Spin Physics with Jets at STAR

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The spin physics program from jet detection at STAR is presented in order of increasing luminosity requirements, hence by year. **(1)** In year 1 it will be technically feasible, given one transversely polarized beam and collisions, for STAR to measure A_T with the baseline detector. In excess of 10k low p_T (> 15 GeV) jet events can be accumulated in several days at low luminosity. A measurement of A_T consistent with zero will place a limit on higher twist effects that could complicate the subsequent measurements of A_{LL}. **(2)** In year 2, A_{LL} can be measured from an inclusive low p_T jet sample giving an indication of the magnitude of ΔG in the neighborhood of $x = 0.1$. Since the observable A_{LL} is quadratic in ΔG, this result will not determine the sign of ΔG. **(3)** In year 2 and beyond, a high statistics dijet sample, > 10M events, can be used to determine A_{LL} as a function of x partons for $0.05 < x < 0.25$. Cuts are imposed on the sample to insure that the jets represent the partons from the hard scattering: no third jet, p_T balance, back-to-back in ϕ. Assuming a sign for ΔG or using the sign determined by the direct photon analysis, $\Delta G(x)$ may be extracted from the data subject to uncertainties in the production processes and in the polarized quark distributions. **(4)** Given integrated luminosity of 800 pb^{-1} per year, it should be possible to measure A_{pv} from a high p_T (> 45 GeV) inclusive jet sample as described in the subsequent 5 pages. (For motivation see the previous talk by J.M. Virey.) Page 1 shows the $\hat{p_T}$ distribution for an event sample passing a level 0 trigger using the electromagnetic calorimeter. At the level 3 trigger were track information from the TPC is available, jets are reconstructed and an event sample is selected with $p_T^j > 45$ GeV, see page 2. The calculation of the standard model (SM) A_{pv} expected in this sample is shown on pages 3 and 4. The last figure (p. 5) shows the departure from SM A_{pv} as a function of $M_{Z'}$ for $\hat{p_T} = 60$, 80, and 100 GeV. For $M_{Z'} = 600$ GeV, the observed A_{pv} increases 30% therefore a measurement to < 10% uncertainty is required to look for this effect. As pointed out by Virey, current limits from $p\bar{p}$ colliders assume SM couplings for new Z'. Since this coupling is not determined by theory, there is a substantial window of opportunity at RHIC to search for these effects. **(5)** The third fundamental leading twist partonic structure function $h_1(x)$ may be determined from A_{TT} measured in high p_T dijet events.

Parity-violating spin asymmetries

BNL
4-28-98

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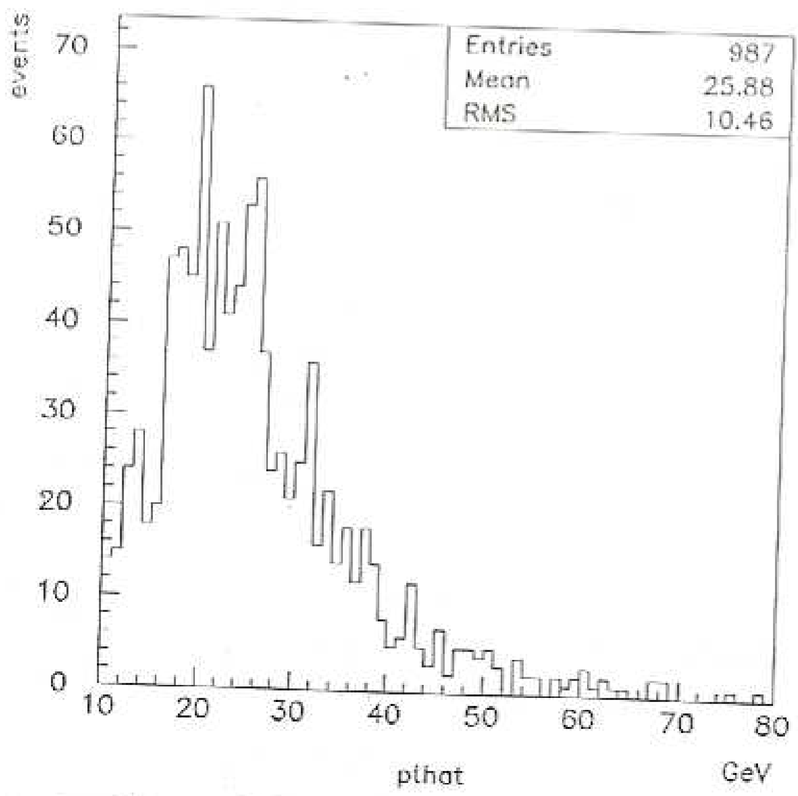
STAR

