Alternative Theories at the Weak Scale

CLIC Conceptual Design Report

WG1 - CLIC Physics Potential

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(and with M. Battaglia, F. Coradeschi, S. Rienmann)

Motivations of our study

- Identify physics cases where CLIC can do better than LHC & ILC
  - better =
    - find new particles,
    - be sensitive to new dynamics,
    - measure new couplings.
  - don't aim to be exhaustive.
  - concentrate on models with strong dynamics
    (since they were not covered in previous studies).

- Two directions
  - models of strong EW symmetry breaking:
    - look at strong dynamics of WL, *in progress*
    - look at strong dynamics of the Higgs boson, ➲
    - discrete symmetries of strong sector. ➲
  - search for heavy resonances. ➲ *initial stage*

Higgs as a PGB

One solution to the hierarchy pb:
Higgs transforms non-linearly under some global symmetry

Higgs=Pseudo-Goldstone boson (PGB)

$SO(4)/SO(3) \Rightarrow G/H$ spontaneous breaking by strong dynamics

Examples: SO(5)/SO(4): 4 PGBs=$W^{\pm}_L$, Z_L, h ↔ Minimal Composite Higgs Model

SO(6)/SO(5): 5 PGBs=H, a ↔ Next MCHM

3 scales:

UV completion

$4\pi f$ — 10 TeV

$m_\rho = g_\rho f$ — usual resonances of the strong sector } not directly accessible to LHC

v — 246 GeV Higgs = light resonance of the strong sector ⇒ indirect probes

Continuous interpolation between SM and TC

$$\xi = \frac{v^2}{f^2} = \frac{(\text{weak scale})^2}{(\text{strong coupling scale})^2}$$

$\xi = 0$

SM limit

all resonances of strong sector, except the Higgs, decouple

$\xi = 1$

Technicolor limit

Higgs decouple from SM; vector resonances like in TC

General couplings of a composite Higgs

A single scalar degree of freedom neutral under $SU(2)_L \times SU(2)_R/SU(2)_V$

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + b_3\frac{h^3}{v^3} + \dots\right) - \lambda \bar{\psi}_L \Sigma \psi_R \left(1 + c\frac{h}{v} + c_2\frac{h^2}{v^2} + \dots\right)$$

$$V(h) = \frac{1}{2}m_h^2 h^2 + d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \dots$$

- SM: $a=b=c=d_3=d_4=1$ & $b_3=c_2=0$
- coset model: all these parameters are simple functions of ξ

  for instance: SO(5)/SO(4):

$$a = \sqrt{1-\xi} \qquad c = \left(\sqrt{1-\xi}, \frac{1-2\xi}{\sqrt{1-\xi}}\right) \qquad d_3 = \sqrt{1-\xi}$$

$$b = 1 - 2\xi$$

$$b_3 = -\frac{4}{3}\xi\sqrt{1-\xi} \qquad c_2 = -(\xi, 4\xi) \qquad d_4 = \left(1 - \frac{7}{3}\xi, \frac{1 - 28/3\xi(1-\xi)}{1-\xi}\right)$$

$\Sigma = e^{i\sigma^a \pi^a / v}$

Goldstone of $SU(2)_L \times SU(2)_R/SU(2)_V$

$D_\mu \Sigma \approx W_\mu$

LHC (to a certain extent) and ILC are "good" in measuring Higgs anomalous couplings, ie 'a' and 'c' in general or ξ if the coset structure is already established, but no (or very limited) access to strong dynamics

CLIC can improve these measurements *Abdelhak and Andre's talks*

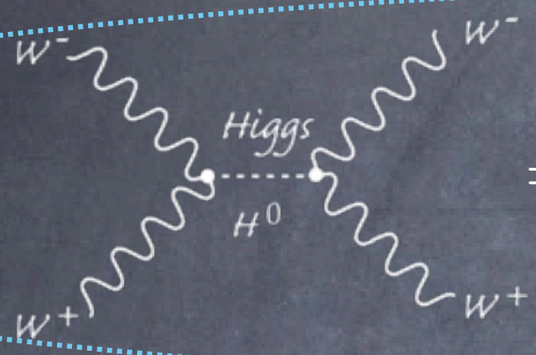
but we want to look at qualitatively different processes!

