TSSAs in Drell Yan

Leonard Gamberg*Penn State Berks

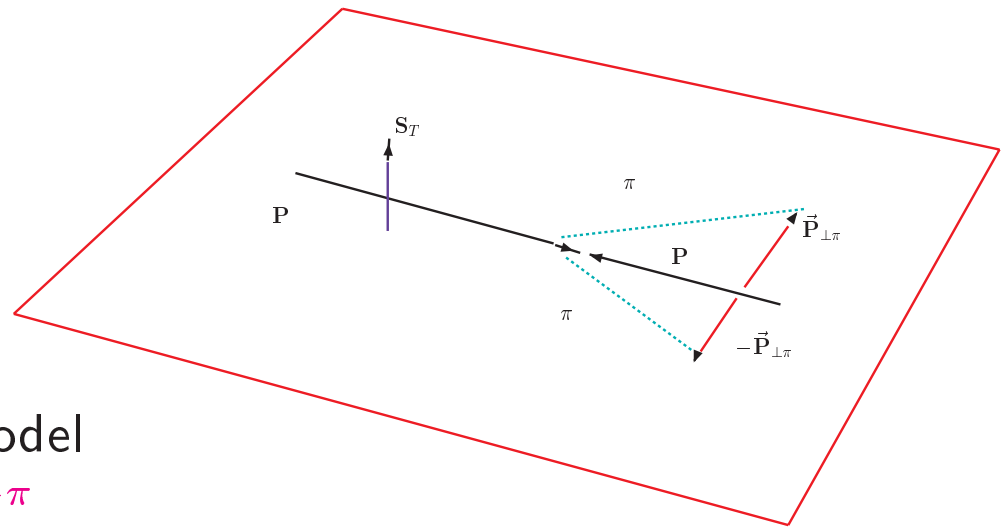
Future RHIC SPIN

- Remarks Transverse Spin effects in AAs in DRELL YAN
- ⋆ Reaction Mechanisms: Beyond Co-linearity ISI/FSI Twist Two Effects in DRELL YAN
- ⋆ Flavor Dependence in Unintegrated "T-odd" TMDs Distribution/ in Spect. FRMWK
- ⋆ Theoretical Issues in DRELL YAN
- ⋆ T-odd $\cos 2\phi$ & asymmetry in DRELL YAN
- Conclusions

* G. R. Goldstein (Tufts)

Transverse SPIN Observables SSA (TSSA)

$$\Delta\sigma \sim i\mathbf{S}_T \cdot (\mathbf{P} \times \boldsymbol{P}_{\pi\perp})$$



- ⋆ Co-linear factorized QCD-parton model
  $\Delta\sigma^{pp^\uparrow \to \pi X} \sim f_a \otimes f_b \otimes \Delta\hat{\sigma} \otimes D^{q\to\pi}$
  Requires helicity flip in hard part $\Delta\hat{\sigma} \equiv \hat{\sigma}^+ - \hat{\sigma}^-$

- $|\perp/\top\rangle = (|+\rangle \pm i|-\rangle) \Rightarrow A_N = \frac{d\hat{\sigma}^\perp - d\hat{\sigma}^\top}{d\hat{\sigma}^\perp + d\hat{\sigma}^\top} \sim \frac{2\, Im\, f^{*+} f^-}{|f^+|^2 + |f^-|^2}$

- ⋆ Requires relative phase btwn helicity amps

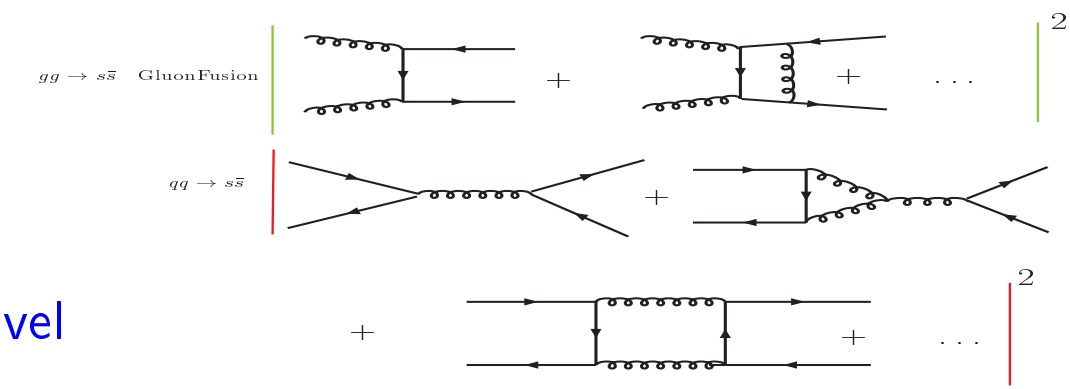
- QCD interactions conserve helicity $m_q \to 0$ & Born amplitudes real!

- ⋆ Kane, Repko, PRL:1978 Generally $A_N \sim \frac{m_q \alpha_s}{P_T}$ small

Early test-Λ Production ($pp \to \Lambda^{\uparrow} X$)

- Need strange quark to polarize a Λ $\quad P_\Lambda = \frac{d\sigma^{pp\to\Lambda^{\uparrow}X} - d\sigma^{pp\to\Lambda^{\downarrow}X}}{d\sigma^{pp\to\Lambda^{\uparrow}X} + d\sigma^{pp\to\Lambda^{\downarrow}X}}$

