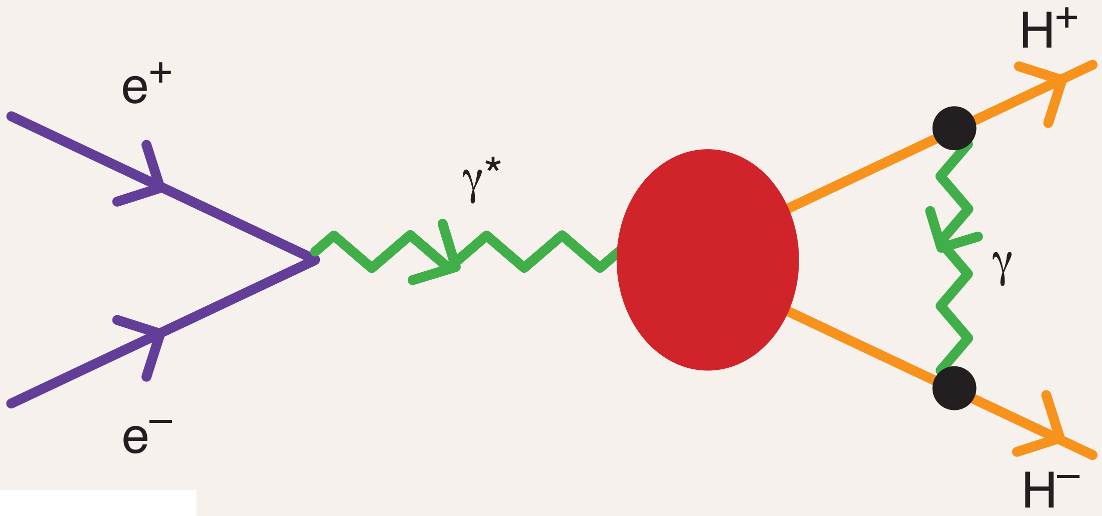
Possibility: Atomic protonium

Hyde-Wright, sjb

- Sommerfeld-Schwinger factor C dual to Bohr spectrum below threshold
- Coulomb-bound proton-antiproton amplitudes decay via annihilation to mesons KeV binding energies
- P-waves: Photon decays
- True muonium, true tauonium bound states

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\beta}{4s} CD = \frac{\alpha^2\beta}{4s} C \left[\mid G_M \mid^2 (1 + cos^2\theta) + \frac{1}{\tau} \mid G_E \mid^2 sin^2\theta \right]$$

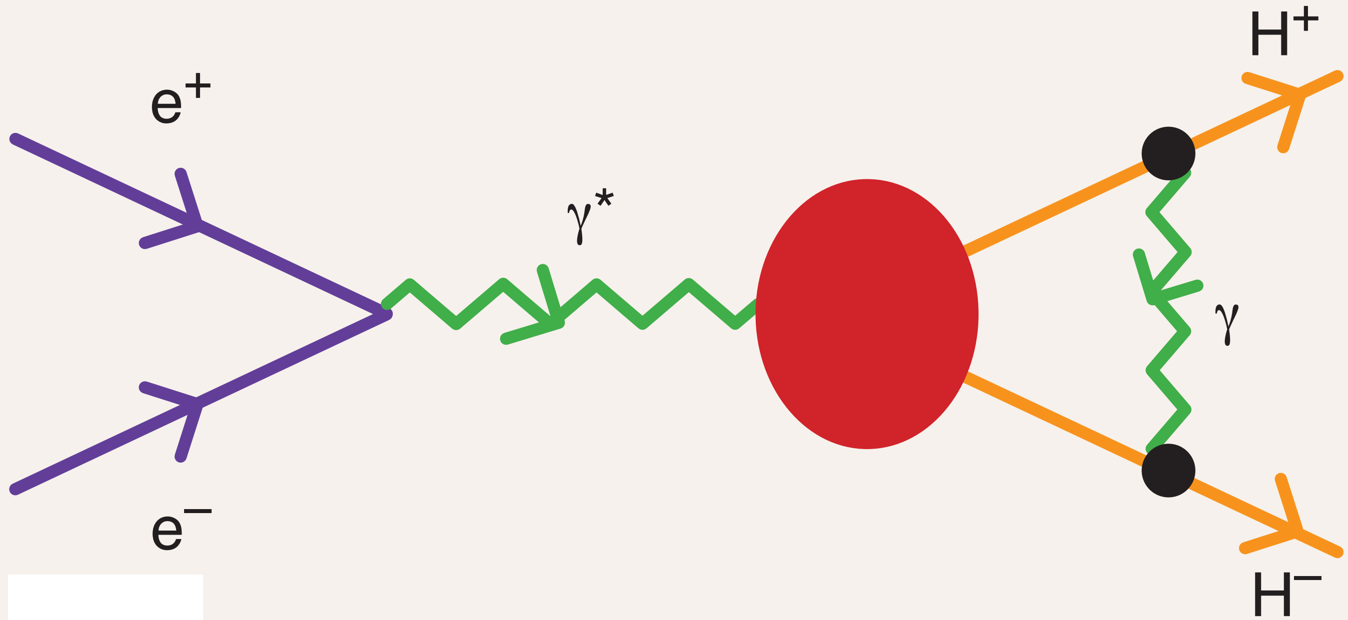


Coulomb correction is part of current matrix element

Coulomb final-state phases:
different for different partial waves!

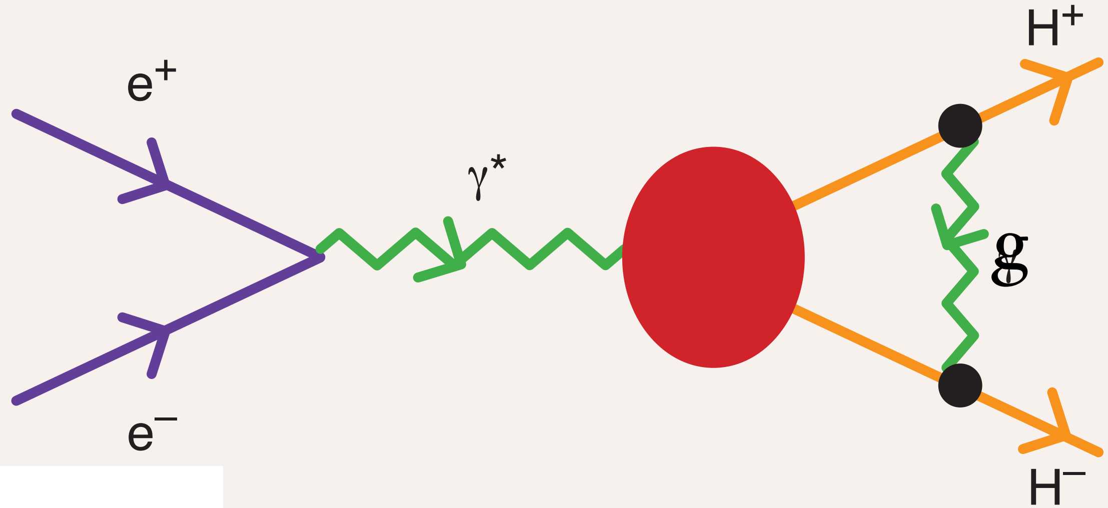
Coulomb phases can give Py SSA even at threshold

FSI from Coulomb Interactions



Coulomb phase different in G_E and G_M
Produces polarization asymmetry $A_\perp$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\beta}{4s}CD = \frac{\alpha^2\beta}{4s}C\left[\mid G_M \mid^2 (1+cos^2\theta) + \frac{1}{\tau} \mid G_E \mid^2 sin^2\theta\right]$$



QCD analog:

$$C = \frac{y}{1 - exp(-y)} \qquad y = \pi\alpha M/\beta\sqrt{s}$$

Hoang, Kuhn, Tuebner, sjb

$\alpha \to C_F\alpha_s$ Small BLM scale

Actually part of Hadron Form Factor! QCD Coulomb phases

Spin Asymmetries and the Baryon Form Factors

Dubnickova, Dubnicka, Rekalo; Rock

Carlson, Hiller, Hwang, sjb

- Phase difference between timelike form factors produces Single-Spin Asymmetry Py normal to production plane
- Polarization of initial leptons not necessary for Py: $\vec{k} \times \vec{p} \cdot \vec{S}_p$
- Analyze final state baryon spin from second scattering or decay
- Strong Discriminant of Models
- Three polarizations: Px, Py, Pz

Spin Asymmetries and the Baryon Form Factors

Dubnickova, Dubnicka, Rekalo; Rock

Carlson, Hiller, Hwang, sjb

$$\mathcal{P}_y = \frac{\sin 2\theta \,\mathrm{Im} G_E^* G_M}{D\sqrt{\tau}} = \frac{(\tau - 1)\sin 2\theta \,\mathrm{Im} F_2^* F_1}{D\sqrt{\tau}}$$

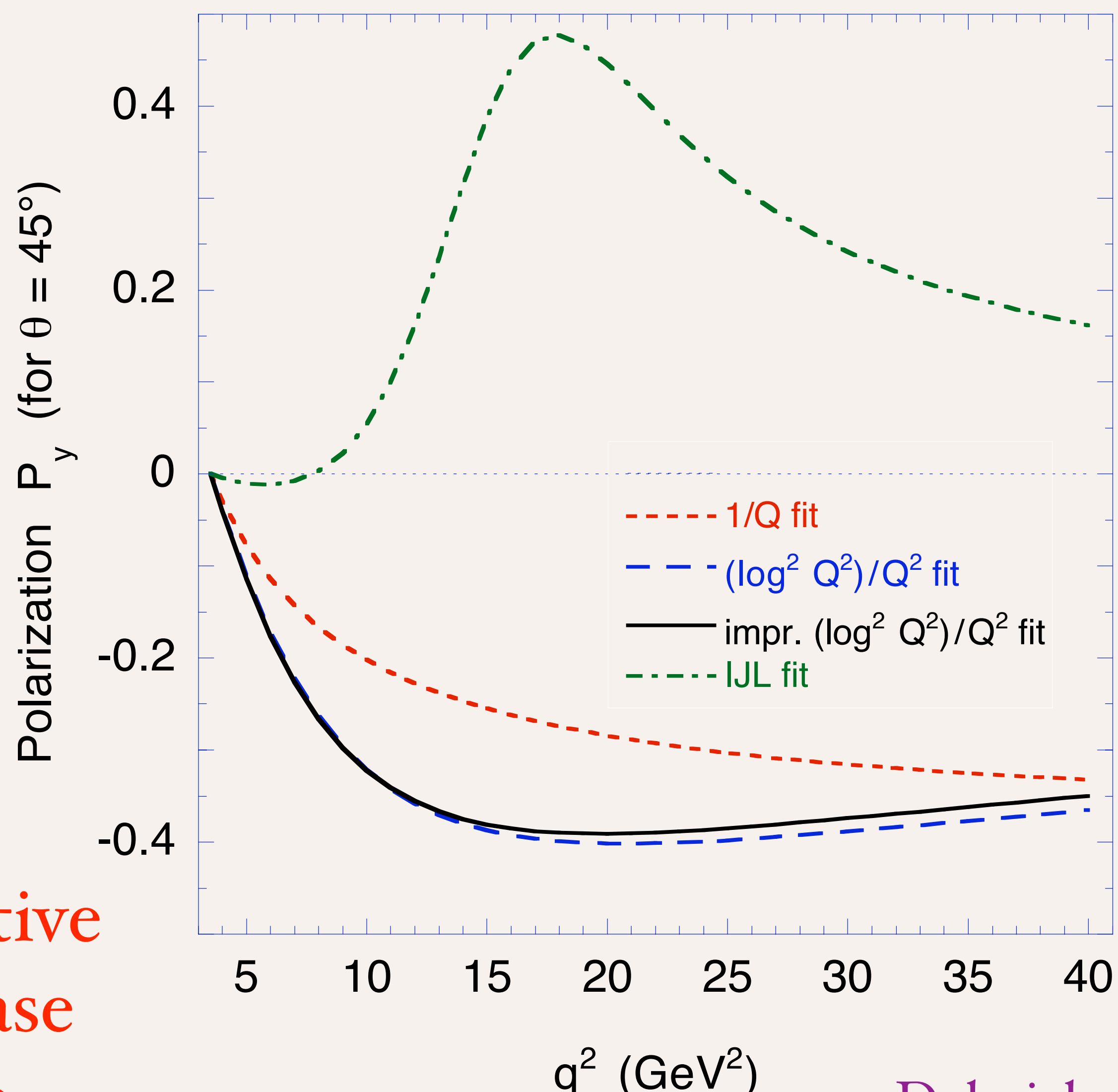
$$\vec{k} \times \vec{p} \cdot \vec{S}_p$$

