Exploring the wee partons

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Univ. Tübingen

Symposium for Gerhard, 02/19/2020

Outline:

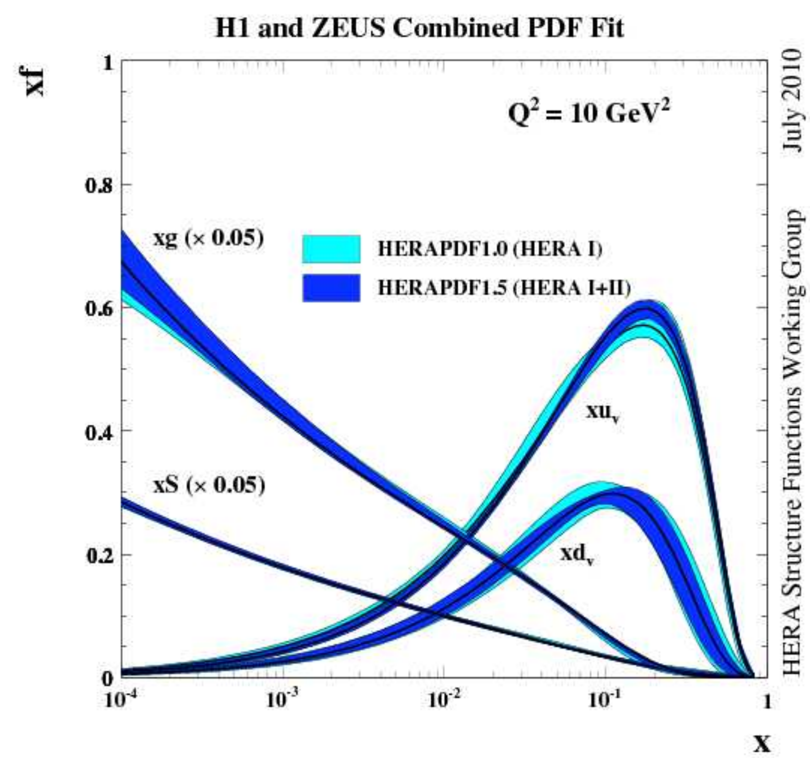
- Highlights of research with muon DIS: four examples
- T-odd helicity observable at COMPASS

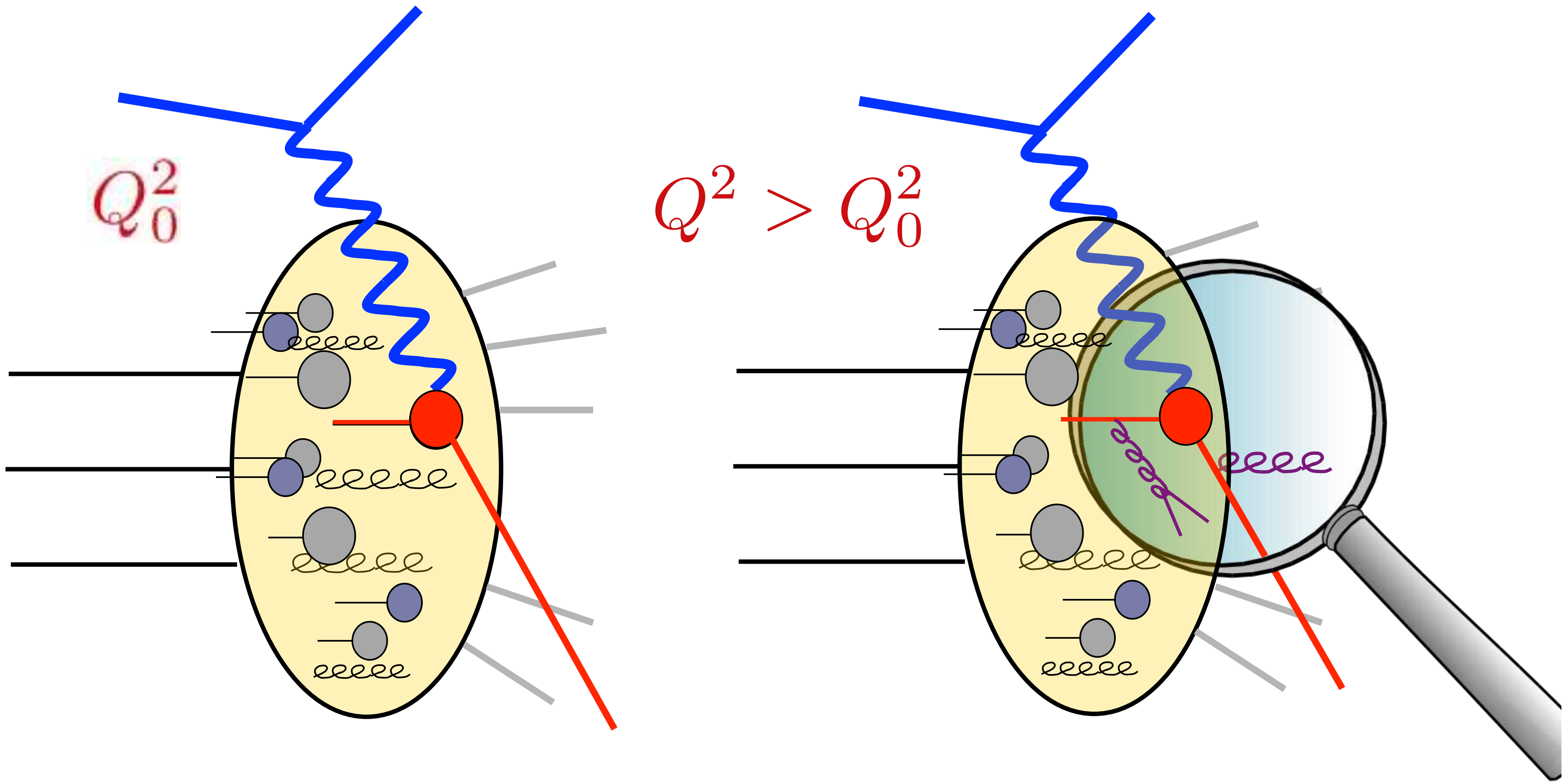
Feynman's "wee" partons:

low-x → everything "non-valence"

- by no means play a small role:
  vital for understanding hadrons, e.g. spin structure

- wee partons abound:





- copious QCD radiation – (DGLAP) evolution
  integral part of nucleon structure
- interplay with non-perturbative hadronic content:
  flavor asymm., spin structure, gluons, nuclear effects

- For decades, Gerhard’s research has been at the **forefront of the exploration of hadrons in the “wee parton” regime**

- always pushing the limits of what was state-of-the-art at a given time

- inspiring and motivating theorists

Let’s celebrate this with a few examples…

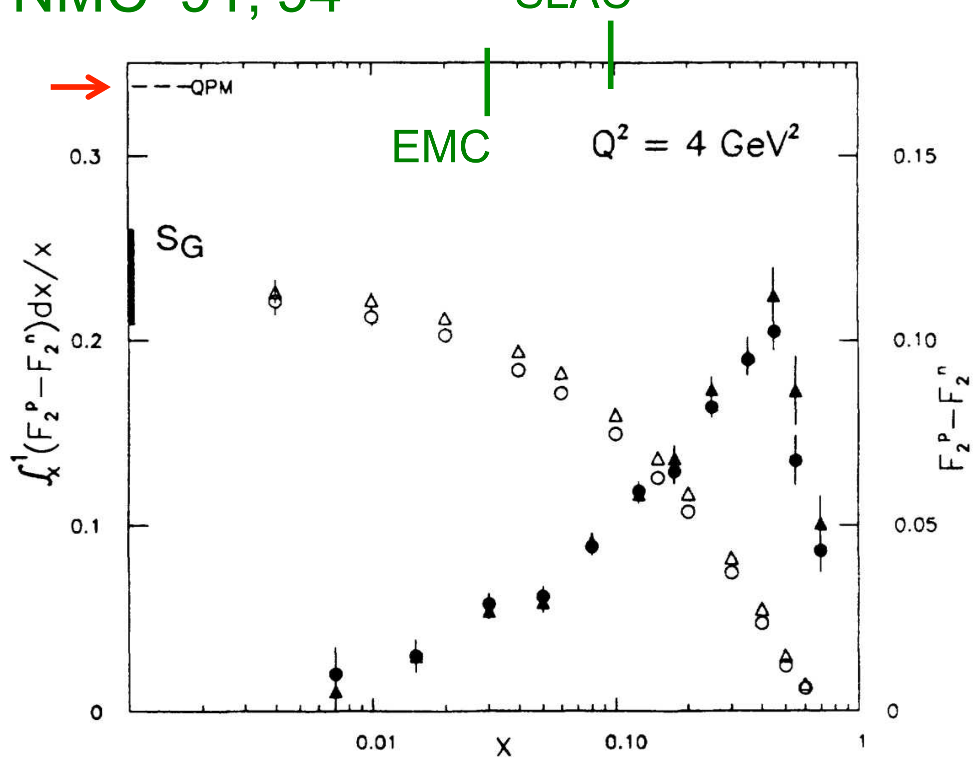
Pushing the boundaries:
The Gottfried sum

In parton model:

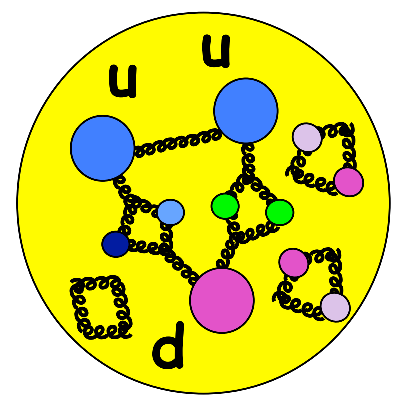
$$\int_0^1 \frac{dx}{x}(F_2^p - F_2^n) = \frac{1}{3}\int_0^1 (u_v - d_v)\,dx + \frac{2}{3}\int_0^1 (\bar{u} - \bar{d})\,dx$$

