2nd QCD group meeting, NCTS
June 28, 2018

Angular distributions of pion-induced Drell-Yan process at large xF

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Outline

- Longitudinally polarized γ^*toward x_F=1
- Theoretical interpretation: higher-twist effect
- A new QCD factorization at large x_F limit
- Summary & Questions

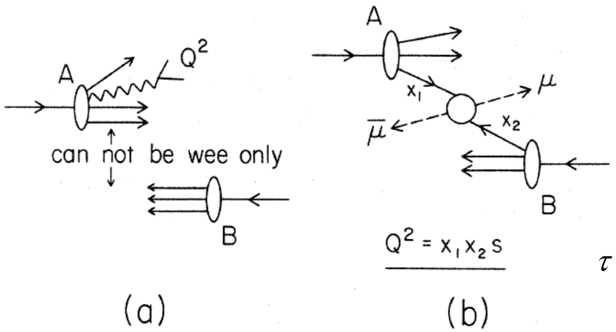
The Drell-Yan Process

S.D. Drell and T.M. Yan, PRL 25 (1970) 316

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)

On the basis of a parton model studied earlier we consider the production process of large-mass lepton pairs from hadron-hadron inelastic collisions in the limiting region, $s\to\infty$, Q^2/s finite, Q^2 and s being the squared invariant masses of the lepton pair and the two initial hadrons, respectively. General scaling properties and connections with deep inelastic electron scattering are discussed. In particular, a rapidly decreasing cross section as $Q^2/s\to 1$ is predicted as a consequence of the observed rapid falloff of the inelastic scattering structure function νW_2 near threshold.



$$\tau = \frac{Q^2}{s} = x_1 x_2$$

FIG. 1. (a) Production of a massive pair Q^2 from one of the hadrons in a high-energy collision. In this case it is kinematically impossible to exchange "wee" partons only. (b) Production of a massive pair by parton-antiparton annihilation.

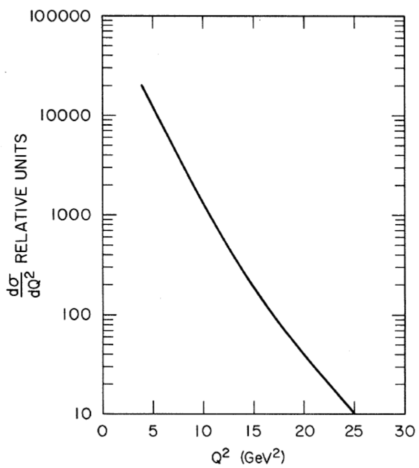
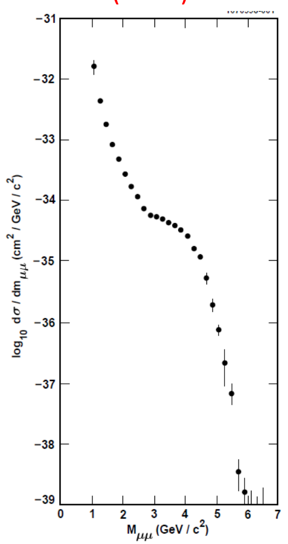


FIG. 2. $d\sigma/dQ^2$ computed from Eq. (10) assuming identical parton and antiparton momentum distributions and with relative normalization.

PRL 25 (1970) 1523



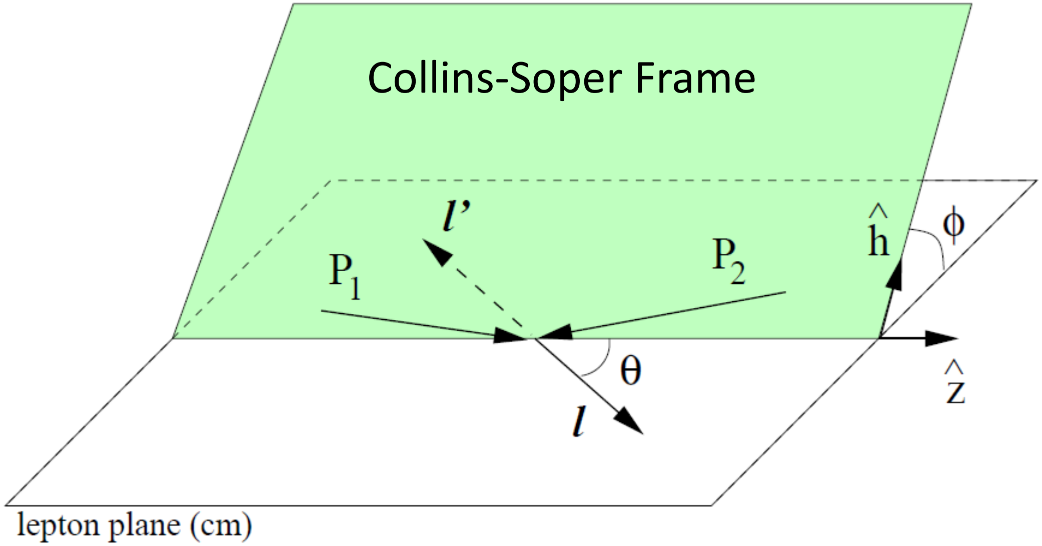
$$\frac{d\sigma}{dQ^2} = \left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(\frac{1}{Q^2}\right)\mathfrak{F}(\tau) = \left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(\frac{1}{Q^2}\right)\int_0^1 dx_1 \int_0^1 dx_2 \delta(x_1x_2-\tau)\sum_a \lambda_a{}^{-2} F_{2a}(x_1) F_{2\bar{a}}{}'(x_2),$$

Angular Distribution in the "Naïve" Drell-Yan

VOLUME 25, NUMBER 5 PHYSICAL REVIEW LETTERS 3 AUGUST 1970

(3) The virtual photon will be predominantly transversely polarized if it is formed by annihilation of spin-$\frac{1}{2}$ parton-antiparton pairs. This means a distribution in the di-muon rest system varying as $(1+\cos^2\theta)$ rather than $\sin^2\theta$ as found in Sakurai's[10] vector-dominance model, where θ is the angle of the muon with respect to the time-like photon momentum. The model used in Fig.

Angular Distributions of Lepton Pairs



$$\lambda = \frac{2-3A_0}{2+A_0}$$

$$\mu = \frac{2A_1}{2+A_0}$$

$$\nu = \frac{2A_2}{2+A_0}$$

$$\frac{d\sigma}{d\Omega} \propto (1+\lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi)$$

$$\propto [(1+\cos^2\theta) + \frac{A_0}{2}(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{A_2}{2}\sin^2\theta\cos 2\phi]$$

$q\bar{q}$ annilation parton model: O(α_s^0) λ=1, μ=ν=0; $A_0 = A_2 = 0$

pQCD: O(α_s^1), ; $1-\lambda-2\nu = \frac{4(A_0-A_2)}{2+A_0} = 0$; $A_0 = A_2$

Lam-Tung Relation [PRD 18 (1978) 2447]

Angular Distribution

I.R. Kenyon, Rep. Prog. Phys. 45 (1982) 1261

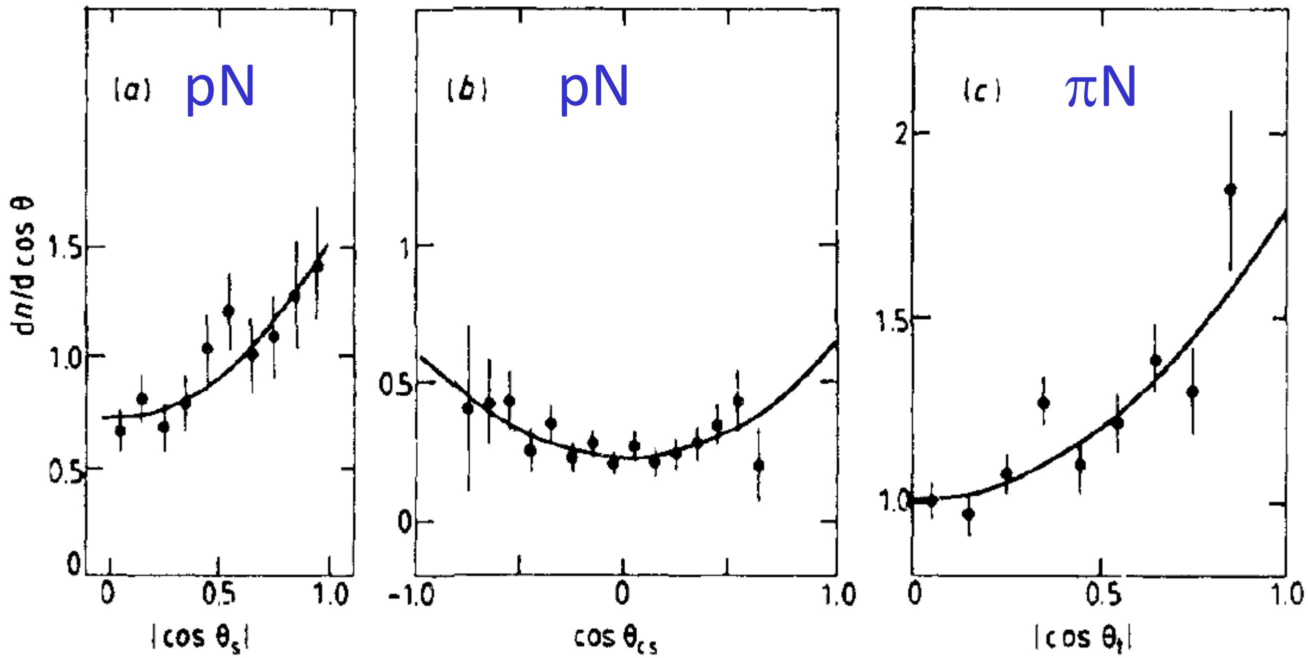


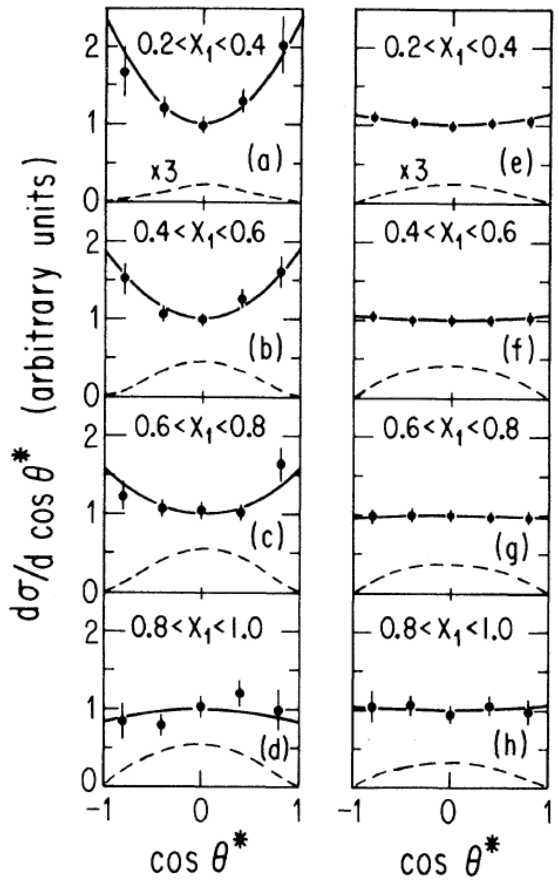
Figure 17. Measurements of the decay angular distribution of lepton pairs by Kourkoumelis *et al* (1980), Antreasyan *et al* (1980) and Badier *et al* (1980a). Fits to the form $1+\alpha\cos^2\theta$ are shown as full curves and are discussed in the text. (*a*) ISR ABCS, $4.5 < M < 8.7$ GeV, (*b*) ISR CHFMNP, $6 < M < 8$ GeV, (*c*) NA3, π^- 200 GeV, $4 < M < 6$ GeV, $p_t < 1$ GeV.

