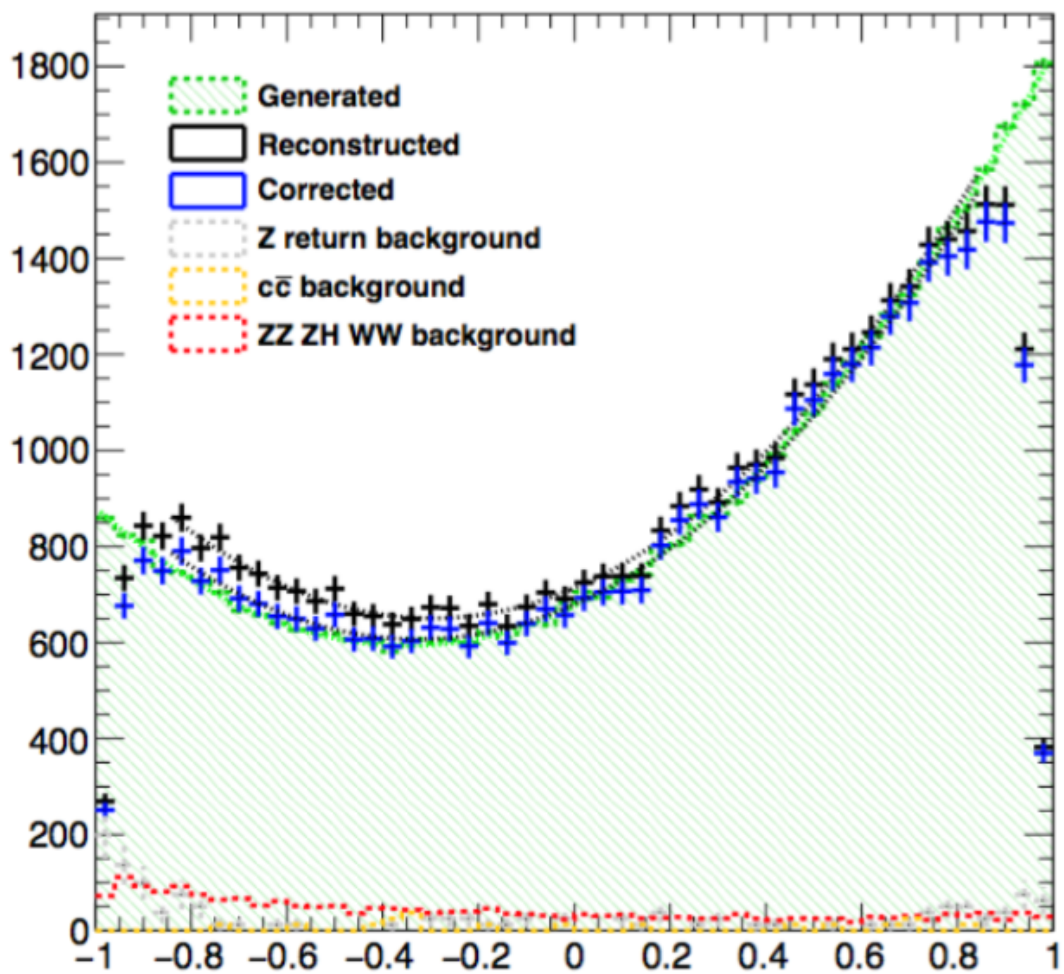
$$e^+e^- \rightarrow f\overline{f}$$



M. E. Peskin

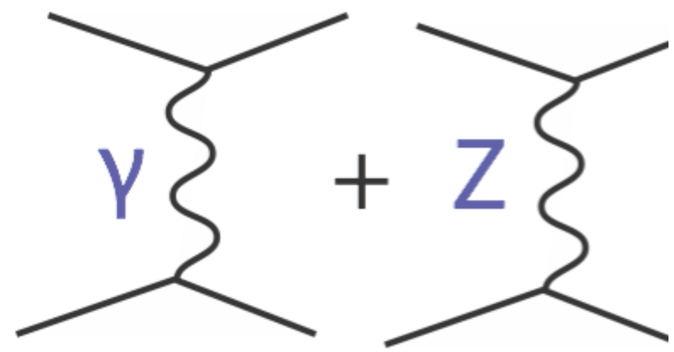
LCWS 2018
October 2018

We are excited about the prospects for studying the Higgs boson with high precision at the ILC, but should not forget the importance of other Standard Model interactions.

The method of Effective Field Theory for determining Higgs couplings has highlighted the role of $e^+e^- \to W^+W^-$ and has led to new attention to this reaction.

For a different reason, it is time to give renewed attention to fermion pair production. This reaction can give direct access to certain types of new physics. Today we are looking for all new windows into the TeV scale. This is one.

The SM phenomenology of $e^+e^- \to f\overline{f}$ is very simple. At the tree level, the diagrams are only



At the 1-loop level, this was the original process studied by Passarino and Veltman in 1979. The SM prediction is known to the 0.1% level.

The tree-level angular distributions are:

$$\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \to f_L \overline{f}_R) = \frac{\pi\alpha^2}{2s}\mathcal{A}_{LL}(1+\cos\theta)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \to f_R \overline{f}_L) = \frac{\pi\alpha^2}{2s}\mathcal{A}_{LR}(1-\cos\theta)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^-_R e^+_L \to f_L \overline{f}_R) = \frac{\pi\alpha^2}{2s}\mathcal{A}_{RL}(1-\cos\theta)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^-_R e^+_L \to f_R \overline{f}_L) = \frac{\pi\alpha^2}{2s}\mathcal{A}_{RR}(1+\cos\theta)^2$$

There are 4 helicity amplitudes, and each of the 4 can be isolated by measuring the polarized cross sections and forward-backward asymmetries.

The process gives independent information for each final-state SM species: e μ, τ, u/d, s, c, b. Tau polarization is available as an extra handle.

