Electromagnetic Nuclear Properties: Summary

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Intense Electron Beams Workshop
Cornell University
June 18, 2015

Massachusetts Institute of Technology

Topics

- Proton form factor
- Pion electroproduction
- Møller

A lot of interesting results on all energy scales. This is only snapshot of stuff accessible at ERLs.

Why?

What is measured in ep elastic scattering?

The charge distribution of the nucleon.

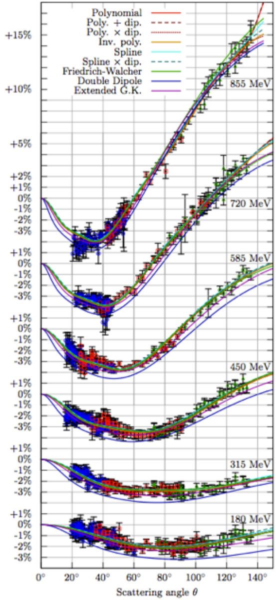
Why is that interesting?

Generally: fundamental property of nucleons - but most of the interest is at large Q^2.

Except: ongoing issues with radii and two-photon exchange. Impact on hyperfine theory uncertainties. Suggestions of structures in form factors. Etc.

R. Gilman

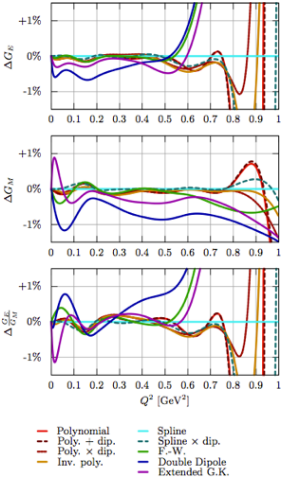
J. Bernauer et al., PRL 105, 242001 (2010)



Largest & best ep data set ever

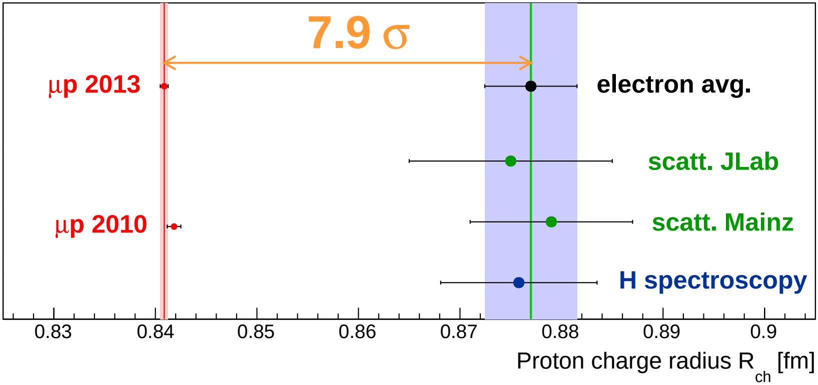
Left: Various fits vs. cross sections, all relative to "standard dipole"

Right: variation in fits to data, relative to spline. Some fits have poor χ^2, so uncertainty less than variation.



$r_p = 0.879 \pm 0.008$ fm

Motivation I

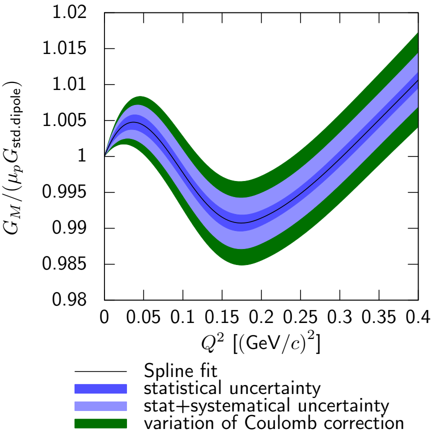


Motivation I

From the 2014 Review of Particle Physics

Until the difference between the ep and μp values is understood, it does not make sense to average the values together. For the present, we give both values. *It is up to the workers in this field to solve this puzzle.*

But wait, there is more: Motivation II

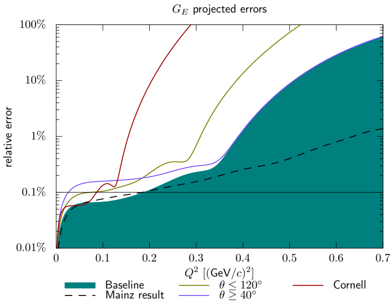


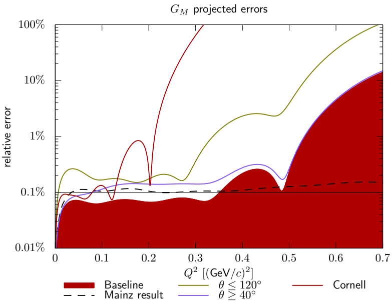
- Up-Down-Up structure in magnetic Form factor
- Gives rise to small radius ~ 0.77 fm
- Not seen before
  - Older fits approach from below
  - Lack of data!

