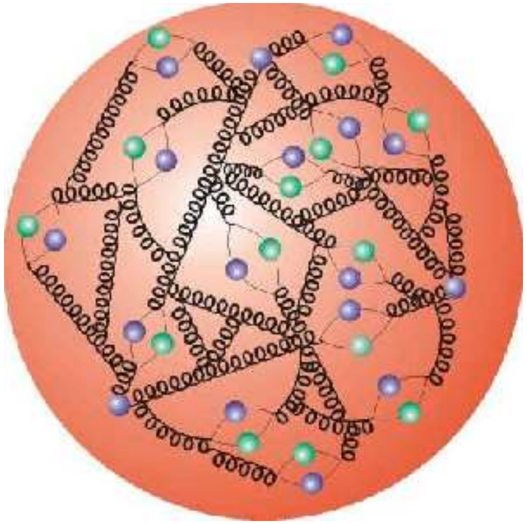
Nucleon structure studies with the COMPASS experiment at CERN



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International Conference on New Frontiers in Physics
Kolymbari, Aug.23-30, 2015

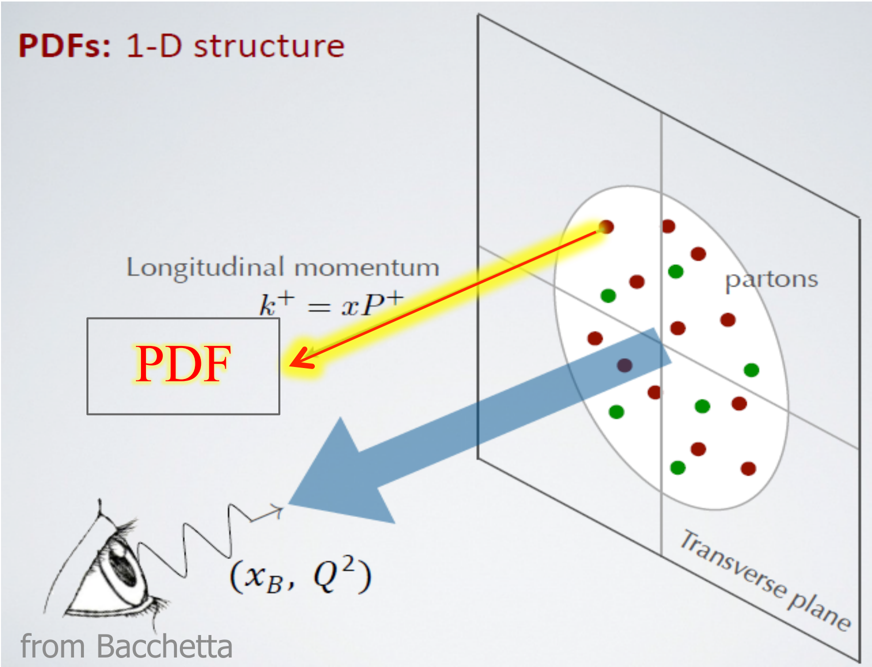
Nucleon structure studies with COMPASS

- COMPASS I
  - Longitudinally polarized DIS and SIDIS
  - Transversely polarized SIDIS
- COMPASS II
  - Deeply-Virtual Compton Scattering (DVCS)
  - Massive lepton pairs from Drell-Yan process
- Not covered in this talk
  - Hadron spectroscopy, etc…
    - Talk by F. Nerling this afternoon

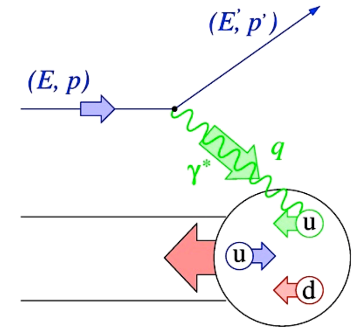
Muon beam

Hadron beams

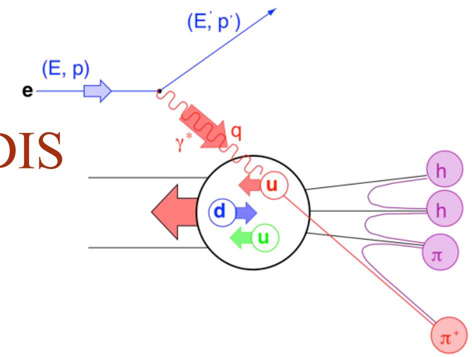
COMPASS – physics and tools 1/2



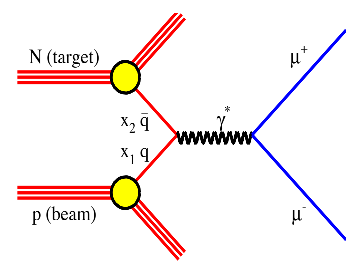
Deep Inelastic Scattering (DIS)



Semi-Inclusive DIS (L or T)

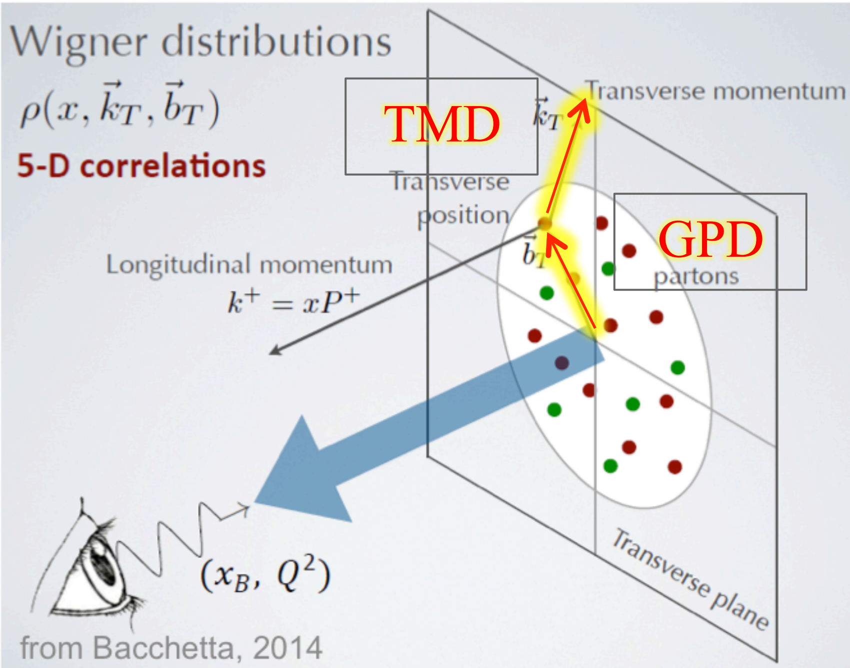


Drell-Yan process

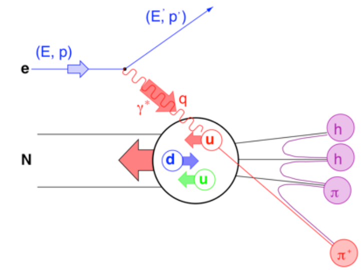


Fundamental non-perturbative quantities:
Parton Distribution Functions PDF (x)

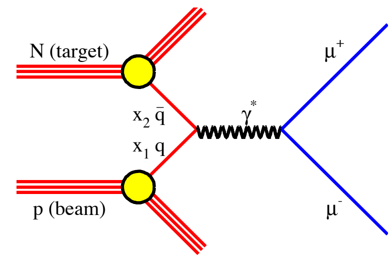
COMPASS – physics and tools 2/2



Semi-Inclusive DIS



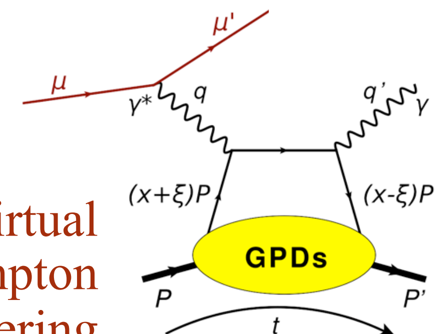
Drell-Yan process



Transversity Momentum Distributions: TMD (x,k_T):
probe the transverse parton momentum dependence

Generalized Parton Distributions : GPD (x,b_T):
probe the transverse parton distance dependence

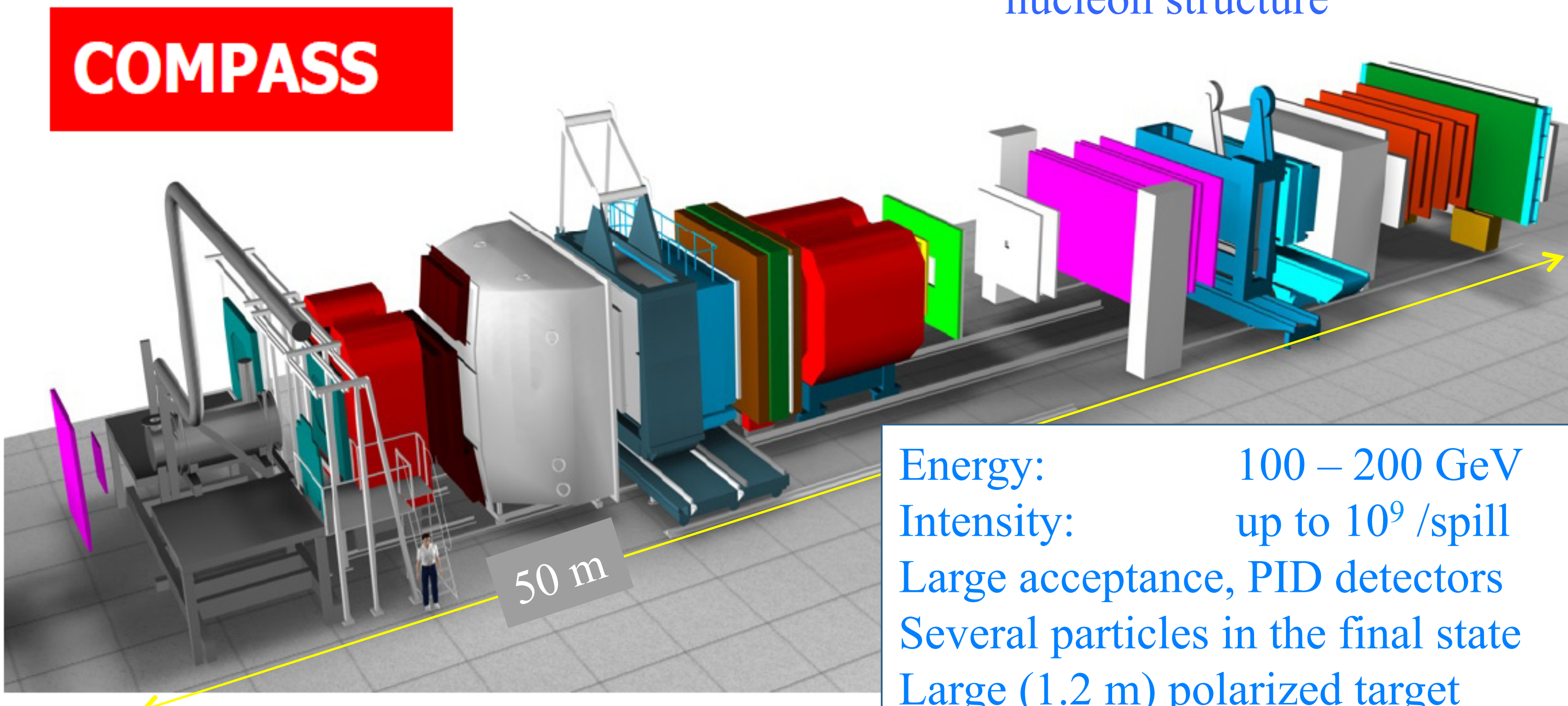
Deeply Virtual Compton Scattering



COMPASS explores the multi-dimensional structure of the nucleon

COMPASS – a fixed target experiment at CERN

- A very versatile setup
- Several beams available: μ^+, μ^-, h+, h^-, e^- => Several ways of probing the nucleon structure

