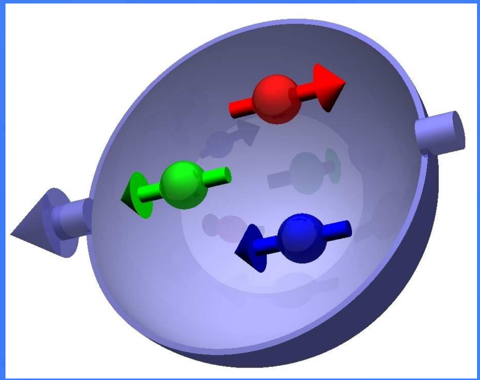
Where is the Spin of the Nucleon hidden?

E.C. Aschenauer

DESY-ZEUTHEN

The Spin Structure of the Nucleon



Naive Parton Model:

$$\mathbf{\Delta u_v + \Delta d_v = 1}$$

$$\Longrightarrow \mathbf{\Delta u_v = \frac{4}{3}, \Delta d_v = \frac{-1}{3}}$$

BUT

1988 EMC measured:

Σ = 0.123 $\pm$ 0.013 $\pm$ 0.019

$\Longrightarrow$ Spin Puzzle

$$\mathbf{\frac{1}{2} = \frac{1}{2}(\Delta u_v + \Delta d_v)}$$

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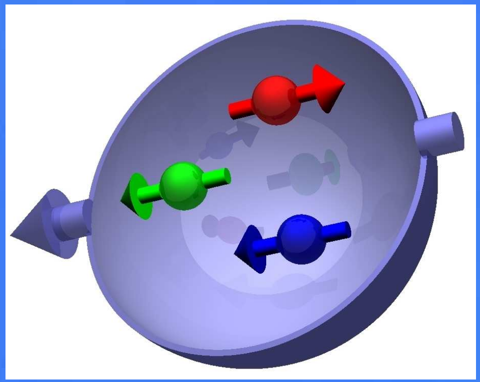

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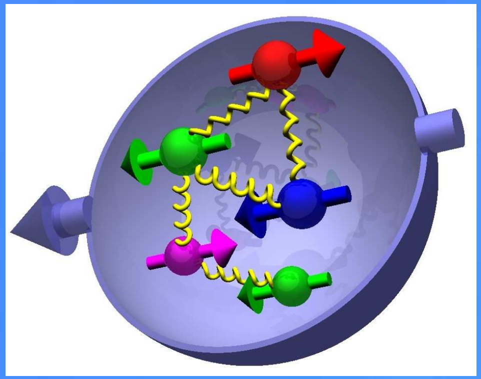


F_2 from HERA tells:

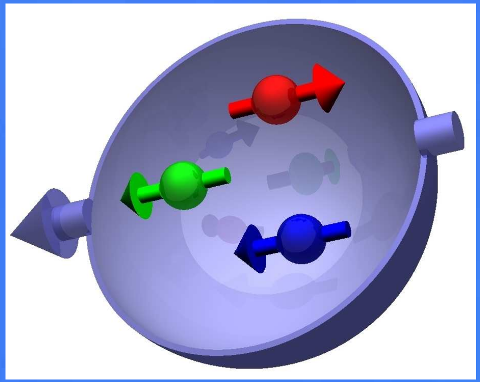
Gluons are important !

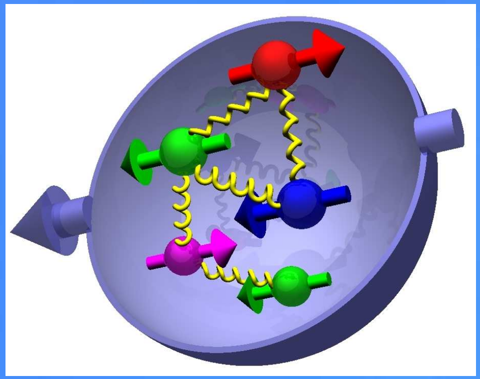
$\Longrightarrow$ **sea quarks** $\mathbf{\Delta q_s}$

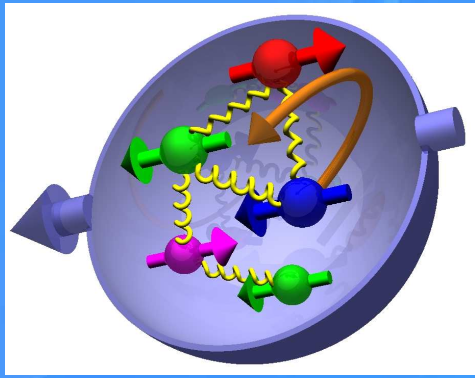
$\Longrightarrow$ $\mathbf{\Delta G}$

$$\frac{1}{2} = \frac{1}{2}(\mathbf{\Delta u_v} + \mathbf{\Delta d_v} + \underbrace{\Delta q_s}_{\mathbf{\Delta u_s, \Delta d_s, \Delta \bar{u}, \Delta \bar{d}, \Delta s, \Delta \bar{s}}}) + \mathbf{\Delta G}$$

The Spin Structure of the Nucleon







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Full description of J_q & J_g

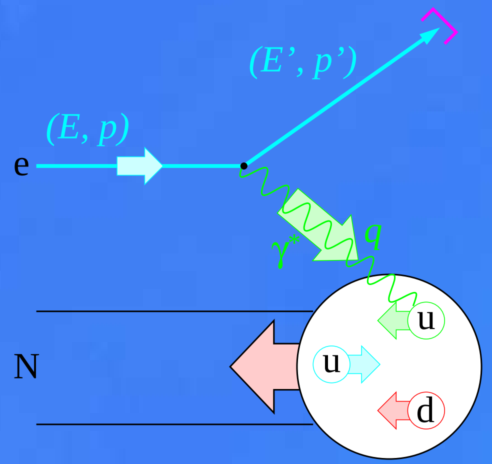
needs

orbital angular momentum

$$\frac{\mathbf{1}}{\mathbf{2}} = \frac{\mathbf{1}}{\mathbf{2}} \underbrace{(\Delta u_v + \Delta d_v + \Delta q_s)}_{\mathbf{\Delta\Sigma}} + \mathbf{\Delta G} + \mathbf{L_q} + \mathbf{L_g}$$

DIS Kinematics

Inclusive Scattering:



detect scattered lepton

$$Q^2 \stackrel{lab}{=} 4EE' \sin^2(\tfrac{\theta}{2}) \qquad \nu \stackrel{lab}{=} E - E'$$

$$W^2 \stackrel{lab}{=} M^2 + 2M\nu - Q^2$$

$$x \stackrel{lab}{=} \frac{Q^2}{2M\nu} \qquad y \stackrel{lab}{=} \frac{\nu}{E} = \frac{p \cdot q}{p \cdot k}$$

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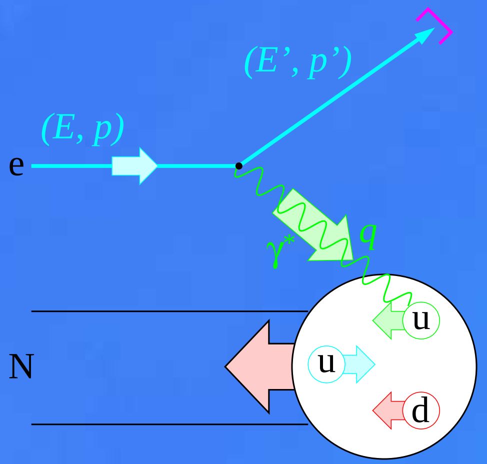

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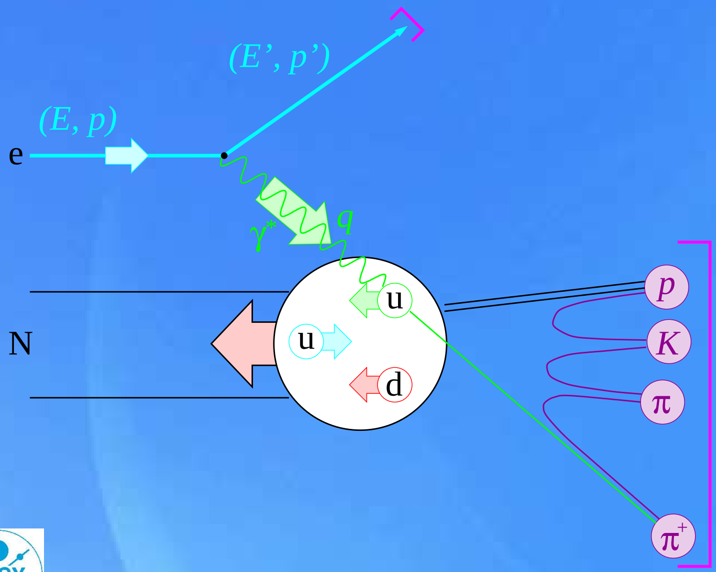
Semi-Inclusive Scattering:



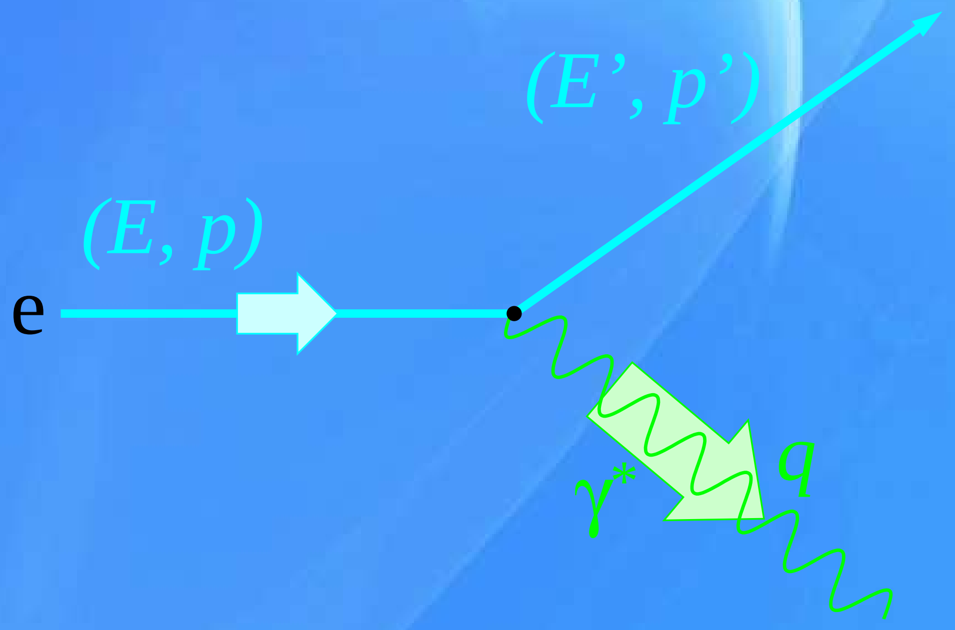
detect scattered lepton and produced hadrons

$$\eta = \frac{log(E^h_{cm} - p^h_{||})}{2*(E^h_{cm} + p^h_{||})}$$

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

Experimental Prerequisites

- **Longitudinally polarized lepton beam**



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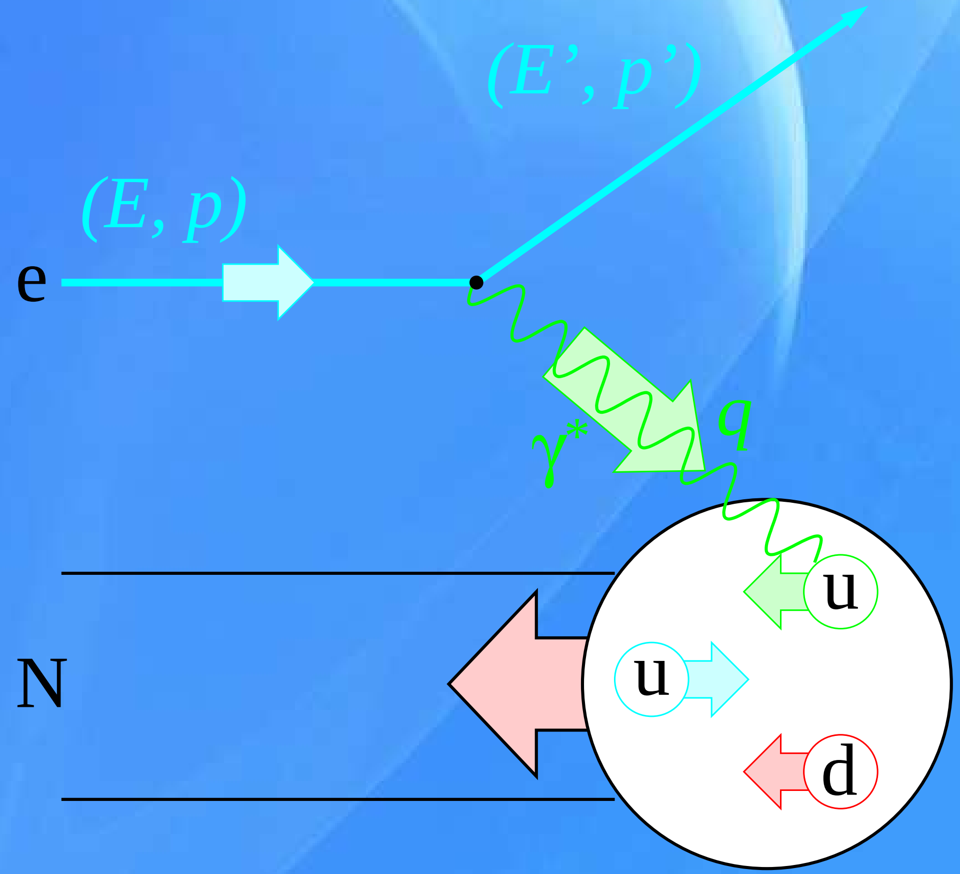
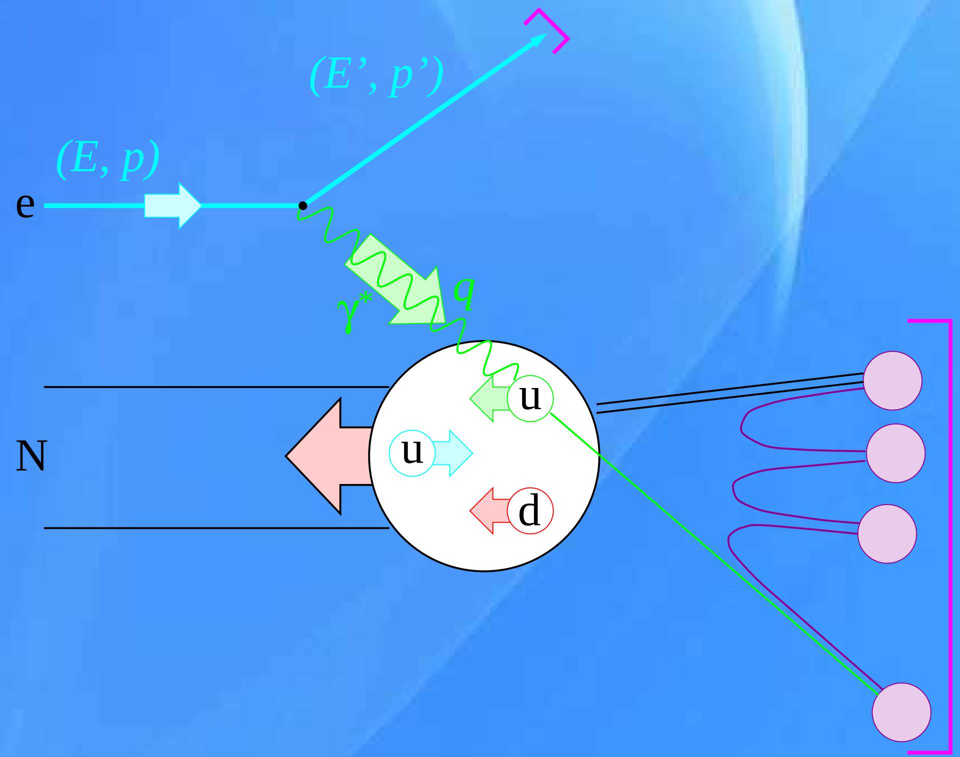
- **Longitudinally polarized lepton beam**
- **Longitudinally polarized nuclear target**



Experimental Prerequisites

- **Longitudinally polarized lepton beam**
- **Longitudinally polarized nuclear target**
- **Large geometrical acceptance**
  - **small angles:**
    limited by synchrotron radiation
  - **big angles:**
    limited by money



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- Longitudinally polarized lepton beam
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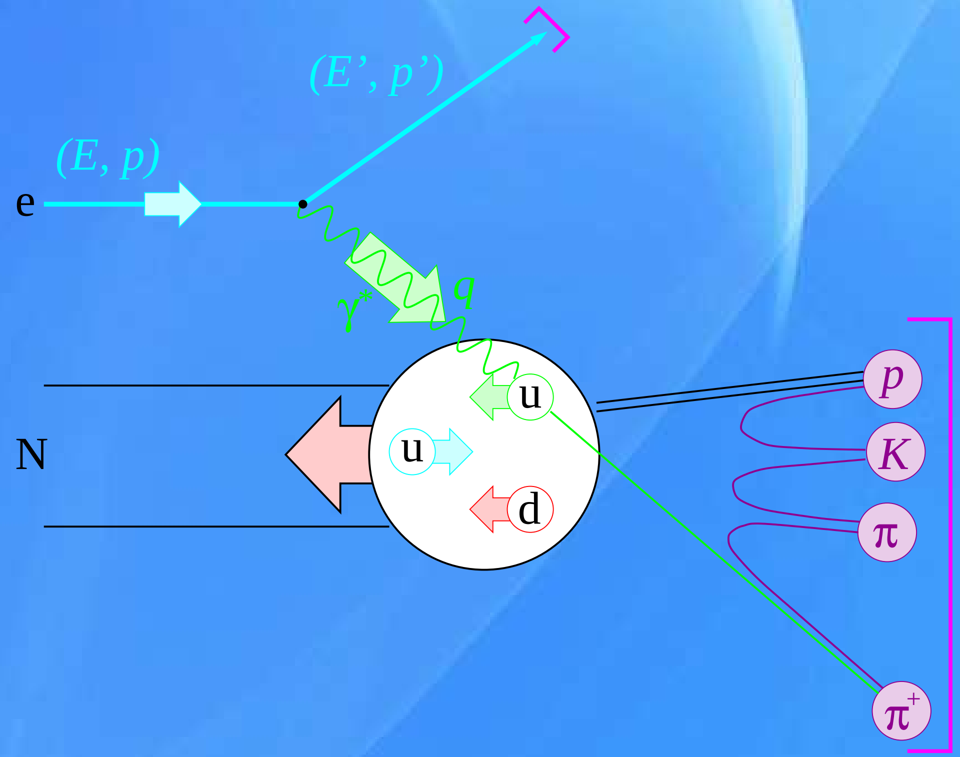

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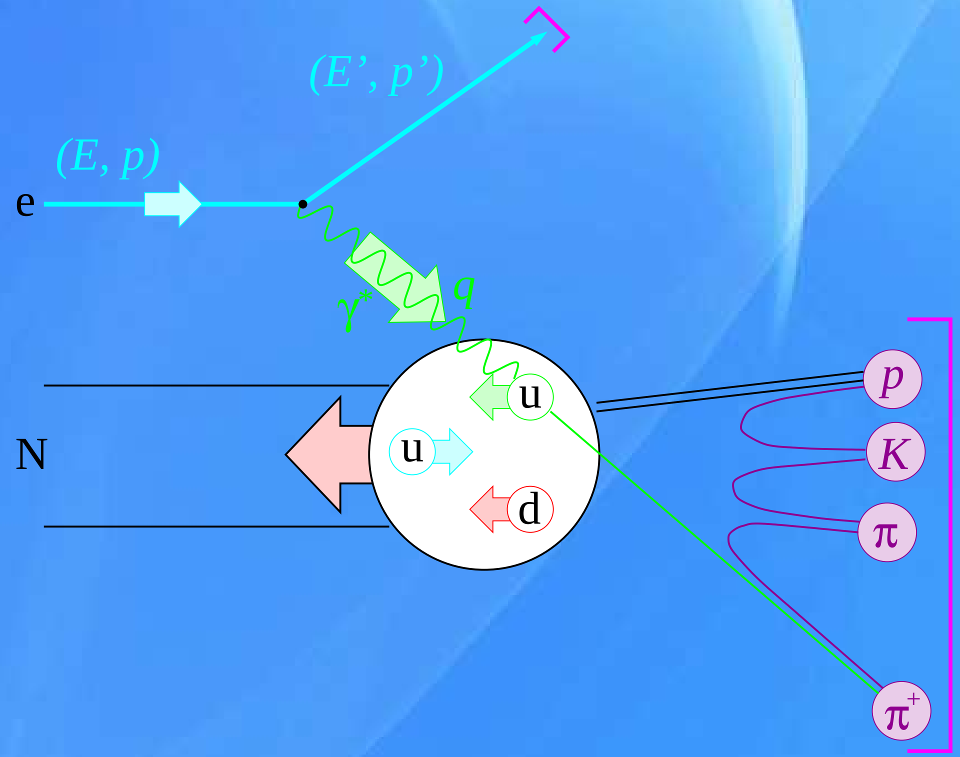
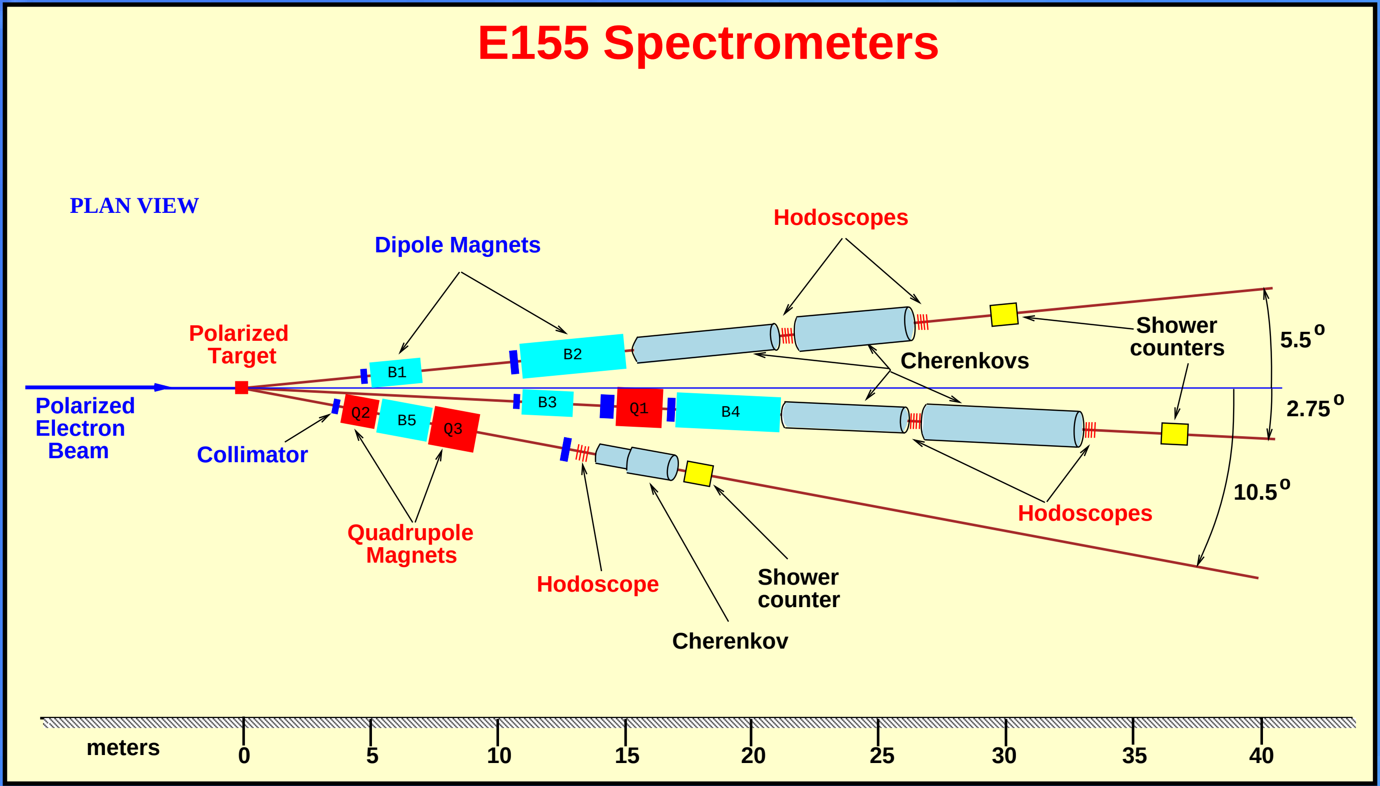


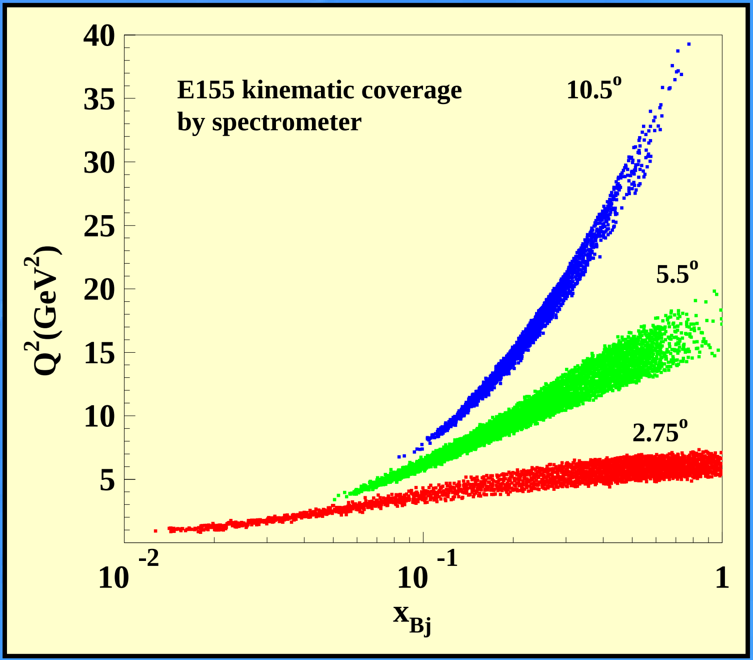
so far only "fixed target" experiments at:

SLAC CERN DESY

The SLAC Spectrometers



Inclusive Scattering only

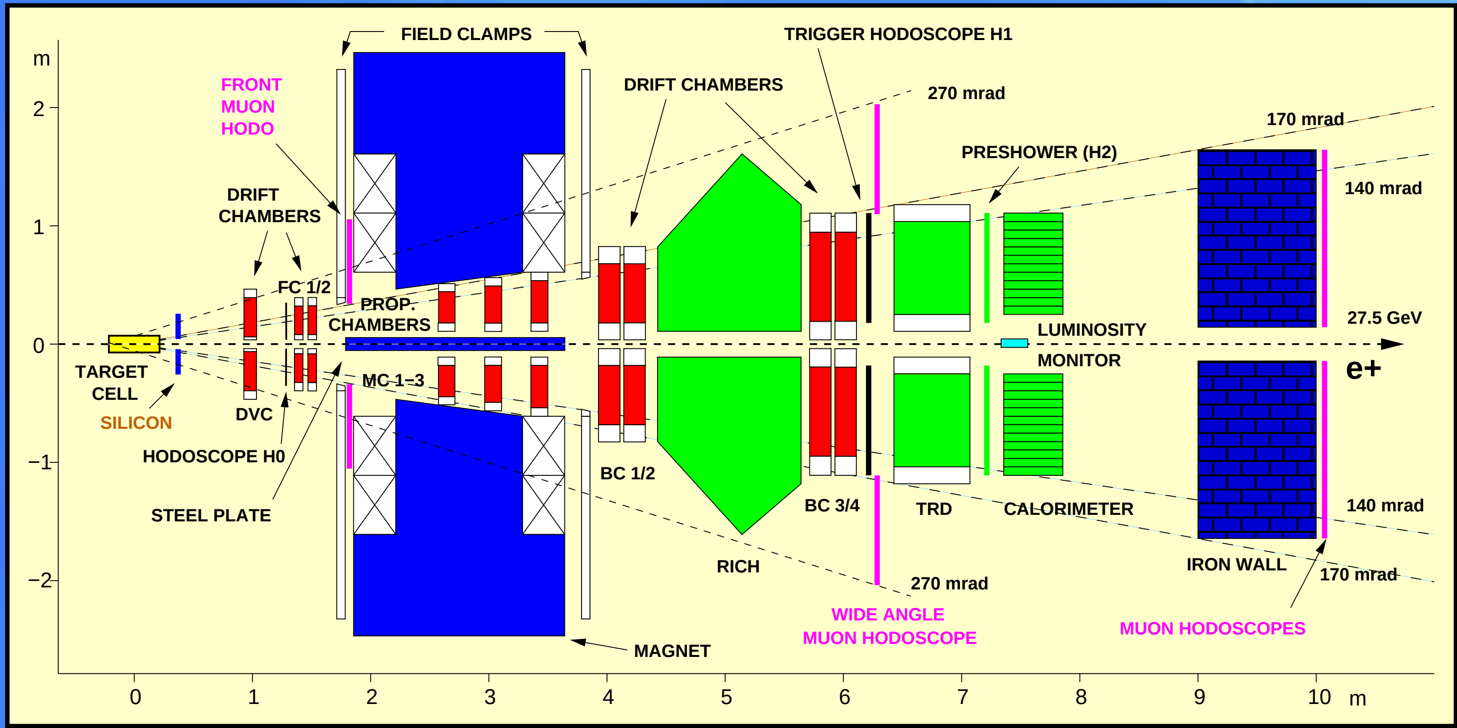


Reconstruction: very small angular coverage

Target: polarized solid state targets (NH_3 / LiD)
Big dilution factor

Particle ID: Lepton-Hadron separation

The HERMES Detector



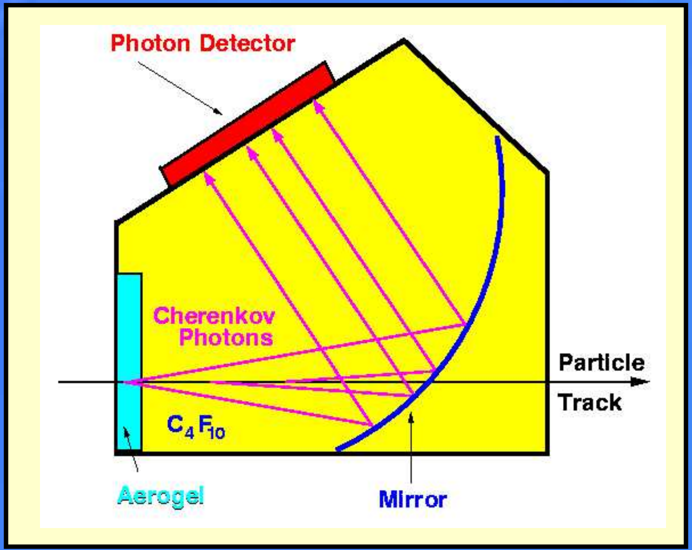
Kinematic Range: 0.02 $\leq$ x $\leq$ 0.8 at $Q^2 \geq 1GeV^2$ and W $\geq$ 2GeV
$\Theta_x \leq$ 175 mrad, 40 mrad $\leq \Theta_y \leq$ 140 mrad

Reconstruction: δp/p 1.0 - 2.0%, $\delta\Theta \leq$ 0.6mrad

Internal Gas Target: $\overrightarrow{He}$, $\overrightarrow{D}$, $\overrightarrow{H}$, $H^{\uparrow}$ unpol: H_2, D_2, He, N_2, Ne, Ar, Kr

Particle ID: TRD, Preshower, Calorimeter
$\Rightarrow$ 1997: $\check{C}$erenkov 1998 $\Rightarrow$: RICH + Muon-ID

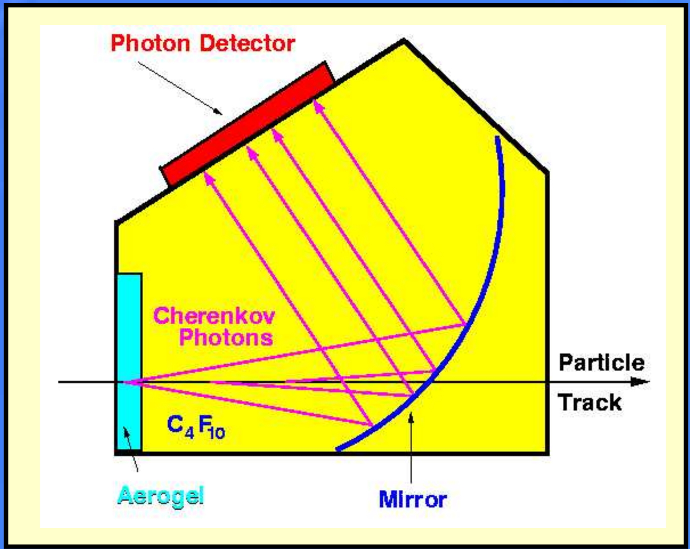
The HERMES RICH



Dual Radiator RICH

Aerogel: n = 1.03
C_4F_{10}: n = 1.0014

The HERMES RICH



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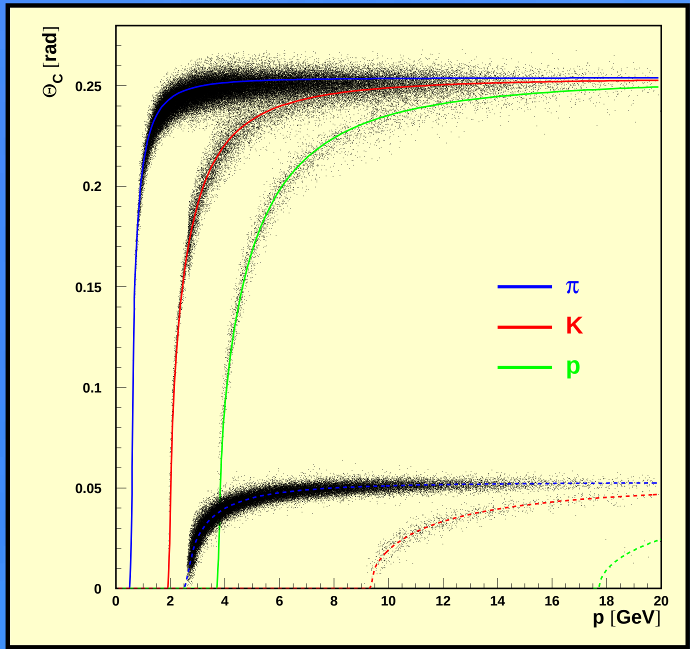

Particle idetification:

$$\cos\Theta_c = \frac{1}{\beta n}$$

threshold behaviour:

$$p = \frac{m\beta c}{\sqrt{1-\beta^2}}$$

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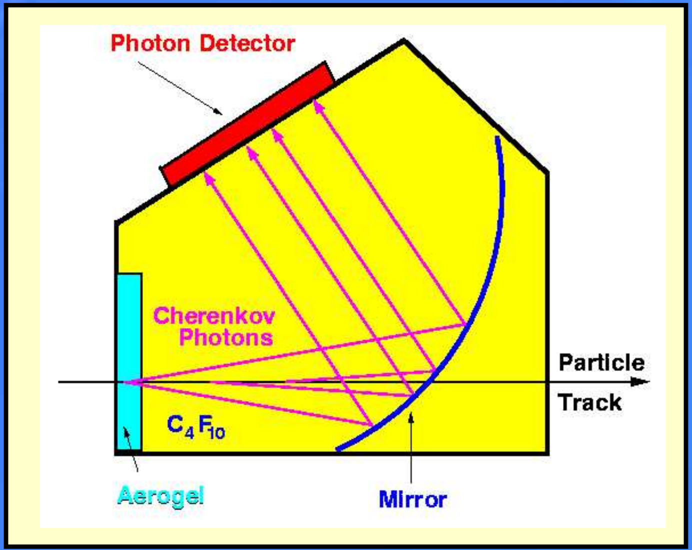

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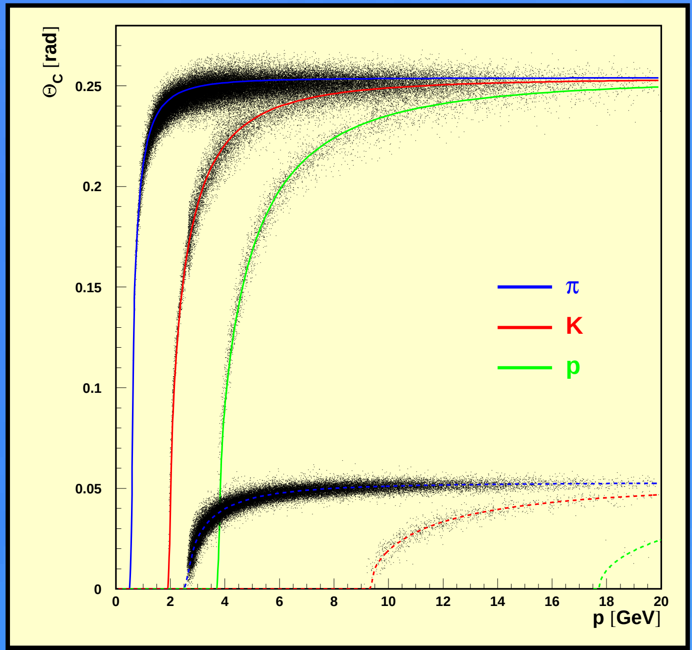

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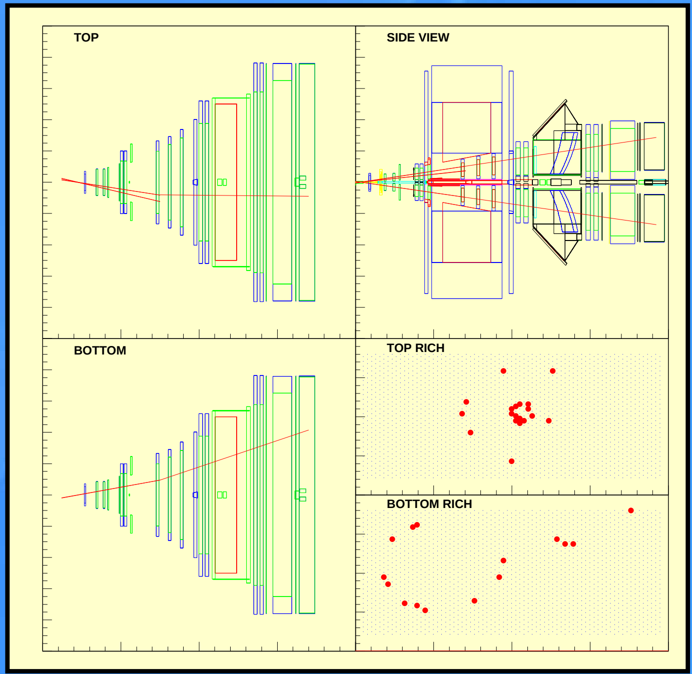
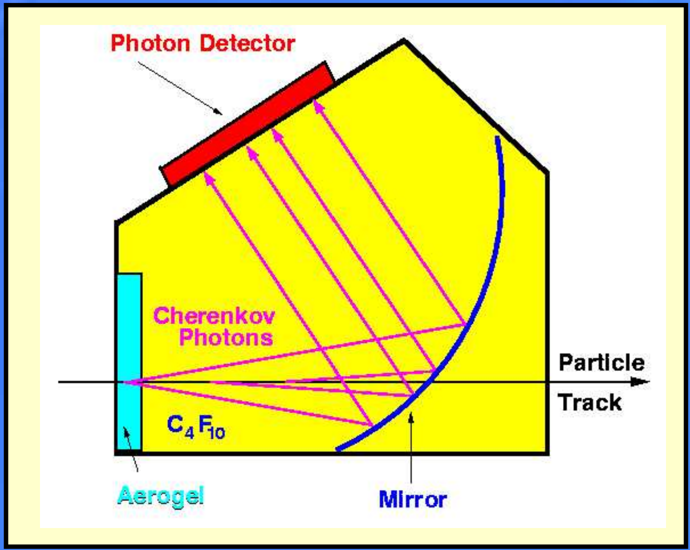


Real πK event

The HERMES RICH



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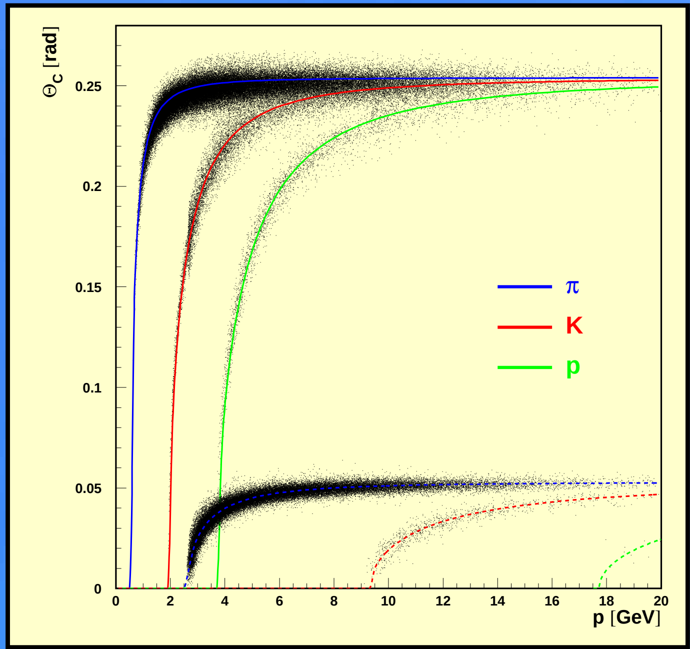

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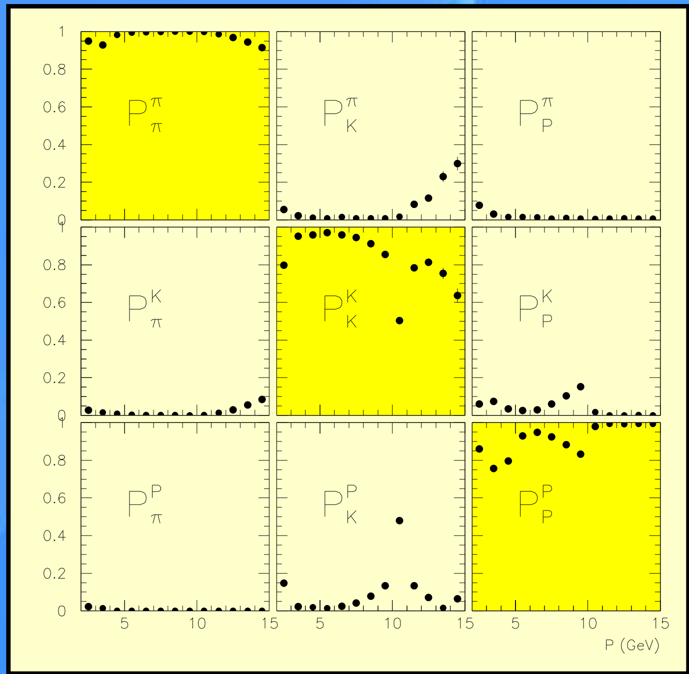


detection efficencies
misidentifications

Lab	Experiment	Year	Beam			Tar get			Measure
			Energy	Type	P_B	Type	P_T	f	
SLAC	E80	75	10-16 GeV	e^-	0.85	H-butanol	0.50	0.13	A_1^p
	E130	80	16-23 GeV	e^-	0.81	H-butanol	0.58	0.15	A_1^p
	E142	92	19-26 GeV	e^-	0.39	^{3}He	0.35	0.35	g_1^n
	E143	93	10-29 GeV	e^-	0.85	NH_3	0.70	0.15	g_1^p
	"	"	"	"	"	ND_3	0.25	0.24	g_1^d
	E154	95	48 GeV	e^-	0.83	^{3}He	0.38	0.55	g_1^n
	E155	97	48 GeV	e^-	0.81	NH_3	0.80	0.15	g_1^p
	"	"	"	"	"	LiD	0.22	0.36	g_1^d
	E155X	99	29/32 GeV	e^-	0.81	NH_3	0.70	0.16	g_2^p
	"	"	"	"	"	LiD	0.22	0.36	g_2^d
CERN	EMC	85	200 GeV	μ^+	0.79	NH_3	0.78	0.16	g_1^p
	SMC	92	100 GeV	μ^+	0.81	D-butanol	0.40	0.19	$g_1^{d,n}$
	"	93	190 GeV	μ^+	0.80	H-butanol	0.86	0.12	g_1^p, g_2^p
	"	94/95	"	μ^+	0.80	D-butanol	0.50	0.20	g_2^d
	"	96	"	μ^+	0.80	NH_3	0.89	0.16	g_1^p
DESY	HERMES	95	28 GeV	e^+	0.55	^{3}He	0.46	1.00	g_1^n
	"	96/97	"	"	"	H	0.88	1.00	g_1^p
	"	98-00	"	$e^{-/+}$	"	D	0.85	1.00	g_1^d, b_1^d
	"	$\geq$ 01	"	$e^\pm$	"	H	0.85	1.00	
CERN	COMPASS	$\geq$ 01 "	160 GeV "	μ^+ "	0.80 0.80	NH_3 LiD	0.90 0.50	0.16 0.50	
BNL	RHIC	$\geq$ 01	200 GeV	p	0.70	200 GeV p	0.70	1.0	

Polarized Deep Inelastic Scattering

Cross Section: $\frac{d^2\sigma}{d\Omega dE^2} = \frac{\alpha^2 E'}{Q^2 E} \underbrace{L_{\mu\nu}(k,q,s)}_{\text{leptonic}} \underbrace{W^{\mu\nu}(P,q,S)}_{\text{hadronic}}$

$L_{\mu\nu}$: **purely electromagnetic $\Longrightarrow$ calculable in QED**

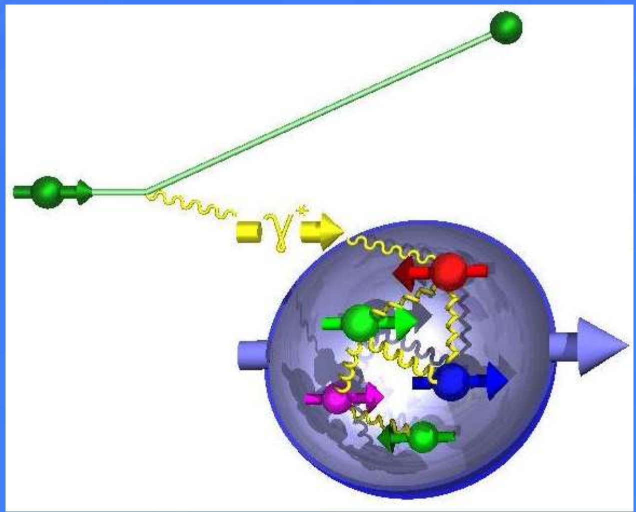
$$W^{\mu\nu} = -g^{\mu\nu} F_1(x,Q^2) + \frac{p^\mu p^\nu}{\nu} F_2(x,Q^2)$$
$$+ i\epsilon^{\mu\nu\lambda\sigma} \frac{q_\lambda}{\nu} \left(S_\sigma g_1(x,Q^2) + \frac{1}{\nu}(p\cdot q S_\sigma - S\cdot q p_\sigma) g_2(x,Q^2) \right)$$

(for spin 1 Target)
$$-b_1(x,Q^2) r_{\mu\nu} + \frac{1}{6} b_2(x,Q^2)(s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu})$$
$$+\frac{1}{2} b_3(x,Q^2)(s_{\mu\nu} - u_{\mu\nu}) + \frac{1}{2} b_4(x,Q^2)(s_{\mu\nu} - t_{\mu\nu})$$

F_1,F_2: **Unpolarized Structure Functions**
$\Longrightarrow$ **describe momentum distribution of quarks**

g_1,g_2: **Polarized Structure Functions**
$\Longrightarrow$ **describe spin distribution of quarks**

Virtual Photon Asymmetry



$\sigma_{3/2} \sim \mathbf{q}^{-}(\mathbf{x})$

$\vec{S}_{\gamma}$ + $\vec{S}_{N}$ = 3/2

$\vec{S}_{N}$ = $-\vec{S}_{q}$

- **Virtual photon γ^* can only couple to quarks of opposite helicity**

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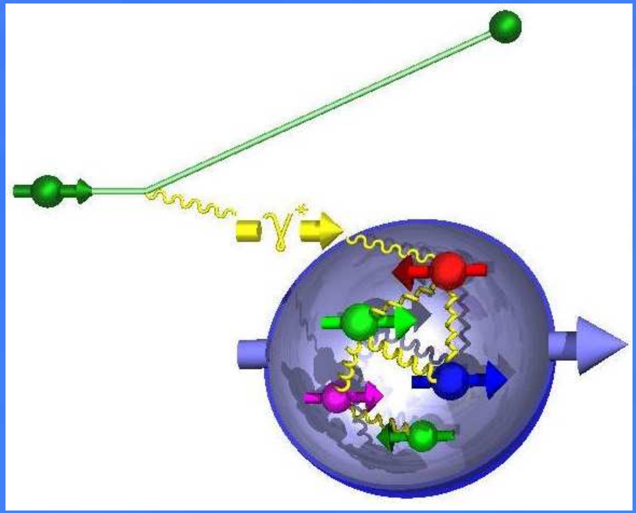

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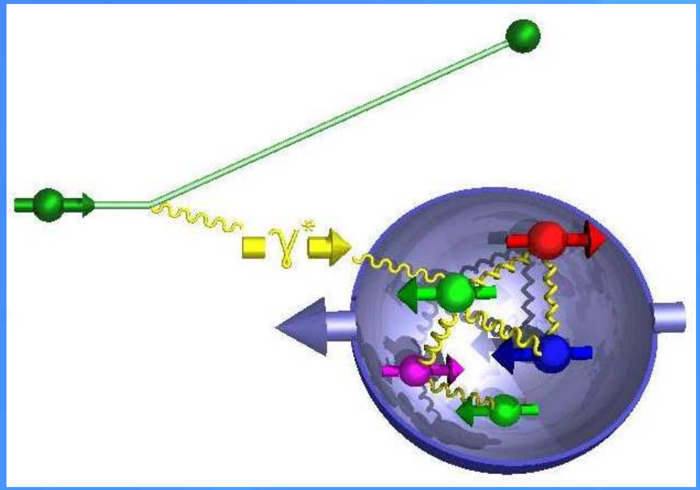

$\sigma_{1/2} \sim \mathbf{q}^{+}(\mathbf{x})$

$\vec{S_\gamma}$ + $\vec{S_N}$ = 1/2

$\vec{S_N}$ = $\vec{S_q}$

- **Virtual photon γ^* can only couple to quarks of opposite helicity**
- **Select $\mathbf{q}^{+}(\mathbf{x})$ or $\mathbf{q}^{-}(\mathbf{x})$ by changing the orientation of target nucleon spin or helicity of incident lepton beam**

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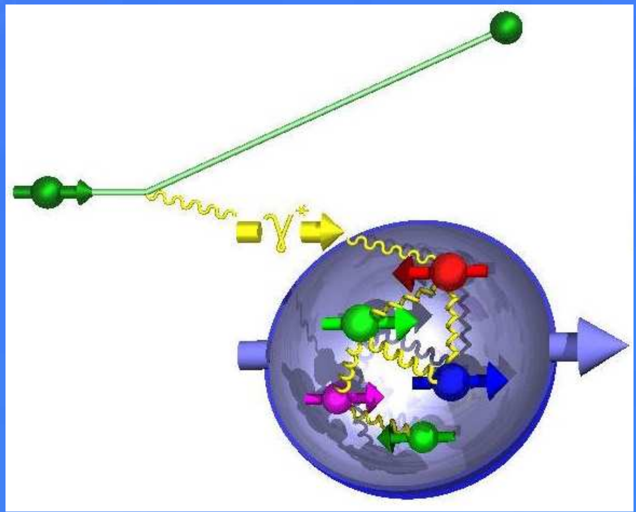
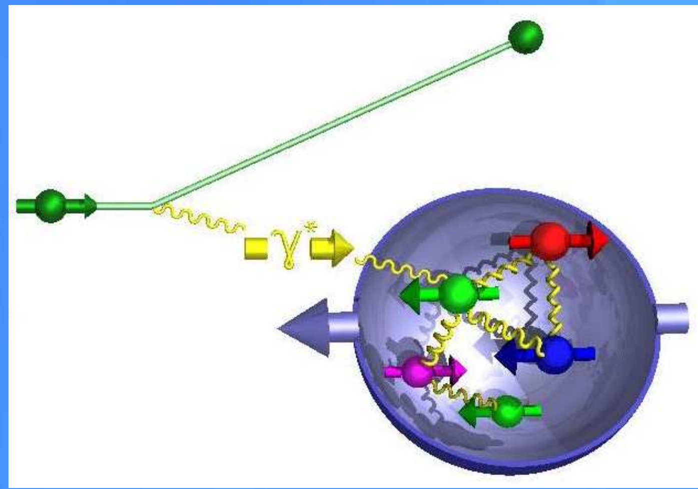


$\sigma_{3/2} \sim \mathbf{q^-(x)}$

$\vec{S}_\gamma + \vec{S}_N = 3/2$

$\vec{S}_N = -\vec{S}_q$



$\sigma_{1/2} \sim \mathbf{q^+(x)}$

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- **Virtual photon γ^* can only couple to quarks of opposite helicity**
- **Select $\mathbf{q^+(x)}$ or $\mathbf{q^-(x)}$ by changing the orientation of target nucleon spin or helicity of incident lepton beam**

Quark Helicity Distributions:

$$\Delta q_f(x) := q_f^+(x) - q_f^-(x)$$ $(f : u, d, s, \overline{u}, \overline{d}, \overline{s})$

$F_1(x)$ = $\frac{1}{2}\sum_i e_i^2(q_i^+(x) + q_i^-(x))$ = $\frac{1}{2}\sum_i e^2 q_i(x)$

$2xF_1$ measures the momentum distribution of quarks

$g_1(x)$ = $\frac{1}{2}\sum_i e_i^2(q_i^+(x) - q_i^-(x))$ = $\frac{1}{2}\sum_i e^2 \Delta q_i(x)$

g_1 measures the spin distribution of quarks

Virtual Photon Asymmetries:

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

Measurable Asymmetries:

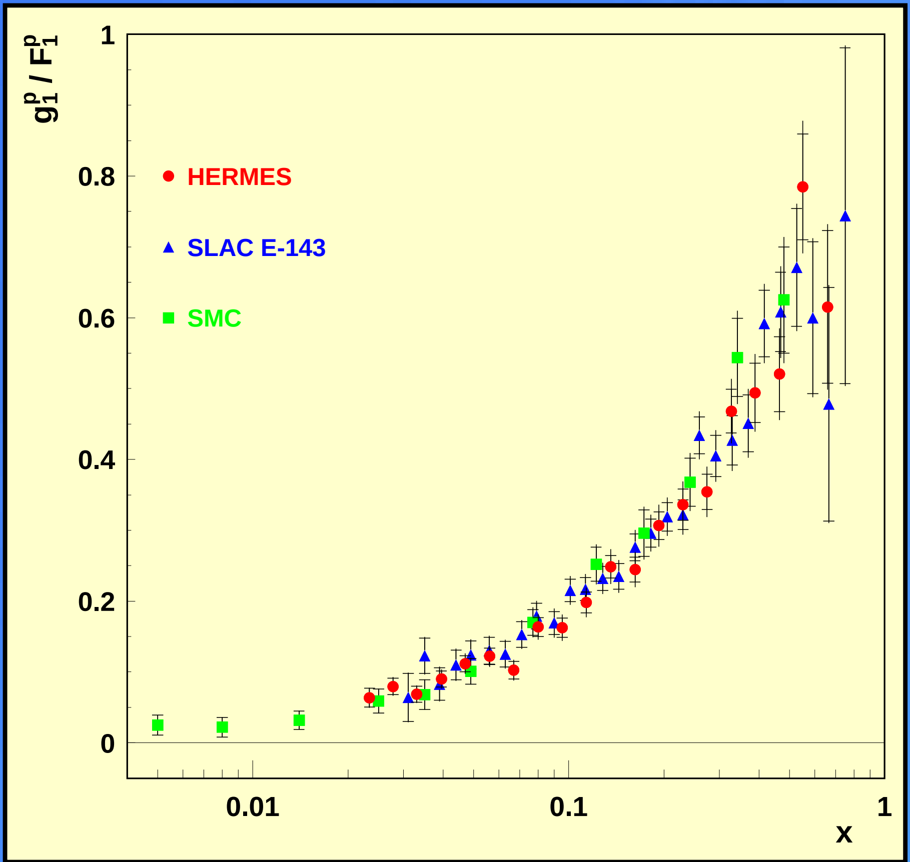
$$A_\parallel = \frac{\sigma^{\rightleftarrows} - \sigma^{\rightrightarrows}}{\sigma^{\rightleftarrows} + \sigma^{\rightrightarrows}} \qquad A_\perp = \frac{\sigma^{\uparrow\rightarrow} - \sigma^{\uparrow\leftarrow}}{\sigma^{\uparrow\rightarrow} + \sigma^{\uparrow\leftarrow}}$$

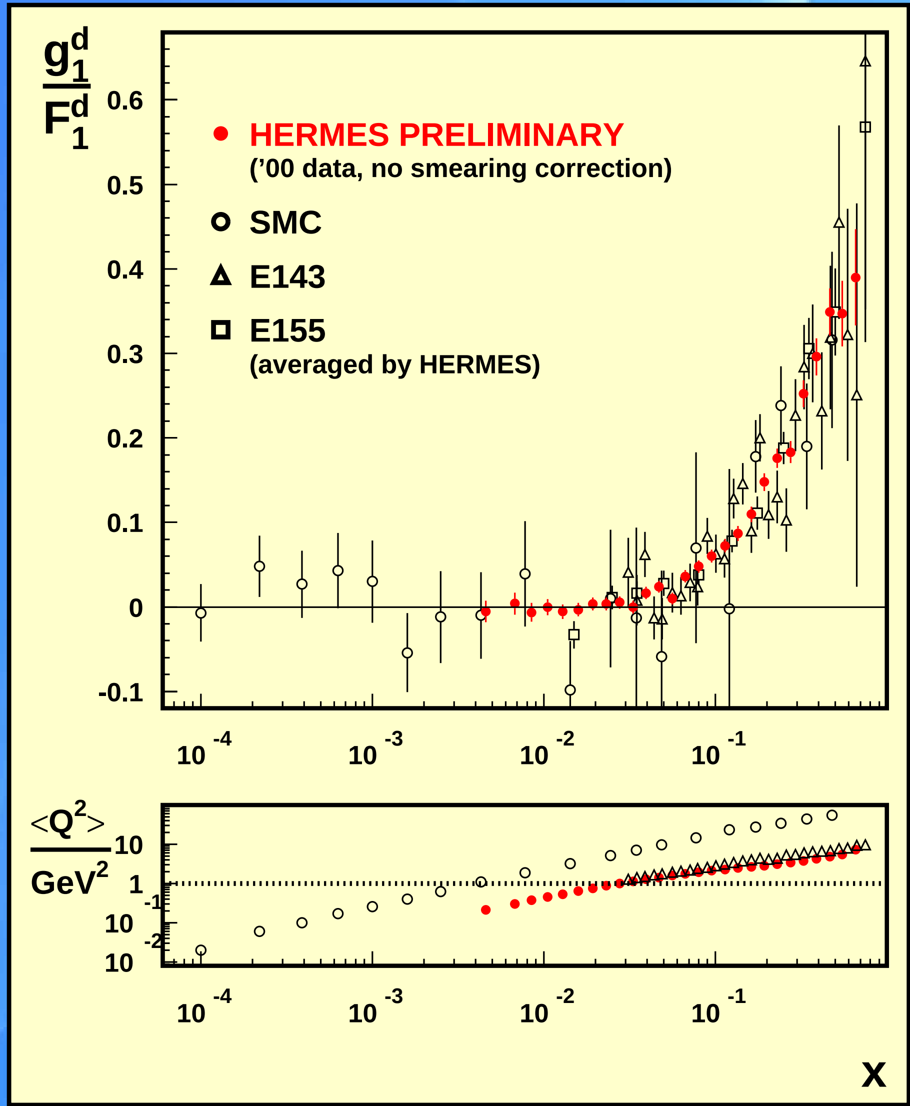
$$A_\parallel = D(A_1 + \eta A_2) \qquad A_\perp = d(A_2 + \xi A_1)$$

With: $D, d, R, \epsilon, \gamma, \xi, \eta$ **being kinematic factors**

World data on $g_1(x, Q^2)/F_1(x, Q^2)$

Proton $>$ Deuterium



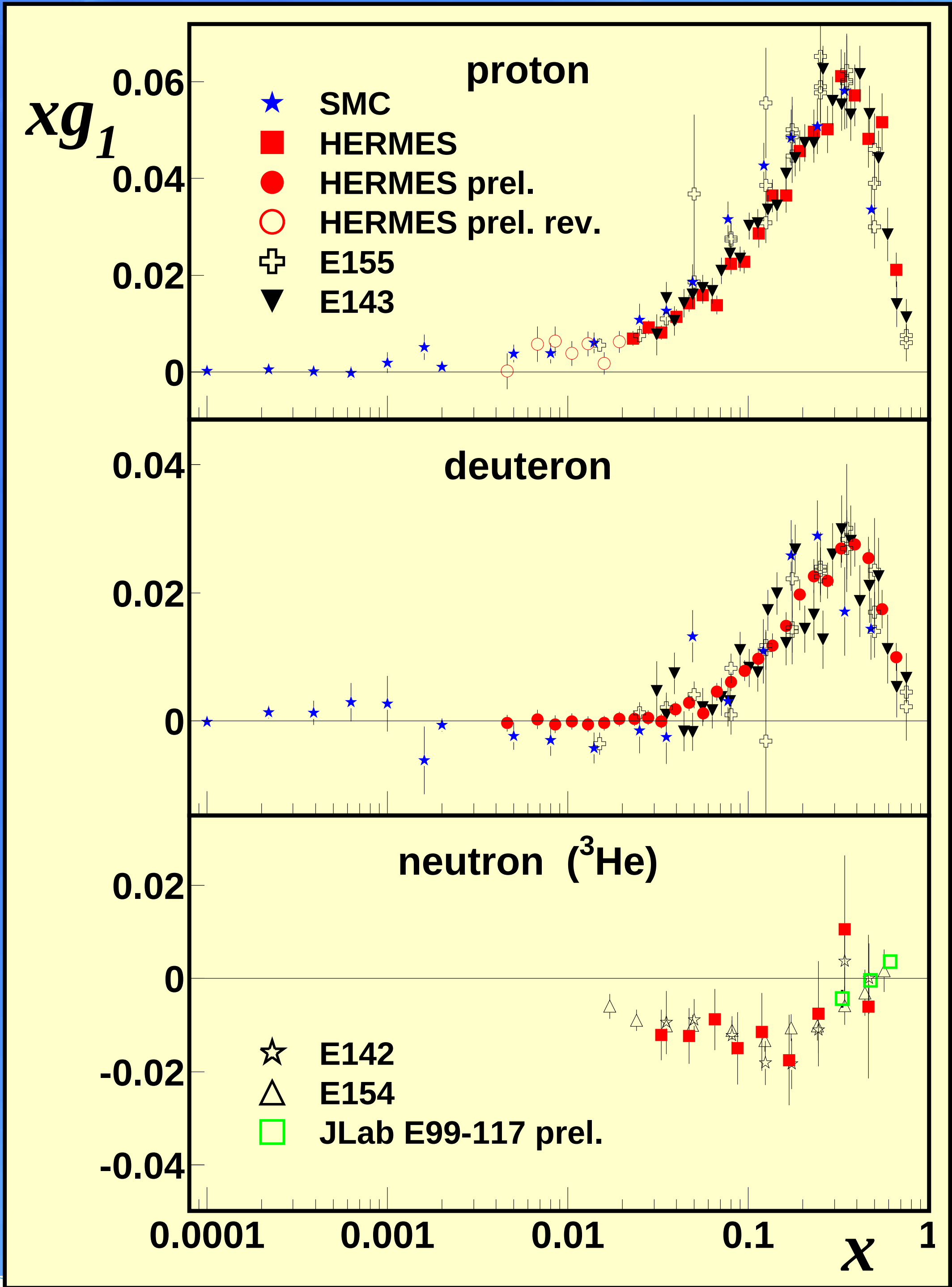


$$\mathbf{A}_{||} = \frac{1}{P_b P_t} \frac{N^{\leftrightarrows} L^{\rightrightarrows} - N^{\rightrightarrows} L^{\leftrightarrows}}{N^{\leftrightarrows} L^{\rightrightarrows} + N^{\rightrightarrows} L^{\leftrightarrows}}$$

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

Data given at measured $< Q^2 >$: 0.02 - 58 GeV^2

World data on $g_1(x, Q^2)$



$$g_1^p > g_1^D > g_1^n$$

Neglecting sea quarks

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

$$d : p + n$$

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

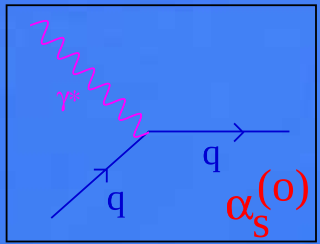
Isospin rotation

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

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

What does a sophisticated model say?

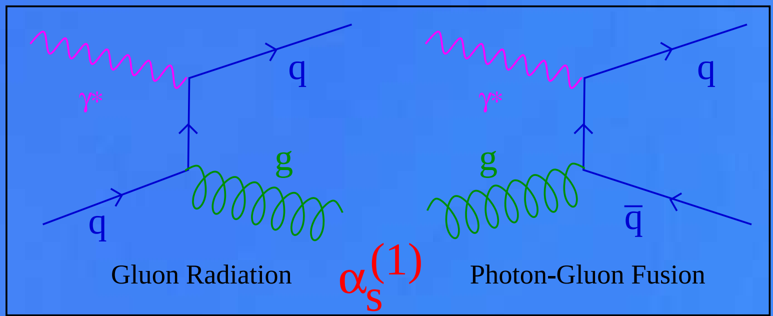
Beyond the Naive Parton Model



$\Longrightarrow$ **No gluons**

$$g_1^0(x) = \frac{1}{2}\sum e_q^2\, \Delta q(x)$$

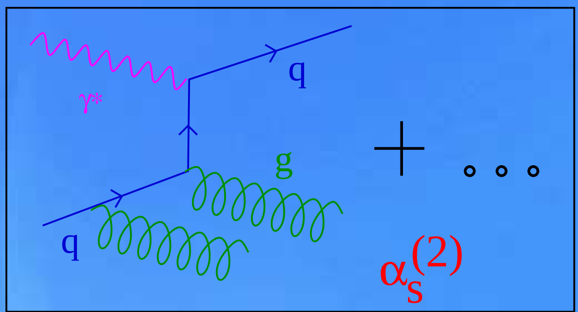
⇩



$\Longrightarrow$ **Quarks are re-defined with the inclusion of ΔG (weak dependence)**

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

⇩



$\Longrightarrow$ **g_1 becomes explicitly ΔG dependent**

$$g_1^{NLO}(x,Q^2) = g_1^{LO}(x,Q^2) + \frac{\alpha_s}{2\pi}\,\frac{1}{2}\sum e_q^2\left[\Delta q(x,Q^2)\otimes C_q + \Delta G(x,Q^2)\otimes C_G\right]$$

NLO-QCD Fit

- **In NLO there are two independent NS distributions and $\Delta\Sigma$ and ΔG**

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

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

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$$\frac{d}{d\ln Q^2}\Delta q_{NS} = \frac{\alpha_s}{2\pi} P^{NS}_{qq} \otimes \Delta q_{NS}$$
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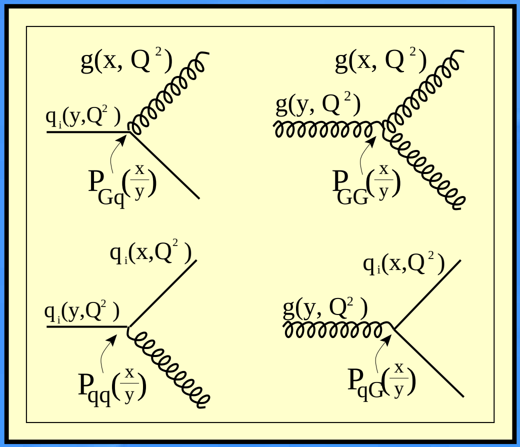
Splitting Functions



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- **Each distribution is parameterized at a starting Q_0^2:**

$$x\Delta q_i(x, Q_0^2) = \eta_i A_i \underbrace{x^{a_i}}_{\text{low } x} \overbrace{(1 + \gamma_i x + \rho_i x^{\frac{1}{2}})}^{\text{medium } x} \underbrace{(1-x)^{b_i}}_{\text{high } x}$$

NLO-QCD Fit

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- **Each distribution is parameterized at a starting Q^2_0:**

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- **They are evolved to Q^2_{meas} using the evolution equations to obtain g_1^{calc}**

NLO-QCD Fit

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- **The χ^2 is minimized $\chi^2 = \sum_{data}(g_1^{meas} - g_1^{calc})^2/\sigma^2_{stat}$**

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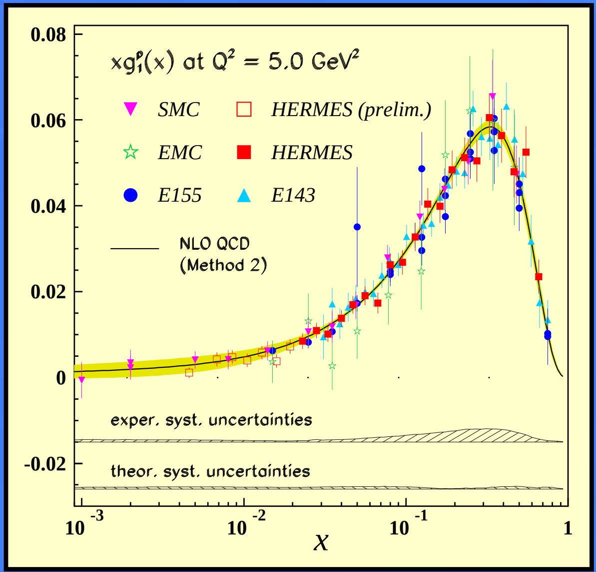
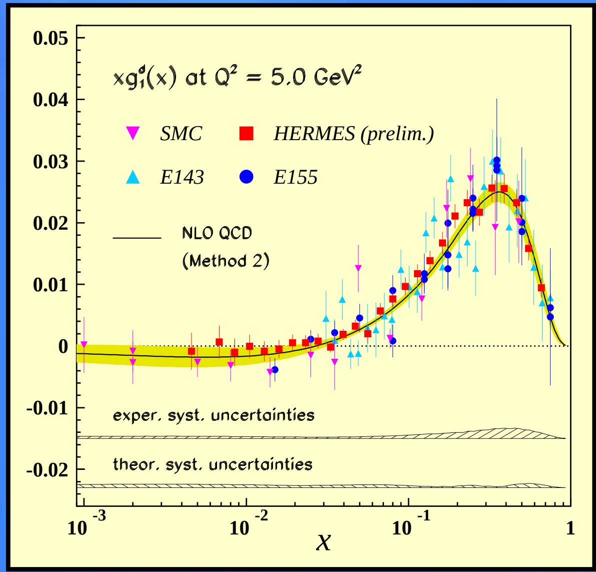
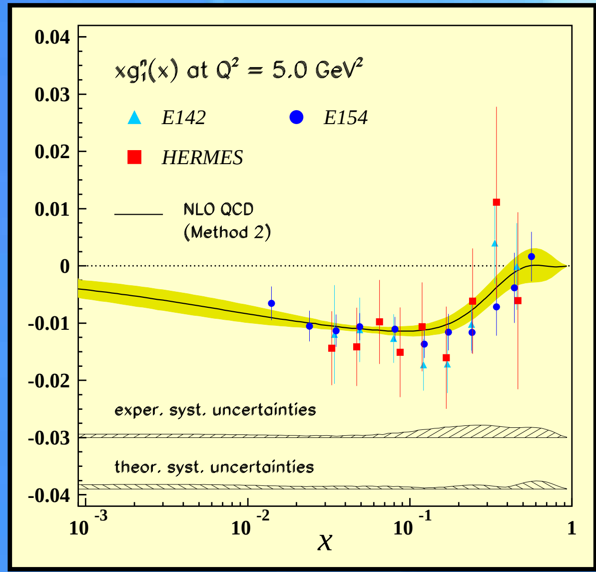
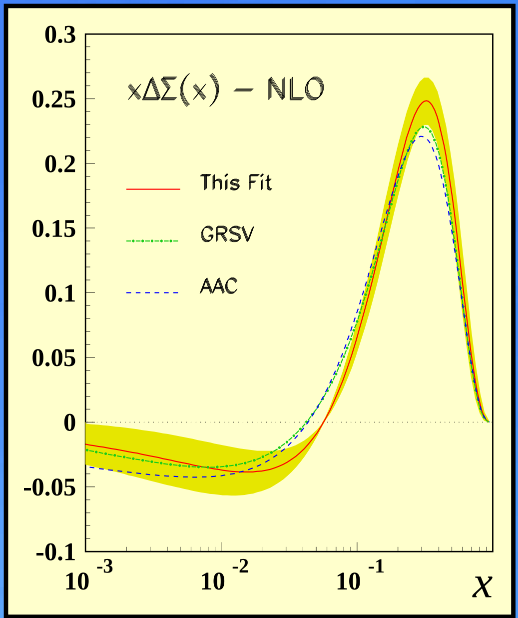
- The χ^2 is minimized $\chi^2 = \sum_{\mathrm{data}} (g_1^{\mathrm{meas}} - g_1^{\mathrm{calc}})^2 / \sigma^2_{\mathrm{stat}}$
- The parameters $a, b, \gamma, \ldots$ are evaluated

NLO-QCD Fit Results for $g_1(x, Q^2)$









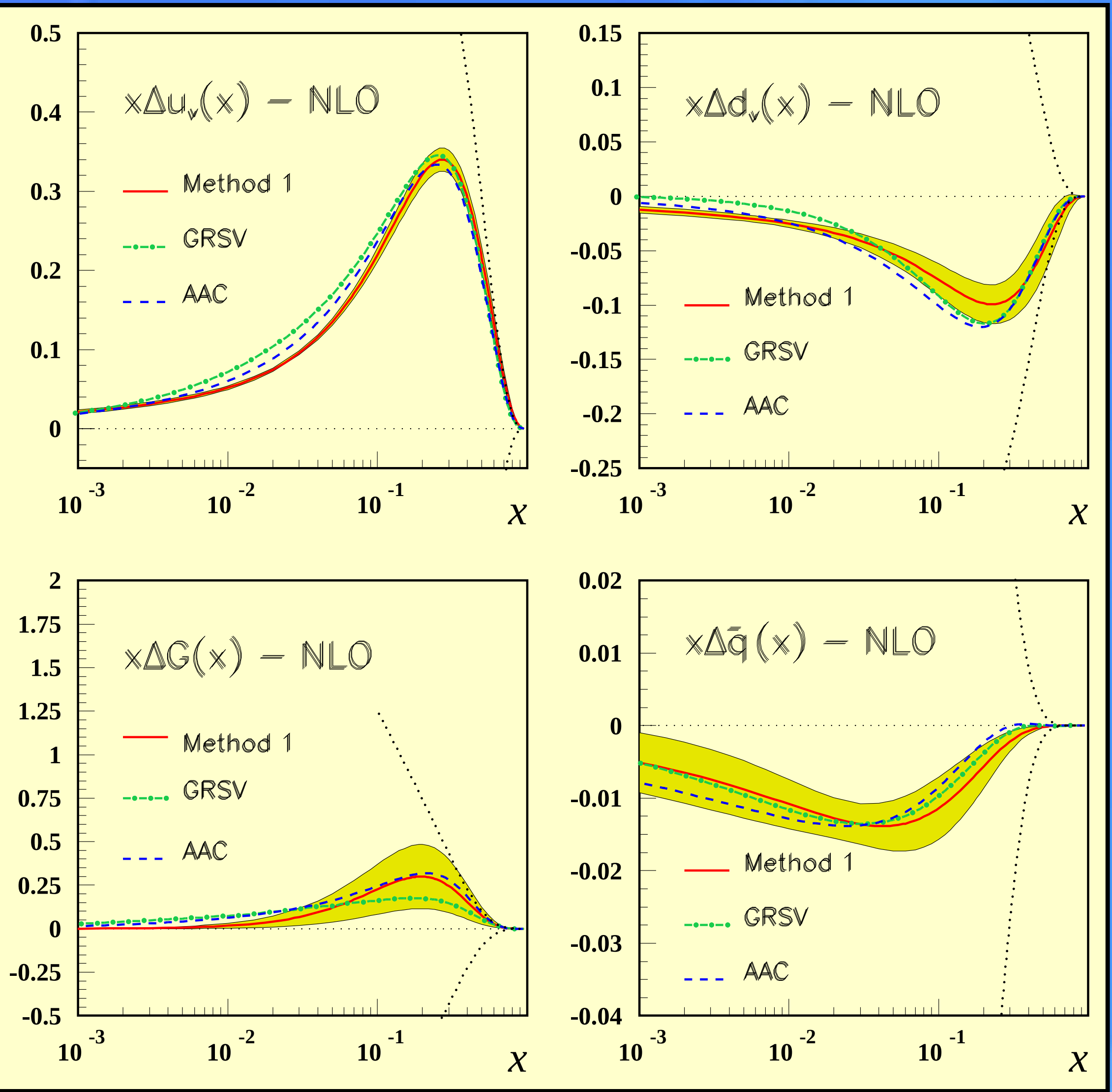
Good Description of $g_1^{p,d,n}(x, Q^2)$

BUT:

$$\Delta\Sigma = 0.201 \pm 0.103 \neq 1$$

Who carries the spin ?