  Dharmartna & Goldstein PRD 1990

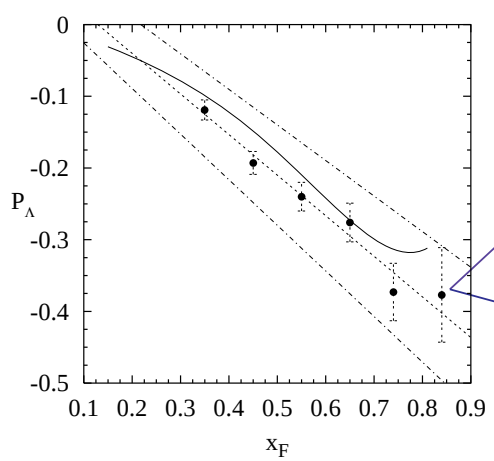


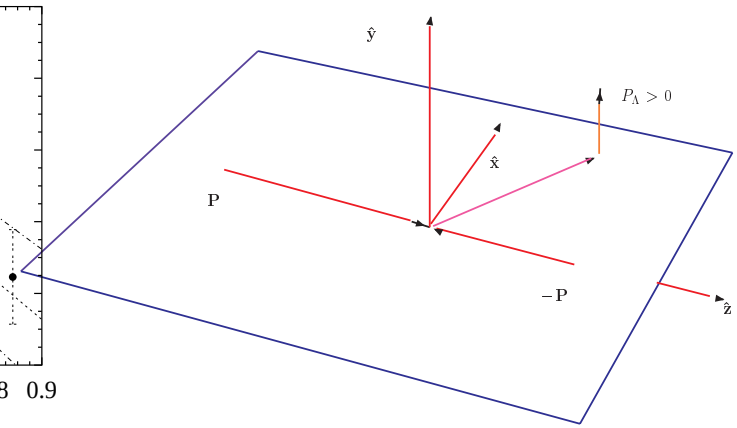
Phases in *hard part* $\hat{\Delta\sigma}$
interference of loops and tree level

- Polarization $P_\Lambda \sim \frac{m_s \alpha_s}{P_T}$–twist 3 & small $\approx 5\%$ as predicted
- Experiment *glaringly at odd with this result*

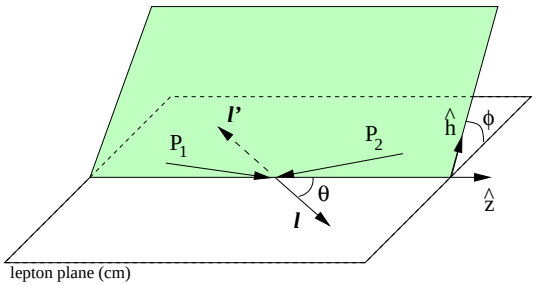
  P_Λ in $p - p$ scattering-Fermi Lab

  Heller,...,Bunce PRL:1983





Azimuthal Asymmetry–Unpolarized DRELL YAN



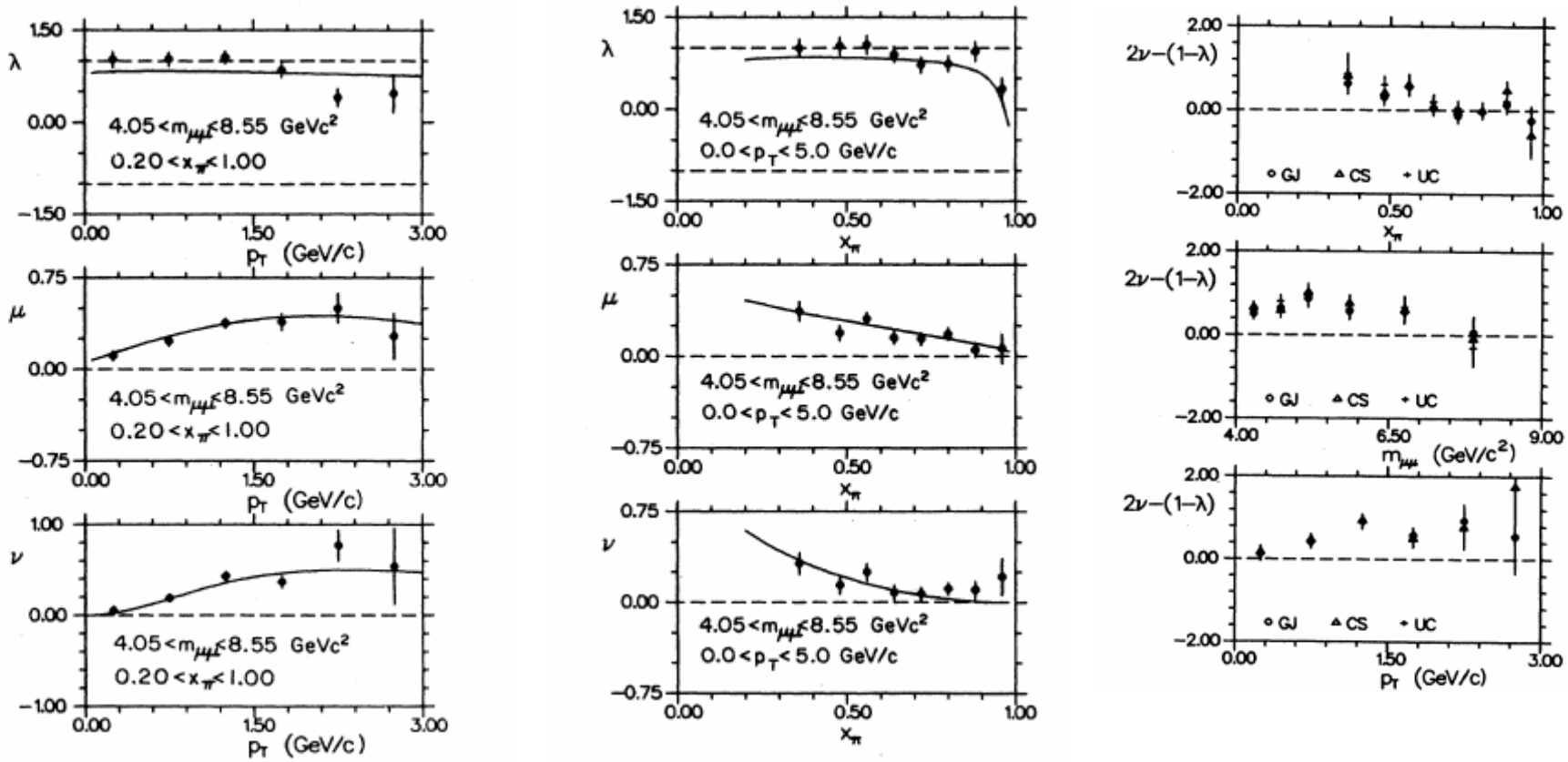
$\pi^- + p \rightarrow \mu^+ + \mu^- + X$ E615,Conway et al. 1986, NA10, ZPC(1986)

