Questions in Hadron Physics

From Fixed Target Deep Inelastic Scattering
to the Relativistic Heavy Ion Collider

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Lecture 1 C

Stony Brook University

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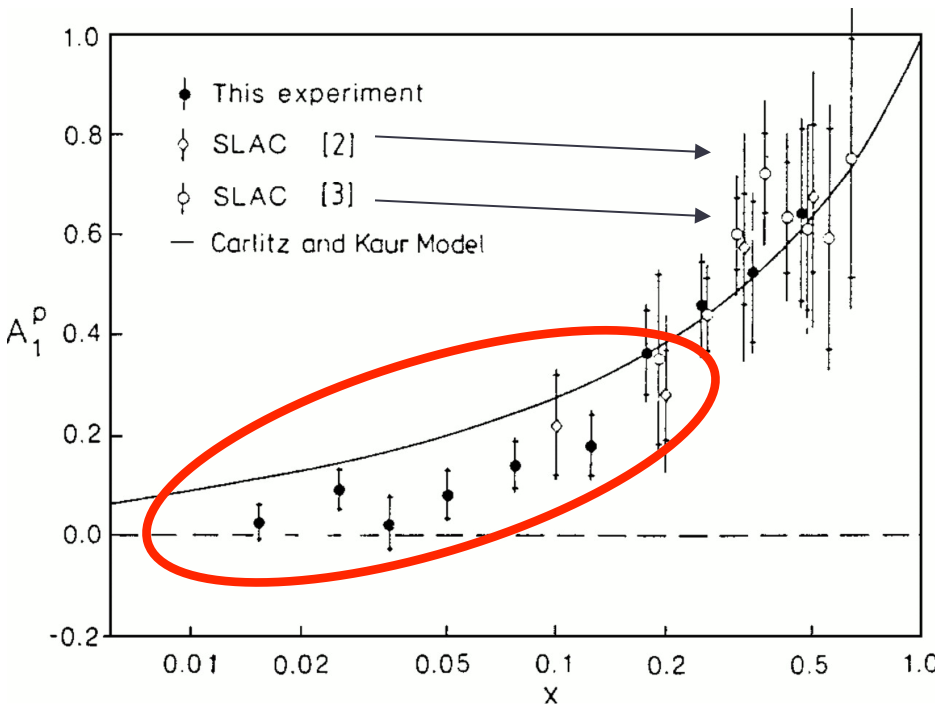
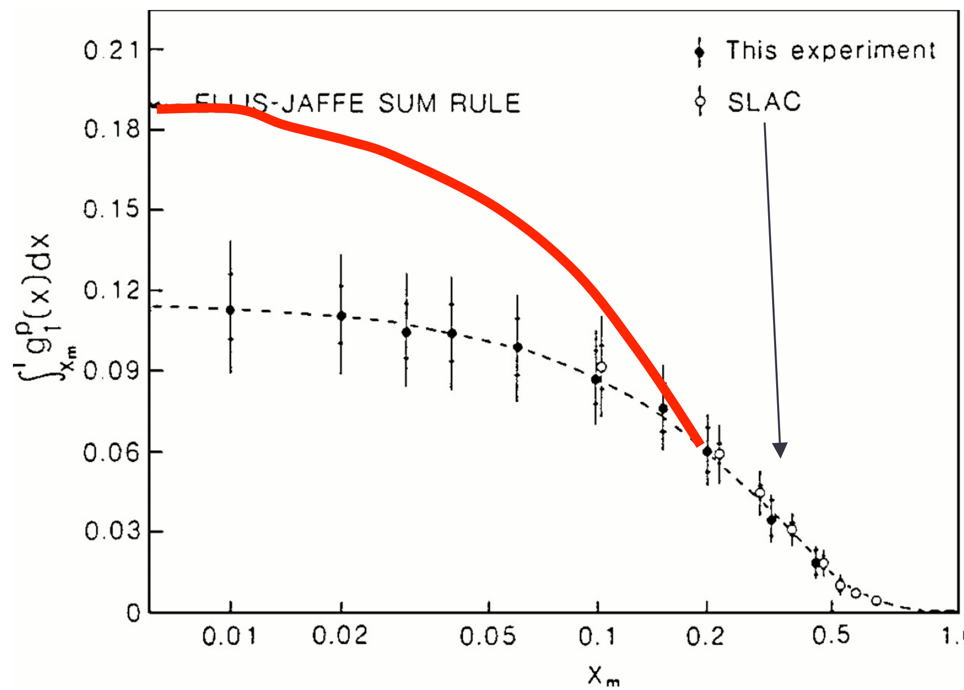
Proton Spin Crisis (1989)!





$\Delta\Sigma$ = (0.12) +/- (0.17) (EMC, 1989)

$\Delta\Sigma$ = 0.58 expected from E-J sum rule….

Aftermath of the EMC Spin "Crisis"

Naïve quark model yields: $\Delta u = 4/3 \text{ and } \Delta d = -1/3 \Longrightarrow \Delta\Sigma = 1$

Relativistic effects included quark model: $\Delta\Sigma = 0.6$

After much discussions, arguments an idea that became emergent, although not without controversy: "gluon anomaly"

- True quark spin is screened by large gluon spin:

$$\Delta\Sigma(Q^2) = \Delta\Sigma' - N_f \frac{\alpha_S(Q^2)}{2\pi} \Delta g(Q^2$$

Altarelli, Ross
Carlitz, Collins
Mueller et al.

- But there were strong alternative scenarios proposed that blamed the remaining spin of the proton on:
  - Gluon spin (same as above)
  - Orbital motion of quarks and gluons (OAM)

Jaffe, Manohar
Ji et al

It became clear that precision measurements of nucleon spin constitution was needed!

Natural questions about Nucleon's Spin

Do the quarks & anti-quarks really carry so little a spin of the proton?: ➔ A better precision on $\Delta\Sigma$ measurement highly needed.

$\Delta\Sigma$ contains quark as well as anti-Quark spin ➔Photons do not distinguish between them! Do the quarks and anti-Quarks cancel each others spin? i.e. are they anti-aligned for some reason?

Is the gluon's contribution to nucleon spin large? ➔ Is the "anomaly" scenario true? How would we do a direct determination of gluon's spin?

Is there an orbital motion of the quarks and gluons contributing to the nucleon spin?

Improved precision of polarized DIS experiments with good particle identification promised answers to the 1st question:

- Improve precision on $\Delta\Sigma$ and its quark/anti-quark separation

Gluon's contribution to nucleon spin:

- Global analysis of DIS data analyses at Next to Leading Order
- Direct determination with photon-gluon (open charm production)
- Launching of a new method: polarized proton-proton scattering

Methods to tag internal motion of partons inside the nucleon without breaking the proton:

- Deeply Virtual Compton Scattering experiments
- *Will come back to this in later lectures*

Other spin rule(s) and tests of QCD:

- Bjorken spin sum rule (1966): Strong test of QCD

$$\boxed{\Gamma_1^p - \Gamma_1^n = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_1^{\mathrm{NS}}}$$

Where

$$C_1^{\mathrm{NS}} = 1 - c_1^{\mathrm{NS}}\left(\frac{\alpha_s(Q^2)}{\pi}\right) - c_2^{\mathrm{NS}}\left(\frac{\alpha_s(Q^2)}{\pi}\right)^2 - c_3^{\mathrm{NS}}\left(\frac{\alpha_s(Q^2)}{\pi}\right)^3 - O(c_4^{\mathrm{NS}})\left(\frac{\alpha_s(Q^2)}{\pi}\right)^4$$

- Efremov, Leader, Teryaev sum rule:

$$\int_0^1 dx\; x\left[g_1^{\mathrm{valence}}(x) + 2g_2^{\mathrm{valence}}(x)\right] = 0$$

- Burkhardt Cottingham Sum rule $$\int_0^1 dx\ g_2(x) = 0$$

- Understanding higher twist corrections at low Q^2…..

See review by S. E. Kuhn, J.-P Chen, E. Leader, arXiv: 0812.3535v2 [hep-ph] 11 Feb 2009

Improved precision on $\Delta\Sigma$ and flavor separation:

SMC and COMPASS experiments at CERN
E142-E155 experiments at SLAC
HERMES experiment at DESY
Hall A, B, C at Jefferson Laboratory

Mostly tried to reach pQCD region, Inclusive, no particle ID
Mostly Semi-Inclusive, with good particle ID
Mostly lower beam energies, precision mostly in the non-pQCD regime

Experimental Essentials

Facility & Beam Energy	Target types	Lepton beam	Minimum x_{Bj} reached
SLAC & JLab 9-49 GeV	solid/gas	Polarized e source	Xmin ~ 0.01
DESY 27 GeV	Internal (DESY) gas	Sokolov Ternov effect, e+/-	Xmin ~ 0.02
CERN 100-190 GeV	solid	Muons(+) from pion decay	Xmin ~ 0.003

- False asymmetries were controlled by:
  - Rapid variation of beam polarization (SLAC & JLab)
  - Rapid variation of target polarization (HERMES@DESY)
  - Simultaneous measurement of two oppositely polarized targets in the same beam (SMC & COMPASS@CERN)

Asymmetry Measurement

$$\frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}} = A_{measured} = P_{beam} \cdot P_{target} \cdot f \cdot A_{||}$$

