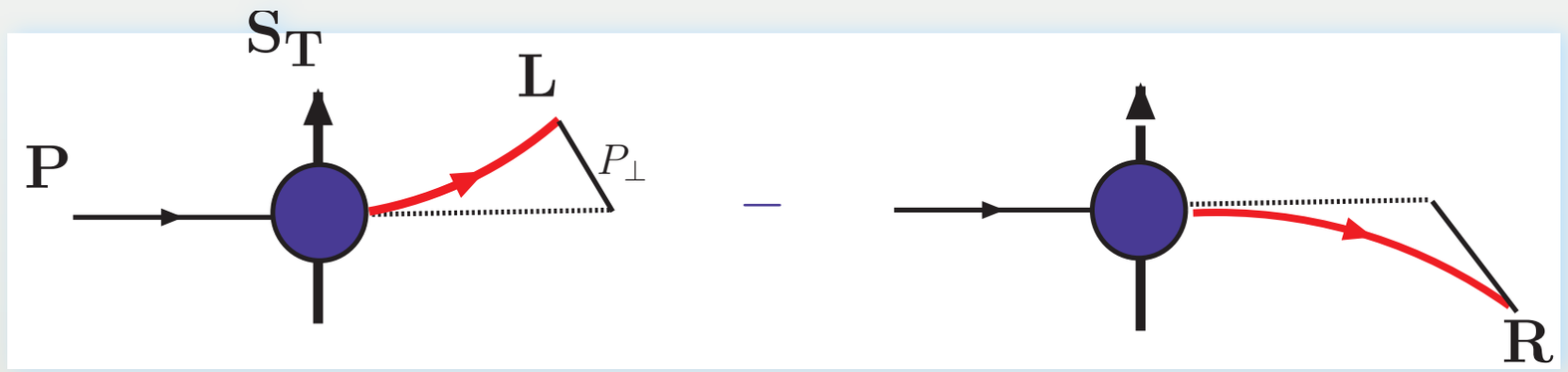
Transverse Spin Phenomena and Their Impact on QCD
In Honor of Gary Goldstein's 70th Birthday
October 28-29, 2010

Transverse SPIN Observables SSA (TSSA) $P^{\uparrow}P \to \pi X$

- **Single Spin Asymmetry**



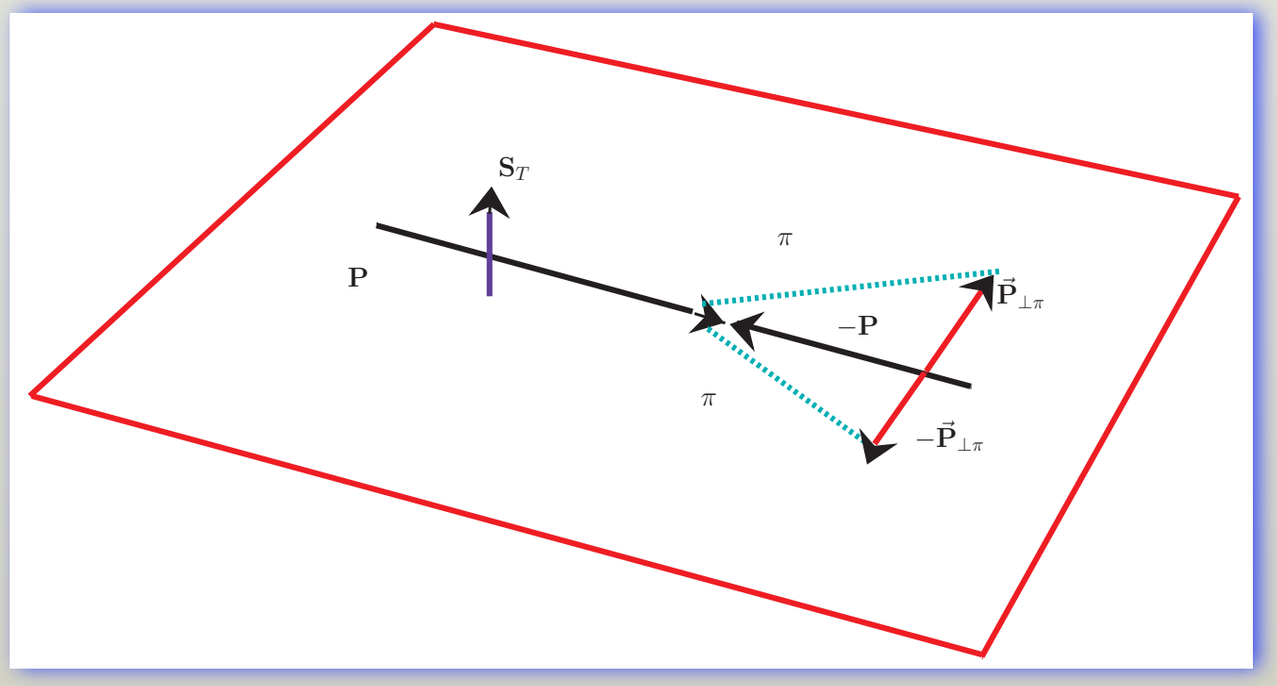
Parity Conserving interactions: SSAs Transverse Scattering plane

$$\Delta\sigma \sim iS_T \cdot (\mathbf{P} \times P_{\perp}^{\pi})$$

- **Rotational invariance** $\sigma^{\downarrow}(x_F, \boldsymbol{p}_{\perp}) = \sigma^{\uparrow}(x_F, -\boldsymbol{p}_{\perp})$

$\Rightarrow$ ***Left-Right Asymmetry***

$$\boldsymbol{A_N} = \frac{\sigma^{\uparrow}(x_F,\boldsymbol{p}_{\perp}) - \sigma^{\uparrow}(x_F,-\boldsymbol{p}_{\perp})}{\sigma^{\uparrow}(x_F,\boldsymbol{p}_{\perp}) + \sigma^{\uparrow}(x_F,-\boldsymbol{p}_{\perp})} \equiv \Delta\sigma$$



The Status of Transverse Spin Physics . . .

