University of Virginia
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Three Dimensional Imaging of the Proton and Atomic Nuclei

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Old Dominion University
Norfolk VA

- 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 (someone else's talk)
- The Future

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?

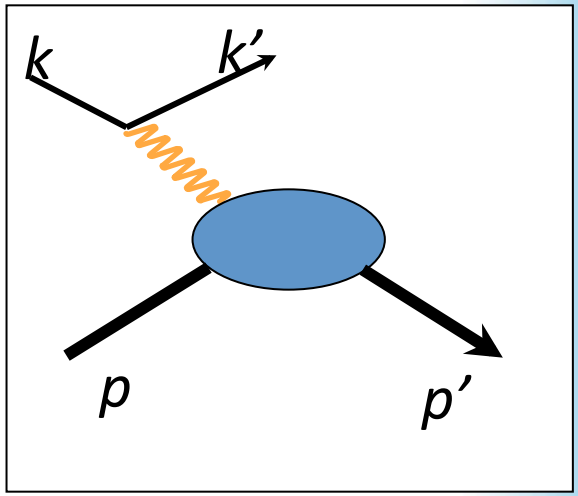
Elastic Electron Scattering on the proton, 1950s – 2010s

- 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.

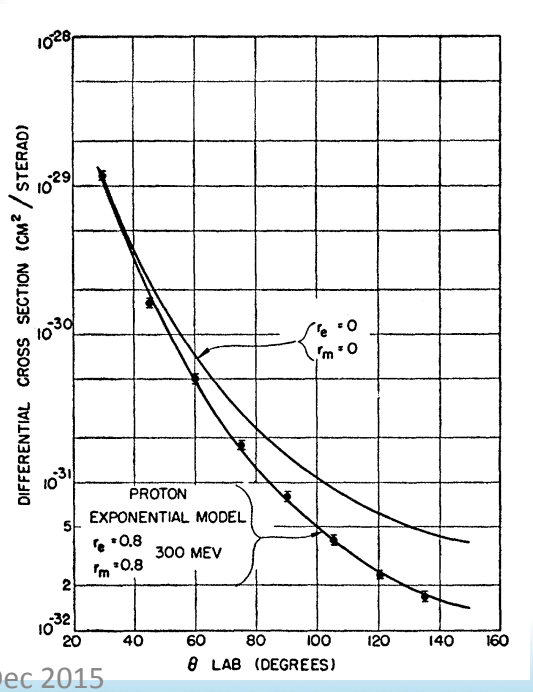
$$q^{\mu} = \left(k - k'\right)^{\mu}$$

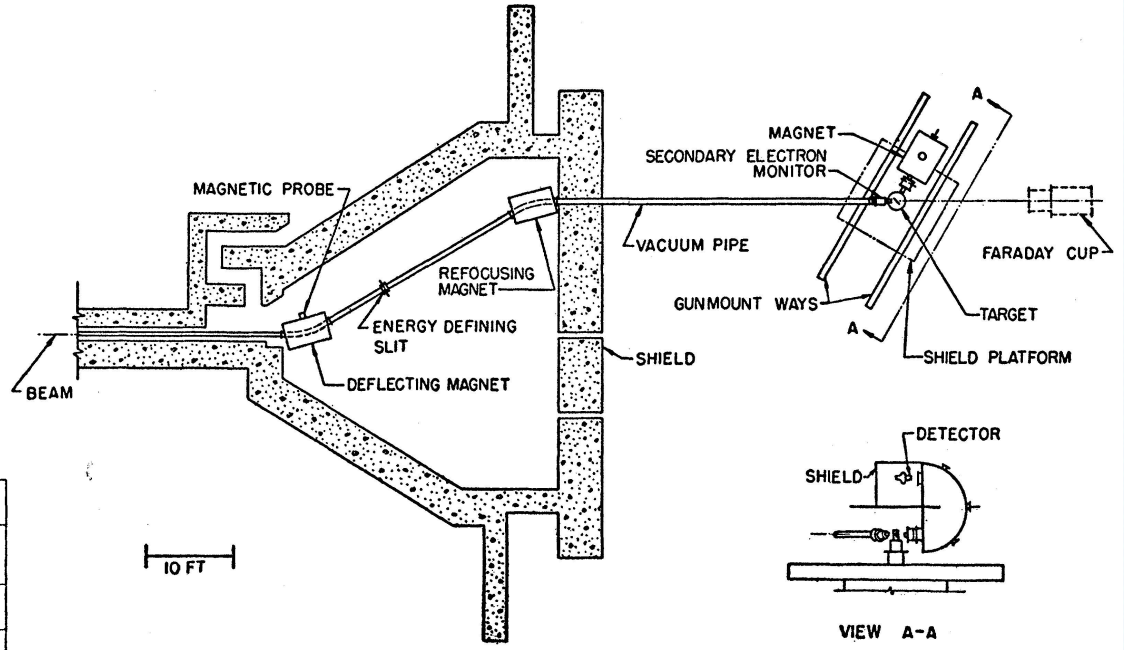


R. Hofstadter, *et al*., Phys Rev 1956

- Nobel Prize, 1961

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





2014 PDG review:

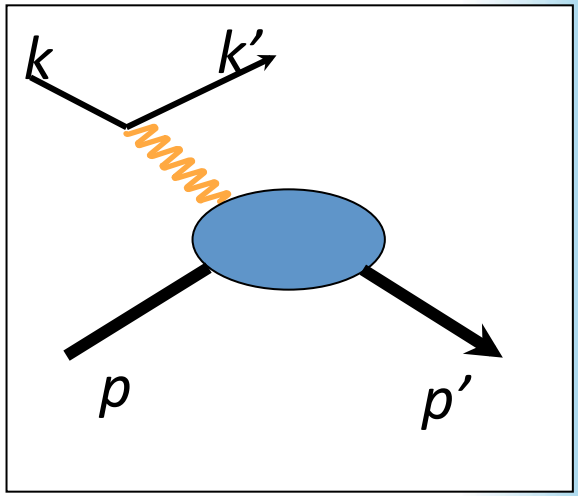
- (e,e') (Mainz…): r_{rms}= 0.879(8) fm
- H Atomic levels: r_{rms} = 0.877(5) fm
- μp`Hydrogen': r_{rms} = 0.8409(4) fm

The Proton is not an Elementary Particle:

- Anomalous Magnetic moment,
  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 $q = p' - p$ $(Q^2 = -q^2 > 0)$:

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

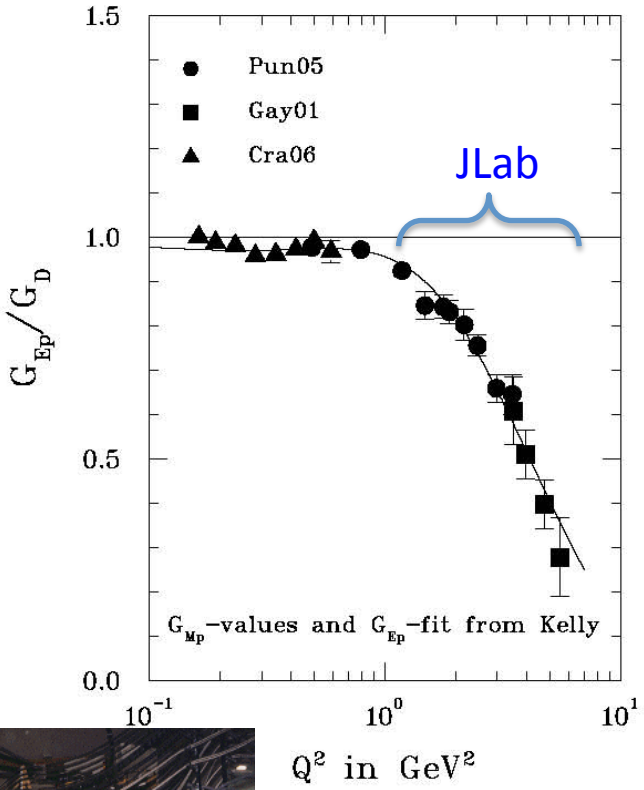
- Macroscopic Limits
  - $F_1(0) = 1$ $F_2(0) = \kappa$
    - O.Stern 1933: $\kappa_p = 1.5 \pm 0.2$
    - 2014 PDG review $\kappa_p = 1.792847356(023)$
- $G_M(Q^2) = F_1 + F_2$
- $G_E(Q^2) = F_1 - Q^2/(4M^2)F_2$

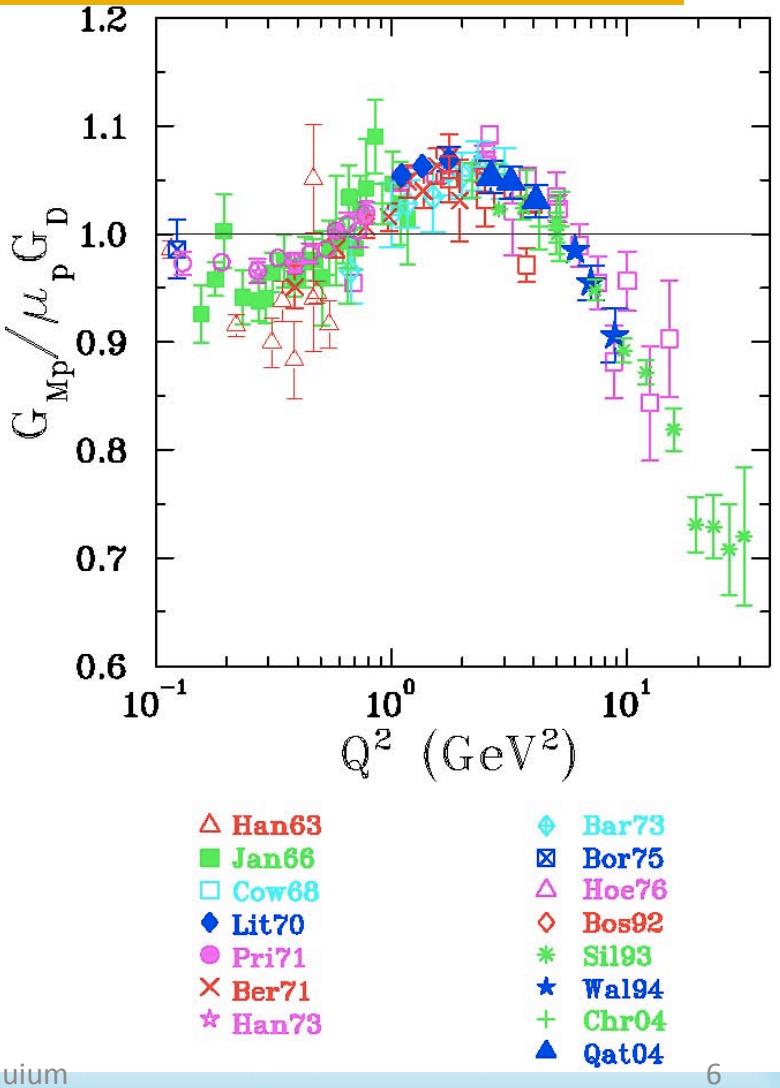


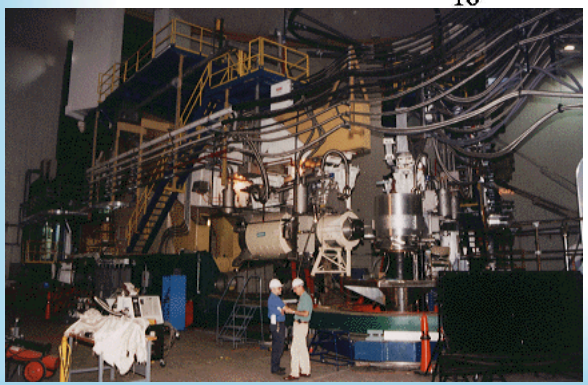
Elastic Electron Scattering Today

- 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.





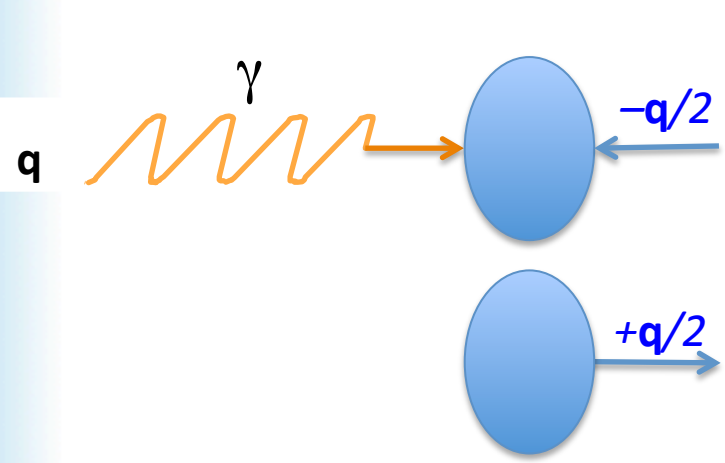


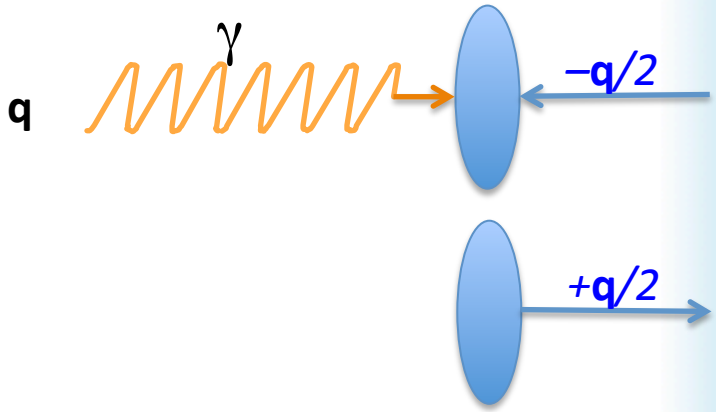
Form Factors and Densities

- 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: $q^{\mu}_{\text{Breit}} = [0, (Q^2)^{1/2}]$
  $\mathbf{P} = -\mathbf{q}/2$, $\mathbf{P'} = +\mathbf{q}/2$ (zero energy transfer)

- At each $|\mathbf{q}| = [Q^2]^{1/2}$, $G_E(Q^2)$ samples the charge distribution of a differently boosted proton.

Lorentz contracted protons:



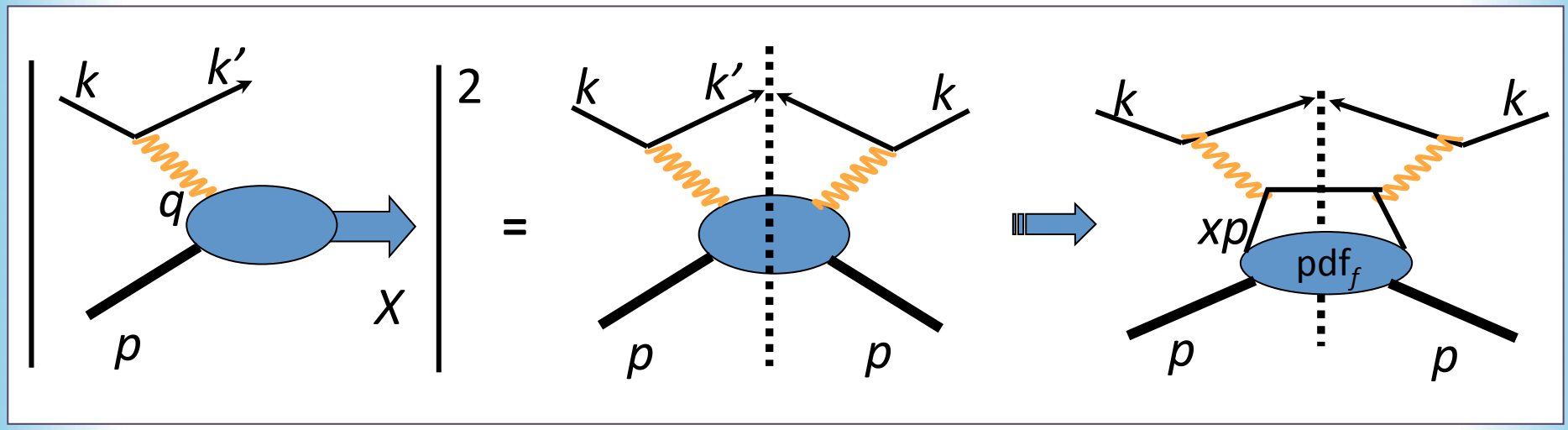


Lepton Scattering

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

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

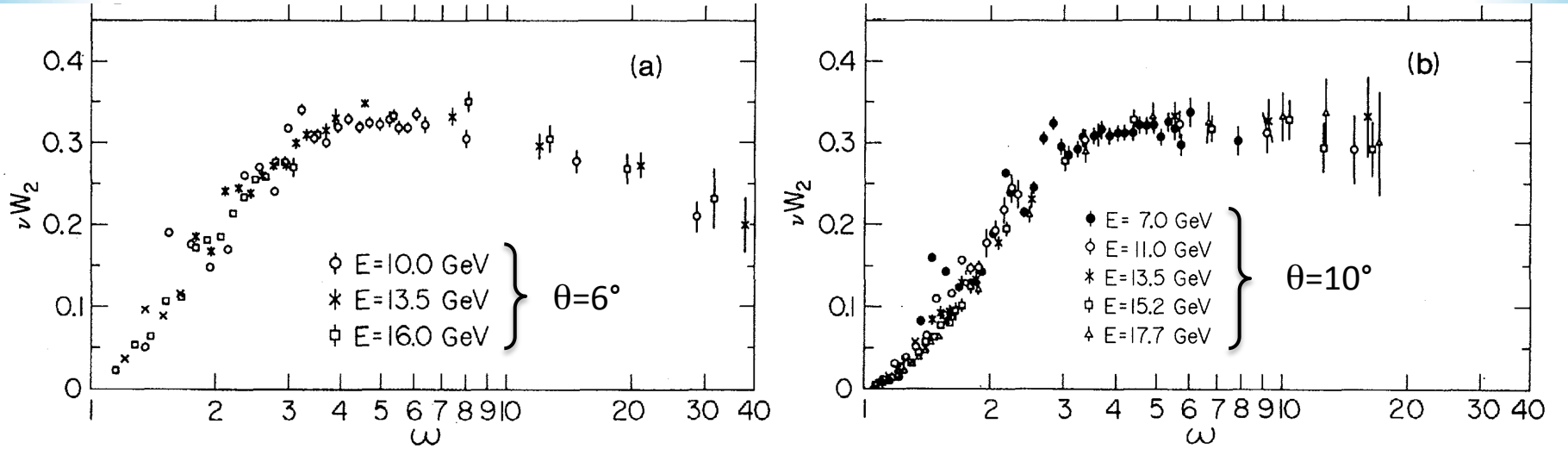
$d\sigma =$



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

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

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



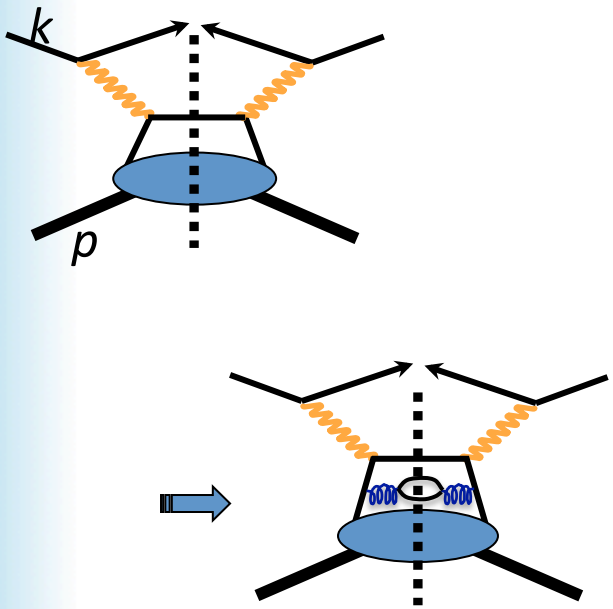
- Universal behavior of the cross section as a function of single variable $\omega = 1/x = 2q\bullet P/Q^2$

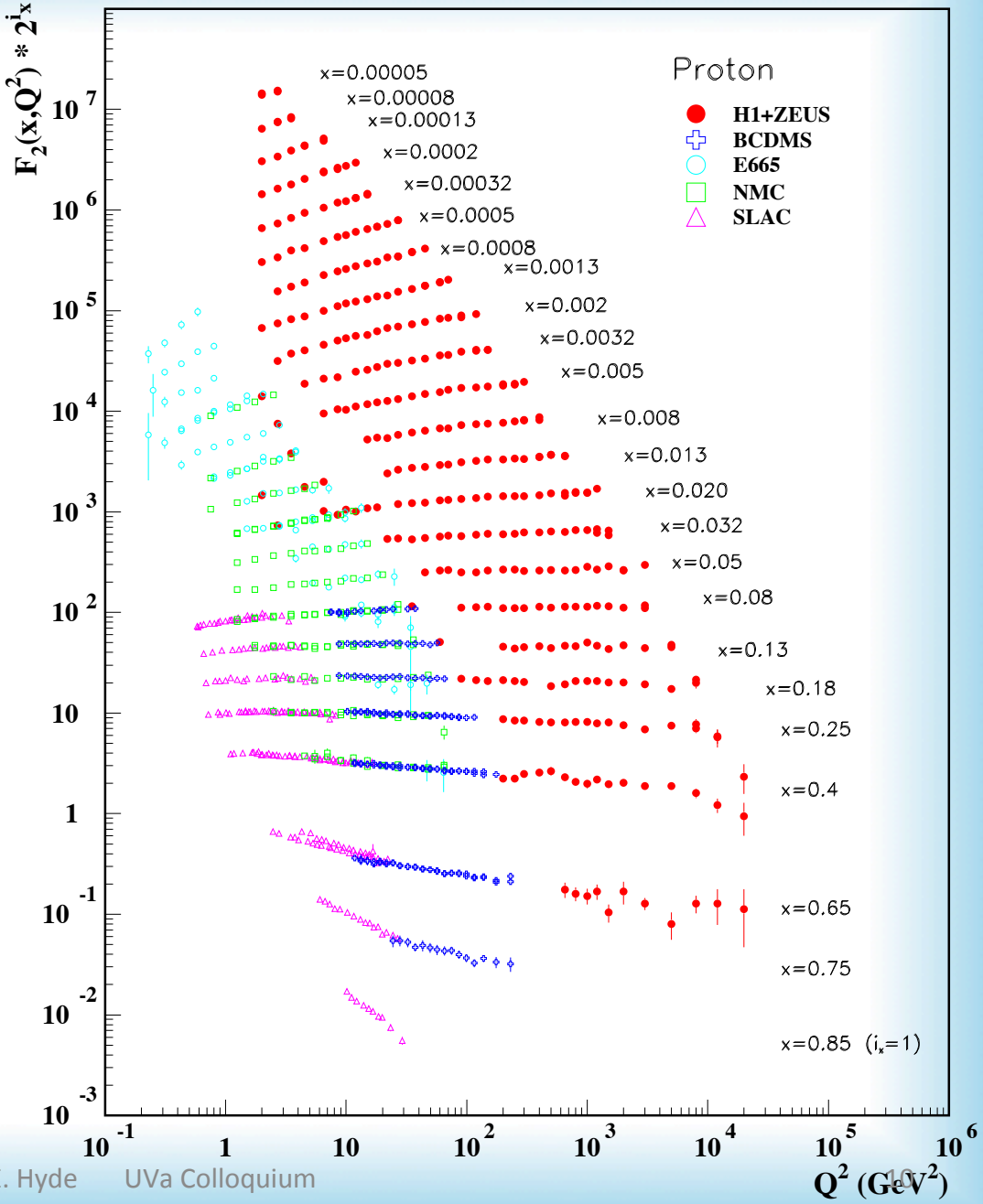
Protons are made of Quarks and Gluons, described by QCD.

- Scaling violations:

  As Q^2 increases: $q \rightarrow q + g$

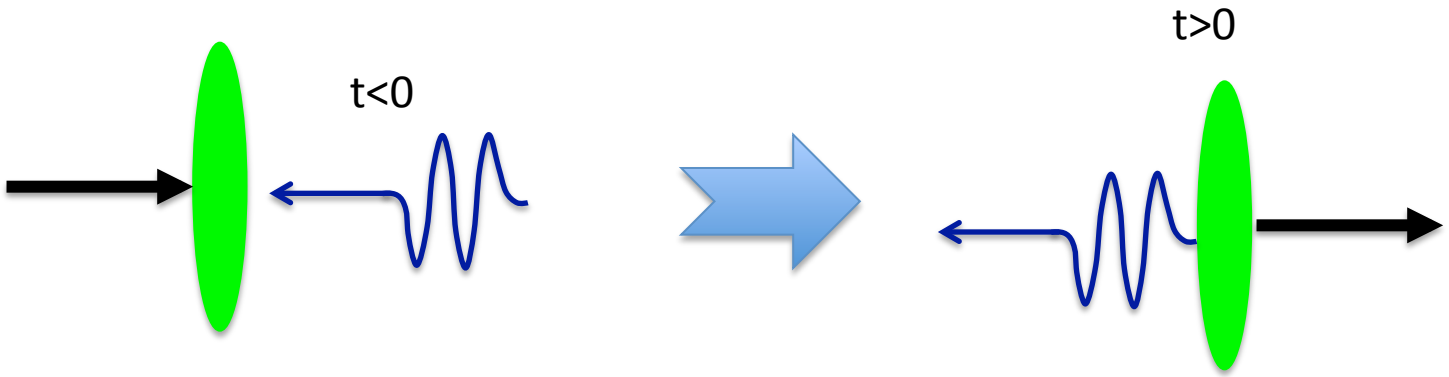
  $g \rightarrow q + \bar{q}$





How to Image the Proton?

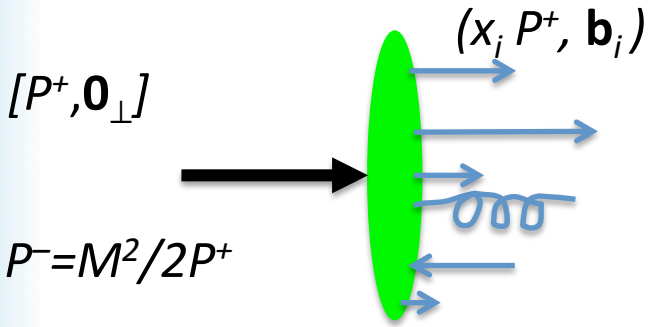
- A relativistic proton moving in the *+z*-direction.
- Illuminate it with a photon moving in *–z*-direction.
  - Photon-quark scattering samples the proton at equal light-cone times $x^+ = ct + z$
  - Astronomy, the farther we look in distance (+z), the farther back in time we are observing (–t).

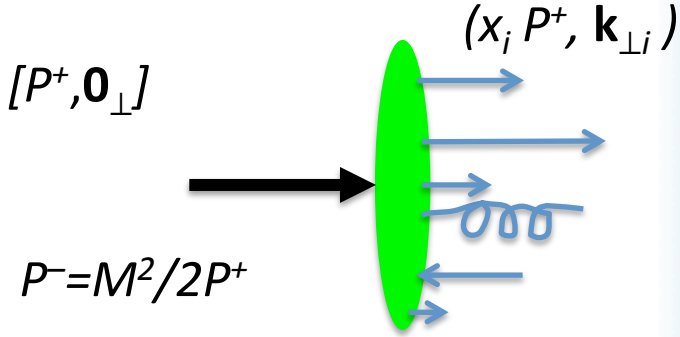


Quantize at equal light-cone times x^+, Dirac's Front-form dynamics.

- Hamiltonian = `P^-', $M^2 = P^2$ ➔ $M^2 = 2P^+P^- - \mathbf{P}_\perp$
- Proton has definite $P^+ = (E+P_z)/\sqrt{2}$,
- Proton is spatially localized in transverse plane

Proton structure in transverse impact parameter or momentum space





Partonic Fluctuations

$$\sum_i x_i = 1$$
$$\sum_i \mathbf{b}_i x_i = 0$$

$$\sum_i x_i = 1$$
$$\sum_i \mathbf{k}_{\perp,i} = 0$$

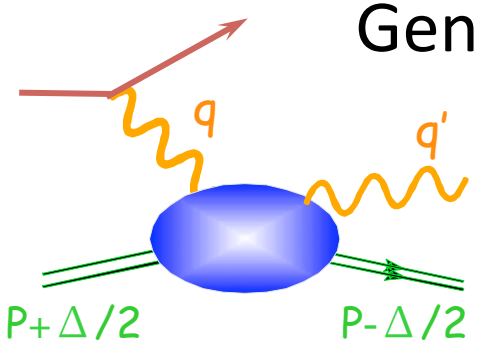
Virtual `Energy'

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

Deeply Virtual Compton Scattering

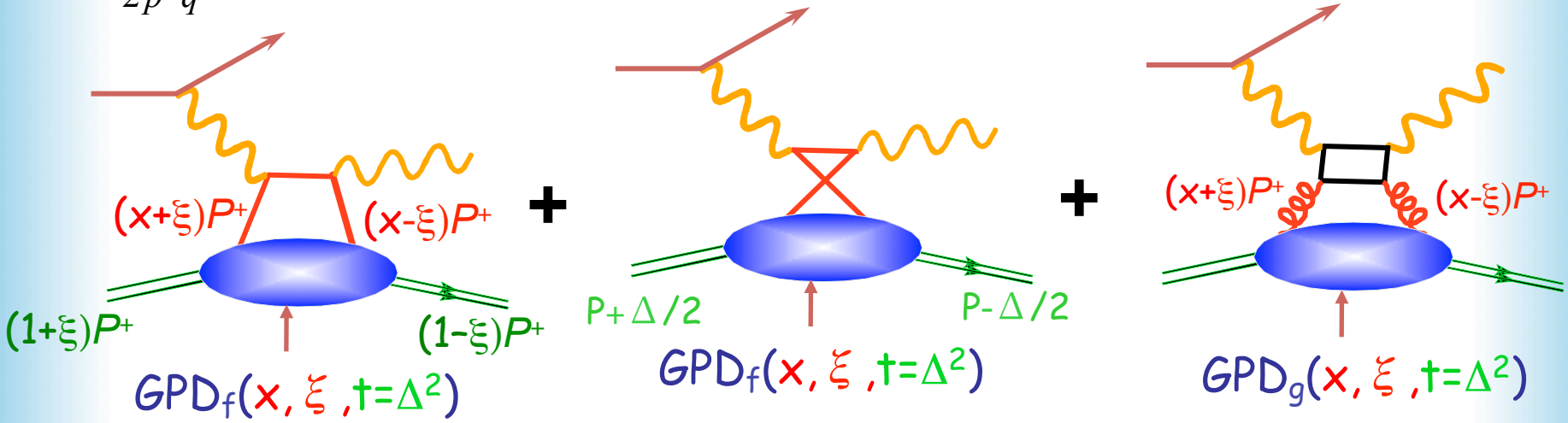
Generalized Parton Distributions

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



QCD Scaling limit, Q^2 large

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



- Symmetrized Bjorken variable: $\xi = \dfrac{-(q+q')^2}{2(q+q')\cdot P} \xrightarrow[\Delta^2 << Q^2]{} \dfrac{x_B}{2-x_B}$

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

Imaging Quarks and Gluons: Deeply Virtual Exclusive Reactions

- $ep \rightarrow ep\gamma$, $ep \rightarrow eN\pi$, $ep \rightarrow epV$: $V=\rho\omega\phi$…
  - *(e,e')* kinematics in DIS regime:
    - Incoherent sum of partons (quarks and gluons) of momentum fraction fixed by electron kinematics ($x_{Bj} = Q^2/(W^2-M^2)$)
    - Proton→proton (or neutron) elastic transition:
      - Momentum transfer to target $\Delta^\mu = (q-q')^\mu$
        Fourier transform of spatial density in transverse plane
  - (1+2) Tomographic image:
    - Distribution of quark momenta along one axis and the spatial density in the plane transverse to this axis
      [Generalized Parton Distributions = GPDs]
  - J. Xi, A.Radyushkin 1997, D. Mueller et al, 1994
  - Hermes, HERA, JLab, COMPASS (CERN) experiments
- Image gluons *via* $ep \rightarrow epJ/\Psi$, $ep \rightarrow ep\phi$

GPDs: Correlations of Spatial, Momentum, and Spin d.o.f.

$$\text{Vector}: H_f(x,\xi,t), E_f(x,\xi,t) \Leftarrow \int e^{iP^+z^-}\, dz^- \left\langle P+\Delta/2 \left| \overline{\Psi}(+z^-)\gamma^+\Psi(-z^-) \right| P-\Delta/2 \right\rangle$$

$$\text{Axial}: \tilde{H}_f(x,\xi,t), \tilde{E}_f(x,\xi,t) \Leftarrow \int e^{iP^+z^-}\, dz^- \left\langle P+\Delta/2 \left| \overline{\Psi}(+z^-)\gamma^+\gamma_5\Psi(-z^-) \right| P-\Delta/2 \right\rangle$$

Forward limits

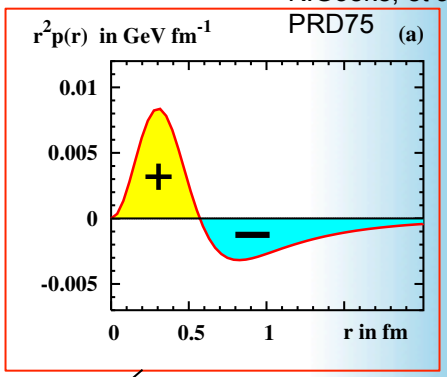
$$H_f(x,0,0) = q_f(x)$$

$$\tilde{H}_f(x,0,0) = \Delta q_f(x)$$

First Moments

$$\int_{-1}^{1} dx [H,E]_f(x,\xi,\Delta^2) = \left[F_1, F_2\right]_f(-\Delta^2)$$

