Extracting Higgs Couplings from e+e- Data at 250 GeV and Above

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There are many reasons to expect new interaction beyond those of the Standard Model

dark matter, origin of electroweak symmetric breaking, baryon/antibaryon excess, origin of the quark and lepton mass spectrum

New physics is out there somewhere. How do we get there ?

Plan A:

The scale of electroweak symmetry breaking — 250 GeV — is the milestone.   Build a collider that can produce new particles in that energy range.

Now we have this collider, and the plan is not working out so well. Nevertheless, with higher event samples at LHC, there is still opportunity.

Plan B:

Study the most mysterious particles of the Standard Model, Higgs and Top, with high precision.

first science driver of the US P5 strategic plan:
"Use the Higgs boson as a new tool for discovery"

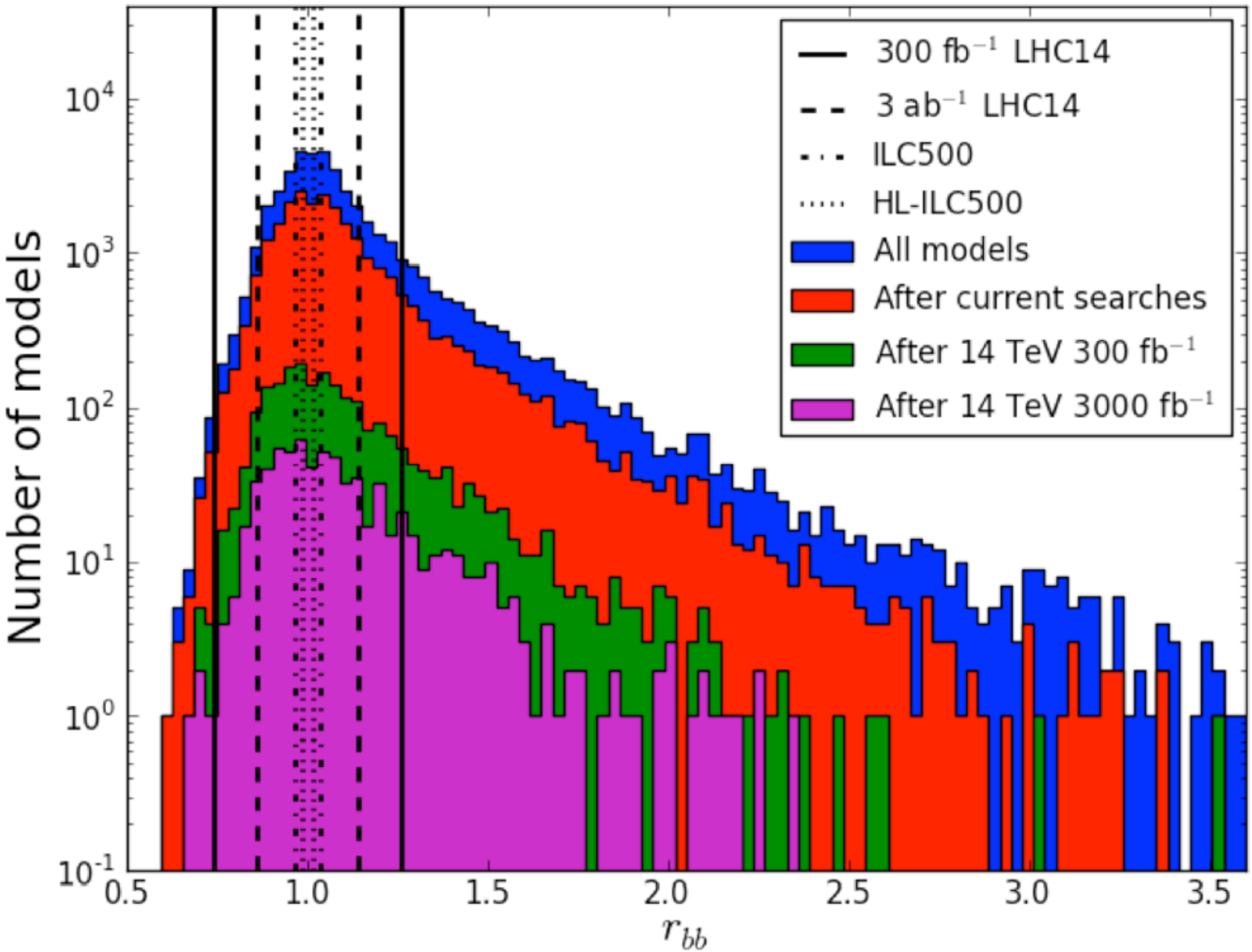
This requires high precision in Higgs boson measurements. Typically, BSM effects are less than 10% in Higgs couplings (Decoupling Theorem). The current level of agreement of Higgs couplings with the Standard Model is completely to be expected. To discover BSM effects, we likely need levels of precision possible only with e+e- colliders.

These two plans move in orthogonal directions. They target different classes of models.

Both are potentially can break through to new physics beyond the Standard Model, and give us rich information about what is there.

High energy physics desperately needs concrete information about what is beyond the Standard Model. We should be pursuing both paths.

$\Gamma(h \to b\bar{b})/(SM)$



Cahill-Rowley, Hewett, Ismail, Rizzo

Each Higgs coupling has its own personality and is guided by different types of new physics. This is something of a caricature, but, still, a useful one.

fermion couplings - multiple Higgs doublets

gauge boson couplings - Higgs singlets, composite Higgs

γγ, gg couplings - heavy vectorlike particles

tt coupling - Higgs/top compositeness

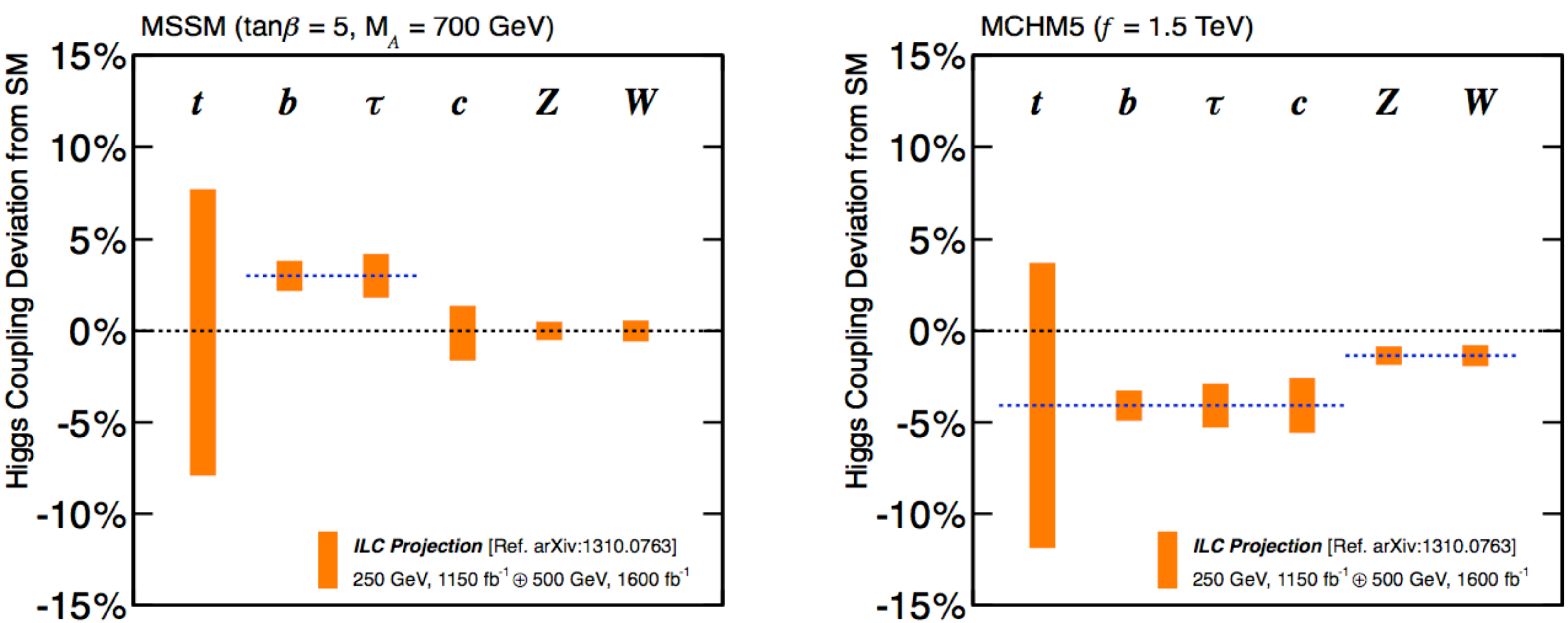
hhh coupling (large deviations) - baryogenesis

This means that the precision study of Higgs is multi-dimensional.

Models of new physics predict patterns of deviations from the SM predictions that are different for different schemes.

For example:

SUSY　　　　Composite Higgs



Kanemura, Tsumura, Yagyu, Yokoya

In this talk, I would like to discuss a technical aspect of this program. Once we have data on Higgs production cross sections in e+e-, how do we extract the Higgs couplings ?