$$\mathcal{P}_x = -P_e \frac{2\sin\theta \,\mathrm{Re} G_E^* G_M}{D\sqrt{\tau}}$$

$$\mathcal{P}_z = P_e \frac{2\cos\theta |G_M|^2}{D}$$

$$\frac{\mathcal{P}_y}{\mathcal{P}_x} = \frac{\cos\theta}{P_e}\frac{\mathrm{Im}\, G_M^* G_E}{\mathrm{Re}\, G_M^* G_E} = \frac{\cos\theta}{P_e}\tan(\delta_E - \delta_M)$$

$$\mathcal{P}_y = \frac{\sin 2\theta\, \mathrm{Im} G_E^* G_M}{D\sqrt{\tau}} = \frac{(\tau - 1)\sin 2\theta\, \mathrm{Im} F_2^* F_1}{D\sqrt{\tau}}$$

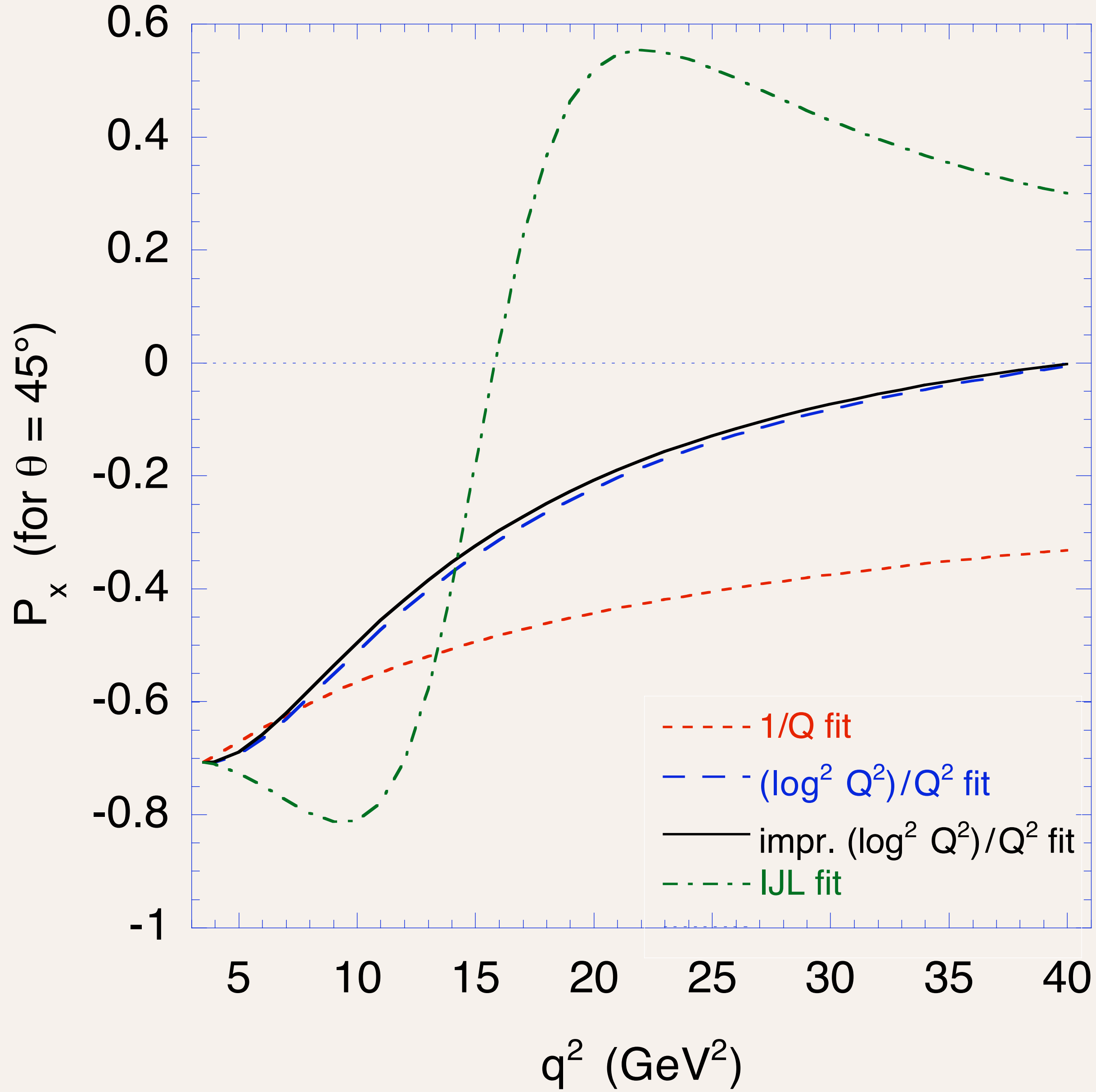


$$\vec{k} \times \vec{p} \cdot \vec{S}_p$$

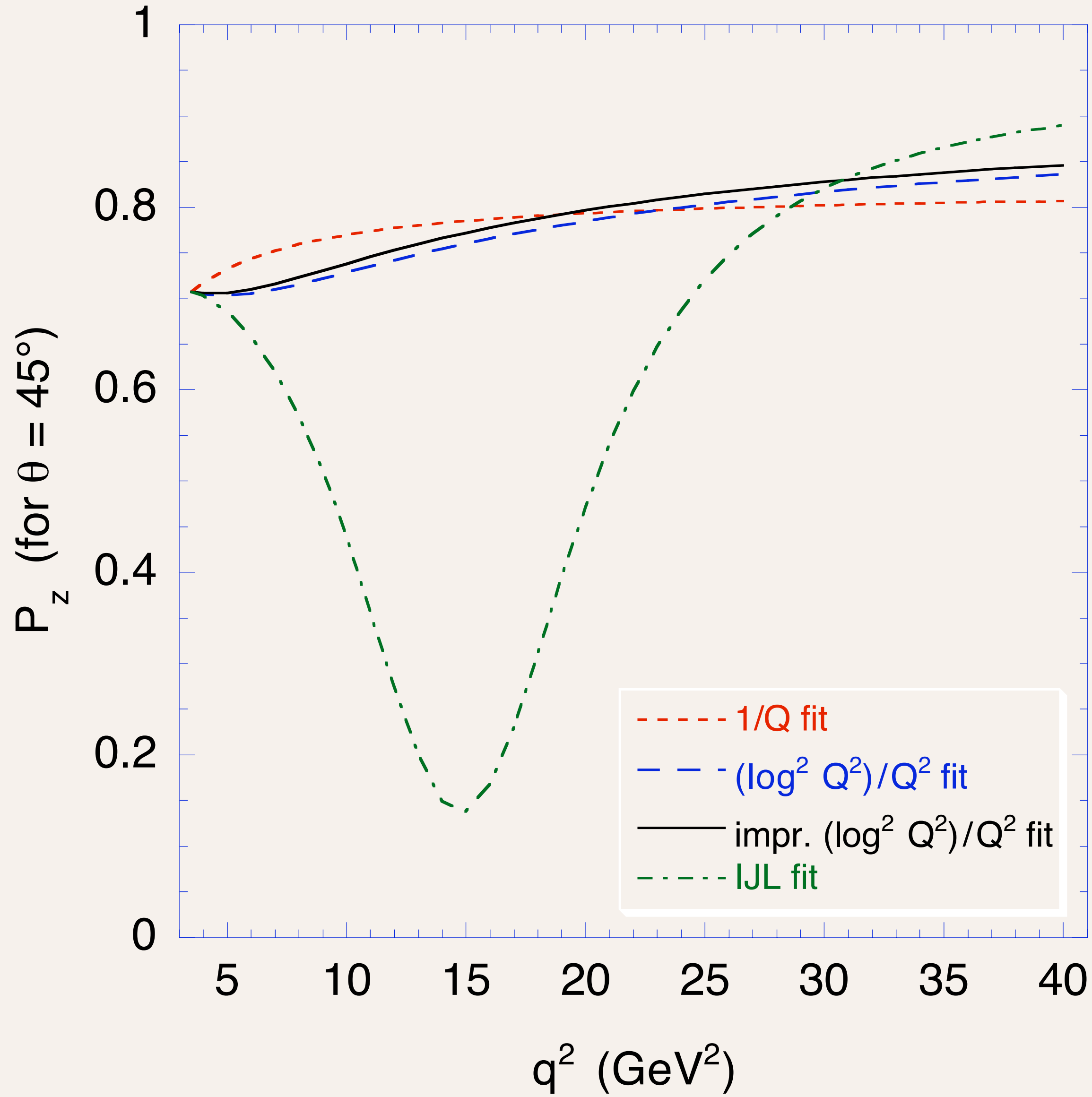
Baldini: relative G_E, G_M phase needed to separate F_1,F_2!

Dubnickova, Dubnicka, Rekalo; Ro
Carlson, Hiller, Hwang, sjb

$$\mathcal{P}_x = -P_e \frac{2\sin\theta\,\mathrm{Re}G_E^* G_M}{D\sqrt{\tau}}$$



$$\mathcal{P}_z = P_e \frac{2\cos\theta |G_M|^2}{D}$$



Single-spin asymmetry $\mathcal{P}_y$ for QED

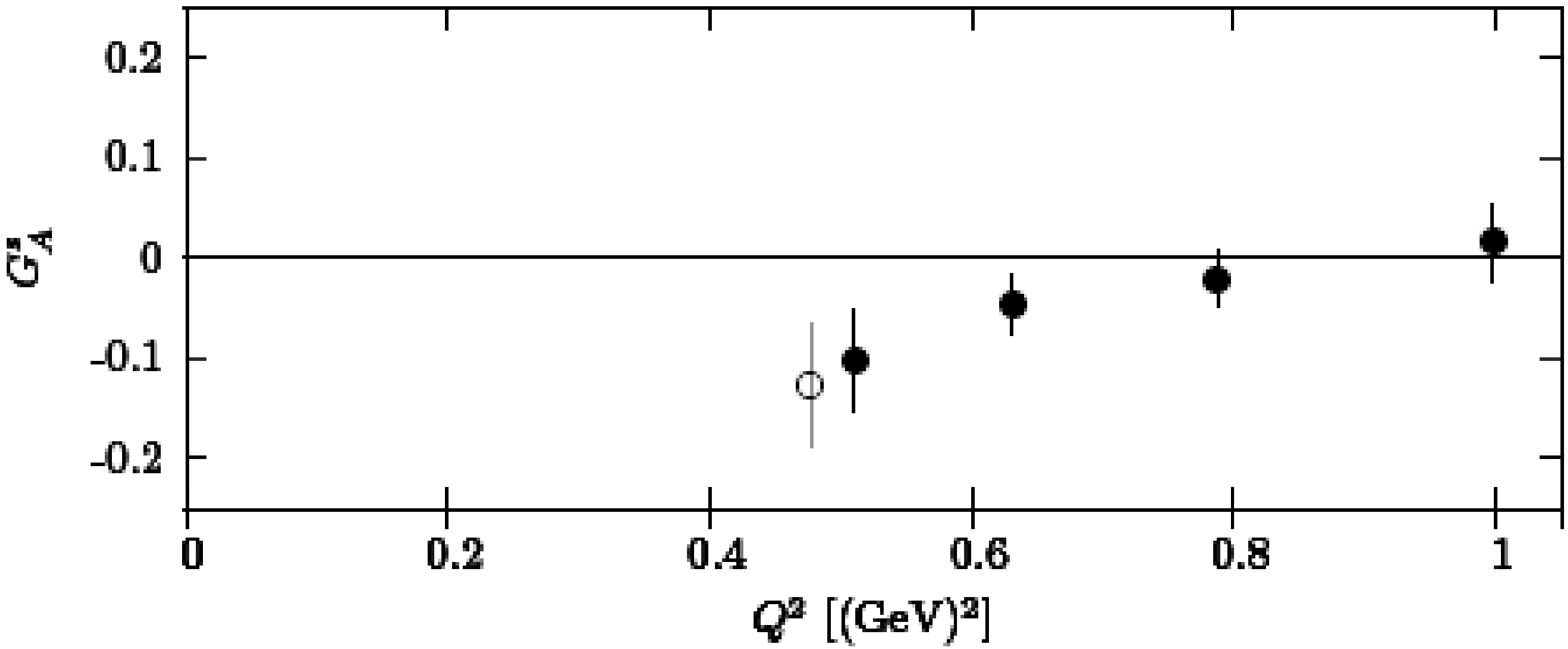
$$e^+e^- \to \tau^+\tau^-$$

Sensitive to the imaginary part of the timelike Schwinger correction to the lepton anomalous moment and Pauli form factor.