NLO-QCD Fit Results for Different Flavors



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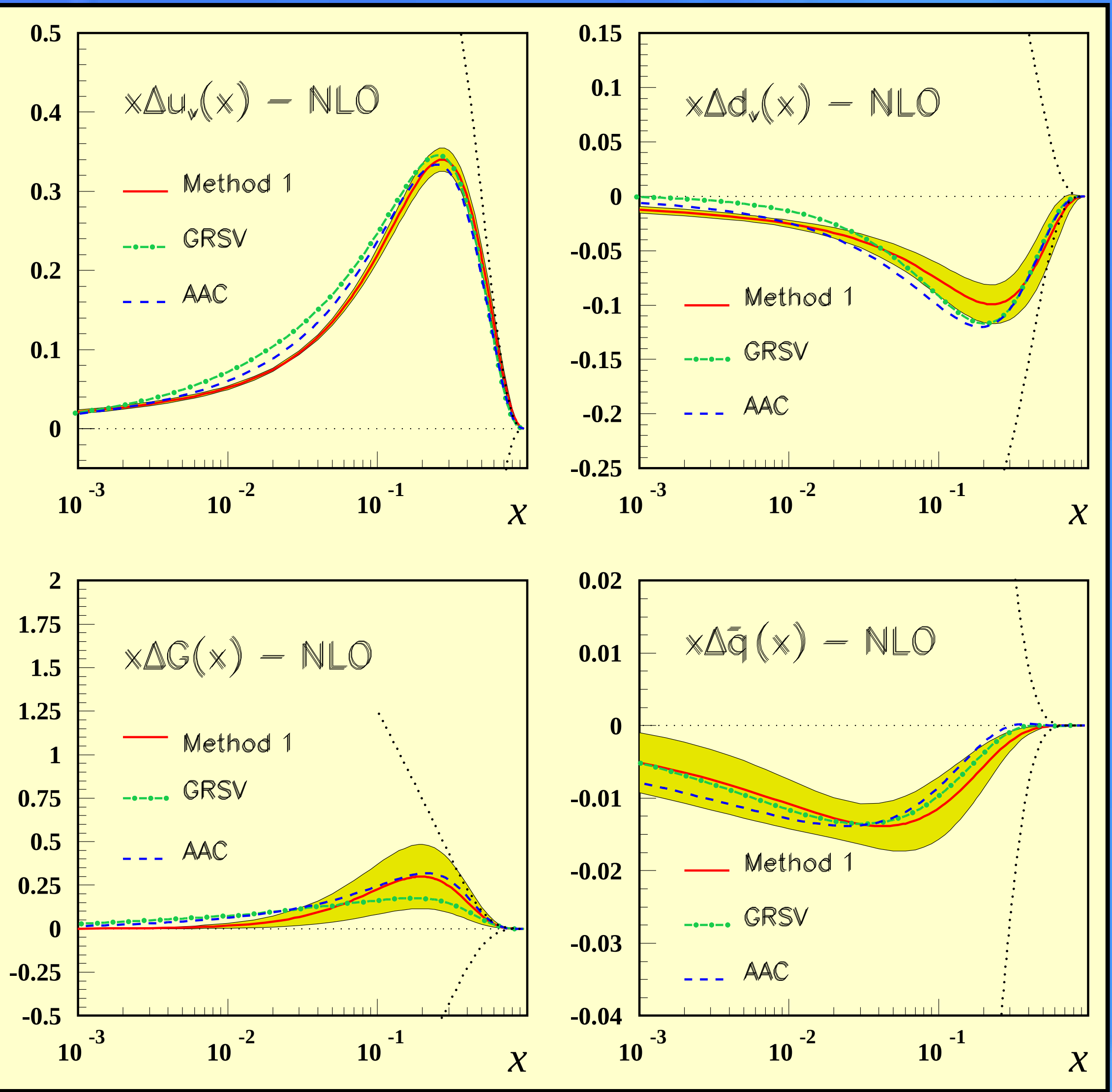
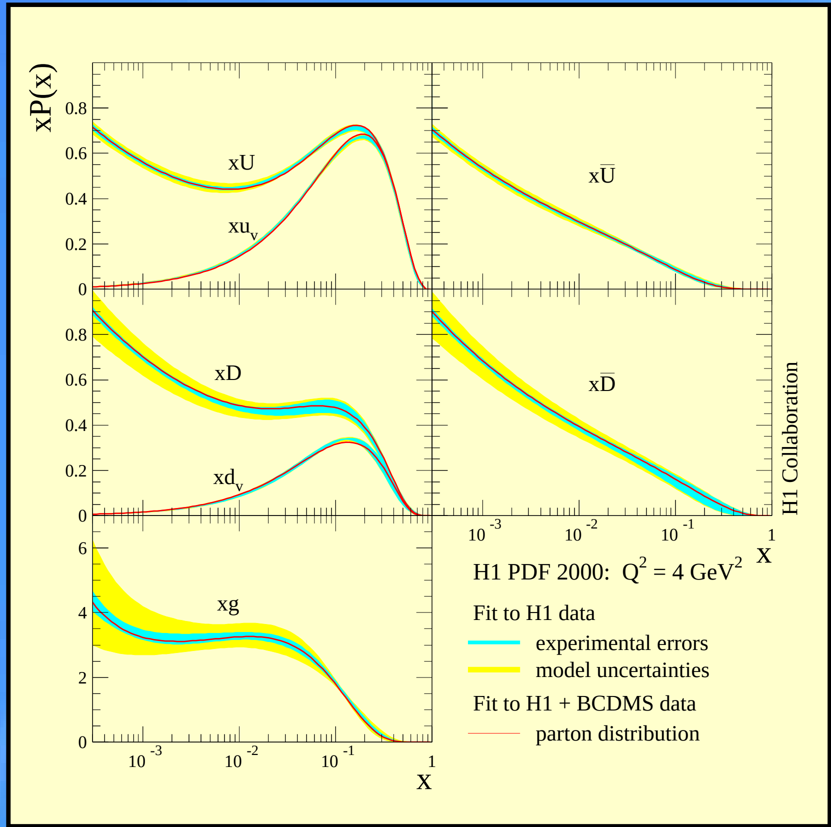
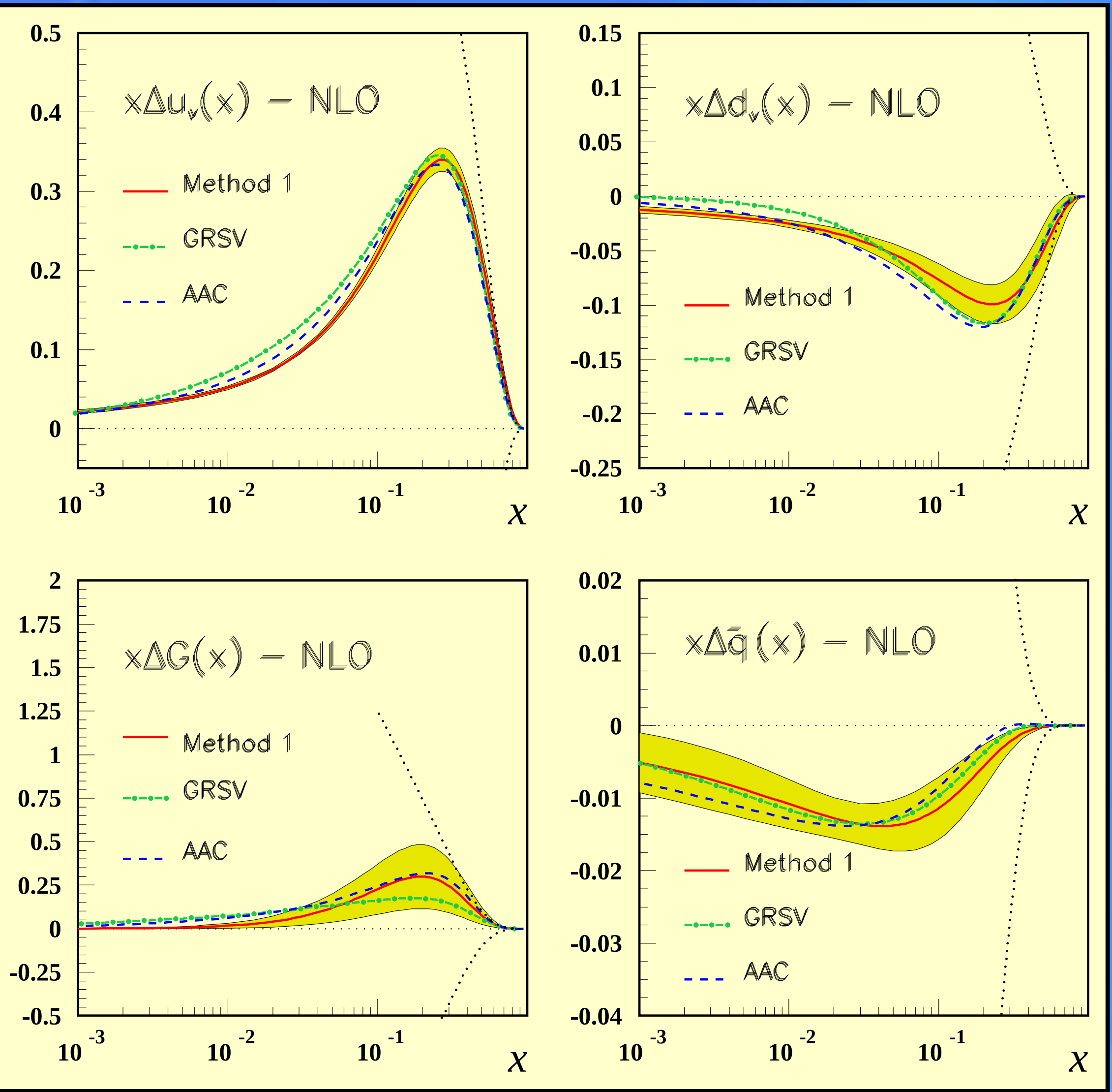


Δu_v and Δd_v well determined

Comparable accuracy as in unpolarised case



NLO-QCD Fit Results for Different Flavors



Δu_v and Δd_v well determined

$\Delta s(\bar{q})$ = -0.070 $\pm$ 0.028 (stat.) < 0

BUT

$$\Delta u_s = \Delta\bar{u} = \Delta d_s = \Delta\bar{d} = \Delta s = \Delta\bar{s}$$

is assumed

unpolarized PDFs:
SU(2) flavor symmetry breaking

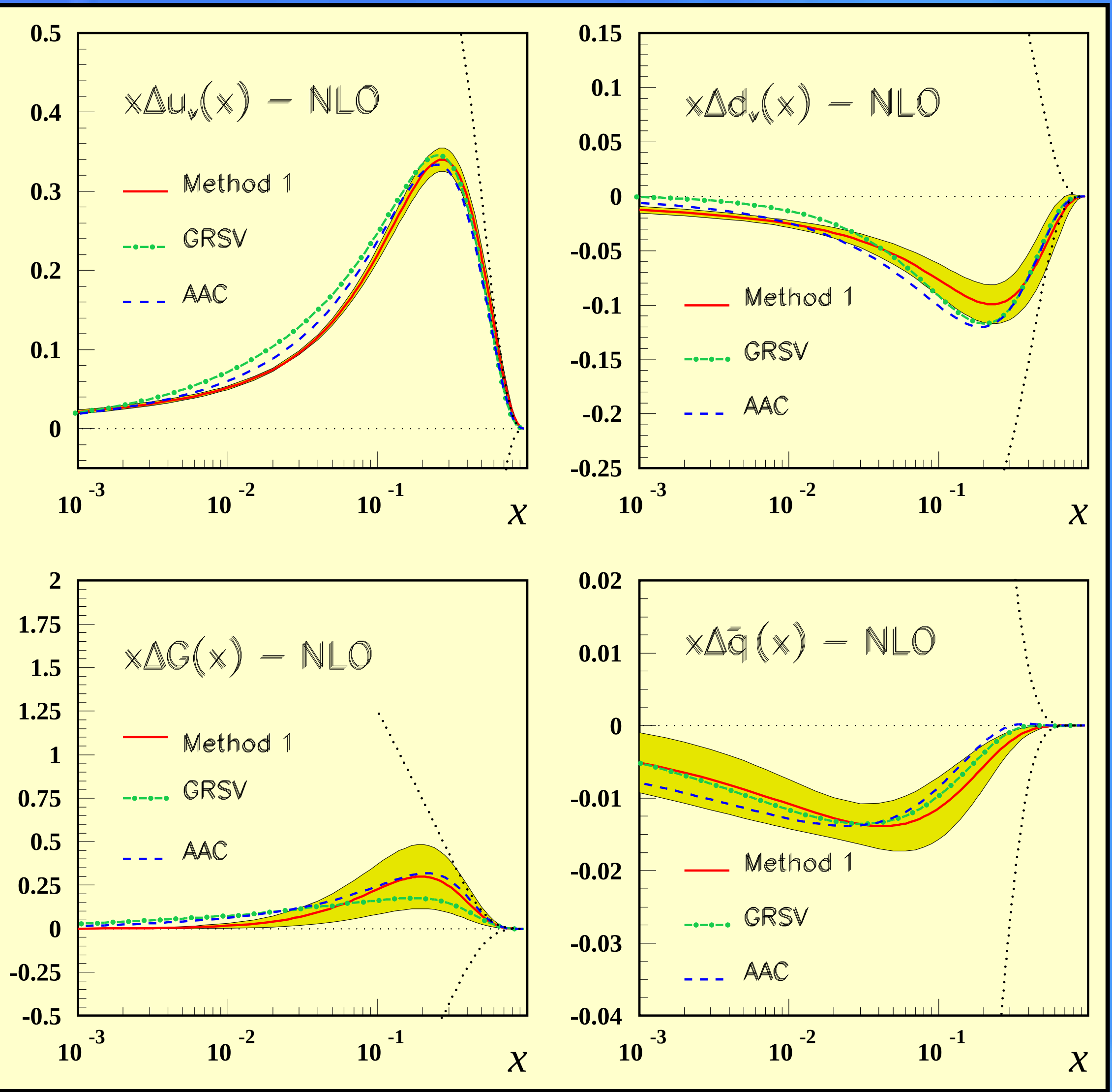
ΔG = 0.616 $\pm$ 0.388 (stat.) > 0

BUT Big error $\Longrightarrow$ small Q^2 lever arm

GRSV: Glück et al. hep/ph 0011215
AAC: Goto et al. hep/ph 0001046

at Q^2 = 4 GeV^2

NLO-QCD Fit Results for Different Flavors



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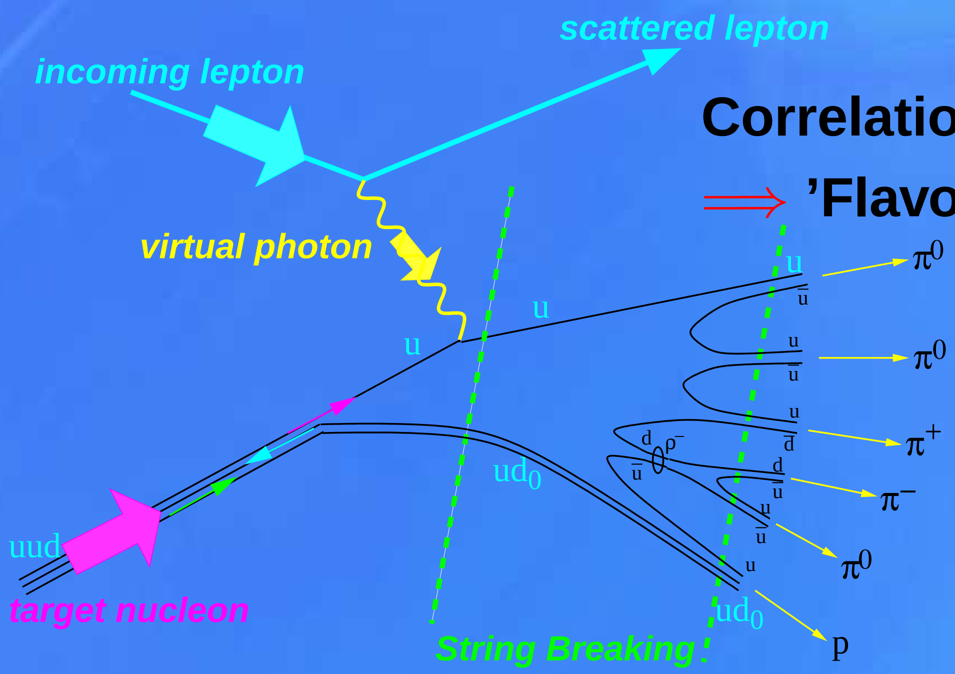
at Q^2 = 4 GeV^2

more direct access to ΔG and Δq_s desirable

Semi-inclusive DIS



Correlation between detected hadron and struck q_f

$\Longrightarrow$ **'Flavor - Separation'**

Inclusive DIS:

$$\Delta\Sigma = (\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s})$$

Semi-inclusive DIS:

Δu, $\Delta\bar{u}$, Δd, $\Delta\bar{d}$, Δs, $\Delta\bar{s}$

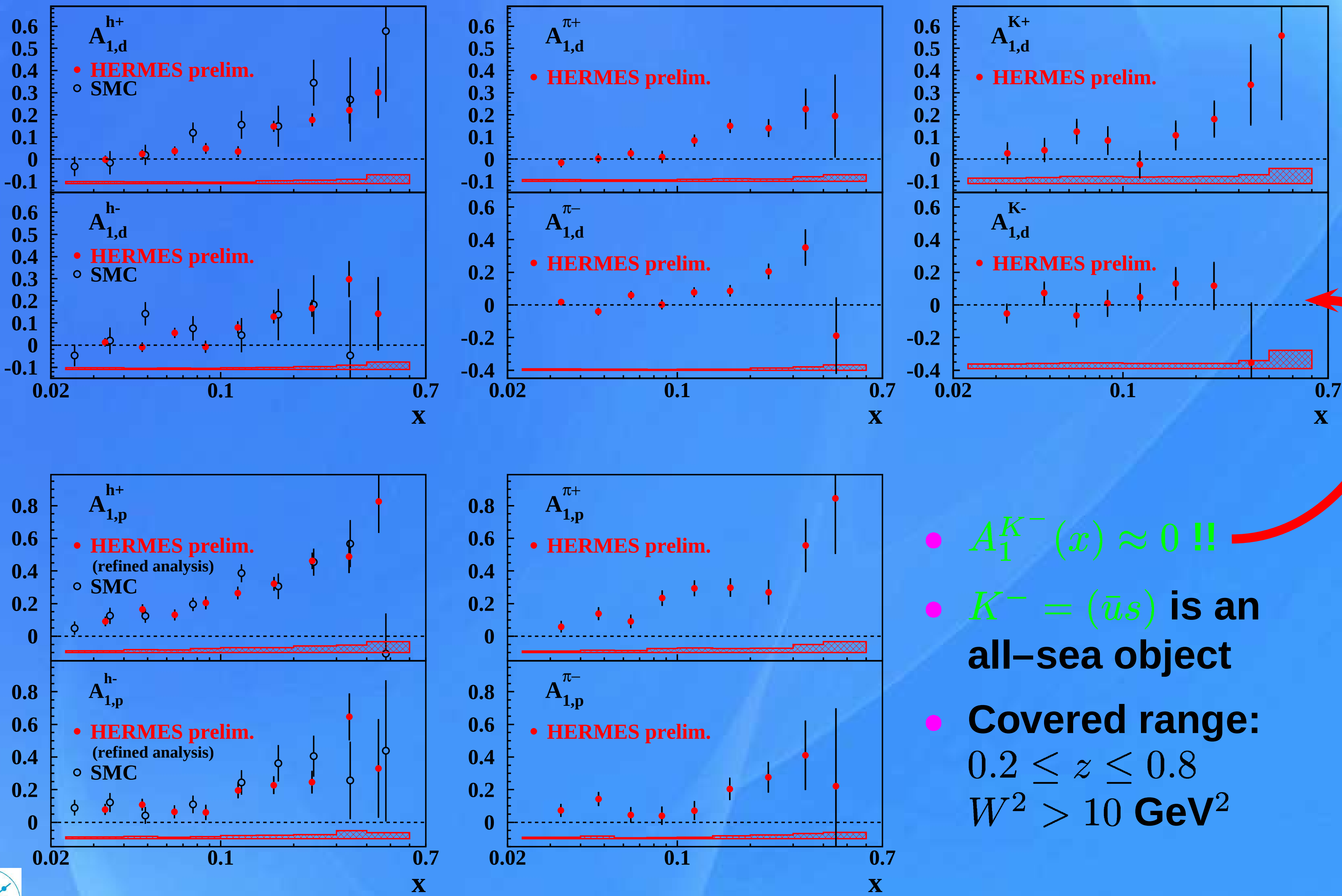
In LO-QCD:

$$A_1^{\mathrm{h}}(x,Q^2) = \frac{\sigma^h_{1/2} - \sigma^h_{3/2}}{\sigma^h_{1/2} + \sigma^h_{3/2}} = \frac{1+R(x,Q^2)}{1+\gamma^2} \cdot \frac{\sum_f e_f^2 \Delta q_f(x,Q^2) \int dz D_f^{\mathrm{h}}(z,Q^2)}{\sum_f e_f^2 q_f(x,Q^2) \int dz D_f^{\mathrm{h}}(z,Q^2)}$$

$(\Delta q_f), q_f$ **(Polarized) quark distributions**

$D_f^{\mathrm{h}}(z)$ **fragmentation functions giving the probability that a (struck) quark of flavor f fragments into a hadron of type h**

Measured Hadron Asymmetries



- $A_1^{K^-}(x) \approx 0$!!
- $K^- = (\bar{u}s)$ is an all–sea object
- **Covered range:**
  $0.2 \leq z \leq 0.8$
  $W^2 > 10$ GeV^2

Δq-Extraction

- **Rewrite Photon-Nucleon Asymmetry**

$$\mathbf{A_1^h(x)} \overset{\mathbf{g_2=0}}{\simeq} \mathbf{C} \cdot \sum_{\mathbf{q}} \underbrace{\frac{e_q^2 q(x) \int dz D_q^{\mathrm{h}}(z)}{\sum_{q'} e_{q'}^2 q'(x) \int dz D_{q'}^{\mathrm{h}}(z)}}_{P_q^h(x,z)} \frac{\mathbf{\Delta q(x)}}{\mathbf{q(x)}}$$

- **Purity $P_q^h(x,z)$: probability hadron h originates from an event with struck quark f; completely unpolarized quantity**

- **Extract $\mathbf{\Delta q}$ by solving:**

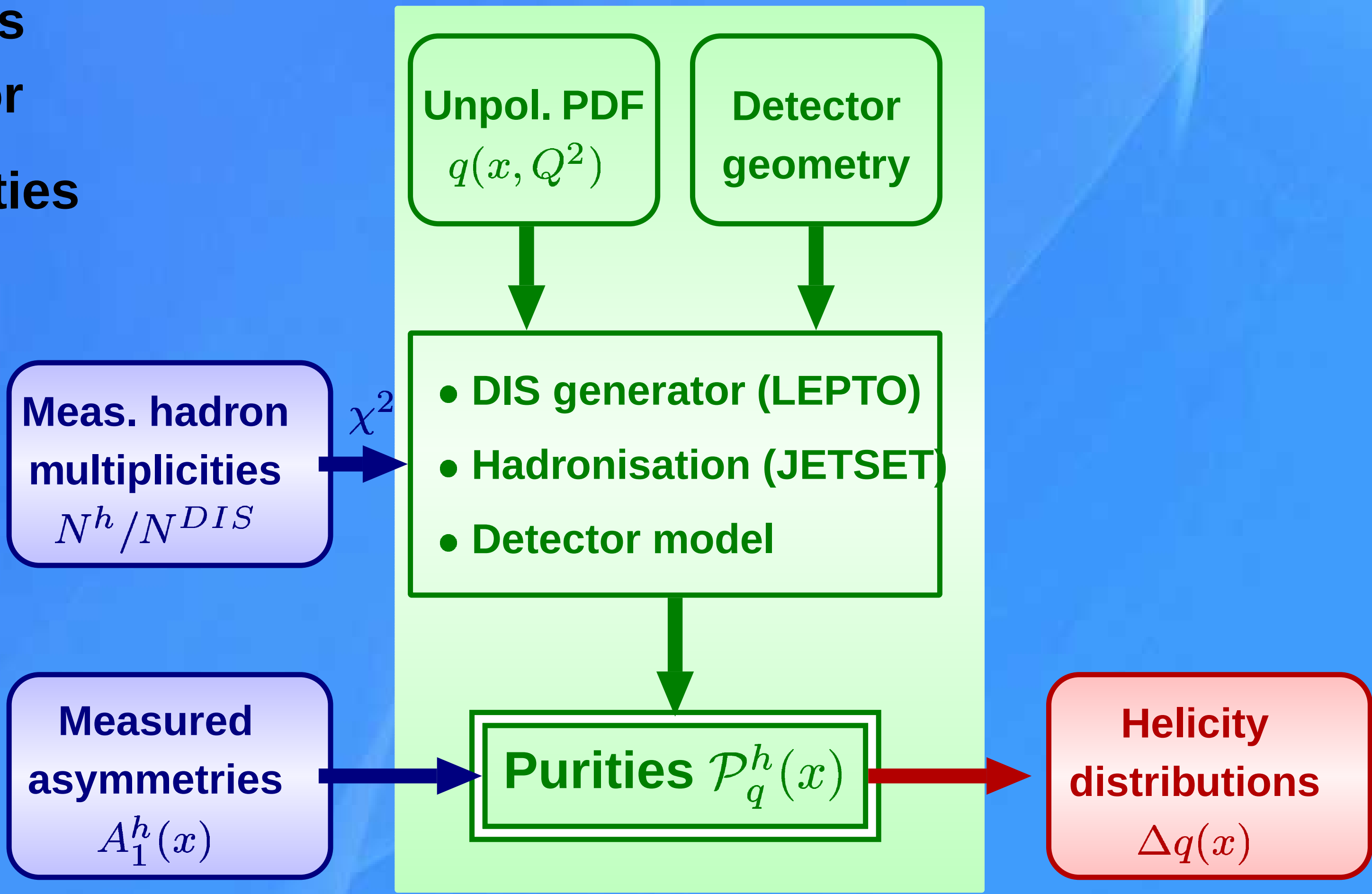
$$\vec{\mathcal{A}} = \mathcal{P}\vec{\mathcal{Q}}$$

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

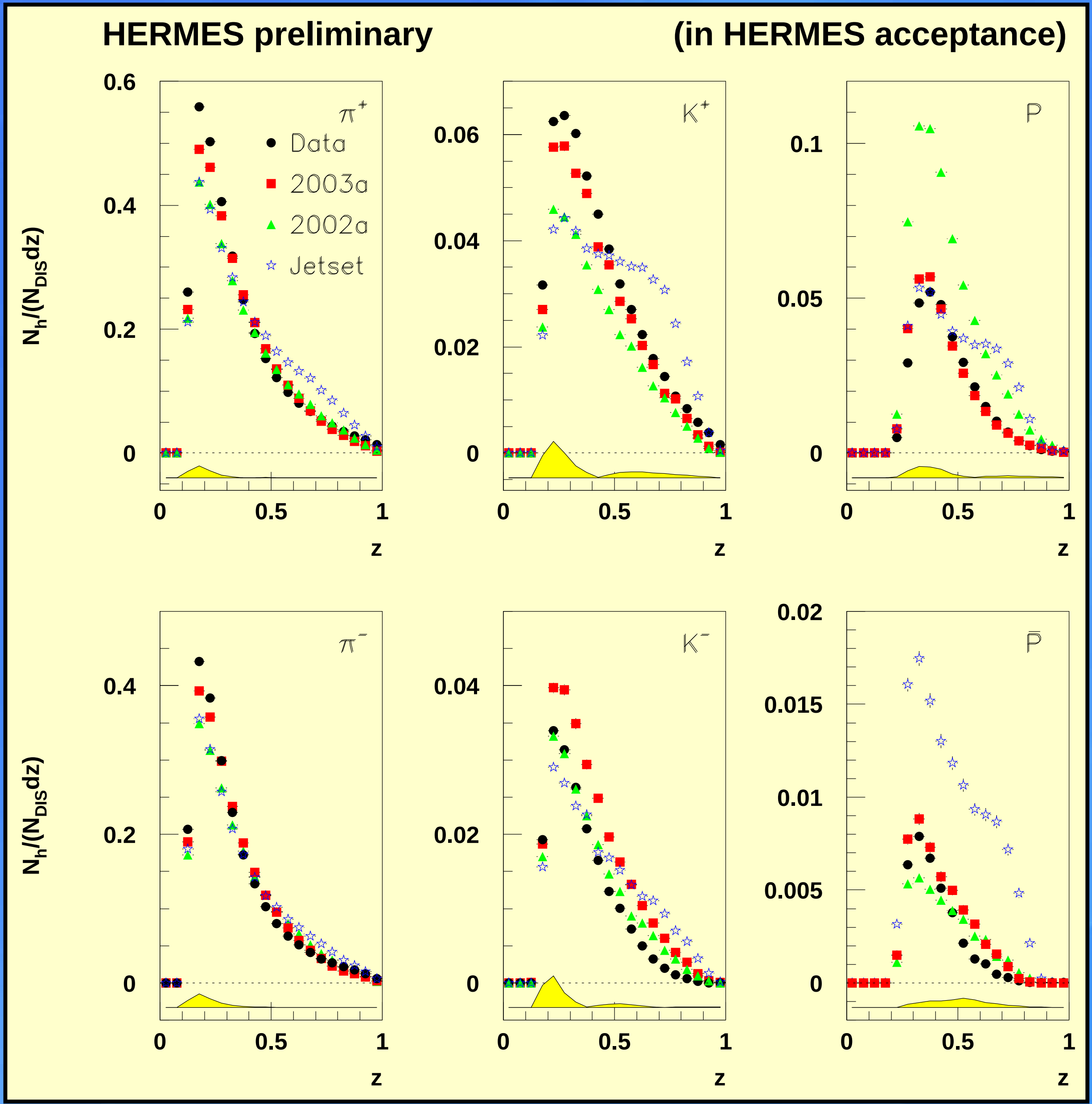
$$\vec{\mathcal{Q}} = \left(\frac{\mathbf{\Delta u}}{\mathbf{u}}, \frac{\mathbf{\Delta d}}{\mathbf{d}}, \frac{\mathbf{\Delta \bar{u}}}{\mathbf{\bar{u}}}, \frac{\mathbf{\Delta \bar{d}}}{\mathbf{\bar{d}}}, \frac{\mathbf{\Delta s + \Delta \bar{s}}}{\mathbf{s + \bar{s}}}\right)$$

Generation of Purities (HERMES)

