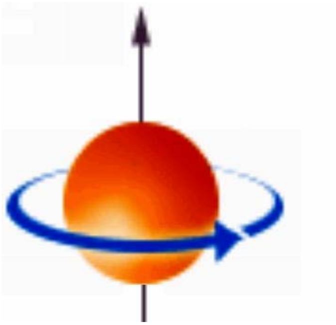
January 7, 2010
KEK, hadron physics



Spin Measurements in Lepton Scattering

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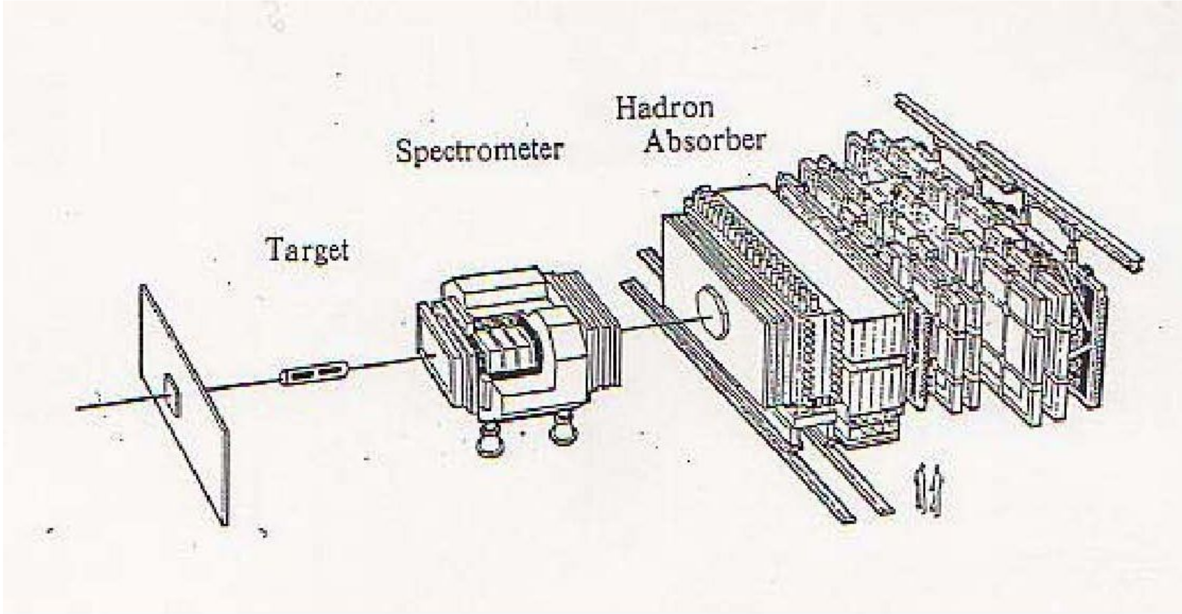
Contents

1. Introduction

EMC Experiment
(1988)

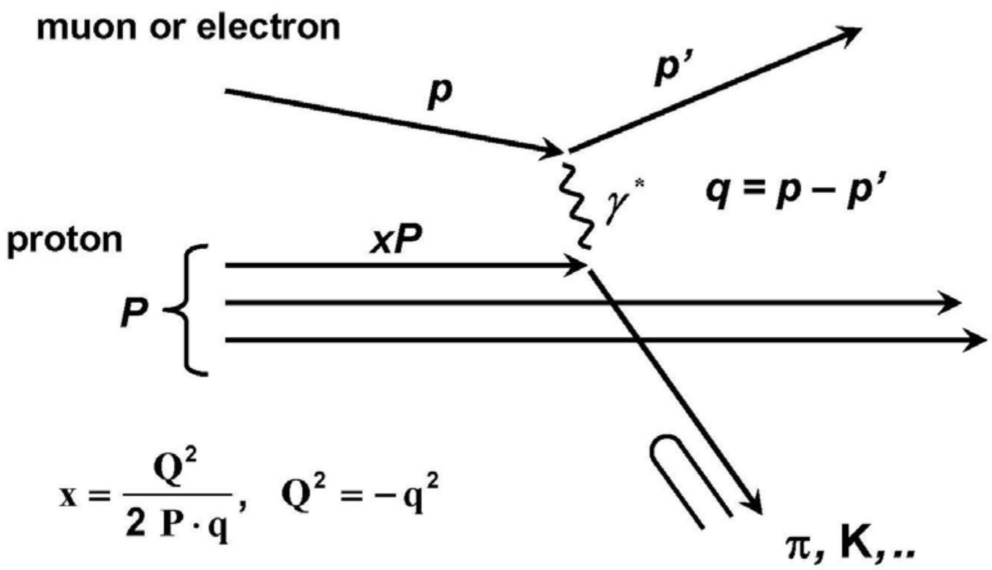


Muon – Proton Deep Inelastic Scattering at CERN

E = 100, 120, 200 GeV $\quad P_\mu \approx 76\%$ $\quad P_T \approx 75-80\%$ $\quad NH_3$

$$A = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}}$$

Lepton-proton deep inelastic scattering



$$x = \frac{Q^2}{2\,P\cdot q}, \quad Q^2 = -q^2$$

$$A = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} \longrightarrow A_1 = \frac{A}{D} \longrightarrow A_1 \approx \frac{g_1(x)}{F_1(x)}$$

depolarization factor

$$g_1(x) = \frac{1}{2}\sum e_i^2\,(q_i^+(x) - q_i^-(x))$$

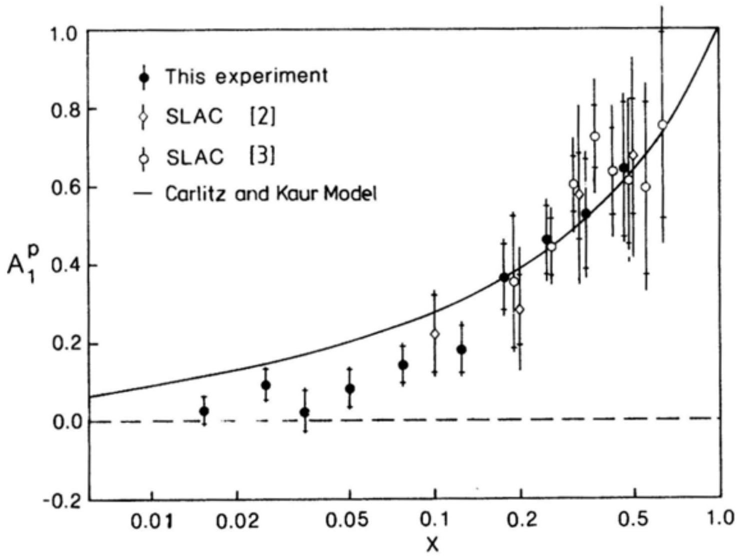
x **and** ***Q*²** **are determined** **<u>event by event</u>**

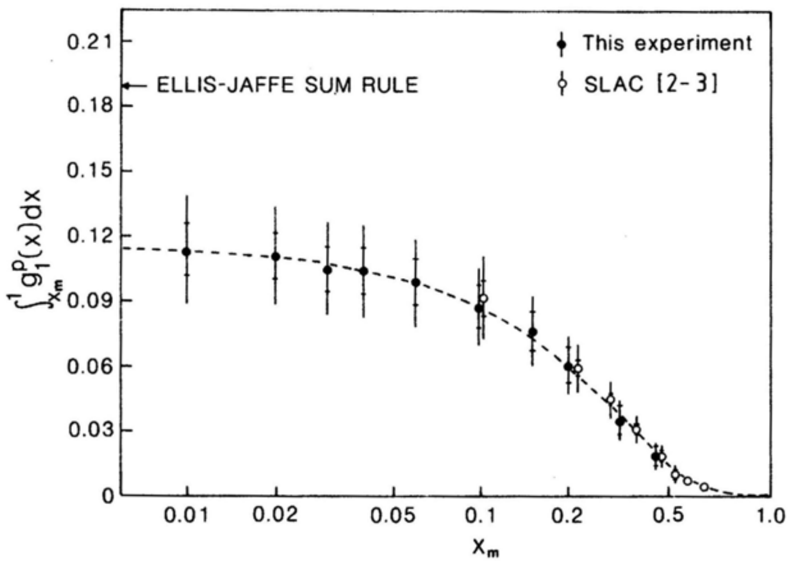
x**: the fraction of the momentum carried by the quark**

