Top quark polarization

A probe of new physics

at

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by

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SUSY	ED	TC	LH
	CP violation	CP violation	CP violation
Fermion mass	Fermion mass	Fermion mass	Fermion mass
		Scale hierarchy	Scale hierarchy

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Polarization observables and decay pattern are most important features to study new particles.

Top quark & new physics

Top quark's coupling to the SM particles are subjected to modification due to new particlesi/interactions.

$$t\bar{t}\phi := g_{t\bar{t}\phi}(S_t + iP_t\gamma_5)$$

$$t\bar{t}V := g_V \left[\gamma^\mu(f_{1L}P_L + f_{1R}P_R) + \frac{i\sigma^{\mu\nu}}{m_W}\, q_\nu \,(f_{2L}P_L + f_{2R}P_R)\right]$$

Top quark's couplings to the new particles leads to associated productions; polarization of top quark can be used to probe the new particles couplings and properties.

$\Rightarrow$ **Study of new physics can be done via study of top quark.**

Top quark properties

	Measurement	SM prediction
Mass	171.4 ± 2.1 GeV	-
Charge	Not 4/3 (94% CL)	2/3
F_0	0.59 ± 0.14	0.75
F_+	$< 0.10 (95\% \, CL)$	0
Spin	-	1/2

$\Rightarrow$ **Need to know top quark properties precisely.**

We assume spin of top quark to be 1/2 and charge to be 2/3, an in the SM, for rest of our study of new physics.

top-quark : A looking glass

The mass of the top-quark is very large ($m_t \sim 172$ GeV)

- top-mass being close to electro-weak scale, its couplings are sensitive to EWSB. Any new physics of EWSB (or mass generation) affects top-couplings with other particles.

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- the decay lepton angular distribution is insensitive to the anomalous tbW couplings, and hence a pure probe of new physics in top-production process; observed for top-pair production at e^+e^- (Rindani, Grzadkowski) as well as $\gamma\gamma$ collider (Ohkuma, Godbole).

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We have a clean looking glass for new physics.

Anomalous t-decay

Anomalous tbW vertex :

$$\Gamma^\mu = \frac{g}{\sqrt{2}} \left[\gamma^\mu (f_{1L} P_L + f_{1R} P_R) - \frac{i\sigma^{\mu\nu}}{m_W} (p_t - p_b)_\nu \, (f_{2L} P_L + f_{2R} P_R) \right]$$

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- In the SM, $f_{1L} = 1$, $f_{1R} = 0$, $f_{2L} = 0$, $f_{2R} = 0$.
- Contribution from $f_{1R},\ f_{2L}$ are proportional to m_b.

Lepton distribution

$$AB \longrightarrow t \;\; P_1 \ldots P_{n-1}$$
$$\hookrightarrow b \;\; W^+$$
$$\hookrightarrow l^+ \nu$$

Lepton distribution is independent of anomalous tbW coupling if

- t-quark is on-shell; narrow-width approximation for t-quark,

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- narrow-width approximation for W-boson,
- b-quark is mass-less,
- $t \to bW(\ell\nu_\ell)$ is the only decay channel for t-quark.

Decay distribution

Narrow-width approximation for t-quark $\Rightarrow$

$$\overline{|\mathcal{M}|^2} = \frac{\pi\delta(p_t^2 - m_t^2)}{\Gamma_t m_t} \sum_{\lambda,\lambda'} \rho(\lambda,\lambda')\Gamma(\lambda,\lambda')$$

where,

$$\rho(\lambda,\lambda') = M_\rho(\lambda)\, M_\rho^*(\lambda') \quad \text{and} \quad \Gamma(\lambda,\lambda') = M_\Gamma(\lambda)\, M_\Gamma^*(\lambda').$$

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$$\begin{aligned} d\sigma &= \sum_{\lambda,\lambda'} \left[\frac{(2\pi)^4}{2I} \rho(\lambda,\lambda') \delta^4(k_A + k_B - p_t - \sum_i^{n-1} p_i) \frac{d^3 p_t}{2E_t (2\pi)^3} \prod_i^{n-1} \frac{d^3 p_i}{2E_i (2\pi)^3} \right] \\ &\times \left[\frac{1}{\Gamma_t} \left(\frac{(2\pi)^4}{2m_t} \Gamma(\lambda,\lambda') \delta^4(p_t - p_b - p_\nu - p_\ell) \frac{d^3 p_b}{2E_b (2\pi)^3}\, \frac{d^3 p_\nu}{2E_\nu (2\pi)^3} \right) \frac{d^3 p_\ell}{2E_\ell (2\pi)^3} \right]. \end{aligned}$$

Decay distribution

Production part ($\phi_t = 0$) :

$$\int \frac{d^3 p_t}{2E_t (2\pi)^3} \prod_i^{n-1} \frac{d^3 p_i}{2E_i (2\pi)^3} \; \frac{(2\pi)^4}{2I} \rho(\lambda, \lambda') \delta^4 \left(k_A + k_B - p_t - \left(\sum_i^{n-1} p_i \right) \right)$$

$$= d\sigma_{2\to n}(\lambda, \lambda') \, dE_t \, d\cos\theta_t.$$

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Decay part (in rest rest frame of t-quark) :

$$\frac{1}{\Gamma_t}\,\frac{(2\pi)^4}{2m_t}\int \frac{d^3p_\ell}{2E_\ell(2\pi)^3}\;\frac{d^3p_b}{2E_b(2\pi)^3}\;\frac{d^3p_\nu}{2E_\nu(2\pi)^3}\;\Gamma(\lambda,\lambda')\delta^4(p_t - p_b - p_\nu - p_\ell)$$

$$= \frac{1}{32\Gamma_t m_t}\,\frac{E_\ell}{(2\pi)^4}\,\frac{\langle\Gamma(\lambda,\lambda')\rangle}{m_t E_\ell}\; dE_\ell\, d\Omega_\ell\, dp_W^2 \ .$$

Angular brackets stands for averaging over $\phi = (\phi_b - \phi_\ell)$.

Decay density matrix

In the rest frame of t-quark, we have

$$\langle\Gamma(\pm,\pm)\rangle = g^4 m_t E_\ell^0 \,|\Delta_W(p_W^2)|^2 \,(1 \pm \cos\theta_l) \times F(E_\ell^0),$$
$$\langle\Gamma(\pm,\mp)\rangle = g^4 m_t E_\ell^0 \,|\Delta_W(p_W^2)|^2 \,(\sin\theta_l e^{\pm i\phi_l}) \times F(E_\ell^0).$$

where $\Delta_W(p_W^2) = \frac{1}{p_W^2 - m_W^2 + i\Gamma_W m_W}$

$$F(E_\ell^0) = \Bigg[(m_t^2 - m_b^2 - 2p_t \cdot p_l)\left(|f_{1L}|^2 + \Re(f_{1L}f_{2R}^*)\frac{m_t}{m_W}\frac{p_W^2}{p_t.p_l}\right)$$
$$- \quad 2\Re(f_{1L}f_{2L}^*)\,\frac{m_b}{m_W}\,p_W^2 - \Re(f_{1L}f_{1R}^*)\,\frac{m_b\, m_t}{p_t.p_l}\,p_W^2\Bigg]$$

In general,

$$\langle\Gamma(\lambda,\lambda')\rangle = (m_t E_\ell^0)\,|\Delta(p_W^2)|^2\, g^4\, A(\lambda,\lambda')\, F(E_\ell^0)$$

Angular distribution of lepton

Combining production and decay part, we have

$$d\sigma = \frac{1}{32\,\Gamma_t m_t (2\pi)^4} \left[\sum_{\lambda,\lambda'} d\sigma_{2\to n}(\lambda,\lambda') \times g^4 A^{c.m.}(\lambda,\lambda') \right]$$
$$\times \; dE_t \; d\cos\theta_t \; d\cos\theta_\ell \; d\phi_\ell$$
$$\times \; E_\ell \; F(E_\ell) \; |\Delta(p_W^2)|^2 \; dE_\ell \; dp_W^2$$

and

$$\Gamma_t \propto \int E_\ell \; F(E_\ell) \; |\Delta(p_W^2)|^2 \; dE_\ell \; dp_W^2$$

Contribution from anomalous tbW couplings cancels between numerator and denominator, if $t \to bW$ is the only decay channel.

