IBS Workshop on Prospects of Particle Physics and Cosmology

Dec. 6th, 2018

Fermion Pair Production in Gauge-Higgs Unification Models

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Work with M. Peskin

- Ideally, we would like to have a theory in which we can compute the Higgs potential and understand the EWSB.
- SUSY has been studied extensively, quantitatively.
- Higgs boson as a composite Goldstone boson of a new strong dynamics. It is not studied as thoroughly as SUSY.
- Is there a calculable, predictive approach to a new strong interaction?

- There is an interesting approach to composite Higgs based on following ideas:

  1) Randall-Sundrum geometry.
  - Dynamics in the 5th dimension models strong interaction.
  - 5D wavefunction models composite structure of fermions.
  - New resonances appear as KK states.

  2) Gauge-Higgs unification
  - Higgs as A_5^A, a part of the 5D bulk gauge symmetry.
  - We can compute the Higgs potential → predictive model.

  3) Dynamical EWSB by top quark condensation.

  4) "Little Hierarchy" $s^2 = v^2/f^2 \ll 1$

- These ideas were actively pursued in the early 2000's by Hall, Nomura, Agashe, Contino, Pomarol, Hosotani and others.

- Under this framework, we have studied how to generate the 2nd order phase transition in Higgs phase diagram. arXiv:1709.07909

- Also, we have built a realistic model under SO(5) x U(1) symmetry and examined its parameter space thoroughly.
arXiv:1810.12352

- In this talk, I will introduce a systematic, analytic study of fermion pair production cross sections in bulk RS models.
I will focus on possible mass generation schemes for the bottom quark and its implication in $e^+e^- \to b\bar{b}$ processes.
arXiv:1811.07877

5D Geometry

AdS5 bulk

UV

$k = 1/z_0 \sim 100 \text{ TeV}$

UV cutoff scale

IR

$k_R = 1/z_R \sim 1 - 2 \text{ TeV}$

Scale of the strong interaction

Fermions in RS

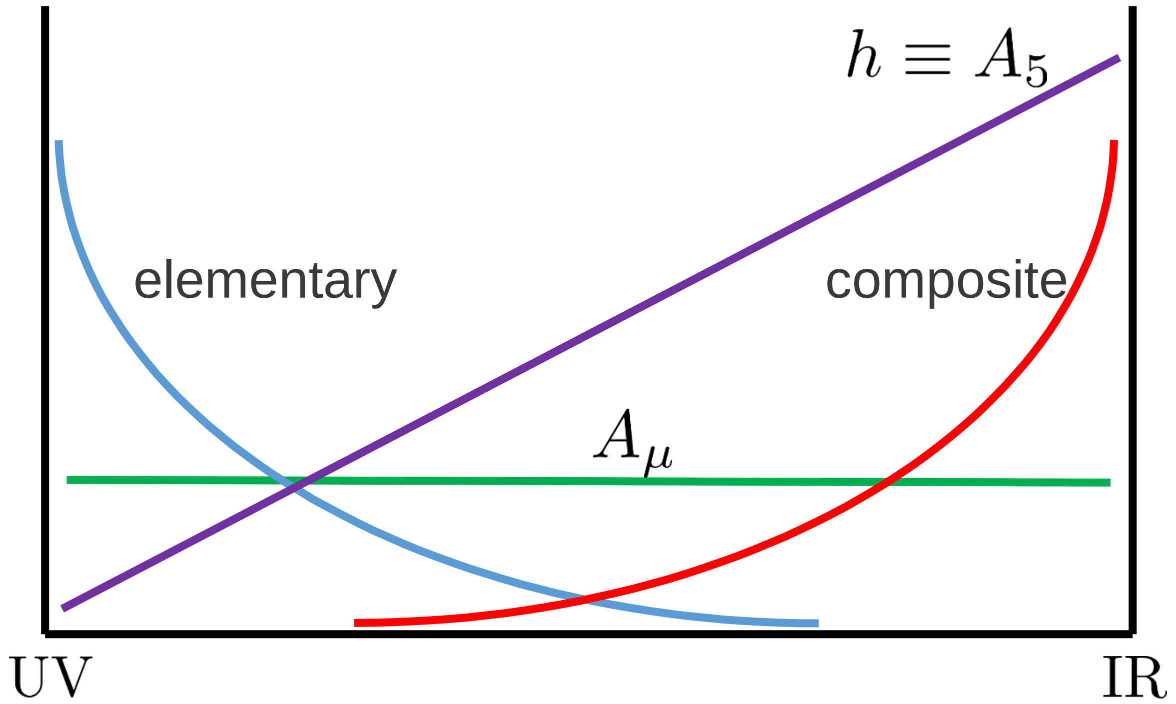
- In 5d, fermions have mass term, $c = m/k$
- Divide the 5D fermion according to 4D chirality $\Psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$
- Appropriate boundary conditions give chiral zero modes.

$$(++) \ : \ \begin{pmatrix} f_L(c,z)\, u_L(p)\, e^{-ip\cdot x} \\ 0 \end{pmatrix}$$

$$(--) \ : \ \begin{pmatrix} 0 \\ f_R(c,z)\, u_R(p)\, e^{-ip\cdot x} \end{pmatrix}$$

Fermion Partial Compositeness

- c determines 5D profile of the massless mode $f(c, z)$.



	$c < -1/2$	$-1/2 < c < 1/2$	$1/2 < c$
L	IR	IR	UV
R	UV	IR	IR

Warm-up: RS QED

- Consider a process $f_1\bar{f}_1 \to f_2\bar{f}_2$

- The scattering amplitude of s-channel pair production is

$$i\mathcal{M} = \Big(i\bar{v}_{f_1}(k_1)\gamma^m u_{f_1}(k_2)\Big)\Big(-i\eta_{mn}S(p)\Big)\Big(i\bar{u}_{f_2}(k_3)\gamma^n v_{f_2}(k_4)\Big)$$

- For a massless gauge boson in a 4D theory (e.g. QED) :

$$S(p) = \frac{g^2}{p^2}$$

- In the RS model, we have

$$S_{RS}(p) = \int_{z_0}^{z_R} \frac{dz_1}{(kz_1)^4} \int_{z_0}^{z_R} \frac{dz_2}{(kz_2)^4} \left|f_1(z_1)\right|^2 \left|f_2(z_2)\right|^2 \Big(Q_1\, \mathcal{G}(z_1, z_2, p)\, Q_2\Big)$$

where $f_1(z_1), f_2(z_2)$: 5D fermion wavefunctions

$$\eta_{mn}\mathcal{G}(z_1, z_2, p) = \langle \mathcal{A}_m(z_1, p)\mathcal{A}_n(z_2, -p)\rangle$$

Note, $S_{RS}(p)$ is explicitly calculable!

