The spin-directed momentum transfer model of polarized hyperon production

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(presented by S.Liuti)

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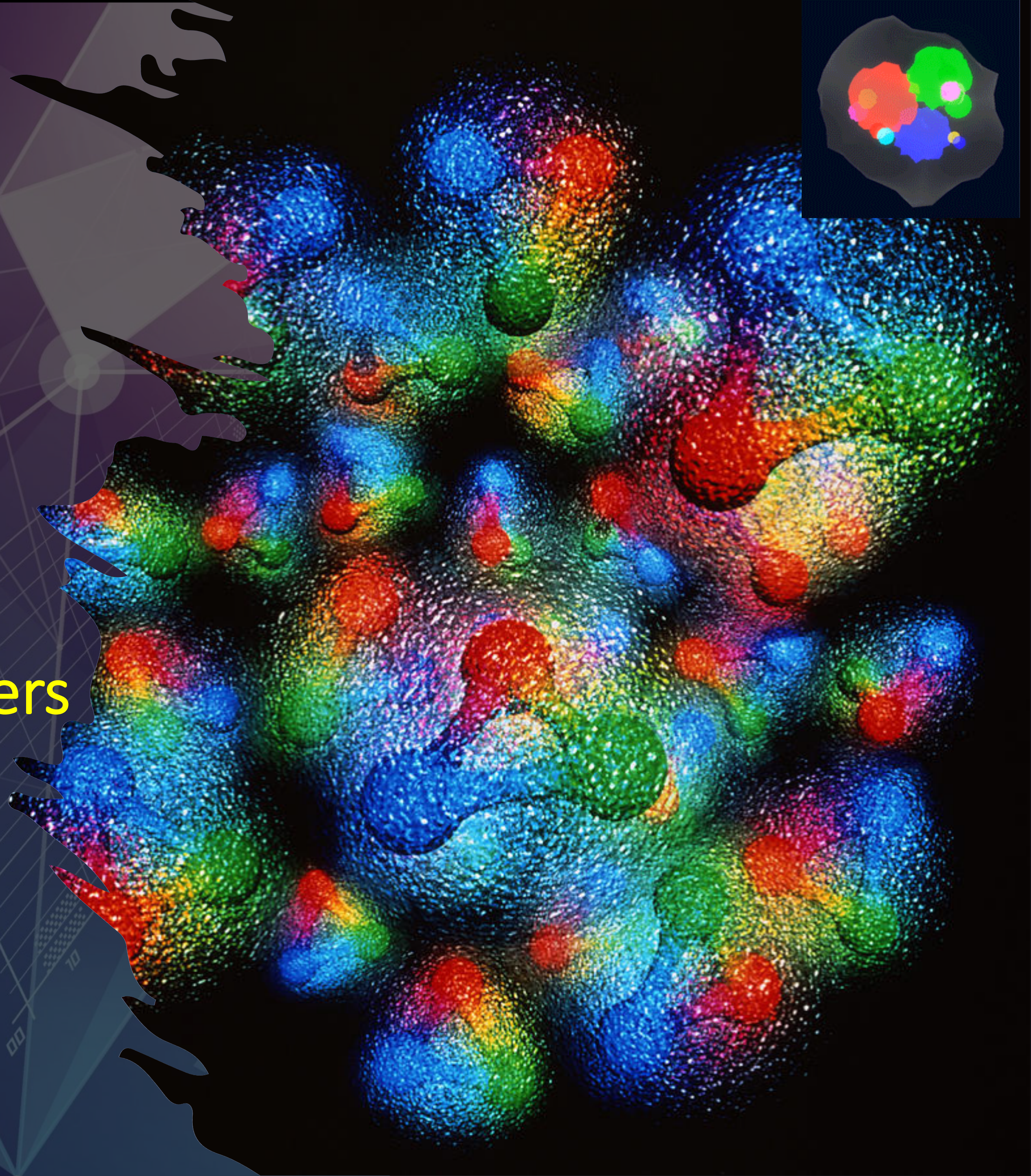

