

# Gluon Polarization Measurements in COMPASS

Bernhard Ketzer

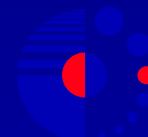
Technische Universität München / CERN  
*on behalf of the COMPASS collaboration*

Gordon Research Conference on Photonuclear Reactions  
1 - 6 August 2004

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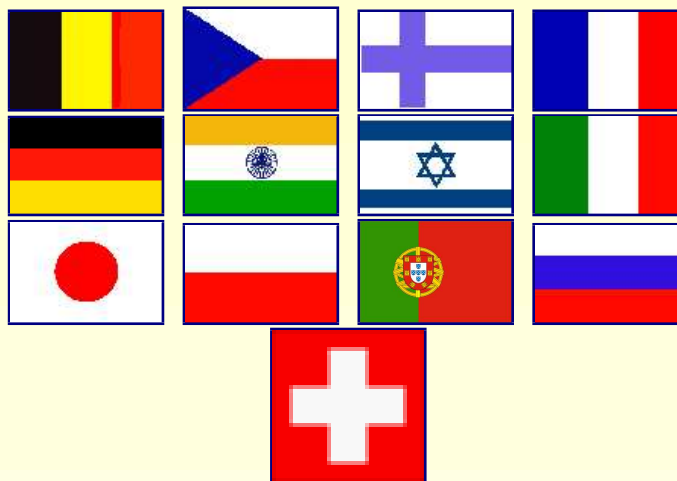
## Outline

- Physics Program
- Spin of the Nucleon
- COMPASS Spectrometer
- Open Charm Production
- High  $p_T$  Hadron Pairs
- Summary and Outlook



# The COMPASS Collaboration

COmmon  
Muon and  
Proton  
Apparatus for  
Structure and  
Spectroscopy



220 physicists

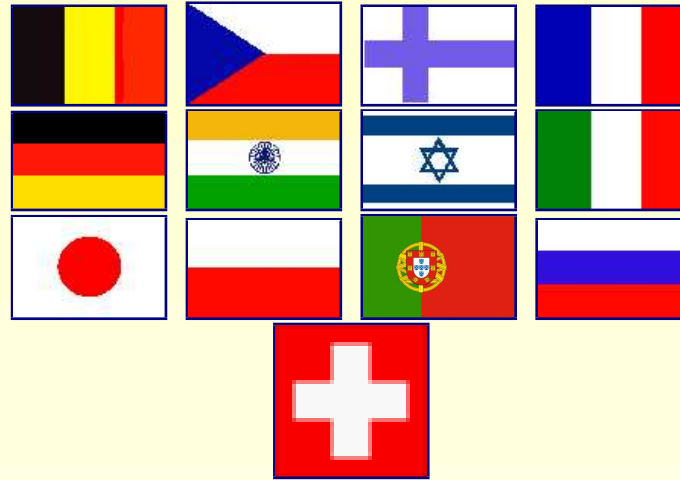
28 institutes

13 countries

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$Q^2$



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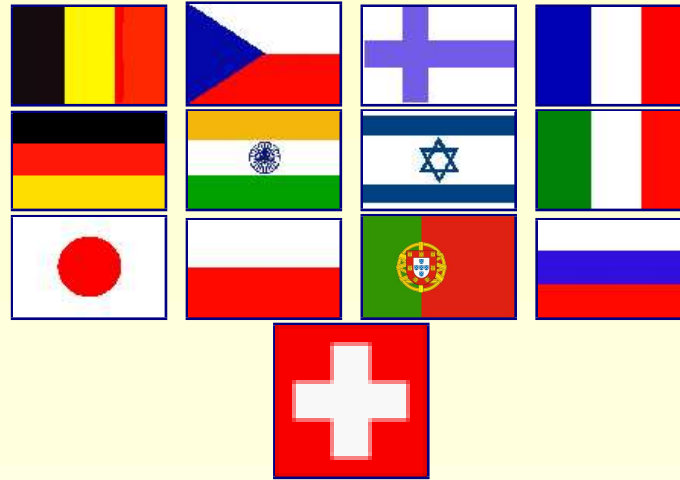
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## Scattering

- Strong interaction at large distances
- Effective field theories, e.g.  $\chi$ PT
  - Polarizabilities of  $p$ ,  $\pi$ ,  $K$
  - Radiative transitions of  $\pi$ ,  $K$
  - Chiral anomaly

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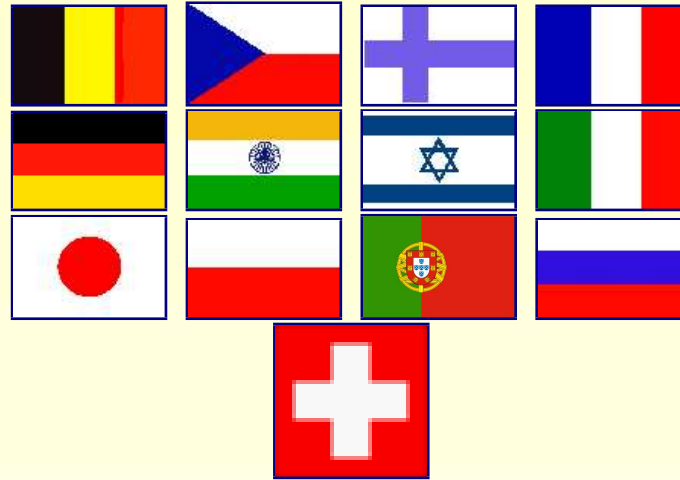
## Spectroscopy

- Mass spectrum of hadrons
- Confinement
  - Gluonic excitations
  - Non- $q\bar{q}$  mesons, hybrids, molecules
  - Heavy – light quark systems: HQET

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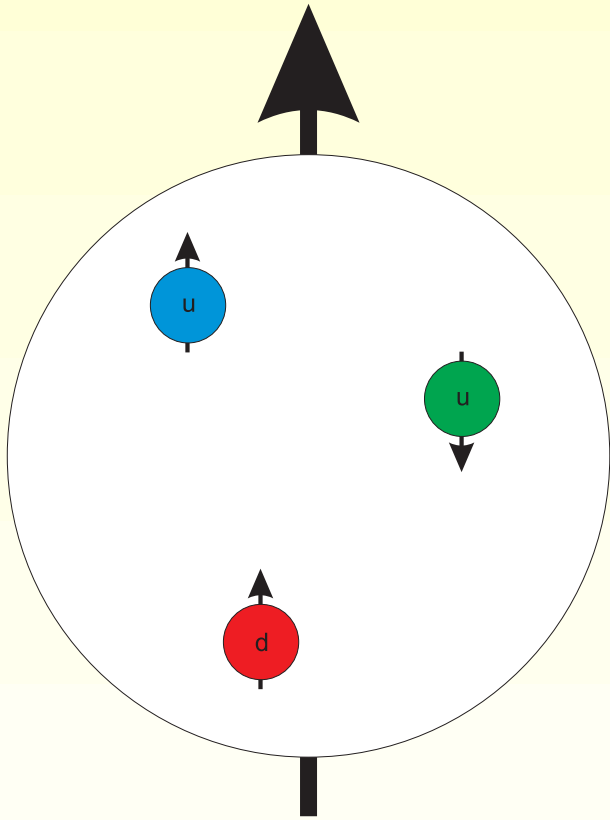
## DIS

- Quasi-free quarks and gluons
- Dynamics of nucleon constituents
  - Gluon contribution  $\Delta G$  to nucleon spin
  - Pol. quark distributions  $\Delta q(x)$
  - Transverse spin distributions  $\Delta_T q(x)$

# The Spin Composition of the Nucleon

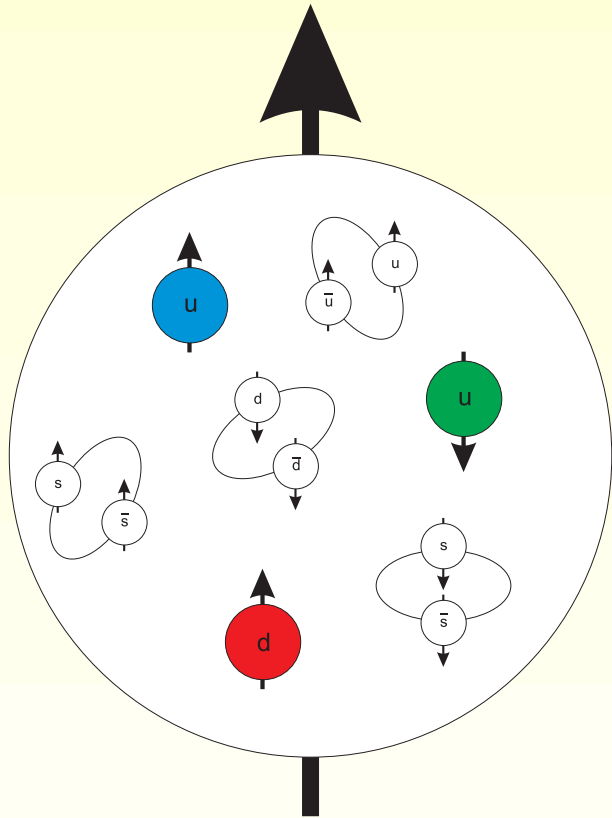
$$\langle S_z \rangle = \frac{1}{2} = \frac{1}{2} \Delta \Sigma$$

- Static constituent quark model:  
 $\Delta \Sigma = \Delta u_v + \Delta d_v = 1, \Delta q = q^\uparrow - q^\downarrow$



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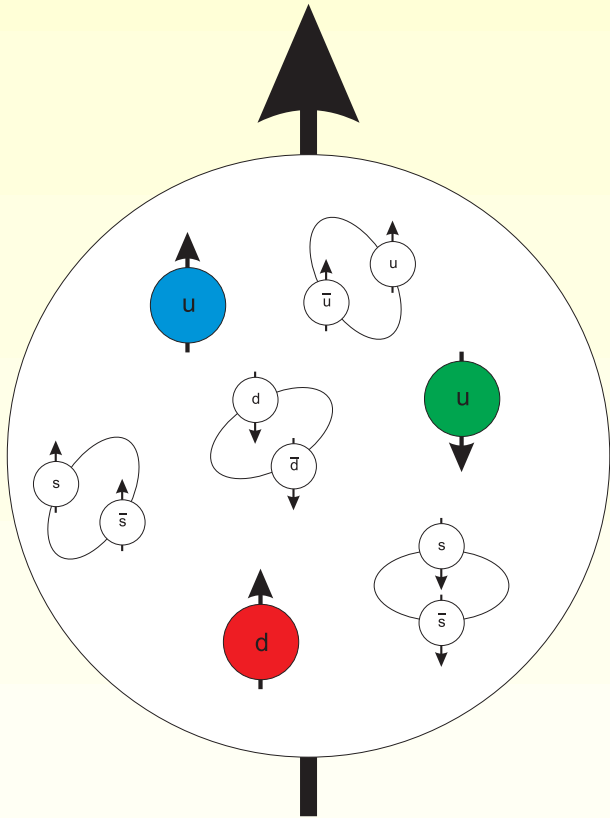


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- QPM +  $SU(3)_f$ : Ellis-Jaffe sum rule  
 $\Delta \Sigma = \Delta u + \Delta d + \Delta s = 0.579 \pm 0.026$   
 $\Delta s = 0$

[Close et al., Phys. Lett. B**316**, 165 (1993)]

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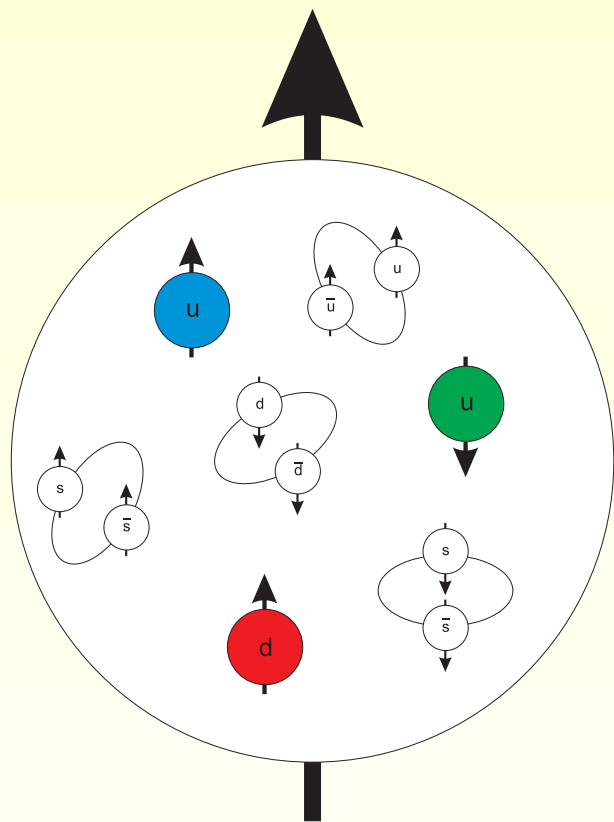


