


Unraveling the mysteries of the proton

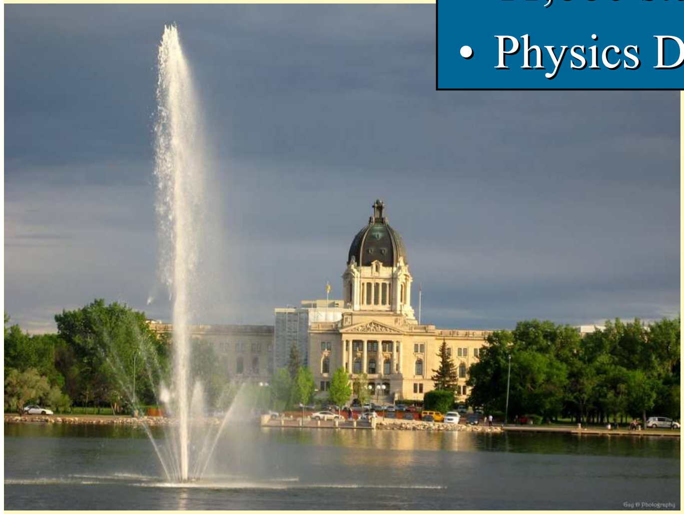
Garth Huber

UNIVERSITY OF REGINA

Prairie Universities Physics Seminar Series, November, 2009.

University of Regina:

- Wide range of Undergraduate and Graduate programs and Research, but no Medical School.
- Only Comprehensive University on Prairies.
- 11,886 students, incl. 1,467 Grad Students (2009).
- Physics Dept. offers B.Sc., M.Sc. and Ph.D.



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A Historical Perspective

The static properties of the proton are well known: m_p, S, μ_p, e.

1933: First measurement of the proton's magnetic moment.

Stern measures $\mu_p \approx 2.79\mu_N$. A point-like Dirac particle would have $\mu_p = q/(2e)\mu_N$ (much smaller!). The proton is not a point particle.

Nobel Prize 1943 – O. Stern.

1950-1960: What is the size of the proton?

Early elastic scattering experiments at Stanford (Hofstadter et al.) show proton charge radius ~0.8fm.

Nobel Prize 1961 – R. Hofstadter.

1960-1990: What is the internal structure of the proton?

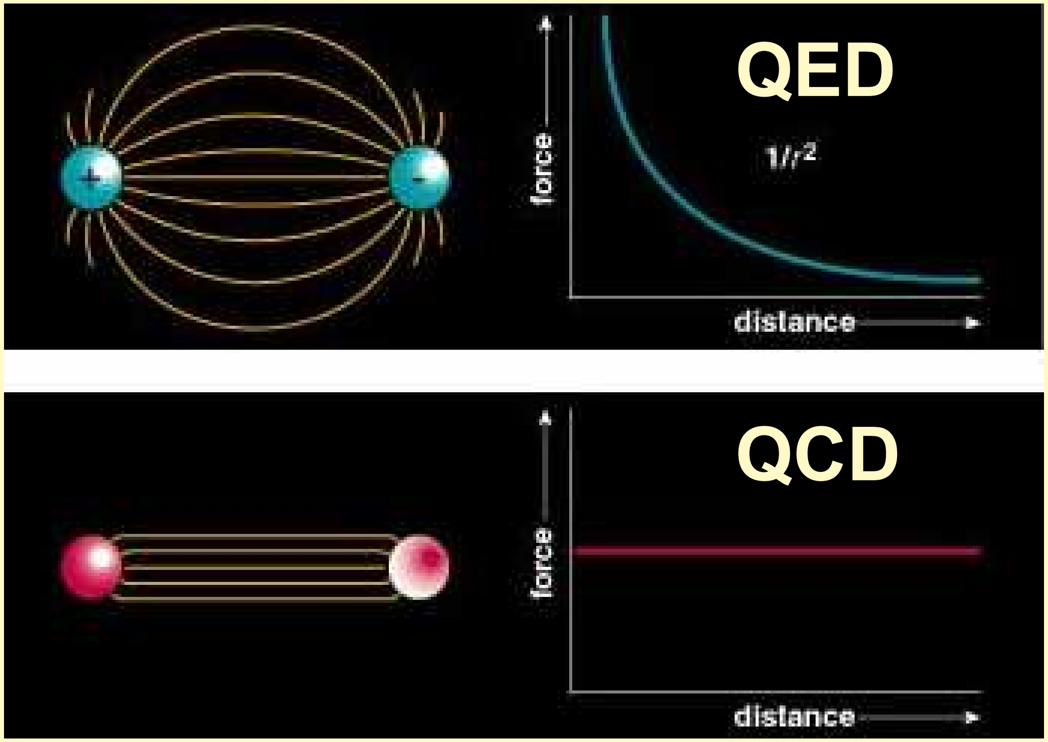
Deep Inelastic Electron Scattering, discover quarks in "scaling" of structure functions, measure spin and momentum distributions.

Nobel Prize 1990 – J. Friedman, H. Kendall, R. Taylor.

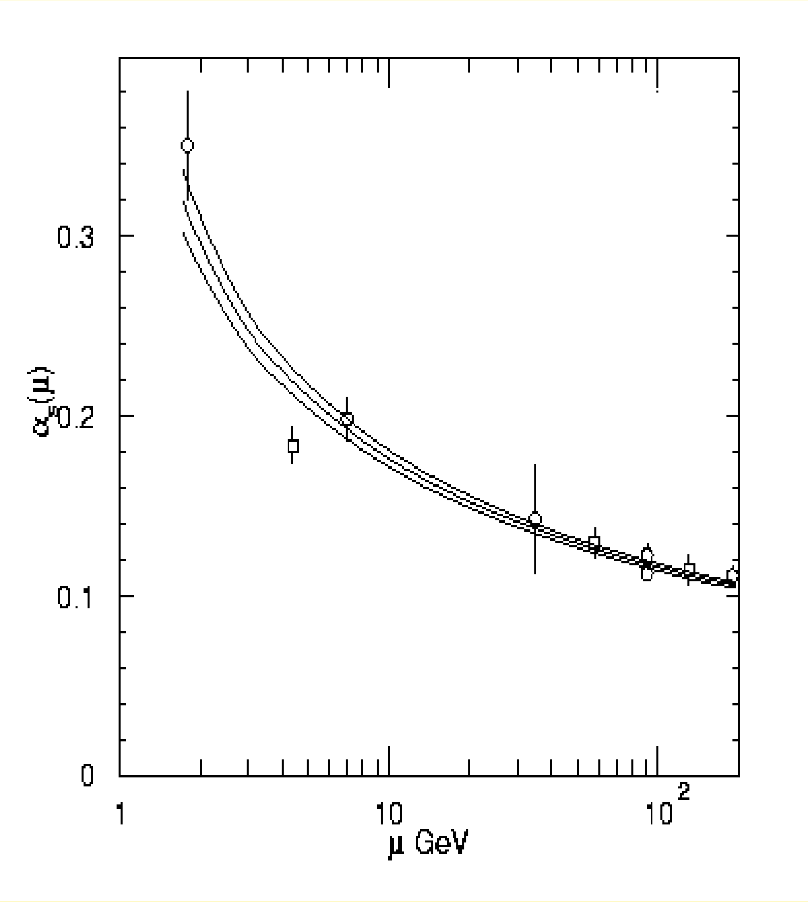
Today: Quantitative description of the proton's properties in terms of its underlying constituents.

Quantum Electrodynamics
Quantum Chromodynamics

The gluons of QCD carry color charge and interact strongly (in contrast to the photons of QED).



QCD's Dual Nature



Short Distance Interaction:

- Short distance quark-quark interaction is feeble.
  - Quarks inside protons behave as if they are nearly unbound.
  - Asymptotic Freedom.
- perturbative QCD (pQCD).

Long Distance Interaction:

- Quarks strongly bound within hadrons.
  - Color confinement (strong QCD).
- QCD calculations extremely difficult.
- **QCD-based models are often used, but experimental data needed to validate approaches used.**

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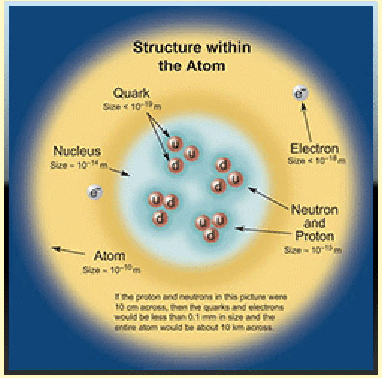
Mysteries of Proton Structure

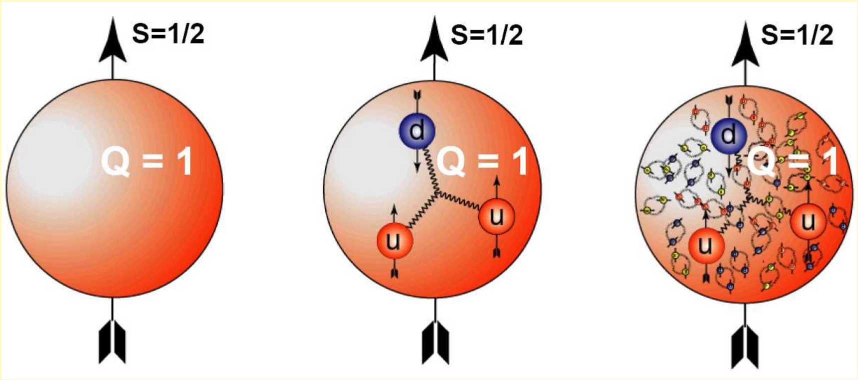


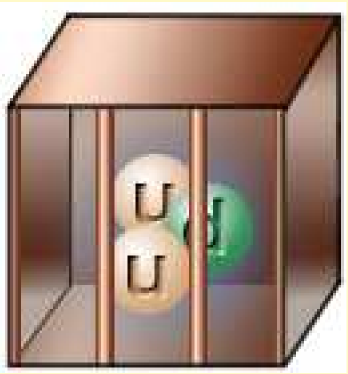
- Where does the proton's mass come from?

$$u \;+\; u \;+\; d \;=\; \text{proton}$$

$$\text{mass:}\;\; 0.003 + 0.003 + 0.006 \neq 0.938$$

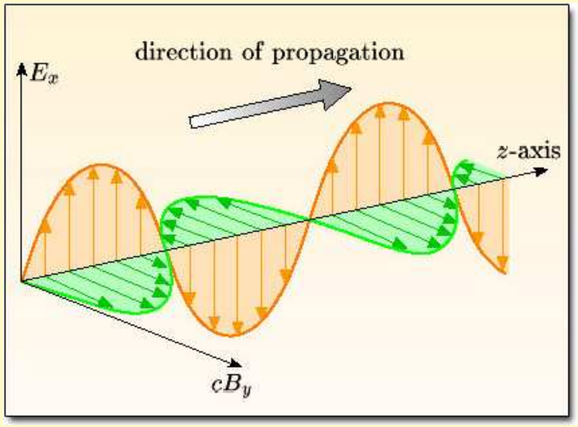
- How are the proton's electric/magnetic densities related to the quark momentum/spin distributions?
- Where does the proton's spin ½ come from?





- Confinement: Why don't we see free quarks?