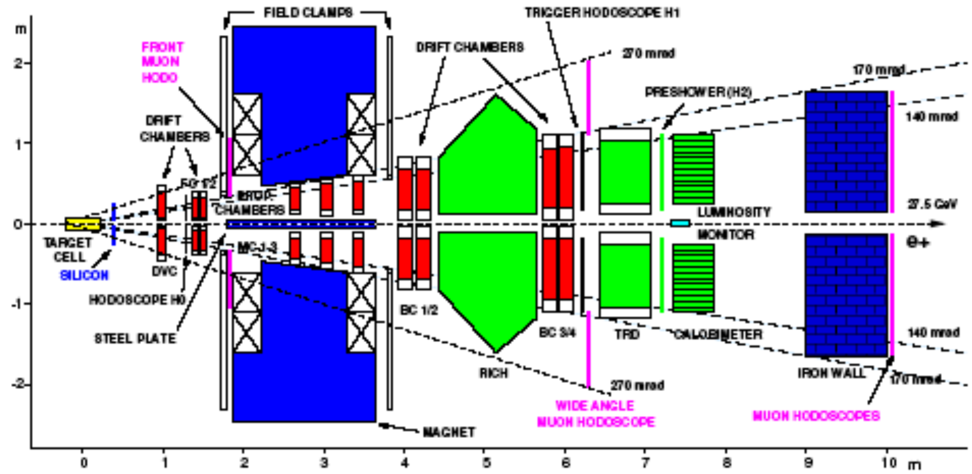
- f = dilution factor proportional to the polarizable nucleons of interest in the target "material" used, for example for NH_3, f=3/17
- D is the depolarization factor, kinematics, polarization transfer from polarized lepton to photon, D ~ y^2

$$g_1 \approx \frac{A_{||}}{D} \cdot F_1 \approx \frac{A_{||}}{D} \frac{F_2}{2 \cdot x}$$

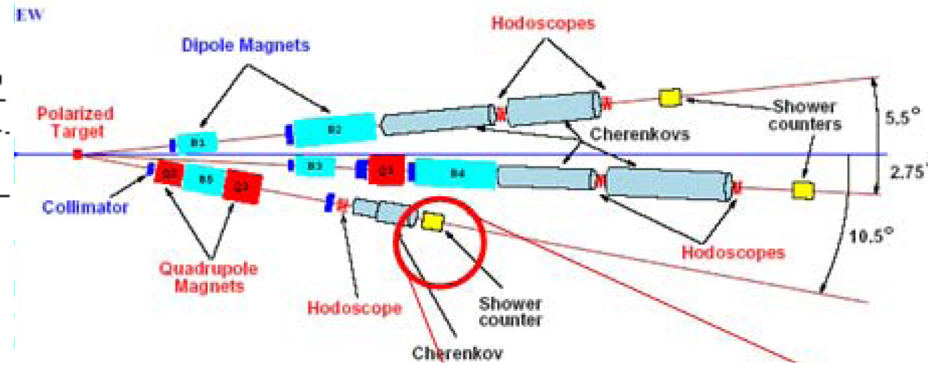
- Note that
  - Recall that there is a huge rise of F_2 at low x (large rise in gluon radiation by quarks at low x)
  - Large g_1 at low x could still result from **small asymmetries**

A SHORT REVIEW OF EXPERIMENTS & DATA

Experiments



HERMES at DESY



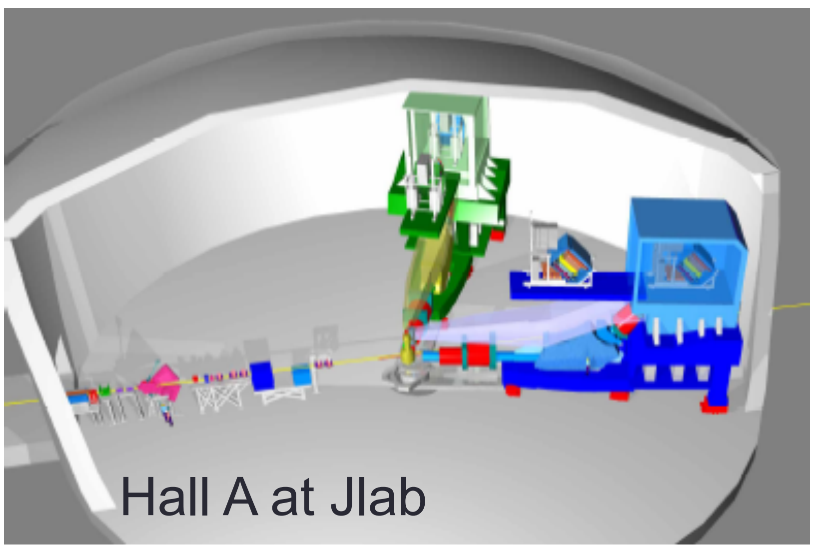
- high energy beams
- large angular acceptance
- broad kinematical range

two stages spectrometer
Large Angle Spectrometer (SM1)
Small Angle Spectrometer (SM2)

variety of tracking detectors

SciFi	*Straws*
Silicon	*DC*
Micromega	*MWPC*
(P)GEM	*LDC*

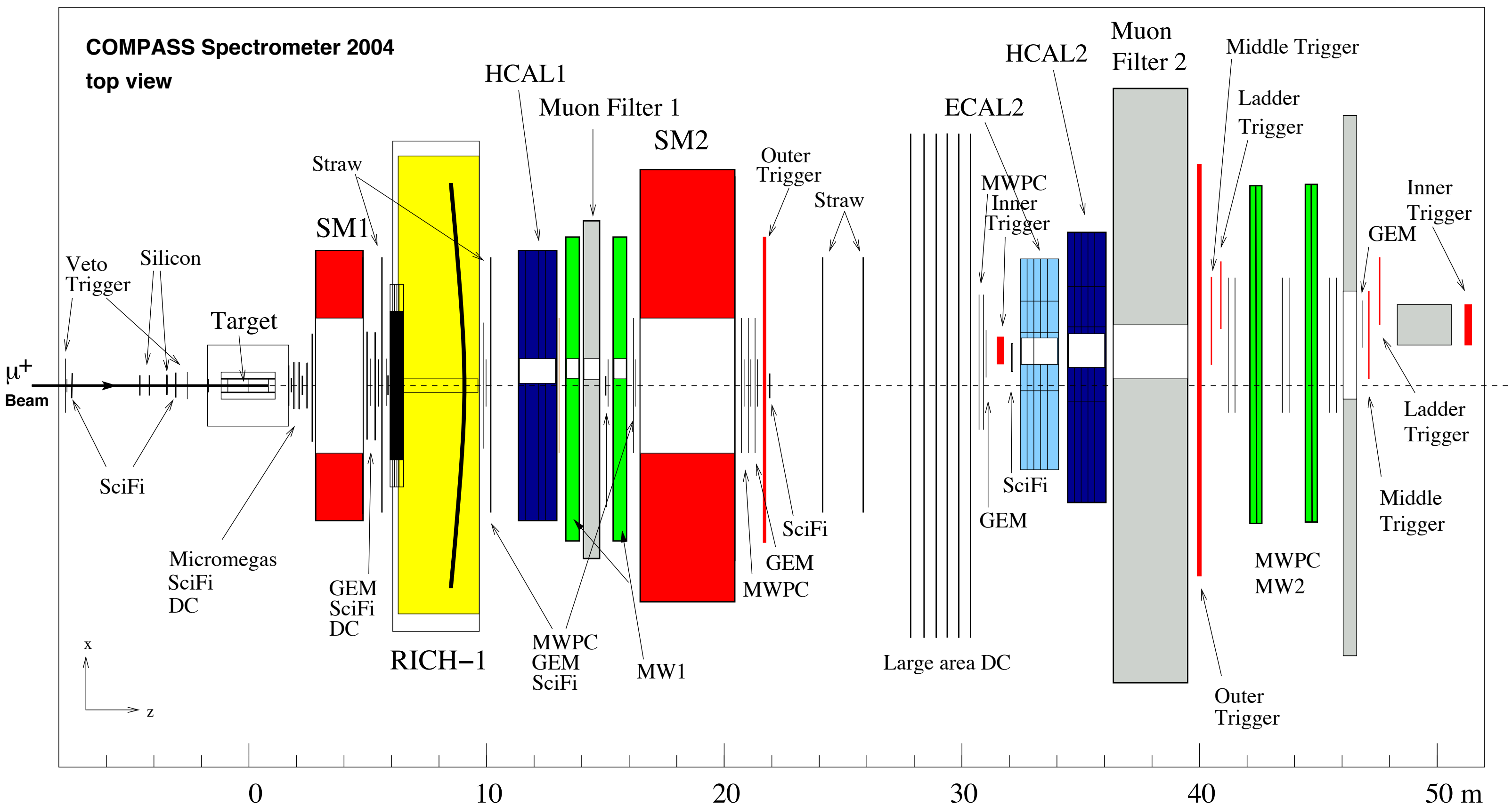
to cope with different particle flux
from $\theta = 0$ to $\theta \approx 200$ mrad
with a good azimuthal acceptance



Hall A at Jlab

SMC,COMPASS at CERN

COMPASS at CERN



- Multiple tracking devices (to increase redundancy)
- Multiple Particle ID detectors

Comparison

exp	E_b (GeV)	x	Q^2 (GeV^2)	P_b
HERMES	27.6 $e^{\pm}$	0.02-0.6	1 - 15	$\pm$0.55
COMPASS	160 μ	0.003 - 0.6	1 - 100	-0.76
JLAB	<6 e^{-}	0.1 - 0.7	1 - 4.5	$\pm$0.7

exp	P_t	target	$\mathcal{L}$ (cm^{-2}s^{-1})
HERMES	0.85	$\vec{\mathrm{H}}, \vec{\mathrm{D}}$	10^{31}
COMPASS	0.50	$\vec{\mathrm{Li}}\vec{\mathrm{D}}$	$5 \cdot 10^{32}$
Hall A	0.35	$^3\vec{\mathrm{He}}$	10^{36}
CLAS	0.8 (0.3)	NH_3 (ND_3)	10^{34}

