The spin correlation in top quark production:

QCD corrections vs anomalous couplings

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Massive Particles $\leftrightarrow$ New Physics ?

- (Not) Beyond the Standard Model

  Spin Degrees of Freedom
  Sensitive to the Structure of Interactions

- Top Decays before Hadronization (Kühn, ...)

  Can Measure Top Quark Spin !!

The Size of New Physics
At Most, Nearly Equal to the R.C. (QCD)

in collaboration with

Y. Kiyo, K. Morii, T. Nasuno (Hiroshima)
S. Parke (FNAL)

♣ Spin Correlation in Top Production and Decay

Want to Know

$$\begin{aligned} e^-e^+ &\to t_\uparrow \bar{t}_\uparrow \quad , \quad t_\uparrow \bar{t}_\downarrow \quad , \quad t_\downarrow \bar{t}_\uparrow \quad , \quad t_\downarrow \bar{t}_\downarrow \\ &\to b\, \bar{l}\, \nu \quad , \quad b\, q\, \bar{q} \quad , \quad \bar{b}\, l\, \bar{\nu} \quad , \quad \bar{b}\, \bar{q}\, q \end{aligned}$$

- Traditional Approach

  Helicity Basis

  This is Fine for $\beta \to 1$

- New Approach Mahlon, Parke and Shadmi

  Clever Choice of Spin Basis

  $$\beta \simeq \frac{1}{2}$$

  for a Realistic Collider

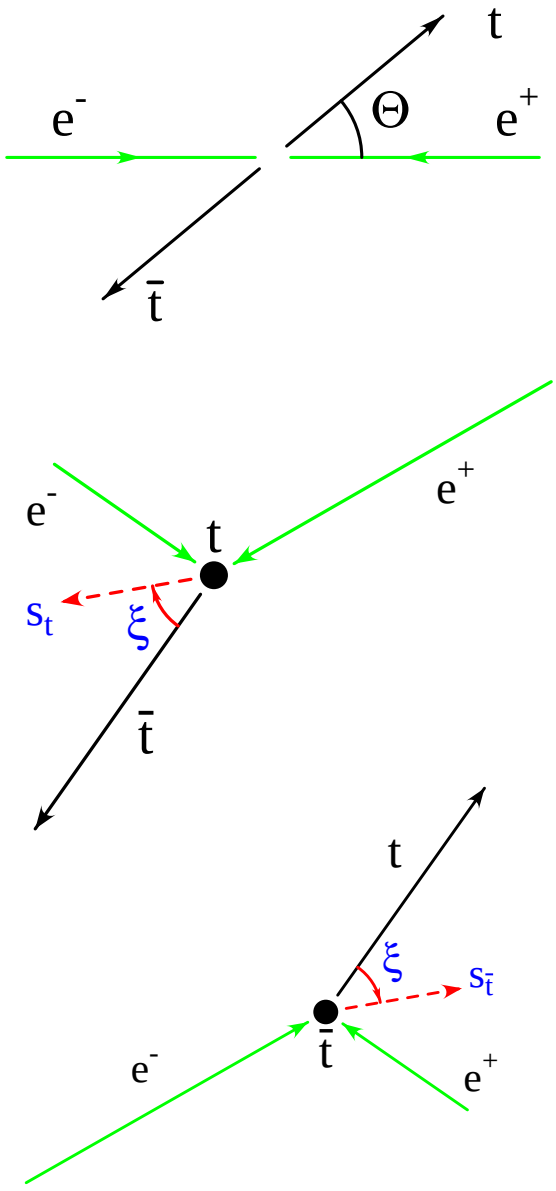
e.g. $M_{\rm top} = 175\text{GeV}$ $\beta = 0.484$ for $\sqrt{s} = 400\text{GeV}$

