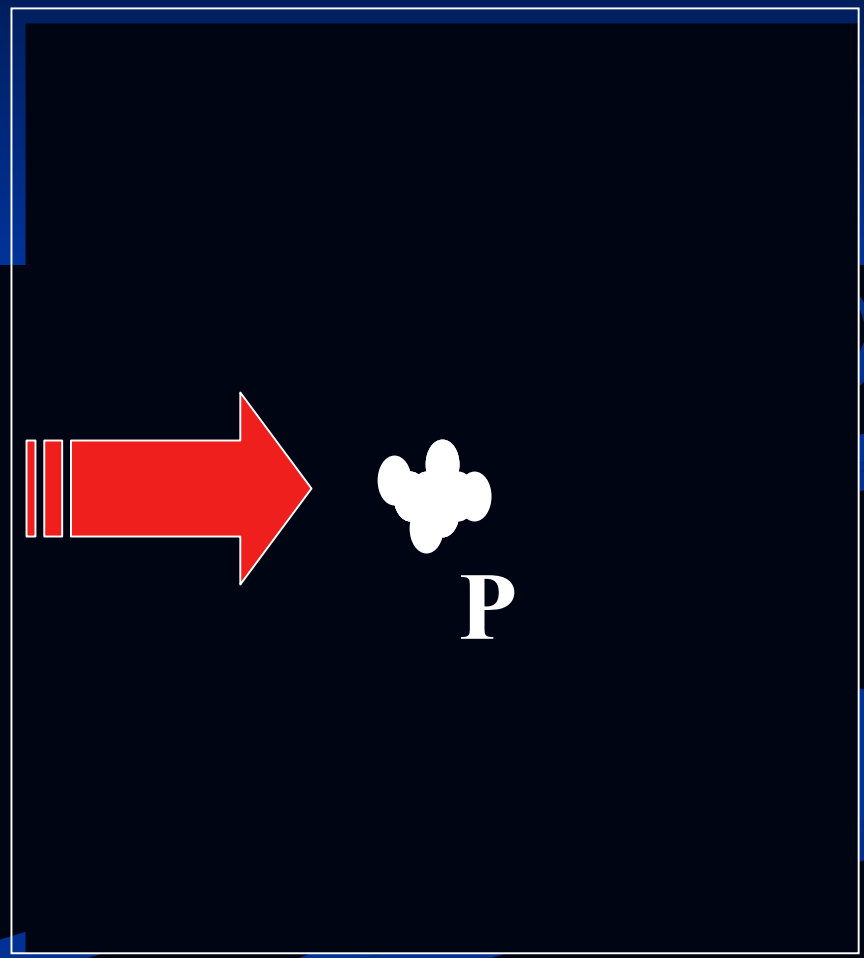

”How We Came
to Understand
Confinement”

The Ubiquitous Little Proton

- From Chemistry, the "Hydrogen Ion"
- Tastes rather sour; "lemonade"
- The small round dot of Ernest Rutherford



Form Factors, More than Fudge Factors

A form factor is a GENERAL expansion…

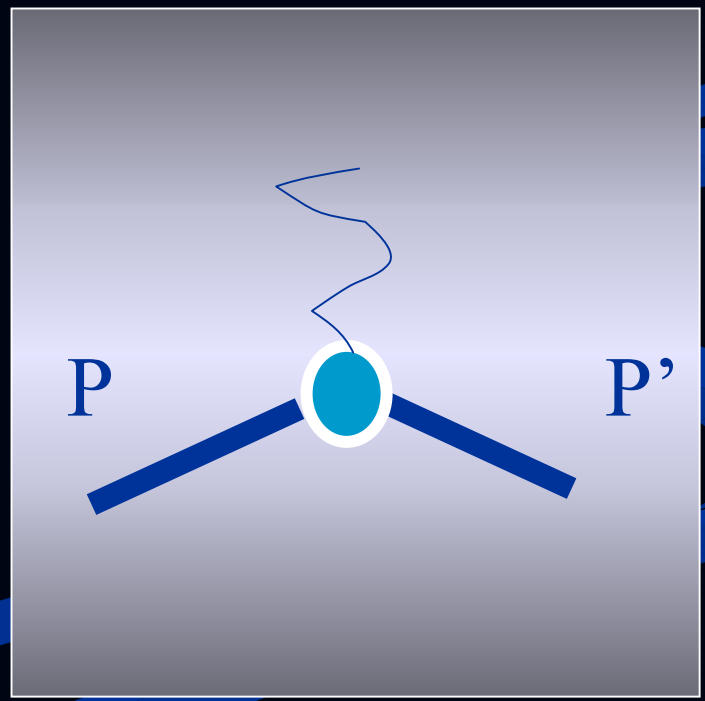
$$M = \sum_{\alpha}^{All} M_{\alpha} = form - factors$$

Sum over all possible irreps of relevant groups!

What Rosenbluth Did

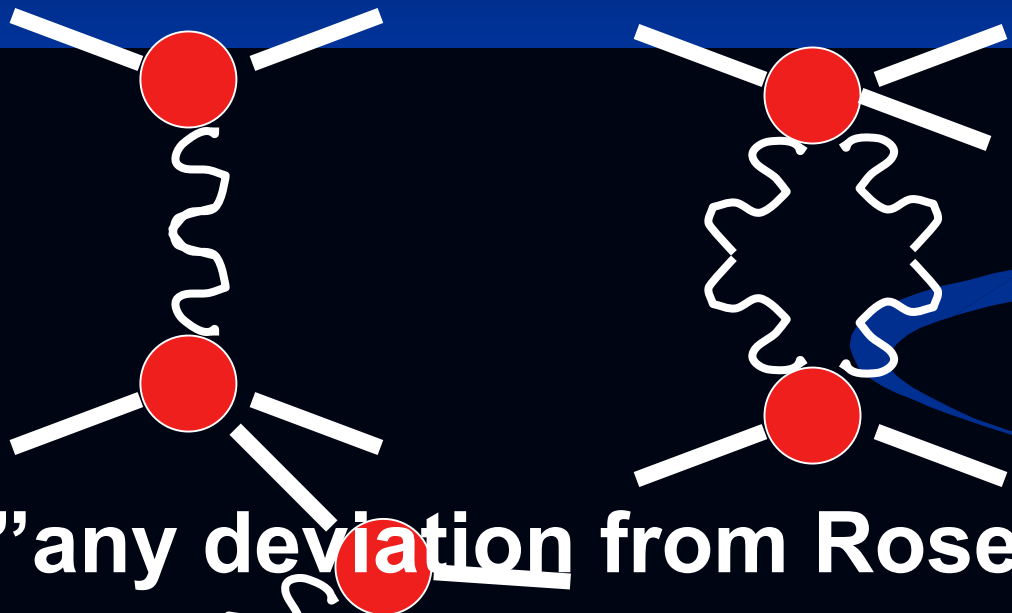
$$\langle p',s'|J^{\mu}_{EM}|ps\rangle = \bar{u}(p',s')\left[\, e\,\gamma^{\mu}F_1(Q^2) + i\frac{\sigma^{\mu\nu}}{2m}e\kappa F_2(Q^2)\,\right] u(p,s)$$

- Lorentz symmetry:
  (1/2,0)+(0,1/2)
  ->(1/2,1/2)
- P, T
- Gauge Singlet
- Chirality +, -



Form factors are *observable* matrix elements

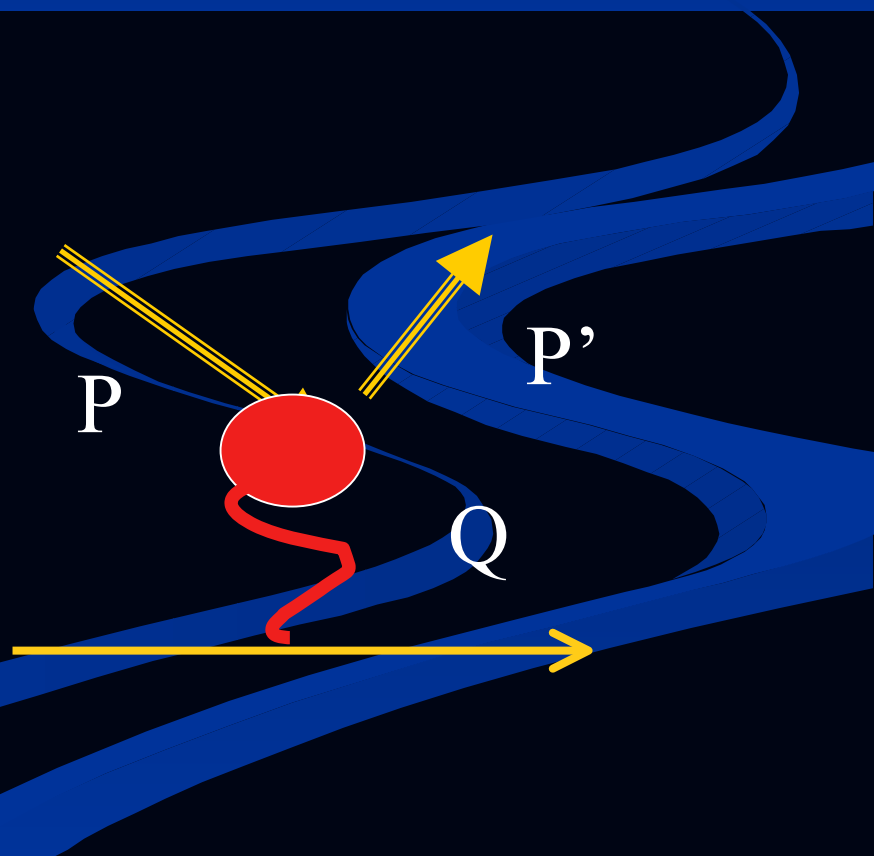
- Once measured, use it forever.
- Know your operator!!



