Physics at "Low" Q^2

Exploring Structures in Non-perturbative QCD at (Relatively) Hard Scales

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① Proton Structure

spin-dependent parton distribution functions of the proton

② Diffraction

"soft" processes at the highest energies

③ Generalized Parton Distributions

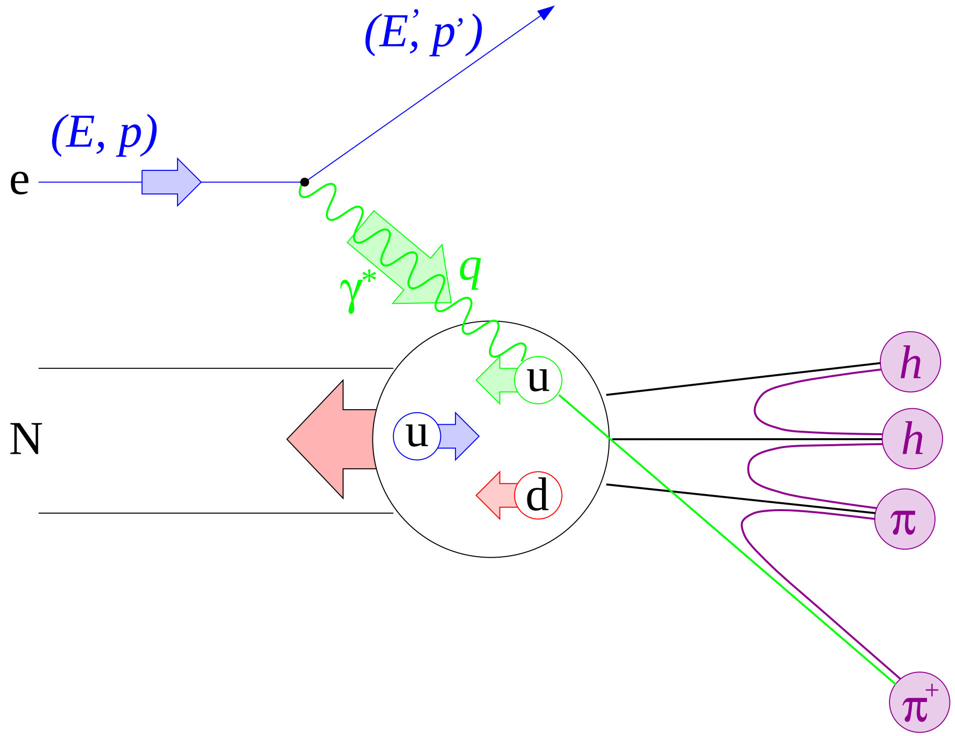
mapping out the proton wavefunction

④ Hadron Formation

spin and scale dependence of the fragmentation process

Deep-Inelastic Scattering

Q^2 = -mass^2 of virtual photon > 1 GeV^2
W^2 = mass^2 of $\gamma^* p$ system > 4 GeV^2



study partonic substructure of

- ***proton target***
  $\Rightarrow$ parton distribution functions $q(x, Q^2)$
- ***hadron formation***
  $\Rightarrow$ fragmentation functions $D(z, Q^2)$

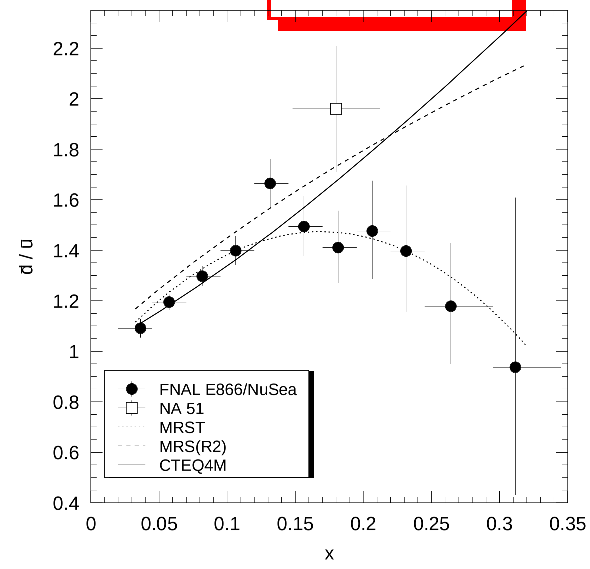
	beam	target	$\langle Q^2 \rangle$
current experiments			
H1,ZEUS	27.6 GeV $e^{\pm}$	900 GeV p	$\gg 10$ GeV^2
HERMES	27.6 GeV $e^{\pm}$, polarized	fixed p,d, polarized	2.5 GeV^2
CLAS	4 – 6 GeV e^-, polarized	fixed p,d, polarized	1.3 GeV^2
future experiments			
COMPASS	100 – 200 GeV μ, polarized	fixed p,d, polarized	10 GeV^2
STAR, PHENIX	250 GeV p, polarized	250 GeV p, polarized	M_W^2

Flavor Structure of the Proton

- **Constituent Quark Model**
  Pure valence description: proton = 2 u + d

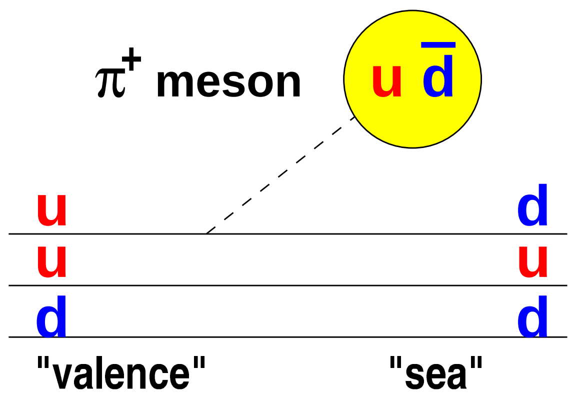
- **Perturbative Sea** Sea quark pairs from $g \to q\bar{q}$ should be flavor symmetric: $\bar{u} = \bar{d}$

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



Non-perturbative models : alternate deg's of freedom

Meson Cloud Models

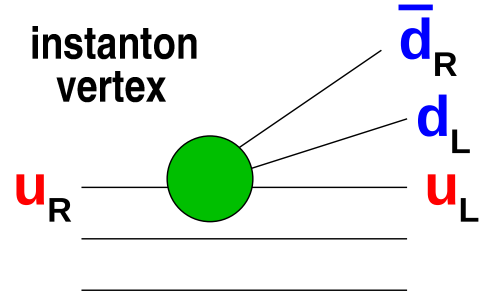


Quark sea from cloud of 0^- mesons: $\bar{d} > \bar{u}$

Chiral-Quark Soliton Model

- quark degrees of freedom in a pion mean-field
- nucleon = chiral soliton
- one parameter: dynamically-generated quark mass
- expand in $1/N_c$: $\bar{d} > \bar{u}$

Instantons



'tHooft instanton vertex $\sim \bar{u}_R u_L \bar{d}_R d_L$

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

Spin Structure of the Proton

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

"You think you understand something?
Now add spin ..." – *R. Jaffe*

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**

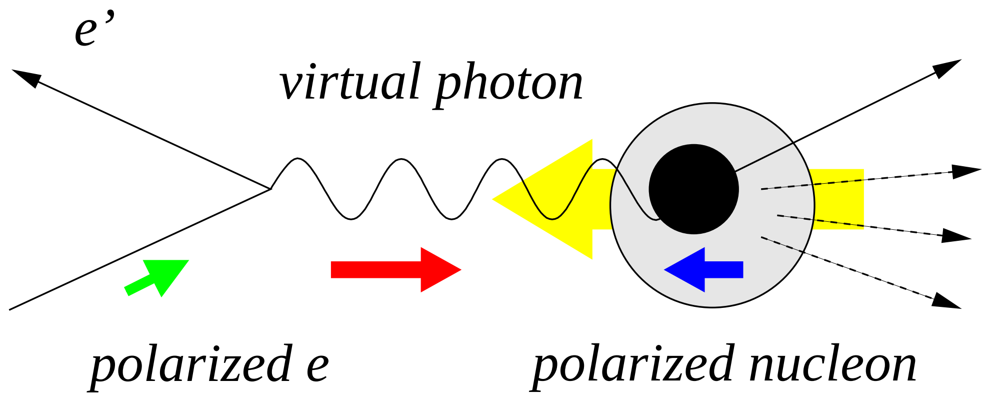
$\Delta u = +4/3,\ \Delta d = -1/3 \rightarrow$ $\Delta\Sigma = 1$

- **Relativistic Quark Model**

orbital angular momentum is important

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

Polarized Deep-Inelastic Scattering



From NLO-QCD analysis of inclusive DIS measurements ...

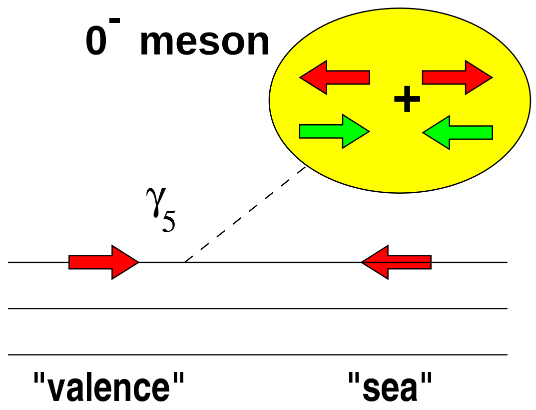
SMC, PRD 58 (1998) 112002

- $\Delta\Sigma = 0.38$ (in AB scheme)
- $\Delta G = 1.0^{+1.9}_{-0.6}$ (in AB scheme)
  $\rightarrow$ barely constrained, positive value favored
- $\Delta s = -0.02$ to -0.15 (model dependent)
  $\rightarrow$ slight negative sea-quark polarization?

Anti-quark Spin in the Proton

Meson Cloud Models

Li, Cheng, hep-ph/9709293



$\rightarrow \Delta q_{valence} > 0$

$\rightarrow \Delta q_{sea} < 0$, but ...

$\Rightarrow$ $\Delta\bar{q} = 0$

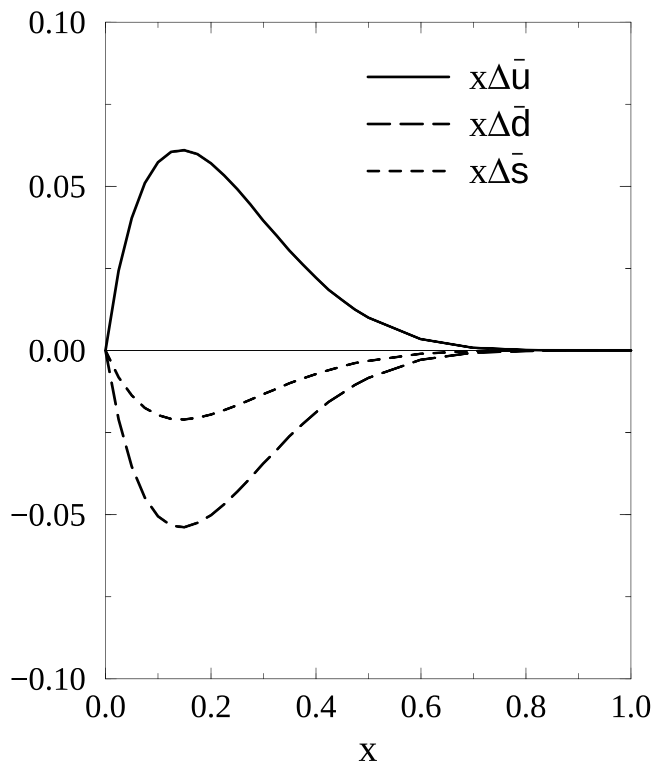
"Higher-order" cloud of vector mesons can generate a small polarization.

