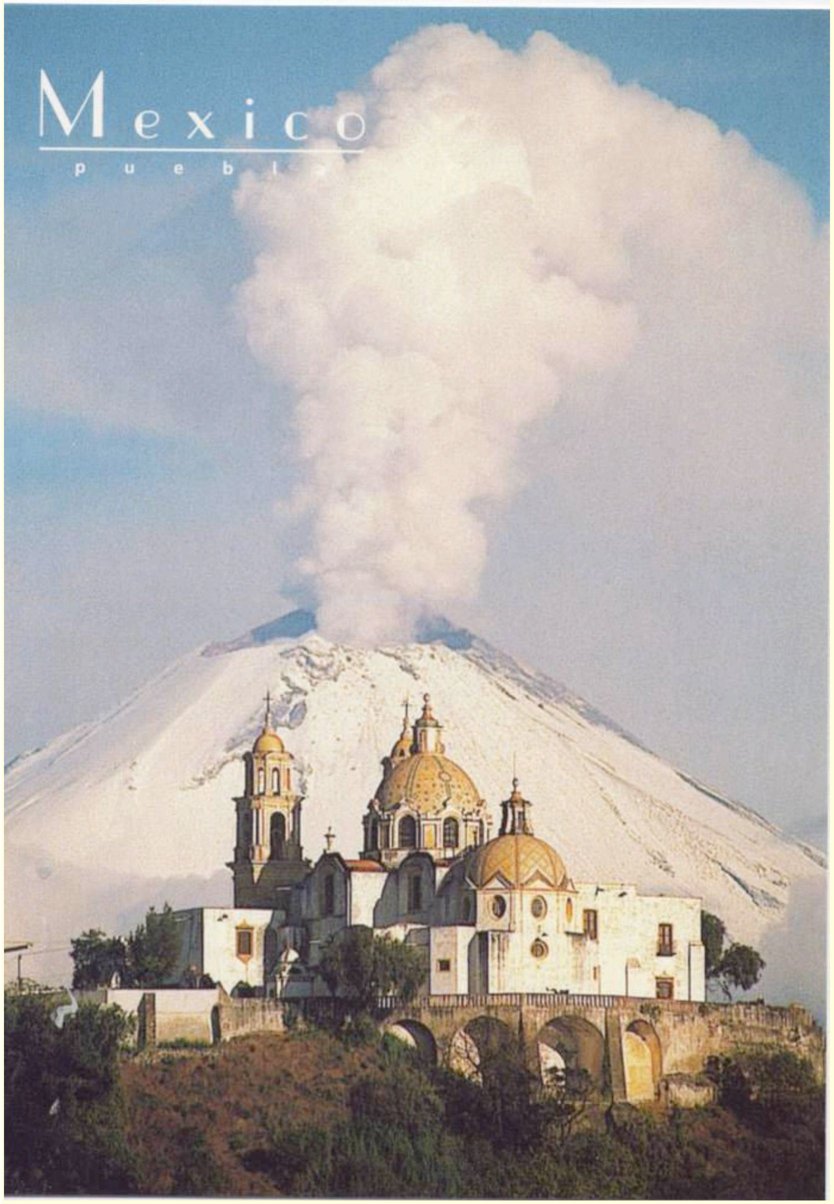
Curiosity & Fascination of Spin is Universal!

1955 Bohr & Pauli trying to understand the dynamics of a tippy-top toy



Polarized Parton Distributions: Experimental Measurements & Excitement

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CTEQ Summer School
Puebla, Mexico
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Understanding Nucleon Structure

- Nucleons are made up of
  - Quarks
    - Valence quarks
    - Sea quarks
  - Gluons

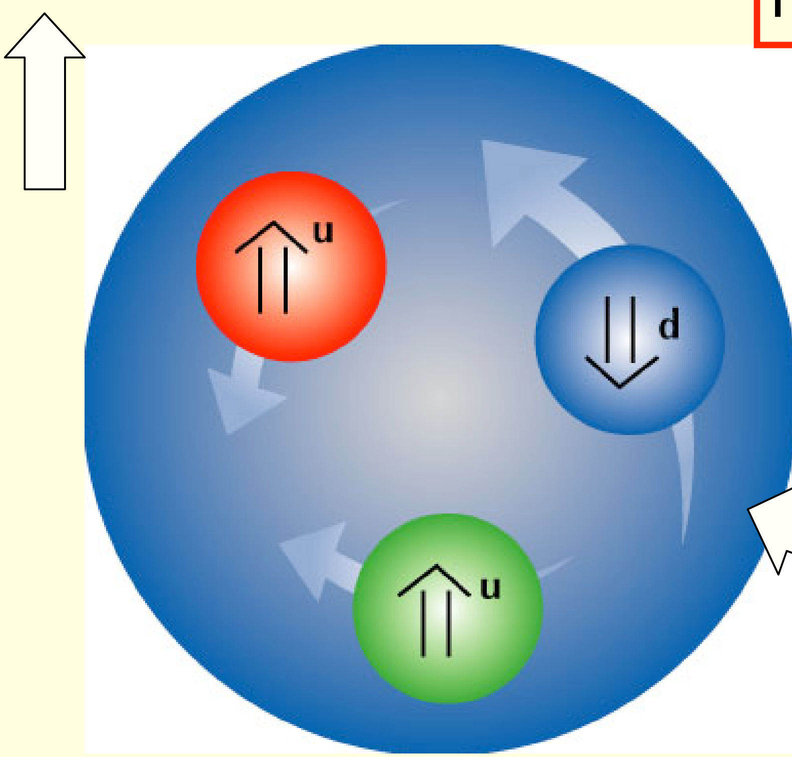
- Quarks and gluons carry 50% (each) of the linear momentum of the nucleons

- *What about the nucleon spin? How would one start to explore?*

Nucleon's Spin A Simple Model!

- Protons and Neutrons are spin 1/2 particles
- Quarks that constitute them are also spin 1/2 particles
  - And there are three of them in the nucleons:

Proton: u u d   Neutron: u d d

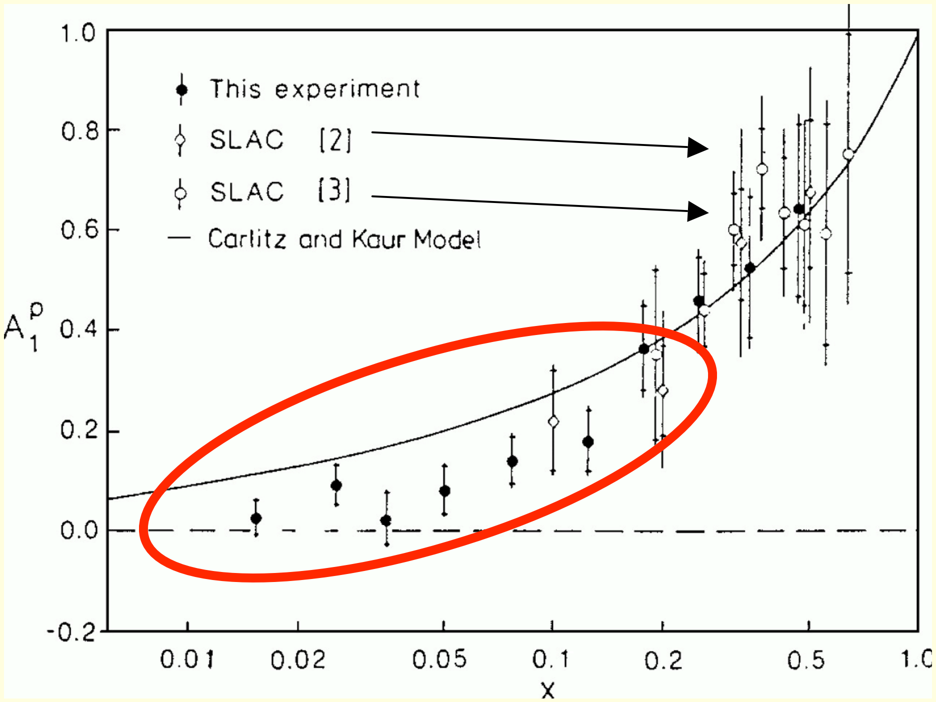


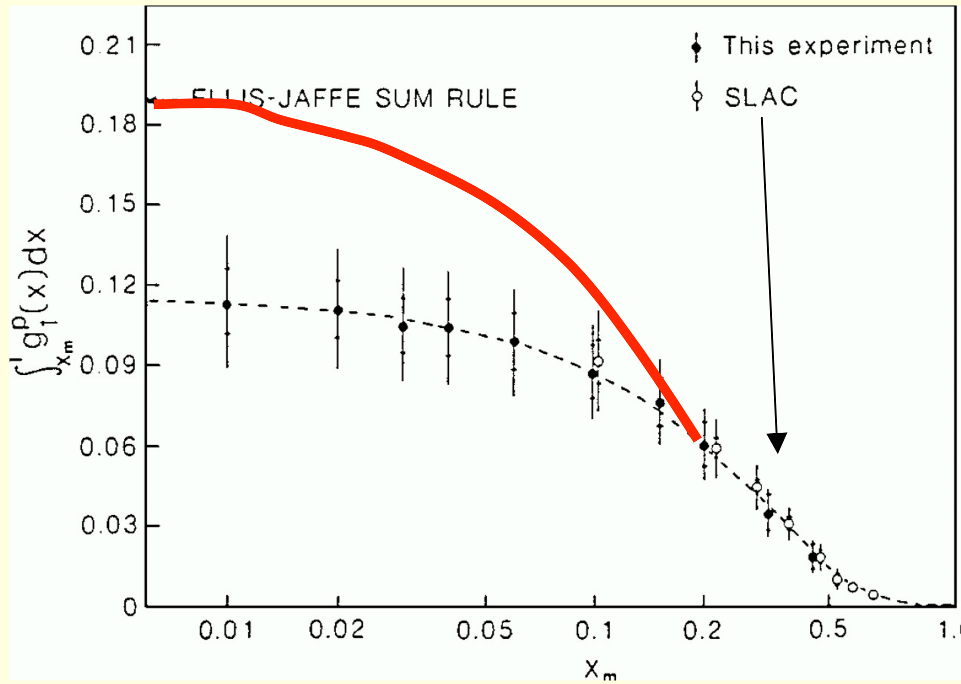
S_{proton} = Sum of all quark spins!

$$1/2 \overset{?}{=} 1/2 + 1/2 + 1/2$$

$$1/2 = 1/2 - 1/2 + 1/2$$

Proton Spin Crisis (1989)!

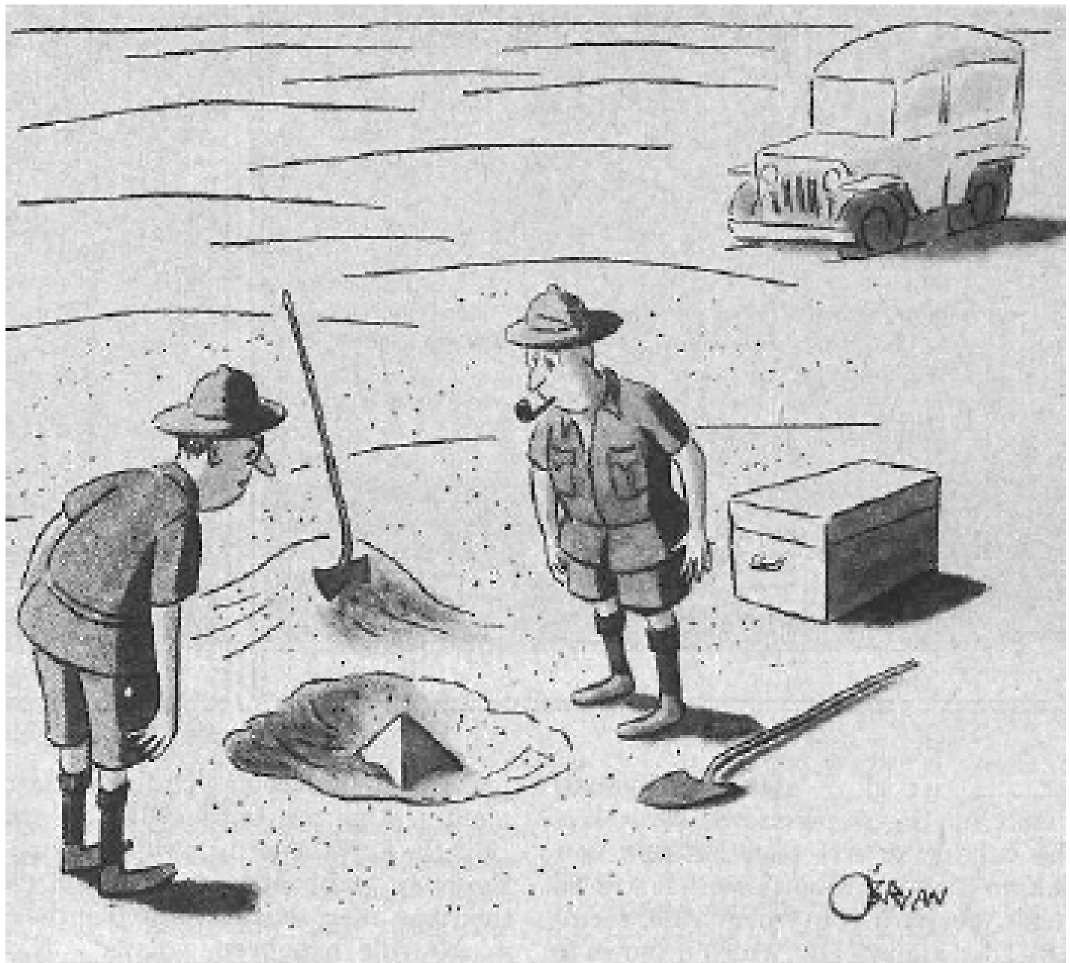




Quarks Don't Carry the Proton the Spin "1/2"

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

How significant is this?

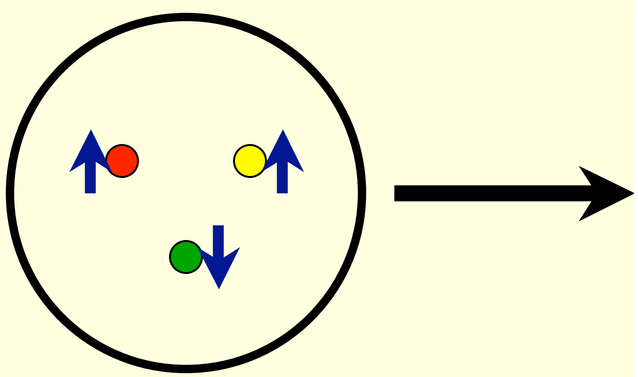


"This could be the discovery of the century. Depending, of course, on how far down it goes."

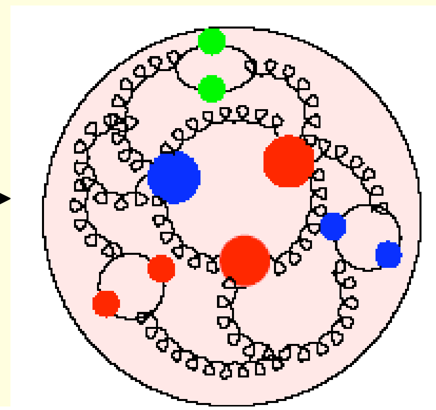
What's Wrong?....Think... Think...(1990s)

- Nucleon Spin is subtle: There aren't only quarks, there are **gluons** and further, **quarks and gluons may be moving around in orbits adding** to the TOTAL SPIN!

Quark Model



QCD + Orbital motion



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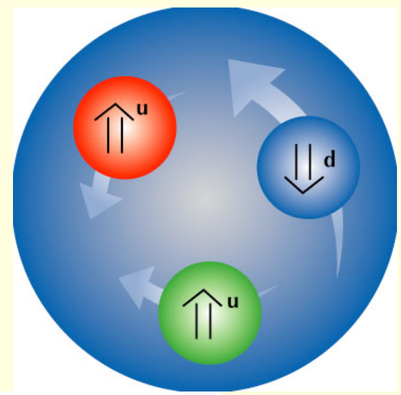


$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma}_{0.12} + \underbrace{\Delta G}_{\text{Significant(?)}} + \underbrace{l_{Q\&G}}_{???}$$

Overview

- **Spin structure functions: some formalism**
- **Experimental basics**
  – What is needed
  – How is it accomplished experimentally

- **Brief review of past and present fixed target experiments**
  – CERN, SLAC & DESY
  – Inclusive & Semi-inclusive DIS date sets
  – Evaluating polarized parton distributions (NLO pQCD)

- **A new and exciting technique**
  – Physics with polarized pp collisions at RHIC
  – RHIC, polarimetry, experiments, measurements
  – RHIC Future

Some Formalism

Some of it you may have Seen Earlier

Polarized Cross Section & Spin SFs

- Lepton Nucleon Cross Section:

$$\frac{d^3\sigma}{dxdyd\phi} = \frac{\alpha^2 y}{2Q^4} L_{\mu\nu}(k,q,s,)W^{\mu\nu}(P,q,S)$$

Nucleon spin

Lepton spin

- Lepton tensor $L_{\mu\nu}$ controls the kinematics (QED)

- Hadronic tensor $W^{\mu\nu}$ nucleon structure

$$W^{\mu\nu}(P,q,S) = -(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2})F_1(x,Q^2) + (p^\mu - \frac{P\cdot q}{q^2}q^\mu)(p^\nu - \frac{P\cdot q}{q^2}q^\nu)\frac{1}{P\cdot q}F_2(x,Q^2)$$

$$-i\epsilon^{\mu\nu\lambda\sigma}q_\lambda \left[\frac{MS_\sigma}{P\cdot q}(g_1(x,Q^2) + g_2(x,Q^2)) - \frac{M(S\cdot q)P_\sigma}{P\cdot q} g_2(x,Q^2)\right]$$

Structure Functions & PDFs

- The F_1 and F_2 are unpolarized structure functions or momentum distributions
- The g_1 and g_2 are polarized structure functions or spin distributions
- In QPM
  - $F_2(x) = 2xF_1$ (Calan Gross relation)
  - $g_2 = 0$ (Twist 3 quark gluon correlations)

$$F_1(x) = \frac{1}{2}\Sigma_f e_f^2 \{q_f^+(x) + q_f^-(x)\} = \frac{1}{2}\Sigma_f e_f^2 q_f(x)$$

$$g_1(x) = \frac{1}{2}\Sigma_f e_f^2 \{q_f^+(x) - q_f^-(x)\} = \frac{1}{2}\Sigma_f e_f^2 \Delta q_f(x)$$

Nucleon spin & Quark Probabilities

- Define

$$\Delta q = q^{+} - q^{-}$$

  - With q^+ and q^- probabilities of quark & anti-quark with spin parallel and anti-parallel to the nucleon spin

- Total quark contribution then can be written as:

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

- And the proton spin then becomes:

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

First Moments of SPIN SFs

- With $$\Delta q = \int \Delta q(x)dx$$

$$\Gamma_1^p = \frac{1}{2}\left[\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right]$$

$$= \frac{1}{12}\underbrace{(\Delta u - \Delta d)}_{a_3=g_a} + \frac{1}{36}\underbrace{(\Delta u + \Delta d - 2\Delta s)}_{a_8} + \frac{1}{9}\underbrace{(\Delta u + \Delta d + \Delta s)}_{a_0}$$

$a_3=g_a$
Neutron decay

a_8
(3F-D)/3
Hyperon Decay

a_0
$\Delta\Sigma$

$$\Gamma_1^{p,n} = \frac{1}{12}\left[\pm a_3 + \frac{1}{\sqrt{3}}a_8\right] + \frac{1}{9}a_0$$

Spin Sum Rules

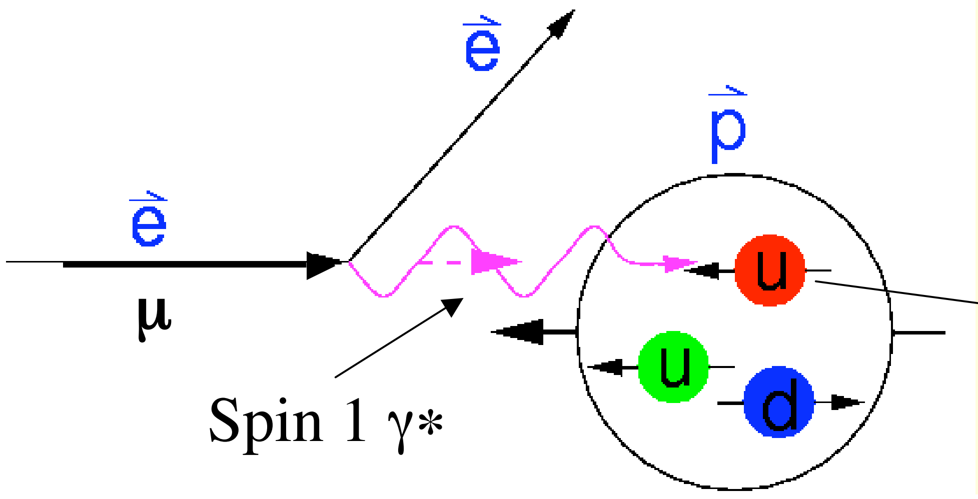
- Bjorken sum rule (PRD 9 (1966) 1467)
  - $\Gamma_1^p - \Gamma_1^n = (g_a/6)$
  - If wrong, QCD is wrong!

