QED Radiative Corrections to DVCS: Outstanding Issues

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Deeply Virtual Compton Scattering: From Observables to GPDs

Ruhr-Universität Bochum, February 10-12, 2014

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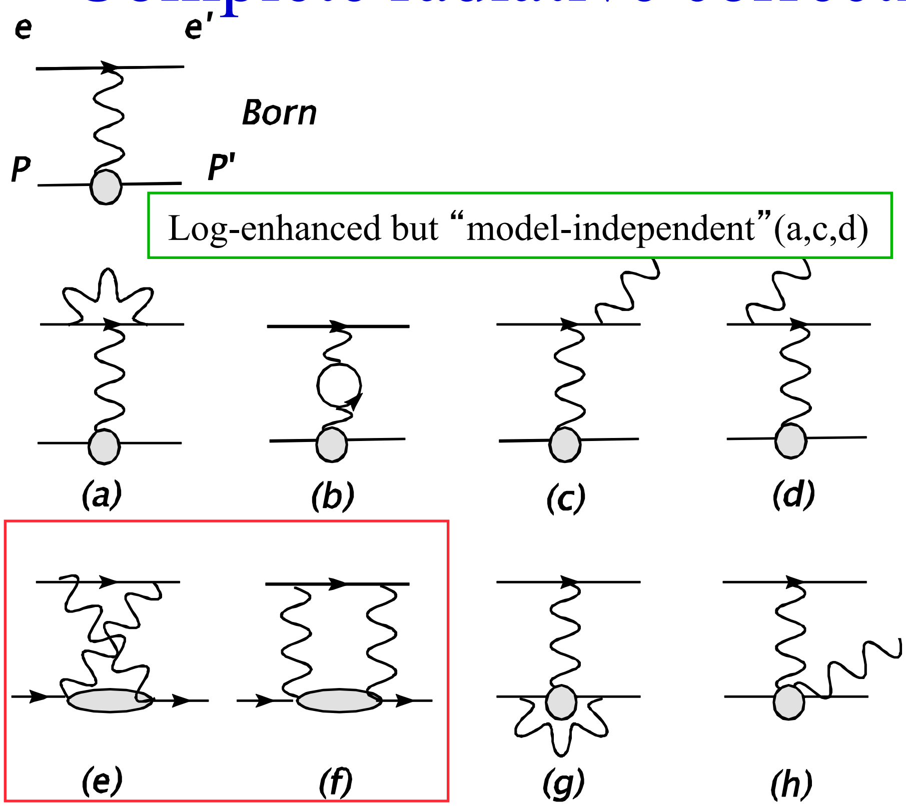
Plan of talk

Radiative corrections for charged lepton scattering

- Soft photon emission, spin independence
- Single-Spin Asymmetries of a Bethe-Heitler process
- Two-Photon exchange for DVMP
- Implications for DVCS
- Outlook

Complete radiative correction in O(α_{QED})



Radiative Corrections to elastic ep:

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

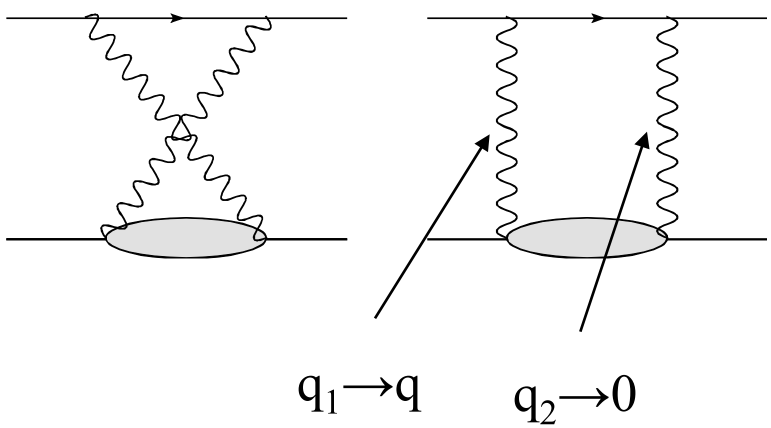
Two-photon corrections: no large logs, but dependent on nucleon structure

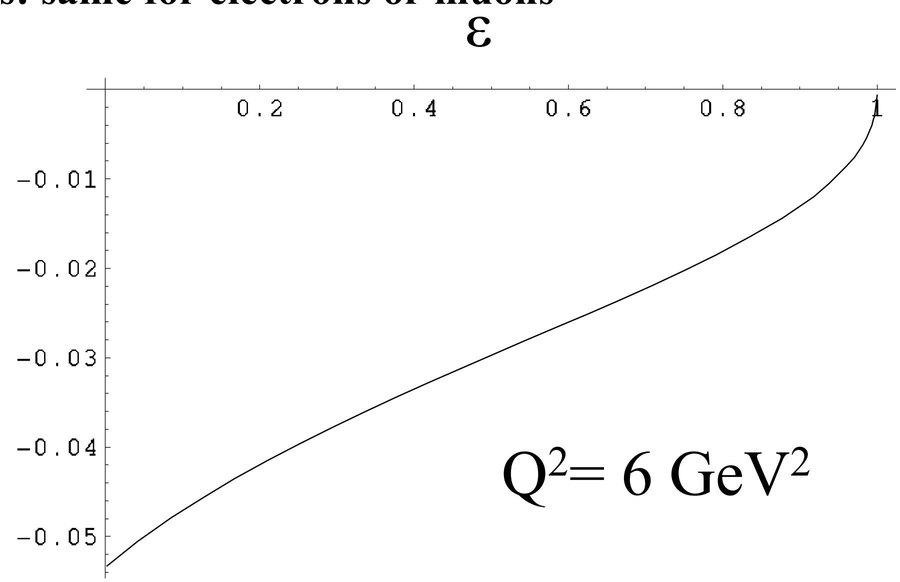
Basic Approaches to QED Corrections

- L.W. Mo, Y.S. Tsai, Rev. Mod. Phys. 41, 205 (1969); Y.S. Tsai, Preprint SLAC-PUB-848 (1971).
  - Considered both elastic and inelastic inclusive cases. No polarization.
- D.Yu. Bardin, N.M. Shumeiko, Nucl. Phys. B127, 242 (1977).
  - Covariant approach to the IR problem. Later extended to inclusive, semi-exclusive and exclusive reactions with polarization.
    - RADGEN: Monte Carlo of p(e,e')X including radiative events
- E.A. Kuraev, V.S. Fadin, Yad.Fiz. 41, 7333 (1985); E.A. Kuraev, N.P.Merenkov, V.S. Fadin, Yad. Fiz. 47, 1593 (1988).
  - Developed a method of electron structure functions based on Drell-Yan representation; currently widely used at e^+e^- colliders.

