Top pair production at e^+e^- colliders from a Composite Higgs Scenario

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Based on:

Barducci, DC, Moretti, Pruna; in preparation and 1311.3305

FCC-ee (TLEP) Physics Workshop (TLEP9)

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Motivations

☑ the Higgs resonance observed at the LHC opened up the stage of particle properties determination and made the physics case for future accelerators stronger than ever

☑ theoretical arguments supporting the importance of sub-percent precision for the Higgs couplings determination continue to grow ... especially to find hints for non Standard Model Higgs (ILC and CLIC can reach model independent 0.5-3%, TLEP can do even better)

☑ An e+e- collider has also a great potential on top physics: mass and width measurements 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 (weak vs strong forces)?

Try to answer within a Composite Higgs Scenario

- ☑ The 125 GeV Higgs-like signal observed at the LHC could not be the "fundamental" Standard Model Higgs

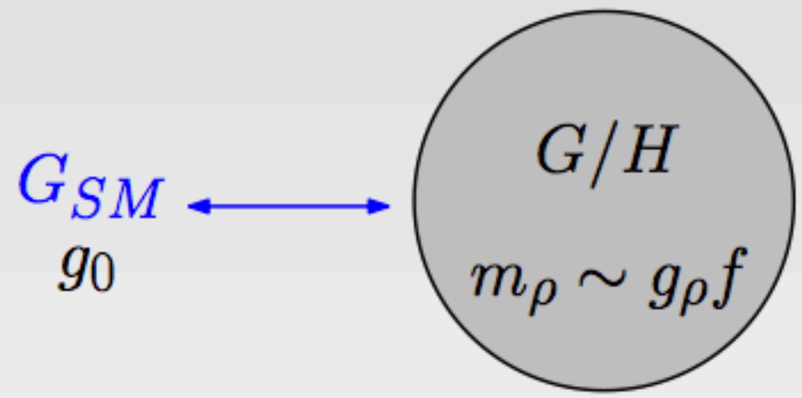
- ☑ Explore BSM scenarios: Higgs as Nambu-Goldstone boson provides an elegant solution for naturalness

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

- ☑ Minimal effective calculable description: the 4-Dimensional 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

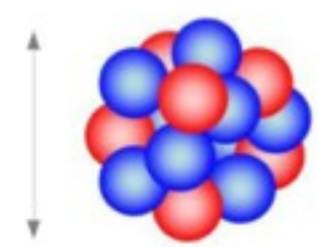
How to get an Higgs mass?

- 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

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

$l \sim 1/\Lambda_{com}$



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

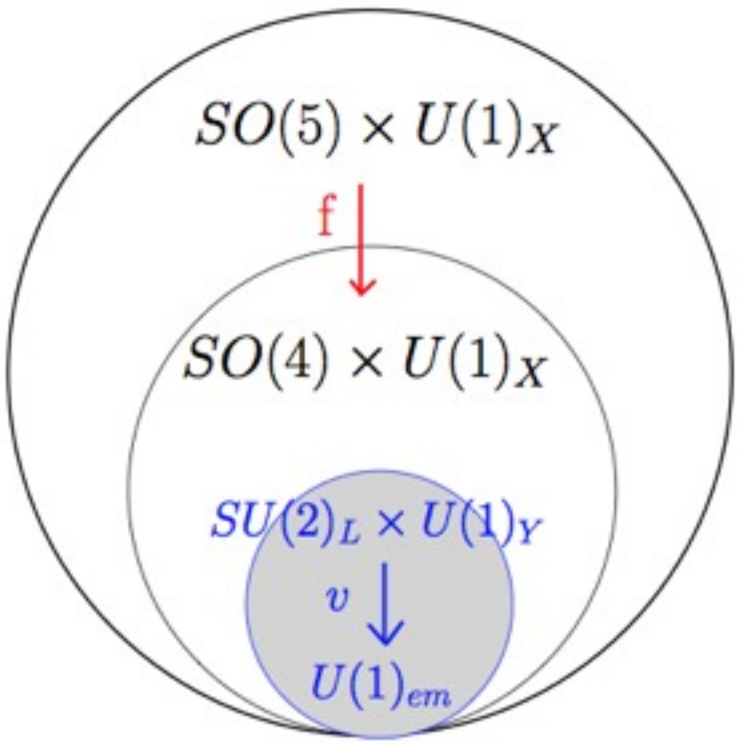
MINIMAL MODEL with $SU(2)_C$

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

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

Higgs = pseudo-GB

$(m_h \ll m_\rho)$



Explicit Models in 4D

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

4D Effective descriptions:

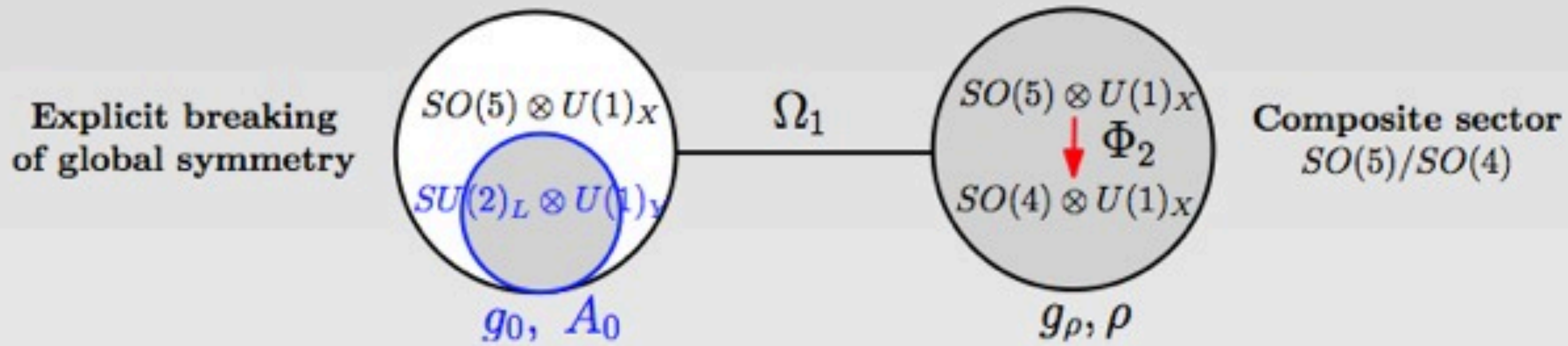
- Simplified model (two sectors without GB) Contino, Kramer, Son, Sundrum '07
- General low-energy effective description of a GB Higgs (CCWZ) Giudice, Grojean, Pomarol, Rattazzi '07
- Add the lightest composite resonance Contino et al. 1109.1570; De Simone et al. 1211.5663; Grojean et al.1306.4655

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



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

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

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

- Non linear structure ↔ GB Higgs
- GB decay constant

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

- Composite spectrum

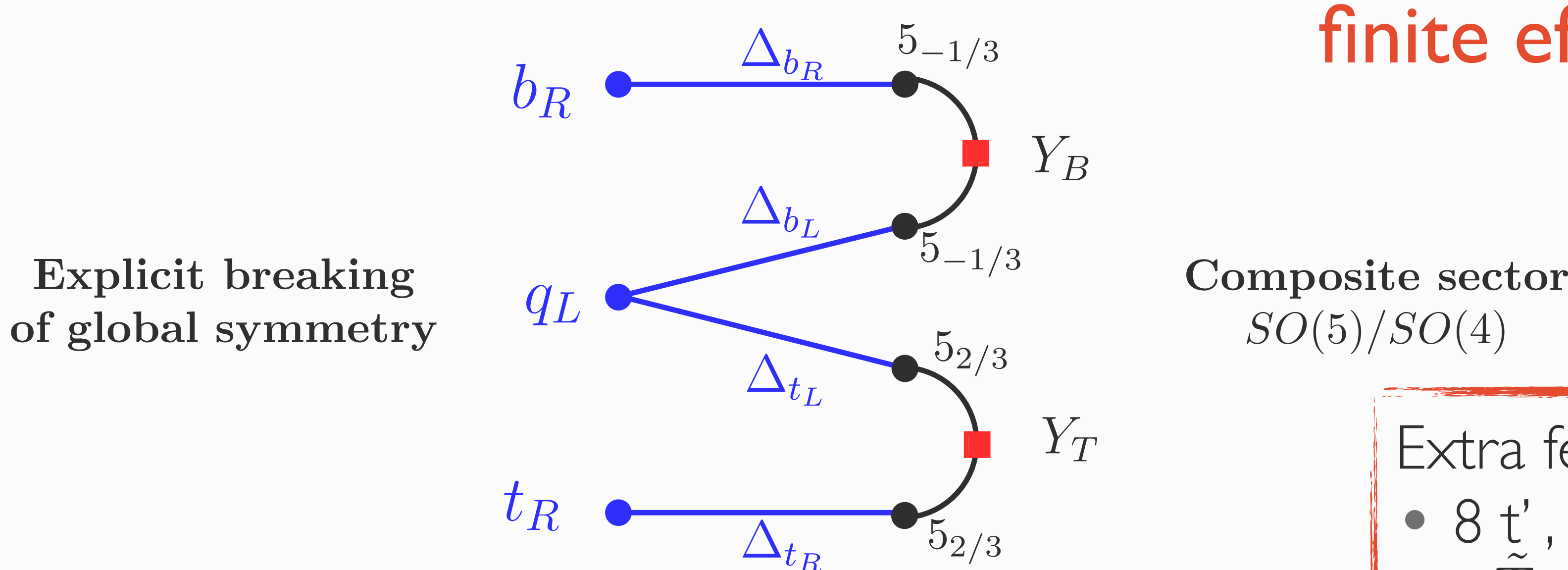
$$SO(4) \to m_\rho^2 = \frac{g_\rho^2 f_1^2}{2}, \qquad \frac{SO(5)}{SO(4)} \to m^2_{a_1} = \frac{g_\rho^2(f_1^2 + f_2^2)}{2}$$

Fermion sector: which representation?

A phenomenolgical choice (protecting $Zb\bar{b}$) Agashe, Contino, da Rold, Pomarol '06

$$\mathbf{5}_{2/3} = \underbrace{\mathbf{2}_{1/6}}_{q_L} \oplus \mathbf{2}_{7/6} \oplus \underbrace{\mathbf{1}_{2/3}}_{u_R}, \quad \mathbf{5}_{-1/3} = \mathbf{2}_{5/6} \oplus \underbrace{\mathbf{2}_{1/6}}_{q_L} \oplus \underbrace{\mathbf{1}_{-1/3}}_{d_R}, \quad Y = T_{3R} + X$$

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



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

Strong sector: resonances + Higgs bound state

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

Spectrum:

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

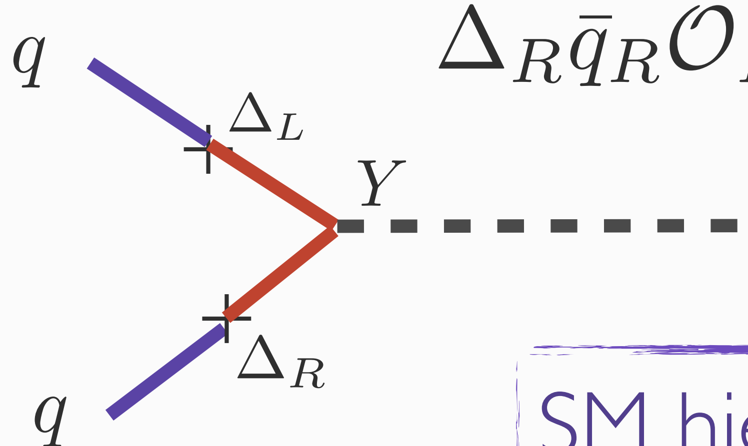
$g_\rho =$ strong coupling

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

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

0

Linear elementary-composite couplings (partial compositeness)



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

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

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

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

Implementation of the 4DCHM

- Calculable 4D description: good framework to study general CHM features
- The particle spectrum is quite large and also the parameter space

  - SM leptons: e, μ, τ, and ν_e, ν_μ, ν_τ
  - SM quarks; u, d, c, s, t, b
  - SM gauge bosons: $\gamma, Z^0, W^\pm, g$
  - 5 extra neutral gauge bosons: $Z'_{i=1,\ldots,5}$
  - 3 extra charged gauge bosons: $W'^{\pm}_{i=1,2,3}$
  - 8 extra charged 2/3 fermions: $t'_{i=1,\ldots,8}$
  - 8 extra charged -1/3 fermions: $b'_{i=1,\ldots,8}$
  - 2 charged 5/3 fermions: $T'_{i=1,2}$
  - 2 charged -4/3 fermions: $B'_{i=1,2}$
  - 1 Higgs boson