⇒ Lepton angular distribution is independent of anomalous tbW interactions.

Energy distribution of lepton

The E_ℓ distribution (in the lab frame) depends both on

- anomalous tbW couplings $\Rightarrow$ **new physics in t-decay**
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The E_ℓ^0 distribution (in the top-rest-frame) depends only on the possible **new physics in t-decay.**

$$\frac{d\sigma}{dE_\ell^0} \propto \int E_l^0 F(E_l^0)\, |\Delta(p_W^2)|^2\, dp_W^2$$

Independent of production mechanism of t-quark !!

Polarization of t-quark

Polarized cross-sections :

$$\int \frac{d^3 p_t}{2E_t(2\pi)^3} \left(\prod_{i=1}^{n-1} \frac{d^3 p_i}{2E_i(2\pi)^3} \right) \frac{(2\pi)^4}{2I} \rho(\lambda, \lambda') \; \delta^4 \left(k_A + k_B - p_t - \left(\sum_{i=1}^{n-1} p_i \right) \right) = \sigma(\lambda, \lambda').$$

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Total cross-section :

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Polarization density matrix :

$$P_t = \frac{1}{2} \begin{pmatrix} 1+\eta_3 & \eta_1 - i\eta_2 \\ \eta_1 + i\eta_2 & 1-\eta_3 \end{pmatrix},$$

$$\begin{aligned} \eta_3 &= \left(\sigma(+,+) - \sigma(-,-)\right)/\sigma_{tot} \\ \eta_1 &= \left(\sigma(+,-) + \sigma(-,+)\right)/\sigma_{tot} \\ i\,\eta_2 &= \left(\sigma(+,-) - \sigma(-,+)\right)/\sigma_{tot} \end{aligned}$$

Polarization of t-quark

Polarization through leptonic decay of t-quark :

$$\frac{\eta_3}{2} = \frac{\sigma(p_\ell.s_3 < 0) - \sigma(p_\ell.s_3 > 0)}{\sigma(p_\ell.s_3 < 0) + \sigma(p_\ell.s_3 > 0)}$$

$$\frac{\eta_2}{2} = \frac{\sigma(p_\ell.s_2 < 0) - \sigma(p_\ell.s_2 > 0)}{\sigma(p_\ell.s_2 < 0) + \sigma(p_\ell.s_2 > 0)}$$

$$\frac{\eta_1}{2} = \frac{\sigma(p_\ell.s_1 < 0) - \sigma(p_\ell.s_1 > 0)}{\sigma(p_\ell.s_1 < 0) + \sigma(p_\ell.s_1 > 0)}$$

$$s_i.s_j = -\delta_{ij} \qquad p_t.s_i = 0$$

For $p_t^\mu = E_t(1, \beta_t \sin\theta_t, 0, \beta_t \cos\theta_t)$, we have

$$s_1^\mu = (0, -\cos\theta_t, 0, \sin\theta_t),\ s_2^\mu = (0,0,1,0),\ s_3^\mu = E_t(\beta_t, \sin\theta_t, 0, \cos\theta_t)/m_t.$$

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Angular distribution in lab frame can be used as a qualitative measure of the t-polarization.

Polarization through angular distribution

For demonstration, we chose $\gamma\gamma \to t\bar{t}$ process with/without Higgs exchange contribution.

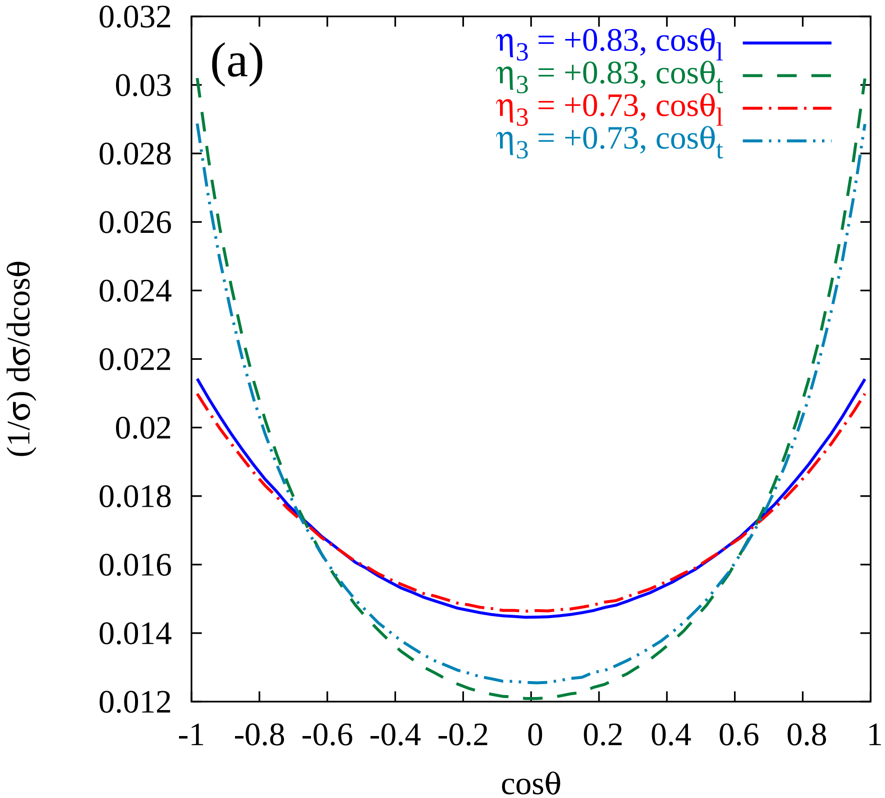
$m_\phi = 500$ GeV; $\Gamma_\phi = 2.5$ GeV,
$S_t = 0.2,\ P_t = 0.4,\ S_\gamma = 4.0 + i\,0.5$ and $P_\gamma = 1.25 + i\,2.0$.