SMC Target (left) vs. Reconstructed VTX

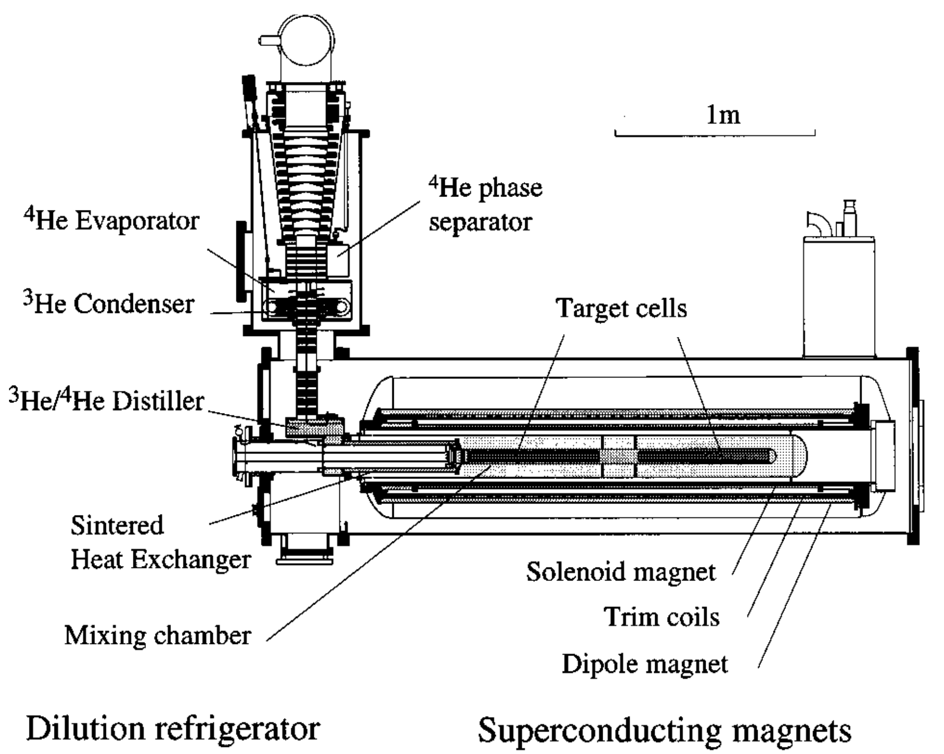
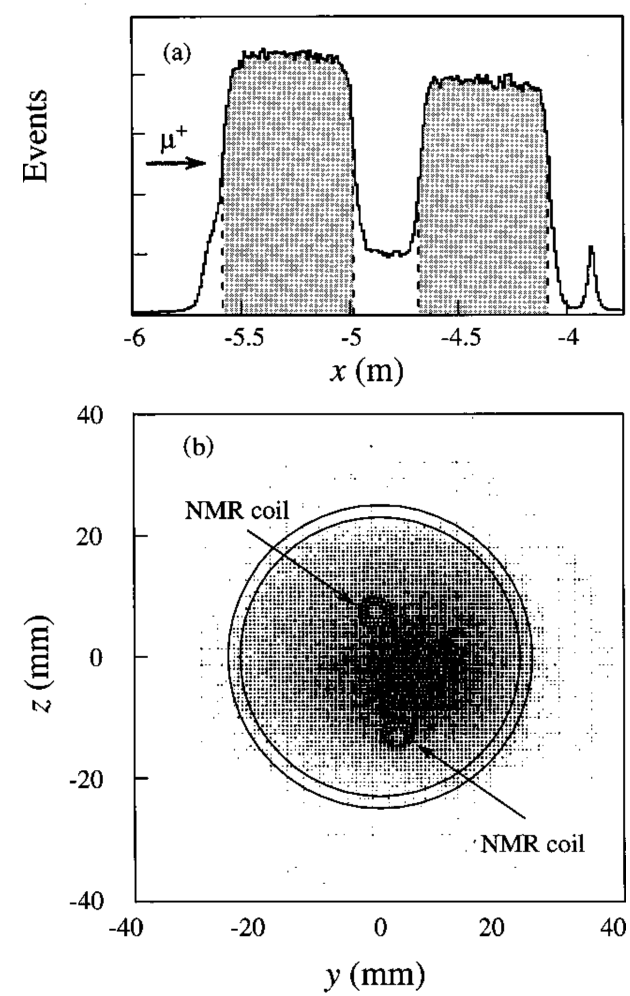
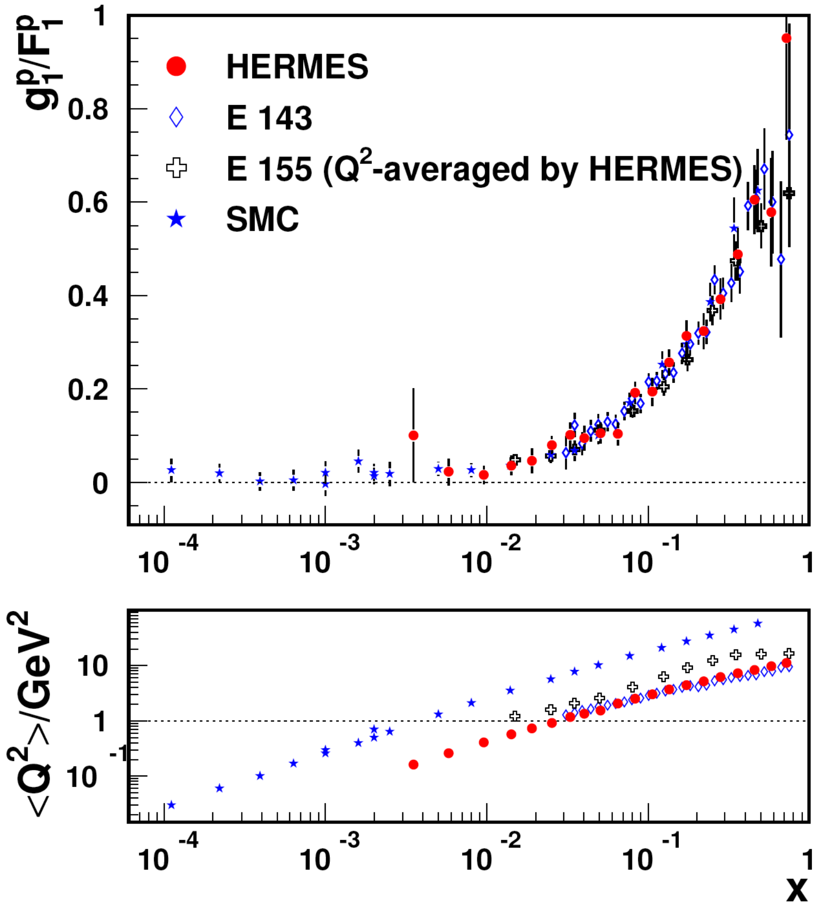


FIG. 8. Cross section of the SMC polarized target.

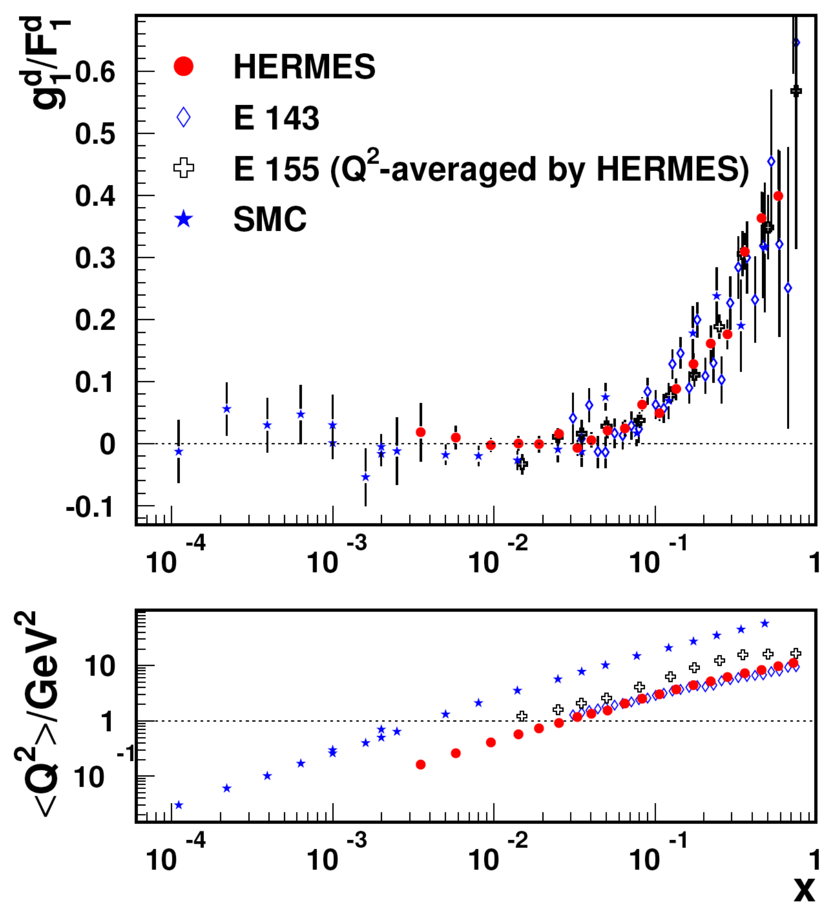


Measurements:

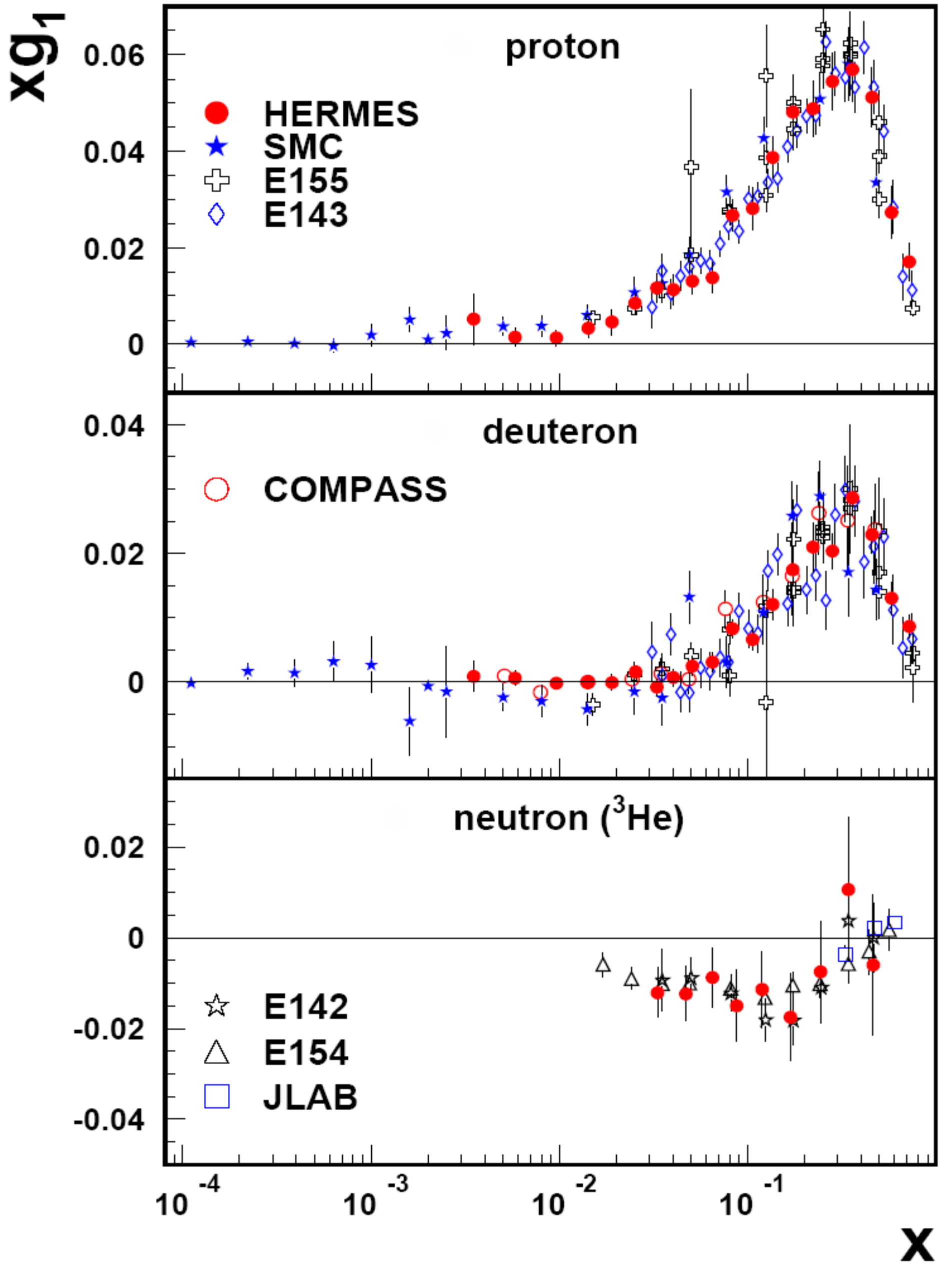
Proton Target

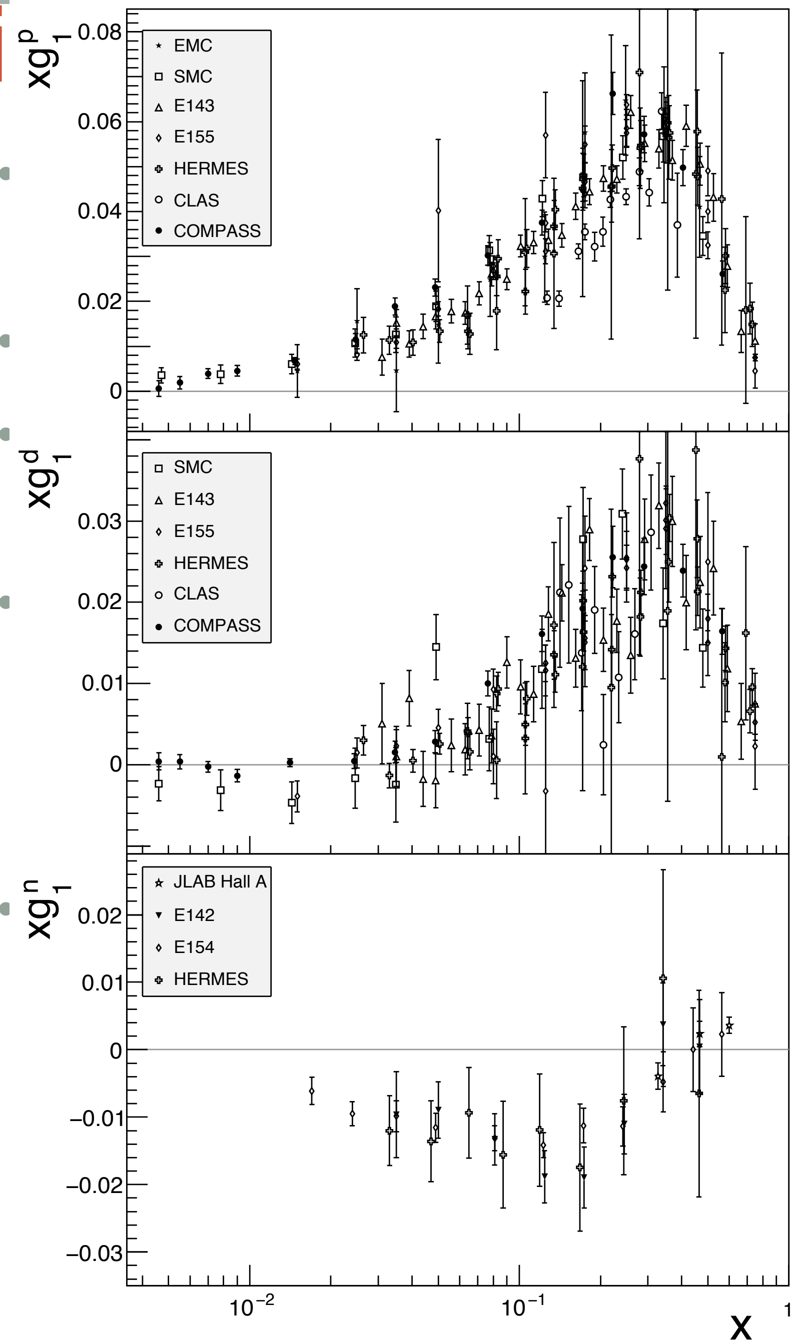


Deuteron Target



Spin structure Functi



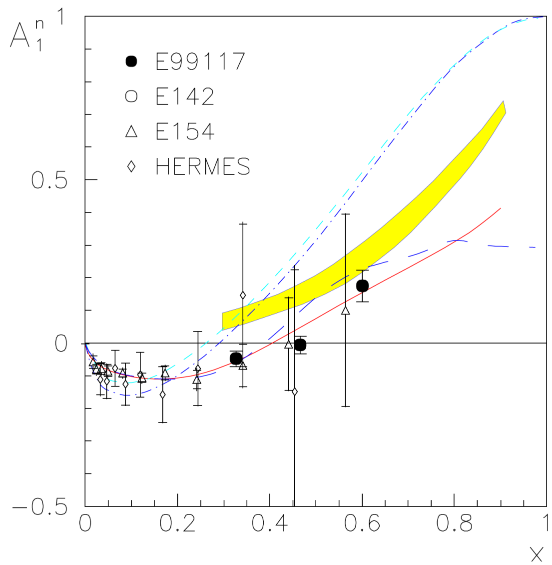


nde

Some fundamental tests of QCD?

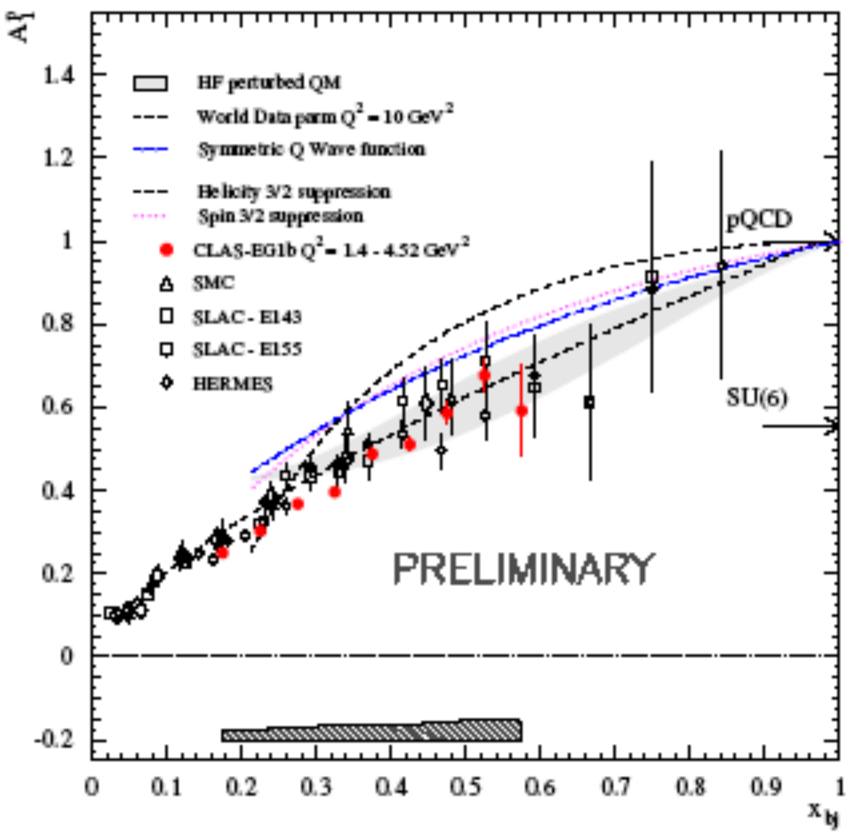
- So far we have focused only about:
  - Low x behavior of spin structure function
  - Its Q^2 evolution
  - Because those were needed to check various high energy sum rules