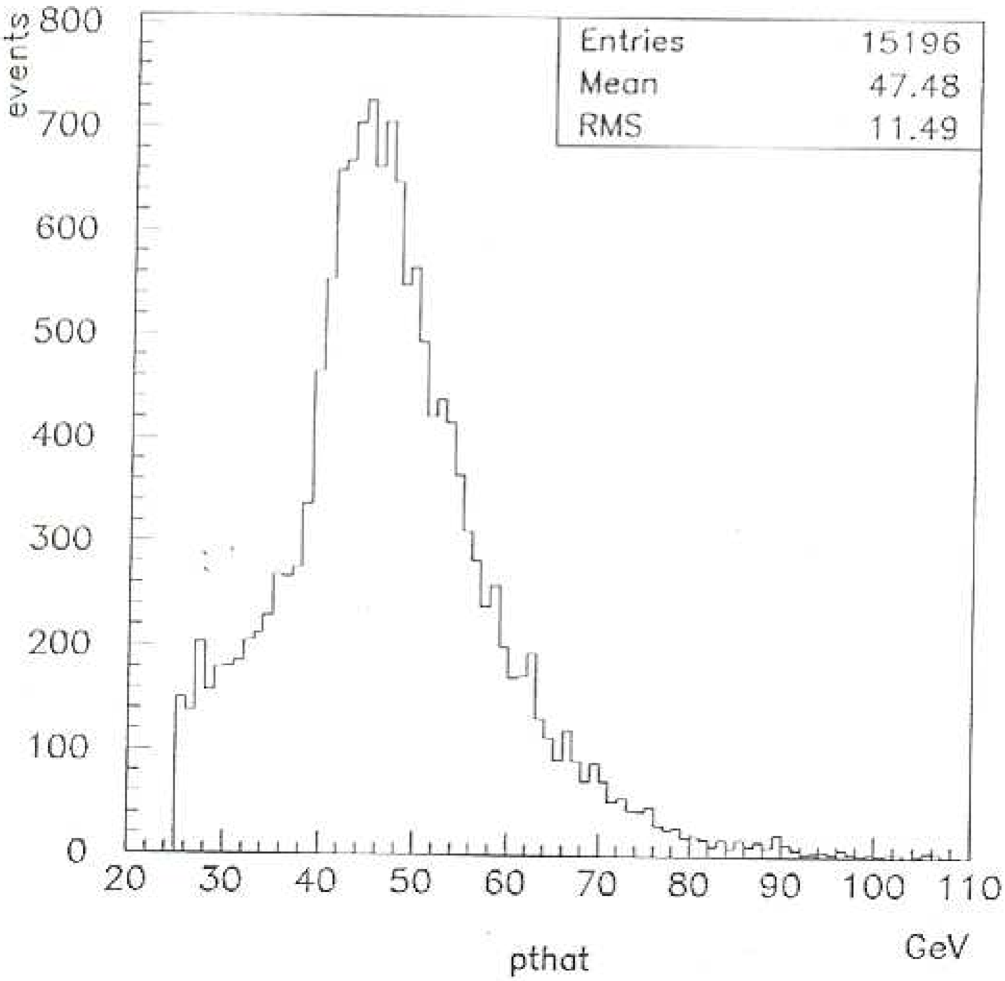
- pp scattering at $\sqrt{s} = 500\,\text{GeV}$
- polarized protons
- inclusive jet production
- Parity-violating asymmetry

$$A_{LL}^{PV} = \frac{d\sigma_{--} - d\sigma_{++}}{d\sigma_{--} + d\sigma_{++}}$$

- Largest effect: t-channel, same flavor, interference between g and Z



Select events passing a level 0 trigger tower .8x.8 in EM calorimeter



select events with a jet, $R = .7$
$E_T > 45$ GeV $|\eta| < 0.8$

the trigger is 50% efficient but
there is 33% dead time

Calculation of A_{PV}:

- Numerator

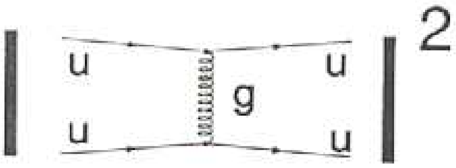
$$\int(\mathrm{u}\,\Delta\mathrm{u})\left(\frac{\mathrm{d}\hat\sigma}{\mathrm{d}\hat{\mathrm{p}}_{\mathrm{T}}}\right)_{\mathrm{gZ}}^{\mathrm{uu}\to\mathrm{uu}}+\int(\mathrm{d}\,\Delta\mathrm{d})\left(\frac{\mathrm{d}\hat\sigma}{\mathrm{d}\hat{\mathrm{p}}_{\mathrm{T}}}\right)_{\mathrm{gZ}}^{\mathrm{dd}\to\mathrm{dd}}+\int(\mathrm{u}\,\Delta\mathrm{d},\mathrm{d}\,\Delta\mathrm{u})\left(\frac{\mathrm{d}\hat\sigma}{\mathrm{d}\hat{\mathrm{p}}_{\mathrm{T}}}\right)_{\mathrm{gW}}^{\mathrm{ud}\to\mathrm{ud}}$$

- Denominator

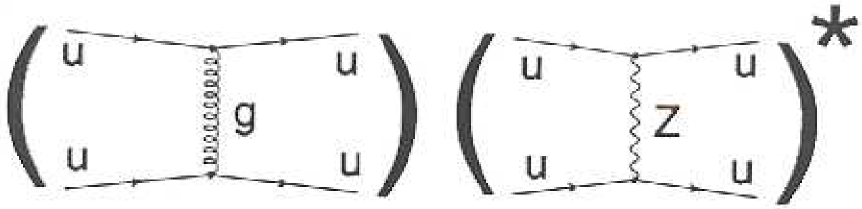
$$\int(\mathrm{u}\,\mathrm{u})\left(\frac{\mathrm{d}\hat\sigma}{\mathrm{d}\hat{\mathrm{p}}_{\mathrm{T}}}\right)_{\mathrm{gg}}^{\mathrm{uu}\to\mathrm{uu}}+\int(\mathrm{d}\,\mathrm{d})\left(\frac{\mathrm{d}\hat\sigma}{\mathrm{d}\hat{\mathrm{p}}_{\mathrm{T}}}\right)_{\mathrm{gg}}^{\mathrm{dd}\to\mathrm{dd}}+\int(\mathrm{u}\,\mathrm{d})\left(\frac{\mathrm{d}\hat\sigma}{\mathrm{d}\hat{\mathrm{p}}_{\mathrm{T}}}\right)_{\mathrm{gg}}^{\mathrm{ud}\to\mathrm{ud}}$$

where *e.g.*

$\left(\frac{\mathrm{d}\hat\sigma}{\mathrm{d}\hat{\mathrm{p}}_{\mathrm{T}}}\right)_{\mathrm{gg}}^{\mathrm{uu}\to\mathrm{uu}} \propto$



$\left(\frac{\mathrm{d}\hat\sigma}{\mathrm{d}\hat{\mathrm{p}}_{\mathrm{T}}}\right)_{\mathrm{gZ}}^{\mathrm{uu}\to\mathrm{uu}} \propto$



$$\propto (C_L^u)^2 - (C_R^u)^2$$

$\mathrm{C}_{\mathrm{L}}^{\mathrm{u}} = \frac{1}{2} - \frac{2}{3}\sin^2\theta_{\mathrm{W}} \approx 0.35$ $\qquad$ $\mathrm{C}_{\mathrm{R}}^{\mathrm{u}} = -\frac{2}{3}\sin^2\theta_{\mathrm{W}} \approx -0.16$

800 pb^{-1} : ++ +- -+ --

16 nb × 800 pb^{-1} × 33% (trigger) = 4M events

2M for A_{PV}

$A_{PV}(\hat{p}_T)$:

$\hat{p}_T$ = (GeV)	A_{PV}
35	.0007
45	.0018
55	.004
65	.007
75	.012
85	.019
95	.026
105	.036

$A_{PV}(E_T^j > 45\,GeV) = 0.003 \pm 0.001 \pm 0.0006\ (sys)$

systematic error : 10% P and $\mathcal{L}$
12% threshold uncertainty
4% jet energy scale
3% neutral hadrons
15% PDF's

