Looking for *Wtb* anomalous couplings in top pair decays

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Summary

Introduction

Reminder

- The Higgs boson may exist or not (most people hope it)
- Supersymmetry may exist or not (some people hope it)
- New fermions may exist or not (fewer people hope it)
- The top quark definitely exists (we are happy for it) and we must study its properties at LHC

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Top quark properties

- Mass ☞
  - Possibly new physics influence
  - Measured at Tevatron
  - But no standard theory for masses
- Couplings ☞
  - Sensitive to new physics corrections
  - Predicted in the SM
  - May be measured / bounded
- Spin ☞ Testable in top production and decay

Probing top couplings

- Wtb vertex ☞ [top decays $t \to W^+ b$ — [many authors]; single top LHC — [Boos et al., EPJC '99]]
- Ztt, γtt ☞ [$t\bar{t}Z$, $t\bar{t}\gamma$ at LHC — [Baur et al., PRD '05,'06]; $t\bar{t}$ at ILC]
- gtt ☞ [$t\bar{t}$ at LHC — [Cheung, PRD '96]; $t\bar{t}g$ at ILC — [Rizzo, PRD '94]]
- Ztq, γtq, gtq ☞ FCN production and decay [many authors]

General Wtb vertex

$$\begin{aligned} \mathcal{L} &= -\frac{g}{\sqrt{2}} \bar{b}\, \gamma^\mu \left(V_L P_L + V_R P_R \right) t\, W_\mu^- \\ & \quad - \frac{g}{\sqrt{2}} \bar{b}\, \frac{i \sigma^{\mu\nu} q_\nu}{M_W} \left(g_L P_L + g_R P_R \right) t\, W_\mu^- + \text{h.c.} \end{aligned}$$

(Additional terms p^μ, etc. rewritten with Gordon identities)

V_R, g_L, g_R zero at tree level

$V_L \simeq 1$, normalised to unity

V_R, g_L, g_R expected to be (very) small

Top decays and W helicity

Equivalent descriptions of $t \to W^+ b \to \ell^+ \nu b$

- ℓ angular distribution $\leftrightarrow$ angular asymmetries
  in W rest frame, determined by W^+ helicity fractions
- ℓ energy distribution $\leftrightarrow$ energy asymmetries
  in t rest frame, determined by W^+ helicity fractions and W boost

ℓ angular distribution in W rest frame

Assume t, W on shell

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell^*} = \frac{3}{8}(1+\cos\theta_\ell^*)^2 F_R + \frac{3}{8}(1-\cos\theta_\ell^*)^2 F_L + \frac{3}{4}\sin^2\theta_\ell^* F_0$$

θ_ℓ^* angle between $\left[\begin{array}{l} \ell \text{ momentum in } W \text{ rest frame} \\ W \text{ momentum in } t \text{ rest frame} \end{array}\right.$

$\theta_\ell^* = \pi - \theta_{\ell b}$ $\quad$ $\theta_{\ell b}$ angle between ℓ and b in W rest frame

$\Gamma(t \to W^+ b) = \Gamma_R + \Gamma_L + \Gamma_0$ $\quad$ $F_i = \Gamma_i/\Gamma$

F_i ➜ determine ℓ distribution

W helicity fractions

$(x_W = M_W/m_t, \ \ x_b = m_b/m_t, \ \ |\vec{q}\,| = W$ momentum)

