International Workshop on Physics with Positrons at Jefferson Lab (JPos17)

Charge and Spin Asymmetries in Elastic Lepton-Nucleon Scattering

Oleksandr Koshchii
Adviser: Andrei Afanasev
The George Washington University

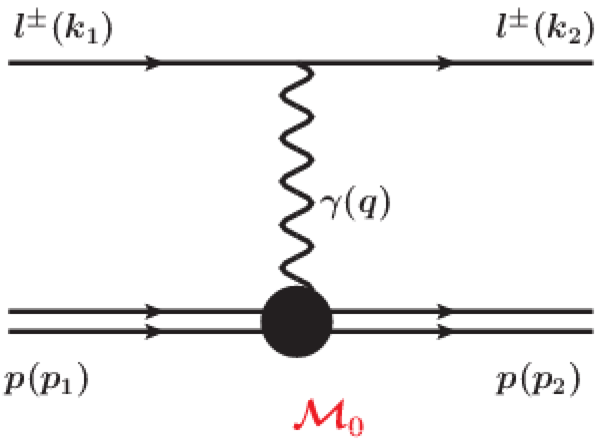
Jefferson Lab,
Newport News, VA, September 15, 2017

Outline

- Charge asymmetry in elastic lp scattering
- The proton radius puzzle and MUSE experiment
- Soft TPE in approach of Tsai and bremsstrahlung interference contributions for massive leptons
- Helicity-flip transitions: σ-meson exchange in the t-channel in kinematics of MUSE
- Target-normal single-spin asymmetries (SSA)
- Conclusion

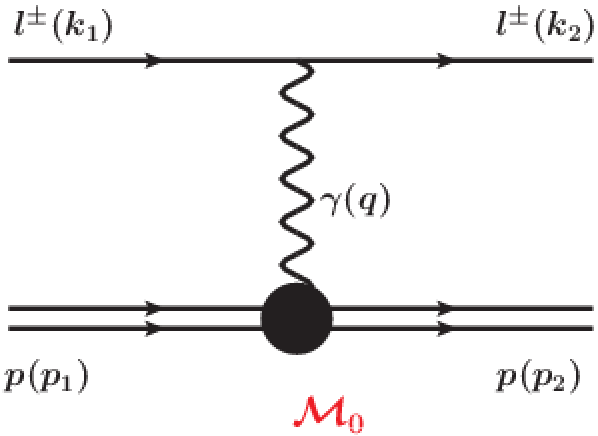
Intro: Charge Asymmetry

- Charge asymmetry in unpolarized elastic lepton-proton scattering:



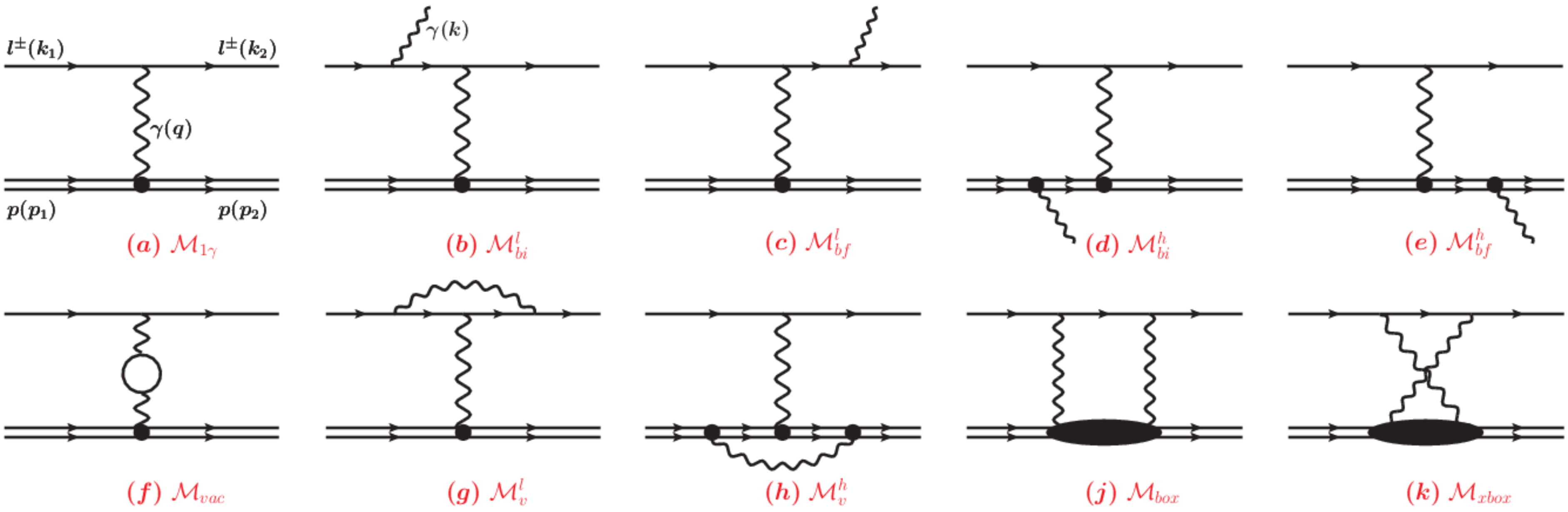
$$A \equiv \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

Lepton-Proton Scattering: Born Approximation



- Differential Cross Section: $d\sigma \propto |M_0|^2$
- Lepton Coupling: $\pm ie\gamma_\mu$ Coupling Constant: $\alpha = \dfrac{e^2}{4\pi}$
- No asymmetry in Born ($\propto \alpha^2$) Approximation

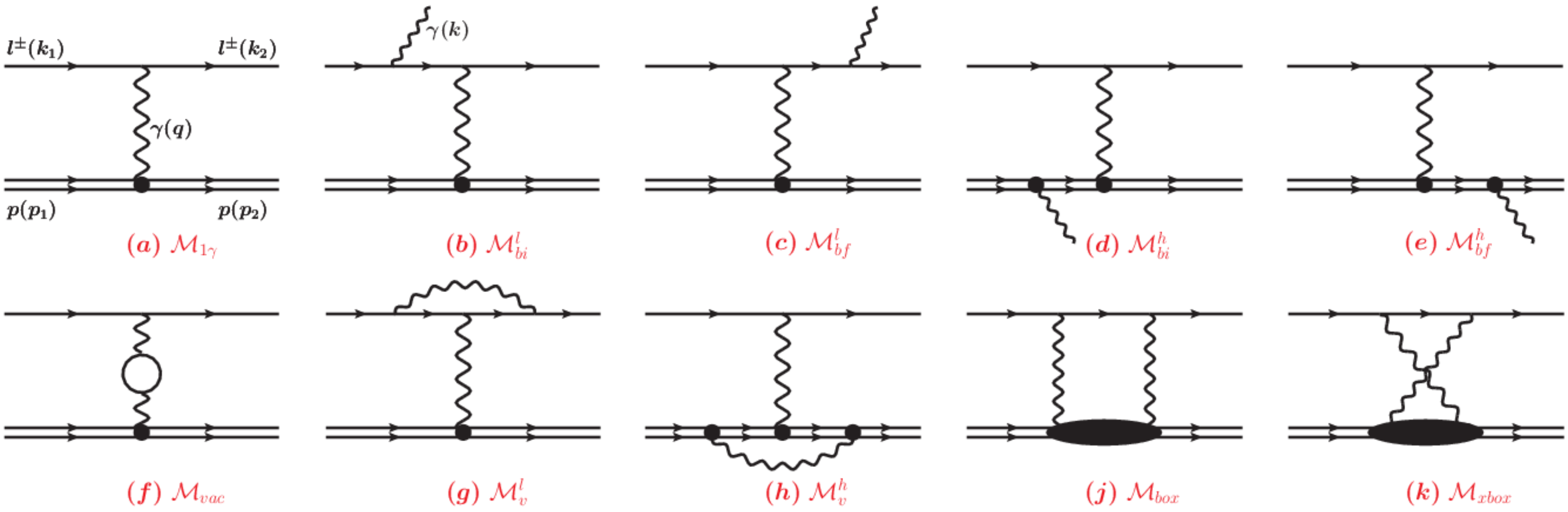
Lepton-Proton Scattering: Higher Order Diagrams



- Leading and next-to-leading order contributions:

$$|M|^2 = |M_0|^2 + |M^l_{1\gamma}|^2 + |M^h_{1\gamma}|^2 + 2\,\mathrm{Re}\left[M_0^* M_{vac}\right] + 2\,\mathrm{Re}\left[M_0^* M^l_{vert}\right]$$
$$+ 2\,\mathrm{Re}\left[M_0^* M^h_{vert}\right] + 2\,\mathrm{Re}\left[\left(M^l_{1\gamma}\right)^* M^h_{1\gamma}\right] + 2\,\mathrm{Re}\left[M_0^* M_{2\gamma}\right] + O\left(\alpha^4\right)$$