Calculate "Cross Section" with
Arbitrary Orientation of Top Spin

Including

QCD Corrections and Anomalous Couplings

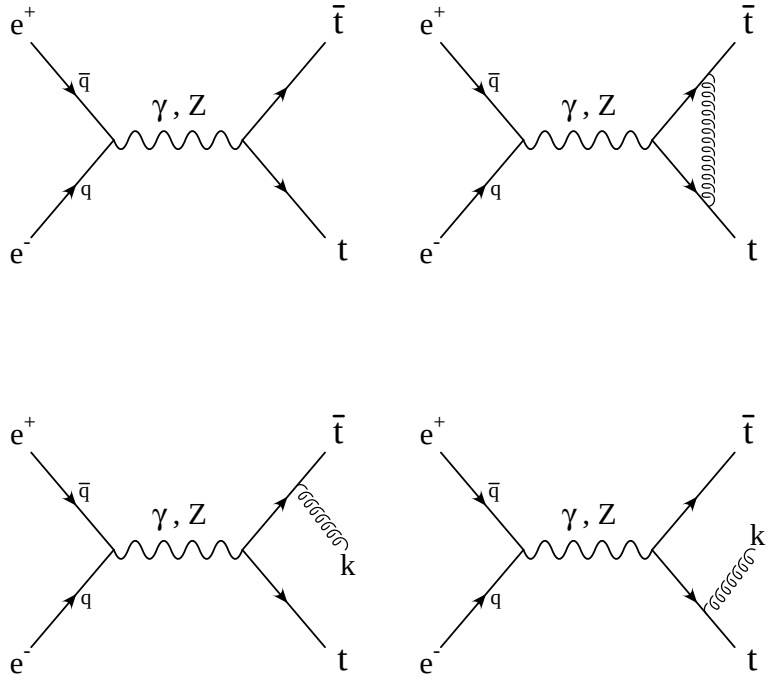
♣ Choice of Spin



All Vectors are in the Production Plane

♣ Spin Correlation in SM

Diagrams:



♡ Tree-level and Opitmal Spin Basis

$$\frac{d\sigma}{d\cos\theta}(e_L^- e_R^+ \to t_\uparrow \bar{t}_\uparrow) = \frac{d\sigma}{d\cos\theta}(e_L^- e_R^+ \to t_\downarrow \bar{t}_\downarrow)$$
$$= \left(\frac{3\pi\alpha^2}{2s}\beta\right) |(A_{LR}\cos\xi - B_{LR}\sin\xi)|^2$$

$$\frac{d\sigma}{d\cos\theta}(e_L^- e_R^+ \to t_\uparrow \bar{t}_\downarrow \text{ or } t_\downarrow \bar{t}_\uparrow)$$
$$= \left(\frac{3\pi\alpha^2}{2s}\beta\right) |(A_{LR}\sin\xi + B_{LR}\cos\xi \pm D_{LR})|^2$$

Parameters:

$$\begin{aligned} A_{LR} &= [(f_{LL}+f_{LR})\sqrt{1-\beta^2}\,\sin\theta]/\,2 \\ B_{LR} &= [f_{LL}(\cos\theta+\beta)+f_{LR}(\cos\theta-\beta)]/\,2 \\ D_{LR} &= [f_{LL}(1+\beta\cos\theta)+f_{LR}(1-\beta\cos\theta)]/\,2 \\ f_{IJ} &= -Q_t + Q_I^e\,Q_J^t\,\frac{1}{\sin^2\theta_W}\,\frac{s}{s-M_Z^2} \end{aligned}$$

- Helicity Basis

$$\xi = \pm\,\pi$$

Nothing Interesting Happens !!

- Off - Diagonal Basis

$$\tan\xi = \frac{A_{LR}}{B_{LR}} = \frac{(f_{LL}+f_{LR})\sqrt{1-\beta^2}\,\sin\theta}{f_{LL}(\cos\theta+\beta)+f_{LR}(\cos\theta-\beta)}$$

$$\Downarrow$$

$$\frac{d\sigma}{d\cos\theta}\,(e_L^-e_R^+ \to t_\uparrow\bar{t}_\uparrow \text{ and } t_\downarrow\bar{t}_\downarrow) = 0$$

$$\frac{d\sigma}{d\cos\theta}\,(e_L^-e_R^+ \to t_\uparrow\bar{t}_\downarrow \text{ or } t_\downarrow\bar{t}_\uparrow) = \left(\frac{3\pi\alpha^2}{2s}\beta\right)\left|\left(\sqrt{A_{LR}^2+B_{LR}^2}\mp D_{LR}\right)\right|^2$$

Numerically $|f_{LL}| \gg |f_{LR}|$

$$\frac{d\sigma}{d\cos\theta}\,(e_L^-e_R^+ \to t_\downarrow\bar{t}_\uparrow) \simeq 0$$

♡ QCD One-Loop Calculation

Results are Modified by Two plus one Effects

- Modified Magnetic Moment from Vertex Correction
- Spin Flip Effect from Real Gluon Emission
- Top and Anti-top are not Produced Back-to-Back