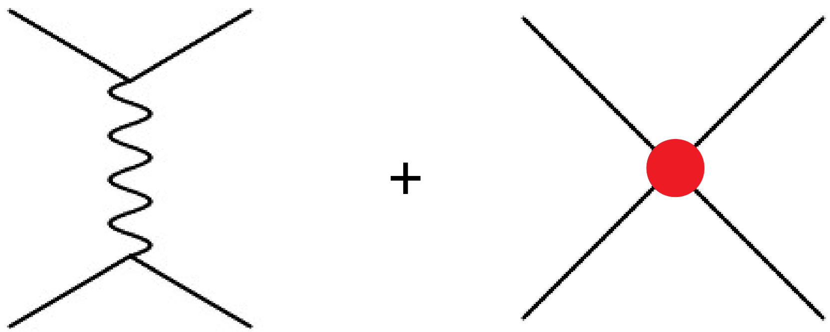
- We focus on the reactions $e^+e^- \to f\bar{f}$,
where we assume that electrons are structureless
i.e. their wavefunctions are localized in the UV brane.
Then we have

$$S_{RS}(p) = \int_{z_0}^{z_R} \frac{dz}{(kz)^4} \left|f_f(z)\right|^2 \Big(Q_e\, \mathcal{G}(z_0, z, p)\, Q_f\Big) = Q_e \langle \mathcal{G}(z_0, z, p)\rangle Q_f$$

Gauge Boson Propagators

- Deviations of $S_{RS}(p) = Q_e \langle \mathcal{G}(z_0, z, p) \rangle Q_f$ away from $\frac{g^2}{p^2}$ can be considered as a form factor for the photon or effects of the new strong resonances (KK states).
- $\mathcal{G}(z_1, z_2, p)$ is a complicated combination of Bessel functions.
- We can obtain further insight by expanding it for $p \ll k_R$
- Four possible combinations of the gauge field boundary conditions: $(++), (+-), (-+), (--)$

- First consider a gauge field with $(++)$ boundary conditions. This includes a massless zero mode and KK states.
  1) a photon propagator
  2) a contact interaction representing the KK states



- Indeed, we have $S_{(++)}(p) = g^2 \left[\frac{1}{p^2} + \frac{\delta_{KK}}{k_R^2} + \cdots \right]$

  where $\delta_{KK} = \frac{1}{4}\left(-\frac{1}{L_B} + \left\langle \frac{z^2}{z_R^2} \right\rangle + 2 \left\langle \frac{z^2}{z_R^2} \log \frac{z_R}{z} \right\rangle \right)$

δ_{KK} encapsulates effects of all KK states.

Note, more composite fermion → larger δ_{KK}

- $(+-)$ gauge field does not have a zero mode.

  → No photon contribution

$$S_{(+-)}(p) = -\frac{g_5^2 k}{2k_R^2}\left(1 - \left\langle \frac{z^2}{z_R^2} \right\rangle\right)$$

- $(-+), (--)$ gauge fields vanish on the UV boundary.

  → do not couple to UV-localized electron.

$$S_{(-+)}(p) = S_{(--)}(p) = 0$$

SO(5) x U(1) Model

Agashe, Contino, Pomarol

AdS5 bulk

UV

$$k = 1/z_0 \sim 100 \text{ TeV}$$

UV cutoff scale

IR

$$k_R = 1/z_R \sim 1 - 2 \text{ TeV}$$

Scale of the strong interaction

SO(5) x U(1) Model

Agashe, Contino, Pomarol

SM gauge symmetry

$SU(2)_L \times U(1)_Y$

AdS5 bulk

$SO(5) \times U(1)_X$

Custodial symmetry protects T

$SO(4) \times U(1)_X$

UV

$k = 1/z_0 \sim 100 \text{ TeV}$

UV cutoff scale

IR

$k_R = 1/z_R \sim 1 - 2 \text{ TeV}$

Scale of the strong interaction

$SO(5)/SO(4)$: Higgs as Goldstone bosons (A_5 zero mode)

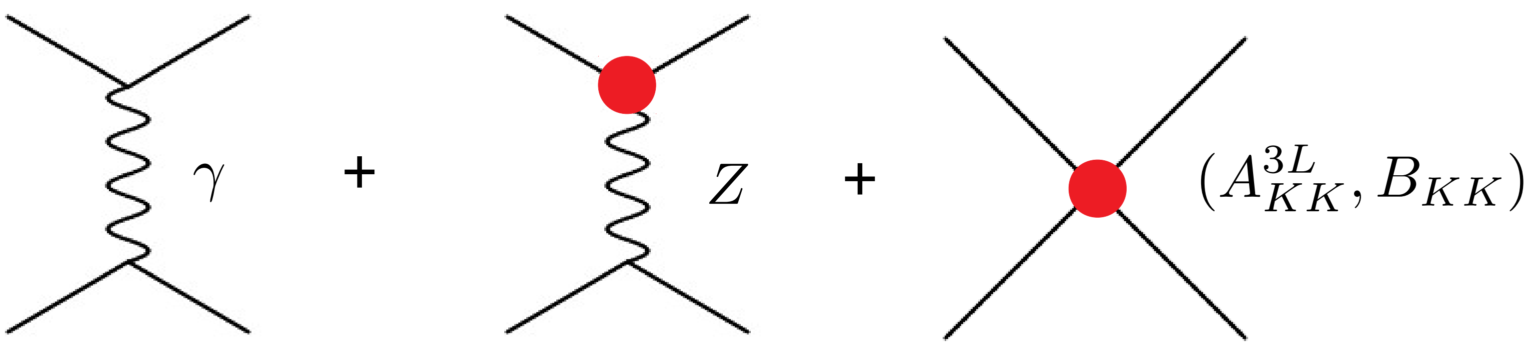
$$Y = T_R^3 + X \quad \text{and} \quad Q = T_L^3 + T_R^3 + X$$

Typical masses in this setting : $Z' \sim 2.4 k_R$

- Neutral gauge field boundary conditions :

$$A^{3L}\,(++),\;\; B\,(++),\;\; Z'\,(-+),\;\; A^{35}(--)$$

- Two zero modes of (A^{3L}, B) give (γ, Z).
- KK states of (A^{3L}, B) generate contact interactions, but those of (Z', A^{35}) do not.
- After EWSB, Z gets massive and can have a form factor related to the "Little Hierarchy" parameter $s^2 = v^2/f^2$



