Imprints of Composite Higgs Models at e+e- 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, arXiv:1504.05407

Outline

☑ The Higgs resonance discovered at the LHC makes the physics case for future accelerators stronger than ever

☑ Theoretical arguments supporting the importance of sub-percent precision for the Higgs coupling determination continue to grow ... especially to find hints for non Standard Model Higgs

☑ An e+e- collider has a great potential on top physics: mass, width and precise coupling determination, very important for NP (partial compositeness)

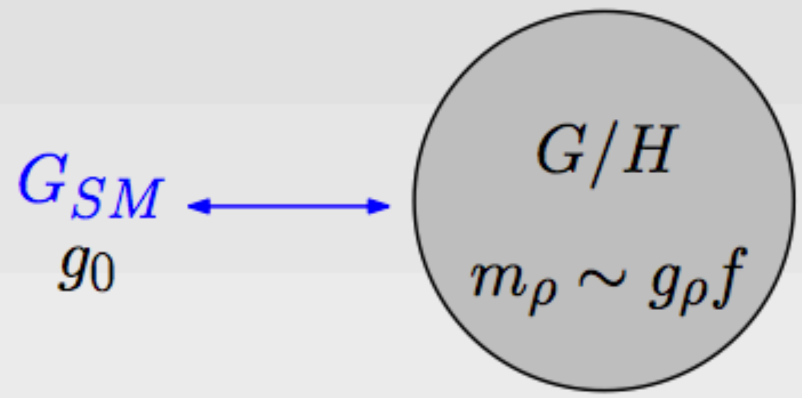
QUESTION: To which level of precision do we need to measure the Higgs and top couplings to probe the dynamics behind the EW symmetry breaking mechanism? Try to answer within a Composite PNGB Higgs Scenario

☑ 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)

☑ Phenomenology at future e+e- colliders

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?

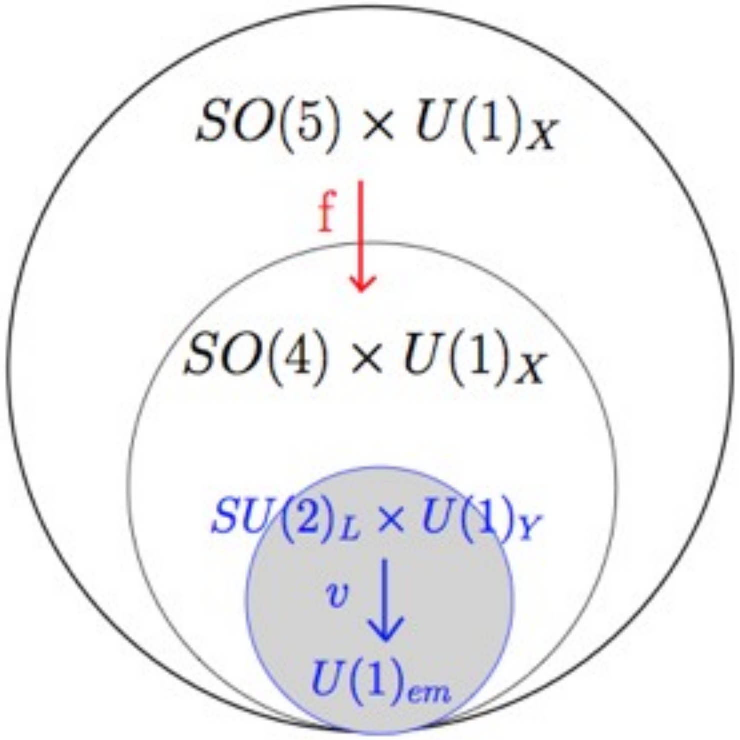
- $G/H \supset \mathbf{4}$, $G_{SM} \subset H$
- Computable Higgs mass: finite 1-loop effective potential
- Need for composite resonances!
- Not too large tuning $\xi = \frac{v^2}{f^2}$, $v = 246$ GeV, $f \sim 1$ TeV

MINIMAL MODEL with $SU(2)_C$

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

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

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

minimum for UV finite Higgs potential

Spectrum:

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

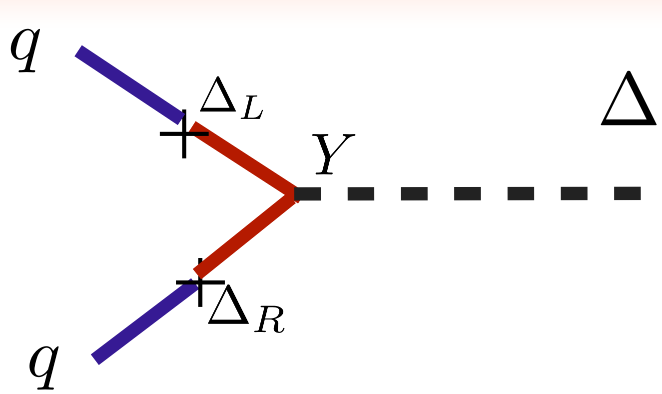
g_ρ= strong coupling

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

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

0

Linear elementary-composite couplings (partial compositeness)



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

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

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

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

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

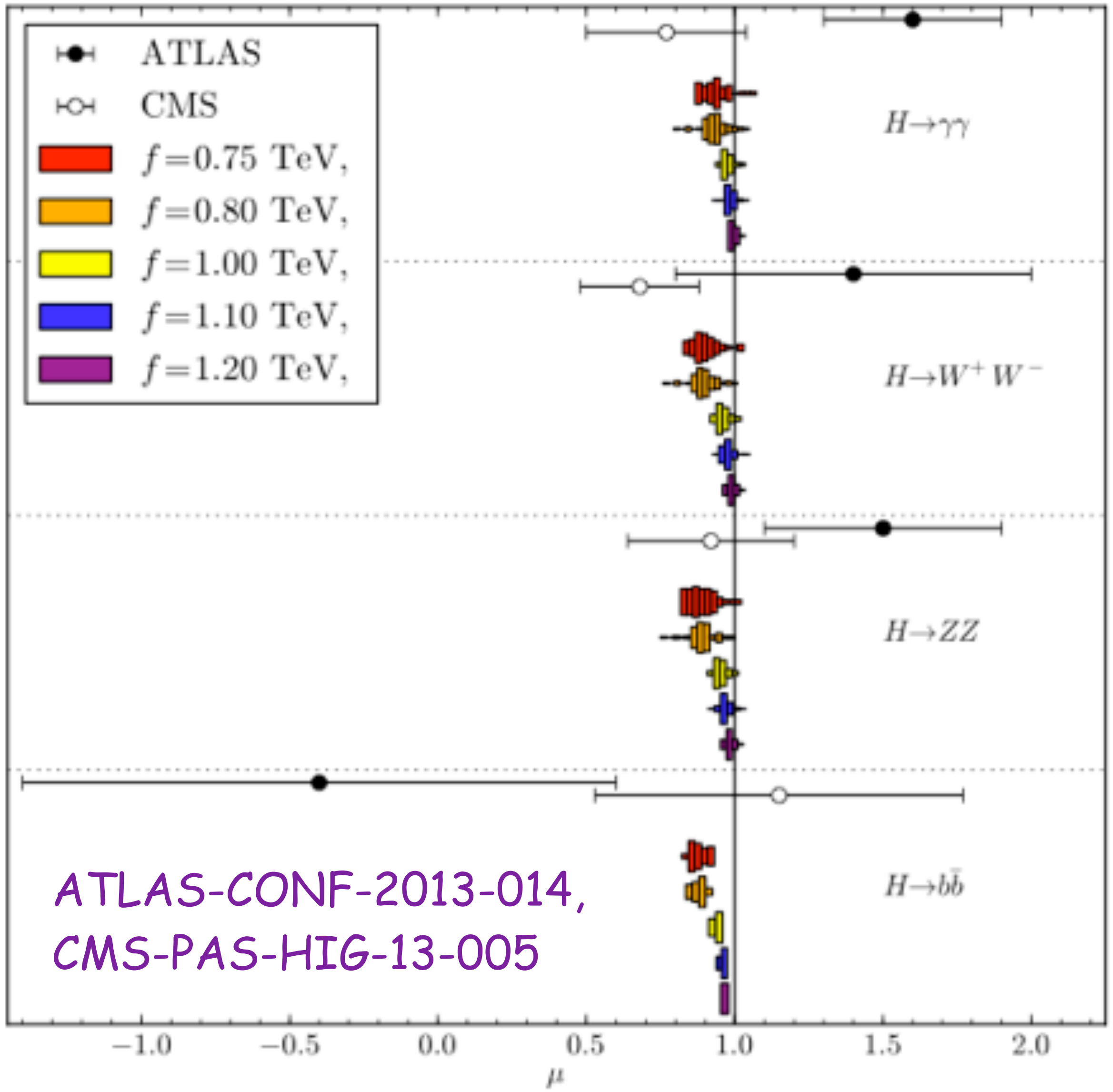
- Fermion parameter range for the scan:
  - 500 GeV $\leq m_*, \Delta_{t_L}, \Delta_{t_R}, Y_T, m_{Y_T}, Y_B, m_{Y_B} \leq$ 5000 GeV
  - 50 Gev $\leq \Delta_{b_L}, \Delta_{b_R} \leq$ 500 GeV (partial compositeness spirit)

- 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

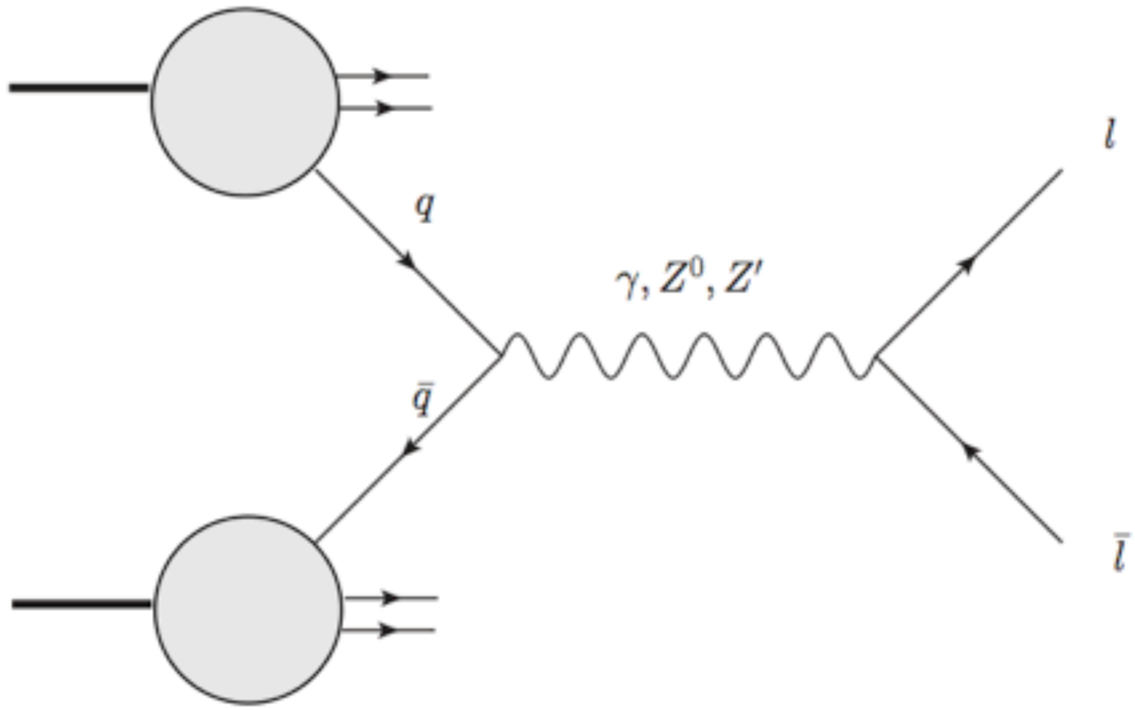
Quarks can annihilate also in Z' (and W')

tree-level processes

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

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

$l = e, \mu$



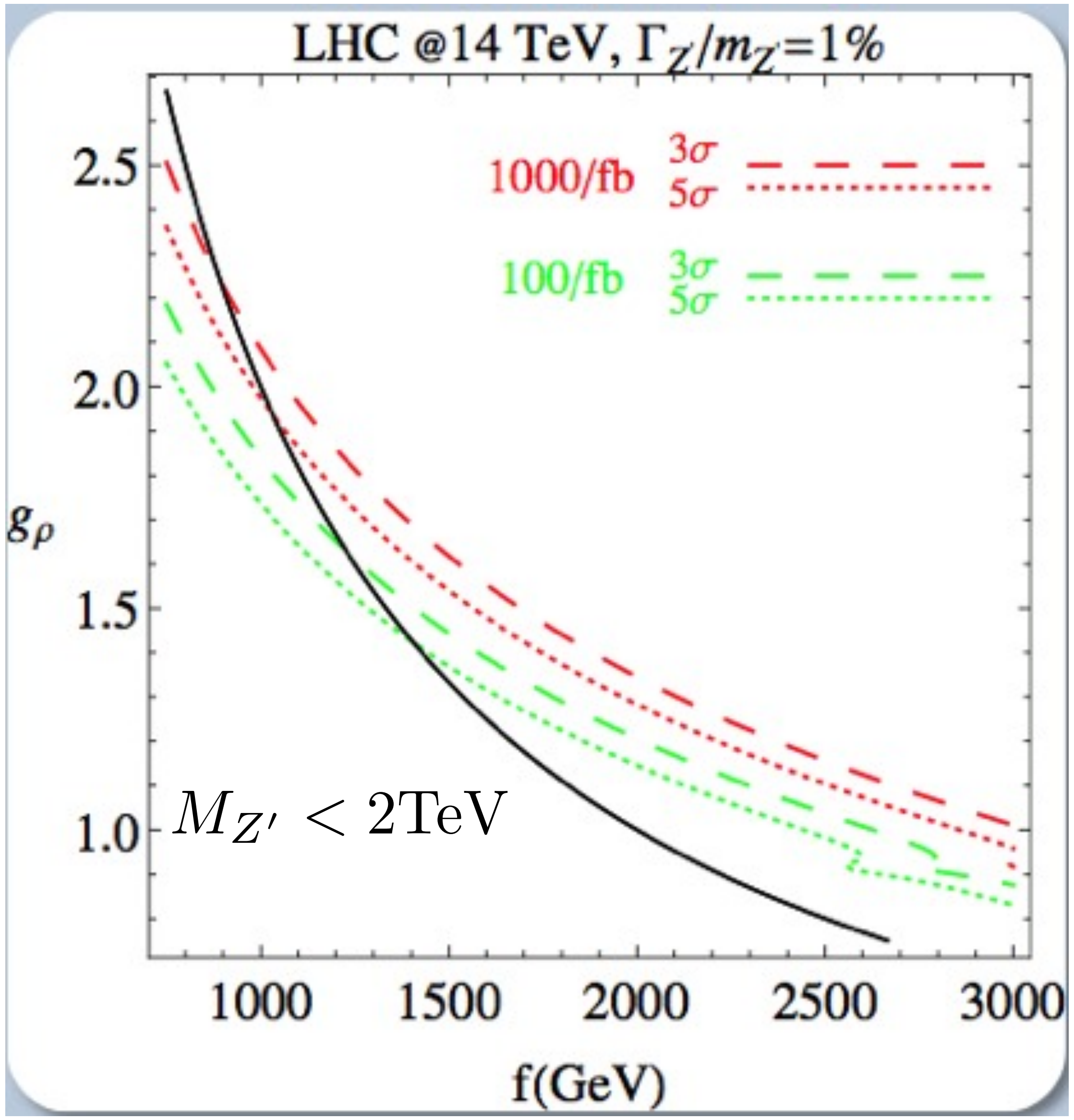
Z' (W') could be discovered as peak in the di-lepton invariant mass (missing-energy invariant mass) spectrum $Z' = Z_2, Z_3, Z_5 \quad W' = W_2, W_3$