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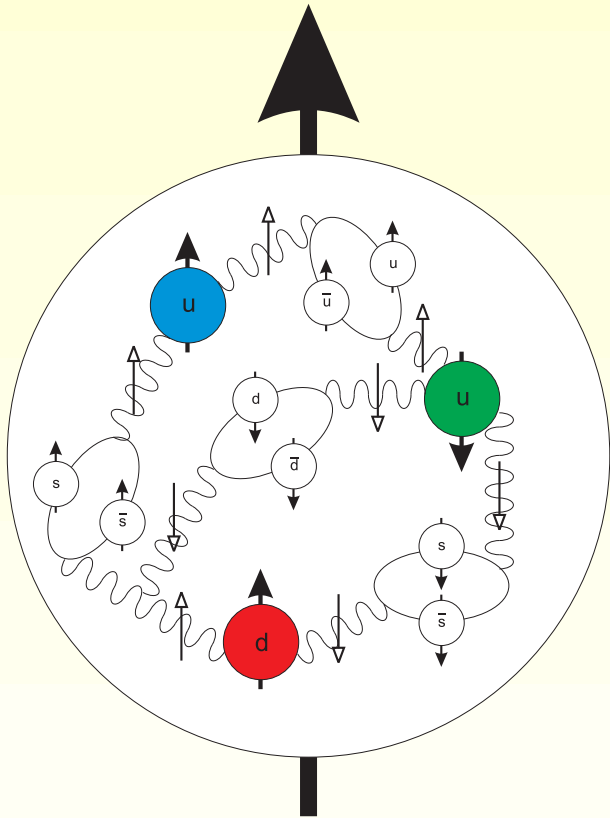


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**Where is the rest?**

# The Spin Composition of the Nucleon

$$\langle S_z \rangle = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G$$



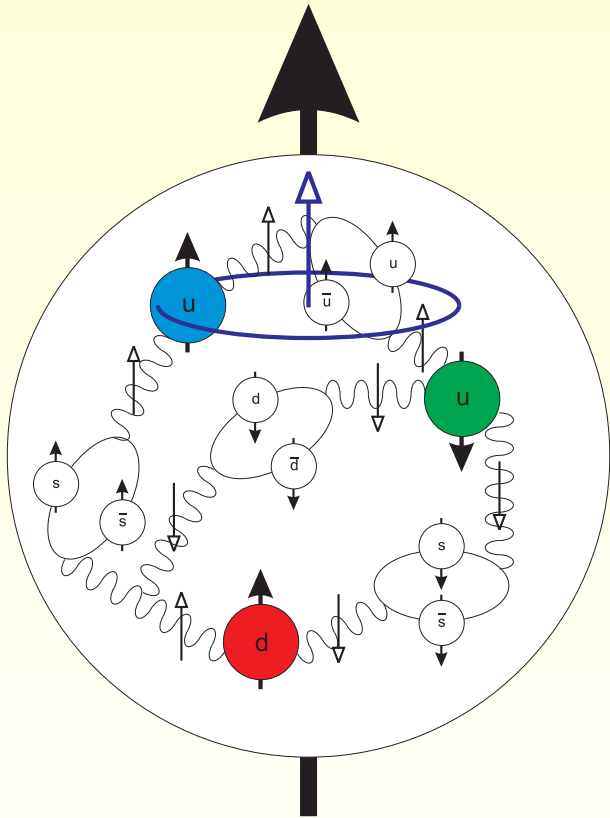
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## Where is the rest?

- Gluon polarization  $\Delta G$

# The Spin Composition of the Nucleon

$$\langle S_z \rangle = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_G$$



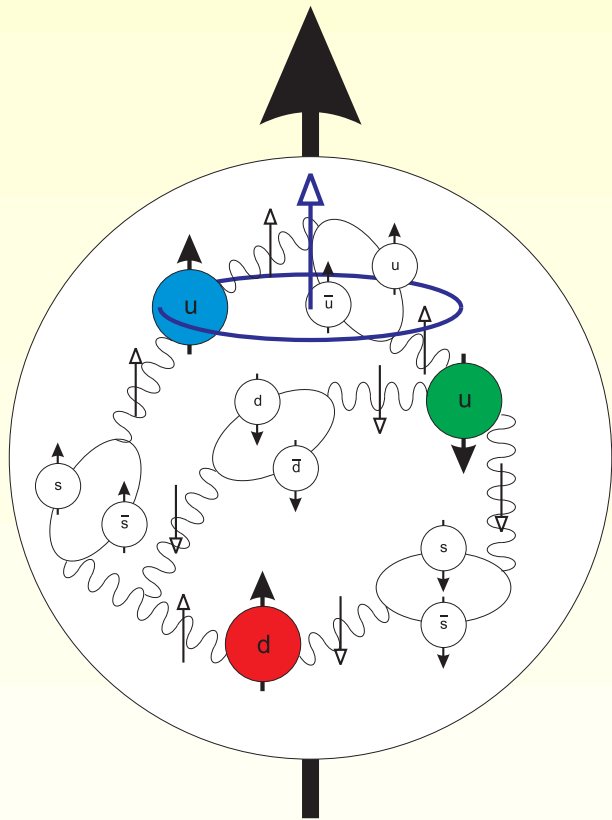
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## Where is the rest?

- Gluon polarization  $\Delta G$
- Orbital angular momenta  $L_q, L_G$

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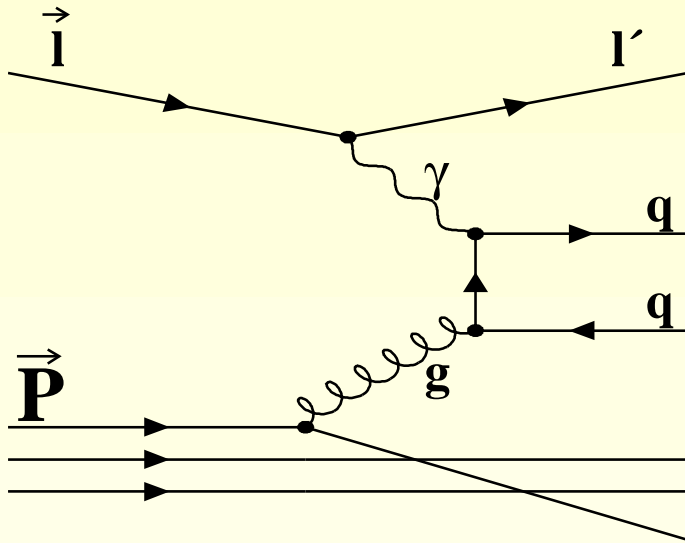
## Where is the rest?

- Gluon polarization  $\Delta G$
- Orbital angular momenta  $L_q, L_g$

**Measure  $\Delta G$ !**

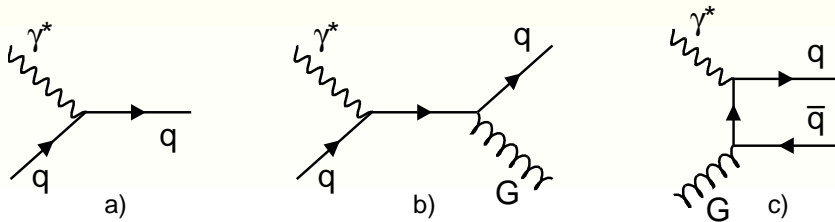
# $\Delta G$ in COMPASS

## Semi-inclusive DIS:



## Double spin asymmetry:

$$A_{PGF} = \frac{N^{\Rightarrow} - N^{\Leftarrow}}{N^{\Rightarrow} + N^{\Leftarrow}}$$



## Open charm production:

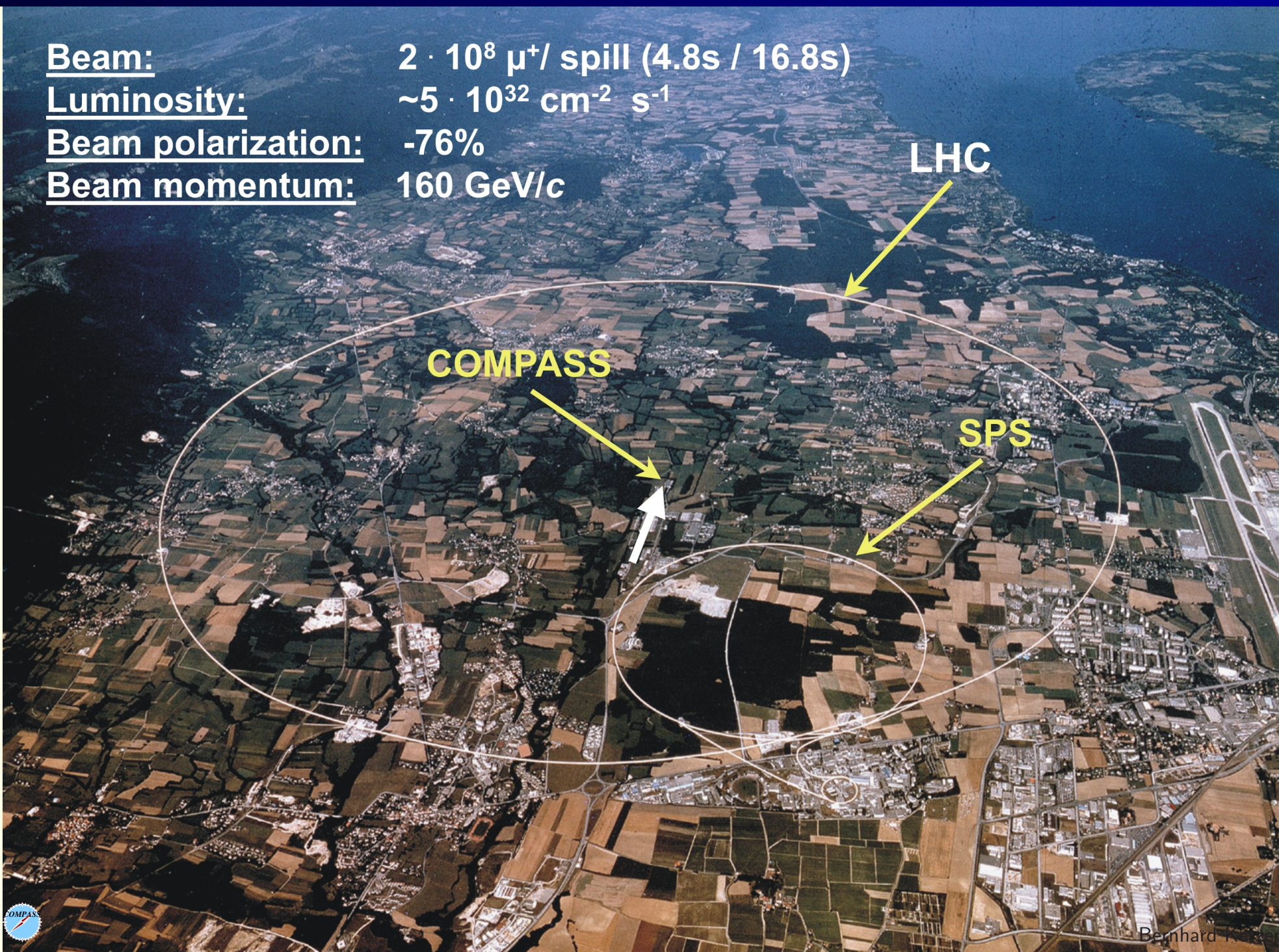
- No constituent charm quarks in nucleon
- Suppressed in hadronization
- In leading order only via PGF
- $\hat{s}_{\min} = 4m_{q_c}^2 \Rightarrow$  theory understood
- Low statistics

## High $p_T$ hadron pairs:

- Light quarks: u, d
- High  $p_T \Rightarrow$  LO DIS suppressed
- Competing process: QCD Compton
- High statistics

# COMPASS at CERN

Beam:  $2 \cdot 10^8 \mu^+$ / spill (4.8s / 16.8s)  
Luminosity:  $\sim 5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$   
Beam polarization: -76%  
Beam momentum: 160 GeV/c