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

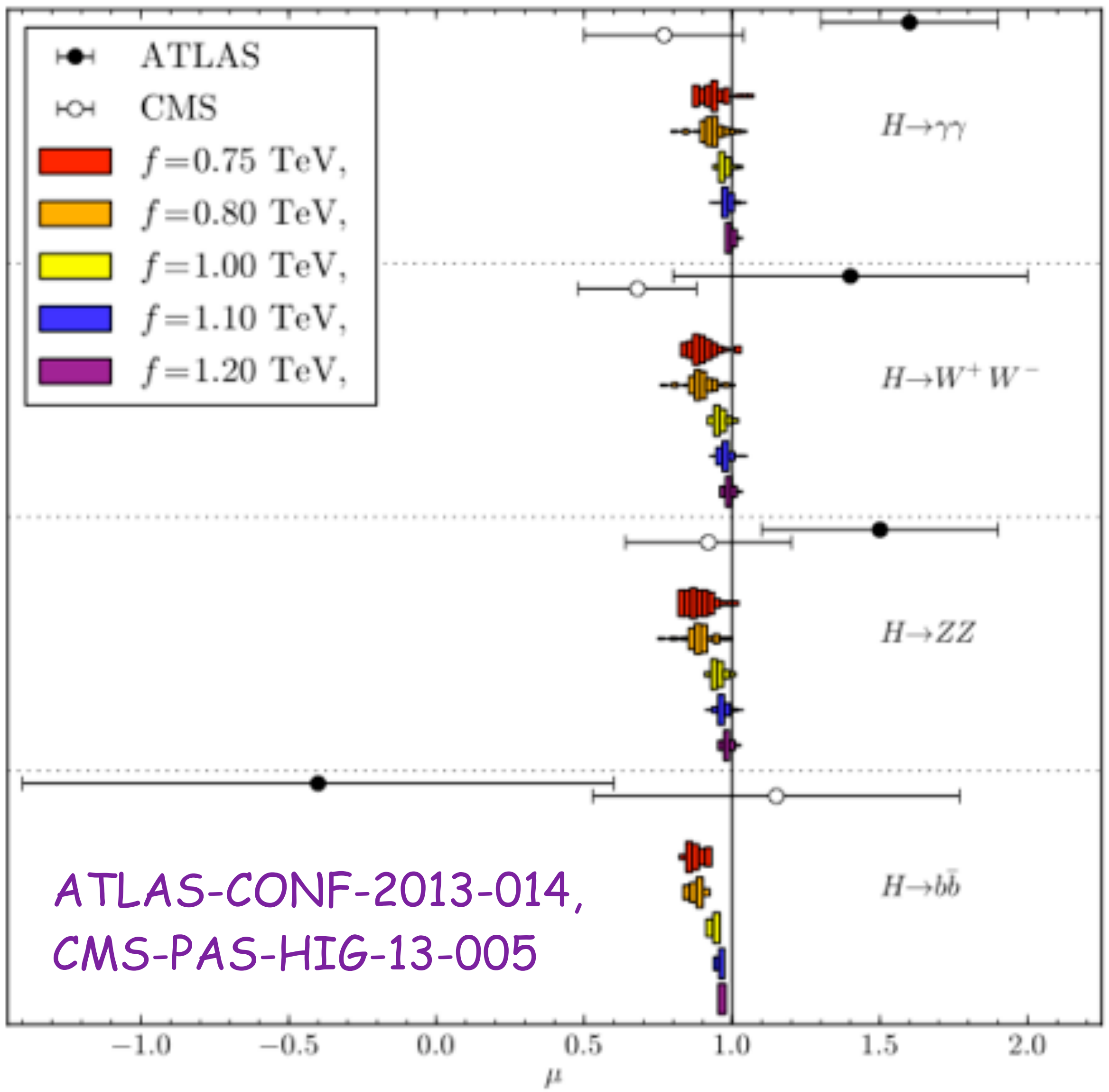
LanHEP: package for the automated generation of Feynman rules
Semenov, arXiv:1005.1909
CalcHEP: package for automated calculations of physical observables
Belyaev et al, Comput. Phys. Commun. 184 (2013) 1729
HEPMDB: model available at https://hepmdb.soton.ac.uk

- 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 compositness spirit)

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

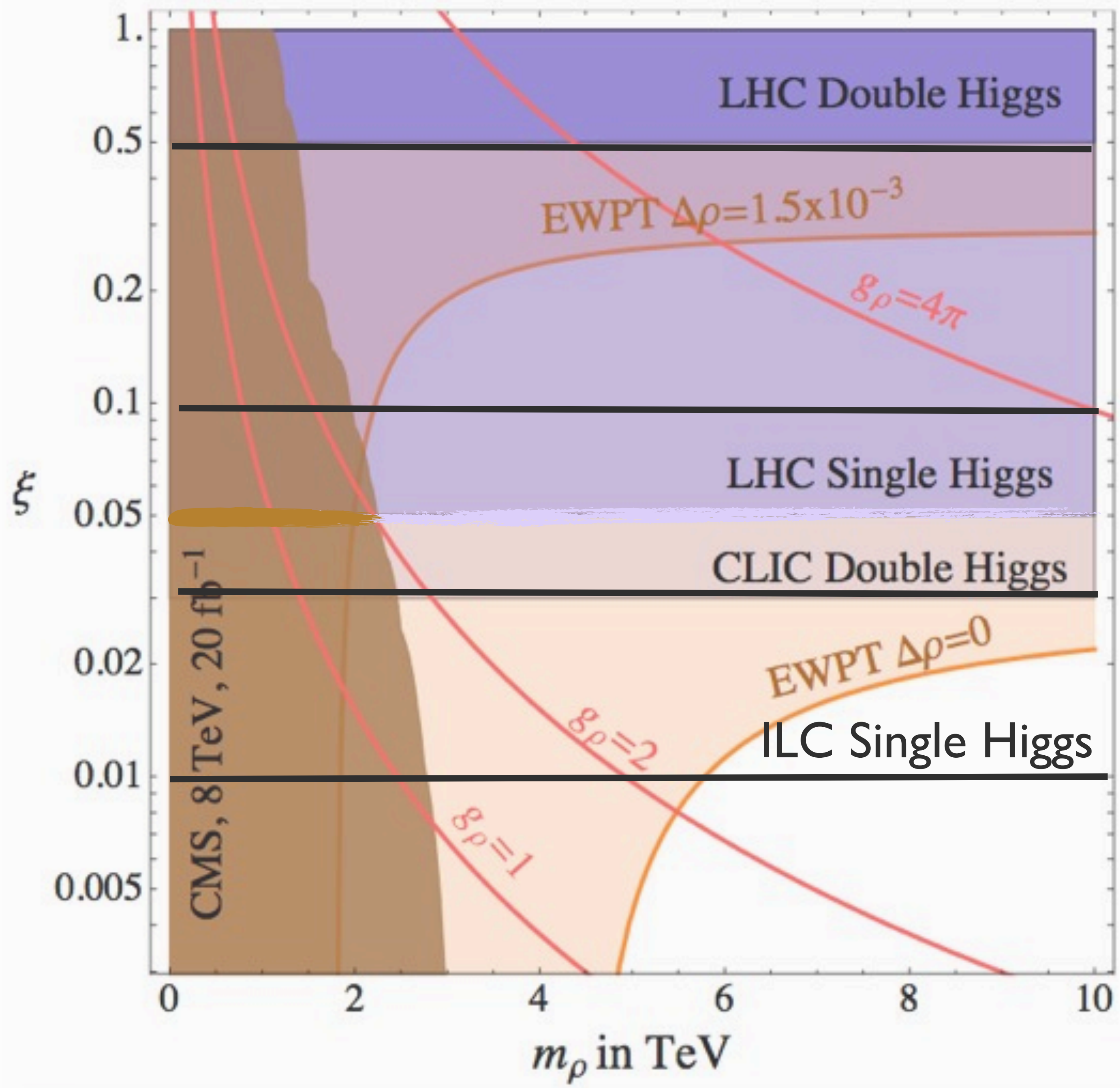
if the LHC will not measure deviations from the SM in single Higgs production larger than 10% and does not discover any new particle with a clear role ....

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 $300 fb^{-1}$

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

ILC 250GeV 250fb^{-1}

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

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

EWPT mainly from deviations on g_{hVV}

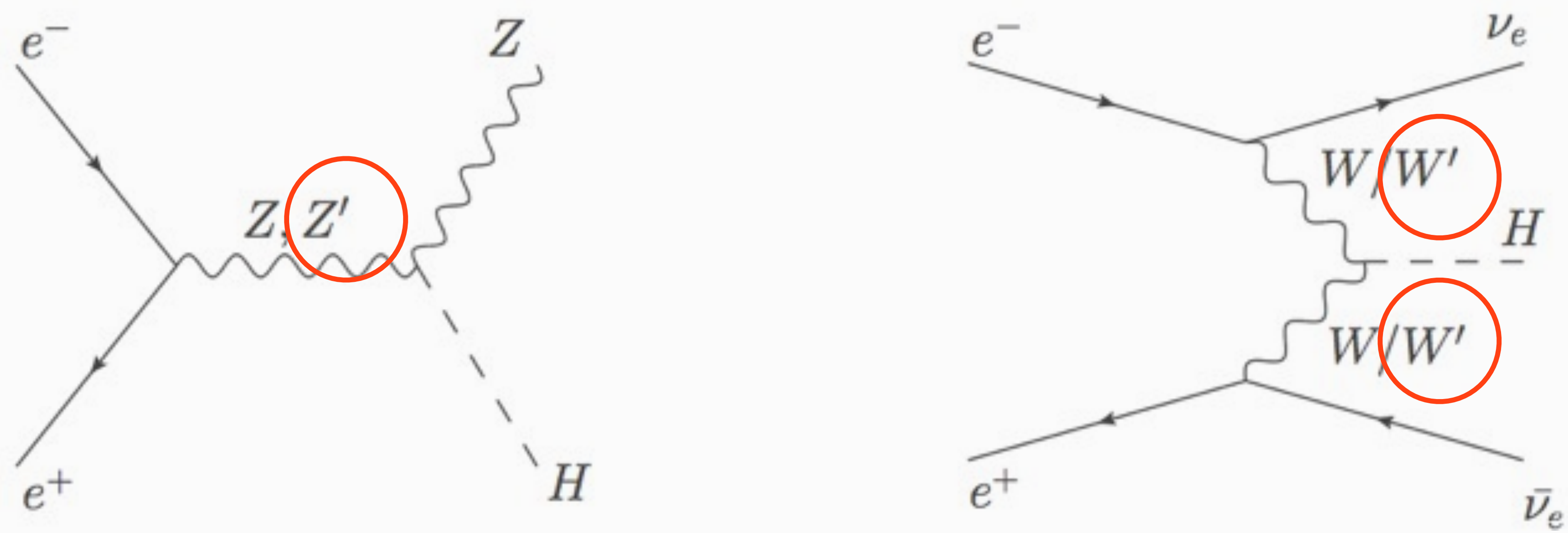
To the sensitivity on $\xi = v^2/f^2$ it corresponds a reach on the compositeness scale $\Lambda = 4\pi f$ (Ex. Λ =30-40 TeV @ILC)

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)

$(\sqrt{s}(\mathrm{GeV}), L(fb^{-1})$ =(250,250), (500,500),(1000,1000)

Single Composite Higgs Boson produced via HS and VBF



Extra Gauge bosons W' and Z' can be exchanged

We have performed parameter scans for various benchmark points of the 4DCHM with $M_{Z',W'} \sim 2$ TeV

