Nucleon-Delta electromagnetic form factors

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In collaboration with M. T. Peña

Electromagnetic structure of hadrons: annihilation and scattering processes - GDR-PH-QCD, Meeting Groupe 2

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1. Spectator quark model

2. $\gamma^* N \to \Delta$ reaction
   - Form factors
   - Dalitz decay

3. Nucleon form factors in timelike region

4. Conclusions

Motivation and goals

- Study the reaction $\gamma^* N \to R$ (or $R \to \gamma^* N$)
  - spacelike region ($q^2 < 0$)
  - timelike region ($q^2 > 0$)

$R = \Delta, ...$

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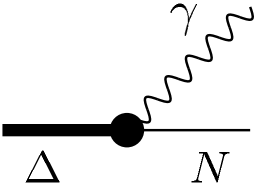
Framework: quark model $\oplus$ effective pion cloud

Kinematics $(\gamma^* N \to \Delta)$



Δ rest frame

$$P_\Delta = (W,0,0,0); \quad P_N = (E_N,0,0,-|\mathbf{q}|); \quad q = (\omega,0,0,|\mathbf{q}|)$$

Timelike $q^2 > 0$

$$\omega = \frac{W^2 - M^2 + q^2}{2W}$$

$$|\mathbf{q}|^2 = \frac{[(W+M)^2 - q^2][(W-M)^2 - q^2]}{4W^2}$$

$$E_N = \frac{W^2 + M^2 - q^2}{2W}$$

Spacelike $Q^2 > 0$

$$\omega = \frac{W^2 - M^2 - Q^2}{2W}$$

$$|\mathbf{q}|^2 = \frac{[(W+M) + Q^2][(W-M)^2 + Q^2]}{4W^2}$$

$$E_N = \frac{W^2 + M^2 + Q^2}{2W}$$

TL: $q^2 \leq (W-M)^2$

$\gamma^* N \to \Delta$ transition form factors

$\gamma N \to \Delta$:

$$J^\mu = \bar{u}_\beta(P_+) \left[G_1 q^\beta \gamma^\mu + G_2 q^\beta P^\mu + G_3 q^\beta q^\mu - G_4 g^{\beta\mu} \right] \gamma_5 u(P_-)$$

u_β Rarita-Schwinger spinor   3 independent form factors

$$q_\mu J^\mu = 0 \Rightarrow G_4 = (M_\Delta + M_N) G_1 + \tfrac{1}{2}(M_\Delta^2 - M_N^2) G_2 - Q^2 G_3$$

$$G_M^* = \tfrac{M_N}{3(M_N+M_\Delta)} \left\{ \left[(3M_\Delta + M_N)(M_\Delta + M_N) + Q^2\right] \frac{G_1}{M_\Delta} + (M_\Delta^2 - M_N^2) G_2 - 2Q^2 G_3 \right\}$$

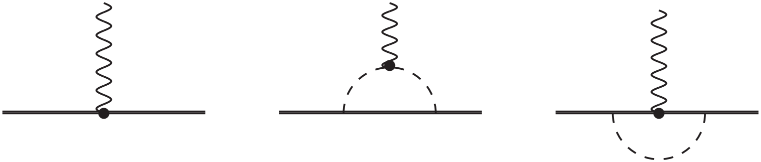
$$G_E^* = \tfrac{M_N}{3(M_N+M_\Delta)} \left\{ (M_\Delta^2 - M_N^2 - Q^2) \frac{G_1}{M_\Delta} (M_\Delta^2 - M_N^2) G_2 - 2Q^2 G_3 \right\}$$

$$G_C^* = \tfrac{M_N}{3(M_N+M_\Delta)} \left\{ 4M_\Delta G_1 + (3M_\Delta^2 + M_N^2 + Q^2) G_2 + 2(M_\Delta^2 - M_N^2 - Q^2) G_3 \right\}$$

Dalitz decay

$$|G_T(Q^2; M_\Delta)|^2 = |G_M^*(Q^2; M_\Delta)|^2 + 3|G_E^*(Q^2; M_\Delta)|^2 - \frac{Q^2}{2M_\Delta^2} |G_C^*(Q^2; M_\Delta)|^2$$