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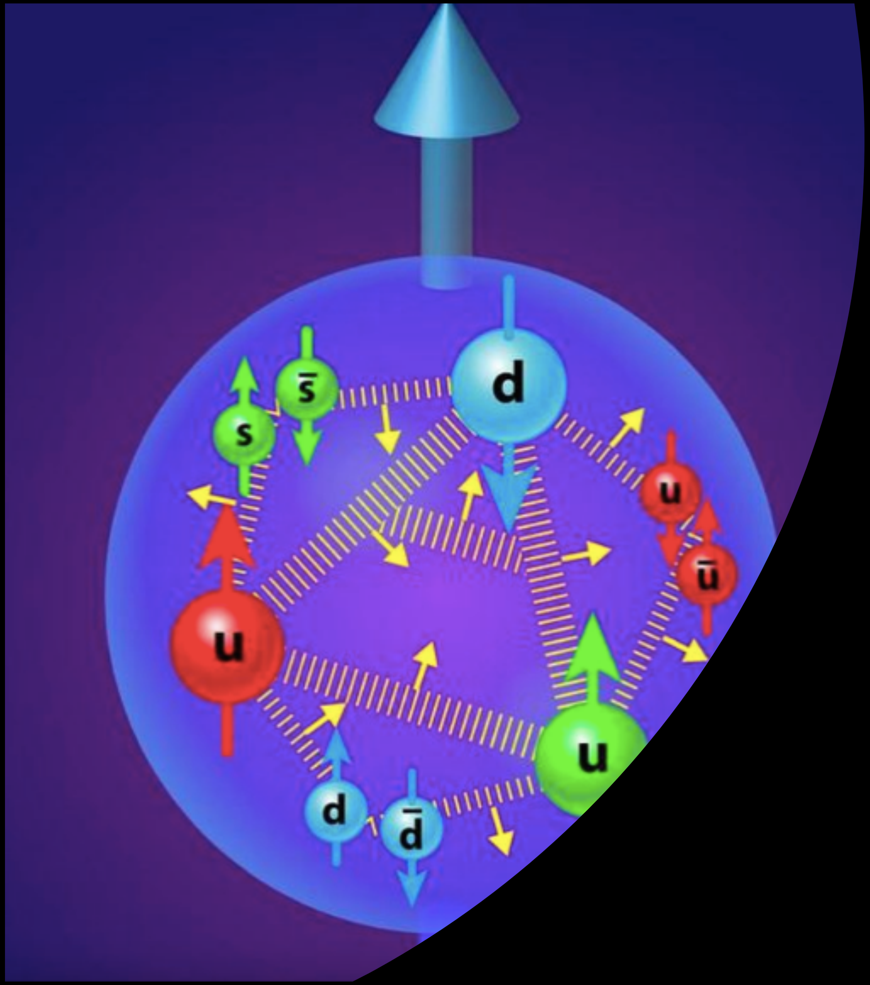
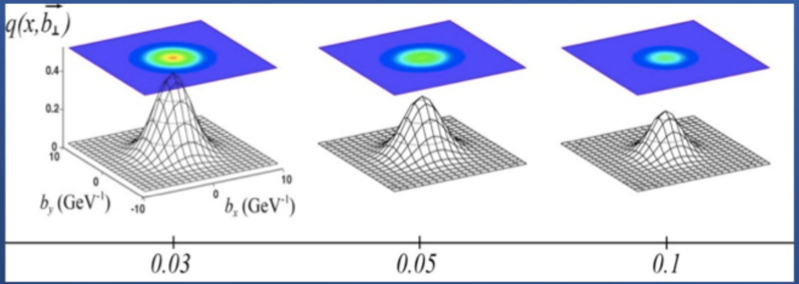
- The proton spin remains a mystery
- The flavor composition of the nucleon form factor remains a mystery
- The perspective of the EIC has opened more possibilities for studying different types exclusive experiments beyond DVCS-type from proton targets
- These new channels will allow us to understand nucleon spin is divided between gluons and orbital angular momentum

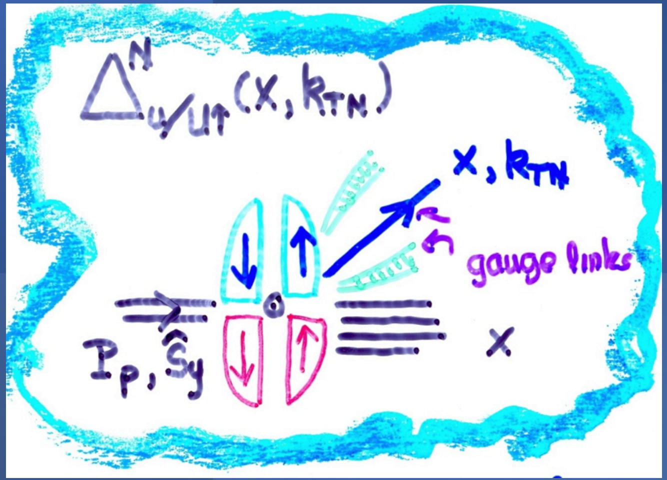


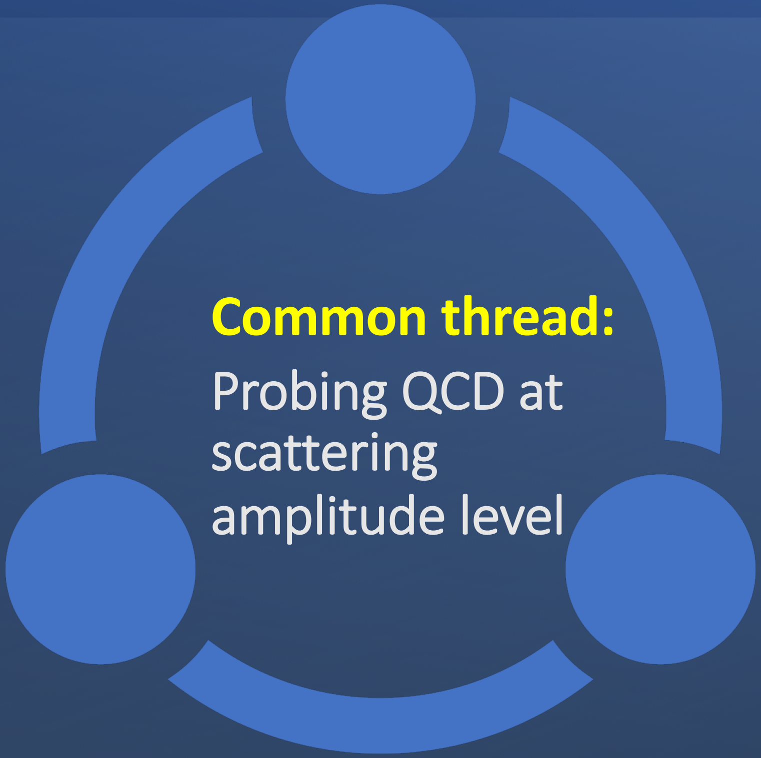
- How is hadronic spin generated as a collective phenomenon from the proton/neutron constituents?
- What is the role of gluons?
- How do we test this dynamics?

