Nucleon Spin & Flavor Structure
... and Fragmentation too

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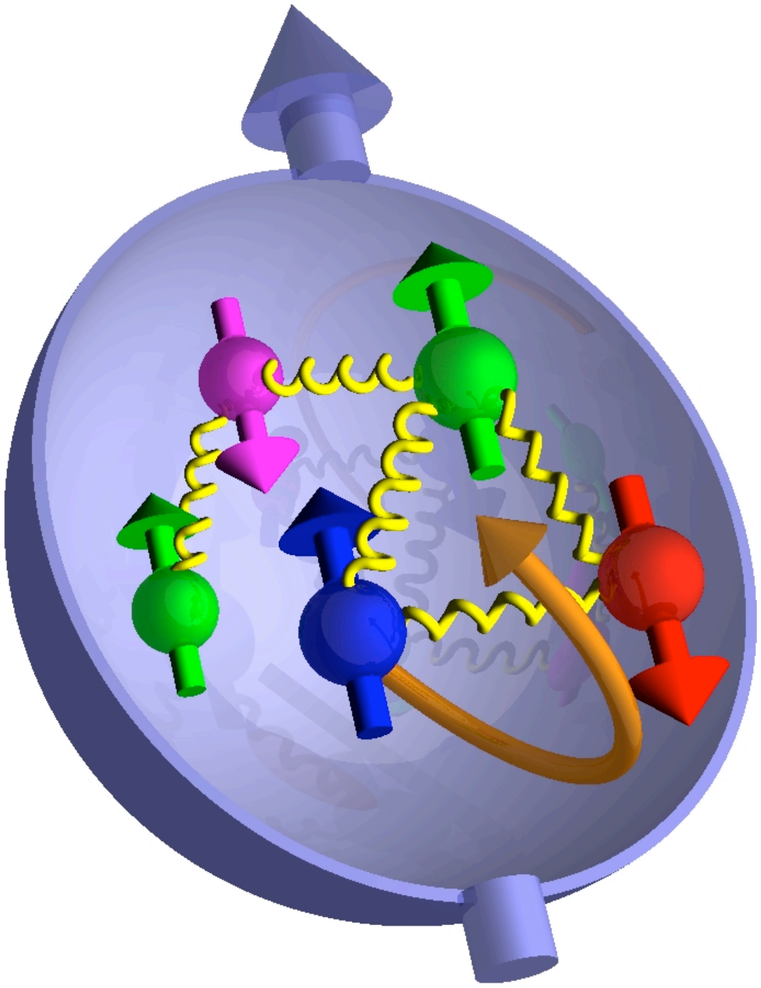
- ***Quark Models:***
  how to think about the proton?
- ***Deep-Inelastic Scattering:***
  parton distribution functions
  and fragmentation functions
- ***The Spin Puzzle***
  and quark polarization
- ***Single-Spin Asymmetries:***
  new structures within the proton
  and the fragmentation process



The Wacky World of Quarks

The Quark Model

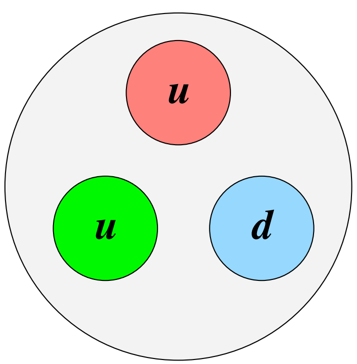
Hadrons are composed of **quarks** with :

❶ **flavor**: u,c,t (charge +2/3) d,s,b (charge -1/3) ❷ **color**: R,G,B ❸ **spin**: 1/2

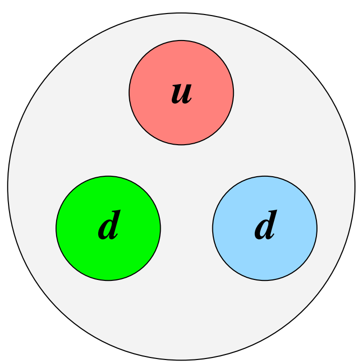
Each hadron observed in nature is white ("color singlet")

➢ **Baryons** 3-quark systems, with colors RGB

➢ **Mesons** quark + antiquark with colors $C\bar{C}$



proton



neutron

*The **spectrum** of observed hadrons is (roughly) explained:*

Mesons: Spin 0

π^+	$u\bar{d}$
π^-	$d\bar{u}$
π^0	$u\bar{u} \oplus d\bar{d}$
K^+	$u\bar{s}$
K^-	$s\bar{u}$
K^0	$d\bar{s}$
$\overline{K^0}$	$s\bar{d}$
η	$u\bar{u} \oplus d\bar{d} \oplus s\bar{s}$
η'	$u\bar{u} \oplus d\bar{d} \oplus s\bar{s}$

Mesons: Spin 1

ρ^+	$u\bar{d}$
ρ^-	$d\bar{u}$
ρ^0	$u\bar{u} \oplus d\bar{d}$
K^{*+}	$u\bar{s}$
K^{*-}	$s\bar{u}$
K^{*0}	$d\bar{s}$
$\overline{K^{*0}}$	$s\bar{d}$
ϕ	$s\bar{s}$
ω	$u\bar{u} \oplus d\bar{d} \oplus s\bar{s}$

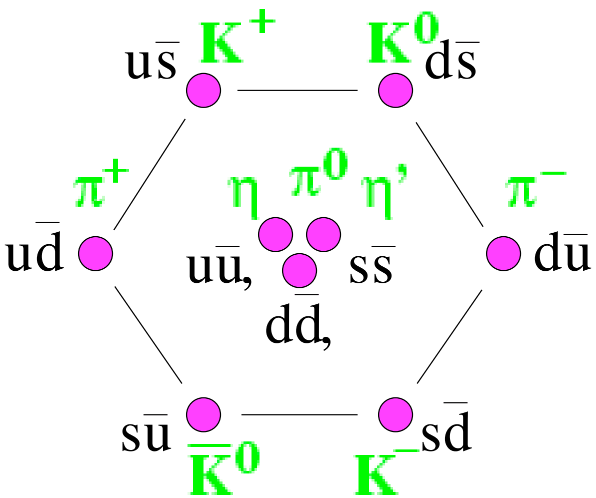
Baryons: Spin 1/2

p	uud
n	udd
Σ^+	uus
Σ^0	uds
Σ^-	dds
Λ	uds
Ξ^0	uss
Ξ^-	dss

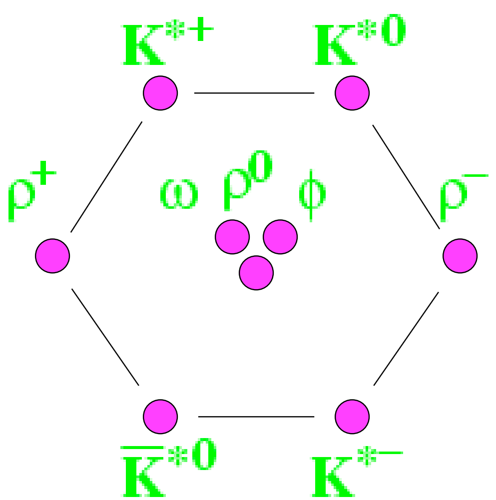
Hadronic Multiplets

- **MESONS =** $q\bar{q}$
- **BARYONS =** qqq or $\overline{qqq}$

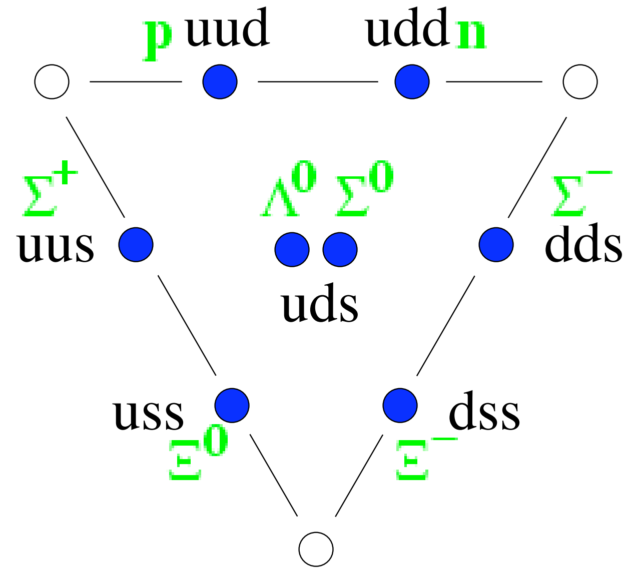
SPIN 0 (↑↓)



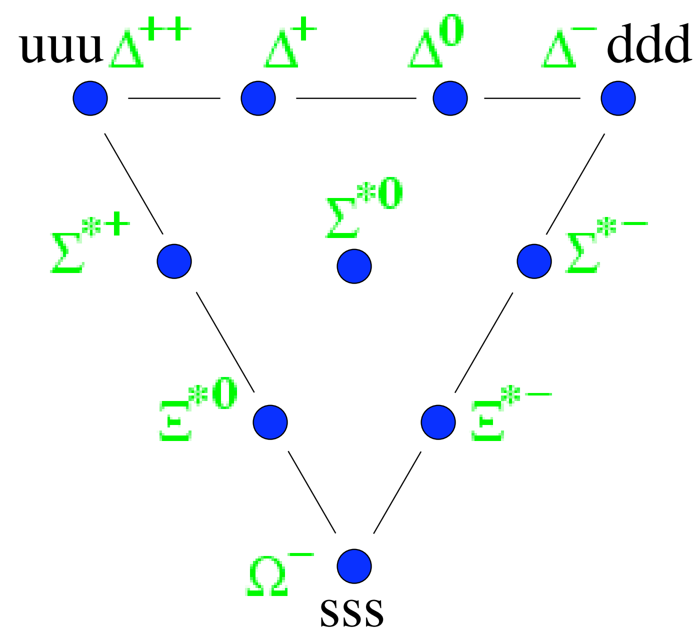
SPIN 1 (↑↑)



SPIN 1/2 (↑↓↑)



SPIN 3/2 (↑↑↑)



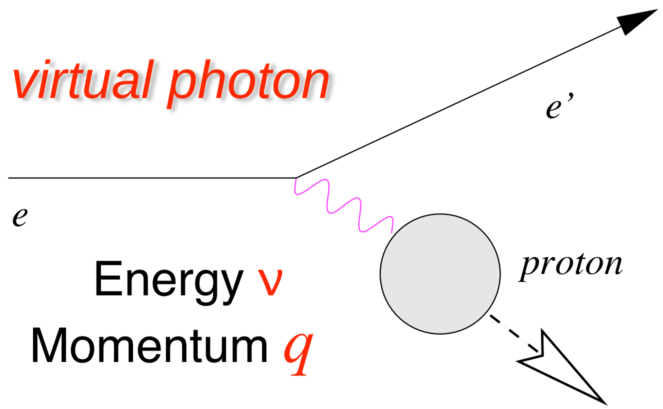
Murray Gell-Mann, 1964:

"A search for stable quarks ... at the highest energy accelerators would help to reassure us of the non-existence of real quarks."

Electron Scattering and Scaling

Elastic scattering from the proton:

virtual photon

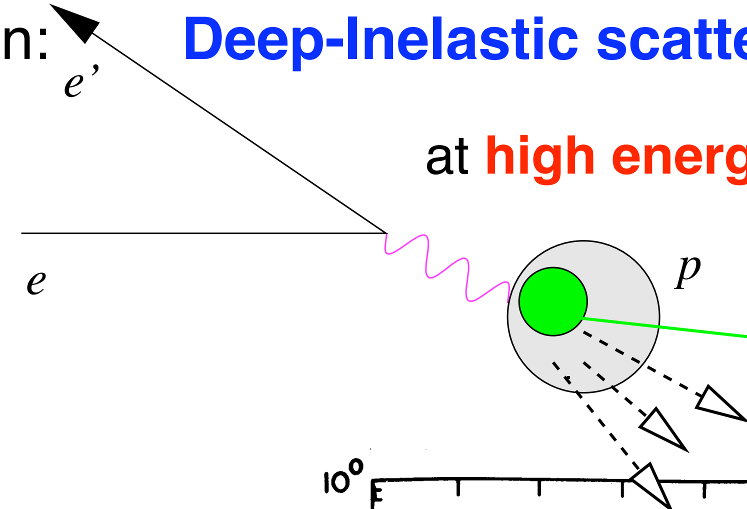


Energy ν

Momentum q

Deep-Inelastic scattering (DIS):

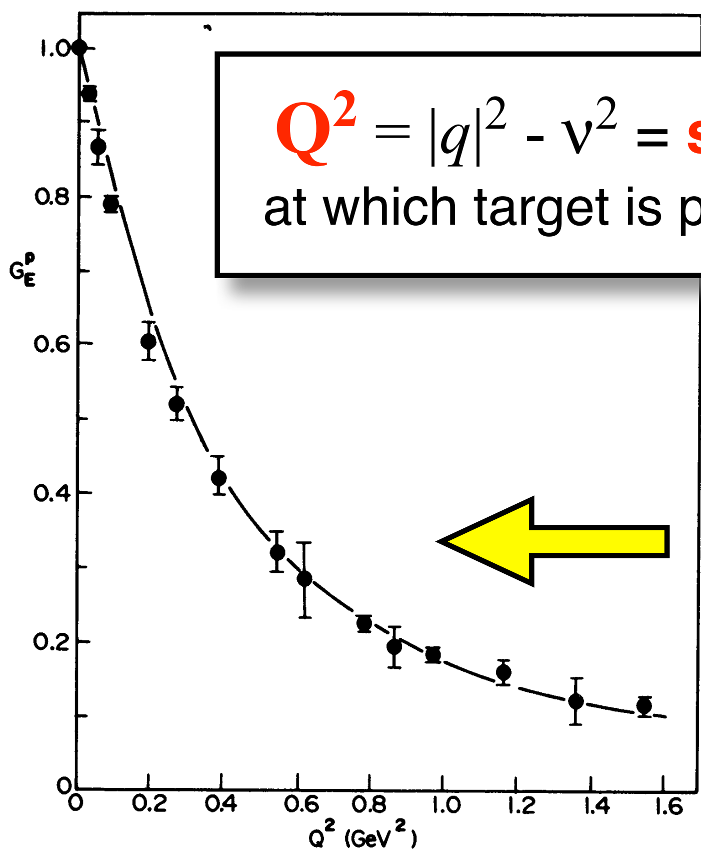
at **high energies** you see ...



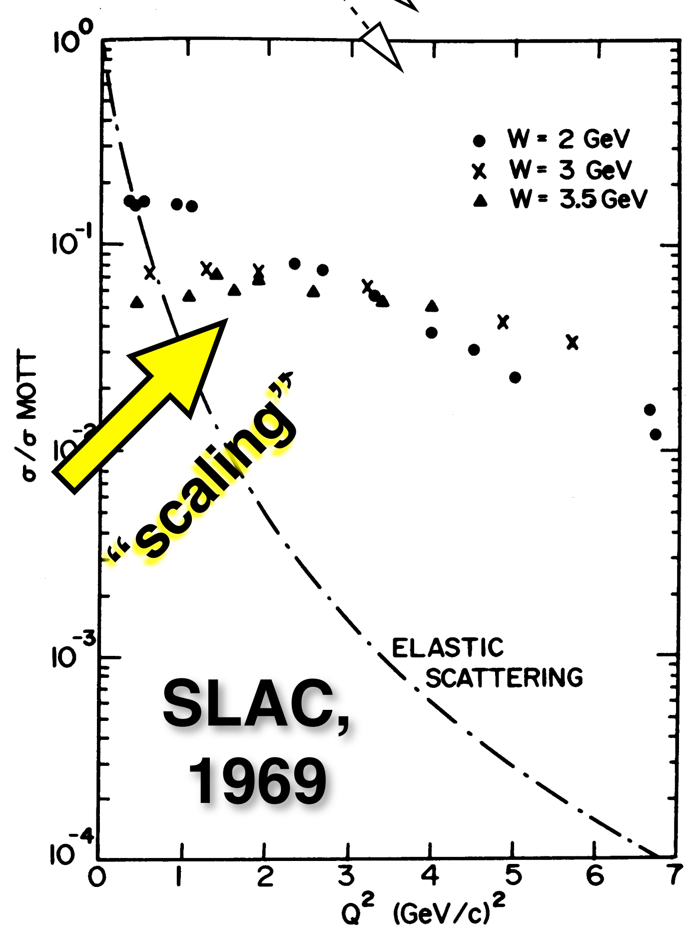
hard, pointlike constituents !

$Q^2 = |q|^2 - \nu^2$ = **scale**

at which target is probed



$$\frac{\sigma(Q^2)}{\sigma_{point}(Q^2)}$$

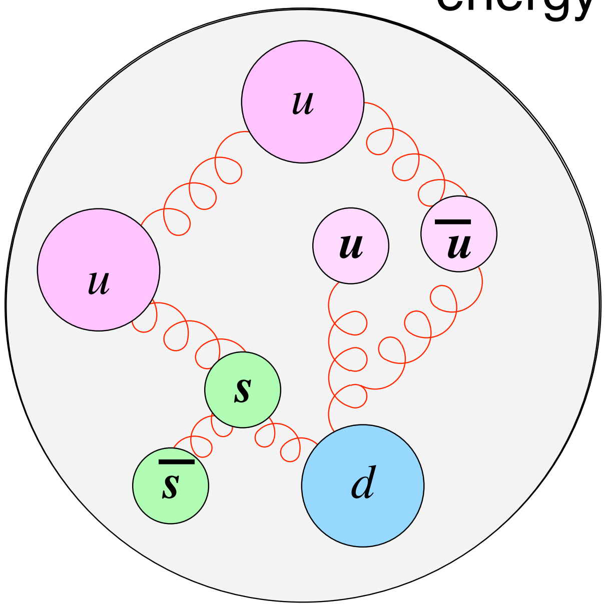


"scaling"

SLAC, 1969

Parton Distribution Functions

Let's look ***inside*** the proton: **Deep-Inelastic Scattering** (DIS) with high energy beams ⇒ a rich substructure is revealed!



sea quarks : virtual quark-antiquark pairs that fluctuate in and out of the vacuum!

gluons : carriers of the strong force

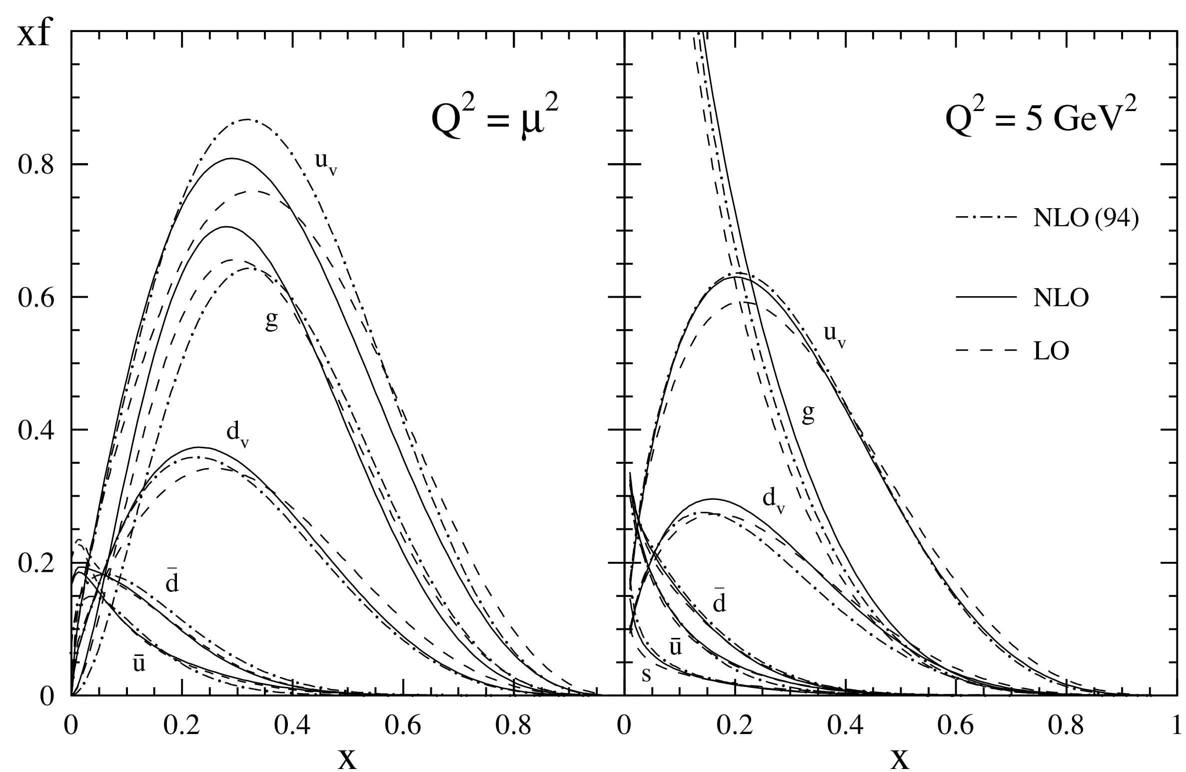
x fraction of proton momentum carried by struck quark

$q(x)$ parton distribution func^{n}
(number density for quark flavor q)

3 **constituent quarks** of mass ≈ 350 MeV

⬇

∞ many **current quarks** with bare masses ≈ 5 MeV



Quantum Chromodynamics

The Theory of the Strong Interaction

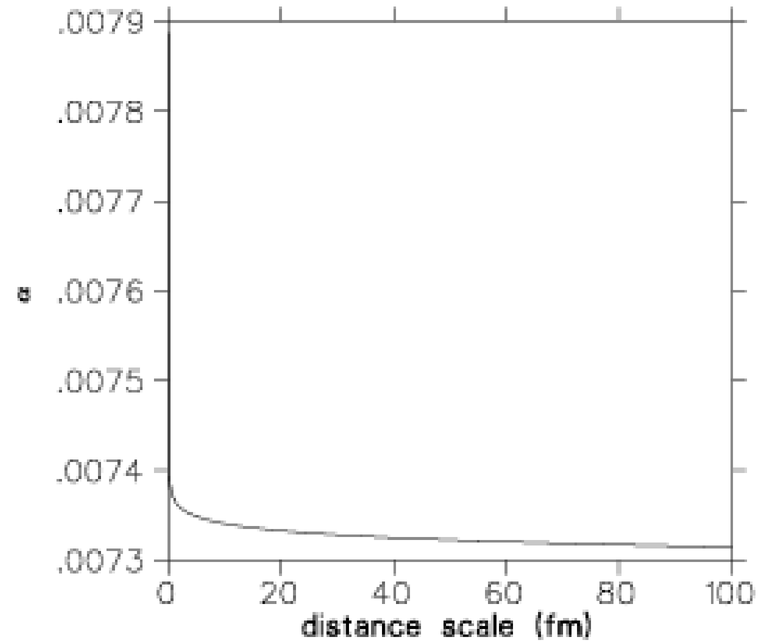
$$\mathcal{L}_{\mathrm{QCD}} = -\Psi\left\{\gamma_\mu[\partial_\mu - \frac{i}{2}g\lambda^a A^a_\mu(x)] + M\right\}\Psi - \frac{1}{4}\mathcal{F}^a_{\mu\nu}\mathcal{F}^a_{\mu\nu}$$

The End.