Lepton-Proton Scattering: Higher Order Diagrams



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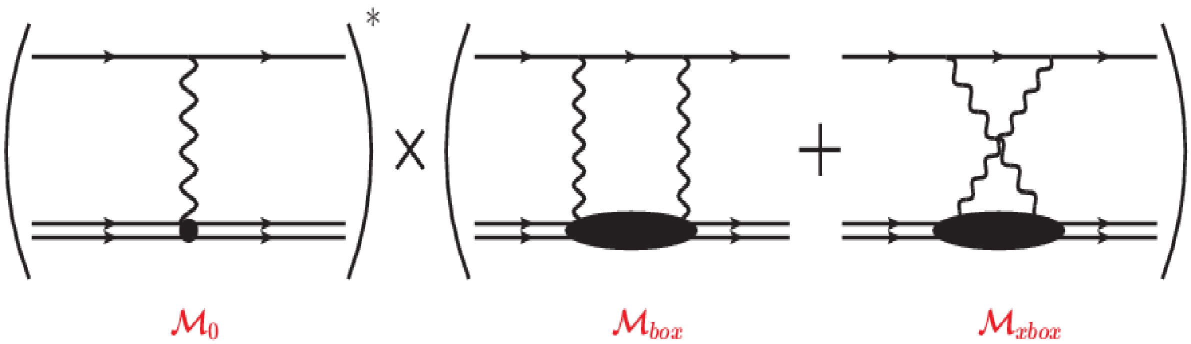
$$+ 2\,\mathrm{Re}\left[M_0^{*} M^{h}_{vert}\right] + 2\,\mathrm{Re}\left[\left(M^{l}_{1\gamma}\right)^{*} M^{h}_{1\gamma}\right] + 2\,\mathrm{Re}\left[M_0^{*} M_{2\gamma}\right] + O\left(\alpha^4\right)$$

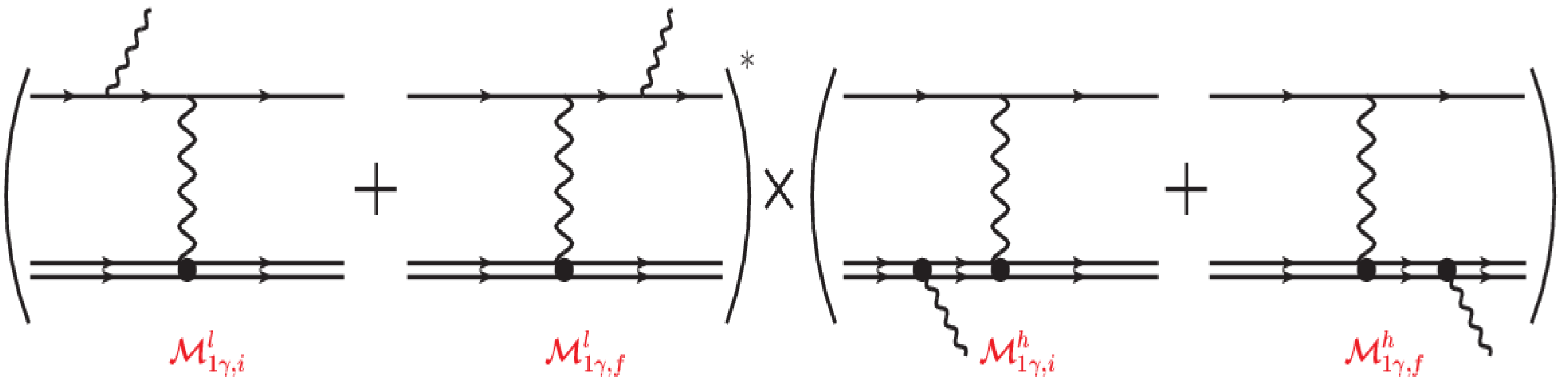
Charge-Dependent Contributions

- Lepton Coupling: $\pm ie\gamma_\mu$

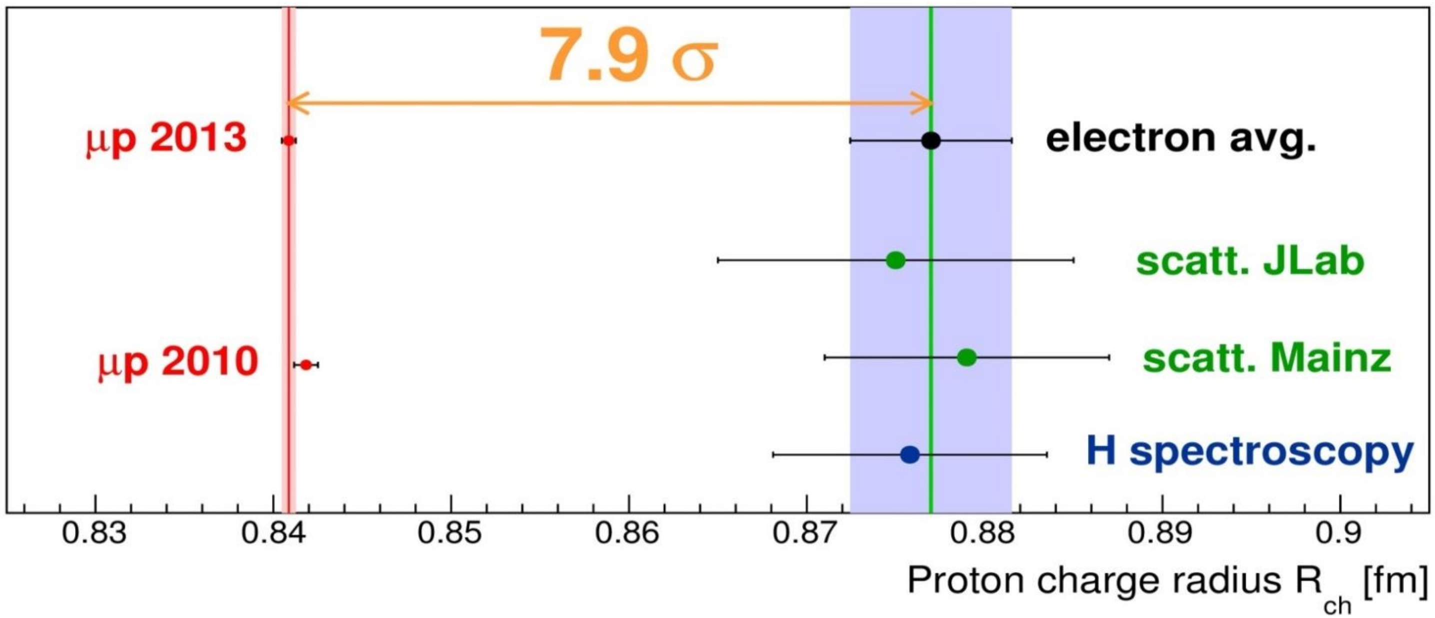
$M_0^* M_{2\gamma}$:



$\left(M_{1\gamma}^{l}\right)^* M_{1\gamma}^{h}$:



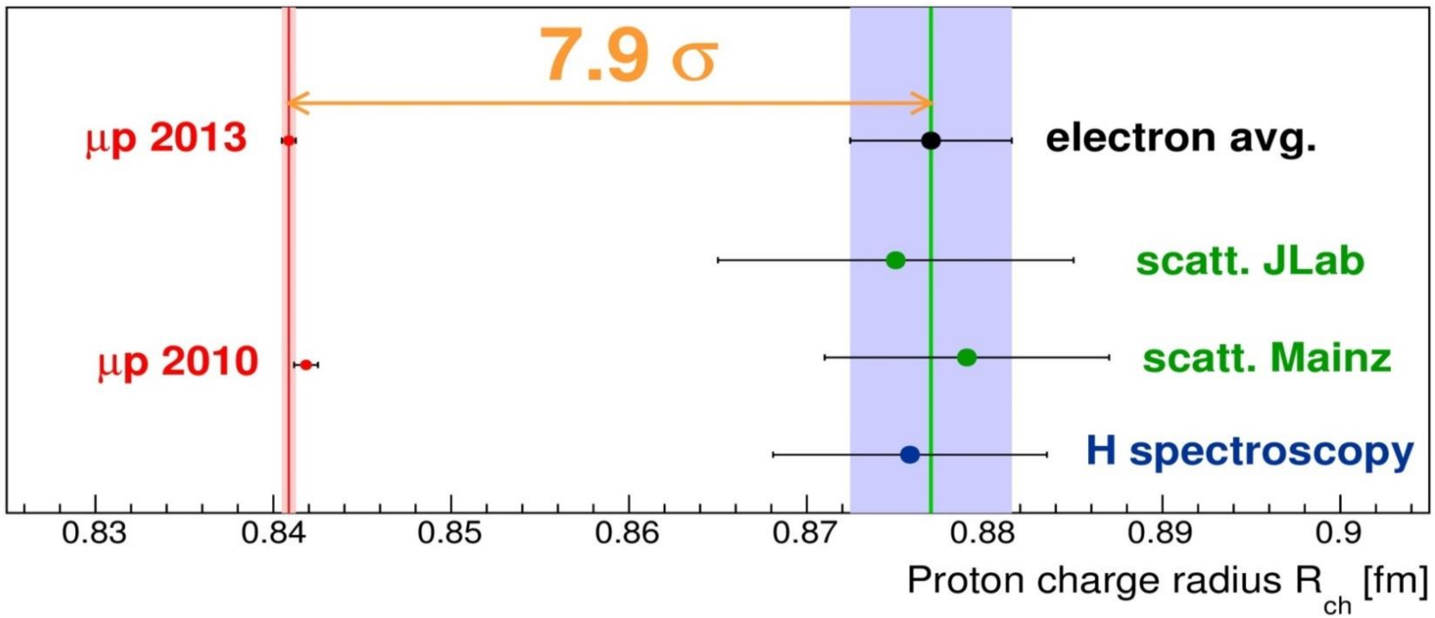
The Proton Radius Puzzle



[https://www.psi.ch/muonic-atoms/]

