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Search for CP-violation and new physics at polarized hadron and lepton colliders[1]

(Could CP- and T-violation be tested in polarized proton collisions at RHIC?)

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Outlook:

- The measurable single- and double-spin asymmetries which could be an indication of CP-violation and new physics in $W^{\pm}$- and Z^0-production by polarized quarks and leptons are discussed.
- RHIC sensitivity to "illegal" (in the Standard Model) correlations is evaluated.

[1]Supported in part by the U.S. Department of Energy Grant DE-FG0292ER40713.

Justification (Why to do?)

"Look where most theorists predict that nothing will be found."
M. J. Tannenbaum, 1995

Why New Physics? The expectations for New Physics at the scale of **hundreds of GeV** are high. Since 1977 *(B. W. Lee et al; M. Veltman.)*, it is well understood that SM of electroweak interactions would experience quite serious complications if some new physics (Higgs? Compositeness? ...?) does not show up at the energies below ~1 TeV. The energy range **just above or even about W- and Z-masses** is not excluded.

Why *CP*? CP-symmetry is broken. However, **nothing is known about the nature** of either ***CP*-odd phase** in CKM-matrix or **CKM quark mixing** itself.

- The various approaches to understanding the baryon asymmetry of the Universe require large CP-violation, i.e., CP-violating terms in the lagrangian of the same order as the gauge coupling.

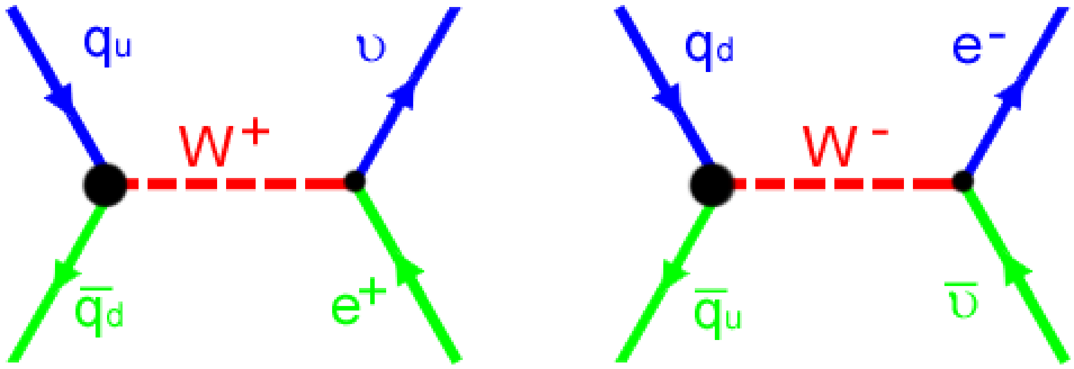
- C. J.-C. Im, G. L. Kane and P. J. Malde, Phys. Lett. **B317** (1993) 454: *"At the present time published limits do not exist for the size of most* CP*-violating processes at 100 GeV scale. Thus heretofore undetected large (~50%)* CP*-violation could occur in some processes at high energy hadron colliders."*

Why now? Just in months ahead, the first high luminosity collisions of two polarized proton beams are expected to occur at RHIC in BNL at $\sqrt{s}$ up to 500 GeV. In polarized particle collisions, the presence of **two axial vectors** of initial polarizations **fully controlled** by the experimenters, dramatically increases the number of **available for tests correlations and asymmetries**.

What to do?

- Choose the **cleanest** available processes to search for New Physics beyond SM. At RHIC, those are:

$$q\overline{q} \to W^{\pm} \to l\overline{l} \qquad \text{and} \qquad q\overline{q} \to Z^0 \to l\overline{l}$$



- Look for correlations and asymmetries that are either **strongly suppressed** or **strictly prohibited** in SM.

T-odd correlations in $q\overline{q}$ C.M. system:

$$\boldsymbol{k}\cdot[\boldsymbol{\zeta}_q \times \boldsymbol{p}]\ ; \quad \boldsymbol{k}\cdot[\boldsymbol{\zeta}_q \times \boldsymbol{p}]\ ; \quad \boldsymbol{k}\cdot[\boldsymbol{\zeta}_q \times \boldsymbol{\zeta}_{\overline{q}}]\ ; \quad \boldsymbol{p}\cdot[\boldsymbol{\zeta}_q \times \boldsymbol{\zeta}_{\overline{q}}].$$

$\boldsymbol{p}$ is the quark momentum ($\boldsymbol{p} \equiv \boldsymbol{p}_q$);
$\boldsymbol{k}$ is the lepton momentum ($\boldsymbol{k} \equiv \boldsymbol{k}_\nu$ or $\boldsymbol{k} \equiv \boldsymbol{k}_{e^-}$);
$\boldsymbol{\zeta}_q$ is the quark polarization;
$\boldsymbol{\zeta}_{\overline{q}}$ is the antiquark polarization.