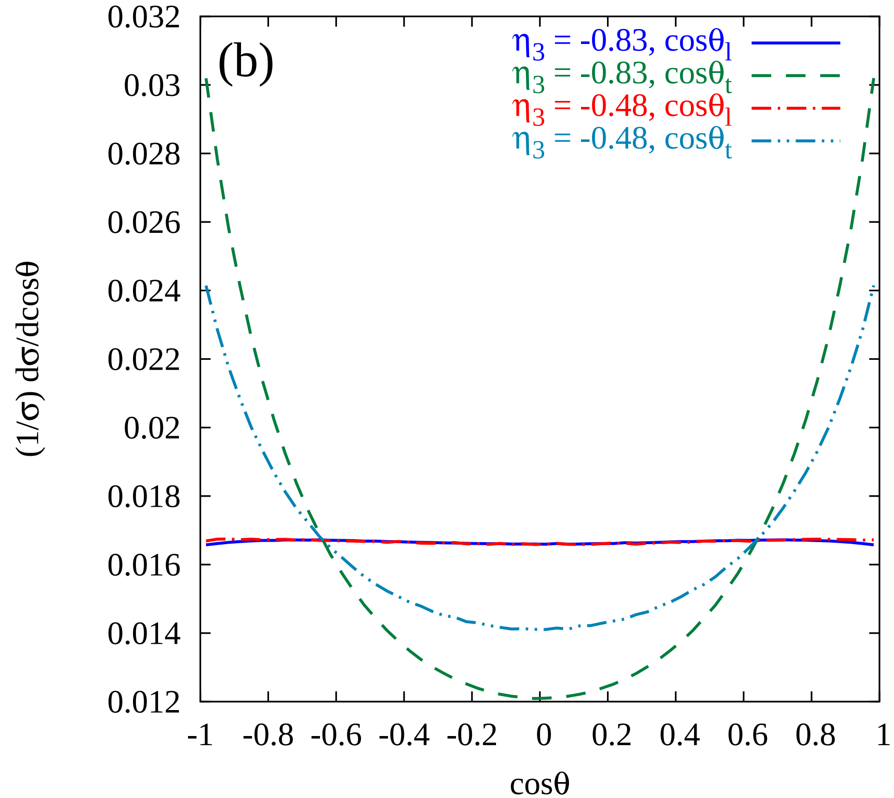
Polarized ideal photon spectrum is used.

Assumptions :

- t-quark is on-shell
- anomalous tbW couplings are small
- W-boson is on-shell
- b-quark is mass-less and
- $t \to bW$ is the only decay channel for t-decay

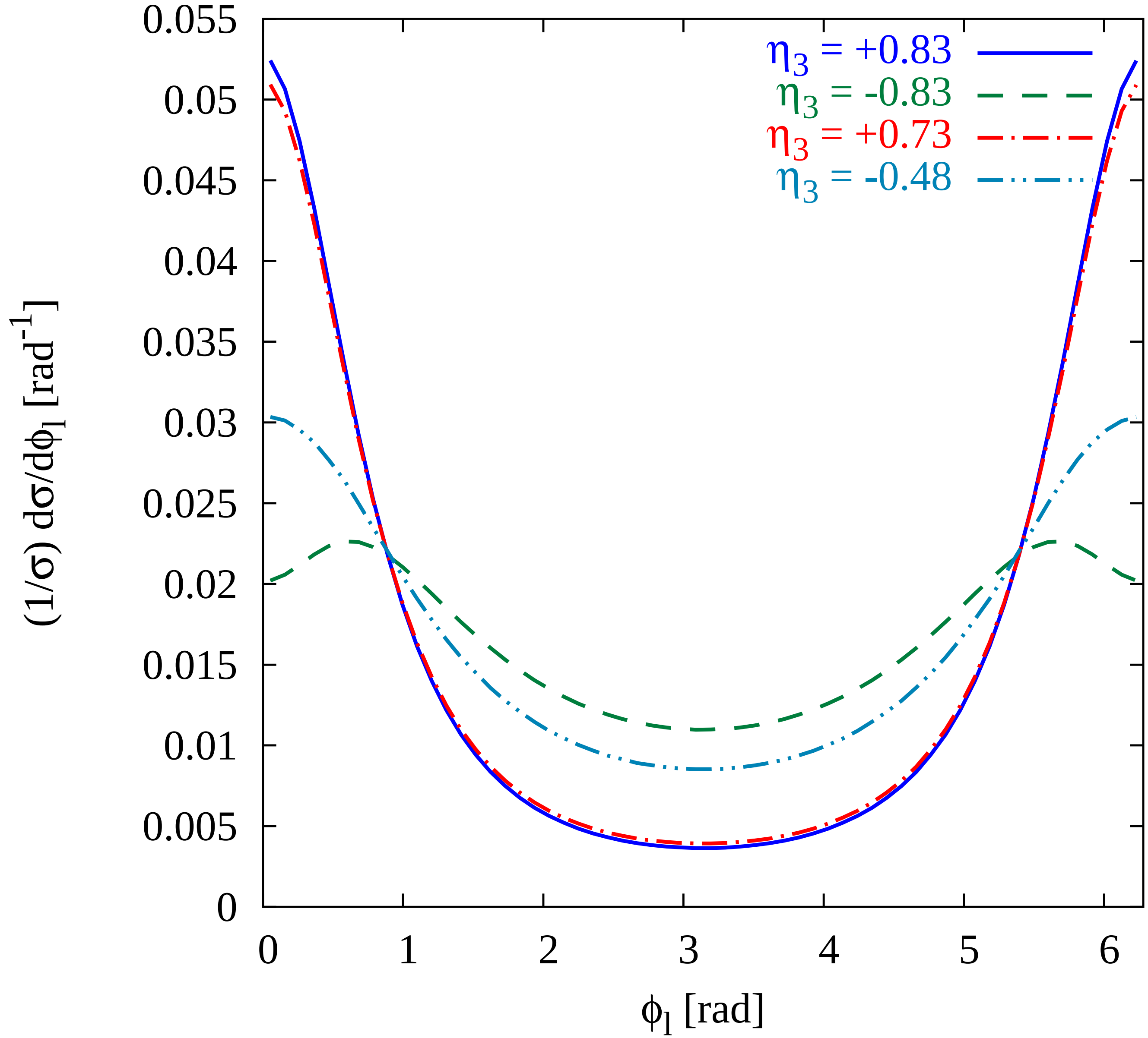
Polarization through angular distribution