…”any deviation from Rosenbluth cannot be attributed to our ignorance of the strong coupling..

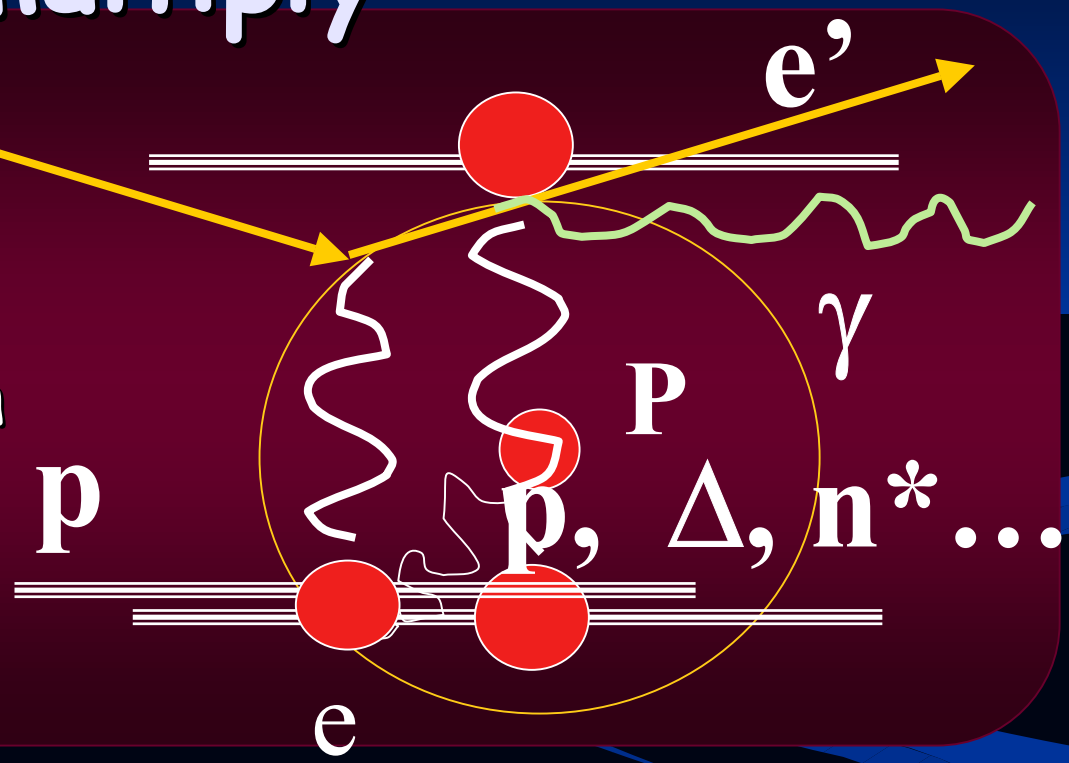
Matrix Elements and Factorization

- Once a matrix element is measured, you must get the same value in a new measurement



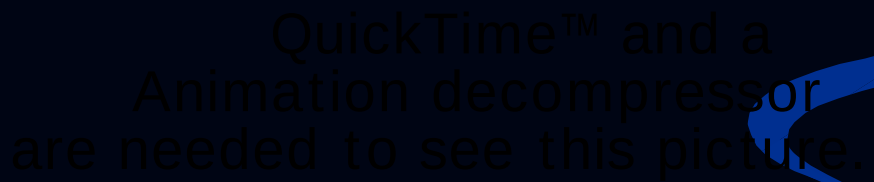
Factorization: amplitudes multiply

- It is the same matrix element perturbatively measured again in atomic physics
- **It is the same matrix element perturbatively measured again perturbatively in EM part of pp scattering**



…do not neglect resonant interference

quantum mechanics is more than diagrams



Interpretation ca 1960

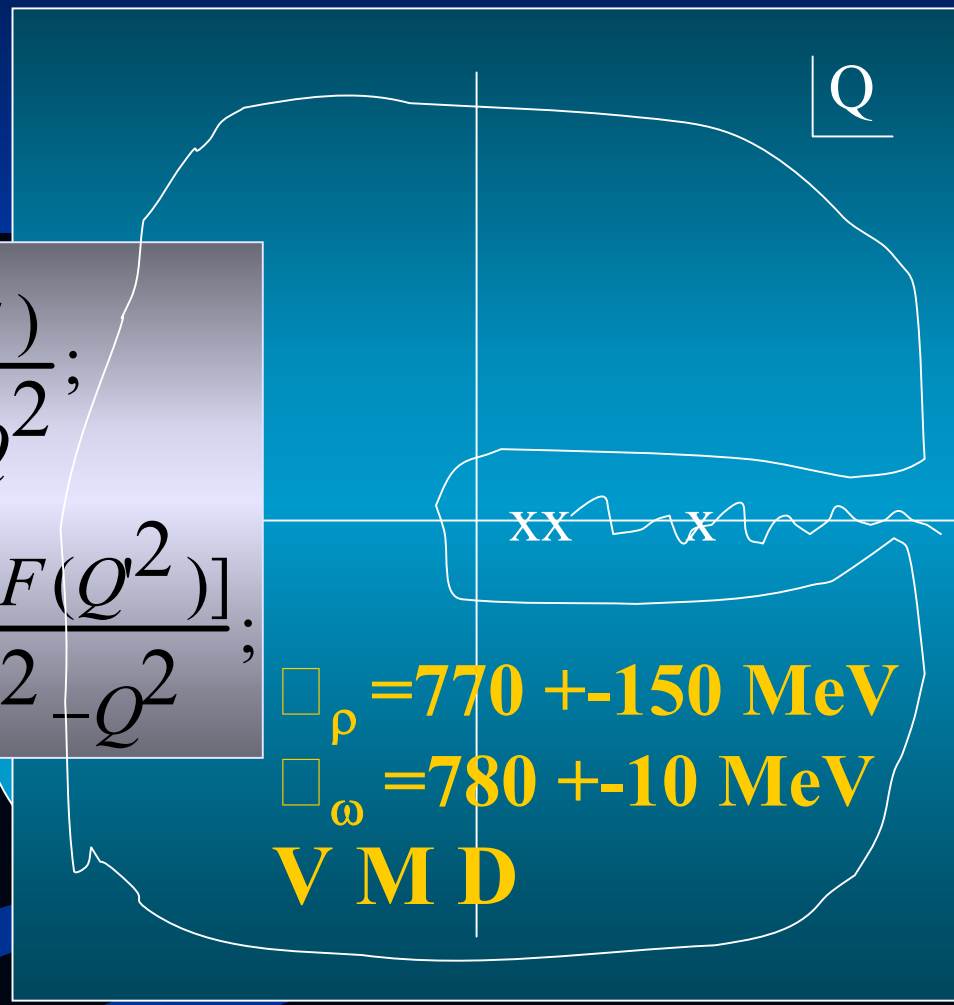
- Assuming an instantaneous point-like probe, static charge distribution $\rho(x)$,

$$G_E(Q^2) = \int d^3x \;\; \rho(\vec{x}) \;\; e^{i\vec{Q}\cdot\vec{x}}$$

Analyticity, i.e. Causality

$$F(Q^2) = \frac{1}{2\pi i}\oint dQ'^2 \frac{F(Q'^2)}{Q'^2 - Q^2};$$

$$\mathrm{Re}[F(Q^2)] = \frac{1}{\pi} P\int dQ'^2 \frac{\mathrm{Im}[F(Q'^2)]}{Q'^2 - Q^2};$$