At least one quark must be transversely polarized, but …

CP-violation may also show up in the perfectly T-even asymmetries!

EXAMPLE:

Phenomenological interaction lagrangians:

(*G. L. Kane, G. A. Ladinsky, and C. P. Yuan, Phys.Rev.* ***D45*** *(1992) 124*)

Charged current:

$$L_c = \frac{g}{2\sqrt{2}}\{[W_\mu^- \overline{q}_d \gamma^\mu (f_1^+ + f_1^- \gamma_5) q_u + \text{h.c.}] + \qquad \text{“\underline{Vector}”}$$
$$+\frac{1}{\Lambda}[\partial_\nu W_\mu^- \overline{q}_d \sigma^{\mu\nu} (f_2^+ + f_2^- \gamma_5) q_u + \text{h.c.}]\} \qquad \text{“\underline{Tensor}”}$$

where $\gamma_5 = -i\gamma^0\gamma^1\gamma^2\gamma^3$ and $\sigma^{\mu\nu} = \frac{1}{2}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$; Λ is the “natural” energy scale for the “tensor” coupling; q_u and q_d are for the “upper” and “lower” quarks, respectively.

The usual $(V-A)$-interactions correspond to $f_1^+ = f_1^- = 1$, and all $f_{2,3}^\pm = 0$. ***CP*- and *T*-symmetries are broken if any or all $f_i^\pm$ are complex.**

Neutral current:

$$L_n = \frac{g}{2\sqrt{2}}\{[Z_\mu^0 \overline{q} \gamma^\mu (f_1^+ + f_1^- \gamma_5) q] + \frac{1}{\Lambda}[\partial_\nu Z_\mu^0 \overline{q} \sigma^{\mu\nu} (f_2^+ + f_2^- \gamma_5) q]\}$$

Formfactors $f_1^\pm$ and f_2^+ are real; ***CP*- and *T*-symmetries are broken with nonzero and purely imaginary formfactor f_2^-:**

$$f_2^- \equiv i\,\mathrm{Im}(f_2^-) \neq 0$$

Cross sections:

$$\frac{d\hat{\sigma}}{d\Omega} \simeq \frac{g^4 \cdot \hat{S} \cdot (\mid M_{fi} \mid^2_{vv} + \sqrt{\hat{S}} \mid M_{fi} \mid^2_{vt} /\Lambda + \hat{S} \mid M_{fi} \mid^2_{tt} /\Lambda^2)}{64 \cdot [(\hat{S} - M^2_{W,Z})^2 + \frac{\Gamma^2_{W,Z}}{2}(\hat{S} + M^2_{W,Z}) + \frac{\Gamma^4_{W,Z}}{16}]}$$

where $M_{W,Z}$ and $\Gamma_{W,Z}$ are the $W^{\pm}$- or Z^0-peak mass and width, respectively.

In the most interesting for $\mid M_{fi} \mid^2_{vv}$ and $\mid M_{fi} \mid^2_{tt}$ case of **both quarks transversely polarized**,

$$\begin{aligned}
\mid M_{fi} \mid^2_{vv} &= \frac{\mid f_1^+ + f_1^- \mid^2}{4}[1 + \boldsymbol{n_p} \cdot \boldsymbol{n_k}]^2 + \\
&+ \frac{\mid f_1^+ - f_1^- \mid^2}{4}[1 - \boldsymbol{n_p} \cdot \boldsymbol{n_k}]^2 + \\
&+ \{\mid f_1^+ \mid^2 - \mid f_1^- \mid^2\} \times \\
&\quad \{(\boldsymbol{\zeta_q^\perp} \cdot \boldsymbol{n_k})(\boldsymbol{\zeta_{\bar{q}}^\perp} \cdot \boldsymbol{n_k}) - \tfrac{1}{2}(\boldsymbol{\zeta_q^\perp} \cdot \boldsymbol{\zeta_{\bar{q}}^\perp})[1 - (\boldsymbol{n_p} \cdot \boldsymbol{n_k})^2]\} \pm \\
&\pm \mathrm{Im}(f_1^+ f_1^{*-}) \times \\
&\quad \{\boldsymbol{n_k} \cdot [\boldsymbol{\zeta_q^\perp} \times \boldsymbol{n_p}](\boldsymbol{\zeta_{\bar{q}}^\perp} \cdot \boldsymbol{n_k}) + \boldsymbol{n_k} \cdot [\boldsymbol{\zeta_{\bar{q}}^\perp} \times \boldsymbol{n_p}](\boldsymbol{\zeta_q^\perp} \cdot \boldsymbol{n_k})\}
\end{aligned}$$