$$= \frac{1}{3} + \frac{2}{3}\int_0^1 (\bar{u} - \bar{d})\,dx$$

NMC '91,'94



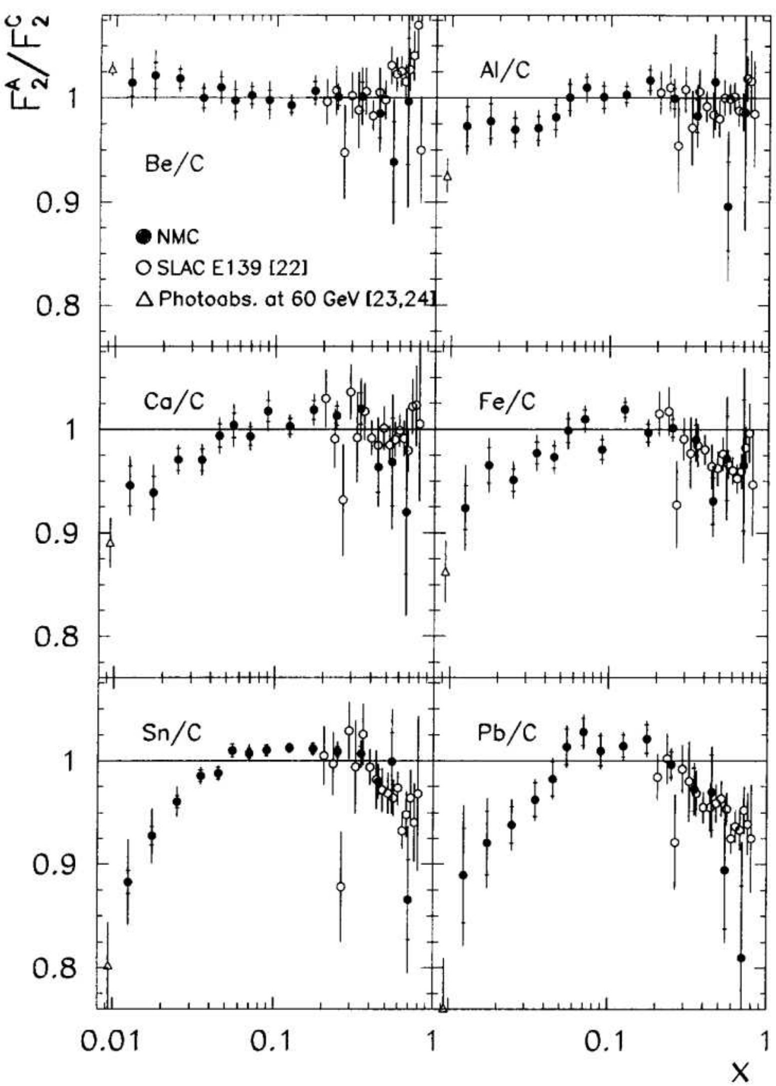
$$F_2^p - F_2^n = 2F_2^d \frac{1 - F_2^n/F_2^p}{1 + F_2^n/F_2^p}$$



(not from radiation!)

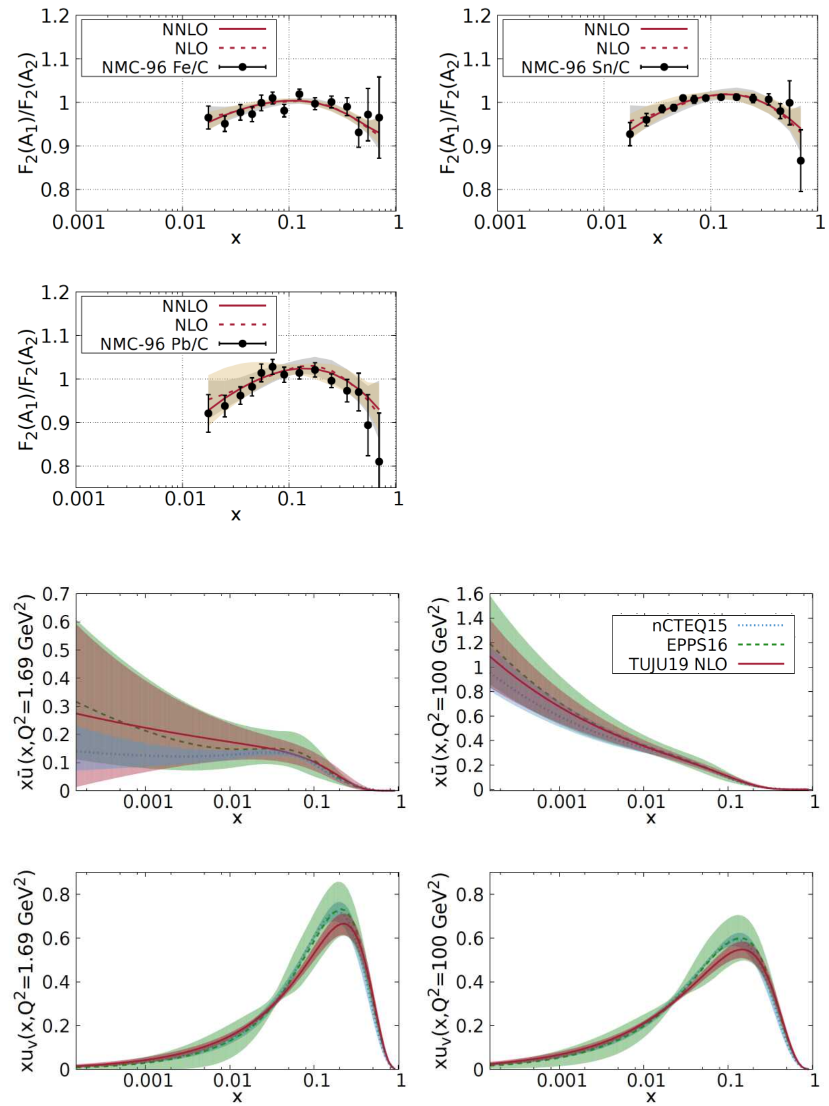
Pushing the boundaries:
The nucleus

NMC ‘96

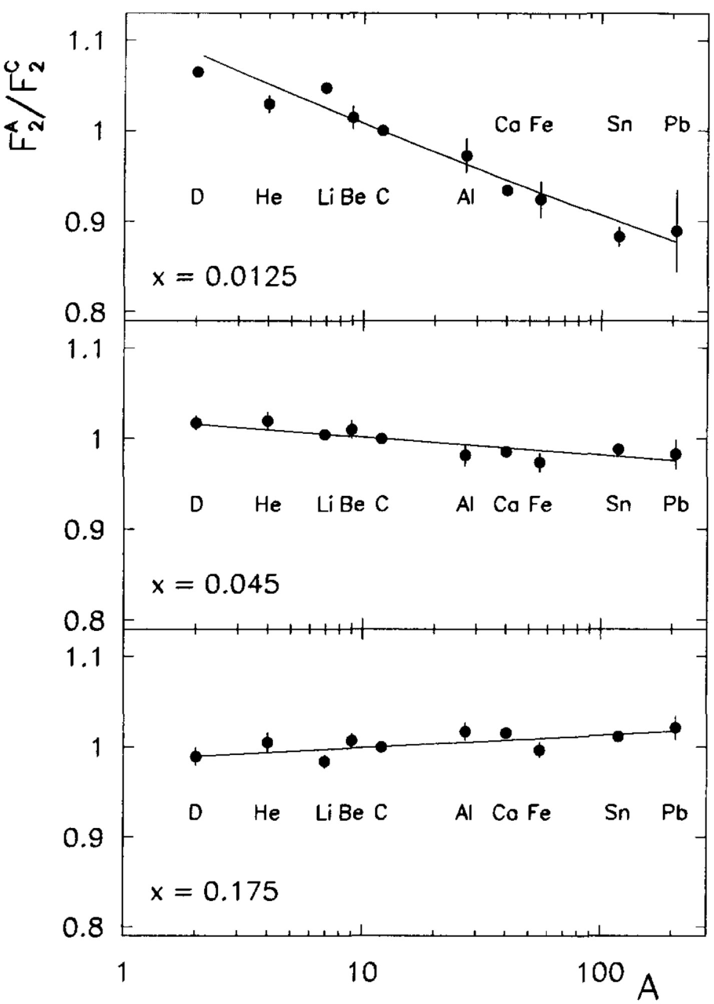


(along with E665)

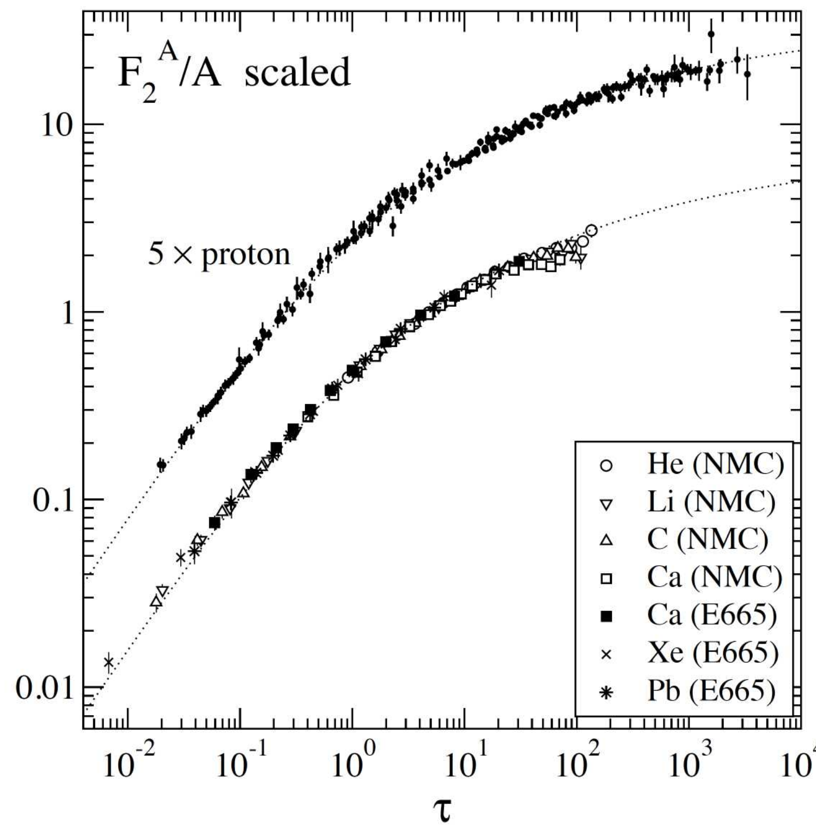
NNLO: Walt, Helenius, WV 2019



NMC ‘96



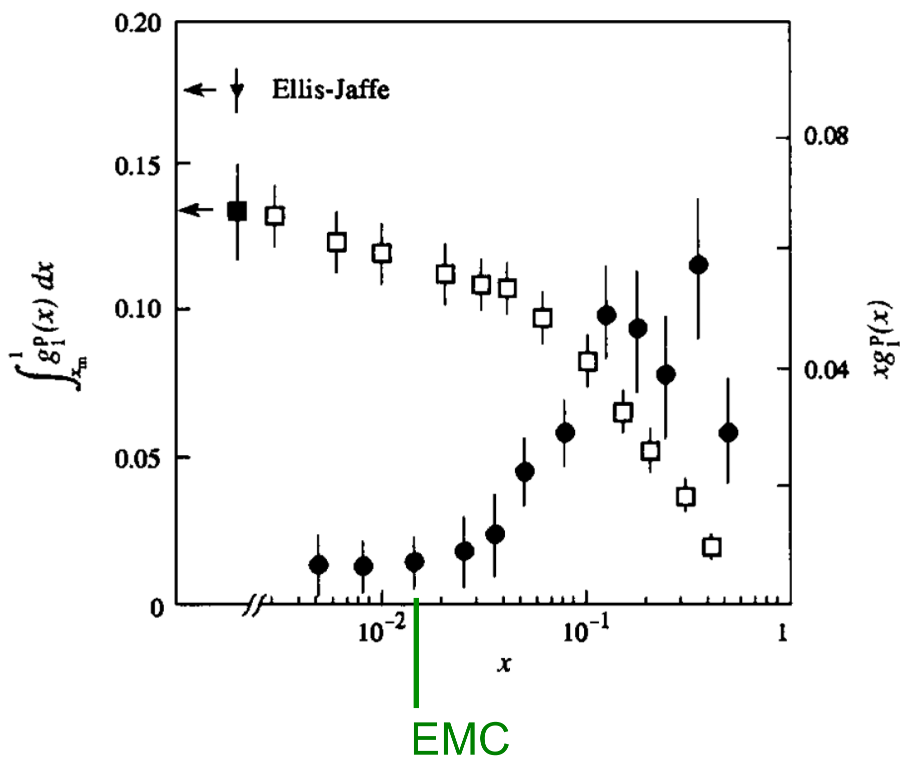
Freund, Rummukainen, Weigert, Schäfer



$$\tau = \left(\frac{x_B}{x_0}\right)^{2\lambda} \frac{Q^2}{A^{1/3}}$$

Pushing the boundaries:

The proton spin



SMC '94

$$\Delta Q \equiv \int_0^1 dx\,(\Delta q + \Delta\bar{q})$$

$$\propto \langle P, s \,|\, \bar{\psi}_q\,\gamma^\mu\gamma_5\,\psi_q \,|\, P, s\rangle$$

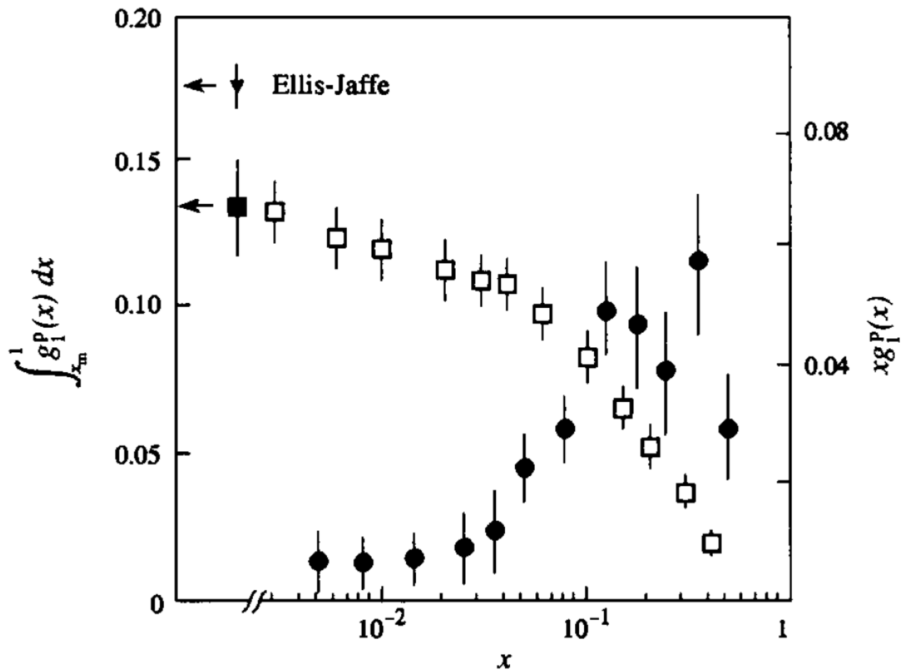
$$\int_0^1 dx\,g_1(x,Q^2) = \frac{1}{2}\left(\frac{4}{9}\Delta U + \frac{1}{9}\Delta D + \frac{1}{9}\Delta S\right)$$

$$= \frac{1}{12}\Delta a_3 + \frac{1}{36}\Delta a_8 + \frac{1}{9}\Delta\Sigma$$

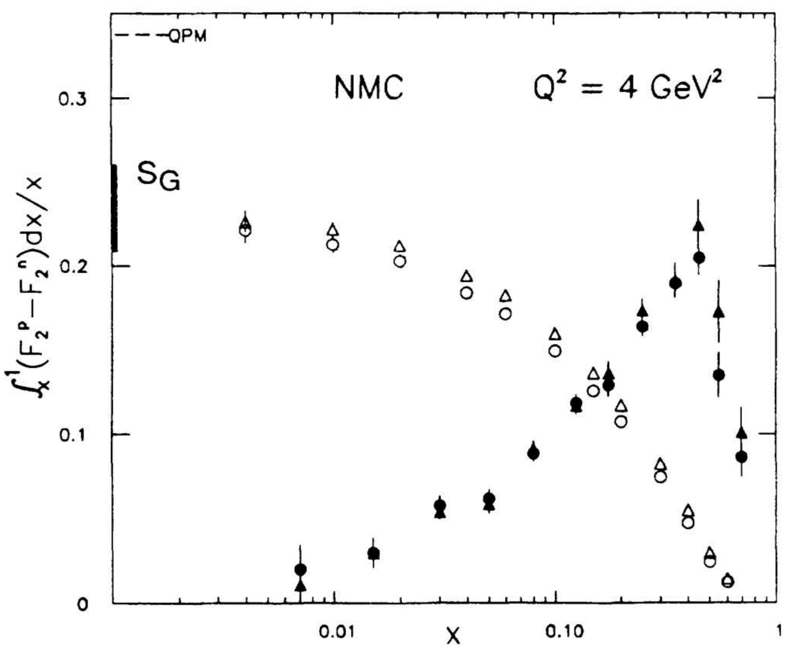
symmetry

$$\approx 0.18 + \frac{1}{3}\Delta S$$

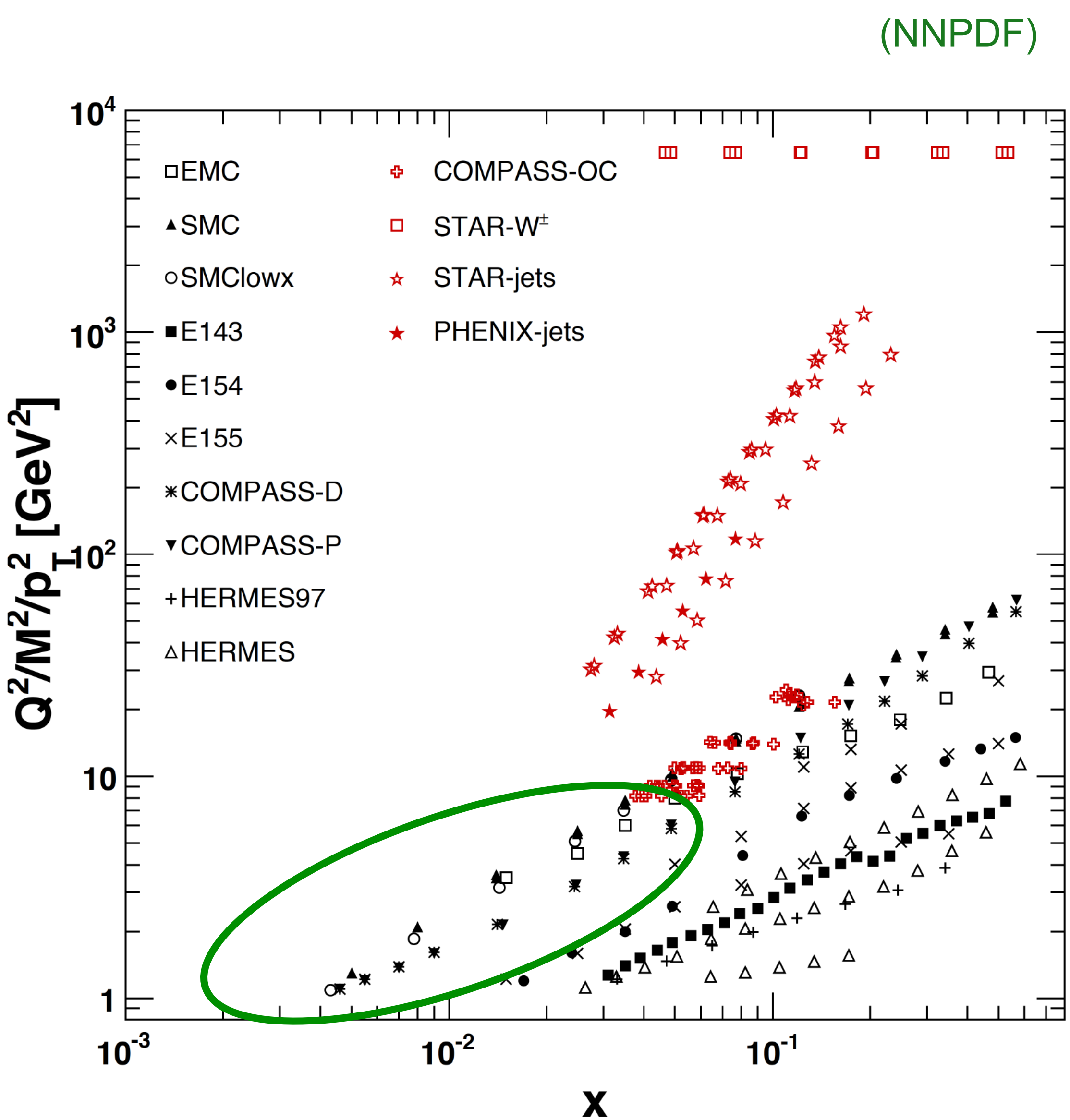
(not from radiation!)



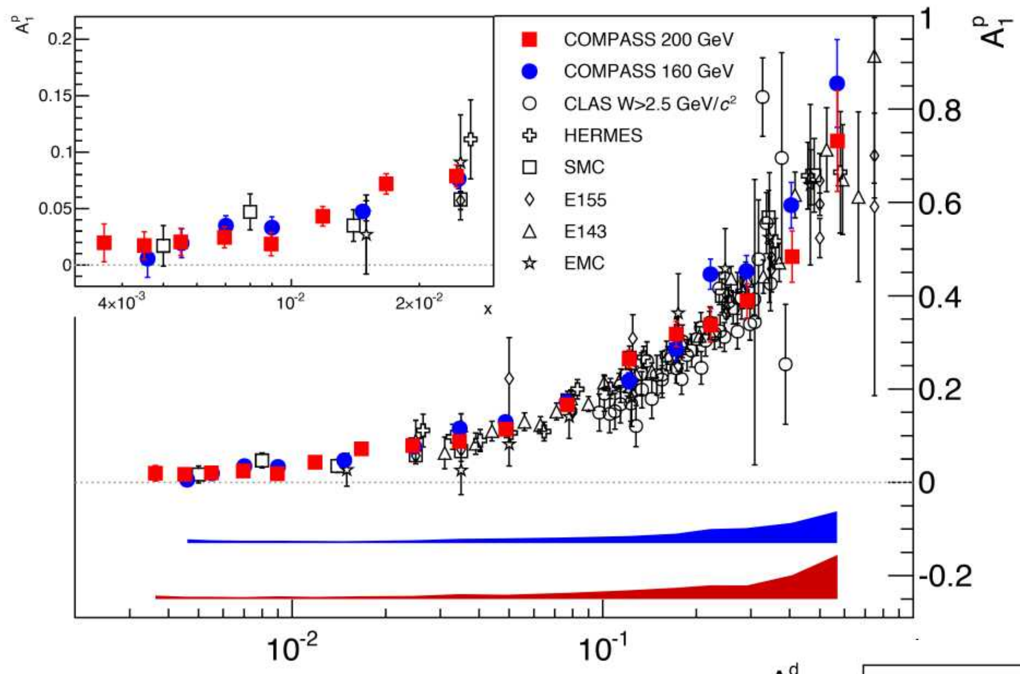
Ellis-Jaffe
$\int_{x_m}^{1} g_1^p(x)\,dx$
$xg_1^p(x)$
0.20
0.15
0.10
0.05
0
0.08
0.04
10^{-2}
10^{-1}
1
x