Different Coulomb phases for F1, F2

Strange Electromagnetic and Axial Nucleon Form Factors

A combined analysis of HAPPEx, G^0, and BNL E734 data



First determination of the strange axial form factor.

Stephen Pate

G0 & E734
[to be published]

HAPPEx & E734
[Pate, PRL 92 (2004) 082002]

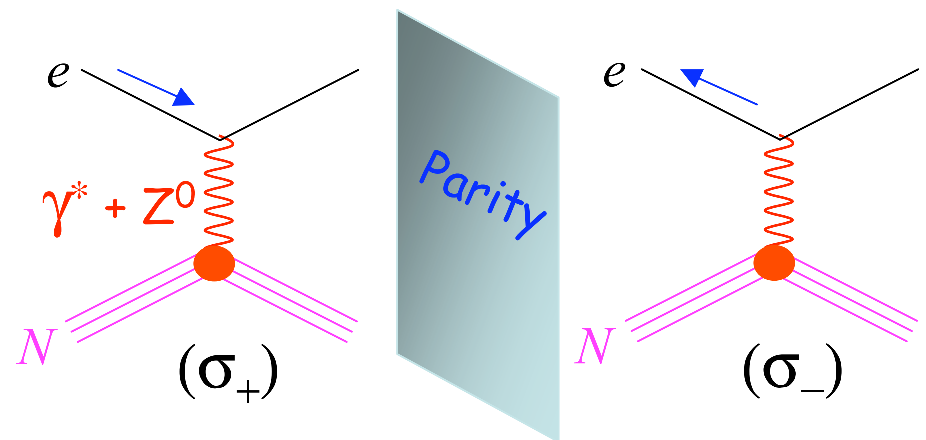
S. Kox

S. Pate

Parity Violation experiments

Weak form factors measurements

- EM and Weak contributions but $M_Z \ll M_\gamma$ in our energy domain
  - Must get rid of the dominant M_γ^2 term
  - ↳ Parity violation (PV) in polarized elastic electrons scattering on unpolarized proton target



$(\sigma_+) \neq \sigma_-(=P(\sigma_+))$

PV Asymmetry

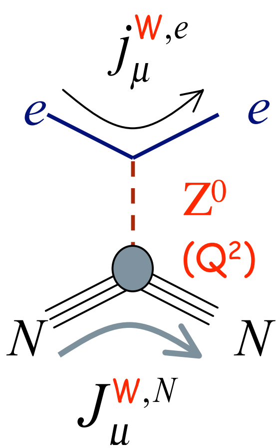
$$A_{PV} \equiv \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \approx \frac{\Re e\left(M^\gamma . M^Z\right)}{\left|M^\gamma\right|^2}$$

- Systematic errors (normalization) cancel in the ratio
- A_{PV} : 1 ppm to 50 ppm (part per million : 10^{-6}) for $Q^2 = 0.1 - 1.\ (GeV/c)^2$
- $A_{PV} = A_0\ (s = 0) + A_S$
  - ↳ Need to reach a precision of a few % (stat. + syst.) on A_{PV} !

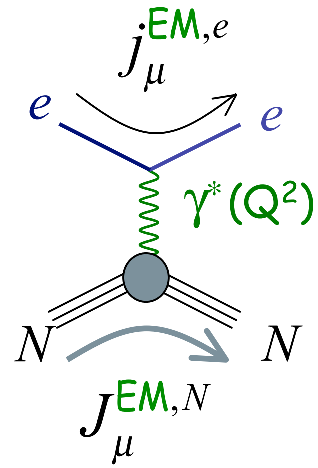
S. Kox

A

V



X



V

V

Interference gives parity violation

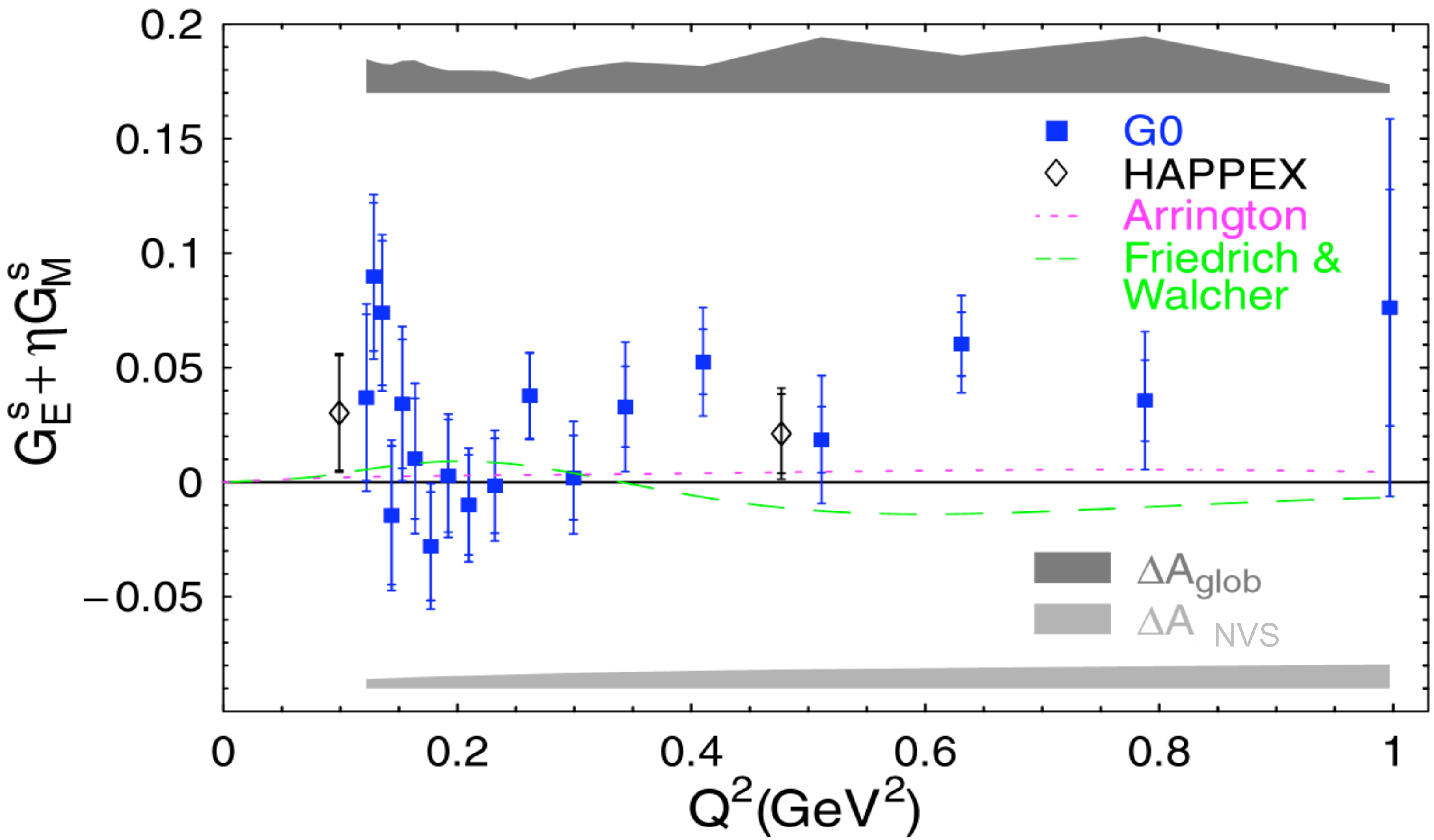
$$G_{E,M}^{(\gamma,N)} = \sum_{q=u,d,s} Q_q \, G_{E,M}^{(q,N)} \qquad G_{E,M}^{(Z,N)} = \sum_{q=u,d,s} c_V^q \, G_{E,M}^{(q,N)}$$

Flavor	Q_q	C^q_V
u, c, t	2/3	$1 - 8/3 \sin^2\theta_W$
d, s, b	-1/3	$-1 + 4/3 \sin^2\theta_W$

$$A_{PV} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \frac{\varepsilon G_E^{(\gamma,p)} G_E^{(Z,p)} + \tau G_M^{(\gamma,p)} G_M^{(Z,p)} - \left(1 - 4\sin^2\theta_W\right) \varepsilon' G_M^{(\gamma,p)} G_A^e}{\varepsilon \left(G_E^{(\gamma,p)}\right)^2 + \tau \left(G_M^{(\gamma,p)}\right)^2}$$

Strange Quark Contribution : Q^2 dependence

D. S Armstrong et al., PRL 95, 092001 (2005)



S. Kox

EM form factors
- parameterization

A_{NVS} subtraction
-SM, axial FF

Some conclusions

- Good agreement with HAPPEX data measured at similar kinematics

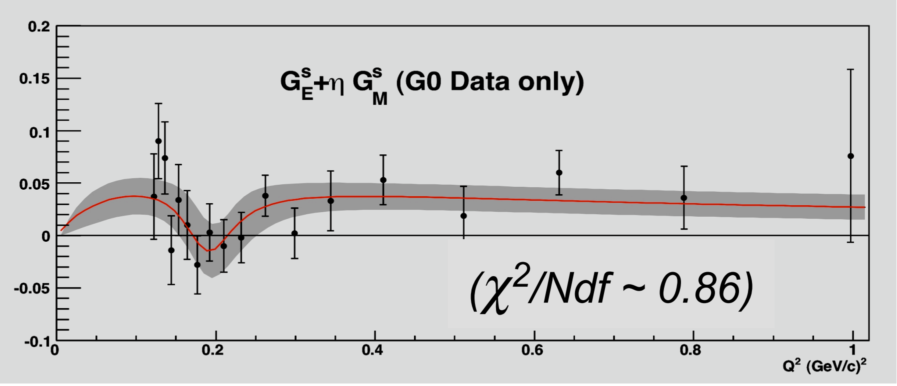
→ A null strange quark contribution ($G^s_E = G^s_M = 0$) is rejected at 90 % CL

