New Results from the COMPASS–Experiment

presented by

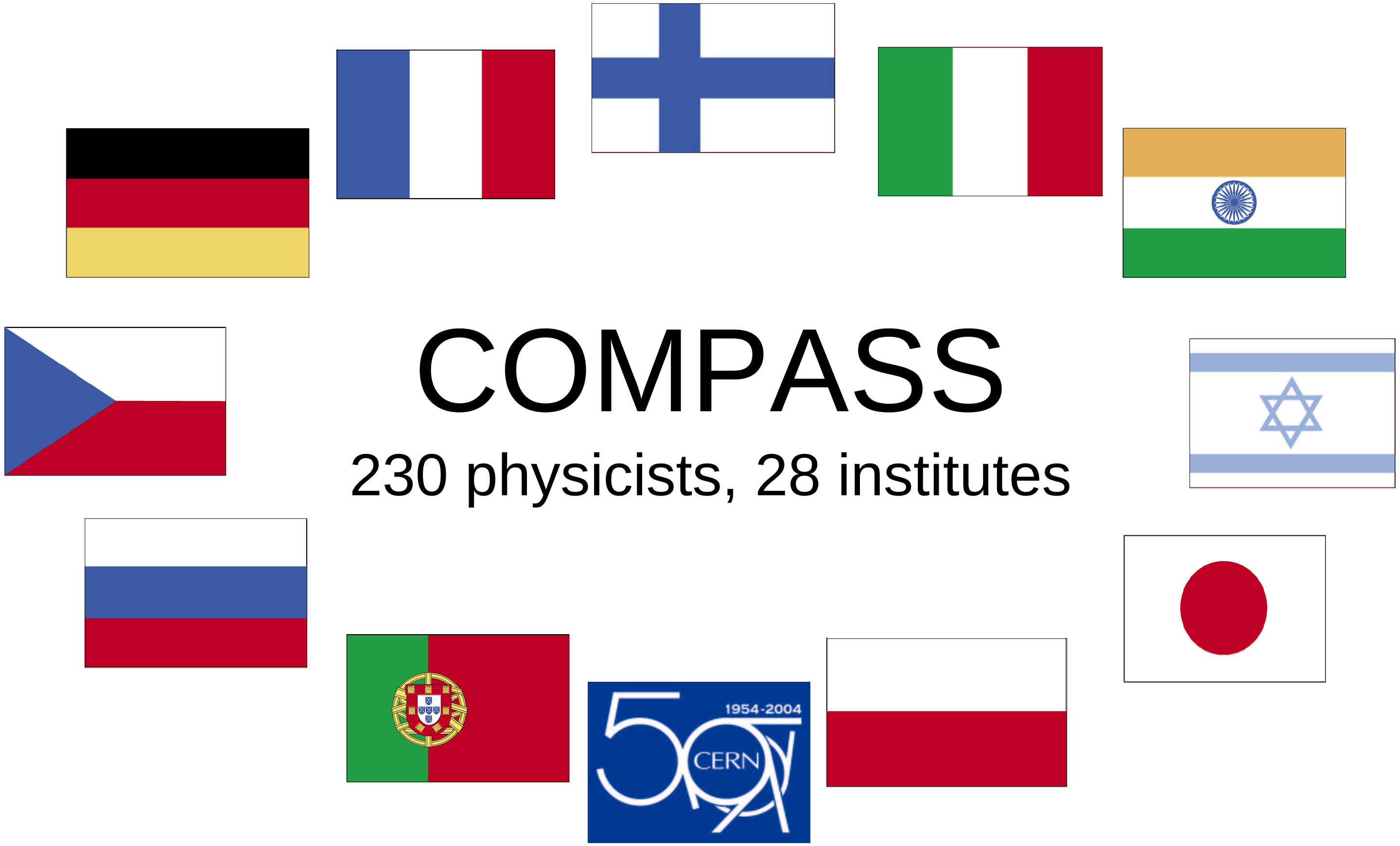
M. Leberig (CERN)

Outline of the Talk

- Introduction
- The experimental setup
- Selection of results:
  - Longitudinal spin physics
    - Quark helicity contribution
    - Gluon helicity contribution
  - Transversity
  - Exclusive ρ^0 production
- Summary and Outlook

Introduction

The COMPASS Collaboration

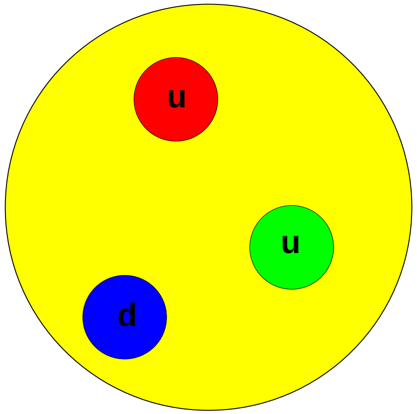


approved: 1997, start of construction: 1998, technical run: 2001, data taking since 2002

The Physics Case

- **Physics program with muon beam** (results)
  - The spin structure of the nucleon
    - Gluon polarization
    - Polarized parton distributions
    - Transversity
  - Spin effects in Λ production
  - Exclusive vector meson production
  - Azimuthal asymmetry (Cahn)
  - Pentaquarks
- **Physics program with hadron beams** (data to come)
  - Polarizability of pions and kaons (2004)
  - Glueballs and hybrids
  - Semi–leptonic decay of charmed hadrons
  - Double charmed hadrons

The Spin of the Nucleon



Naive Parton Model:

$$\Rightarrow \Delta\Sigma = \Delta u_v + \Delta d_v = 1$$

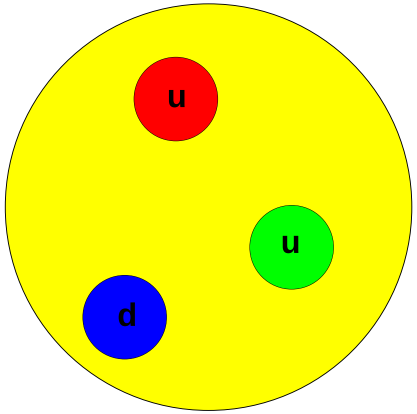
$$\Delta q = q^{\uparrow\uparrow} - q^{\uparrow\downarrow}$$

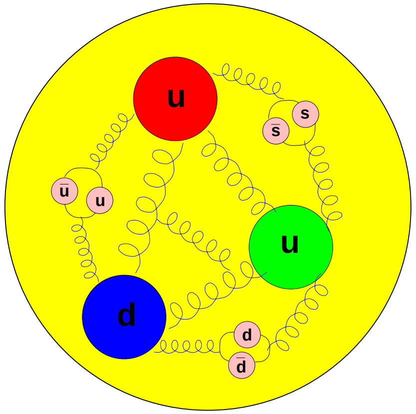
In 1988 EMC measured:

$$\Delta\Sigma = 0.12 \pm 0.09 \pm 0.14$$

$$S_N = \frac{1}{2} = \frac{1}{2}\Delta\Sigma$$

The Spin of the Nucleon





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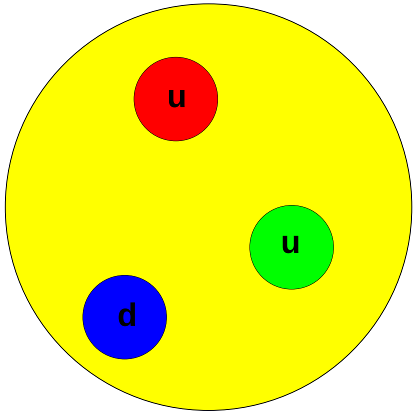
gluons are important in unpolarized case

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

The Spin of the Nucleon



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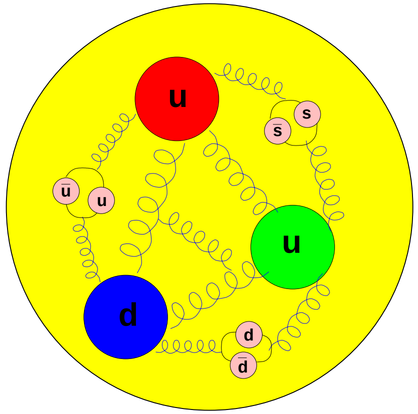

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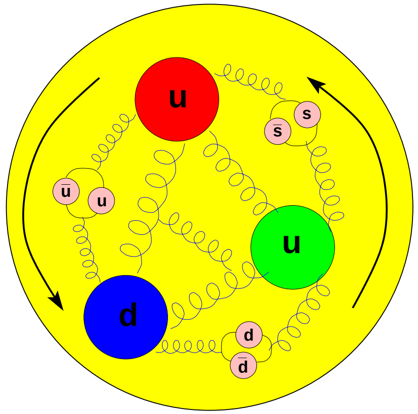
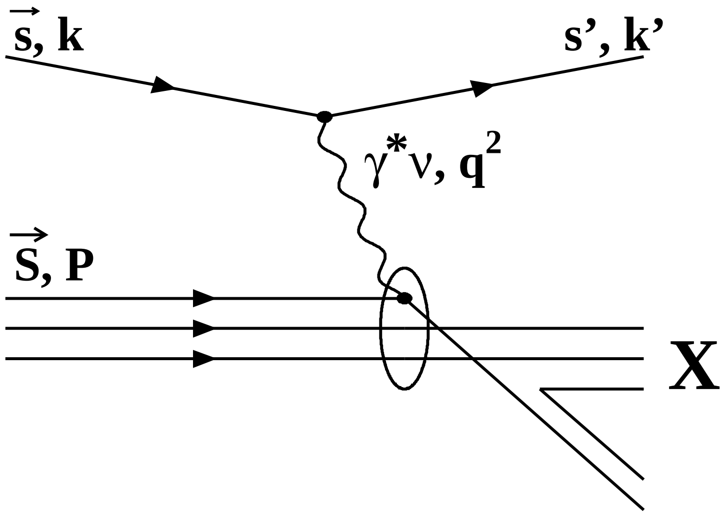


complete description:
orbital angular momenta

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

Polarised Deep Inelastic Scattering



detect scattered lepton only ⇒ inclusive
and at least one hadron of the final state X ⇒ semi–inclusive

$$Q^2 \stackrel{\text{lab}}{=} 4EE' \sin^2(\theta/2)$$

$$x_{Bj} \stackrel{\text{lab}}{=} \frac{Q^2}{2M\nu}$$

$x_{Bj} \Leftrightarrow$ momentum fraction carried by quark

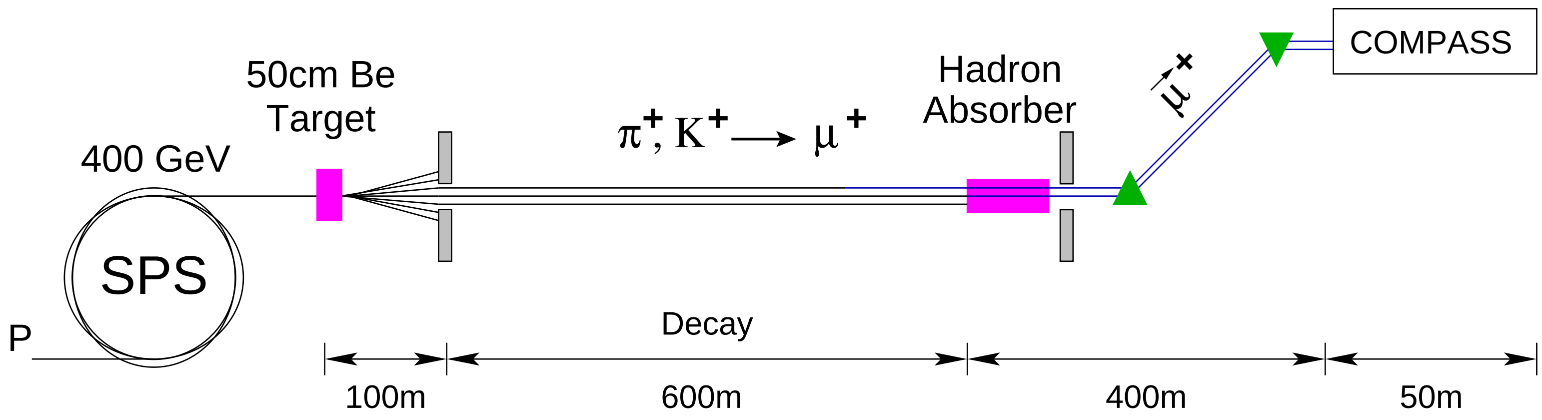
$$\frac{d^2\sigma}{d\Omega dE} = \frac{\alpha^2 E'}{Q^2 E} L_{\mu\nu} W^{\mu\nu}$$

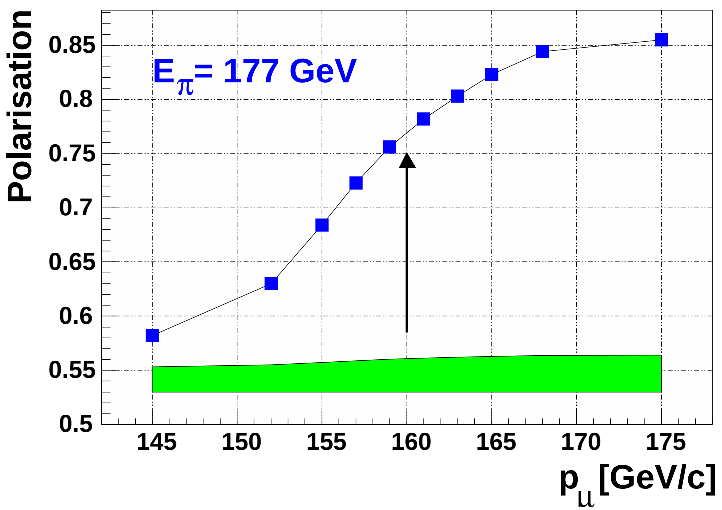
$$\sim \underbrace{c_1 F_1(x,Q^2) + c_2 F_2(x,Q^2)}_{\text{spin independent}} + \underbrace{c_3 g_1(x,Q^2) + c_4 g_2(x,Q^2)}_{\text{spin dependent}}$$

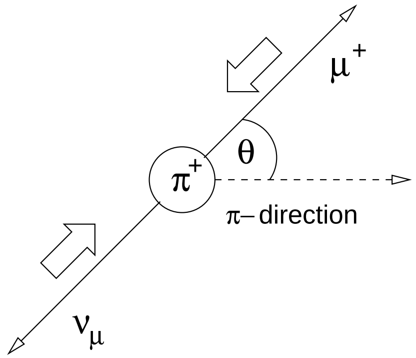
Study of nucleon spin structure ⇔ polarized beam and target