Bjorken x

$$A_1 \approx \frac{g_1(x)}{F_1(x)}$$

$$\int_{x_m}^{1} g_1(x)dx$$





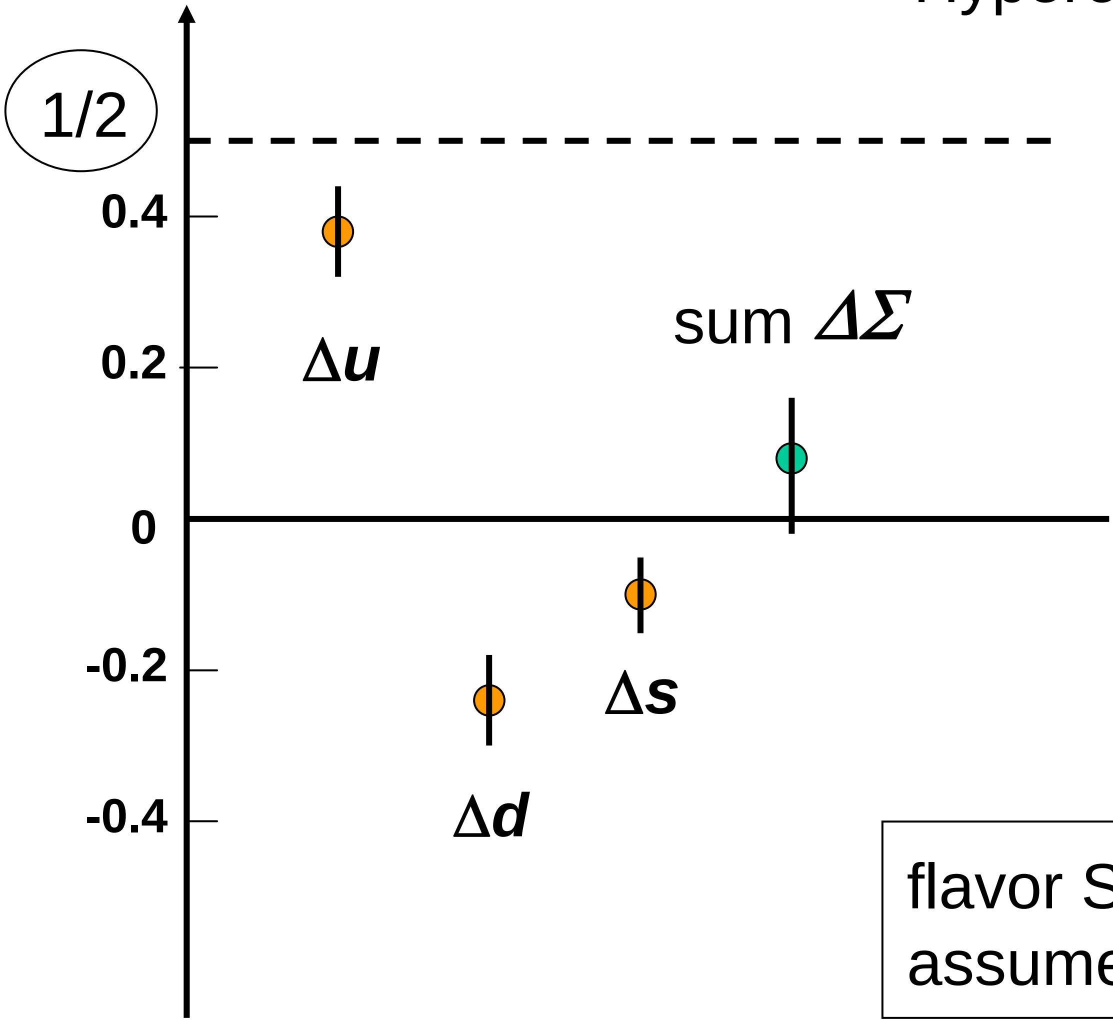
0.01 x 1.0 0.01 x_m 1.0

EMC + SLAC $\int_0^1 g_1(x)dx = 0.126 \pm 0.010 \pm 0.015$

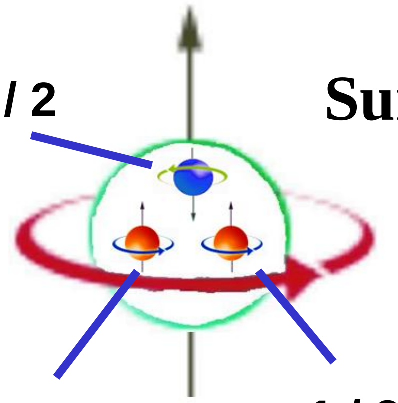
$$\frac{1}{2}\Delta\Sigma = \frac{1}{2}(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}) = 0.060 \pm 0.047 \pm 0.069$$

(12 ± 9.4 ± 13.8) %

EMC + Neutron lifetime
Hyperon weak decays



flavor SU(3) symmetry assumed



SU(6) Quark Wave Functions of Baryons

Sum of Spins of u u d Quarks = Spin of Proton

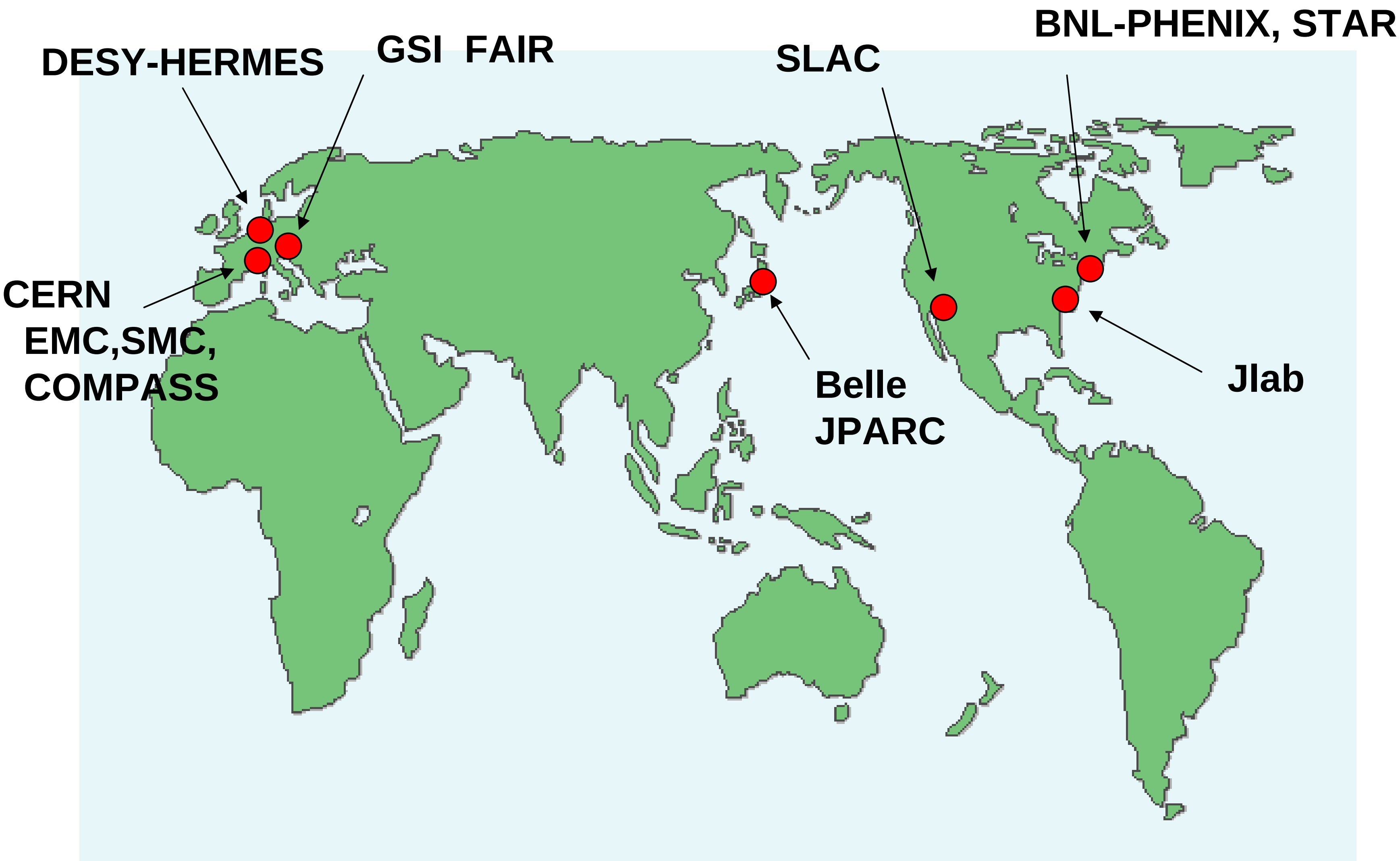
$$\frac{1}{2} + \frac{1}{2} + \left(-\frac{1}{2}\right) = \frac{1}{2}$$

$$\uparrow + \uparrow + \downarrow = \uparrow$$

‘Nucleon Spin Problem’

Measure

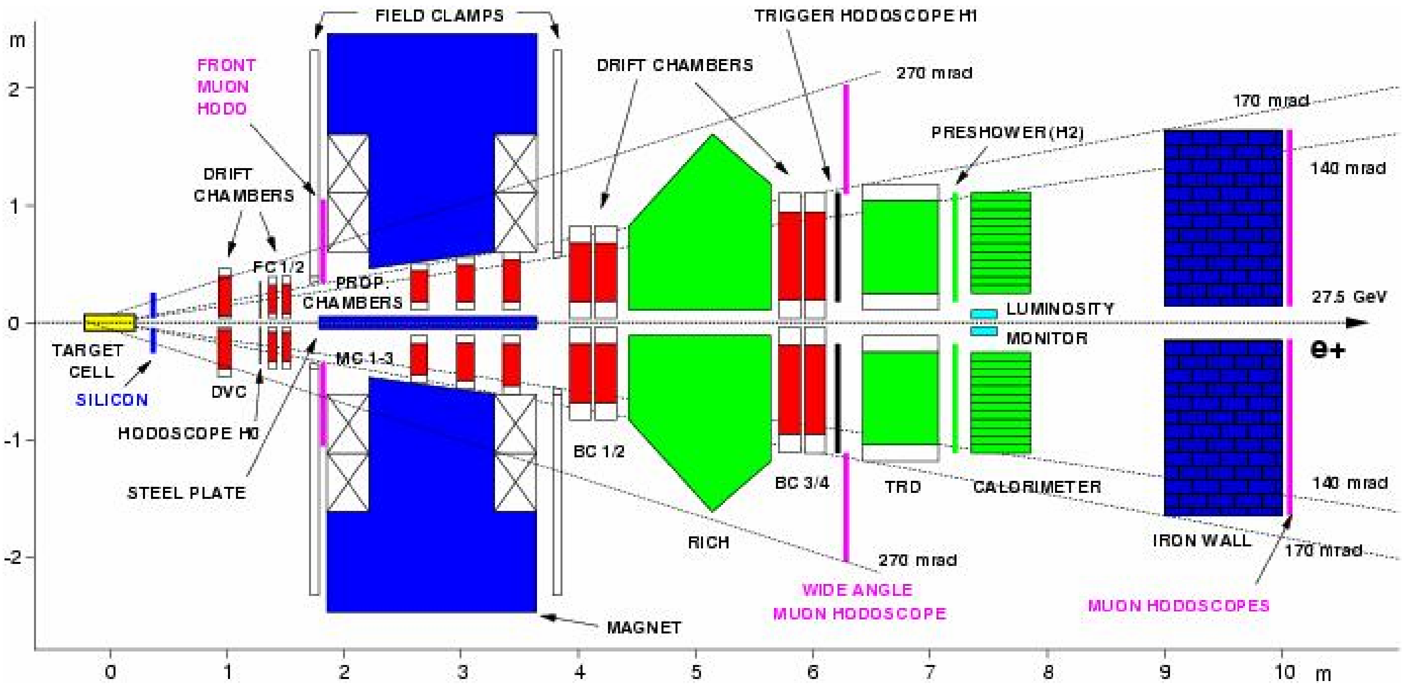
1) **with pure hydrogen and deuterium targets**
2) **down to even smaller x region**



500 ~ 1000 experimental physicists now,
Strong activities of theoretical physicists

HERMES at DESY-HERA (1995-2007)