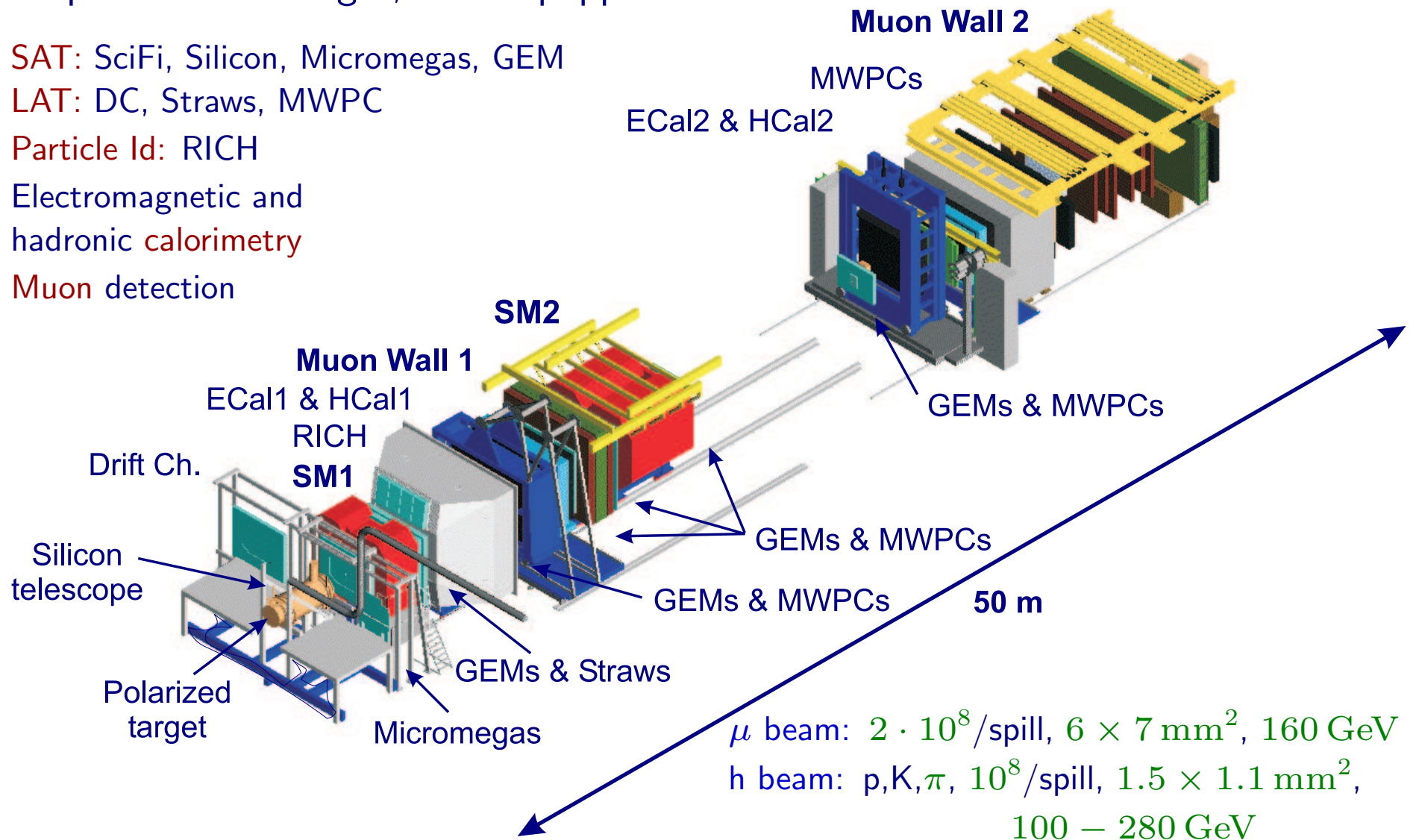


# The COMPASS Spectrometer

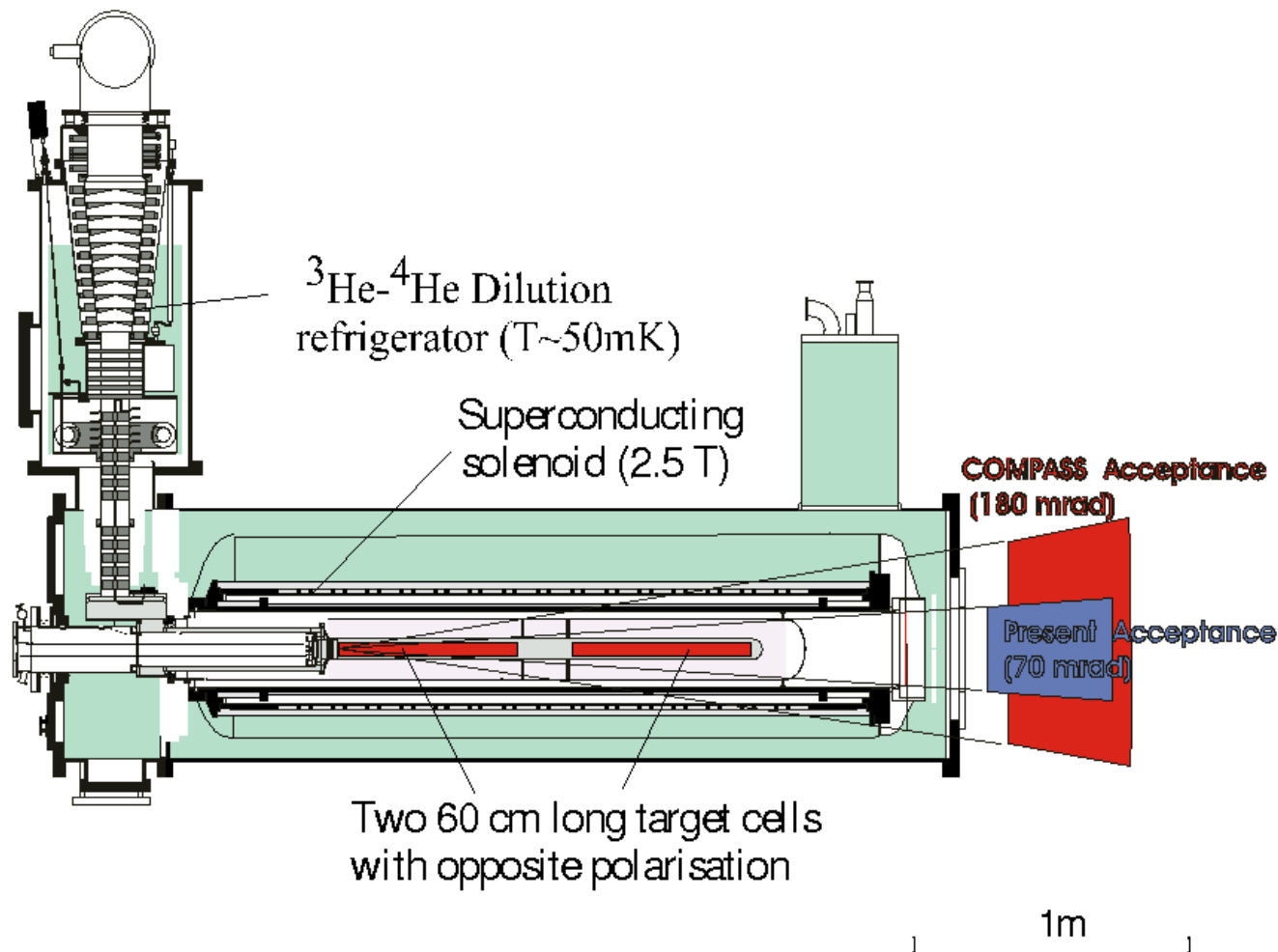
**Fixed target** experiment at the SPS at CERN

Two spectrometer stages, each equipped with

- **SAT**: SciFi, Silicon, Micromegas, GEM
- **LAT**: DC, Straws, MWPC
- **Particle Id**: RICH
- Electromagnetic and hadronic **calorimetry**
- **Muon** detection



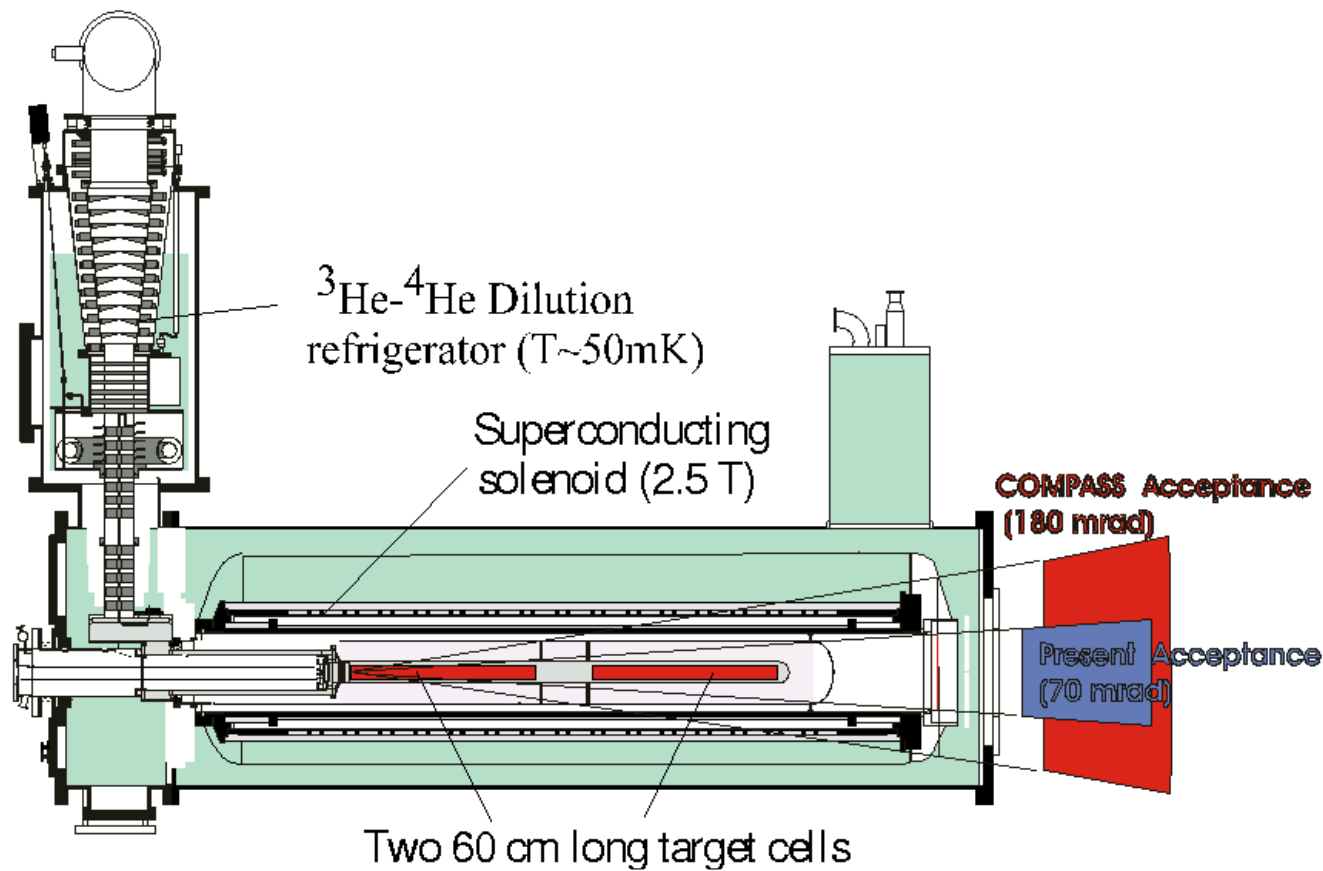
# Polarized Target



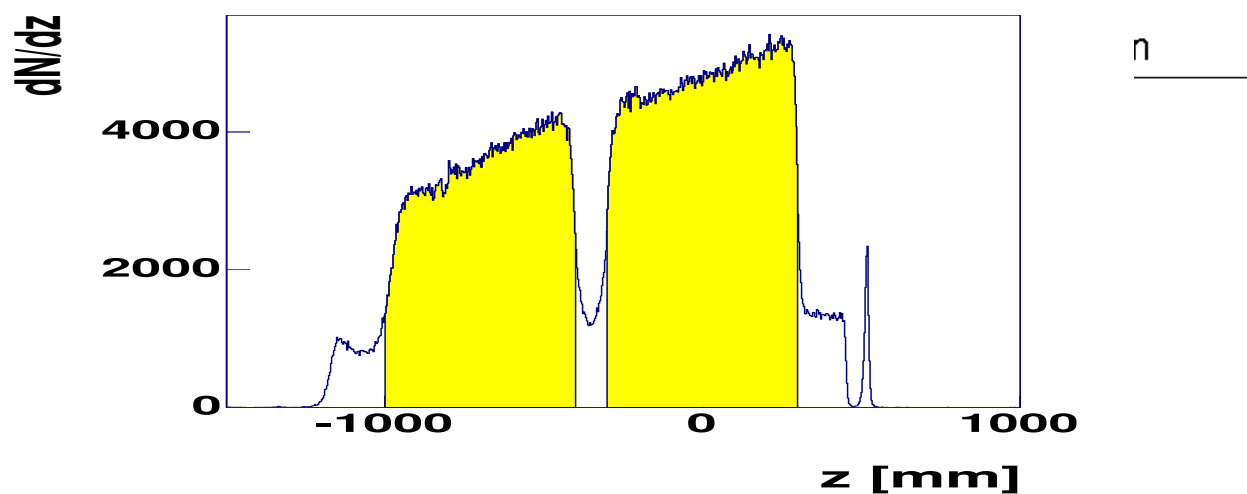
- Solid  $^6\text{LiD}$
- Dilution factor  $f = 40\%$
- Target polarization  $P_t > 50\%$
- Field rotation every 8h