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
- **Already included in experimental data analysis**
- NB: Corresponding effect to polarization transfer and/or asymmetry is zero
- **Correction is independent of lepton mass: same for electrons or muons**





A similar approach can be applied for any exclusive reaction

Semi-inclusive? Problem: soft photons do not resolve short scales

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Exchange of two hard photons

- 2-photon exchange contributions for non-soft intermediate photons
  - Can estimate based on a text-book example from *Berestetsky, Lifshitz, Pitaevsky: Quantum Electrodynamics - originally due to Gorshkov, Gribov, Lipatov, Frolov (1967)*
  - Double-log asymptotics of electron-quark backward scattering

$$\delta = -\frac{e_q e}{8\pi^3} \log^2 \frac{s}{m_q{}^2}$$

  - Negative sign for backward ep-scattering; zero for forward scattering → Can (at least partially) mimic the electric form factor contribution to the Rosenbluth cross section
  - Numerically ~3-4% (for SLAC kinematics and m_q~300 MeV)
  - **Motivates a more detailed calculation of 2-photon exchange at quark level**

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Full Calculation of Bethe-Heitler Contribution

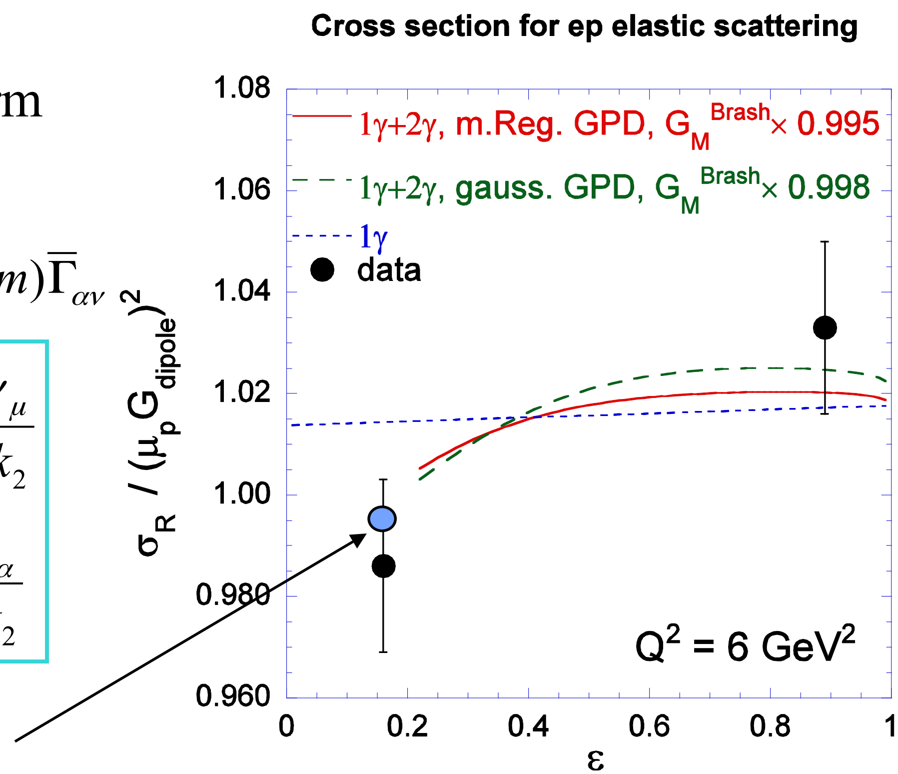
*Additional work by AA et al., using MASCARAD (**Phys.Rev.D64:113009,2001**)*
Full calculation including soft and hard bremsstrahlung

Radiative leptonic tensor in full form
AA et al, ***PLB 514, 269 (2001)***

$$L^r_{\mu\nu} = -\frac{1}{2} Tr(\hat{k}_2 + m)\Gamma_{\mu\alpha}(1+\gamma_5 \hat{\xi}_e)(\hat{k}_1 + m)\overline{\Gamma}_{\alpha\nu}$$

$$\Gamma_{\mu\alpha} = \left(\frac{k_{1\alpha}}{k\cdot k_1} - \frac{k_{2\alpha}}{k\cdot k_2}\right)\gamma_\mu - \frac{\gamma_\mu \hat{k}\gamma_\alpha}{2k\cdot k_1} - \frac{\gamma_\alpha \hat{k}\gamma_\mu}{2k\cdot k_2}$$

$$\Gamma_{\alpha\nu} = \left(\frac{k_{1\alpha}}{k\cdot k_1} - \frac{k_{2\alpha}}{k\cdot k_2}\right)\gamma_\nu - \frac{\gamma_\alpha \hat{k}\gamma_\nu}{2k\cdot k_1} - \frac{\gamma_\nu \hat{k}\gamma_\alpha}{2k\cdot k_2}$$



Additional effect of full soft+hard brem → +1.2% correction to ε-slope

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Rad.Correction to Single-Spin Asymmetries of VCS

- Evaluation of QED radiative corrections for single-spin asymmetries in Virtual Compton Scattering experiments with CLAS (see also earlier calculations by Vanderhaeghen et al. (2000) for beam SSA in VCS)
  - Since VCS is studied through interference with Bethe-Heitler process, its properties need to be understood precisely
  - If the QED correction to the asymmetries is a few per cent, it alters interpretation of VCS measurements in terms of GPDs
  - Earlier calculations for a related process of radiative Moller scattering $e^- + e^- \rightarrow e^- + e^- + \gamma$ show large SSA (up to 20%, see Arbuzov et al., Phys. Atom. Nuclei, **59**, 841 (1996))

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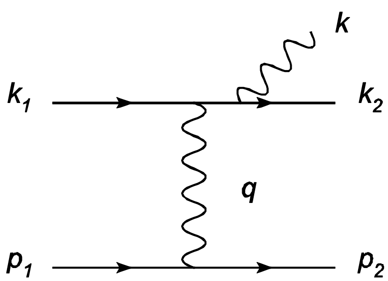
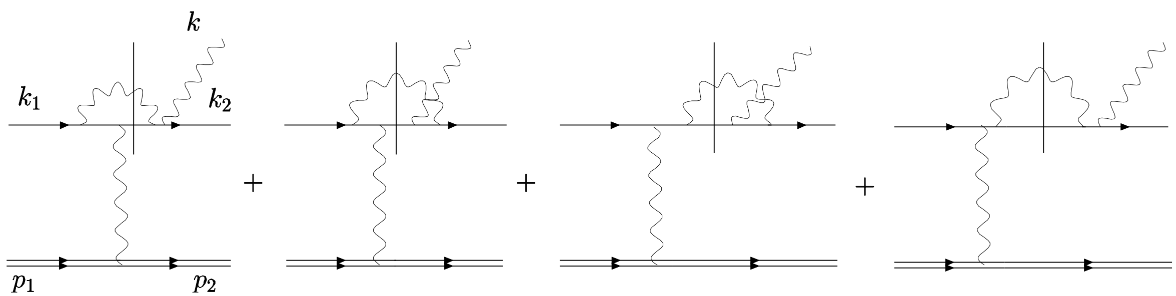
Feynman Diagrams

- SSA in Bethe-Heitler process is due to interference between (real) tree-level amplitude and QED loops = O(α) correction that contain absorptive parts



Tree-level real amplitude



QED loop diagrams

Formalism

AA, Konchatnij, Merenkov, *Single-spin asymmetries in the Bethe-Heitler process e- + p ---> e- + gamma + p from QED radiative corrections,* J.Exp.Theor.Phys.102:220-233, 2006; hep-ph/0507059

- Beam SSA

$$A^e = \frac{\alpha}{4\pi} \frac{\mathrm{Re}(P^{(1)}_{\mu\nu} H_{\mu\nu})}{B_{\mu\nu} H_{\mu\nu}}$$

