Recent HERMES Results on Meson Production

$\Rightarrow$ Spin Asymmetries in Semi-inclusive Meson Production
$\Rightarrow$ Spin Asymmetries in Exclusive Meson Production
$\Rightarrow$ Hard Exclusive $\pi^+\pi^-$ Pair Production
($\Rightarrow$ Observation of the Θ^+ Pentaquark State)
$\Rightarrow$ Quark Fragmentation in Nuclei

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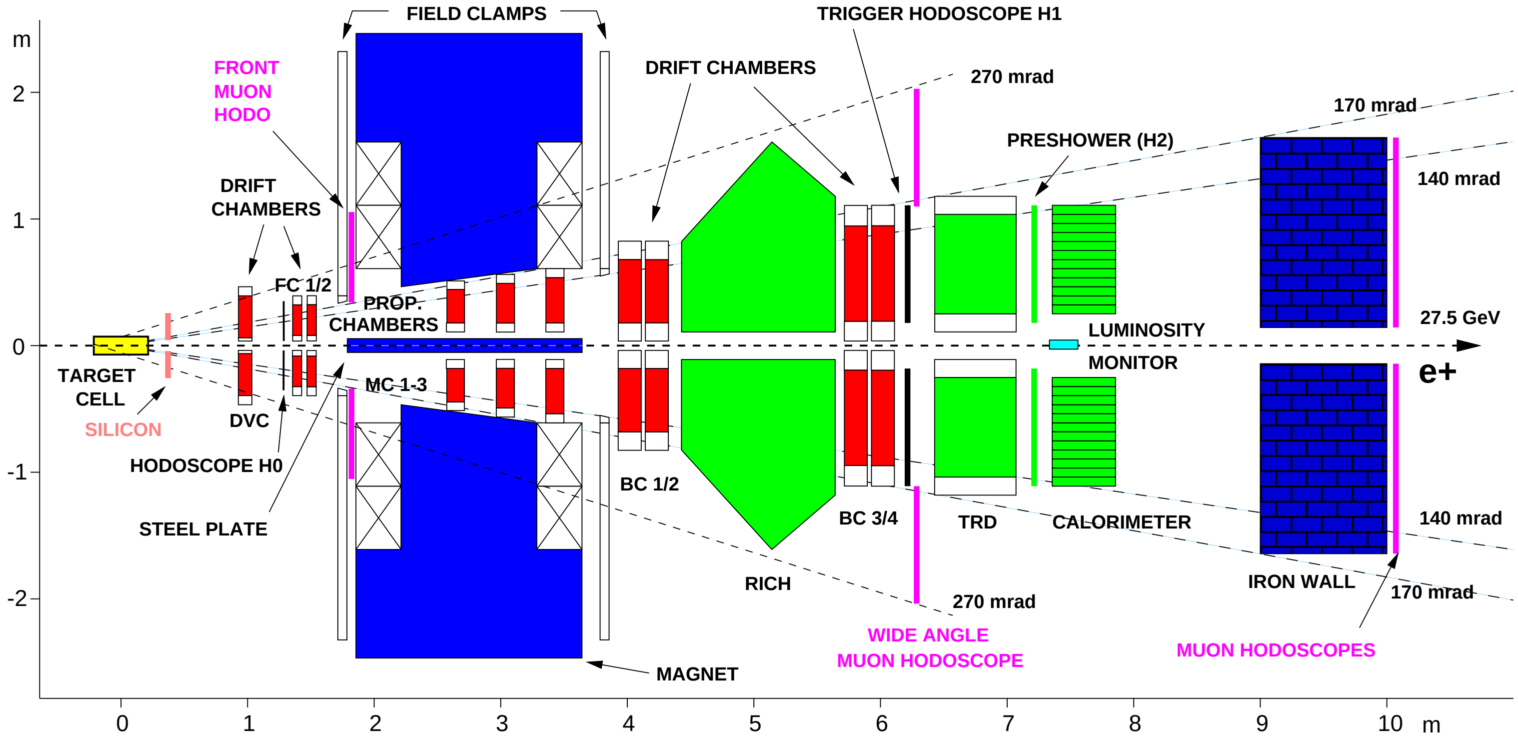
on behalf of the HERMES Collaboration

The HERMES Experiment @ DESY

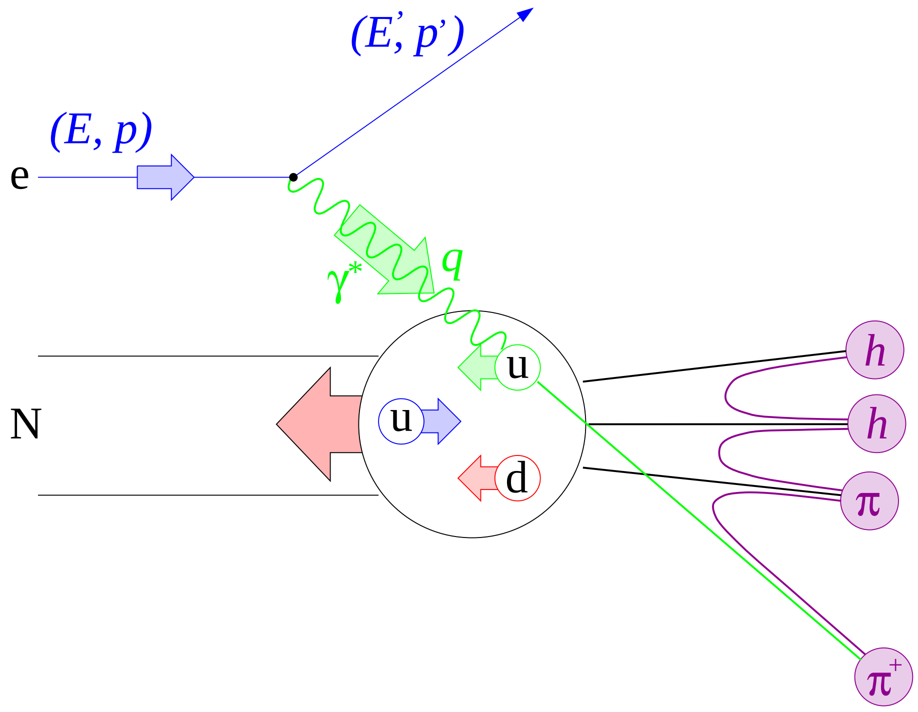


- 27.6 GeV HERA e-beam
- Internal Gas Target : $\vec{\text{He}}$, $\vec{\text{H}}$, $\vec{\text{D}}$, H↑; unpol : H_2, D_2, He, N, Ne, Kr, Xe
- Resolution : $\Delta p/p = 1.4 - 2.5$ %, $\Delta\theta < 0.6$ mrad
- Lepton/Hadron Separation : TRD, Preshower, Calorimeter
- Hadron ID : Cherenkov (1995-97) - RICH (1998- ...)

Semi-inclusive Deep Inelastic Scattering

HERMES → study nucleon spin structure in terms of quarks and gluons through polarized deep-inelastic scattering

- ☞ HERMES-I (1995-2000) : longitudinally polarized beam and target
- ☞ HERMES-II (2002-...) : transversely polarized target



$$Q^2 = -q^2 = -(k - k')^2$$

$$\nu \overset{\text{lab}}{=} E - E'$$

$$x = \frac{Q^2}{2\,M\,\nu}$$

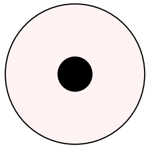
$$z \overset{\text{lab}}{=} \frac{E_h}{\nu}$$

⇒ Cross section contains quark distribution and fragmentation functions

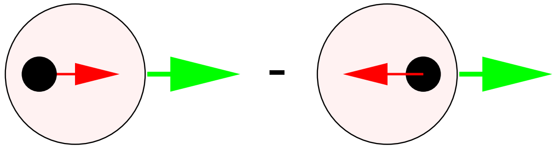
$$\sigma^{eN \to ehX} \sim \sum_q f^{N \to q} \otimes \sigma^{eq \to eq} \otimes D^{q \to h}$$

Distribution Functions

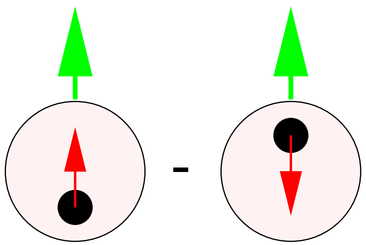
In leading twist, integrating over quark transverse momenta, 3 DFs :

f_1 =  : unpolarized quarks in unpolarized nucleons

$\Rightarrow$ Unpolarized DF $q(x)$: spin averaged, very well known

g_1 =  : longitudinally polarized quarks in longitudinal nucleons

$\Rightarrow$ Helicity DF $\Delta q(x) \equiv q^{\overset{\rightarrow}{\Rightarrow}}(x) - q^{\overset{\rightarrow}{\Leftarrow}}(x)$: helicity difference, well known (HERMES-I)

h_1 =  : transversely polarized quarks in transverse nucleons

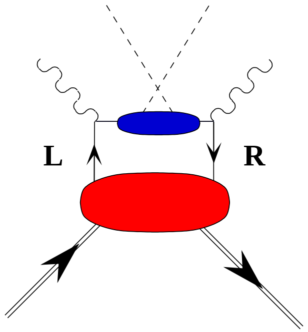
$\Rightarrow$ Tranversity $\delta q = q^{\uparrow\Uparrow} - q^{\uparrow\Downarrow}$: helicity flip, unkwnown (HERMES-II)

Transversity

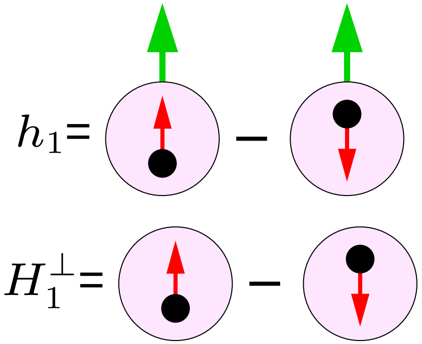
- $f_1(x)$ and $g_1(x)$ can be measured in inclusive DIS;
  $h_1(x)$ is chiral-odd $\rightarrow$ need another chiral-odd object to access transversity

☞ Consider quark transverse momentum in distribution and fragmentation functions and measure transversity via single-spin azimuthal asymmetries in $e + p \rightarrow e + h + X$ on a polarized target