$\vec{S}_T \cdot \left(\vec{P} \times \vec{P}_\Lambda\right)$

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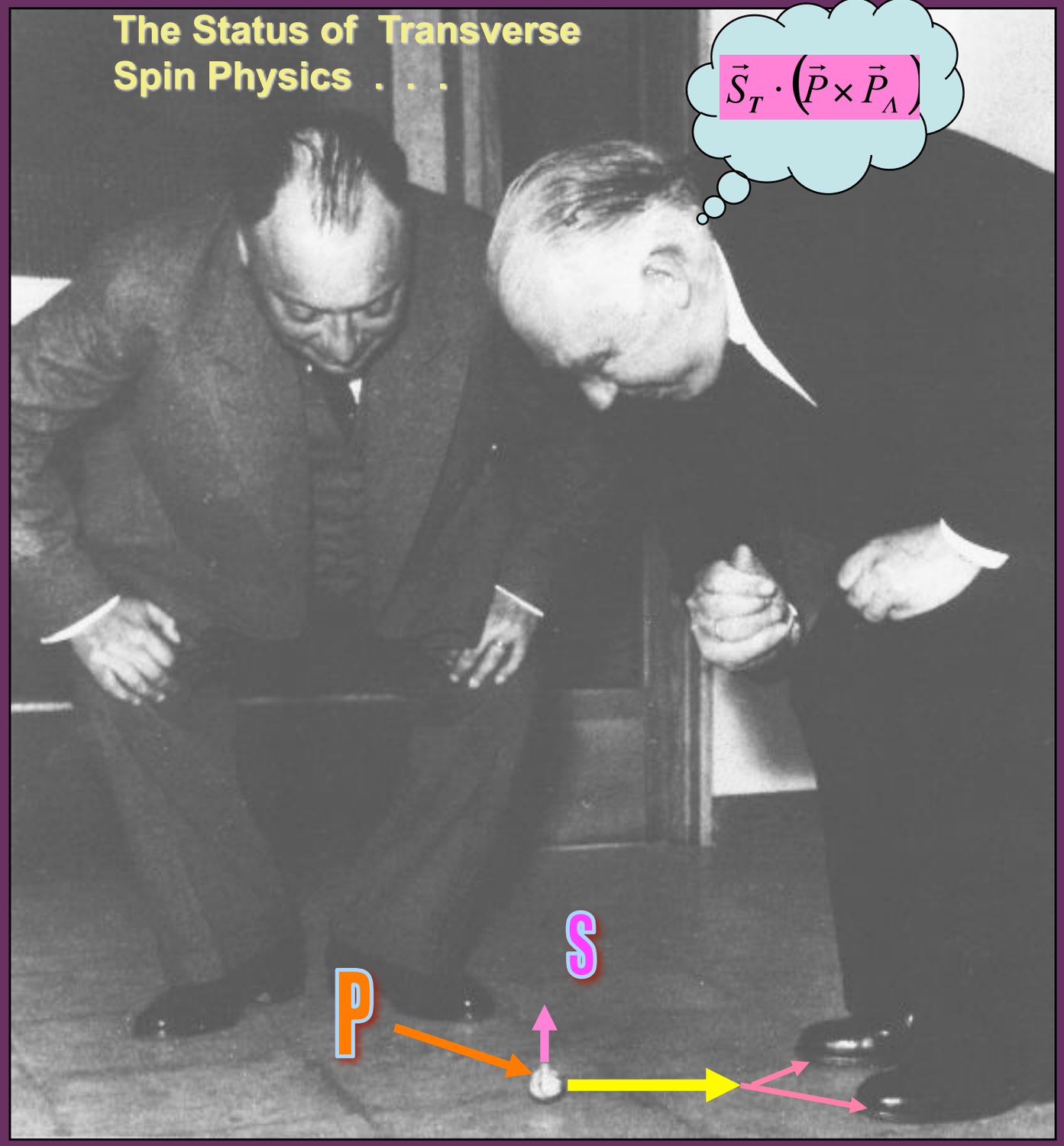


Present here aspects of transversity and transverse spin polarization phenomena

- Gary Goldstein and Mike Moravcsik, Ann. Phys. 98, 128 (1976); Ann. Phys. 142, 219 (1982)
- John Ralston & Davison Soper NPB 152 (1979)
- Dennis Sivers, Phys. Rev. D 41, 83 (1990); 43, 261 (1991)
- Bob Jaffe & Xiangdong Ji, Phys. Rev. Lett. 67, 552 (1991)
- Jacques Soffer, Phys. Rev. Lett. 74, 1292 (1995)
- Gary Goldstein, Bob Jaffe and Xiangdong Ji, Phys. Rev. D52, 5006 (1995)

Aspects of transversity and transverse spin polarization phenomena

Present here who have been instrumental in Gary's Career

- Kamesh Wali, Ph.D advisor of Gary
- Lou Cavellie
- Jeff Owens

Special Thanks to JLAB

- David Richards JLAB for support encouragement guiding us through
- Theory Group-Mike Pennington, Wally Melnitchouk and Christain Weiss
- Staff support Mary Fox, Ruth Bizot

- Simonetta Liuti who's conceived of the idea to celebrate GaryFEST as a workshop at JLAB
- Proceedings ....!!!