Probes used to Investigate Proton Structure



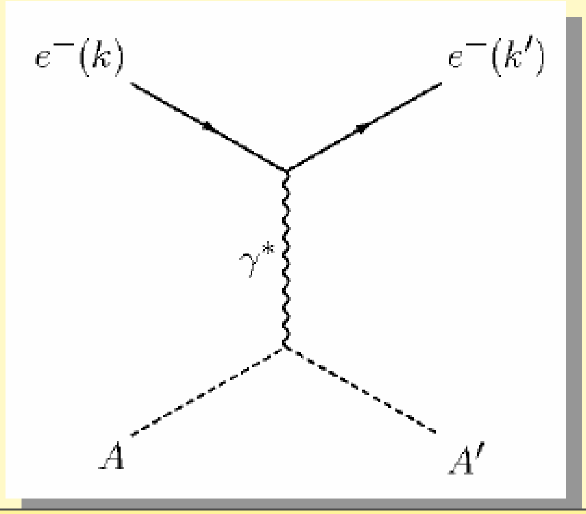
Real Photons (γ):

- *Created in hard electron deceleration (Bremsstrahlung).*
- *Zero Rest Mass: E=pc*
- *Equivalently: $Q^2=p^2c^2-E^2=0$*
- *Observation Scale: R≈h/p.*
- *Electric Polarization Transverse to Propagation.*

Virtual (Spacelike) Photons (γ*):

- *Created in larger θ electron scattering.*
- *E≠pc: Heisenberg Principle: $\Delta E \Delta t \geq \hbar/2$*
- *$Q^2=p^2c^2-E^2>0$*

  If we define $m^2c^4=E^2-p^2c^2$, then $Q^2>0$ implies imaginary virtual photon mass.
- *Observation Scale: $R \approx (\hbar c)/Q$.*
- *Transverse and Longitudinal Electric Polarizations permitted.*

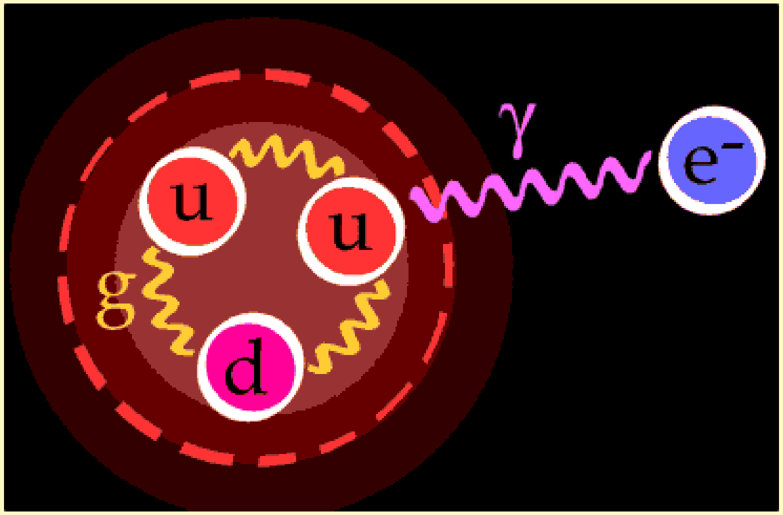


Virtual Photon Energy $= E - E'$

Virtual Photon Momentum $= \vec{k} - \vec{k}'$

Why Use Electromagnetic Probes?

- **Electromagnetic force well understood.**
  - Use the known properties of EM interaction to investigate proton internal structure.



Technical advancements:
Intense CW electron beams.
Polarized targets & beams.

Luminosity:
(SLAC, 1978) ~ 8×10^{31} cm^{-2}-s^{-1}
(JLab, 2009) ~ 4×10^{38} cm^{-2}-s^{-1}

$$d = 1 \rightarrow 0.1\,\mathrm{fm} \quad \Leftrightarrow \quad Q^2 = 0.1 - 10\,(\mathrm{GeV/c})^2$$

Probe Proton via Elastic Scattering of Electrons

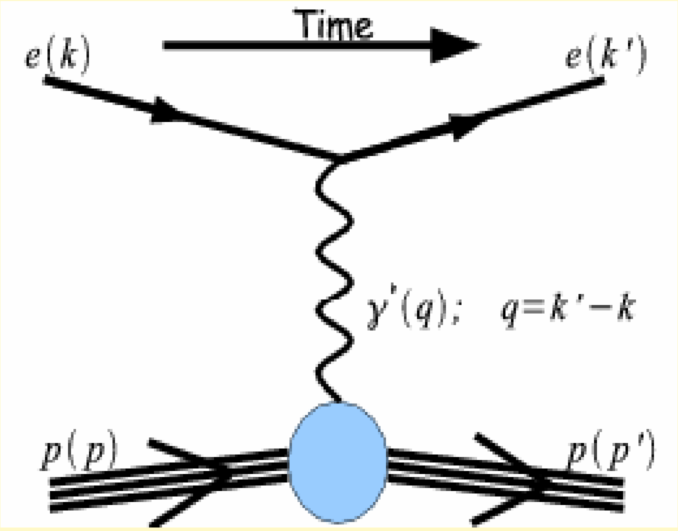
In an elastic scattering, we have the same kind and number of particles in the initial and final states

$$e+p \rightarrow e+p$$

Elastic Form Factors

Scattering cross section from a spinless, point-like particle:

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{\alpha^2}{Q^2}\left(\frac{E'}{E}\right)^2 \cot^2\frac{\theta_e}{2}$$



General form for scattering cross from an extended target:

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{\substack{\text{point}\\\text{object}}} \left|F(Q^2)\right|^2$$

In the case of an infinitely massive target, the form factor is simply the Fourier transform of the charge distribution.

$$F(Q^2) = \int \rho(\vec{x}) e^{i\vec{q}\cdot\vec{x}/\hbar} d^3x$$

Proton Elastic Form Factors

- For a spin ½ target, two Form Factors are needed to parameterize our ignorance of the proton's internal structure.

Expression in terms of Electric (G_E) and Magnetic (G_M) form factors.

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma_{Mott}}{d\Omega}\right)\frac{1}{1+\tau}\left[G_E^2 + \frac{\tau}{\varepsilon}G_M^2\right] \text{ where } \tau, \varepsilon \text{ are kinematic factors.}$$

Alternately, in terms of spin non-flip (F_1) and spin flip (F_2) form factors.

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma_{Mott}}{d\Omega}\right)\left\{F_1^2 + \tau\left[F_2^2 + 2(F_1 + F_2)^2 \tan^2\frac{\theta}{2}\right]\right\}$$

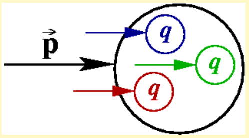
Measurements allow us to test our understanding of proton structure by comparison to QCD based predictions.

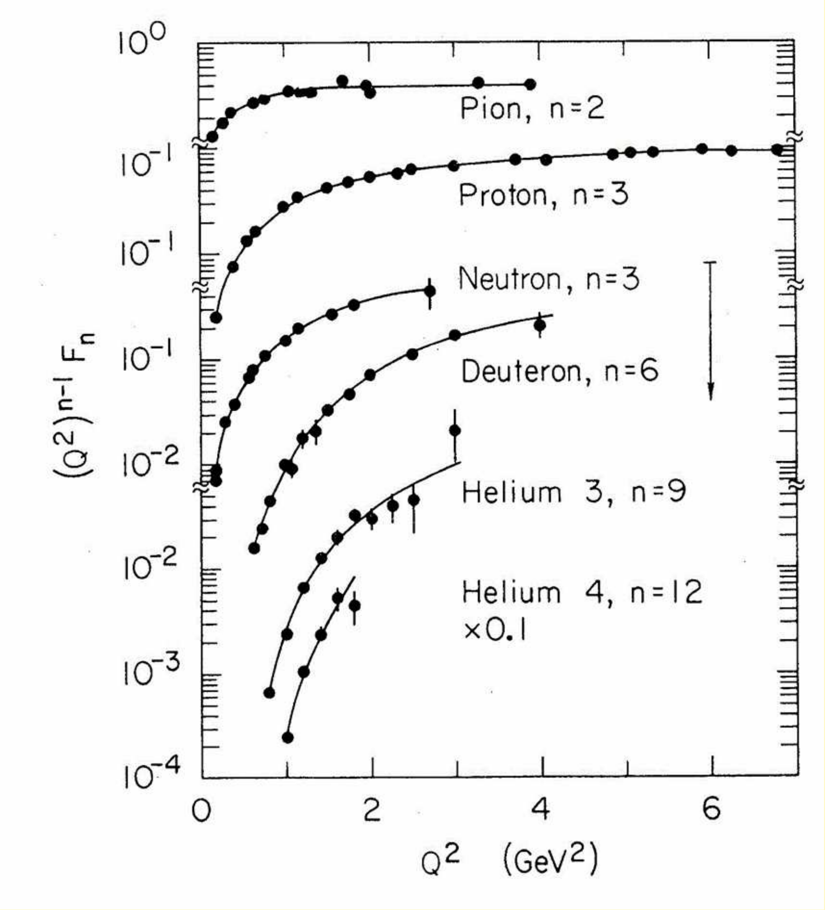
An early pQCD Prediction:

- Dimensional Scaling at Large Momentum

At infinite momentum, quarks are asymptotically free.

- Equivalent to turning off the strong interaction.
- The hadron becomes a collection of free quarks with equal longitudinal momenta.





S.J. Brodsky, G.P. Lepage "Perturbative QCD", A.H. Mueller, ed., 1989.

Dimensional analysis of the hadron scattering amplitude in terms of the participating fields yields

$$F(Q^2) \propto \frac{1}{(Q^2)^{n-1}}$$

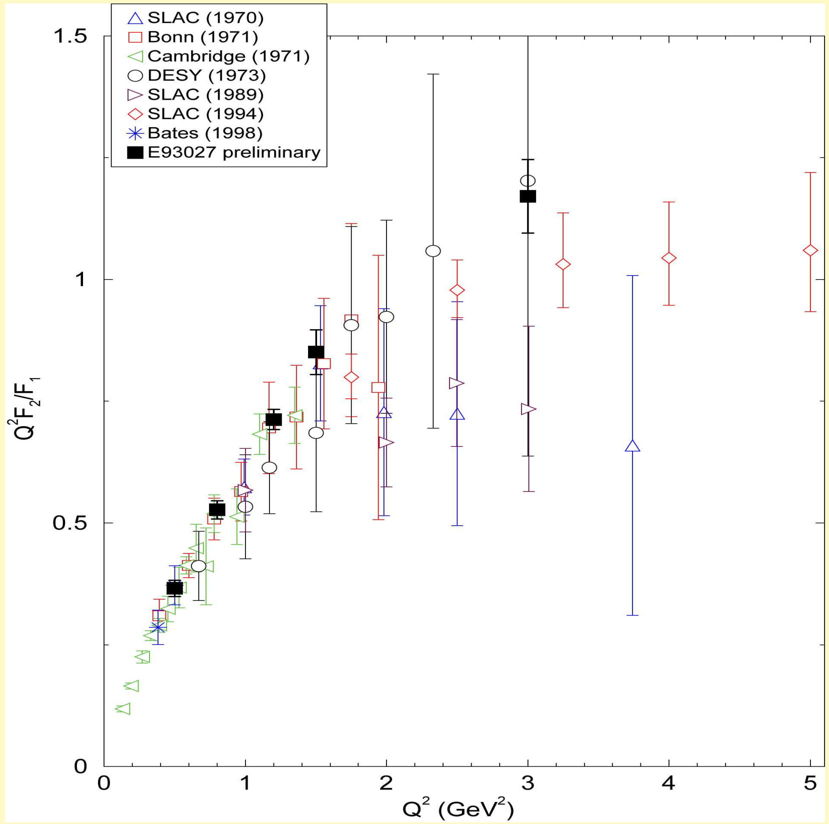
Proton Electromagnetic Form Factors

pQCD Dimensional Scaling Rule:

- $F_1(Q^2) \sim 1/Q^4$ (n=3).
- $F_2(Q^2) \sim 1/Q^6$ (n=3 with spin flip).
  - $Q^2 F_2/F_1 \sim$constant.

- Data indicate onset of pQCD scaling at only $Q^2 \approx 2$ GeV^2.
  - Seems low, given that the argument is made for infinite momentum.

World proton data set, 1997.