125 GeV Higgs boson produced via HS at a e+e- collider

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

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

* = decoupl. limit

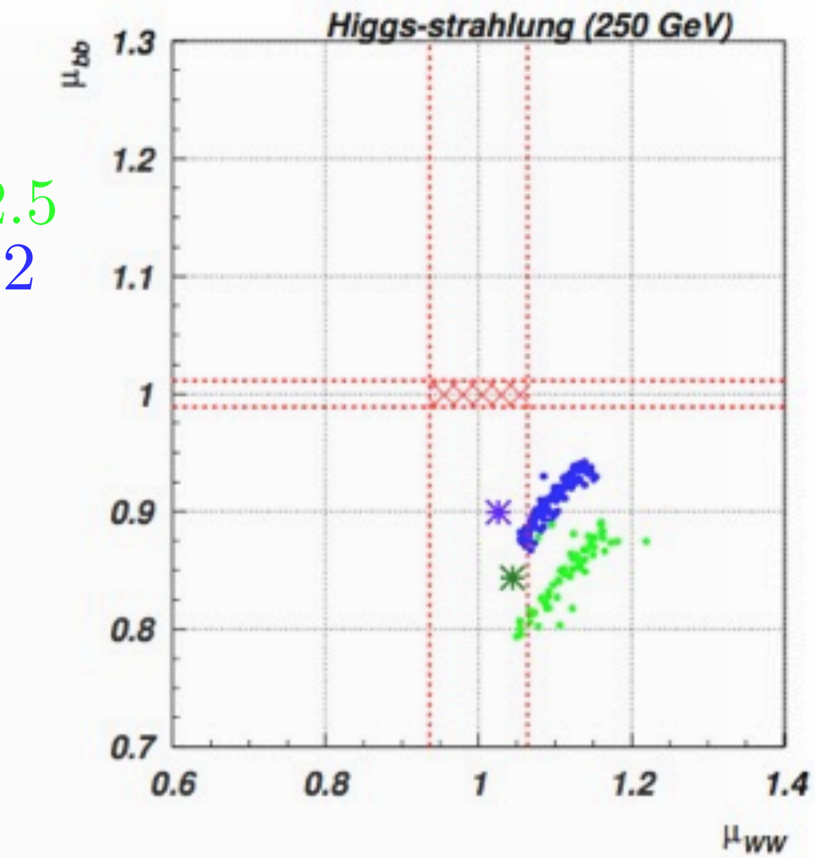
$$\mu_i = \frac{\sigma(e^+e^- \to HX)_{\rm 4DCHM} {\rm BR}(H \to i)_{\rm 4DCHM}}{\sigma(e^+e^- \to HX)_{\rm SM} {\rm BR}(H \to i)_{\rm SM}}$$

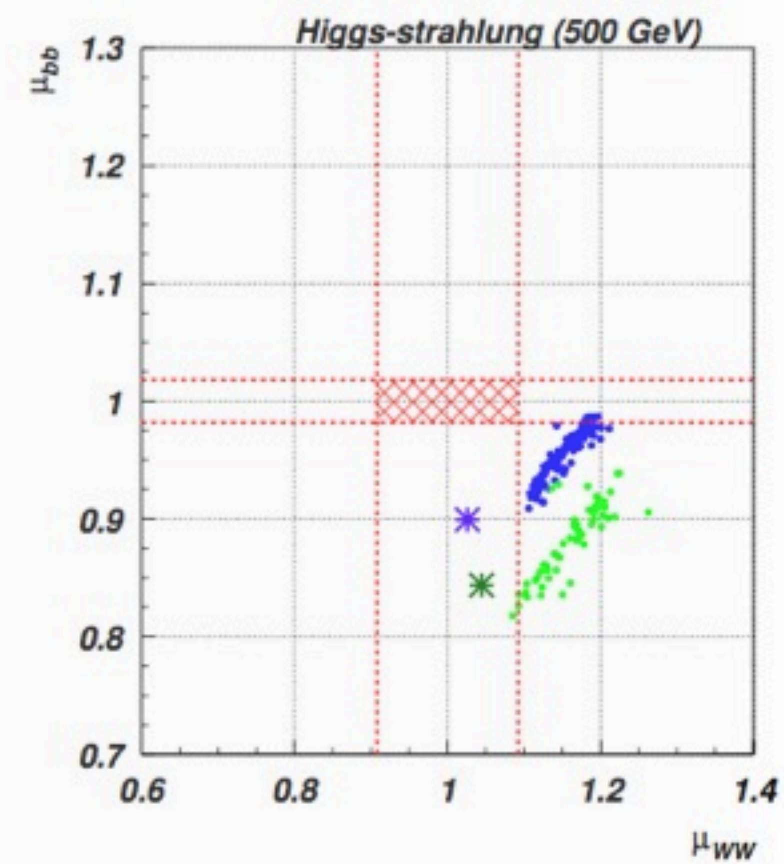
$$i = b\bar{b},\ \ W^+W^-$$

expected accuracies for the μ_i are shown

ILC TDR 1306.6352

ILC Higgs White Paper 1310.0763





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

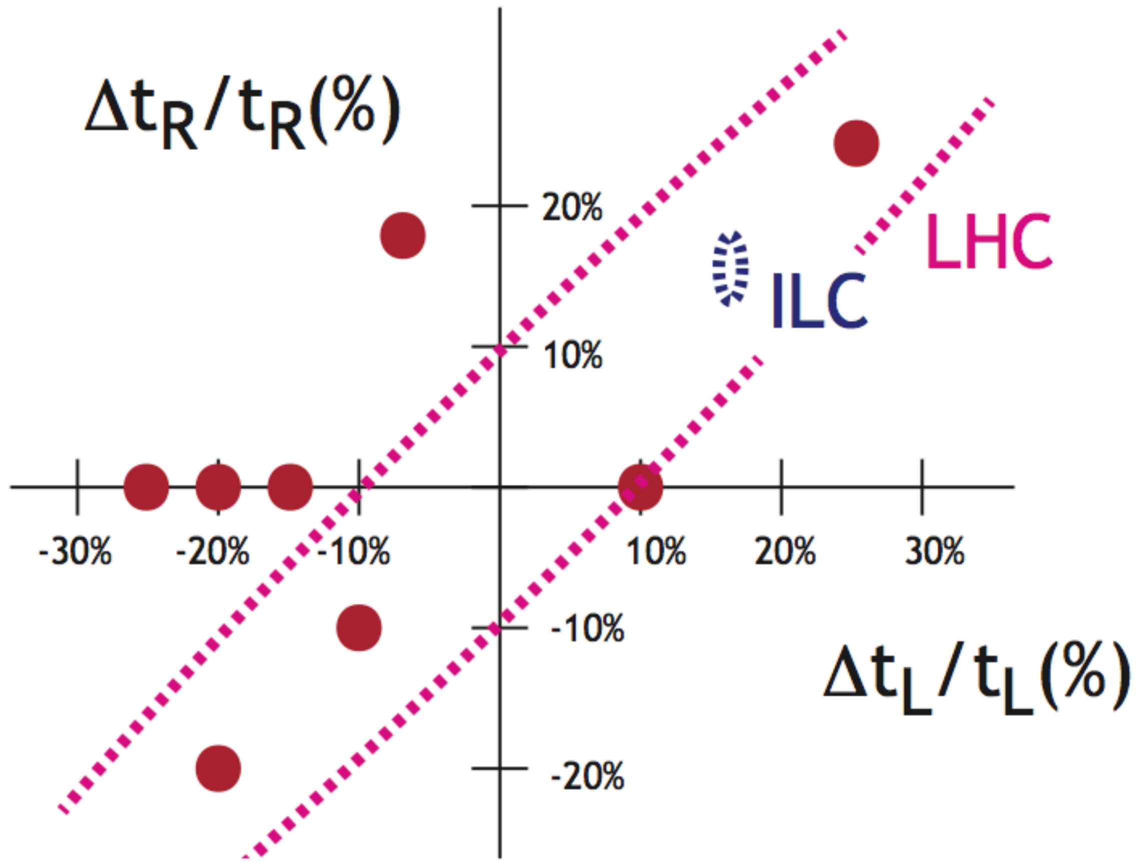
This feature is common to other processes

Top quark precision physics at an e+e- collider

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

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

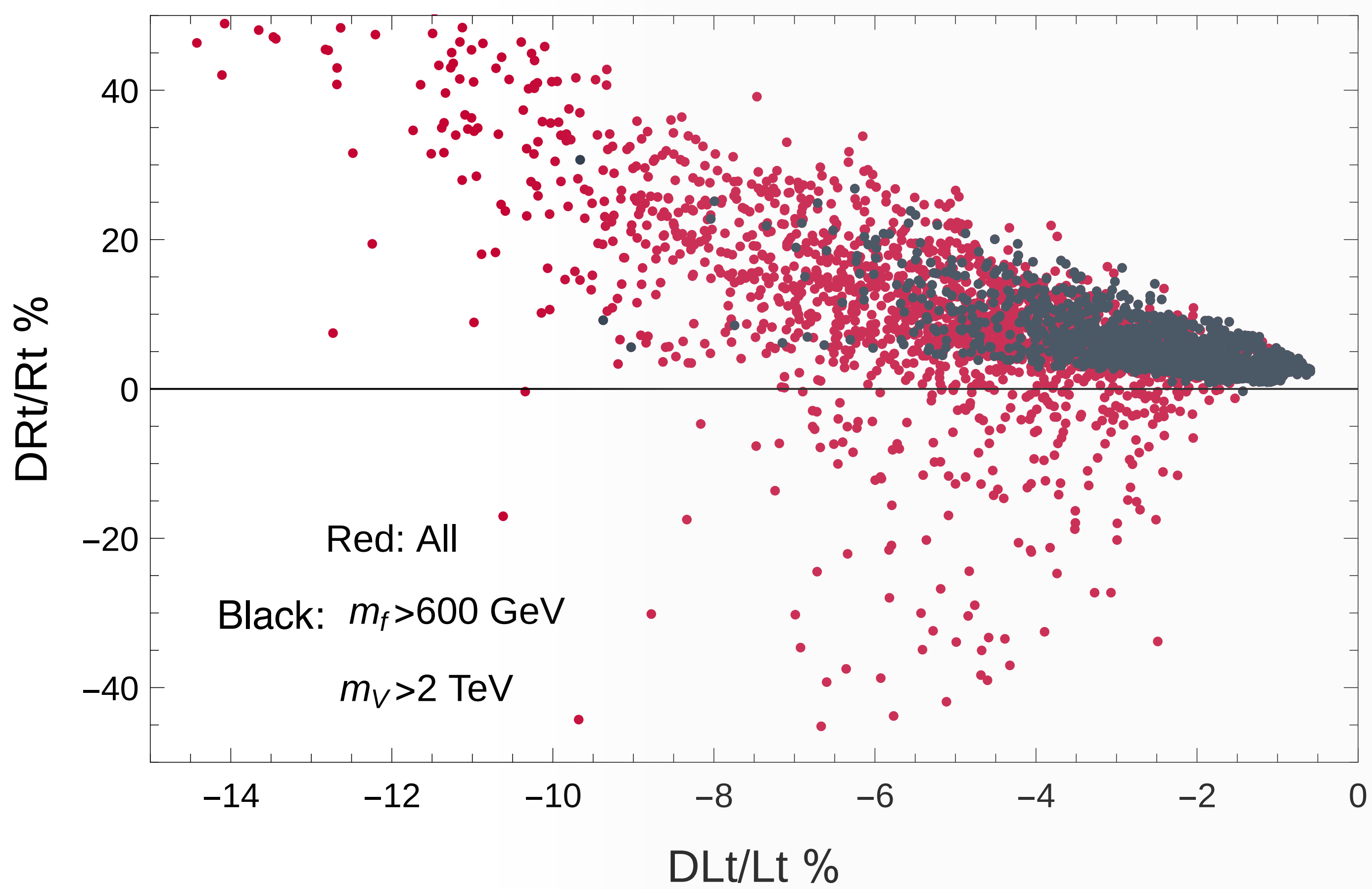
Richard 1403.2893; Grojean, LCWS14 talk



sensitivities: LHC ~ 10%
HL-LHC ~ 4%
ILC(500) < 1% with polarized beams

Barducci, DC, Moretti, Pruna, in preparation

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



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

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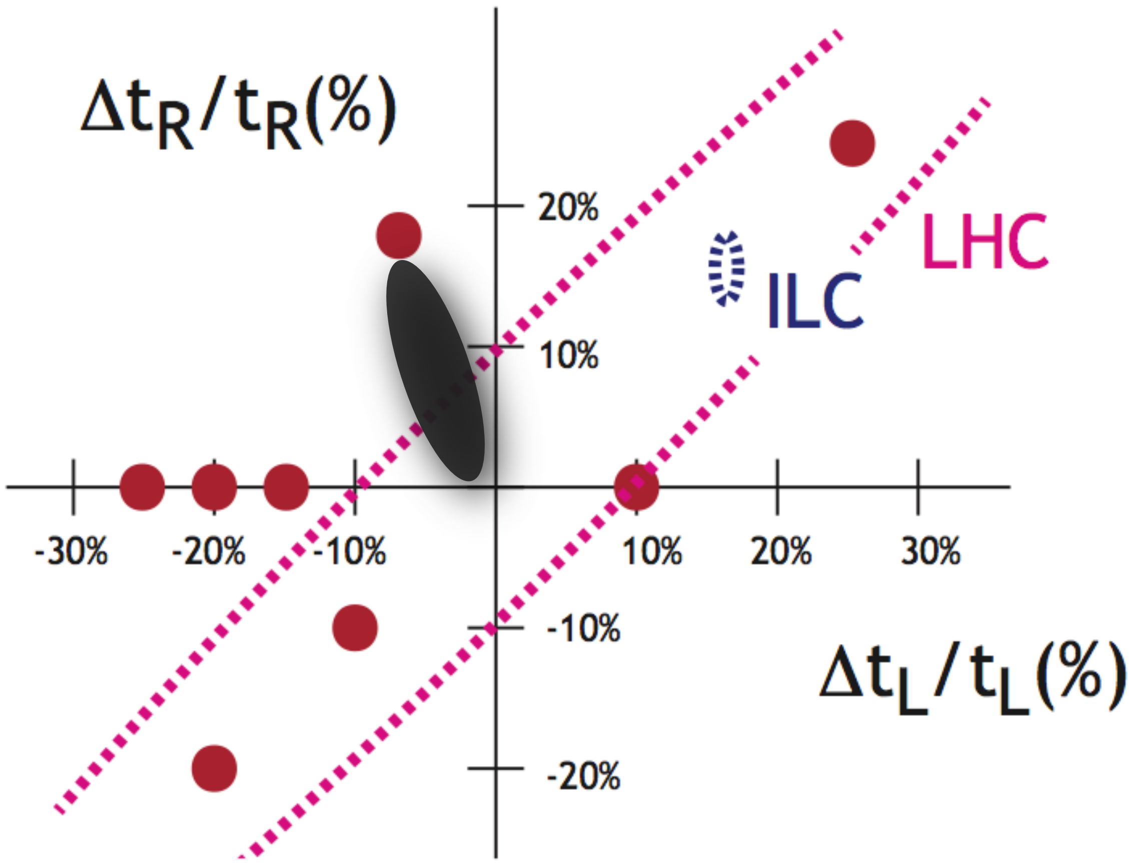