The Experimental Setup

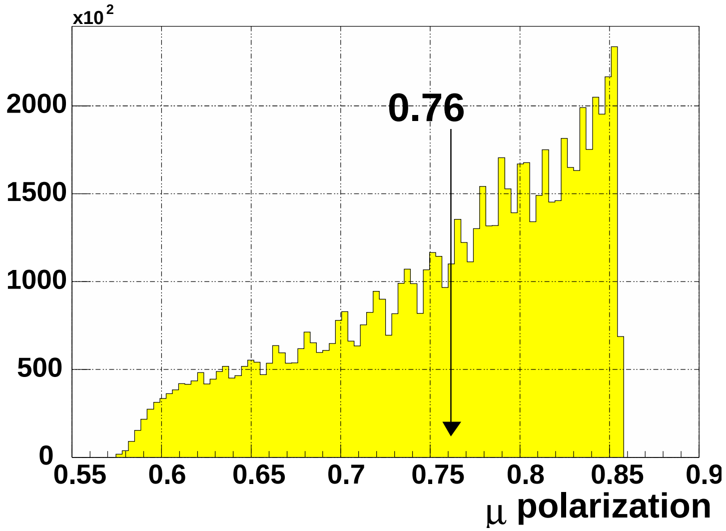
The Polarised Muon Beam



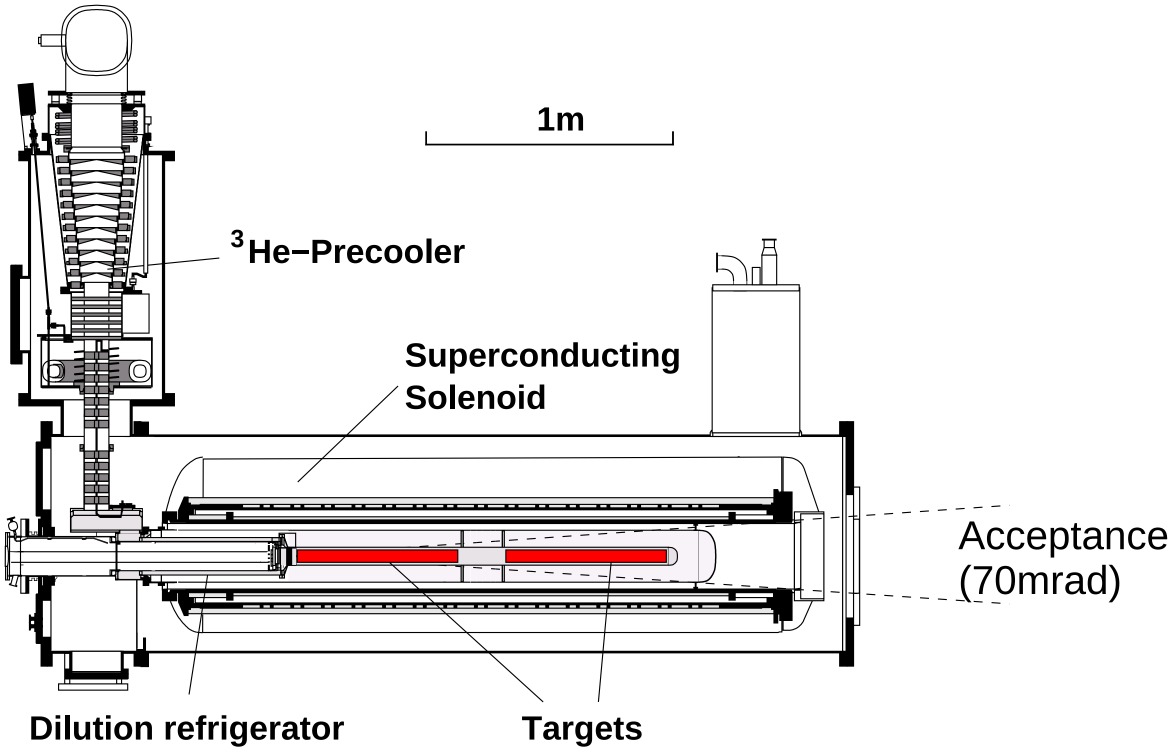




Energy	160 GeV
Intensity	$2 \cdot 10^8 \mu/$Spill
Polarisation	$\approx 76\,\%$



The Polarised Target



- Target material ^{6}LiD ($P_{max} = 55\,\%$, $f \approx 0.4$)
- 2.5 T Solenoid field (Homogeneity: $\pm 1.5 \cdot 10^{-5}$)
- ^{3}He/^{4}He dilution refrigerator ($T_{min} \approx$ 50 mK)
- Dynamic Nuclear Polarization
- Two 60 cm long target cells with opposite polarisation

- COMPASS magnet ready for 2006 $\Rightarrow$ 180 mrad acceptance

The Polarised Target

- **To be measured:**

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

- **Flux normalization?**

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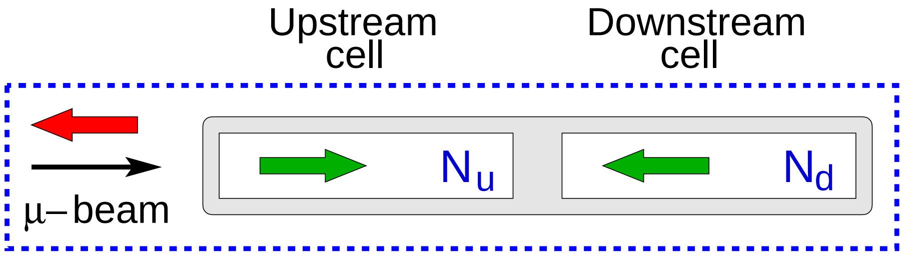
- **Flux normalization:**

$$A = \frac{N_u - N_d}{N_u + N_d}$$

- **Acceptance difference?**



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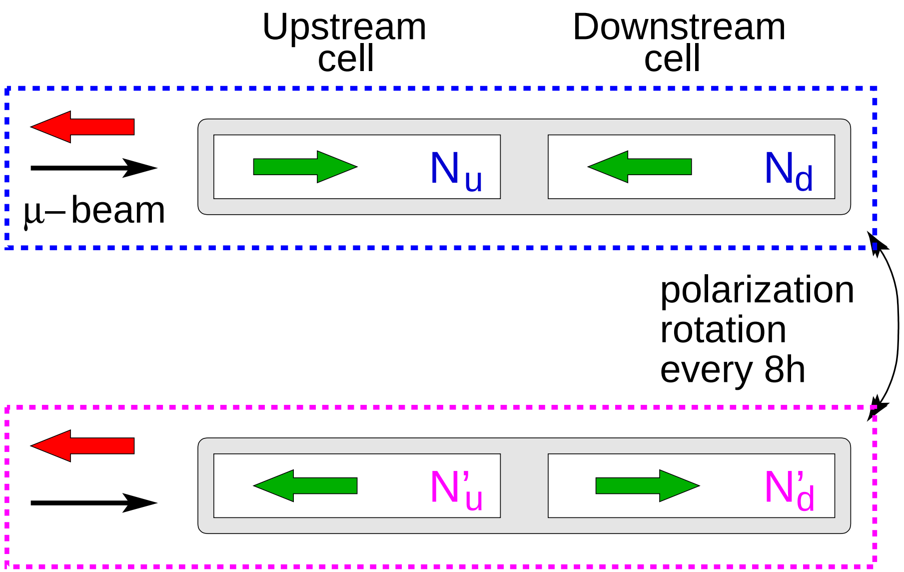
  Polarisation rotation



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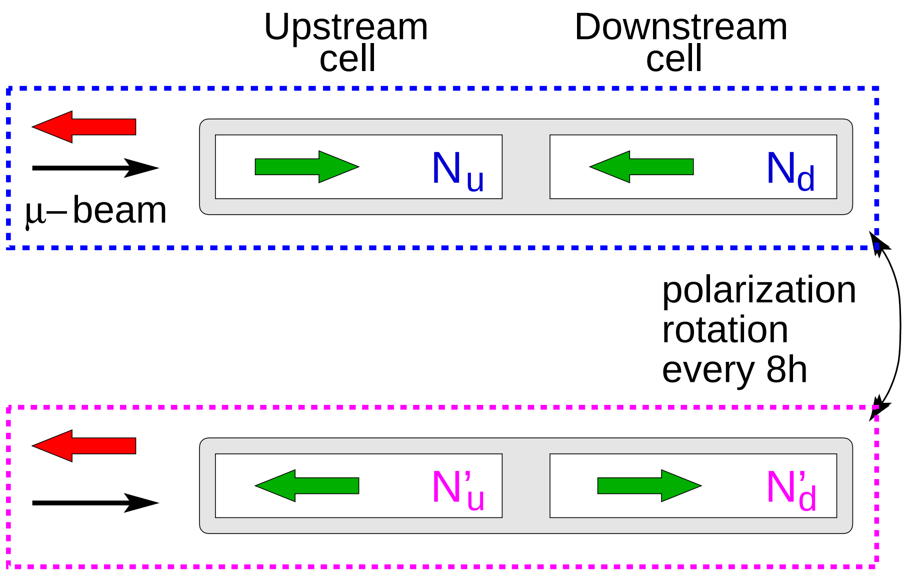
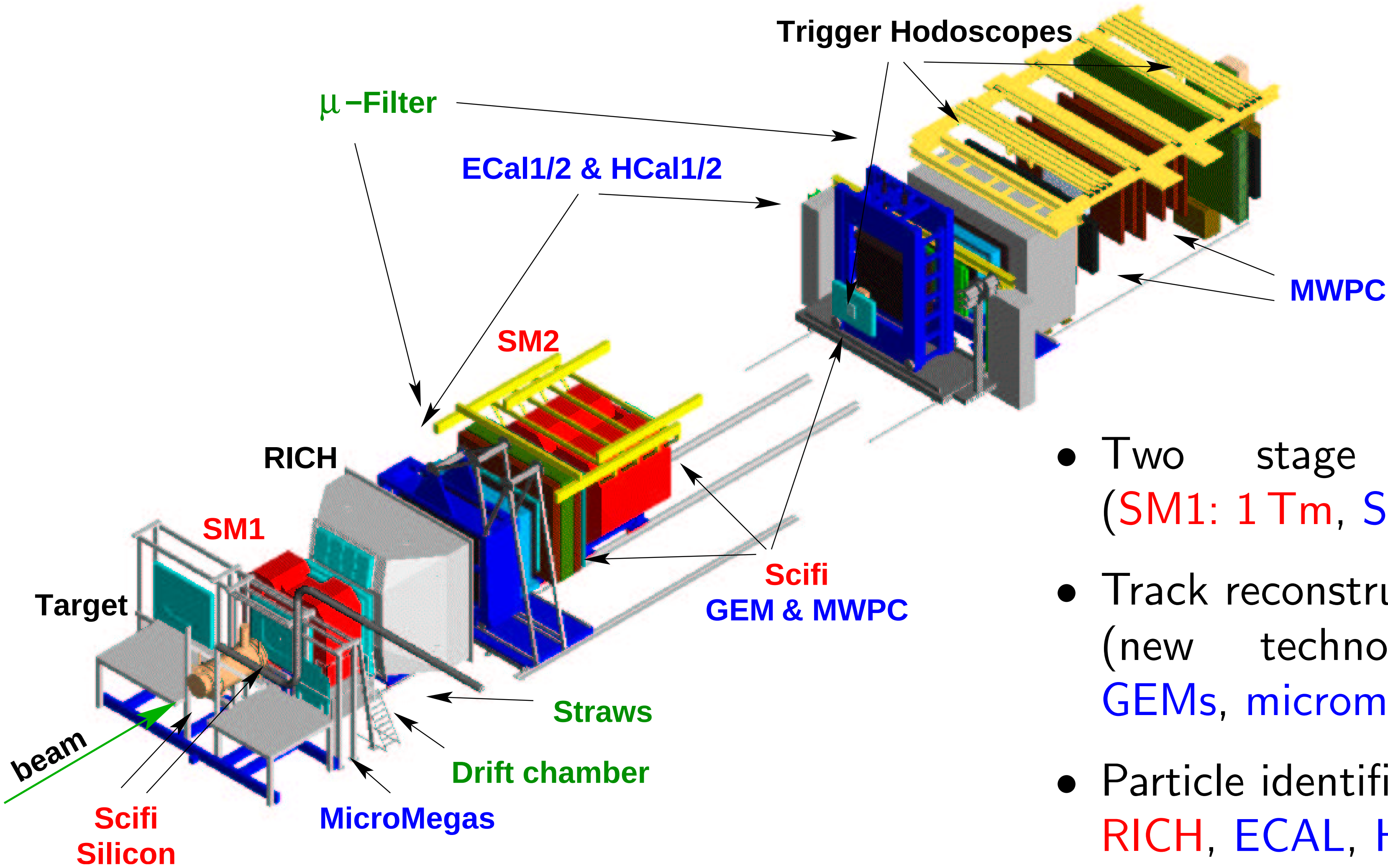


- **Take average asymmetry:**

$$\Rightarrow A = \frac{A + A'}{2} = \frac{1}{2}\left(\frac{N_u - N_d}{N_u + N_d} + \frac{N'_d - N'_u}{N'_u + N'_d}\right)$$

$\Rightarrow$ Minimization of bias

The COMPASS Spectrometer



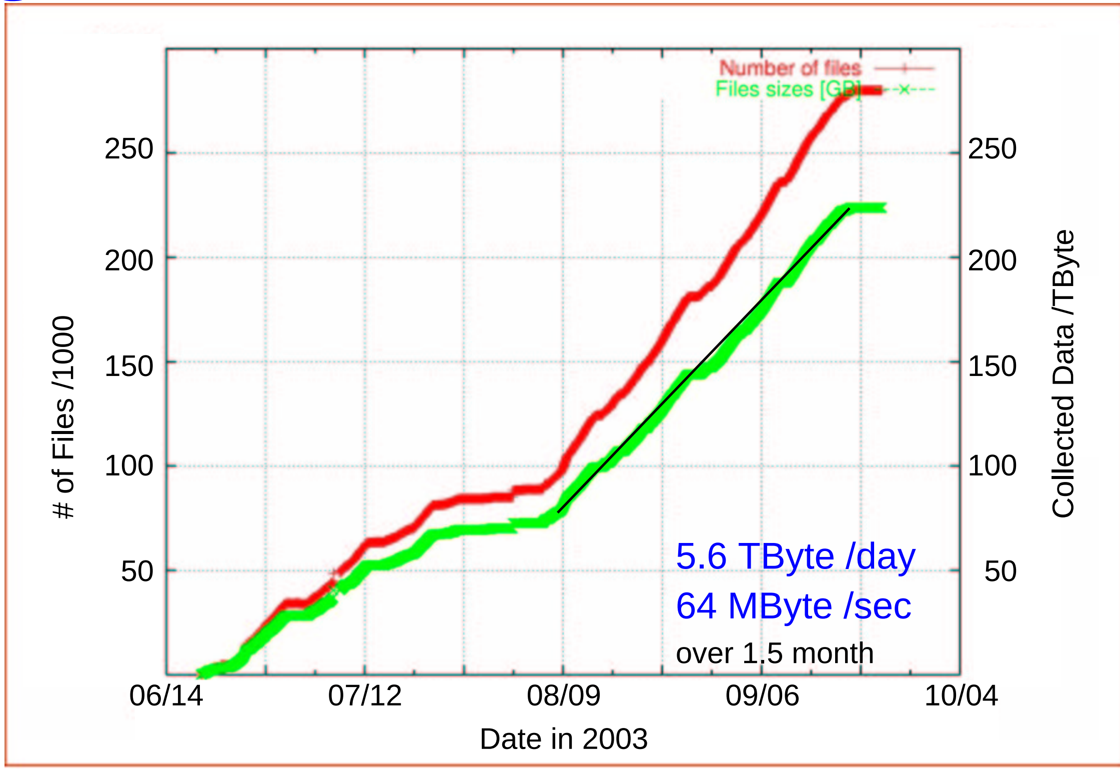
- Two stage spectrometer (SM1: 1 Tm, SM2: 5.2 Tm)
- Track reconstruction (new technologies: scifis, GEMs, micromegas, straws)
- Particle identification RICH, ECAL, HCALs, μF

Data Taking 2002–2004

	2002	2003	2004
Beam Time	106d	90d	109d
Preparation	30d	7d	3d
ϵ_{acc}	0.90	0.63	0.67
$\epsilon_{spectro}$	0.77	0.83	0.87
Raw Events $/10^9$	5.8	8.6	14.1
with Vertex $/10^9$	2.2	2.5	4.0
Data /TByte	200	250	400

$\epsilon_{spectro}^{max} \approx 0.9$ extrapolated

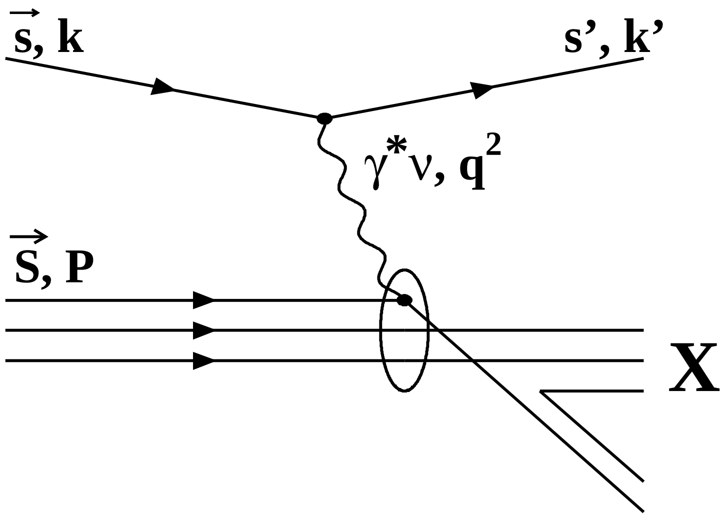
(pol. rotation, start/stop of runs, ...)