$\gamma^* N \to \Delta$: electromagnetic interaction



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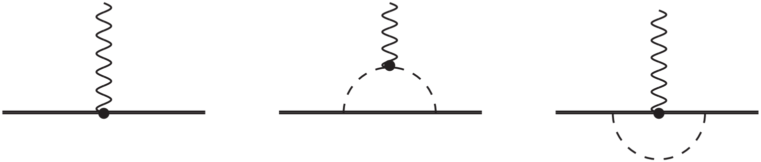

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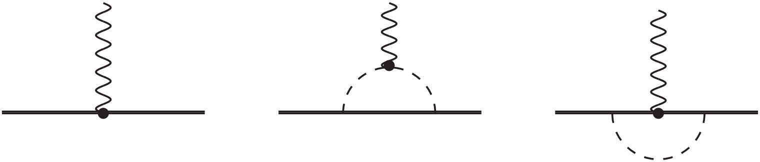

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separation is model deppendent ...

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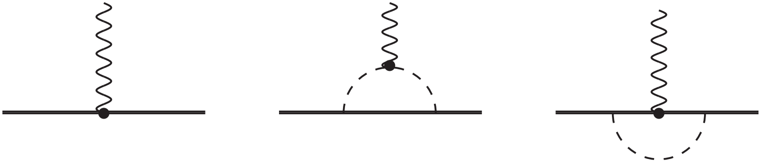

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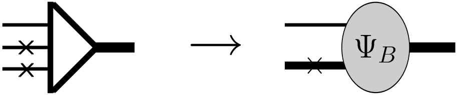
separation is model deppendent ...
but dependence can be reduced using lattice QCD data
[for large m_π only $G_X^\pi \approx 0$]

Spectator QM: wave functions

- Baryons as a qqq system F. Gross, GR and M. T. Peña: PRC 77, 015202 (2008); PRD 85, 093005 (2012)



[spectator framework] system with 2 on-shell q and a off-shell quark
$\Rightarrow$ qq pair replaced by a *effective* diquark with mass m_D

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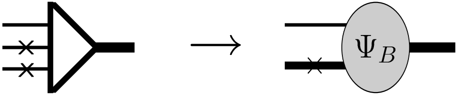

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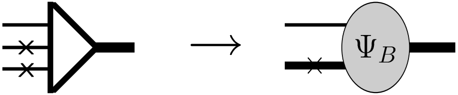

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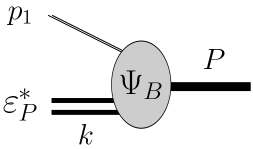
  $B =$ **diquark** $\oplus$ **quark**

$$\Psi_B = \sum \text{(color)} \otimes \text{(flavor)} \otimes \text{(spin)} \otimes \text{(orbital)} \otimes \underbrace{\psi_B(P,k)}_{\text{radial}}$$



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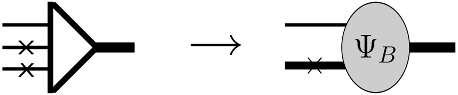

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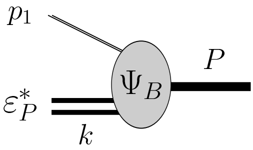


- Phenomenological radial wf ψ_B (momentum scale parameters)

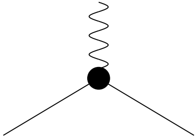
Spectator QM: quark current (VMD at quark level)

- Constituent quarks (quark form factors)

$$
\begin{aligned}
j_I^\mu &= \left[\frac{1}{6} f_{1+} + \frac{1}{2} f_{1-} \tau_3\right] \gamma^\mu + \\
&\quad \left[\frac{1}{6} f_{2+} + \frac{1}{2} f_{2-} \tau_3\right] \frac{i\sigma^{\mu\nu} q_\nu}{2M_N}
\end{aligned}
$$

quark-antiquark

$\oplus$ gluon dressing



Quarks with anomalous magnetic moments κ_u, κ_d

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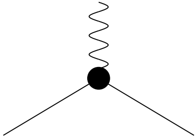

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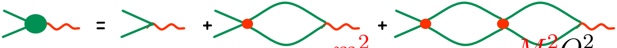
- Vector meson dominance parameterization: PRC77 015202 (2008)



$$f_{1\pm} = \lambda_q + (1-\lambda_q)\frac{m_v^2}{m_v^2+Q^2} + c_\pm\frac{M_h^2 Q^2}{(M_h^2+Q^2)^2}$$

$$f_{2\pm} = \kappa_\pm\left\{d_\pm\frac{m_v^2}{m_v^2+Q^2} + (1-d_\pm)\frac{M_h^2}{M_h^2+Q^2}\right\}$$