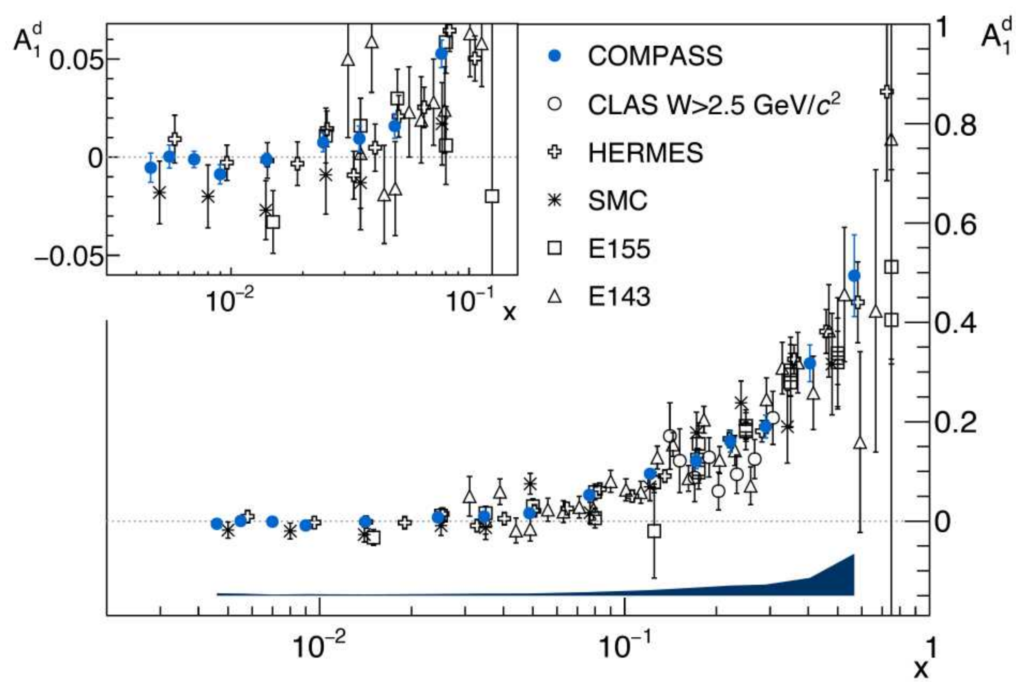
QPM
NMC
$Q^2 = 4\ GeV^2$
S_G
$\int_x^1 (F_2^p - F_2^n)\,dx/x$
0.3
0.2
0.1
0
0.01
0.10
1
X



(NNPDF)
Q²/M²/p_T² [GeV²]
x
EMC
SMC
SMClowx
E143
E154
E155
COMPASS-D
COMPASS-P
HERMES97
HERMES
COMPASS-OC
STAR-W±
STAR-jets
PHENIX-jets



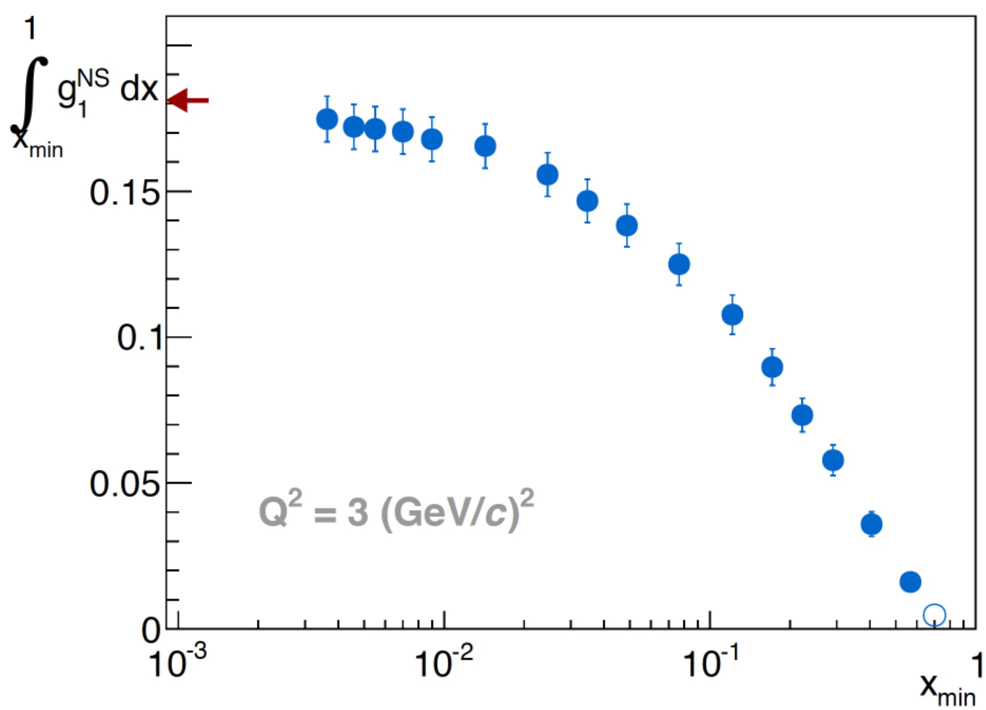
COMPASS 200 GeV
COMPASS 160 GeV
CLAS W>2.5 GeV/c²
HERMES
SMC
E155
E143
EMC
A₁ᵖ
x



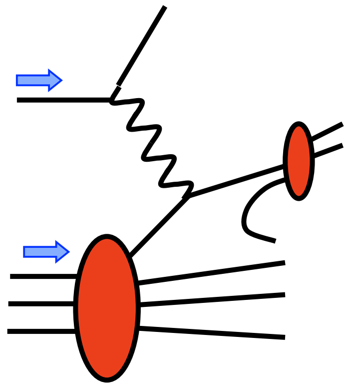
COMPASS
CLAS W>2.5 GeV/c²
HERMES
SMC
E155
E143
A₁ᵈ
x

Running Bjorken integral:

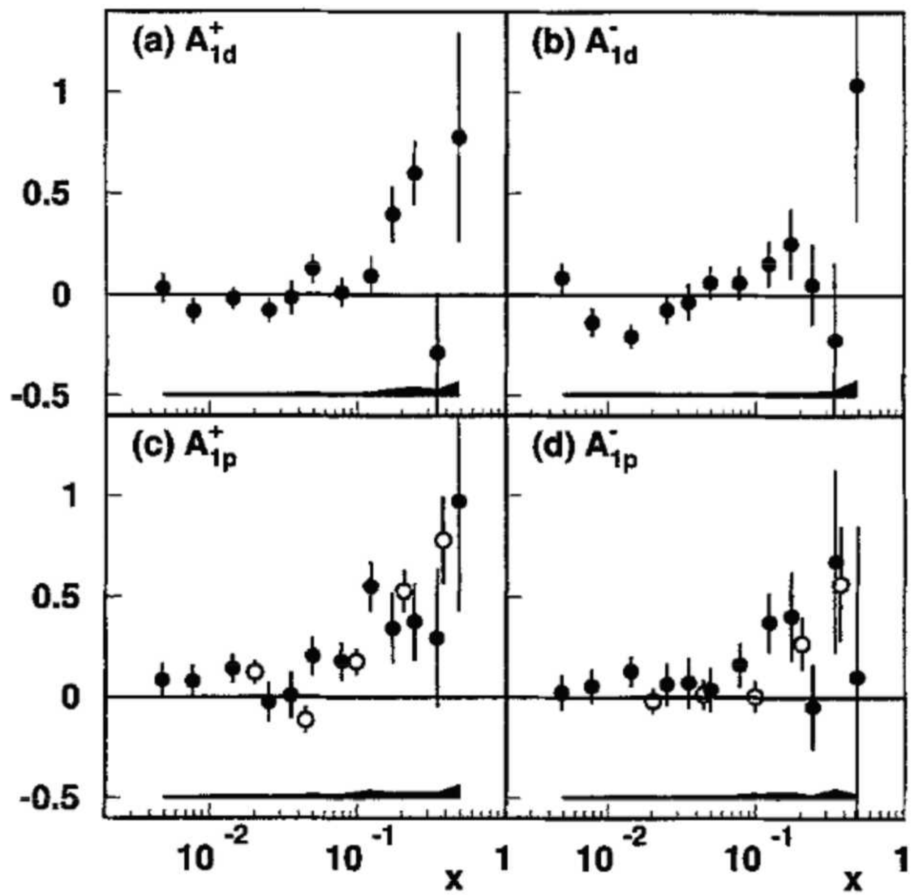
$$\int_0^1 dx\,(g_1^p - g_1^n) = \frac{1}{6}\,g_A \times \left(1 - \frac{\alpha_s(Q^2)}{\pi} + \ldots\right)$$



Pushing the boundaries:
Beyond inclusive



SMC ‘96



Future semi-inclusive spin physics at CERN

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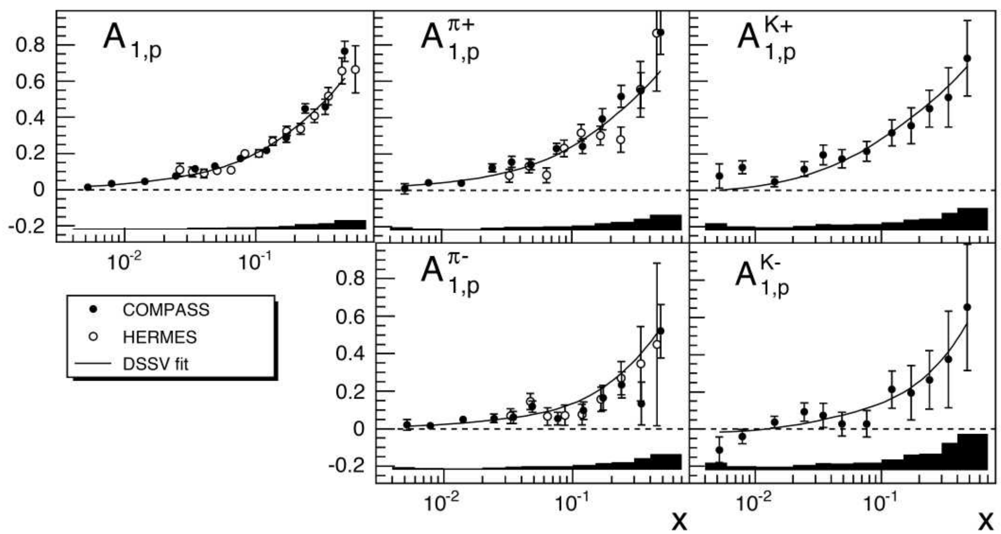
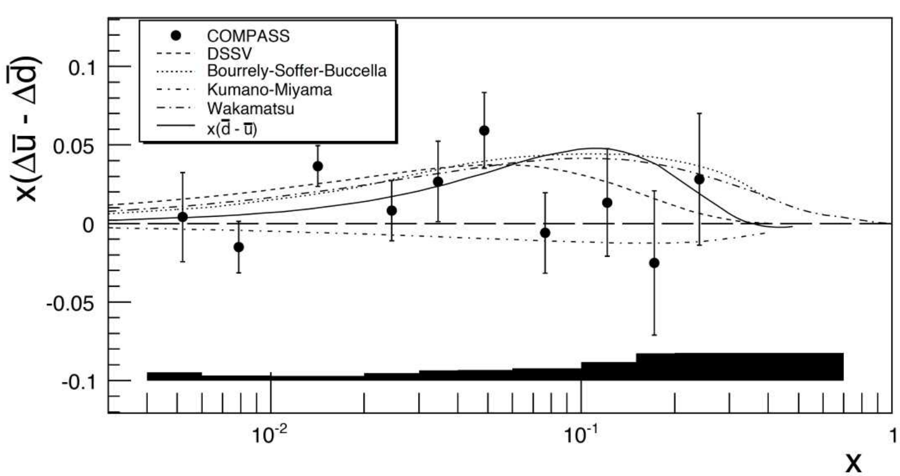
Abstract

