Nuclear Physics School
25—29 June 2018

Three Dimensional Imaging of Protons, Neutrons, and Nuclei
양성자, 중성자 및 핵의 3 차원 이미징

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Introducing Physics Faculty at ODU www.odu.edu/physics

- Six Nuclear Experiment
- Six Nuclear/Particle Theory
- Four Accelerator Physics
- Three Atomic and Condensed Matter Theory
- Four Atomic, Molecular and Optical Experiment
- One Materials Science

➔ Graduate student applications welcome!

Outline

- The Challenge of Imaging
- Elastic and Deep Inelastic Scattering
- Two Solutions to the Challenge:
  - Deep Virtual Exclusive Scattering:
    - Spatial Imaging
  - Semi-Inclusive Deep Inelastic Scattering
    - Momentum Imaging (A. Deshpande)
- The Future
  - JLab @ 12 GeV
  - Ultra-peripheral Collisions at LHC
  - Electron Ion Collider (My Lecture #3)

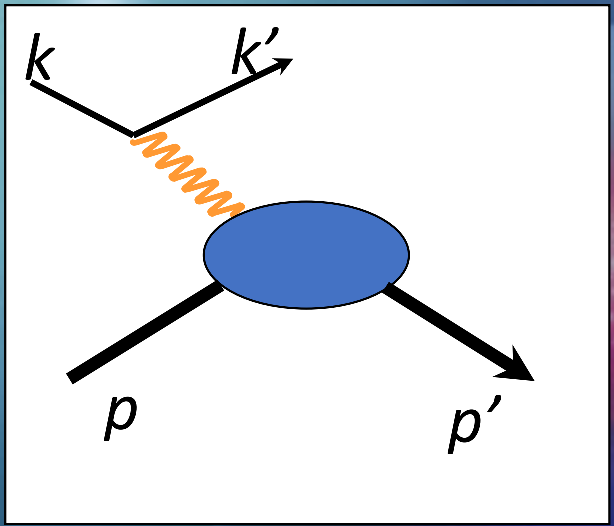
The Challenge

- The construction of an image implies that the object being observed is unaffected by the measurement
- The proton rms charge radius ~ 10^{-15} m (1 fm)
  - To image something this small requires that it absorb momenta of the order
    $pc > \hbar c/(1\text{ fm}) = 200$ MeV
  - But the proton mass $Mc^2 = 938$ MeV
  - Imaging the proton requires disturbing the proton
    - Is it even physically sensible to talk about imaging the proton?

Elastic Electron Scattering on the proton, 1950s – 2010s

- Wave equation $\Box A^{\mu} = j^{\mu}$
  - Interaction $\int dx A(x)\cdot J(x)$
- An electron makes a transition from momentum state ***k*** to ***k'***:
  - Current $j^{\mu}(q)$ generates a vector potential $A^{\mu}(x) \sim e^{-iq\cdot x} j^{\mu}(q)/q^2$
  - This vector potential then interacts with the current density $J^{\mu}(x)$ of the proton.