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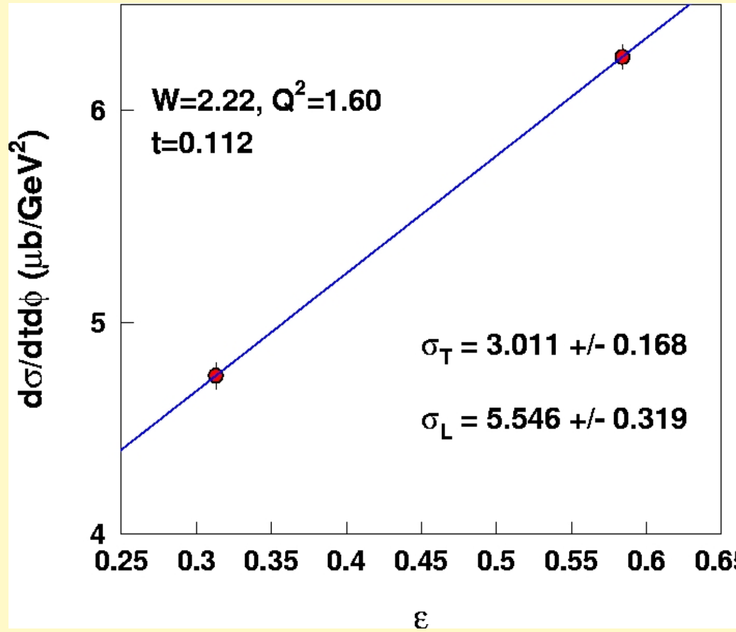
Historic F_1,F_2 (or G_M,G_E) Measurement Method

"Rosenbluth" Separation:

- Challenging technique that requires delicate comparison of data at two different electron beam energies.



Vary the virtual-photon polarization:

$$\varepsilon = \left(1 + 2 \frac{(E_e - E_{e'})^2 + Q^2}{Q^2} \tan^2 \frac{\theta_{e'}}{2} \right)^{-1}$$

$$\frac{d\sigma^{el}}{dQ^2} \rightarrow \varepsilon G_E(Q^2) + \tau G_M(Q^2)$$

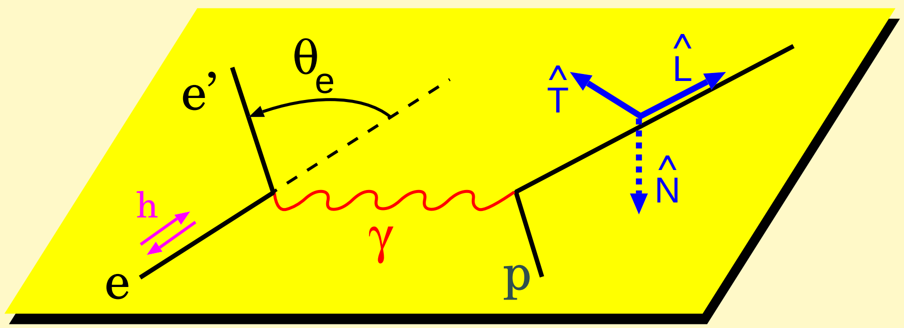
Magnetic contribution dominates cross section at high Q^2:

– F_1 data of fairly good quality.

Electric contribution at few % level:

– F_2 difficult to measure.

Polarization transfer technique

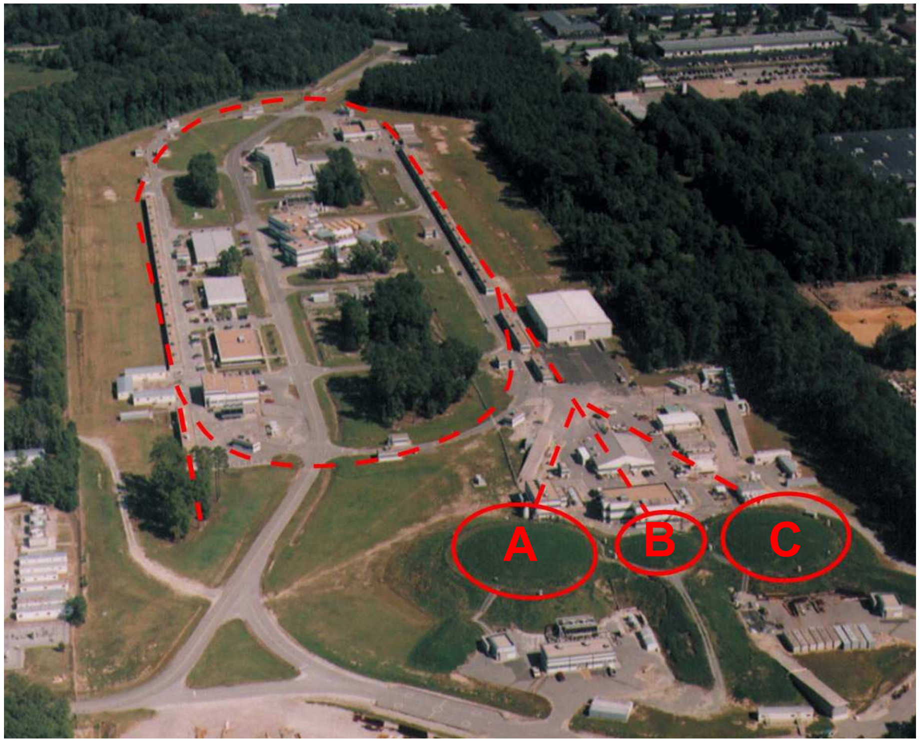


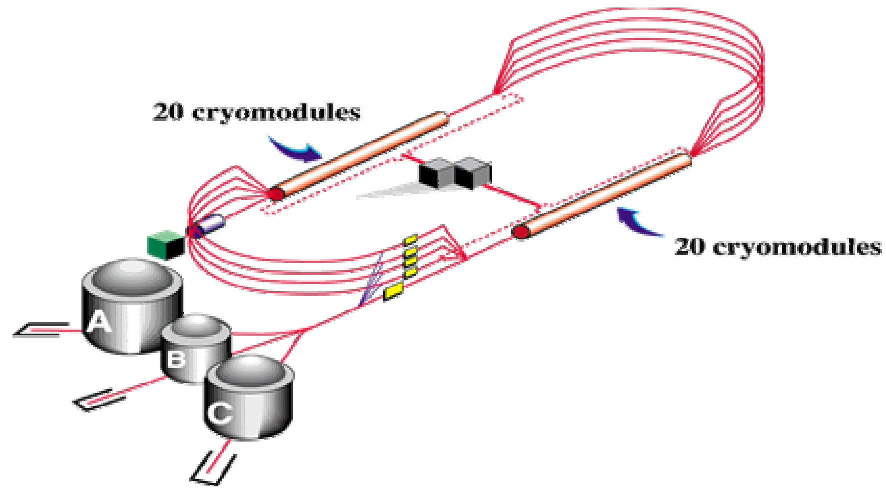
Technique based on recent technological advances:

- **requires an intense electron beam with high polarization.**
- **need to measure the polarization of the recoil nucleon.**

$$\frac{G_E}{G_M} = -\frac{p_t}{p_l}\frac{E+E'}{2m}\tan\left(\frac{\theta_e}{2}\right)$$

Simultaneous measurement of transverse and longitudinal polarization components provides an accurate measurement of the form factor ratio.





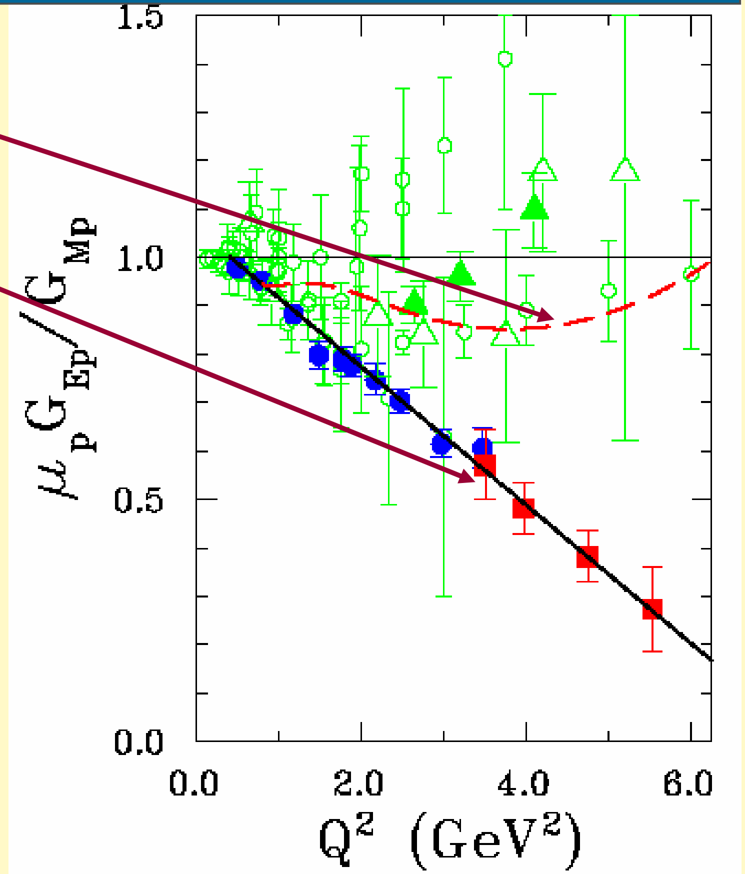
Two 1.5 GHz Superconducting Linear Accelerators provide intense electron beam optimized for Nucleon & Nuclear structure studies.

- **Beam energy E → 6 GeV.**
- **Beam current >100 μA.**
- **Up to 85% beam polarization.**
- Experiments in all 3 Halls can receive beam simultaneously.

Crisis: Data Sets Disagree Violently

Dashed = fit to Rosenbluth results

Solid = fit to Recoil-Polarization results

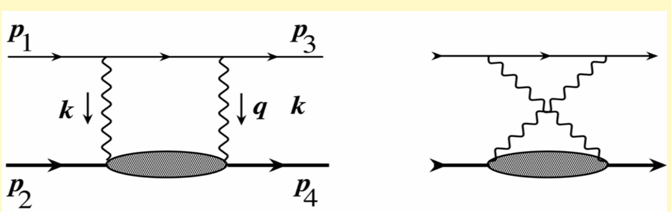


O. Gayou et al, PRL **88**(02)092301.

Current Understanding:

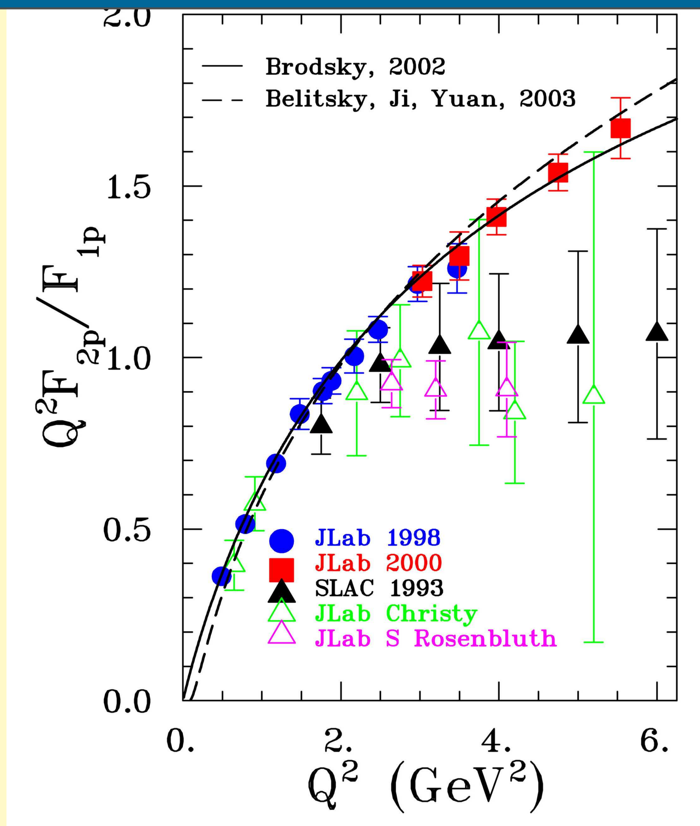
- Difference is due to breakdown of Born single photon exchange approximation.
- 2γ contributions have much larger influence on Rosenbluth (compared to Polarization) method.

