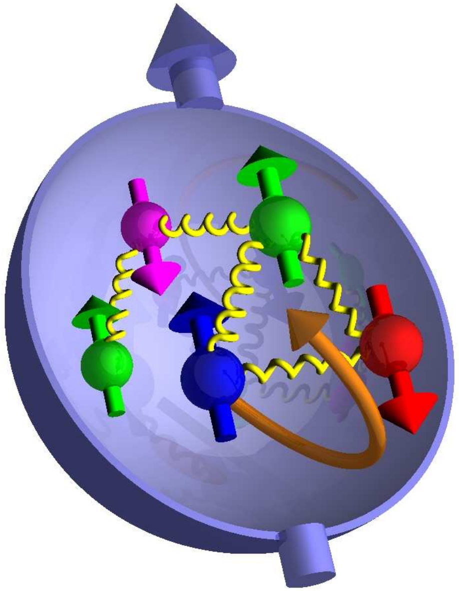
New Results from HERMES



- ⇒ Inclusive Deep-Inelastic Scattering
- ⇒ NLO QCD analysis
- ⇒ $b_1(x)$ Measurement
- ⇒ Δq-extraction
- ⇒ Double Spin Asymmetries in VM Production
- ⇒ Q^2-Dependence of ρ^0 Nuclear Transparency
- ⇒ Quark Fragmentation in Nuclei

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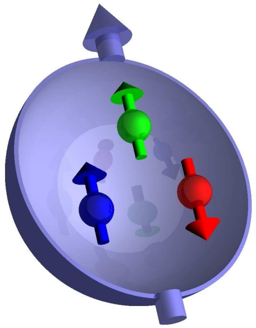
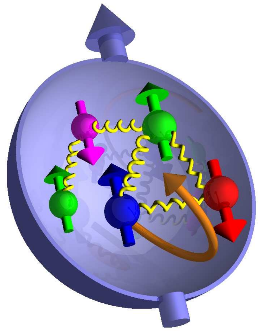
University of Gent

on behalf of the HERMES Collaboration

Spin Structure of the Nucleon



Naive Parton Model :
only valence quarks ($\Delta u_v + \Delta d_v = 1$)
EMC 1988 : $\Delta\Sigma = 0.123 \pm 0.013 \pm 0.019$



☞ Include also gluons,
sea quarks
& orbital angular momentum

$$S_z = \frac{1}{2}\hbar = \frac{1}{2}\Big(\underbrace{\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}}_{\Delta\Sigma}\Big) + \Delta g + L_z^q + L_z^g$$

$$\Delta q = \int_0^1 \mathrm{d}x \cdot \Delta q(x)$$: first moments of helicity densities

$\Delta\Sigma$	☜	inclusive scattering	Δq	☜	semi-inclusive scattering
Δg	☜	NLO QCD analysis, high-p_t hadrons	$L_{q,g}$	☜	GPD's ?

Polarized Deep Inelastic Scattering

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega\mathrm{d}E^2} = \frac{\alpha^2 E'}{Q^2 E} L_{\mu\nu}(k,q,s) W^{\mu\nu}(P,q,S)$$

$L_{\mu\nu}$: exactly calculable in QED

$$W^{\mu\nu} = -g^{\mu\nu} F_1(x,Q^2) + \frac{p^\mu p^\nu}{\nu} F_2(x,Q^2) + i\epsilon^{\mu\nu\lambda\sigma} \frac{q_\lambda}{\nu} \left(S_\sigma\, g_1(x,Q^2) + \frac{1}{\nu}\left(p\cdot q S_\sigma - S\cdot q p_\sigma\right) g_2(x,Q^2)\right)$$

Quark Parton Model :

F_1, F_2 : unpolarized structure functions $\Rightarrow$ momentum distribution of quarks

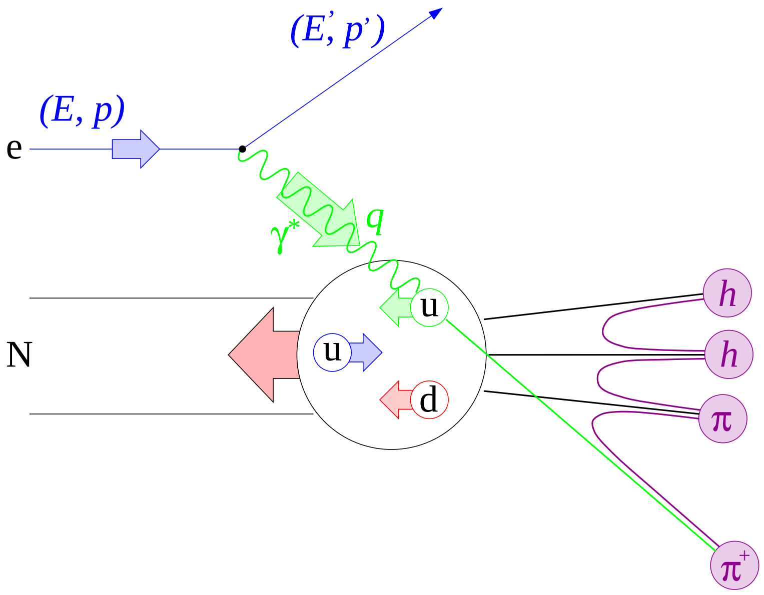
$$F_1(x) = \frac{1}{2}\sum_q e_q^2 \left[q^+(x) + q^-(x)\right] = \frac{1}{2}\sum_q e_q^2\, q(x)$$

$$F_2(x) = 2x\, F_1(x)$$

g_1, g_2 : polarized structure functions $\Rightarrow$ spin distribution of quarks

$$g_1(x) = \frac{1}{2}\sum_q e_q^2 \left[q^+(x) - q^-(x)\right] = \frac{1}{2}\sum_q e_q^2\, \Delta q(x)$$

Polarized Deep Inelastic Scattering



Measure double spin asymmetries :

$$A_{\parallel} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} = D\,(A_1 + \eta\, A_2)$$

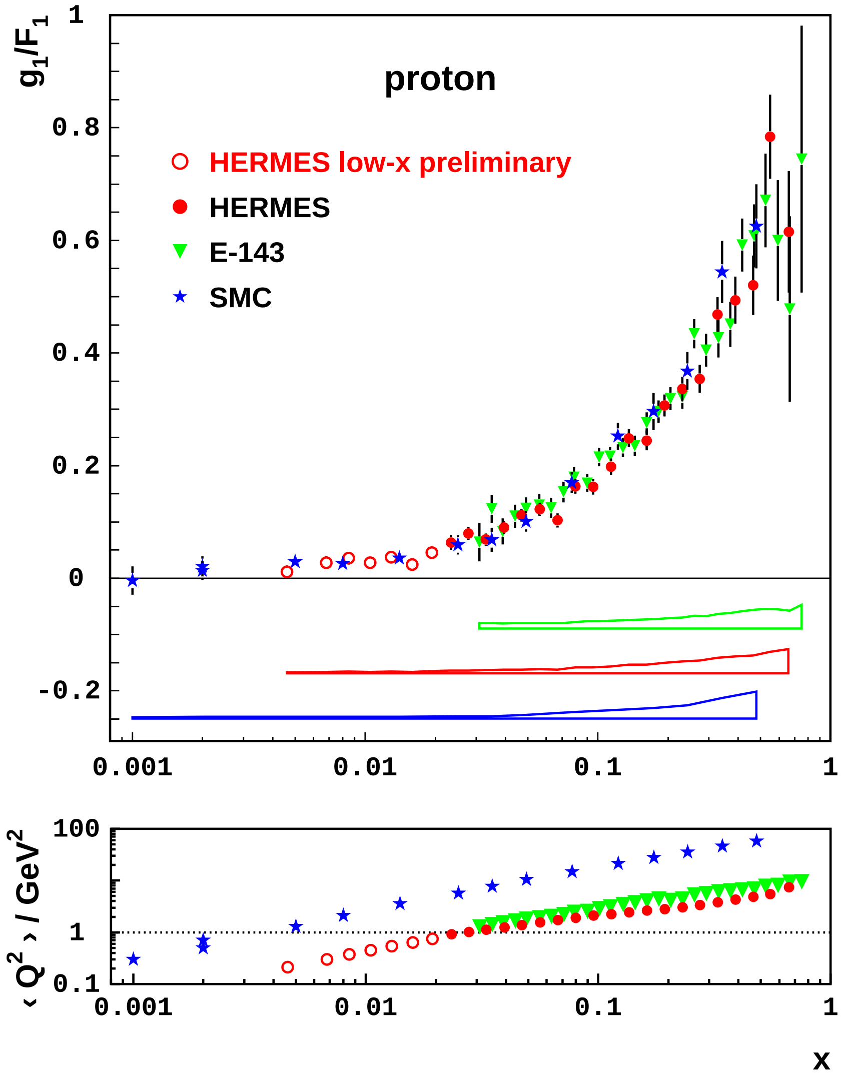
$$A_1 = \frac{\sigma^{1/2} - \sigma^{3/2}}{\sigma^{1/2} + \sigma^{3/2}} = \frac{g_1(x) - \gamma^2\, g_2(x)}{F_1(x)}, \qquad A_2 = \frac{\sigma_{TL}}{\sigma_T} = \frac{\gamma(g_1(x) + g_2(x))}{F_1(x)}$$

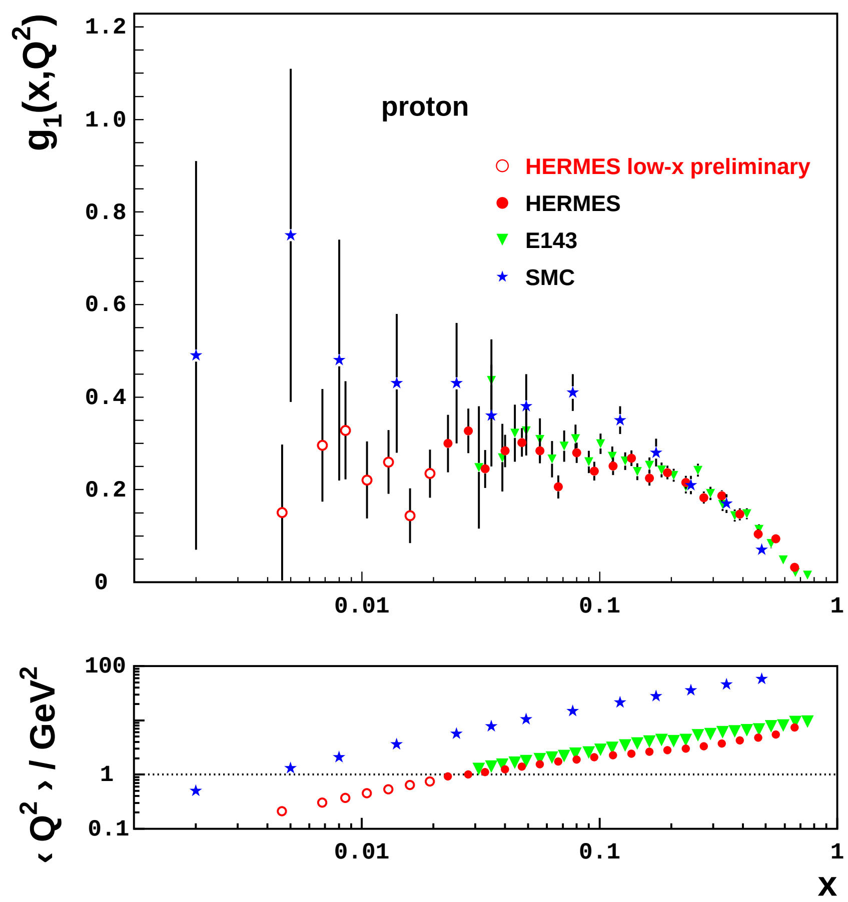
$$g_1(x) = \frac{F_1(x)}{1+\gamma^2}\left[\frac{A_{\parallel}(x)}{D} + (\gamma - \eta)A_2\right]$$

☞ $F_1 = \frac{(1+\gamma^2)}{2x(1+R)}\, F_2$

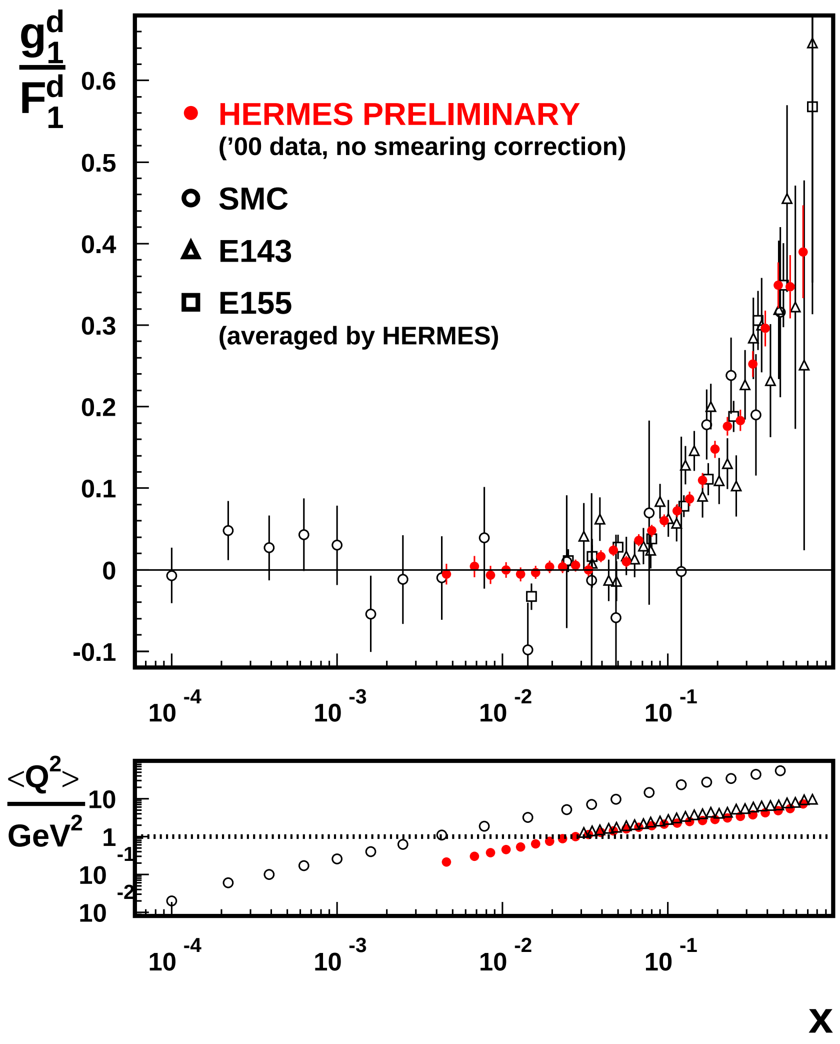
Use $A_2^n = 0$ or fit to A_2^p data or $A_2^d = A_2^{WW}$