Outline

- **Transverse structure spin Effects in TSSAs**
- **Gauge links-Color Gauge Inv.-"T-odd" TMDs**
- **T-odd PDFs via FSIs ... Summing gauge link**

"QCD calc " **FSIs Gauge Links-Color Gauge Inv. "T-odd" TMDs**

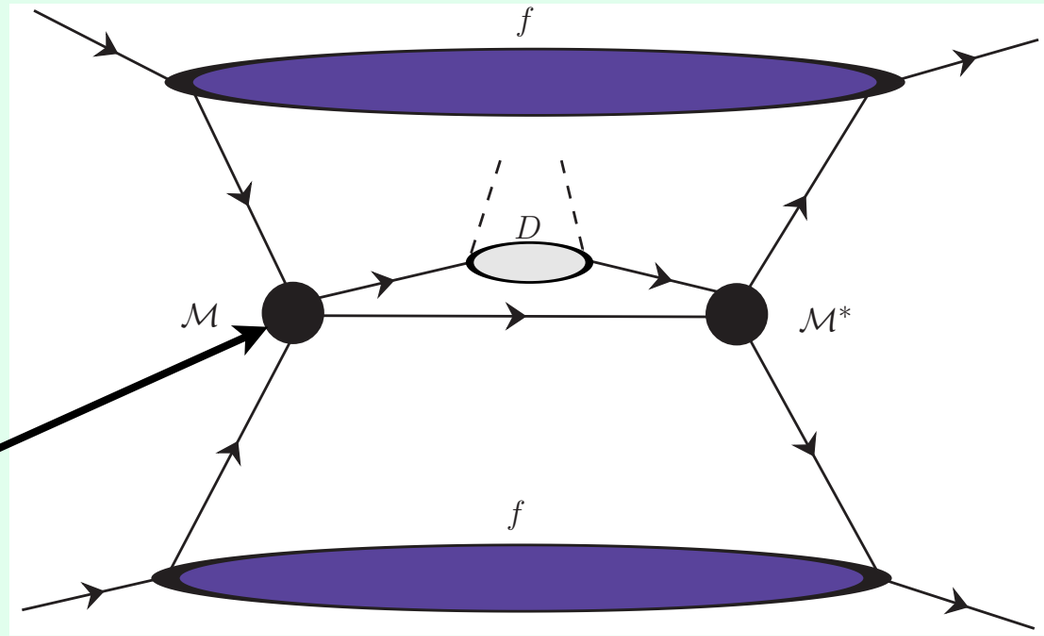
- Generalizing the Generalized Parton Model (GPM)--effects of FSI and ISI on color structure
- Connection to twist three & Gluonic Poles
- Universality and gluonic poles in fragmentation

Transverse Polarization in Inclusive Reactions $P^{\uparrow} P \to \pi X$

e.g. Goldstein & Owens NPB 76

Transv. polarization cross section "interference" of helicity flip and non-flip amps.

quark-quark scattering



Elastic scattering of 2 quarks of different flavor

6 independent helicity Amps $M_{\lambda'_{q_1},\lambda'_{q_2};\lambda_{q_1},\lambda_{q_2}}$

$$M_{++,++} \equiv \Phi_1 \quad M_{--,++} \equiv \Phi_2 \quad M_{+-,+-} \equiv \Phi_3$$

$$M_{-+,+-} \equiv \Phi_4 \quad M_{-+,++} \equiv \Phi_5 \quad M_{++,+-} \equiv \Phi_6$$

$$A_N = \frac{\hat{\sigma}^{\uparrow} - \hat{\sigma}^{\downarrow}}{\hat{\sigma}^{\uparrow} + \hat{\sigma}^{\downarrow}} \sim \mathrm{Im}\left[\Phi_6(\Phi_1 + \Phi_3)^* - \Phi_5(\Phi_2 - \Phi_4)^*\right]$$

Interference of helicity flip and non-flip amps

1) requires breaking of chiral symmetry m_q/E

2) phases require higher order corrections

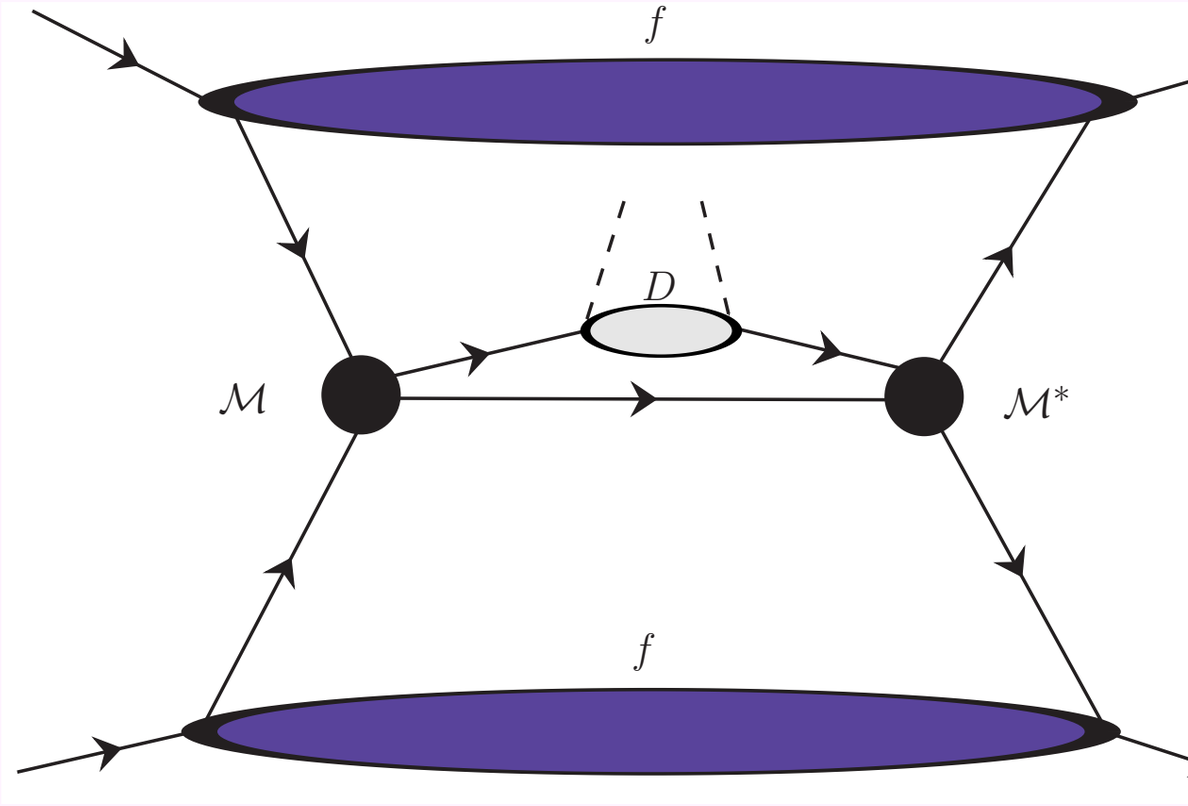
Collinear factorized QCD parton dynamics