Bound States in QED and QCD

QED

Coupling α = 1/137 is weak at relevant scales



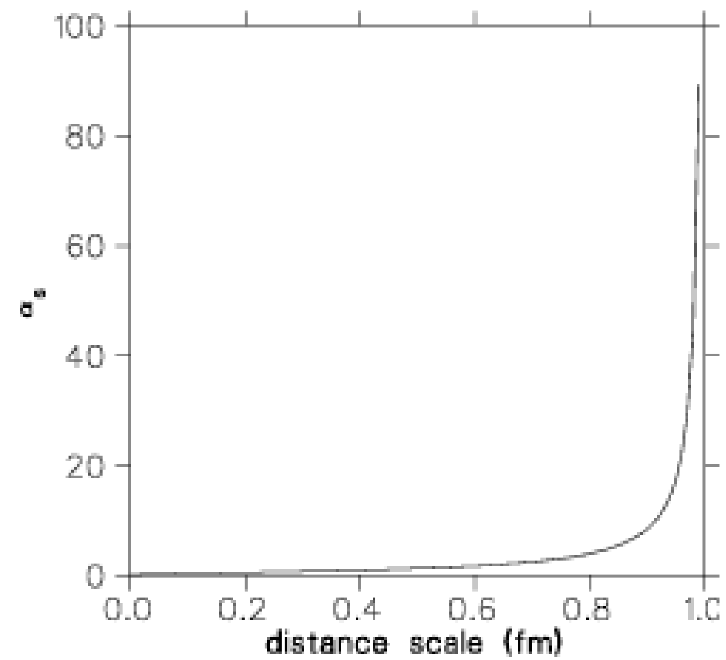
✔ **Perturbation theory** works very well

✔ **Non-relativistic** quantum mechanics ok

e.g. Hydrogen: binding E = 13.6 eV << M_{elec} = 511 keV

QCD

Coupling α_s ***blows up*** at relevant scales !

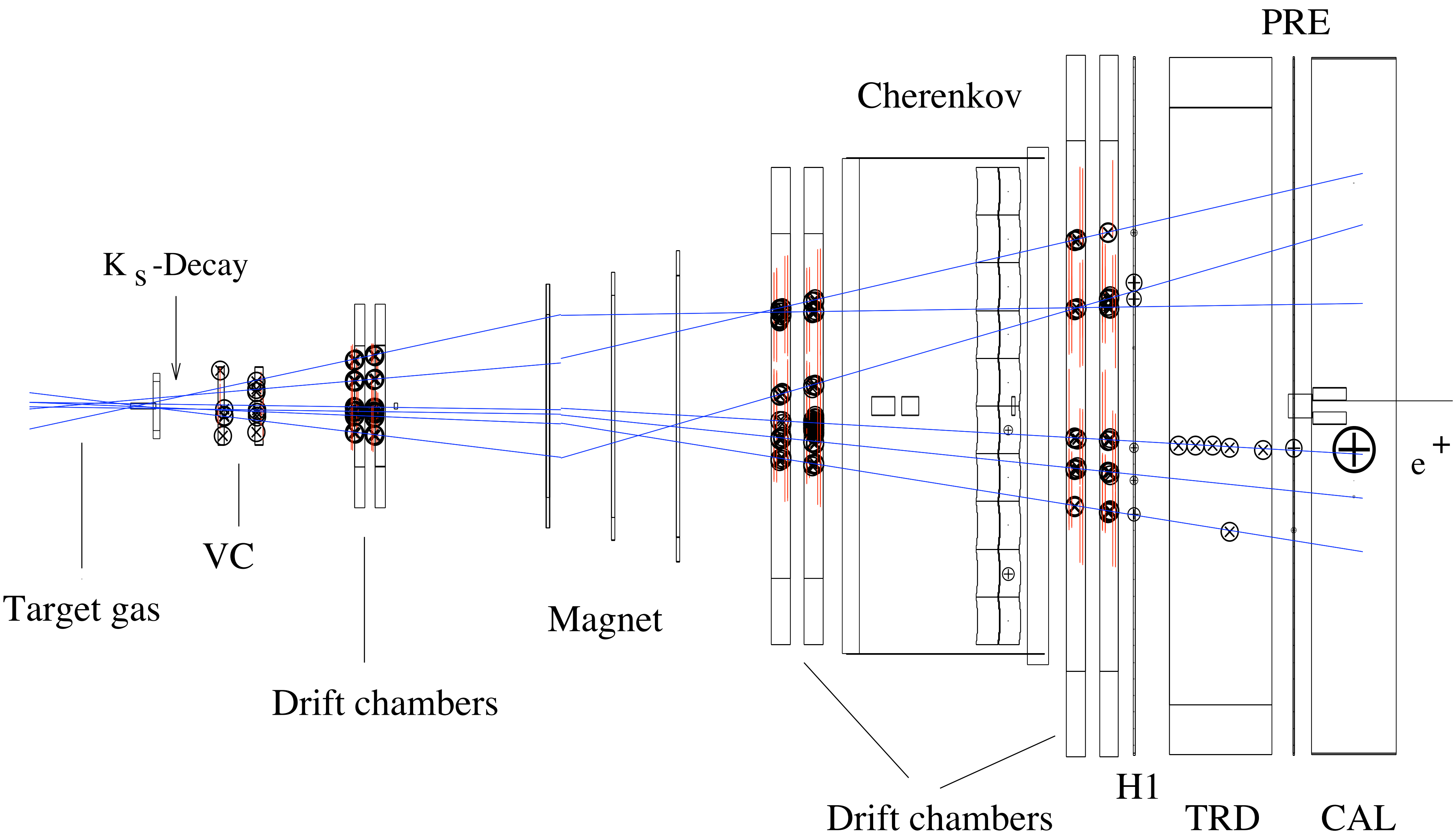


✘ **Perturbation** theory **impossible**

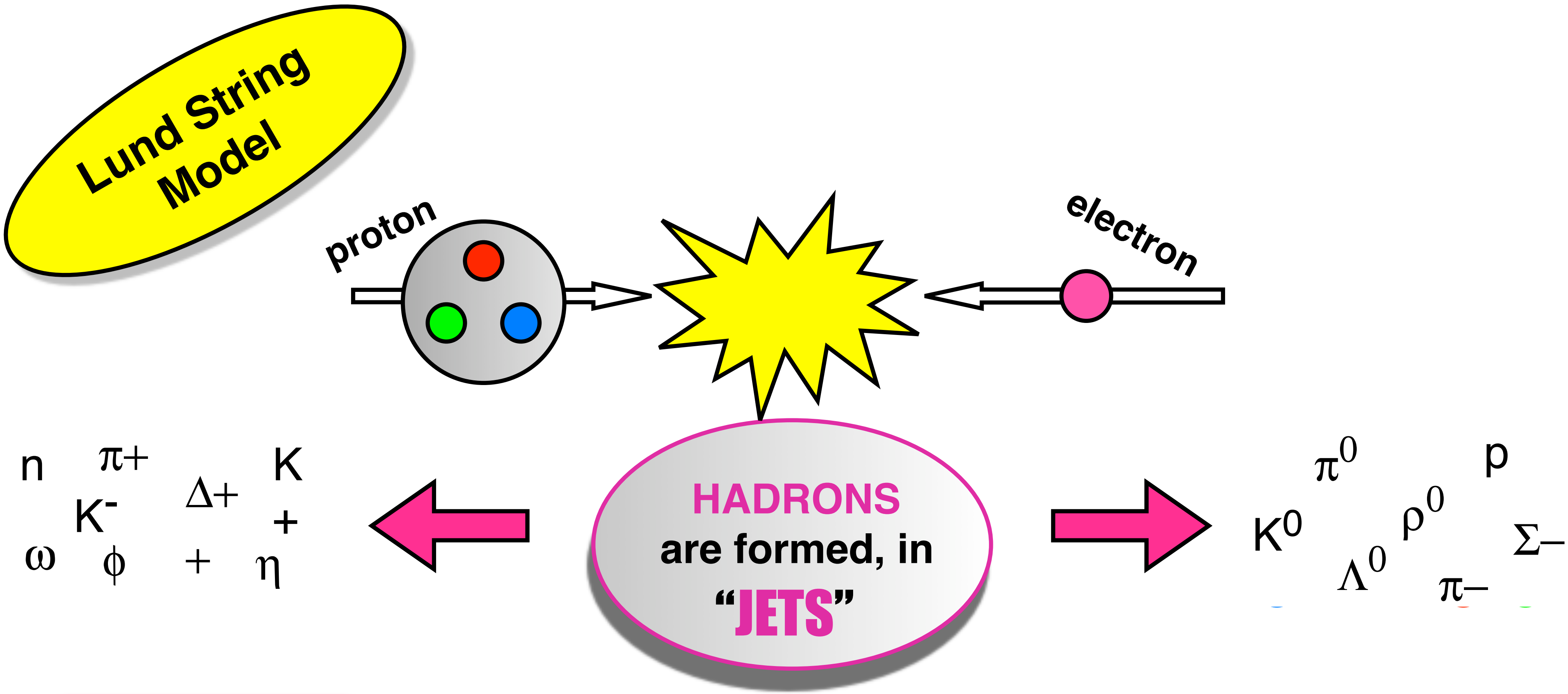
✘ Bound systems inherently **relativistic**

e.g. Proton: Mass = 938 MeV >> bare m_{quark} = 5 MeV !

And here's something else we can't calculate ...



What Happens in a High Energy Collision



$$z \equiv E_h / E_q$$

Confinement at Work !

Creation of **hadrons** from **struck quark**: the **"fragmentation process"**

Fragmentation Functions

$$D_q^h(z)$$

*describe **number density** of **hadrons** of type h and energy-fraction z produced from a **struck quark** of flavor q*

$$z \equiv E_h / E_q$$

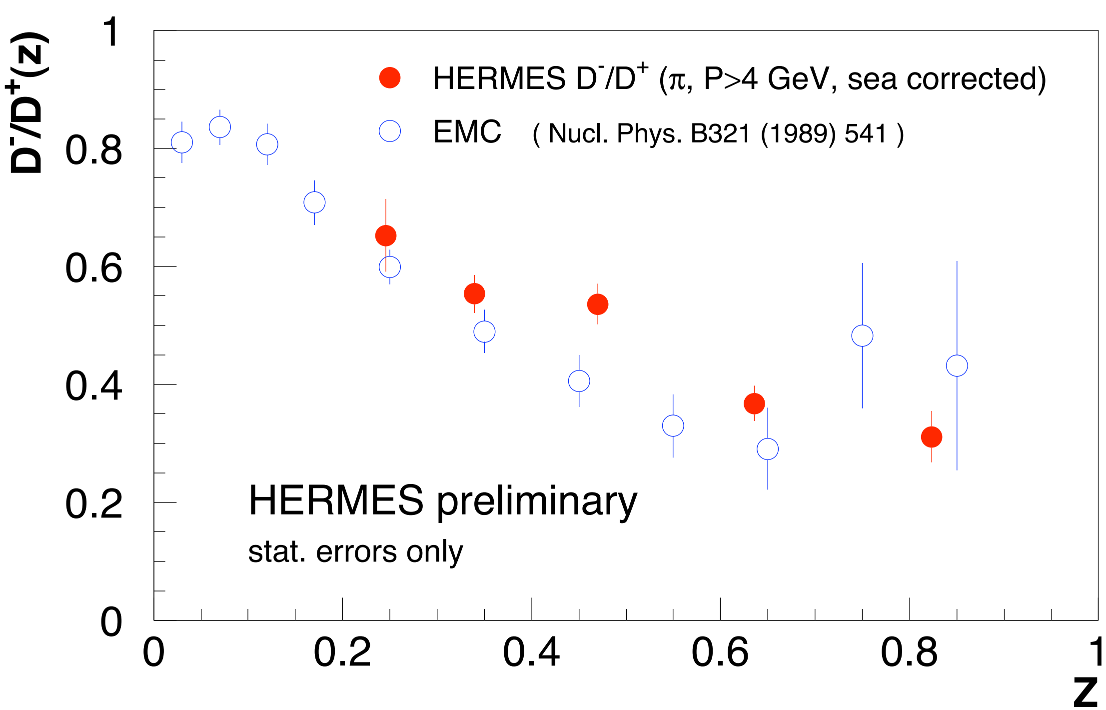
Symmetries: **favored / disfavored** FF's for pions:

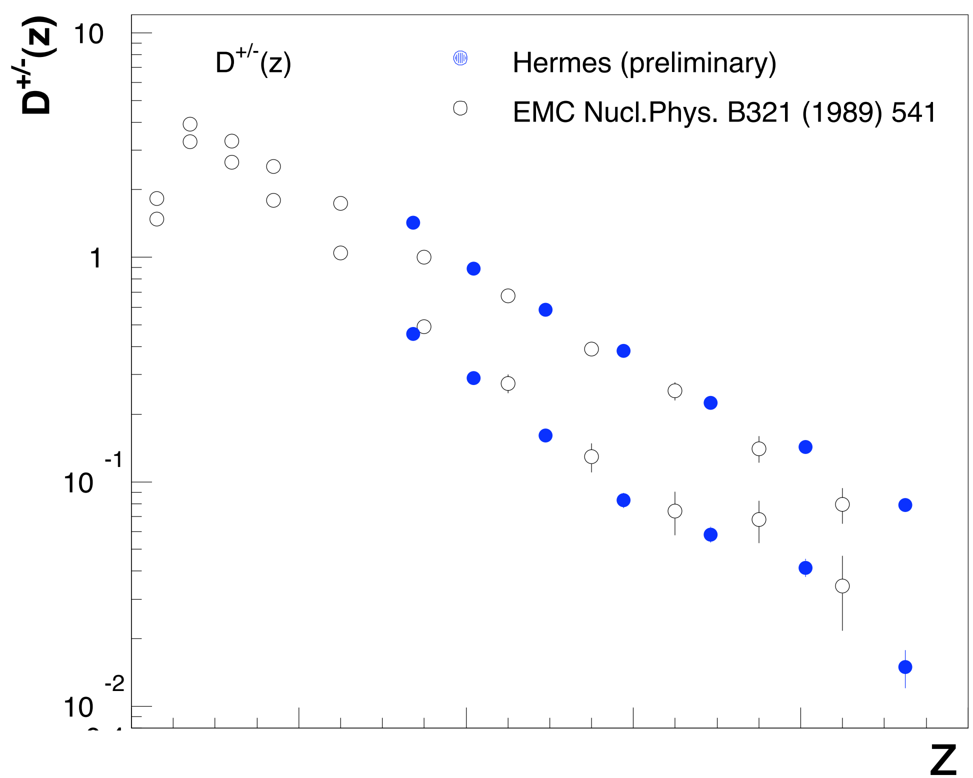
$$D_{\text{fav}}(\text{or } D^+) \equiv D_u^{\pi^+} = D_d^{\pi^-} = D_{\bar{d}}^{\pi^+} = D_{\bar{u}}^{\pi^-}$$

$$D_{\text{dis}}(\text{or } D^-) \equiv D_u^{\pi^-} = D_d^{\pi^+} = D_{\bar{d}}^{\pi^-} = D_{\bar{u}}^{\pi^+}$$

$$D_{\text{s}} \equiv D_s^{\pi^+} = D_s^{\pi^-} = D_{\bar{s}}^{\pi^+} = D_{\bar{s}}^{\pi^-}$$

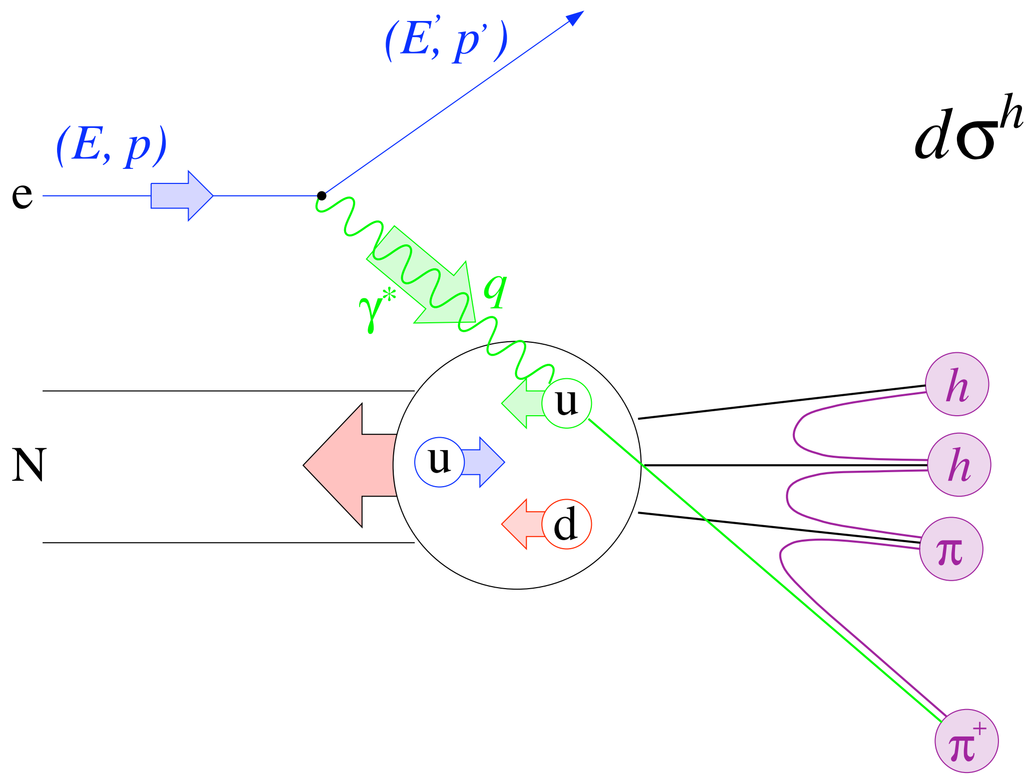
(based on charge-conjugat^n and isospin symmetry)





Semi-Inclusive Deep-Inelastic Scattering (SIDIS)

*In SIDIS, a **hadron h** is detected in **coincidence** with the scattered lepton:*



Factorization of the cross-section:

$$d\sigma^h \sim \sum_q e_q^2 \, q(x) \cdot \hat{\sigma} \cdot D^{q \to h}(z)$$

The perturbative part

Cross-section for elementary photon-quark ***subprocess***

Large energies ➡ asymptotic freedom
➡ can calculate!

The Distribution Function

momentum ***distribution of quarks q*** within their proton bound state

➡ **lattice QCD** progressing steadily

The Fragmentation Function

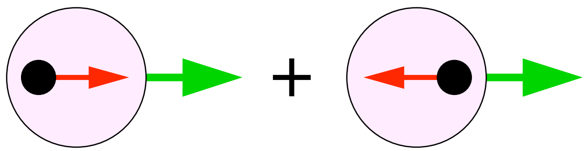
momentum ***distribution of hadrons h*** formed from quark *q*

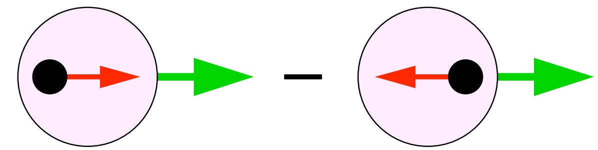
➡ not even lattice can help ...