S. Kox

Speculation …

Strange Form factors extraction

- Fit of the world data set (H, He) with sum of 2 strange Form Factors
  - Use parameterization for their Q^2 dependence (G^p_M and G^n_E types)
    - $G^s_M(Q^2) = \dfrac{G^s_M(0)}{\left(1+Q^2/\Lambda^{s\,2}_M\right)^2}$ *(proton)*
    - $G^s_E(Q^2) = \dfrac{a_1 Q^2}{1+b_1Q^2+b_2Q^4+b_3Q^6}$ *(neutron)*

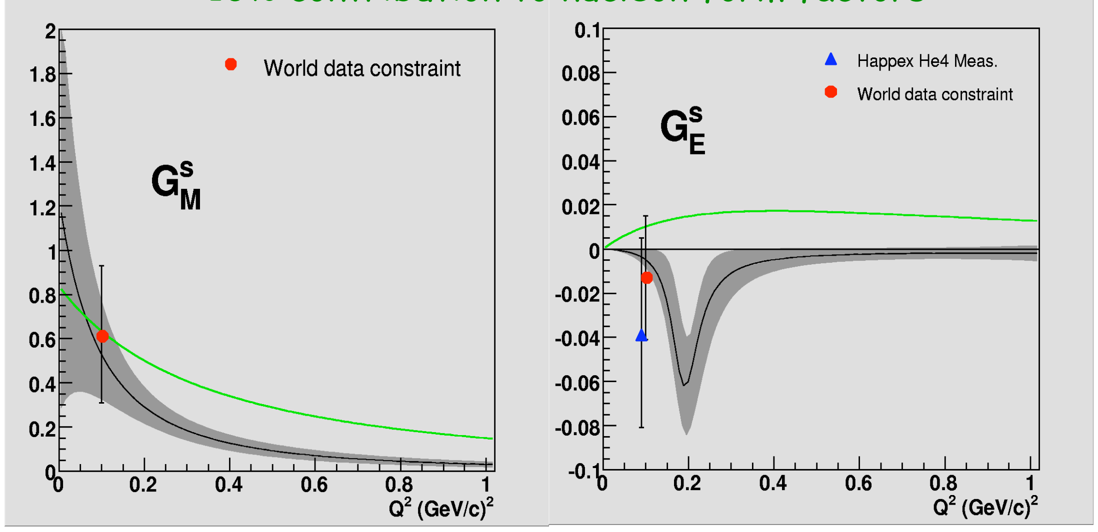


From the fit

- Large positive value for $G^s_M(0)$
- E and M contributions have opposite sign
- Sharp Q^2 dependence

→ Need additional data (separation) to come to any firm conclusion

— 10% contribution to nucleon form factors



Origin of nonzero strange quark contribution to vector current of nucleons

VMD (ϕ) or different $s(x)$ and $\overline{s}(x)$ distribution?

Roelof Bijker, Riska, Thomas

Intrinsic strangeness $\Lambda(uds) + K(\bar{s}u)$ Fluctuation

Burkardt,Warr

Evidence from charm production in charged current DIS reactions

Ma, sjb, Thomas

Intrinsic heavy quarks:
Dimension 6 $\frac{G^3_{\mu\nu}}{m^2_Q}$ operator

Polyakov et al.

Intrinsic charm at high x

Origin of nonzero strange quark contribution to vector current of nucleons

Analog in atomic physics:

intrinsic muons strongly asymmetric in tauonium

$[\tau^+ e^-]$:
μ^- attracted to τ^+
μ^+ attracted to e^-

$\Lambda(uds) + K(\bar{s}u)$ Fluctuation

Burkardt, Warr

Ma, sjb, Thomas

Evidence for nonzero strange quark contribution to vector current of nucleons

Roelof Bijker , Iachello

ϕ contribution to vector current

ϕ couples in t channel to proton via ggg

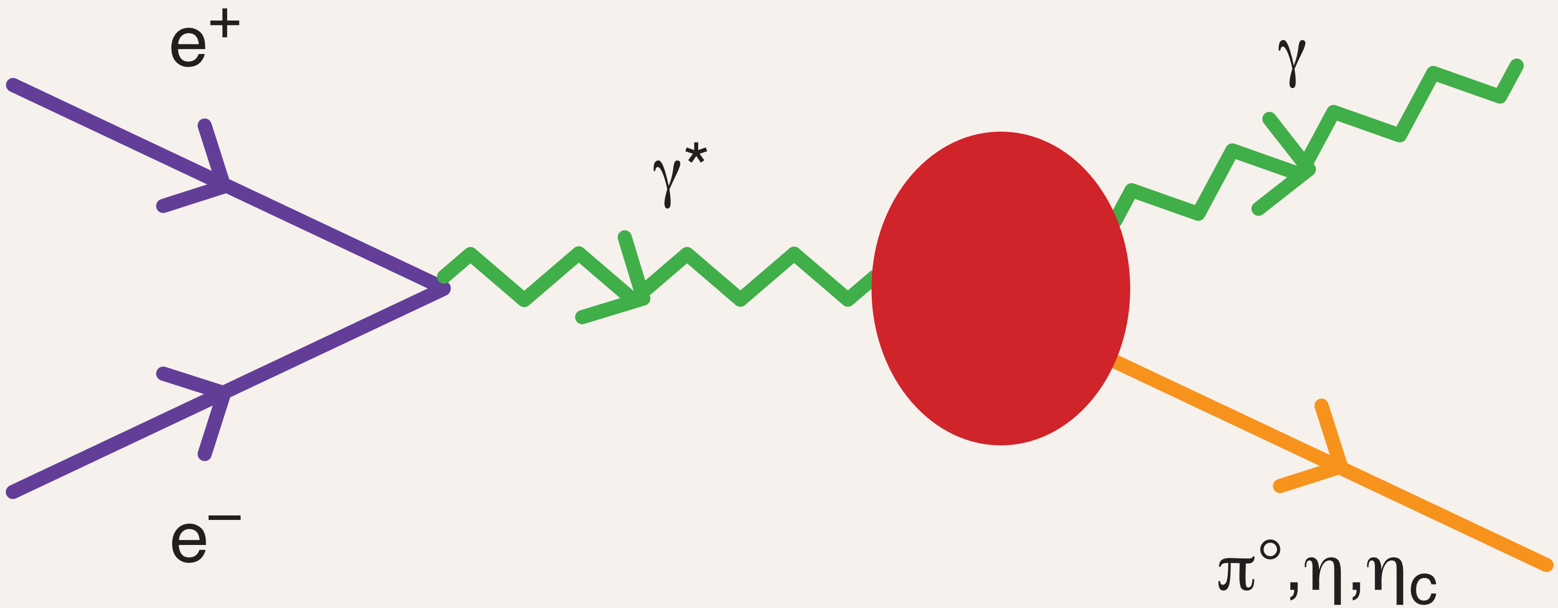
OZI suppressed but not zero

analogous to electron-loop
light-by-light contribution
to muon $g-2$

Novel Timelike Experiments

Timelike photon-to-meson transition form factor

No background from radiative return



$$F_{\gamma M}(Q^2) = \frac{4}{\sqrt{3}} \int_0^1 dx \phi_M(x, \widetilde{Q}) T^H_{\gamma \to M}(x, Q^2).$$

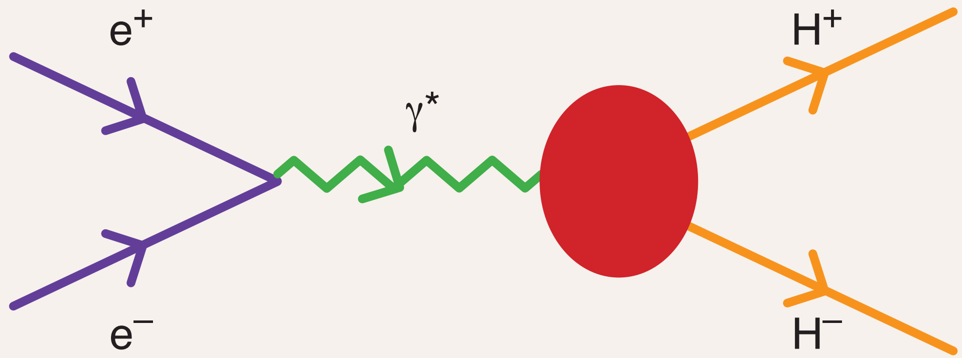
Basic measure of QCD

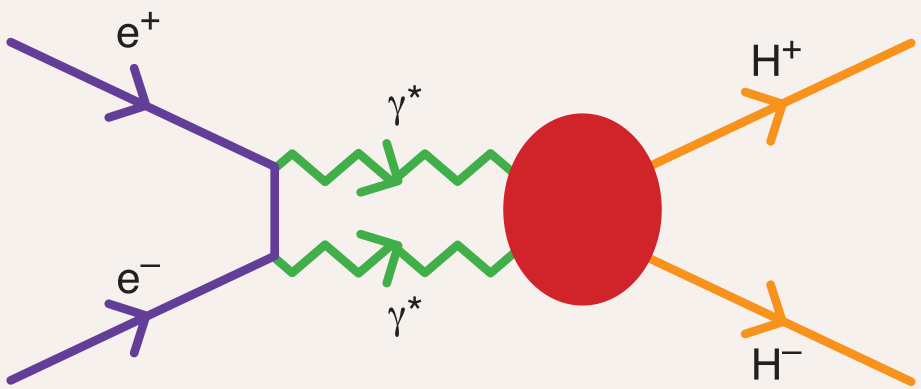
Annihilation Channels: ISR and Direct Annihilation

