Neutrino Scattering on Nucleon

and Parton Distribution Functions

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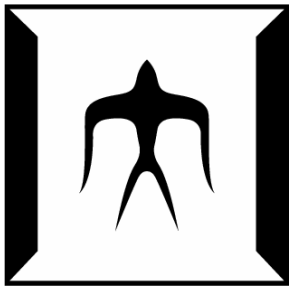


Tokyo Institute of Technology

Contents

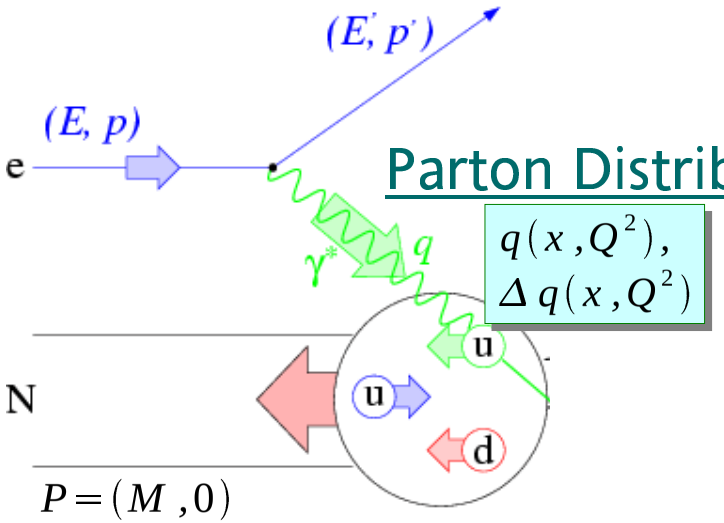
- Deep Inelastic Scattering (DIS)
- Unpolarized Parton Distribution Functions
  - Structure functions: $F_{1,2,3}(x,Q^2)$
- Polarized Parton Distribution Functions
  - Structure functions: $g_1(x, Q^2)$
- Neutrino beam and polarized target
- Summary

Deep Inelastic Scattering (DIS)

$$l + N \rightarrow l' + X$$

Structure Function

$F_i(x, Q^2),\ g_i(x, Q^2)$



Parton Distribution

$q(x, Q^2),$
$\Delta q(x, Q^2)$

DIS variables:

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

$$\nu = \frac{P \cdot q}{M} = E - E'$$

$$x = \frac{Q^2}{2M\nu},\quad y = \frac{q \cdot P}{p \cdot P} = \frac{\nu}{E}$$

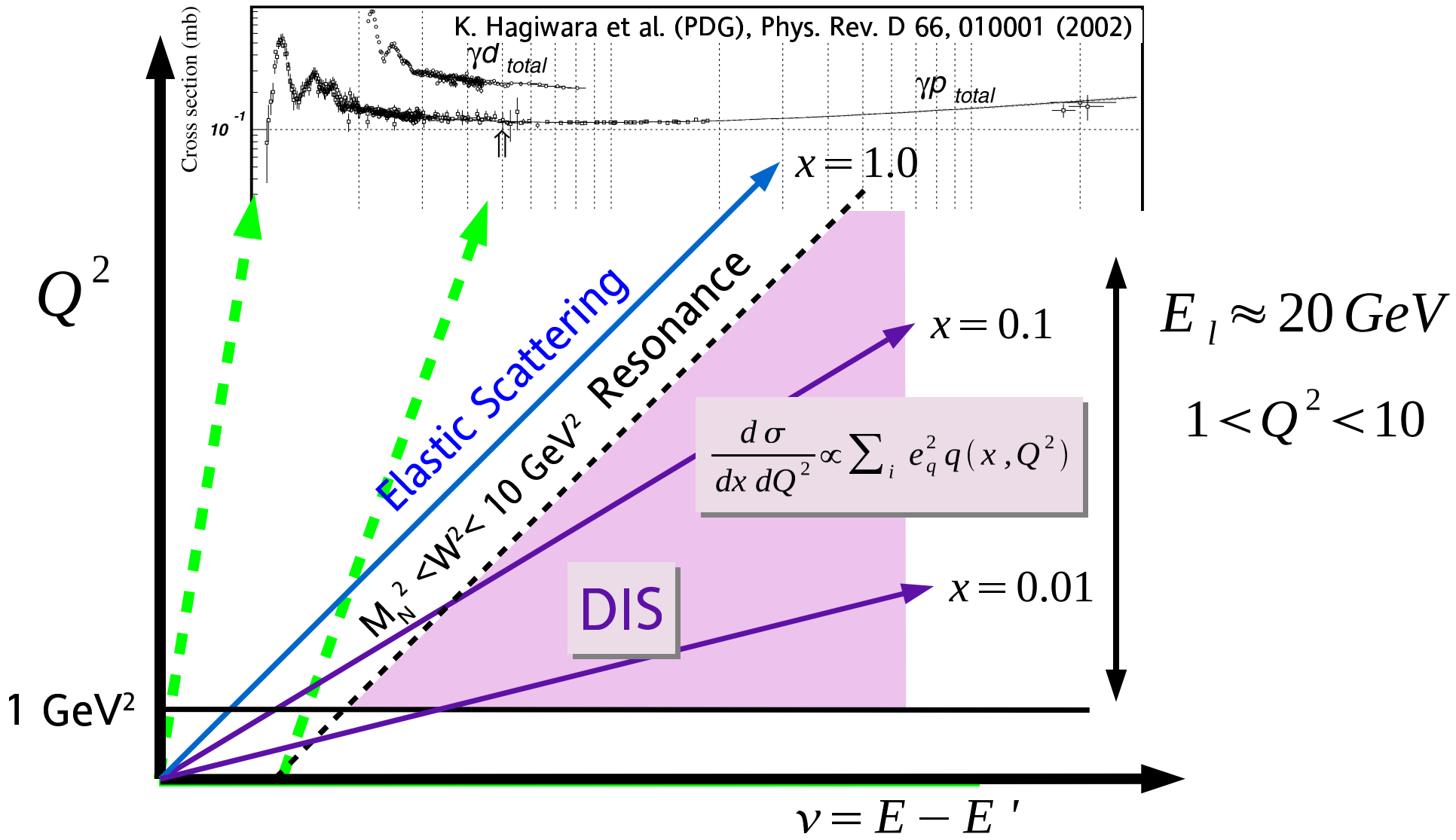
$$W^2 = (q + P)^2,\quad s = (p + P)^2$$

$$\frac{d\sigma}{dx\, dQ^2} \propto L_{\mu\nu} W^{\mu\nu} \propto \sum_i e_q^2 q(x)$$