- In total 240 units of computing power (P4 3 GHz) in 9 centers around Europe
- Processing of raw data at CERN with 120 units:
  800 TByte $\equiv$ 800 000 jobs batch, each running 8 hours $\Rightarrow$ 8 TByte of DST
- Final data analysis distributed to different computer centers (e.g. CERN, gridka, Trieste)

Quark Contribution to the Spin of the Nucleon

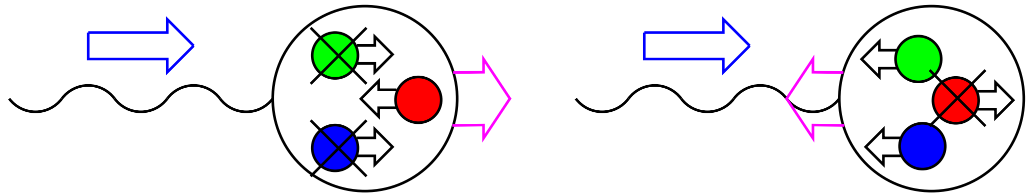
Virtual Photon Asymmetry



- **Quark distributions:**

$$\Delta q(x) := q^{\uparrow\uparrow}(x) - q^{\uparrow\downarrow}(x) \qquad q(x) := q^{\uparrow\uparrow}(x) + q^{\uparrow\downarrow}(x)$$

- **Photoabsorbtion:**



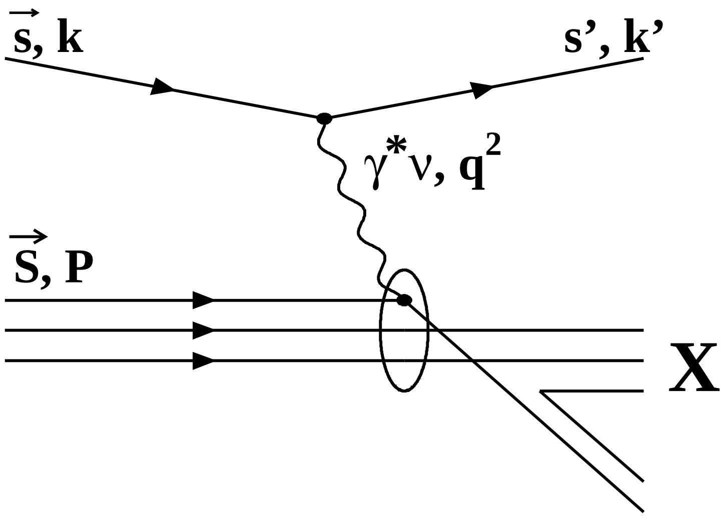
$$\sigma^{\Uparrow\uparrow} \propto \sum_q e_q^2 (q^{\uparrow\downarrow} + \bar{q}^{\uparrow\downarrow}) \qquad \sigma^{\Uparrow\downarrow} \propto \sum_q e_q^2 (q^{\uparrow\uparrow} + \bar{q}^{\uparrow\uparrow})$$

- γ**–nucleon asymmetry:**

$$A_1 = \frac{\sigma^{\Uparrow\downarrow} - \sigma^{\Uparrow\uparrow}}{\sigma^{\Uparrow\downarrow} + \sigma^{\Uparrow\uparrow}} = \frac{\sum_q e_q^2 \left(q^{\uparrow\uparrow} - q^{\uparrow\downarrow} + \bar{q}^{\uparrow\uparrow} - \bar{q}^{\uparrow\downarrow}\right)}{\sum_q e_q^2 \left(q^{\uparrow\uparrow} + q^{\uparrow\downarrow} + \bar{q}^{\uparrow\uparrow} + \bar{q}^{\uparrow\downarrow}\right)} = \frac{\sum_q e_q^2 (\Delta q + \Delta \bar{q})}{\sum_q e_q^2 (q + \bar{q})}$$

The Inclusive Asymmetry A_1

- **Inclusive DIS:**
  - Detection of μ and μ'
  - Hadronic final state unobserved



- **Measure μ–nucleon asymmetry:**

$$A_{\mu N} = \frac{1}{P_t f P_b}\left(\frac{N_{\Uparrow\downarrow} - N_{\Uparrow\uparrow}}{N_{\Uparrow\downarrow} + N_{\Uparrow\uparrow}}\right)$$

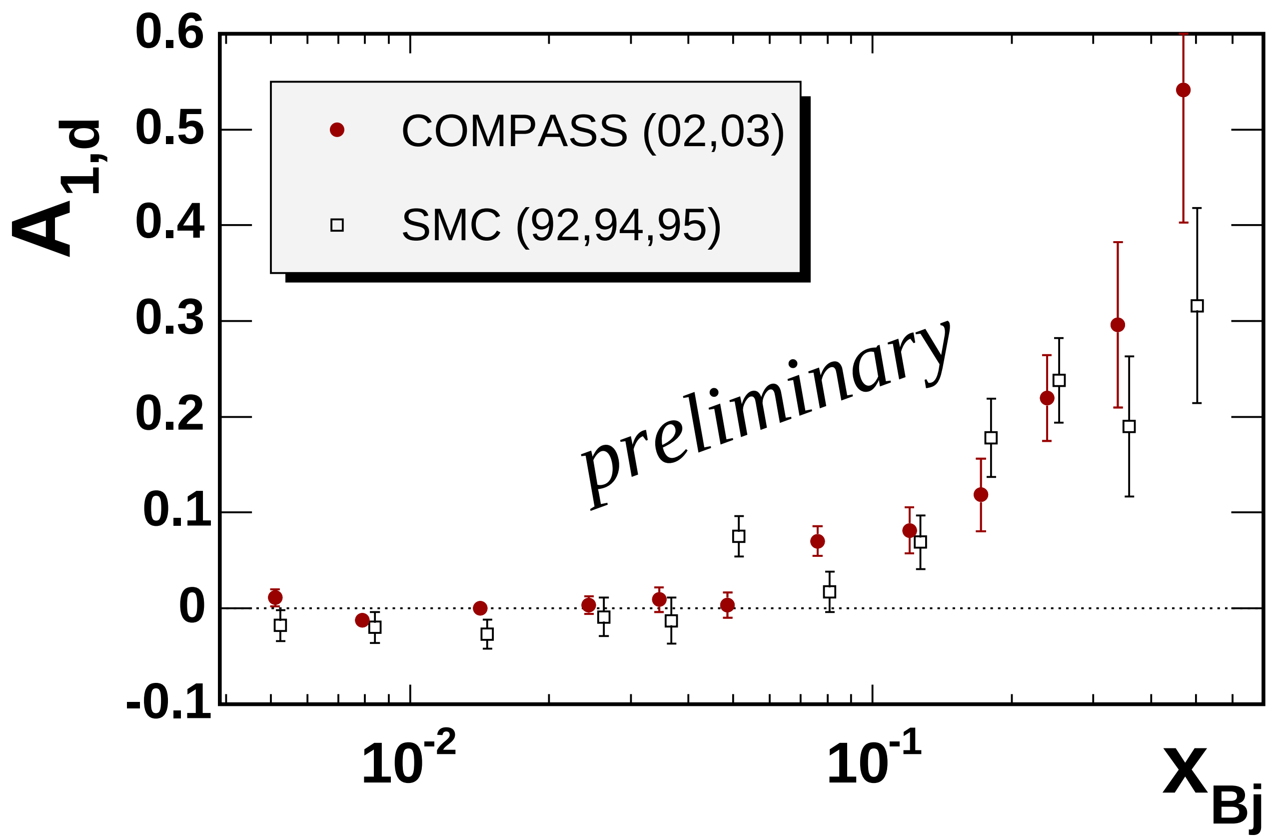
- **γ–nucleon asymmetry:**

$$\frac{A_{\mu N}}{D} \approx A_1 = \frac{\Sigma e_q^2\,(\Delta q + \Delta\bar{q})}{\Sigma e_q^2\,(q + \bar{q})}$$

- Δq and $\Delta\bar{q}$ can not be separated

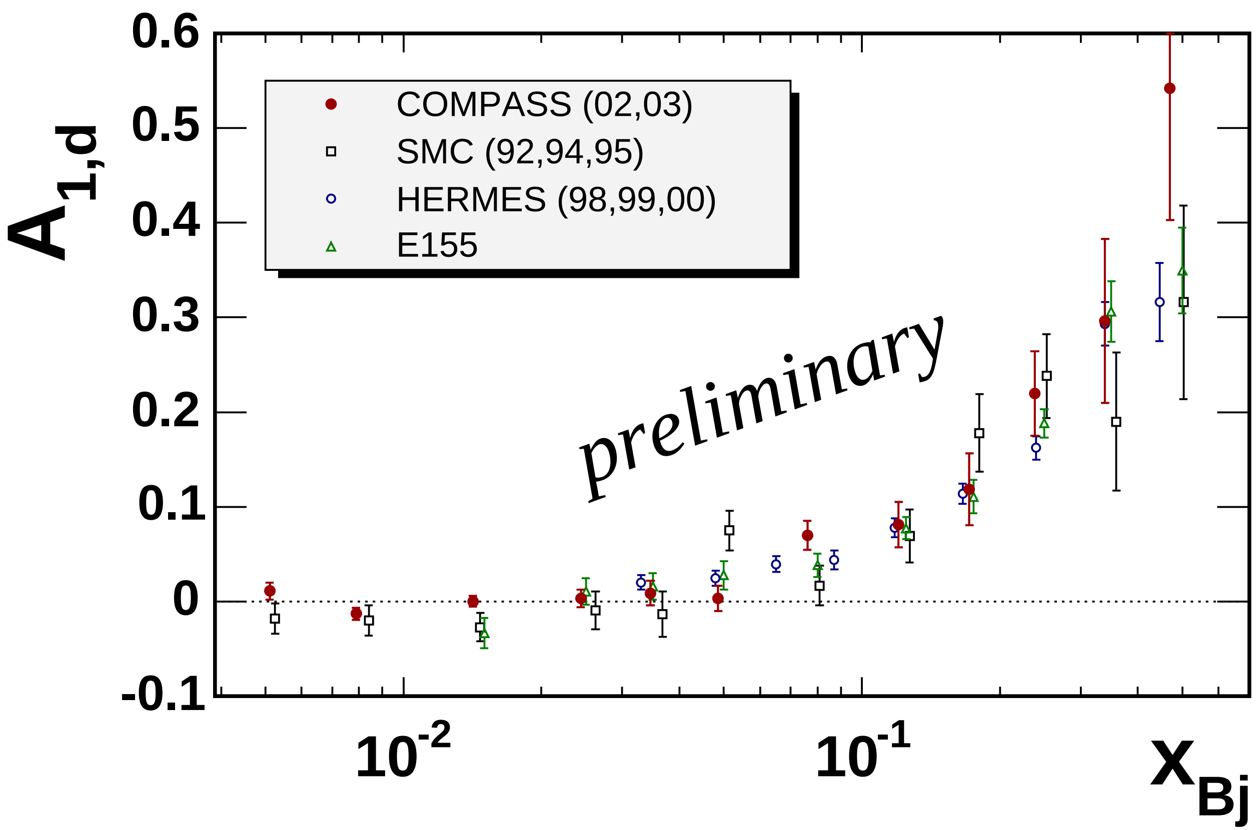
- with neutron and hyperon decay data $+$ assumption of $\mathrm{SU}_f(3)$: $\Delta u + \Delta\bar{u}$, $\Delta d + \Delta\bar{d}$ and $\Delta s + \Delta\bar{s}$ can be determined

Result of the inclusive Measurement ($Q^2 > 1$ GeV^2)



- COMPASS is a new generation experiment:
  - Better statistics than SMC in $\sim 1/3$ beam time
  - 5 times higher luminosity
  - Better dilution factor
- Systematic errors under study (smaller than statistical)

Result of the inclusive Measurement ($Q^2 > 1\,\text{GeV}^2$)



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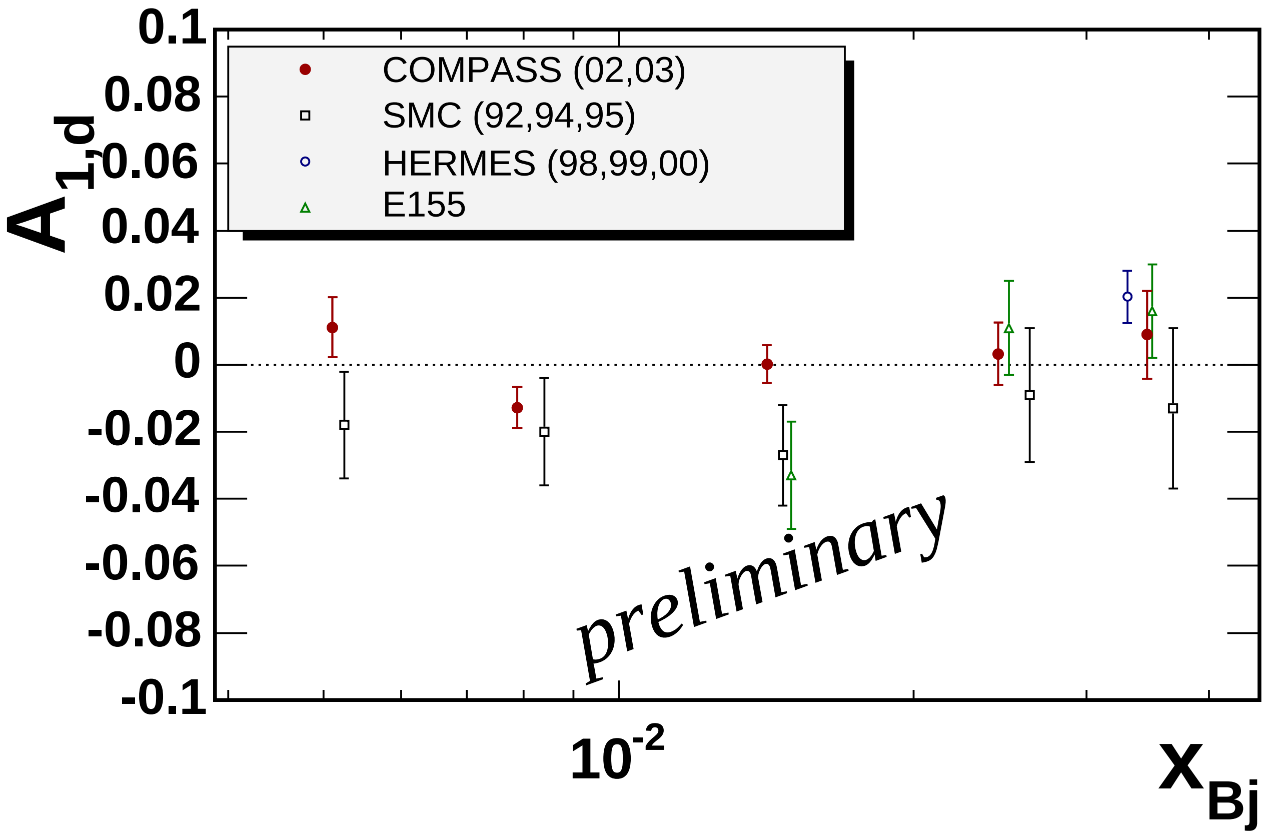
Result: Inclusive Asymmetry ($Q^2 > 1$ GeV^2)



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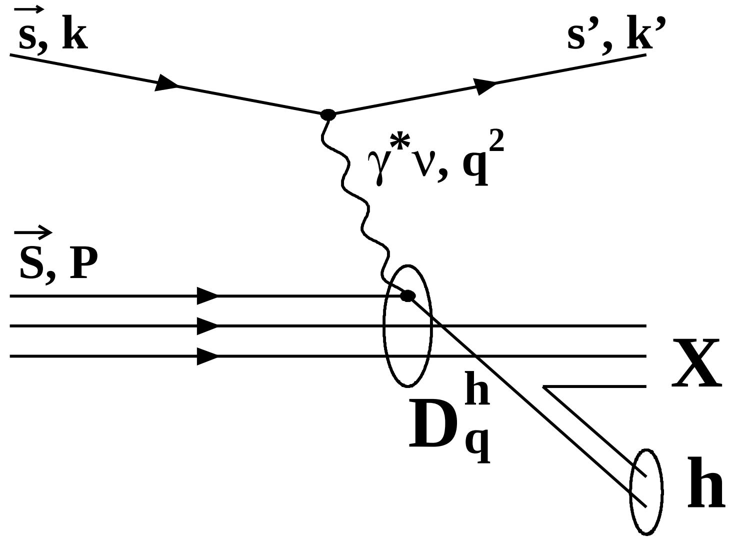
- **low x region important for precision of first moment $\Rightarrow \Delta\Sigma$**
- **COMPASS has the potential to digest high luminosity $\Rightarrow$ high precision results**

Semi–inclusive Asymmetries



- **Semi–inclusive Measurement:**
  - Detection of μ and μ'
  - Plus at least one hadron h
  - Fragmentation independent of scattering
  - Fragmentation function: $D_q^h(z)$ with $z = \frac{E_h}{\nu}$