Our standard method, used in the ILC TDR, CLIC CDR, ILC white paper for Snowmass:

Multiply each SM Higgs coupling by a parameter κ_I ,
10 parameters in all, fit these to the e+e- rates.

$$\sigma(e^+e^- \to Zh) \sim \kappa_Z^2$$

gives the absolute scale of couplings, and gives the hZZ coupling directly. Other Higgs couplings can be extracted from branching ratios and from

$$\frac{\sigma(e^+e^- \to Zh)}{BR(h \to ZZ)} \sim \Gamma_h$$

Unfortunately, this method is not actually model-independent. The hZZ coupling can actually contain two distinct structures:

$$\mathcal{L} = \eta_Z \frac{2m_Z^2}{v} h Z_\mu Z^\mu + \zeta_Z \frac{h}{v} Z_{\mu\nu} Z^{\mu\nu}$$

The possible presence of ζ_Z ruins the simple relation between the h production cross section and the decay width:

$$\begin{aligned}
\sigma(e^+e^- \to Zh) &= (SM) \cdot (1 + 2\eta_Z + (5.5)\zeta_Z) \\
\Gamma(h \to WW^*) &= (SM) \cdot (1 + 2\eta_W - (0.78)\zeta_W) \\
\Gamma(h \to ZZ^*) &= (SM) \cdot (1 + 2\eta_Z - (0.50)\zeta_Z) \ ,
\end{aligned}$$

To resolve this problem, we need a way to constraint the parameter ζ_Z .

We can do this by taking advantage of SU(2)xU(1) gauge invariance. The SM is the most general gauge-invariant Lagrangian with dimension 4 terms only. Parametrize new physics by adding the most general set of dimension 6 gauge-invariant operators. This introduces 84 new unknown coefficients.

Fortunately, the number of operators needed for the analysis of Higgs couplings is only

9 operators modifying h, γ, W, Z interactions
5 operators modifying h coupling to b, c, τ, μ, g

plus 2 parameters accounting invisible and exotic Higgs decays.

There is one more operator that shifts the triple Higgs coupling. It does not enter this analysis.

I ignore leptonic current-current interactions. This assumption is testable with $e^+e^- \to \mu^+\mu^-$. I ignore CP violating interactions. These can be bounded independently and enter this analysis only in quadratic terms.

I work at the tree level and to linear order in dimension-6 coefficients.

Coming soon to an arXiv near you:

Improved Formalism for Precision Higgs Coupling Fits

Tim Barklow, Gautier Durieux, Keisuke Fujii, Christophe Grojean, Jaiyin Gu, Sunghoon Jung, Robert Karl, Jenny List, Tomohisa Ogawa, Michael E. Peskin, Junping Tian, and Kechen Wang

We use this set of 10 operators for h, γ, W, Z. This is a small modification of the "Warsaw basis" of Grzadkowski, Iskrzynski, Misiak, and Rosiek.

$$
\begin{aligned}
\Delta\mathcal{L} = & \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 \\
& + \frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu} \\
& + \frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu} \\
& + i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + +4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L) \\
& + i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .
\end{aligned}
$$

The only effect of c_6 is to shift the triple Higgs coupling.

The dimension-6 operator coefficients shift the Standard Model parameters, so we must add the 4 important Standard Model parameters to the fit.

$$g, g', v, \lambda$$

In all, our fit has 4 + 9 + 5 + 2 = 20 parameters.

However, information from e+e- colliders is very rich. We can determine these 20 parameters using information from precision EW, $e^+e^- \to W^+W^-$ and single-h production processes. So this analysis has a beautiful interplay of all aspects of e+e- physics.

Precision electroweak inputs:

$$\alpha(m_Z), G_F, m_W, m_Z, m_h, A_{LR}(\ell), \Gamma(Z \to \ell^+\ell^-)$$

Inputs from $e^+e^- \to W^+W^-$: (5 phenomenological parameters, but 2 relations within the deviations due to dimension 6 operators:

$$g_{1Z}, \kappa_A, \lambda_A$$

An important input from LHC:

$$BR(h \to \gamma\gamma)/BR(h \to ZZ)$$

These give 11 very tight constraints on the 4+9 parameters for h, γ, W, Z interactions.

The 2 parameters that remain to be determined are:

$$c_H : \qquad \eta_W = \eta_Z = (1 - \frac{1}{2} c_H)$$

(Higgs field strength renormalization; appears in all Higgs couplings)

$$c_{WW} : \qquad \zeta_W = 8 c_{WW}$$

coefficient of the hWW and hZZ interaction through gauge field strengths.

We can determine these from measurements of

$$e^+ e^- \to Zh$$

Total cross section for $e^+e^- \to Zh$

$$\sigma = \frac{2}{3}\frac{\pi\alpha_w^2}{c_w^4}\frac{m_Z^2}{(s-m_Z^2)}\frac{2k_Z}{\sqrt{s}}(2+\frac{E_Z^2}{m_Z^2})\cdot Q_Z^2 \cdot \left[1+2a+2\,\frac{3\sqrt{s}E_Z/m_Z^2}{(2+E_Z^2/m_Z^2)}\,b\right]$$

The a and b coefficients depend on beam polarization:

$e_L^- e_R^+$

$$Q_{ZL} = (\frac{1}{2}-s_w^2)\ , \qquad a_L = -c_H$$

$$b_L = c_w^2(1+\frac{s_w^2}{1/2-s_w^2}\frac{s-m_Z^2}{s})(8c_{WW})$$

$e_R^- e_L^+$

$$Q_{ZR} = (-s_w^2)\ , \qquad a_R = -c_H$$

$$b_R = c_w^2(1-\frac{s-m_Z^2}{s})(8c_{WW})$$

Also, a produces a $\sin^2\theta$ angular distribution and dominantly longitudinal Z polarization. This is a small effect at 250 GeV but becomes larger at higher energy.

Simplified fit with only c_H, c_{WW}, plus parameters for b, c, g, τ, μ, invisible and exotic Higgs decays. We input the ILD full simulation expectations for 250 GeV, 2 ab-1. Higgs coupling errors in % :

	κ fit	pol. only	angl. only	both	full EFT fit
$g(hb\bar{b})$	3.4	1.2	3.7	1.2	1.5
$g(hc\bar{c})$	3.6	1.9	4.0	1.9	2.1
$g(hgg)$	3.6	1.7	3.9	1.7	1.9
$g(hWW)$	3.6	0.45	3.5	0.43	1.0
$g(h\tau\tau)$	3.4	1.3	3.7	1.3	1.6
$g(hZZ)$	3.6	0.44	3.3	0.42	1.0
$g(h\mu\mu)$	13	13	15	13	14
$g(hb\bar{b})/g(hWW)$	1.2	1.1	1.2	1.1	1.1
$g(hWW)/g(hZZ)$	3.5	0.19	0.24	0.19	0.033
Γ_h	6.9	2.6	7.2	2.6	3.1
$\sigma(e^+e^- \to Zh)$	0.71	0.71	0.83	0.70	0.70
$BR(h \to inv)$	0.3	0.3	0.4	0.3	0.3
$BR(h \to other)$	1.6	1.6	1.9	1.6	1.6

Now consider the full 20-parameter fit:

ILC 250 GeV, 2 ab-1 80% / 30 % polarization

compare this to:

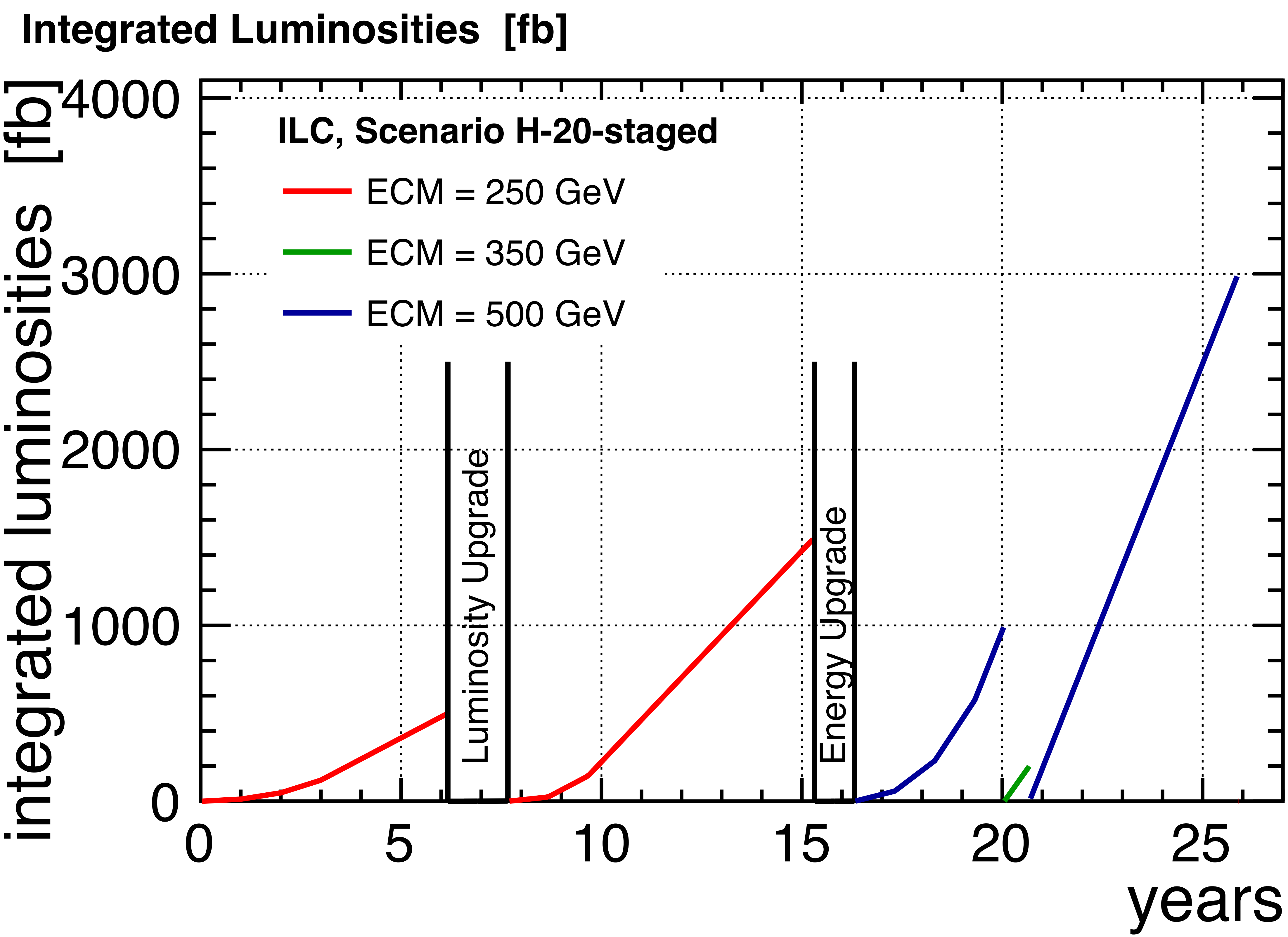
CLIC 380 GeV, 2 ab-1 80%/0% polarization