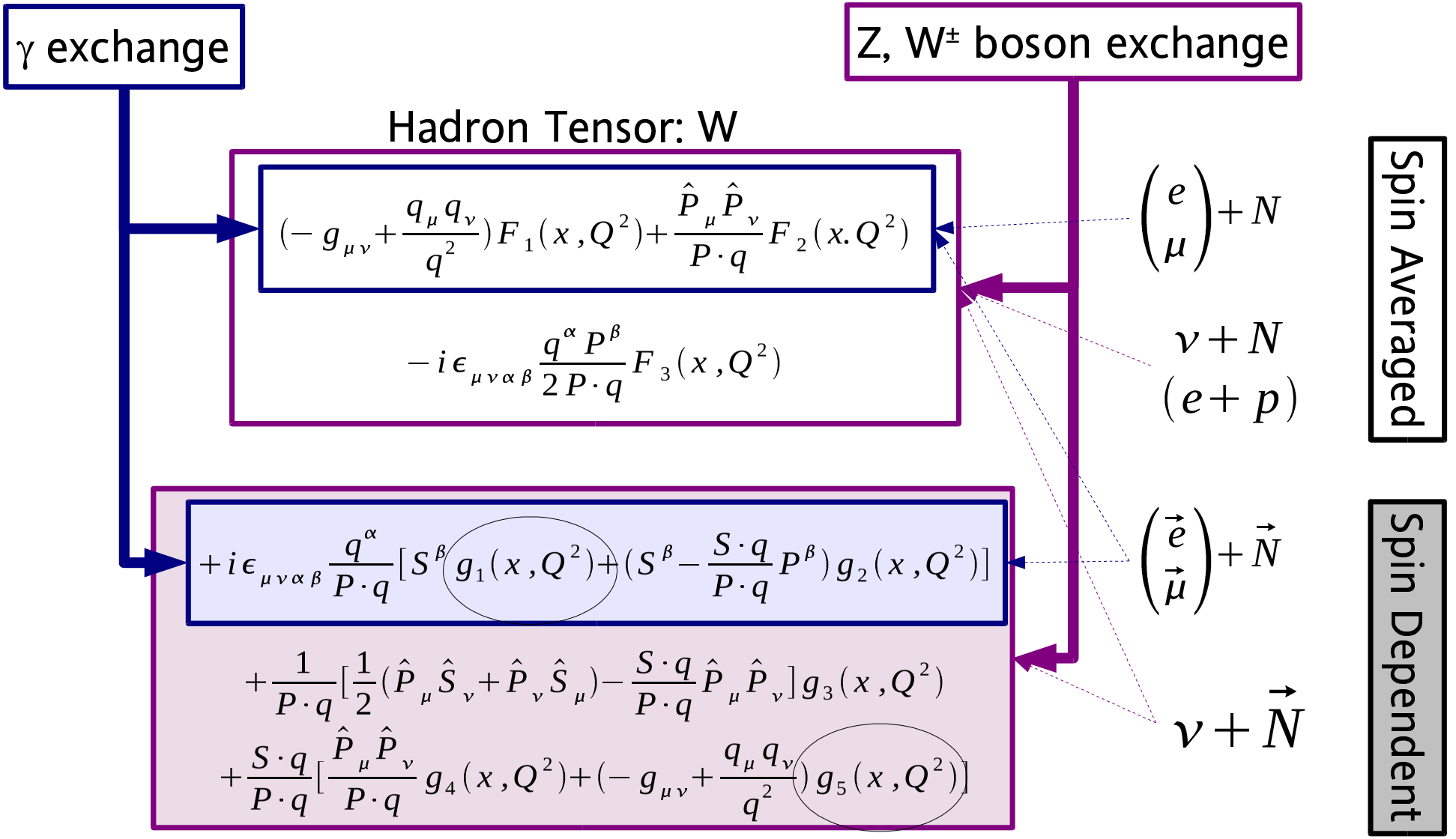
lepton tensor

Hadron tensor

Resonance / DIS regions



Hadron Tensor



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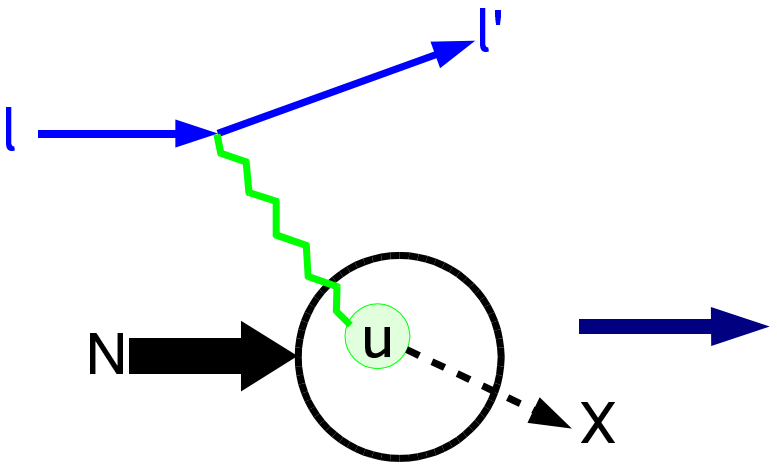
Unpolarized Charged Lepton and Unpolarized Target



$$\begin{pmatrix} e \\ \mu \end{pmatrix} + N \rightarrow \begin{pmatrix} e' \\ \mu' \end{pmatrix} + X$$

$$(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}) F_1(x, Q^2) + \frac{\hat{P}_\mu \hat{P}_\nu}{P \cdot q} F_2(x. Q^2)$$

$$\hat{P}_\mu = P_\nu - \frac{P \cdot q}{q^2} q_\mu, \quad \hat{S}_\mu = S_\mu - \frac{S \cdot q}{q^2} q_\mu$$

Quark Parton Model :