- The expansion of the neutral boson propagator in small $s^2,\, p^2/k_R^2$

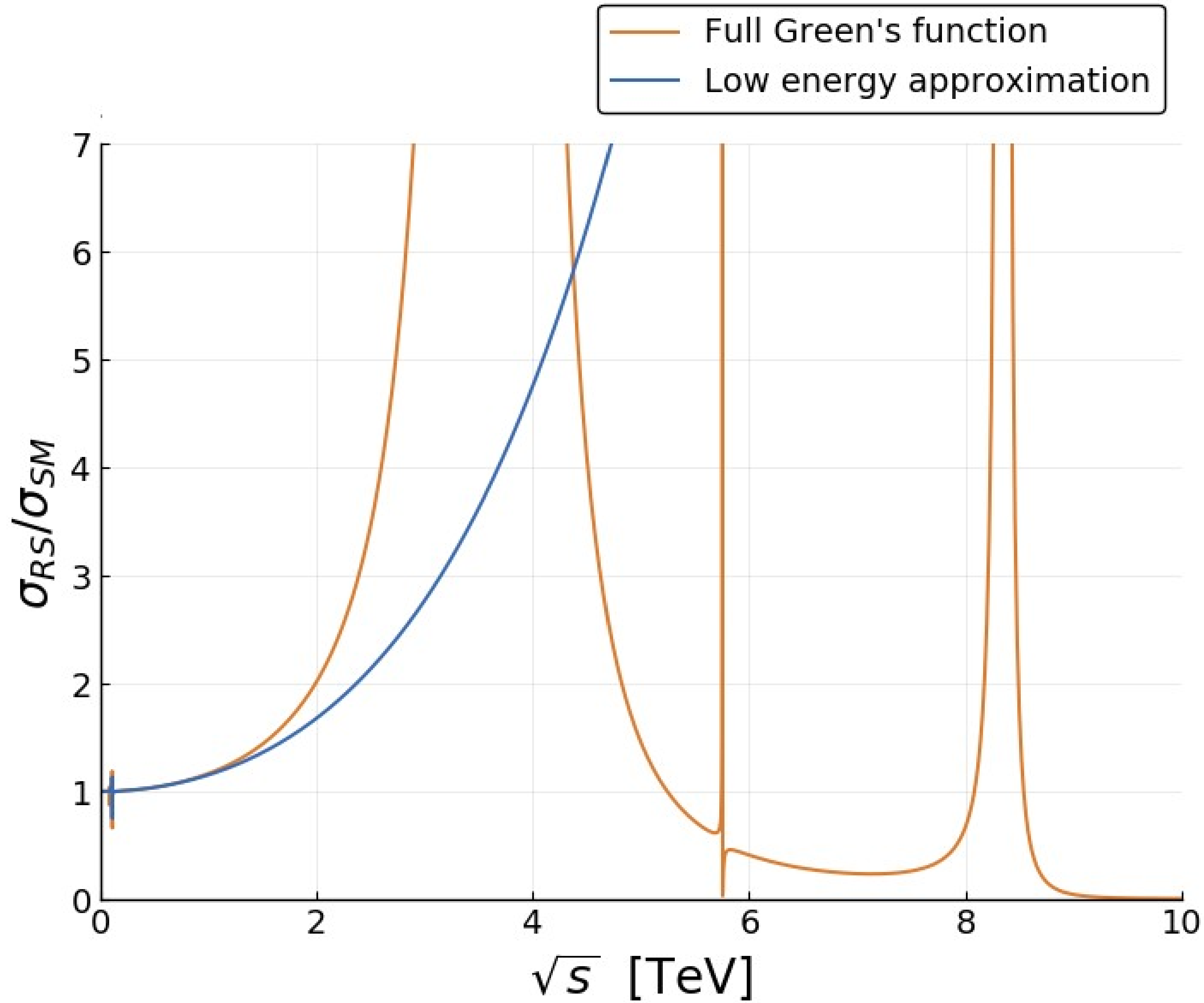
$$S(p) = \frac{e^2}{p^2}\, Q_e Q_f + \frac{g_{eff}^2}{c_w^2}\, \frac{1}{p^2 - m_Z^2}\, \left(T_e^{3L} - s_*^2 Q_e\right) \left(T_f^{3L} - s_*^2 Q_f + \delta Q_f\right)$$
$$+ \frac{g^2}{k_R^2}\left[\delta_{KK}^{W}\, T_e^{3L}\, T_f^{3L} + \frac{s_w^2}{c_w^2}\, \delta_{KK}^{B}\, Y_e\, Y_f\right]$$

- Deviations in (g_{eff}, s_*^2) are of order $\frac{m_Z^2}{4k_R^2} = 0.1\%$ for $k_R = 1.5\ \mathrm{TeV}$
- Two dominant sources of deviations:

$$\delta Q = \left(\frac{s^2}{2}\left(-T^{3L} + T^{3R}\right) + \frac{s}{\sqrt{2}} T^{35}\right)\left\langle \frac{z^2}{z_R^2}\right\rangle$$

$$\delta_{KK}^{W,B} = \frac{1}{4}\left(-\frac{1}{L_{W,B}} + \left\langle \frac{z^2}{z_R^2} + 2\frac{z^2}{z_R^2}\log\frac{z_R}{z}\right\rangle\right)$$

- Except in δQ, the entire expression is in terms of (T^{3L}, Y)



Full Green's function
Low energy approximation
0
1
2
3
4
5
6
7
σ_{RS}/σ_{SM}
0
2
4
6
8
10
$\sqrt{s}$ [TeV]

Dynamical EWSB by the Top Quark

- In the most attractive models,
  the top quark condensation drives the EWSB.
- Then, t_L, t_R should be in the same multiplet.
  For example, the top quark embedding in 5 of SO(5) should be

$$\Psi_t = \begin{bmatrix} \begin{pmatrix} \chi_t(-+) & t_L(++) \\ \chi_b(-+) & b_L(++) \end{pmatrix} \\ t_R(--) \end{bmatrix}_{2/3}$$

Higgs in SO(5)/SO(4) pairs up
the left and right-handed zero-modes
and make the top massive.

- Tune v^2/f^2 using a competing top partner multiplet;
  see arXiv:1709.07909 arXiv:1810.12352

Natural Mass Hierarchy between top & bottom

- The bottom quark is massless at this stage.

$$\Psi_t = \left[\begin{matrix} \begin{pmatrix} \chi_t(-+) & t_L(++) \\ \chi_b(-+) & b_L(++) \end{pmatrix} \\ t_R(--) \end{matrix} \right]_{2/3}$$

Natural Mass Hierarchy between top & bottom

- Consider an additional multiplet Ψ_b with X = -1/3.

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

Natural Mass Hierarchy between top & bottom

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$$\sin\beta$$

- Mix it with Ψ_t on the UV boundary,
  so that the Higgs pairs up b_L and b_R through $\sin\beta$.

$$\frac{m_b^2}{m_t^2} \sim \tan^2\beta \times \left(\frac{z_0}{z_R}\right)^{2(c_b - c_t)}$$

- β of order-one can still give a large mass hierarchy, if $c_b > c_t$.
- Large c_b means a very composite b_R
  → possibly, sizable cross section deviations

Natural Mass Hierarchy between top & bottom

- Consider an additional multiplet Ψ_b with X = -1/3.

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

- Custodial symmetry for $Z \to bb$ Agashe, Contino, Da Rold, Pomarol

$$\begin{aligned} b_L &: T^{3L} = T^{3R} = -\frac{1}{2} \\ b_R &: T^{3L} = T^{3R} = 0 \end{aligned} \qquad \Longrightarrow \qquad \delta Q = 0$$

- The effects of the RS structure come only from the contact term.