The Spin Puzzle

A particular puzzle: Where does the proton spin come from?

$$q(x) = q^{\uparrow}(x) + q^{\downarrow}(x) \qquad \Delta q(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$$





only three possibilities ⇒

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

❶ Quark polarization

$$\Delta\Sigma \equiv \int dx\; (\Delta u(x) + \Delta d(x) + \Delta s(x) + \Delta\bar{u}(x) + \Delta\bar{d}(x) + \Delta\bar{s}(x))$$ ≈ 20% only

❷ Gluon polarization

$$\Delta G \equiv \int dx\; \Delta g(x)$$ **?**

❸ Orbital angular momentum

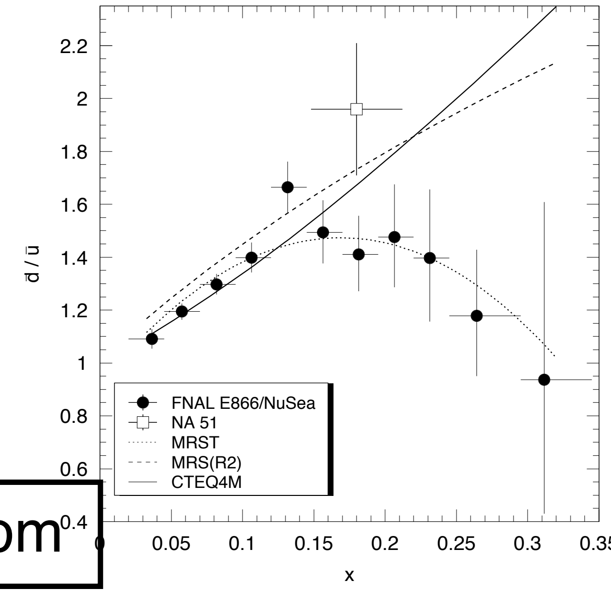
$$L_z \equiv L_q + L_g$$ **?**

In friendly, **non-relativistic** bound states like atoms & nuclei (& constituent quark model), particles are in ***eigenstates of L***

Not so for bound, ***relativistic Dirac particles*** ... Noble "l" is ***not a good quantum number***

Flavor Structure of the Proton

E866: $\bar{d}/\bar{u} > 1$



Constituent Quark Model

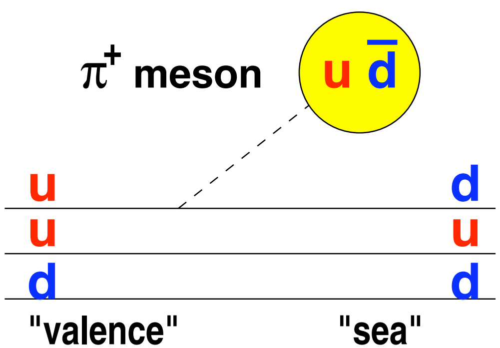
Pure valence description: proton = $2u + d$

Perturbative Sea

Sea quark pairs from $g \rightarrow q\bar{q}$ should be flavor symmetric: $\bar{u} = \bar{d}$

Non-perturbative models: alternate deg's of freedom

Meson Cloud Models

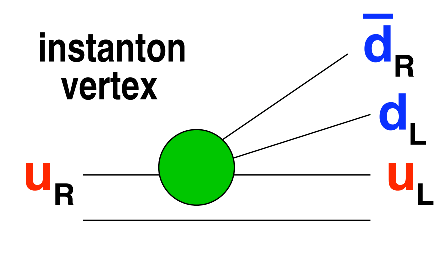


Quark sea from cloud of 0^- mesons: $\bar{d} > \bar{u}$

Chiral-Quark Soliton Model

- quark degrees of freedom in a pion mean-field
- nucleon = chiral soliton
- one parameter: dynamically-generated quark mass
- expand in $1/N_c$

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



'tHooft instanton vertex

$\sim \bar{u}_R u_L \bar{d}_R d_L$

Spin Structure: SU(6) Proton Wave Function in CQM

The 3 quarks are **identical fermions** ⇒ ψ **antisymmetric** under exchange

$$\psi = \psi(\text{color}) * \psi(\text{space}) * \psi(\text{spin}) * \psi(\text{flavor})$$

❶ **Color**: All hadrons are color singlets = **antisymmetric**

$$\psi(\text{color}) = 1/\sqrt{6}\,(\text{RGB - RBG + BRG - BGR + GBR - GRB})$$

❷ **Space**: proton has $l = l' = 0 \rightarrow \psi(\text{space})$ = **symmetric**

❸ **Spin**: $2 \otimes 2 \otimes 2 = (\,3_S \oplus 1_A\,) \otimes 2 = 4_S \oplus 2_{MS} \oplus 2_{MA}$

- 4_S symmetric states have spin 3/2, e.g. $\left|\frac{3}{2},+\frac{3}{2}\right\rangle = \uparrow\uparrow\uparrow$
- 2_{MS} and 2_{MA} have spin 1/2 and **mixed symmetry**:
  S or A under exchange of *first 2* quarks only, e.g.

$$\left|\frac{1}{2},+\frac{1}{2}\right\rangle_{MS} = (\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow - 2\uparrow\uparrow\downarrow)/\sqrt{6} \qquad \left|\frac{1}{2},+\frac{1}{2}\right\rangle_{MA} = (\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow)/\sqrt{2}$$

❹ **Flavor**: symmetry groups SU(2)-spin and SU(3)-color are exact ...

- strong force is ***flavor blind***
- constituent q masses ***similar***: $m_u, m_d \approx$ 350 MeV, $m_s \approx$ 500 MeV

➡ SU(3)-flavor is ***approximate*** for u, d, s

SU(3)-flavor gives $3 \otimes 3 \otimes 3 = 10_S \oplus 8_{MS} \oplus 8_{MA} \oplus 1_A$

➤ **Proton**: $\psi(s{=}1/2)$ from spin $2_{MS}, 2_{MA}$ $\otimes$ $\psi(uud)$ from flavor $8_{MS}, 8_{MA}$

$$|p^\uparrow\rangle = (u^\uparrow u^\downarrow d^\uparrow + u^\downarrow u^\uparrow d^\uparrow - 2u^\uparrow u^\uparrow d^\downarrow + \text{ 2 permutations})/\sqrt{18}$$

➤ Count the number of quarks with spin up and spin down:

$$\langle p^\uparrow|\hat{N}(u^\uparrow)|p^\uparrow\rangle = \frac{30}{18} = \frac{5}{3} \qquad \langle p^\uparrow|\hat{N}(d^\uparrow)|p^\uparrow\rangle = \frac{6}{18} = \frac{1}{3}$$

$$\langle p^\uparrow|\hat{N}(u^\downarrow)|p^\uparrow\rangle = \frac{6}{18} = \frac{1}{3} \qquad \langle p^\uparrow|\hat{N}(d^\downarrow)|p^\uparrow\rangle = \frac{12}{18} = \frac{2}{3}$$

➤ Quark contributions to proton spin are:

$$\Delta u = N(u^\uparrow) - N(u^\downarrow) = +\frac{4}{3} \qquad \Delta d = N(d^\uparrow) - N(d^\downarrow) = -\frac{1}{3}$$

$$\Rightarrow \Delta\Sigma = \Delta u + \Delta d + \Delta s = 1$$

All spin present & accounted for!

CQM / SUR(6) Scorecard

✔ Baryon Magnetic Moments

$$\mu_B = \sum_q \mu_q \Delta q \quad \text{where} \quad \mu_q \sim e_q / m_q$$

- take constituent quark masses
- take $\mu_u = -2\mu_d$, $\mu_s = 2\mu_d/3$

  and fit μ_d to data

B	Magnetic Moment		Expt
p	$(4\mu_u - \mu_d)/3$	2.7	2.79
n	$(4\mu_d - \mu_u)/3$	-1.8	-1.91
Σ^+	$(4\mu_u - \mu_s)/3$	2.6	2.48
Σ^-	$(4\mu_d - \mu_s)/3$	-1.0	-1.16
Ξ^0	$(4\mu_s - \mu_u)/3$	-1.4	-1.25
Ξ^-	$(4\mu_s - \mu_d)/3$	-0.5	-0.68
Λ	μ_s	-0.6	-0.61
$\Lambda\Sigma^0$	$(\mu_d - \mu_u)/\sqrt{3}$	-1.6	-1.60

Note: $\mu_B \sim (e_q/m_q)\Delta q \sim |e_q|(\Delta q - \Delta\bar{q})$

⇒ *observable sensitive to* ***valence quarks***

✘ Hyperon β-Decay

- parity-violating weak decay
- decay products parallel to spin
- sensitive to $\sum_q (\Delta q + \Delta\bar{q})$

Decay Parameter	SU(6)	Expt
$F = (\Delta u - \Delta s)/2$	0.67	0.46
$D = (\Delta u - 2\Delta d + \Delta s)/2$	1.00	0.80

⇒ *Constutent Quark Model* ***lacks sea quarks***

Spin Structure of the Proton

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Parton Distribution Functions

unpolarized: $q(x) = q^{\uparrow}(x) + q^{\downarrow}(x)$

polarized: $\Delta q(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$

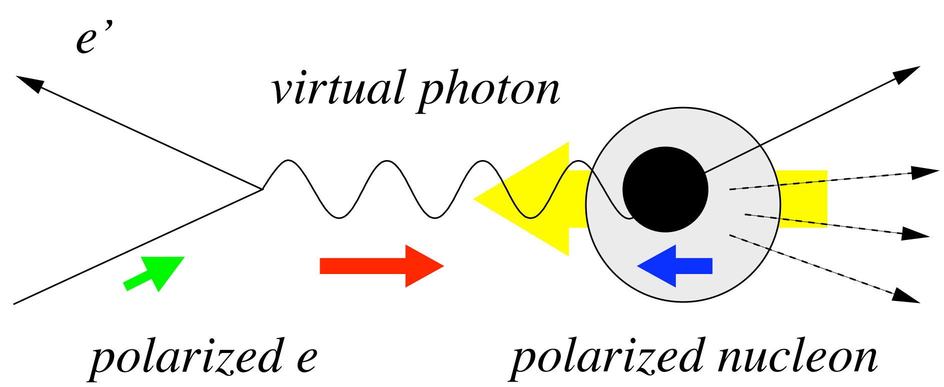
Constituent Quark Model

$$\Delta u = +\frac{4}{3}, \;\; \Delta d = -\frac{1}{3} \;\; \rightarrow \;\; \boxed{\Delta\Sigma = 1}$$

Relativistic Quark Model

$$\boxed{\Delta\Sigma \simeq 0.60 - 0.75} \qquad L_q = \frac{1}{2}(1 - \Delta\Sigma)$$

Polarized Deep-Inelastic Scattering



From NLO-QCD analysis of inclusive DIS measurements + hyperon β-decay ...

- $\Delta\Sigma = 0.19 \pm 0.07$ ($\overline{\text{MS}}$ scheme)

The Spin ~~Crisis~~! Puzzle

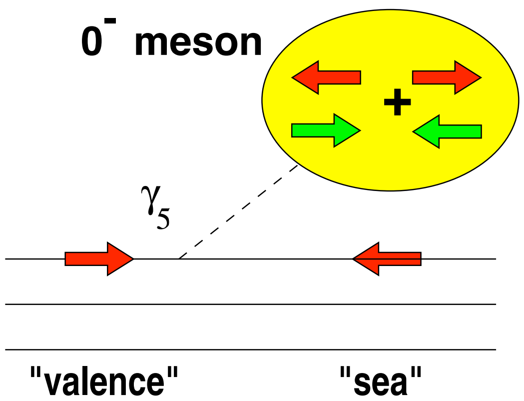
- $\Delta G = 1.0^{+1.9}_{-0.6}$ (AB scheme)

→ barely constrained, value > 0 favored

Anti-quark Spin in the Proton Sea

Meson Cloud Models

Li, Cheng, hep-ph/9709293



- $\Delta q_{\text{valence}} > 0$
- $\Delta q_{\text{sea}} < 0$
- $\Delta \bar{q} = 0$

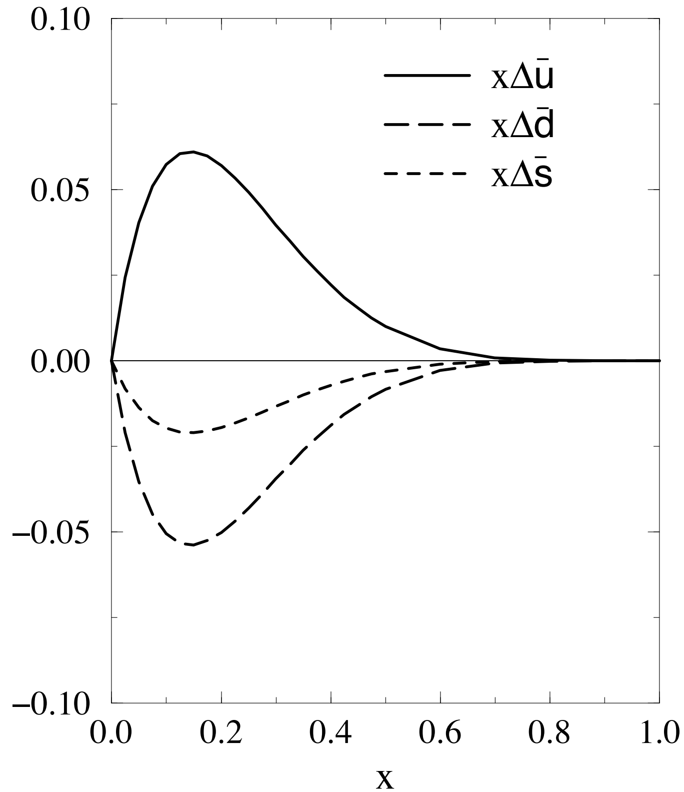
"Higher-order" cloud of vector mesons can generate a small polarization.

Chiral-Quark Soliton Model

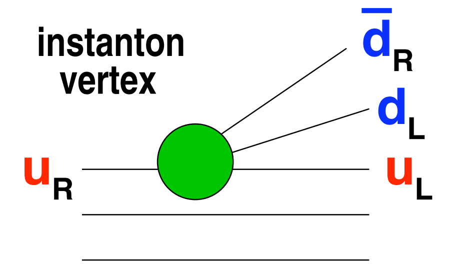
Goeke et al, hep-ph/0003324

Light sea quarks polarized:

$$\Delta \bar{u} \simeq -\Delta \bar{d} > 0$$



Instanton Mechanism

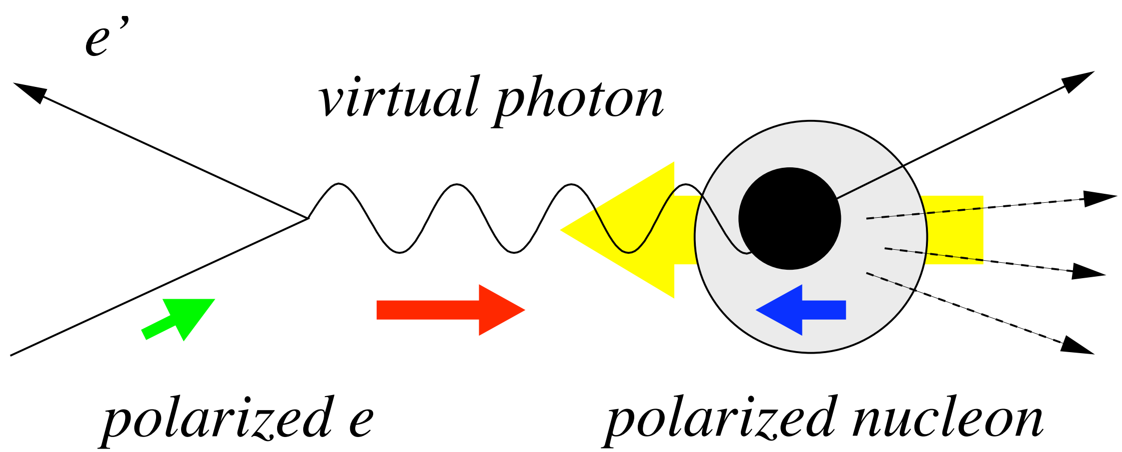


'tHooft instanton vertex $\sim \bar{u}_R u_L \bar{d}_R d_L$ transfers helicity from valence u quarks to $d\bar{d}$ pairs

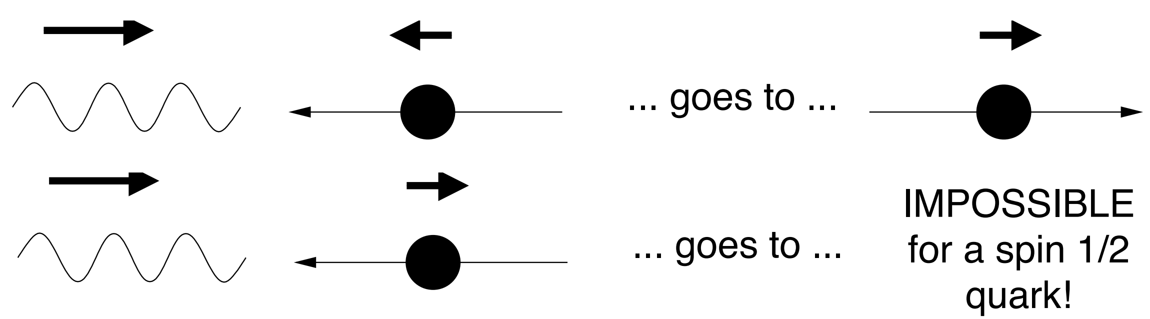
Quark Helicity Distributions $\Delta q(x)$: Results

Spin-Dependent Deep Inelastic Scattering (DIS)

Polarized lepton beams incident on polarized nucleon targets



The **polarized virtual photon** selects certain quark polarizations :



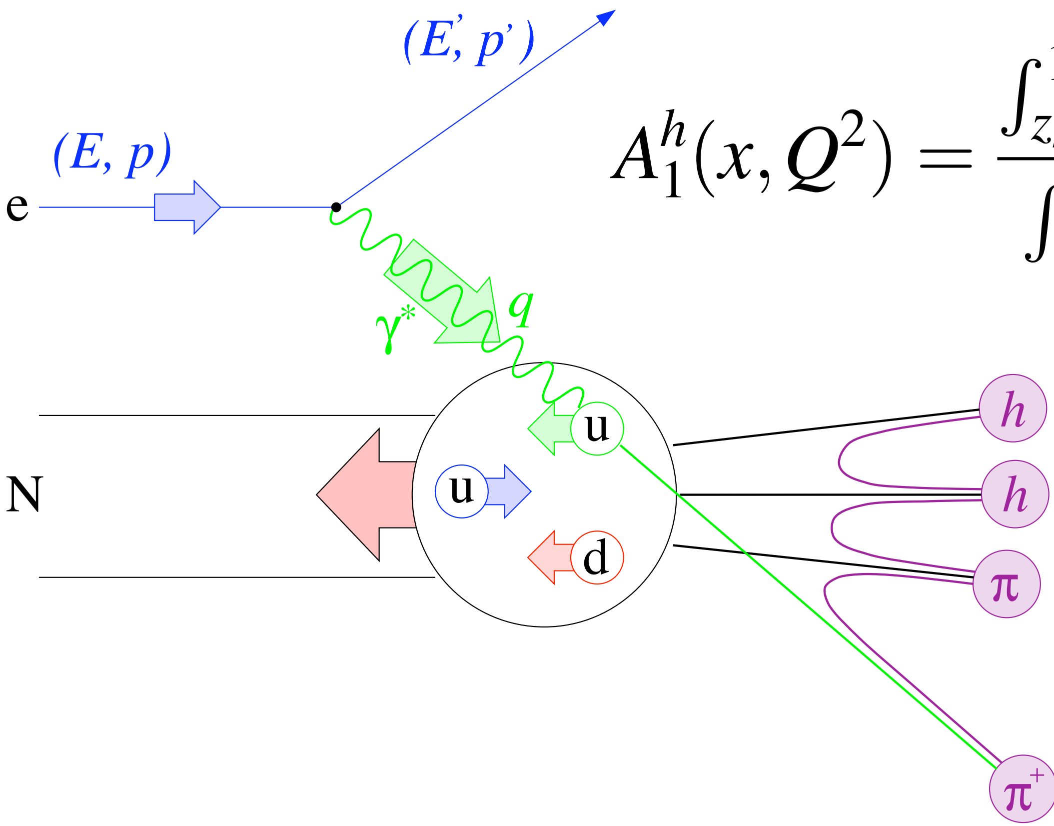
Double spin asymmetries are measured :

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \simeq \frac{g_1}{F_1} = \frac{\sum_q e_q^2 \, \Delta q(x, Q^2)}{\sum_q e_q^2 \, q(x, Q^2)}$$

Polarized Semi-Inclusive DIS (SIDIS)

In SIDIS, a hadron h is detected in coincidence with the scattered lepton:

Flavor Tagging: Flavor content of observed hadron *h* is related to flavor of **struck quark *q*** via the **fragmentation functions *D*(*z*)**



$$A_1^h(x,Q^2) = \frac{\int_{z_{min}}^1 dz \sum_q e_q^2 \, \Delta q(x,Q^2) \cdot D_q^h(z,Q^2)}{\int_{z_{min}}^1 dz \sum_q e_q^2 \, q(x,Q^2) \cdot D_q^h(z,Q^2)}$$

