Semi-Inclusive Reactions Workshop (SIR 2005)
JLab, May 20, 2005

Origin of the Nucleon Sea via Target Fragmentation

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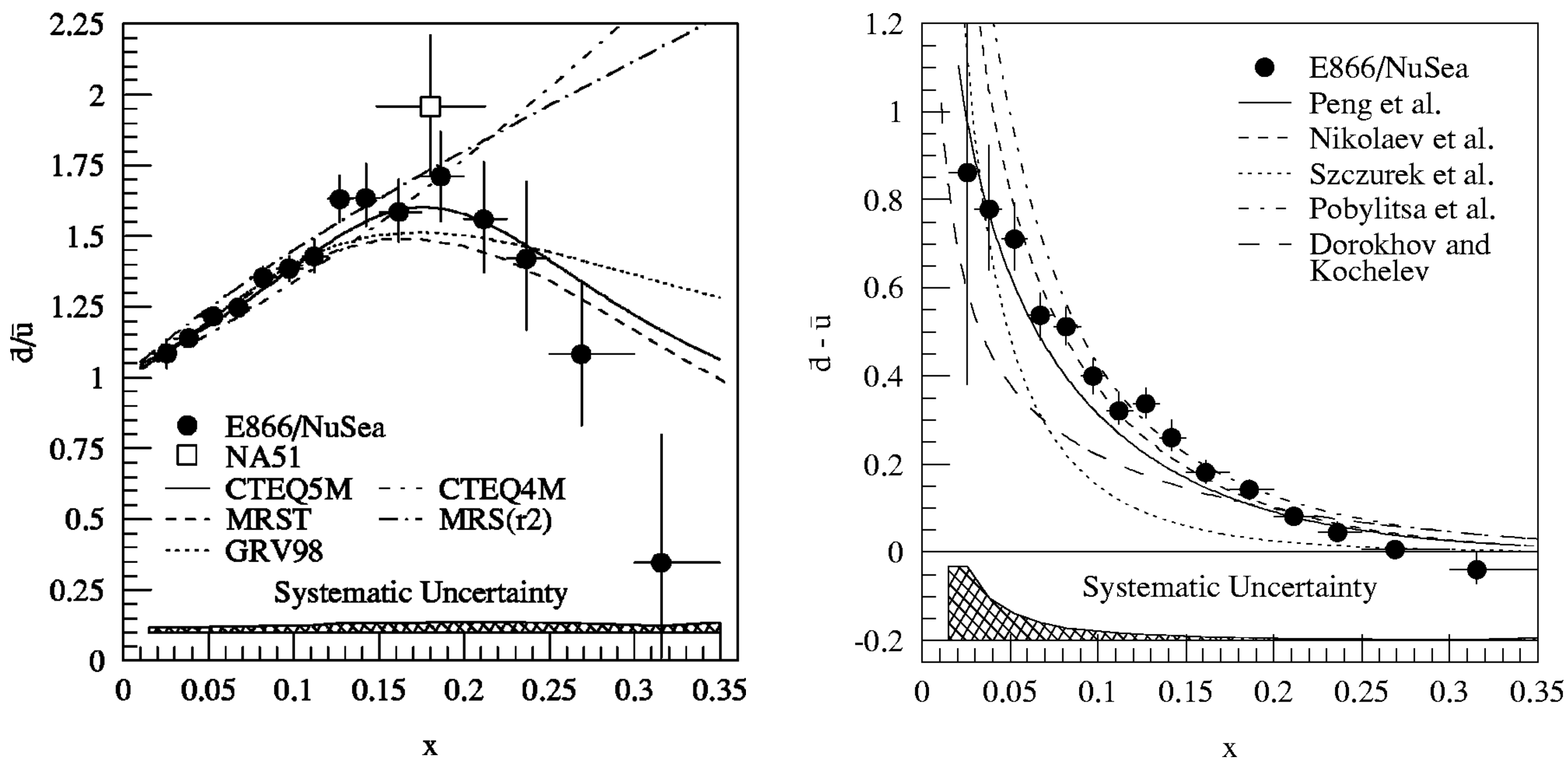
Outline

- Motivation: flavor and spin content of N
- Chiral symmetry
- Semi-inclusive DIS
  - probe of π (and K) cloud of N
- Outlook

Flavor asymmetry of proton sea

Large $\bar{d} - \bar{u}$ asymmetry in proton observed in DIS (NMC) and Drell-Yan (CERN NA51 and FNAL E866) experiments



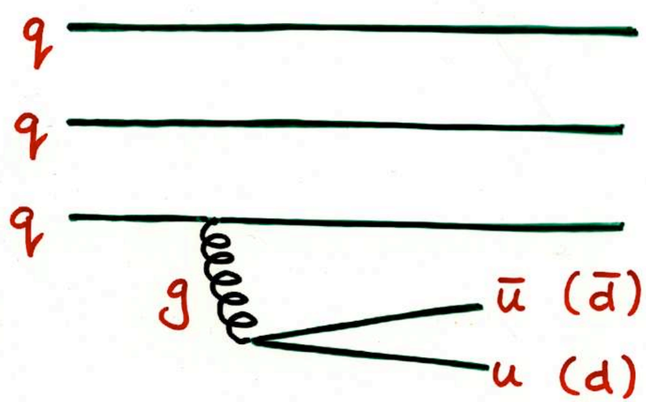
$$\int_0^1 dx\ (\bar{d}(x) - \bar{u}(x)) = 0.118 \pm 0.012$$

Towell et al., Phys. Rev. D 64 (2001) 052002

Flavor asymmetry of proton sea

Large $\bar{d} - \bar{u}$ asymmetry in proton observed in DIS (NMC) and Drell-Yan (CERN NA51 and FNAL E866) experiments

Naively expect symmetric sea from pQCD



$$\bar{d} = \bar{u}$$

Large flavor asymmetry reveals importance of

⟹ *nonperturbative* dynamics

(*e.g.* pion cloud)

Why is $\bar{d} \neq \bar{u}$?

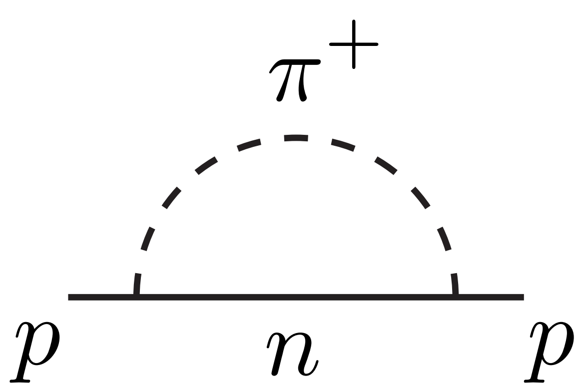
Pion cloud

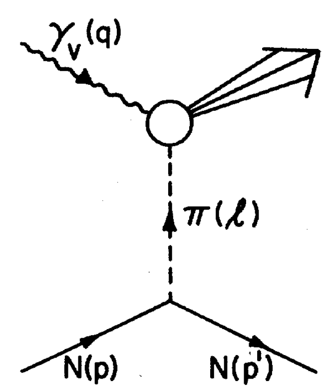
some of the time the proton
looks like a neutron & π^+

(Heisenberg Uncertainty Principle)

$$p \rightarrow \pi^+ \, n \rightarrow p$$

"BUT, HEISENBERG — YOU MUST BE CERTAIN ABOUT SOMETHING!"





Sullivan, Phys. Rev. D5 (1972) 1732

Why is $\bar{d} \neq \bar{u}$?

Pion cloud

some of the time the proton looks like a neutron & π^+

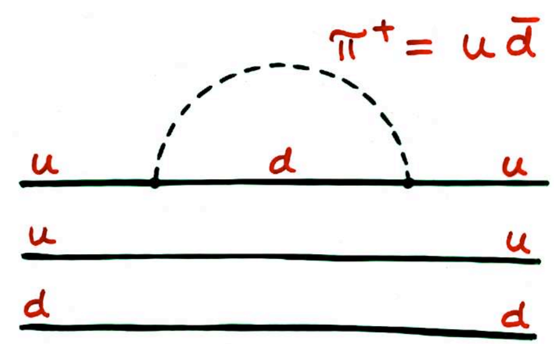
(Heisenberg Uncertainty Principle)