	Muon	Electron
Spectroscopy	0.8409(4)	0.8758(77)
Scattering	???	0.8770(60)

The Proton Radius Puzzle



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	Muon	Electron
Spectroscopy	0.8409(4)	0.8758(77)
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→ **Muon Scattering Experiment (MUSE) at PSI, Switzerland**

MUSE at PSI

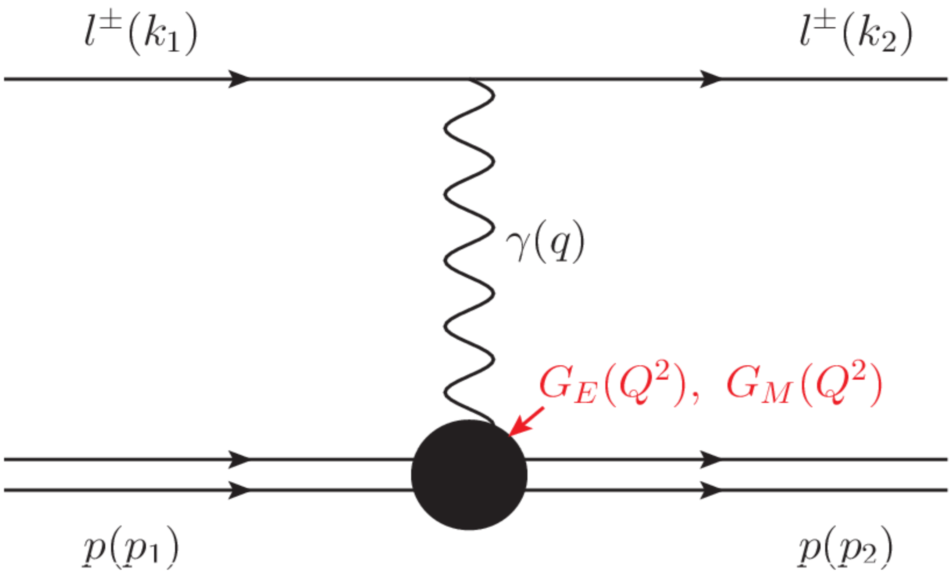
- Will measure simultaneously elastic $e^{\pm}p$ and $\mu^{\pm}p$ scattering:

  - Direct Access to TPE Corrections

- First signicant μp scattering radius determination, at roughly the same level as done in previous scattering experiments:

  - Theoretical estimations beyond the Born approximation are required. Ultrarelativistic limit, $\varepsilon \gg m$, cannot be applied to scattering of muons in kinematics of MUSE.

Theoretical Background: Born Approximation



Lab Frame :

$$k_1 = (\varepsilon_1, \vec{k}_1),$$
$$k_2 = (\varepsilon_2, \vec{k}_2),$$
$$p_1 = (M, 0),$$
$$p_2 = (E_2, \vec{p}_2),$$
$$Q^2 = -q^2 = -(k_1 - k_2)^2 > 0.$$

$G_E(Q^2),\ G_M(Q^2)$ ⟶ **Electric and Magnetic form factors**

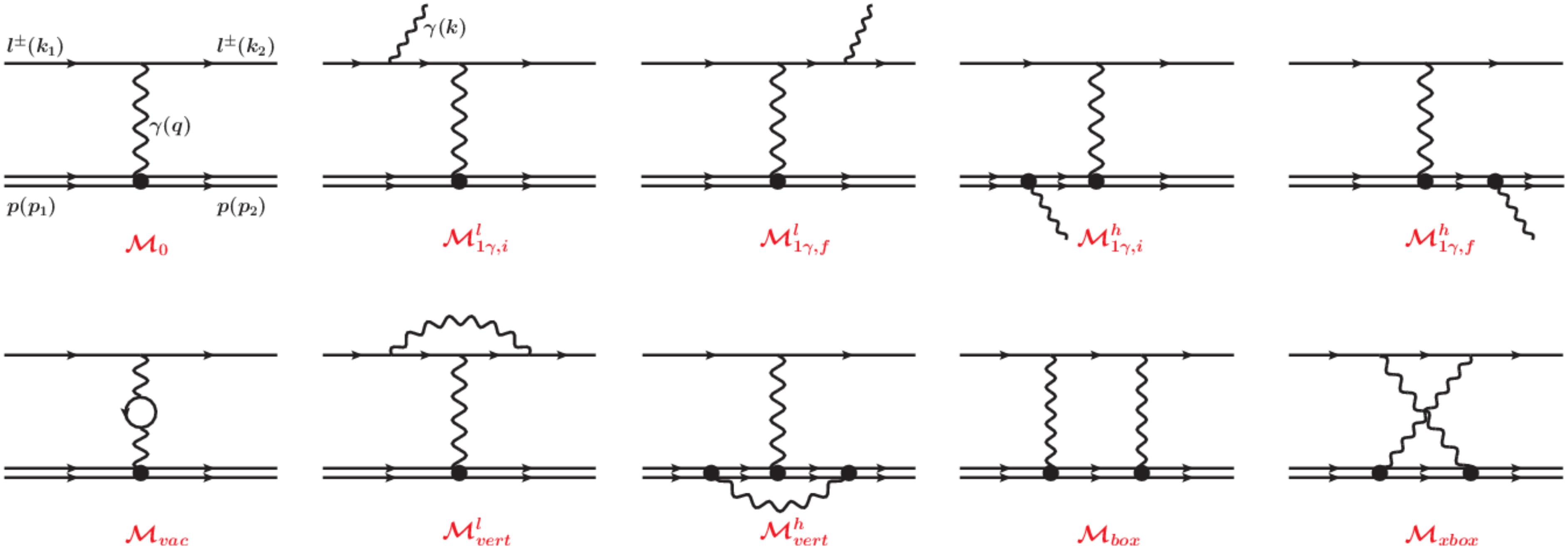
Charge radius definition:

$$\langle r^2 \rangle = -6 \left. \frac{dG_E(Q^2)}{dQ^2} \right|_{Q^2=0}$$

Rosenbluth separation:

$$\frac{d\sigma_0}{d\Omega} \propto G_E^2(Q^2) + \frac{\tau}{\in} G_M^2(Q^2)$$

Standard Higher Order Corrections



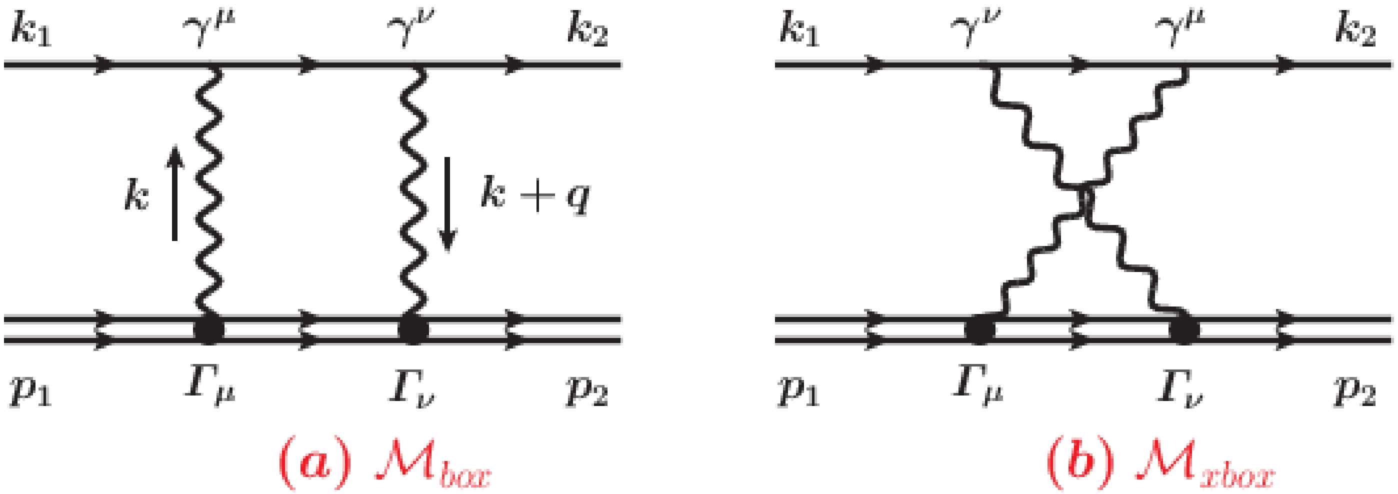
$$|M|^2 = \sum_i |M_i|^2 = |M_0|^2 (1+\delta)$$

$$d\sigma^{\exp} = d\sigma_0 (1+\delta)$$

Need to know this value to extract the radius!

Need estimations of δ!