Positron 27.6 GeV, longitudinally polarized, ~ 53%

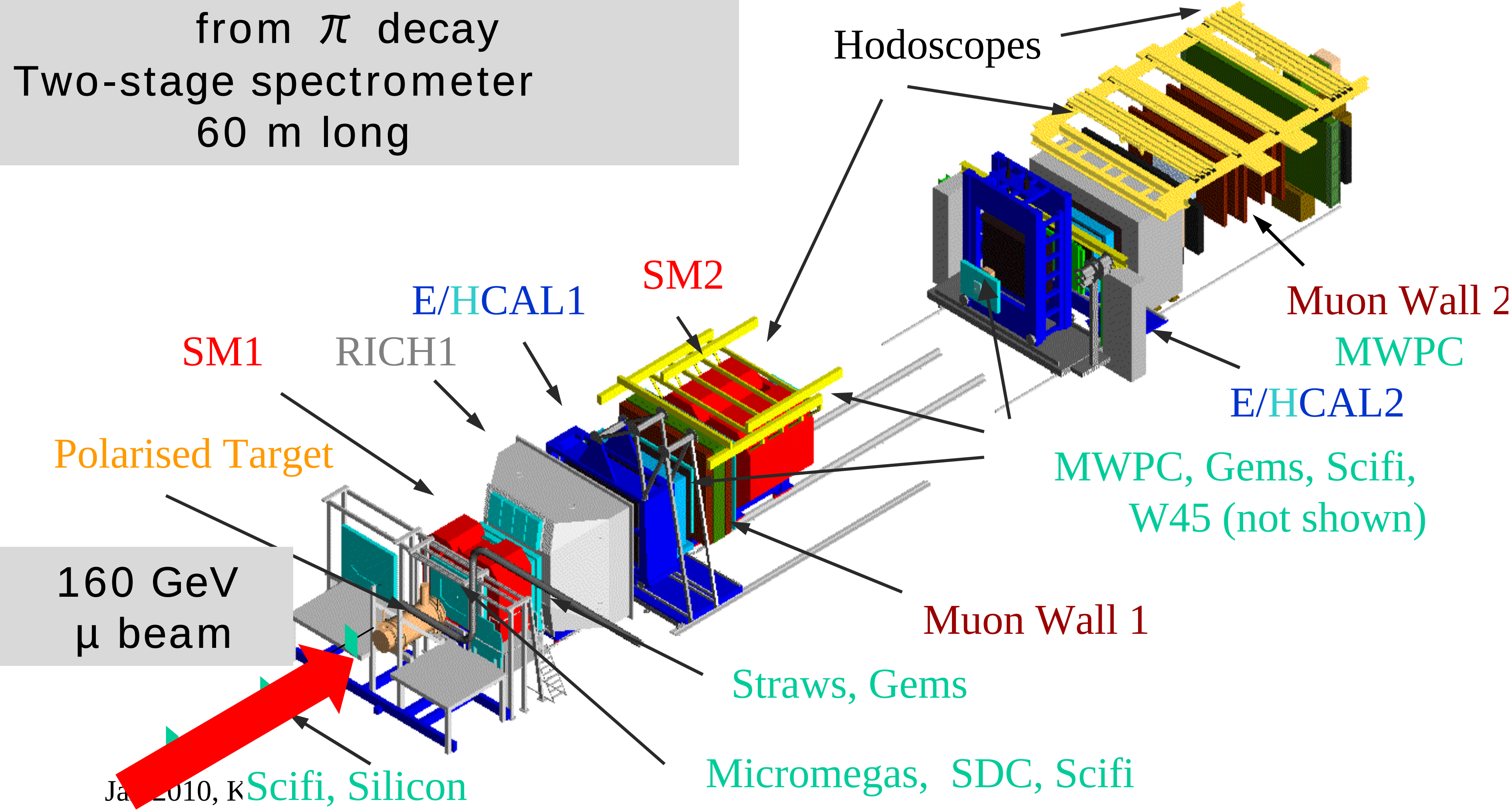


Polarized Proton and Deuteron Targets,

Particle ID: hadron ID with RICH

COMPASS at CERN (2002 -)

Beam: 160 GeV μ^+, pol. 80%
from π decay
Two-stage spectrometer
60 m long



Physics Program (Example of HERMES)

Positron beam /
Electron beam

Inclusive DIS

Semi-inclusive DIS

DVCS, Exclusive Mesons

[GPD]

Longitudinally Polarized Targets, p, d, ^{3}He

g_1

Δu, Δd, Δs, ...

Transversely Polarized Target, p

Sivers Effect
Collins Effect

Unpolarized Targets: Spin Averaged p, d,

High Density p, d, Nuclear Targets

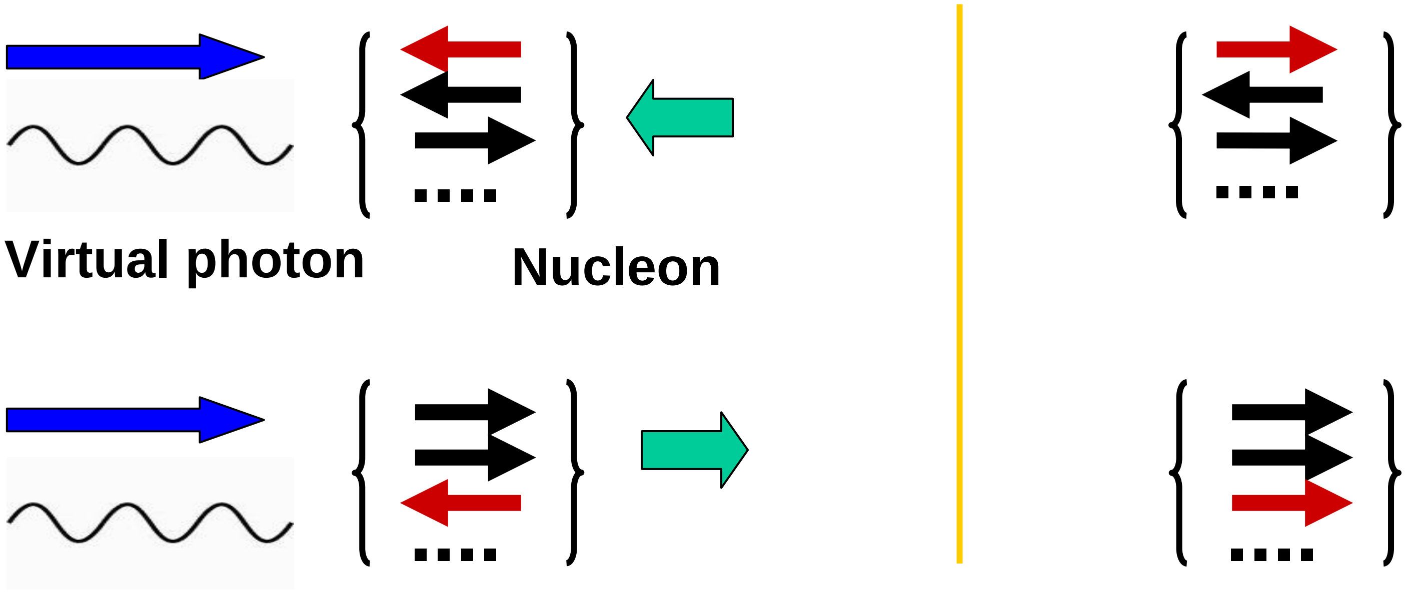
Multiplicity
Boer- Mulders Function

2. Longitudinal Spin - Helicity Distributions of Quarks and Gluons

Double-spin asymmetry

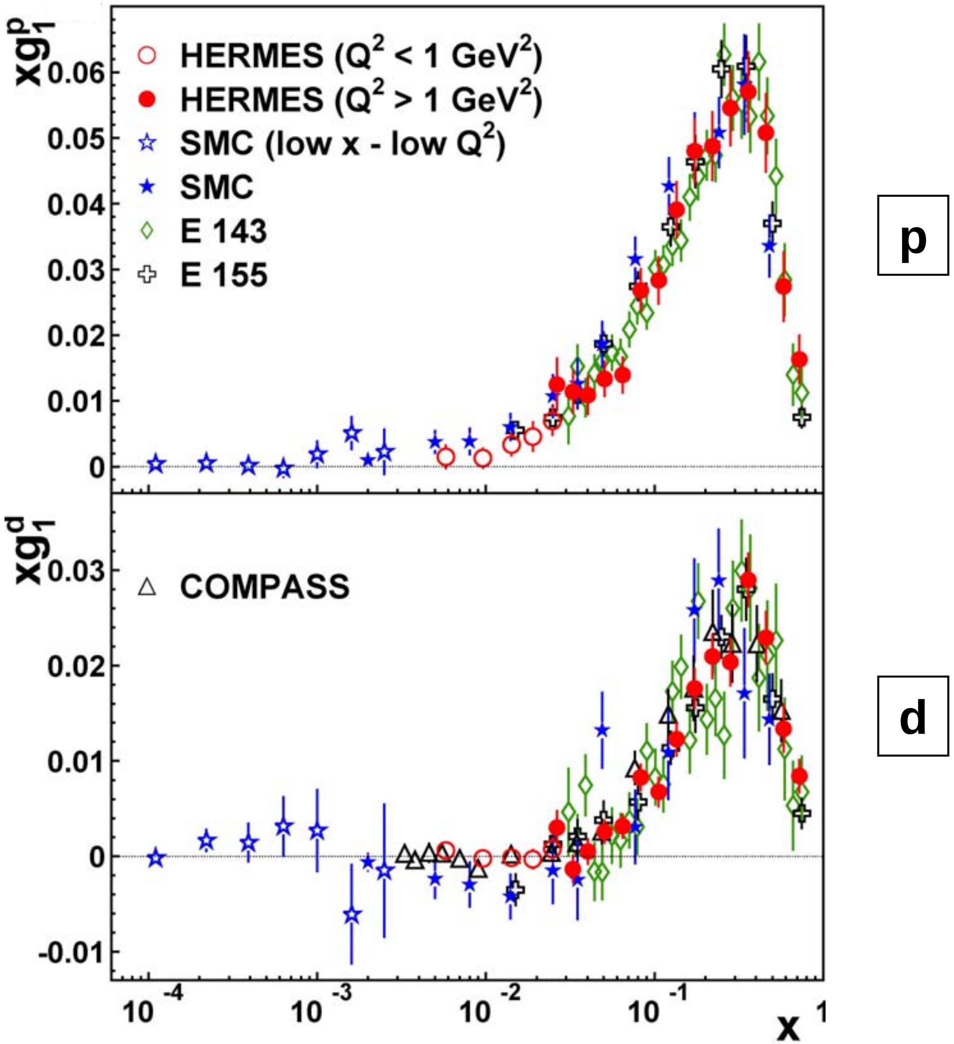
$$\vec{e} + \vec{N} \rightarrow e' + X$$

Beam and target, both polarized



$$A_1(x,z) = \frac{\sigma_{\substack{\rightarrow \\ \leftarrow}}(x) - \sigma_{\substack{\rightarrow \\ \rightarrow}}(x)}{\sigma_{\substack{\rightarrow \\ \leftarrow}}(x) + \sigma_{\substack{\rightarrow \\ \rightarrow}}(x)}$$