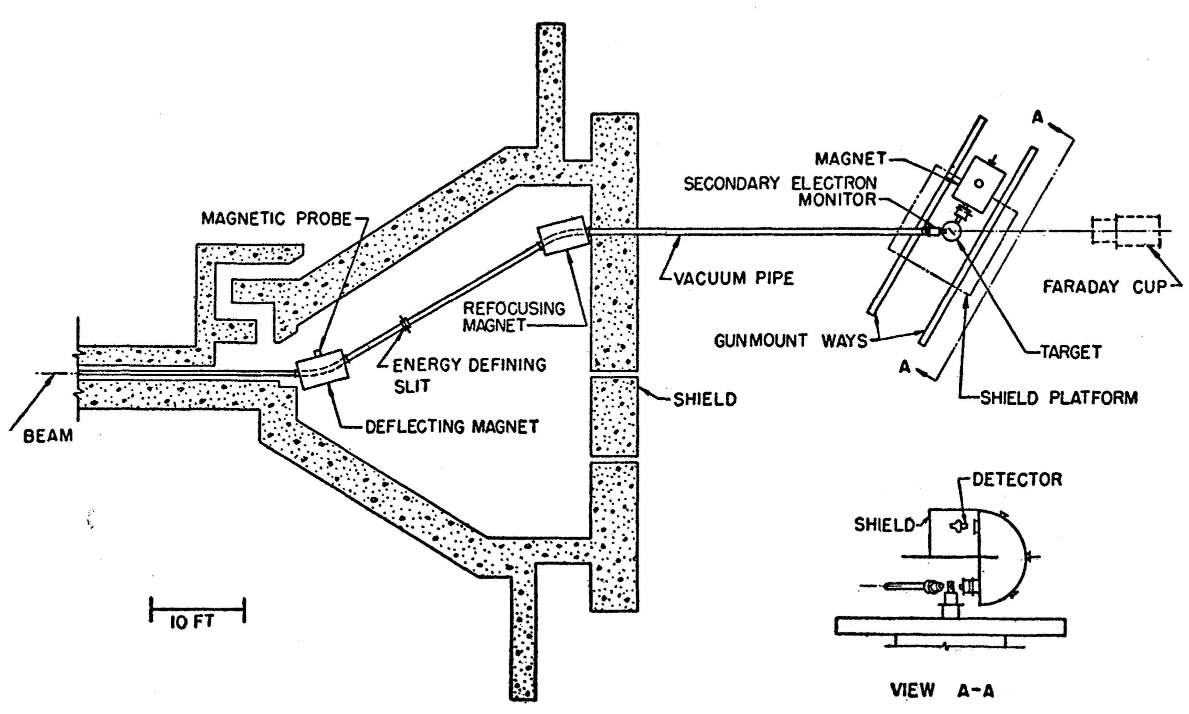
$$q^{\mu} = (k - k')^{\mu}$$

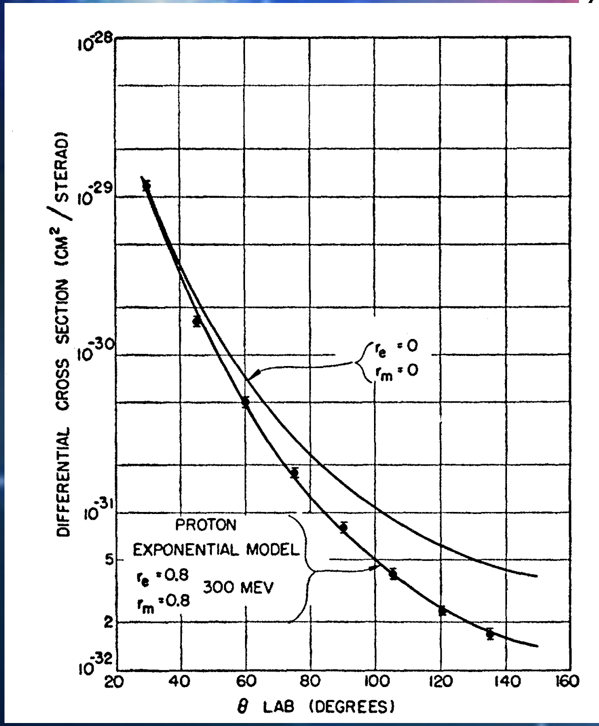


R. Hofstadter, *et al.*, Phys Rev 1956

- Nobel Prize, 1961

$$\sqrt{\left\langle r^2 \right\rangle_{Ch}} = 0.7 \pm 0.1\, fm$$





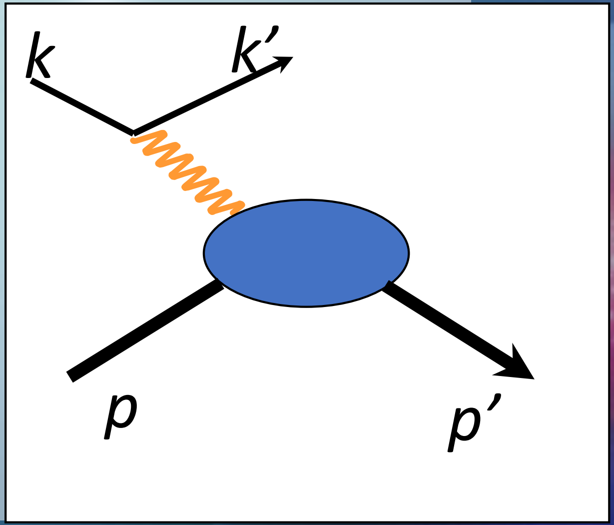
2014 PDG review:

- (e,e') (Mainz…): r_{rms}= 0.879(8) fm
- H Atomic levels: r_{rms} = 0.877(5) fm
- μp`Hydrogen': r_{rms} = 0.8409(4) fm
- More recent updates….new experiments coming

The Proton is not an Elementary Particle:

- Anomalous Magnetic Moment
  - $\mu = \frac{e\hbar}{Mc}[1+\kappa]$
  - Otto Stern (1933): $\kappa_p = 1.5 \pm 0.2$
  - 2014 PDG review: $\kappa_p = 1.792847356(023)$
- Charge and Current Densities
  - General EM current for a Dirac spin-1/2 nucleon to make a transition from a state (p,s) to (p',s') with $q = p' - p$ $(Q^2 = -q^2 > 0)$:

$$J^\mu(q) = \bar{U}(p',s')\left[\gamma^\mu F_1(Q^2) - \frac{[\gamma^\mu,\gamma^\nu]q_\nu}{4M}F_2(Q^2)\right]U(p,s)$$

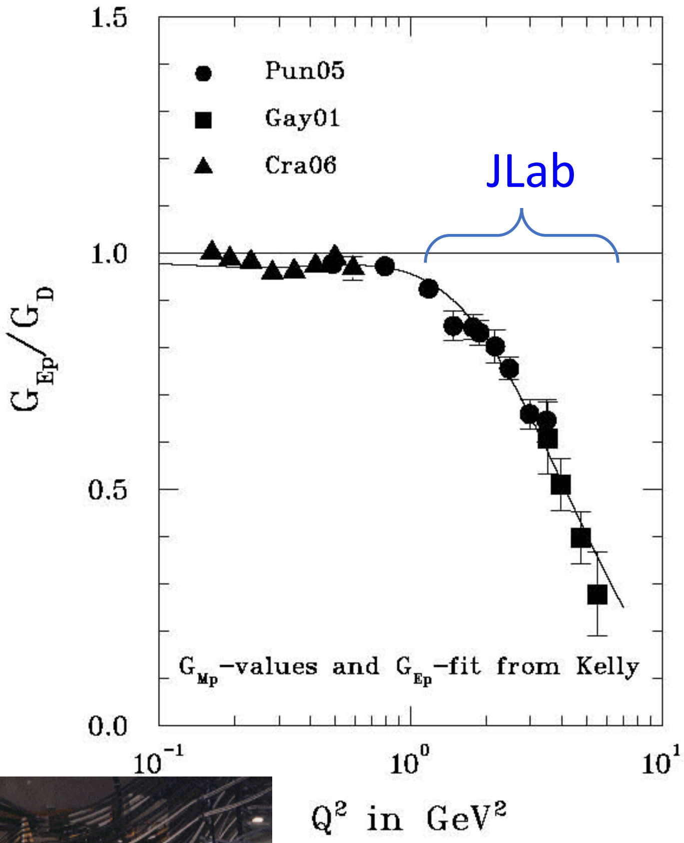


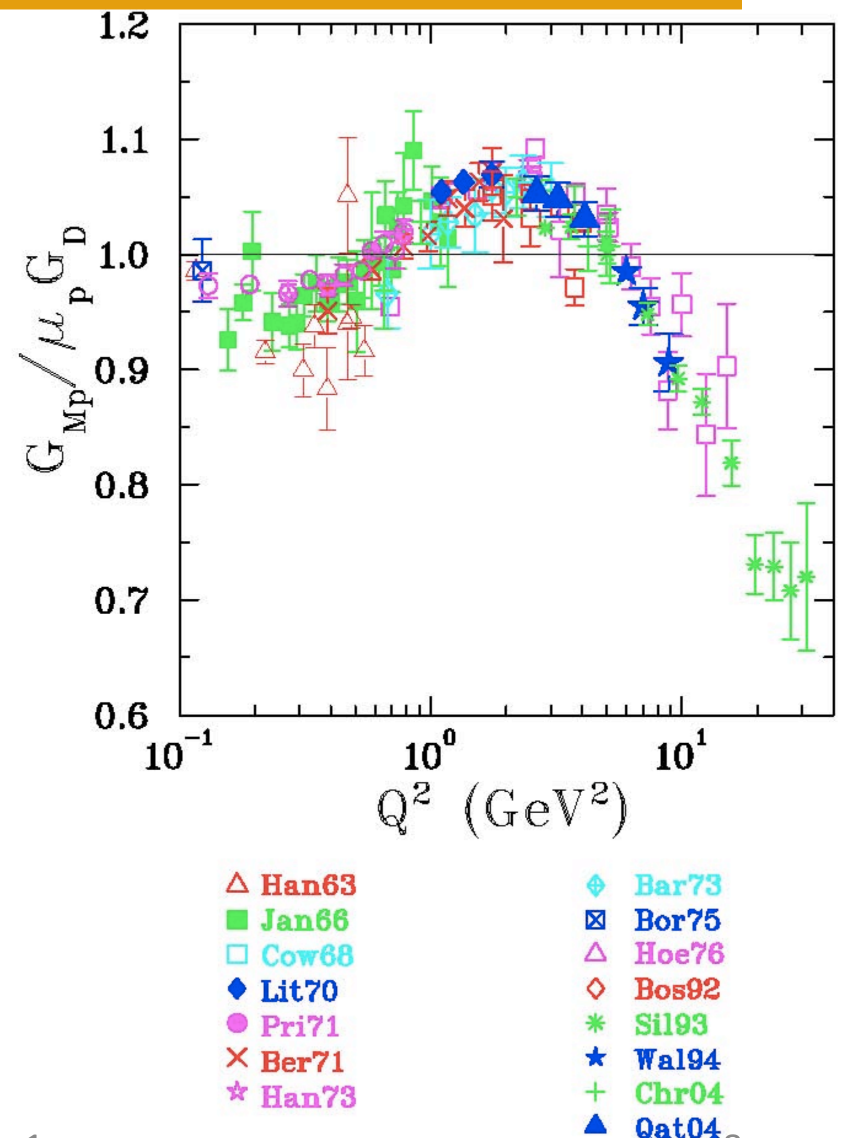
- Macroscopic Limits
  - $F_1(0) = 1$ $F_2(0) = \kappa$
- $G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$
- $G_E(Q^2) = F_1(Q^2) - [Q^2/(4M^2)]\, F_2(Q^2)$