Strong dynamics in the Higgs sector

Strong EW symmetry breaking

WW → WW: strong interactions of W_L

Giudice, Grojean, Pomarol, Rattazzi '07



$$= -(1-\xi) g^2 \frac{E^2}{M_W^2}$$

no exact cancellation
of the growing amplitudes

$$\mathcal{A}\left(W_L^a W_L^b \to W_L^c W_L^d\right) = \mathcal{A}(s,t,u)\delta^{ab}\delta^{cd} + \mathcal{A}(t,s,u)\delta^{ac}\delta^{bd} + \mathcal{A}(u,t,s)\delta^{ad}\delta^{bc} \qquad \mathcal{A} = \left(1 - a\right)\frac{s}{v}$$

Marginal sensitivity at LHC but need large L
and not competitive with the measurement of 'a' via anomalous couplings

WW → 2h: strong interactions of h

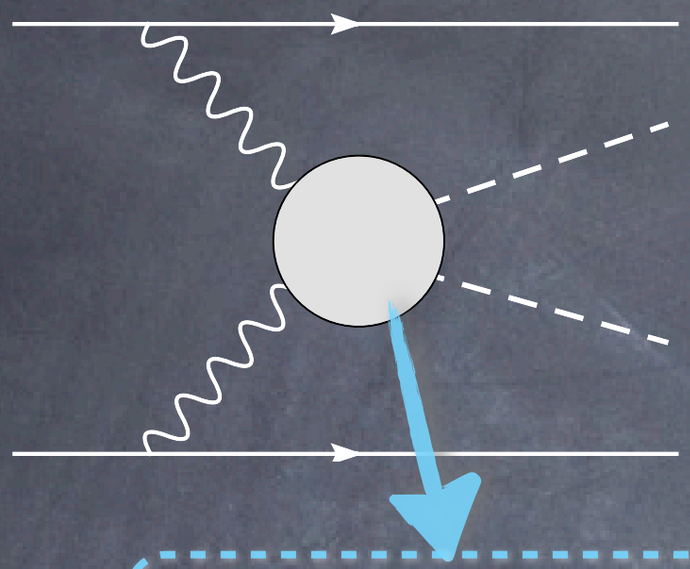
Contino, Grojean, Moretti, Piccinini, Rattazzi '10

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to hh\right) = \mathcal{A}\left(W_L^+ W_L^- \to hh\right) = \left(b - a^2\right)\frac{s}{v^2}$$

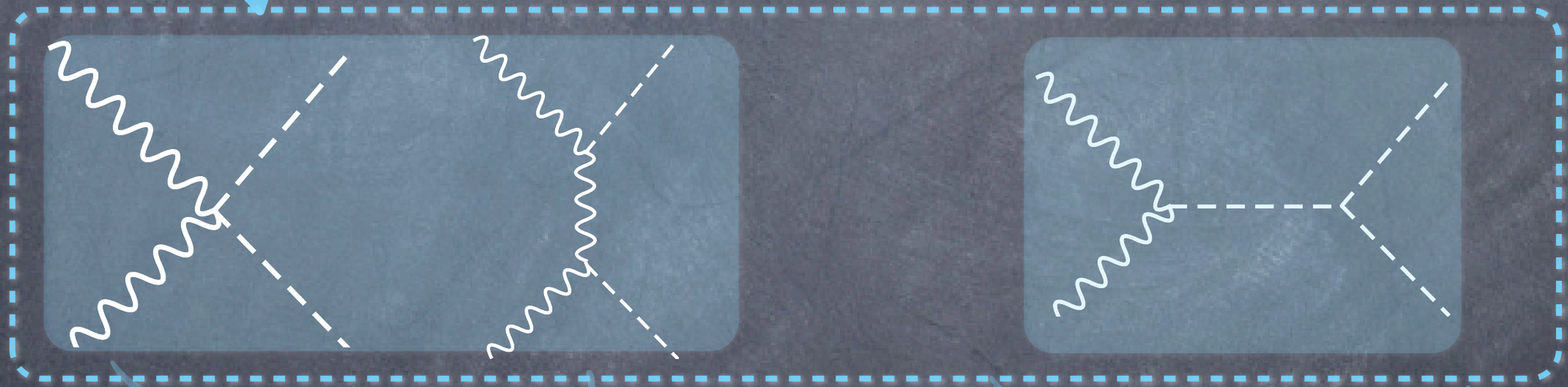
CLIC has access to a new interaction, 'b', almost totally hidden at LHC and ILC

distinction between 'active' (higgs) and 'passive' (dilaton) scalar in EWSB dynamics

WW → 2h: 'b' and 'd_3'



$$V(h) = \frac{1}{2} m_h^2 h^2 + d_3 \frac{1}{6} \left(\frac{3m_h^2}{v}\right) h^3 + d_4 \frac{1}{24} \left(\frac{3m_h^2}{v^2}\right) h^4 + \dots$$



$$\mathcal{A} \underset{m_{hh}^2 \gg m_W^2}{\sim} \left(b - a^2\right) \frac{4m_{hh}^2}{v^2}$$

asymptotic behavior
sensitive to strong interaction

$$\mathcal{A} \underset{m_{hh}^2 \sim 4m_h^2}{\sim} \text{cst.} + 3ad_3 \frac{m_h^2}{v^2}$$

threshold effect
'anomalous coupling'

WW → 2h @ CLIC

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm 'in progress

$$\frac{d\sigma/dX}{d\sigma_{SM}/dX} = a^4\left(1+\kappa_1\,\delta b+\kappa_2\,\delta d_3+\kappa_3\,\delta b^2+\kappa_4\,\delta {d_3}^2+\kappa_5\,\delta b\times\delta d_3\right)$$