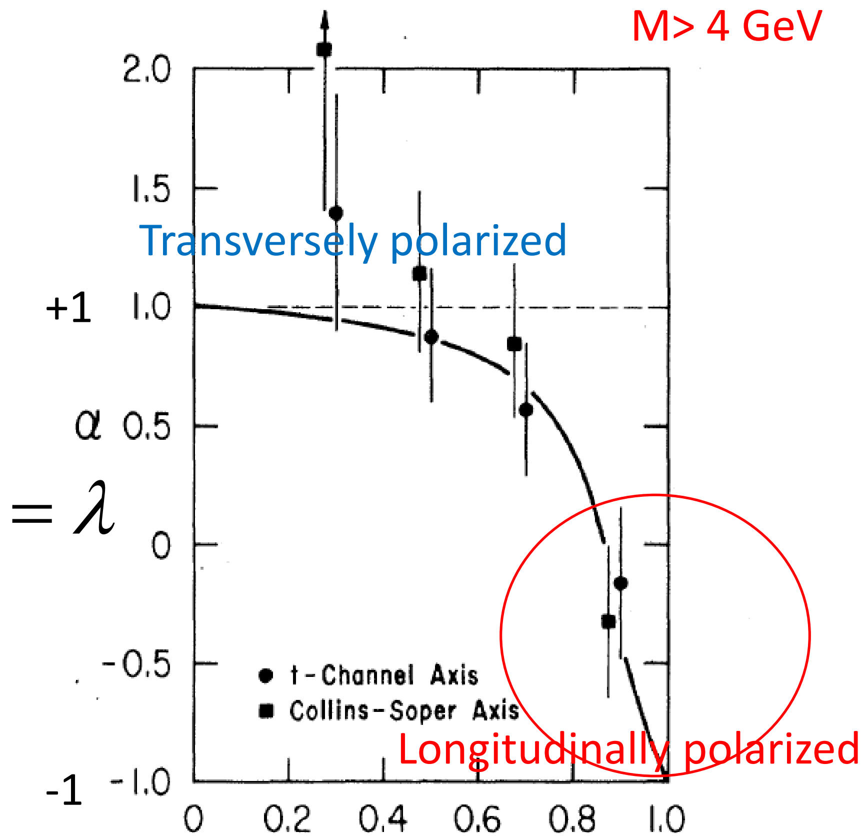
$$d\sigma(\Omega) \propto (1+\cos^2\theta)$$

CIP (PRL 43, 1219 (1979))

225 GeV pion-

M> 4 GeV

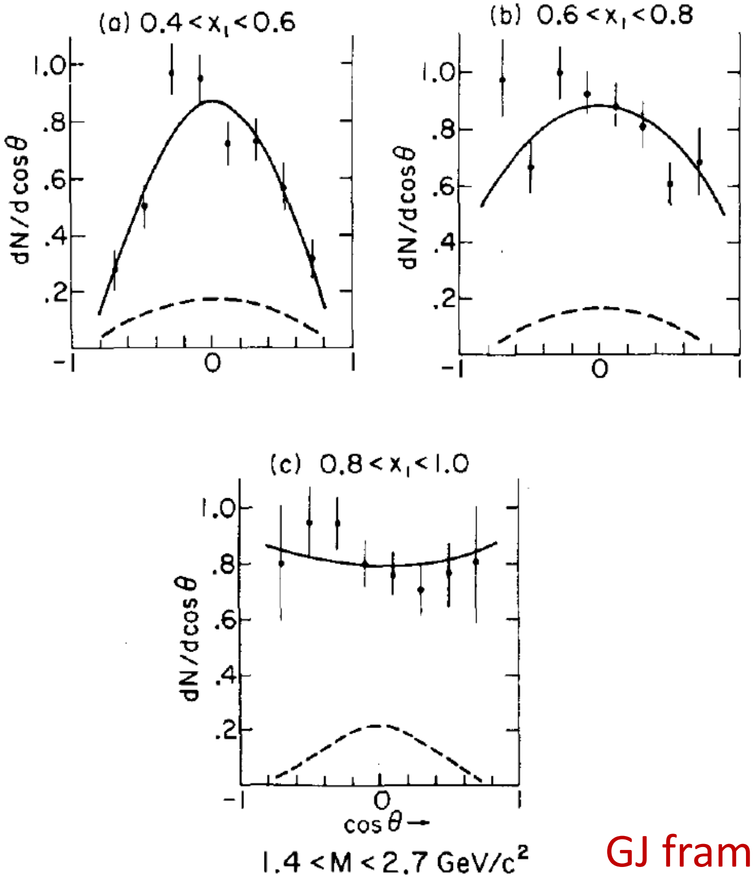




x_π

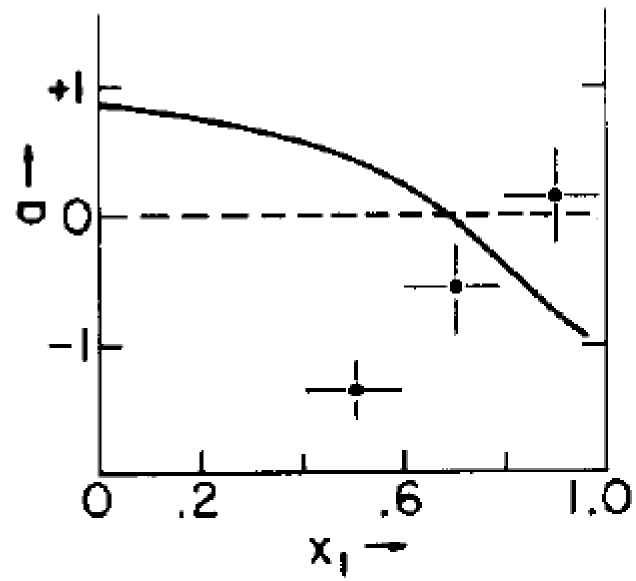
$\cos\theta$ GJ frame

Youngquist et al. (PLB 95, 457 (1980))



22 GeV pion-

1.4<M<2.7 GeV



GJ frame

NA3 (ZPC 11, 195 (1981))

150 GeV pion-

M> 4.5 GeV

$$d\sigma \propto (1-x_1)^2(1+\cos^2\theta)+\frac{4}{9}\frac{P_T^2}{M^2}\sin^2\theta + \frac{2}{3}\frac{P_T}{M}(1-x_1)\sin 2\theta\cos\phi \qquad (6)$$

which is expected to be true only at large x_1, $(x_1 \to 1)$ in the Gottfried-Jackson frame.

$$\frac{d\sigma}{dx_1\, d\cos\theta\, d\phi} = P + QH + RH^2$$

with

$$P=(1-x_1)^2(1+\cos^2\theta)$$

$$Q=\frac{P_T}{M}(1-x_1)\sin 2\theta\cos\phi$$

$$R=\frac{P_T^2}{M^2}\sin^2\theta .$$

From (6), H results to be $H=2/3$ when $x_1 \to 1$. From our

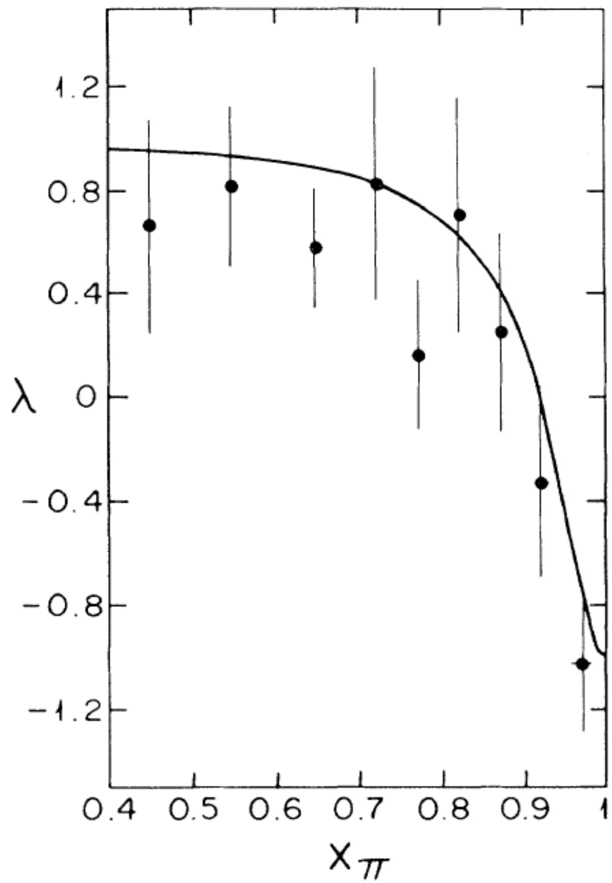
If higher-twist effect exists, H= $\frac{2}{3}$ when $x_1 \to 1$.

$H=0.40 \pm 0.10$ for $x_1 > 0.7$ (2900 events)
$H=0.20 \pm 0.10$ for $x_1 > 0.85$ (770 events).

GJ frame

As can be seen, this result is not compatible with the predicted value, and the variation of H as a function of x_1 seems to exclude that $H \to 2/3$ when $x_1 \to 1$.