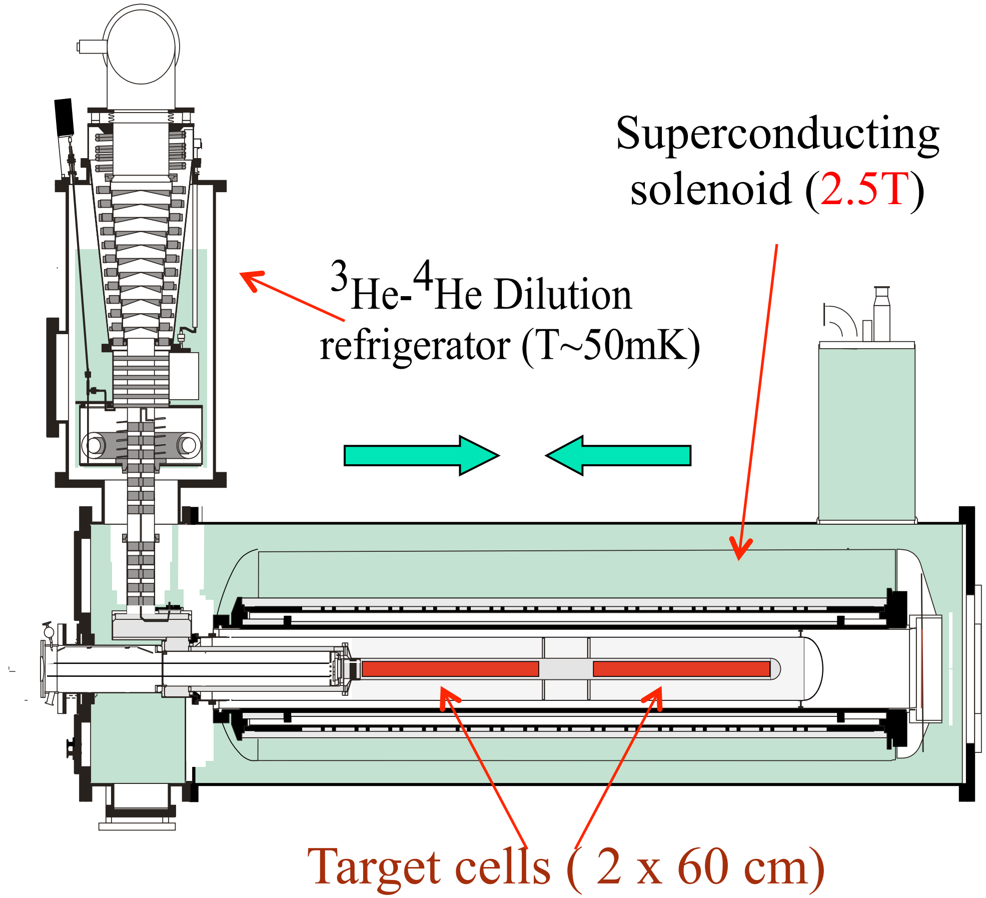


Energy: 100 – 200 GeV
Intensity: up to 10^9 /spill
Large acceptance, PID detectors
Several particles in the final state
Large (1.2 m) polarized target

"Minor" changes to the setup – switch between various physics programs

COMPASS – polarized target

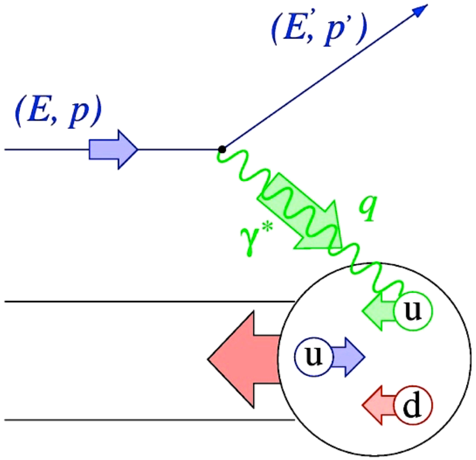
- High magnetic field
- High field uniformity
- Very low temperature
- L or T polarization



Largest polarized target in the world

Deep-Inelastic Lepton Scattering

- Interaction due to one single photon
- Scattering from nearly free partons



$$\frac{d^2\sigma^{\Rightarrow\rightarrow}}{d\Omega dE} + \frac{d^2\sigma^{\Leftarrow\rightarrow}}{d\Omega dE} = \frac{8\alpha^2 E'^2}{Q^4}\left[2W_1 \sin^2\frac{\theta}{2} + W_2 \cos^2\frac{\theta}{2}\right]$$

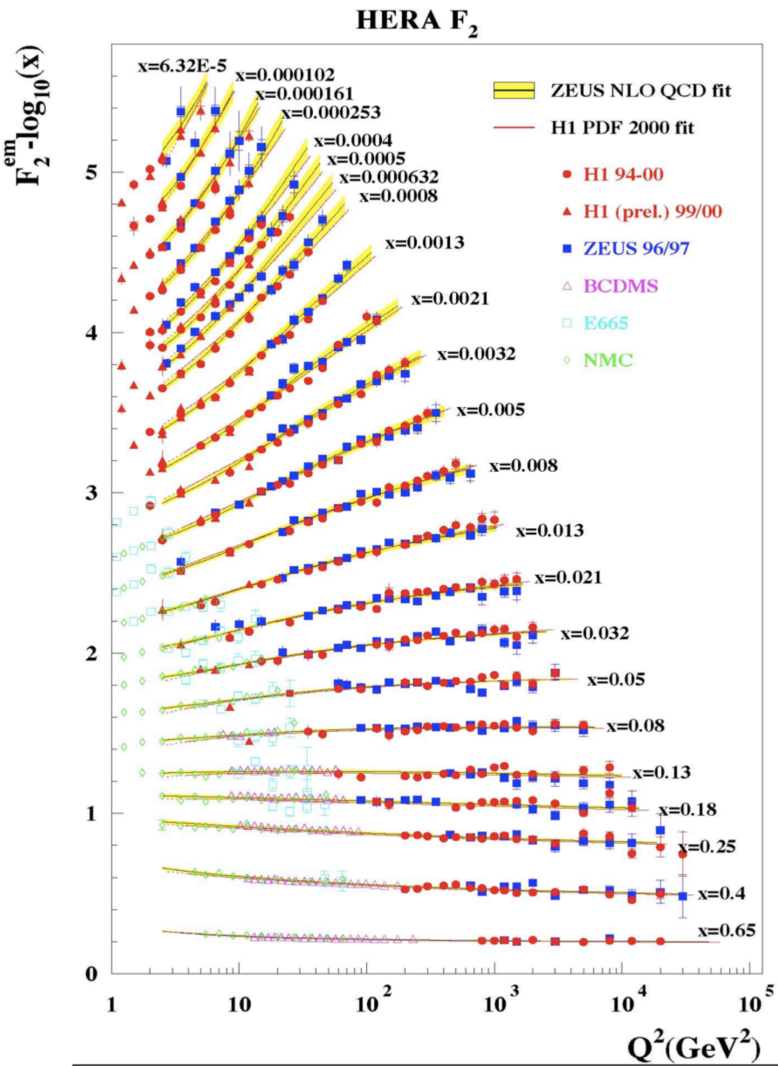
$$\frac{d^2\sigma^{\Rightarrow\rightarrow}}{d\Omega dE} - \frac{d^2\sigma^{\Leftarrow\rightarrow}}{d\Omega dE} = \frac{4\alpha^2 E'}{Q^2 E}\left[M(E + E'\cos\theta)G_1 - Q_2 G_2\right]$$

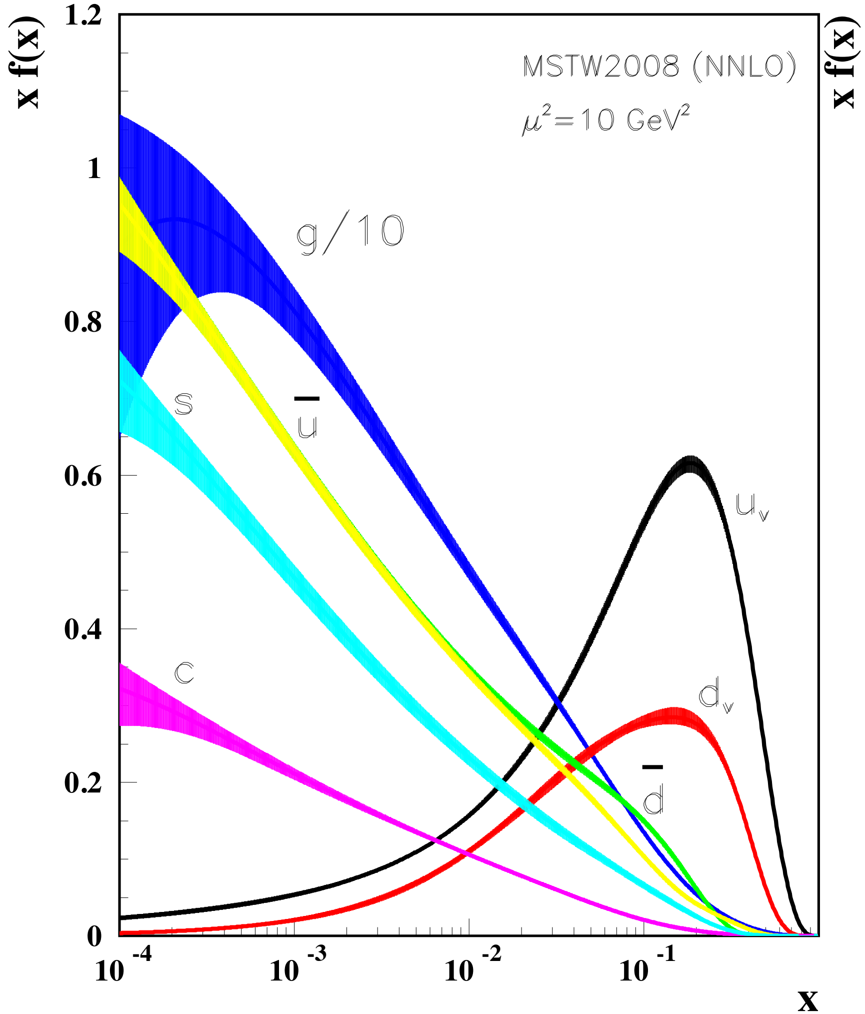
- Structure functions depend on x only (Bjorken, 1968)
  - Q^2 dependence is governed by the QCD evolution

$$\left.\begin{aligned} MW_1(Q^2,\nu) &\rightarrow F_1(x) \\ \nu W_2(Q^2,\nu) &\rightarrow F_2(x) \end{aligned}\right\} \text{Unpol.} \qquad \left.\begin{aligned} M^2\nu G_1(Q^2,\nu) &\rightarrow g_1(x) \\ M\nu^2 G_2(Q^2,\nu) &\rightarrow g_2(x) \end{aligned}\right\} \text{Pol.}$$

Measurements of the DIS structure functions give access to the Parton Distribution Functions (PDF)

Unpolarized measurements and QCD fits





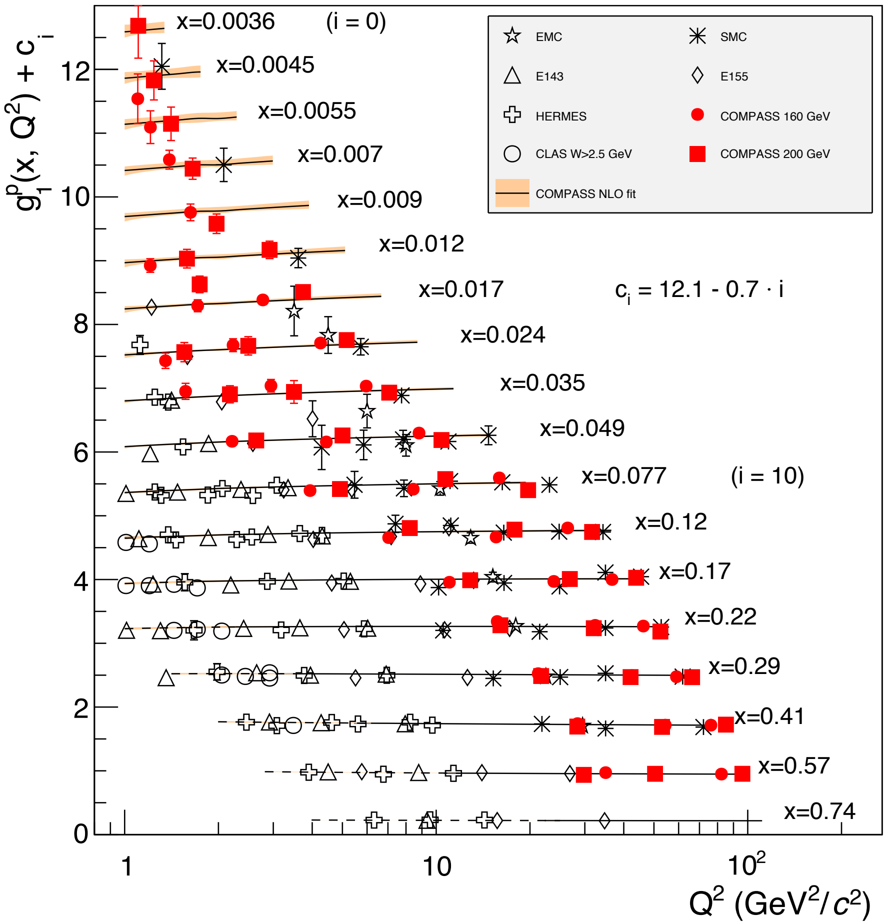
Data span over 5 decades of Q^2 ! –> unpolarized PDFs