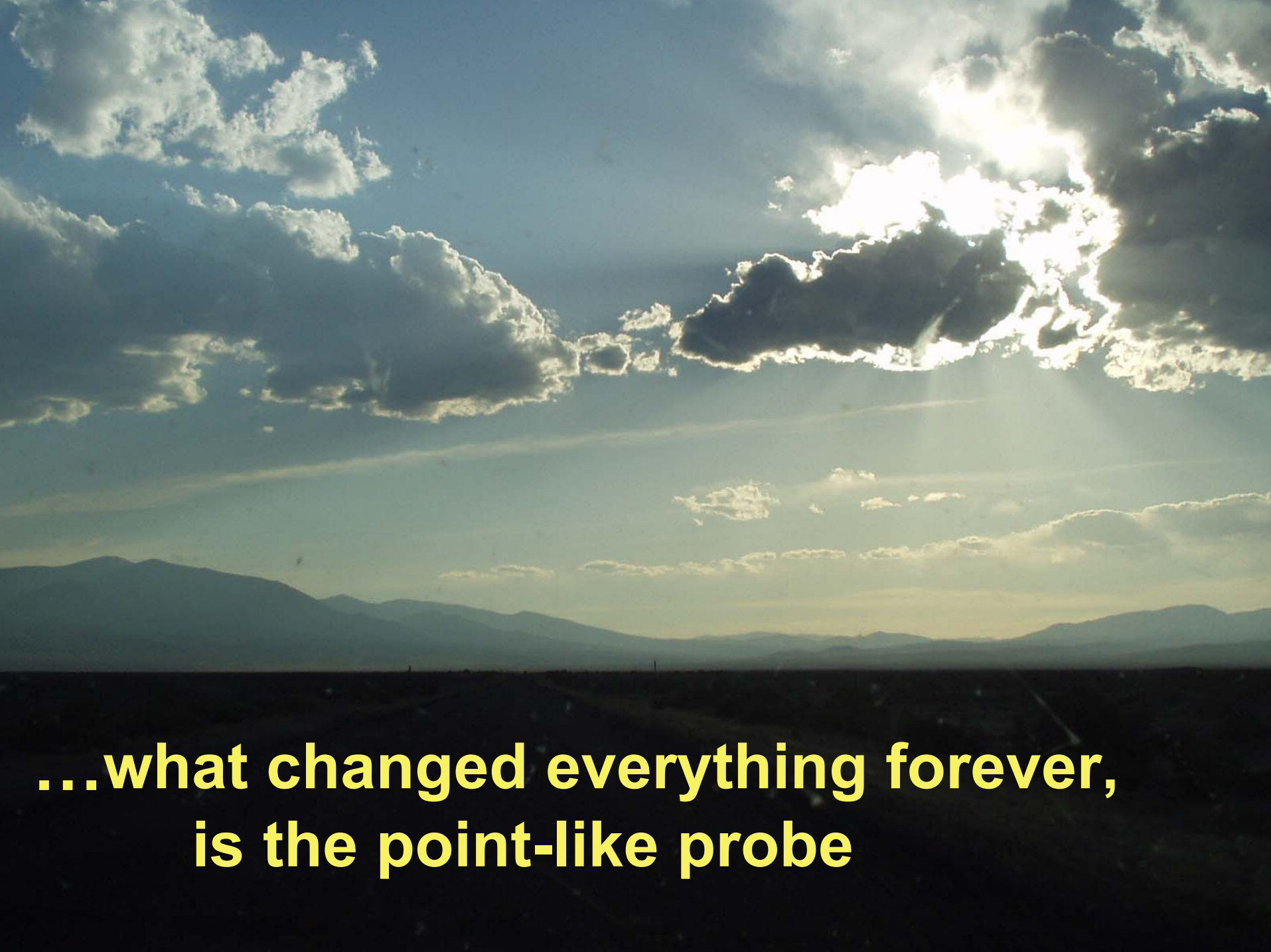
$\square_\rho$ =770 +-150 MeV

$\square_\omega$ =780 +-10 MeV

V M D

THUS, an internally self-consistent theory existed already 40 years ago

…which has nearly faded into oblivion

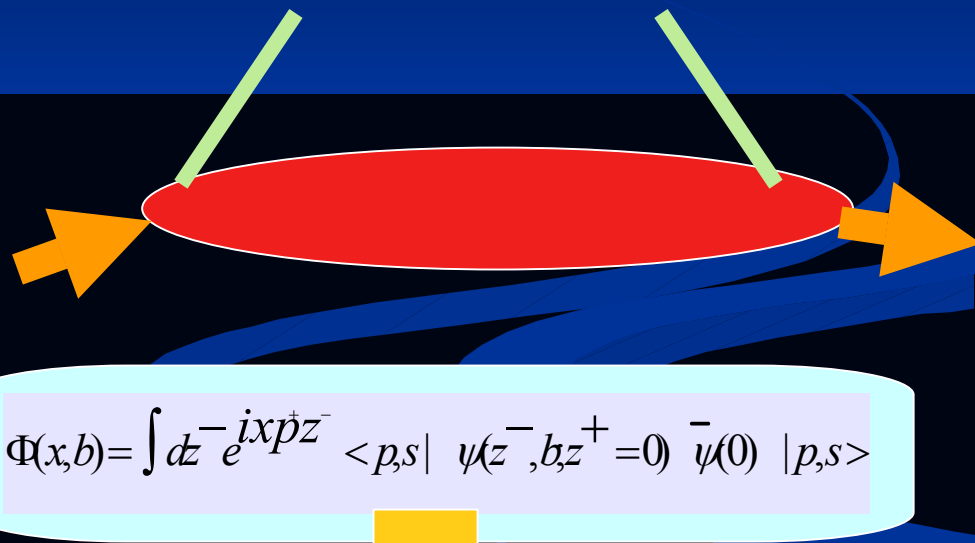

…what changed everything forever,
is the point-like probe

Factorization and form factors of quarks

$$\Phi(x,b) = \int dz^- e^{-ixP^+z^-} \langle p,s| \bar{\psi}(z^-,b_\perp,z^+=0)\, \psi(0)\, |p,s\rangle$$

Parton distributions are integrated form factors

- Forward scattering is integrated over transverse separation b
- Functions of Feynman x



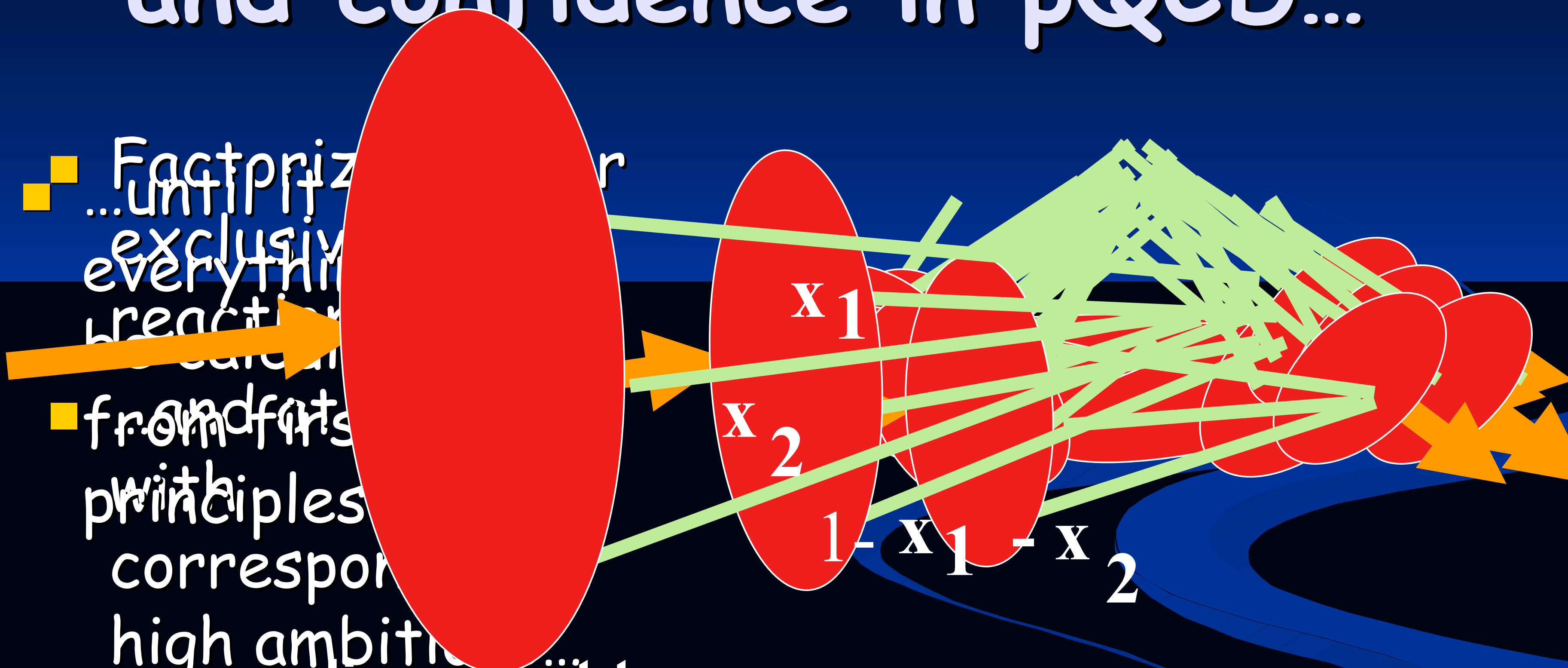
$$\Phi(x,b) = \int dz^- e^{ixp^+z^-} \langle p,s| \; \psi(z^-,b,z^+=0) \; \bar{\psi}(0) \; |p,s\rangle$$

$$q(x,Q^2) = \Phi(x,b^2 \approx 1/Q^2)$$

An era of great discoveries and confidence in pQCD…

- Factoriz… r exclusiv… reactio… andfat… with… correspon… high ambitio…

…until it everythi… be calcul… from firs… principles…



….and needing next to no information

about the hadrons themselves …

(Fade to black)

What Jlab Taught Us

- Magnificent
- Structure functions in Resonance Region
- No Longer in Denial

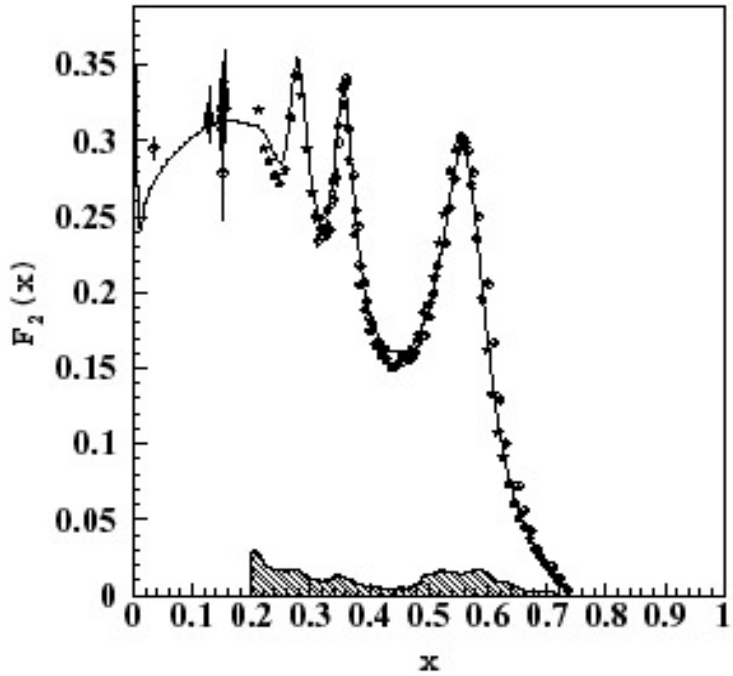


FIG. 6: Structure function $F_2(x, Q^2)$ at $Q^2 = 0.775$ GeV^2: stars represent experimental data obtained in the present analysis with systematic errors indicated by the hatched area, empty circles show data from previous experiments [7, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44] and the solid line represents the parametrization from Ref. [14].