Model-independent TPE Calculation



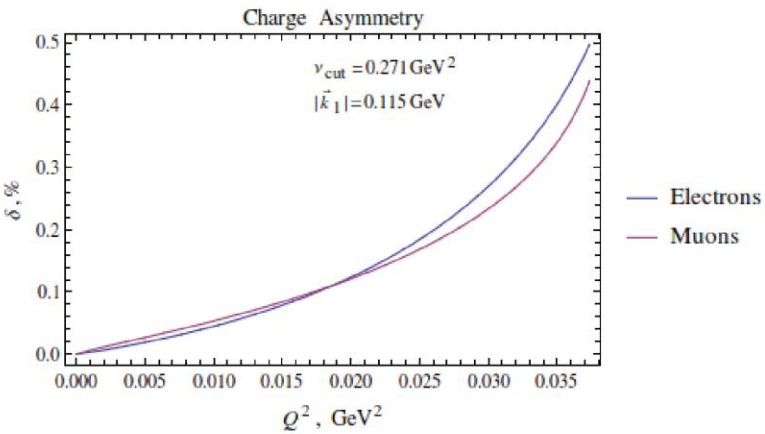
Soft Photon Approximation: $k \to 0$

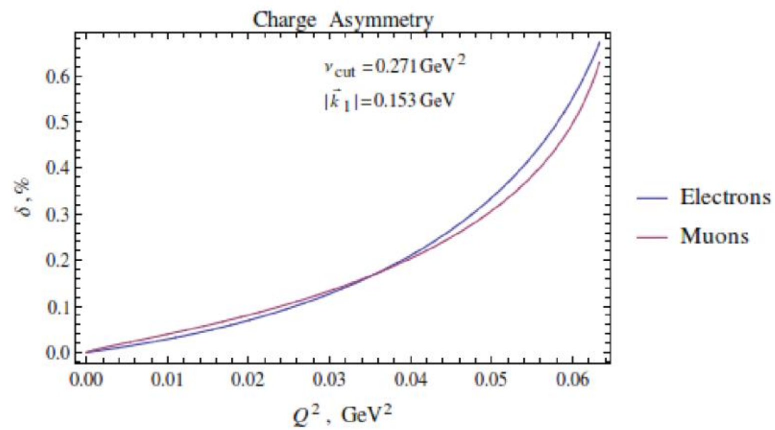
Two prescriptions: **[Mo, Tsai, Rev Mod Phys 1969]**

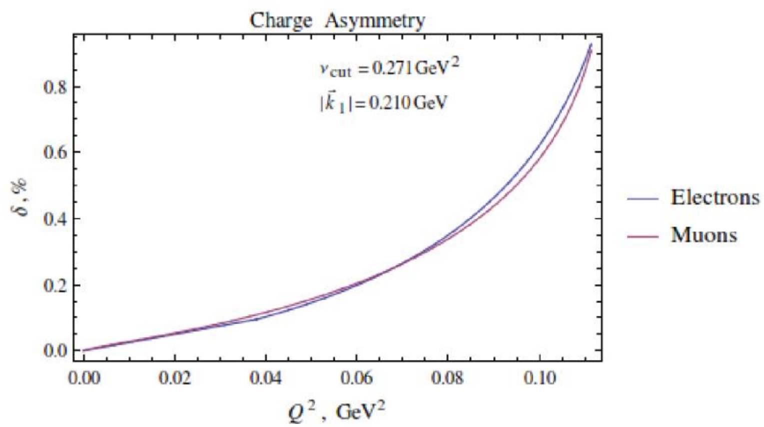
[Maximon, Tjon, Phys Rev C 2000]

Comparison: **[Gerasimov, Fadin, Phys At Nucl 2015]**

Asymmetry Comparison





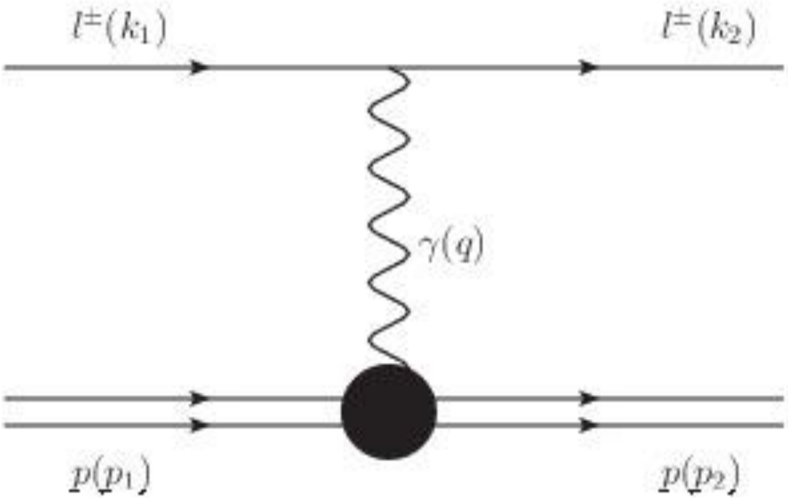


[Koshchii, Afanasev , Phys Rev D, 2017]

Extra contribution to be considered: helicity-flip transitions ($\sim m_l$)

σ-meson exchange in t-channel

Consider the interference between following diagrams:



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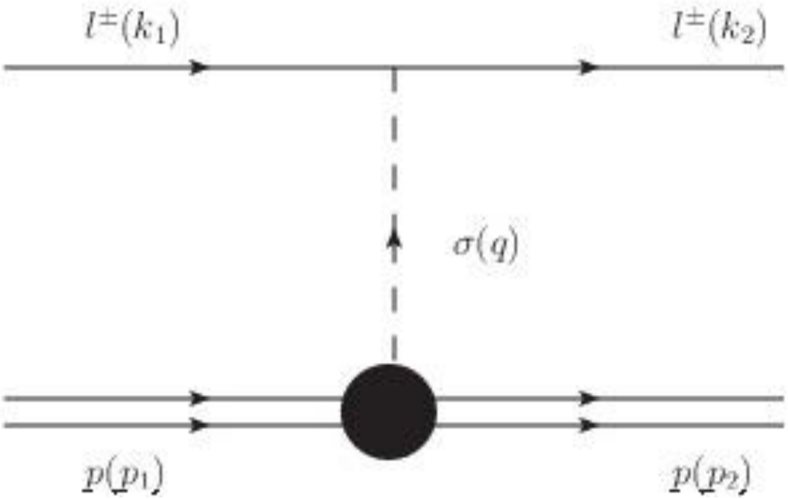

$$j_\mu^\nu = \bar{u}(k_2)\gamma_\mu u(k_1)$$

$$J_\mu^\nu = \bar{U}(p_2)\left(\gamma_\mu F_1(Q^2) + \frac{i\sigma_{\mu\nu}q_\nu}{2M}F_2(Q^2)\right)U(p_1)$$

$$j_\mu^s = f_s\ \bar{u}(k_2)u(k_1)$$

$$J_\mu^s = \bar{U}(p_2)U(p_1)$$

σ-meson exchange in t-channel

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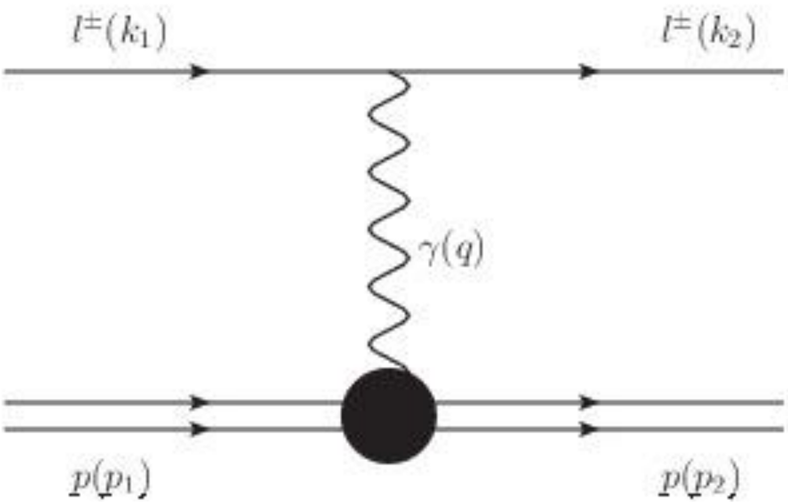
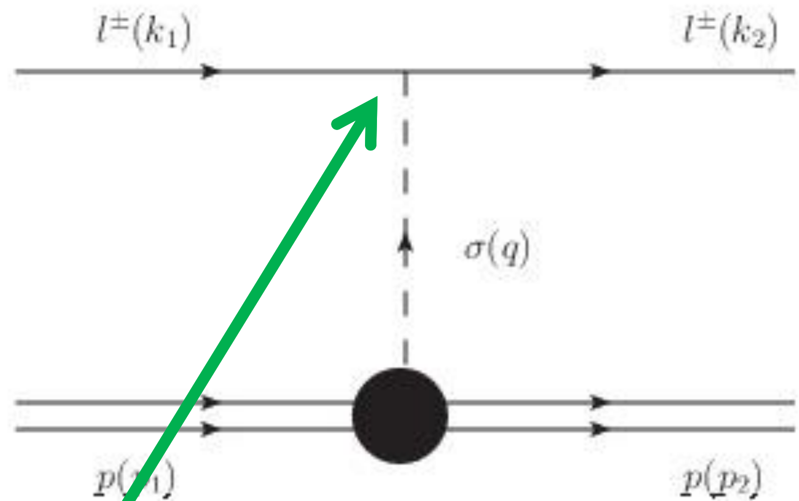