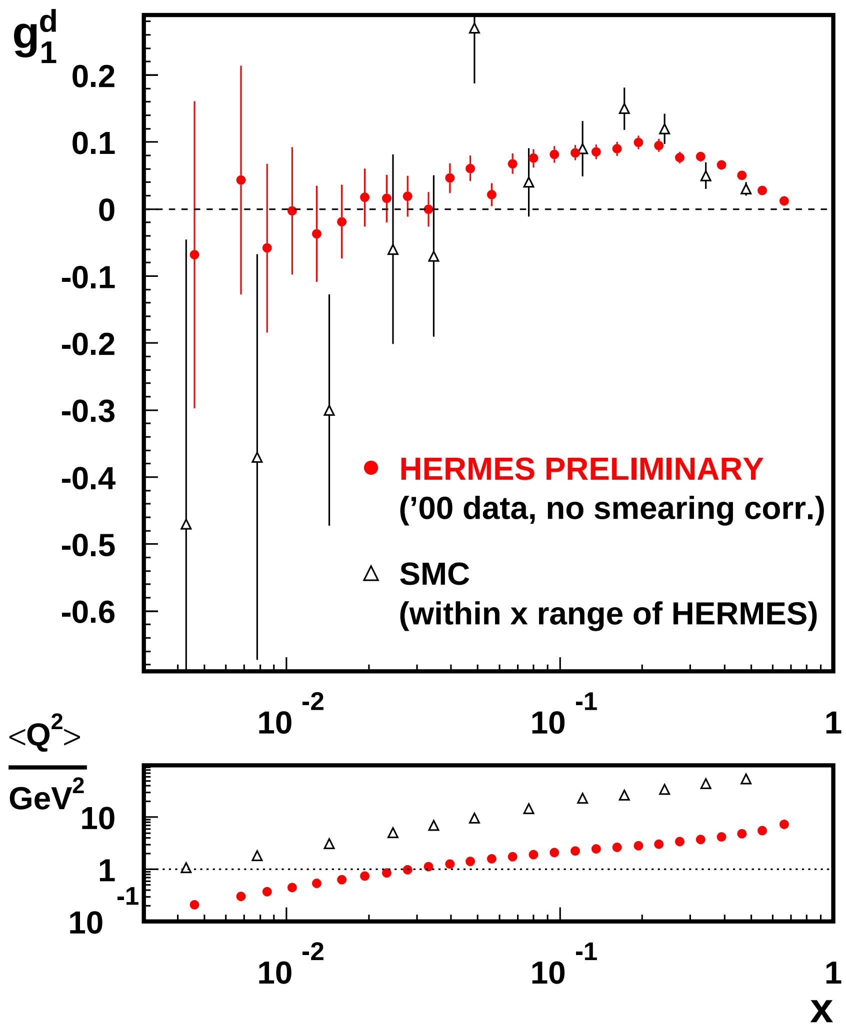
$g_1^p(x)$ from Hydrogen



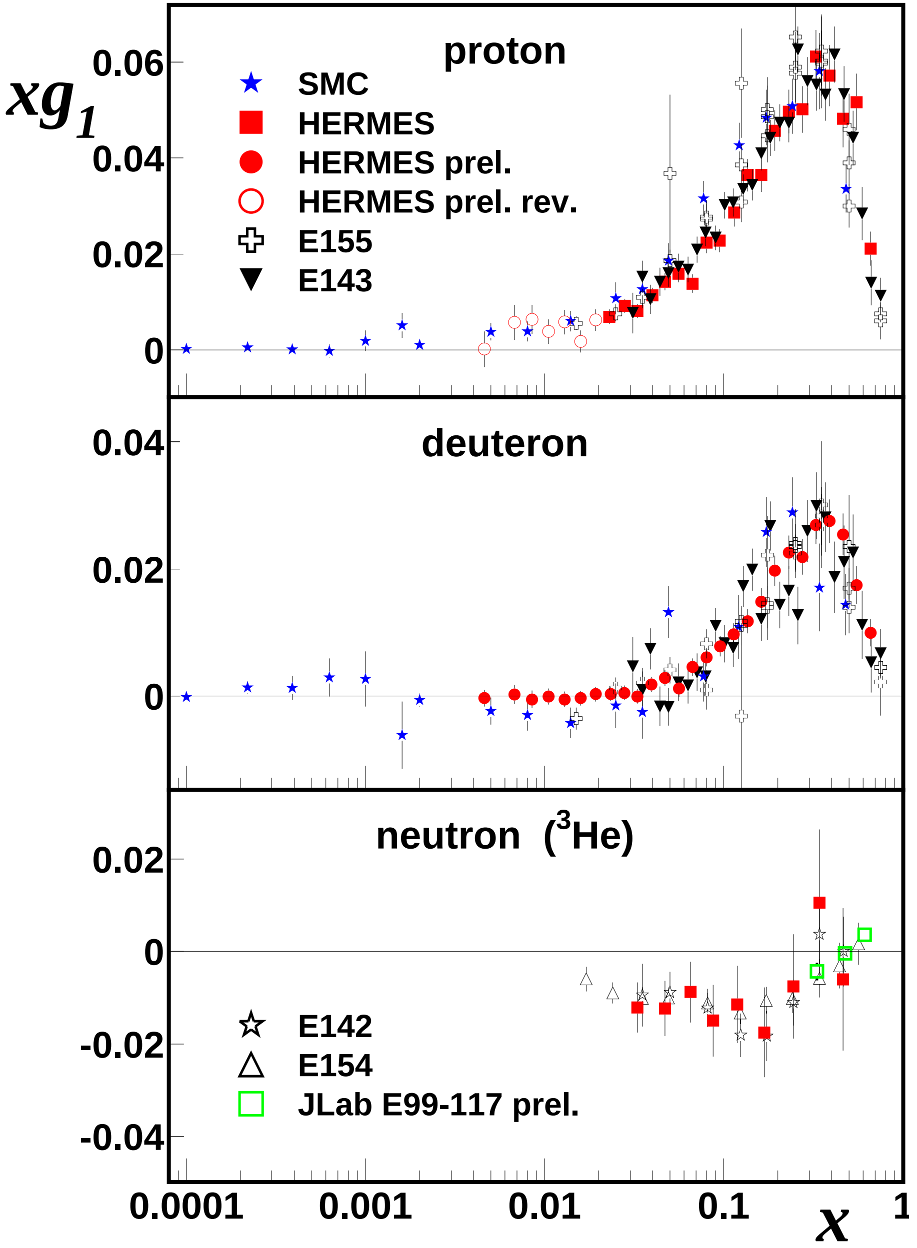


$g_1^d(x)$ from Deuterium





World Data on $xg_1(x)$



$$g_1^p > g_1^d > g_1^n$$

Neglecting sea quark contributions :

$$p : 2 \cdot \frac{4}{9}\Delta u_p + \frac{1}{9}\Delta d_p$$

$$d : p + n$$

$$n : 2 \cdot \frac{1}{9}\Delta d_n + \frac{4}{9}\Delta u_n$$

or $2 \cdot \frac{1}{9}\Delta u_p + \frac{4}{9}\Delta d_p$

$\Delta u_p > 0$ $\Delta d_p < 0$

NLO QCD Fit

- 0th order : $g_1^0(x) = \frac{1}{2}\sum_q e_q^2 \Delta q(x)$, no Q^2 dependence

- LO : gluon radiation, photon-gluon fusion

  ☞ Redefinition of quark distributions including Δg

  $g_1^{LO}(x, Q^2) = \frac{1}{2}\sum_q e_q^2 \Delta q(x, Q^2)$

- NLO :

  $g_1^{NLO}(x, Q^2) = \frac{1}{2}\sum_q e_q^2 \left[\Delta q + \Delta q(x, Q^2) \otimes C_q + \Delta g(x, Q^2) \otimes C_g\right]$

  2 independent NS distributions + $\Delta\Sigma$ + Δg :

$$\Delta q_{NS}^p = \frac{1}{2}(2\Delta u - \Delta d - \Delta s), \qquad \Delta q_{NS}^n = \frac{1}{2}(2\Delta d - \Delta u - \Delta s)$$

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

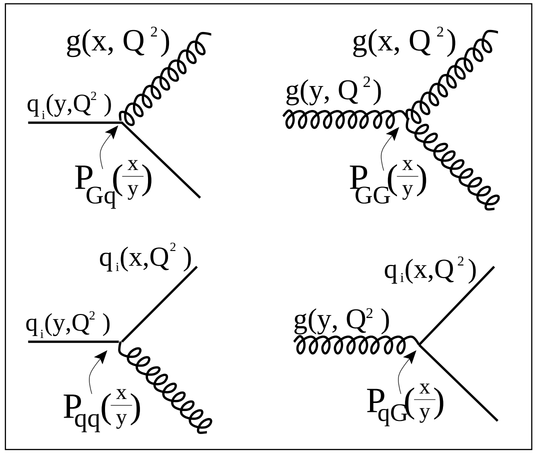
NLO QCD Fit

Q^2 evolution :

$$\frac{\mathrm{d}}{\mathrm{d}\ln Q^2}\Delta q^{NS}(x,Q^2) = \frac{\alpha_s(Q^2)}{2\pi} P_{qq} \otimes \Delta q^{NS}$$

$$\frac{\mathrm{d}}{\mathrm{d}\ln Q^2}\begin{pmatrix} \Delta\Sigma(x,Q^2) \\ \Delta g(x,Q^2) \end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi}\begin{pmatrix} P_{qq} & 2\,N_f\,P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} \Delta\Sigma \\ \Delta g \end{pmatrix}$$

Splitting Functions



Parametrization of parton distributions at input scale Q_0^2 :

$$x\Delta q_i(x,Q_0^2) = \eta_i A_i x^{a_i}(1-x)^{b_i}\left(1+\gamma_i x+\rho_i x^{1/2}\right)$$

NLO QCD Fit

- ☞ Use g_1/F_1 or A_1 data on p, d and n

  from EMC, E142, HERMES, E154,

  SMC, E143, E155

  with $Q^2 > 1.0$ GeV^2 cut

- ☞ 2 independent methods :

Mellin Transform & Finite Differences

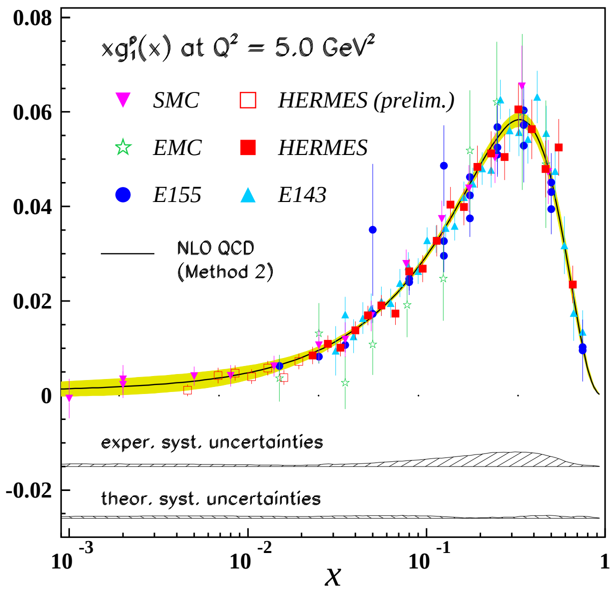
Choice of Parameters

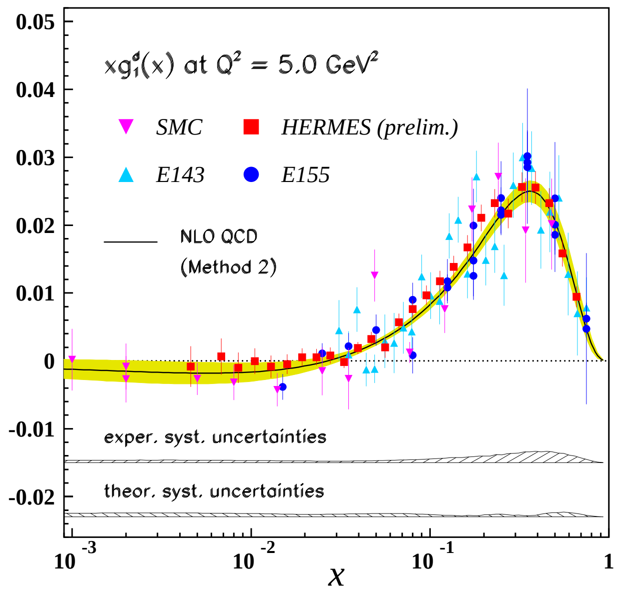
$$x\Delta q_i(x, Q_0^2) = \eta_i A_i x^{a_i}(1-x)^{b_i}(1+\gamma_i x+\rho_i x^{\frac{1}{2}})$$