K.Goeke, et al PRD75



Forces

Second Moments:

$$\int x dx H_f(x,\xi,t) = +M_{2f}(t) + \frac{4}{5}\xi^2 d_{1f}(t)$$

$$\int x dx E_f(x,\xi,t) = -M_{2f}(t) + \frac{4}{5}\xi^2 d_{1f}(t) + 2J_f(t)$$

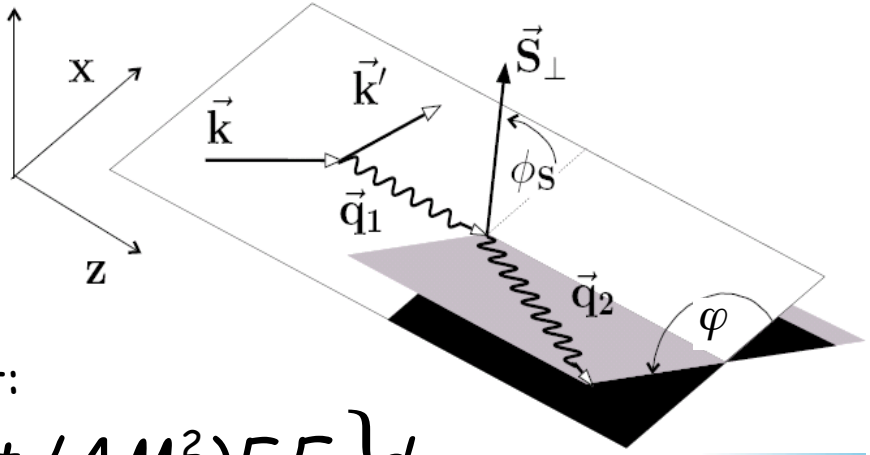
Proton Spin

X. Ji: Angular Momentum Sum Rule

$$\int_{-1}^{1} x dx \left[H_f(x,\xi,0) + E_f(x,\xi,0)\right] = 2J_f$$

Exploiting the harmonic structure of DVCS with polarization

The difference of cross-sections is a key observable to extract GPDs



With polarized beam and unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\varphi \left\{ F_1 H + \xi(F_1 + F_2)\tilde{H} + (t/4M^2)F_2 E \right\} d\varphi$$

With unpolarized beam and Long. polarized target:

$$\Delta\sigma_{UL} \sim \sin\varphi \left\{ F_1 \tilde{H} + \xi(F_1 + F_2) H + (t/4M^2)F_2 E \right\} d\varphi$$

With unpolarized beam and Transversely polarized target:

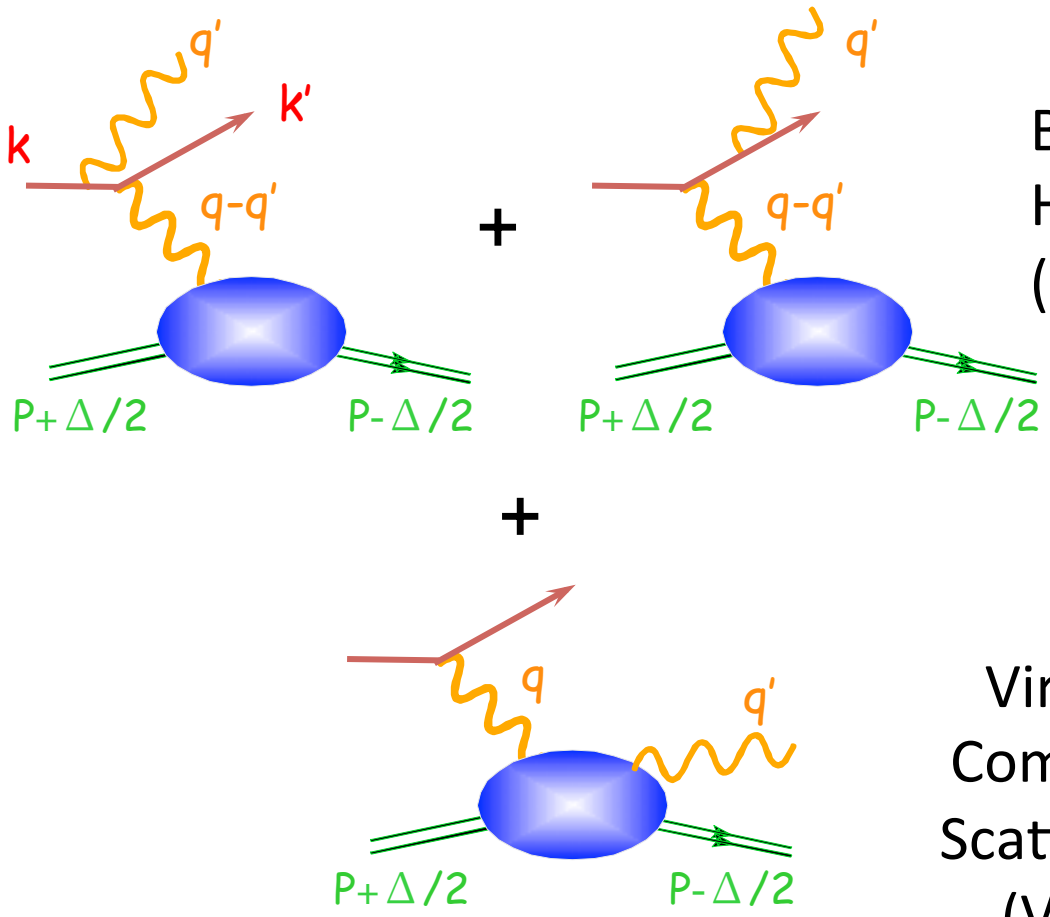
$$\Delta\sigma_{UT} \sim \cos\varphi \sin(\phi_S - \varphi) \left\{ (t/4M^2)F_2 H - (t/4M^2)F_1 E + \ldots \right\} d\varphi$$

Separations of CFFs $H(\pm\xi,\xi,t)$, $\tilde{H}(\pm\xi,\xi,t)$, $E(\pm\xi,\xi,t)$,…

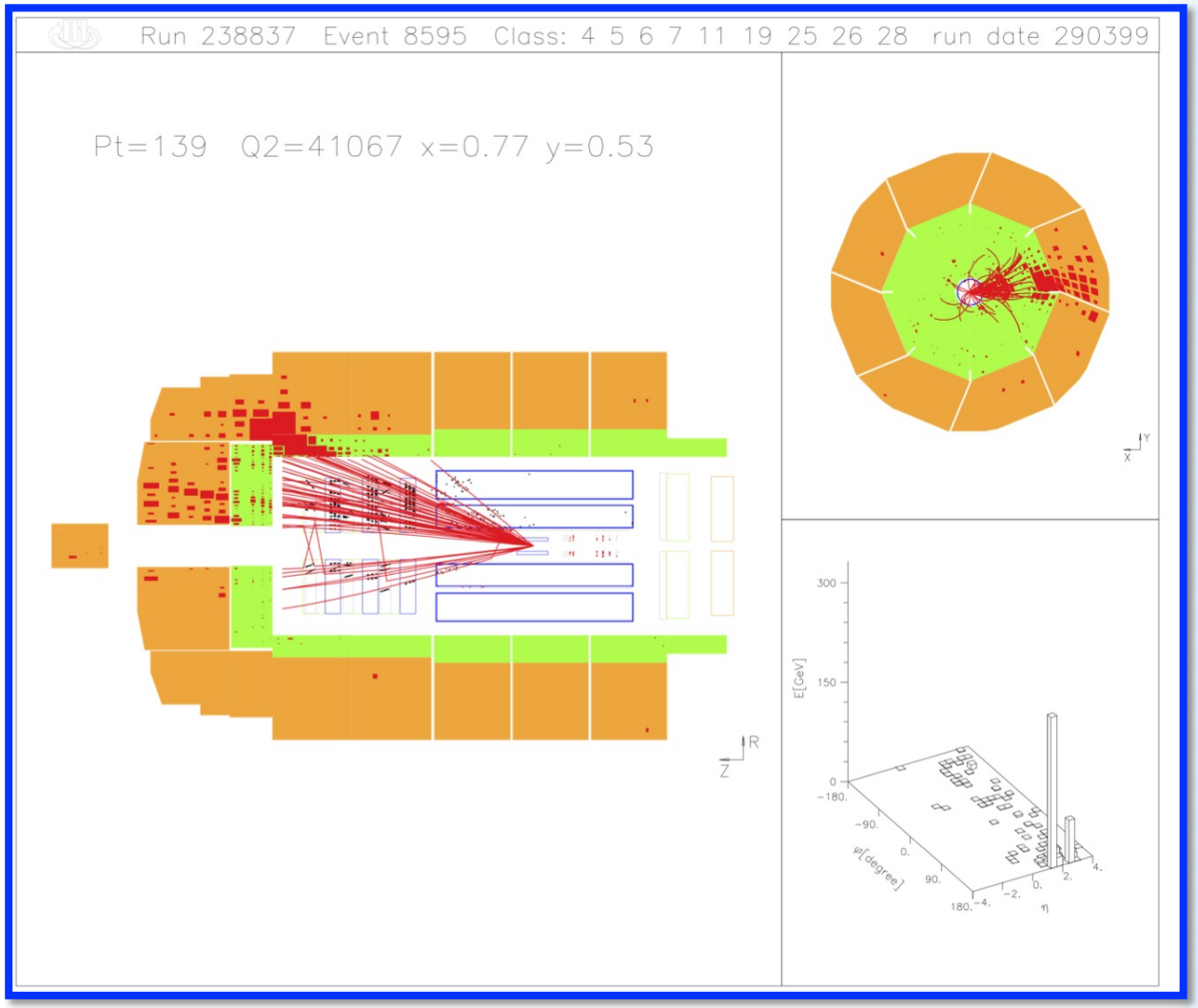
Measuring GPDs

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

- HERA (2001 – 2007)
- HERMES (2001 – 2007)
- JLab 6 GeV (2001 – 2012)
- JLab 12 GeV (2014 –
- COMPASS (2016 –
- EIC (2025+?

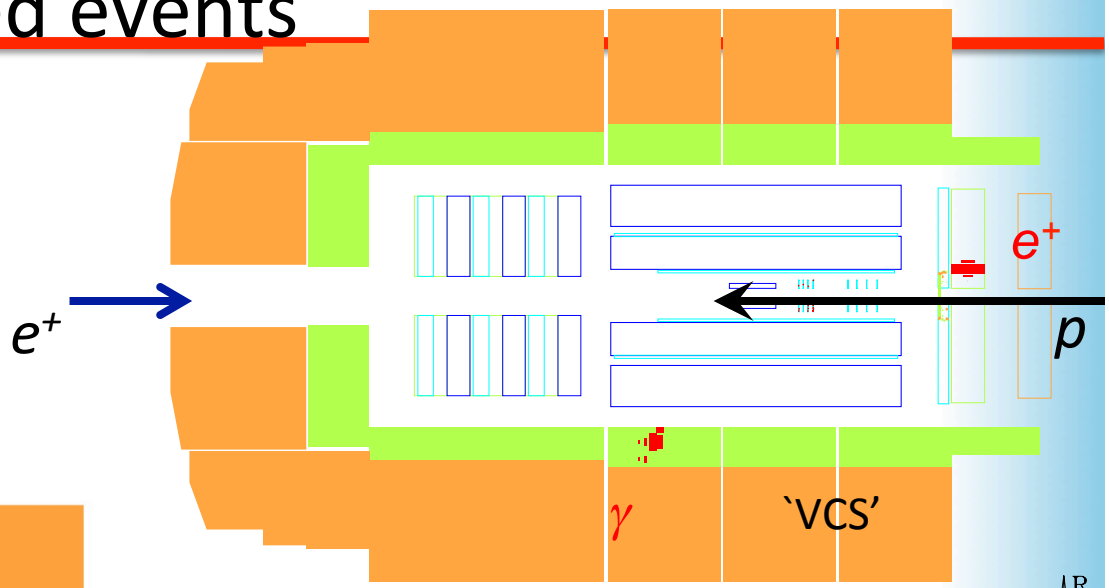


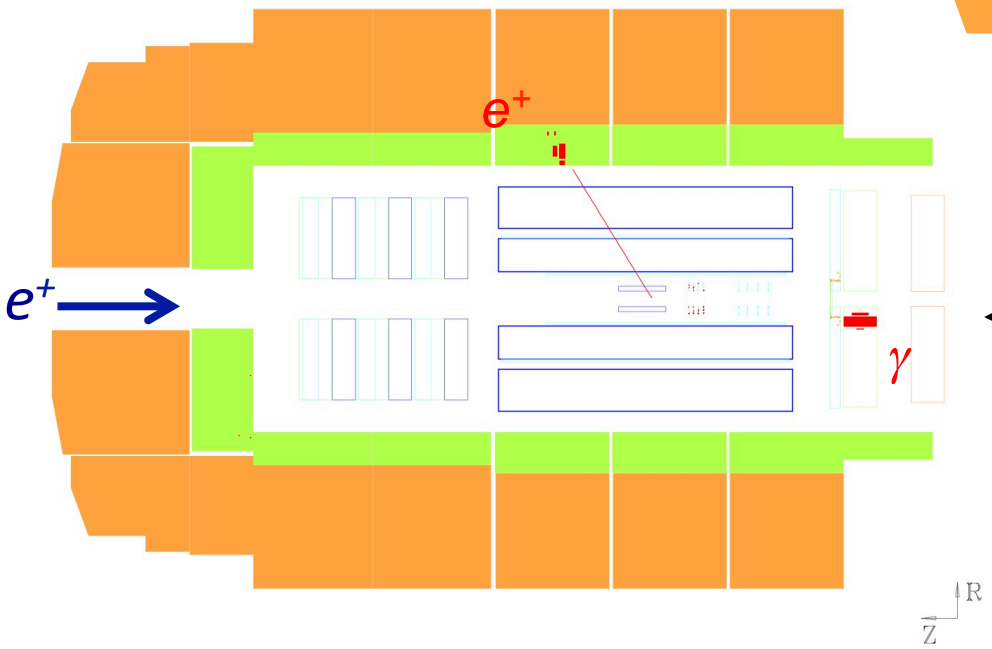
HERA DIS Event ep→νX



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

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

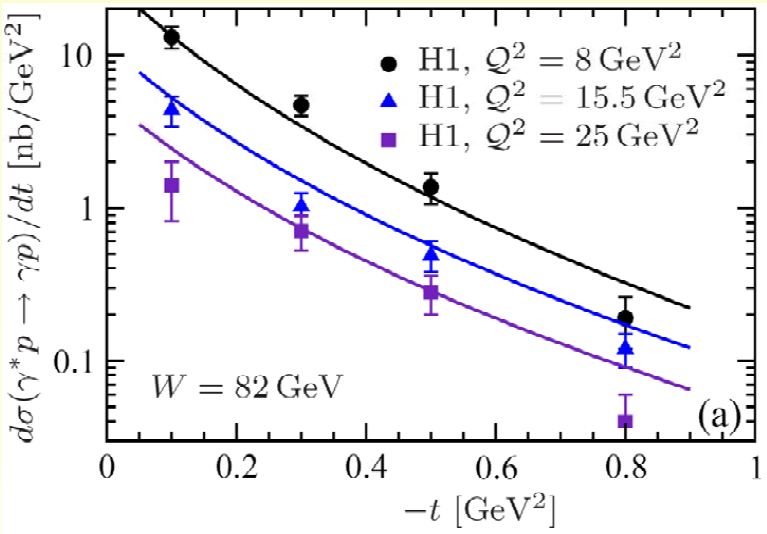


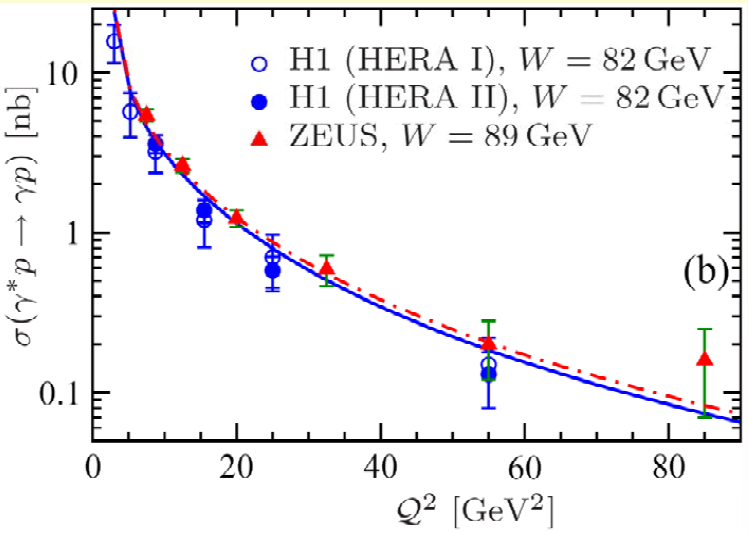


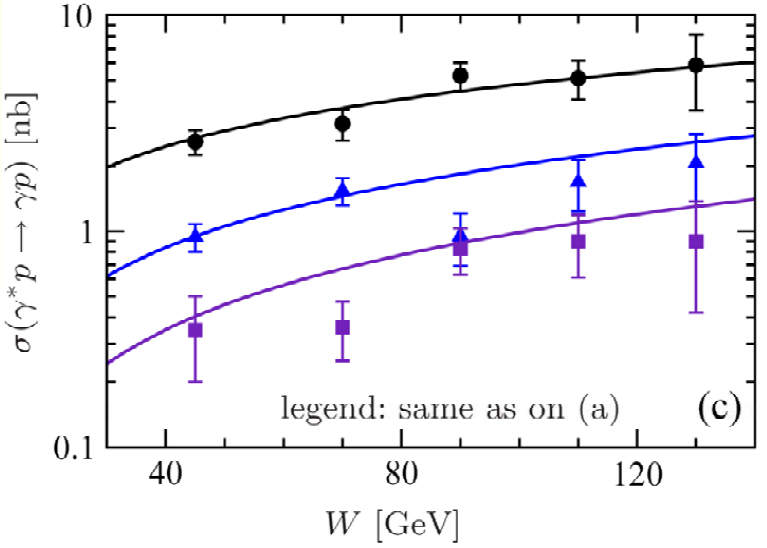
p

`Bethe-Heitler'