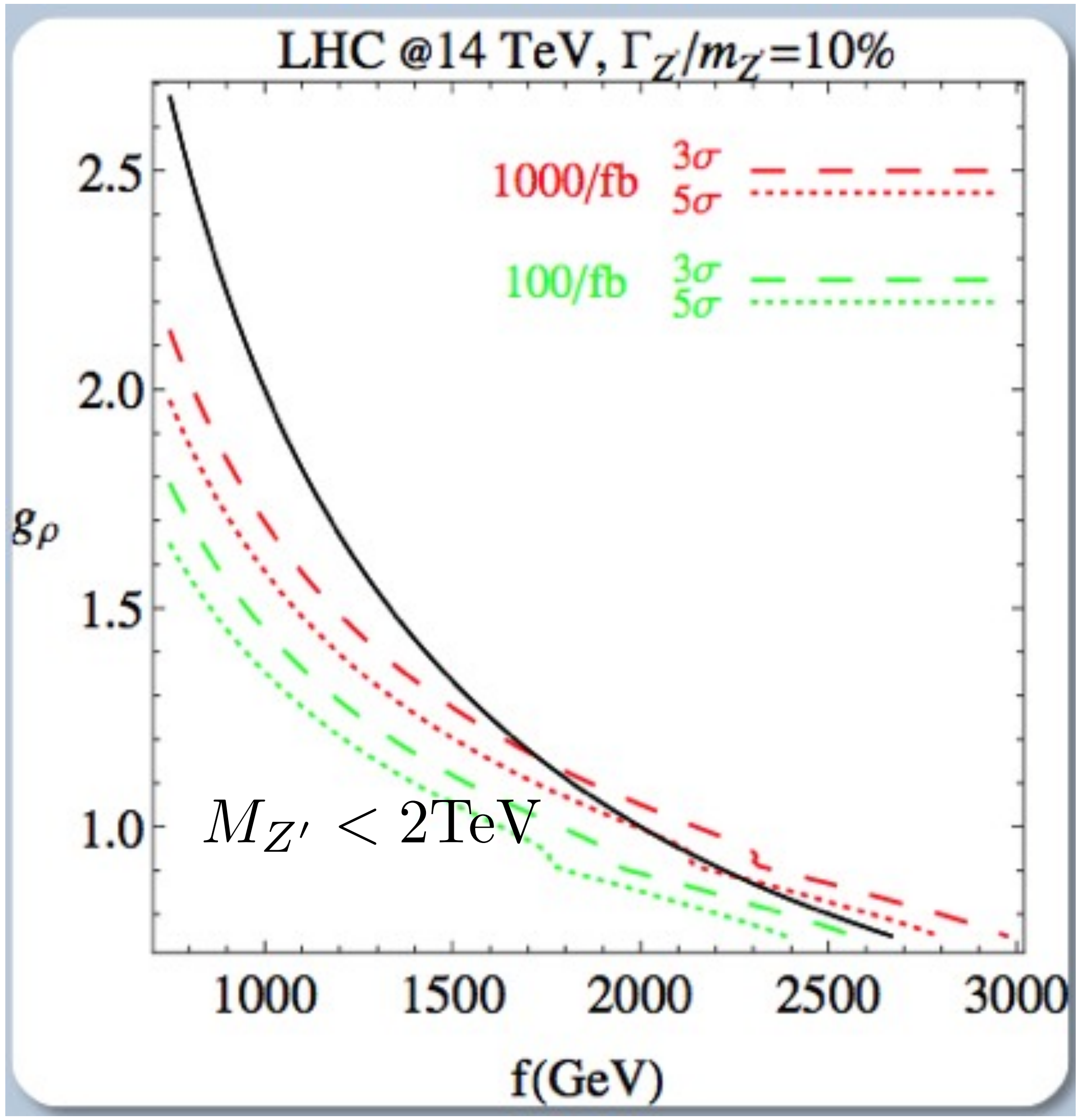
- Bounds on the mass of new Z' and W' **crucially depend on their widths** (large width if the threshold for the decay into $T\bar{T}$ is reached)
- The analysis of the Z' and W' line shapes could reveal the presence (or not) of light extra fermions

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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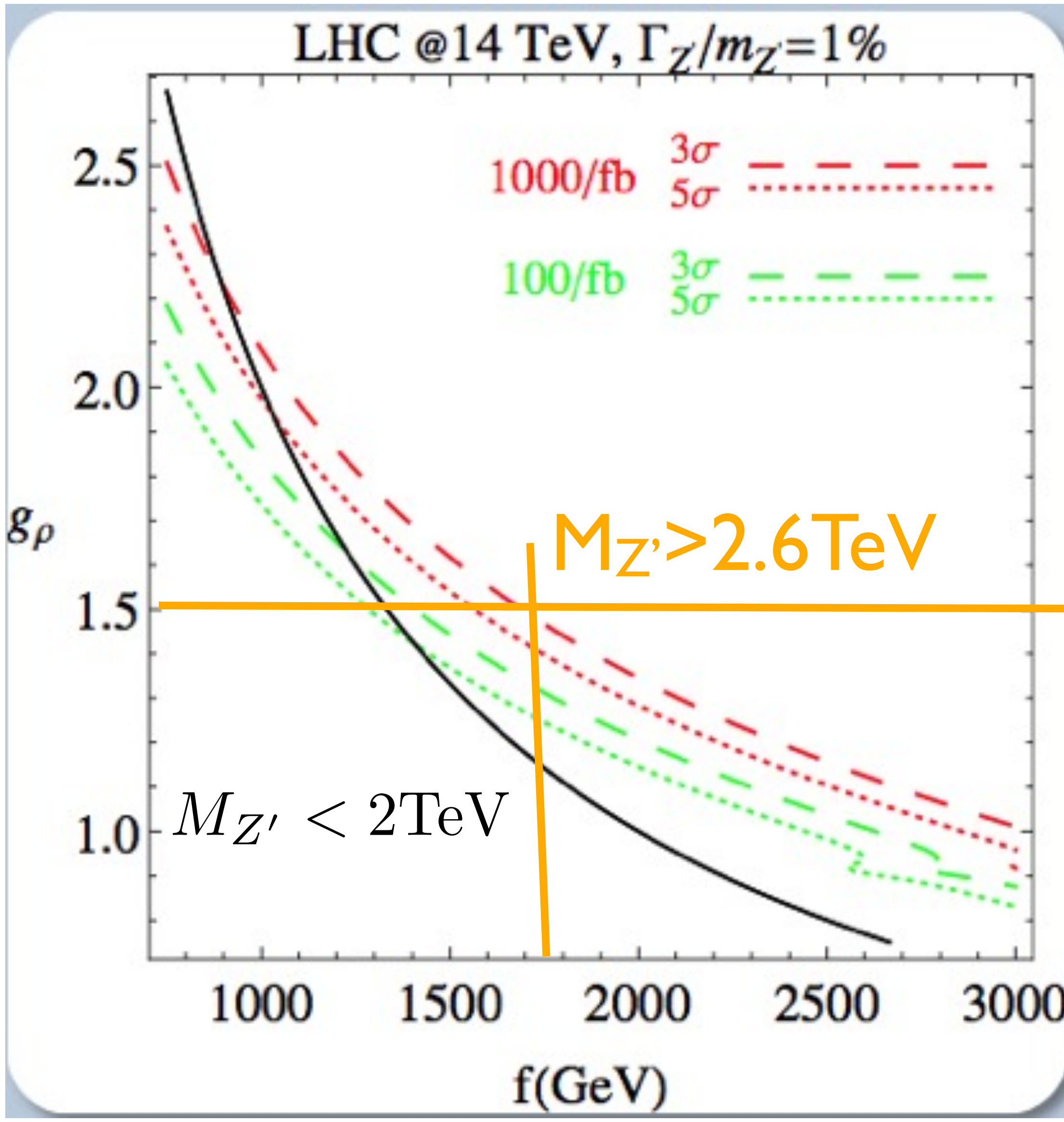
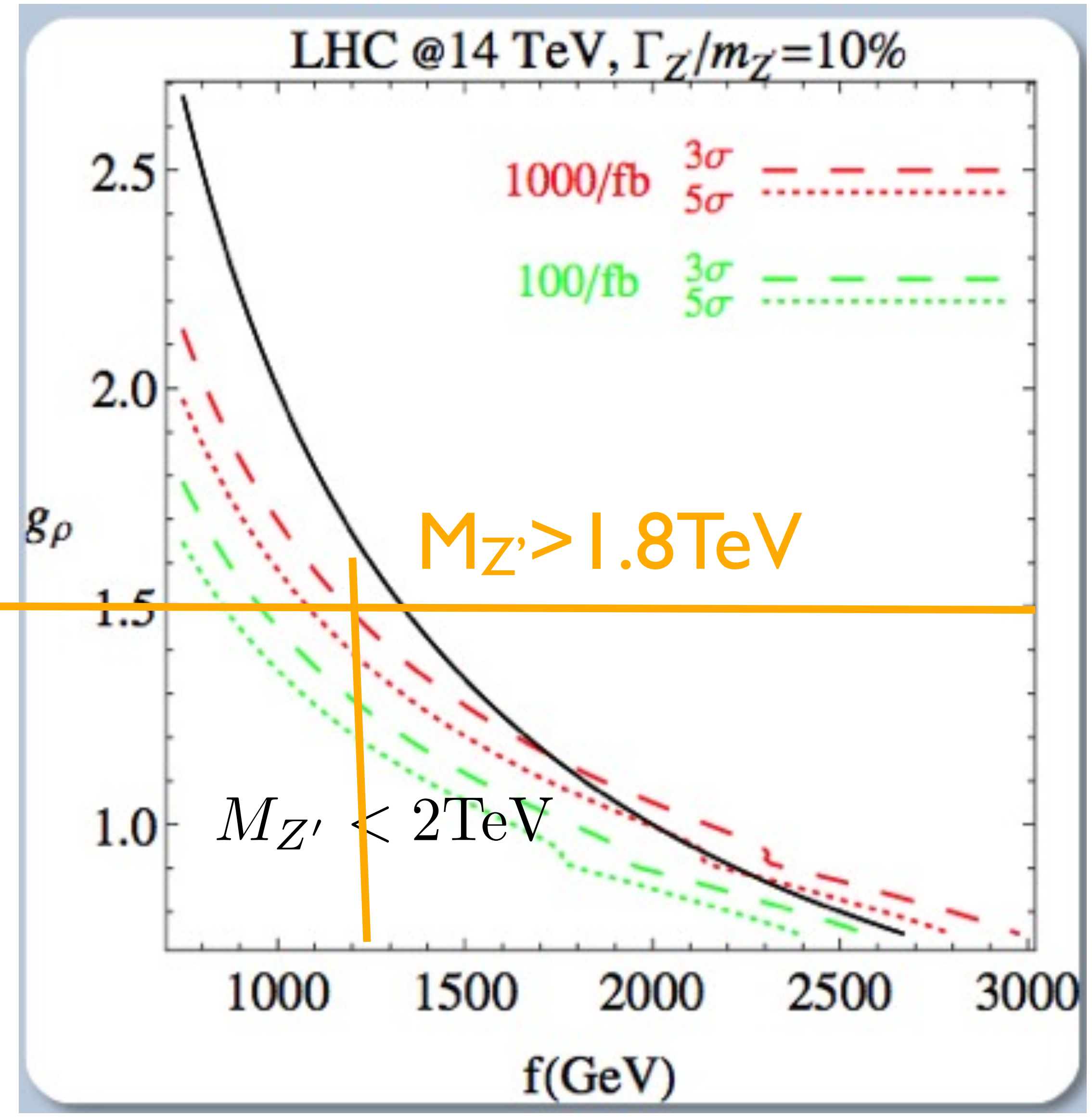




$\Gamma_{Z'}/M_{Z'} = 1\%$ $\Gamma_{Z'}/M_{Z'} = 10\%$

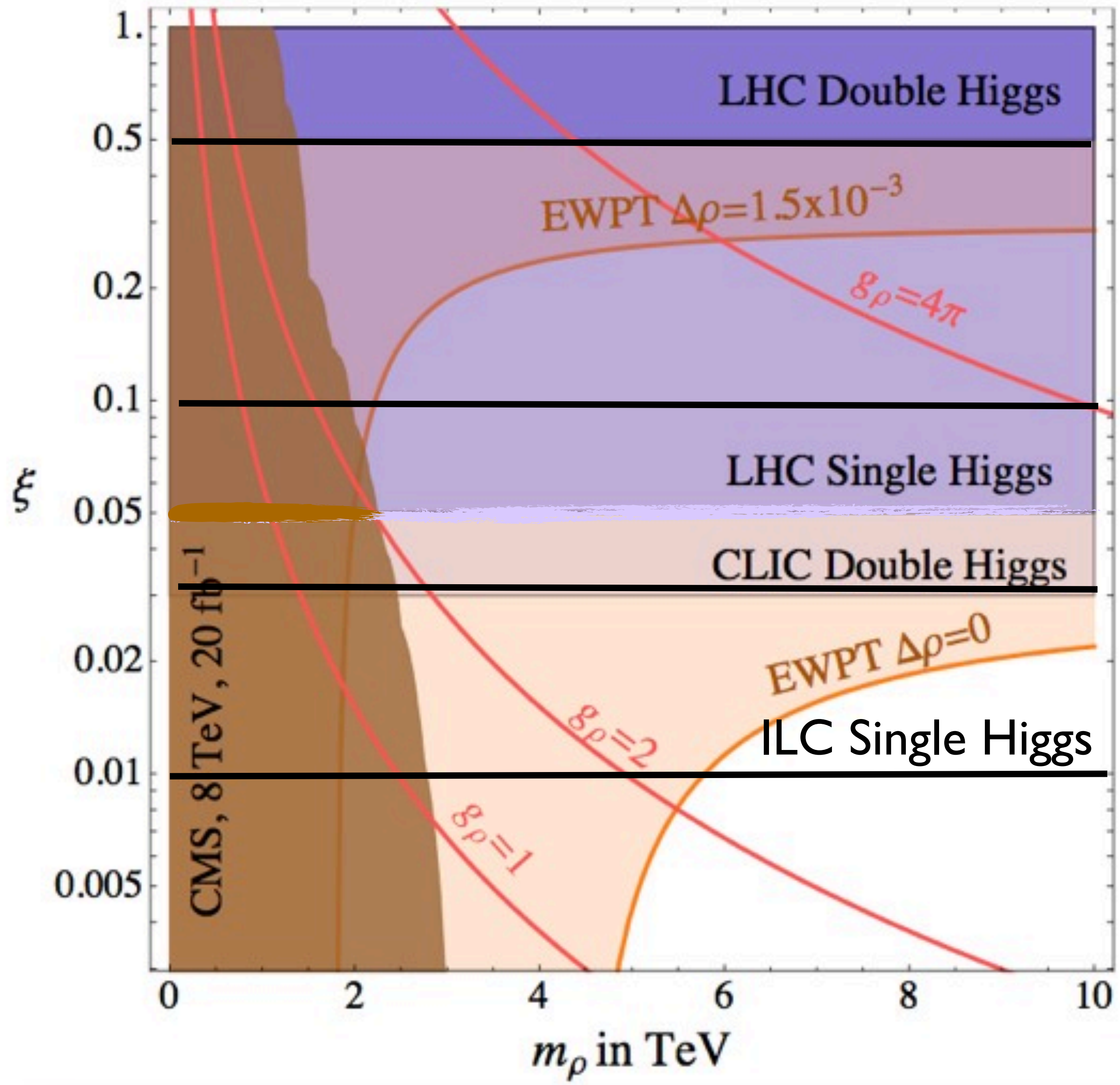
small width is mandatory for Z' detection in DY processes if the LHC will not measure deviations from the SM in single Higgs production larger than 10% and does not discover any new particle with a clear role ....

