Features of HolographicModel

de Teramond sjb

- Ratio of proton to Delta trajectories= ratio of zeroes of Bessel functions.
- One scale Λ_{QCD} determines hadron spectrum (slightly different for mesons and baryons)
- Only quark-antiquark, qqq, and g g hadrons appear at classical level
- Covariant version of bag model: confinement+conformal symmetry

New Perspectives in QCD from AdS/CFT

- Need to understand QCD at the Amplitude Level: hadron wavefunctions!

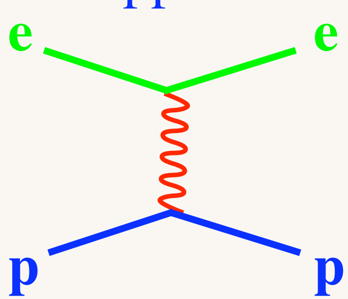
- Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space

- Impact of ISI and FSI: Single Spin Asymmetries, Diffractive Deep Inelastic Scattering, Shadowing, Antishadowing

John Arrington

Rosenbluth extractions of G_E and G_M

In the Born approximation:



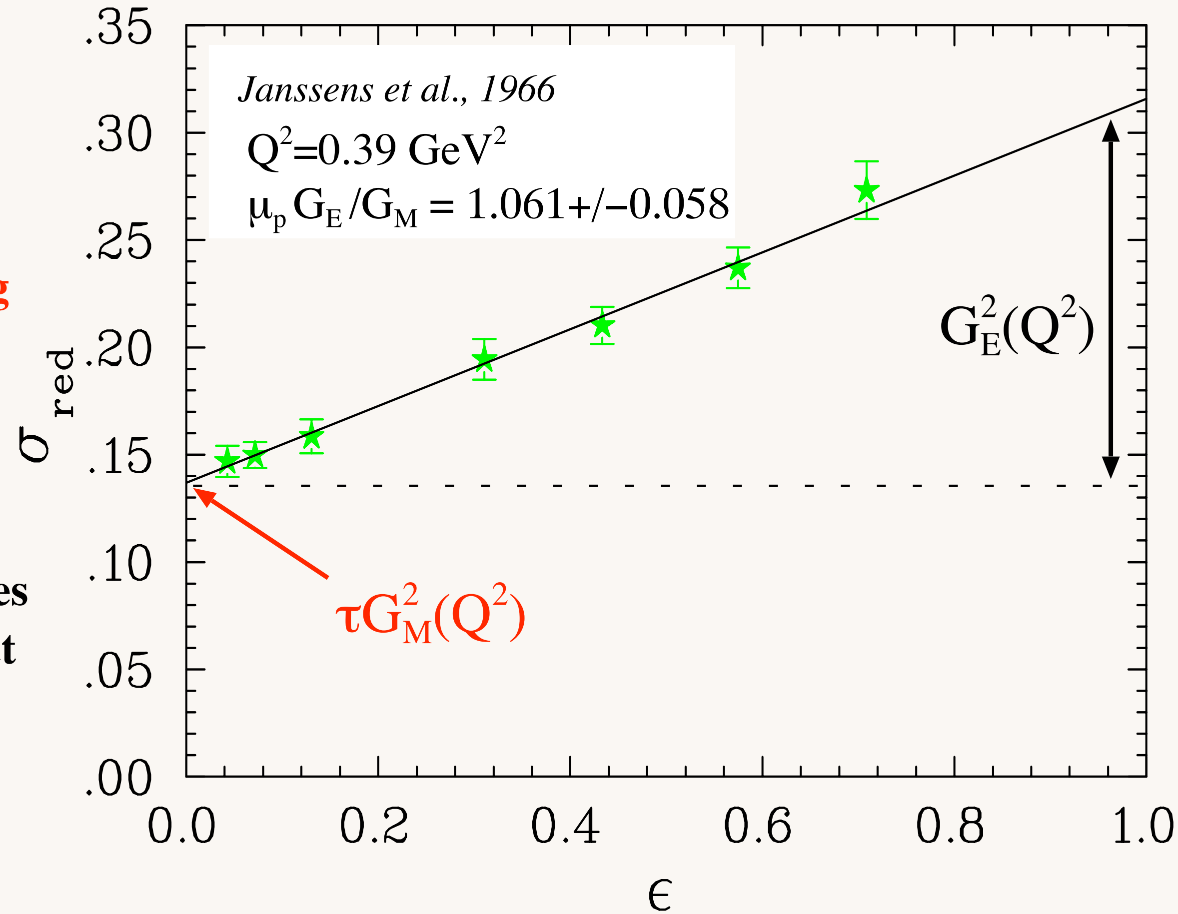
$$\sigma_R = \frac{d\sigma}{d\Omega}\frac{\varepsilon(1+\tau)}{\sigma_{Mott}} = \tau G_M^2(Q^2) + \varepsilon G_E^2(Q^2)$$

$\tau = Q^2/(2M)^2$

Initial Rosenbluth measurements consistent with form factor scaling

$G_M(Q^2) \cong \mu_p G_E(Q^2)$

For large Q^2 values, τG_M^2 dominates and G_E^2 becomes difficult to extract

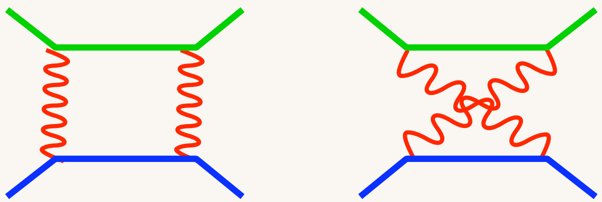


Studies of two-photon effects ('50s and '60s)

John Arrington

***Definitive test*: Positron-proton scattering vs. electron-proton scattering**

$$R \equiv \frac{\sigma_{e+}}{\sigma_{e-}} = \frac{(A_{1\gamma}+A_{2\gamma})^2}{(A_{1\gamma}-A_{2\gamma})^2} \approx 1 + 4\,\mathrm{Re}(A_{2\gamma}/A_{1\gamma})$$



e+/e–

<R> = 1.003+/–0.005

*J. Mar et al., PRL **21**, 482(1968) and refs therein*

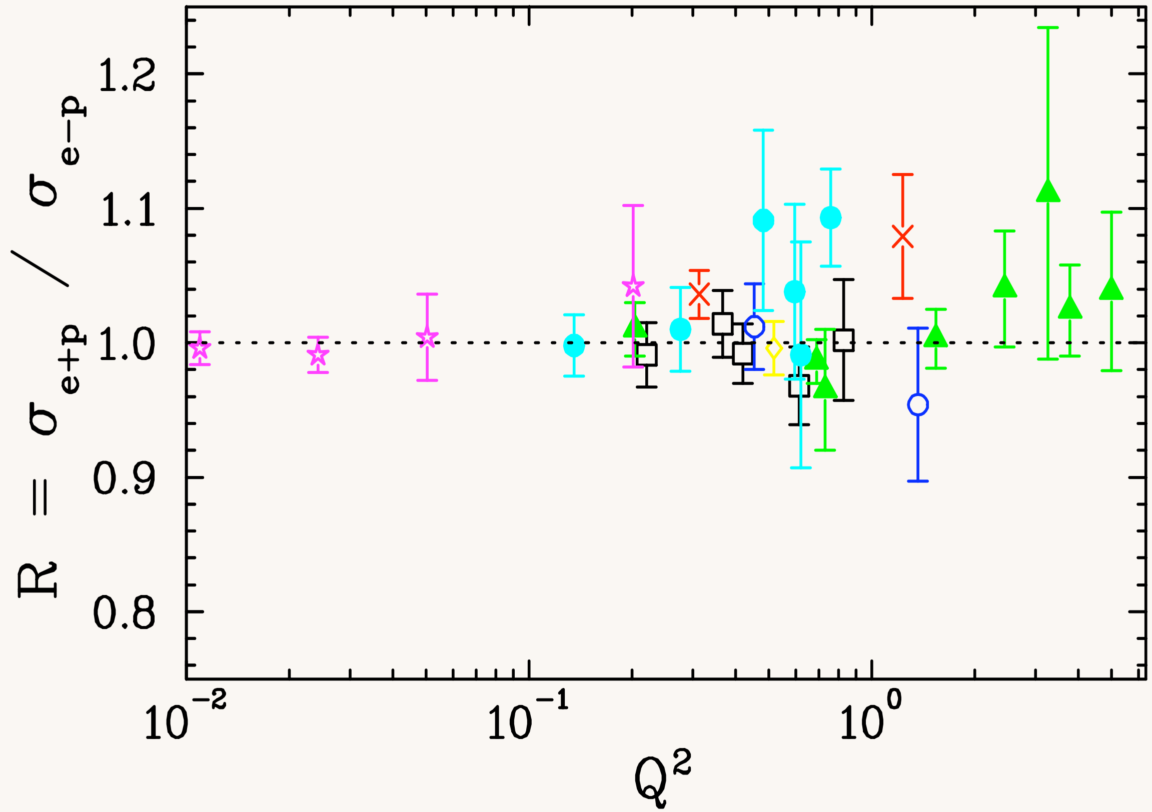
μ+/μ–

<R> = 0.993+/–0.006

*L. Camilleri et al., PRL **23**, 149 (1969)*

($Q^2 < 1$ GeV^2)

One-photon approximation assumed to be good to ~1%



However: Low luminosity of secondary e+/μ beams meant that precise limits were only available for low Q^2 and/or small scattering angles

G_E/G_M from Polarization Transfer

Use polarized electron beam, unpolarized proton target, measure the polarization transferred to the struck proton

$$P_L = M_p^{-1}\ (E+E')\sqrt{\tau(1+\tau)}\ G_M^2 \tan^2(\theta_e/2)$$

Polarization along $\boldsymbol{q}$

$$P_T = 2\sqrt{\tau(1+\tau)}\ G_E G_M \tan(\theta_e/2)$$

Polarization perpendicular to $\boldsymbol{q}$ (in the scattering plane)

$$P_N = 0$$

Polarization normal to scattering plane

N. Dombey, Rev. Mod. Phys. 41, 236 (1969)

$$\boxed{\frac{G_E}{G_M} = -\frac{P_T}{P_L}\frac{(E+E')\tan(\theta_e/2)}{2M_p}}$$

G_E/G_M goes like *ratio* of two components

--> insensitive to absolute polarization, analyzing power

--> less sensitive to radiative corrections

Comparison of different electron polarizations

--> cancellation of false asymmetries

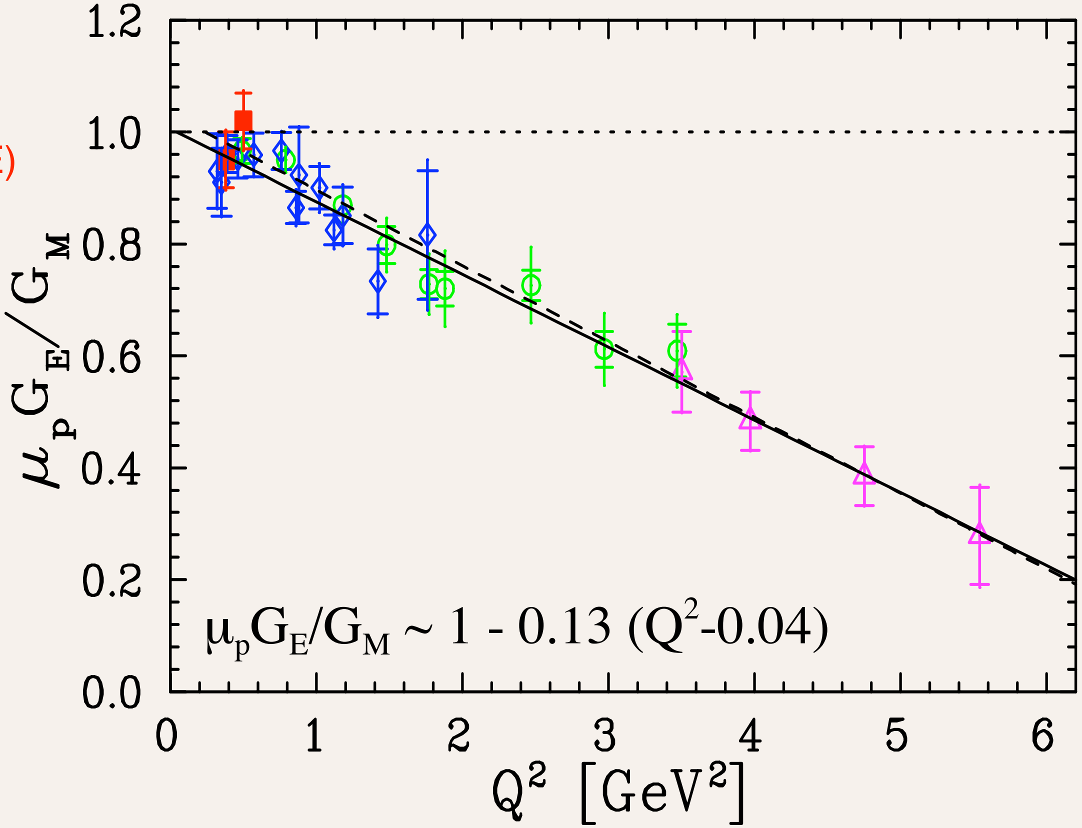
Also useful for neutron (where $G_E << G_M$, so L-T very difficult)

G_E/G_M from Polarization Transfer

MIT-Bates:
B. D. Milbrath, *et. al.*, PRL **82** (1999) 2221(E)

Jefferson Lab:
M. K. Jones, *et. al.*, PRL **84** (2000) 1398
O. Gayou, *et. al.*, PRC **64** (2001) 038202
O. Gayou, *et. al.*, PRL **88** (2002) 092301

Mainz:
Th. Pospischil, *et. al.*, EPJA **12**, (2001) 125
(low Q^2 - not shown in figure)



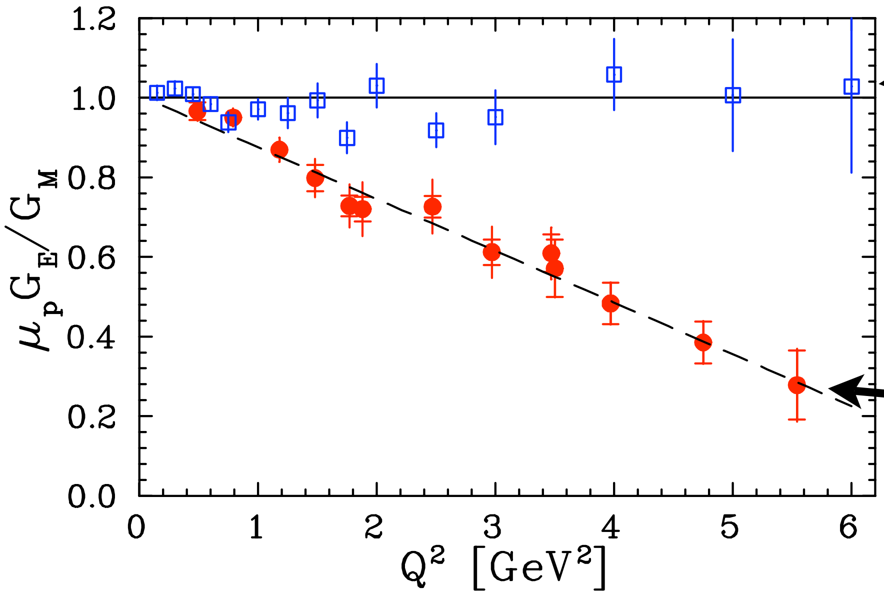
Surprising result: $\mu_p G_E \neq G_M$ **at large** Q^2

Predicted by Iachello!

- -Renewed interest in nucleon form factors, nucleon structure
- -New examination of long-standing pQCD predictions
- -Highlighted the role of relativity, angular momentum
- -Generated interest outside of the field

Articles in Science News, Physics Today, New York Times, USA Today, etc...

Proton G_E/G_M Ratio



Rosenbluth (Longitudinal-Transverse) Separation

Polarization Transfer

LT

$$\sigma_R = G_M^2(Q^2) + \frac{\varepsilon}{\tau} G_E^2(Q^2)$$

$$\tau = Q^2/4M^2$$

$$\varepsilon = \left[1 + 2(1+\tau)\tan^2\theta/2\right]^{-1}$$

G_E/G_M from slope in ε plot

PT

$$\frac{G_E}{G_M} = -\sqrt{\frac{\tau(1+\varepsilon)}{2\varepsilon}}\,\frac{P_T}{P_L}$$

$P_{T,L}$ polarization of recoil proton

Wally Melnitchouk

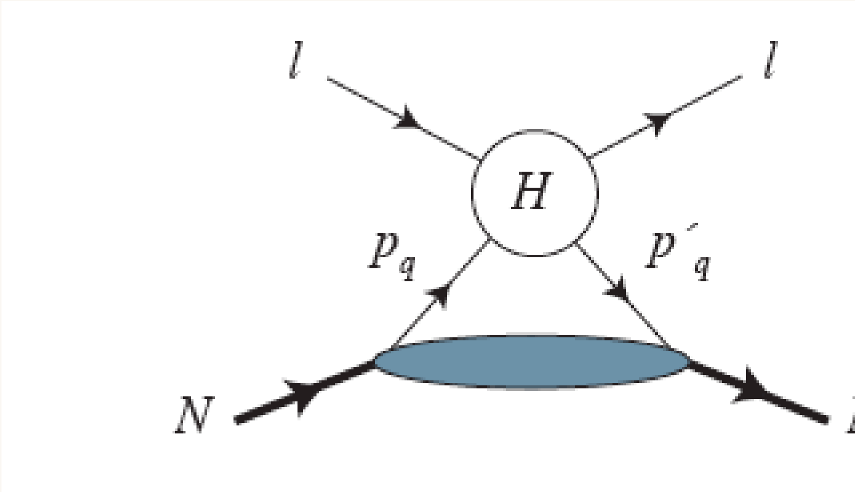
- Polarization transfer Jlab measurement of space-like form factor: G_E/G_M decreasing; revolution!