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

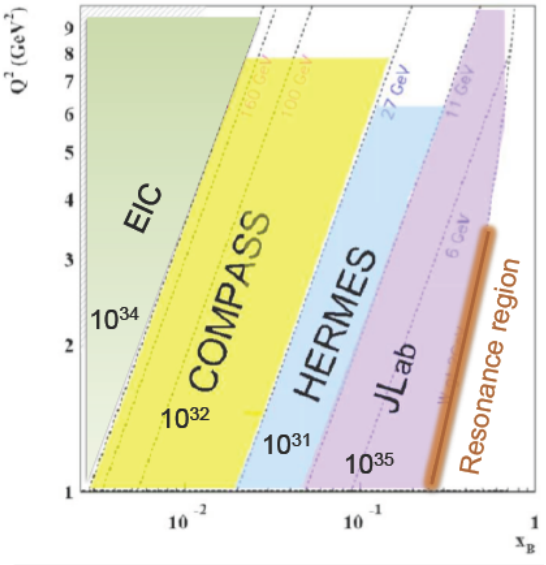
b) Q^2-Dependence: Validation of QCD factorization

c) Longitudinal momentum fraction $x = Q^2/(W^2–M^2)$

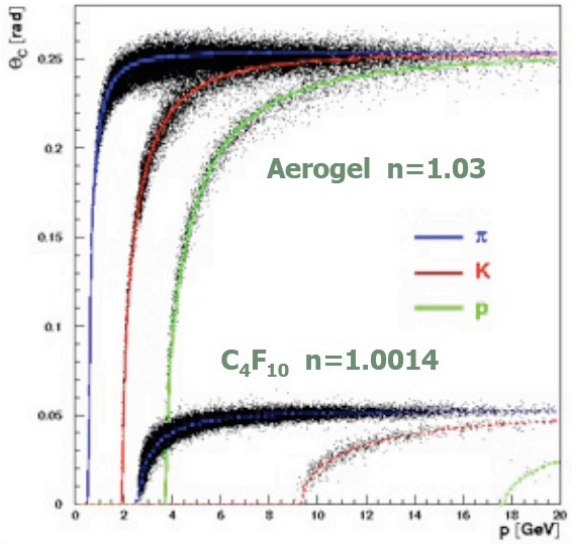
HERMES overview

27.6 GeV e+/e- HERA beam

Access to valence and sea



Electron and Hadron ID

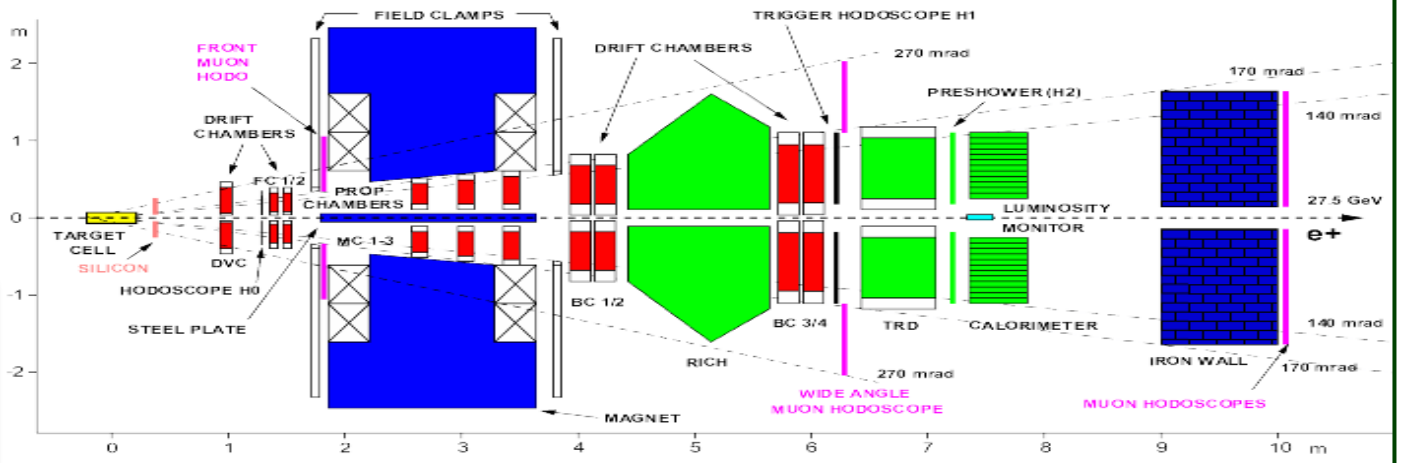


hermes

Data taking: 95-07

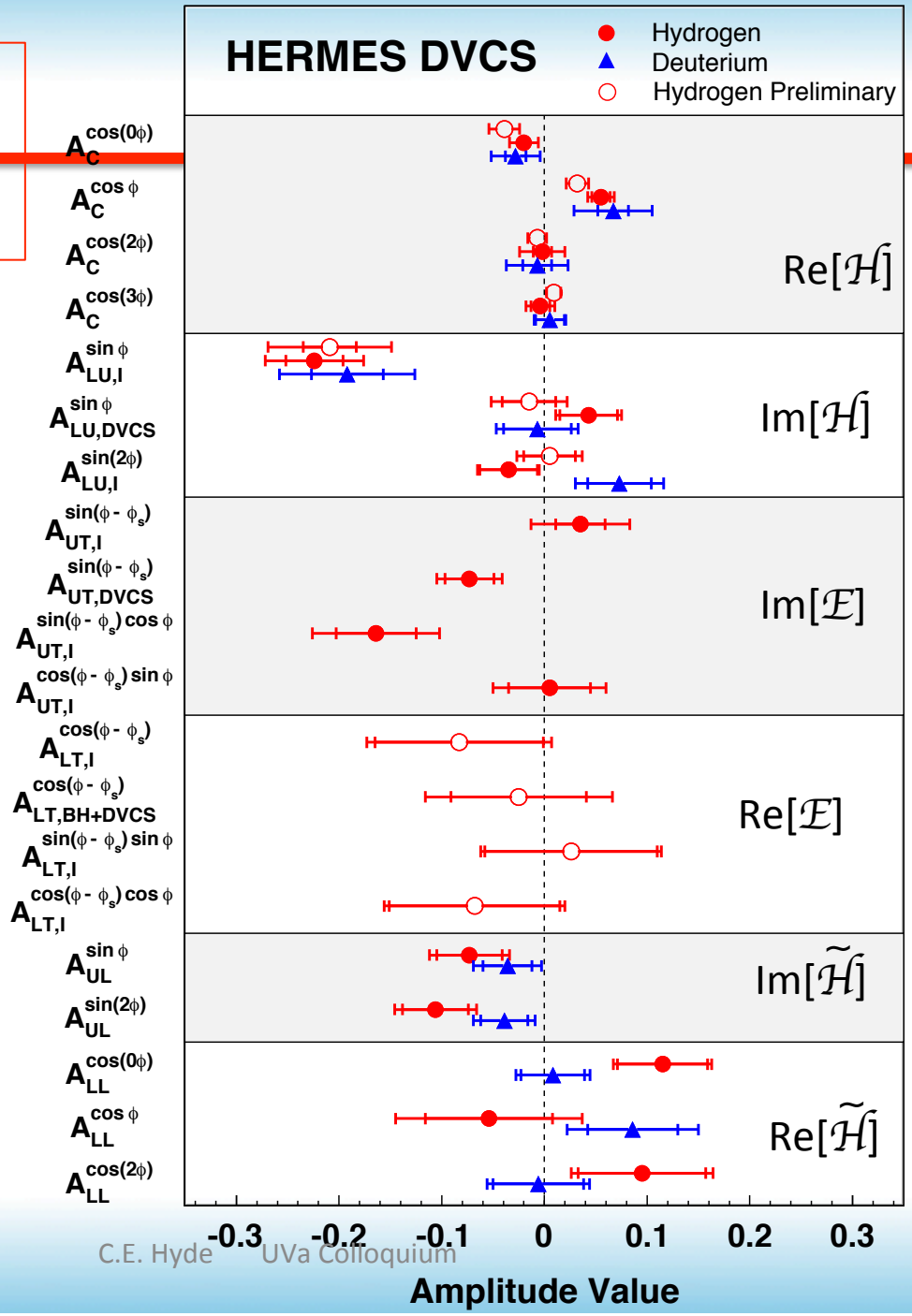
Internal gaseous target
(no nuclear effects)

96-00 (H/D) Lpol + Upol
02-05 (H) Tpol + Upol
06-07 (H/D) Upol+Recoil



HERMES summary

- averaged over Q^2 and t
- Transversely polarized H^- target → sensitivity to $E(\xi,\xi,\Delta^2)$, $\xi \approx 0.1$



DVCS Asymmetries

e^+e^-

Beam Spin Asymmetry

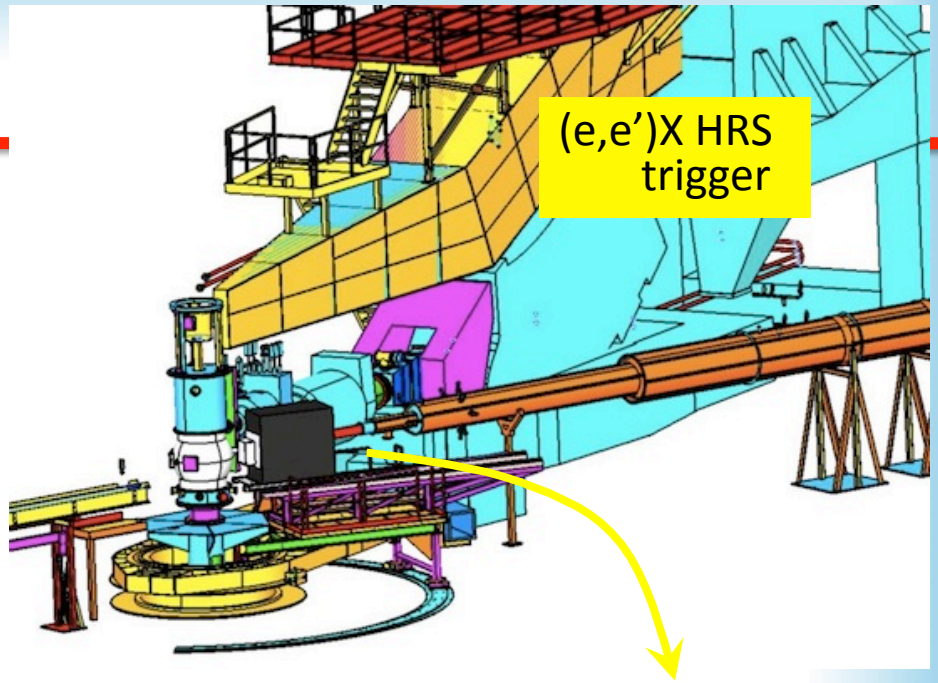
Transverse target Single Spin

Beam & Transverse Target Double Spin

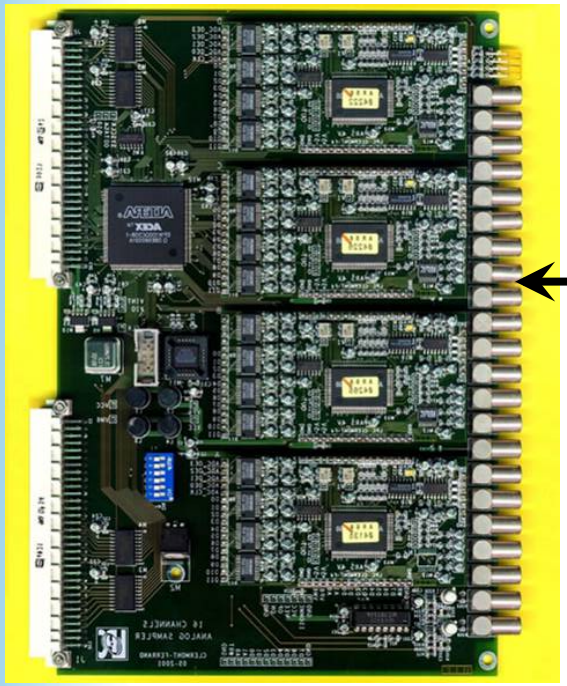
Longitudinal Target

DVCS: JLab Hall A 2004, 2010, 2014-2016

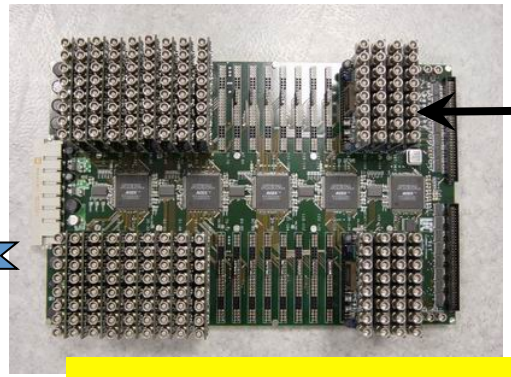
$L \geq 10^{37}$ cm^2/s
Precision cross sections
- Test factorization
- Calibrate Asymmetries



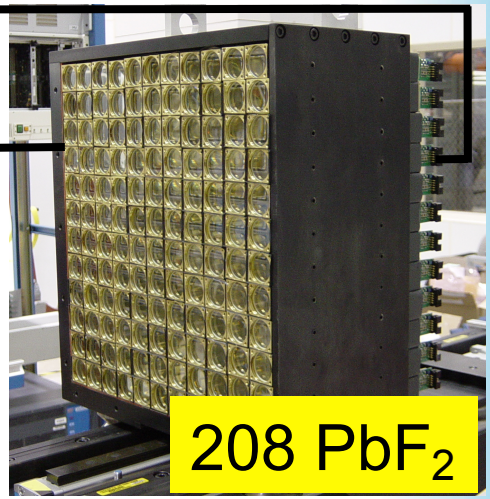
$\vec{e}$



16chan VME6U: ARS
128 samples@1GHz



Digital Trigger
Validation

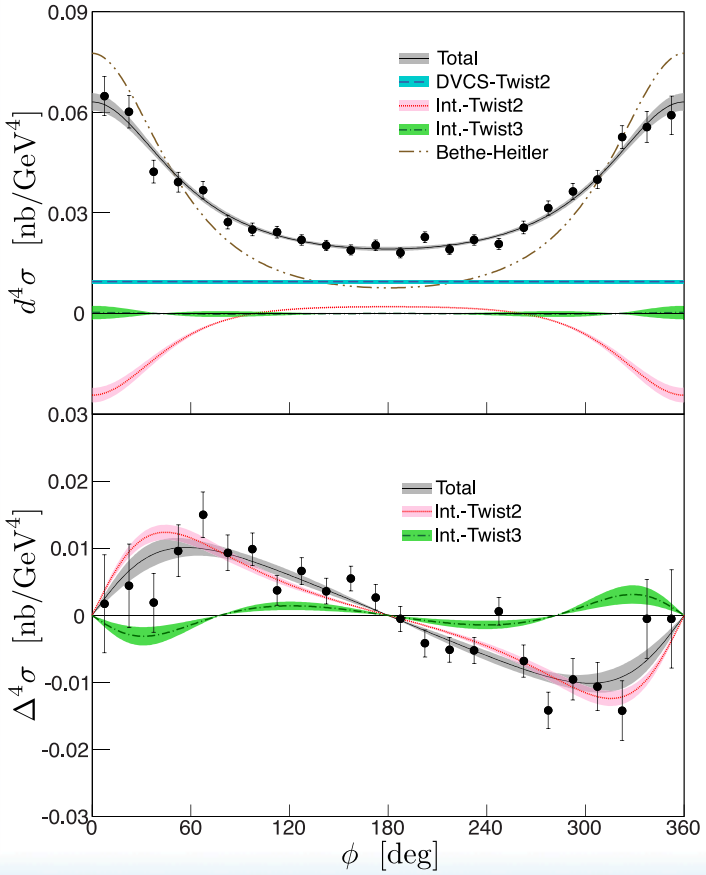


208 PbF_2

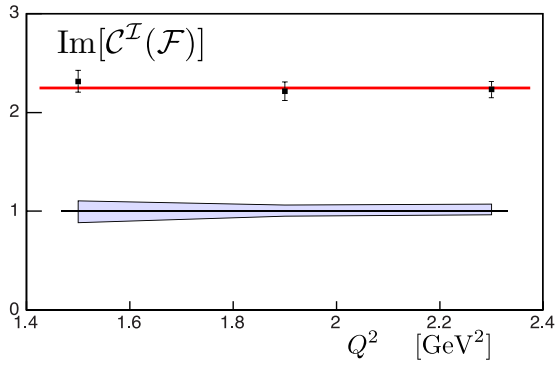
Hall A Results: Scaling Tests

- Q^2=2.3 GeV^2, x_{Bj}=0.36, t=–0.23 GeV^2

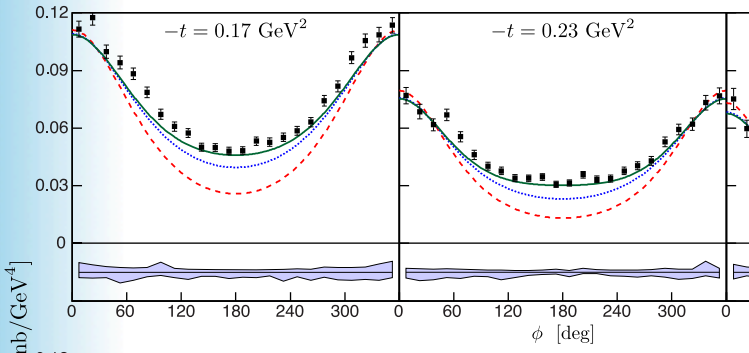
PRL**97**:262002 (2006)
C. Muñoz Camacho, *et al.*,
PRC **92**, 055202 (2015)
M.Defurne, *et al.*,