Three methods

- Modern Rosenbluth
- ISR
- Polarization

Projected perfomance

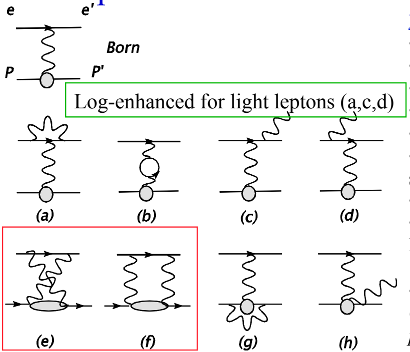




Systematics

- Point like target to reduce acceptance uncertainty
- Study systematics with **many high precision** measurements
  - many energies
  - many angles
- Experiment time will be (mostly) set-up!
- Theoretical corrections!

Complete radiative correction in O(α_{em})



Radiative Corrections:

- Electron vertex correction (a)
- Vacuum polarization (b)
- Electron bremsstrahlung (c,d)
- Two-photon exchange (e,f)
- Proton vertex and VCS (g,h)
- Corrections (e-h) depend on the nucleon structure

•Meister&Yennie; Mo&Tsai

•Further work by Bardin&Shumeiko; Maximon&Tjon; AA, Akushevich, Merenkov;

•Guichon&Vanderhaeghen' 03:
Can (e-f) account for the Rosenbluth vs. polarization experimental discrepancy? Look for ~3% ...

Main issue: Corrections dependent on nucleon structure

Model calculations:

•Blunden, Melnitchouk,Tjon, Phys.Rev.Lett.**91**:142304,2003

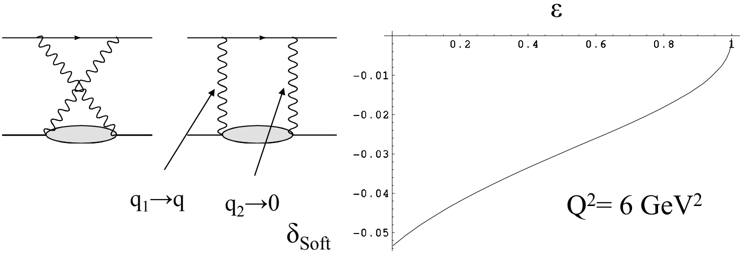
•Chen, AA, Brodsky, Carlson, Vanderhaeghen, Phys.Rev.Lett.**93**:122301,2004

Bremsstrahlung for Relativistic vs Nonrelativistic Lepton Scattering

- Accelerated charge always radiates, but the magnitude of the effect depends on kinematics
- See Bjorken&Drell (Vol.1, Ch.8):
  - For large $Q^2 >> m_e^2$ the rad.correction is enhanced by a large logarithm, $\log(Q^2/m_e^2) \sim 15$ for GeV^2 momentum transfers
  - For small $Q^2 << m_e^2$, rad.correction suppressed by Q^2/m_e^2
  - For intermediate $Q^2 \sim m_e^2$, neither enhancement nor suppression, rad correction of the order $2\alpha/\pi$
- Implications for COMPASS @CERN: rad. corrections reduce for $\log(Q^2/m_\mu^2) \sim 3$ by about a factor of 5 compared to electrons (*good news!*) and become comparable in magnitude to two-photon effects (*bad news!*)

Separating *soft* 2-photon exchange

- Tsai; Maximon & Tjon (k→0); similar to Coulomb corrections at low Q^2
- Grammer &Yennie prescription PRD 8, 4332 (1973) (also applied in QCD calculations)
- Shown is the resulting (soft) QED correction to cross section
- **<u>Already included in experimental data analysis for elastic ep</u>**
  - <u>Also done for pion electroproduction in AA, Aleksejevs, Barkanova, Phys.Rev. D88 (2013) 5, 053008 (inclusion of lepton masses is straightforward)</u>



Lepton mass is not essential for TPE calculation in ultra-relativistic case;
Two-photon effect below 1% for lower energies and $Q^2 < 0.1 GeV^2$

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Coulomb and Two-Photon Corrections

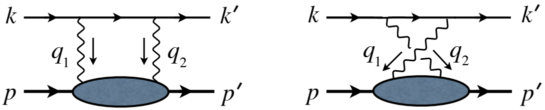
- Coulomb correction calculations are well justified at lower energies and Q2
- Hard two-photon exchange (TPE) contributions cannot be calculated with the same level of precision as the other contributions.
- Two-photon exchange is independent on the lepton mass in an ultra-relativistic case.
- Issue: For energies ~ mass TPE amplitude is described by 6 independent generalized form factors; but experimental data on TPE are for ultrarelativistic electrons, hence independent info on 3 other form factors will be missing.
- Theoretical models show the trend that TPE has a smaller effect at lower Q^2 . The reason is that "hard" TPE amplitudes do not have a $1/Q^2$ Coulomb singularity, as opposed to the Born amplitude.