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

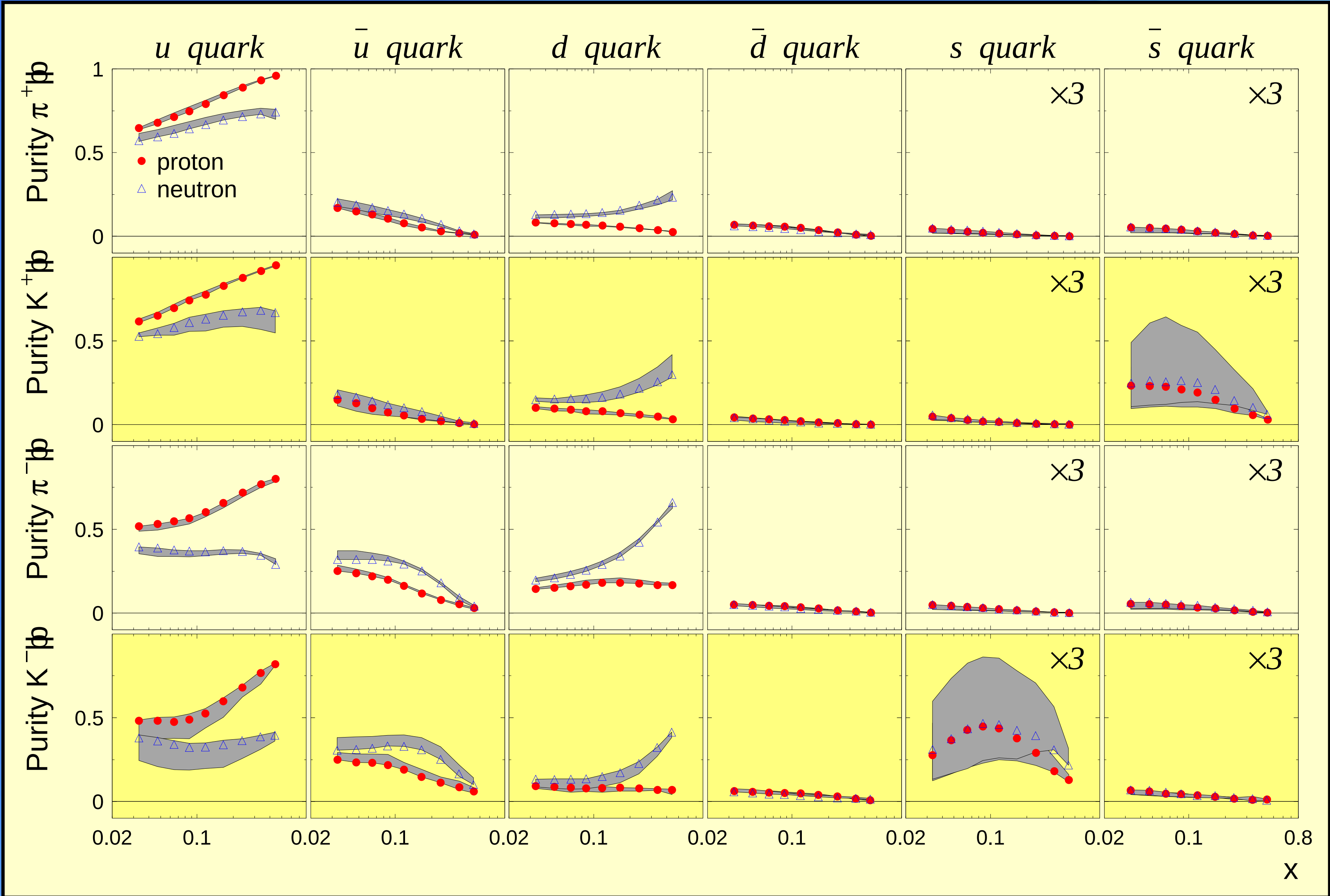


JETSET-Fragmentation Function



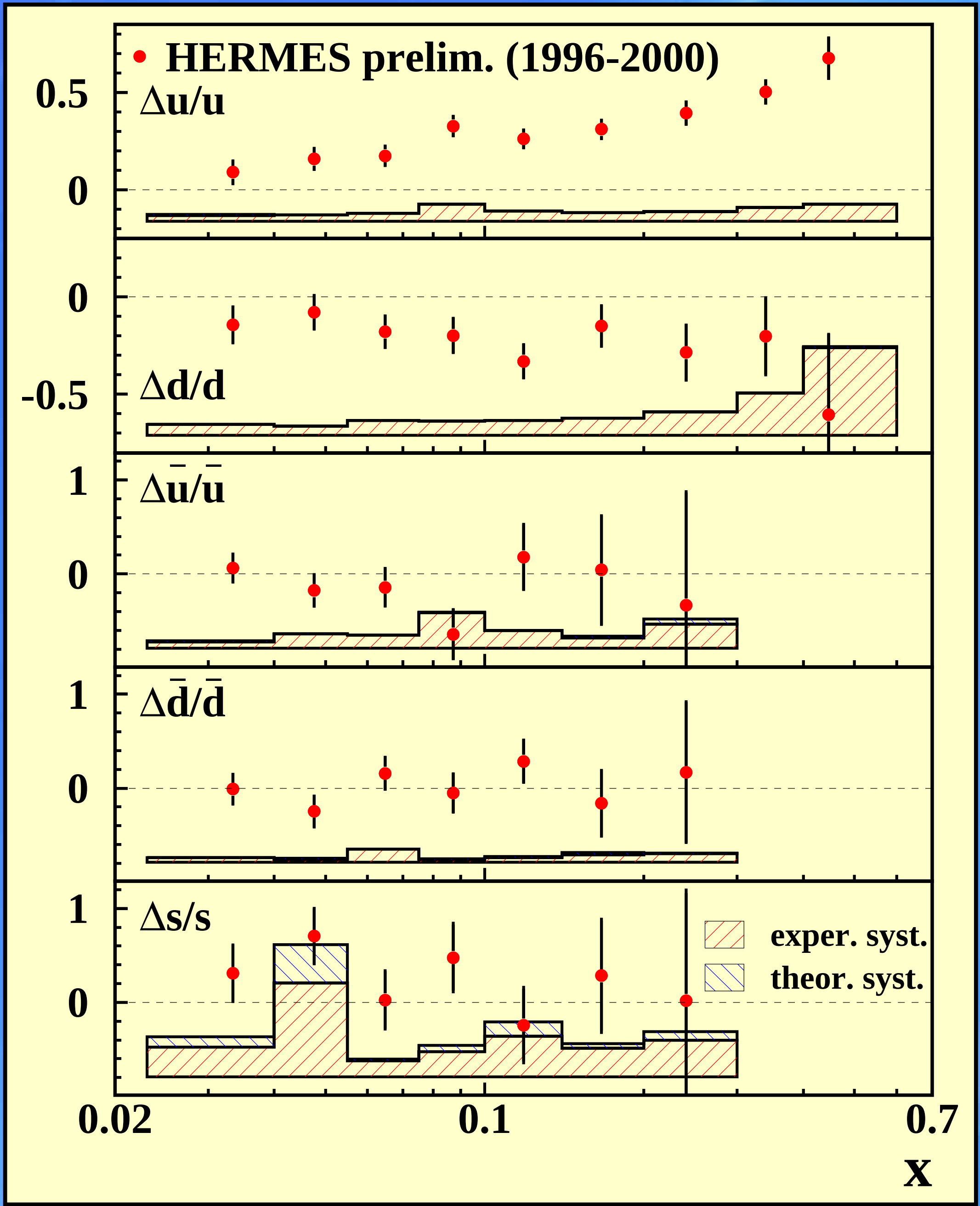
- **JETSET default does not describe HERMES data**
- **Use measured hadron multiplicities $N^h(z)/N_{DIS}$ to tune the JETSET fragmentation model $\Longrightarrow$ FF $D_u^{\pi+}, D_d^{\pi+}, D_u^{\pi-}, D_d^{\pi-}, D_u^{K+}, D_s^{K+}, \ldots$**

Purities (HERMES)

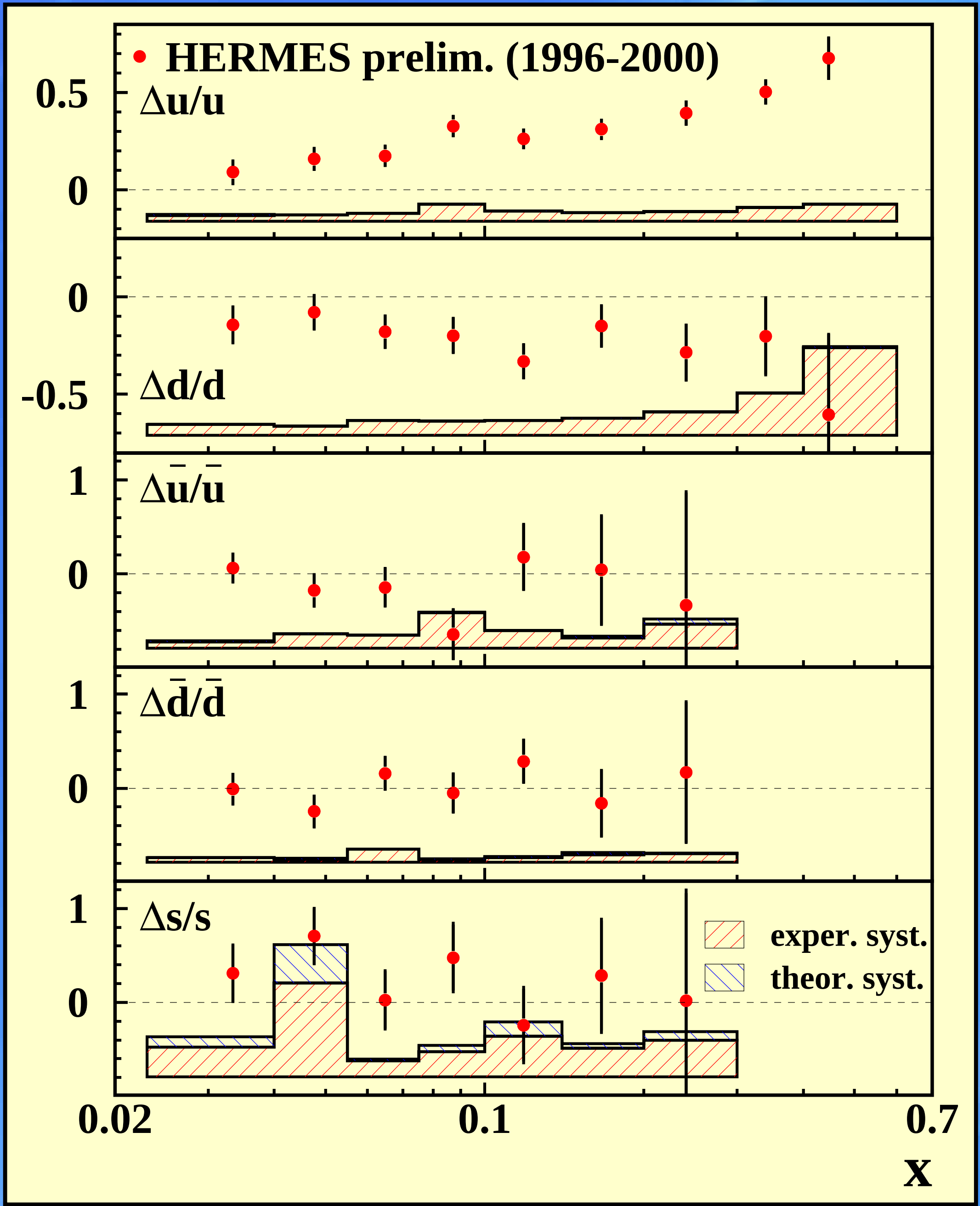


Syst. uncertainties from PDF sets and LUND parameters

Quark Polarizations



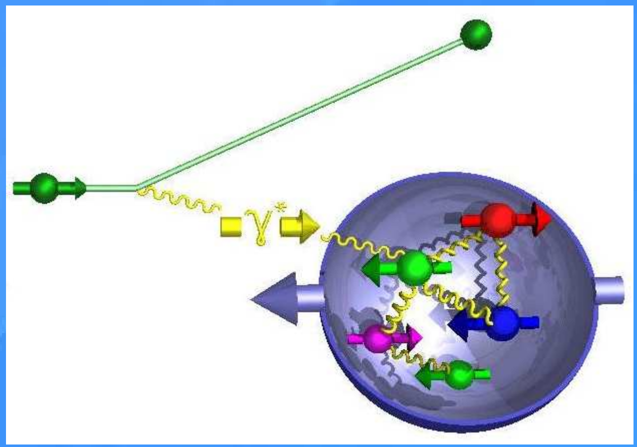
$$\frac{\Delta q_f(x)}{q_f(x)} := \frac{q_f^+(x)}{q_f(x)} - \frac{q_f^-(x)}{q_f(x)}$$



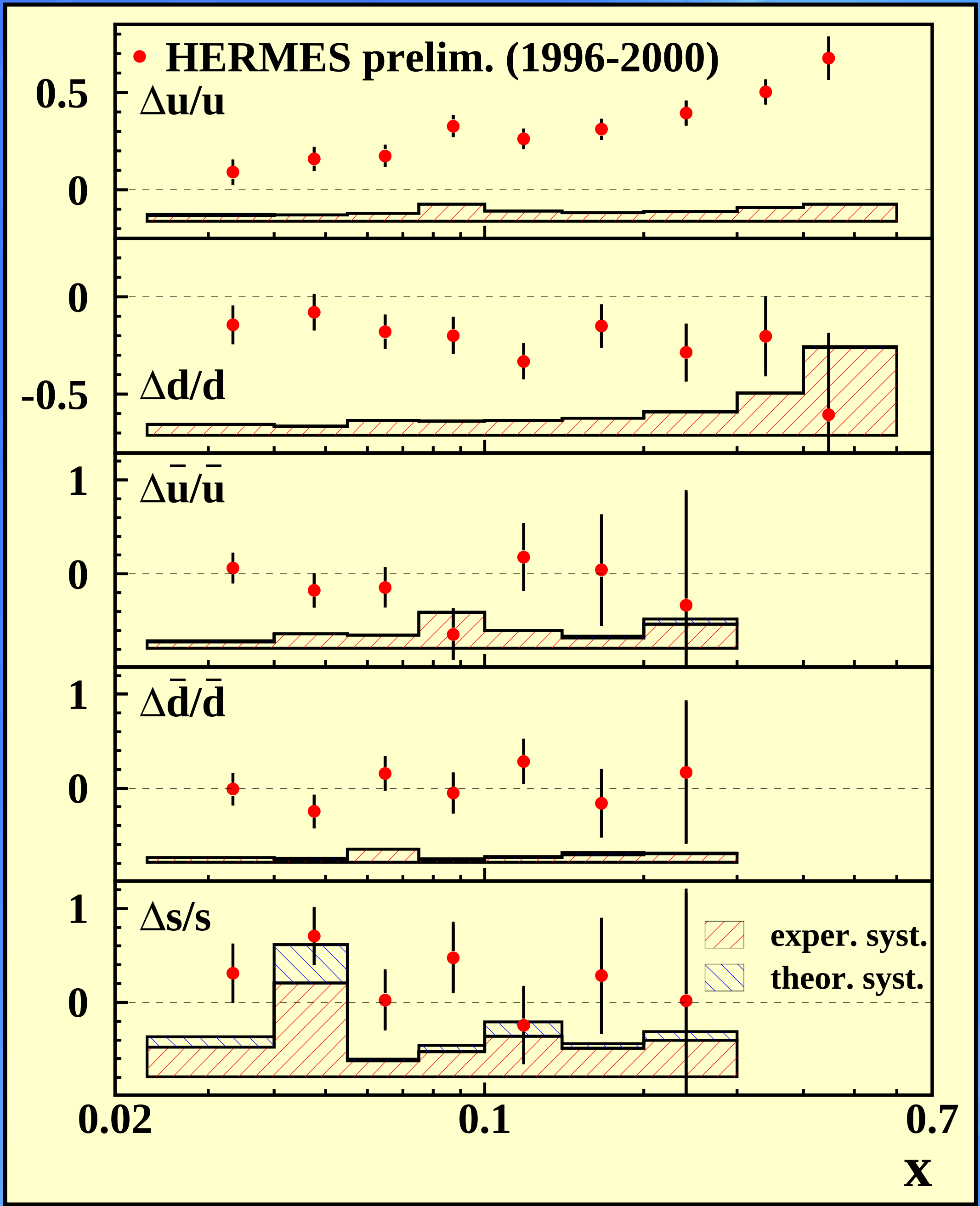
Quark Polarizations

$$\frac{\Delta q_f(x)}{q_f(x)} := \frac{q_f^+(x)}{q_f(x)} - \frac{q_f^-(x)}{q_f(x)}$$

- $\Delta u(x)/u(x) > 0$
  $\Longrightarrow$ **polarized parallel to the proton spin**



Quark Polarizations



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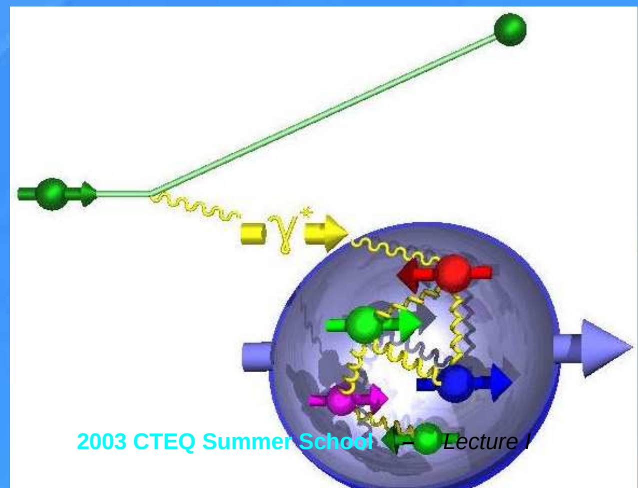
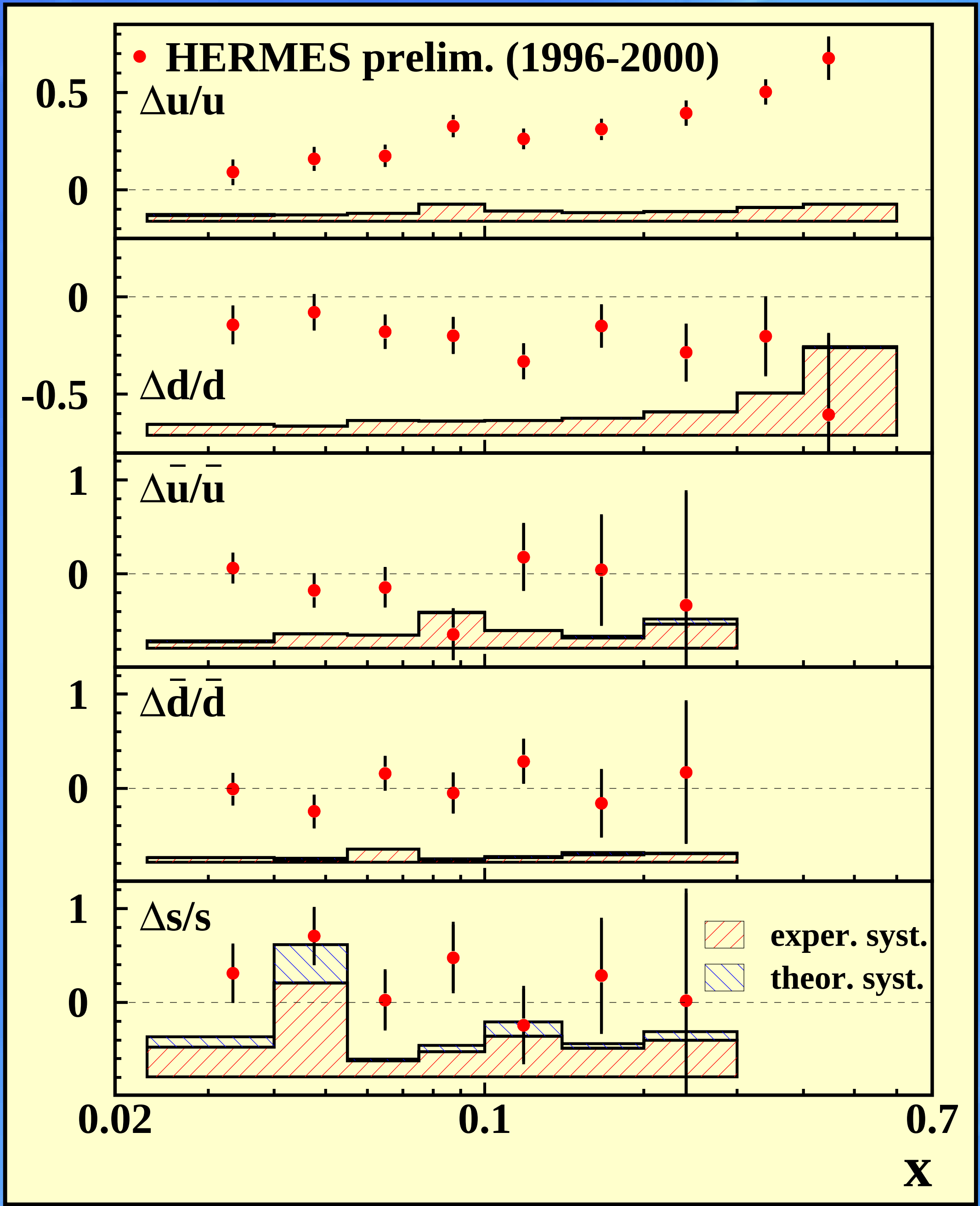
- $\Delta d(x)/d(x) < 0$
  $\Longrightarrow$ **polarized opposite to the proton spin**





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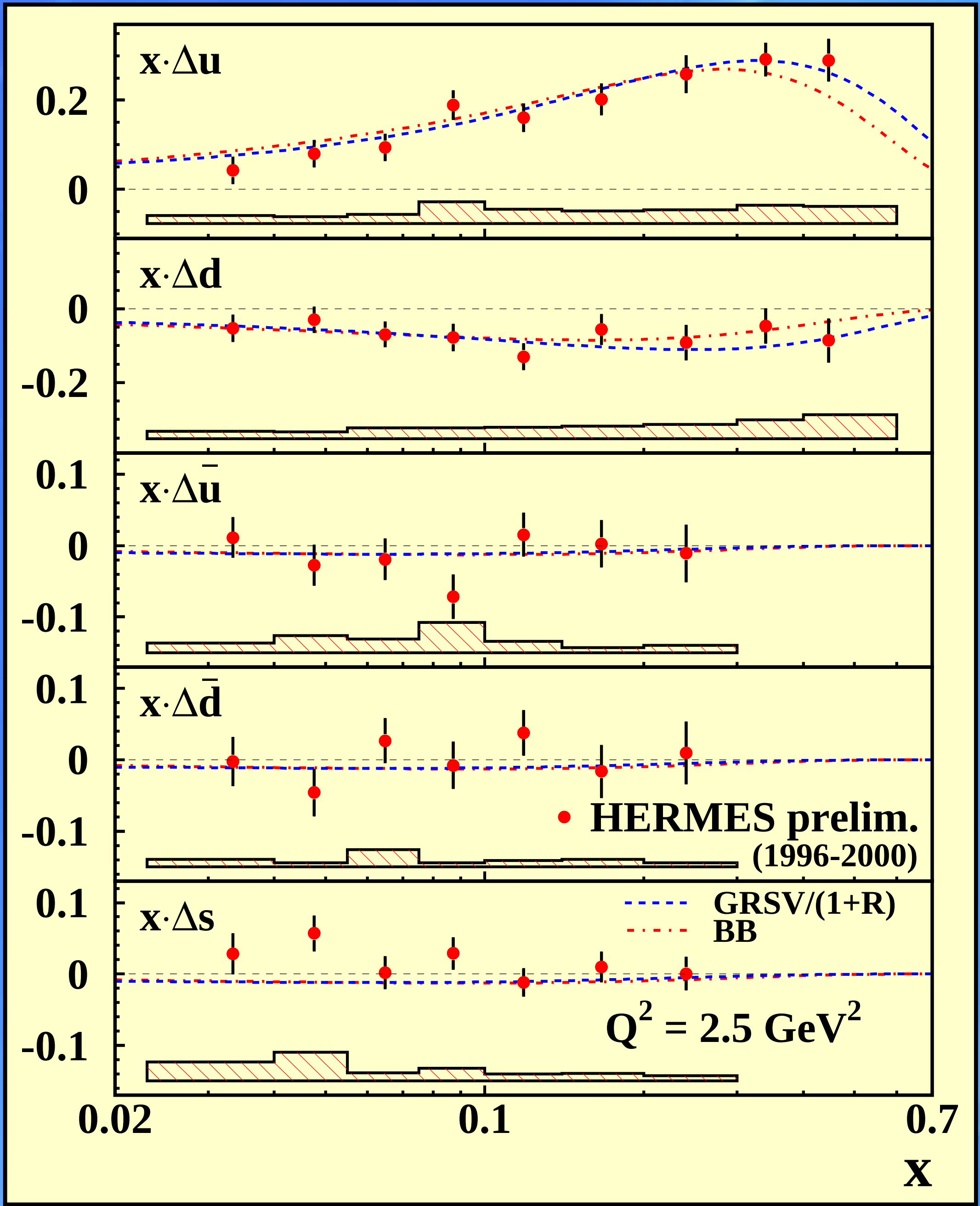
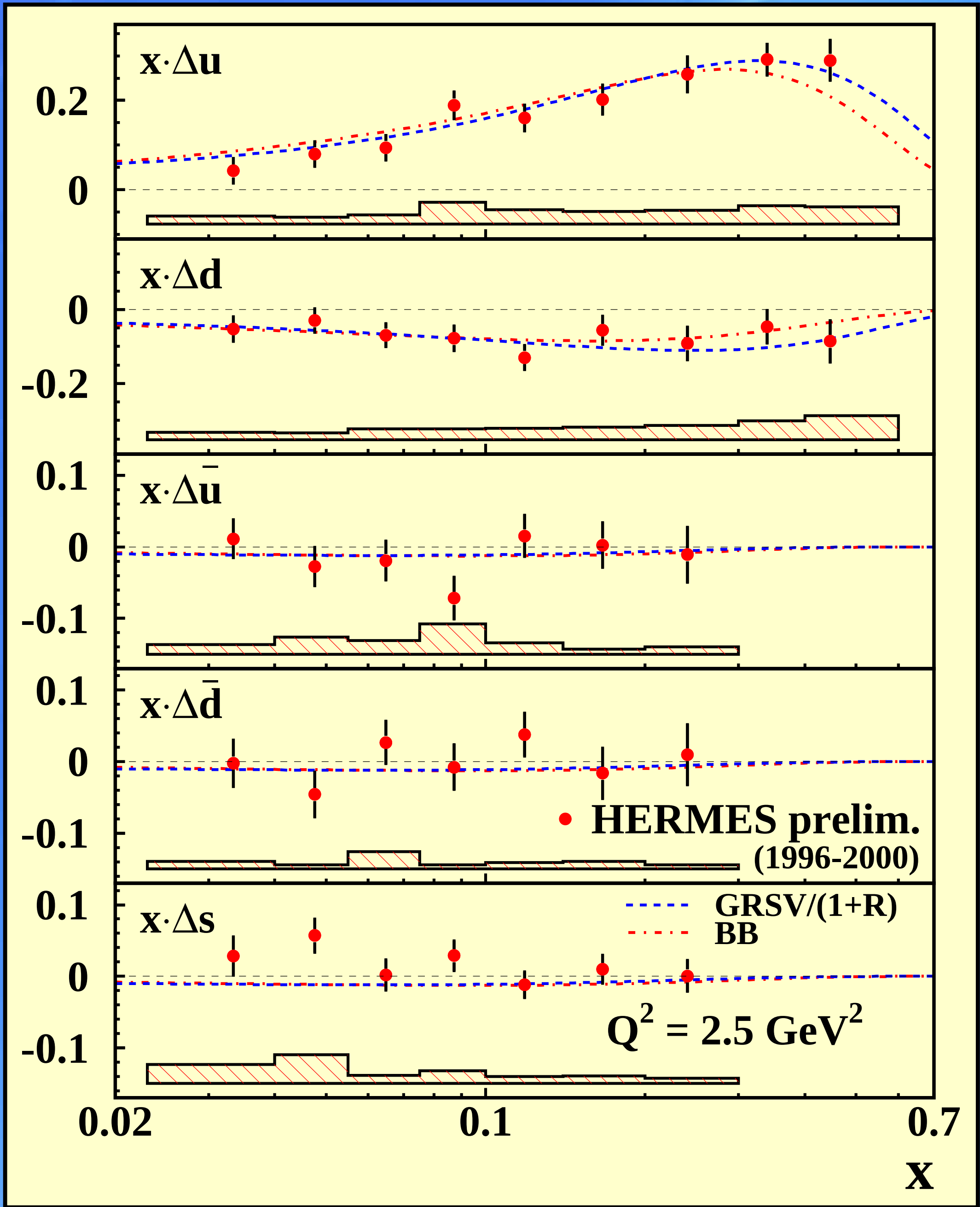
- $\Delta d(x)/d(x) < 0$
  $\Longrightarrow$ **polarized opposite to the proton spin**
- $\frac{\Delta\bar{u}}{\bar{u}} \sim \frac{\Delta\bar{d}}{\bar{d}} \sim \frac{\Delta s + \Delta\bar{s}}{s + \bar{s}} \sim 0$