Chiral-Quark Soliton Model

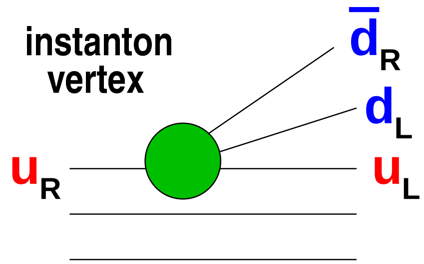
Goeke et al, hep-ph/0003324

Light sea quarks polarized:

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



Instanton Mechanism



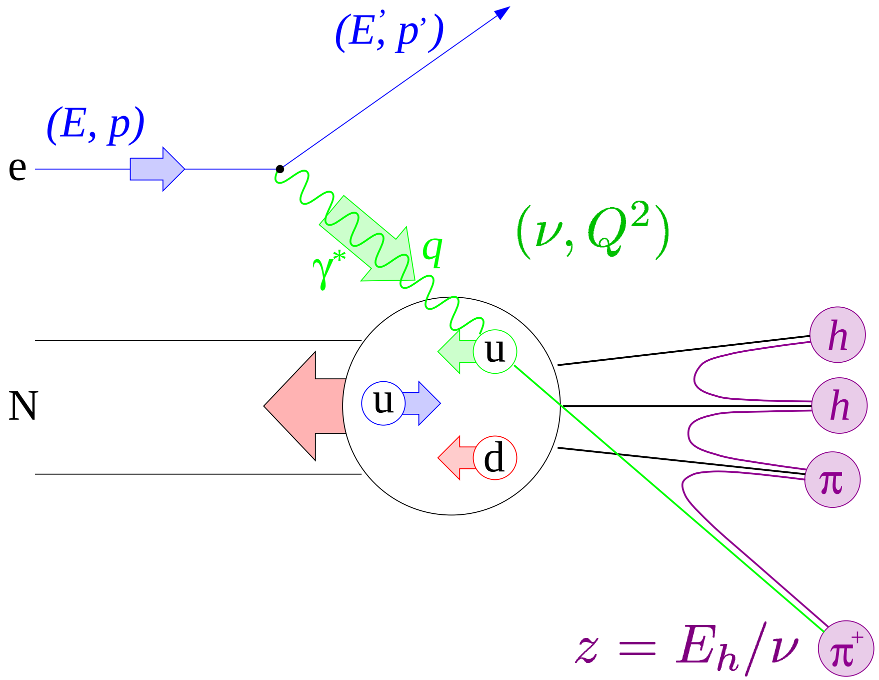
'tHooft instanton vertex $\sim \bar{u}_R u_L \bar{d}_R d_L$ transfers helicity from valence u quarks to $d\bar{d}$ pairs

$$\Delta\bar{d} > 0, \quad \Delta\bar{u} < 0\ ?$$

No such calculation yet performed ...

Quark Polarization from Semi-Inclusive DIS

In ***semi-inclusive DIS*** a hadron h is detected in coincidence with the scattered lepton



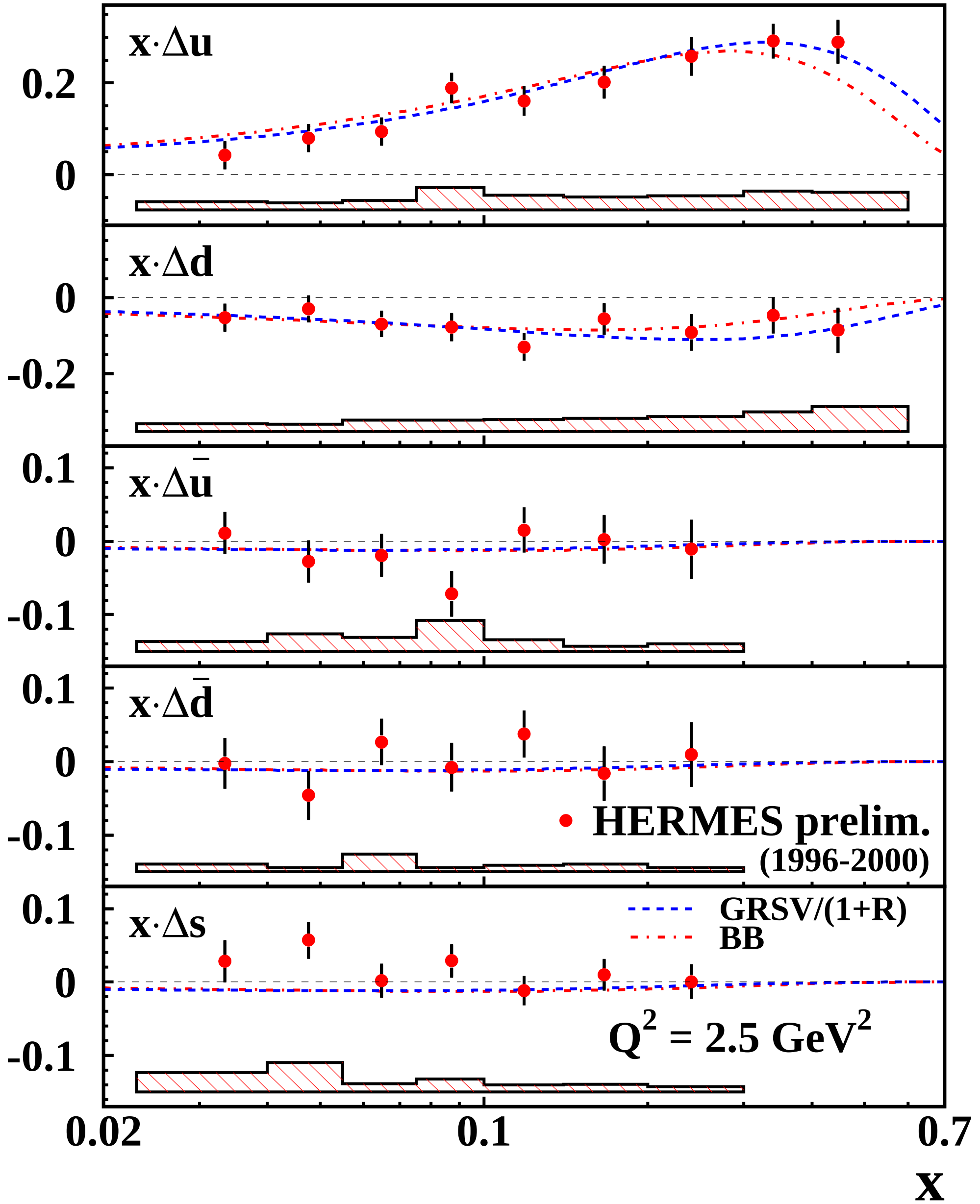
Goal: Flavor Separation
of quark and antiquark helicity distributions

Technique: Flavour Tagging

The flavour content of the final state hadrons is related to the flavour of the struck quark through the agency of the **fragmentation functions** $D_q^h(z, Q^2)$. In LO QCD:

$$\frac{d\sigma_h^{\uparrow\downarrow}}{dz} - \frac{d\sigma_h^{\uparrow\uparrow}}{dz} = \sum_q e_q^2 \, \Delta q(x, Q^2) \cdot D_q^h(z, Q^2)$$

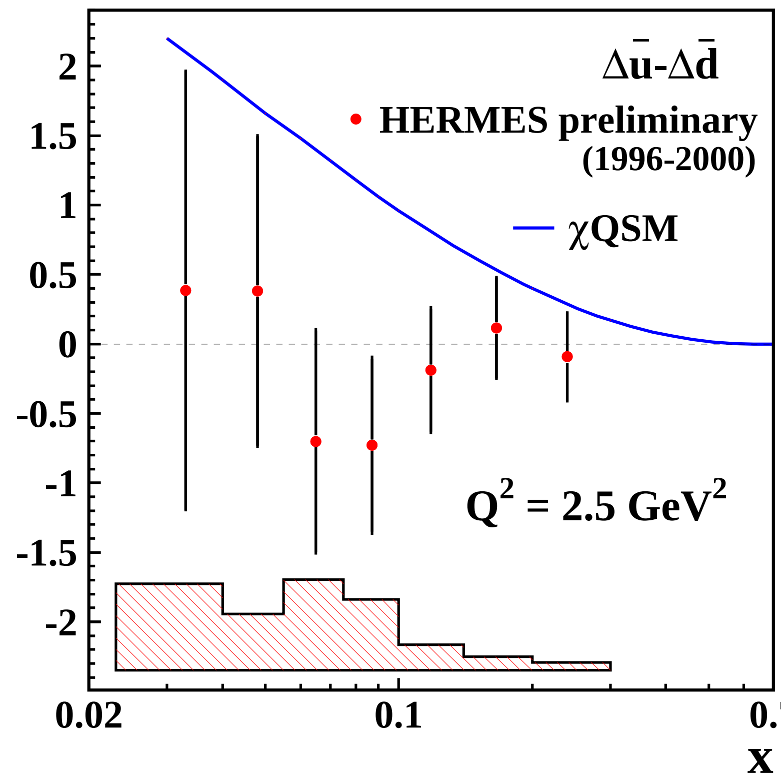
Latest Δq Results from HERMES



First 5-flavor fit to $\Delta q(x)$

($\Delta s(x) = \Delta \bar{s}(x)$ assumed)

- positive Δs favored
- $\Delta \bar{u} - \Delta \bar{d}$ consistent with 0



New Spin-Structure Function: Transversity $\delta q(x)$

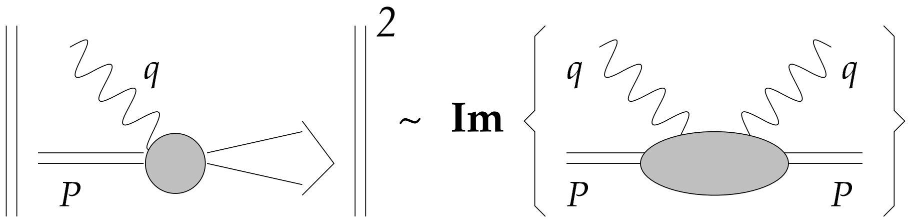
Fundamental Matrix Elements

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

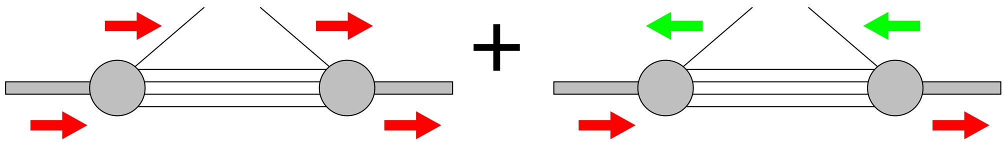
tensor charge $\langle PS|\overline{\psi}\sigma^{\mu\nu}\psi|PS\rangle = \int_0^1 dx\ \delta q(x) - \delta\overline{q}(x)$ $\rightarrow$???

Forward Helicity Amplitudes

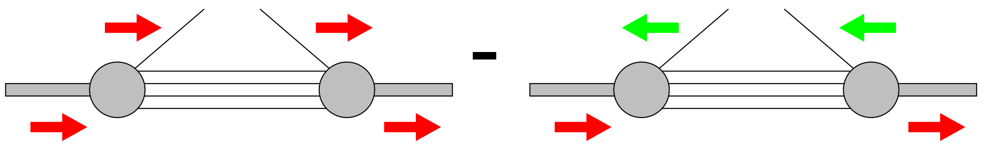


(optical theorem applied to DIS)

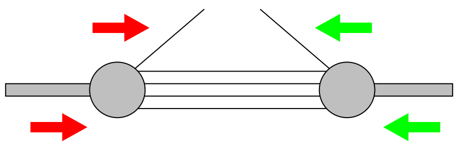
$q(x) \sim$



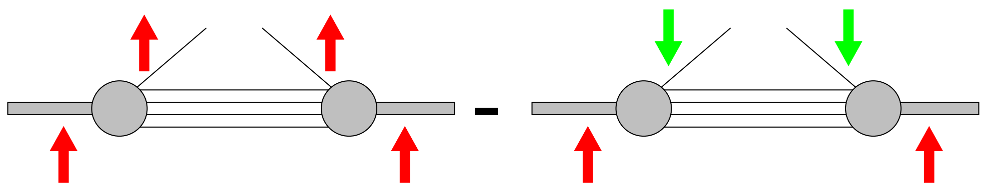
$\Delta q(x) \sim$



$\delta q(x) \sim$



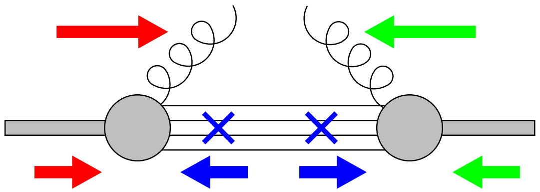
... but in transverse basis ...



Properties of Transversity

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

- **No Gluons**

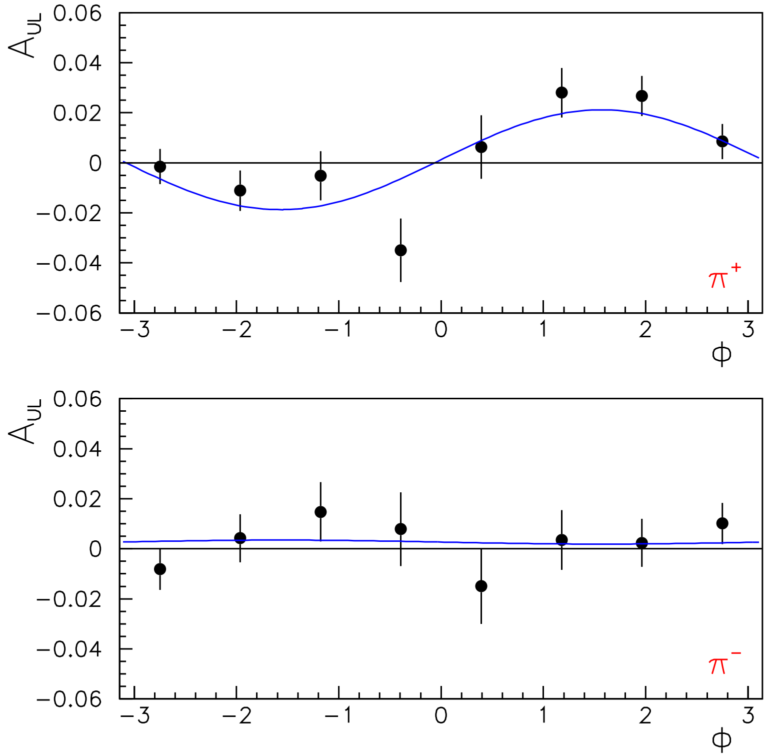


Angular momentum conservation: $\Lambda - \lambda = \Lambda' - \lambda'$
$\Rightarrow$ transversity has ***no gluon*** component
$\Rightarrow$ different Q^2 ***evolution*** than $\Delta q(x)$

- **Chiral Odd**

$\Rightarrow$ only measurable in ***semi-inclusive*** DIS, via a chiral-odd fragmentation function.