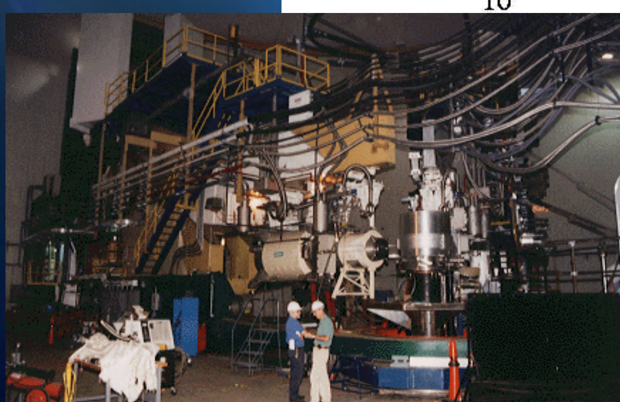
Elastic Electron Scattering Today

- Ratios to `Dipole' $G_D = [1+Q^2/\Lambda^2]^{-2}$, $\Lambda^2 = 0.71$ GeV^2

- Extensive new low-Q^2 data (Mainz, MIT, JLab)
- Experiments at JLab 12 GeV (2016+) looking for zero crossing in G_E.

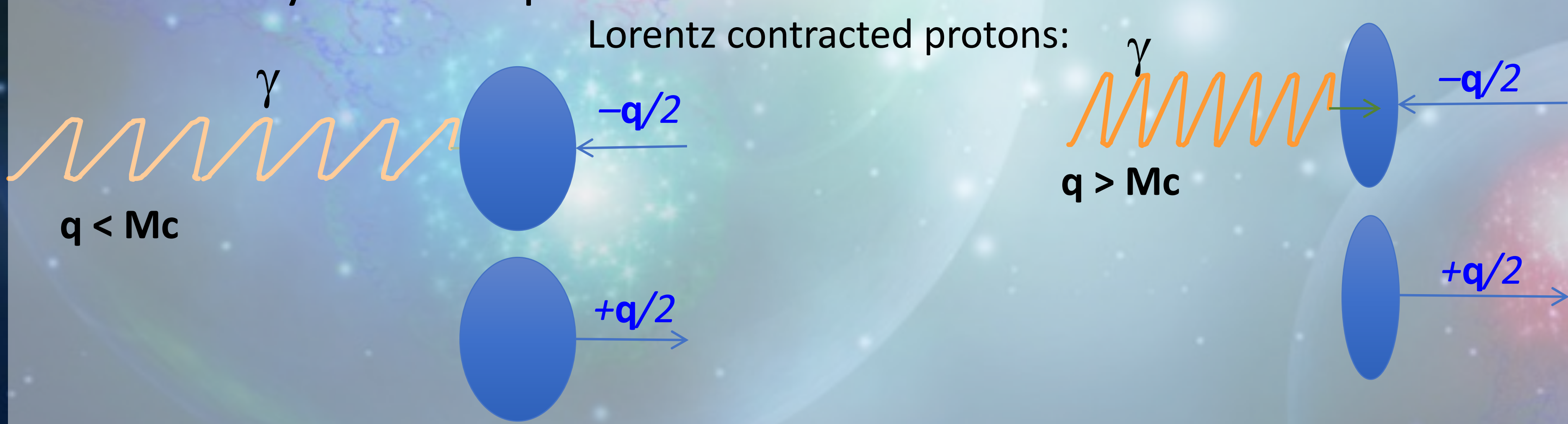






Form Factors and Densities

- Naively, $G_E(Q^2)$ is the Fourier transform of the charge density. But this only works for $Q^2 << M_p^2$
- Consider H(e,e)p in the `Breit' Frame: $q^\mu{}_{\text{Breit}} = [0, (Q^2)^{1/2}]$
  P$=-$**q**$/2$, **P'**$=+$**q**$/2$ (zero energy transfer)
- At each |**q**|=$[Q^2]^{1/2}$, $G_E(Q^2)$ samples the charge distribution of a differently boosted proton.

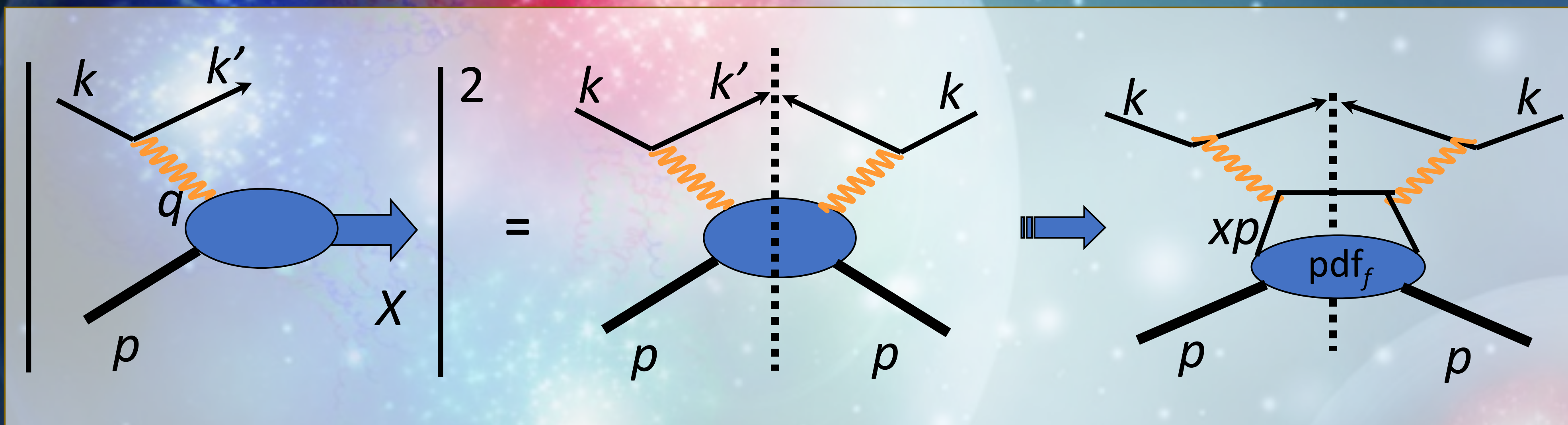


Lepton Scattering II. DIS

Deep Inelastic Scattering: $e + p \rightarrow e' + X$

$Q^2 = -q^2 = (k-k')^2$ $\quad x_{Bj} = Q^2/(2p\cdot q)$ $\quad y = q\bullet p/k\bullet p$