Poles: $m_v = m_\rho$ and $M_h = 2M_N$ (short range): Parameters $\Longleftarrow$ Nucleon

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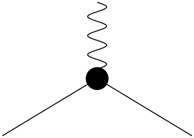

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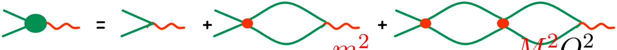

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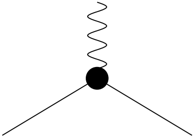

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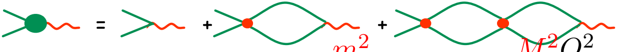

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- Parametrization can be generalized for $\neq$ regimes: lattice, nuclear med.
- Timelike regime: $Q^2 = -q^2$; $m_\rho \to m_\rho - i\frac{\Gamma_\rho}{2}$

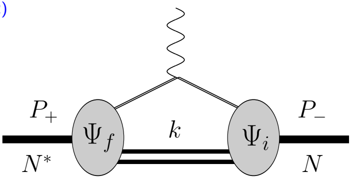
Quark current j_I^μ $\bigoplus$ Baryon wave function $\Psi_B \Rightarrow J^\mu$

Transition current J^μ in spectator formalism

Gross et al PR 186 (1969); PRC 45, 2094 (1992)

Gross, GR and Peña, PRC77 015202 (2008); PRD D85, 093005 (2012)

Relativistic impulse approximation:



$$J^\mu = 3 \sum_\lambda \int_k \bar{\Psi}_f(P_+,k) j_I^\mu \Psi_i(P_-,k)$$

diquark on-shell

$$q = P_+ - P_-, \qquad P = \tfrac{1}{2}(P_+ + P_-), \qquad Q^2 = -q^2$$

Spacelike: $\gamma^* N \to \Delta$, G_M^*, S-states

- Model with S-wave for the nucleon (N) and Δ: $G_E^* = G_C^* = 0$
  GR, MT Peña and F Gross EPJ A36, 329 (2008)

$$G_M^B(Q^2) = \frac{8}{3\sqrt{3}} \frac{M}{M+W} f_v \int_k \psi_\Delta \psi_N,$$

where

$$f_v = f_{1-} + \frac{W+M}{2M} f_{2-}$$

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- **Quark degrees of freedom insuficient to explain data !!**
  $\int_k \psi_\Delta \psi_N \big|_{Q^2=0} \leq 1 \Rightarrow G_M^B(0) \leq 2.07$;

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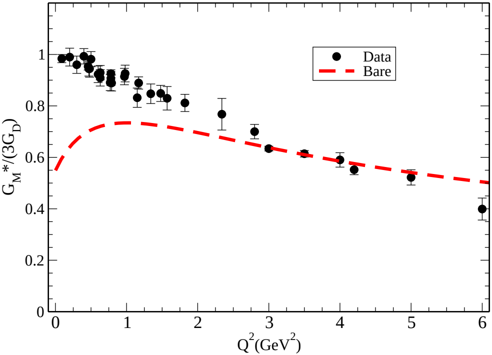
  Classical problem:
  Sato and Lee, PRC 63, 055201 (2001); Kamalov et al, PRC 64, 032201 (2001)

Spacelike: G_M^* (valence)

GR and MT Peña PRD 80, 013008 (2009) - $G_D = \left(1 + \frac{Q^2}{0.71}\right)^{-2}$



- Valence quark model underestimates the **data** ...

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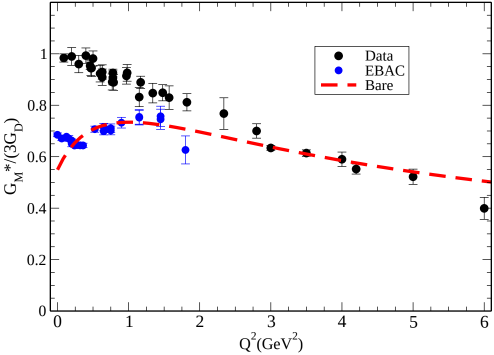


- Valence quark model ≈ EBAC/Jlab (pion cloud removed)

Spacelike: G_M^* (pion cloud)

Including pion cloud ...