Various Approaches (circa 2003-2008)

Low to moderate Q^2:

hadronic: $\mathrm{N} + \Delta + \mathrm{N}^*$ etc.

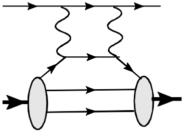
- as Q^2 increases more and more parameters, less and less reliable



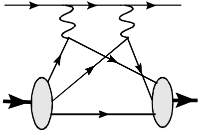
(PGB *et al.*, Phys. Rev. Lett **91**, 142304 (2003))

Moderate to high Q^2:

- GPD approach: assumption of hard photon interaction with 1 active quark
  - Embed in nucleon using Generalized Parton Distributions
  - Valid only in certain kinematic range ($|s,t,u| \gg M^2$)



"handbag"



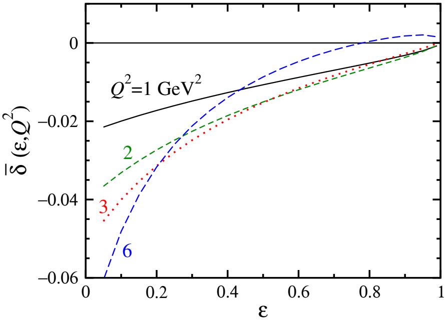
"cat's ears"

(Afanasev *et al.*, Phys. Rev. D **72**, 013008 (2005))

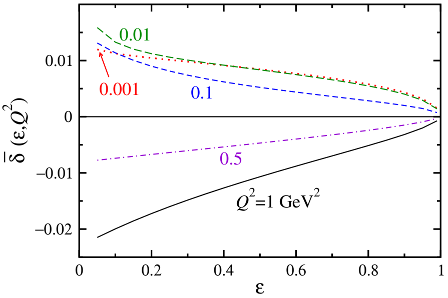
- pQCD: recent work indicates two active quarks dominate

Nucleon (elastic) intermediate state

P. Blunden



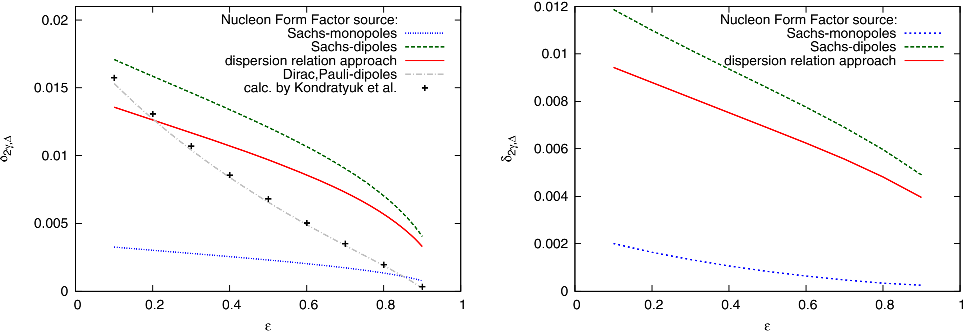
- positive slope
- vanishes as $\varepsilon \rightarrow 1$
- nonlinearity grows with increasing Q^2
- G_M dominates in loop integral



- changes sign at low Q^2
- agrees well with static limit for point particle (no form factors in loop and $Q^2 \rightarrow 0$)
- G_E dominates in loop integral

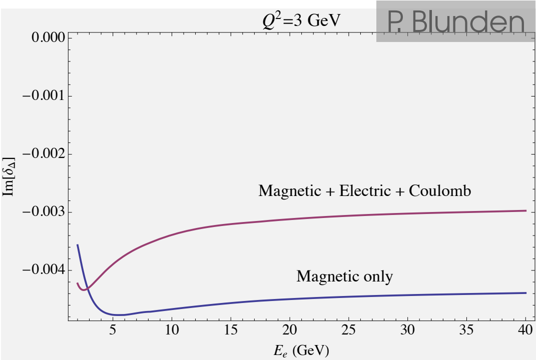
Lorenz *et al.*, Phys. Rev. D **91**, 014023 (2015)

P. Blunden

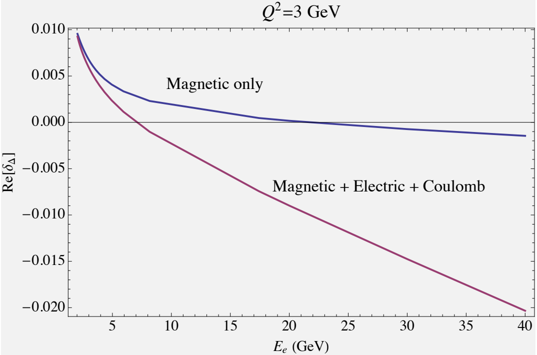


- Used $\gamma N\Delta$ form factors fit to recent data
- Find smaller results than Kondratyuk & PGB
  - (consistent with softer form factor Λ=0.75 GeV than for nucleon)
- Claim substantial effect on the determination of the proton charge radius from scattering data