CIP (PRL 55, 2649 (1985))



80 GeV pion-

M> 4 GeV

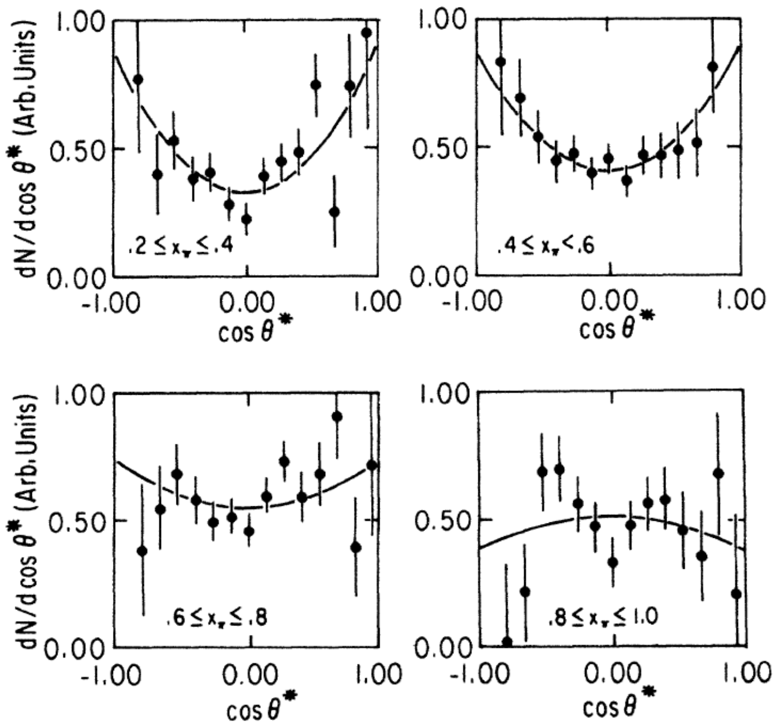
GJ frame

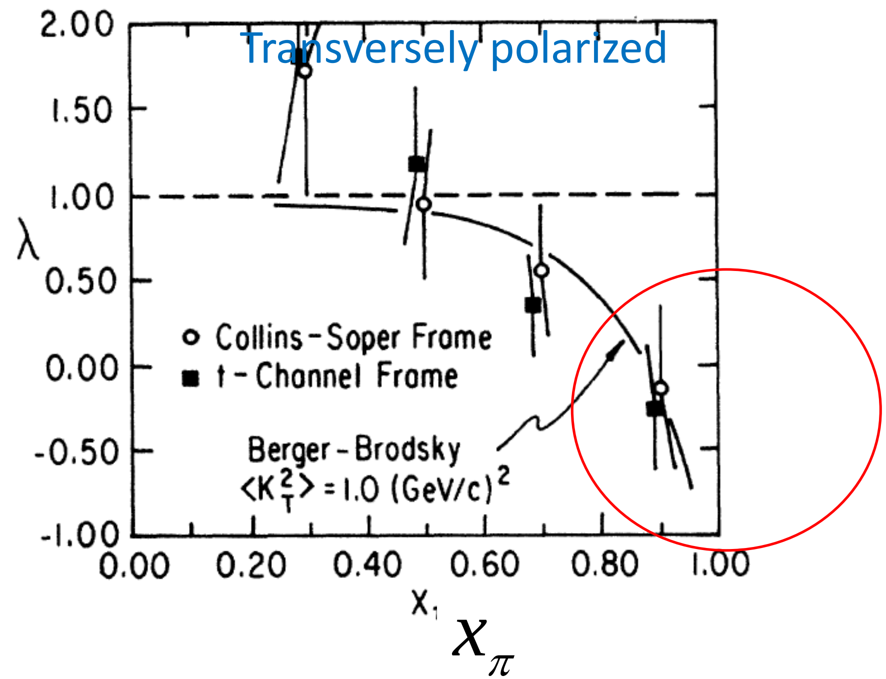
$$\frac{d^2\sigma}{dx_\pi d\cos\theta} \propto x_\pi \left[(1-x_\pi)^2 (1+\cos^2\theta) + \frac{4}{9} \frac{\langle k_T^2 \rangle}{M^2} \sin^2\theta \right]$$

E615 (PRD 34, 315 (1986))

252 GeV pion-

M> 4 GeV



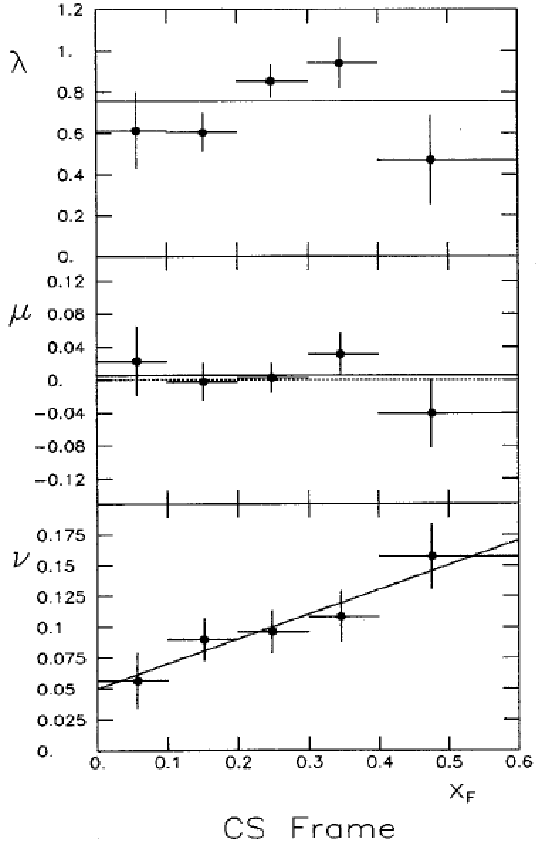


t-channel frame GJ frame

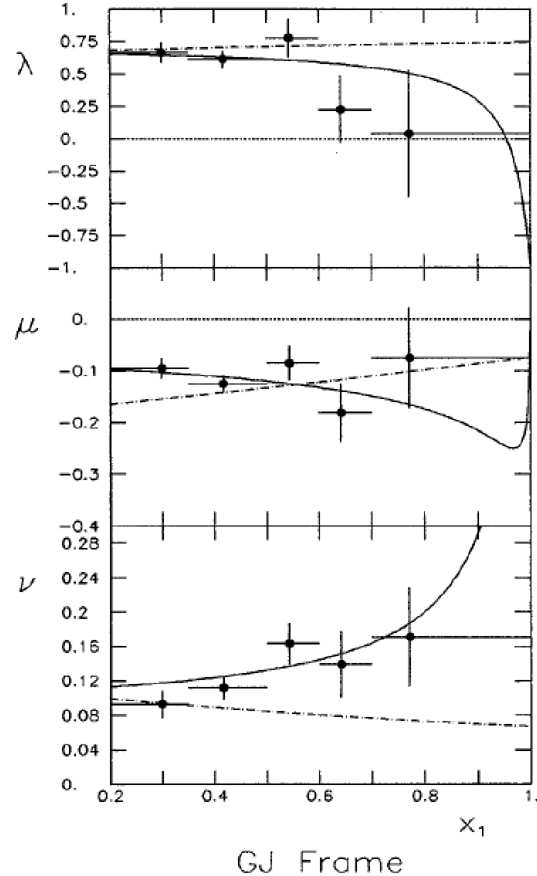
$\cos\theta$

Longitudinally polarized

NA10 (ZPC 31, 513 (1986))



Collins-Soper frame

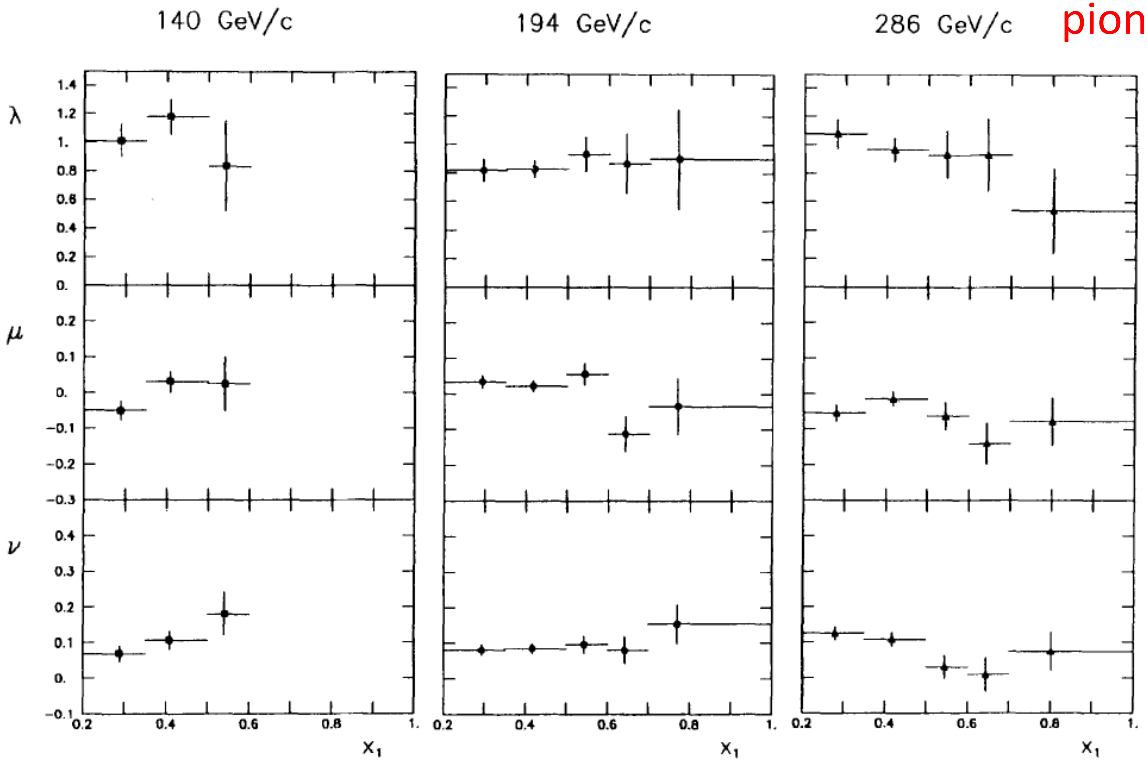


GJ frame

194 GeV pion-

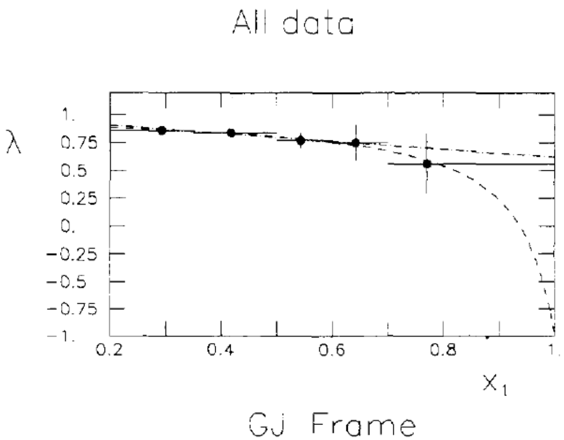
M> 4 GeV

NA10 (ZPC 37, 545 (1988))