- Measure timelike form factors
- All Exclusive channels
- p + Delta

Solodov

Exclusive Two-Photon Process





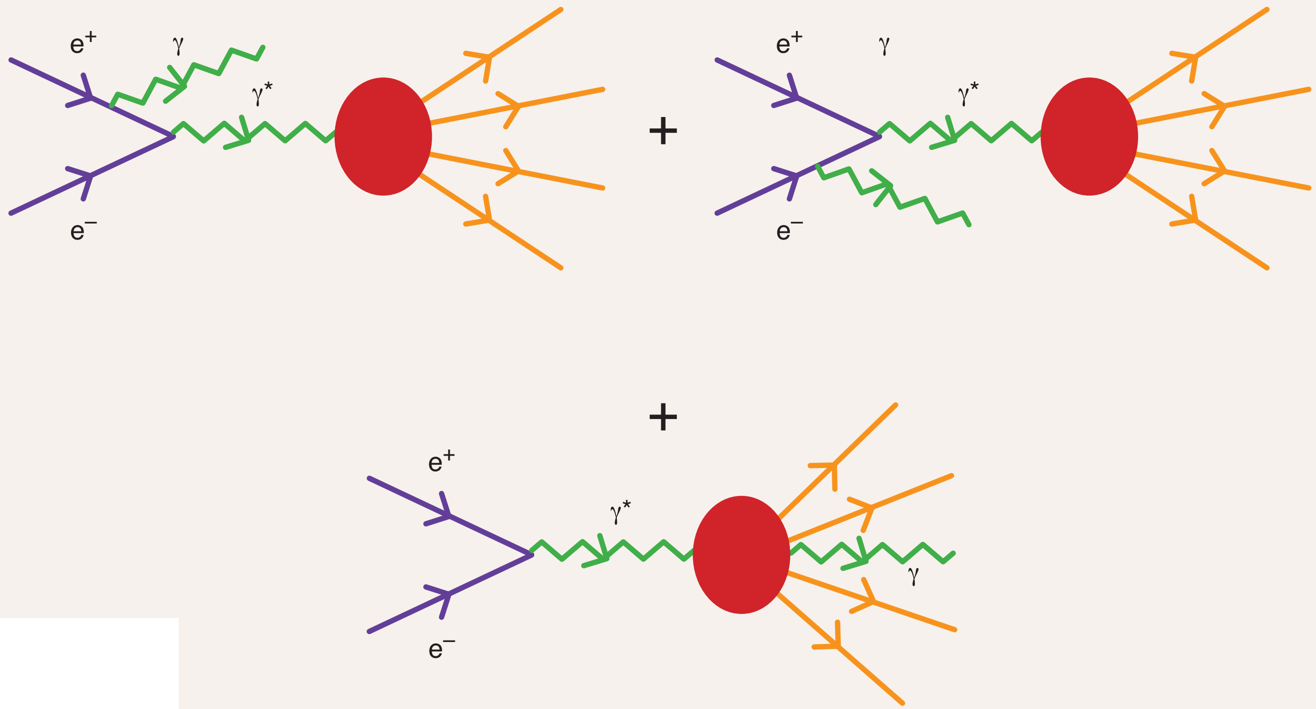
Interference produces charge asymmetry

Critical test of two-photon explanation of Rosenbluth failure

Afanasev, Carlson, Chen, Vanderhaeghen, sjb

Interference of ISR and FSR

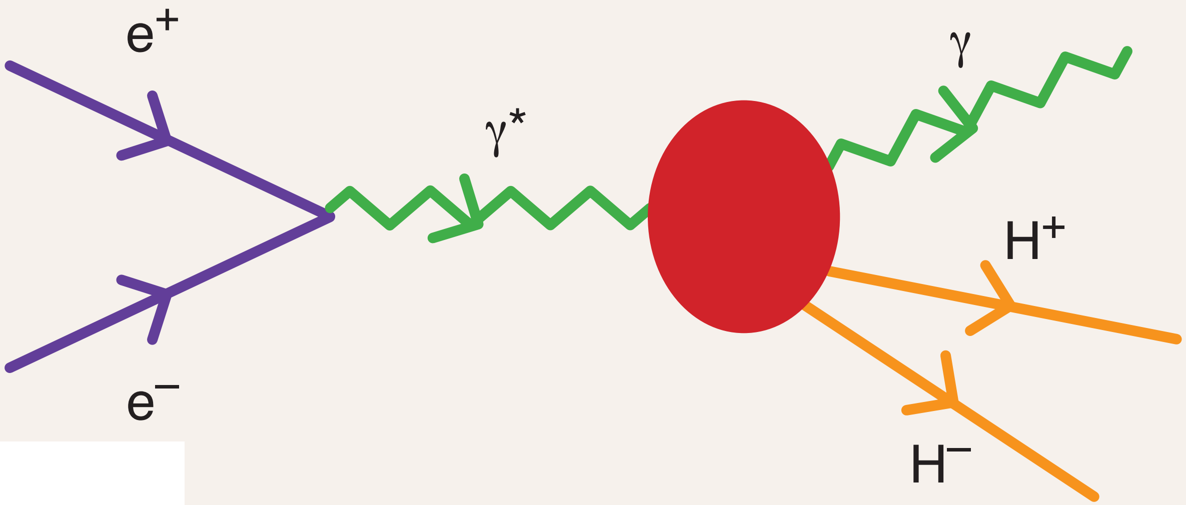
Produces electron-positron charge asymmetry



Timelike Annihilation DVCS

Afanasev, Carlson, Salme, sjb (in progress)

New window into hadron physics

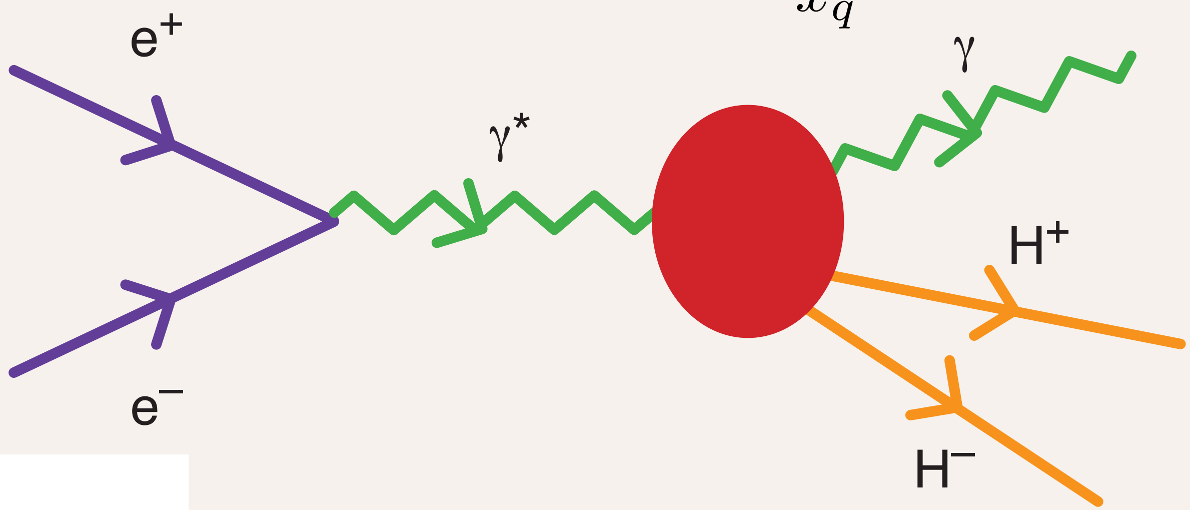


$$M(\gamma^* \to H^+ H^- \gamma) \leftrightarrow M(\gamma^* H \to \gamma H)$$

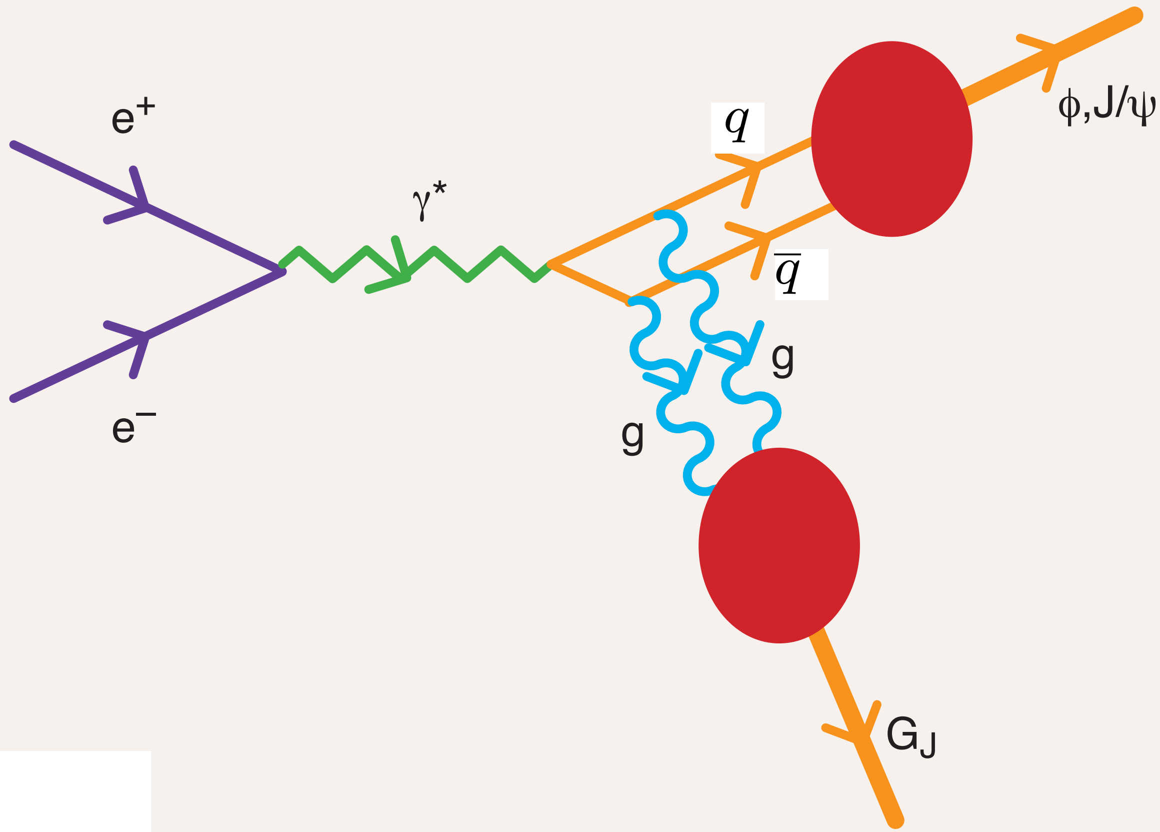
Interference with ISR produces charge asymmetry

Assume Dominance of J=0 Fixed Pole (seagull)

$$R^{p\overline{p}}_{2\gamma}(q_1^2, q_2^2, s) = \frac{T(\gamma_1^*\gamma_2^* \to H\overline{H})}{T(\gamma_1^*\gamma_2^* \to \mu^-\mu^+)} = (e_u^2 + e_d^2)\langle\frac{1}{x_q}\rangle F_H(s) \ .$$



$$M(\gamma^* \to H^+H^-\gamma) \leftrightarrow M(\gamma^* H \to \gamma H)$$



Gluonium Factory

S. J. Brodsky, A. S. Goldhaber and J. Lee, Phys. Rev. Lett. **91**, 112001 (2003) [arXiv:hep-ph/0305269].

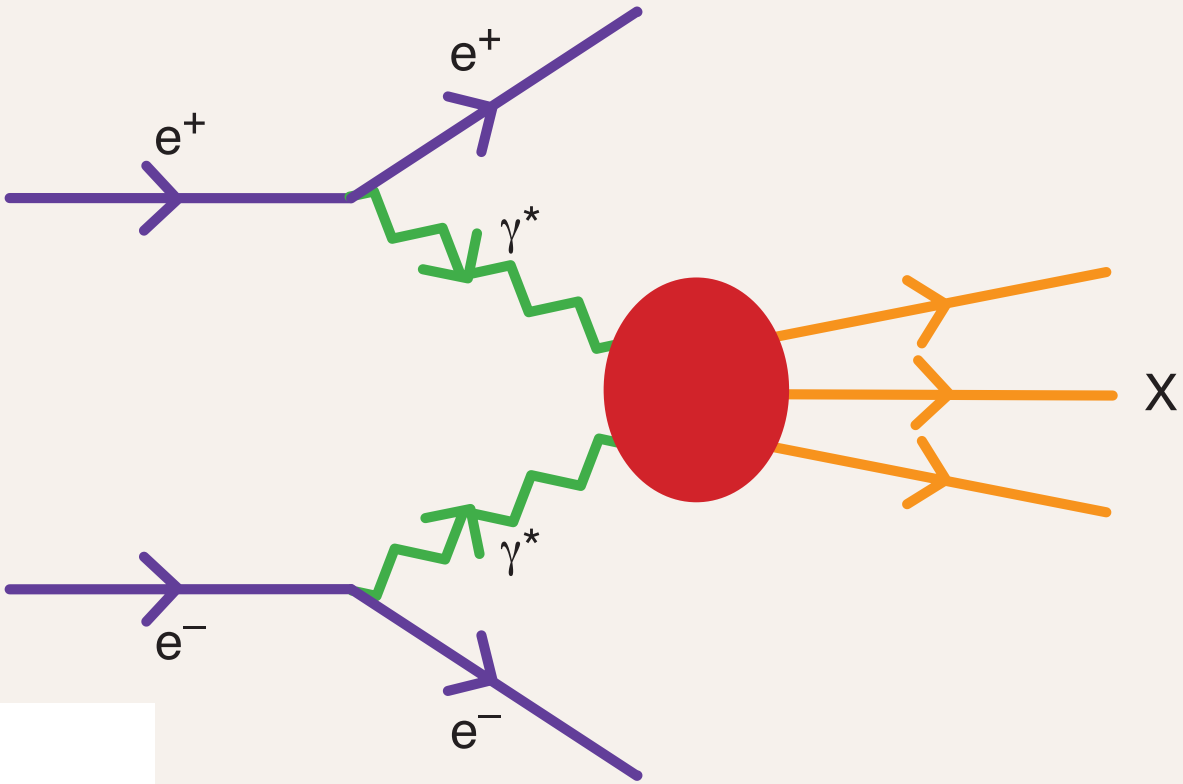
Coyne, DeGrand, sjb

Belle Associated Charm Anomaly

$$R_{J/\psi} \equiv \frac{\sigma(e^+e^- \to J/\psi \;\; c\bar{c})}{\sigma(e^+e^- \to J/\psi \;\; X)} = 0.8$$