Plot vs. energy instead of ε



- Imaginary part well-behaved
- Dispersive integral also well-behaved
  (e.g. vanishes at $\varepsilon \to 0$)

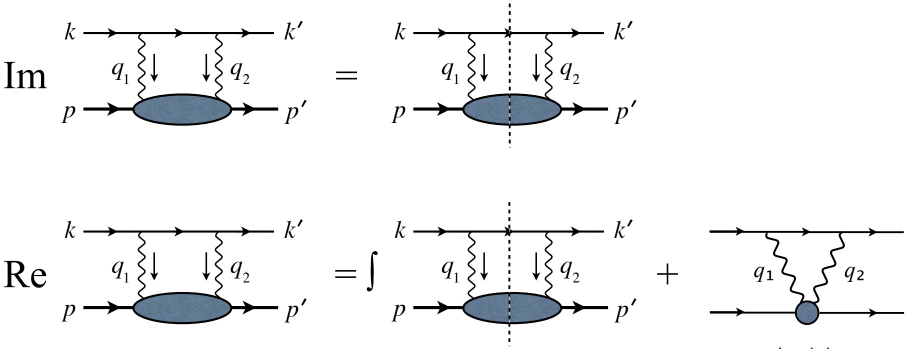


- Real part from loop calculation diverges linearly with energy (violation of Froissart bound)
- Problem due to momentum-dependent vertices, uncontrained by on-shell condition

P. Blunden

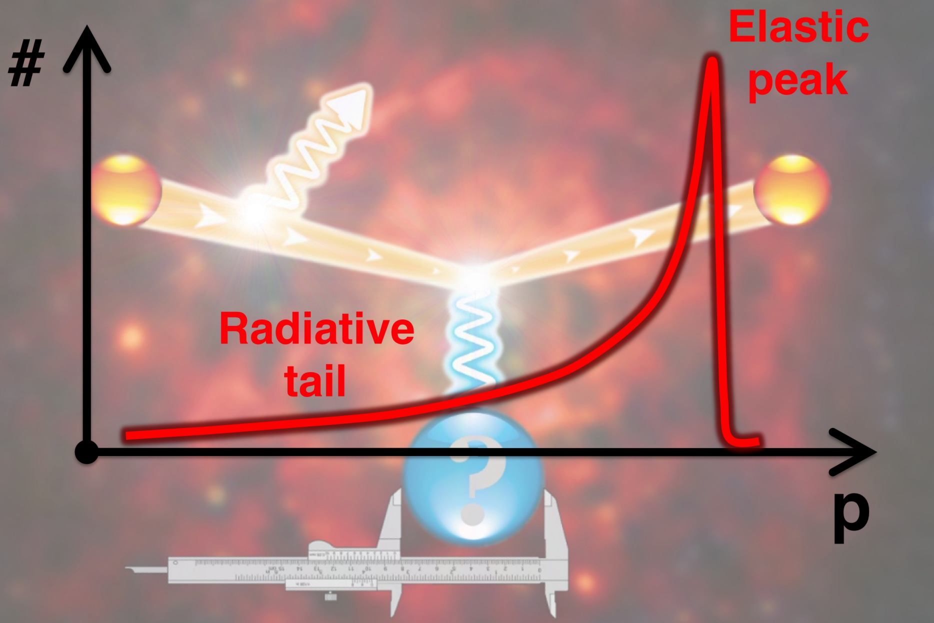
Why? Isn't this contrary to Cutkowsky rules?

Loop | Dispersive



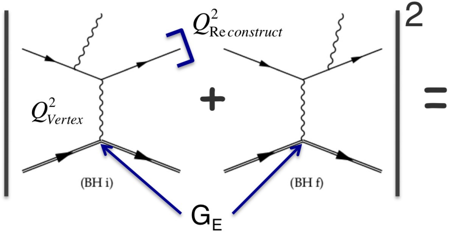
contact term
Im part = 0

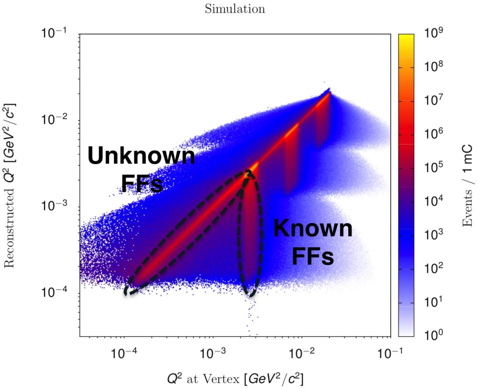
ISR Experiment at MAMI



Initial state radiation

- Radiative tail dominated by coherent sum of two Bethe-Heitler diagrams.