The polarization effects are of order 1, with

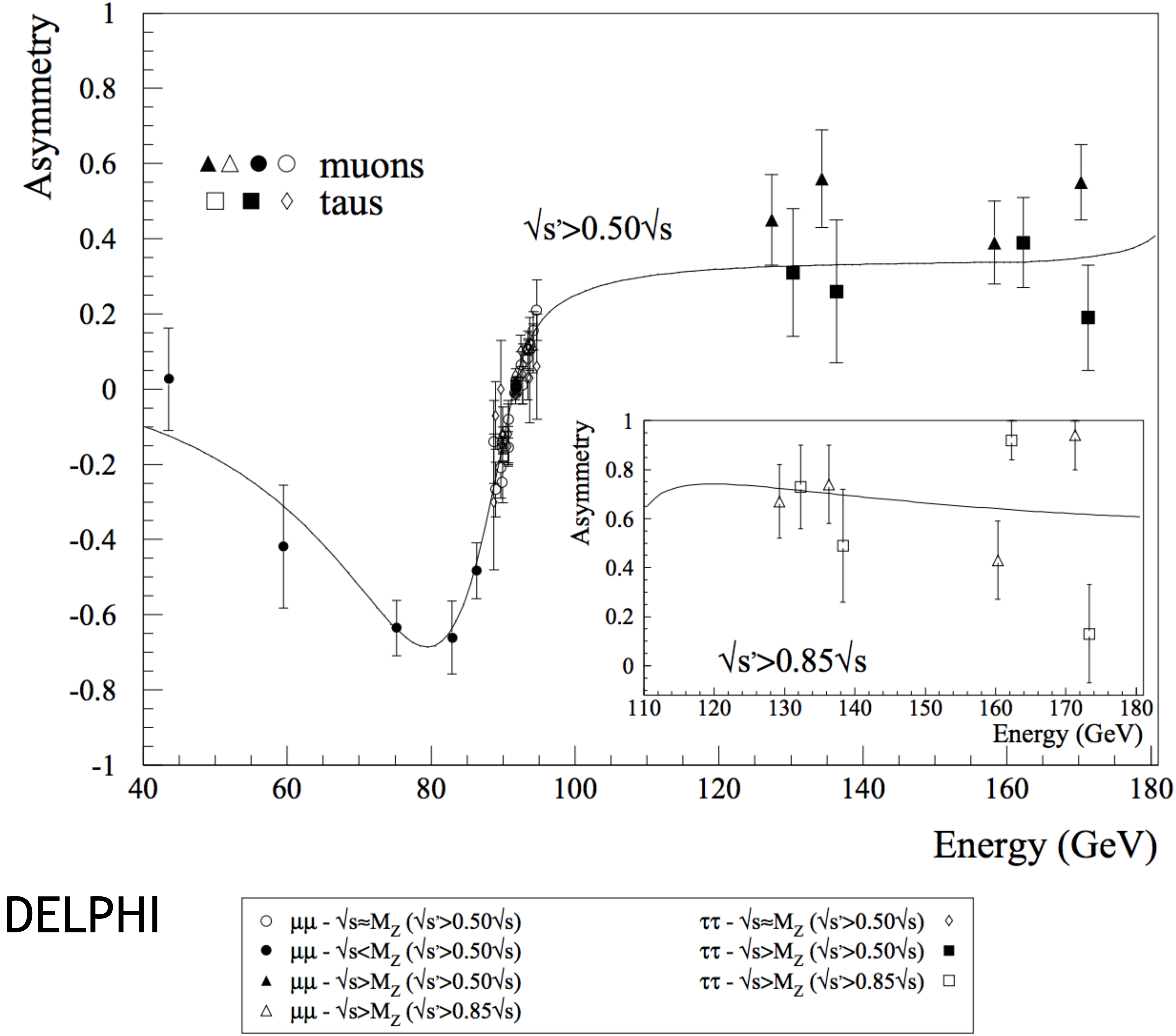
constructive interference in

$$e^-_L e^+_R \to f_L \overline{f}_R, \quad e^-_R e^+_L \to f_R \overline{f}_L$$

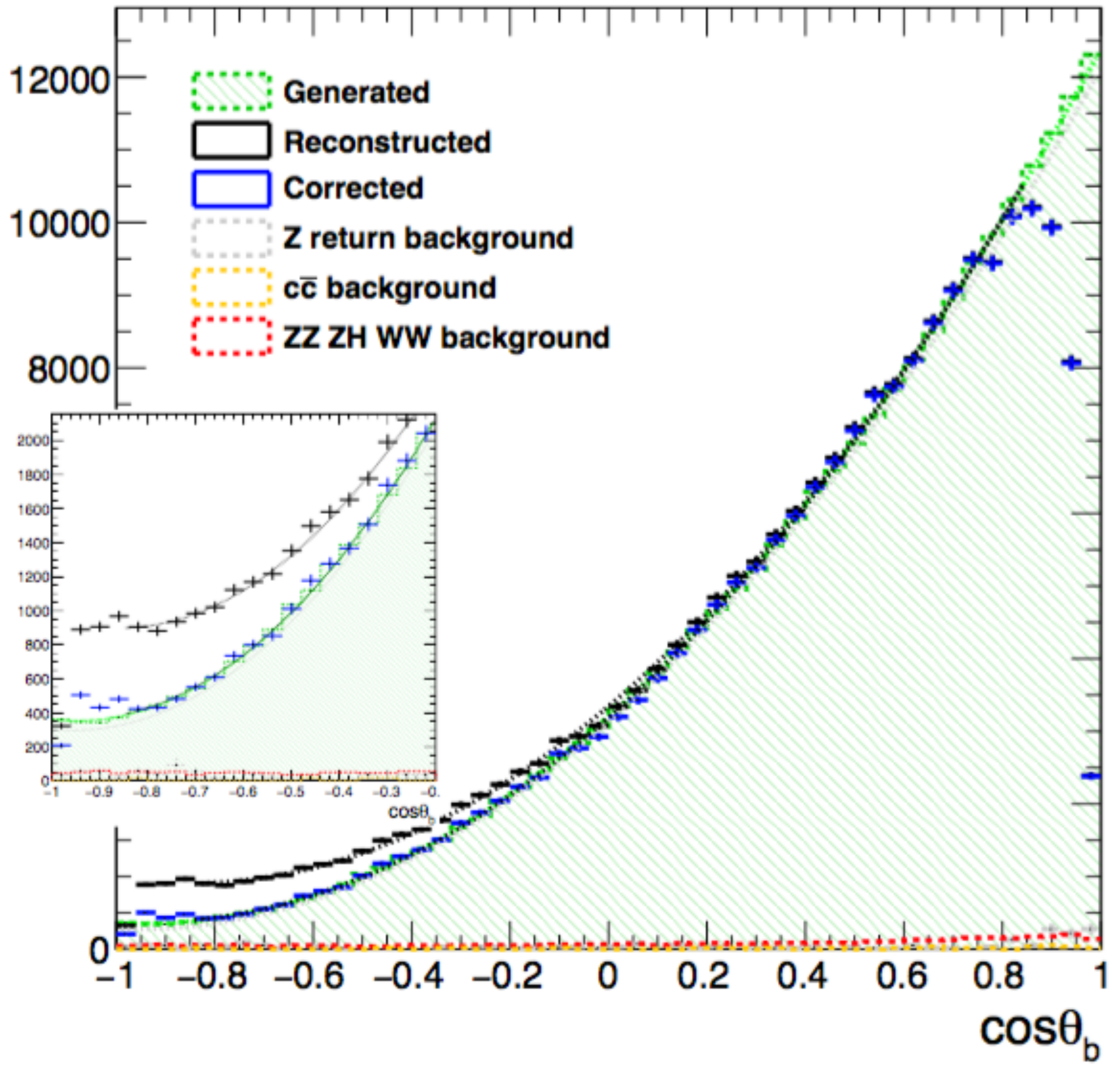
(w 2:1 ratio of cross sections)

destructive interference in

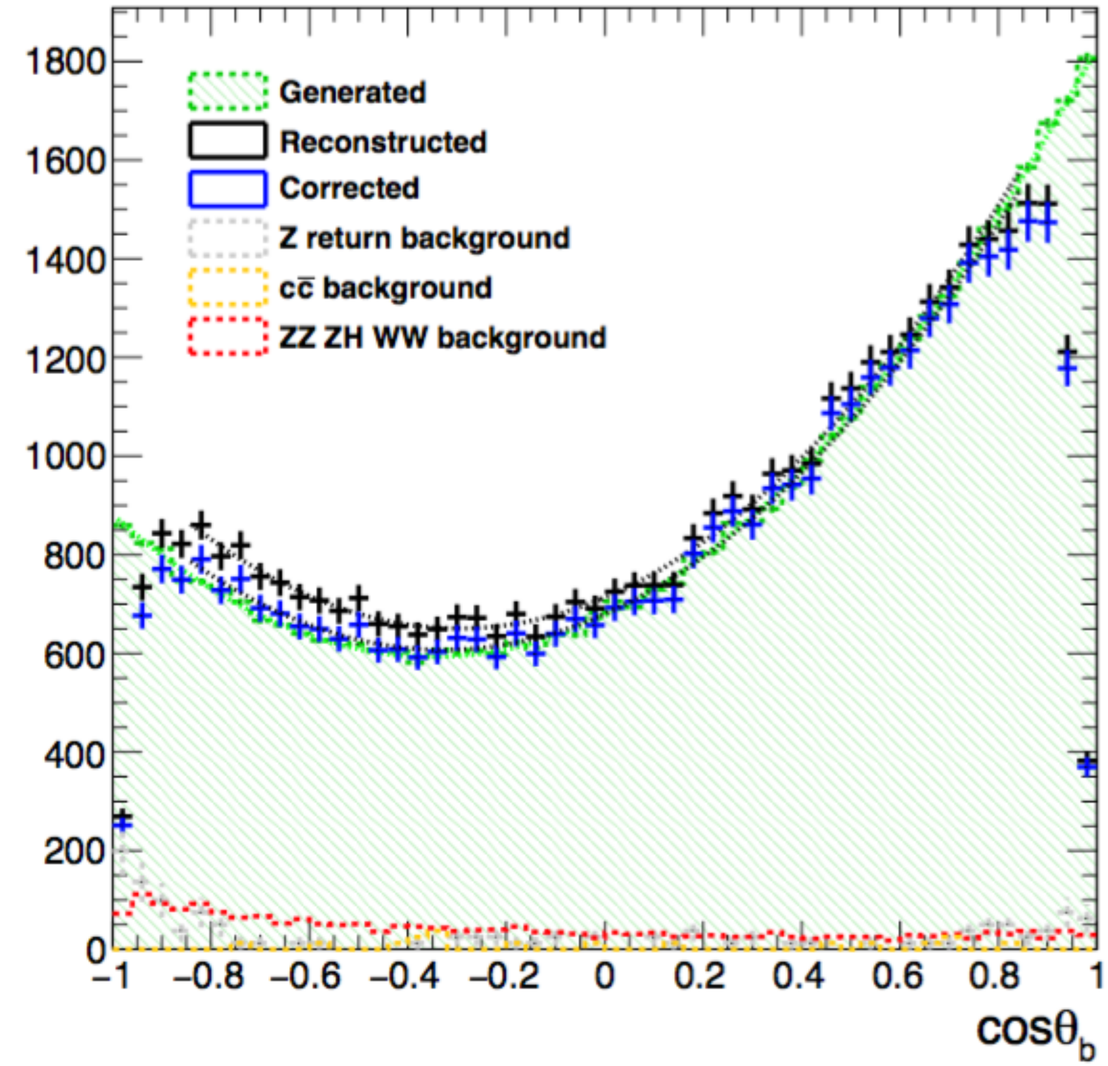
$$e^-_L e^+_R \to f_R \overline{f}_L, \quad e^-_R e^+_L \to f_L \overline{f}_R$$



Asymmetry
muons
taus
√s'>0.50√s
√s'>0.85√s
Energy (GeV)
DELPHI
μμ - √s≈M_Z (√s'>0.50√s)
μμ - √s<M_Z (√s'>0.50√s)
μμ - √s>M_Z (√s'>0.50√s)
μμ - √s>M_Z (√s'>0.85√s)
ττ - √s≈M_Z (√s'>0.50√s)
ττ - √s>M_Z (√s'>0.50√s)
ττ - √s>M_Z (√s'>0.85√s)



$$e^-_L e^+_R \to b\bar{b}$$



$$e^-_R e^+_L \to b\bar{b}$$

ILD w. vertex charge

Bilokhin, Poeschl, Richard

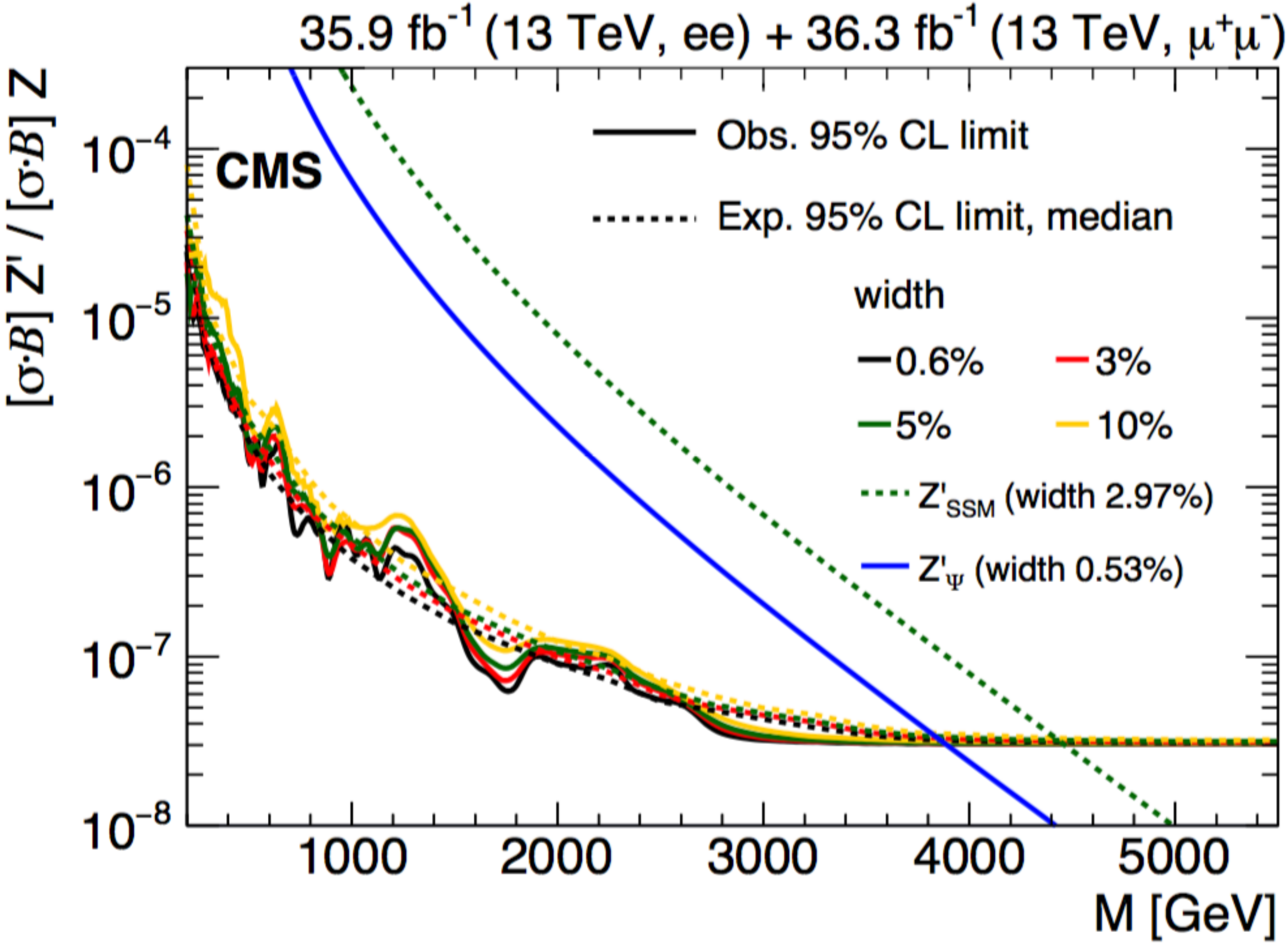
Unfortunately, while BSM effects on Higgs come from almost every type of new physics model, the BSM effects on these observables are more specialized.