Calculate Single Spin Correlation

$$\frac{d\sigma}{d\cos\theta}(e_L^- e_R^+ \to t_\uparrow X)$$

Numerical Results I

$$\frac{d\sigma}{d\cos\theta}(e_L^- e_R^+ \to t_\uparrow X)$$
$$= (1+\kappa)\frac{d\sigma^0}{d\cos\theta}(e_L^- e_R^+ \to t_\uparrow X) + \frac{d\sigma^R}{d\cos\theta}(e_L^- e_R^+ \to t_\uparrow X)$$

$\sigma_{\rm tot}$ and K-factor

$\sqrt{s}$ (GeV)	α_s	$\sigma^0_{\rm tot}$ (pb)	$\sigma^1_{\rm tot}$ (pb)	κ
400	0.098	0.871	1.113	0.278
800	0.091	0.353	0.373	0.057

Numerical Results II

$$\frac{\frac{d\sigma^R}{d\cos\theta}(e^-_L e^+_R \to t_\uparrow X)}{(1+\kappa)\frac{d\sigma^0}{d\cos\theta}(e^-_L e^+_R \to t_\uparrow X)} < 10\% \sim \text{a few } \%$$

Tiny Spin Flip Effect $\rightarrow$ Soft Gluon Dominates

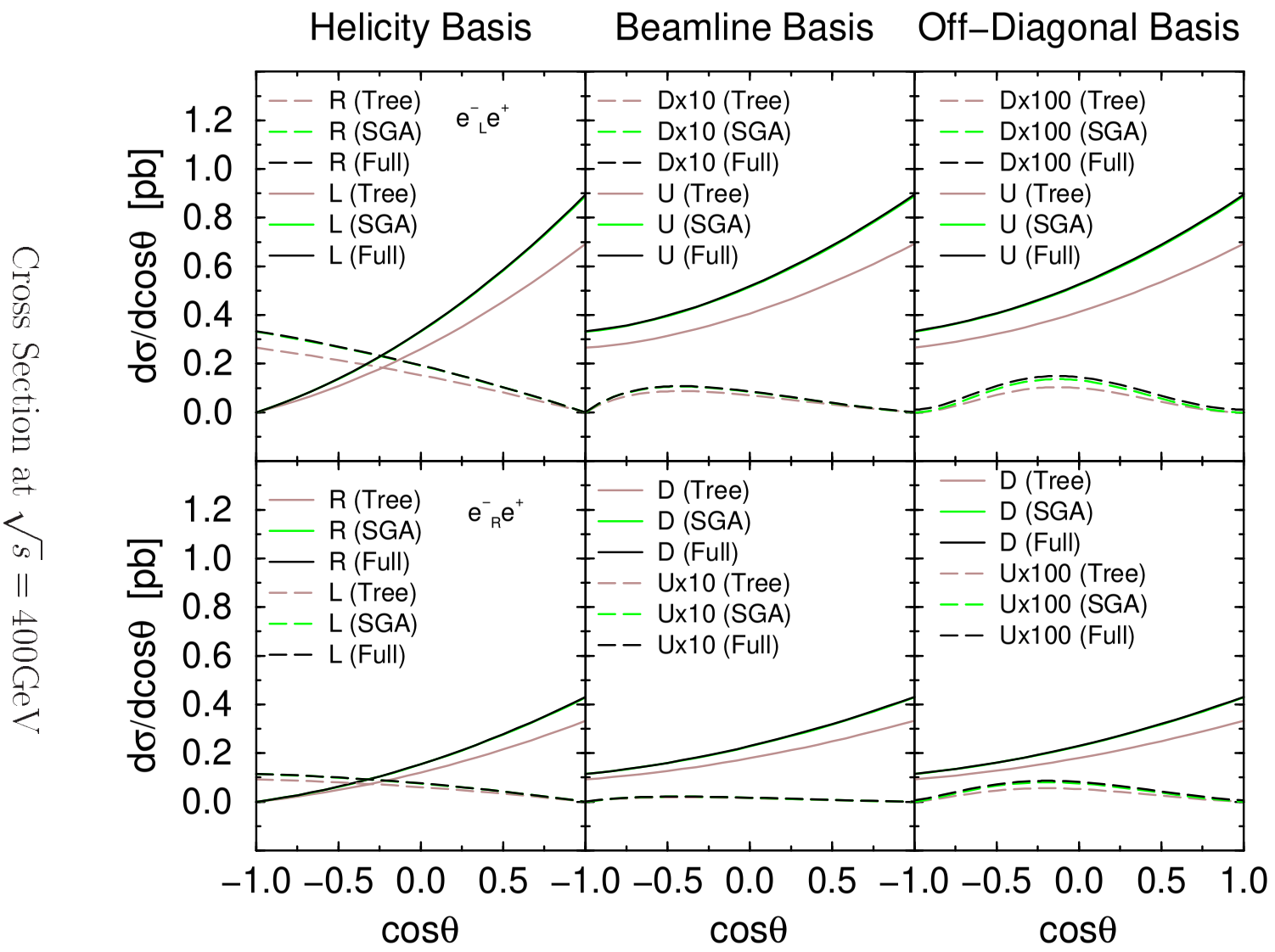
Numerical Results III

Fraction of $\sigma_{\rm tot}$ in Dominant Spin

$\sqrt{s}$ (GeV)	β	Helicity	Off-Diagonal
400	0.484	0.6636 0.6681	0.9988 0.9985
800	0.899	0.8318 0.8350	0.9735 0.9682

- QCD Corrections to Spin Correlation VERY SMALL
  - Main Effect is K-factor
  - Does NOT change Spin Configuration
  - SGA is an Excellent Approximation (See Figs.)

- Off-Diagonal Basis is a Good Choice for $\beta \sim 0.5$
  - Some Spin States are Zero or Negligible



Cross Section at $\sqrt{s} = 400\mathrm{GeV}$

♣ Anomalous Couplings

Assume the Anomalous Couplings for $t - \bar{t} - \gamma/Z$