$$j^{v}_{\mu} = \bar{u}(k_2)\gamma_{\mu}u(k_1)$$

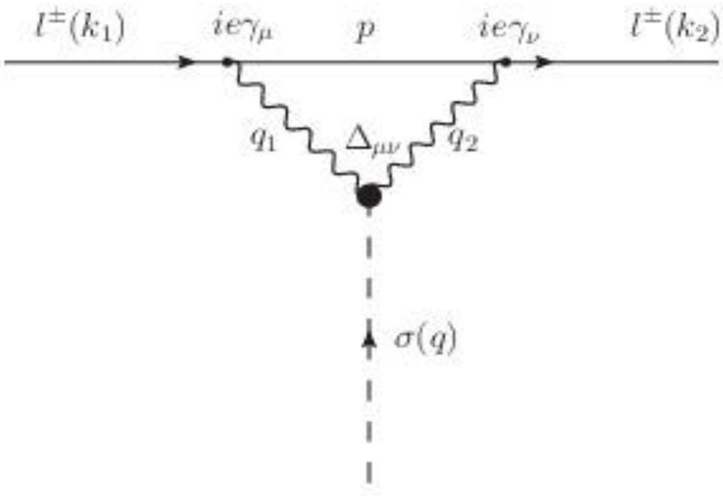
$$J^{v}_{\mu} = \bar{U}(p_2)\left(\gamma_{\mu}F_1(Q^2) + \frac{i\sigma_{\mu\nu}q_{\nu}}{2M}F_2(Q^2)\right)U(p_1)$$

$$j^{s}_{\mu} = f_s\ \bar{u}(k_2)u(k_1)$$

$$J^{s}_{\mu} = \bar{U}(p_2)U(p_1)$$

The coupling of σ to lepton is described via form factor f_s

Model to calculate f_s

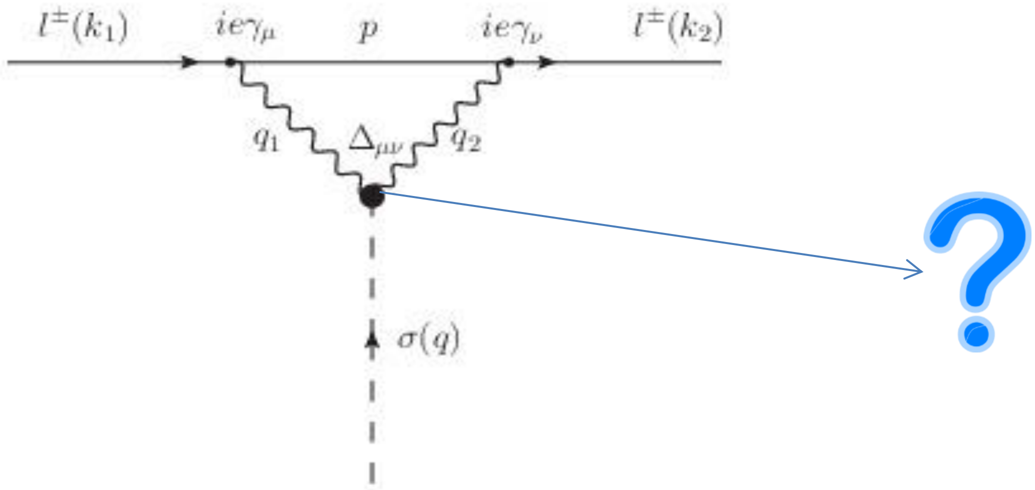


Corresponding amplitude

$$T = ie^4 \int \frac{d^4 p}{(2\pi)^4} \; \bar{u}(k_2) \; \frac{\gamma_\nu (\not{p} + m)\gamma_\nu}{p^2 - m^2} \; u(k_1) \frac{1}{q_1^2} \Delta_{\mu\nu} \frac{1}{q_2^2}$$

Everything that is sandwiched between spinors is the form factor!

Model to calculate f_s



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Everything that is sandwiched between spinors is the form factor!

Vertex description

The most general form to describe the vertex:

$$\Delta_{\mu\nu} = A_s(q^2;q_1^2,q_2^2)\left(g_{\mu\nu}(q_1\cdot q_2) - q_1^{\nu}q_2^{\mu}\right) + B_s(q^2;q_1^2,q_2^2)\left(q_1^2 q_2^{\mu} - (q_1\cdot q_2)q_1^{\mu}\right)\left(q_2^2 q_1^{\nu} - (q_1\cdot q_2)q_2^{\nu}\right)$$

[A.E. Dorokhov et. al. Eur. Phys. J. C (2012)]

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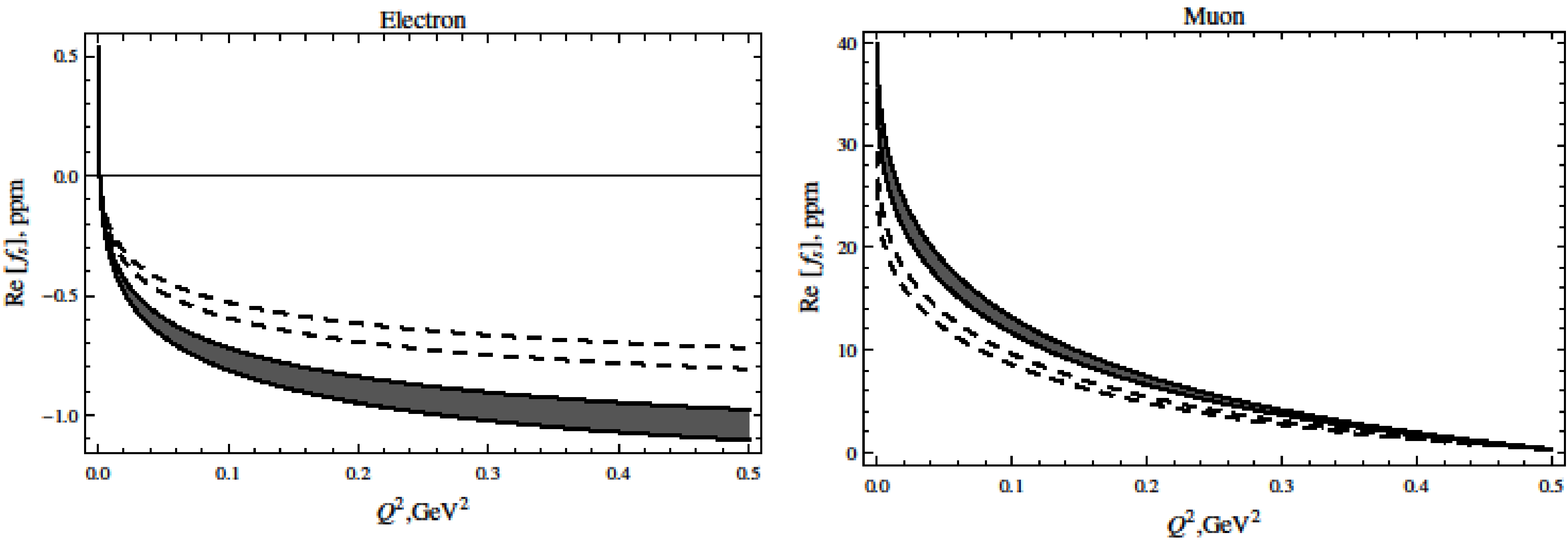
[A.E. Dorokhov et. al. Eur. Phys. J. C (2012)]

Vector meson dominance (VMD) model for transverse photons:

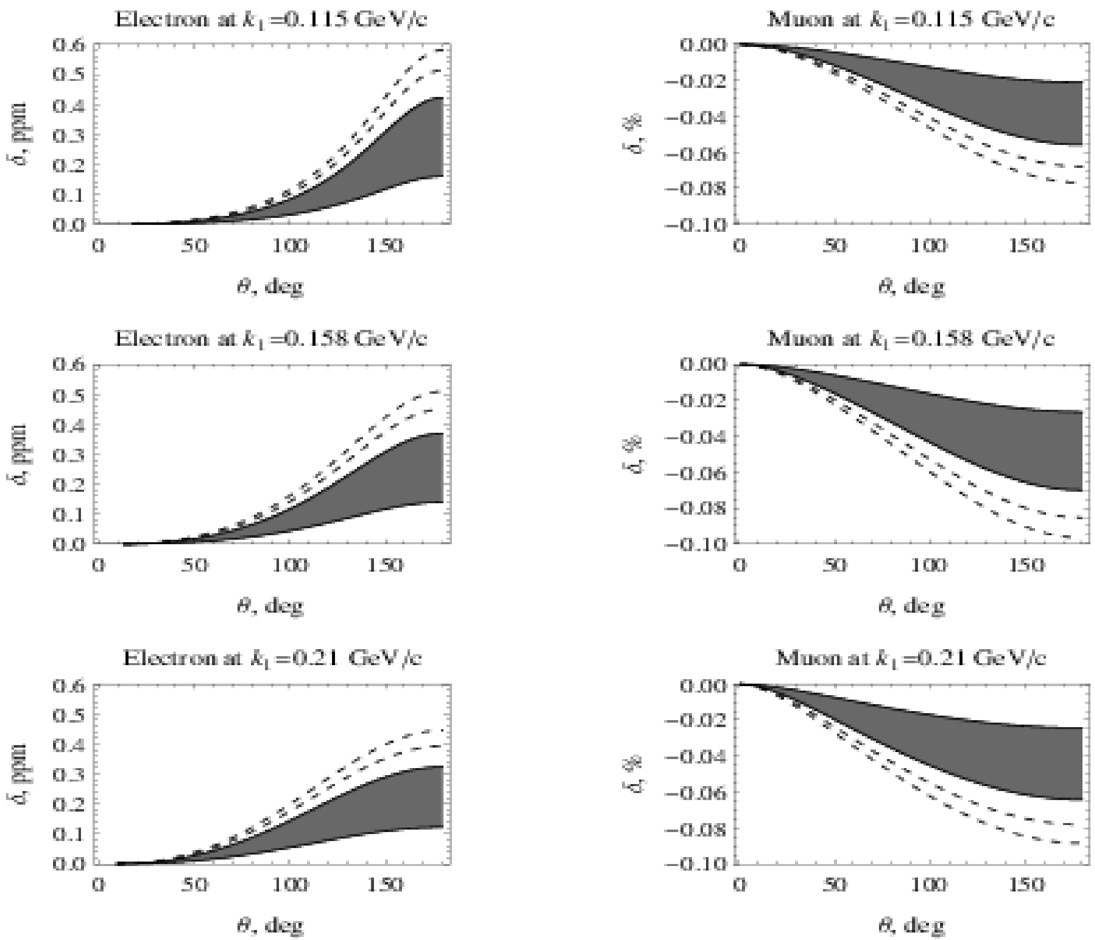
$$A_s(q^2;q_1^2,q_2^2) = \frac{g_{\sigma\gamma\gamma}\; m_\rho^4}{\left(m_\rho^2 - q_1^2\right)\left(m_\rho^2 - q_2^2\right)}$$

Obtained experimentally

Results: Form Factor f_s



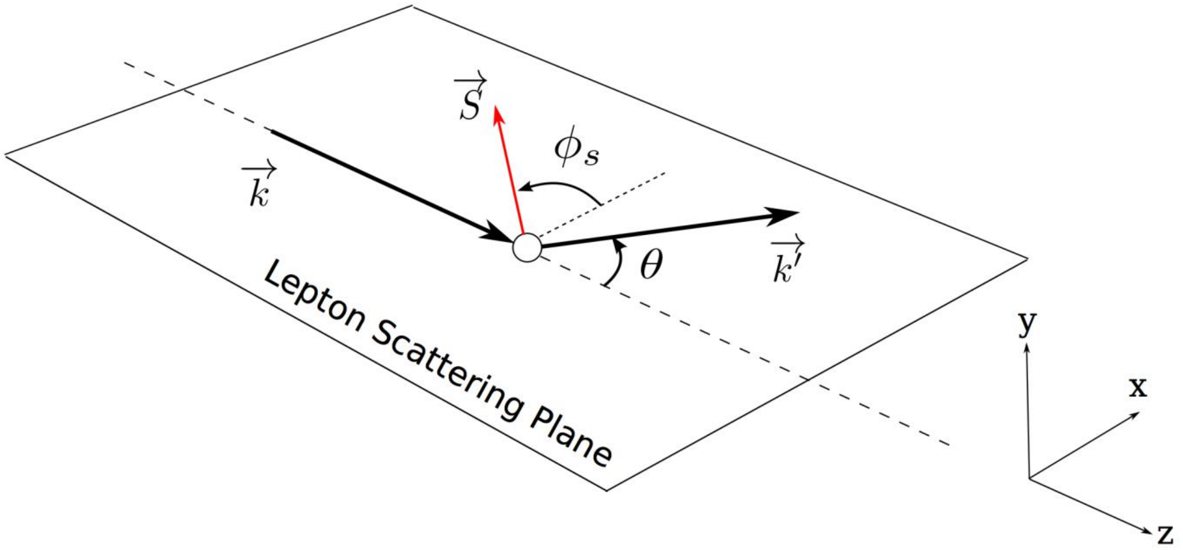
Results: Correction δ



[Koshchii, Afanasev, Phys Rev D, 2016]

Target Normal Single Spin Asymmetry (SSA)

- Target normal SSA in elastic lepton-nucleon scattering:



$$A_n \equiv \frac{d\sigma_{\uparrow} - d\sigma_{\downarrow}}{d\sigma_{\uparrow} + d\sigma_{\downarrow}}$$

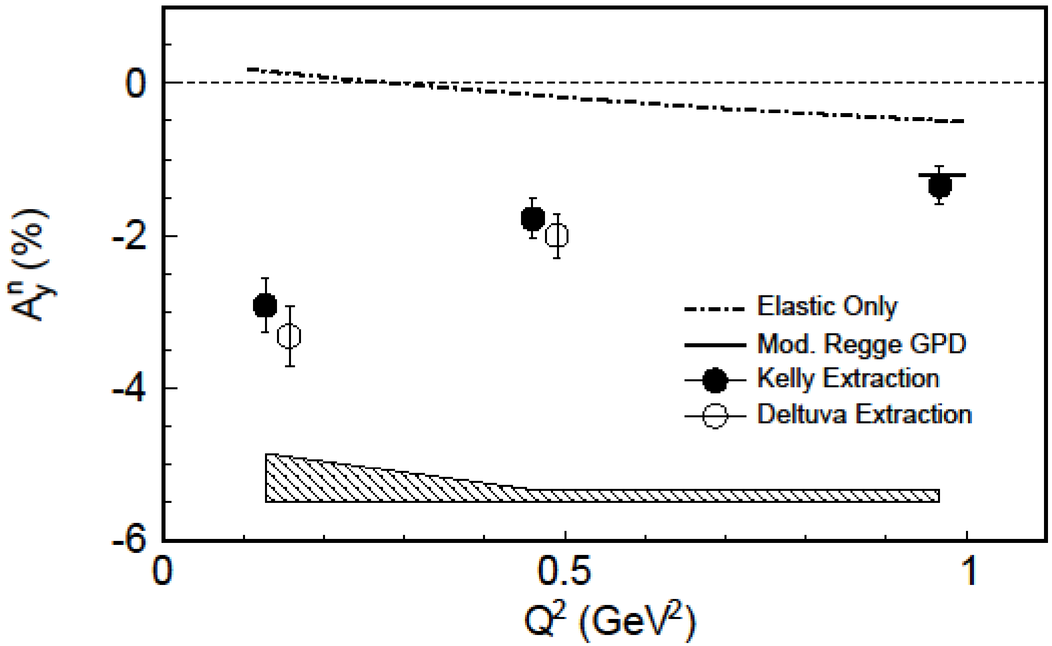
Normal SSA: Theory

$$A_n \approx \frac{2\,\mathrm{Im}\left(\sum_{spin} T_{1\gamma}^{*} \cdot Abs\left[T_{2\gamma}\right]\right)}{\sum_{spin} \left|T_{1\gamma}\right|^{2}}$$

[de Rujula, Kaplan, Rafael, Nucl. Phys. B 1971]

- Target-Normal SSA in elastic $l^{\pm}N$ scattering contribute with different signs. Corresponding sum will provide information on contributions beyond TPE
- Absorptive part of TPE amplitude can be used to obtain real part of the TPE amplitude through dispersive relations

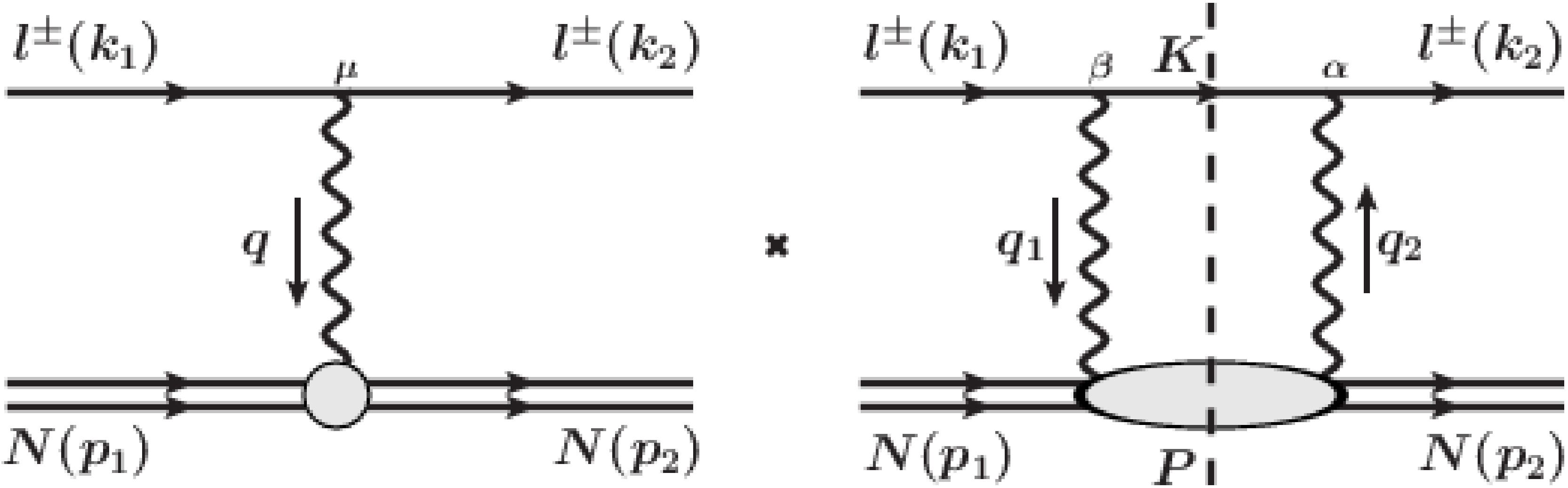
Target-Normal SSA: Neutron



[Y.-W. Zhang, et al, Phys Rev Lett 2015]

