Precision results on the spin structure function g_1 of the proton, the deuteron and the neutron from the HERMES experiment

Caroline Riedl

INFN/LNF

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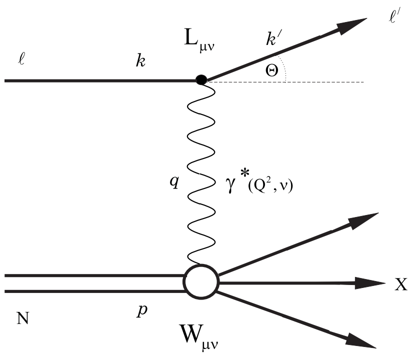
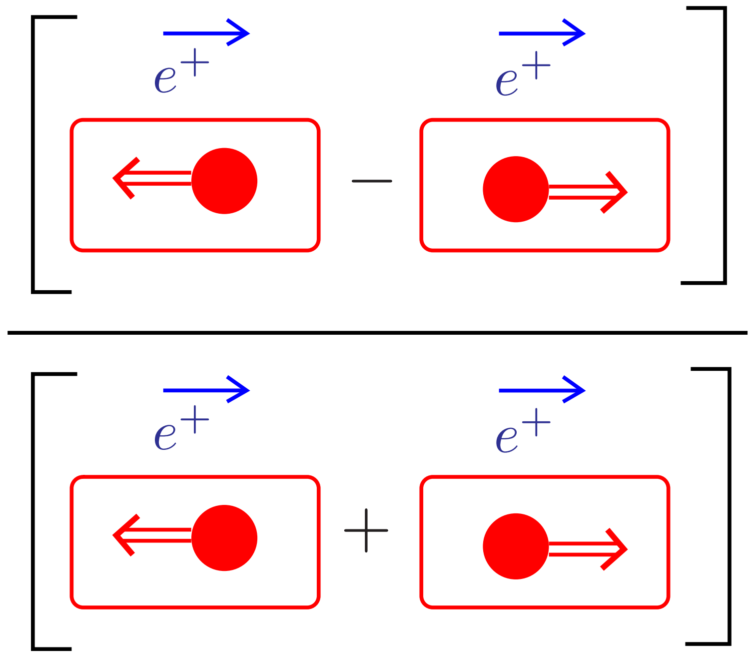


Inclusive asymmetry $A_\parallel$

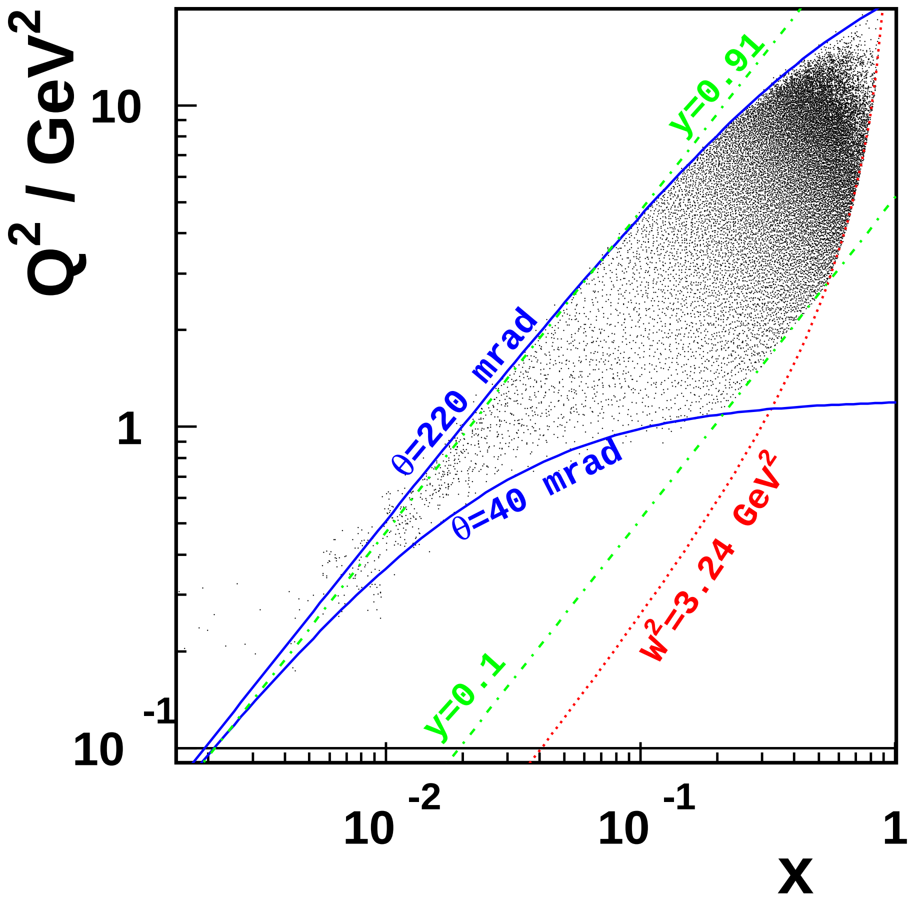
$A_\parallel = \frac{1}{\langle P_B P_z \rangle} \cdot$



$\sim \frac{g_1}{F_1}$

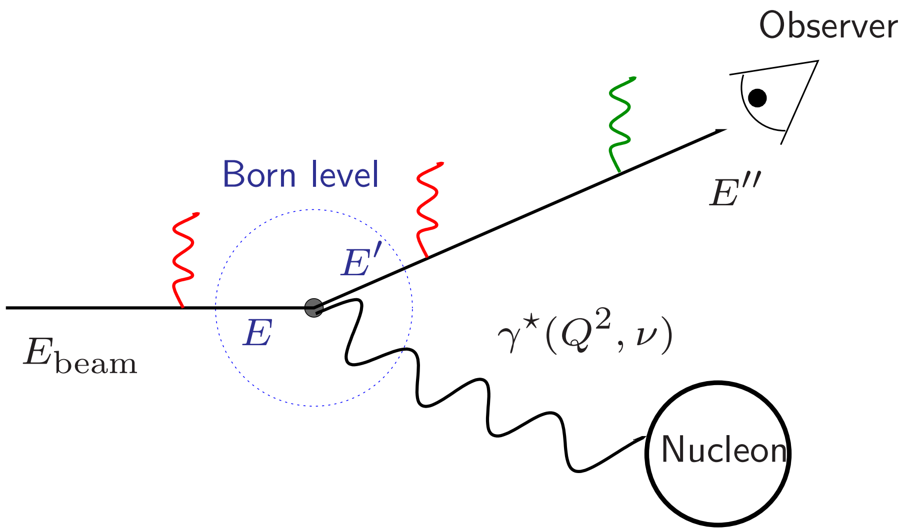
- Polarized positron beam: $\langle P_B \rangle \approx 0.53$, $E_B = 27.6$ GeV
- Polarized fixed target: gaseous hydrogen or deuterium, $\langle P_z \rangle \approx 0.85$

Inclusive data sample



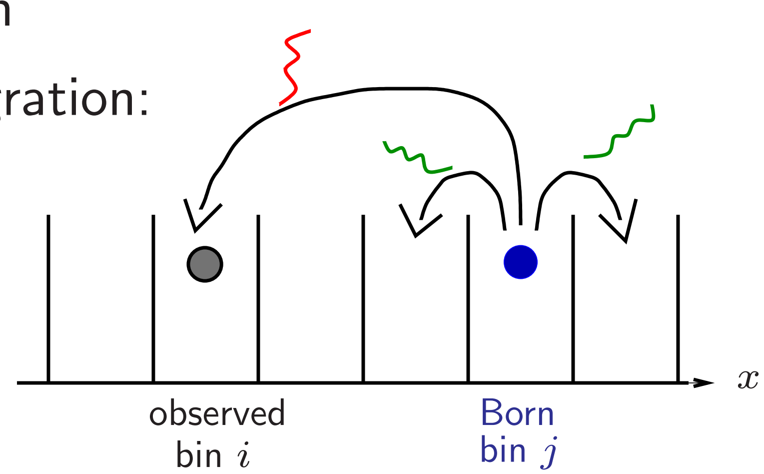
- Leading lepton
- Fiducial volume defines active area of spectrometer
- Kinem. cuts: $0.0021 < x < 0.85$, $Q^2 > 0.1$ GeV^2
- 20 bins in x-Bjørken

From the observed to the true bin



QED radiative effects and detector smearing

bin migration:



Unfolding of kinematic migrations

- Measured asymmetry $A_{\parallel}^{\text{meas}}$ diluted by background $\Delta\sigma$
  $\Rightarrow$ to be removed to get asymmetry on Born level $A_{\parallel}^{\text{Born}}$:

$$A_{\parallel}^{\text{Born}}(j) = -1 + \frac{2}{\sigma_{\text{Born}}^{\text{U}}(j)} \cdot \sum_{i=1}^{n} [S']^{-1}(j,i) \times$$

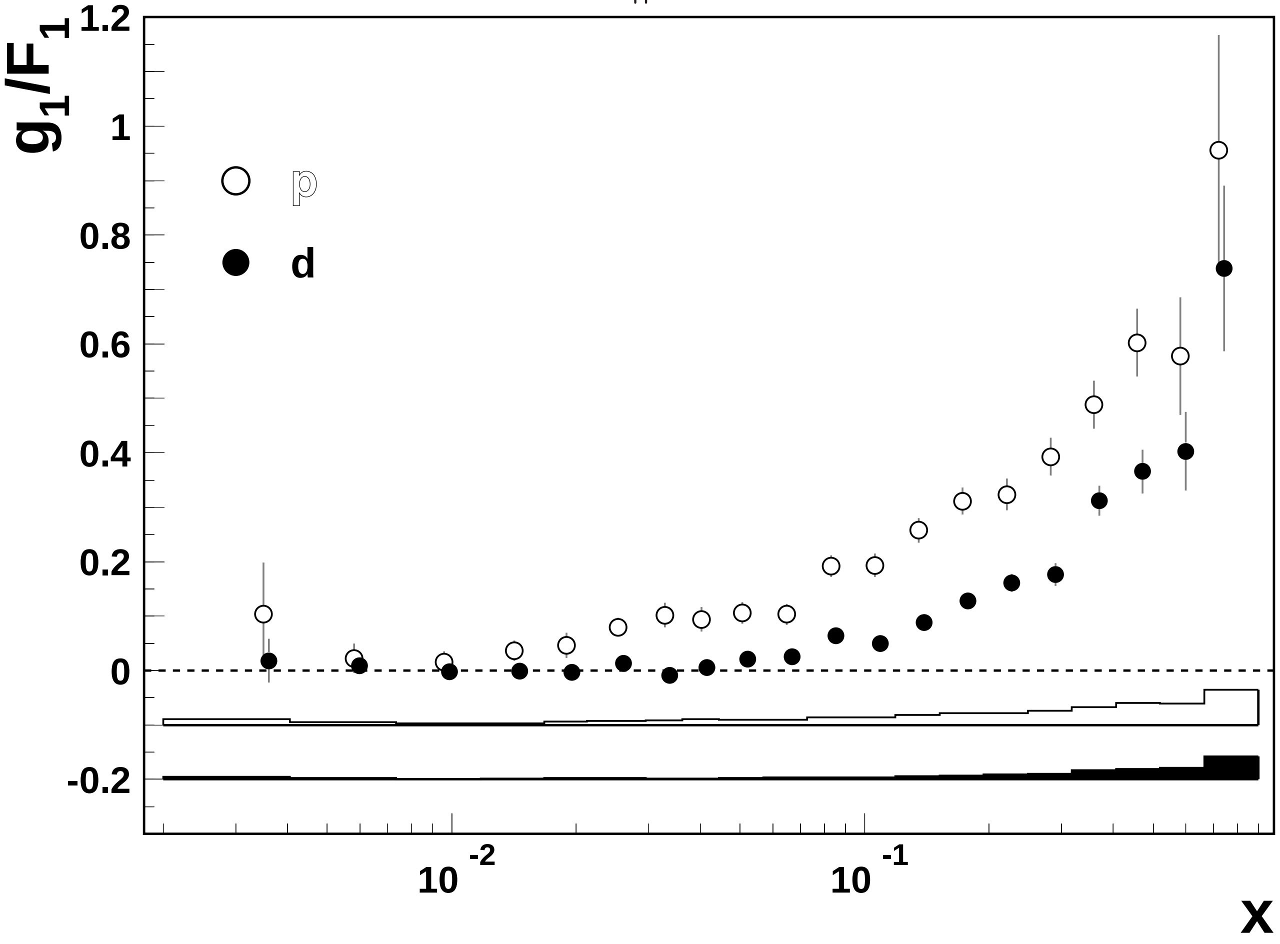
$$\left[A_{\parallel}^{\text{meas}}(i)\sigma_{\text{X}}^{\text{U}}(i) - \Delta \overset{\frown}{\sigma}^{\text{P}}(i) + \sum_{k=1}^{n} S^{-}(i,k)\sigma_{\text{Born}}^{\text{U}}(k) \right]$$

$$A_{\parallel}^{\text{Born}} \equiv A_{\parallel}^{\text{meas}} \cdot \left(1 + \frac{\Delta\sigma^{\text{U}}}{\sigma_{\text{Born}}^{\text{U}}} \right) - \frac{\Delta\sigma^{\text{P}}}{\sigma_{\text{Born}}^{\text{U}}}$$