CEPC 250 GeV, 5 ab-1, 0 polarization

FCC-ee 250 GeV 20 ab-1, 0 polarization

full ILC, above + 500 GeV, 4 ab-1, 80%/30% polarization

a possible ILC run plan with staging (Jenny List)



	2 ab^{-1} w. pol.	2 ab^{-1} 380 GeV	5 ab^{-1} no pol.	20 ab^{-1} no pol.	full ILC 250+500 GeV
$g(hb\bar{b})$	1.5	1.2	1.1	0.7	0.6
$g(hc\bar{c})$	2.1	3.7	1.5	0.8	1.1
$g(hgg)$	1.9	2.0	1.4	0.8	0.9
$g(hWW)$	1.0	0.53	0.8	0.54	0.31
$g(h\tau\tau)$	1.6	2.0	1.2	0.7	0.8
$g(hZZ)$	1.0	0.53	0.8	0.53	0.31
$g(h\mu\mu)$	14	11	9.0	4.5	8.6
$g(hbb)/g(hWW)$	1.1	1.2	0.8	0.4	0.5
$g(hWW)/g(hZZ)$	0.033	0.029	0.036	0.03	0.02
Γ_h	3.1	2.6	2.3	1.3	1.5
$\sigma(e^+e^- \to Zh)$	0.70	0.56	0.49	0.25	0.56
$BR(h \to inv)$	0.3	0.5	0.3	0.2	0.3
$BR(h \to other)$	1.6	1.4	1.2	0.6	1.1

Is this good enough ?   Can we really have sensitivity to BSM physics ?

There will always be BSM models with very small modifications of the Higgs couplings. As the scale of new physics increases, any BSM model tends to the predictions of the Standard Model.

However, we can choose a variety of BSM models with new particle masses so large they cannot be seen at the HL-LHC and ask whether we can discover BSM in these models by modification of the Higgs couplings.

Our catalog:

- a PMSSM model with b squarks at 3.4 TeV, gluino at 4 TeV
- a Type II 2 Higgs doublet model with $m_A = 600 \text{ GeV}, \tan\beta = 7$
- a Type X 2 Higgs doublet model with $m_A = 450 \text{ GeV}, \tan\beta = 6$
- a Type Y 2 Higgs doublet model with $m_A = 600 \text{ GeV}, \tan\beta = 7$
- a Little Higgs model with T-parity with $f = 785 \text{ GeV}, m_T = 2 \text{ TeV}$
- a Little Higgs model with T-parity with couplings to 1st and 2nd generation with $f = 1 \text{ TeV}, m_T = 2 \text{ TeV}$

- A Higgs-radion mixing model with $m_r = 500\ \mathrm{GeV}$
- a model with a Higgs singlet at $2.8\ \mathrm{TeV}$ creating a Higgs portal to dark matter and large λ for electroweak baryogenesis

Higgs coupling modification in these models, in %

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [21]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.05	+0.1	+0.3
2	Type II 2HD [22]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [22]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [22]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Little Higgs w. T-parity [24]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
6	Little Higgs w. T-parity [25]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
7	Higgs-Radion [26]	-1.5	- 1.5	10.	-1.5	-1.5	-1.5	-1.0	-1.5
8	Higgs Singlet [27]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

χ^2 separation: χ^2 of one model if another is realized:

ILC 250 GeV, 2 ab-1:

	SM	1	2	3	4	5	6	7	8
SM	0	41	59	66	144	9.2	13	22	12
1	41	0	47	164	68	31	72	77	56
2	59	47	0	124	96	35	122	123	96
3	66	164	124	0	368	73	79	92	80
4	144	68	96	368	0	125	201	203	179
5	9.2	31	35	74	125	0	34	51	29
6	13	72	122	79	201	34	0	18	12
7	22	77	123	92	203	51	18	0	4.5
8	12	56	96	80	179	29	12	4.5	0

χ^2 separation: χ^2 of one model if another is realized:

ILC 250 GeV, 2 ab-1 + 500 GeV, 4 ab-1

	SM	1	2	3	4	5	6	7	8
SM	0	110	204	101	327	41	56	68	56
1	110	0	127	314	149	90	249	225	185
2	203	127	0	329	143	126	452	391	328
3	101	314	329	0	688	140	138	172	153
4	327	149	143	688	0	265	567	512	459
5	41	90	126	140	265	0	134	153	88
6	56	249	452	138	567	134	0	72	62
7	68	225	391	173	512	153	72	0	21
8	56	185	328	153	459	88	62	21	0

This program, and similar precision Higgs programs at other possible future e+e- colliders, allows us to discover new physics beyond the reach of LHC and to discriminate between possible models of new physics at high confidence.

More fodder for top enthusiasts:

At Top@LC2016, my student Jong-Min Yoon presented a new Randall-Sundrum model with innovations that allowed a large little hierarchy. We have studied that model in more detail in the past year. The paper will appear soon. Here are some snapshots.

The model has 8 parameters:

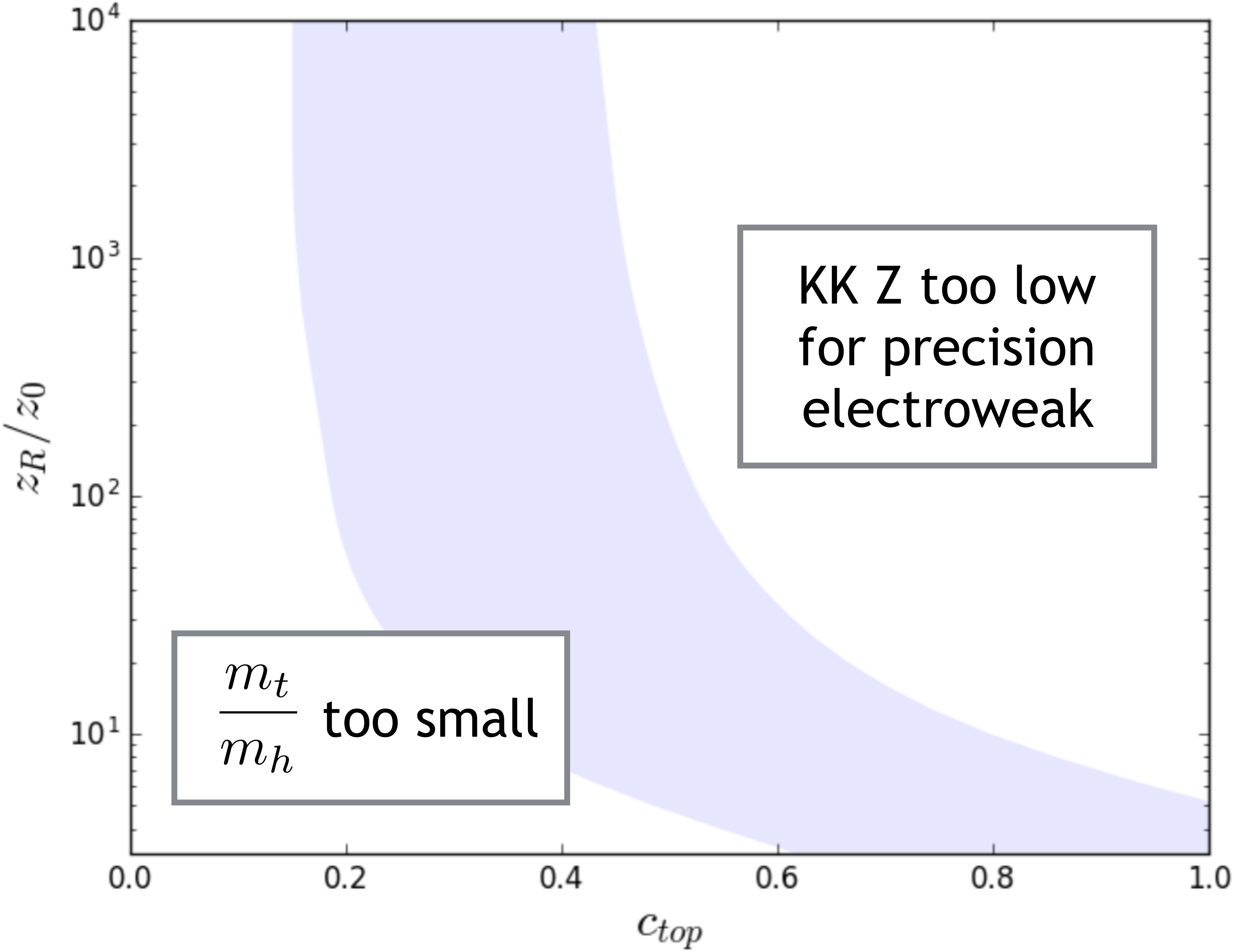
$$z_R,\ z_0,\ c_t,\ c_T,\ g_5,\ g_X,\ a_L,\ a_Y$$