- Time-like data from Babar: G_E/G_M increasing

- Rosenbluth unreliable

- G_E-G_M scaling wrong

- Possible problem for PQCD

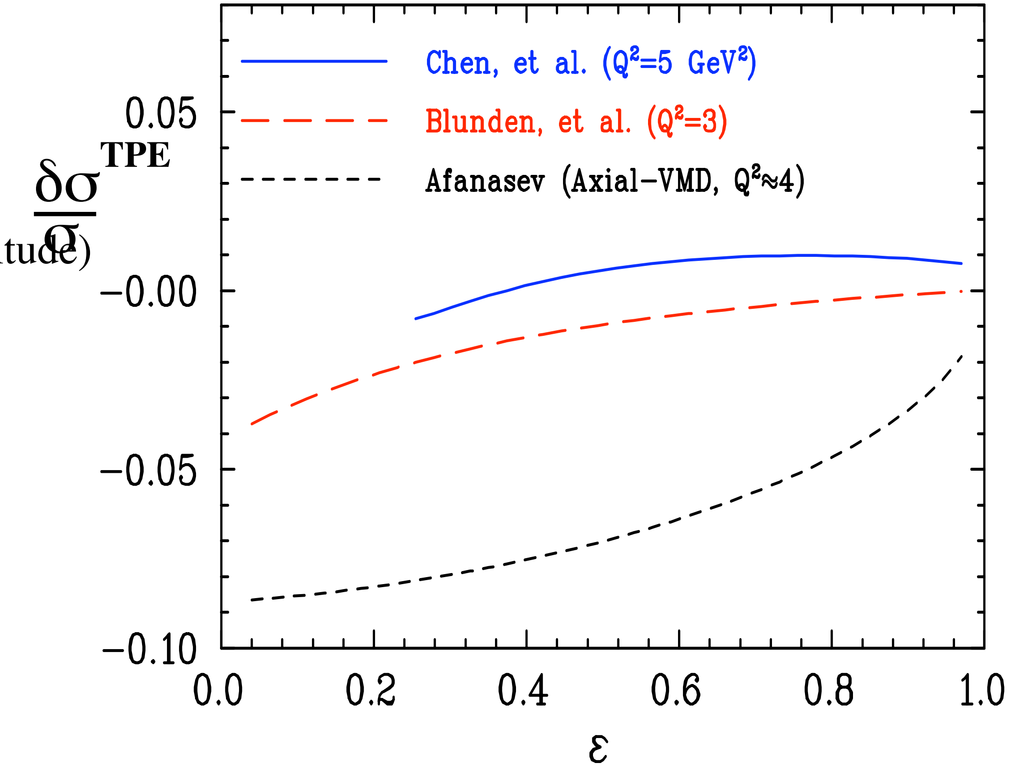


- Two-Photon exchange to the rescue. Resonance model vs. parton handbag -- need both even to get Thomson limit, LET

P. Blunden, W. Melnitchouk, and J. Tjon, PRL 91 142304 (2003)
-Improved calculation of box diagrams, (unexcited intermediate state only)

Chen, Afanasev, Brodsky, Carlson, Vanderhaeghen: PRL 93 122301 (2004)
-GPD based model, γ-q coupling
-Not valid at low Q^2 or ε values

A. Afanasev, private communication
-Axial-VMD model
-Provides ε-dependence (arbitrary magnitude)
-*Out of date, included for completeness*



My summary:

1) Calculations differ in magnitude and ε-dependence, but rapidly improving

2) **<u>All</u> show small effects at large ε**
<u>All</u> show decrease at low ε
<u>All</u> show weak Q^2-dependence

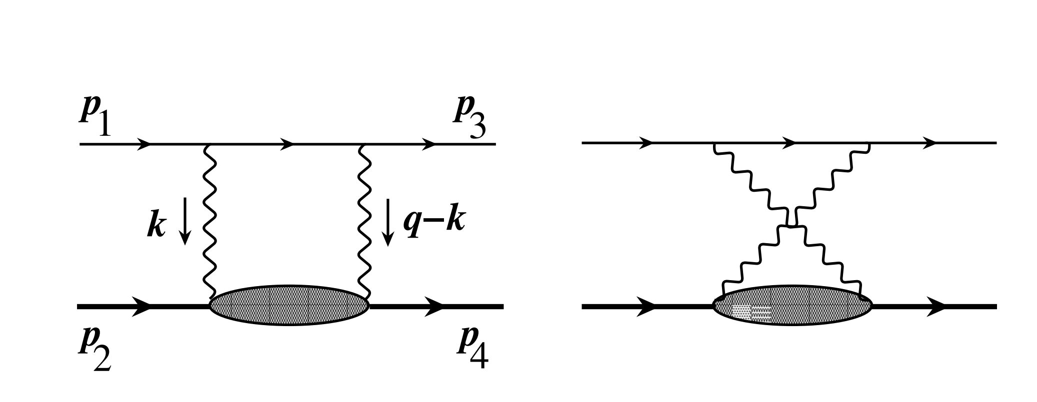
➡ Consistent with e+/e- ratios and observed form factor discrepancy

Other relevant works: P.A.M. Guichon and M. Vanderhaeghen, PRL 91, 142302 (2003)
-Generalized formalism for elastic scattering beyond Born approximation

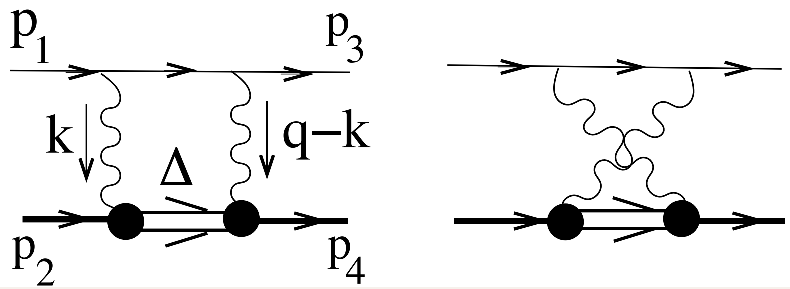
M. Rekalo and E. Tomasi-Gustafsson, EPJ A22, (2004);
E. Tomasi-Gustafsson, F. Lacroix, C. Duterte, G.I. Gakh, EPJ A24 (2005)
-Model-independent properties, connection of time-like and space-like regimes

Wally Melnitchouk
Jefferson Lab

+ J.Tjon (Maryland/JLab), P. Blunden, S. Kondratyuk (Manitoba)



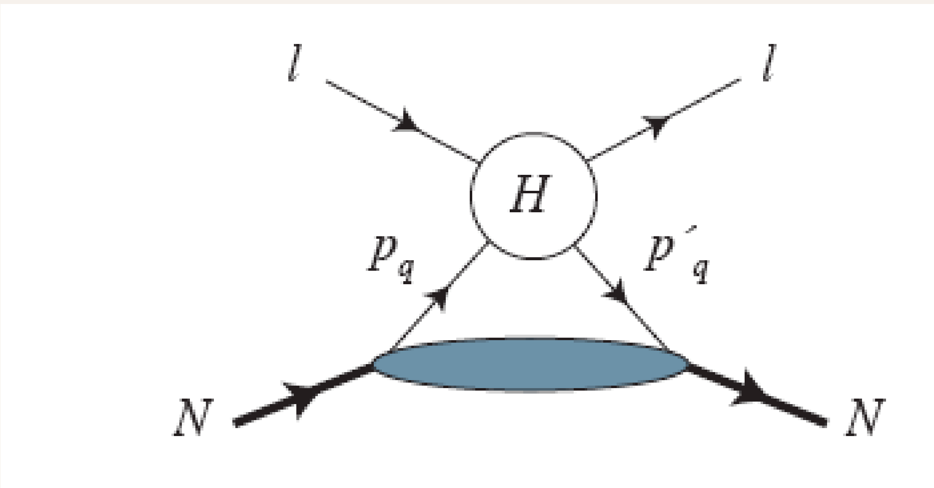
Two-photon exchange amplitude with Δ intermediate state

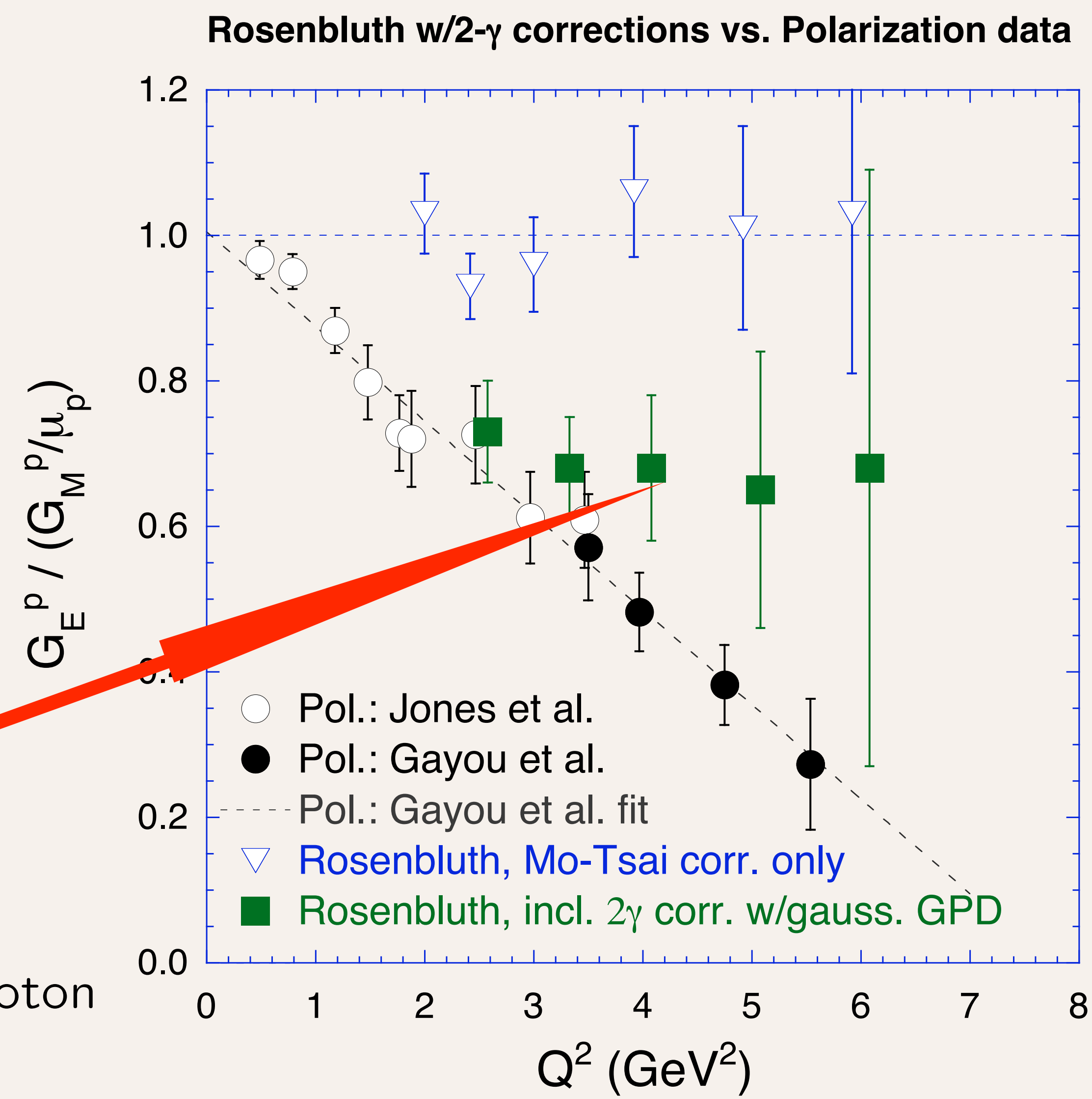


But: Cannot use Dirac/Feynman propagator

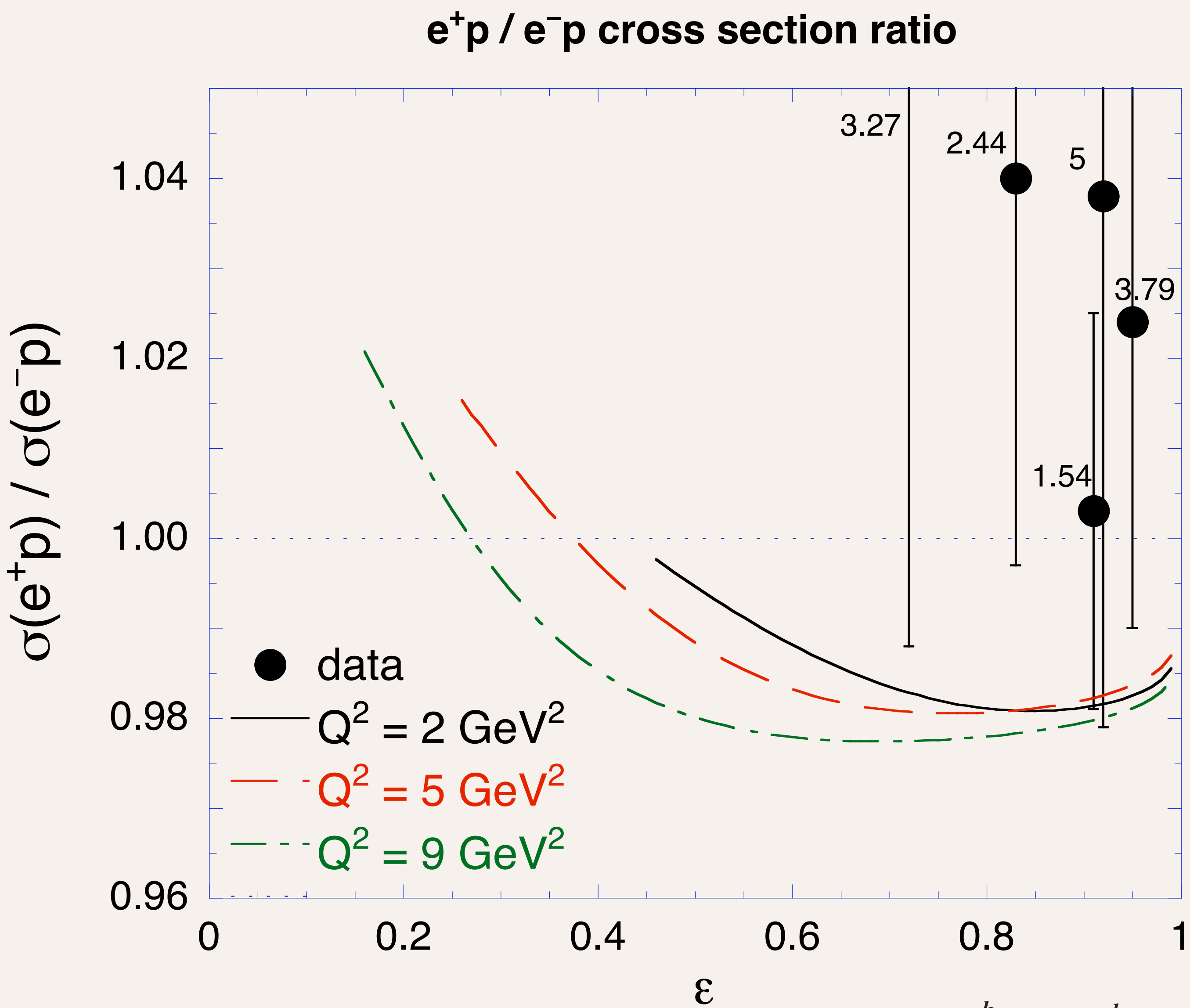
Contains Delta Delta Delta intermediate state with full strength

Afanasev, Carlson, Chen, Vanderhaeghen, sjb

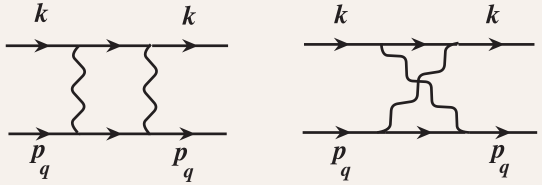




Interference of one-photon and two-photon exchange



Interference of one-photon and two-photon exchange



JLab E05-017 (Hall C): Improved Rosenbluth data

Proton detection can give factor of 2-3 improvement over world's L-T data on G_E / G_M