pion-

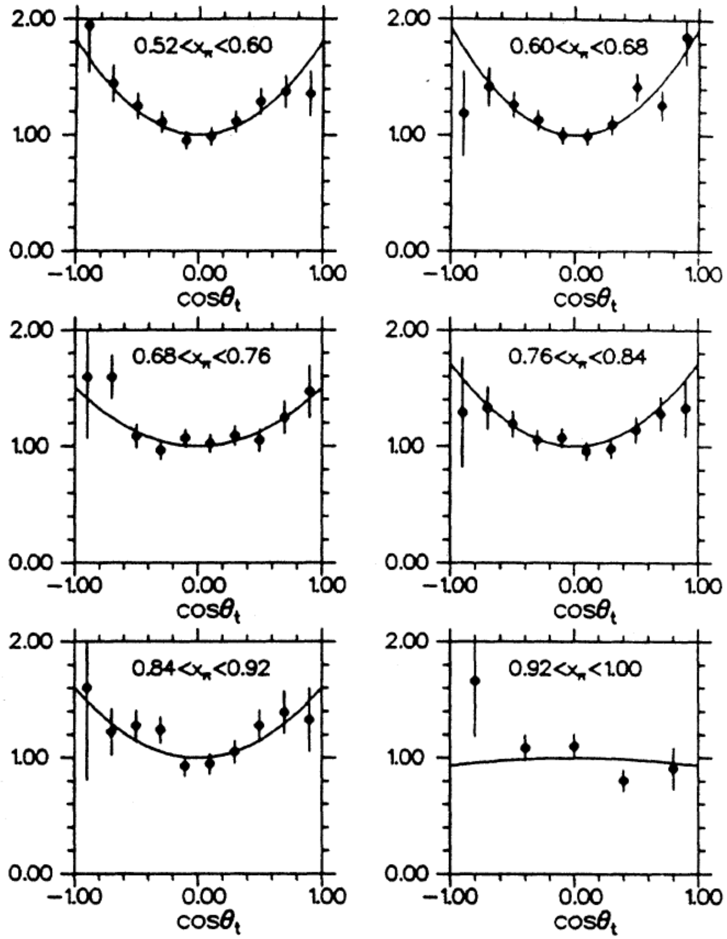
M> 4 GeV



GJ frame

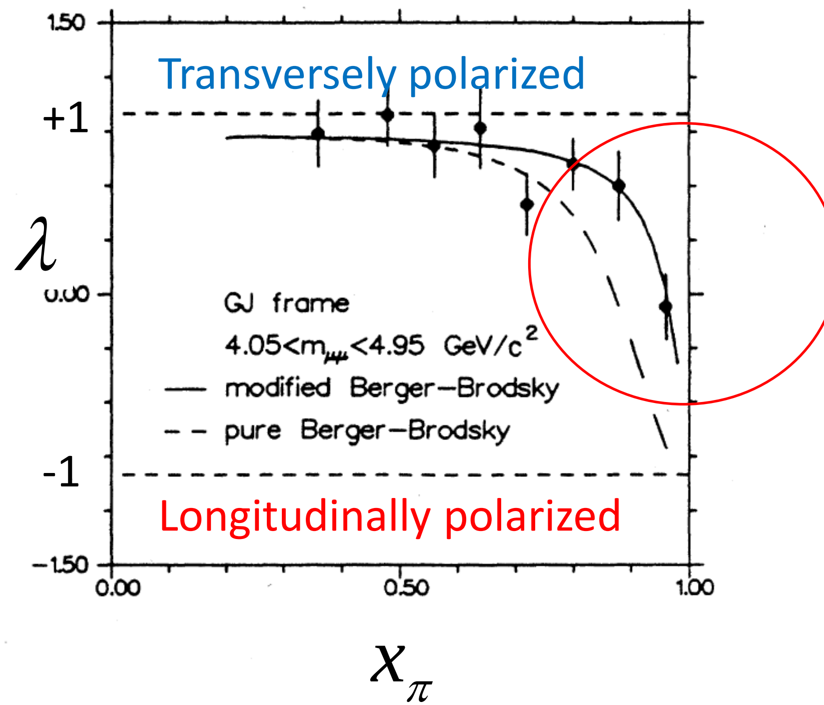
No statistically significant evidence to support the change of polarization at large x1.

E615 (PRD 39, 92 (1989))



252 GeV pion-

M> 4 GeV



GJ-channel frame

$\cos\theta$

E615 (PRD 44, 1909 (1989))

253 GeV pion-

M> 3 GeV

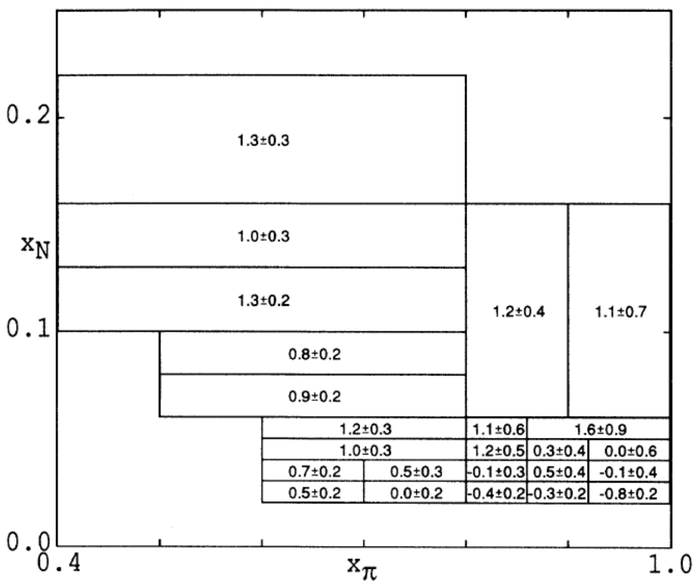
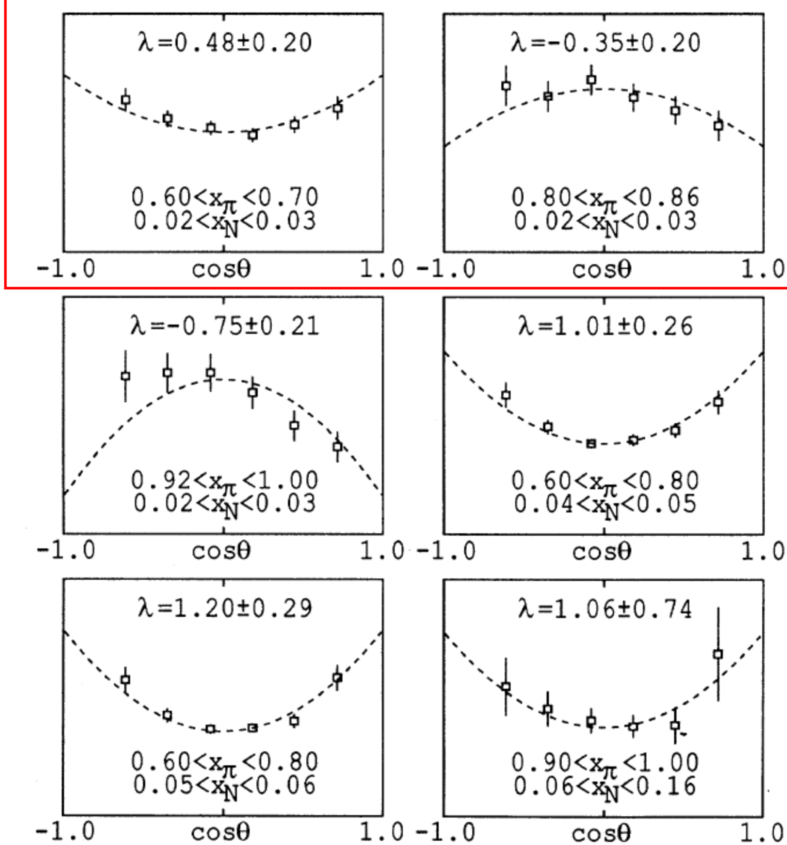


FIG. 13. The measured value of λ from fits of the form $d\sigma/d\cos\theta \propto 1+\lambda\cos^2\theta$ for each x_π-x_N bin.



GJ-channel frame $\cos\theta$

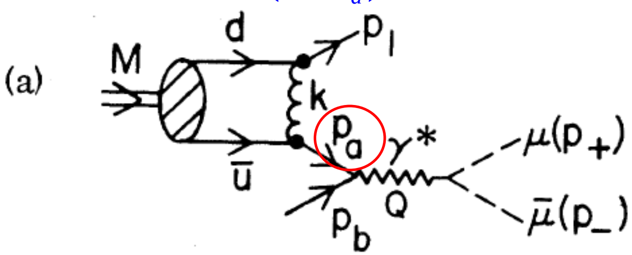
Observation of longitudinally polarized γ^* toward x_F=1

Year	Exp	E_π (GeV)	M_{min} (GeV)	Observation
1979	CIP	225	4	YES
1980	Youngquist et al.	22	1.4	NO
1981	NA3	150	4.5	NO
1985	CIP	80	4	YES
1986	E615	252	4	YES
1986	NA10	194	4	YES
1988	NA10	140, 194, 286	4	NO
1989	E615	252	4	YES
1989	E615	252	3	YES

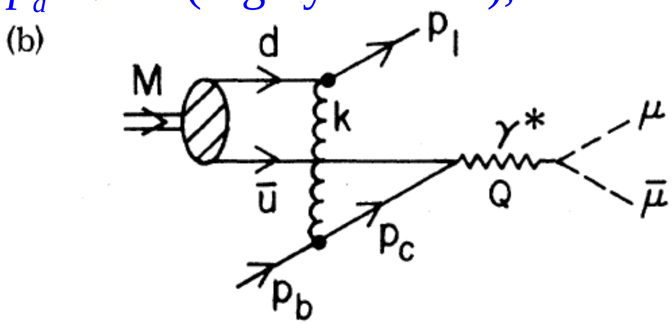
Berger and Brodsky (PRL 42, 940, (1979)) : Higher-twist Effect at large x_π