$$\Delta\sigma^{pp^\uparrow\to\pi X} \sim f_a \otimes f_b \otimes \Delta\hat{\sigma} \otimes D^{q\to\pi}$$

$$\Delta\hat{\sigma} \equiv \hat{\sigma}^\uparrow - \hat{\sigma}^\downarrow$$

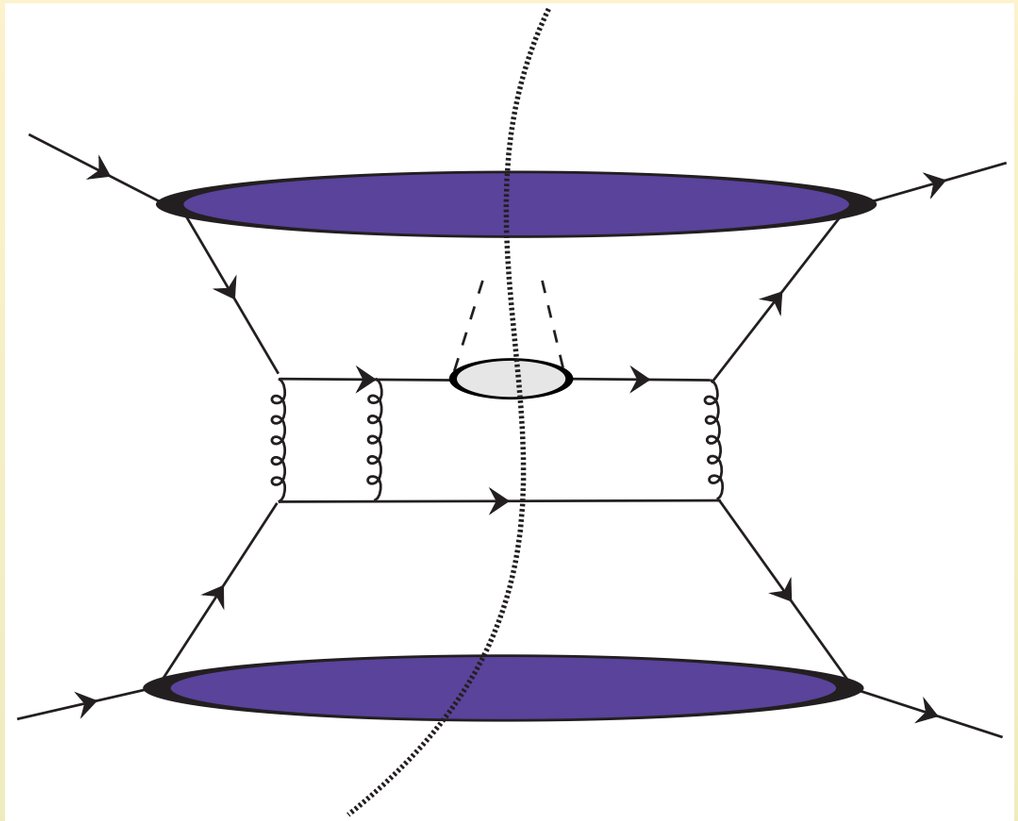
$$|\uparrow / \downarrow\rangle = (|+\rangle \pm i|-\rangle)$$

$$\hat{a}_N = \frac{\hat{\sigma}^\uparrow - \hat{\sigma}^\downarrow}{\hat{\sigma}^\uparrow + \hat{\sigma}^\downarrow} \sim \frac{\mathrm{Im}\left(\mathcal{M}^{+*}\mathcal{M}^-\right)}{|\mathcal{M}^+|^2 + |\mathcal{M}^-|^2}$$