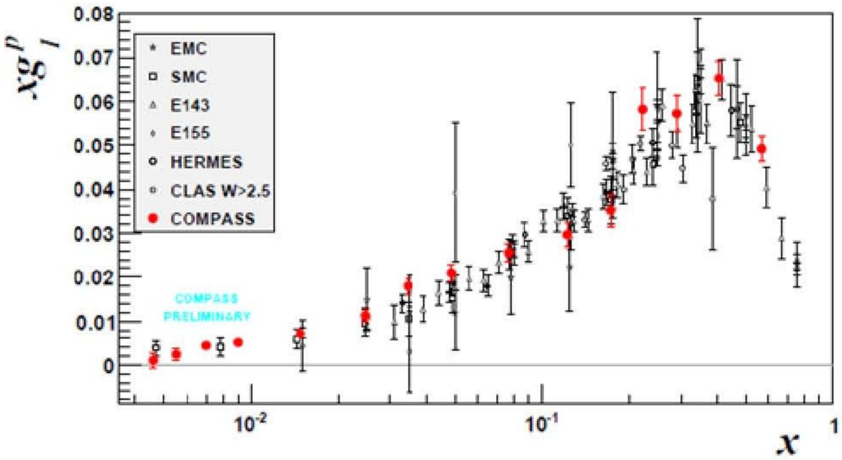
Xg_1



$$\Delta\Sigma = 0.2 - 0.3$$

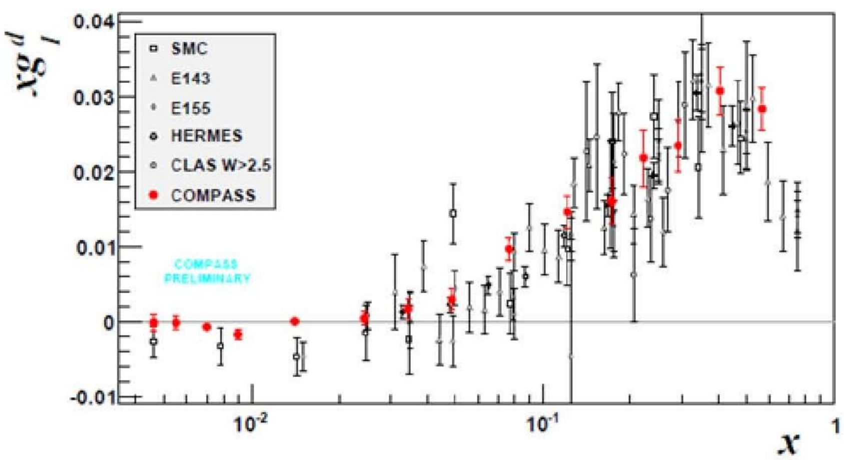
20 – 30%

p



- COMPASS 2007

d



- COMPASS 2002-2006

HERMES:

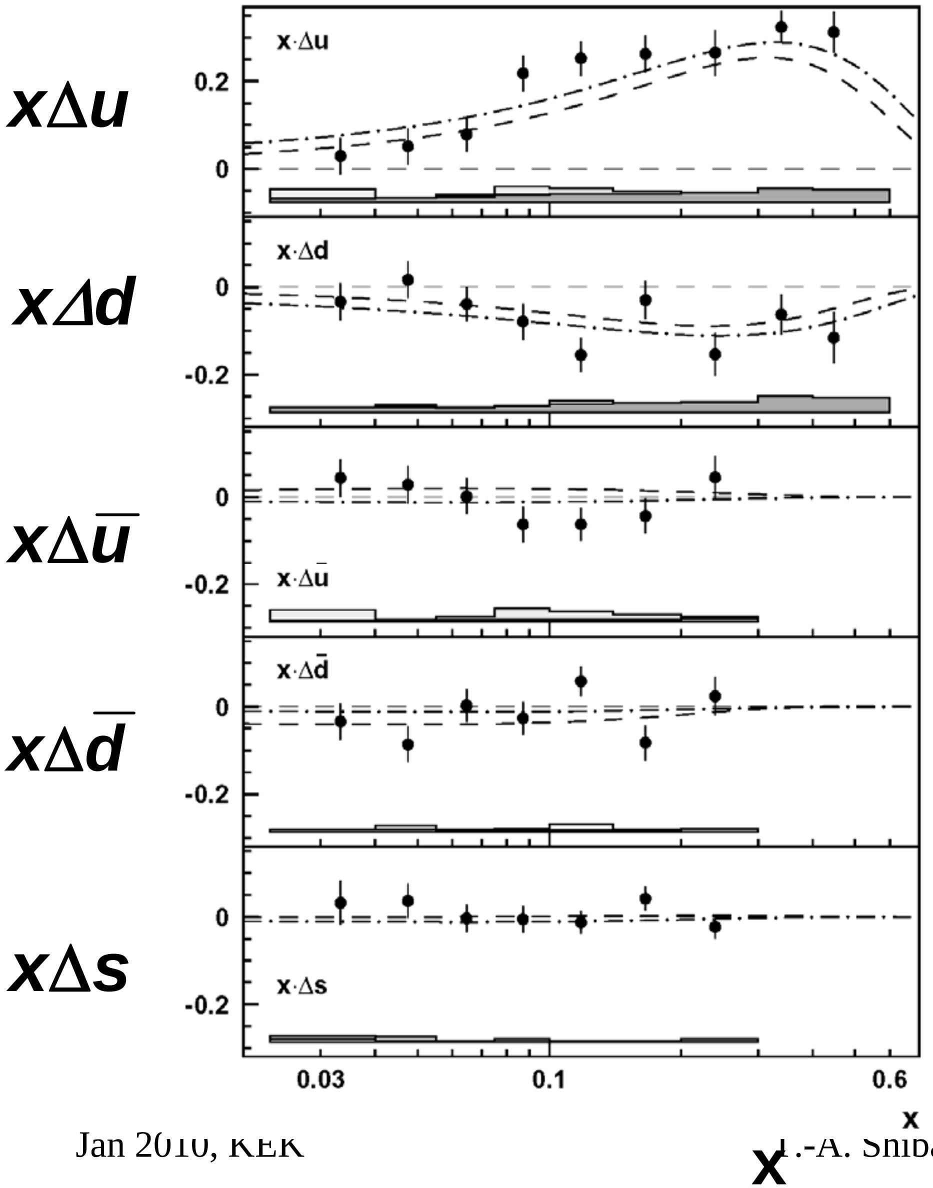
From g_1^d **at 0.021 < x < 1,**

$$\Delta\Sigma = \mathbf{0.330 \pm 0.011}(\textit{theo}) \pm \mathbf{0.025}(\mathrm{exp.}) \pm \mathbf{0.028}(\textit{evol.})$$

33%

HERMES

Flavor Separation, Quark Helicity Distributions



Result: $\Delta u > 0$

$\Delta d < 0$

$\Delta \bar{q} \approx 0$

- x bin by bin analysis
- No functional forms are assumed.
- No first moments are assumed.
- Helicity conservation not assumed $\frac{\Delta d}{d} \to 1$ as $x \to 1$ etc.

Error band – systematic error

— · — / — — — — QCD fits to inclusive measurements

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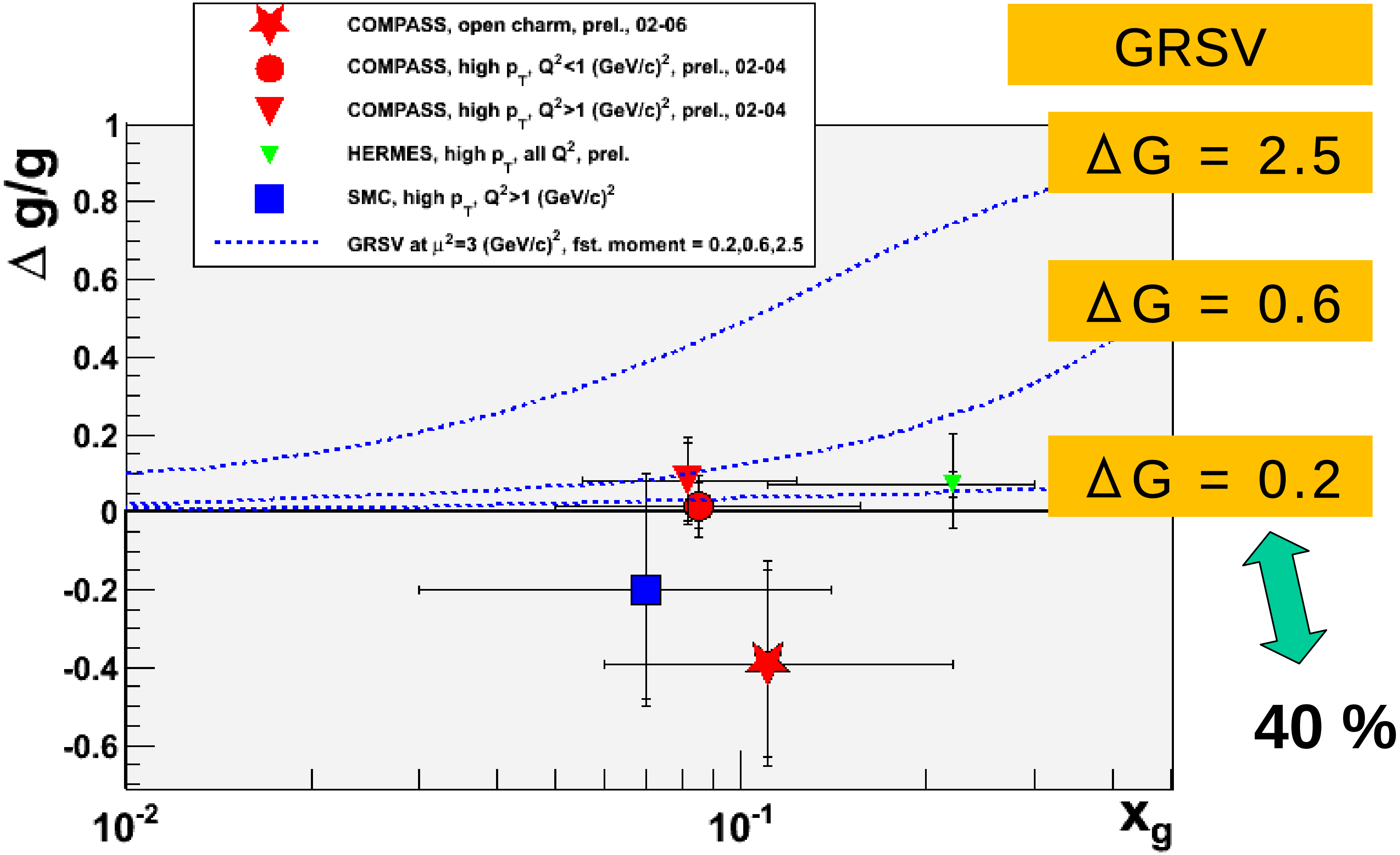
Gluon Spin