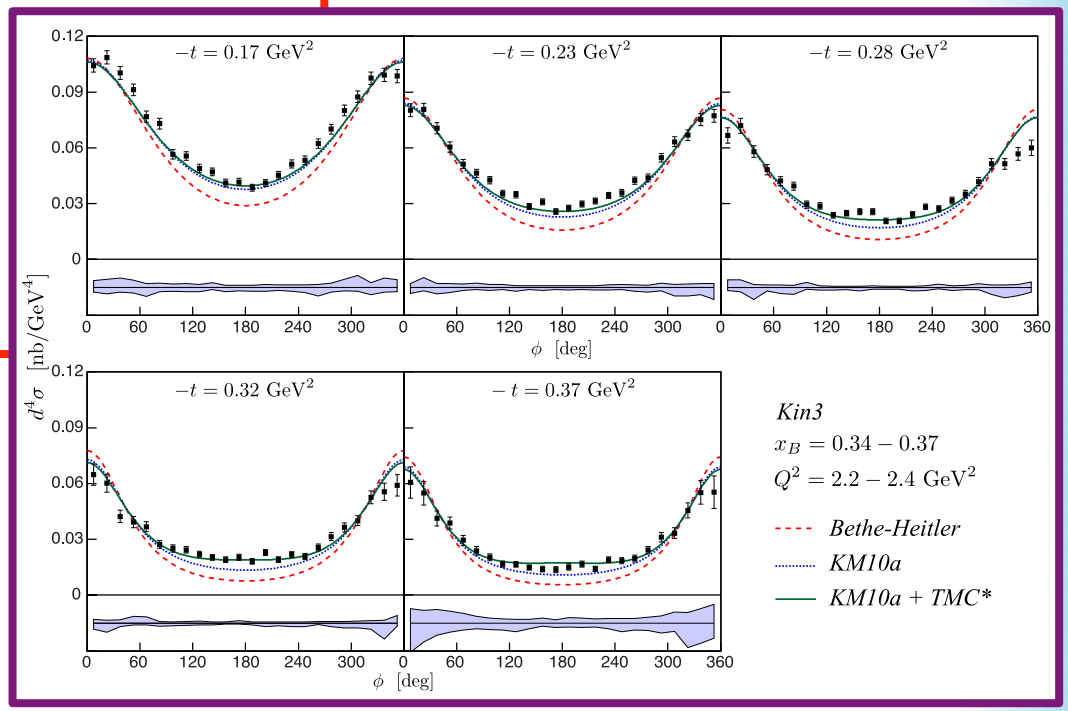
- Empirical extraction
  - Leading-twist (GPD);
  - Higher-twist terms
- Test Q^2-independence of GPD terms



Unpolarized Cross Sections: Model Consistency ➔ Scaling



Kin2
$x_B = 0.34 - 0.38$
$Q^2 = 1.8 - 2.0$ GeV^2
Bethe-Heitler
KM10a
*KM10a + TMC**



Kin3
$x_B = 0.34 - 0.37$
$Q^2 = 2.2 - 2.4$ GeV^2
Bethe-Heitler
KM10a
*KM10a + TMC**

DVCS in CLAS @ 6 GeV

- H(e,e'γp)
- Longitudinally polarized NH_3 target.
- Add:

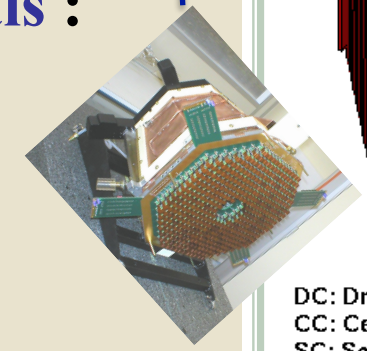
5 Tesla Solenoid

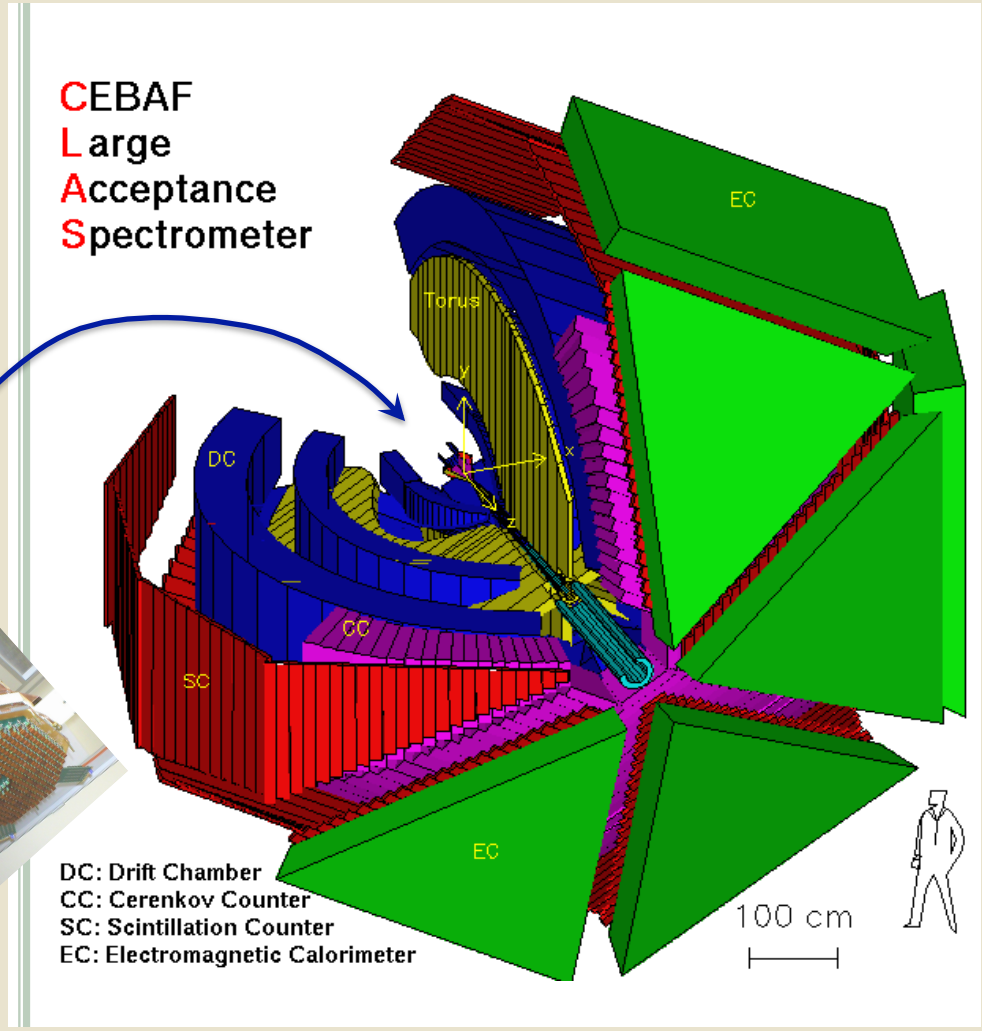
420 $PbWO_4$ crystals :

~10x10x160 mm^3

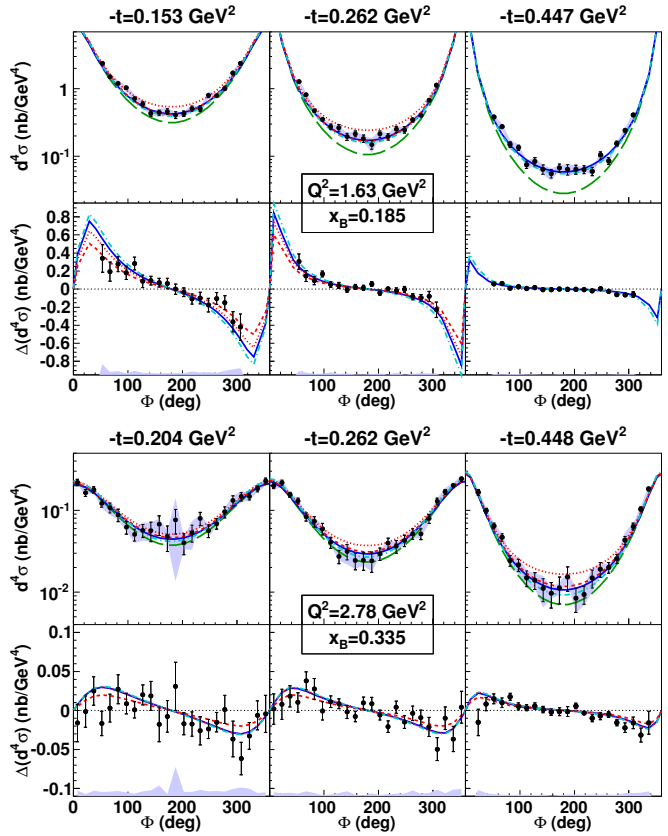
APD+preamp readout

Orsay / Saclay / ITEP / Jlab





CLAS DVCS (unpolarized Target)



H.S. Jo, F.-X Girod, *et al.*, Phys.Rev.Lett. 115 (2015) 21, 212003

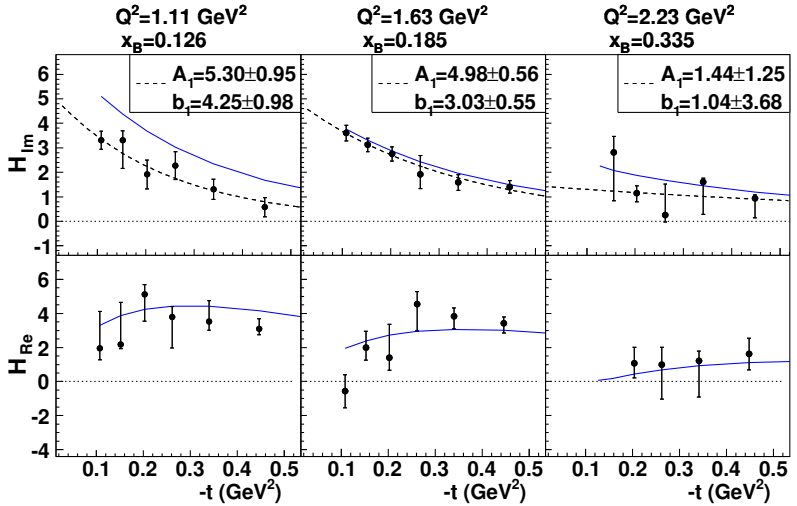
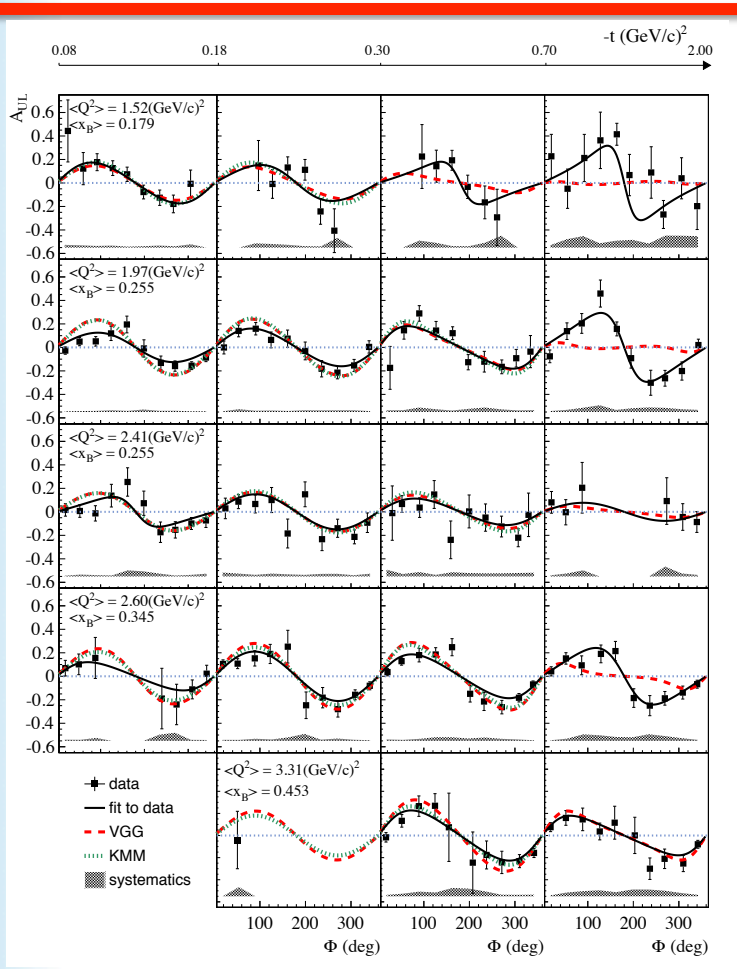


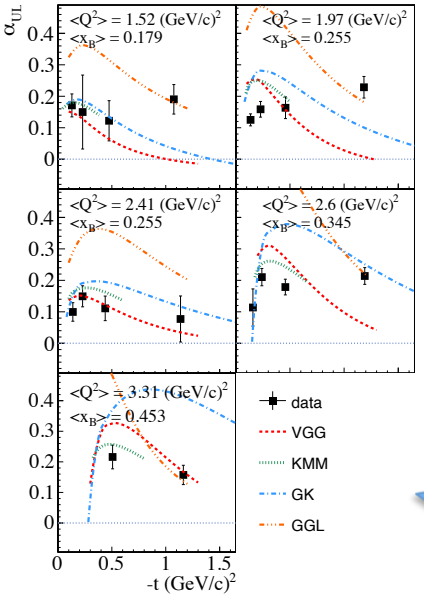
FIG. 5. (Color online) Results of the CFF fit of our data

Model-dependent extraction of Re and Im parts of the $H(\xi,\xi,t)$ Compton form Factor (unpolarized GPD)

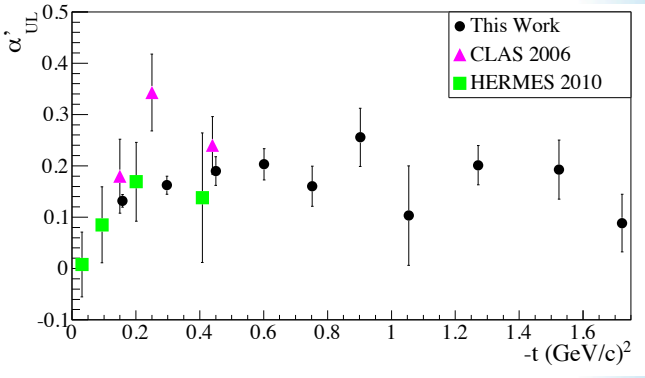
CLAS: Longitudinally Polarized Protons Target-Spin Asymmetries

A_{UL}





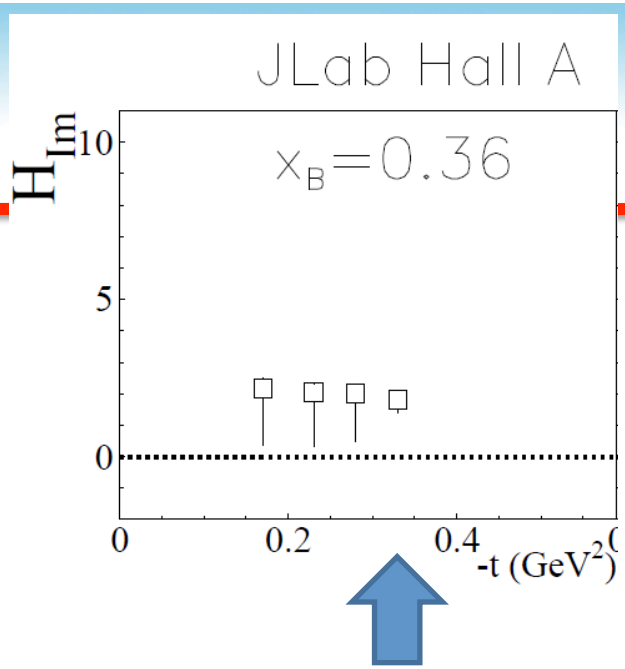
S. Pisano, *et al.*, Phys.Rev. **D91** (2015) 5, 052014



- Spatial distribution of quark helicity
- On to to 11 GeV!