$$p \to \pi^+ \, n \to p$$

at the quark level

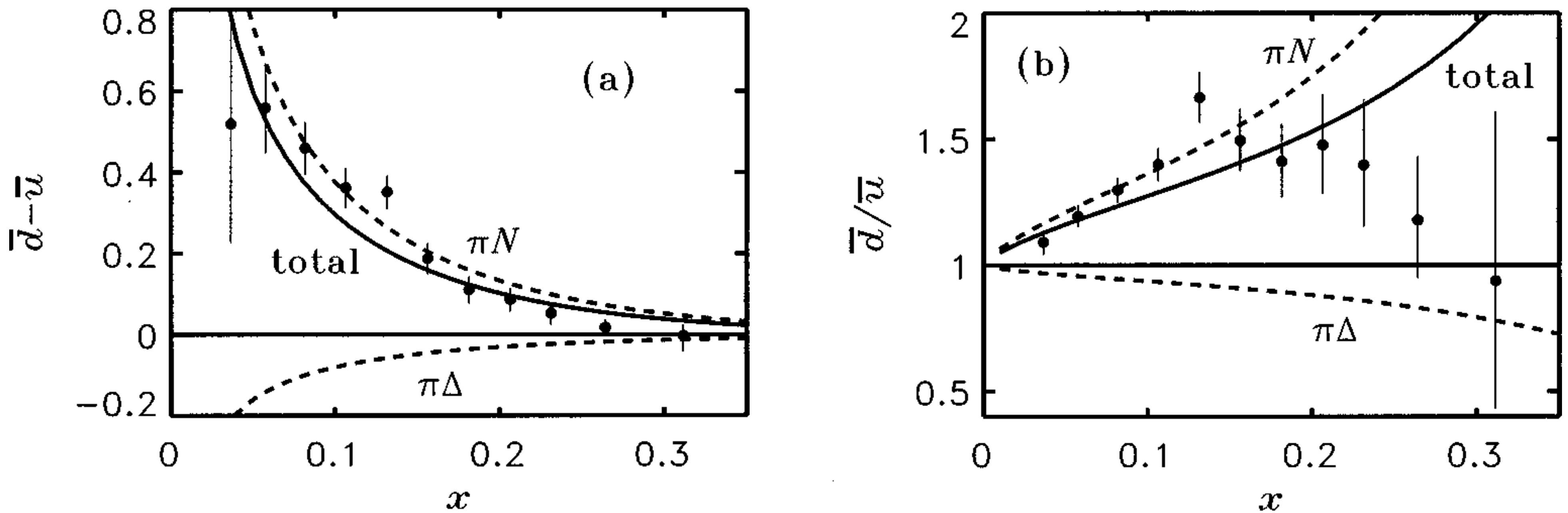
$$uud \to (udd)(\bar{d}u) \to uud$$

$$\Rightarrow \quad \bar{d} > \bar{u} \, !$$



Thomas, Phys. Lett. 126B (1983) 97

Pion cloud contributions to flavor asymmetry in proton sea



WM, Speth, Thomas, Phys. Rev. D59 (1998) 014033

⟹ good description of data at $x < 0.2$

⟹ difficult to understand downturn at large x

Why is $\bar{d} \neq \bar{u}$?

Pauli blocking

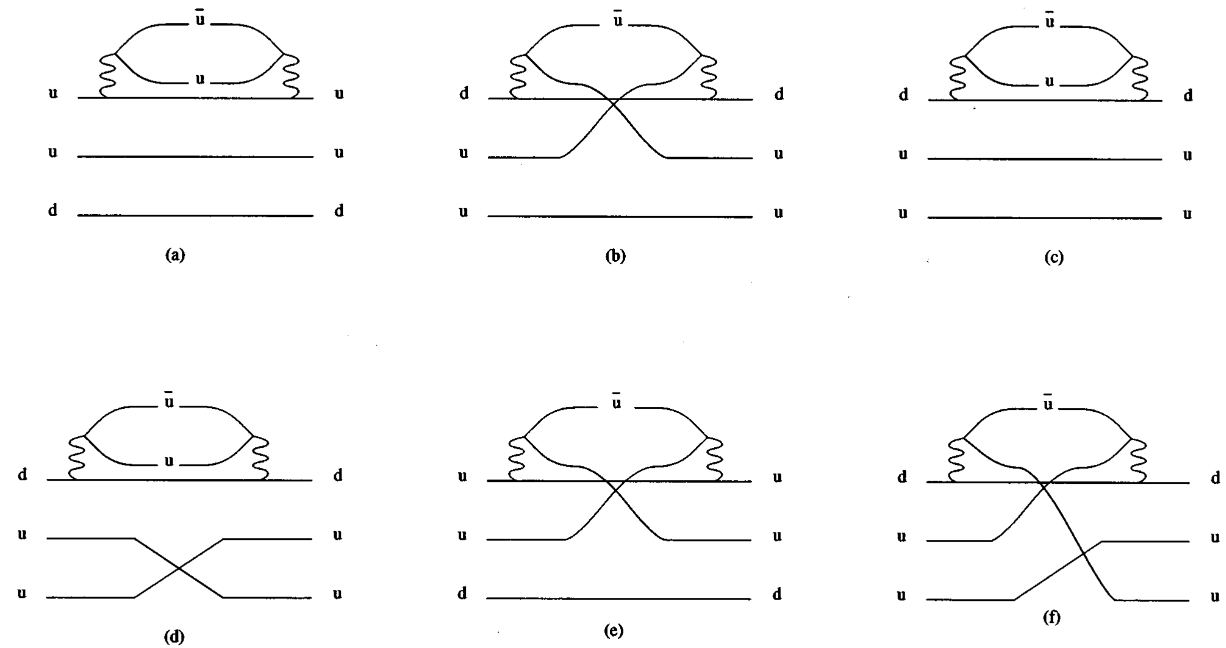
proton has more valence u than d

$\Longrightarrow$ easier to create $d\bar{d}$ than $u\bar{u}$?

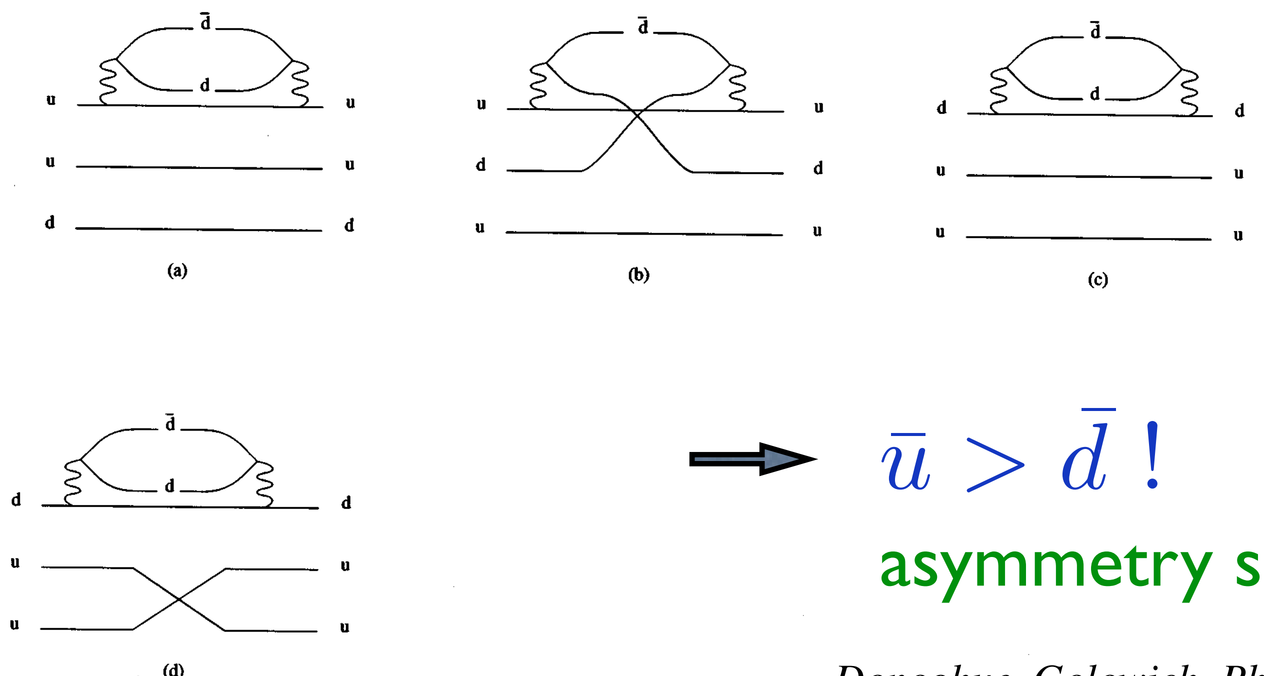
Field, Feynman, Phys. Rev. D15 (1977) 2590

Explicit calculations of antisymmetrization effects in $g \rightarrow u\bar{u}$ and $g \rightarrow d\bar{d}$

$u\bar{u}$



$d\bar{d}$



$\bar{u} > \bar{d}$!

asymmetry small

Donoghue, Golowich, Phys. Rev. D15 (1977) 3421

Steffens, Thomas, Phys. Rev. C55 (1997) 900

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Field, Feynman, Phys. Rev. D15 (1977) 2590

Explicit calculations of antisymmetrization effects in $g \longrightarrow u\bar{u}$ and $g \longrightarrow d\bar{d}$

$\Longrightarrow$ perturbative effects small

$\Longrightarrow$ nonperturbative ??