First glimpse from spin-azimuthal asymmetry for π production at HERMES



Future: DIS with ***transverse target polarization*** at HERMES Run 2, COMPASS, RHIC-spin

Proton Spin Structure: Status

- ***quark polarization*** $\Delta q(x)$:

  $\rightarrow$ first 5-flavor separation from HERMES
  $\rightarrow$ $\Delta\bar{q}(x)$ consistent with zero, in contrast to χQSM model predictions

- ***transversity*** $\delta q(x)$:

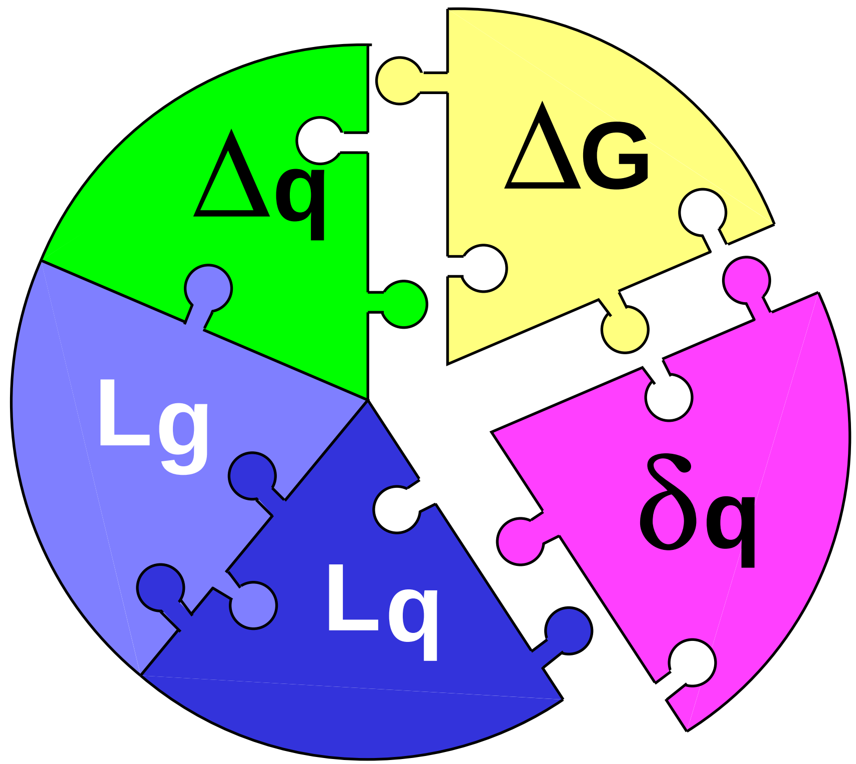
  $\rightarrow$ a new window on quark spin
  $\rightarrow$ azimuthal asymmetries from HERMES successfully modelled in terms of $\delta q(x)$

- ***gluon polarization*** $\Delta G(x)$:

  $\rightarrow$ some indications that $\Delta G > 0$ ...
  $\rightarrow$ RHIC-spin and COMPASS will provide some answers!

- ***orbital angular momentum*** L:

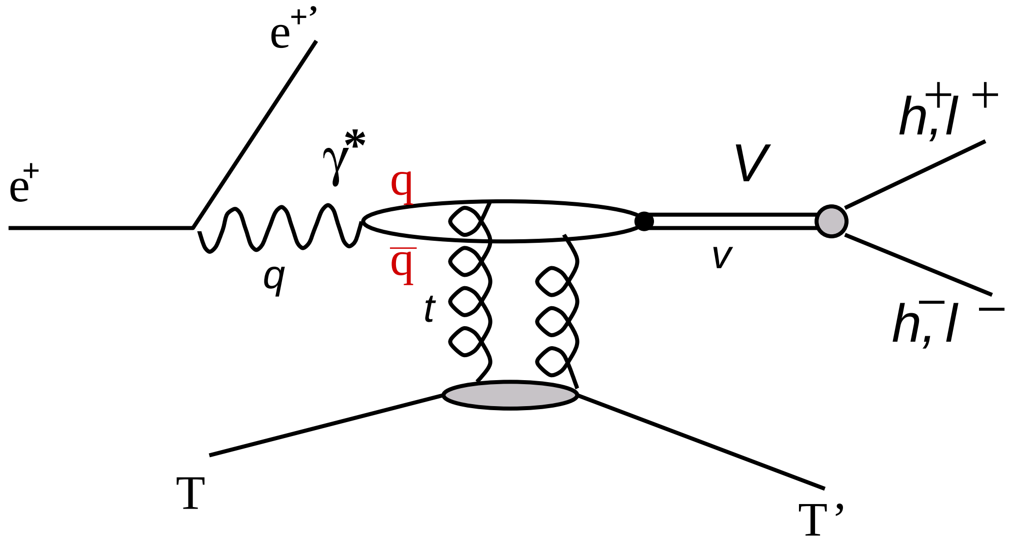
  $\rightarrow$ how to measure? $\rightarrow$ GPD's ...



Diffractive Vector Meson Production

Even at highest energies $W = 10 - 300$ GeV, diffractive processes are alive and well

e.g. **Diffractive Vector Meson producⁿ**



A new class of factorization theorems allows pQCD analysis of exclusive processes at high scales

pQCD picture: 2-gluon exchange

→ **fast rise** of xsec with $\mathbf{W}$

$$\sigma_L \sim \frac{[x\,\mathbf{g(x)}]^2}{Q^6} \quad \text{and} \quad x \approx \frac{Q^2}{W^2}$$

$$g(x) \sim x^{-(1+\lambda)} \quad \text{with} \quad \lambda \approx 0.2$$

$$\Rightarrow \sigma_L \sim W^{0.8}$$

3 scales

- t = momentum transfer to target

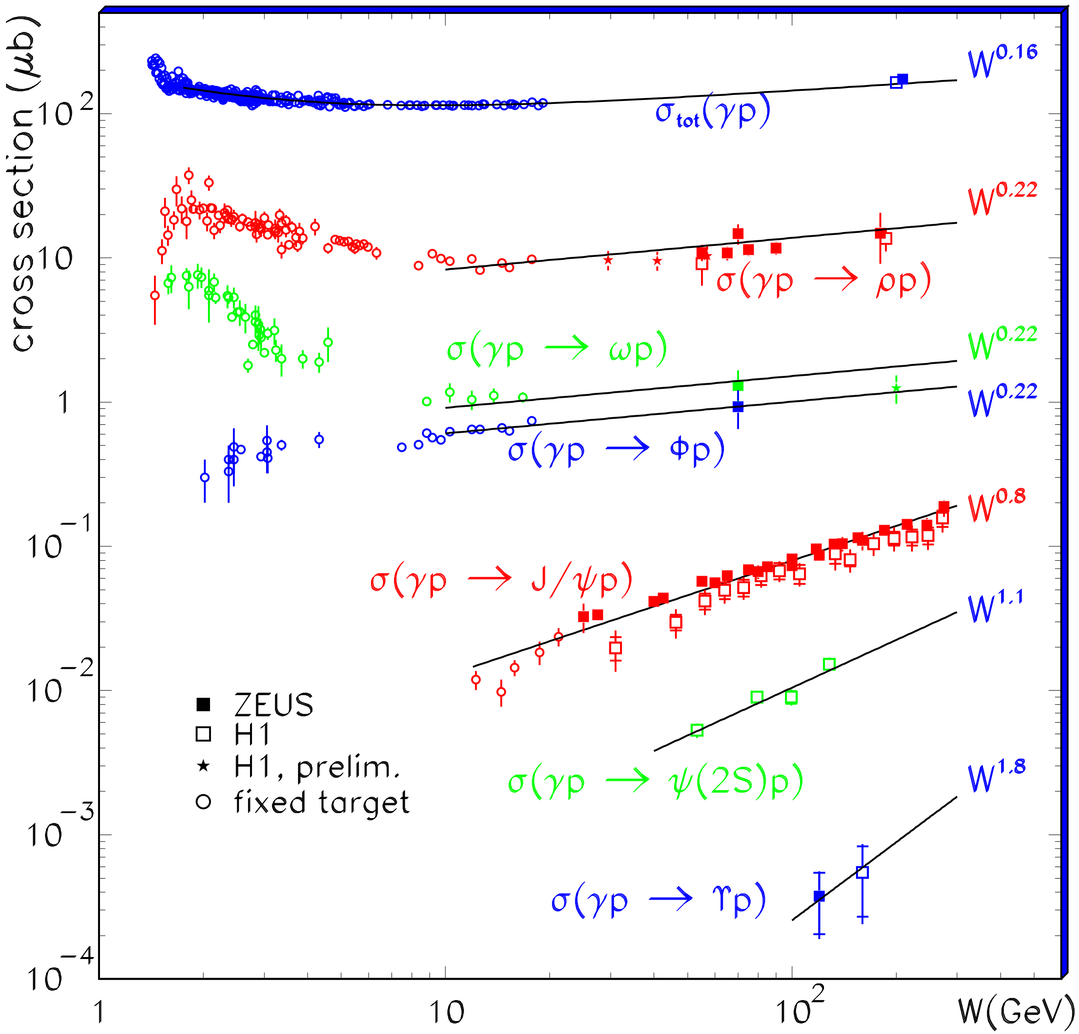
  $\rightarrow$ $\sigma \sim e^{-bt}$ @ low t

  $\rightarrow b$ reflects ***size*** of scattered p'cles
- Q^2 = photon virtuality
- m_{VM} = mass of vector meson

Soft → Hard Transitions

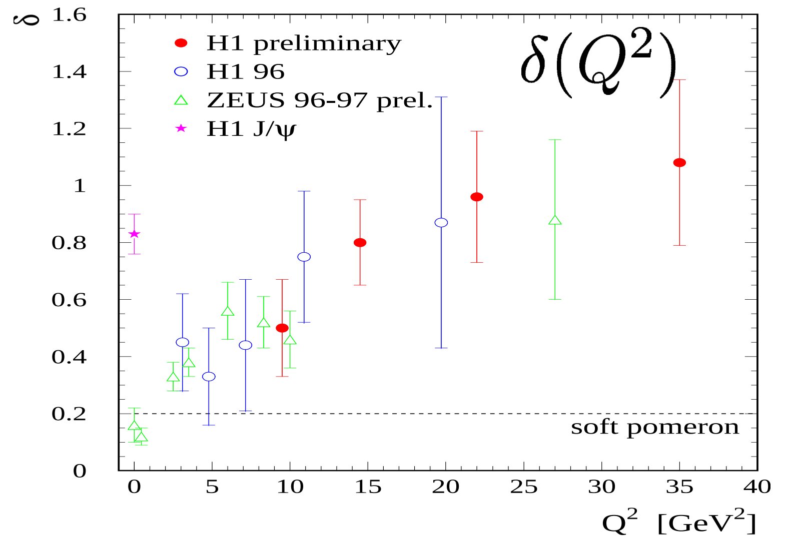
Photoproduction ($Q^2 = 0$)

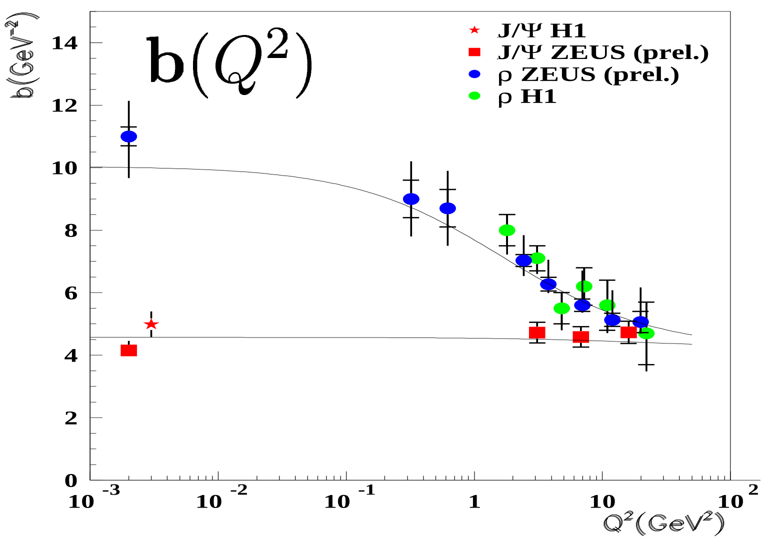
onset of hard behavior: ***charm mass*** (J/ψ)