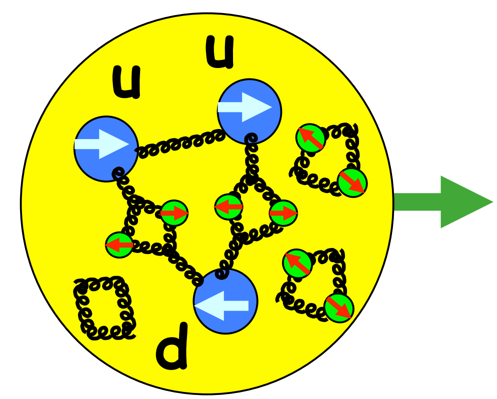
A direct measurement of the gluon polarisation $\Delta g/g$ is mandatory for a further clarification of the internal spin structure of the nucleon. We propose a new muon experiment at CERN to measure the gluon polarisation using open charm production, which is linked to the gluon distribution via the photon-gluon fusion process. Experimentally this requires to measure the cross section asymmetry for D meson production in polarised deep inelastic muon scattering from a polarised target. The experiment is similar to the one of the SMC but requires additional detectors and a general upgrade. The gluon polarisation could be determined with a precision of $\delta(\Delta g/g) = 0.15$. Simultaneously other semi-inclusive asymmetries can be studied.