- **Asymmetries:**

$$A_1^h = \frac{1}{P_t f P_b D}\left(\frac{N^h_{\Uparrow\downarrow} - N^h_{\Uparrow\uparrow}}{N^h_{\Uparrow\downarrow} + N^h_{\Uparrow\uparrow}}\right) = \frac{\sum_q e_q^2 \left(\Delta q(x) \int D_q^h(z)dz + \Delta\bar{q}(x) \int D_{\bar{q}}^h(z)dz\right)}{\sum_q e_q^2 \left(q(x) \int D_q^h(z)dz + \bar{q}(x) \int D_{\bar{q}}^h(z)dz\right)}$$

since $D_q^h \neq D_{\bar{q}}^h$ separation of quarks and anti-quarks

- in principle full flavour separation possible (Δu, $\Delta\bar{u}$, Δd, $\Delta\bar{d}$, Δs, $\Delta\bar{s}$)
- proton and deuteron data needed

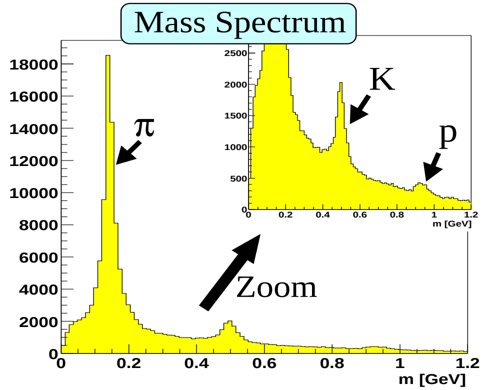
Asymmetries to be measured

$$\vec{A}_1 = \{ A_1, A_1^{h+}, A_1^{h-}, A_1^{K+}, A_1^{K-}, A_1^{K_S^0} \}$$

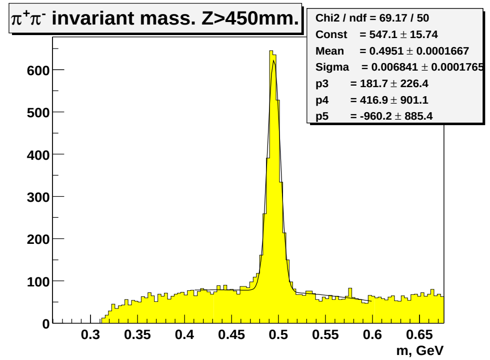
Inclusive Asymmetry

90% of hadrons are pions

RICH PID
Threshold: $p_K > 9$ GeV

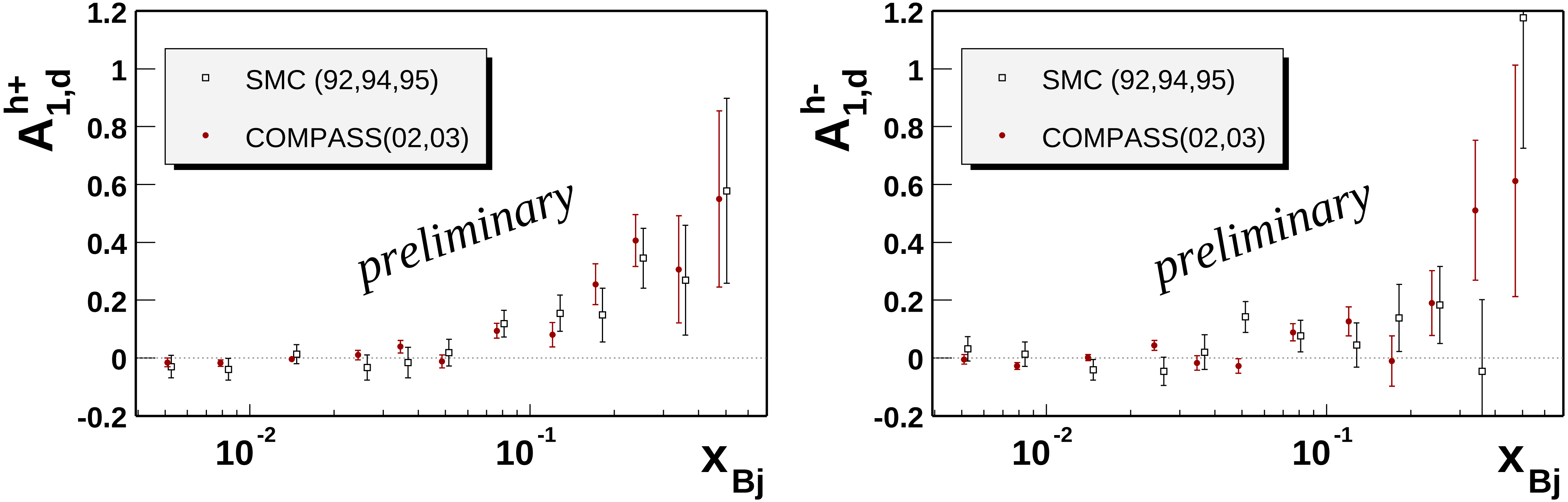


Secondary vertices produced by track coming from interac–tion point



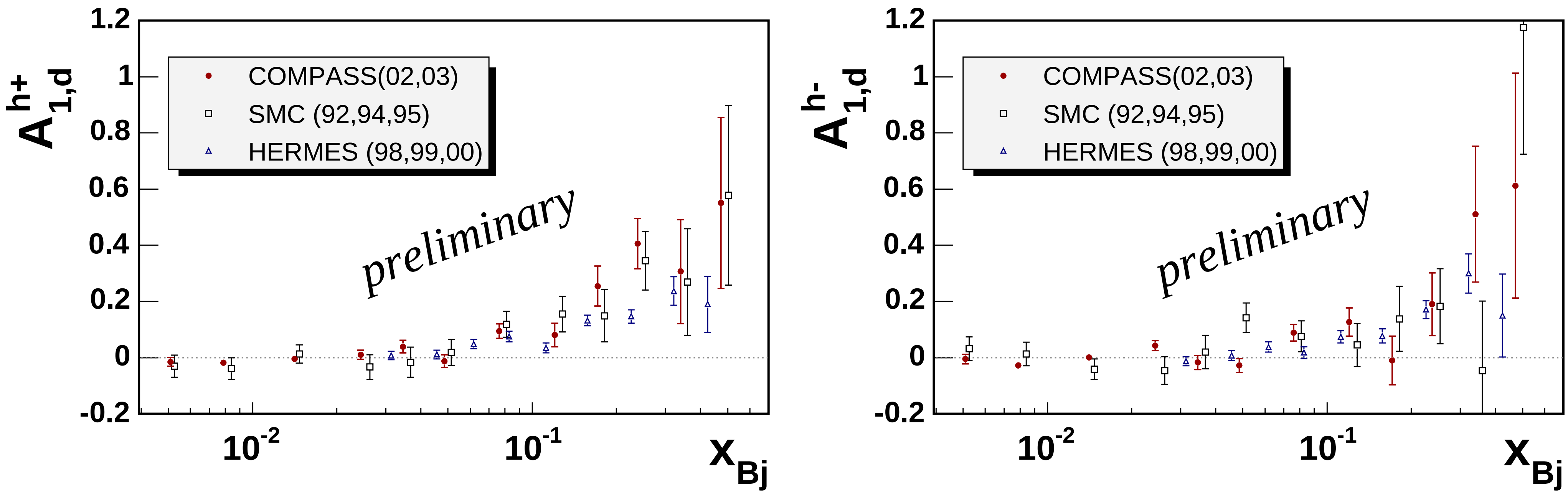
$$\vec{A}_1 = \mathcal{B}(q(x), D_q^h(z))\vec{\Delta q}$$

Result: Semi–Inclusive Asymmetries



- Smaller statistical error than SMC in all x_{Bj}

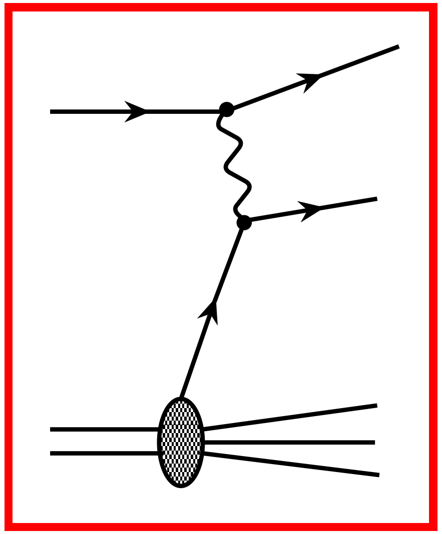
Result: Semi–Inclusive Asymmetries



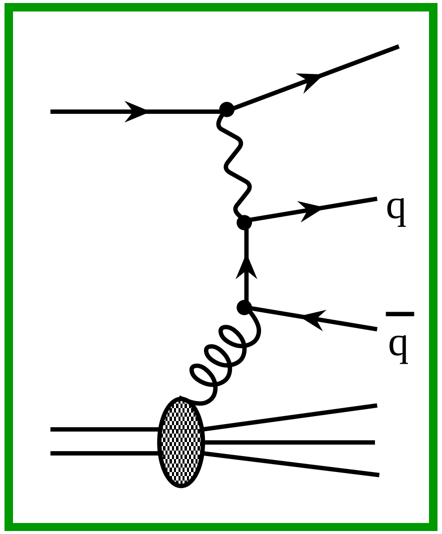
- High sensitivity in the region of $x < 0.03 \Rightarrow$ sea quarks
- Average hadron multiplicity 1.9 $\Rightarrow$ good potential for semi–inclusive asymmetries
- Even better with new target magnet

Gluon Contribution to the Spin of the Nucleon

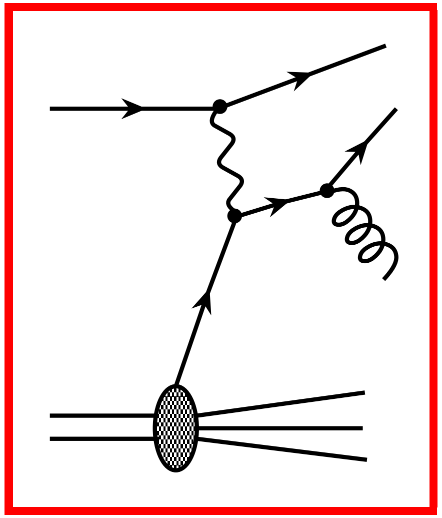
Photon Gluon Fusion



Leading Order



Photon–Gluon–Fusion



QCD–Compton

- **Strategies to suppress background:**

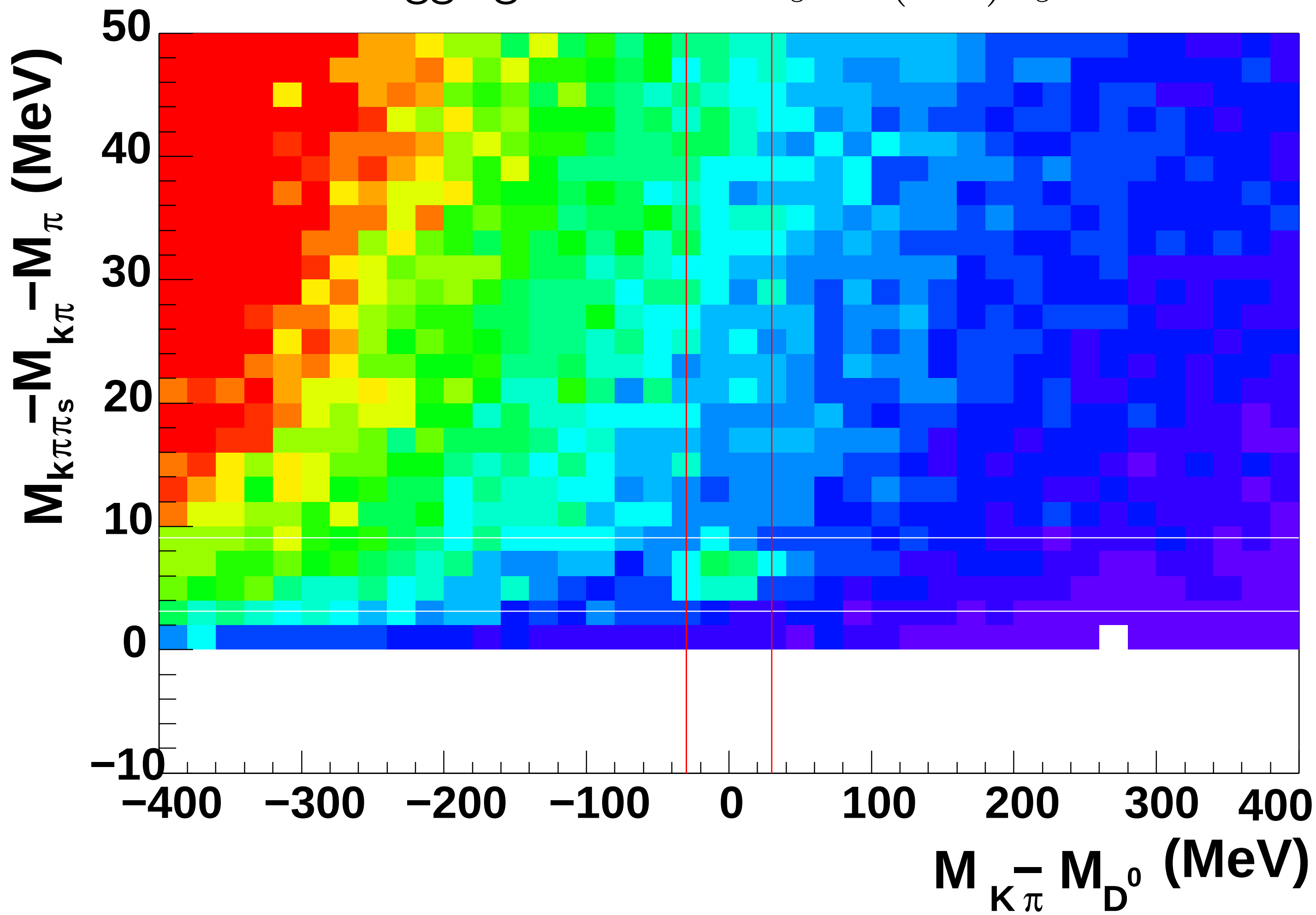
  Open Charm Production (unique)
  $q = c \Rightarrow$ 1.2 D^0 per event
  'no' charm in nucleon or fragmentation
  $\Rightarrow$ 'no' background

  Hadron Pair with high p_t
  σ_{k_t}(intr.) ~ 450 MeV
  σ_{p_t}(frag.) ~ 350 MeV

- **Feature:** pQCD scale is set by $\hat{s} > 4m_c^2$ or $\hat{s} > (p_{t_1} + p_{t_2})^2 \Rightarrow$ explore all Q^2

Open Charm Detection

D^* tagging: $D^* \rightarrow D^0\pi_s \rightarrow (K\pi)\pi_s$

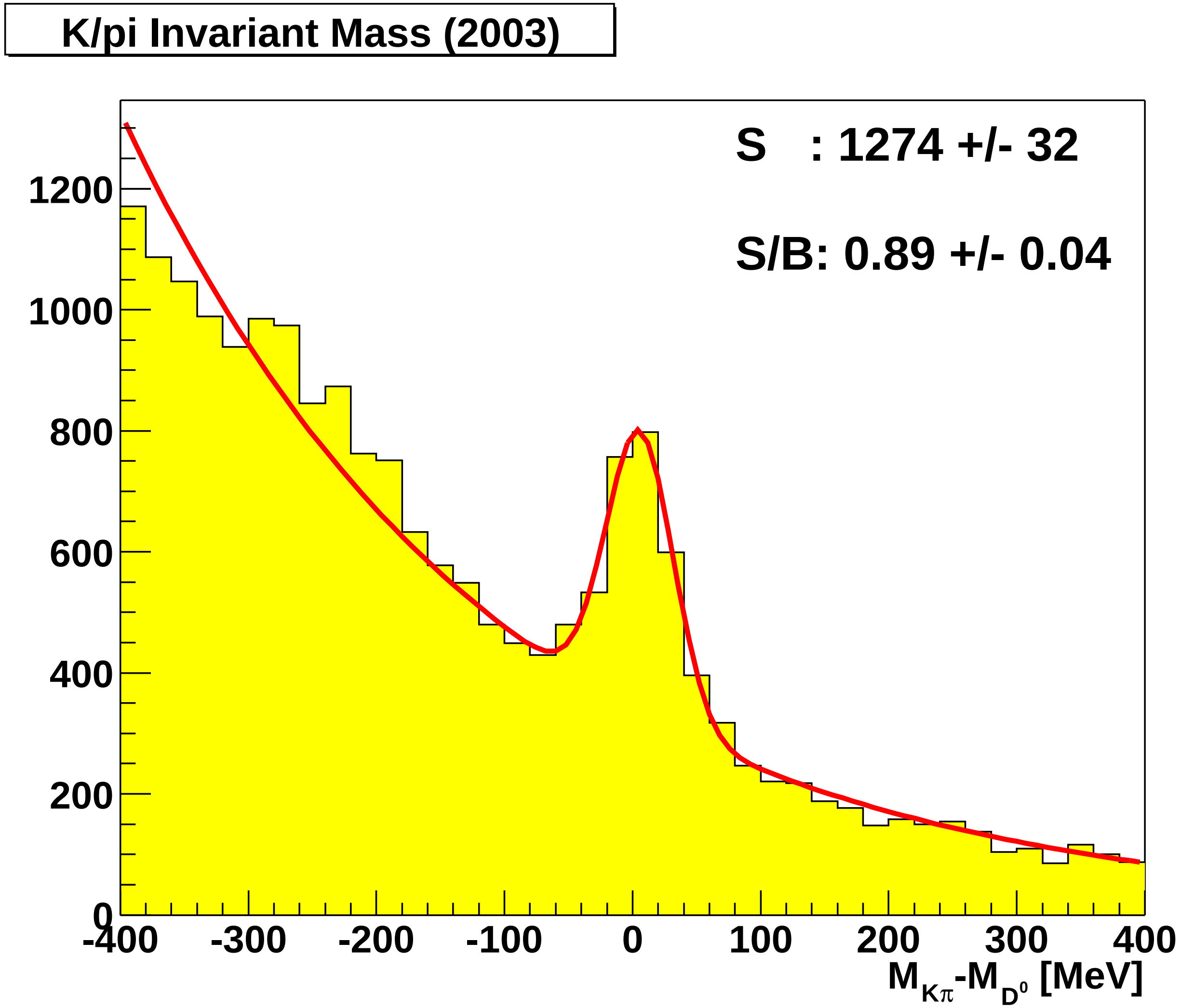


- No vertex reconstruction possible

$\Rightarrow$ Kaon identification by RICH essential

Use cut on the mass difference $M_{K\pi\pi} - M_{K\pi} - M_\pi$ to extract D^0–signal