$$
\begin{aligned}
\Gamma_0 \quad = \quad & \frac{g^2 |\vec{q}\,|}{32\pi} \left\{ \frac{m_t^2}{M_W^2} \left[|V_L|^2 + |V_R|^2 \right] \left(1 - x_W^2 - 2x_b^2 - x_W^2 x_b^2 + x_b^4 \right) - 4x_b \, \mathrm{Re}\, V_L V_R^* \right. \\
& + \left[|g_L|^2 + |g_R|^2 \right] \left(1 - x_W^2 + x_b^2 \right) - 4x_b \, \mathrm{Re}\, g_L g_R^* \\
& \left. -2 \frac{m_t}{M_W} \mathrm{Re} \, \left[V_L g_R^* + V_R g_L^* \right] \left(1 - x_W^2 - x_b^2 \right) + 2 \frac{m_t}{M_W} x_b \, \mathrm{Re} \, \left[V_L g_L^* + V_R g_R^* \right] \left(1 + x_W^2 - x_b^2 \right) \right\} \\
\Gamma_{R,L} \quad = \quad & \frac{g^2 |\vec{q}\,|}{32\pi} \left\{ \left[|V_L|^2 + |V_R|^2 \right] \left(1 - x_W^2 + x_b^2 \right) - 4x_b \, \mathrm{Re}\, V_L V_R^* \right. \\
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& \pm \frac{g^2}{64\pi} \frac{m_t^3}{M_W^2} \left\{ -x_W^2 \left[|V_L|^2 - |V_R|^2 \right] + \left[|g_L|^2 - |g_R|^2 \right] \left(1 - x_b^2 \right) \right. \\
& \left. + 2x_W \, \mathrm{Re} \, \left[V_L g_R^* - V_R g_L^* \right] + 2x_W x_b \, \mathrm{Re} \, \left[V_L g_L^* - V_R g_R^* \right] \right\} \\
& \times \left(1 - 2x_W^2 - 2x_b^2 + x_W^4 - 2x_W^2 x_b^2 + x_b^4 \right)
\end{aligned}
$$

W helicity fractions

$(x_W = M_W/m_t, \quad x_b = m_b/m_t, \quad |\vec{q}\,| = W$ momentum$)$

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See

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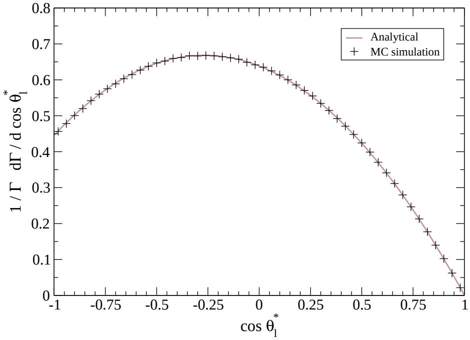
\end{aligned}$$

Influence of finite width corrections

But . . . is this a good approximation? Yes!



Finite width corrections do not affect angular distribution

Equivalent parameter sets

Helicity fractions	Helicity ratios
$F_i = \Gamma_i/\Gamma$	$\rho_{R,L} \equiv \Gamma_{R,L}/\Gamma_0$
$F_R + F_L + F_0 = 1$	independent quantities
$\rho_{R,L} = F_{R,L}/F_0$	$F_0 = (1+\rho_R+\rho_L)^{-1}$ $F_{R,L} = \rho_{R,L}\,(1+\rho_R+\rho_L)^{-1}$

They can be obtained from a fit to ℓ distribution

They are sensitive to anomalous couplings

Which one is better? See experimental precision

ℓ angular asymmetries in W rest frame

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell^*} = \frac{3}{8}(1+\cos\theta_\ell^*)^2 F_R + \frac{3}{8}(1-\cos\theta_\ell^*)^2 F_L + \frac{3}{4}\sin^2\theta_\ell^* F_0$$

Take $t \in [-1,1]$ fixed and define asymmetries

$$A_t = \frac{N(\cos\theta_\ell^* > t) - N(\cos\theta_\ell^* < t)}{N(\cos\theta_\ell^* > t) + N(\cos\theta_\ell^* < t)}$$

$$\left.\begin{array}{lcl} t = 0 & ☞ & A_{\mathrm{FB}} = \frac{3}{4}(F_R - F_L) \\ t = -(2^{2/3}-1) & ☞ & A_+ = 3\beta[F_0 + (1+\beta)F_R] \\ t = (2^{2/3}-1) & ☞ & A_- = -3\beta[F_0 + (1+\beta)F_L] \\ & & (\beta \equiv 2^{1/3}-1) \end{array}\right]$$