Cross Sections of $e^+e^- \to b\bar{b}$

- At a linear collider with polarized beams, we can measure independently all four helicity cross sections.

$$\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \to b\bar{b}) = \Sigma_{LL}(s)\ (1+\cos\theta)^2 + \Sigma_{LR}(s)(1-\cos\theta)^2$$

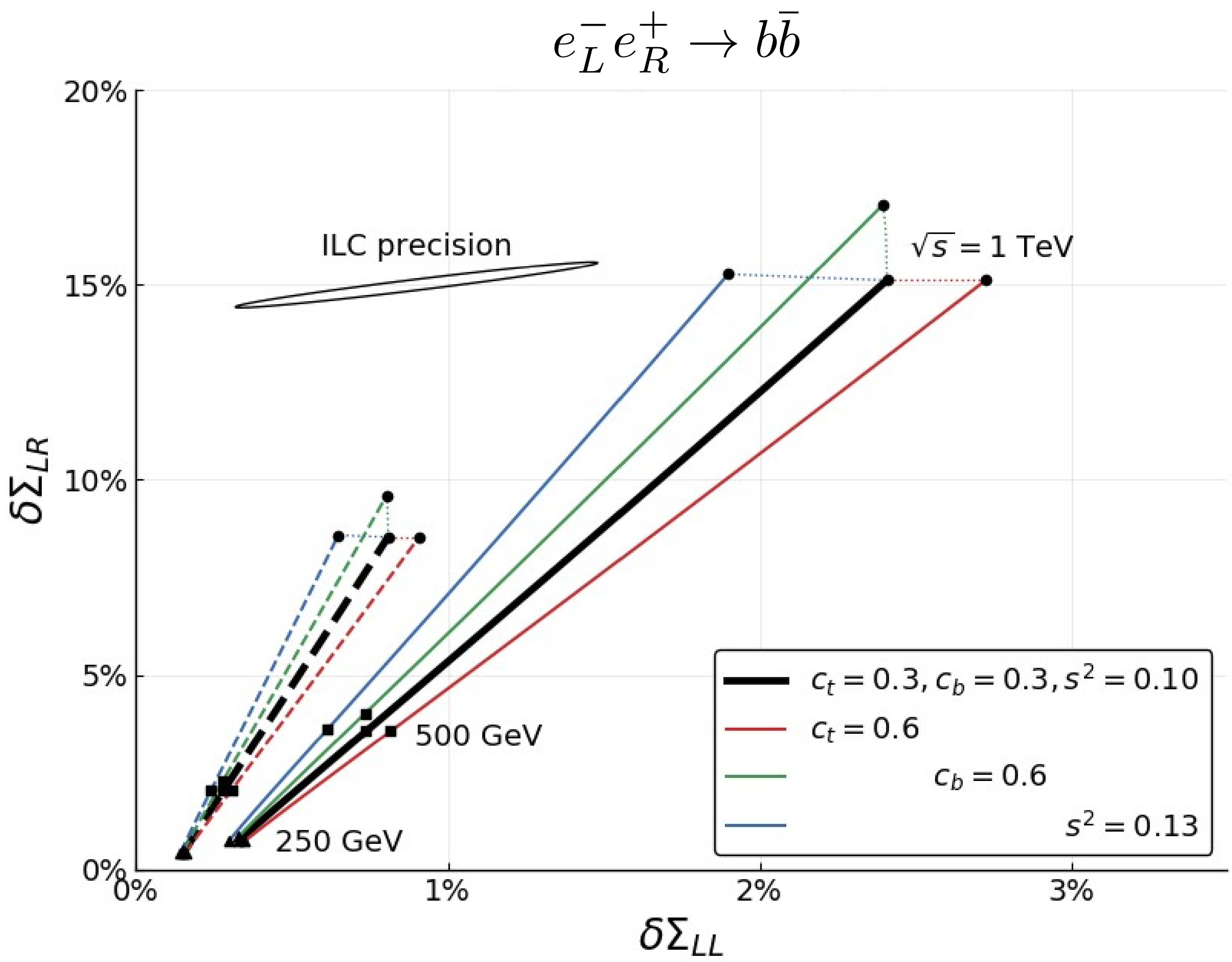
$$\frac{d\sigma}{d\cos\theta}(e^-_R e^+_L \to b\bar{b}) = \Sigma_{RL}(s)\ (1-\cos\theta)^2 + \Sigma_{RR}(s)(1+\cos\theta)^2$$

- Study deviations of the RS models compared to the SM.

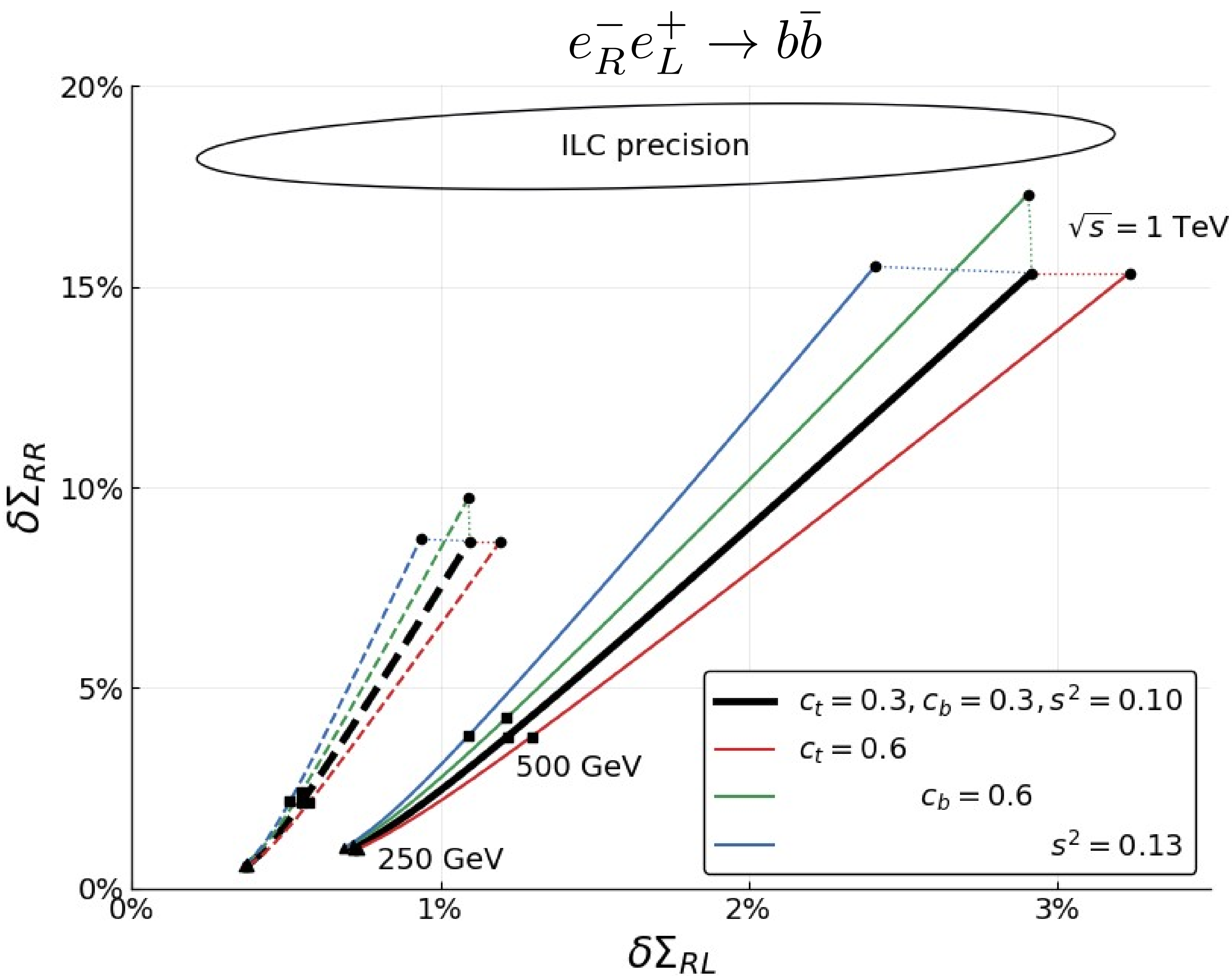
$$\delta\Sigma = \frac{\Delta\Sigma}{\Sigma_{SM}}$$