Ross, Sachrajda, Nucl. Phys. B149 (1979) 497
Steffens, Thomas, Phys. Rev. 55 (1997) 900

Polarization asymmetry of proton sea

Neither pQCD nor meson cloud contribute significantly to $\Delta\bar{d} - \Delta\bar{u}$

But Pauli Exclusion Principle (antisymmetrization)

$$\longrightarrow \quad \Delta\bar{u} - \Delta\bar{d} \approx \frac{5}{3}(\bar{d} - \bar{u})$$

Schreiber, Signal, Thomas, Phys. Rev. D44, 2653 (1991)

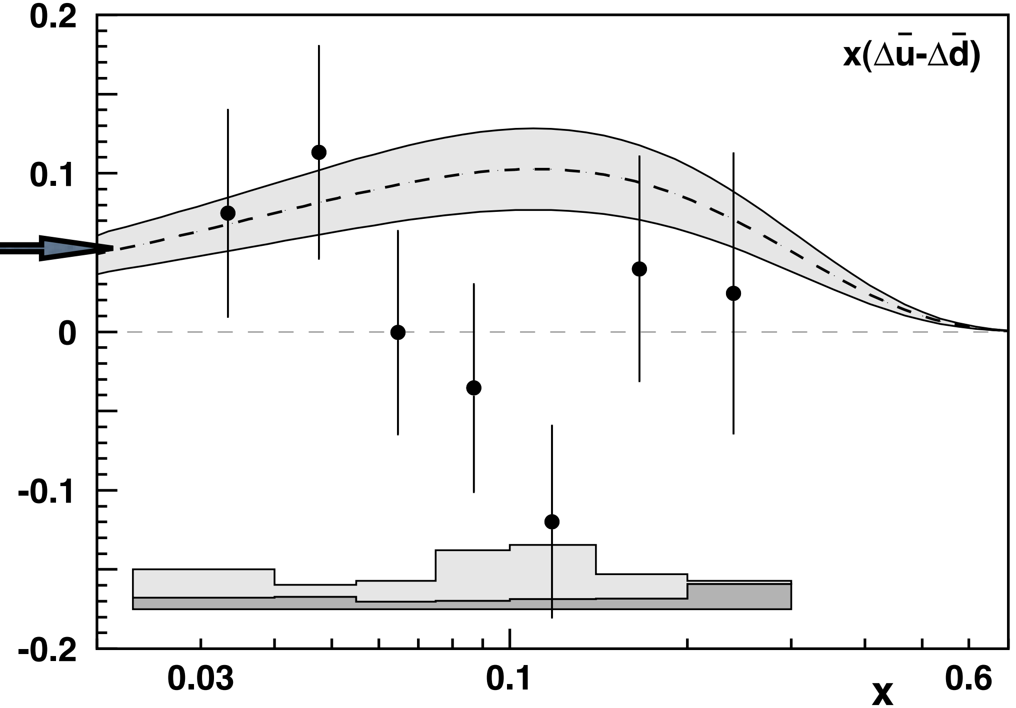
Steffens, Phys. Rev. C55, 900 (1997)

Disentangle origin of unpolarized and polarized asymmetries in sea via *semi-inclusive DIS*

Polarization asymmetry of proton sea

chiral soliton model

Dressler, Goeke, Polyakov, Weiss, Eur. Phys. J. C14 (2000) 147



Airapetian et al. [HERMES], Phys. Rev. Lett. 92 (2004) 012005

current data cannot distinguish between zero and small nonzero $\Delta\bar{u} - \Delta\bar{d}$

Pion cloud at high energy

Is there any (more direct) evidence for π cloud in DIS?

Theoretically, a pion cloud component exists in QCD

⟶ *leading nonanalytic* contribution to moments calculated *model-independently* from chiral perturbation theory

Thomas, WM, Steffens, Phys. Rev. Lett. 85 (2000) 2892

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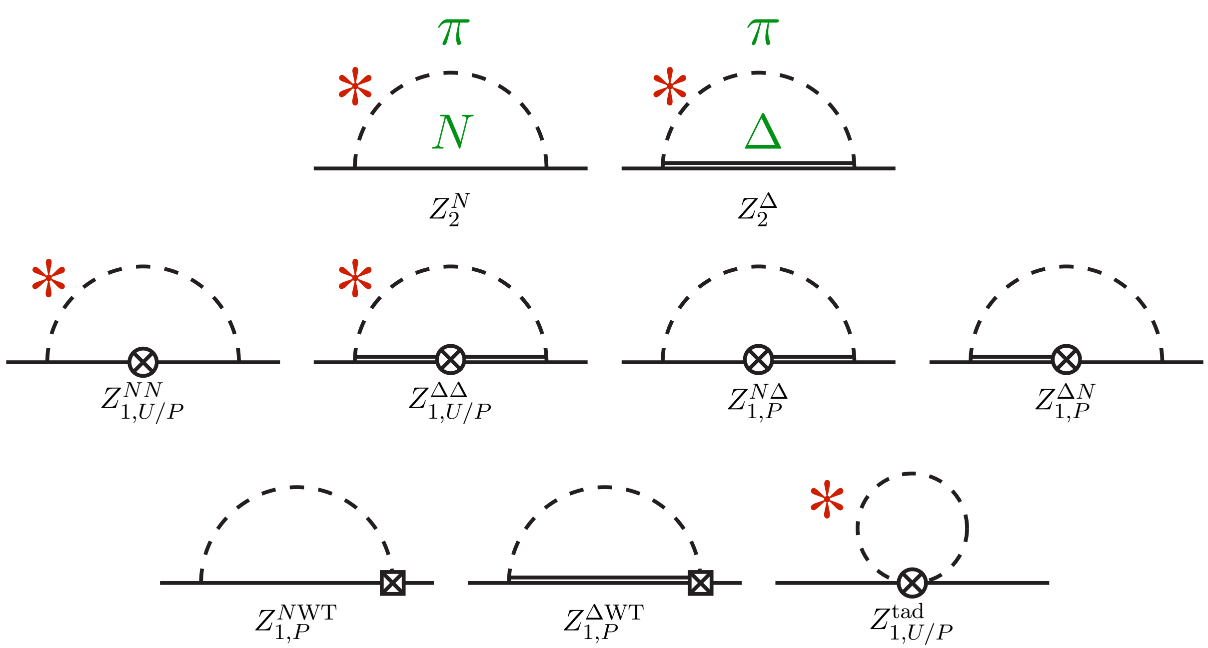


* unpolarized only

Pion cloud at high energy

Is there any (more direct) evidence for π cloud in DIS?

Theoretically, a pion cloud component exists in QCD

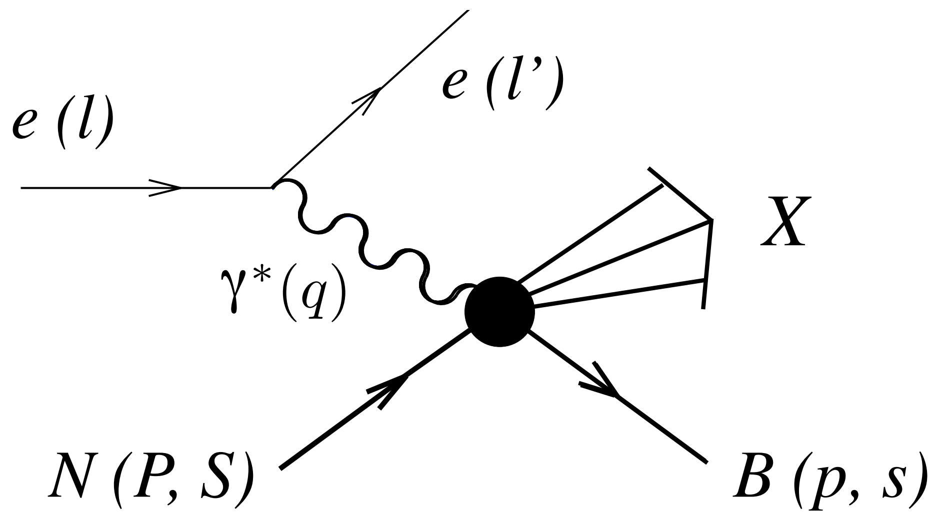
$$\int dx\ x^n\ (\bar{d} - \bar{u}) = a_n(1 + c_{\mathrm{lna}} m_\pi^2 \log m_\pi^2) + b_n m_\pi^2 + \cdots$$

$$c_{\mathrm{lna}} = -(1 + 3g_A^2)/(4\pi f_\pi)^2$$

Detmold et al., Phys. Rev. Lett. 87 (2001) 172001
also Arndt, Savage (2001), Ji, Chen (2001)