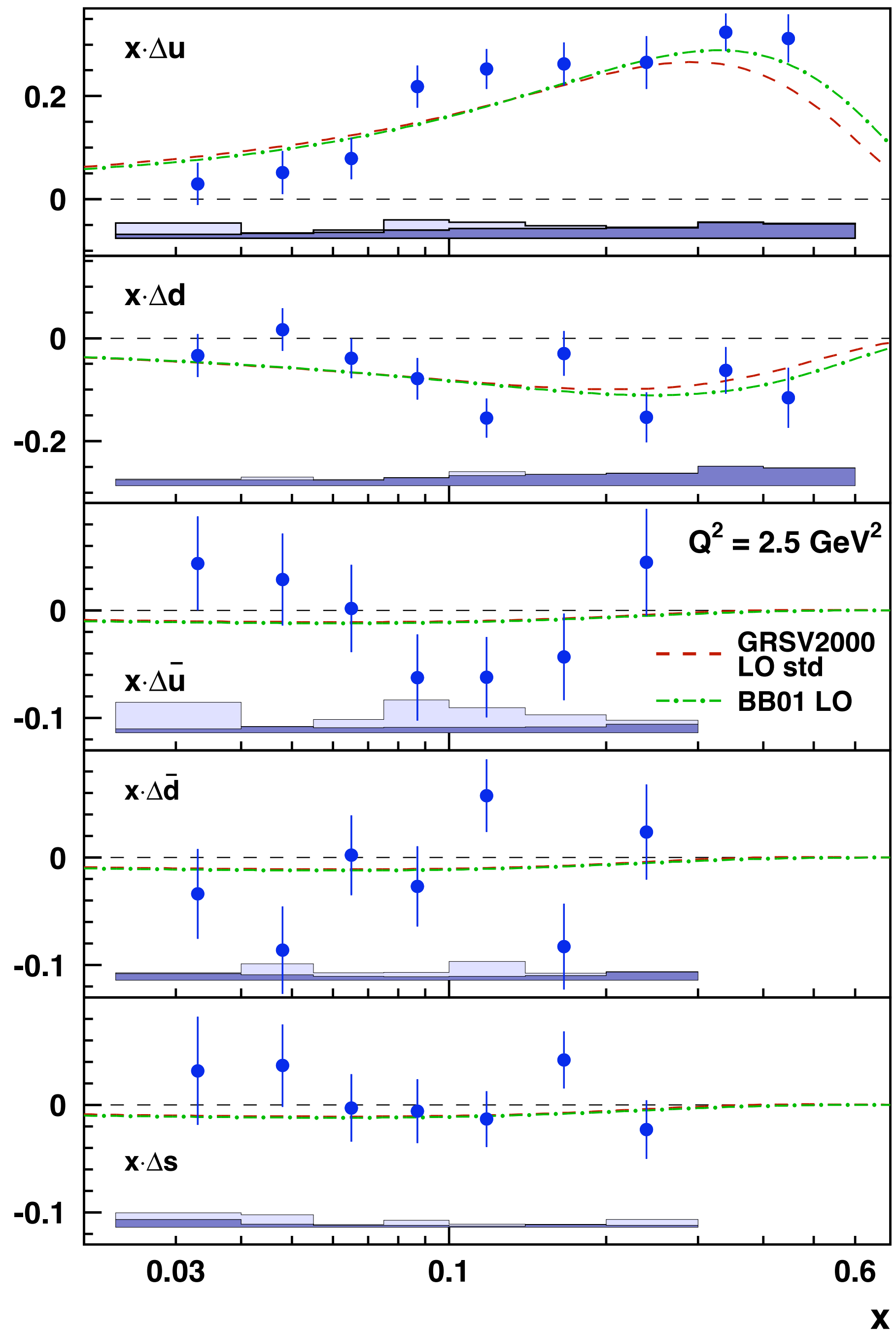
Rewriting ...

$$A_1^h(x,z) = \sum_q P_q^h(x,z) \frac{\Delta q(x)}{q(x)}$$

Purity matrix* P_q^h *= probability that hadron h came from struck quark q

Purities are *spin-independent* ... compute using Monte Carlo tuned to *unpolarized* data

Final Δq Measurement from HERMES Run 1

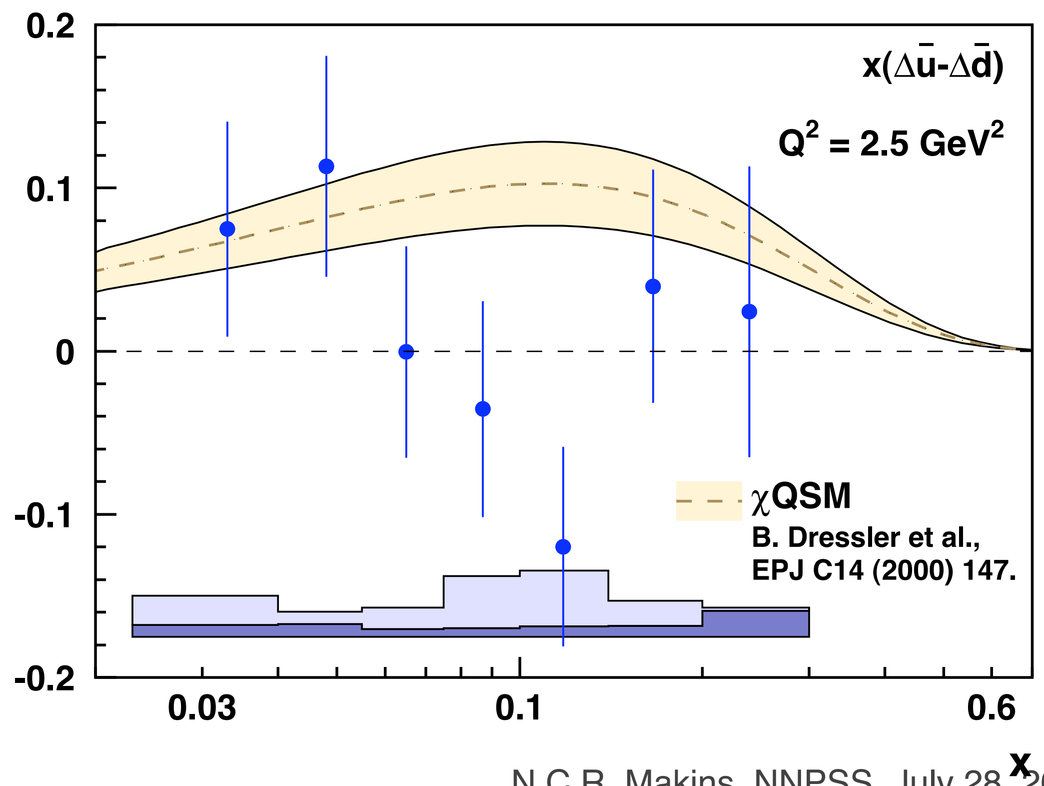


using polarized data 1996–2000:

$$A_{1,p}, A^{\pi^\pm}_{1,p}, A_{1,d}, A^{\pi^\pm}_{1,d}, A^{K^\pm}_{1,d}$$

First 5-flavor fit to Δq(x)

No evidence of anti-quark polarization, or flavor-asymmetry thereof



New Analysis: Isoscalar extraction of Δs

Extract isoscalar combinations of $\Delta q(x)$:

$$\Delta S(x) \equiv \Delta s(x) + \Delta \bar{s}(x)$$
$$\Delta Q(x) \equiv \Delta u(x) + \Delta \bar{u}(x) + \Delta d(x) + \Delta \bar{d}(x)$$

Asymmetries measured form isoscalar deuteron data:

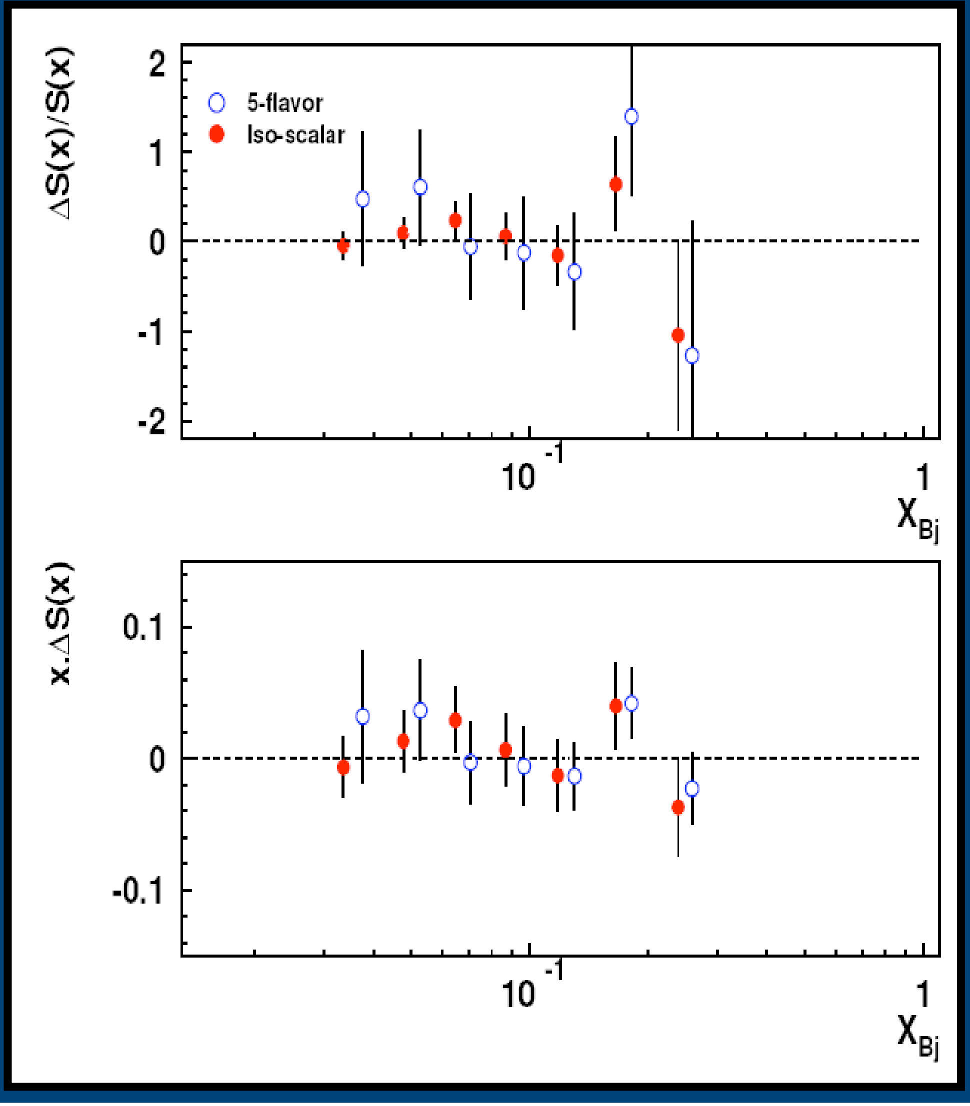
$$\begin{pmatrix} A_d(x) \\ A_d^{K^+ + K^-}(x) \end{pmatrix} = C_R \begin{pmatrix} p_q & p_s \\ P_q^{K^+ + K^-} & P_S^{K^+ + K^-} \end{pmatrix} \begin{pmatrix} \Delta Q(x)/Q(x) \\ \Delta S(x)/S(x) \end{pmatrix}$$

- Inclusive purities are simple combinations of unpolarized PDFs.

$$P_Q(x) = \frac{5Q(x)}{5Q(x) + 2S(x)}, P_S(x) = \frac{2S(x)}{5Q(x) + 2S(x)}$$

- Kaon purities can be computed from the unpolarized K multiplicity assuming only charge symmetry in fragmentation.

$$D_q^{K^+ + K^-}(x) = D_{\bar{q}}^{K^+ + K^-}$$

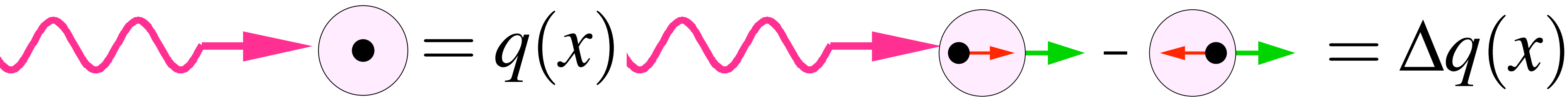


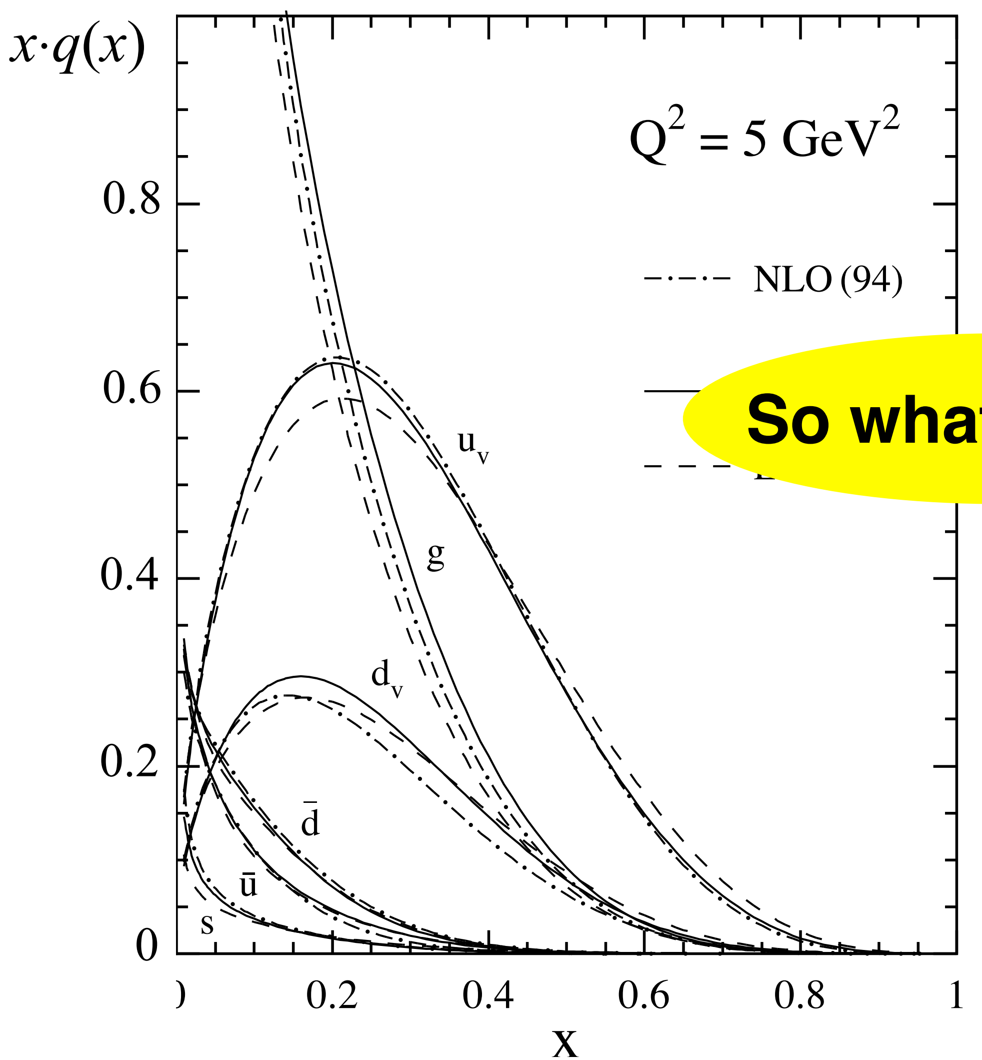
Excellent agreement -- No MC Dependence

Single-Spin Asymmetries

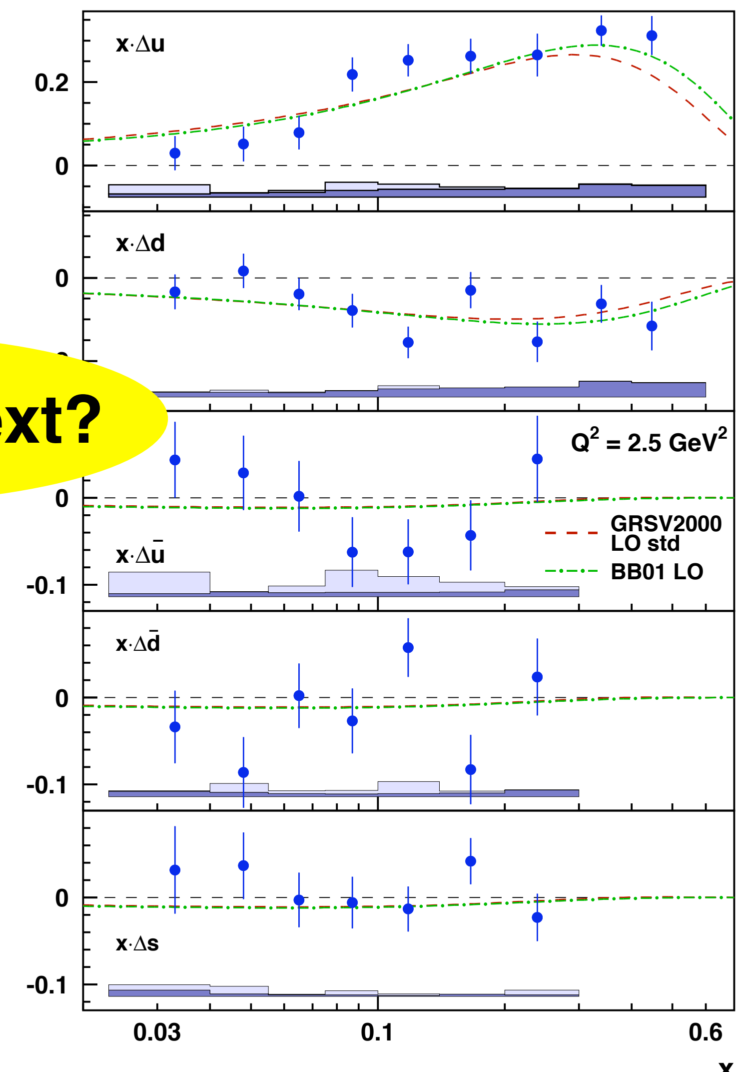
Unpolarized PDF's

Polarized PDF's

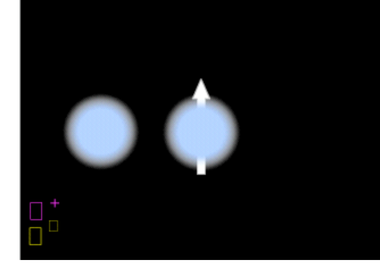


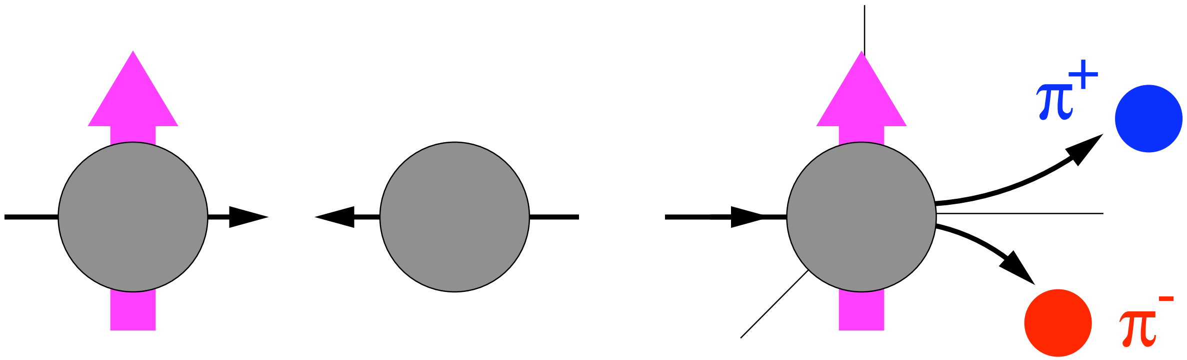


So what's next?



Fermilab E704: $p^{\uparrow}p \rightarrow \pi X$ at 400 GeV

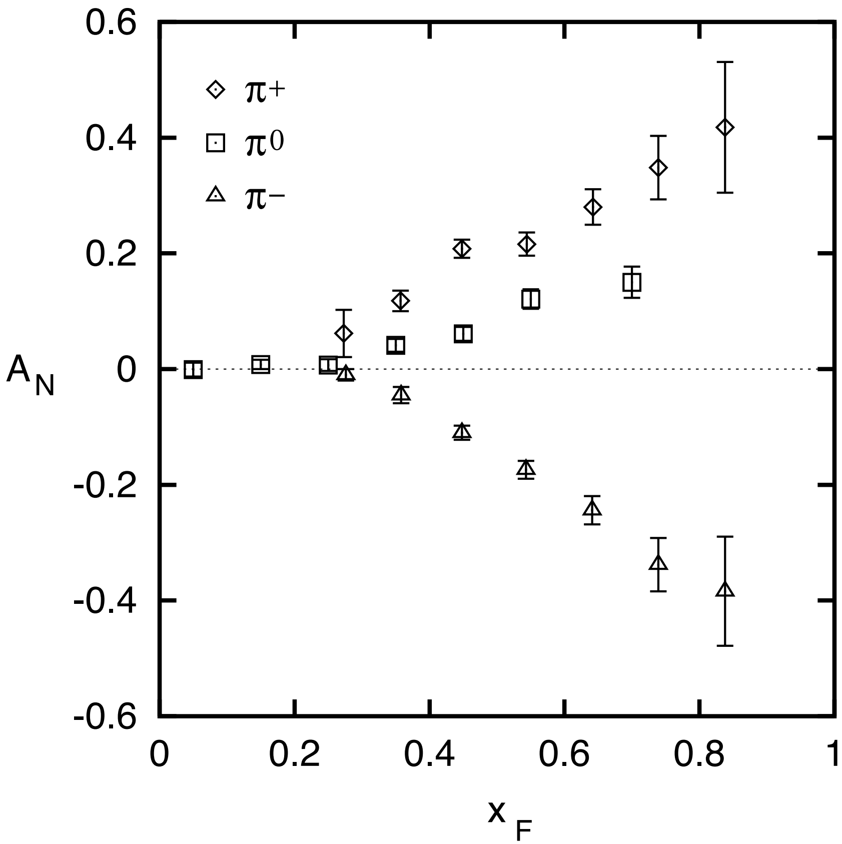




Analyzing Power

$$A_N = \frac{1}{P_{\text{beam}}} \frac{N^{\pi}_{\text{left}} - N^{\pi}_{\text{right}}}{N^{\pi}_{\text{left}} + N^{\pi}_{\text{right}}}$$

Huge single-spin asymmetry !