Determine F_i without fits

Asymmetries depend on anomalous couplings …

See

Better or worse? See experimental precision

ℓ energy in t rest frame

Related to $\cos\theta_\ell^*$ by boost

$$E_\ell = \frac{1}{2}(E_W + |\vec{q}\,|\cos\theta_\ell^*) \quad E_W, |\vec{q}\,| \text{ constants}$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{dE_\ell} = \frac{1}{(E_{\max}-E_{\min})^3}\left[3(E_\ell-E_{\min})^2 F_R + 3(E_{\max}-E_\ell)^2 F_L \right.$$
$$\left. +6(E_{\max}-E_\ell)(E_\ell-E_{\min}) F_0\right]$$

with $E_{\max} = (E_W + |\vec{q}\,|)/2$, $E_{\min} = (E_W - |\vec{q}\,|)/2$

Descriptions equivalent but larger errors for E_ℓ

Top pair decays and $t\bar{t}$ spin correlations

Top decay: distributions in t rest frame

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_X} = \frac{1}{2}(1+\alpha_X\cos\theta_X) \qquad X = \ell, \nu, b, W^+, q, \bar{q}'$$

θ_X angle between X momentum and top spin

SM tree level (no anomalous couplings)

$$\alpha_{\ell^+} = \alpha_{\bar{q}'} = 1 \quad \alpha_\nu = \alpha_q = -0.31 \quad \alpha_{W^+} = -\alpha_b = 0.41$$

☞ Information on anomalous couplings and t polarisation

Antitop: $\alpha_{\bar{X}} = -\alpha_X$ if CP conserved

Top quarks produced (almost) unpolarised in $gg, q\bar{q} \to t\bar{t}$

☞ compare distribution of $\left[\begin{array}{l} X \text{ from } t \text{ decay} \\ \bar{X}' \text{ from } \bar{t} \text{ decay} \end{array} \right.$

Double distribution in helicity basis:

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta_X \, d\cos\theta_{\bar{X}'}} = \frac{1}{4}(1 + C\,\alpha_X \alpha_{\bar{X}'} \cos\theta_X \cos\theta_{\bar{X}'})$$

$$\begin{aligned} C &\equiv \frac{\sigma(t_R\bar{t}_R) + \sigma(t_L\bar{t}_L) - \sigma(t_R\bar{t}_L) - \sigma(t_L\bar{t}_R)}{\sigma(t_R\bar{t}_R) + \sigma(t_L\bar{t}_L) + \sigma(t_R\bar{t}_L) + \sigma(t_L\bar{t}_R)} \\ &\simeq 0.31 \quad \text{(SM tree-level)} \end{aligned}$$

CP: $\sigma(t_R\bar{t}_R) = \sigma(t_L\bar{t}_L)$ P: $\sigma(t_R\bar{t}_L) = \sigma(t_L\bar{t}_R)$

Opening angle distribution:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi_{X\bar{X}'}} = \frac{1}{2}(1 + D\,\alpha_X \alpha_{\bar{X}'} \cos\varphi_{X\bar{X}'})$$

$\varphi_{X\bar{X}'}$ angle between
- X momentum in t rest frame
- $\bar{X}'$ momentum in $\bar{t}$ rest frame

$D \simeq 0.217$ (SM tree-level)

Define asymmetries

$$A_{X\bar{X}'} \equiv \frac{N(\cos\theta_X \cos\theta_{\bar{X}'} > 0) - N(\cos\theta_X \cos\theta_{\bar{X}'} < 0)}{N(\cos\theta_X \cos\theta_{\bar{X}'} > 0) + N(\cos\theta_X \cos\theta_{\bar{X}'} < 0)} = \frac{1}{4} C \alpha_X \alpha_{\bar{X}'}$$

$$\tilde{A}_{X\bar{X}'} \equiv \frac{N(\cos\varphi_{X\bar{X}'} > 0) - N(\cos\varphi_{X\bar{X}'} < 0)}{N(\cos\varphi_{X\bar{X}'} > 0) + N(\cos\varphi_{X\bar{X}'} < 0)} = \frac{1}{2} D \alpha_X \alpha_{\bar{X}'}$$

