Recent HERMES Results on Meson Production

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

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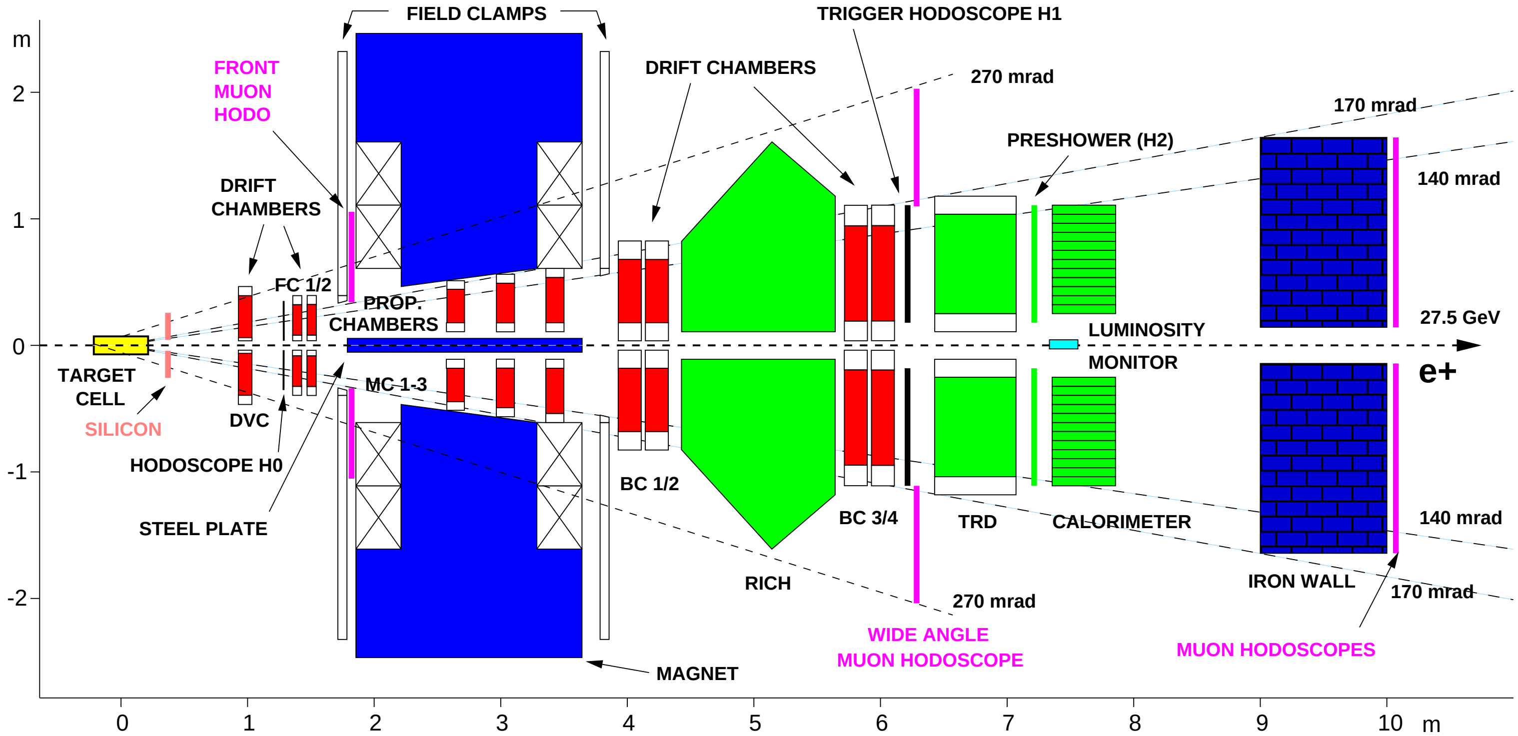
on behalf of the HERMES Collaboration

hermes

The HERMES Experiment @ DESY



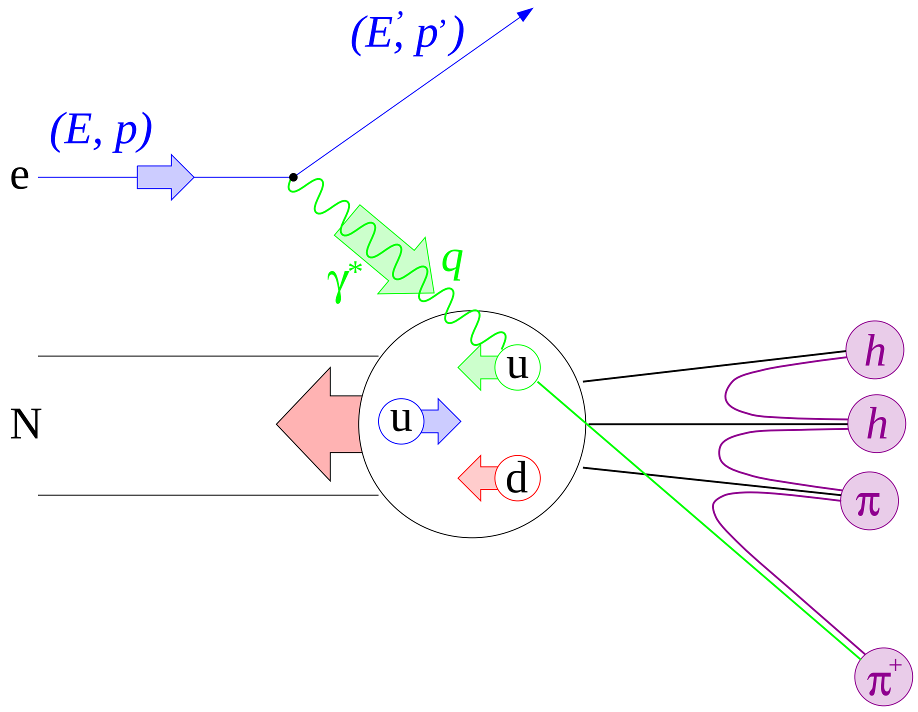
- 27.6 GeV HERA e-beam
- Internal Gas Target : $\vec{\text{He}}$, $\vec{\text{H}}$, $\vec{\text{D}}$, H↑; unpol : H_2, D_2, He, N, Ne, Kr, Xe
- Resolution : $\Delta p/p = 1.4 - 2.5$ %, $\Delta\theta < 0.6$ mrad
- Lepton/Hadron Separation : TRD, Preshower, Calorimeter
- Hadron ID : Cherenkov (1995-97)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

Semi-inclusive Deep Inelastic Scattering

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

$\Rightarrow$ HERMES-I (1995-2000) : longitudinally polarized beam and target

$\Rightarrow$ HERMES-II (2002-...) : transversely polarized target



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

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

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

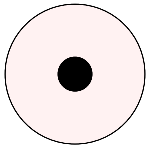
$$z \overset{\text{lab}}{=} \frac{E_h}{\nu}$$

$\Rightarrow$ Cross section contains quark distribution and fragmentation functions

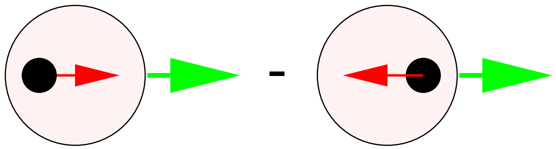
$$\sigma^{eN \to ehX} \sim \sum_q f^{N \to q} \otimes \sigma^{eq \to eq} \otimes D^{q \to h}$$

Distribution Functions

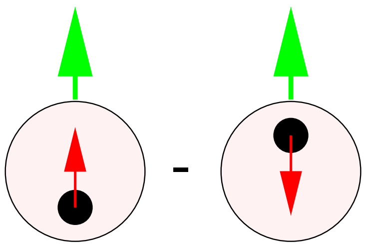
In leading twist, integrating over quark transverse momenta, 3 DFs :

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)

Quark Helicity DF

HERMES-I : longitudinal (semi)-inclusive double spin asymmetries

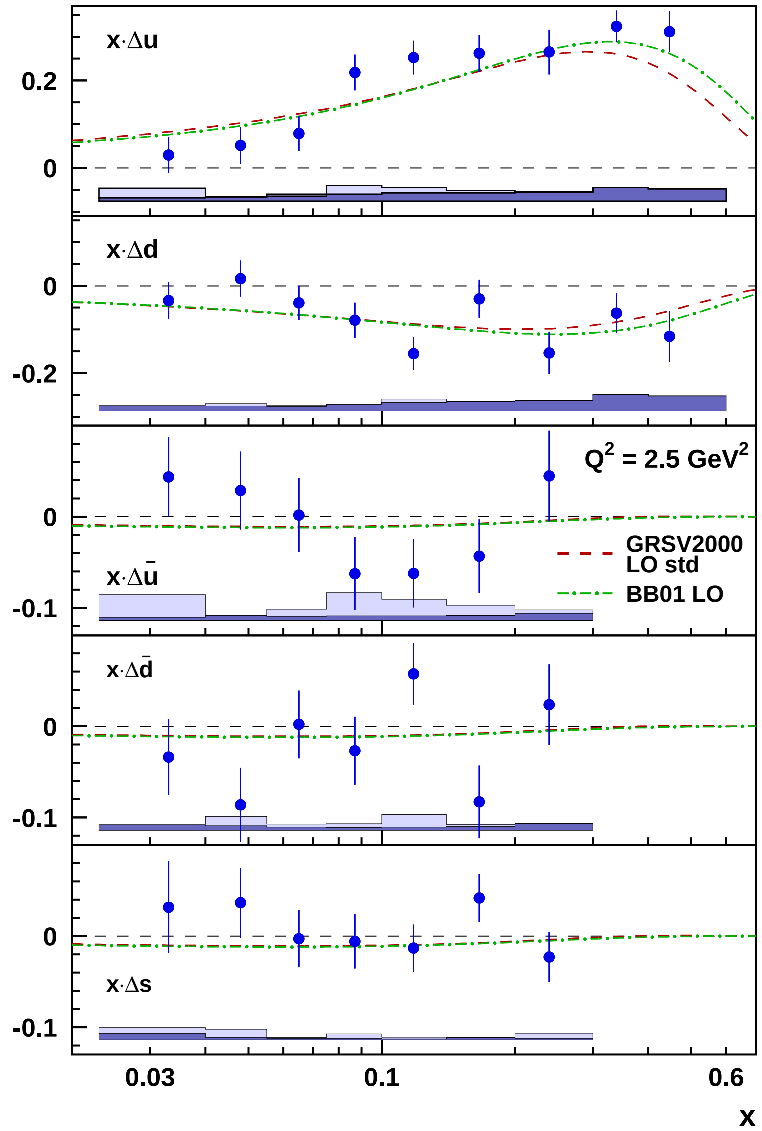
$$A_1^h(x) = \sum_q P_q^h(x) \frac{\Delta q(x)}{q(x)} \frac{(1+R(x))}{(1+\gamma^2)}$$