GPDs



Spin-directed momentum transfers (D. Sivers)

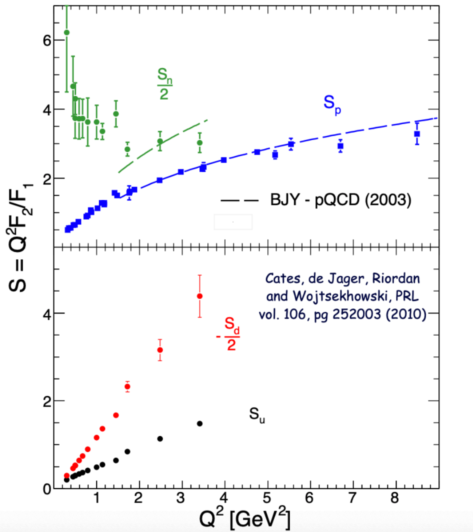




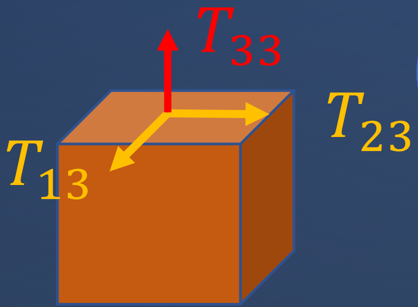
Common thread:

Probing QCD at scattering amplitude level

Flavor form factors



Cates, de Jager, Riordan and Wojtsekhowski, PRL vol. 106, pg 252003 (2010)



Energy Momentum Tensor

This means quark and gluon distributions

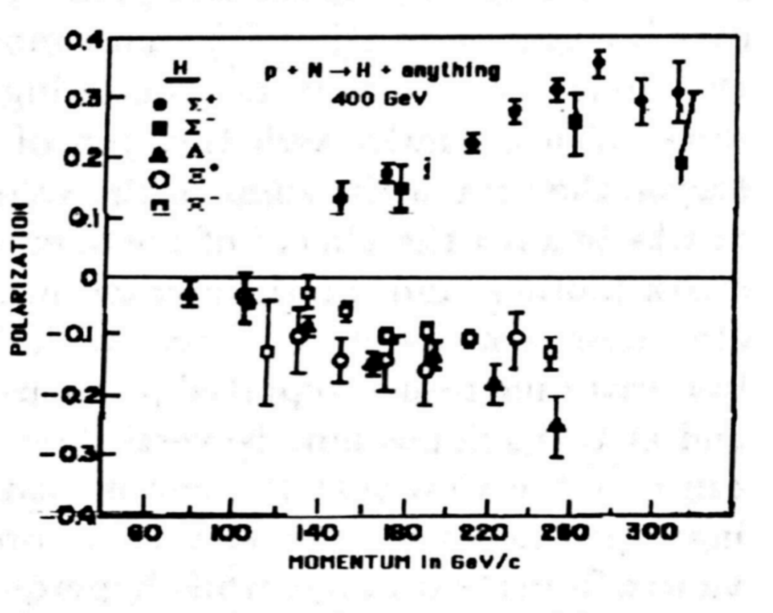
Transverse Polarized Hyperon Production

$A + B \rightarrow C^{\uparrow} + X$

Experiments on hyperon production performed during more than three decades have shown that the hyperon polarization is significant

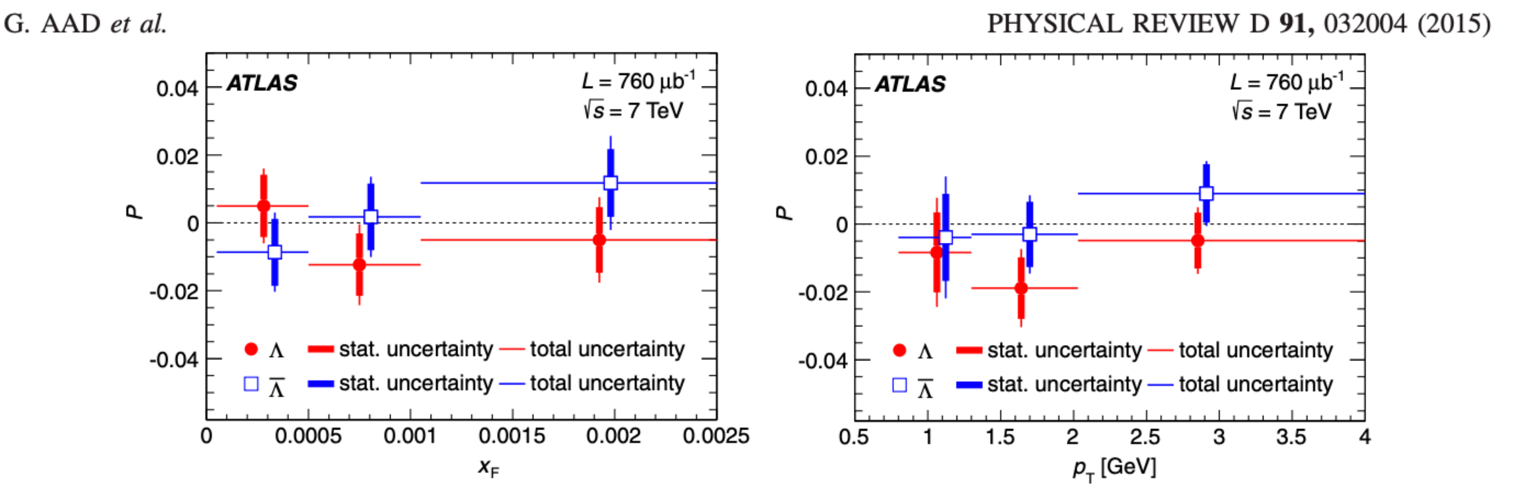
From BNL, Fermilab ….