Collins effect : $A \sim h_1(x)\, H_1^{\perp}(z)$



h_1 combined with chiral-odd Collins FF $H_1^{\perp}$

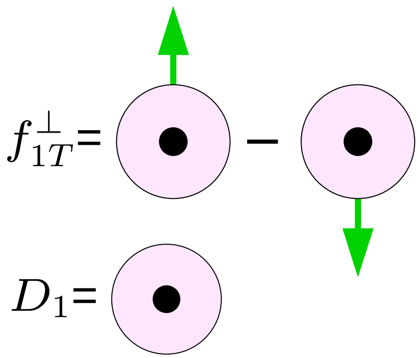


$\rightarrow$ Influence of quark's polarization on transverse momentum acquired in fragmentation process orthogonal to its transverse polarization

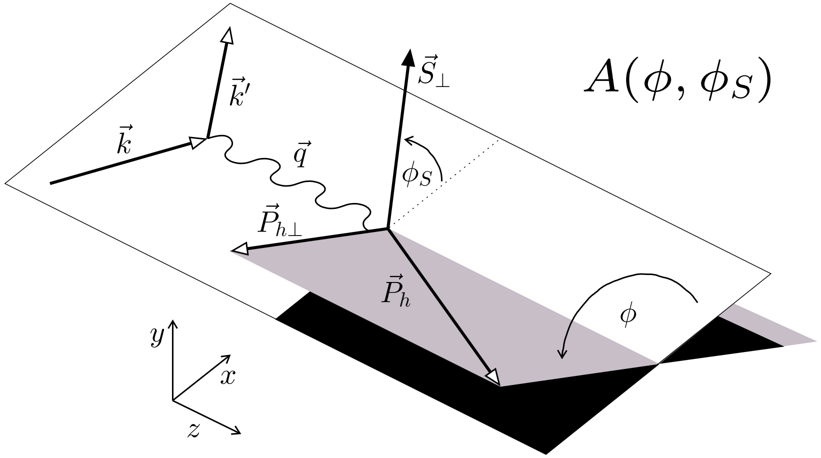
Sivers effect : $A \sim f_{1T}^{\perp}(x)\, D_1(z)$

Sivers function $f_{1T}^{\perp}$

$\rightarrow$ Struck quark "remembers" transverse momentum it had in the target and influences transverse momentum of produced hadrons



Azimuthal Asymmetry for Transverse Target Polarization



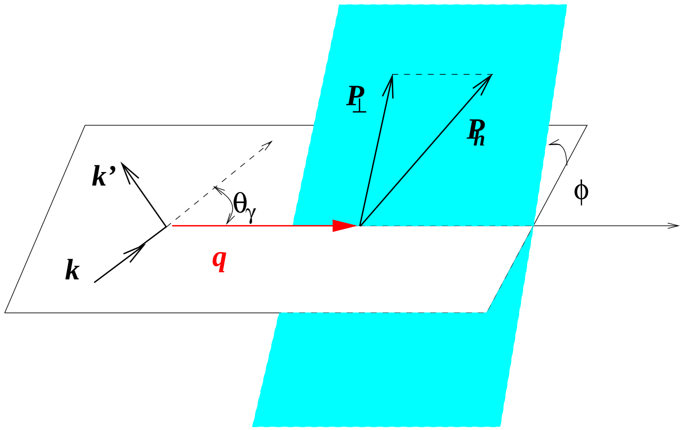
$$
\begin{aligned}
A(\phi,\phi_S) &= \frac{1}{S_\perp}\frac{N^\uparrow(\phi,\phi_S)-N^\downarrow(\phi,\phi_S)}{N^\uparrow(\phi,\phi_S)+N^\downarrow(\phi,\phi_S)} \\
&\sim \ldots\sin(\phi+\phi_S)\sum_q e_q^2\cdot\mathcal{I}\left[\ldots h_1^q(x,\vec{p}_T^{\,2})\cdot H_1^{\perp q}(z,\vec{k}_T^{\,2})\right] \\
&+ \ldots\sin(\phi-\phi_S)\sum_q e_q^2\cdot\mathcal{I}\left[\ldots f_{1T}^{\perp q}(x,\vec{p}_T^{\,2})\cdot D_1^q(z,\vec{k}_T^{\,2})\right] \\
&+ \ldots
\end{aligned}
$$

$\mathcal{I}$: convolution integral over quark transverse momenta $\Rightarrow$ $P_{h\perp}$ weighted asymmetry :

$$
\begin{aligned}
\frac{1}{S_\perp}\frac{\sum_{i=1}^{N^\uparrow(\phi,\phi_S)}P_{h\perp\,i}-\sum_{i=1}^{N^\downarrow(\phi,\phi_s)}P_{h\perp\,i}}{N^\uparrow(\phi,\phi_S)+N^\downarrow(\phi,\phi_S)} &\sim \ldots\sin(\phi+\phi_S)\sum_q e_q^2\cdot h_1^q(x)\cdot H_1^{\perp(1)q}(z) \\
&+ \ldots\sin(\phi-\phi_S)\sum_q e_q^2\cdot f_{1T}^{\perp(1)q}(x)\cdot D_1^q(z)
\end{aligned}
$$

$\Rightarrow$ Extract moments $A^{\sin(\phi+\phi_S)}$ and $A^{\sin(\phi-\phi_S)}$ by 2-dimensional fit to $A(\phi,\phi_S)$

Azimuthal Asymmetry for Longitudinally Polarized Target



$\phi_S = 0, \pi$, Collins and Sivers cannot be distinguished

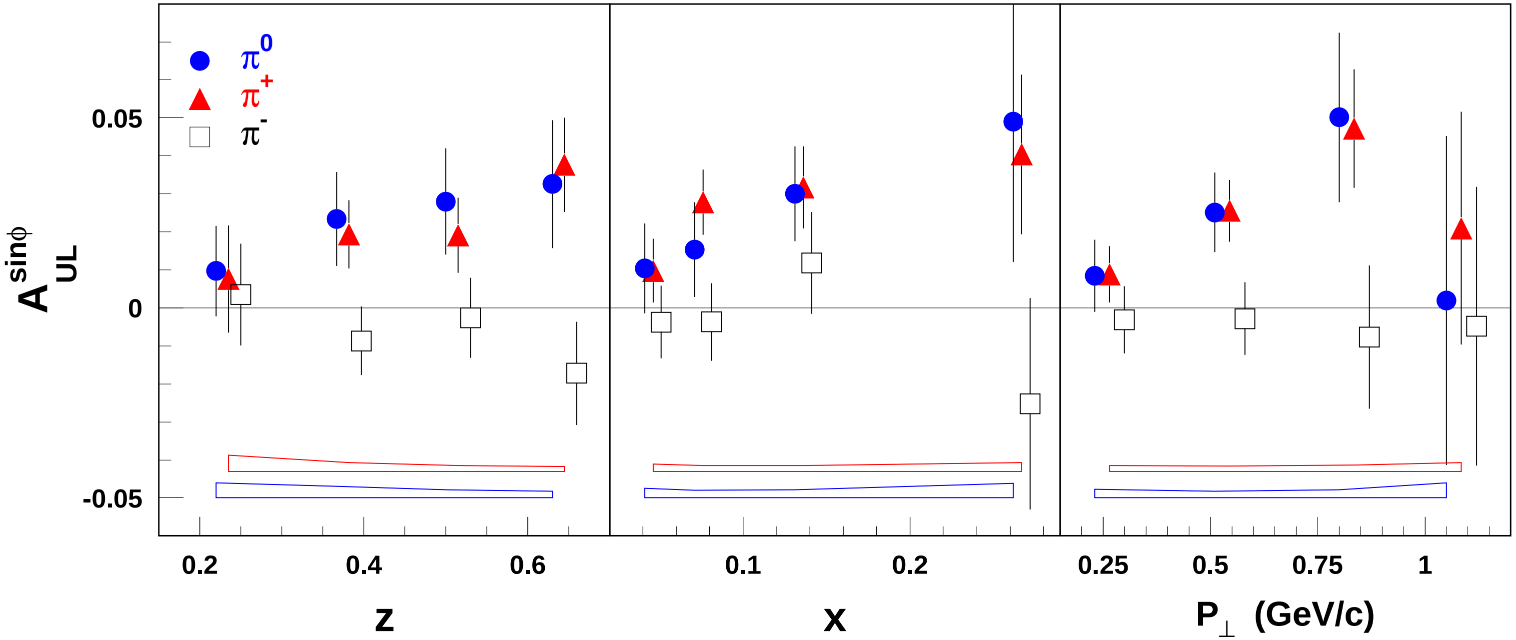
$$A_{UL}^{\sin\phi} = \frac{1}{|S_L|} \frac{\sum_{i=1}^{N^{\rightarrow}} \sin(\phi_i) - \sum_{i=1}^{N^{\leftarrow}} \sin(\phi_i)}{\frac{1}{2}[N^{\rightarrow} + N^{\leftarrow}]}$$

$$\sim \ldots S_T[\ldots h_1 \cdot H_1^{\perp(1)}] + \ldots S_L[\ldots h_L \cdot H_1^{\perp(1)} - \ldots h_{1L}^{\perp(1)} \cdot \tilde{H}]$$

$e + \vec{p} \rightarrow e + \pi + X$

$0.2 < z < 0.7$

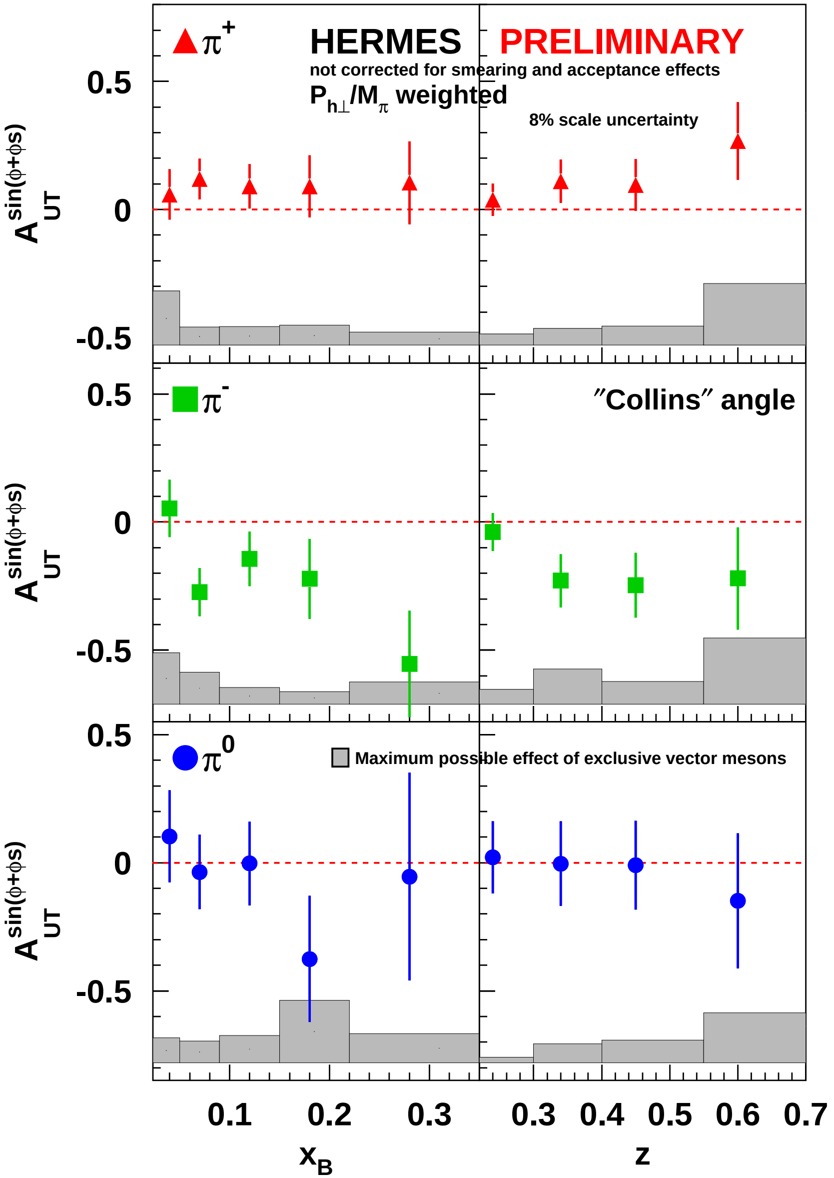
$S_T/S \propto \sin\theta_\gamma$
~ 15 %