$$F_2(x) = x \sum_q e_q^2 (q(x) + \bar{q}(x))$$

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

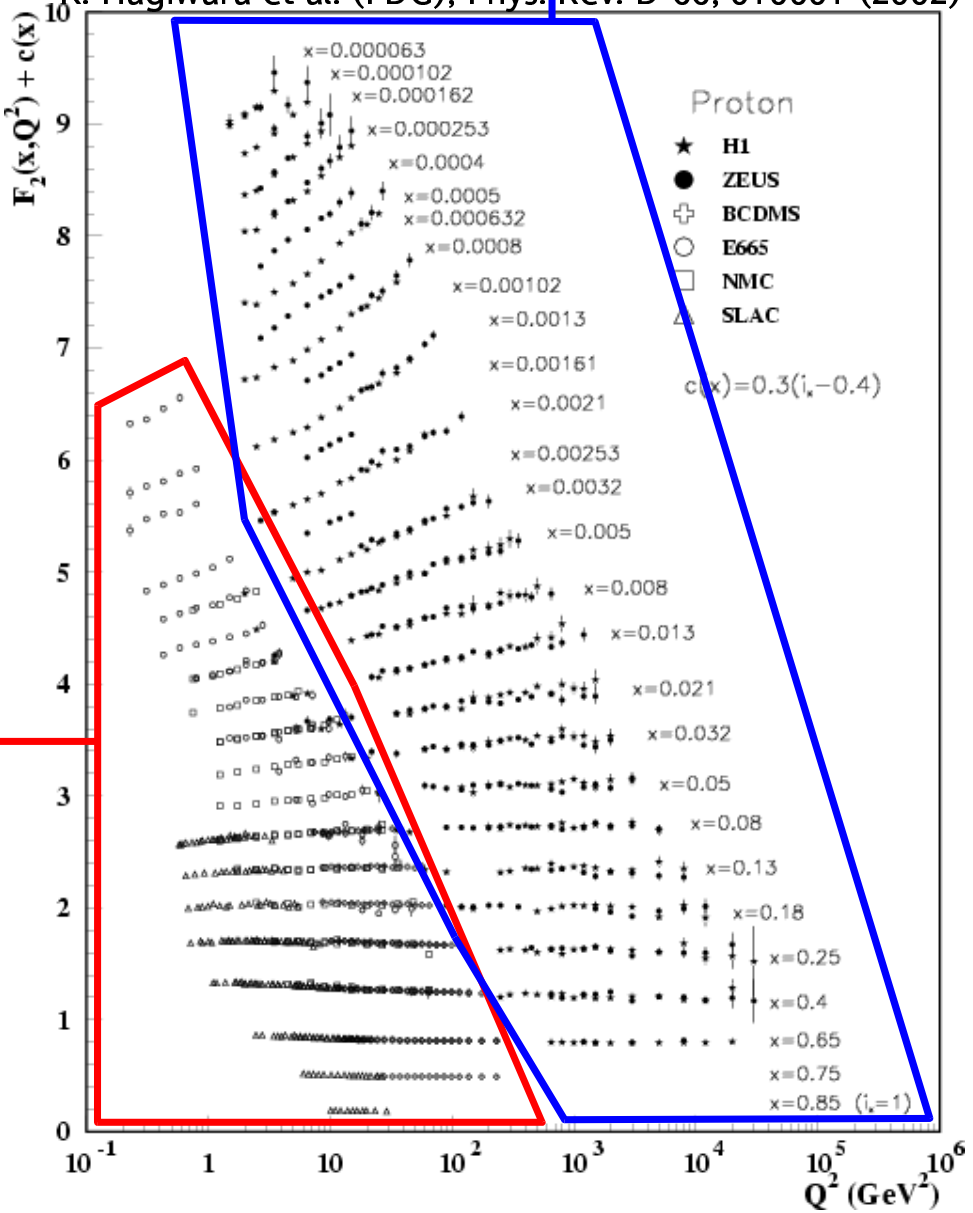
F_2 structure function

$$F_2(x) = x \sum_q e_q^2 \left(q(x) + \bar{q}(x) \right)$$

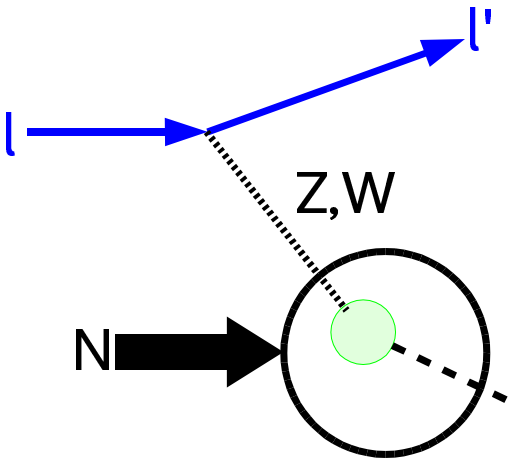
e-p @HERA

Charged Lepton Beams
NMC, BCDMS, E665, ...

K. Hagiwara et al. (PDG), Phys. Rev. D 66, 010001 (2002)



Weak Current DIS



Neutrino Scattering (W exchange),
Electron Scattering (Z exchange)

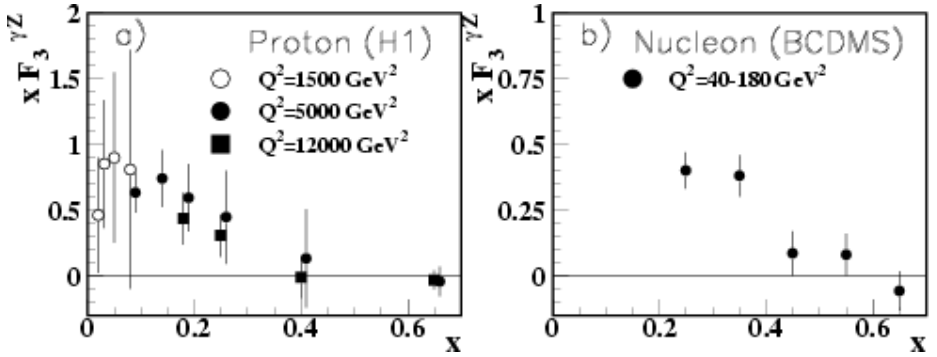
$$(-g_{\mu\nu}+\frac{q_\mu q_\nu}{q^2})F_1(x,Q^2)+\frac{\hat{P}_\mu \hat{P}_\nu}{P\cdot q}F_2(x.Q^2)$$
$$-i\epsilon_{\mu\nu\alpha\beta}\frac{q^\alpha P^\beta}{2P\cdot q}F_3(x,Q^2)$$

Quark Parton Model :

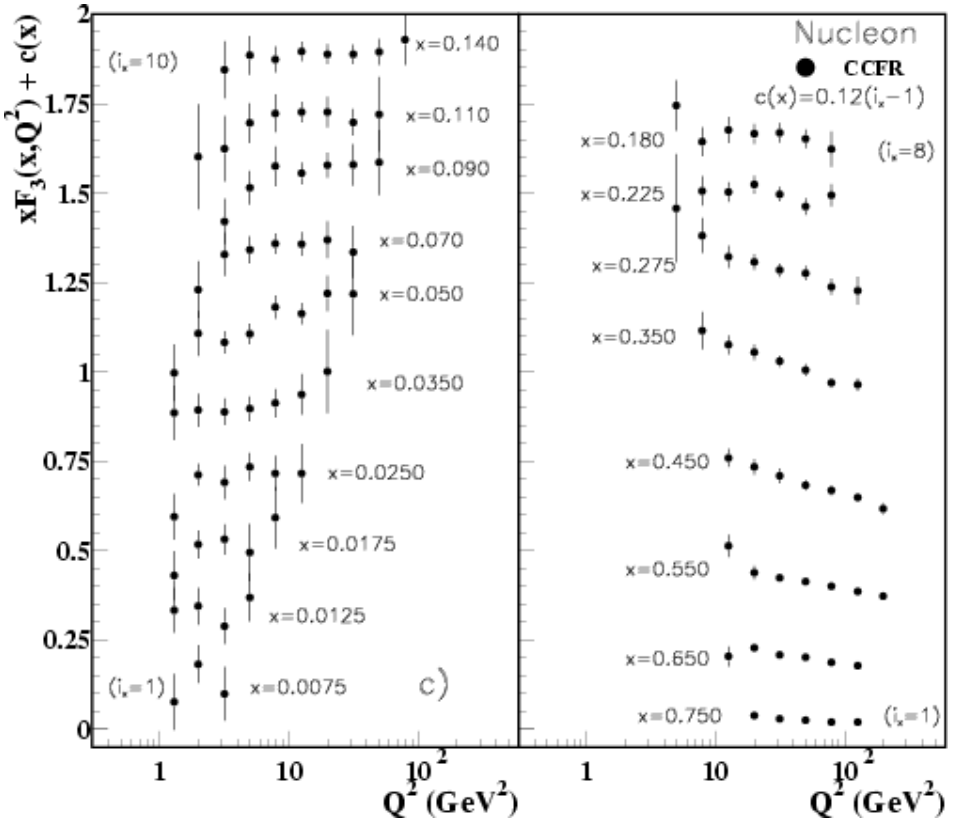
$$F_3^Z=\sum_q 2\,g_V^q\,g_A^q(q(x)-\bar{q}(x))$$
$$F_3^{W^+}(x)=2(-\bar{u}(x)+d(x)+s(x)-\bar{c}(x)\ldots)$$
$$F_3^{W^-}(x)=2(u(x)-\bar{d}(x)-\bar{s}(x)+c(x)\ldots)$$