$d\sigma =$

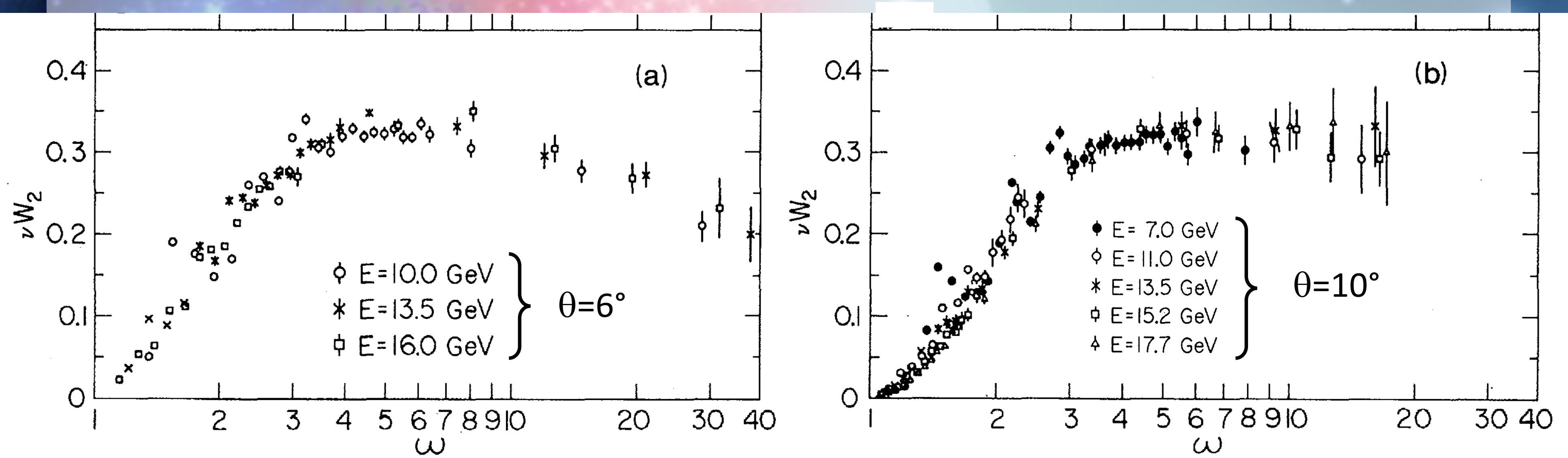


$$\frac{d\sigma}{dx_{Bj}dQ^2} \to \frac{4\pi\alpha^2}{x_{Bj}Q^4}\left[1-y+\frac{y^2}{2}\right]\sum_f\left[2x_{Bj}q_f^2\mathrm{pdf}_f(x_{Bj},\ln Q^2)\right]$$

Parton (quark or gluon) Distribution Function (PDF)

The proton is made of charged spin-1/2 constituents

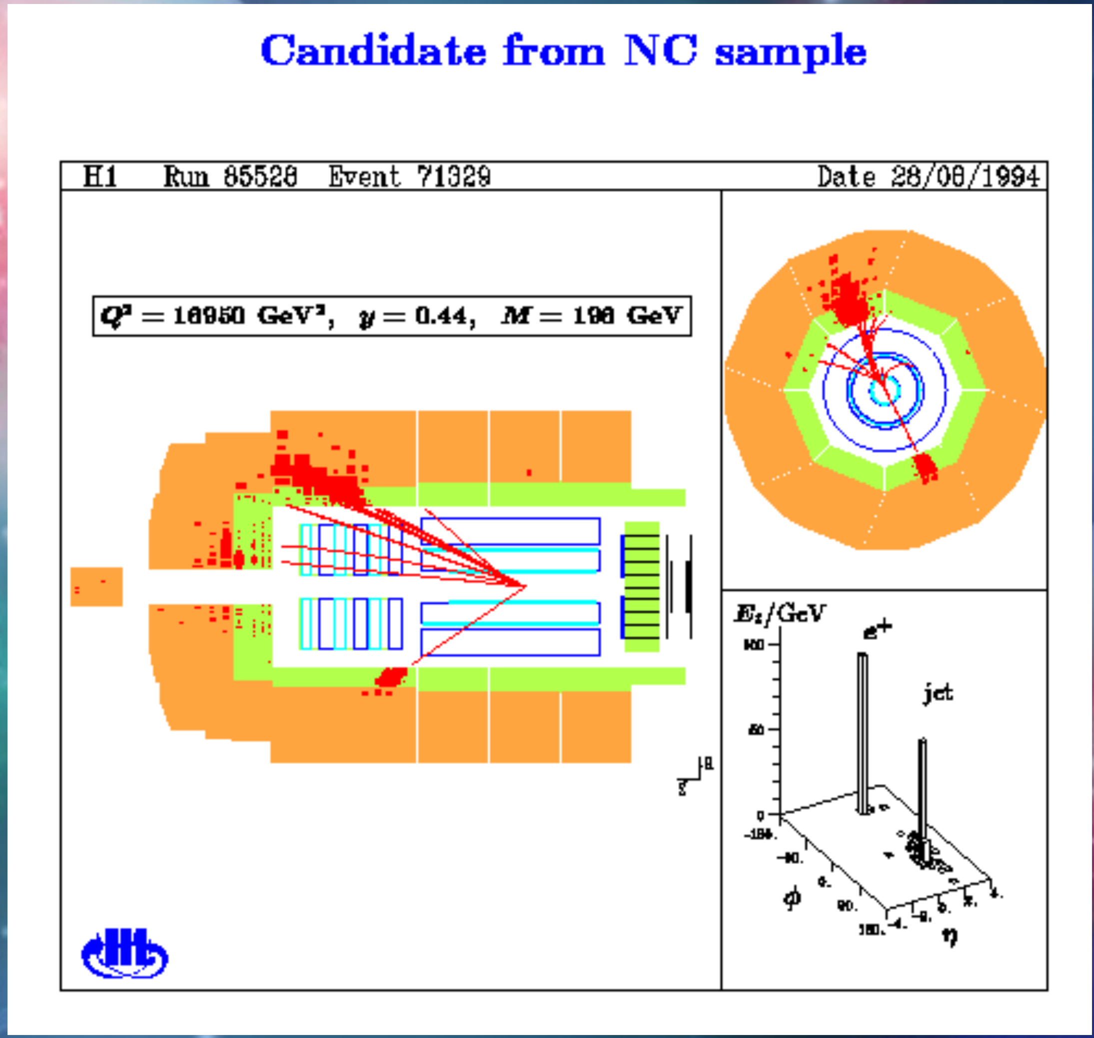
- M. Breidenbach *et al* PRL **23** (1969) 935
  Friedman, Kendal, Taylor, Nobel Prize 1990