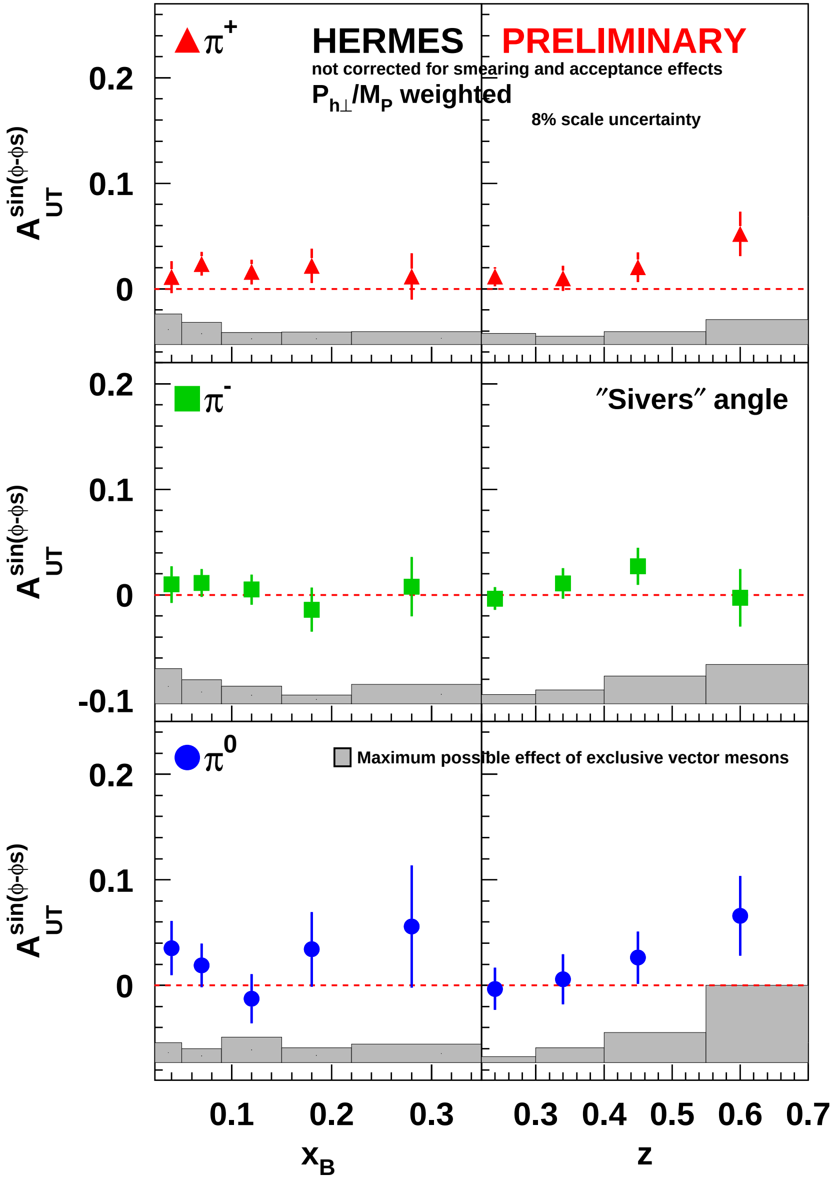
[A. Airapetian *et al.*, Phys. Rev. Lett. 84 (2000) 4047; Phys. Rev. D64 (2001) 097101; Phys. Lett. B562 (2003) 182]

☞ Collins fragmentation function $H_1^{\perp}$ non-zero (?)

$P_{h\perp}$ Weighted Asymmetries on Transverse Target

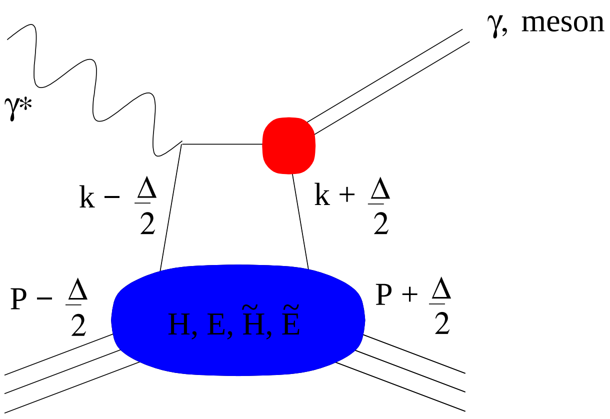


$$A^{\sin(\phi+\phi_S)} \sim h_1(x) \cdot H_1^{\perp(1)}(z)$$



$$A^{\sin(\phi-\phi_S)} \sim f_{1T}^{\perp(1)}(x) \cdot D_1(z)$$

Generalized Parton Distributions



- For $Q^2 >>$ and $t << Q^2$, factorization for longitudinal photons
- 4 GPDs in leading twist :
  $H(x, \xi, t)$, $E(x, \xi, t)$ unpolarized;
  $\tilde{H}(x, \xi, t)$, $\tilde{E}(x, \xi, t)$ polarized

  H, $\tilde{H}$ conserve nucleon helicity;
  E, $\tilde{E}$ flip nucleon helicity

☞ New observables in hard exclusive scattering; related to standard PDF and form factors :

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

$$\int_{-1}^{+1} \mathrm{d}x\, H^q(x, \chi, t) = F_1^q(t), \qquad \int_{-1}^{+1} \mathrm{d}x\, E^q(x, \chi, t) = F_2^q(t), \qquad \ldots$$

- Ji's sum rule : $J_q = \frac{1}{2}\Delta q + L_q = \frac{1}{2}\int_{-1}^{+1} \mathrm{d}x\, x\, [H^q + E^q]$

  $\Rightarrow$ access to orbital angular momentum

- Unpolarized cross section contain quadratic combinations of GPDs;
  new information from polarized measurements

Generalized Parton Distributions

Final state quantum numbers select different GPDs :

- DVCS : H, E, $\tilde{H}$, $\tilde{E}$
  $\Rightarrow$ Beam charge asymmetry ($e^+ \leftrightarrow e^-$) $\sim$ Re$(T^{BH}T^{DVCS})$
  $\Rightarrow$ Beam-spin Azimuthal Asymmetry $\sim$ Im$(T^{BH}T^{DVCS})$
  [A. Airapetian *et al.*, Phys. Rev. Lett. 87 (2001) 182001]
  $\Rightarrow$ Nuclear DVCS

- Pseudoscalar meson production (π, η ...) : $\tilde{H}$, $\tilde{E}$
  $\Rightarrow$ Cross section exclusive π^+ production ($\rightarrow$ talk Cynthia Hadjidakis)
  $\Rightarrow$ Transverse single spin asymmetries

- Vector meson production (ρ, ω, ϕ ...) : H, E
  $\Rightarrow$ Cross section exclusive ρ^0 (ω, ϕ) production
  [A. Airapetian *et al.*, Eur. Phys. J. C17 (2000) 389]
  $\Rightarrow$ Transverse single spin asymmetries

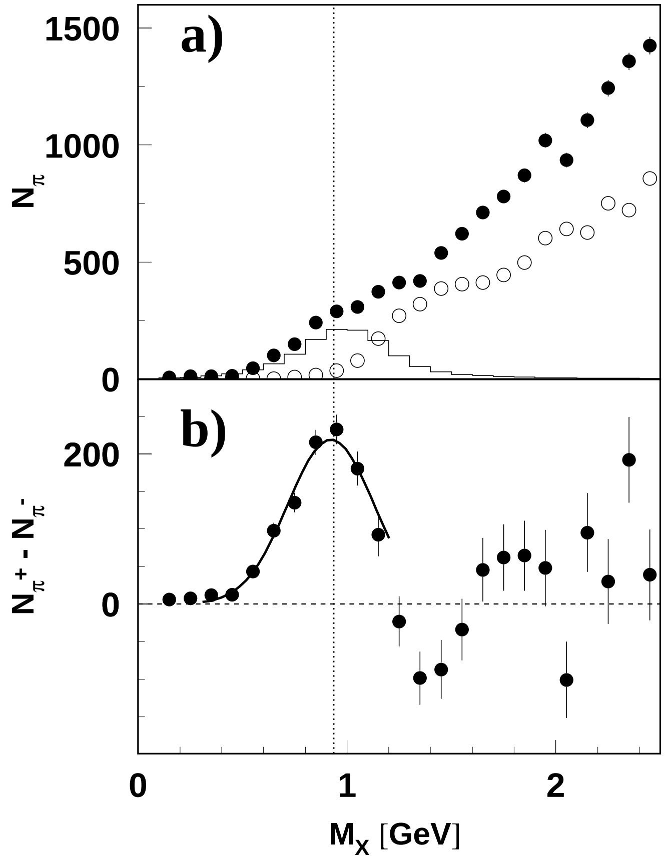
- Pion pair production : H, E
  $\Rightarrow$ Angular distributions

Single Spin Azimuthal Asymmetry for Exclusive π^+ Production

- Large SSA for longitudinal photons of transverse target expected due to interference of $\tilde{E}$ and $\tilde{H}$ amplitudes
- With longitudinal target polarization : $\sigma_S \sim [S_\perp \sigma_{\mathcal{L}} + S_\parallel \sigma_{\mathcal{LT}}] \, A_{UL}^{\sin\phi} \sin\phi$