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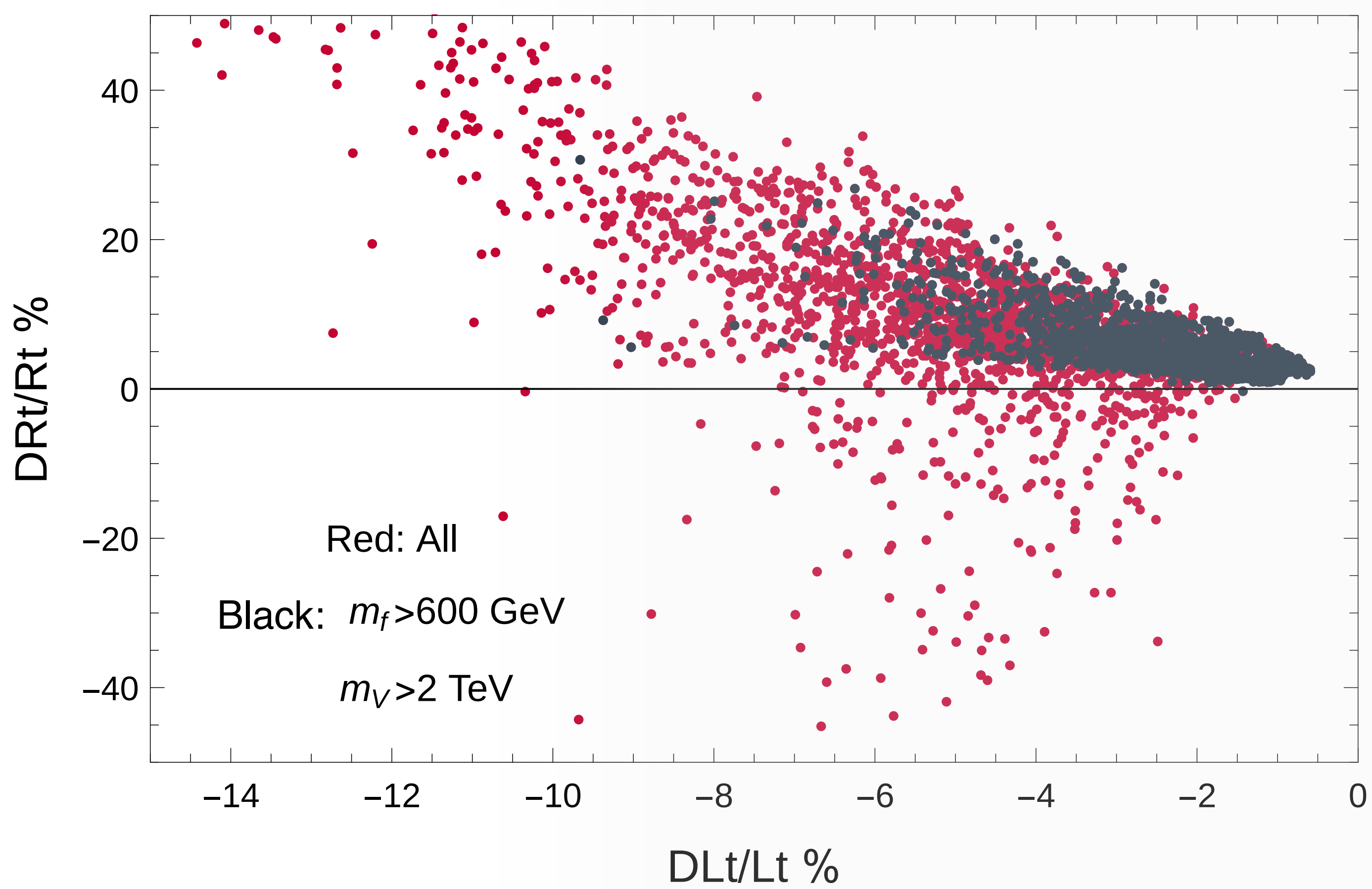

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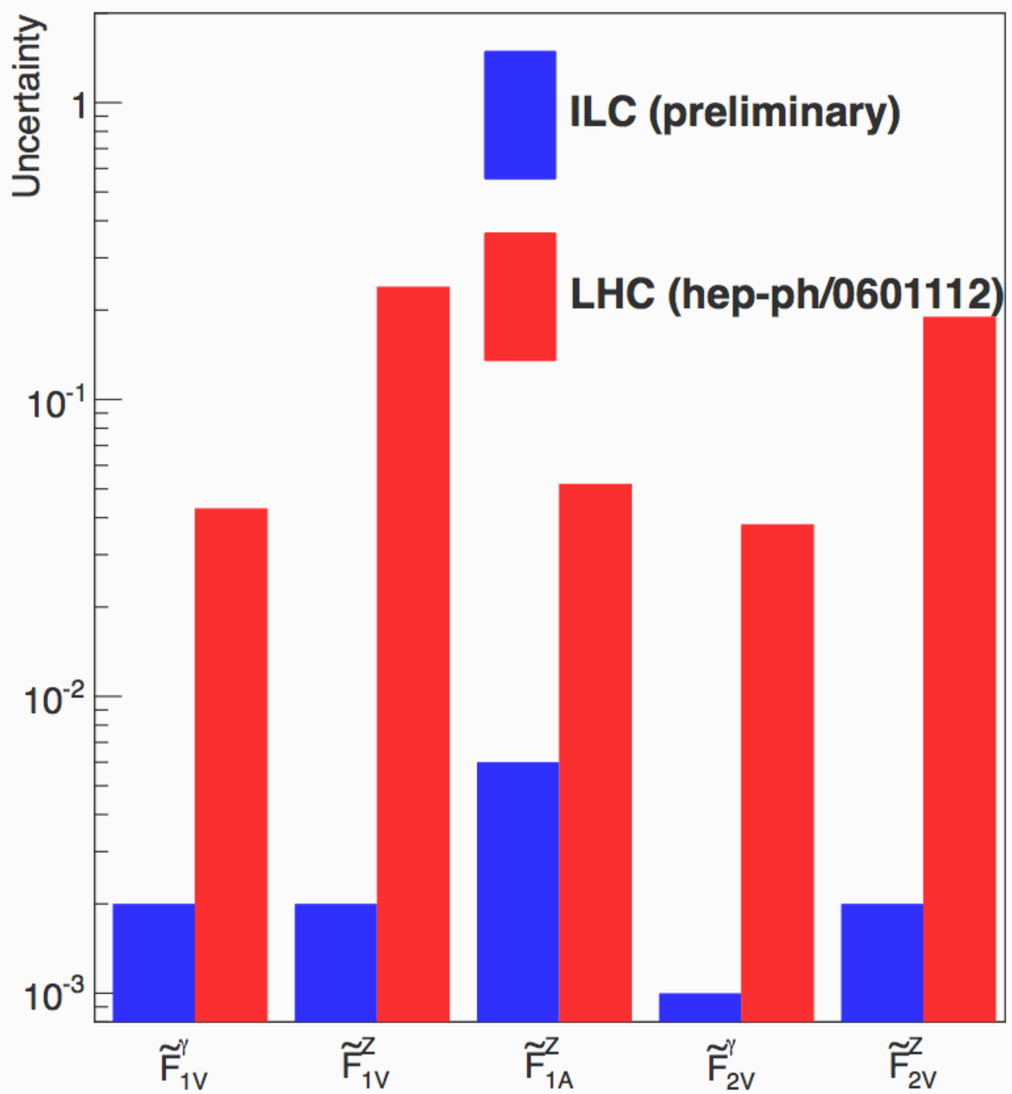
Top quark couplings to Z and γ

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



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

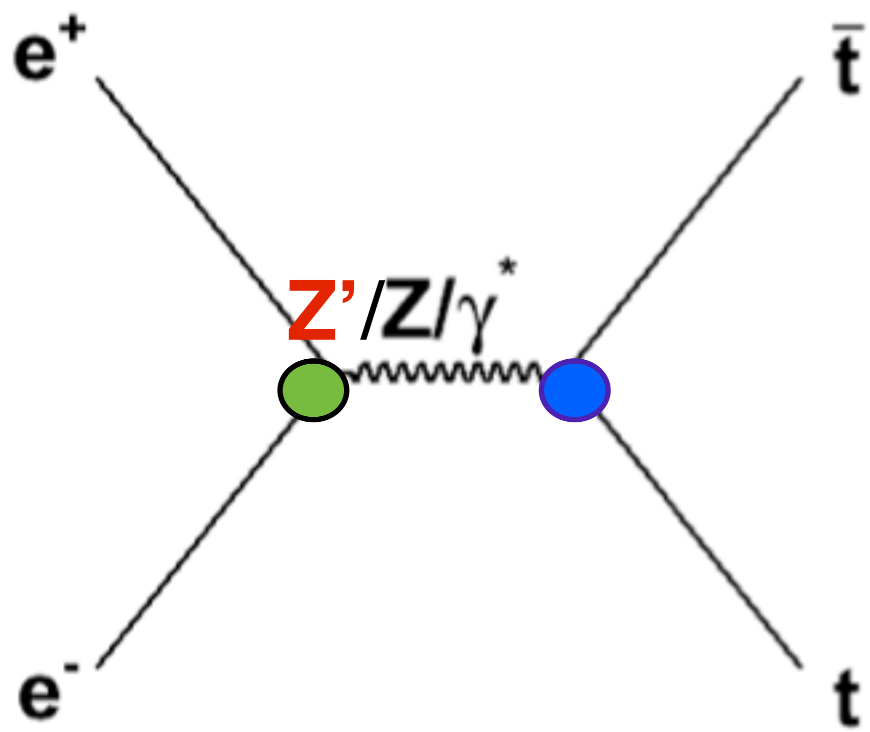
(Amjad et al. 1307.8102)

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

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

Top pair production within the 4DCHM

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



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 $M_{Z'}$

Born approximation - QCD and EW corrections and EW not included

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

Observables:

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

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

☑ Double and Single Spin Asymmetries

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

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

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

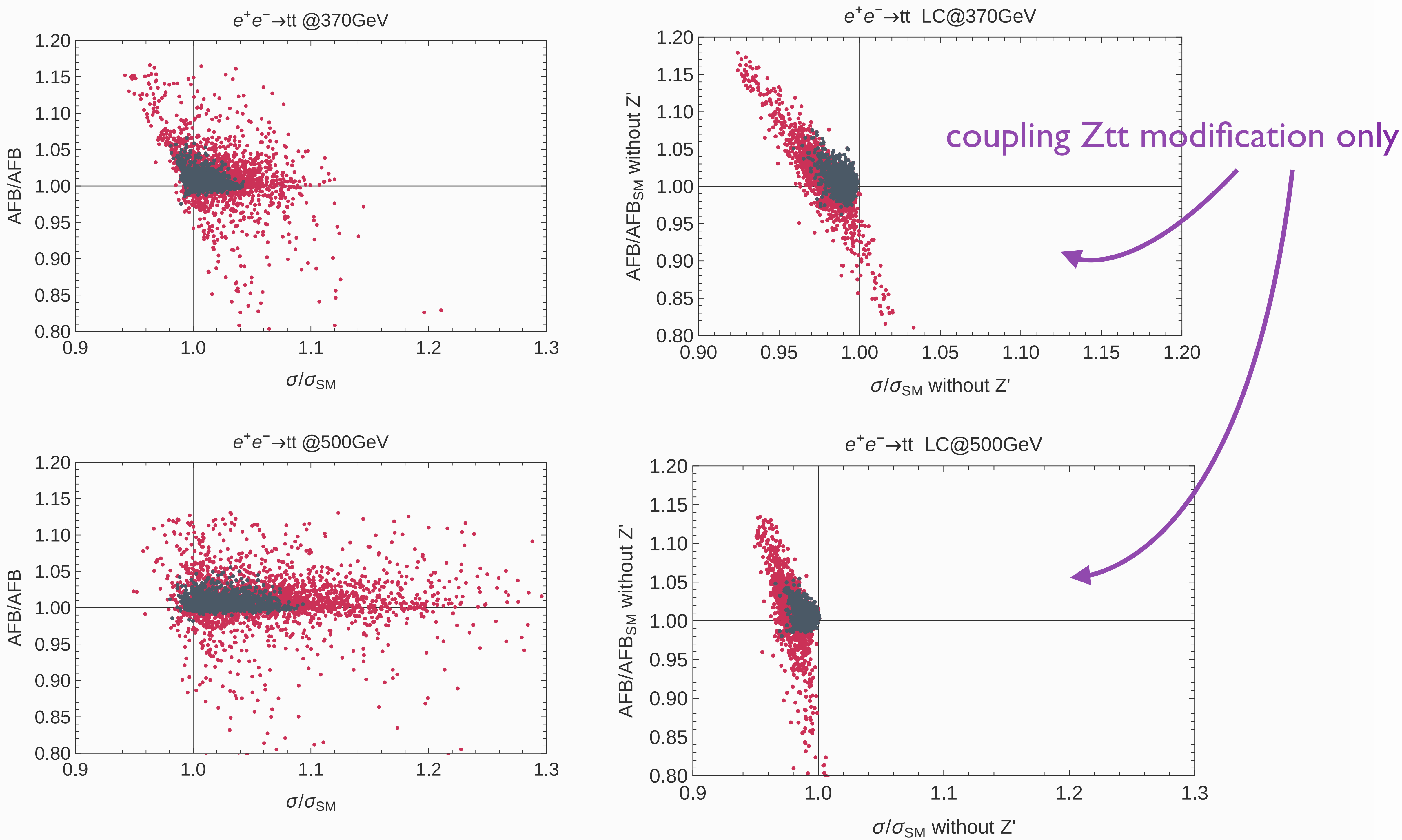
- Asymmetries are extracted as coefficients in the angular distribution of the top (antitop) decay products: ex. A_L and A_{LL} are related to the helicity angle distribution (see M.Vos talk)

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

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

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

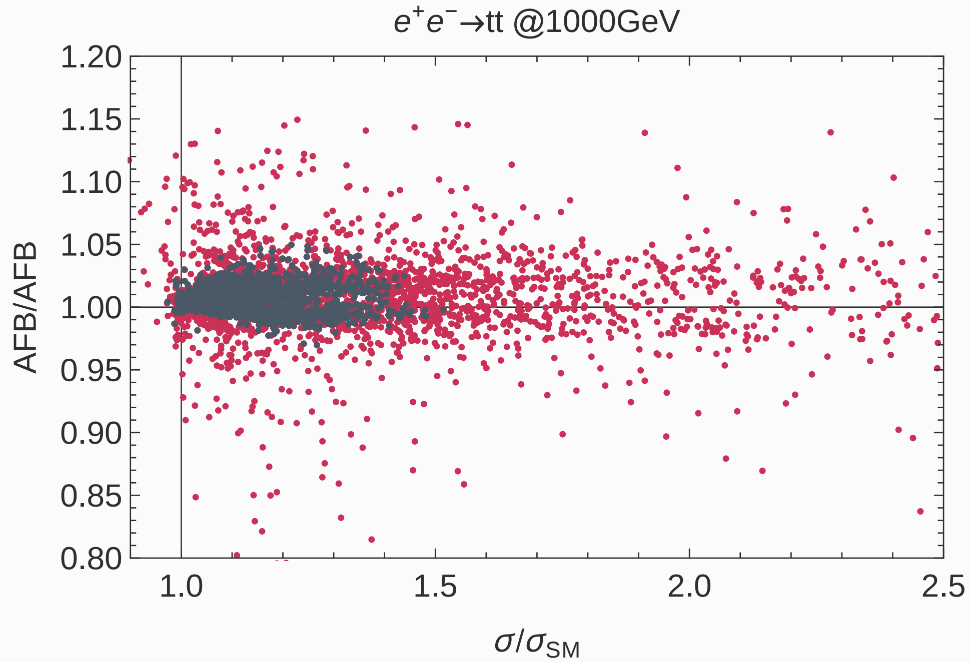
With or without Z' exchanges @ 370, 500 GeV

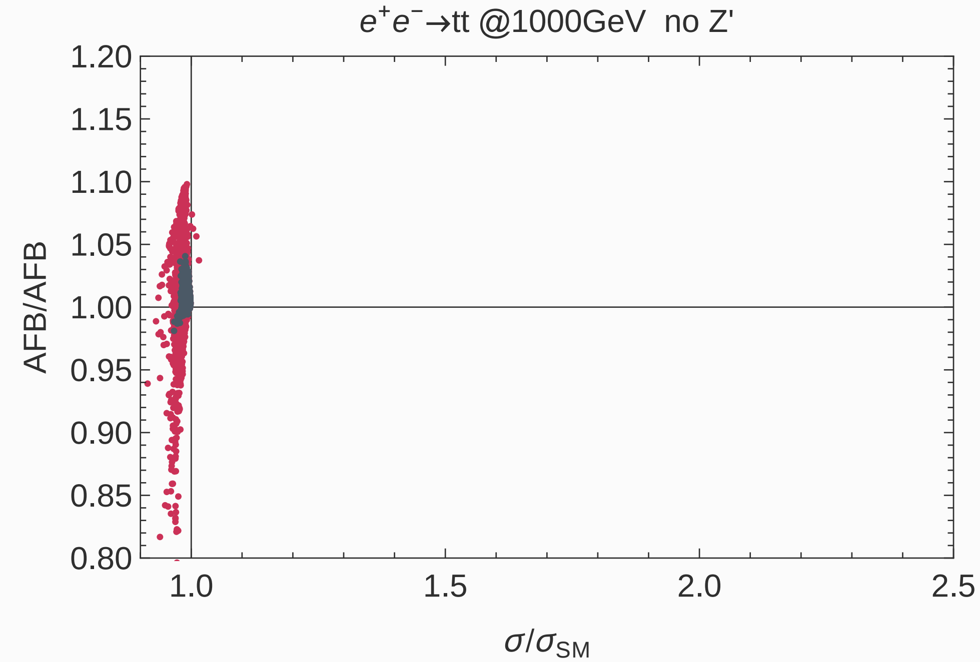


red: all points f=0.75-1.5, g_s=1.5-3, black: M_T>600GeV $M_{Z'}$>2TeV

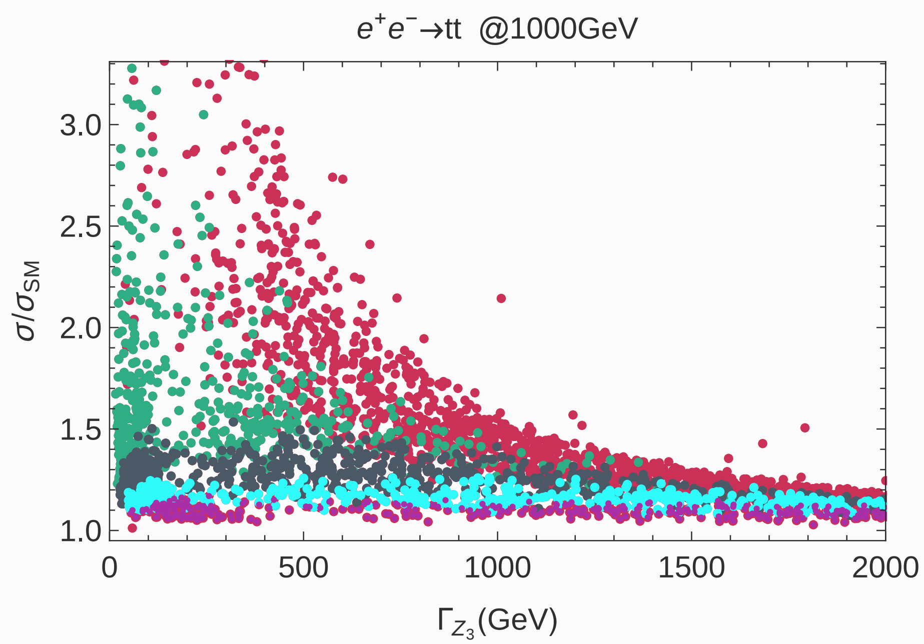
With or without Z' exchanges @ 1000 GeV

up to 40% deviation in the x-sect !



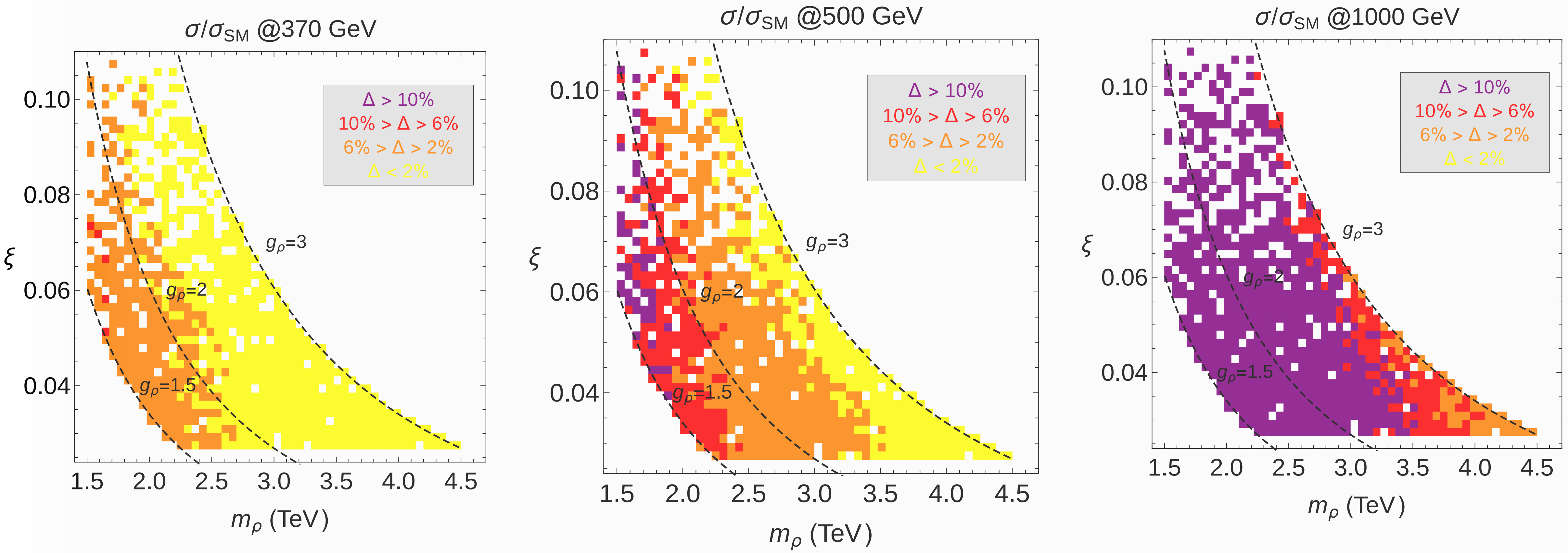


Interference of the Z' with the SM plays a crucial role



red: all points, green M_T>600GeV, black: M_T>600GeV $M_{Z'}$>2TeV, cyan: M_T>600GeV $M_{Z'}$>2.5TeV, purple: M_T>600GeV $M_{Z'}$>3TeV