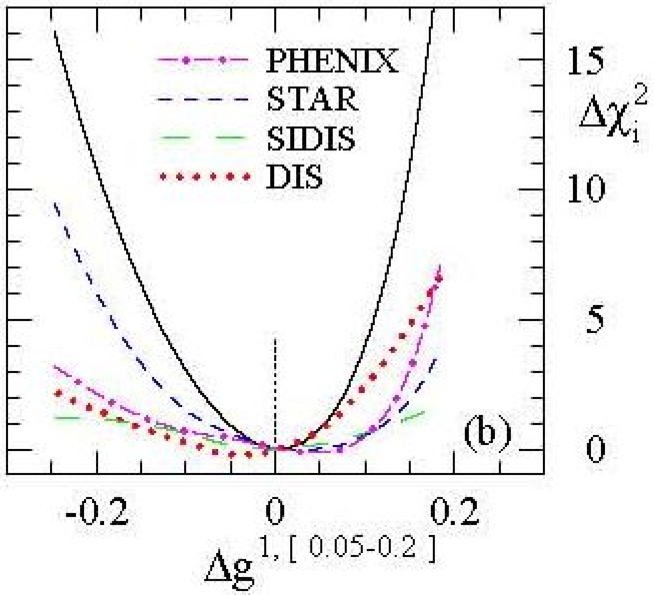


Global Analysis and Gluon Spin Contribution

D. de Florian et al. Phys.Rev.Lett.101:072001, 2008. DSSV08

Data of deep inelastic lepton scattering and proton-proton collision

$$x\Delta f_j(x, Q_0^2) = N_j x^{\alpha_j} (1-x)^{\beta_j} (1 + \gamma_j \sqrt{x} + \eta_j x)$$



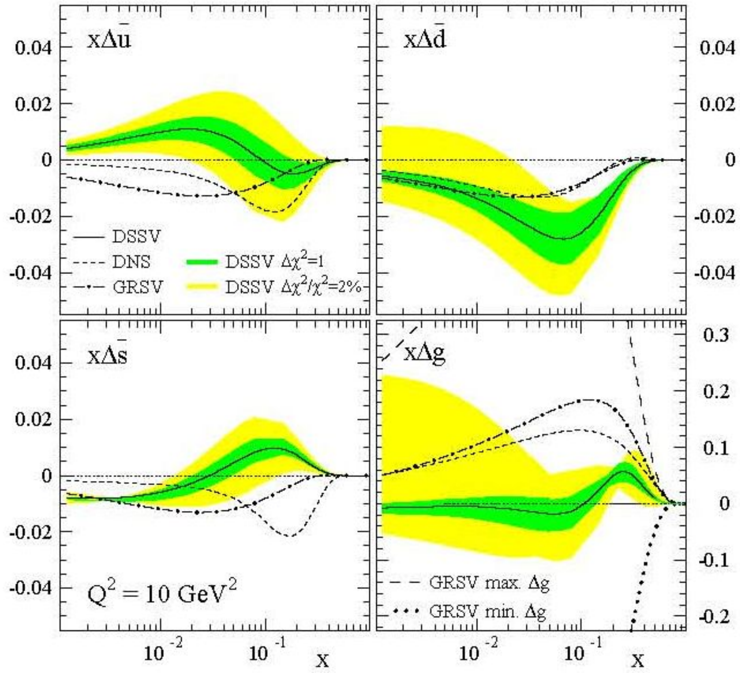


FIG. 2: Our polarized sea and gluon densities compared to previous fits [6, 8]. The shaded bands correspond to alternative fits with $\Delta\chi^2 = 1$ and $\Delta\chi^2/\chi^2 = 2\%$ (see text).

- **(Inclusive) DIS data give a constraint on the positive side**
- **PHENIX data also give a constraint on the positive side**
- **STAR data give a constraint on the negative side**

see also AAC, LSS06,…

DSSV08

$[0.001-1]$

$\Delta g = 0.013^{+0.106}_{-0.120} \quad \Delta\chi^2 = 1$ Gluon spin contribution, 2.6%+21%-24%

$\Delta g = 0.013^{+0.702}_{-0.314} \quad \frac{\Delta\chi^2}{\chi^2} = 2\%$ 2.6%+140%-63%

$\Delta\Sigma = 0.366^{+0.042}_{-0.062} \quad \frac{\Delta\chi^2}{\chi^2} = 2\%$ 37%+4%-6%

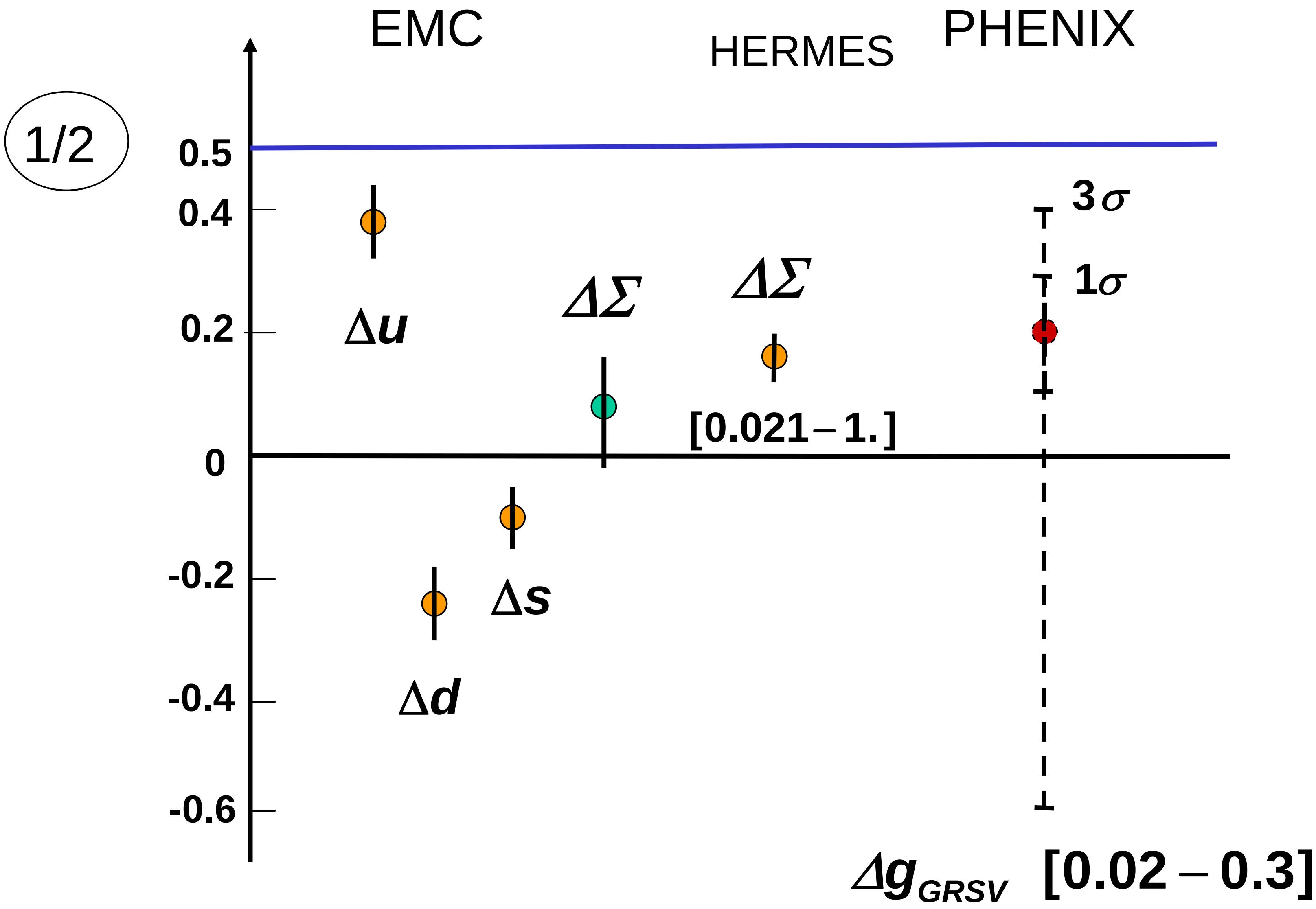
Polarized p+p collider PHENIX and STAR

PHENIX, Phys. Rev. Lett. 103, 012003, 2009 GRSV

$[0.02-0.3]$

$\Delta g = 0.20 \pm 0.10 \pm 0.10 \quad \Delta\chi^2 = 1 \ or \ 1\sigma$ 40%±20%±20%

$\Delta g = 0.20 + 0.20 - 0.8 \pm 0.10 \quad \Delta\chi^2 = 9 \ or \ 3\sigma$ 40%+40%-160%±20%


EMC
HERMES
PHENIX
1/2
0.5
0.4
0.2
0
-0.2
-0.4
-0.6
Δu
Δd
Δs
ΔΣ
ΔΣ
[0.021 – 1.]
3σ
1σ
Δg_GRSV [0.02 – 0.3]

3. Transverse Spin – Sivers Function, Transversity

Sivers Effect

Correlation between the nucleon spin and the momentum direction of the quarks in it.