Global analyses of GPD data

- K. Kumericki, D. Mueller, M. Murray,
  - arXiv:1301.1230 hep-ph, arXiv:1302.7308 hep-ph
- M. Guidal, H.Moutarde,
  - EPJA **42** (2009) 71.
- P.Kroll, M. Diehl
  - **Eur.Phys.J. C73 (2013) 2397**
- M. Guidal,
  - PLB **689** (2010) 159, PLB **693** (2010) 17.
- S. Liutti, G. Goldstein,
  - Phys.Rev. D84 (2011) 034007
- LO or NLO implemented
- Dynamic twist-3 formalism known, not implemented in global analysis yet.
  - Finite $-t/Q^2$, M^2/Q^2 corrections up to kinematic twist-4. V. Braun, *et al*, Phys.Rev. D89 (2014) 074022.



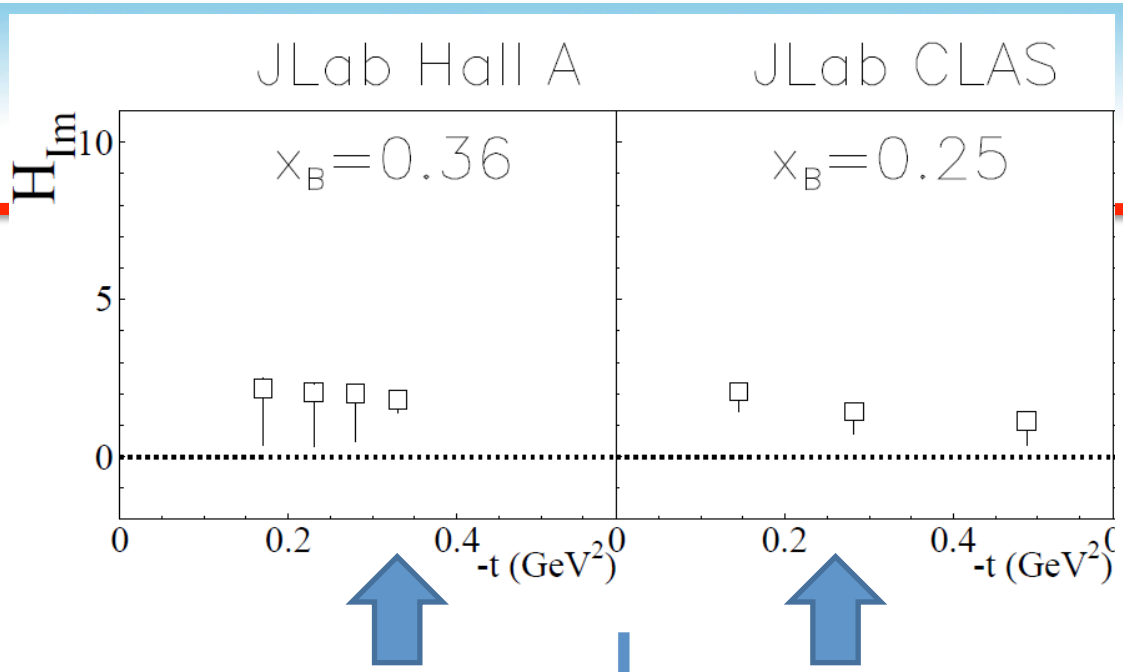
unpol. cross section

+

helicity-dependent cross section

- **χ^2 minimization**

$$\Delta\sigma_{LU} \sim \sin\phi \; \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - kF_2\mathcal{E}\}\, d\phi$$



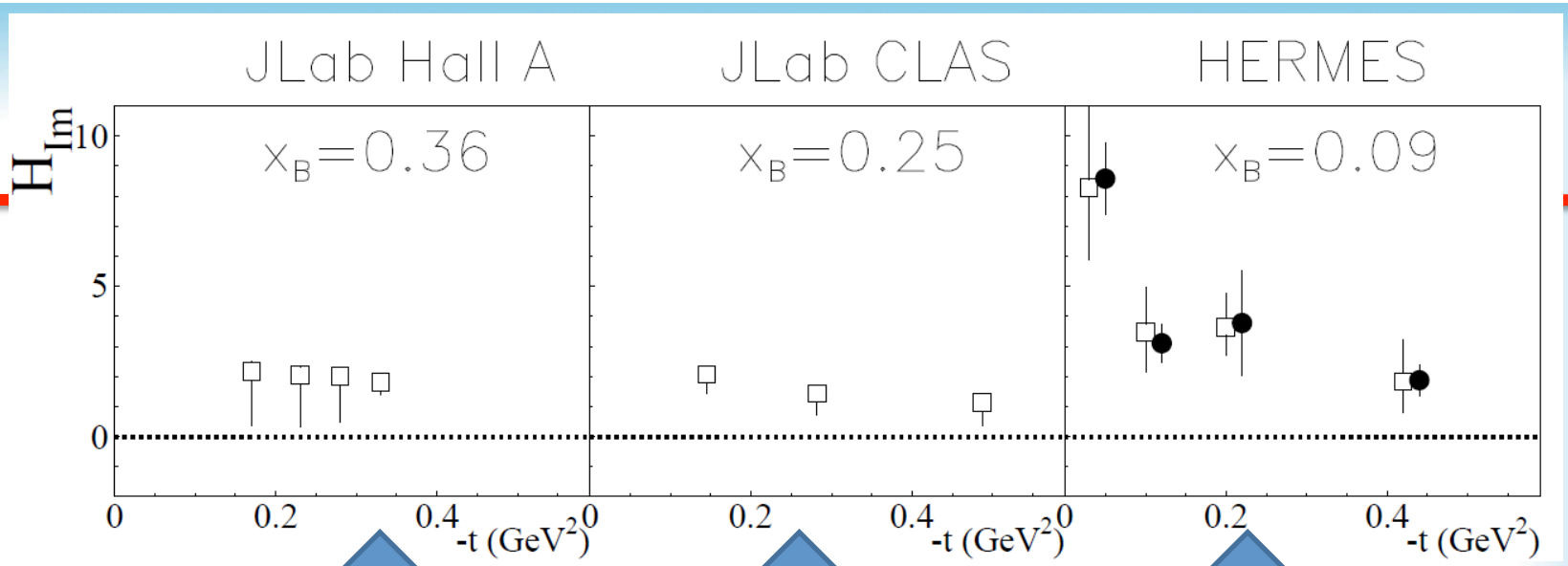
unpol. cross section
+
helicity-dependent cross section

beam spin asym.
+
long. pol. tar. asym

- **χ^2 minimization**

$$\Delta\sigma_{LU} \sim \sin\phi\ \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$$

$$\Delta\sigma_{UL} \sim \sin\phi\,\mathrm{Im}\{F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi kF_2\,\widetilde{\mathcal{E}} + \ldots\}d\phi$$



unpol. cross section + helicity-dependent cross section

beam spin asym. + long. pol. tar. asym

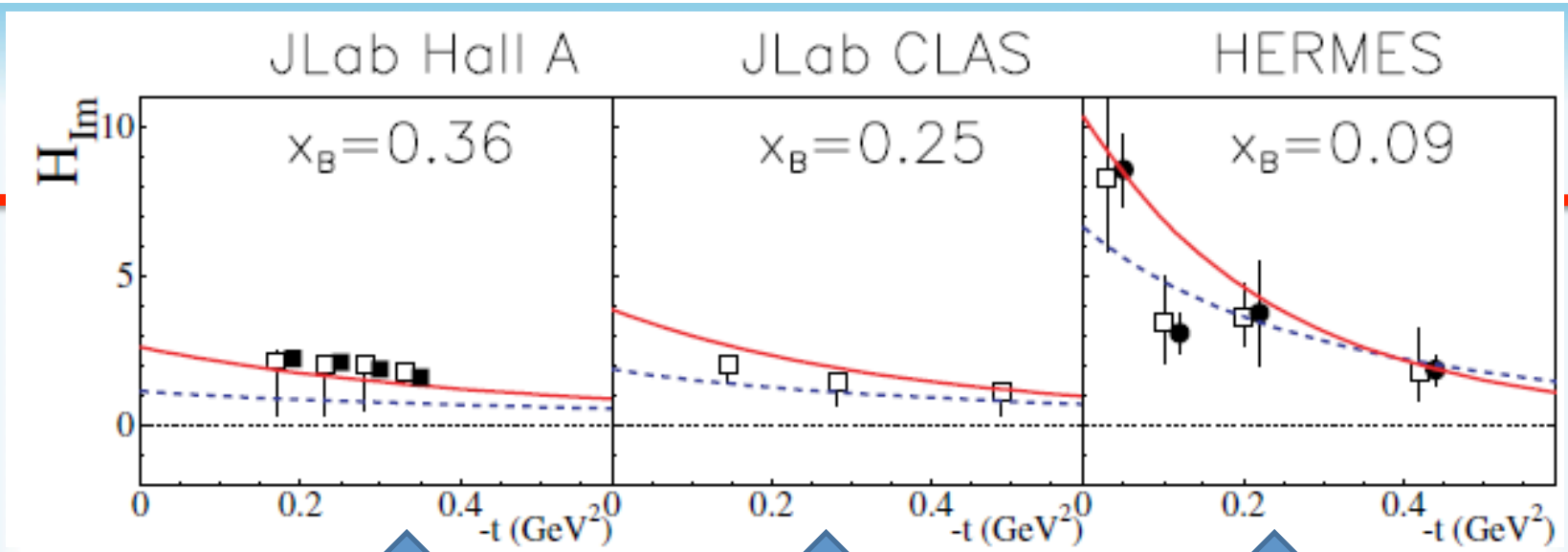
beam charge asym. + beam spin asym + …

□ **χ^2 minimization**

● **linearization**

$\Delta\sigma_{LU} \sim \sin\phi\ \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\mathcal{H} - kF_2\mathcal{E}\}d\phi$

$\Delta\sigma_{UL} \sim \sin\phi\,\mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi kF_2\,\mathcal{E} + \ldots\}d\phi$



unpol.sec.eff.
+
beam pol.sec.eff.

beam spin asym.
+
long. pol. tar. asym

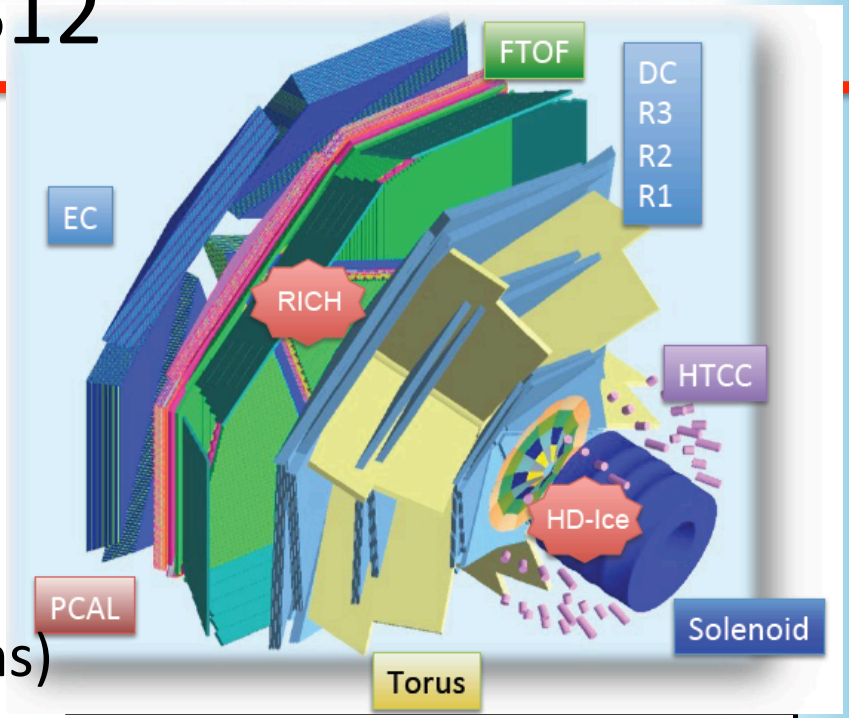
beam charge asym.
+
beam spin asym
+
…

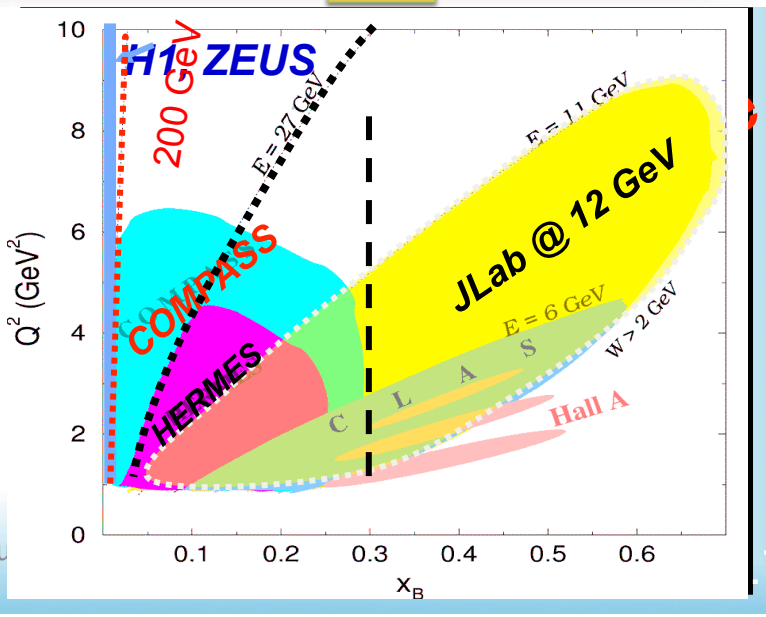
- χ^2 minimization
- linearization
- Moutarde10 model/fit
- VGG model
- KM10 model/fit

As x_B = *0.09* → *0.25* → *0.36*
t-slope flattens
Proton shrinks!

Hall B @ 11 GeV: CLAS12

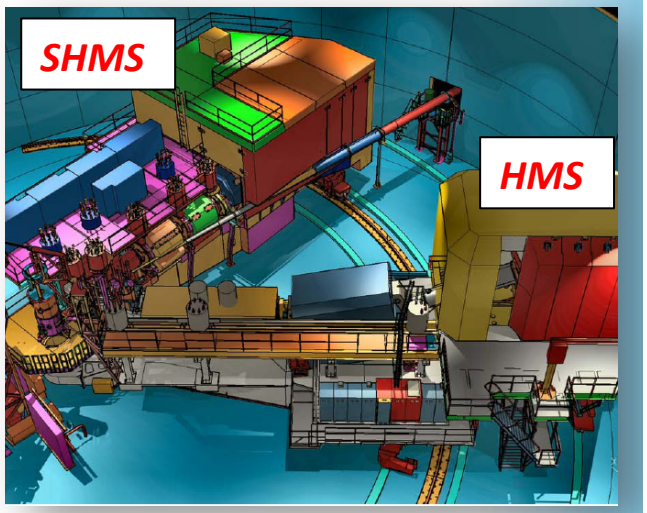
- Wide kinematic coverage
- Over-complete exclusivity
- High multiplicity mesonic final states
  - $\rho \rightarrow \pi\pi$, $\omega \rightarrow \pi\pi\pi$, $\phi \rightarrow KK$
- Timelike Compton Scattering (TCS)
  - $\gamma\, p \rightarrow p\, e^+\, e^-$, (Quasi-real Photons)
  - $\gamma\, p \rightarrow p\, J/\Psi$
- Cross section systematic errors 5-10%
- Longitudinally polarized NH_3, ND_3
- Transversely polarized HD-ice target in development