Osipenko et al '03

N->D Transition versus Q^2

Frolov 99
Stoler 02
and see

Carlson

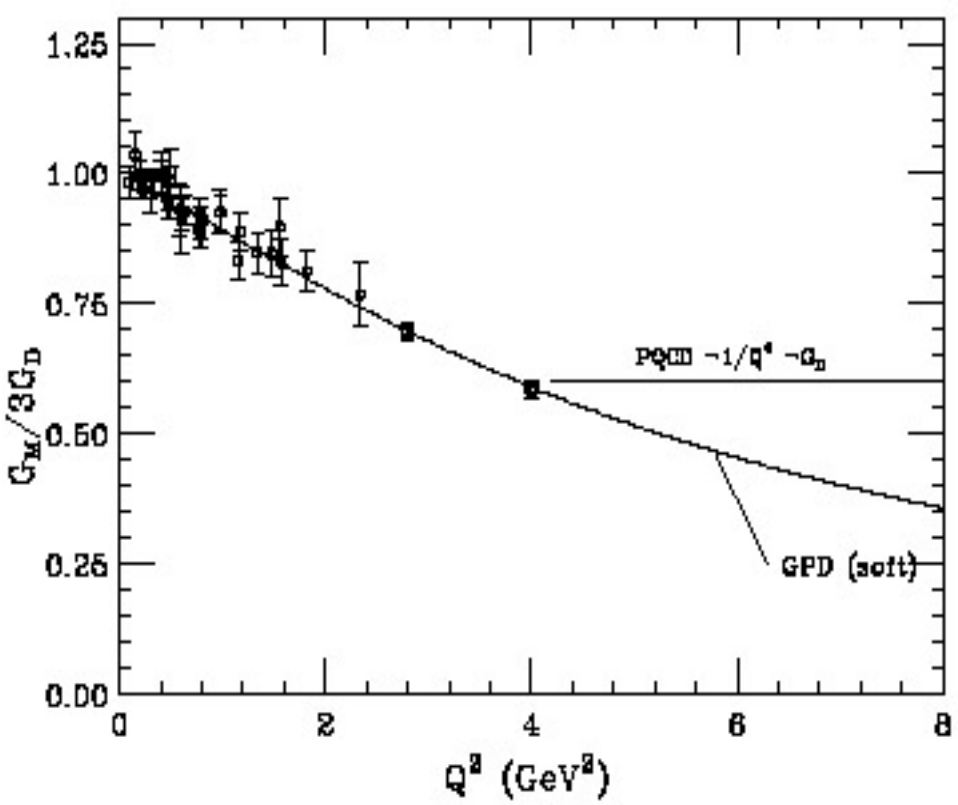


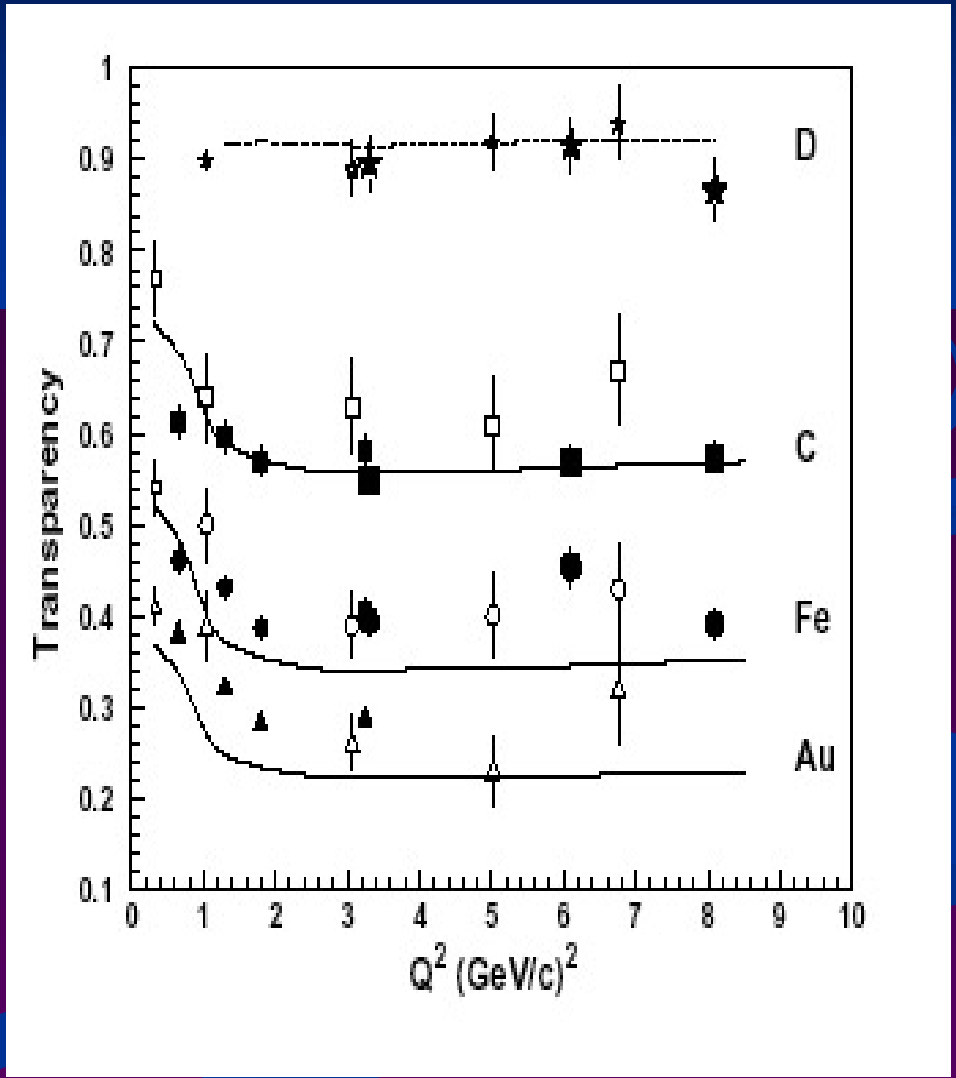
Figure 12: The $N \to \Delta$ magnetic form factor $G_M^*(Q^2)$ relative to the dipole $G_D = 3/(1+0.71Q^2)^2$. The data points for Q^2 below 2.8 GeV^2 are from a compilation of ref. [26]. Those at $Q^2 = 2.8$ and 4.0 GeV^2 are recent JLab data [11]. The horizontal line reflects the $1/Q^4$ asymptotic PQCD shape, and the curve denoted GPD is discussed in the text.

JLAB delivers…

- Color transparency
- A =10-100
- A (e,e'p) matrix elements are form factors!!

Garrow et al '01

Dutta et al '03



Proton QF2/F1 aversus Q^2

What Jlab Taught Us

- Just as often wrong as right
- It is not the fault of "pQCD"

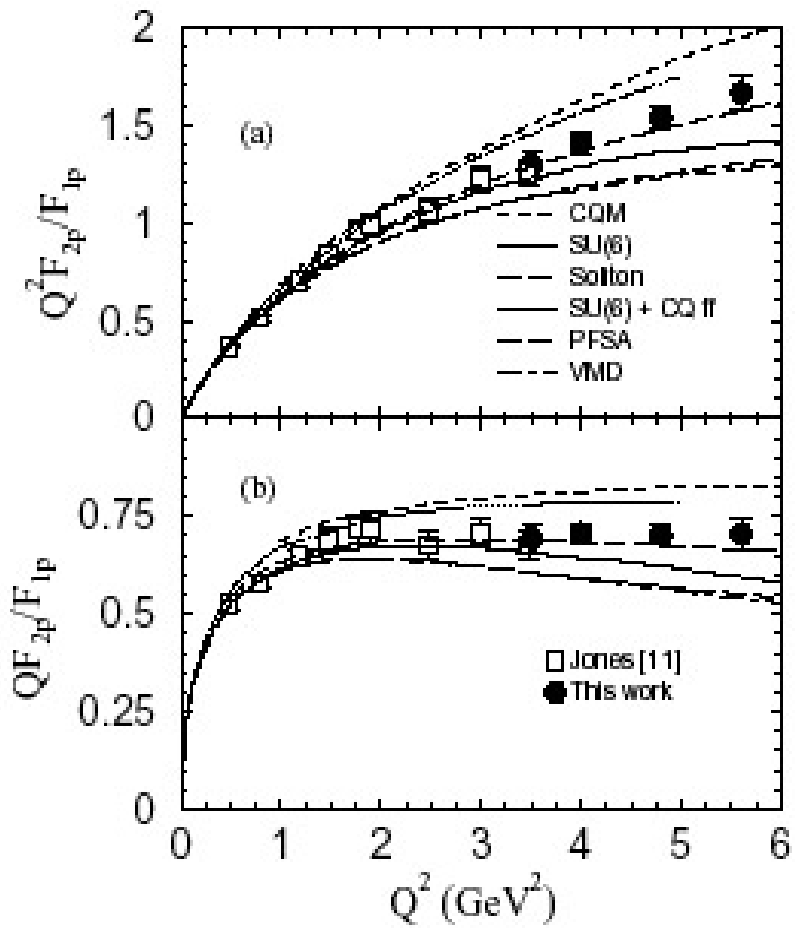


FIG. 4. Same legend as Fig. 3, for (a) Q^2F_{2p}/F_{1p} and (b) QF_{2p}/F_{1p}.