Open Charm Detection



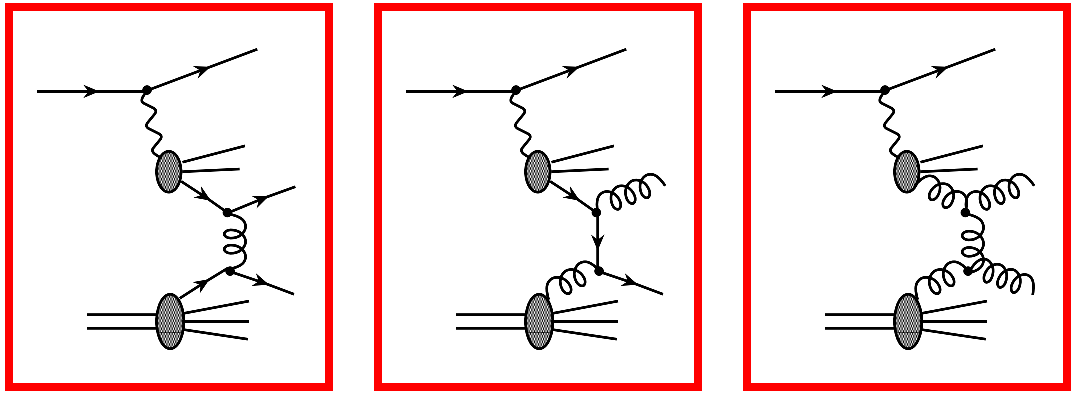
- ≈ 1300 D^0s from D^* reconstructed in 2003
- Expected statistical error on $\Delta G/G$ from 2002–2004 data: 0.24
- Almost no systematic uncertainty due to physics background (golden channel)
- explore other D^0 decay channels ...
- Take more data ...

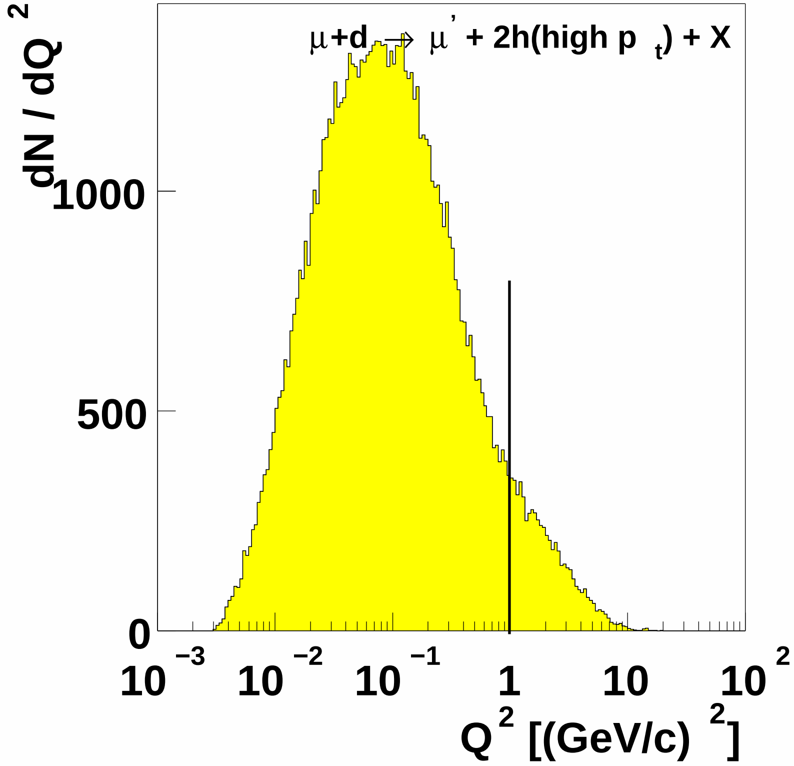
Additional Background for high p_t at small Q^2

- **Vector–Meson–Dominance:**
  will be measured at COMPASS for ρ^0 which is the dominant component of the photon
- **Resolved Photon:**
  - Asymmetry depends on the spin structure of the photon

  $\Rightarrow$ additional systematic uncertainties to extract $\Delta G/G$

  $\Rightarrow$ at first analysis only $Q^2 > 1$ events ($\approx 10\,\%$)





High–p_t Asymmetry for $Q^2 > 1\,$GeV^2

- **Asymmetry:**

$$A^{\gamma^* N \to hhX} = \frac{\Delta G}{G} \langle \frac{\hat{a}_{LL}^{PGF}}{D} \rangle \frac{\sigma_{PGF}}{\sigma_{tot}} + A_1^d \left(\langle \frac{\hat{a}_{LL}^{LO}}{D} \rangle \frac{\sigma_{LO}}{\sigma_{tot}} + \langle \frac{\hat{a}_{LL}^{QCDC}}{D} \rangle \frac{\sigma_{QCDC}}{\sigma_{tot}} \right)$$

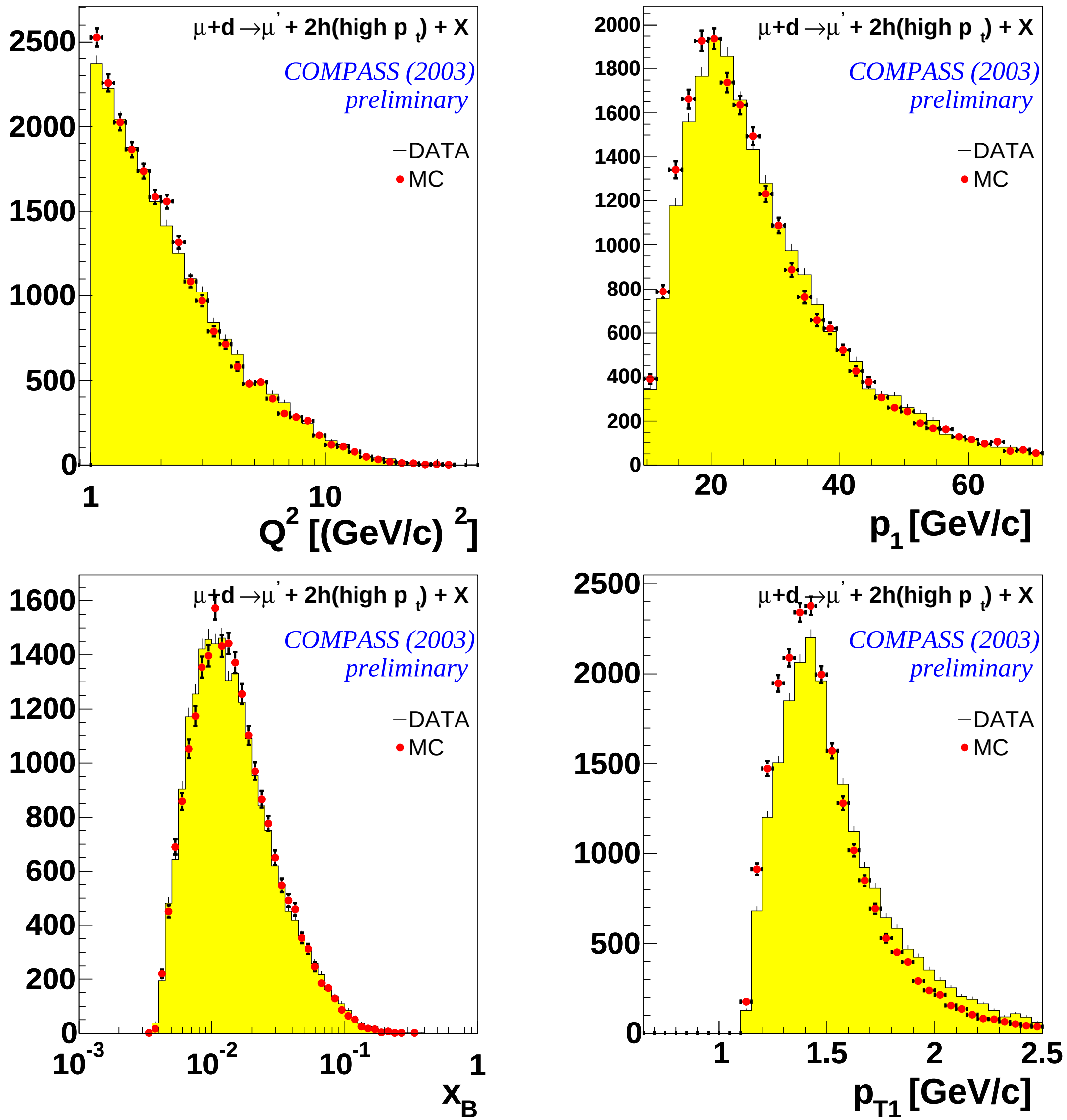
  - use additional cut $x_{Bj} < 0.05 \Rightarrow A_1^d$ small
  - red quantities must be extracted from Monte–Carlo

- **Cuts:**
  - Current fragmentation: $x_F > 0.1$ and $z > 0.1$
  - Radiative corrections/ photon polarisation: $0.1 < y < 0.9$
  - High p_t: $p_{t,1}, p_{t,2} > 0.7\,$GeV and $p_{t,1}^2 + p_{t,2}^2 > 2.5\,$GeV^2

- **Measurement:** (2002/03 data)

$$A^{\gamma^* N \to hhX} = -0.015 \pm 0.080(\text{stat.}) \pm 0.013(\text{syst.})$$

Data Monte–Carlo Comparison

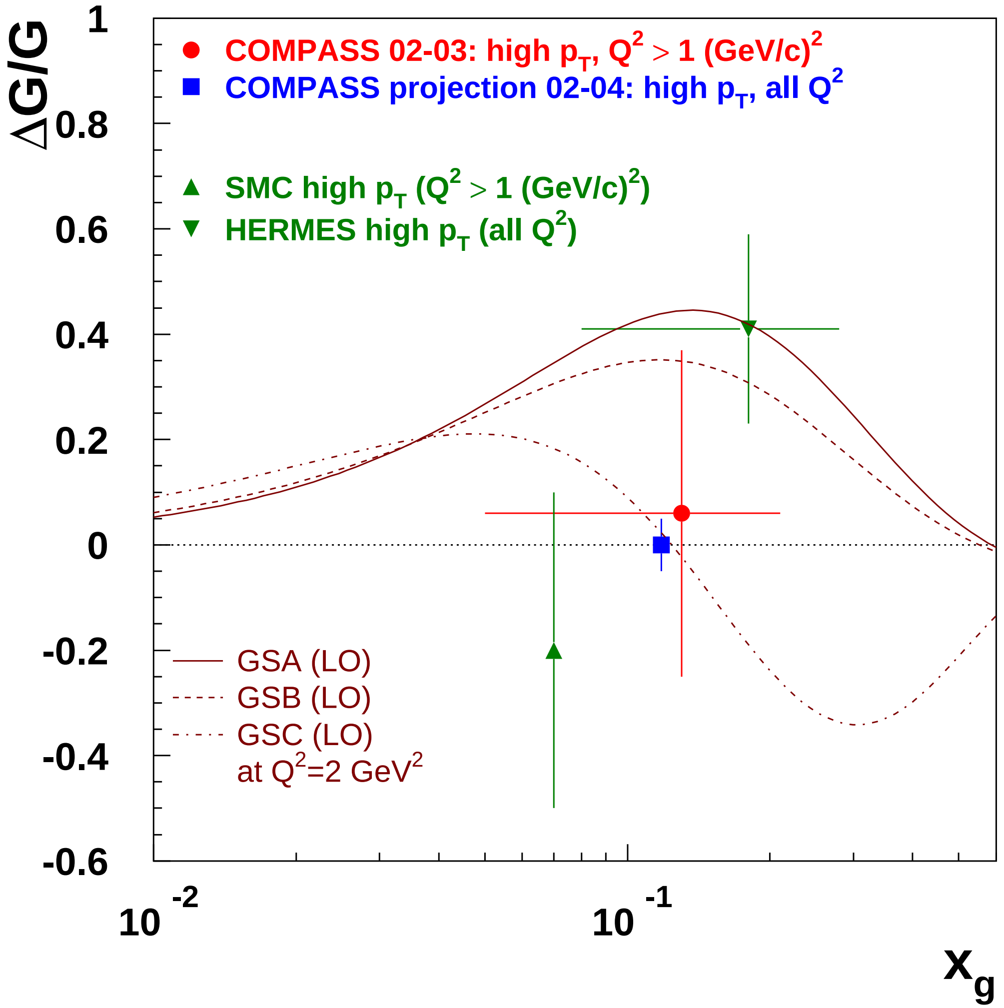


- LEPTO Monte Carlo with RADGEN for $Q^2 > 1\,\text{GeV}^2$
- Description not yet perfect $\Rightarrow$ large systematic error
- Fraction of PGF events determined in LEPTO:

$$\frac{\sigma_{PGF}}{\sigma_{tot}} = 0.34 \pm 0.07$$

$$\langle \frac{\hat{a}_{LL}^{PGF}}{D} \rangle = -0.75 \pm 0.05$$

COMPASS result for $\Delta G/G$



From 2002 and 2003 data:

$$\Delta G/G = 0.06 \pm 0.31(\text{stat.}) \pm 0.06(\text{syst.})$$

$\langle x_g \rangle = 0.13$, RMS $= 0.08$

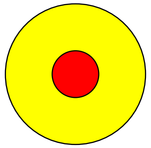
all Q^2 data from 2002–2004:

$\Rightarrow$ Statistical error on $\Delta G/G$ of 5 %

Single high p_t hadron analysis started...