$$\begin{aligned}
\mid M_{fi} \mid^2_{tt} &= \frac{1}{2}\{1 - (\boldsymbol{n_p} \cdot \boldsymbol{n_k})^2\} \times \{\mid f_2^+ \mid^2 + \mid f_2^- \mid^2 - \\
&\quad -(\mid f_2^+ \mid^2 - \mid f_2^- \mid^2)(\boldsymbol{\zeta_q^\perp} \cdot \boldsymbol{\zeta_{\bar{q}}^\perp}) + \\
&\quad +2\,\mathrm{Im}(f_2^+ f_2^{*-})(\boldsymbol{n_p} \cdot [\boldsymbol{\zeta_q^\perp} \times \boldsymbol{\zeta_{\bar{q}}^\perp}])\}
\end{aligned}$$

- $\boldsymbol{n_p} = \boldsymbol{p}/\mid \boldsymbol{p} \mid$;
- $\boldsymbol{n_k} = \boldsymbol{k}/\mid \boldsymbol{k} \mid$.
- Only the main order terms are kept, neglecting those suppressed by the powers of $M_q/\sqrt{\hat{S}}$ and $M_l/\sqrt{\hat{S}} \ll 1$;

$| M_{fi} |^2_{vv}$: "Vector-Vector":

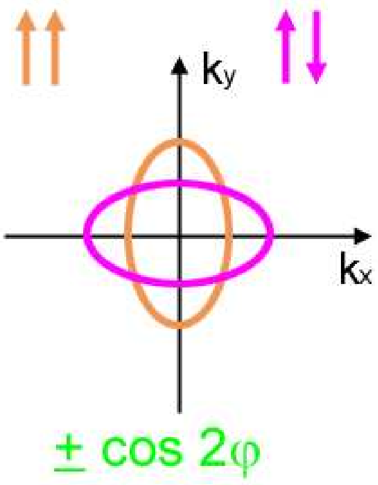
(Potentially) Large double-spin asymmetries:

***T*-even** (and *CP*-even in this particular model): A_{TT}:

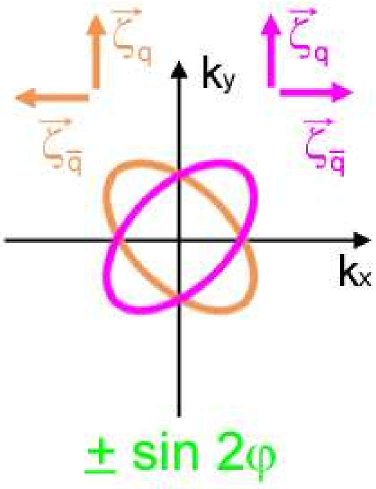
Allowed in Z- but strictly prohibited in tree-level V-A W-production

$$A \propto (| f_1^+ |^2 - | f_1^- |^2)\{(\boldsymbol{\zeta}_q^\perp \cdot \boldsymbol{n}_k)(\boldsymbol{\zeta}_{\bar{q}}^\perp \cdot \boldsymbol{n}_k) - \tfrac{1}{2}(\boldsymbol{\zeta}_q^\perp \cdot \boldsymbol{\zeta}_{\bar{q}}^\perp)[\mathbf{1} - (\boldsymbol{n}_p \cdot \boldsymbol{n}_k)^2]\}$$