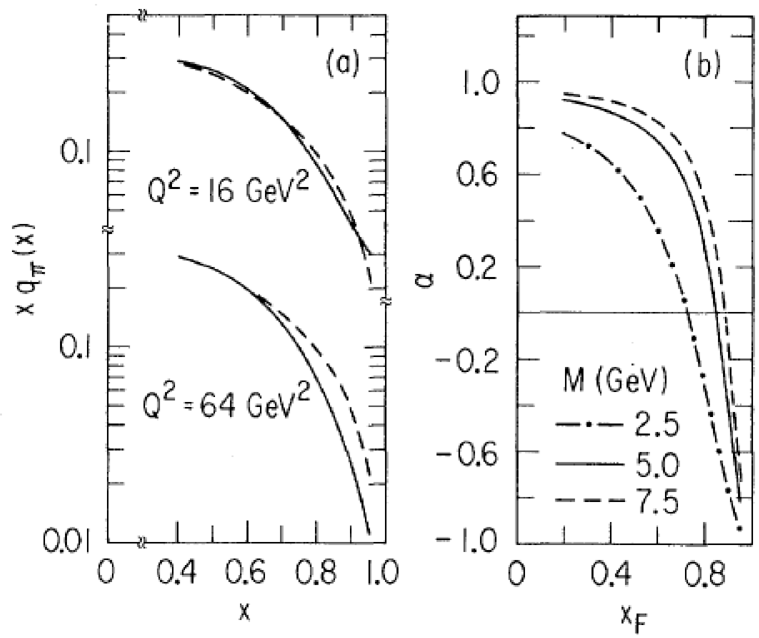
$$p_a^2 = -\frac{k_{Ta}^2 + x_a m^2 - x_a(1-x_a)m_\pi^2}{(1-x_a)}$$

$$d\sigma \propto (1+\alpha\cos^2\theta)$$



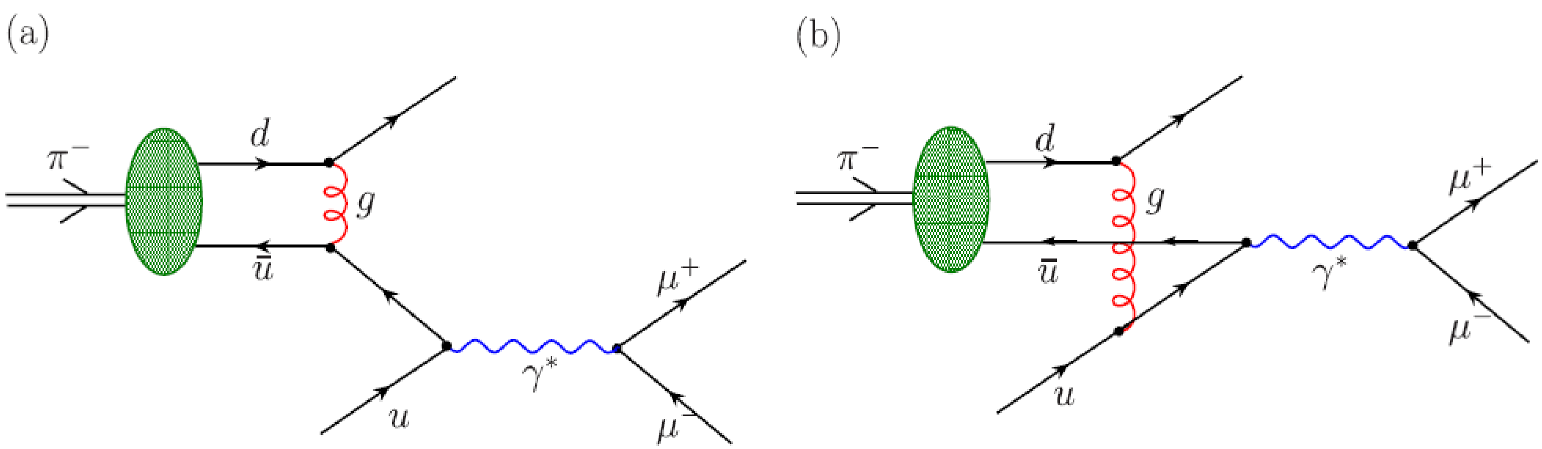
$$p_a^2 \rightarrow -\infty(\text{highly offshell}),\ \text{when } x_a \rightarrow 1.$$





$$d\sigma \propto (1-x_\pi)^2(1+\cos^2\theta) + \frac{4x_\pi^2\langle k_T^2\rangle}{9m_{\mu\mu}^2}\sin^2\theta$$

Brandenburg et al. (PRL 73, 939 (1994)) Higher-twist Effect & Pion Distribution Amplitude



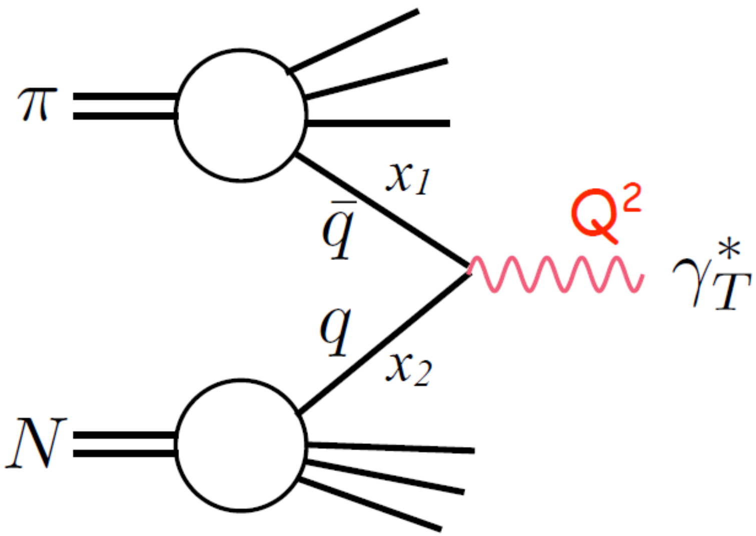
$$\frac{Q^2\, d\sigma(\pi^- N \to \mu^+\mu^- X)}{dQ^2\, dQ_T^2\, dx_L\, d\Omega} = \frac{1}{(2\pi)^4}\frac{1}{64}\int_0^1 dx_u \boxed{G_{u/N}(x_u)} \int_0^1 dx_{\bar{u}}\, \frac{x_{\bar{u}}}{1 - x_{\bar{u}} + Q_T^2/Q^2} \boxed{|M|^2}$$
$$\times\, \delta(x_L - x_{\bar{u}} + x_u - Q_T^2 s^{-1}(1 - x_{\bar{u}})^{-1})$$
$$\times\, \delta(Q^2 - s x_u x_{\bar{u}} + Q_T^2(1 - x_{\bar{u}})^{-1}) + \{u \to \bar{d}, \bar{u} \to d\}.$$

$$M = \int_0^1 dz\, \phi(z, \tilde{Q}^2) T\,,$$

Pion distribution amplitude: distribution of LC momentum fractions in the lowest-particle number valence Fock state.

P. Hoyer, M. Jrvinen and S. Kurki, JHEP 0810 (2008) 086, arXiv: 0808.0626

Drell-Yan in the Bj limit: $Q^2 \to \infty$ at fixed x



$$Q^2 = x_1 x_2 s \to \infty$$

x_1, x_2 ; $x_F = x_1 - x_2$ fixed

Transversely polarized photon, since quarks are ~ on-shell

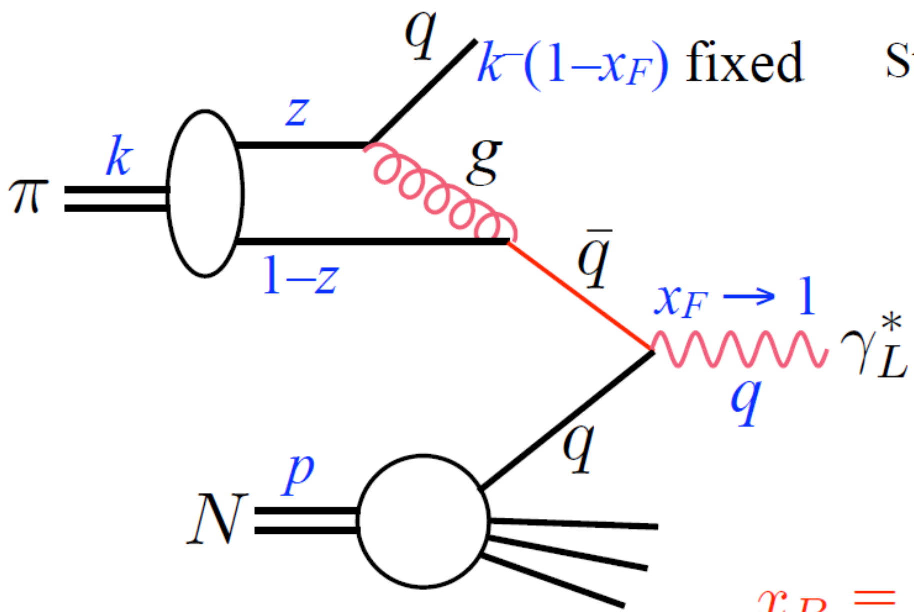
Leading twist: One active parton in beam and target hadrons

Spectators are incoherent with the hard subprocess

Factorization: $$\sigma = f_{\bar{q}/\pi}(x_1) f_{q/N}(x_2) \hat{\sigma}(\bar{q}q \to \gamma^*)$$

Higher twist corrections are of order $\frac{1}{Q^2}\frac{1}{1-x}$

Drell-Yan in the BB limit: $Q^2 \to \infty$ at fixed $Q^2(1-x_F)$



Stopped parton coherent with γ^*

$\bar{q}$, g virtualities of order Q^2

$\Rightarrow$ *higher twist process*

: Longitudinal polarization

$$x_B \equiv \frac{q^+}{p^+} = \frac{Q^2}{2q \cdot p} = \frac{Q^2}{s} \quad \text{fixed}$$