Polarized structure function $g_1(x)$ – world data

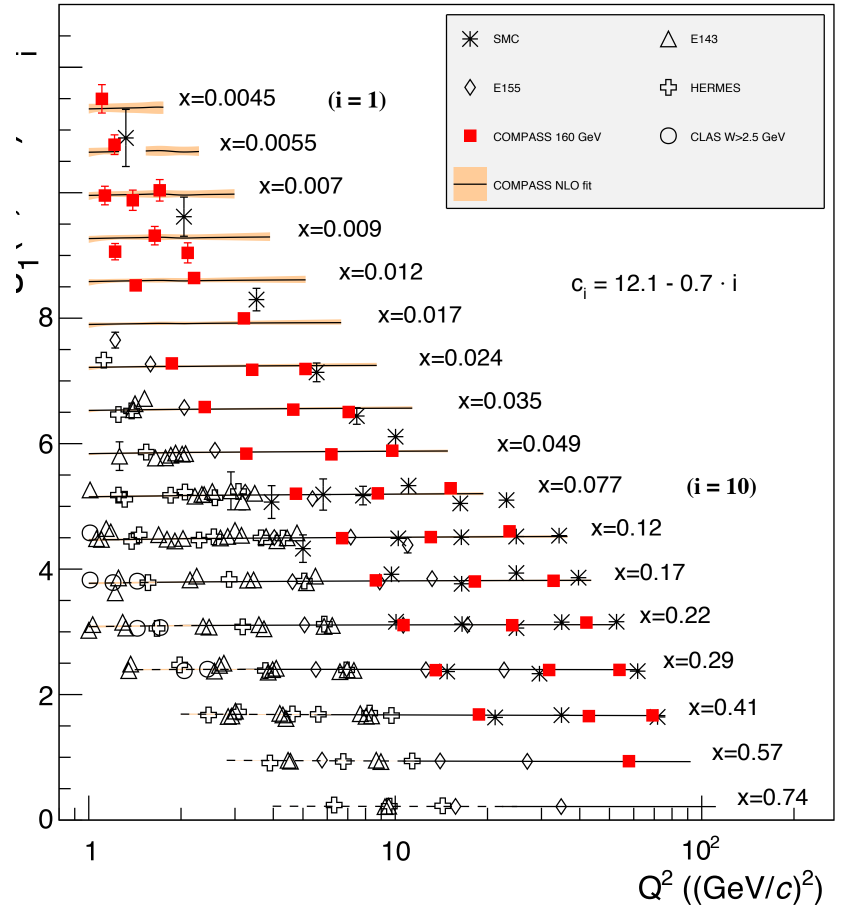
Data are used as input to a global QCD fit

$$g_1(x) = A_1(x)\frac{F_2(x)}{2x(1+R)}$$

PROTON DATA

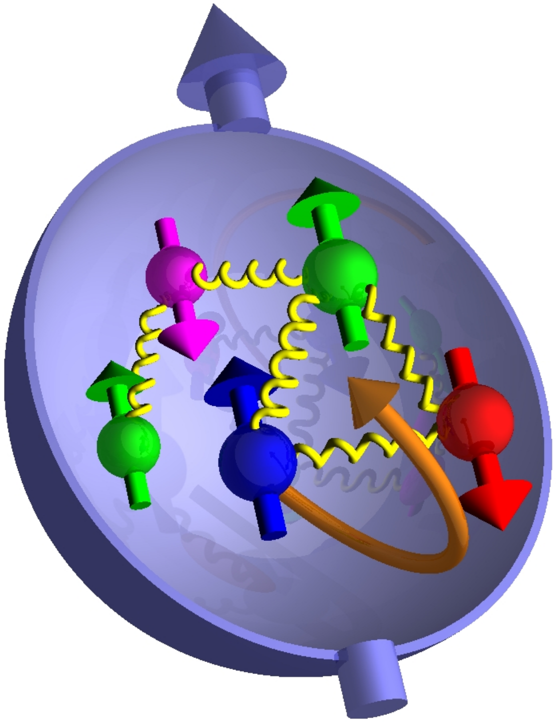


DEUTERON DATA



Reminder: the proton spin problem

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

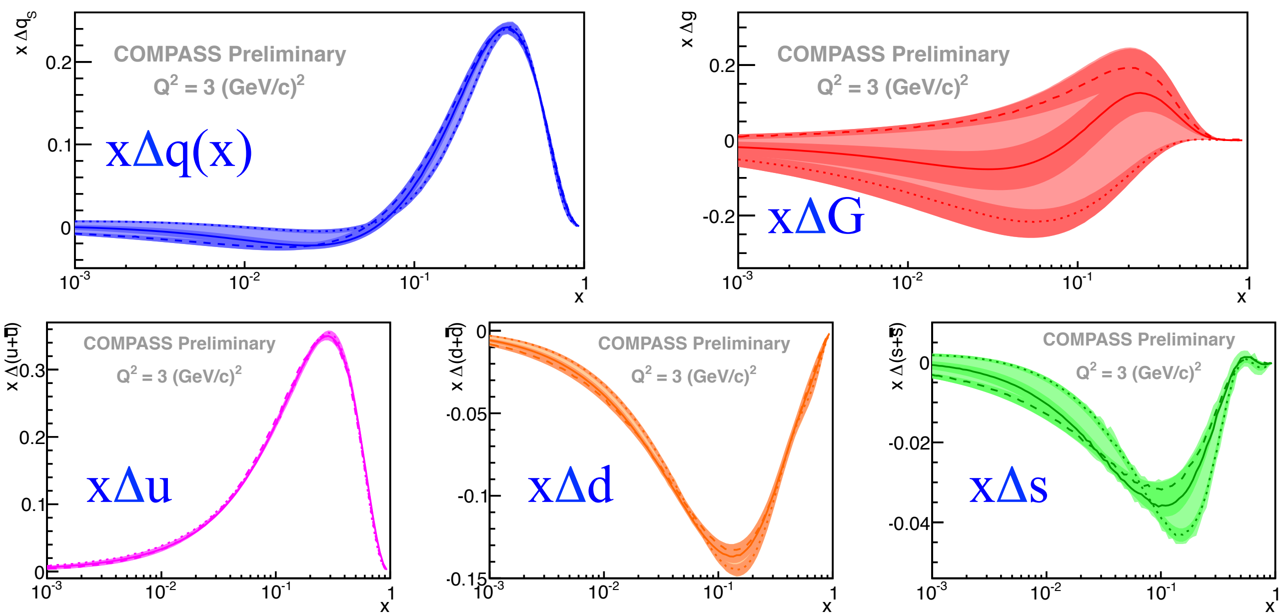


Naive quark model	: $\Delta\Sigma = 1.0$
Relativistic quark model	: $\Delta\Sigma \approx 0.6$
Experiment	: $\Delta\Sigma \approx 0.3$

Physics goals: Improve accuracy on $\Delta\Sigma$, measure ΔG, try to access L

COMPASS NLO pQCD fit to $g_1(x)$

- Inputs: world data, functional forms, assume SU(3)
  - ▸ ΔG is determined through DGLAP evolution (NLO)



Integral values:

Quark spin contribution $\Delta\Sigma = 0.30 \pm 0.04$

Gluon spin contribution: large uncertainties, even sign not clear!

Strange quark contribution is negative ! ($\Delta s = -0.10$)

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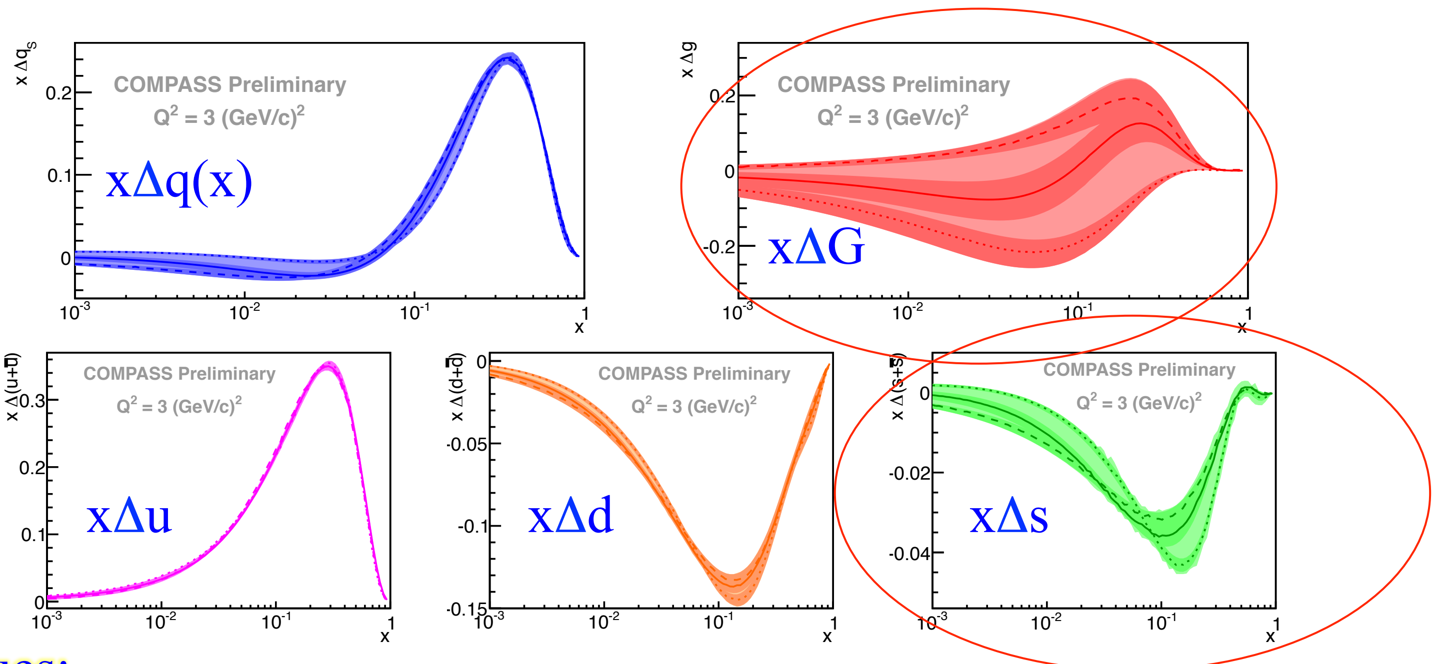
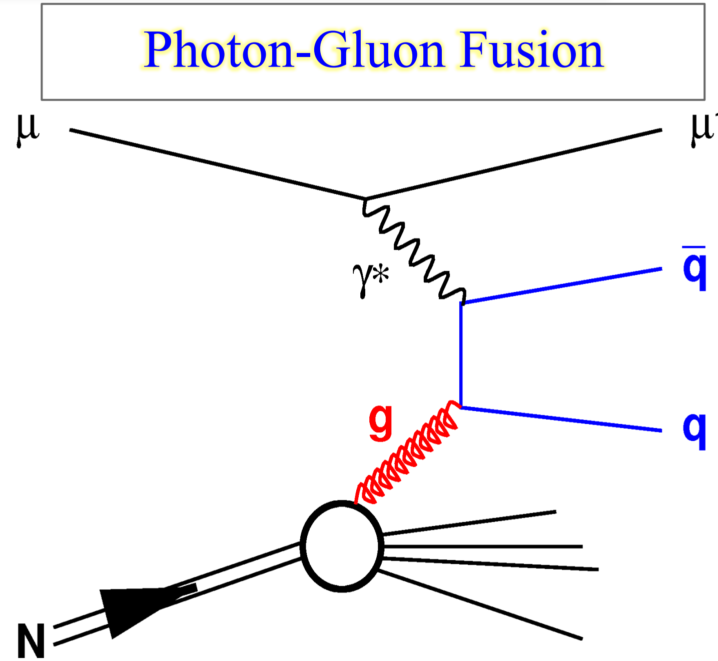


Integral values:

Quark spin contribution $\Delta\Sigma = 0.30 \pm 0.04$
Gluon spin contribution: large uncertainties, even sign not clear!
Strange quark contribution is negative ! ($\Delta s = -0.10$)

Contribution of gluons to the nucleon spin

- Gluons: spin 1, no charge
- Tool : Photon-Gluon Fusion (PGF)



- Identify the PGF process?

1. Detect charmed quarks: clean signature, but limited statistics
   "Open Charm" method

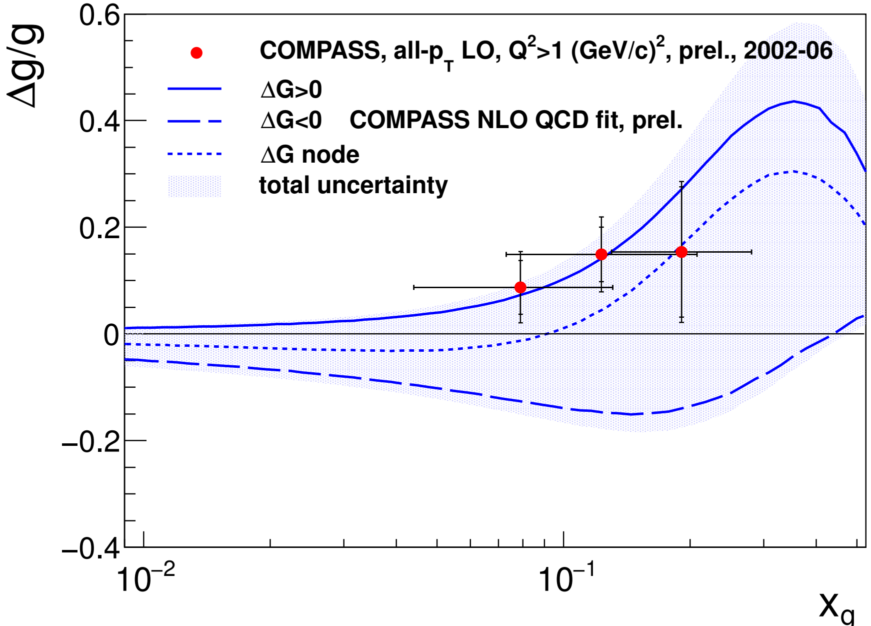
$$D^0 \rightarrow K^-\pi^+ \text{ and } D^* \rightarrow D^0\pi$$