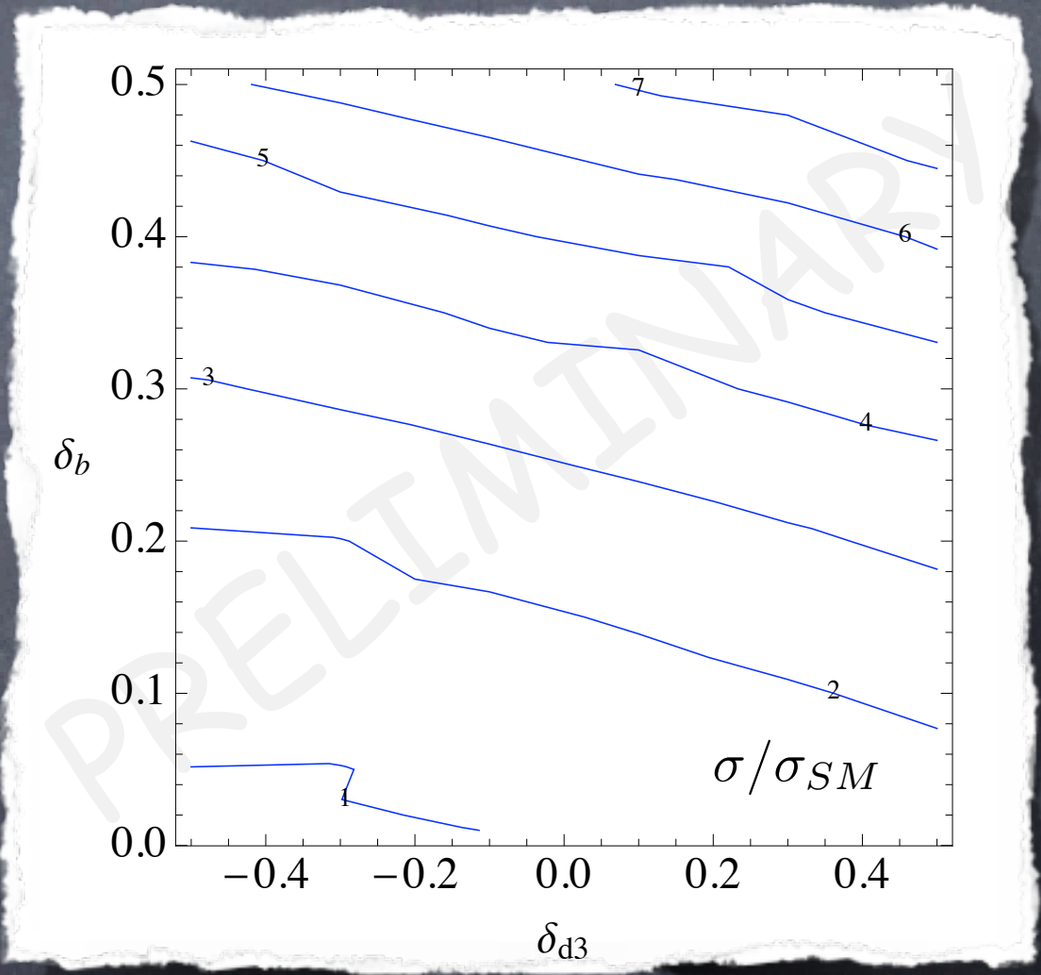
$$\delta b = 1-b/a^2 \qquad \delta d_3 = 1-d_3/a$$

Total cross section

e.g., Barger et al. hep-ph/0301097

cannot break the degeneracy between 'b' and 'd_3'