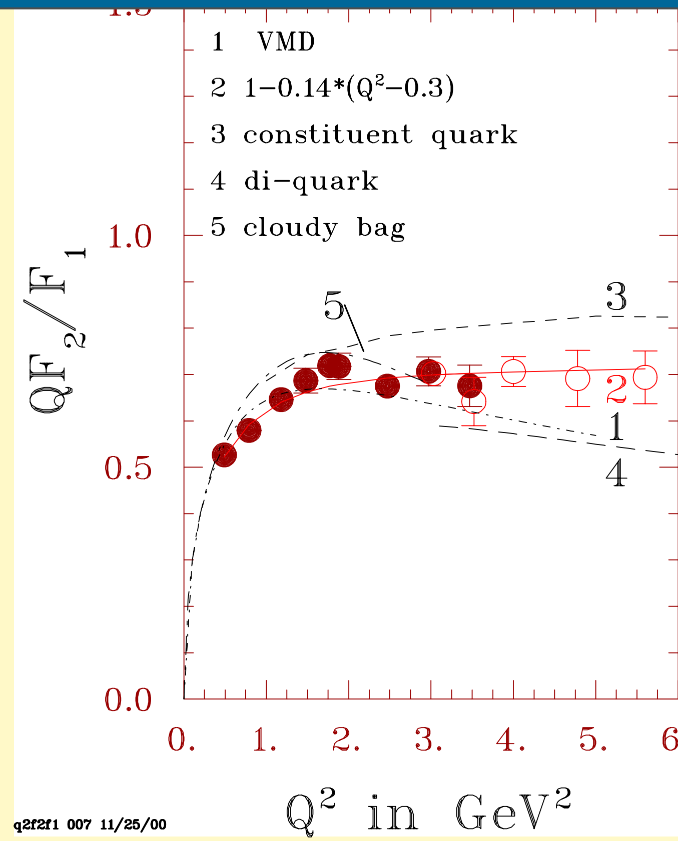
(P. Blunden et al, PRL **91**(03)142304).



WHAT THIS MEANS: Elastic cross sections are accurate, but the polarization transfer measurements better represent G_E^p.

Jefferson Lab Proton F_2/F_1 Data





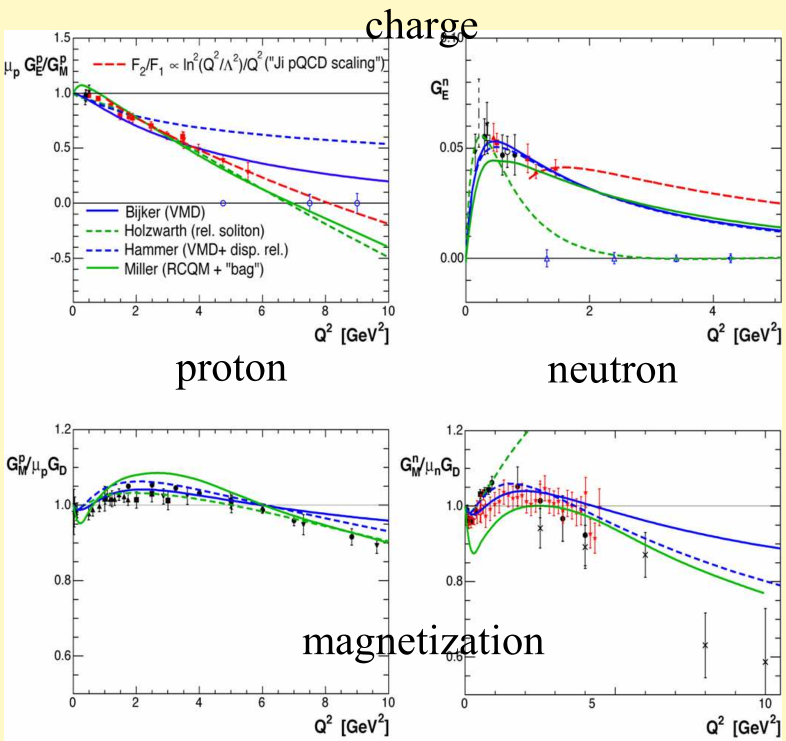
- **JLab data show that Q^2 scaling was "premature".**
- The data instead show a remarkable scaling with *Q*, which was not anticipated.
- Data are dominated by soft QCD contributions which give rise to *Q*-like scaling (Belitsky, Ji, Yuan, PRL **91**(03) 092003).

Physical Interpretation of G_E, G_M Data

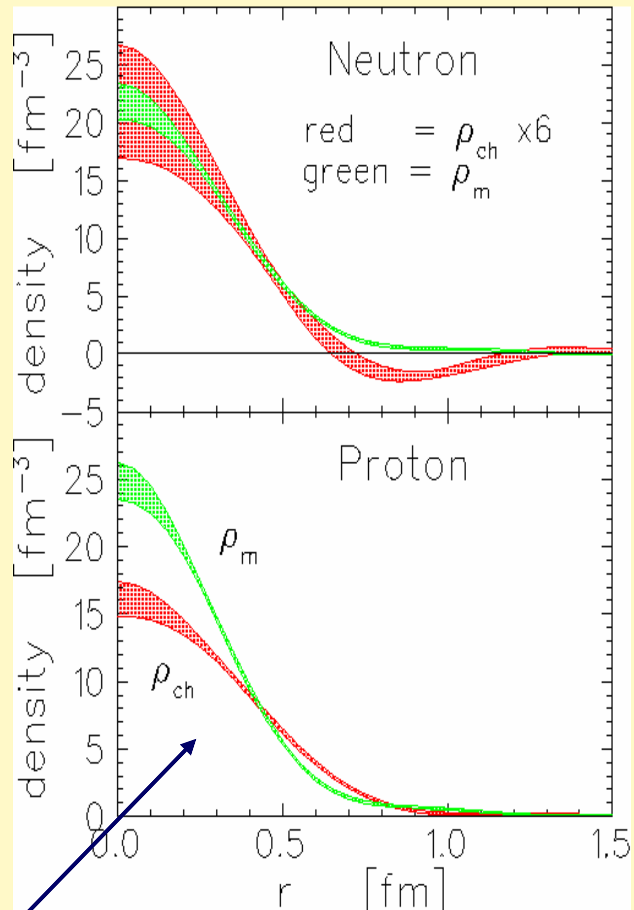
Because of nucleon recoil and Lorentz contraction (Relativity!) effects:

→ G_E, G_M not directly related to nucleon's ρ_{ch}, ρ_M distributions.

→ **Gain intuition via model to perform global analysis of p and n form factors.**



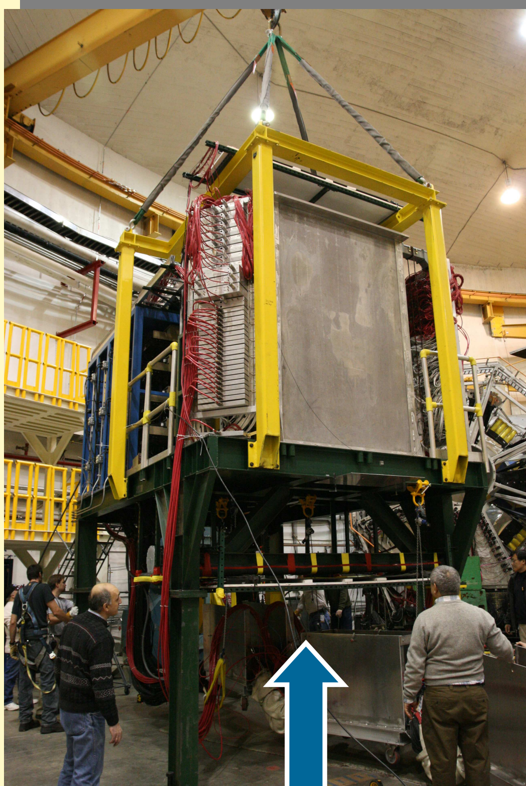
J.J. Kelly, PRC **66** (2002) 065203

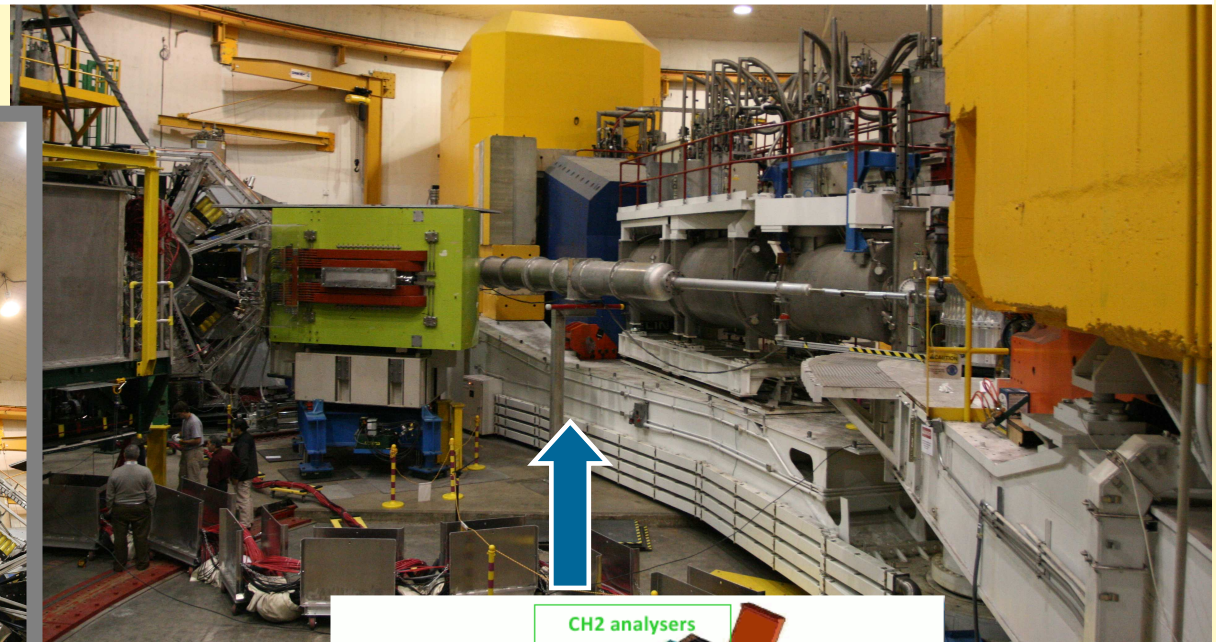


Kelly interprets JLab polarization data in terms of charge depletion in interior of proton.