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 ..... $\longrightarrow$ (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 $300fb^{-1}$

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

ILC 250GeV 250fb^{-1}

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

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

EWPT mainly from deviations on g_{hVV}

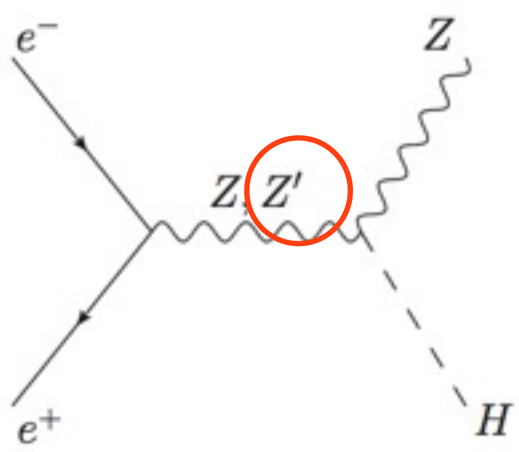
To the sensitivity on $\xi = v^2/f^2$ it corresponds a reach on the compositeness scale $\Lambda = 4\pi f$ (Ex. Λ =30-40 TeV @ILC)

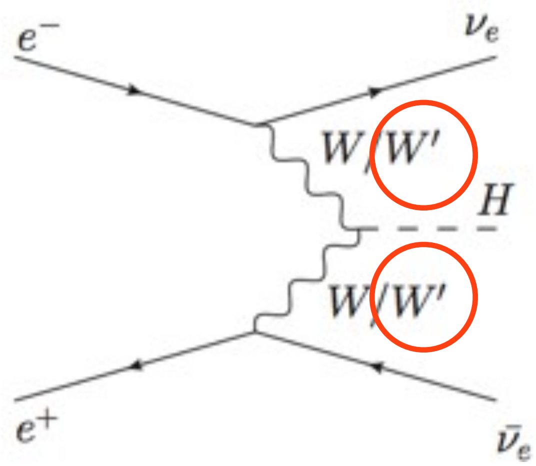
but the model details often matter!

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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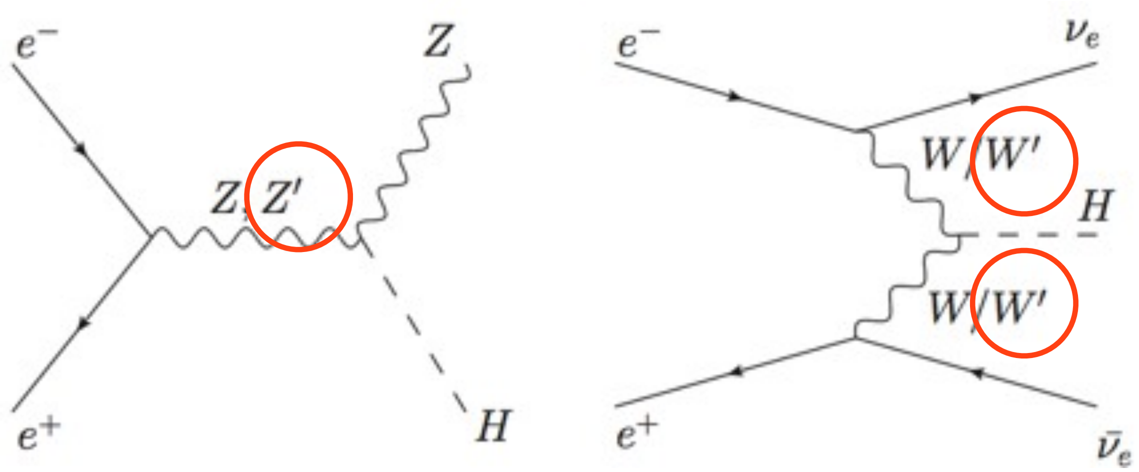


Extra Gauge bosons Z' and W' can be exchanged

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

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

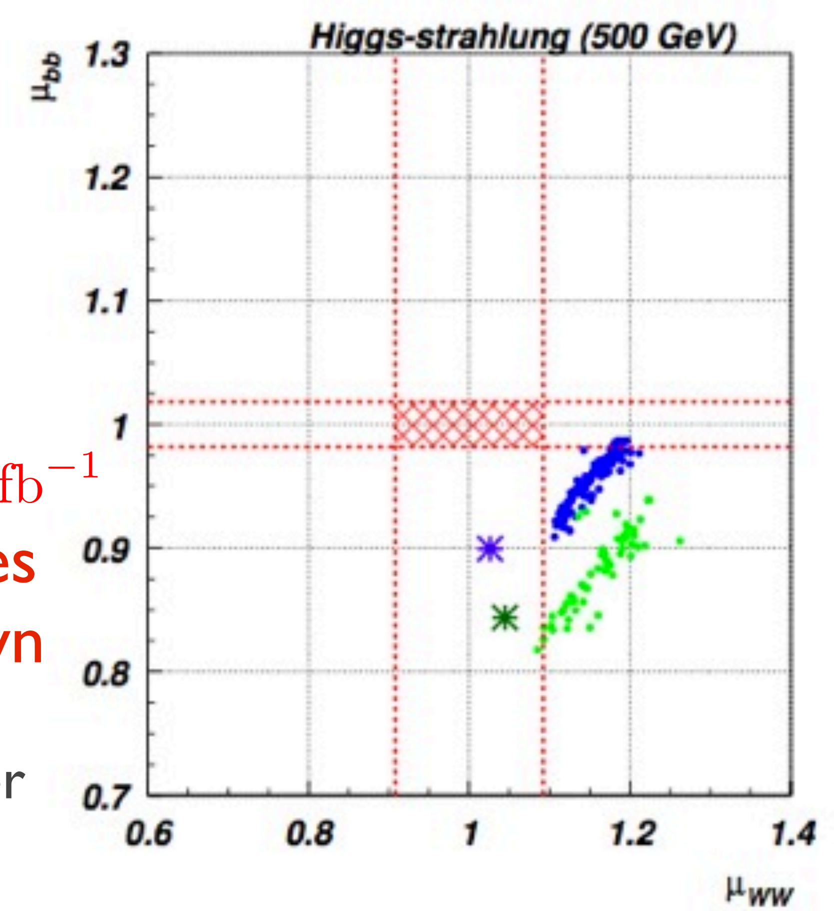
$\sqrt{s} = 500\ \mathrm{GeV}, \mathcal{L} = 500\mathrm{fb}^{-1}$

expected accuracies for the μ_i are shown

ILC TDR 1306.6352

ILC Higgs White Paper 1310.0763

Snowmass 1310.8361



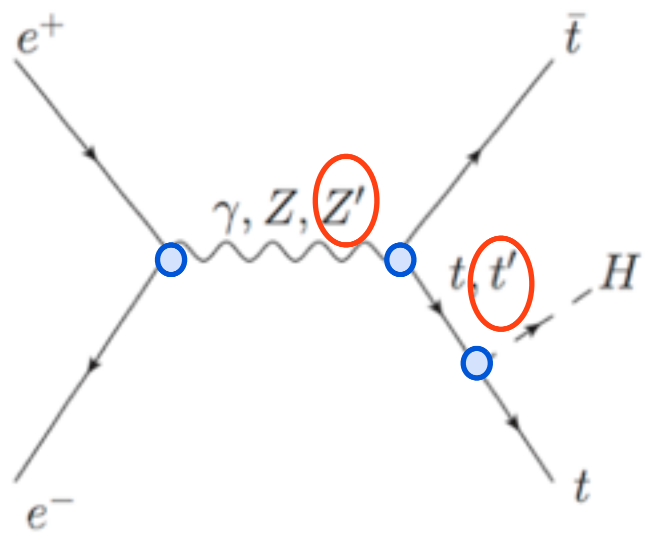
$f = 800\ GeV,\ g_\rho = 2.5$

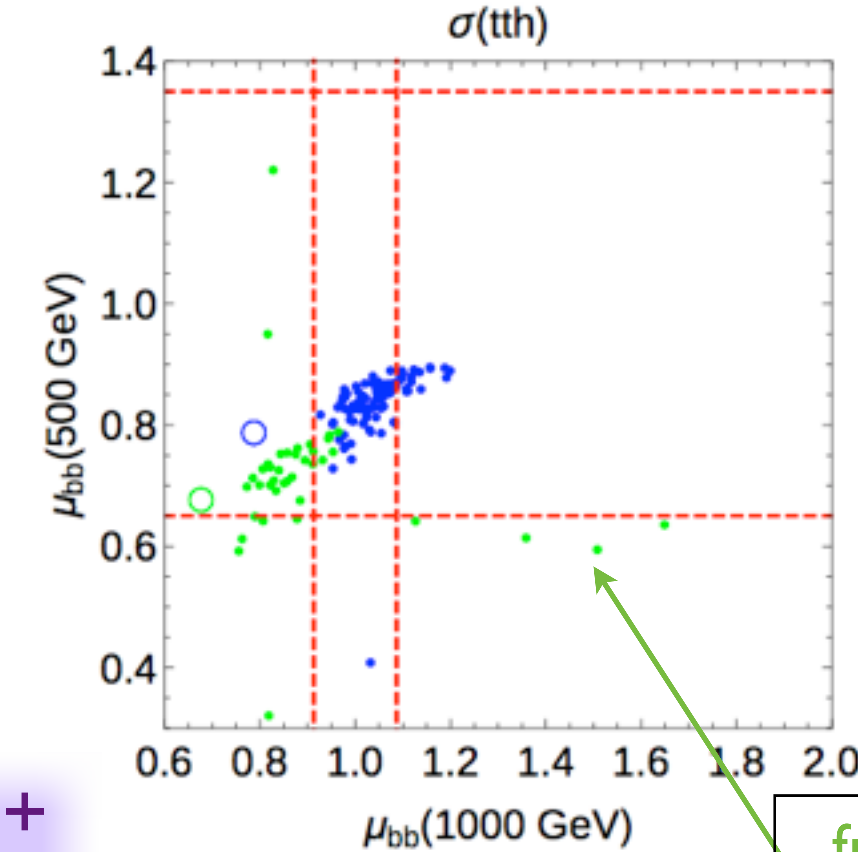
$f = 1000\ GeV,\ g_\rho = 2$

* = decoupl. limit

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

Top Yukawa coupling from $e^+e^- \to t\bar{t}H$ measurement





expected accuracies for μ_{bb} are shown

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

scan over the fermion parameters with Mt'>700GeV

from resonant t' exchange

Coupling modifications + extra Z' and t' exchanges

o = decoupl. limit
only coupling rescaling
no extra matter

$$\mu_{bb} = \frac{\sigma(e^+e^- \to Ht\bar{t})_{4DCHM}\mathrm{BR}(H \to b\bar{b})_{4DCHM}}{\sigma(e^+e^- \to Ht\bar{t})_{SM}\mathrm{BR}(H \to b\bar{b})_{SM}}$$

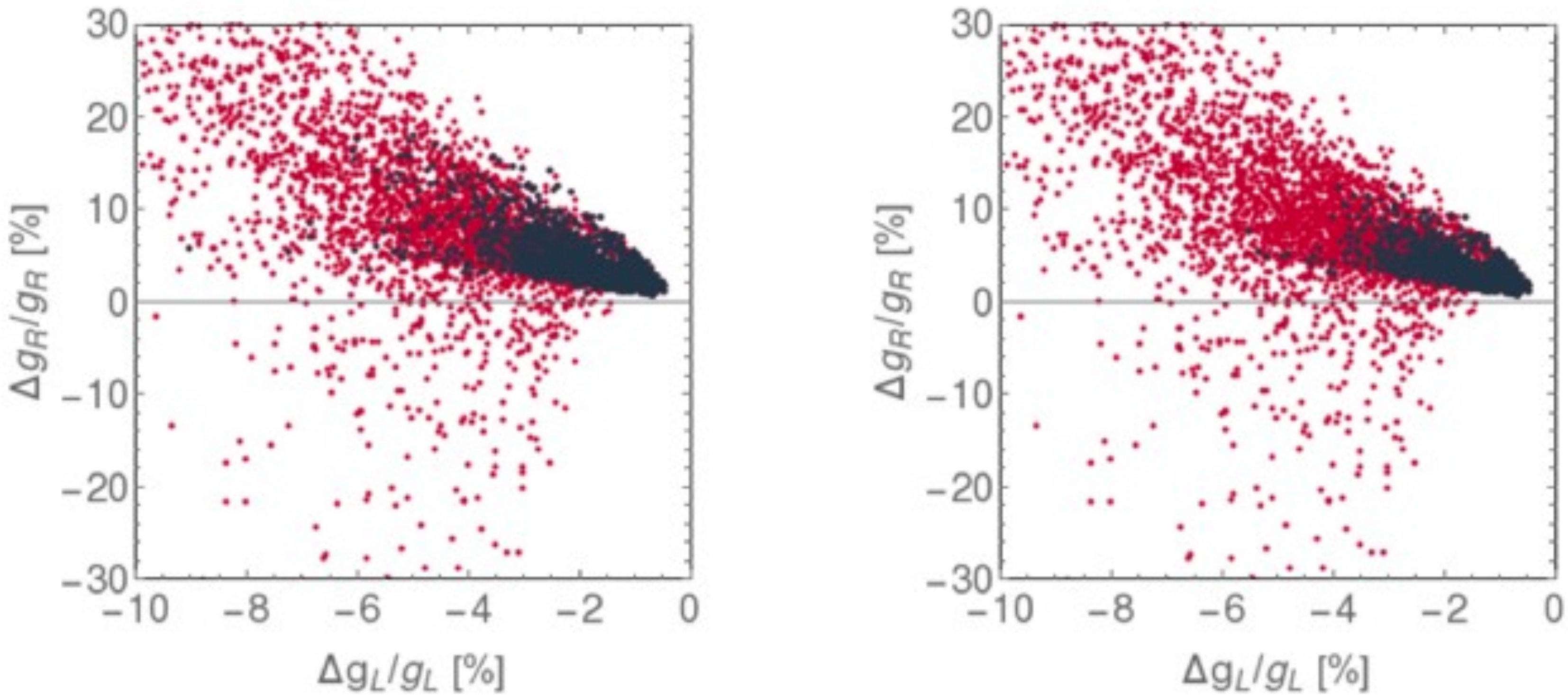
The potential of a future e+e- collider in assessing CHMs and their finite mass effects is very significant also via top-quark processes