Sensitive to new physics:

- in production (C, D) [Bernreuther et al., PRD '98] [Cheung, PRD '97]
- in decay $(\alpha_X, \alpha_{\bar{X}'})$

See

Measurement of spin correlation parameters

Spin asymmetries less sensitive to anomalous couplings ▸ See

Use expected precisions [Hubaut et al., EPJC '05]
to constrain uncertainty [JAAS & Coimbra group, in prep.]

$$A_{\ell\ell'} \rightarrow C = 0.310 \pm 0.024\,(\text{exp})\ {}^{+2\times10^{-5}}_{-0.0003}\ (\delta g_R)\ {}^{+2\times10^{-5}}_{-4\times10^{-6}}\ (\delta g_L)\ {}^{+0}_{-0.0062}\ (\delta V_R)$$

$$A_{\ell j} \rightarrow C = 0.310 \pm 0.045\,(\text{exp})\ {}^{+0.0005}_{-0.0007}\ (\delta g_R)\ {}^{+0.0002}_{-0.0009}\ (\delta g_L)\ {}^{+0.0001}_{-0.0095}\ (\delta V_R)$$

$$\tilde{A}_{\ell\ell'} \rightarrow D = 0.217 \pm 0.011\,(\text{exp})\ {}^{+4\times10^{-6}}_{-0.0002}\ (\delta g_R)\ {}^{+1\times10^{-5}}_{-2\times10^{-6}}\ (\delta g_L)\ {}^{+0}_{-0.0042}\ (\delta V_R)$$

$$\tilde{A}_{\ell j} \rightarrow D = 0.217 \pm 0.024\,(\text{exp})\ {}^{+8\times10^{-5}}_{-0.0003}\ (\delta g_R)\ {}^{+0.0001}_{-0.0006}\ (\delta g_L)\ {}^{+7\times10^{-5}}_{-0.0066}\ (\delta V_R)$$

Top pair decays and CP violation

Until now we have assumed real V_R, g_L, g_R

. . . but this may not be the full story . . .

Helicity fractions depend on phases through interference terms

More important for g_R ☞ larger phase effects See

$g_R = \pm 0.055$ gives 3σ effect, $g_R = \pm 0.055i$ gives $\simeq 0.3\sigma$

Spin correlation asymmetries do not help See

Can CP violating asymmetries help? Perhaps . . .

CP violation in top decays

CP-violating asymmetry [Bernreuther et al., PLB '93]

$$T_2 = (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-})$$

(for dilepton channel only)

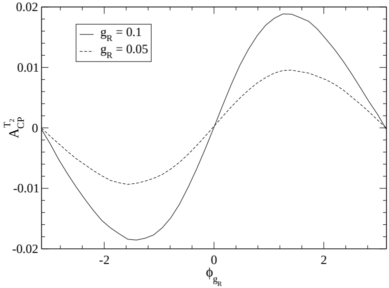
☞ $$A_{CP}^{T_2} = \frac{N(T_2 > 0) - N(T_2 < 0)}{N(T_2 > 0) + N(T_2 < 0)}$$

Momenta measured
- in t, $\bar{t}$ rest frames (larger A)
- in laboratory frame (smaller A)

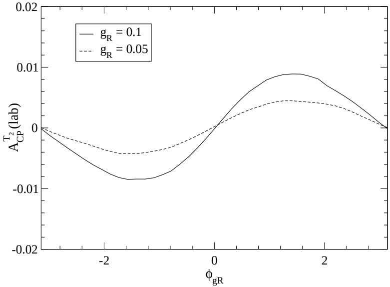
Sensitive to g_R but not to V_R and g_L

CP violation in top decays

$t, \bar{t}$ rest frames



laboratory



Measurable?