Diffractive ρ production

onset of hard behavior: ***high Q^2***





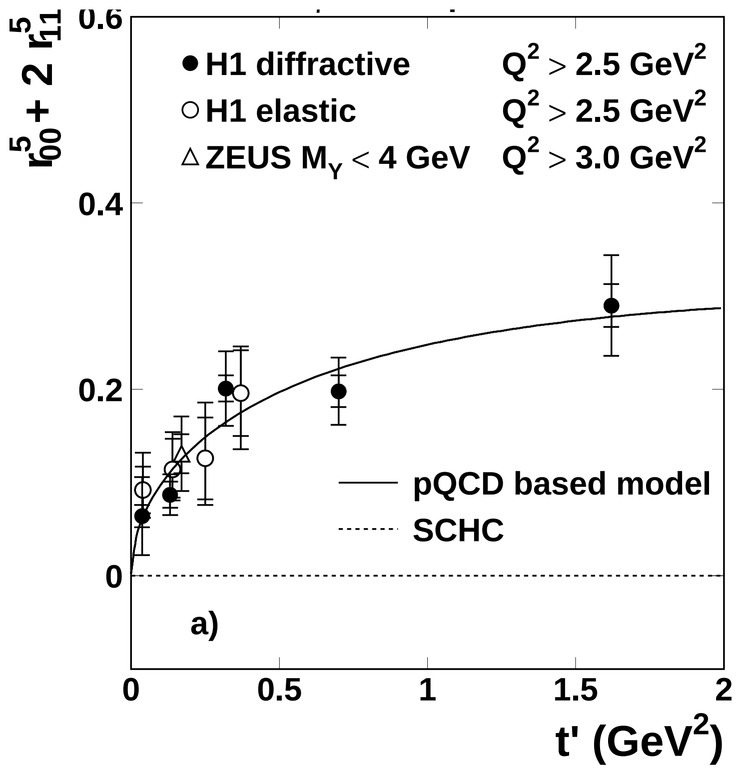
N.C.R. Makins, ICHEP 2002, Amsterdam

Spin-Density Matrix Elements at High t

Angular distribution of $\rho \to \pi\pi$ decay gives info about **transition amplitudes** $T_{\lambda_\rho \lambda_\gamma}$

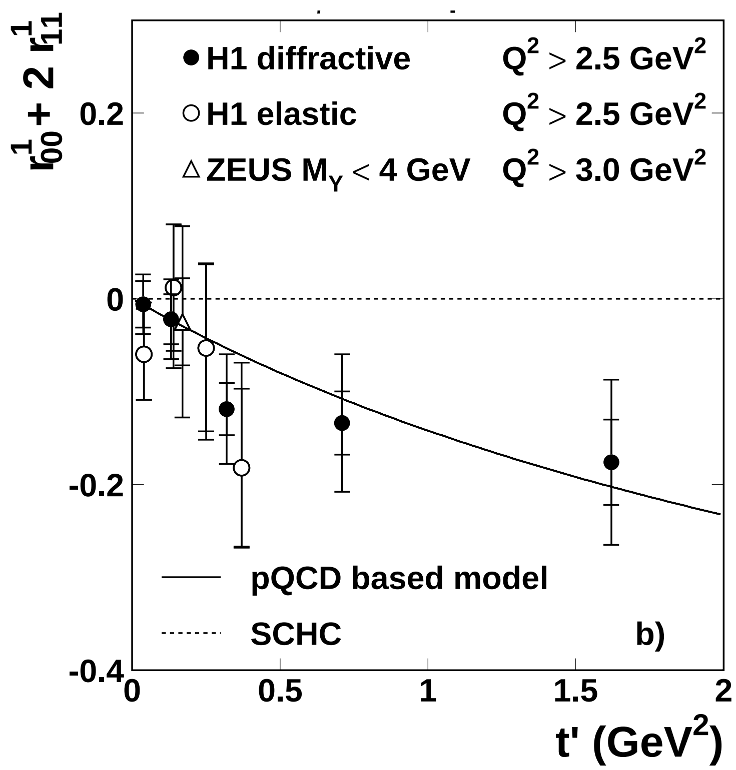
at low t: s-channel helicity conservation (SCHC) ➡ only T_{00} and T_{11} non-zero

SDME combination # 1 $\sim T_{01}$



→ single-flip amplitude significant at high t

SDME combination # 2 $\sim T_{01}/T_{1-1}$

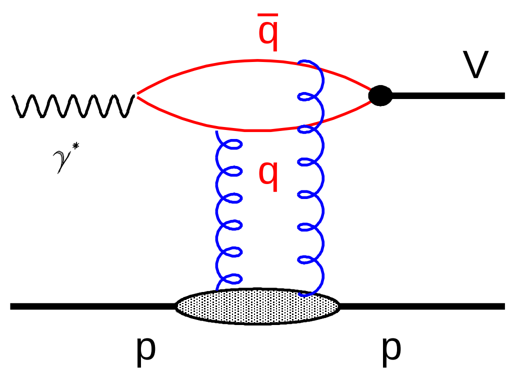


→ single-flip $\gg$ double-flip amplitude

Measurements well described by pQCD model of 2-gluon exchange

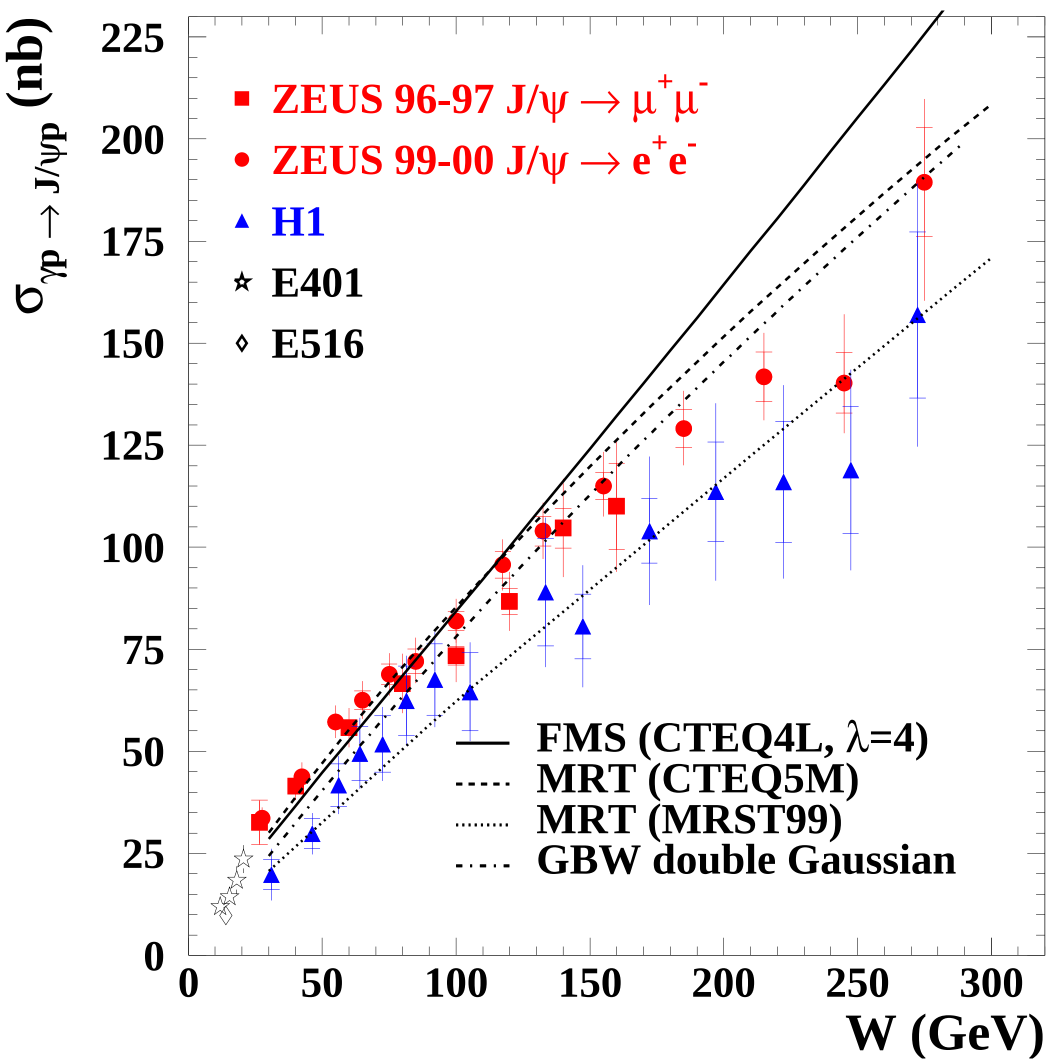
Gluon Density from $\gamma p \to J/\psi\, p$

Diffractive J/ψ production well described by pQCD 2-gluon exchange models



Should be possible to extract $g(x)$**!**

- $W = 250$ GeV $\to x = 10^{-4}$
- data precise enough to distinguish between different PDF sets →
- ... but theoretical uncertainties make extraction impossible at present: higher-twist correc's and ***skewing*** ...

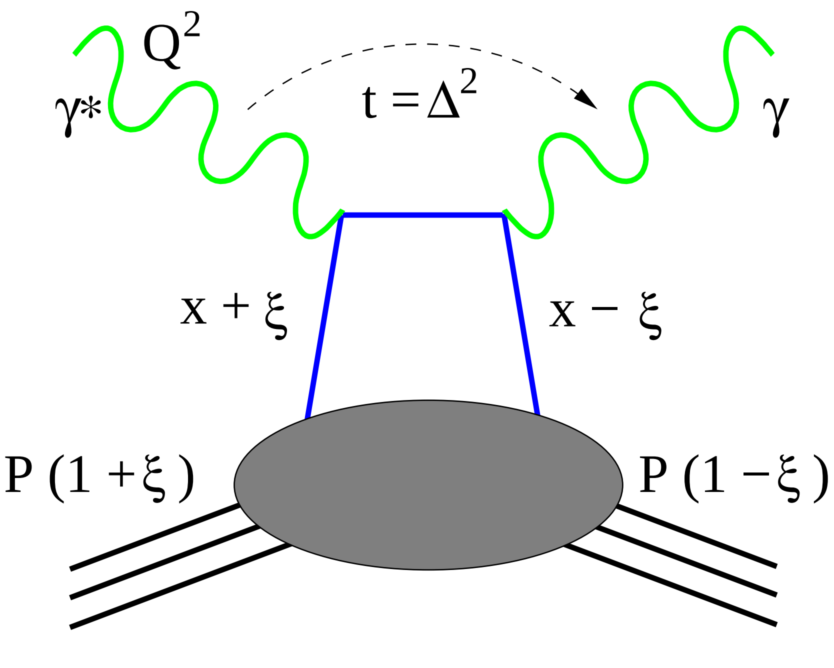


Generalized Parton Distributions

Analysis of ***hard exclusive processes*** leads to a new class of parton distributions.

