Composite Higgs models and $t\bar{t}$ production at future e^+e^- colliders

Daniele Barducci

S. De Curtis, S. Moretti and G.M. Pruna

JHEP1402 005 and JHEP1508 127

LFC15: Physics Prospects for Linear and Other Future Colliders After the Discovery of the Higgs

ECT* Trento

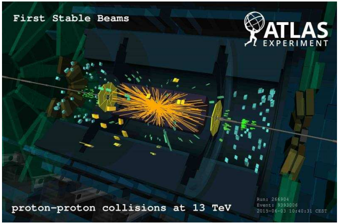
8th September 2015

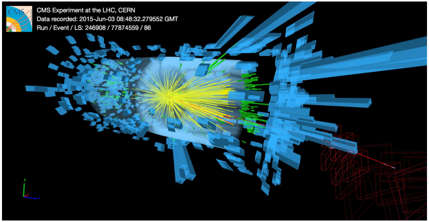
Outline

- Introduction
- The Higgs as a pseudo Goldstone Boson
- LHC signatures for a Composite Higgs
- Higgs and $t\bar{t}$ production at an e^+e^- collider
- Conclusions

Status of the LHC experiment

The LHC run-2 era just started with the first 13 TeV collisions





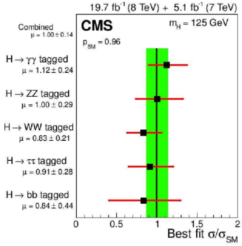
Clearly too soon for new results, but great expectations for LHC13

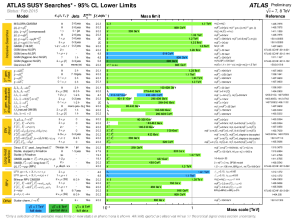
- Study of the properties of the Higgs boson and top quark
- Updates of existing (non)SUSY searches for physics BSM

Status of the LHC experiment

What did we learn from LHC run-1?

- A 125 GeV scalar has been discovered: (a)the Higgs boson
  - Its properties are compatible with the SM hypothesis
- No signs of (non)SUSY NP so far
  - Model dependent bounds on masses of extra states are $\sim$ TeV

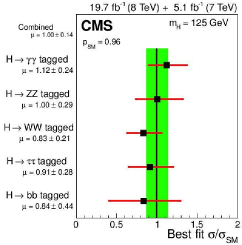


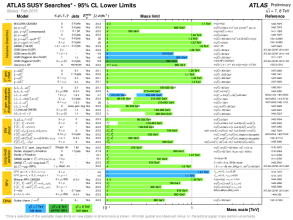


Status of the LHC experiment

What did we learn from LHC run-1?

- A 125 GeV scalar has been discovered: (a)the Higgs boson
  - Its properties are compatible with the SM hypothesis
- No signs of (non)SUSY NP so far
  - Model dependent bounds on masses of extra states are $\sim$ TeV



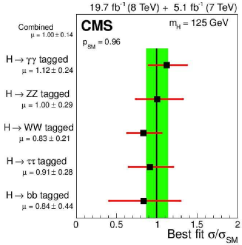


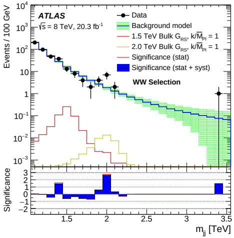
Some 2-3σ excesses observed: NP is behind the corner?

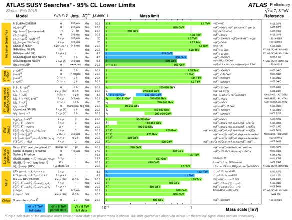
Status of the LHC experiment

What did we learn from LHC run-1?

- A 125 GeV scalar has been discovered: (a)the Higgs boson
  - Its properties are compatible with the SM hypothesis
- No signs of (non)SUSY NP so far
  - Model dependent bounds on masses of extra states are $\sim$ TeV







Some 2-3σ excesses observed: NP is behind the corner?

Status of the LHC experiment

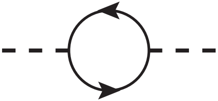
- If no new states will be seen at the LHC, precision measurements of Higgs and top quark properties can shed light to BSM physics
- These two particles are in fact the ones more intimately related to the mechanism of EWSB
- From this point of view an e^+e^- machine (ILC, CLIC, TLEP) has a great potential

Question: To which level of precision do we need to measure the Higgs and top quark couplings to probe the dynamics behind EWSB?