Solve matrix equation :

$$\vec{A}(x) = \mathcal{P}(x) \cdot \vec{Q}(x)$$

with

$$\vec{A}(x) = (A_{1p}, A_{1p}^{\pi^+}, A_{1p}^{\pi^-}, A_{1d}, A_{1d}^{\pi^+}, A_{1d}^{\pi^-}, A_{1d}^{K^+}, A_{1d}^{K^-})$$

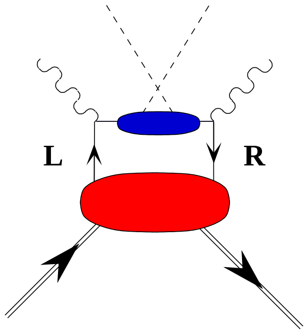


Transversity

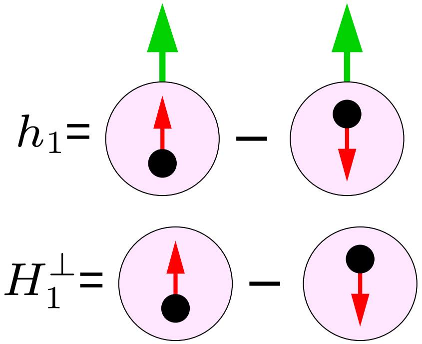
- $f_1(x)$ and $g_1(x)$ can be measured in inclusive DIS;
  $h_1(x)$ is chiral-odd $\longrightarrow$ need another chiral-odd object to access transversity

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

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



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

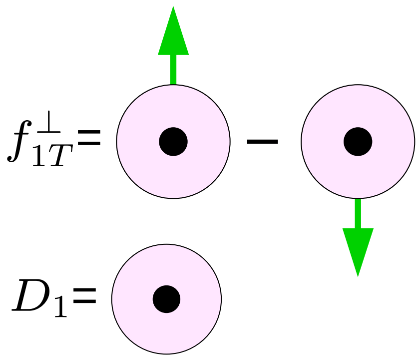


$\longrightarrow$ Influence of quark's polarization on transverse momentum acquired in fragmentation process orthogonal to its transverse polarization

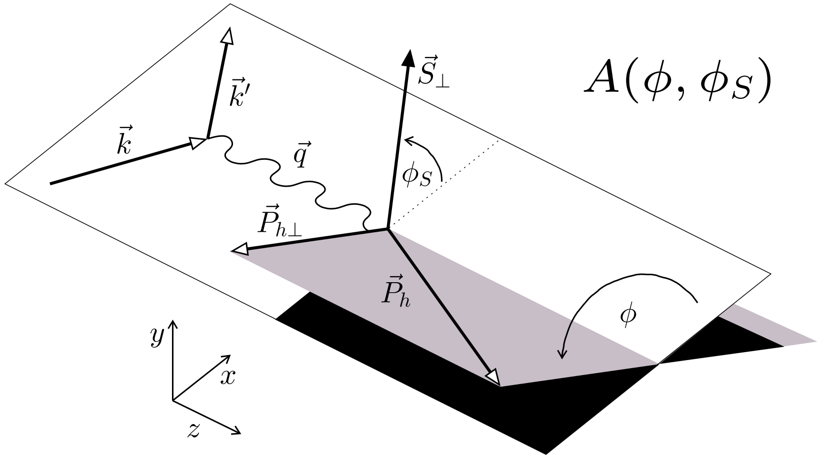
Sivers effect : $A \sim f_{1T}^{\perp}(x)\, D_1(z)$

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

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



Azimuthal Asymmetry for Transverse Target Polarization



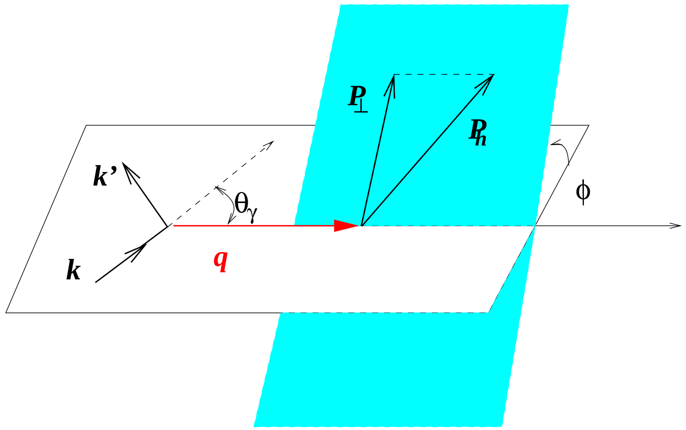
$$
\begin{aligned}
A(\phi,\phi_S) &= \frac{1}{S_\perp}\frac{N^\uparrow(\phi,\phi_S)-N^\downarrow(\phi,\phi_S)}{N^\uparrow(\phi,\phi_S)+N^\downarrow(\phi,\phi_S)} \\
&\sim \ldots \sin(\phi+\phi_S)\sum_q e_q^2\cdot\mathcal{I}\left[\ldots h_1^q(x,\vec{p}_T^{\,2})\cdot H_1^{\perp q}(z,\vec{k}_T^{\,2})\right]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

$\mathcal{I}$: 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

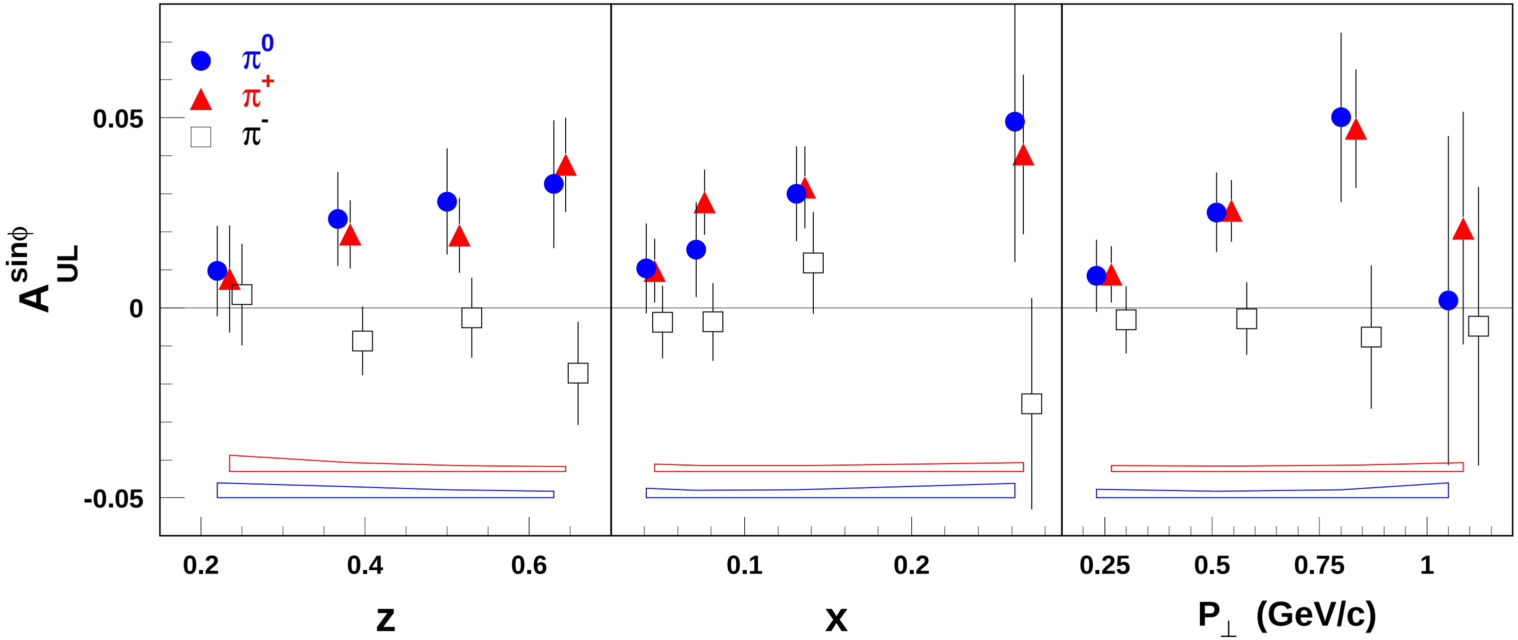
$$A_{UL}^{\sin\phi} = \frac{1}{|S_L|} \frac{\sum_{i=1}^{N^{\rightarrow}} \sin(\phi_i) - \sum_{i=1}^{N^{\leftarrow}} \sin(\phi_i)}{\frac{1}{2}[N^{\rightarrow} + N^{\leftarrow}]}$$

