Kinematic distributions in top decay

A probe of new physics and top-polarization

at

TOP09 : Top quark Physics

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CERN, Geneva

by

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in collaboration with

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top-quark : A looking glass

The mass of the top-quark is very large ($m_t \sim 175$ GeV)

- its decay width ($\Gamma_t \sim 1.5$ GeV) is much larger than the typical scale of hadronization, i.e. it decays before getting hadronized. The spin information of top-quark is translated to the decay distribution.

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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, $f_{1L} = 1$, $f_{1R} = 0$, $f_{2L} = 0$, $f_{2R} = 0$.
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$$\frac{1}{\Gamma_t} \frac{d\Gamma_t}{d\cos\theta_f} = \frac{1}{2}\Big(1 + \alpha_f \; P_t \; \cos\theta_f \Big)$$

$$\alpha_l = 1 - \mathcal{O}(f_i^2)$$

$$\alpha_b = -\left[\frac{m_t^2 - 2m_W^2}{m_t^2 + 2m_W^2} \right] + \Re(f_{2R}) \left[\frac{8 m_t m_W (m_t^2 - m_W^2)}{(m_t^2 + 2m_W^2)^2} \right] + \mathcal{O}\left(\frac{m_b}{m_W}, f_i^2 \right)$$

Lepton distribution

$$AB \longrightarrow t \; P_1 \ldots P_{n-1}$$

$$t \longrightarrow b \; W^+$$

$$W^+ \longrightarrow l^+ \, \nu$$

Lepton distribution is independent of anomalous tbW coupling if

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

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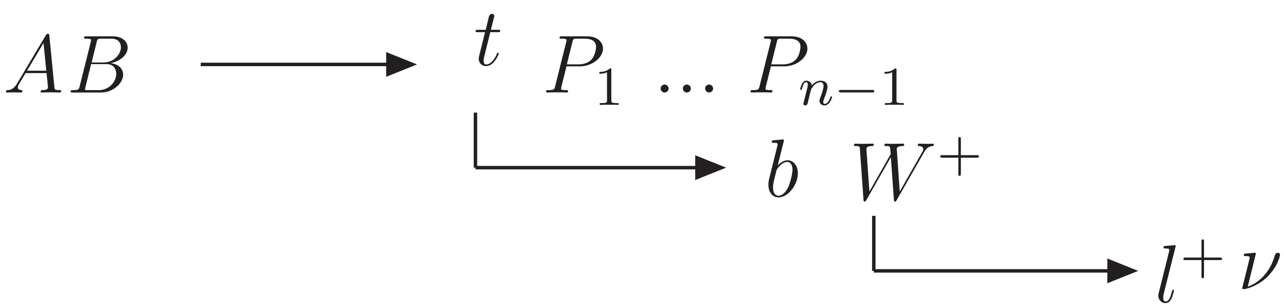

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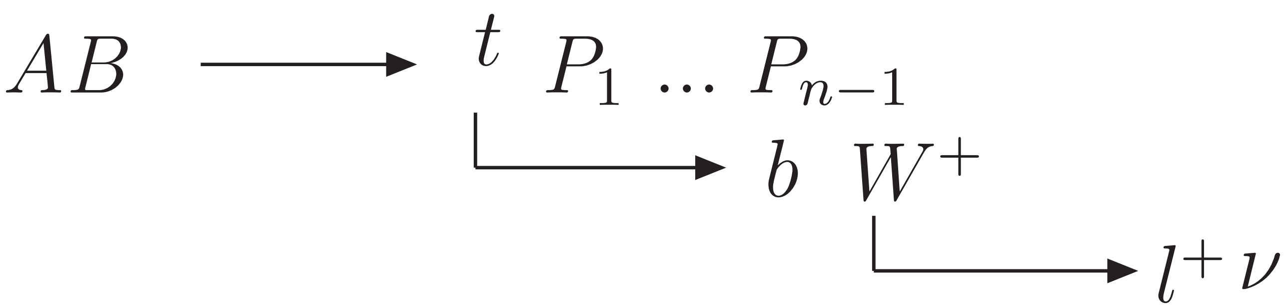

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- anomalous couplings $f_{1R},\; f_{2R}$ and f_{2L} are small,
- narrow-width approximation for W-boson,
- b-quark is mass-less,
- $t \to bW(\ell\nu_\ell)$ is the only decay channel for t-quark.

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 ϕ_b about $\vec{p}_l$.