Polarized Quark Densities



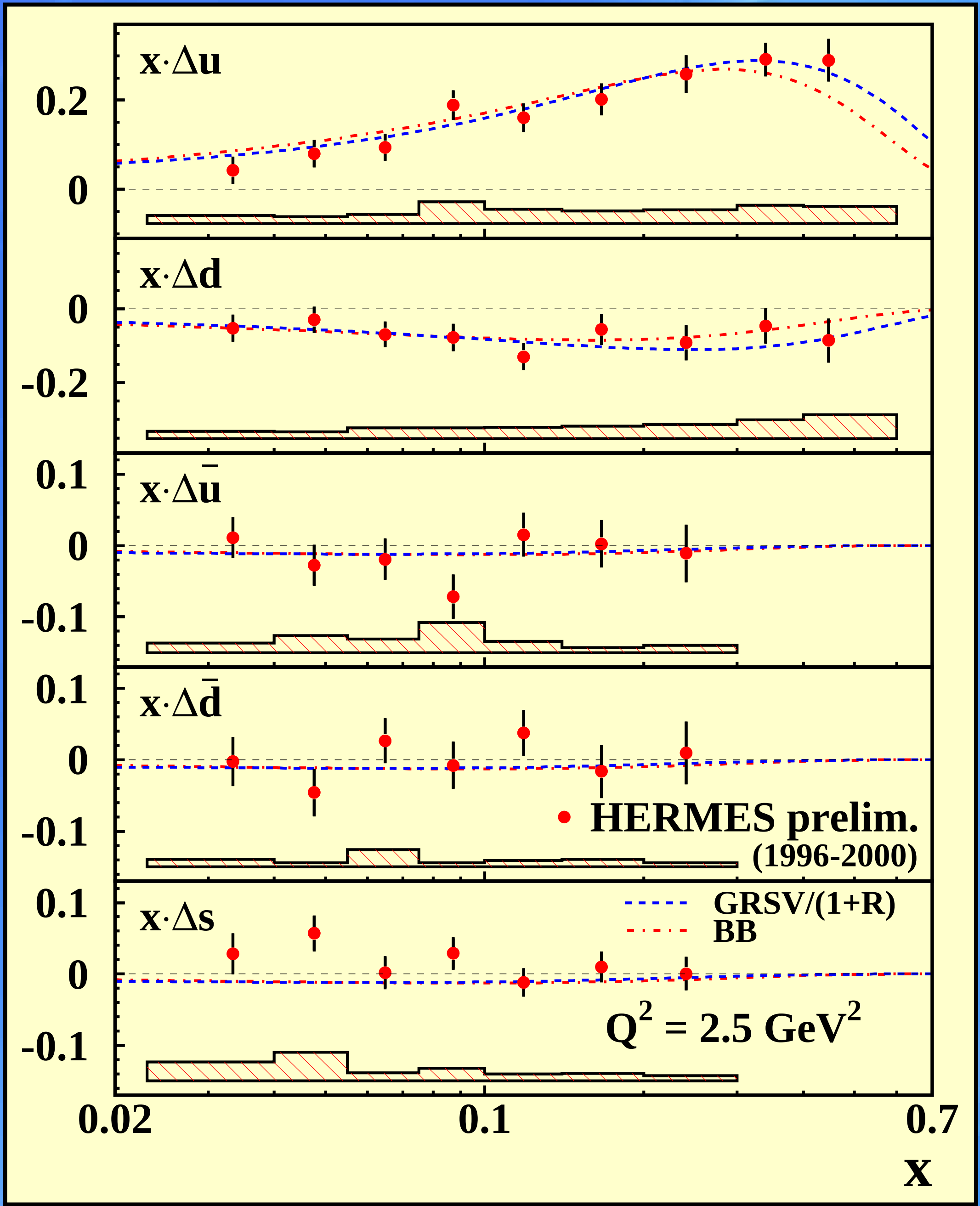
$$\Delta q_f(x) := q_f^+(x) - q_f^-(x)$$

Polarized Quark Densities



$$\Delta q_f(x) := q_f^+(x) - q_f^-(x)$$

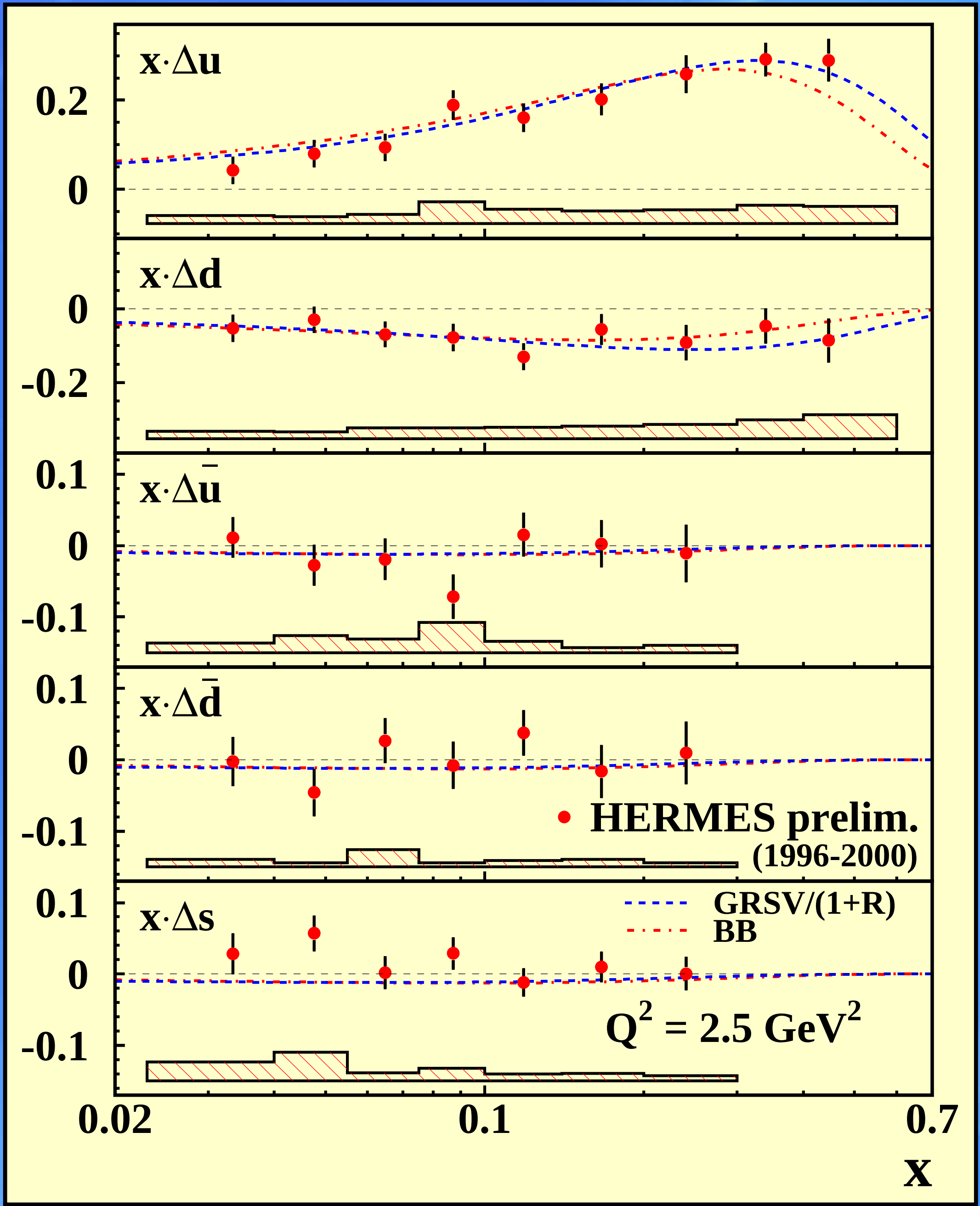
- $\Delta u(x)$ and $\Delta d(x)$ good agreement with NLO-QCD fit



Polarized Quark Densities

$$\boldsymbol{\Delta q_f(x) := q_f^+(x) - q_f^-(x)}$$

- $\Delta u(x)$ **and** $\Delta d(x)$
  good agreement with NLO-QCD fit
- $\Delta\bar{u}(x), \Delta\bar{d}(x) \sim 0$



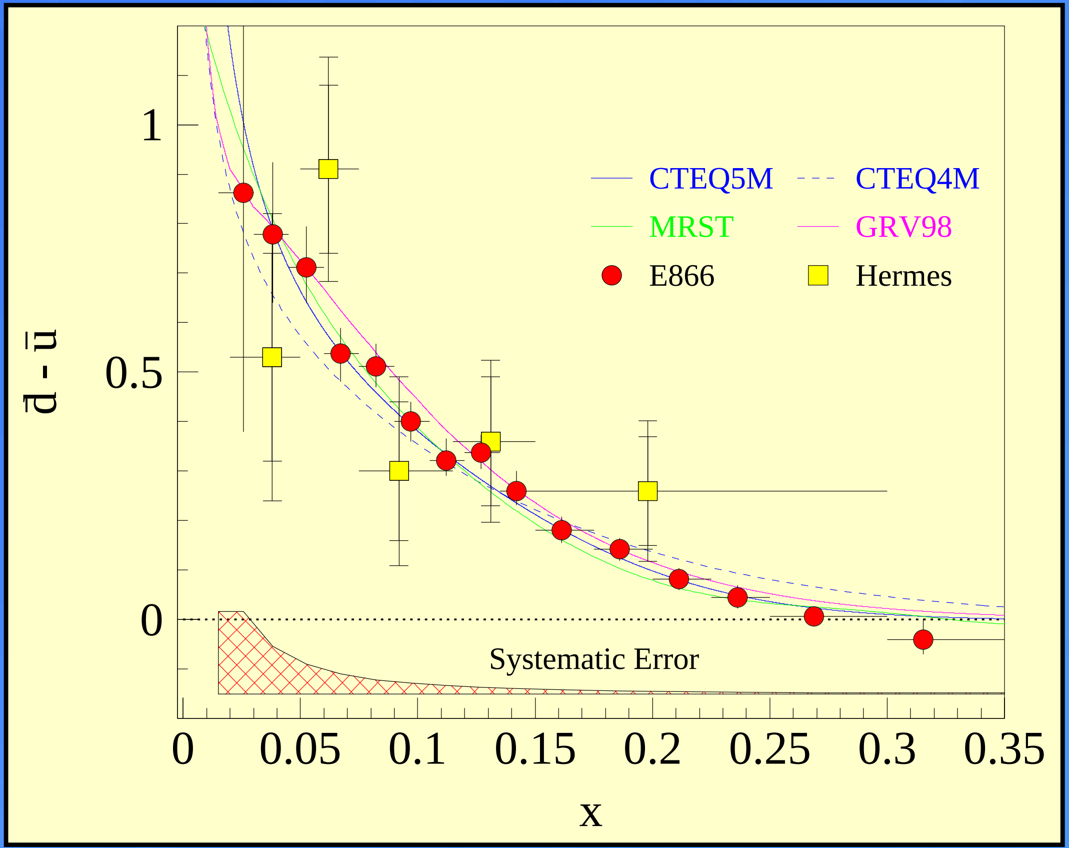
Polarized Quark Densities

$$\Delta q_f(x) := q_f^+(x) - q_f^-(x)$$

- $\Delta u(x)$ and $\Delta d(x)$ good agreement with NLO-QCD fit
- $\Delta\bar{u}(x), \Delta\bar{d}(x) \sim 0$
- No indication for $\Delta s(x) < 0$

SU(2)-Flavor Symmetry Breaking(?)

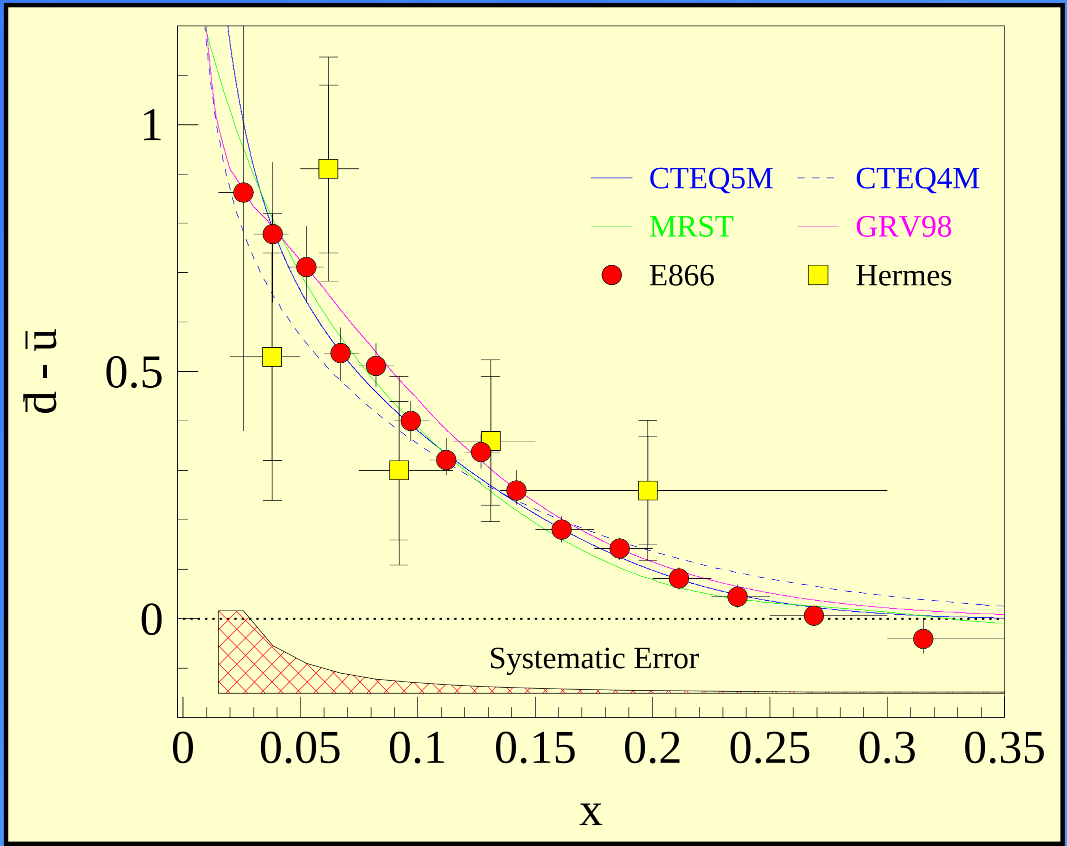
Unpolarised



Strong breaking of SU(2)-Flavor Symmetry

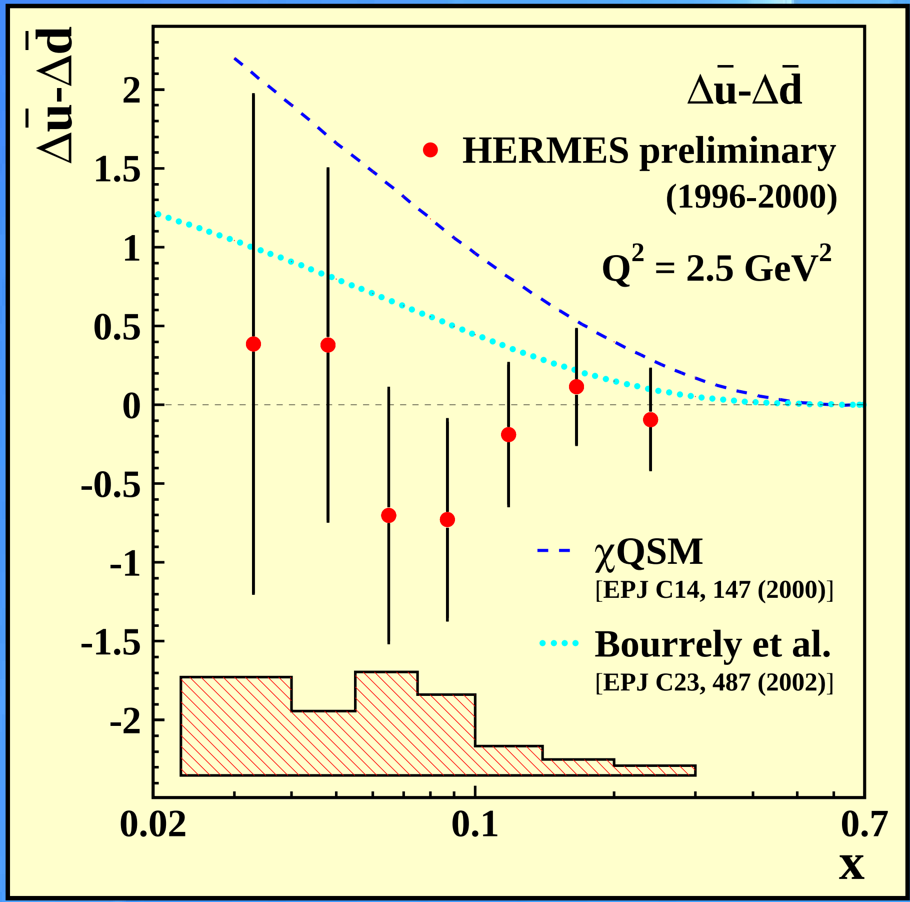
SU(2)-Flavor Symmetry Breaking(?)

Unpolarised



Strong breaking of SU(2)-Flavor Symmetry

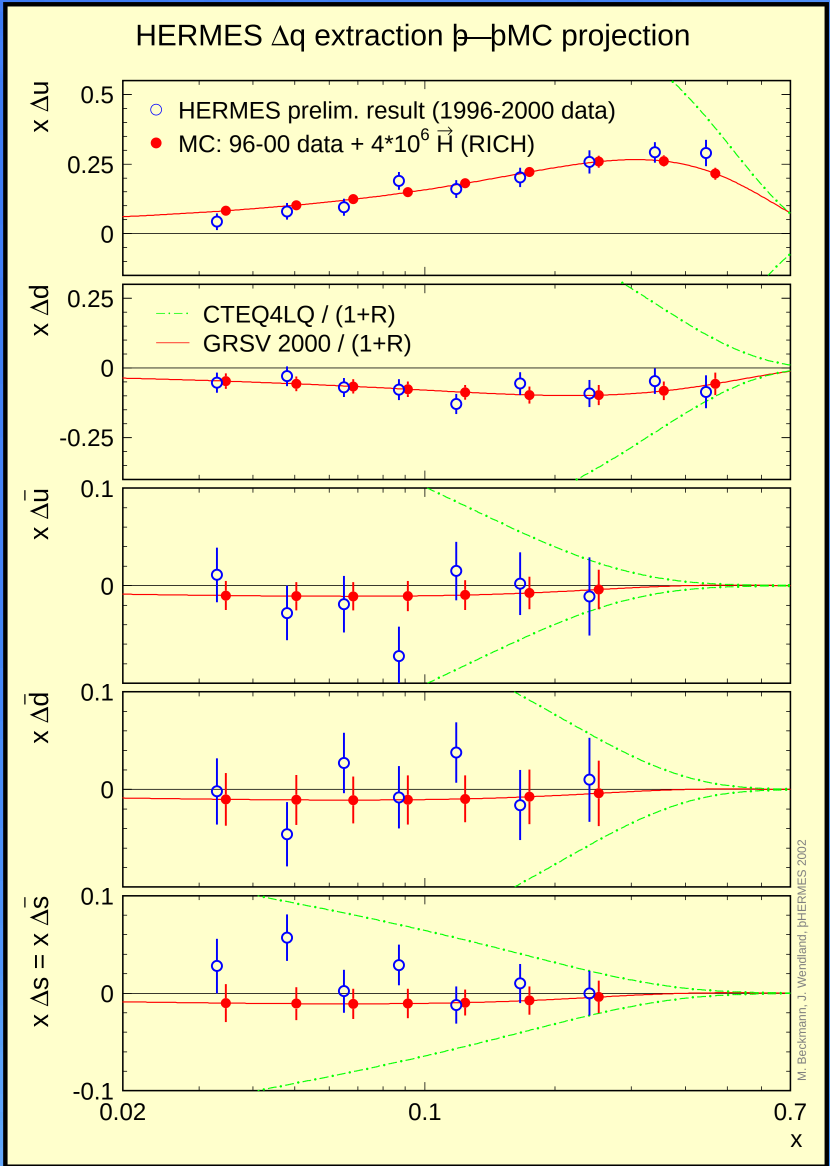
Polarised

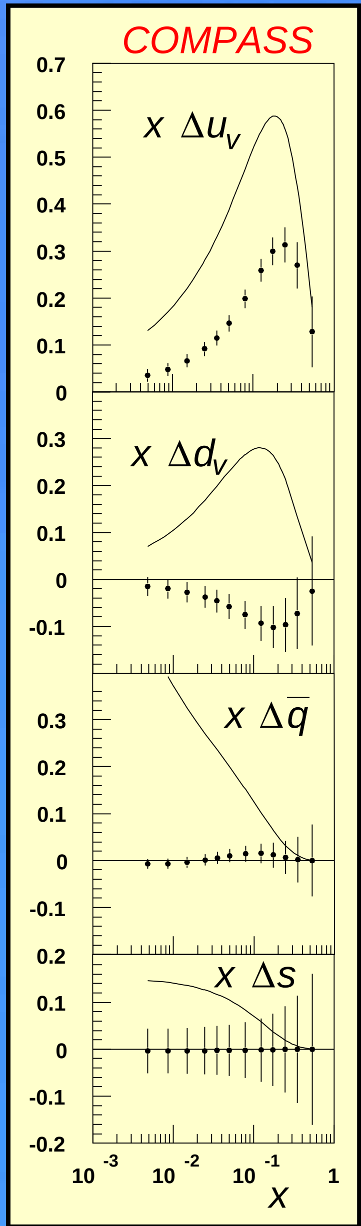


No significant breaking of SU(2)-Flavor Symmetry $\Delta\bar{u} \sim \Delta\bar{d}$

More Data needed

Future of Polarized Quark Densities





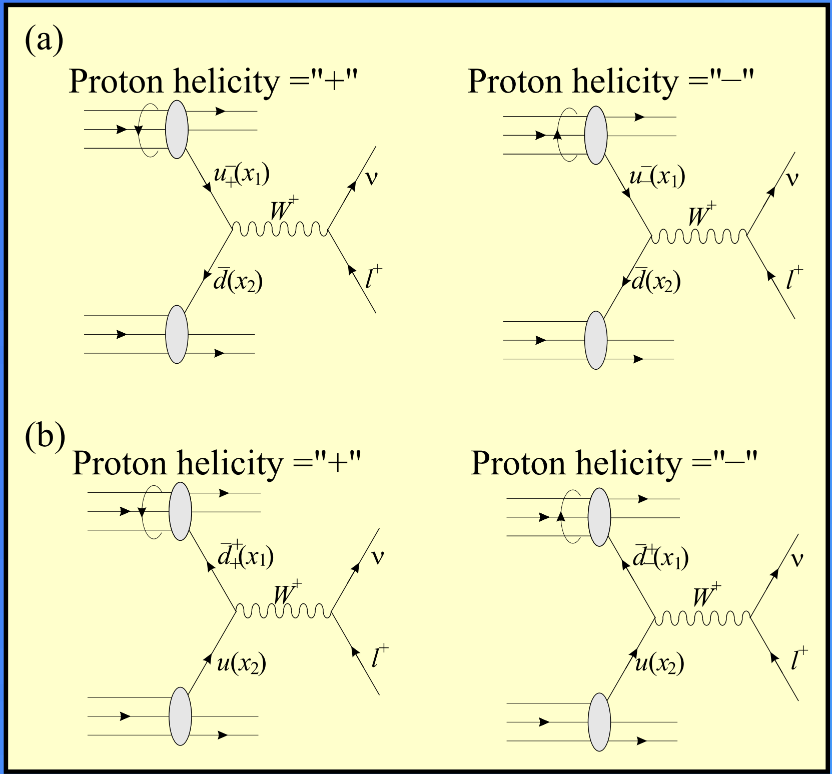
In DIS:

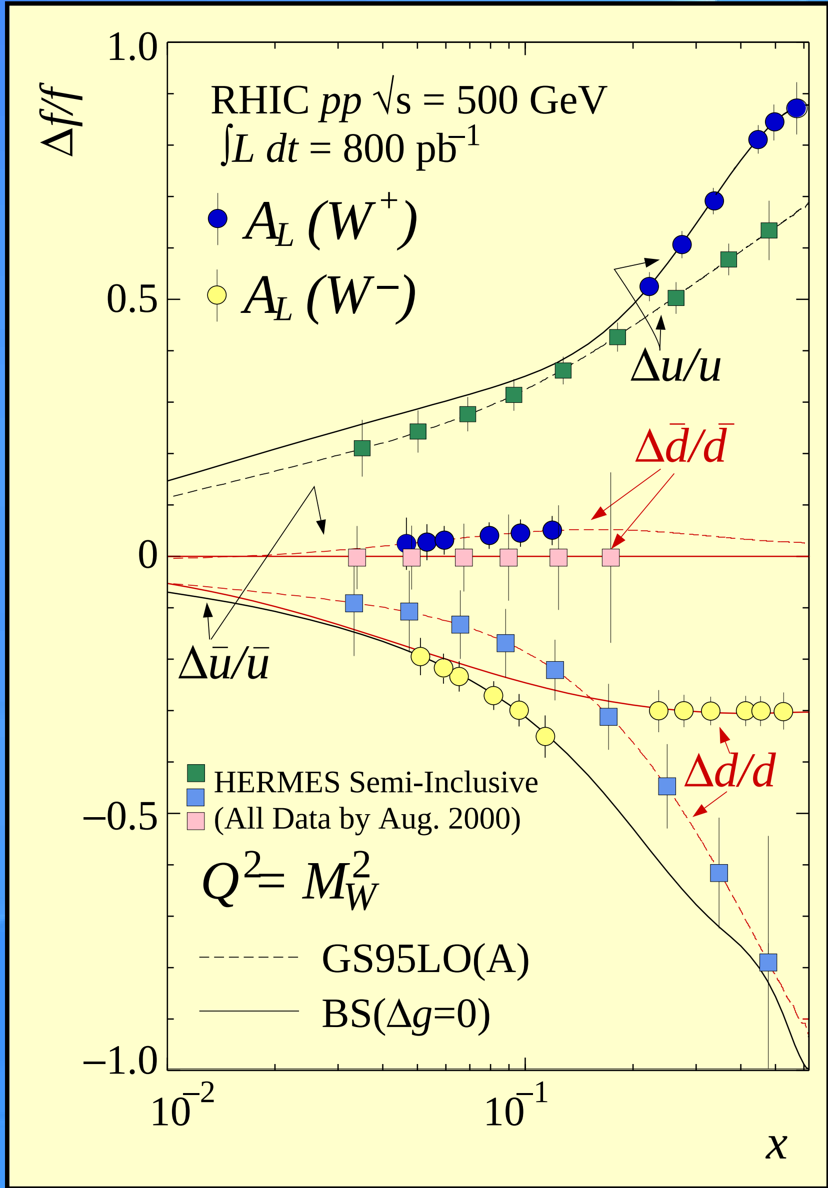
HERMES
additional 4 Million DIS with polarized $\vec{\mathrm{H}}$ and the RICH