Zeuthen workshop
1995

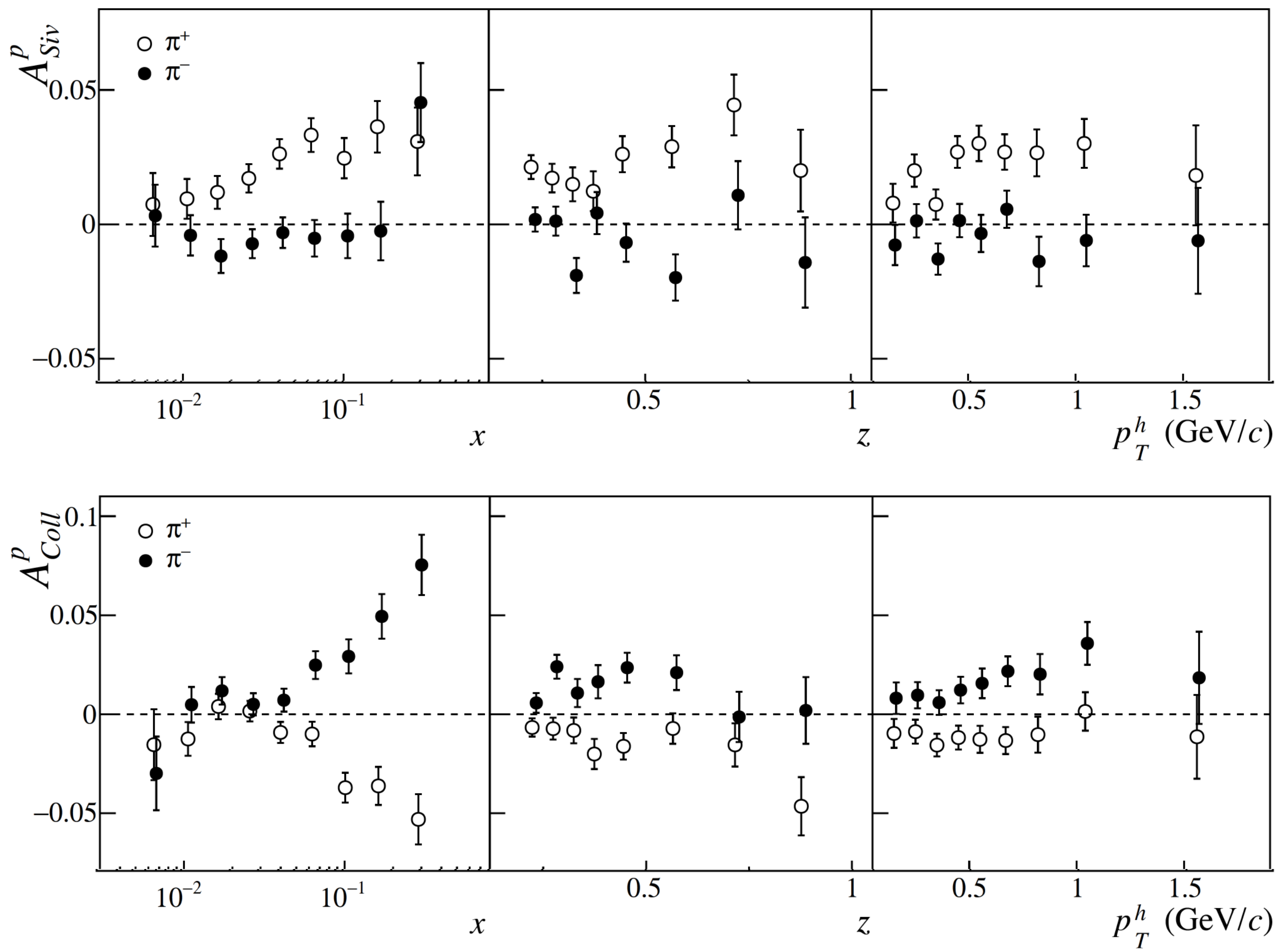


COMPASS 2010





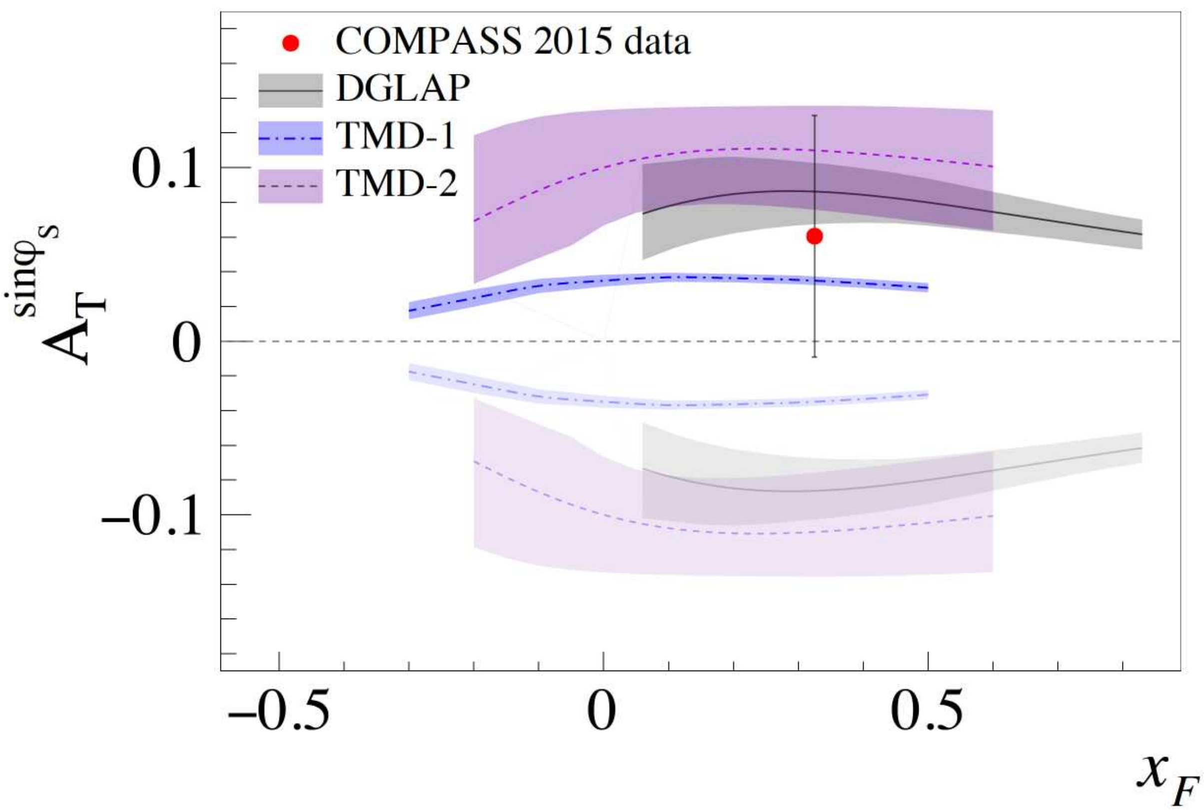
- and, Δg from charm and high-p_T



COMPASS 2015

- plus: weighted asymmetries, gluon Sivers, …

Drell-Yan program as natural new avenue



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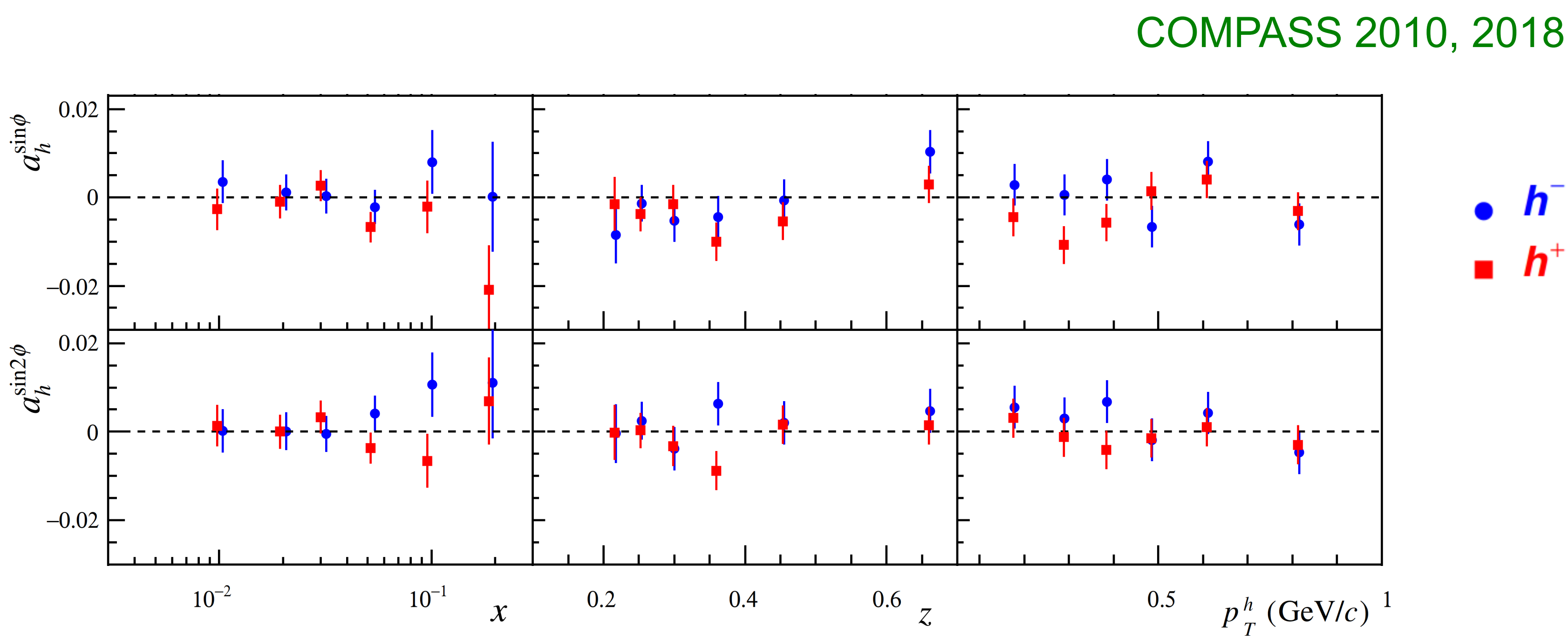
M. Abele, M. Aicher,
F. Piacenza, A. Schäfer, WV

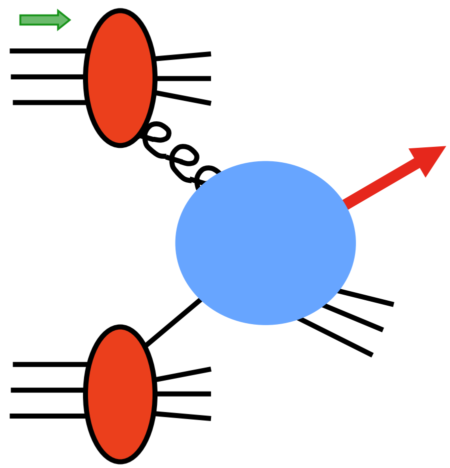


$$a_{h^\pm}(\phi) = a_{h^\pm}^{0} + a_{h^\pm}^{\sin\phi}\sin\phi + a_{h^\pm}^{\sin 2\phi}\sin 2\phi + a_{h^\pm}^{\sin 3\phi}\sin 3\phi + a_{h^\pm}^{\cos\phi}\cos\phi$$

$$a(\phi) = \frac{\mathrm{d}\sigma^{\leftarrow\Rightarrow} - \mathrm{d}\sigma^{\leftarrow\Leftarrow}}{|P_L|(\mathrm{d}\sigma^{\leftarrow\Rightarrow} + \mathrm{d}\sigma^{\leftarrow\Leftarrow})} = -\frac{\mathrm{d}\sigma_{0L} + P_\mu \mathrm{d}\sigma_{LL} - \tan\theta_\gamma\left(\mathrm{d}\sigma_{0T} + P_\mu \mathrm{d}\sigma_{LT}\right)}{\mathrm{d}\sigma_{00} + P_\mu \mathrm{d}\sigma_{L0}}$$

$$\begin{aligned}\mathrm{d}\sigma_{0L} \quad \propto \quad & \varepsilon x h_{1L}^{\perp}(x) \otimes H_1^{\perp}(z)\sin(2\phi) \\ & + \sqrt{2\varepsilon(1+\varepsilon)}\frac{M}{Q}x^2\left(h_L(x)\otimes H_1^{\perp}(z) + f_L^{\perp}(x)\otimes D_1(z)\right)\sin\phi\end{aligned}$$

- A_L for single-inclusive process:



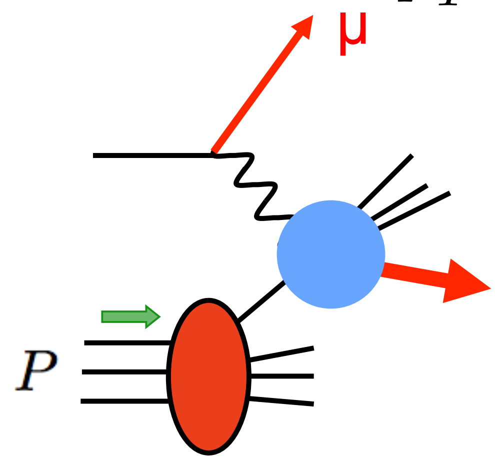
$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

$A_L \neq 0$ requires parity violation

(requires $\vec{p} \cdot \vec{S}_L$)

- (key to RHIC W boson physics)

- however:



$\vec{p}_T^{\,\ell}$

$\vec{p}_T^{\,\text{jet}}$

P even

"T-odd"

$$A_L \sim \vec{S}_L \cdot \left(\vec{p}_T^{\,\ell} \times \vec{p}_T^{\,\text{jet}}\right) \quad \sim \sin\phi$$

and $$A_L \sim \vec{S}_L \cdot \left(\vec{p}_T^{\,\ell} \times \vec{p}_T^{\,\text{jet}}\right) \left(\vec{p}_T^{\,\ell} \cdot \vec{p}_T^{\,\text{jet}}\right) \sim \sin\phi\,\cos\phi$$

$$= \frac{1}{2}\sin(2\phi)$$

$$A_L = \mathcal{A}\sin\phi + \mathcal{B}\sin(2\phi)$$

Hagiwara, Hikasa, Kai

cf. Sivers effect

$$\langle f \,|\, \hat{T} \,|\, i \,\rangle = \mathcal{M}_{fi} \, (2\pi)^4 \, \delta^4(P_f - P_i)$$

- states $|i\rangle, |f\rangle$ with reversed momenta and spins: $|\tilde{i}\rangle, |\tilde{f}\rangle$
- T invariance: $|\mathcal{M}_{fi}|^2 = |\mathcal{M}_{\tilde{i}\tilde{f}}|^2$
- "T odd": $|\mathcal{M}_{fi}|^2 - |\mathcal{M}_{\tilde{f}\tilde{i}}|^2$

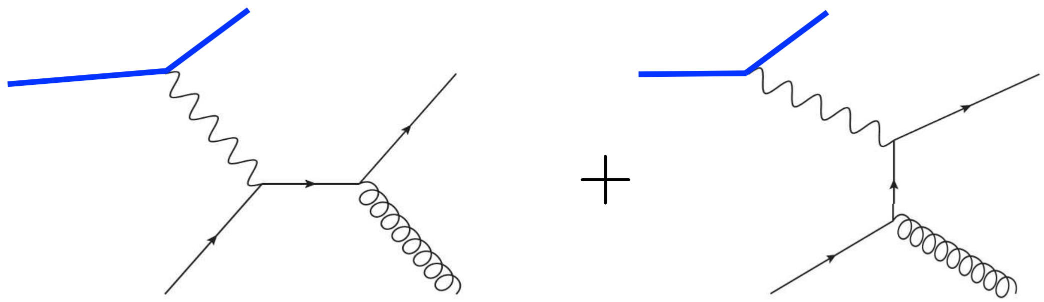
$$= -2\,\mathrm{Im}\Big(\mathcal{M}^*_{fi}\,\alpha_{fi}\Big) - |\alpha_{fi}|^2$$

where

$$i\alpha_{fi} \equiv \mathcal{M}_{fi} - \mathcal{M}^*_{if} = i \sum\!\!\!\!\!\!\!\int_X \mathcal{M}^*_{Xf}\,\mathcal{M}_{Xi}\,(2\pi)^4\,\delta^4(P_X - P_i)$$

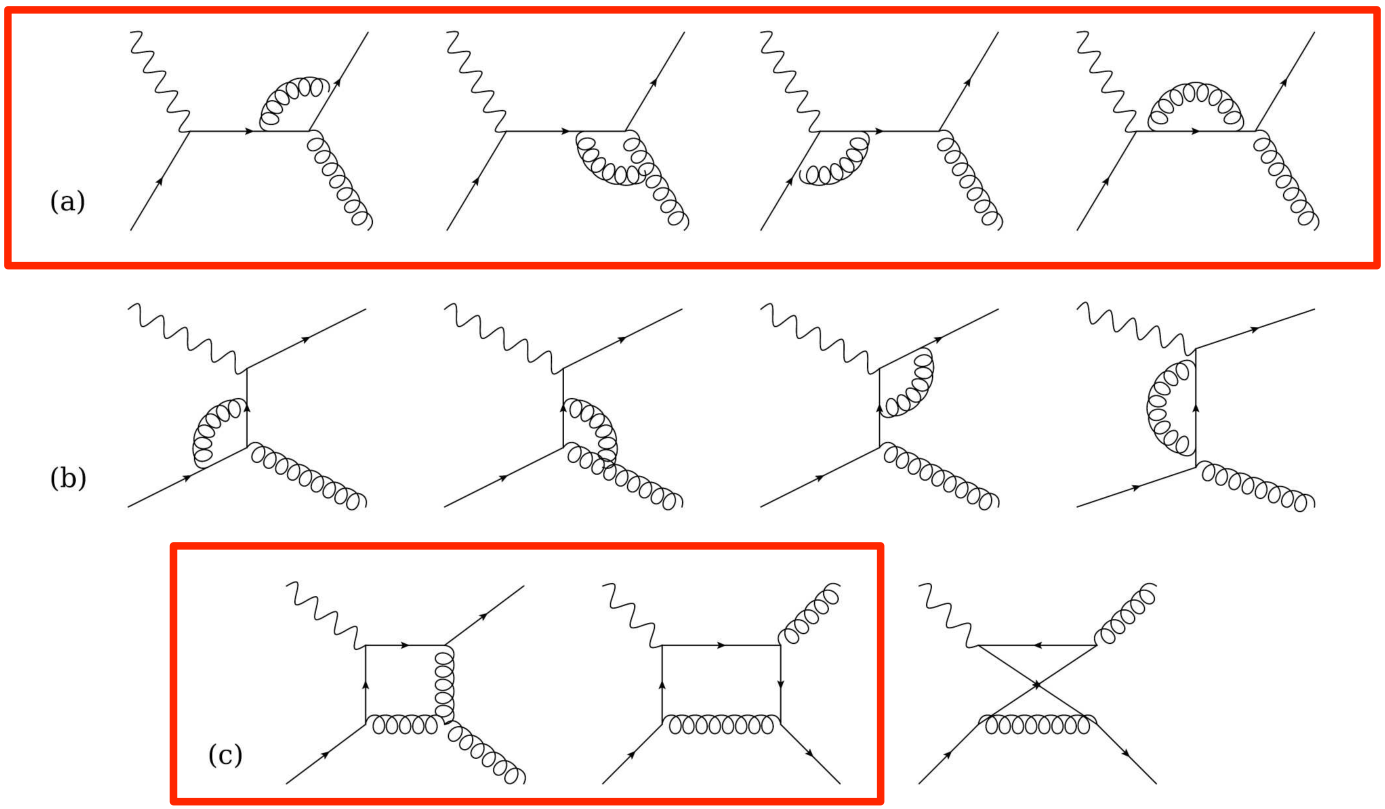
- → interference of Born with 1-loop diagrams