- Huge Probability for associated charm pair
- Theory estimates (Bodwin) $R_{J/\psi} \simeq 0.1$
- Measure $R_\phi \equiv \dfrac{\sigma(e^+e^- \to \phi \;\; s\bar{s})}{\sigma(e^+e^- \to \phi \;\; X)}$

Photon-Photon Collisions



Doubly-Virtual Photon Processes

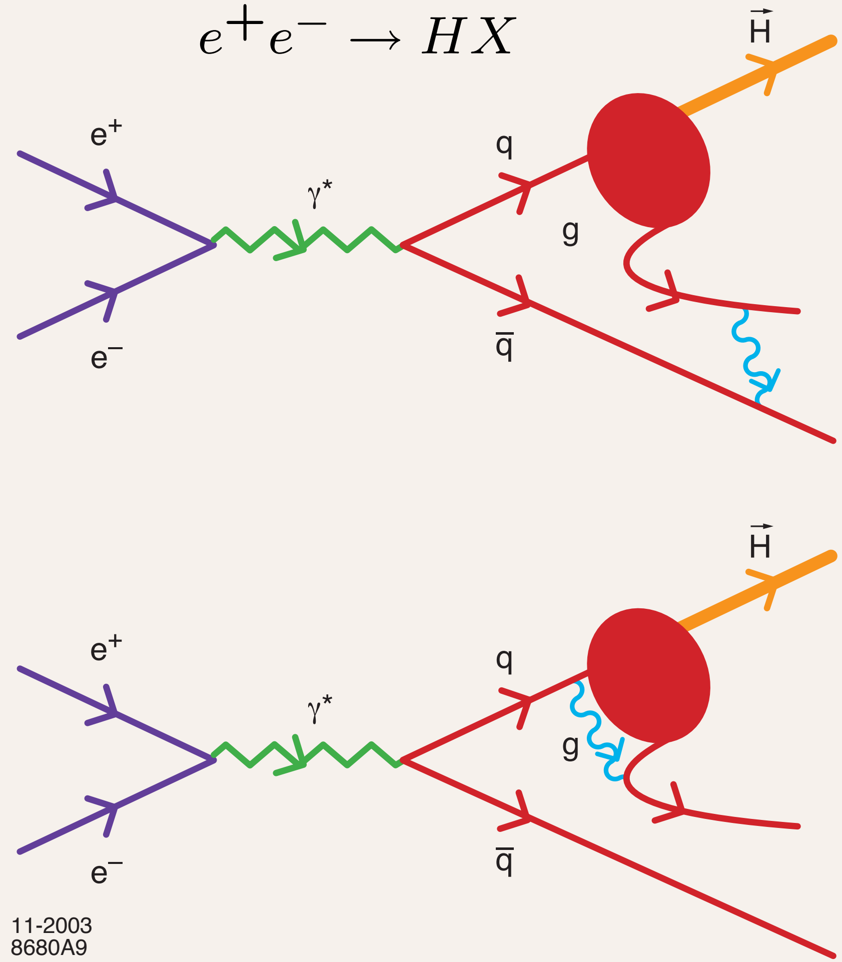
Threshold pion production:

$$e^+e^- \to p\overline{p}\ \pi^0, p\overline{n}\ \pi^-$$

- Beautiful soft-pion theorems for
- Rotated proton distribution amplitudes
- Extend PQCD predictions, measure axial vector form factors
- Braun, Polyakov et al. U. Mueller

$e^+e^- \to HX$

Hwang, Schmidt, sjb



Relative phases for different L produce Sivers SSA

$\vec{S}_H \cdot \vec{p}_e \times \vec{p}_H$

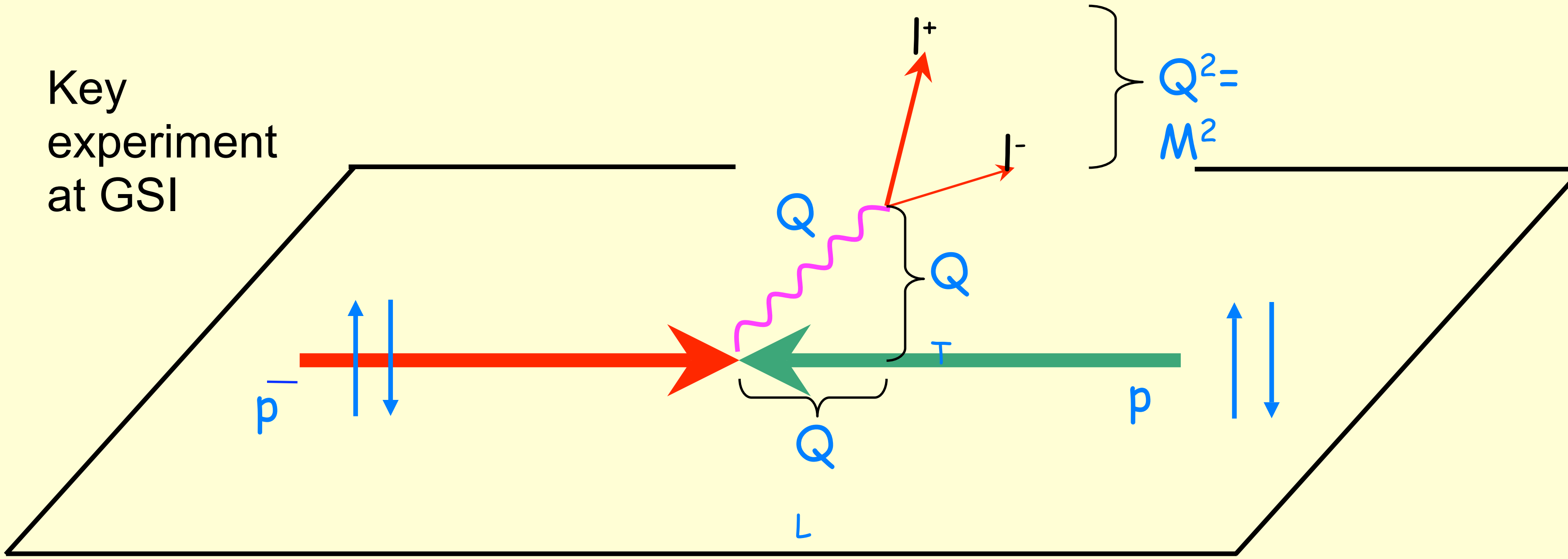
Pseudo T-odd Correlation

The Future

- Frascati: Upgrade of Daphne 1.2 GeV/beam, high Luminosity 10^{32}/sec/cm^2
- GSI Fair : Panda, PAC -- Test Color transparency T, A_{NN}
- BES
- VEPP-2000
- Jlab 12 GeV
- J-Parc: neutrino charged and neutral current form factors

Transversity in Drell-Yan Processes

Polarized Antiproton Beam → Polarized Proton Target
(both transversely polarized)



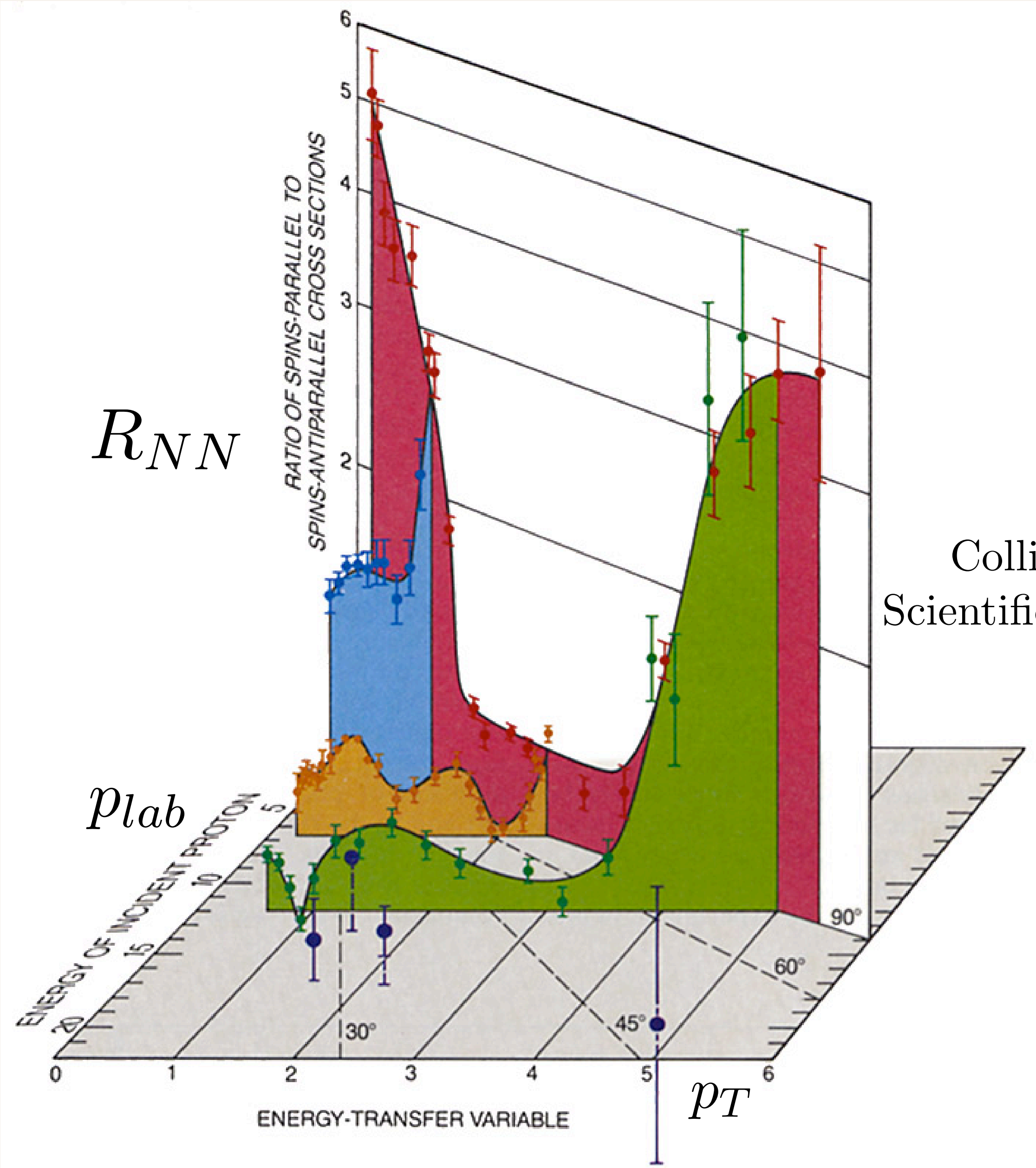
$$A_{TT} \equiv \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^2 h_1^q(x_1, M^2) h_1^{\bar{q}}(x_2, M^2)}{\sum_q e_q^2 q(x_1, M^2) \bar{q}(x_2, M^2)}$$