- $H_{\mu\nu}$ and $B_{\mu\nu}$ are standard hadronic and leptonic tensors in the leading order
- $P_{\mu\nu}$ is calculated from loop diagrams using Cutkosky cuts and doing analytic 2-dimensional integration

$$P^{(1)}_{\mu\nu} = i(k_1 k_2 q \nu)[B_1 \widetilde{k}_{1\mu} + B_2 \widetilde{k}_{2\mu}] - i(k_1 k_2 q \mu)[B_1^* \widetilde{k}_{1\nu} + B_2^* \widetilde{k}_{2\nu}]$$

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Expression for beam SSA

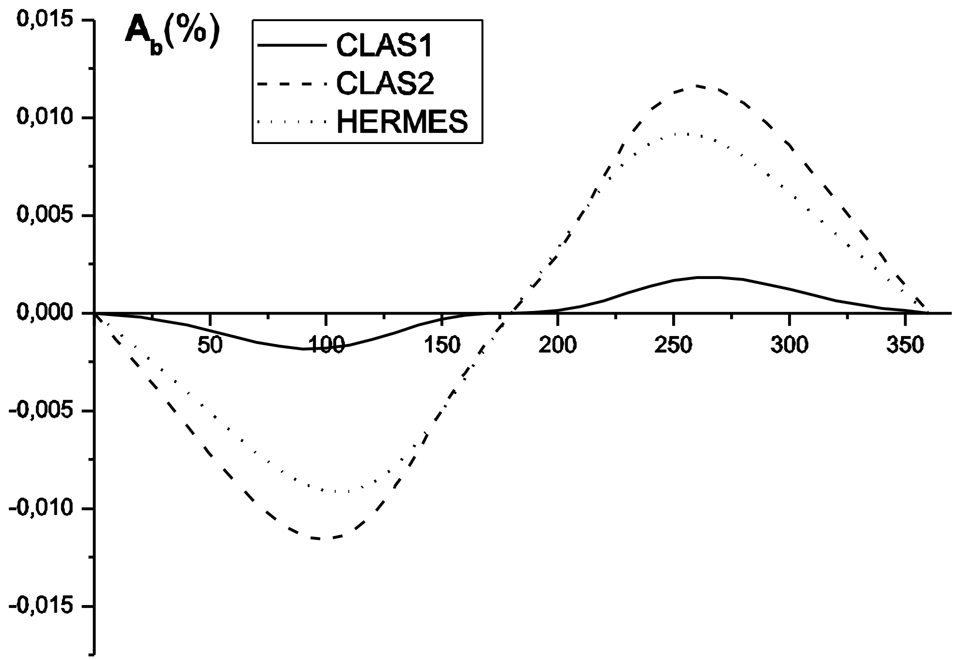
$$P^{(1)}_{\mu\nu} H_{\mu\nu} = \frac{2\pi(k_1 k_2 q p_1)}{st}(F_1^2 - \frac{q^2}{4M^2}F_2^2)[(2V - s + q^2)\overline{B}_1 + (2X - s - u)\overline{B}_2],$$

$$\overline{B}_1 = \frac{2(u^2 - 2s^2 - su)}{uc} + \frac{2bc}{c^2} + \frac{4b^2}{t^2} - \frac{4b}{t}(1 + \frac{b}{t})\log(1 + \frac{t}{u}),$$

$$\overline{B}_2 = \frac{6s}{c} - \frac{2(2b - t)}{t} + 4(-1 + \frac{ub}{t^2} - \frac{s}{t})\log(1 + \frac{t}{u})$$

- Results are expressed in terms of analytic functions of Mandelstam invariants
- Free of infrared and mass singularities
- No large logarithms appear
- In addition to α, proportional to q^2 that is small in DVCS kinematics
- Similar formulas obtained for target SSA; similar suppression takes place

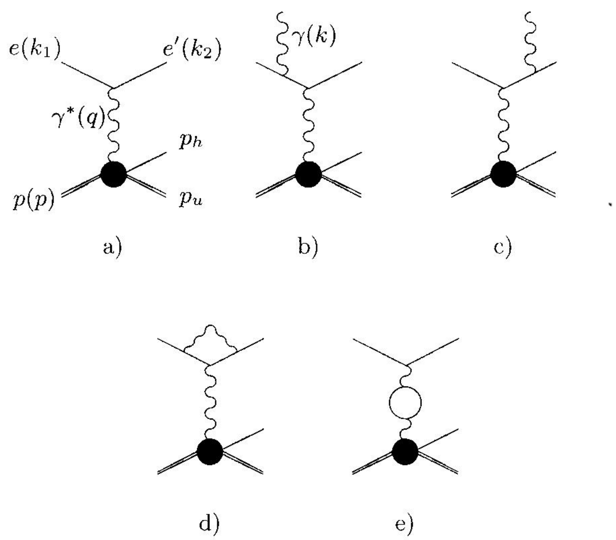
Numerical results



Asymmetry less than 0.015% due to O(α)+additional kinematic suppression

RC for Exclusive Electroproduction of Pions

- **AA, Akushevich, Burkert, Joo, Phys.Rev.D66, 074004 (2002)**
  - Conventional RC, precise treatment of phase space, <u>no peaking approximation</u>, no dependence on hard/soft photon separation; Can be used for any exclusive electroproduction of 2 hadrons, e.g., d(e,e' p)n (EXCLURAD code)



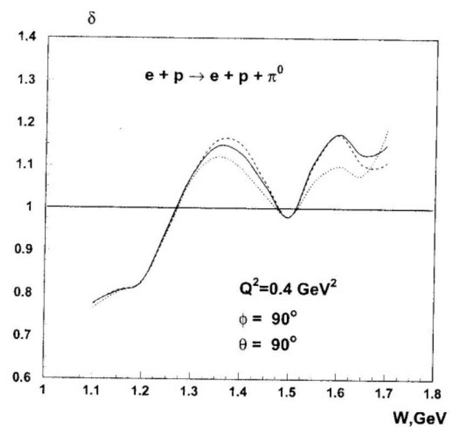
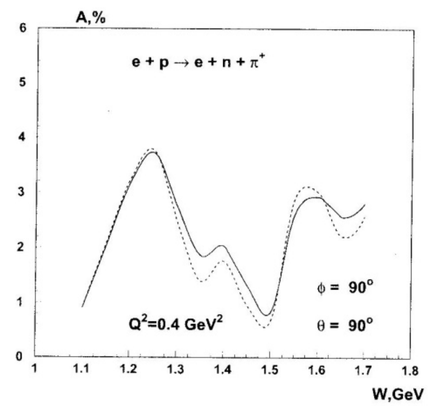


FIG. 3: W-dependence of RC to the cross section of neutral pion production. The models used are MAID2000 (solid curve), MAID'98 [34] (dashed curve) and AO [35] (dotted curve).