2. Detect light quarks: high statistics, but large physical background
   "Hadron production" method

Rely on a Monte-Carlo estimate of the background

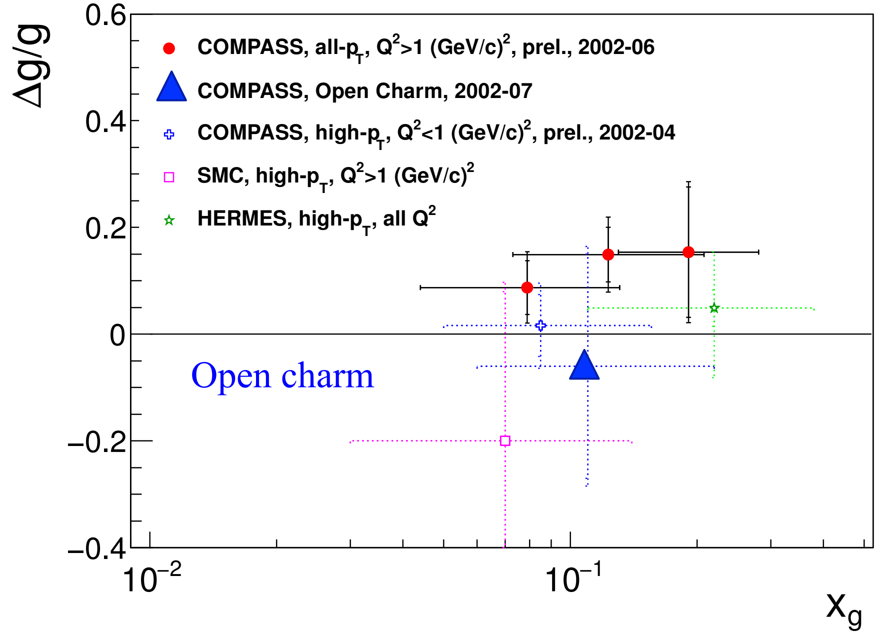
ΔG/G results

Hadron production



$\Delta G/G = 0.113 \pm 0.038$ (stat)± 0.035(sys)

World direct ΔG/G extraction (LO)



Data suggest positive value of ΔG/G (2σ)
Most precise direct measurements today

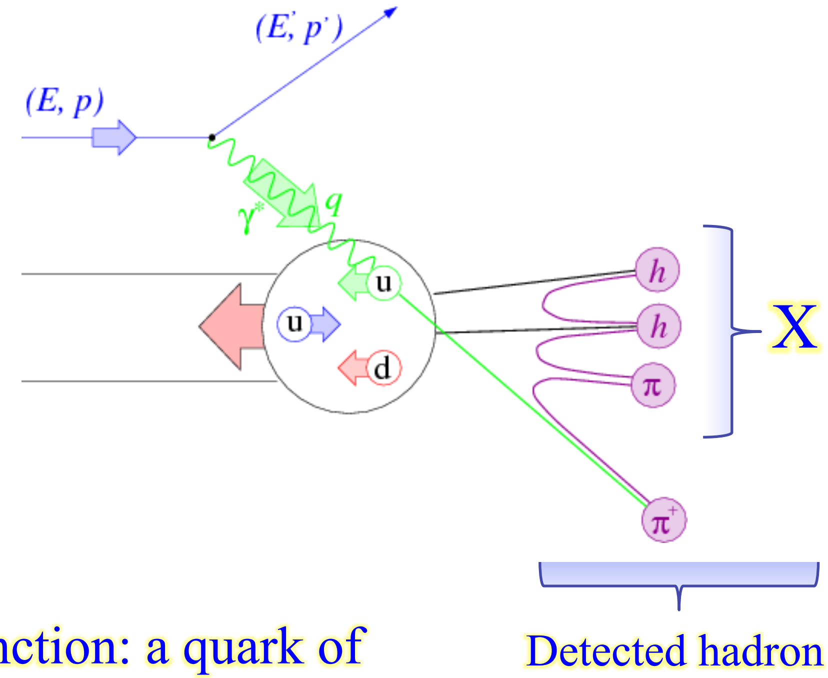
Polarized Semi-Inclusive DIS (SIDIS)

Polarized PDF

$$A_1^h = \frac{\sum_f e_f^2 \boxed{\Delta q(x,Q^2)} D_{1f}^h(z,Q^2)}{\sum_f e_f^2 q(x,Q^2) D_{1f}^h(z,Q^2)}$$

Un-polarized PDF

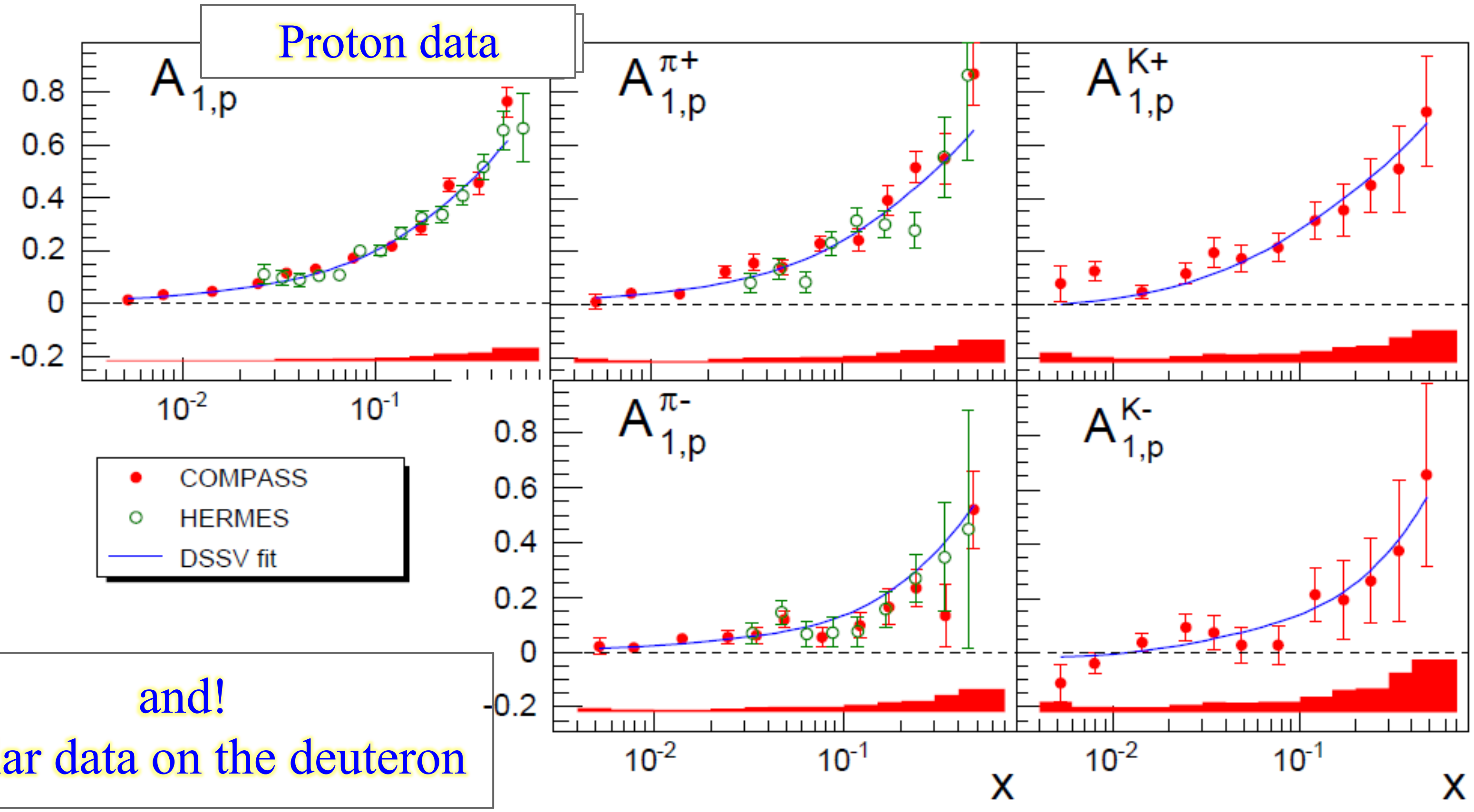
Fragmentation function: a quark of flavor *f* becomes a hadron *h*



$$z = \frac{E_h}{E - E'}$$

Polarized SIDIS is sensitive to the shape of the polarized PDFs in the nucleon: $\Delta u(x)$, $\Delta d(x)$, $\Delta s(x)$

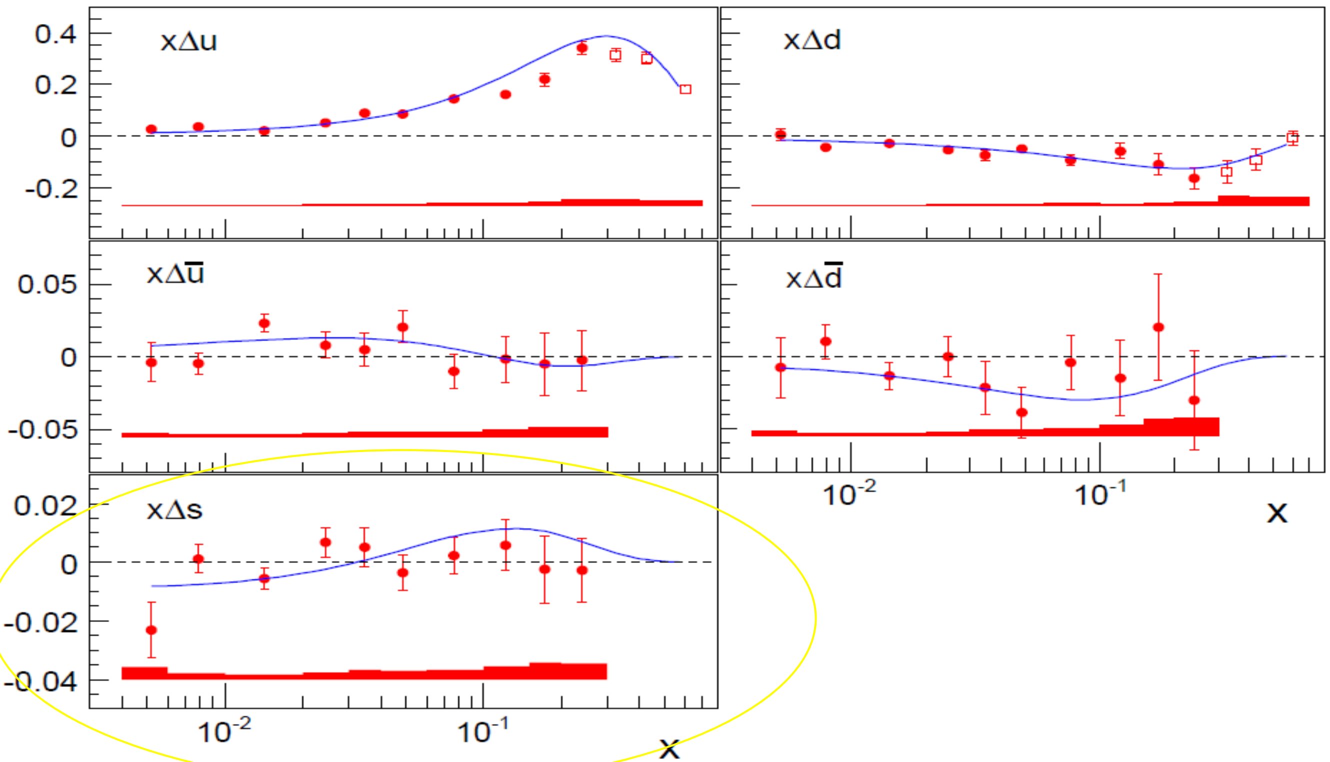
SIDIS asymmetries: World proton data



and!
similar data on the deuteron

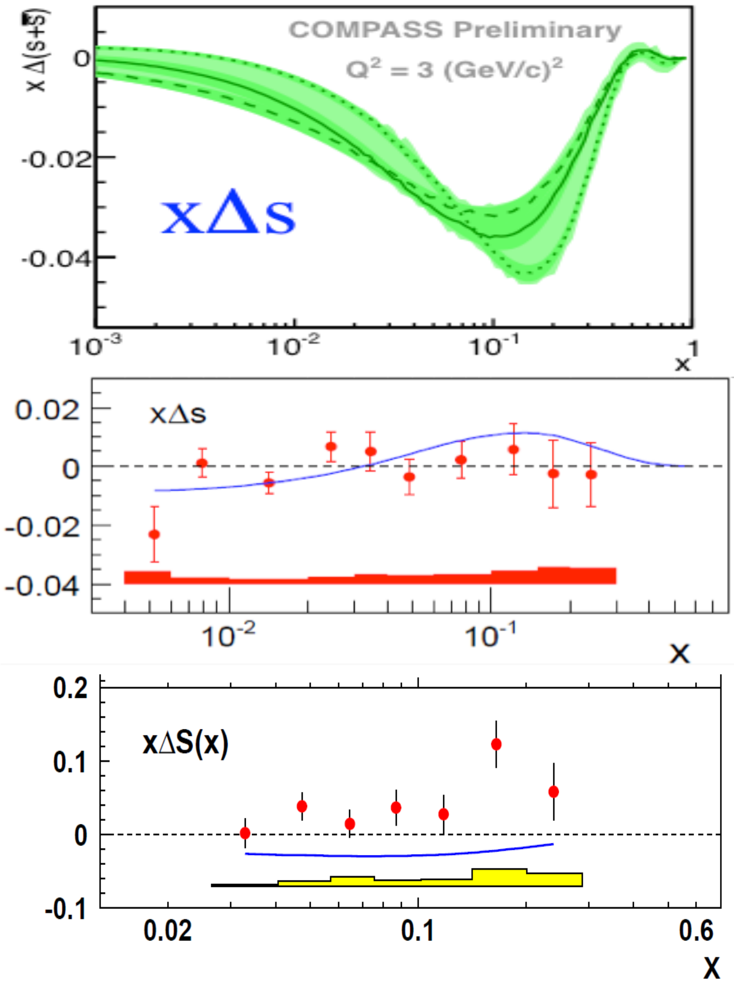
LO QCD fit to all 10 asymmetries -> simultaneous extraction of : $\Delta u(x)$, $\Delta d(x)$, $\Delta s(x)$ and $\Delta\bar{u}(x)$, $\Delta\bar{d}(x)$, $\Delta\bar{s}(x)$

Polarized PDFs as determined by pSIDIS



$\Delta u(x)$, $\Delta d(x)$, $\Delta \bar{u}(x)$, $\Delta \bar{d}(x)$: as expected from pDIS
However: $\Delta s(x)$ is compatible with zero !