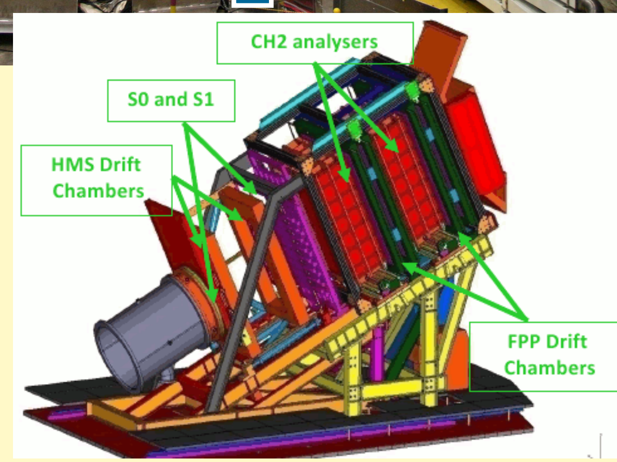
The Trek Upward in Q^2:
Probing the Proton at Shorter Distance Scales

2007 JLab Hall C experiment with Improved Detectors





New Lead Glass Calorimeter
Used for Electron Detection

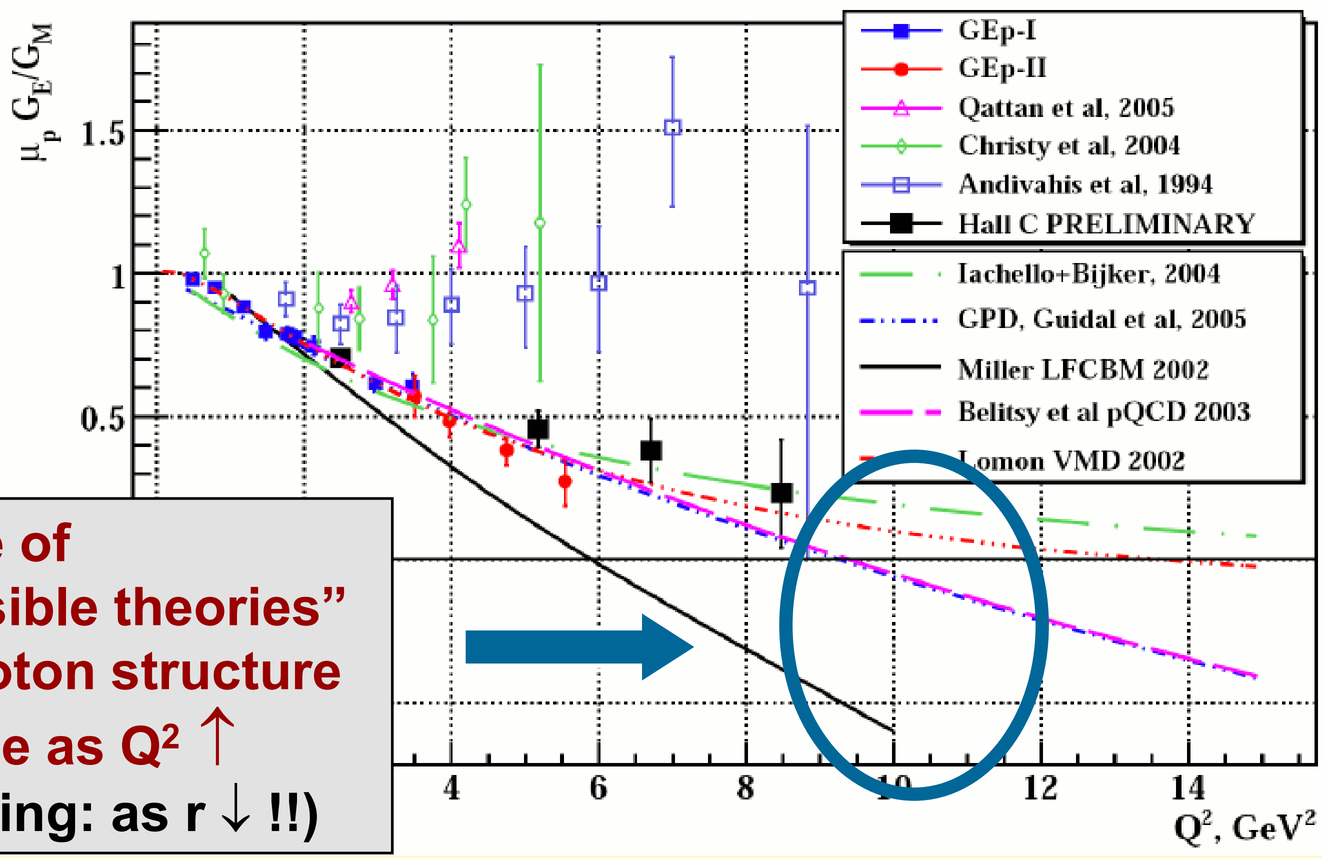


New Proton Polarimeter (inside HMS shield hut)

The Trek UPWARD in Q^2:

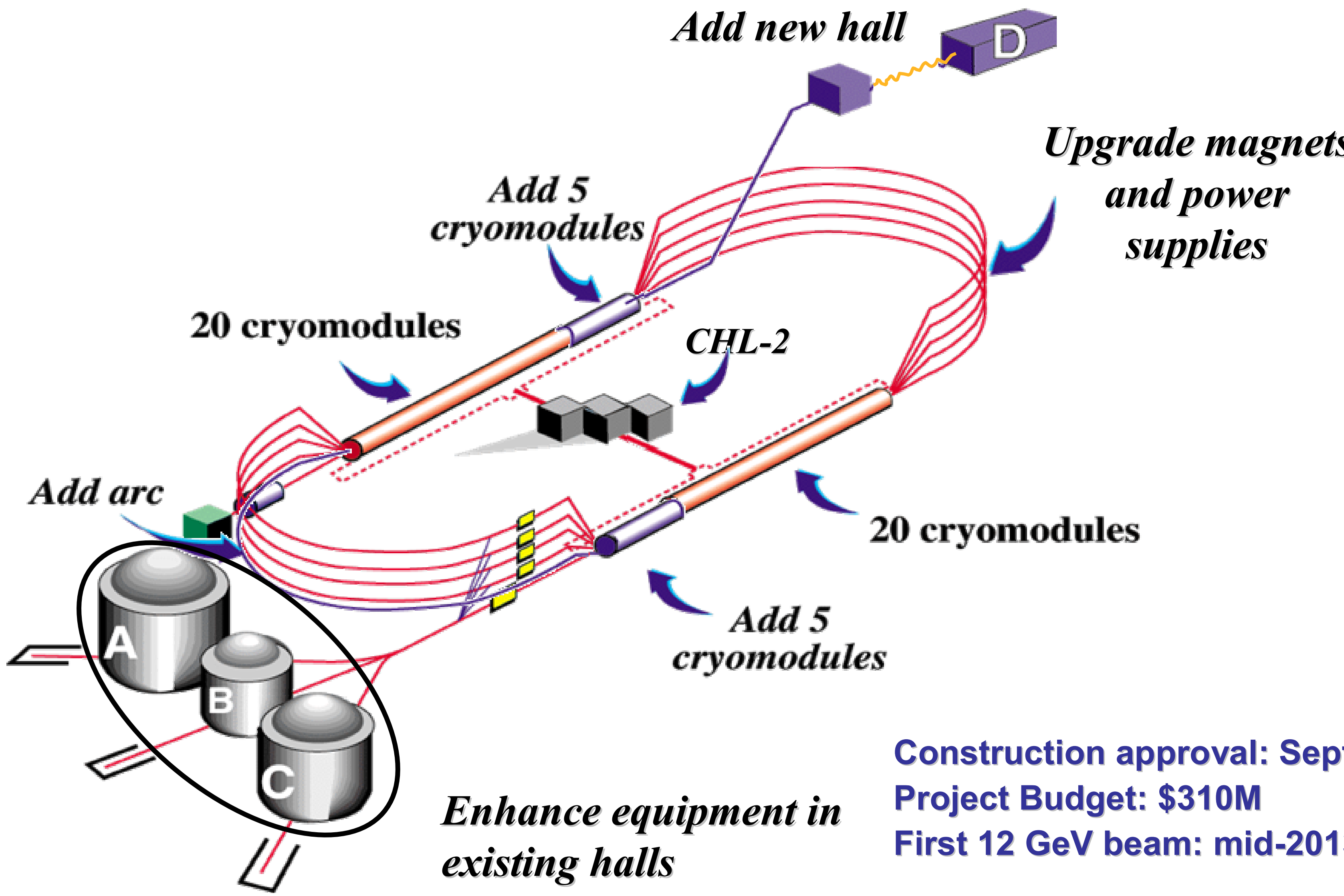
A Brief Snapshot of What can be learned by extending UP

Preliminary Results Courtesy of Andrew Puckett



Range of "plausible theories" for proton structure diverge as Q^2 ↑ (meaning: as r ↓ !!)

Jefferson Lab 12 GeV Upgrade

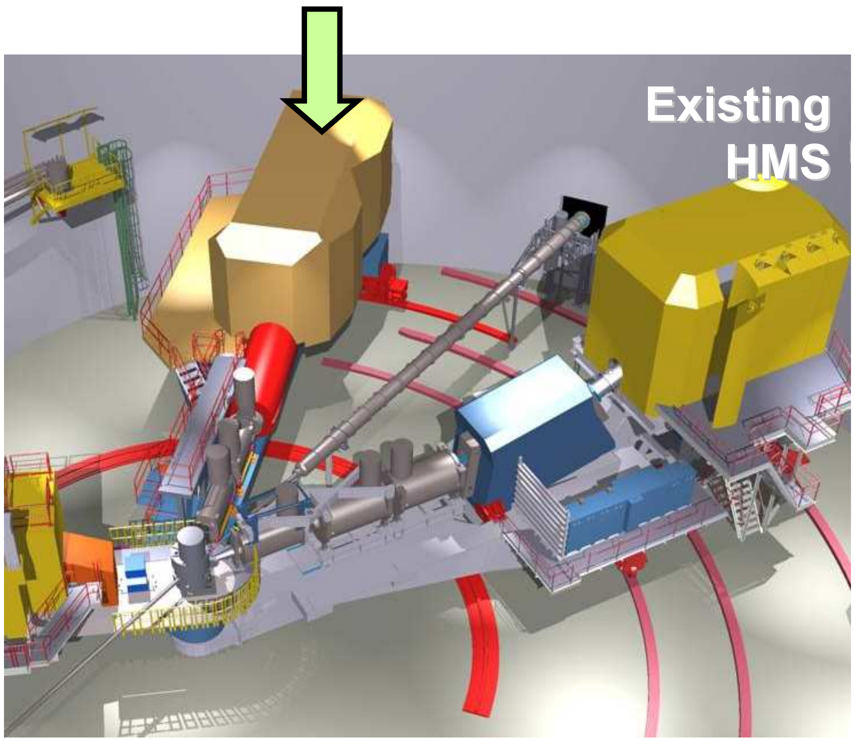


Construction approval: Sept/08
Project Budget: $310M
First 12 GeV beam: mid-2013

Upgrade of JLab Hall C

New Super-High Momentum Spectrometer (SHMS):

Momentum: 2-11 GeV/c
Scattering Angle: $5.5^o < \theta < 40^o$
Acceptance: 5msr, $-11\% < \delta p/p < +22\%$



- **Upgrade will allow upper limit of G_E^p/G_M^p data to be extended from Q^2=8.5 to 14 GeV^2.**
- **Canadians are playing a significant role in shaping the physics program of the new facility.**
- **UofR Responsible for Heavy Gas (C_4F_8O) Čerenkov needed for good π/K separation.**

Probe Proton via Inelastic Scattering of Electrons

"New" particles created in the final state. e.g. $e^-p \rightarrow e^-p\pi^o$, $e^-p \rightarrow e^-pK^+K^-$

Since there are many inelastic states, it is common to average over them: $e^-p \rightarrow e^-X^+$

Of particular importance is the *scaling* variable: $x = Q^2/2pq$.
Corresponds to the momentum fraction carried by struck parton (quark) in the infinite momentum limit.

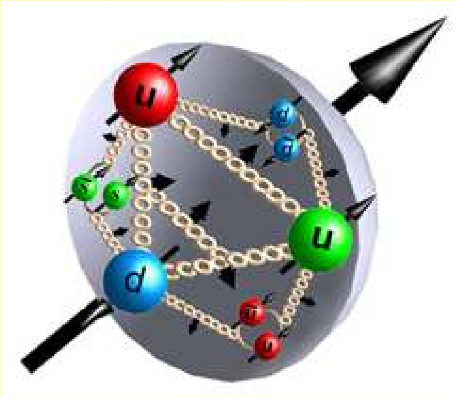
Valence Quarks vs. Sea Quarks

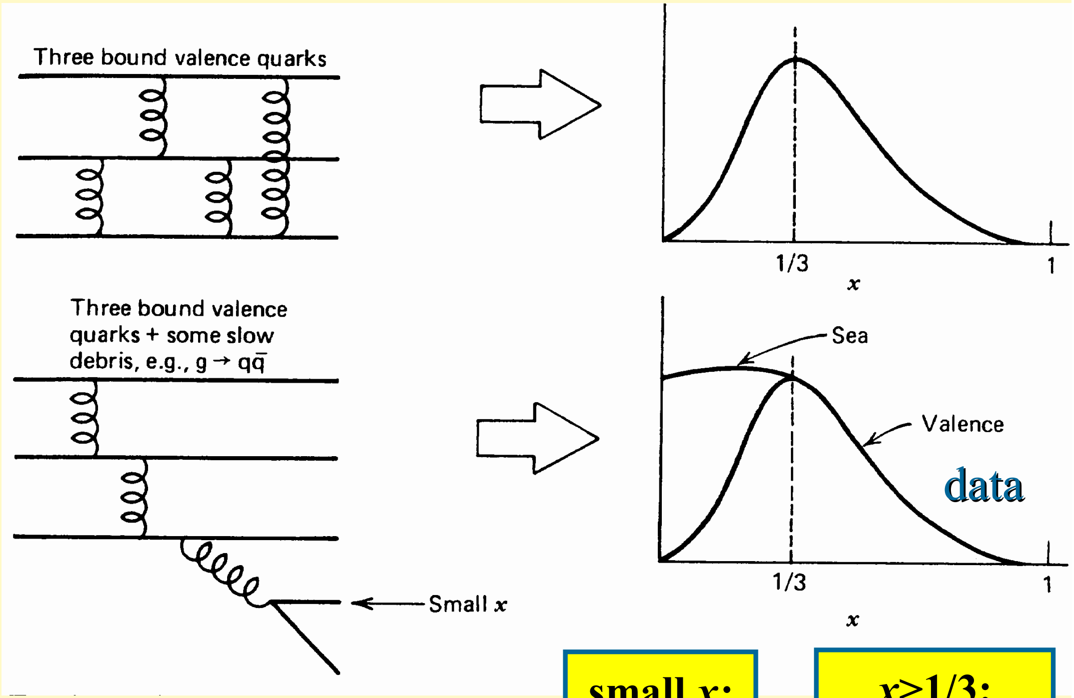
Write cross section in terms of Structure Functions F_1, F_2.