- Universal behavior of the cross section as a function of single variable $\omega = 1/x = 2q\bullet P/Q^2$

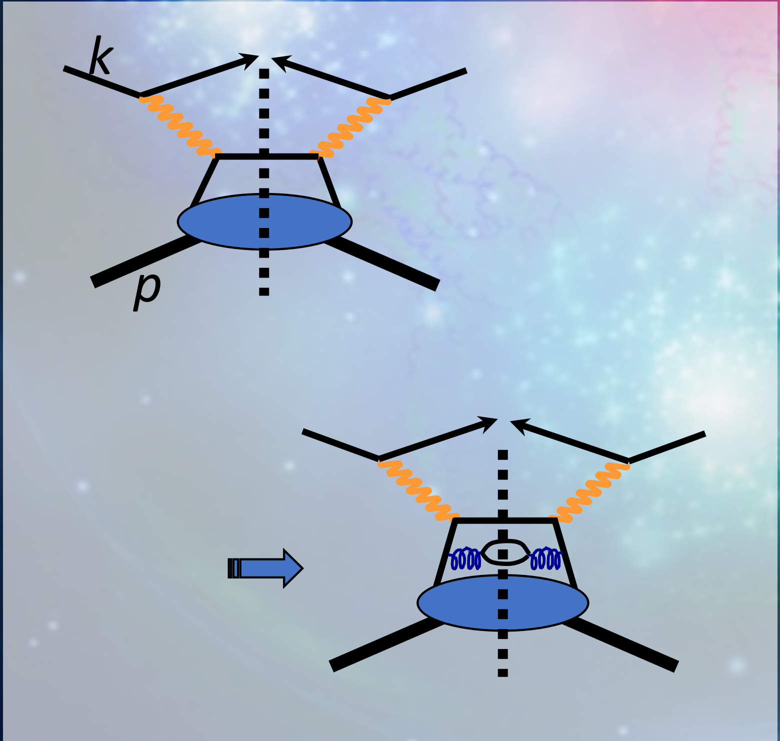
Factorization: $e + p \rightarrow e' + X$

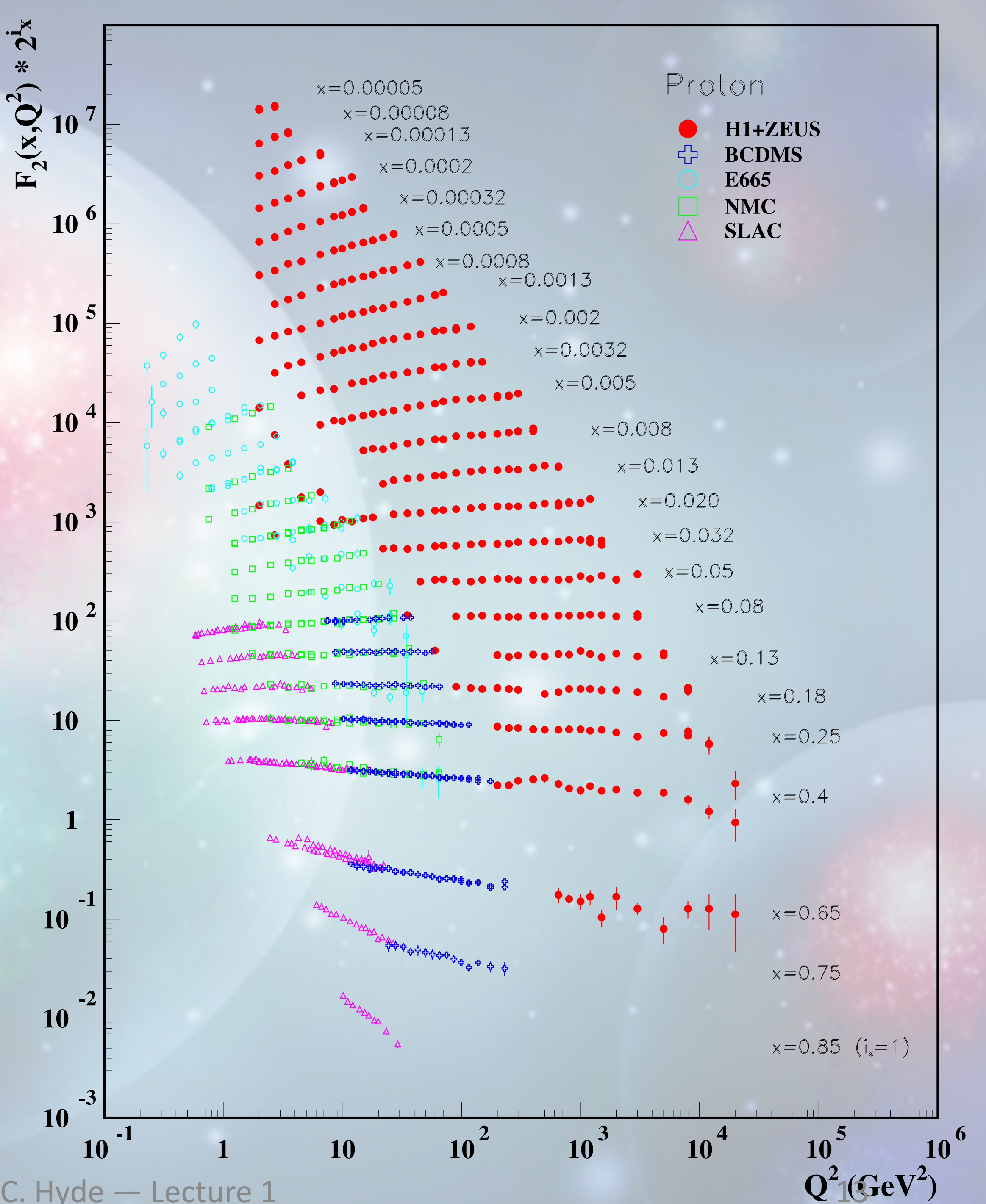
- Adding up all possible final states of mesons + 1 baryon, mesons+2baryons + 1 anti-baryon…
- Mathematically behaves the same as if the virtual photon was absorbed on a free quark
  - *Plus corrections of order $1/Q^2$…*



Protons are made of Quarks and Gluons, described by QCD.

- **Scaling violations:**
  As Q^2 increases: $q \to q + g$
  $g \to q + \bar{q}$





How to Image the Proton?