WARNING: the extraction of the top-Yukawa coupling in NP schemes, like this one, cannot simply rely on the rescaling of the couplings predicted by the model

Top quark precision physics at an e+e- collider

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

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)

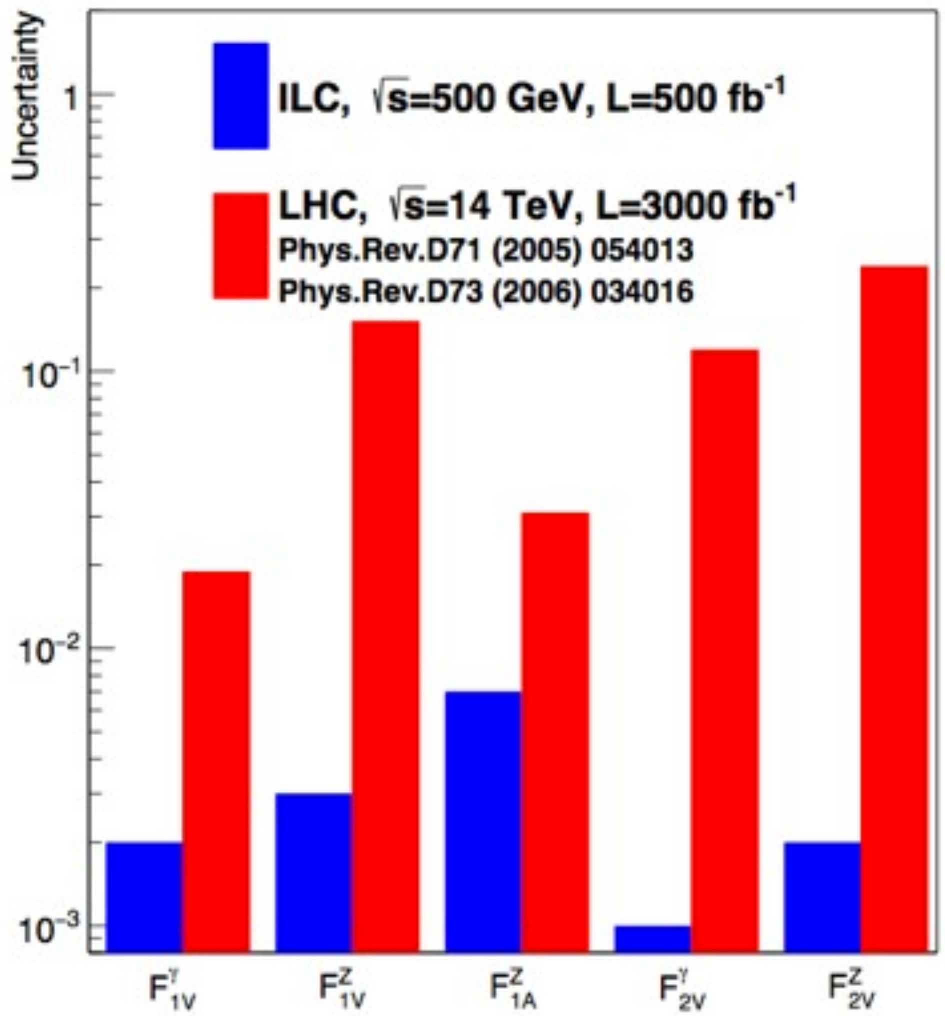
compliant with direct search limits and EWPT bounds (S,T, Zb_Lb_L)

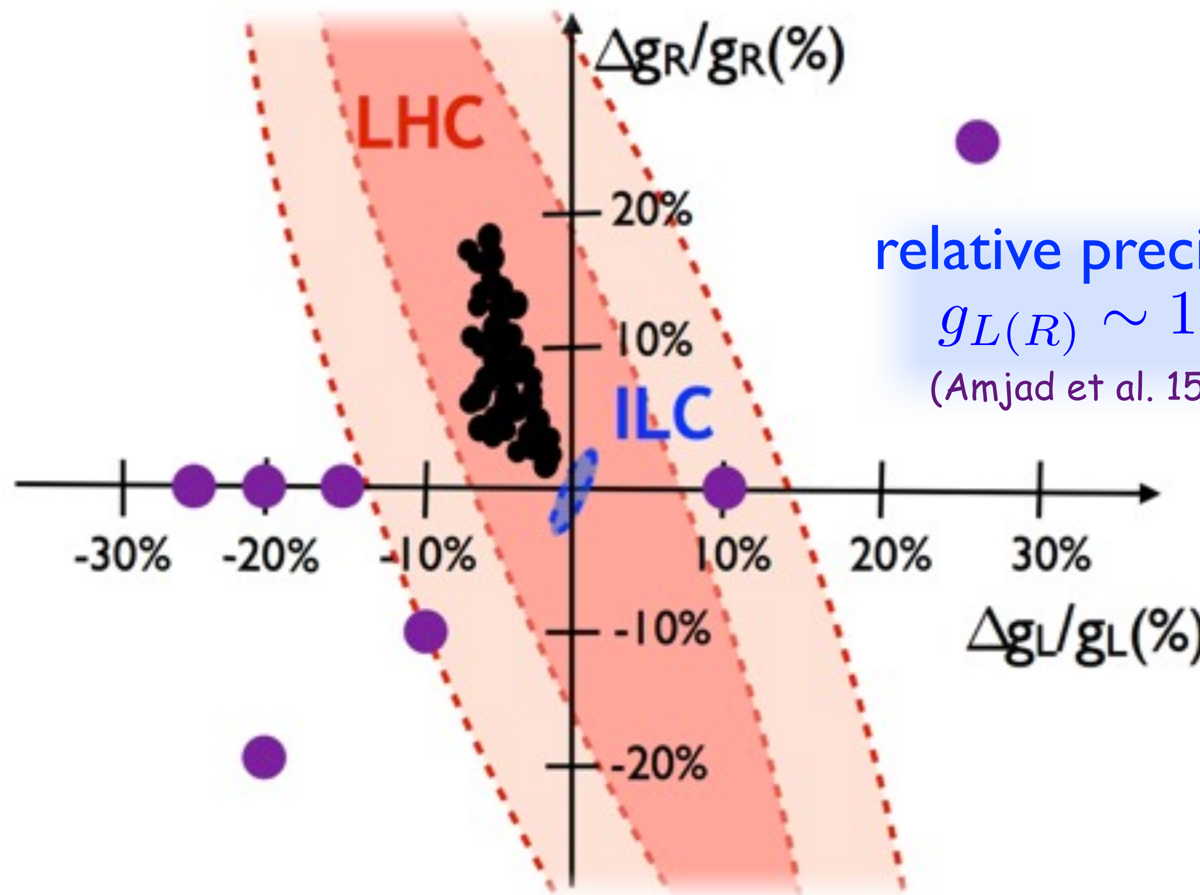
(Grojean, Matsedonskyi, Panico 1306.4655)

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)





relative precision on
$g_{L(R)} \sim 1.0(2.5)$
(Amjad et al. 1505.06020)

sensitivities:
LHC ~ 10%, HL-LHC ~ 5%
ILC(500) < 1% with polarized beams
(ILC-TDR 1306.6352; Amjad et al. 1505.06020)

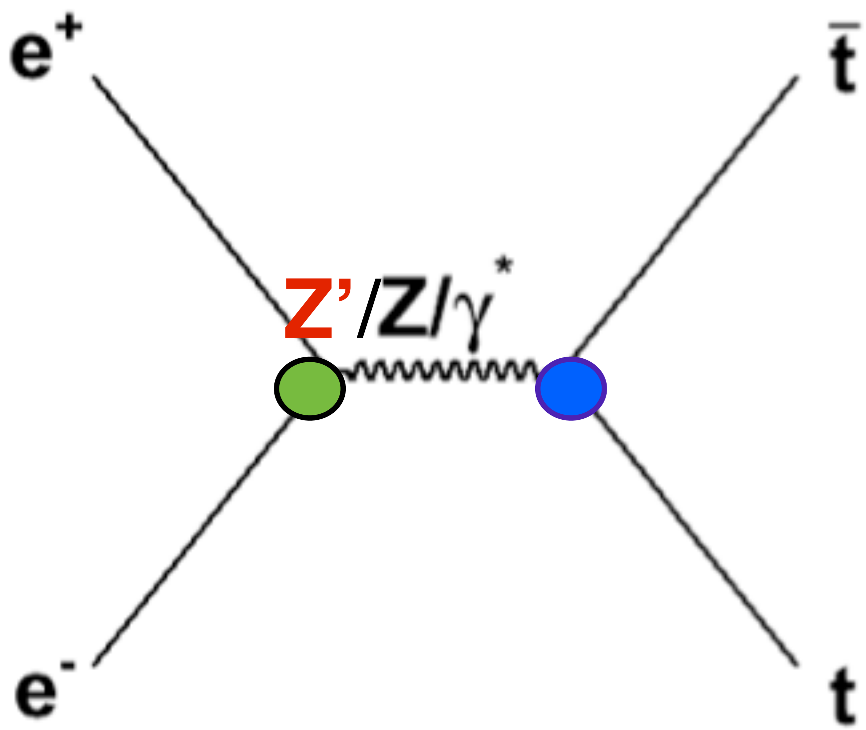
Measure x-section and A_{FB} for 2 beam polarizations:
$P(e^-)$=+/-80%, $P(e^+)$=+/-30%
Polarization needed to disentangle Z-boson and photon form factors

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 pair production within the 4DCHM

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



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 $M_{Z'}$

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 $\mathcal{O}/\mathcal{O}_{\mathrm{SM}}$

Observables:

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

☑ 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

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

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

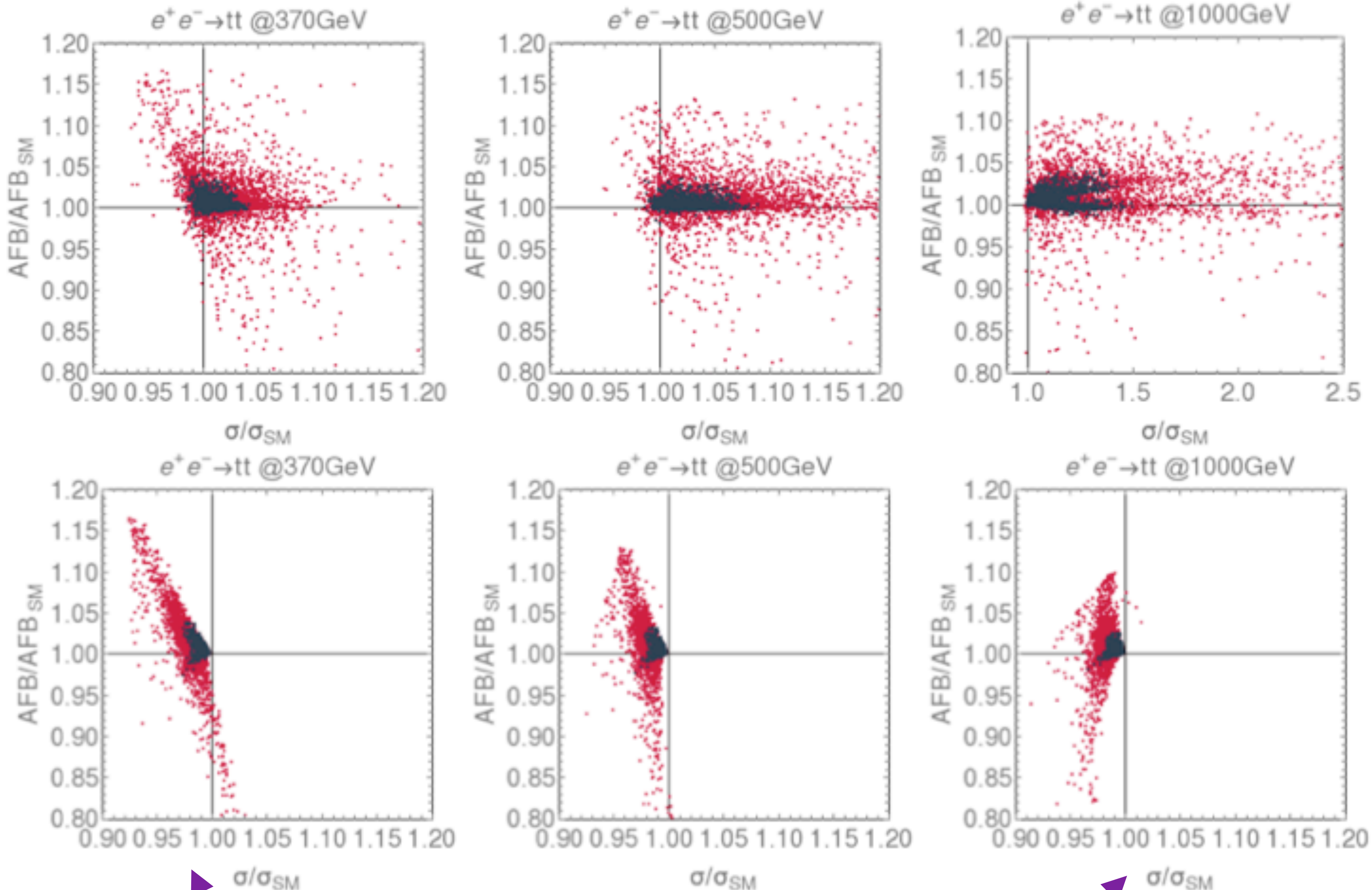
θ^* is the polar angle in the $t\bar{t}$ rest frame
N(+,-) is the number of events with +1 (-1) helicity for top (antitop)

- Spin asymmetries focus on the helicity structure of the final state fermions. Leptons from top (antitop) semi-leptonic decays are used as spin analyzers, see Khiem et al. 1503.04247 for top quark form factor extraction using top polarization observables at ILC 500
- A_L and A_{LL} are related to the helicity angle distribution (Amjad et al. 1307.8102)
- 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