Other asymmetries, e.g. based on products

$$
\begin{aligned}
T_1 &= \hat{e} \cdot (\vec{p}_{\ell+} - \vec{p}_{\ell-}) \, (\vec{p}_{\ell+} \times \vec{p}_{\ell-}) \cdot \hat{e} \\
T_3 &= (\vec{p}_t - \vec{p}_{\bar{t}}) \cdot (\vec{p}_{\ell+} \times \vec{p}_{\ell-}) \\
\Delta_1 &= E_{\ell+} - E_{\ell-} \\
\Delta_2 &= \vec{p}_{\bar{t}} \cdot \vec{p}_{\ell+} - \vec{p}_t \cdot \vec{p}_{\ell-} \\
\Delta_3 &= \cos\theta_{\ell+} - \cos\theta_{\ell-}
\end{aligned}
$$

Insensitive to CP-violating g_R, g_L, V_R

☞ Test CP violation in production [Schmidt, Peskin, PRL '92] [Bernreuther et al., PLB '93] [Khater, Osland, NPB '03]

Summary

- Many ways to study *Wtb* vertex, some better than others

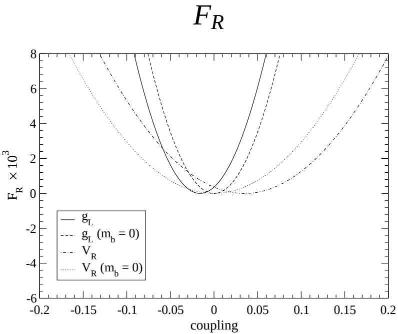
  ☞ João's talk

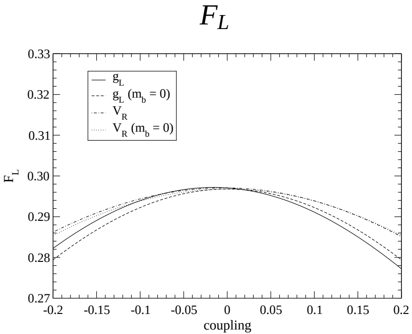
- Constraining the *Wtb* vertex as far as possible can help disentangle new physics in production

  (spin correlations, CP violation)

- There are lots of work still to do ...

Effect of m_b in helicity fractions





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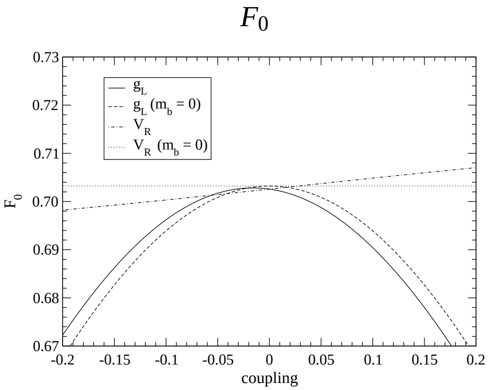
Effect of m_b in helicity fractions



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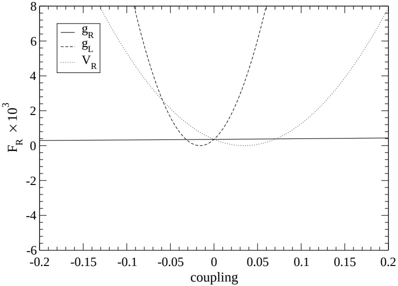
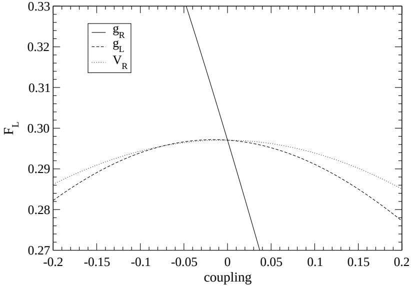
Dependence of F_i on anomalous couplings