Gayou et al PRL '02

Jones et al PRL '01

Wha

- Explain?

Walker ‘94
Arrington’ 03

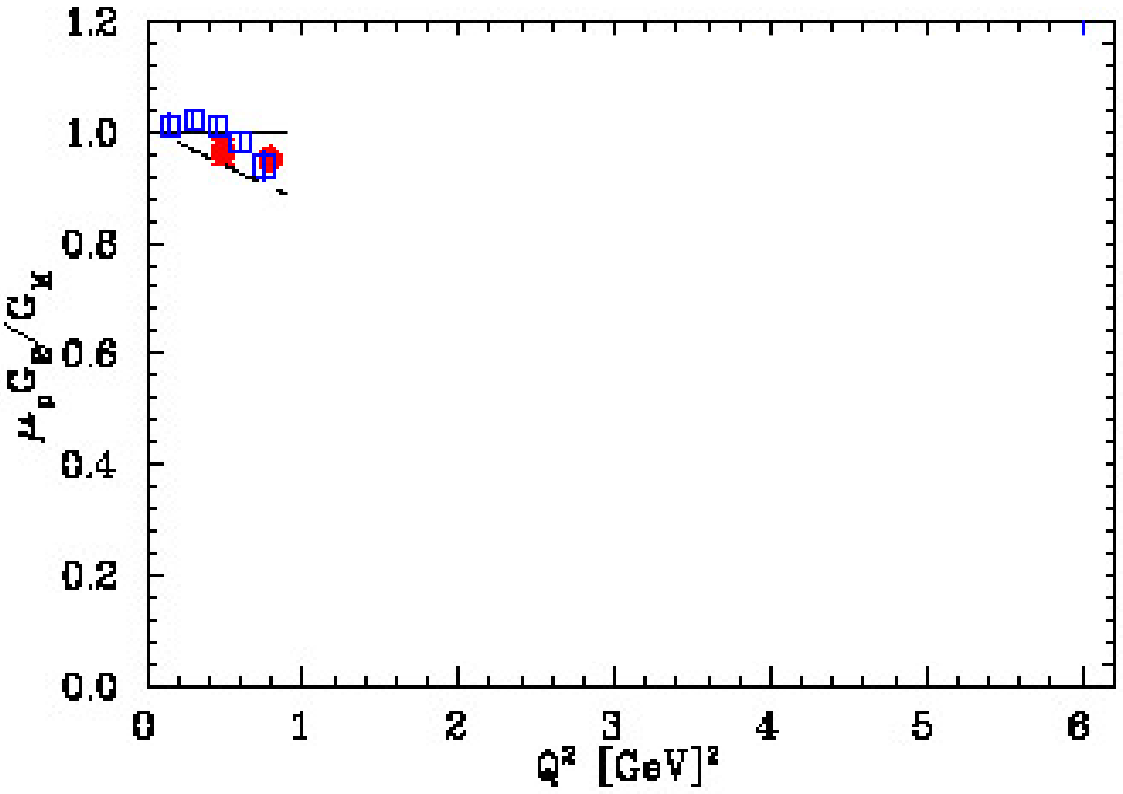


FIG. 1: Ratio of electric to magnetic form factor as extracted by Rosenbluth measurements (hollow squares) and from the JLab measurements of recoil polarization (solid circles). The dashed line is the fit to the polarization transfer data.

Read carefully…

- Combined Fit $\chi 2/dof \sim 1$

Arrington' 03

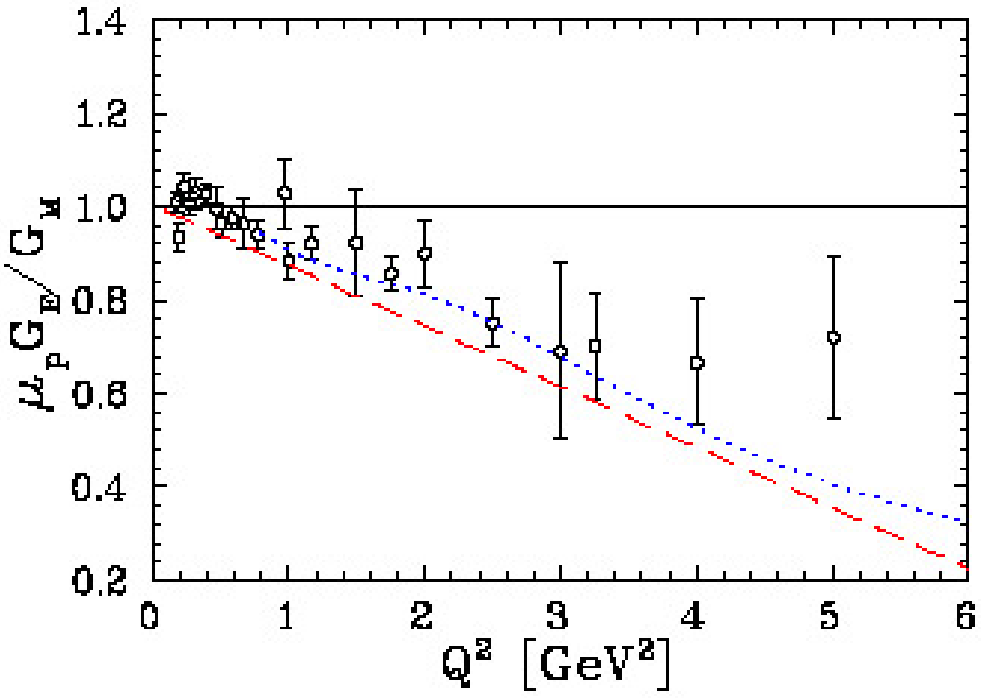
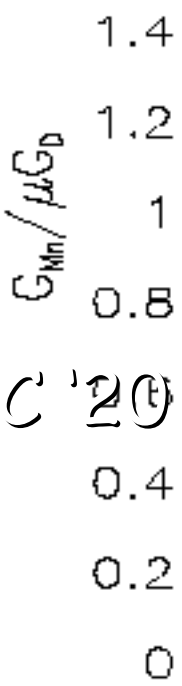


FIG. 10: Ratio of electric to magnetic form factor as determined from combined fit of cross section and polarization transfer data. The dotted line is the result of the fit, and the circles are the results from the direct L-T separations using the normalization factors determined from the global fit.

G_M^n / ^{4}He DIS

- 12 GeV
- Xu et al, PRC '20
- (M. Jones et al , private comm.)



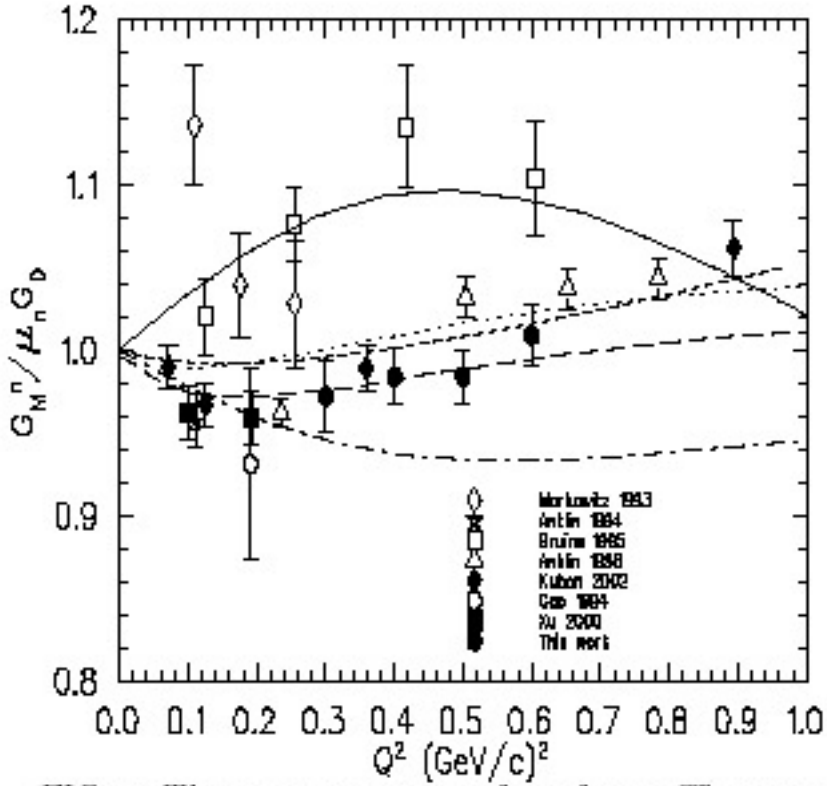


FIG. 2. The neutron magnetic form factor G_M^n in units of the standard dipole form factor $(1+Q^2/0.71)^{-2}$, at Q^2 values of 0.3 to 0.6 $(\mathrm{GeV/c})^2$ extracted using PWIA calculations. Also shown are published measurements since 1990 and a few selected theoretical models. The Q^2 points of Anklin 94 [4] and Gao 94 [8] have been shifted slightly for clarity. The solid curve is a recent cloudy bag model calculation [28], the long dashed curve is a recent calculation based on a fit of the proton data using dispersion theory arguments [29], and the dotted curve is a recent analysis based on the vector meson dominance model [30]. The dashed curve is a skyrme/soliton model calculation [31], and the dash-dotted curve is a relativistic quark model calculation [32].