Decay density matrix

In the rest frame of t-quark, we have

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

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

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

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

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

and

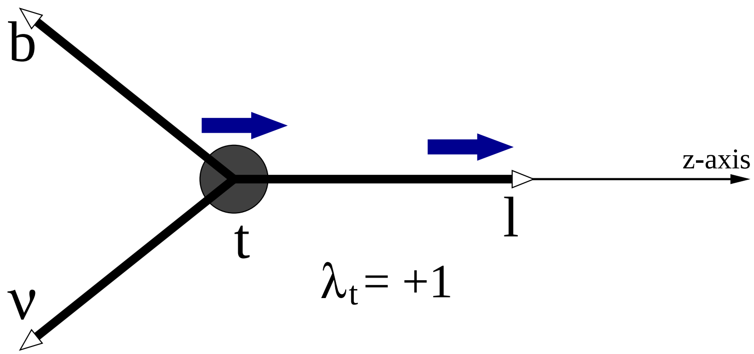
$$\Gamma_t \propto \int E_\ell\, F(E_\ell)\, dE_\ell\, dp_W^2$$

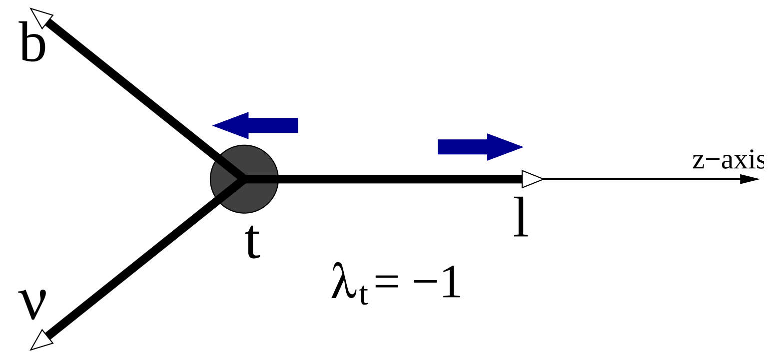
Contribution from anomalous tbW couplings cancels between numerator and denominator, if $t \to bW$ is the only decay channel.

⇒ Lepton angular distribution is independent of anomalous tbW interactions.

Angular distribution of lepton

(Thanks to Peskin)





$$\mathcal{M}(t_\uparrow;\phi_b=0)=C_{SM}+\mathcal{O}(f_i)$$

$$\mathcal{M}(t_\uparrow;\phi_b)=\mathcal{M}(t_\uparrow;\phi_b=0)\,e^{-i(0)\phi_b}$$

$$\mathcal{M}(t_\downarrow;\phi_b=0)=0+\mathcal{O}(f_i)$$

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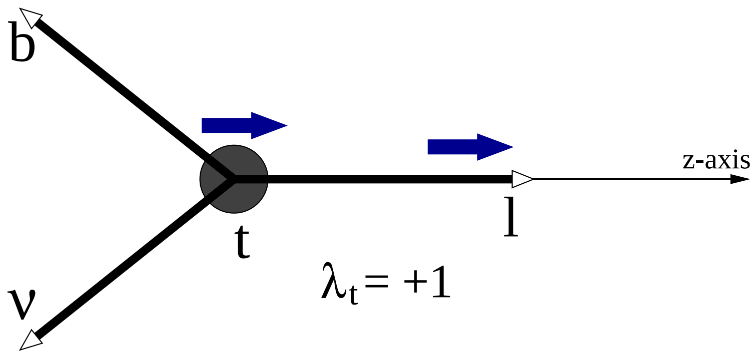

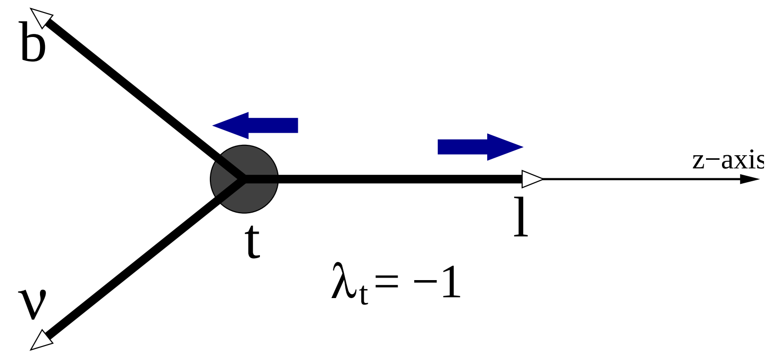

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The density matrix of the configuration is:

$$\Gamma_t \propto \begin{bmatrix} 1+\mathcal{O}(f_i)+\mathcal{O}(f_i^2) & (\;)\; e^{-i\phi_b} \\ (\;)\; e^{i\phi_b} & \mathcal{O}(f_i^2) \end{bmatrix}$$