QCD-Parton Model doesn't account for large "AA"

$\lambda,\ \mu,\ \nu$ **depend on** $s, x, m^2_{\mu\mu}, p_T$

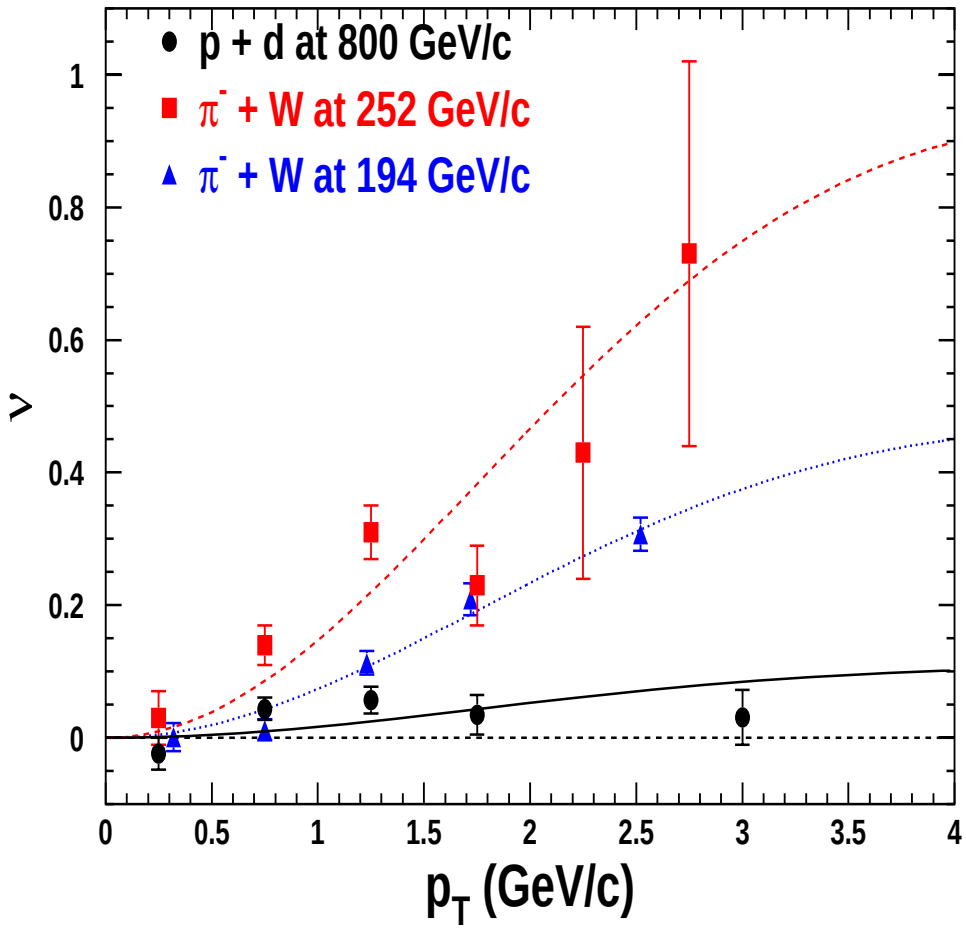
$$\frac{dN}{d\Omega} = (\frac{d\sigma}{d^4q})^{-1}\frac{d\sigma}{d^4q d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1+\lambda\cos^2\theta+\mu\sin^2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$

- Violation of Lam-Tung relation- (NNLO QCD) $1-\lambda-2\nu \neq 0$ (Mirkes Ohnemus, PRD 1995)
- *Unexpectedly large* $\cos 2\phi$ – $\nu \sim 10-30\%$ AA
- *Suggests a Non-Pertb. origin!*



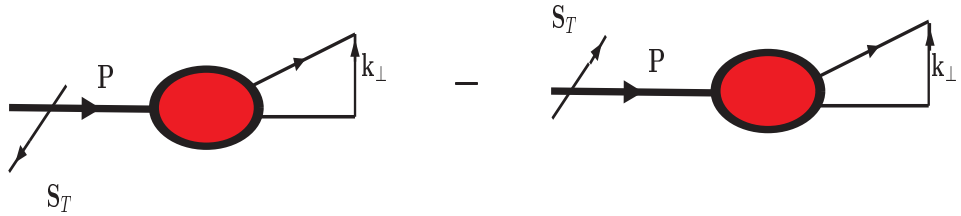
Lam-Tung Relationship Violated

Anomalous RESULTS Valence versus Sea or Cancellation



Two Scales $\boldsymbol{q}_T \sim k_\perp << \sqrt{Q^2}$ TSSAs from "T-Odd" **TMD** Extend to Drell Yan

- Sivers PRD: 1990,Collins NPB: 1993, Boer 1999 (DY)
  TSSA associated with "T-odd" correlation *transverse* spin and momenta