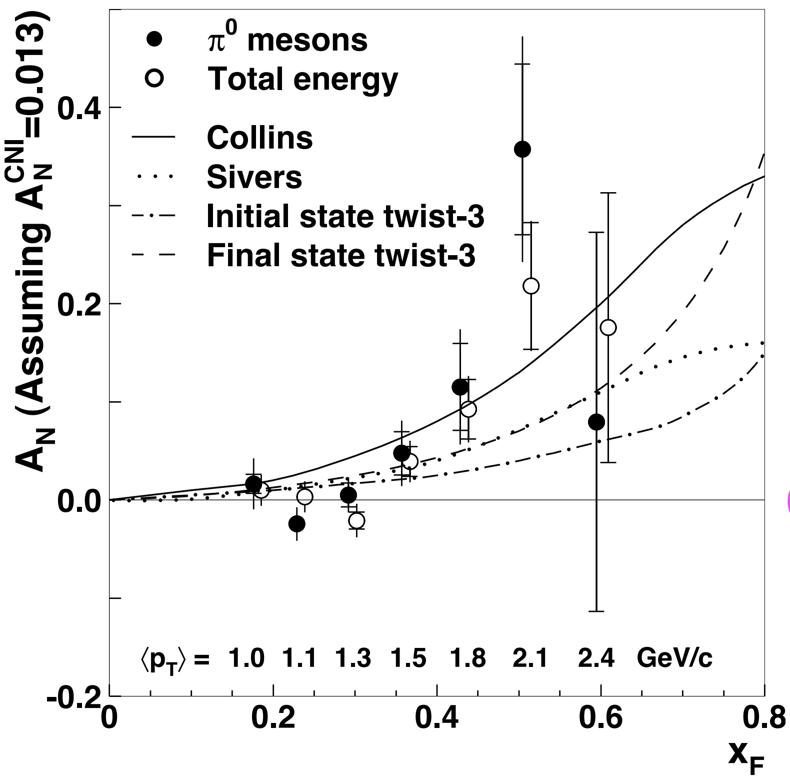


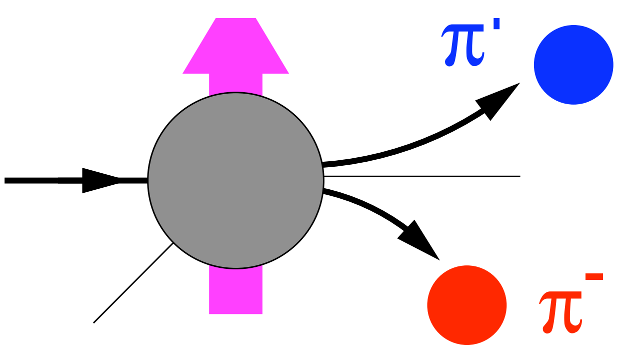
- Opposite sign for $\pi^+ = u\bar{d}$ than for $\pi^- = d\bar{u}$
- Effect larger for forward production
- Observable: $\vec{S}_{\text{beam}} \cdot (\vec{p}_{\text{beam}} \times \vec{p}_{\pi})$
  odd under naive Time-Reversal

Surprising observation! ..... Why?

SSA's at high-energies

Now confirmed at STAR at much higher energies





T-odd observables

SSA observables $\sim \vec{\mathbf{J}} \cdot (\vec{\mathbf{p_1}} \times \vec{\mathbf{p_2}})$
$\Rightarrow$ ***odd*** under naive ***time-reversal***

Since QCD amplitudes are T-even, must arise from **interference** between **spin-flip** and non-flip amplitudes with **different phases**

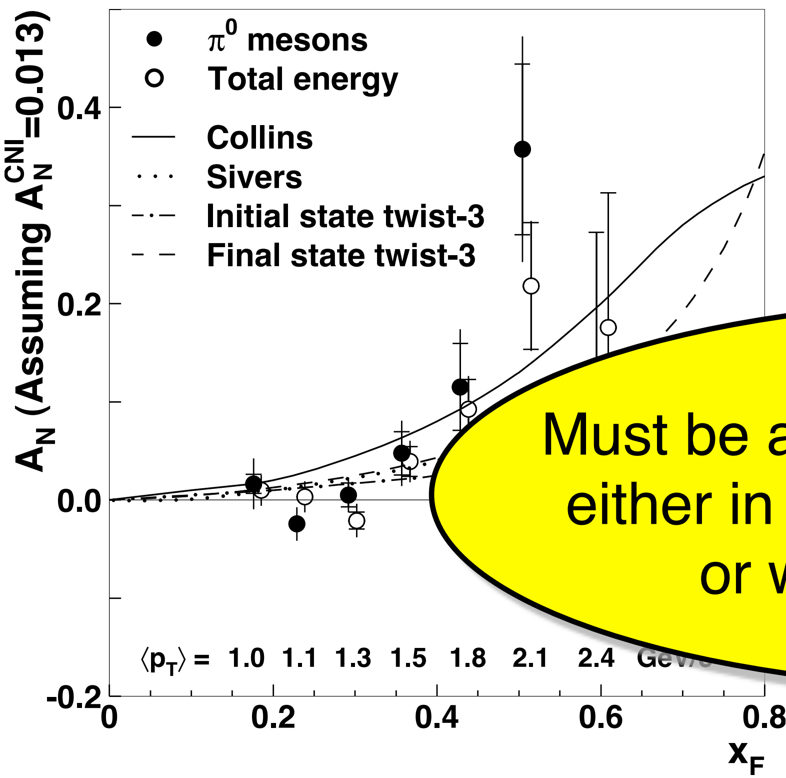
Can't come from perturbative subprocess xsec:

- q helicity flip suppressed by $m_q/\sqrt{s}$
- need α_s-suppressed loop-diagram to generate necessary phase

At hard (enough) scales, SSA's must arise from soft physics: T-odd distribution / fragmentation functions

SSA's at high-energies

Now confirmed at STAR at much higher energies



T-odd observables

SSA observables $\sim \vec{\mathbf{J}} \cdot (\vec{\mathbf{p_1}} \times \vec{\mathbf{p_2}})$

$\Rightarrow$ ***odd*** under naive ***time-reversal***

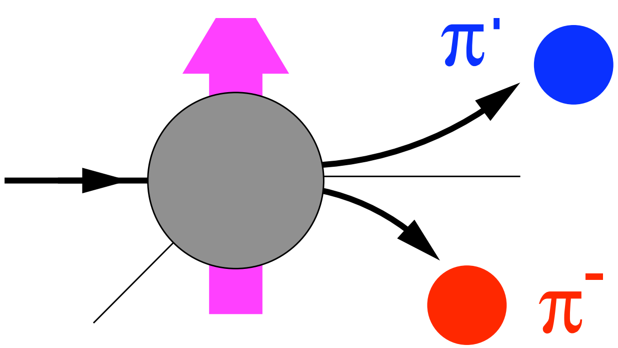
Since QCD amplitudes are T-even, must arise between **spin-flip** and **different phases**

Must be a new, spin-orbit structure
either in the fragmentation process
or within the proton itself

ubprocess xsec:

d by $m_q/\sqrt{s}$

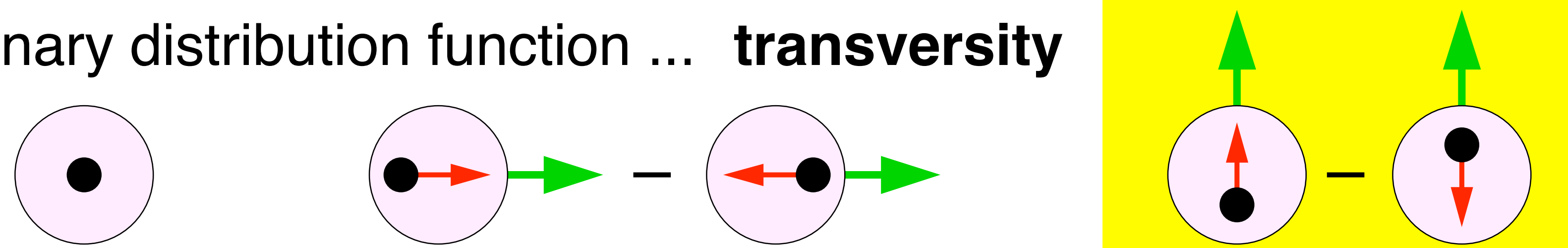
- need α_s-suppressed loop-diagram to generate necessary phase



At hard (enough) scales, SSA's must arise from soft physics: T-odd distribution / fragmentation functions

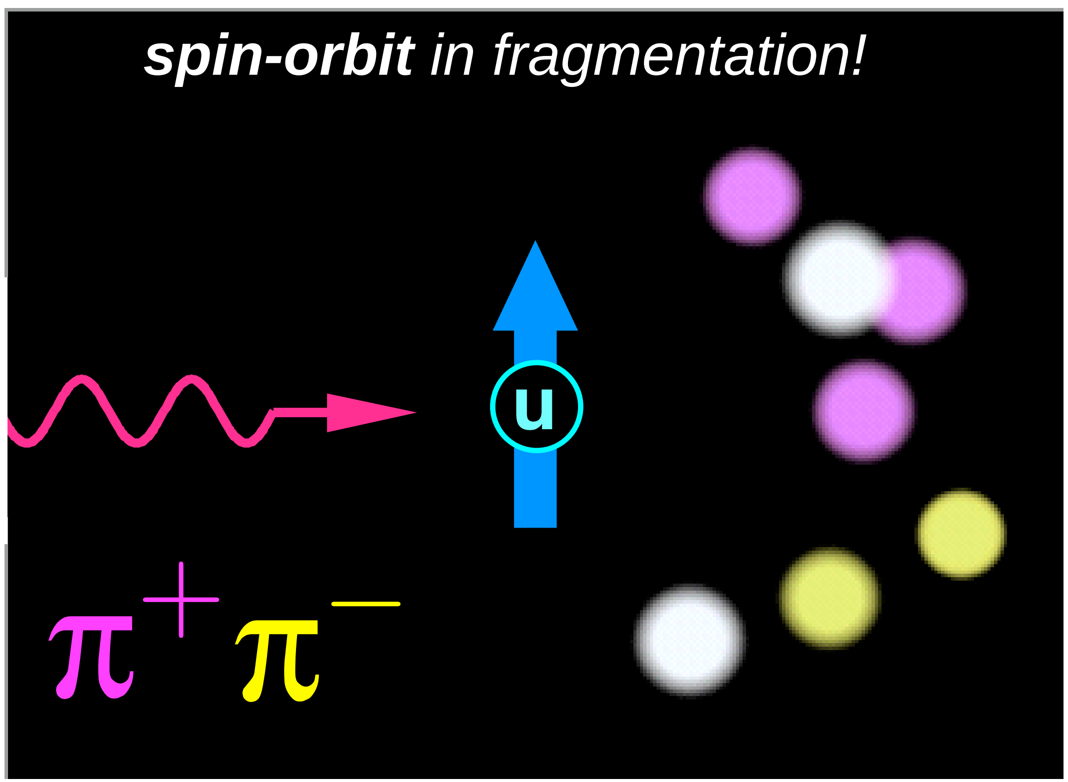
E704 Possible Mechanism #1: The “Collins Effect”

Need an ordinary distribution function ... **transversity**

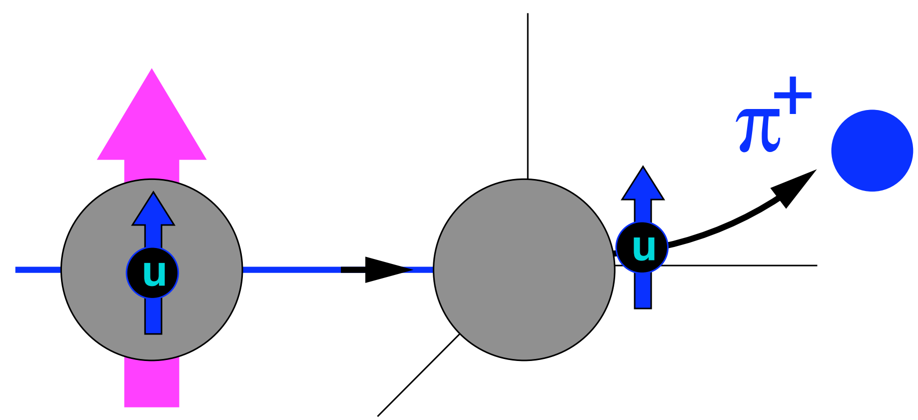


$q(x)$ $\Delta q(x)$ $h_1(x)$

... with a new, **T-odd “Collins” fragmentation function** $H_1^\perp(z, p_T)$



E704 effect:



$$h_1(x) \otimes H_1^\perp(z, p_T)$$

Transversity: The Third Structure Function

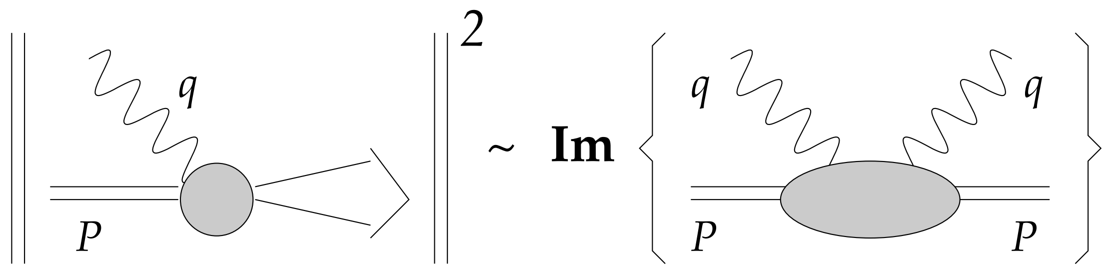
Proton Matrix Elements

vector charge $\langle PS|\overline{\psi}\gamma^{\mu}\psi|PS\rangle = \int_0^1 dx\; q(x) - \overline{q}(x) \rightarrow$ # valence quarks

axial charge $\langle PS|\overline{\psi}\gamma^{\mu}\gamma_5\psi|PS\rangle = \int_0^1 dx\; \Delta q(x) + \Delta\overline{q}(x) \rightarrow$ net quark spin

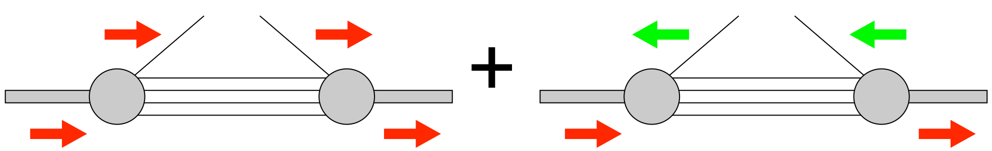
tensor charge $\langle PS|\overline{\psi}\sigma^{\mu\nu}\gamma_5\psi|PS\rangle = \int_0^1 dx\; \delta q(x) - \delta\overline{q}(x) \rightarrow$???

Forward Helicity Amplitudes

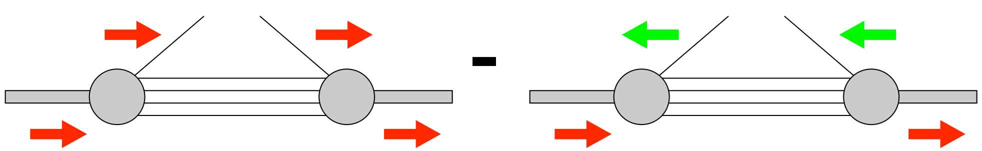


(optical theorem applied to DIS)

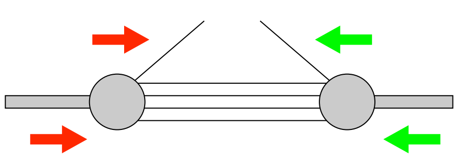
$q(x) \sim$



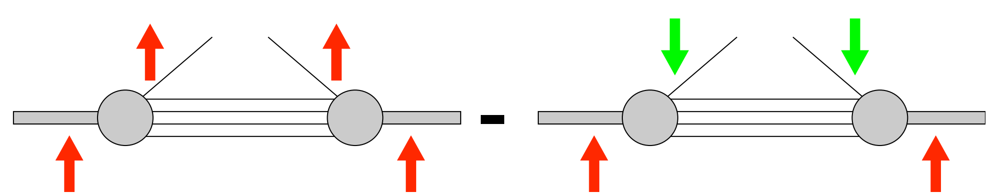
$\Delta q(x) \sim$



$\delta q(x) \sim$



... but in transverse basis ...

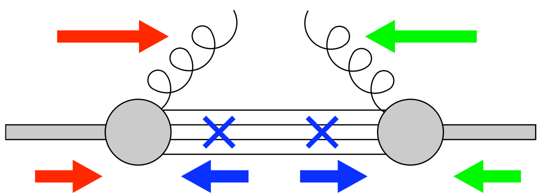


Properties of Transversity

- **In Non-Relativistic Case,** boosts and rotations commute: $\delta q(x) = \Delta q(x)$

  ... but bound quarks are highly ***relativistic*** in nature

- **No Gluons**



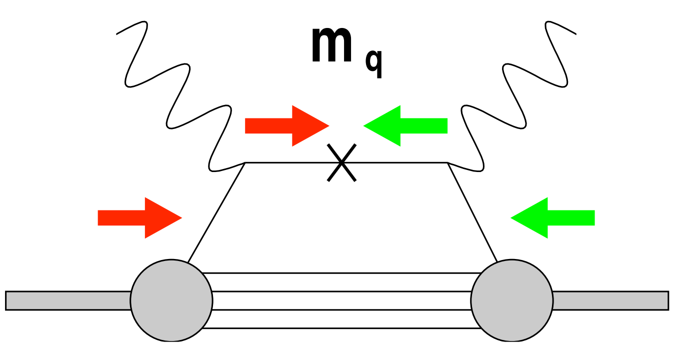
Angular momentum conservation: $\Lambda - \lambda = \Lambda' - \lambda'$

$\Rightarrow$ transversity has ***no gluon*** component

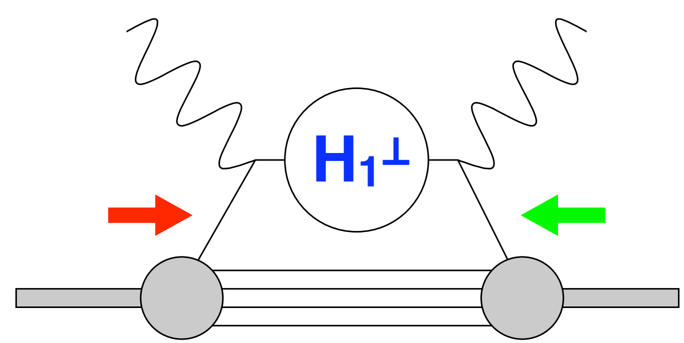
$\Rightarrow$ different Q^2 ***evolution*** than $\Delta q(x)$

- **Chiral Odd**

Helicity flip amplitudes occur only at $\mathcal{O}(m_q/Q)$ in inclusive DIS ...



but they are observable in e.g. **semi-inclusive** reactions



Properties of Transversity

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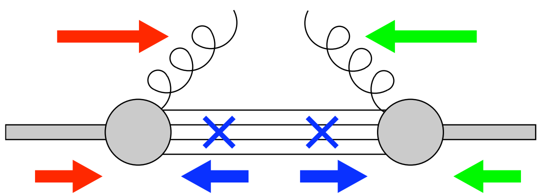

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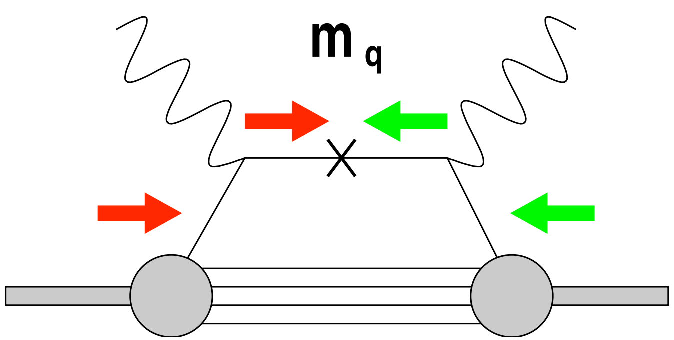


tensor charge = "***pure valence***" object

→ promising for LQCD comparison?