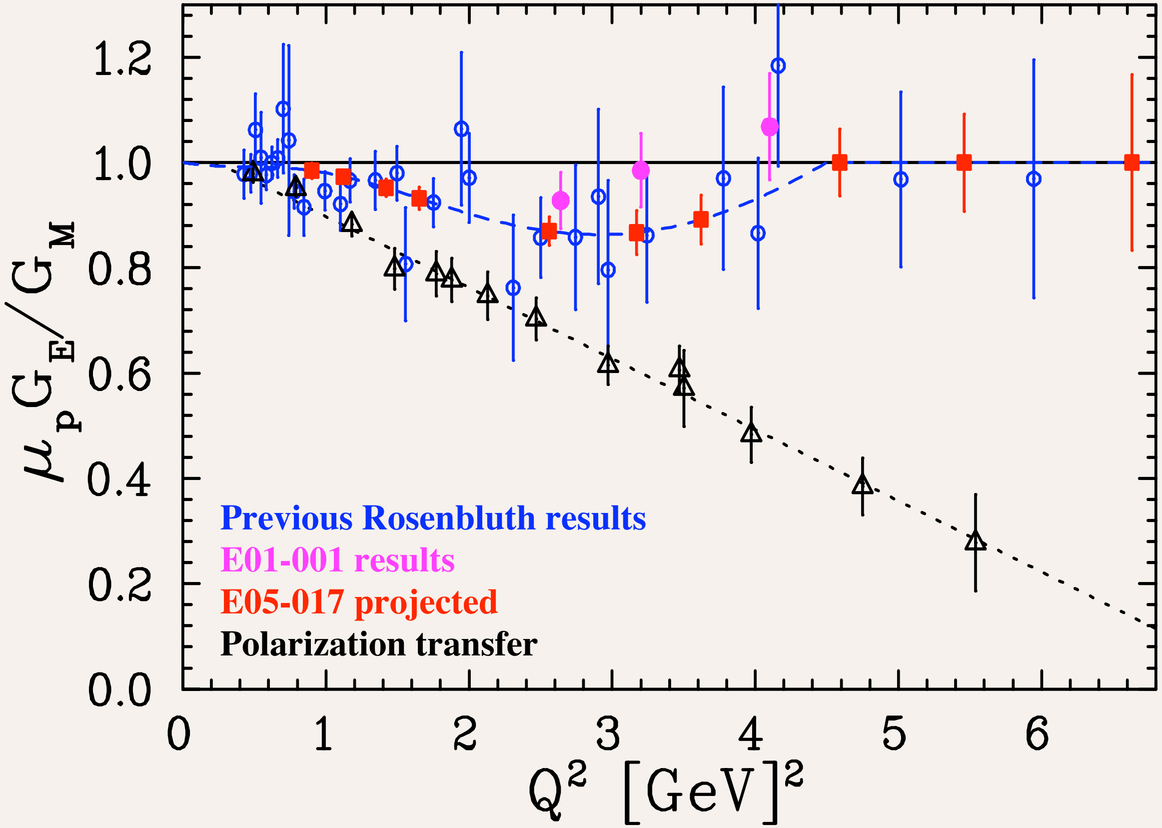
(as demonstrated by E01-001)

*I.A.Qattan, et al., PRL **94**, 142301 (2005)*

LT-PT comparisons provide $\Delta\sigma^{TPE}$ with 50-100% uncertainty

Reduce to 20-30% for Q^2>1-2

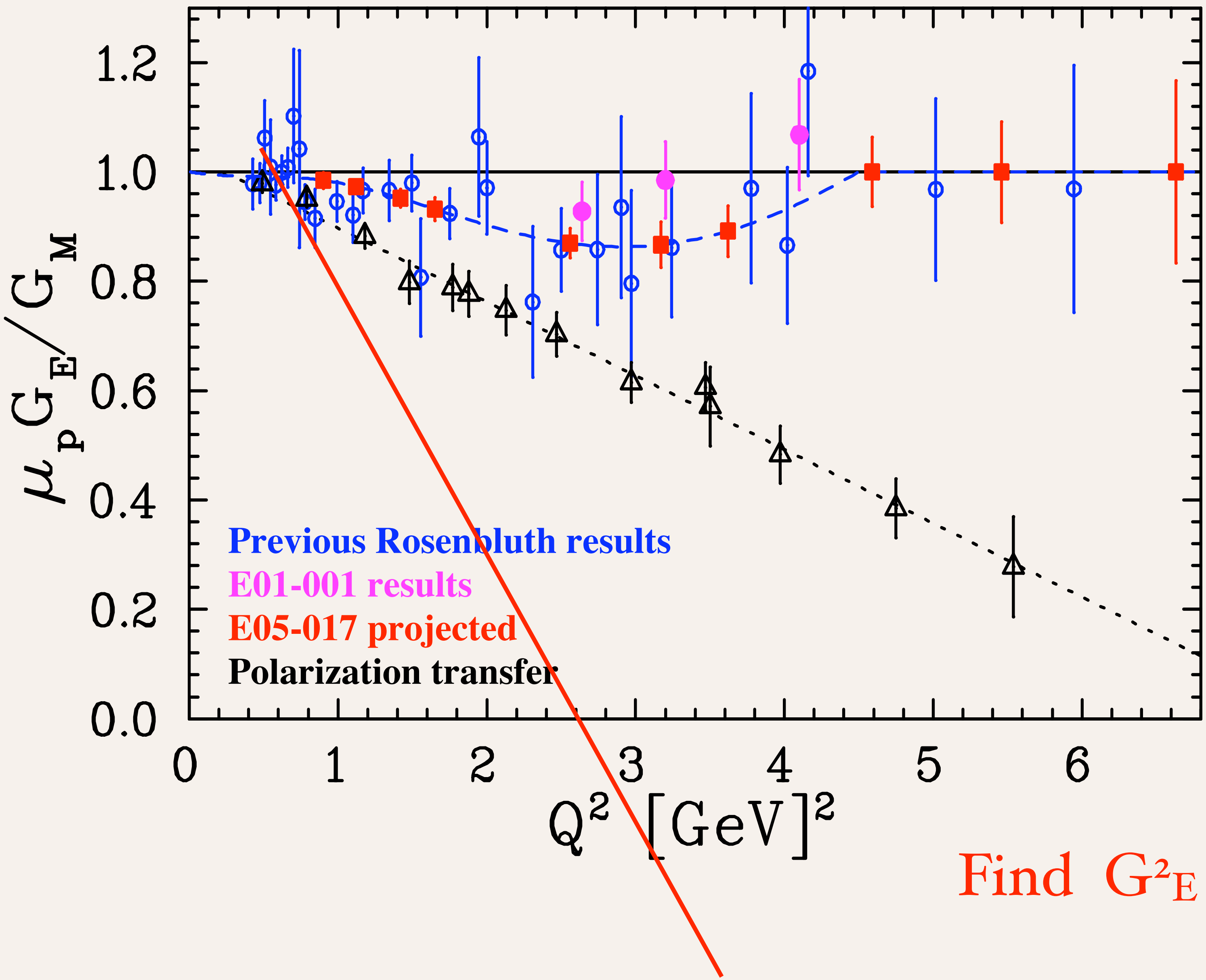
At lower Q^2, positron-electron comparisons will determine the size of $\Delta\sigma^{TPE}$



Reduce TPE uncertainties on G_M by factor of 2-3 for all Q^2, ***at or below the experimental uncertainties*** (if ε-dependence known)

Final step: better knowledge of ε-dependence of amplitudes

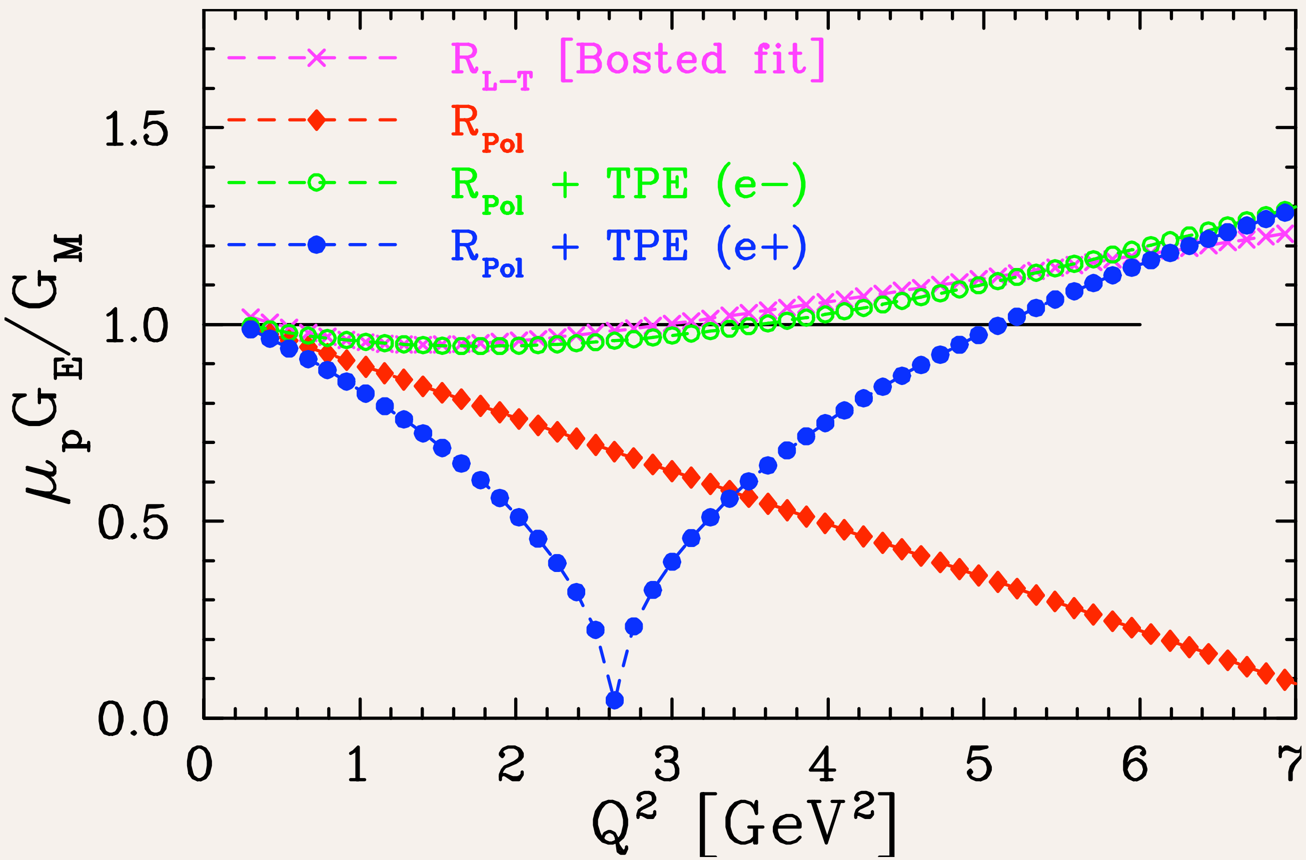
On another planet: Measure GE/GM using Rosenbluth with positron-proton scattering



Find $G^2_E < 0$!!

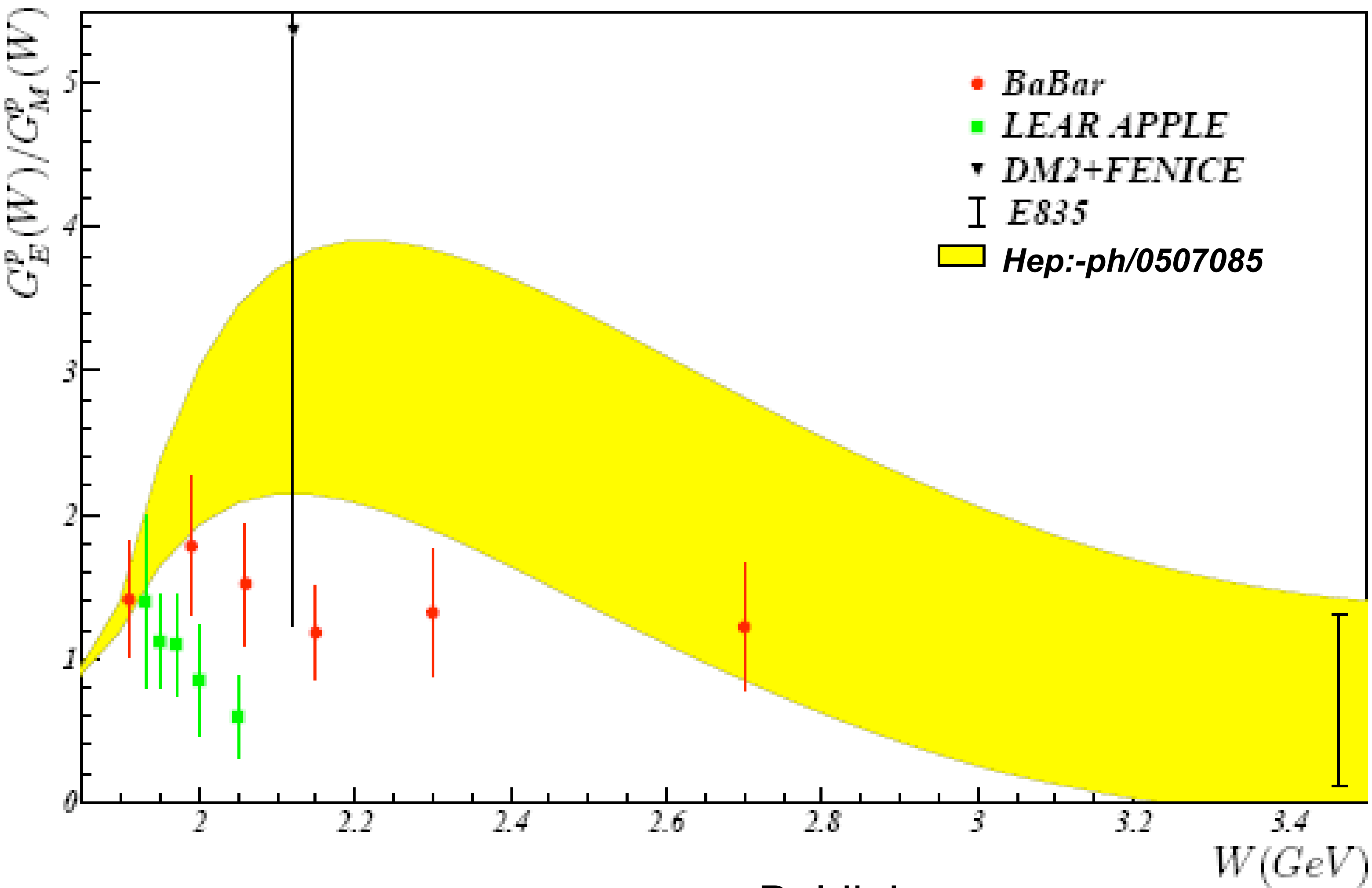
On another planet: Measure G_E/G_M using Rosenbluth with positron-proton scattering

J. Arrington



Would find square of G_E negative!