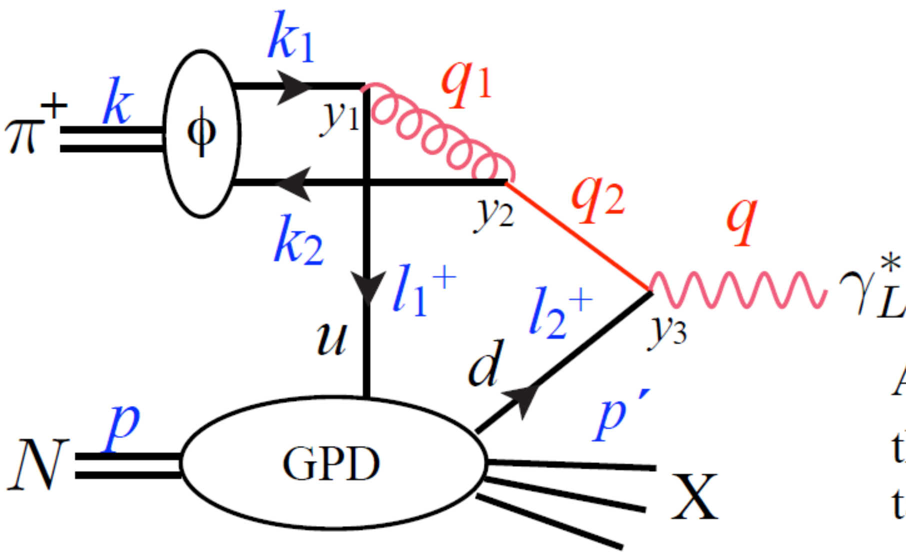
The hadronic mass

$$M_X^2 \equiv (k+p-q)^2 \simeq (1-x_B)[s(1-x_F)+m_N^2] \quad \text{fixed}$$

Stopped quark is comoving with the target.
Its interactions in the target affect the hard subprocess.

Hence the stopped quark should be connected to the target:

$k_1 = (0^+, zk^-, \boldsymbol{k}_\perp)$
$k_2 = (0^+, (1-z)k^-, -\boldsymbol{k}_\perp)$



Since $q_1^2 \approx -zk^- l_1^+ \to \infty$

the pion wave function contributes through its *distribution amplitude* ϕ

Also q_2^2, q_1^-, $q_2^- \to \infty$, hence the space-time separation of the target interaction points y_1, y_3 is

$$|\boldsymbol{y}_{1\perp} - \boldsymbol{y}_{3\perp}| = \mathcal{O}(1/Q) \to 0$$
$$|y_1^+ - y_3^+| = \mathcal{O}(1/Q^2) \to 0$$
$$|y_1^- - y_3^-| = \mathcal{O}(1/\ell_1^+) \text{ finite}$$

For each final state X the target matrix element is given by a GPD with skewness

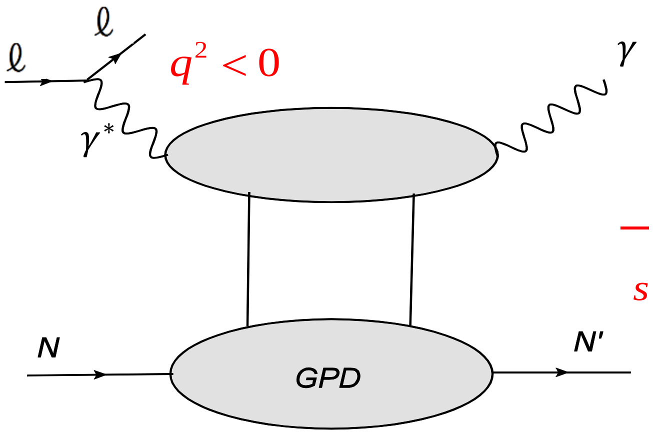
$$l_2^+ - l_1^+ = q^+ = x_B\, p^+$$

Using perturbative propagators for the gluon q_1 and d-quark q_2 and adding three more diagrams we get

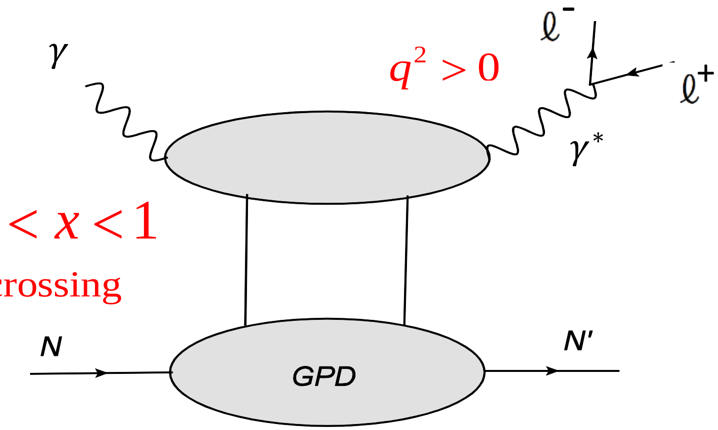
Extraction of **GPDs**
Space-like vs. Time-like Processes

Muller et al., PRD 86 031502(R) (2012)

Deeply Virtual Compton Scattering (DVCS)



Time-like Compton Scattering (TCS)

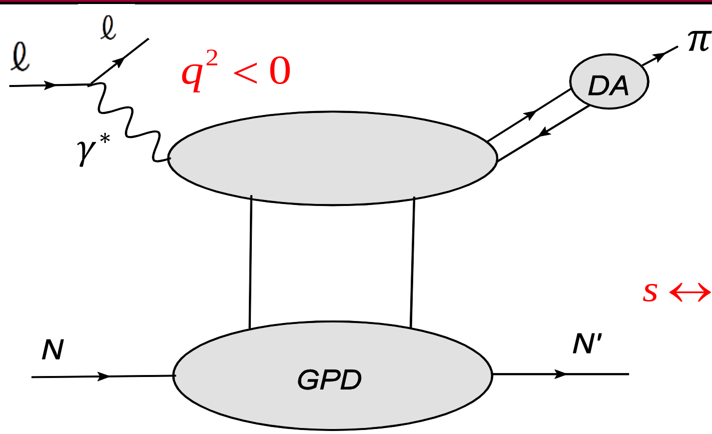


$t < 0$

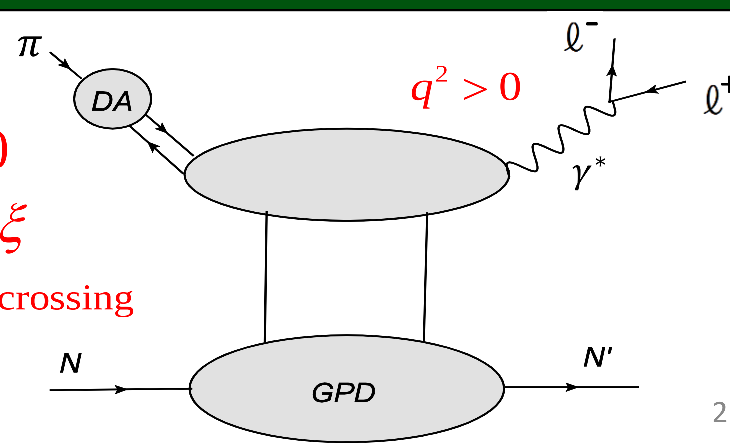
$-1 < x < \xi, \xi < x < 1$

$s \leftrightarrow u$ channel crossing

Deeply Virtual Meson Production (DVMP)



Exclusive meson-induced DY



$t < 0$

$|x| < \xi$

$s \leftrightarrow u$ channel crossing

Factorization at fixed $Q^2(1-x)$ (P. Hoyer, et al, JHEP 10, 086 (2008))

$$\frac{d\sigma(\pi^+ N \to \gamma_L^* X)}{dM_X^2} = \frac{2(eg^2 C_F)^2}{Q^2 s^2 (1-x_B) N_c} \times \int dx\, dx'\, C(x_B, x) C^*(x_B, x')\, f_{d\bar{u}/p}(x_B, x_M; x, x')$$

where $$C(x_B, x) \equiv \int_0^1 dz\, \phi_\pi(z) \left(\frac{e_u}{1-z} \frac{1}{x_B + x + i\varepsilon} + \frac{e_d}{z} \frac{1}{x - i\varepsilon} \right)$$

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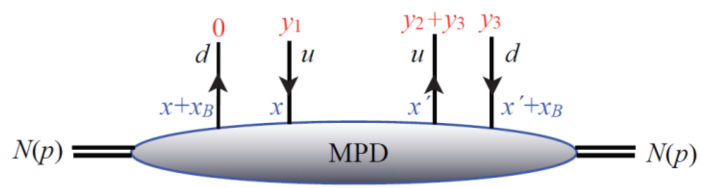
The MultiParton Distribution



$$f_{d\bar{u}/p}(x_B, x_M; x, x') = \frac{1}{4(4\pi)^3} \int dy_1^- dy_2^- dy_3^- dy_3^+ \exp\left\{\tfrac{1}{2} i \left[-y_1^- l_1^+ + y_2^- l_1^{+\prime} - y_3^- q^+ + y_3^+ x_M p^- \right]\right\}$$
$$\times \langle N(p) | \bar{\psi}_d(y_3) \gamma^+ \gamma_5\, \psi_u(y_2 + y_3)\, \bar{\psi}_u(y_1) \gamma^+ \gamma_5\, \psi_d(0) | N(p) \rangle_{y_{i\perp}=0;\ y_1^+ = y_2^+ = 0}$$

Large xF limit

- **Bj limit ($Q^2 \to \infty$, at fixed x_1)**,
  cross sections = **pion PDF** * **nucleon PDF** * hard kernel
- **BB limit ($Q^2 \to \infty$, at fixed $Q^2(1 - x_F)$)**,
  cross sections = |**pion DA**|^2 * **nucleon multi-parton distribution** * hard kernel
- **Exclusive DY**,
  cross sections = |**pion DA** * **nucleon GPD** * hard kernel |^2