Parallel spins



Perpendicular spins

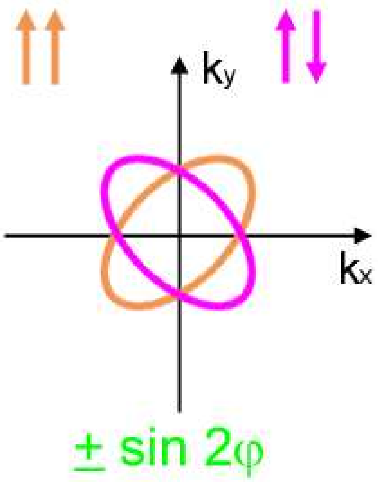


***T*-odd** (and *CP*-odd in this particular model): 45^o rotated A_{TT}:

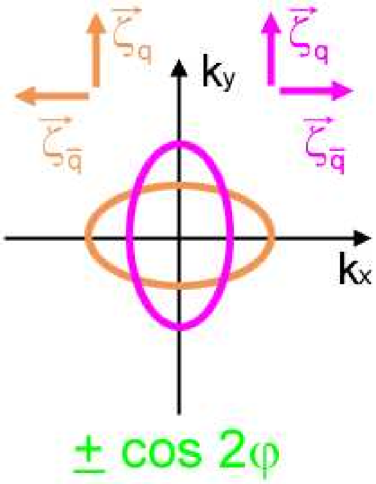
Strictly prohibited at tree-level SM for both W- and Z-productions

$$A \propto \pm \mathrm{Im}(f_1^+ f_1^{*-})\{\boldsymbol{n}_k \cdot [\boldsymbol{\zeta}_q^\perp \times \boldsymbol{n}_p](\boldsymbol{\zeta}_{\bar{q}}^\perp \cdot \boldsymbol{n}_k) + \boldsymbol{n}_k \cdot [\boldsymbol{\zeta}_{\bar{q}}^\perp \times \boldsymbol{n}_p](\boldsymbol{\zeta}_q^\perp \cdot \boldsymbol{n}_k)\}$$

Parallel spins



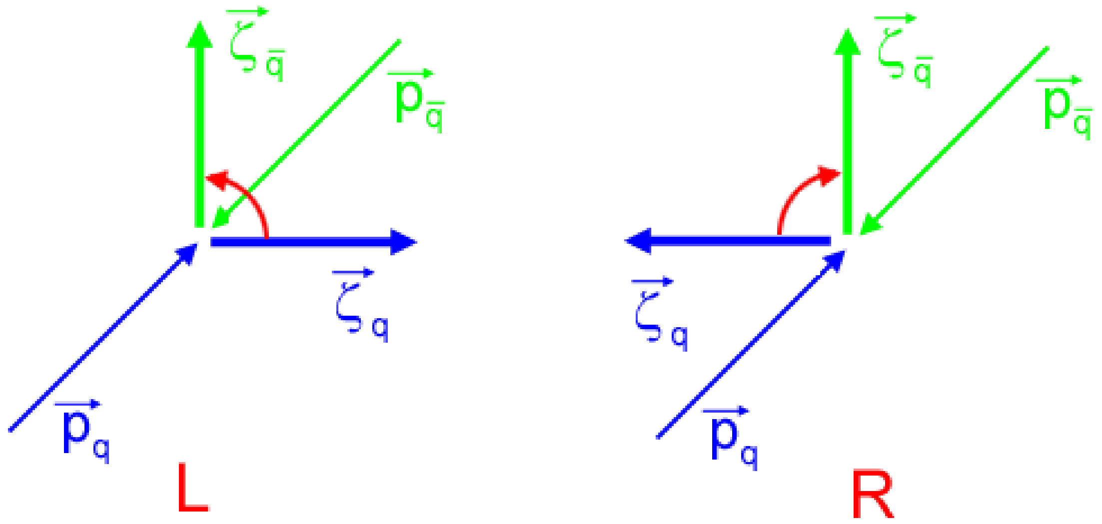
Perpendicular spins



$\mid M_{fi} \mid^2_{tt}$: **"Tensor-Tensor":**

(Potentially) **Large *T*-odd double-spin asymmetry** $\Delta\sigma_\perp$:

$$\frac{d\sigma_\perp}{d\Omega} \propto T\text{-even} + \mathrm{Im}(f_2^+ f_2^{*-})(\boldsymbol{n_p} \cdot [\boldsymbol{\zeta_q^\perp} \times \boldsymbol{\zeta_{\bar{q}}^\perp}])$$



$$\Delta\sigma_\perp = \sigma_\perp^R - \sigma_\perp^L \propto \mathrm{Im}(f_2^+ f_2^{*-})$$