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

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

$0.2 < z < 0.7$

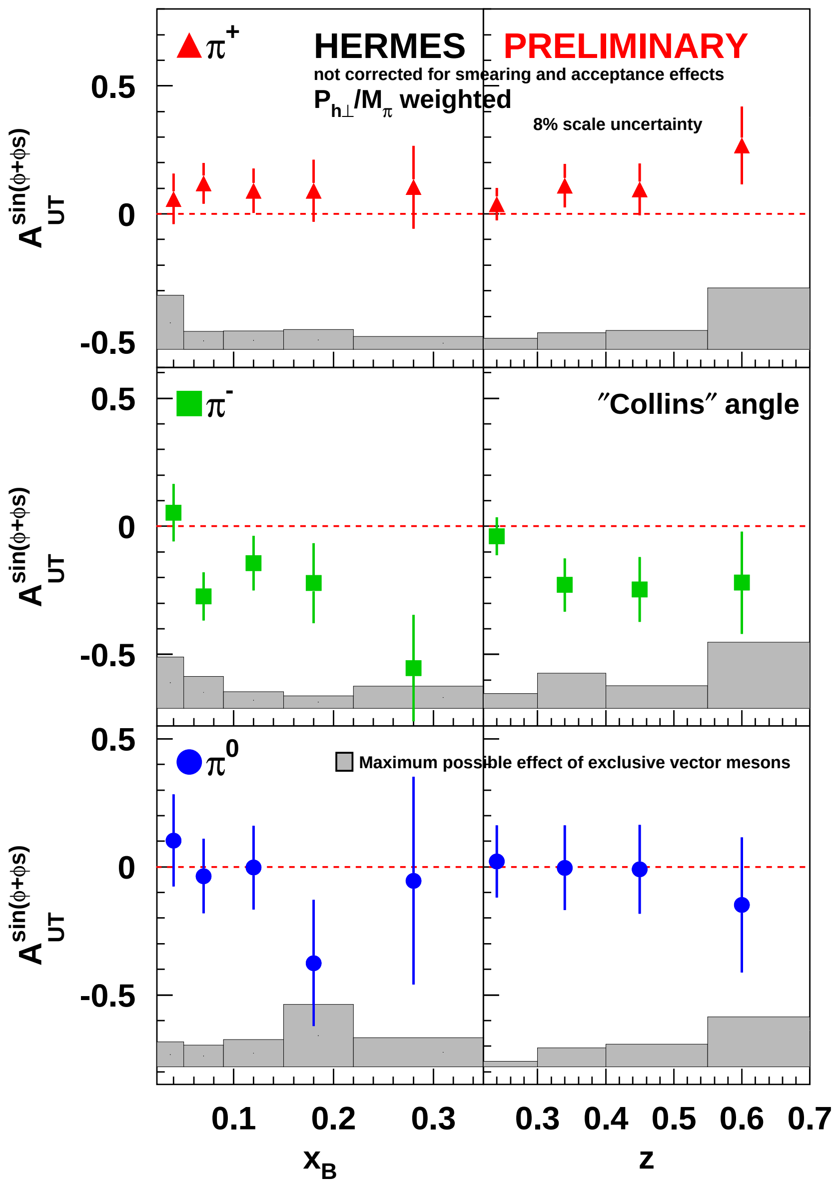
$S_T/S \propto \sin\theta_\gamma$
~ 15 %



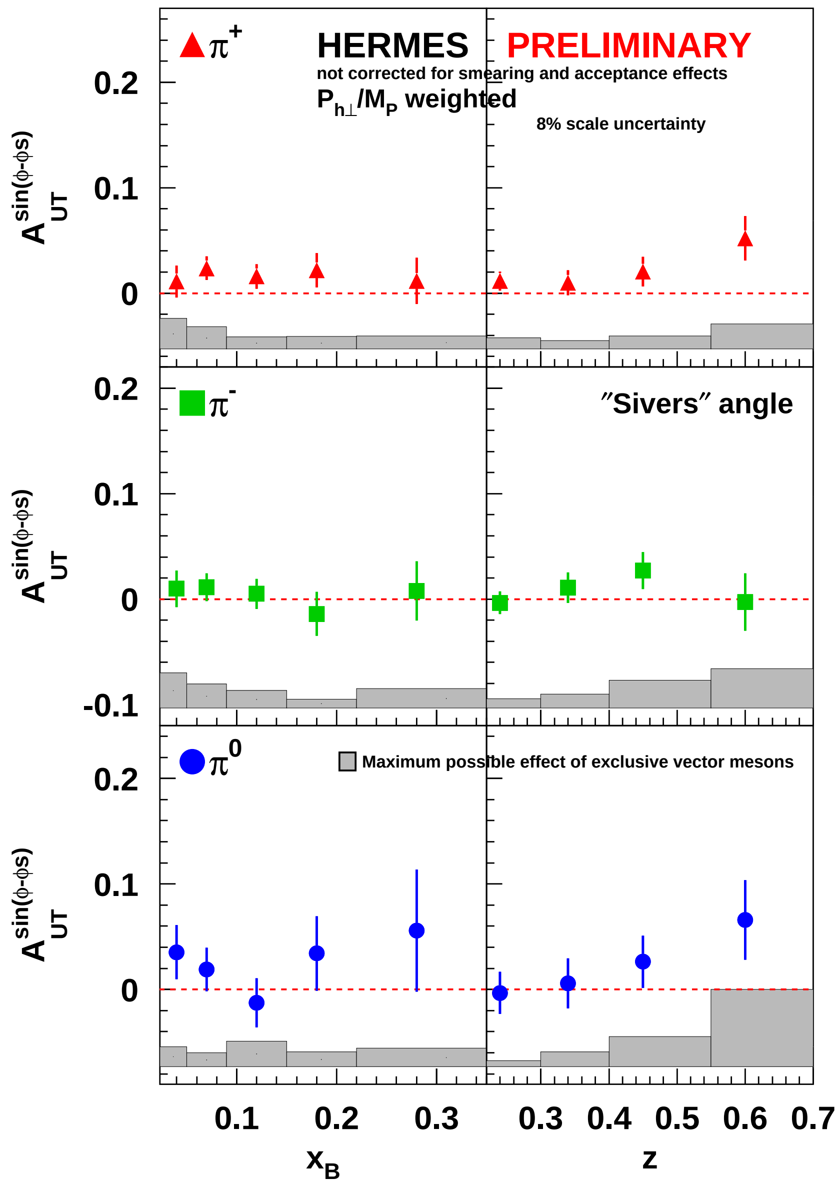
[A. Airapetian *et al.*, Phys. Rev. Lett. 84 (2000) 4047; Phys. Rev. D64 (2001) 097101; Phys. Lett. B562 (2003) 182]

$\Rightarrow$ Collins fragmentation function $H_1^\perp$ non-zero (?)

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

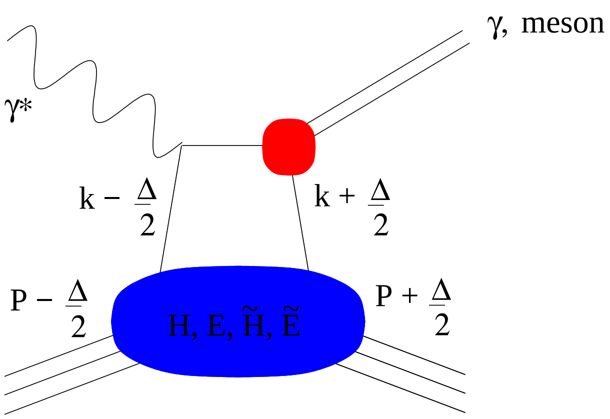


$$A^{\sin(\phi+\phi_S)} \sim h_1(x) \cdot H_1^{\perp(1)}(z)$$



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

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

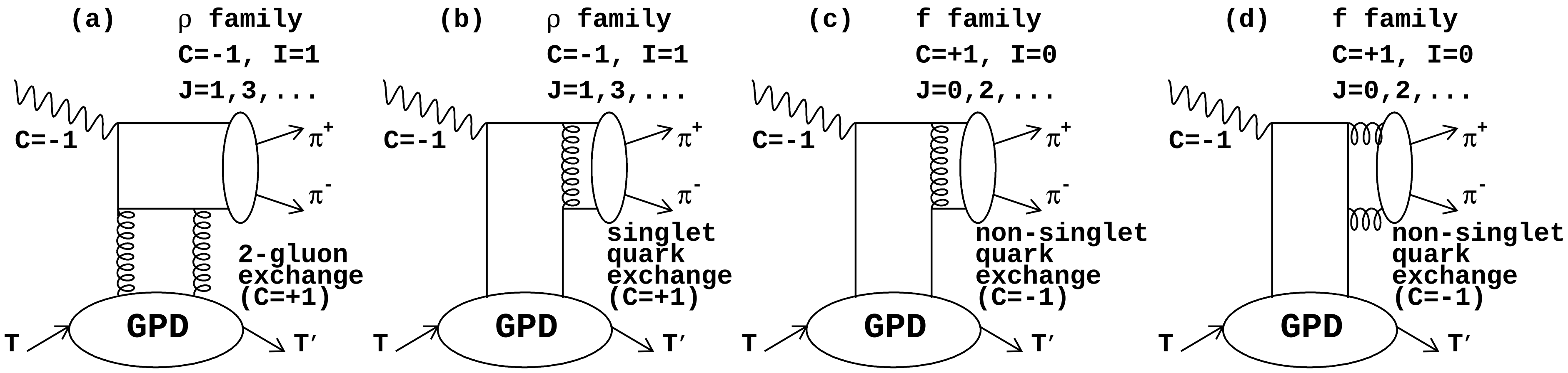
$\Rightarrow$ New observables in hard exclusive scattering; related to standard PDF and form factors :

$$H^q(x,0,0) = q(x), \qquad \tilde{H}^q(x,0,0) = \Delta q(x),$$
$$\int_{-1}^{+1} \mathrm{d}x\, H^q(x,\chi,t) = F_1^q(t), \qquad \int_{-1}^{+1} \mathrm{d}x\, E^q(x,\chi,t) = F_2^q(t), \qquad \ldots$$

- 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
- Finale state quantum numbers select different GPDs

Hard Exclusive $\pi\pi$ Pair Production

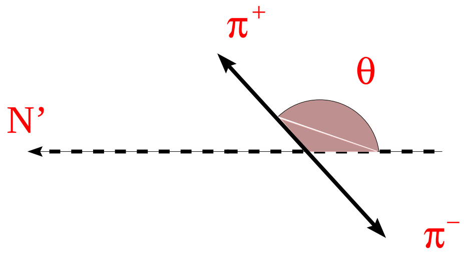


- pion pairs are formed by gluon exchange (isovector pairs) or quark exchange (isovector + isoscalar pairs)

  $\Rightarrow$ 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

$\Rightarrow$ Study P_1 (and P_3), sensitive to interferences :