- Ellis-Jaffe sum rule (PRD 9 (1974) 1444)
  - Evaluated individual values of p and n first moments of spin structure functions assuming $\Delta s = 0$
  - $\Delta\Sigma \sim 0.6$

- Measurements of first moments to verify these basic sum rules became the main motivations for the first generation of experiments (Polarized Deep Inelastic Scattering)
  - E80, E130 at SLAC and EMC at CERN

How is Quark Spin measured?

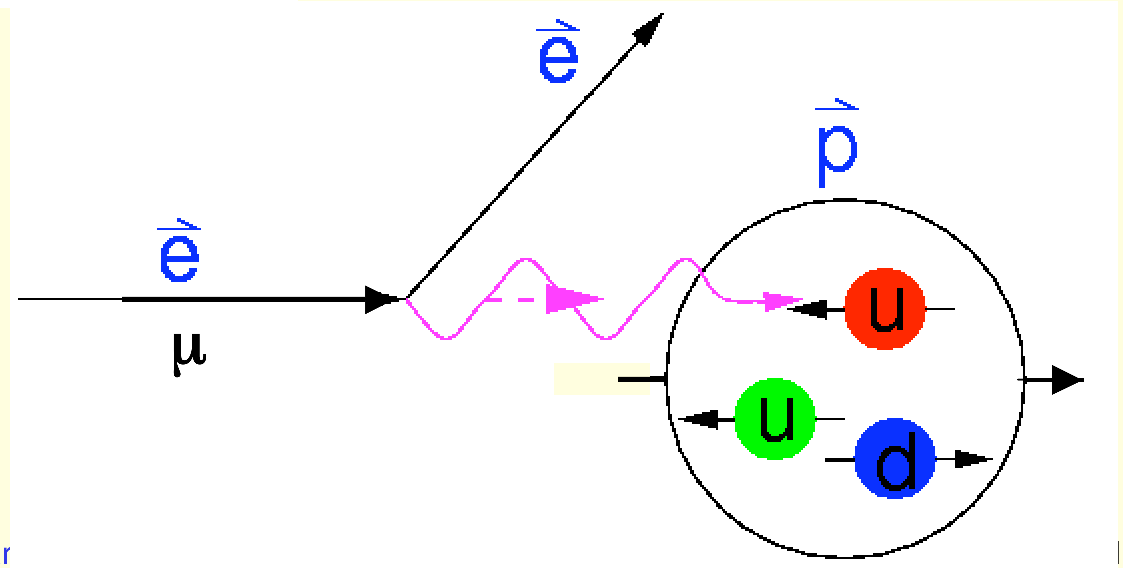
- Deep Inelastic polarized electron or muon scattering



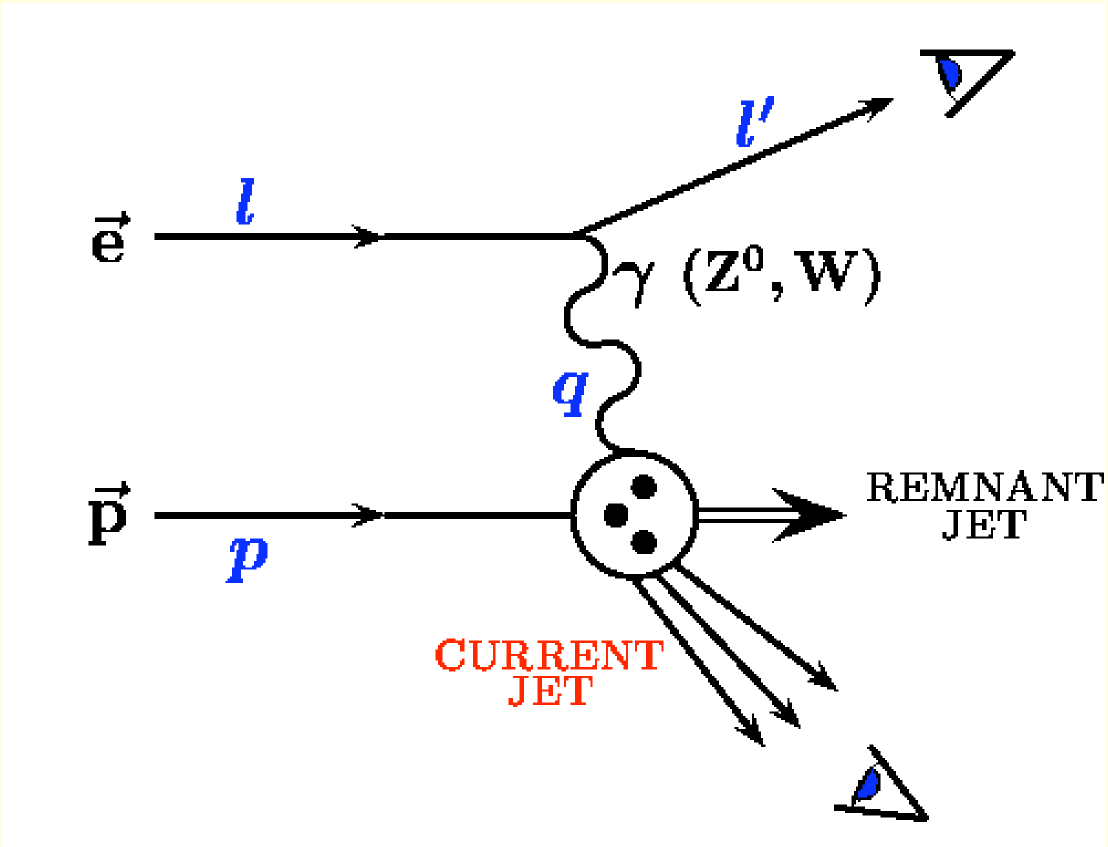
$$A_{\gamma^* p} = \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}$$

Spin 1/2 quarks

$$\lambda = \frac{\text{Constant}}{p}$$



Deep Inelastic Scattering



$$Q^2 = -q^2 = sxy$$

$$x = \frac{Q^2}{2p \cdot q}$$

$$y = \frac{p \cdot q}{p \cdot l}$$

$$s = 4E_e E_p$$

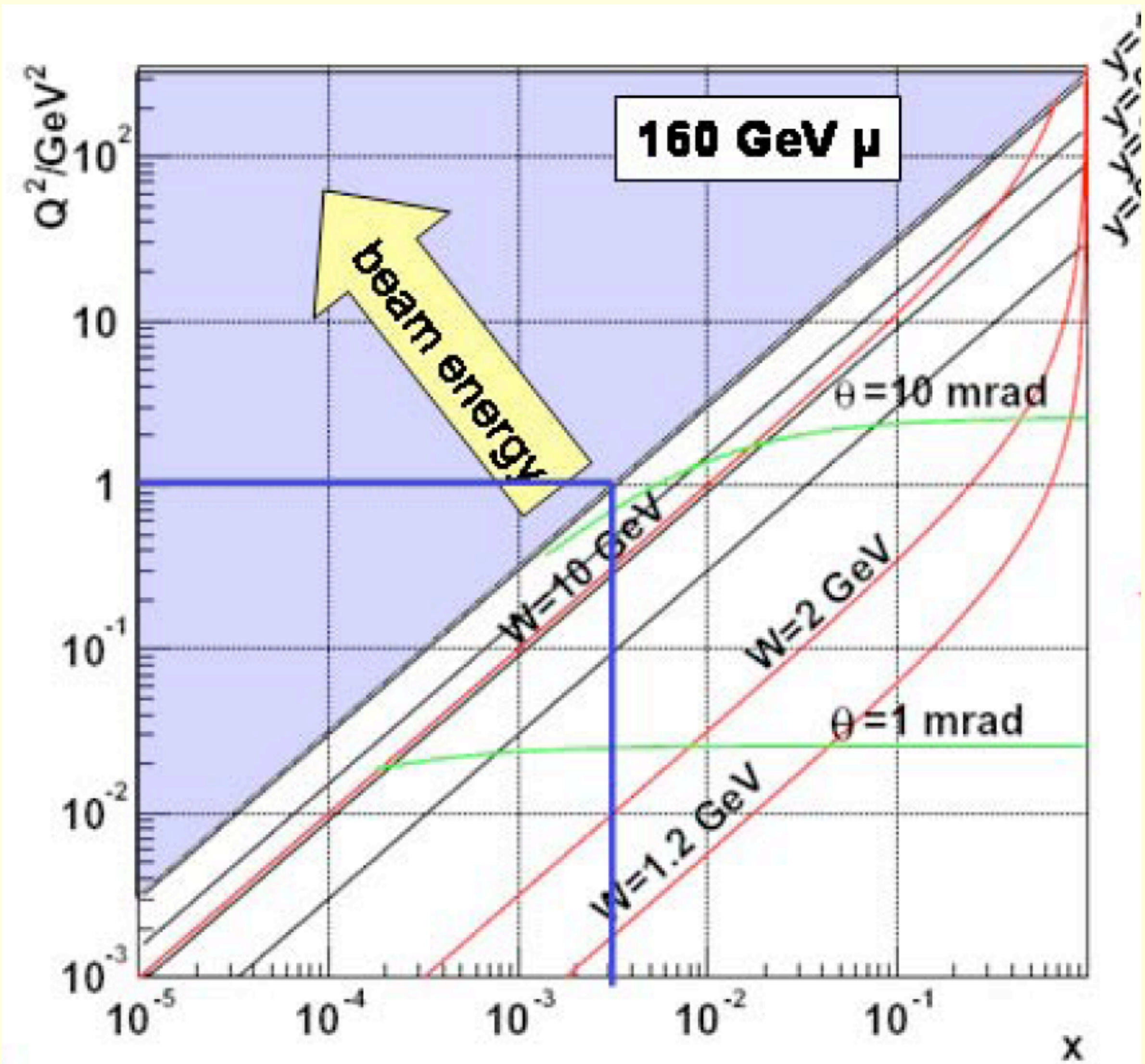
$$W = (q+p)^2$$

Inclusive DIS: only measure the scattered electron

Semi-Inclusive DIS: Inclusive + Current Jet remnants

Exclusive DIS: Semi-Inclusive + Target Jet remnants

EXAMPLE OF DIS KINEMATIC REACH



- CERN experiment with muon beam 160 GeV/c
- Plot of Q^2 vs. x
- Lines of constant y and W shown
- Blue line indicates an "adhoc" limit of Q^2 > 1 GeV^2 or DIS
- *For Spin Sum Rule Verification: measurements over a large x range and constant and high Q^2 value*

Second Generation Experiments

- Spin Crisis!
  - Ellis Jaffe Spin Rule violated in proton
  - While **not fundamental**, it was unexpected!
  - Needed better accuracy to verify the EJ spin sum rule violation

- Test of Bj spin sum rule became urgent:
  - Measurement of **neutron spin structure** function also warranted
  - Needed polarized neutron targets

- Three major experimental efforts initiated (late 1980s/ early 1990s)
  - Spin Muon Collaboration at CERN
    - Mostly inclusive, but also did semi-inclusive physics in late 1990s
  - E143 at SLAC
    - Mostly inclusive
  - HERMES at DESY
    - Proposed a new technique: gas target in a cell in the electron storage ring
    - Late on commissioning, but later lead the era of semi-inclusive DIS

Experimental Basics

Experimental Needs

Polarized target, polarized beam

- Up to very recent times only fixed target polarized DIS experiments
- Polarized target: hydrogen(proton), deuteron (proton+neutron), Helium (2 protons + neutron)
- Polarized beams: electron, positron, muon used in DIS experiments

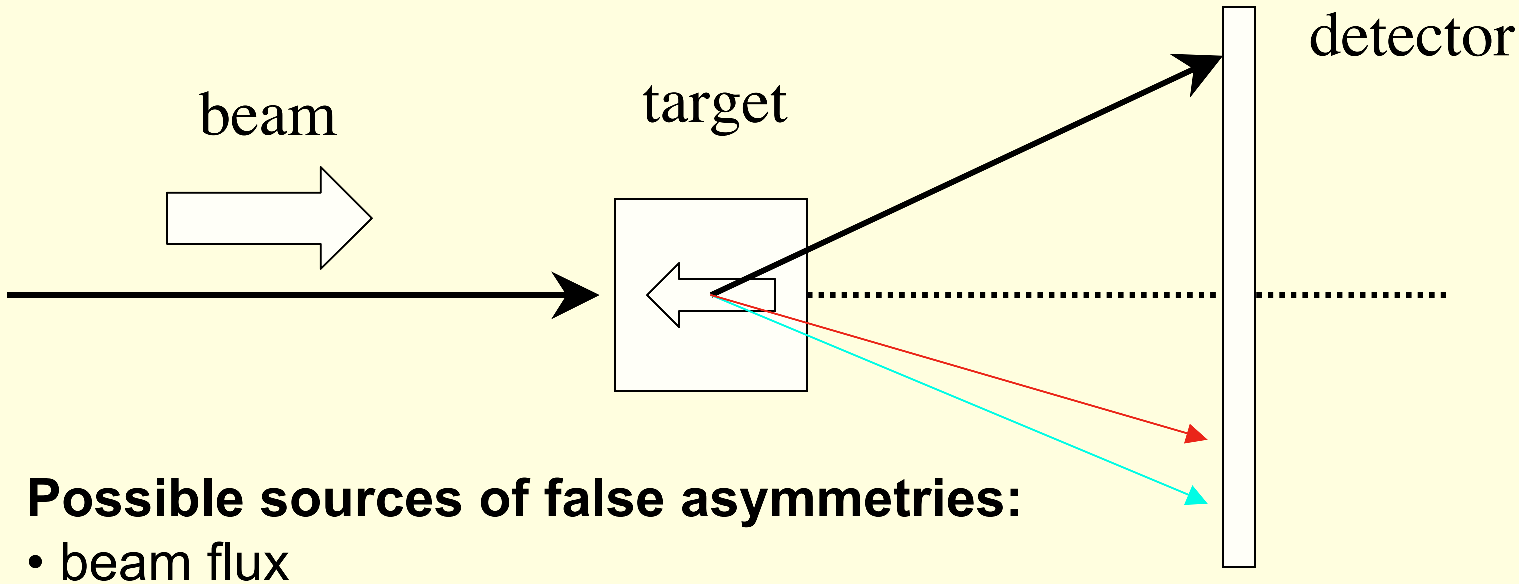
Determine the kinematics: measure with high accuracy:

- Energy of **incoming lepton**
- Energy, direction of **scattered lepton**: energy, direction
- Good identification of **scattered lepton**
- *In case of semi-inclusive and exclusive extend this to current and jet fragments including particle identification*

Control of false asymmetries:

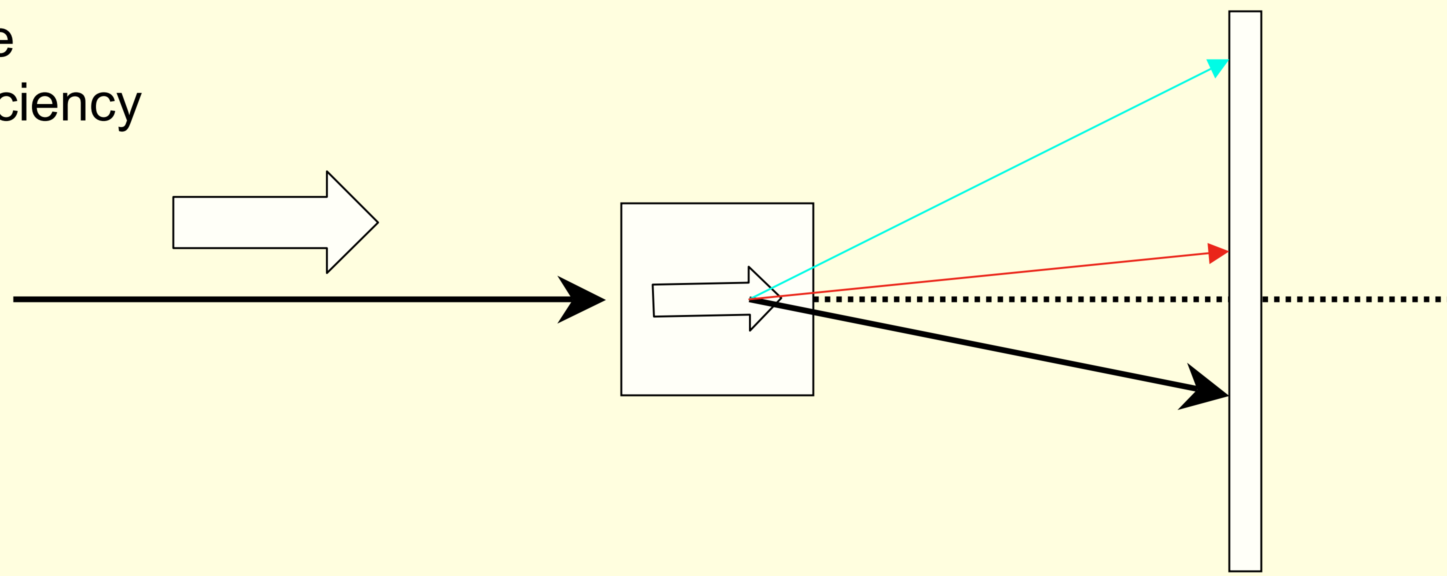
- Need excellent understanding and control of **false asymmetries** (time variation of the detector efficiency etc.)