- Polarized ^3He target – effective neutron target
- Beam energies: 1.245, 2.425, 3.605 GeV

Target-Normal SSA Calculation



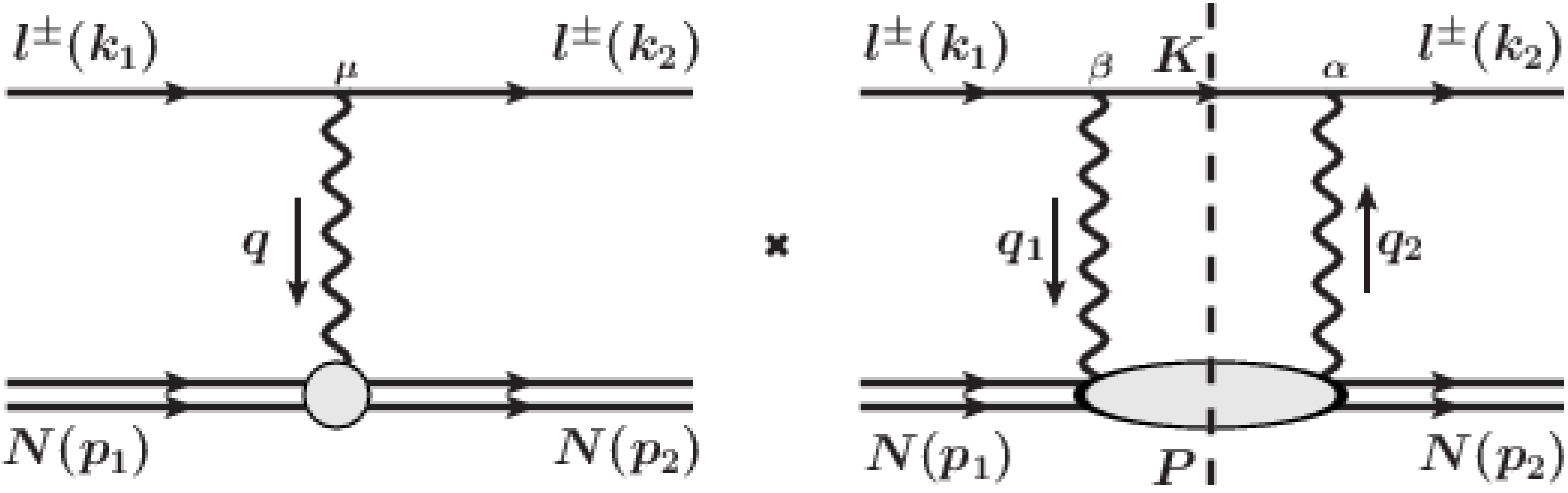
$$A_n = \frac{\alpha Q^2}{8\pi D(s,t,u)} \int \frac{d^3K^*}{2E_K} \frac{1}{Q_1^2 Q_2^2} \mathrm{Im}\left(\sum_{spin} L^{\mu\alpha\beta} H_{\mu\alpha\beta} \right)$$

$$\sum_{spin} H_{\mu\alpha\beta} = \frac{1}{2} Tr\left[\left(\not{p}_1 + M \right)\left(1 - \gamma_5 \not{S} \right) \Gamma_\mu \left(\not{p}_2 + M \right) W_{\alpha\beta} \right]$$

The most general form for $W_{\alpha\beta}$:

[R. Tarrach, IL Nuovo Cimento 1975] - 18 invariant amplitudes

Target-Normal SSA Calculation



Optical Theorem Approach ($Q^2 \ll s$):

[Afanasev, Merenkov, Phys Rev D 2004] Beam-normal SSA

Electroabsorption Amplitudes ($\mathrm{P} \leq 2\ GeV$):

[Pasquini, Vanderhaeghen, Phys Rev C 2004] Beam- and target-normal SSA

$W_{\alpha\beta}$ parametrization

Elastic contribution:

$$W_{\alpha\beta} = 2\pi\delta\left((p_1+q_1)^2 - M^2\right)\bar{U}(p_1)\Gamma_\beta(q_1^2)\left(\not{p}_1 + \not{q}_1 + M\right)\Gamma_\alpha(q_2^2)U(p_2)$$

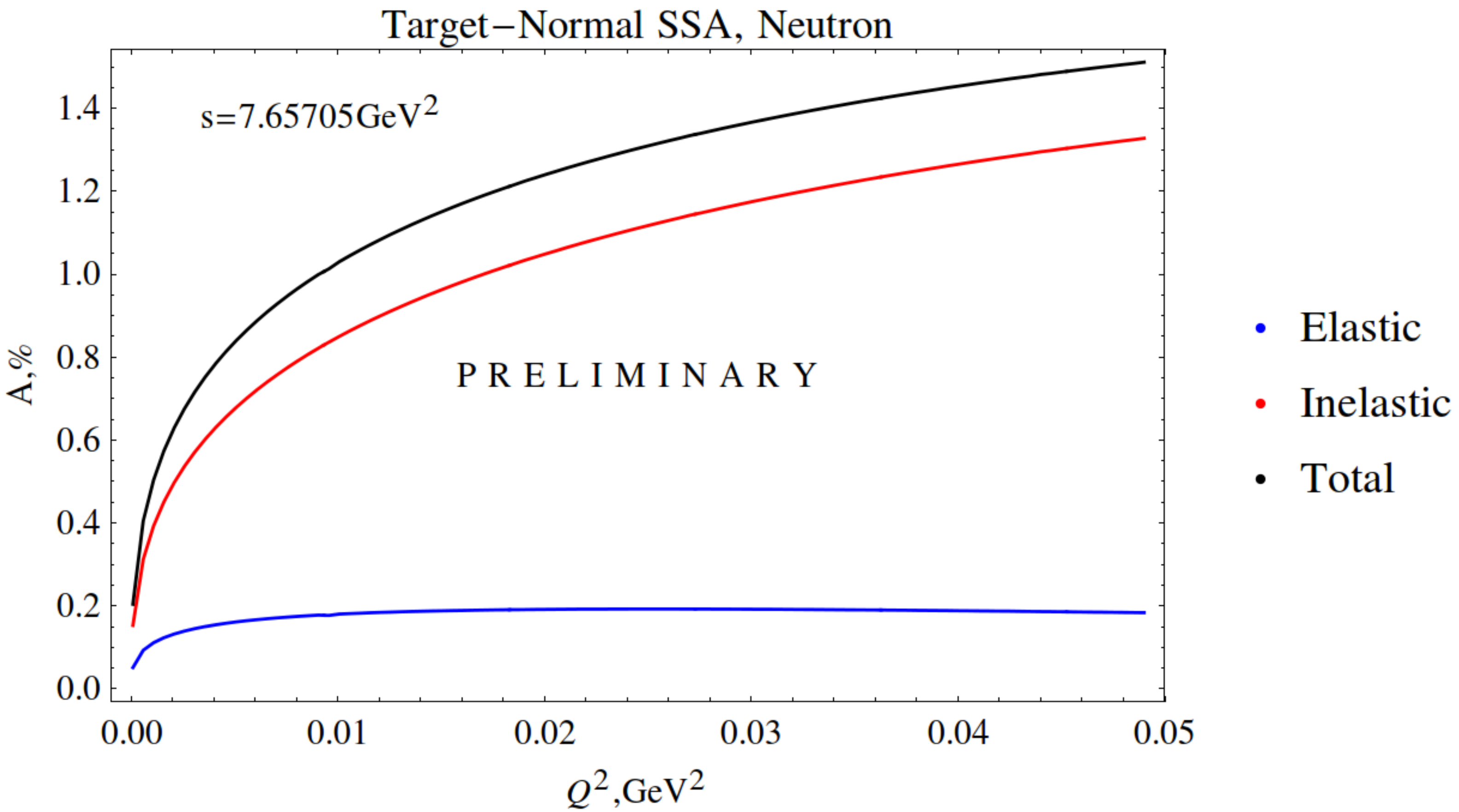
Nearly forward inelastic parametrization:

$$W_{\alpha\beta} = \left(\tau_1\right)_{\alpha\beta} W_1 + \left(\tau_2\right)_{\alpha\beta} W_2$$