F_3 structure function

$e+p$, $\mu+\mathrm{C}$



$\nu+\mathrm{Fe}$



K. Hagiwara et al. (PDG), Phys. Rev. D 66, 010001 (2002)

$$F_3^Z = \sum_q 2\, g_V^q\, g_A^q\,(q(x)-\bar{q}(x))$$

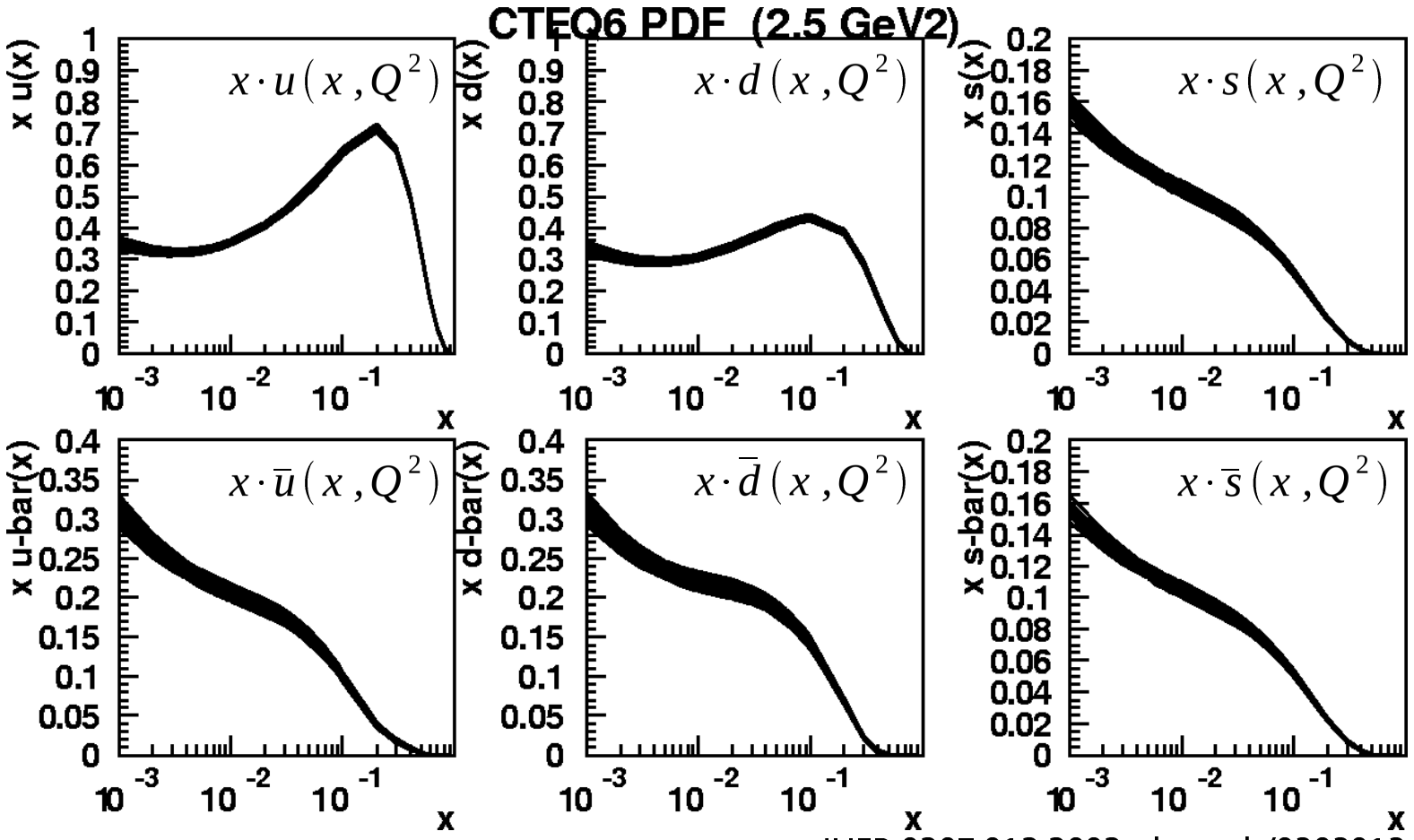
$$F_3^{W^+}(x) = 2(-\bar{u}(x)+d(x)+s(x)-\bar{c}(x)\ldots)$$

$$F_3^{W^-}(x) = 2(u(x)-\bar{d}(x)-\bar{s}(x)+c(x)\ldots)$$

$$F_2(x) = x\sum_q e_q^2\,(q(x)+\bar{q}(x))$$

Extract Parton Distributions (perturbative QCD)

Unpolarized Parton Distributions



JHEP 0207:012,2002 , hep-ph/0303013

charm quark, gluon distributions were also extracted.

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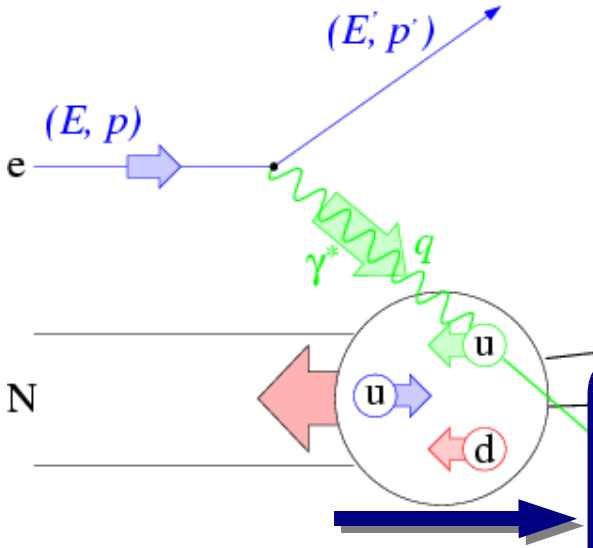
With Polarized Beam & Target



$$\begin{pmatrix}\vec{e}\\ \vec{\mu}\end{pmatrix}+\vec{N}\rightarrow\begin{pmatrix}e'\\ \mu'\end{pmatrix}+X$$

$$(-g_{\mu\nu}+\frac{q_\mu q_\nu}{q^2})F_1(x,Q^2)+\frac{\hat{P}_\mu\hat{P}_\nu}{P\cdot q}F_2(x.Q^2)$$
$$+i\epsilon_{\mu\nu\alpha\beta}\frac{q^\alpha}{P\cdot q}[S^\beta g_1(x,Q^2)+(S^\beta-\frac{S\cdot q}{P\cdot q}P^\beta)g_2(x,Q^2)]$$

$$A_1=\frac{d\sigma^{\uparrow\downarrow}-d\sigma^{\uparrow\uparrow}}{d\sigma^{\uparrow\downarrow}+d\sigma^{\uparrow\uparrow}}\simeq\frac{g_1}{F_1}\longrightarrow g_1(x)=\frac{1}{2}\sum_q e_q^2(\Delta q(x)+\Delta\bar{q}(x))$$