Semi-inclusive baryon production

Look for unique traces of π cloud in SIDIS



Kinematics (target rest frame)

$$t \equiv (P-p)^2 = -p_\perp^2/\zeta + t_{\max}$$

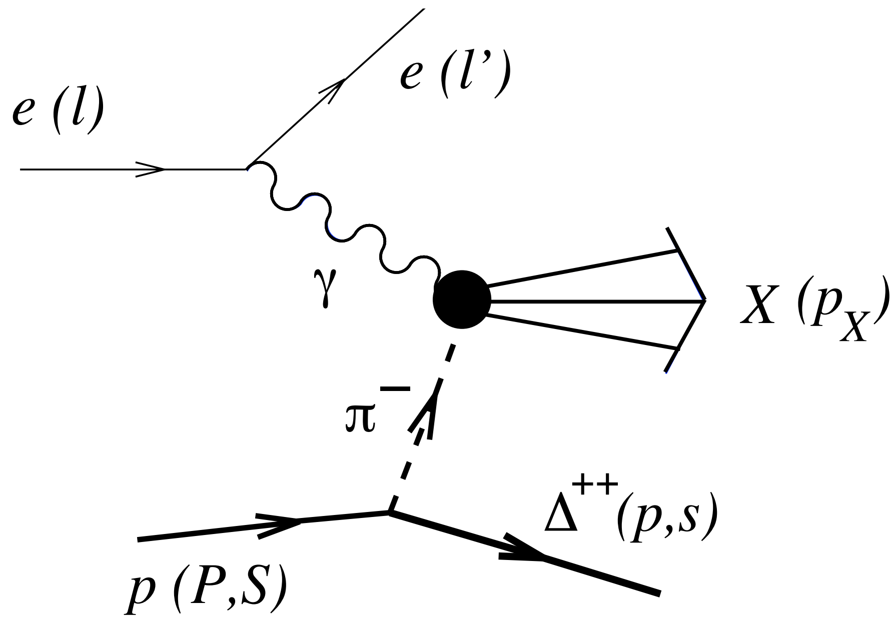
$$\zeta = p \cdot q / P \cdot q$$

$$t_{\max} = -(M_B^2 - M^2\zeta)(1-\zeta)/\zeta$$

α angle between γ^* and B

t-channel pion exchange

$e.g.$ Δ production



Differential cross section

$$\frac{d^5\sigma}{dx\,dQ^2\,d\zeta\,dp_T^2\,d\phi} \propto \frac{f_{\pi N\Delta}^2}{16\pi^2 m_\pi^2}\,\frac{\mathcal{T}^{S\ s}(t)\ \mathcal{F}_{\pi\Delta}^2}{(t-m_\pi^2)^2}\,L_{\mu\nu}(l,q)\ W_\pi^{\mu\nu}(k,q)$$

$\mathcal{F}_{\pi\Delta}(p_\perp^2,\zeta)$

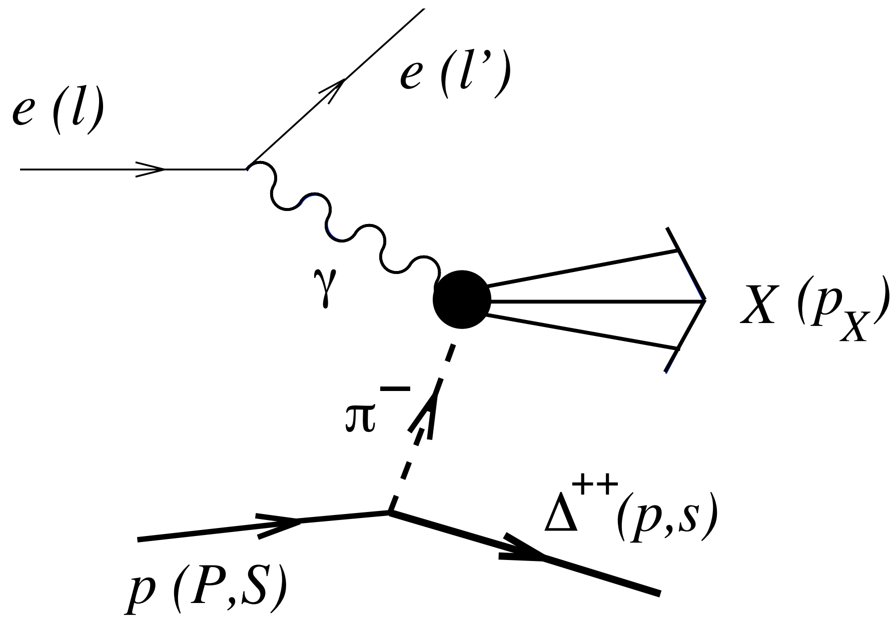
$\pi N\Delta$ form factor

$W_\pi^{\mu\nu} \sim -g^{\mu\nu}\ F_{2\pi}(x,Q^2)$

pion structure function

t-channel pion exchange

$e.g.$ Δ production



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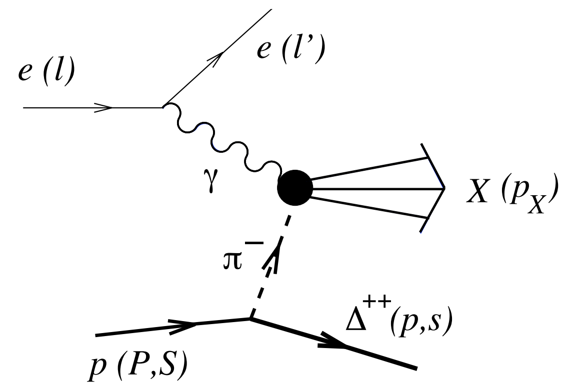
$$\mathcal{T}^{S\ s}(t) = \mathrm{Tr}[u(P,S)\bar{u}(P,S)\ u_\alpha(p,s)\bar{u}_\beta(p,s)](P-p)^\alpha(P-p)^\beta$$

Rarita-Schwinger (spin-3/2) spin-vector

t-channel pion exchange



In TRF, π and Δ emitted collinearly

⟹ selection rule for s=3/2:

$$\mathcal{T}^{S\pm\frac{3}{2}}(t) = 0$$

For s=1/2:

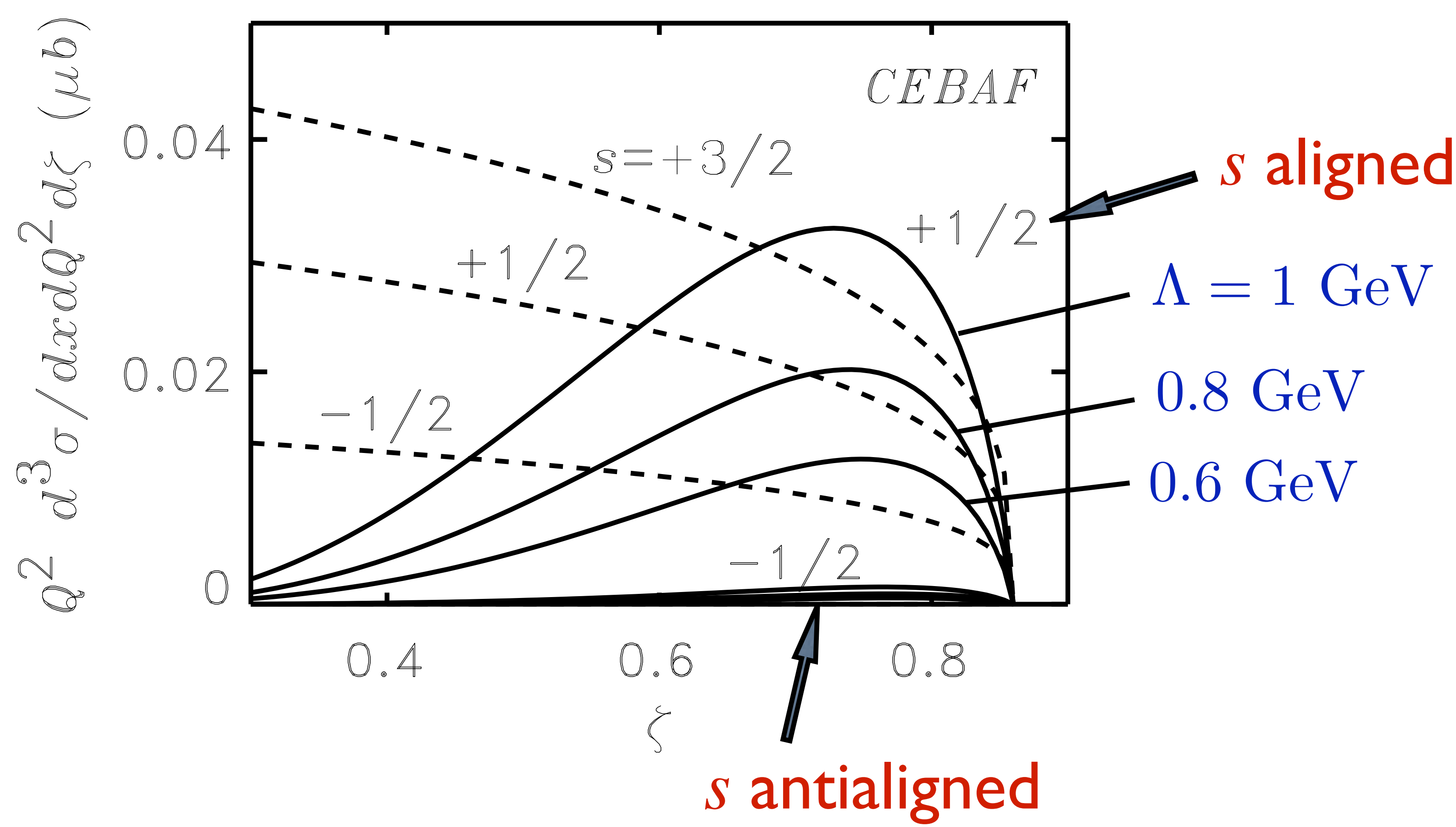
$$\mathcal{T}^{\frac{1}{2}\pm\frac{1}{2}}(t) = \frac{1}{12M_\Delta^2}\left[(M_\Delta - M)^2 - t\right]\left[(M_\Delta^2 + M)^2 - t\right]^2 \times (1 \pm \cos\alpha)$$