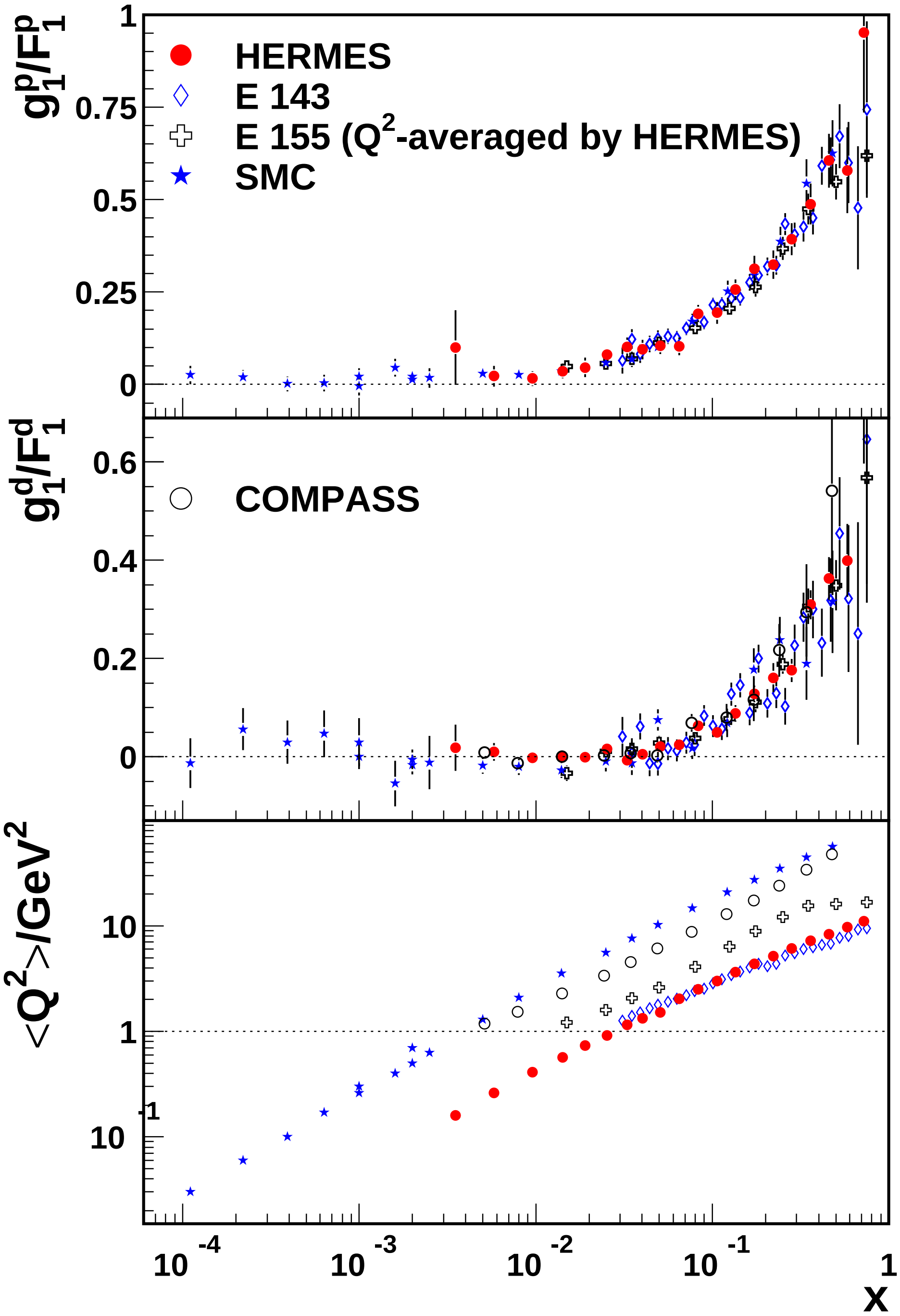
- Monte Carlo productions:
  √ Radiative corrections (RADGEN)
  √ Detector model (GEANT)
  √ Matrix $S(i,j)$ with event migrations from bin j to i

- Unfolding of migrations :
  √ Removes *systematic* correlations, introduces *statistical* corr.
  √ No iteration needed
  √ Algorithm (almost) model-independent

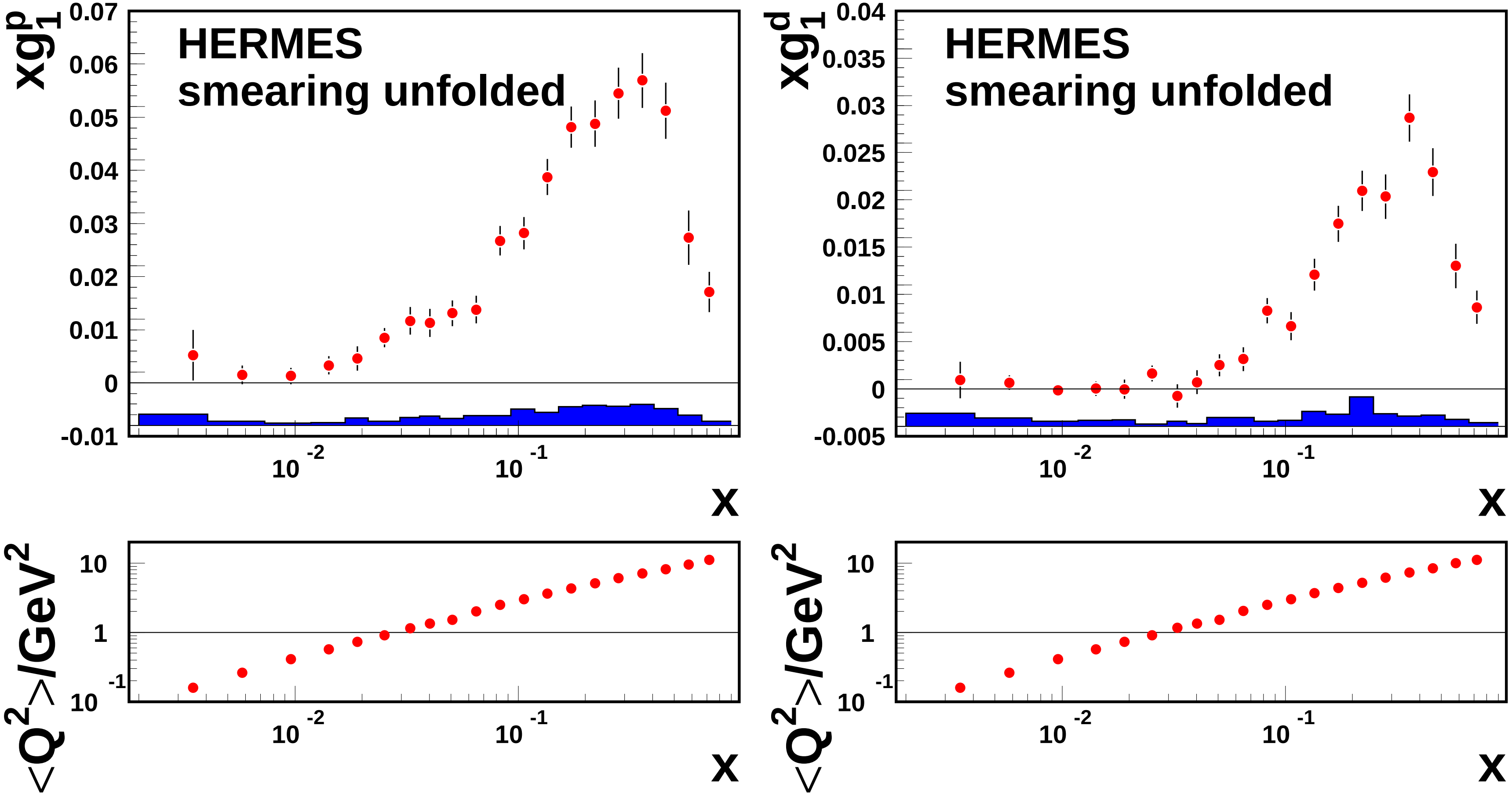
HERMES: $g_1/F_1 \sim A_\parallel$ (proton, deuteron)



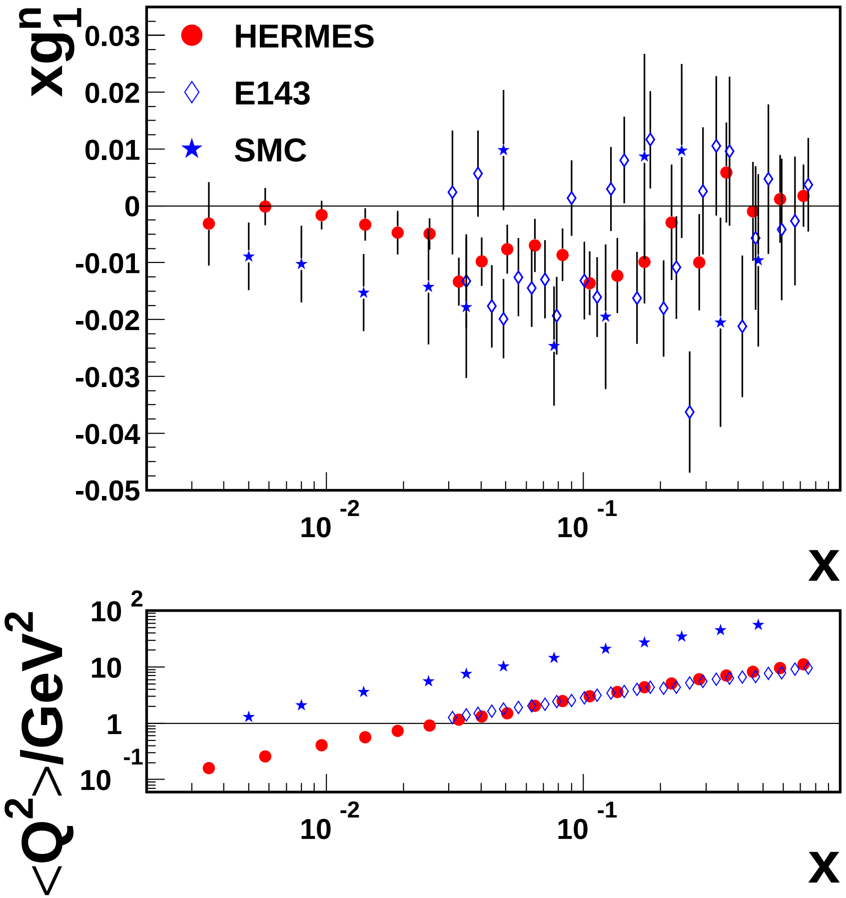
World data on $g_1/F_1 \sim A_\parallel$



Spin structure function xg_1 of p and d



Neutron xg_1 from proton and deuteron data



Extracted from

$$g_1^{\mathrm{d}} = \frac{1}{2}\left(1 - \frac{3}{2}\omega_D\right)(g_1^{\mathrm{p}} + g_1^{\mathrm{n}}),$$

with $\omega_D = 0.05$

Moments of g_1

- Evolution to common $Q_0^2 = 5$ GeV^2:

$$M = \int_{x_s}^{x_f} g_1(x, Q_0^2)\mathrm{d}x = \sum_i \left[\frac{g_1}{F_1}(\langle x_i \rangle, \langle Q_i^2 \rangle) \int_{x_i}^{x_{i+1}} F_1(x, Q_0^2)\mathrm{d}x \right]$$

$$\delta M = \sum_i \sum_j \mathrm{cov}(i,j) \int_{x_i}^{x_{i+1}} F_1(x, Q_0^2)\mathrm{d}x \int_{x_j}^{x_{j+1}} F_1(x, Q_0^2)\mathrm{d}x$$

- HERMES ($x_s = 0.021$, $x_f = 0.9$, $Q_0^2 = 5$ GeV^2, only data $Q^2 > 1$ GeV^2):

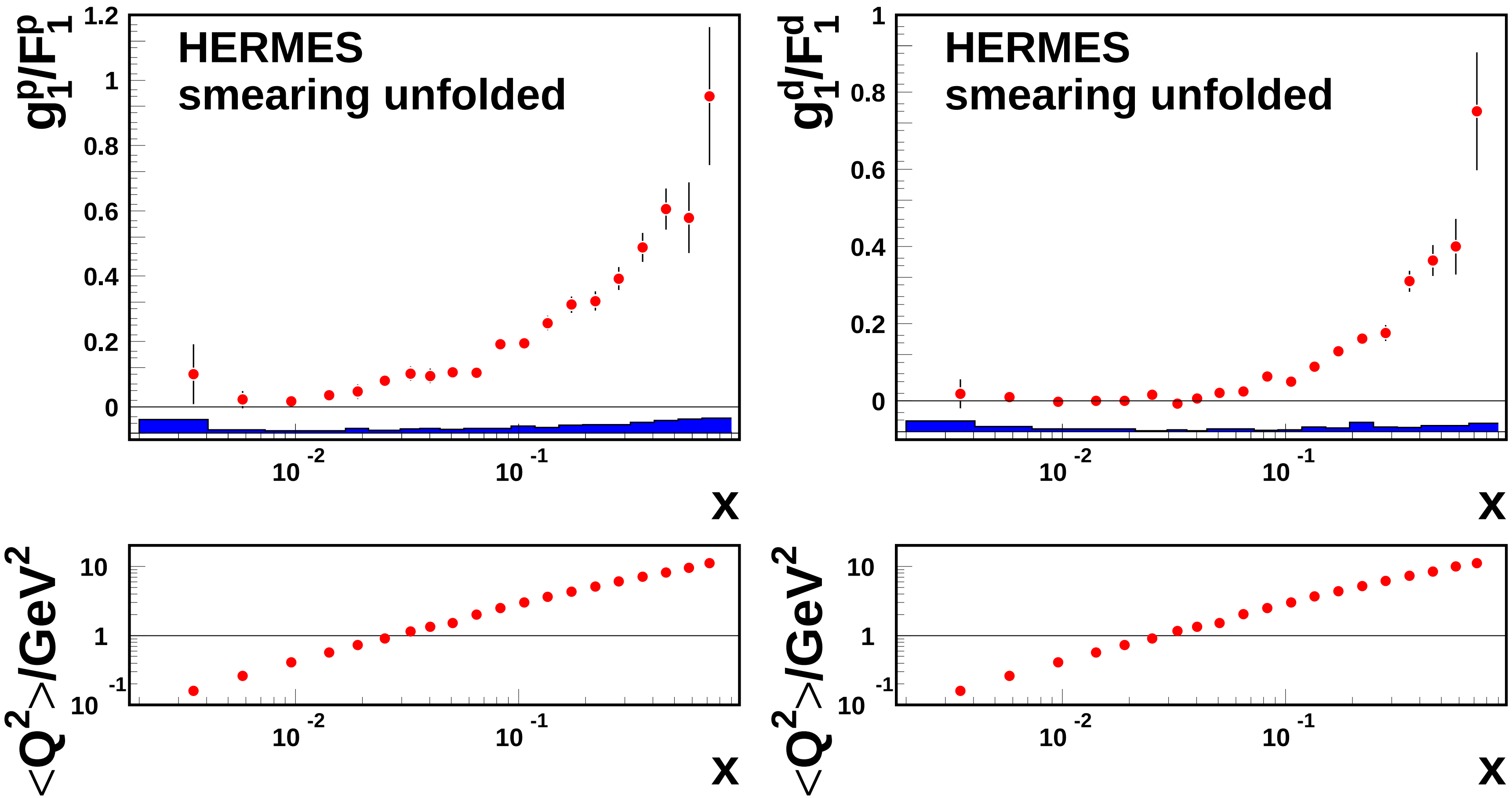
Target	M
proton	$0.1245 \pm 0.0033(\mathrm{stat}) \pm 0.0080(\mathrm{sys})$
deuteron	$0.0454 \pm 0.0016(\mathrm{stat}) \pm 0.0023(\mathrm{sys})$
"n=2d-p"	$-0.0263 \pm 0.0047(\mathrm{stat}) \pm 0.0100(\mathrm{sys})$