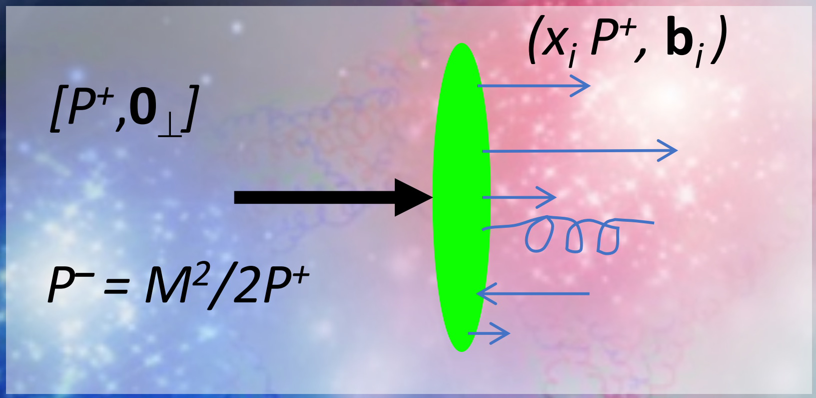
- A relativistic proton moving in the *+z*-direction.
- Illuminate it with a photon moving in *–z*-direction.
  - Photon-quark scattering samples the proton at equal light-cone times $x^+ = ct + z$
  - Astronomy, the farther we look in distance (+z), the farther back in time we are observing (–t).

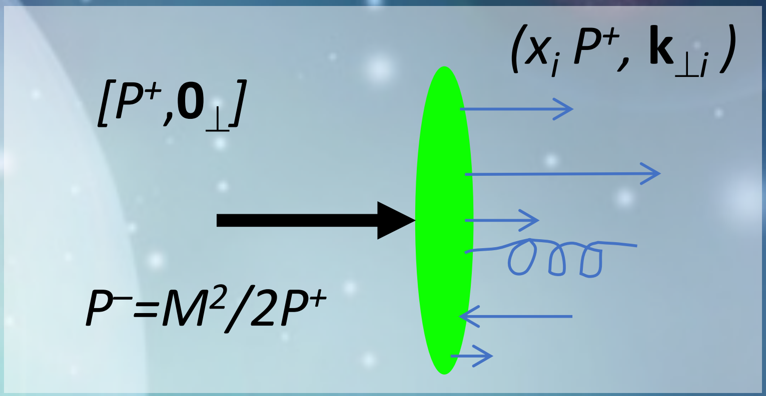
- Quantize at equal light-cone times x^+, (Dirac's Front-form dynamics).
  - Hamiltonian = \`P^-', $M^2 = P^2 \Rightarrow M^2 = 2P^+P^- - \mathbf{P}_\perp$
  - Proton has definite $P^+ = (E+P_z)/\sqrt{2}$,
  - Proton is spatially localized in transverse plane (Soper 1972)

(1+2)-Dimensional Proton structure:

Transverse

impact parameter space | momentum space





Partonic Fluctuations

$$\sum_i x_i = 1 \qquad \sum_i x_i = 1$$

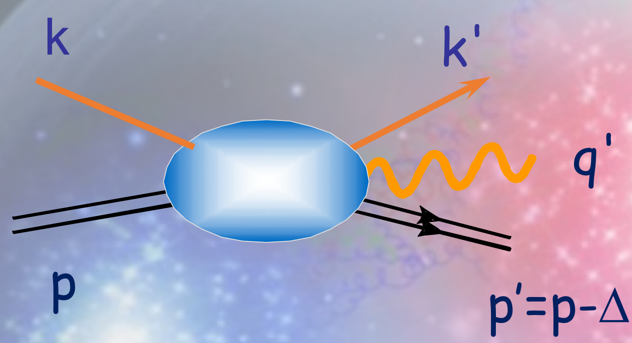
$$\sum_i \mathbf{b}_i x_i = 0 \qquad \sum_i \mathbf{k}_{\perp,i} = 0$$

Virtual `Energy'

$$P^- = \frac{1}{2P^+}\sum_i \frac{(\mathbf{k}_{\perp,i})^2}{x_i} > \frac{M^2}{2P^+}$$

Bethe-Heitler (BH) and Virtual Compton Scattering (VCS)

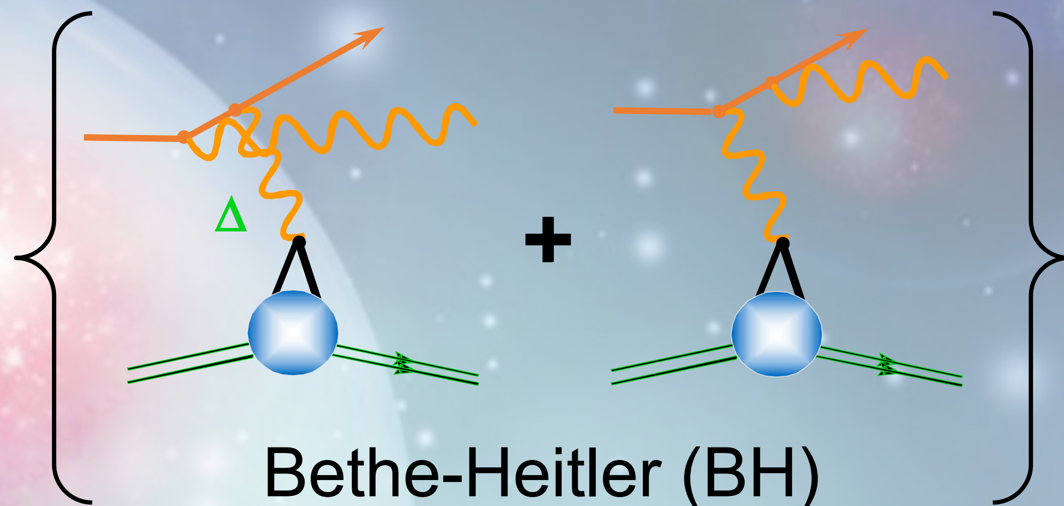
$e\,p \rightarrow e\,p\,\gamma$



$\Delta^{\mu} = (p' - p)^{\mu}$

$t = (p' - p)^2 = \Delta^2$

=



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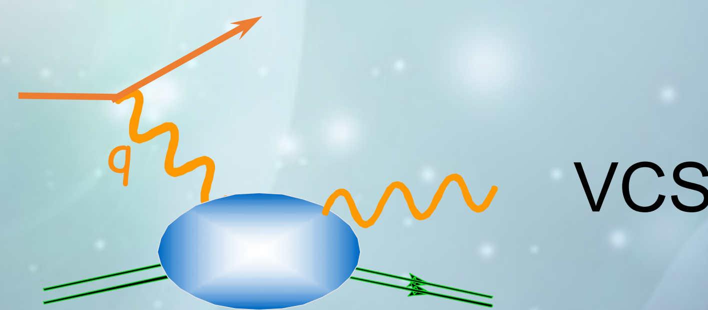
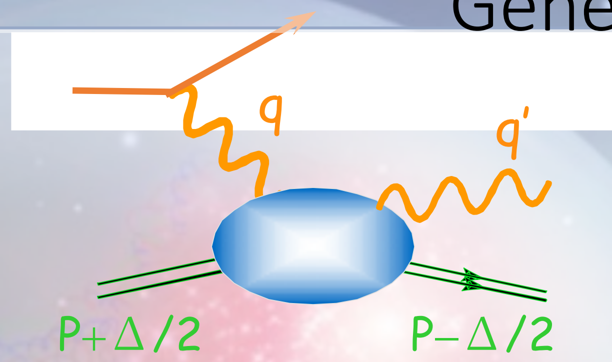