- $e + p \rightarrow e + \pi^+ + n$
- No detection of recoiling nucleon

☞ Use missing mass for $e + p \rightarrow e + \pi^+ + X$; subtract non-exclusive background via π^- production

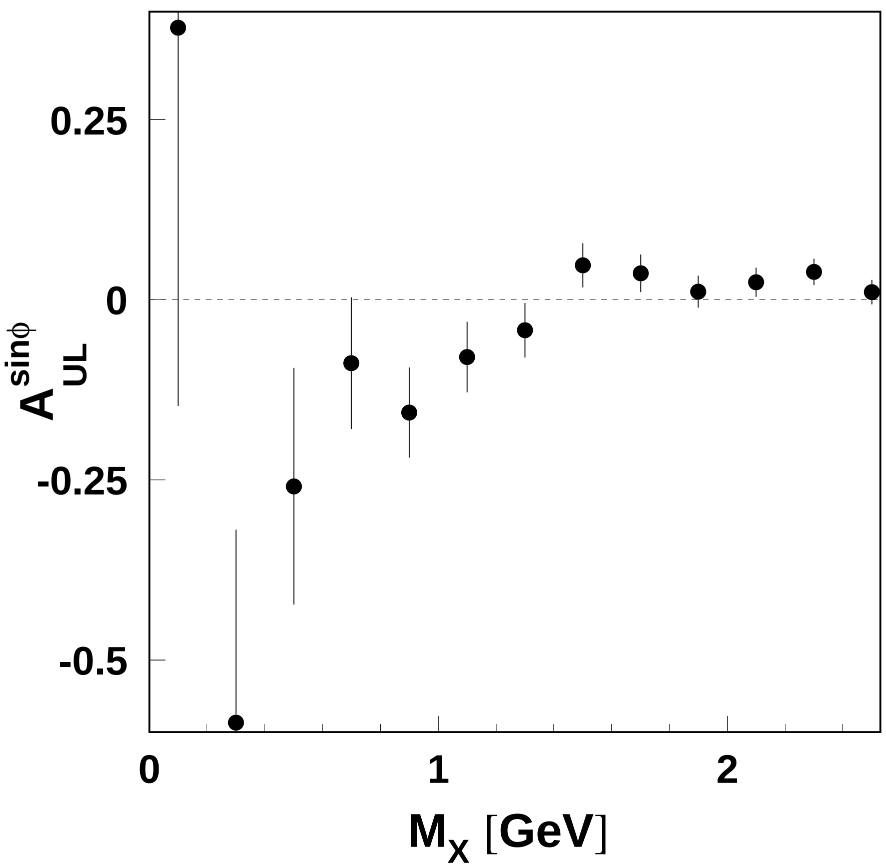


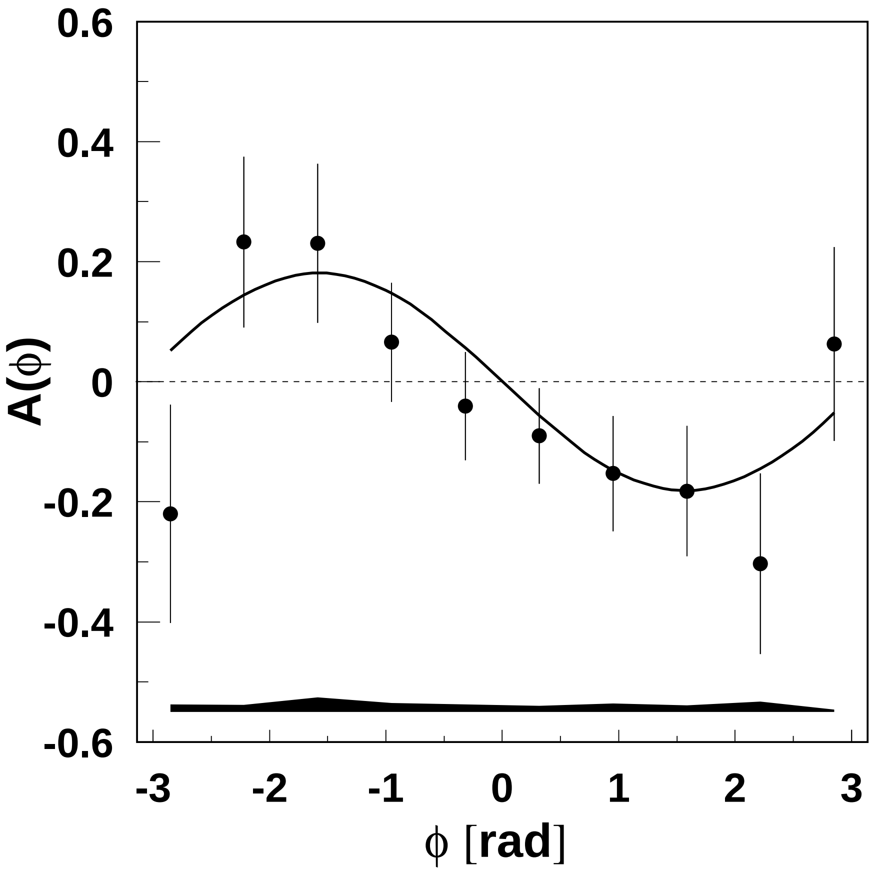
- M_X resolution (from MC) about 230 MeV
- Normalize π^- to π^+ production for $1.3 < M_X < 2.0$ GeV
- Contributions of (non-exclusive) $\pi^+ + \Delta^0$, $\pi^+ + (N\pi)$, $\pi^+ + (N\pi\pi)$

Single Spin Azimuthal Asymmetry for Exclusive π^+ Production

$$A(\phi) = \frac{1}{|S|}\frac{N_e^{\uparrow}(\phi) - N_e^{\downarrow}(\phi)}{N_e^{\uparrow}(\phi) + N_e^{\downarrow}(\phi)} = A_{UL}^{\sin\phi} \cdot \sin\phi$$

$$|S| = 0.88,\ S_{\perp}/|S| \sim 0.16$$

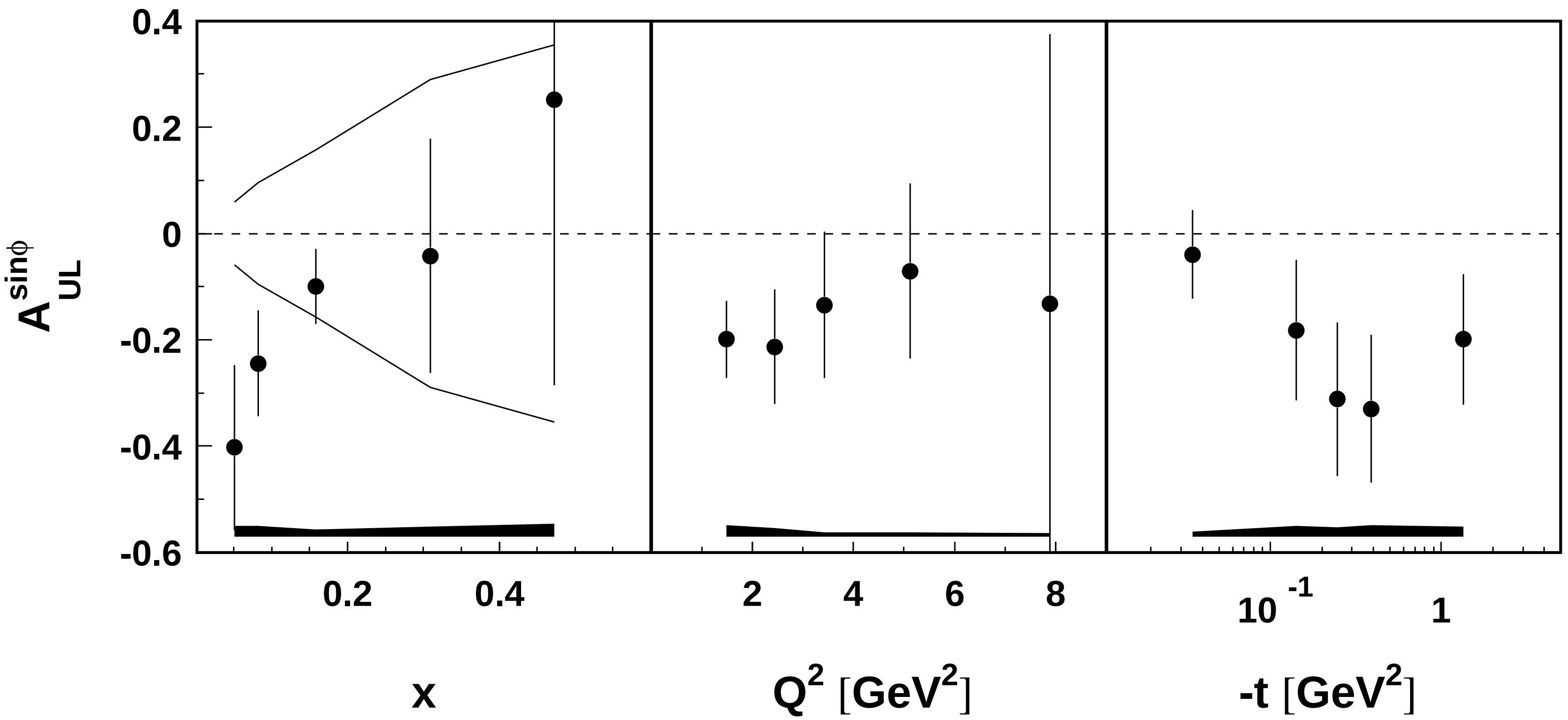




$A_{UL}^{sin\phi} = -0.18 \pm 0.05 \pm 0.02$; $\sin 2\phi$, $\cos\phi$, $\cos 2\phi$ moments are zero

Single Spin Azimuthal Asymmetry for Exclusive π^+ Production

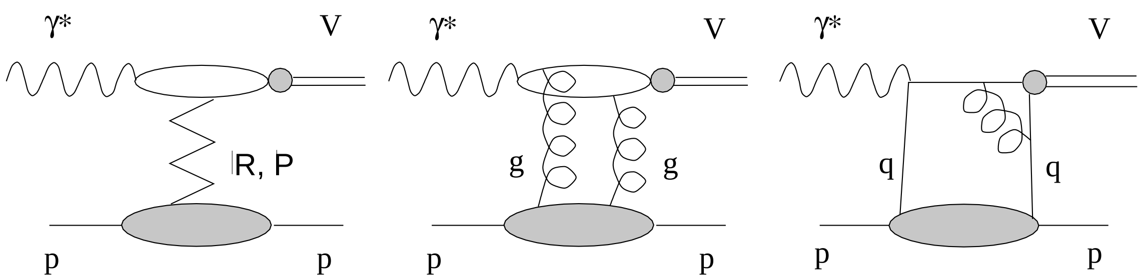
[A. Airapetian *et al.*, Phys. Lett. B535 (2002) 85]