Cross Sections of $e^+e^- \to b\bar{b}$

- The parameter space depends on four parameters: $k_R,\ c_b,\ c_t,\ s^2$
  - k_R : scale of the new strong interaction.
    The most optimistic choice from S parameter: $k_R = 1.5\ \mathrm{TeV}$
    larger k_R → suppressed deviations $\delta\Sigma$
  - c_b : determines the 5D shape of b_R
    larger c_b → more composite b_R → larger $\delta\Sigma_{LR,RR}$
  - c_t : determines the 5D shape of b_L
    larger c_t → more composite b_L to fit m_t → larger $\delta\Sigma_{LL,RL}$
  - s^2 : proportional to the strength of the new strong interaction
    larger s^2 → more elementary b_L to fit m_t → smaller $\delta\Sigma_{LL,RL}$



$e^-_L e^+_R \to b\bar{b}$
20%
15%
10%
5%
0%
0%
1%
2%
3%
$\delta\Sigma_{LR}$
$\delta\Sigma_{LL}$
ILC precision
$\sqrt{s} = 1$ TeV
500 GeV
250 GeV
$c_t = 0.3, c_b = 0.3, s^2 = 0.10$
$c_t = 0.6$
$c_b = 0.6$
$s^2 = 0.13$



$e^-_R e^+_L \to b\bar{b}$
ILC precision
$\sqrt{s} = 1$ TeV
500 GeV
250 GeV
$c_t = 0.3, c_b = 0.3, s^2 = 0.10$
$c_t = 0.6$
$c_b = 0.6$
$s^2 = 0.13$
$\delta\Sigma_{RR}$
$\delta\Sigma_{RL}$
20%
15%
10%
5%
0%
0%
1%
2%
3%

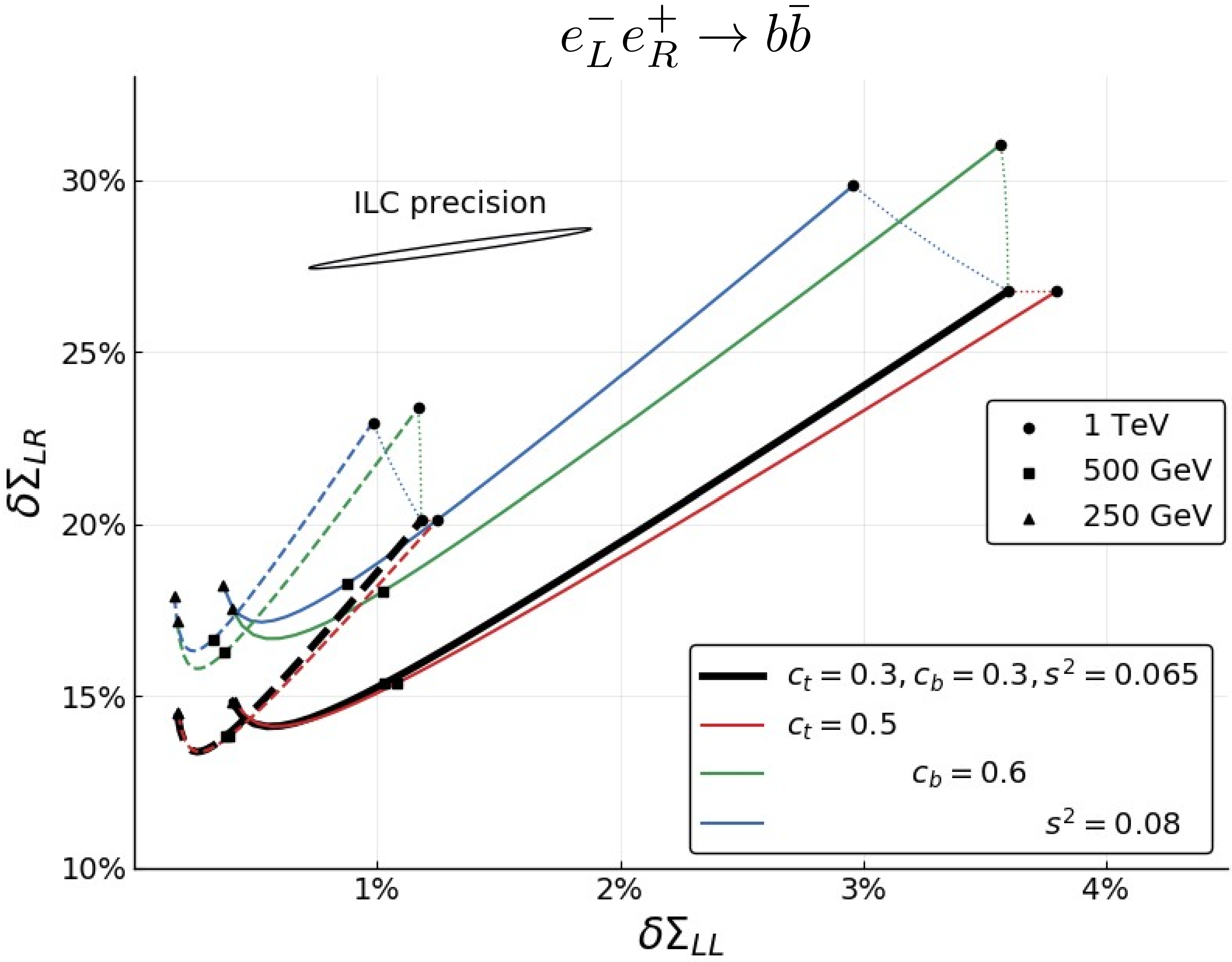
b_R in 4 of SO(5)

- Nonzero δQ if b_L or b_R is embeded in 4 of SO(5).
- b_L in 4 is unfavored by $Z \to bb$ constraints unless $k_R > 3\ \mathrm{TeV}.$
- b_R in 4 is also constrained, but a substantial parameter space remains still at $k_R = 1.5\ \mathrm{TeV}.$