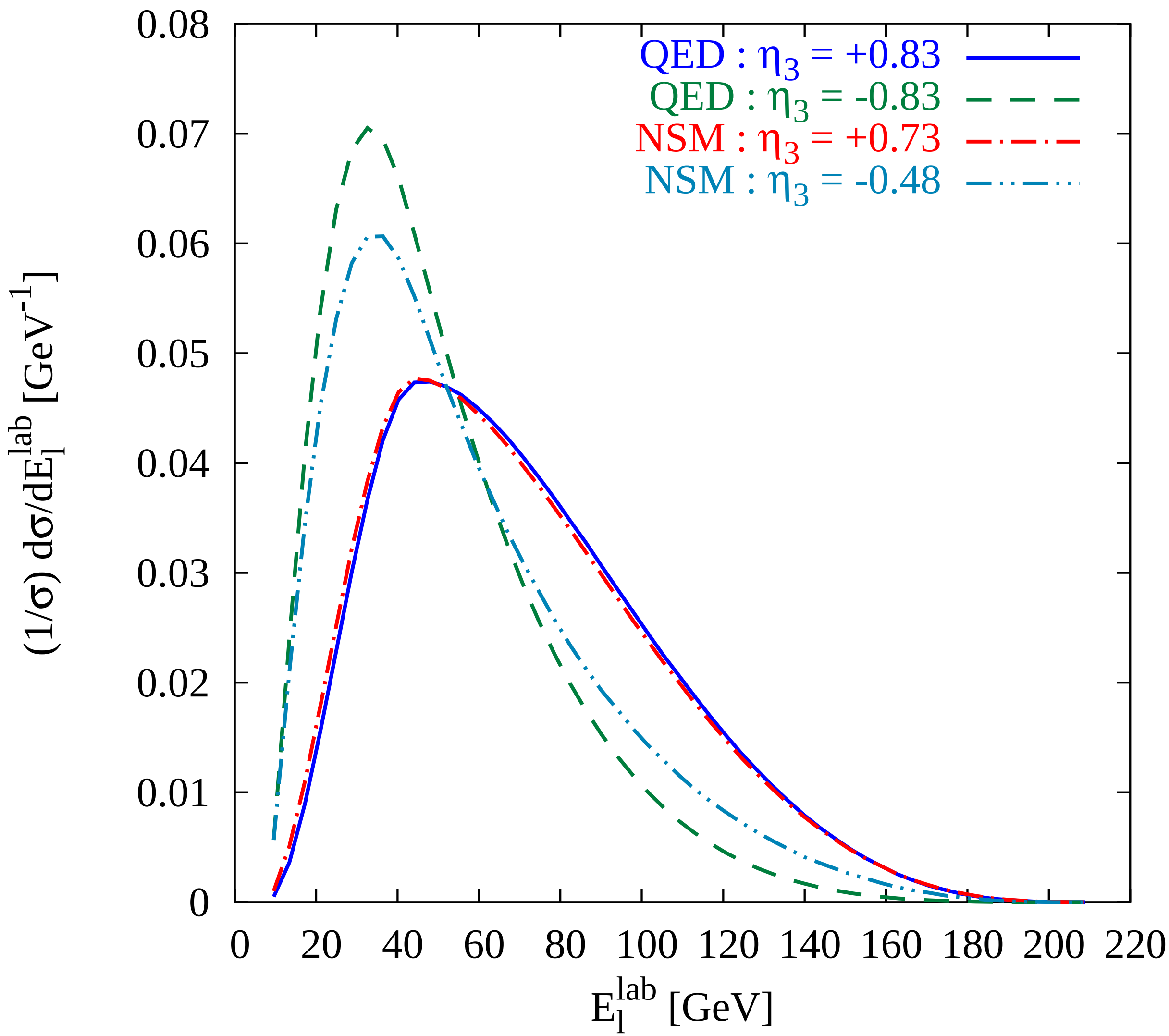


$\eta_1 = 0$ and $\eta_2 = 0$

Polarization through angular distribution



Energy distribution



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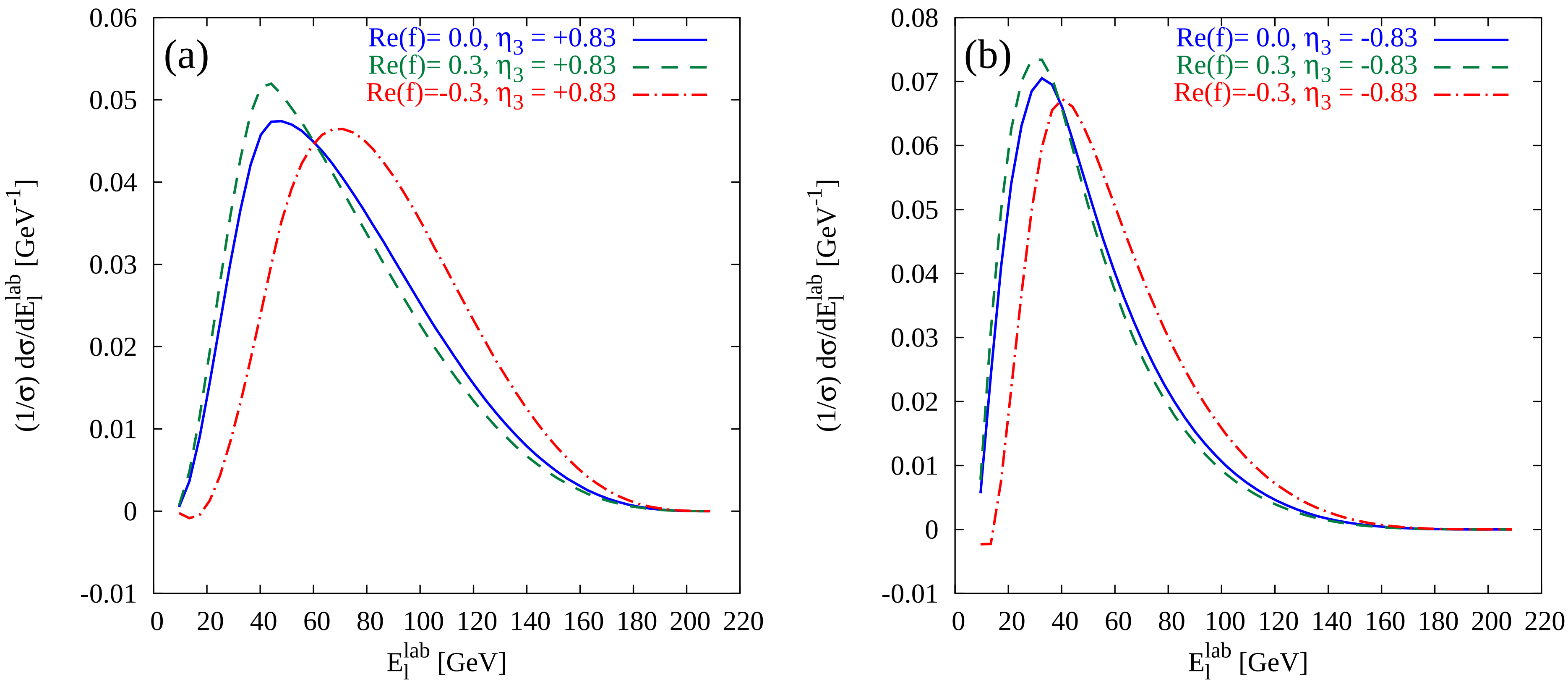