☞ Asymmetry arises from longitudinal target polarization component at low x; asymmetry vanishes in forward limit

☞ No clear theoretical interpretation yet

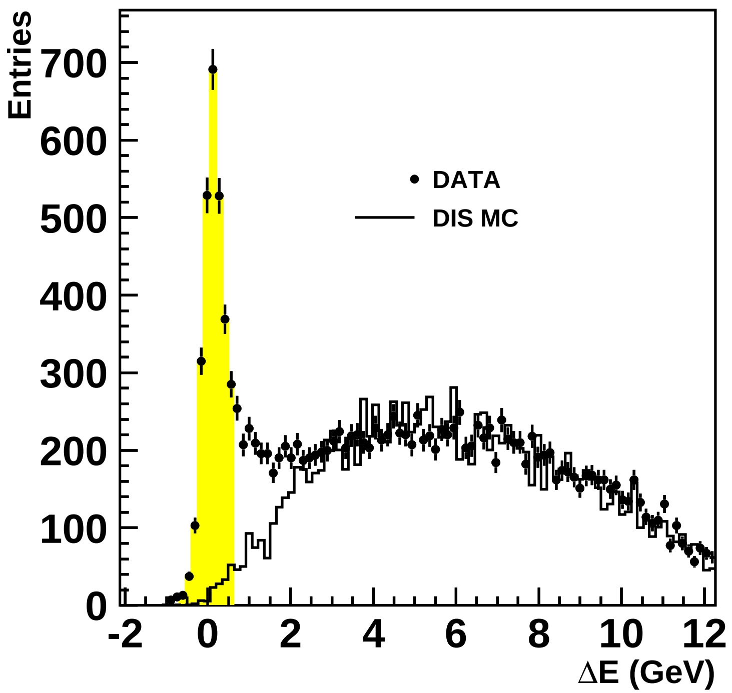
Exclusive Vector Meson Production @ HERMES



$$e + p, A \rightarrow e + p + \rho^0, \omega, \phi$$

$$0.5 < Q^2 < 5.0 \text{ GeV}^2,$$
$$4.0 < W < 6.0 \text{ GeV},$$
$$t < 0.5 \text{ GeV}^2$$

ρ^0, ω production at HERMES is dominated by quark exchange,
ϕ production dominated by gluon exchange



No detection of recoiling particle

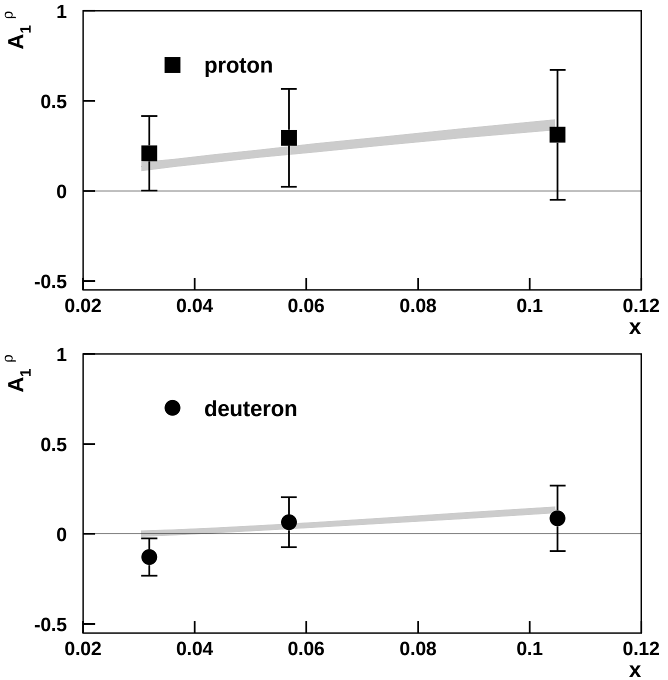
$$\rightarrow \text{Exclusivity : } \Delta E = \frac{(M_X^2 - M_p^2)}{2\, M_p}$$

Double Spin Asymmetry in VM Production

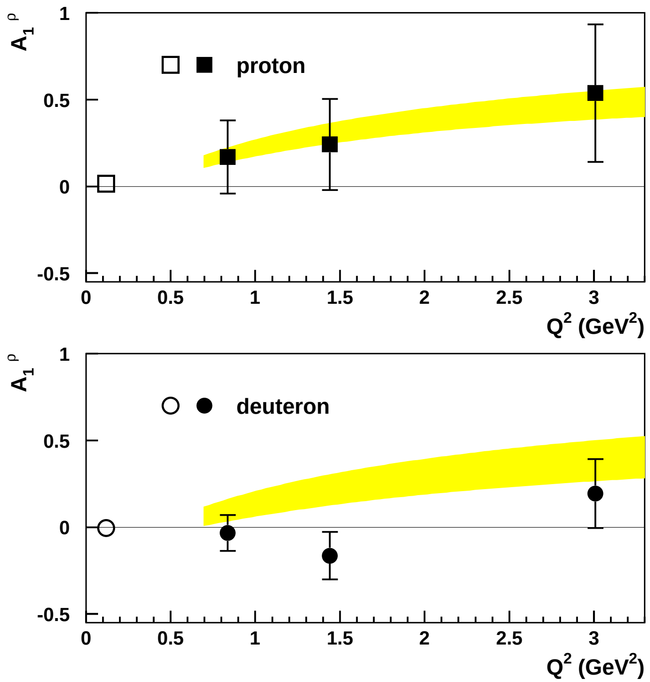
[A. Airapetian *et al.*, Eur. Phys. J. C29 (2003) 171]

$$A_{\parallel} \equiv \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} \qquad A_1 = \frac{A_{\parallel}}{D} - \eta\sqrt{R}$$

$$\begin{array}{lclclcl} < A_1^{p,\rho} > & = & 0.23 \pm 0.14 \pm 0.02 & \quad & < A_1^{d,\rho} > & = & -0.040 \pm 0.076 \pm 0.013 \\ < A_1^{p,\phi} > & = & 0.20 \pm 0.45 \pm 0.03 & \quad & < A_1^{d,\phi} > & = & 0.17 \pm 0.27 \pm 0.02 \end{array}$$

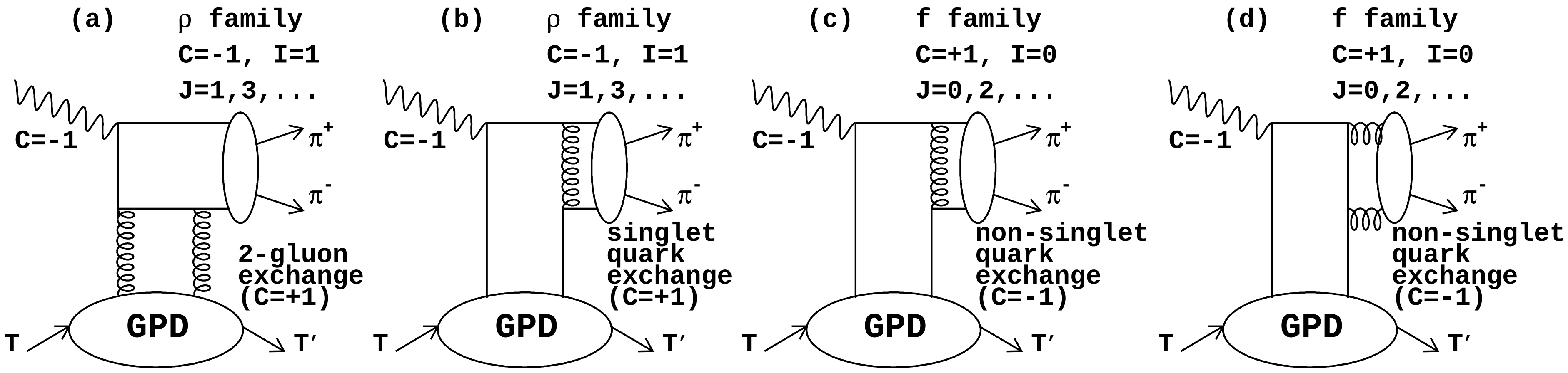


$A_1^\rho = 2\ A_1^N/(1+(A_1^N)^2)$ (Fraas)
Asymmetry due to unnatural parity
$P = -(-1)^J$ or di-quark exchange



Regge model with parameter fits to g_1^p and F_2^p (Kochelev *et al.*)

Hard Exclusive $\pi\pi$ Pair Production

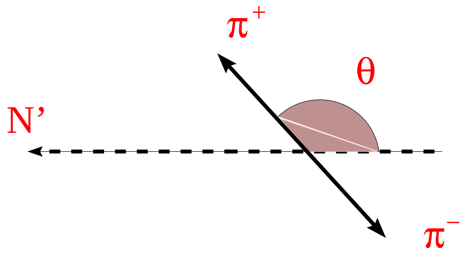


- pion pairs are formed by gluon exchange (isovector pairs) or quark exchange (isovector + isoscalar pairs)

  $\Rightarrow$ study interference between $I = 1$ (ρ-family) and $I = 0$ (f-family) channels to get information on small isoscalar channel

  $\Rightarrow$ new constraints on certain combinations of GPDs
- HERMES : $ep \rightarrow ep\pi^+\pi^-$ and $ed \rightarrow ed\pi^+\pi^-$
- Intensity densities (Legendre moments) :

$$< P_l(\cos\theta) >^{\pi\pi} = \frac{\int_{-1}^{+1} \mathrm{d}\cos\theta\, P_l(\cos\theta) \frac{\mathrm{d}\sigma^{\pi\pi}}{\mathrm{d}\cos\theta}}{\int_{-1}^{+1} \mathrm{d}\cos\theta \frac{\mathrm{d}\sigma^{\pi\pi}}{\mathrm{d}\cos\theta}}$$



Hard Exclusive $\pi\pi$ Pair Production

$$\frac{\mathrm{d}\sigma^{\pi^+\pi^-}}{\mathrm{d}\cos\theta} \propto \sum_{JJ'\lambda\lambda'} \rho^{JJ'}_{\lambda\lambda'} Y_{J\lambda}(\theta,\phi) Y^*_{J'\lambda'}(\theta,\phi)$$

with $\rho^{JJ'}_{\lambda\lambda'}$ pion pair spin density matrix

☞ Study P_1 (and P_3), sensitive to interferences :

$$< P_1(\cos\theta) > = < \cos\theta > = \frac{1}{\sqrt{15}} \left[4\sqrt{3}\rho^{21}_{11} + 4\rho^{21}_{00} + 2\sqrt{5}\rho^{10}_{00} \right]$$