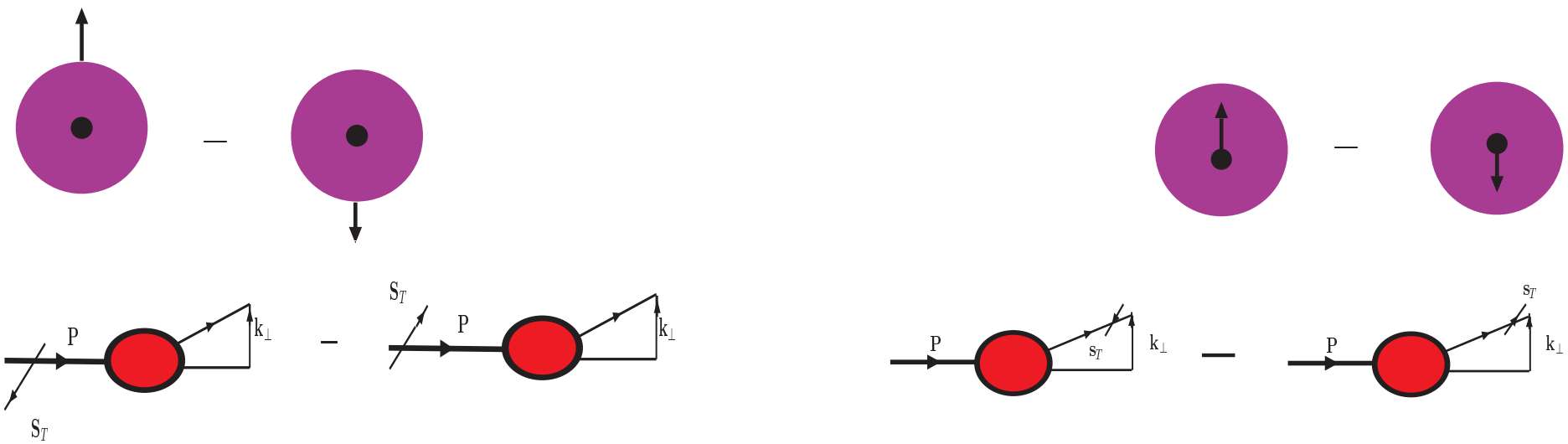
$$\Delta\sigma^{pp^\uparrow \to \ell^+\ell^- X} \sim f \otimes \Delta\bar{f}^\perp \otimes \hat{\sigma}_{Born} \quad \Rightarrow i\boldsymbol{S}_T \cdot (\boldsymbol{P} \times \boldsymbol{k}_\perp) \to f_{1T}^\perp(x, \boldsymbol{k}_\perp)$$

⋆ No Fragmentation-Access to TMPDFs

Transverse Spin-Momentum Correlations in Drell Yan

Correlation of transversely polarized *quark spin* with intrinsic $\boldsymbol{k}_\perp$

$$i\mathsf{s}_T \cdot (\boldsymbol{k}_\perp \times \boldsymbol{P}) \to h_1^\perp(x, \boldsymbol{k}_\perp)$$



$h_1^\perp(x, k_\perp)$ Transversely/unpolarized quarks in unpolarized/transversly nucleons $f_{1T}^\perp(x, k_\perp)$

- ⋆ Observed non-trivial (HERMES) $\sin\phi_{hs}$ & $\cos 2\phi$-AA(maybe) in lepto-production

$$e\,P \to\ e'\,\pi\,X$$

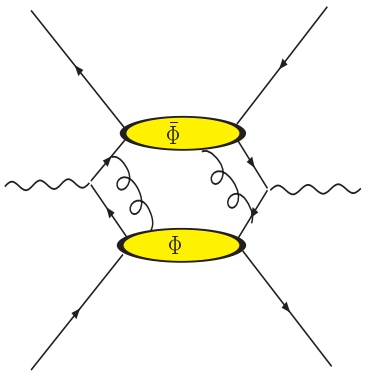
- ⋆ SHOULD Explore $\sin\phi_{hs}$ & $\cos 2\phi$-AA in Drell Yan

$\pi^- + p \to \mu^+ + \mu^- + X$ Compass

$p + p \to \mu^-\mu^+ + X$ RHIC-II

T-Odd Effects Incorp. thru Color Gauge Invariant Factorized QCD via Wilson Line

- Leading twist Gauge Invariant Distribution Functions
  Boer, Mulders: NPB 2000, Ji, Ma, Yuan 2002, 2004, 2005, Boer et al NPB 2003



$$d\sigma = L_{\mu\nu}\mathcal{W}^{\mu\nu} \Rightarrow$$

Drell YAN Hadronic Tensor

$$\mathcal{W}^{\mu\nu}(q, P, \bar{P}) = \int d^2\boldsymbol{p}_T d^2\boldsymbol{k}_T \delta^2(\boldsymbol{p}_T + \boldsymbol{q}_T - \boldsymbol{k}_T)\, \mathrm{Tr}[\Phi(x, \boldsymbol{p}_T)\gamma^\mu \bar{\Phi}(\bar{x}, \boldsymbol{k}_T)\gamma^\nu] + (q \leftrightarrow -q\ ,\ \mu \leftrightarrow \nu)$$

Class of loops sum to yield *factorized* color gauge invariant hadronic tensor into distribution Φ

$$\Phi(p, P) = \int \frac{d^3\xi}{2(2\pi)^3} e^{ip\cdot\xi} \langle P|\overline{\psi}(\xi^-, \xi_\perp)\mathcal{G}^\dagger_{[\xi^-,\infty]}|X\rangle\langle X|\mathcal{G}_{[0,\infty]}\psi(0)|P\rangle|_{\xi^+=0}$$

$$\mathcal{G}_{[\xi,\infty]} = \mathcal{G}_{[\xi_T,\infty]}\mathcal{G}_{[\xi^-,\infty]}, \quad \text{where} \quad \mathcal{G}_{[\xi^-,\infty]} = \mathcal{P}exp(-ig\int_{\xi^-}^{\infty} d\xi^- A^+)$$

Source of T-Odd Contributions to TSSA and AA

- "T-odd" distribution-fragmentation functions enter transverse momentum dependent correlators at *leading twist* Boer, Mulders: PRD 1998