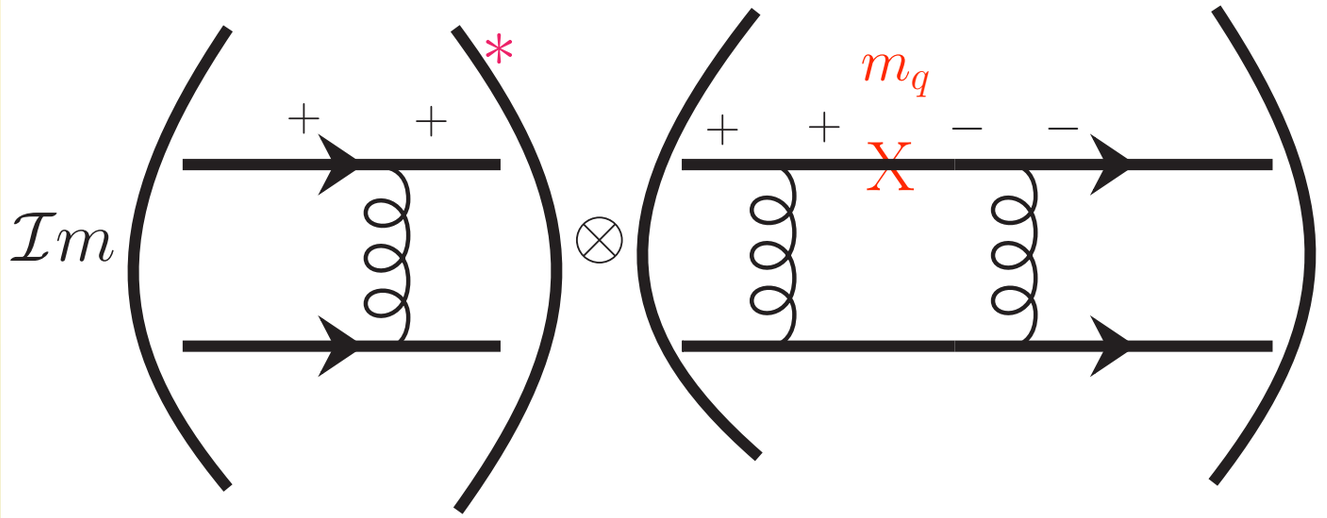


⋆ **TSSA requires relative phase btwn *different* helicity amps**

Factorization Theorem & SSAs at Partonic level



$$\Delta\hat{\sigma} \sim \mathcal{I}m[M^*{}_+ M_-]$$



- **Born amps are real -- need "loops"----> phases**
- **QCD interactions conserve helicity up to corrections** $\mathcal{O}\left(\frac{m_q}{E_q}\right)$

Twist three and trivial in chiral limit

$A_N \propto \frac{m_q}{E}\alpha_s$ at the partonic level

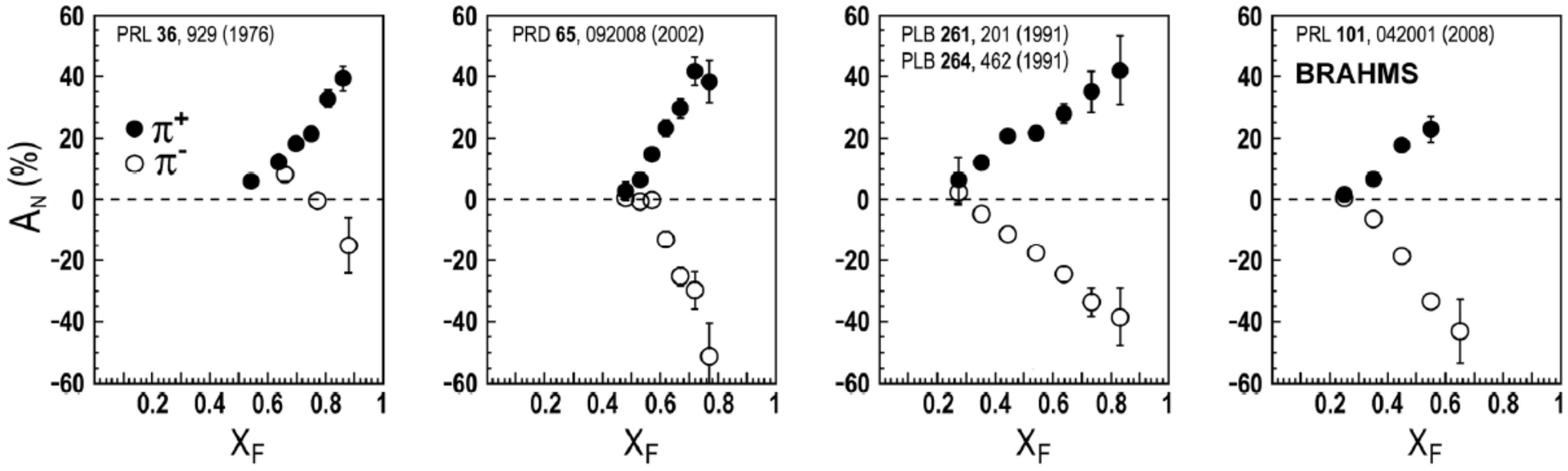
Kane & Repko, PRL: 1978

Large Transverse Polarization in Inclusive Reactions

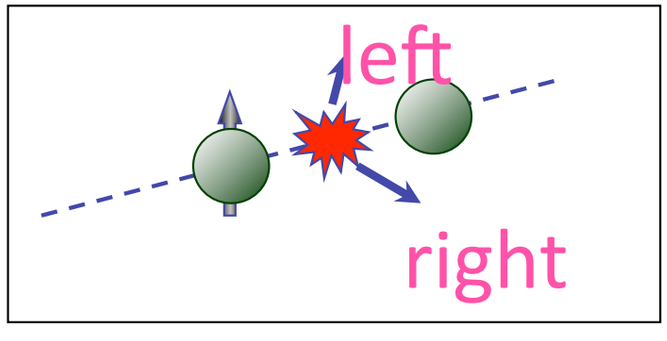
Transverse Single-Spin Asymmetries: From Low to High Energies!