In the e+e- literature, 2-fermion processes are mainly discussed in terms of new Z' bosons, coming from an extension of the SM gauge group

$$SU(3) \times SU(2) \times U(1) \subset SO(10) \subset E_6$$

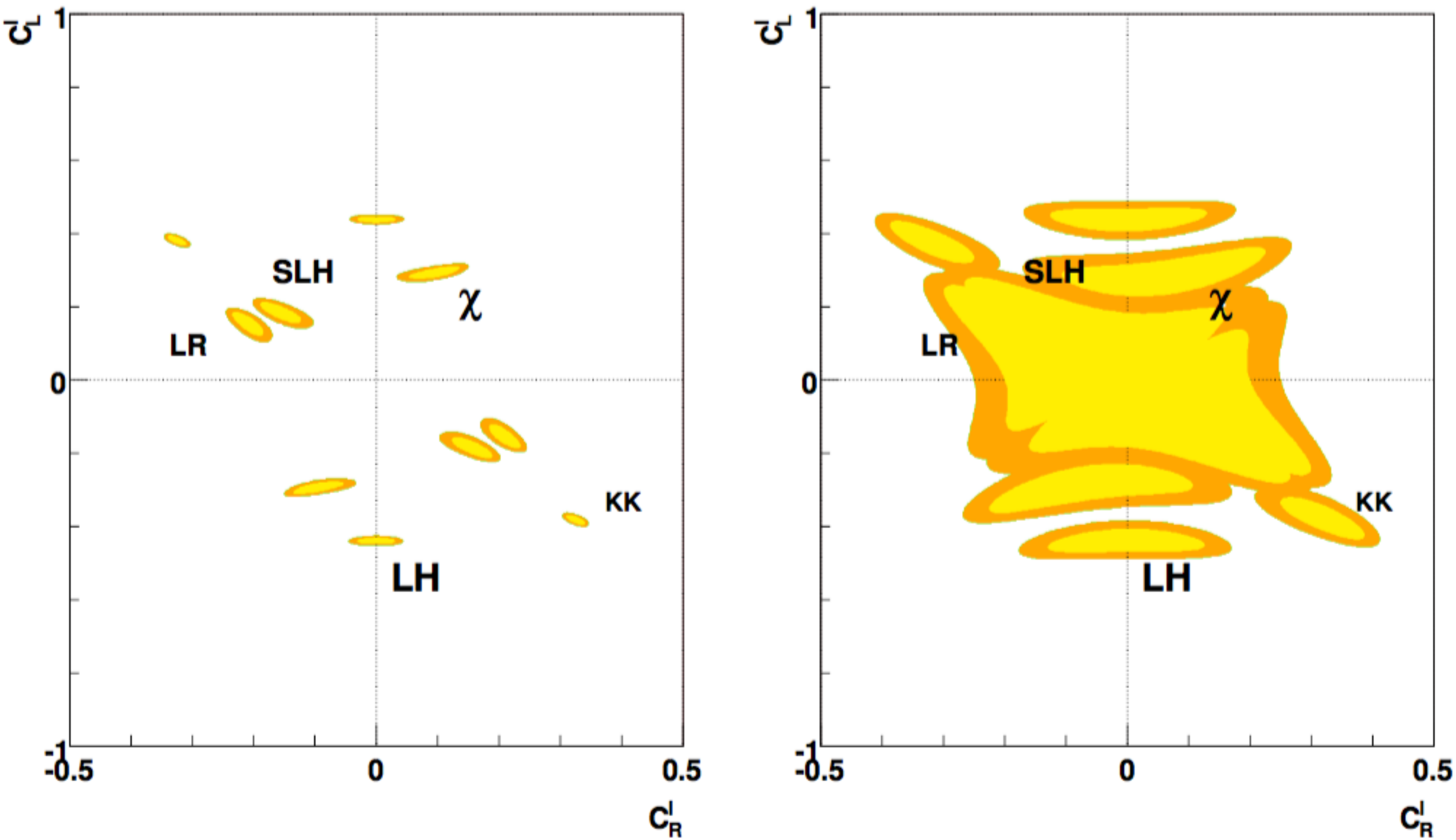
LHC constraints on these bosons are already quite strong.

(Note, though, that sequential Z' is an overly optimistic target.)



35.9 fb^{-1} (13 TeV, ee) + 36.3 fb^{-1} (13 TeV, $\mu^+\mu^-$)
CMS
Obs. 95% CL limit
Exp. 95% CL limit, median
width
0.6%
3%
5%
10%
Z'_{SSM} (width 2.97%)
Z'_Ψ (width 0.53%)
$[\sigma \cdot B]$ Z' / $[\sigma \cdot B]$ Z
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
1000
2000
3000
4000
5000
M [GeV]

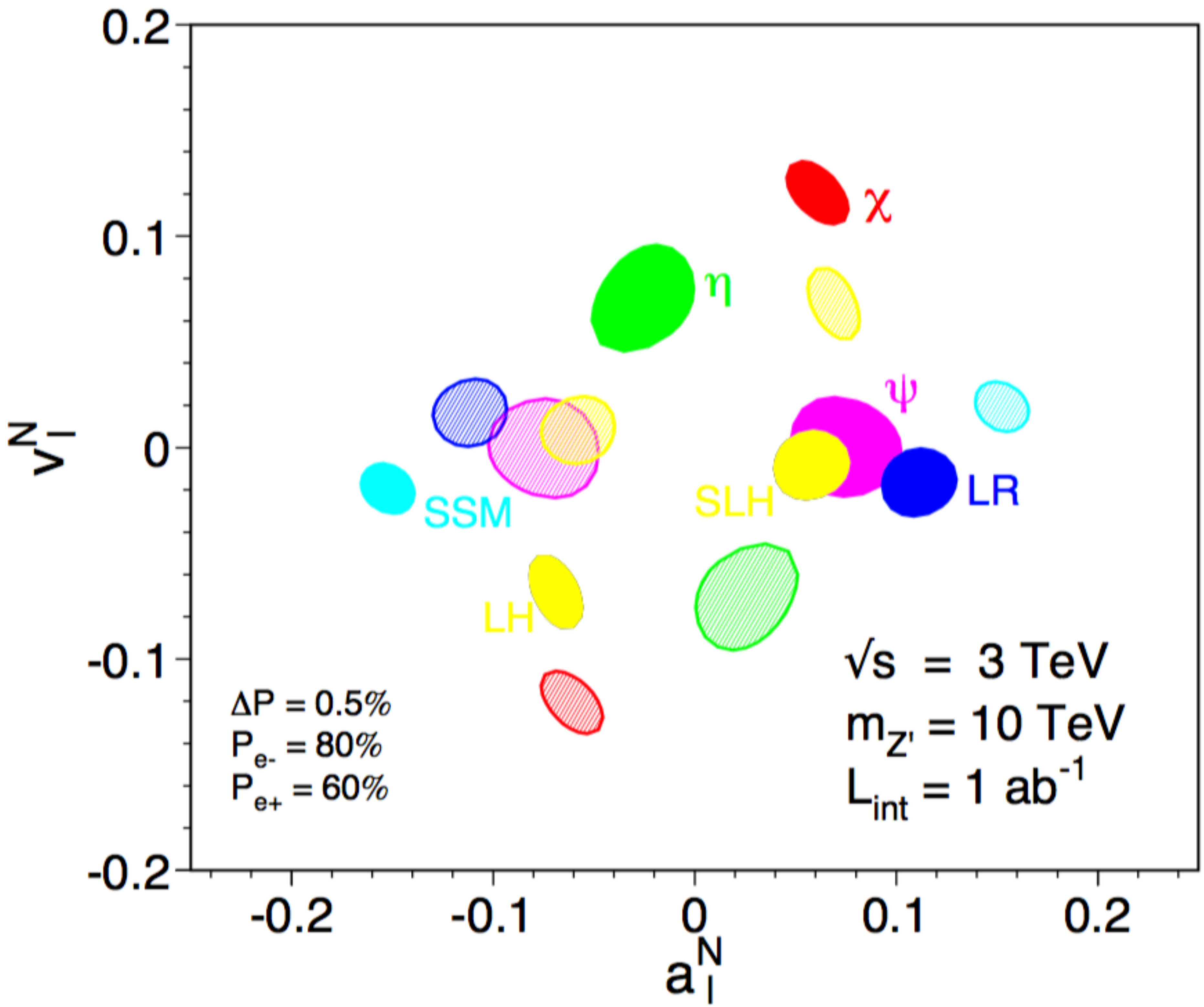
lepton L and R couplings to a Z' boson



m(Z') = 2 TeV   m(Z') = 4 TeV

500 GeV; 1 ab-1   ILC TDR

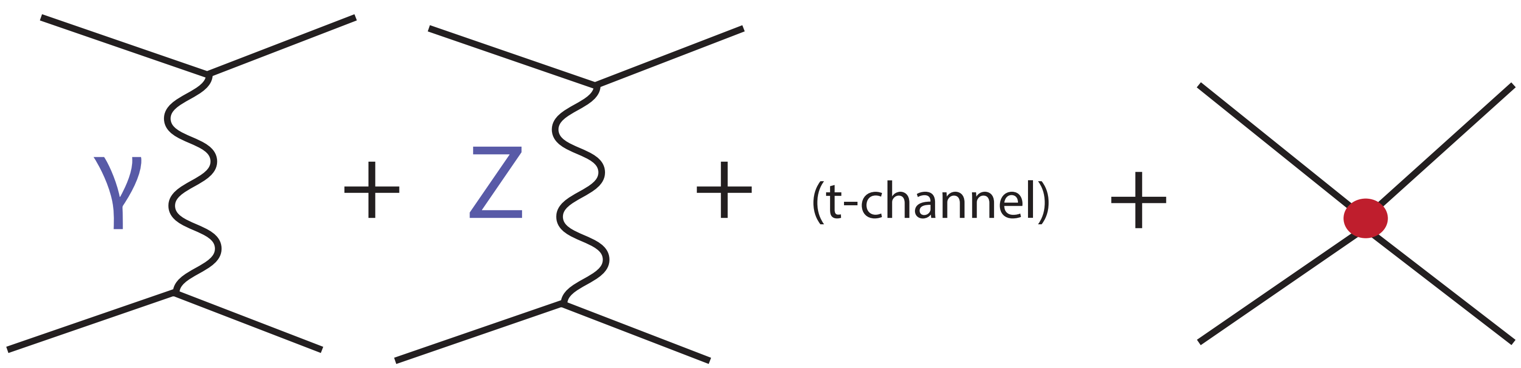
This opportunity is still there at the highest CLIC energies:



CLIC CDR

A more promising target is the possible composite structure of leptons. Compositeness is modeled by a contact interaction mediated by new forces.