$$\alpha = \hat{S}\cdot\hat{s} = \hat{p}_z$$

⟹ spins of target and recoil baryon correlated

$S = +1/2$ target

$E = 8\ \mathrm{GeV},\ x = 0.14,\ Q^2 = 2\ \mathrm{GeV}^2$

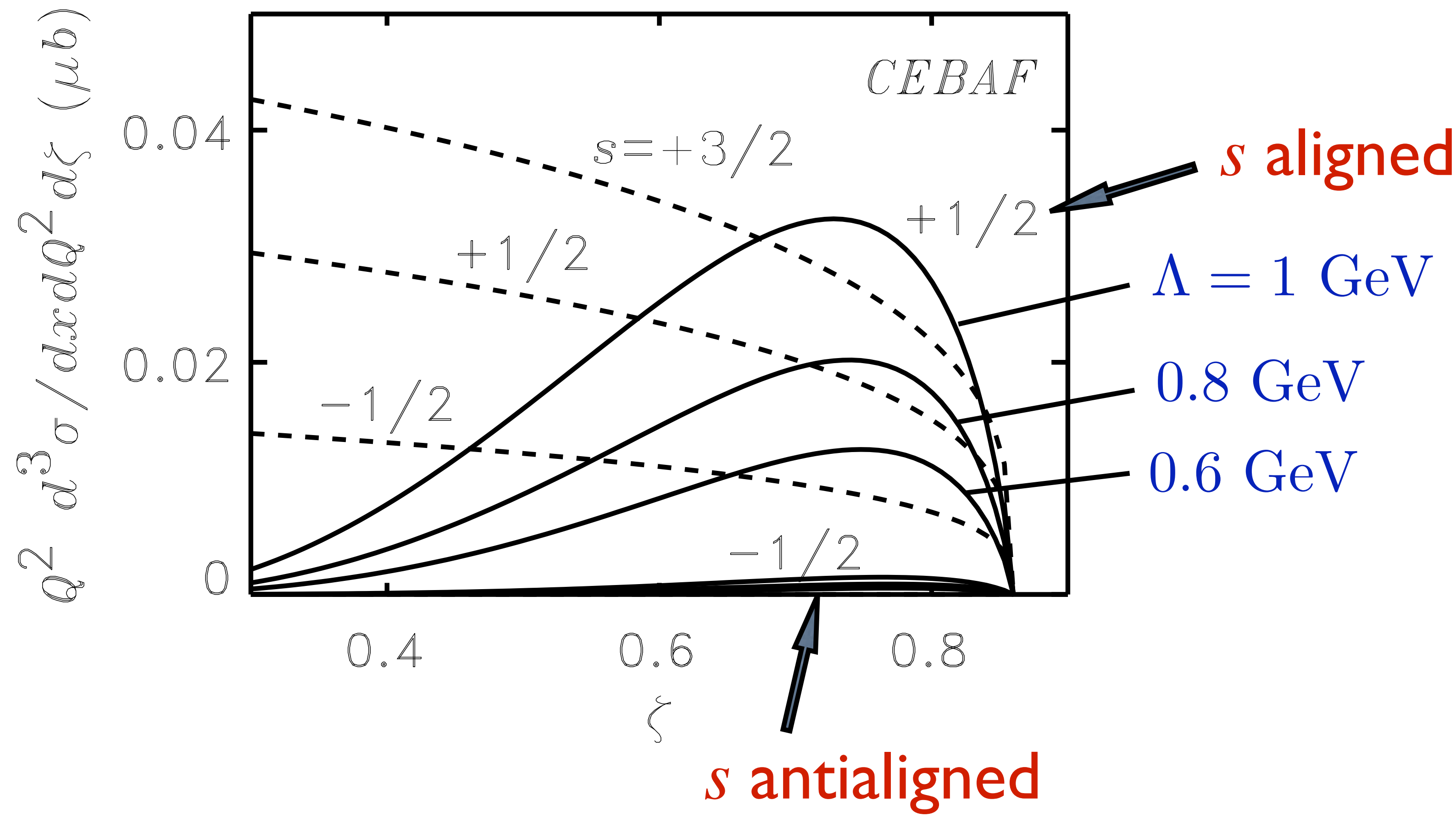


$$\mathcal{F}_{\pi\Delta} = \left(\frac{\Lambda^2 + M^2}{\Lambda^2 + s_{\pi\Delta}}\right)^2$$

$$s_{\pi\Delta} = (m_\pi^2 + p_\perp^2)/(1-\zeta) + (M_\Delta^2 + p_\perp^2)/\zeta$$

$$\langle n \rangle_{\pi\Delta} \approx \{0.01, 0.02, 0.04\}$$

$S = +1/2$ target $\quad E = 8$ GeV, $x = 0.14$, $Q^2 = 2$ GeV^2



$\Longrightarrow$ strong correlation between spins of target p and Δ^{++}

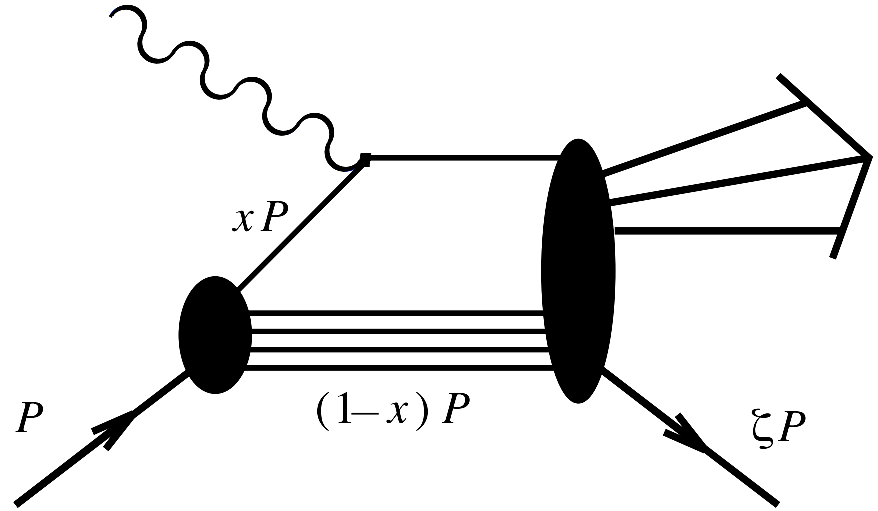
Fragmentation backgrounds

Uncorrelated spectator ("diquark") fragmentation

$$\frac{d^4\sigma^{(s)}}{dx\,dQ^2\,dz\,dp_T^2} \propto \mathcal{F}_{p\uparrow}(x, Q^2)\ \widetilde{D}^s_{p\uparrow - q\uparrow\downarrow}(z, p_T^2)$$

$$D^s_{p\uparrow - q\uparrow\downarrow}\left(z = \frac{\zeta}{1-x}\right)\ \varphi(p_T^2)$$

spin-dependent fragmentation function
for spectator "diquark" $\rightarrow \Delta^{++}$



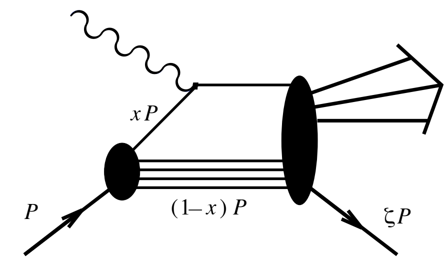
At large z dominant fragmentation: $uu \rightarrow \Delta^{++}$

$$D_{uu} \approx \alpha(1-z)^{\beta}\ , \qquad \alpha \approx 0.68\ , \quad \beta \approx 0.3$$

with $D_{ud} \approx 0.1 D_{uu}$

EMC, Nucl. Phys. B264, 739 (1986)

Spin-dependent fragmentation



Assume "diquark" retains helicity during decay
($q\bar{q}$ pair creation independent of struck q helicity)

$\Longrightarrow$ produced baryon contains helicity of "diquark"

$e.g.\;\; q^\uparrow q^\uparrow \to \Delta^\Uparrow \;,\;\; q^\uparrow q^\uparrow \to \Delta^\uparrow$ allowed

$q^\uparrow q^\uparrow \to \Delta^\Downarrow$ not allowed

$$\{\Uparrow, \uparrow, \downarrow, \Downarrow\} \Longleftrightarrow \{s = +3/2, +1/2, -1/2, -3/2\}$$

Use SU(6) symmetry to relate different $qq \to \Delta^{++}$ fragmentation functions $D^s_{qq_{j\,(j_z)}}$