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

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

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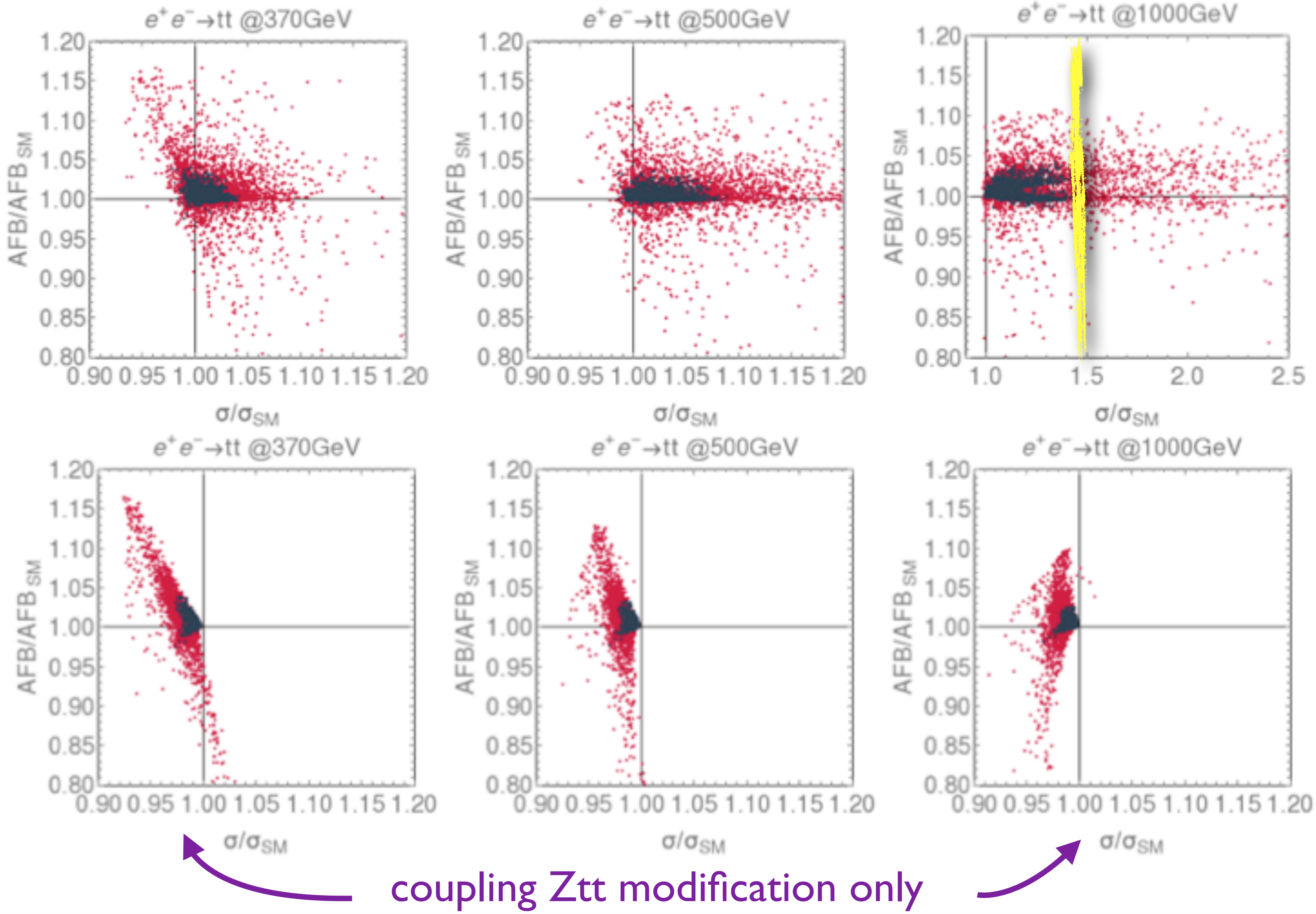
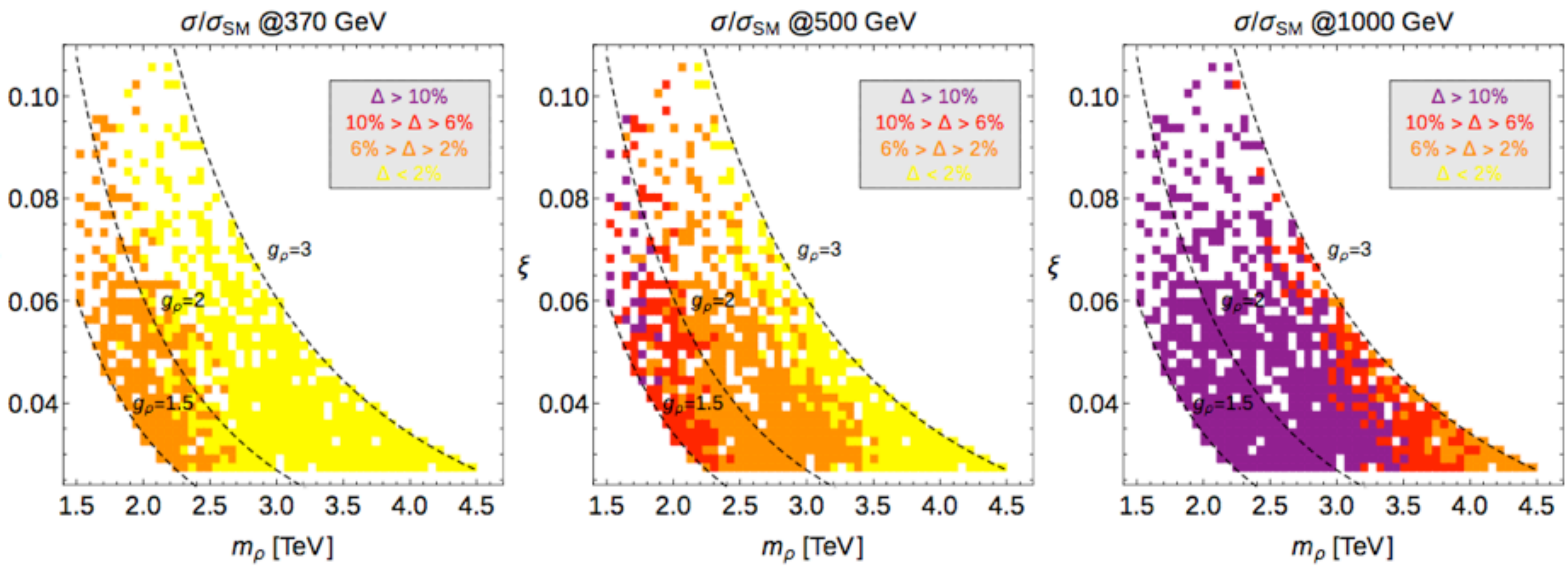


Interference of the Z' with the SM plays a crucial role

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>800GeV. For each point we have selected the configuration corresponding to the maximal deviation

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

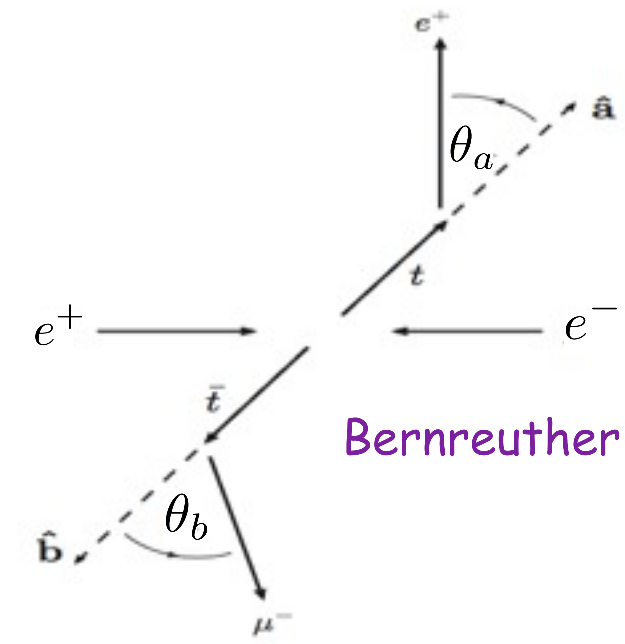
Single Spin Asymmetry A_L

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

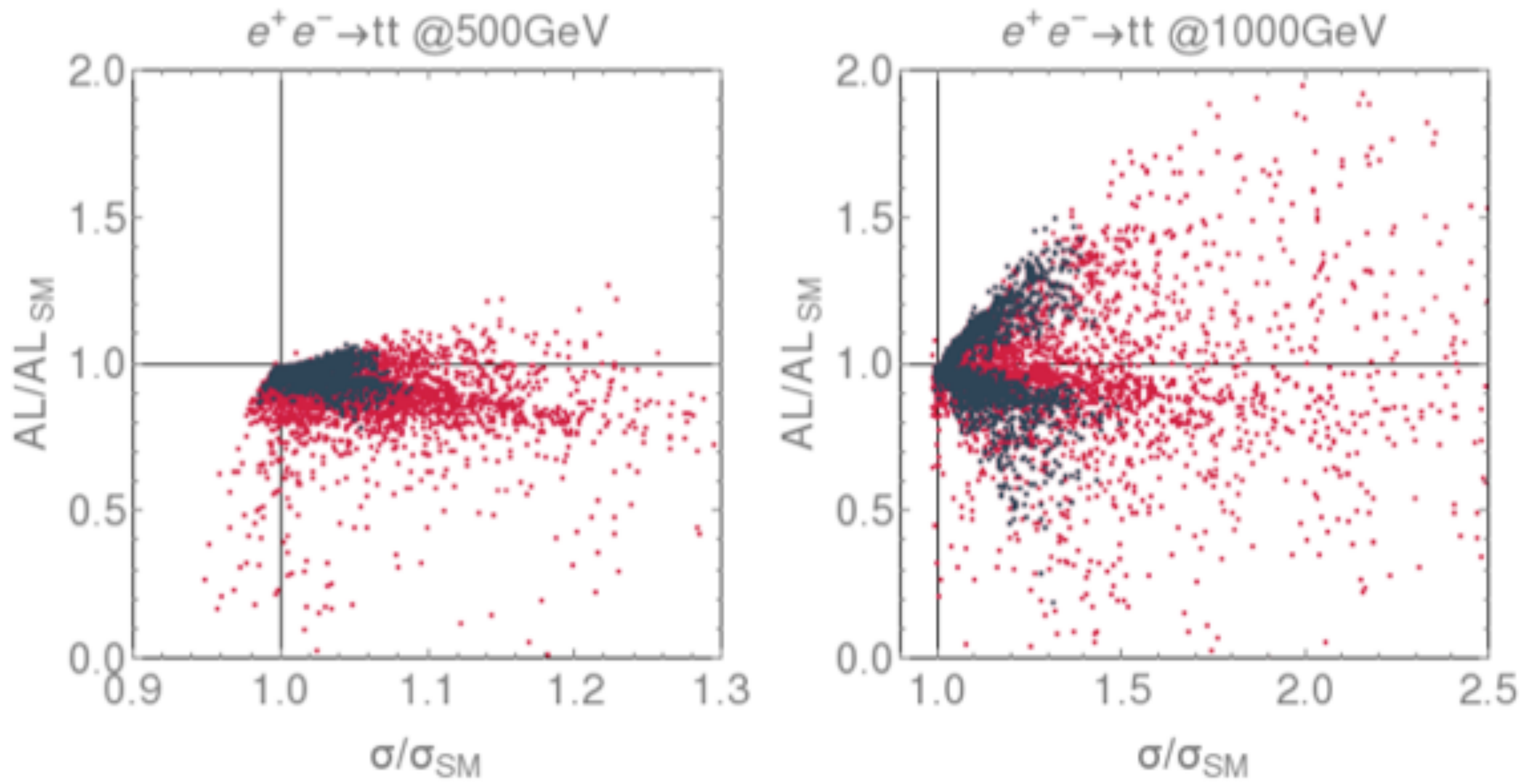
$$B_1 \sim A_L(t),\ B_2 \sim A_L(\bar{t}),\ C \sim A_{LL}$$

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

helicity angle distribution



Bernreuther 0805.1333

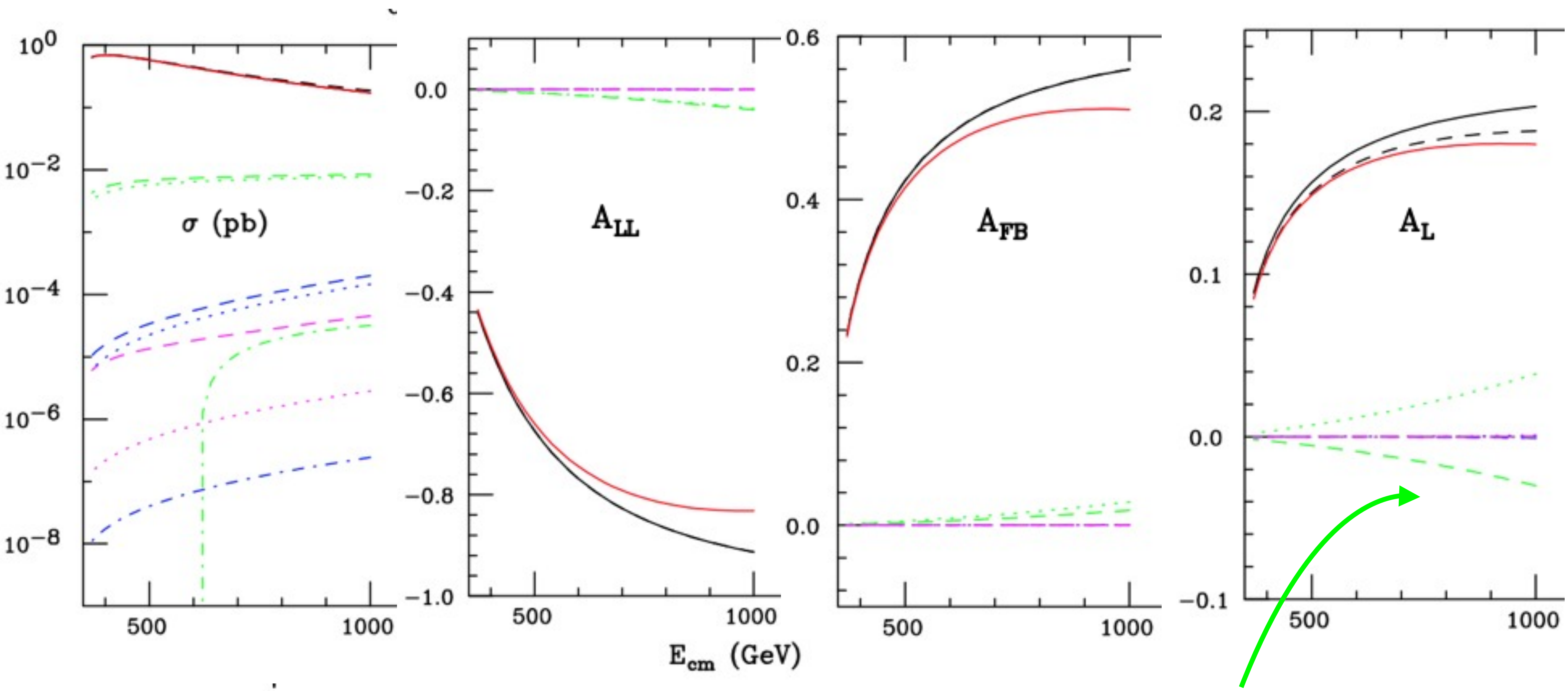


large deviations of both signs @ 1000GeV mainly due to the SM-Z's interference

A_L 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}

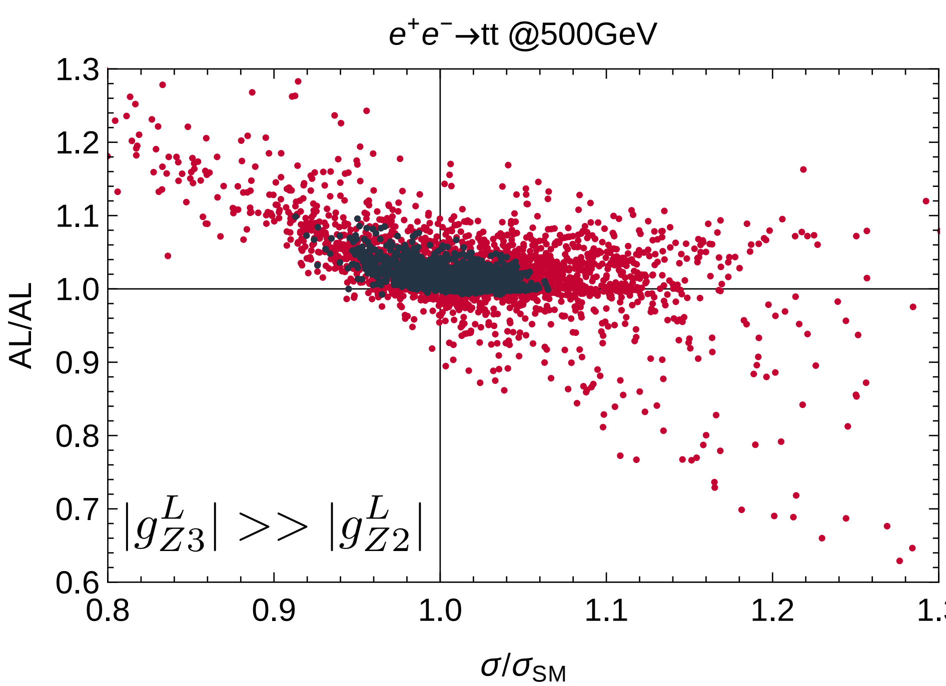
A_L is unique in offering the chance to separate Z_2 and Z_3 as they contribute with opposite signs (beam polarization could help)