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



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

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

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

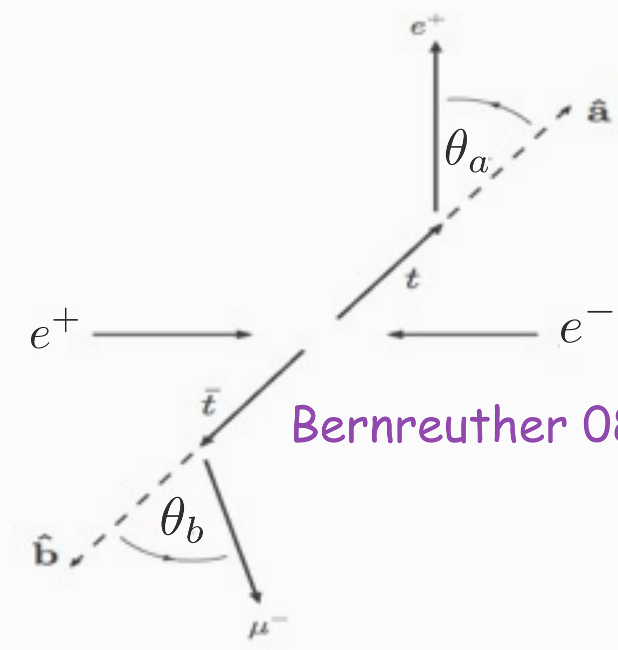
Single Spin Asymmetry A_L

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

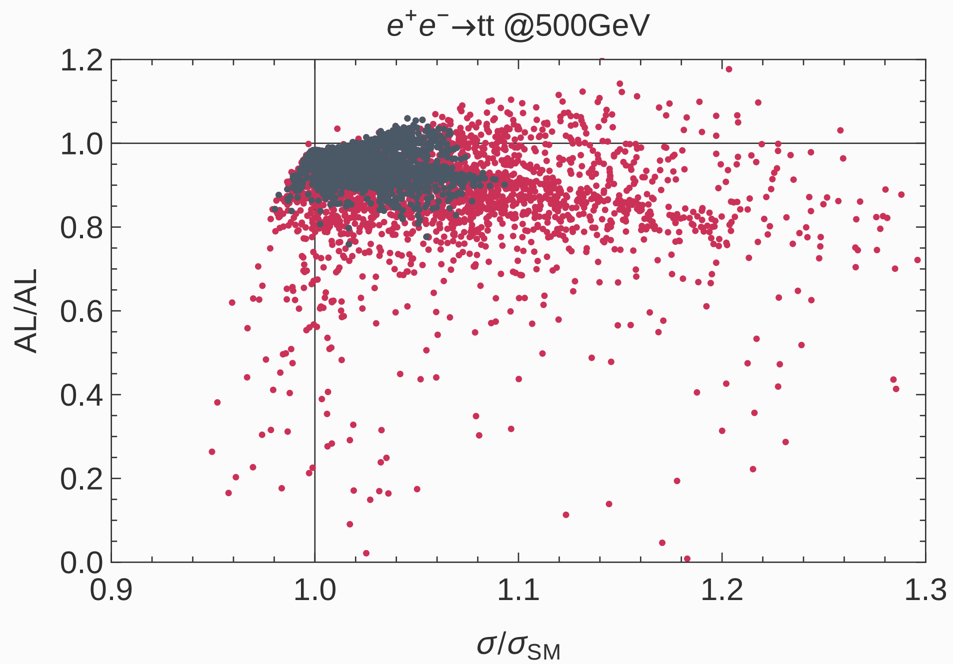
$$B_1 \sim A_L(t),\ B_2 \sim A_L(\bar{t}),\ C \sim A_{LL}$$

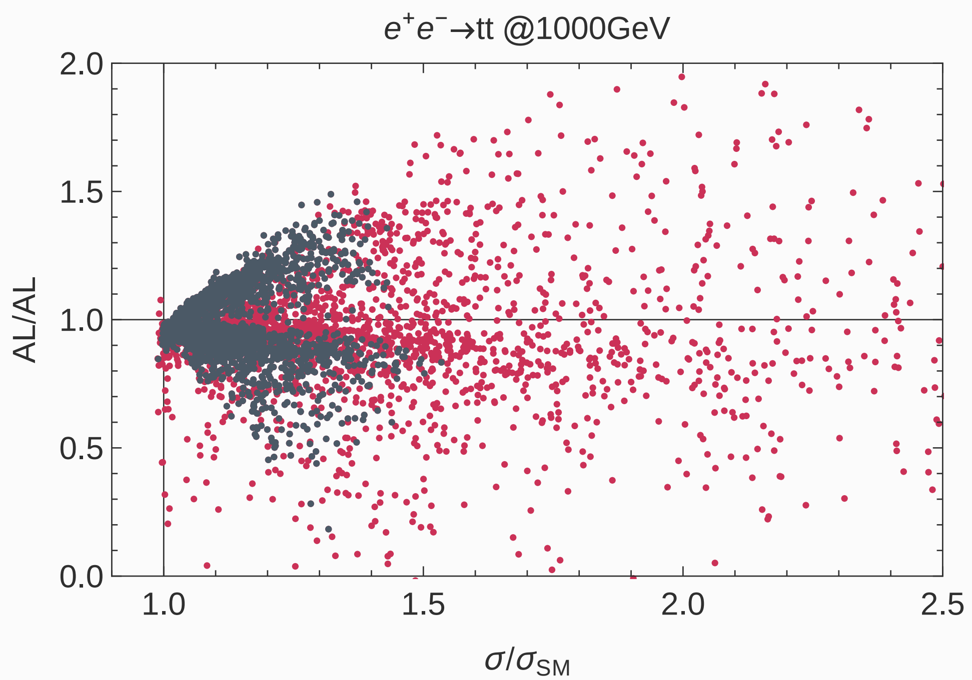
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_a} = \frac{1}{2}[1 + A_L\cos\theta_a]$$

helicity angle distribution



Bernreuther 0805.1333

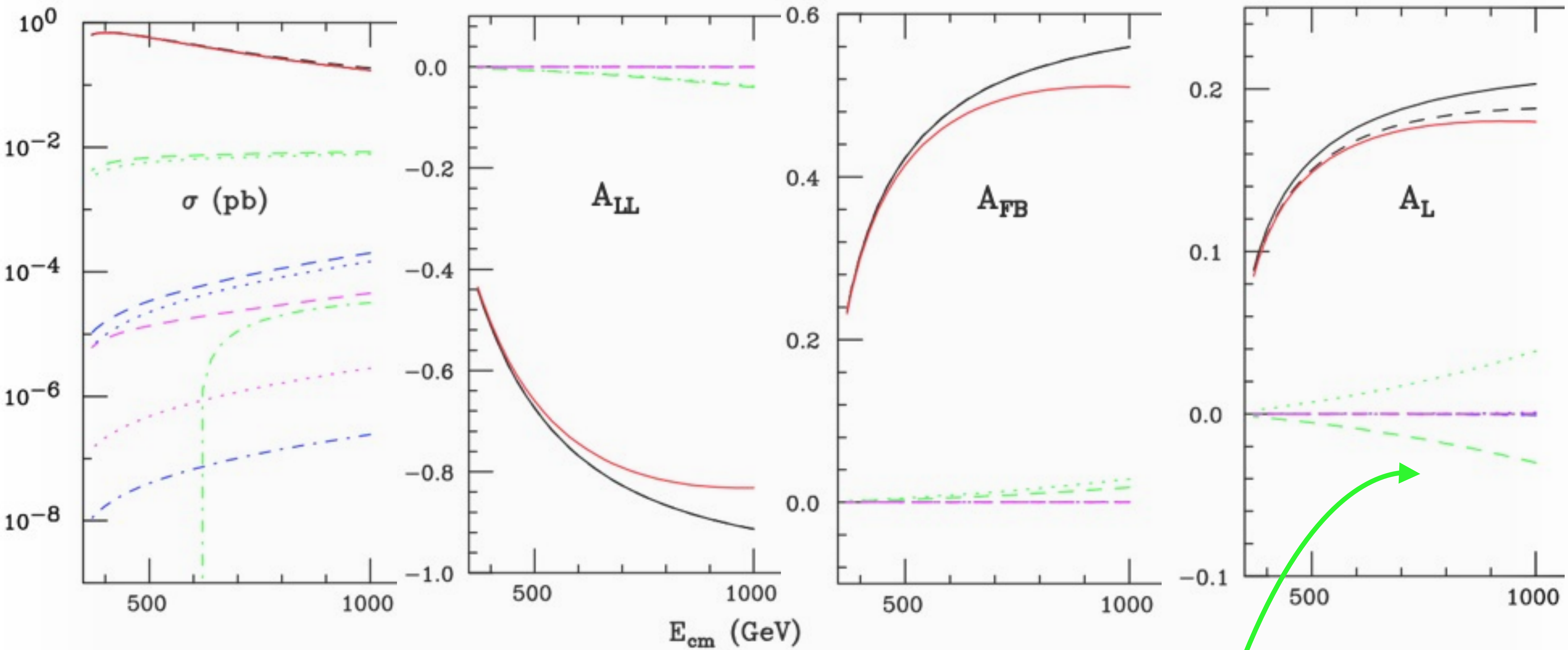




deviations of both signs @ 1000GeV mainly due to the SM-Z's interference

Disentangling the effects

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



solid: |SM|^2

dashed: |4DCHM|^2

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

dashed: Int(SM,Z2)

dotted: Int(SM,Z3)

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

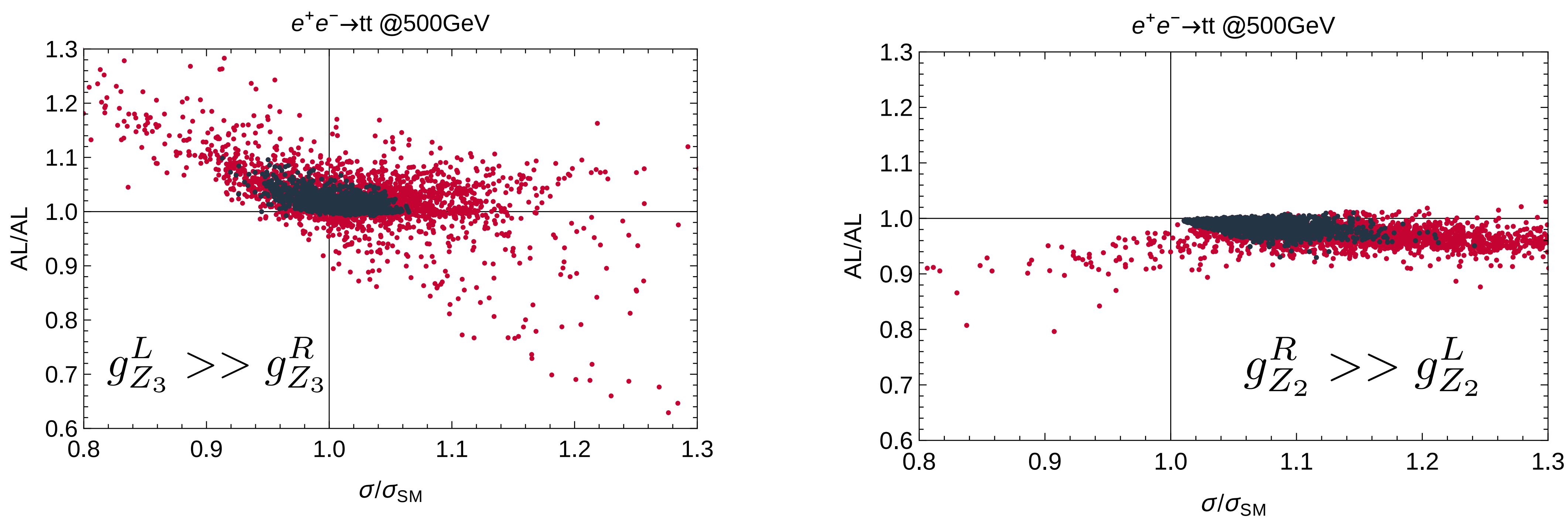
A_L is unique in offering the chance to separate Z_2 and Z_3 as they contribute in opposite directions

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)

the size of the deviations for pol. beams is roughly the same of the unpol.