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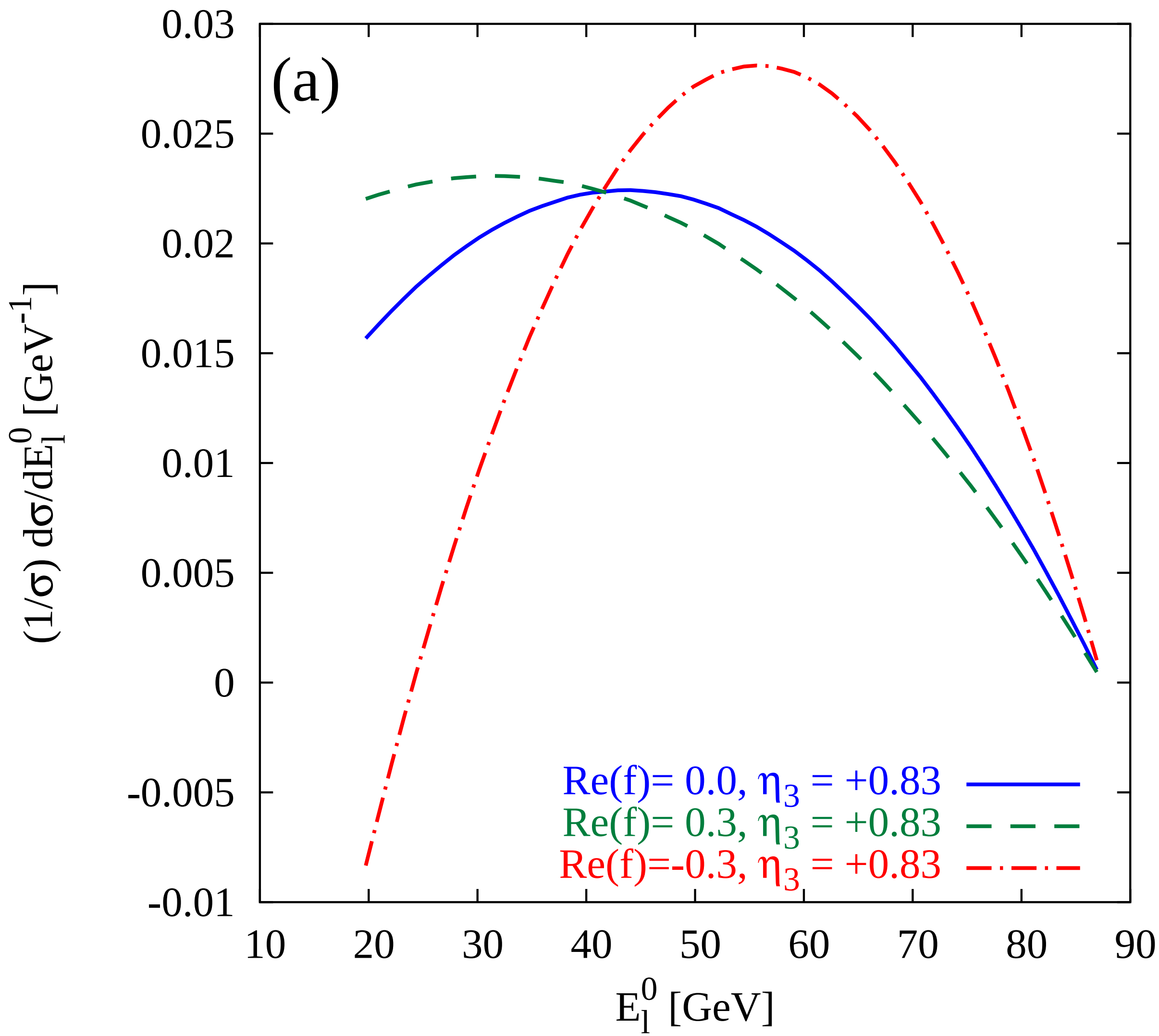

SUSY Higgs: $\gamma\gamma \to t\bar{t}$

CPX scenario

MSSM parameters	Values
$\tan\beta$	3 - 40 (used for scan)
m_{H^+}	150-500 GeV (used for scan)
μ	2 TeV, $\Phi_\mu = 0$
M_1, M_2	200 GeV, $\Phi_{1,2} = 0$
M_3	1 TeV, $\Phi_3 = 90^\circ$
$m_{\tilde{q},\tilde{l}}$	500 GeV
$A_{t,b}$	1 TeV, $\Phi_{t,b} = 90^\circ$
A_τ	500 GeV, $\Phi_\tau = 90^\circ$

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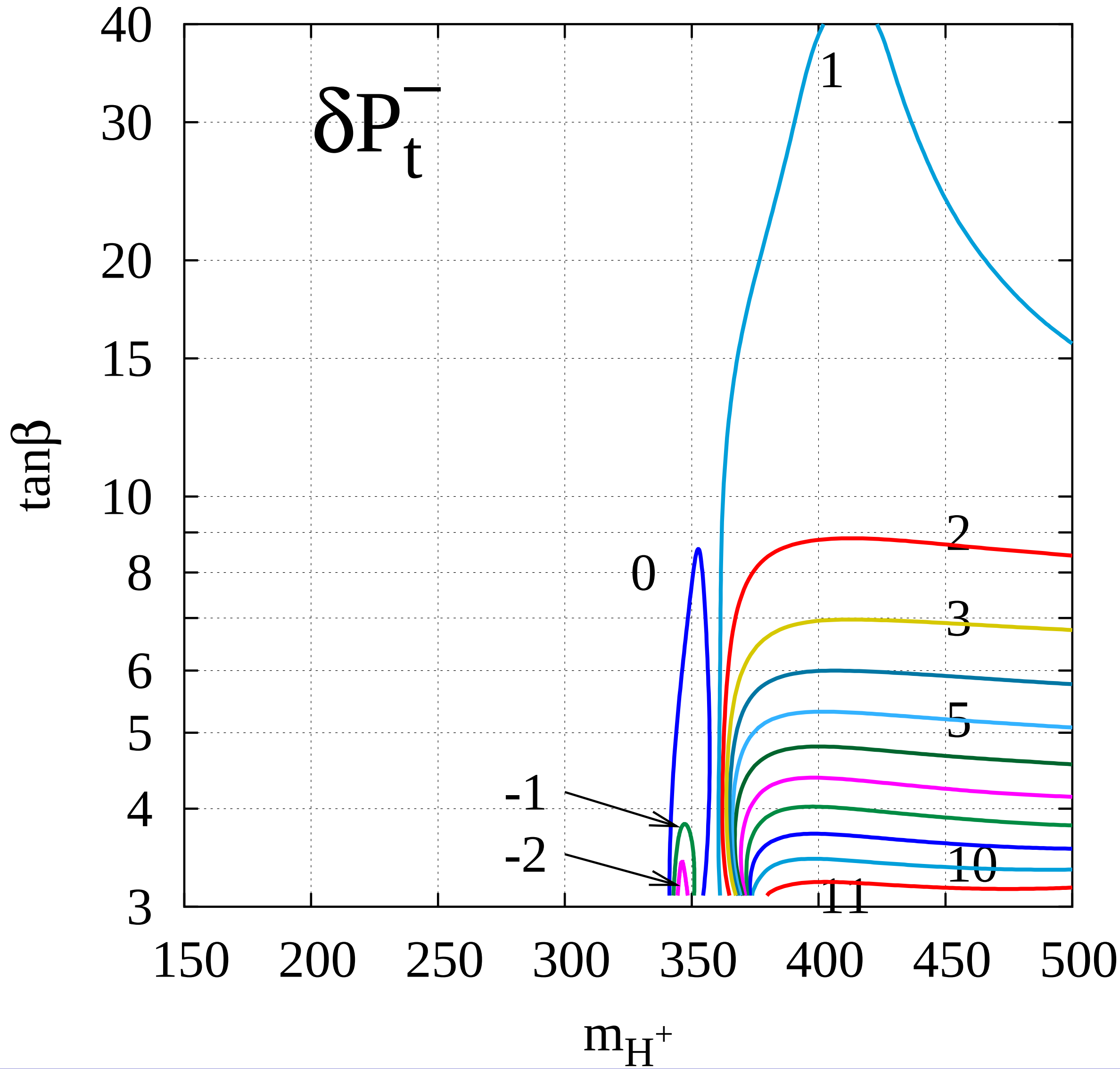

Flat extra-dimensions: $pp \to t\bar{t}$

In the models of flat extra-dimensions, there is a KK-tower of excitations corresponding to each SM gauge bosons and fermions.

Signal channel in pp collision:

$$q\bar{q} \to V \to t\bar{t}$$

$$V \equiv \gamma,\ Z,\ g,\ \gamma^{(1)},\ Z^{(1)},\ g^{(1)}$$

The pure SM backgound:

$$gg \to V \to t\bar{t}$$

All KK-excitations contribute to a resonance in $m_{t\bar{t}}$ distribution. The presence of Z and $Z^{(1)}$ is responsible for finite polarization of top quark.