The complete amplitude for $e^+e^- \to e^+e^-$ is given by



so the contact interaction correction is of relative order

$$1/(\alpha\Lambda^2)$$

that is, it is surprisingly large.

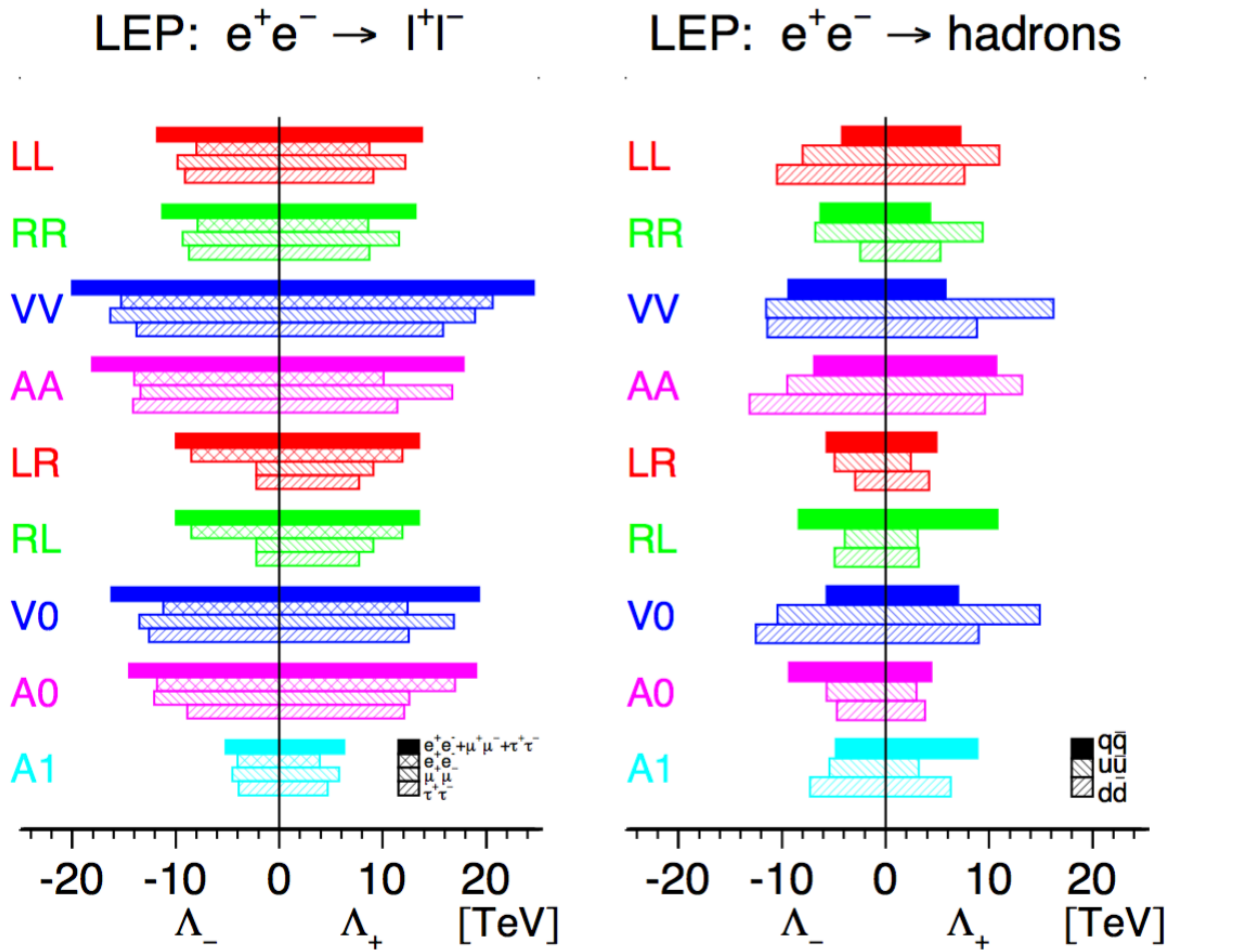
Eichten, Lane, MEP

Within the context of Effective Field Theory, the 2-fermion reactions are parametrized by 4 operators, corresponding directly to the 4 observable helicity cross sections:

$$\mathcal{L} = \frac{2\pi\eta_{LL}}{\Lambda^2}\overline{e}_L\gamma^\mu e_L \ \overline{f}_L\gamma_\mu f_L \ + \ \frac{2\pi\eta_{LR}}{\Lambda^2}\overline{e}_L\gamma^\mu e_L \ \overline{f}_R\gamma_\mu f_R$$

$$+\frac{2\pi\eta_{RL}}{\Lambda^2}\overline{e}_R\gamma^\mu e_R \ \overline{f}_L\gamma_\mu f_L \ + \ \frac{2\pi\eta_{RR}}{\Lambda^2}\overline{e}_R\gamma^\mu e_R \ \overline{f}_R\gamma_\mu f_R$$

Set the largest η parameter to 1; this defines a compositeness scale Λ. LEP 2 at 200 GeV set limits on the compositeness scale of about 8 TeV.



LEP EWWG report 2013

How far can we go beyond LEP 2 ?

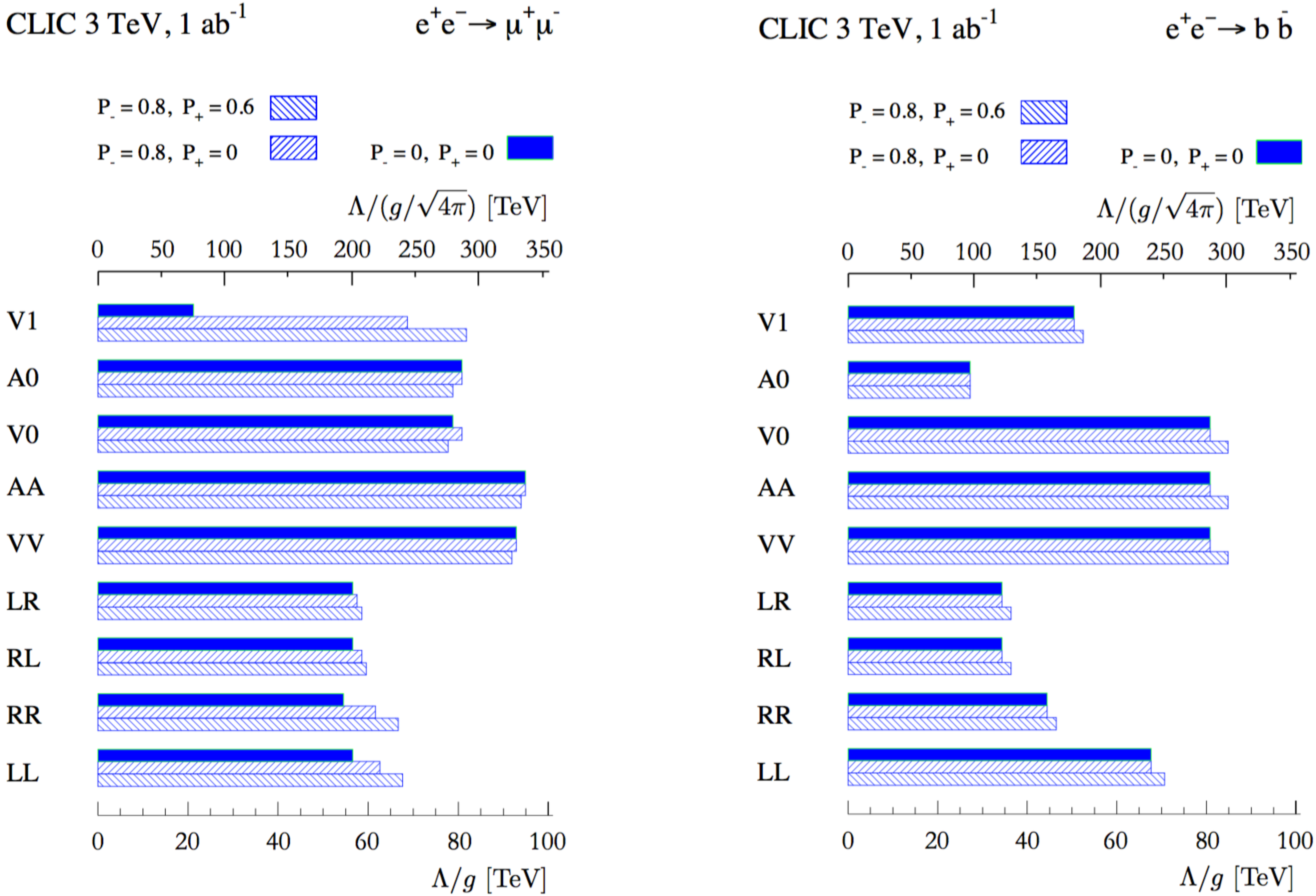
Significance of an anomaly from BSM physics

$$\propto (\sigma \ \mathcal{L})^{1/2} \cdot s/m_Z^2$$

LEP 2   200 GeV   4 experiments x 250 pb-1

ILC   250 GeV   2 ab-1

Statistically, we can discover anomalies that are a factor of 60 smaller; increase in Λ reach of ~ 8.