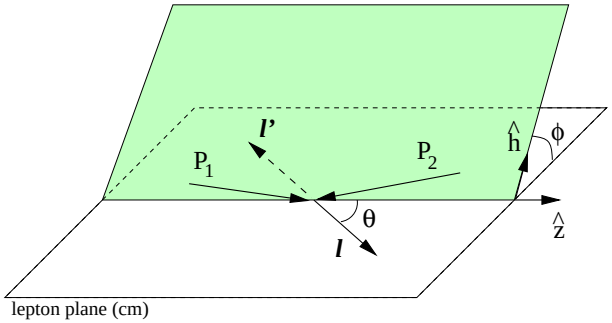
$$\Phi(x,\boldsymbol{p}_\perp)=\frac{1}{2}\{f_1(x,\boldsymbol{p}_\perp)\not{n}_+ + h_1^\perp(x,\boldsymbol{p}_\perp)\frac{\sigma^{\alpha\beta}p_{T\alpha}n_{+\beta}}{M} + f_{1T}^\perp(x,\boldsymbol{p}_\perp)\frac{\epsilon^{\mu\nu\rho\sigma}\gamma^\mu n_+^\nu p_\perp^\rho S_T^\sigma}{M}\cdots\}$$

$$\bar{\Phi}(\bar{x},\boldsymbol{p}_\perp)= \quad \bar{f}_1(x,\boldsymbol{p}_\perp)\not{n}_+ + \bar{h}_1^\perp(x,\boldsymbol{p}_\perp)\frac{\sigma^{\alpha\beta}p_{T\alpha}n_{+\beta}}{M} + \bar{f}_{1T}^\perp(x,\boldsymbol{p}_\perp)\frac{\epsilon^{\mu\nu\rho\sigma}\gamma^\mu n_+^\nu p_\perp^\rho S_T^\sigma}{M}\cdots$$

<u>DY cross section</u>

$$\begin{aligned}
d\sigma_{\lambda,\Lambda}^{N\bar{N}\to\ell^+\ell^-X} \quad &\propto \quad f_1\otimes d\hat{\sigma}^{q\bar{q}\to\ell^+\ell^-}\otimes\bar{f}_1 \\
&+ \quad \left[\frac{k_\perp^2}{Q^2}f_1\otimes d\hat{\sigma}^{q\bar{q}\to\ell^+\ell^-}\otimes\bar{f}_1 + h_1^\perp\otimes d\hat{\sigma}^{q\bar{q}\to\ell^+\ell^-}\otimes\bar{h}_1^\perp\right]\cdot\cos 2\phi \\
&+ \quad |S_T|\cdot h_1\otimes d\hat{\sigma}^{q\bar{q}\to\ell^+\ell^-}\otimes\bar{h}_1^\perp\cdot\sin(\phi+\phi_S) \quad \textit{Collins like} \\
&+ \quad |S_T|\cdot f_{1T}^\perp\otimes d\hat{\sigma}^{q\bar{q}\to\ell^+\ell^-}\bar{f}_1\cdot\sin(\phi-\phi_S) \quad \text{Sivers}
\end{aligned}$$

Sivers & Collins-Mulders Effect in DRELL YAN



$$\bar{p} + p \to \mu^- \mu^+ + X$$

SSAs& T-odd Contribution in Drell Yan (RHIC-II, JPARC & GSI-FAIR)

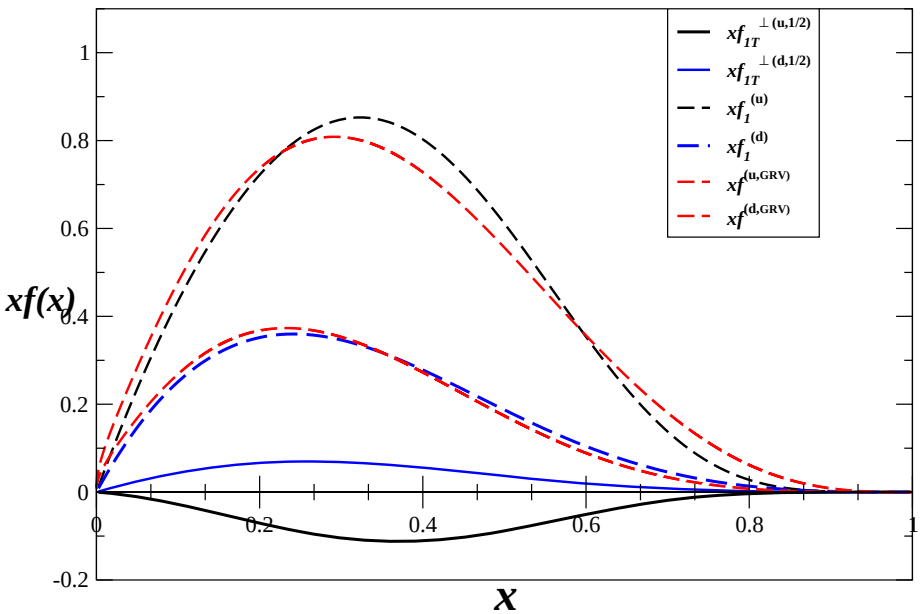
$$\frac{d\Delta\sigma^{\uparrow}}{d\Omega dx_1 dx_2 d\mathbf{q}_T} \propto \sum_a e_f^2 \, |\mathbf{S}_{2_T}| \left\{ -B(y) \, \sin(\phi + \phi_{S_2}) \, \mathcal{F}\left[\hat{\mathbf{h}} \cdot \mathbf{p}_{1_T} \frac{\bar{h}_1^{\perp\, a} \, h_1^a}{M_1}\right] \right.$$