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

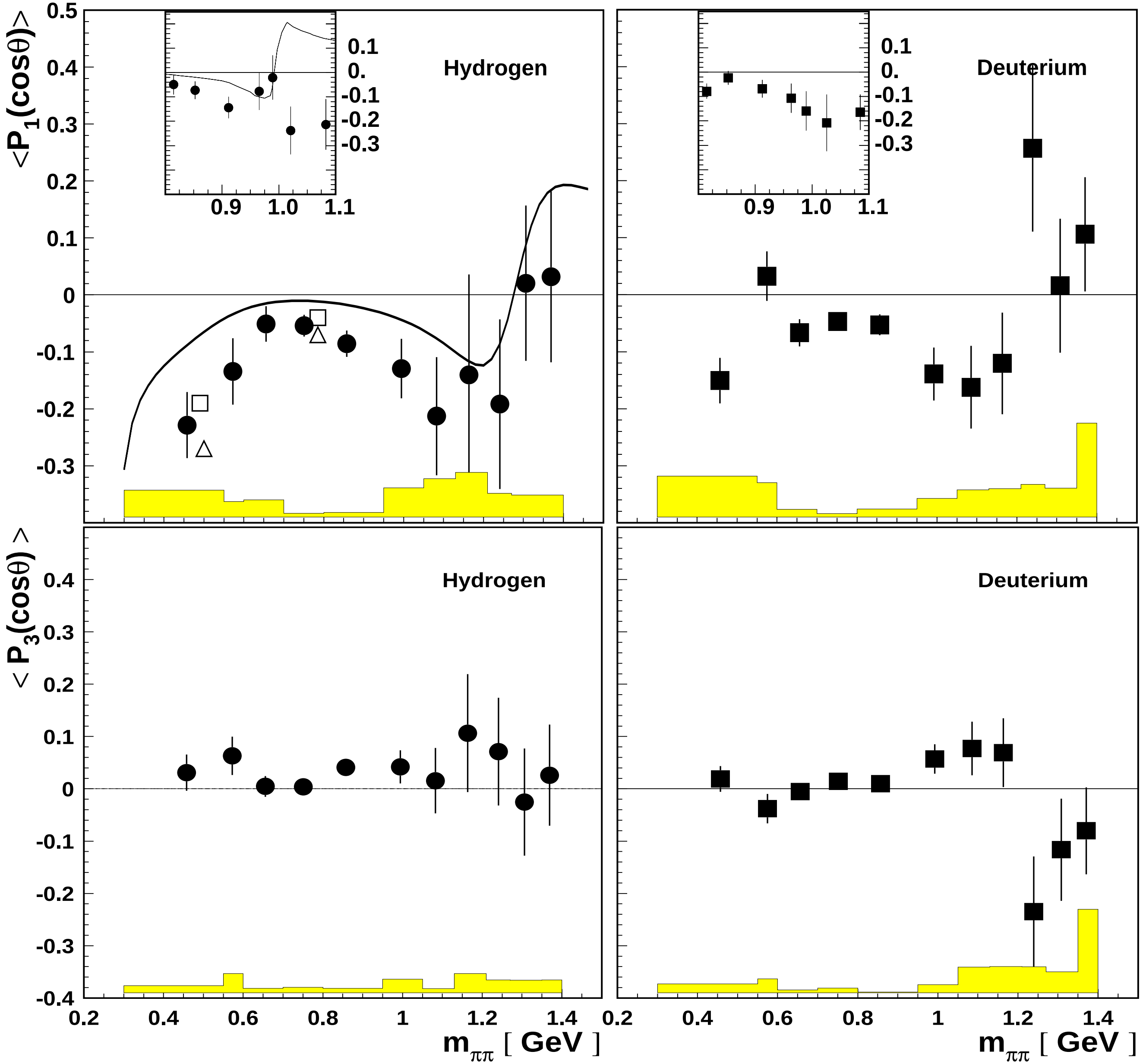
$\Rightarrow$ Sensitive to interference of P-wave with S and D-waves

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

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

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

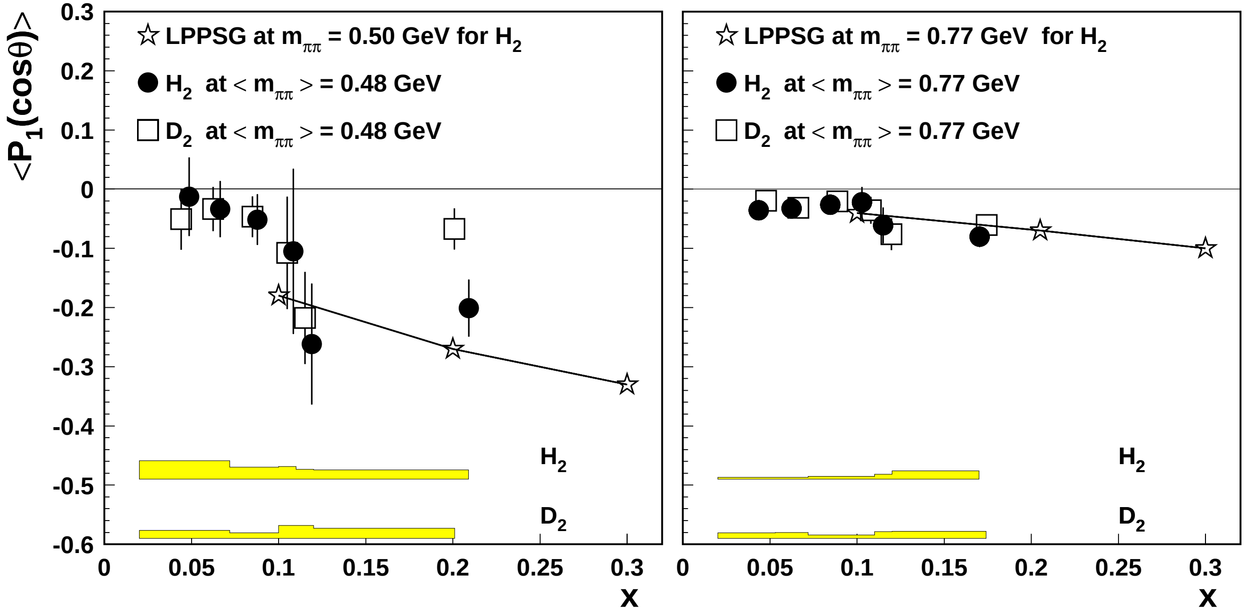
Hard Exclusive $\pi^+\pi^-$ Pair Production



$\Rightarrow$ P_1 : Interference of ρ^0 P-wave with non-resonant $\pi\pi$ S-wave, $f_0(980)$ S-wave and $f_2(1270)$ D-wave

$\Rightarrow$ P_3 : Interference of P and D waves ?

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



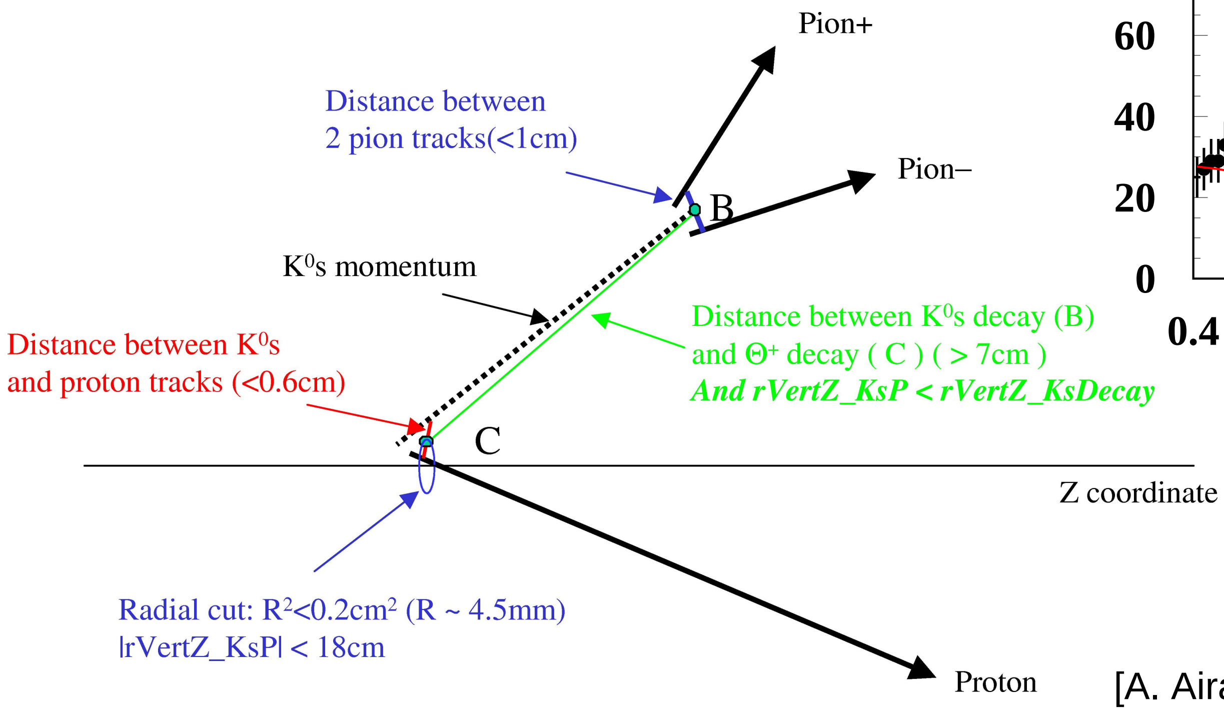
$\Rightarrow$ Exchange of flavor non-singlet ($C = -1$) quark combinations becomes competitive with dominant singlet ($C = +1$) exchange