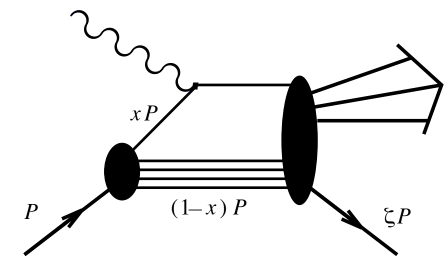
$$D^\Uparrow_{uu_{1(1)}}(z) = 3\; D^\uparrow_{uu_{1(1)}}(z) = \frac{3}{2} D^\uparrow_{uu_{1(0)}}(z) = \frac{3}{2} D^\downarrow_{uu_{1(0)}}(z)$$

with

$$D^\Uparrow_{uu_{1(1)}}(z) = \frac{3}{4} D_{uu}(z)$$

single $q\bar{q}$ pair from vacuum

Spin-dependent fragmentation



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$q\bar{q}$ pair creation independent of struck q helicity

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$$\{\Uparrow, \uparrow, \downarrow, \Downarrow\} \Longleftrightarrow \{s = +3/2, +1/2, -1/2, -3/2\}$$

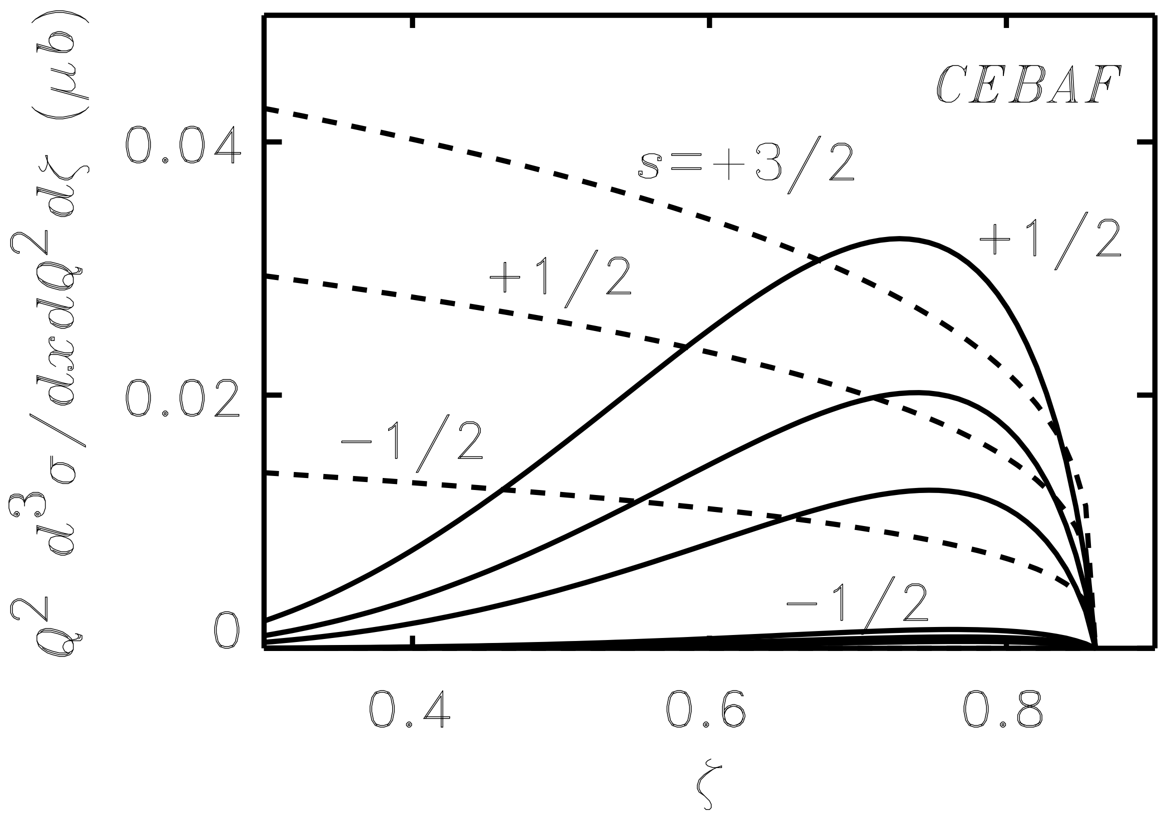
$p_{\perp}$-integrated cross section

$$\Longrightarrow \frac{d^3\sigma^{(s)}}{dx dQ^2 d\zeta} = \left(\frac{2\pi\alpha^2}{M^2E^2x(1-x)}\right)\left(\frac{1}{2x^2} + \frac{4M^2E^2}{Q^4}\left(1 - \frac{Q^2}{2MEx} - \frac{Q^2}{4E^2}\right)\right)$$

$$\times\left[\frac{4x}{9}\left(u_V^{\uparrow}D^s_{ud_{1(0)}} + 2\bar{u}^{\uparrow}\left(\frac{2}{3}D^s_{uu_{1(1)}} + \frac{1}{3}D^s_{uu_{1(0)}}\right) + u_V^{\downarrow}D^s_{ud_{1(1)}} + 2\bar{u}^{\downarrow}\left(\frac{2}{3}D^s_{uu_{1(1)}} + \frac{1}{3}D^s_{uu_{1(0)}}\right)\right)\right.$$

$$\left. + \frac{x}{9}\left(d_V^{\uparrow}D^s_{uu_{1(0)}} + 2\bar{d}^{\uparrow}\left(\frac{2}{3}D^s_{uu_{1(1)}} + \frac{1}{3}D^s_{uu_{1(0)}}\right) + d_V^{\downarrow}D^s_{uu_{1(1)}} + 2\bar{d}^{\downarrow}\left(\frac{2}{3}D^s_{uu_{1(1)}} + \frac{1}{3}D^s_{uu_{1(0)}}\right)\right)\right]$$

$S = +1/2$ target $\quad E = 8\ \mathrm{GeV},\ x = 0.14,\ Q^2 = 2\ \mathrm{GeV}^2$



- weaker correlation between spins of target p and Δ^{++} from diquark fragmentation

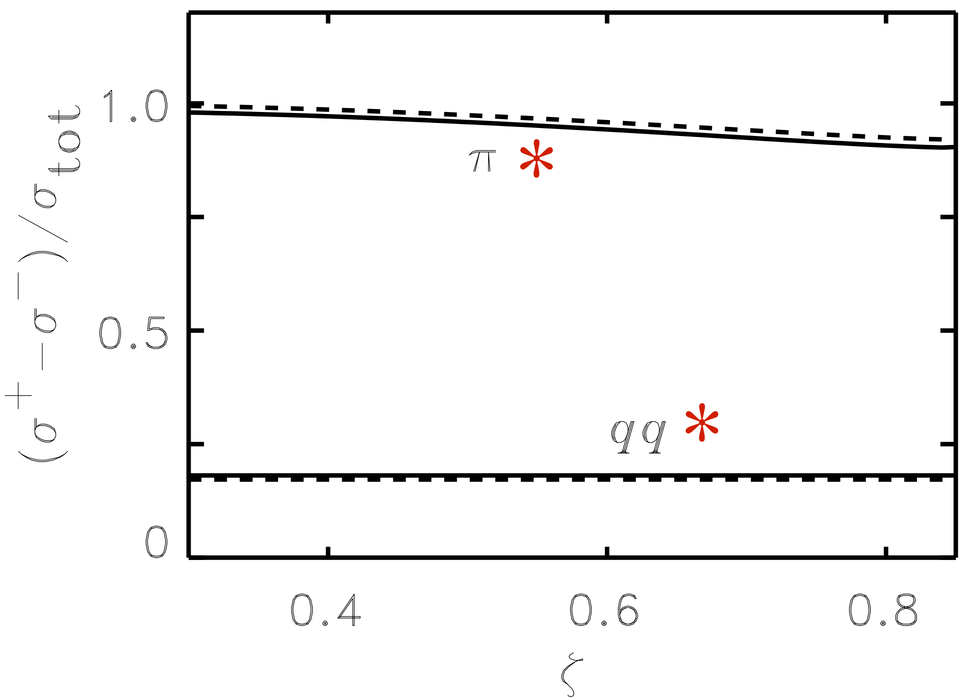
- Δ^{++} produced in ratio $s = +3/2 : +1/2 : -1/2 : -3/2$

$$\approx \quad 3 \quad : \quad 2 \quad : \quad 1 \quad : \quad 0$$

Polarization asymmetry

Differences between π-exchange and fragmentation models enhanced through polarization asymmetries

$$\sigma^{\pm} \equiv Q^2 d^3\sigma^{(s=\pm 1/2)}/dx dQ^2 d\zeta$$



→ independent of $\pi N \Delta$ form factor !