→ functions of Q^2 and x (not just Q^2 as for Form Factors).

$$\frac{d\sigma}{dE'd\Omega} = \left(\frac{\alpha\hbar}{2E\sin^2(\theta/2)}\right)^2 \left[\frac{2F_1(x,Q^2)}{M}\sin^2(\theta/2) + \frac{2MxF_2(x,Q^2)}{Q^2}\cos^2(\theta/2)\right]$$

VALENCE QUARKS: qqq required for correct nucleon quantum numbers.
SEA QUARKS: virtual q:anti-q pairs allowed by uncertainty principle.

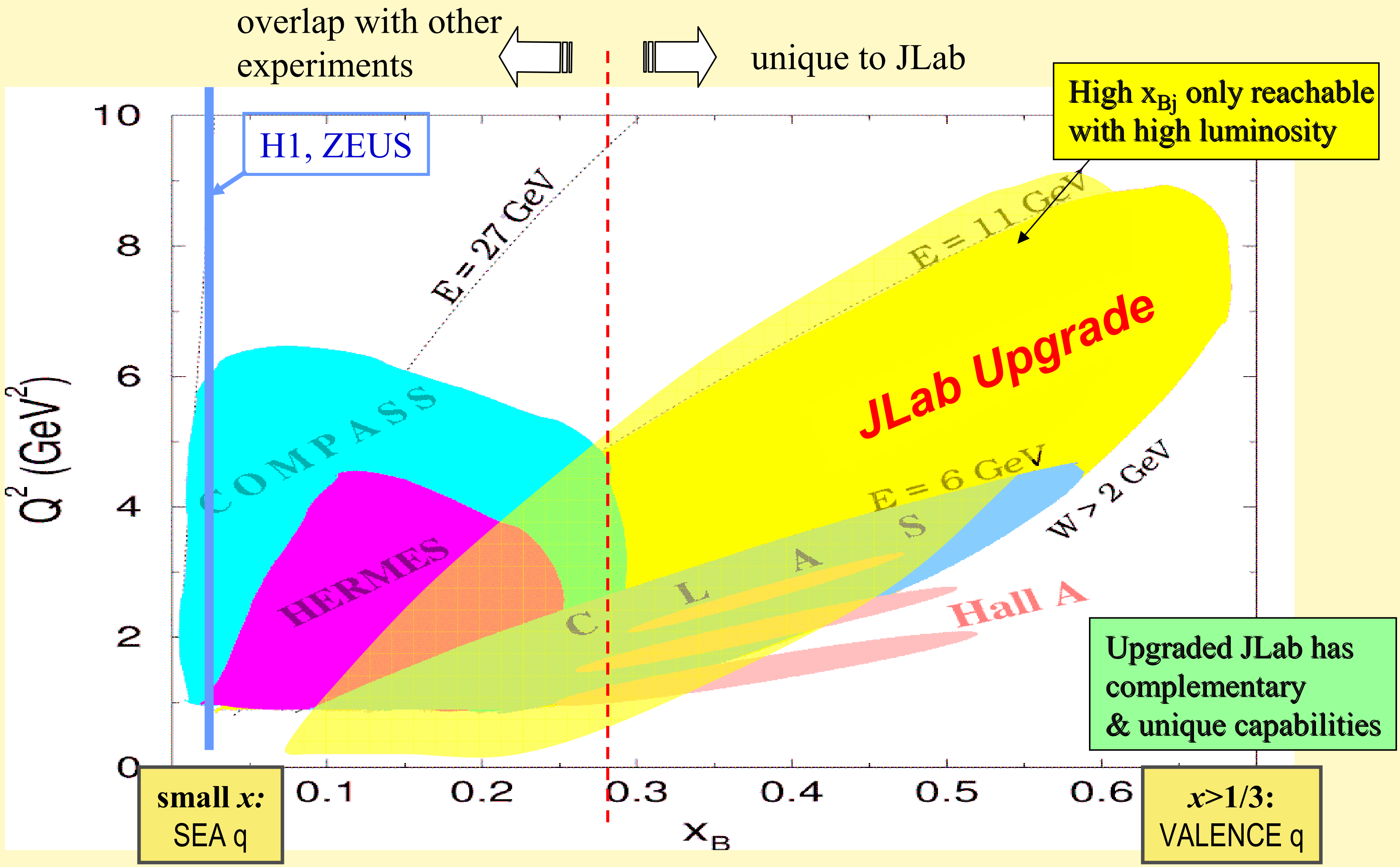




small x: SEA q

x>1/3: VALENCE q

Deep Inelastic Scattering Experiments - Kinematics Coverage of the 12 GeV Upgrade



Structure Function Measurements: Spin and Flavor Dependence of Valence Parton Distribution Functions

- In over 35 years of study of Deep Inelastic Scattering, no one has had the facilities to map out the crucial region where proton structure is dominated by valence quarks.
  - **Large x:** sea quarks are effectively "stripped away".
- Region is fundamental to our understanding of proton structure: i.e. how nonperturbative QCD works!
  - Role of di-quark correlations?
  - Role of hard scattering: pQCD / Lattice QCD guidance?
  - Breaking of SU(6) $[u,\bar{u},d,\bar{d},s,\bar{s}]$ symmetry?

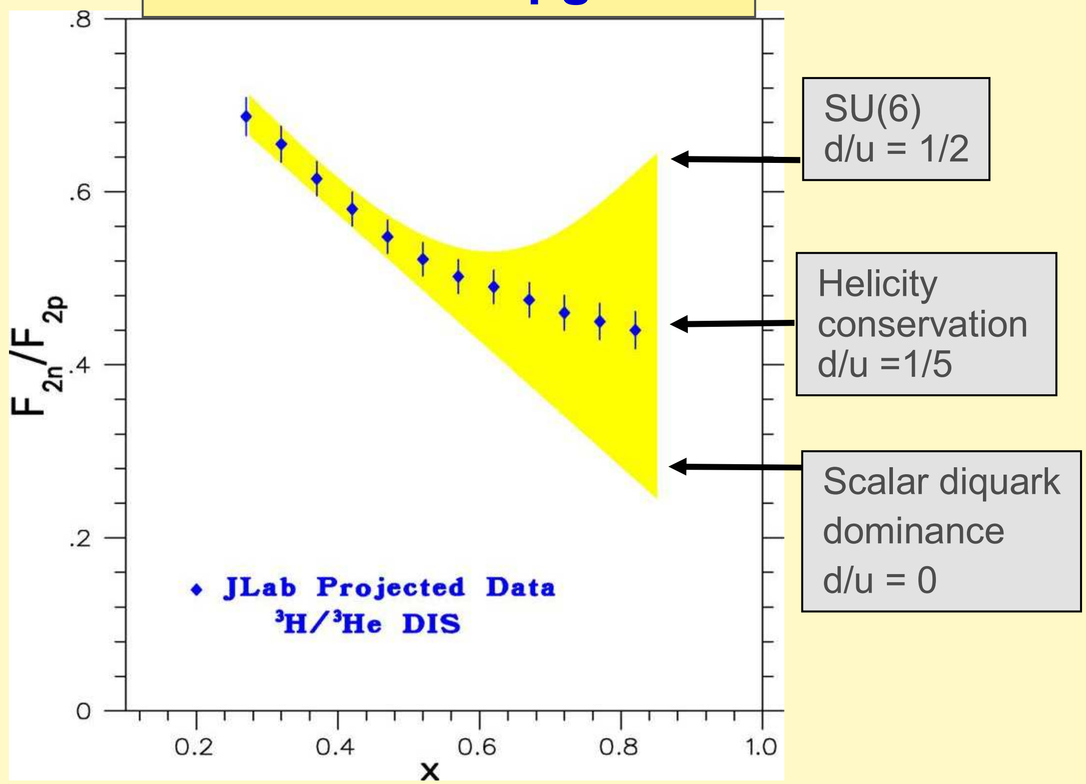
Large x F_{2n}/F_{2p} measurements to greatly improve our knowledge of Valence d-Quark Momentum Distributions

There are many testable relationships between Structure Functions!

Quark momentum distribution *f(x)=dP/dx*. Structure function for inelastic scattering off quark with momentum *x* and charge e_i:

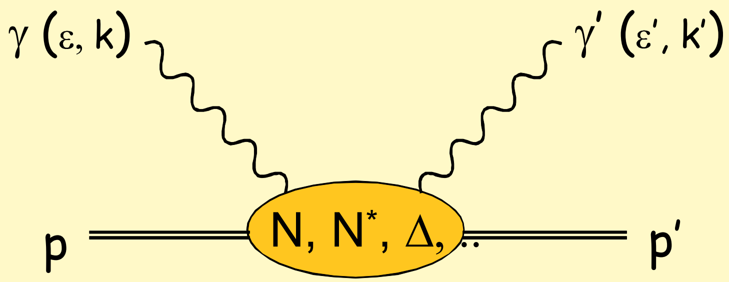
$$F_1 = \frac{e_i^2 f(x)}{2} \text{ and } F_2 = e_i^2 x f(x)$$

Hall C Projected Data after 12 GeV Upgrade



Present Uncertainty

Probe Proton via Compton Scattering of Real Photons



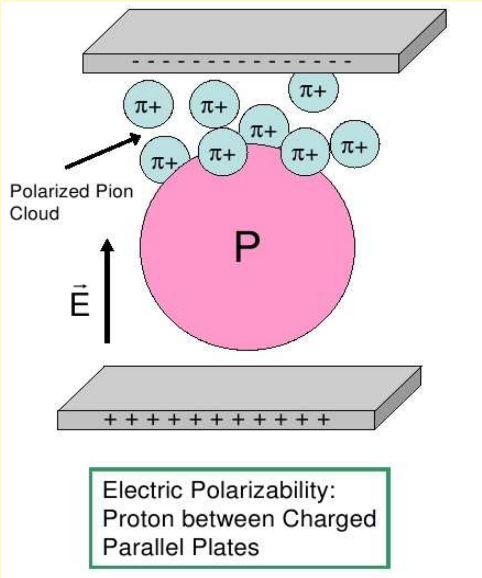
Proton Polarizabilities

$$H_{eff}^{(2)} = \frac{1}{2}\alpha_{E1}\vec{E}^2 + \frac{1}{2}\beta_{M1}\vec{H}^2$$

- **Proton's Internal Structure enters Hamiltonian at 2nd order as Electric & Magnetic Polarizabilities.**
- Determine α_{E1}, β_{M1} from angular distribution.

Proton's Electric & Magnetic polarizabilities well understood.

– Response of proton's internal degrees of freedom to static Electric and Magnetic fields in real Compton scattering.



Polarizabilities are fundamental nucleon structure observables.