$q = u, \bar{u}, d, \bar{d}, \ldots$

M invariant Mass of lepton pair

F. Rathsman

Spin Correlations in Elastic $p-p$ Scattering

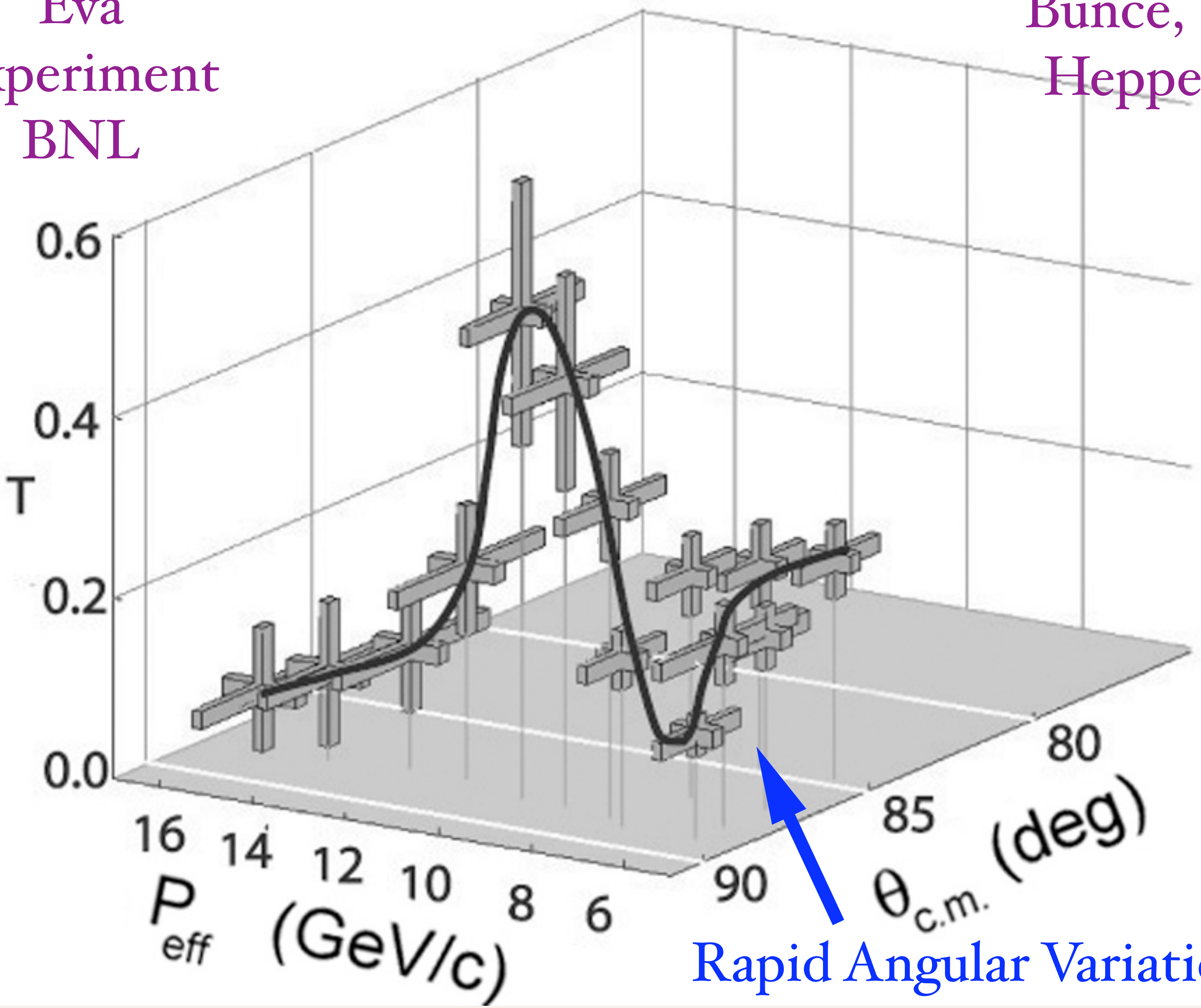


Ratio reaches 4:1 !

Collisions Between Spinning Protons (A. D. Krisch)
Scientific American, 255, 42-50 (August, 1987).

Eva Experiment BNL

Bunce, Carroll, Heppelman...



Rapid Angular Variation!

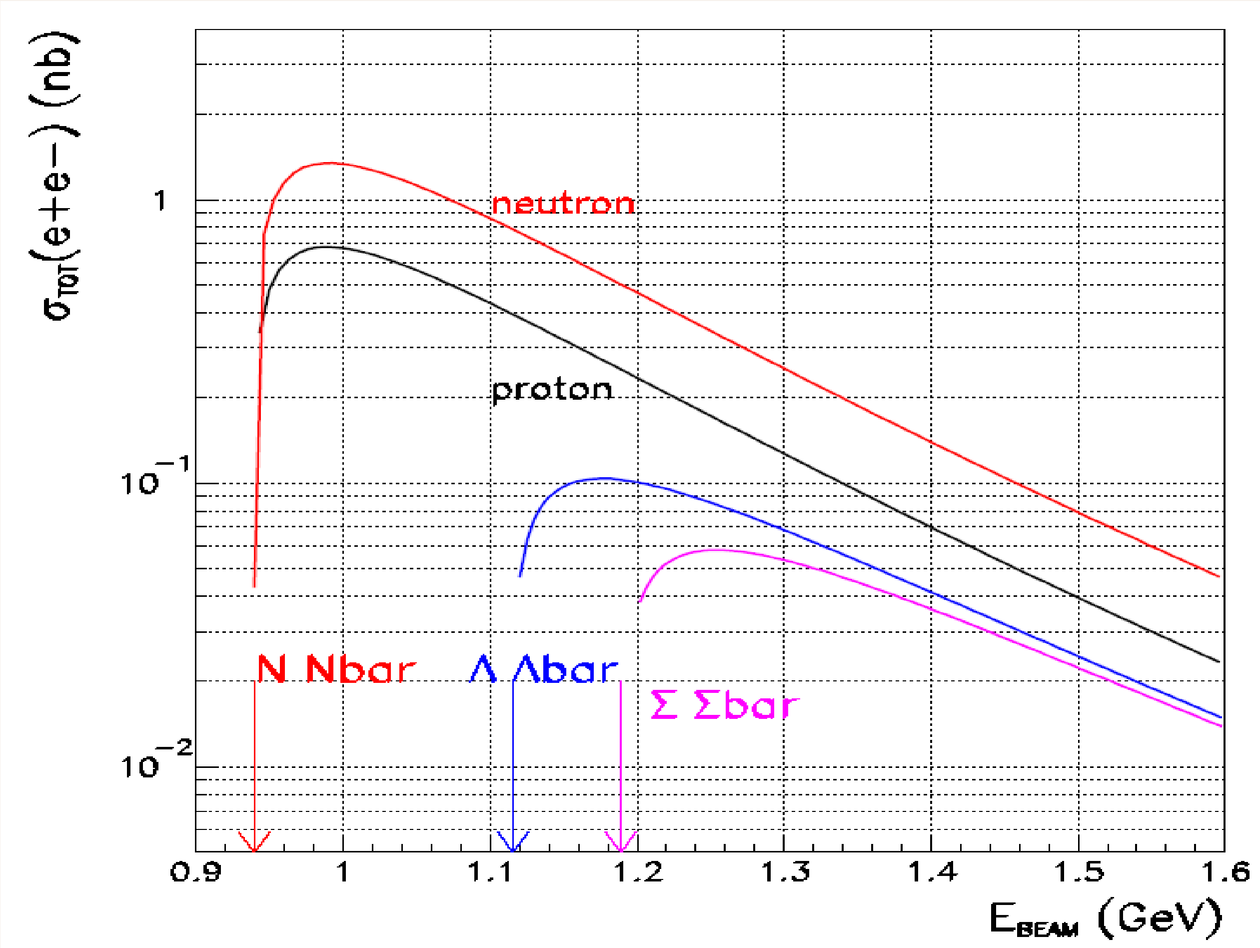


Fig. 10. *Total cross section for* $e^+e^- \to h\bar{h}$ *above nucleon-antinucleon threshold. For proton, neutron and* Λ*, the curves are normalized to the experimental data, the curve for* Σ *is extrapolated from the one for* Λ.

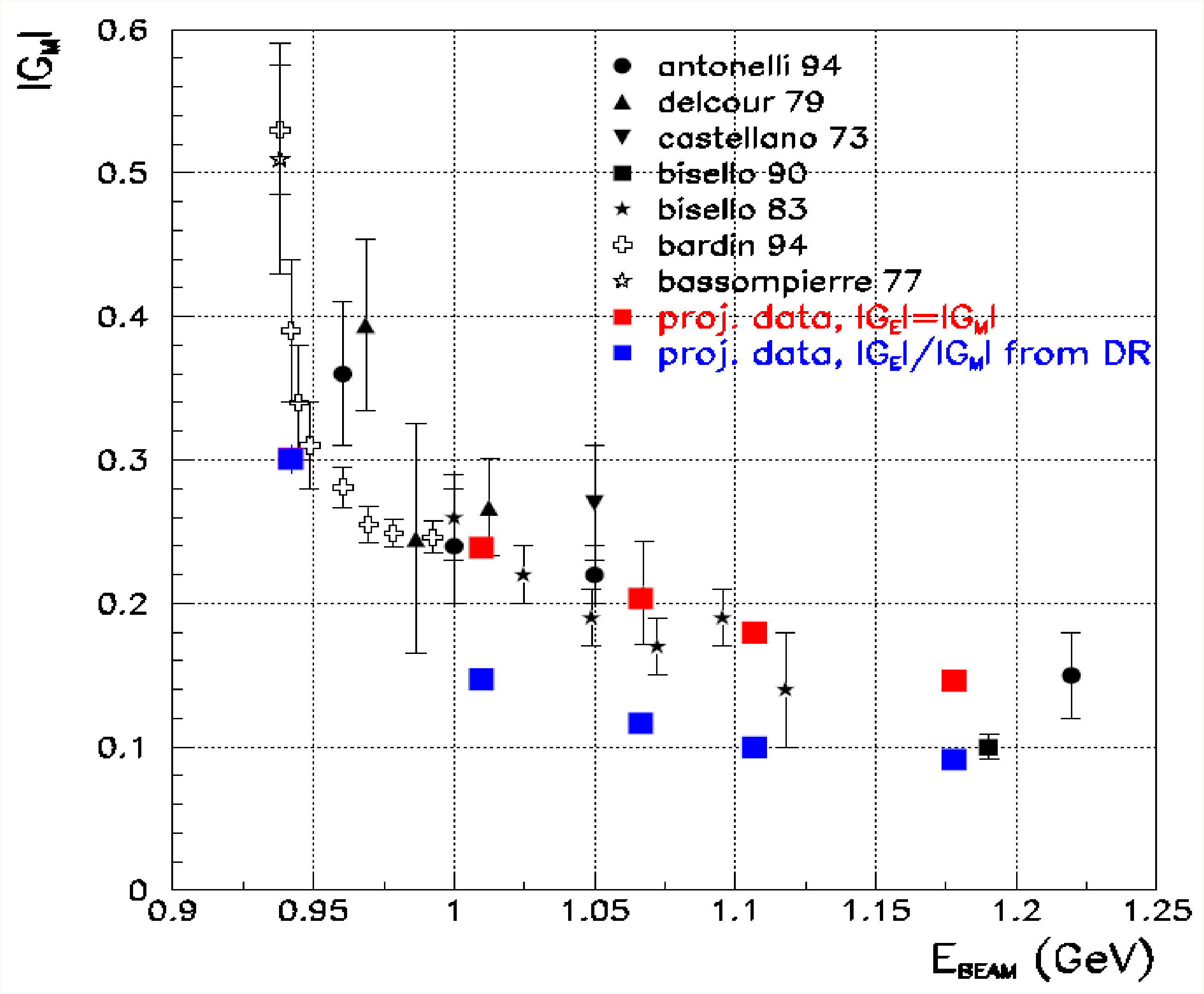


Fig. 15. *Projected proton magnetic FF results for the two hypothesis on the electric to magnetic FFs ratio, compared with actual experimental values.*