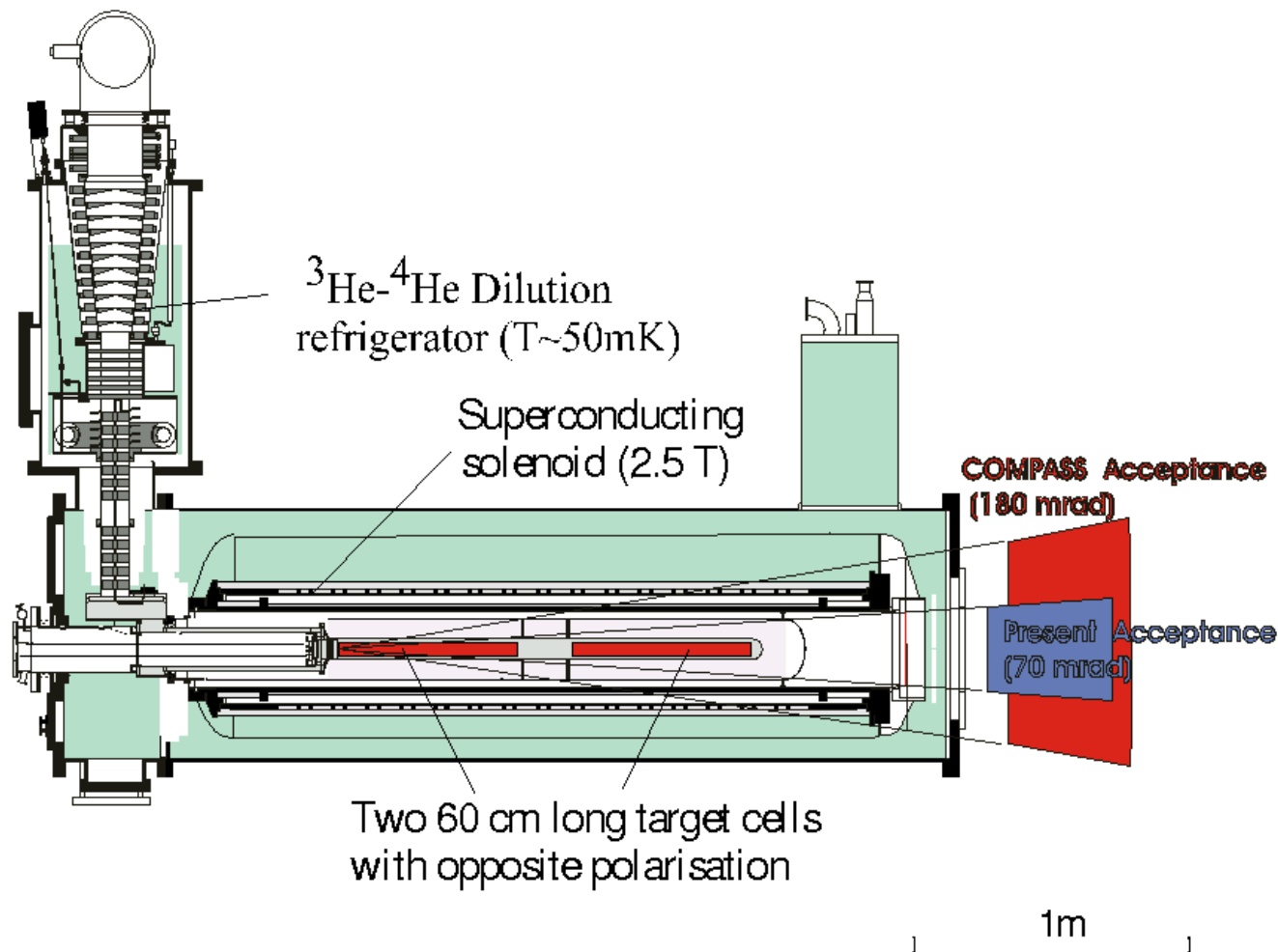
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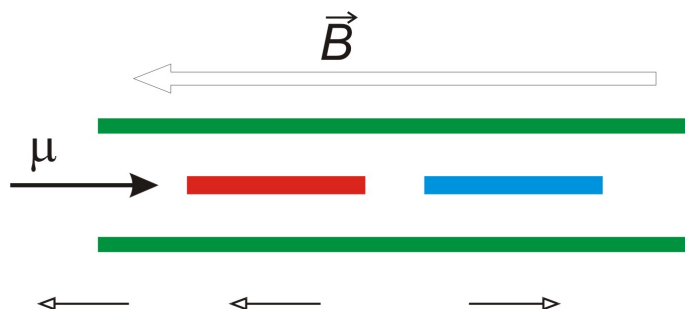
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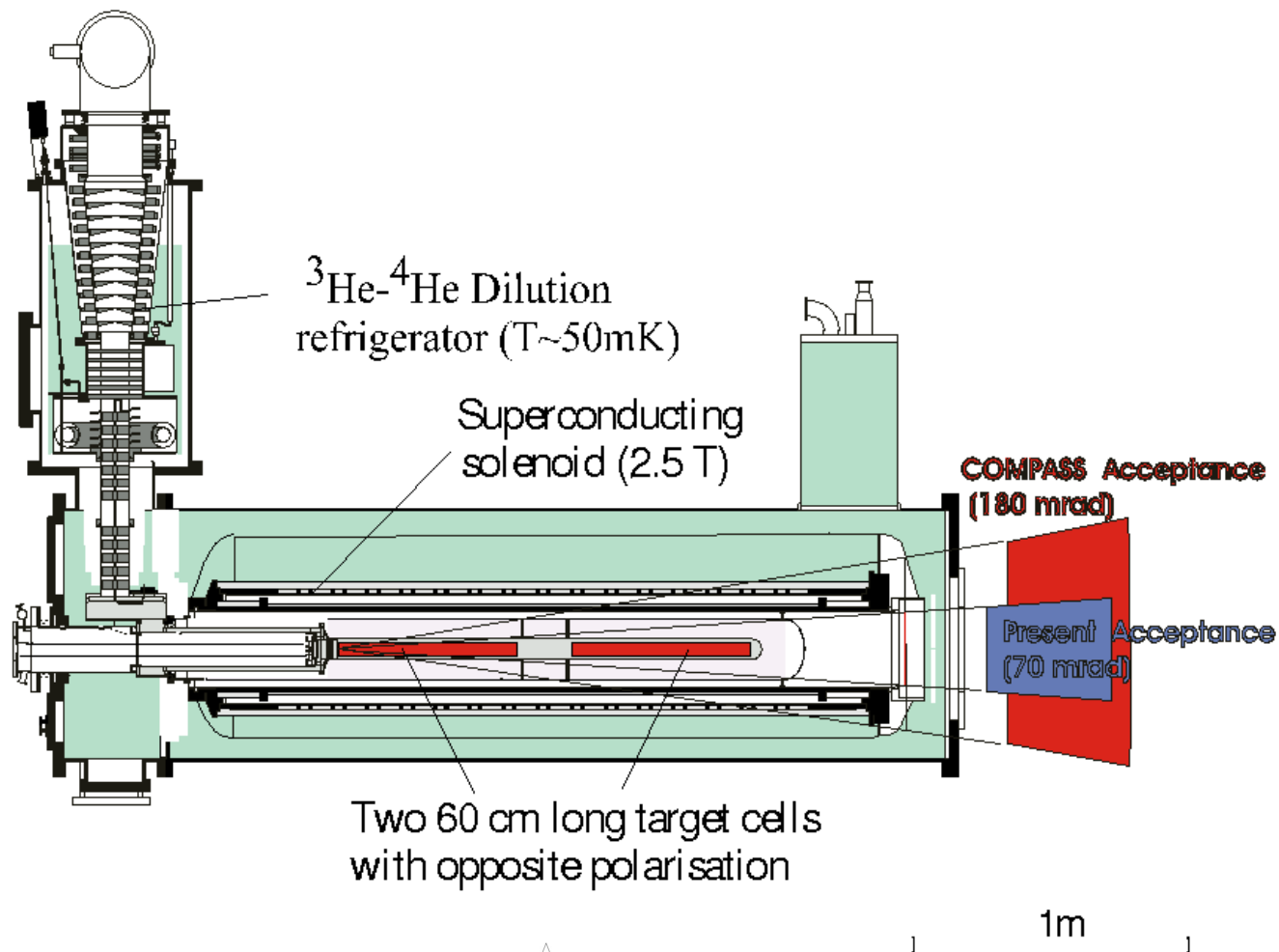
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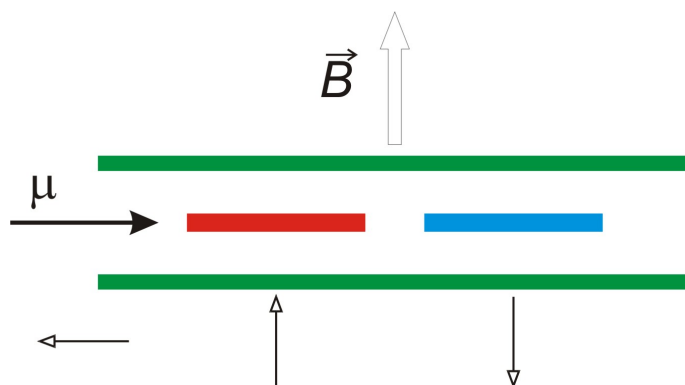
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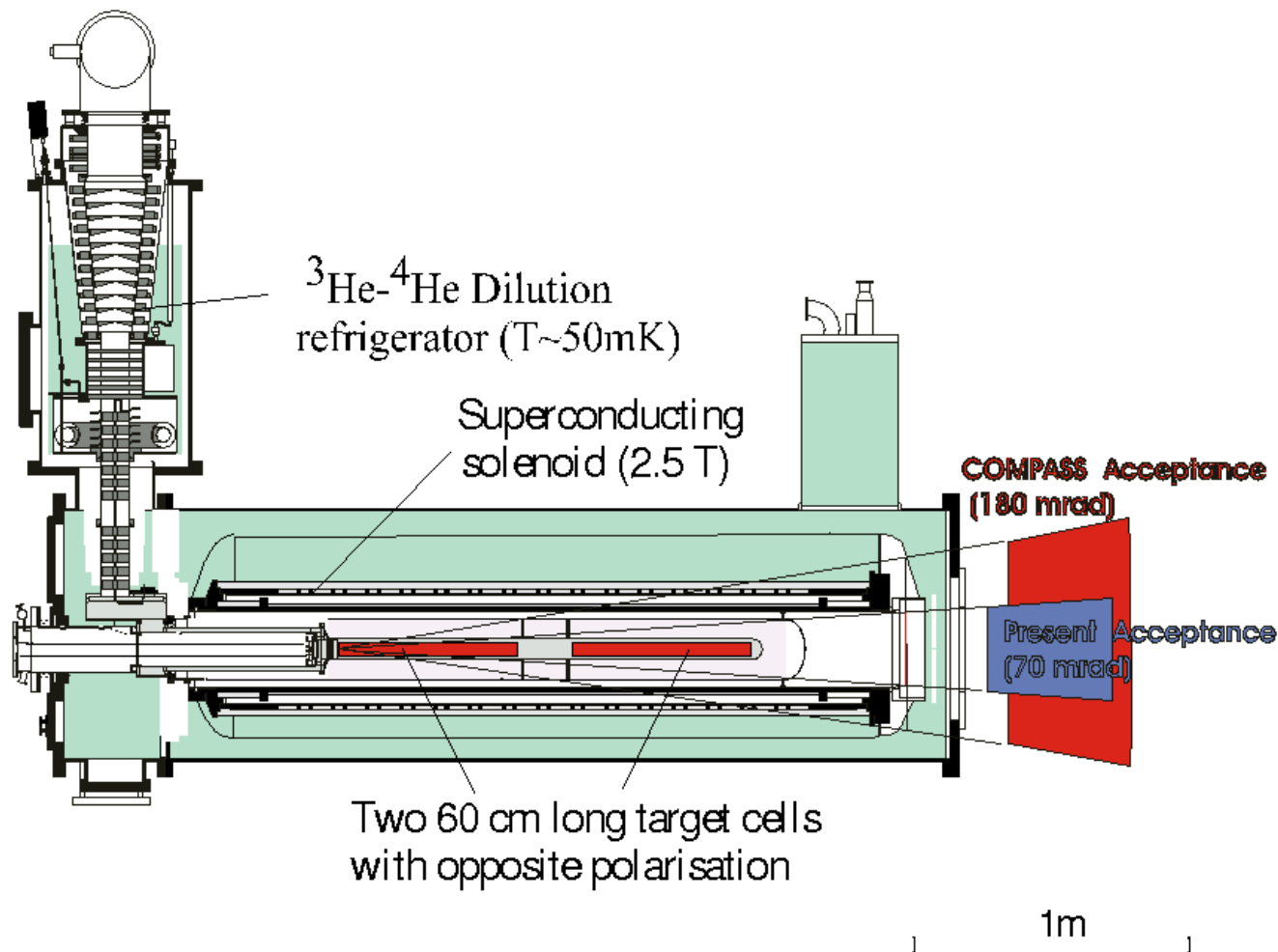
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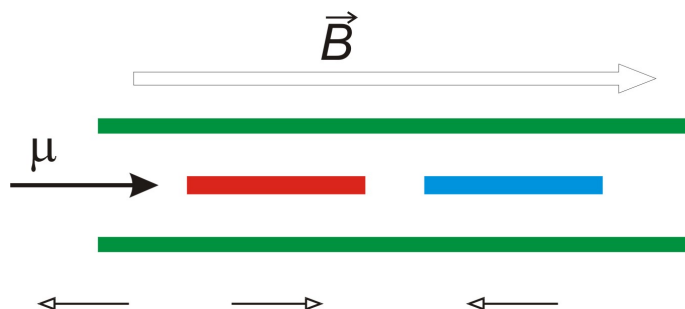
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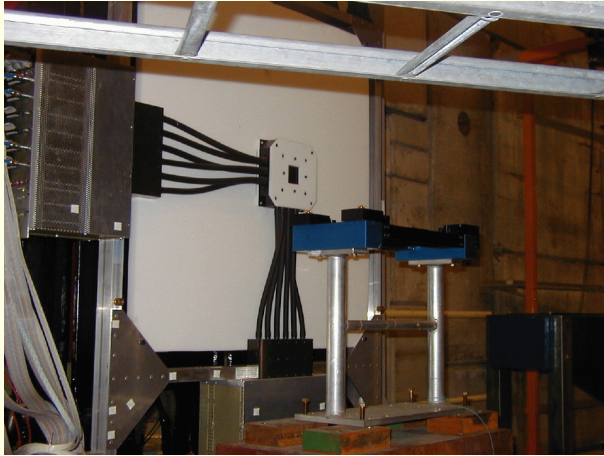
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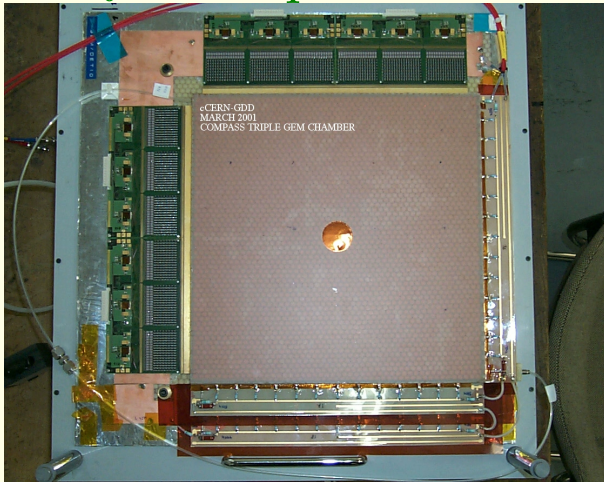