$$\Delta q(x)=q^+(x)-q^-(x)$$

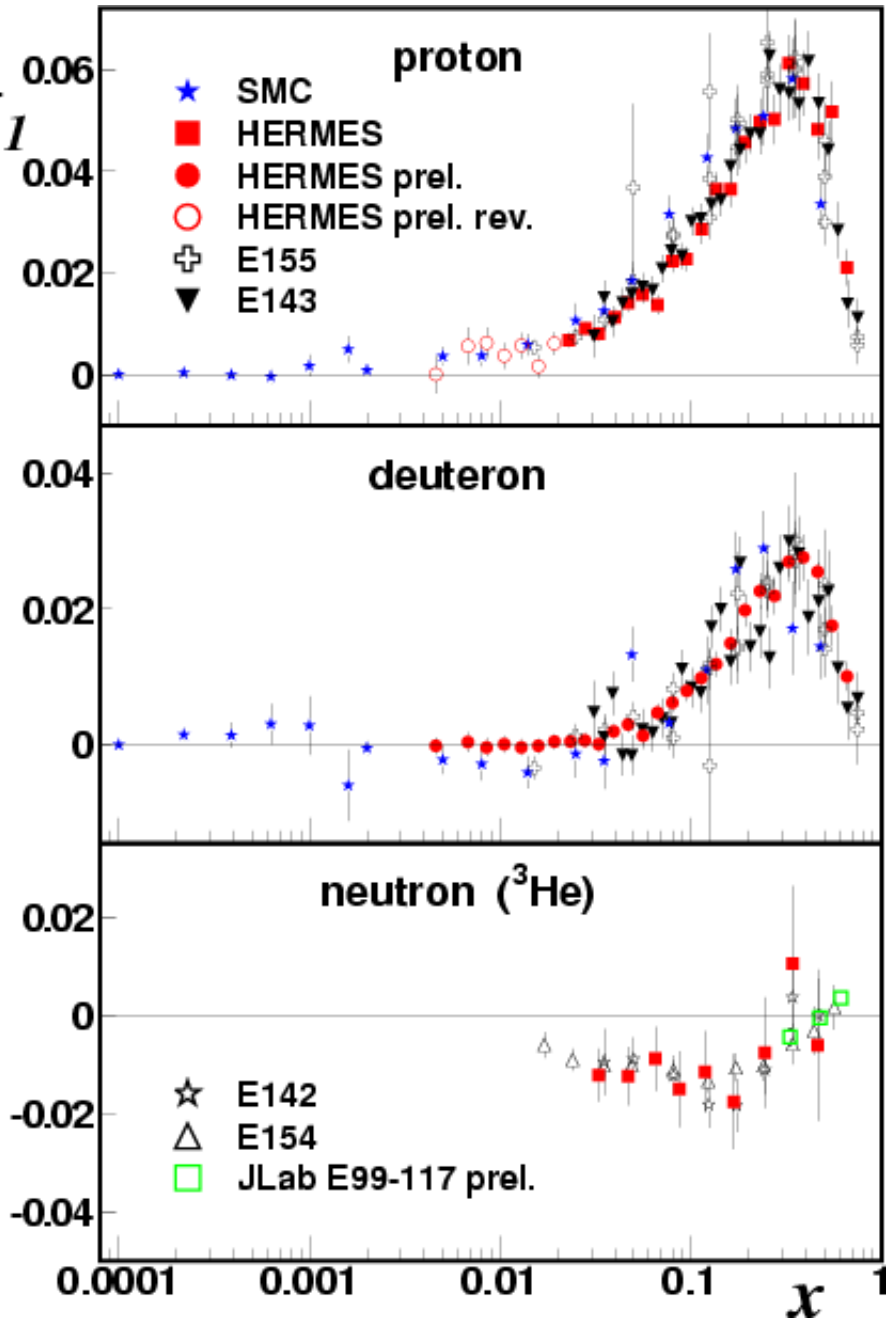
Polarized Beam & Target

$$\begin{pmatrix}\vec{e}\\ \vec{\mu}\end{pmatrix}+\vec{N}\rightarrow\begin{pmatrix}e'\\ \mu'\end{pmatrix}+X$$

$$g_1=\frac{1}{2}\sum_{q=u,d,s}e_q^2(\Delta q(x)+\Delta\bar{q}(x))$$

Experiments:

CERN(EMC, SMC, COMPASS),
DESY(HERMES)
SLAC(E142, ..., E155),
J-Lab



Polarized PDF

NLO QCD Analysis

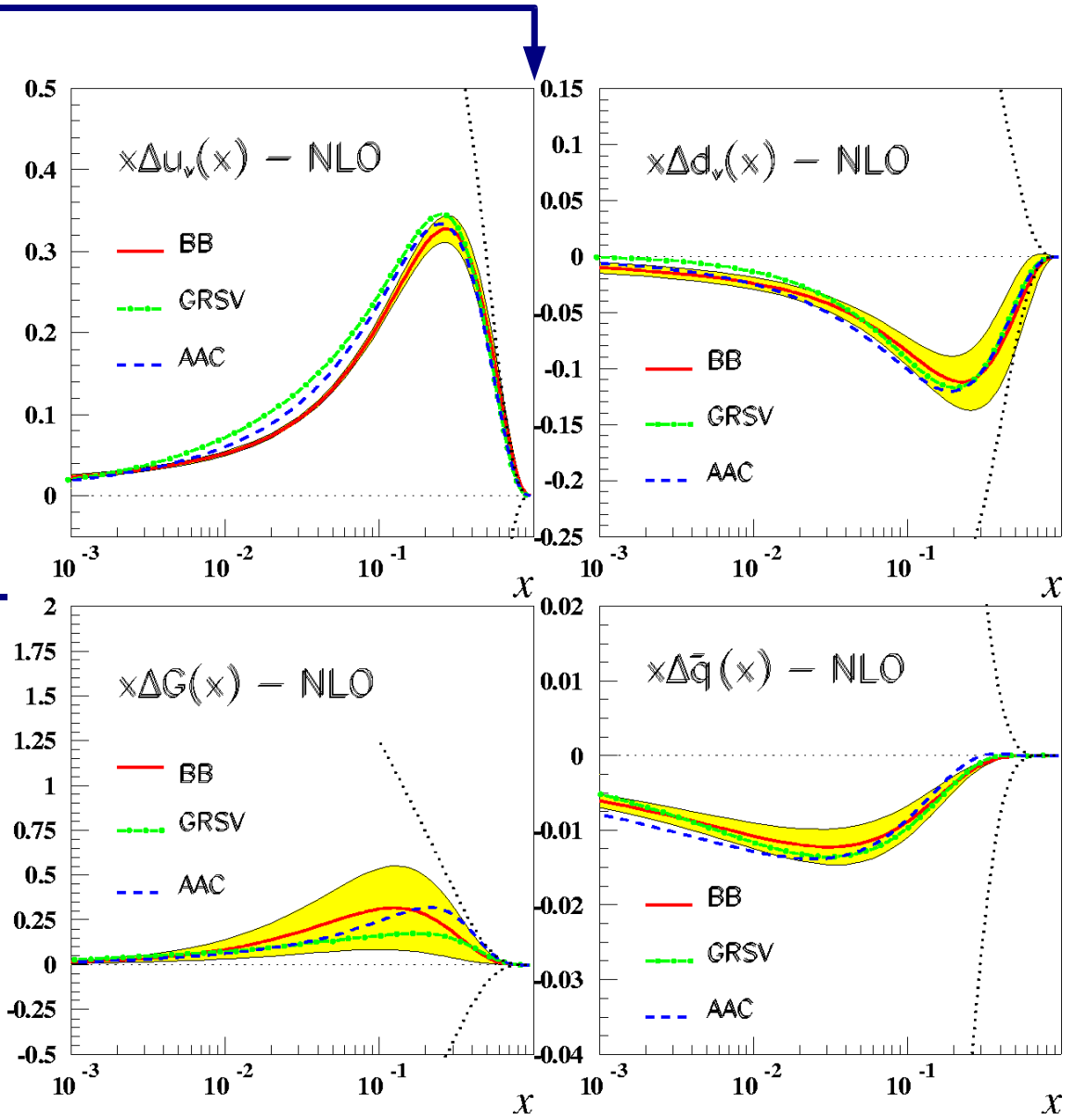
$$g_1(x,Q^2)$$
$$\downarrow$$
$$\Delta u_v(x),\ \Delta d_v(x),\ \Delta \bar{q}(x)$$
$$\Delta G(x)$$

3 quark distributions
+ gluon distribution

$$\left(\Delta\Sigma, \Delta q_p^{NS}, \Delta q_n^{NS}, \Delta G\right)$$

With the other constrains:

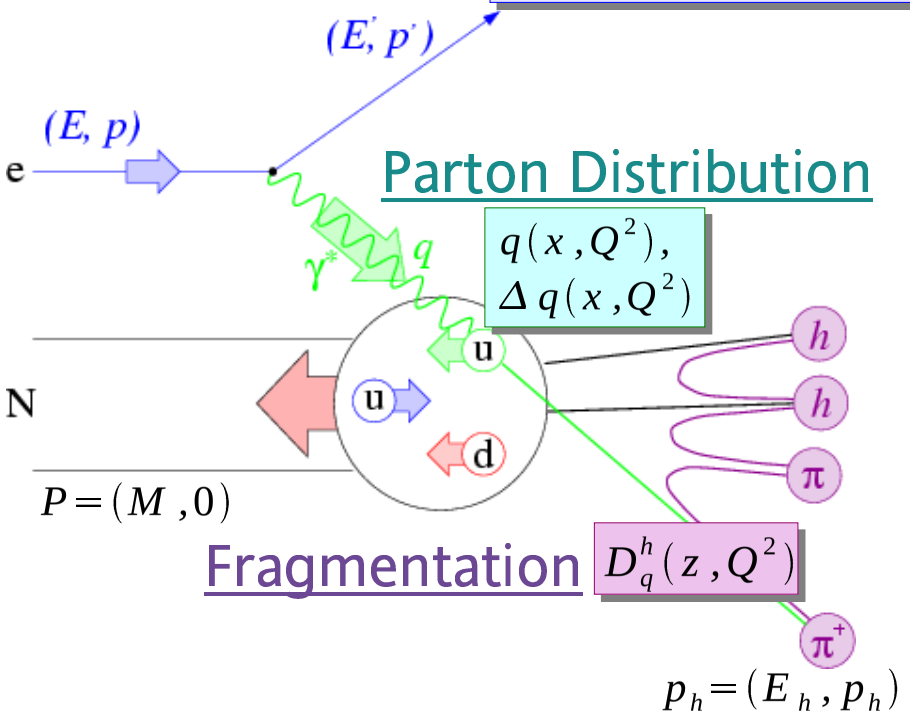
$$\int_0^1 dx\, \Delta s(x) \simeq -0.1$$