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

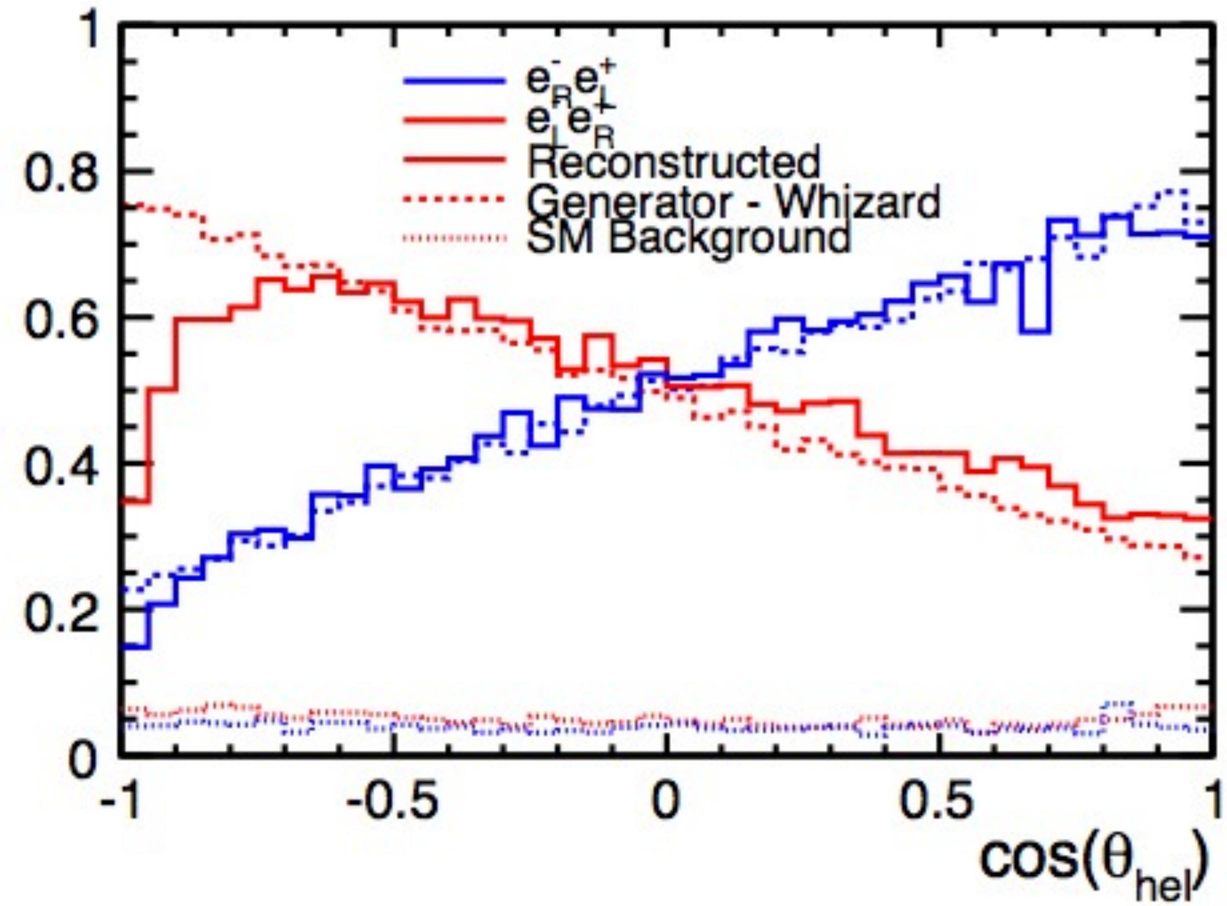
Z_2 and Z_3 interference have opposite signs. A_L is a good observable if e+e- beam polarization is available to deduce the presence of nearly degenerate resonances

Slope of the helicity angle distribution

Amjad et al. 1307.8102

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

The helicity angle distribution is used with the x-sect and A_{FB} to extract the top EW couplings. If NP is present, the slopes change



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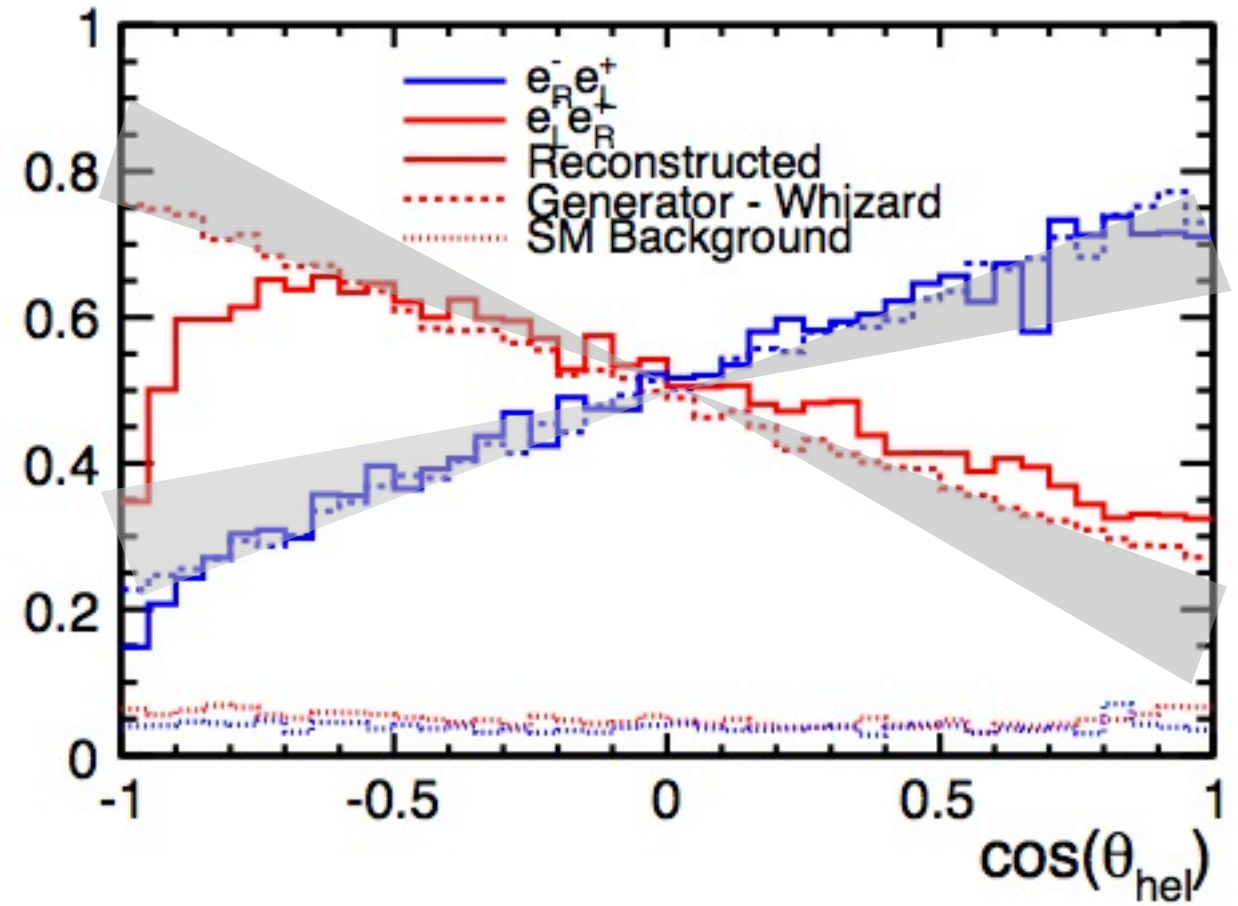

~50% deviations in A_L

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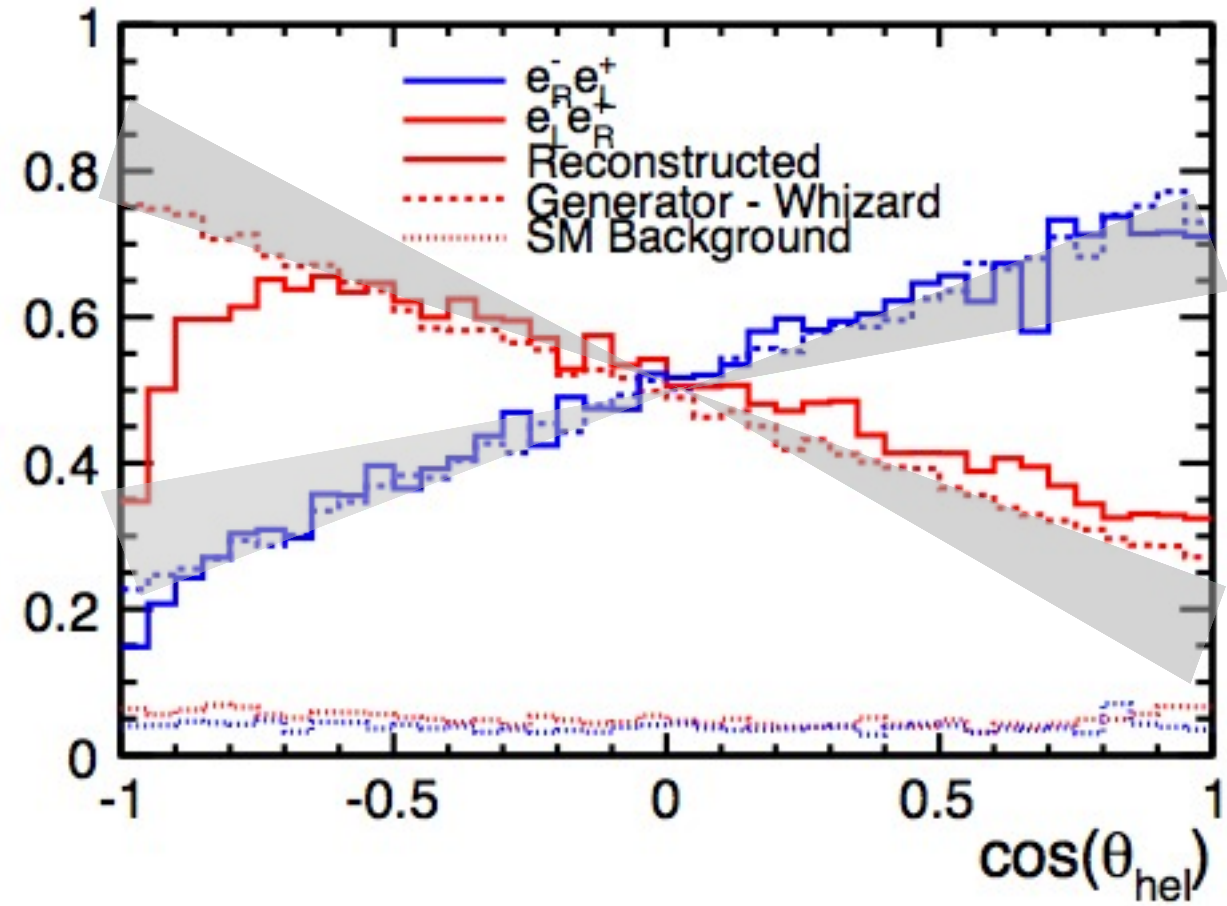


The helicity angle distribution is used with the x-sect and A_{FB} to extract the top EW couplings. If NP is present, the slopes change

~50% deviations in A_L

Warning: the deviations do not come only 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 testing indirectly the salient features of composite Higgs models

- 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 which could be accessible at LHC run2 (mainly DY processes). Other possible signatures: extra fermions (in the mass region accessible to LHC run2)

- If nothing is seen, or, better, if the LHC will give some evidence, e^+e^- machines will give 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

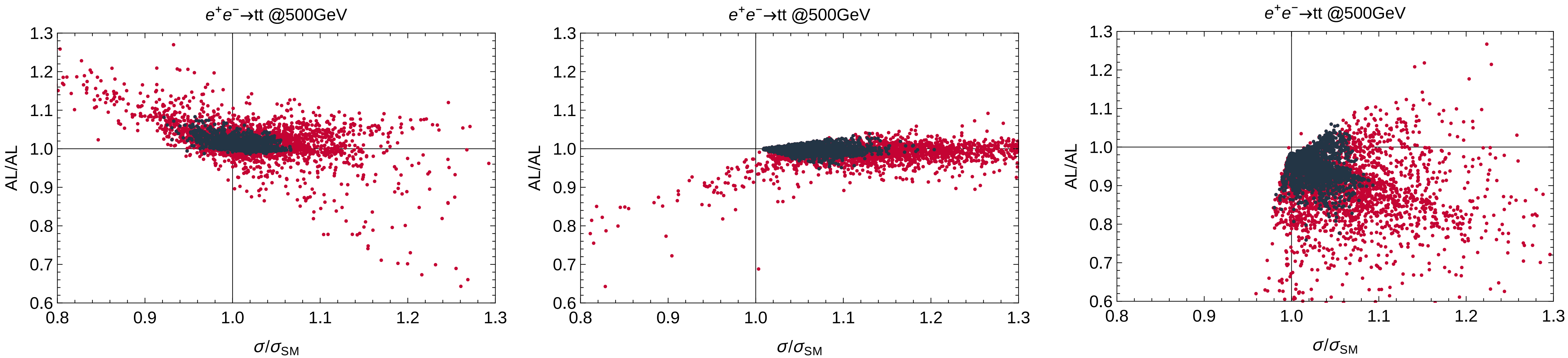
BACKUP SLIDES

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)

the size of the deviations for pol. beams is roughly the same of the unpol.