Cleanest example: Deeply Virtual Compton scattering

DVCS



"handbag diagram"

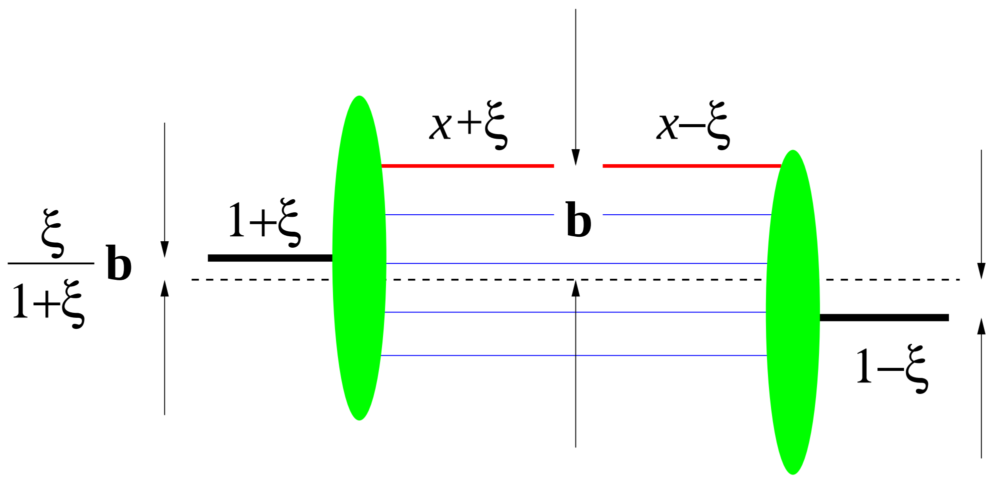
Four new distributions:

helicity conserving $\rightarrow H(x, \xi, t), E(x, \xi, t)$
helicity-flip $\rightarrow \tilde{H}(x, \xi, t), \tilde{E}(x, \xi, t)$

Bjorken $\mathbf{x}$: average quark momentum fraction

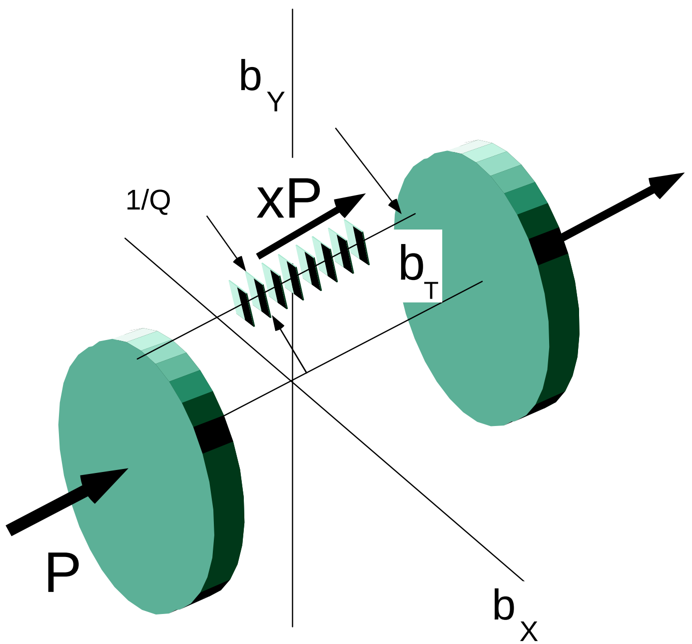
"skewing parameter" ξ

$\rightarrow$ mismatch between quark momenta
$\Rightarrow$ sensitive to partonic ***correlations***



"Femto-photography" of the proton

Fourier transform of ***t-dependence***
$\to$ impact-parameter space



➡ ***spatial distribution*** of partons !

Connection to Many Observables

- **DIS structure functions:** forward limit

$$q(x) = H^q(x, \xi = 0, t = 0)$$

$$\Delta q(x) = \tilde{H}^q(x, \xi = 0, t = 0)$$

- **Elastic form factors:** first moments

$$GM(t) = \int_{-1}^{1} dx \sum_q \left[H^q(x,\xi,t) + E^q(x,\xi,t)\right]$$

$$GE(t) = \int_{-1}^{1} dx \sum_q \left[H^q(x,\xi,t) + \frac{t}{4M^2} E^q(x,\xi,t)\right]$$

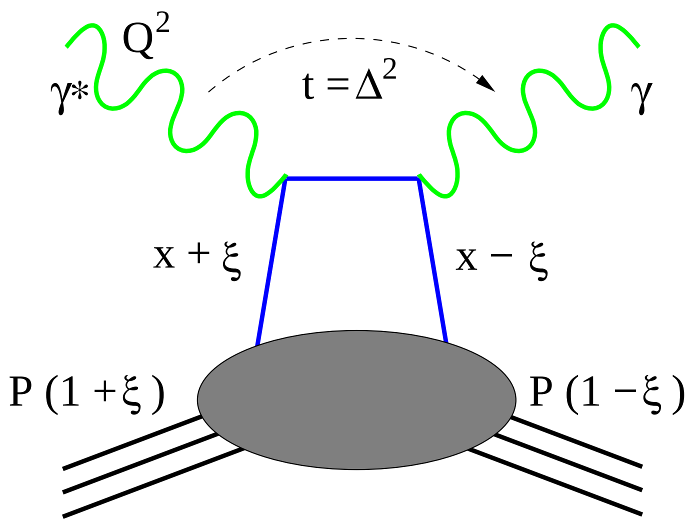
- **Angular momentum $J^q = \frac{1}{2}\Delta\Sigma + L^q$!**

$$J^q = \frac{1}{2}\int_{-1}^{1} x\, dx \left[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)\right]$$

GPD's offer a complete description of the proton wavefunction

Modelling the GPD's

- t–**dependence** from elastic form factors
- ξ**– (skewedness)** and x**– dependence**
  $\rightarrow$ interpolate between 2 regions:



- $|x| > \xi$
  $\rightarrow x_1, x_2$ both > 0 (quarks)
  or both < 0 (antiquarks)

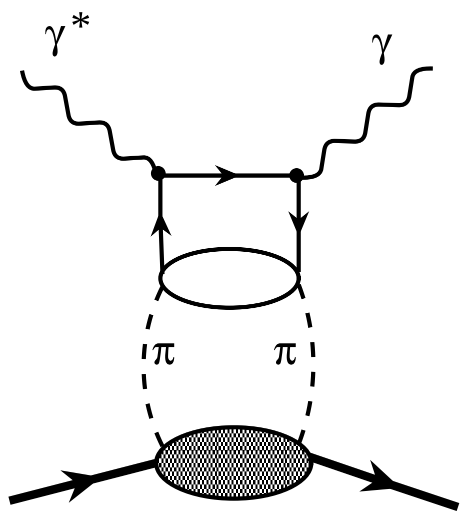
  $\Rightarrow$ **PDF's** recovered in limit $\xi \rightarrow 0$

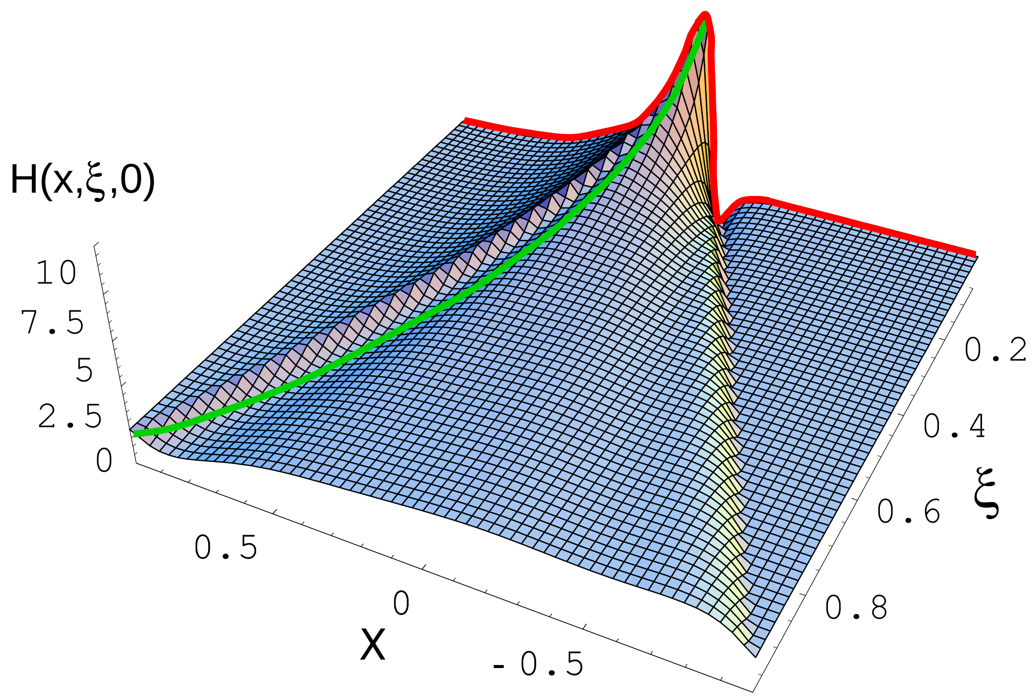
Model of $H^d(x, \xi, t = 0)$ (forward limit)

Vanderhaeghen, Guichon, Guidal, PRD 60 (99) 094017

- $|x| < \xi$
  $\rightarrow$ see correlation between q and $\bar{q}$

  $\Rightarrow$ **"meson-like"** distributions as $\xi \rightarrow 1$

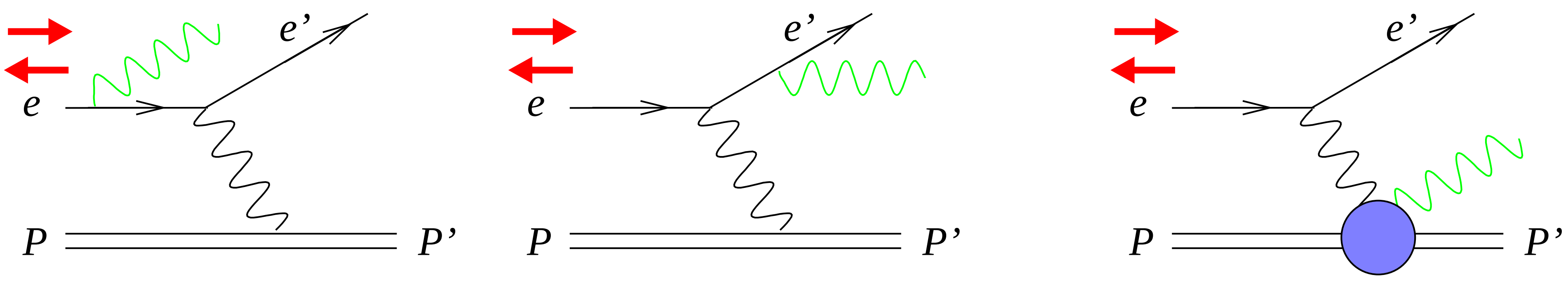




DVCS: Beam-Spin Azimuthal Asymmetry

At intermediate energies, Bethe-Heitler cross-section $\gg$ DVCS ...

⇒ explore ***interference***, using ***polarized beams***



Beam-Spin Asymmetry ➡

$$A_{\mathrm{LU}}(\phi_\gamma) = \frac{\sigma_\rightarrow - \sigma_\leftarrow}{\sigma_\rightarrow + \sigma_\leftarrow}$$

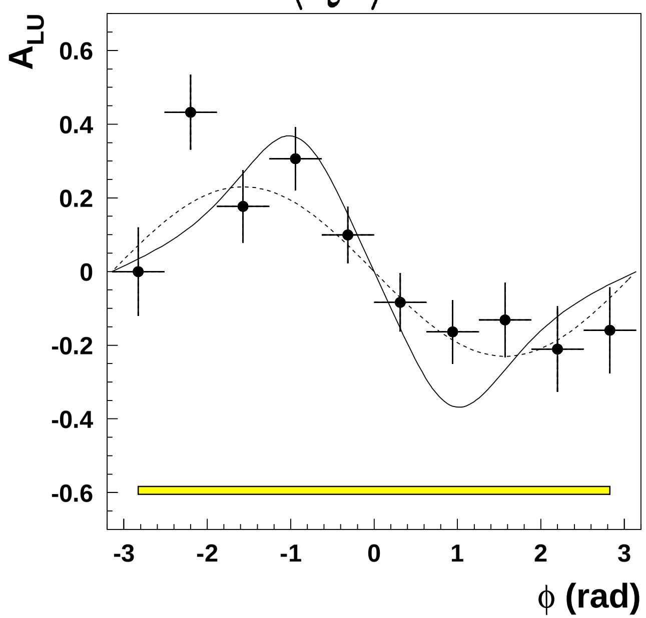
$$\sim \mathbf{Im}\,(\mathbf{BH} \cdot \mathbf{DVCS}^*)\,\sin\phi_\gamma$$