The strange quark puzzle



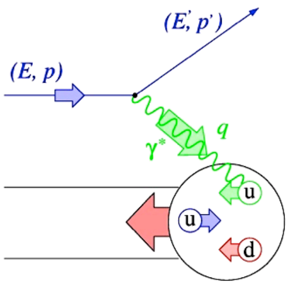
Compass DIS fit
$\Delta s = -0.09 \pm 0.01 \pm 0.01$

COMPASS SIDIS
$\Delta s = -0.01 \pm 0.01 \pm 0.02$

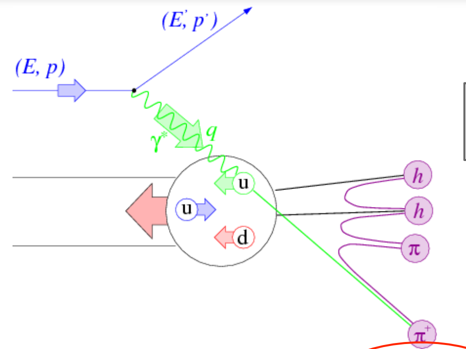
HERMES SIDIS
$\Delta s = +0.037 \pm 0.019 \pm 0.027$

Large disagreement between DIS QCD fits and SIDIS

Δs puzzle: what about Fragmentation Functions?



DIS



SIDIS

$$A_1 = \frac{\sum_f e_f^2 \Delta q(x,Q^2)}{\sum_f e_f^2 q(x,Q^2)}$$

$$A_1^h = \frac{\sum_f e_f^2 \Delta q(x,Q^2) D_{1f}^h(z,Q^2)}{\sum_f e_f^2 q(x,Q^2) D_{1f}^h(z,Q^2)}$$

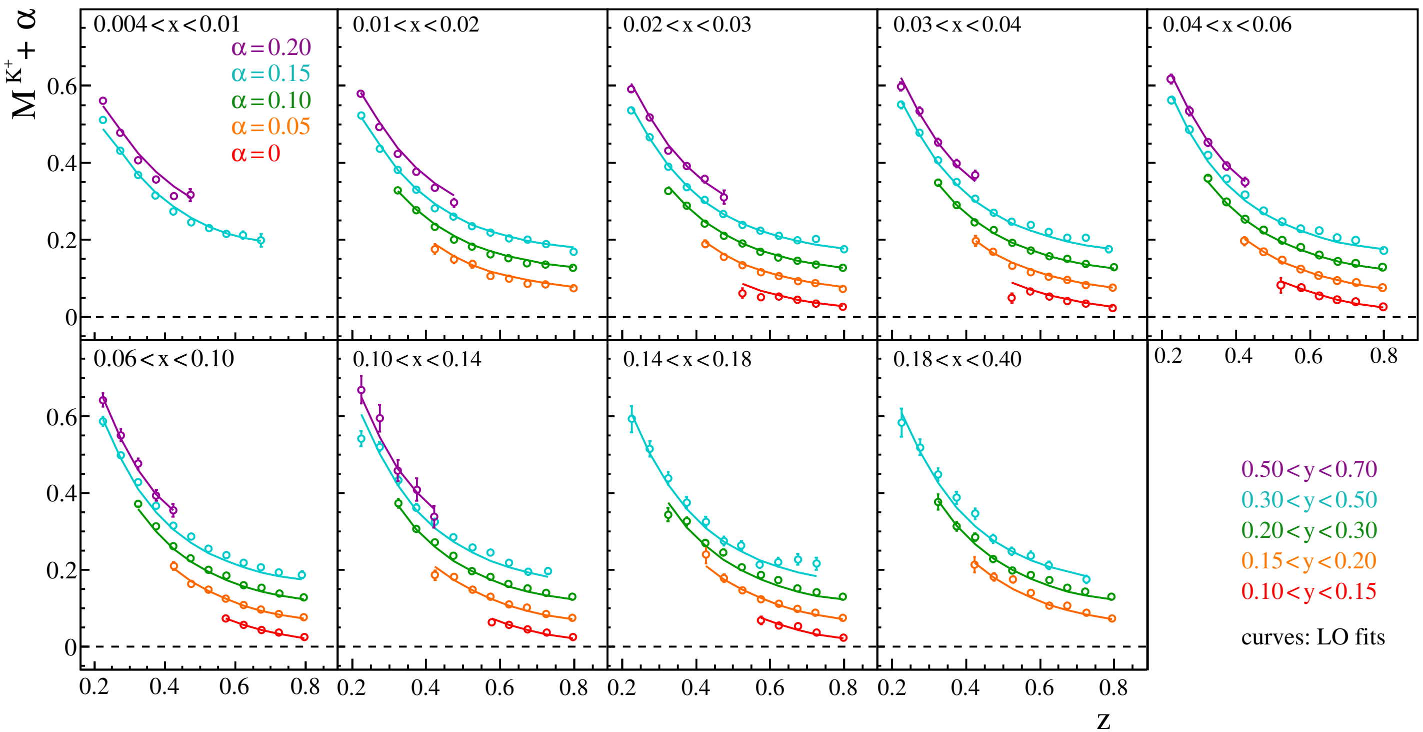
- An independent measurement of $D_1(z,Q^2)$: hadron multiplicities

$$M^K(x,y,z) = \frac{N^K(x,y,z)/\Delta z}{N^{DIS}(x,y)}$$

$$M^K = \frac{\sum_f e_f^2 q(x,Q^2) D_f^K(z,Q^2)}{\sum_f e_f^2 q(x,Q^2)}$$

Fragmentation Functions can be determined through a QCD fit to pion and kaon multiplicities

Kaon (K^+) multiplicities $M^K(z)$: in 9 x bins



$$M^{K+}(x,z,Q^2) = \frac{2\bar{s}D_{str} + 4(u+d)D_{fav} + (u+d+5(\bar{u}+\bar{d})+2s)D_{unf}}{5(u+d+\bar{u}+\bar{d})+2(s+\bar{s})}$$

$$M^{K-}(x,z,Q^2) = \frac{2sD_{str} + 4(\bar{u}+\bar{d})D_{fav} + (5(u+d)+\bar{u}+\bar{d}+2\bar{s})D_{unf}}{5(u+d+\bar{u}+\bar{d})+2(s+\bar{s})}$$

$$zD_i(z, Q_0^2) = N_i z^{\alpha_i}(1-z)^{\beta_i}(1+\gamma_i(1-z)^{\delta_i}) \quad i = fav$$

$$zD_i(z, Q_0^2) = N_i z^{\alpha_i}(1-z)^{\beta_i} \quad i = str, unf, glu$$

Similar results for K^-

QCD (LO) fit to K^+ and K^- kaon multiplicities -> FF

Kaon Fragmentation Function (COMPASS fits)

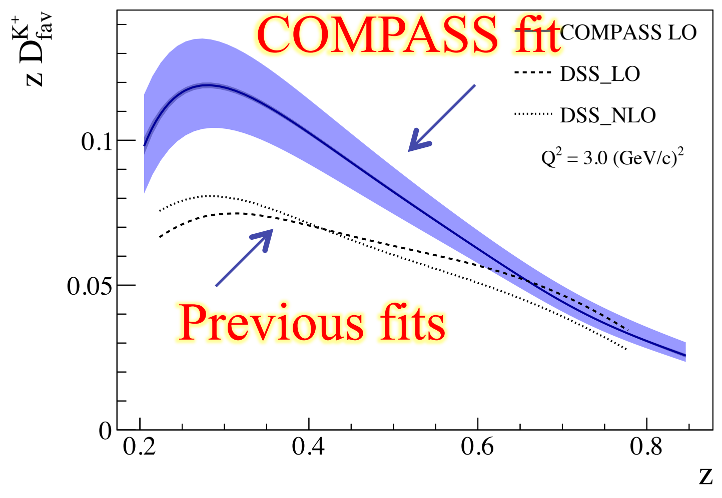
Favoured $D_{fav}^{K} = D_{fav}^{K\pm} = D_{u}^{K+} = D_{\bar{u}}^{K-}$

Unfavoured $D_{unf}^{K} = D_{unf}^{K\pm} = D_{\bar{u}}^{K+} = D_{s}^{K+} = D_{u}^{K-} = D_{\bar{s}}^{K-} = D_{d}^{K\pm} = D_{\bar{d}}^{K\pm}$

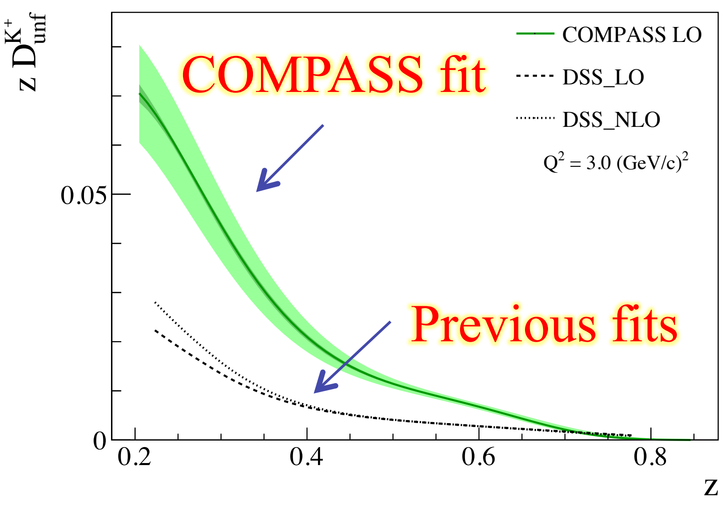
Strange $D_{str}^{K} = D_{str}^{K\pm} = D_{\bar{s}}^{K+} = D_{s}^{K-}$

$K^{+} = (u,\bar{s})$
$K^{-} = (\bar{u},s)$

Favored FF



Unfavored FF



Favored and unfavored FF are well determined
Strange FF : to be released in the next weeks

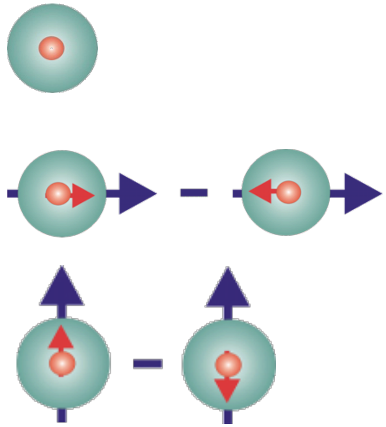
Transversity structure functions

- Transversity?
  - Transversely polarized quarks in a transversely polarized nucleon (to the direction of the virtual photon)
  - Third distribution function (leading twist)

Momentum distribution $F_1(x)$

Helicity distribution $g_1(x)$

Transversity distribution $h_1(x)$



$$A_{\text{Coll}} = \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot \Delta_T^0 D_q^h(z, p_T^h)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h(z, p_T^h)}$$

The three PDF fully describe the longitudinal momentum and spin structure of the nucleon