F_R



F_L



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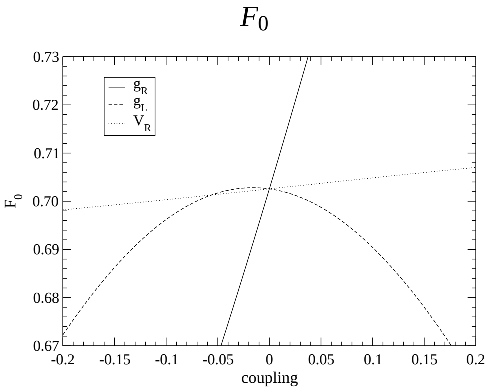
Dependence of F_i on anomalous couplings



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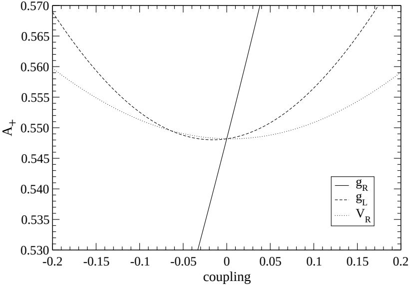
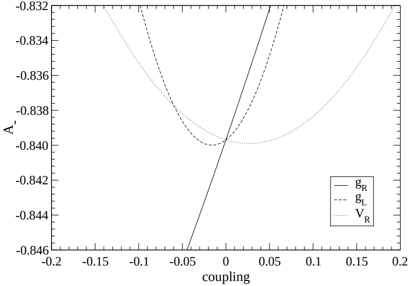
Dependence of asymmetries on anomalous couplings

A_+ A_-





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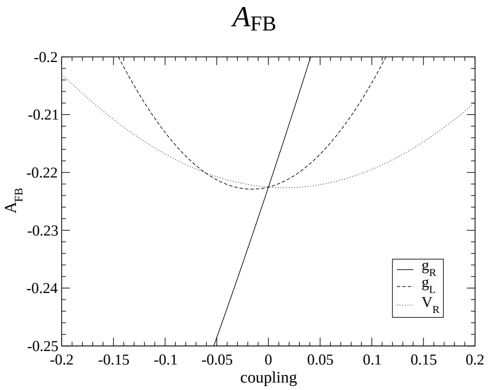
Dependence of asymmetries on anomalous couplings



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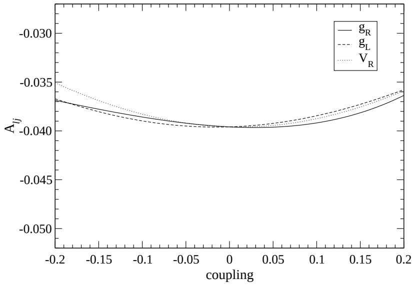
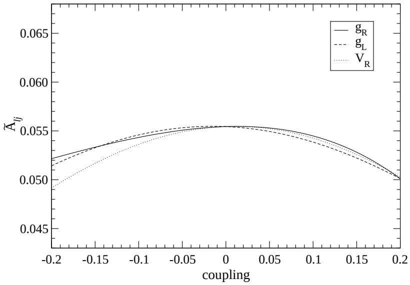
Dependence of spin asymmetries on anomalous couplings

$A_{\ell j}$



$\tilde{A}_{\ell j}$



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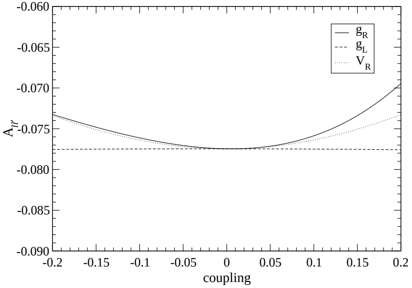
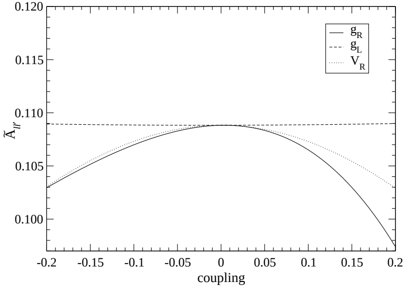
Dependence of spin asymmetries on anomalous couplings