- HERMES moments compatible with E143, E155 and SMC

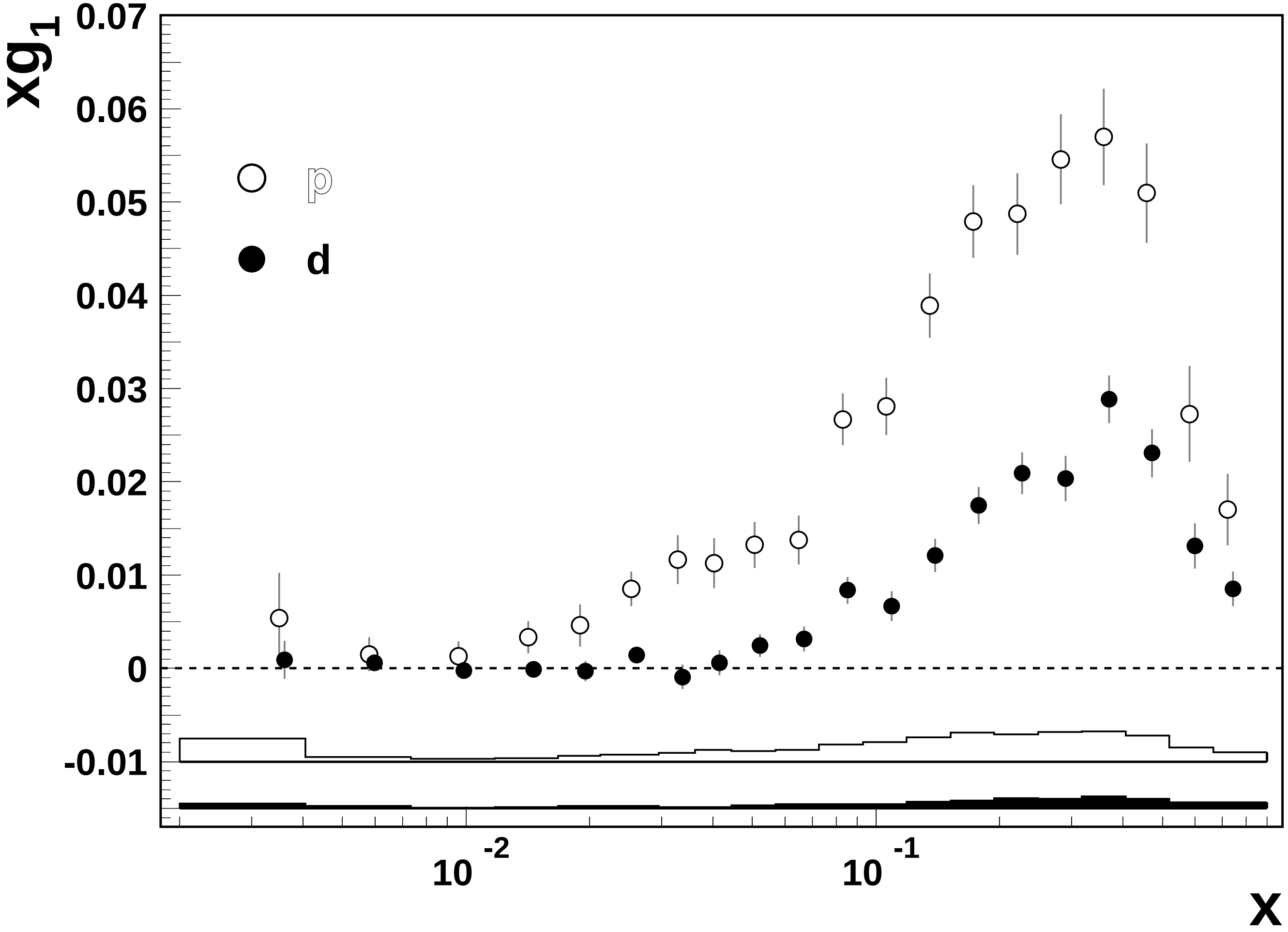
Summary

- Final results on spin structure function g_1 from HERMES data (proton, deuteron):
  - Corrected for QED radiative effects and detector smearing
  - Correction algorithm introduces statistical correlations between bins and removes systematic correlations
- Comparison to world data:
  - Proton: HERMES data comparable to most precise results (SLAC, CERN); good agreement
  - Deuteron: so far most precise determination; results agree with COMPASS, but show systematic disagreement with SMC data for $x \lesssim 0.02$
  - Neutron (from p and d): Best statistical accuracy; HERMES g_1 shows no drop-off at small-x as suggested by SMC
- Calculated g_1 moments in the measured range in agreement with CERN and SLAC results
- Long HERMES publication on g_1 in preparation (soon to come)

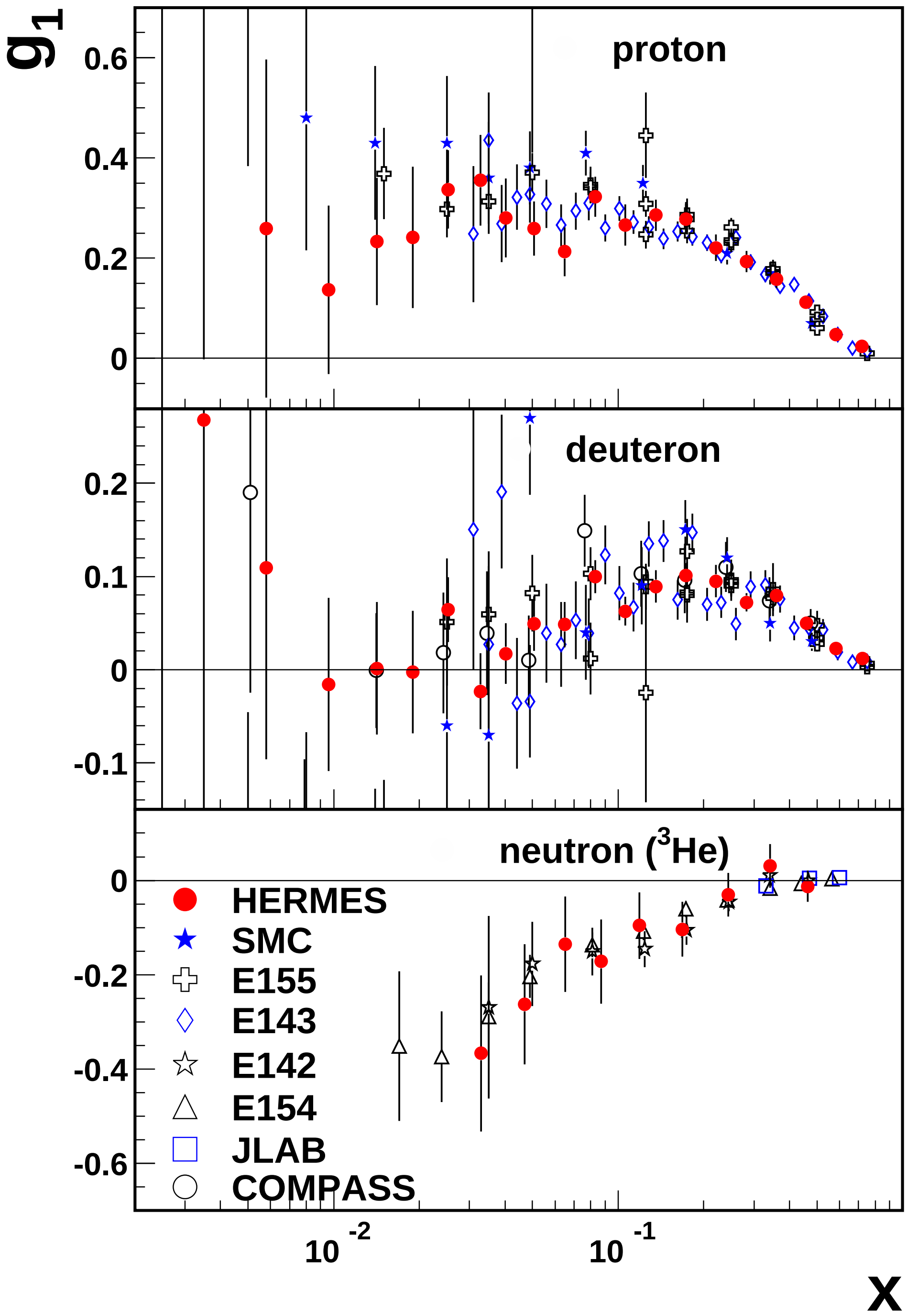
g_1/F_1 of the proton and of the deuteron



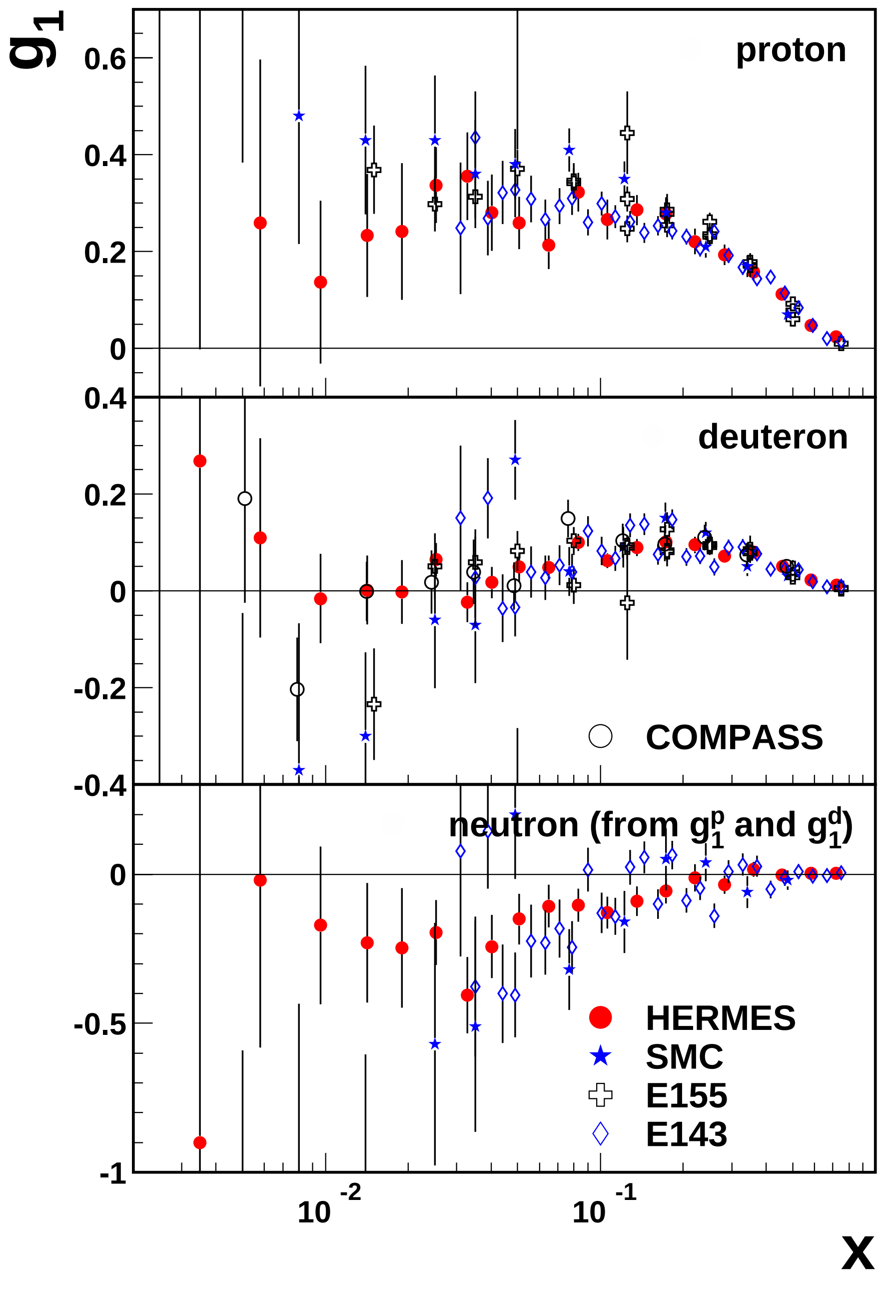
HERMES: xg_1 (proton, deuteron)