CLIC 3 TeV, 1 ab^{-1}
$e^+e^- \to \mu^+\mu^-$
$P_- = 0.8,\ P_+ = 0.6$
$P_- = 0.8,\ P_+ = 0$
$P_- = 0,\ P_+ = 0$
$\Lambda/(g/\sqrt{4\pi})$ [TeV]
0 50 100 150 200 250 300 350
V1
A0
V0
AA
VV
LR
RL
RR
LL
0 20 40 60 80 100
Λ/g [TeV]
CLIC 3 TeV, 1 ab^{-1}
$e^+e^- \to b\,\bar{b}$
$P_- = 0.8,\ P_+ = 0.6$
$P_- = 0.8,\ P_+ = 0$
$P_- = 0,\ P_+ = 0$
$\Lambda/(g/\sqrt{4\pi})$ [TeV]
0 50 100 150 200 250 300 350
V1
A0
V0
AA
VV
LR
RL
RR
LL
0 20 40 60 80 100
Λ/g [TeV]

This study becomes particularly interesting in the light of our uncertainty on the nature of the Higgs boson.

On one hand, it is our faith as physicists that the Higgs field should be comprehensible. In the world that we imagine, we should be able to compute the Higgs potential and understand its qualitative form from physical arguments.

On the other hand, models of the Higgs potential predicted new particles in the mass range below 1 TeV that have not been observed at the LHC.

How do we reconcile these views? Where are the new particles ?

Theorists have many answers to this question.

"SUSY will save the day." But, at a higher mass scale than previously expected.

Understanding the Higgs mass requires input from gravity, cosmology ("relaxion", anthropics).

[The problem is too hard. Think about dark matter instead.]

The Higgs boson is composite, with new strong interactions at the 10 TeV scale. Most attractively, Higgs is a Goldstone boson of these new interactions, allowing the Strong Interaction Scale >> TeV scale.

What is striking to me is our lack of theoretical understanding of the composite Higgs hypothesis.

Scaled up QCD = Technicolor does not work.

For other types of strong interaction theories our theoretical tools are rather poor.

Experimental input is desperately needed! New probes are needed beyond those offered by LHC.

Direct study of the Higgs boson is sensitive to many types of composite Higgs models.

Two-fermion processes can also play a role here.

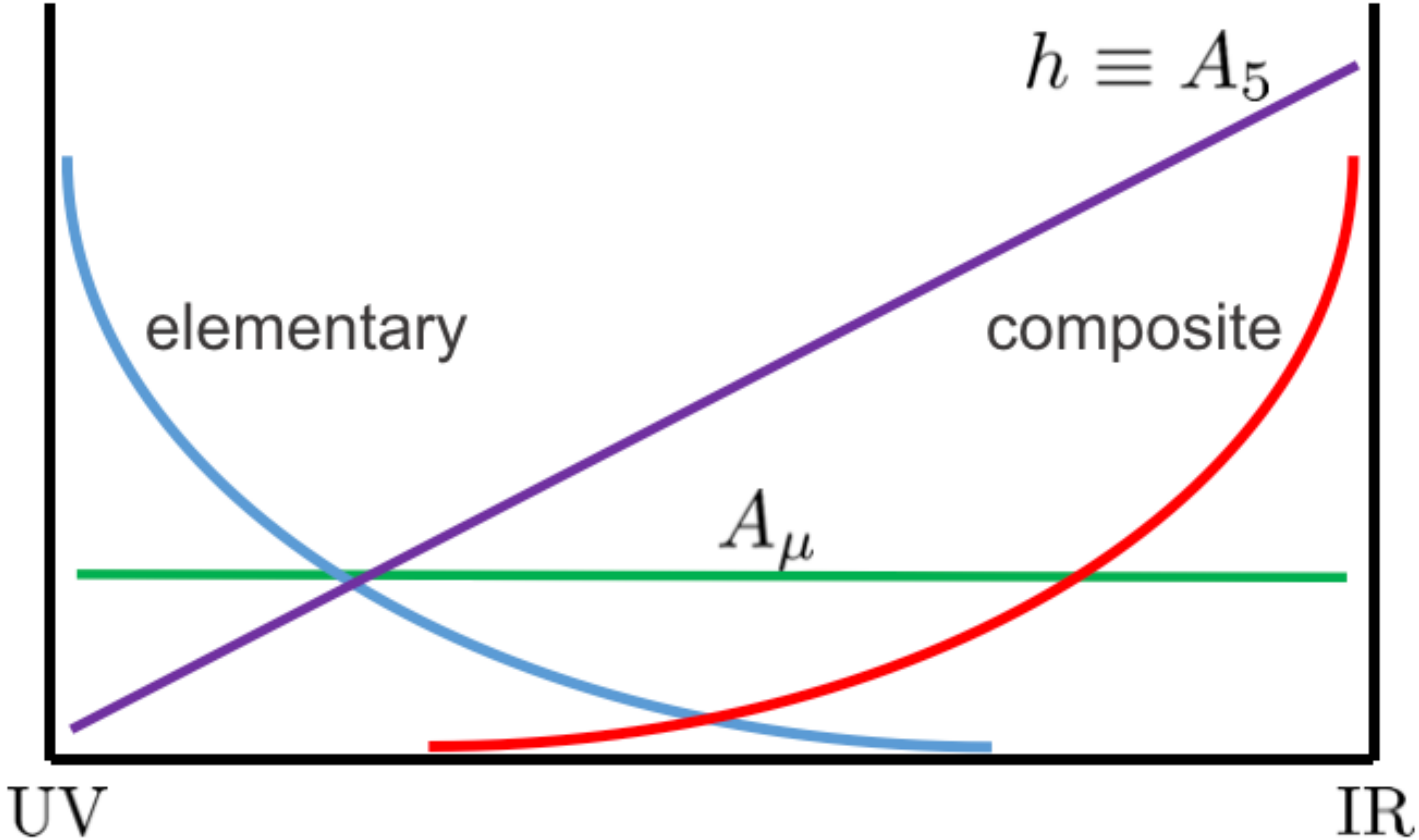
A theoretical method that I find very interesting is Randall-Sundrum theory:

model new strong interactions by
dynamics in a bounded 5th dimension

strong-interaction resonances become Kaluza-Klein resonances

Higgs is the 5th component of a 5d gauge boson

chiral fermions are “zero modes” of 5d fermion fields. Their geometrical form indicates their level of elementary or composite structure.



The form of the fermion zero modes depends on a parameter c:

	$c < -1/2$	$-1/2 < c < 1/2$	$1/2 < c$
ψ_{L0}	IR	IR	UV
ψ_{R0}	UV	IR	IR

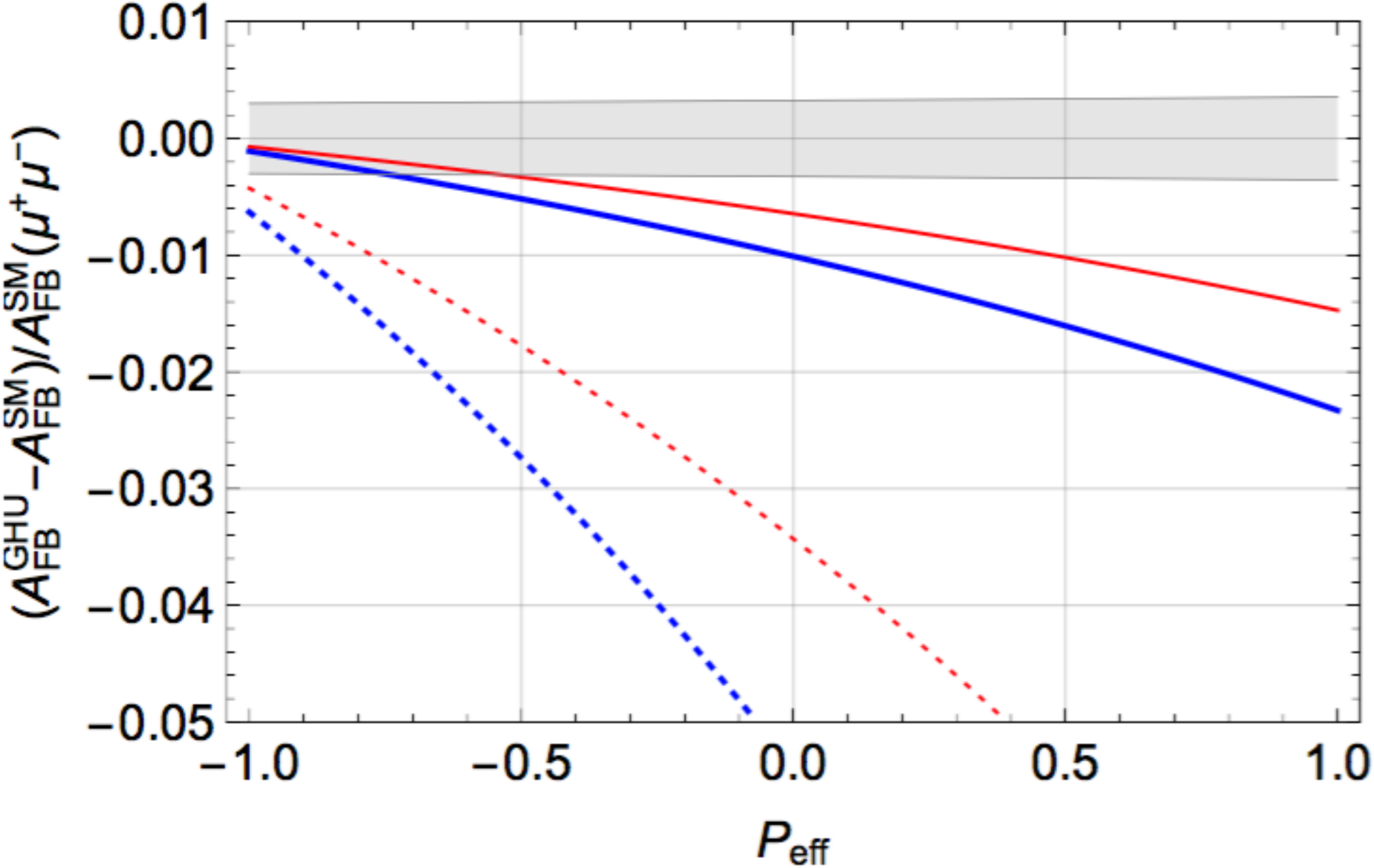
Funatsu et al. (Hosotani + collaborators) argued that this class of models can give significant corrections to 2-fermion reactions.

These effects grow as s/k_R^2 , where k_R is the RS scale.

Thus, these corrections can be small at the Z but visible with high precision (and polarization) at the ILC.

Expect particularly large effects for the 3rd generation. In the most attractive models, top quark condensation drives the Higgs phase transition. Then t_L and b_L must be partially composite.