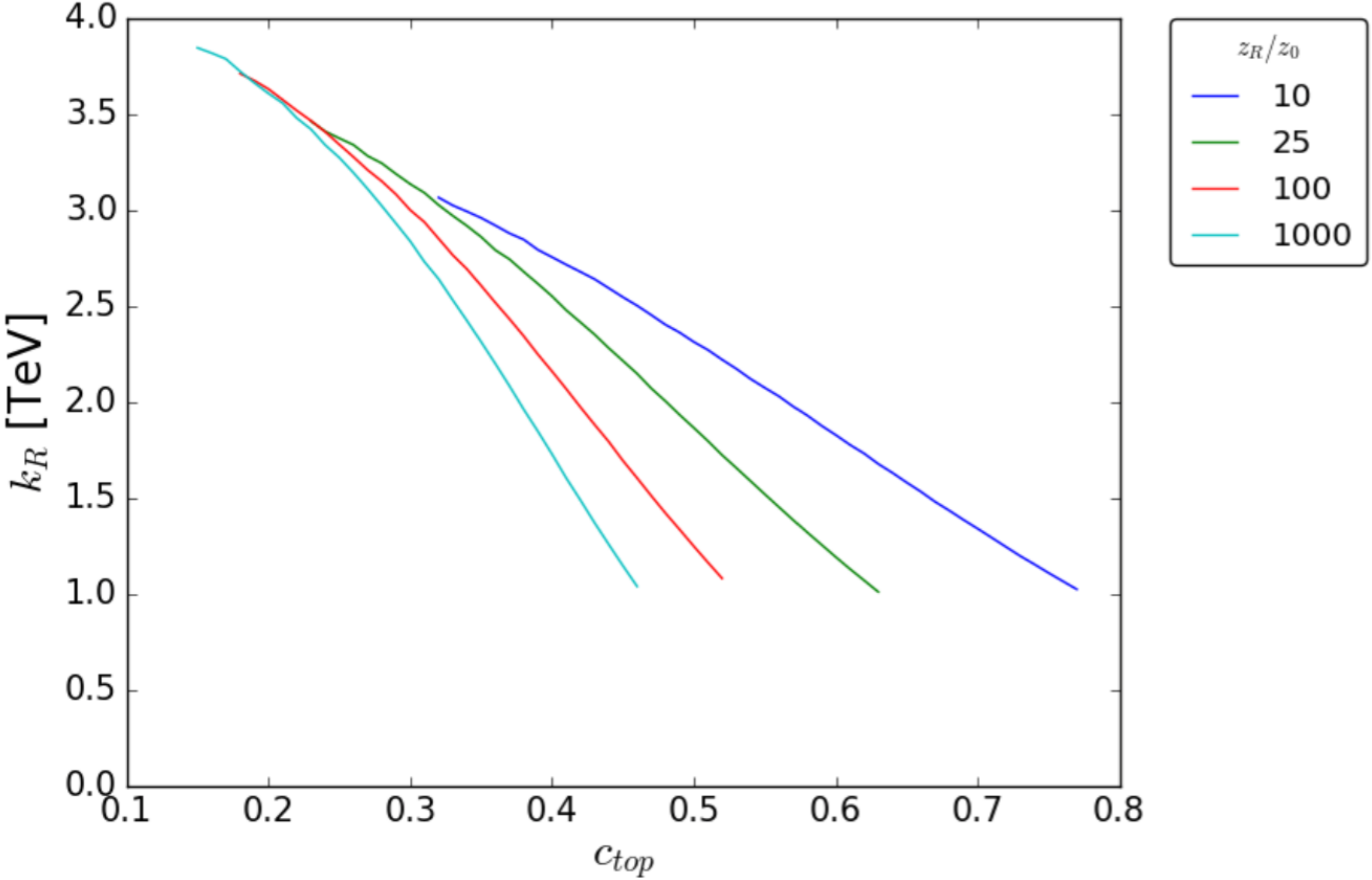
These are constrained by 5 observables:

$$e\ , m_W,\ m_Z,\ m_t\ , m_h$$

Also, the Higgs potential is quite independent of the parameter a_Y. So, effectively, we have a 2-dimensional parameter space.

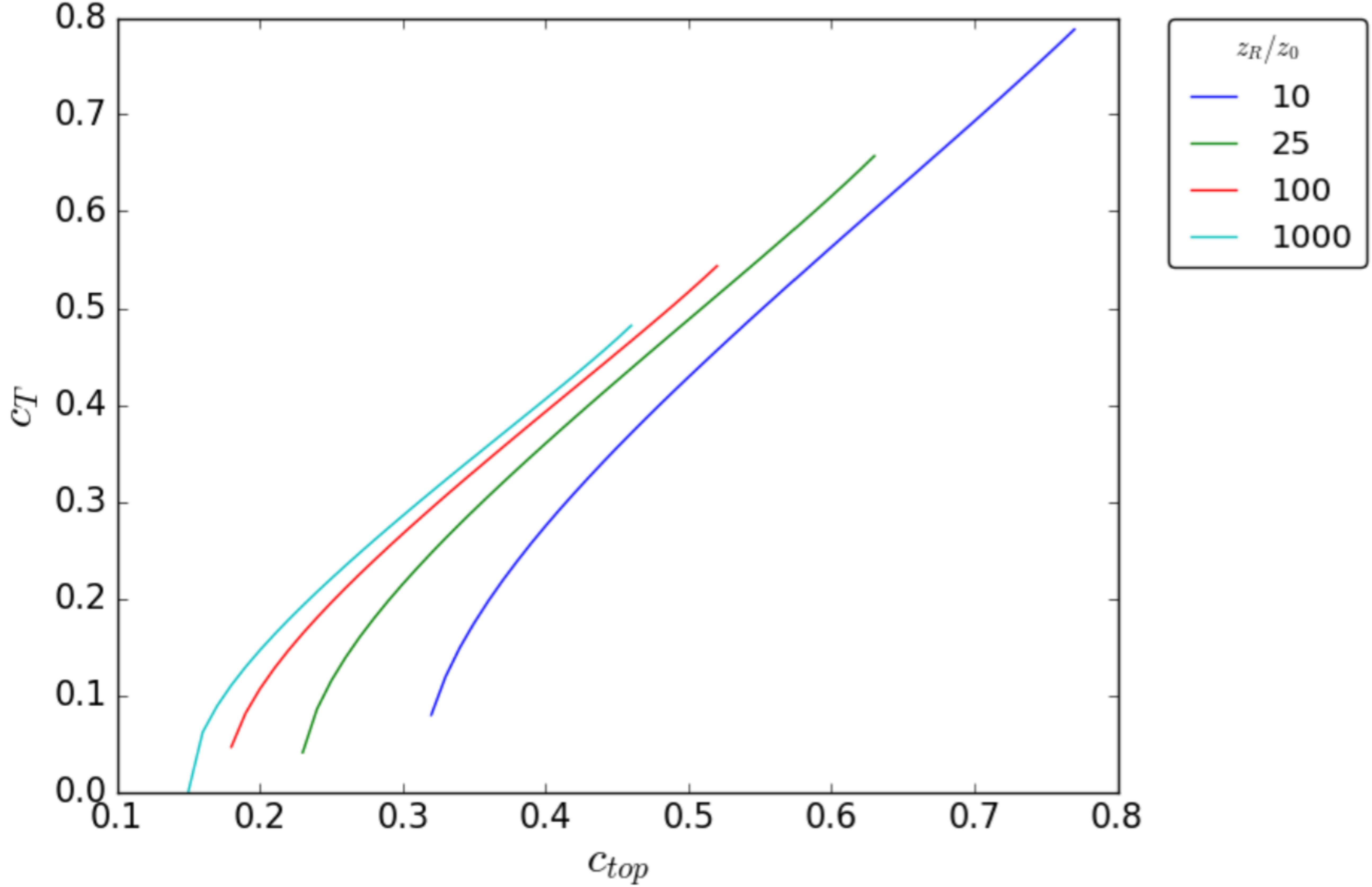
It is easiest to think of this parameter space as parametrized by the KK scale (a few times k_R) and the ratio z_R/z_0. This latter ratio is constrained by flavor physics, since light flavors will couple to the Higgs sector at the UV brane. We have not yet studied those constraints, so for the moment we propose $z_R/z_0 \sim 100$.


KK Z too low for precision electroweak
$\frac{m_t}{m_h}$ too small
z_R/z_0
c_{top}
10^4
10^3
10^2
10^1
0.0
0.2
0.4
0.6
0.8
1.0