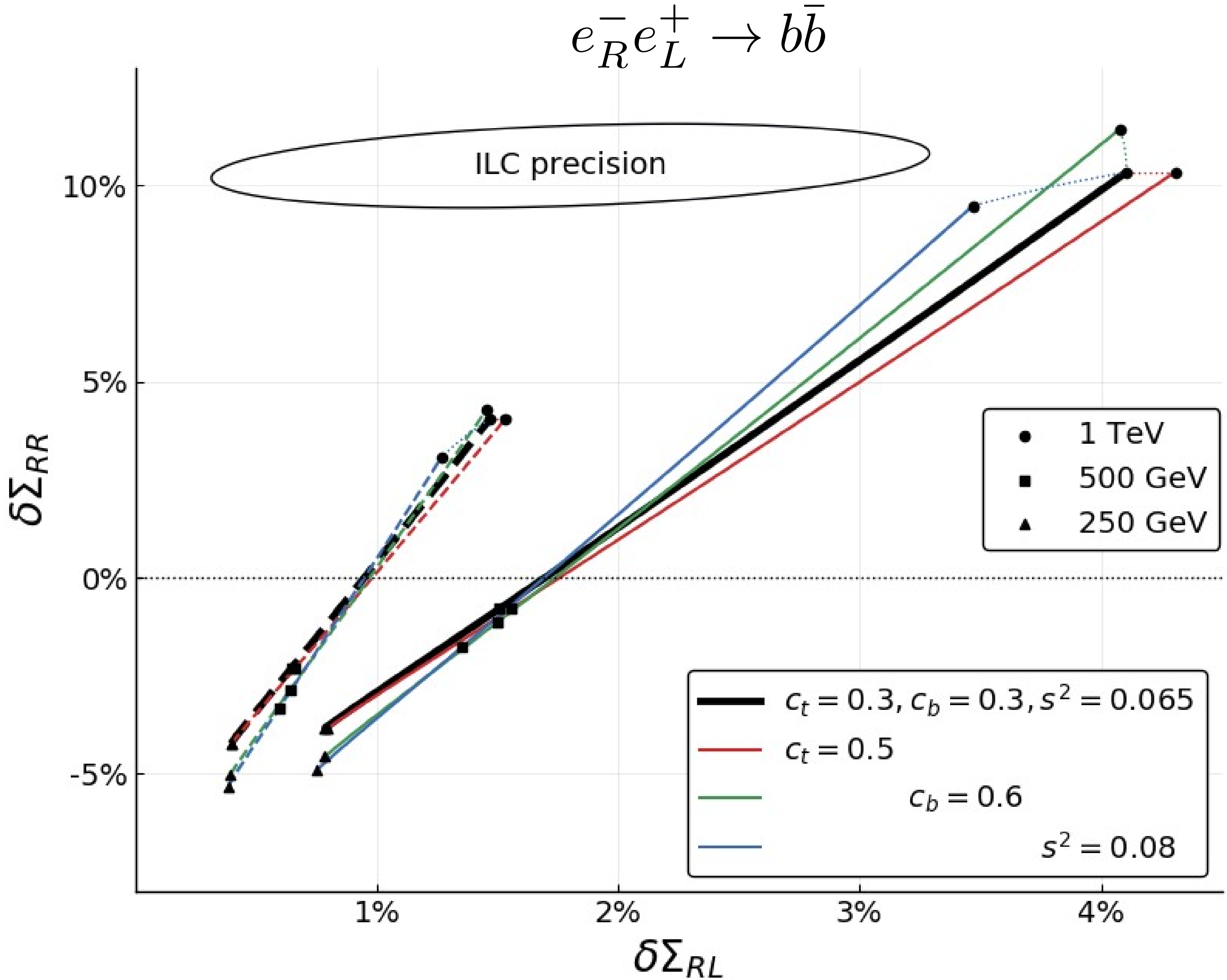
$$\delta Q^{\mathbf{4}}_{b_R} = -\frac{s^2}{4}\left(\frac{1+2c_b}{3+2c_b}\right)$$

- The effect of nonzero δQ is largest on the Z pole.
- We consider a case with b_L in 5 and b_R in 4 of SO(5).

$$\Psi_t = \begin{bmatrix} \begin{pmatrix} \chi_t(-+) & t_L(++) \\ \chi_b(-+) & b_L(++) \end{pmatrix} \\ t_R(--) \end{bmatrix}_{2/3} \qquad \Psi_b = \begin{bmatrix} t'_L(-+) \\ b'_L(-+) \\ t'_R(-+) \\ b_R(--) \end{bmatrix}_{1/6}$$



$e^-_L e^+_R \to b\bar{b}$
ILC precision
1 TeV
500 GeV
250 GeV
$c_t = 0.3, c_b = 0.3, s^2 = 0.065$
$c_t = 0.5$
$c_b = 0.6$
$s^2 = 0.08$
30%
25%
20%
15%
10%
1%
2%
3%
4%
$\delta\Sigma_{LR}$
$\delta\Sigma_{LL}$