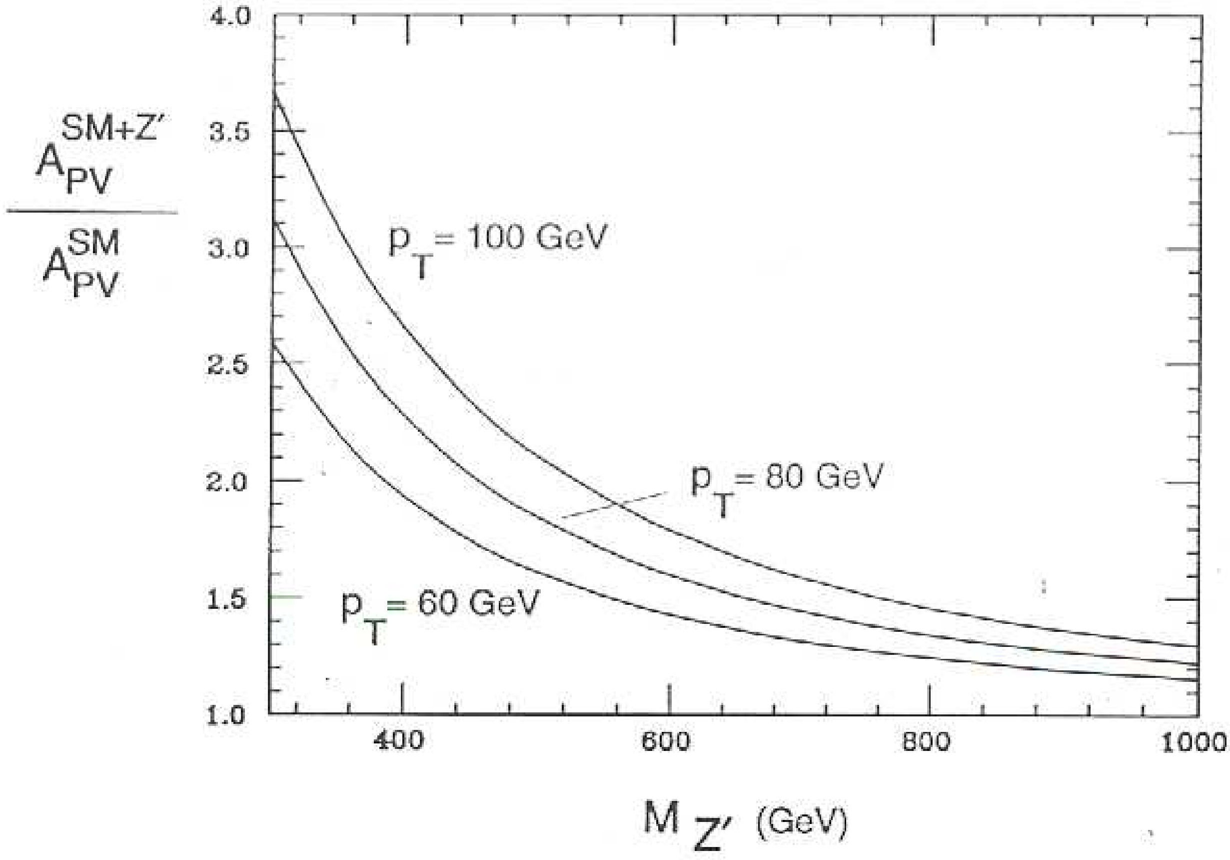
Leptophobic Z'

[Lopez-Nanopoulos, hep-ph/9605359]

- Leptophobia is *natural* in flipped SU(5)

$$10 = \{\begin{pmatrix} u_L \\ d_L \end{pmatrix}, d_R, \nu_R\}; \quad \bar{5} = \{\begin{pmatrix} e_L \\ \nu_L \end{pmatrix}, u_R\}; \quad 1 = e_R$$

Leptons (L) uncharged $\Rightarrow$ Z' must not "see" $\bar{5}$
Z' may "see" 10: several quarks (no leptons)



For 600 GeV leptophobic Z', just above current Fermilab reach:

$A_{PV} = 0.004$ in standard model: 0.003

Need at least a 10% measurement to see this.

Could large CP-violation be detected in polarized proton collisions at RHIC?

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The measurable asymmetries which could be an indication of CP- and/or T-violation in charged current leptoproduction by polarized protons are discussed.

Summary

What is discussed?

- The single- and double-spin leptoproduction asymmetries and their relative sensitivities to CP-odd terms of the phenomenological charged current lagrangian.
- Crude estimates for spurious "T-odd-like" asymmetries due to initial and final state interactions and the possible ways to distinguish them from the true CP-violating effects.

What is not discussed?

- The nature of CP-violating phenomenological terms (Higgs, Leptoquarks, Supersymmetry, ...).
- The (model dependent) limits to CP-odd asymmetries at the energy scale of $W^\pm/Z^0$ mass, arising from low energy searches for CP- and T-violation.
- The dilution of asymmetries due to (strong/loose?) correlations of quarks' and antiquarks' polarizations to the polarizations of colliding protons.

Conclusion

(i) The measurement of T-odd correlations on the order of at least $\sim 10^{-2}$ is possible in polarized proton collisions at RHIC.
(ii) The observation of nonzero T-odd correlations in $W^\pm \to e(\mu)\nu$ mode would be a strong indication of CP- and/or T-violation at about the weak coupling scale.