Beam-Charge Asymmetry

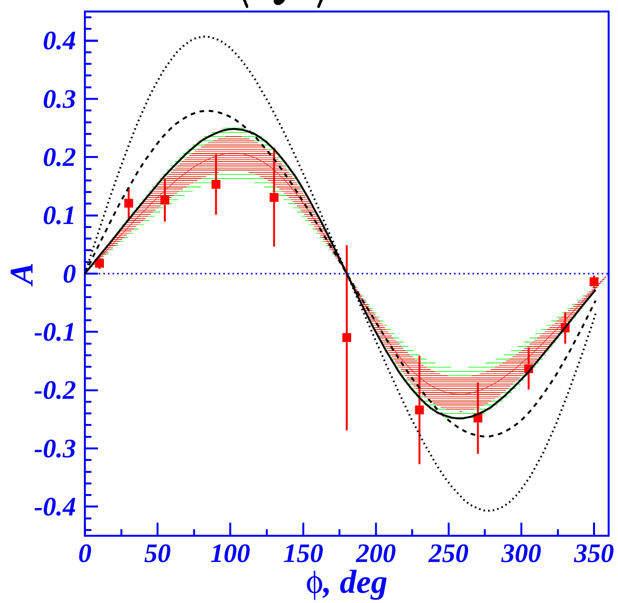
$$\sim \mathbf{Re}\,(\mathbf{BH} \cdot \mathbf{DVCS}^*)\,\cos\phi_\gamma$$

also measured, at HERMES

HERMES: $\langle Q^2 \rangle$ = 2.6 GeV^2



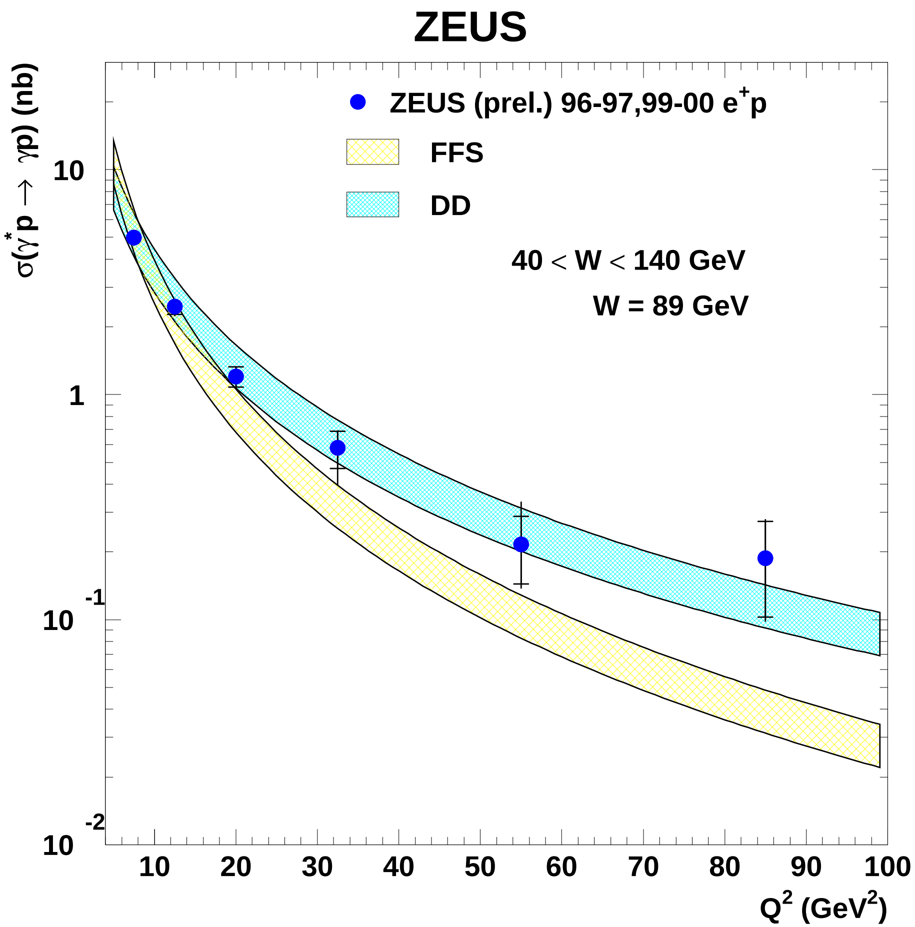
CLAS: $\langle Q^2 \rangle$ = 1.3 GeV^2

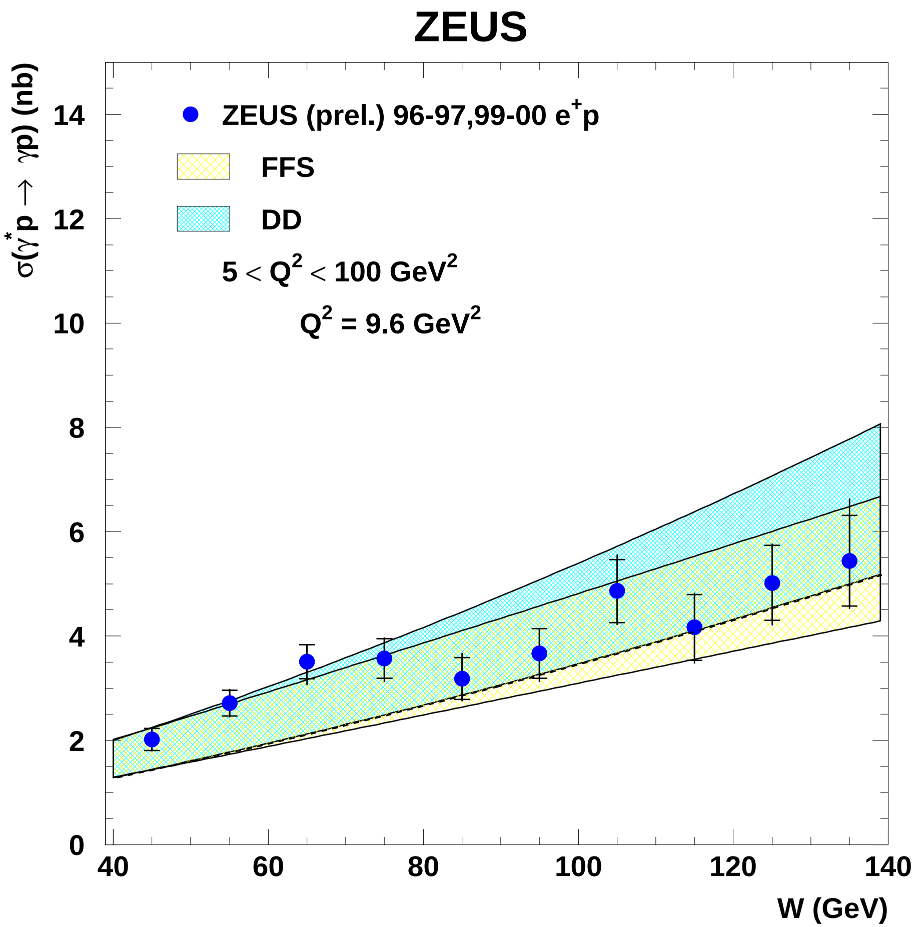


DVCS Cross-Section from H1 and ZEUS

At high energies, DVCS > BH $\rightarrow$ measure cross-section ...

high-energy DVCS explores gluon GPD's ($x \sim 1/W^2$)





DVCS xsec agrees well with semi-classical dipole model (Donnachie & Dosch)

DVCS Cross-Section from H1 and ZEUS

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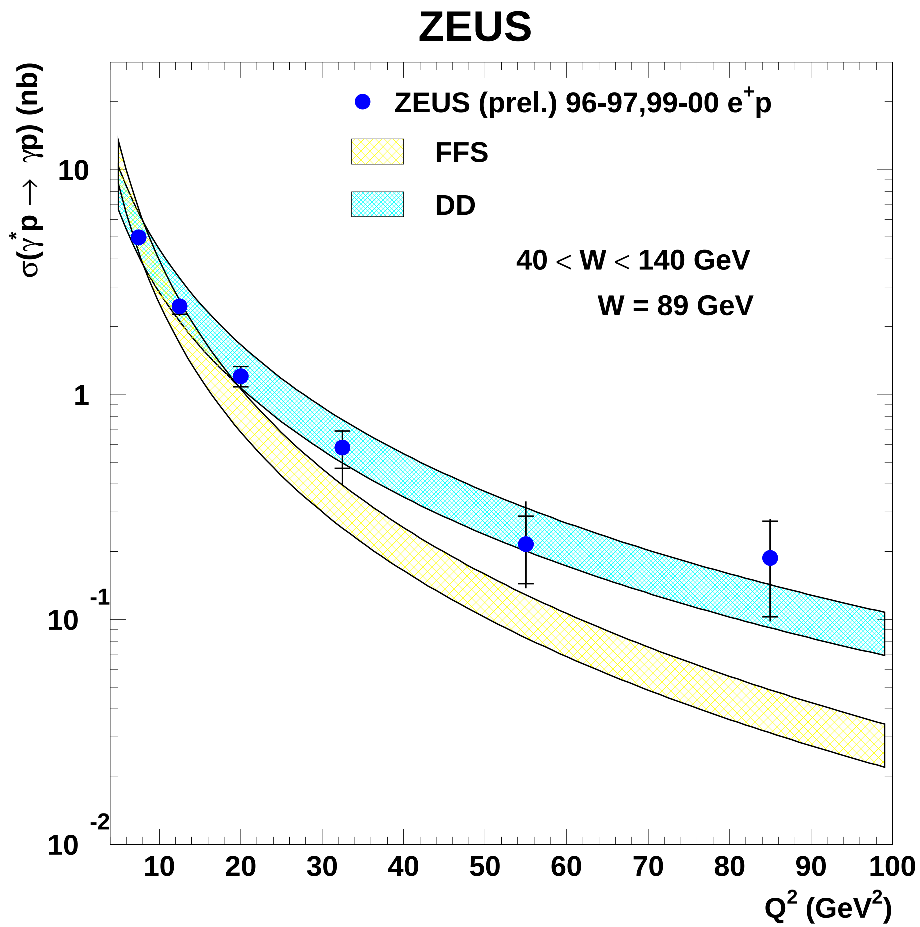
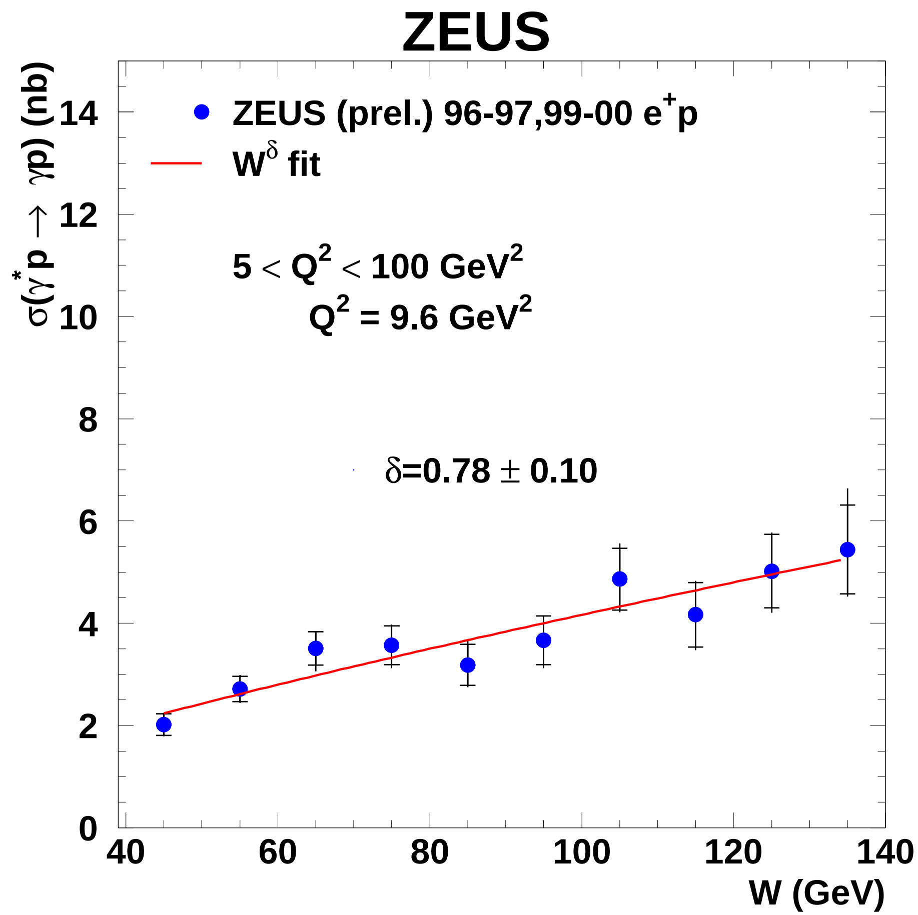
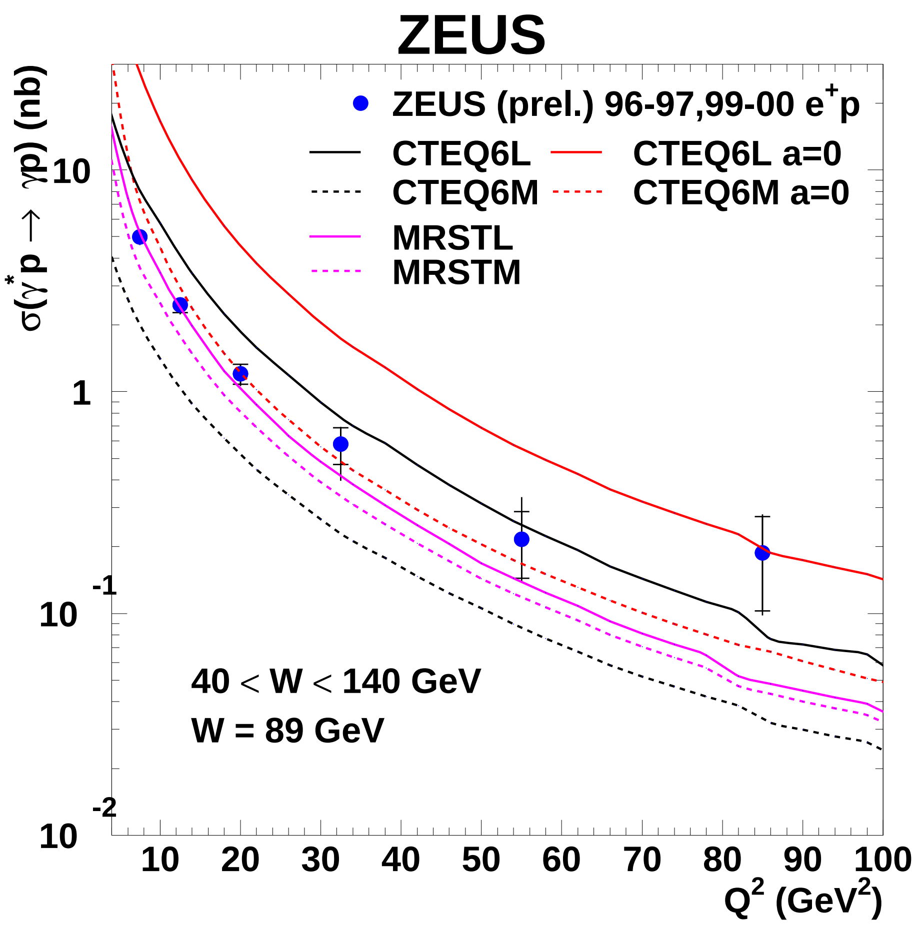
high-energy DVCS explores gluon GPD's ($x \sim 1/W^2$)