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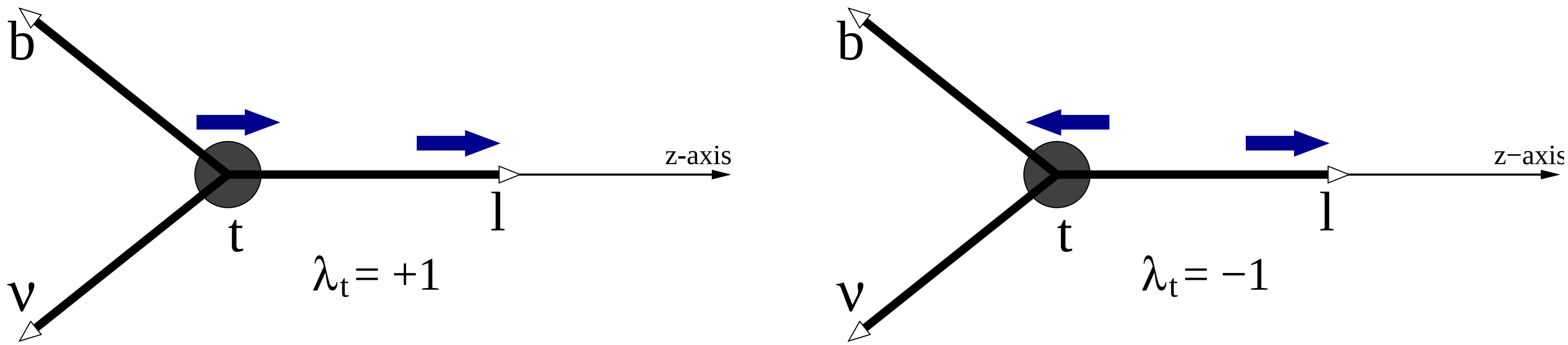

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Integration over ϕ_b gives:

$$\langle\Gamma_t\rangle \propto \begin{bmatrix} 1+\mathcal{O}(f_i)+\mathcal{O}(f_i^2) & 0 \\ 0 & \mathcal{O}(f_i^2) \end{bmatrix}.$$

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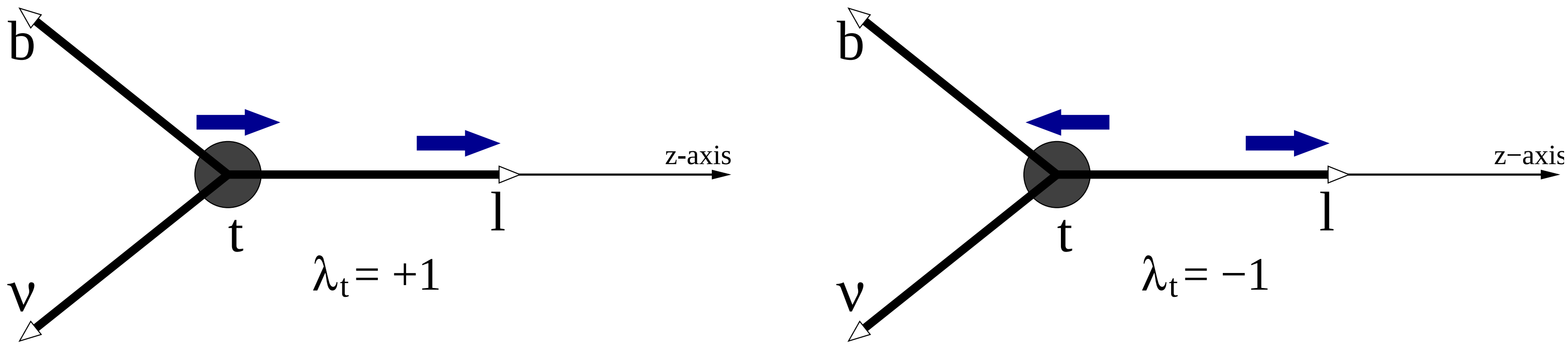

$$\mathcal{M}(t_\uparrow; \phi_b = 0) = C_{SM} + \mathcal{O}(f_i) \qquad \mathcal{M}(t_\downarrow; \phi_b = 0) = 0 + \mathcal{O}(f_i)$$

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Neglecting the terms of $\mathcal{O}(f_i^2)$ we get:

$$\langle \Gamma_t \rangle \propto (1 + \mathcal{O}(f_i)) \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix},$$

Angular distribution of lepton

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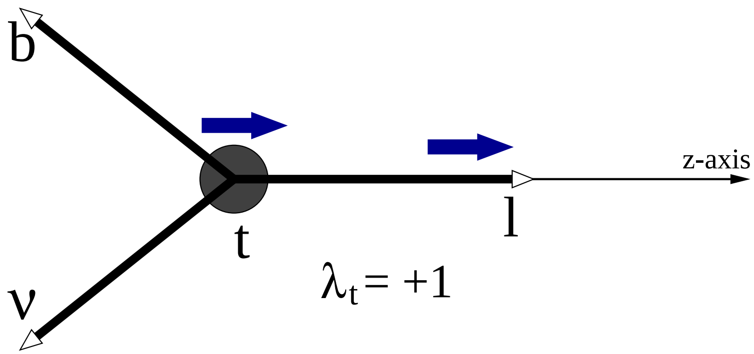