- BaBar $|G_E/G_M|$ measurements *vs* previous ones and dispersion relation prediction (yellow) based on JLab space-like G_E/G_M and analyticity

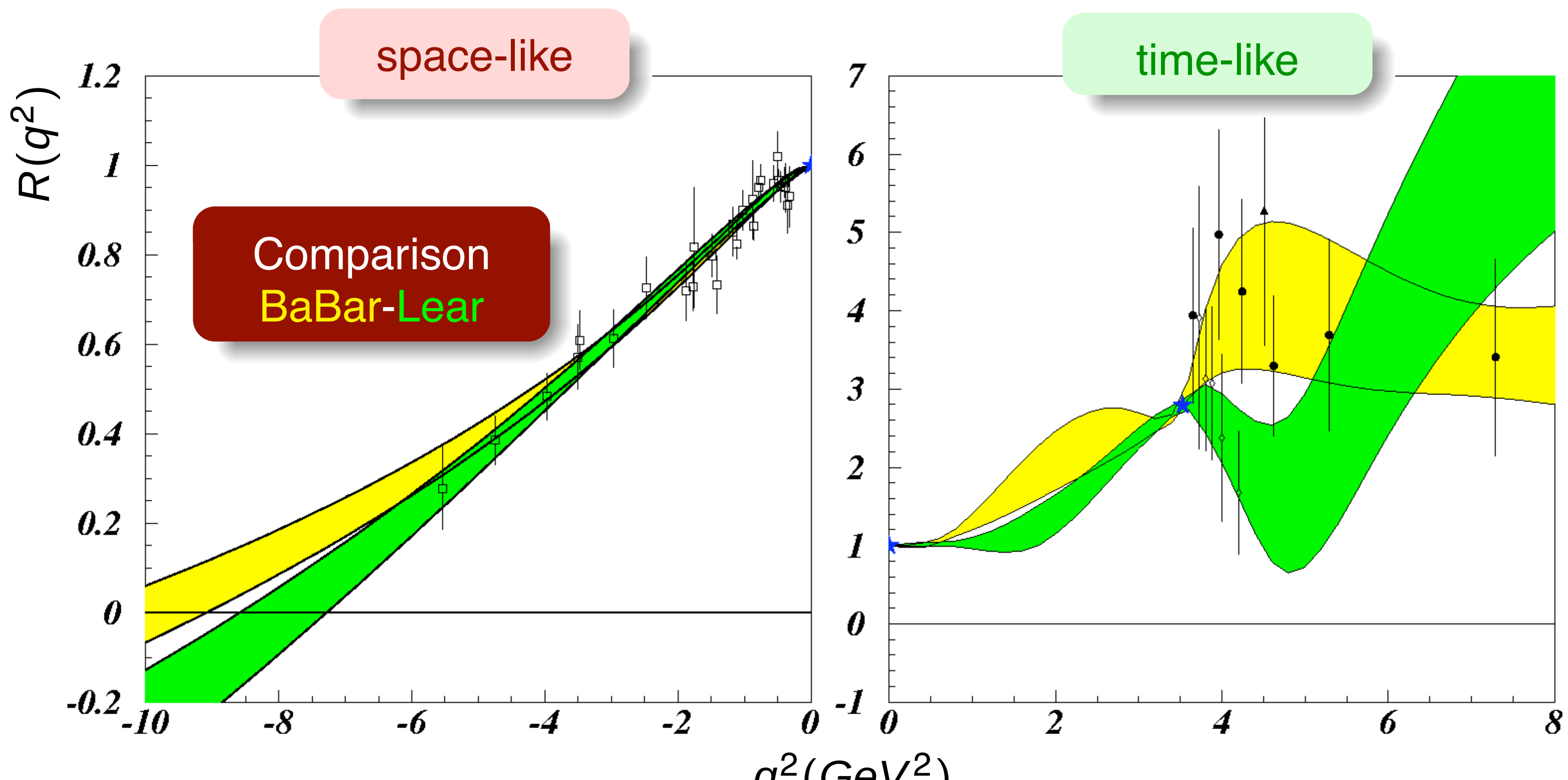


Baldini

$R(q^2)$

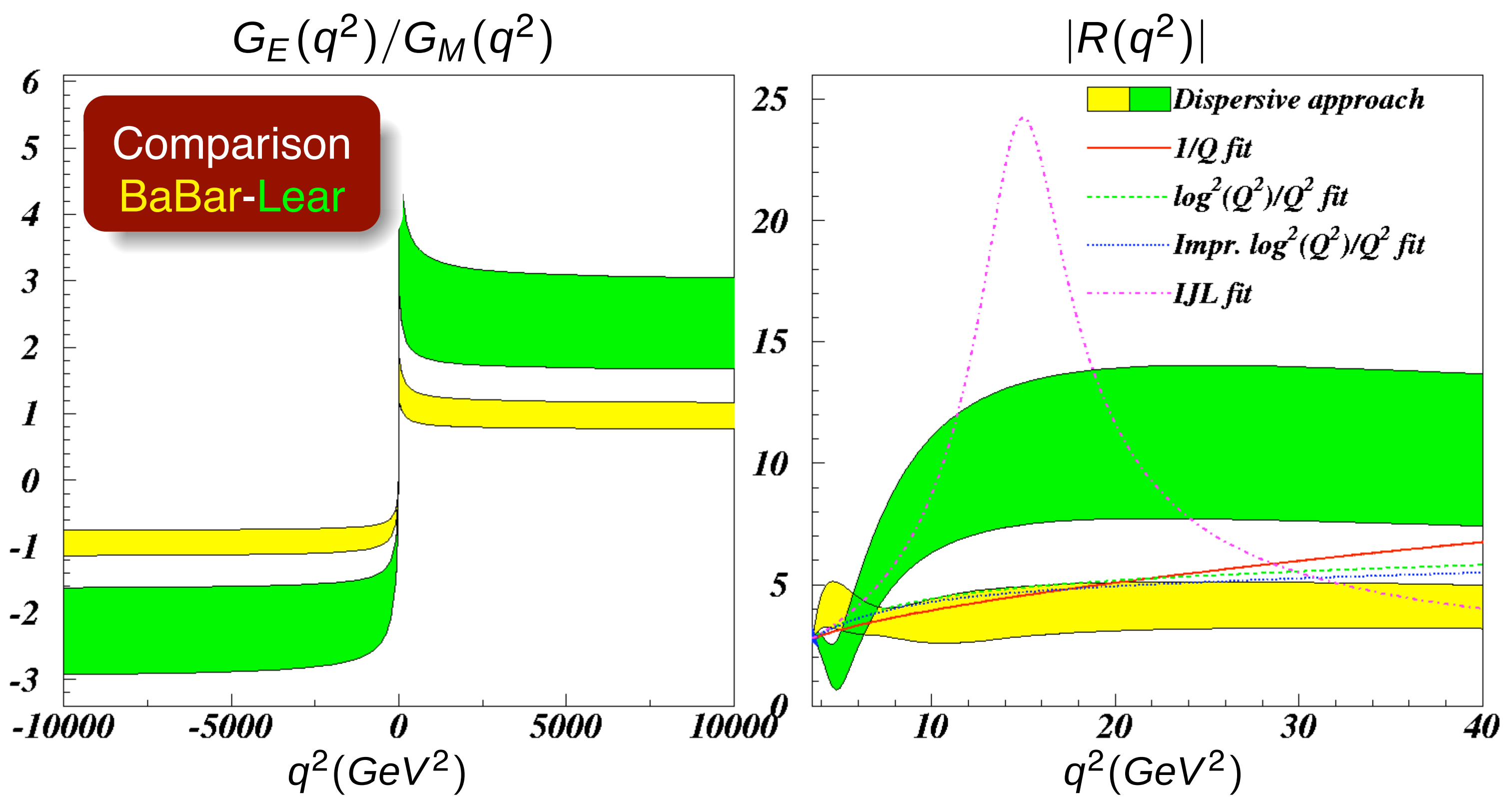
Simone Pacetti **Ratio $|G_E^p(q^2)/G_M^p(q^2)|$ and dispersion relations**

Reconstructed R in space-like and time-like region



$$R(q^2) = \mu_p \frac{G_E(q^2)}{G_M(q^2)}$$

Asymptotic behaviour of R and comparison with some existing models



Simone Pacetti **Ratio $|G_E^p(q^2)/G_M^p(q^2)|$ and dispersion relations**

Asymptotic value and space-like zero

Real asymptotic values for R

$$R_{\text{BaBar}}(\infty) = 2.65 \pm 0.55 = (0.95 \pm 0.20)\mu_p$$
$$R_{\text{Lear}}(\infty) = 6.4 \pm 1.9 = (2.3 \pm 0.7)\mu_p$$

BaBar in agreement with the scaling law $|G_E| \simeq |G_M|$ but with opposite sign

Asimptotic behaviour of F_2/F_1

$$\lim_{s\to\infty} \frac{s}{4M_N^2}\frac{F_2}{F_1} = \frac{R(\infty)}{\mu_p} - 1 = \begin{cases} -0.05 \pm 0.20 & \text{BaBar} \\ 1.3 \pm 0.7 & \text{Lear} \end{cases}$$

F_2/F_1 decreases like $(1/s)$ (Lear) or faster (BaBar) as s diverges

Space-like zero

The analysis foresees, in a model-independent way, the presence of a space-like zero t_0 for R

$$t_0^{\text{BaBar}} = (-10 \pm 1)\ GeV^2$$
$$t_0^{\text{Lear}} = (-7.9 \pm 0.7)\ GeV^2$$

BaBar only!

In spite of this the asymptotic scaling law seems preserved

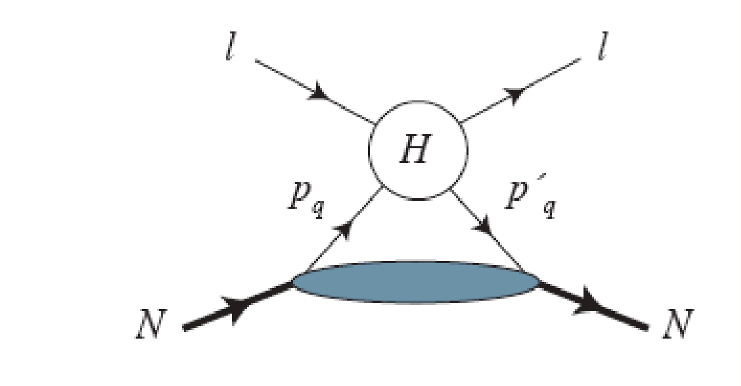
N05

Remarks on two-photon correction

Need to check input against all data on Compton amplitude

$\gamma p \to \gamma p$, $\gamma\gamma \to p\bar{p}$,
including large s, t

DVCS:
$\gamma^* p \to \gamma p$
$\gamma^*\gamma^* \to p\bar{p}$
$\gamma^* \to p\bar{p}\gamma$



Hiller, Carlson, Huang, sjb

Difference of hfs in hydrogen $(e^- p)$
and muonium $(e^- \mu^+)$.

Measure $e^\pm p$ Charge asymmetry

Need to combine parton-based and hadron-based models

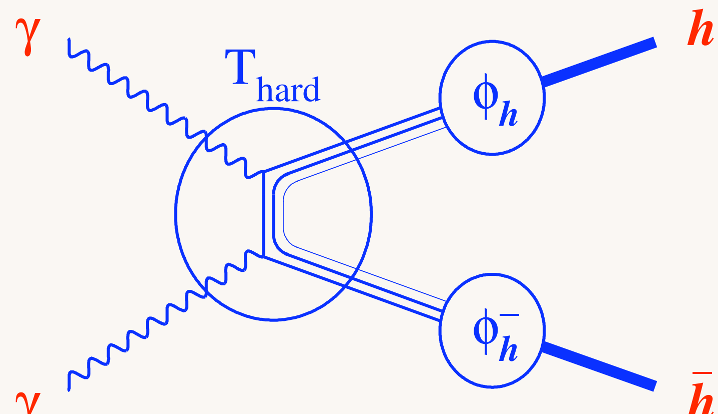
Cannot use Feynman propagator
for composite spin-1/2 systems
e.g. $He^+(e^- \alpha)$

Mechanism for low energy theorem for composite systems

Primack, sjb

Study of $\gamma\gamma \to p\bar{p}$ Production at Belle

Chen-Cheng Kuo (Belle Collaboration)



- **General theory of hard exclusive process in QCD:**

$\frac{d\sigma}{dt} \propto s^{2-n_c} f(\theta^*)$

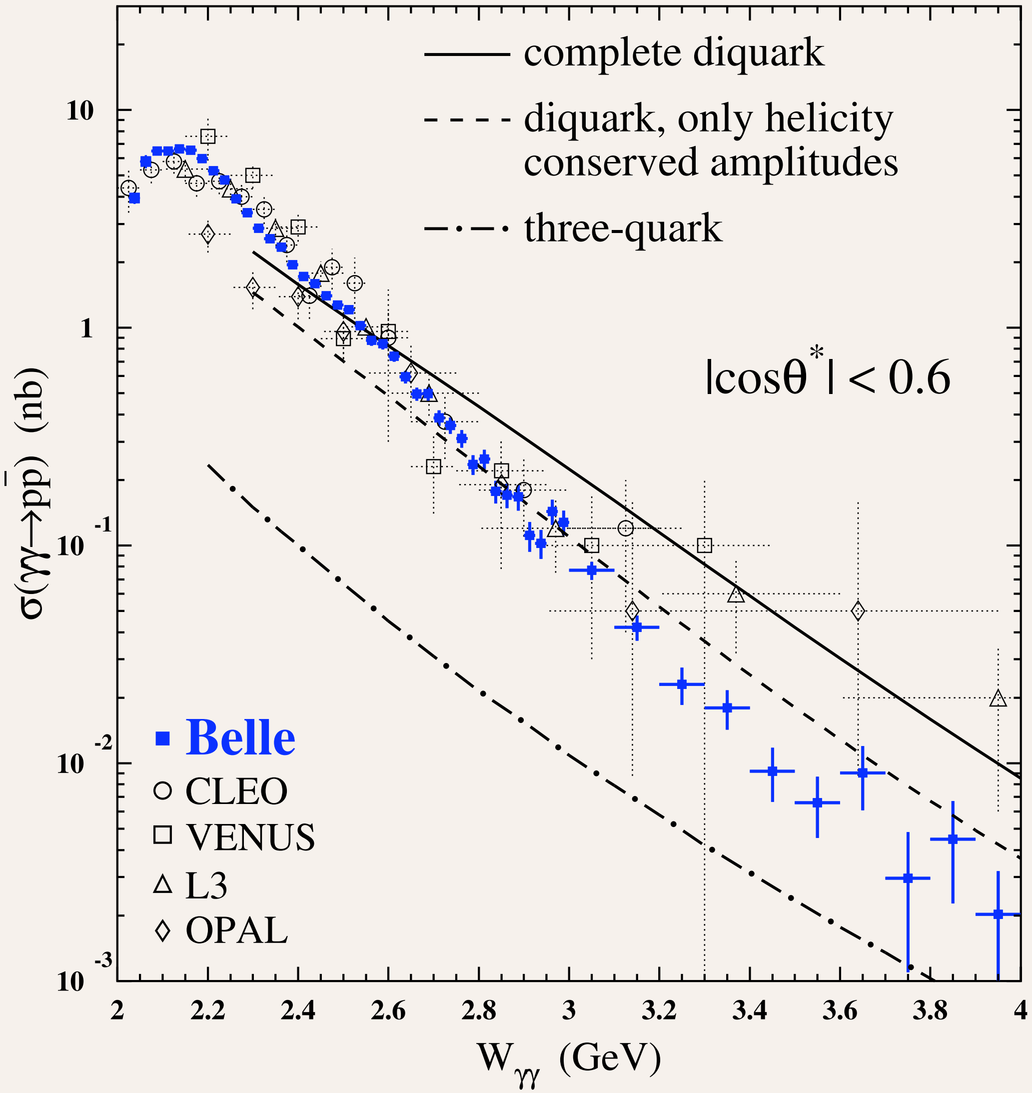
(as $s \to \infty$; $s \equiv W^2_{\gamma\gamma}$)

if $n_c = 8$, then $\sigma \propto W^{-10}_{\gamma\gamma}$

Three-quark picture using proton wave function based on QCD sum rules:

$$\frac{d\sigma(\gamma\gamma \to \mathcal{B}\bar{\mathcal{B}})}{d|\cos\theta^*|} \propto \frac{W_{\gamma\gamma}^{-10} f'(\theta^*)}{1-\cos^2\theta^*}$$

Measured Cross Sections for $\gamma\gamma \to p\bar{p}$

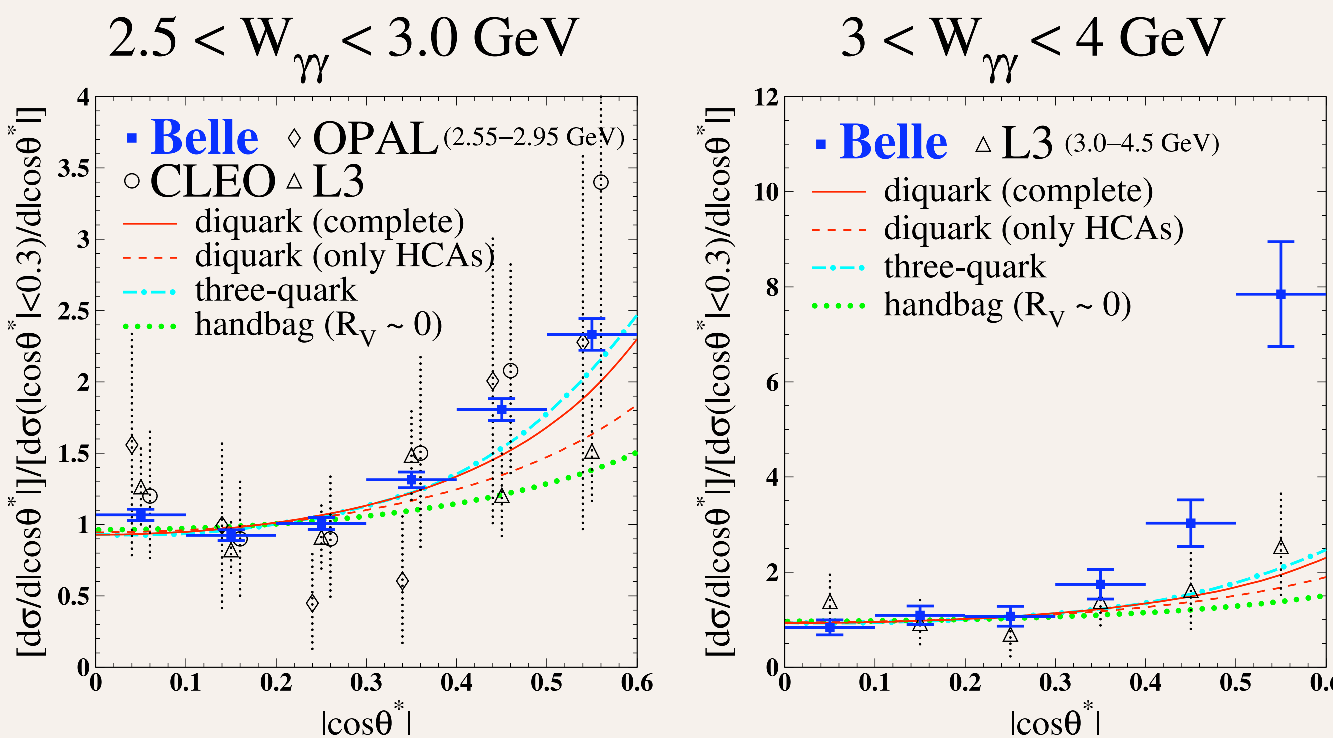


(η_c contribution included)

fitted n	range of $W_{\gamma\gamma}$ (GeV)
$15.1^{+0.8}_{-1.1}$	2.5–2.9
$12.4^{+2.4}_{-2.3}$	3.2–4.0