→ Ideal for constraining QCD-based models of nucleon structure.

Proton Spin Polarizabilities

If include spin, next term in Hamiltonian:

$$H_{eff}^{(3)} = -\frac{1}{2}\left[\begin{array}{l}\gamma_{E1E1}\vec{\sigma}\cdot\vec{E}\times\dot{\vec{E}}+\gamma_{M1M1}\vec{\sigma}\cdot\vec{H}\times\dot{\vec{H}} \\ +2\gamma_{E1M2}H_{ij}\sigma_i E_j - 2\gamma_{M1E2}E_{ij}\sigma_i H_j\end{array}\right]$$

involves one field derivative wrt either time or space $\dot{\vec{E}} = \partial_t \vec{E}, \quad E_{ij} = \frac{1}{2}\left(\nabla_i E_j + \nabla_j E_i\right)$

e.g. γ_{M1E2} excited by electric quadrupole (E2) radiation
and decays by magnetic dipole (M1) radiation

- **Proton's spin polarizabilities nearly unknown.**
  - "Stiffness" of proton spin against EM-induced deformations relative to the spin axis.
  - Fundamentally connected to the proton's spin structure.
- **Requires asymmetry measurements using linearly and circularly polarized photon beams and polarized proton target.**

How to Measure Spin Polarizabilities

- Linearly polarized photons, parallel and perpendicular to the scattering plane, unpolarized target.

$$\Sigma_3 = \frac{\sigma^{||} - \sigma^{\perp}}{\sigma^{||} + \sigma^{\perp}}$$

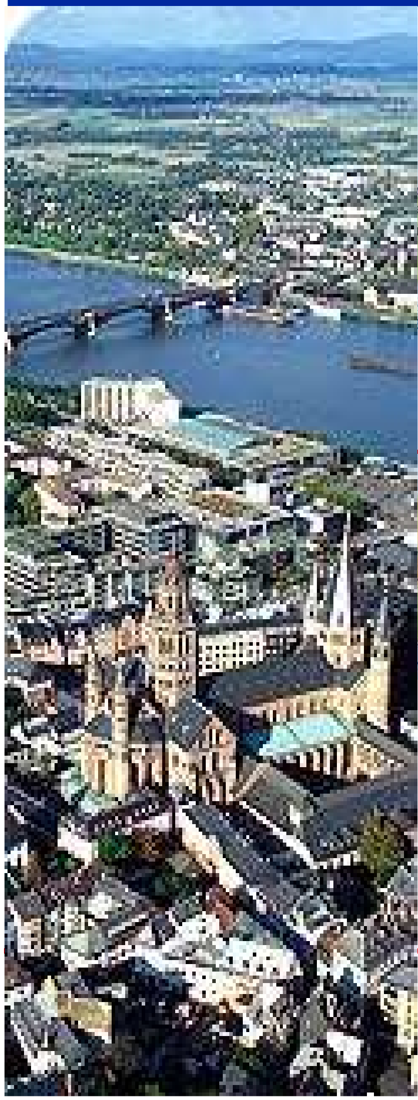
- Circularly polarized photons (left-handed (L) and right-handed (R)), longitudinally polarized target.

$$\Sigma_{2z} = \frac{\sigma^R_{+z} - \sigma^L_{+z}}{\sigma^R_{+z} + \sigma^L_{+z}} = \frac{\sigma^R_{+z} - \sigma^R_{-z}}{\sigma^R_{+z} + \sigma^R_{-z}}$$

- Circularly polarized photons (left-handed (L) and right-handed (R)), transversely polarized target.

$$\Sigma_{2x} = \frac{\sigma^R_{+x} - \sigma^L_{+x}}{\sigma^R_{+x} + \sigma^L_{+x}} = \frac{\sigma^R_{+x} - \sigma^R_{-x}}{\sigma^R_{+x} + \sigma^R_{-x}}$$

Mainz Microtron MAMI



Major facility upgrade:

- Upgraded accelerator.
- Upgraded detectors.
- New frozen spin target.

“Ultimate” polarized observables laboratory:

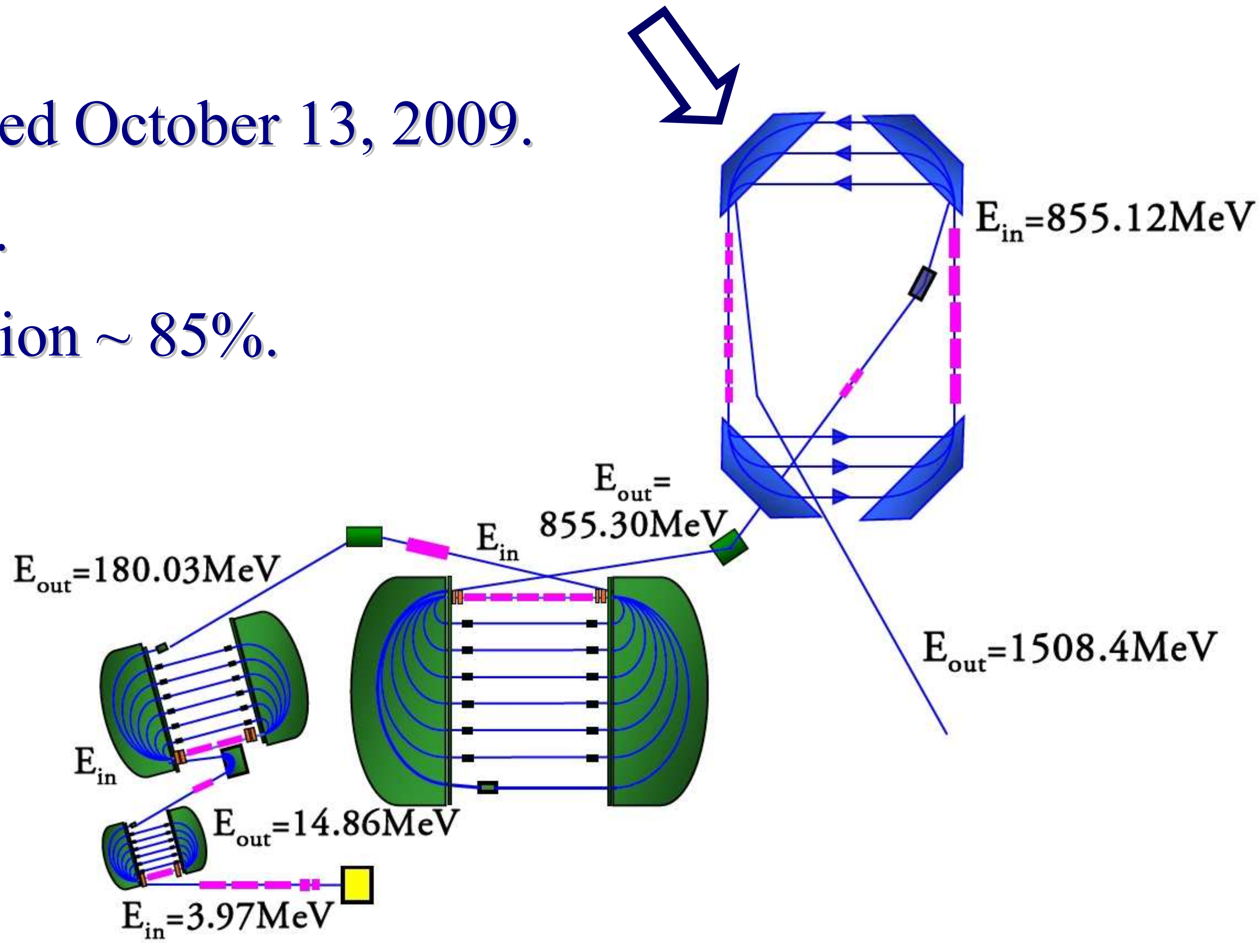
→ polarized beam.
→ polarized target.
→ recoil polarization.

Nearly 4π Detector Coverage.

Mainz Microtron MAMI
Accelerator Complex

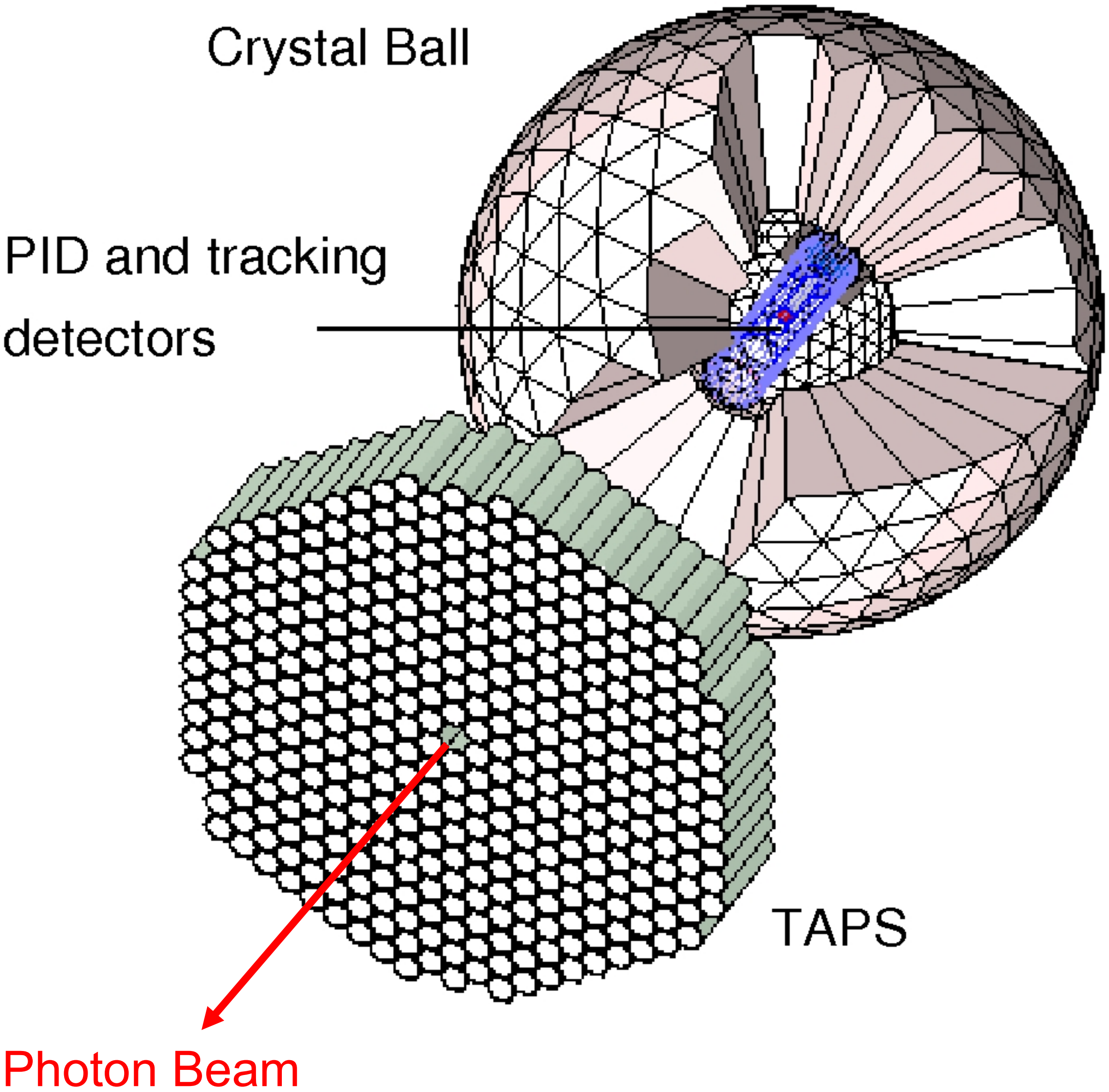
New MAMI-C Accelerator

- 1604 MeV achieved October 13, 2009.
- Current ≤ 100 μA.
- Electron Polarization ~ 85%.