GR, M. T. Peña and F. Gross, EPJA 36, 329 (2008)

$$G_M^* = G_M^B + G_M^\pi$$

large Q^2 (pQCD): $G_M^\pi \propto 1/Q^8$

Phenomenologic parametrization of the pion cloud component

$$G_M^\pi = \lambda_\pi (3 G_D) \left(\frac{\Lambda_\pi^2}{\Lambda_\pi^2 + Q^2} \right)^2$$

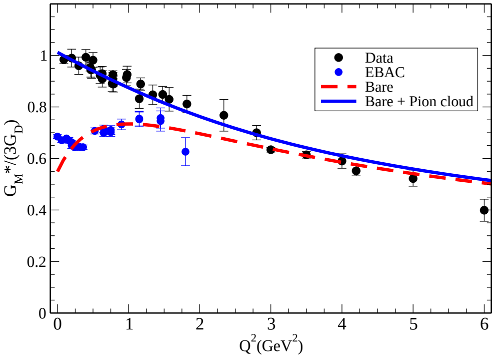
λ_π : strength of pion cloud (% of π cloud at $Q^2 = 0$) $\lambda_\pi = 0.44$

$G_D = \left(\frac{\Lambda_N^2}{\Lambda_N^2 + Q^2} \right)^2$, $\Lambda_N^2 = 0.71$ GeV^2: dipole form factor

Λ_π^2: pion cloud cutoff (≈ 1.5 GeV^2)

Spacelike: G^*_M (valence + pion cloud) [phenomenological]

GR and MT Peña PRD 80, 013008 (2009)



- Bare ≈ EBAC model $\oplus$ $G_M^\pi = \lambda_\pi \left(\frac{\Lambda_\pi^2}{\Lambda_\pi^2 + Q^2} \right)^2 (3G_D)$ $\qquad \frac{G_M^B(0)}{3G_D} \leq 0.7$

Spacelike: Δ with D states

Δ wave function: EPJA 36, 329 (2008); PRD 78, 114017 (2008); PRD 80, 013008 (2009)

$$\Psi_\Delta = N\left[\Psi_S + a\Psi_{D3} + b\Psi_{D1}\right]$$

$$S = 0 \oplus \frac{3}{2}, \quad D3 = 2 \oplus \frac{3}{2}, \quad D1 = 2 \oplus \frac{1}{2}$$

$$\begin{aligned} G_M^* &\Leftarrow S, D3, D1 \\ G_E^* &\Leftarrow D3, D1 \\ G_C^* &\Leftarrow D1 \end{aligned}$$

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- S-state: G_M^* fited to EBAC data – PRD 78, 114017 (2008)
  EBAC: **Diaz et al PRC 75, 015205 (2007)** Fixes G_M^π

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- S-state: G_M^* fited to EBAC data – PRD 78, 114017 (2008)
  EBAC: **Diaz et al PRC 75, 015205 (2007)** Fixes G_M^π
- D-states: G_E^*, G_C^* fited to lattice data (only valence quark effects)
  PRD 80, 013008 (2009) D-states $\approx 1\%$

Spacelike: Extension for lattice

GR and MT Peña, JPG 36, 115011 (2009)

- Quark current (VMD): $j_I^\mu = j_1 \gamma^\mu + j_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_N}$

  $j_I^\mu(M_N; m_\rho, M_h = 2M_N) \to j_I^\mu(M_N^{latt}; m_\rho^{latt}, 2M_N^{latt})$
- Wave functions:
  $\Psi_B(\{M_B\}) \to \Psi_B(\{M_B^{latt}\})$

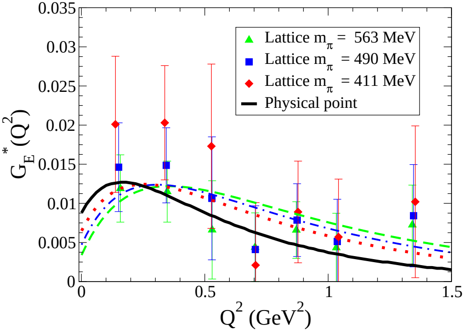
$\Rightarrow$ Implicit m_π dependence in G_X [Form factors]

- For large m_π: $G_X^\pi \approx 0$
- G_X given only by G_X^B (valence quark)
- G_X^B can be compared with lattice (or fited)