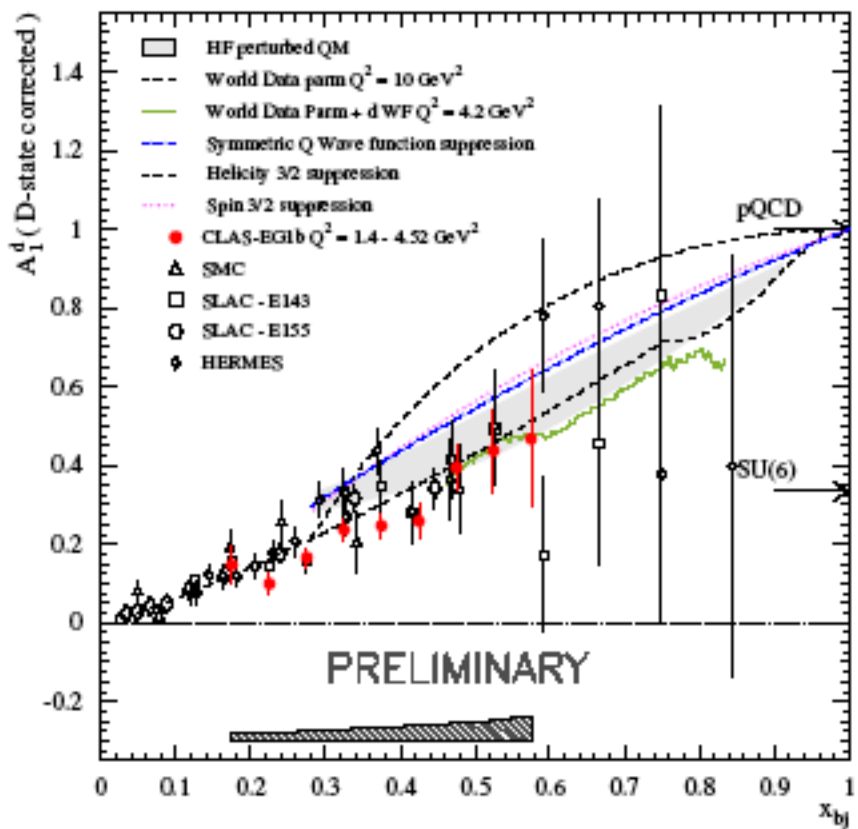
- ***What about high x?***
  - A region were we know gluons do NOT play a dominant role
  - Should we not test the predictions of structure functions and their behavior in this region?
  - Motivation for Jefferson Laboratory Physics



High x measurements

- Jlab focused on high x measurements: ***Luminosity Crucial!***
- A_1 of proton, neutron and deuteron
- pQCD predicts A_1=1 when x=1



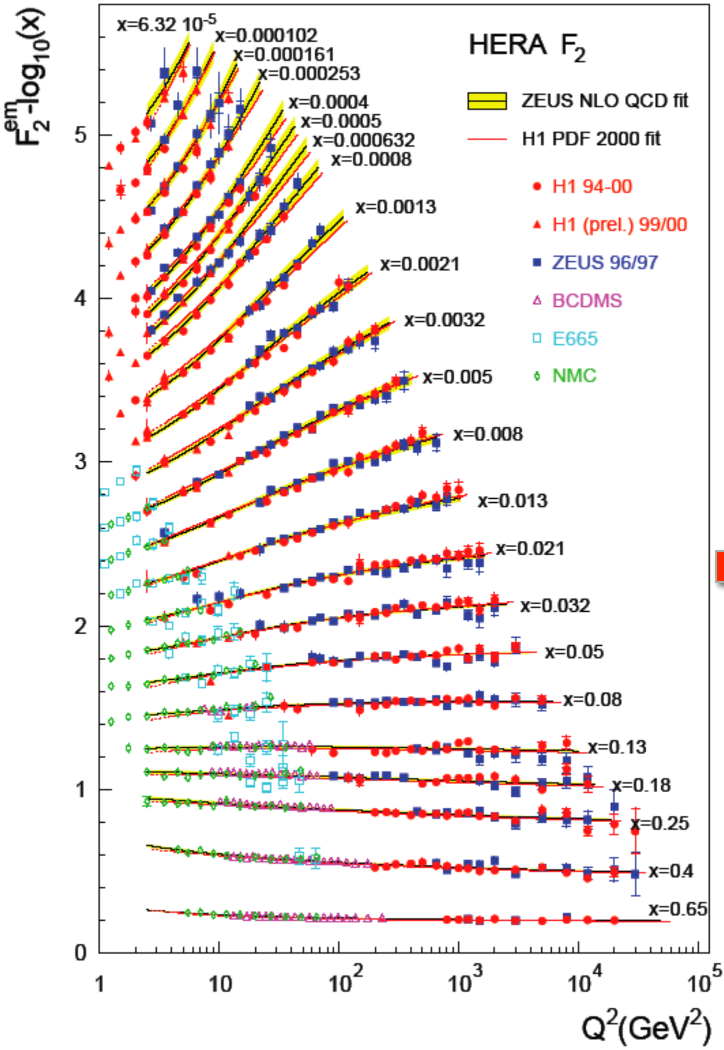


GET POLARIZED PARTON DISTRIBUTIONS

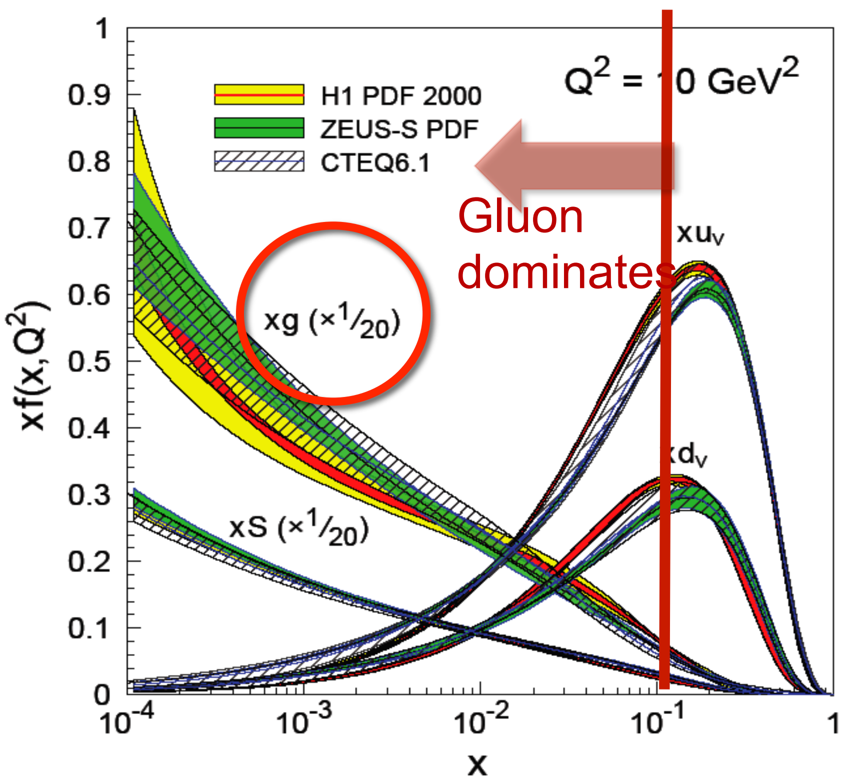
Next-to-Leading Order Perturbative QCD with DGLAP equation

SIMILAR IN SPIRIT TO WHAT IS DONE IN UNPOALRIZED PDFS…. CTEQ, MRST…

Similar to extraction of PDFs at HERA (RECALL)



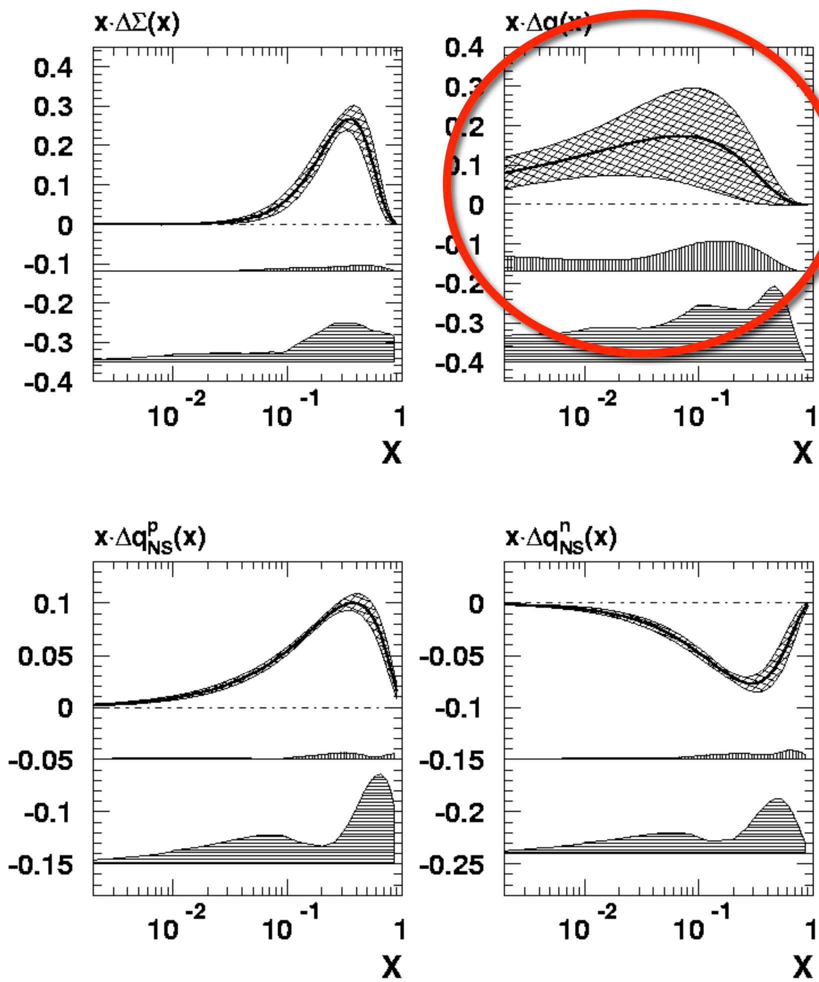
NLO pQCD analyses: fits with **linear** DGLAP* equations