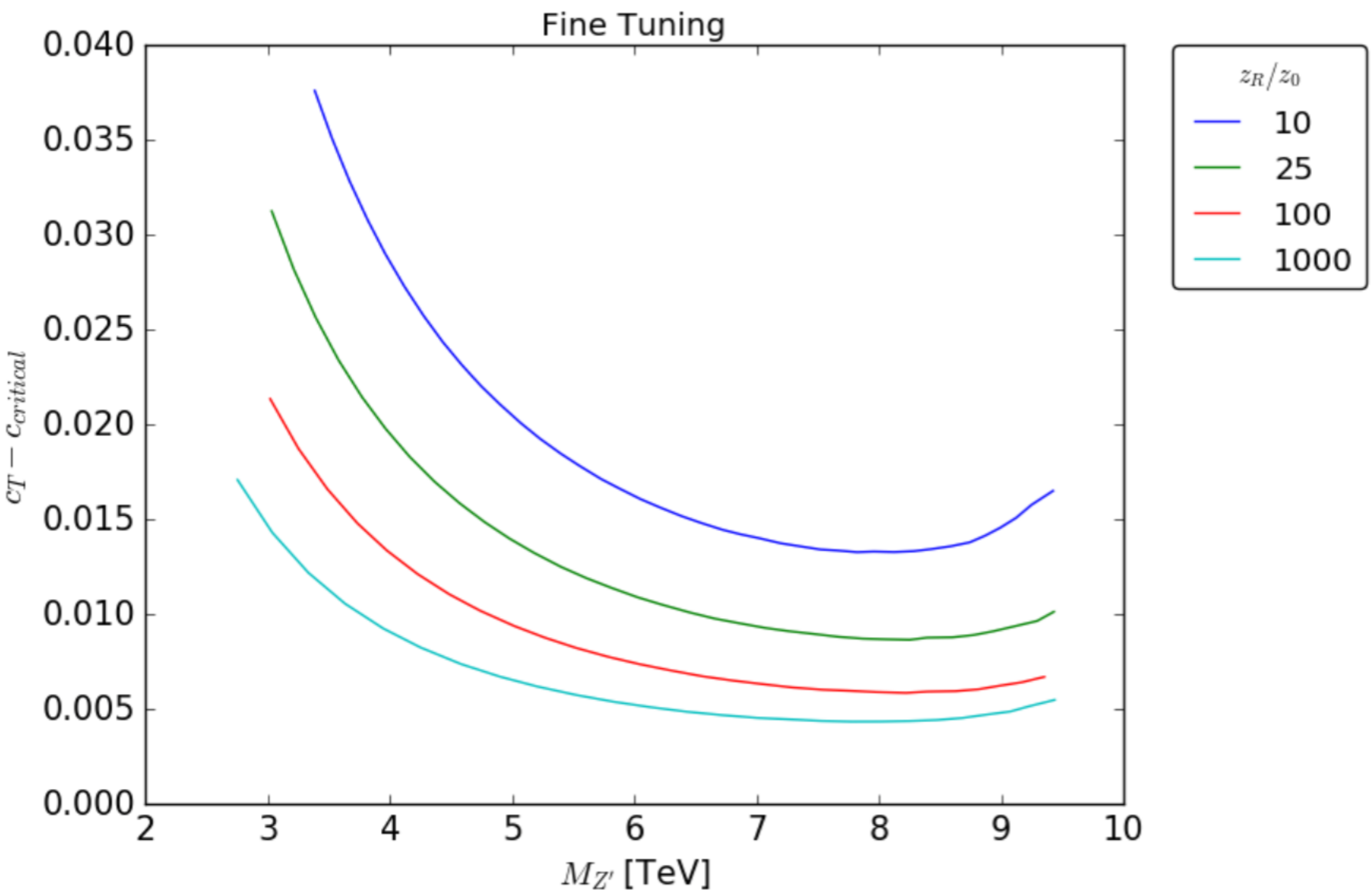


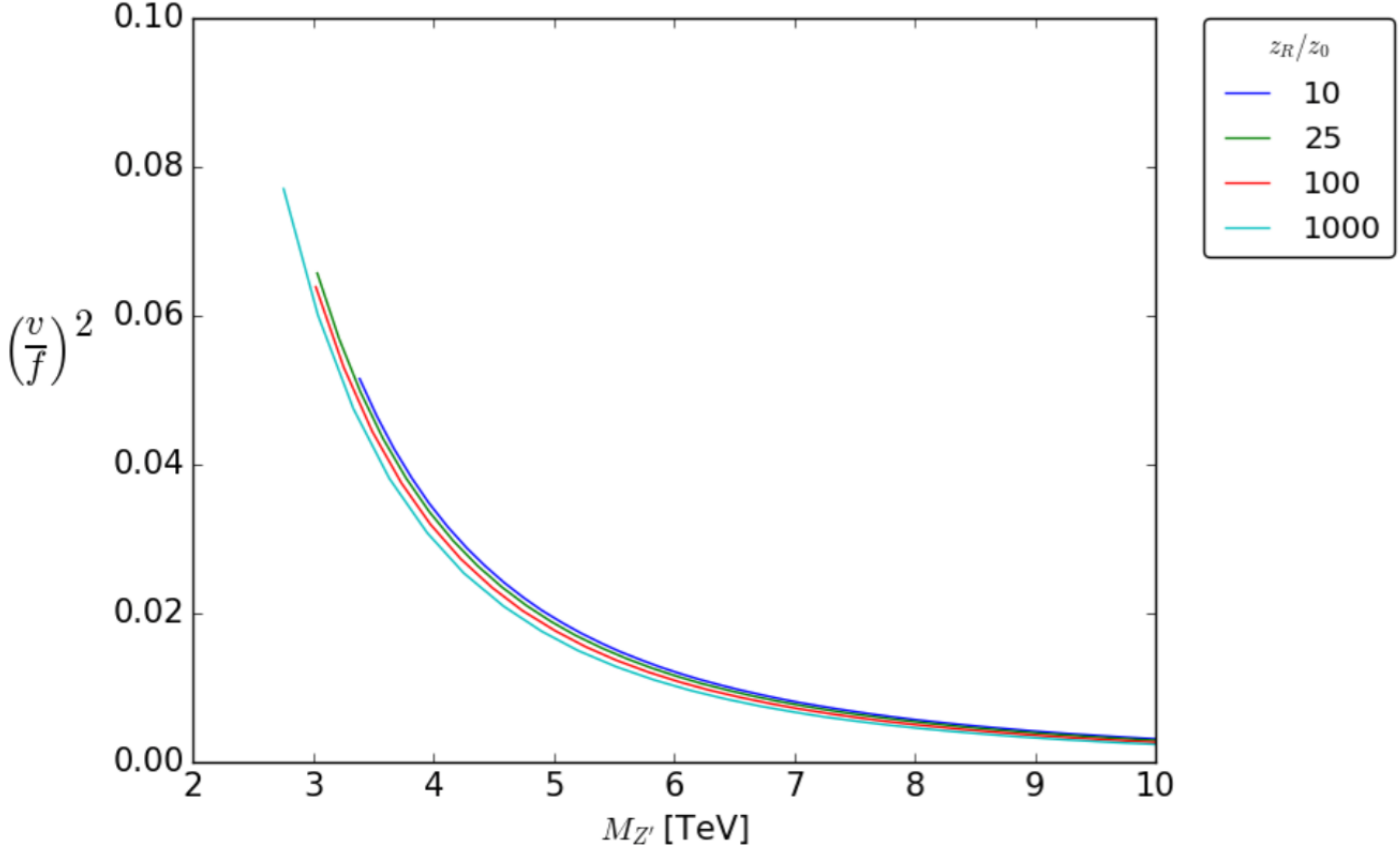
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
k_R [TeV]
c_{top}
z_R/z_0
10
25
100
1000

working points for $c_t,\ c_T$



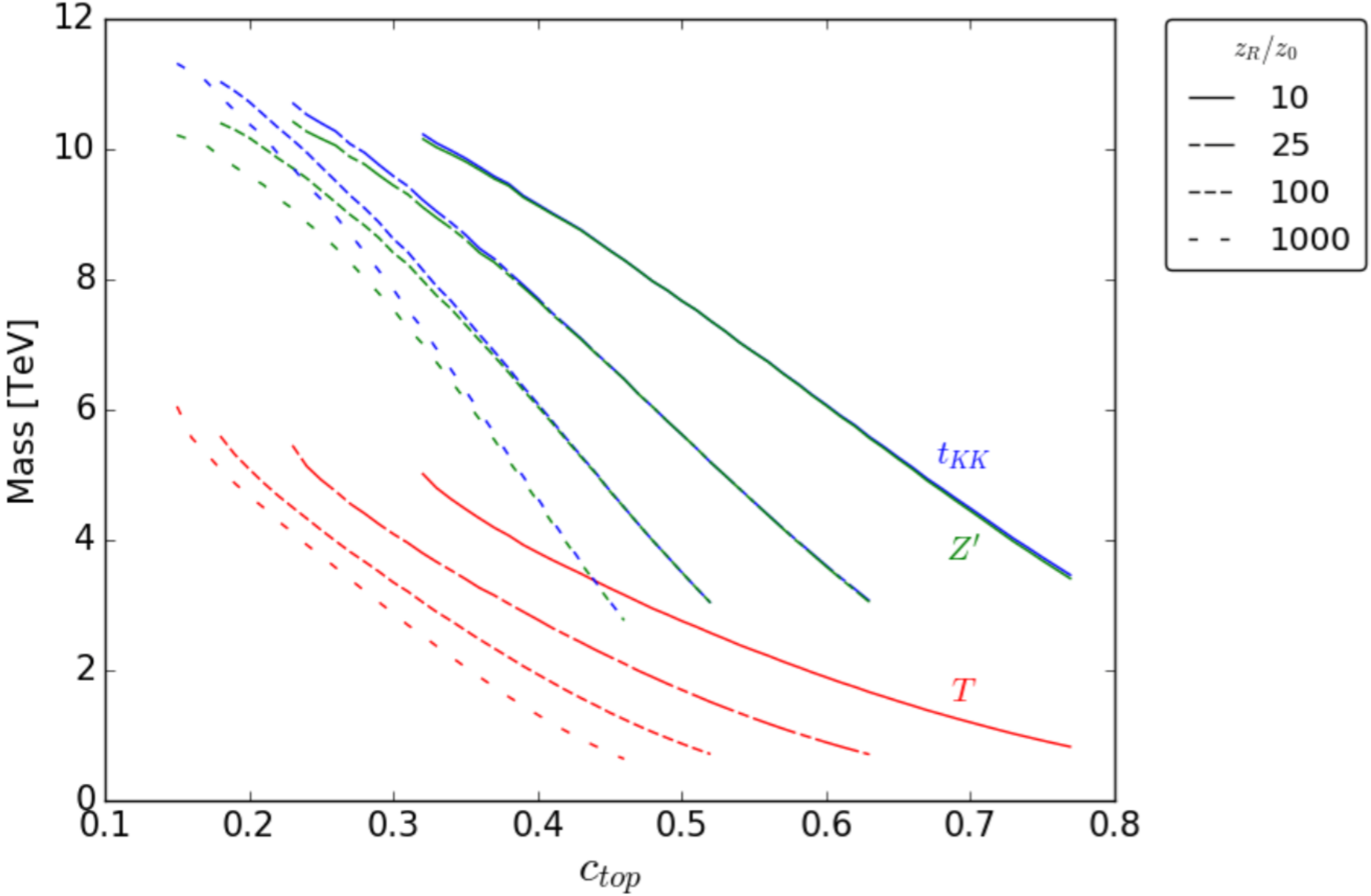
a possible fine tuning measure: $c_T - c_{T,critical}$