* assumes no interference

→ deviation from partonic prediction will indicate strength of π-exchange contribution

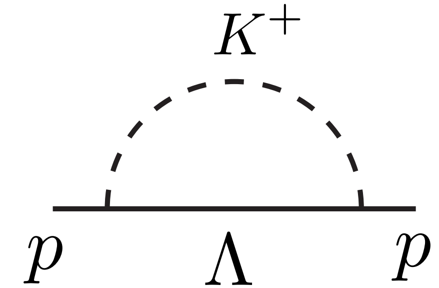
→ place *lower* limit on $\langle n \rangle_{\pi\Delta}$

K cloud and Λ production

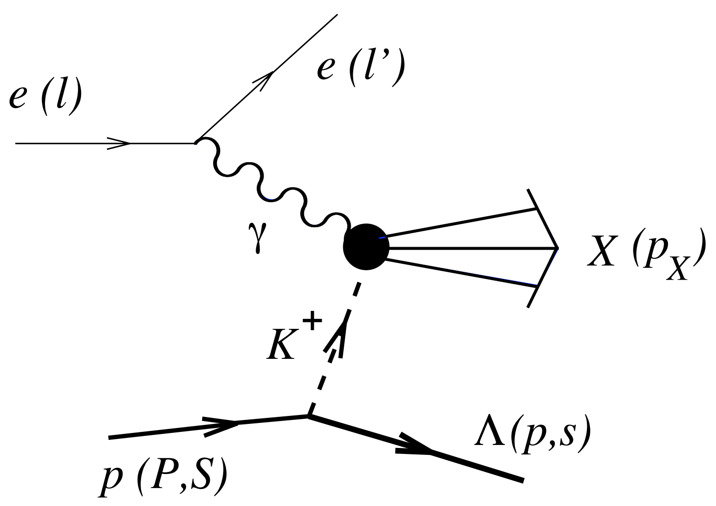
K cloud model of strangeness in N

$$p^{\uparrow} \rightarrow \Lambda^{\downarrow} K^{+} \rightarrow p^{\uparrow}$$

$$(uud)^{\uparrow} \rightarrow \left[(ud)_0 \; s^{\downarrow}\right] \; (u\bar{s})_0$$

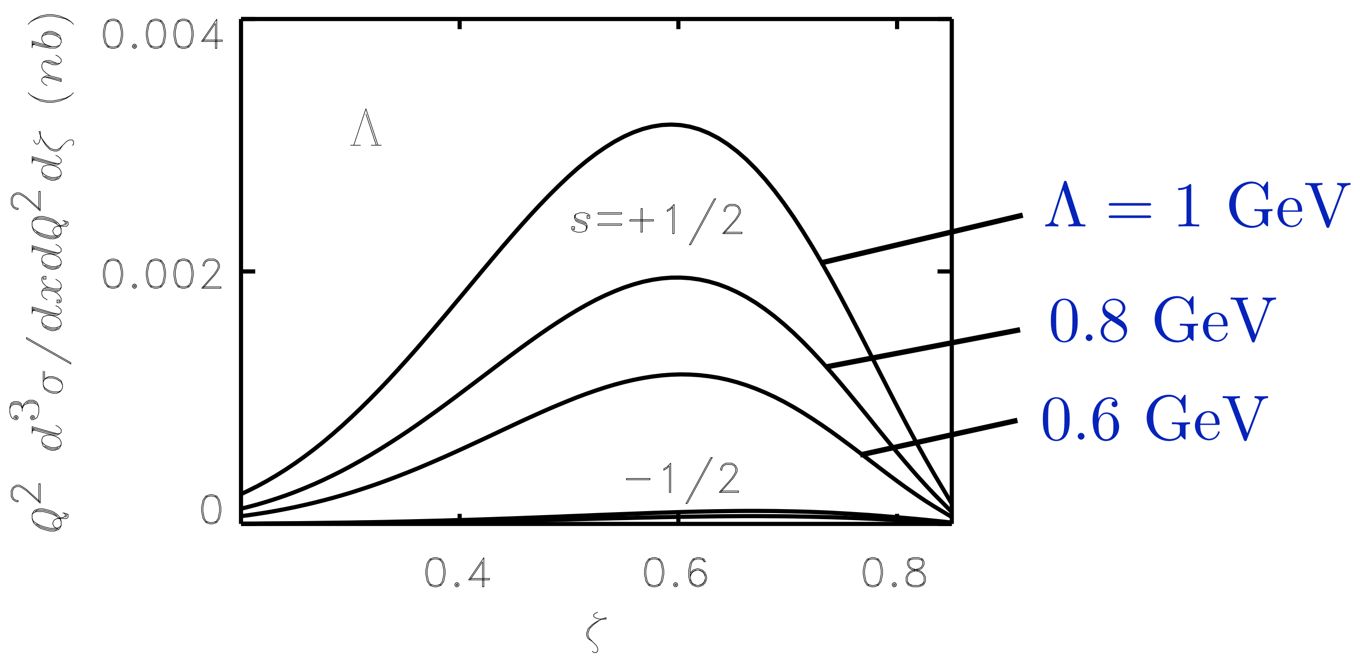


SIDIS from K cloud



$$\mathcal{T}^{+\frac{1}{2}\;\pm\frac{1}{2}}(t) = \frac{1}{2}\left((M_\Lambda - M)^2 - t\right) \times \left(1 \pm \cos\alpha\right)$$

K cloud and Λ production



$\Longrightarrow$ strong correlation between spins of target p and Λ

... in contrast with $qq \to \Lambda$ fragmentation

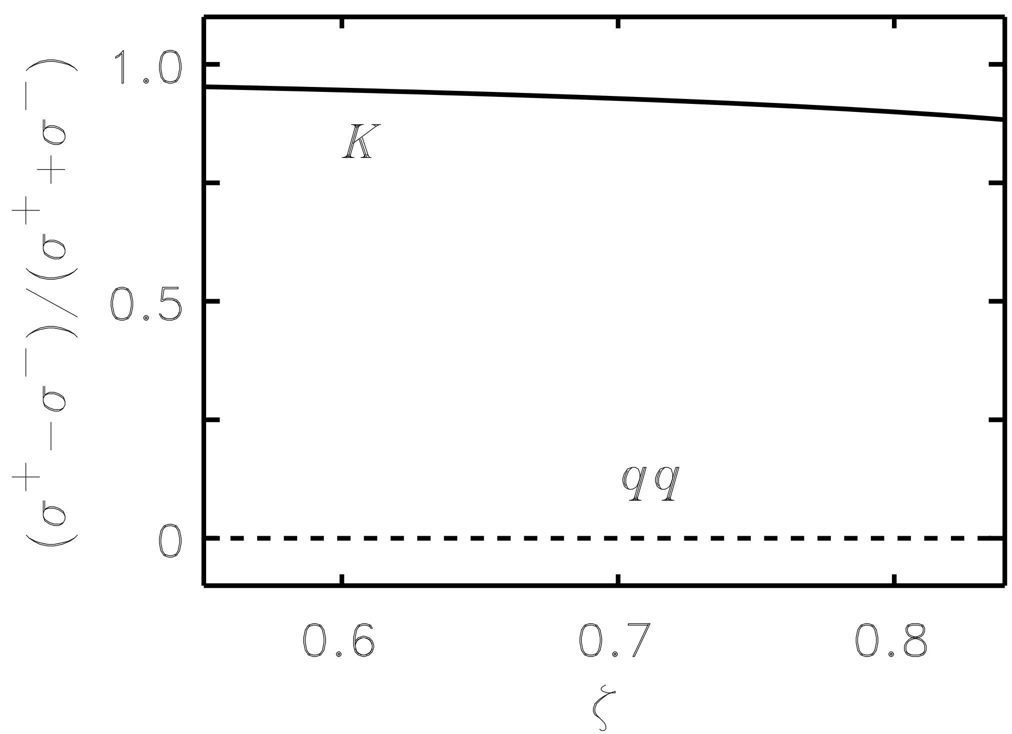
K cloud and Λ production

In SU(6) limit s quark carries spin of Λ

$$\Lambda^{\uparrow\downarrow} \sim (ud)_0 \, s^{\uparrow\downarrow}$$

- leading fragmentation function $D_{ud_{0(0)}}^{\Lambda^{\uparrow\downarrow}}$

- equal probability to form $\Lambda^{\uparrow}$ and $\Lambda^{\downarrow}$



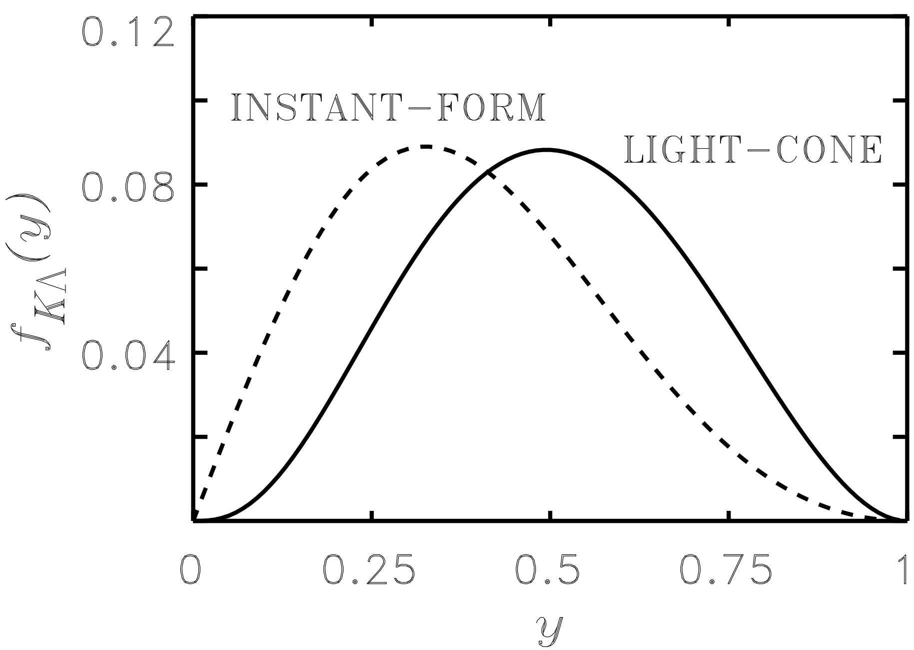
- expect small (zero?) asymmetry from fragmentation