Schematic of Spin Experiment



Possible sources of false asymmetries:

- beam flux
- target size
- detector size
- detector efficiency



An Ideal Situation: Imaginary!

$$A_{measured} = \frac{N^{\rightarrow\leftarrow} - N^{\rightarrow\rightarrow}}{N^{\rightarrow\leftarrow} + N^{\rightarrow\rightarrow}}$$

$$N^{\leftarrow\rightarrow} = N_b \cdot N_t \cdot \sigma^{\leftarrow\rightarrow} \cdot D_{acc} \cdot D_{eff}$$

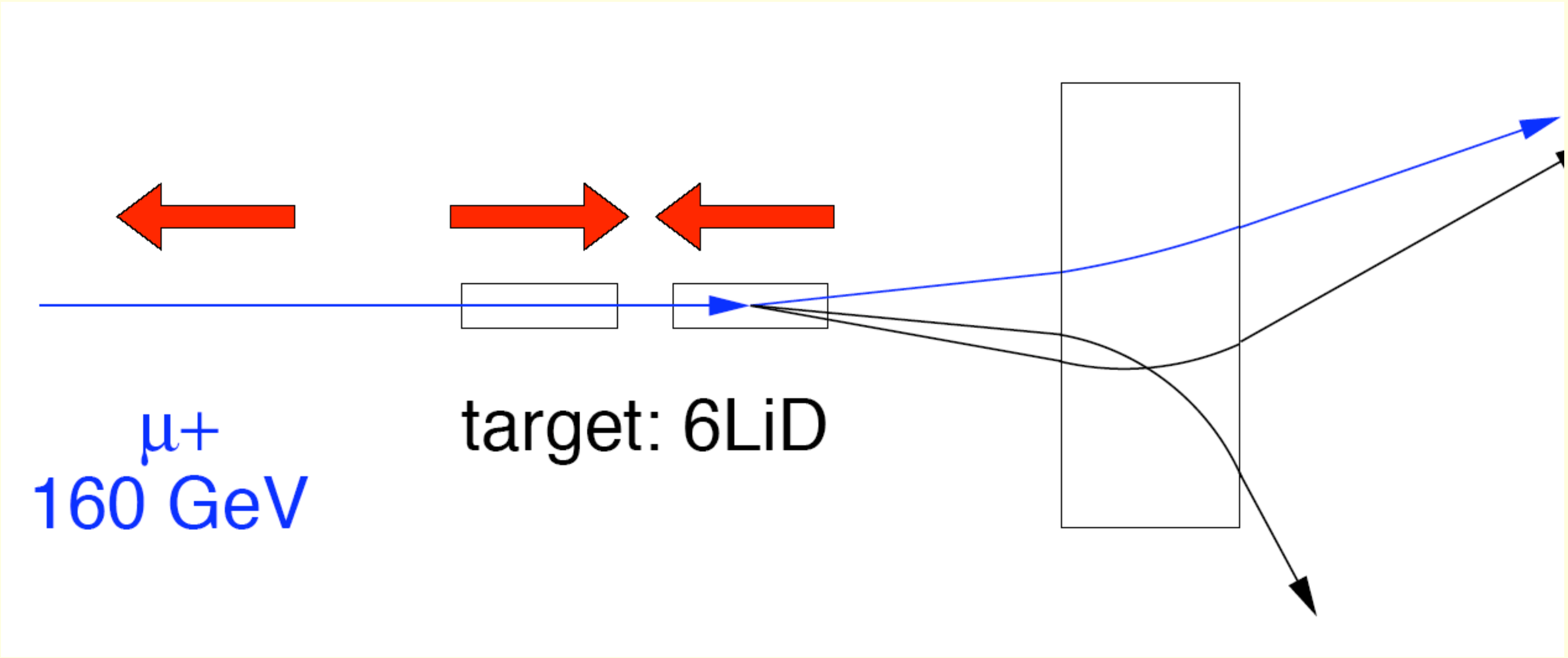
$$N^{\rightarrow\rightarrow} = N_b \cdot N_t \cdot \sigma^{\rightarrow\rightarrow} \cdot D_{acc} \cdot D_{eff}$$

ONLY ON PAPER CAN THIS REALLY HAPPEN!

$$A_{measured} = \frac{\sigma^{\rightarrow\leftarrow} - \sigma^{\rightarrow\rightarrow}}{\sigma^{\rightarrow\leftarrow} + \sigma^{\rightarrow\rightarrow}}$$

COMPASS Setup

- Typical Fixed target experiment setup (EMC, SMC similar)



- Target polarization direction reversed every 6-8 hrs
- Typically experiments try to limit false asymmetries to be about 10 times smaller than the physics asymmetry of interest

Experimental Essential

- Beam and target history of SLAC, CERN and DESY setups

Beam energy	Target	Lepton beam	Xmin attained
SLAC 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)
  - Rapid variation of target polarization (HERMES)
  - Simultaneous measurement of two oppositely polarized targets in the same beam (SMC/CERN)

Asymmetry Measurement

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

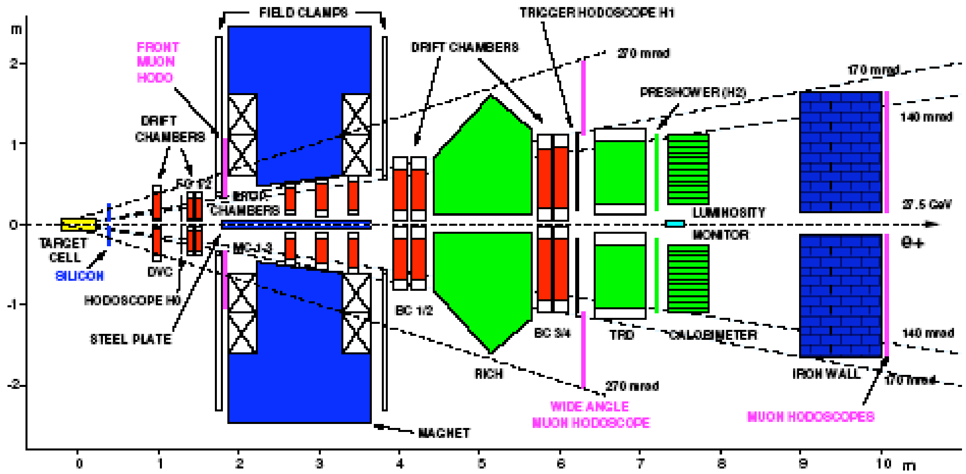
- f = dilution factor proportional to the polarizable nucleons of interest in the target “material” used, for example for NH_3, f=3/17

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

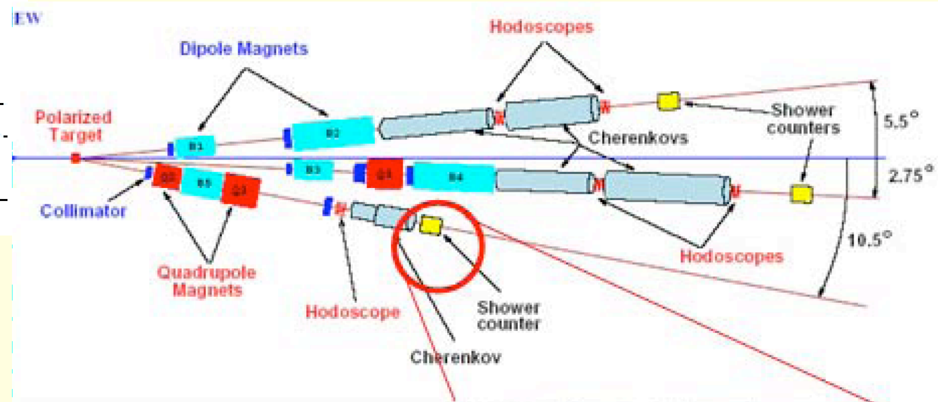
- D is the depolarization factor, kinematics, polarization transfer from polarized lepton to photon, D ~ y^2
- Note that
  - Recall that there is a huge rise of F_2 at low x
  - Large g_1 may still mean **small asymmetries**

A short review of experiments & Data

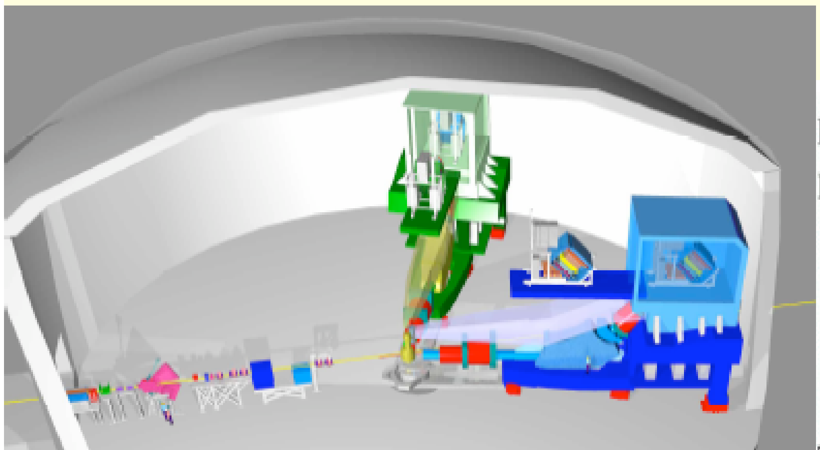
Experiments



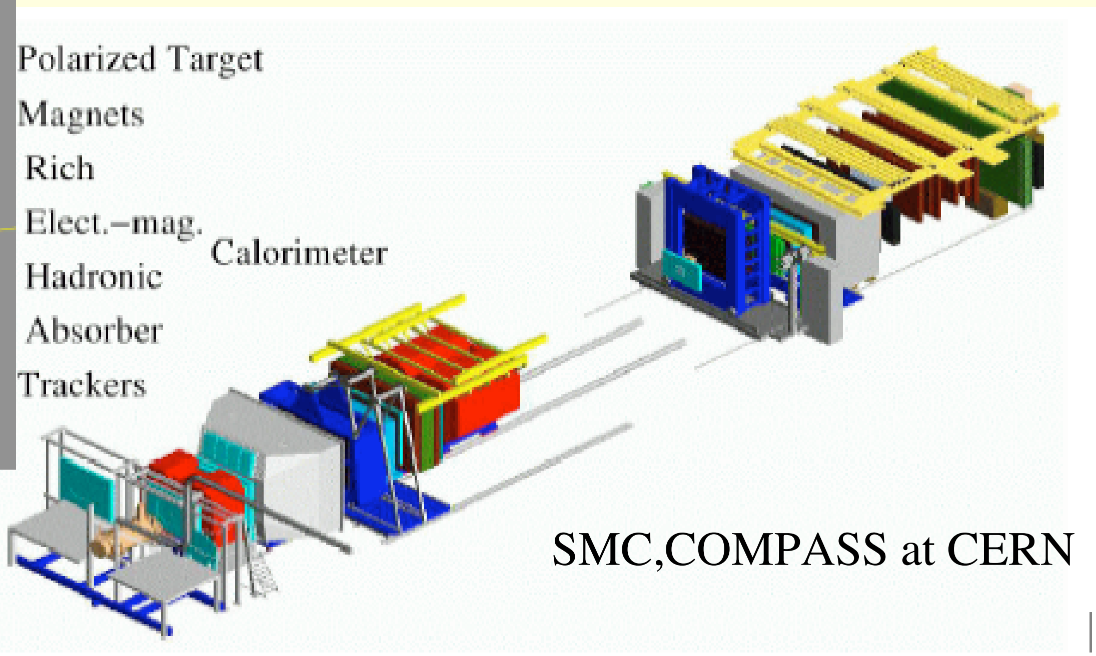
HERMES at DESY



E155 etc. SLAC



Hall A at Jlab



SMC,COMPASS at CERN

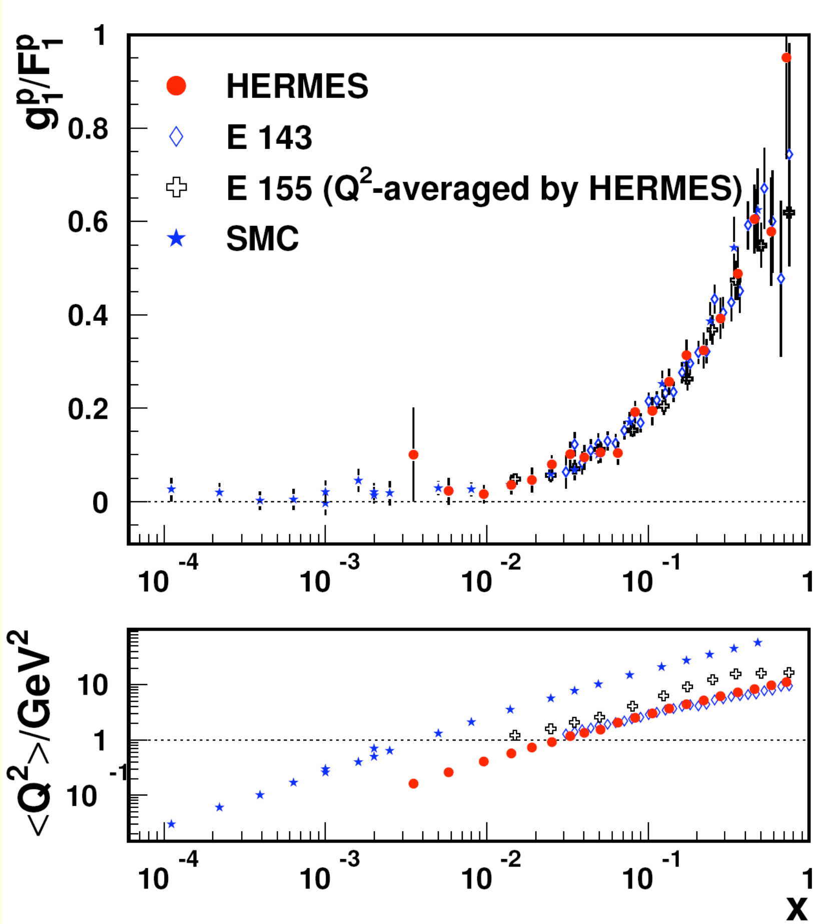
Comparison

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

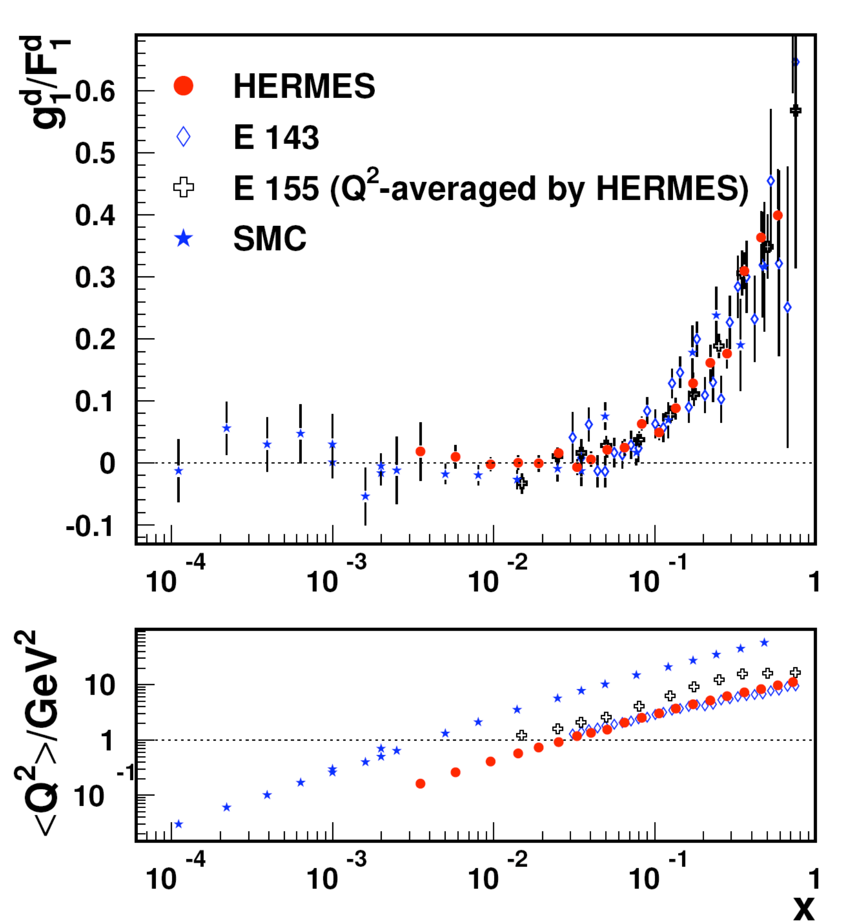
exp	P_t	target	$\mathcal{L}$ (cm^{-2}s^{-1})
HERMES	0.85	$\vec{H}$, $\vec{D}$	10^{31}
COMPASS	0.50	$\vec{Li}\vec{D}$	$5 \cdot 10^{32}$
Hall A	0.35	$^3\vec{He}$	10^{36}
CLAS	0.8 (0.3)	NH_3 (ND_3)	10^{34}

Measurements So Far

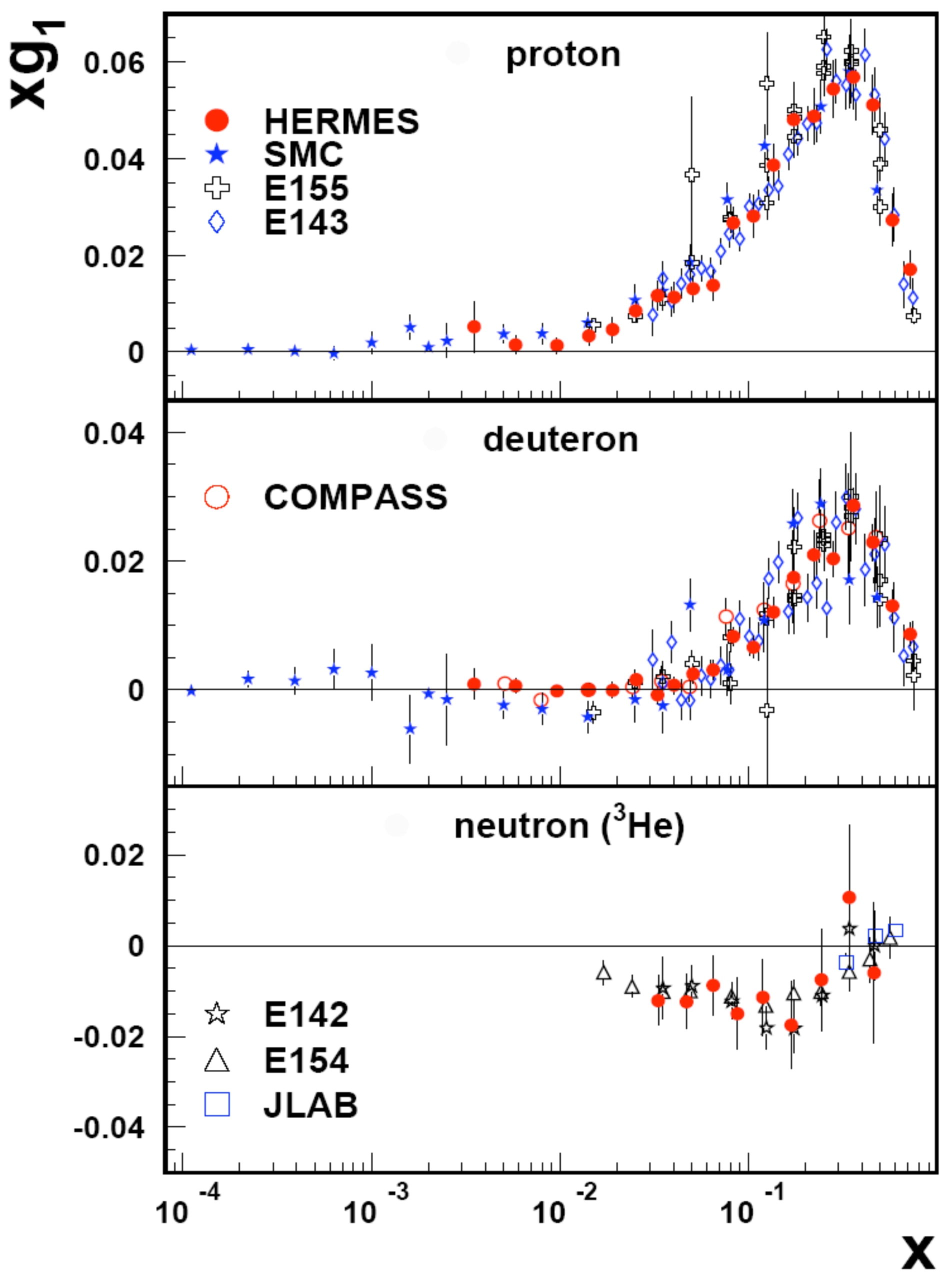
Proton Target



Deuteron Target

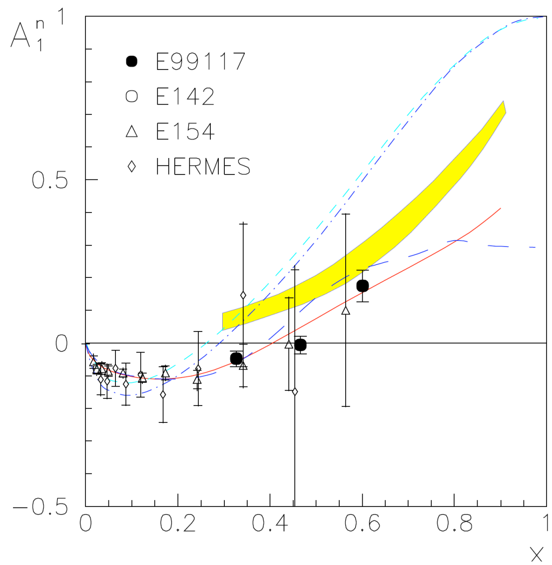


Spin structure Functions



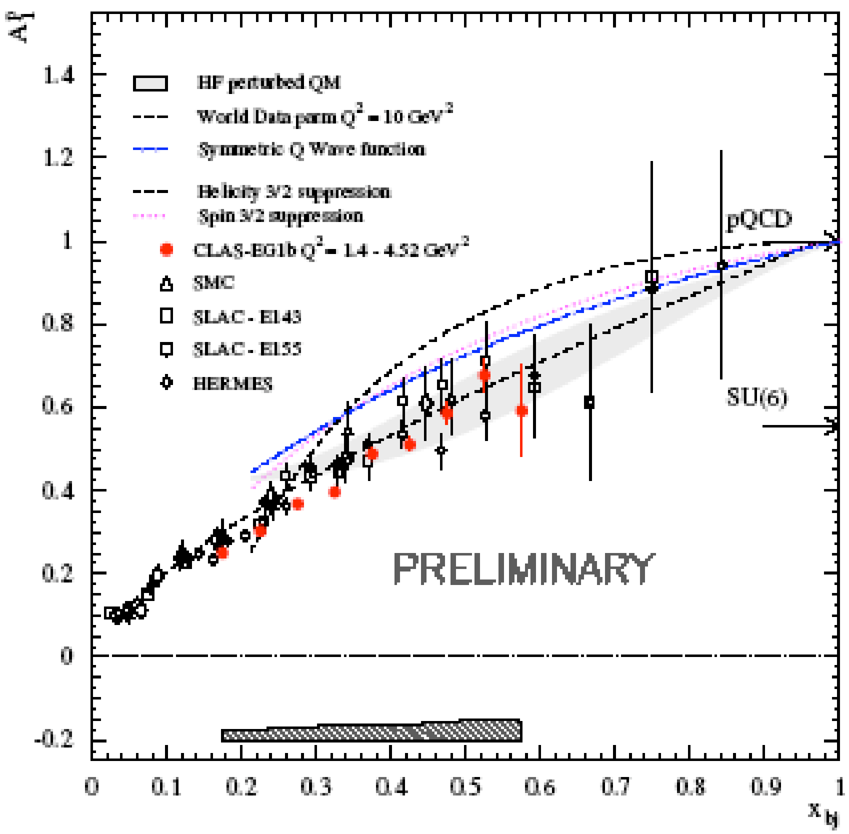
- Measurements over the last twenty odd years
- SMC measure lowest x
- SLAC/Jlab measure highest x
- Data consistent amongst all experiments over a large range of Q^2