BRAHMS

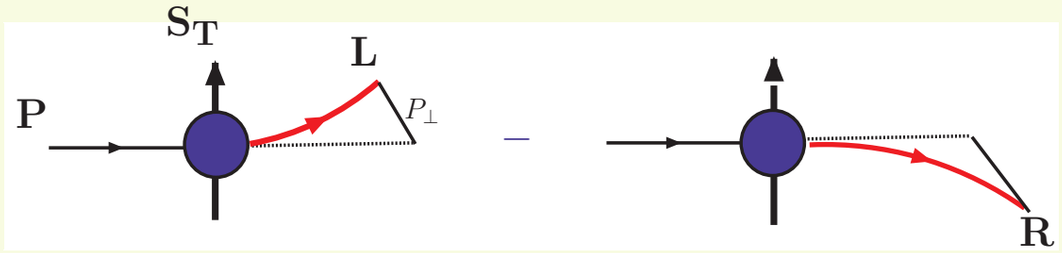
p_{beam}=12 Gev/c	p_{beam}=22 Gev/c	p_{beam}=200 Gev/c	
ANL	BNL	FNAL	RHIC
$\sqrt{s}$=4.9 GeV	$\sqrt{s}$=6.6 GeV	$\sqrt{s}$=19.4 GeV	$\sqrt{s}$=62.4 GeV
← Fixed target →			Collider