COMPASS
will extend to lower x
expected luminosity:
2 fb^{-1} / year

Future of Polarized Quark Densities at RHIC

$\frac{\Delta q}{q}$ via parity violating asymmetry in $W^{\pm}$ production





$$A_L(W^+) = \frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

$$W^+ \Longrightarrow u + \bar{d} \qquad W^- \Longrightarrow d + \bar{u}$$

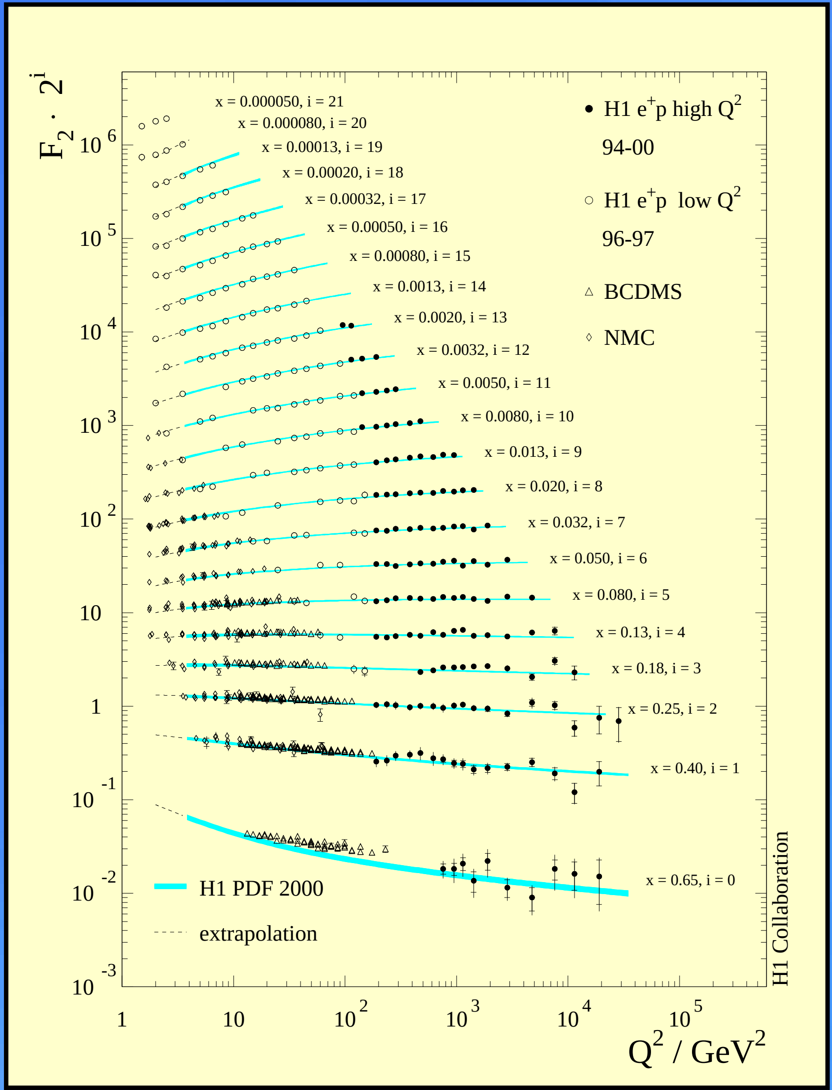
$$x_1 >> x_2 \Longrightarrow \frac{\Delta u}{u} \qquad x_2 >> x_1 \Longrightarrow \frac{\Delta\bar{d}}{\bar{d}}$$

How to measure ΔG

- **"Indirect" from scaling violation**

How to measure ΔG

- "Indirect" from scaling violation
  Remember unpolarised case:



How to measure ΔG

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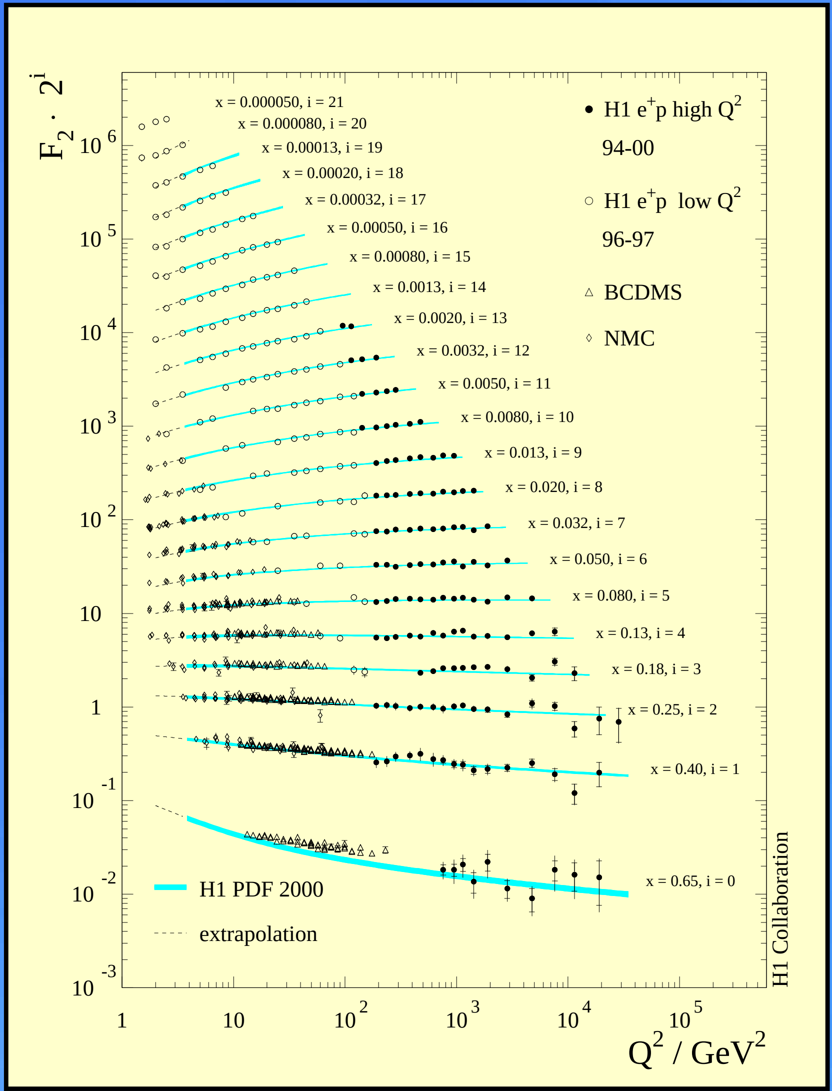
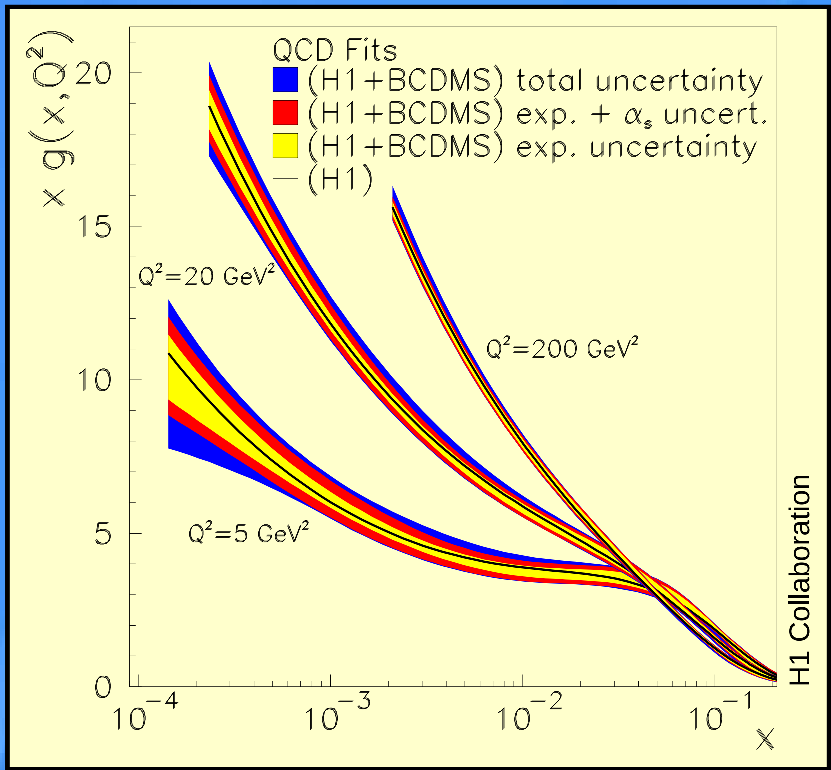


$\Longrightarrow$ big $Q^2 - x_{bj}$ lever arm

$\Longrightarrow$ very accurate $G(x)$



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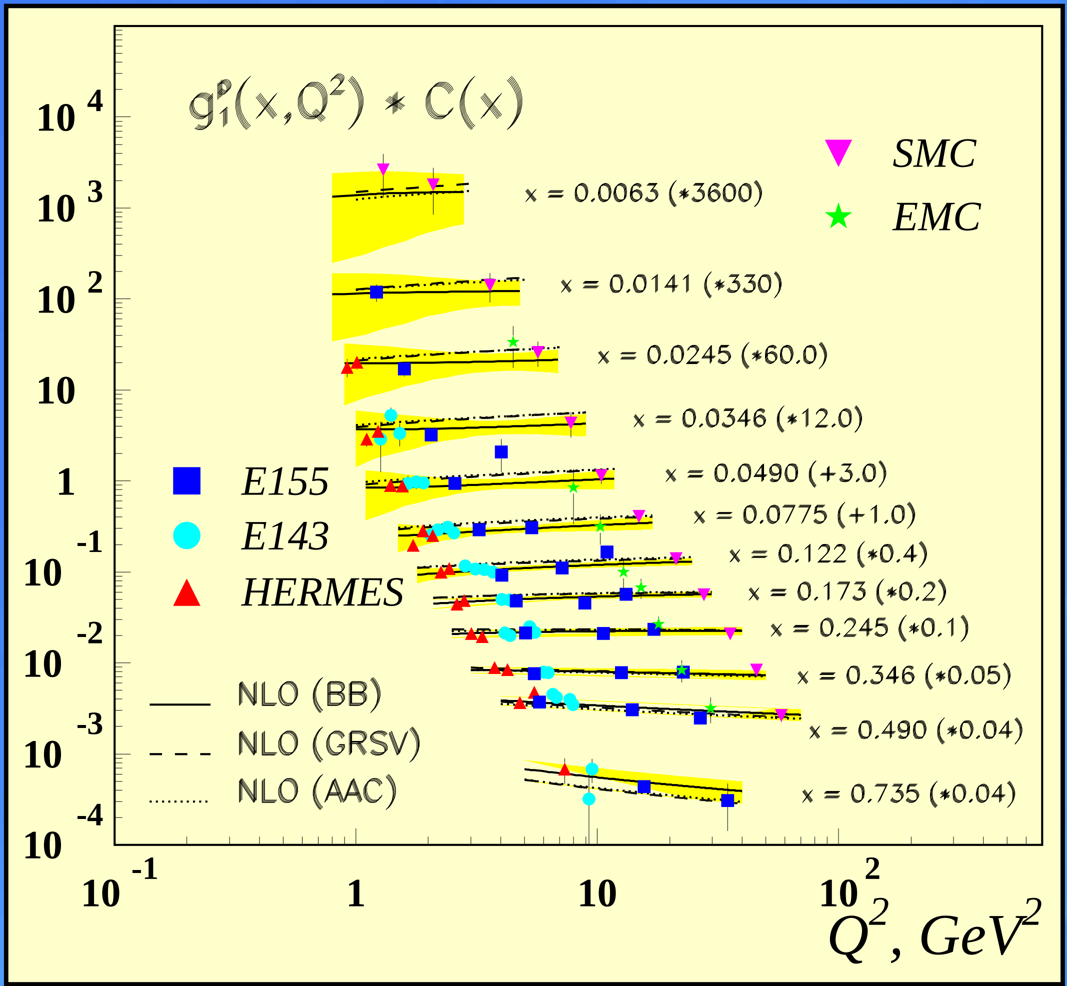

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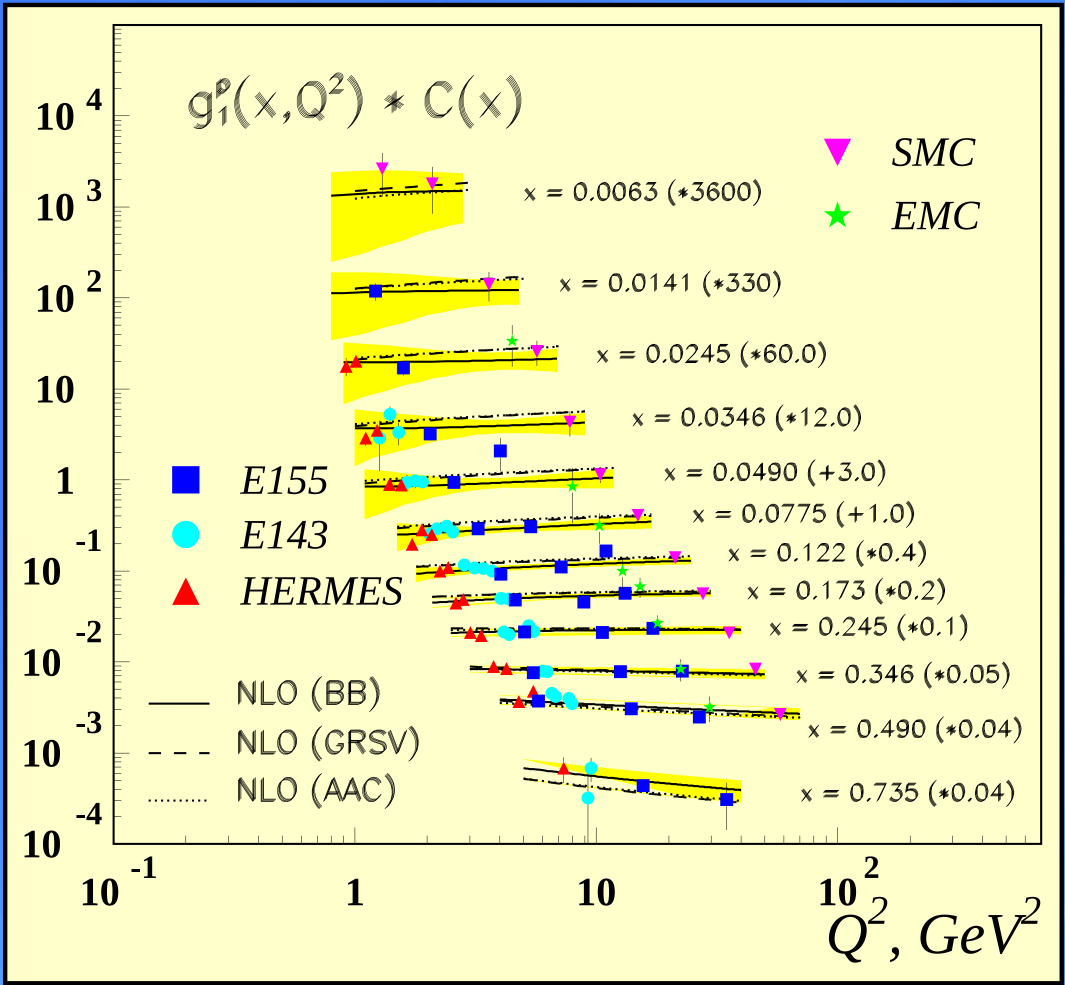
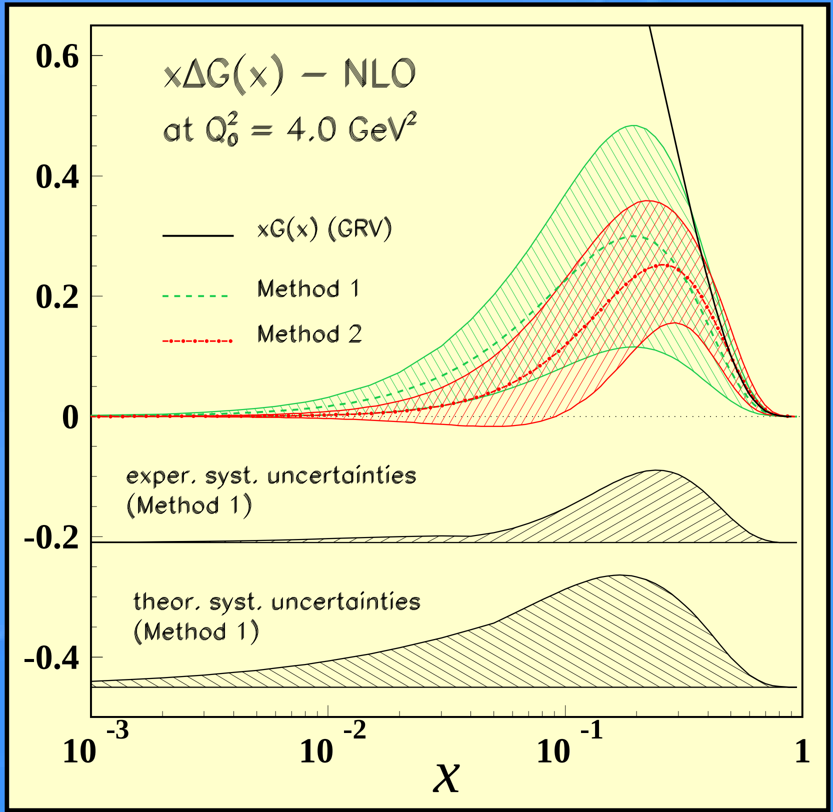


- fixed target experiments
  $\Longrightarrow$ small $Q^2 - x_{bj}$ lever arm
- determines only sign of $\Delta G(x)$



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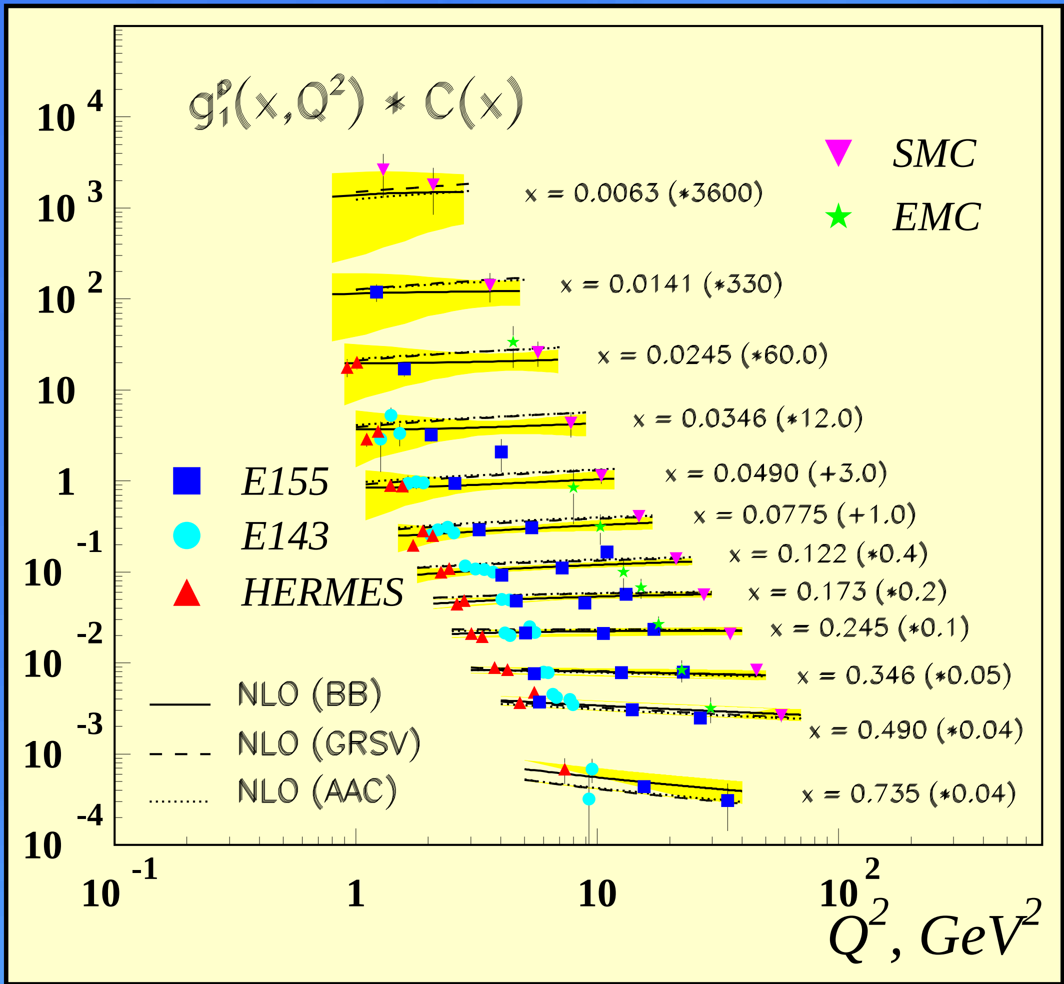

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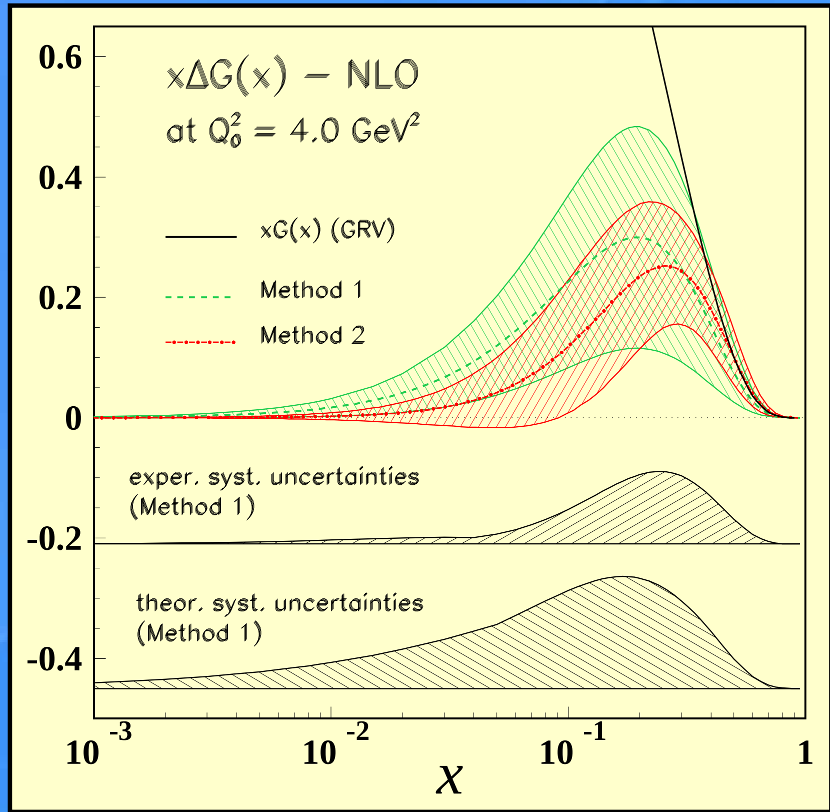
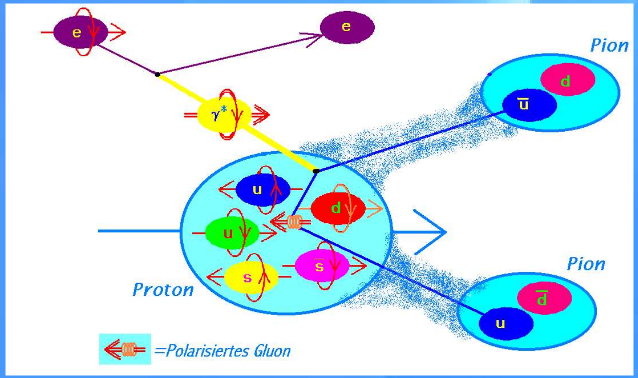


$\Longrightarrow$ Alternative extraction methods are needed

Direct Measurements of ΔG

Isolate the photon-gluon fusion process (PGF)



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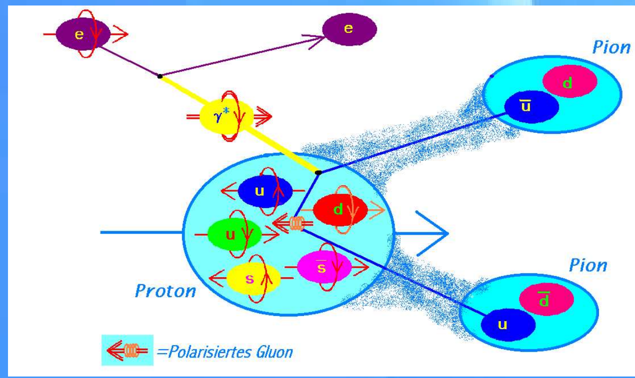
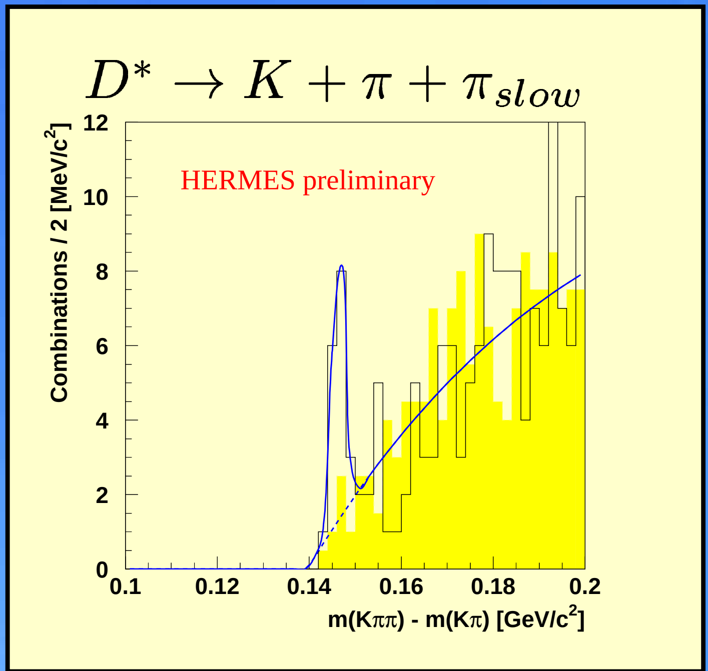


Heavy Quark Production

$c\bar{c} \Rightarrow$ **reconstruct D*, D^0**

$$\mathbf{A}_{||} = \frac{\mathbf{N}_{\mathbf{c\bar{c}}}^{\leftrightarrows} - \mathbf{N}_{\mathbf{c\bar{c}}}^{\rightrightarrows}}{\mathbf{N}_{\mathbf{c\bar{c}}}^{\leftrightarrows} + \mathbf{N}_{\mathbf{c\bar{c}}}^{\rightrightarrows}}$$

$$\mathbf{A}^{\gamma \mathbf{p} \rightarrow \mathbf{c\bar{c}}} \sim \mathbf{\Delta G / G}$$