*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

Global analysis of Spin SF

ABFR analysis method by SMC PRD 58 112002 (1998)



- World's all available g_1 data
- Coefficient and splitting functions in QCD at NLO
- Evolution equations: DGLAP

$$f(x) = x^{\alpha}(1-x)^{\beta}(1+ax+bx^2)$$

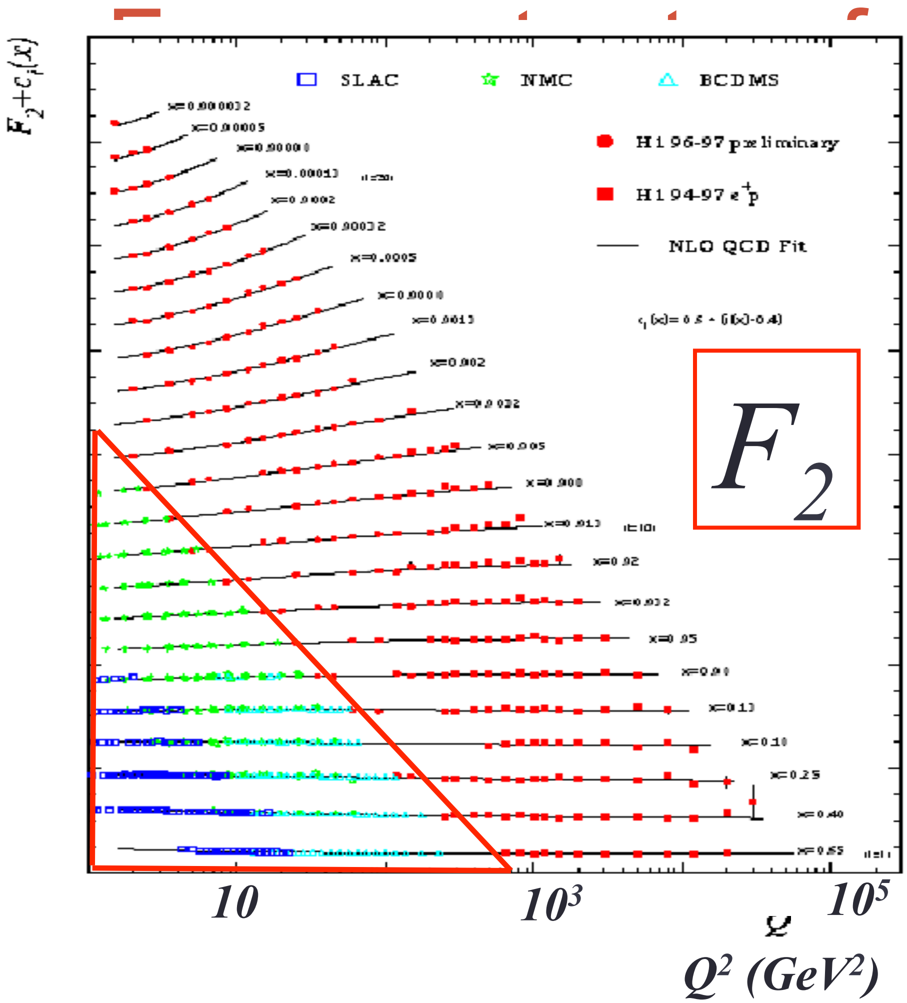
- Quark distributions fairly well determined, with small uncertainty
  - $\Delta\Sigma$ = 0.23 +/- 0.04
- Polarized Gluon distribution has largest uncertainties
  - ΔG = 1 +/- 1.5

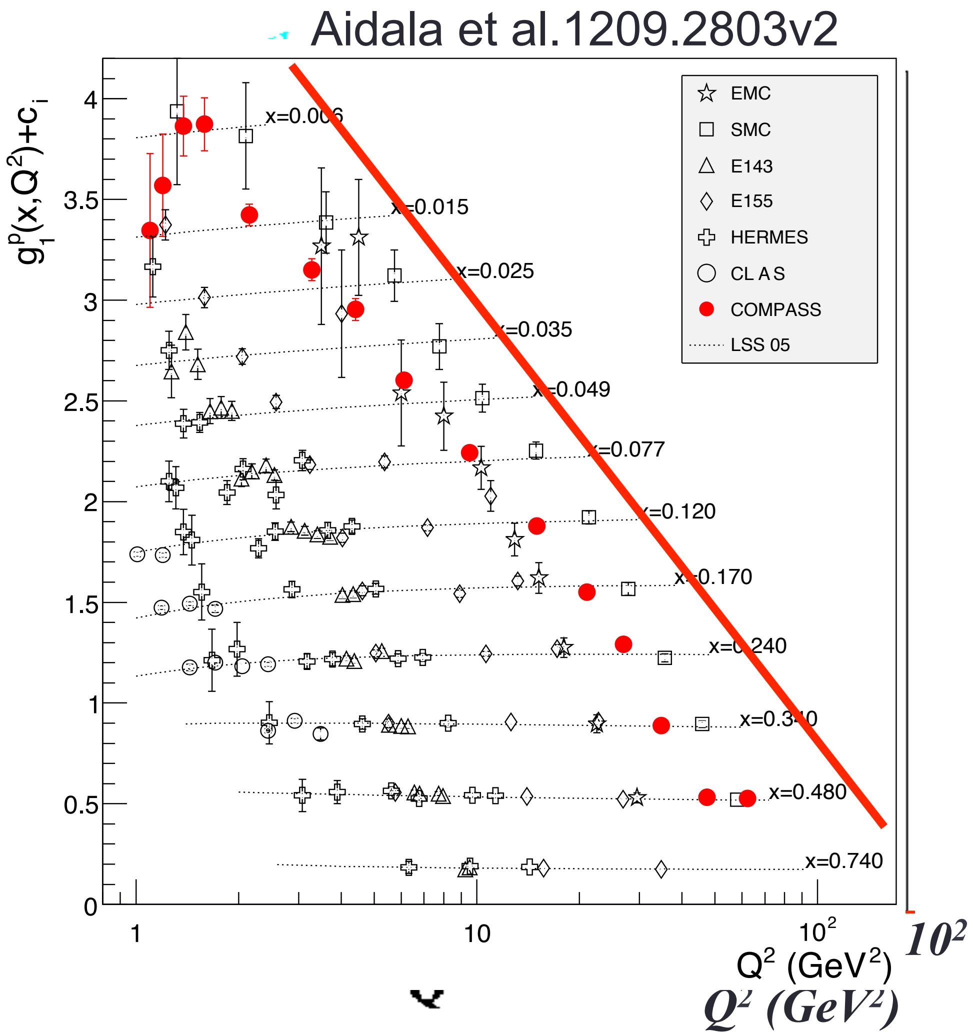
Consequence:

- Quark + Anti-Quark contribution to nucleon spin is definitely small: Ellis-Jaffe sum violation confirmed

$$\Delta\Sigma = 0.23 \pm 0.03$$

- Is this small ness due to some cancellation between quark +anti-quark polarization: Semi-Inclusive data could address this.
- The gluon's contribution seemed to be large! $\Delta G = 1 \pm 1.5$
- While I am only presenting one global analysis result: Most NLO analyses by theoretical and experimental collaboration consistent with HIGH gluon contribution
  - Anomaly scenario gained weight
  - Direct measurement of gluon spin with other probes warranted. Seeded the RHIC Spin program

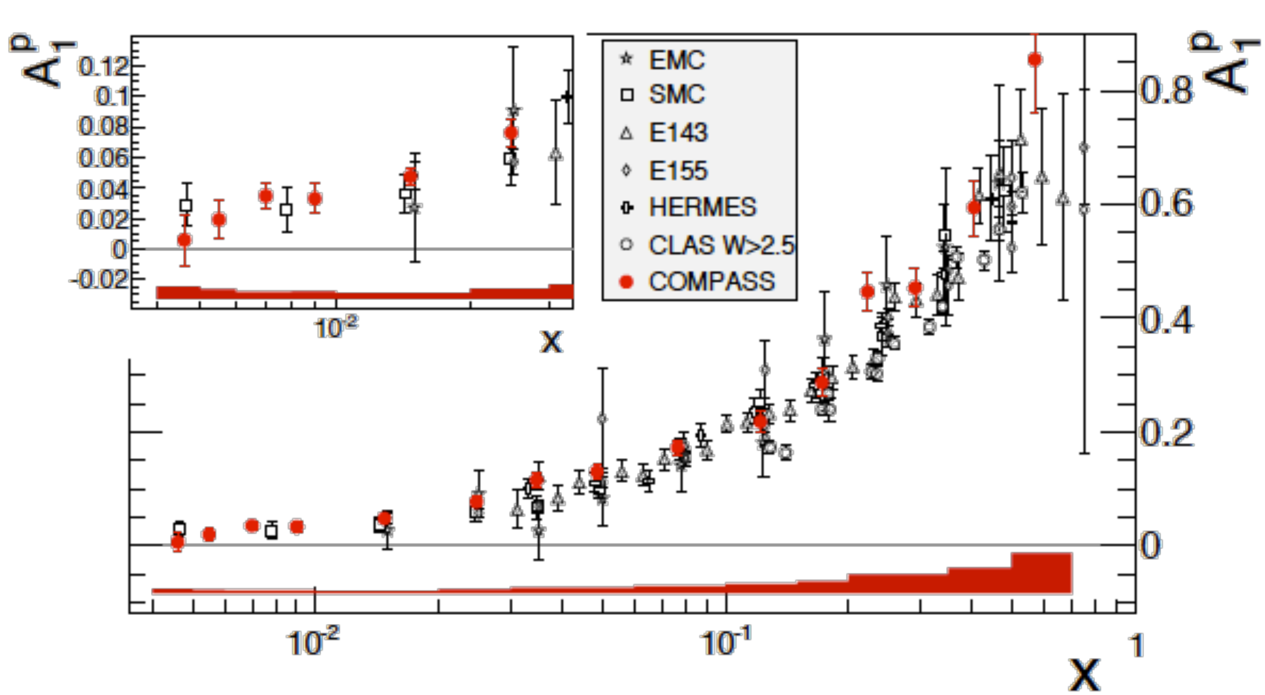




Large amount of polarized data since 1998… but not in NEW kinematic region!