- Born diagrams for $\mu p \to \mu h X$:



real

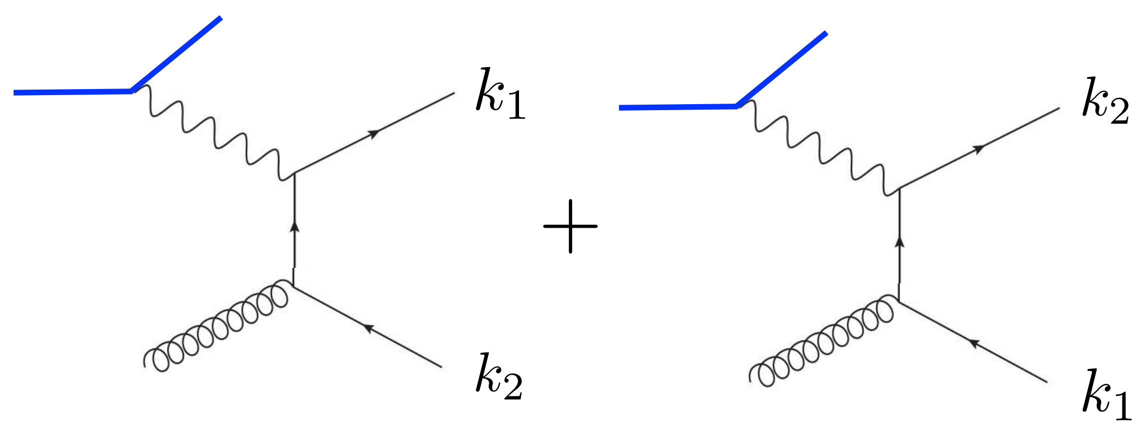
- 1-loop



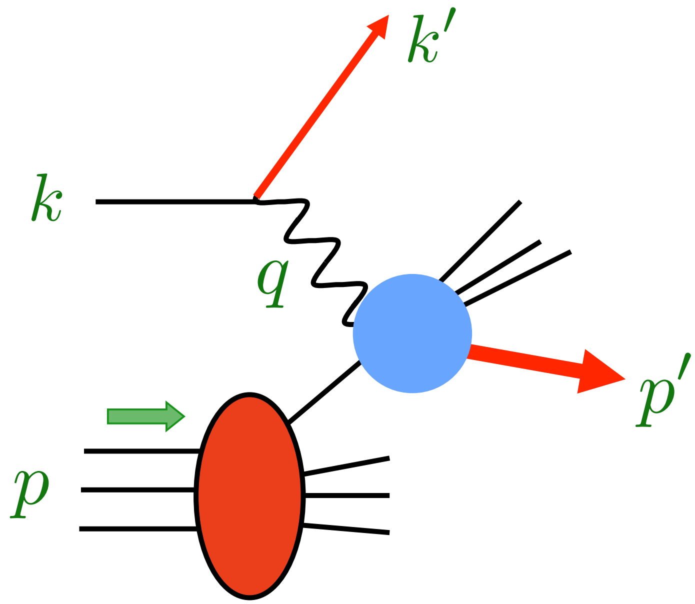
- imaginary part must be finite

- still, individual diagrams have poles
  → dimensional reg. (need γ^5 and $\varepsilon^{\mu\nu\rho\sigma}$)
  ('t Hooft-Veltman-Breitenlohner-Maison)

- also gluon channel:



- DIS kinematics:



$$x = \frac{Q^2}{2p\cdot q}, \quad y = \frac{p\cdot q}{p\cdot k}$$

$$z = \frac{p\cdot p'}{p\cdot q}, \quad \kappa^2 = \frac{{p'_\perp}^2}{Q^2}$$

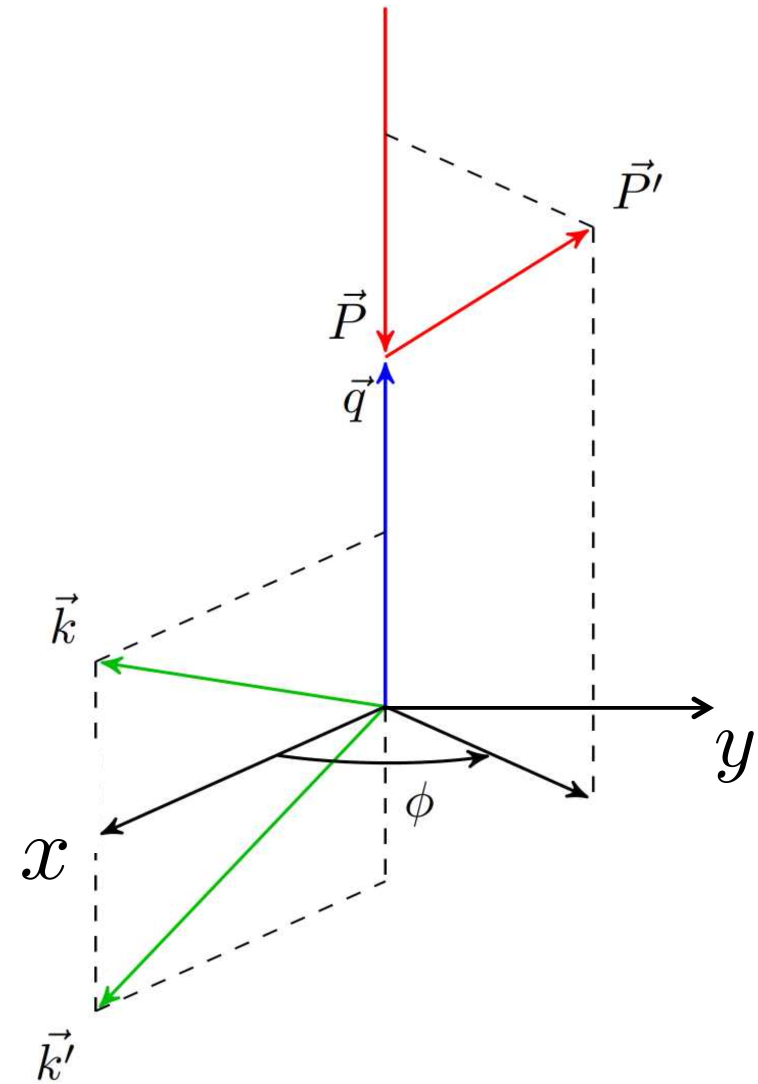
- best evaluated in Breit frame:

$$q = (0, 0, 0, Q)$$

$$p = \left(\frac{Q}{2x}, 0, 0, -\frac{Q}{2x}\right)$$

$$k = (k_0, k_\perp, 0, Q/2)$$

$$p' = (p'_0, p'_\perp \cos\phi, p'_\perp \sin\phi, p'_3)$$



$$\frac{\mathrm{d}\Delta\sigma}{\mathrm{d}x\ \mathrm{d}Q^2\ \mathrm{d}z\ \mathrm{d}\kappa^2\ \mathrm{d}\phi} = \frac{\pi\alpha^2 y^2}{4Q^4 z} L^{\mu\nu}\Delta W_{\mu\nu} \qquad \kappa^2 = \frac{P_T'^2}{Q^2}$$

$$L_{\mu\nu} = 2\left(k_\mu k'_\nu + k_\nu k'_\mu + \frac{q^2}{2} g_{\mu\nu}\right)$$

$$\Delta W_{\mu\nu} = \sum_{a,b} \int_x^1 \frac{\mathrm{d}\xi}{\xi} \int_z^1 \frac{\mathrm{d}\eta}{\eta^2} D_a^H(\eta) e_{ab} \Delta H_{\mu\nu}^{ab} \Delta f_b^p(\xi)$$

- for partonic process $\gamma^*(q) + b(p) \to a(p') + X$:

$$\Delta H_{\mu\nu}^{ab} = \int d\mathcal{PS}\ \left(|\mathcal{M}^+|^2_{\mu\nu}(b \to a) - |\mathcal{M}^-|^2_{\mu\nu}(b \to a) \right)$$

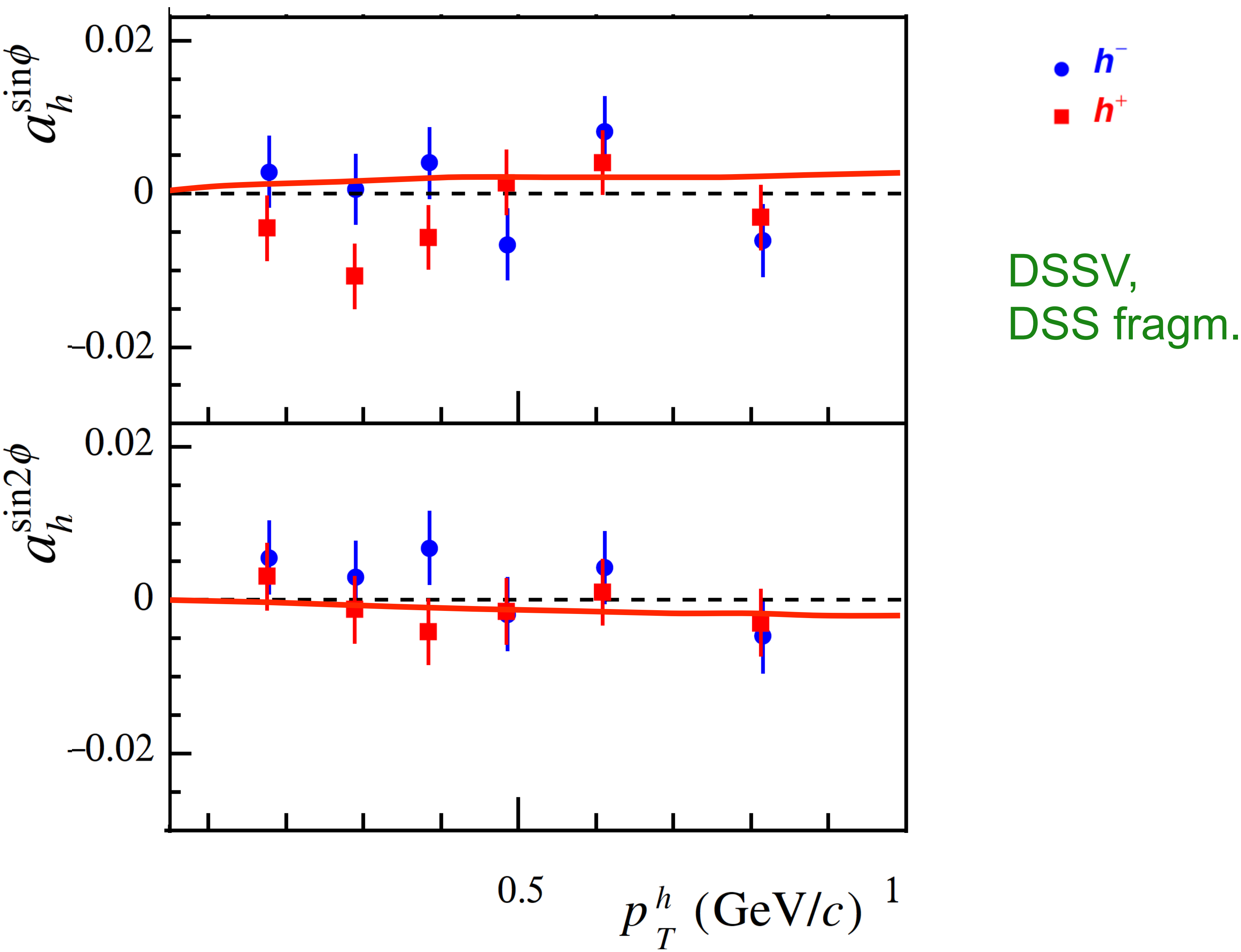
$$L^{\mu\nu}\Delta W_{\mu\nu} = \sum_{a,b}\int_x^1 \frac{\mathrm{d}\xi}{\xi}\int_z^1 \frac{\mathrm{d}\eta}{\eta^2} D_a^H(\eta)\Delta f_b^p(\xi)\frac{2\hat{z}e_{ab}}{(2\pi)^3 y^2}\left(\mathcal{A}^{ab}\sin\phi + \mathcal{B}^{ab}\sin(2\phi)\right)$$
$$\times\,\delta\left(\hat{\kappa}^2 - \frac{1-\hat{x}}{\hat{x}}\hat{z}(1-\hat{z})\right)$$