World data on g_1

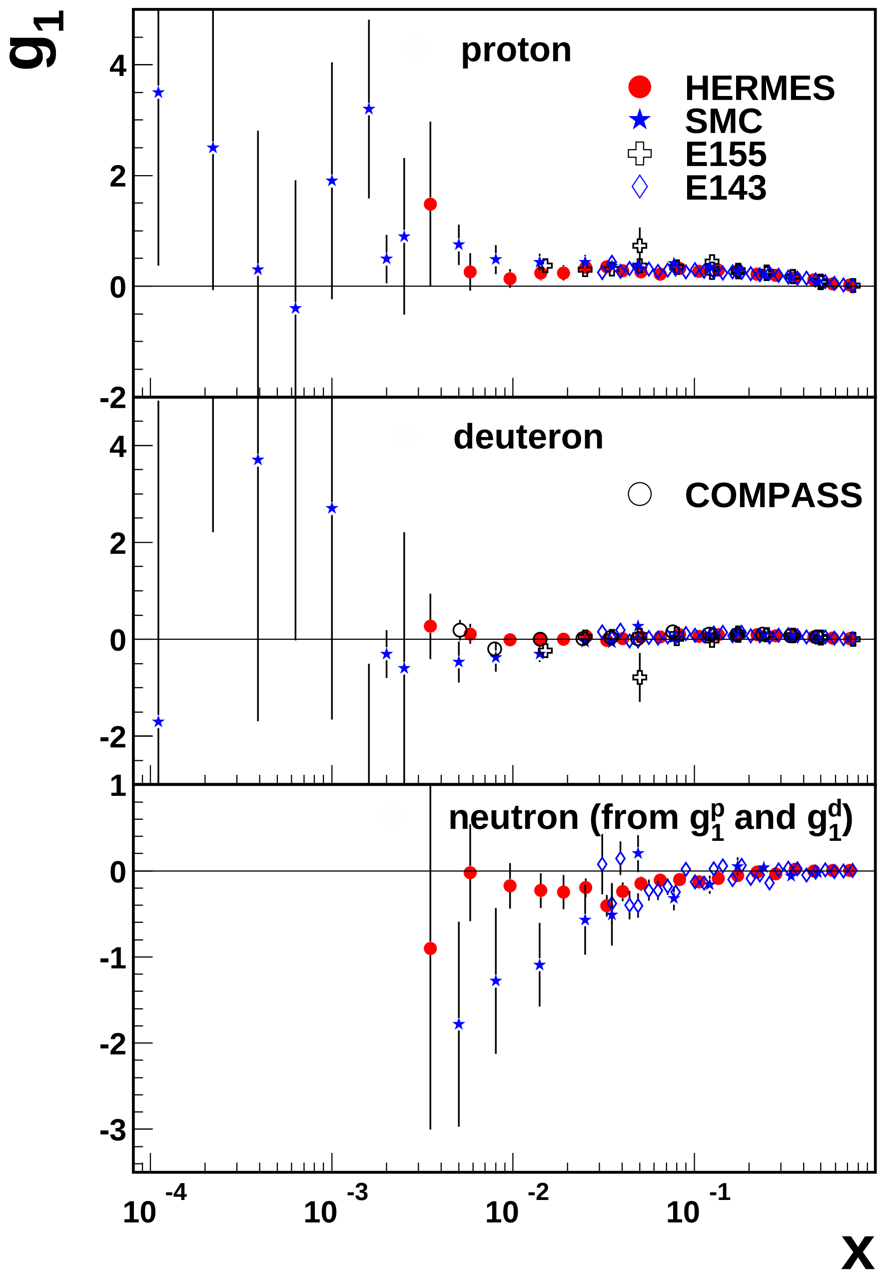


World data on g_1 (neutron)



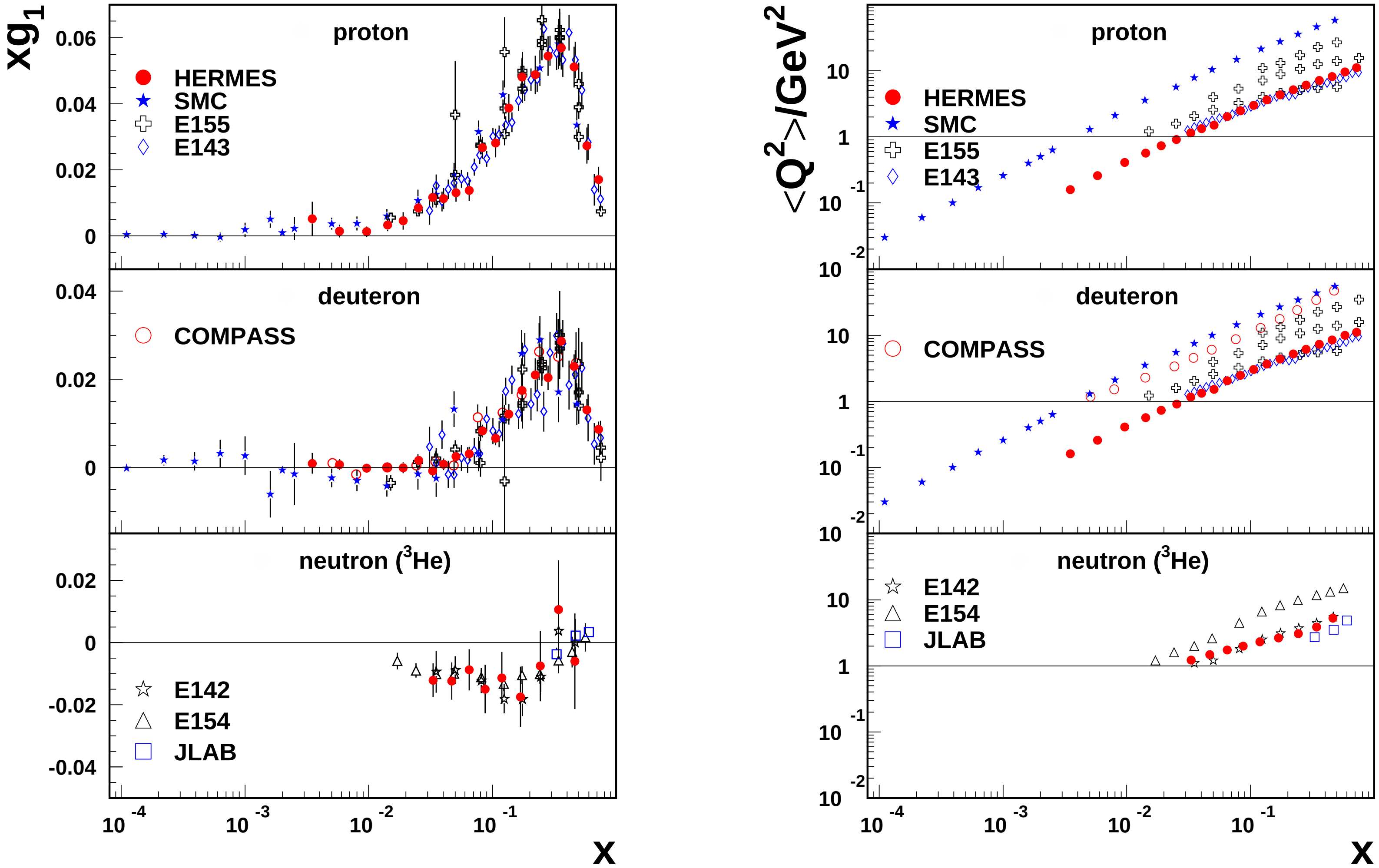
$$g_1^{\mathrm{d}} = \frac{1}{2}\left(1 - \frac{3}{2}\omega_D\right)\left(g_1^{\mathrm{p}} + g_1^{\mathrm{n}}\right), \text{ with } \omega_D = 0.058$$

World data on g_1 (neutron)



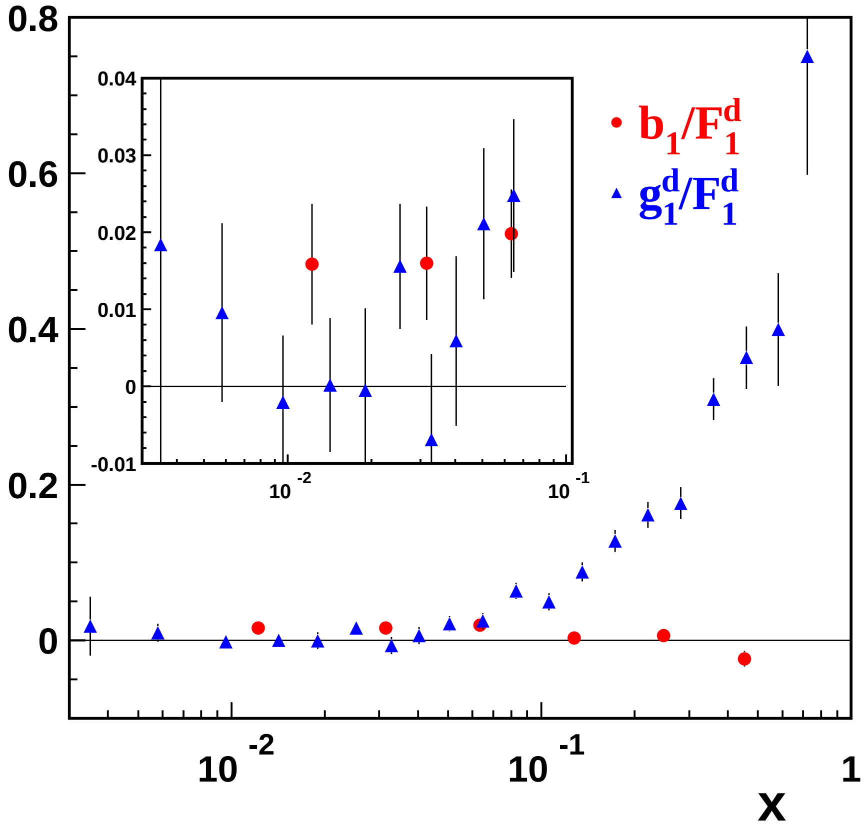
$g_1^{\mathrm{d}} = \frac{1}{2}\left(1 - \frac{3}{2}\omega_D\right)\left(g_1^{\mathrm{p}} + g_1^{\mathrm{n}}\right)$, with $\omega_D = 0.058$