CP-conjugation:

$$\sigma_\perp^R(q_u\overline{q}_d) \overset{CP}{\to} \sigma_\perp^L(q_d\overline{q}_u) \qquad \sigma_\perp^L(q_u\overline{q}_d) \overset{CP}{\to} \sigma_\perp^R(q_d\overline{q}_u)$$

Corollary:

***CP*-even** (spurious): $\Delta\sigma_\perp(q_d\overline{q}_u) = -\Delta\sigma_\perp(q_u\overline{q}_d)$

***CP*-odd** (true): $\Delta\sigma_\perp(q_d\overline{q}_u) = +\Delta\sigma_\perp(q_u\overline{q}_d)$

$\mid M_{fi} \mid^2_{vt}$: "Vector-Tensor" interference:

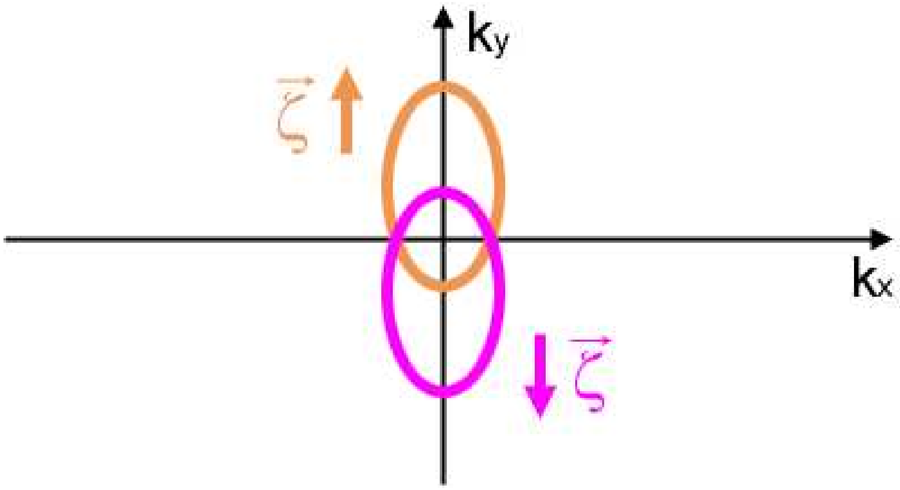
$$
\begin{aligned}
\mid M_{fi} \mid^2_{vt} \;=\;& (\boldsymbol{n_k} \cdot \boldsymbol{n_p}) \times \\
\times\;& \{ \mathrm{Re}[(f_1^+ f_2^{*+} \mp f_1^- f_2^{*-}) + \lambda_{\overline{q}}(\mp f_1^+ f_2^{*-} + f_1^- f_2^{*+})](\boldsymbol{n_k} \cdot [\boldsymbol{\zeta}_{\boldsymbol{q}}^{\perp} \times \boldsymbol{n_p}]) - \\
-\;& \mathrm{Im}[(f_1^+ f_2^{*-} \mp f_1^- f_2^{*+}) + \lambda_{\overline{q}}(\mp f_1^+ f_2^{*+} + f_1^- f_2^{*-})](\boldsymbol{\zeta}_{\boldsymbol{q}}^{\perp} \cdot \boldsymbol{n_k}) + \\
+\;& \mathrm{Re}[(f_1^+ f_2^{*+} \pm f_1^- f_2^{*-}) - \lambda_{q}(\pm f_1^+ f_2^{*-} + f_1^- f_2^{*+})](\boldsymbol{n_k} \cdot [\boldsymbol{\zeta}_{\overline{\boldsymbol{q}}}^{\perp} \times \boldsymbol{n_p}]) + \\
+\;& \mathrm{Im}[(f_1^+ f_2^{*-} \pm f_1^- f_2^{*+}) - \lambda_{q}(\pm f_1^+ f_2^{*+} + f_1^- f_2^{*-})](\boldsymbol{\zeta}_{\overline{\boldsymbol{q}}}^{\perp} \cdot \boldsymbol{n_k}) \} + \\
\\
+\;& \mathrm{Re}[(\mp f_1^+ f_2^{*-} + f_1^- f_2^{*+}) + \lambda_{\overline{q}}(f_1^+ f_2^{*+} \mp f_1^- f_2^{*-})](\boldsymbol{n_k} \cdot [\boldsymbol{\zeta}_{\boldsymbol{q}}^{\perp} \times \boldsymbol{n_p}]) - \\
-\;& \mathrm{Im}[(\mp f_1^+ f_2^{*+} + f_1^- f_2^{*-}) + \lambda_{\overline{q}}(f_1^+ f_2^{*-} \mp f_1^- f_2^{*+})](\boldsymbol{\zeta}_{\boldsymbol{q}}^{\perp} \cdot \boldsymbol{n_k}) + \\
+\;& \mathrm{Re}[(\pm f_1^+ f_2^{*-} + f_1^- f_2^{*+}) - \lambda_{q}(f_1^+ f_2^{*+} \pm f_1^- f_2^{*-})](\boldsymbol{n_k} \cdot [\boldsymbol{\zeta}_{\overline{\boldsymbol{q}}}^{\perp} \times \boldsymbol{n_p}]) + \\
+\;& \mathrm{Im}[(\pm f_1^+ f_2^{*+} + f_1^- f_2^{*-}) - \lambda_{q}(f_1^+ f_2^{*-} \pm f_1^- f_2^{*+})](\boldsymbol{\zeta}_{\overline{\boldsymbol{q}}}^{\perp} \cdot \boldsymbol{n_k})
\end{aligned}
$$