Transversity

Transverse Quark Distribution

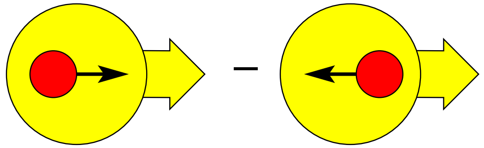
$q(x) =$ 

unpolarized
quark and nucleon

Vector–charge:

$$\langle PS|\overline{\psi}\gamma^{\mu}\psi|PS\rangle = \int_0^1 q(x) - \bar{q}(x)\, dx$$

$q(x)$: Spin averaged
well known

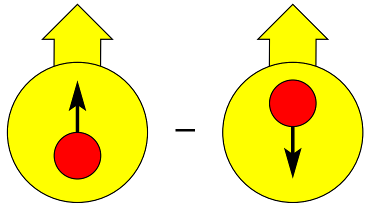
$\Delta q(x) =$ 

longitudinally polarized
quark and nucleon

Axial–charge:

$$\langle PS|\overline{\psi}\gamma^{\mu}\gamma_5\psi|PS\rangle = \int_0^1 \Delta q(x) + \Delta\bar{q}(x)\, dx$$

$\Delta q(x)$: Helicity difference
known

$\Delta_T q(x) =$ 

transversely polarized
quark and nucleon

Tensor–charge:

$$\langle PS|\overline{\psi}\sigma^{\mu\nu}\gamma_5\psi|PS\rangle = \int_0^1 \Delta_T q(x) - \Delta_T\bar{q}(x)\, dx$$

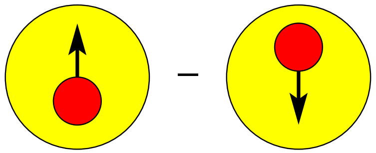
$\Delta_T q(x)$: Helicity flip
unknown

All three PDFs equally important to describe the nucleon $\Rightarrow$ measure transversity

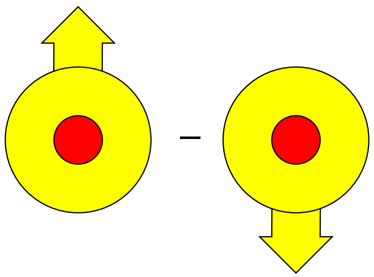
Measurement of the Quark Transversity

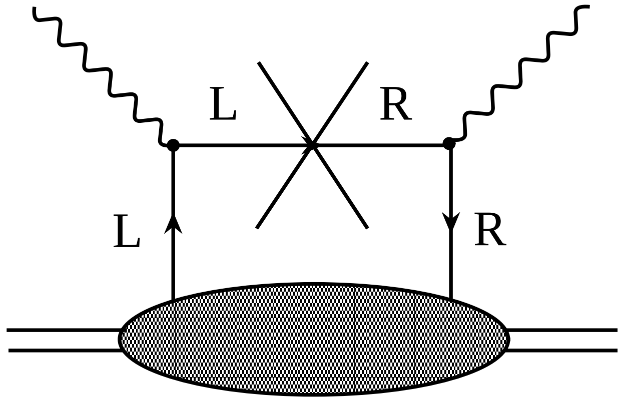
- Transversity can not be measured in inclusive DIS as quark helicity must flip $\Rightarrow$ SIDIS

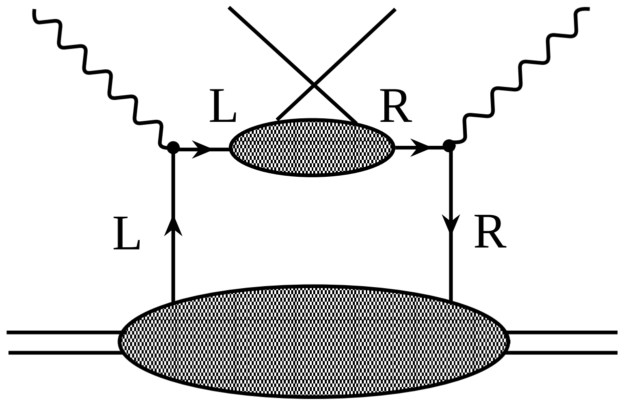
- Measure polarisation of struck quark, e.g. by measuring azimuthal asymmetries of produced hadrons $\Rightarrow$ Collins–Effect

$\Delta D =$ 

- Such an asymmetry can also come from unpolarized quarks with transverse momentum $\Rightarrow$ Sivers–Effect

$f_{1T}^{q} =$ 





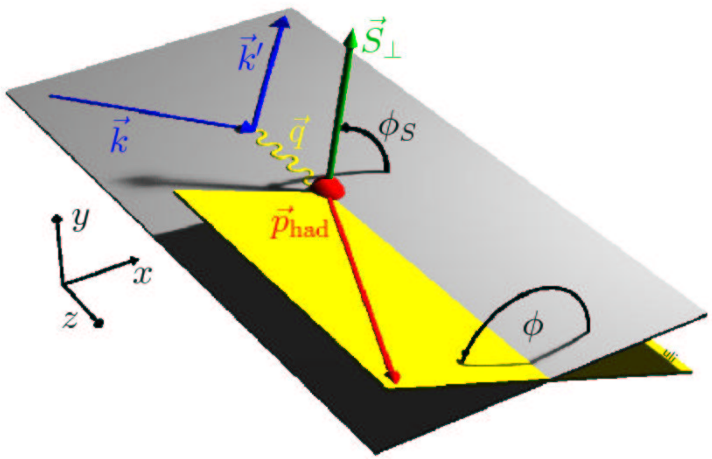
Collins and Sivers Effect

Using a transversely polarized target allows to disentangle Collins and Sivers–Effect.

$$A_T^h = \frac{1}{|S_T|}\frac{\sigma^{\Uparrow}-\sigma^{\Downarrow}}{\sigma^{\Uparrow}+\sigma^{\Downarrow}}$$

$$\sim \ldots\sin(\phi+\phi_s-\pi)\frac{\sum_i e_i^2\Delta_T q_i(x)\Delta D_{q_i}^h(z)}{\sum_i e_i^2 q_i(x) D_{q_i}^h(z)} \quad \text{Collins–Effect}$$

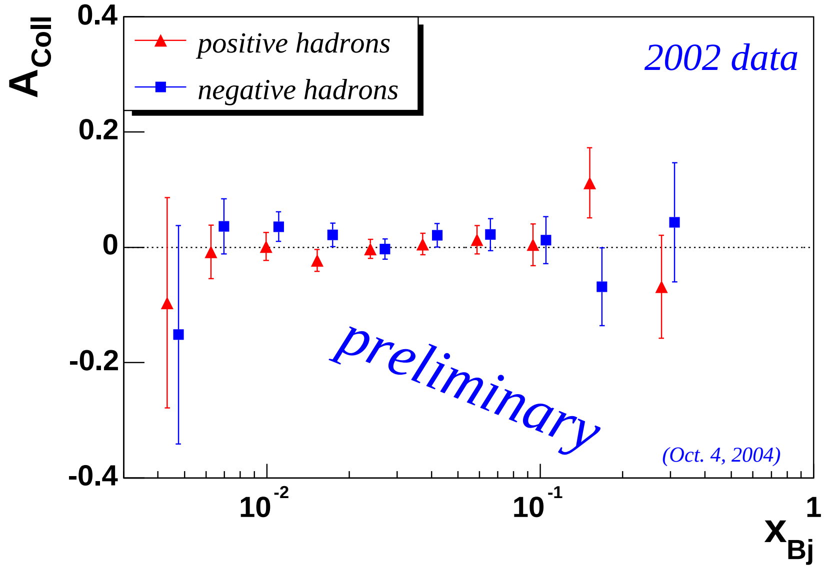
$$+\ldots\sin(\phi-\phi_s)\frac{\sum_i e_i^2 f_{1T}^{\perp i}(x) D_{q_i}^h(z)}{\sum_i e_i^2 q_i(x) D_{q_i}^h(z)} \quad \text{Sivers–Effect}$$

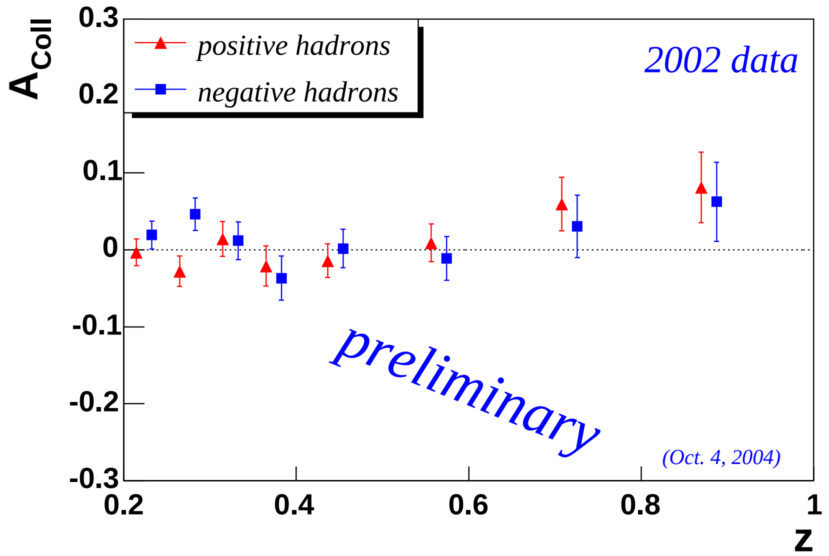


- $\Delta_T q_i(x)$ transversity DF
- $f_{1T}^{\perp i}(x)$ Sivers DF
- $q_i(x)$ unpolarized DF
- $\Delta D_{q_i}^h(z)$ Collins FF
- $D_{q_i}^h(z)$ unpolarized FF

Measure Collins FF in other reactions (e.g. $e^+e^- \to hh$)
Measure Collins–Effect at different values of x_{Bj}

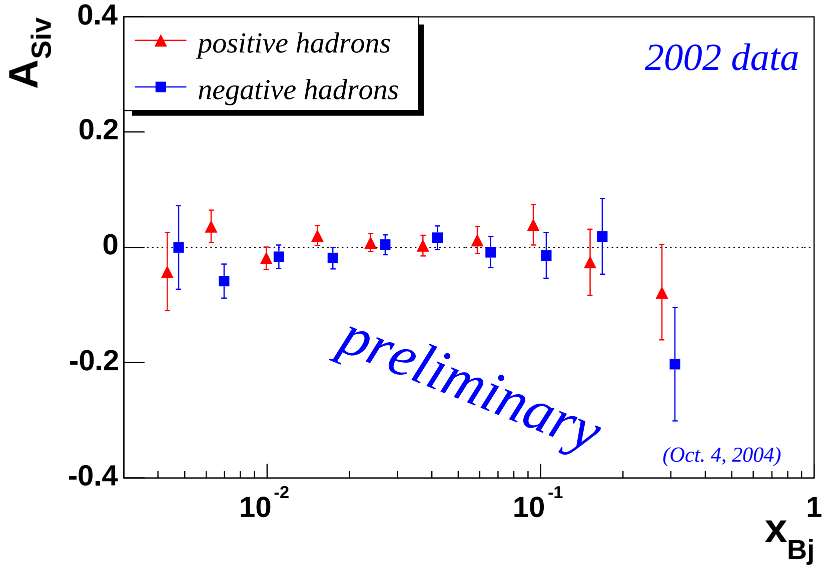
First Measurement of Collins–Asymmetry on Deuteron

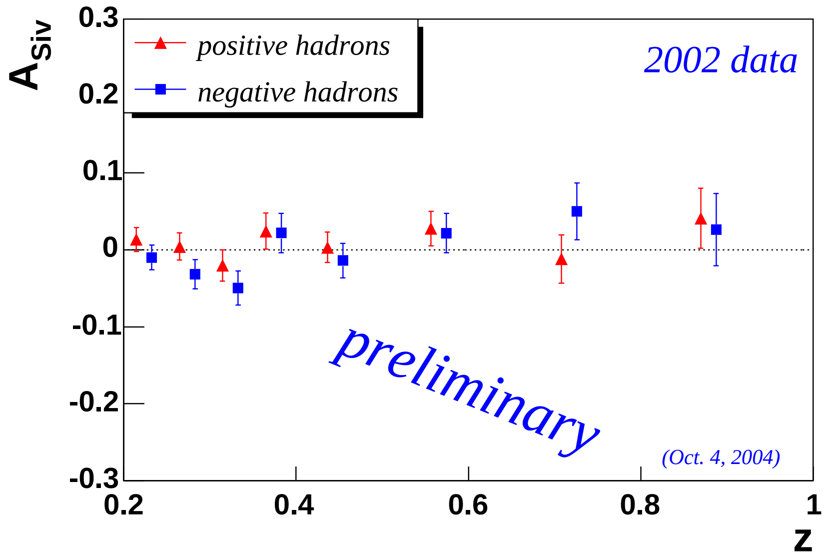




- Asymmetry seems to be small but in non relativistic limit $h_1 \rightarrow g_1$:
  - Cancellation $A^p_{Coll} \approx -A^n_{Coll}$
  - Collins fragmentation function $\Delta D^h_{q_i}$ is small
- Measure with proton target
- Use different quark polarimeter:
  - Measure transverse polarization of Λ
  - Azimuthal dependence of plane of leading and next to leading hadron

First Measurement of Sivers–Asymmetry on Deuteron





- Sivers–asymmetry seems to be small

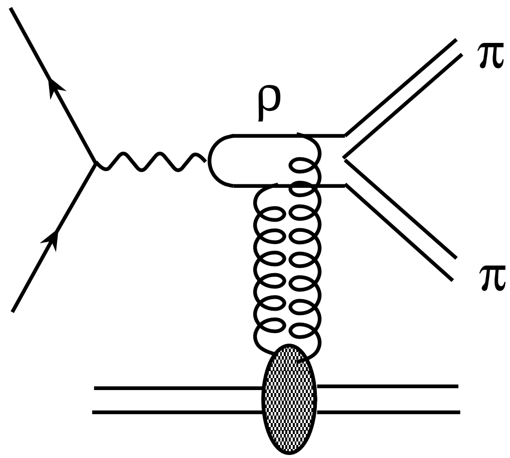
$\Rightarrow$ Sivers distribution function of the deuteron is small