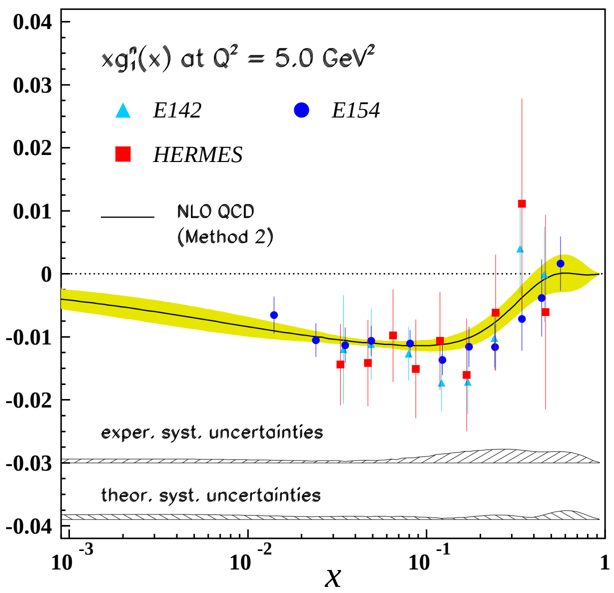
Method 1	Method 2
$\overline{MS}$	$\overline{MS}$
Mellin Transform	Finite differences
Δu_v, Δd_v, $\Delta\bar{q}_s$, ΔG	Δq^p_{NS}, Δq^n_{NS}, $\Delta\Sigma$, ΔG
symmetric sea: $\Delta\bar{q}_s = \Delta\bar{u}_s = \Delta\bar{d}_s = \Delta s = \Delta\bar{s}$	no assumption (in the fit)
η_{u_v}, η_{d_v} fixed by F,D γ_{u_v}, $\gamma_{d_v} \neq 0$ fixed $\left.\begin{array}{l} a_G = a_{sea}+1 \\ \left.\frac{b_{\bar{q}_s}}{b_G}\right\vert_{pol} = \left.\frac{b_{\bar{q}_s}}{b_G}\right\vert_{unpol} \end{array}\right\\}$ * $b_{\bar{q}_s} = 8.08$, $b_G = 5.61$ $\gamma_{\bar{q}_s} = 0$, $\gamma_G = 0$ $\rho = 0$ for all densities $\rightarrow$ 7 fit parameters	$\eta_{q_p^{NS}}$, $\eta_{q_n^{NS}}$ fixed by F,D $\gamma_{q_p^{NS}} = \gamma_{q_n^{NS}} \neq 0$ fixed { no such relations $b_G = 5.61$ $\gamma_\Sigma \neq 0$ fixed, $\gamma_G = 0$ $\rho = 0$ for all densities $\rightarrow$ 7 fit parameters
$\Lambda^{(4)}_{QCD} = 291 \pm 30\ MeV$ $Q_0^2 = 4\ GeV^2$ data: $Q^2 > 1\ GeV^2$	$\alpha_s(M_Z^2) = 0.117 \pm 0.002$ $Q_0^2 = 4\ GeV^2$ data: $Q^2 > 1\ GeV^2$

* lead to positivity for $\Delta\bar{q}_s$ and ΔG

NLO QCD Fit



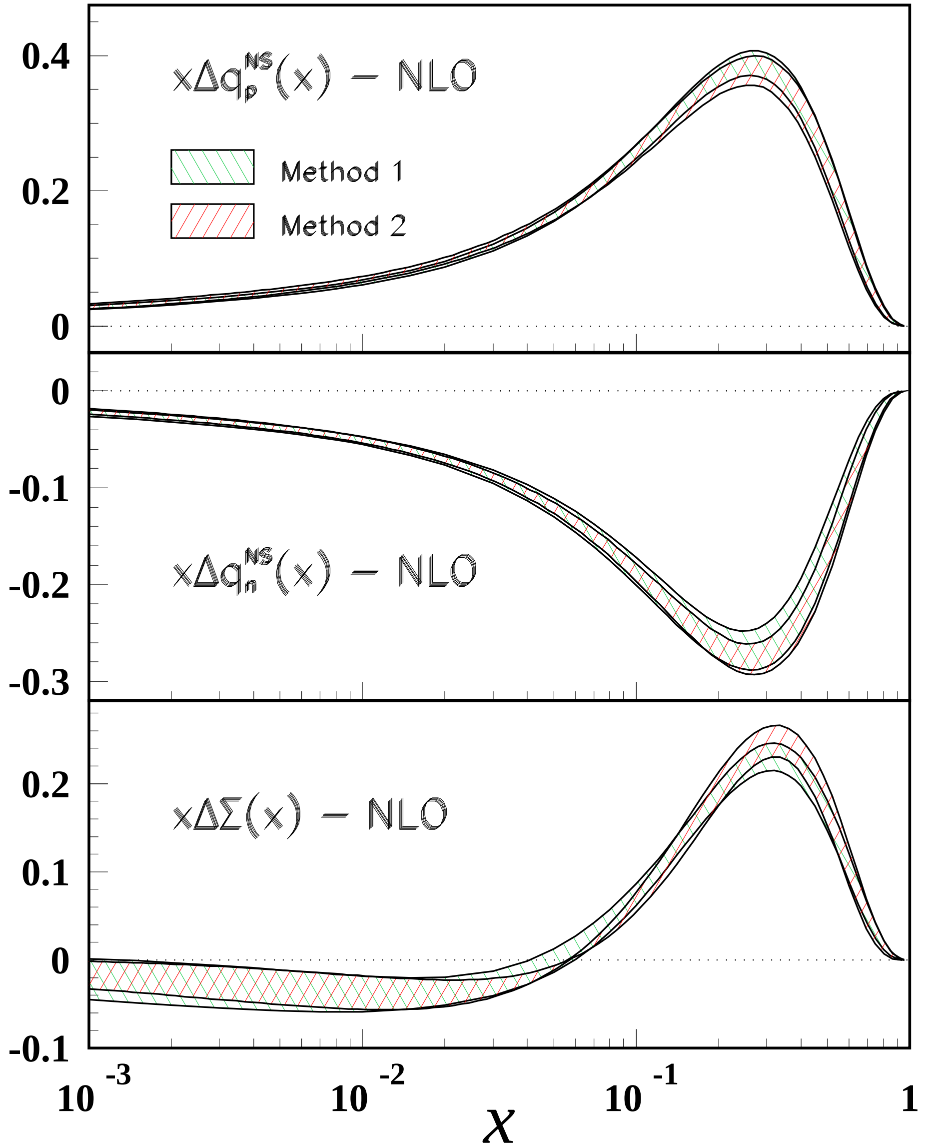




☞ Fits are performed on $g_1(x, Q^2)$

and give a good final description

NLO QCD Fit



$Q_0^2 = 4.0$ GeV^2

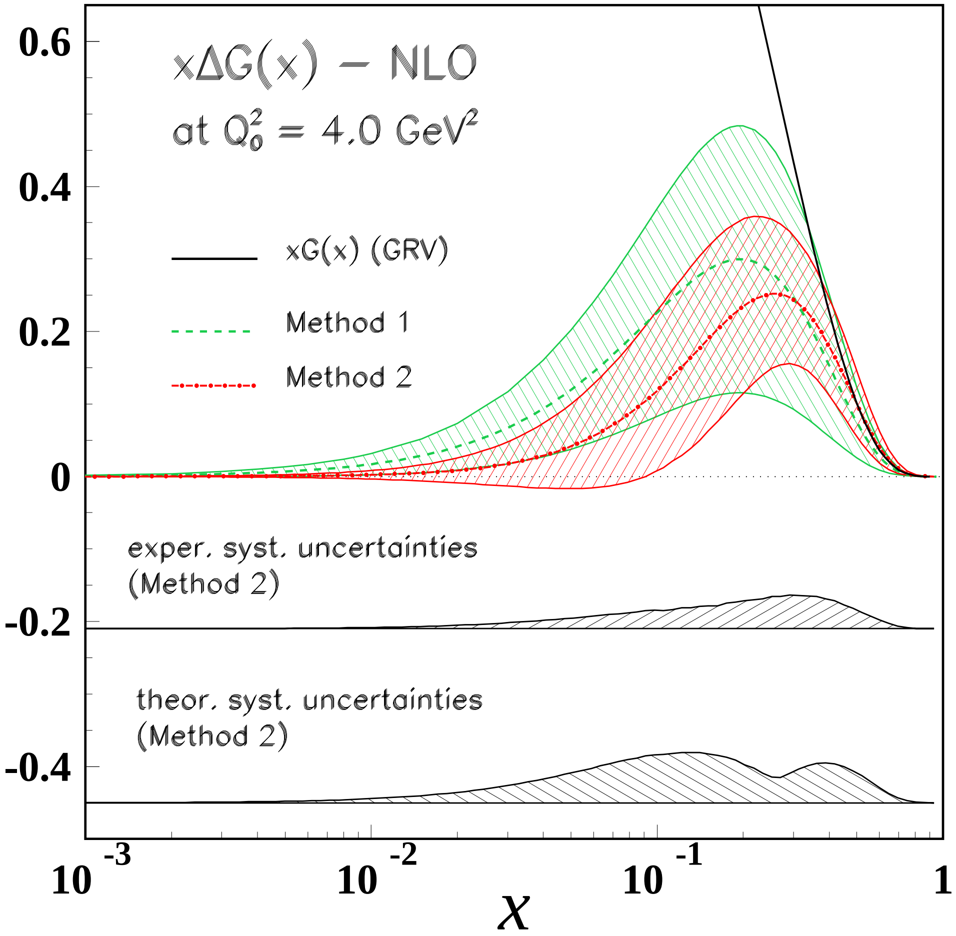
☞ $\Delta\Sigma = 0.201 \pm 0.103$

☞ valence quarks dominate

☞ $\Delta\bar{q}_s = -0.070 \pm 0.028$

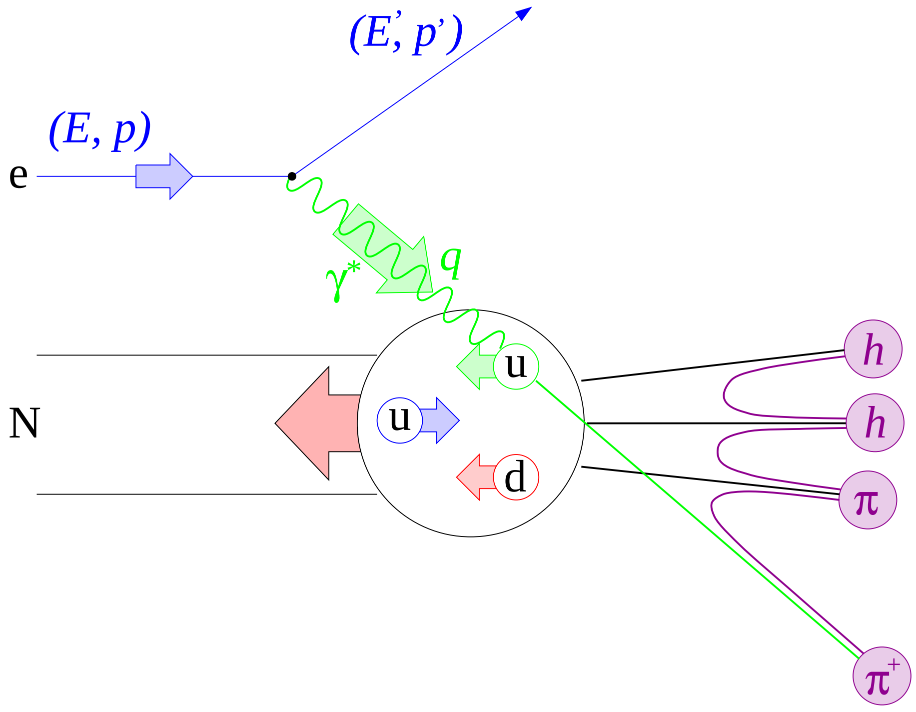
very small sea quark polarization

NLO QCD Fit



☞ ΔG still largely unconstrained ...

Semi-Inclusive Deep Inelastic Scattering



$$\vec{e} + \vec{N} \longrightarrow e + h + X$$

☞ Flavor tagging : correlation between fast hadron and struck quark flavor

Factorization of cross section :

$$\sigma^h(x, Q^2, z) \propto \sum_q e_q^2 \, q(x, Q^2) \, D_q^h(z, Q^2)$$

$D_q^h(z, Q^2)$: fragmentation functions, $h = \pi^{\pm,0}, K^{\pm} \ldots$

Δq-Extraction

$$A_1^h(x,Q^2) = \frac{\sigma_h^{1/2} - \sigma_h^{3/2}}{\sigma_h^{1/2} + \sigma_h^{3/2}} \simeq C \cdot \sum_q \underbrace{\frac{e_q^2 q(x,Q^2) \int \mathrm{d}z D_q^h(z,Q^2)}{\sum_{q'} e_{q'}^2 q'(x,Q^2) \int \mathrm{d}z D_{q'}^h(z,Q^2)}}_{P_q^h(x,Q^2)} \frac{\Delta q}{q}(x,Q^2)$$