Large uncertainty in gluon polarization (+/-1.5) results from lack of wide Q^2 arm

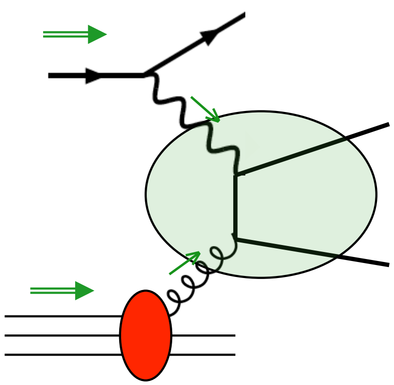
COMPASS data

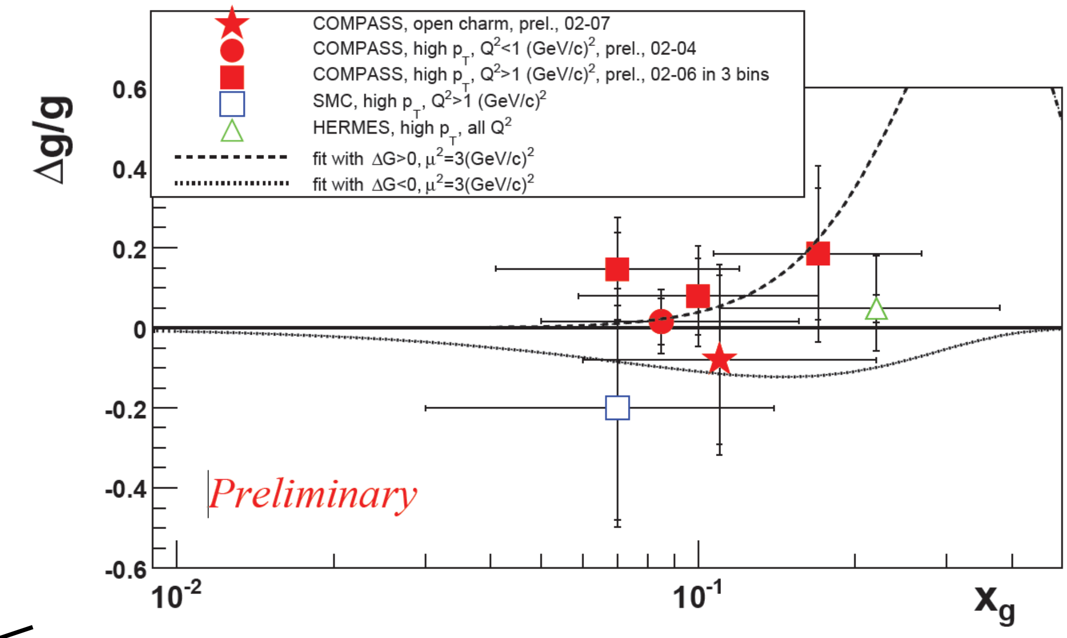


- Precision!
- Consistent with previous data sets
- Measurement range the same as the previous muon beam experiment SMC at CERN
- Not much help in furthering the cause of extracting gluon distribution through NLO analyses…

Photon-Gluon Fusion: access to Gluon's spin contribution

Most recent COMPASS data:

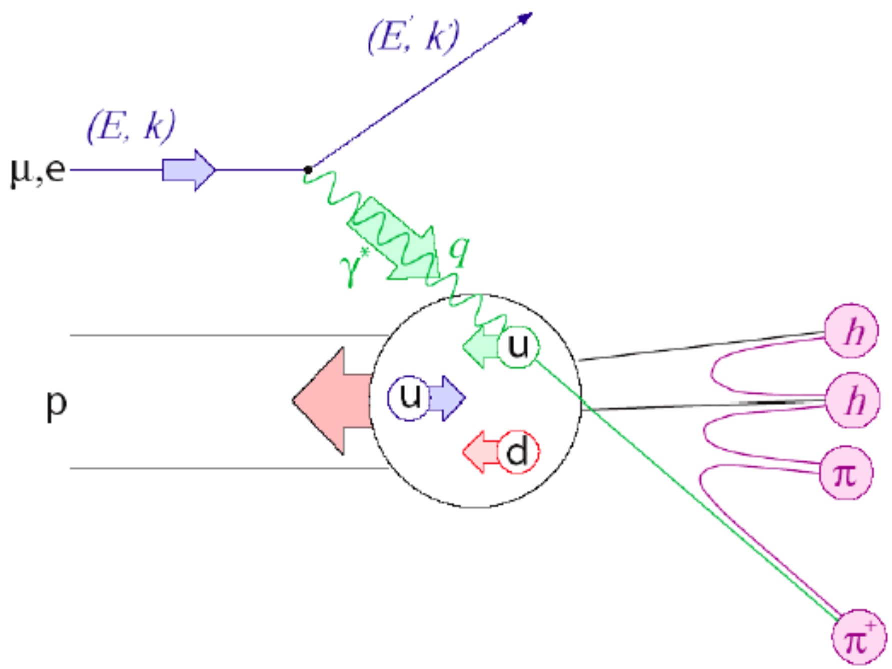




Flavor separation of quarks/anti-quark spin:

Do quarks and anti-quarks work against each other to reduce the $\Delta\Sigma$?

Flavor tagging: semi-inclusive DIS



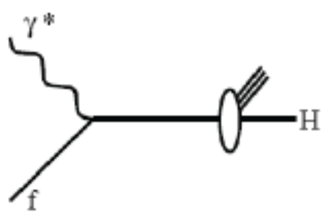
Method led
By HERMES
Now COMPASS
Jlab Experiment

- Inclusive DIS + *detect additional beam/target fragments*
- Selectively tagging *pions, kaons* separates the flavors involved in interactions, needs Particle ID
- Purity and efficiency of tagging studied extensively using MC simulations to overcome our ignorance in fragmentation process.

Significance of SIDIS

- In addition to scattered lepton, a hadron is observed and tagged, some times even identified.
- Probability to find a hadron H with fractional momentum z of the parton which evolved in to that hadron H: $D_f^H(z,Q^2)$
- pQCD predicts the Q^2 dependence identical to that of PDFs
- We get frag. functions from e+e- collisions (LEP, NOW BELLE)
- The reason we learn from the SIDIS data:

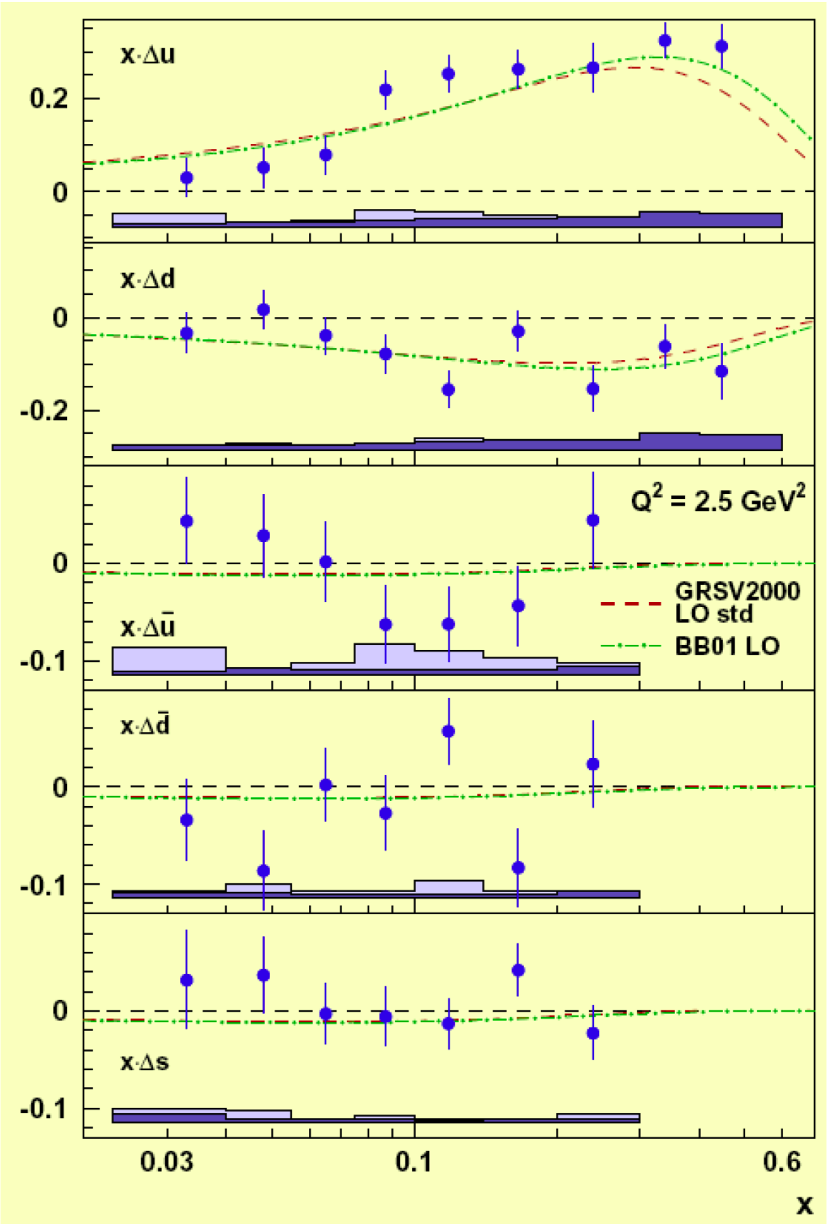
at LO:



$$d\Delta\sigma \sim \sum_{q=u,\bar{u},\ldots,\bar{s}} \Delta q(x,Q^2) \boxed{D_q^H(z,Q^2)}$$

extra weight for each quark

breaks the $\Delta q + \Delta\bar{q}$ deadlock of DIS plus better flavor separation