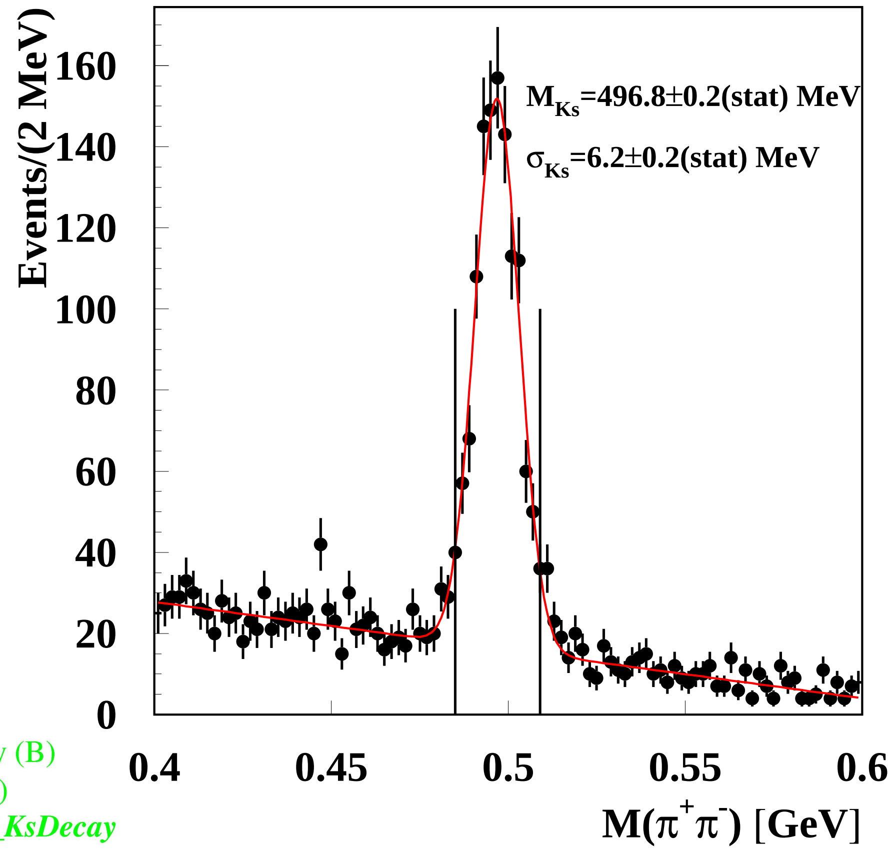
[B. Lehmann-Dronke *et al.*, Phys. Rev. D63 (2001) 114001] (with gluon GPD included),
[B. Lehmann-Dronke *et al.*, Phys. Lett. B475 (2000) 147] (without gluon GPD)

Observation of the Θ^+ Pentaquark State

Quasi-real photoproduction :

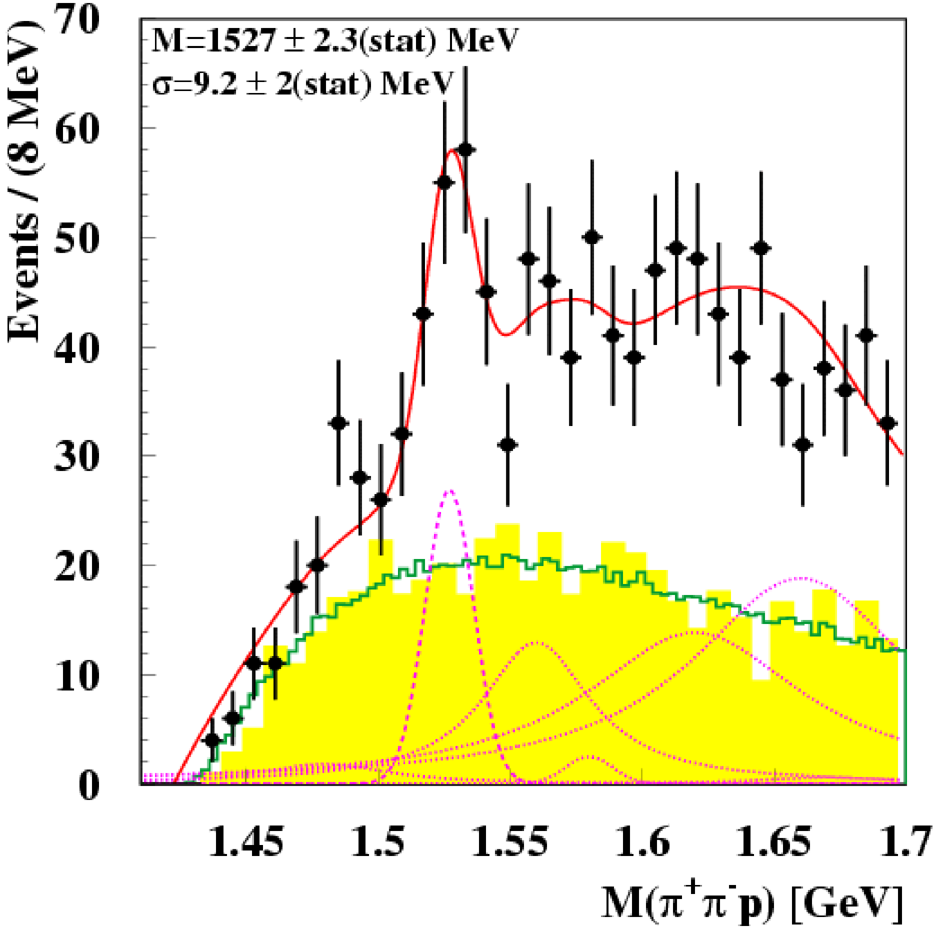
$$\begin{aligned} e + D &\rightarrow \Theta^+ + X \\ &\rightarrow K_s^0 + p + X \\ &\rightarrow \pi^+ + \pi^- + p + X \end{aligned}$$





[A. Airapetian *et al.*, Phys. Lett. B585 (2004) 213]

Observation of the Θ^+



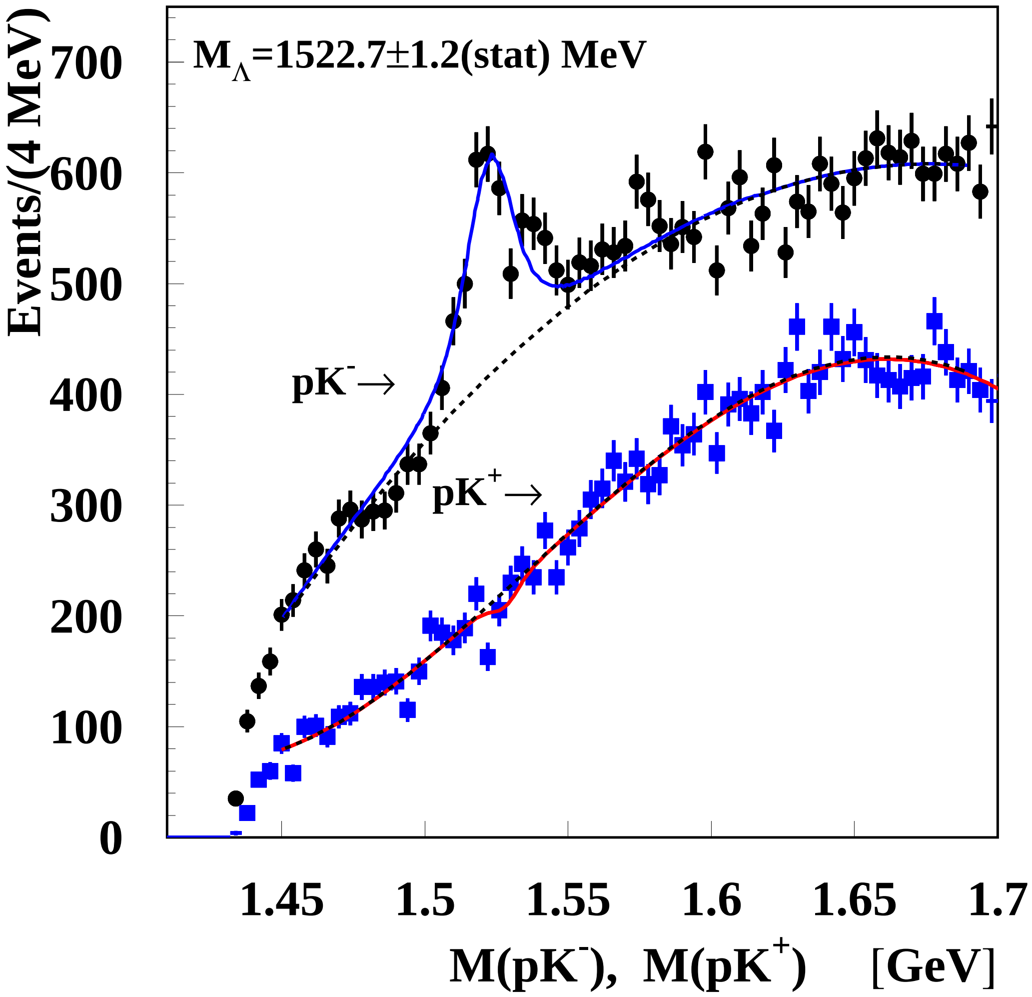
- Use RICH for hadron PID
- suppress $\Lambda(1116) \to p\pi^-$
- Background : PYTHIA or mixed event background + 6 known Σ^{*+} hyperons

$\Rightarrow$ Θ^+ :

Mass = $1527.0 \pm 2.3 \pm 2.1$ MeV
FWHM = $22 \pm 5 \pm 2$ MeV
Signif : $N_s/\delta N_s = 4.3\sigma$ (true)

- Cross section estimate :
  100 - 220 nb ± 25 % (stat)
  (Integrated lumi = 250 pb^{-1},
  toy model MC acceptance = 0.05 %,
  branching ratio to pK_S^0 = 1/4)