Used in data analysis at Jlab (and MIT, HERMES, MAMI,…)

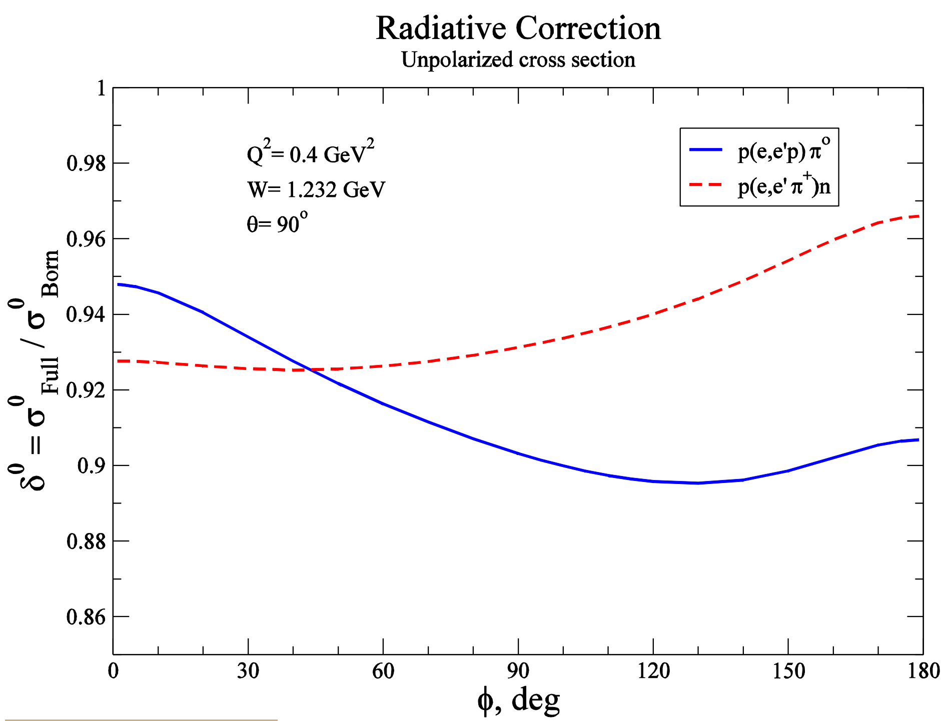
Radiative Corrections for Exclusive Processes

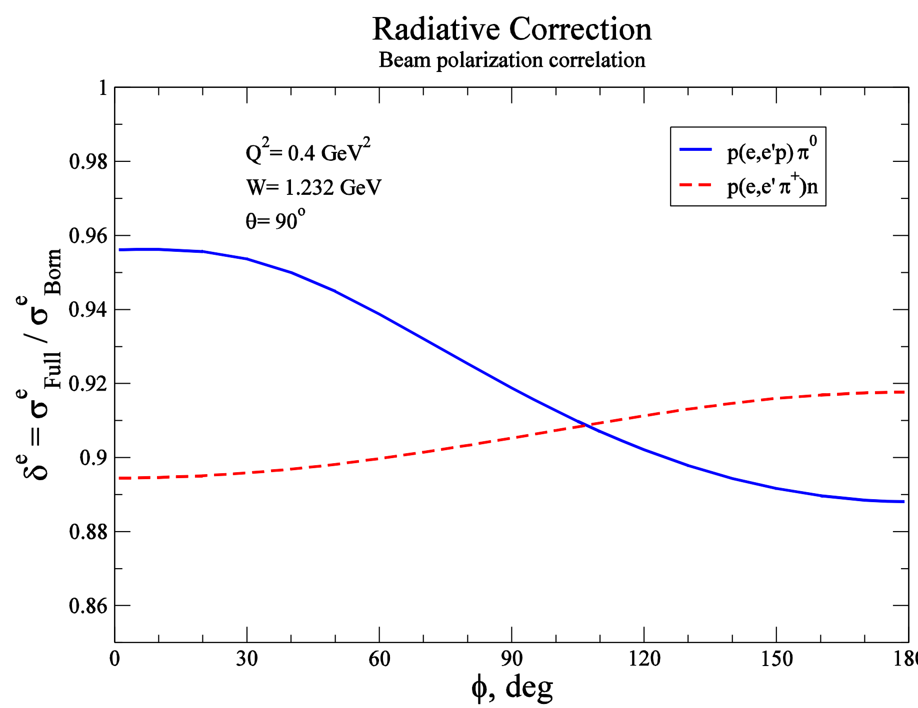
- Photon emission is a part of any electron scattering process: accelerated charges radiate
- Exclusive electron scattering processes such as $p(e,e' h_1)h_2$ are in fact inclusive $p(e,e' h_1)h_2\ n\gamma$,

  where we can produce an infinite number of low-energy photons
- But low-energy photons do not affect polarization observables, thanks to Low theorem

Exclurad updated to include polarization (work with K. Joo)

- Corrections to single-spin beam and target asymmetries and double-spin beam-target asymmetry
  - Target polarized along the beam direction





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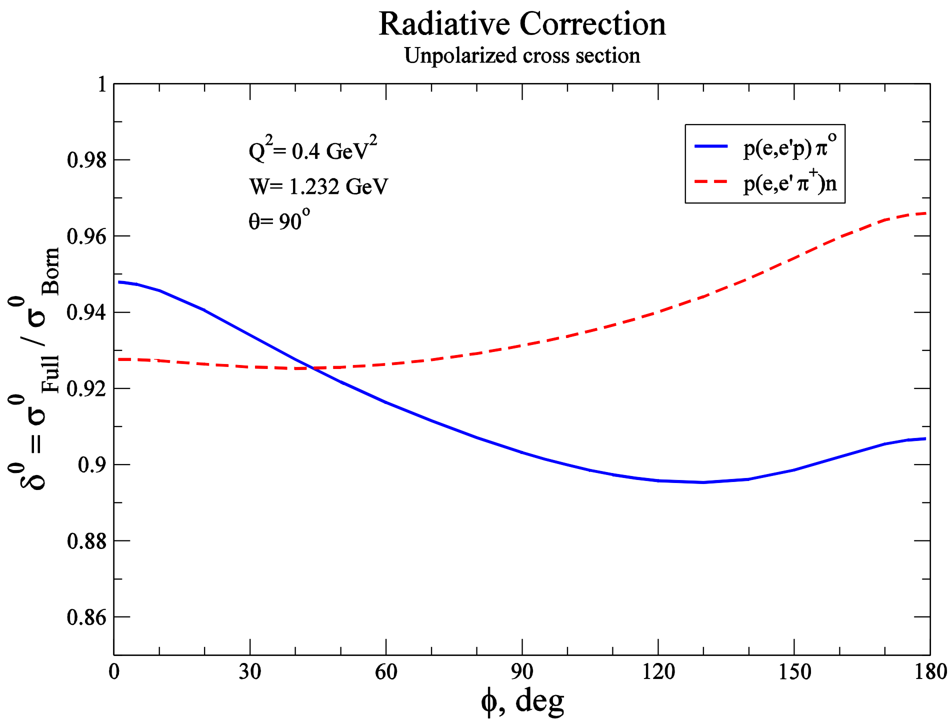
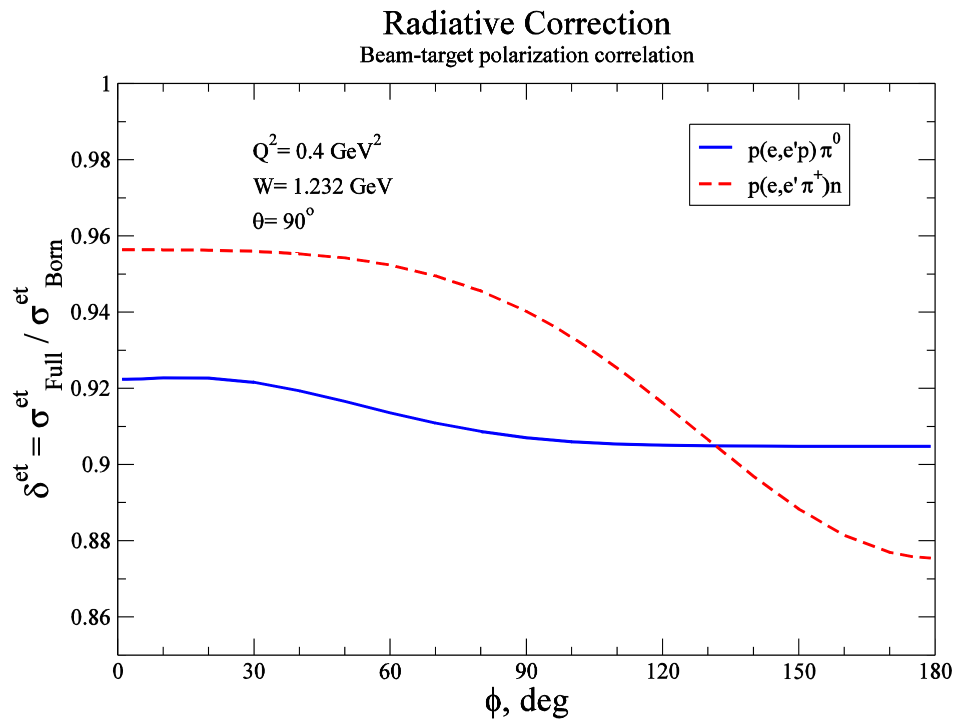
RC for beam-target asymmetry