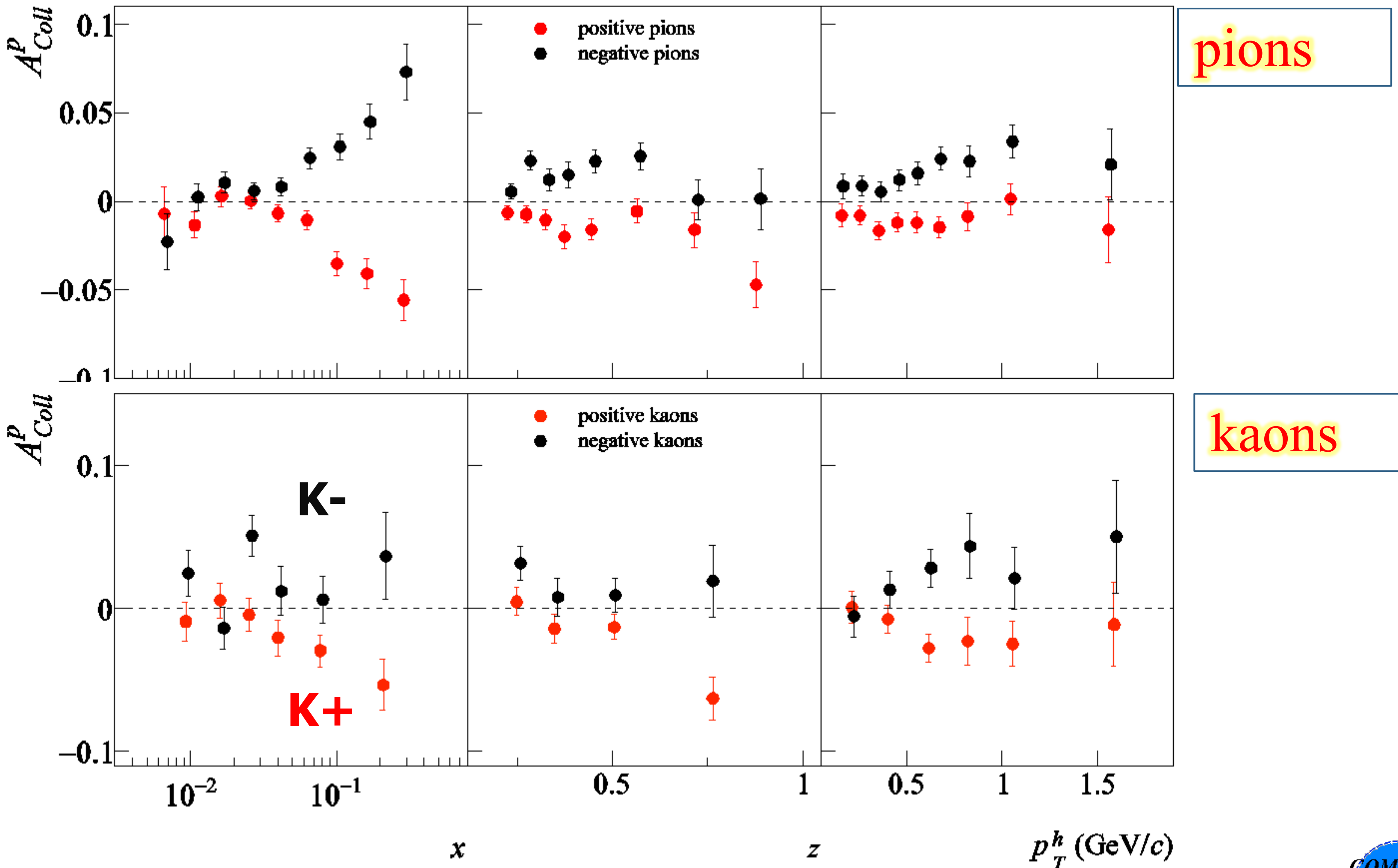
Transverse Momentum Dependent PDFs

"TMDs"

nucleon polarization

quark polarization	U	L	T
U	f_1 – ***number density*** q		$f_{1T}^{\perp}$ – ***Sivers***
L		g_1 – ***helicity*** Δq	g_{1T}
T	$h_1^{\perp}$ – ***Boer-Mulders***	$h_{1L}^{\perp}$	h_1 – ***transversity*** $h_{1T}^{\perp}$ – ***pretzelosity***

Transverse (Collins) asymmetries



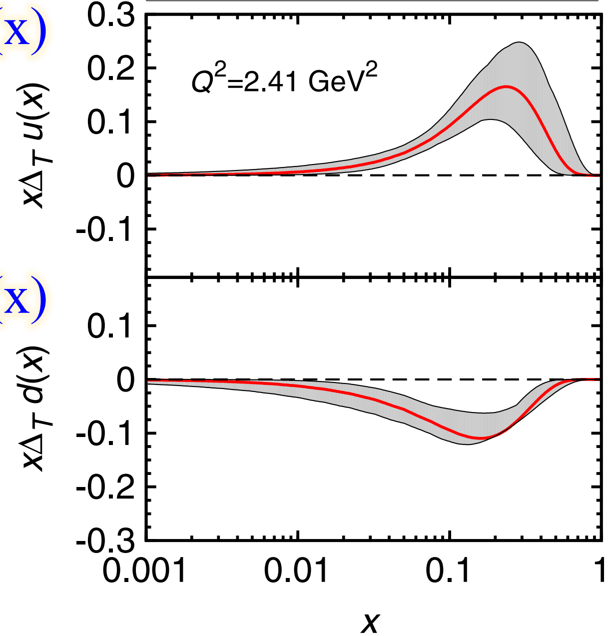
Transversity QCD fit

Anselmino et al. Phys. Rev. D87 (2013) 094019

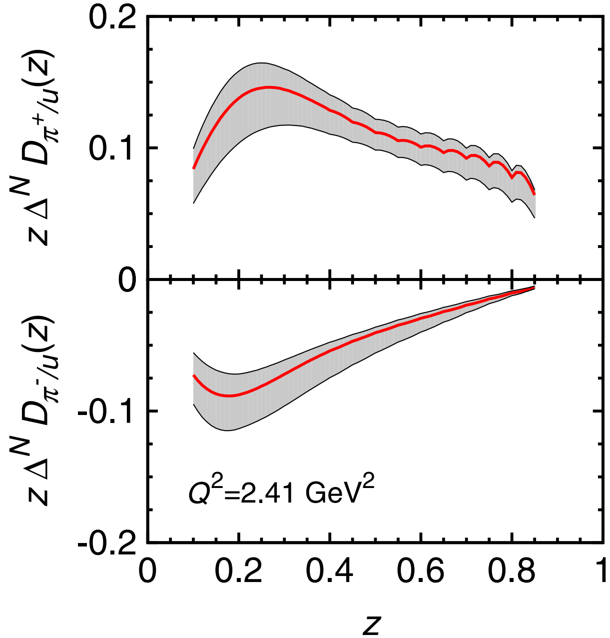
Transversity PDFs

$x\Delta_T u(x)$

$x\Delta_T d(x)$



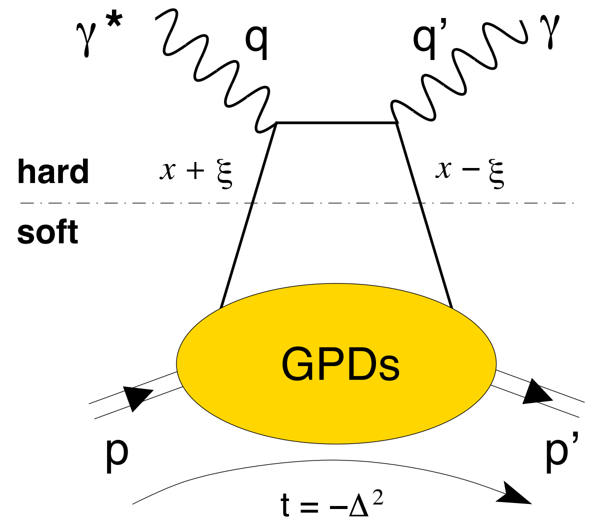
Collins FFs



QCD fits : simultaneous extraction of both transversity PDFs and Transversity (Collins) FFs

Generalized Parton Distributions (GPD)

- GPD: correlation between the long. momentum x and the transverse position b_T
- Measured in exclusive reactions



- 4 GPDs:

  $H, \widetilde{H}$ conserve nucleon helicity

  $E, \widetilde{E}$ flip nucleon helicity

Depend on 3 variables:
x (not x_B), ξ, t

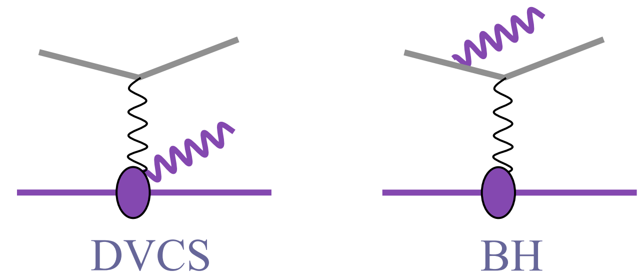
- Unpolarized target: GPD H
- Polarized target: GPD E

Measurement of H probes the transverse size of the nuucleon as as a function of the parton longitudinal momentum

DVCS and BH cross section for μ^+ and μ^-

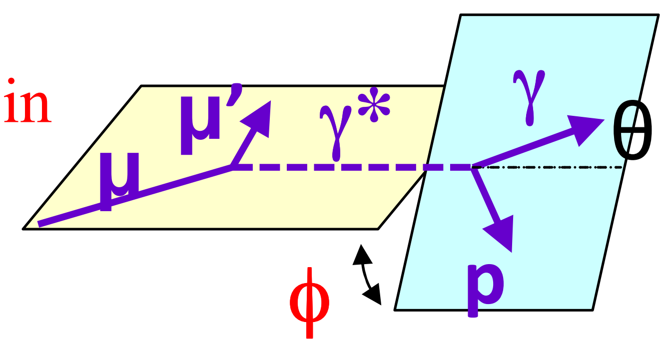
Cross section for $\mu p \to \mu p \gamma$

DVCS and BH (known) processes:



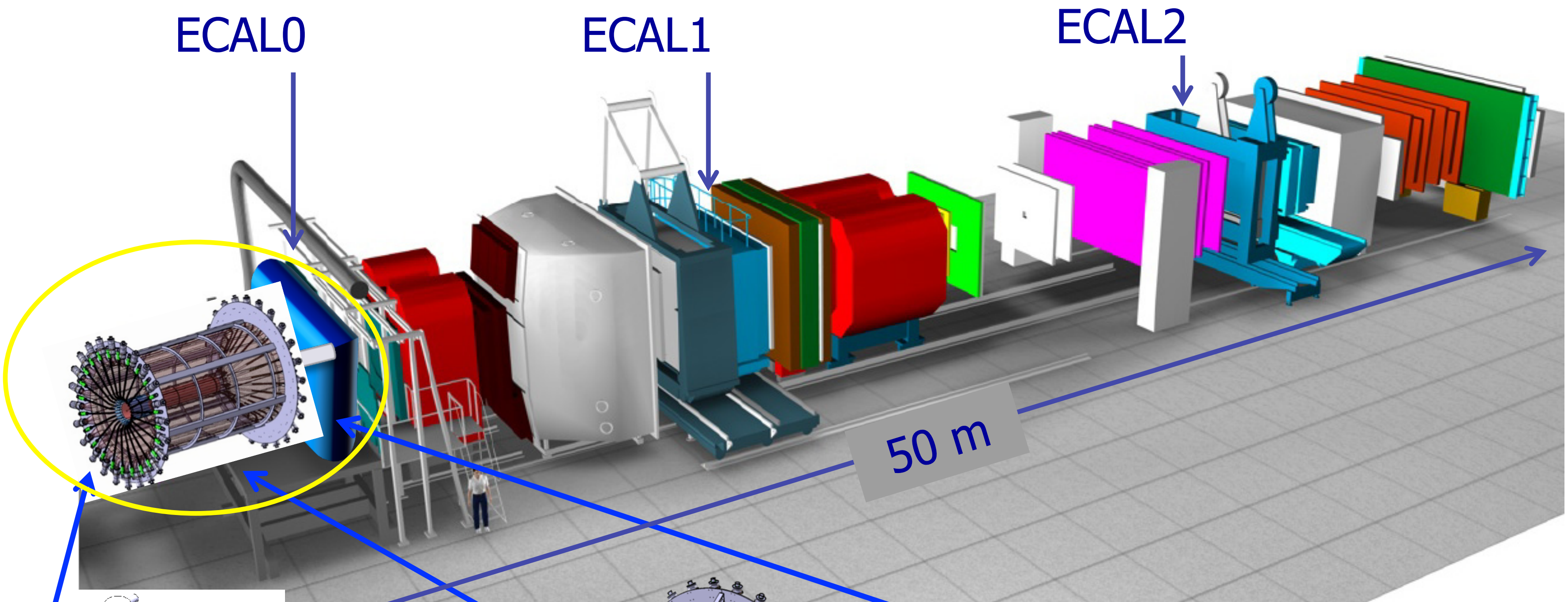
$$\boxed{d\sigma = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu\, d\sigma^{DVCS}_{pol} + e_\mu a^{BH} \mathrm{Re}\, A^{DVCS} + e_\mu P_\mu a^{BH}\, \mathrm{Im}\, A^{DVCS}}$$

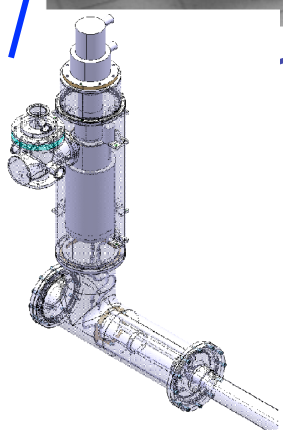
- COMPASS beams: opposite charge/spin
  - Charge-and-Spin Sum
  - Charge-and-Spin Difference



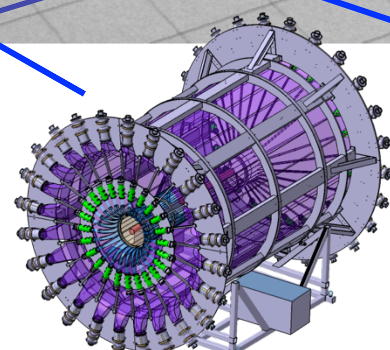
Access both Re(H) and Im(H) by measuring the Sum and the Difference
S