$\mathcal{P} = -0.8,\ \mathcal{P}' = +0.3$ $\mathcal{P} = +0.3,\ \mathcal{P}' = -0.8$ unpolarized beams

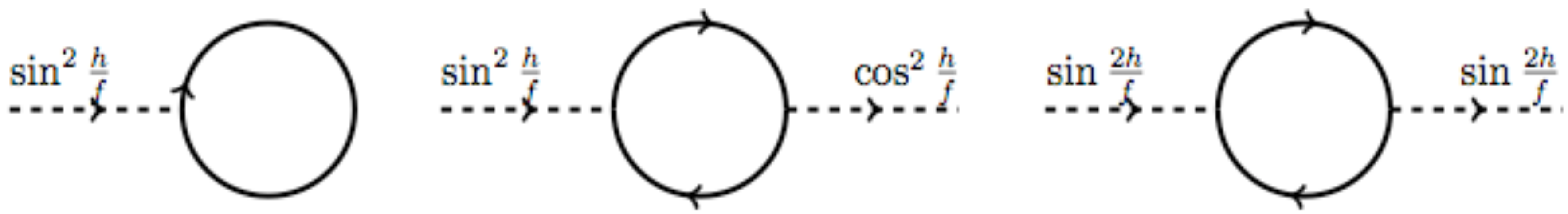
corrections to A_L depend from the sign of the SM-Z's interference top Yukawa coupling

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

Coleman-Weinberg effective potential generated at 1-loop

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

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

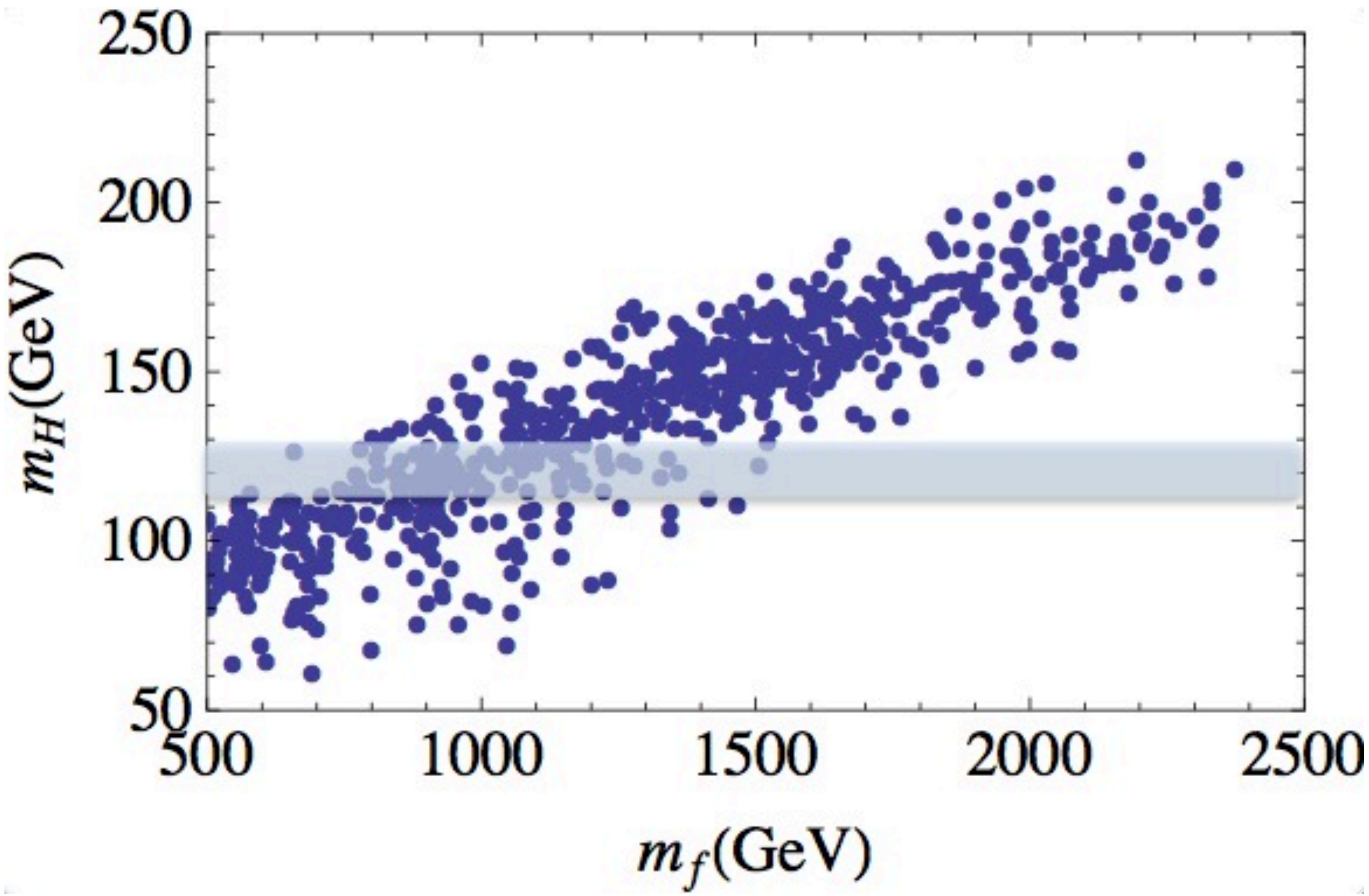


UV finite in the 4DCHM

Correlation with the lightest extra fermion mass

DC, Redi, Tesi '11

$f = 800$ GeV, $\xi \sim 0.1$



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

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

Z' and W' decay channels

Z' main branching ratios

SMALL WIDTH	LARGE WIDTH

SMALL WIDTH

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

LARGE WIDTH

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

mandatory for leptonic DY processes

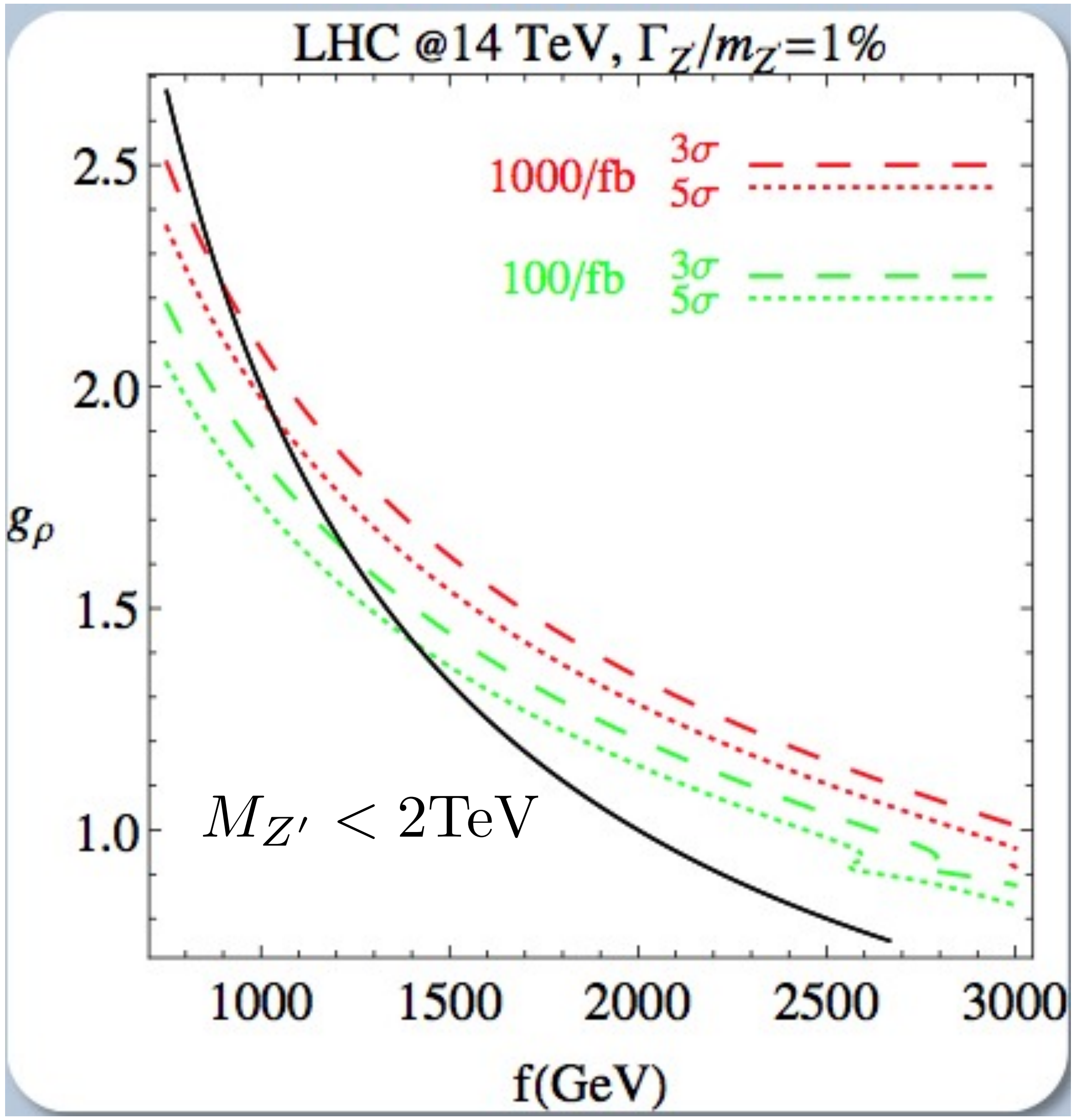
Analogous for the W'

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

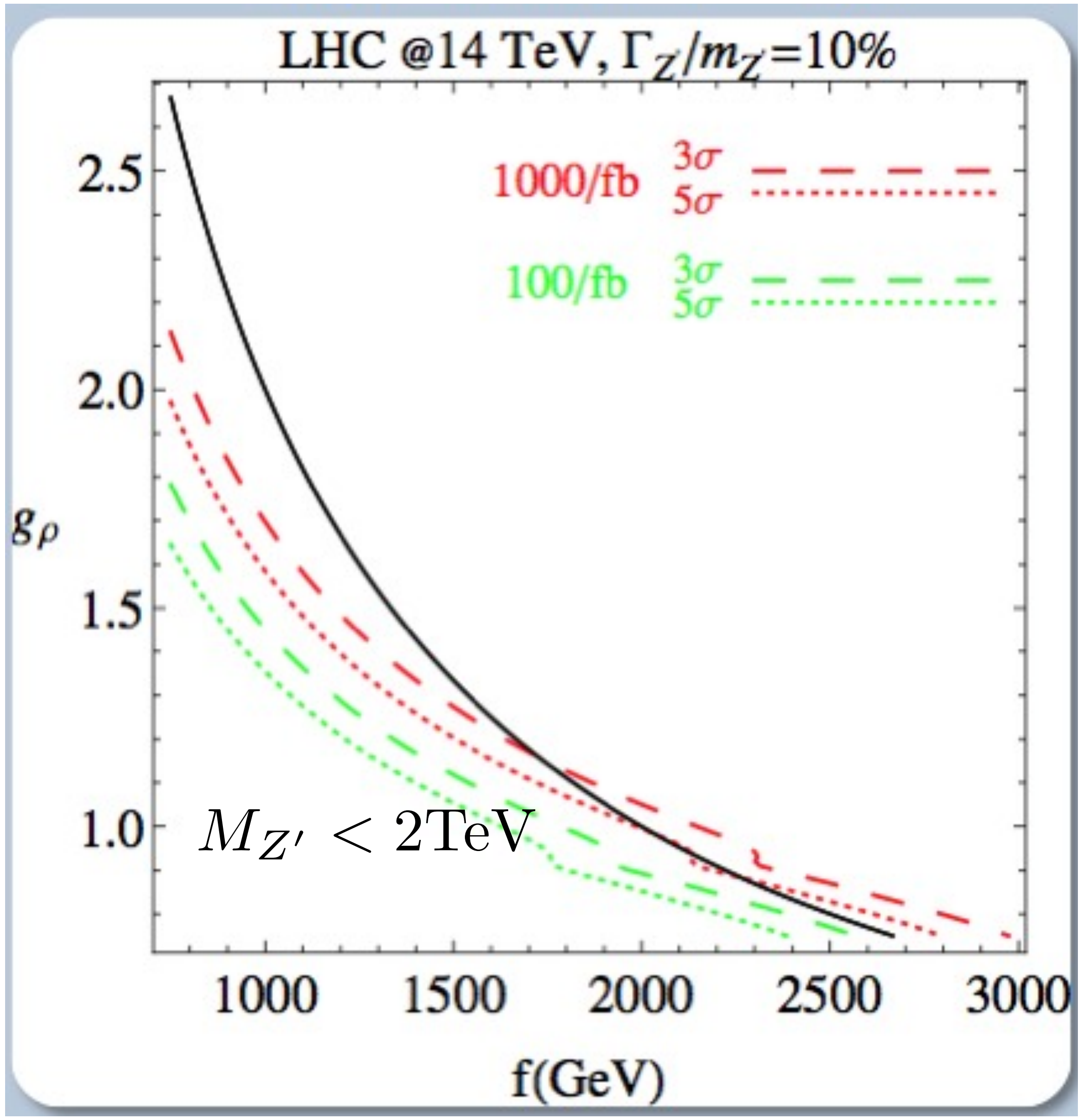
Calculating significance, neutral channel - 14 TeV LHC

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

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



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



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