$$\Gamma^V_\mu = g^V \left\{ \gamma^\mu \left[Q^V_L \omega_- + Q^V_R \omega_+ \right] + \frac{(t-\bar{t})_\mu}{2m} \left[G^V_L \omega_- + G^V_R \omega_+ \right] \right\}$$

- QCD at One Loop (Note SGA is Enough)

$$\begin{aligned} Q^V_{LR} &\sim 1 + \mathcal{O}(\alpha_s) \\ G^V_R + G^V_L &\sim \mathcal{O}(\alpha_s) \quad , \quad G^V_R - G^V_L = \mathcal{O}(\alpha_s^2) \sim 0 \end{aligned}$$

- CP Odd Anomalous Coupling

$$G^V_R - G^V_L = i\, f^V_3 \neq 0 \sim \mathcal{O}(\alpha_s)$$

$$\begin{aligned} & M(e^-_L e^+_R \to t_\uparrow \bar{t}_\uparrow, t_\downarrow \bar{t}_\downarrow) \\ &= \mp 4\pi\alpha \left[\left(\hat{A}_{LR} - C_{LR} \right) \cos\xi - \hat{B}_{LR} \sin\xi \pm i E_{LR} \right) \Big] \end{aligned}$$

$$\begin{aligned} & M(e^-_L e^+_R \to t_\uparrow \bar{t}_\downarrow, t_\downarrow \bar{t}_\uparrow) \\ &= 4\pi\alpha \left[\left(\hat{A}_{LR} - C_{LR} \right) \sin\xi + \hat{B}_{LR} \cos\xi \pm \hat{D}_{LR} \right) \Big] \end{aligned}$$

where

$$\begin{aligned} \hat{O}_{LR} &\propto Q^V_{LR} \sim 1 + \mathcal{O}(\alpha_s) \\ C_{LR} &\propto G^V_R + G^V_L \sim \mathcal{O}(\alpha_s) \\ E_{LR} &\propto G^V_R - G^V_L = i\, f^V_3 \end{aligned}$$

♣ How to Detect Anomalous Coupling

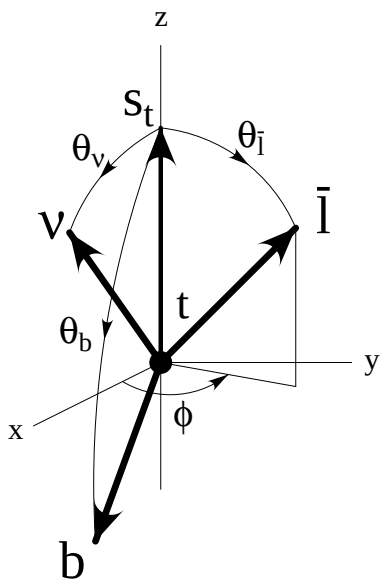
- Cross Section Itself $\leftrightarrow$ No
- Angular Distribution of Decay Product