We will try to answer within a Composite Higgs scenario

The Higgs as a Composite pNGB

The instability of the Higgs mass under radiative corrections requires the protection by a symmetry


$\propto \Lambda^2$

The basic idea [Georgi and Kaplan '80s]

- Higgs as a bound state of a strongly interacting sector at a scale $f \gg v$
- A light Higgs can arise as a GB of a SSB $G \to H$ in the strong sector

The strong sector symmetry is then explicitly broken

- A radiative potential that can trigger EWSB is generated
- The Higgs acquires then a (small) mass

The most economical symmetry breaking is $SO(5) \to SO(4)$ [Agashe et. al '05s]

- 4 GBs, identifiable with the usual Higgs doublet
- Custodial symmetry for protection of the ρ parameter

The Higgs as a Composite pNGB

Besides the Higgs, the strong sector delivers other resonances

- Spin 1 states: heavy gluons and EW resonances (ρ^0 and $\rho^\pm$)
- Spin 1/2 states: top partners and exotic quarks

Discrete models describing the composite degrees of freedom that can be accessible at the LHC have been studied [Panico et. al '11, De Curtis et al. '11]

As a framework for our analysis we take the 4DCHM [De Curtis et al. 1110.1613]

- $SO(5) \to SO(4)$ breaking pattern for the Higgs boson
- $SO(5)_L \otimes SO(5)_R \to SO(5)_V$ for extra EW vector resonances
- Extra fermions embedded in $SO(5)$ multiplet, MCHM5 [Agashe et al. '05]
- For $\sim$ TeV scale top partners, $m_H \sim 125$ GeV

The 4DCHM

Lagrangian of the gauge sector

$$\mathcal{L} \supset \frac{f^2}{2}(D^\mu \Phi)^T (D_\mu \Phi) + \frac{f^2}{4} Tr[(D_\mu \Omega)^\dagger (D^\mu \Omega)] + \mathcal{L}_{\text{kin.}}$$

- $\Phi = e^{ih^a T^{\hat{a}}} \delta_{i5}$ $\Omega = e^{i\theta_a T^a}$ $T^{a,\hat{a}}$ H and G/H generators

Lagrangian of the fermionic sector

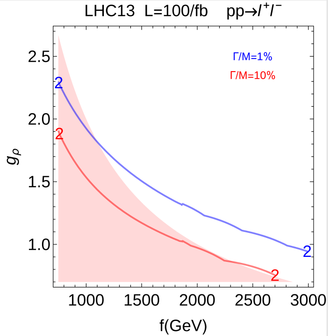
$$\begin{aligned}\mathcal{L} \supset\ & (\Delta_{t_L} \bar{q}_L^{el} \Omega \Psi_T + \Delta_{t_R} \bar{t}_R^{el} \Omega \Psi_{\tilde{T}} + h.c.) \\ & + \bar{\Psi}_{T,\tilde{T}} (i\not{D} - m_*) \Psi_{T,\tilde{T}} \\ & - (Y_T \bar{\Psi}_{T,L} \Phi^T \Phi \Psi_{\tilde{T},R} + m_{Y_T} \bar{\Psi}_{T,L} \Psi_{\tilde{T},R} + h.c.)\end{aligned}$$

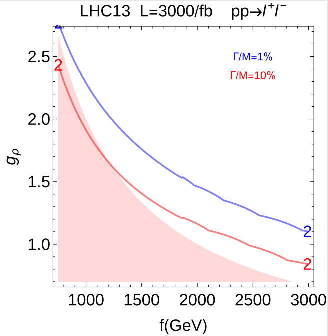
- $\Psi_{T,\tilde{T}}$ embedding of extra fermions

The 4DCHM at the LHC

ρ **resonances** | Top partners | Higgs sector

- Generally rather heavy, > 2 TeV, due to EWPTs
- Searched for in dilepton or diboson channels
  Possible explanation to the ATLAS excess? [Thamm et. al '15, Low et al. '15]
- Constrainable if narrow, that is no decays in top partners are open

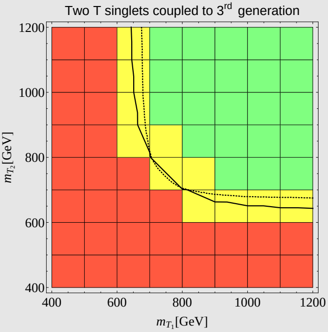


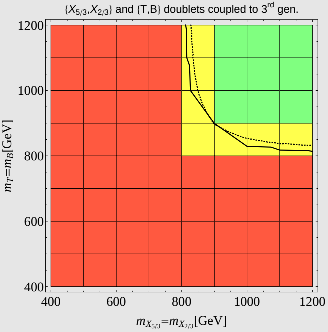


The 4DCHM at the LHC

ρ resonances | **Top partners** | Higgs sector

- For naturalness reason at the TeV scale
- Rich phenomenology, stronger constraints if an extended sector is present