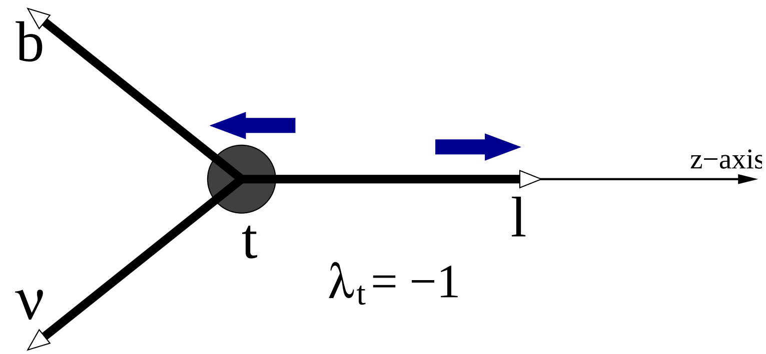

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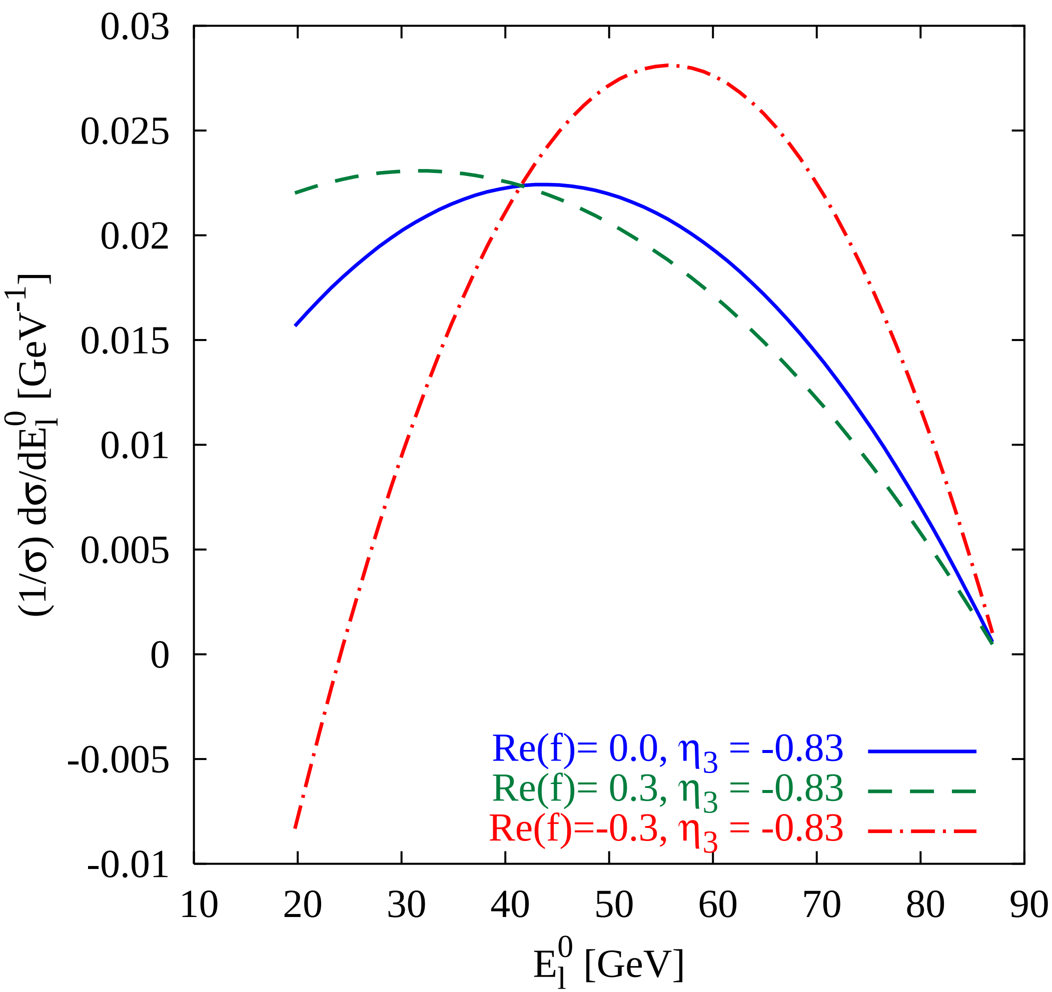
Rotation of $\vec{p}_l$ to (θ_l, ϕ_l) gives:

$$\langle\Gamma_t\rangle \propto (1 + \mathcal{O}(f_i)) \begin{bmatrix} 1 + \cos\theta_l & \sin\theta_l e^{i\phi_l} \\ \sin\theta_l e^{-i\phi_l} & 1 - \cos\theta_l \end{bmatrix},$$

Lepton's angular distribution remains unchanged.
E_l **distribution is changed.**