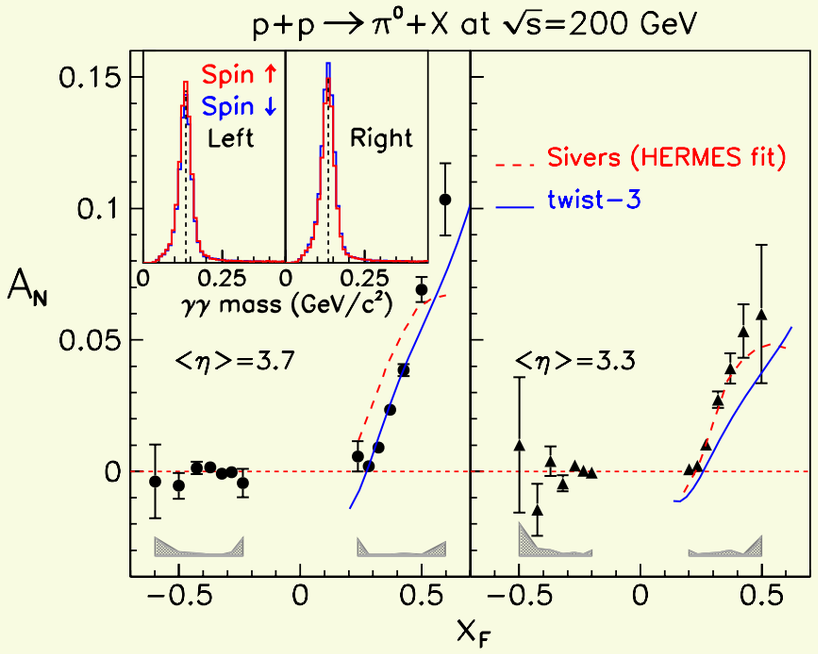


$$x_F = 2p_{long}/\sqrt{s}$$



Modern Era Transverse SSA's at $\sqrt{s}$ = 62.4 & 200 GeV at RHIC





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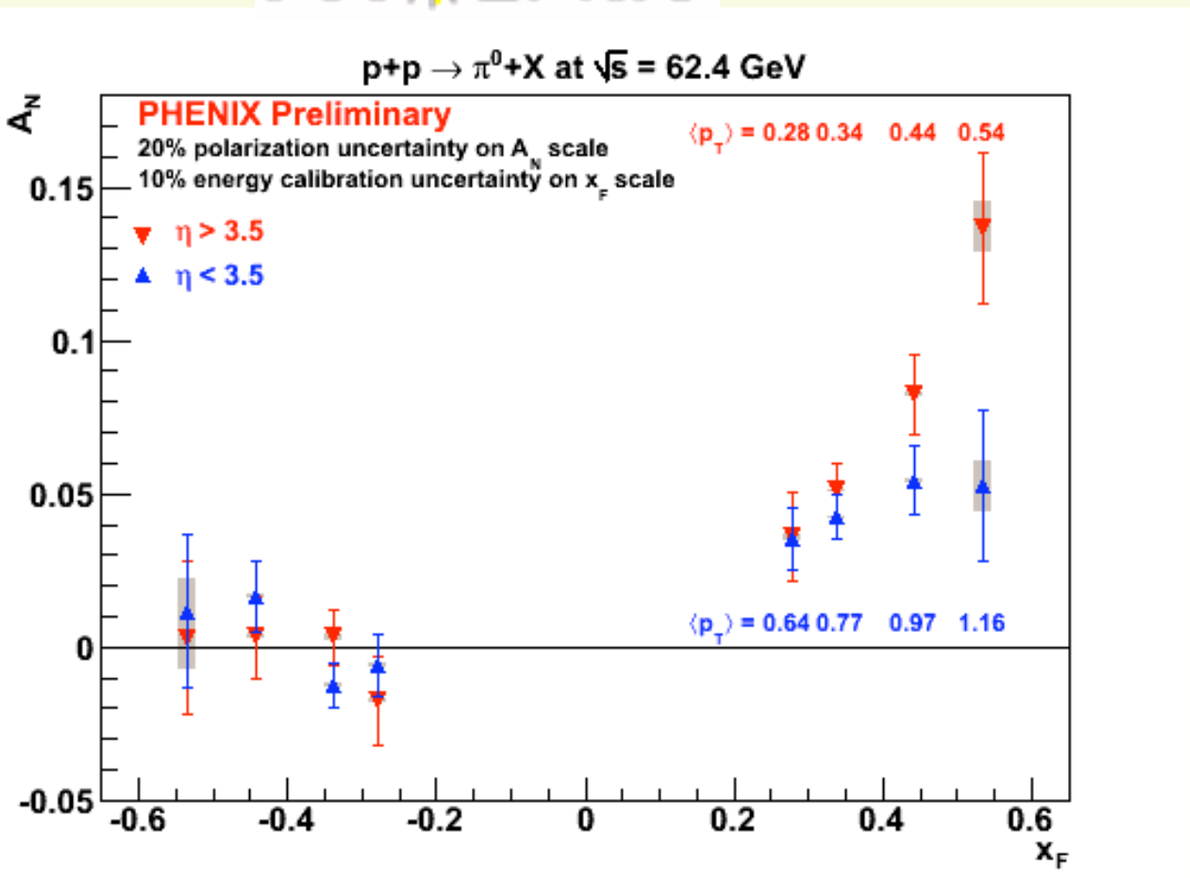
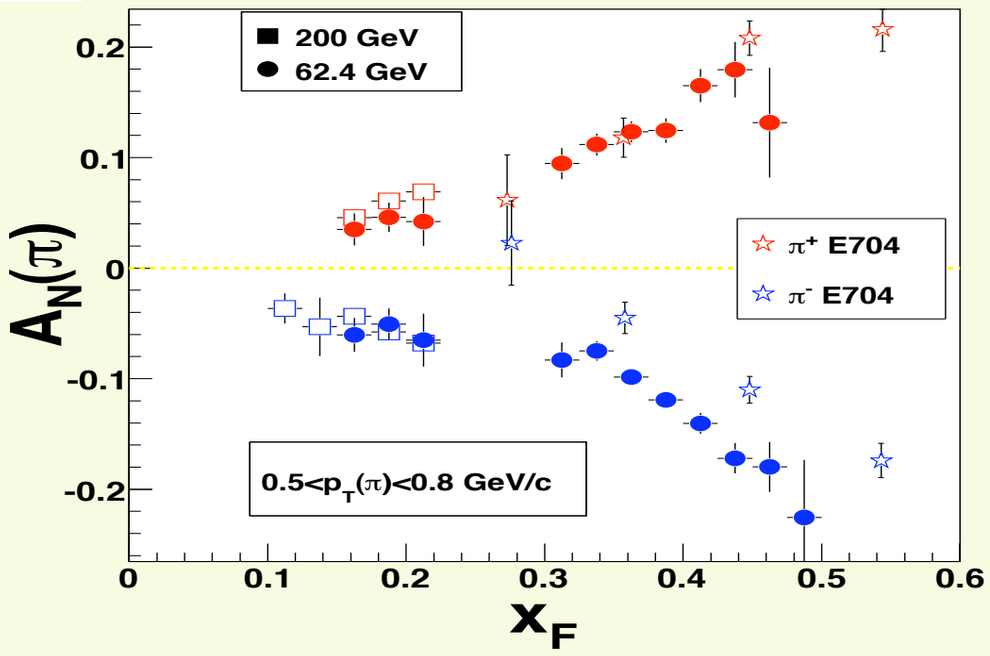


BRAHMS

PRL101, 042001 (2008)



Polarization in inclusive Λ and $\overline{\Lambda}$ production at large p_T

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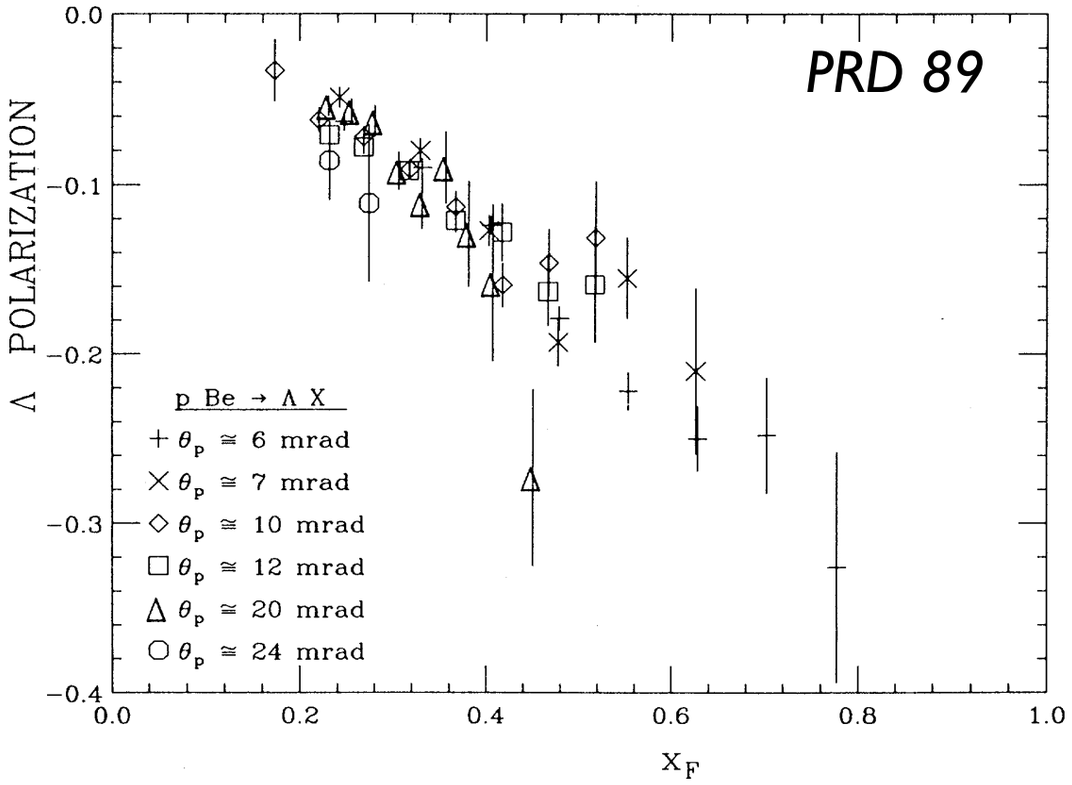