Issues to address in more details

(i) RHIC sensitivity to the broken CP- and/or T-symmetries in both quark and lepton coupling sectors, including also hadron decay modes of $W^\pm$ (and probably even Z^0 ?)
(ii) Separation of "true" T-odd correlation from the "spurious" asymmetries.
(iii) Systematic errors due to the experimental tolerances (spin alignment, etc)
(iv) Predictions of various models as well as the limitations to CP- and/or T-violating asymmetries at RHIC energies, arising from the earlier accomplished experiments.
(v) Search for other CP- and T-violating processes that might be potentially interesting for Spin Physics Program at RHIC.
(vi) ...(???)

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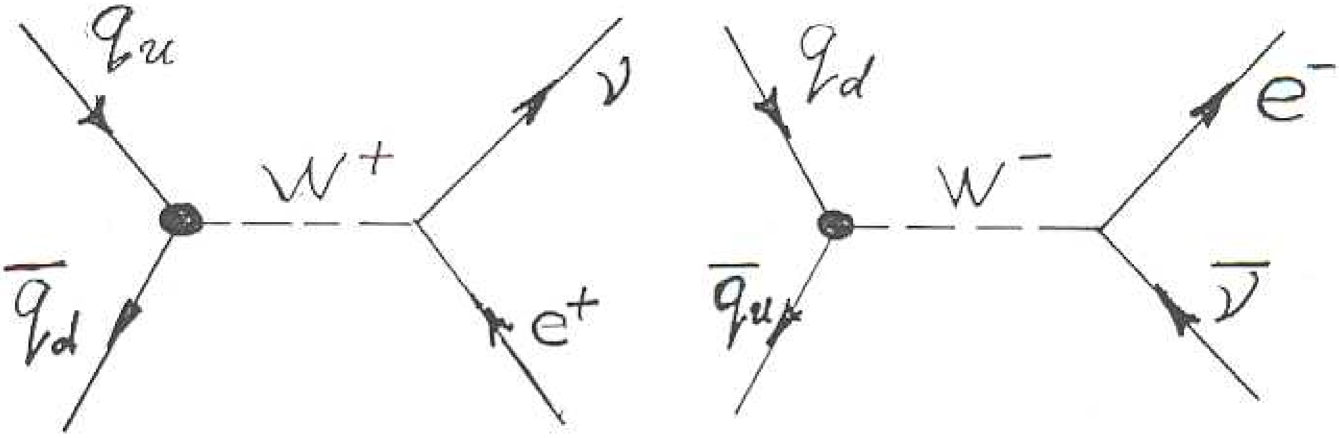
If free polarized quarks could be collided at RHIC



Disclamer: There is (almost?) no hope to measure at RHIC CP-violating asymmetries due to CP-odd phase in CKM-matrix.

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

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

$\boldsymbol{p}$ is momentum of quark ($\boldsymbol{p} \equiv \boldsymbol{p}_q$);

$\boldsymbol{k}$ is momentum of lepton ($\boldsymbol{k} \equiv \boldsymbol{k}_\nu$ or $\boldsymbol{k} \equiv \boldsymbol{k}_{e^-}$);

$\boldsymbol{\zeta}_q$ is polarization of quark;

$\boldsymbol{\zeta}_{\overline{q}}$ is polarization of antiquark.

At least one quark has to be transversely polarized.

Phenomenological interaction lagrangian:

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

$$L = \frac{g}{\sqrt{2}}\{[W_\mu^- \overline{q}_d \gamma^\mu (f_1^L P_- + f_1^R P_+) q_u + \text{h.c.}] - \frac{1}{M_W}[\partial_\nu W_\mu^- \overline{q}_d \sigma^{\mu\nu}(f_2^L P_- + f_2^R P_+) q_u + \text{h.c.}] + \frac{1}{M_W}[\partial^\mu W_\mu^- \overline{q}_d (f_3^L P_- + f_3^R P_+) q_u + \text{h.c.}]\}$$

where $P_\pm = \frac{1}{2}(1 \pm \gamma_5)$, $i\sigma^{\mu\nu} = -\frac{1}{2}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$.