Energy distribution of lepton

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



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

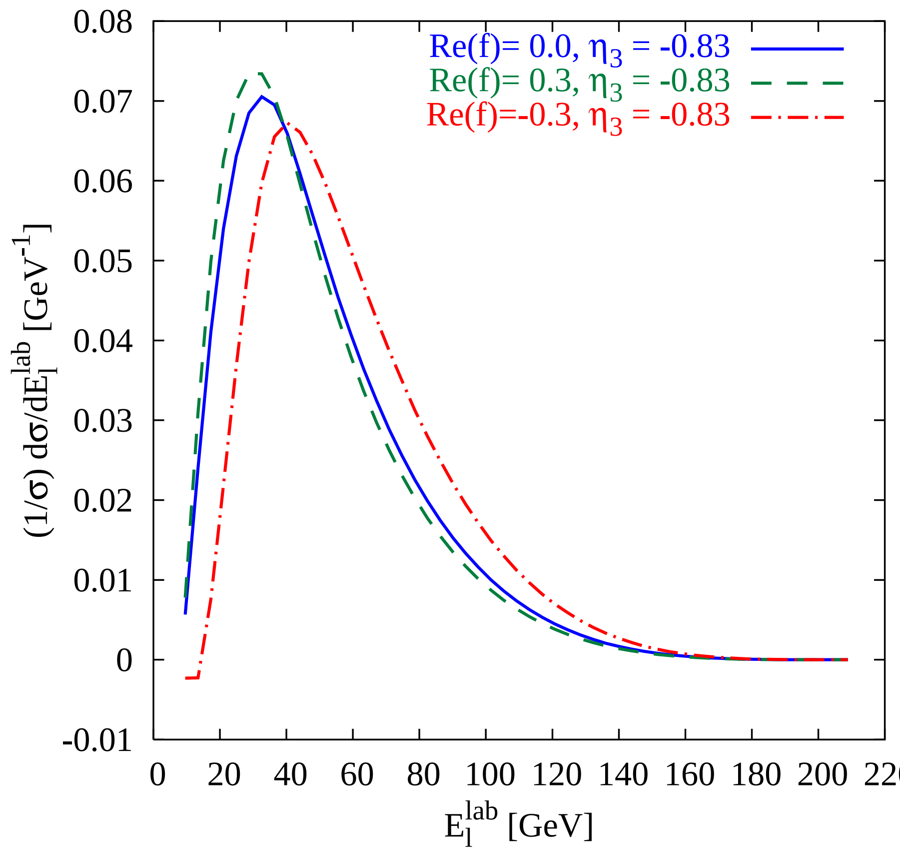
Independent of production mechanism of t-quark !!

Energy distribution of lepton

The E_ℓ distribution (in the lab frame) depends on

- the anomalous couplings in the tbW vetex

$\Rightarrow$ **new physics in t-decay**



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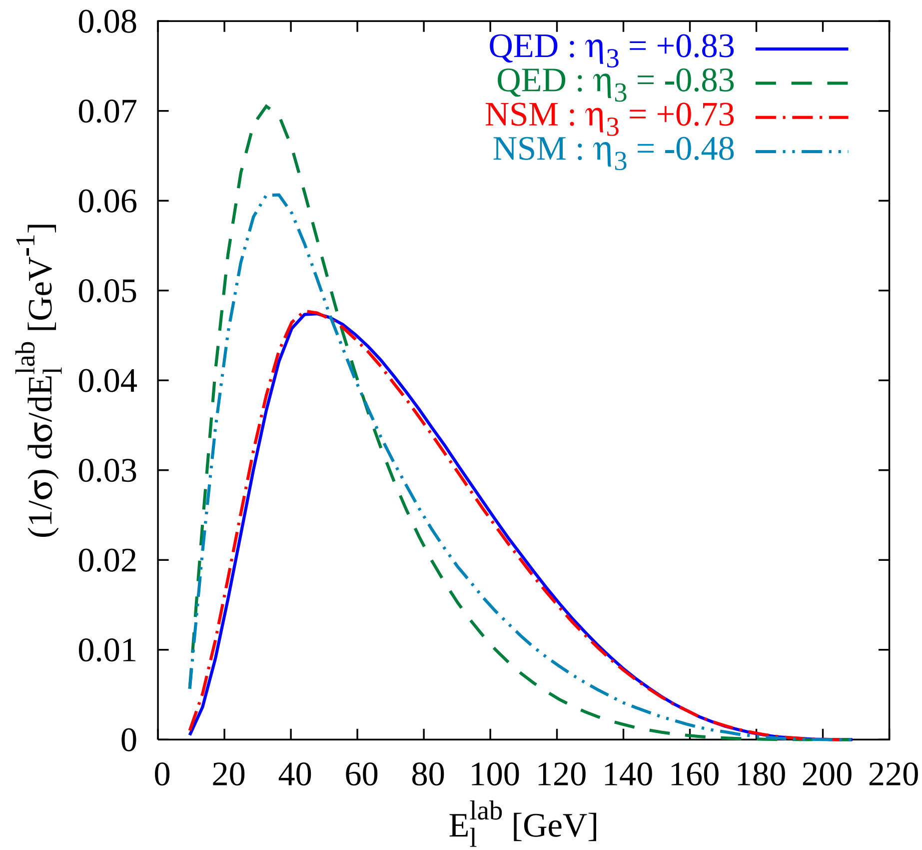
- the energy distribution and the polarization of t-quark $\Rightarrow$ **dynamics of t-production**



Polarization of t-quark

Polarized cross-sections :

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

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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

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

Polarization of t-quark

η_2 : transverse polarization normal to the production plane.