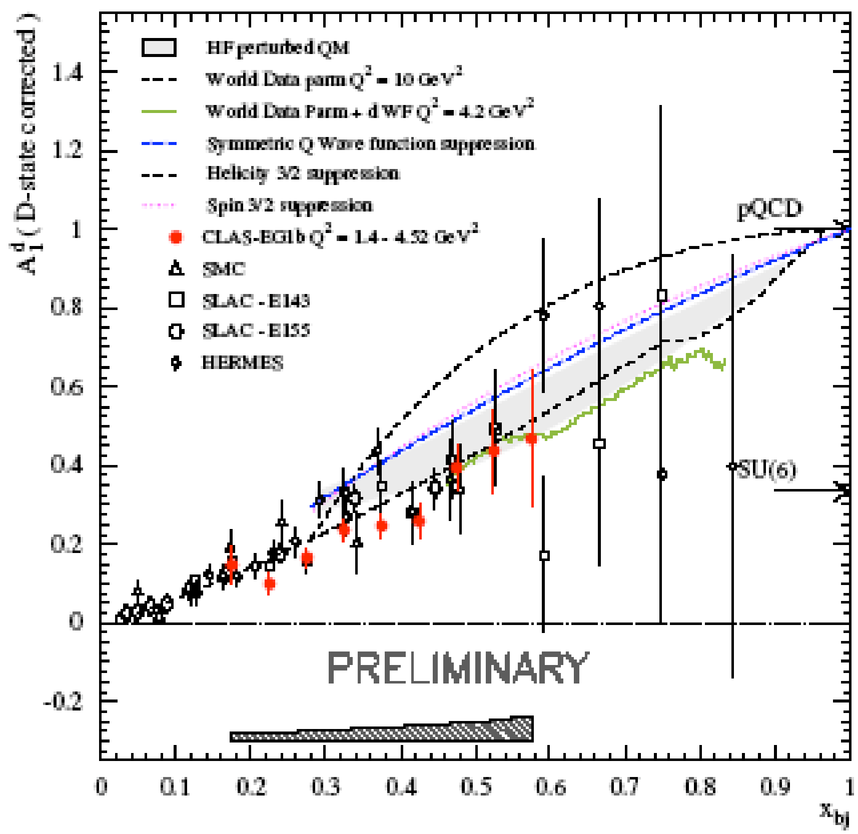
- *But there should be differences if gluon polarization is sizable, the the spin structure functions should evolve with* Q^2



High x measurements

- Jlab focused on high x measurements
- A_1 of proton, neutron and deuteron
- pQCD predicts A_1=1 when x=1



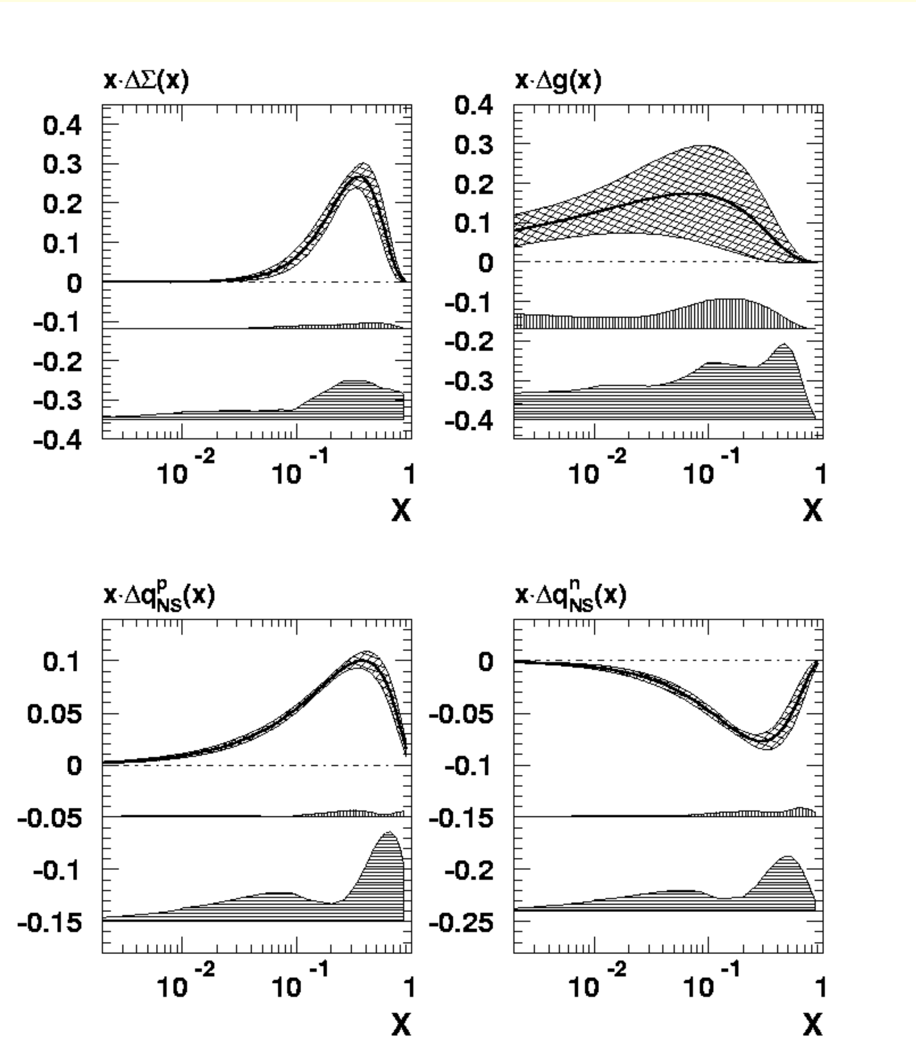


Get Polarized Parton distributions

Next-to-Leading Order Perturbative QCD with DGLAP equation

SIMILAR IN SPIRIT TO WHAT CTEQ DOES!
YOU HEARD ABOUT IT IN DETAIL

Scaling Violations of Spin SF

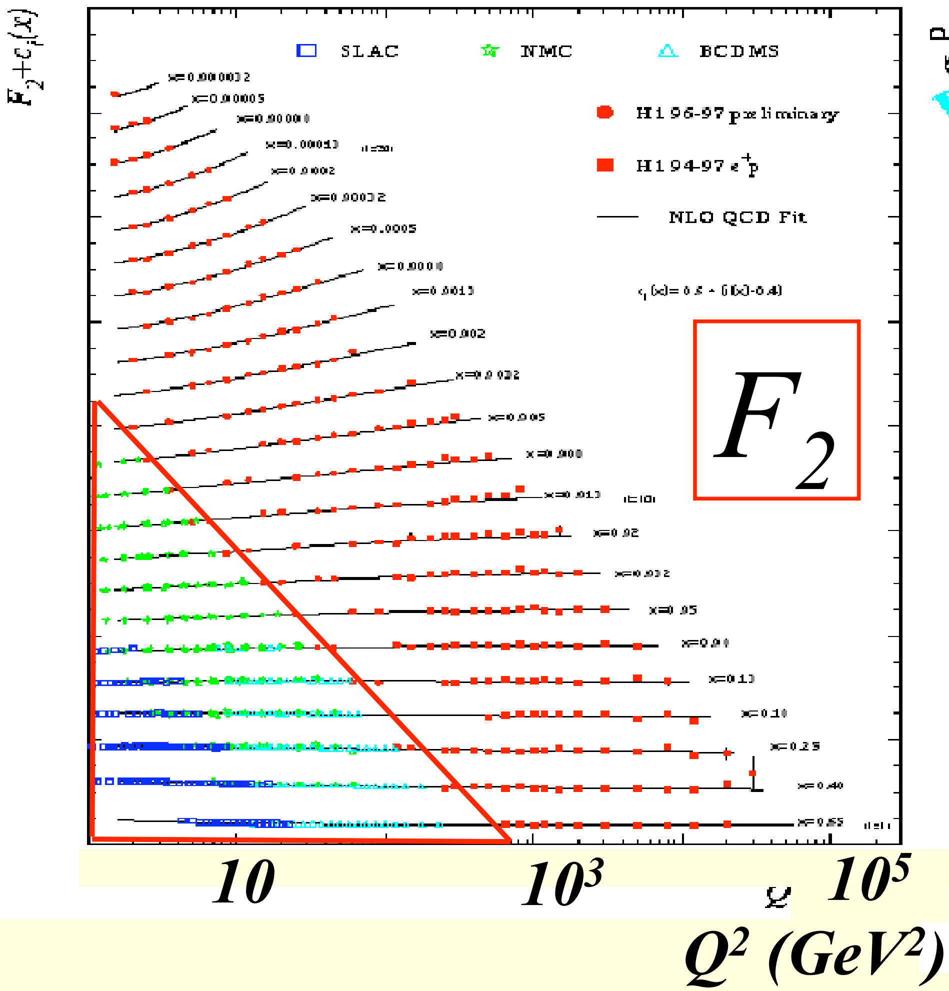


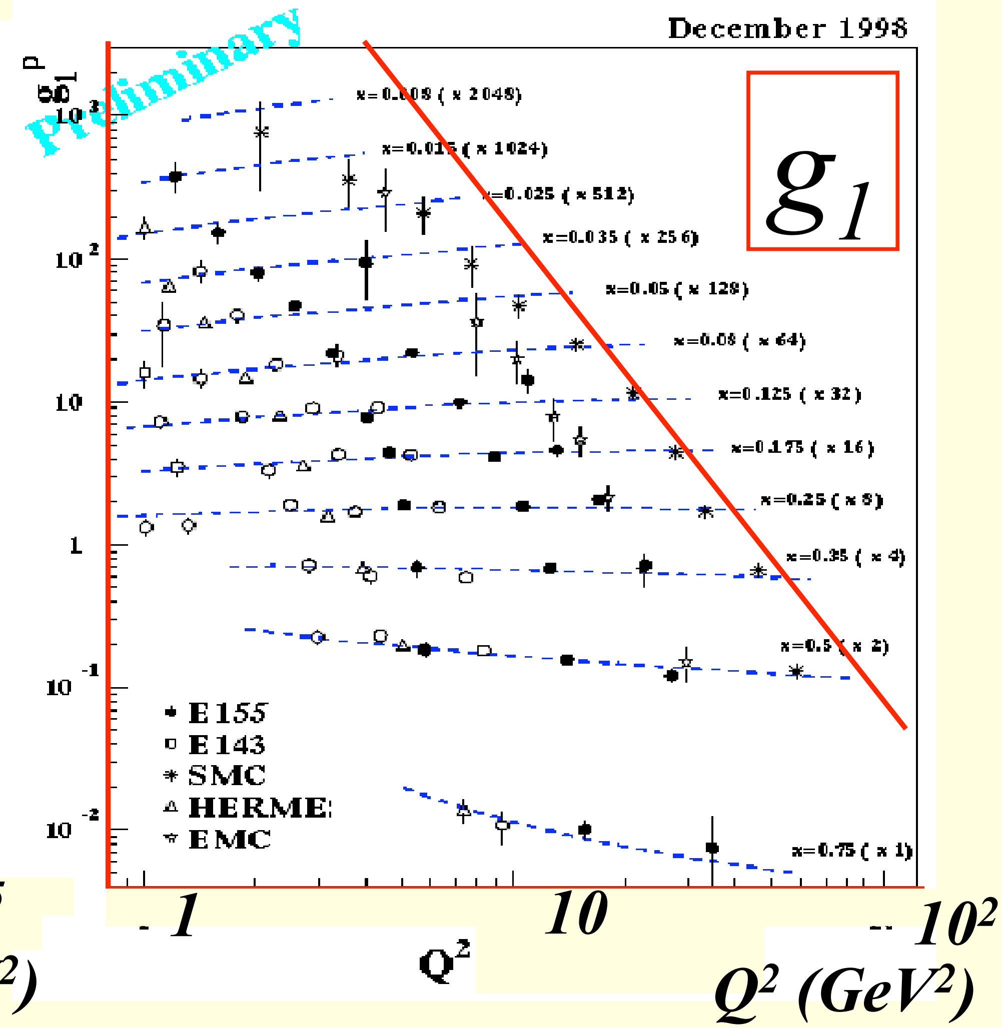
- World's all available g_1 data
- Coefficient and splitting functions in QCD at NLO
- Evolution equations: DGLAP

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

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

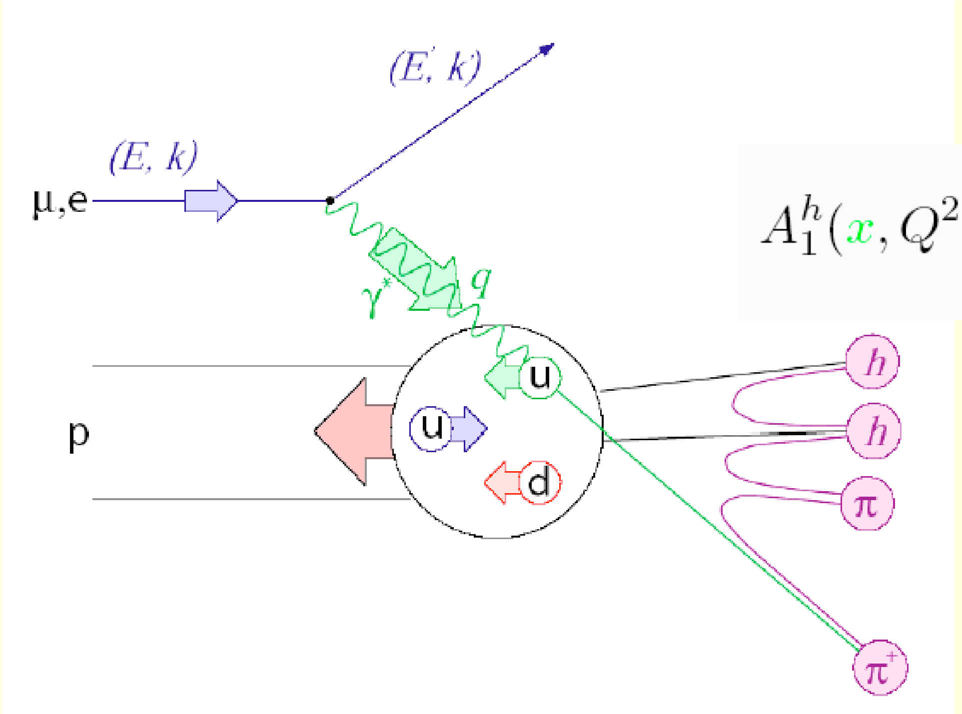
Our Knowledge of Structure Functions



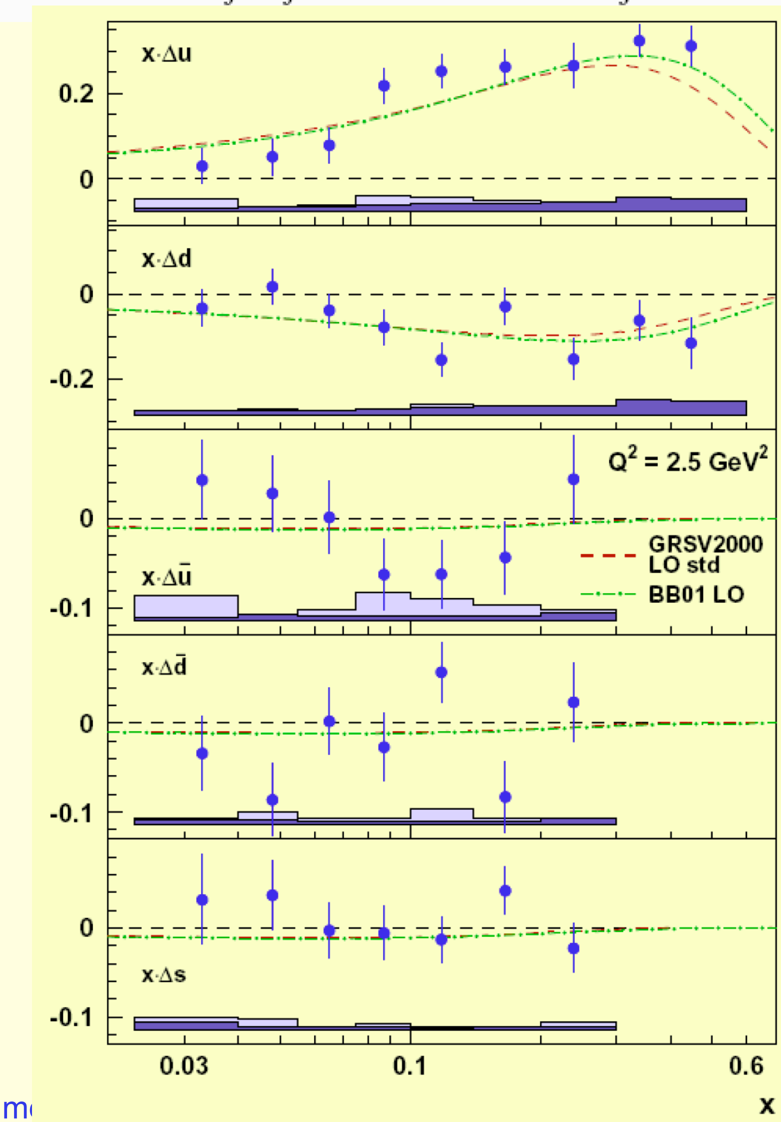


Large amount of polarized data since 1998… but not in NEW kinematic region!