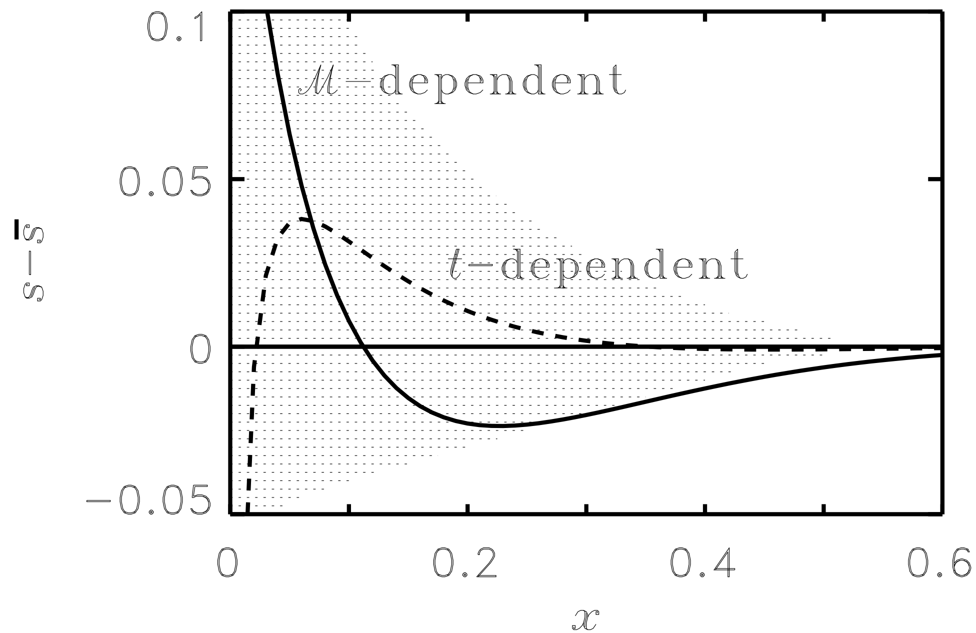
Summary

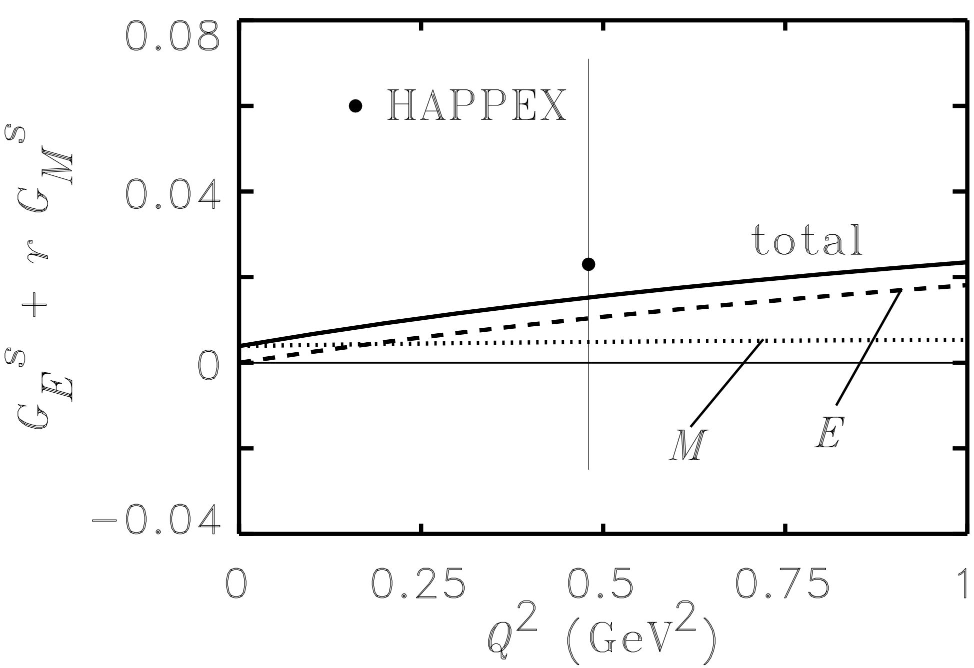
- Production of baryons $(\Delta^{++},\ \Lambda)$ in semi-inclusive DIS can reveal signature of t-channel meson exchange

- Provide direct evidence of chiral physics in flavor and spin parton distributions of N

- Compare with JLab data !







WM, Malheiro (1997)

Gottfried sum rule

Integrated difference of p and n structure functions

$$S_G = \int_0^1 dx \; \frac{F_2^p(x) - F_2^n(x)}{x}$$
$$= \frac{1}{3} + \frac{2}{3} \int_0^1 dx \; (\bar{u}(x) - \bar{d}(x))$$

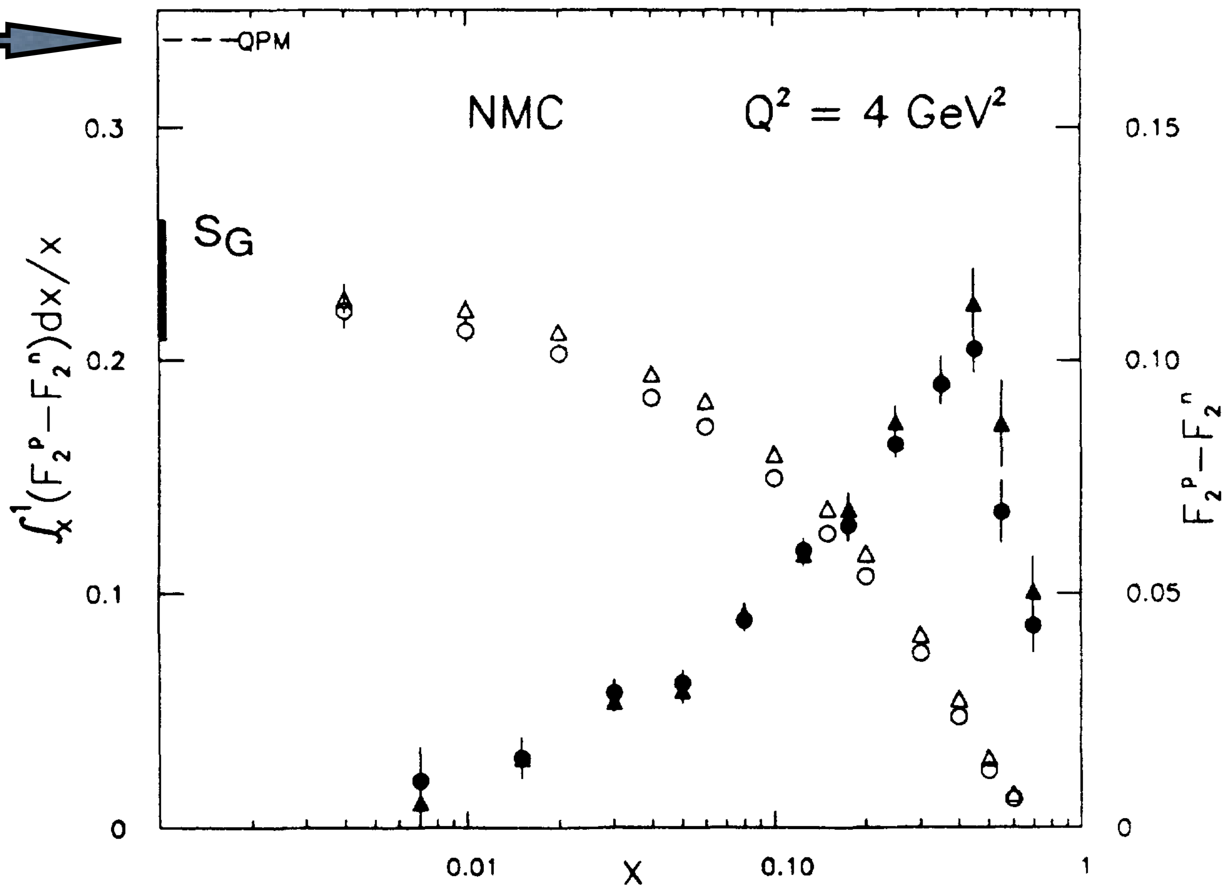
Experiment: $S_G = 0.235 \pm 0.026$

NMC, Phys. Rev. D 50 (1994) 1

$\Longrightarrow$ $\bar{d}(x) \neq \bar{u}(x)$ flavor asymmetric sea!

Saturation of Gottfried sum rule

$\bar{d} = \bar{u}$



NMC, Phys. Rev. D 50 (1994) 1