A2 Collaboration JOHANNES GUTENBERG UNIVERSITÄT MAINZ

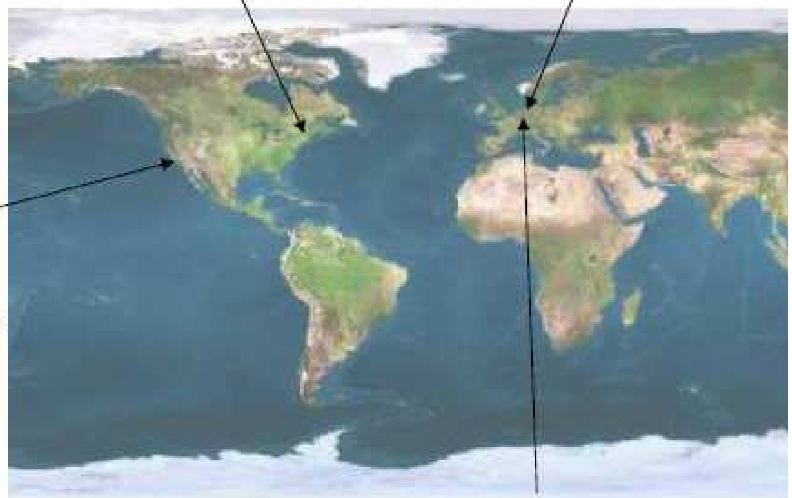
Nearly 4π Solid Angle Detector Coverage

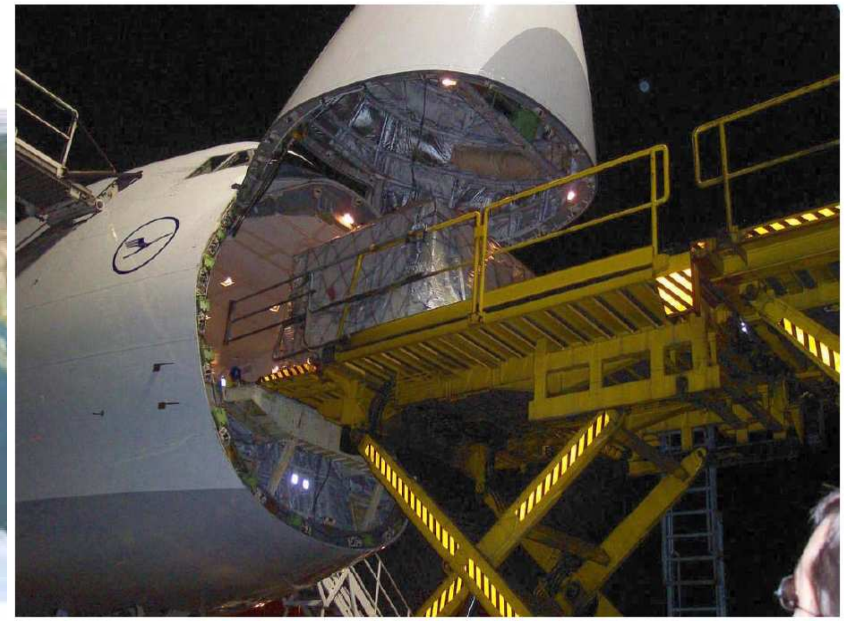


- 672 NaI(Tl) in CB
- ➔ 384 BaF2 in TAPS
- ➔ 24 plastics in PID
- ➔ 384 plastics in TAPS veto
- ➔ 320 strips in MWPC
- ➔ 480 wires in MWPC

- Gives:
- ➔ Energy
- ➔ Time
- ➔ Position
- ➔ Particle Type

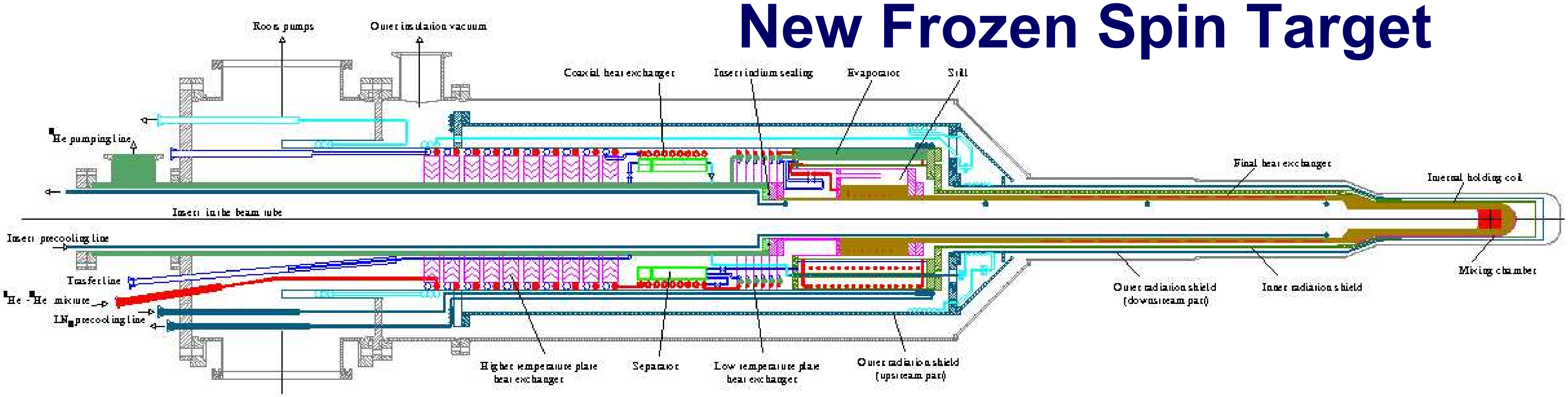
Crystal Ball Detector Arrival at Frankfurt Airport

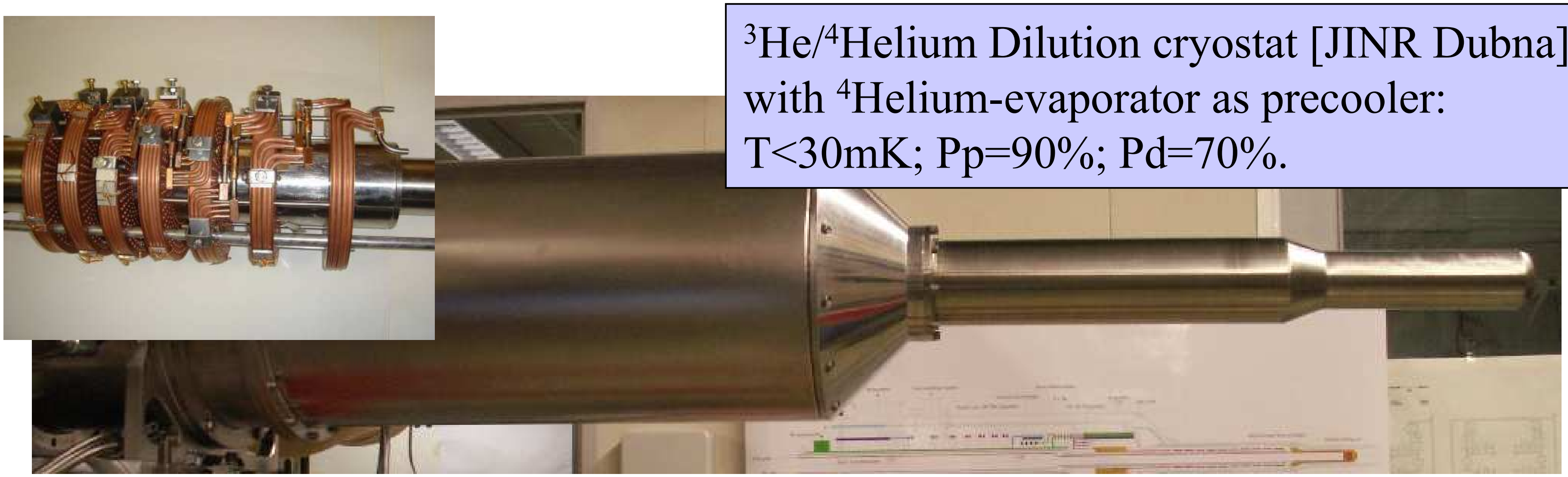




- Accurate separation of final states → good detector resolution.
- Sensitivity to small σ processes → 4π detector acceptance, large γ flux.
- Access to polarization observables → polarized beam, target, recoil.

New Frozen Spin Target

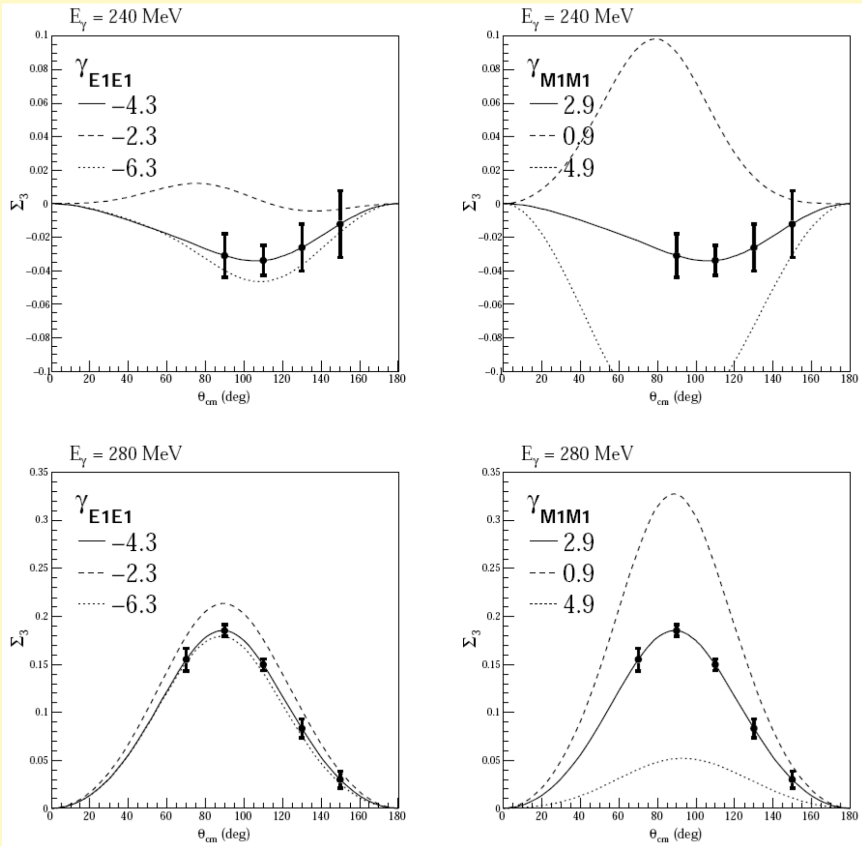




^{3}He/^{4}Helium Dilution cryostat [JINR Dubna] with ^{4}Helium-evaporator as precooler: T<30mK; Pp=90%; Pd=70%.

- Uses DNP to achieve ~ 90 % proton, 80 % deuteron, 50% neutron pol.
- Needs: Horiz. Dilution cryostat, polarizing magnet, microwave, NMR
- Two holding coils: solenoid → longitudinal, saddle coil → transverse

Predicted Spin Polarizability Sensitivity



$$\Sigma_3 = \frac{\sigma^{\parallel} - \sigma^{\perp}}{\sigma^{\parallel} + \sigma^{\perp}}$$

- ◆Linearly polarized photons, parallel and perpendicular to the scattering plane, unpolarized target.
- ◆100 hr. measurement.
- ◆To run in phases over next ~2 yrs.

- Curves from:
  - B. Pasquini, D. Drechsel, M. Vanderhaeghen, PRC **76** 015203 (2007).
  - B. Pasquini, D. Drechsel, M. Vanderhaeghen, Phys. Rept. **378** 99 (2003).

Summary

The past decade has seen good progress in developing a quantitative understanding of the electromagnetic structure of the proton.

Much credit goes to technical advances in:

→ Intense polarized electron beam delivery.

→ Improved detectors, recoil polarimetry techniques.

→ Frozen spin polarized targets.

QCD has shown itself to be a much richer field than originally expected as a result of the improved level of precision of the data.

In the next few years, we look forward to a much more detailed understanding of the proton's electromagnetic and spin structure.