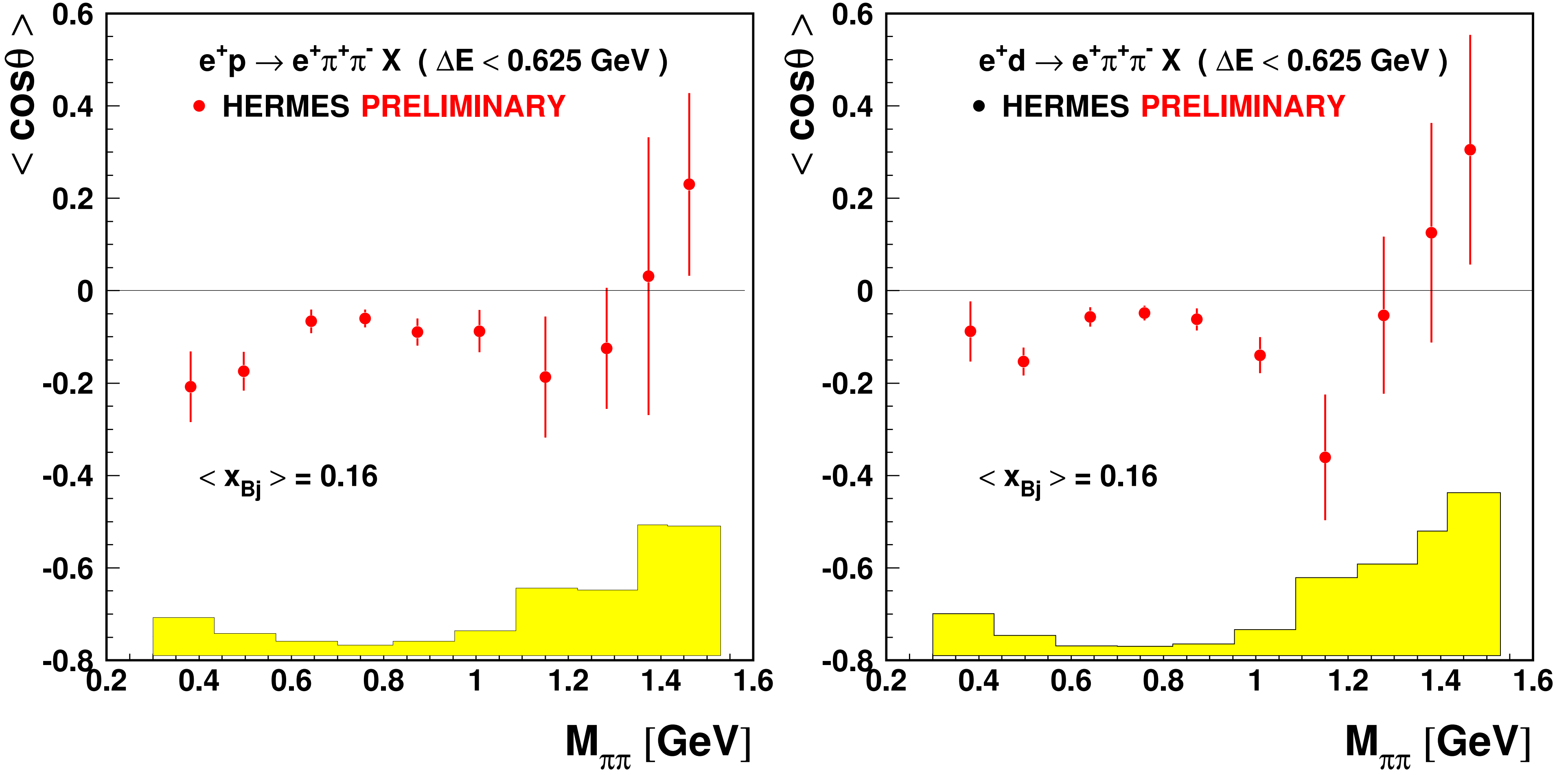
$\Rightarrow$ Sensitive to interference of P-wave with S and D-waves

$$< P_3(\cos\theta) > = \frac{1}{7\sqrt{5}} \left[-12\rho^{21}_{11} + 6\sqrt{3}\rho^{21}_{00} \right]$$

$\Rightarrow$ Sensitive to interference of P-wave with D-wave

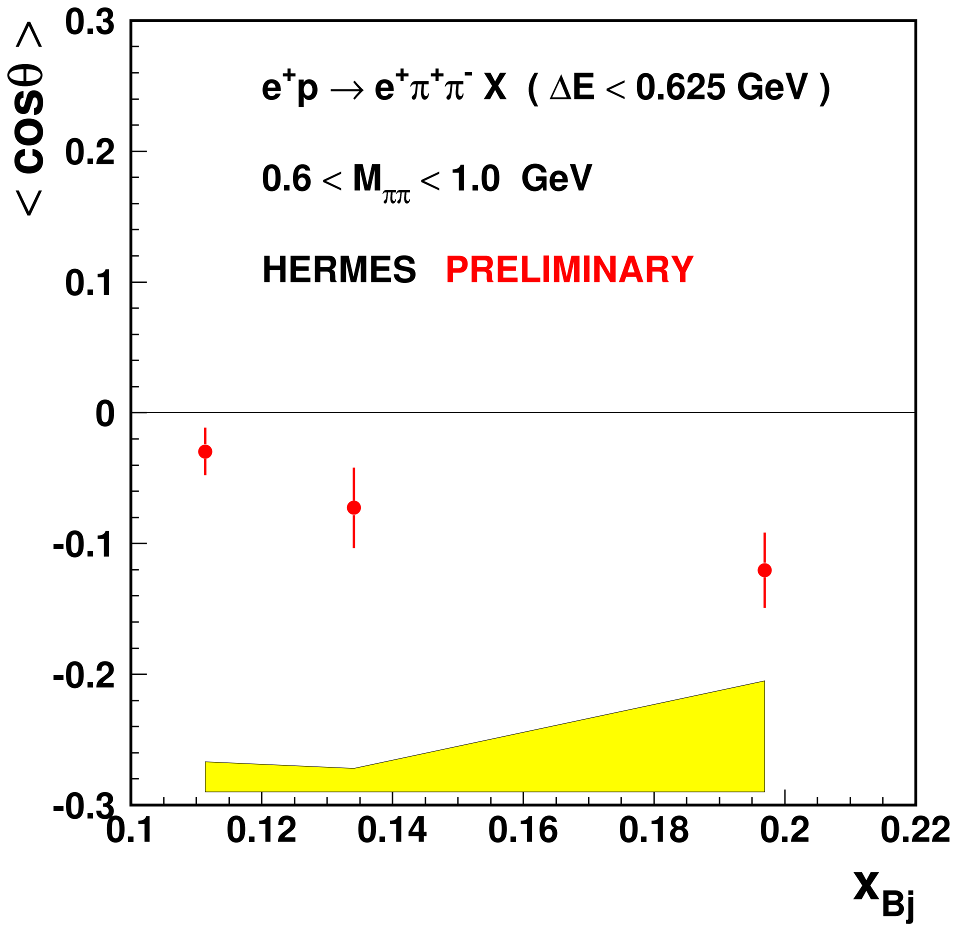
Combinations of $< P_1 >$ and $< P_3 >$ can be used to disentangle different contributions

Hard Exclusive $\pi^+\pi^-$ Pair Production



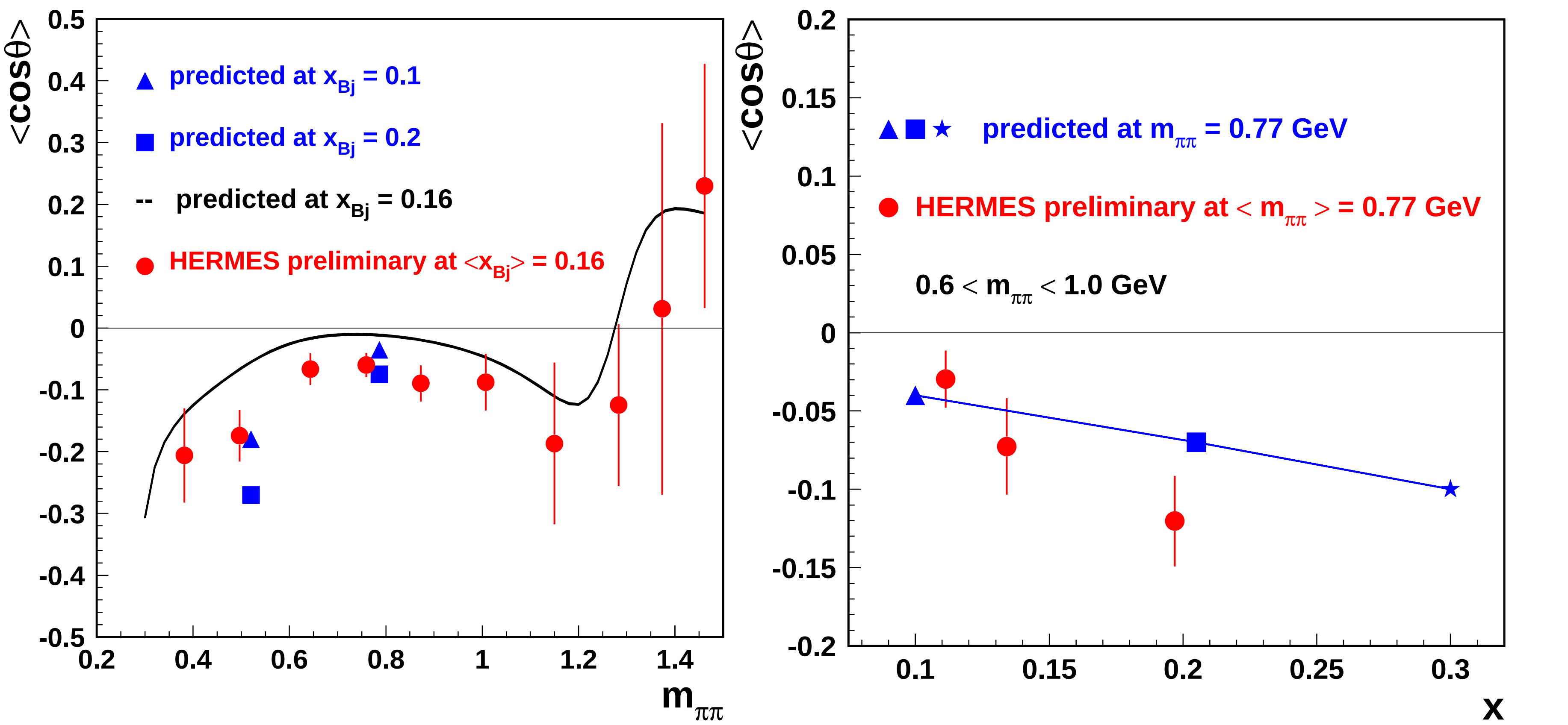
☞ Interference of ρ^0 P-wave with non-resonant $\pi\pi$ S-wave, $f_0(980)$ S-wave and $f_2(1270)$ D-wave