Flavor Separation

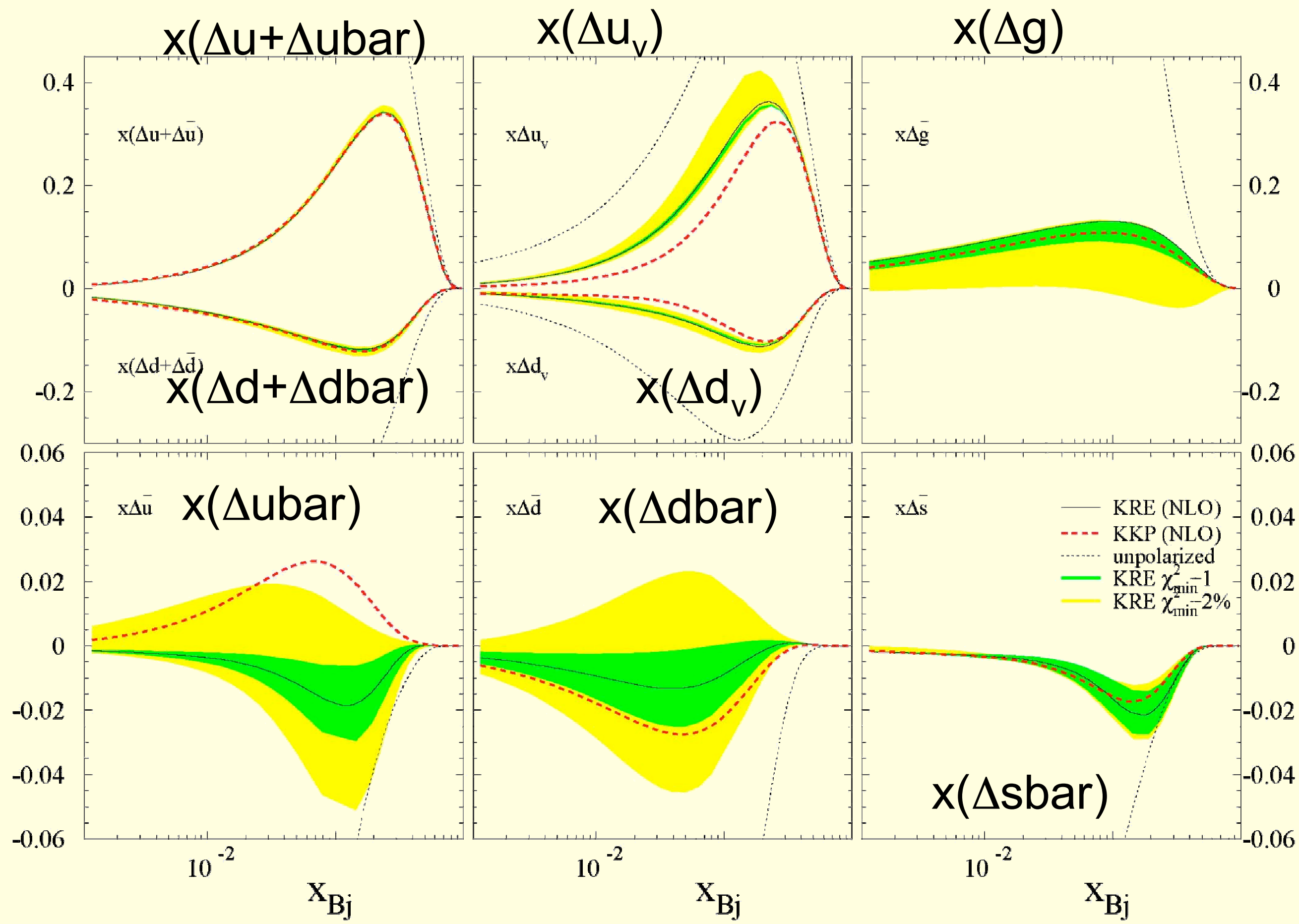


$$A_1^h(x,Q^2) = \frac{\int \mathrm{d}z \sum_f e_f^2 \Delta q_f(x,Q^2)\cdot D_f^h(z,Q^2)}{\int \mathrm{d}z \sum_f e_f^2\ q_f(x,Q^2)\cdot D_f^h(z,Q^2)}$$



- 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.

Semi-Inclusive DIS Data & NLO pQCD



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

So where are we?

- Quarks carry very small fraction of nucleon spin
  – We know this with very good accuracy

- Gluon contribution to the nuleon spin, largely unknown
  – Limited in DIS by: limited x-Q^2 range available for DGLAP evolution equations to be effective in pinning down the scaling violations
    - Measure low x and high Q^2 ranges as in HERA but with polarized beams
  – For OTHER direct methods: photon-gluon fusion process pT range of fixed target experiments rather small
    - Interpretation of measured asymmetries in terms of gluon distribution arguable

- ***We need new techniques!***

A Next Frontier in Nucleon Spin Experiments

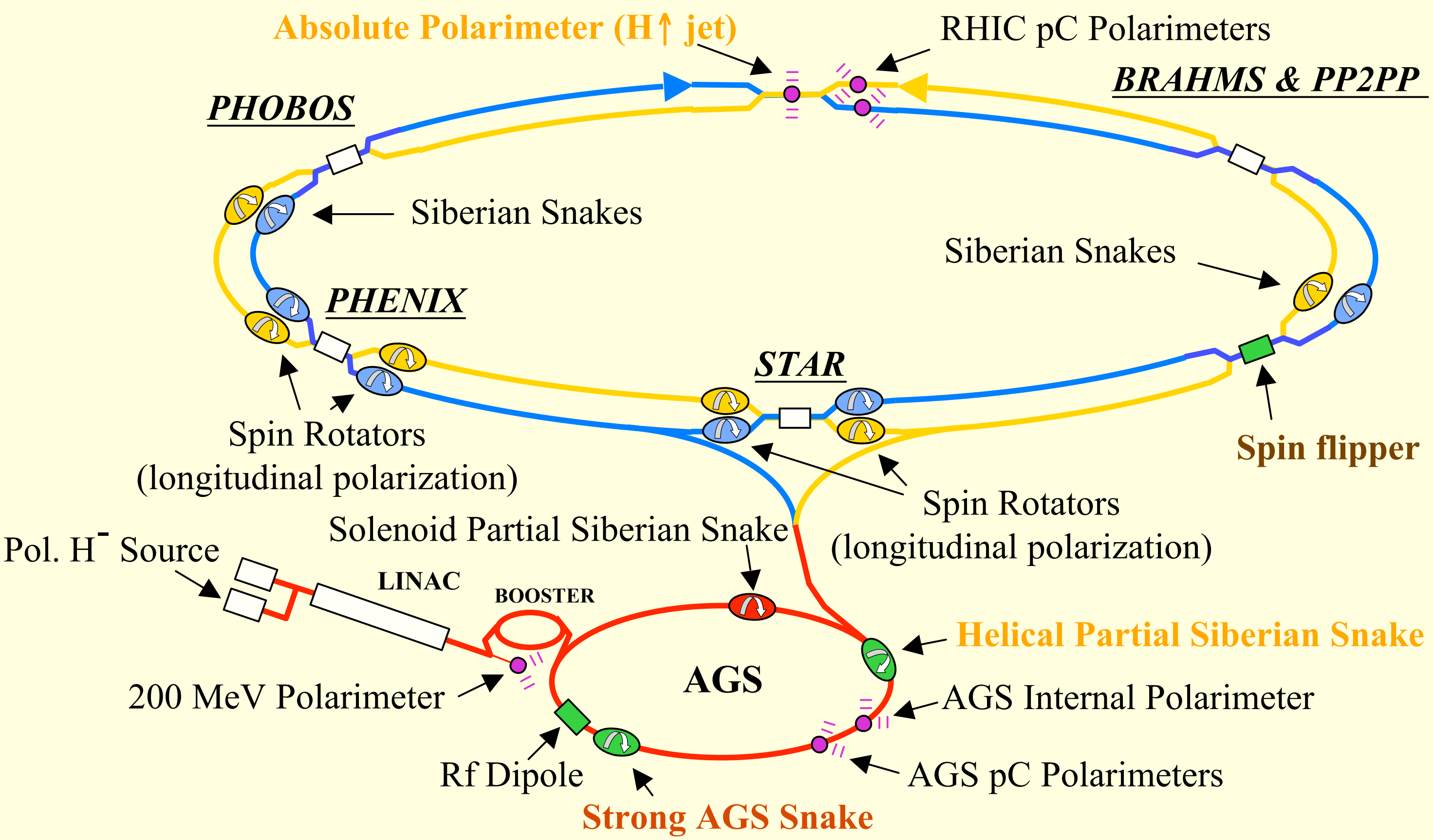
“ ***A mechanic who wishes to do his work, should first sharpen his tools***.”

Chapter 15, “The Analects” attributed to Confucius

Quoted by Xiaomin Zu, Allen Caldwell at DIS’05

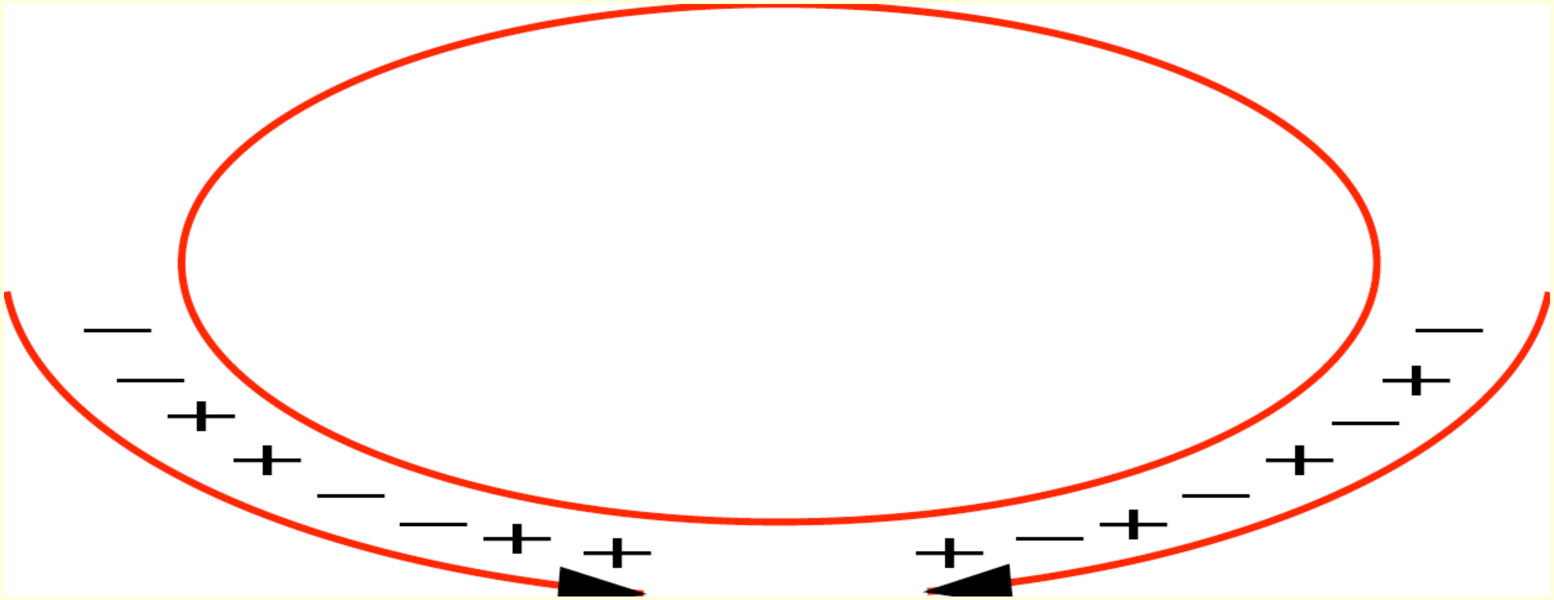
We need to go to higher energies, lower x, or both…. Some how explore experimentally, with techniques more suitable for gluon distribution.

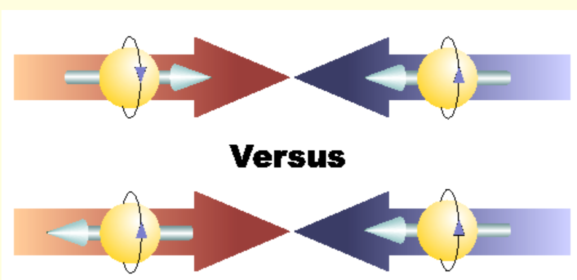
RHIC Polarized Collider

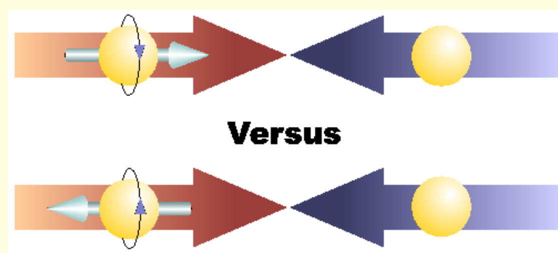


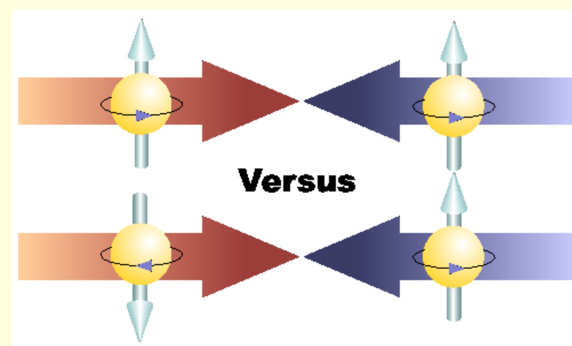
- Installed and commissioned during FY04 run
- Plan to be commissioned during FY05 run
- Installed and plan to be commissioned during FY05 run

Exquisite Control of Systematics





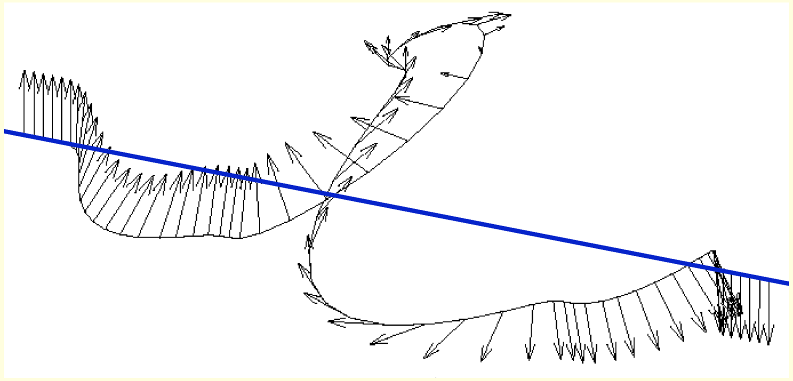




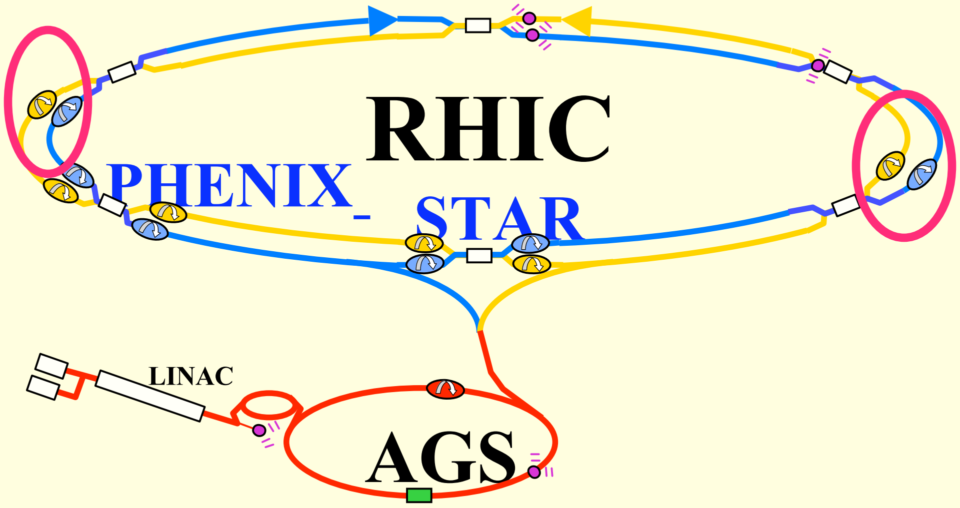
Siberian Snakes at RHIC

(Funded by RIKEN Institute in Japan)

Depolarizing Resonance:
Spin tune = no. of spin kicks
Imperfection resonances:
 --magnet errors & mis-alignements
Intrinsic resonances:
 --vertical focusing fields



Effect of depolarizing resonances averaged out by rotating spin by large angles on each turn



RIKEN/BNL

4 helical dipoles ➔ S. snake
2 snakes in each ring
   -- axes orthogonal to each other

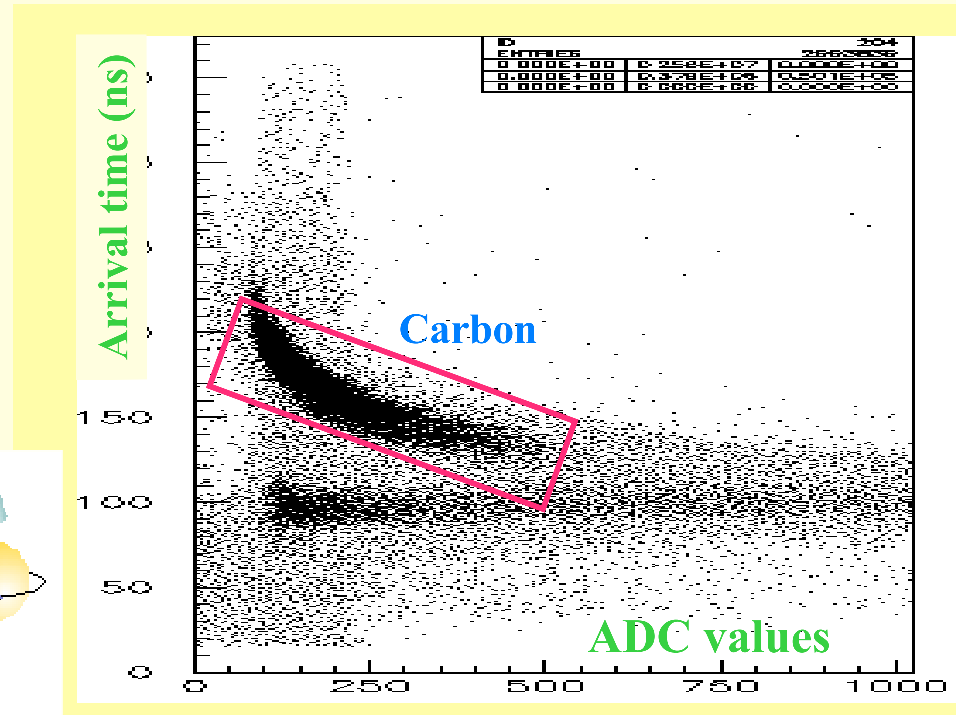
Proton beam polarimetry (I)

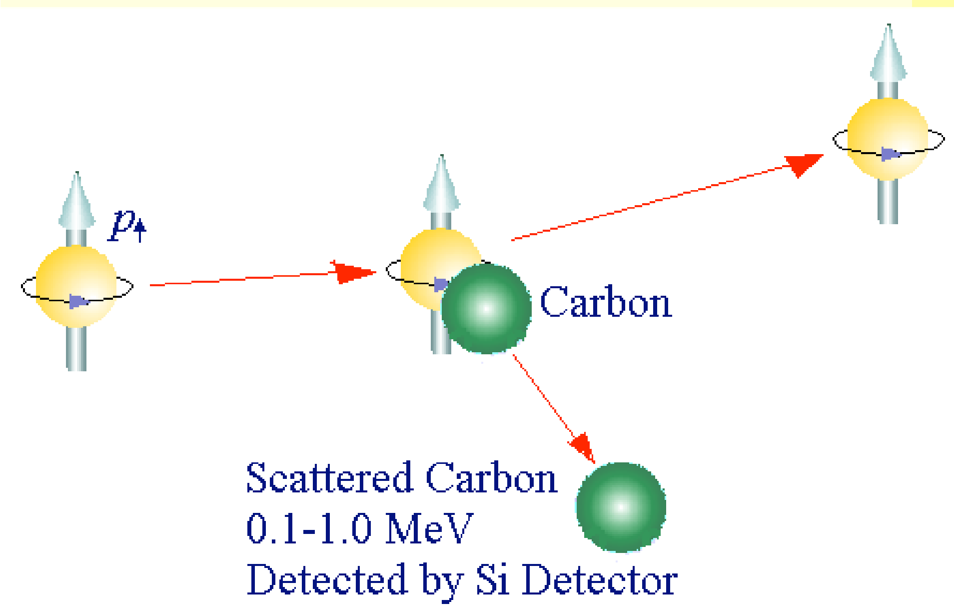
(AGS-E950 Experiment 1999/2000)