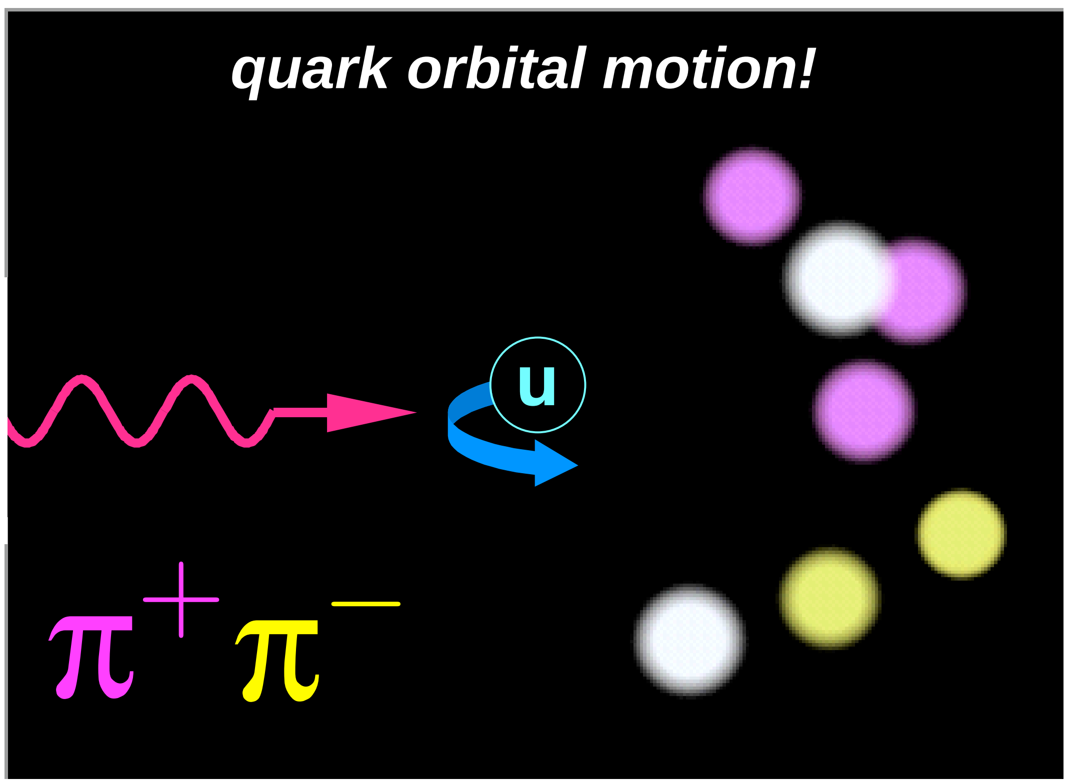
E704 Possible Mechanism #2: The "Sivers Effect"

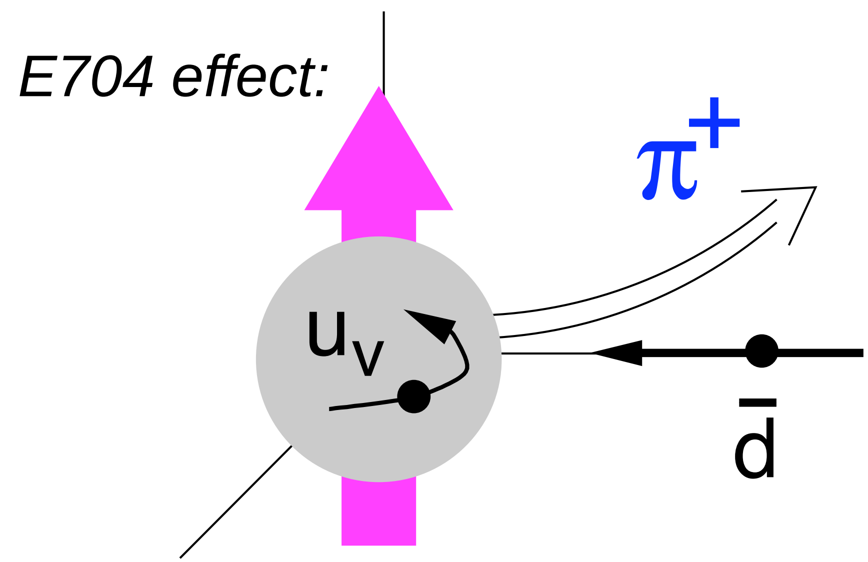
Need the ordinary fragmentation function $D_1(z)$

... with a new, **T-odd "Sivers" distribution function** $f_{1T}^{\perp}(x, k_T)$

Phenomenological model of **Meng & Chou**:

Forward π+ produced from **orbiting valence-u quark** by recombination at *front surface* of beam protons





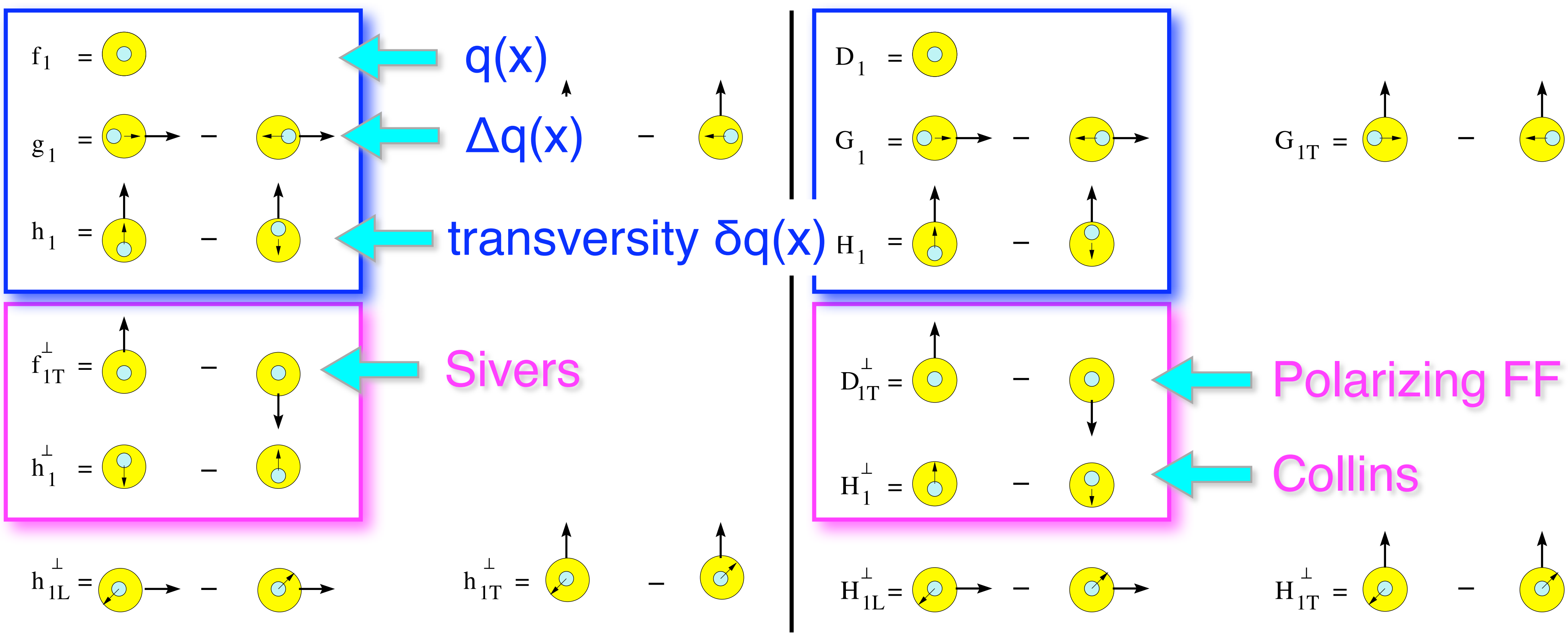
$$f_{1T}^{\perp}(x, k_T) \otimes D_1(z)$$

Functions surviving on integration over Transverse Momentum

The others are sensitive to ***intrinsic*** $\boldsymbol{k_T}$ in the nucleon & in the fragmentation process

Mulders & Tangerman, NPB 461 (1996) 197

Distribution Functions | Fragmentation Functions

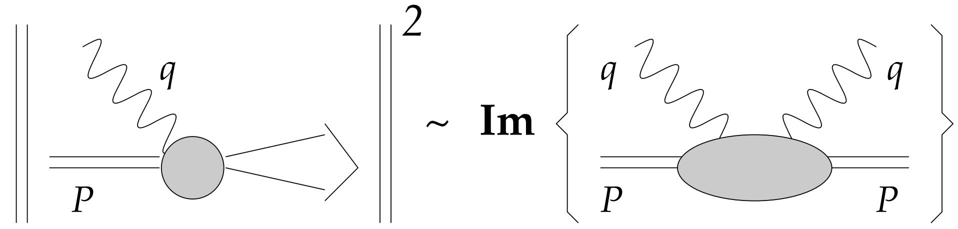


Functions Odd under naive Time Reversal

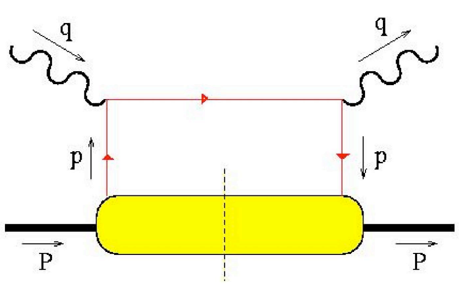
One T-odd function required to produce ***single-spin asymmetries*** in SIDIS

The Leading-Twist Sivers Function: Can it Exist in DIS?

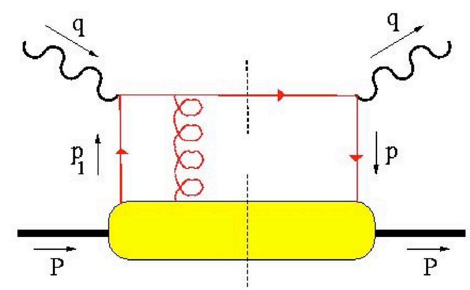
A T-odd function like $f_{1T}^{\perp}$ ***must*** arise from ***interference*** ... but a distribution function is just a forward scattering amplitude, how can it contain an interference?



Brodsky, Hwang, & Schmidt 2002



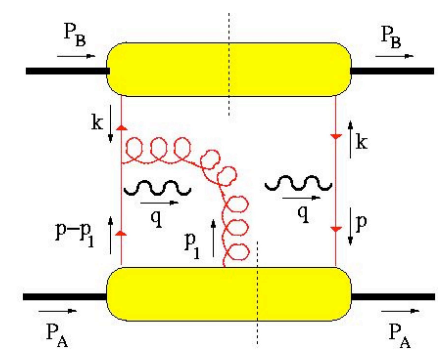
can interfere with



and produce a T-odd effect! (also need $L_z \neq 0$)

It looks like higher-twist ... but no, these are soft gluons = "gauge links" required for color gauge invariance

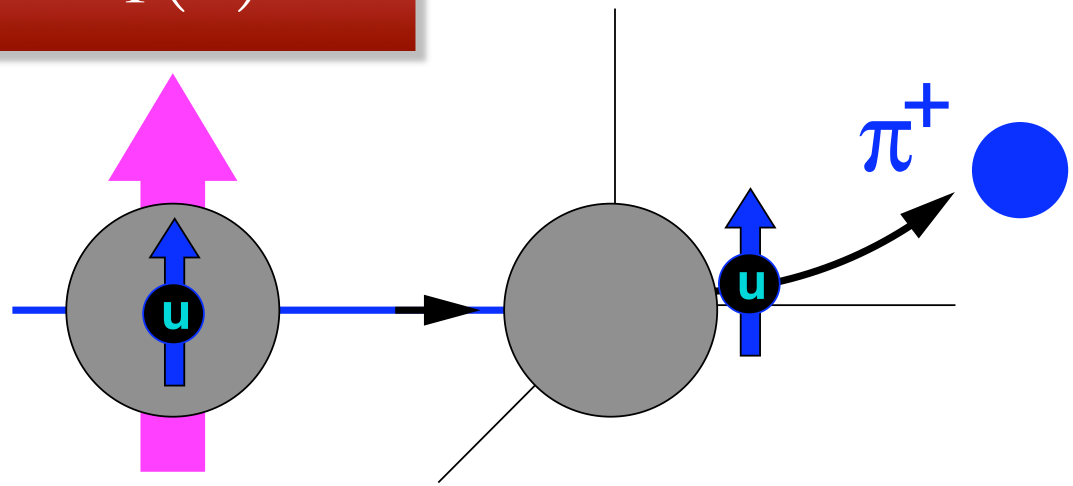
Such soft-gluon reinteractions with the soft wavefunction are ***final (or initial) state interactions*** ... and may be ***process dependent*** ! → new ***universality issues***



e.g. Drell-Yan

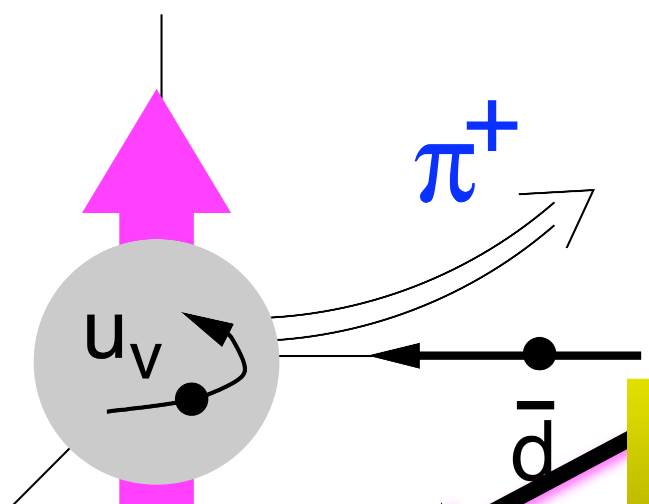
Photo-Album of our New Friends!

Transversity
$h_1(x)$



Collins Function
$H_1^\perp(z, p_T)$

<u>T-Odd</u> observables require <u>interference</u> between a spin-flip and a non-flip amplitude



Sivers Function
$f_{1T}^\perp(x, k_T)$

Favored / Disfavored Frag Functions

$$D_{\rm fav} \equiv D^{u\rightarrow\pi^+} = D^{d\rightarrow\pi^-} = \ldots$$

$$D_{\rm dis} \equiv D^{u\rightarrow\pi^-} = D^{d\rightarrow\pi^+} = \ldots$$

In Search of T-Odd Functions:
HERMES Run 2

Electro-Production of Pions with Tranvserse Target

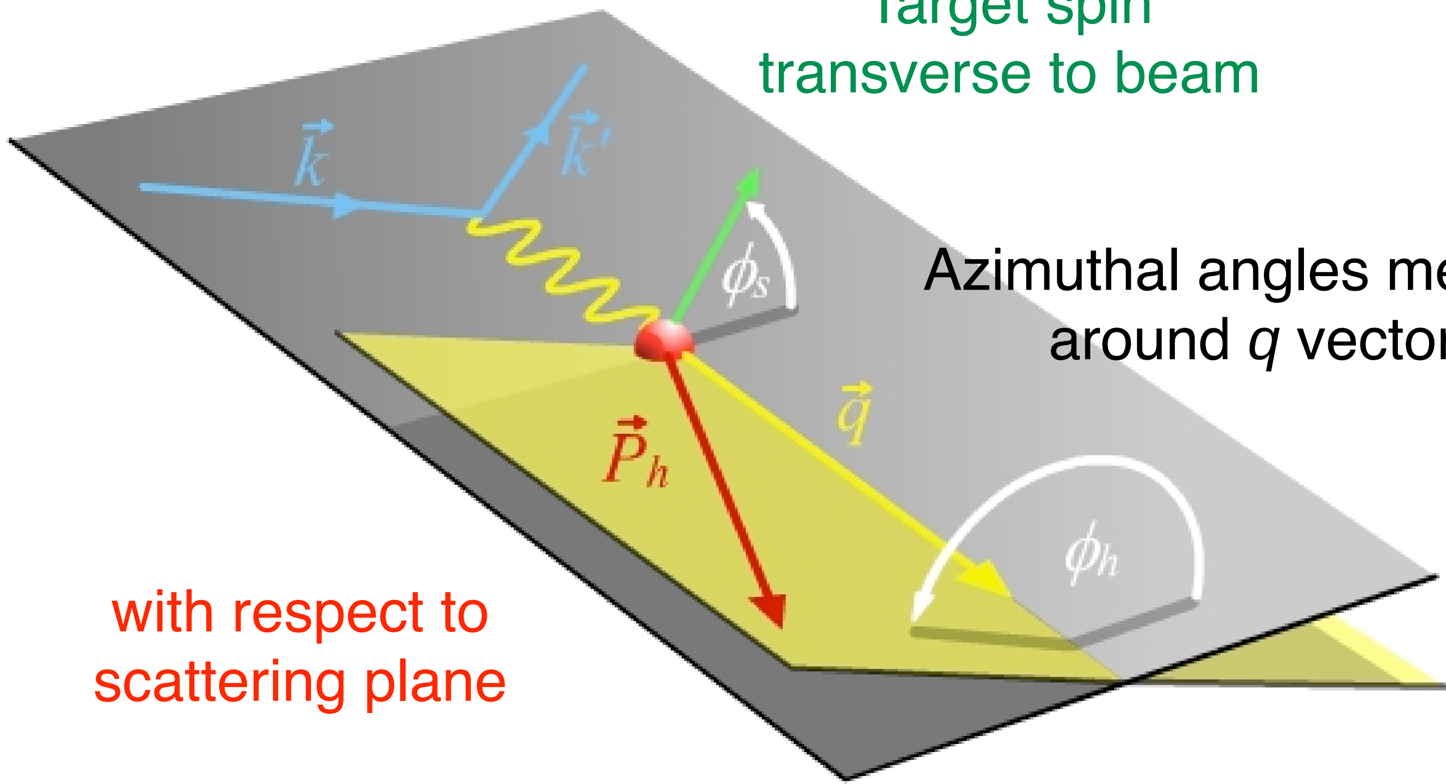
Switched from longitudinal to **transverse** target polarization in 2002 ...

Measure dependence of pion production on **two azimuthal angles**

Electron beam defines scattering plane

Target spin transverse to beam

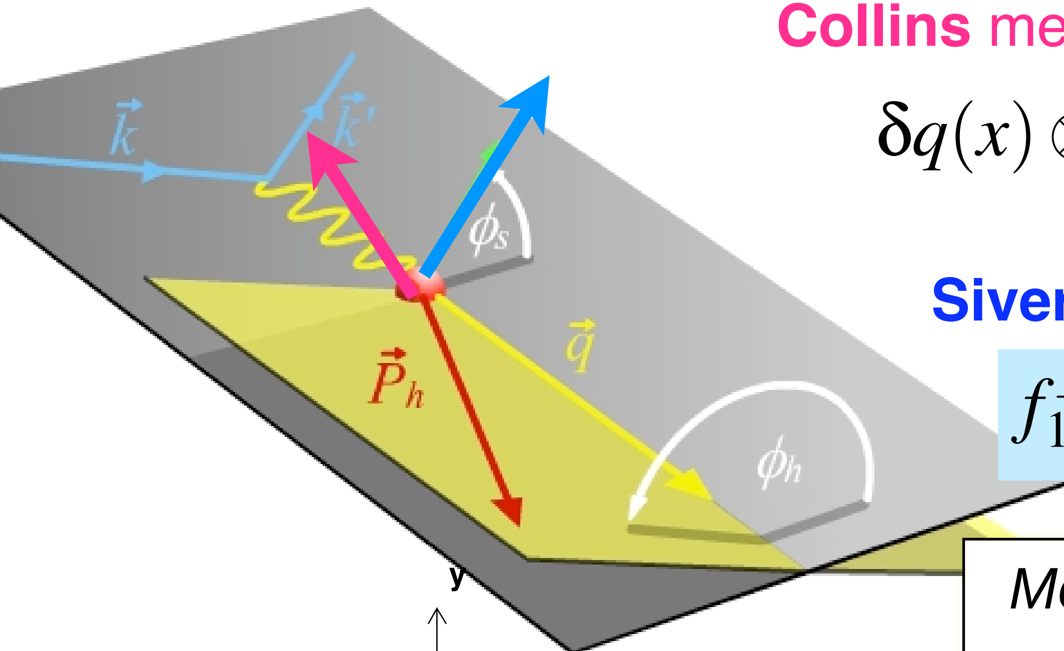
Azimuthal angles measured around q vector ...