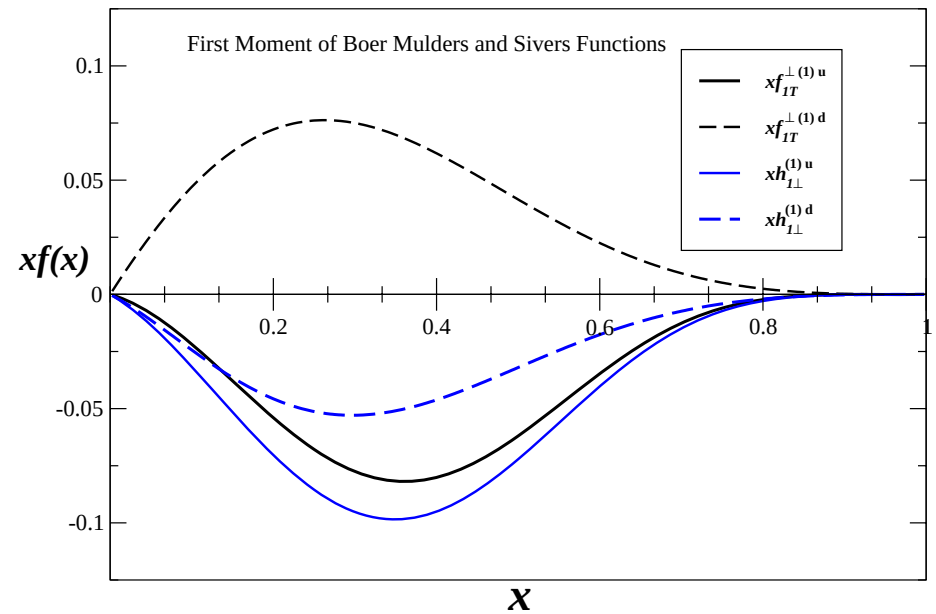
$$\left. + A(y) \, \sin(\phi - \phi_{S_2}) \, \mathcal{F}\left[\hat{\mathbf{h}} \cdot \mathbf{p}_{2_T} \frac{\bar{f}_1^a \, f_{1T}^{\perp\, a}}{M_2}\right] \; ... \right\} ,$$

Flavor Dependence: Results & Phenomenolgy

Flavor-dependent PDFs from diquark models: $u = \frac{3}{2}s + \frac{1}{2}a$, $d = a$,

moments: $h_1^{\perp(n/2)}(x) = \int d^2\vec{p}_T \, \frac{|\vec{p}_T|^n}{2M^n} h_1^{\perp}(x, \vec{p}_T^{\,2})$

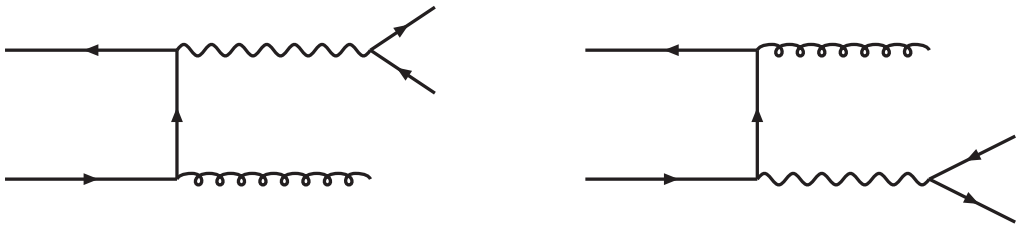




- Comparison to $f_1^{(u,d)}$ (Glück, Reya, Vogt) $\longrightarrow$ parameters of the model, e.g. diquark masses, normalization...
- Comparison to parameterization of Sivers function $f_{1T}^{\perp}$ $\longrightarrow$ size and sign of FSI.
- Boer Mulders up and down are negative is spectator model

Theory ISSUES

- Gluon bremstrulang Collins PRL: 1979, recent wk. Boer Vogelsang 2006 competes with convolution of $h_1^\perp \otimes \bar{h}_1^\perp$



- Sudakov Suppression $q_T << Q^2$ due to exponentiation of soft gluon contributions. Boer 1999, 2001
- Qui Sterman, Ji Yuan Vogelsang approach 2006 $q_T \sim Q$. . .

Numerical study of Sudakov suppression

$$\frac{d\sigma}{dQ^2 dy d^2\boldsymbol{q}_T d\Omega} = \int d^2b\, e^{-i\boldsymbol{b}\cdot\boldsymbol{q}_T}\tilde{W}(\boldsymbol{b}, Q; x_A, x_B) + Y(\boldsymbol{q}_T, Q; x_A, x_B)$$

with $\tilde{f} \to \tilde{\Phi}$

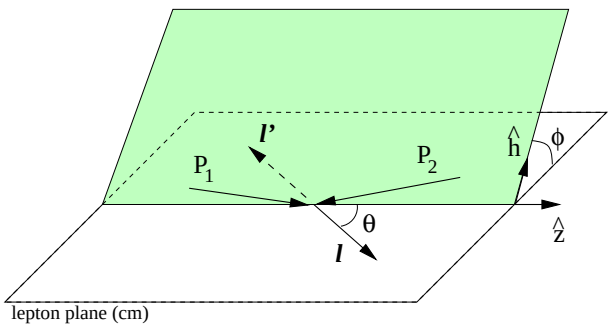
$$\begin{aligned}\tilde{W}(\boldsymbol{b}, Q; x_A, x_B) &= \sum_a \tilde{\Phi}_{a/A}(x_A, \boldsymbol{b}; 1/b, \alpha_s(1/b)) \sum_b \tilde{\Phi}_{b/B}(x_B, \boldsymbol{b}; 1/b, \alpha_s(1/b)) \\ &\quad \times e^{-S(b,Q)}\, H_{ab}\left(x_A, x_B, Q; \alpha_s(Q)\right)\, \tilde{U}(\boldsymbol{b}; 1/b, \alpha_s(1/b))\end{aligned}$$

Scale choice is such that b dependence of soft factor $\tilde{U}$ appears only at NLLA

$$\tilde{\Phi}(x, \boldsymbol{b}) = \frac{M}{2}\left\{\tilde{f}_1(x, \boldsymbol{b}^2)\,\frac{\not{P}}{M} + \left(\frac{\partial}{\partial b^2}\tilde{h}_1^{\perp}(x, \boldsymbol{b}^2)\right)\frac{2\not{b}\not{P}}{M^2}\right\}$$