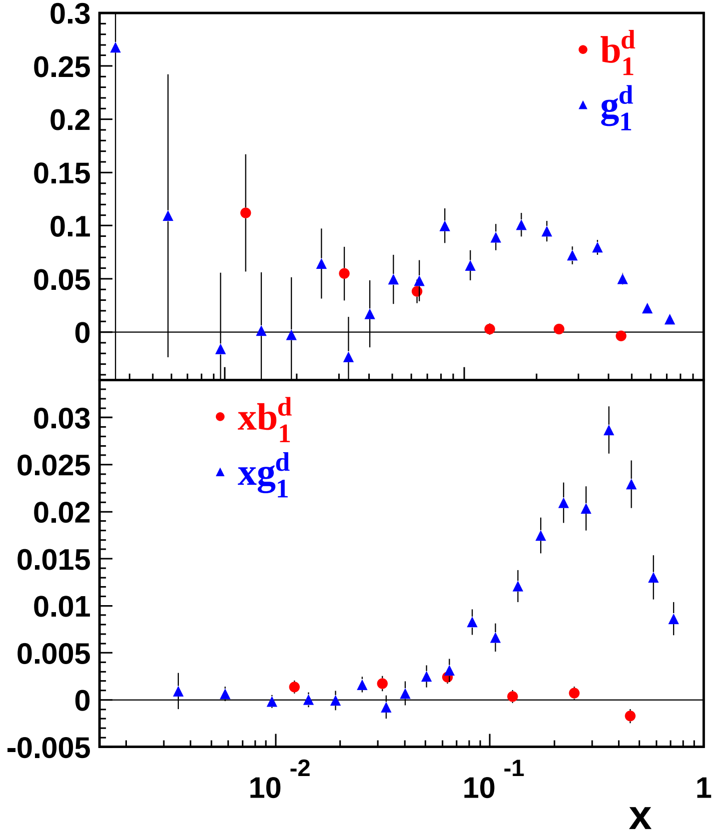
World data on xg_1



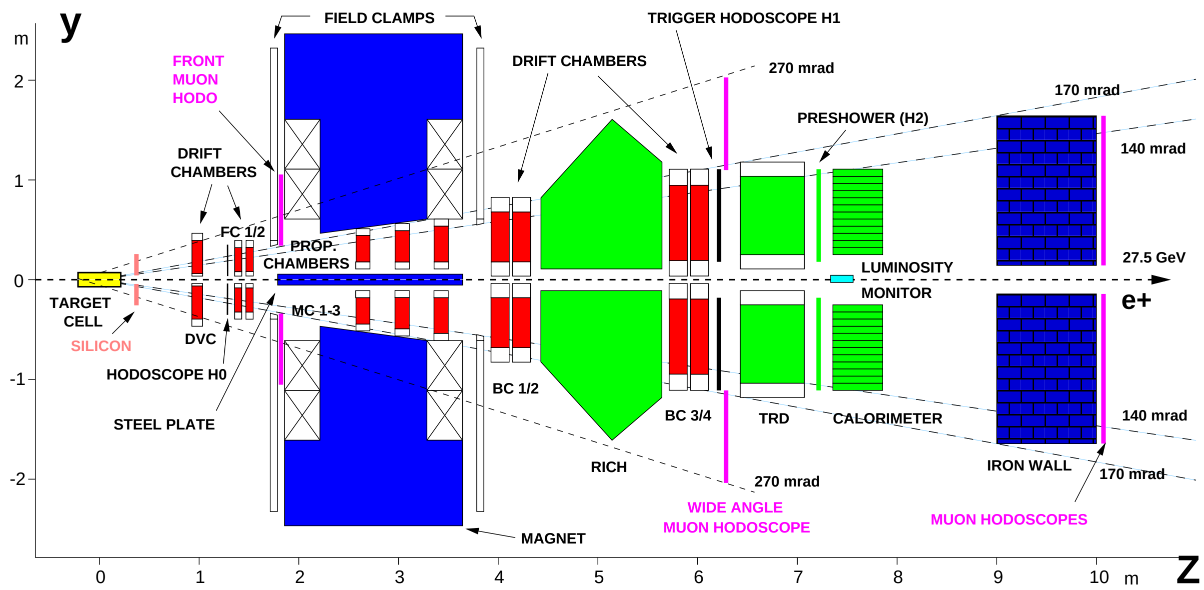
hermes

Comparison: Tensor vs. Vector asymmetry





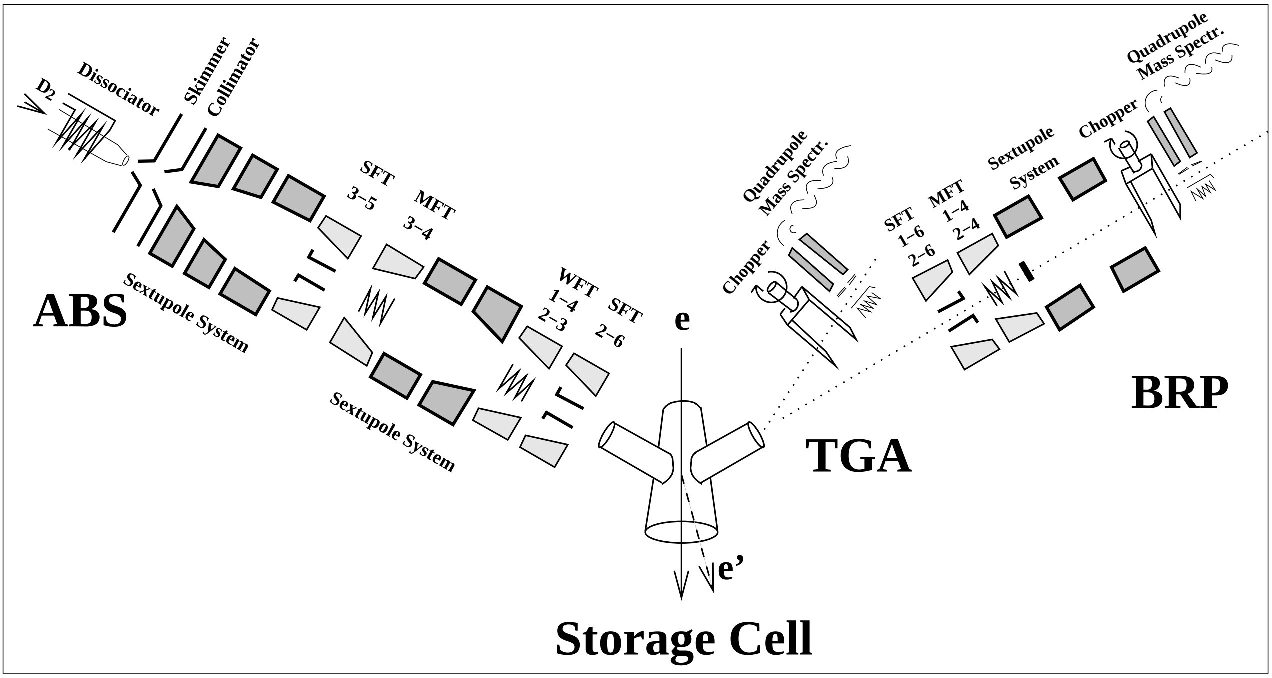
The HERMES spectrometer



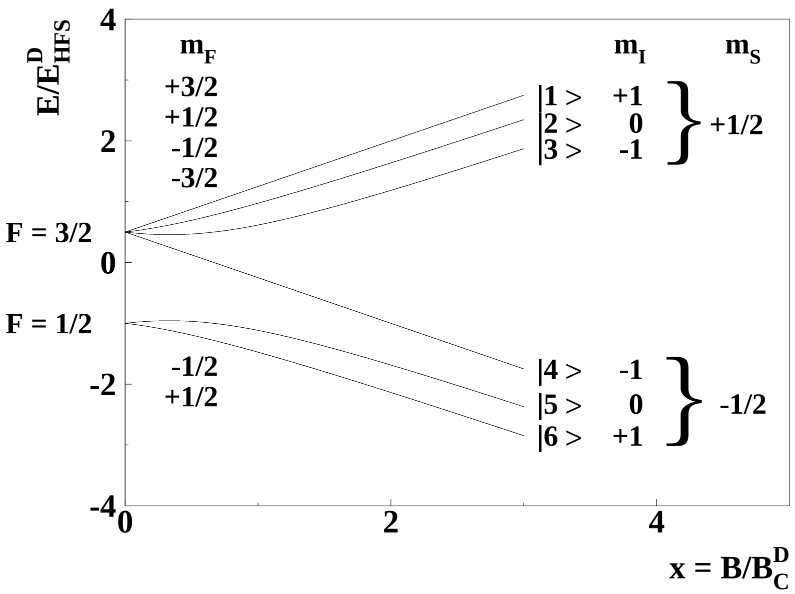
- Acceptance: $40 < \theta < 220$ mrad
- Momentum resolution: $\frac{\delta p}{p} \approx 2\%$;
  Angular resolution: $0.3 - 0.6$ mrad;
- Calorimeter: $\frac{\delta E}{E} \approx \frac{(5.1 \pm 1.1)}{\sqrt{E[\mathrm{GeV}]}}\%$

- PID: RICH, TRD, preshower, calo
- Efficiency of electron ID: 98-99 %
- Hadron contamination: $< 1\%$

The HERMES-target



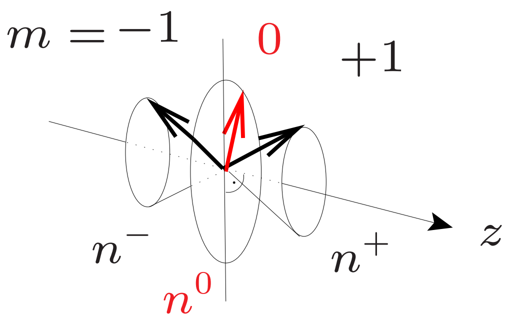
Hyperfine splitting in a magnetic field for deuterium:



Polarized atomic gas target

Proton: $m = \pm\frac{1}{2}$

Deuteron (Spin-1):



Polarizations:

vector $P_z = \frac{n^+ - n^-}{n^+ + n^- + n^0}$

tensor $P_{zz} = \frac{(n^+ + n^-) - 2n^0}{n^+ + n^- + n^0}$

$|P_z| \leq 1, \ -2 \leq P_{zz} < 1$

HERMES target: ABS + gas analyzing system

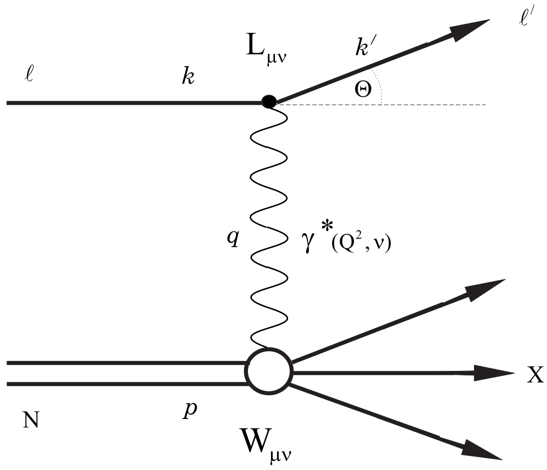
Special:

- Hyperfine states can be selected separately
- Negative P_{zz} reachable!

target state	injected	P_z	P_{zz}
vector +	n^+	$+0.85$	$+0.80$
vector −	n^-	-0.84	$+0.85$
tensor +	$n^+ + n^-$	-0.01	$+0.89$
tensor −	n^0	-0.01	-1.66

$\Rightarrow$ High P_{zz} (at P_z=0) reachable

Deeply inelastic lepton-nucleon scattering (inclusive measurement)



LORENTZ invariant kinematic variables

- square of four-momentum transfer

$$Q^2 = -q^2 \overset{\text{Lab.}}{\simeq} 2EE'(1 - \cos\Theta)$$

- Bjørken scale variable

$$x = \frac{Q^2}{2\mathbf{pq}} = \frac{Q^2}{2M\nu} \qquad 0 \leq x \leq 1$$

- electron energy transferred to the nucleon

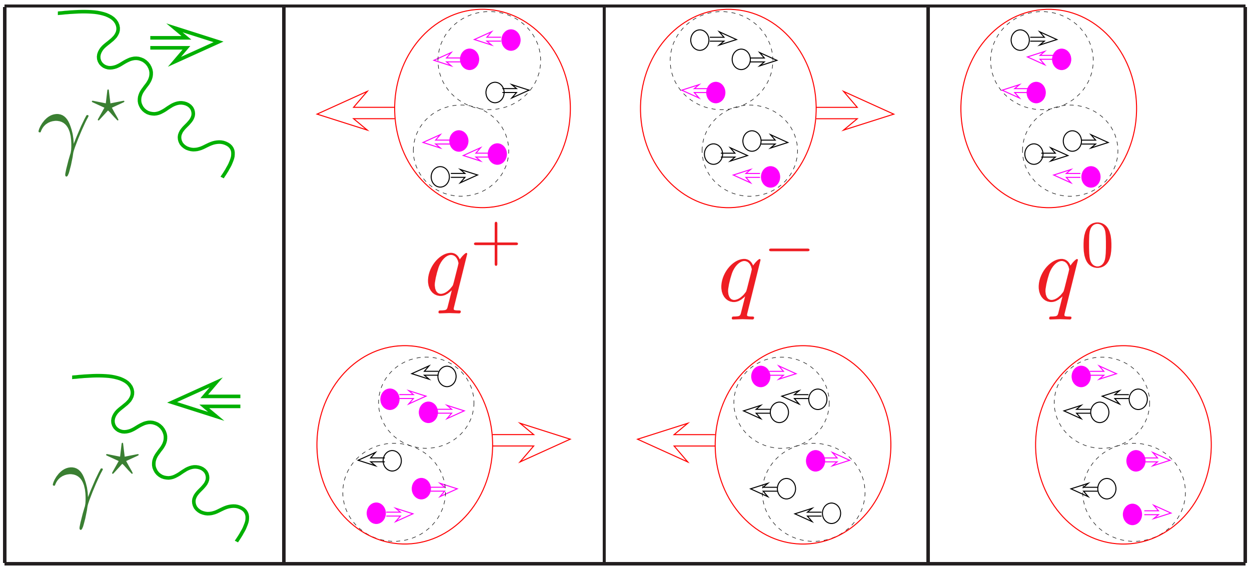
$$\nu = \frac{\mathbf{pq}}{M} \overset{\text{Lab.}}{\simeq} E - E'$$

- fraction of electron energy transferred to the nucleon

$$y = \frac{\mathbf{pq}}{\mathbf{pk}} \overset{\text{Lab.}}{=} \frac{\nu}{E} \qquad 0 \leq y \leq 1$$

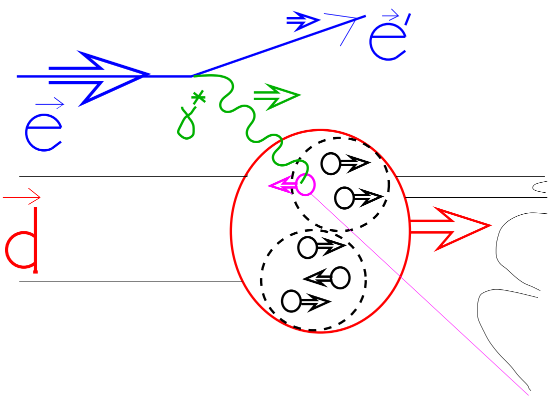
Structure functions in the QPM

Quark densities $q(x, Q^2)$



Spin-$\frac{1}{2}$ (proton)	Spin-1 (deuteron)
$F_1 = \frac{1}{2}\sum_q e_q^2 \left(q^+ + q^-\right)$	$F_1 = \frac{1}{3}\sum_q e_q^2 \left(q^+ + q^- + q^0\right)$
$g_1 = \frac{1}{2}\sum_q e_q^2 \left(q^+ - q^-\right)$	$g_1 = \frac{1}{2}\sum_q e_q^2 \left(q^+ - q^-\right)$
	$b_1 = \frac{1}{2}\sum_q e_q^2 \left(2q^0 - (q^+ + q^-)\right)$

Structure functions and interaction



x-section for DIS:

$$\frac{d^2\sigma}{dE'd\Omega}\Big|_{\text{Born}} = \frac{\alpha^2}{2MQ^4}\frac{E'}{E}L_{\mu\nu}W^{\mu\nu}$$

Leptonic and hadronic tensor each separable in

{symmetric}, spin *in*dependent and

[anti-symmetric], spin dependent part ⇒

$$L_{\mu\nu}W^{\mu\nu} = \underbrace{L_{\{\mu\nu\}}W^{\{\mu\nu\}}(F_1, F_2, b_1, b_2, b_3, b_4)}_{\text{unpolarized}} + $$

$$+ \underbrace{iL_{[\mu\nu]}W^{[\mu\nu]}(g_1, g_2)}_{\text{polarized inclusive x-section}}$$

(⇒ b_1 not sensitive to beam polarization, but implicitly dependent on target spin)

Leptonic and hadronic tensor

$$L^{\mu\nu} = L^{\{\mu\nu\}} \quad + \quad iL^{[\mu\nu]}(s)$$

spin *in*dependent and {symmetric}

spin dependent and [anti symmetric]

$$W^{\mu\nu} = W^{\{\mu\nu\}}(F_1, F_2) \quad + \quad iW^{[\mu\nu]}(g_1, g_2) +$$

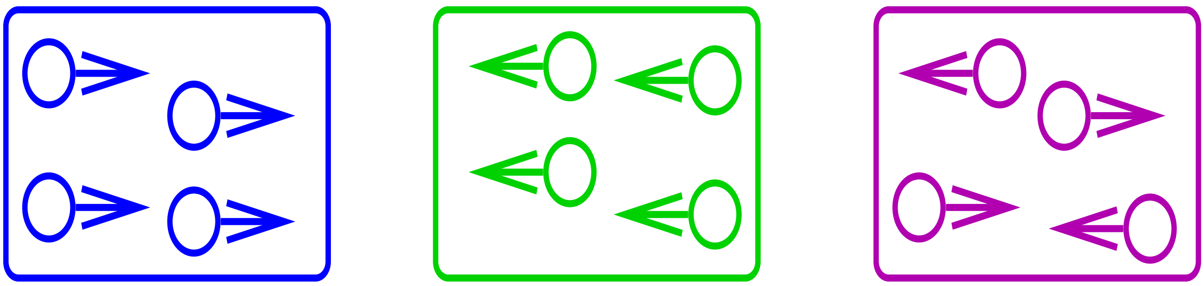
$$+W^{\{\mu\nu\}}(b_1, b_2, b_3, b_4)$$

implicitly dependent on target spin
(additionally and only for Spin-1)

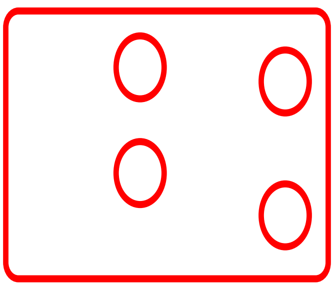
Inclusive spin physics at HERMES

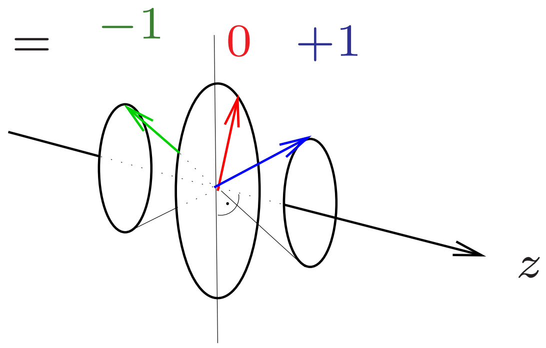
Measure (E, θ) of pol. DIS electron off pol. target:

$P_z = +1$ $\qquad$ $P_z = -1$ $\qquad$ $P_z = 0$



$P_z = 0 \quad P_{zz} = -2$





Deuteron spin states

$$A_{\parallel} \;=\; \frac{1}{\langle P_B P_z \rangle} \cdot \frac{\left(\frac{N^{\stackrel{\rightarrow}{\Leftarrow}}}{L^{\stackrel{\rightarrow}{\Leftarrow}}}\right) - \left(\frac{N^{\stackrel{\rightarrow}{\Rightarrow}}}{L^{\stackrel{\rightarrow}{\Rightarrow}}}\right)}{\left(\frac{N^{\stackrel{\rightarrow}{\Leftarrow}}}{L^{\stackrel{\rightarrow}{\Leftarrow}}}\right) + \left(\frac{N^{\stackrel{\rightarrow}{\Rightarrow}}}{L^{\stackrel{\rightarrow}{\Rightarrow}}}\right)} \sim D \frac{g_1}{F_1}$$

$$A_{zz} \;=\; \frac{1}{\langle P_{zz} \rangle} \cdot \frac{\frac{2}{3}\left(\frac{N^{\stackrel{\rightarrow}{\Leftarrow}}}{L^{\stackrel{\rightarrow}{\Leftarrow}}} + \frac{N^{\stackrel{\rightarrow}{\Rightarrow}}}{L^{\stackrel{\rightarrow}{\Rightarrow}}} + \frac{N^{\Leftrightarrow}}{L^{\Leftrightarrow}}\right) - 2\left(\frac{N^0}{L^0}\right)}{\frac{2}{3}\left(\frac{N^{\stackrel{\rightarrow}{\Leftarrow}}}{L^{\stackrel{\rightarrow}{\Leftarrow}}} + \frac{N^{\stackrel{\rightarrow}{\Rightarrow}}}{L^{\stackrel{\rightarrow}{\Rightarrow}}} + \frac{N^{\Leftrightarrow}}{L^{\Leftrightarrow}}\right) + \left(\frac{N^0}{L^0}\right)} = -\frac{2}{3}\frac{b_1}{F_1}$$

Inclusive asymmetries

- Measured cross section:

$$\sigma = \sigma^{\mathrm{U}} \left[1 - P_B P_z A_\parallel + \frac{1}{2} P_{zz} A_{zz} \right]$$

- Inclusive vector asymmetry :

$$A_\parallel = \frac{1}{\langle P_B P_z \rangle} \cdot \frac{\left(\frac{N^{\stackrel{\rightarrow}{\Leftarrow}}}{L^{\stackrel{\rightarrow}{\Leftarrow}}} \right) - \left(\frac{N^{\stackrel{\rightarrow}{\Rightarrow}}}{L^{\stackrel{\rightarrow}{\Rightarrow}}} \right)}{\left(\frac{N^{\stackrel{\rightarrow}{\Leftarrow}}}{L^{\stackrel{\rightarrow}{\Leftarrow}}} \right) + \left(\frac{N^{\stackrel{\rightarrow}{\Rightarrow}}}{L^{\stackrel{\rightarrow}{\Rightarrow}}} \right)}$$

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

Kinematic variables:

$$\gamma = \frac{\sqrt{Q^2}}{\nu}, \qquad \eta = \eta(x, Q^2), \qquad D = \frac{P_{\gamma^\star}}{P_{\mathrm{B}}}$$

- Inclusive tensor asymmetry :

$$A_{zz} = \frac{1}{\langle P_{zz} \rangle} \cdot \frac{\frac{2}{3} \left(\frac{N^{\stackrel{\rightarrow}{\Leftarrow}}}{L^{\stackrel{\rightarrow}{\Leftarrow}}} + \frac{N^{\stackrel{\rightarrow}{\Rightarrow}}}{L^{\stackrel{\rightarrow}{\Rightarrow}}} + \frac{N^{\Leftrightarrow}}{L^{\Leftrightarrow}} \right) - 2 \left(\frac{N^0}{L^0} \right)}{\frac{2}{3} \left(\frac{N^{\stackrel{\rightarrow}{\Leftarrow}}}{L^{\stackrel{\rightarrow}{\Leftarrow}}} + \frac{N^{\stackrel{\rightarrow}{\Rightarrow}}}{L^{\stackrel{\rightarrow}{\Rightarrow}}} + \frac{N^{\Leftrightarrow}}{L^{\Leftrightarrow}} \right) + \left(\frac{N^0}{L^0} \right)} = -\frac{2}{3} \frac{b_1}{F_1}$$

Vector asymmetry

Virtual photon asymmetries:

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

$$A_2(x) = \frac{\sigma_{\mathrm{TL}}}{\sigma_{\mathrm{T}}} = \frac{\gamma(g_1(x) + g_2(x))}{F_1(x)}$$

$\Rightarrow$ write $A_{\|}$ as:

$$A_{\|} = D(A_1 + \eta A_2)$$

Used parameterizations

$$\begin{aligned} A_2 &\sim M_\mathrm{p}\frac{x}{\sqrt{Q^2}} \\ F_2^\mathrm{p} &= F_2^\mathrm{p}(\mathrm{ALLM}), \qquad F_2^\mathrm{d} = \frac{1}{2}\,F_2^\mathrm{p}\,\underbrace{(\frac{F_2^\mathrm{n}}{F_2^\mathrm{p}})}_{\mathrm{NMC}} \\ R &= R(1990) \end{aligned}$$

with

$$R = \sigma_\mathrm{L}/\sigma_\mathrm{T}$$

and using

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

Kinematic variables:

$$\begin{aligned} \gamma &= \frac{\sqrt{Q^2}}{\nu} \\ \eta &= \eta(x, Q^2) \\ D &= \frac{P_{\gamma^\star}}{P_\mathrm{beam}} \end{aligned}$$

Monte Carlo productions

$$A_{\mathrm{Born}} = A_{\mathrm{X}} \cdot \left(1 + \frac{\Delta\sigma^{\mathrm{U}}}{\sigma^{\mathrm{U}}_{\mathrm{Born}}}\right) - \frac{\Delta\sigma^{\mathrm{P}}}{\sigma^{\mathrm{U}}_{\mathrm{Born}}}$$

- Two MC samples with same input parameterizations F_2(ALLM), $R \equiv \sigma_L/\sigma_T$(1990), A_{Born}

1. eXperimental MC: $\Delta\sigma^{\mathrm{P(U)}}$
   $\rightsquigarrow$ Observed cross section
   $\surd$ Radiative corrections (RADGEN)
   $\surd$ Tracking through detector (GEANT)
   $\Rightarrow$ contains info about bin migrations:
   $\surd$ Migration matrix $M(i,j)$
   $\surd$ Background from outside acceptance $\Delta \overset{\curvearrowright}{\sigma}$
2. Born MC: $\sigma^{\mathrm{U}}_{\mathrm{Born}}$
   $\rightsquigarrow$ Born cross section within HERMES acceptance

- MC data 9 times higher statistical accuracy as real data
- MC data subject to same cuts as real data

Unfolding of kinematic migrations

- Unfolding: Removes systematic correlations at the cost of introducing statistical correlations
- Unfolding algorithm:
  $\surd$ No iteration needed
  $\surd$ Use eXp and Born MC to correct asymmetry
- Smearing matrix $S(i,j)$:

$$S(i,j) \equiv \frac{M(i,j)}{\sigma_{\mathrm{Born}}(j)}$$

$\leadsto$ invert $\longrightarrow$ "un-smearing" matrix!

- A_{X} corrected in every bin for unpolarized and polarized background (not re-sorting event by event)

$$A_{\mathrm{Born}}(j) = -2 + \frac{6}{\sigma^{\mathrm{U}}_{\mathrm{Born}}(j)} \cdot \sum_{i=1}^{n} [S']^{-1}(j,i) \times$$

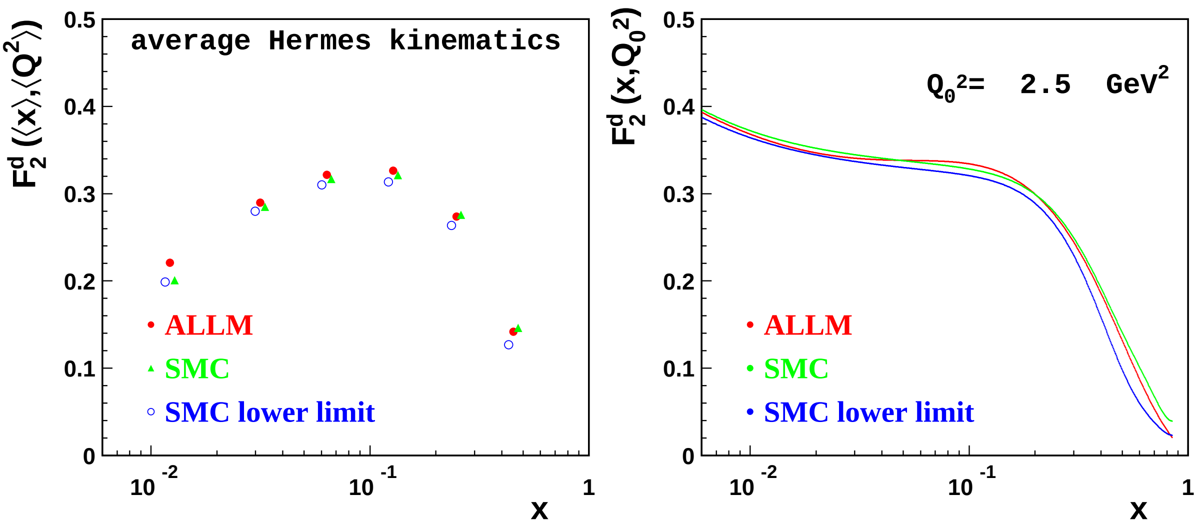
$$\left[\frac{1}{2} A_{\mathrm{X}}(i) \sigma^{\mathrm{U}}_{\mathrm{X}}(i) - \frac{1}{2} \Delta \overset{\curvearrowleft}{\sigma}^{\mathrm{P}}(i) + \sum_{k=1}^{n} S^{-}(i,k) \sigma^{\mathrm{U}}_{\mathrm{Born}}(k) \right]$$

Model independence of unfolding

$$S(i,j) \equiv \frac{M(i,j)}{\sigma_{\text{Born}}(j)}$$

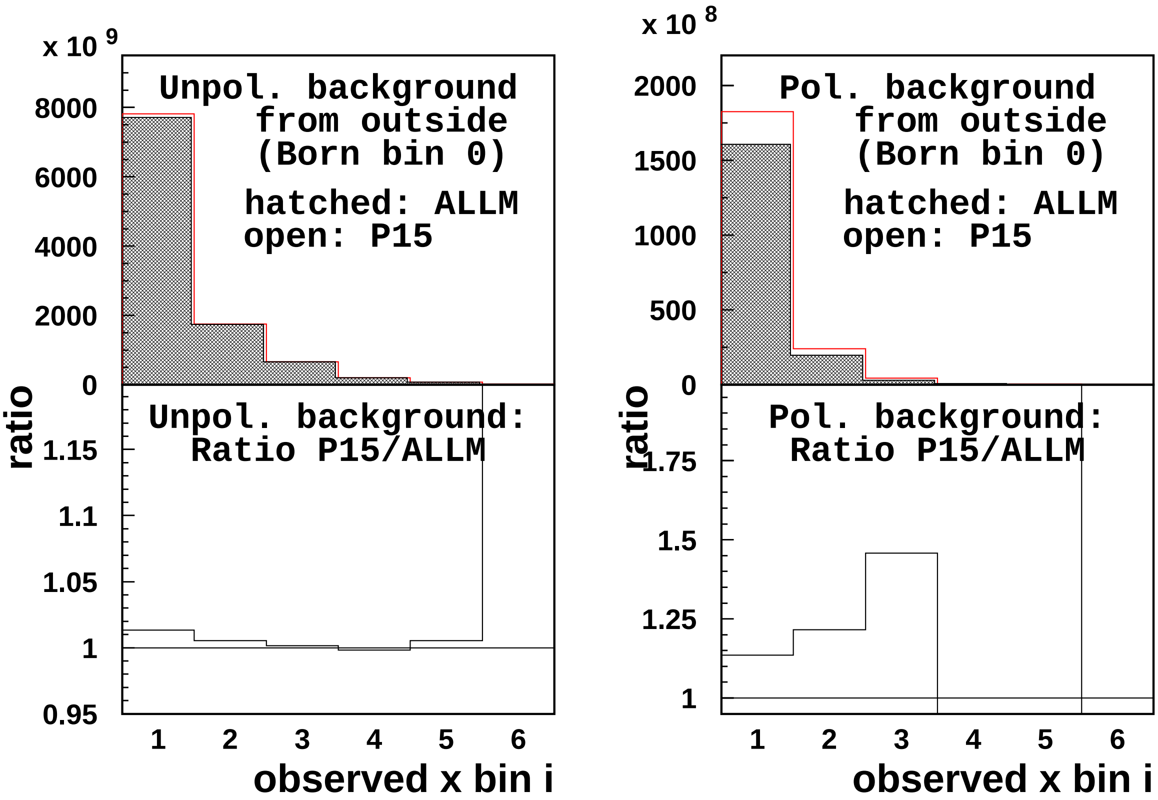
- Both ● and ● scale with # of generated events in Born bin j
- # of generated events controlled by input parameterizations

⇒ algorithm is independent of MC input parameterization
except for polarized background entering acceptance $\Delta \overset{\curvearrowright}{\sigma}^{\mathrm{P}}$
⇒ close-to model independent