- $\boldsymbol{n_p} = \boldsymbol{p}/\mid \boldsymbol{p} \mid$;
- $\boldsymbol{n_k} = \boldsymbol{k}/\mid \boldsymbol{k} \mid$;
- $\lambda_q = (\boldsymbol{\zeta_q} \cdot \boldsymbol{p_q})/ \mid \boldsymbol{p_q} \mid$ is quark helicity.
- $\lambda_{\overline{q}} = (\boldsymbol{\zeta_{\overline{q}}} \cdot \boldsymbol{p_{\overline{q}}})/\mid \boldsymbol{p_{\overline{q}}} \mid$ is antiquark helicity.
- Only the main order terms are kept, neglecting those suppressed by the powers of $M_q/\sqrt{\hat{S}}$ and $M_l/\sqrt{\hat{S}} \ll 1$;

$| M_{fi} |^2_{vt}$: "Vector-Tensor" interference:
(Potentially) Large **single-spin** asymmetries:

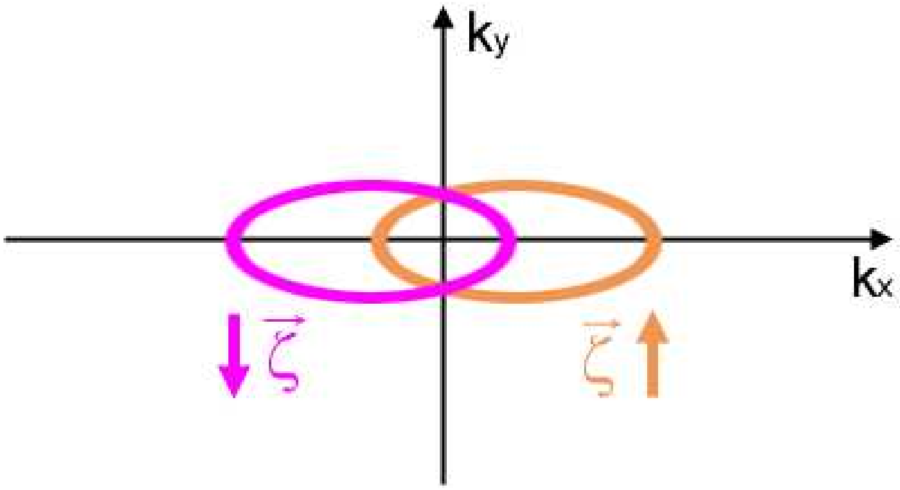
T-even (but P-odd)... and $\boldsymbol{CP}$**-odd** in this particular model:

$$A \propto \pm \operatorname{Im}(f_1 f_2^*)(\boldsymbol{n_k} \cdot \boldsymbol{\zeta}^{\perp})$$



T-odd (but P-even)... and $\boldsymbol{CP}$**-even** in this particular model:

$$A \propto \operatorname{Re}(f_1 f_2^*)(\boldsymbol{n_k} \cdot [\boldsymbol{\zeta} \times \boldsymbol{n_p}])$$