Furthermore, assume Gaussian k_T dependence for f_1 (with Gaussian width R_u^2) and $h_1^{\perp}$ (with Gaussian width $R^2 > R_u^2$)

Unpolarized DRELL YAN $\cos 2\phi$



$$\bar{p} + p \to \mu^- \mu^+ + X$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}\left(1 + \lambda\cos^2\theta + \mu\sin^2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right) \tag{1}$$

Angles refer to the lepton pair orientation in their rest frame relative to the boost direction and the initial hadron's plane. Asymmetry parameters, λ, μ, ν, depend on s, x, $m^2_{\mu\mu}$, q_T

Boer PRD: 1999, Boer, Brodsky, Hwang PRD: 2003 Collins SoperPRD: 1977 subleading twist

- Leading twist $\cos 2\phi$ azimuthal asymmetry depends on T-odd distribution $h_1^\perp$.

$$\nu = \frac{2\sum_a e_a^2 \mathcal{F}\left[(2\boldsymbol{p}_\perp\cdot\boldsymbol{k}_\perp - \boldsymbol{p}_\perp\cdot\boldsymbol{k}_\perp)\frac{h_1^\perp(x,\boldsymbol{k}_T)\bar{h}_1^\perp(\bar{x},\boldsymbol{p}_T)}{M_1 M_2}\right]}{\sum_{a,\bar{a}} e_a^2 \mathcal{F}[f_1\bar{f}_1]} \tag{2}$$

Convolution integral

$$\mathcal{F} \equiv \int d^2\boldsymbol{p}_\perp d^2\boldsymbol{k}_\perp \delta^2(\boldsymbol{p}_\perp + \boldsymbol{k}_\perp - \boldsymbol{q}_\perp) f^a(x,\boldsymbol{p}_\perp)\bar{f}^a(\bar{x},\boldsymbol{k}_\perp)$$

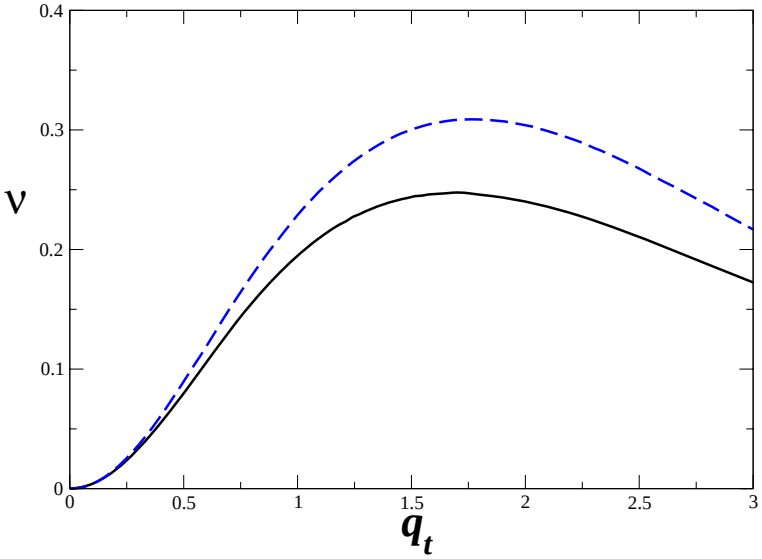
Higher twist comes

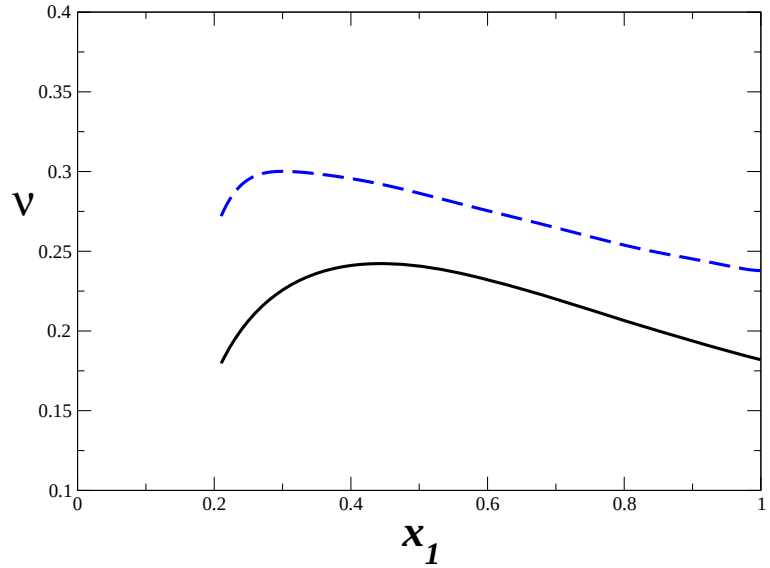
$$\nu = \frac{2\sum_a e_a^2 \mathcal{F}\left[(2\boldsymbol{p}_\perp \cdot \boldsymbol{k}_\perp - \boldsymbol{p}_\perp \cdot \boldsymbol{k}_\perp)\frac{h_1^\perp(x,\boldsymbol{k}_T^2)\bar{h}_1^\perp(\bar{x},\boldsymbol{p}_T)}{M_1 M_2}\right] + \nu_4[w_4 f_1 \bar{f}_1])}{\sum_{a,\bar{a}} e_a^2 \mathcal{F}[f_1 \bar{f}_1]}$$

where Collins SoperPRD: 1977 subleading twist

$$\nu_4 = \frac{\frac{1}{Q^2}\sum_a e_a^2 \mathcal{F}\left[w_4\, f_1(x,\boldsymbol{k}_\perp)\bar{f}_1(\bar{x},\boldsymbol{p}_\perp)\right]}{\sum_a e_a^2 \mathcal{F}\left(f_1(x,\boldsymbol{k}_\perp)\bar{f}_1(\bar{x},\boldsymbol{p}_\perp)\right)},$$

where the weight $w_4 = 2\left(\hat{\boldsymbol{h}} \cdot (\boldsymbol{k}_\perp - \boldsymbol{p}_\perp)\right)^2 - (\boldsymbol{k}_\perp - \boldsymbol{p}_\perp)^2$