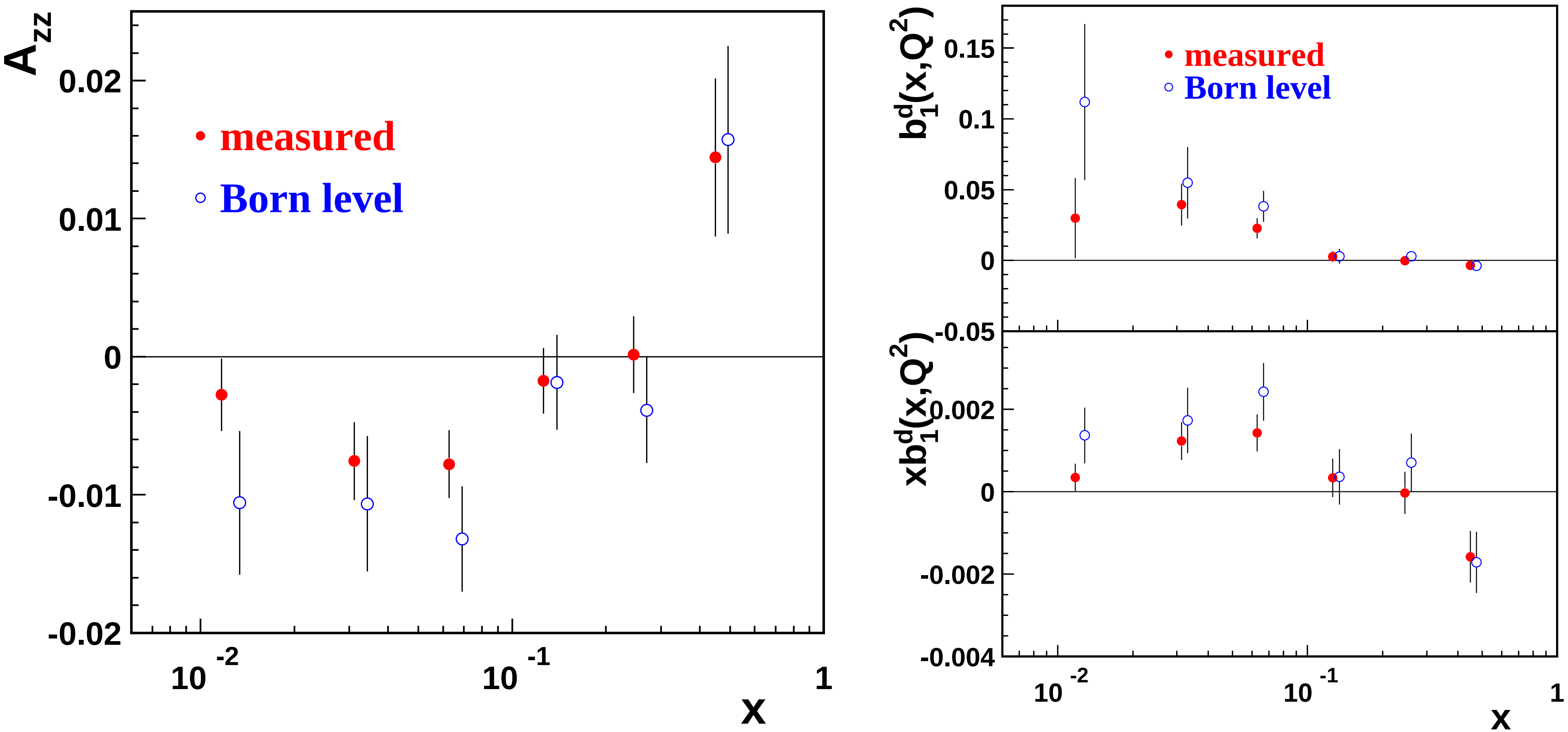
Impact of MC parameterizations

- Compare $\Delta\overset{\curvearrowright}{\sigma}$ from F_2(ALLM) and F_2(SMC)



- Unfolding results compatible within statistics
- No systematic error assigned

Comparison: Measured and Born level



Covariance and correlation matrix

Covariance matrix for unfolded asymmetry:

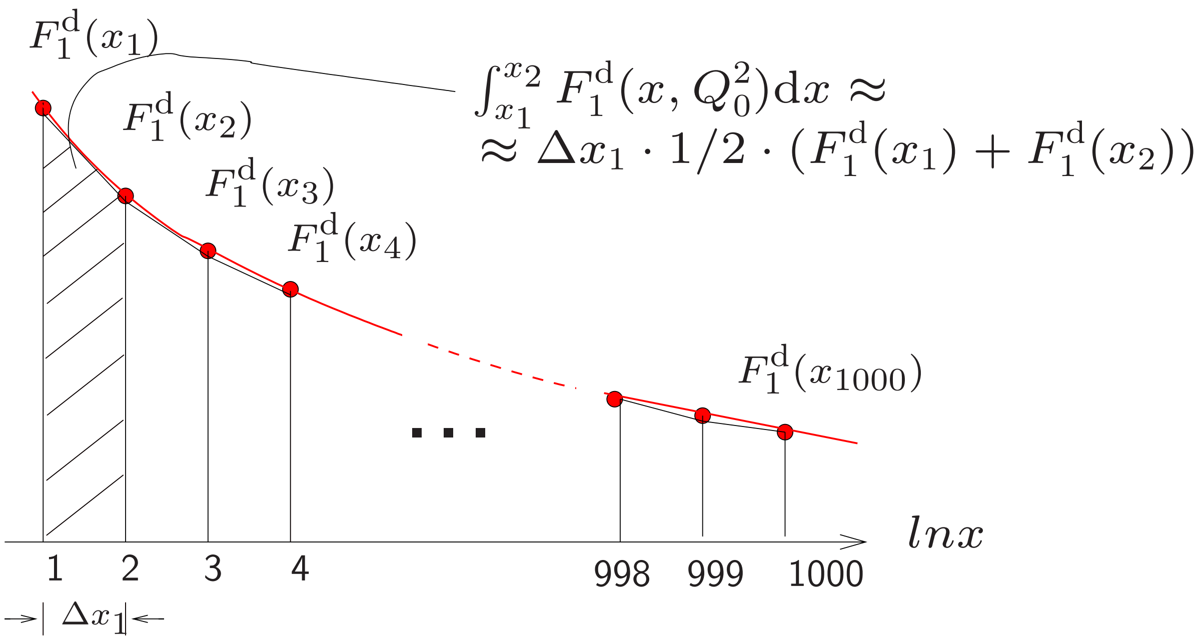
$$\mathrm{cov}(j,i) = \sum_{k=1}^{n} \frac{\partial A_{\mathrm{Born}}(j)}{\partial A_{\mathrm{X}}(k)} \frac{\partial A_{\mathrm{Born}}(i)}{\partial A_{\mathrm{X}}(k)} \delta A_{\mathrm{X}}^2(k)$$

$\Rightarrow$ Correlation matrix:

$$\mathrm{corr}(j,i) = \frac{\mathrm{cov}(j,i)}{\delta A_{\mathrm{Born}}(j)\delta A_{\mathrm{Born}}(i)}$$

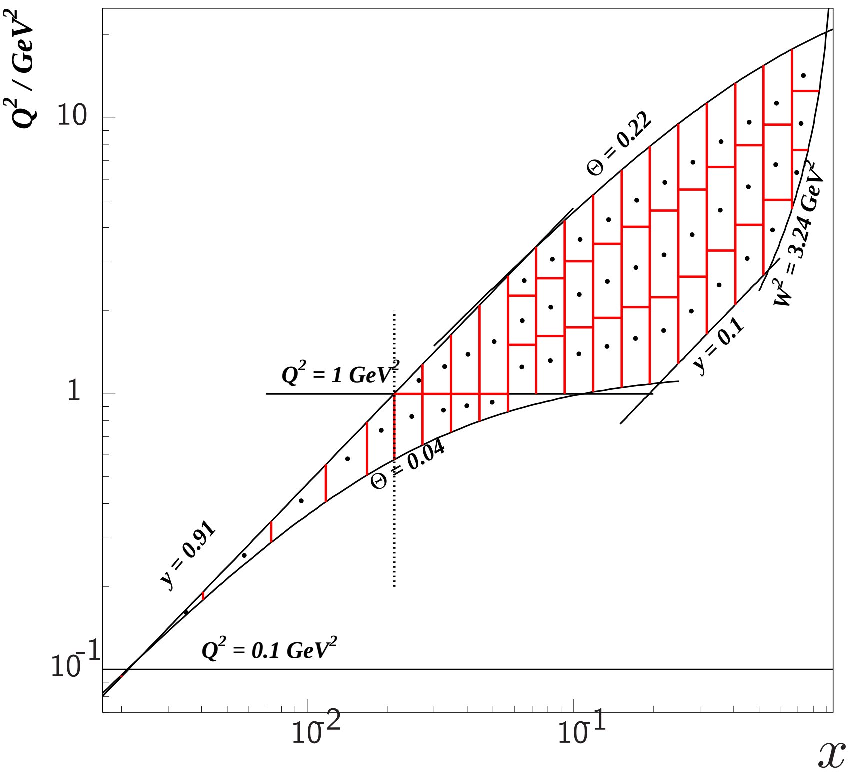
with

$$\begin{aligned} \mathrm{cov}(j,j) &= \delta A_{\mathrm{Born}}^2(j) \\ \mathrm{corr}(j,j) &= 1 \end{aligned}$$



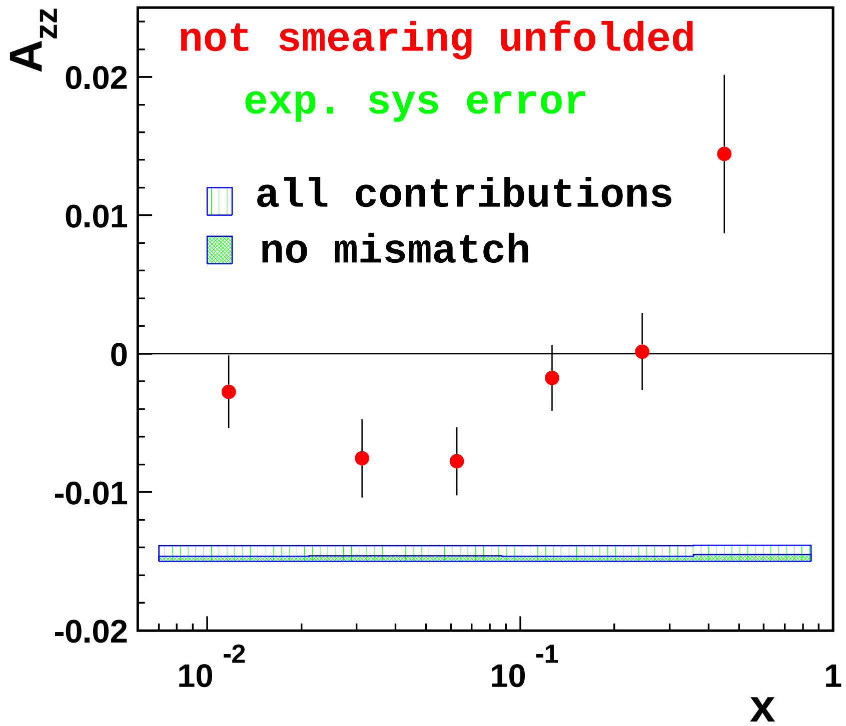
2-dimensional binning in x and Q^2

- 46 bins in x and Q^2 (20 in x, at most 3 in Q^2):



- Benefit of binning in Q^2:
  - Higher average Q^2
  - Improvement of statistical power after unfolding (diagonal element of correlation matrix)
- $A_{\|}$ unfolded in x and Q^2, then Q^2-average of g_1/F_1

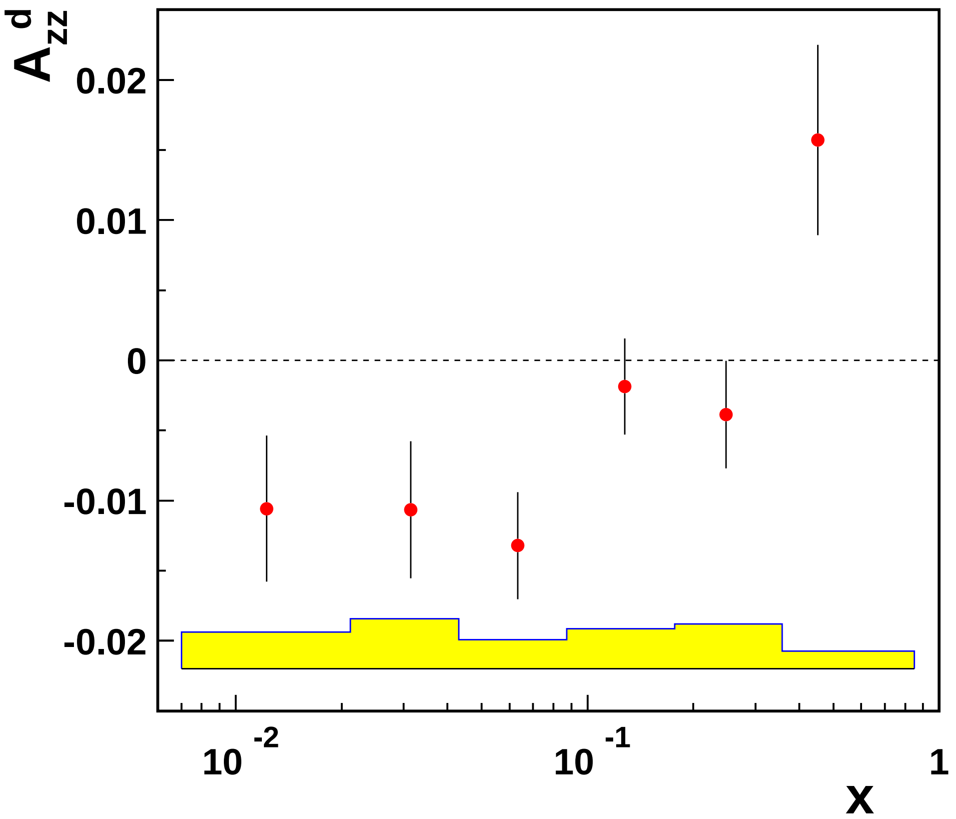
Measured tensor asymmetry

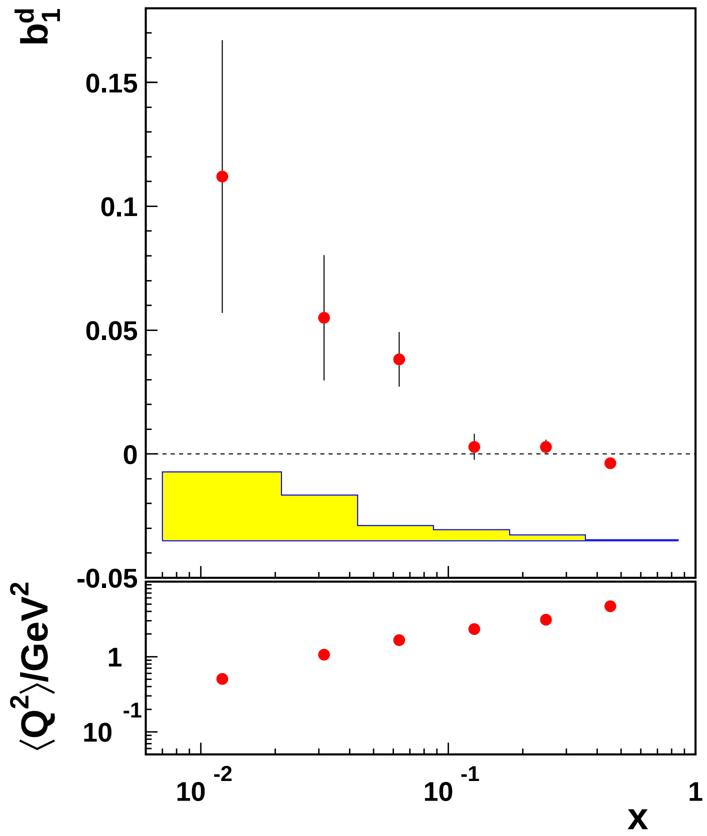


Experimental systematic uncertainties:

- Target nuclear polarization, density, residual shell electron polarization
- Hadron contamination
- "Mismatch" between two methods to obtain vector averaged data sample

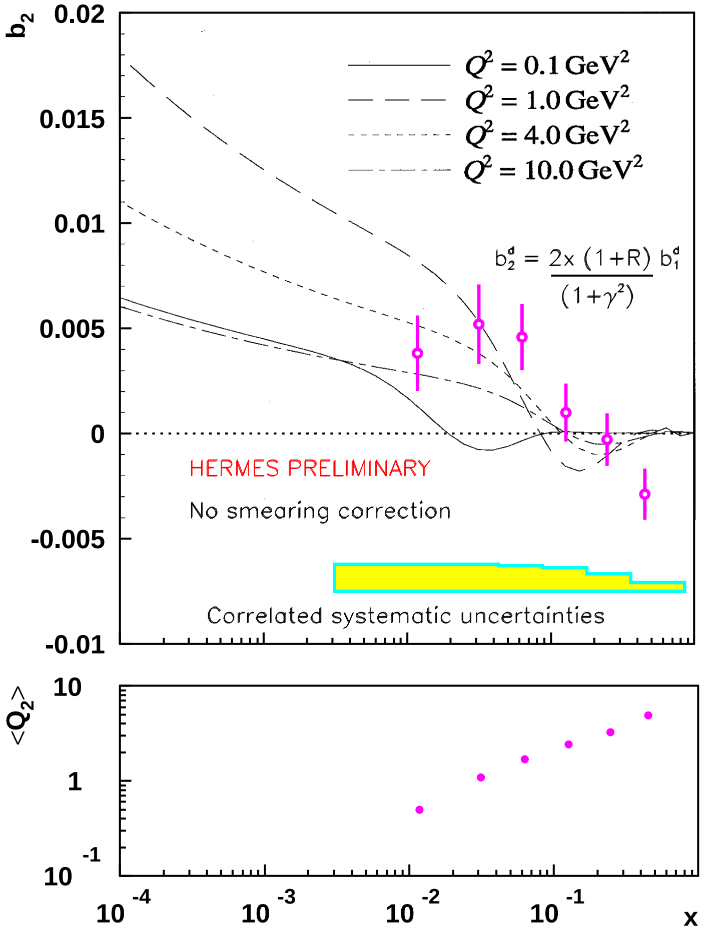
Final results: Tensor analysis





Systematic uncertainties: experimental + electromagnetic background + detector misalignment (MC studies)

$b_1^{\rm d}$, $b_2^{\rm d}$ and model calculations



$\mathcal{O}(b_1^{\rm d}) \overset{\surd}{\longleftrightarrow}$ latest model calculations

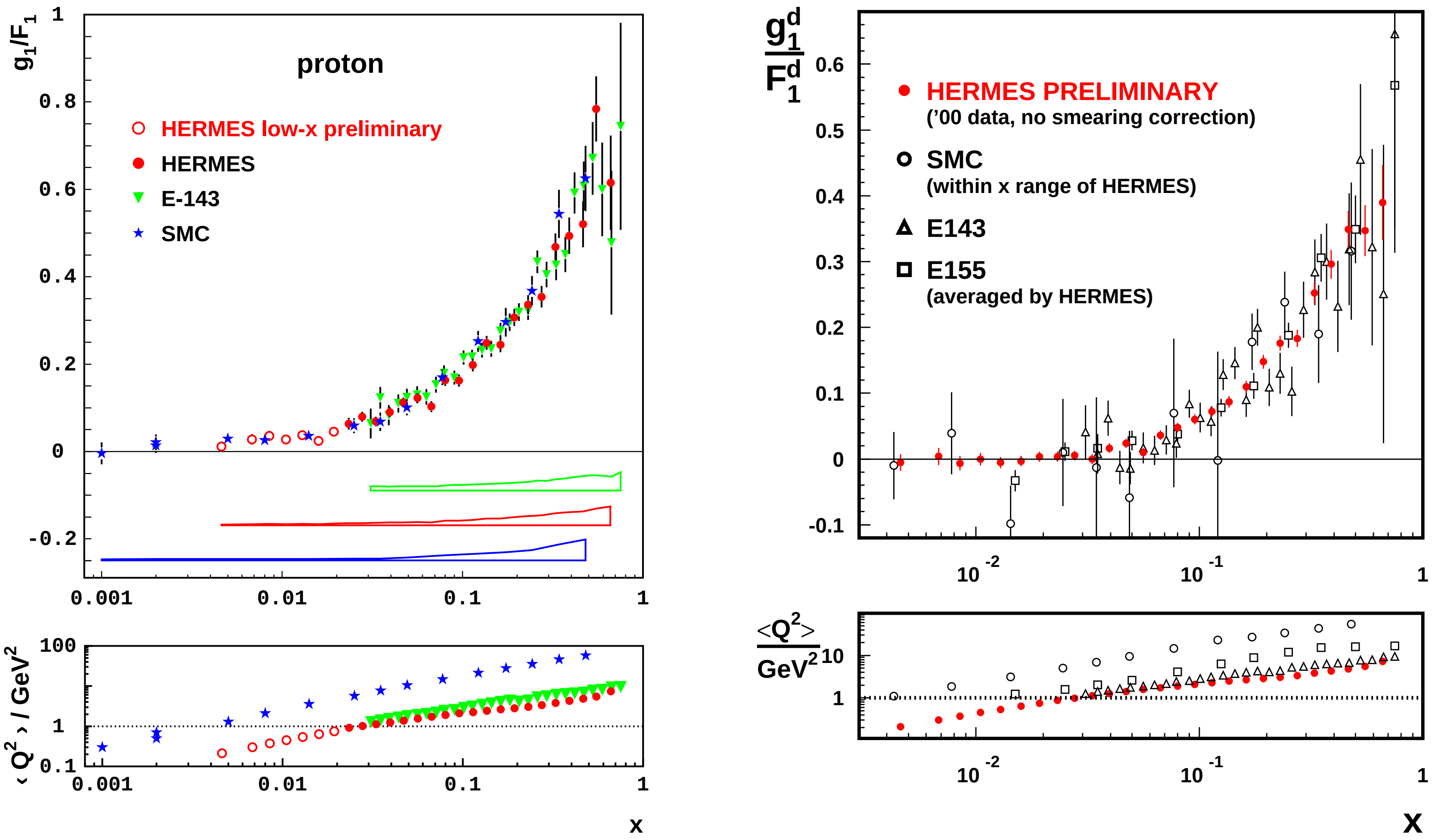
- deuteron: D-state admixture
  $\Rightarrow$ el. quadrupole moment $\neq 0$

  $\hookrightarrow$ double scattering mechanisms with a significant contribution to b_1 at small x (e.g. Nikolaev *et al.*, *Phys. Lett.* B **398** (1997) 245)
- Callan-Gross relation $\Rightarrow$

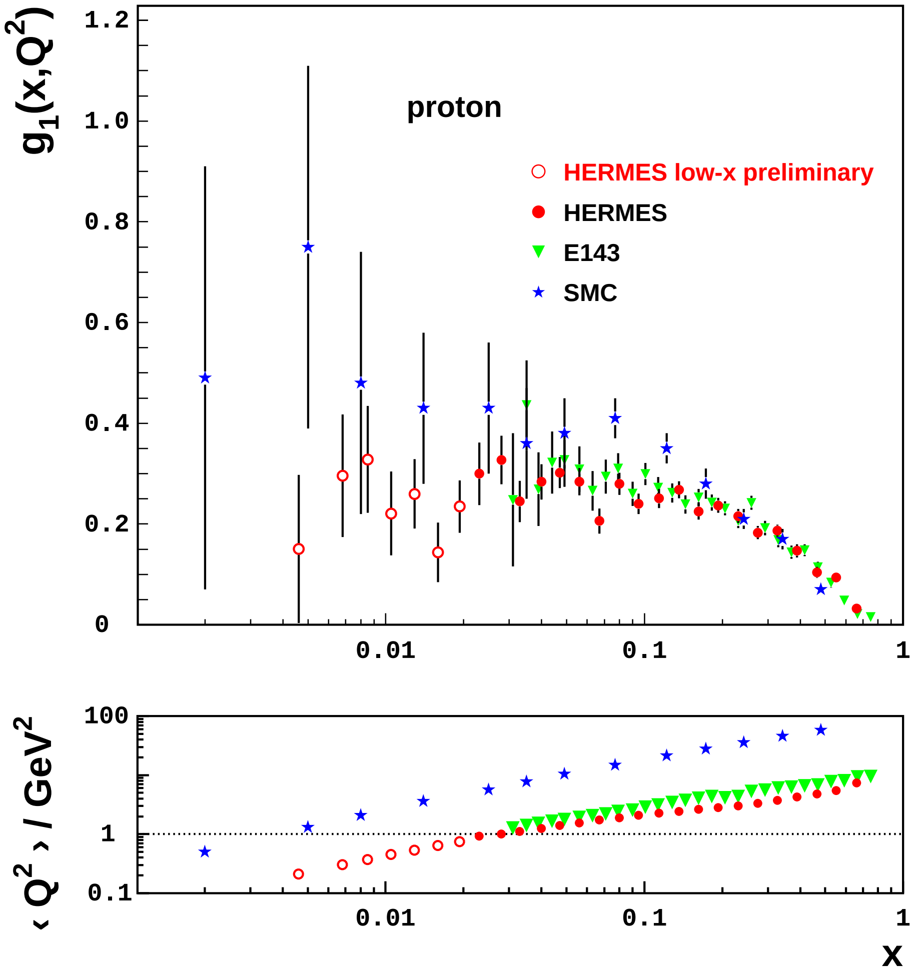
$$b_2^{\rm d} = \frac{2x(1+R)}{1+\gamma^2} b_1^{\rm d}$$

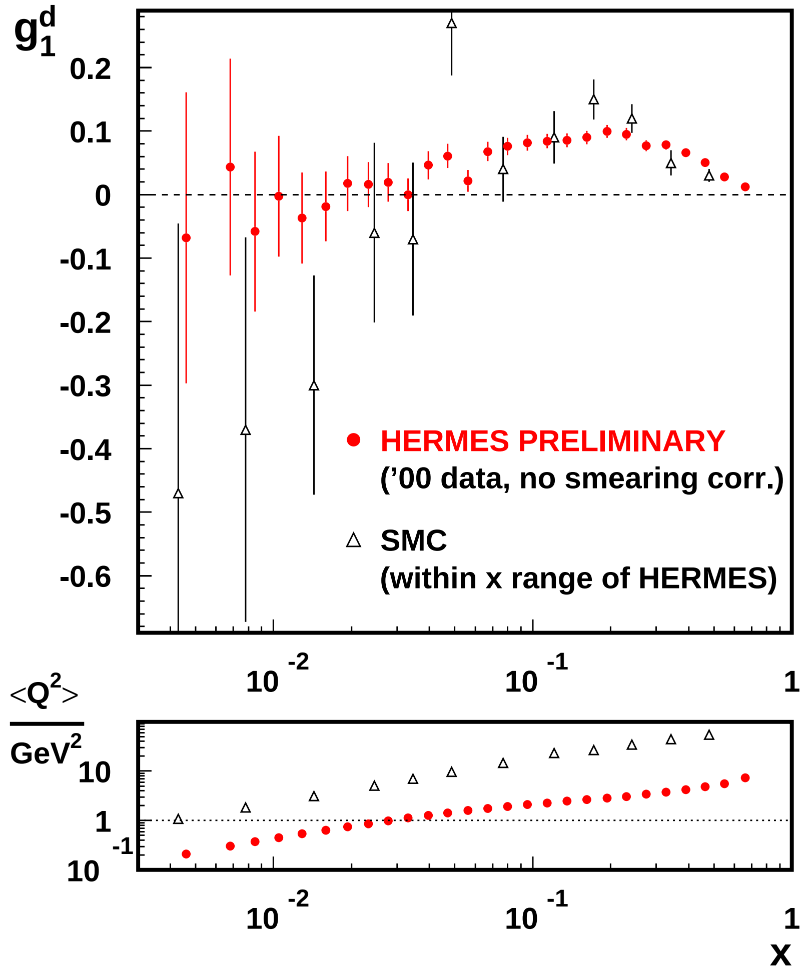
Theory curves: Bora *et al.*, *Phys. Rev.* D **57** (1998) 6906

Old HERMES release: g_1/F_1 of p and d



Old HERMES release: g_1 of p and d





Old HERMES release: g_1 world data