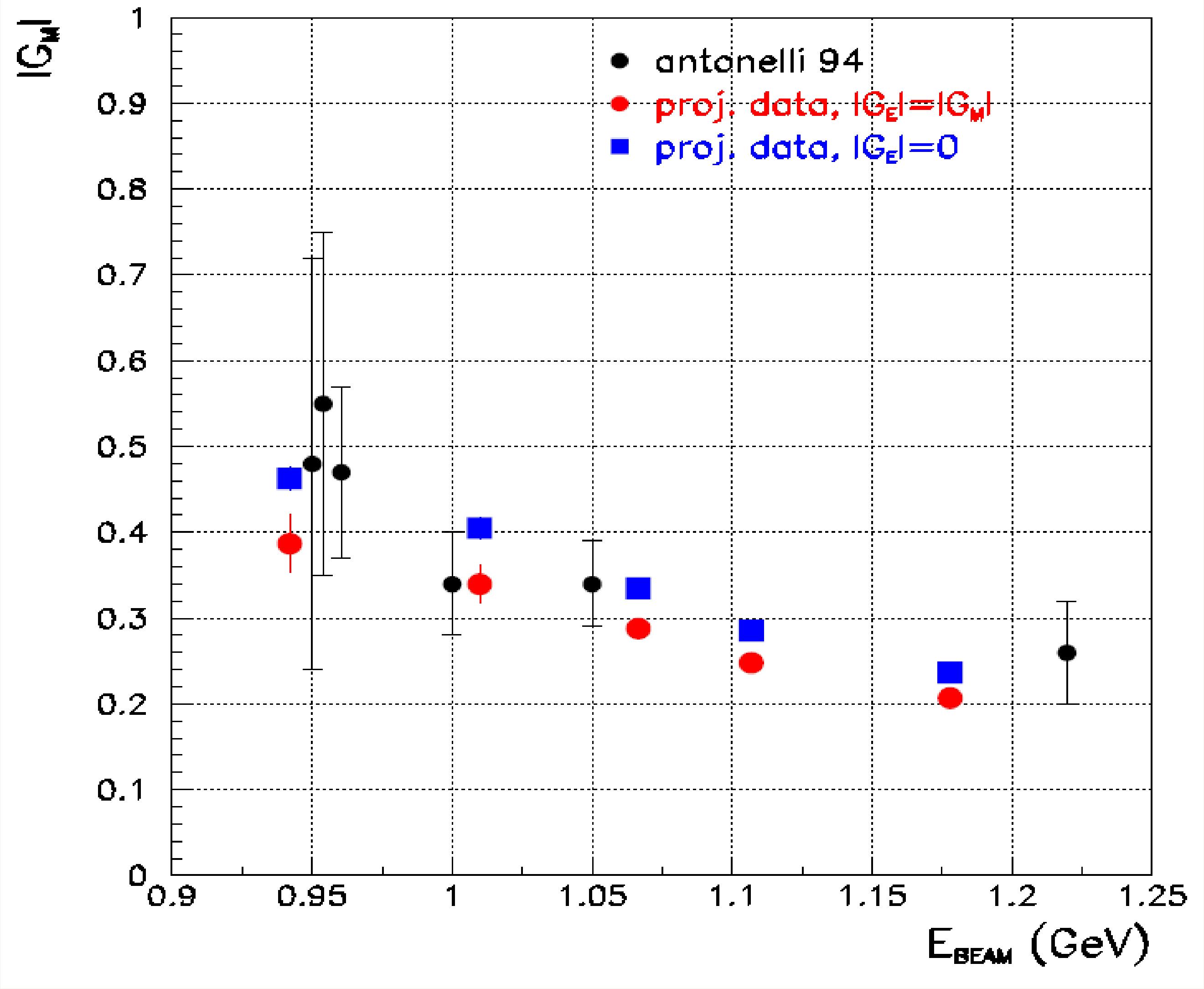
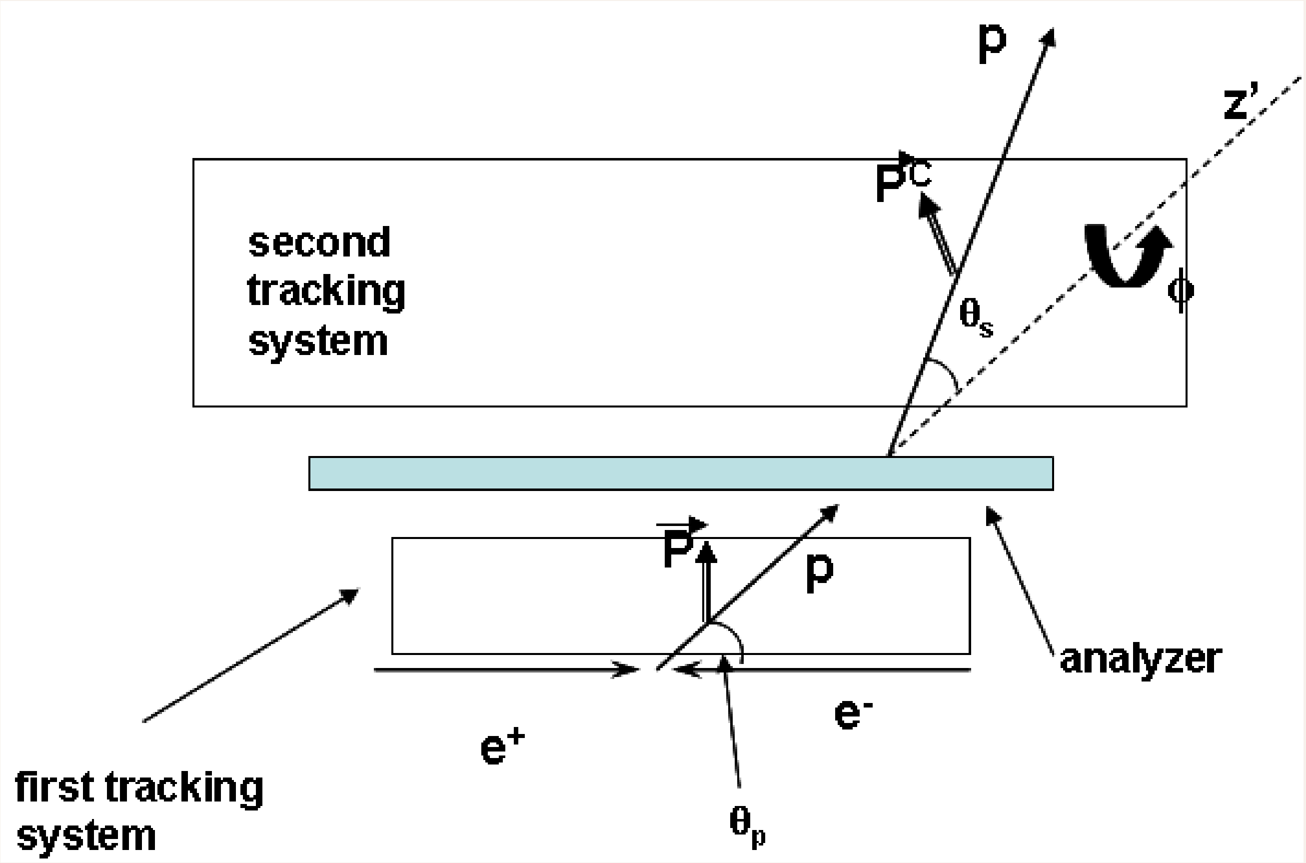
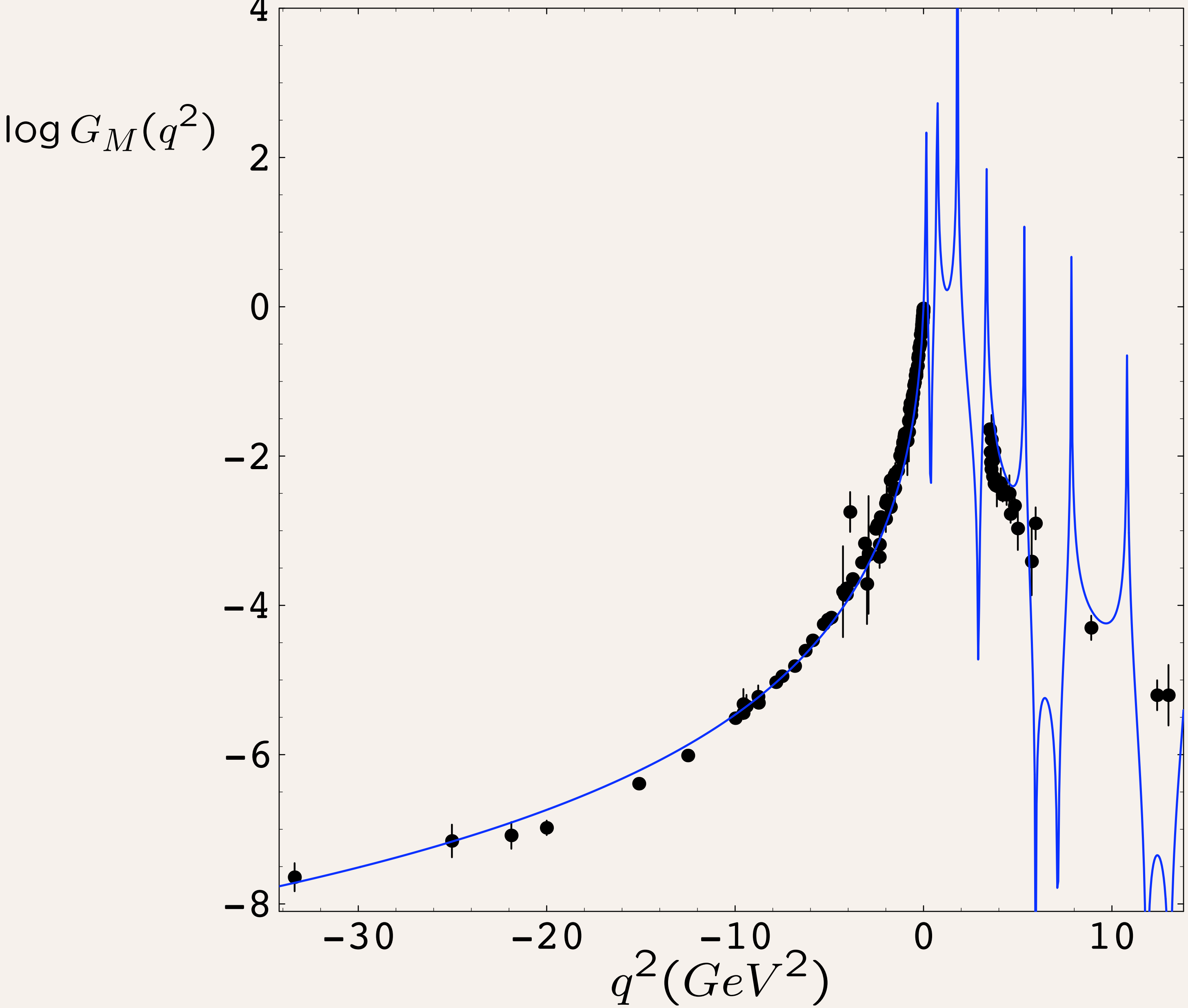


Fig. 18. *Projected neutron magnetic FF results for the two hypothesis on the electric to magnetic FFs ratio, compared with FENICE experimental data.*



$$R = \frac{N_R - N_L}{N_R + N_L} = \frac{2}{\pi}\langle A_C\rangle\langle P_y\rangle,$$

Prediction of AdS/CFT Holographic Model



Thanks to the organizers!

Enzo De Sanctis, Rinaldo Baldini, Donatella Pierluigi, Alessandra Fantoni

"Unique Form of Continuity in Space" by *Umberto Boccioni*

N05

Workshop on Nucleon Form Factors

Frascati, 12-14 October, 2005