Perform Convolution integral L.G., Goldstein PLB: 2007

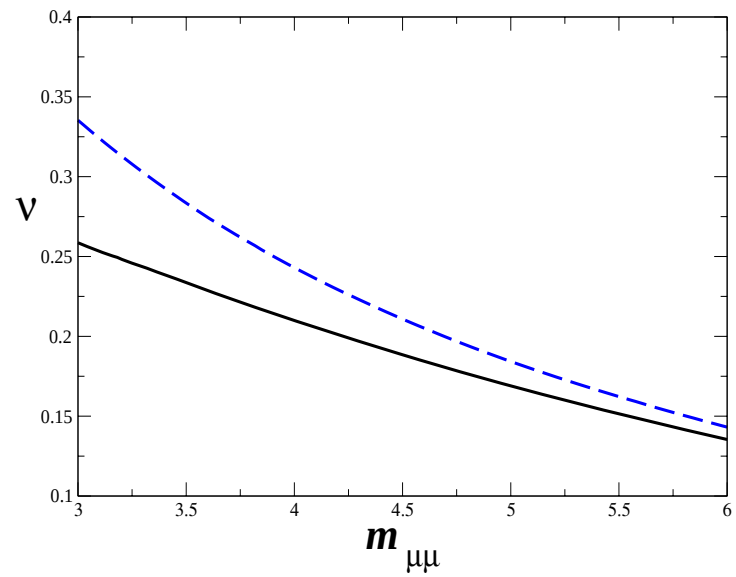
$s = 50\,\mathrm{GeV}^2$, $x = [0.2 - 1.0]$,

$q = [3.0 - 6.0]$ GeV, $\boldsymbol{q}_T = 0 - 2.0\,\mathrm{GeV}$

q_T^2/Q^2 corrections

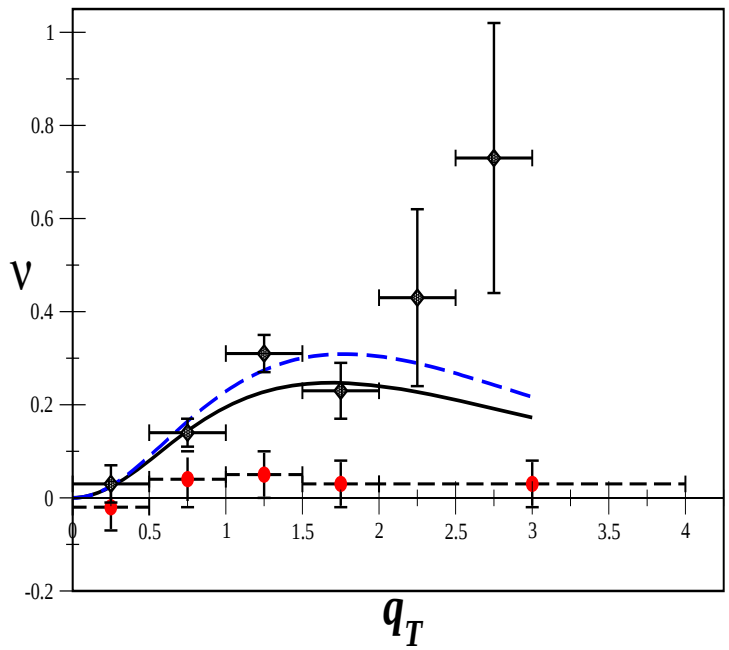
$x_1 x_2 = \frac{Q^2(1+q_T^2/Q^2)}{s}$

q_T/Q can be order 0.5



Sea Quark Boer Mulders

Gamberg & Goldstein Plb 2007



- ν plotted as a function of q_T for $s = 50\ \mathrm{GeV}^2$, $x[0.2 - 1.0]$, and $Q[3 - 6]\ \mathrm{GeV}/c$. Solid line leading twist contribution ν_2, dashed line leading and sub-leading twist $(\nu_2 + \nu_4)$.
- Data: Diamonds are for E615 $\pi^- + p$ at 252 GeV/c. Circles are for E866 $p + d$ at 800 GeV/c Peng, Zu hep-ex/0609005.
- Horizontal bars refer to bin size, vertical error bars refer to statistical uncertainties.
- One of pair of structure functions in convolution involve sea anti-quarks, the $\bar{h}_1^{\perp(sea)}$ for $N \to \bar{u}$ or $\bar{d}$.
- Suppressed by another factor of α_s in our approach (as well as possible kinematic factors) w/ data suggest that sea structure BM function roughly $\frac{1}{3}$ of the magnitude of predicted valence quark structure function.

SUMMARY

- Going beyond the collinear approximation in PQCD recent progress has been achieved characterizing transverse SSA and azimuthal asymmetries through "rescattering" mechanisms which generate T-odd, intrinsic transverse momentum, $k_\perp$, dependent *distribution and fragmentation* functions at leading twist
- Central to this understanding is the role that transversity properties of quarks and hadrons pocess terms of correlations between transverse momentum and transverse spin in QCD hard scattering

- The tranversity programs Belle, HERMES, RHIC, have uncovered large effects and near term Hall-A Transversity will start to check flavor structure of T-odd TMDs
- Future DRELL - YAN at RHIC-II experiments could uncover the Boer Mulders sea-quark and valence function

⋆ Azimuthal asymmetries in Drell Yan and SSA can be measured at GSI-PAX, JPARC as well

⋆ Transverse spin effects are more than h_1