☞ Purities : probability that hadron h originates from event with struck quark q

- Spin independent quantities
- Can be calculated with Monte Carlo

☞ Extract Δq from

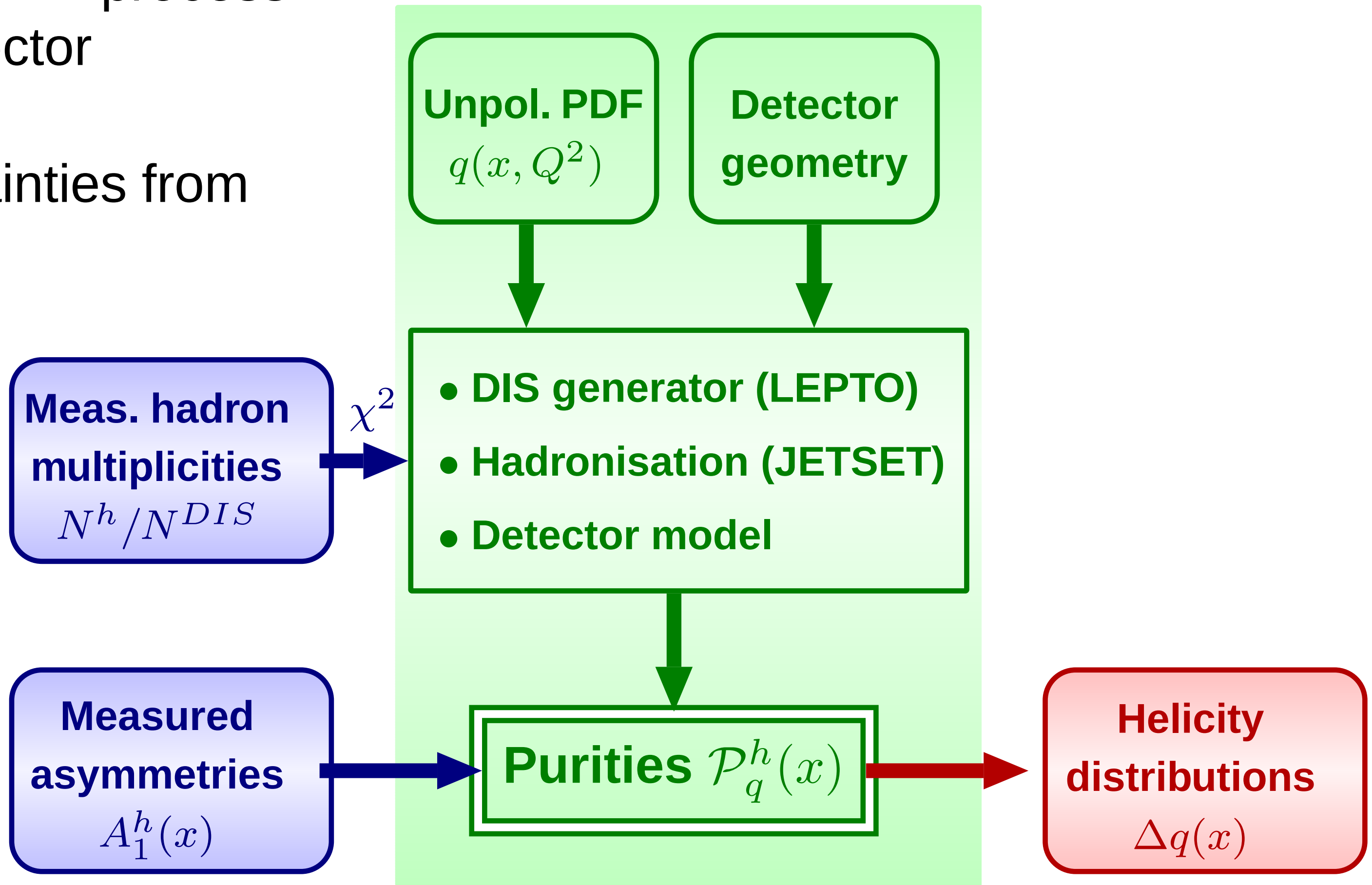
$$\vec{A} = P \cdot \vec{Q}$$

$$\vec{A} = \left(A_{1,p}(x), A_{1,d}(x), A_{1,p}^{\pi^\pm}(x), A_{1,d}^{\pi^\pm}(x), A_{1,d}^{K^\pm}(x) \right)$$

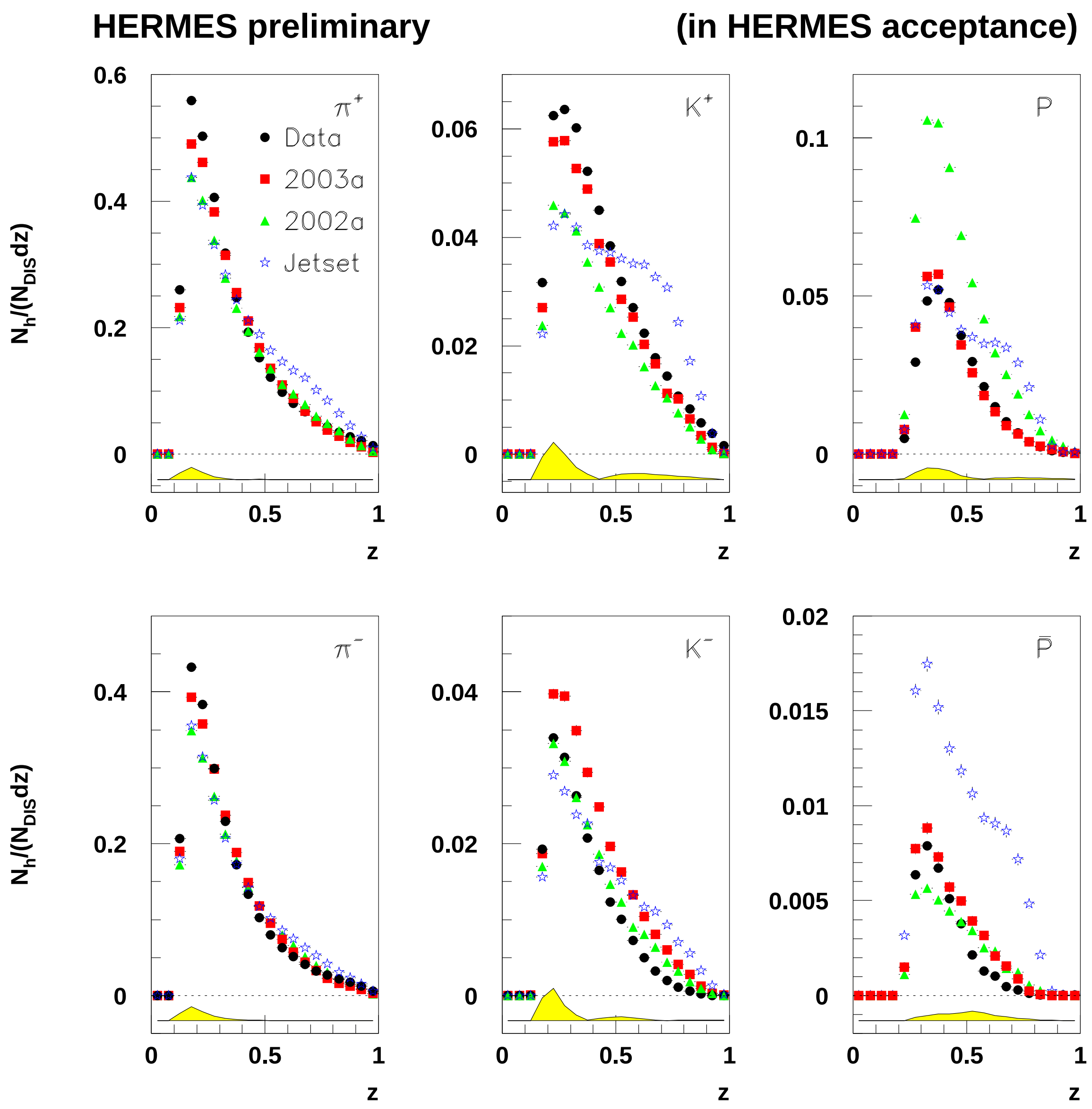
$$\vec{Q} = \left(\frac{\Delta u}{u}, \frac{\Delta d}{d}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta \bar{d}}{\bar{d}}, \frac{\Delta s + \Delta \bar{s}}{s + \bar{s}} \right)$$

Generation of Purities

- Use Monte Carlo model of DIS process (LEPTO), fragmentation process (JETSET) and detector
- Systematic uncertainties from
  . Use of alternative PDF sets (GRV98LO, CTEQ5L)
  . Variation of fragmentation parameters



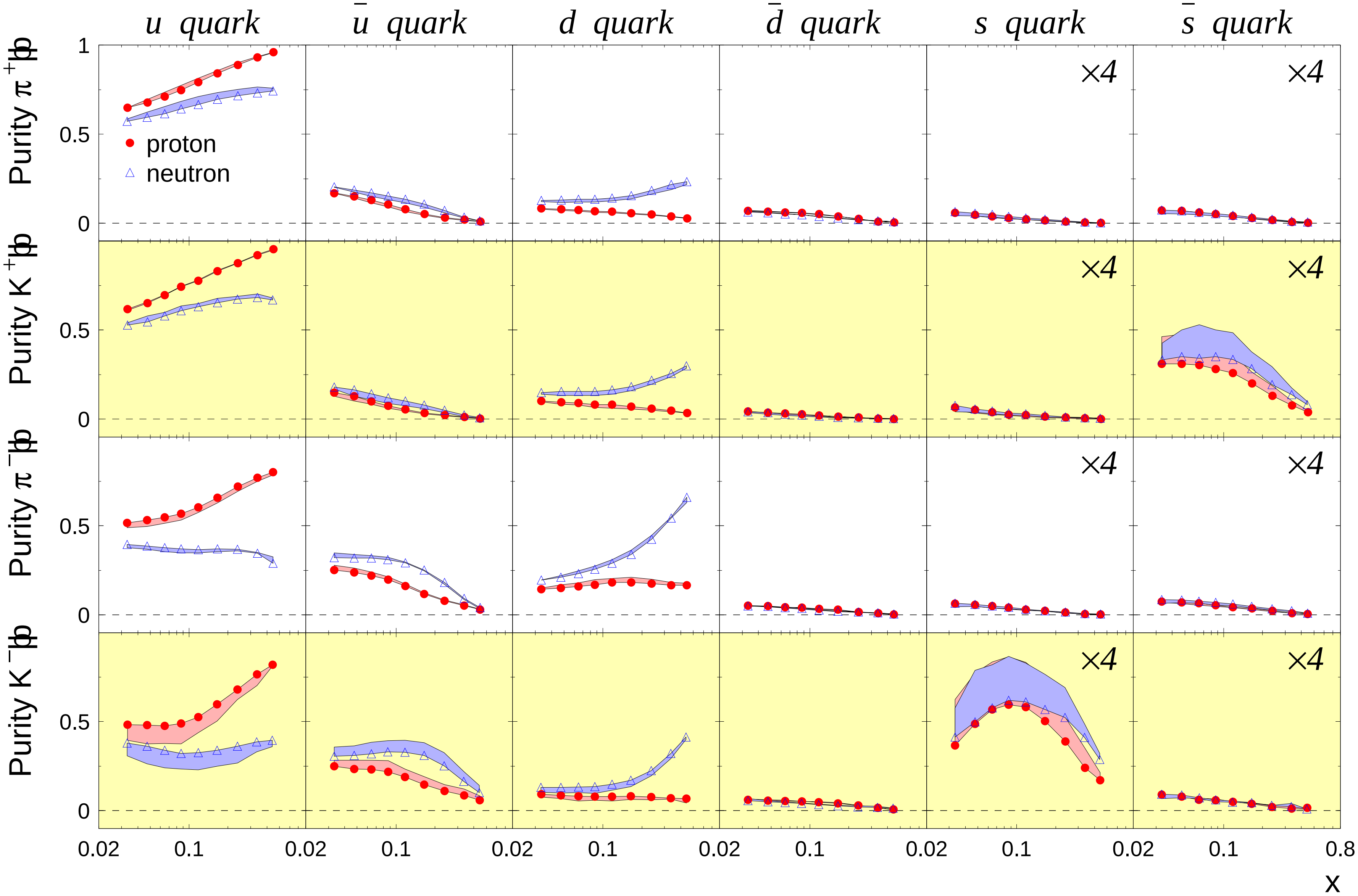
Tuning of LUND Fragmentation Model



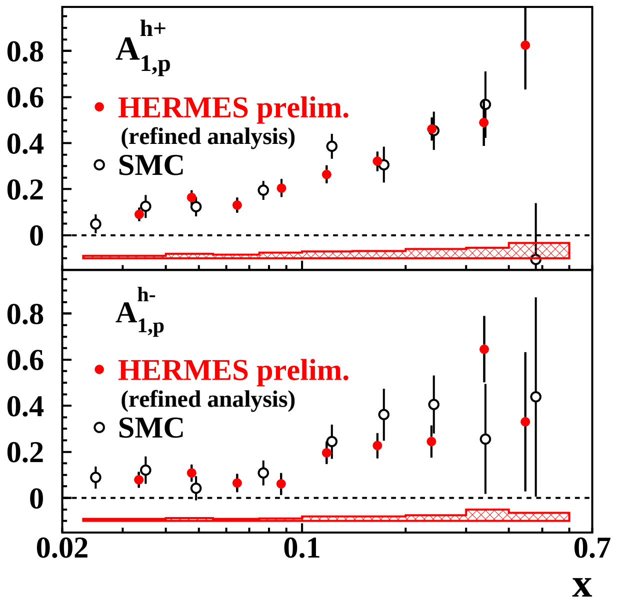
Default JETSET settings don't work for HERMES

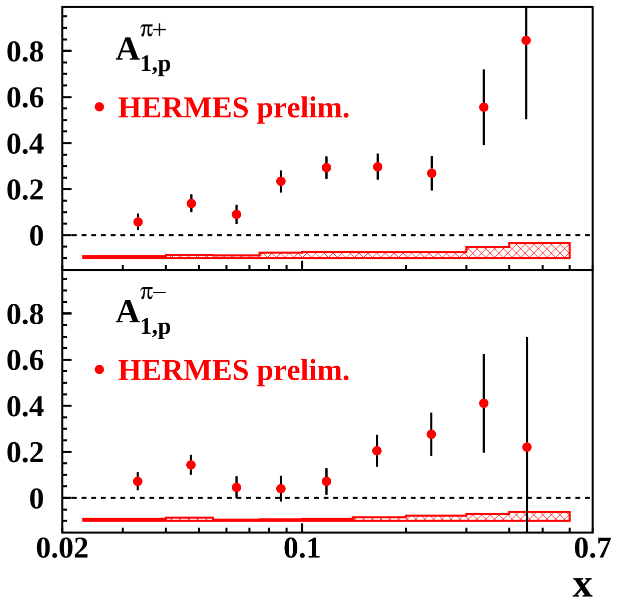
☞ Use hadron production ratios and measured hadron multiplicities N^h/N^{DIS} in (iterative) tuning procedure