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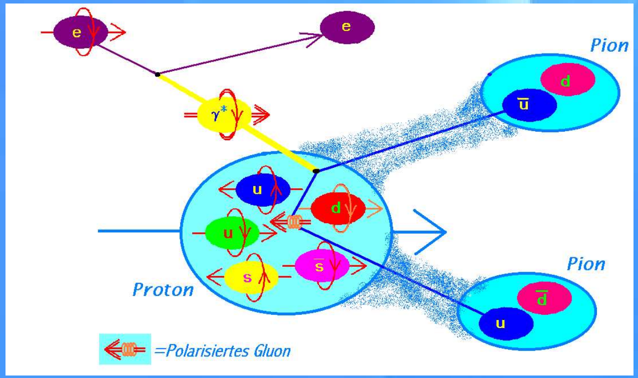

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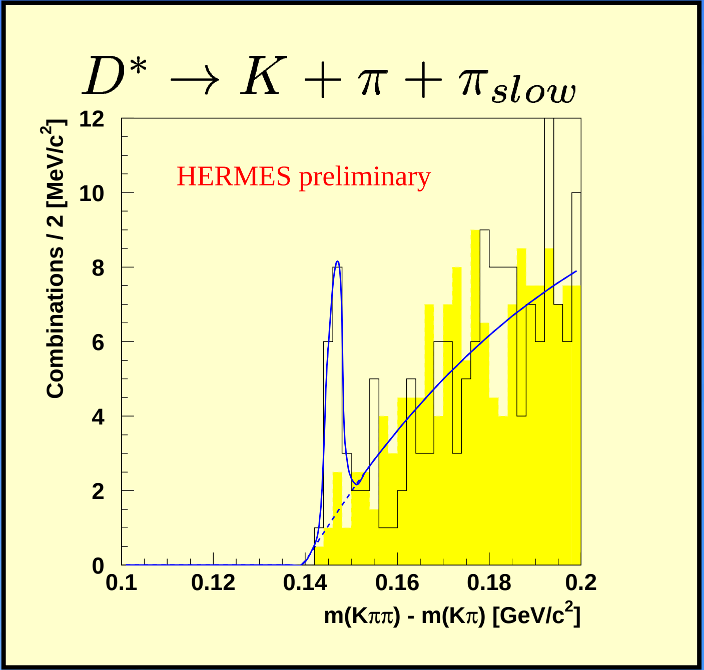


HIGH-P_T

pairs of high-P_T hadrons

$$\mathbf{p_T(h_1^{\pm}, h_2^{\mp}) > 1GeV}$$

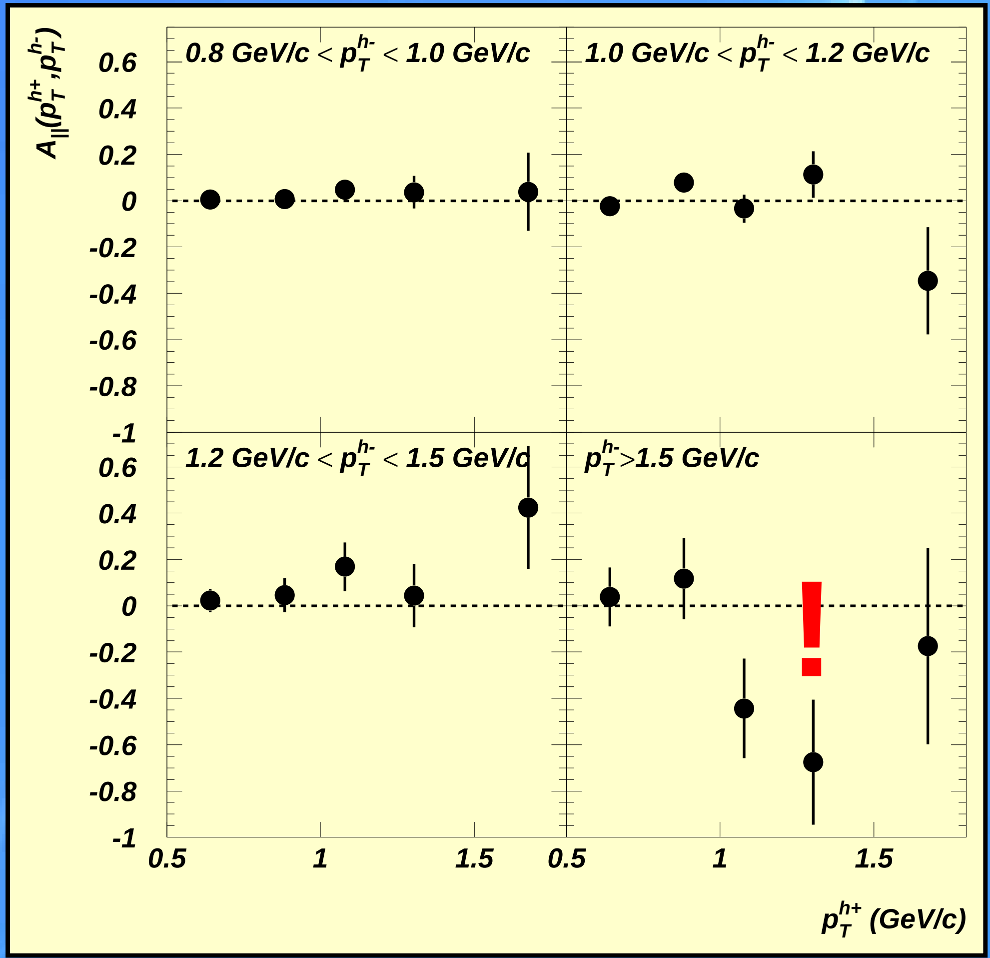
$$\mathbf{A}_{||} = \frac{\mathbf{N}^{\leftrightarrows}_{\mathbf{h_1^{\pm}h_2^{\mp}}} - \mathbf{N}^{\rightrightarrows}_{\mathbf{h_1^{\pm}h_2^{\mp}}}}{\mathbf{N}^{\leftrightarrows}_{\mathbf{h_1^{\pm}h_2^{\mp}}} + \mathbf{N}^{\rightrightarrows}_{\mathbf{h_1^{\pm}h_2^{\mp}}}}$$

$$\mathbf{A}^{\gamma^* \mathbf{p} \rightarrow \mathbf{h_1^{\pm}} + \mathbf{h_2^{\mp}}} \sim \mathbf{\Delta G/G}$$

additionally:
use identified hadrons

The HERMES hunt for ΔG

- **Reaction:** $\gamma^* p \rightarrow h_1^\pm + h_2^\mp + X$
- **select two oppositely charged hadrons**
- **low Q^2 range ($Q^2 > 0$ GeV^2)**
  $\Longrightarrow$ **increase statistics**
  $\Longrightarrow$ **scale of hard sub-processes $\hat{p}_T^2$**
- **require $p_T(h_1,h_2) > 0.5$ GeV, M(2π) > 1.0 GeV**
  $\Longrightarrow$ **removes resonances ρ and ϕ**
- $$A_{||} = \frac{N^{\leftleftarrows... }_{h_1^\pm h_2^\mp} - N^{\rightrightarrows}_{h_1^\pm h_2^\mp}}{N^{\leftrightarrows}_{h_1^\pm h_2^\mp} + N^{\rightrightarrows}_{h_1^\pm h_2^\mp}} \text{ vs. } p_T(h_1^\pm, h_2^\mp)$$



Negative asymmetry in DIS unexpected

Interpretation ?!

Four different processes can contribute:

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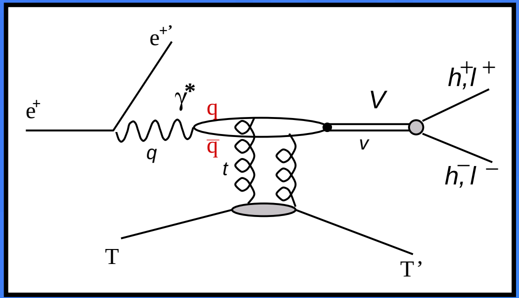

VMD

$$\mathbf{A_{VMD} = 0}$$

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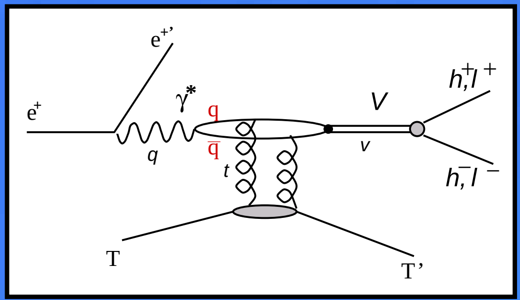

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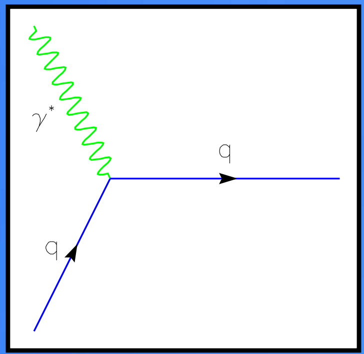

DIS

$$\mathbf{A_{DIS} \sim \frac{\Delta q}{q}}$$

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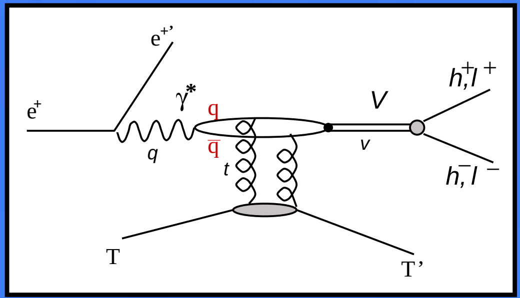

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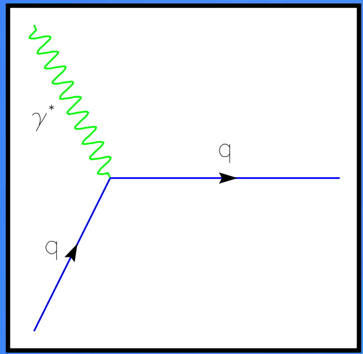

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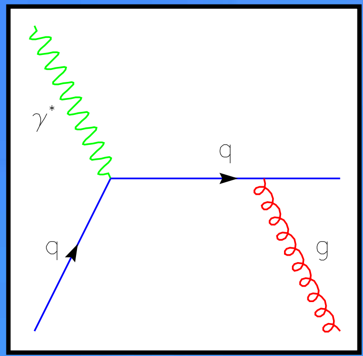

QCDC

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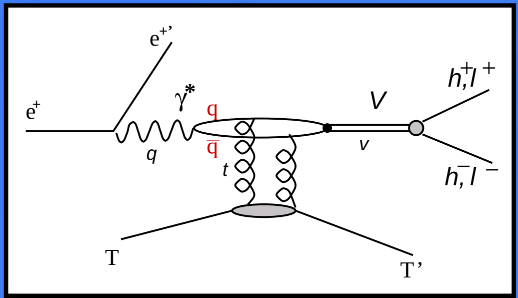

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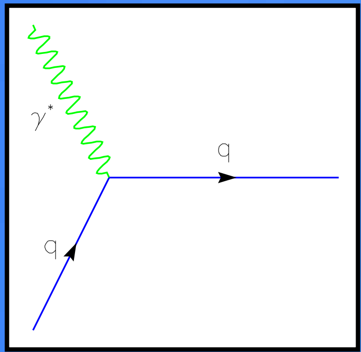

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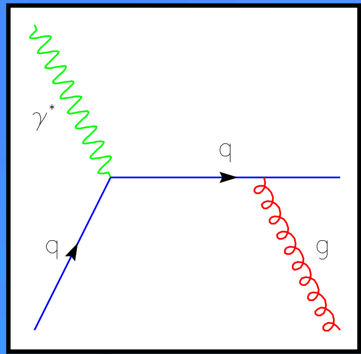

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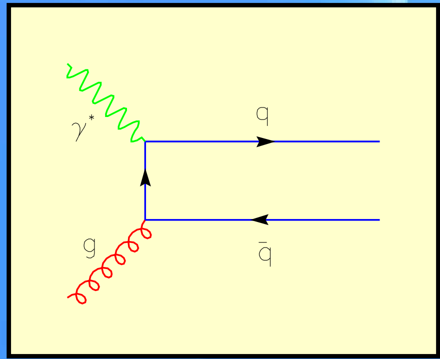

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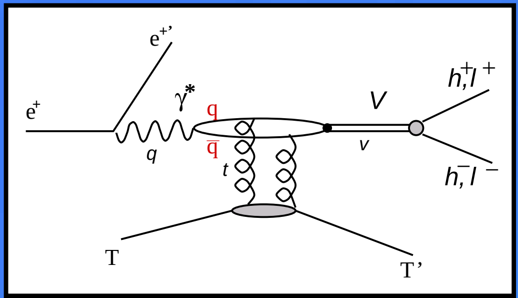

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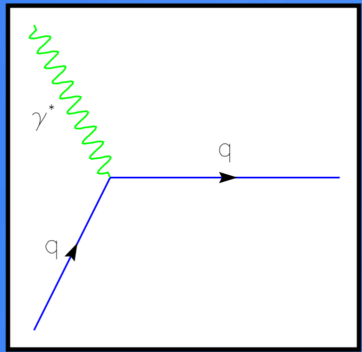

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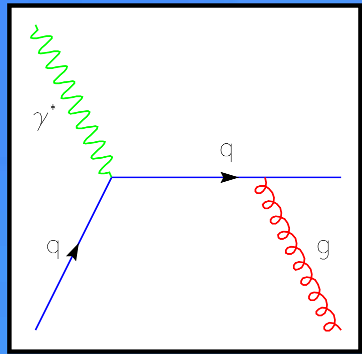

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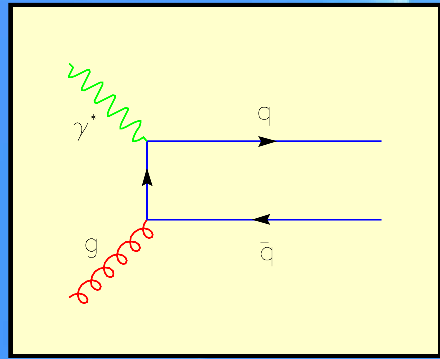

PGF

$$\mathbf{A_{PGF} \sim \frac{\Delta G}{G}}$$

$$\mathbf{A_{\parallel} \sim \sum_{i=1}^{4} f_i \cdot A_i \sim (f_{QCDC} A_{QCDC} + f_{PGF} A_{PGF})}$$

$$\mathbf{A_{PGF} \approx \langle \hat{a}(\gamma g \to q\bar{q}) \rangle \langle \frac{\Delta G}{G} \rangle = \underbrace{\langle \hat{a}_{PGF} \rangle}_{-1} \langle \frac{\Delta G}{G} \rangle}$$

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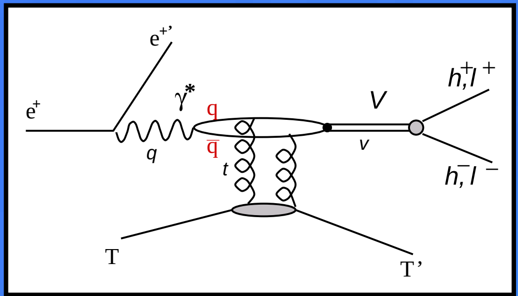

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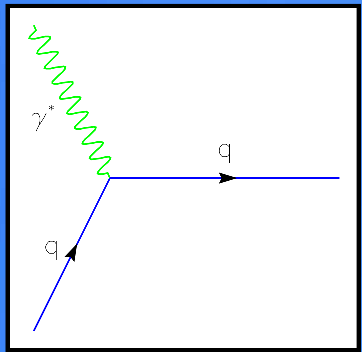

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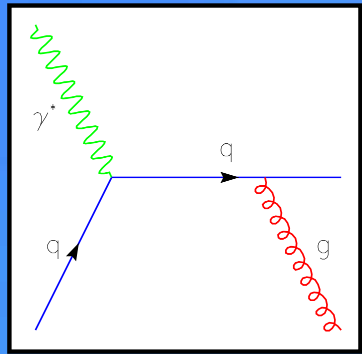

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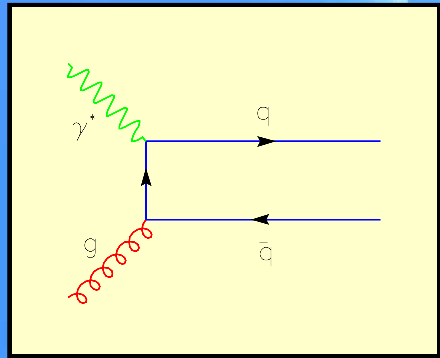

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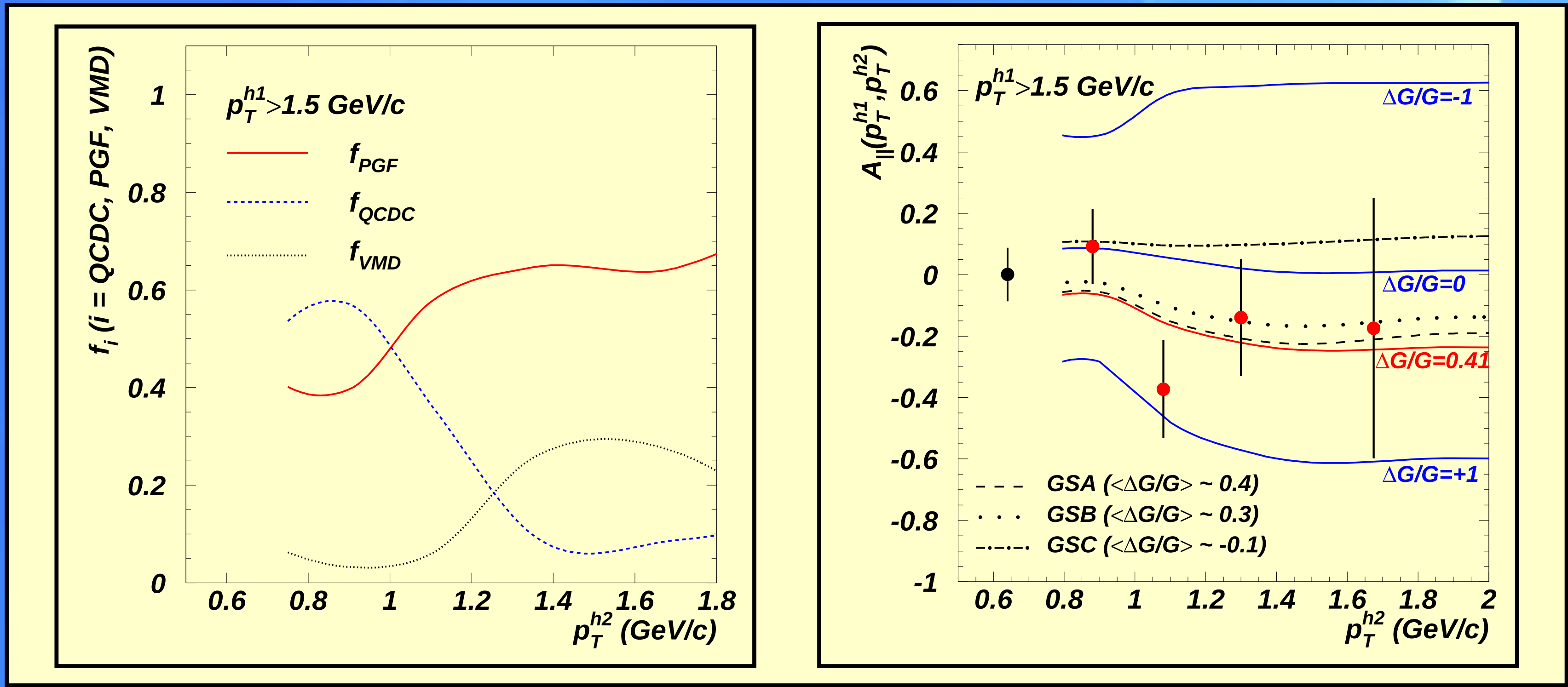
.. estimate their relative contributions f_i using Monte Carlo

$\Longrightarrow \Delta G/G$

Pairs of high-P_T Hadrons



within LO pQCD and PYTHIA5 MC model

$\Delta G/G$ **=** $0.41 \pm 0.18\ (\mathrm{stat.}) \pm 0.03\ (\mathrm{exp.syst.})$

at $\langle x_G \rangle = 0.17$ **and** $\langle \hat{p}_T^2 \rangle = 2.1$ **GeV**^{2}

Extraction strongly Model dependent
More data on polarised Deuterium available

$\Longrightarrow$ **Different Data needed to get** $\Delta G/G$

COMPASS

- **pairs of high p$_T$ hadrons**
  $\Longrightarrow \mathbf{\Delta G/G : 0.04 < x_g < 0.2}$
- **Heavy Quark Production ($\mathbf{c\bar{c}}$)**
  $\Longrightarrow \mathbf{\Delta G/G : x_g \sim 0.2}$

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RHIC

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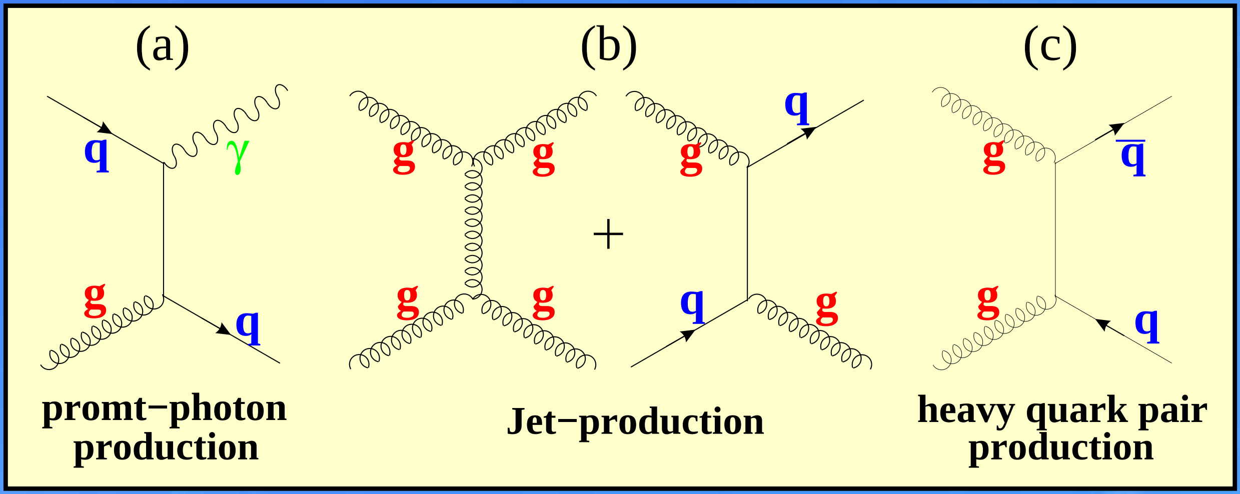

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- **Prompt Photon Production**
  ($\mathbf{pp \longrightarrow \gamma(jet)X}$)
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  $\Longrightarrow \mathbf{\Delta G/G : 0.02 < x_g < 0.2}$

$\Delta G/G$ *in 2010*

COMPASS

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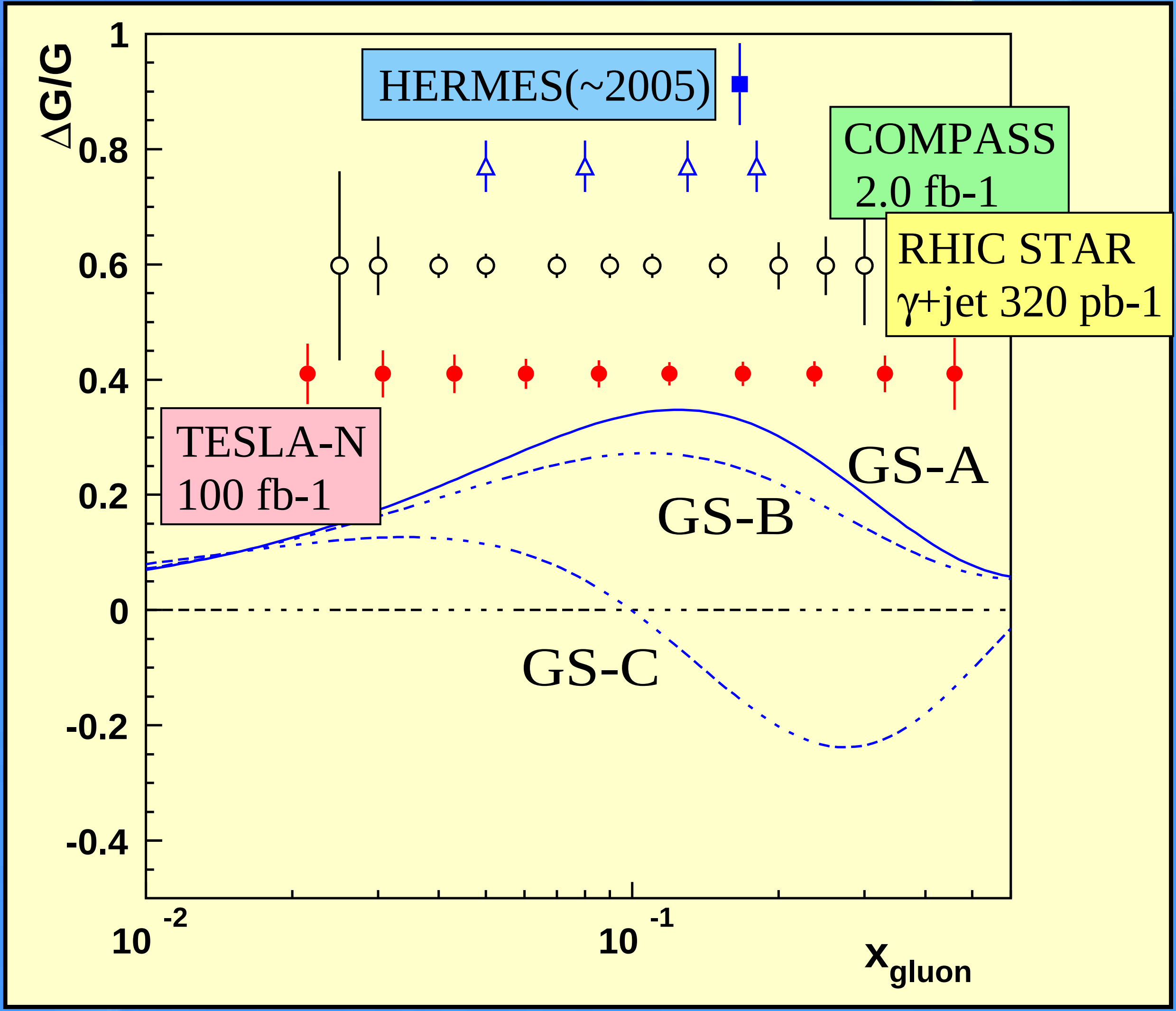

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  - $g_1(x)$ **high precision data on proton, deuteron and neutron**

Summary

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  - **very precise determination of $\mathbf{\Delta u}$ and $\mathbf{\Delta d}$ from NLO-QCD fits**

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    $\Longrightarrow$ $\Delta s(\bar{s})$ and $\Delta\bar{u} - \Delta\bar{d}$

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- $\Delta G(x)/G(x)$

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    $\Longrightarrow$ $\Delta s(\bar{s})$ **and** $\Delta\bar{u} - \Delta\bar{d}$
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  - **first indication of sign from**
    $\Longrightarrow$ **scaling violation of** $g_1(x)$
    $\Longrightarrow$ **isolating PGF (pairs of high** p_T **hadrons)**

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    $\Longrightarrow$ **scaling violation of $g_1(x)$**
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  - $\Delta G(x)/G(x)$ **needs results from RHIC and COMPASS**