- distribution at large m_{hh}^2 → δb
- distribution near threshold → δd_3



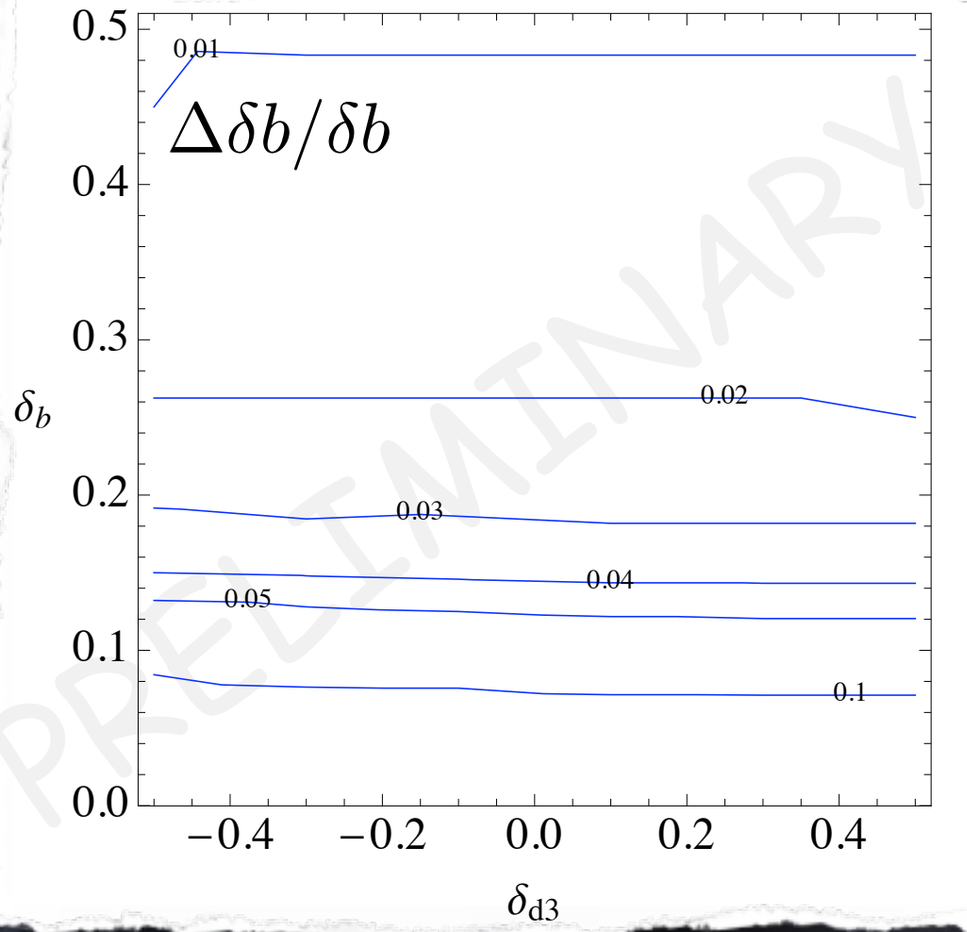
CLIC @3TeV

WW → 2h @ CLIC

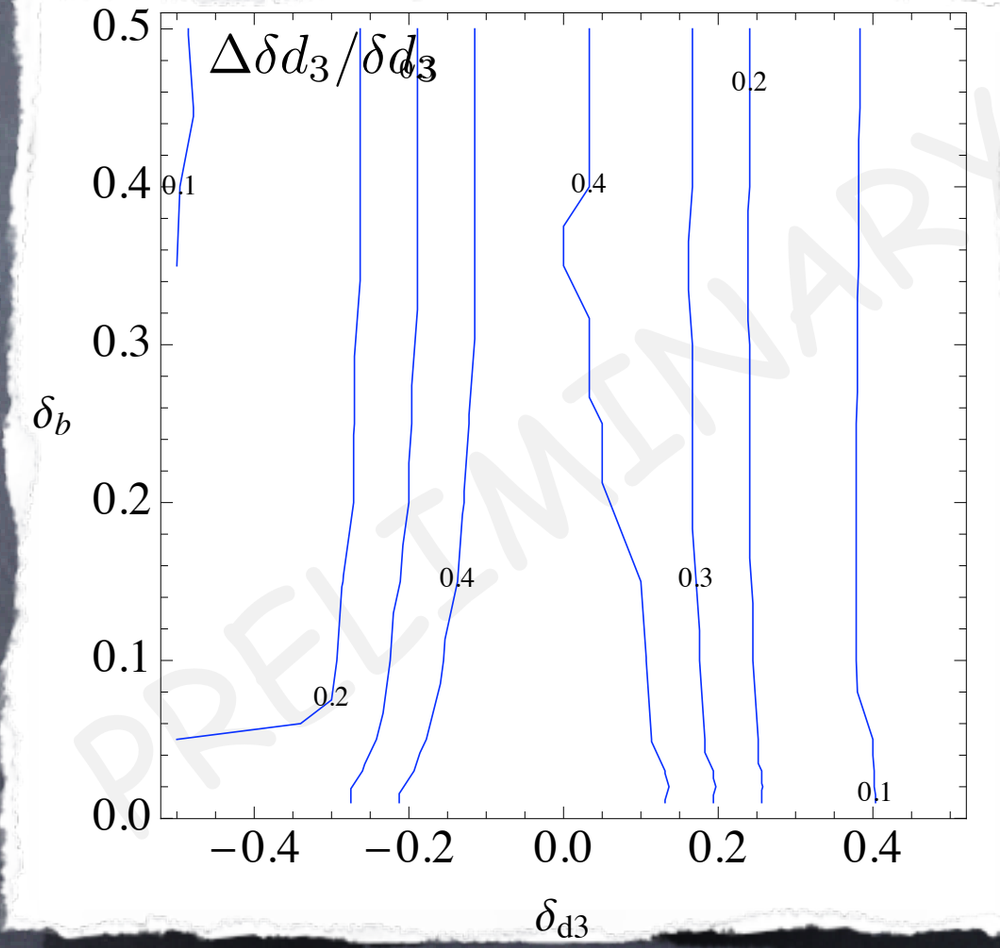
Contino, Grojean, Pappadopoulo, Rattazzi, Thamm 'in progress