If kinematic cuts for the radiated photon are tight (below 2nd pion production threshold, correction to polarization asymmetry is under <1%)





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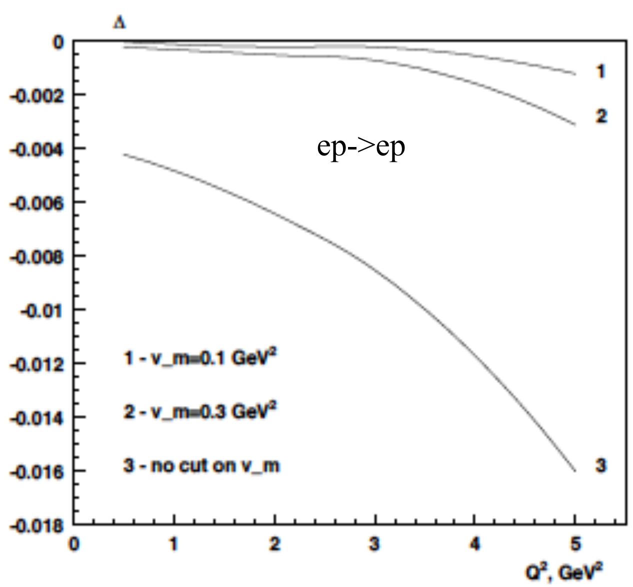
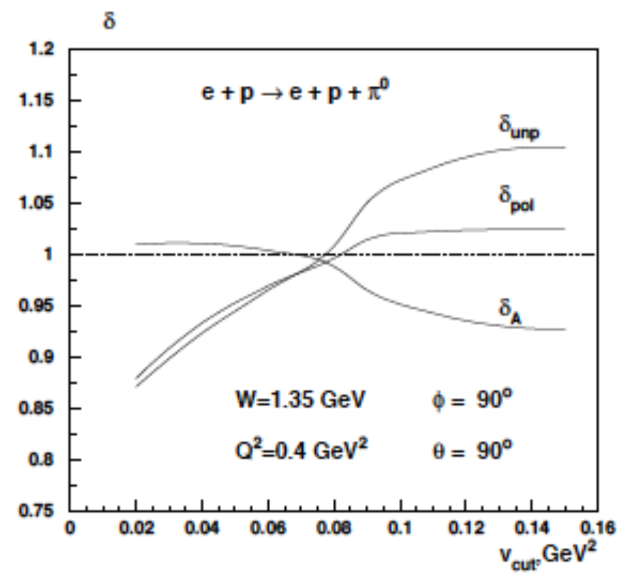
RC for Spin Asymmetries

- RC is zero for soft photons (can be enforced by kinematic cuts for brem photons, but not for TPE)

  =>RC to spin asymmetries strongly depend on kinematic cuts
- Important to use no soft approximation for calculations of spin asymmetries

RC dependence on the cuts



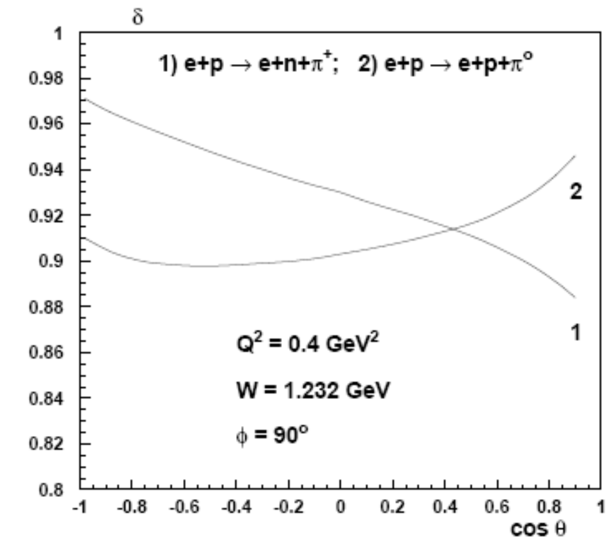


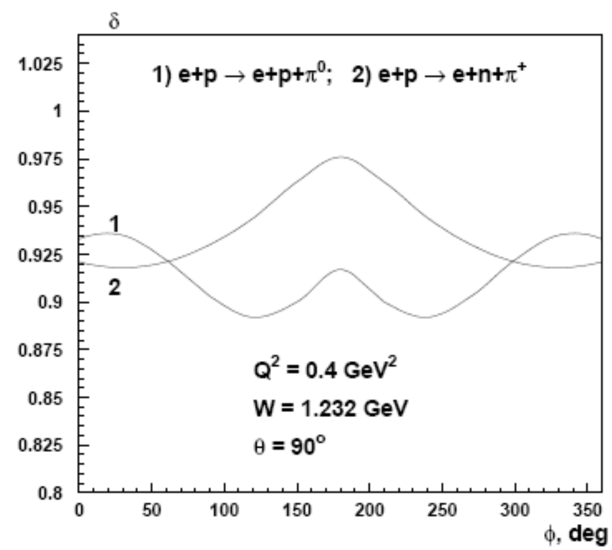
Spin-independence of soft terms in RC

- Soft-photon corrections are spin-independent
  - Corrections due to (double)bremsstrahlung were calculated by Vanderhaeghen et al Phys.Rev.C62:025501,2000 in a soft-photon approximation.- estimated corrections to cross section ~25%; to single-spin asymmetry ~5% (AA: *seems too large to me*)

Angular Dependence of Rad.Corrections

- Rad.Corrections introduce additional angular dependence on the experimentally observed cross section of electroproduction processes, both exclusive and semi-inclusive





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Rad.Corrections to e^+e^- pair production