ILC 250 GeV



Funatsu, Hatanaka, Hosotani, Orikasa

If the Higgs potential is associated with the partial compositeness of the top quark, what does this imply for other 3rd generation particles ?

Necessarily, t_R is highly composite, predicting corrections to the t electroweak form factors.

$$\Psi_t = \begin{bmatrix} \begin{pmatrix} \chi_t(-+) & t_L(++) \\ \chi_b(-+) & b_L(++) \end{pmatrix} \\ t_R(--) \end{bmatrix}_{2/3} \qquad \Psi_b = \begin{bmatrix} \begin{pmatrix} t'(-+) & \chi_b(-+) \\ b'(-+) & \psi_b(-+) \end{pmatrix} \\ b_R(--) \end{bmatrix}_{-1/3}$$

$\sin\beta$

$$m_b^2 \approx m_t^2 \cdot s_\beta^2 \cdot \frac{(2c_b+1)}{(2c_t+1)} \left(\frac{z_R}{z_0}\right)^{2(c_t-c_b)}$$

One strategy for a small m_b/m_t is to push b' to the IR. This yields a highly composite b_R.

With Jongmin Yoon, I have been trying to map the parameter space that is swept out by these models.

The parameter space depends on four parameters:

$s^2 = v^2/f^2$ "Little Hierarchy"

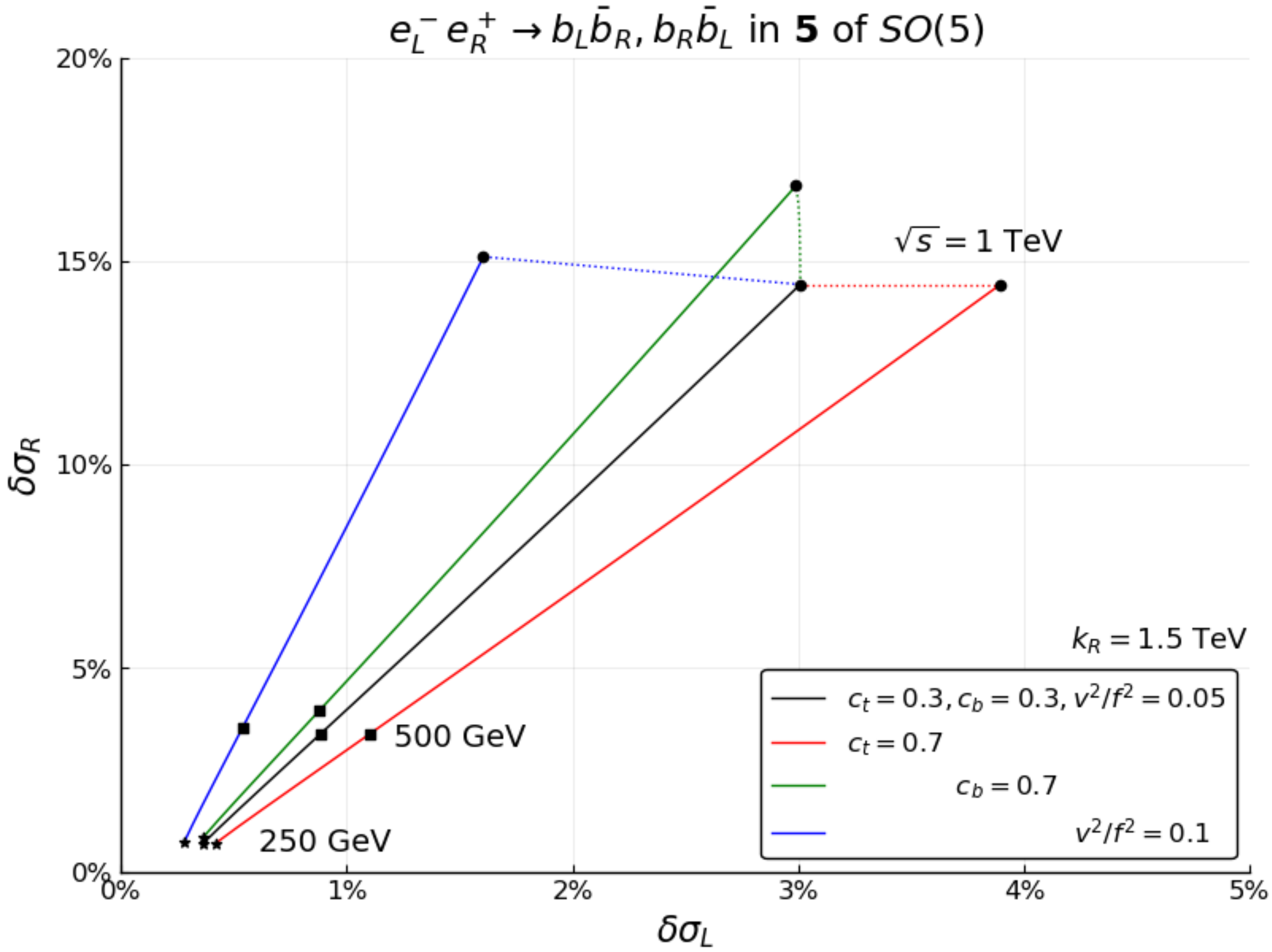
k_R RS scale parameter

c_t, c_b fermion mass/shape parameters

For k_R we make the most optimistic choice:

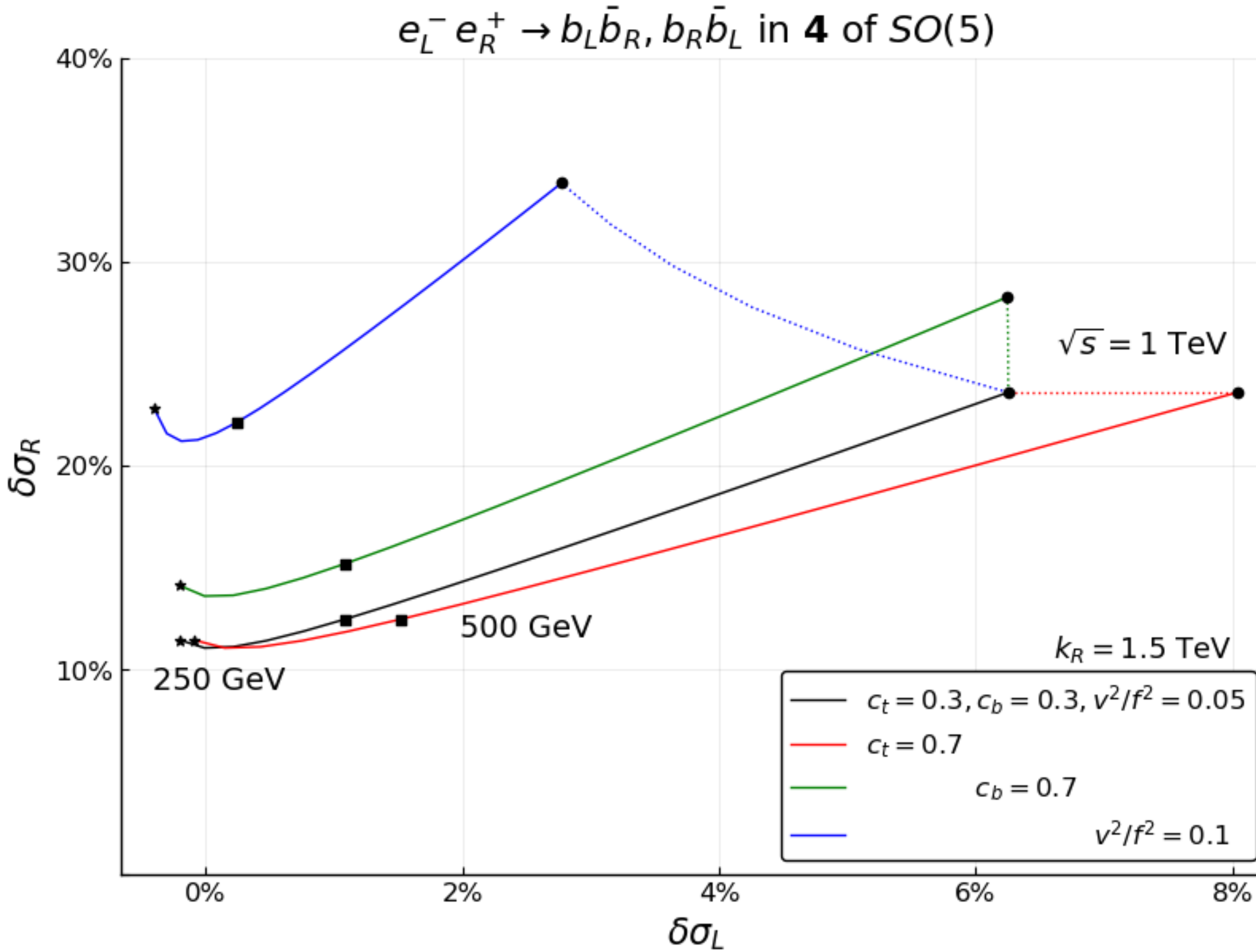
$k_R = 1.5 \text{ TeV}$ (limited by S parameter)

The effects at 250 GeV are not large in all scenarios, but they are large in some scenarios, providing tests of the mechanism of b quark mass generation.