Nucl. Phys. B636 (2002) 225-263 Phys. Rev. D63 (2001) 094005 Phys. Rev. D62 (2000) 034017

DIS: Quark Flavor Tagging

Structure Function $F_i(x,Q^2),\ g_i(x,Q^2)$



Flavor Tagging: $z=\frac{P\cdot p_h}{P\cdot q}=\frac{E_h}{\nu}$

Hadron in coincidence with the scattered lepton

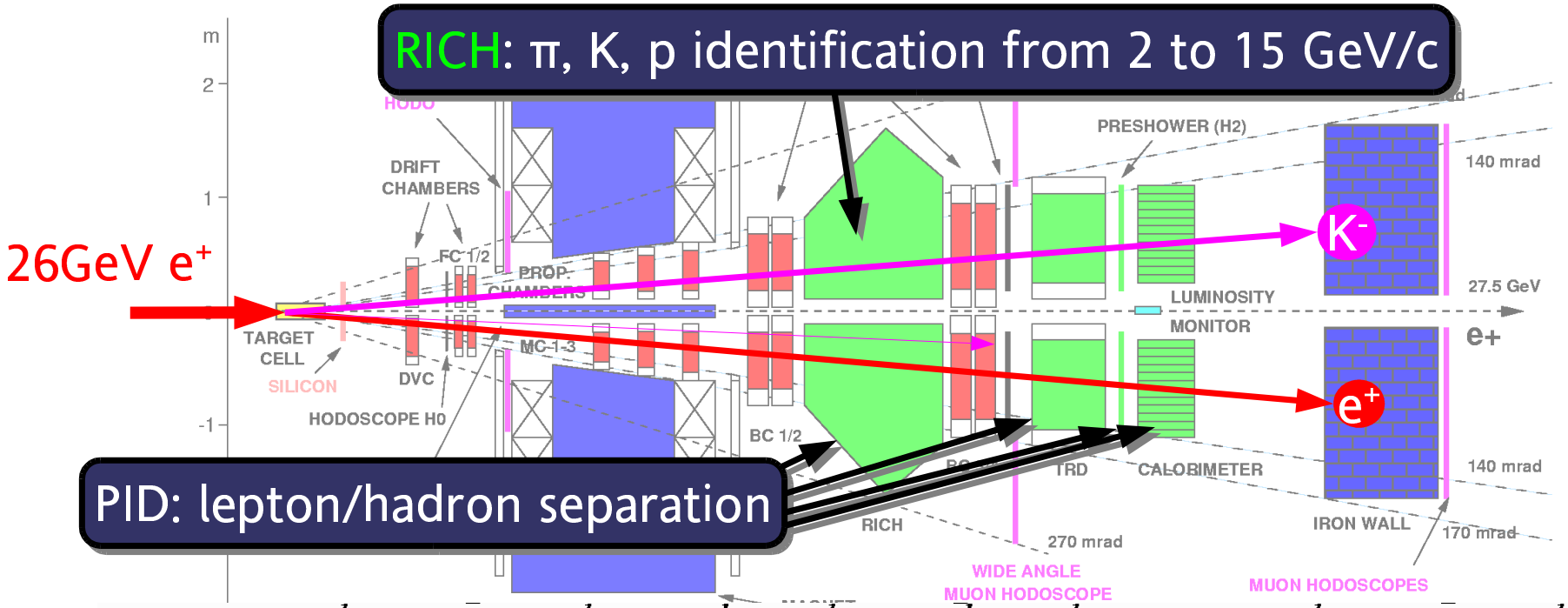
Hadron carries information on quark flavor through fragmentation process

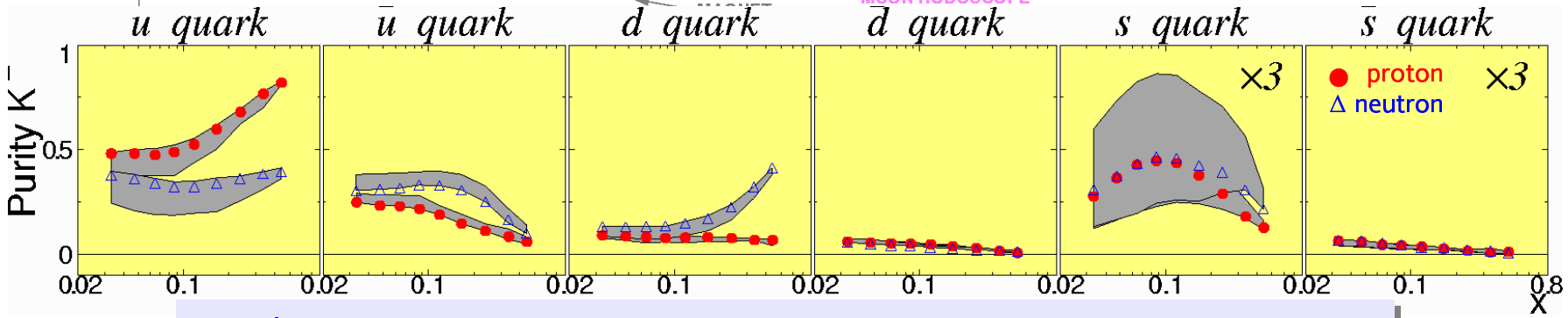
$$\frac{d\sigma^h}{dx\,dQ^2}\propto\sum_i e_q^2\,q(x,Q^2)D_q^h(z,Q^2)$$

Flavor Tagging @ HERMES

RICH: π, K, p identification from 2 to 15 GeV/c

PID: lepton/hadron separation





Purity K⁻:

Which quark was hit by virtual photon, when K⁻ was observed?

PDF LO extraction
by flavor tagging

$$A_1^h(x) = \frac{d\sigma_h^{\uparrow\downarrow} - d\sigma_h^{\uparrow\uparrow}}{d\sigma_h^{\uparrow\downarrow} + d\sigma_h^{\uparrow\uparrow}} = \sum_q P_q^h(x) \cdot \frac{\Delta q(x)}{q(x)}$$