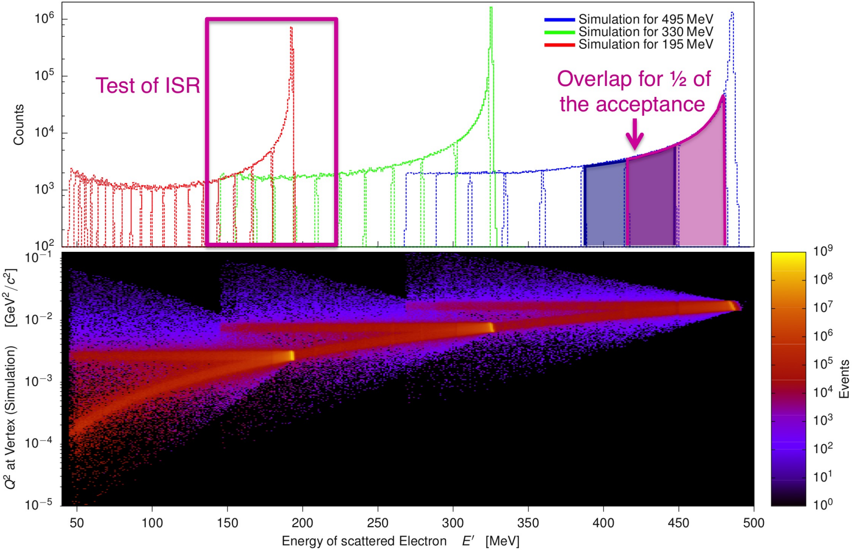




- In data ISR can not be distinguished from FSR.
- **Combining data with the simulation, ISR information can be reached**.
- Idea behind new MAMI experiment to extract $\mathbf{G_e^p}$ at $\mathbf{Q^2 \sim 10^{-4}\ (GeV/c)^2}$
- Redundancy measurements at higher Q^2 for testing this approach in a region, where FFs are well known.

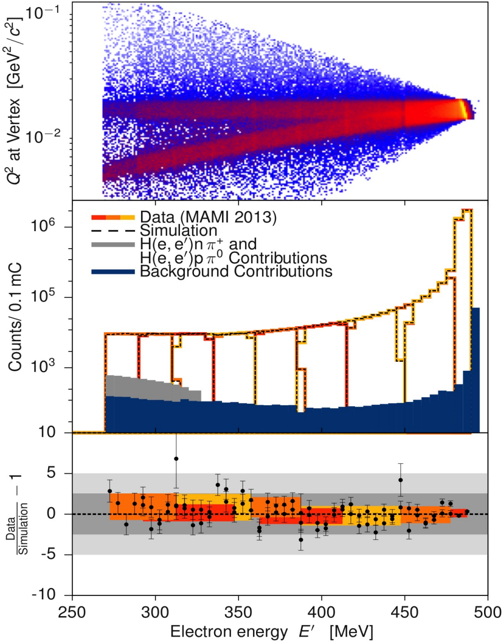
Kinematic settings of the full experiment

- Measured kinematic points and corresponding Q^2 at vertex.
- Three kinematic regions overlap to verify ISR approach.



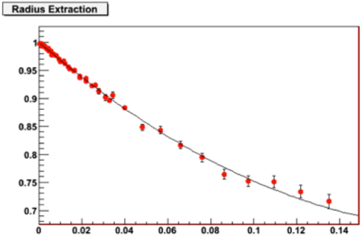
Preliminary Results

- First results for 495 MeV setting.
- Data are normalized to 0.1mC using Förster probe & Spec-A.
- Only basic kinematic cuts considered.
- Pion production processes contribute ~10% at smallest momenta.
- Contributions from target wall not negligible.
- **Agreement between data and simulation justifies use of `Simul++`.**

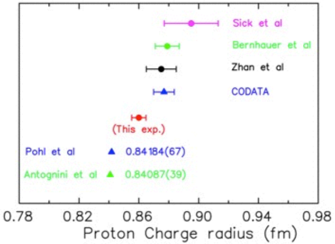


PRAD: Low Q^2 and Proton Radius

JLab Hall B PRAD:
Gasparian, Dutta, Gao, Khandaker, et al.
Small-angle low Q^2 scattering into the PRIMEX calorimeter, cross calibrating ep to Moller scattering.



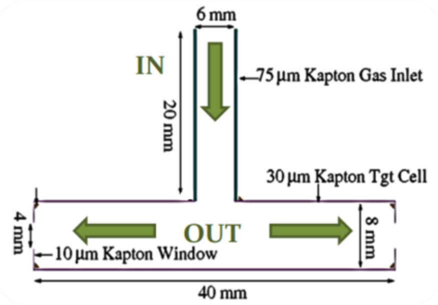
G_E vs Q^2 data simulated, to show radius out = radius in



Projected result

PRAD

JLab Hall B PRAD has A priority.
Expected to run in 2016.
"10 nA" beam on a 25 K cooled gas target, 10^{18} atoms/cm^2.
L ≈ 10^{29}/cm^2/s



Note: this sort of technique first used with 100-200 mA, 2-GeV electron in VEPP-3, with cell increasing target density x15 from about 10^{11}/cm^2 to 3×10^{12}/cm^2.
Drifilm coating kept cell atoms highly polarized.
R. Gilman et al., PRL 65 (1990)
(Authors alphabetical.)