Using other notations,

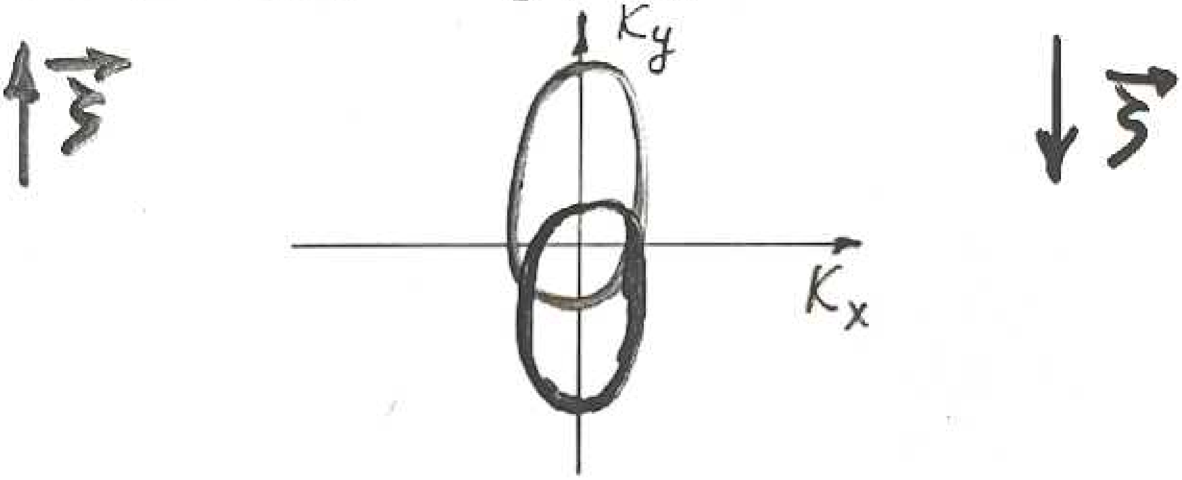
$$L = \frac{g'}{\sqrt{2}}\{[W_\mu^- \overline{q}_d \gamma^\mu (1 - \eta\gamma_5) q_u + \text{h.c.}] + \dots\}$$

***CP*- and *T*-symmetries are broken if**

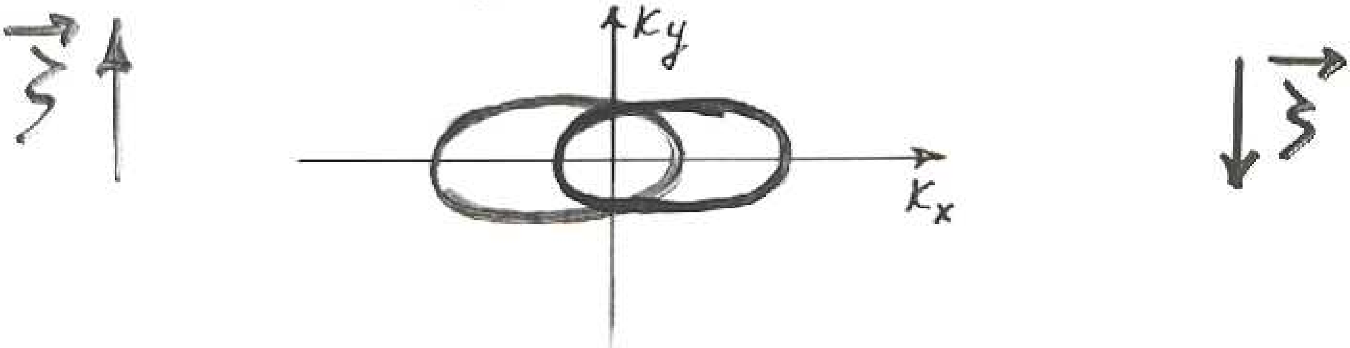
$$\text{Im}\{\eta\} \neq 0.$$

Single-spin asymmetries:

<u>T-even (but P-odd)</u>: $A \propto \frac{M_q}{S}(\boldsymbol{k} \cdot \boldsymbol{\zeta})$



<u>T-odd</u>: $A \propto \mathrm{Im}\{\eta\} \frac{M_q}{S^{3/2}} \boldsymbol{k} \cdot [\boldsymbol{\zeta} \times \boldsymbol{p}]$



Small double-spin asymmetries:

<u>**T-even**</u>: $A \propto \frac{M_q^2}{S^2}(\boldsymbol{\zeta}_q \cdot \boldsymbol{k})(\boldsymbol{\zeta}_{\bar{q}} \cdot \boldsymbol{k})$

<u>**T-odd**</u>:

<u>Both quarks transversely polarized:</u>

$$A \propto \mathrm{Im}\{\eta\} \frac{M_q^2}{S^{3/2}} \boldsymbol{k} \cdot [\boldsymbol{\zeta}_q \times \boldsymbol{\zeta}_{\bar{q}}]$$