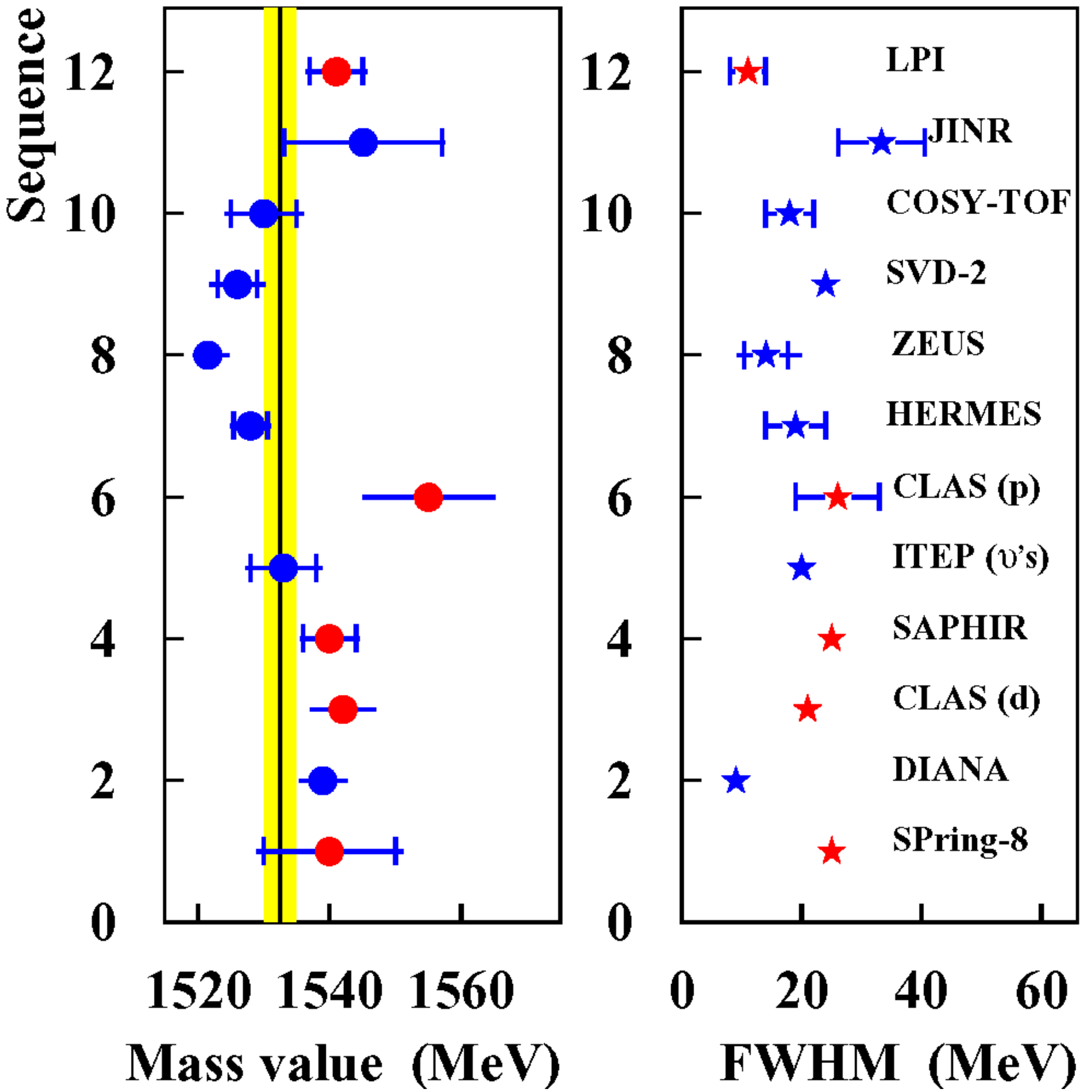
Searching for the Θ^{++}



- Examine $pK^{\pm}$ channel
- Clear signal of $\Lambda(1520)$ in pK^{-}
- No signal of Θ^{++} in pK^{-} ...

$\Rightarrow$ Θ^{+} is not isotensor, but rather isoscalar

Θ^+ in Other Experiments



nK^+
pK_S^0

World average :

$M_{\Theta^+} = 1532.5 \pm 2.4$ MeV

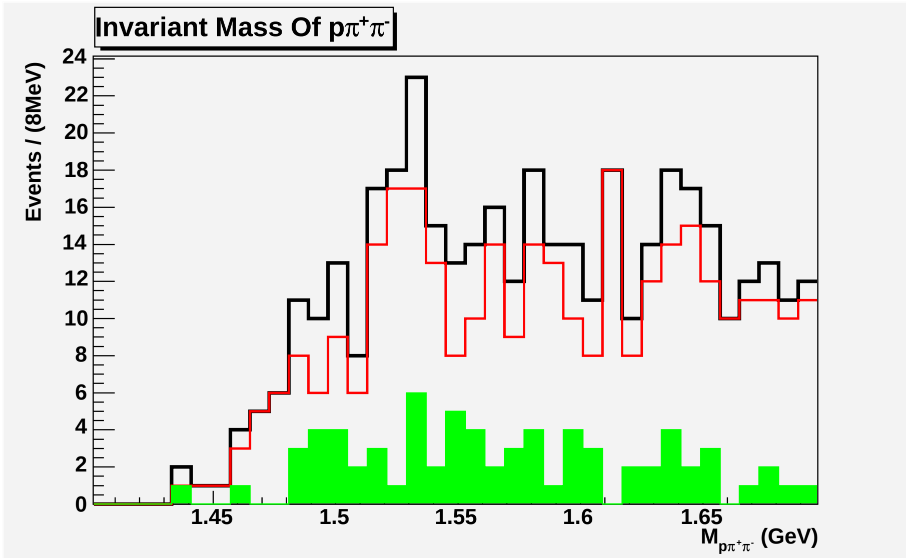
Θ^+ with Additional Hadron

$\Rightarrow$ Add a 4th hadron :

. Θ^+ production process ?

. Suppress background ?

Remove $\gamma p \longrightarrow \phi p \longrightarrow K_L^0 K_S^0 p$



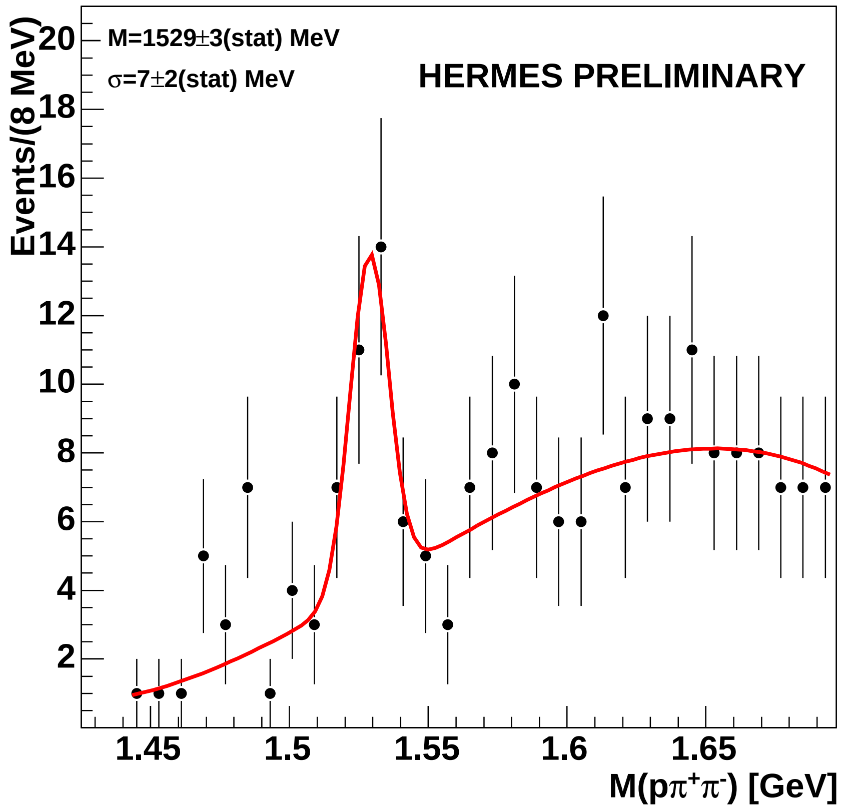
4th hadron = anything; 4th hadron = π;
4th hadron = not π

Remove $p(K^*)^\pm \longrightarrow pK_S^0\pi^\pm$
K^* cut : $|M(K_S\pi) - 892| < 75$ MeV

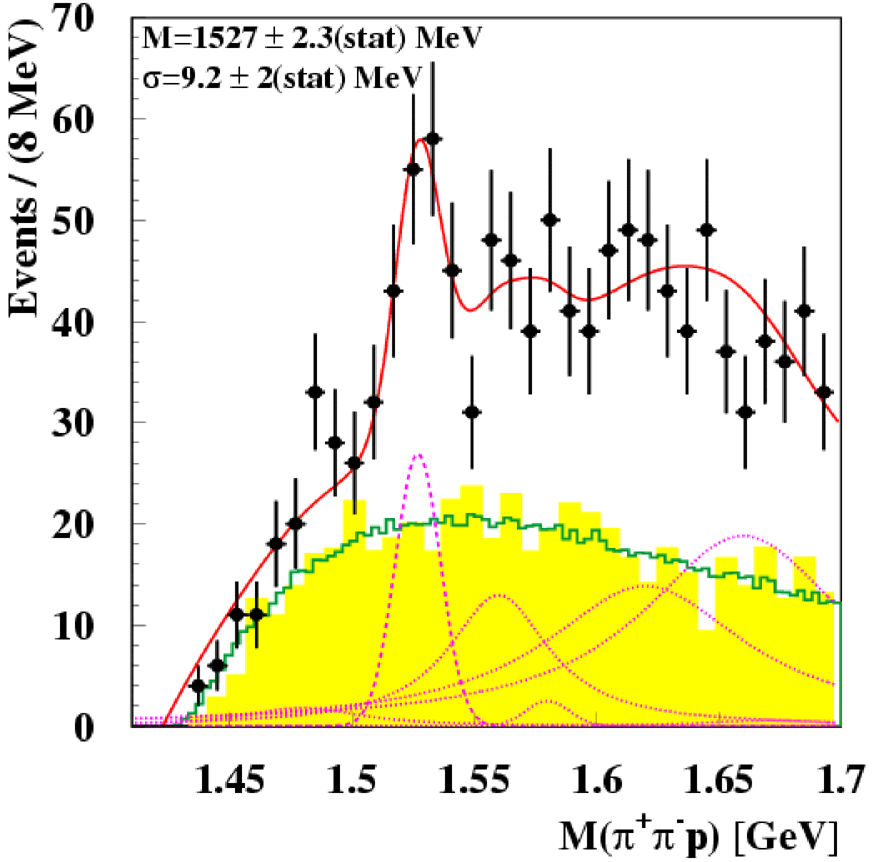
Λ veto : $|M(p\pi^-_{4th}) - 1.116| < 0.006$ GeV

$\Rightarrow$ Can 4th hadron come from exclusive process ? $\gamma p \longrightarrow \bar{K}^0\Theta^+$ or $\gamma n \longrightarrow K^-\Theta^+$
K^0 decay pions or K^- go backwards ...