- VCS = ”Pump-Probe” experiment on Proton
- BH-VCS interference
  - Access to amplitude and phase of VCS amplitude

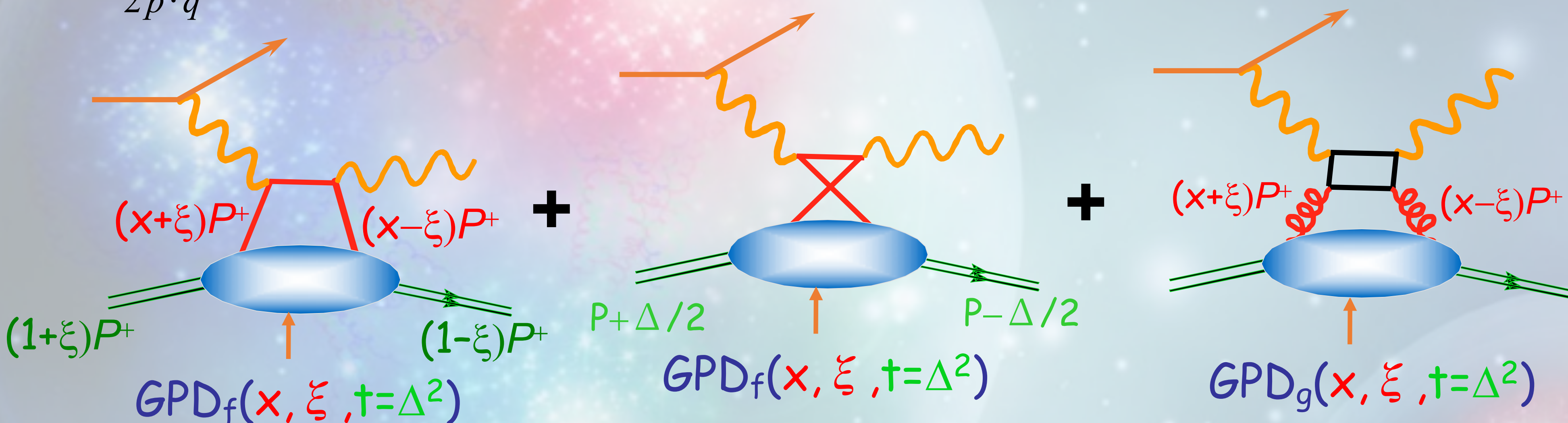
Deeply Virtual Compton Scattering
Generalized Parton Distributions

$e\,p \rightarrow e\,p\,\gamma$

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



QCD Scaling limit, Q^2 large



- Symmetrized Bjorken variable:

$$\xi = \frac{-(q+q')^2}{2(q+q')\cdot P} \xrightarrow[\Delta^2 << Q^2]{} \frac{x_B}{2-x_B}$$

- $\Delta = (q-q')$, Fourier conjugate to impact parameter **b** of active parton

ep→epγ: Factorization doubts delayed publication ~ 1 year

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Gauge-Invariant Decomposition of Nucleon Spin

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(Received 20 March 1996)

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11 July 1996
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Physics Letters B 380 (1996) 417–425

Scaling limit of deeply virtual Compton scattering

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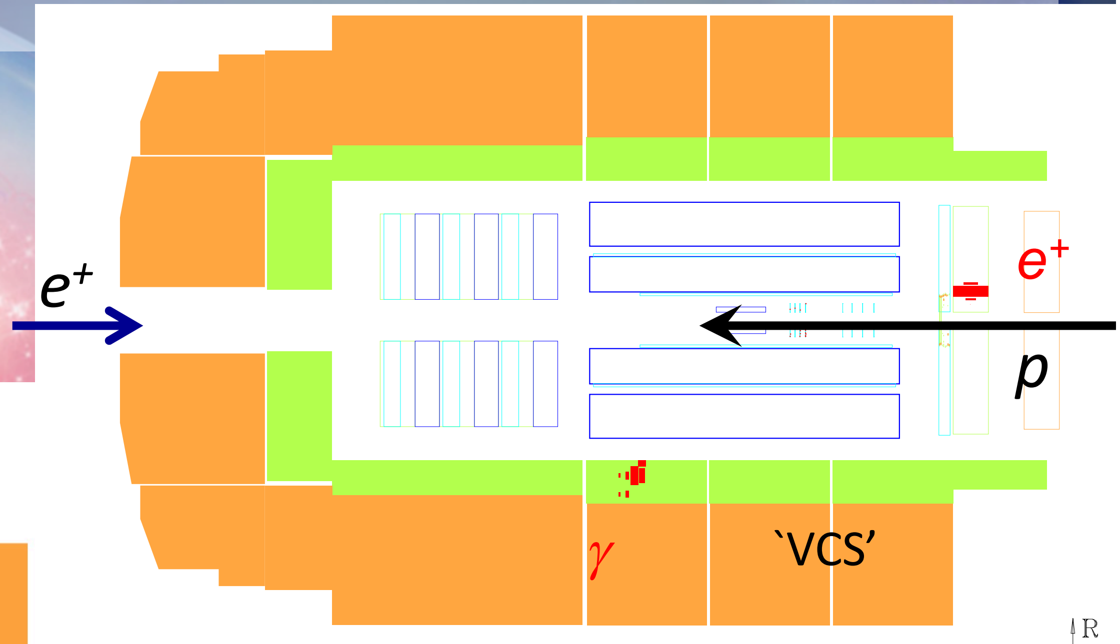
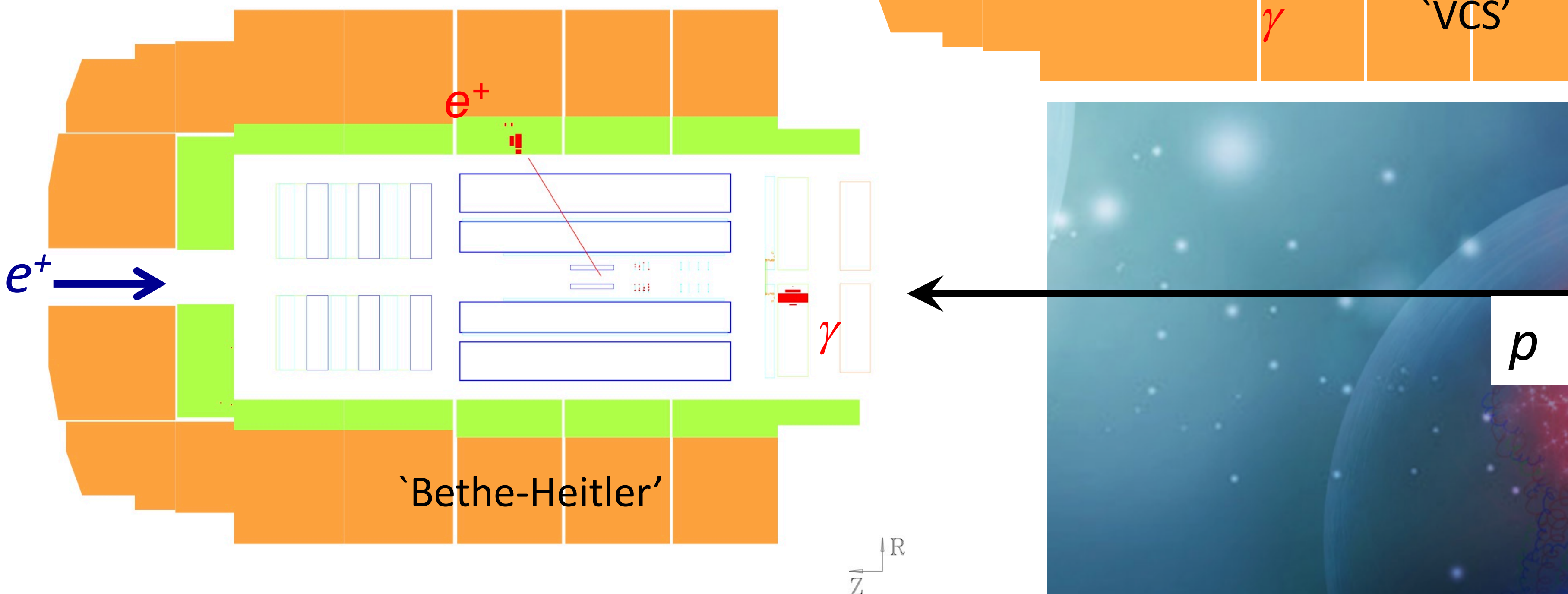
Received 18 April 1996
Editor: H. Georgi