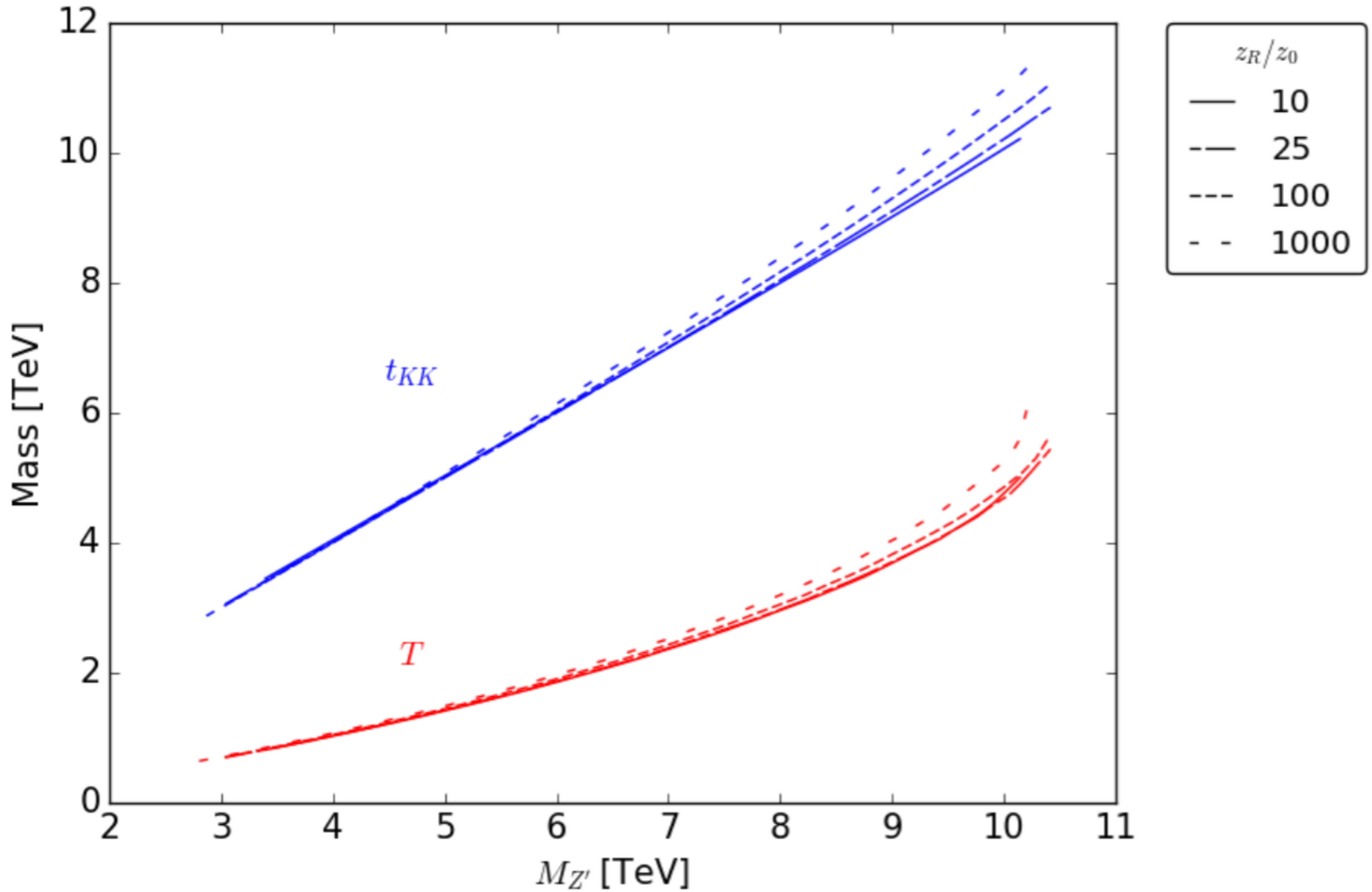


0.10
0.08
0.06
0.04
0.02
0.00
$\left(\frac{v}{f}\right)^2$
2
3
4
5
6
7
8
9
10
$M_{Z'}$ [TeV]
z_R/z_0
10
25
100
1000

mass spectra of KK states



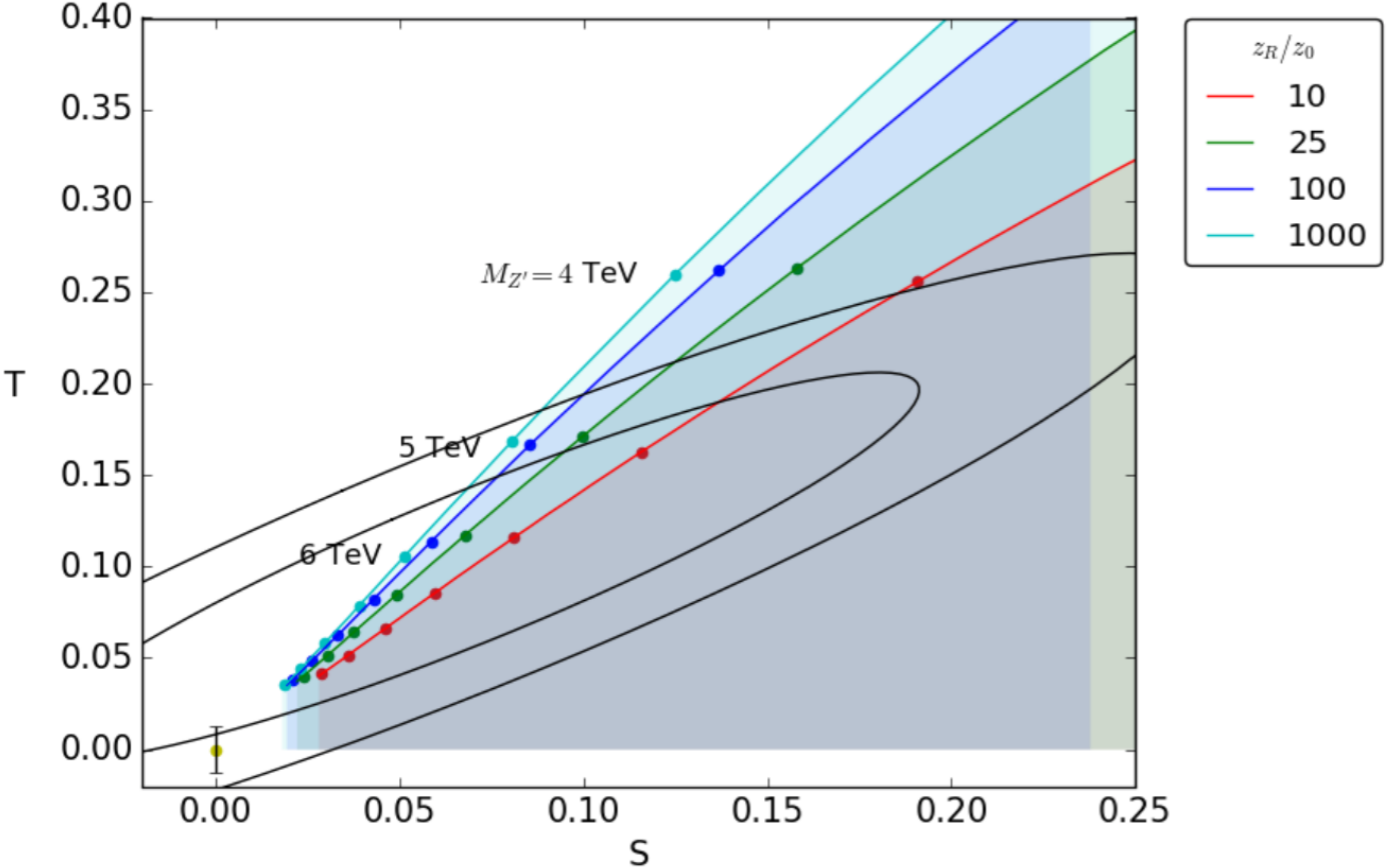
It is convenient to relate all KK masses to the mass of the Z recurrence, which plays the most important role in precision electroweak corrections.