- Bounds obtained with the program XQCAT

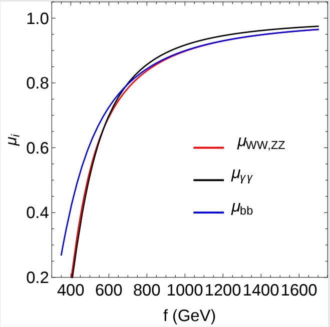
[DB et. al '14, https://launchpad.net/xqcat]

The 4DCHM at the LHC

ρ resonances | Top partners | **Higgs sector**

- Modification of the Higgs couplings

  $g_{ffH}/g_{ffH}^{SM} = (1-2\xi)/\sqrt{1-\xi}$ $\quad g_{VVH}/g_{VVH}^{SM} = \sqrt{1-\xi}$ $\quad \xi = v^2/f^2$
- Different rates for Higgs production and decay
- General reduction of the signal rates



After the LHC

- Suppose that the LHC will not measure large enough deviations in the Higgs couplings and does not discover any new particle...
- How can we disentangle the possibility of a Composite Higgs arising from strong dynamics?

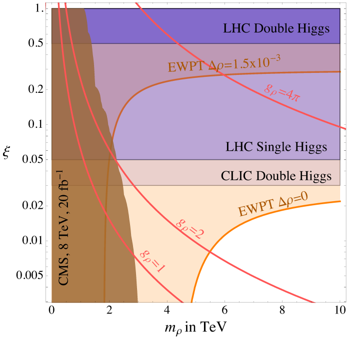
An electron-positron collider (clean environment for precision measurements) can help in detecting small deviations for Higgs and top production

Different prototypes of circular and linear machines have been proposed
ILC, CLIC, TLEP

We can test the Composite Higgs idea within a lepton collider environment

Composite Higgs at lepton colliders

Parametrisation of the Higgs couplings by means of an effective Lagrangian [Contino et al. '13]



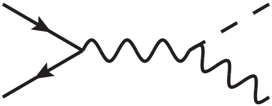
Expected sensitivities at

- LHC13 300/fb
- CLIC 3TeV 1/ab

High sensitivity expected on the composite scale $\Lambda = 4\pi f$, $\xi = v^2/f^2$

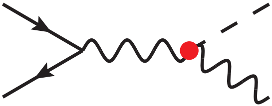
The details of the model however matter...!

Higgs production via Higgs-Strahlung and VBF



Sources of modifications

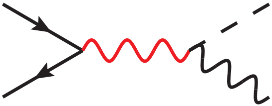
Higgs production via Higgs-Strahlung and VBF



Sources of modifications

- Higgs couplings modification, $\xi = v^2/f^2$
  - $g_{ffH}/g_{ffH}^{SM} = (1-2\xi)/\sqrt{1-\xi}$
  - $g_{VVH}/g_{VVH}^{SM} = \sqrt{1-\xi}$

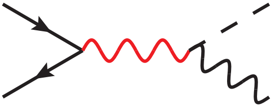
Higgs production via Higgs-Strahlung and VBF



Sources of modifications

- Higgs couplings modification, $\xi = v^2/f^2$
  - $g_{ffH}/g_{ffH}^{SM} = (1-2\xi)/\sqrt{1-\xi}$
  - $g_{VVH}/g_{VVH}^{SM} = \sqrt{1-\xi}$
- Extra states involved in the production processes

Higgs production via Higgs-Strahlung and VBF



Sources of modifications

- Higgs couplings modification, $\xi = v^2/f^2$
  - $g_{ffH}/g_{ffH}^{SM} = (1-2\xi)/\sqrt{1-\xi}$
  - $g_{VVH}/g_{VVH}^{SM} = \sqrt{1-\xi}$
- Extra states involved in the production processes

We can study the production rates

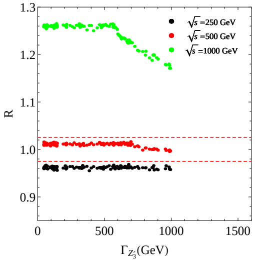
$$\mu_{YY} = \frac{\sigma_{ee\to H} \cdot Br_{H\to YY}}{\sigma_{ee\to H}^{SM} \cdot Br_{H\to YY}^{SM}}$$