- **Transverse momentum dependent:** $f_{1T}^{\perp q}(x, p_T^2)$
- **Naïve time reversal odd**

A few ideas exist to relate it to orbital angular momentum of quarks

HERMES

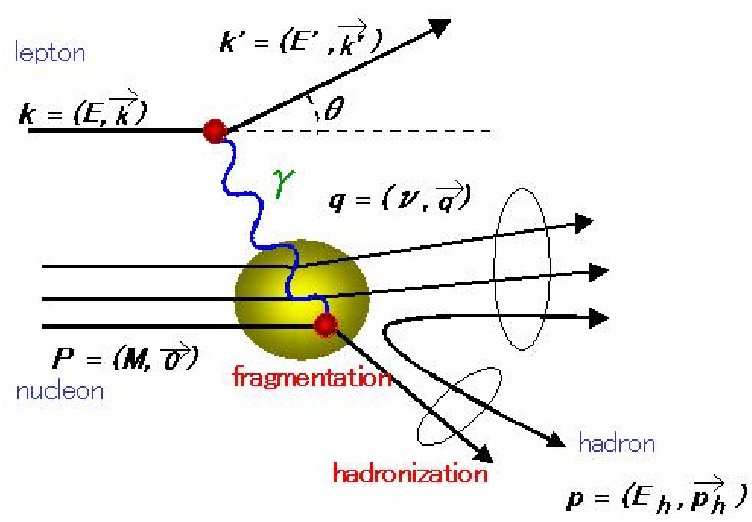
A. Airapetian et al., Phys. Rev. Lett. 94 (2005) 012002

A. Airapetian et al., Phys. Rev. Lett. 103 (2009) 152002

Measure x, Q^2 event by event

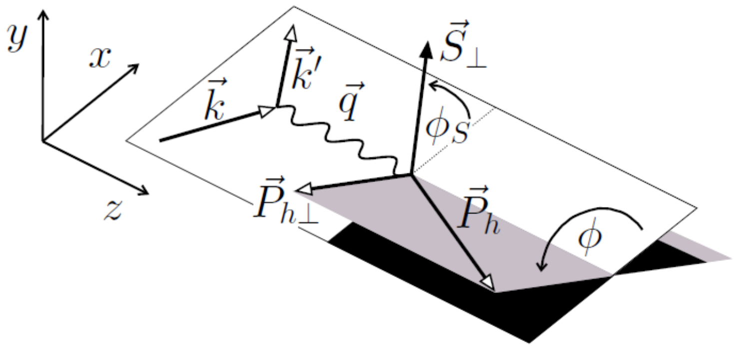
Semi-inclusive measurement

Determine $z = \frac{P_h}{\upsilon}$ event by event



Sivers Effect: $\sin(\phi - \phi_S)$ modulation

$$\sigma(\phi,\phi_S) = \sigma_{UU}\{1 + 2 < \cos\phi >_{UU} \cos\phi + 2 < \cos 2\phi >_{UU} \cos 2\phi$$
$$+ |S_T| [\, 2 < \sin(\phi - \phi_S) >_{UT} \underline{\sin(\phi - \phi_S)} + \ldots]\}$$

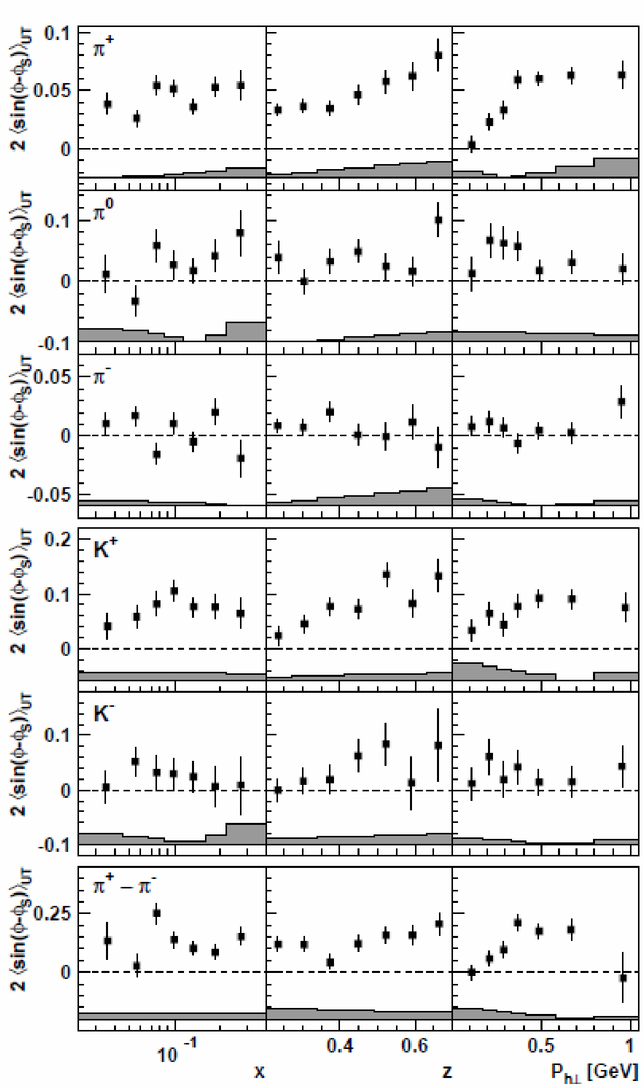


$$2 < \sin(\phi - \phi_S) >_{UT} = -\frac{\Sigma e^2 f_{1T}^{\perp q}(x, p_T^2) \otimes D_1^q(z, K_T^2)}{\Sigma e_q^2 f_1^q(x) D_1^q(z)}$$

Measure ϕ, ϕ_S event by event

Results

$$2 < \sin(\phi - \phi_S) >_{UT}$$



π^+ π^0 π^- K^+ K^- $\pi^+ - \pi^-$

X Z $P_{h\perp}$

Scattering on *u* quark dominant

Positive amplitude

⇨ **negative** $f_{1T}^{\perp u}$

'Pion difference asymmetry'

$$A_{UT}^{\pi^+-\pi^-}(\phi-\phi_s) \equiv \frac{1}{|S_T|}\frac{(\sigma_{U\uparrow}^{\pi^+}-\sigma_{U\uparrow}^{\pi^-})-(\sigma_{U\downarrow}^{\pi^+}-\sigma_{U\downarrow}^{\pi^-})}{(\sigma_{U\uparrow}^{\pi^+}-\sigma_{U\uparrow}^{\pi^-})+(\sigma_{U\downarrow}^{\pi^+}-\sigma_{U\downarrow}^{\pi^-})}$$

Contributions of exclusive ρ cancel

- **Sivers Effect was observed for π^+, π^0, K^+ as well as $\pi^+ - \pi^-$, with Transversely Polarized Proton Target at HERMES**
- **Positive Sivers Amplitudes suggest negative $f_{1T}^{\perp u}$**
- **Comparison with other experiments (COMPASS d / p etc.) will be useful. Q^2 evolution, etc.**

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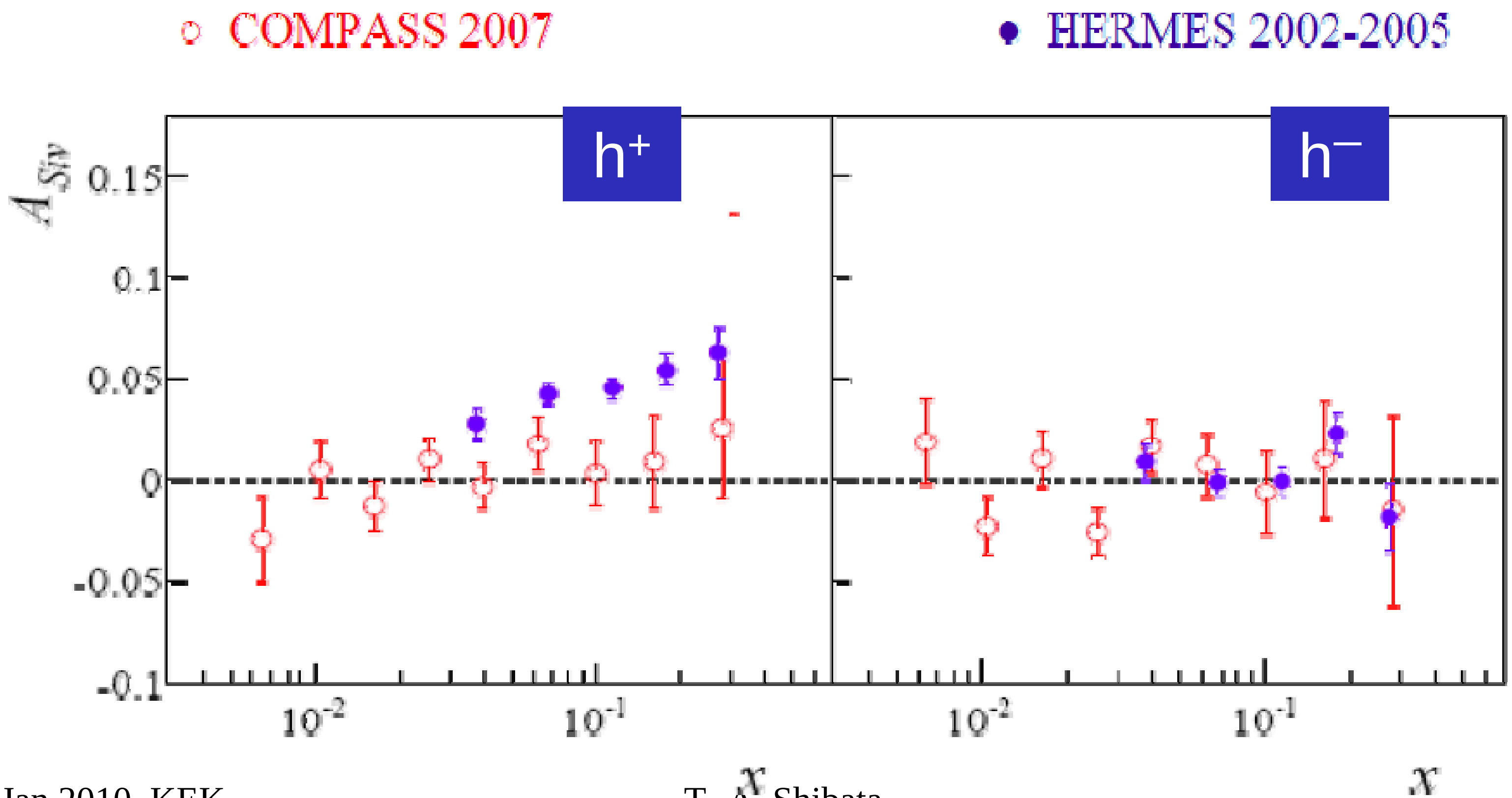
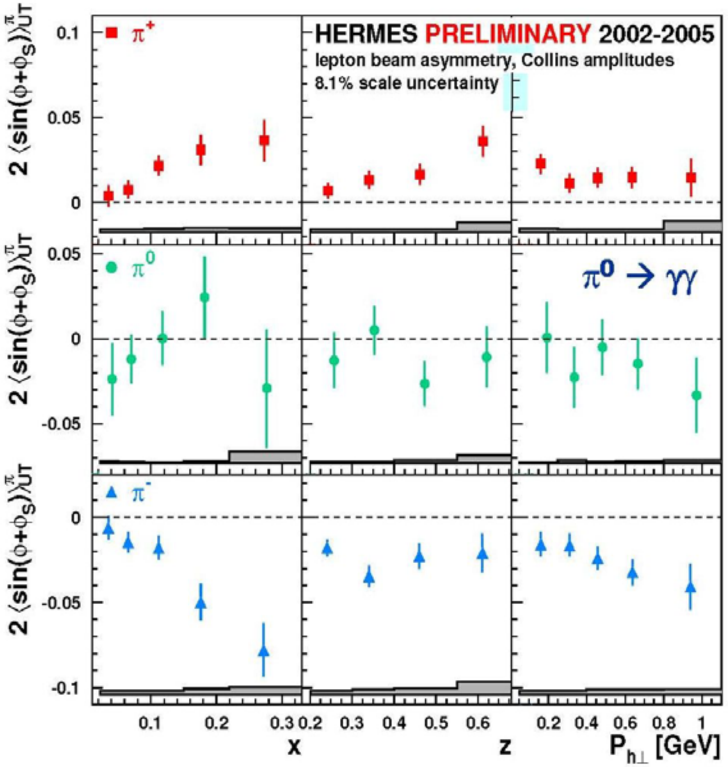
Proton Sivers Asymmetry - COMPASS