We computed the corrections to the S and T parameters. The S parameter receives a tree level correction proportional to $1/m_{Z'}^2$. The T parameter receives corrections only from loops. At 1-loop, these have an interesting structure:

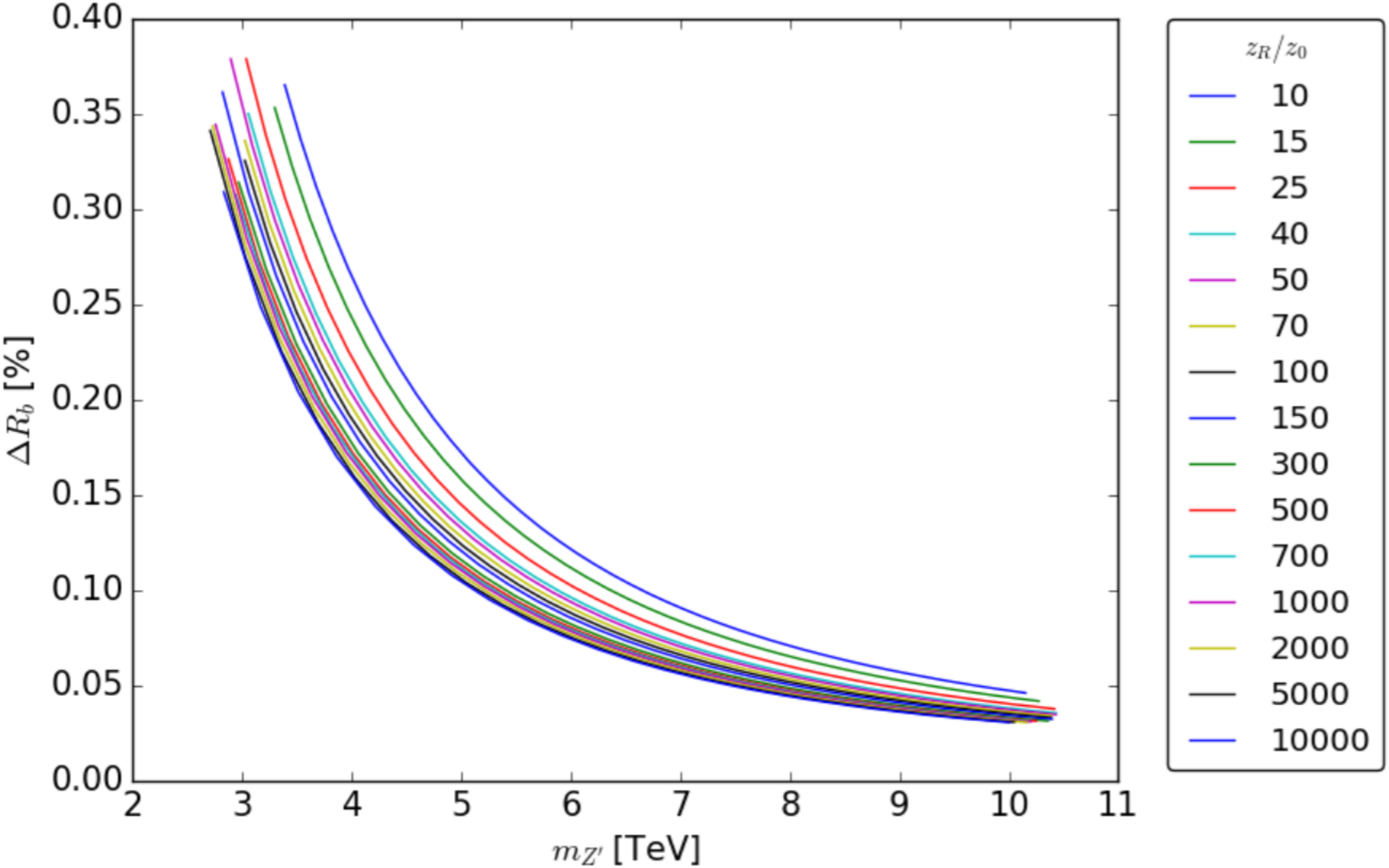
$$T = \frac{3m_t^2}{16\pi s_w^2 c_w^2 m_Z^2} + A\frac{m_t^4}{F^2}\log\frac{\Lambda^2}{m_t^2}$$

where A is predicted but Λ^2 is given by a divergent integral. This reflects the inadequacy of the 5-d treatment beyond leading order. Still, we can use this structure to estmate the correction.

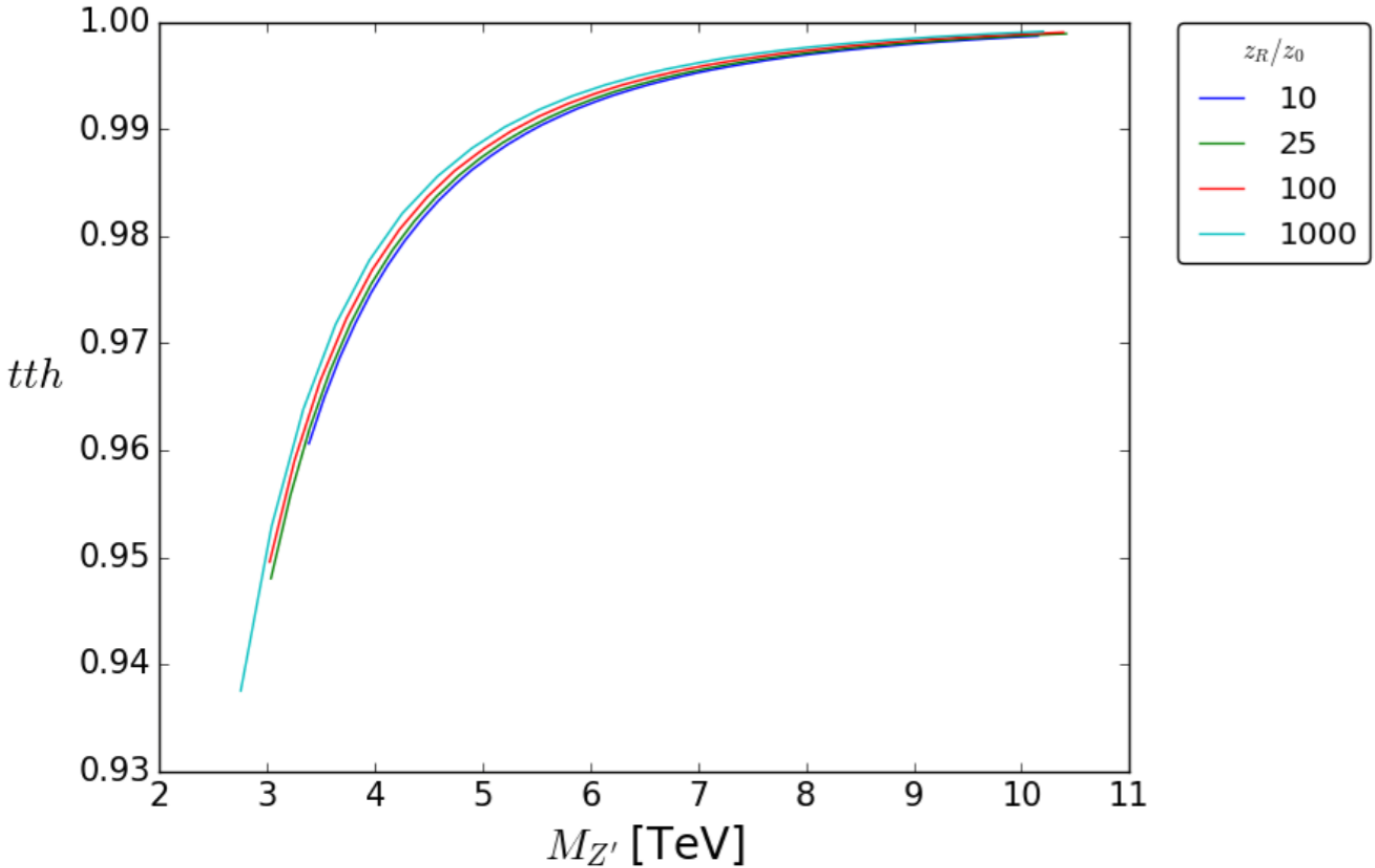


z_R/z_0
10
25
100
1000
$M_{Z'} = 4$ TeV
5 TeV
6 TeV
T
S
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.00
0.05
0.10
0.15
0.20
0.25

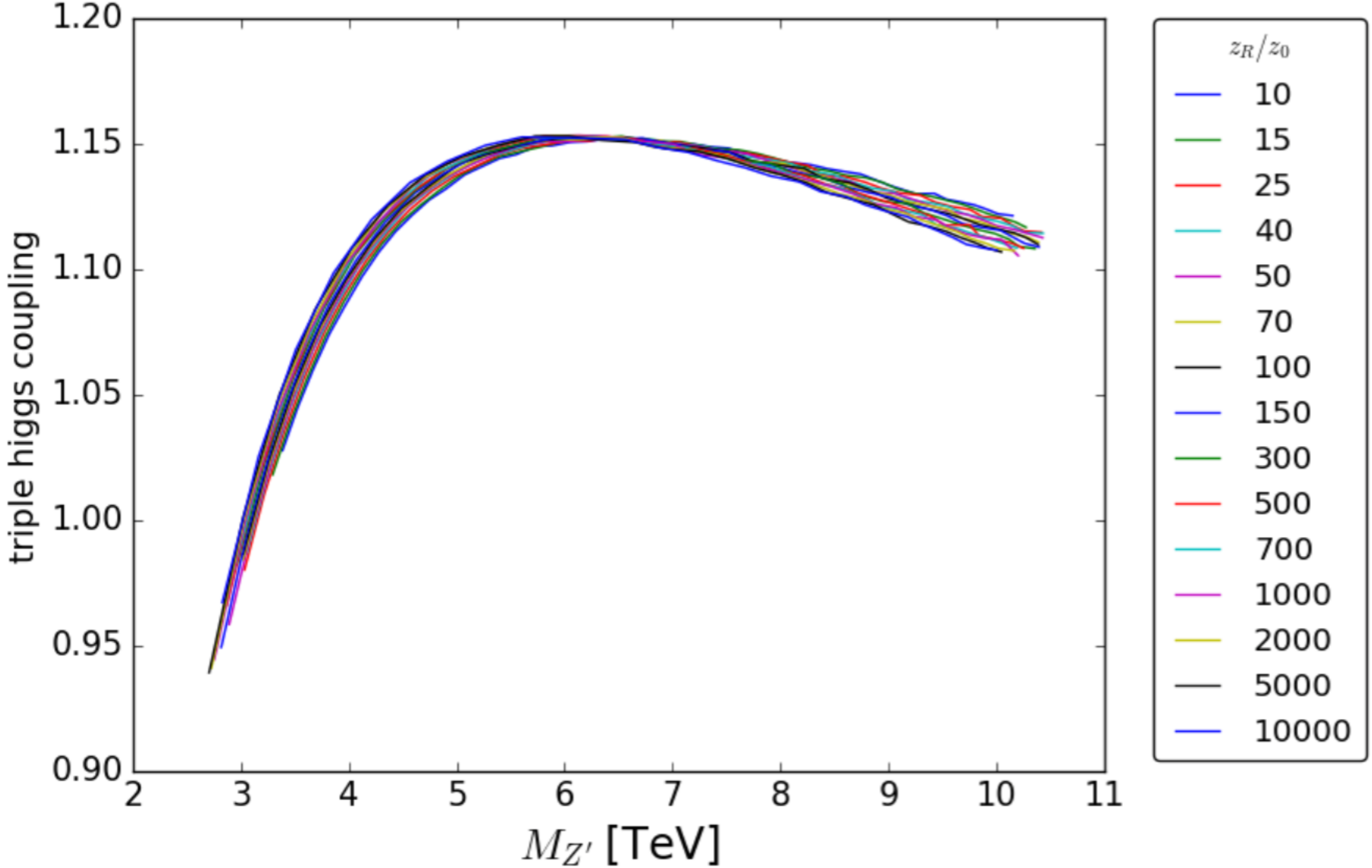
tree level corrections to $Z \to b\bar{b}$ are controlled, as expected.