Carbon filament target ($5\mu g/cm^2$) in the RHIC beam

Measure recoil carbon ions at q~90°

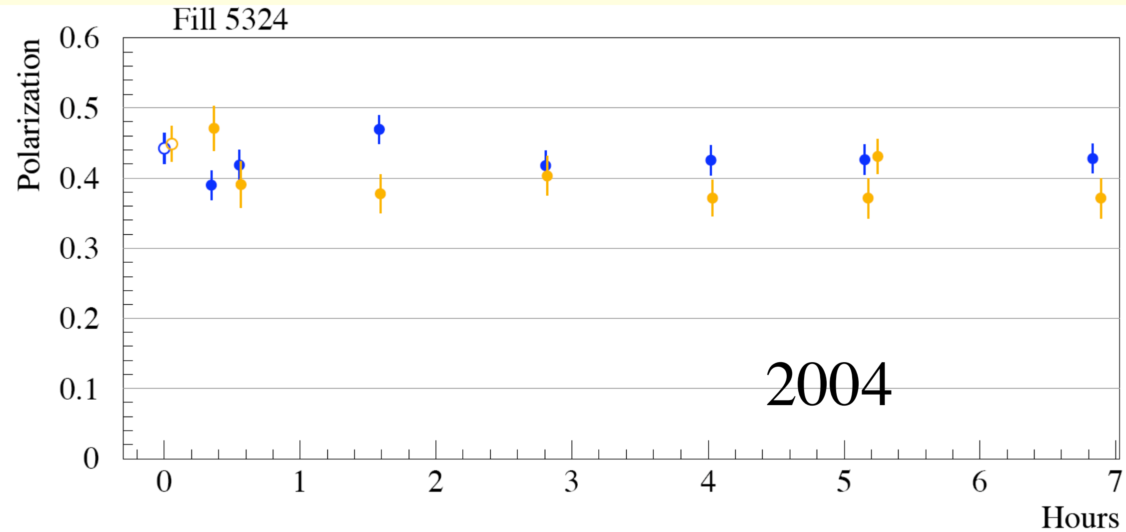
100 keV < E_{carbon} < 1 MeV





ANL, BNL, Kyoto, RIKEN/RBRC & Yale Collaboration

Polarization Performance



- 2005 ~45-55% beam polarization routinely achieved
- *Absolute beam polarization ΔP/P = +/- 0.07 with H-Jet Polarimeter*
  - Polarized atomic gas jet (92+/-2)% polarization (BR polarimeter)
  - Tgt pol. Reversed/8 min
  - Si detectors for pp elastic scattering: left/right asym
  - Study w.r.t. sign of the tg polarization flipping each bunch every 200ns
  - Absolute polarization is determined

RUN	#proton/ bunch [x10^9]	#bunch	Beta* (m)	Emittance (πμm)	Luminosity 10^{30} cm^{-2}s^{-1}	Pol. (%)
2001-2002	70	55	3	25	1	15-25
2002-2003	100	55	1	25	3	25-35
2005-	100	56-110	0.85	10-15	10	>45
Design	200	112	1	20	80	70

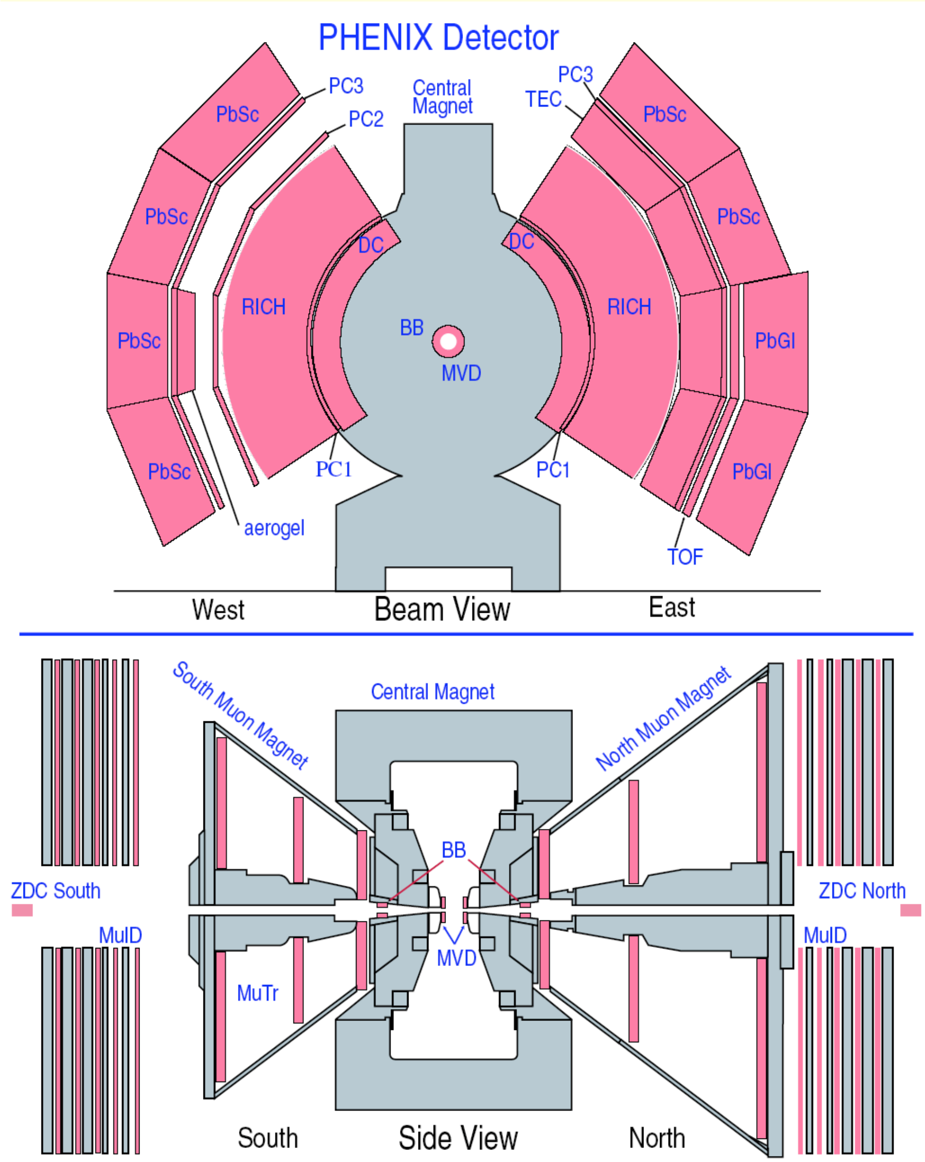
RHIC Spin Physics Program

- *Direct measurement* of polarized gluon distribution *using multiple probes: Measure* *double spin asymmetry* A_{LL} *in*
  - *gg,qg* $\rightarrow \pi^{0,+,-} + X$
  - *gg* $\rightarrow$ *c-cbar, b-bbar + X*
  - *gq* $\rightarrow \gamma + X$

- Direct measurement of *anti-quark polarization* using parity violating production of $W^{+/-}$ in single spin A_L
  - u + dbar $\rightarrow W^+ + \nu_l$ and ubar + d $\rightarrow W^- + \nu_l$

- Transverse spin: Transversity & transverse spin effects: possible connections to orbital angular momentum?

PHENIX Detector at RHIC

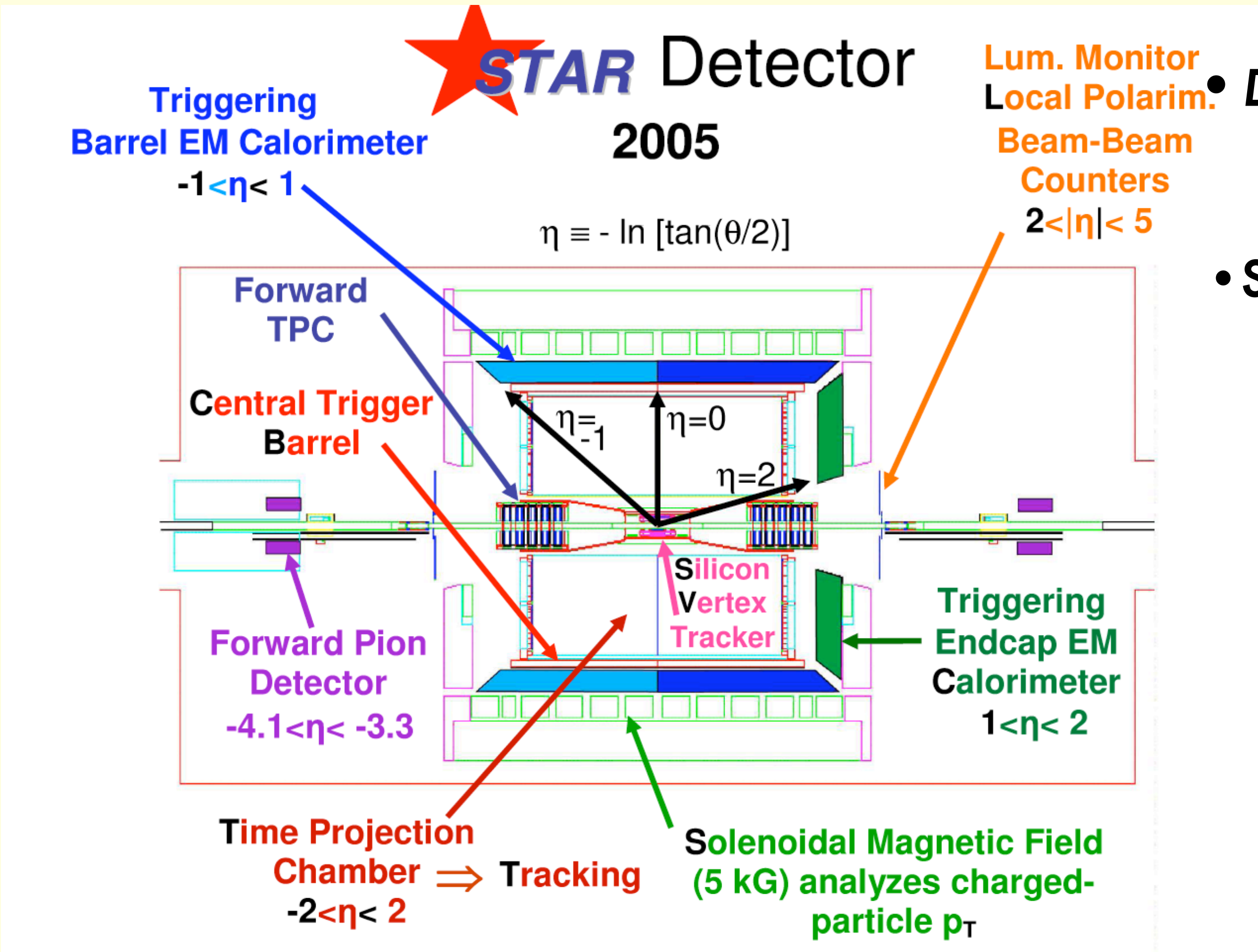


- ***Design philosophy:***
  - ***High resolution limited acceptance***
  - ***High rate capability DAQ***
  - ***Excellent triggers for rare events***
- Central arm
  - Tracking: Drift chambers, pad chambers, time expansion chamber
  - Superb EM Calorimetry PbGl, PbSc

    $\Delta\phi x \Delta\eta$~0.01 x 0.01

    π^0 to 2γ resolved up to 25 GeV pT
  - Particle Identification: RICH, TOF
- Forward Muon Arms:
  - Muon tracker, muon identifiers
- Global detectors:
  - Beam beam collision (BBC) counter, Zero Degree Calorimeters (ZDCs)
- Online monitoring, calibration and production

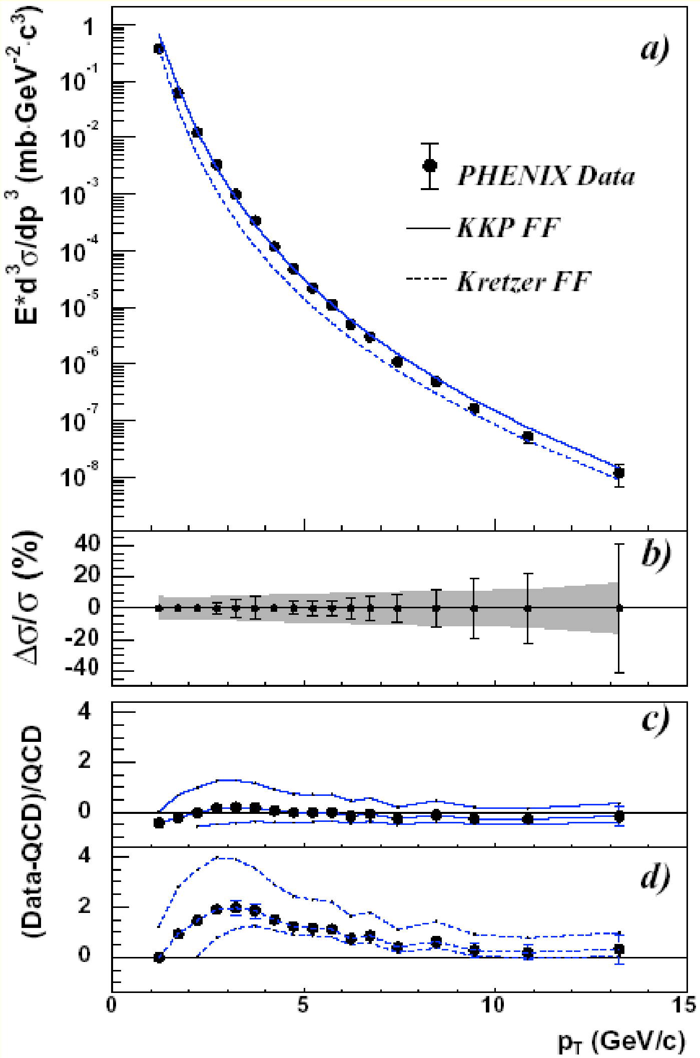
STAR Detector at RHIC



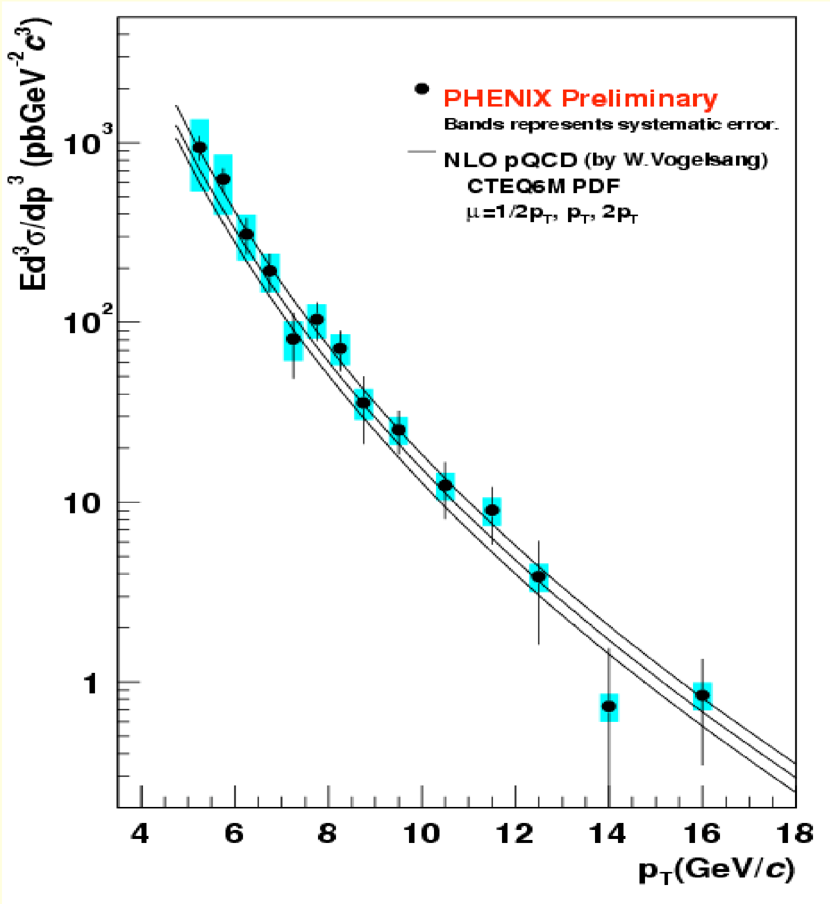
- *Design Philosophy:*
  - *Maximize acceptance*
  - *lower resolution*
- **Subsystems:**
  - $\phi = 2\pi$ acceptance in EM calorimetry
    Barrel and EndCap
    Total: $-1 < \eta < 2$
  - Time Projection Chamber
  - Separate Forward pion detector
  - Silicon vertex tracker
  - Beam-Beam Counters
  - Zero Degree Calorimeter

Cornerstone to the RHIC Spin program

pp → π X



pp → γ X

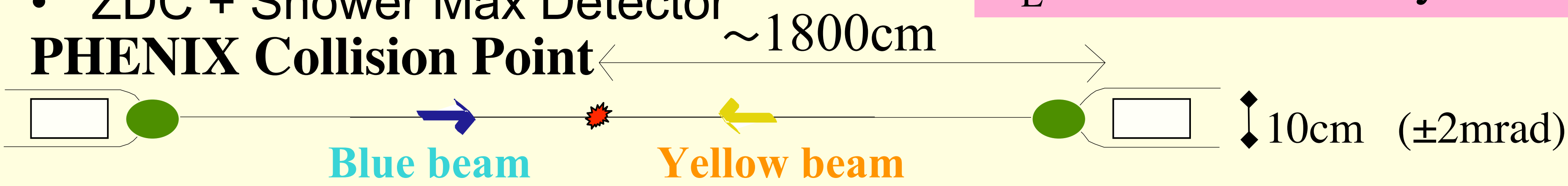


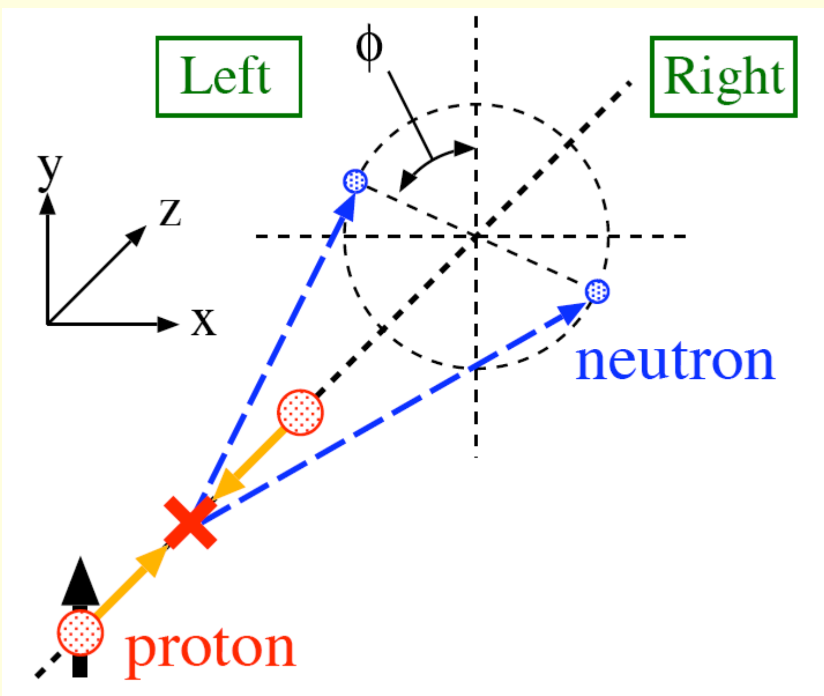
Unpolarized data are well described by NLO