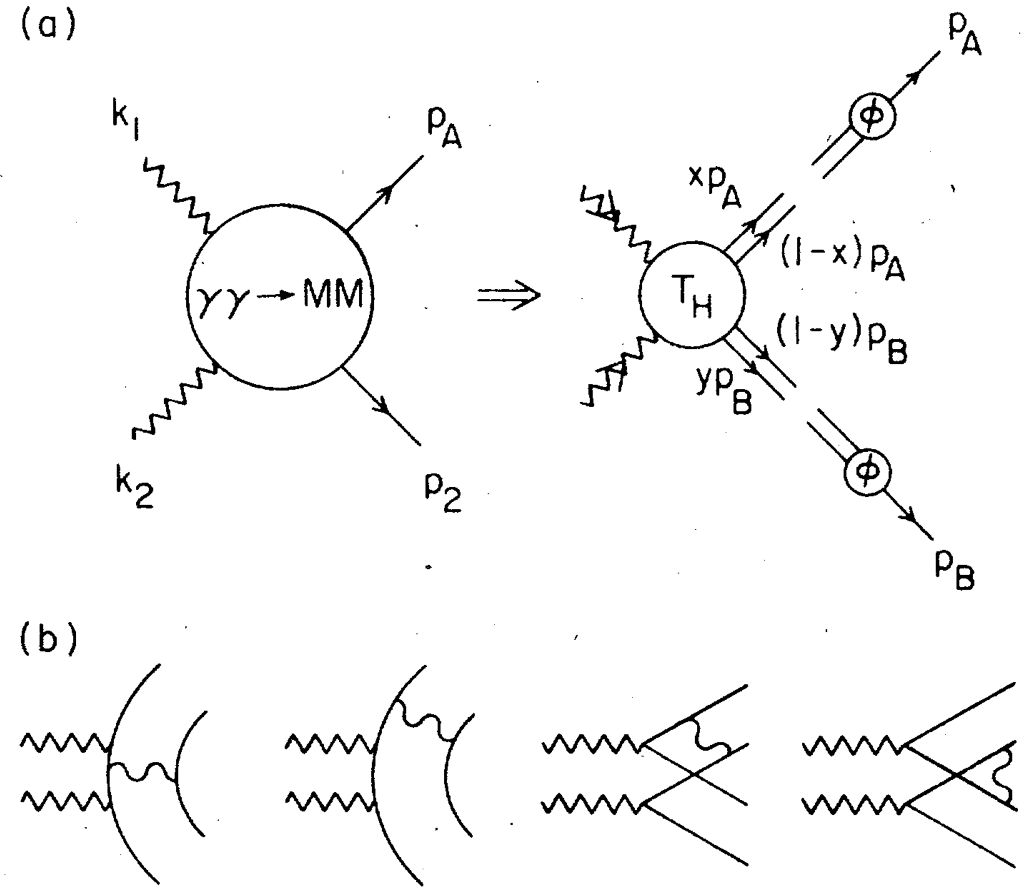
- Steeper fall in $W_{\gamma\gamma}$ than pQCD $n = 10$ ($n = 10$ not rejected for $W_{\gamma\gamma} > 3.2$ GeV)
- Decreasing n in $W_{\gamma\gamma}$ (indication of a transition to asymptotic predictions)

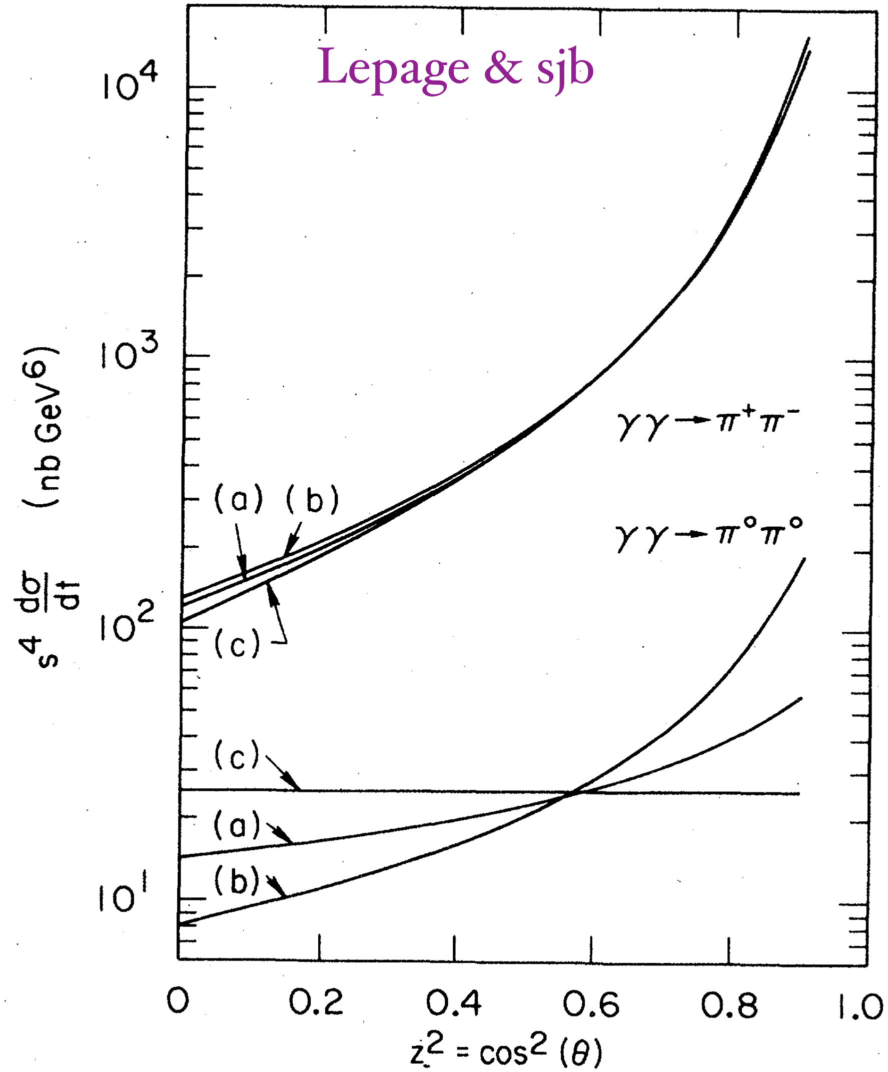
Angular Distribution at Higher Energies and Predictions



- **Ascending trend is a general feature of pQCD due to the hard scattering amplitude:** $\frac{d\sigma}{d|\cos\theta^*|} \propto \frac{1}{tu} \propto \frac{1}{1-\cos^2\theta^*}$
- **Handbag contribution with R_V^p neglected:** $\frac{d\sigma}{d|\cos\theta^*|} \propto \frac{1}{1-\cos^2\theta^*}$
- **Steeper enhancement of data at higher $|\cos\theta^*|$ must be explained**

Baryon Regge exchange
s >>- t, -u





$$\frac{\frac{d\sigma}{dt}(\gamma\gamma\to\pi^+\pi^-)}{\frac{d\sigma}{dt}(\gamma\gamma\to\mu^+\mu^-)} \sim \frac{4\,|F_\pi(s)|^2}{1-\cos^4\theta_{c.m.}}$$

Crucial test: neutral suppression

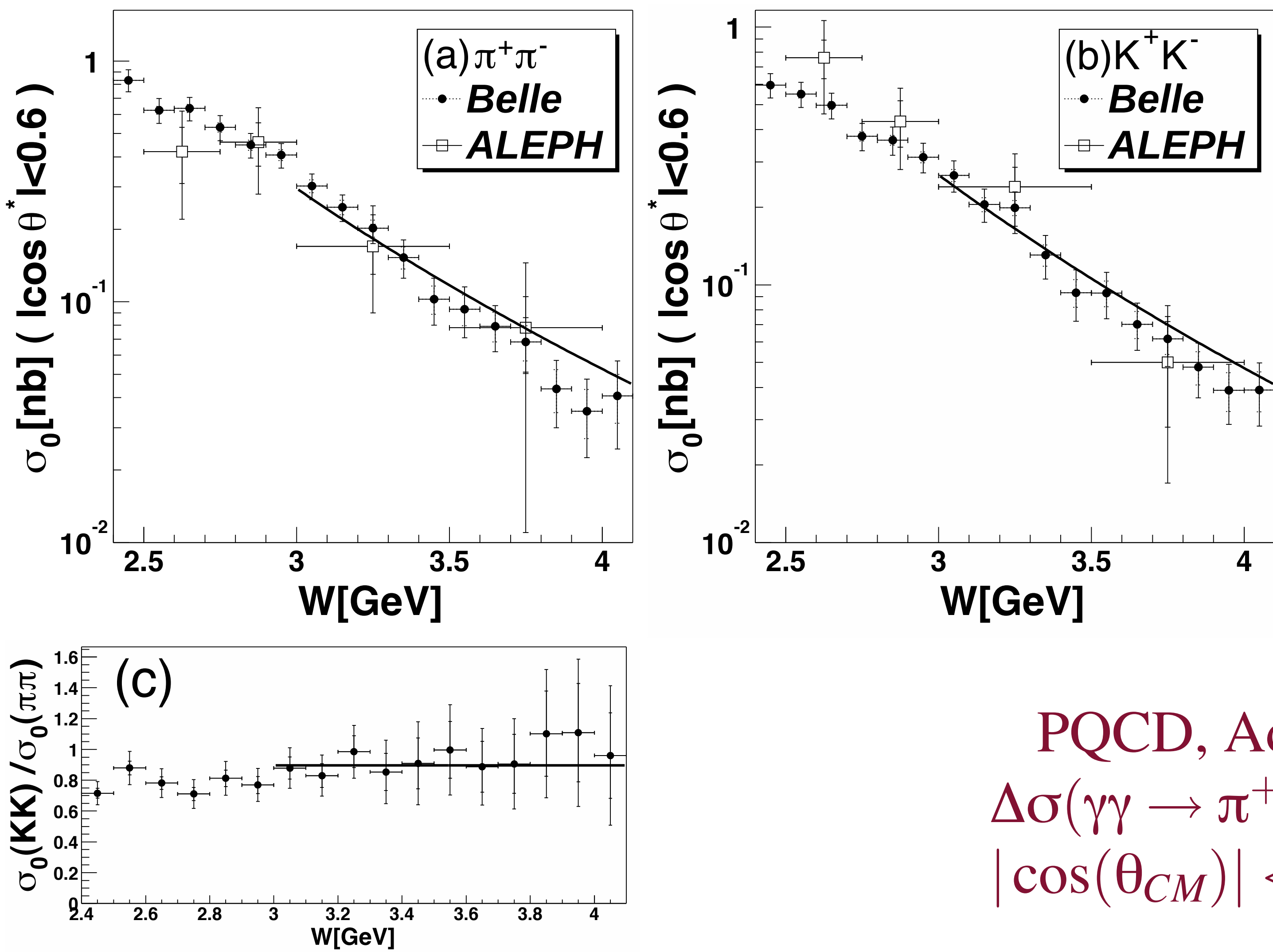


Fig. 5. Cross section for (a) $\gamma\gamma\to\pi^+\pi^-$, (b) $\gamma\gamma\to K^+K^-$ in the c.m. angular region $|\cos\theta^*| < 0.6$ together with a W^{-6} dependence line derived from the fit of $s|R_M|$. (c) shows the cross section ratio. The solid line is the result of the fit for the data above 3 GeV. The errors indicated by short ticks are statistical only.

Two Photon Reactions

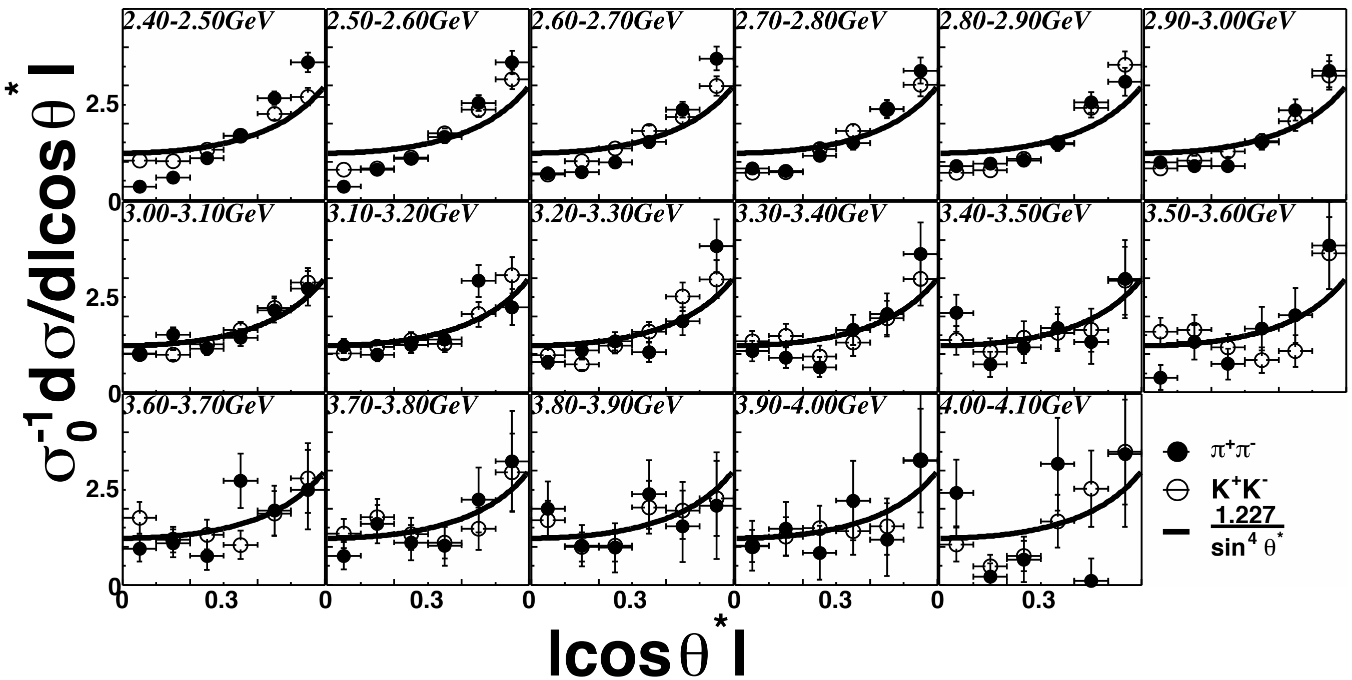
Hard Exclusive Processes: Fixed angle

PQCD, AdS/CFT:

$\Delta\sigma(\gamma\gamma \to \pi^+\pi^-, K^+, K^-) \sim 1/W^6$

$|\cos(\theta_{CM})| < 0.6$

PQCD: $$\frac{d\sigma}{d|\cos\theta^*|}(\gamma\gamma \to M^+M^-) \approx \frac{16\pi\alpha^2}{s}\frac{|F_M(s)|^2}{\sin^4\theta^*},$$



Angular dependence of the cross section, $\sigma_0^{-1} d\sigma/d|\cos\theta^*|$, for the $\pi^+\pi^-$(closed circles) and K^+K^-(open circles) processes. The curves are $1.227 \times \sin^{-4}\theta^*$. The errors are statistical only.

