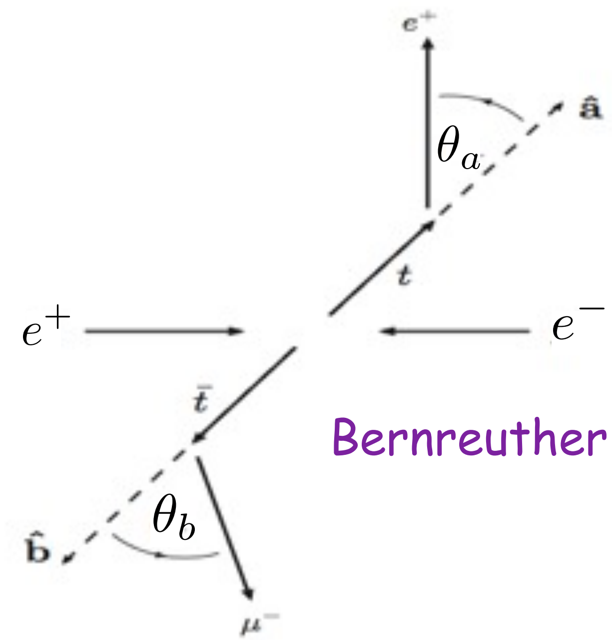
Single Spin Asymmetry A_L

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

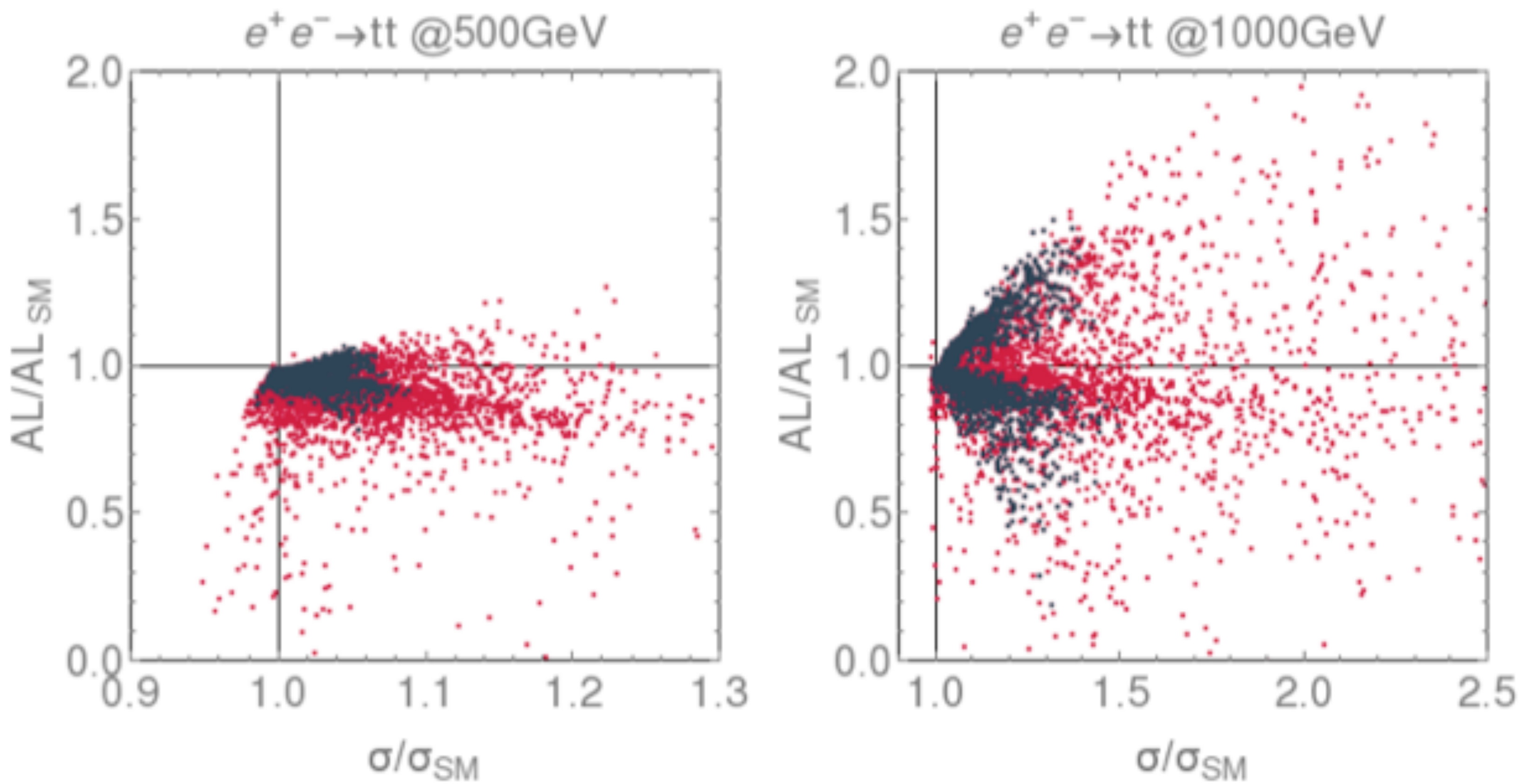
$$B_1 \sim A_L(t),\ B_2 \sim A_L(\bar{t}),\ C \sim A_{LL}$$