Polarized electron-positron beams

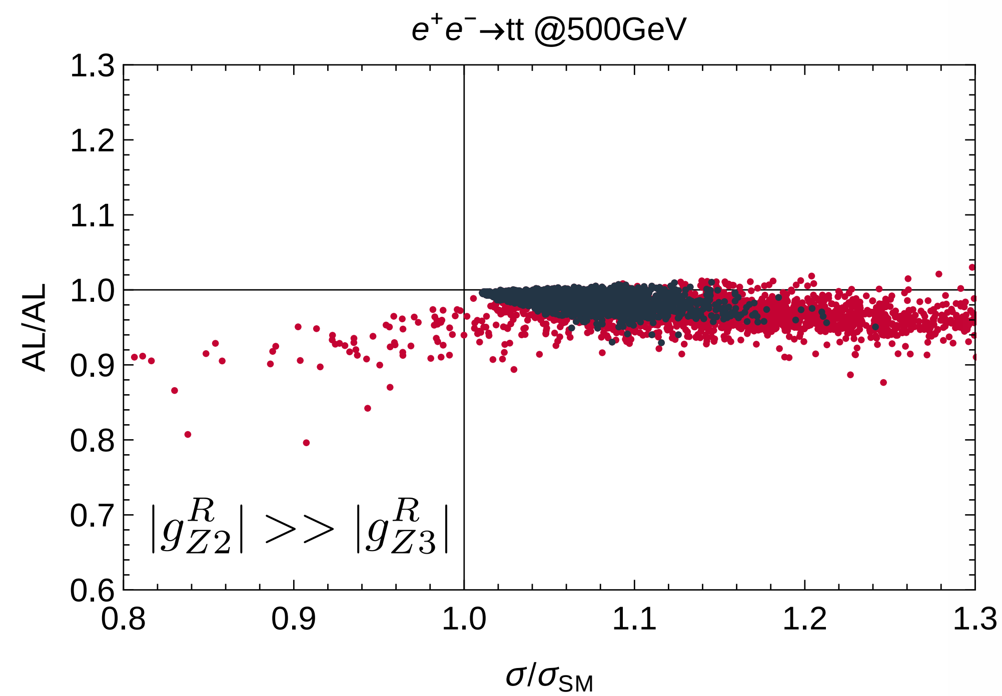
$$\sigma_{\mathcal{P},\mathcal{P}'} = \frac{1}{4}[(1-\mathcal{P}\mathcal{P}')(\sigma_{-,+}+\sigma_{+,-})+(\mathcal{P}-\mathcal{P}')(\sigma_{+,-}-\sigma_{-,+})]$$

$\sigma(-,+)=\sigma(e^-_L,e^+_R)$, $\mathcal{P}(\mathcal{P}')$ polarization degree for electrons (positrons)

deviations ~10% at 500 GeV (roughly the same of the unpol.)



$\mathcal{P}=-1,\ \mathcal{P}'=+1$



$\mathcal{P}=+1,\ \mathcal{P}'=-1$

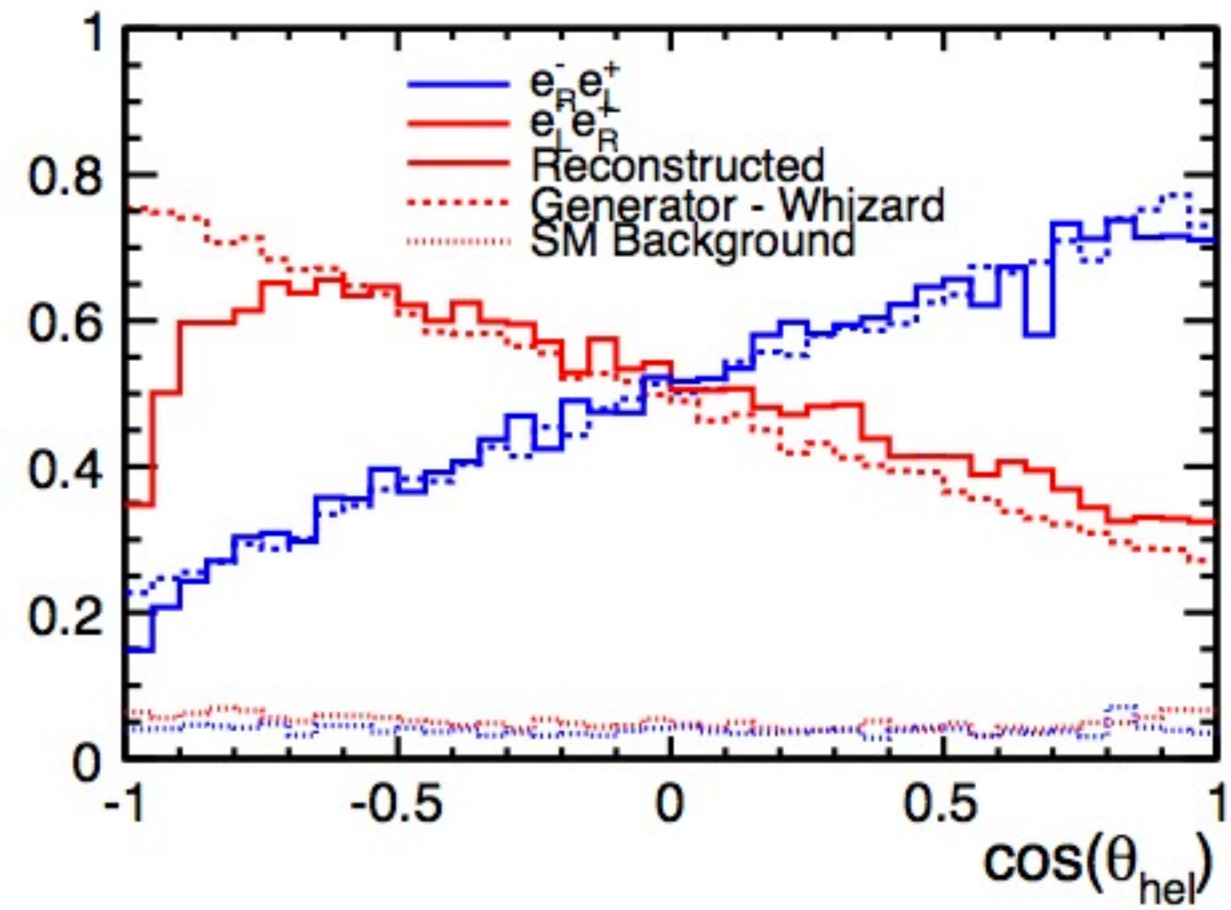
Z_2 and Z_3 interference have opposite signs. A_L is a good observable if e+e- beam polarization is available to deduce the presence of nearly degenerate resonances

Slope of the helicity angle distribution

Amjad et al. 1307.8102

the angle of the lepton from the W boson in the top rest frame

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{hel}} = \frac{1}{2}(1 + A_L\cos\theta_{hel})$$



AL can be derived from the slope of the helicity angle distribution. Better reconstruction for P,P'=+1,-1.

$$(\delta A_L)_{stat+syst} > 4\%$$

If NP is present, the slopes change

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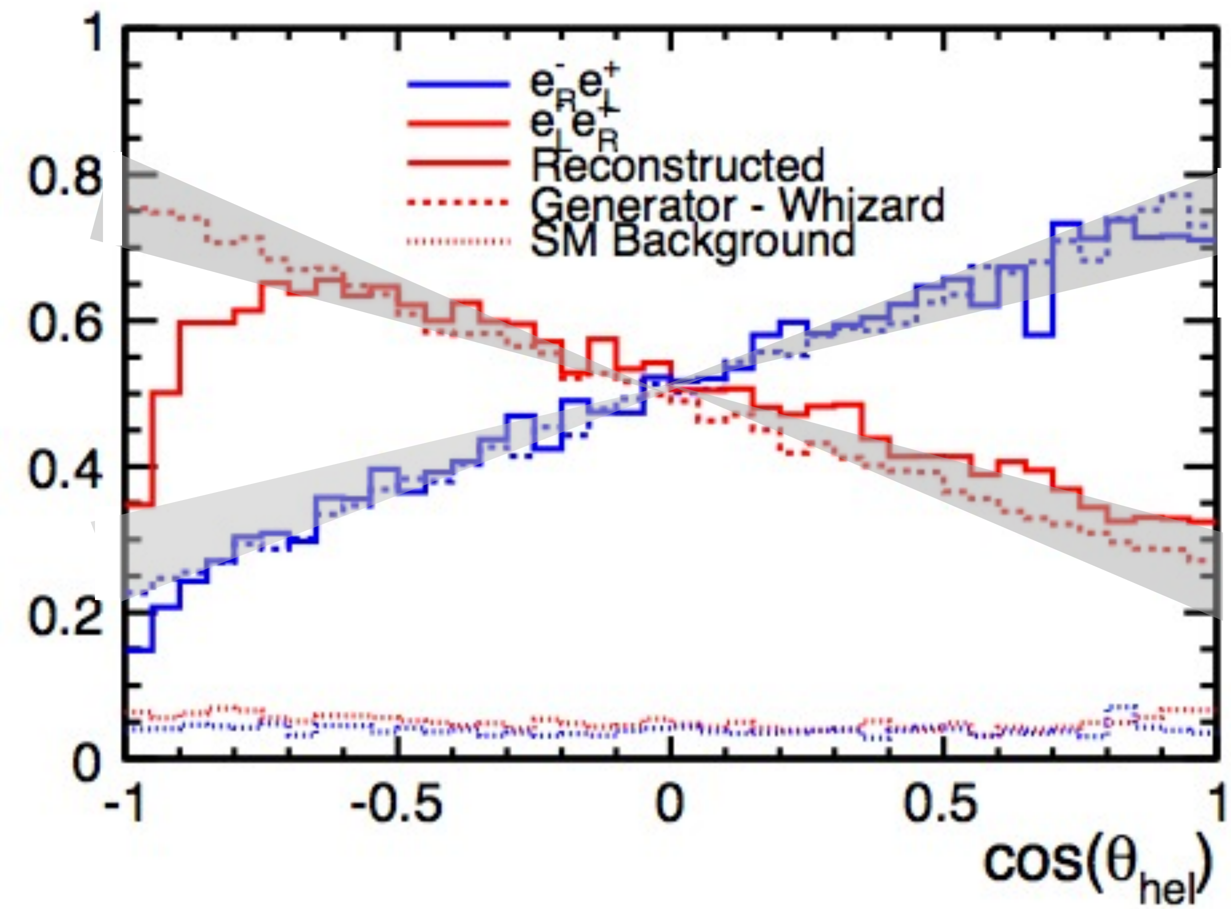

4DCHM~10% deviations in A_L @500GeV

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Amjad et al. 1307.8102

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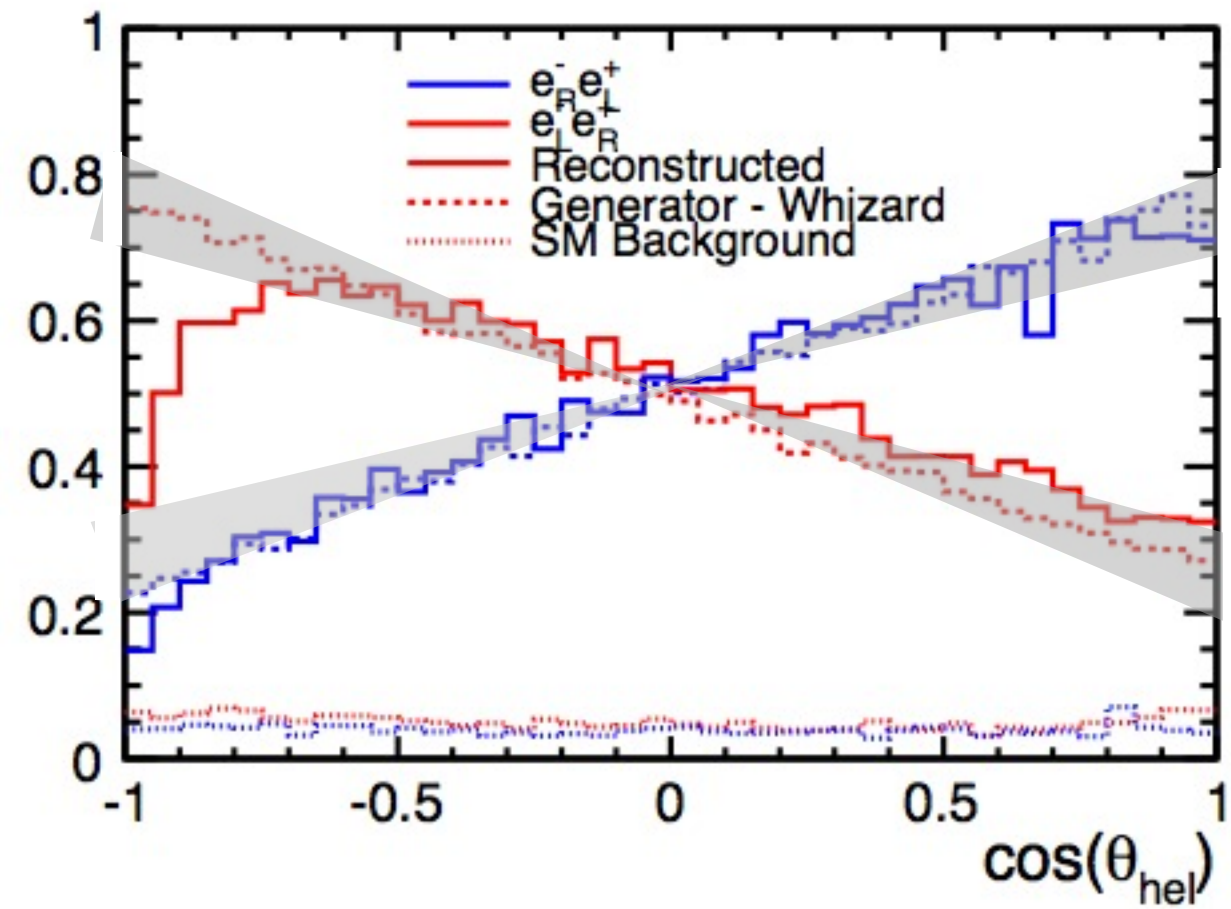