# New Detector Technologies



## Sci-Fi

- 21 planes
- $\sigma_t \sim 350$  ps



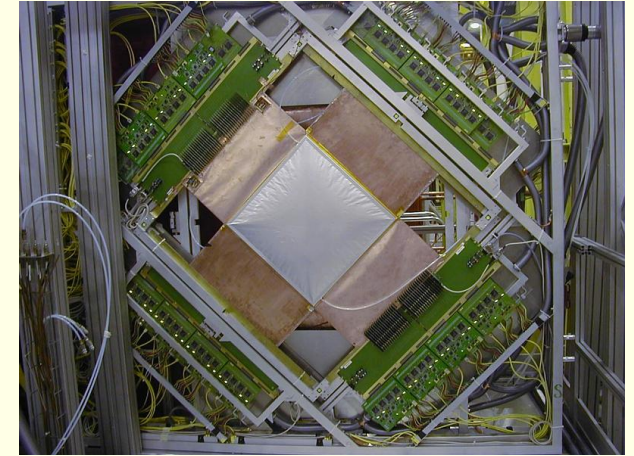
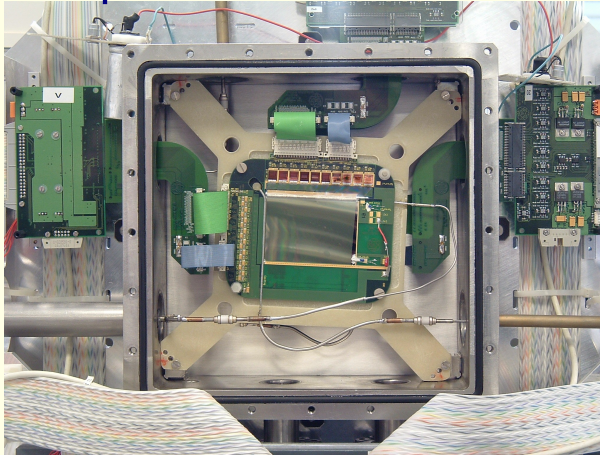
## GEM

- 44 planes
- $31 \times 31$  cm<sup>2</sup>, 2-D



## Cryogenic Si

- 12 planes
- operation at 130 K

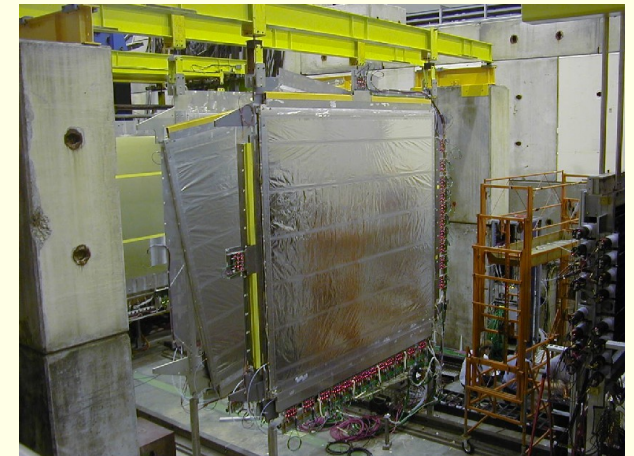
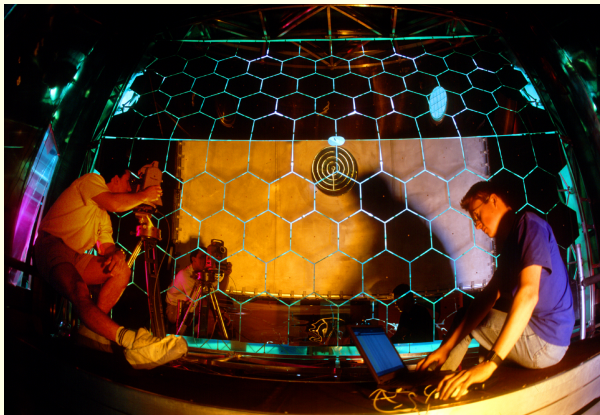


## MicroMeGas

- 12 planes
- $40 \times 40$  cm<sup>2</sup>

## RICH

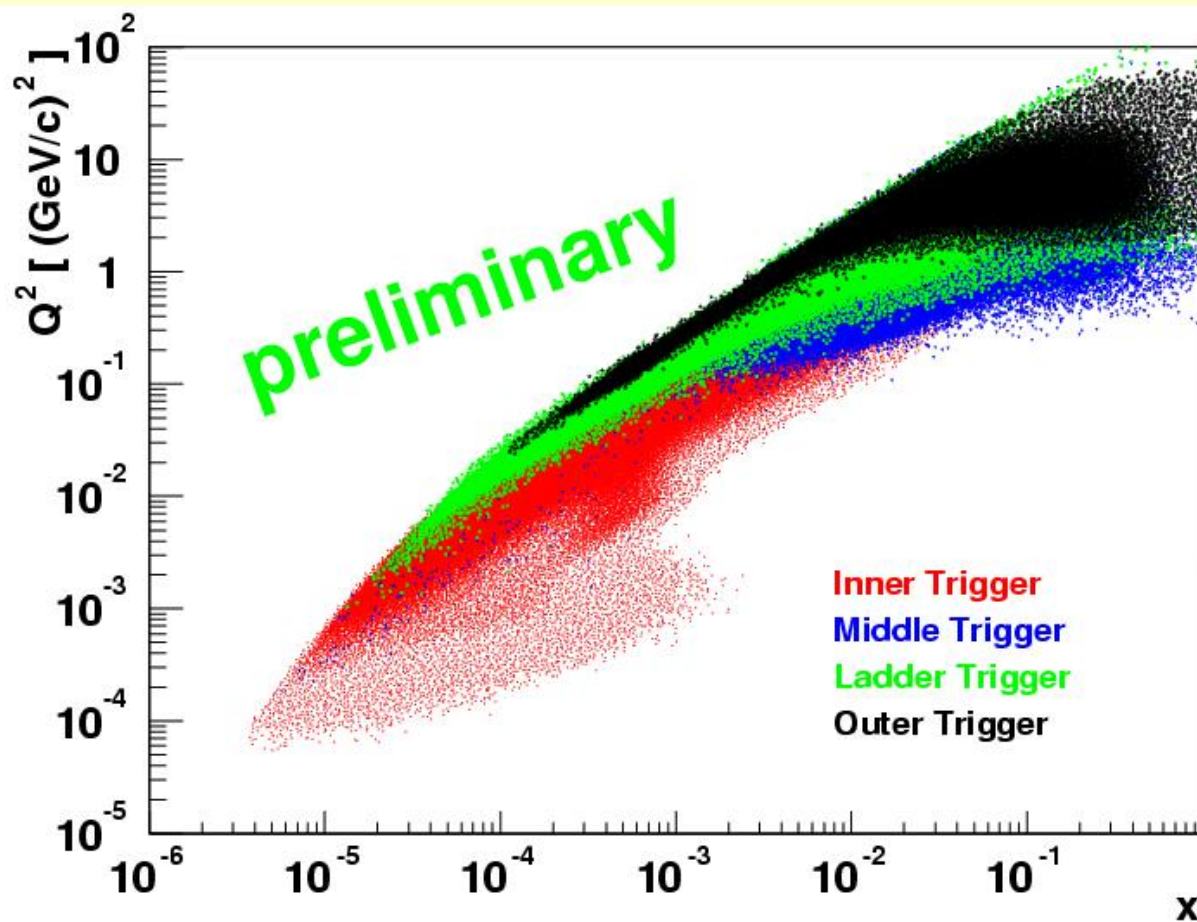
- C<sub>4</sub>F<sub>10</sub> radiator gas
- CsI + MWPC readout



## Straws

- 15 planes
- $3.2 \times 2.4$  m<sup>2</sup>

# Spectrometer Acceptance



- Access to small  $x$  and
- very small  $Q^2$

## Run 2002:

- 200 TB of data
- $3.8 \cdot 10^9$  trigger
- $570 \cdot 10^6$  ev. with reconstructed  $\mu/\mu'$
- $29 \cdot 10^6$  inclusive ev. with  $Q^2 > 1 \text{ GeV}^2/c^2$

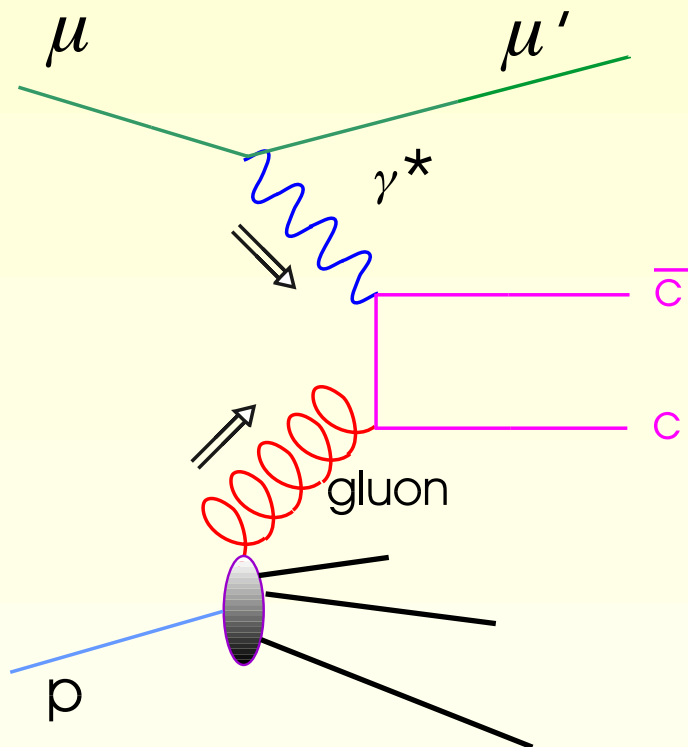
## Run 2003:

- 242 TB of data
- Large  $Q^2$  trigger upgrade

## Run 2004:

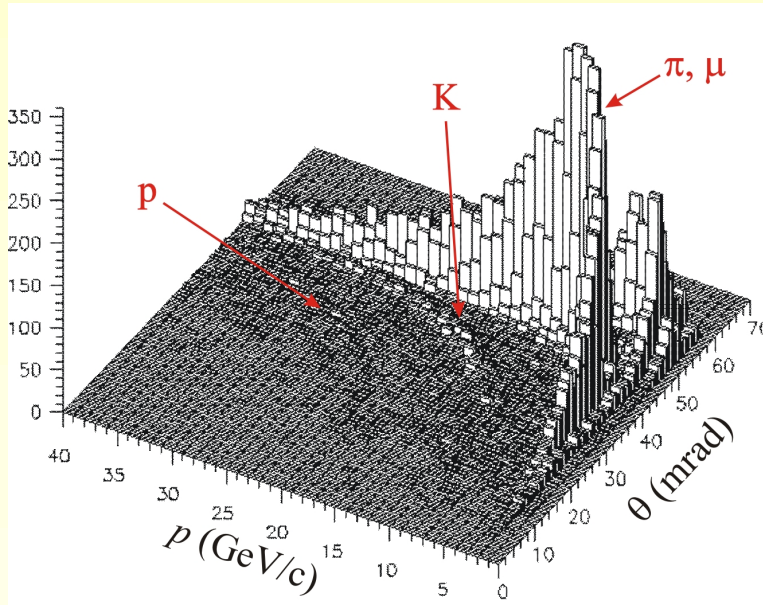
- Ongoing
- Twice the statistics of previous years (?)