P_H



$H = \Lambda, \Sigma, \Xi, \ldots$

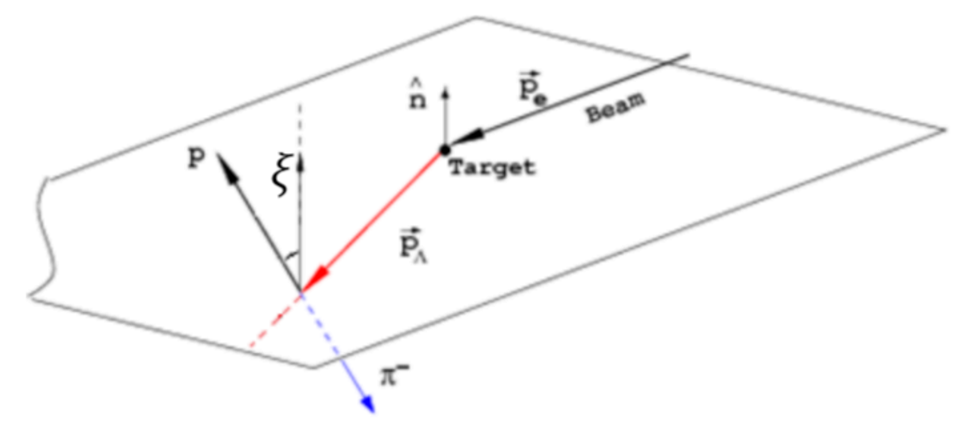
To the LHC ….


G. AAD *et al.* PHYSICAL REVIEW D **91,** 032004 (2015)

P_Λ=-0.010 $\pm$0.005

$$\Lambda \to p\pi^-$$

Due to their self-analyzing weak decay, the polarization of Λ hyperons polarization P_Λ can be accessed by inspecting the angular distribution of the protons produced in the decay



$$\frac{1}{N}\frac{dN}{d\cos\xi} = 1 + \alpha_\Lambda P_\Lambda \cos\xi$$

SSA

$$P_\Lambda = \frac{d\sigma^{lp\to l'\Lambda^\uparrow X} - d\sigma^{lp\to l'\Lambda^\downarrow X}}{d\sigma^{lp\to l'\Lambda^\uparrow X} + d\sigma^{lp\to l'\Lambda^\downarrow X}}$$

$$P_\Lambda = \frac{\Im m(\mathcal{M}^*_{nonflip}\mathcal{M}_{flip})}{\sigma_{unpol}}$$

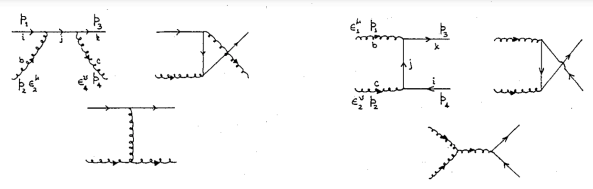
1) The flip amp is different from 0
2) The non-flip amp has opposite phase to the flip one

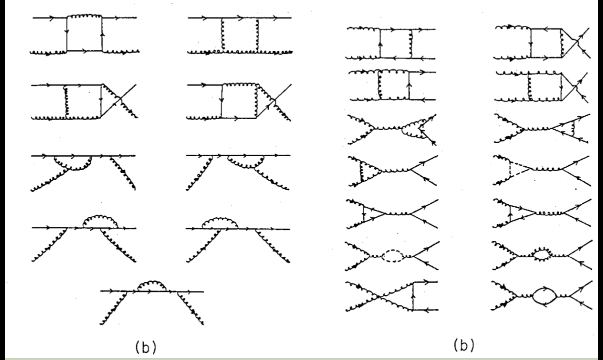
Which mechanisms can generate the quantum interference that can produce transverse polarization?

1. The perturbative approach

Dharmaratna, Goldstein ‘90’s

- Hard scattering of partons
- gluon fusion produces a polarized s quark





The polarization depends linearly on the quark mass → its value increases for heavy quarks