Valence Models, Pretty Good

- Miller and Frank
- Agrees with pQCD that F2/F1 due to quark
  Orbital Angular Momentum, aka "OAM"

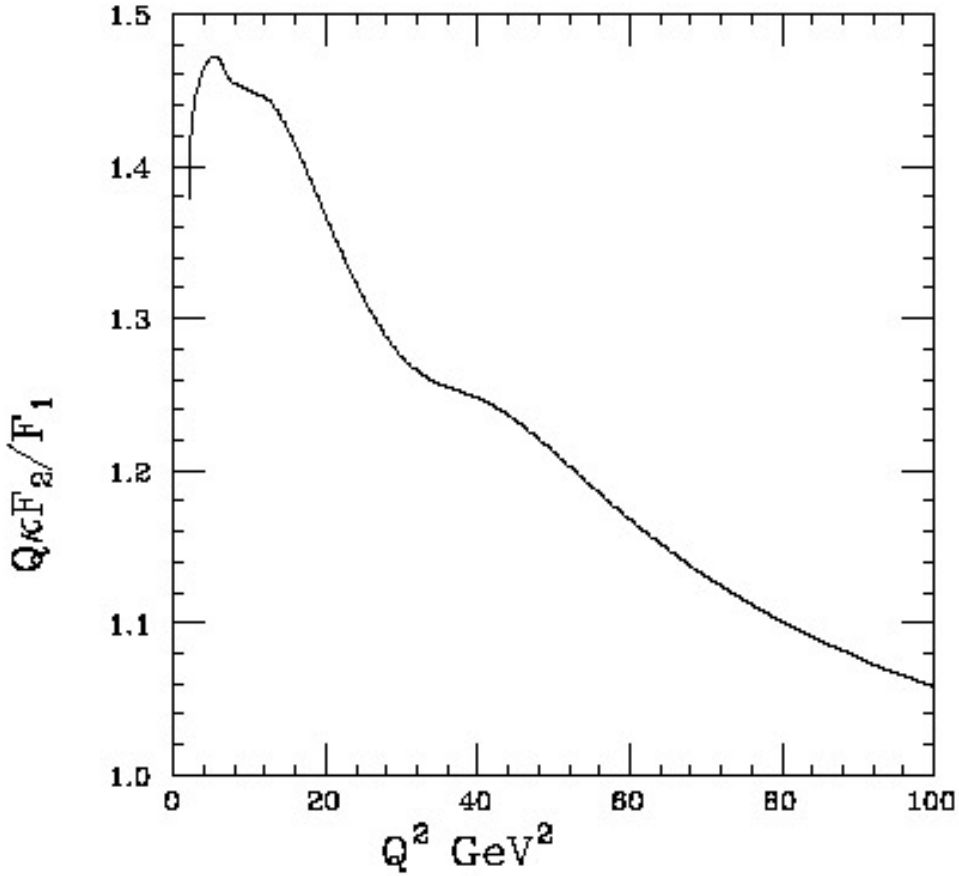
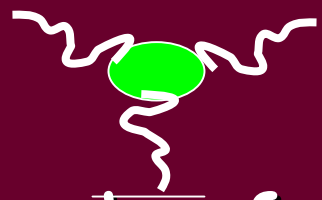


FIG. 7. High Q^2 behavior of $Q\kappa F_2/F_1$

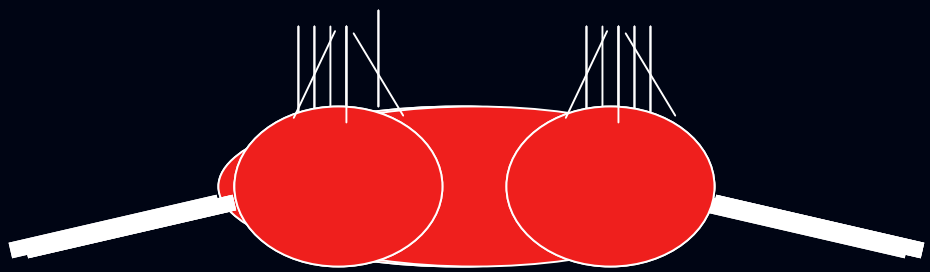
Every theorist had to take a pledge to reform

- "perturbaholics anonymous"



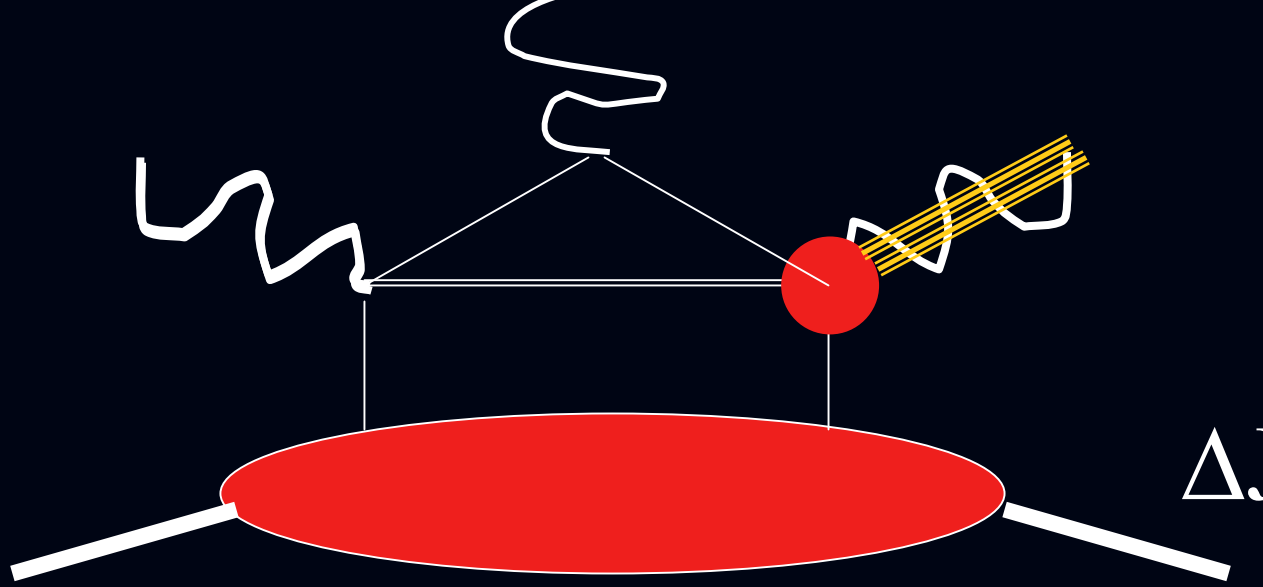
- It is not the fault of "pQCD"

How it works in pQCD



- Ambition: Low
- Predictability: Low
- Safety: High
- Model Dependence: Very High