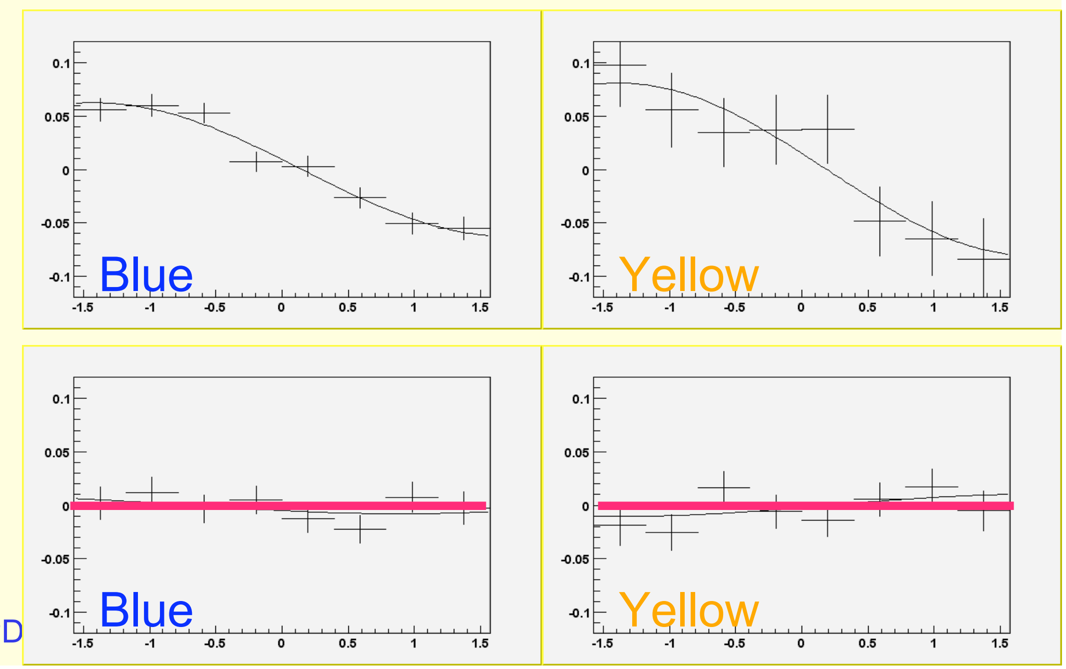
PHENIX Local Polarimeter

- Spin Rotator Magnets enable longitudinal collisions in IRs
- PHENIX discovered at low pT and high xF an analyzing power in neutron production in pp collisions at 100 GeV
- ZDC + Shower Max Detector

$P_L/P > 0.99$ blue & yellow



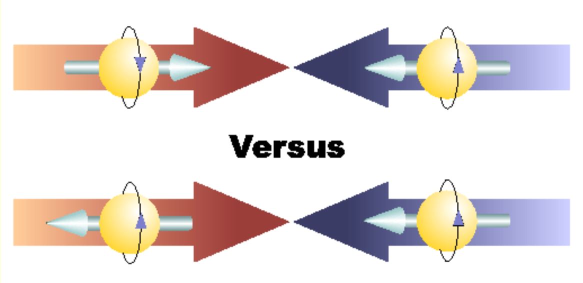




Double spin asymmetry

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{|P_B P_Y|} \frac{N_{++}/L_{++} - N_{+-}/L_{+-}}{N_{++}/L_{++} + N_{+-}/L_{+-}}$$

++ same helicity
+– opposite helicity

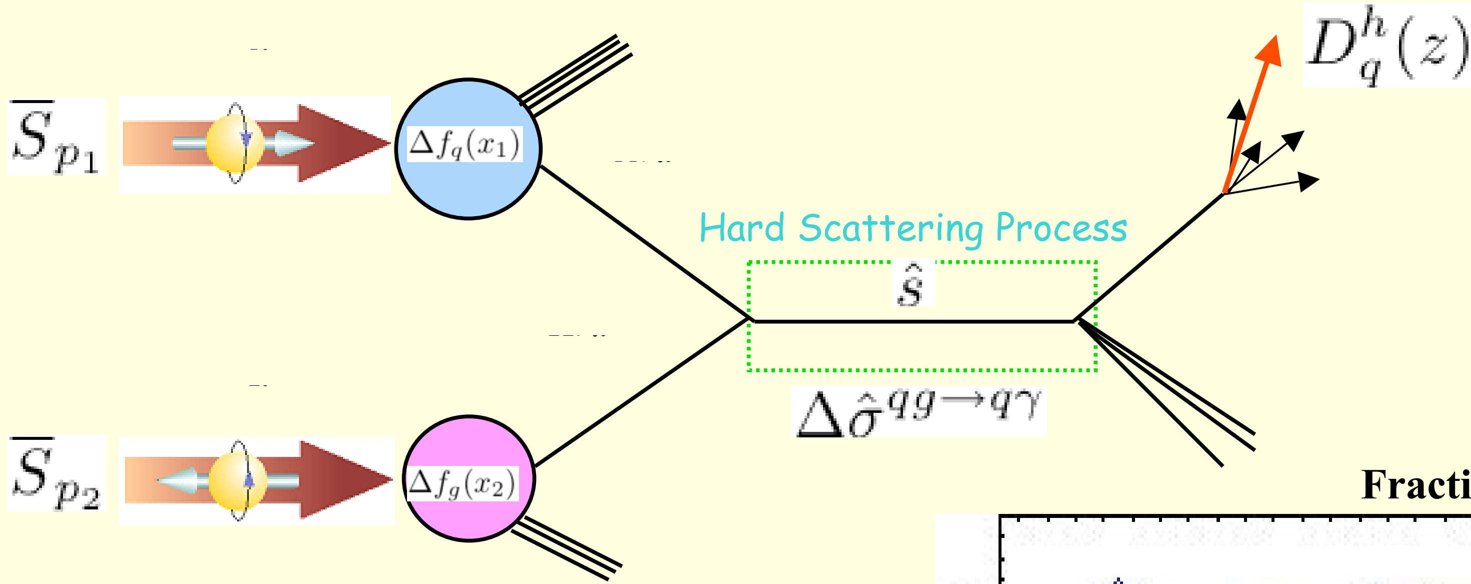


(P) Polarization – absolute scale and "longitudinal"ness
- Local Polarimeter: Longitudinal-ness of proton spins

(L) Relative Luminosity – bunch to bunch variation
- BBC vs. ZDC vs. (anything else) vs. bunch number
- Bunch crossing every 200 ns
- Studies indicate variations < 2.5 x 10^{-4}

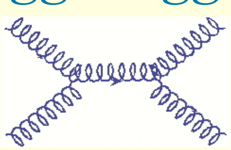
(N) Number of π^0s – triggers and efficiencies etc.

Double Spin: Leading hadrons



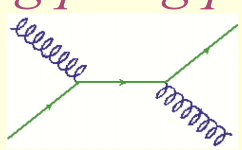
$h = \pi^0$

$gg \to gg$



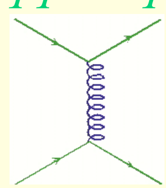
$\propto \frac{\Delta G}{G}\frac{\Delta G}{G}$

$gq \to gq$



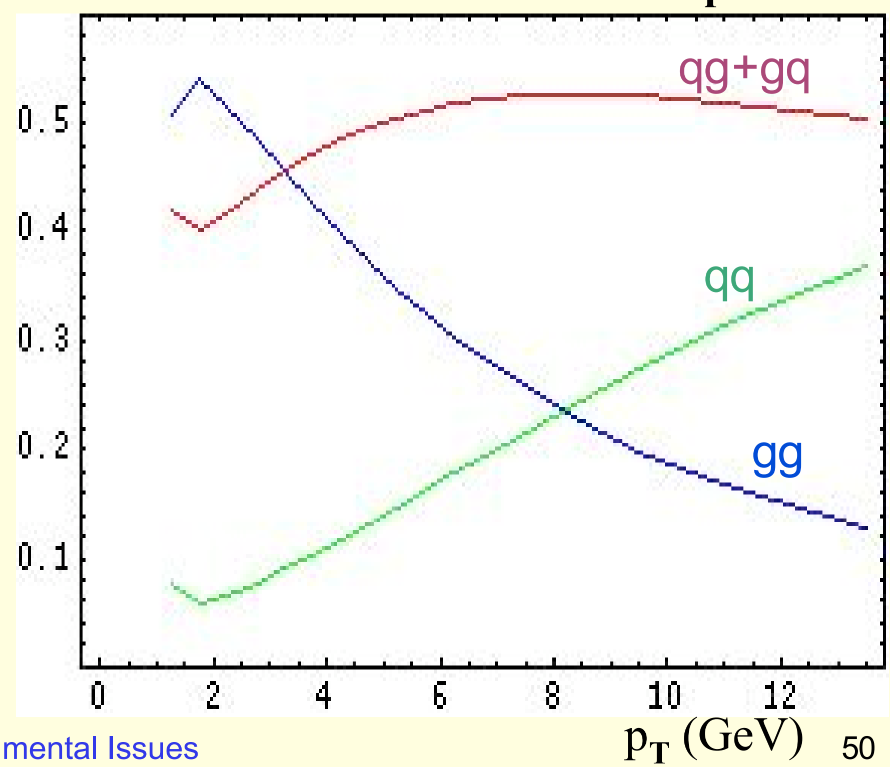
$\propto \frac{\Delta q}{q}\frac{\Delta G}{G}$

$qq \to qq$



$\propto \frac{\Delta q}{q}\frac{\Delta q}{q}$

Fraction of π^0 produced



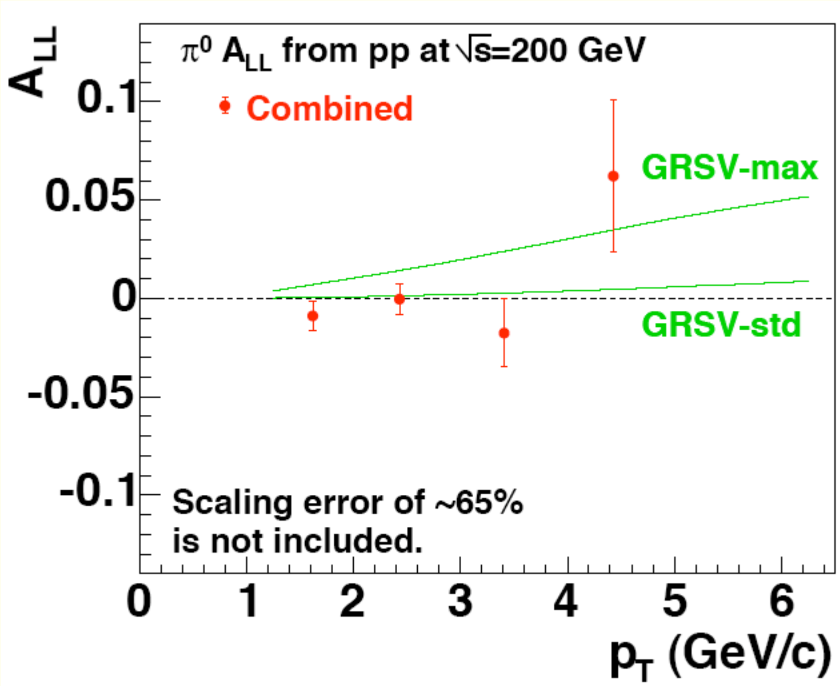
Gluon Spin Program has begun!

- Data taken in 4 weeks in Run 3 & 4 days of 2004
- Longitudinal polarization at PHENIX
  - *forward neutron production based local polarimetry*
  - *Relative luminosity variations less than 2.5 x 10^{-4}*

	Run Time	Int. Lum.	Pol.	P^4L
Run 3 (2003)	4 weeks	220 nb^{-1}	27%	1.17 nb^{-1}
Run 4 (2004)	4 days	75 nb^{-1}	40%	1.92 nb^{-1}

Double helicity asymmetry in inclusive mid-rapidity neutral pion production for polarized -pp collisions at Sqrt(s)=200 GeV hep-ex/0404027, Published OnLine: PRL 93, 202002 (2004)

Comparison with theory



- GRSV-std: best fit to DIS data

$$\int_0^1 \Delta G(x)dx \sim \ 0.7 \text{ at } Q^2 \ 1 \text{ GeV}^2$$

- GRVS-max

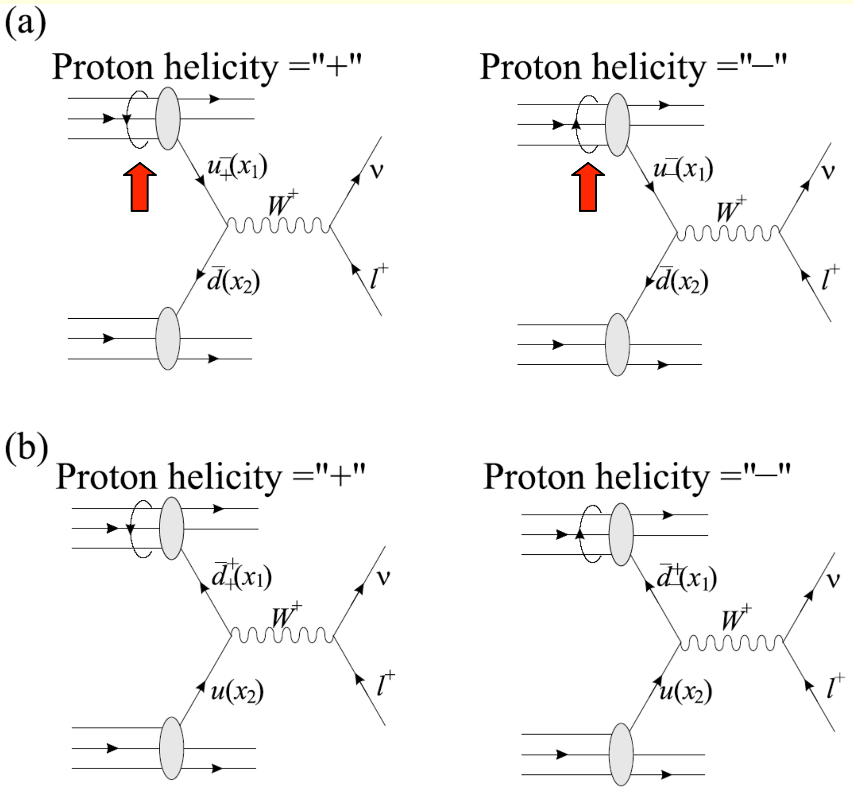
$$\Delta G(x) = G(x) \text{ at } Q^2_{\text{input}} = \ 0.40 \text{ GeV}^2$$

- Data prefers the GRSV-std curve (and hence the gluon distribution and its first moment)
  - B. DeJager et al. Phys. Rev. D67, 0504005 (2003)

	GRSV-std	GRSV-max
4 points (1-5 GeV/c)	21-24%	0.00-6%
3 points (2-5 GeV/c)	27-29%	0.01-13%

ΔQ-ΔQBAR AT RHIC VIA W PRODUCTION

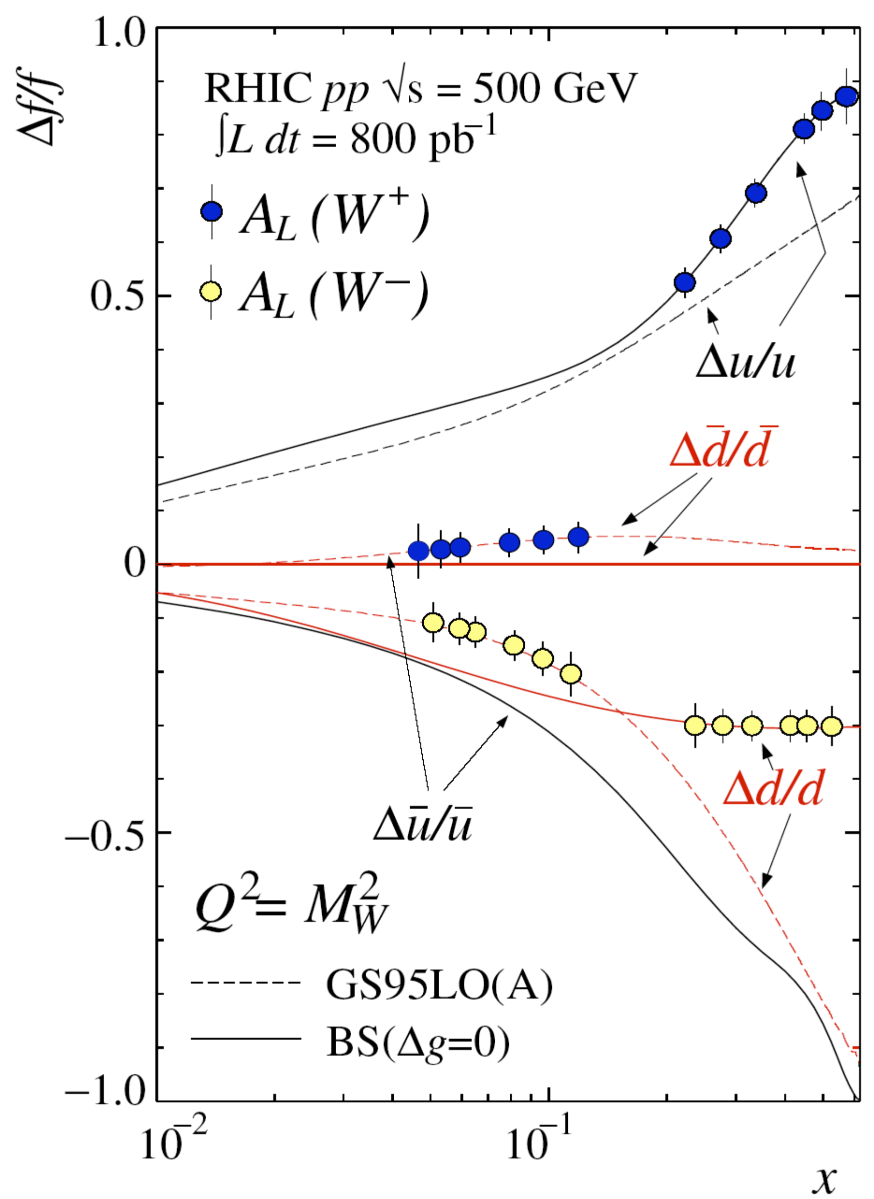
- Single longitudinal scattering asymmetry A_L
- W production dominated by u,ubar, d,dbar quarks with minimal contamination from c,cbar,s,sbar quarks
- W+ implies (u+dbar) and W- implies (ubar+d) at leading order



$$A_L^{W^+} = \frac{u_-^-(x_1)d(x_2) - u_+^-(x_1)d(x_2)}{u_-^-(x_1)\bar{d}(x_2) + u_+^-(x_1)\bar{d}(x_2)} = \frac{\Delta u(x_1)}{u(x_1)}$$

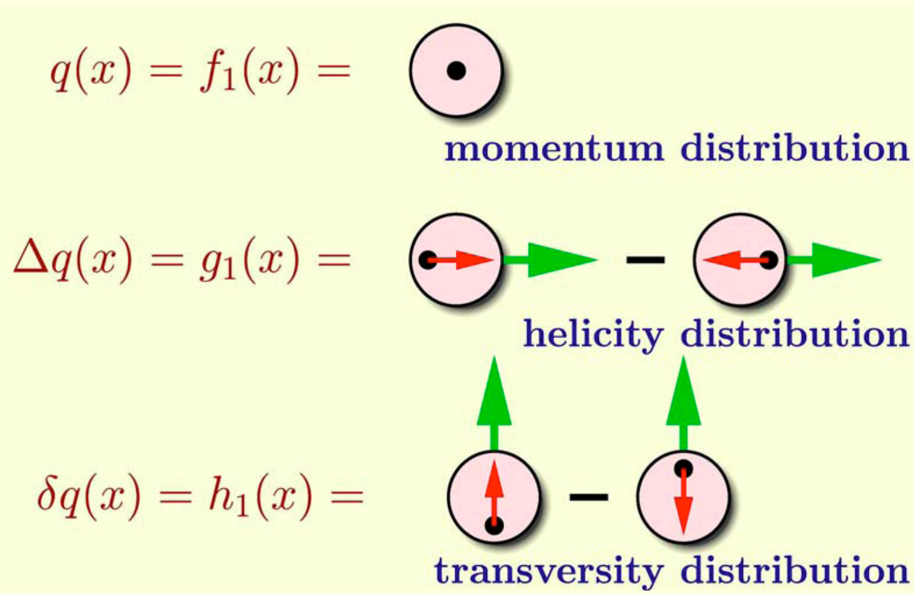
$$A_L^{W^-} = \frac{\bar{d}_-^+(x_1)u(x_2) - \bar{d}_+^+(x_1)u(x_2)}{\bar{d}_-^+(x_1)u(x_2) - \bar{d}_+^+(x_1)u(x_2)} = -\frac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}$$