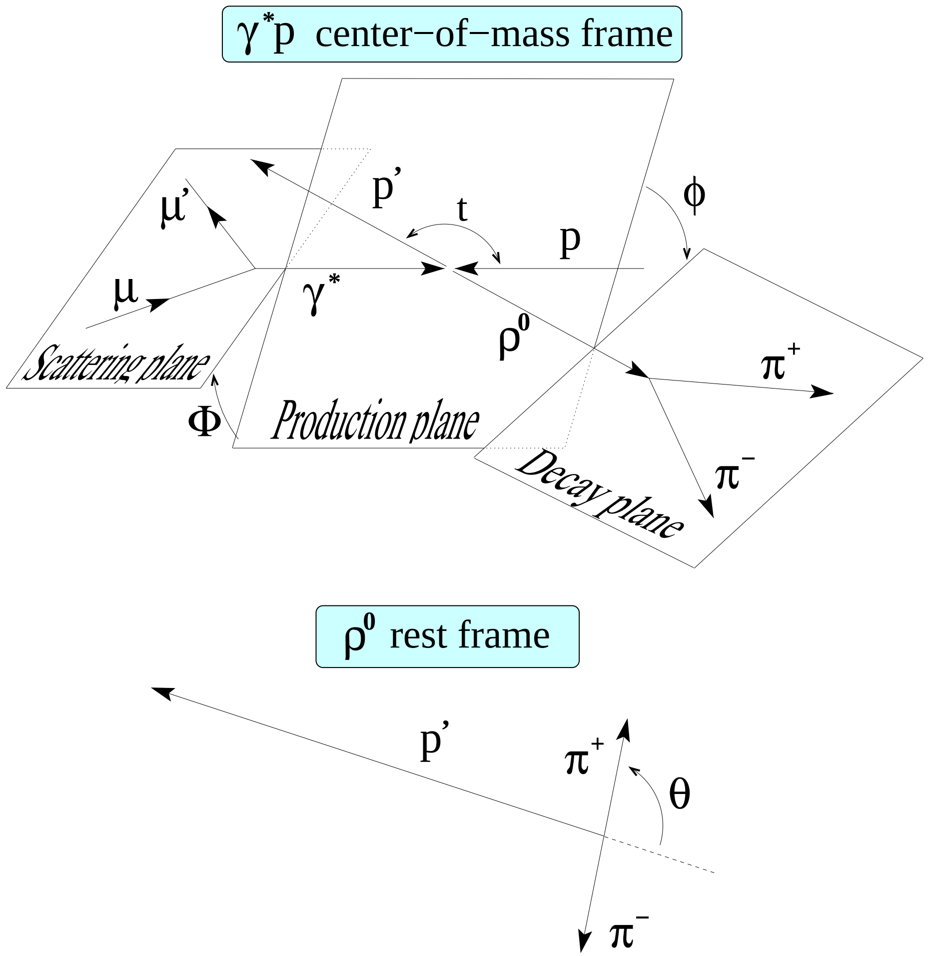
- Measure with proton target

Exclusive ρ^0 Production

Exclusive ρ^0 Production

- Incoherent ρ^0 production:
  $\mu + N \rightarrow \mu' + N' + \rho^0$

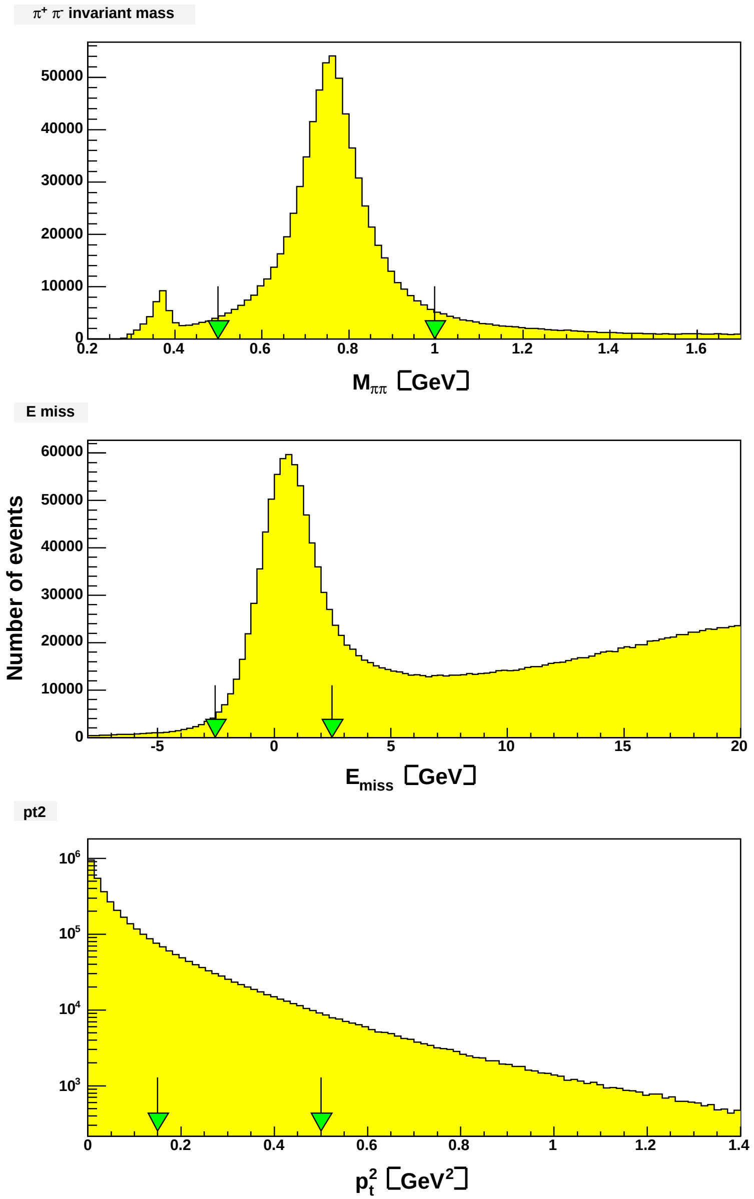




- Determination of Spin–Density–Matrix of ρ^0 from $W(\cos\theta, \phi, \Phi)$
- Check s–channel helicity conservation (helicity of γ^* entirely transfered to ρ^0)
- Determination $R = \sigma_L/\sigma_T$ assuming SCHC

also used $\psi = \phi - \Phi$

Data Selection



- Topology:
  beam track + scattered muon + 2 additional tracks of opposite charge (assume π)
- Kinematical Cuts:
  - $E'_\mu > 20$ GeV
  - $Q^2 > 0.01$ GeV^2
  - $\nu > 30$ GeV
- Hadron Cuts:
  - $0.5 < m_{\pi\pi} < 1$ GeV
  - $-2.5 < E_{miss} < 2.5$ GeV
  - $0.15 < p_t^2 < 0.5$ GeV^2
- 695 500 events selected from 2002 data
- 3d–analysis will be done in future ⇒ 1d–angular distributions

Measured Angular Distributions

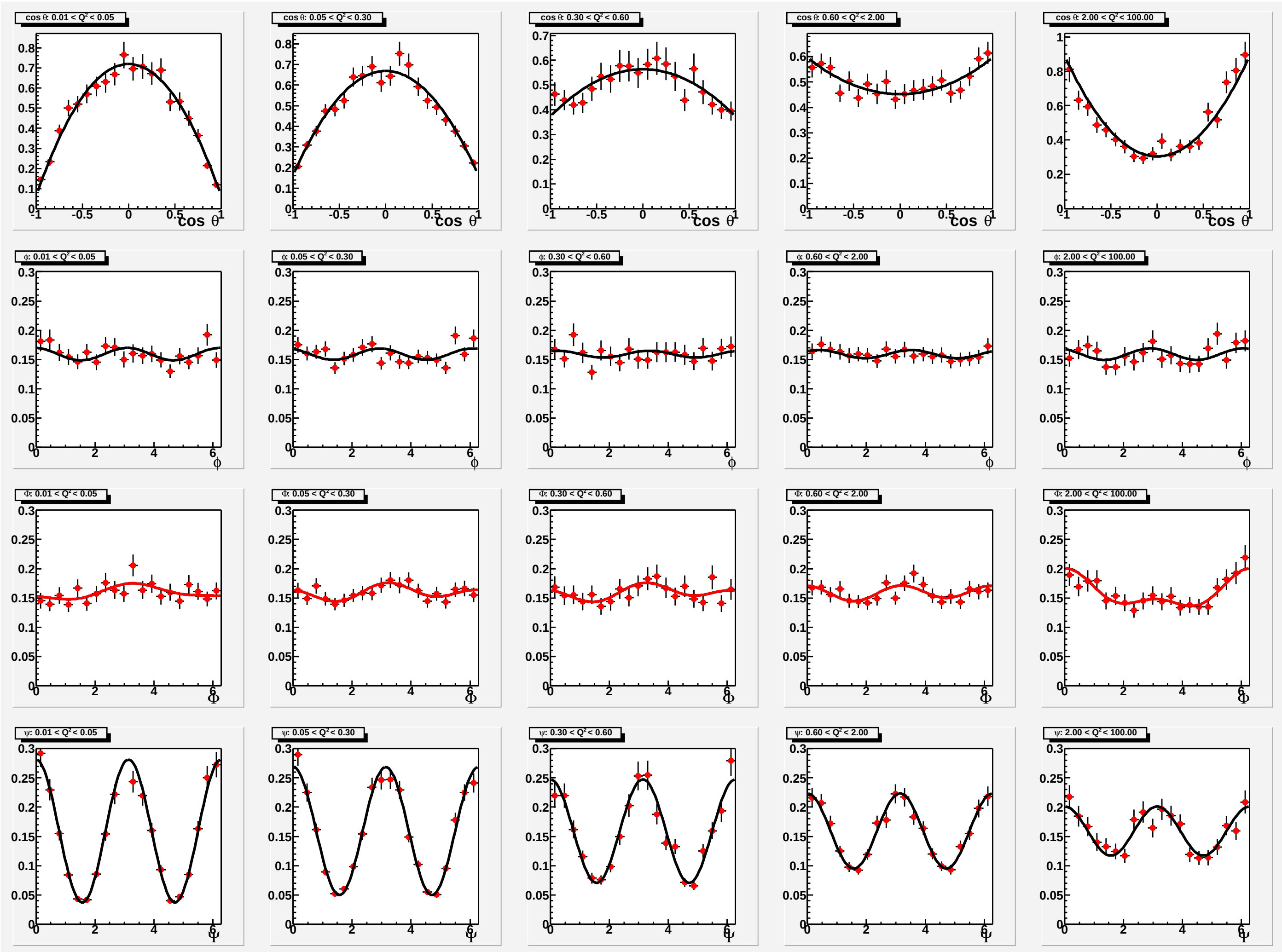
0.01 < Q^2 < 0.05 < Q^2 < 0.3 < Q^2 < 0.6 < Q^2 < 2.0 < Q^2

$\cos\theta$

ϕ

Φ

ψ

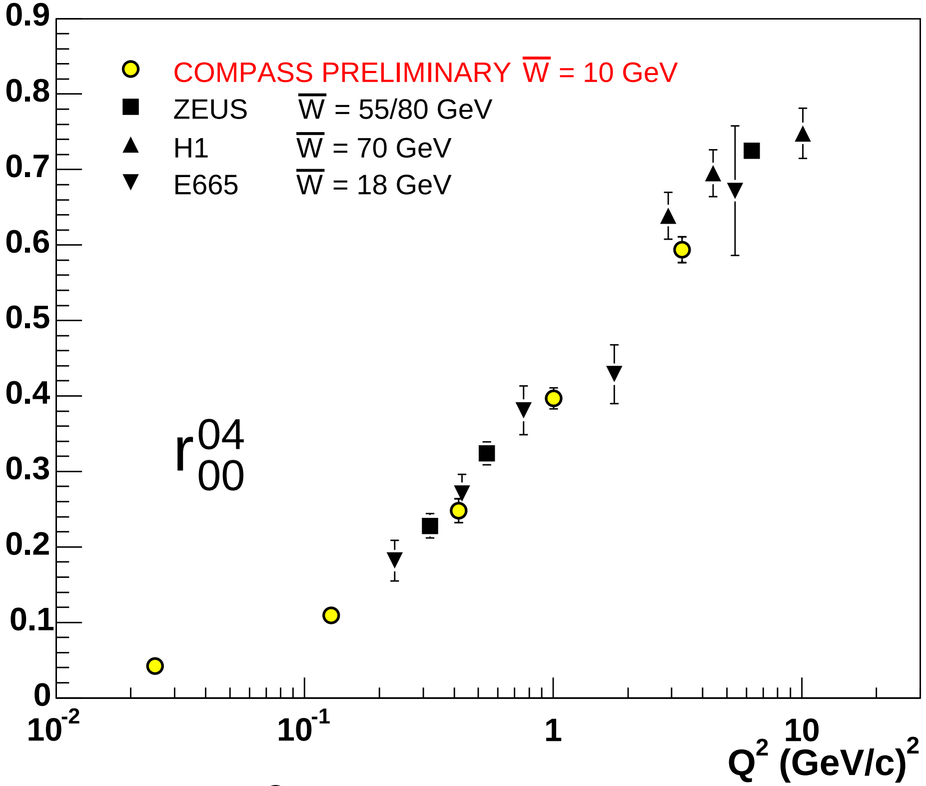


Acceptance and smearing corrected.

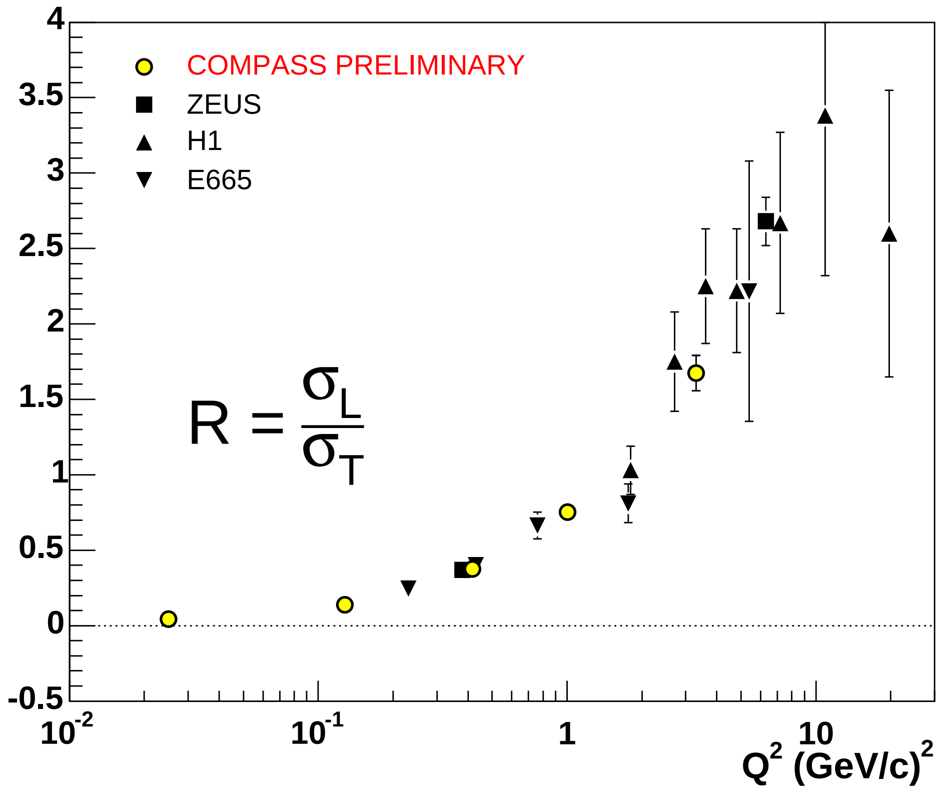
Results

if SCHC is assumed:

$$r^{04}_{00} = \frac{(\epsilon+\delta)R}{1+(\epsilon+\delta)R}$$

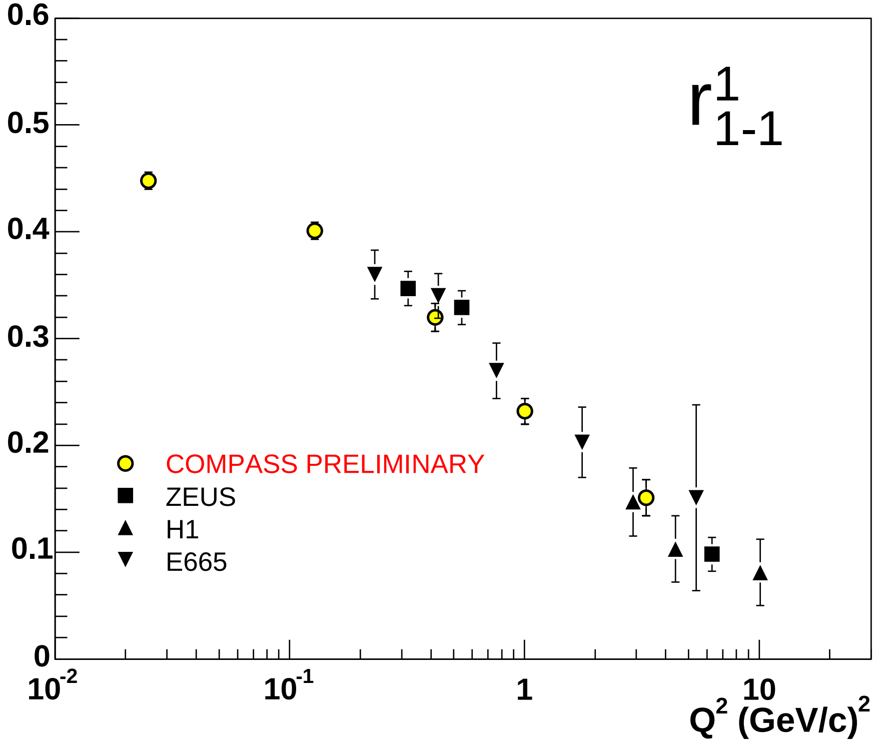


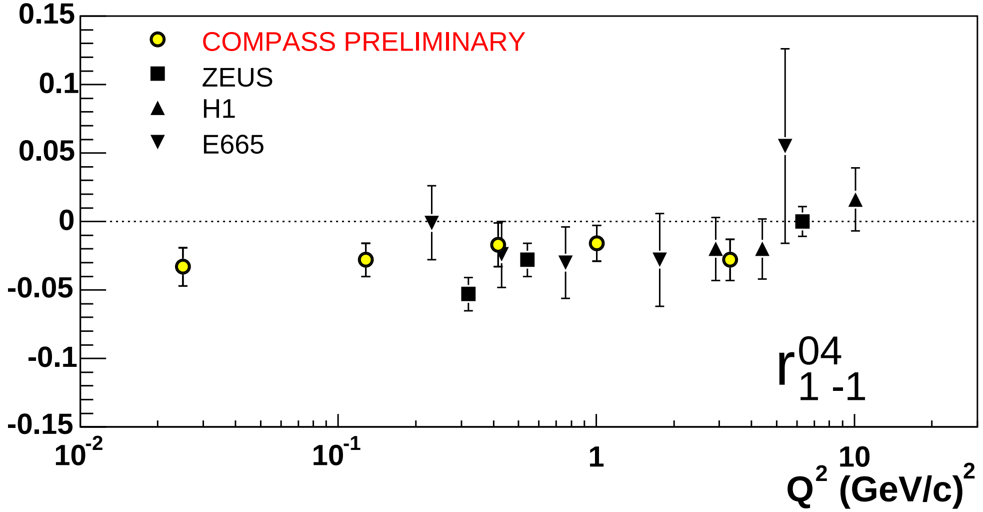
$$W(\cos\theta) = \frac{3}{4}[(1-r^{04}_{00}) + (3r^{04}_{00}-1)\cos^2\theta]$$