where

$$\mathcal{A}^{ab} = \sqrt{1-y}(2-y)i\frac{\hat{\kappa}}{2\hat{x}}\left[\frac{1}{\hat{x}}\Delta h_8^{ab} + \left(\hat{z} + \frac{\hat{\kappa}^2}{\hat{z}}\right)\Delta h_9^{ab}\right]$$
$$\mathcal{B}^{ab} = -(1-y)i\frac{\hat{\kappa}^2}{\hat{x}}\Delta h_9^{ab}$$

$$\Delta h_8^{qq} = -8i\pi\alpha_s^2(Q)\frac{\hat{x}^3(1-\hat{x}-\hat{z})}{(1-\hat{x})(1-\hat{z})}$$
$$\times\left[\frac{1}{2}C_F C_A + C_F\left(C_F - \frac{C_A}{2}\right)\left(\frac{3-\hat{z}}{1-\hat{z}} + \ln(\hat{z})\frac{2}{(1-\hat{z})^2}\right)\right]$$

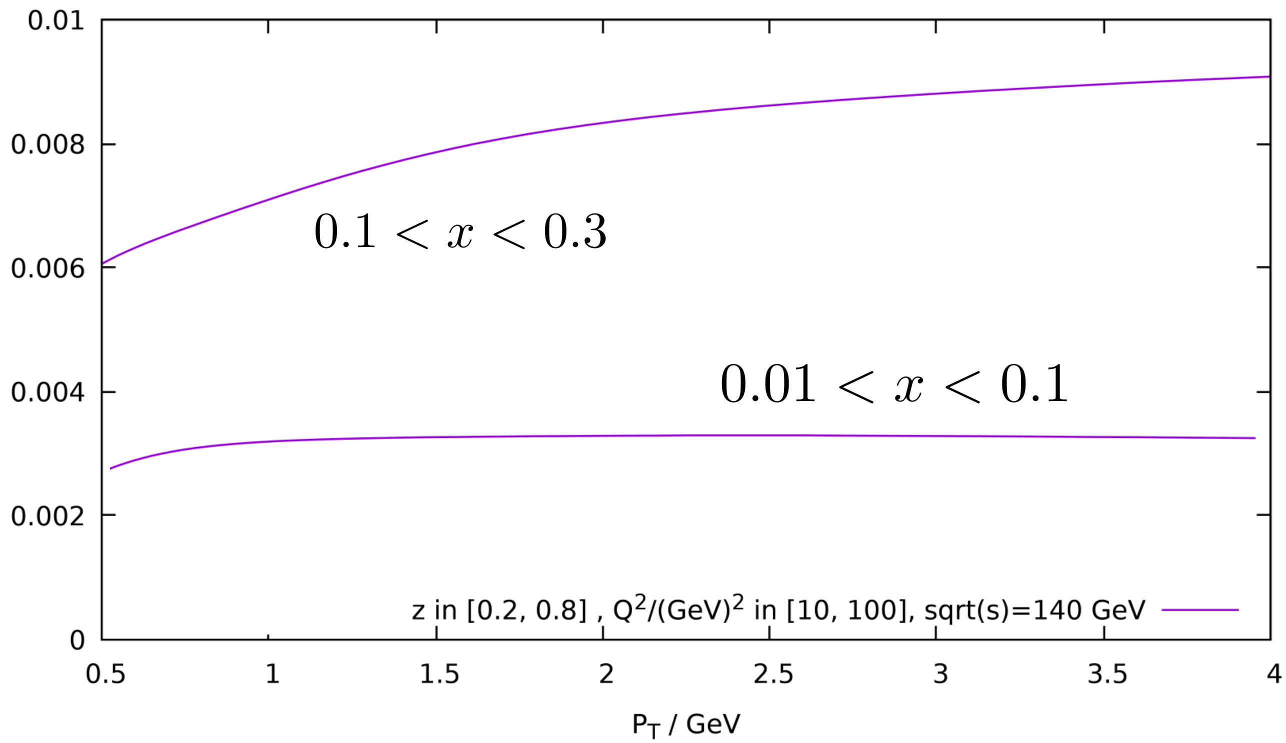
$$\Delta h_9^{qq} = 8i\pi\alpha_s^2(Q)\frac{\hat{x}^3}{(1-\hat{x})(1-\hat{z})}$$
$$\times\left[\frac{3}{2}C_F C_A + C_F\left(C_F - \frac{C_A}{2}\right)\left(\frac{1-3\hat{z}}{1-\hat{z}} + \ln(\hat{z})\frac{2(1-2\hat{z})}{(1-\hat{z})^2}\right)\right]$$



$a_h^{\sin\phi}$
0.02
0
-0.02
$a_h^{\sin 2\phi}$
0.02
0
-0.02
0.5
1
p_T^h (GeV/c)
h^-
h^+
DSSV,
DSS fragm.

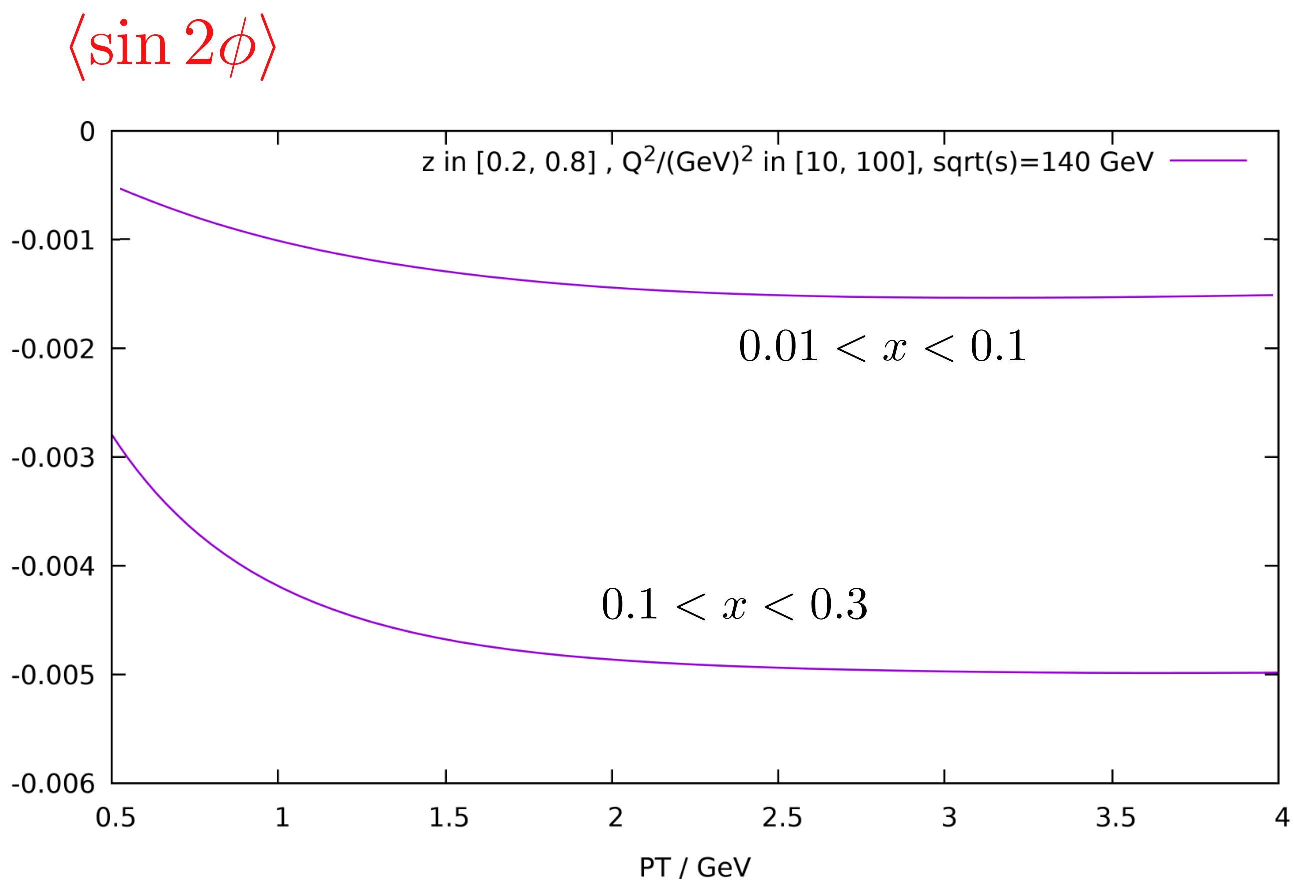
EIC:

$\langle \sin \phi \rangle$



$ep \to e' \pi^+ X$

DSSV,
DSS fragm.



⟨sin 2φ⟩
z in [0.2, 0.8] , Q2/(GeV)2 in [10, 100], sqrt(s)=140 GeV
0.01 < x < 0.1
0.1 < x < 0.3
0
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006
0.5
1
1.5
2
2.5
3
3.5
4
PT / GeV

Thank you, Gerhard !