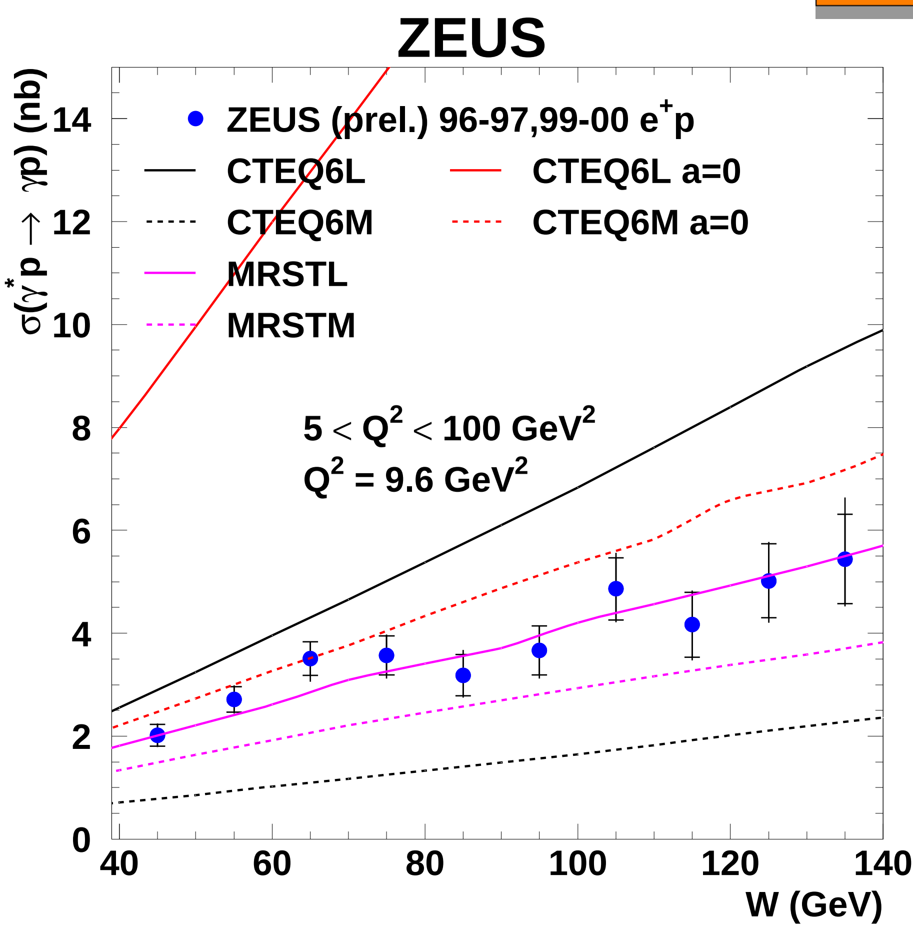




W-dependence matches $W^{0.8}$ behaviour of hard meson production

DVCS: Comparison with GPD Calculations





Precise new data have potential to constrain GPD's

- Calculations by Freund & McDermott, based on LO (solid) and NLO (dashed) PDF's
- explore ***correlation parameter a:*** $\sim x$-range over which quarks are correlated

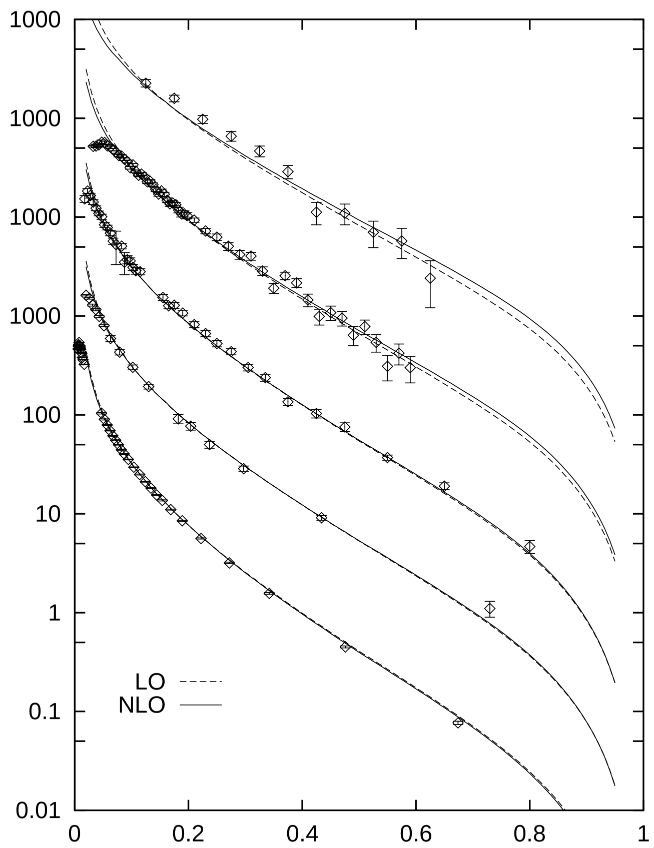
Hadronization: The Long-Range Dynamics of Confinement

What do we know?

The Lund String Model

Phenomenlogical description in terms of colour-string breaking and parton clustering.

Evolution of the fragmentation functions



A Tool for hadron structure studies

(e.g. flavour-tagging)

$$D_1 = D_u^{\pi+} = D_d^{\pi-} = \ldots$$

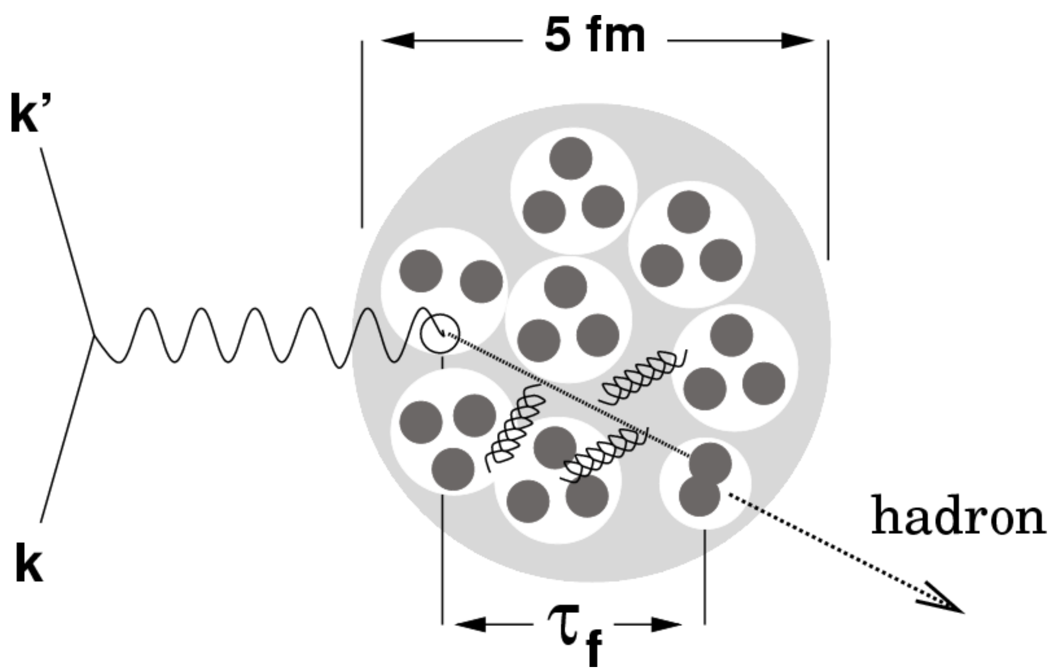
$$D_2 = D_d^{\pi+} = D_u^{\pi-} = \ldots$$

What are we not so sure about?

- **Spin transfer**:
  Is the spin of the struck quark communicated to the hadronic final state?
- **Single-spin asymmetries**:
  How important is intrinsic transverse momentum?
  ⇒ phase coherence?
  ⇒ access to new structure functions
- **Space-time structure**:
  How long does it take to form a hadron?

The Space-Time Structure of Fragmentation

By embedding the fragmentation process within a nucleus, one can use the nuclear radius as a yardstick against which to measure the **time scale of hadron formation**.



Single Time Scale Model

Postulate: hadron formation time is a constant (τ_h), apply Lorentz boost

$$\tau_f = \tau_h \frac{E_h}{m_h} = \tau_h \frac{z\nu}{m_h}$$

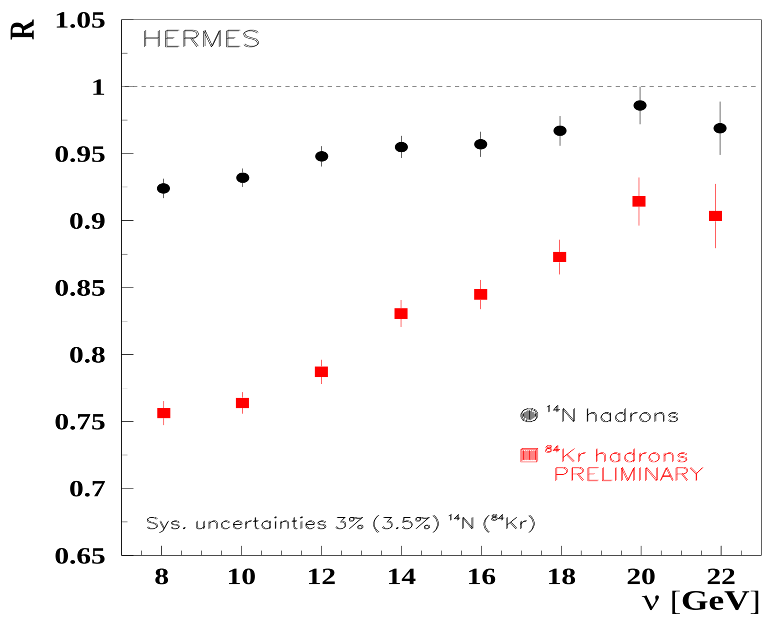
$\rightarrow \tau_f$ depends on ν, and z, m_h

Once hadron is formed, will be suppressed by final state interactions with nuclear medium
$\Rightarrow$ study hadron multiplicity ratio

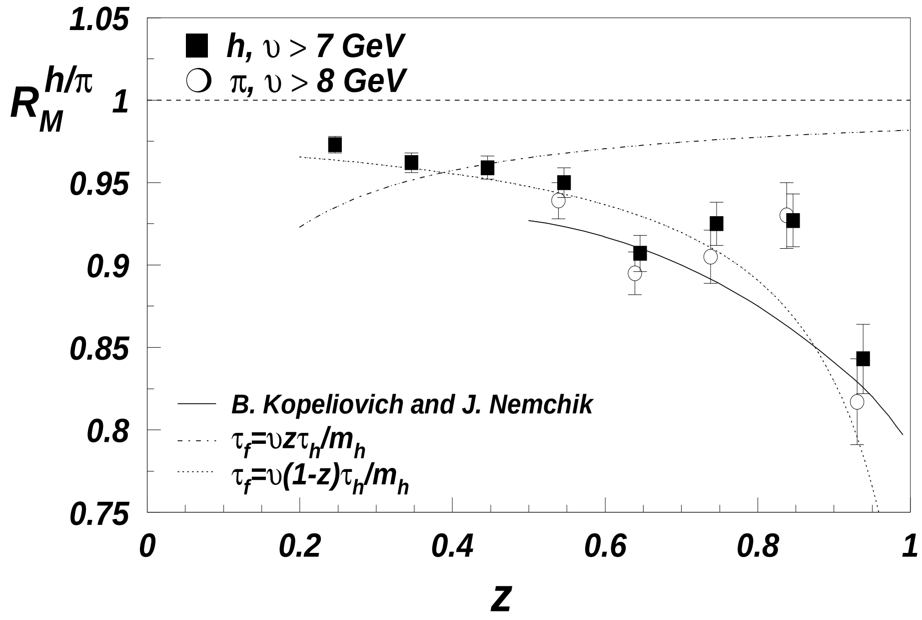
$$R_A^h(z,\nu) = \left(\frac{1}{N_e}\frac{d^2N_h}{dz\,d\nu}\right)_A \Big/ \left(\frac{1}{N_e}\frac{d^2N_h}{dz\,d\nu}\right)_D$$

Hadron Attenuation at HERMES

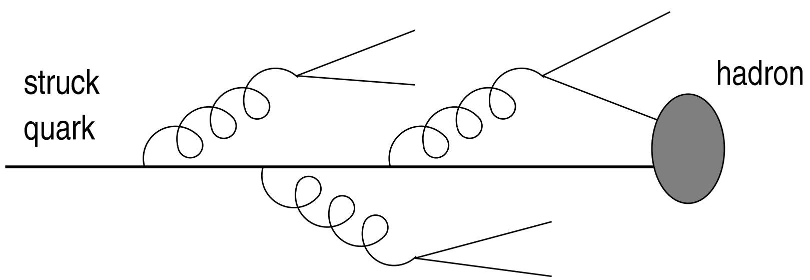
ν dependence shows the expected Lorentz behavior ...