R. Gilman

Cornell vs. PRAD

How would intense Cornell electron beam be better than PRAD type experiment?

- Increase beam about 6 orders of magnitude, reduce target thickness, get equal or better rate.
- Beam is polarized - go to polarized atomic source and get similar rates to PRAD, but with added benefit of form factor ratio measurements from asymmetries, as well as cross section measurements.
- With polarized beam+target, measure directly form factor ratio and relative cross sections. Limits effect of certain radiative corrections, which are important to get right to get G_M at low Q^2.

Note also using a gas or atomic beam target minimizes the external radiative corrections.

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Summary:
SSA in Elastic ep- and eA-Scattering

- VCS amplitude in *beam asymmetry* is enhanced in different kinematic regions compared to *target asymmetry* or corrections to *Rosenbluth cross section*
- *Physics probe of an absorptive part of a non-forward Compton amplitude*
- *Important systematic effect for PREX,* Q_{weak}
- Mott asymmetry in small-angle ep-scattering above the pion threshold is controlled by quasi-real photoproduction cross section with photon energy approximately matching beam energy – similarity with Weizsacker-Williams Approximation – collinear photon exchange
- *Due to excitation of inelastic intermediate states* A_n *is*

(a) not suppressed with beam energy and

(b) does not grow with Z (proportional to instead A/Z)

(c) At small angles ~θ (vs θ^3 *for Coulomb distortion)*

- Confirmed experimentally for a wide range of beam energies

Outlook

- Beam and target SSA for elastic electron scattering probe imaginary part of virtual Compton amplitude.
  - Beam SSA: target helicity flip^2+nonflip^2
  - Target SSA: Im[target helicity flip*nonflip]
  - Ideal "4π detector" to probe electroproduction amplitudes for a variety of final states (π, 2π, etc)
- Beam SSA for nuclear targets in good agreement with theory except for a high-Z target 208Pb. Interesting nuclear physics effects beyond two-photon exchange
- Beam SSA in Reaction $A(e_{pol},\pi)X$ probes strong final-state interactions – due to "fifth stucture function"

in A(e,e' π)X

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Virtual Photon Tagging: Probing Confinement Scale QCD

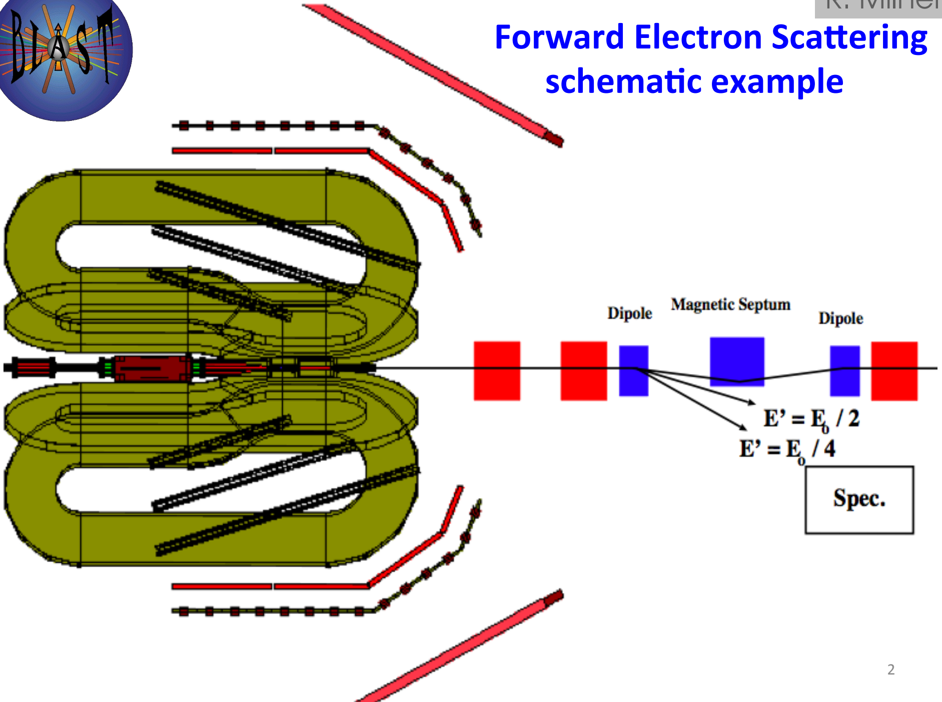
R. G. Milner for A.M. Bernstein, MIT
Cornell Workshop
June, 2015

Symmetry Tests in Photo-pion Production
A.M. Bernstein
AIP Conf. Proc. **1563**, 159 (2013)

Physics Opportunities

- γN -> πN amplitudes: chiral symmetry predictions
- Use proton, D, and ^{3}He thin gas targets => recoil detection
- Test first principle few-body calculations
- Test isospin violation: m_d-m_u
- Measure NN charge symmetry violations
- Measure Compton scattering -> nucleon polarizabilities
- Elastic ep scattering -> proton charge radius