HERMES Purities



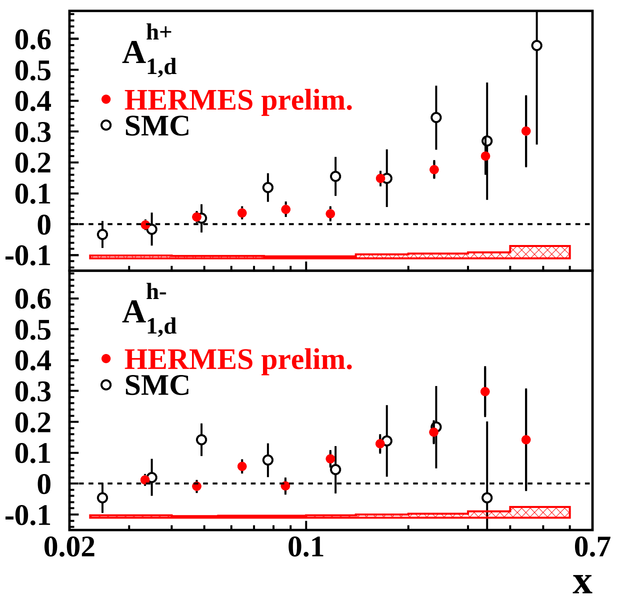
Measured Hadron Asymmetries

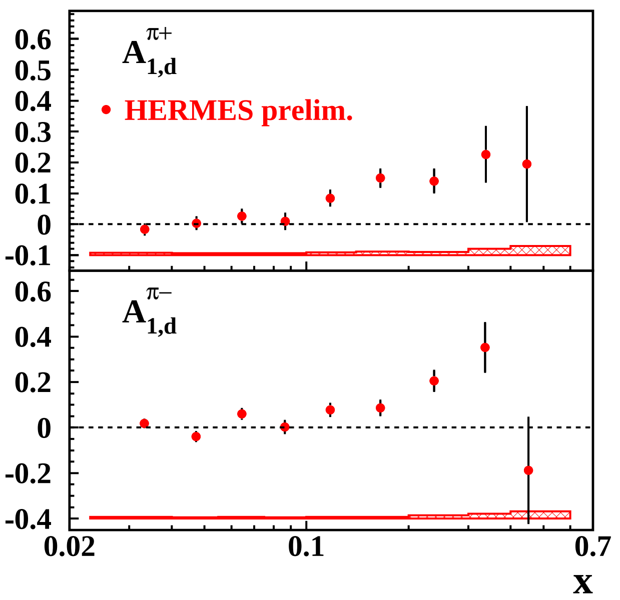


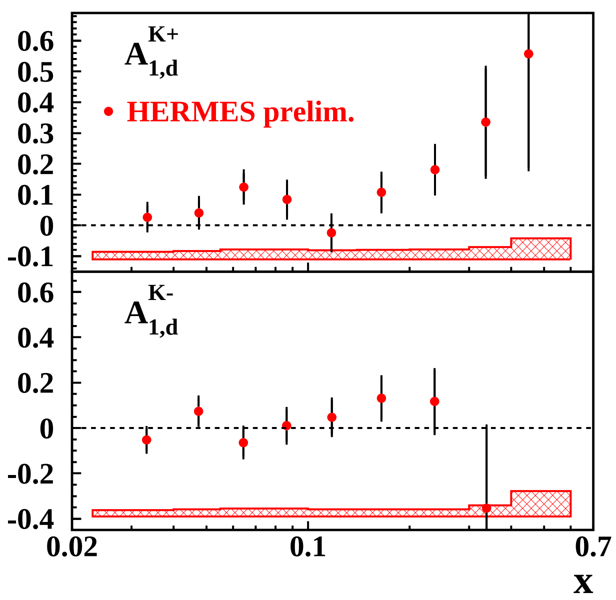


Kinematical range :

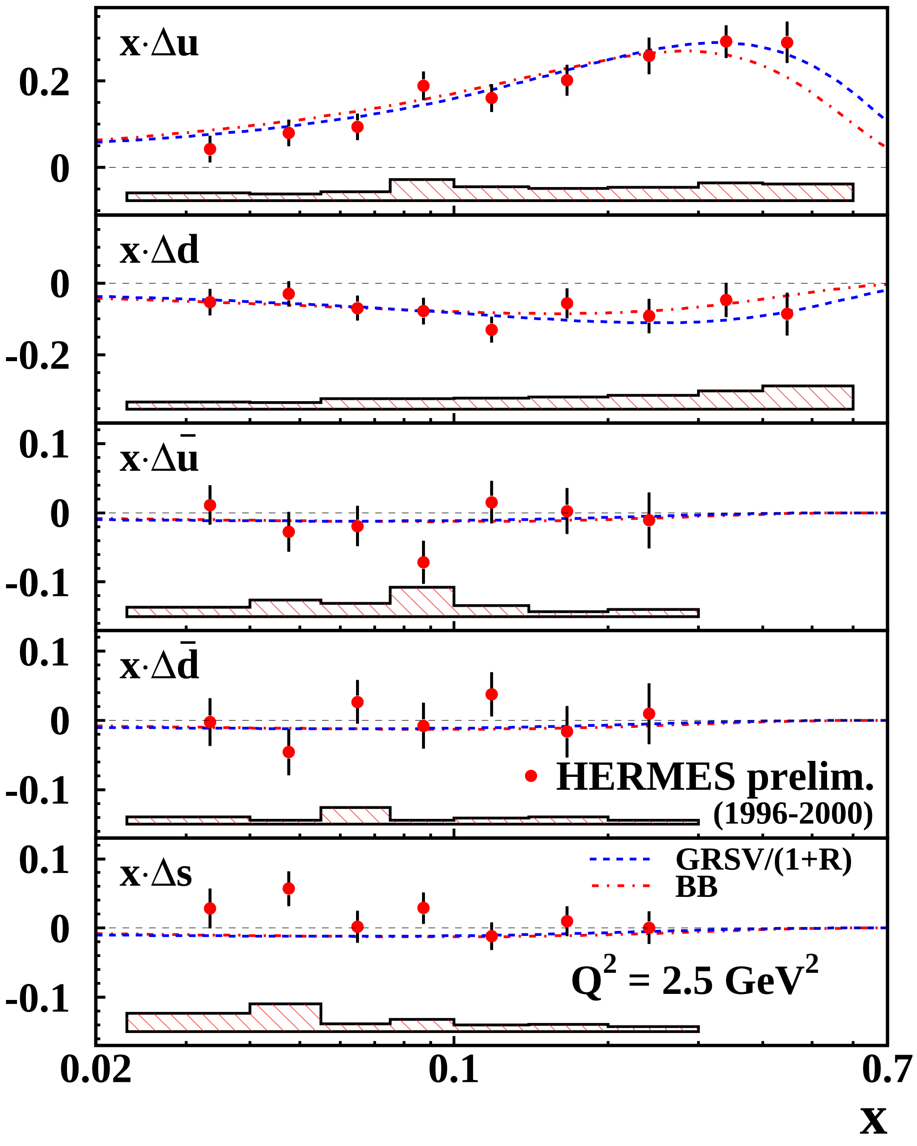
$$0.023 \leq x \leq 0.6$$
$$0.2 \leq z \leq 0.8$$







Polarized Quark Distributions



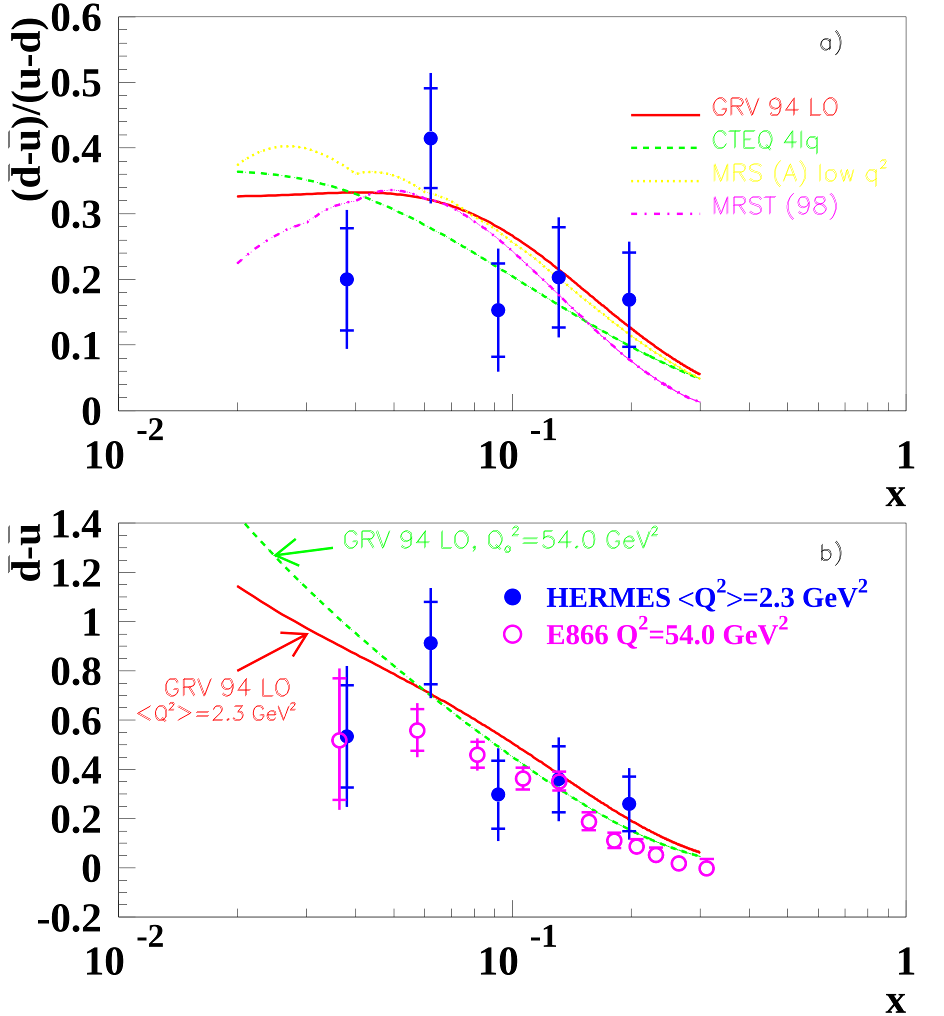
- u-quark strongly polarized
- d-quark strongly anti-polarized
- Quark sea polarization small and

$$\frac{\Delta\bar{u}}{\bar{u}} \sim \frac{\Delta\bar{d}}{\bar{d}} \sim \frac{\Delta s + \Delta\bar{s}}{s + \bar{s}} \sim 0$$

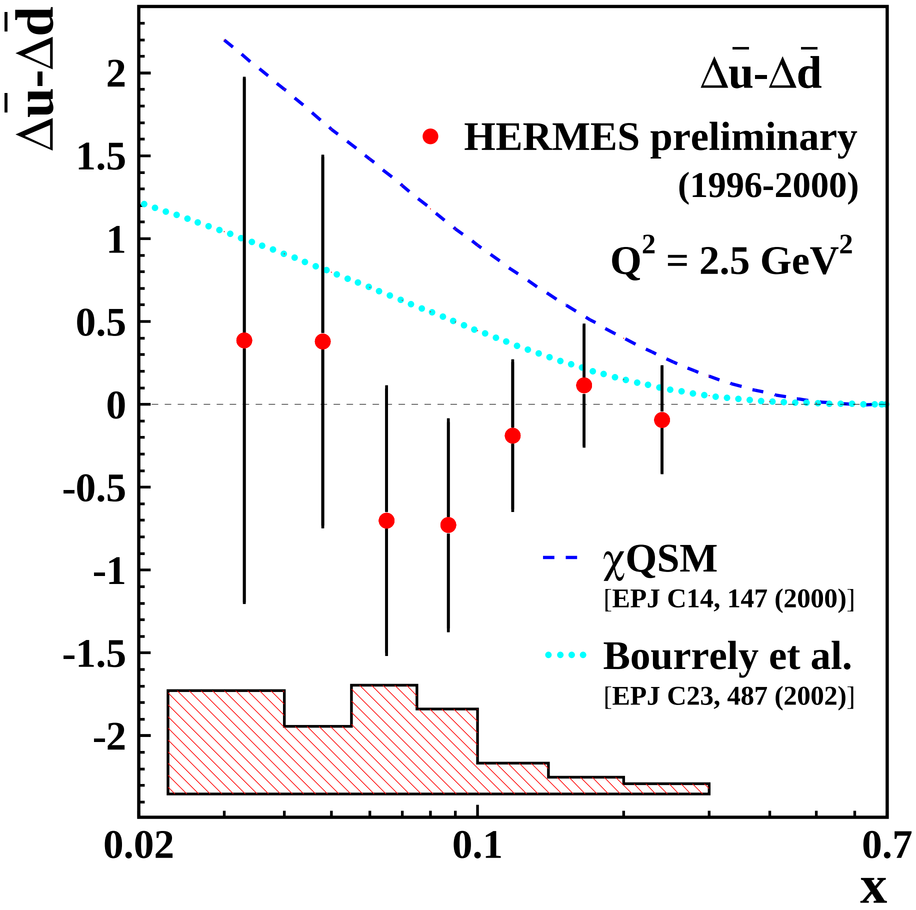
- No indication of negative strange sea polarization
- Good agreement with LO-QCD fits

Light Quark Sea Flavor Asymmetry

Unpolarized



Polarized



☞ No evidence of flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$ in the light quark sea !