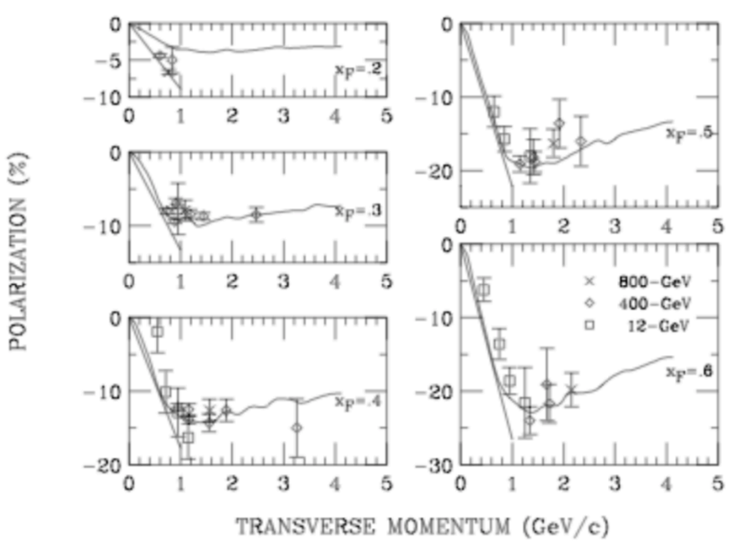
$$\mathcal{P} = \alpha_s \frac{m(p^2 - k^2\cos^2\theta)}{24k\,\sin\theta D}\left((N_1+N_2)Y_+ + (N_1-N_2)Y_- + N_3\ln\frac{p-k}{p+k} + N_4 + 18k^3\sin^2\theta\cos\theta(\Sigma_1+\Sigma_2)\right)$$

To make quantitative predictions the model needs to be improved with a semiclassical recombination mechanism

1) x_F of quark is smaller than experimental one but gets boosted by rescaling from non perturbative mechanism

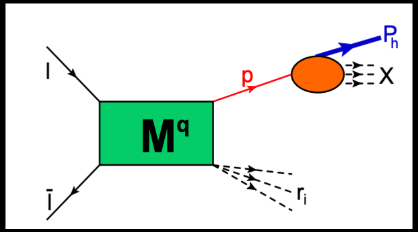
2) It works in the assumption of TMD factorization

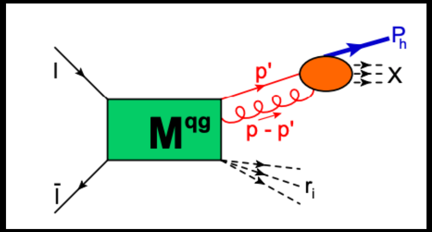
3) It contributes to the current fragmentation region



2. Twist three interference from quark current fragmentation

Pitonyak et al., 2019





1) A phase difference is introduced by the twist three amplitude for the current fragmentation

2) It works in the assumption of TMD factorization

3) It contributes to the current fragmentation region

Kane Pumplin Repko (KPR) Factorization

In the limit $m_q \rightarrow 0$ there exists within QCD perturbation theory a symmetry that is strongly broken in the nonperturbative sector of the theory.

The existence of this symmetry ensures that all parity-even single spin asymmetries in hard-scattering processes can be absorbed into the transverse-momentum dependence of the fragmentation functions.

D. Sivers

$$A_N = \alpha_S \frac{m_q}{\sqrt{s}} f_{TN}(\theta_{CM}, k_{TN})$$

G. Kane, J. Pumplin and W. Repko, PRL **41** (1978)

$$k_{TN} = \mathbf{k}_C \cdot (\mathbf{s} \times \mathbf{p_A})$$

Spin-directed momentum transfer

3. Target fragmentation through $^3P_0$ mechanism

Sivers (2011)
Goldstein, SL, Sivers (2023)

Based on KPR factorization: Spin flip dynamics generating final hadron spin is in the target fragmentation function (fracture function)

Spin-directed momentum transfer framework allows us to define kinematic variables involved in the underlying spin-orbit dynamics.

To produce a net hyperon transverse spin the quark orbital angular momentum between the initial and final states must differ by one unit.

Four distinct spin-directed momentum transfer configurations/polarized fracfuns

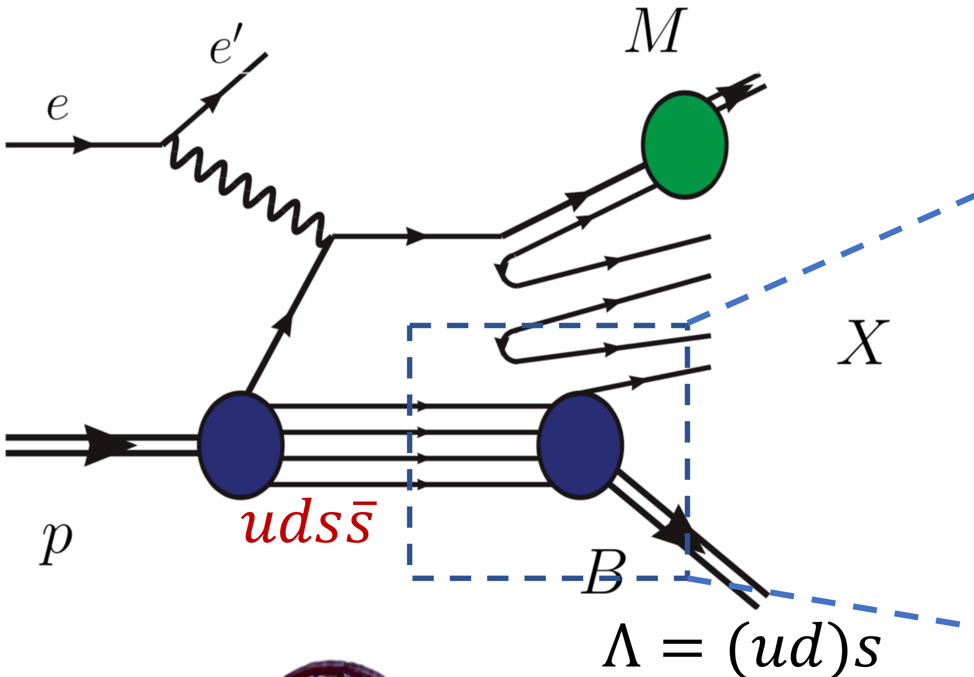
$$\Delta M^{q}_{B,p^\uparrow}(x, k_{TN}; z, p^B_T)$$