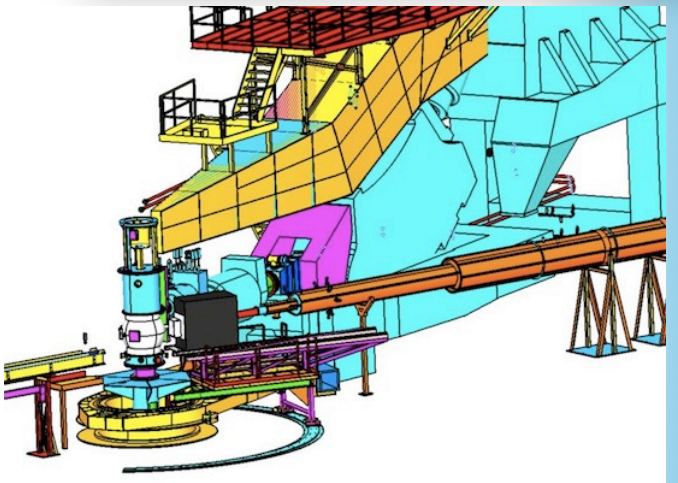




GPDs at JLab: Halls A & C @ 11 GeV

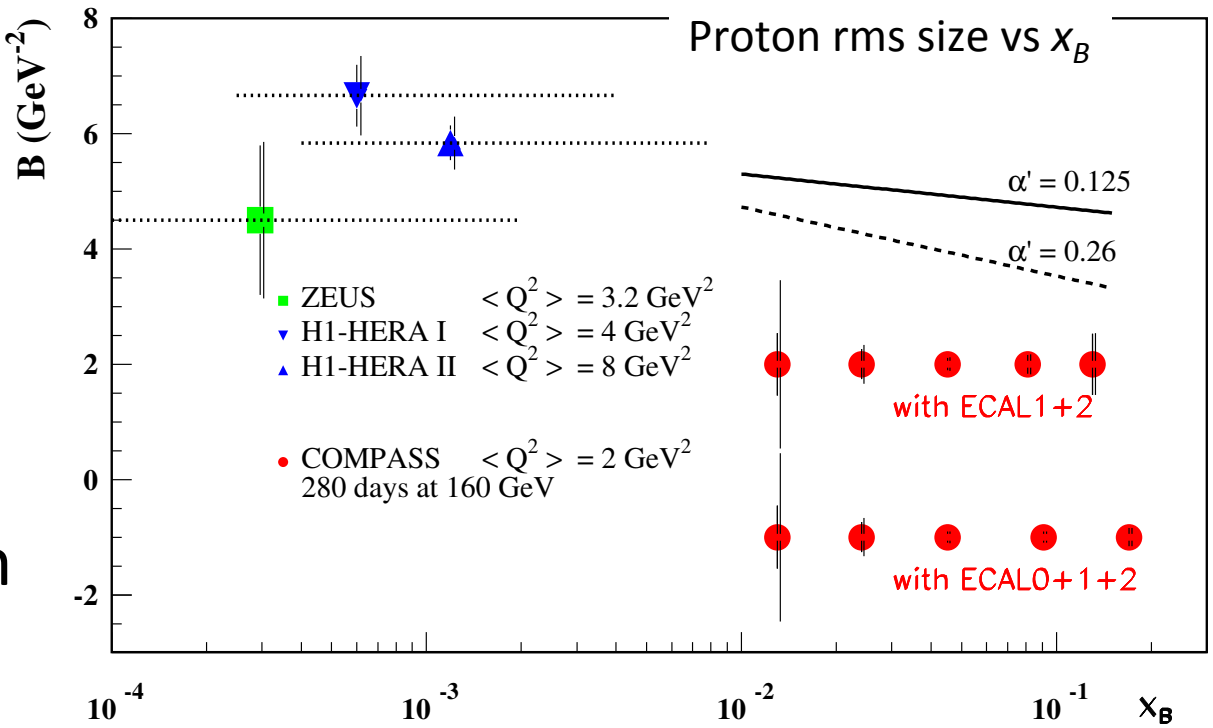
- Hall C: 12 GeV: HMS x SHMS
  - L/T separations:
    H$(e,e'\pi^+)n$, $H(e,e'K^+)\Lambda$
- Halls A & C:
  Spectrometer × Calorimeter
  - DVCS & Exclusive π^0.
    - Hall A 2014-2015
  - H$(e,e'\gamma)p$ H$(e,e'\gamma\gamma)p$
    - Exclusivity by missing mass
  - dσ systematic errors ≤ 4%
  - Polarized ^{3}He (L & T) possible

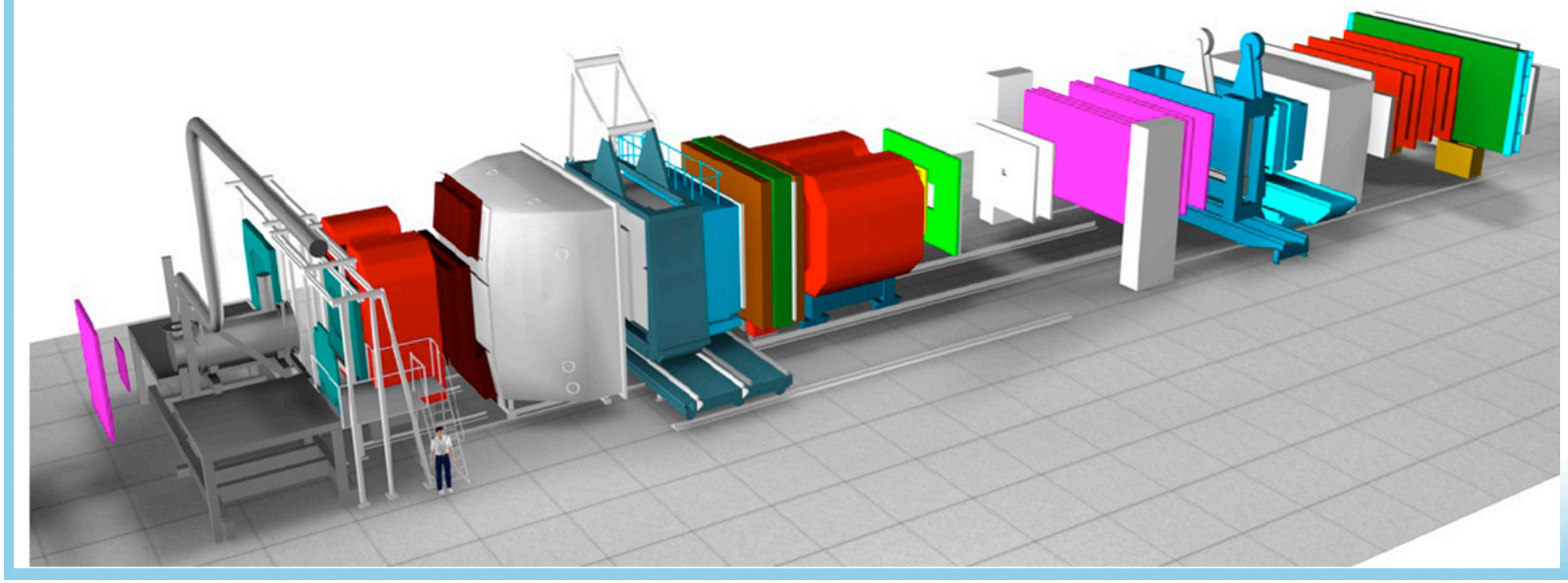




COMPASS

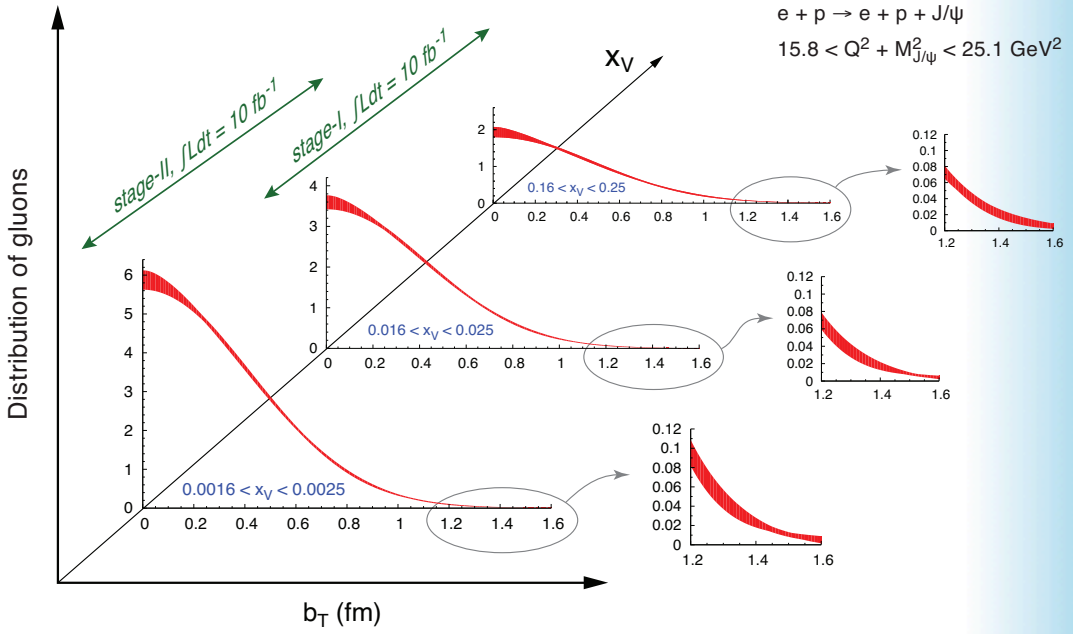
- 200 GeV $\mu^+\uparrow$, $\mu^-\downarrow$
- $\mathcal{L} = 10^{32}$ /cm^2/s
- 2016+
  After Drell-Yan run





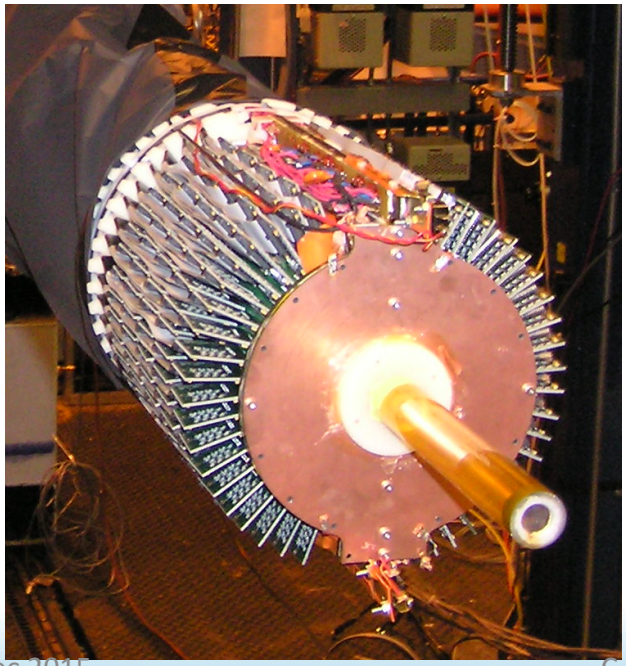
Electron-Ion Collider

- JLab and BNL designs
  - $s = 2k(E+P) \geq 4000$ GeV^2
  - $\mathcal{L} > 10^{33}$ /cm^2/sec (proton)
- Longitudinal and transversely polarized light ion beams
- Unpolarized from H to U
- Spectator tagging: D, ^{3}He
  - Inclusive and Deep virtual
- ArXiv 1212.1701

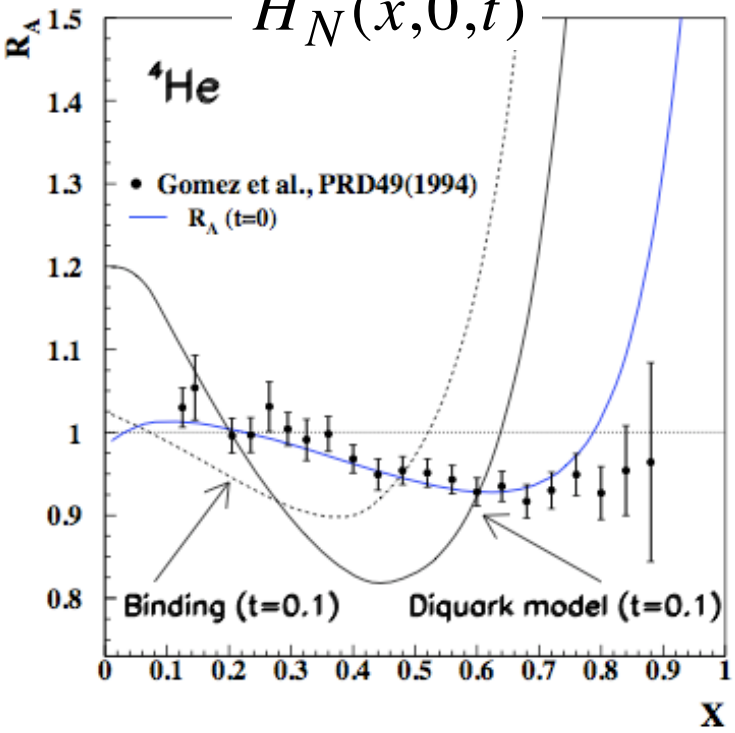


Nuclei Too! CLAS: ^{4}He(e,e'γα)

- Only one GPD on spin 0 target
  - $H(\xi,\xi,t)=(4/9)H_u+(1/9)\,H_u$.
  - $G_E=\int dx[(2/9)H_u-(1/9)H_u]$.
  - EMC effect on GPDs
  - BoNuS GEM radial TPC



$$\frac{H_{He}(x,0,t)}{H_N(x,0,t)}$$



[t=0.0] →EMC effect,
[t=-0.1]→ GPD
(Liuti & Taneja, Guzey & Strickman)

Conclusions

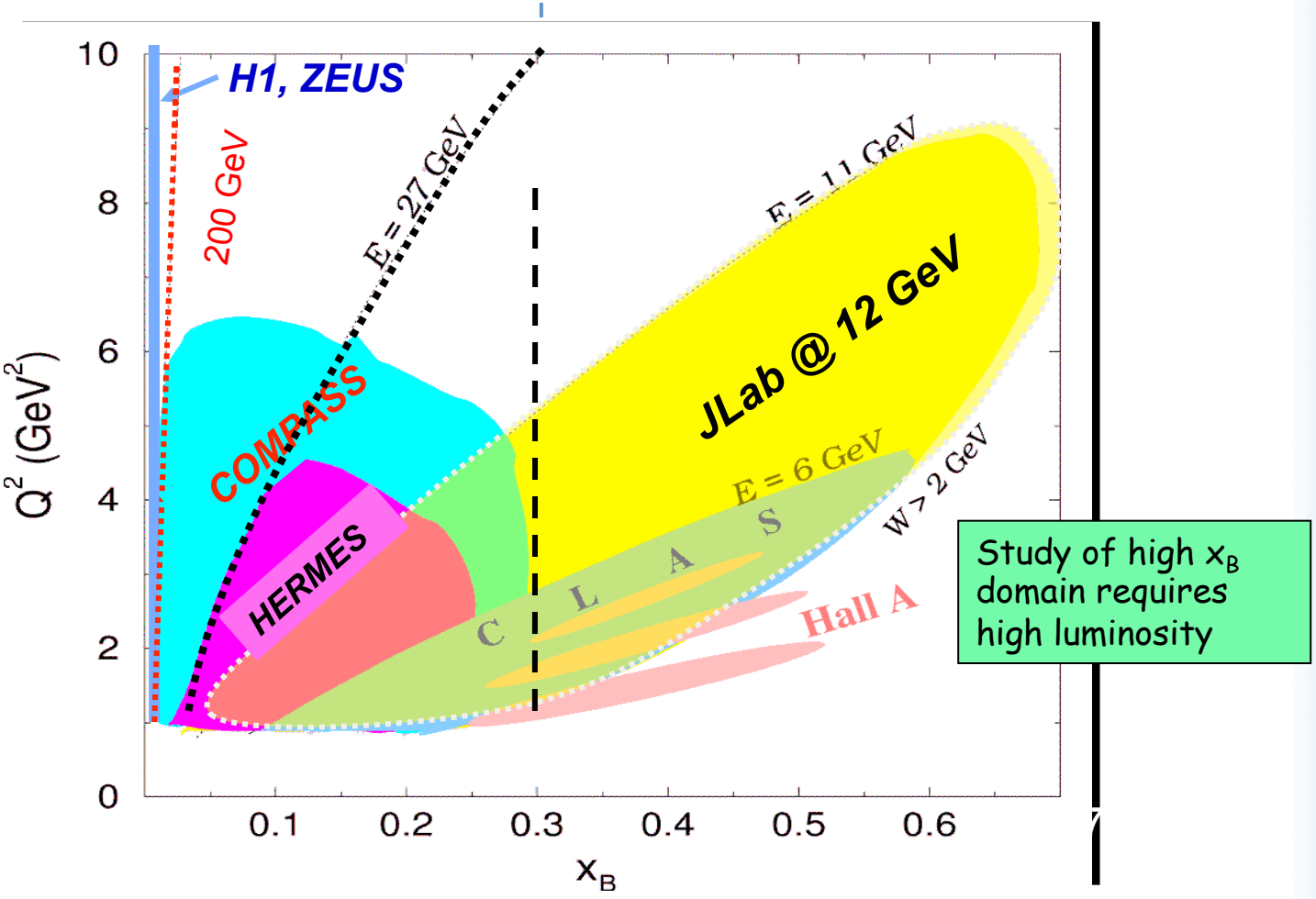
- Spatial Imaging ***is*** possible (in 1+2 dimensions)
- New experimental and theoretical tools are helping us to understand how QCD generates
  - The mass of ordinary matter (98%)
  - The spin of the hadrons: proton, neutron, vector mesons…
    - proton spin ~25% from spin of quarks
    - How much is gluons? How much is Orbital Angular Momentum.
  - Spatial distribution of charge and matter in hadrons. (non-trivial flavor, momentum-fraction dependence)
  - Nuclear Binding
    - Why is the deuteron (*np*) bound but *nn* not?
    - Why are ^{4}He, ^{6}He(β^- 1sec), ^{8}He(β^- 0.1sec) bound, but not ^{5}He ?