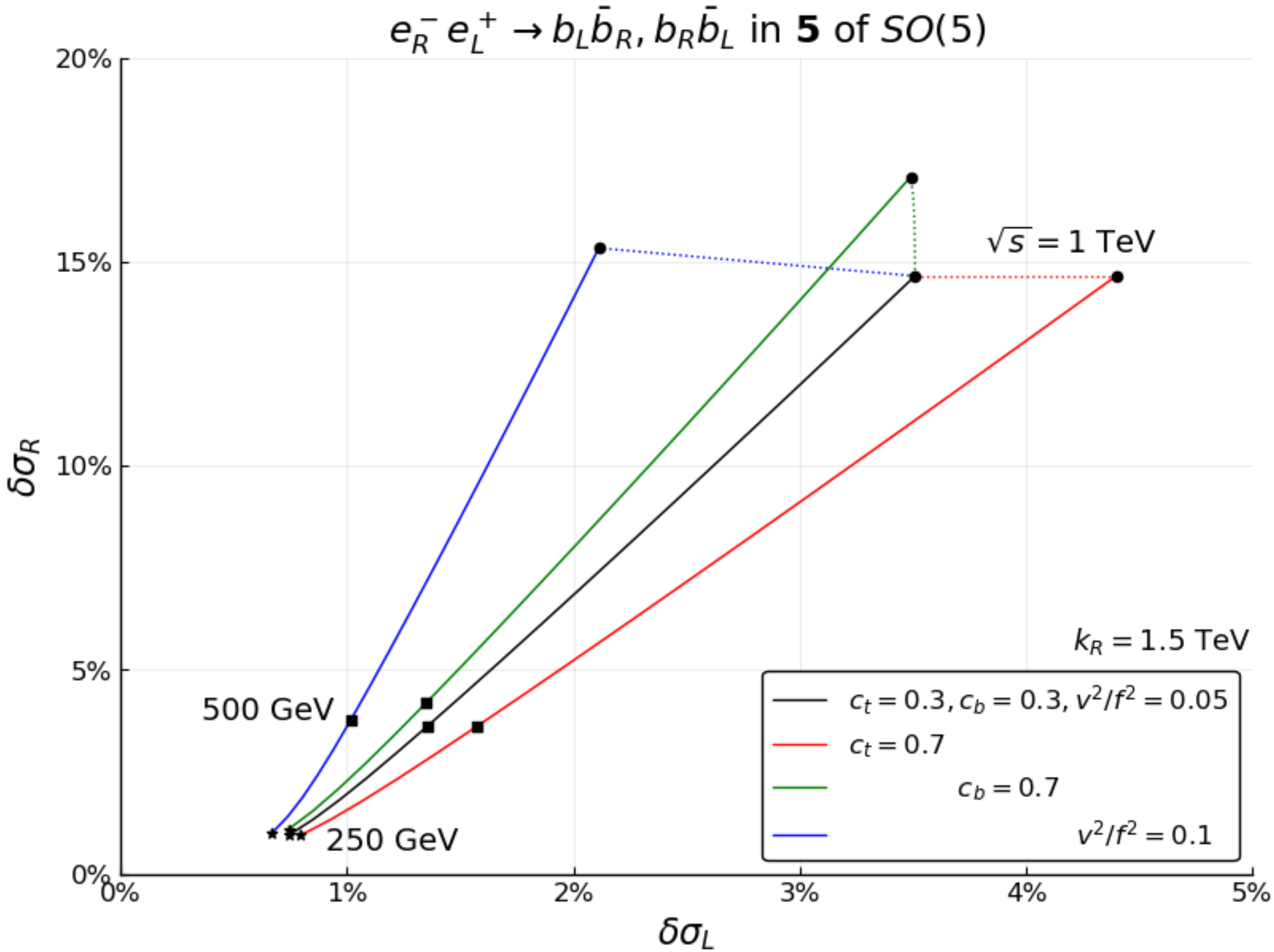


$e_L^- e_R^+ \to b_L \bar{b}_R, b_R \bar{b}_L$ in **5** of $SO(5)$
20%
15%
10%
5%
0%
$\delta\sigma_R$
0%
1%
2%
3%
4%
5%
$\delta\sigma_L$
$\sqrt{s} = 1$ TeV
500 GeV
250 GeV
$k_R = 1.5$ TeV
$c_t = 0.3, c_b = 0.3, v^2/f^2 = 0.05$
$c_t = 0.7$
$c_b = 0.7$
$v^2/f^2 = 0.1$

J Yoon

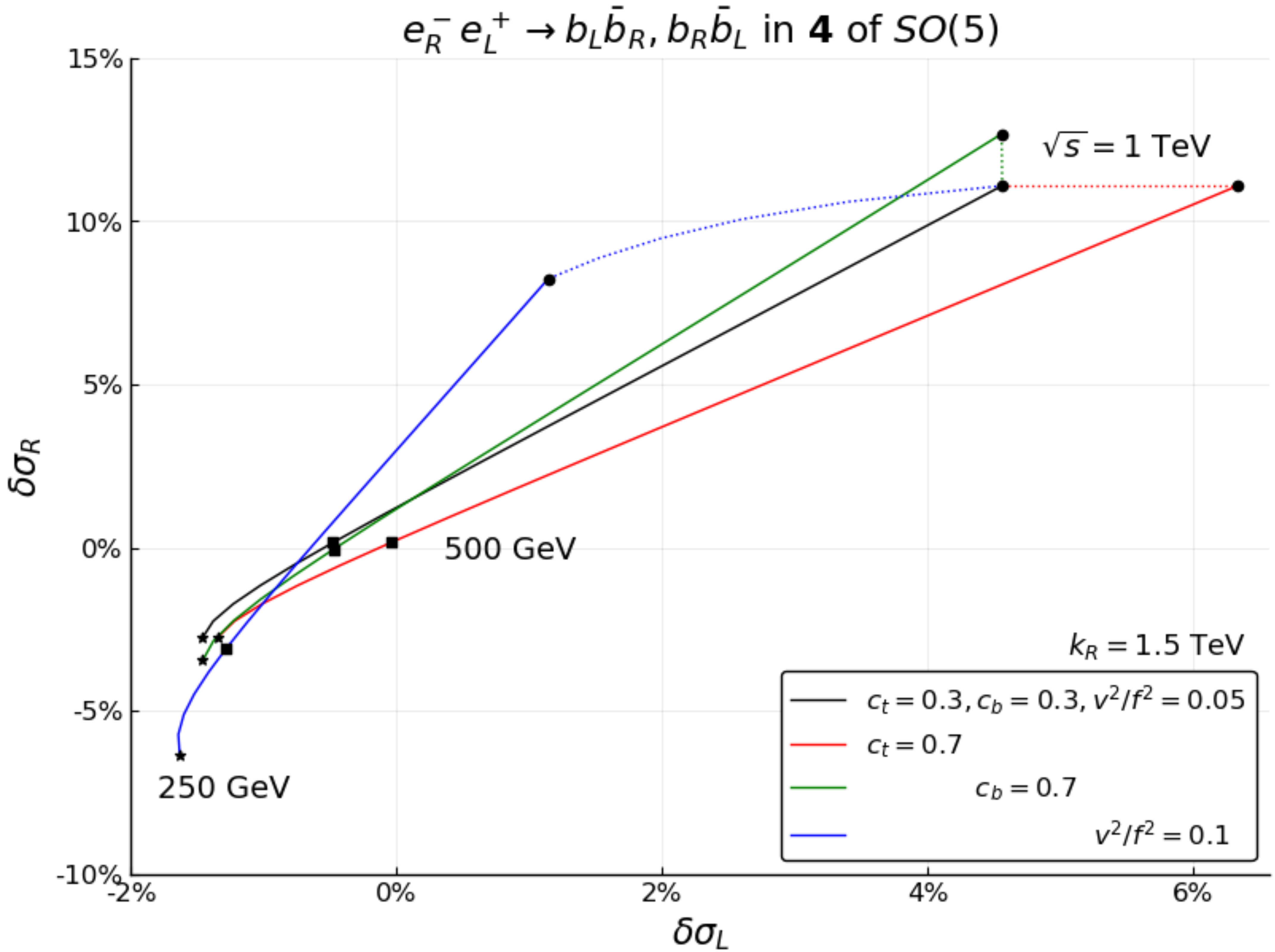

$e_L^- e_R^+ \to b_L \bar{b}_R, b_R \bar{b}_L$ in **4** of $SO(5)$
40%
30%
20%
10%
$\delta\sigma_R$
0%
2%
4%
6%
8%
$\delta\sigma_L$
$\sqrt{s} = 1$ TeV
500 GeV
250 GeV
$k_R = 1.5$ TeV
$c_t = 0.3, c_b = 0.3, v^2/f^2 = 0.05$
$c_t = 0.7$
$c_b = 0.7$
$v^2/f^2 = 0.1$

J Yoon



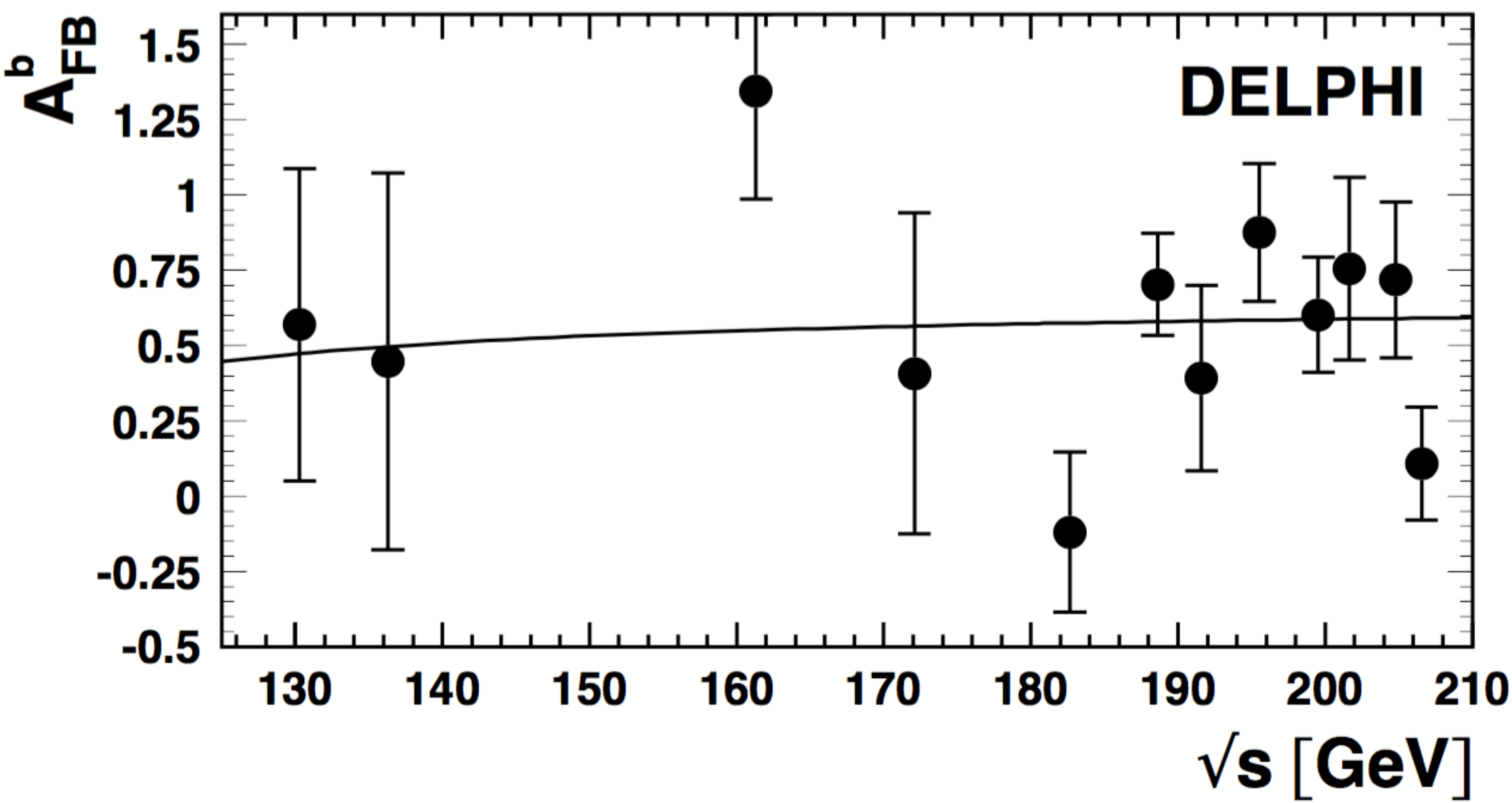
$e_R^- e_L^+ \to b_L \bar{b}_R, b_R \bar{b}_L$ in **5** of $SO(5)$
$\delta\sigma_R$
$\delta\sigma_L$
20%
15%
10%
5%
0%
0%
1%
2%
3%
4%
5%
$\sqrt{s} = 1$ TeV
500 GeV
250 GeV
$k_R = 1.5$ TeV
$c_t = 0.3, c_b = 0.3, v^2/f^2 = 0.05$
$c_t = 0.7$
$c_b = 0.7$
$v^2/f^2 = 0.1$