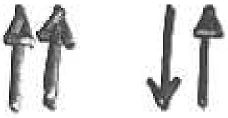
<u>One quark longitudinally polarized:</u>

$$A \propto \mathrm{Im}\{\eta\} \frac{M_q}{S} \boldsymbol{k} \cdot [\boldsymbol{\zeta}_q \times \boldsymbol{\zeta}_{\bar{q}}]$$

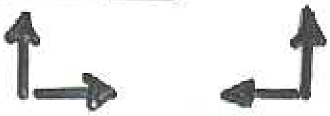
$(1-|\eta|^2)(\vec{\xi}_1\cdot\vec{\xi}_2)$

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

Parallel spins



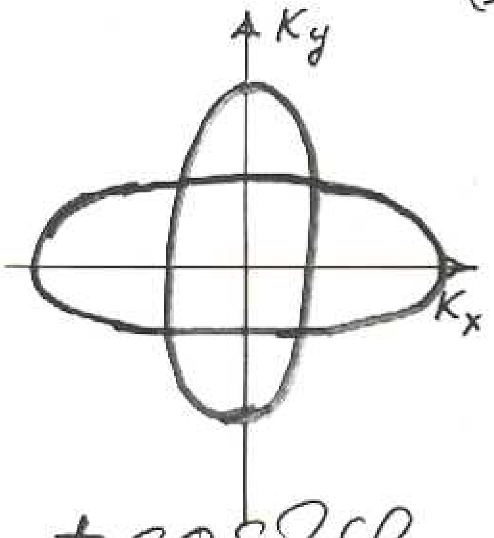
Perpendicular spins



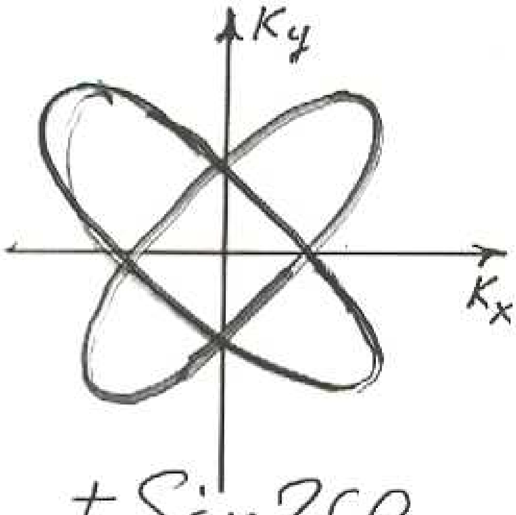
T-even:

$A \propto (1-|\eta|^2)(\boldsymbol{\zeta_q}\cdot\boldsymbol{k})(\boldsymbol{\zeta_{\bar{q}}}\cdot\boldsymbol{k})/S$

[redacted]



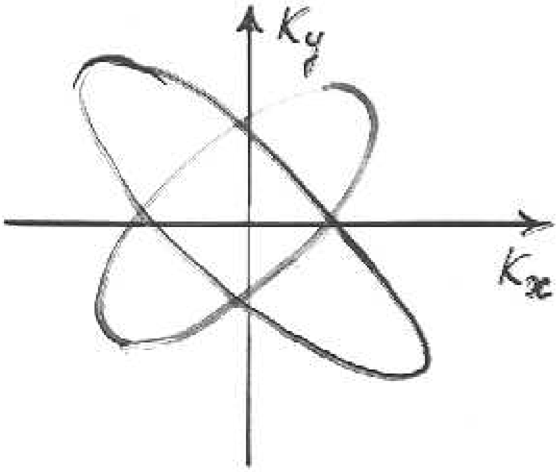
$\pm\cos 2\varphi$



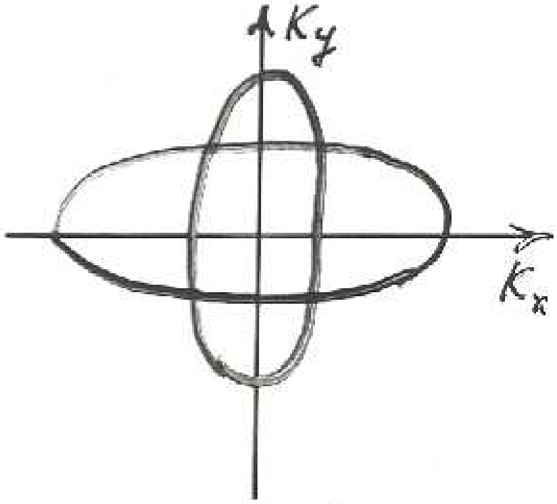
$\pm\sin 2\varphi$

T-odd:

$A \propto \pm\mathrm{Im}\{\eta\}\{\,\boldsymbol{k}\cdot[\boldsymbol{\zeta_q}\times\boldsymbol{p}](\boldsymbol{\zeta_{\bar{q}}}\cdot\boldsymbol{k}) + \boldsymbol{k}\cdot[\boldsymbol{\zeta_{\bar{q}}}\times\boldsymbol{p}](\boldsymbol{\zeta_q}\cdot\boldsymbol{k})\}/S^{3/2}$

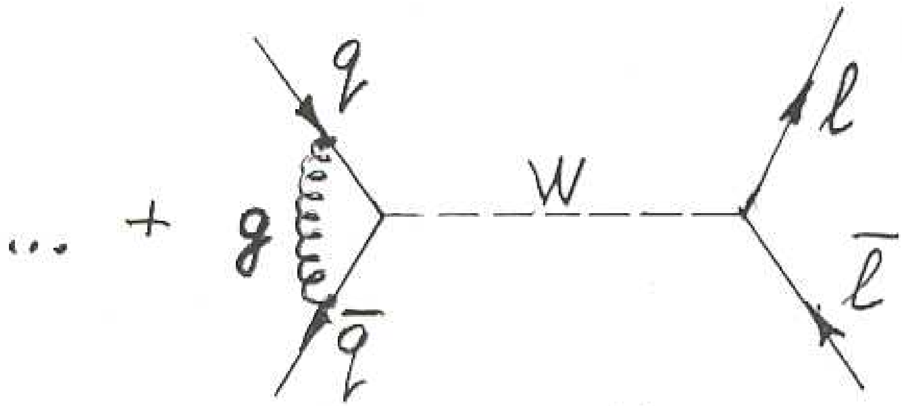


$\pm\sin 2\varphi$



$\pm\cos 2\varphi$

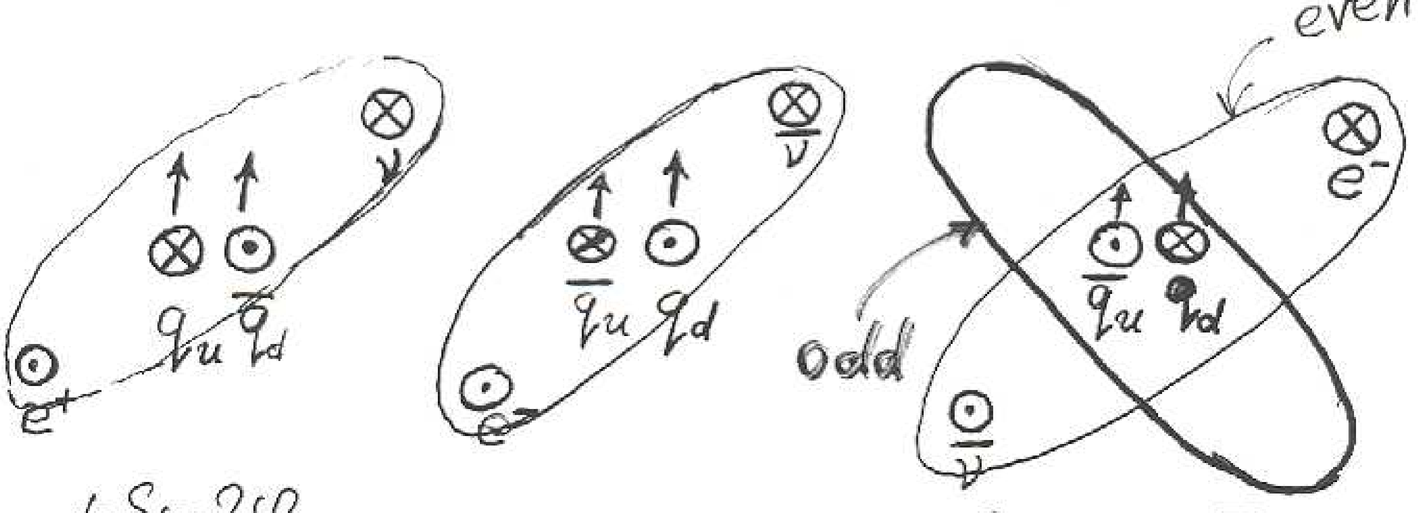
Spurious asymmetries



$$A_s \sim \alpha_s \frac{M_q}{\sqrt{s}} \lesssim 10^{-2} \text{ for } u,d,s,c,b$$

Is there any difference between "true" and "fake" asymmetry?

C CP



$+ \sin 2\varphi$

$+ \sin 2\varphi$ T-even

$- \sin 2\varphi$ T-odd