Hard Exclusive $\pi^+\pi^-$ Pair Production



☞ Exchange of flavor non-singlet ($C = -1$) quark combinations becomes competitive with dominant singlet ($C = +1$) exchange

Hard Exclusive $\pi^+\pi^-$ Pair Production

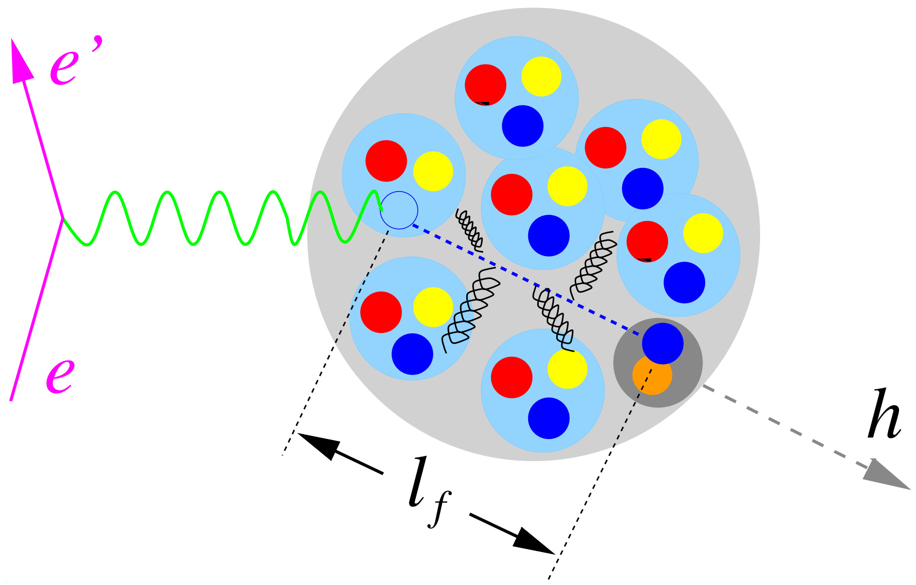


[B. Lehmann-Dronke *et al.*, Phys. Rev. D63 (2001) 114001] (with gluon GPD included),

[B. Lehmann-Dronke *et al.*, Phys. Lett. B475 (2000) 147] (without gluon GPD)

☞ Further constrain GPDs, separation of $q\bar{q}$ and $2g$ exchange contributions, constrains on non-singlet $q\bar{q}$ distribution

Fragmentation in Nuclear Environment



Nucleus acts as an ensemble of targets for the struck quark and produced hadron

☞ Hadron production from nuclei is influenced by pre-hadronized quark interactions & produced hadron interactions with spectator nucleons

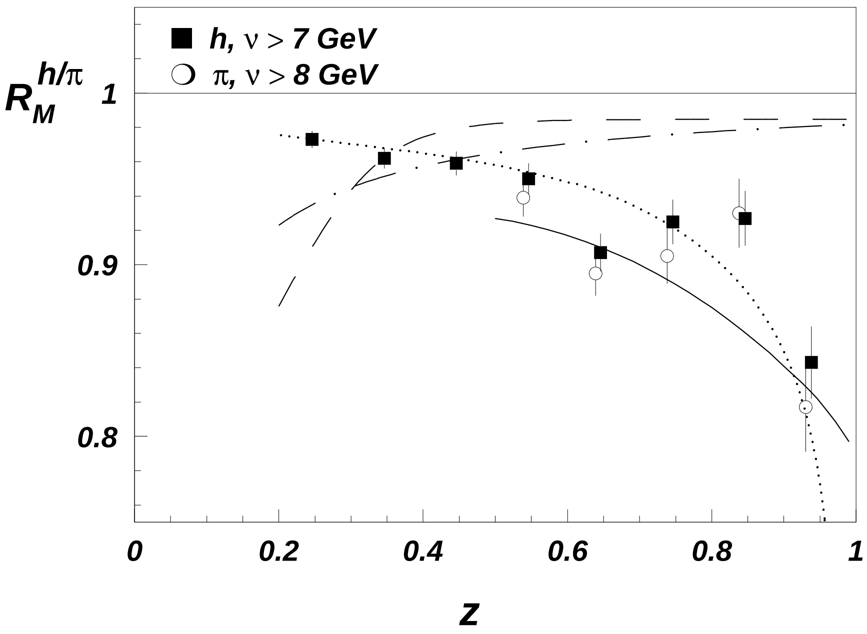
→ Models : hadronization process (phenomenological + QCD based models) + nuclear absorption

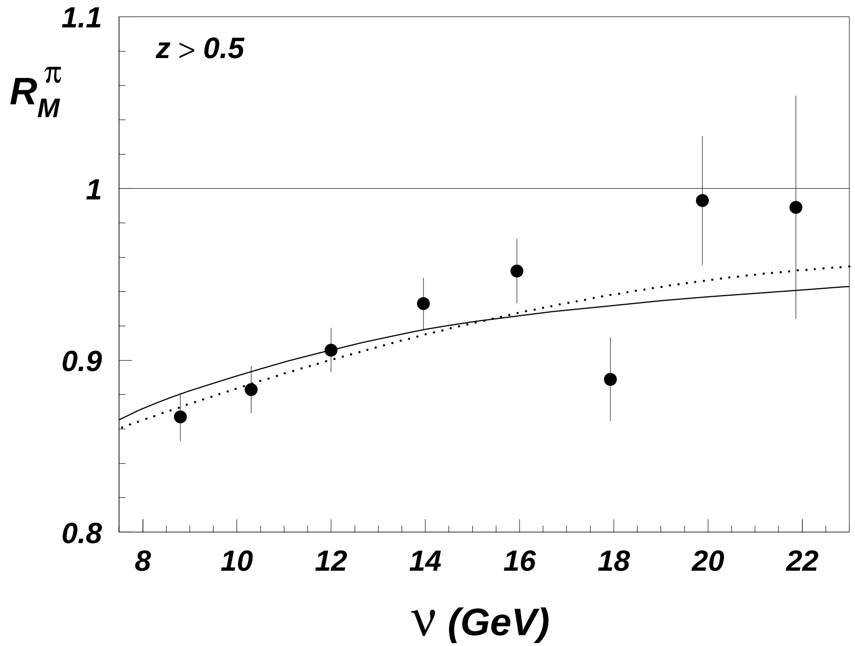
$\tau_f = l_f/c$ hadron formation time

☞ Reduction of multiplicity of $R_M^h(z, \nu, p_t^2, Q^2) = \frac{\left.\frac{N_h(z,\nu,p_t^2,Q^2)}{N_e(\nu,Q^2)}\right|_A}{\left.\frac{N_h(z,\nu,p_t^2,Q^2)}{N_e(\nu,Q^2)}\right|_D}$

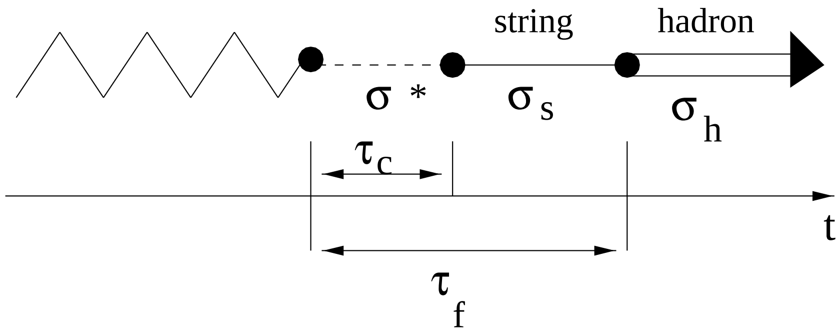
Use HERMES data on ^{14}N, ^{84}Kr, (^{4}He, ^{20}Ne) with $z > 0.2$ & $\nu > 7$ GeV

Charged Hadron Multiplicity Ratios (^{14}N)