# Open Charm Production



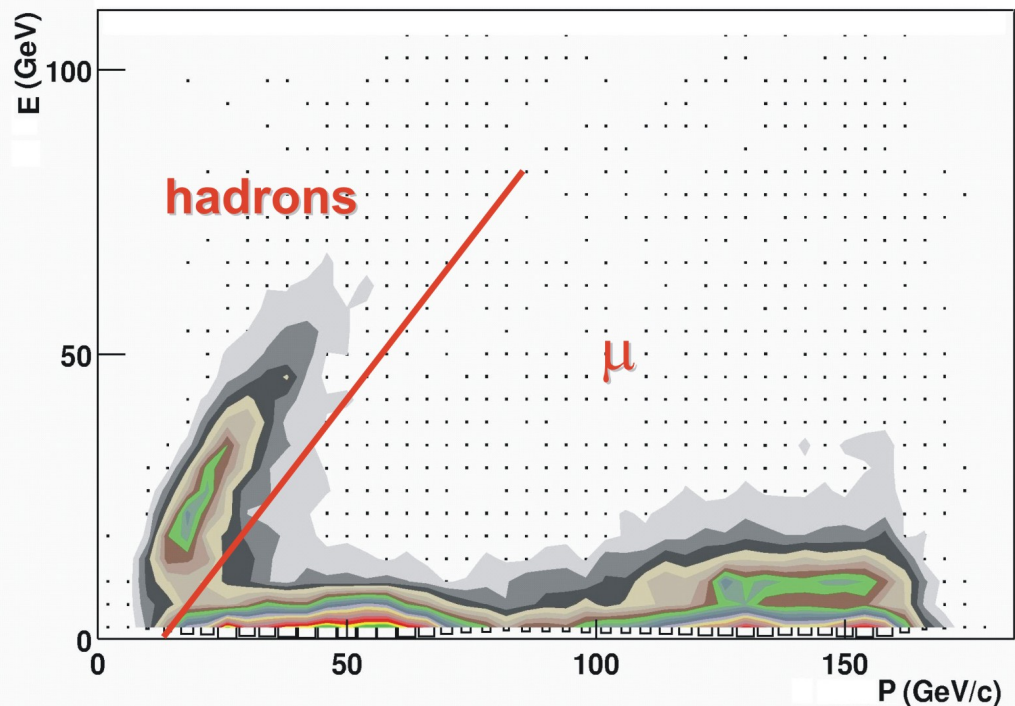
- Hadronization of  $c$  quark:
  - $D^0$  (60%)
  - $D^+$  (20%)
  - $D_s^+$ ,  $\Lambda_c^+$  (10% each)
- Reconstruction of  $D^0 \rightarrow K^- + \pi^+$  (3.83%) + c.c.
- No reconstruction of decay vertex
- Require large transverse momentum
- Require  $D^0$  with minimum energy fraction of virtual photon
- Tagging of  $D^0$  via  $D^{*+} \rightarrow D^0 \pi_s^+ \rightarrow (K^- \pi^+) \pi_s^+ + \text{c.c.}$

# Particle Identification



With **RICH**

and **HCAL**



Essential for reconstruction of D mesons and high  $p_T$  hadrons!



# D\* Mesons

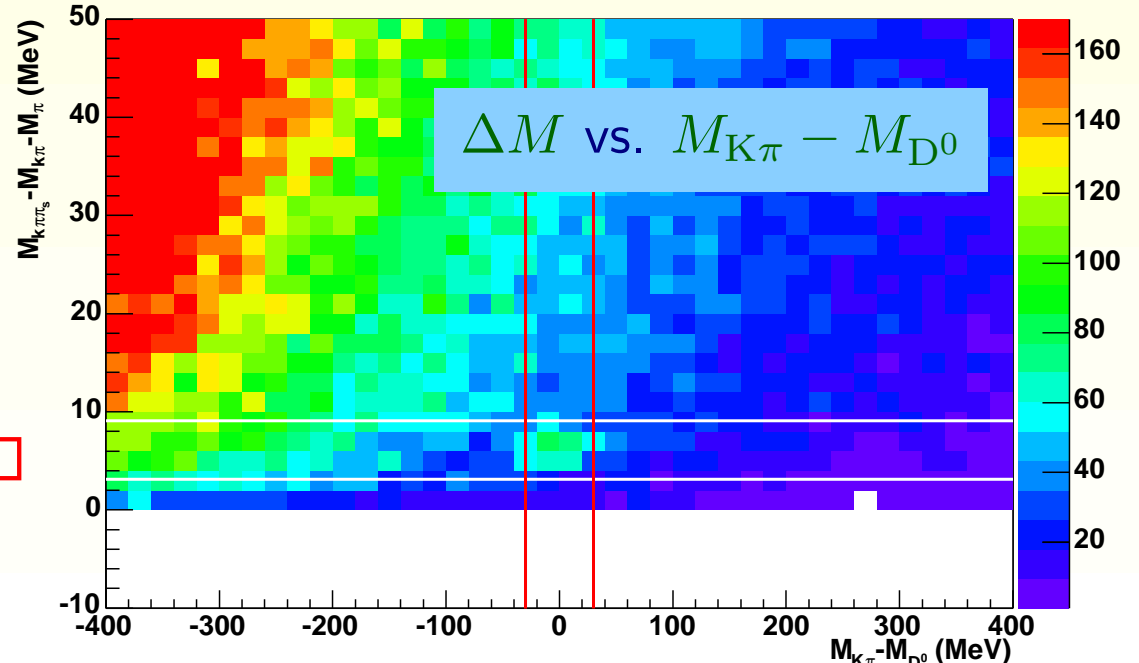
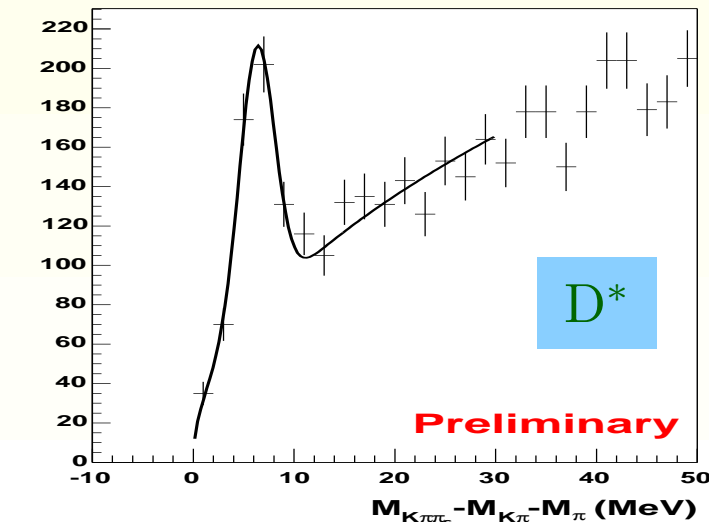
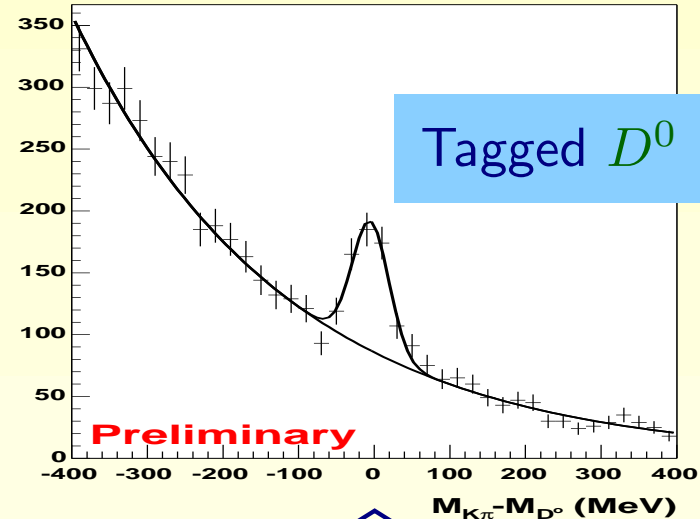
## Selection criteria for

$$D^{*+} \rightarrow D^0 \pi_s^+ \rightarrow (K^- \pi^+) \pi_s^+ \quad (+c.c.)$$

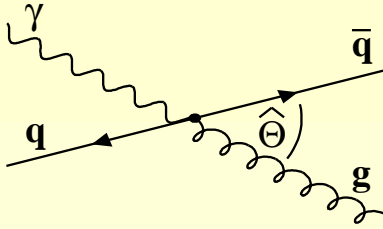
- $z_D > 0.2$ ,  $|\cos \theta^*| < 0.85$  (BG)
- Kaon ID with RICH,  
 $10 \text{ GeV} < p_K < 35 \text{ GeV}$
- Cut around  $D^0$  mass:  
 $|M(K\pi) - M(D^0)| < 30 \text{ MeV}$

## Tagging of $D^0$ :

- $3.1 \text{ MeV} < \Delta M < 9.1 \text{ MeV}$ ,  $\Delta M =$   
 $M(K\pi\pi_s) - M(K\pi) - M(\pi)$



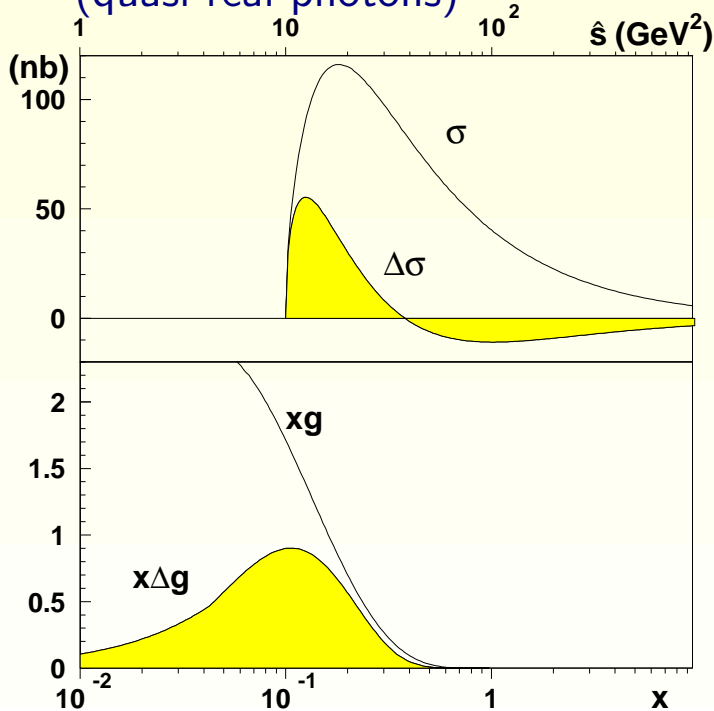
# Open Charm – Cross Section and Asymmetry



## Open charm photoproduction

$$\sigma^{\gamma g \rightarrow c\bar{c}} = \sigma(\hat{s}) + \lambda_\gamma \lambda_g \Delta\sigma(\hat{s})$$

with  $\hat{s} = (q + \eta P)^2 \stackrel{\text{lab}}{\approx} 2\eta\nu M$   
(quasi-real photons)



[Glück, Reya, Z. Phys. C39, 569 (1988)]

## $\gamma N \rightarrow c\bar{c}$ production asymmetry:

$$A^{\gamma N \rightarrow c\bar{c}} = \frac{\Delta\sigma^{\gamma N \rightarrow c\bar{c}}}{\sigma^{\gamma N \rightarrow c\bar{c}}} = \frac{\int_{4m_c^2}^{2M\nu} d\hat{s} \Delta\sigma(\hat{s}) \Delta G(\eta, \hat{s})}{\int_{4m_c^2}^{2M\nu} d\hat{s} \sigma(\hat{s}) G(\eta, \hat{s})}$$

$$= \left\langle \hat{a}_{LL} \frac{\Delta G(\eta, \hat{s})}{G(\eta, \hat{s})} \right\rangle$$

with  $\hat{a}_{LL} = \frac{\Delta\sigma(\hat{s})}{\sigma(\hat{s})}$  (parton asymmetry)

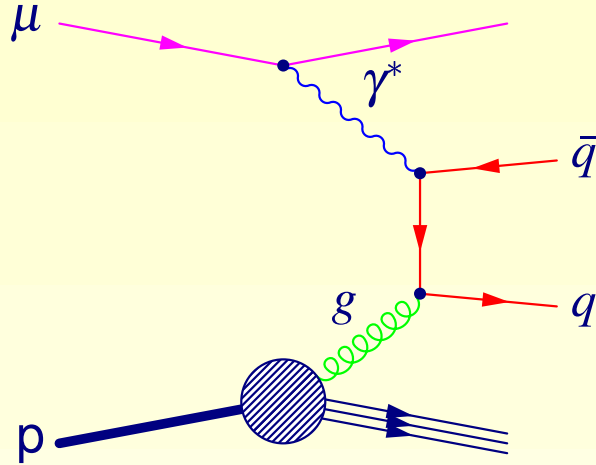
## Experiment:

$$A^{\text{raw}} = \frac{N_d^{\rightarrow\leftarrow} - N_u^{\leftarrow\leftarrow}}{N_d^{\rightarrow\rightarrow} + N_u^{\leftarrow\leftarrow}} = \langle P_b P_t f D \rangle A^{\gamma N \rightarrow c\bar{c}}$$

Acceptance asymmetry for up- and downstream target cells  $\Rightarrow$  flip polarization!