Simplest quantity to measure;

requires reconstruction of t-production plane;

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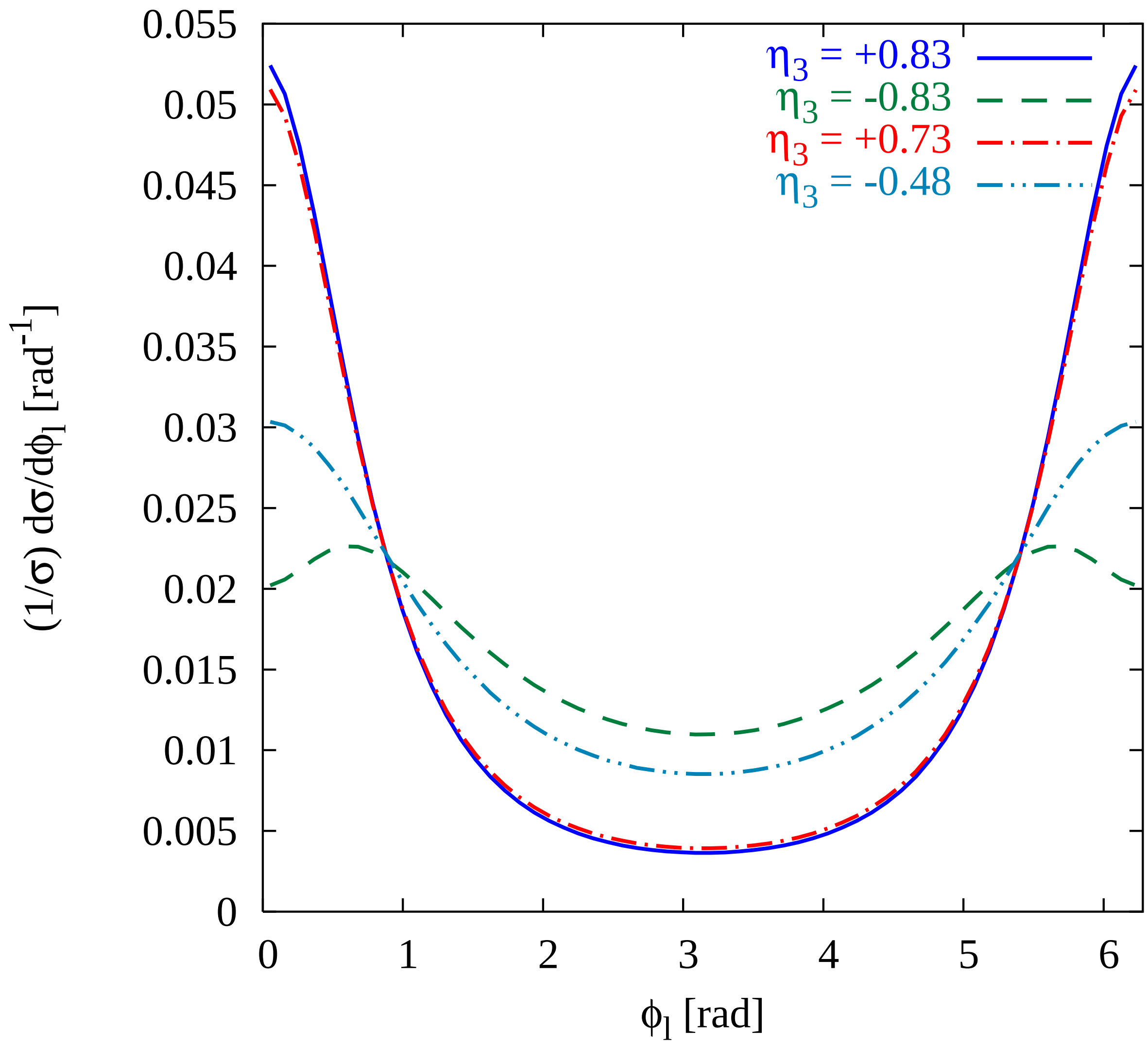
Energy and angular distribution of leptons in lab frame can be used as a measure of the t-polarization.