(dotted) 1 or 2 time-scale models

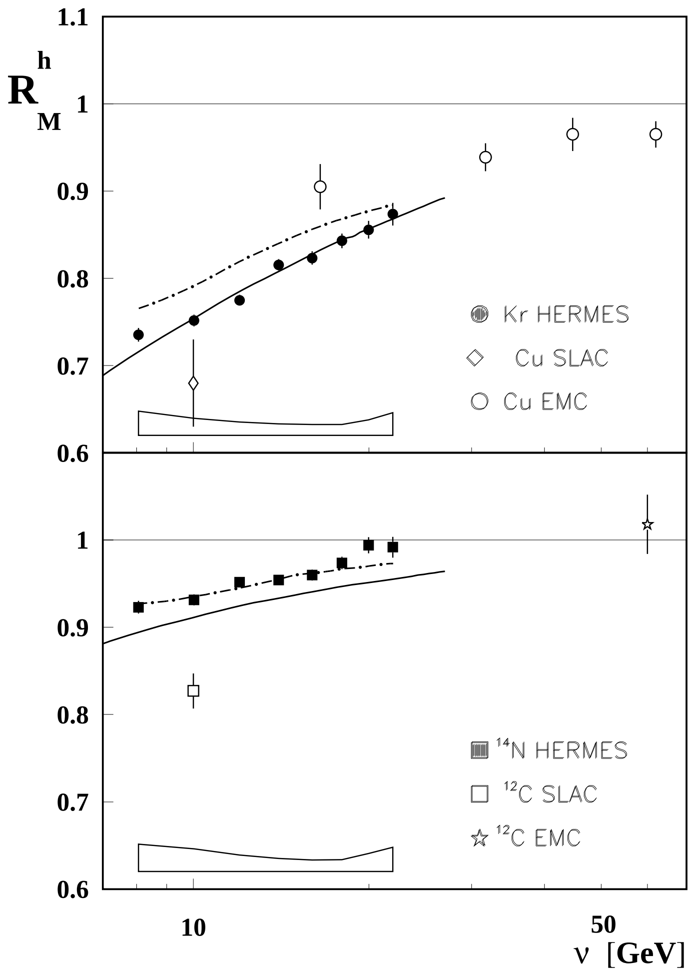


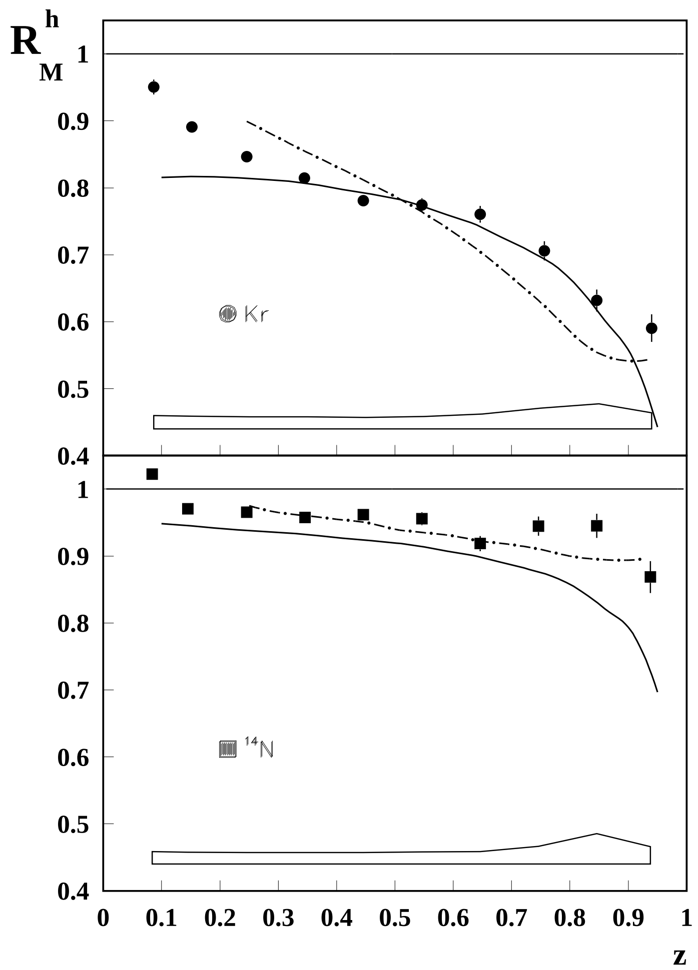
$t_f^h = c_h(1-z)\nu, \quad \sigma^* = 0, \sigma_h = 25$ mb

☞ Formation time fits

(solid, Kopeliovich *et al.*) Gluon bremsstrahlung model for pions

Charged Hadron Multiplicity Ratios (^{14}N, ^{84}Kr)

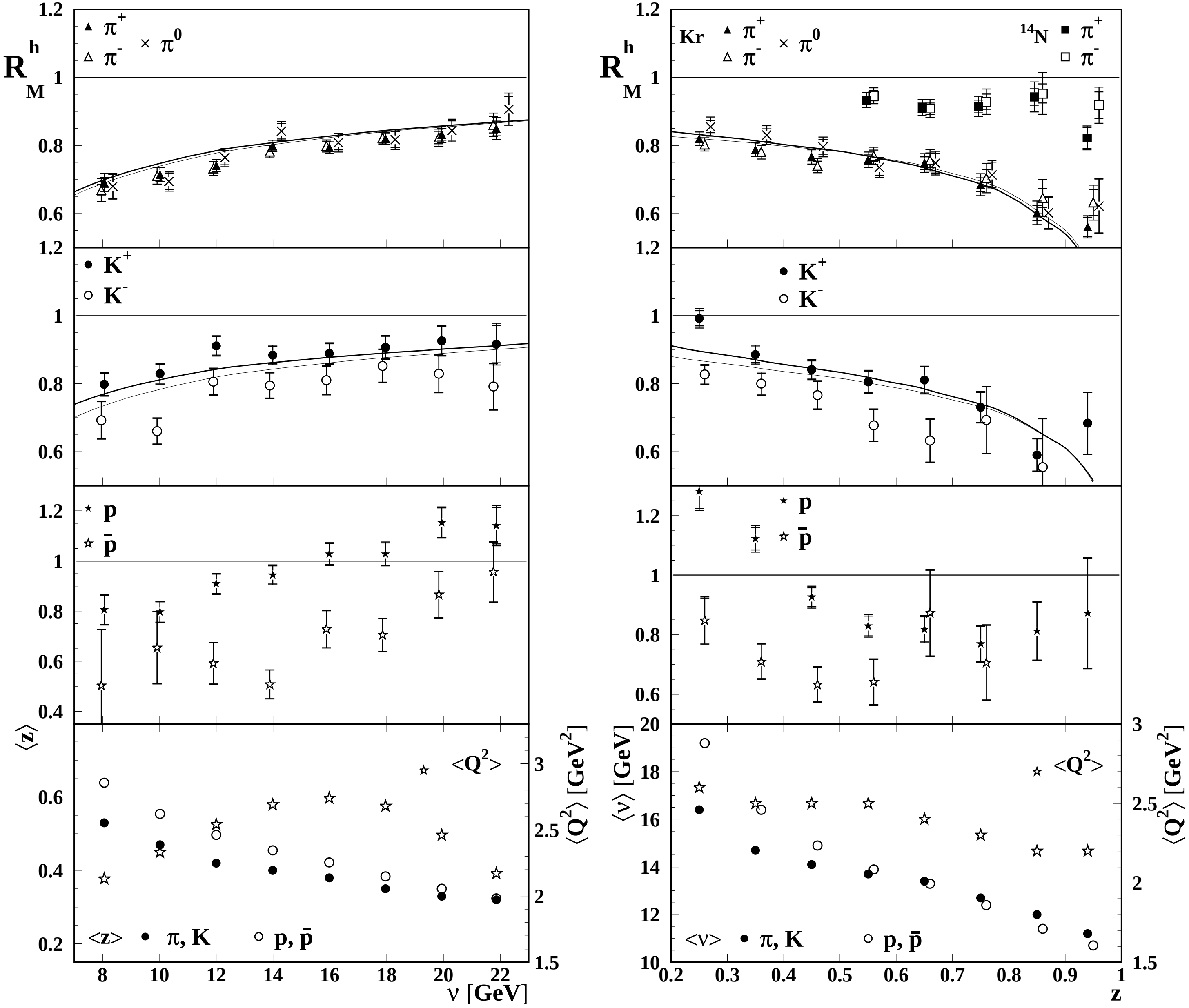




Model calculations : (solid, Accardi *et al.*) rescaling of quark fragmentation functions + nuclear absorption; (dot-dashed, Wang *et al.*) medium modification of parton fragmentation due to multiple scattering and gluon bremsstrahlung (tuned to ^{14}N data)

$\pi^{\pm,0}$, $K^{\pm}$, p & $\bar{p}$ Multiplicity Ratios (^{84}Kr)

[A. Airapetian *et al.*, Phys. Lett. B577 (2003) 37]

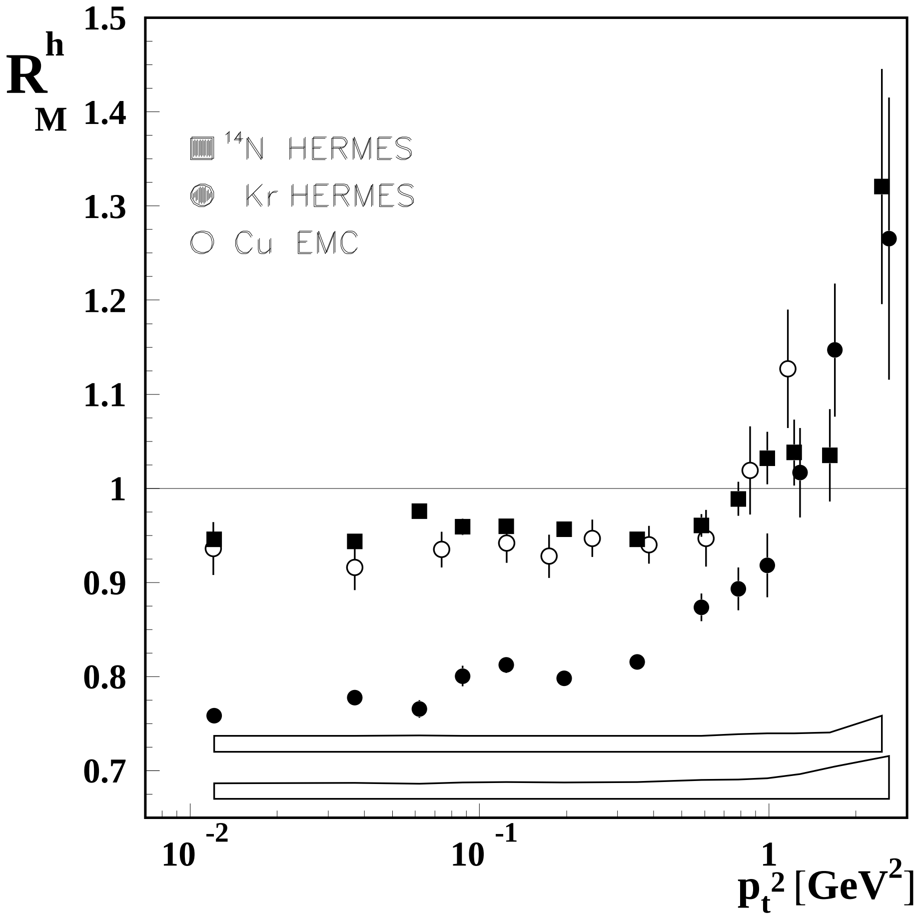


$R_M^{\pi^+} \sim R_M^{\pi^-} \sim R_M^{\pi^0}$, but $R_M^{K^+} > R_M^{K^-}$, $R_M^{p} > R_M^{\bar{p}}$ and $R_M^{p} > R_M^{\pi}$

☞ Different formation times of baryons and mesons; different hadron-nucleon interaction cross sections

☞ Mixing of quark and gluon fragmentation functions (Wang *et al.*); $(1 - R_M^N)/(1 - R_M^{Kr})$ agrees with scaling law $1 - R_M \propto A^{\alpha}$ with predicted $\alpha = \frac{2}{3}$ ($= \frac{1}{3}$ nuclear absorption only)

Attenuation vs. p_t^2



Broadening of p_t distribution on nuclear target due to multiple scattering of propagating quark and hadron, ie. Cronin effect

Effect observed previously in heavy-ion and hadron-nucleus scattering

Enhancement predicted to occur at $p_t \sim 1 - 2$ GeV

Possible A-dependence of Cronin effect in DIS

Summary

- First observation of Sivers effect; large Collins asymmetry for π^+ and π^-
- First measurement of single-spin azimuthal asymmetry in exclusive π^+ production on a longitudinally polarized proton target; asymmetry dominated by longitudinal target polarization component
- Measurement of double spin asymmetry in vector meson production on proton and deuteron
- Measurement of angular asymmetry in hard exclusive $\pi^+\pi^-$ production shows interference of $I = 1$ and $I = 0$
- First measurement of nuclear attenuation of pions, kaons and (anti)protons electroproduction in ^{84}Kr; observation of Cronin effect in DIS