However **z dependence** does ***not***



Gluon Bremsstrahlung Model



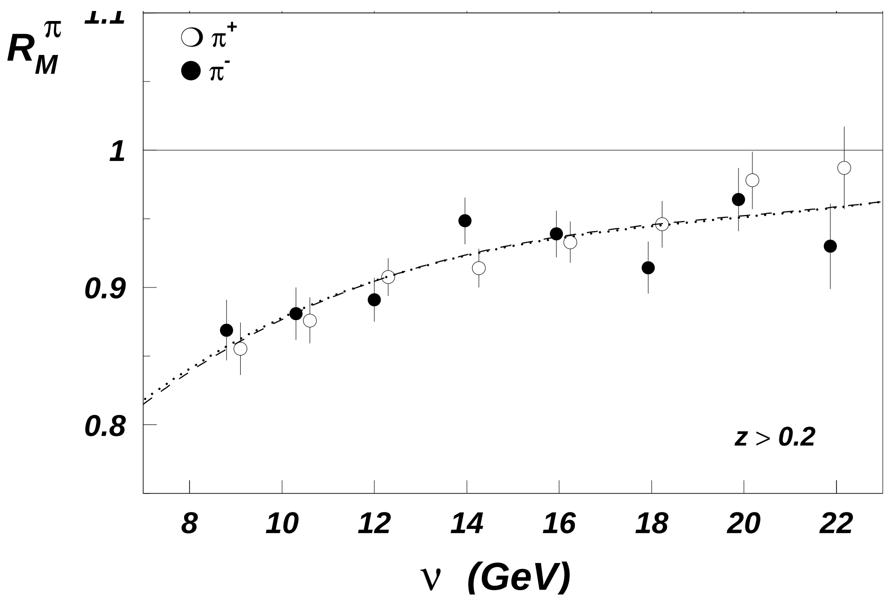
At high z:

$\rightarrow$ few gluons radiated
$\rightarrow$ ***short*** formation time $\tau_f = \nu(1-z)\tau_h/m_h$
$\rightarrow$ larger attenuation by nuclear rescattering

Hadron Formation Time

Good fits obtained with the gluon bremsstrahlung parametrization

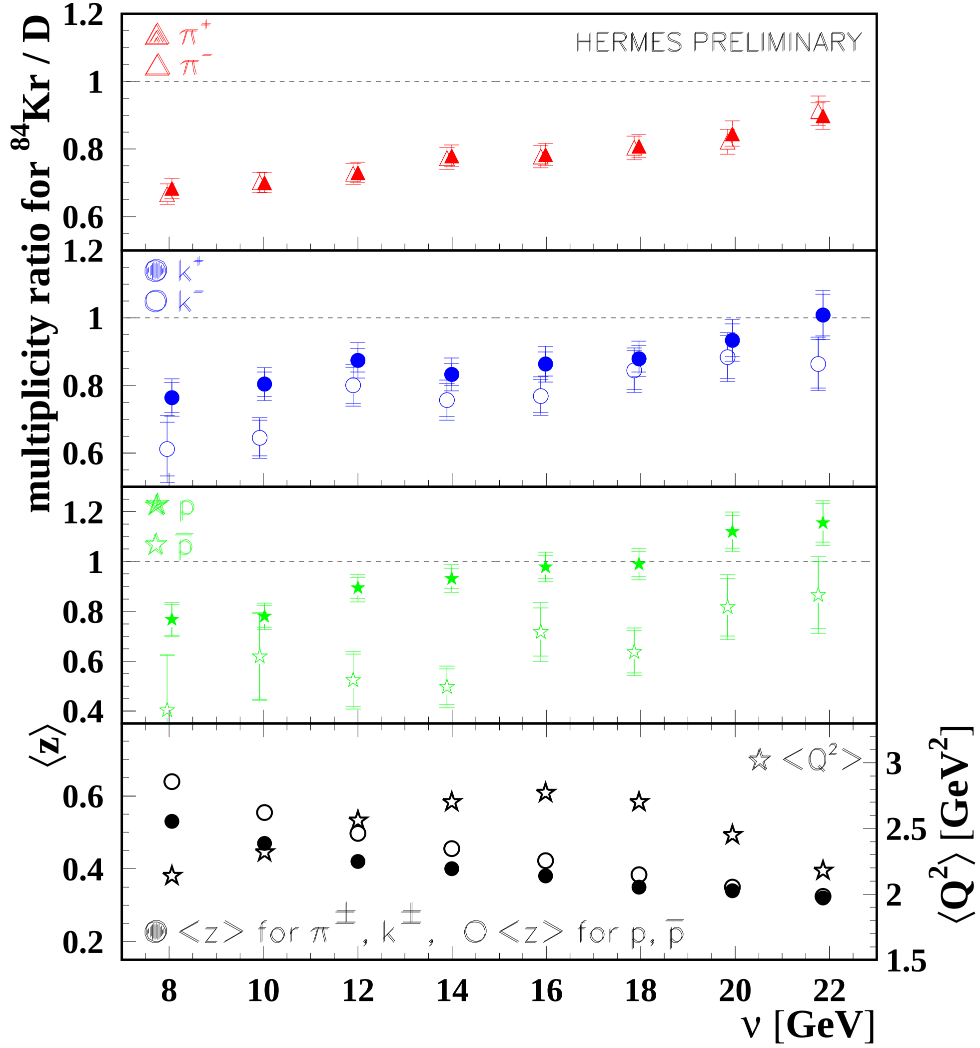
$$\tau_f = \mathbf{c_h} \cdot \nu(1 - z)$$



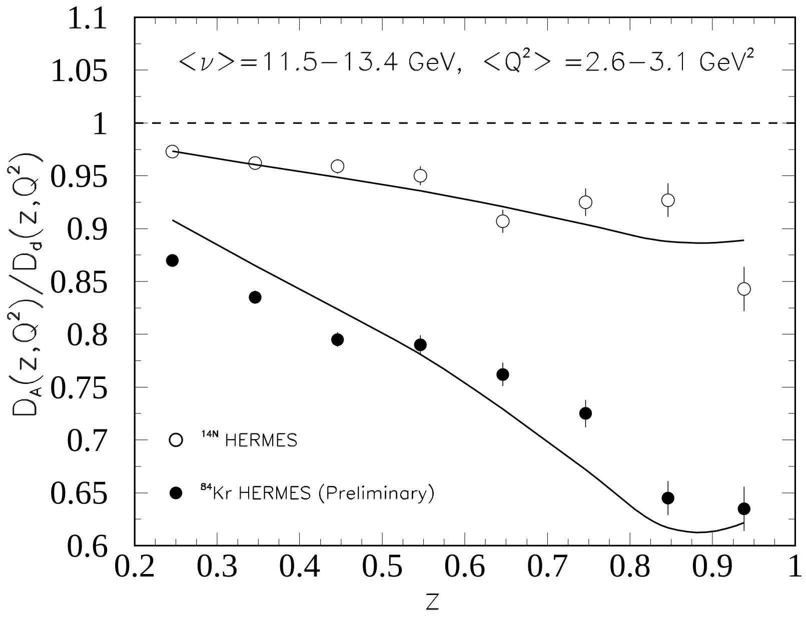
For **pions** :

$$c_{\pi\pm} = 1.4 \pm 0.2 \text{ fm/GeV} \cdot c$$

New RICH detector allows separate measurements for π, K, p



Parton Energy Loss

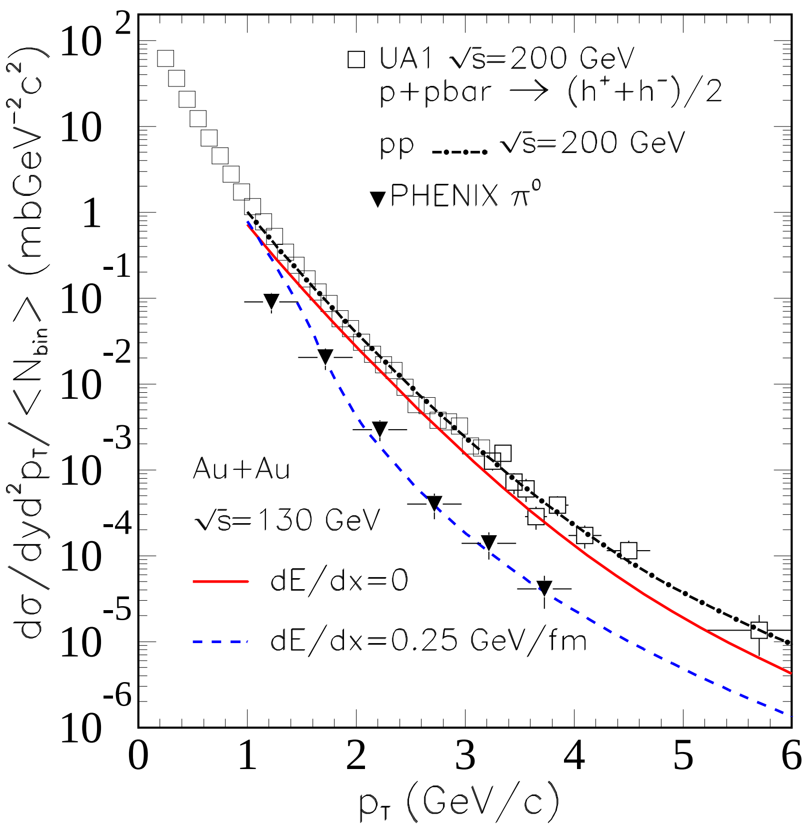


calculated from HERMES $\pi^{\pm}$ data:

X.N. Wang, hep-ph/0111404

$$\overline{D}_f^h(z) \approx \frac{1}{1-\Delta E/E}\, D\left(\frac{z}{1-\Delta E/E}\right)$$

$\Rightarrow$ $dE/dx \approx 0.3$ GeV/fm



and from π^0 yield in Au + Au collisions at PHENIX: $dE/dx \approx 0.25$ GeV/fm

but after correction for expanding system:

$\Rightarrow$ $dE/dx \approx 12$ GeV/fm

Suggests that gluon density in Au + Au at RHIC is 40 $\times$ that inside cold nuclear matter

Conclusions and Outlook

Recent theoretical and experimental progress has given us the tools to explore non-perturbative QCD phenomena at a new level of detail

- **Deep Inelastic Scattering**

  ⇨ explore ***spin-dependence*** of distribution and fragmentation functions

- **Hard Exclusive Processes**

  $\rightarrow$ scattering subprocess at hard scales understood in terms of pQCD ...

  ⇨ explore ***GPD's*** = map of the proton wavefunction

  Can we achieve the same level of understanding here as with F_2?

The Next Round of Experiments

- ***New Experiments:*** COMPASS and RHIC-spin commissioned in 2001

  $\Rightarrow$ precise data on quark and gluon polarization soon forthcoming!

- HERMES Run 2 with ***transverse target*** : focus on transversity
- H1 and ZEUS with ***spin rotators*** :
  polarized beam $\rightarrow$ DVCS interference effects at the highest scales