Higgs production via Higgs-Strahlung and VBF

Lets analyse the inclusive ZH production cross section

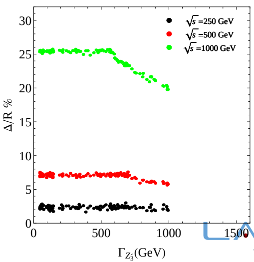
$$R = \sigma/\sigma^{\mathrm{SM}}$$
$$\Delta = R - (g_{ZZH}/g_{ZZH}^{\mathrm{SM}})^2$$

- Deviations from the decoupling limit, no ρs exchanged, can be sizeable even for small $\sqrt{s}$
- Dependence with the ρs widths, indication of interference effects



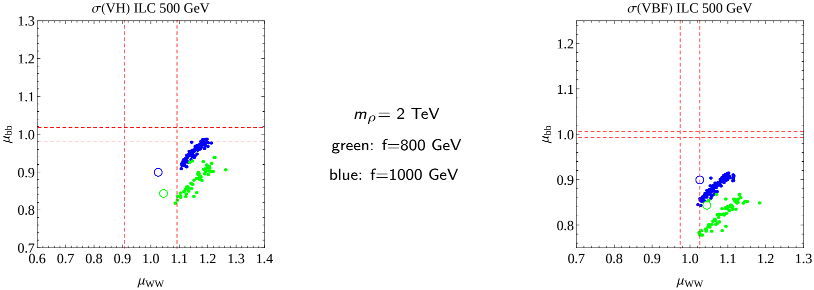
f=1000 GeV

$M_\rho = 2$ TeV



Higgs production via Higgs-Strahlung and VBF

Rates for an e^+e^- collider with $\sqrt{s} = 500$ GeV



$m_\rho = 2$ TeV

green: f=800 GeV

blue: f=1000 GeV

- Circles represent the decoupling limit
- Expected accuracies on μ's from ILC TDR [1306.6352, 1310.0763, 1310.8361]
- Effects of ρ^0 and $\rho^\pm$ extremely important
- Feature common to other processes and $\sqrt{s}$ options

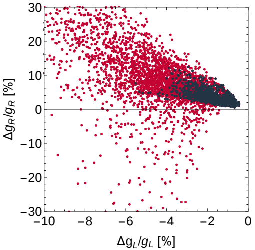
Top pair production

- In CHMs the top quark can have a high composite component
- Beside the Higgs couplings, also the EW $Zt\bar{t}$ coupling can be modified

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

SM tree level: $F_{1A}^\gamma = F_2^X = 0 \quad F_{1V}^\gamma = 2/3 \quad F_{1V}^Z = 1/(4s_\omega c_\omega)(1-8/3s_\omega^2) \quad F_{1A}^Z = 1/(4s_\omega c_\omega)$

$0.75 < f < 1.5$ TeV $\quad 1.5 < g_\rho < 3$



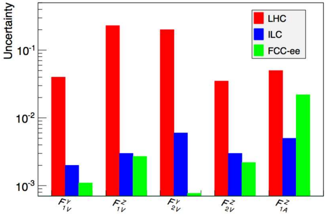
$g_{L,R} = e(F_{1A}^Z \mp F_{1V}^Z) \qquad \Delta g/g = (g - g^{\rm SM})/g^{\rm SM}$

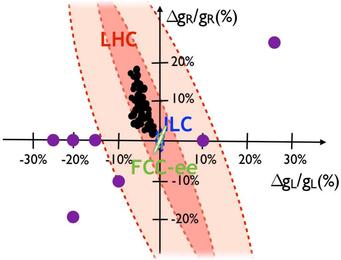
Purple points: $m_\rho > 2$ TeV, $m_T > 1$ TeV
Compliant with EWPTs bounds [Grojean et al. '13]

Max deviations -8/+20% on g_L/g_R

Top pair production

How well can these couplings be measured?