- Usual corrections+charge asymmetric corrections

PHYSICAL REVIEW VOLUME 173, NUMBER 4 20 SEPTEMBER 1968

Second Born Corrections to Wide-Angle High-Energy Electron Pair Production and Bremsstrahlung*

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(Received 15 April 1968)

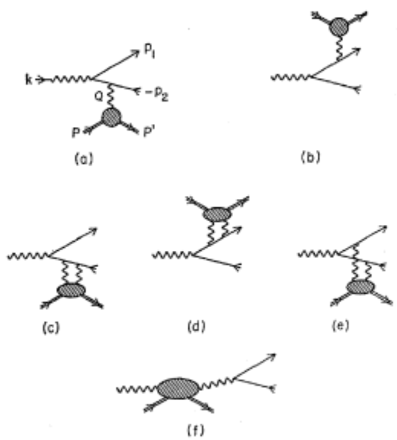

FIG. 1. Feynman diagrams for electron pair production. (a)–(e) give the Bethe-Heitler amplitude through second order in the electromagnetic interaction with the nucleus. Diagram (f) represents the virtual Compton contribution to pair production and includes contributions from the nuclear-pole terms, nucleon and nuclear excitations, and neutral vector-meson production.

Need to be re-visited in view of time-like DVCS measurements at JLAB

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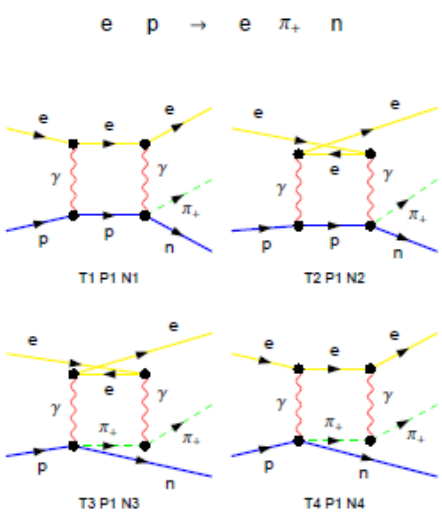
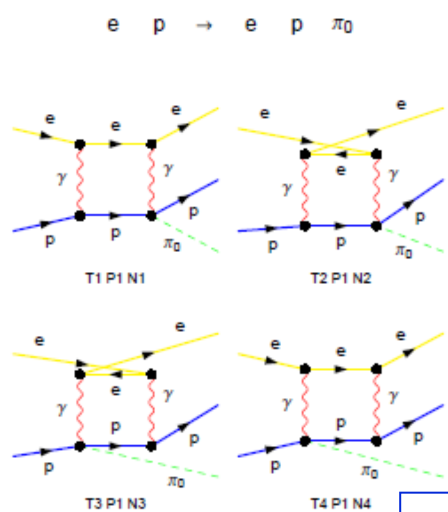
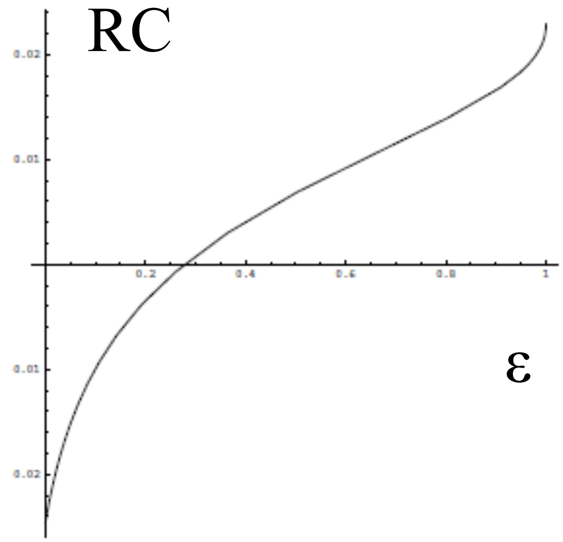
Two-Photon Exchange in Exclusive Electroproduction of Pions (same for muons!)

- Standard contributions: EXCLURAD
- *Additional contributions due to two-photon exchange*, calculated by AA, Aleksejevs, Barkanova, arXiv:1207.1767 (Phys.Rev. D88 (2013) 053008) Calculated in soft-photon approximation







Calculated ε-dependence of TPE correction. Q^2=6 GeV^2, W=3.2 GeV, E_e=5.5 GeV . Shows ±2% variation with ε.

TPE for Pion Production: IR regularization

- AA, Aleksejevs, Barkanova, arXiv:1207.1767 (Phys.Rev. D88 (2013) 053008)
- Need to add real photon emission to cancel IR divergence
- Use a finite photon mass for intermediate steps; photon mass dependence cancels in the end after adding TPE and real-photon emission
- Expressed results in terms of Passarino-Veltman integrals
- Obtained analytic results for the limit

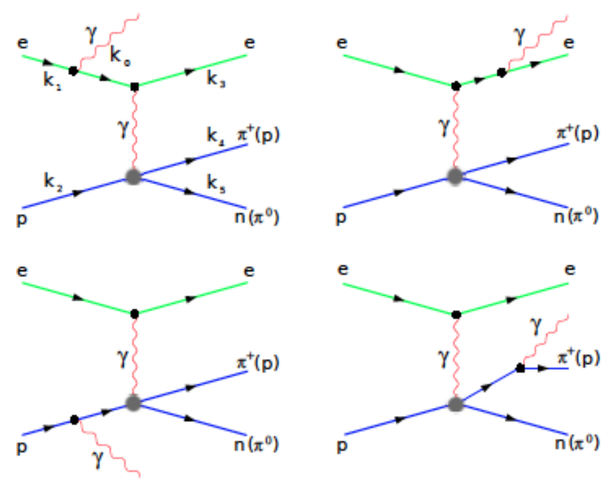
of zero electron mass

"Soft" TPE: a necessary step before includ

"hard" TPE, need to subtract soft terms

at the quark level and add at the hadron

level



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TPE: some details of the calculation

- Brem+TPE, neglecting the electron mass
- Soft photons factorize at the amplitude level,

$$M_1^{SPT} = -\frac{\alpha}{2\pi} S \cdot C_0\left(\{k_1, m_1\}, \{-k_2, m_2\}\right) \cdot M_0.$$

- Passarino-Veltman 3-point scalar integral

$$C_0\left(\{k_i, m_i\}, \{k_j, m_j\}\right) = \frac{1}{i\pi^2} \int d^4 q \frac{1}{q^2} \cdot \frac{1}{(k_i - q)^2 - m_i^2} \cdot \frac{1}{(k_j - q)^2 - m_j^2}.$$

$$\delta_{box}^{SPT} = -\frac{\alpha}{\pi} \mathrm{Re}\left[S \cdot C_0\left(\{k_1, m_1\}, \{-k_2, m_2\}\right) + X \cdot C_0\left(\{k_3, m_3\}, \{k_2, m_2\}\right) + V_3 \cdot C_0\left(\{k_3, m_3\}, \{-k_4, m_4\}\right) + V_1 \cdot C_0\left(\{k_1, m_1\}, \{k_4, m_4\}\right)\right].$$