Θ^+ with Additional π

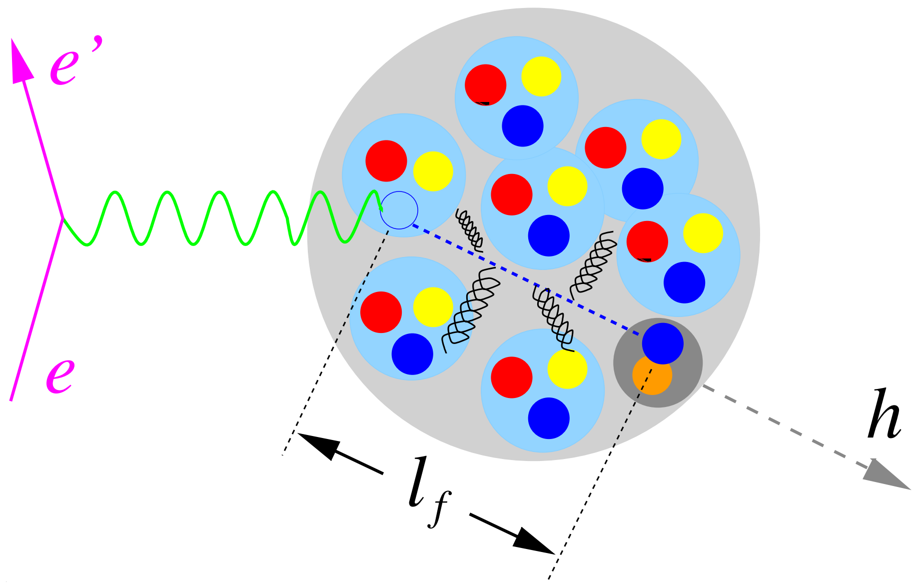


Standard cuts + K^* and Λ veto
signal/background:
2:1



signal/background:
1:3

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

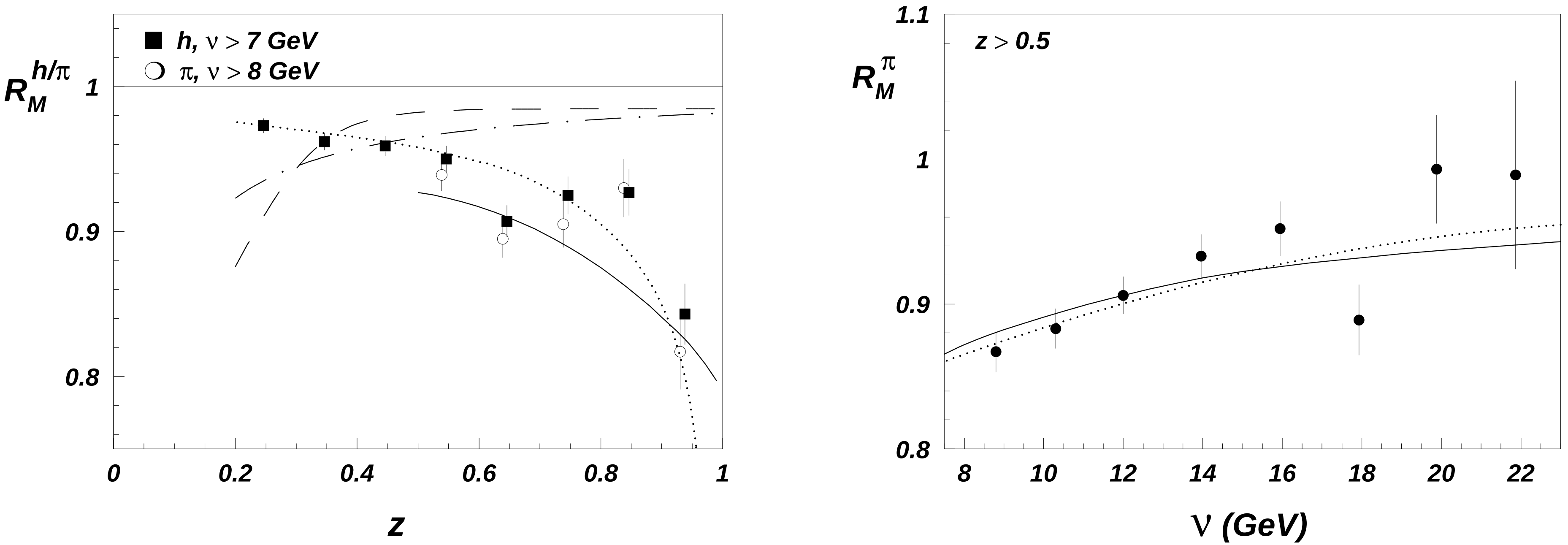
→ Models : hadronization process (phenomenological + QCD based models) + nuclear absorption

$\tau_f = l_f/c$ hadron formation time

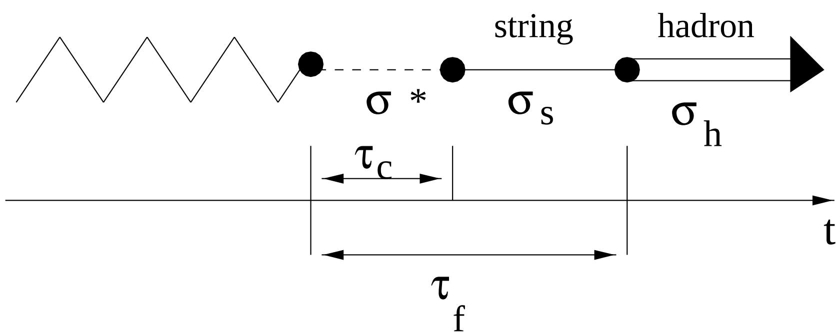
⇒ Reduction of multiplicity of $R_M^h(z,\nu,p_t^2,Q^2) = \frac{\left.\frac{N_h(z,\nu,p_t^2,Q^2)}{N_e(\nu,Q^2)}\right|_A}{\left.\frac{N_h(z,\nu,p_t^2,Q^2)}{N_e(\nu,Q^2)}\right|_D}$

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

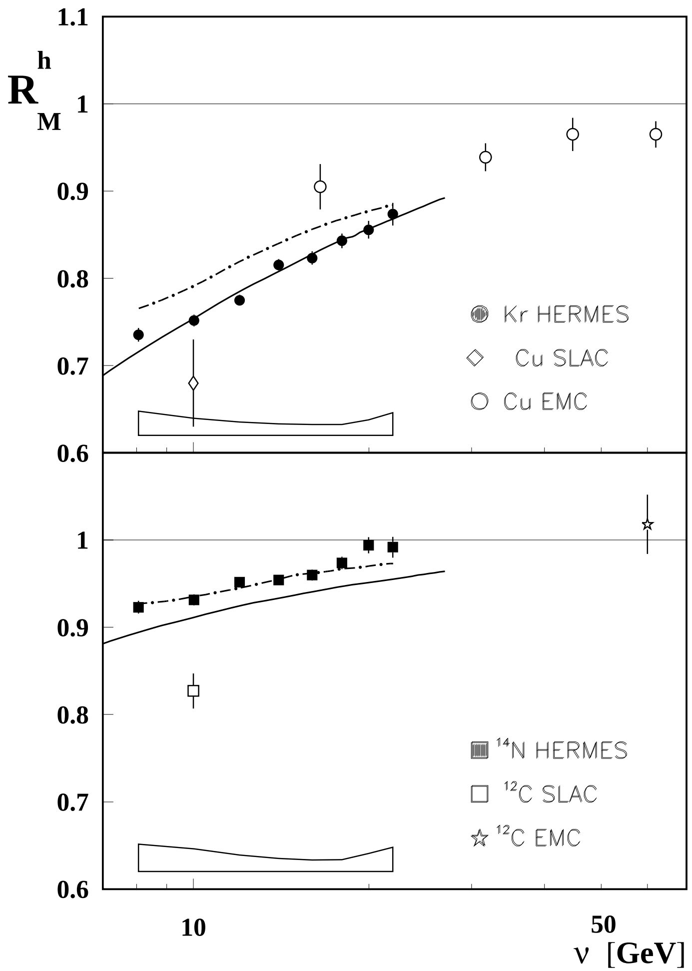


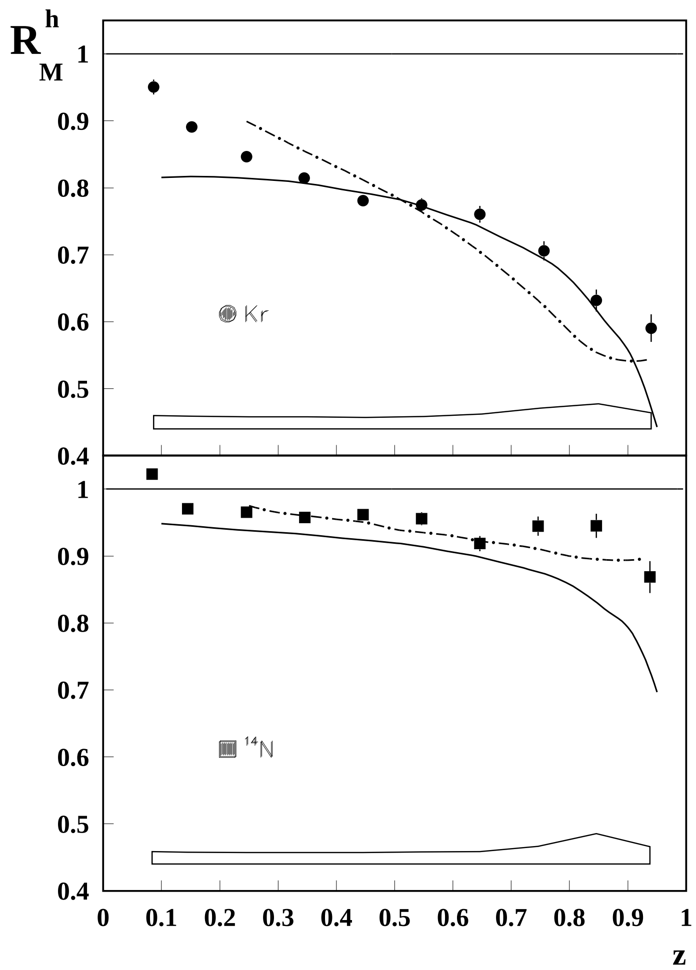
$t_f^h = c_h(1-z)\nu, \quad \sigma^* = 0, \sigma_h = 25$ mb