with respect to scattering plane

ϕ_S **= target spin orientation** ϕ_h **= pion ("hadron")direction**

Separating the Collins & Sivers Mechanisms



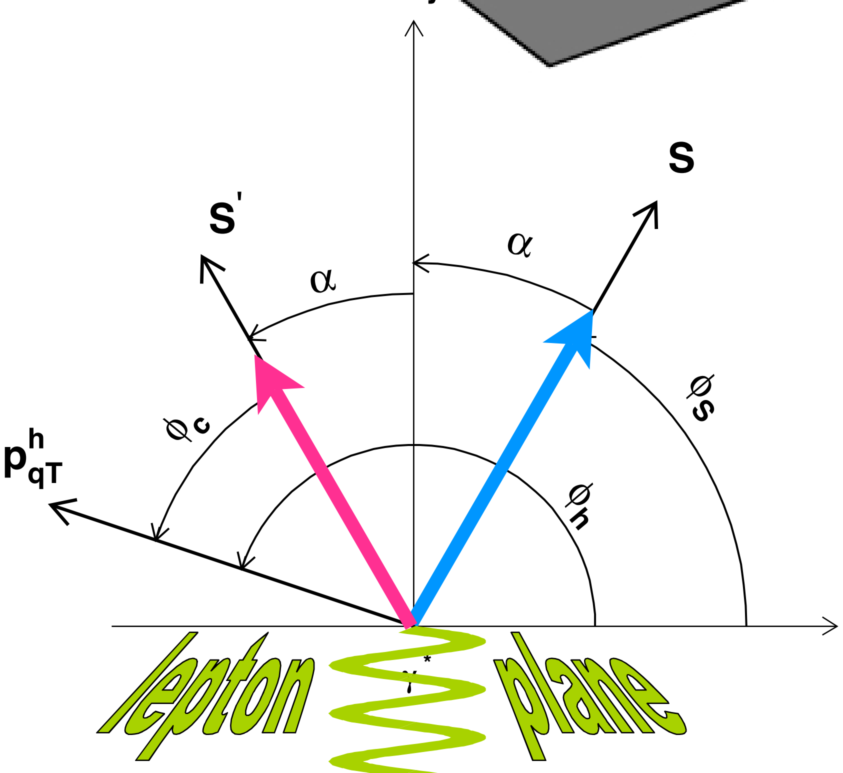
Collins mechanism

$$\delta q(x) \otimes H_1^{\perp}(z, k_T) \Rightarrow \sin(\phi_h + \phi_s)$$

Sivers mechanism

$$f_{1T}^{\perp}(x, k_T) \otimes D_1(z) \Rightarrow \sin(\phi_h - \phi_s)$$

*Measure **azimuthal moments** of SIDIS xsec to **separate the mechanisms***



*Thanks to **linear polarization** of photon ...*

Sivers: $(\phi_h - \phi_S)$

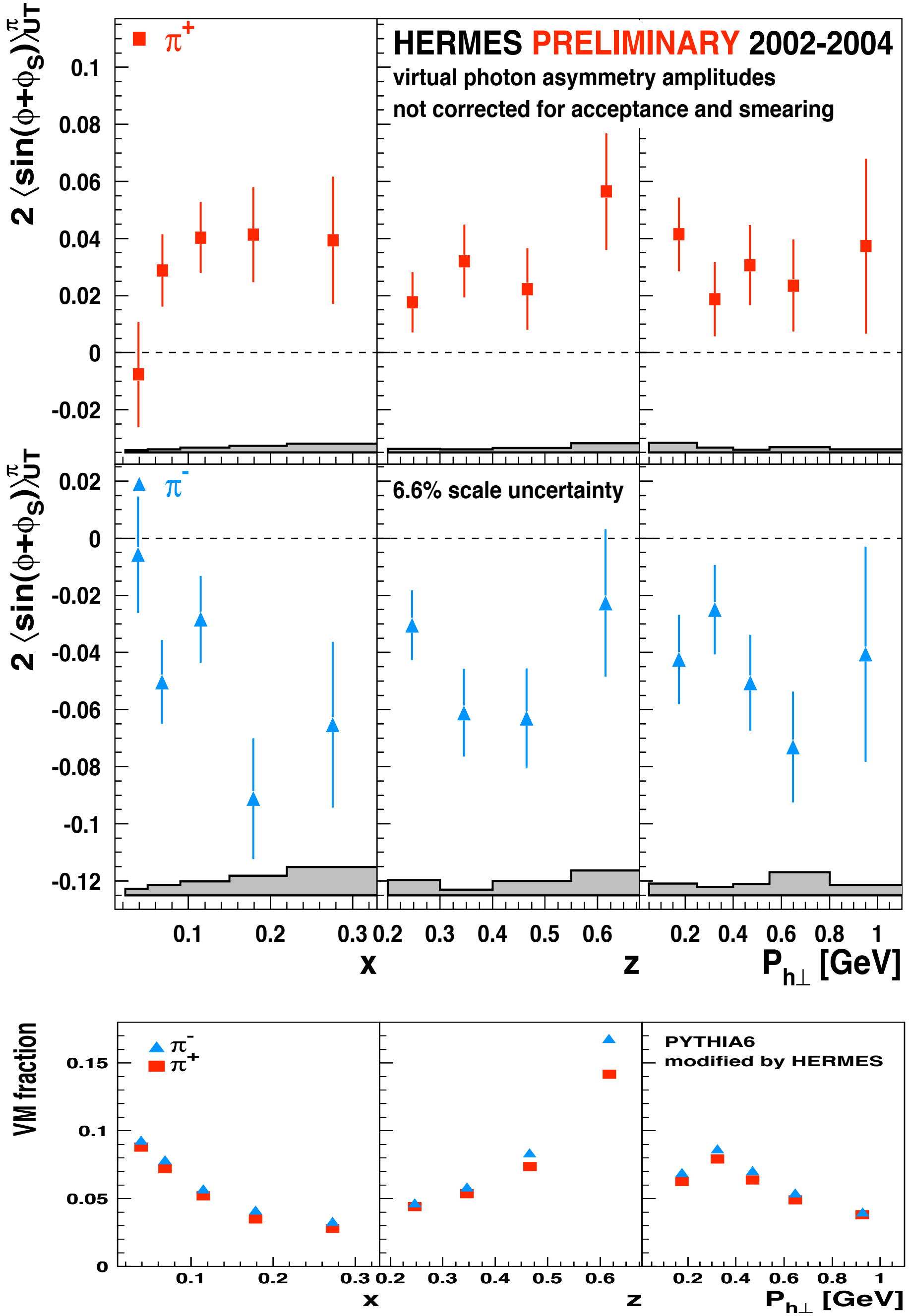
angle of pion relative to **initial** quark spin

Collins: $(\phi_h + \phi_S) = \pi + (\phi_h - \phi_S)$

angle of pion relative to **final** quark spin

SSA Results 1:
Collins Effect

Collins Moments for π^+ π^- from 2002–2004 H$^\uparrow$ Data



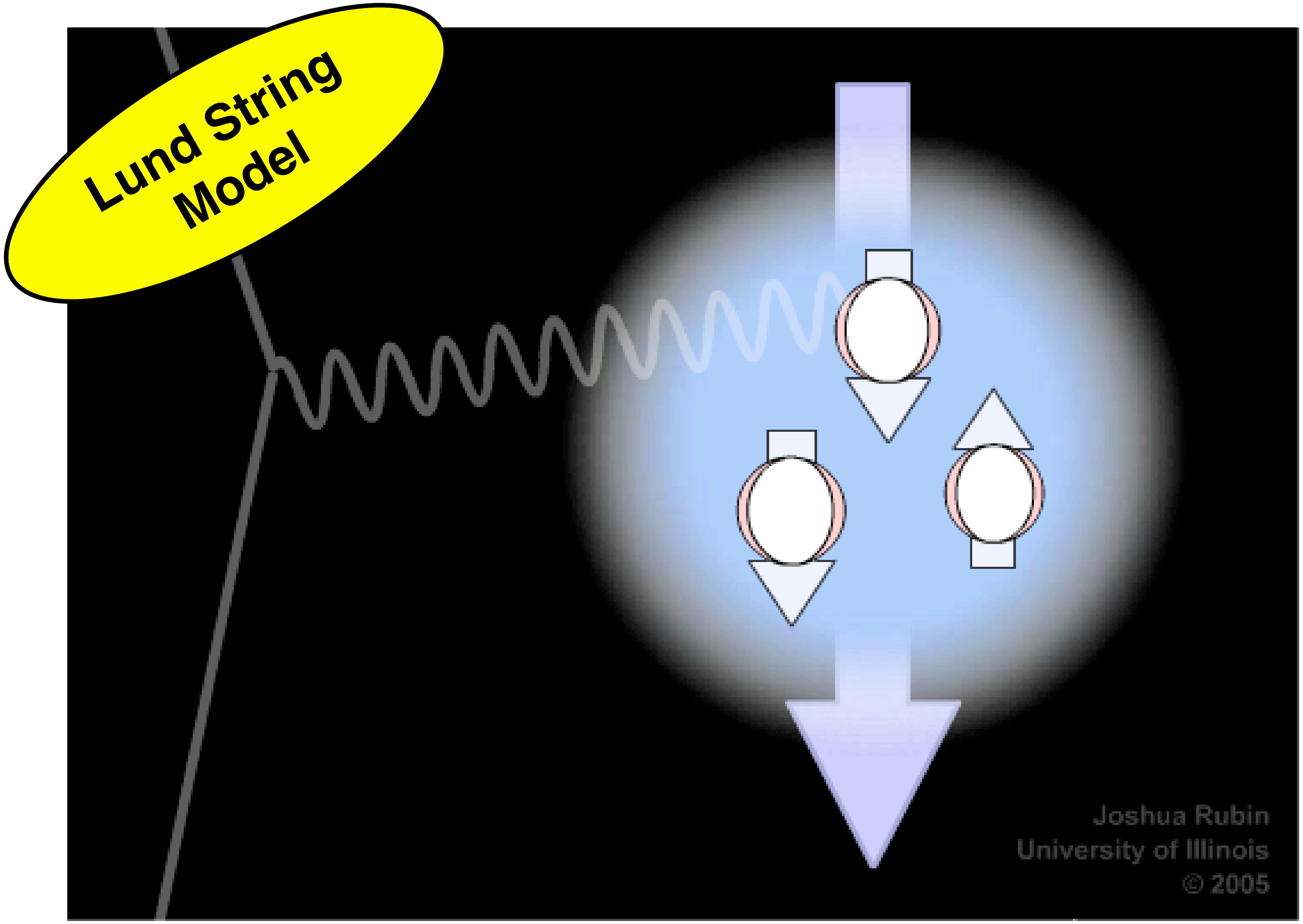
It exists!

- First evidence for **non-zero Collins function** ... and **transversity**!
- Positive for π^+...
  Negative and ***larger*** for π^-...
- Systematic error bands include acceptance and smearing effects, and contributions from unpolarized <cos(2φ)> and <cos(φ)> moments

Understanding the Collins Effect

The Collins function exists! ➡ **spin-orbit** correlations in π formation

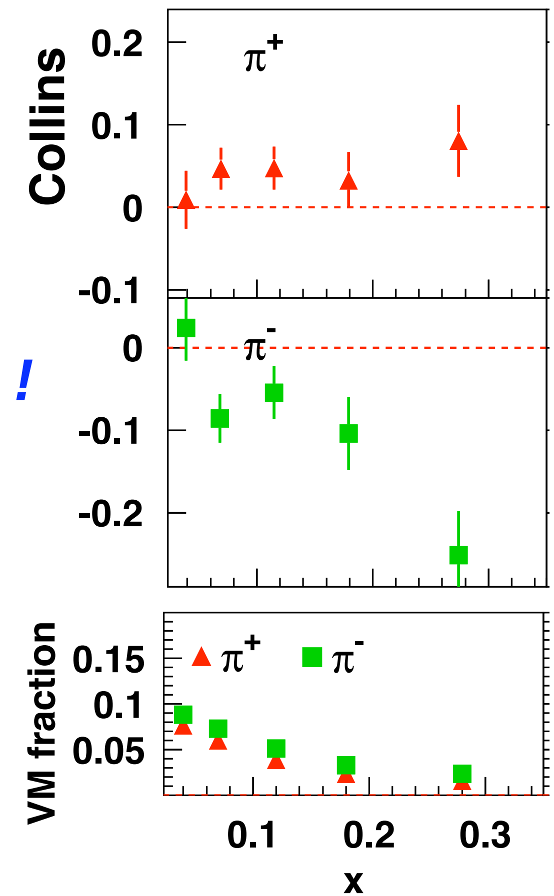
Is the Artru mechanism responsible?



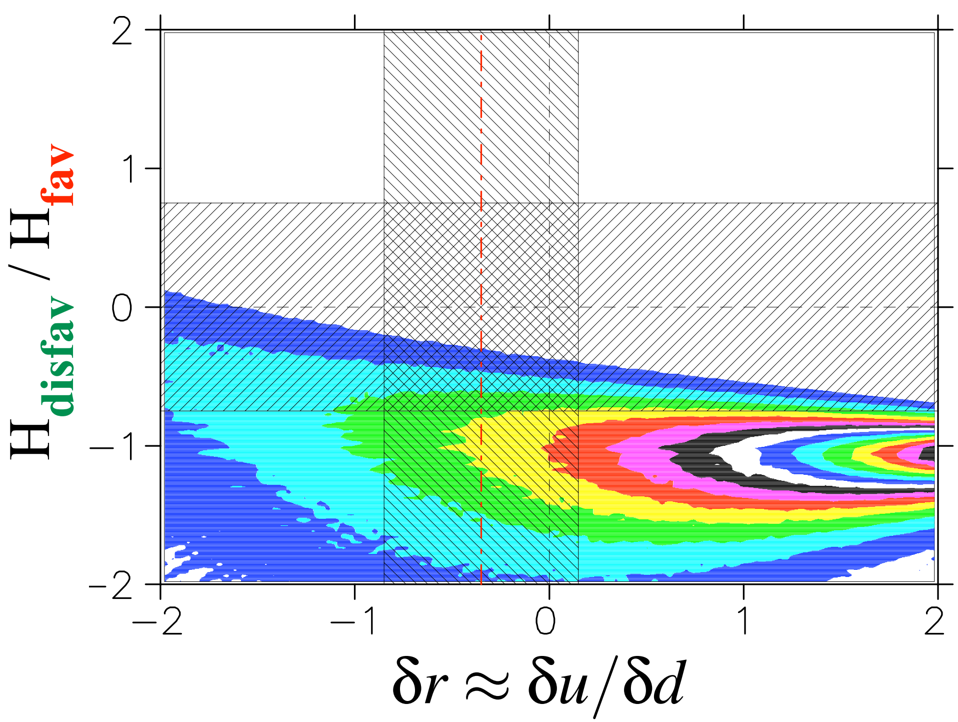
Why are the Collins π⁻ asymmetries so large?

DIS on proton target always dominated by ***u-quark scattering***

- $A_{\mathrm{Col}}^{\pi^+} \sim \delta u \, H_{1,\mathbf{favored}}^{\perp}$ ... expect: **positive**
- $A_{\mathrm{Col}}^{\pi^-} \sim \delta u \, H_{1,\mathbf{disfav}}^{\perp}$ ... expect: **~ zero**



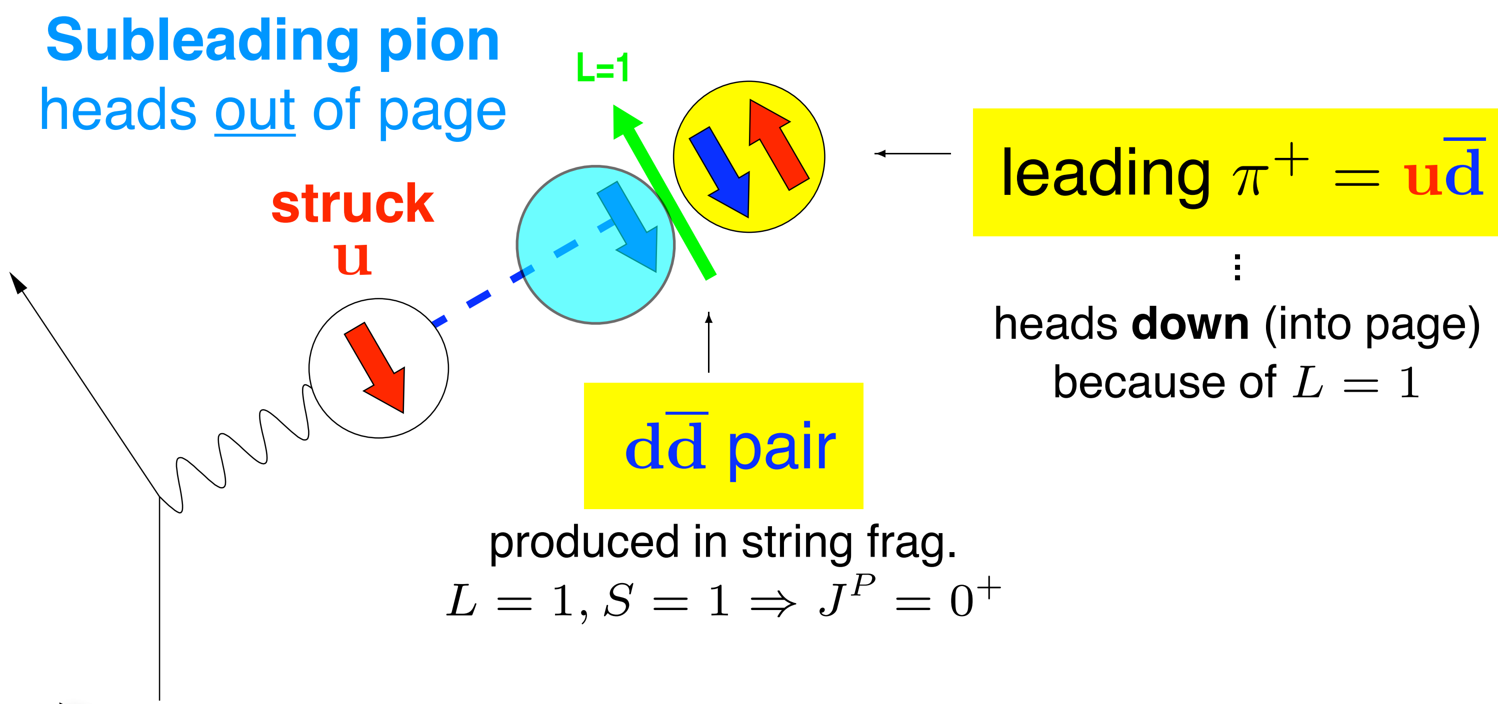
Data indicate ***disfavored*** CollinsFF is ***large*** & ***negative !***



Map out solution space ...
find $H_{\mathbf{disfav}} \approx -H_{\mathbf{fav}}$

Interpretation of Collins Results

Lund model + $^3P_0$ ***hypothesis*** once more:



leading π^+ = **favored** transition, heads into page

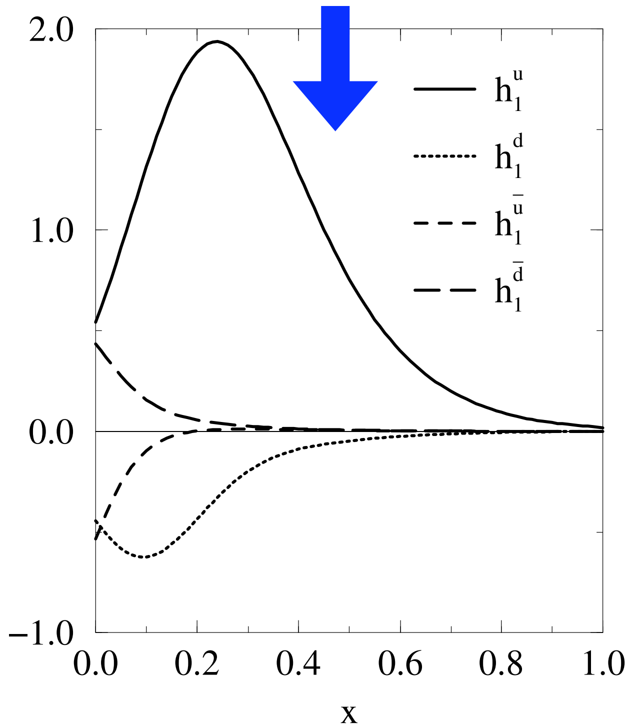
subleading particle (prob π^-) = **disfavored** transition, heads out of page

Perhaps $H_{\mathrm{dis}} \approx -H_{\mathrm{fav}}$ ***is not only reasonable, but likely ?***

Collins Global Fit: HERMES (H target) & COMPASS (D target)

Efremov, Goeke, Schweitzer, hep-ph/0603054

Take $h_1(x)$ from Chiral-Quark Soliton Model:



Fit K_T-integrated favored and unfavored **Collins FF** to **HERMES** data:

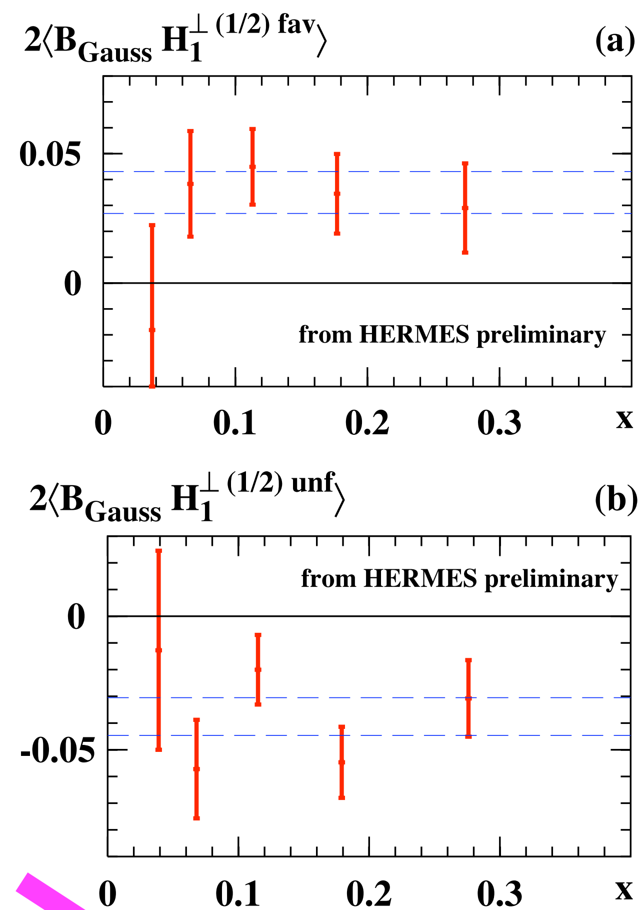
$$H_1^{\rm fav} = H_1^{u/\pi^+} = H_1^{d/\pi^-} = \ldots$$

$$H_1^{\rm unf} = H_1^{u/\pi^-} = H_1^{d/\pi^+} = \ldots$$

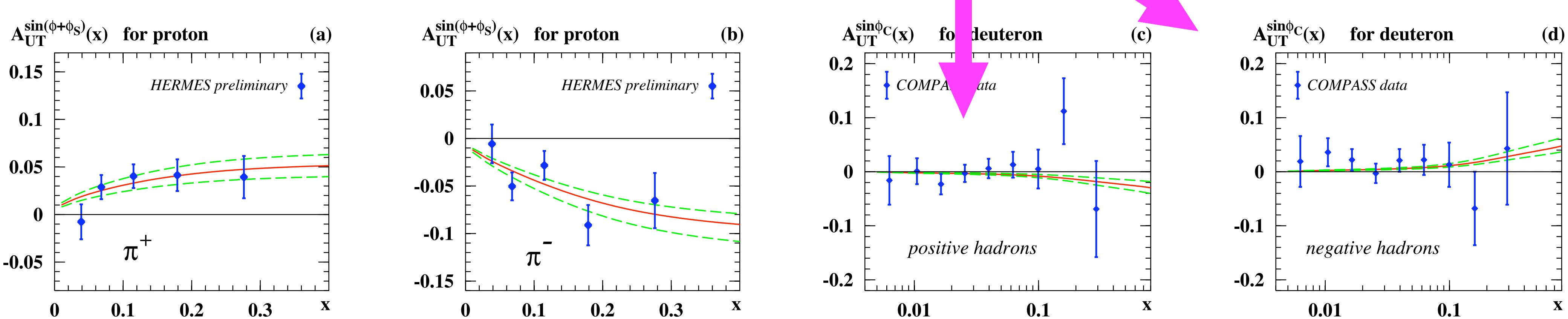
$$B_{\rm Gauss}(z) \equiv 1/\sqrt{1 + z^2 \langle \mathbf{p}_{h_1}^2 \rangle / \langle \mathbf{K}_{H_1}^2 \rangle}$$

Also find

$$H_1^{\rm fav} \approx -H_1^{\rm unf}$$



Gives good fit to **COMPASS**!