Forward Electron Scattering schematic example



Tagged vs. Virtual Photons

In Tagged Photon Experiments:

- Most photons do not interact in the target
- Data taking is limited by rates in the tagger
- Thick targets are required, which limits the energy region
- Polarized targets have extraneous material, e.g. butanol: C, O produce background

Using Virtual photons:

- Is more efficient
- Require **energy > 300 MeV** for pion production experiments
- Detected electrons have interacted in the target
- Thin targets allow **detection of low energy recoils** limited by rates in forward electron counter

Low current ≈ 1 mA

- thin, **windowless** unpolarized gas targets p ≈ 1 mm Hg
- measure low energy π^+, p recoil

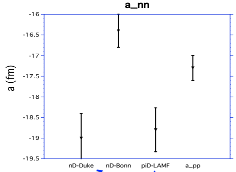
High current ≈ 100 mA

- Utilize windowless **polarized gas targets (transverse and longitudinal)**
- **Polarized electrons** for complete program

Is $a_{nn} = a_{pp}$?
Testing charge symmetry

- NN S-wave scattering lengths
- Measure with $\gamma D \to nn\,\pi^+$
- Check a_{np} with $\gamma D \to np\,\pi^0$

exp. problem



CSB?

nD -> nnp

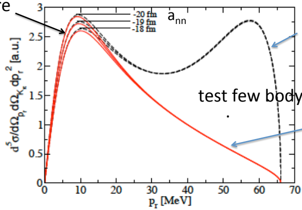
$\pi^- D \to nn\,\pi^0$

$$\gamma D \to nn\pi^+$$

$$\gamma(\vec{k})D \to \; n(\vec{p_1}) + n(\vec{p_2}) + \pi^+(\vec{p_\pi})$$
$$\vec{p_r}(\theta_r, \phi_r) = (\vec{p_1} - \vec{p_2})/2$$

Θ_r = angle between neutron momenta

Measure a_{nn}



θ_r=0

test few body calc.

θ_r=90

Testing Isospin Conservation
$$\gamma N \to \pi N$$

There are 3 isospin matrix elements,
4 reaction channels.
The test of isospin conservation is:

$$A(\gamma p \to \pi^+ n) + A(\gamma n \to \pi^- p)$$
$$= \sqrt{(2)}[A(\gamma n \to \pi^0 n) - A(\gamma p \to \pi^0 p)]$$

A = multipole matrix elements
s wave (E_{0+}), 3 p wave)

Make four measurements to test IS conservation via relation above.

Expect IS breaking from QCD

- $L_{QCD} = L_0\,(m_q \to 0) + L_m$ (quark mass term)
- L_0 has chiral symmetry; spontaneously broken
  ⇒ Nambu-Goldstone Bosons (π, η, K)
  ⇒ ChPT: effective theory of QCD
- $L_m = A(m_u + m_d) + B\,(m_u - m_d)$
  explicitly breaks chiral symmetry,
  B term also breaks IS symmetry
- Strong isospin symmetry violation
  - In general: $(m_d - m_u)/\Lambda_{QCD} \approx 2\%$.
  - However, $\Delta a\,(\pi^o N)/\,a(\pi^o N) \approx 30\ \%$ (Weinberg)
  - **Needs to be tested experimentally:** $\gamma N \to \pi^o N$ near threshold

Extension

All this can/should be repeated for heavier elements!

- Radius/Form factor
    - D, ^{3}He, ^{4}He, Li, C
- Pion
    - D, ^{3}He

Precision Møller Scattering at Low Energies

Charles Epstein

Intense Electron Beams Workshop, Cornell University

June 18, 2015

DARKLIGHT

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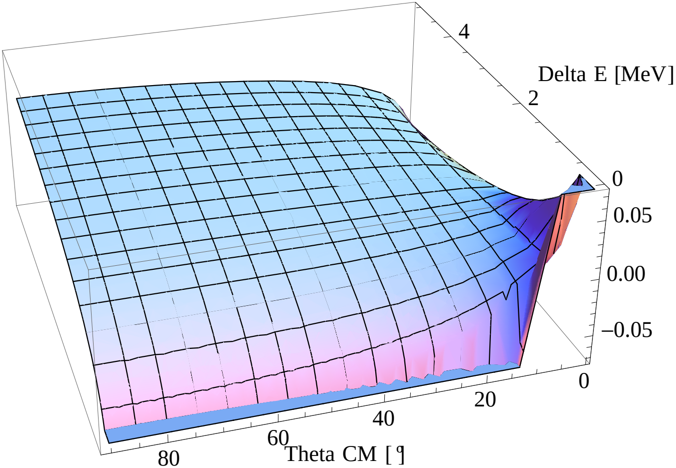
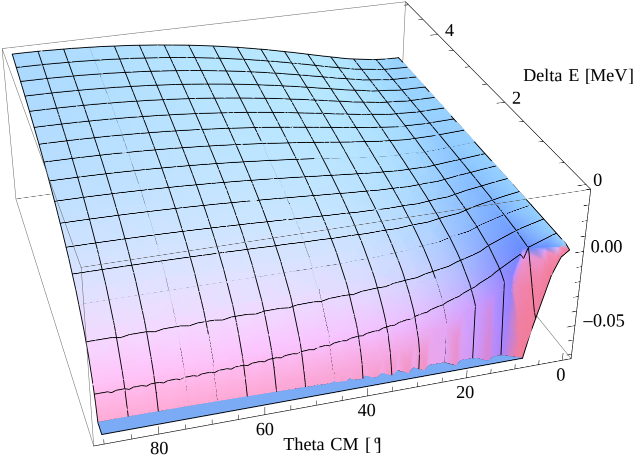
Improper behavior of δ: $\sqrt{s} = 10.16$ MeV (DL)