DVCS run – main new equipment

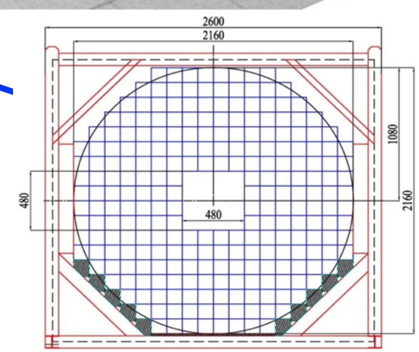




2.5 m long LH target



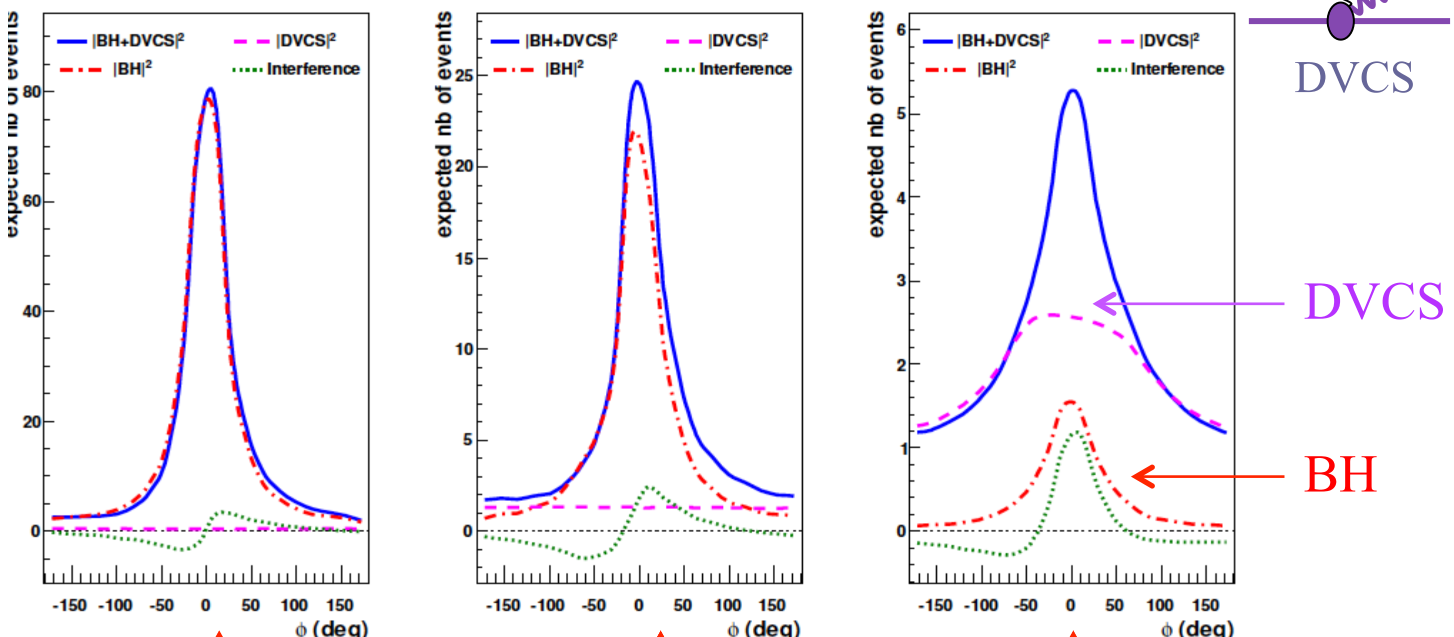
4.0 m longTime-Of-Flight detector: 24 inner and 24 outer slabs

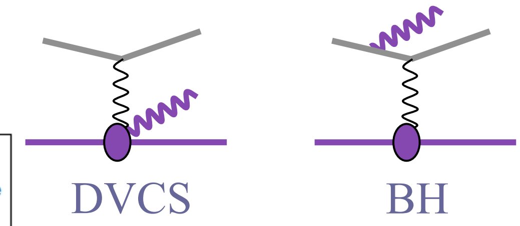


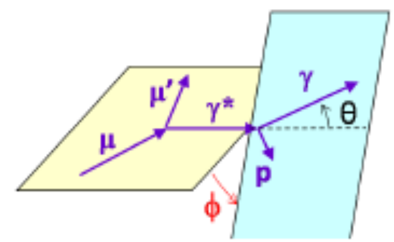
2x2 m^2 electromagnetic calorimeter, ECAL0

DVCS – the COMPASS x_B regions – SIMULATION

$0.005 < x_B < 0.01$ $\quad$ $0.01 < x_B < 0.03$ $\quad$ $x_B > 0.03$







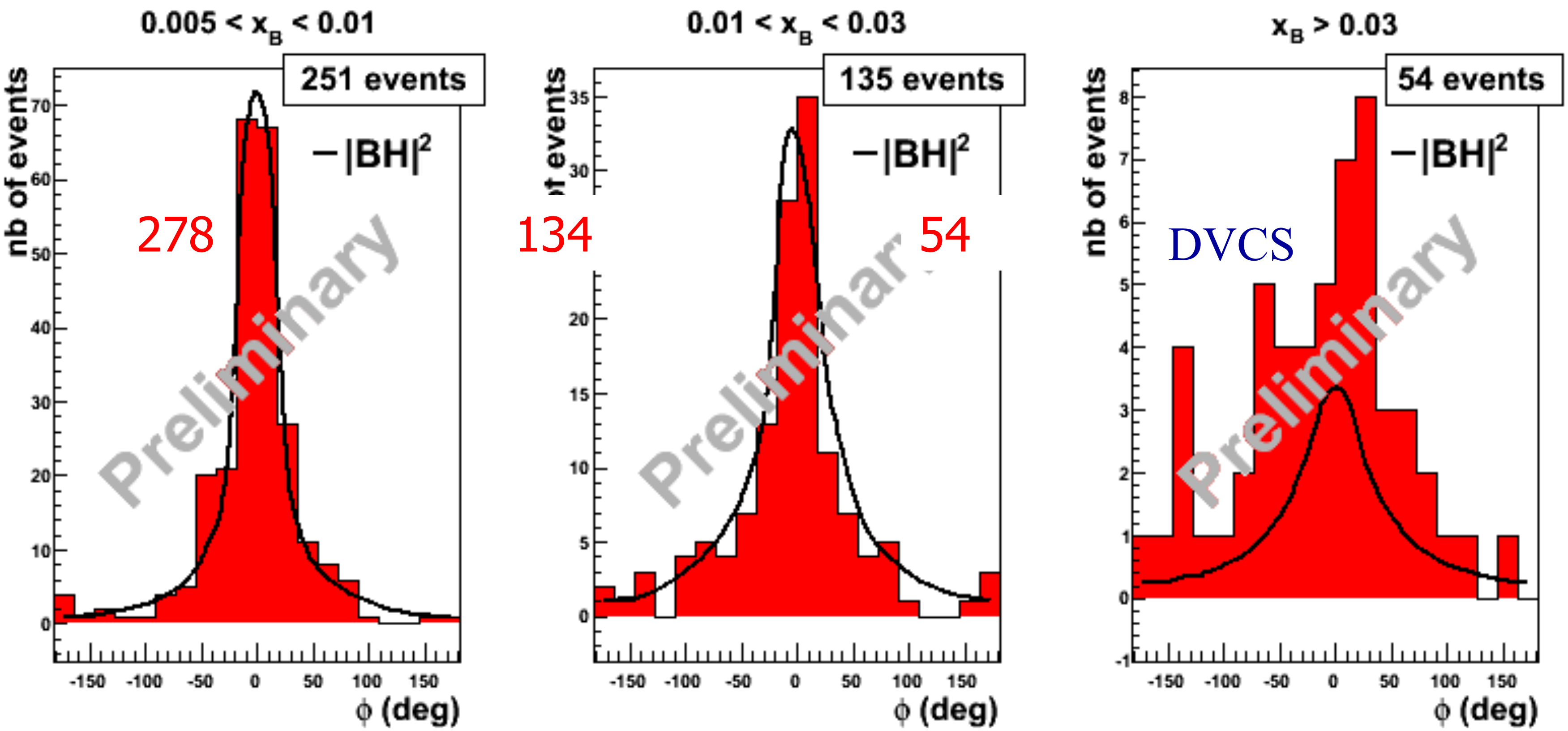
$$d\sigma \propto \left|A^{BH}\right|^2 + \text{Interference} + \left|A^{DVCS}\right|^2$$

Large relative amplitude variation as a function of x

DVCS – the COMPASS x_B regions – REAL DATA

- Test run – 4 days with a 40 cm long H_2 target

2009 data



BH dominance | Interference | DVCS dominance

Successful feasibility measurement

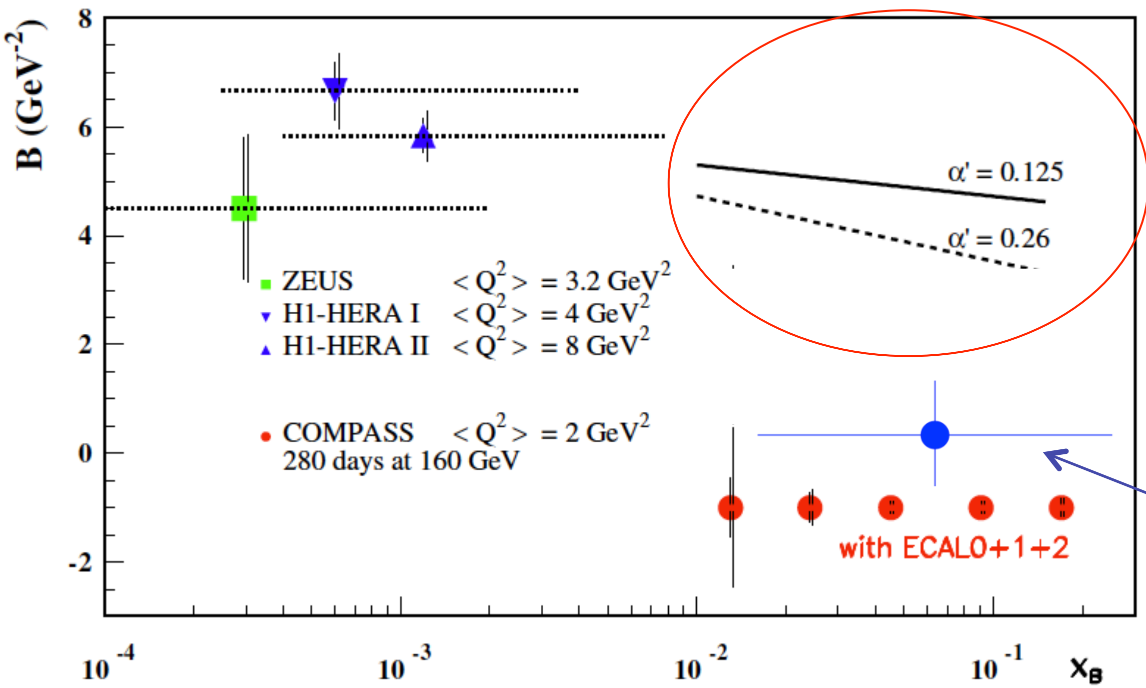
DVCS – SUM of μ^+ and μ^- cross sections

$$S_{CS,U} \equiv d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow}) \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + K s_1^{Int} \sin\phi$$

Integration over ϕ and BH subtraction $\rightarrow$ $d\sigma^{DVCS}/dt \sim \exp(-B|t|)$

$$r_\perp^2(x_B) = 2B(x_B)$$

Expected statistics in 2x6 months of data taking



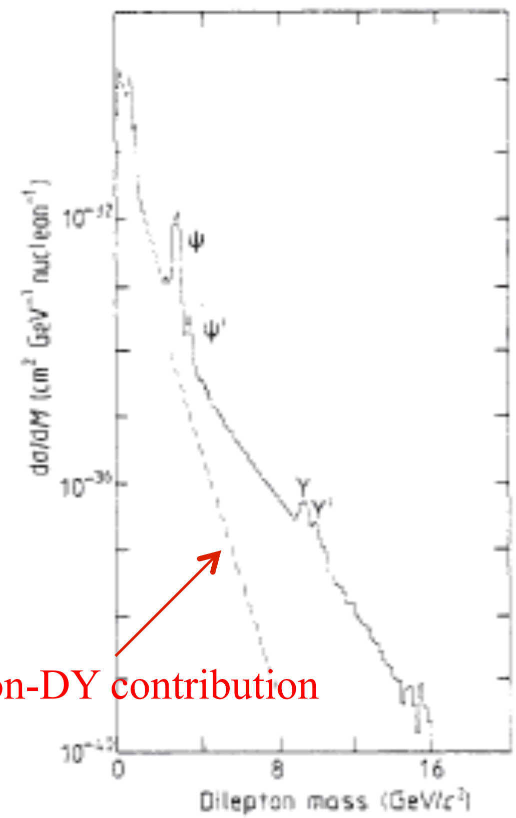
COMPASS domain

2012 test run (4wks)

Measurements of GPD: nucleon "tomography"

Polarized (+ unpolarized) Drell-Yan measurements

Ito et al. PRD 23(1981)604.
(from Kenyon, RPP, 1982)
FERMILAB:



- Drell-Yan cross section:

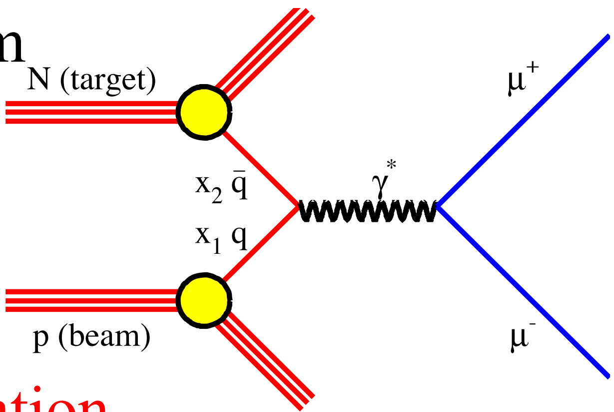
$$\frac{d^2\sigma}{dM^2 dx_F} = \frac{4\pi\alpha^2}{9M^4}\frac{x_1 x_2}{x_1+x_2}\sum_a e_a^2\left[q_a(x_1)\bar{q}_a(x_2)+\bar{q}_a(x_1)q_a(x_2)\right]$$

- Features (parton model):
  - Cross section depends on $\tau = M^2/s$
  - Convolution of quark and antiquark PDFs
  - Can be used to determine PDFs in π, K, p̄
  - Transverse momentum of μμ pair is small
  - No fragmentation process
- Confirmed in QCD
  - Assumptions: factorization

Tung-Mow Yan (SLAC, 1998): *"The process has been so well understood that it has become a powerful tool for precision measurements and new physics"*

COMPASS exclusive setup advantages

- Hadron (pion + kaon + antiproton) beam
- Transversely polarized NH_3 target
- Large muon angular acceptance



- With a negative pion beam: ū/u annihilation

$$\pi^- \vec{p} \rightarrow \mu^+ \mu^- X$$

- COMPASS acceptance
  - Dominated by valence quarks ($x \geq 0.1$)

COMPASS: only place in the world with valence antiquark beams

DY (polarized) cross section expansion

- Full formalism for two spin ½ hadrons
- COMPASS: access 4 TMDs:
  - Boer-Mulders, Sivers, Pretzelosity, Transversity

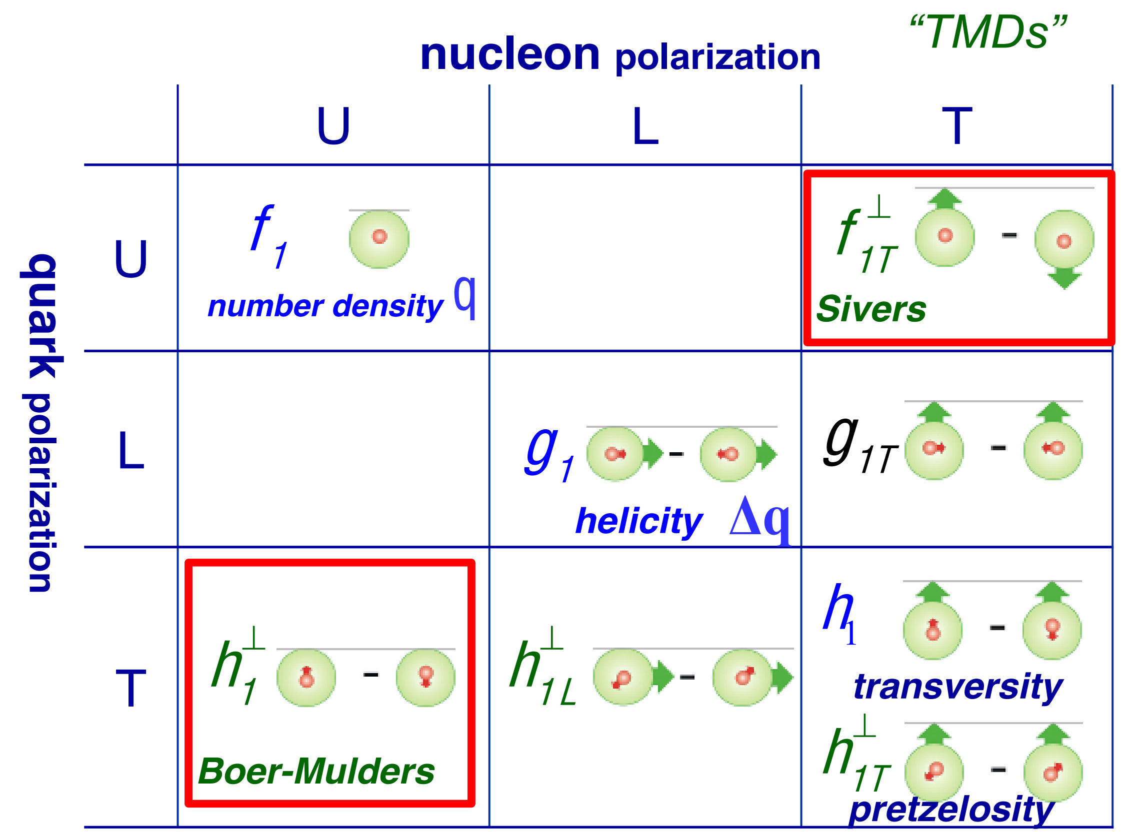
Arnold, Metz and Schlegel, Phys. Rev. D79 (2009) 034005.

- Access 4 TMDs – asymmetry modulations:

Boer-Mulders	$A_U^{\cos 2\phi} \propto 1 + \bar{h}_1^\perp \otimes h_1^\perp \cos 2\phi$
Sivers	$A_T^{\sin\phi} \propto S_T \left[\bar{f}_1 \otimes f_{1T}^\perp \sin \phi_s) \right]$
Pretzelosity	$A_T^{\sin(2\phi+\phi_s)} \propto S_T \left[\bar{h}_1^\perp \otimes h_{1T}^\perp \sin(2\phi + \phi_s) \right]$
Transversity	$A_T^{\sin(2\phi-\phi_s)} \propto S_T \left[\bar{h}_1^\perp \otimes h_1 \sin(2\phi - \phi_s) \right]$
Worm-Gear	Not possible: needs double polarization

All four TMDs are also measured in SIDIS

Transverse Momentum Dependent PDFs



- Sivers: correlation between the quark transverse momentum and the nucleon transverse spin (polarized nucleon)
- Boer-Mulders: correlation between the quark transverse spin and transverse momentum (unpolarized nucleon)

TMDs in Drell-Yan and SIDIS

- SIDIS vs TMD
  - SIDIS: TMD and FF
  - Drell-Yan: two TMDs

$$\sigma^{SIDIS} \propto TMD_p(x,k_T) \otimes D_f^h(z,Q^2)$$

$$\sigma^{DY} \propto TMD_\pi \otimes TMD_p$$

- Factorization

Collins, Soper, Sterman, Adv. Ser. High En Phys. 5, 1988.

  - TMDs (unlike PDFs) can be process dependent ("non-universality")
  - Opposite sign in SIDIS and DY processes:

Sivers:

$$f_{1T}^{\perp}(SIDIS) = -f_{1T}^{\perp}(DY)$$

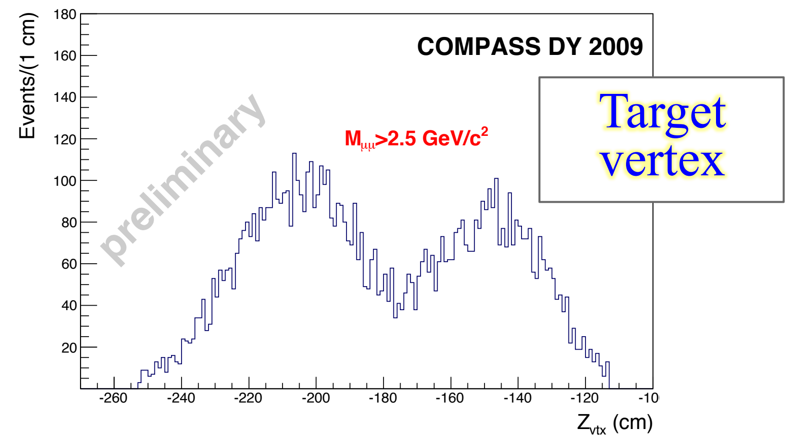
Boer-Mulders:

$$h_1^{\perp}(SIDIS) = -h_1^{\perp}(DY)$$

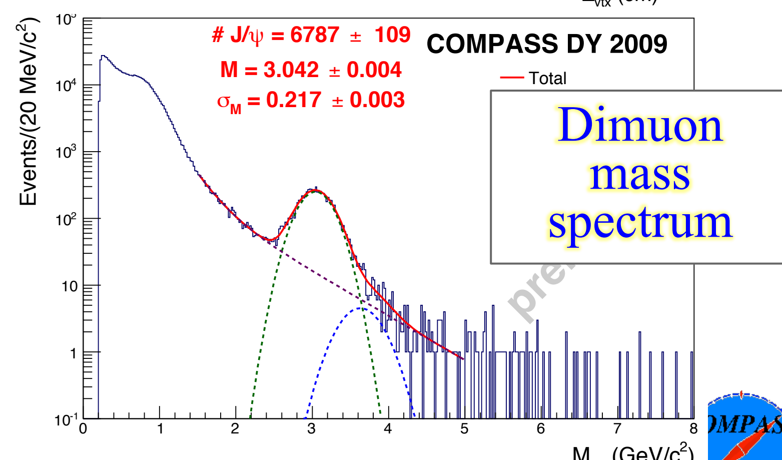
Crucial test of the QCD factorization approach

Drell-Yan – test data taking

- Test setup (3 days in 2009)
  - 190 GeV negative pion beam, $I \leq 1.5\text{x}10^7$/s (instead of 10^8/s)
  - "poor-man" hadron absorber (concrete and steel)
  - two polyethylene target cells
  - preliminary DY trigger

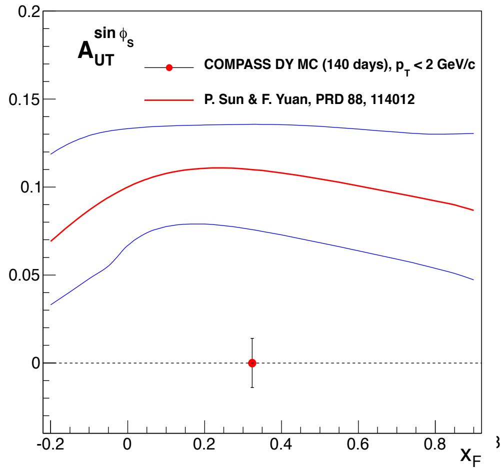


- Results
  - Count rate confirmed
  - Mass resolution as expected
  - Good vertex resolution
  - Low background at high masses

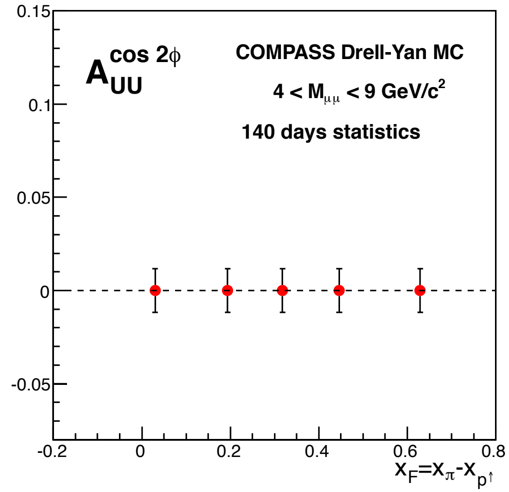


Polarized Drell-Yan – expected results

Sivers



Boer-Mulders



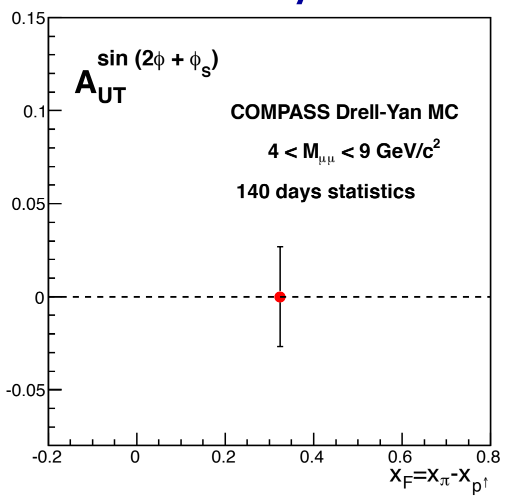
140 days of data

6.10^8 pions/spill

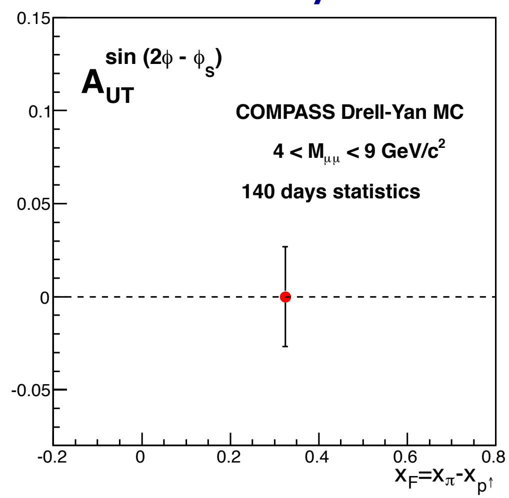
2 x 55 cm NH_3 target

$4 < M_{mm} < 9$ GeV

Pretzelosity



Transversity



Summary

- COMPASS is the largest fixed-target experiment at CERN
- Unique combination of hadron and muon beams of both polarities
- COMPASS has a very versatile experimental setup

- Rich physics program dedicated to both nucleon structure and hadron spectroscopy studies

- Present schedule
  - 2015 : Drell - Yan data taking (1st "year" ≈ 140 days)
  - 2016 : DVCS data taking
  - 2017 : DVCS data taking
  - 2018 : Drell-Yan data taking (2nd year)