Measurement of the $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to K^+K^-$ processes at energies of 2.4–4.1 GeV

Crucial test: neutral suppression

Belle Collaboration

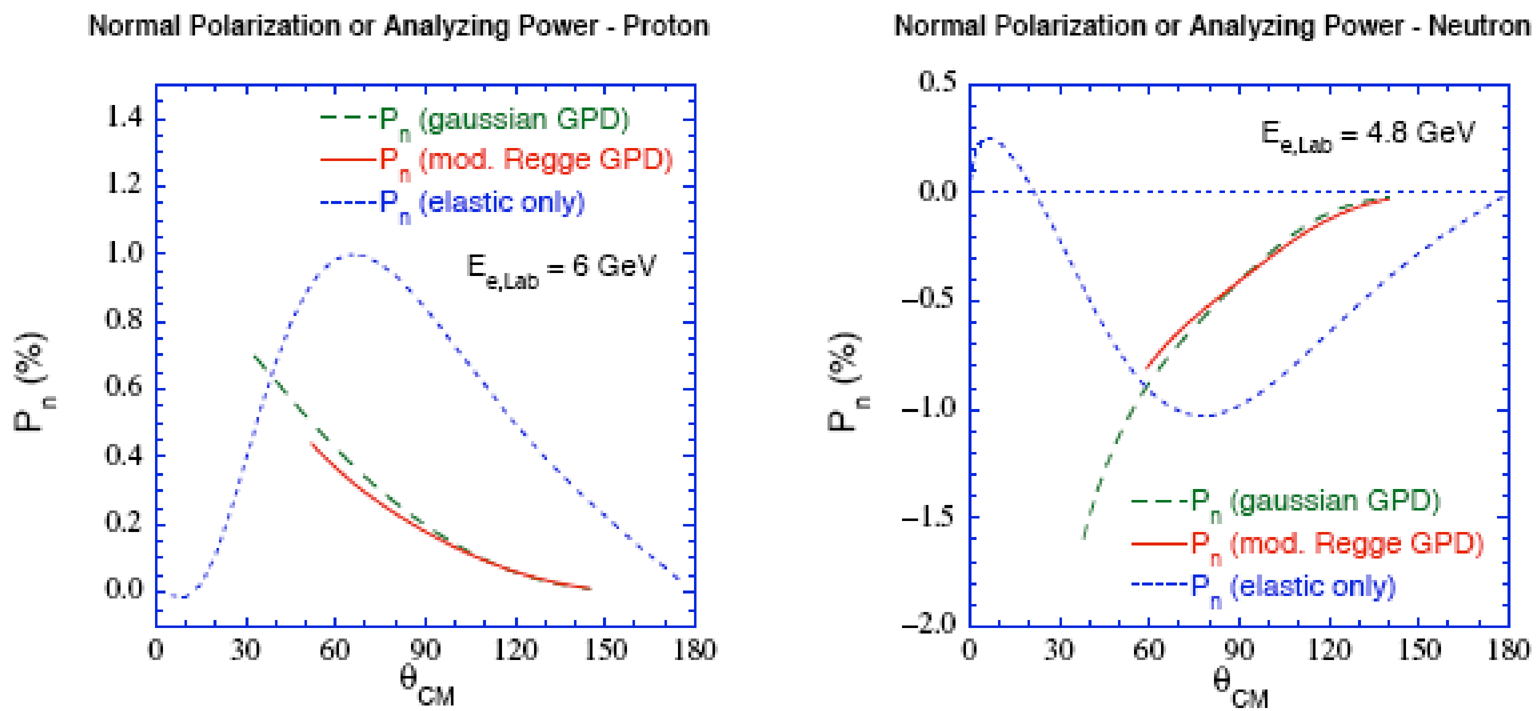


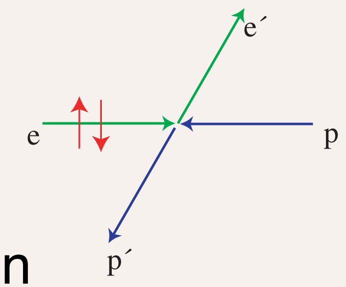
FIG. 5: Nucleon analyzing power, which is equal to normal recoil polarization. The elastic contribution (nucleon intermediate state in the two-photon exchange box diagram) is shown by the dotted curve [27]. The GPD calculation for the inelastic contribution is shown by the dashed curve for the gaussian GPD, and by the solid curve for the modified Regge GPD. The GPD calculation is cut off in the backward direction at $-u = M^2$. In the forward direction the modified Regge GPD result goes down to $Q^2 = 2$ GeV^2 and the gaussian GPD result to $Q^2 = M^2$.

Afanasev, Carlson, Chen, Vanderhaeghen, sjb

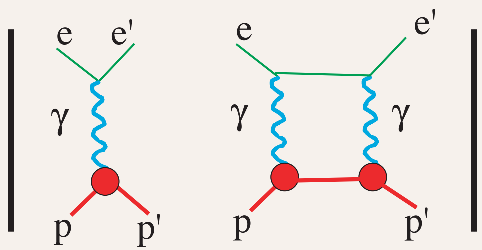
Transverse Asymmetries in Elastic Electron Nucleon Scattering and the Imaginary Part of the Two-Photon Amplitude

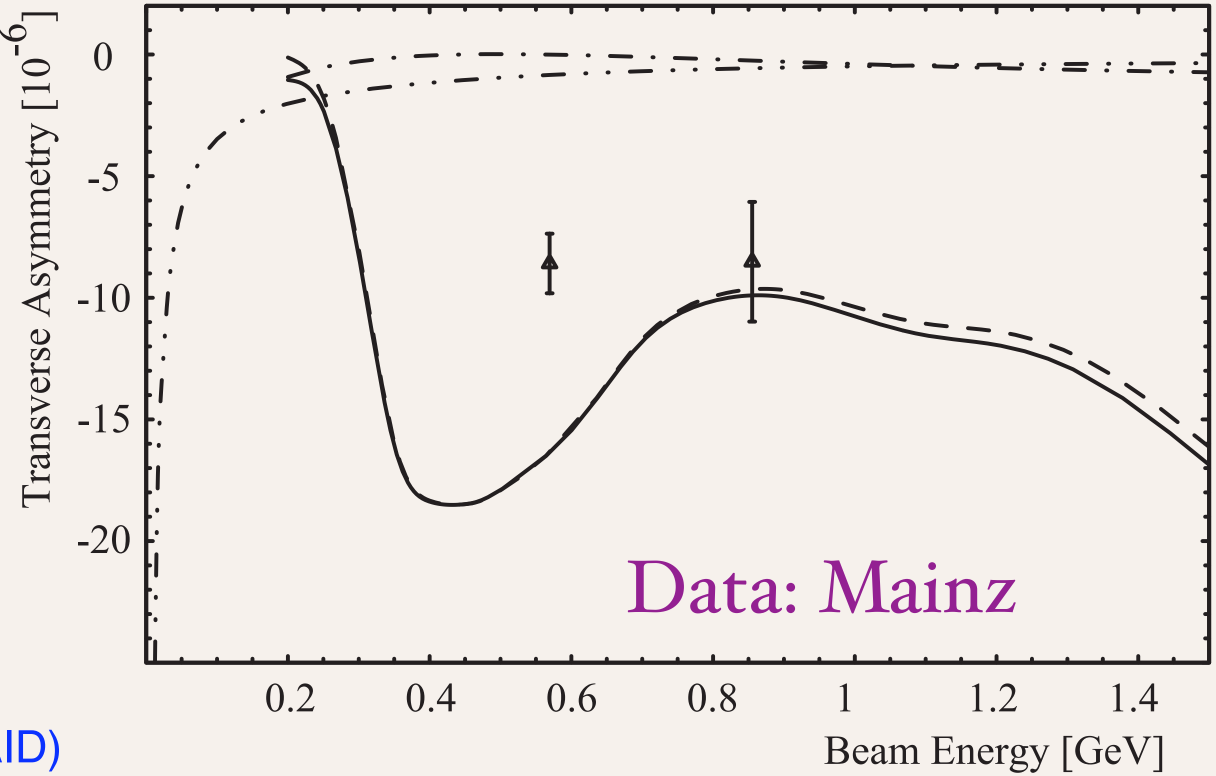
Frank E.Maas

- Single-Spin-Asymmetries: e^- Spin transverse

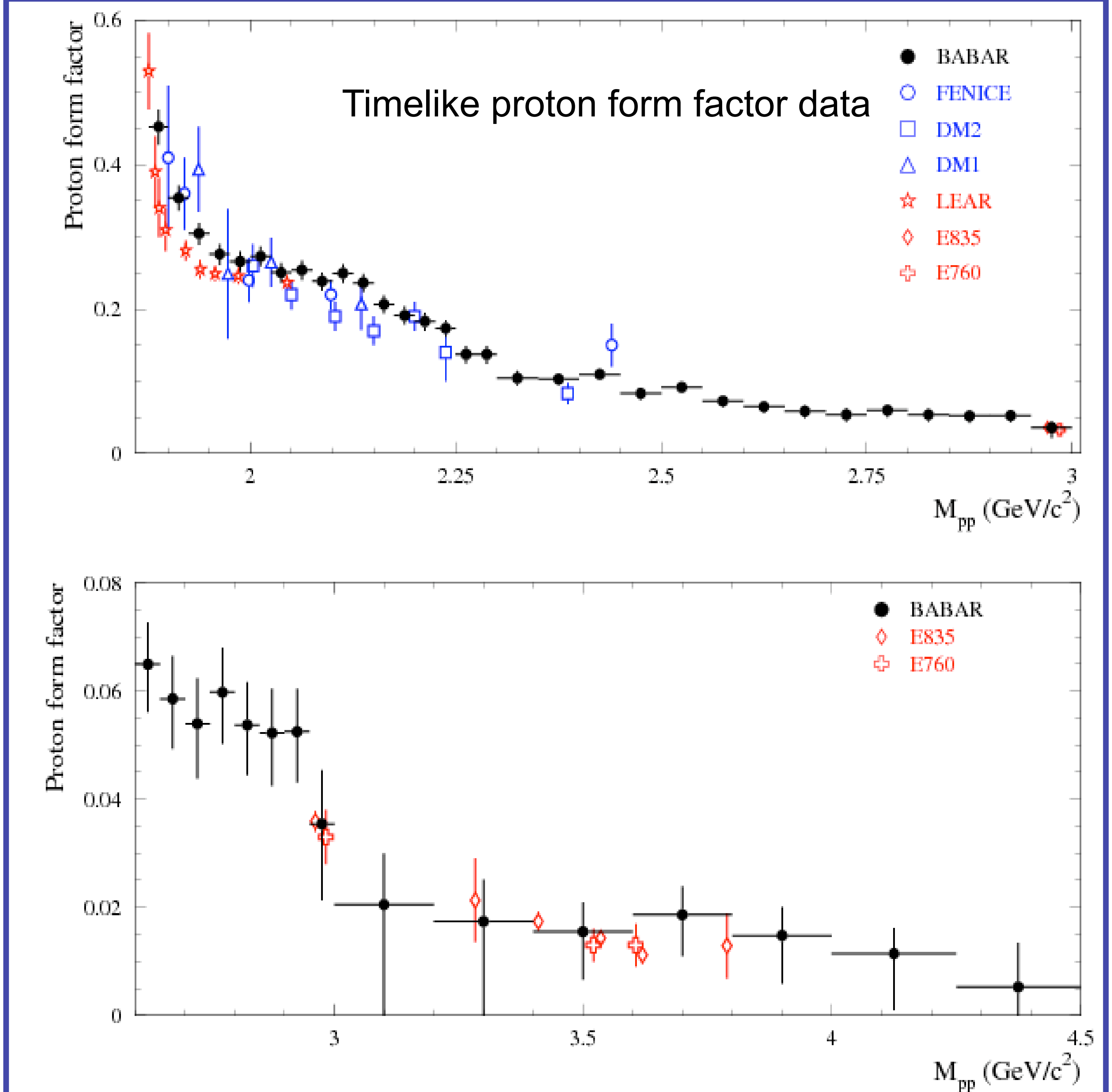


- Transverse Beam Spin Asymmetry (Imaginary Part, only in 2-Photon)





Intermediate State: Proton, πN States (MAID)
(B. Pasquini)



ISR technique

Kuhn et al

Historical ref: Zichichi, Berman, Cabibbo

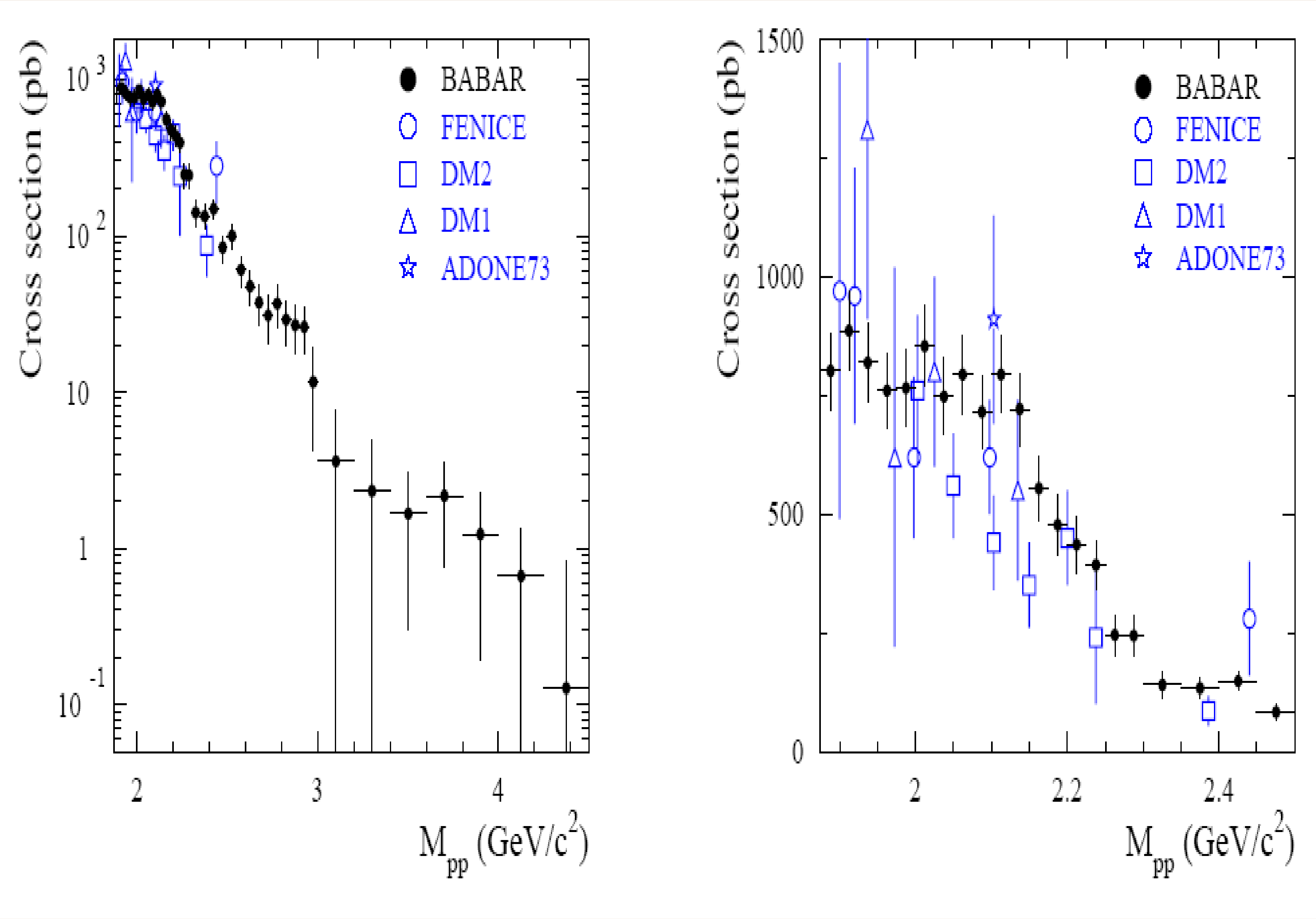
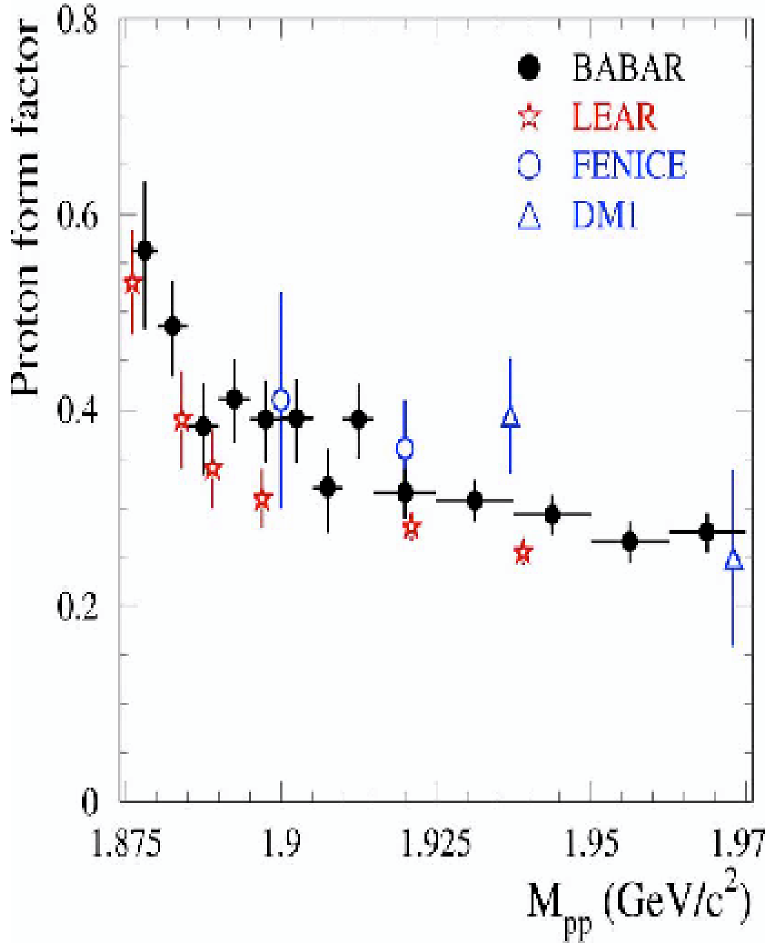