$\delta(\Delta E, \theta)$

(Tsai, 1960)

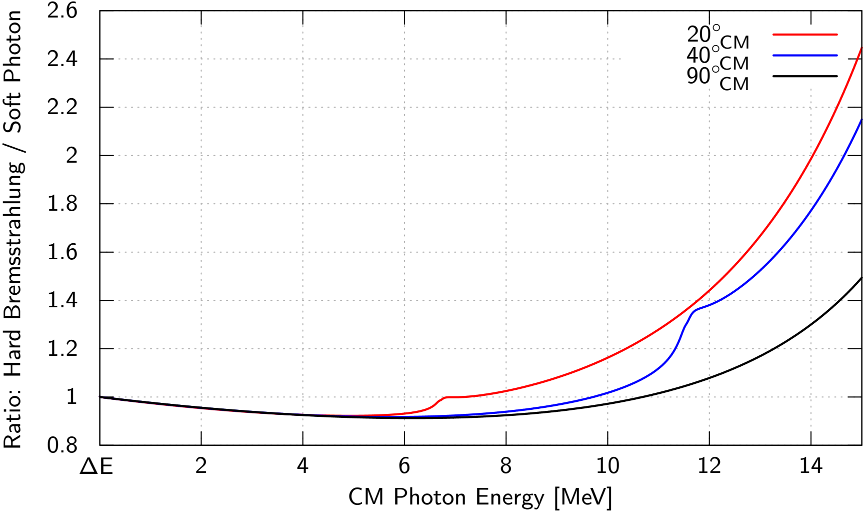
What δ should look like



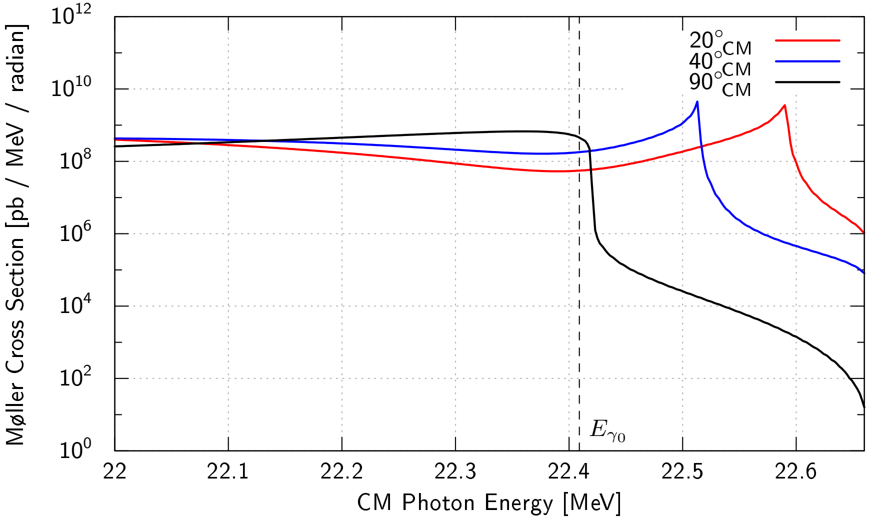
$$\delta(\Delta E, \theta)$$

(Kaiser, 2010)

Ratio of hard/soft cross-sections



Electron Cross-Section at high photon energies



Møller Scattering at 100 MeV

Why measure unpolarized low-energy Møller scattering?

Quantities with few precision data

- Distribution of E at fixed θ: **radiative tail**
  - Verify bremsstrahlung calculation
- Precise electron-electron cross-section vs θ
  - Verify soft-photon radiative corrections $\rightarrow$ beyond URA

Requirements

- Measure electrons with energy 1-5 MeV/c
- Momentum resolution $\delta p/p \sim 1\%$
- Scattering angles 25°-45°

Summary

Ready to go

- unpolarized form factor / radius
- unpolarized pion production
- Møller
- SSA

May need improvements

- Polarized form factor / pion production (dense polarized target)

(Far) Future

- Two-Photon-exchange (positrons)
- Lepton universality (muons)