Deep Inelastic Scattering on Spin 1 Target

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega \mathrm{d}E^2} = \frac{\alpha^2 E'}{Q^2 E} L_{\mu\nu}(k,q,s) W^{\mu\nu}(P,q,S)$$

$L_{\mu\nu}$: exactly calculable in QED

$W^{\mu\nu}$ = $-g^{\mu\nu} F_1(x,Q^2) + \frac{p^\mu p^\nu}{\nu} F_2(x,Q^2)$

$+i\epsilon^{\mu\nu\lambda\sigma} \frac{q_\lambda}{\nu} \left(S_\sigma\, g_1(x,Q^2) + \frac{1}{\nu}\left(p\cdot q S_\sigma - S\cdot q p_\sigma\right) g_2(x,Q^2)\right)$

(for spin 1 target) $-b_1(x,Q^2)\, r_{\mu\nu} + \frac{1}{6} b_2(x,Q^2)\, (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu})$

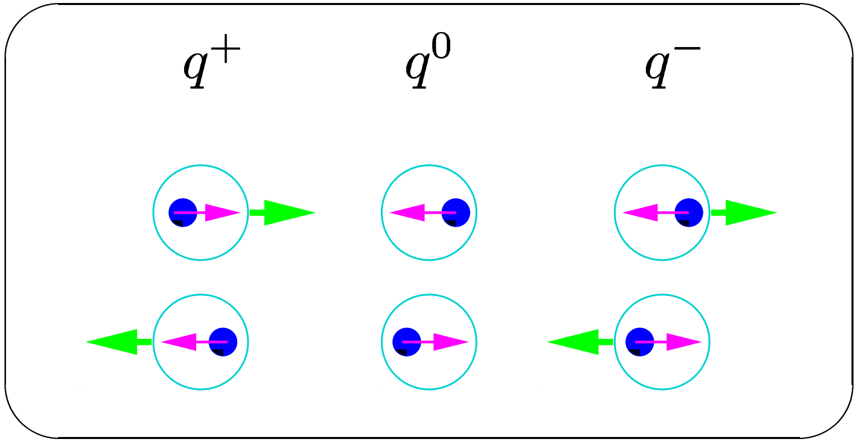
$+\frac{1}{2} b_3(x,Q^2)\, (s_{\mu\nu} - u_{\mu\nu}) + \frac{1}{2} b_4(x,Q^2)\, (s_{\mu\nu} - t_{\mu\nu})$

☞ 4 new structure functions

in the symmetric part of hadronic tensor

$\Rightarrow$ not sensitive to beam polarization

b_1 Structure Function



$$F_1(x) = \frac{1}{3}\sum_q e_q^2\,[q^+(x) + q^-(x) + q^0(x)]$$

$$g_1(x) = \frac{1}{2}\sum_q e_q^2\,[q^+(x) - q^-(x)]$$

$$b_1(x) = \frac{1}{2}\sum_q e_q^2\,[2q^0(x) - (q^-(x) + q^+(x))]$$

$$b_2(x) = 2x\frac{(1+R)}{(1+\gamma^2)}b_1(x)$$

b_3 & b_4 higher twist functions

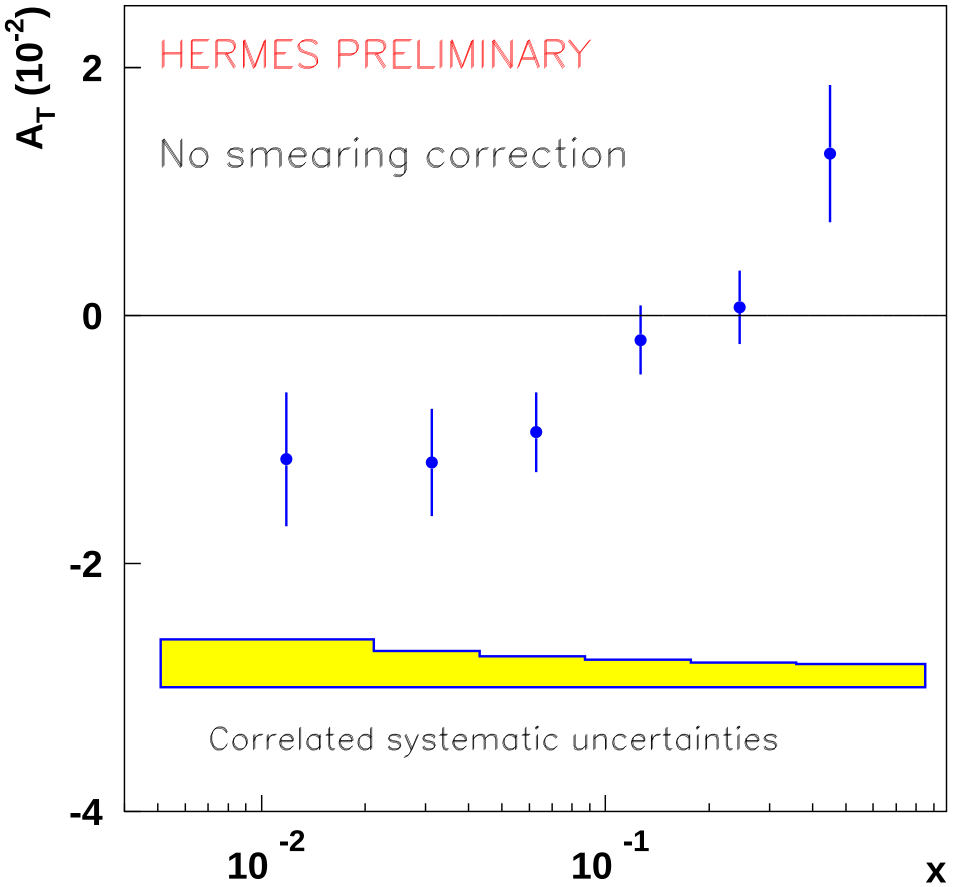
☞ $b_1(x)$ measures difference in parton distributions of $m = 1$ and $m = 0$ target

☞ In principle needed for g_1/F_1 measurement

$$\sigma_{meas} = \sigma_u\left[1 + P_b\,V\,A_{||} + \frac{1}{2}\,T\,A_T\right]$$

HERMES : $< T >= 0.83 \pm 0.03$ $< V >= 10^{-2}$

The Tensor Asymmetry A_T



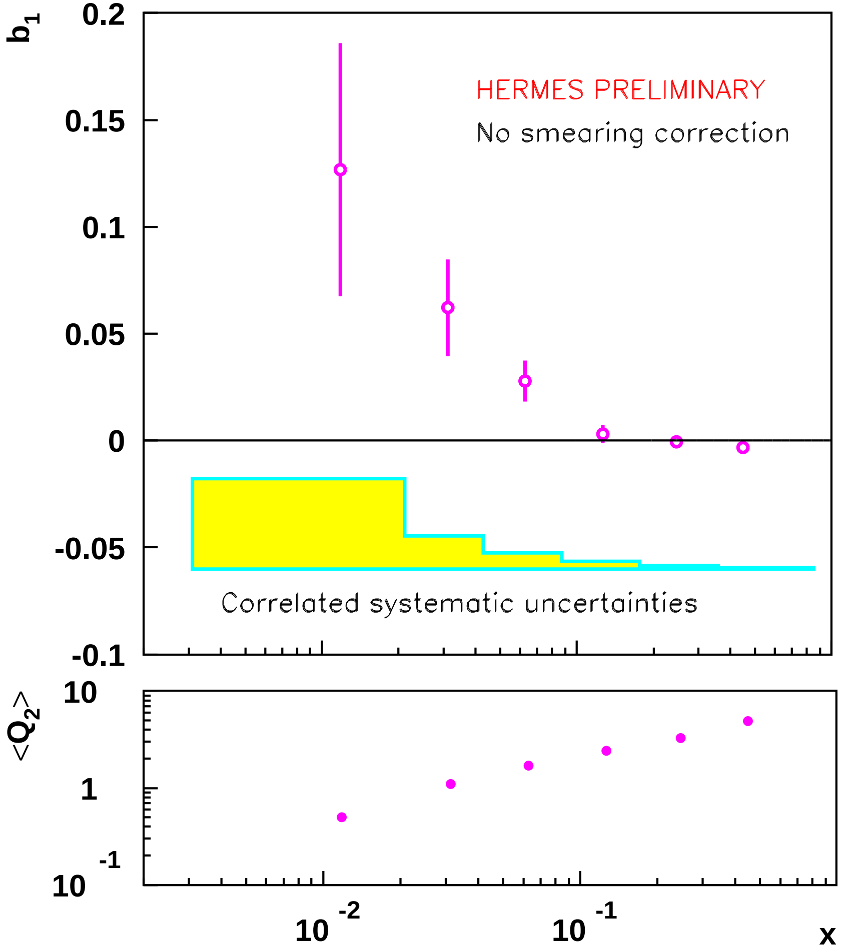
$0.002 < x < 0.85, \quad Q^2 > 0.1$ GeV^2

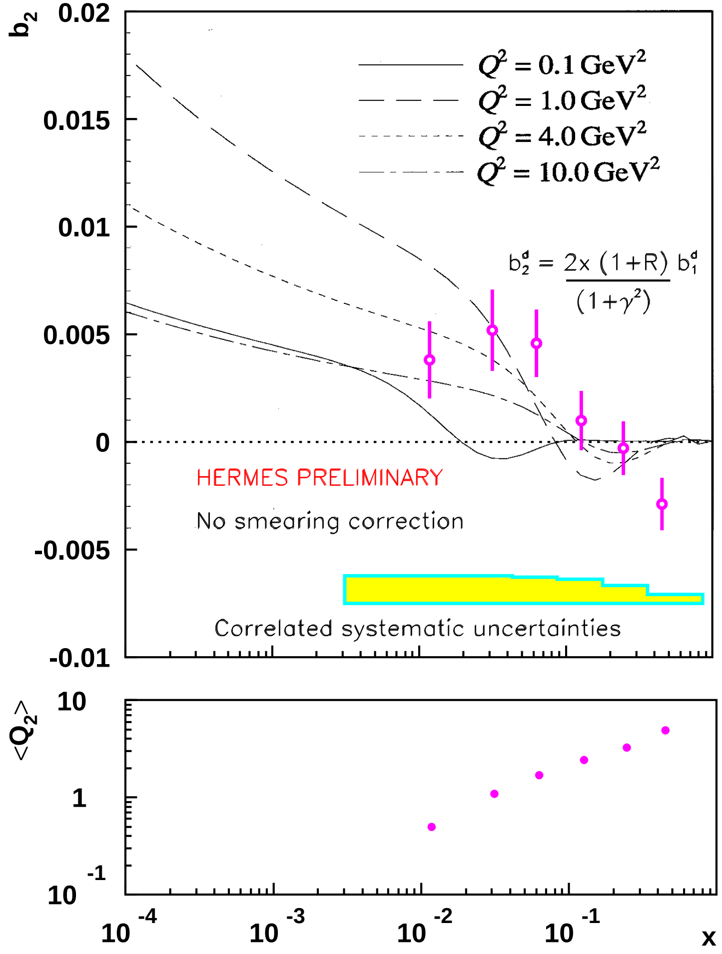
$$A_T = \frac{(\sigma^+ + \sigma^-) - 2\,\sigma^0}{3\,\sigma_u} \sim -\frac{2}{3}\frac{b_1}{F_1}$$

$$A_{\|} = A_{\|}^{meas} \cdot \left[1 + \frac{1}{2}\,T\,A_T\right] \sim \frac{g_1}{F_1}$$

☞ Influence on $A_{\|} < 1\,\%$

$b_{1,2}^d$ Structure Function



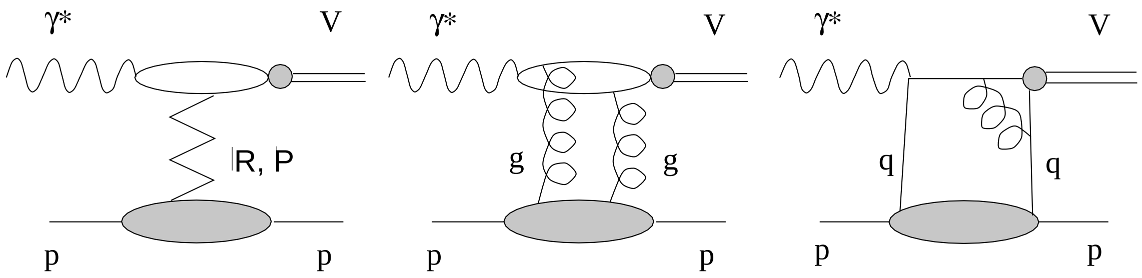


$$b_1^d = -\frac{3}{2} \cdot A_T \cdot F_1^d$$

K. Bora and R.L. Jaffe, PRD57 (1998) 6906

☞ b_2^d signif. different from zero at low x

Exclusive Vector Meson Production @ HERMES



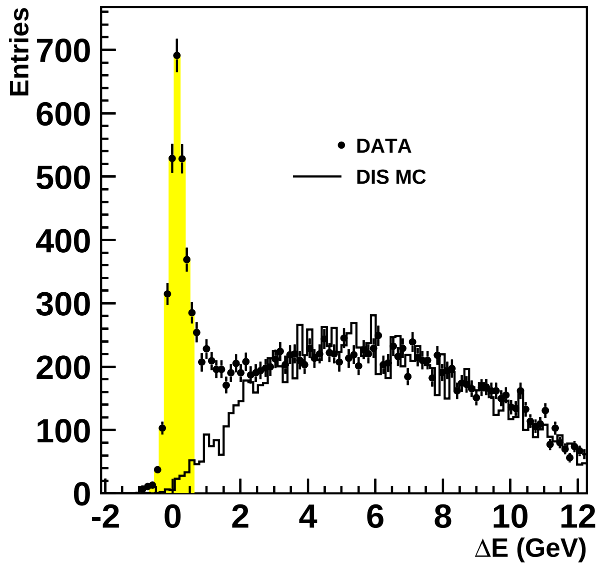
$$e + p, A \rightarrow e + p + \rho^0, \omega, \phi$$

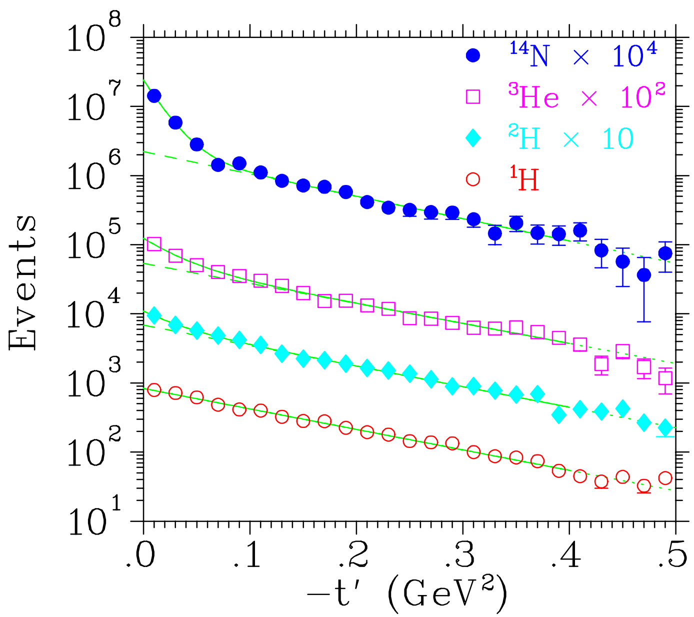
$0.5 < Q^2 < 5.0$ GeV^2,
$4.0 < W < 6.0$ GeV,
$t < 0.5$ GeV^2