J Yoon

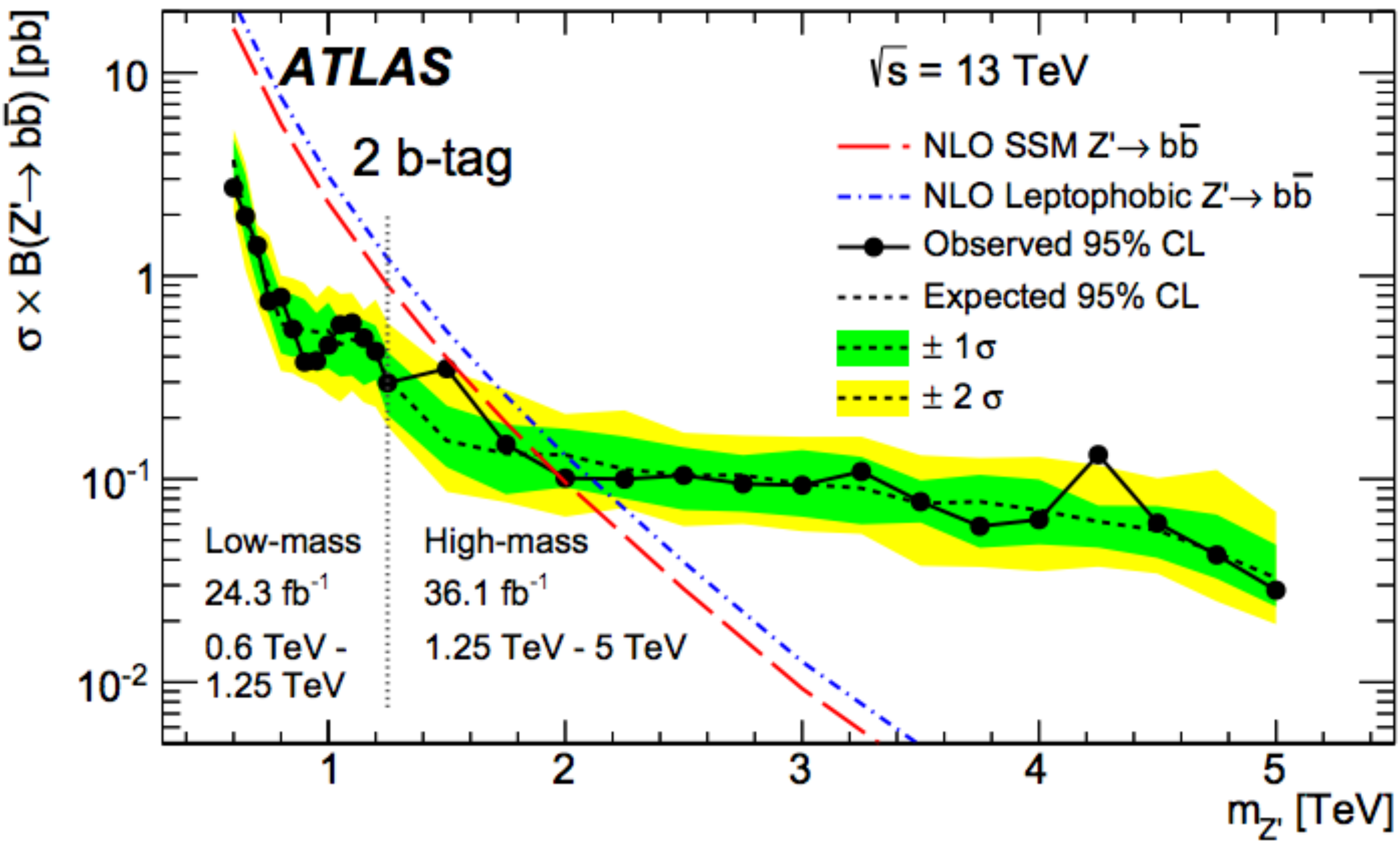


$e_R^- e_L^+ \to b_L \bar{b}_R, b_R \bar{b}_L$ in **4** of $SO(5)$
15%
10%
5%
0%
-5%
-10%
-2%
0%
2%
4%
6%
$\delta\sigma_R$
$\delta\sigma_L$
$\sqrt{s} = 1$ TeV
500 GeV
250 GeV
$k_R = 1.5$ TeV
$c_t = 0.3, c_b = 0.3, v^2/f^2 = 0.05$
$c_t = 0.7$
$c_b = 0.7$
$v^2/f^2 = 0.1$

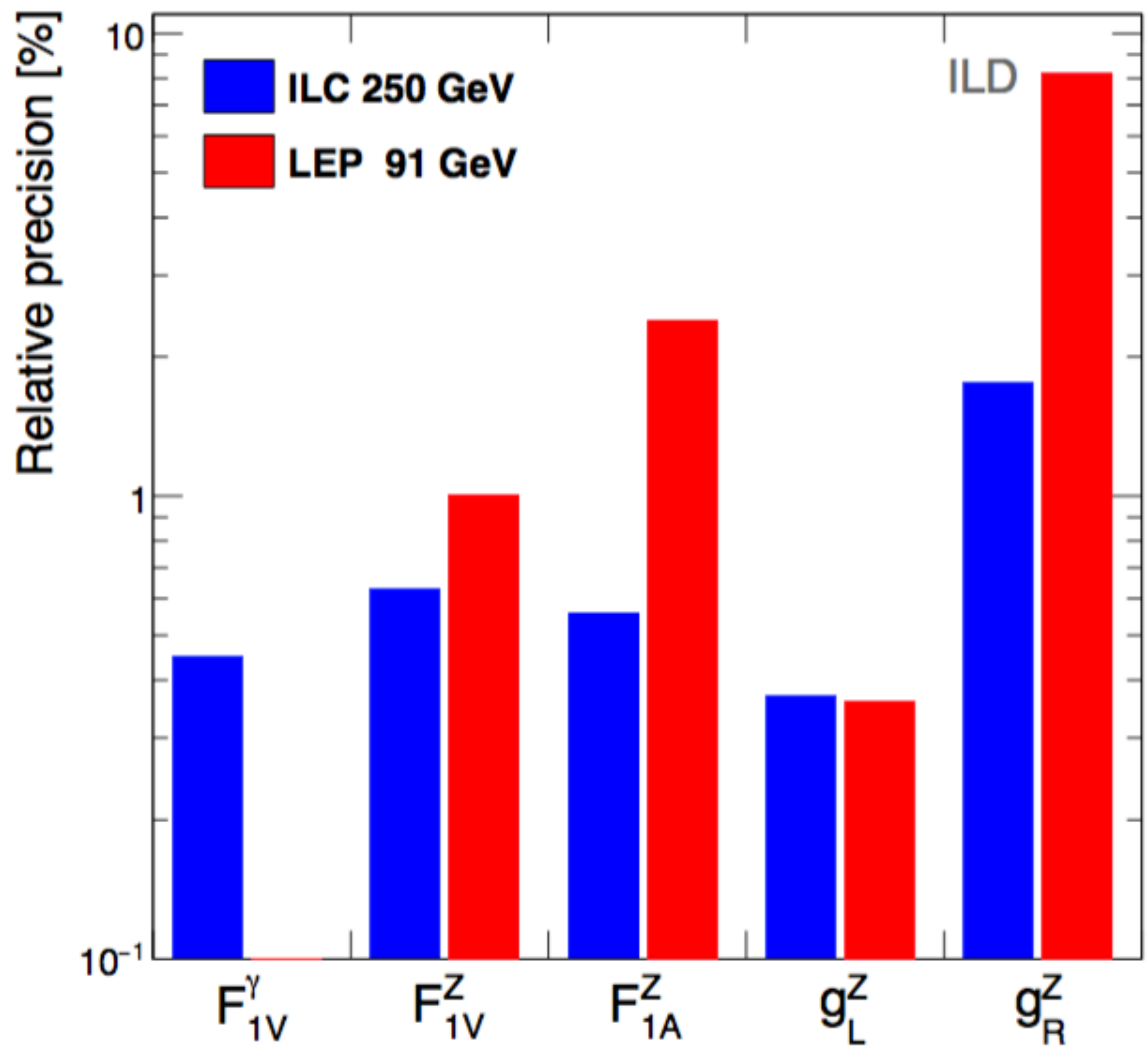
J Yoon



A^b_{FB}
DELPHI
1.5
1.25
1
0.75
0.5
0.25
0
-0.25
-0.5
130
140
150
160
170
180
190
200
210
√s [GeV]



ATLAS
√s = 13 TeV
2 b-tag
NLO SSM Z'→ bb̄
NLO Leptophobic Z'→ bb̄
Observed 95% CL
Expected 95% CL
± 1σ
± 2 σ
Low-mass
24.3 fb-1
0.6 TeV -
1.25 TeV
High-mass
36.1 fb-1
1.25 TeV - 5 TeV
σ × B(Z'→ bb̄) [pb]
10
1
10-1
10-2
1
2
3
4
5
mZ' [TeV]



Bilokhin, Poeschl, Richard

Conclusions:

$e^+e^- \to f\overline{f}$ offers sharp information that is orthogonal to other probes of TeV physics. These are enhanced by the simplicity of e^+e^- cross section and the special capabilities of linear colliders : beam polarization and excellent heavy flavor identification.

These reactions give unique probes of BSM physics. They have special importance for models in which the Higgs boson is composite and the 3rd generation fermions share the new interactions.

The interest begins at 250 GeV. Let's go there !