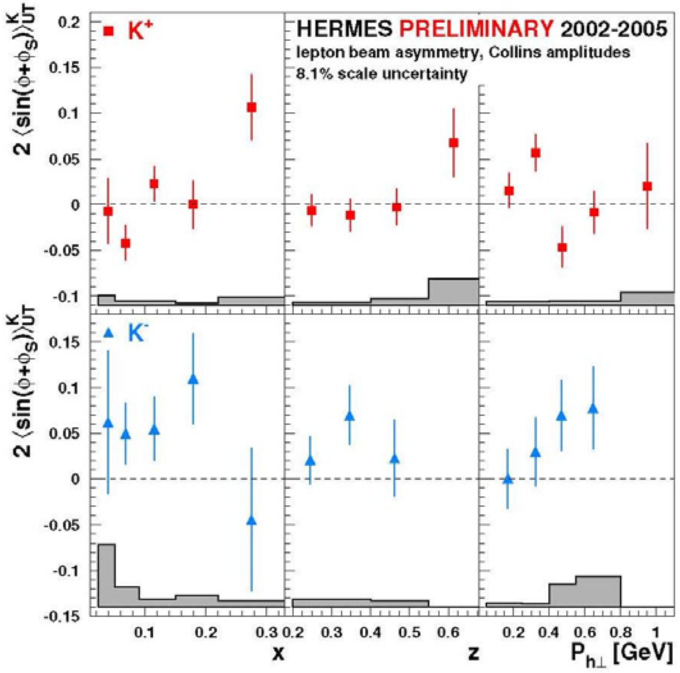
- compatible with zero for the deuteron
- large effect seen by HERMES, not confirmed by COMPASS
- clarification needed



Collins Asymmetry

Proton target $\sin(\phi + \phi_C)$ **modulation**





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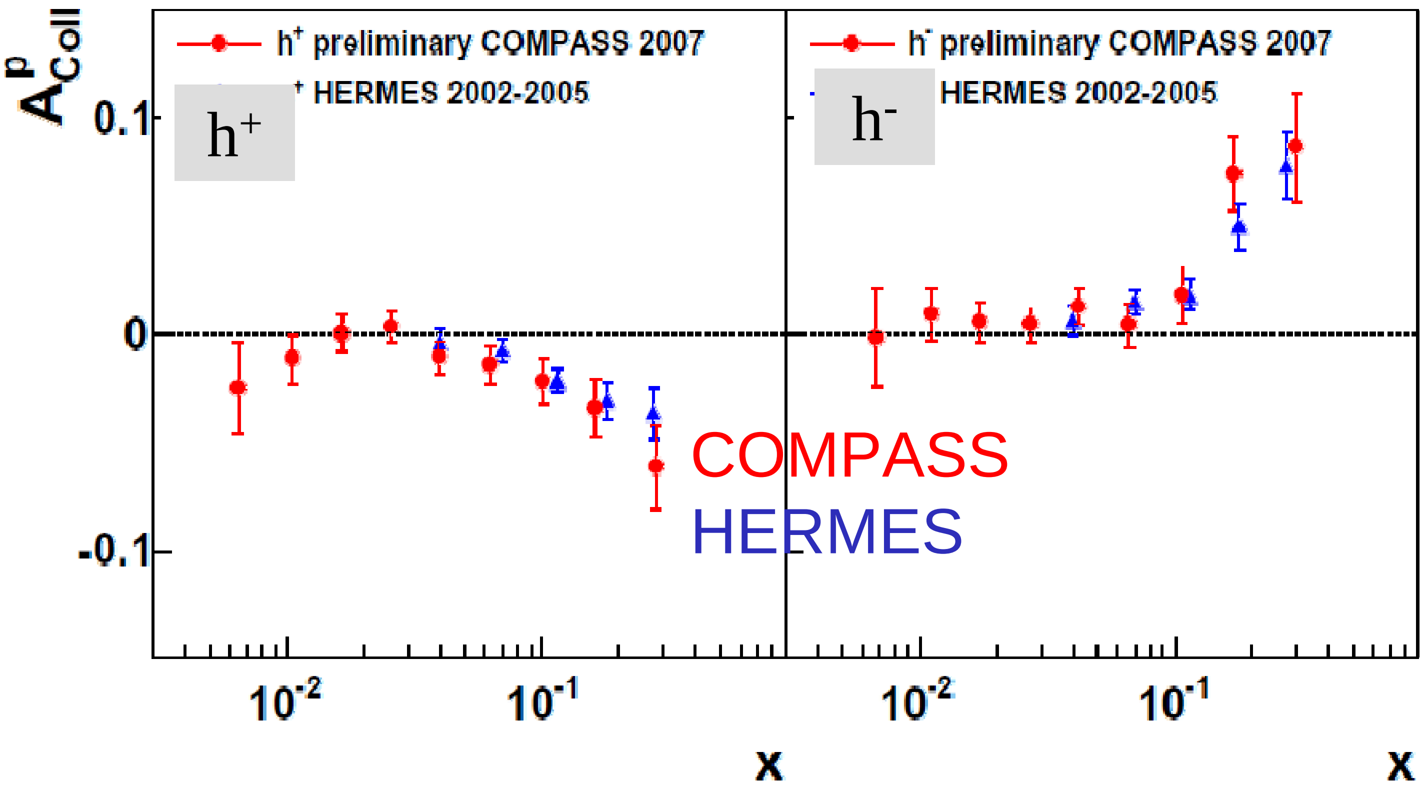
Proton Collins Asymmetry - COMPASS

proton



sign change and $D_{nn} \cong y$ applied for HERMES data

Good agreement

4. Generalized Parton Distributions

Deeply Virtual Compton Scattering, Exclusive Meson Production

Generalized (Off-Forward) Parton Distributions

Deeply Virtual Compton Scattering

Exclusive Meson Production γ

π, ρ, ϕ, ω

Deep Inelastic Scattering
$q, \Delta q$

Generalized Parton Distributions (GPD)

$H^q, E^q, \tilde{H}^q, \tilde{E}^q$

F_1, F_2

Electromagnetic Form Factors
(Elastic Scattering)

Total Angular Momentum J^q

Orbital Angular Momentum L^q

Generalized (Off - Forward) Parton Distributions

$$H^q(x,\xi,t),\ \ E^q(x,\xi,t),\ \ \tilde{H}^q(x,\xi,t),\ \ \tilde{E}^q(x,\xi,t)$$

Forward limit $t \to 0,\ \ \xi \to 0$

$$H^q(x,0,0) = q(x), \quad \tilde{H}^q(x,0,0) = \Delta q(x)$$

Ordinary Quark Distributions

Sum rules, x – integral, sum over q, ...

$$H^q(x,\xi,t) \to F_1(t),\ \ E^q(x,\xi,t) \to F_2(t)$$

Dirac and Pauli Nucleon Form Factors

$$\tilde{H}^q(x,\xi,t) \to g_A(t),\ \ \tilde{E}^q(x,\xi,t) \to h_A(t)$$

Axial-vector and Pseudo-scalar Form Factors

$$\lim_{t\to 0} \frac{1}{2}\int_{-1}^{+1} dx\, x\, [H^q(x,\xi,t) + E^q(x,\xi,t)] = J^q$$

2nd moment

$$J^q = \frac{1}{2}\Delta\Sigma + L_z^q$$

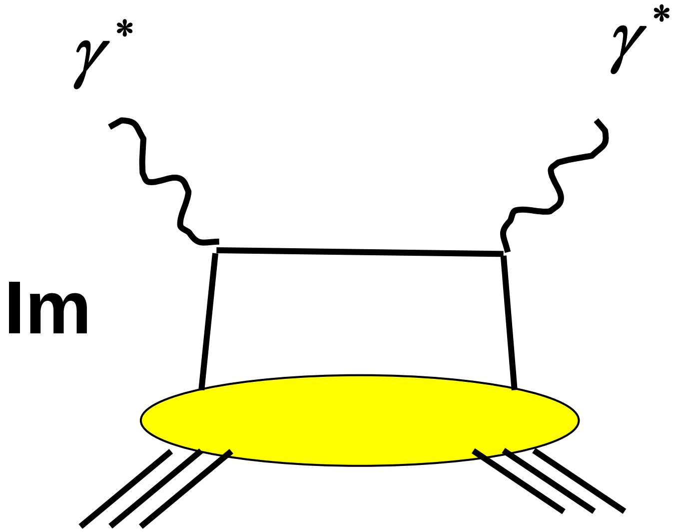
Total angular momentum

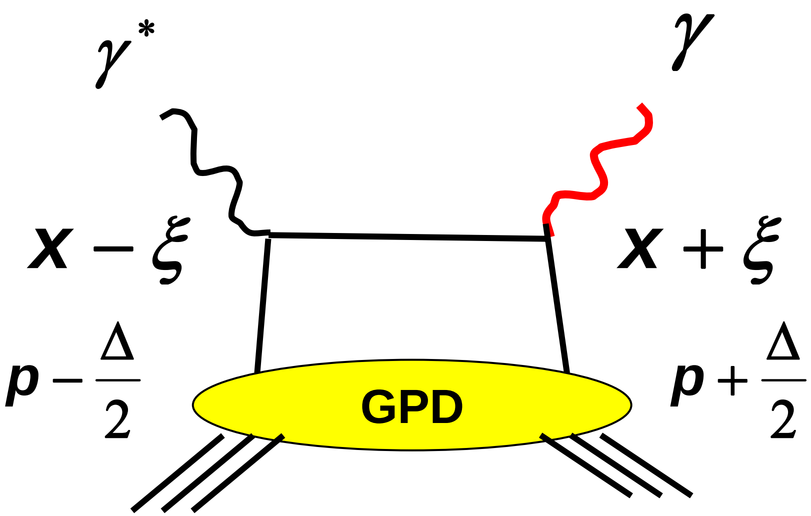
Orbital angular momentum

Coss section for inclusive deep inelastic scattering

Deeply Virtual Compton Scattering (DVCS)