$e^-_R e^+_L \to b\bar{b}$
ILC precision
10%
5%
0%
-5%
1%
2%
3%
4%
$\delta\Sigma_{RR}$
$\delta\Sigma_{RL}$
1 TeV
500 GeV
250 GeV
$c_t = 0.3, c_b = 0.3, s^2 = 0.065$
$c_t = 0.5$
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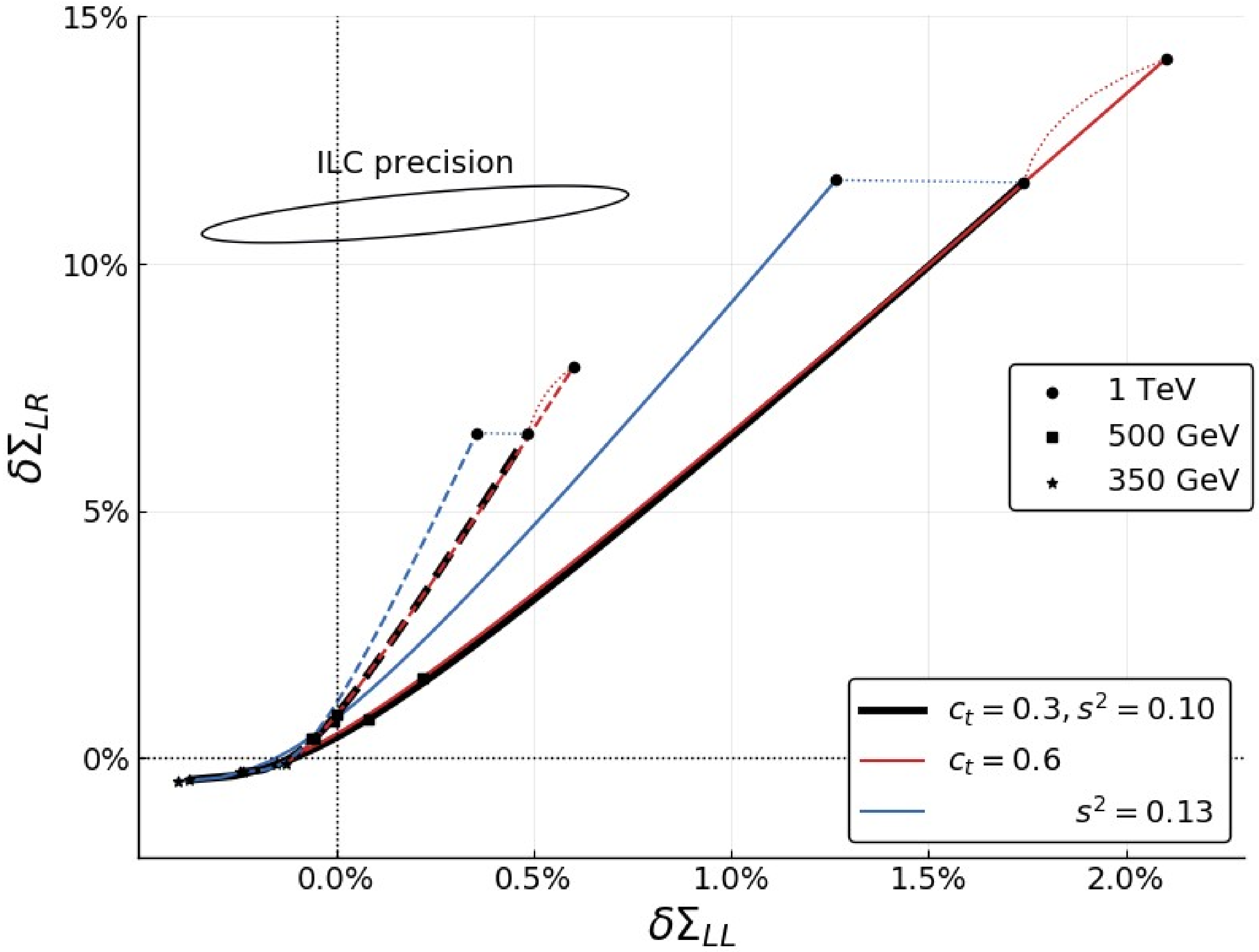
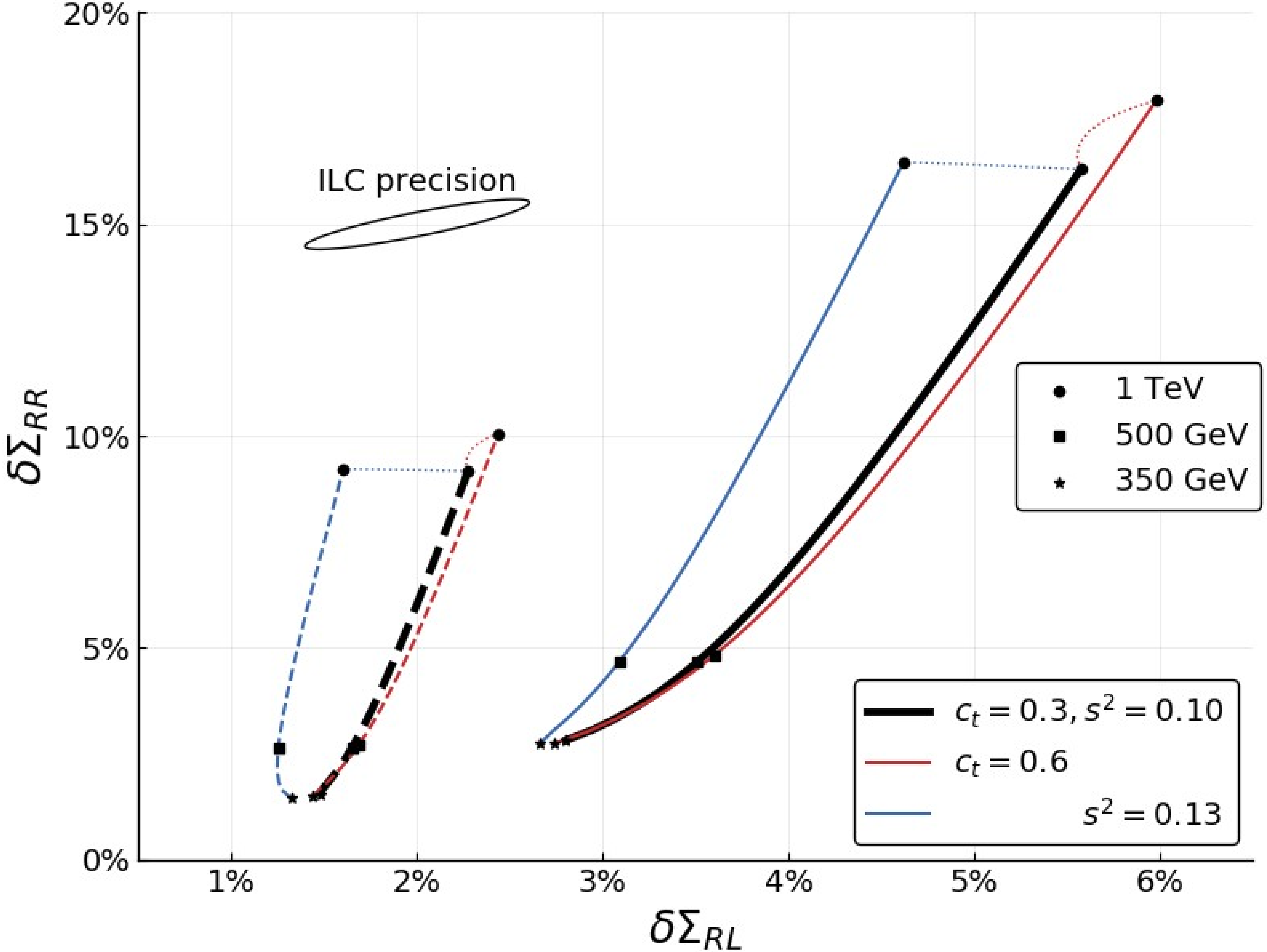
$s^2 = 0.08$

Cross Sections of $e^+e^- \to t\bar{t}$

- Further complications due to the top quark mass.