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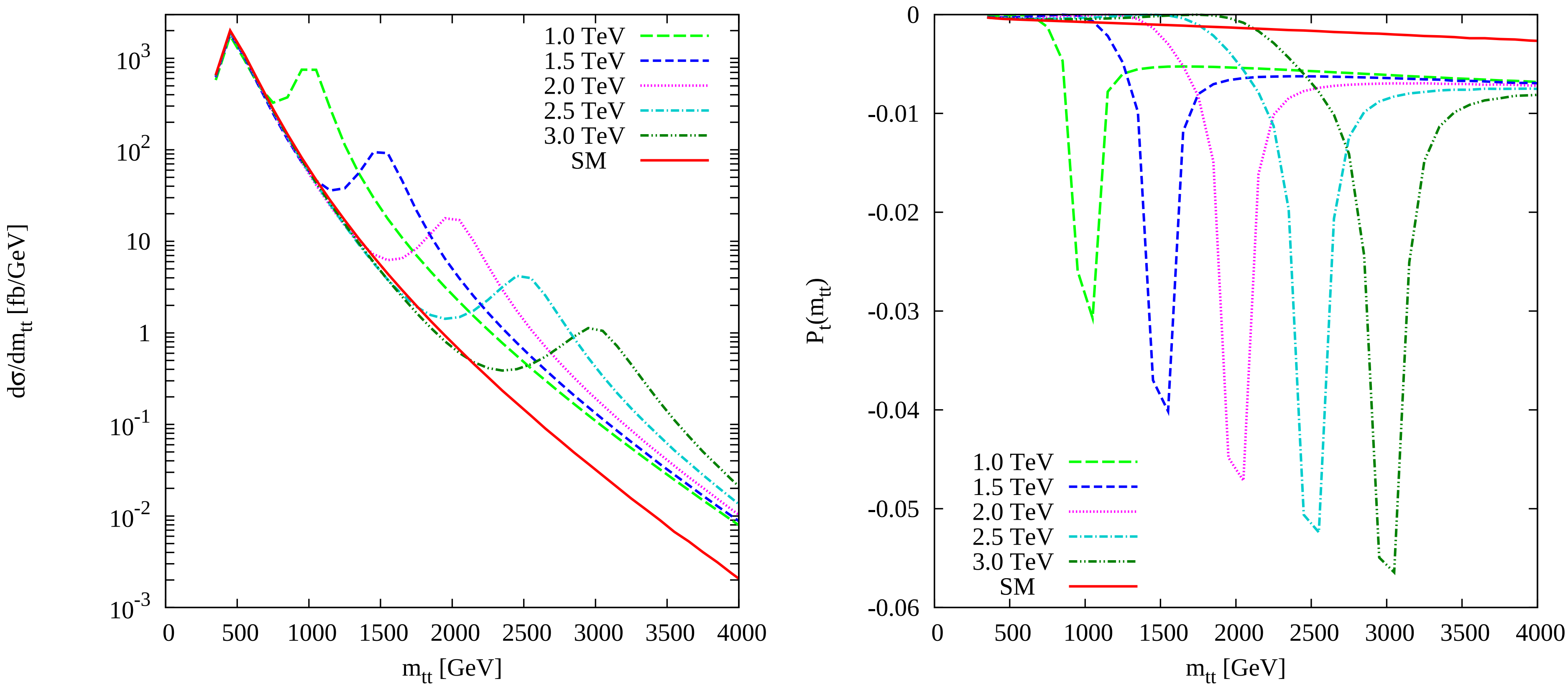


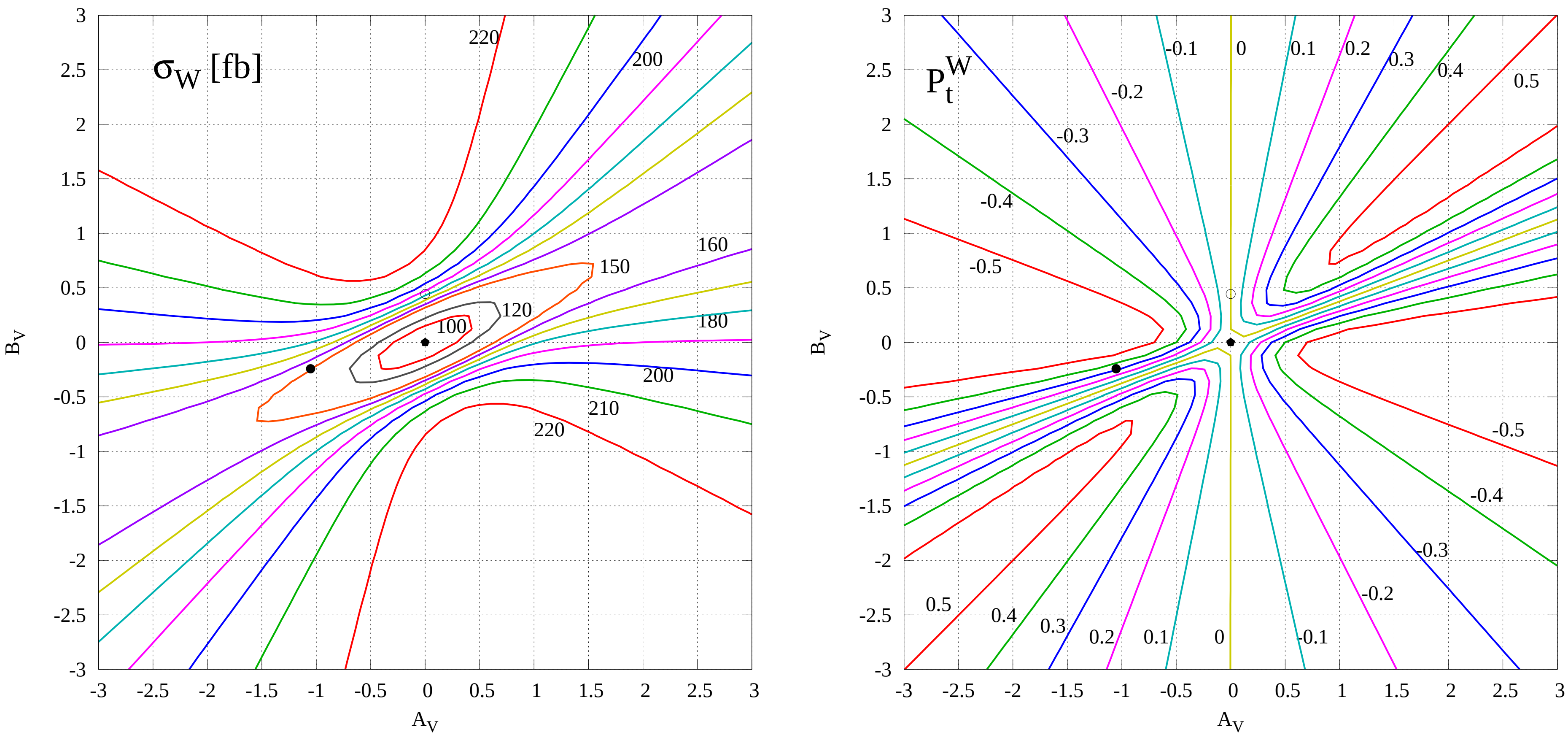
Flat extra-dimensions: $pp \to t\bar{t}$

For $M_{KK} = 2$ TeV, and $|m_{t\bar{t}} - M_{KK}| < 50$ GeV.