LHC $\sim$ 10% (5%)

ILC $<$ 1%, pol. beams [ILC TDR, Amjad]

TLEP $<$ 1% [from Janot '15]

Different BSM scenario [Richard, '14]

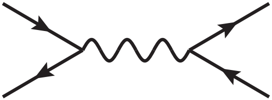
Black points 4DCHM

Blue ILC, Green TLEP [Courtesy of Janot]

QCD corrections under control, EW corrections need further work
Systematics need to be controlled at the % level

Top pair production

We will study $e^+e^- \to t\bar{t}$ for three $\sqrt{s}$ options: 370, 500 and 1000 GeV



Again, three source of modifications to SM processes

- Modification of the Ze^+e^- coupling (negligible)
- Modification of $Zt\bar{t}$ coupling (partial compositness and Z-ρ mixing)
- s-channel exchange of ρ resonances

Total cross section: $\sigma(e^+e^- \to t\bar{t})$
Forward-Backward asymmetry: A_{FB}
Single and double spin asymmetries, A_L and A_{LL}

QCD and EW corrections not included

ISR and Beamstrahlung studied but not important when analysing $\mathcal{O}/\mathcal{O}_{SM}$

Top pair production

$t\bar{t}$ observables

- Total cross section: $e^+e^- \to t\bar{t}$
- $A_{FB} = \frac{N(\cos\theta^*>0)-N(\cos\theta^*<0)}{N(\cos\theta^*>0)+N(\cos\theta^*>0)}$
- $A_{LL} = \frac{N(++)+N(--)-N(+-)-N(-+)}{N_{\rm tot}}$
- $A_L = \frac{N(--)+N(-+)-N(++)-N(+-)}{N_{\rm tot}}$

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

For spin asymmetries, leptons from top decays used as spin analysers [Khiem, '15]

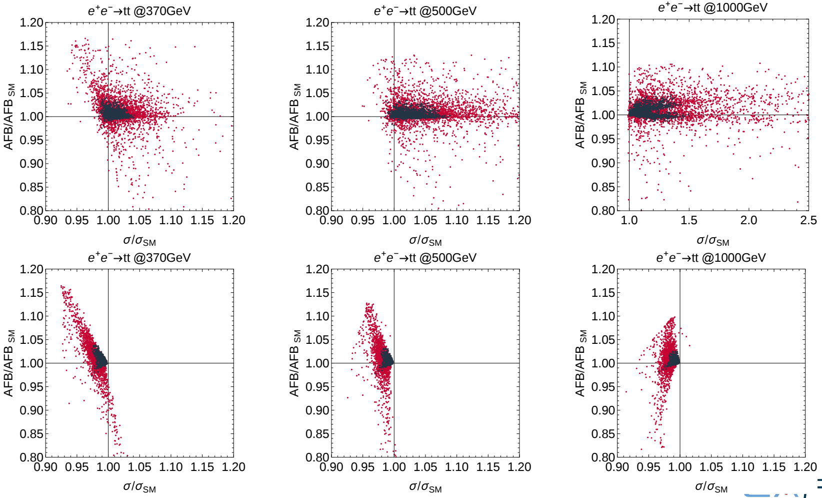
A_L is sensitive to the *r*elative sign of the g_V and g_A couplings of Z and ρs to $t\bar{t}$

Observables defined over the entire $t\bar{t}$ mass spectrum

Codes used based on helicity amplitudes, HELAS, and CalcHEP

Top pair production

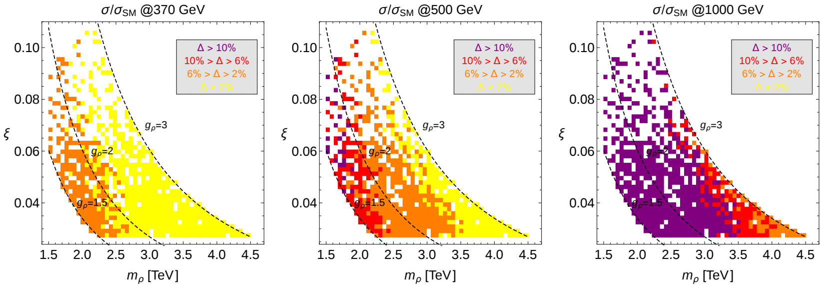
σ and $A_{\rm FB}$ for $\sqrt{s} = 370$, 500 and 1000 GeV, with and without ρs exchange



The presence of the ρs plays a crucial role, even for moderate $\sqrt{s}$ energies

Top pair production

Bound on the composite scale and resonance mass: map in the m_ρ-ξ plane



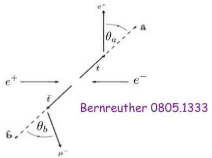
$m_\rho \sim f g_\rho \qquad \xi = v^2/f^2 \qquad \Delta = (\sigma - \sigma^{\rm SM})/\sigma^{\rm SM}$