Fig. 5. *Total cross section* $e^+e^- \to p\bar{p}$ *as measured in two different energy regions.*

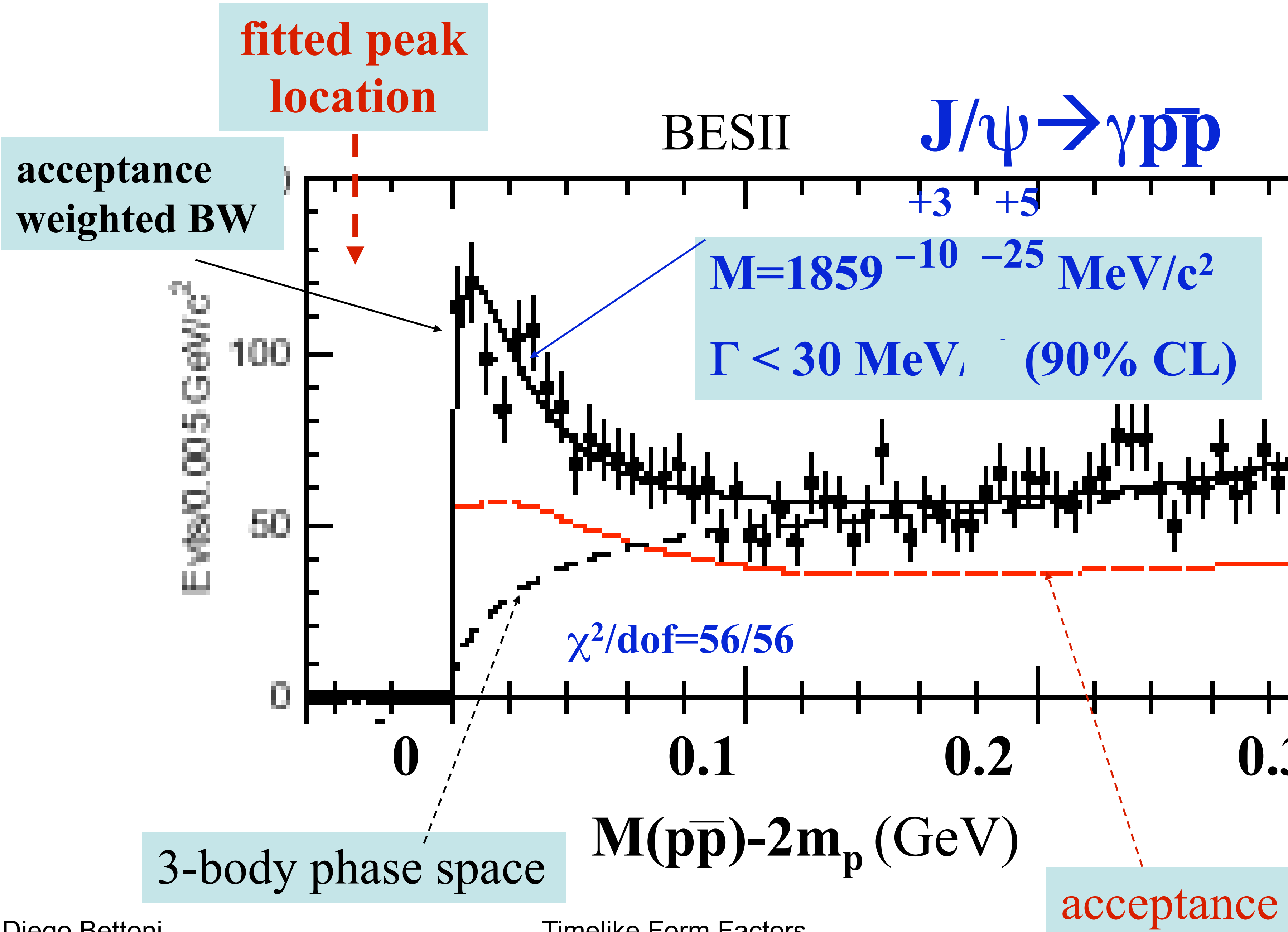
BaBar Measurement using ISR

BaBar measurement very near threshold confirms steep rise of Form Factor



Steep behavior at threshold also seen in other processes

Threshold Enhancement observed by BES



•Negative step at w ~ 2.2 GeV (!?)

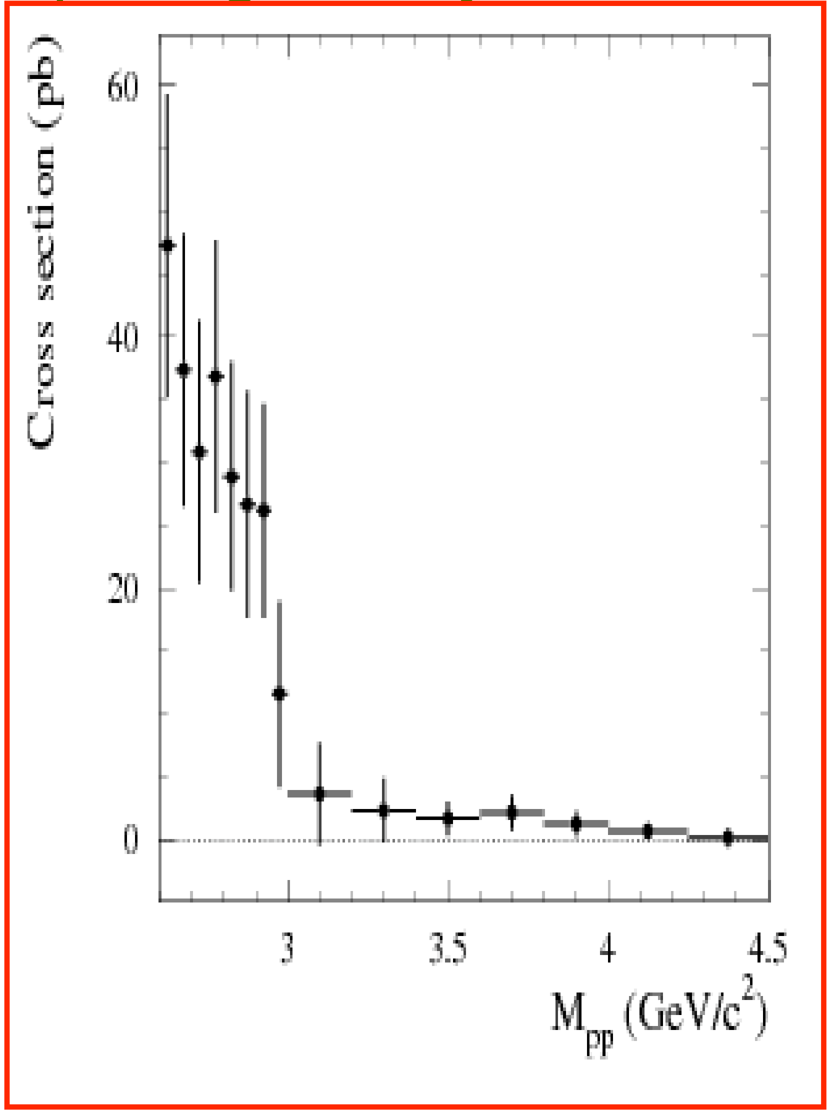
Speculations:

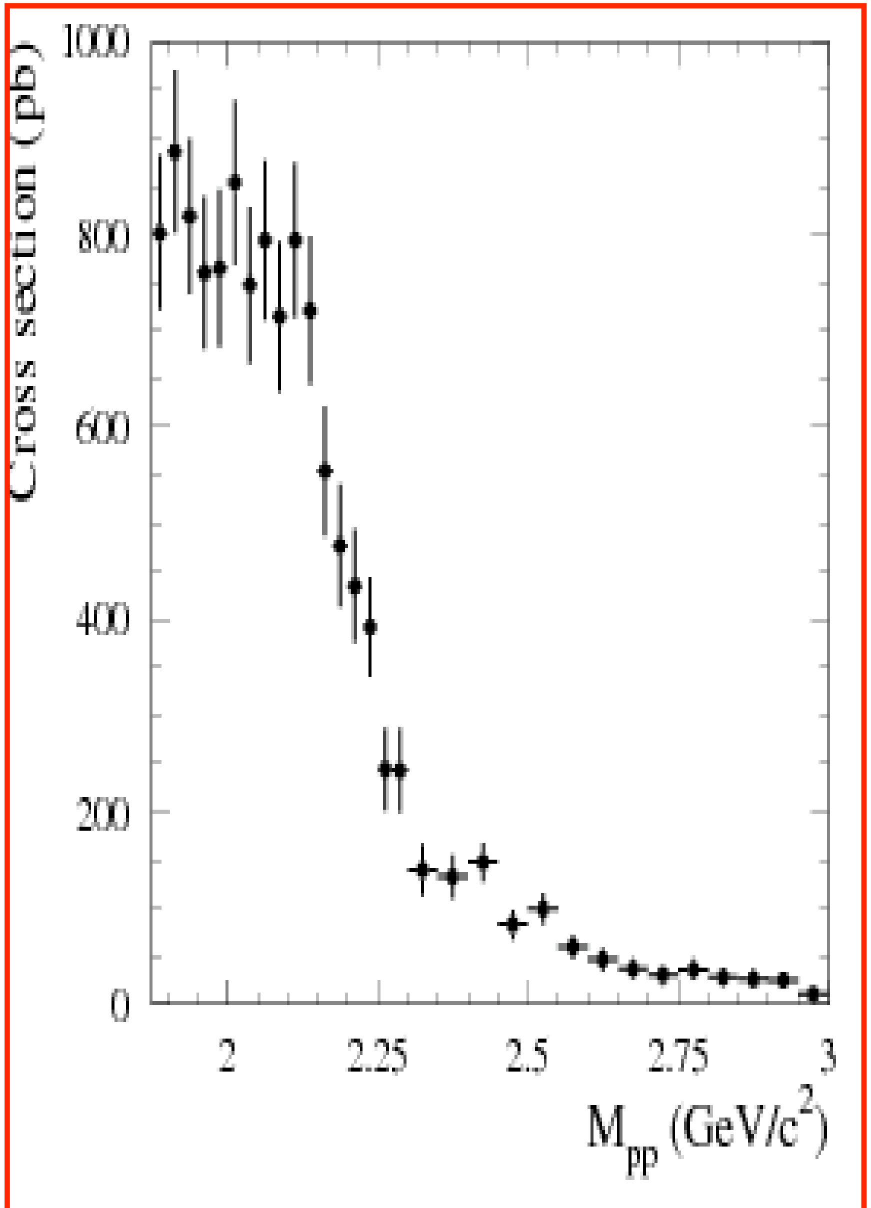
•Strong resonances interference ?

•a new (inelastic) amplitude:

opening of baryonic excitations?

Baldini



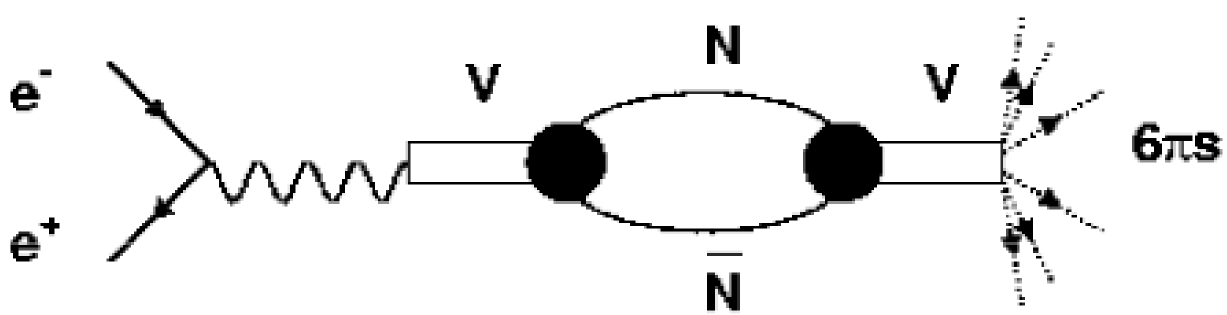


Possible Explanations

- Tail of a narrow resonance below threshold (baryonium ?).
- Dominance of π exchange in $\bar{p}p$ final state interaction.
- Underestimation of the Coulomb correction factor.

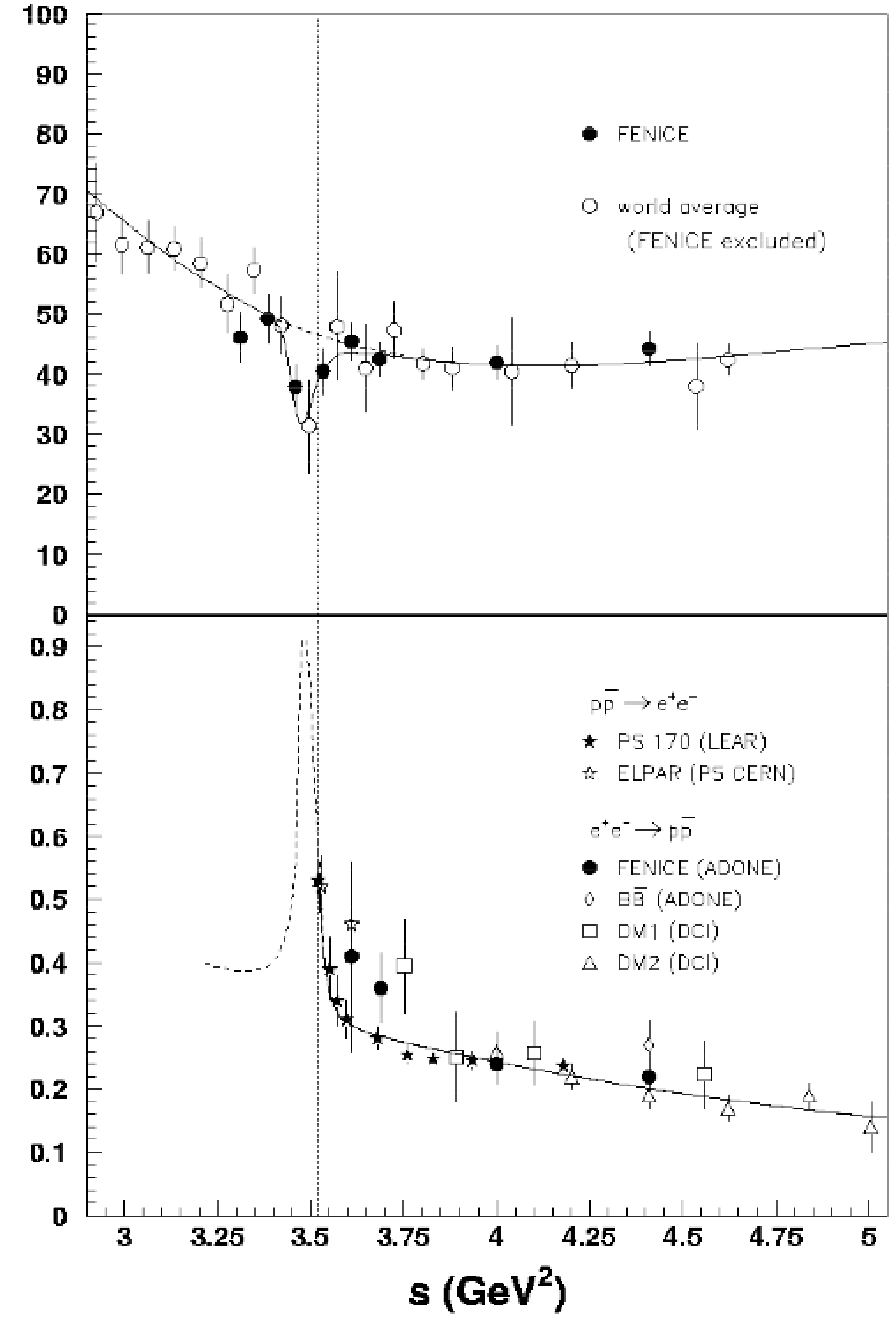
Possible test for baryonium: a vector meson with very small coupling to e^+e^- (and relatively small hadronic width), lying on top of a ρ/ω recurrence, should show up as a dip in some hadronic cross section.