$A_{\ell\ell'}$



$\tilde{A}_{\ell\ell'}$



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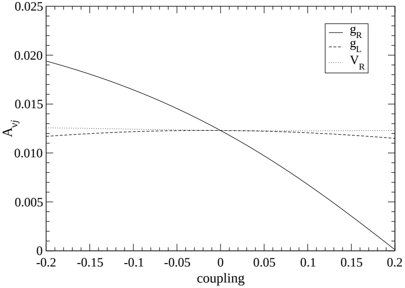
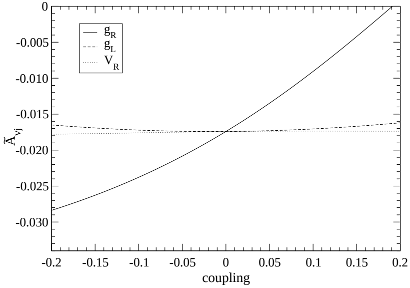
Dependence of spin asymmetries on anomalous couplings

$A_{\nu j}$



$\tilde{A}_{\nu j}$



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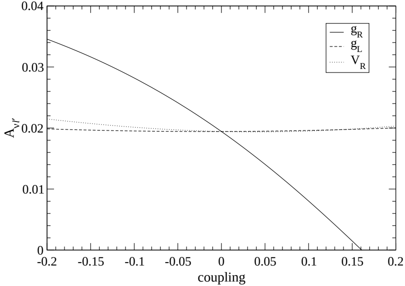
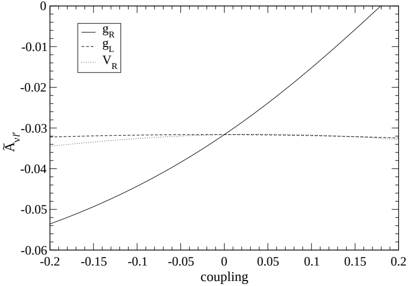
Dependence of spin asymmetries on anomalous couplings

$A_{\nu\ell'}$



$\tilde{A}_{\nu\ell'}$



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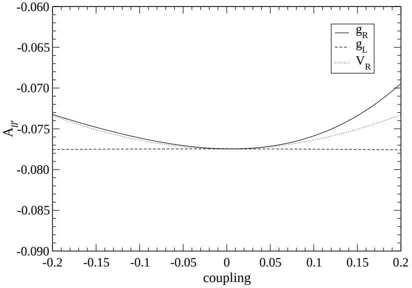
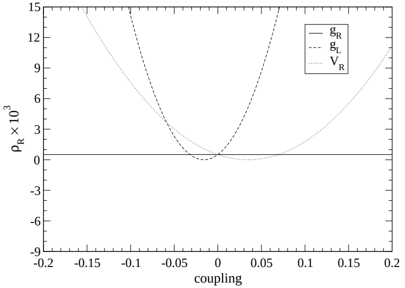
Spin asymmetries: comparison

$A_{\ell\ell'}$



ρ_R



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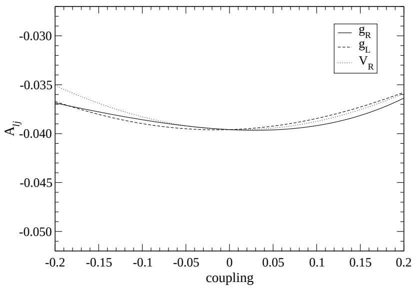
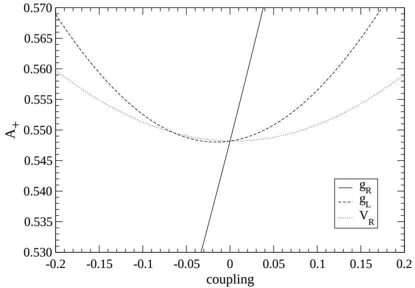
Spin asymmetries: comparison