$\Rightarrow$ Formation time fits

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

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

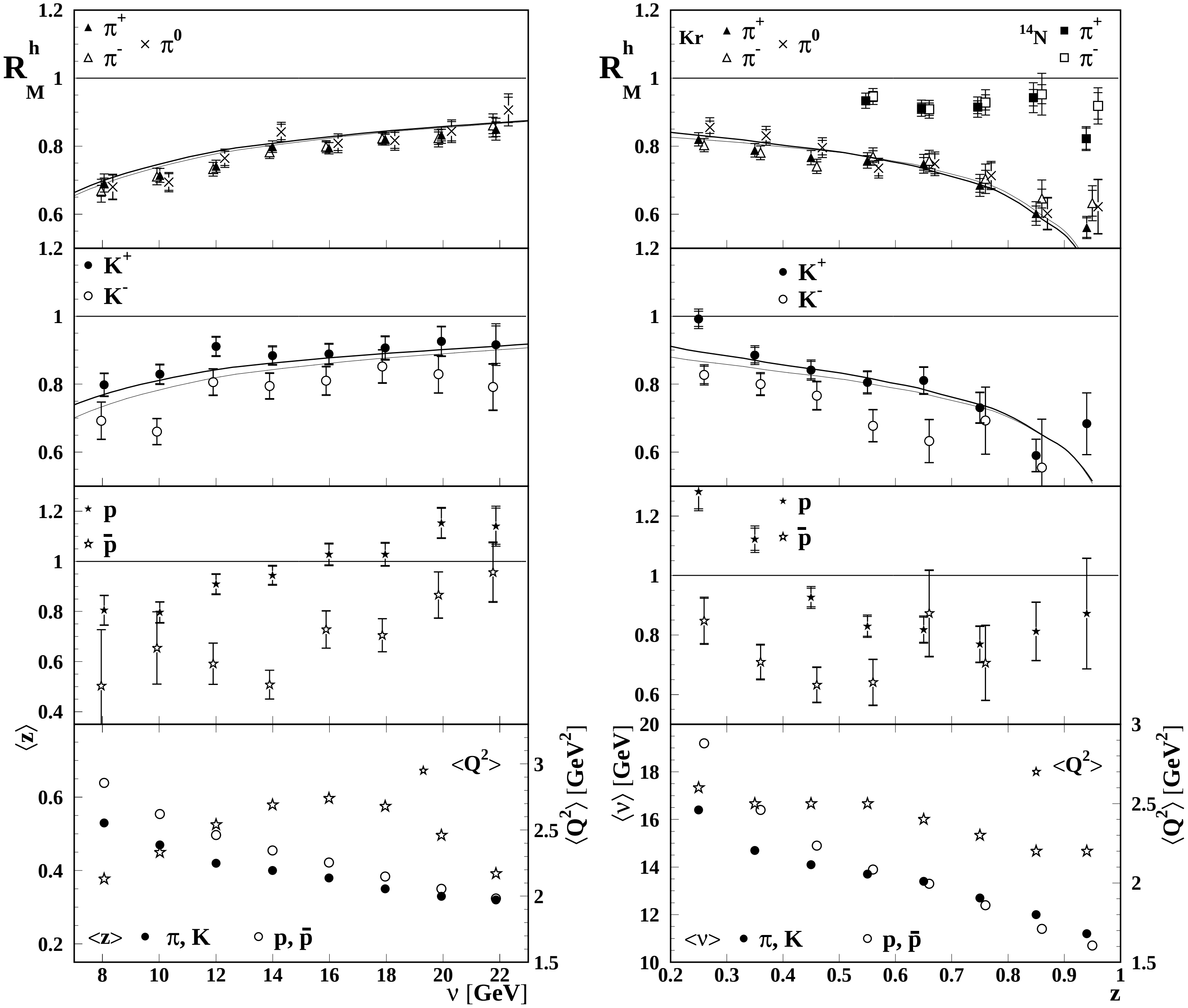




Model calculations : (solid, Accardi *et al.*) rescaling of quark fragmentation functions + nuclear absorption; (dot-dashed, Wang *et al.*) medium modification of parton fragmentation due to multiple scattering and gluon bremsstrahlung (tuned to ^{14}N data)

$\pi^{\pm,0}$, $K^{\pm}$, 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 $R_M^{p} > R_M^{\pi}$

$\Rightarrow$ Different formation times of baryons and mesons; different hadron-nucleon interaction cross sections

$\Rightarrow$ 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)

Double Hadron Attenuation

$\Rightarrow$ Disentangle nuclear absorption and induced energy loss

$$R_{2h}(z_2) = \frac{\left(\frac{dN(z_1,z_2)}{dN(z_1)}\right)_A}{\left(\frac{dN(z_1,z_2)}{dN(z_1)}\right)_D}$$

hadron absorption : $R_{2h} < 1$

$\updownarrow$

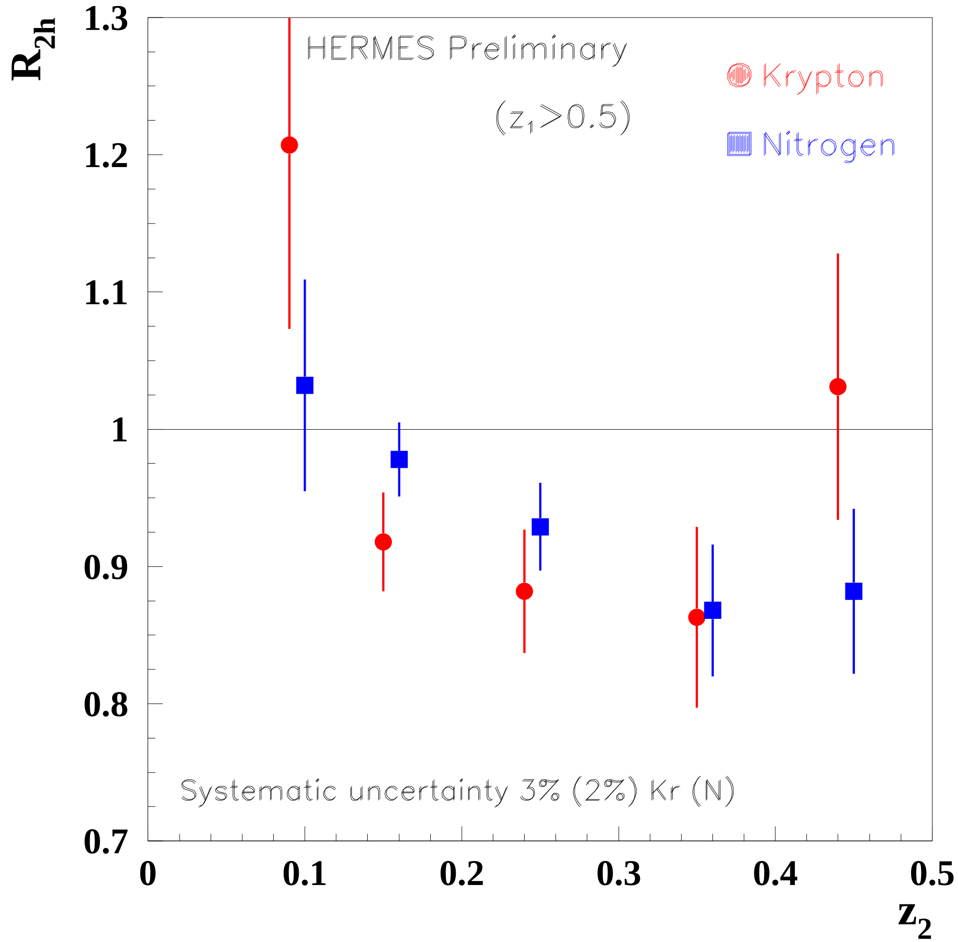
energy loss : $R_{2h} \approx 1$

Select leading - subleading hadron :

$++, --, +0, 0+, -0, 0-, 00$

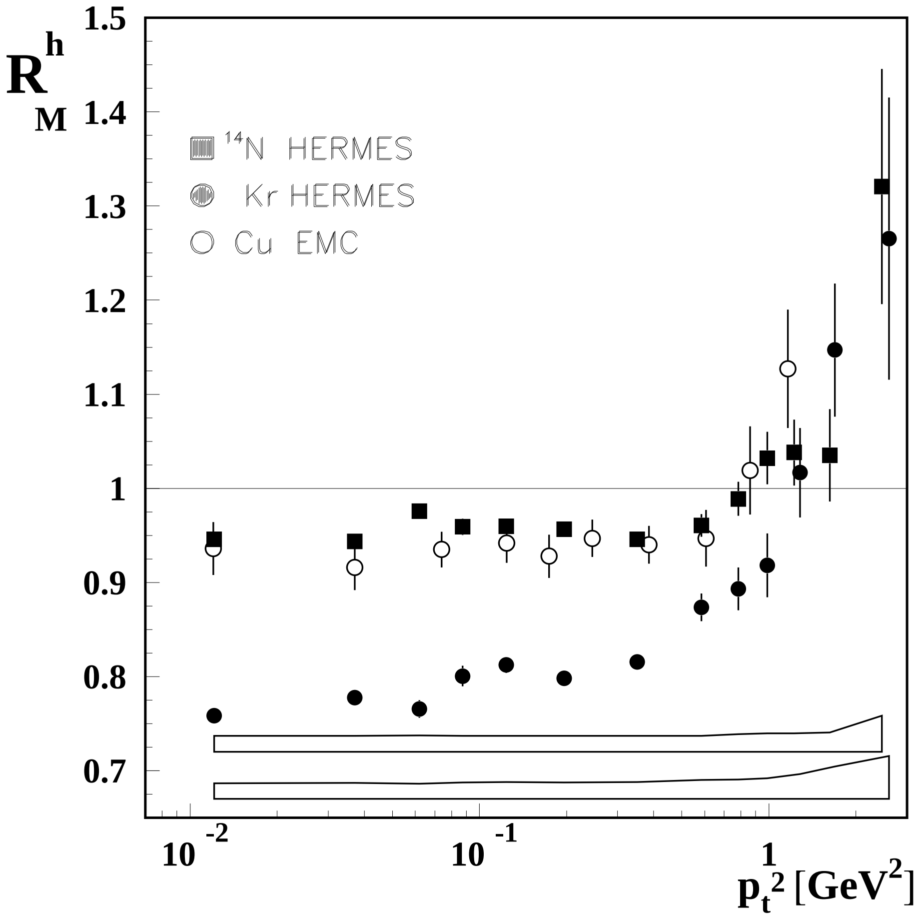
mainly rank-1 and rank-3 hadrons

in lund-string framework



Leading hadron $z_1 > 0.5$

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^-
- Measurement of angular asymmetry in hard exclusive $\pi^+\pi^-$ production shows interference of $I = 1$ and $I = 0$
- Observation of Θ^+ in pK_S^0; requiring additional π improves signal/background
- First measurement of nuclear attenuation of pions, kaons and (anti)protons electroproduction in ^{84}Kr; observation of Cronin effect in DIS