Flavor separation of u,d,ubar,dbar



- With 500 GeV Center of Mass
- 800 pb^{-1} integrated luminosity
- Blue for W+, Yellow for W-
- Various theoretical expectations shown as curves
  - GS95LO is Gehrmann & Stirling, D53, PRD 1995
  - BS is Bourley and Soffer, B445, NP 1996
- Beyond this, heavy quark vs. anti-quark separation at eRHIC

Transversity and Single Spin Asymmetries

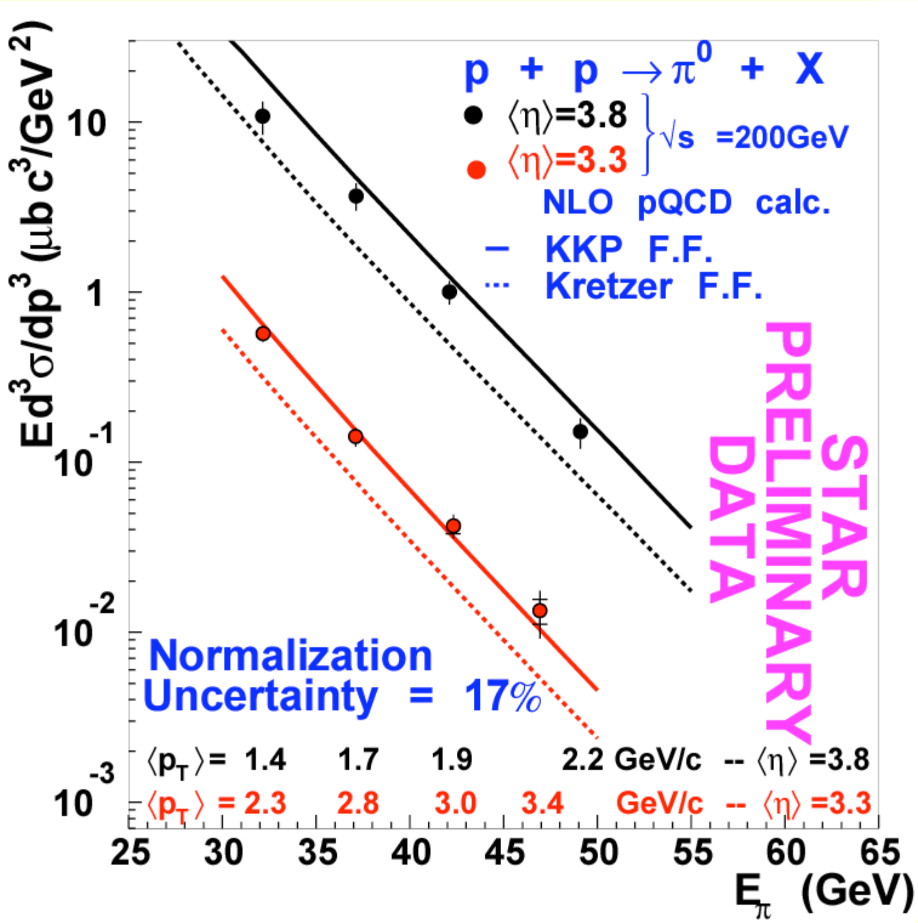


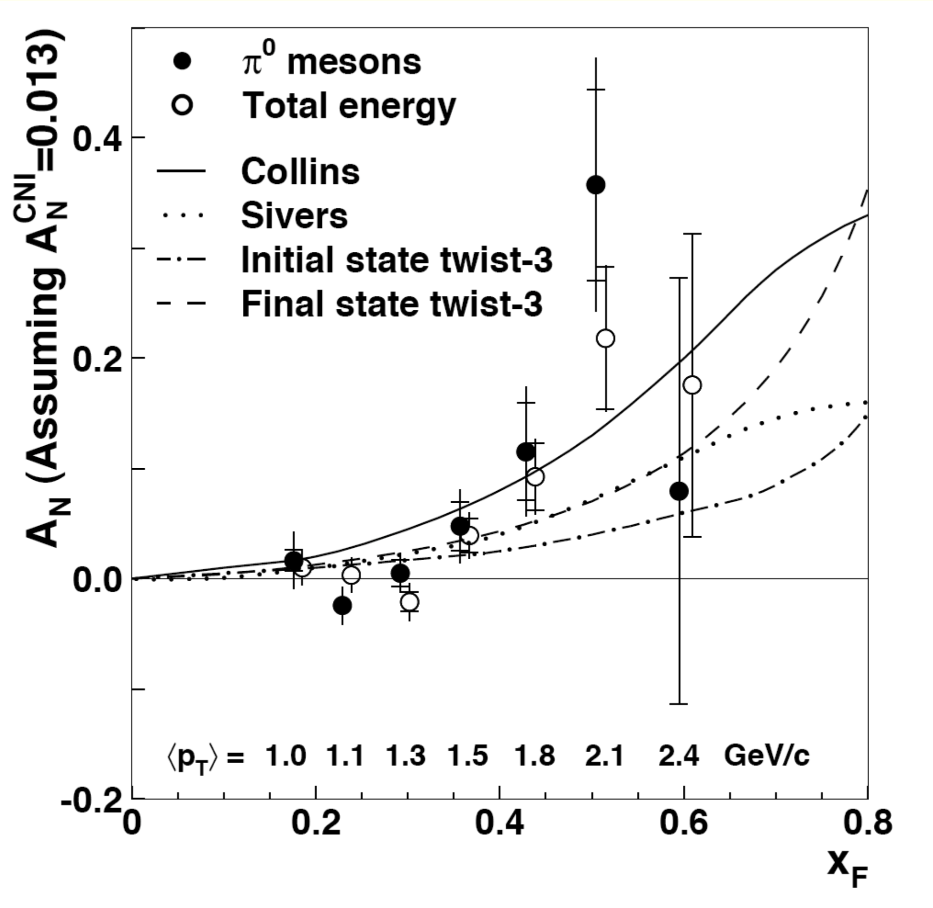
- Some single and double transverse spin effects have been seen in DIS
- DIS2005 web-pages, Plenary talk by D. Rychbosch see summary
- Origin: Siver's effect, Collin's effect, higher twist…or combination…

Recent ideas **relate Sivers effect to existence of orbital angular momentum in quarks (Burkardt),** Collins effect refers to final state effects, and higher twist effects!

I will show a result from RHIC from STAR experiment (large rapidity) neutral pion production. Search by PHENIX in central rapidity results no observed asymmetry.

A_N Results from STAR

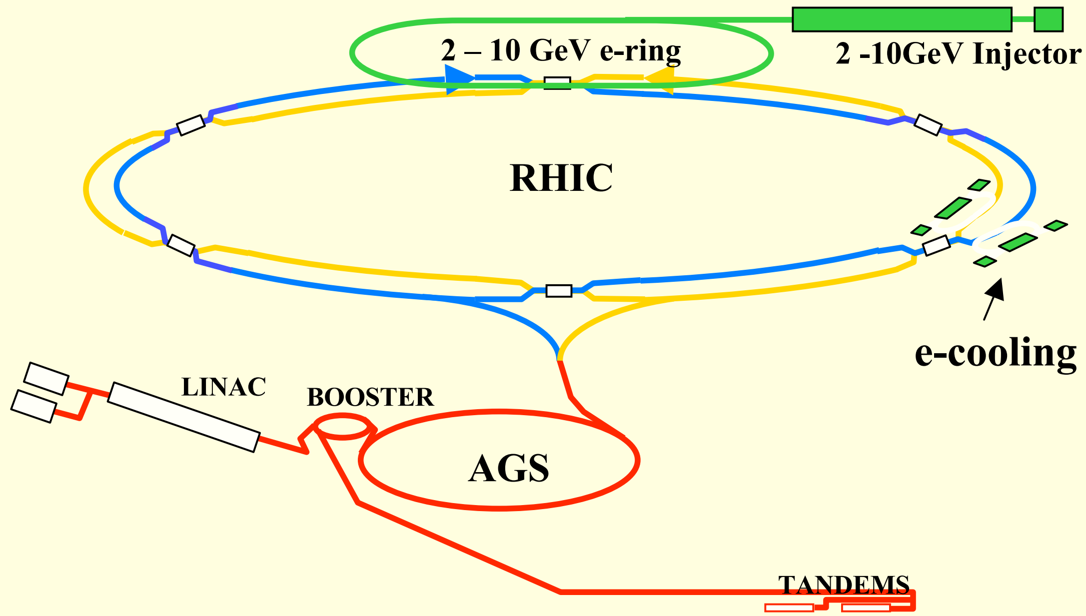




Measured π^0 cross section in this acceptance compares well with NLO calculations

Large asymmetry observed in identified π^0 as well as energy deposited in the calorimeter

Future eRHIC at BNL



- Precision measurements of nucleon spin properties
- Extend the range of x-Q^2 beyond fixed target experiments and RHICpp

- A new device is being proposed…… **to build a polarized electron beam complex next to RHIC complex**
- A polarized e-p(He3) collider, and
- An unpolarized e-A collider to study exotic forms of gluonic matter proposed at very low x: color glass condensate

And Now…
For something Completely Different!

Monty Python's Flying Circus

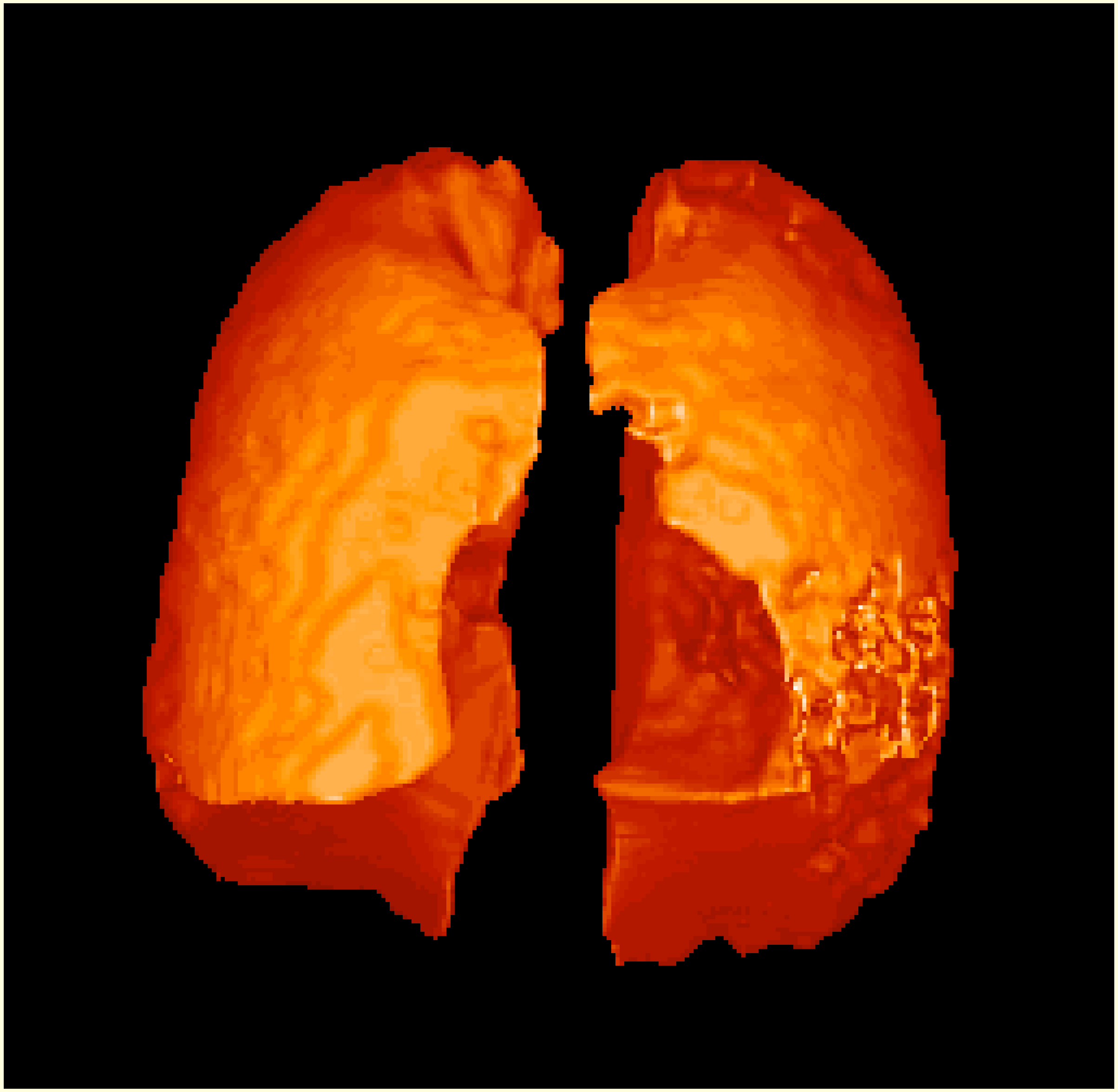
Study of Polarized Neutrons led to...

- What is a neutron rich element that can be (relatively) easily polarized?
  - ^{3}He (Helium) nucleus: has 2 protons and 1 neutron
  - Two proton spins align opposite and we make measurements of the lone "neutron"

- Helium is an inert gas, and for our experiments, polarized Helium needed to be produced in abundance (~1 ltr/day)

- Why not ask patients to inhale polarized ^{3}He? An MRI of the inhaled He would give us information on the medical conditions of the lungs!
  - "Seeing" lungs is very very difficult, they are hollow and dry. Normal MRIs require water/hydrogen to create the signal

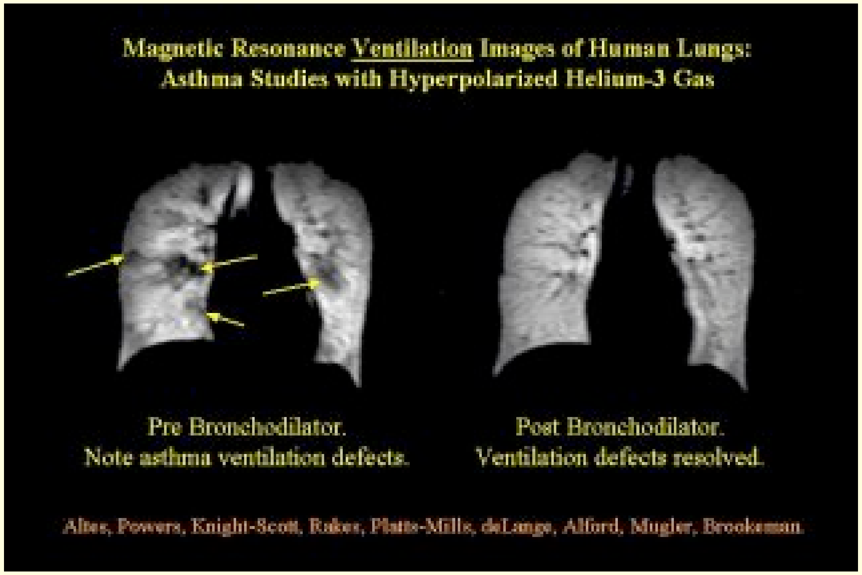
Human Lungs using ^{3}He MRI

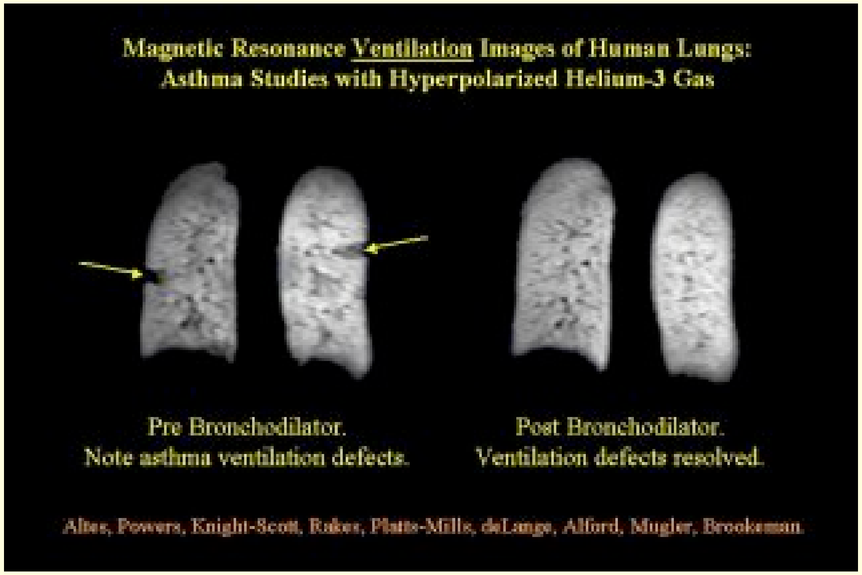


Resolution improved from 2 cm to ~0.1 cm

Princeton
Stony Brook
U. Of Virginia
Caltech

Detects Asthma before Symptoms!





U. Of Virginia

Presently an experimental technique but shows high potential. Due to the relative difficulty with the supply of ^3He, Xenon is being tried. Times scales: 3-7 yrs.

Concluding Remarks

- Fixed target DIS experiments discovered the Spin Crisis
- Theoretical development and new data have shown that it is a puzzle not a crisis

- New techniques such as polarized pp scattering at collider energies are now involved in the nucleon spin investigations.
  - A source of constant excitement in the next few years

- While we do think we have learnt a lot in the last two decades about nucleon spin, if history is any precedence, many more surprises are certainly in store in future.

- We just have to look and search!

Spin Surprises of last 100 Years!

- Stern & Gehrlach (1921) Space quantization associated with direction
- Goudschmidt & Ulhenbeck (1926): Atomic fine structure & electron spin magnetic moment
- Stern (1933) Proton anomalous magnetic moment 2.79 $\mathbf{m}_N$
- Kusch(1947) Electron anomalous magnetic moment 1.00119$\mathbf{m}_0$
- Prescott & Yale-SLAC Collaboration (1978) EW interference in polarized e-d DIS, parity non-conservation

- **European Muon Collaboration (1988/9) Spin Crisis/Puzzle**

- Transverse single spin asymmetries:
  - E704, AGS pp scattering, HERMES (1990s) RHIC Spin (2001)
    single spin neutron production(PHENIX)
    pion production (STAR) at 200 GeV Sqrt(S)

Some "spin" surprises

- (1921) Stern & Gerlach Space quantization associated with direction
- (1926) Goudschmidt & Ulhenbeck: Atomic fine structure & electron spin magnetic moment
- (1933) Stern: Proton anomalous magnetic moment 2.79 $\mathbf{m}_N$
- (1947) Kusch: Electron anomalous magnetic moment 1.00119$\mathbf{m}_0$
- (1978) Prescott & Yale-SLAC Collaboration EW interference in polarized e-d DIS, parity non-conservation
- **(1988/89) European Muon Collaboration Spin Crisis/Puzzle**
- (1990s, 2000-Present) Transverse single spin asymmetries: E704, AGS pp scattering, HERMES (1990s) RHIC Spin (2001-Present)
  - single spin neutron production (PHENIX) at 200 GeV Sqrt(s)
  - pion production (STAR) at 200 GeV Sqrt(S)
- Jefferson laboratory experiments hinting at the proton shape

"Spin" has a high potential for surprises!