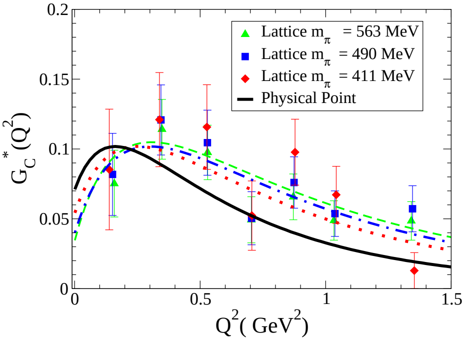
Spacelike: $G_E^*(Q^2)$, $G_C^*(Q^2)$ on lattice [PRD 80, 013008 (2009)]

Fit to lattice QCD data (bare contribution) -small D-state

Alexandrou et al, PRD, 77, 085012 (2008)

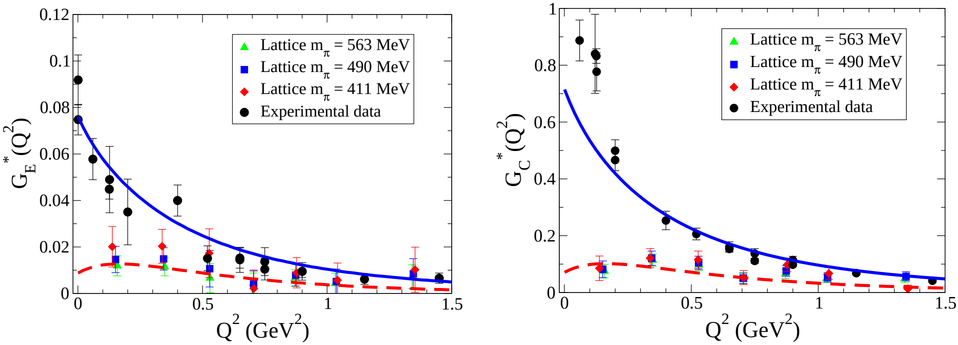


D3 state: 0.72%



D1 state: 0.72%

Spacelike: $G_E^*(Q^2)$, $G_C^*(Q^2)$ (bare + pion cloud) †

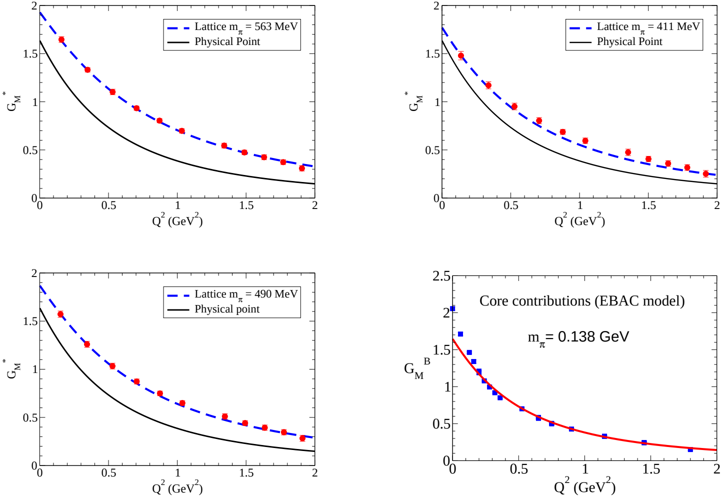


Small valence quark contributions (physical limit)

Important pion cloud contributions (Large N_c; no parameters)

GR, MT Peña PRD 80, 013008 (2009)

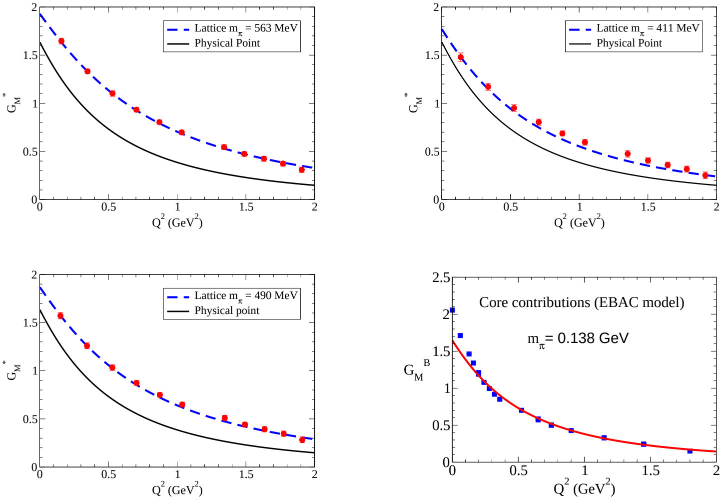
Spacelike: $G_M^*(Q^2)$ on lattice [PRD 80, 013008 (2009)]