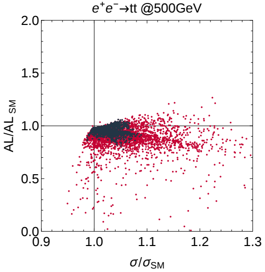
- For each value of m_ρ and ξ we selected the point with maximum Δ
- With a few % uncertainties on σ, sensitivity up to m_ρ=3.5 TeV with $\sqrt{s} = 500$ GeV

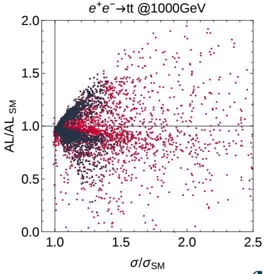
Top pair production

Single spin asymmetry A_L related to the slope of the elicity angle distribution

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



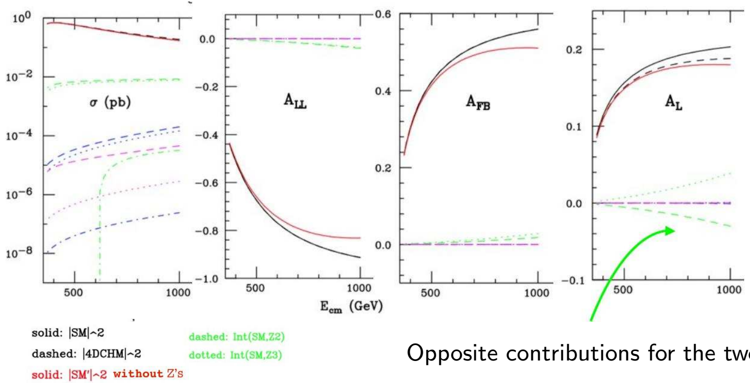




Large deviations of both signs for $\sqrt{s}$=1000 GeV

Top pair production

Disentangling the different contributions in the 4DCHM



Opposite contributions for the two ρs

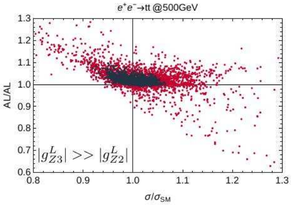
A_L can separate two ρs that contribute with opposite signs (beam polarization)

Top pair production

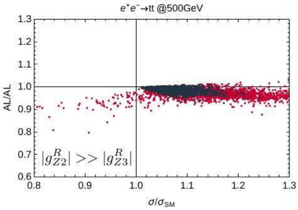
The case of polarized electron beams

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

$\sigma_{-+} = \sigma(e_L^- e_R^+)$ $\mathcal{P}(\mathcal{P}')$ pol. degree for $e^-(e^+)$



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



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

A_L can help to deduce the presence of nearly degenerate resonances

Conclusions

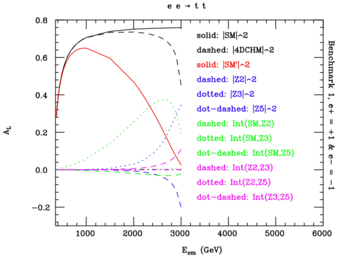
- Models with a Composite Higgs are a compelling alternative to SUSY theories
- Composite scenario with a full particle spectra (ρs, top partners...) can be built
- The 4DCHM embeds the main characteristics of a CHM with partial compositeness
- If nothing is seen at the LHC, or, better, if new states are discovered, e^+e^- machines have the opportunity to test CHMs through precision measurements of Higgs and top couplings
- Interference effects of the new resonances could be crucial and must be taken into account to extract the sensitivities to CHMs

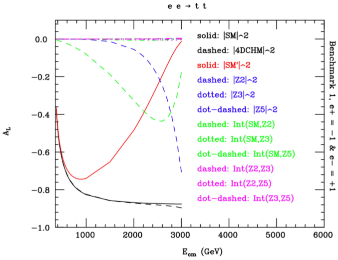
Thank you!

Backup slides

Polarized beams

- $\mathcal{P} = -1$, $\mathcal{P}' = 1$ (left)
- $\mathcal{P} = 1$, $\mathcal{P}' = -1$ (right)





Positive contribution from SM-ρ_L^0 interference

Negative contribution from SM-ρ_R^0 interference

$$g^L_{\rho^0_L} \gg g^R_{\rho^0_L} \qquad g^R_{\rho^0_R} \gg g^L_{\rho^0_R}$$

Backup slides