$$\frac{d\sigma/dX}{d\sigma_{SM}/dX} = a^4\left(1+\kappa_1\,\delta b+\kappa_2\,\delta d_3+\kappa_3\,\delta b^2+\kappa_4\,\delta {d_3}^2+\kappa_5\,\delta b\times\delta d_3\right)$$

$$\delta b = 1 - b/a^2 \qquad \delta d_3 = 1 - d_3/a$$



CLIC @3TeV, 1ab^{-1}
δb sensitivity



CLIC @3TeV, 1ab^{-1}
δd$_3$ sensitivity

WW → 2h: CLIC vs. ILC

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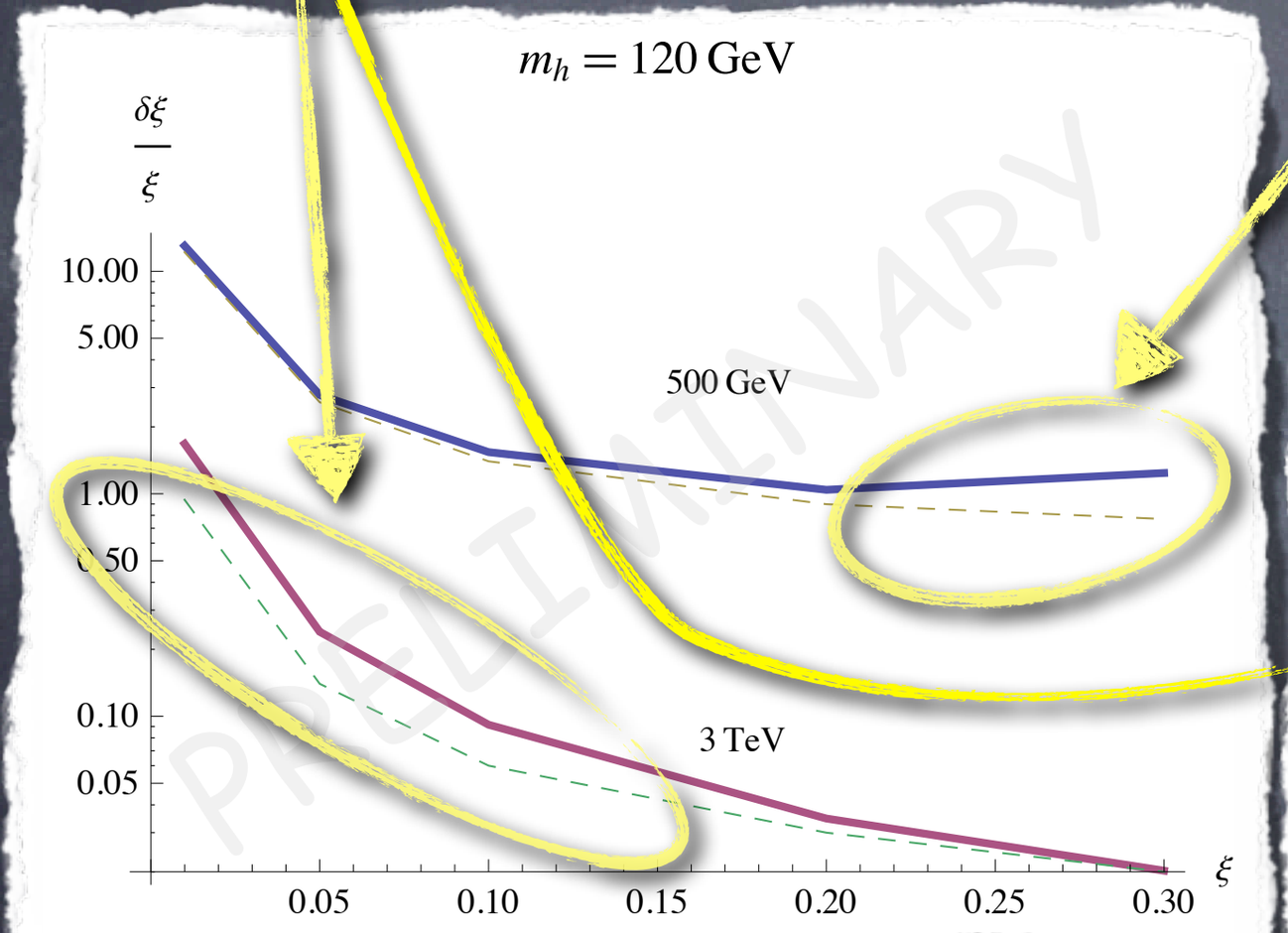
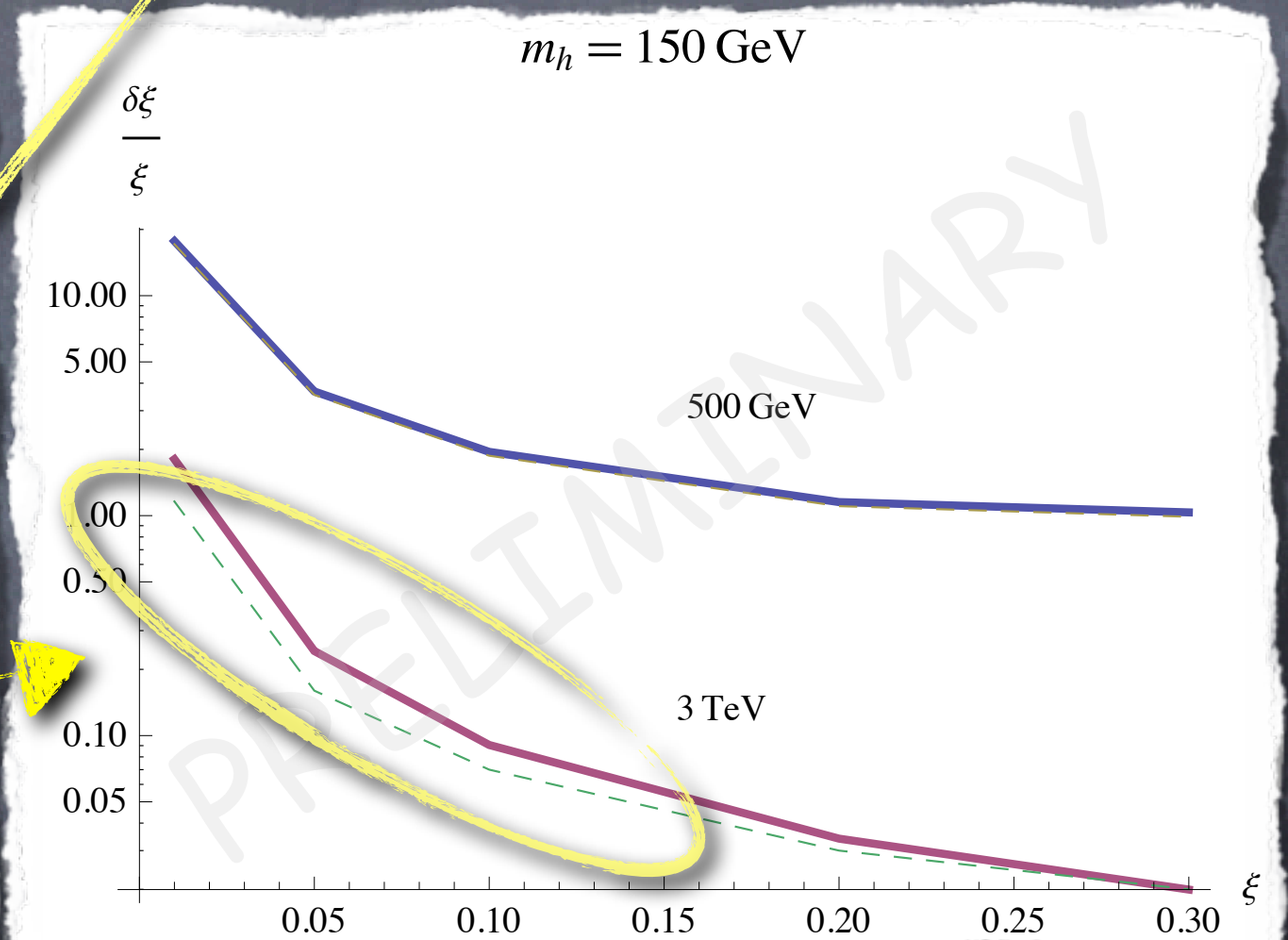
large E