γ* polarization in inclusive DY

Recall: γ* is coherent on the entire $q\bar{q}$ state for

$$Q^2 \lesssim \frac{\Lambda^2}{1-x}$$

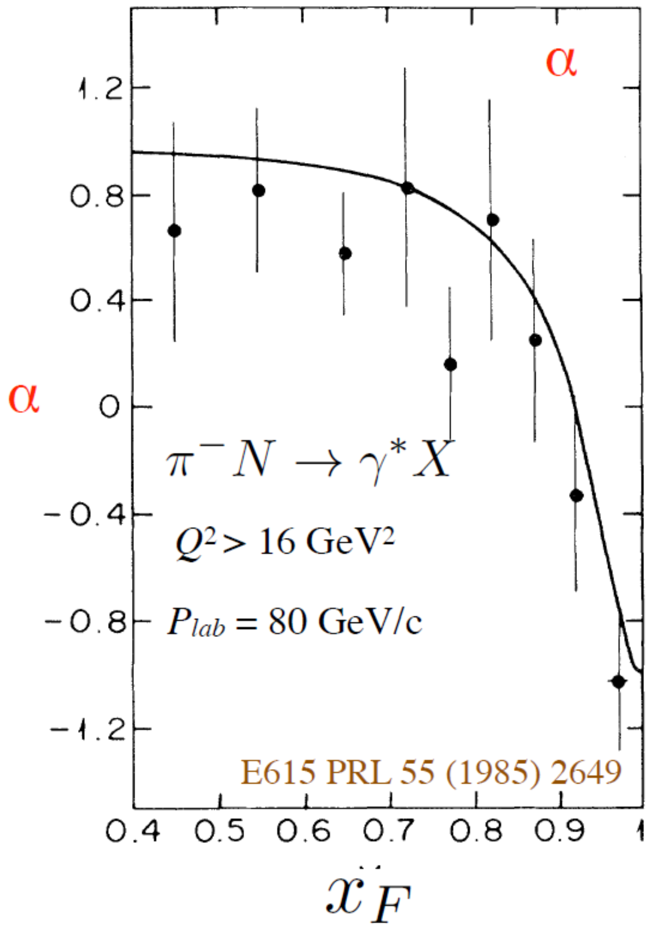
The DY data indicates σ_L dominance for $x_F \gtrsim 0.9$ when $Q^2 \approx 20$ GeV^2 *i.e.*,

$$Q^2(1-x) \lesssim 2\ \text{GeV}^2$$

The "soft scale" $\Lambda^2 \approx 2$ GeV^2 is consistent with that in $\gamma^* p \to \varrho\, p$

The γ* polarization should turn over at fixed $Q^2(1\text{-}x)$, when $Q^2 \gtrsim 2$ GeV^2 .

$$\frac{d\sigma}{d\cos\theta^*} \propto 1 + \alpha\cos^2\theta^*$$



ARTICLES

253 GeV pion-
M> 4 GeV

Higher-twist effects in the reaction $\pi^- N \to \mu^+\mu^- X$ at 253 GeV/c

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(Received 1 April 1991)

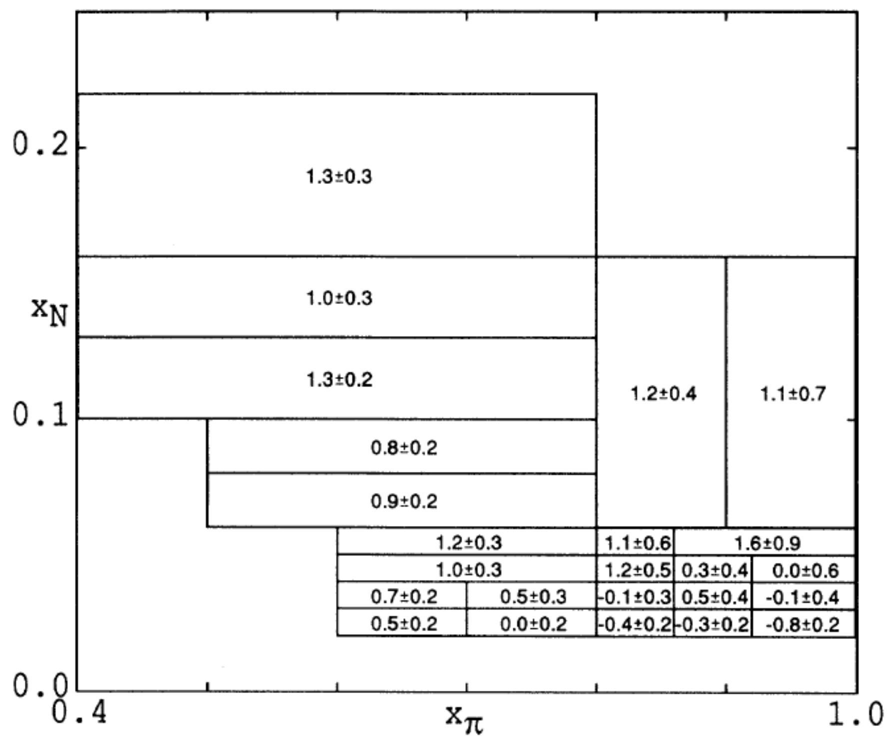
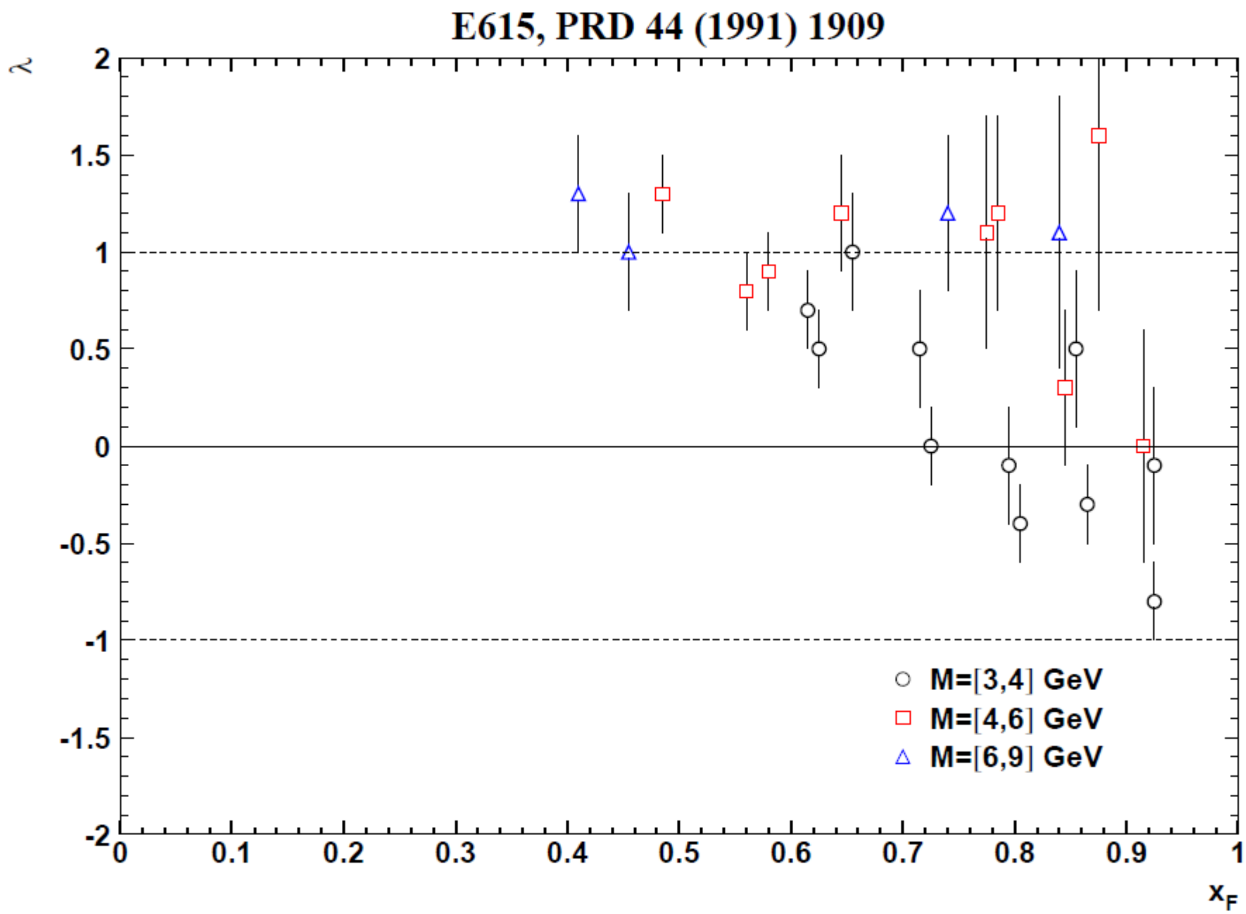


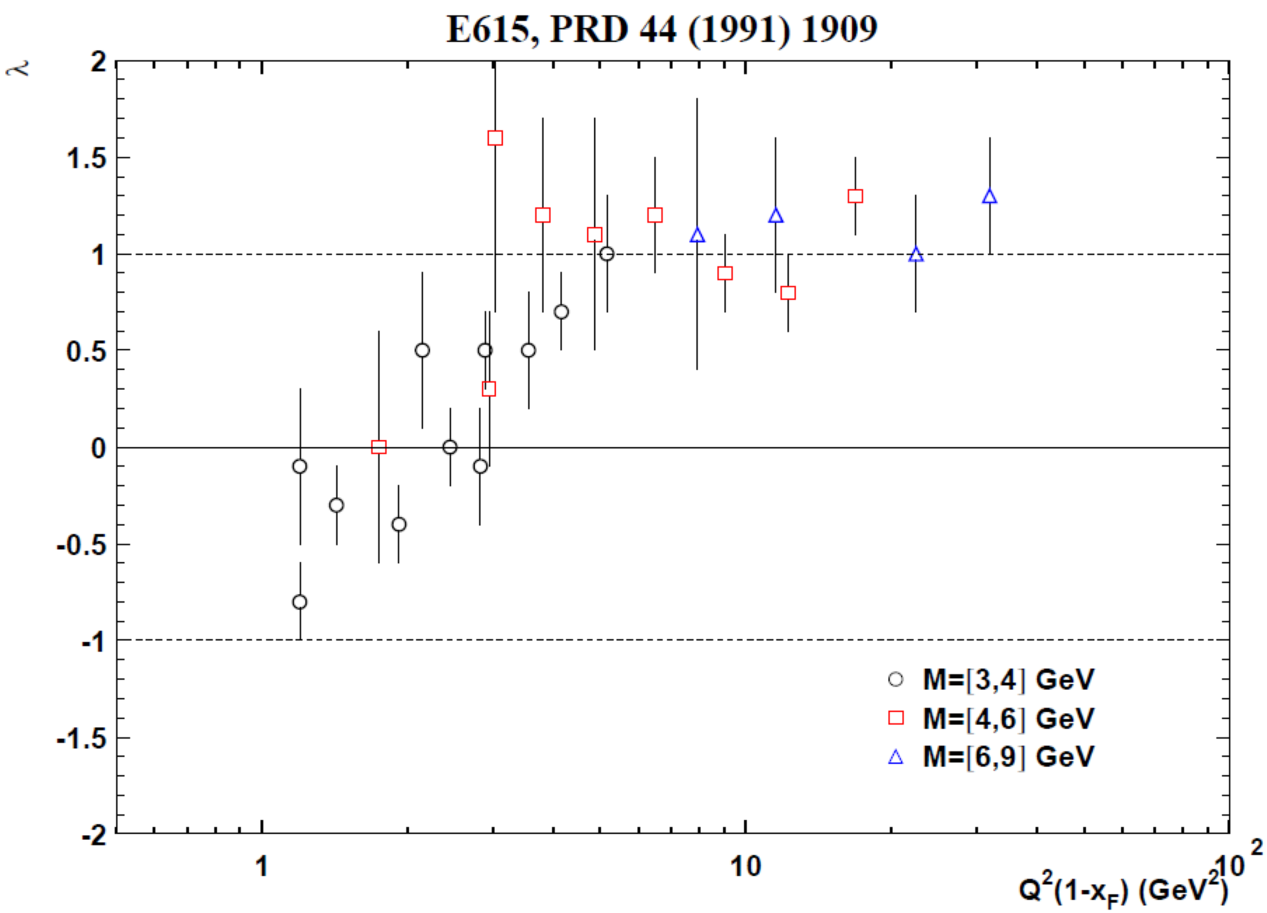
FIG. 13. The measured value of λ from fits of the form $d\sigma/d\cos\theta \propto 1 + \lambda\cos^2\theta$ for each x_π-x_N bin.