Backup Slides

TCS

Deep Virtual Meson Production

Deeply Virtual Exclusive Processes -
Kinematic Coverage



Study of high x_B domain requires high luminosity

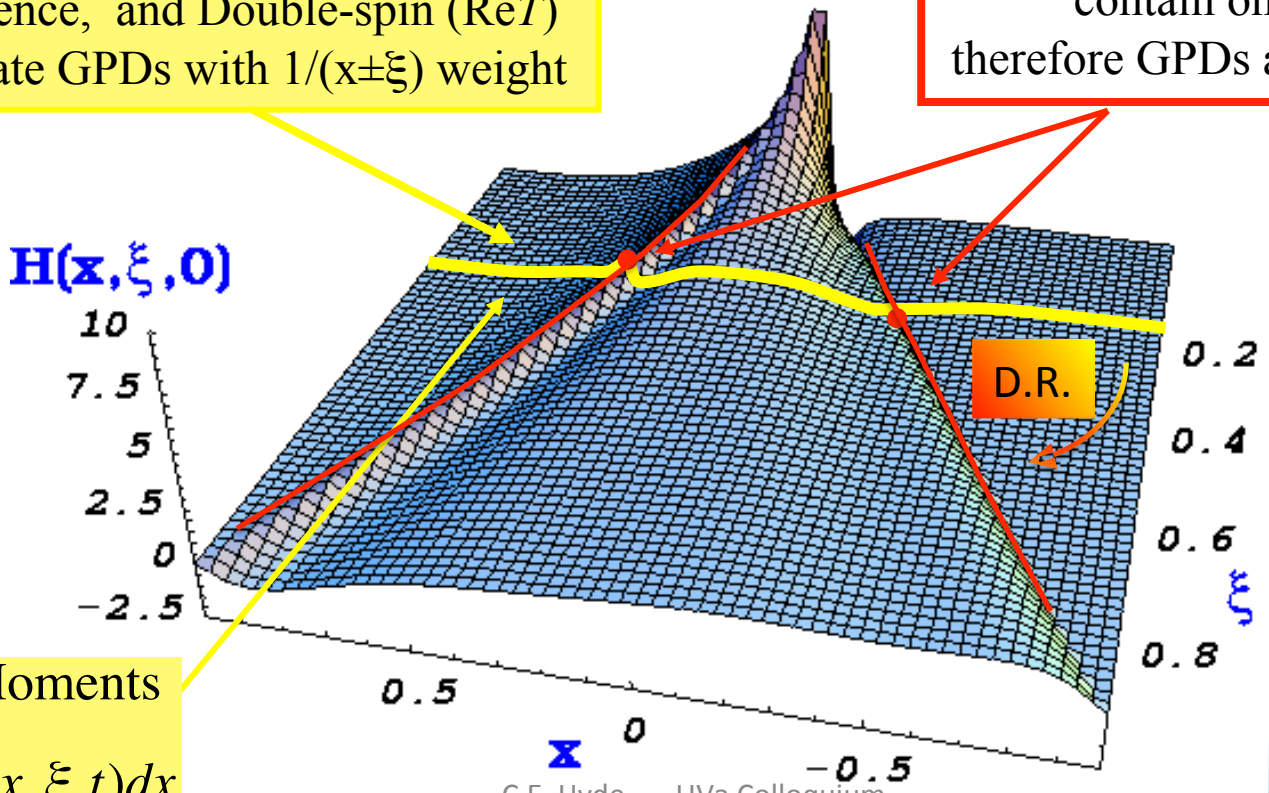
DVCS, GPDs, Compton Form Factors(CFF), and Lattice QCD

(at leading order:)

$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi + i\varepsilon} dx + \ldots \sim P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx - i\pi H(\pm\xi,\xi,t) + \ldots$$

Cross-section (σ), Beam-charge-difference, and Double-spin (Re*T*) integrate GPDs with 1/(x±ξ) weight

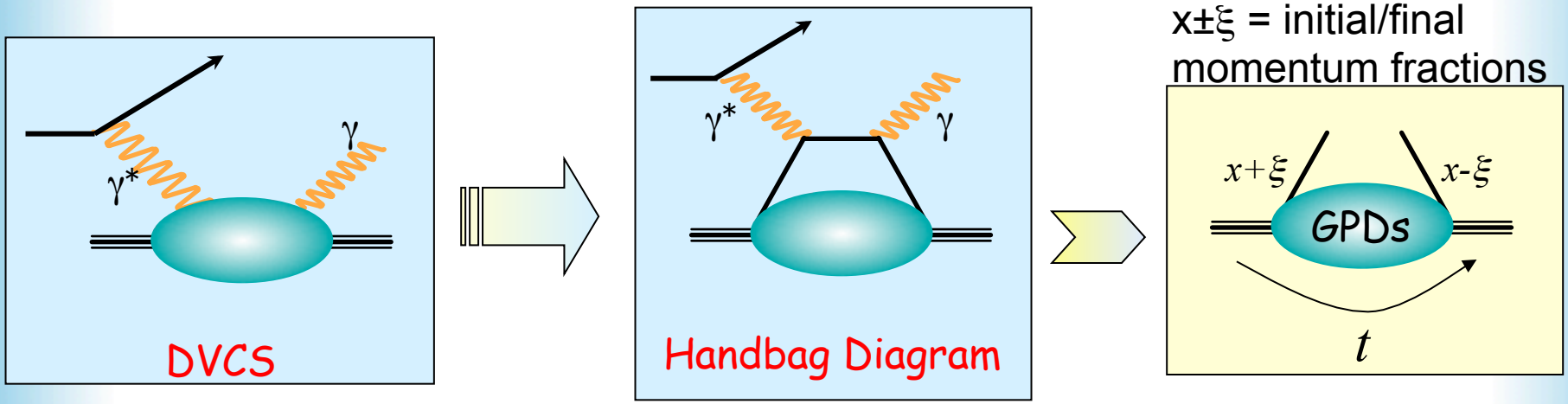
Beam or target spin Δσ contain only Im*T*, therefore GPDs at $x = \xi$ and $-\xi$



Lattice Moments

$= \int x^n H(x,\xi,t)dx$

Spatial distributions and orbital angular momenta of quarks: Deeply Virtual Compton Scattering (DVCS): N(e,e'γN)



Non-Local Off-Forward Matrix Elements

$$T^{\mu\nu}_{DVCS} = \int dz e^{i(q+q')z} \langle p' | T\left[J^{\mu}\left(\frac{z}{2}\right), J^{\nu}\left(-\frac{z}{2}\right)\right] | p \rangle$$

$$\Rightarrow \int dz^{-} e^{i\bar{q}^{+} z^{-} x} \left[t^{\mu\nu} \langle p' | \bar{\psi}\left(\frac{z}{2}\right)\gamma^{+}\psi\left(-\frac{z}{2}\right) | p \rangle + i\varepsilon^{\mu\nu\rho\sigma} q_{\rho} q'_{\sigma} \langle p' | \bar{\psi}\left(\frac{z}{2}\right)\gamma^{+}\gamma_{5}\psi\left(-\frac{z}{2}\right) | p \rangle \right]$$

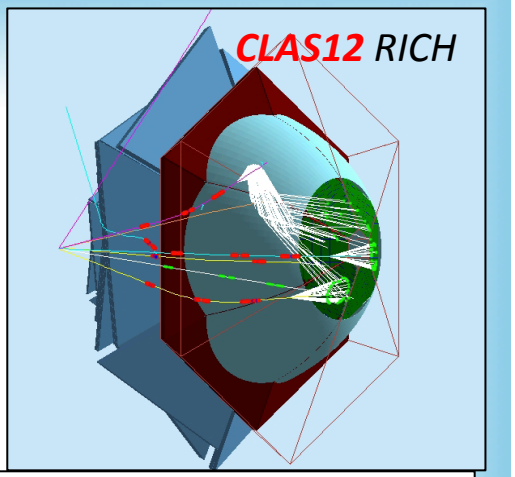
$$q^{+} = (q^{0} + q^{3})/\sqrt{2}$$
$$\gamma^{+} = (\gamma^{0} + \gamma^{3})/\sqrt{2}$$
$$z^{-} = (tc - z^{3})/\sqrt{2}$$

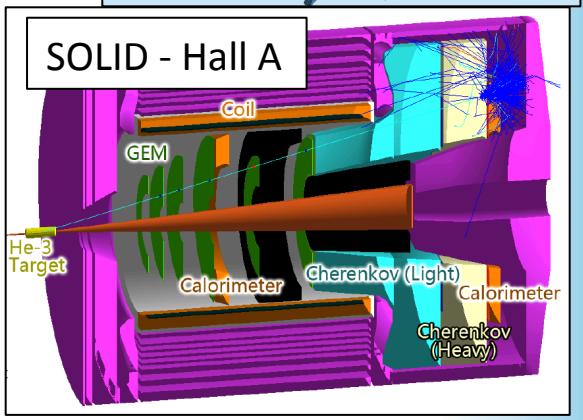
Generalized Parton Distributions: Mueller, Ji, Radyushkin, Factorization: Ji, Osborne, Collins, Freund…

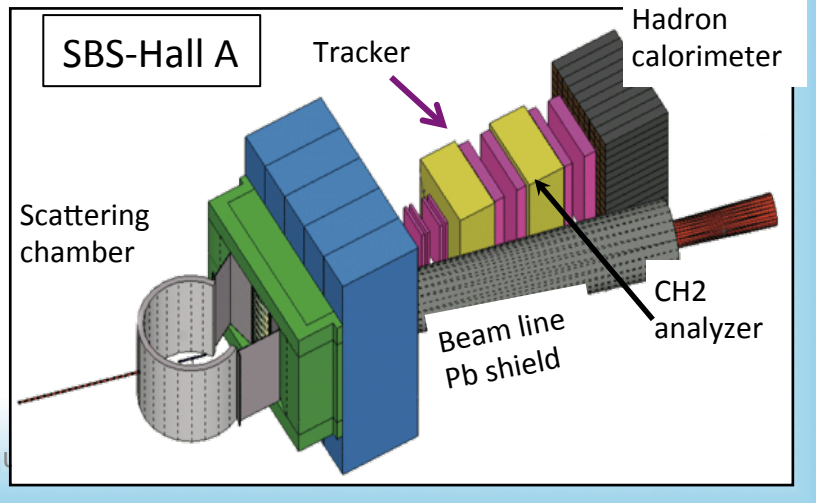
GPDs at JLab: Future Upgrades

(Mostly motivated by non-GPD topics)

- RICH Detector (partial) in CLAS 12: π/K id
  - INFN participation
- **So**lenoidal **L**arge **I**ntensity **D**etector (SoLID) in Hall A (CLEO Solenoid)
  - TCS, J/Ψ
  - Chinese participation
- **S**uper **B**igBite **S**pectrometer
  - Dipole from BNL
  - Funded, under construction
  - GEM trackers for high rates







Time-Like Compton Scattering: $\gamma + p \rightarrow e^+e^-p$

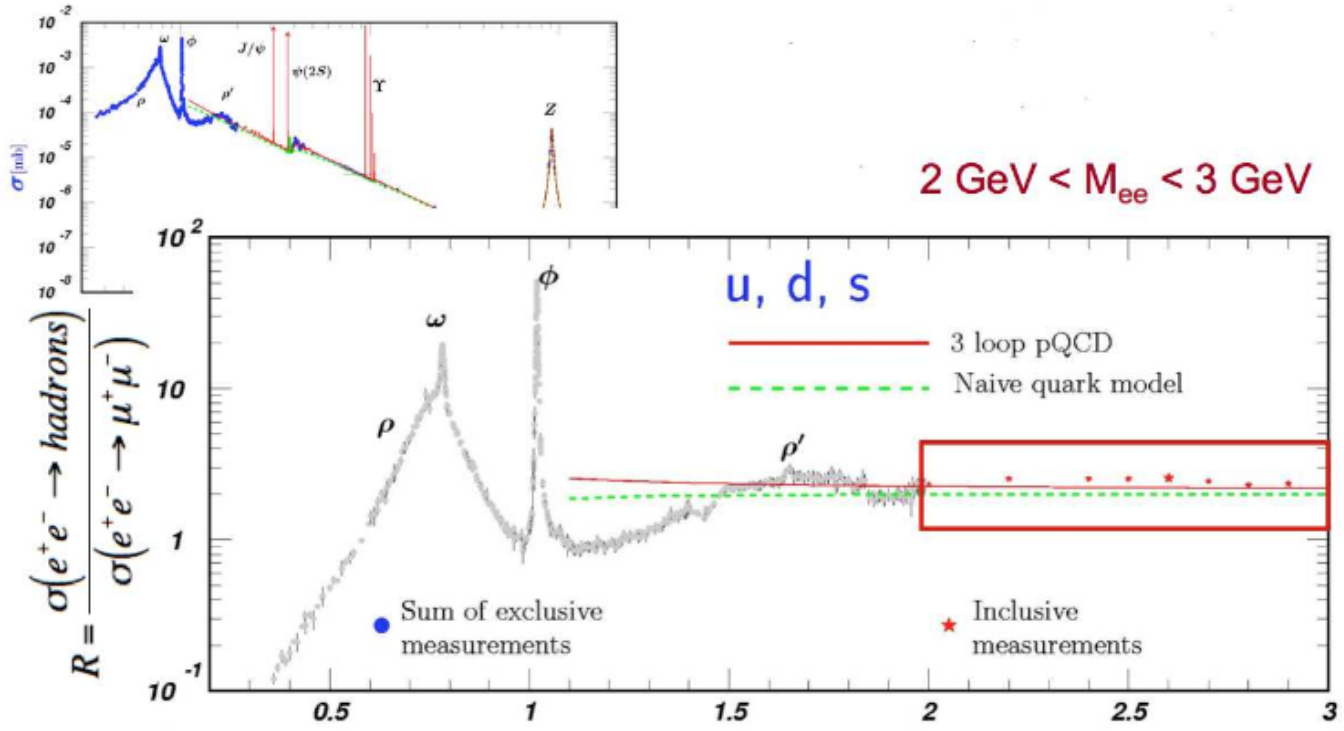
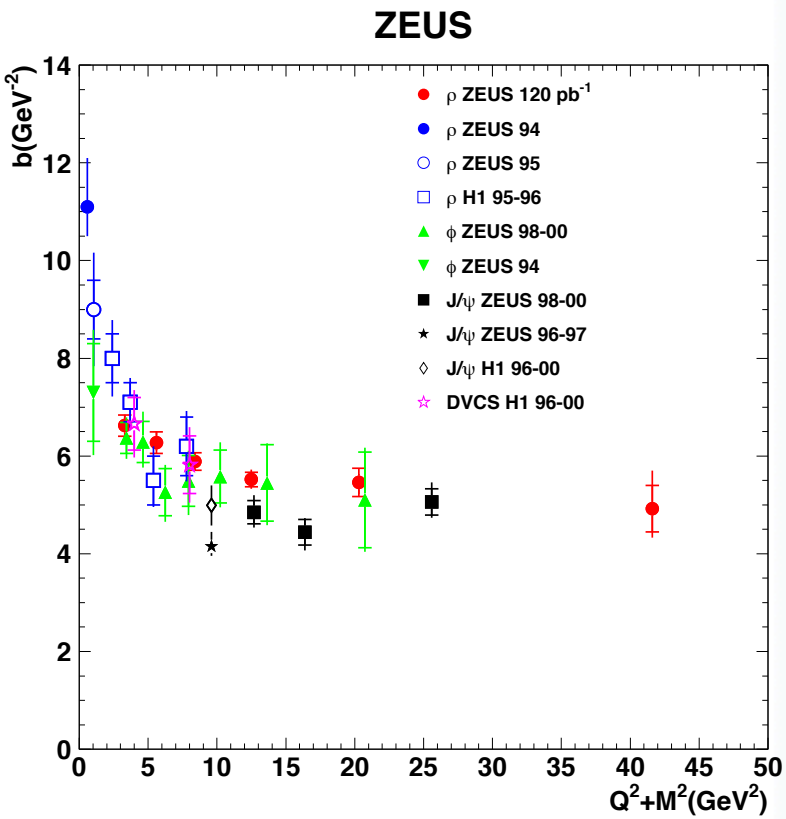


FIG. 4: Measurements of e^+e^- annihilation into hadrons show a resonance-free window between the ρ' and the J/ψ, which is ideal for TCS studies at 12 GeV.

Semi Universal behavior of exclusive reactions at high W^2

- Two views:
  - Extracting leading twist information is hopeless for $Q^2+q'^2<10$ GeV^2
  - Perturbative *t*-channel exchange even for modest Q^2, but convolution of finite size of nucleon and probe.
- Fitting data requires setting scale of gluon pdf $\mu^2 << Q^2$
  - Finite transverse spatial size $b \approx 1/\mu$ of $\gamma \rightarrow V$ amplitude



GWolf 0907.1217

Tomography with Generalized Parton Distributions (M. Burkardt)

- $H(x,t)\gamma^{\mu} + E(x,t)\sigma^{\mu\nu}\Delta_{\nu}$
  - Proton size shrinks as x→ 1.
  - Spatial separation of up- and down-quarks in a transversely polarized proton
- Spin-Flavor dependence to Proton size & profile.
  - M. Burkardt
  - up and down quarks separate in transversely polarized proton

$$\varepsilon_f(x,b_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp \cdot b_\perp} E_f(x,\Delta_\perp)$$

$$q_X(x,b_\perp) = h_q(x,b_\perp) + \frac{1}{2M}\frac{\partial}{\partial y}\varepsilon_q(x,b_\perp)$$