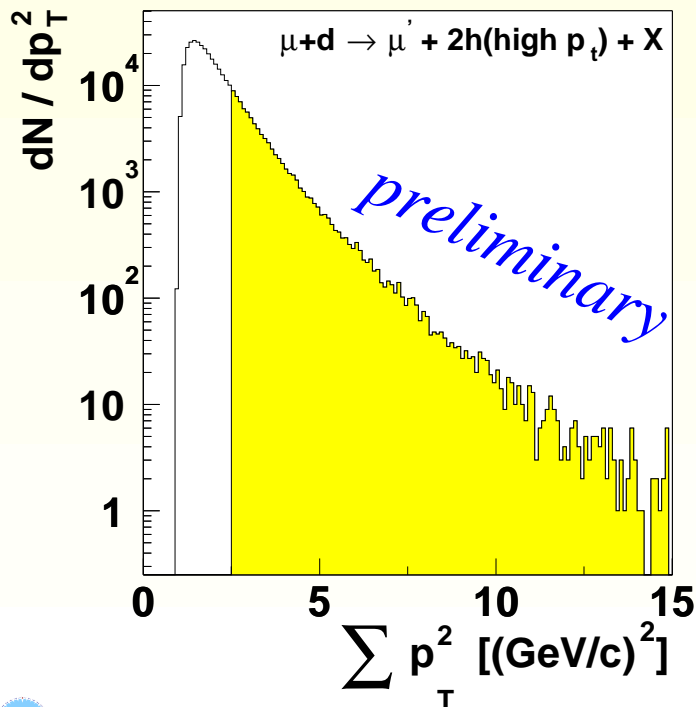
$$A^{\text{raw}} = \frac{1}{2} \left( \frac{N_d^{\rightarrow\leftarrow} - N_u^{\leftarrow\leftarrow}}{N_d^{\rightarrow\rightarrow} + N_u^{\leftarrow\leftarrow}} + \frac{N_u^{\rightarrow\leftarrow} - N_d^{\leftarrow\leftarrow}}{N_u^{\rightarrow\rightarrow} + N_d^{\leftarrow\leftarrow}} \right)$$

# High- $p_T$ hadron pairs



## Event selection:

- Primary vertex inside target:  
 $\mu, \mu', \geq 2h$
- Hadron ID:  $E_{\text{HCAL}}/p > 0.3$
- High  $p_T$  cut:
  - $p_{T1}, p_{T2} > 0.7 \text{ GeV}/c$
  - $p_{T1}^2 + p_{T2}^2 > 2.5 \text{ GeV}^2/c^2$
- Remove vector mesons:  
 $m(h_1 h_2) > 1.5 \text{ GeV}/c^2$
- Select current fragmentation:
  - $x_F = \frac{p_L}{p_L^{\text{max}}} = \frac{2p_L}{\sqrt{s}} > 0.1$
  - $z = \frac{E_h}{\nu} > 0.1$
- Inclusive cuts:
  - No  $Q^2$  cut
  - $0.4 < y < 0.9$



# High- $p_T$ – Asymmetry

**Asymmetry** in production  
of 2 high  $p_T$  hadrons:

$$A^{\gamma N \rightarrow hh} = \frac{1}{2 \langle P_b P_t f D \rangle} \left( \frac{N_d^{\rightarrow} - N_u^{\leftarrow}}{N_d^{\rightarrow} + N_u^{\leftarrow}} + \frac{N_u^{\rightarrow} - N_d^{\leftarrow}}{N_u^{\rightarrow} + N_d^{\leftarrow}} \right)$$

**Run 2002:**

$$A^{\gamma N \rightarrow hh} = -0.065 \pm 0.036(\text{stat}) \pm 0.010(\text{syst})$$

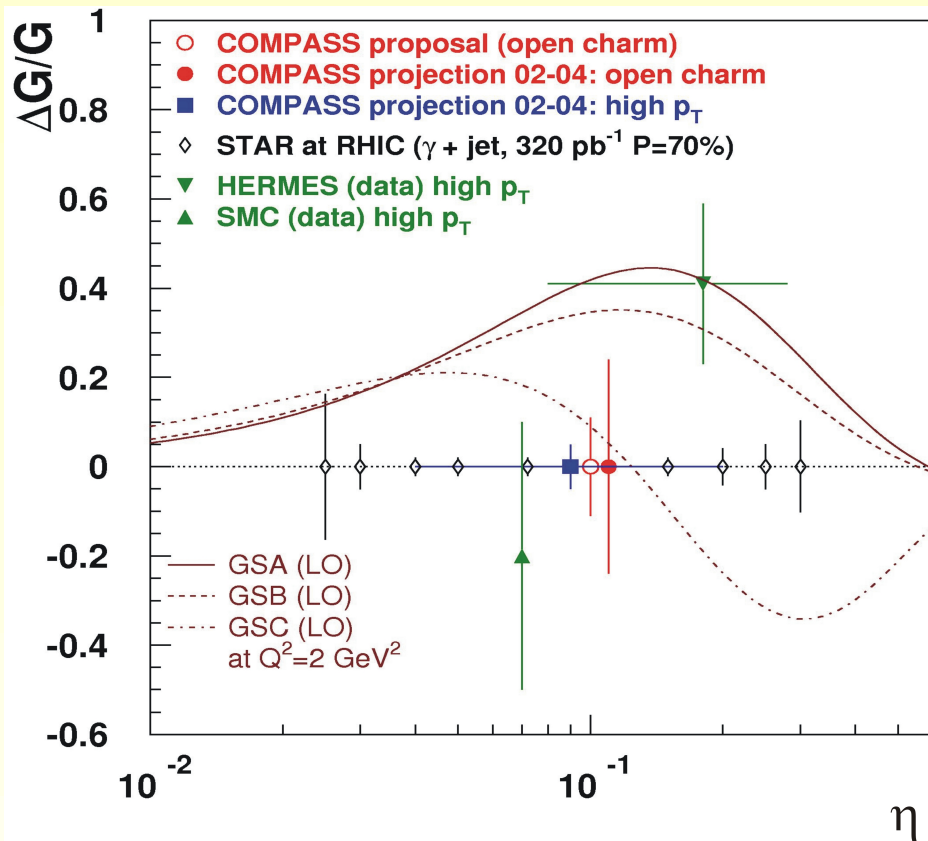
- False asymmetries  $\Rightarrow$  systematic error
  - Subdividing target/spectrometer  $\Rightarrow$  none related to spectrometer
  - Microwave reversal of target polarization  $\Rightarrow$  target movement, filling
- Radiative corrections not yet taken into account (expected to be small:  $y < 0.9$ )

**Extraction of  $\Delta G/G$ :**

$$A^{\gamma N \rightarrow hh} = \left\langle \hat{a}_{LL}^{\gamma N \rightarrow q\bar{q}} \right\rangle \left\langle \frac{\Delta G}{G} \right\rangle \frac{\sigma^{\gamma N \rightarrow q\bar{q}}}{\sigma^{\text{tot}}} + \left\langle \hat{a}_{LL}^{\text{QCDC}} \right\rangle \left\langle \frac{\Delta q}{q} \right\rangle \frac{\sigma^{\text{QCDC}}}{\sigma^{\text{tot}}}$$

- $\hat{a}_{LL}^{\gamma N \rightarrow q\bar{q}} \approx -1$  and  $\hat{a}_{LL}^{\text{QCDC}} \approx 0.5 \Rightarrow \Delta G/G > 0$
- LO DIS suppressed by high  $p_T$  cut (confirmed by LEPTO simulation)
- VMD photon, resolved photon ( $q\bar{q}$ ): negligible spin asymmetry  $\Rightarrow$  dilution of asymmetry
- Fractions of PGF and QCD Compton cross sections to be determined by MC (PYTHIA, LEPTO)

# Accuracy of $\Delta G/G$



**COMPASS** projected 2002-2004:

- $\eta \in [0.07, 0.4]$ ,  $\eta_{\max} = 0.14$
- Open charm:  
 $\delta \left( \frac{\Delta G}{G} \right) \approx 0.24$
- High  $p_T$ :
  - $\sigma^{\text{PGF}} / \sigma^{\text{tot}} \sim 1/4$
  - $\delta \left( \frac{\Delta G}{G} \right) \approx 0.05$  (all  $Q^2$ )
  - $\delta \left( \frac{\Delta G}{G} \right) \approx 0.16$  ( $Q^2 > 1 \text{ GeV}^2$ )

**HERMES (DESY):** High  $p_T$  [Airapetian et al., Phys. Rev. Lett. **84**, 2584 (2000)]

- $\langle \eta \rangle = 0.17$
- $\left\langle \frac{\Delta G}{G} \right\rangle = 0.41 \pm 0.18_{\text{stat}} \pm 0.03_{\text{syst}}$

**STAR (RHIC):**  $q + g \rightarrow \gamma + X$

[RHIC Spin Physics Proposal, 1993]

- $\eta \in [0.03, 0.15]$
- $\delta \left( \frac{\Delta G}{G} \right) \sim 0.05 - 0.15$

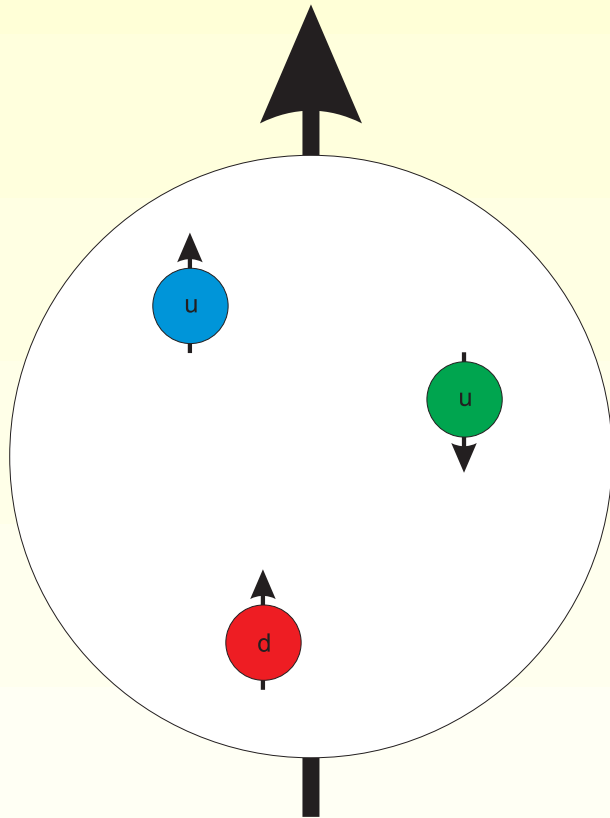
# Summary

- COMPASS has a very **broad physics spectrum**
- Initial layout of **apparatus completed**
- **Data taking** started in 2002, presently ongoing
- Physics analysis shows **first results**
  - First glance at open charm
  - Production asymmetry of high  $p_T$  hadron pairs
  - Transversity: Collins asymmetry
  - Exclusive  $\rho$  and  $\Phi$  production
  - $\Lambda$  polarization
- **Good precision** for  $\Delta G$  expected from 2002-2004 runs
- First pilot run with **hadron beams** in 2004: Polarizabilities of  $\pi$  and  $K$
- **Upgrade** for a second phase after 2005 in preparation
  - Exotic mesons and baryons
  - Charmed mesons and baryons
  - Generalized parton distributions
- **COMPASS ready to run well into LHC era**

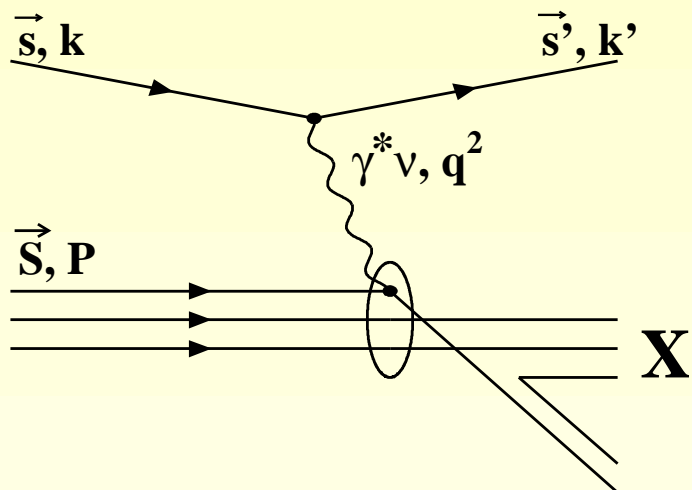
# The Nucleon Spin

$$\langle S_z \rangle = \frac{1}{2} = \frac{1}{2} \Delta \Sigma$$

- Static quark model:  
 $\Delta \Sigma = \Delta u + \Delta d = 1, \Delta q = q^\uparrow - q^\downarrow$



# Deep Inelastic Scattering



Kinematics:

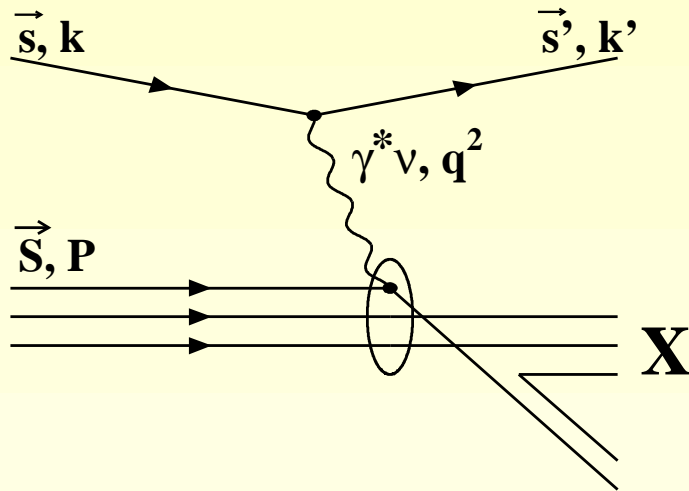
$$q^2 = -Q^2 = (k - k')^2 \stackrel{\text{lab}}{=} -4EE' \sin^2 \frac{\theta}{2}$$

$$x = \frac{-q^2}{2P \cdot k} \stackrel{\text{lab}}{=} \frac{Q^2}{2M(E - E')} = \frac{Q^2}{2M\nu}$$

$$y = \frac{P \cdot q}{P \cdot k} \stackrel{\text{lab}}{=} \frac{\nu}{E}$$



# Deep Inelastic Scattering



Cross section for  $\ell N \rightarrow \ell' X$ :