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

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

Incoherent / coherent diffractive production



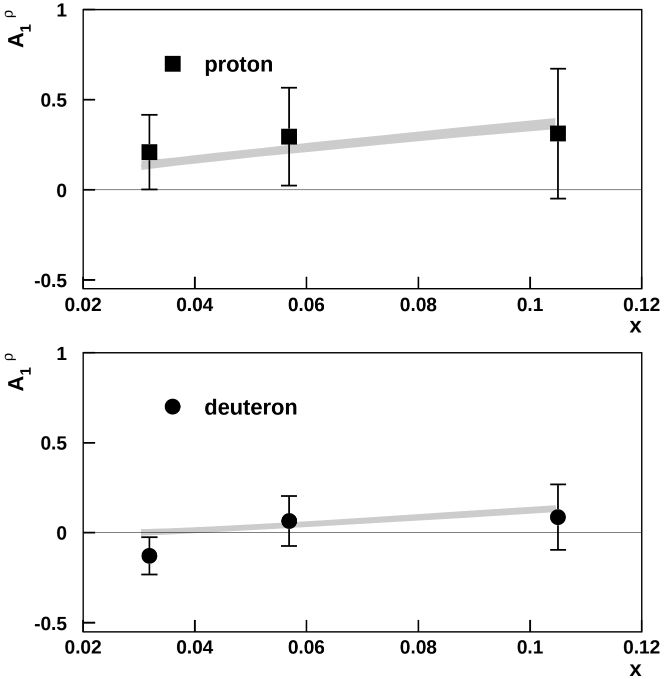


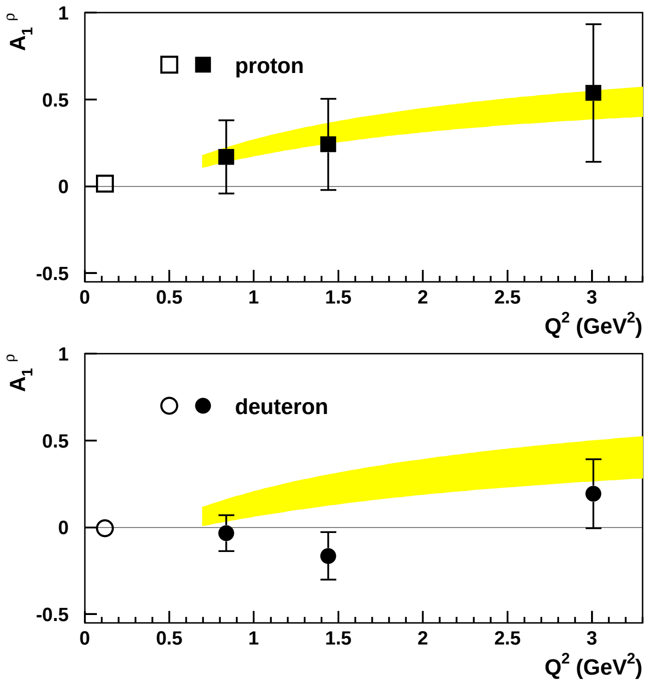
Double Spin Asymmetry in VM Production

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

$$< A_1^{p,\rho} > \; = \; 0.23 \pm 0.14 \pm 0.02 \qquad < A_1^{d,\rho} > \; = \; -0.040 \pm 0.076 \pm 0.013$$

$$< A_1^{p,\phi} > \; = \; 0.20 \pm 0.45 \pm 0.03 \qquad < A_1^{d,\phi} > \; = \; 0.17 \pm 0.27 \pm 0.02$$

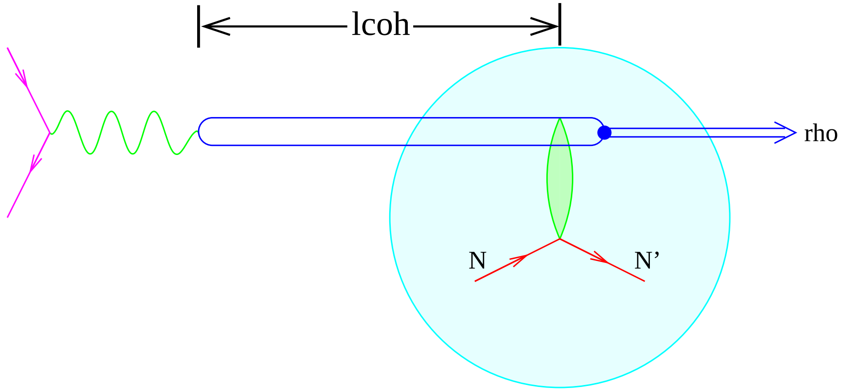




$A_1^{\rho} = 2\ A_1^N/(1+(A_1^N)^2)$ (Fraas)
Asymmetry due to unnatural parity or di-quark exchange

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

Coherence Length Effect in ρ^0 Production



Coherence length : $l_c = \dfrac{2\nu}{Q^2 + M^2_{q\bar{q}}}$

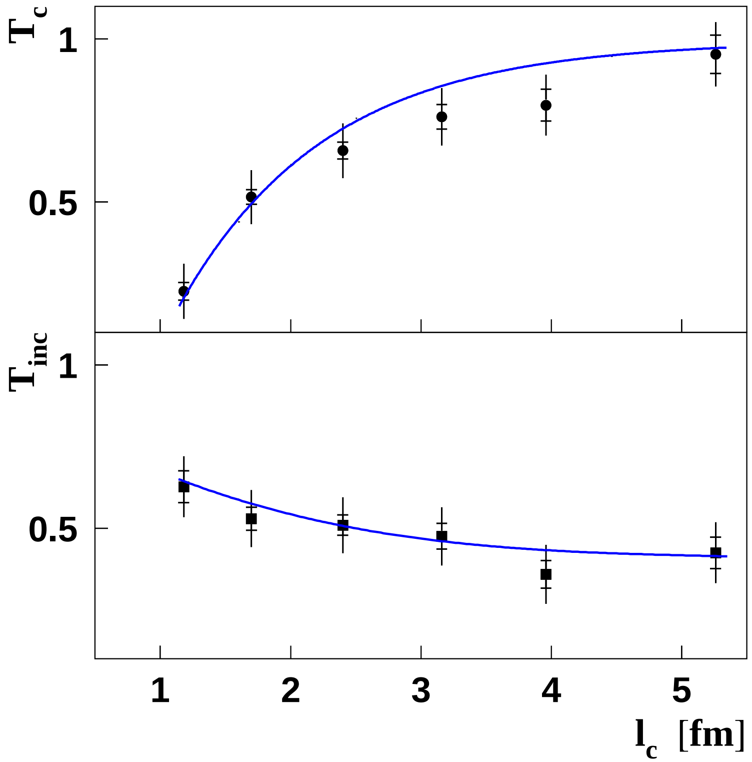
$l_c << r_A$: weak EM ISI
$l_c >> r_A$: hadronic ISI

Examine nuclear transparency : $T = \dfrac{\sigma_A}{A \cdot \sigma_p}$

to look for color transparency (^{14}N data)

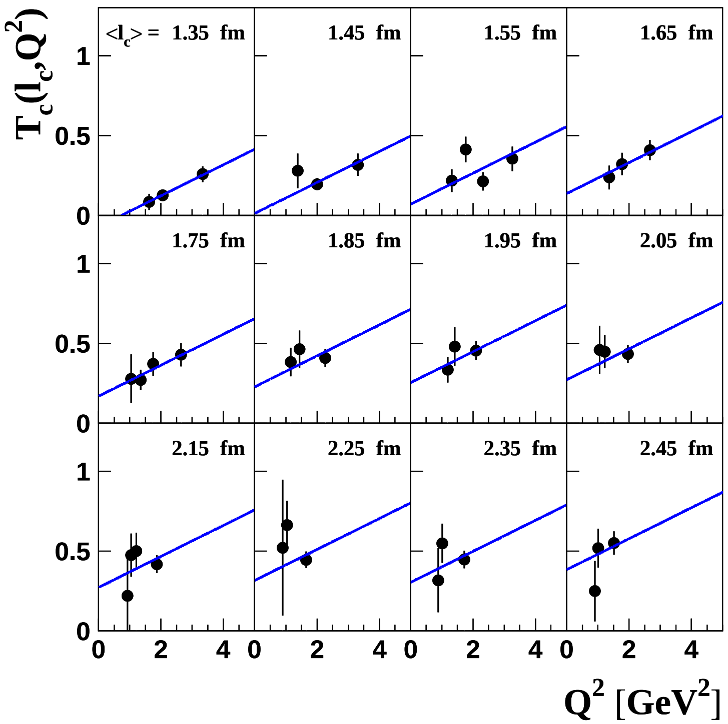
☞ Incoherent production : coherence length effect can minic CT effects for $l_c << r_A$

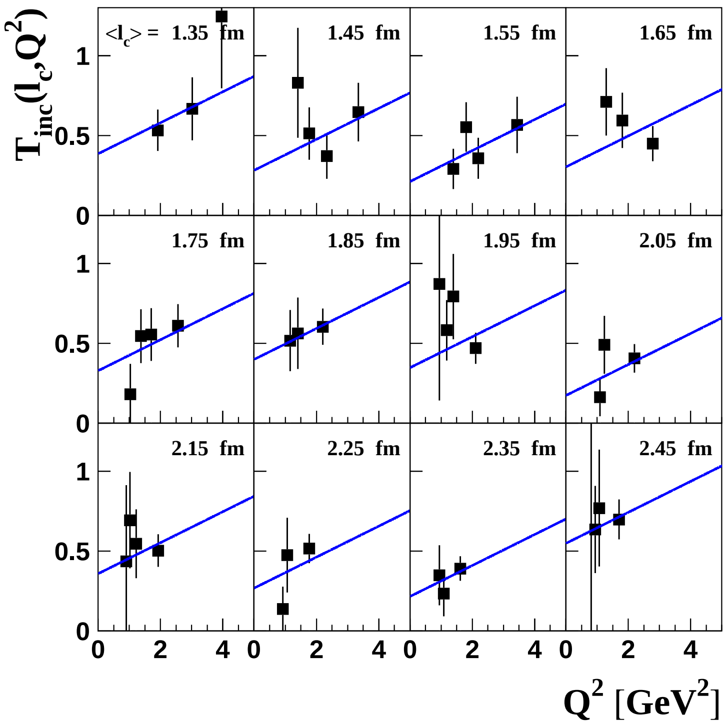
☞ Coherent production : nuclear form factor suppression at small l_c



Color Transparency in ρ^0 Production

☞ Fit Q^2-dependence of $T^{coh/incoh}$ in l_c-bins with common slope

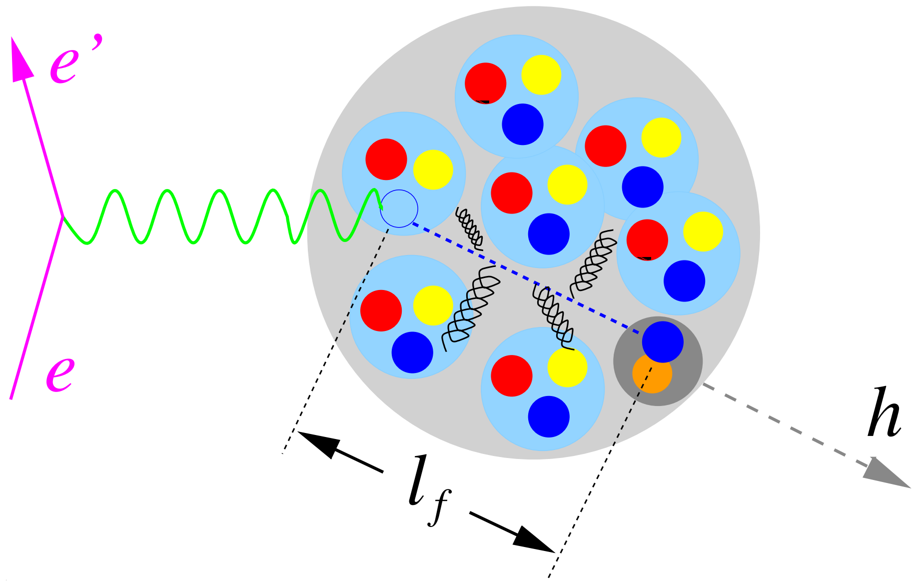




	Q^2-dep. slope	Kopeliovich *et al.*
^{14}N coherent	$0.070 \pm 0.021 \pm 0.017$	0.060
^{14}N incoherent	$0.089 \pm 0.046 \pm 0.020$	0.048

☞ Positive Q^2 slope indication of onset of Color Transparency

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

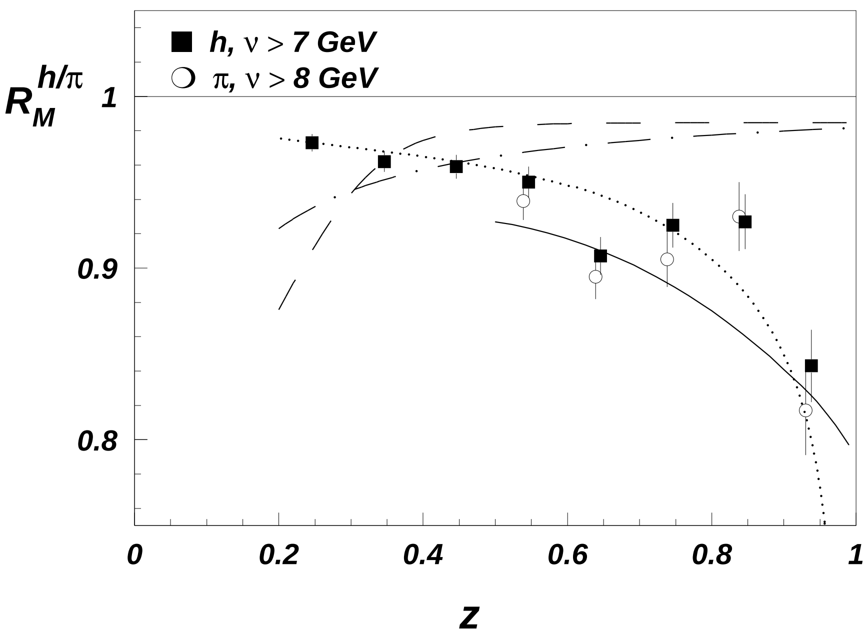
→ Models : hadronization process (phenomenological + QCD based models) + nuclear absorption