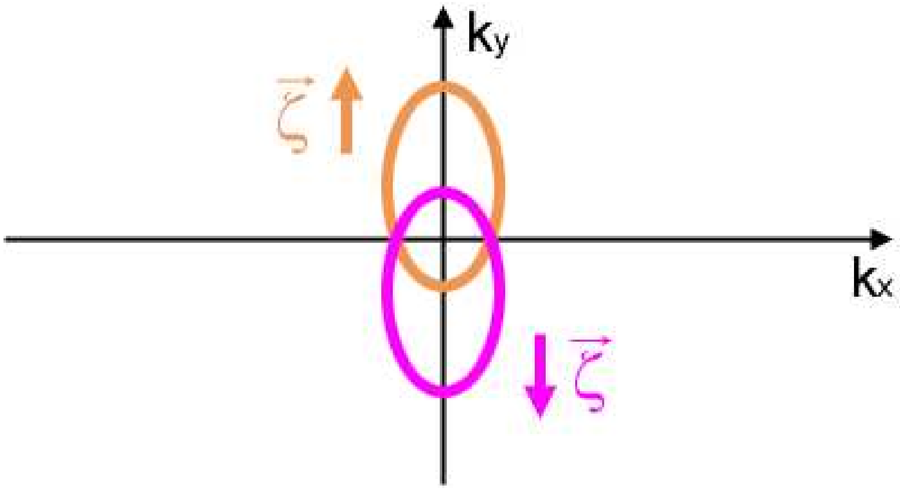


$| M_{fi} |^2_{vt}$: **"Vector-Tensor" interference:**

(Potentially) Large **double-spin** asymmetries:

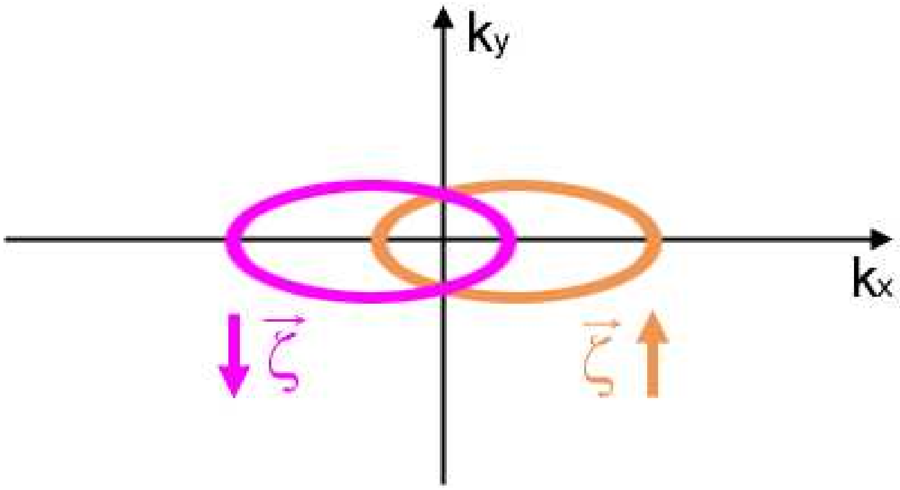
***CP*-odd** (in this particular model):

$$A \propto \lambda_q \, \mathrm{Im}(f_1 f_2^*)(\boldsymbol{n_k} \cdot \boldsymbol{\zeta}^{\perp}_{\overline{\boldsymbol{q}}}) + \ldots$$



***CP*-even** (in this particular model):

$$A \propto \pm\lambda_q \, \mathrm{Re}(f_1 f_2^*)(\boldsymbol{n_k} \cdot [\boldsymbol{\zeta}_{\overline{\boldsymbol{q}}} \times \boldsymbol{n_p}]) + \ldots$$



Back to the Earth (Q & A)

Q: What is the expected RHIC sensitivity to "illegal" asymmetries?

A: At pp-**interaction level**, it is ∼1%.

$W^{\pm}$ **and** Z^0 **event rates at** $\sqrt{s} = 500\ GeV$ **for** $\int L{\cdot}dt = 800\ pb^{-1}$; **Cuts:** $P_T^{e,\mu} > 20\,GeV/c$.