large ξ ie very strong dynamics





distinguishes between strong dynamics and anomalous couplings

——— without kinematical cut on m_{hh}^2

----- with kinematical cut on m_{hh}^2

$L=1ab^{-1}$

Symmetries of the strong dynamics

$W^+W^- \to 3h, Zhh, WWh, WWZ$

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm 'in progress

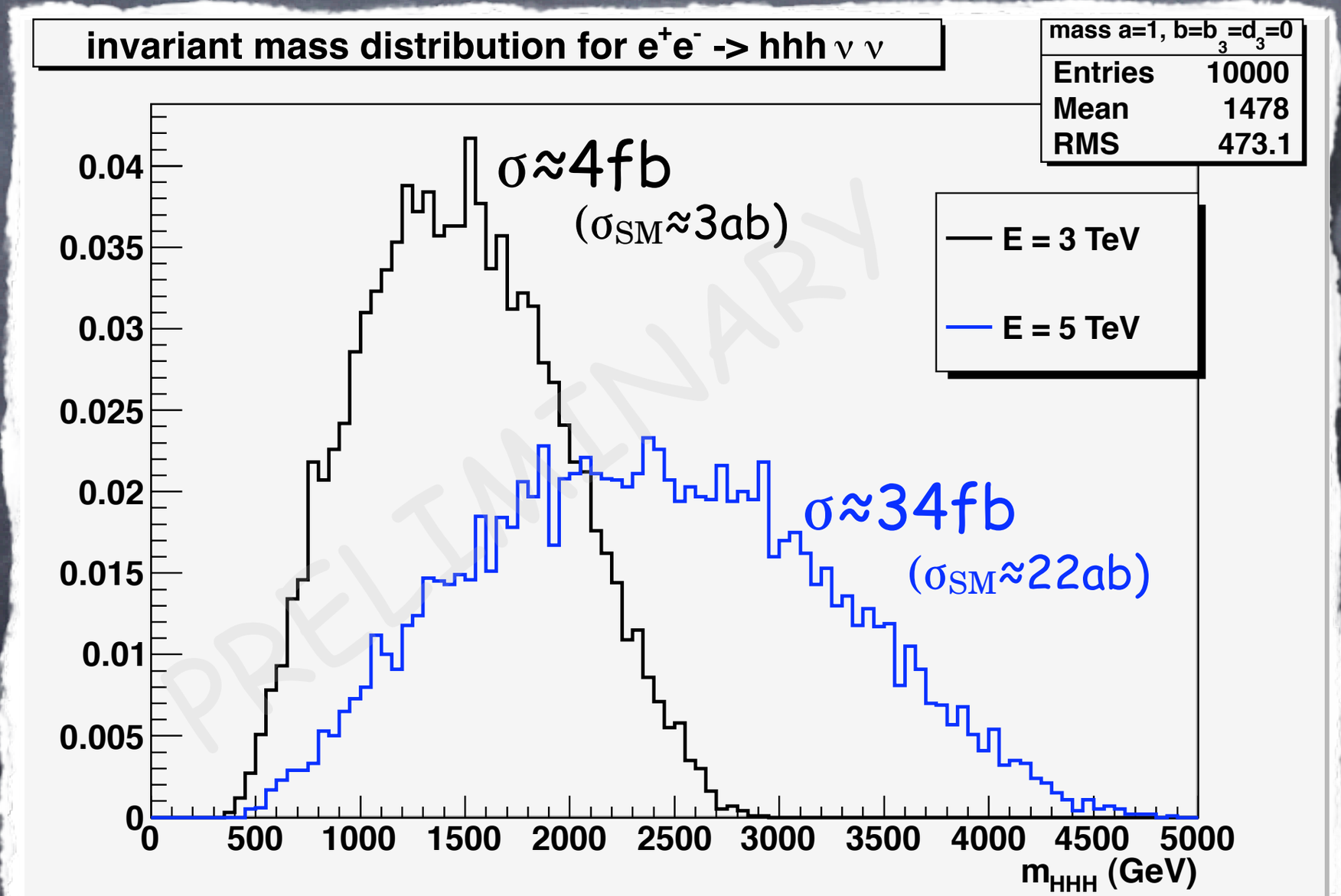
Strong EWSB

$$\sigma_{2\pi\to 3\pi} \sim \frac{1}{8\pi}\frac{E^2}{f^4}\frac{E^2}{(4\pi f)^2}$$

$E/f \leftrightarrow g$

SM

$$\sigma_{2\to 3} \sim \frac{1}{8\pi}\frac{g^2}{v^2}\frac{g^2}{16\pi^2}$$



$W^+W^- \to 3h, Zhh, WWh, WWZ$

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm 'in progress

Probe of possible discrete symmetries in the strong dynamics

G/H symmetric space ⇒ invariance under $\pi \to -\pi$

a process with an odd # of PGBs

requires a coupling breaking the coset structure
ie cannot be mediated by strong interactions alone

$$\mathcal{A}_{WW\to 3h} \sim 4i\frac{s}{v^3}\underbrace{\left(a(b-a^2)-\frac{3}{4}b_3\right)}_{=0 \text{ for symmetric coset}} + \not\sharp\, s \times \underbrace{\left(\frac{m_W}{\sqrt{s}}\right)^2}_{\text{mediated by gauge interactions (breaking of coset structure)}}$$

$W^+W^- \to 3h, Zhh, WWh, WWZ$

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm 'in progress

	3h	Zhh	WWh	WWZ
$\pi \to -\pi$	-	-	-	-
$W_L \to -W_L$ $h \to h$	-	✓	-	✓
$W_L \to W_L$ $h \to -h$	✓	-	✓	-