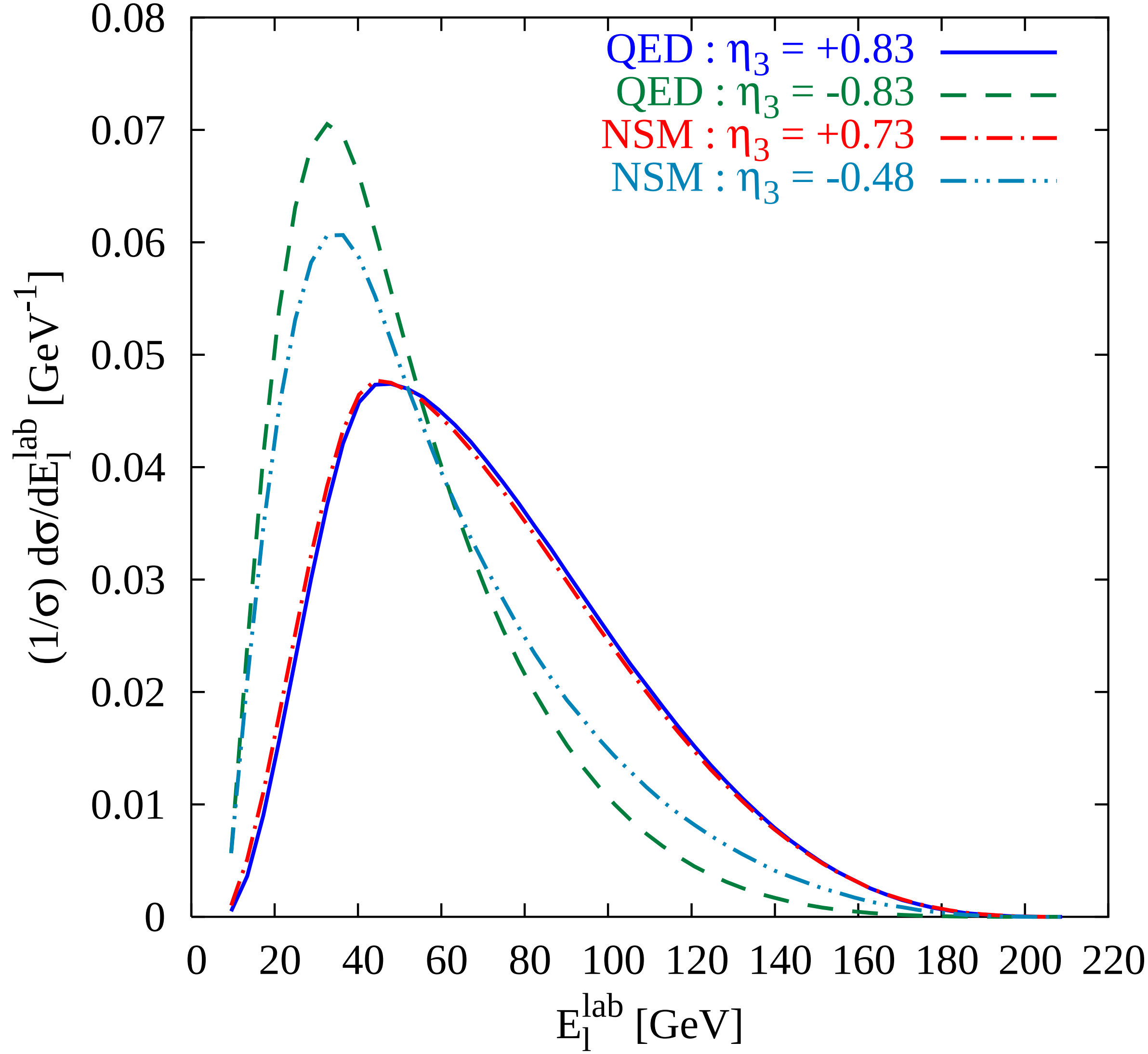
Polarization estimation

Lab frame azimuthal distribution of leptons:



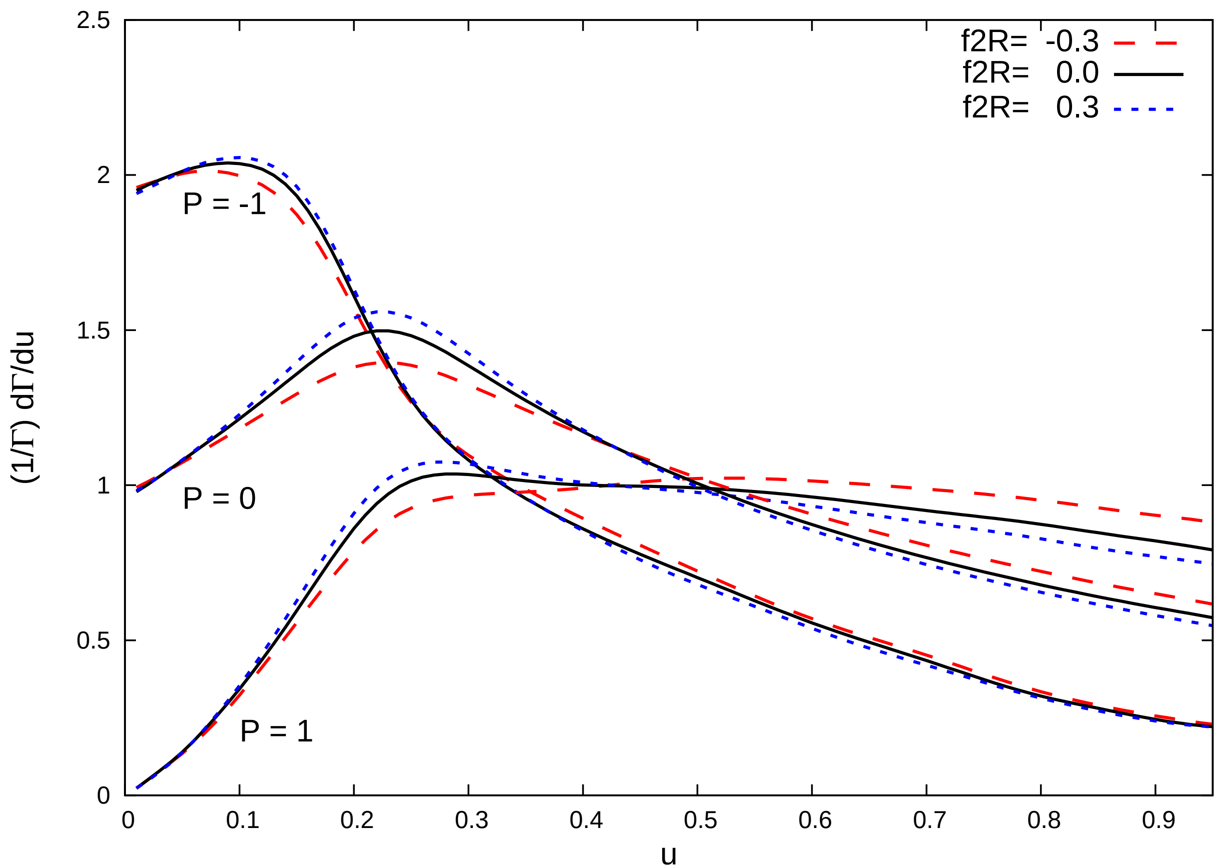
Polarization estimation

Lab frame energy distribution of leptons:



Polarization estimation

Lepton energy fraction in lab frame $u = E_l/(E_l + E_b)$ (Shelton)
(From Rohini's talk)



Polarization estimation

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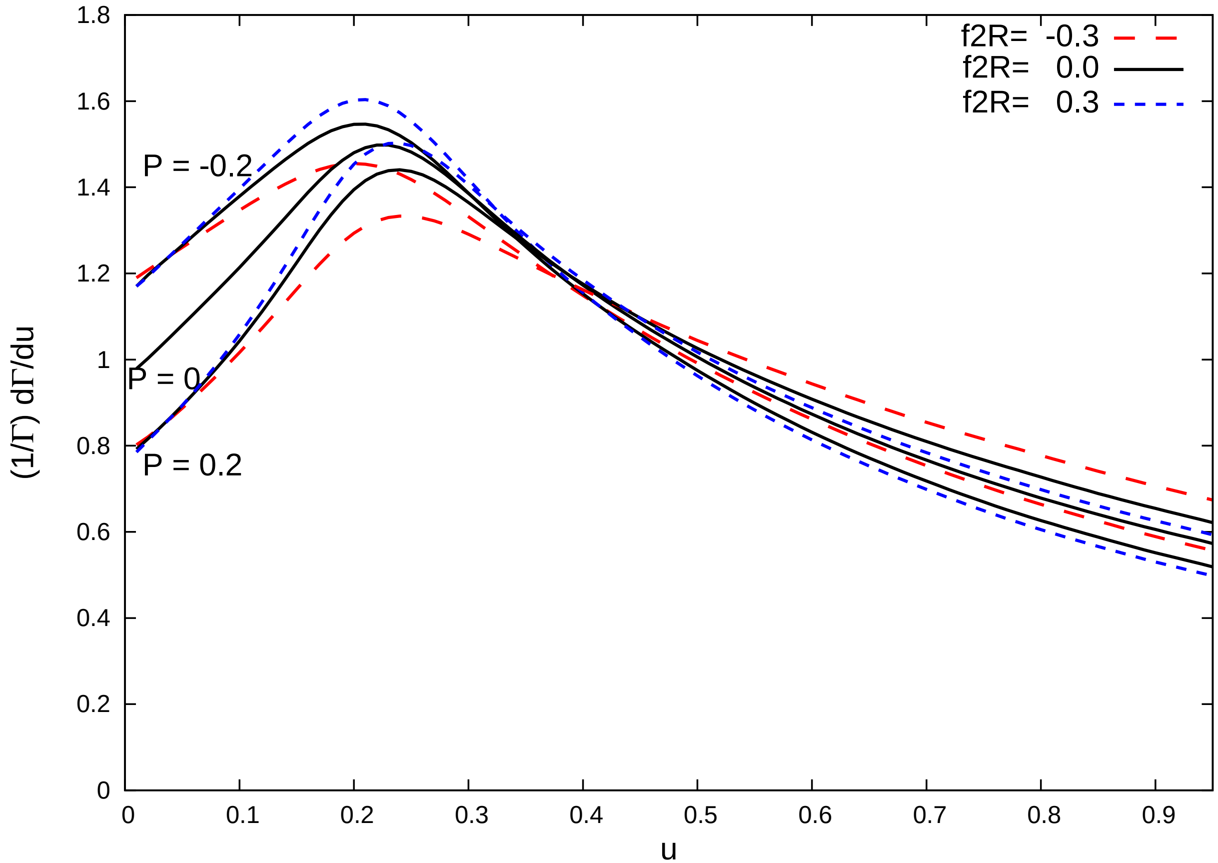

Conclusions

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- Azimuthal and energy distribution of decay lepton in the lab-frame is a good probe of t-polarization.