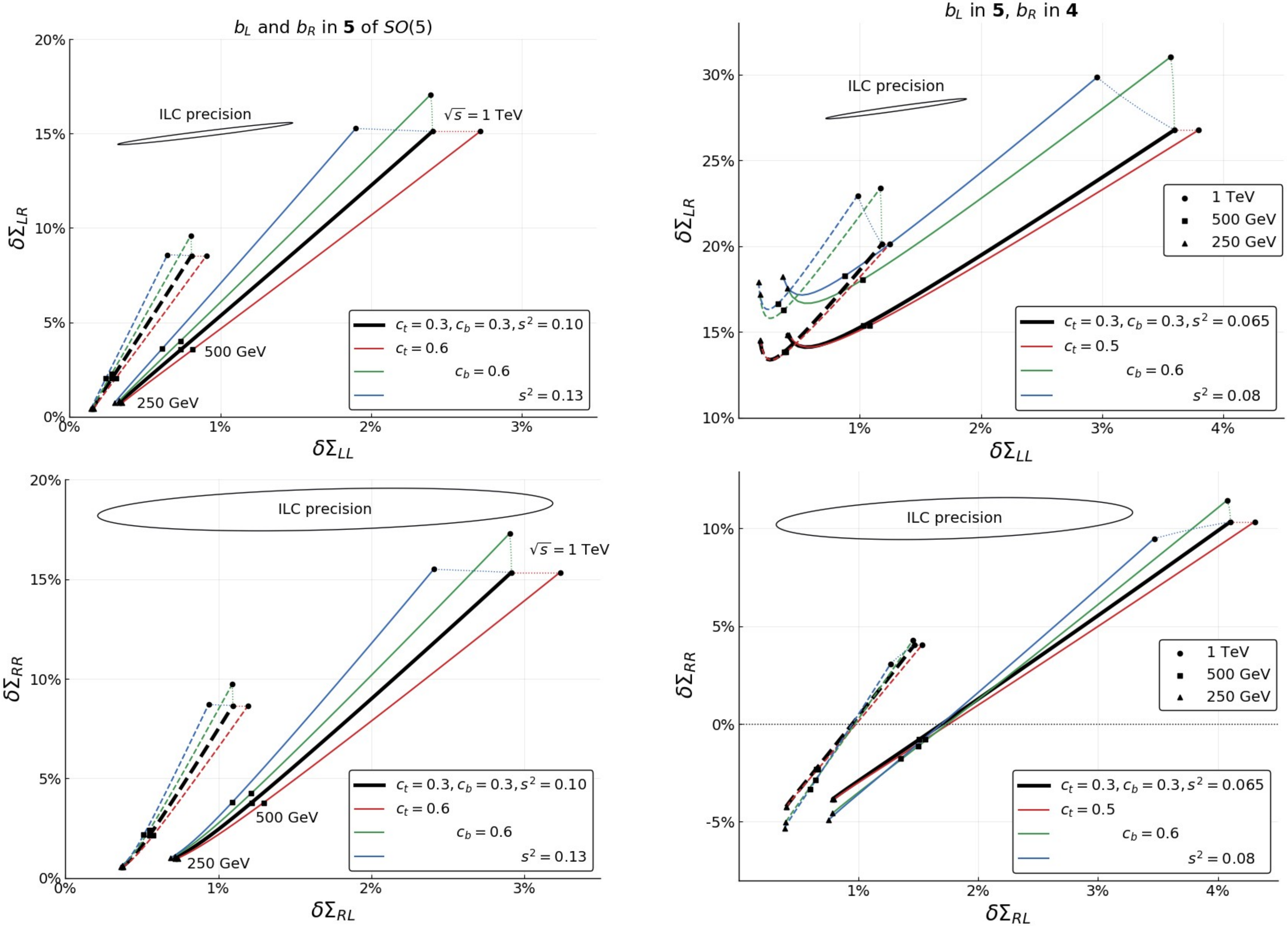


ILC precision
1 TeV
500 GeV
350 GeV
$c_t = 0.3, s^2 = 0.10$
$c_t = 0.6$
$s^2 = 0.13$
20%
15%
10%
5%
0%
1%
2%
3%
4%
5%
6%
$\delta\Sigma_{RR}$
$\delta\Sigma_{RL}$

Summary

- Gauge-Higgs unification models in AdS5 gives a calculable and predictive approach to 4D composite Higgs models.
- $e^+e^- \to f\bar{f}$ processes at linear colliders offer a unique window into new physics, due to its simple cross section, polarized beams, and excellent heavy flavor identification.
- Through an analytic understanding of the RS propagators, we can identify the main sources of deviations from the SM and study quantitatively effect of each parameter.
- There are scenarios in which the expected deviation is already sizable at $\sqrt{s} = 250\,\mathrm{GeV}$.

THANK YOU



b_L and b_R in **5** of $SO(5)$
$\delta\Sigma_{LR}$
$\delta\Sigma_{LL}$
20%
15%
10%
5%
0%
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1%
2%
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ILC precision
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$c_t = 0.6$
$c_b = 0.6$
$s^2 = 0.13$
b_L in **5**, b_R in **4**
$\delta\Sigma_{LR}$
$\delta\Sigma_{LL}$
30%
25%
20%
15%
10%
1%
2%
3%
4%
ILC precision
1 TeV
500 GeV
250 GeV
$c_t = 0.3, c_b = 0.3, s^2 = 0.065$
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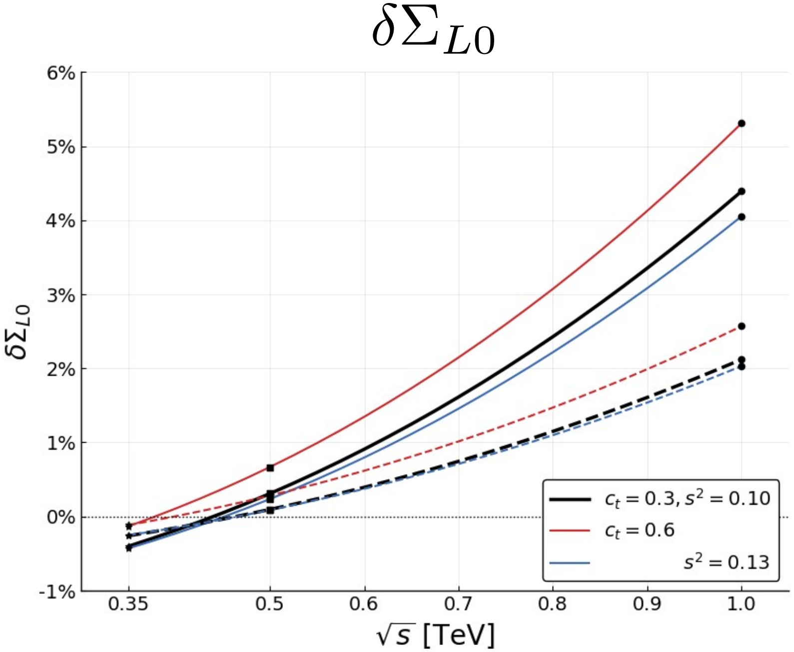
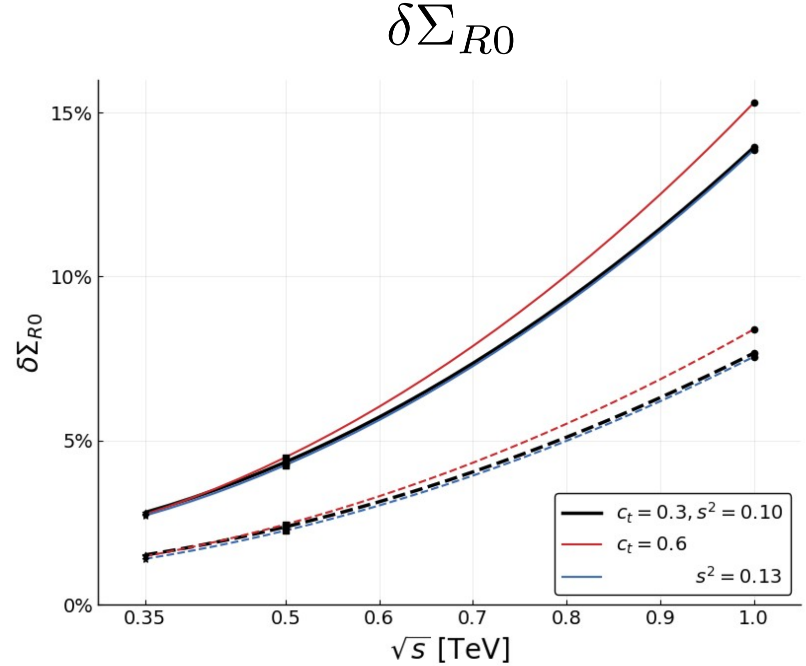
$s^2 = 0.08$

Cross section deviations in the helicity-flip final states $t_L\bar{t}_L, t_R\bar{t}_R$





Cross Sections of $e^+e^- \to t\bar{t}$

- Three further effects due to the top quark mass:
  1) The mass term mixes the left- and right-chirality 5D wavefunctions.
  2) Each helicity amplitude is a combination of both of the 5D Dirac fermions (t_L, t_R).
  3) Nonzero matrix element from T^{35}