FIG. 4. The Λ polarization is shown as a function of x_F for all production angles. Over this range of production angles and within experimental uncertainties, the polarization is angle (or p_T) independent.

$$P_\Lambda = \frac{\sigma^{pp\to\Lambda^\uparrow X} - \sigma^{pp\to\Lambda^\downarrow X}}{\sigma^{pp\to\Lambda^\uparrow X} + \sigma^{pp\to\Lambda^\downarrow X}}$$

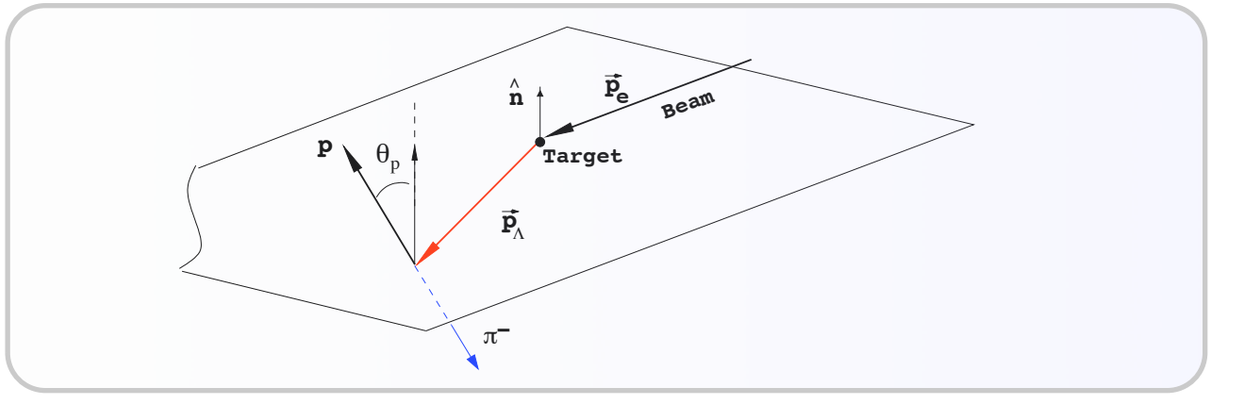

FIG. 1: Schematic diagram of inclusive Λ production and decay. The angle θ_p of the decay proton with respect to the normal $\hat{n}$ to the production plane is defined in the Λ rest frame.

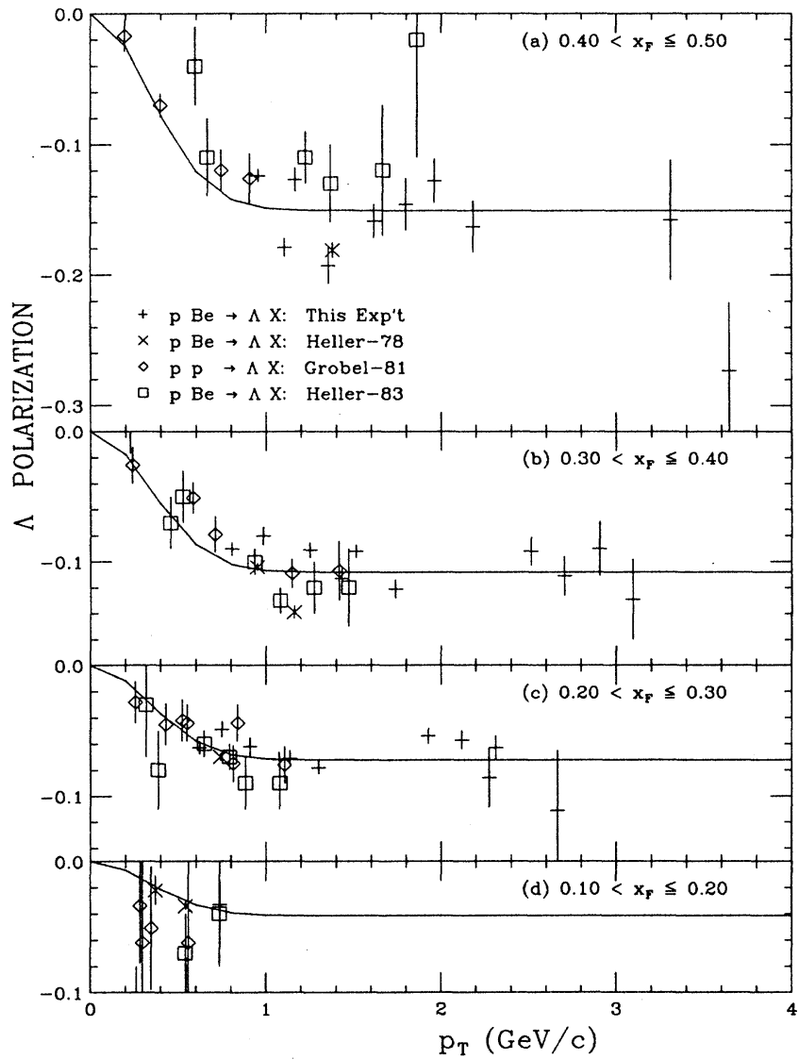

FIG. 5. Inclusive Λ polarization as a function of p_T with x_F restricted to each of the four ranges indicated in (a)–(d). The data plotted are from this experiment and Refs. 3, 23, and 24. All four experiments used the same spectrometer and measurement techniques. Errors when not shown are smaller than the points. The lines are a fit to the p+Be data using Eq. (9). Note

Comment

- Largest TSSA least understood