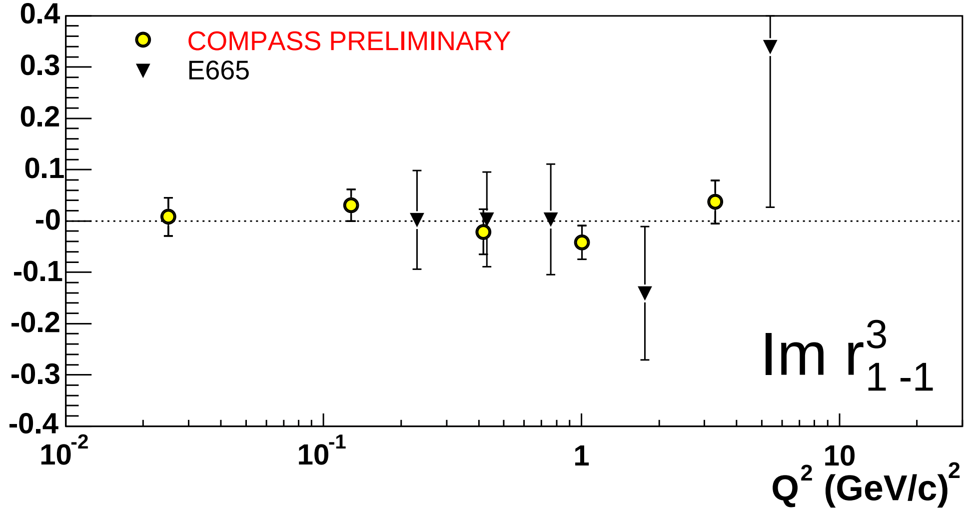


Results

$$W(\psi) = \frac{1}{2\pi}[1 + 2\epsilon r^{1}_{1-1}\cos(2\psi)]$$



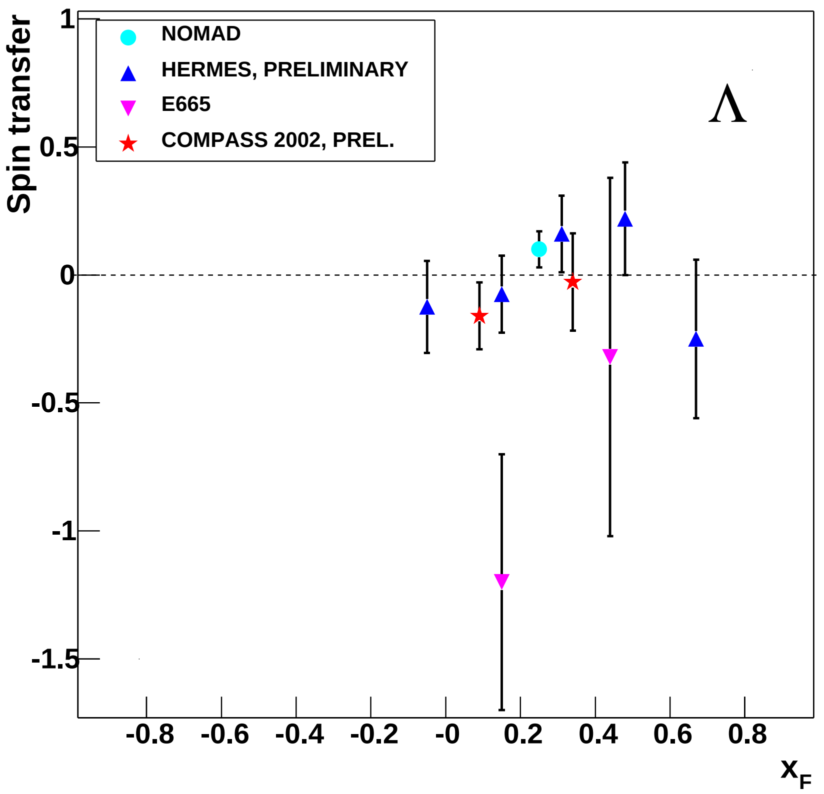


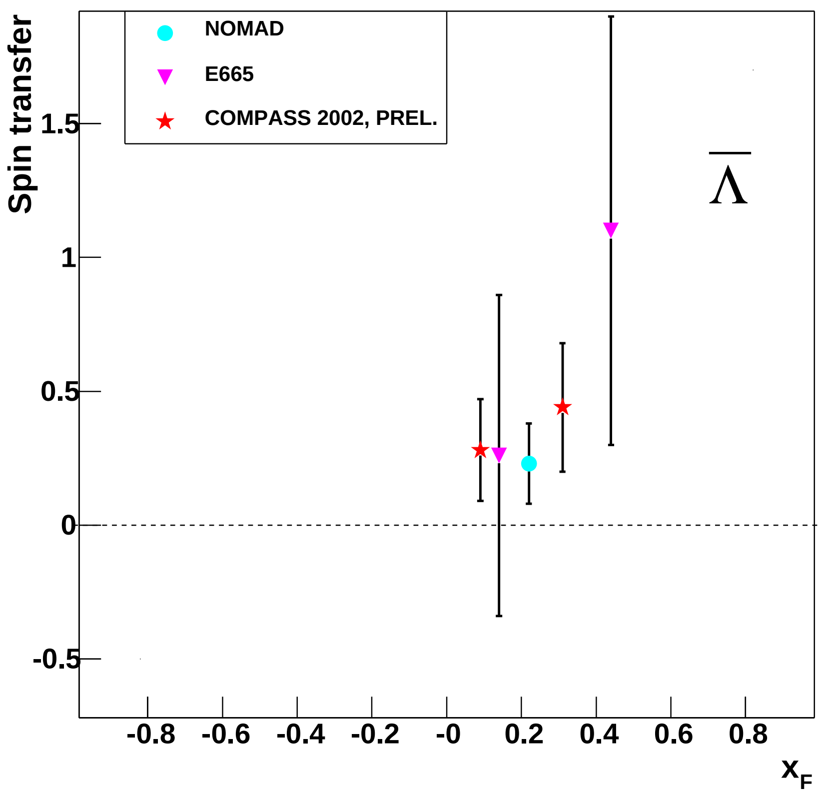


$$W(\phi) = \frac{1}{2\pi}[1 - 2r^{04}_{1-1}\cos(2\phi) + 2P_\mu\sqrt{1-\epsilon^2}Im(r^{3}_{1-1})\sin(2\phi)]$$ if SCHC $\Leftrightarrow r^{04}_{1-1} \equiv 0$

More Results on ...

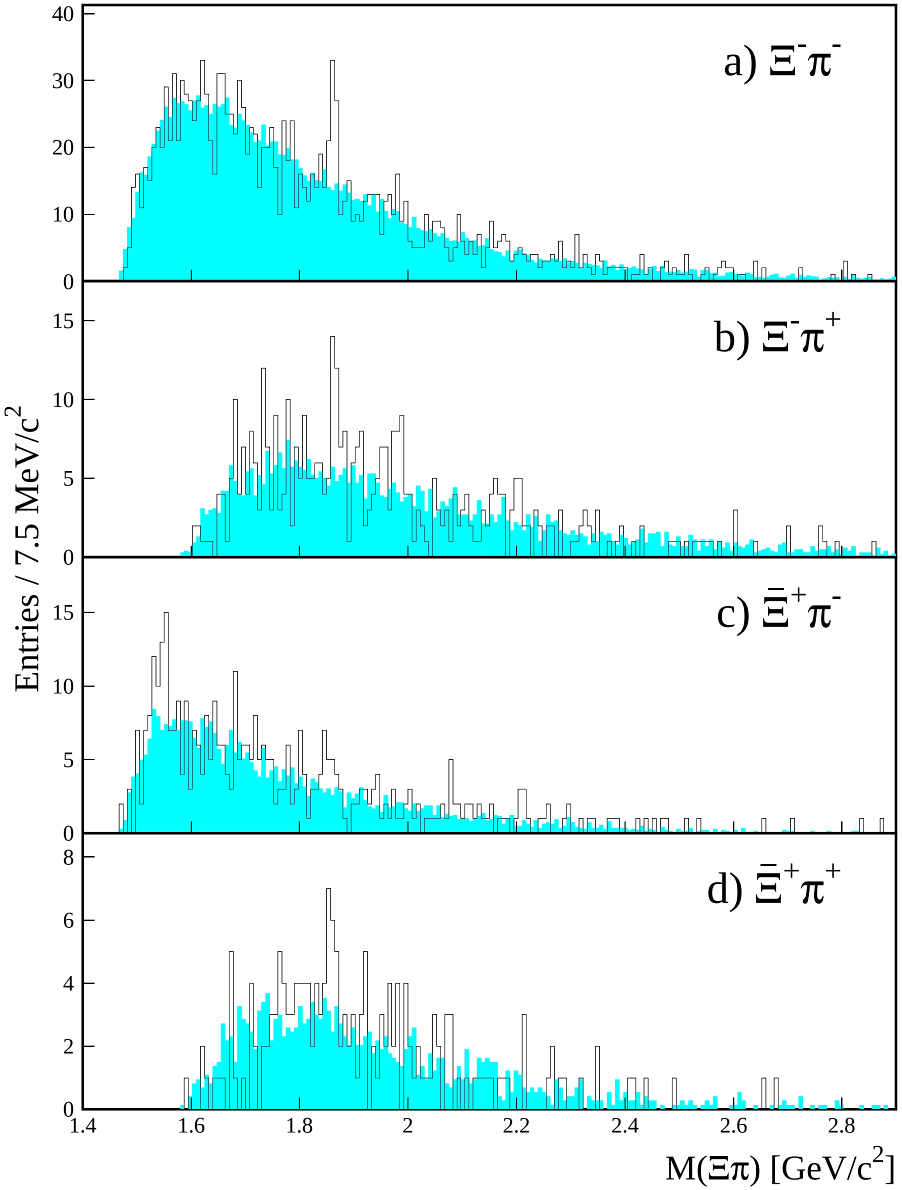
- Λ–physics (2002):
  - Transversal polarisation 185 k Λ, 97 k $\overline{\Lambda}$ (all Q^2)
  - Longitudinal polarisation 8000 Λ, 5000 $\overline{\Lambda}$ ($Q^2 > 1\,\mathrm{GeV}^2$)
    in current fragmentation region observe spin transfer $q \rightarrow \Lambda$



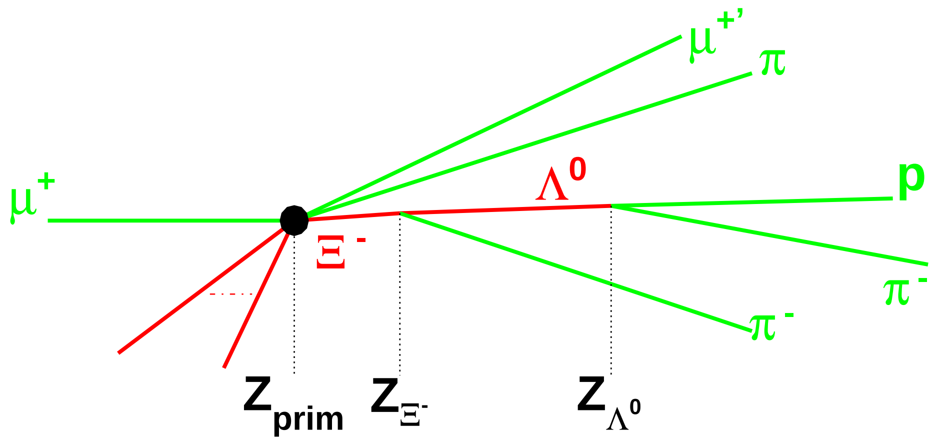


$$S = \frac{P_\Lambda}{P_B D}$$

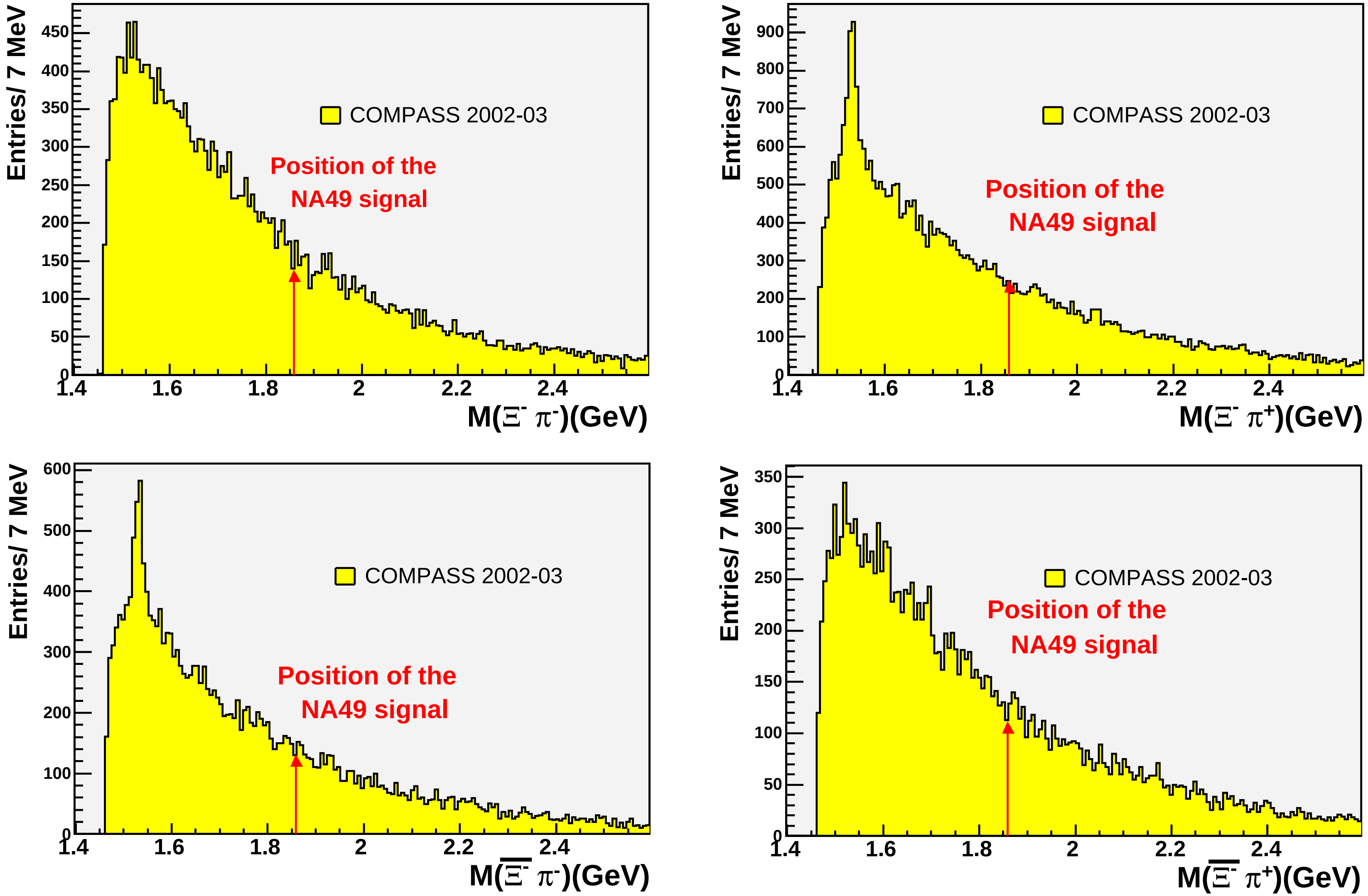
More Results on ... Pentaquarks



- $\Xi^{--} \rightarrow \Xi^-\pi^- \rightarrow \Lambda\pi^-\pi^- \rightarrow p\pi^+\pi^-\pi^-$
- $\Xi^{--}_{3/2} = (ddss\bar{u})$ with $S = 2$
- NA49: 4.2σ evidence at 1862 MeV Phys.Rev.Lett 92(2004)042993
- WA89 and Hera–B can not confirm



More Results on ... Pentaquarks



No Ξ^{--} seen

nice signal for Ξ^{0*} and $\overline{\Xi^{0*}}$

Normalising to Ξ^{-} signal we expect 400 Ξ^{--}

With confidence of 99 % we have less than 70 Ξ^{--}

for $\Xi^{-}\pi$ $-0.05 < x_F < 0.5$

Summary and Outlook

- CERN is again contributing to the nucleon spin puzzle (EMC, SMC, COMPASS)
- COMPASS is a technically challenging experiment:
  - Modern detector technologies and readout
  - High data rate (>60 MByte/s), 300 TByte per year
- First physics results have been produced
- Much more to come ...
- Pilot hadron run started ⇒ Primakoff: π–polarizability, diffractive
- Foreseen to run up to the end of the mid–term plan of CERN (2006–2010)
- During technical stop in 2005 improvement of apparatus:
  - New polarised target magnet ⇒ larger acceptance
  - New RICH readout ⇒ improved particle ID

COMPASS has a large potential, and waits for beam ...

Thanks for the Opportunity

1998

2004