(A. Derevschikov, V. Rykov, K. Shestermanov, and A. Yokosawa. *Report to the SPIN-94.*)

	STAR_b	STAR_b1ec	STAR_b2ec
W^+	64,600	71,500	78,400
W^-	15,000	20,600	26,200
Z^0	2,700	4,200	6,200

	PHENIX_1μ	PHENIX_2μ	PHENIX_e
W^+	4,650	9,300	14,900
W^-	5,050	10,100	2,600
Z^0	25	310[1]	120

[1] ∼700 without P_T-cut.

Q: What is the expected RHIC sensitivity to new physics at **quark level**?

A: In terms of tensor coupling of the considered here phenomenology: $\mid f_2 \mid \frac{M_{W,Z}}{\Lambda}$ down to (3–10)%

O. Martin, A. Schafer, M. Stratmann, and W. Vogelsang. *Phys. Rev.* **D57**, 3084 (1998)

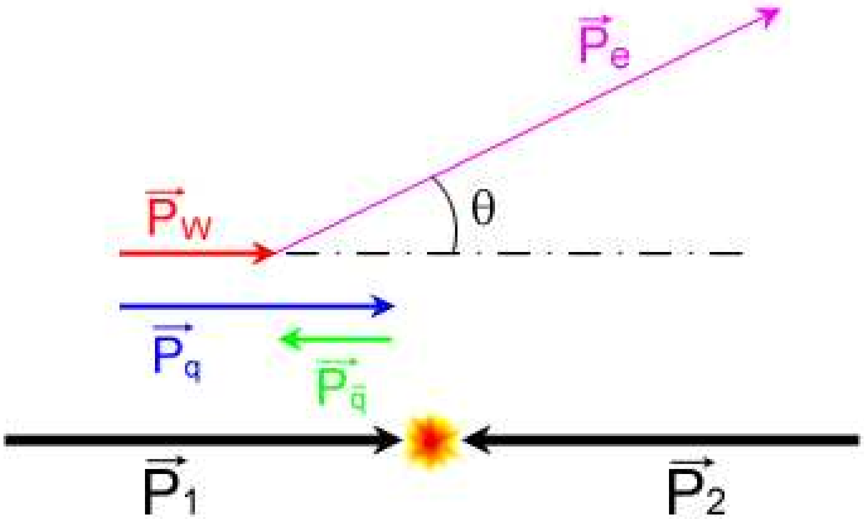
Back to the Earth (Q & A)

Q: Could **"true"** CP-violating asymmetries be **distinguished** from **"spurious"** ones in polarized $p\overline{p}$-, e^+e^--, $\mu^+\mu^-$, $\pounds\overline{\pounds}$-collisions?

A: With **two** polarized beams, YES.

Q: Could **"true"** CP-violating asymmetries be **distinguished** from **"spurious"** ones in polarized pp-collisions?

A: Probably YES if **two valence quarks** participated in the CP/T-odd interactions (needs more study), and, probably, NO if **otherwise** (needs more study).
Important: To compare the signs of asymmetries in CP-conjugate processes, the **directions of motions** and **signs of polarizations** of the incident quark and antiquark must be known.



$$\vec{P}_W = \vec{P}_q + \vec{P}_{\overline{q}} = x_q\vec{P}_1 + x_{\overline{q}}\vec{P}_2 \ \text{ with } x_q > x_{\overline{q}}$$

The kinematics of produced Z^0-bosons will be fully reconstructed. The direction of the $W^{\pm}$-motion can also be determined, measuring $\vec{P}_{e,\mu}$, i.e. $E_{e,\mu}$ and θ (*N. Saito et al, Report to the RSC Workshop, 1995.*). In the "hermetic" (4π) detector this could be done better.

Concluding remarks

- High energy colliders with polarized beams represent a powerful tool to **search for** and **study** New Physics beyond the Standard Model, including CP-violation at the energy scale of W- and Z-masses and above.
- The future e^+e^--, $\mu^+\mu^-$-, and particularly $\underline{p\overline{p}}$-colliders with **two** polarized beams would clearly be the best to search for and study **model independent** CP-violation.
- While **not** absolutely unambiguously and model independent, CP-violation beyond SM could also be tested in **polarized proton** collisions at RHIC by comparison the relative signs of various asymmetries (*if found nonzero*) in (*presumably*) CP-conjugate processes. In the best scenario (*if we are lucky!*), the only alternative to CP-violation might be ... even worse: for example, to completely discard the current picture of $W^\pm$- and Z^0-production from quark-antiquark annihilation.