	$\sigma(pp \to t\bar{t})$ (fb)	P_t
SM	77.9	-1.33×10^{-3}
$SM + \gamma^{(1)}$	185	-2.55×10^{-4}
$SM + Z^{(1)}$	150	-3.26×10^{-1}
$SM + g^{(1)}$	1700	-6.13×10^{-5}
$SM + V_{KK}$	1900	-5.87×10^{-2}

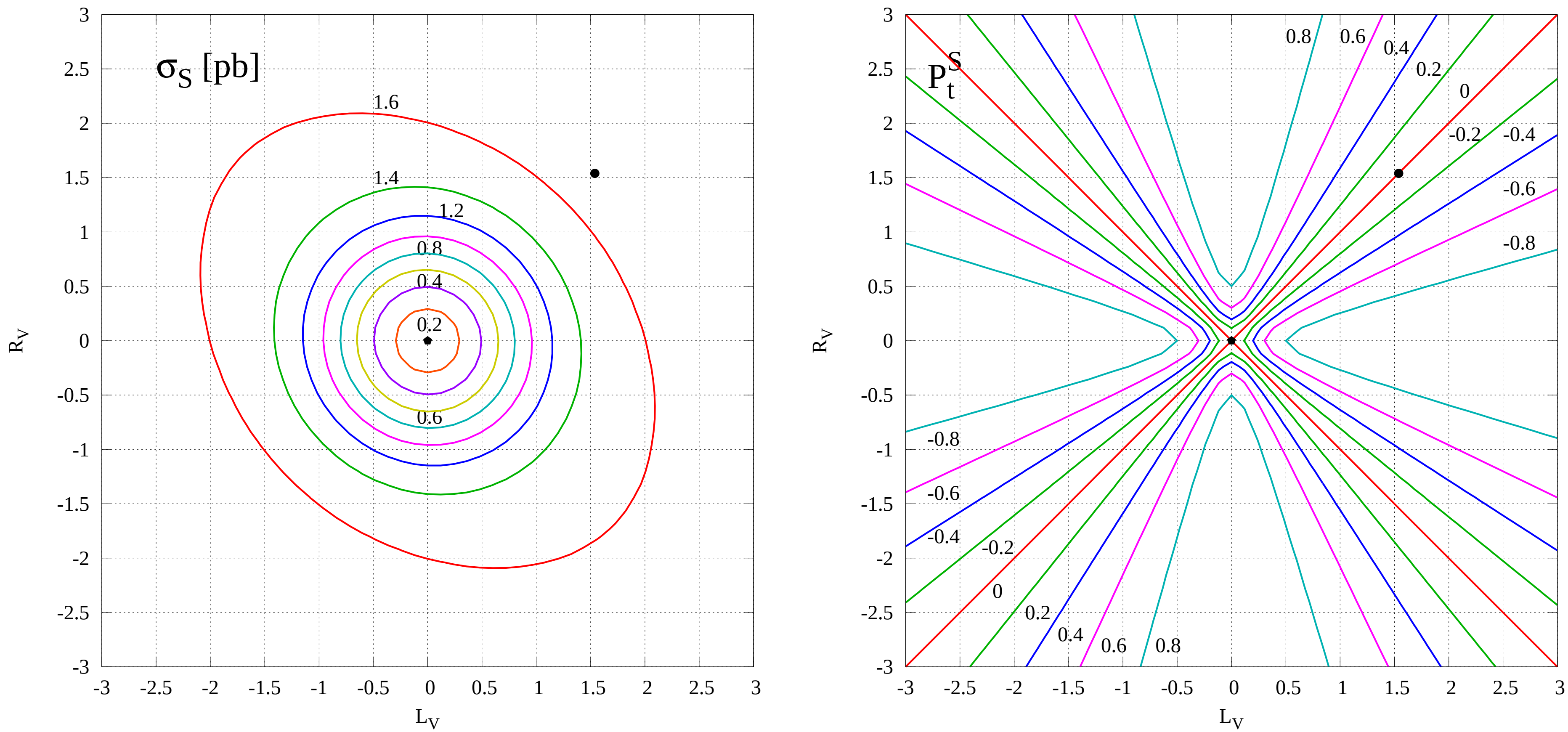
ED: Weak resonance model

$$f_i \bar{f}_i V := A_V \, T_3^{f_i} + B_V \, Q^{f_i} \ ; \ i = L, R$$



ED: Strong resonance model

$$f\bar{f}V := R_V P_R + L_V\ P_L$$



Wrapped extra dimensions

In universal wrapped extra dimension model, with fermion localization in the fifth dimensions, one has differing couplings of V_{KK}

For electro weak boson:

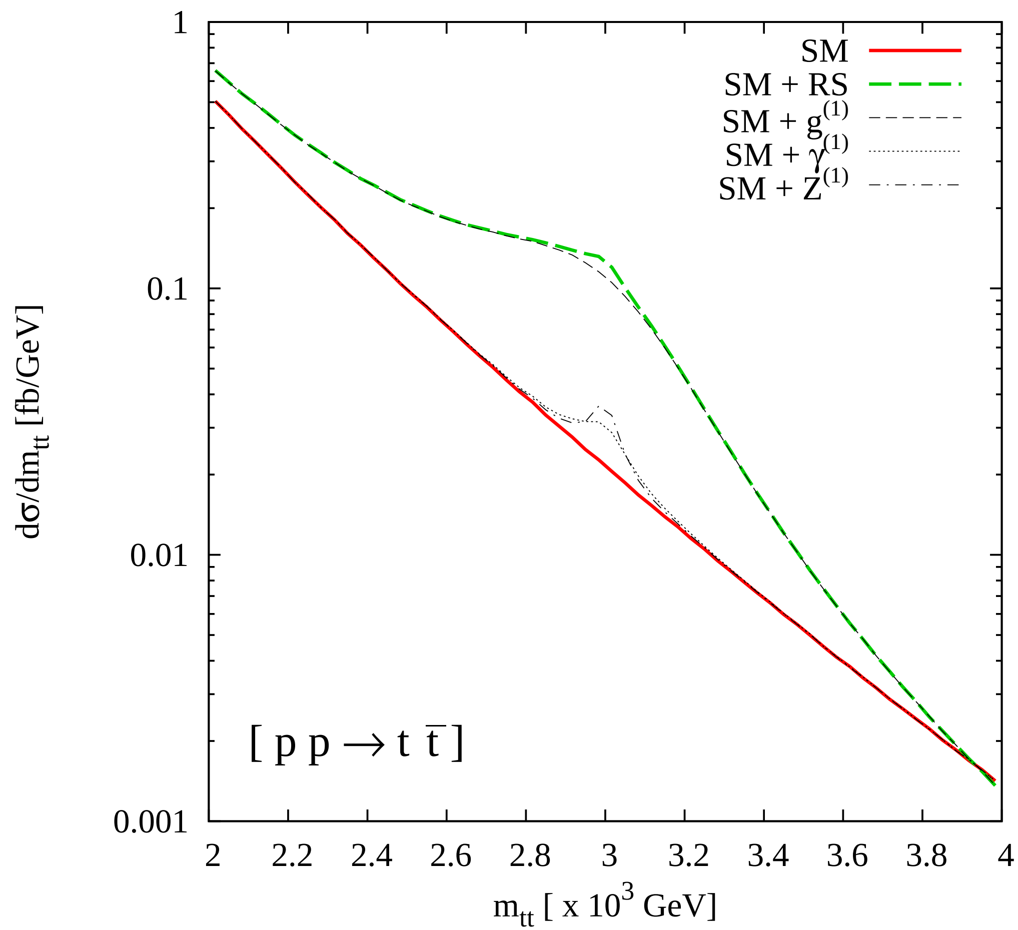
$$f_i \bar{f}_i V := (A_V \, T_3^{f_i} + B_V \, Q^{f_i}) \, Q_V(f_i) \; ; \; i = L, R$$