GPD's are Unobservable



$\Delta J_{\perp} = 1$

...yet capable of pQCD predictions

yet capable of pQCD predictions

predictions perfect for finding OAM

Probably the Proton is not a small ROUND dot…

$$M(b_T) = \int d^2 k_T \; e^{i\vec{k}_T \cdot \vec{b}_T} M(k_T)$$

$$= \sum_m e^{im\phi} \; M_m(b)$$

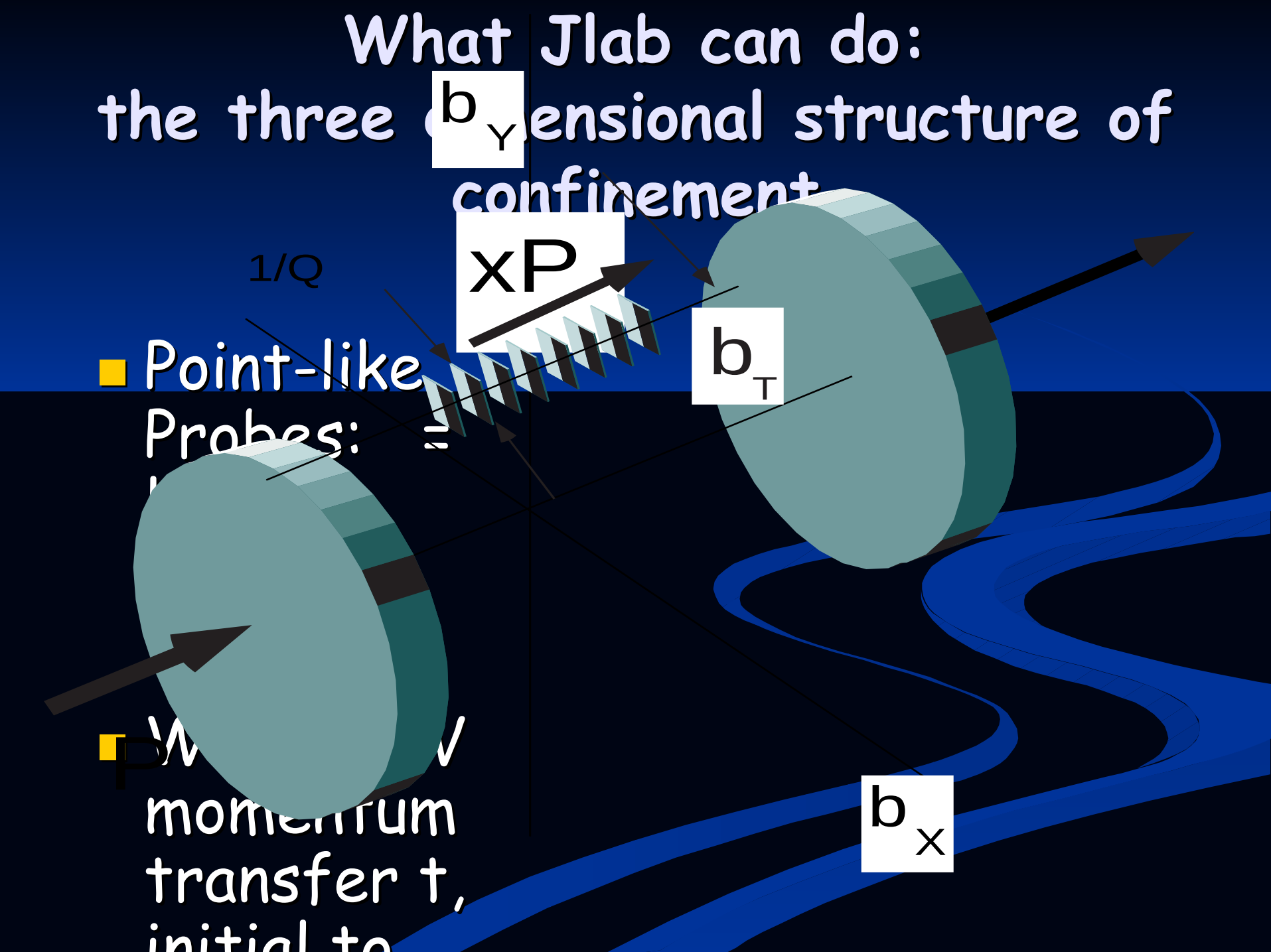
- Orbital Angular Momentum: light cone SO(2) $|m; J^2\rangle$

Ask not how big your theory is.. Ask what it tells us about confinement

- No one scheme *is supposed to* predict everything
- **An infinite number of factorizations**

- It's (about) the 3-Dimensional structure of hadrons

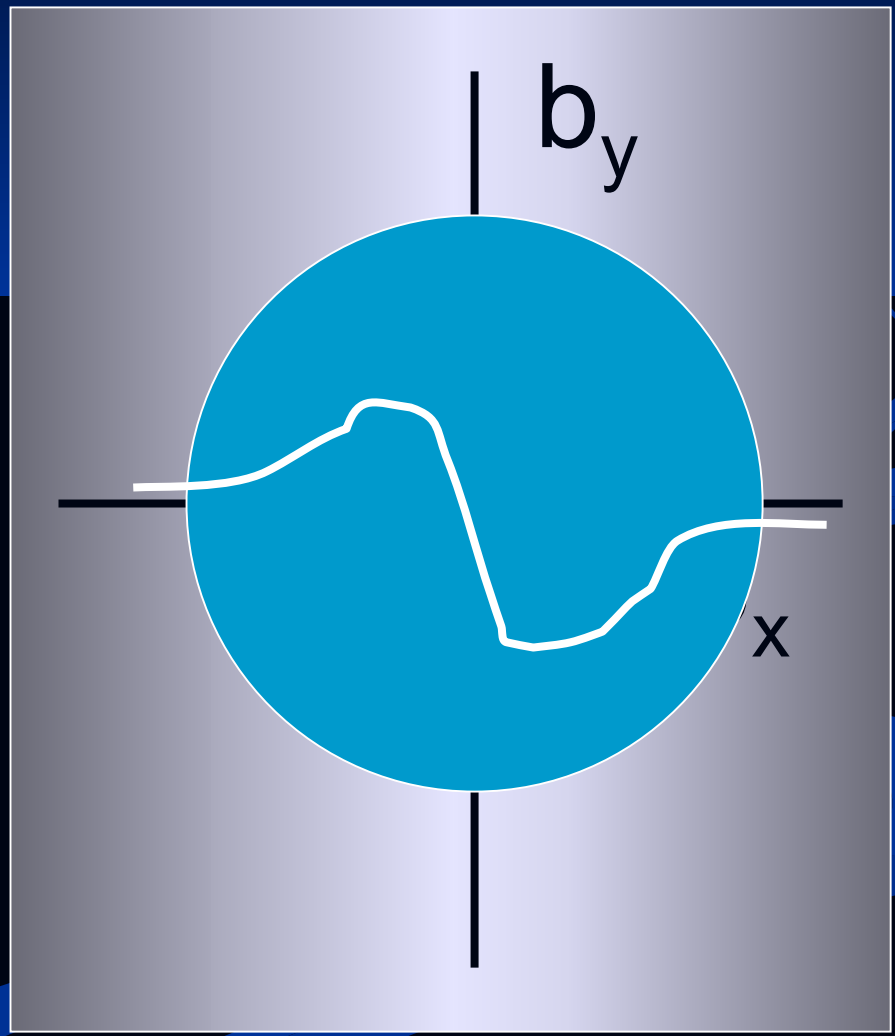
What Jlab can do: the three dimensional structure of confinement



- Point-like Probes:
- momentum transfer t,

Deeply Virtual Exclusives

- The ability to isolate the transverse, *Lorentz invariant,* structure of hadrons



How the transverse coordinate Works

$$M(b_T) = \int d^2\Delta \; e^{i\vec{p}\cdot\vec{\Delta}} \langle p,s| T[J(Q)J(k)]|p+\Delta,s'\rangle$$

…a non-relativistic acting sub-world

of light cone geometry

Confinement is observable

- The interior of a "quantum black hole of color"

  …confinement!

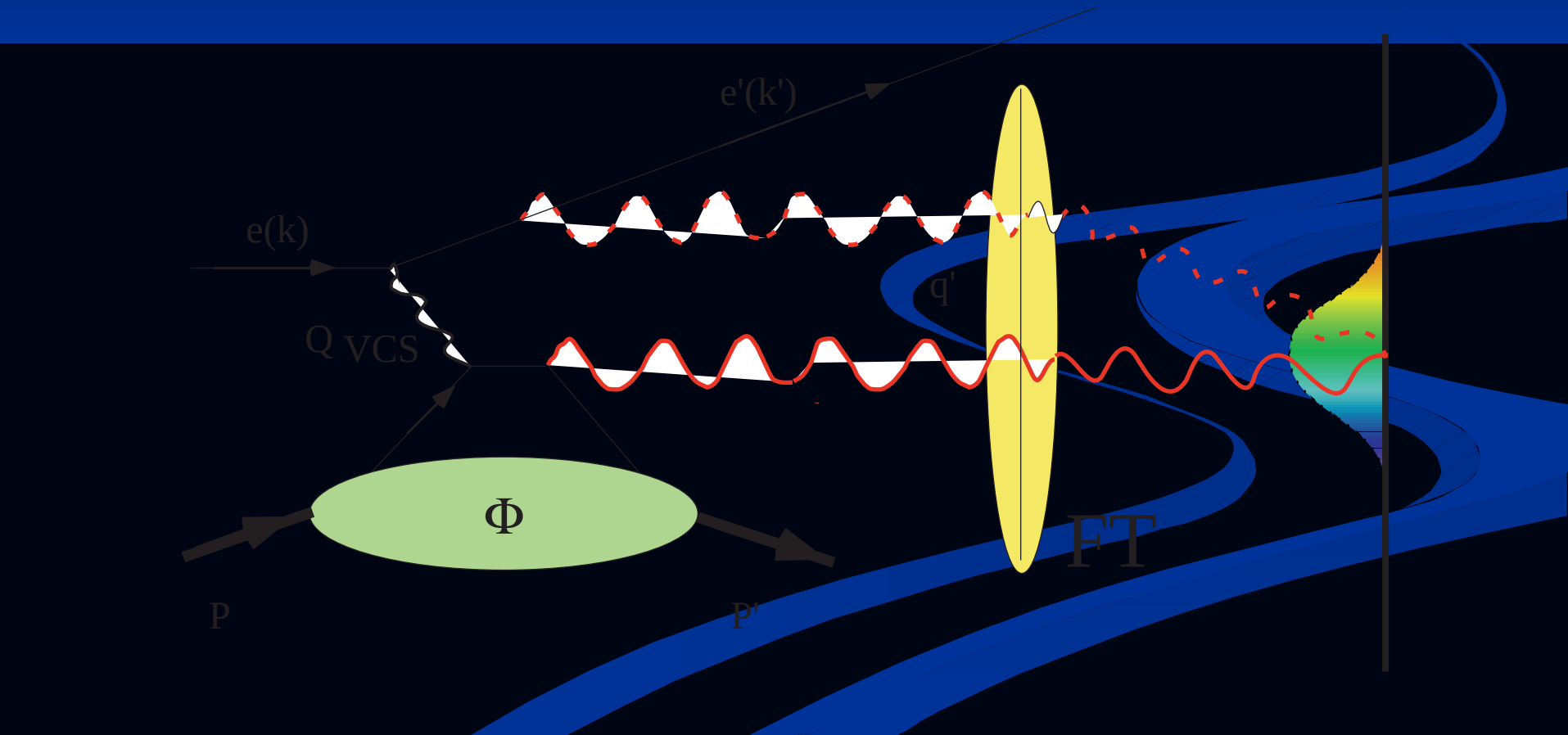
Physics based on *observables*

- GPD's, while exciting, are unobservable
- *Observable* matrix elements maintain the priority