Consider , *e.g.*, the Chain

$$t \to b\,W \to b\,\bar{l}\,\nu$$

Decay Density Matrix for Charged Lepton (with NWA)

$$\frac{d\Gamma_{s_t,s_t'}}{\Gamma_T} \propto \begin{pmatrix} 1+\cos\theta_{\bar{l}} & \sin\theta_{\bar{l}} e^{i\phi_l} \\ \sin\theta_{\bar{l}} e^{-i\phi_l} & 1-\cos\theta_{\bar{l}} \end{pmatrix}_{s_t s_t'} \left[\frac{d\cos\theta_{\bar{l}}\, d\phi_l}{4\pi}\right]$$



in Top Rest Frame with $x-z$ the Production Plane

♣ Sample Quantities of ϕ Dependence

Combine the Decay with the Production Amplitudes

$\downarrow$

Obtain Angular distributions

- $\theta_{\bar{l}} - \phi$ Correlations
- Partially Integrated Asymmetry

$$\sigma^1 = \int_0^{\frac{\pi}{2}} d\phi_l \left(\frac{d\sigma}{d\cos\Theta d\phi_l}\right) \ , \ \sigma^2 = \int_{\frac{-\pi}{2}}^{0} d\phi_{\bar{l}} \left(\frac{d\sigma}{d\cos\Theta d\phi_l}\right)$$

and

$$\mathcal{A}(\Theta) = \frac{\sigma^2 - \sigma^1}{\sigma^2 + \sigma^1}$$

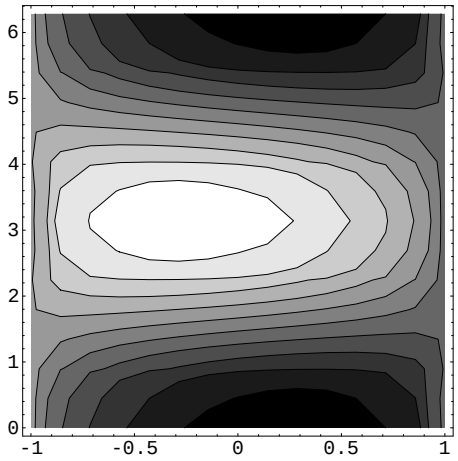
with and without Anomalous Couplings

See Figs.

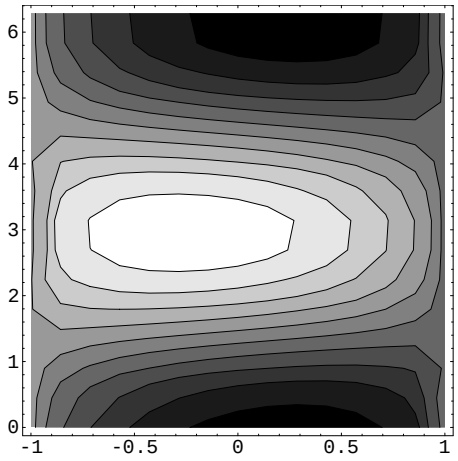
Note:

More Realistic
(Experimentally Easily Accessible)
Quantity Should be Constructed

Helicity Basis at $\cos\Theta = 0.5$

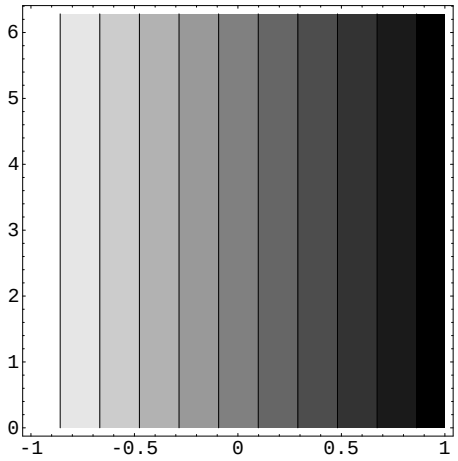


QCD 1 - Loop

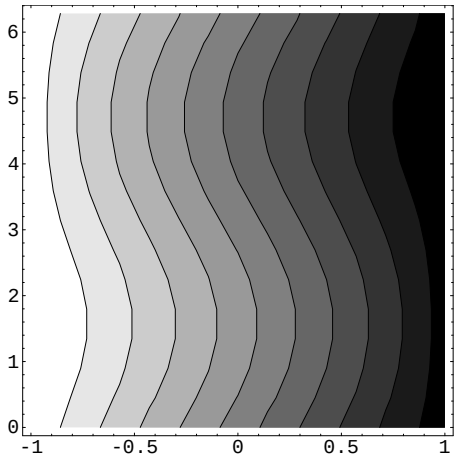


QCD 1 - Loop + Anomalous Coupling $f_3^\gamma = -f_3^Z = 0.2$

Off- Diagonal Basis at $\cos\Theta = 0.5$



QCD 1 - Loop



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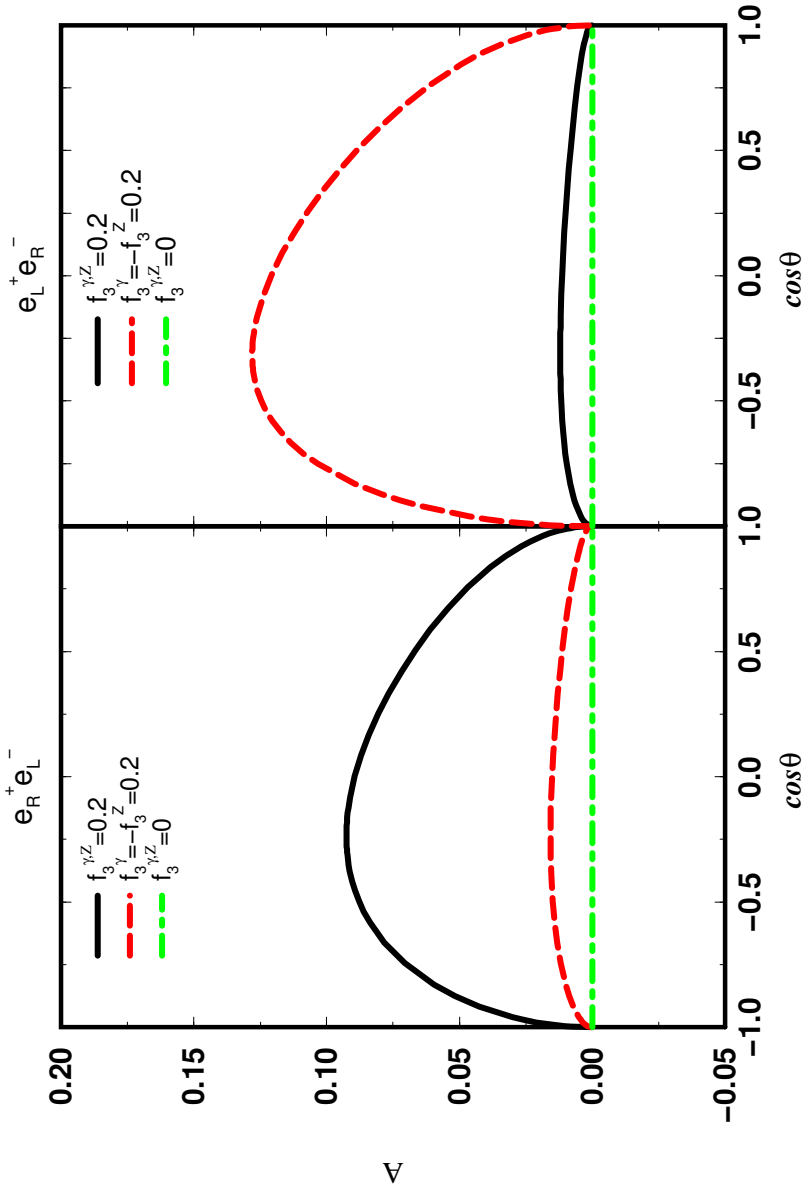

Partially Integrated Asymmetry

♣ Conclusions

- QCD Corrections to Spin Correlation VERY SMALL
  - Main Effect is K-factor
  - Does NOT change Spin Configuration

- Helicity Basis is a Poor Choice for $\beta \sim 0.5$
  - All Spin States Contribute
  - Correlations between Decay Products and Top Spin Very POOR
    Significant Interference between Intermediate Spin States

- Off-Diagonal Basis is a GOOD Choice for $\beta \sim 0.5$
  - Some Spin States are Zero or Negligible
  - Correlations between Decay Products and Top Spin Very STRONG
    Much Smaller Interference between Intermediate Spin States

- A Framework based on the General Spin Basis is Extremely Useful
  - Applicable to Any Process and Model including Heavy Particle
  - Able to Tailor the Spin Basis to the Physics Involved