- Real photon has strongly-interacting substructure:
  - Vector Meson Dominance
  - Total cross section γ+p→ X described by γ→ρ,ω,ϕ… followed by strong interactions
- DIS: Large Q^2 suppresses hadronic content of photon (small size $q\bar{q}$)
  - What about real-photon in DVCS final state?
- Proofs of factorization for DVCS and ep→ ep+meson came soon
  - How large does Q^2 have to be?

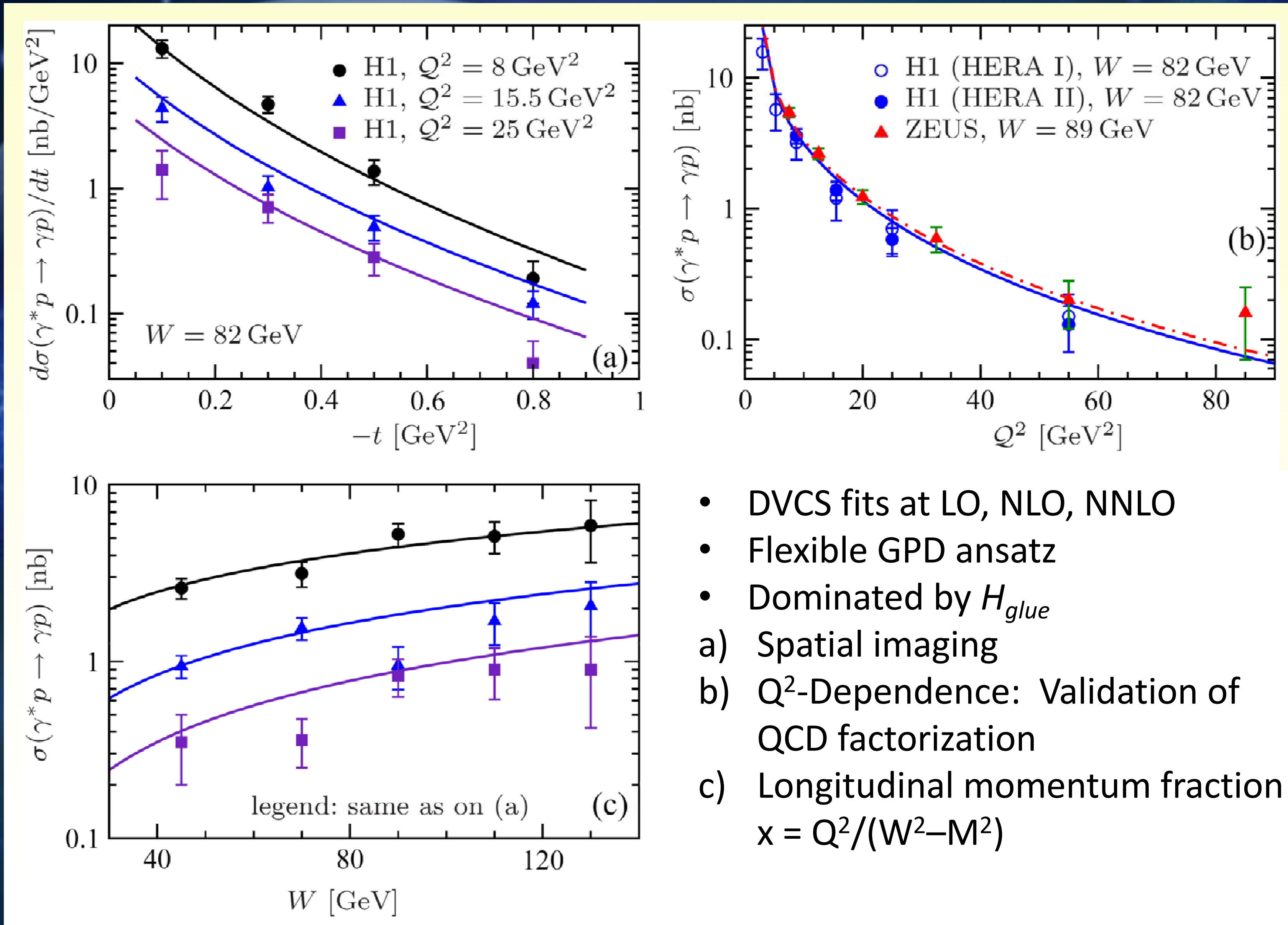
HERA-H1: Sample VCS- and BH-dominated events

ep→eγX
X is ultra-forward (left←)
No visible energy:
dominated by exclusive





HERA DVCS, fits by D.Müller *et al., 2012*



- DVCS fits at LO, NLO, NNLO
- Flexible GPD ansatz
- Dominated by H_{glue}

a) Spatial imaging
b) Q^2-Dependence: Validation of QCD factorization
c) Longitudinal momentum fraction $x = Q^2/(W^2 - M^2)$