Simplified in a small-mass limit, final result reads

$$\delta_{tot}^{SPT} = \delta_{tot}^{IR} + \delta_{tot}^{F}$$

$$\delta_{box}^{IR} = -\frac{\alpha}{\pi} \ln \frac{m_2^2}{\lambda^2} \left[\ln \frac{S}{X} - \ln \frac{V_1}{V_3}\right]$$

$$\delta_{\gamma}^{IR} = -\frac{\alpha}{\pi} \ln \frac{4\Delta\varepsilon^2}{\lambda^2} \left[-\ln \frac{S}{X} + \ln \frac{V_1}{V_3}\right].$$

$$\delta_{box}^{F} = -\frac{\alpha}{\pi}\left[\frac{1}{2}\ln\frac{S}{X} \cdot \ln\frac{S \cdot X}{m_2^4} + \frac{1}{2}\ln\frac{V_3}{V_1} \cdot \ln\frac{V_1 \cdot V_3}{m_4^4} - \pi^2 - Li_2\left(\frac{S + m_2^2}{S}\right) + Li_2\left(\frac{X - m_2^2}{X}\right) + Li_2\left(\frac{V_1 - m_4^2}{V_1}\right) - Li_2\left(\frac{V_3 + m_4^2}{V_3}\right)\right]$$

$$\delta_{\gamma}^{F} = -\frac{\alpha}{\pi}\left[Li_2\left(1 - \frac{\beta_2 \cdot (u_1 - V_1)}{S \cdot m_5^2}\right) + Li_2\left(1 - \frac{m_2^2 \cdot (u_1 - V_1)}{S \cdot \beta_2}\right) - Li_2\left(1 - \frac{\beta_4 \cdot (u_1 - V_1)}{V_1 \cdot m_5^2}\right) - Li_2\left(1 - \frac{m_4^2 \cdot (u_1 - V_1)}{V_1 \cdot \beta_4}\right) - Li_2\left(1 - \frac{\beta_2 \cdot (u_3 - V_3)}{X \cdot m_5^2}\right) - Li_2\left(1 - \frac{m_2^2 \cdot (u_3 - V_3)}{X \cdot \beta_2}\right) + Li_2\left(1 - \frac{\beta_4 \cdot (u_3 - V_3)}{V_3 \cdot m_5^2}\right) + Li_2\left(1 - \frac{m_4^2 \cdot (u_3 - V_3)}{V_3 \cdot \beta_4}\right)\right].$$

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TPE at higher Q^2

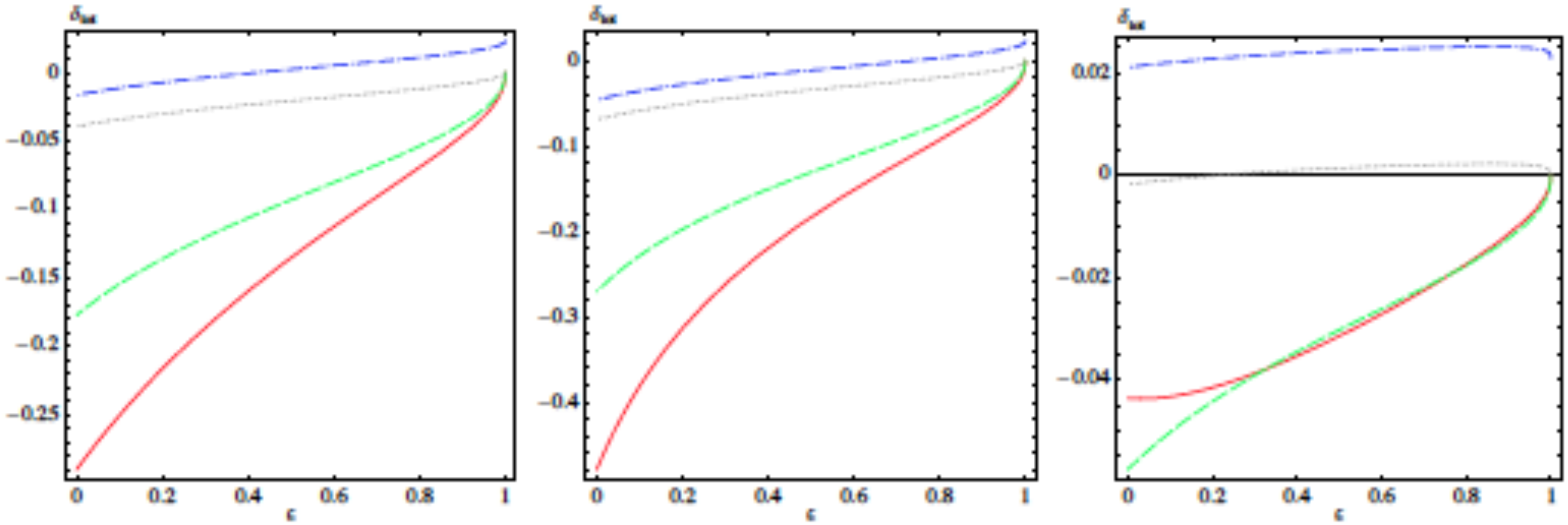

Figure 5: π^0 electroproduction two-photon box correction (for detected proton) dependencies on virtual photon degree of polarization parameter ϵ for momentum transfers $Q^2 = 3.0\,GeV^2$ (left plot), $Q^2 = 7.0\,GeV^2$ (middle plot) and $Q^2 = 0.4\,GeV^2$ (right plot). All plots are given for $\phi_4 = 90^\circ$ and $\theta_4 = 90^\circ$ and $W = 1.232\,GeV$. Dot-dashed curve - SPT, dotted curve - SPT with $\alpha\pi$ subtracted, dashed curve - SPMT, solid curve - FM approach.

TPE effects increase at higher Q^2; SPMT (Maximon-Tjon soft-photon prescription) results in abnormally large corrections

Angular dependence of "soft" corrections arXiv:1207.1767 (~same for DVMP and DVCS)