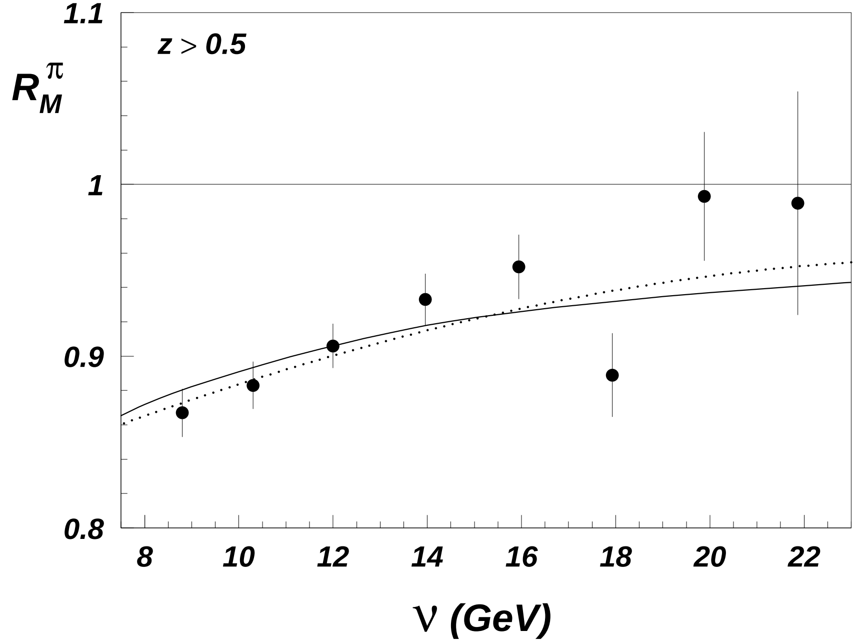
$\tau_f = l_f/c$ hadron formation time

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

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)

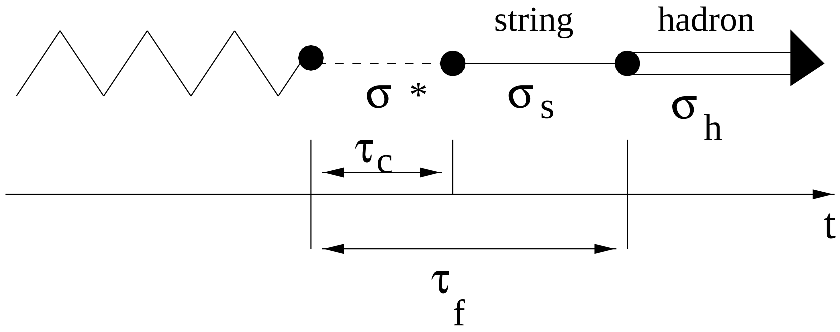




(dotted) 1 or 2 time-scale models

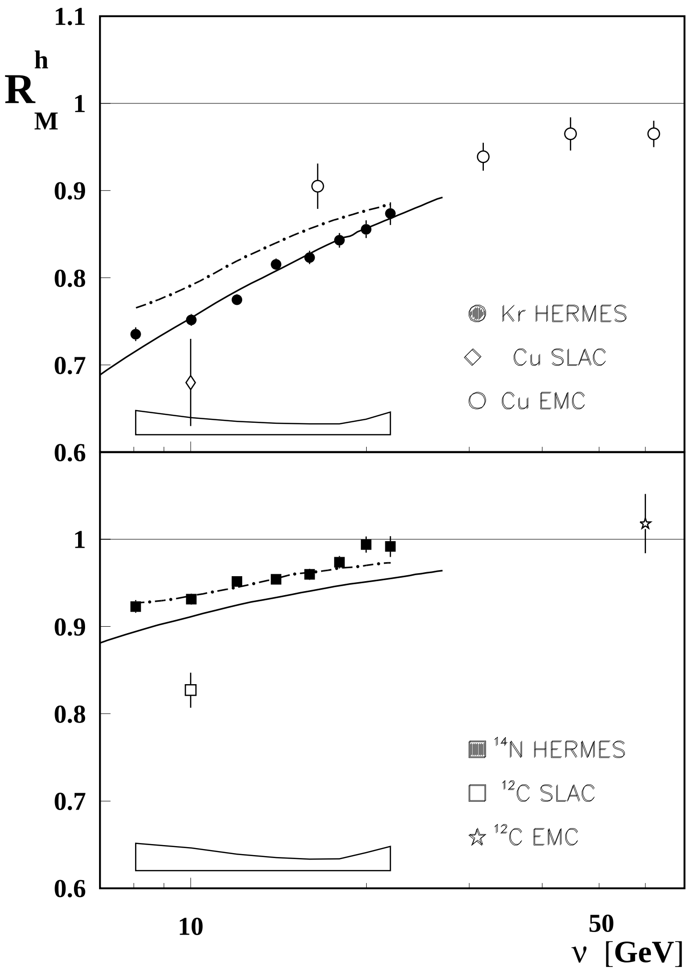
$$t_f^h = c_h(1-z)\nu, \quad \sigma^* = 0, \, \sigma_h = 25 \text{ mb}$$

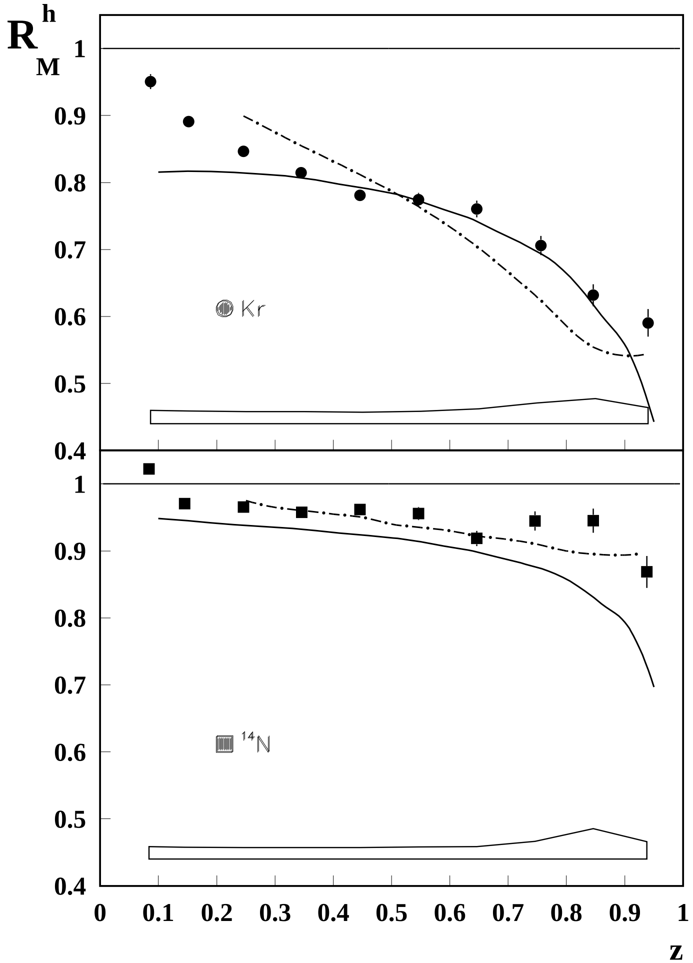
☞ Formation time fits



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

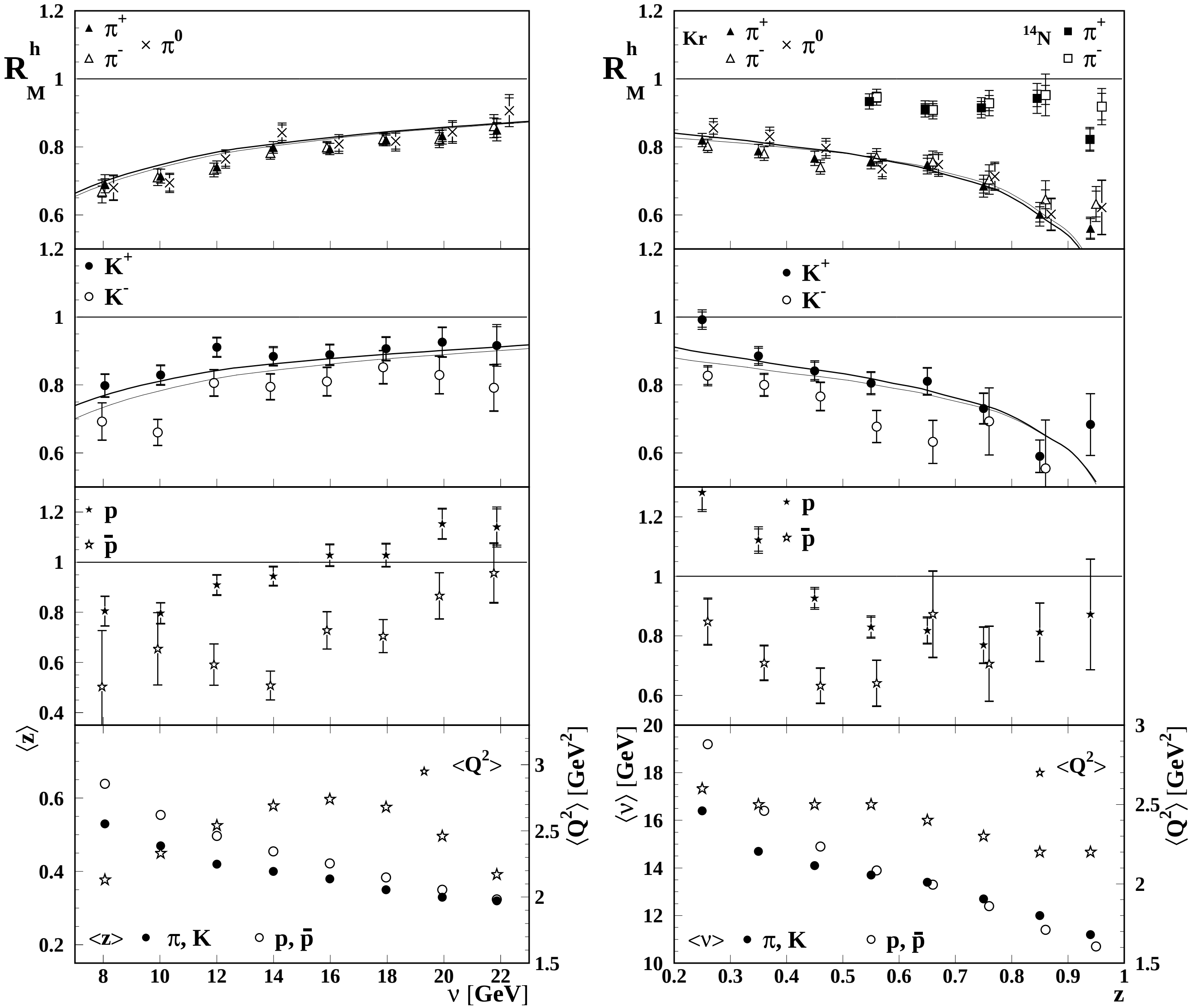
Charged Hadron Multiplicity Ratios (^{14}N, ^{84}Kr)





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)

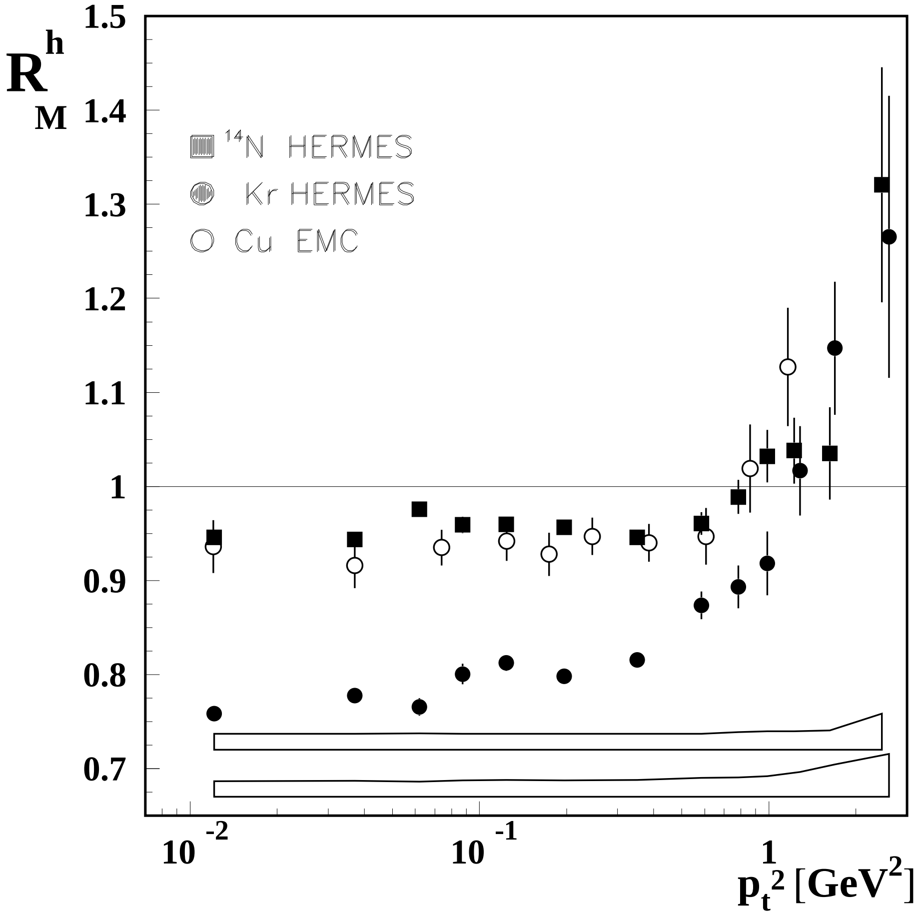


$R_M^{\pi^+} \sim R_M^{\pi^-} \sim R_M^{\pi^0}$, but
$R_M^{K^+} > R_M^{K^-}$, $R_M^{p} > R_M^{\bar{p}}$ and $R_M^{p} > R_M^{\pi}$

☞ 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

- New NLO QCD fit to world data on $g_1(x, Q^2)$
- $\Delta u(x)$ and $\Delta d(x)$ known to good precision, consistent with NLO fits of inclusive data
- First direct extraction of $\Delta \bar{u}(x)$, $\Delta \bar{d}(x)$ and $\Delta s(x)$, no significant polarization of the light quark sea
- First measurement of b_1^d, small but different from zero
- Measurement of double spin asymmetry in vector meson production on proton and deuteron
- Indication of color transparency effect in ρ^0 production on ^{14}N
- First measurement of nuclear attenuation of pions, kaons and (anti)protons electroproduction in ^{84}Kr.
- Observation of Cronin effect in DIS