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

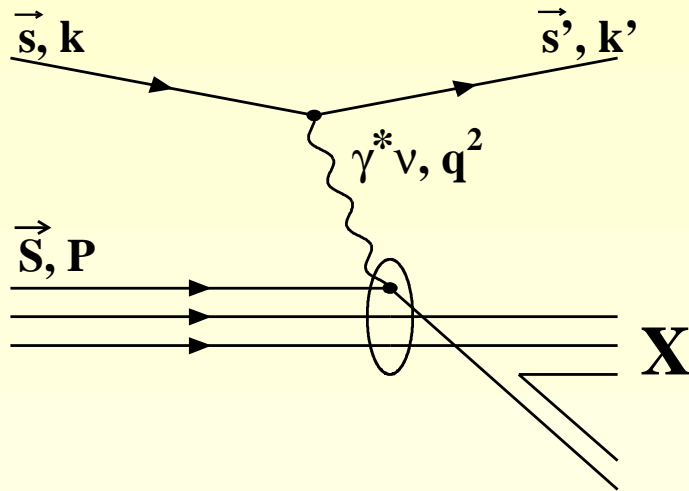
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- Leptonic tensor  $L_{\mu\nu}$ : QED

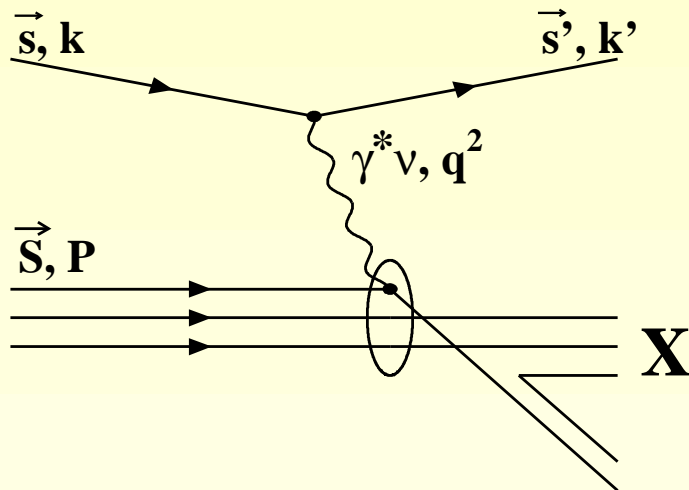
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Cross section for  $\ell N \rightarrow \ell' X$ :

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

- Leptonic tensor  $L_{\mu\nu}$ : QED
- Hadronic tensor  $W^{\mu\nu}$ : parametrized by structure functions

– Spin-averaged:

$$F_1(x, Q^2), F_2(x, Q^2)$$

– Spin-dependent:

$$g_1(x, Q^2), g_2(x, Q^2)$$

# Quark Parton Model

Nucleon described as

- incoherent superposition of free point-like particles with
- spin 1/2 and
- negligible transverse momenta wrt nucleon momentum

Structure functions:

$$F_1(x) = \frac{1}{2} \sum_i e_i^2 q_i(x)$$

$$F_2(x) = x \sum_i e_i^2 q_i(x)$$

$$g_1(x) = \frac{1}{2} \sum_i e_i^2 \Delta q_i(x)$$

$$\text{with } q_i(x) = q_i^{\rightarrow}(x) + q_i^{\leftarrow}(x)$$

$$\Delta q_i(x) = q_i^{\rightarrow}(x) - q_i^{\leftarrow}(x)$$

QPM +  $SU(3)_f$ : sum rules for

$$\Gamma_1^{p,n} = \int_0^1 g_1^{p,n}(x) dx$$

Bjorken:

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6} \left| \frac{g_A}{g_V} \right|$$

Ellis-Jaffe:  $\Delta s = 0$

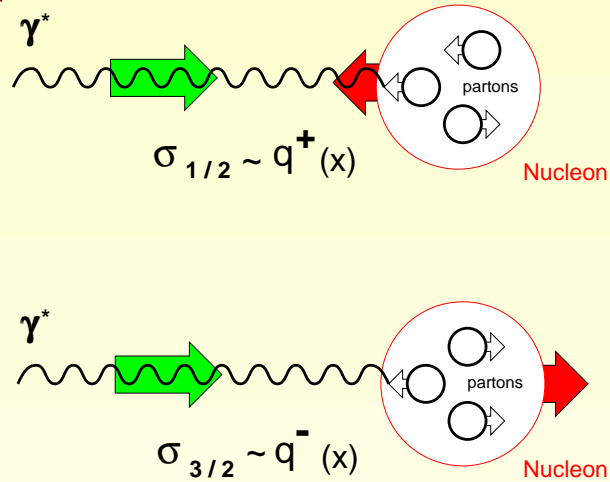
$$\Gamma_1^{p,n} = \frac{1}{12} \left| \frac{g_A}{g_V} \right| \left\{ \pm 1 + \frac{5}{3} \frac{3F/D - 1}{F/D + 1} \right\}$$

[Close et al., Phys. Lett. B**316**, 165 (1993)]

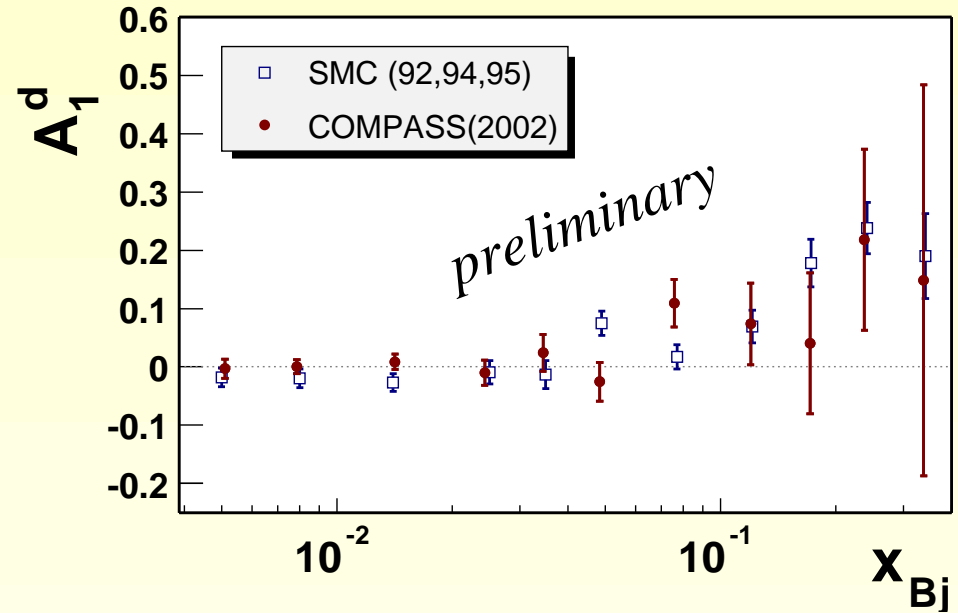
$$\Rightarrow \Delta\Sigma = \Delta u + \Delta d + \Delta s = (0.579 \pm 0.026)$$

# Longitudinal Spin Asymmetry

Experiment:



Helicity conservation



COMPASS:

- $Q^2 > 1 \text{ GeV}^2$ ,  $0.1 < y < 0.9$
- 2002:  $6.5 \cdot 10^6$  events
- 2003/2004: 4 times the statistics
- Study of false asymmetries

Longitudinal spin asymmetry:

$$A_1 = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \approx \frac{g_1(x)}{F_1(x)} \propto \frac{N^{\uparrow\uparrow} - N^{\uparrow\downarrow}}{N^{\uparrow\uparrow} + N^{\uparrow\downarrow}}$$

# $\Delta G$ from QCD Analysis of $g_1$

## QCD-extended QPM:

$$g_1 = g_1(x, Q^2)$$

Scaling violations

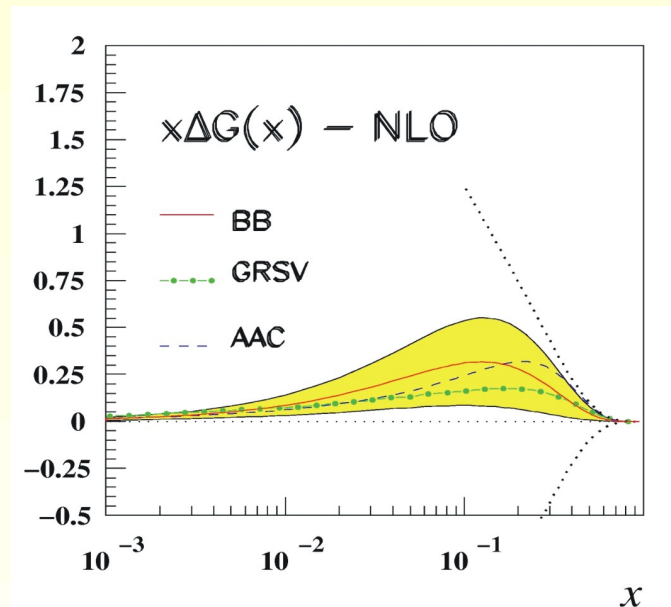
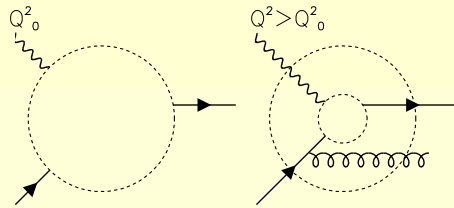
- Parametrize parton distributions  $\Delta q(x, Q^2)$ ,  $\Delta G(x, Q^2)$  at  $Q_0^2$

- DGLAP equations:  $Q^2$  dependence of parton distributions  $\Delta q(x, Q^2)$ ,  $\Delta G(x, Q^2)$

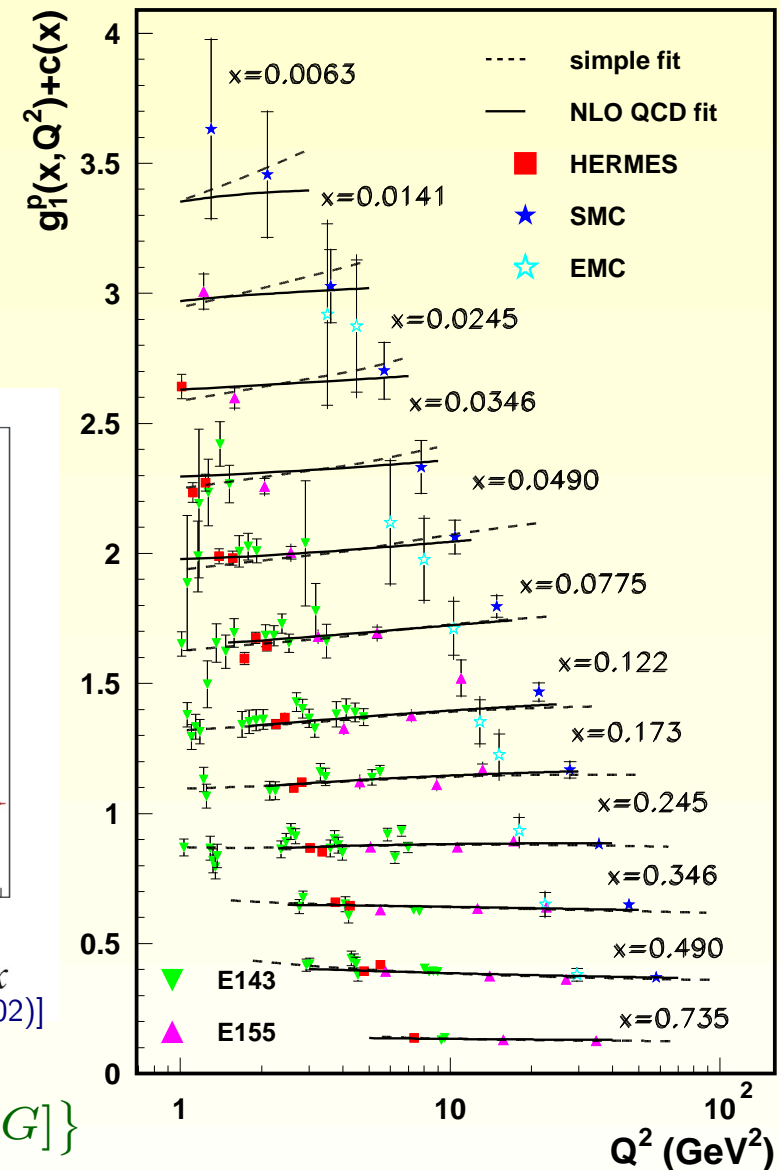
- Calculate  $g_1$  in NLO:

$$g_1(x, Q^2) = \frac{1}{2} \sum_i e_i^2 \left\{ \Delta q + \frac{\alpha}{2\pi} [C_q \otimes 2\Delta q + 2C_G \otimes \Delta G] \right\}$$

- Wilson coefficients  $C_q$ ,  $C_G$  depend on factorization scheme  $\Rightarrow$  separation between  $\Delta\Sigma$  and  $\Delta G$  ambiguous!



[Blümlein et al., Nucl. Phys. B **636**, 225 (2002)]



[Stösslein, Proc. SPIN2000]

# COMPASS Layout 2002/2003