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

helicity angle distribution



Bernreuther 0805.1333

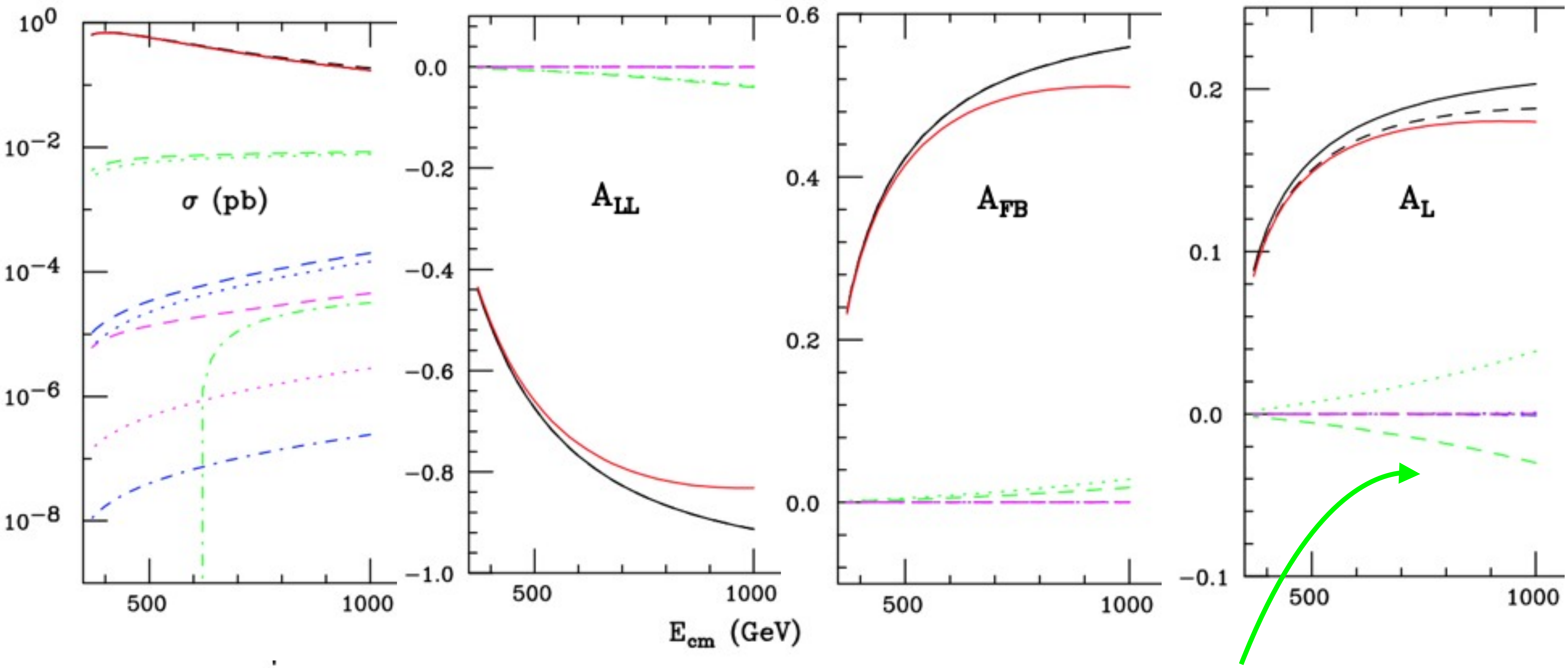


large deviations of both signs @ 1000GeV mainly due to the SM-Z's interference

A_L depends linearly on the couplings so it is sensible to their signs

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 with opposite signs (beam polarization could help)