Collins Global Fit: HERMES (ep) & BELLE (e^+e^-)

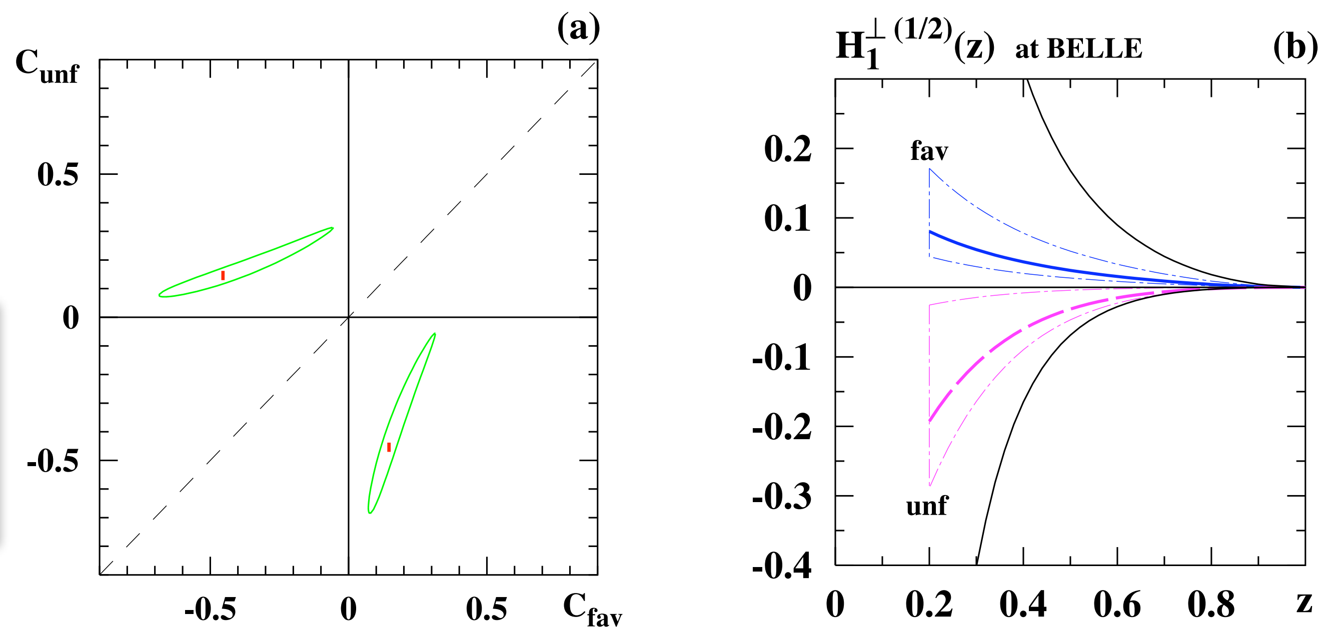
Efremov, Goeke, Schweitzer, hep-ph/0603054

Fit **BELLE** *z*-dependent results to

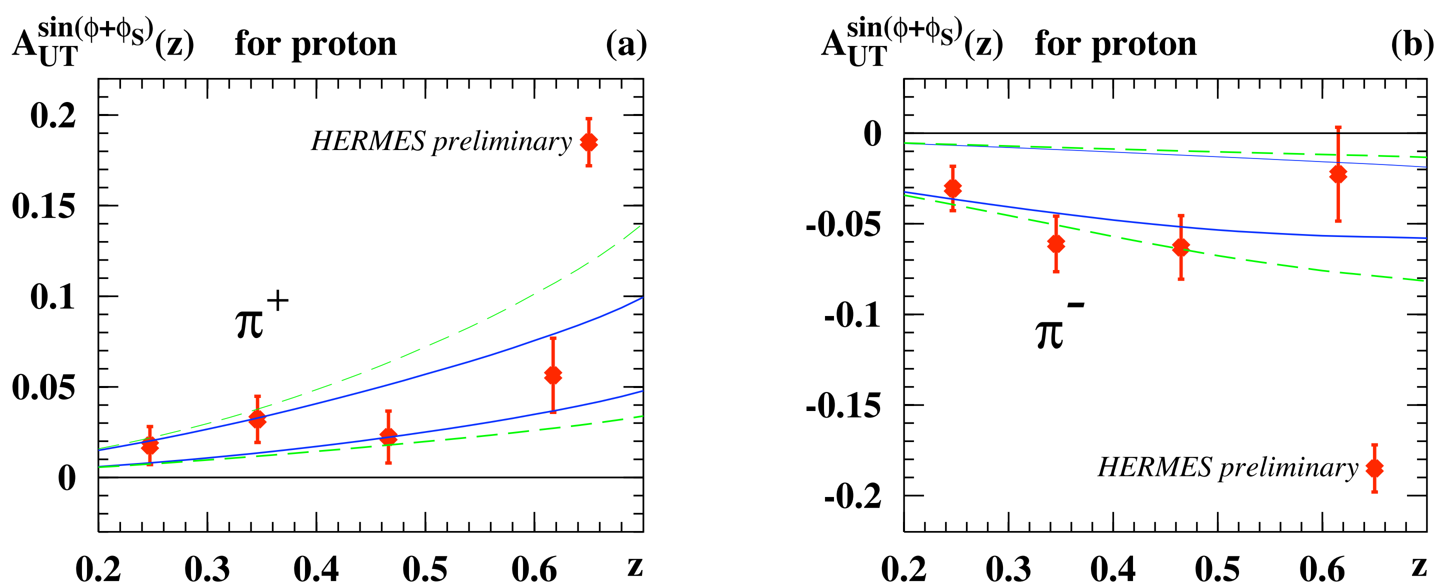
$$H_1^{\perp(1/2)a}(z) = C_a\, z\, D_1^a(z)$$

$C_{fav} = 0.15$, $C_{unf} = -0.45$

and so $H_1^{fav} \approx -H_1^{unf}$

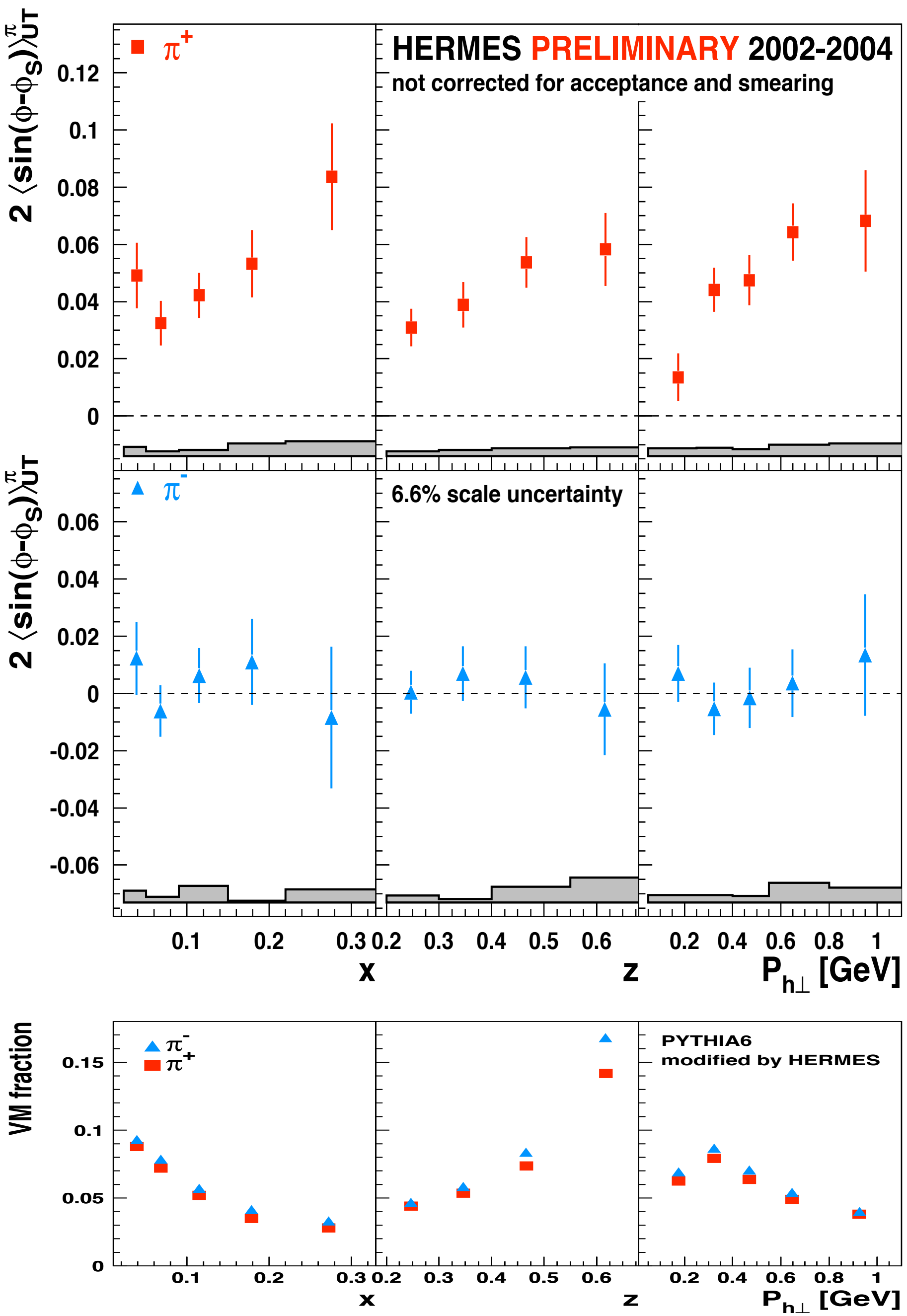


Resulting Collins FF also fit **HERMES** data well



SSA Results 2:
Sivers Effect

Sivers Moments for π^+ π^- from 2002–2004 $H^{\uparrow}$ Data

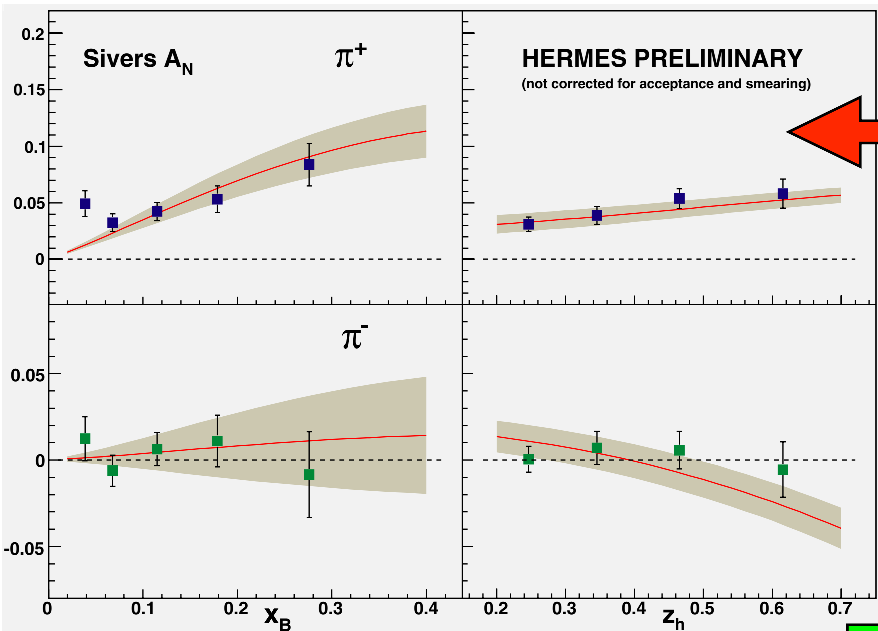


It exists too!

- First evidence for non-zero Sivers function!
- ⇒ presence of non-zero **quark orbital angular momentum**!
- Positive for π^+...
  Consistent with zero for π^-...
- Systematic error bands include acceptance and smearing effects, and contributions from unpolarized $\langle\cos(2\phi)\rangle$ and $\langle\cos(\phi)\rangle$ moments

Sivers Global Fit: HERMES & COMPASS

Vogelsang & Yuan, PRD 72 (2005) 054028



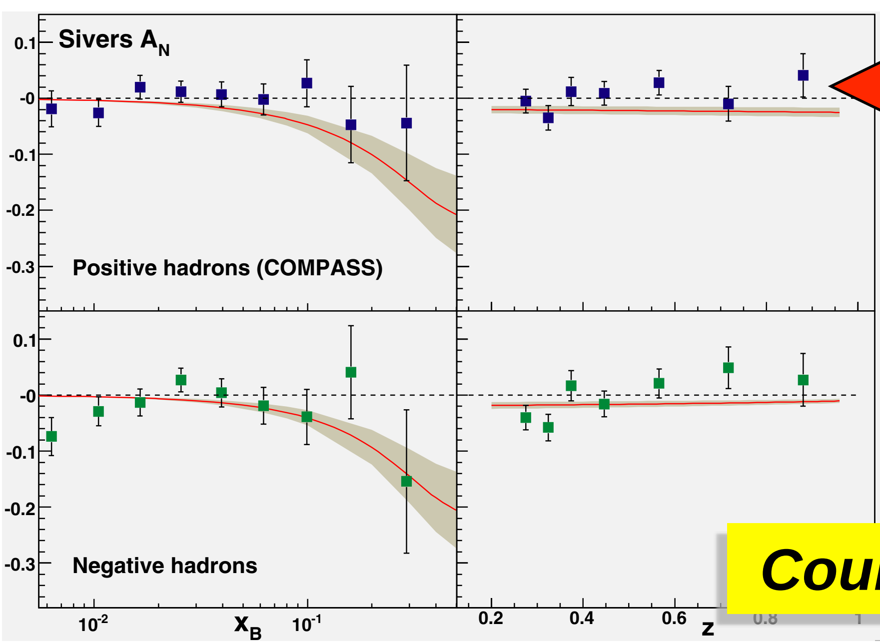
For convenience: $q_T(x) \equiv f_{1T}^{\perp,q}(x)$

Fit HERMES A_{UT} to Sivers func^n of form:

$$\frac{u_T^{(1/2)}(x)}{u(x)} = S_u\, x(1-x), \quad \frac{d_T^{(1/2)}(x)}{u(x)} = S_d\, x(1-x)$$

- assume **no antiquark** Sivers func: $\bar{q}_T(x) = 0$
- unpol PDFs = GRV-LO, unpol FFs = Kretzer

$$S_u = -0.81 \pm 0.07, \quad S_d = 1.86 \pm 0.28$$



Fits COMPASS deuterium data well!

But a surprise! S_d >> S_u!

e.g., large-N_C expectation: $u_T(x) \approx -d_T(x)$

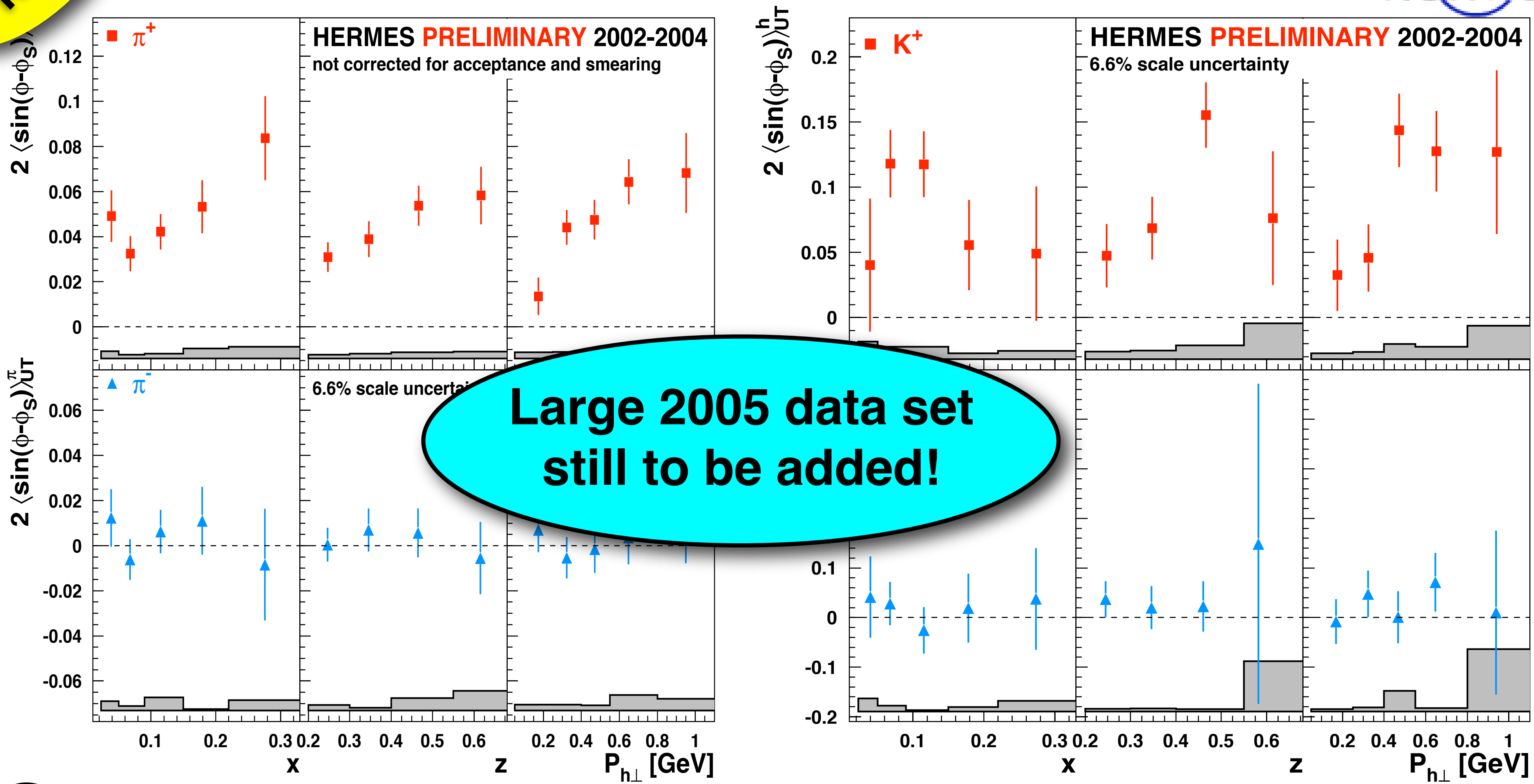
Hmm ... S_u *actually* reflects $u_T + \bar{d}_T/4$

... S_d *actually* reflects $d_T + 4\bar{u}_T$

Could Sivers (and L) be large for antiquarks?

NEW!

Sivers Moments for Kaons from 2002–2004 Data



– Effect about **equal** for $K^- = s\bar{u}$ and $\pi^- = d\bar{u}$ → note: same antiquark ...

\+ Effect *seems* ***larger*** for $K^+ = u\bar{s}$ than $\pi^+ = u\bar{d}$ at $x \approx 0.1$ ... !

→ significant ***antiquark*** Sivers functions? and strongly flavor-dependent?

Conclusions

Quark and gluon polarization

- **quark polarization** is **positive**, but much lower than CQM / bag model expections
- **anti-quark** polarization consistent with zero within measured range, including improved verification of $\Delta s \approx 0$
- data coming in from COMPASS and RHIC-Spin on ΔG ... so far a **modest**, positive value favoured ...

Collins fragmentation function

- **opposite sign** and similar magnitude to **favored** function
  sign of effect supports **$^3P_0$ picture** of color string breaking
- result now **confirmed** by new data from **BELLE**,
  + successful global analyses including **COMPASS** data

Sivers effect is ***non-zero*** in DIS!

- successful global analysis of **HERMES** (H) & **COMPASS** (D)
- ... and suggests large **antiquark** contributions to **orbital *L***
- latest HERMES data on **Kaon produc^n** seem to support this ...