-- Exclusive production of a real photon



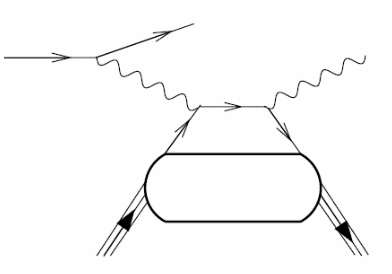


x :Light cone momentum fraction

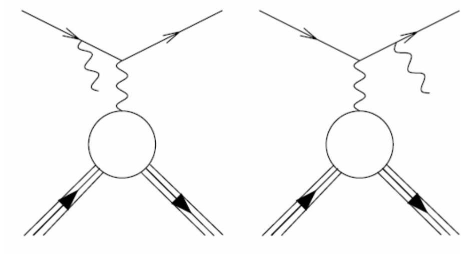
$\xi = \frac{x_{BJ}}{2 - x_{BJ}}$:Exchanged longitudinal momentum fraction

$t = \Delta^2$:Momentum transfer

How to measure DVCS



Deeply Virtual Compton Scattering

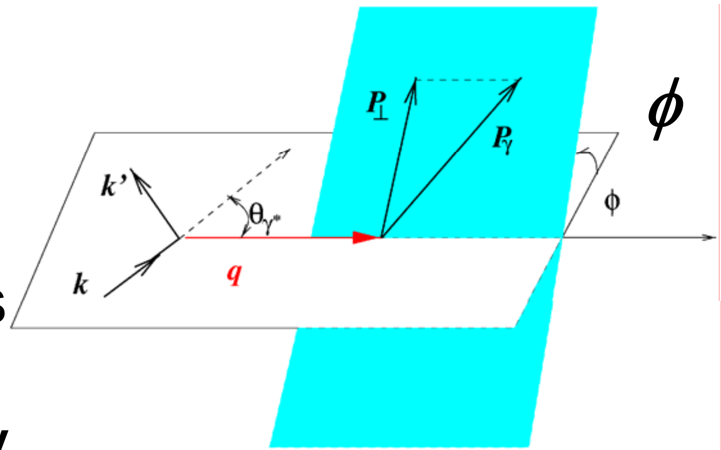


Bethe-Heitler Process, known calculable

$$\frac{d^4\sigma}{d\phi\, dt\, dQ^2 dx} \propto |A_{DVCS} + A_{BH}|^2 = |A_{DVCS}|^2 + |A_{BH}|^2 + I$$

$$\Delta\sigma_{LU} = \sigma(\vec{e}^{\pm}p) - \sigma(\overleftarrow{e}^{\pm}p) \propto \mp\sin\phi \times \mathrm{Im}\, I$$

$$\Delta\sigma_{ch} = \sigma(e^{+}p) - \sigma(e^{-}p) \propto \cos\phi \times \mathrm{Re}\, I$$



Beam-spin asymmetry by HERMES and CLAS

Beam-charge asymmetry by HERMES

-- DVCS-BH Interference, Real and Imaginary

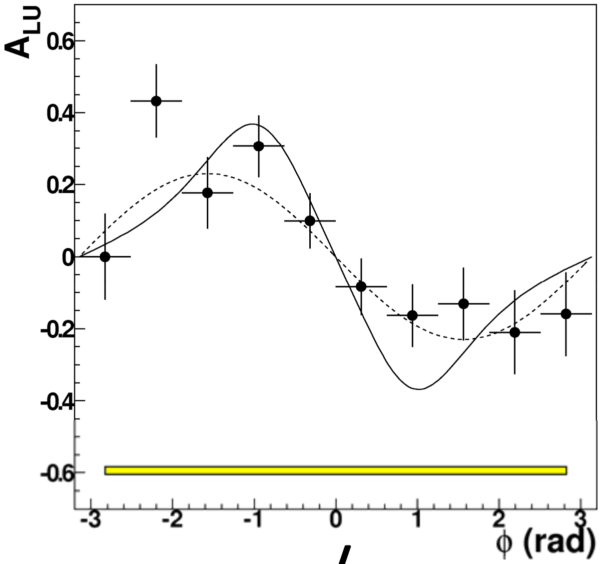
DVCS Cross Section by ZEUS and H1

Deeply Virtual Compton Scattering

First observation of beam-spin asymmetry of DVCS (2001)

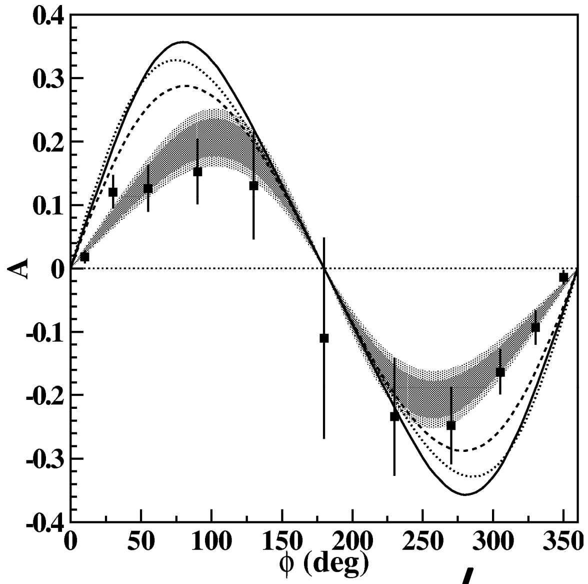
A_{LU}

HERMES (DESY)



ϕ

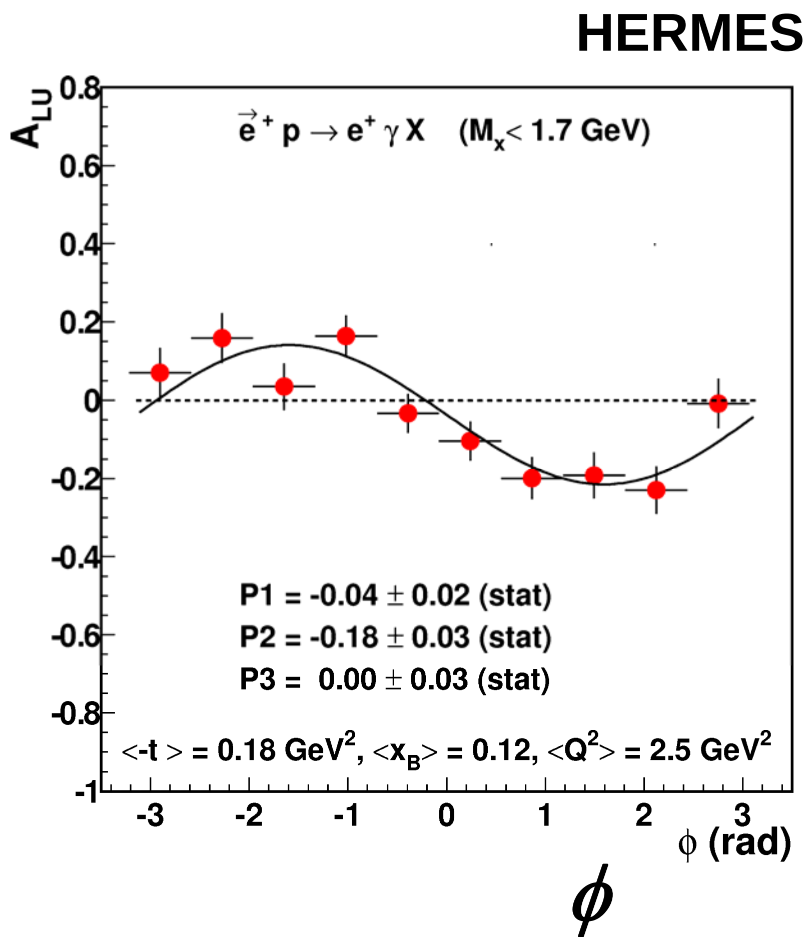
CLAS (JLab)



ϕ

~ 30% effect

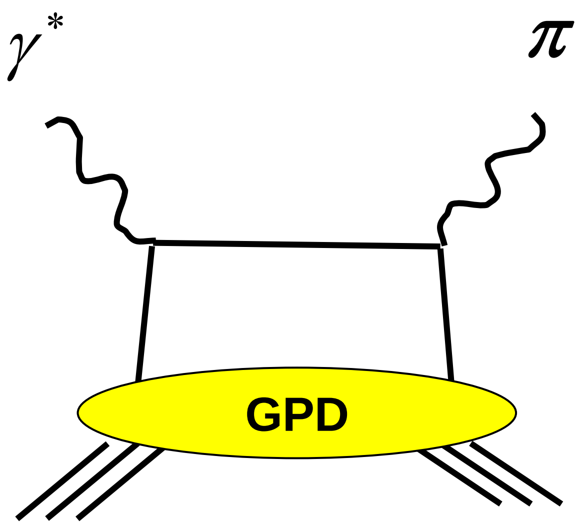
Beam-Spin Asymmetry

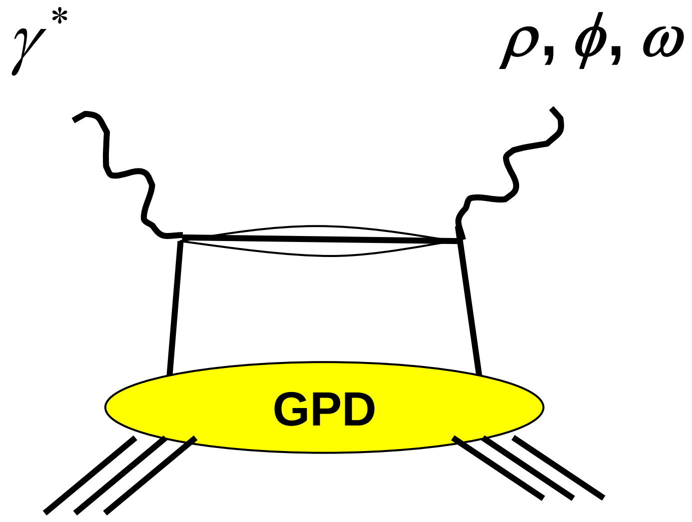


How to extend

Quantum number of final state → **Select different GPD**

Exclusive Meson Productions





Pseudo scalar meson $\tilde{H}^q(x,\xi,t),\ \tilde{E}^q(x,\xi,t)$

Vector meson $H^q(x,\xi,t),\ E^q(x,\xi,t)$

6. Summary

- Lepton scattering is a clean method to explore the nucleon structure. Bjorken x and Q^2 are determined event by event
- Longitudinal Spin -- Helicity Distributions of quarks and gluon
- Transverse Spin -- Sivers Function, Transversity
- Deeply Virtual Compton Scattering and Exclusive Meson Production -- Generalized Parton Distributions
- More results will be obtained from COMPASS, HERMES and Jlab experiments -- complementary to the hadron beam experiments

Acknowledgements to G. Mallot from whom several slides were obtained.