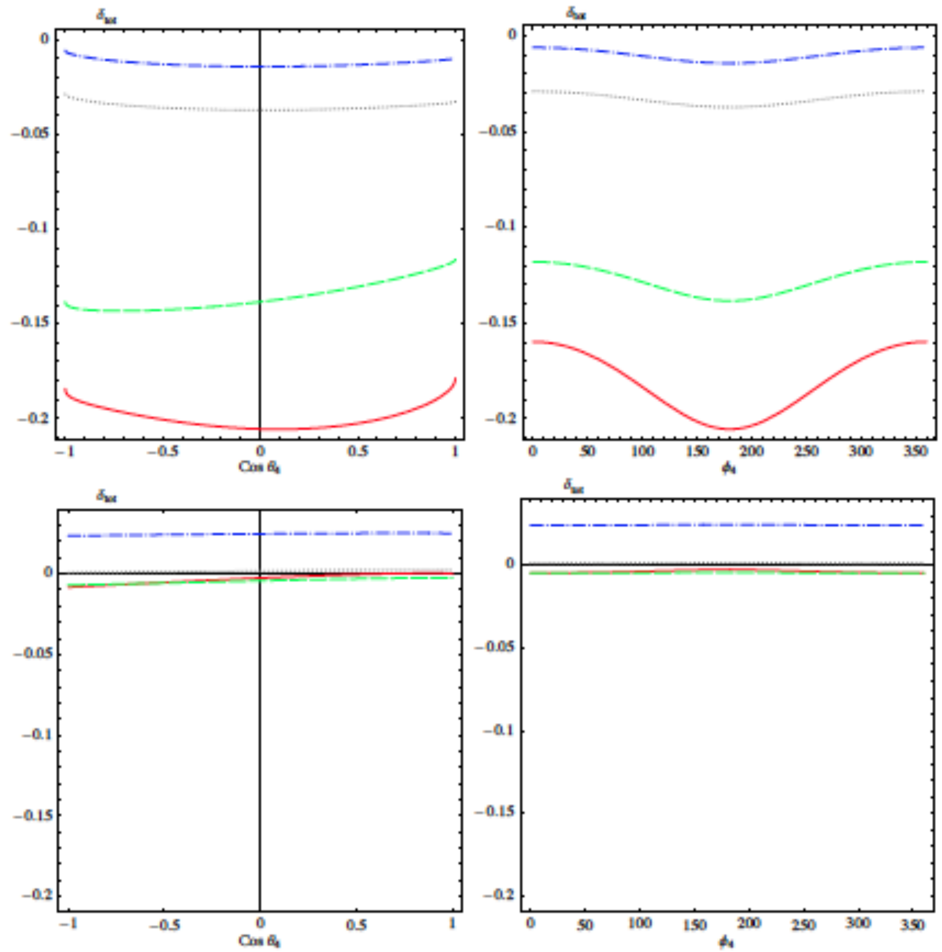

Figure 3: π^0 electroproduction two-photon box correction angular dependencies for the high $Q^2 = 6.36\,GeV^2$ (top row) and low $Q^2 = 0.4\,GeV^2$(bottom row) momentum transfers, $W = 1.232\,GeV$ and $E_{lab} = 5.75\,GeV$. Left column: dependence on $\cos\theta_4$ with $\phi_4 = 180°$. Right column: dependence on ϕ_4 with $\theta_4 = 90°$. Dot-dashed curve - SPT, dotted curve - SPT with $\alpha\pi$ subtracted, dashed curve - SPMT, solid curve - FM approach.

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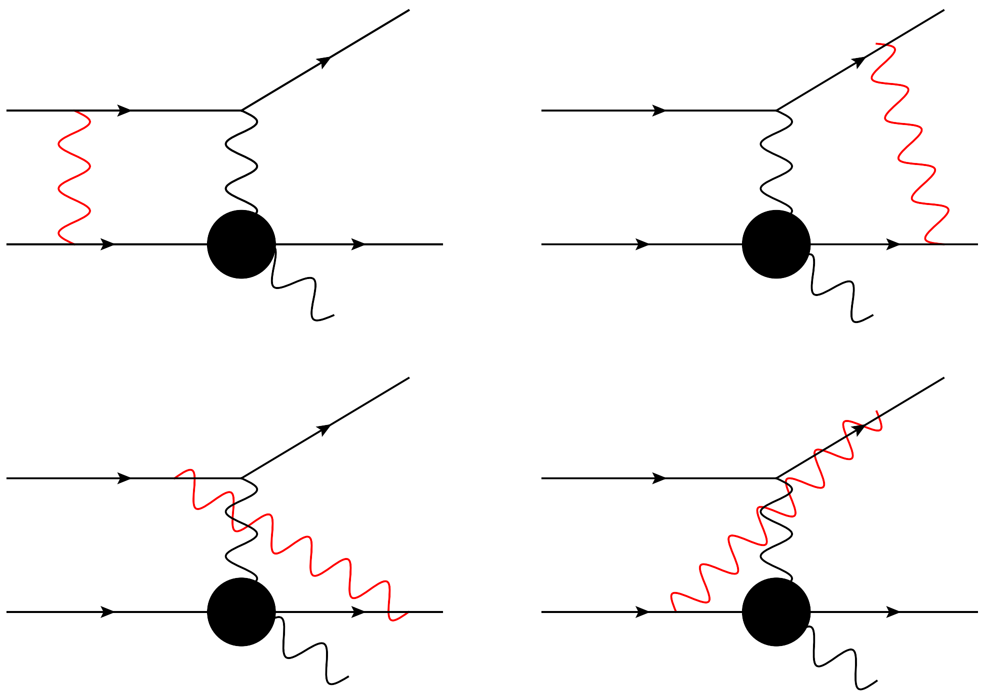
Soft TPE for VCS

- Photon coupling to external charged lines
- Results are independent of hadronic models
- IR-finite due to cancellation with real-photon emission



VCS

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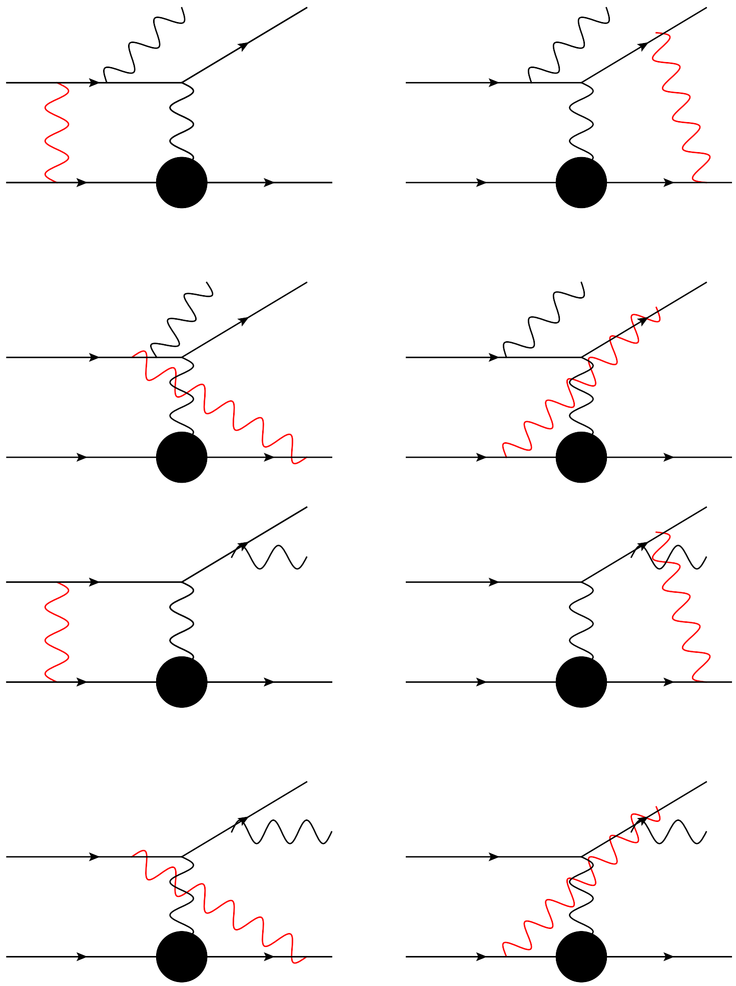
TPE to Bethe-Heitler



For BH+VCS
obtain common "soft factors" that are straightforward to include in RC codes

Important:
TPE corrections to VCS-BH intereference terms are C-even

Summary for TPE calculations

- Demonstrated an ongoing program of TPE calculations for exclusive reactions
- Two-photon exchange calculated in soft approximation for pion electroproduction

  =>Work in progress: TPE effect for VCS+BH.
- Soft-photon contributions expressed in terms of Passarino-Veltman integrals
- Can be added to existing codes and/or generators and studied for specific experimental conditions
- Equally applicable to muon scattering (important for DVMP and DVCS at COMPASS)