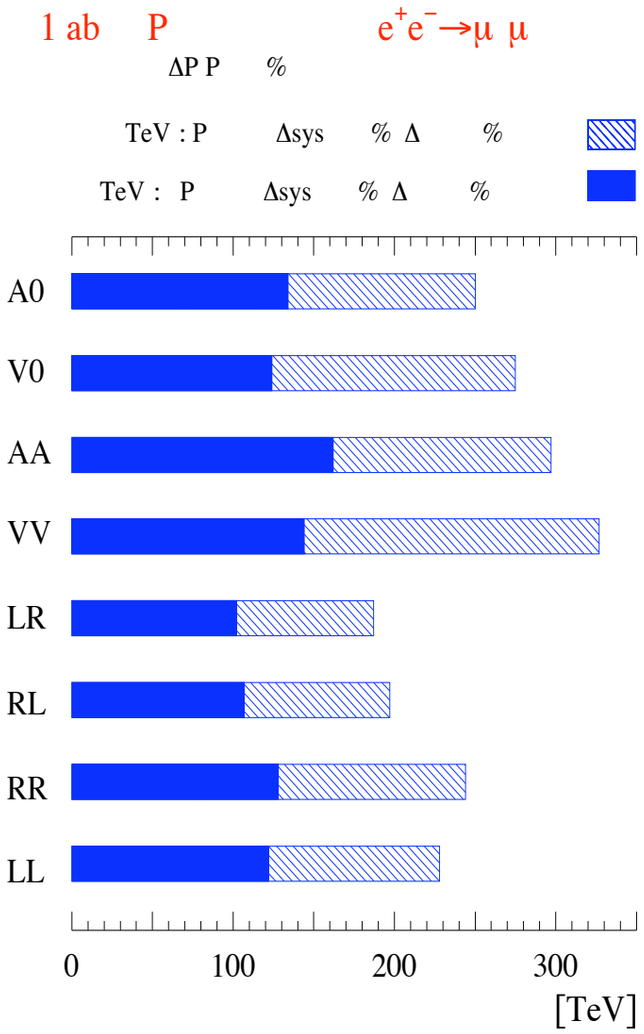
✓ : $\sigma \approx E^4$ - : $\sigma \approx$ cst

Accessing other heavy resonances

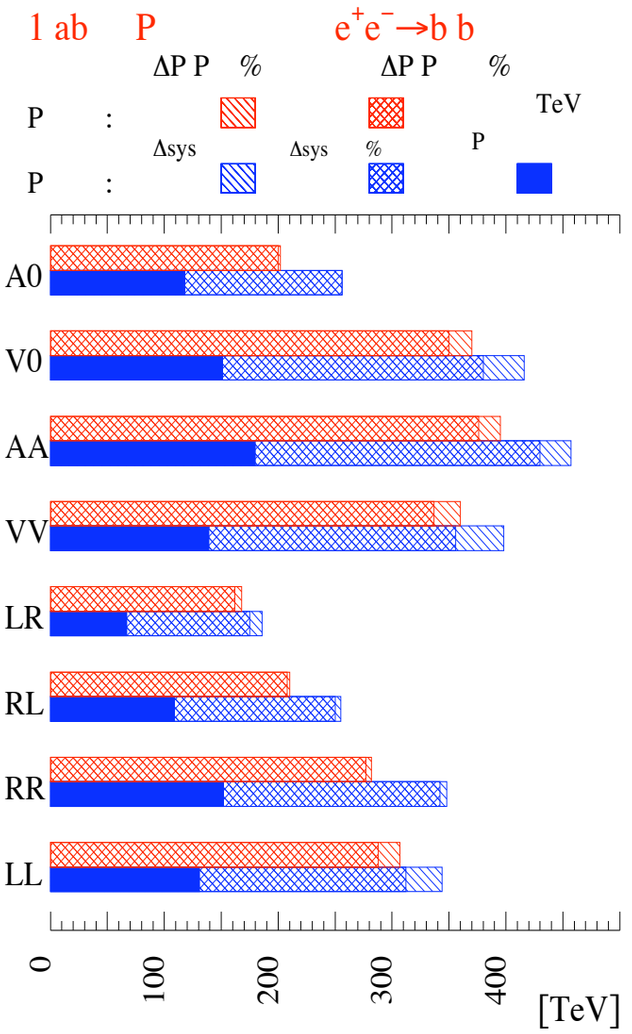
Heavy resonances

Exchange of heavy resonances=fermion contact interactions

$$\mathcal{L}_{CI} = \sum_{i,j=L,R} \eta_{ij} \frac{g^2}{\Lambda_{ij}^2} \left(\bar{e}_i \gamma^\mu e_i\right) \left(\bar{f}_j \gamma^\mu f_j\right)$$



$g^2 = 4$



CLIC study '04

to be updated by S. Riemann

Heavy resonances

Battaglia, Coradeschi 'in progress

Many models of strong interactions with new gauge bosons with large couplings to third generation of quarks

$e^+e^- \to W'/Z' \to tt, bb$

DY production of W' with W/Z final states

$e^+e^- \to Z' \to WW, ZZ$