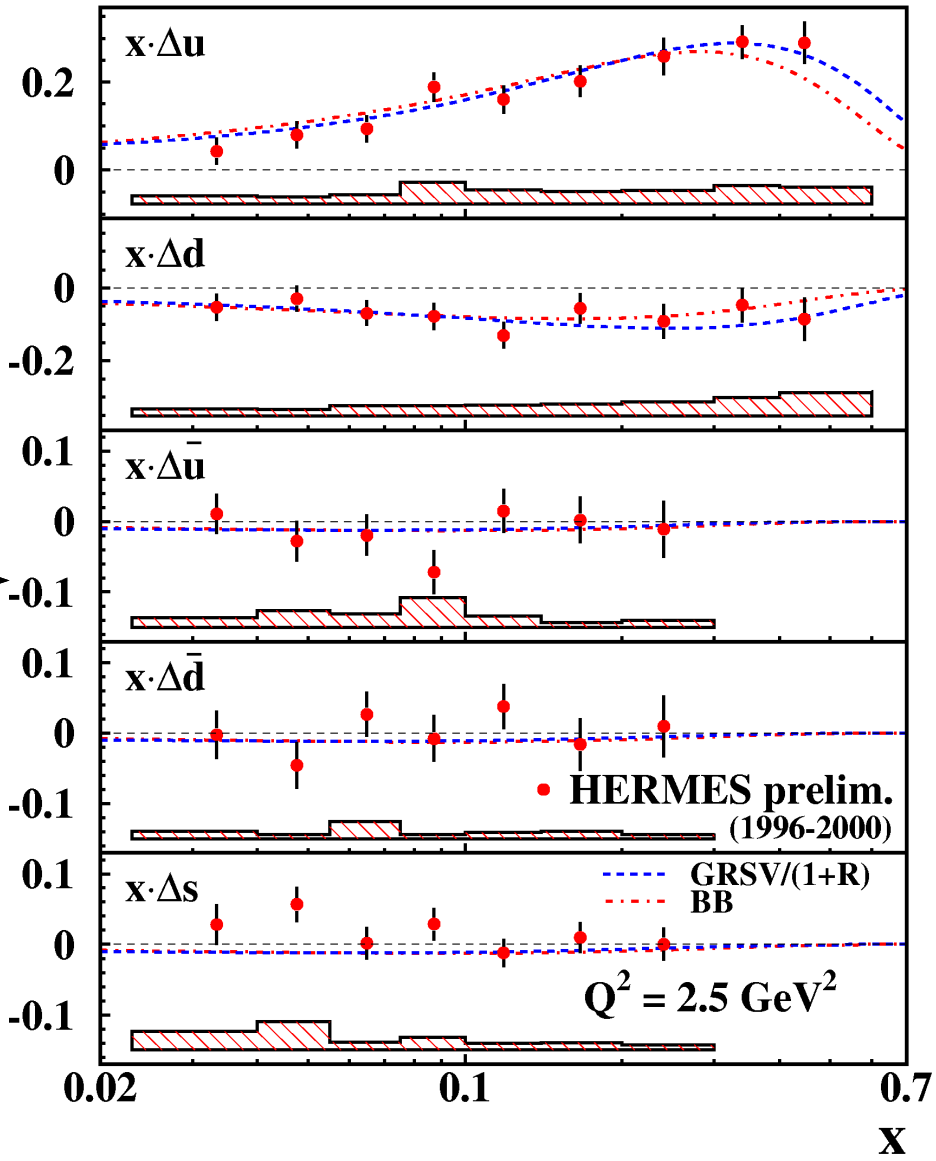
$$\vec{A} = \begin{pmatrix} A_1^p, & A_1^{p,\pi^+}, & A_1^{p,\pi^-}, \\ A_1^d, & A_1^{d,\pi^+}, & A_1^{d,\pi^-}, A_1^{d,K^+}, & A_1^{d,K^-} \end{pmatrix}$$

$P_q^h(x)$: (calculated using Monte Carlo)

Sea quark distributions are consistent with zero within errors

In contrast to the inclusive results (negative Δs)

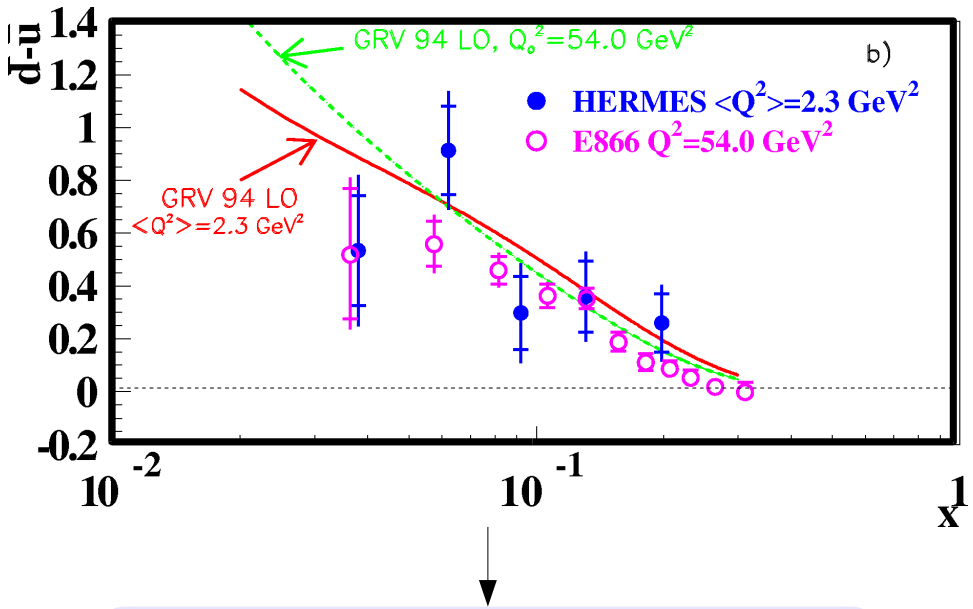
$$\left(\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}, \frac{\Delta s}{s} = \frac{\Delta \bar{s}}{\bar{s}}\right)$$



Light Flavor Symmetry

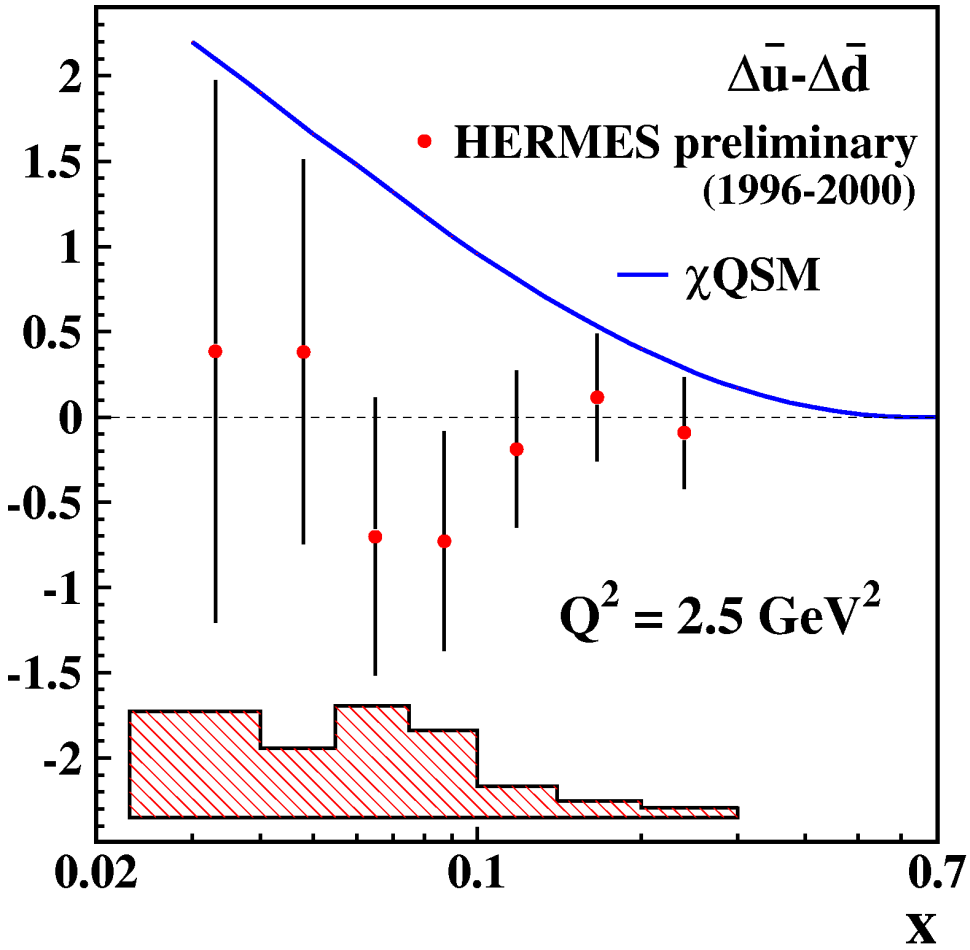
$\bar{d}(x) - \bar{u}(x)$

Phys. Rev. Lett. 81 (1998) 5519-5523



Gottfried Sum Rule Violation

$\Delta\bar{u}(x) - \Delta\bar{d}(x)$



What can we expect in near future?