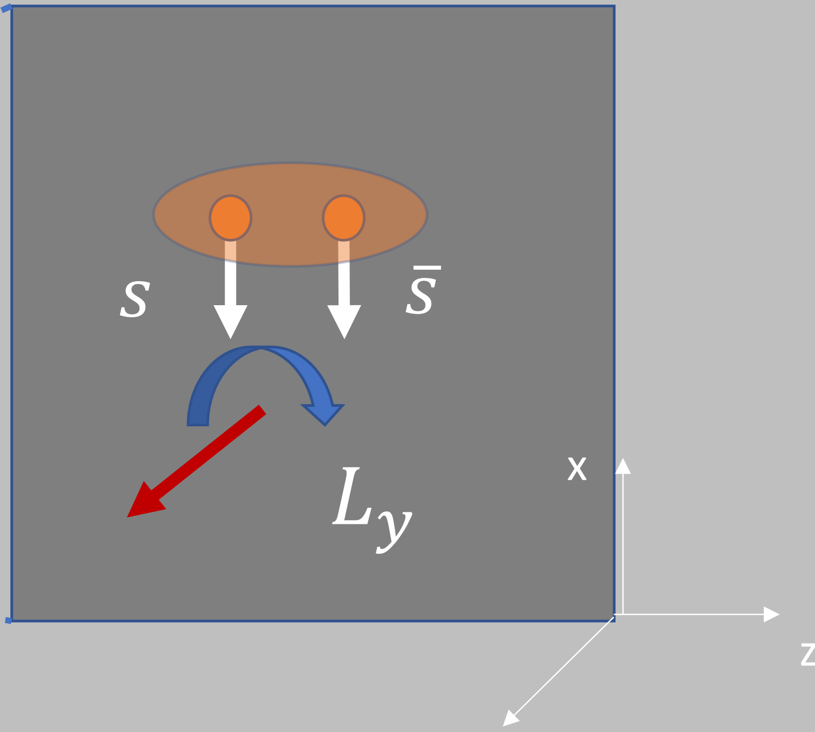
$$\Delta M^{q^\uparrow}_{B,p^\uparrow}(x, k_T; z, p^B_{TN})$$

$$\Delta M^{q}_{B^\uparrow,p^\uparrow}(x, k_T; z, p^B_{TN})$$

$$\Delta M^{q^\uparrow}_{B^\uparrow,p}(x, k_{TN}; z, p^B_T)$$

String breaking mechanism






D. Sivers

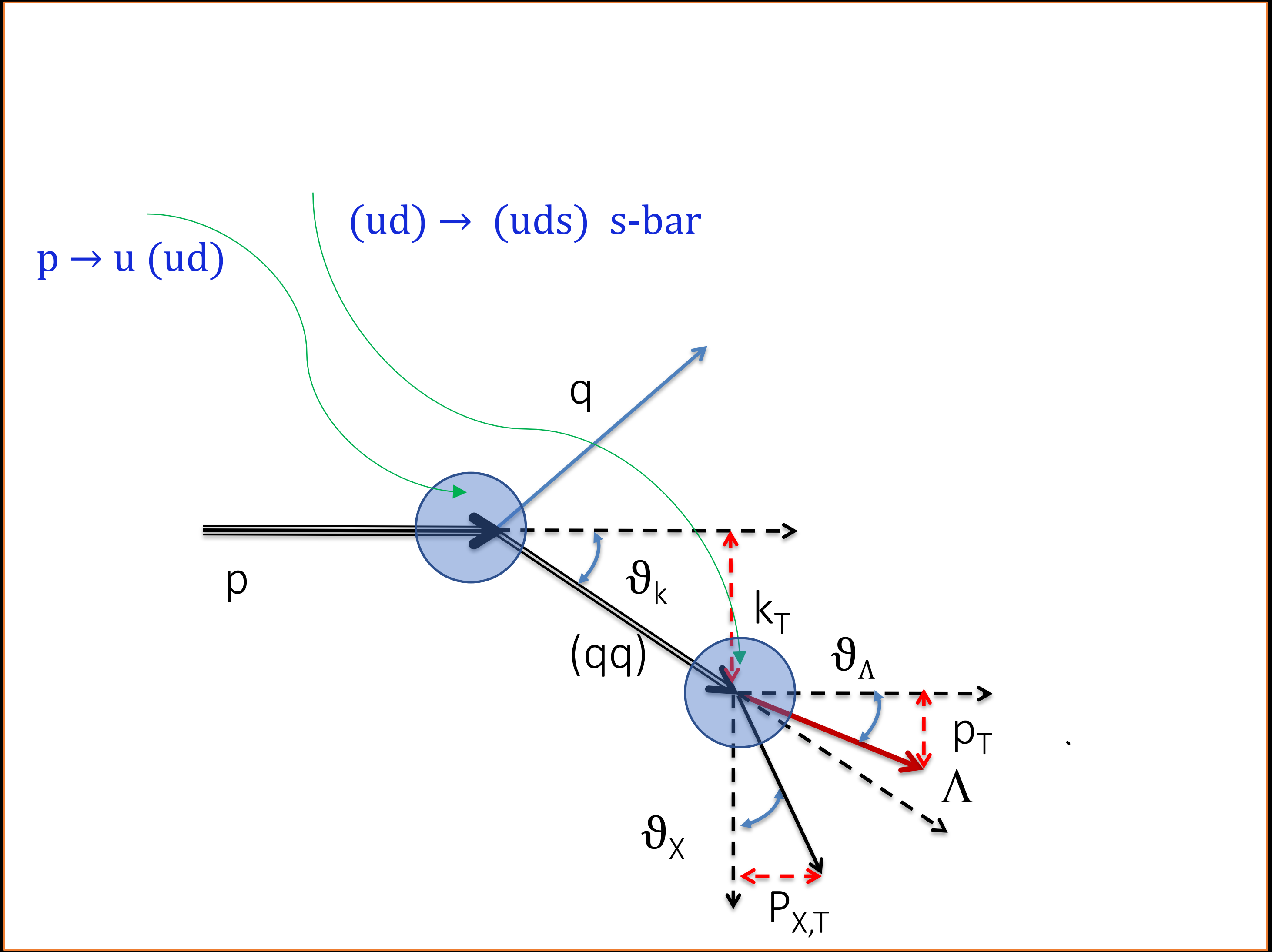
The (ud) diquark is produced with spin S = 0