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4DCHM~10% deviations in A_L @500GeV

Warning: the deviations come from coupling modifications but also from SM-Z' interference. In case of multiple Z's the interferences could be opposite in sign and cancellations in A_L might occur. Beam polarization helps in disentangling the effects

Conclusions

- ☑ Future e+e- machines will have a great potential in discovering imprints of partial compositeness in the top-quark sector

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

- ☑ It describes new spin-1 resonances and extra-fermions which could be accessible at LHC run2

- ☑ If nothing is seen, or, better, if the LHC will give some evidence, e^+e^- machines have the opportunity to test composite Higgs scenarios: precise measurements of the Higgs and top couplings

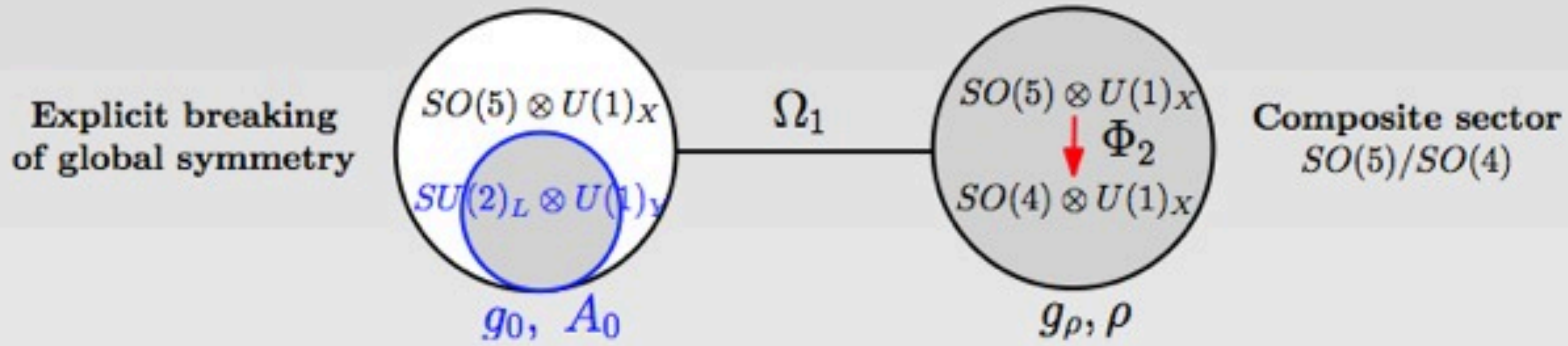
- ☑ Warning: interference effects of the new resonances could be crucial and must be taken into account to extract the sensitivities to CHMs

BACKUP SLIDES

4DCHM = Minimal 4D realization of MCHM5

DC, Redi, Tesi '11

Agashe, Contino, Pomarol '04



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

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

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

- Non linear structure ↔ GB Higgs
- GB decay constant

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

- Composite spectrum

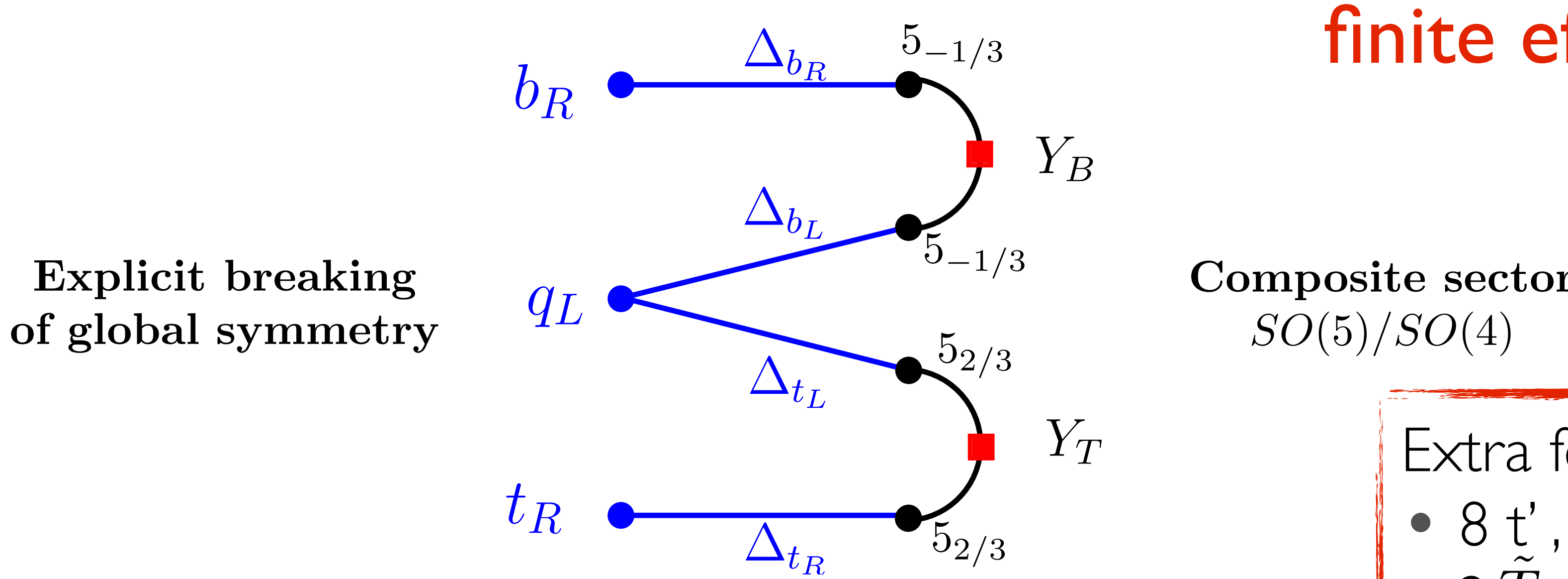
$$SO(4) \to m^2_\rho = \frac{g^2_\rho f^2_1}{2}, \qquad \frac{SO(5)}{SO(4)} \to m^2_{a_1} = \frac{g^2_\rho(f^2_1 + f^2_2)}{2}$$

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



Extra fermions:

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

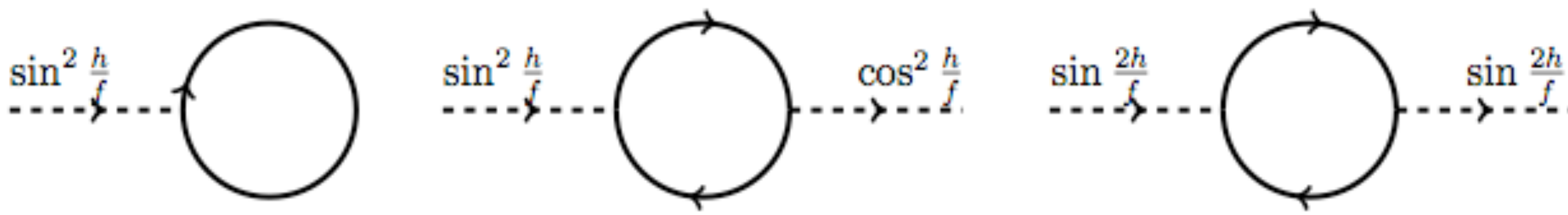
Partial compositeness: 3rd generation quarks only top Yukawa coupling

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

Coleman-Weinberg effective potential generated at 1-loop

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

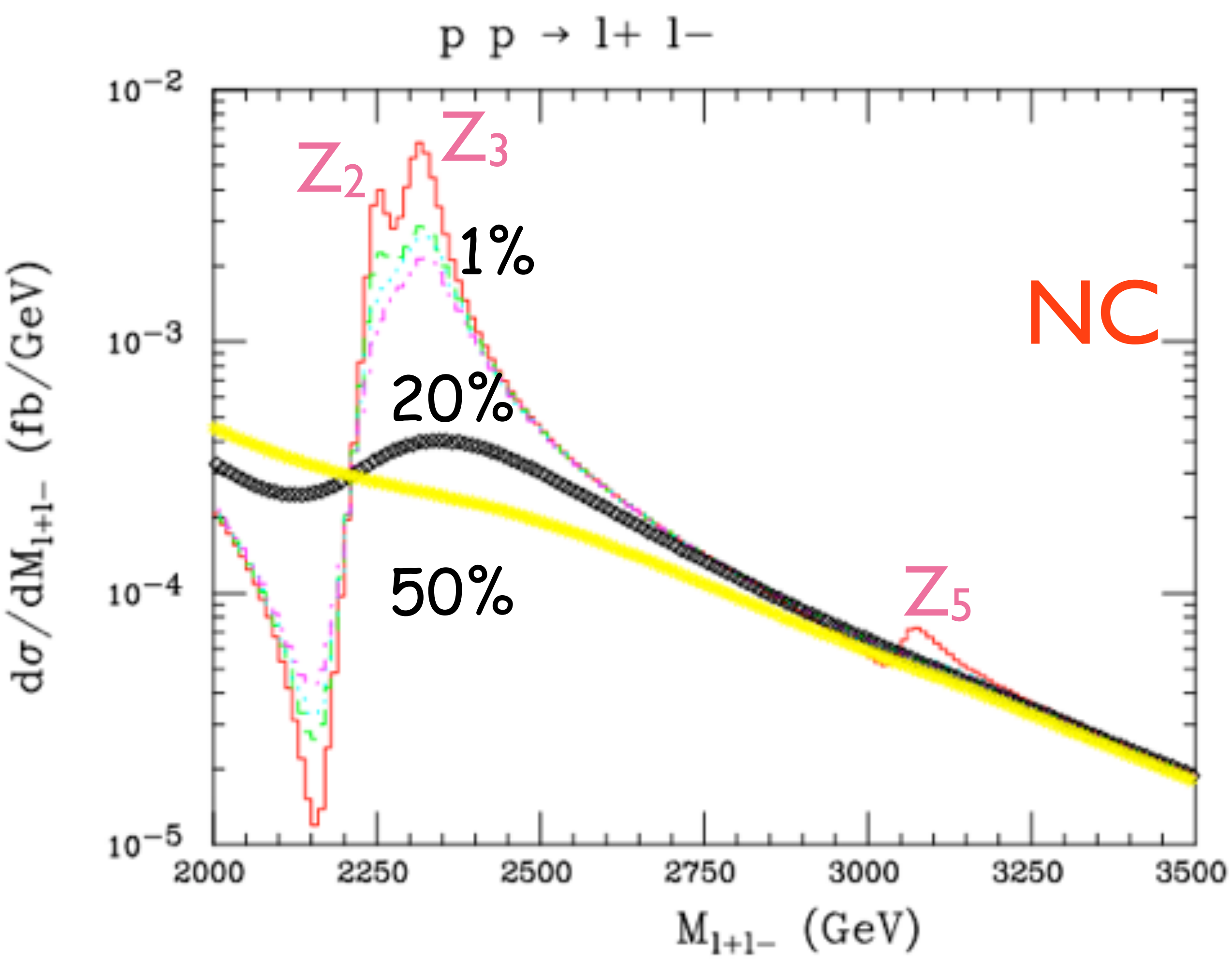
$$V(h)_{fermions} \approx -N_c \int \frac{d^4p}{(2\pi)^4} \left[\frac{\Pi_1^{q_1}}{\Pi_0^q} + \frac{\Pi_1^u}{\Pi_0^u}\right] \sin^2 \frac{h}{f} + N_c \int \frac{d^4p}{(2\pi)^4} \left[\frac{(M_1^u)^2}{p^2 \Pi_0^q \Pi_0^u}\right] \sin^2 \frac{h}{f} \cos^2 \frac{h}{f}$$

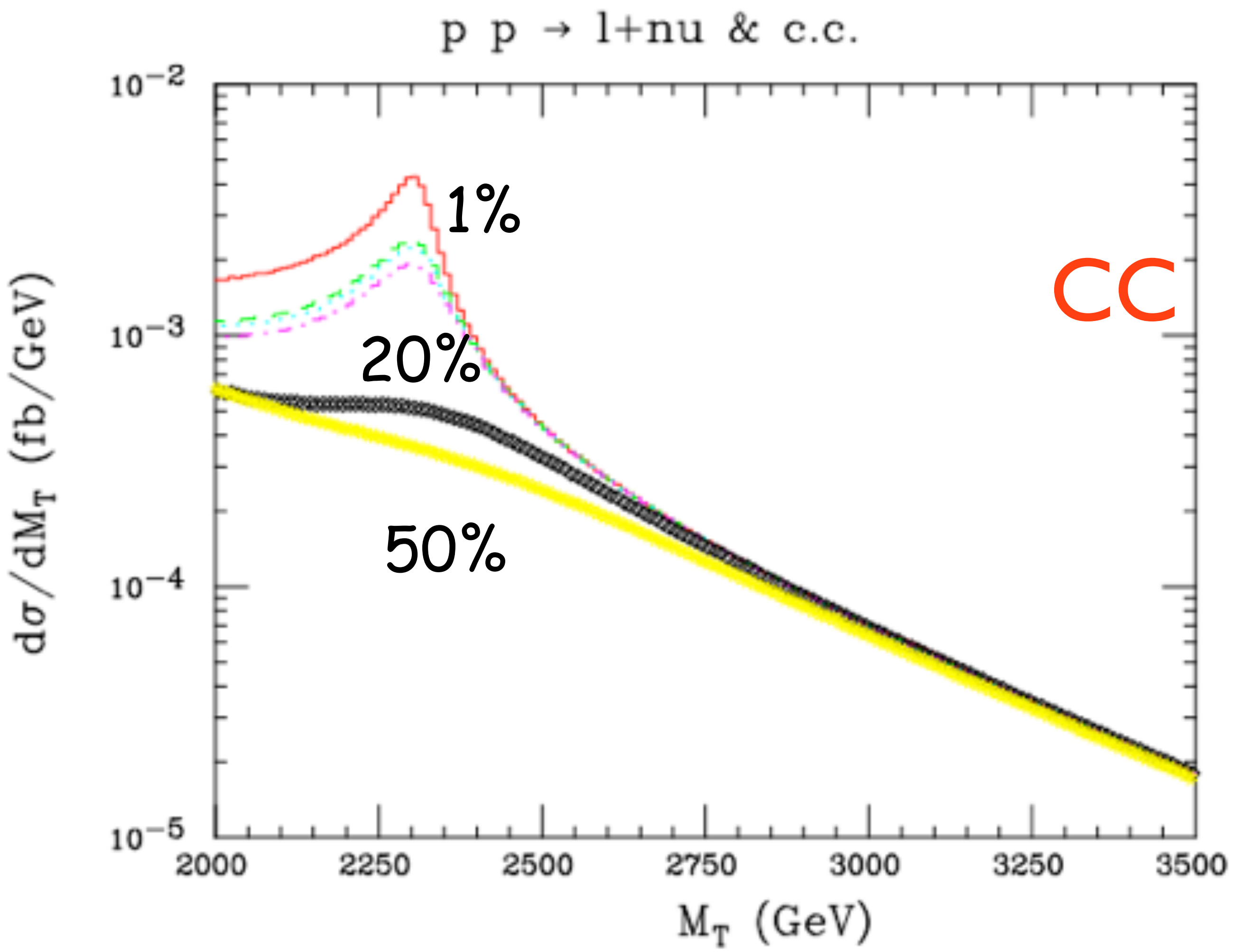


UV finite in the 4DCHM

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 EW coupling determination at the FCC-ee