Flavor Separation

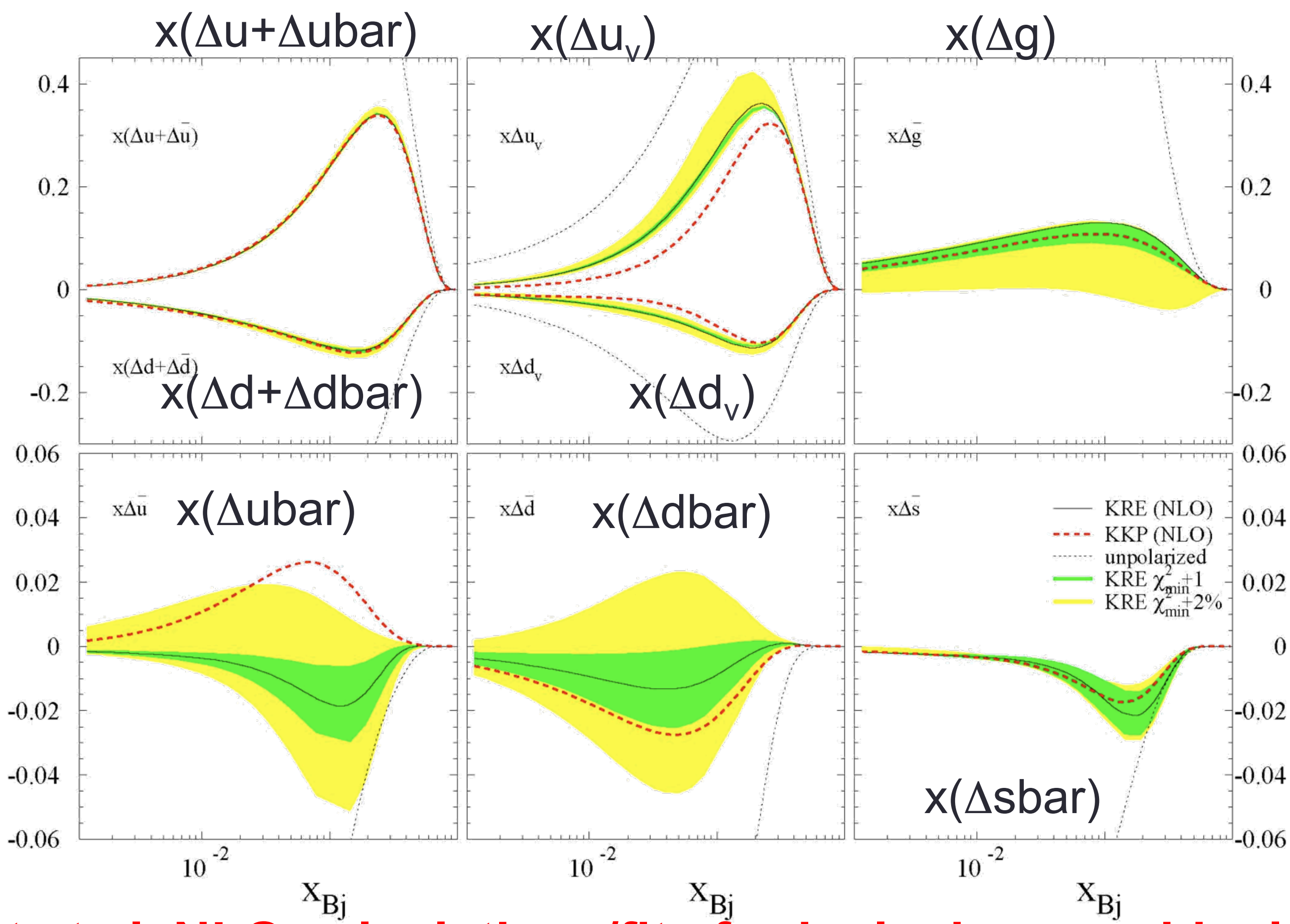
$$A_1^h(x,Q^2) = \frac{\int \mathrm{d}z \sum_f e_f^2 \Delta q_f(x,Q^2)\cdot D_f^h(z,Q^2)}{\int \mathrm{d}z \sum_f e_f^2\ q_f(x,Q^2)\cdot D_f^h(z,Q^2)}$$

- Early 2000

- Charge tagging $\pi^{+/-}$
- Un-polarized fragmentation functions from LEP
- Evolution a la Altarelli Parisi
- Limited information of s, sbar due to lack of data on kaons
- LO extraction, MC used for purity and efficiency studies

Semi-Inclusive DIS Data & NLO pQCD

Circa 2007



- **Sassot et al. NLO calculations/fits for inclusive+semi-inclusive data**
- Largest uncertainties in **polarized gluon & flavor separated anti-quark**

Results/Conclusions

By the time the fixed target polarized DIS experiments were over we learnt conclusively that:

- The quark+anti-quarks, $\Delta\Sigma$, indeed contribute very little
  - $\Delta\Sigma$ = 0.3 +/- **0.03** (recall: 0.12 +/-**0.17** of EMC)
  - The new results were calculated at Next-to-Leading Order pQCD.
  - Low x extrapolations were consistent with pQCD

Ellis Jaffe spin sum rule was still violated

Bjorken Spin rule was found to be correct.

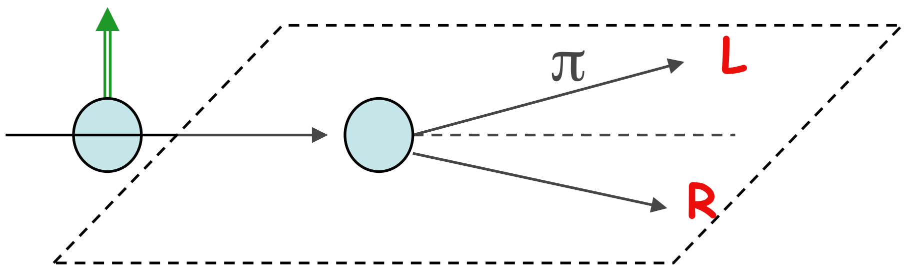
Polarized gluon distribution was found to be LARGE, but with large uncertainties

Dependence of results on Anti-Quark/Quark separation on non-perturbative objects such as Fragmentation functions was a reason for concern….

Transverse Spin Puzzle

Had been observed but ***ignored*** for almost 3 decades…

Transverse spin introduction



$$A_N = \frac{N_L - N_R}{N_L + N_R}$$

$$A_N \sim \frac{m_q}{p_T} \alpha_S$$

Kane, Pumplin, Repko 1978

- Since people starved to measure effects at high p_T to interpret them in pQCD frameworks, this was "neglected" as it was expected to be small….. However….
- Pion production in single transverse spin collisions showed us something different….

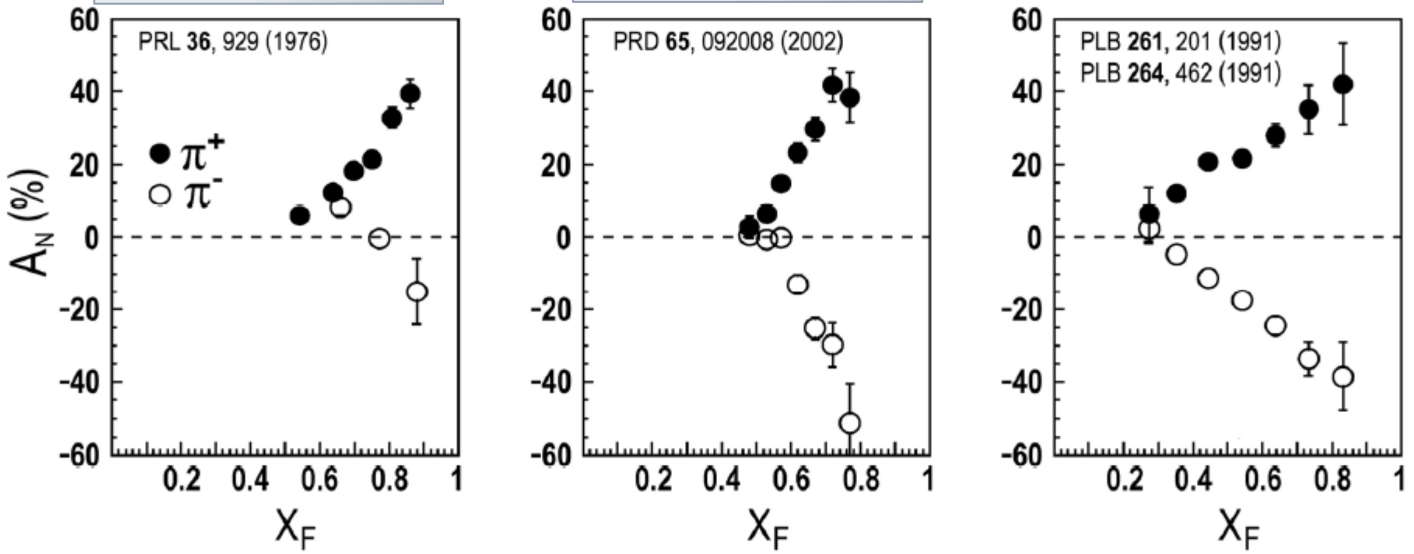
Pion: single transverse spin asymmetries!

$$x_F = P_L / P_L^{\max} = 2P_L/\sqrt{s}$$

ZGS/ANL
√s=4.9 GeV

AGS/BNL
√s=6.6 GeV

FNAL
√s=19.4 GeV



Seeds for RHIC Spin program:

Hadrons are almost full of gluons…. 95% of the mass of the hadrons comes from self interaction of gluons!

So if one wants to study gluons and their spin contribution to proton's spin, ***why not directly explore the gluon spin with polarized proton collisions?***

A very nice measurement of anti-quark polarization was suggested, which <u>did not require</u> fragmentation functions

Curious and bothersome transverse spin asymmetries in p-p scattering persistent in every experiment performed…. US physicists heavily involved… decided to investigate further

Technical know-how of polarizing proton beams at high energy became available!