As the flux tube stretches an ss¯-pair is produced with transverse momentum, k_T

The ss¯- pair have their spins aligned to balance the OAM

Rotational motion generates the breaking of the string

Modeling the $^3P_0$ string breaking mechanism: Double Spectator Model



Double Spectator Model

$$f_{\Lambda_H\Lambda_\gamma,\Lambda} = \sum_{\lambda} g_{\lambda}^{\Lambda_\gamma} \otimes \mathcal{F}^{\Lambda_H}_{\Lambda\lambda}(P,k)$$

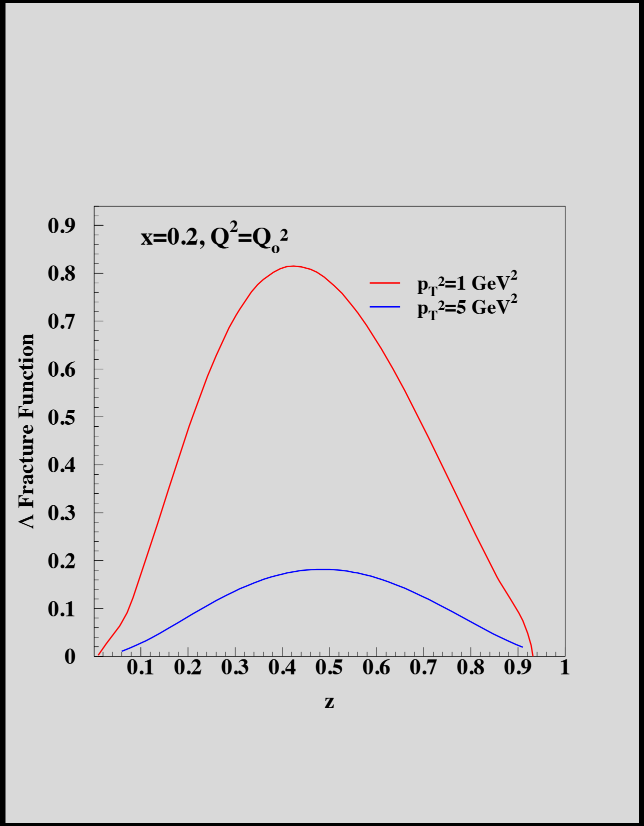
Fracture function
(see F. Benkmothar talk)

$$\mathcal{F}^{\Lambda_H}_{\Lambda,\lambda}(x,k_T,z,p_T,Q^2) = A_{\lambda,\Lambda}\sum_{\Lambda_X} B^{\Lambda_H}_{\Lambda_X}$$

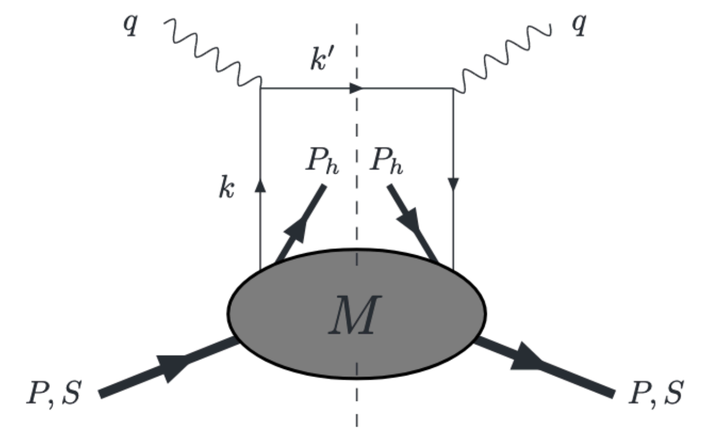
$$A_{\Lambda,\lambda_q} =| \phi_{\lambda_q,\Lambda}(k,p) |^2$$