For strong boson:

$$f \bar{f} V := Q_V(f_R) \, R_V \, P_R + Q_V(f_L) \, L_V \, P_L$$

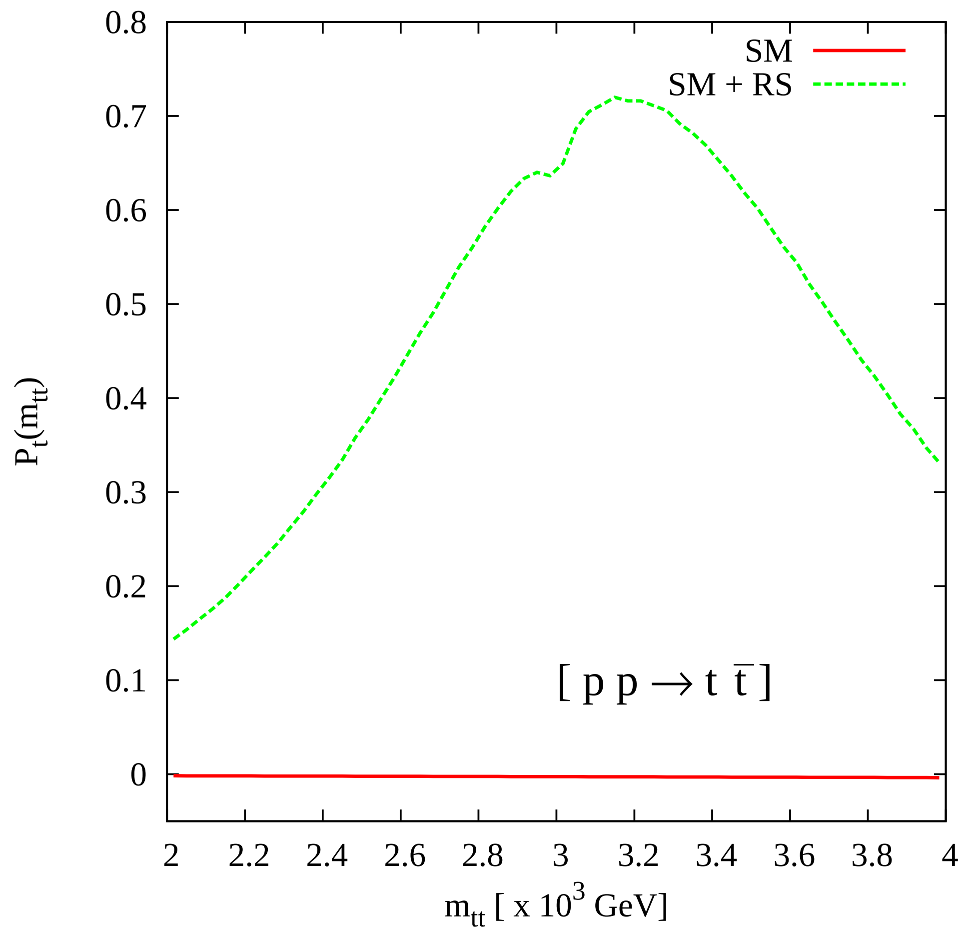
- can explain fermion mass hierarchy,
- can explain A_{FB}^b anomaly thourgh $Z - Z'^{(1)}$ mixing,
- can be probed at LHC upto $M_{KK} = 3$ TeV through polarization.

Wrapped extra dimensions

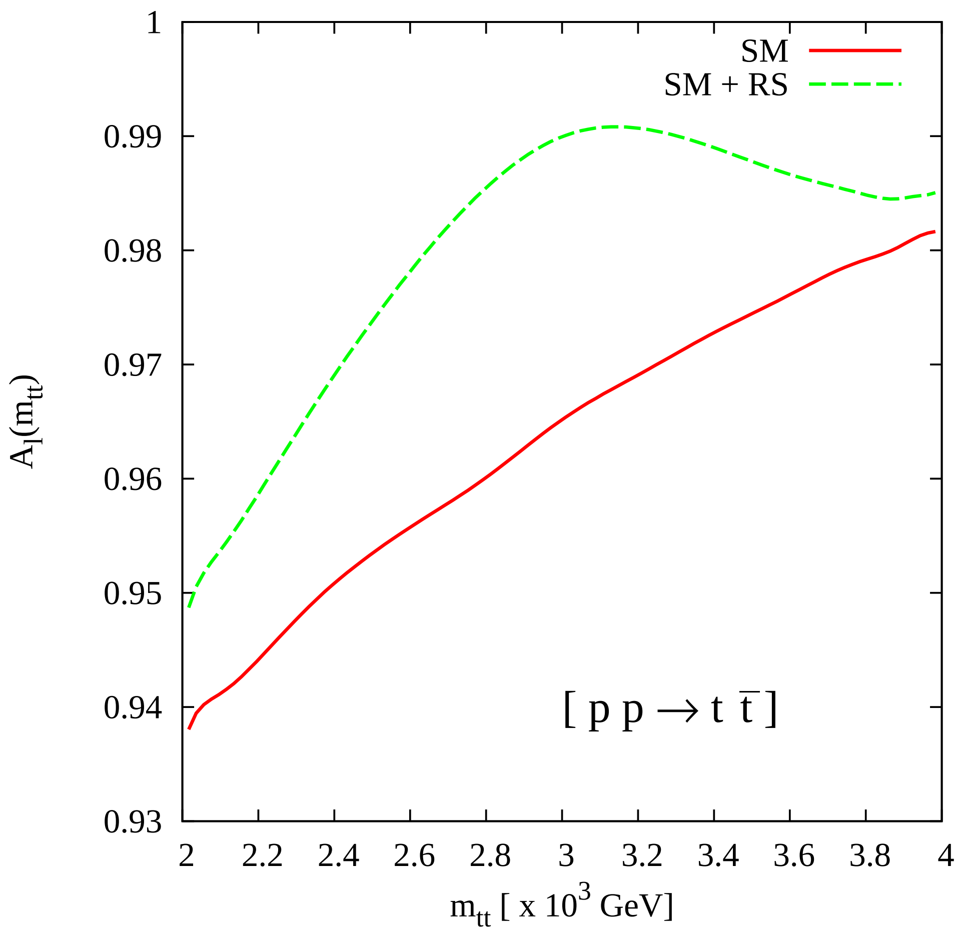


$$\Gamma_{g^{(1)}} = 627 \text{ GeV}, \Gamma_{Z^{(1)}} = 75 \text{ GeV}, \Gamma_{\gamma^{(1)}} = 137 \text{ GeV}.$$

Wrapped extra dimensions



Wrapped extra dimensions



$$A_l = (\sigma(\cos\phi_l > 0) - \sigma(\cos\phi_l < 0))/\sigma_{tot}$$

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- Top quark polarization can be probed at various colliders and it can be instrumental in discovering and characterising new physics.

Ongoing projets

- Spin/polarization measurement of new particles in their cascade decay. Look at azimuthal distributions in the lab frame.
- Likelyhood mapping of SUSY parameters space using MCMC.

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