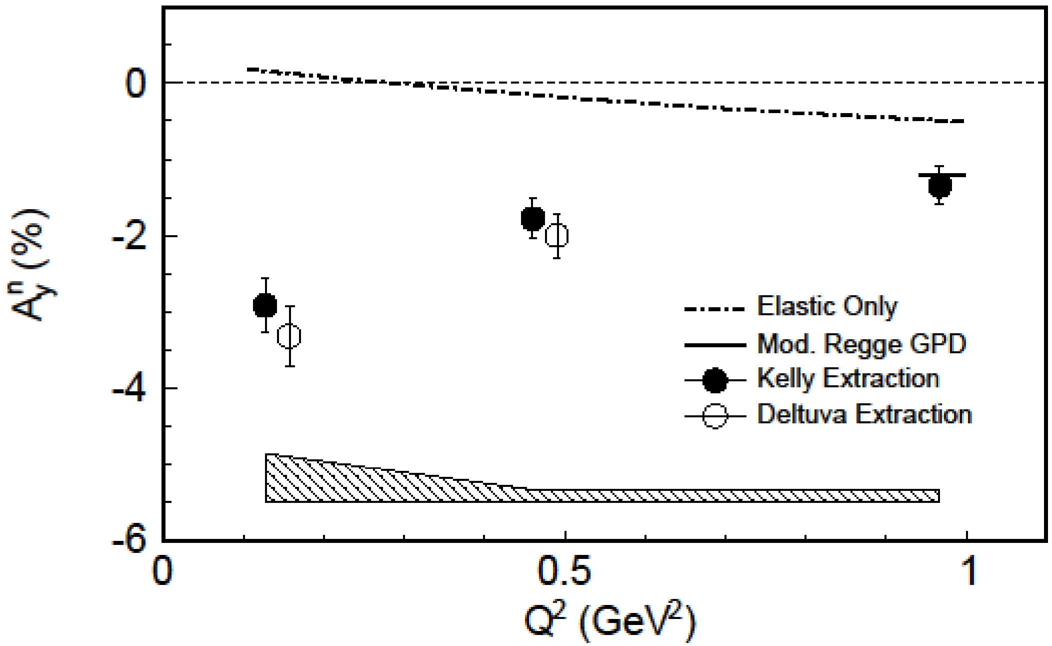
W_1, W_2 - unpolarized neutron structure functions

$\left(\tau_1\right)_{\alpha\beta}, \left(\tau_2\right)_{\alpha\beta}$ - **[R. Tarrach, IL Nuovo Cimento 1975]**

Target-Normal SSA: Preliminary Results



Target-Normal SSA: Neutron



[Y.-W. Zhang, et al, Phys Rev Lett 2015]

- Polarized ^3He target – effective neutron target
- Beam energies: 1.245, 2.425, 3.605 GeV

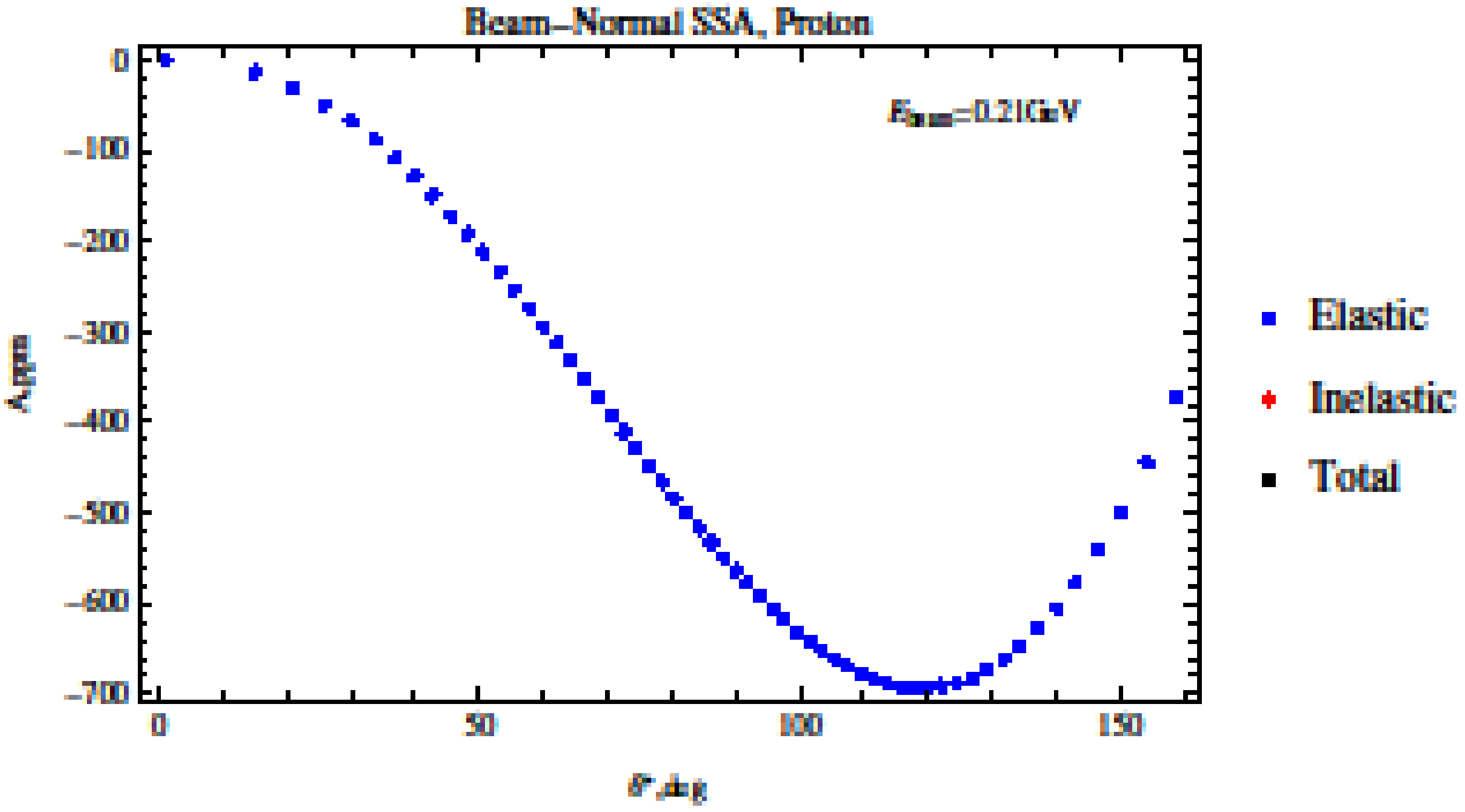
Conclusion

- Analytically generalized the existing soft-photon approximation approach of Tsai to include the lepton’s mass in final expressions
- Estimated the major helicity-flip contribution in kinematics of MUSE coming from the scalar σ-meson exchange in the t-channel
- Calculated (preliminary) neutron-normal SSA using nearly forward Compton scattering tensor

Acknowledgement

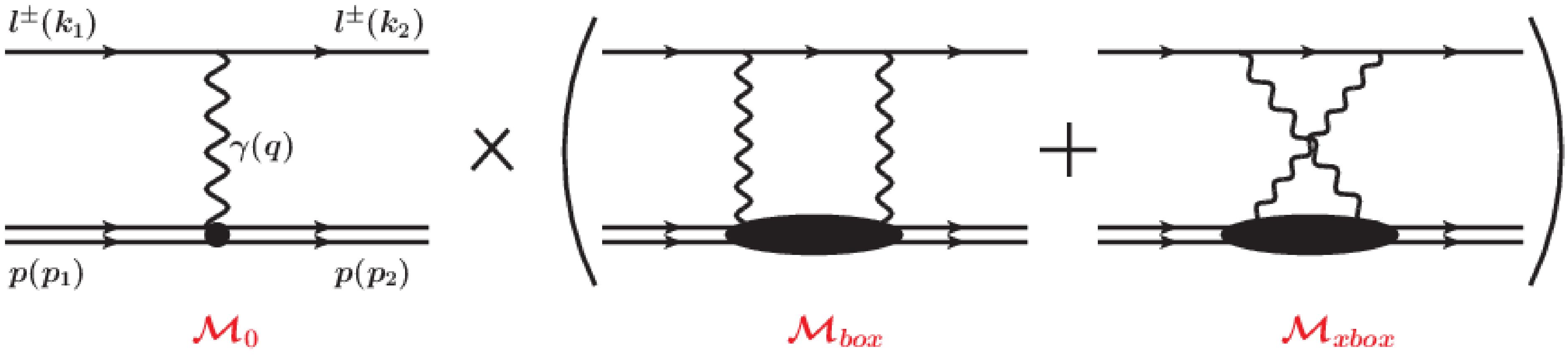
- This presentation was made possible with the support coming from a JLab/JSA fellowship award 2016/17

Back-up



Beam–Normal SSA, Proton
E_{beam}=0.21GeV
0
−100
−200
−300
−400
−500
−600
−700
0
50
100
150
θ*, deg
Elastic
Inelastic
Total

Charge-Dependent Contributions: Calculation



Direct loop calculation:

[Blunden, Melnitchouk, Tjon, 2003 & 2005]

[Tomalak, Vanderhaeghen, Phys Rev D 2014]

Dispersive treatment:

[Gorstein, Phys Lett B 2007]

[Borisyuk, Kobushkin, Phys Rev C 2008]

[Tomalak, Vanderhaeghen, EPJ A 2015]