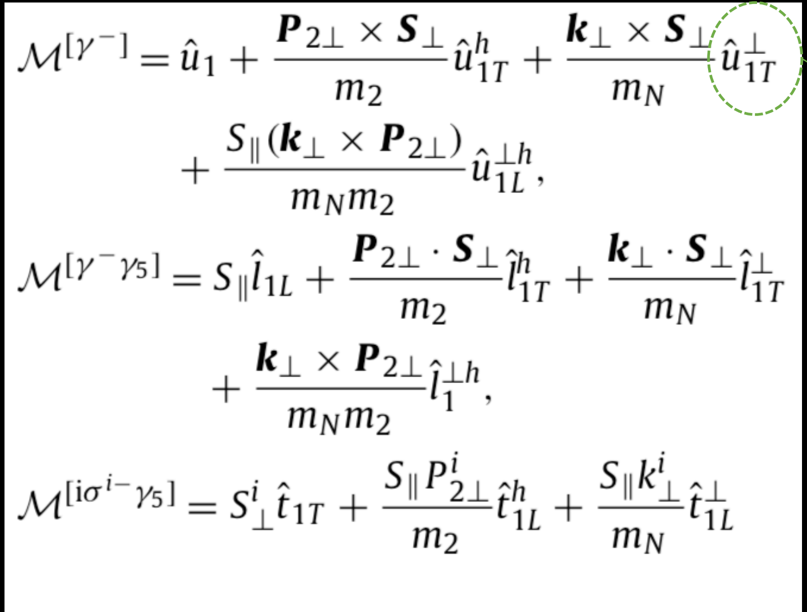
$$\phi_{\Lambda,\lambda_q}(k,p) = \Gamma(k)\frac{\bar{u}(k,\lambda_q)U(p,\Lambda)}{(k^2-m^2)((p-k)^2-M_{qq}^2)}$$

$$B^{\Lambda_B}_{\Lambda_X} = \tilde{\phi}^{*}_{\Lambda_X,\Lambda_B}(p_X,p_B)\tilde{\phi}_{\Lambda_X,\Lambda_B}(p_X,p_B)$$


x=0.2, Q^2=Q_o^2
p_T^2=1 GeV^2
p_T^2=5 GeV^2
Λ Fracture Function
z
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Target fragmentation cross section

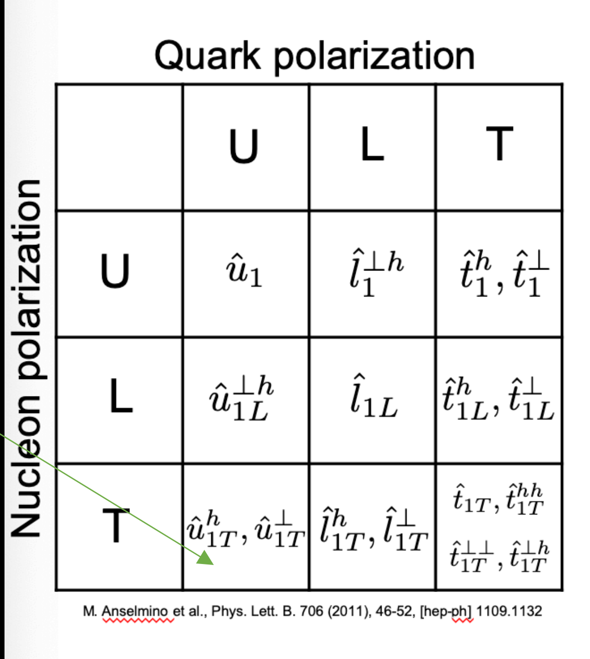




$$\mathcal{M}^{[\gamma^-]} = \hat{u}_1 + \frac{\boldsymbol{P}_{2\perp} \times \boldsymbol{S}_\perp}{m_2}\hat{u}_{1T}^{h} + \frac{\boldsymbol{k}_\perp \times \boldsymbol{S}_\perp}{m_N}\hat{u}_{1T}^{\perp} + \frac{S_\parallel (\boldsymbol{k}_\perp \times \boldsymbol{P}_{2\perp})}{m_N m_2}\hat{u}_{1L}^{\perp h},$$

$$\mathcal{M}^{[\gamma^-\gamma_5]} = S_\parallel \hat{l}_{1L} + \frac{\boldsymbol{P}_{2\perp} \cdot \boldsymbol{S}_\perp}{m_2}\hat{l}_{1T}^{h} + \frac{\boldsymbol{k}_\perp \cdot \boldsymbol{S}_\perp}{m_N}\hat{l}_{1T}^{\perp} + \frac{\boldsymbol{k}_\perp \times \boldsymbol{P}_{2\perp}}{m_N m_2}\hat{l}_{1}^{\perp h},$$

$$\mathcal{M}^{[i\sigma^{i-}\gamma_5]} = S_\perp^i \hat{t}_{1T} + \frac{S_\parallel P_{2\perp}^i}{m_2}\hat{t}_{1L}^{h} + \frac{S_\parallel k_\perp^i}{m_N}\hat{t}_{1L}^{\perp}$$



Quark polarization

Nucleon polarization	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^{h}, \hat{t}_1^{\perp}$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^{h}, \hat{t}_{1L}^{\perp}$
T	$\hat{u}_{1T}^{h}, \hat{u}_{1T}^{\perp}$	$\hat{l}_{1T}^{h}, \hat{l}_{1T}^{\perp}$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}$ $\hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$

M. Anselmino et al., Phys. Lett. B. 706 (2011), 46-52, [hep-ph] 1109.1132

Conclusions

- The proton is a complex, multi-body environment, characterized by vorticose motion of quarks and gluons
- We described a non perturbative QCD string breaking mechanism for polarized Λ production based on KPR factorization

In progress…

- Full calculation of fracture functions cross section
- More to develop: predictions for other hyperon, Σ, Ξ, $\ldots$polarizations and anti-Baryons
- Adding gluonic component to model