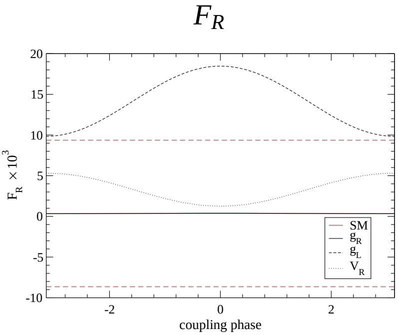
$A_{\ell j}$

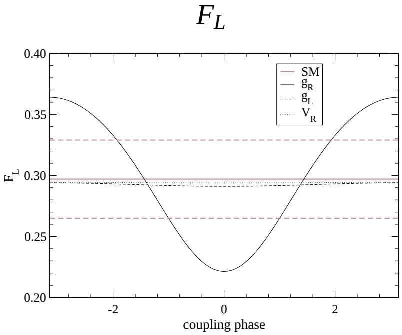


A_+

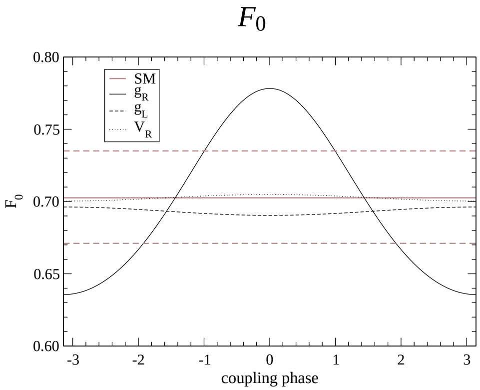


Effect of phases in helicity fractions





Effect of phases in helicity fractions



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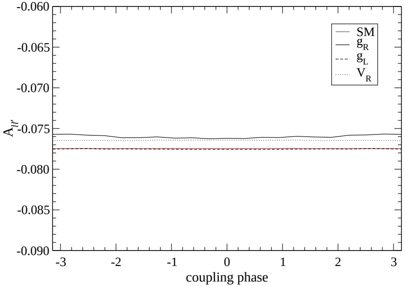
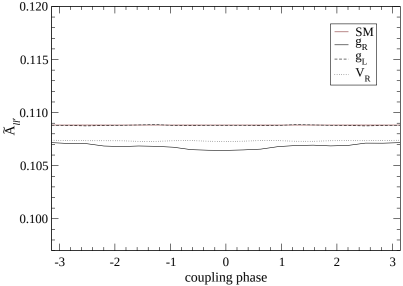
Effect of phases in spin asymmetries

$A_{\ell\ell'}$



$\tilde{A}_{\ell\ell'}$



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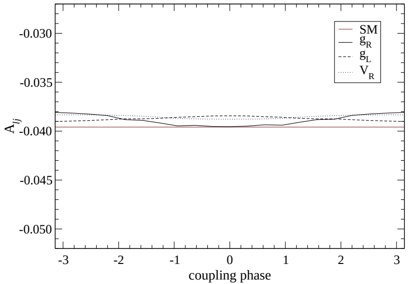
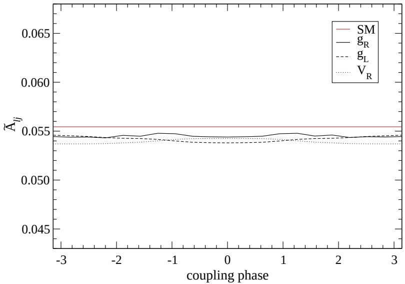
Effect of phases in spin asymmetries

$A_{\ell j}$



$\tilde{A}_{\ell j}$



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