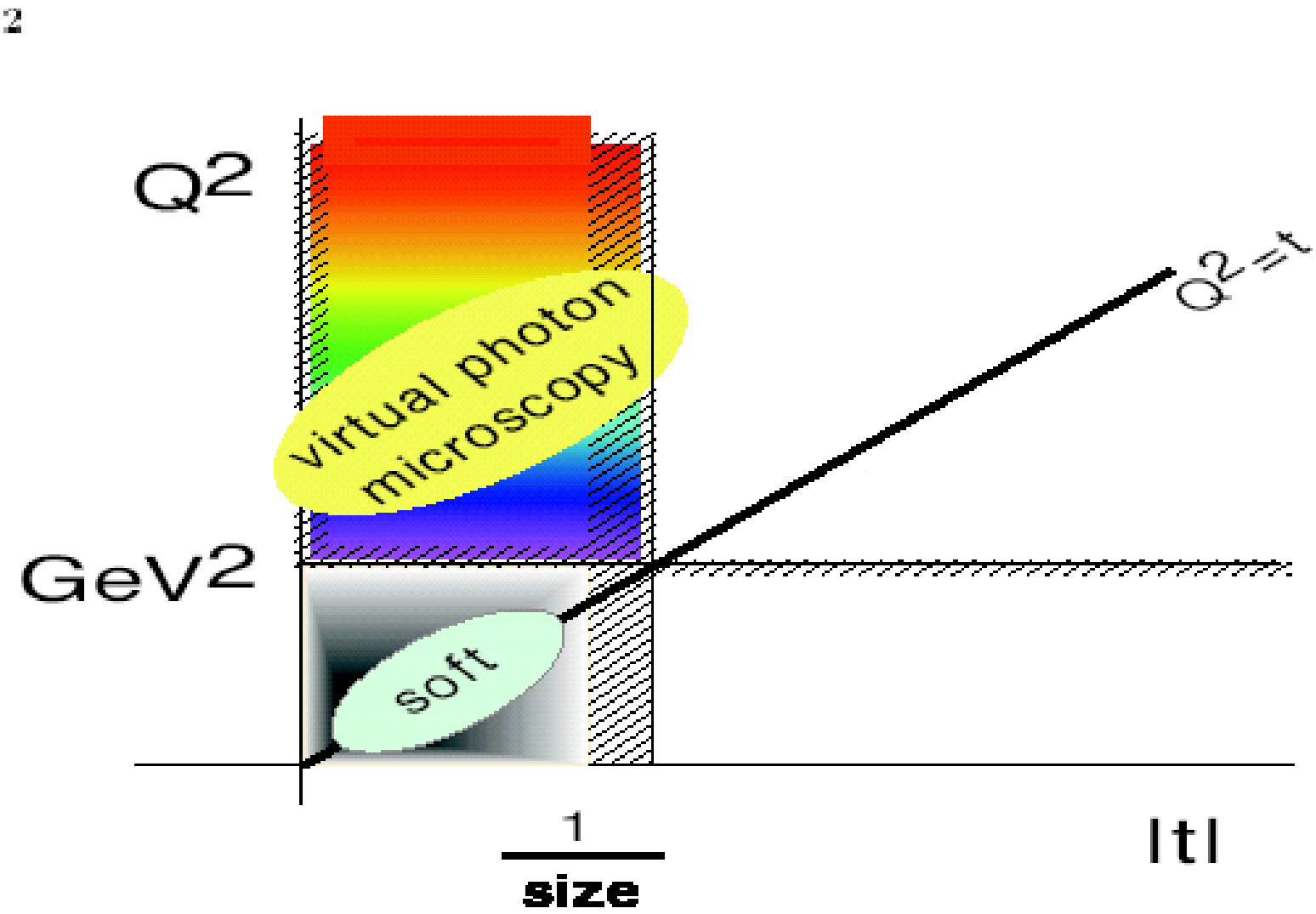
$$\Omega^{V} = \langle p,s| T\{J(z,b=\Delta_T=0)\, J(z',b=\Delta_T=0)\} |p',s'\rangle$$

Transverse Structure 100%

Observable



Method of observation



Deeply Virtual Exclusives

- DVET:Deeply Virtual Transitions !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
- DVEW: Deeply Virtual *semi* Electroweak

(Burkert, E93-050 Hall A)

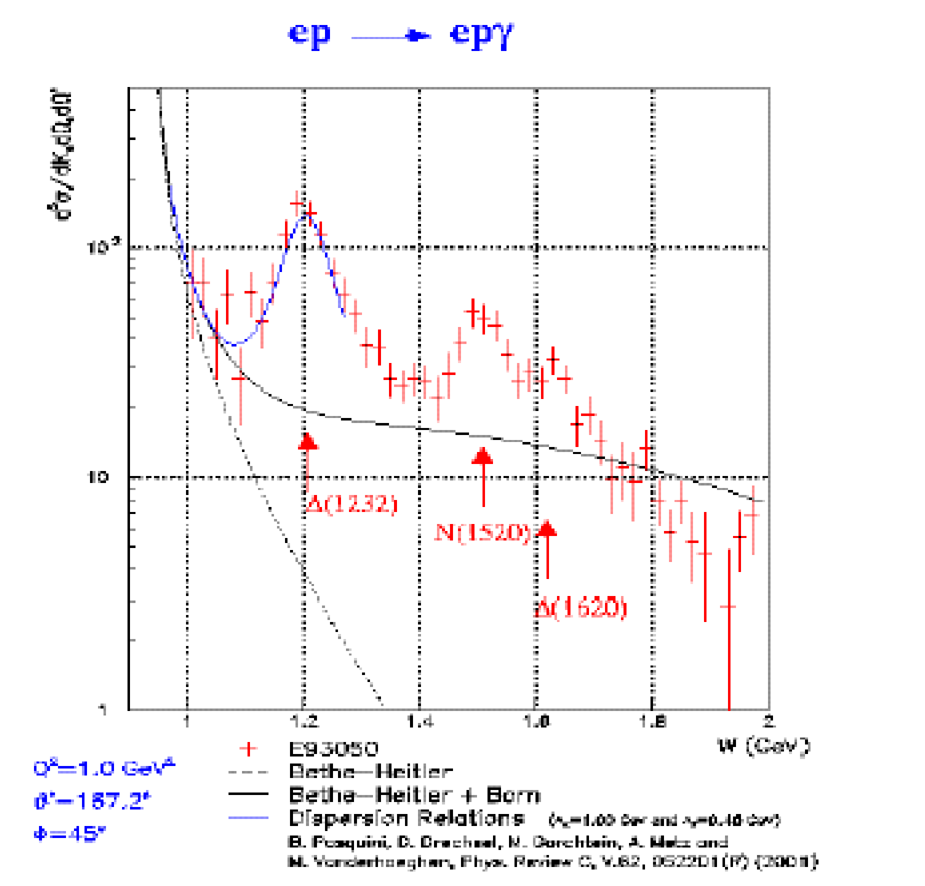
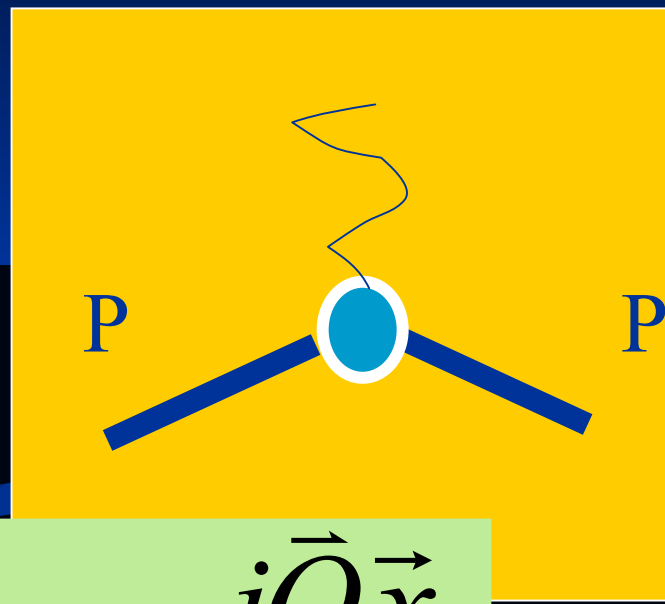


Fig. 10. Differential cross section for virtual Compton scattering at $Q^2 = 1$ GeV^2. The final state photon is in the backward direction relative to the virtual photon.

Interpretation Holds

- Assuming an instantaneous point-like *electroweak* probe,



$$G_{weak}(Q^2) = \int d^3x\ \rho_{weak}(\vec{x})\ e^{i\vec{Q}\cdot\vec{x}}$$

We share high-minded goals. Theorists are united:

JLAB-12 GeV

will measure the *confining three-dimensional structure of hadrons*

Theory and experiment in partnership

- JLAB- 12 GeV : the ultimate confinement explorer
- ENGAGE