Baldini

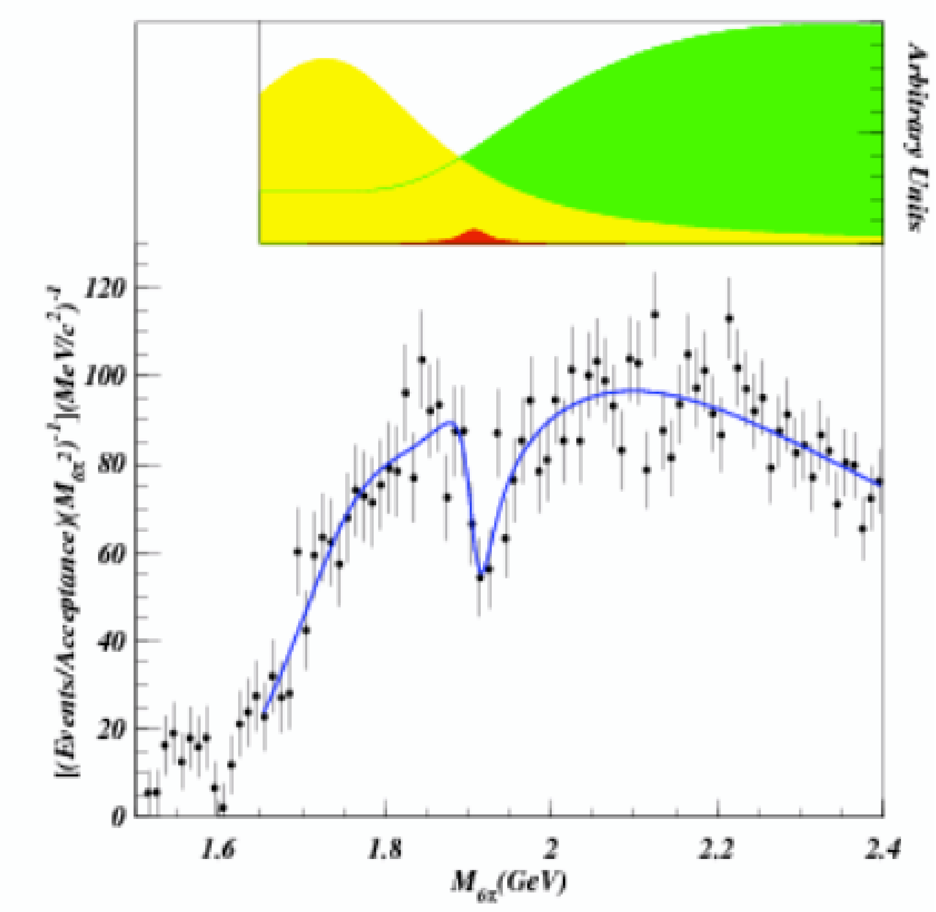


Resonant Structures

The dip in the total multihadronic cross section and the steep variation of the proton form factor near threshold may be fitted with a narrow vector meson resonance, with a mass M ~1.87 GeV and a width Γ ~ 10-20 MeV, consistent with an $N\bar{N}$ bound state.



- Dip observed in 6 π diffractive photoproduction by E687 at Fermilab
- New results from Babar expected soon



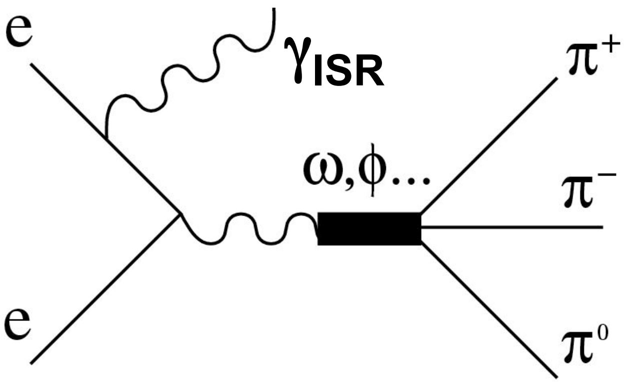
E. Solodov

BINP Novosibirsk

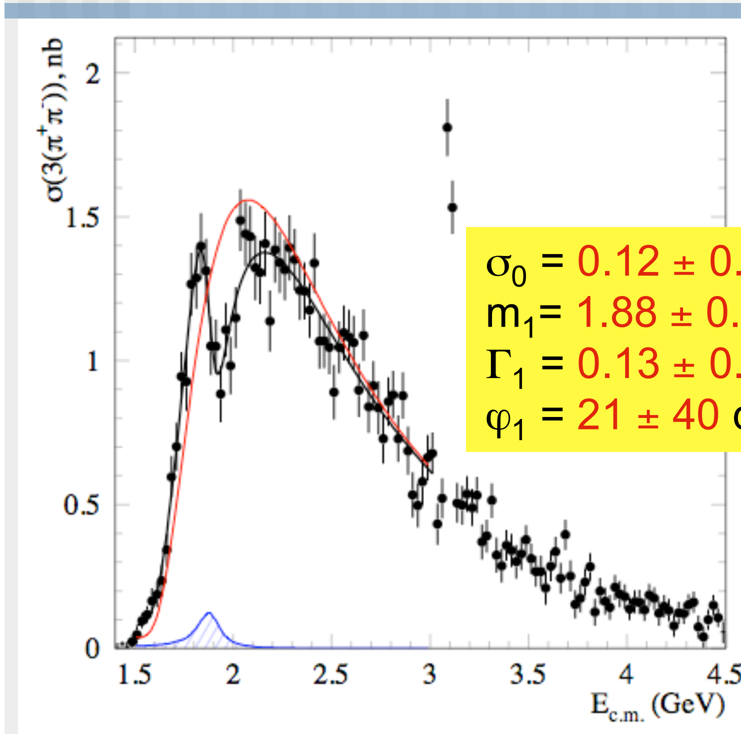
Representing BaBar collaboration

$$\frac{d\sigma(s,x)}{dx\,d(\cos\theta)} = W(s,x,\theta)\cdot\sigma_0\big(s(1-x)\big),$$

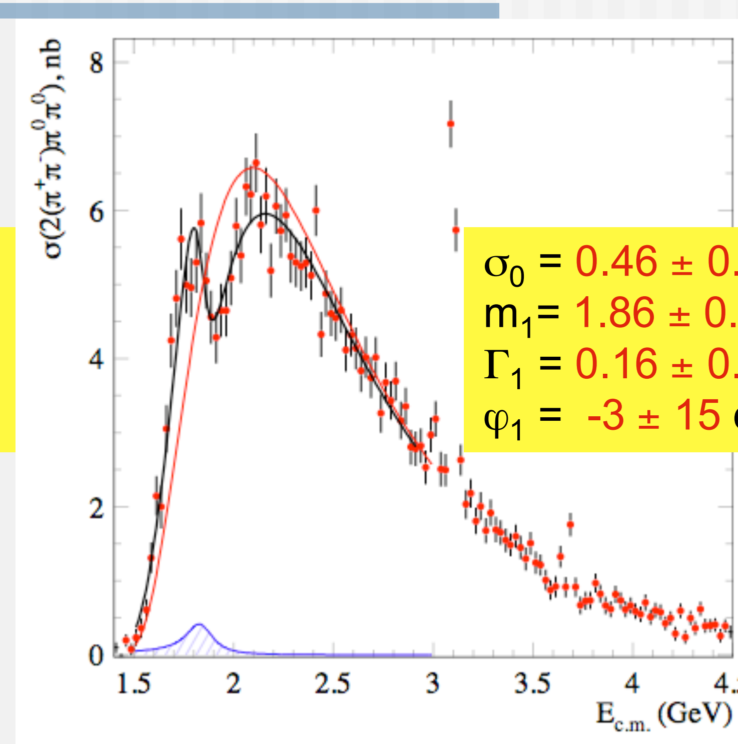
$$W(s,x,\theta) = \frac{\alpha}{\pi x}\left(\frac{2-2x+x^2}{\sin^2\theta} - \frac{x^2}{2}\right),\quad x = \frac{2E_\gamma}{\sqrt{s}}$$



Cross section fit for $3(\pi^+\pi^-)$, $2(\pi^+\pi^-)\pi^0\pi^0$



σ_0 = 0.12 ± 0.03 nb
m_1= 1.88 ± 0.05 GeV/c²
Γ_1 = 0.13 ± 0.03 GeV
φ_1 = 21 ± 40 deg.



σ_0 = 0.46 ± 0.10 nb
m_1= 1.86 ± 0.02 GeV/c²
Γ_1 = 0.16 ± 0.02 GeV
φ_1 = -3 ± 15 deg.

Cross section is described as:
(N.N.Achasov, hep-ph/9609216)

$$\sigma\left(e^+e^- \to V_1 + V_2\right) = \frac{4\pi\alpha^2}{s^{3/2}}\left(\frac{g m_1^2 e^{i\varphi}}{m_1^2 - s - i\sqrt{s}\Gamma_1} + A_{V_1}(s)\right)^2$$

$$A_{V_1}(s) = c_0 + c_1 \frac{e^{\frac{-\beta}{\sqrt{s}-m_0}}}{(\sqrt{s}-m_0)^{2-\alpha}}$$

A_{V1} - Jacob-Slansky model for the continuum.

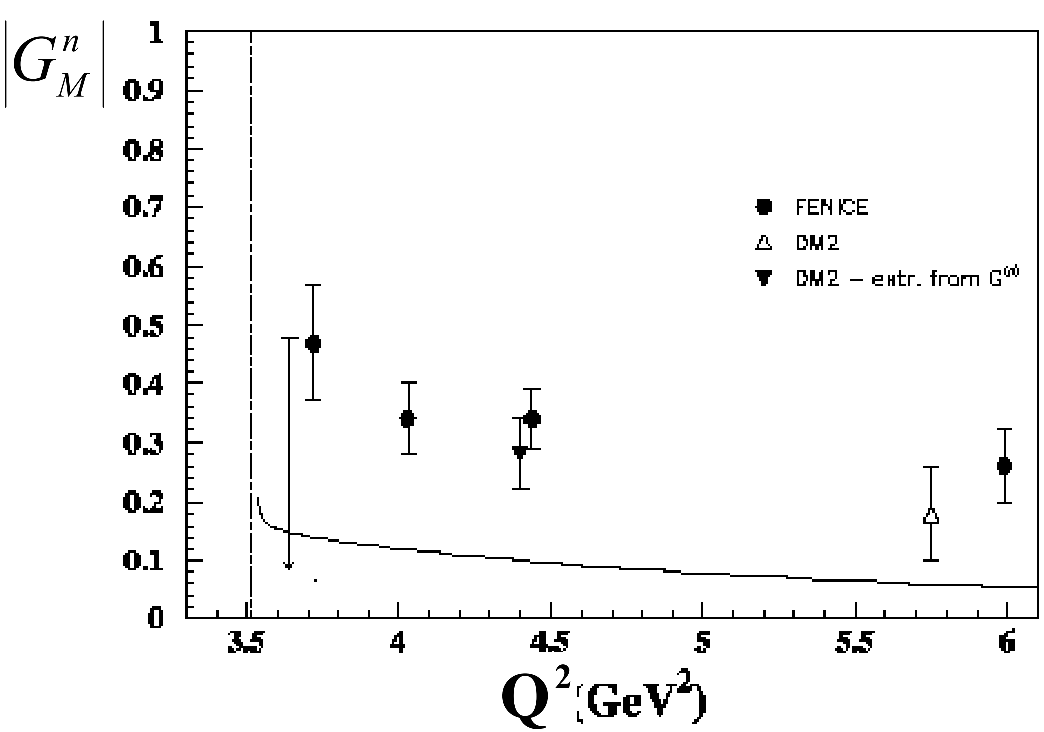
The dip is not well described by single BW !

Neutron Timelike Form Factor

Only one measurement:
FENICE at ADONE

$$1.9 < \sqrt{s} < 2.55 \quad GeV$$

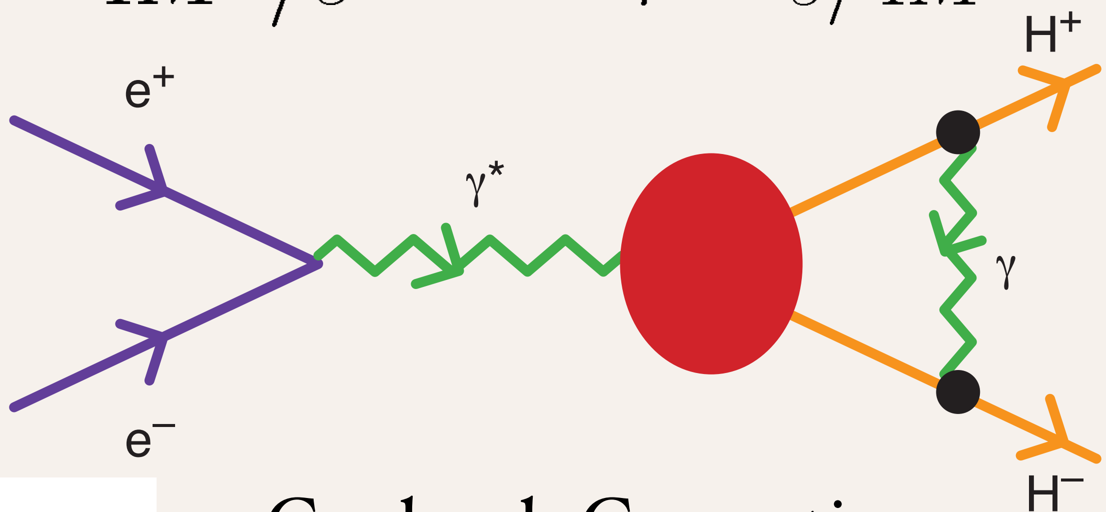
$$\int Ldt = 0.4\ pb^{-1}$$ 80 events



The neutron form factor is bigger than that of the proton !!!

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

$$\beta = \sqrt{1 - 4M^2/s} \qquad \tau = s/4M^2$$



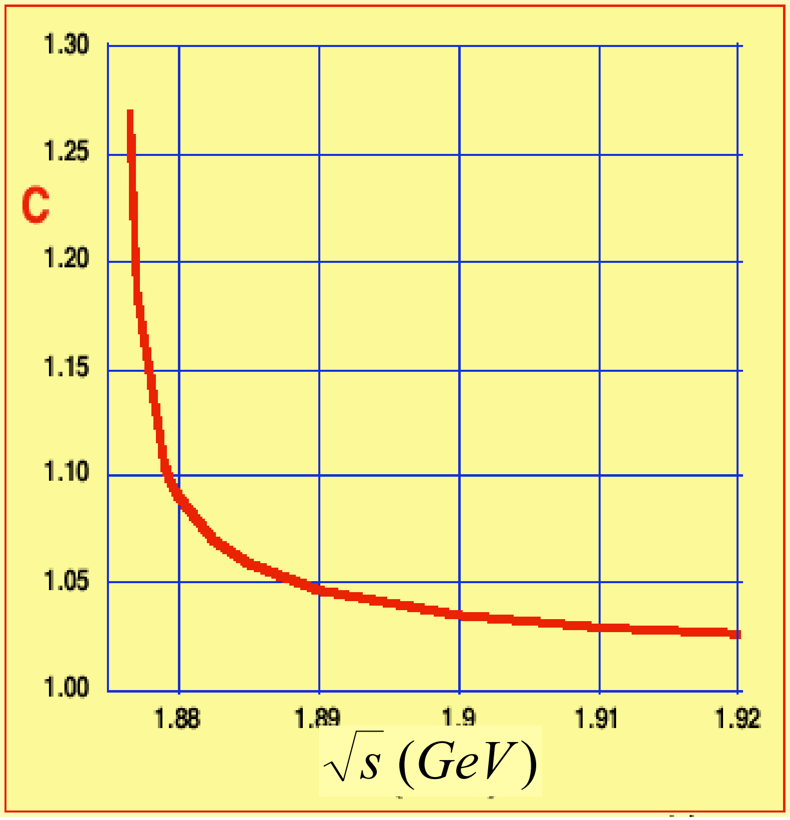
Coulomb Correction

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

Sommerfeld, Schwinger

C is the Coulomb correction factor, taking into account the QED coulomb interaction. Important at threshold.

$$\boxed{C = \frac{1}{1 - e^{-y}}} \qquad y = \frac{\pi \alpha M_N}{\beta \sqrt{s}}$$



$$C \xrightarrow[s \text{®} 4M_N^2]{} \text{®}\ \frac{1}{\beta} \quad \Rightarrow \quad \underline{\sigma \text{ finite}}$$

$$\boxed{\sigma\left(4M_N^2\right) = \frac{\pi^2 \alpha^3}{4M_N^2} \left| G_E(4M_N^2) \right|^2 \approx 0.1\, nb}$$

There is no Coulomb correction in the neutron case.