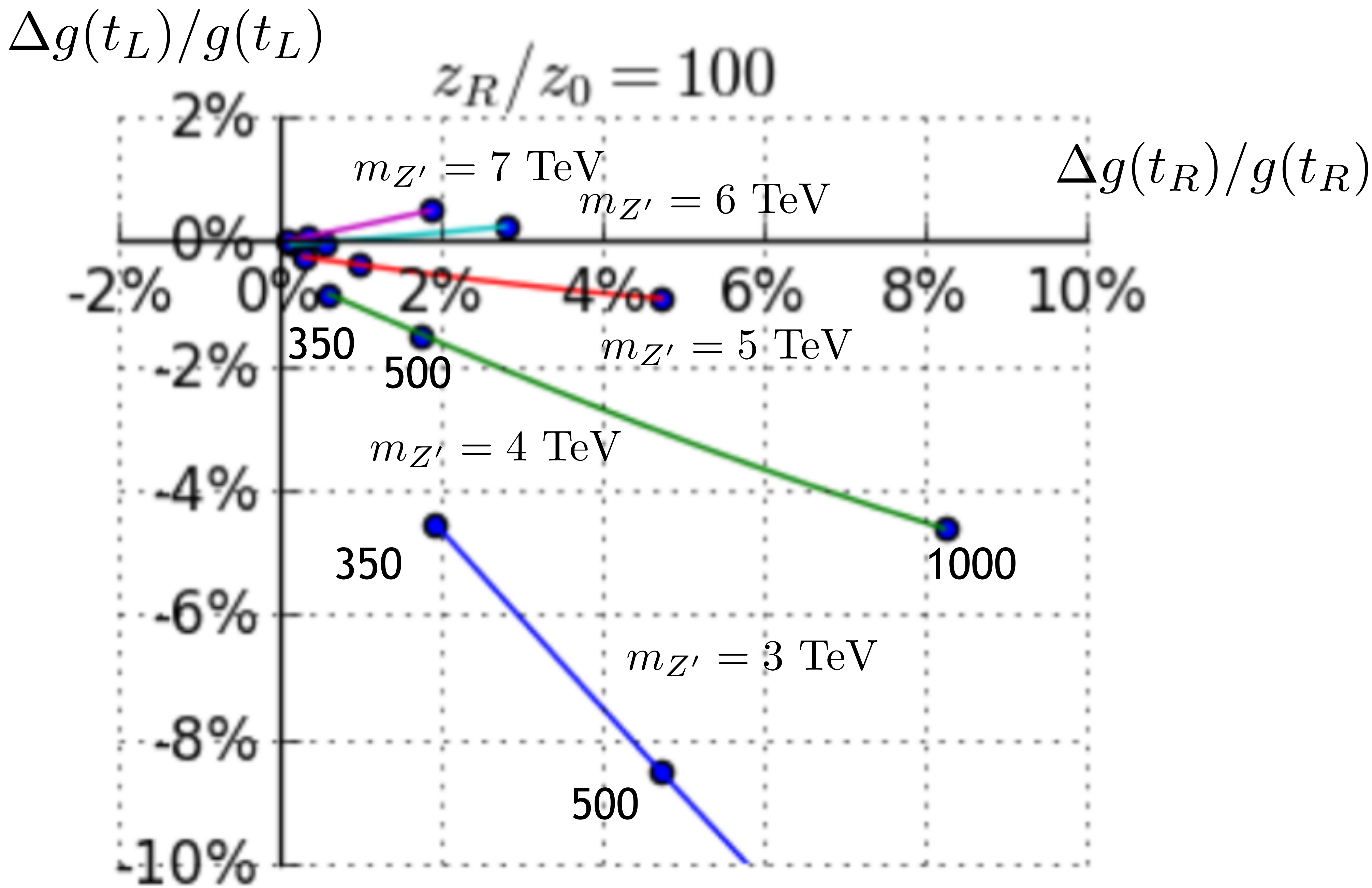
predictions for the tth coupling

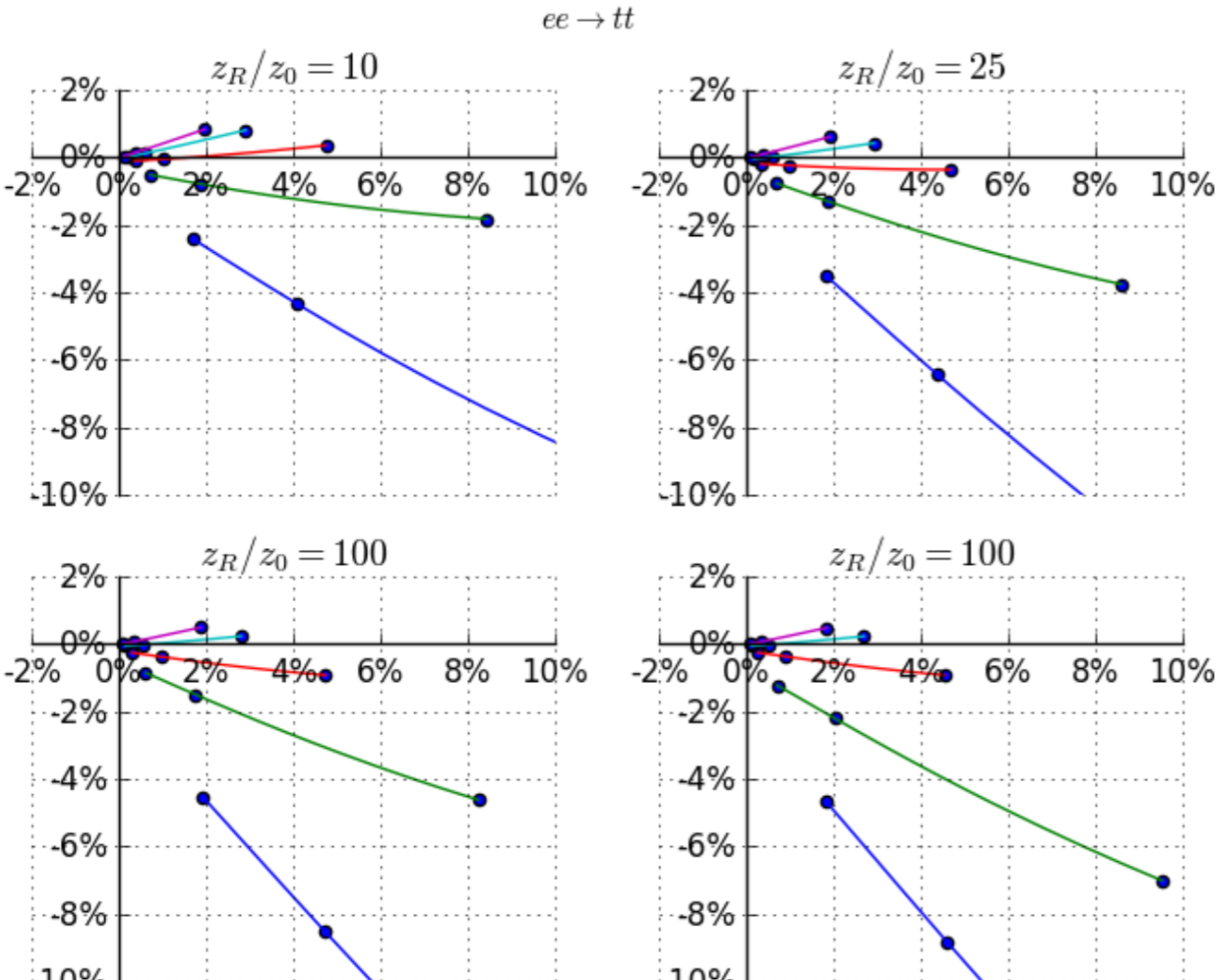


predictions for the triple Higgs coupling



predictions for the effective ttZ coupling that would be measured in $e^+e^- \to t\bar{t}$




$ee \to tt$
$z_R/z_0 = 10$
$z_R/z_0 = 25$
$z_R/z_0 = 100$
$z_R/z_0 = 100$
2%
0%
-2%
-4%
-6%
-8%
-10%
-2%
0%
2%
4%
6%
8%
10%