- Flavor decomposition
  - HERMES(Nealy completed), COMPASS, RHIC-spin: W^{+-}
- Spin dependent Gluon Distribution
  - COMPASS(CERN), RHIC-spin(BNL), …
- Quark Transversity Distributions
  - With transversely polarized target (HERMES/COMPASS)
- PDF @ high-x
- Orbital angular moment by GPD
  - HERMES, Jlab

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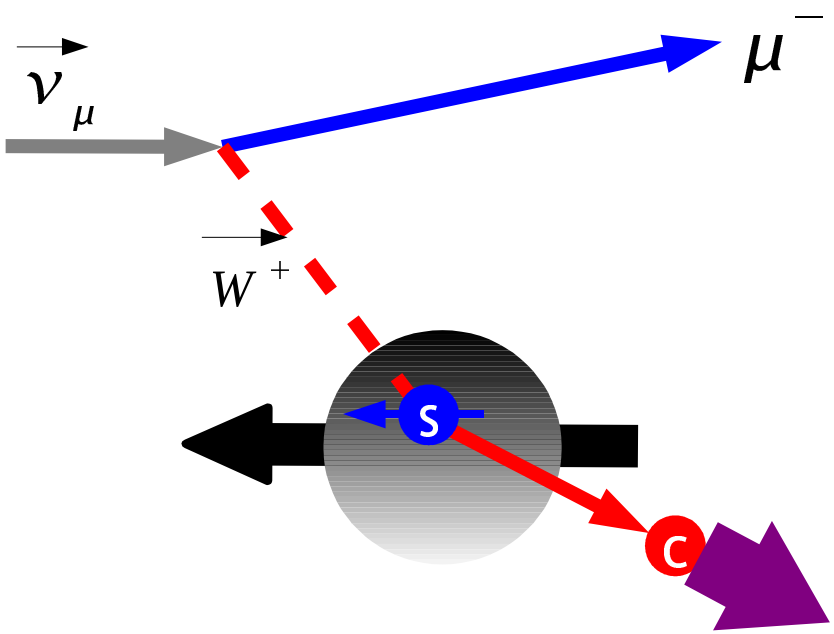
Neutrino Scattering on Pol. Target

$$\nu_\mu + \vec{N} \to \mu + X$$

$$\left(-g_{\mu\nu}+\frac{q_\mu q_\nu}{q^2}\right)F_1(x,Q^2)+\frac{\hat{P}_\mu \hat{P}_\nu}{P\cdot q}F_2(x.Q^2)$$
$$-i\epsilon_{\mu\nu\alpha\beta}\frac{q^\alpha P^\beta}{2P\cdot q}F_3(x,Q^2)$$
$$+i\epsilon_{\mu\nu\alpha\beta}\frac{q^\alpha}{P\cdot q}\left[S^\beta g_1(x,Q^2)+\left(S^\beta-\frac{S\cdot q}{P\cdot q}P^\beta\right)g_2(x,Q^2)\right]$$
$$+\frac{1}{P\cdot q}\left[\frac{1}{2}(\hat{P}_\mu \hat{S}_\nu+\hat{P}_\nu \hat{S}_\mu)-\frac{S\cdot q}{P\cdot q}\hat{P}_\mu \hat{P}_\nu\right]g_3(x,Q^2)$$
$$+\frac{S\cdot q}{P\cdot q}\left[\frac{\hat{P}_\mu \hat{P}_\nu}{P\cdot q}g_4(x,Q^2)+\left(-g_{\mu\nu}+\frac{q_\mu q_\nu}{q^2}\right)g_5(x,Q^2)\right]$$

$$\hat{P}_\mu = P_\nu - \frac{P\cdot q}{q^2}q_\mu, \quad \hat{S}_\mu = S_\mu - \frac{S\cdot q}{q^2}q_\mu$$

Neutrino Scattering on Pol. Target



$$A_1^{W^\pm} = \frac{\sigma(\lambda_W,-1)-\sigma(\lambda_W,+1)}{\sigma(\lambda_W,-1)-\sigma(\lambda_W,+1)} \propto -\frac{g_5^{W^\pm}+\lambda_W g_1^{W^\pm}}{F_1^{W^\pm}-\lambda_W F_3^{W^\pm}/2}$$

$$g_1^{W^+} = \Delta\bar{u}+\Delta d+\Delta\bar{c}+\Delta s$$
$$g_1^{W^-} = \Delta u+\Delta\bar{d}+\Delta c+\Delta\bar{s}$$
$$g_5^{W^+} = \Delta\bar{u}-\Delta d+\Delta\bar{c}-\Delta s$$
$$g_5^{W^-} = -\Delta u+\Delta\bar{d}-\Delta c+\Delta\bar{s}$$

Flavor Tagging:

$$A_{1,c}^{W^+} = \frac{\Delta s^c}{s^c}, \quad A_{1,c}^{W^-} = \frac{\Delta\bar{s}^c}{\bar{s}^c}$$

eliminate u(x) contribution!!

$$\Delta\bar{u}(x),\ \Delta\bar{d}(x),\ \Delta s(x),\ \Delta\bar{s}(x)$$

Neutrino Scattering

Sea Quark Distributions

- Light flavor Symmetry $\Delta \bar{u}(x) \neq \Delta \bar{d}(x)$?
- Strangeness and Anti-strangeness asymmetry

$s(x) \neq \bar{s}(x)$? ← Eur.Phys.J.C12:243-262,2000

$\Delta s(x) \neq \Delta \bar{s}(x)$?

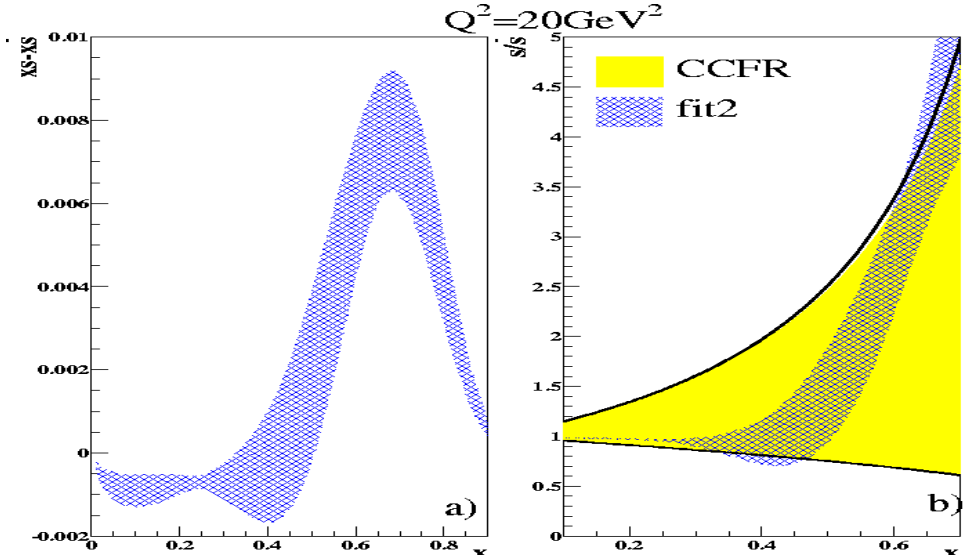


Fig. 17a,b. Results of `fit2` for: **a** the difference $x(s-\bar{s})$ and **b** the ratio $s/\bar{s}$ at $Q^2 = 20\text{GeV}^2$. In the box **b**, the result of CCFR is also shown

Summary

- Charged lepton scattering on unpolarized target:
  - Precise information on unpolarized PDF
- With polarized target:
  - Flavor tagging (HERMES preliminary)
    - Δs is consistently "zero" ≠ DIS + NLO QCD results
    - Very weak sensitivity to anti-strangeness
- Neutrino scattering on nucleon
  - strange and anti-strange symmetry:

$$s(x),\ \bar{s}(x),\ \Delta s(x),\ \Delta \bar{s}(x)$$