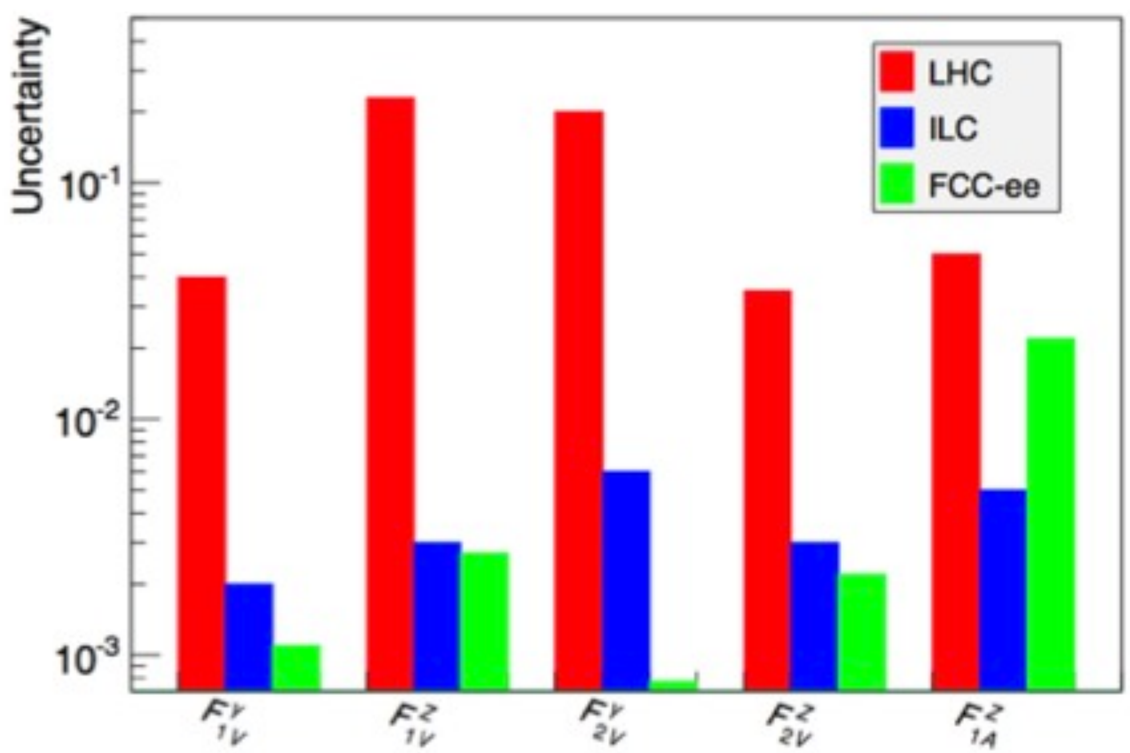
Optimal-observable analysis of lepton angular and energy distributions from top-quark pair production with semi-leptonic decays at FCC-ee with 360 GeV and 2.6 ab^{-1}

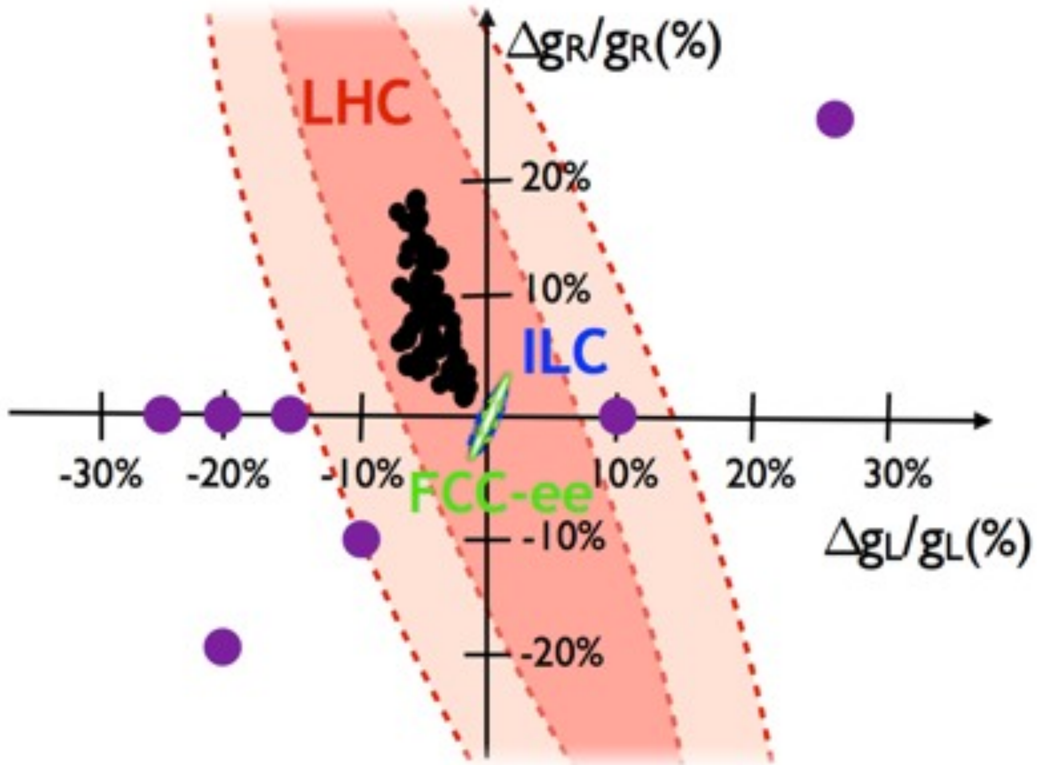
$$t\bar{t} \to (bW)(bW) \to (bqq')(bl\nu)$$

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

$$\frac{d^2\sigma}{dx\, d\cos\theta} = \frac{3\pi\beta\alpha^2(s)}{2s} B_\ell S_\ell(x, \cos\theta)$$

x and θ are the lepton (reduced) energy and polar angle





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})

the sensitivity on F^Z_{1A} can be reduced by a factor 2 by increasing the c.o.m. energy to 420 GeV (Janot 1503.01325)

FCC-ee (360GeV, 2.6 ab^{-1}) < 1%

continuous(dashed): from angular and energy distributions of leptons (b-quarks)

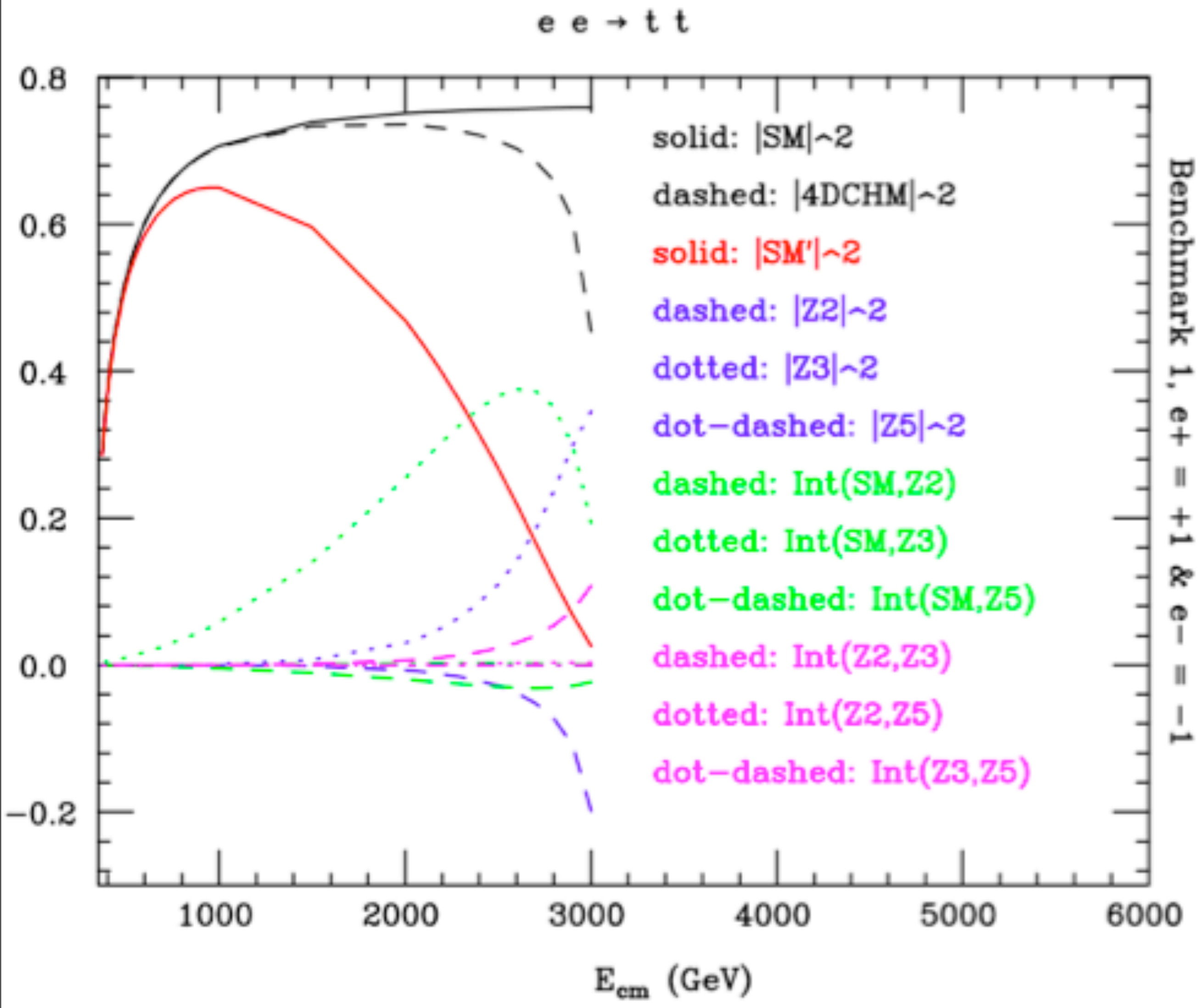
(P.Janot, private communication)

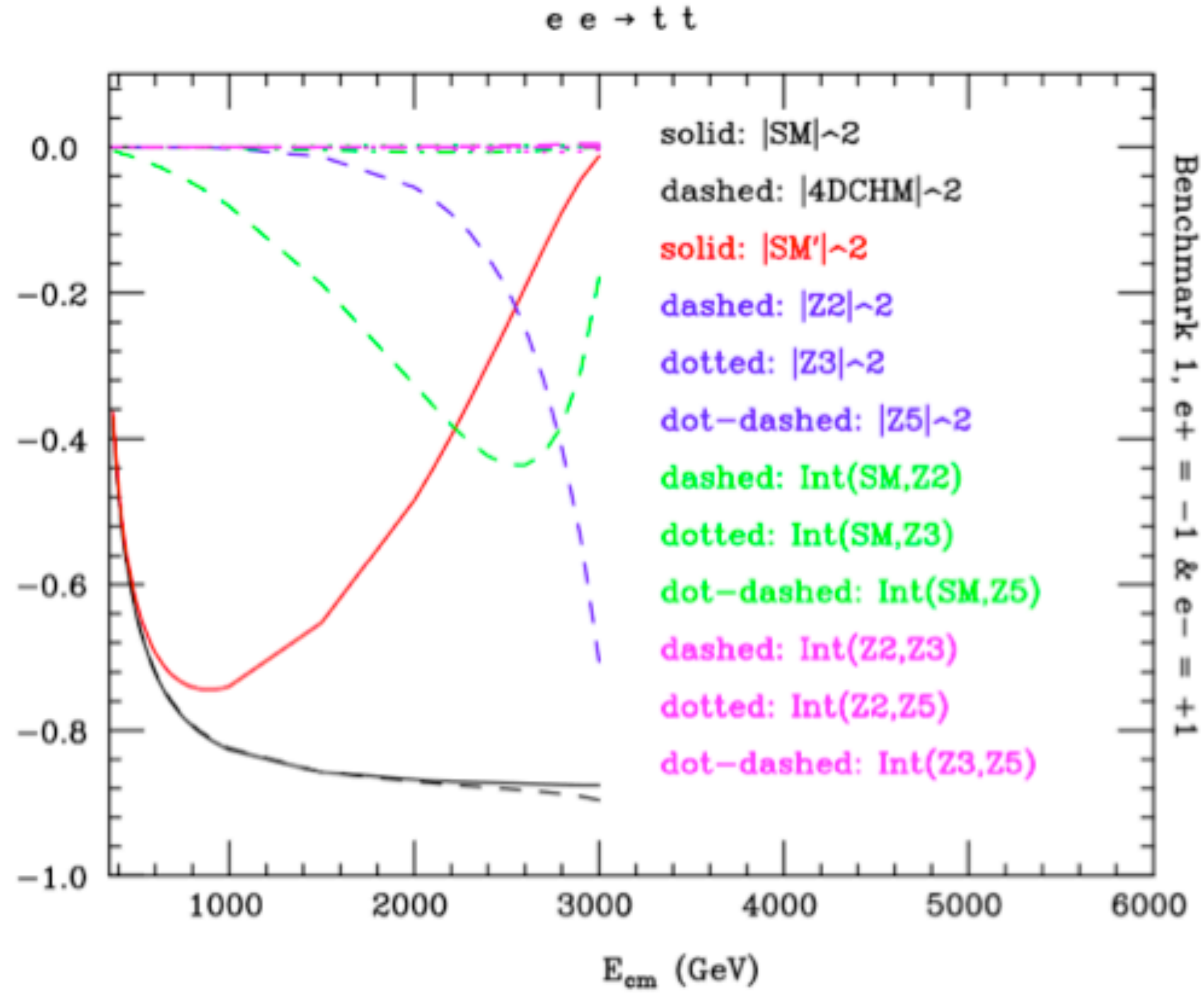
warning: large QCD corr. near threshold , possible underestimation of x-section error

Disentangling the effects

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

Single Spin Asymmetry A_L -polarized beams- P=-1,P'=1 (left) P=1,P'=-1 (right)





Positive contribution from SM-Z_3 interference
negligible SM-Z_2 interference

Negative contribution from SM-Z_2 interference
negligible SM-Z_3 interference

Polarization preferentially selects one or the other of the Z_2 and Z_3 contributions in A_L $\quad g^L_{Z_3} >> g^R_{Z_3} \quad g^R_{Z_2} >> g^L_{Z_2}$