$\lambda(x_F)$



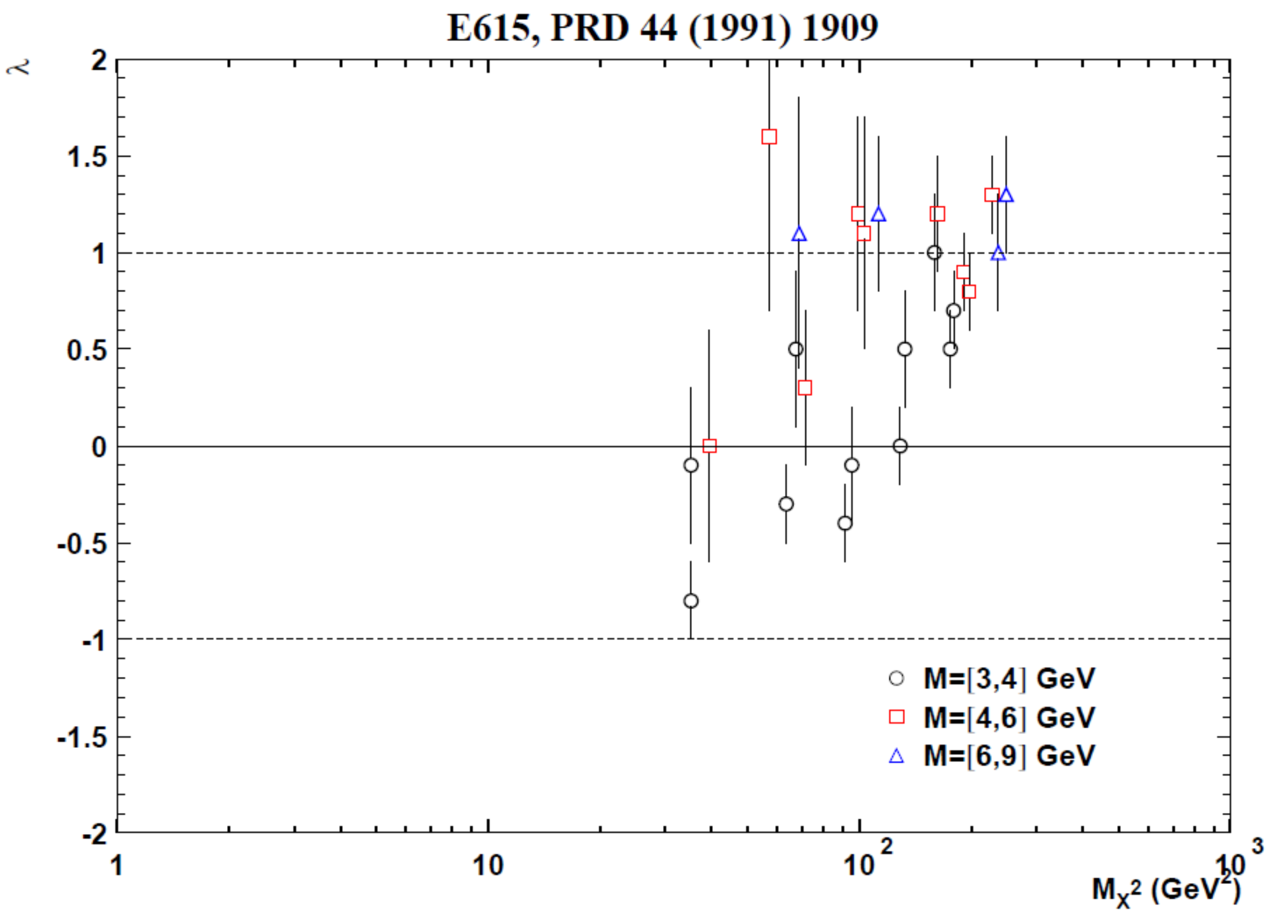
E615, PRD 44 (1991) 1909
λ
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
x_F
M=[3,4] GeV
M=[4,6] GeV
M=[6,9] GeV

$$\lambda(Q^2(1 - x_F))$$



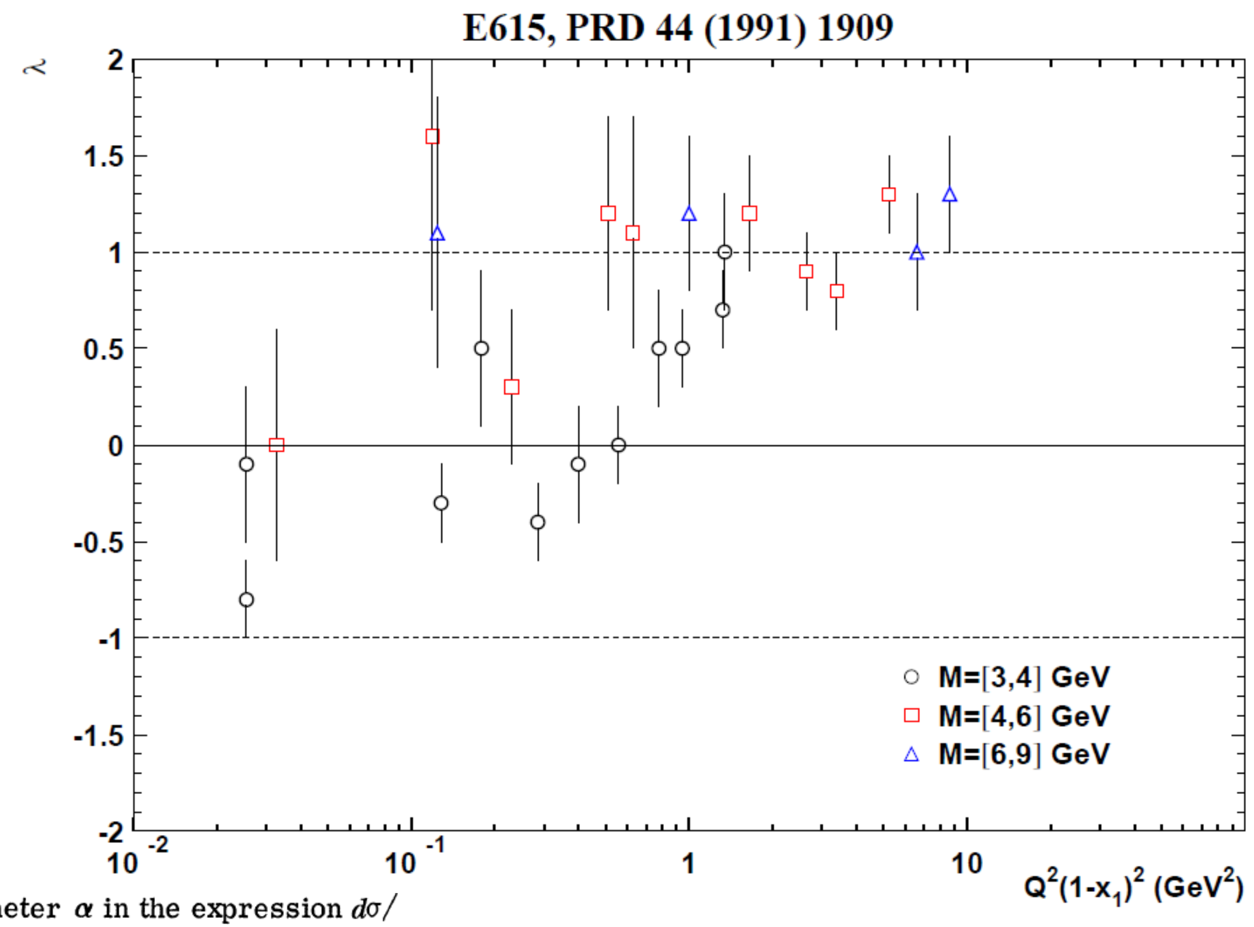
Data scale well!

$\lambda(M_X^2)$



$$M_X^2 \simeq (1 - x_1 x_2)[s(1 - x_F) + m_N^2]$$

$\lambda(Q^2(1-x_1)^2)$



polarization parameter α in the expression $d\sigma/d\cos\theta = 1 + \alpha\cos^2\theta$. In our model, $\alpha = (1-r)/(1+r)$, with

$$r = \tfrac{4}{9}\langle k_{Ta}{}^2\rangle / Q^2(1-x_a)^2. \qquad (7)$$

Berger & Brodsky, PRL 1979

Summary

- A change of virtual photon polarization at large-xF regions was observed in the pion-induced Drell-Yan process. It is interpreted by the “higher-twist” effect where the whole pion is scattered.
- A new QCD factorization scheme at fixed $Q^2(1-x)$ is proposed and E615 data seems to support the claim.

Questions (I)

- What we can learn from the “higher-twist” effect? Pion DA & multi-partion distributions?
- Is such “higher-twist” effect specific to the DY process with the pion beam? How about proton, kaon and anti-proton beams?
- Is there such “higher-twist” effect for the J/psi production with the pion beam?

Questions (II)

- What will be the conclusive experimental evidence of the new QCD factorization? We might need DY data at low-mass and large xF.
- If this new QCD factorization scheme is true, will it work as a bridge to connect the inclusive DY process at large xF to the exclusive one?