Lattice: Alexandrou et al, PRD 77, 085012 (2008)

$\oplus$ EBAC: J. Diaz et al, PRC 75, 015205 (2007)

Spacelike: $G_M^*(Q^2)$ on lattice [PRD 80, 013008 (2009)]



Fit to EBAC; Lattice: S-state $\oplus$ $\mathcal{O}$(D-states)

$\Rightarrow$: G_M^*(lattice) is a prediction (negleting D-states)

Spacelike $\gamma^* N \to \Delta$: Summary

- Model developed for the nucleon and Δ **on-shell** systems
- Valence quark contributions
  - constrained by EBAC results (baryons's core)
  - consistent with lattice data
    for different baryon masses (function of m_π)
- **S-state is the dominate effect** $G_E^* = G_C^* = 0$
- **Pion cloud contribution** constrainined by physical data:
  $G_M^\pi(Q^2; W) = G_M^\pi(Q^2; M_\Delta)$ (independent of M)

Timelike: Extension for timelike [PRD 85, 113014 (2012)]

- Valence quark model applied for $q^2 = -Q^2$ and $M_\Delta \to W$;

$$\frac{m_\rho^2}{m_\rho^2 - q^2} \to \frac{m_\rho^2}{m_\rho^2 - q^2 - i m_\rho \Gamma_\rho}$$

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- Include $\rho-$width (2π cut): Gounaris and Sakurai, PRL 21, 244 (1968)

$$\Gamma_\rho(q^2) = \Gamma_\rho^0 \left(\frac{q^2 - 4m_\pi^2}{m_\rho^2 - 4m_\pi^2} \right)^{3/2} \frac{m_\rho}{q} \theta(q^2 - 4m_\pi^2)$$

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- Pion cloud?

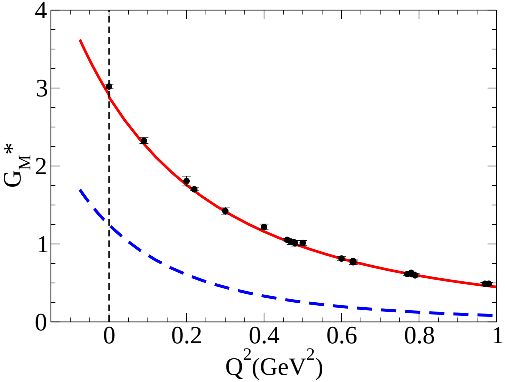
$$G_M^\pi(q^2) = \lambda_\pi (3 G_D) \left(\frac{\Lambda_\pi^2}{\Lambda_\pi^2 - q^2} \right)^2$$

$$G_D(q^2) = \left(\frac{\Lambda_N^2}{\Lambda_N^2 - q^2 - i\Gamma_N \Lambda_N} \right)^2, \qquad \Gamma_N \equiv \Gamma_\rho$$

Naive model (unphysical pole $q^2 = 0.71$ GeV^2): model 1

Timelike: G_M^* for $W = M_\Delta$ (Real part)

S-state approximation $[G_E^* = G_C^* = 0]$ $Q^2 \geq -(W-M)^2$



— — — Bare; —— Total

Timelike: Extension for timelike (2) - Model 1

- Why use G_D for $q^2 < 0$?

$$G_M^\pi(q^2) = \lambda_\pi (3 G_D) \left(\frac{\Lambda_\pi^2}{\Lambda_\pi^2 - q^2} \right)^2$$

Timelike: Extension for timelike (2) - Model 1

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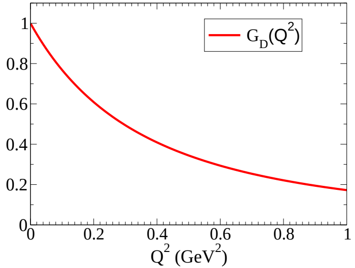
- G_D included for $q^2 < 0$, to provide an extra falloff



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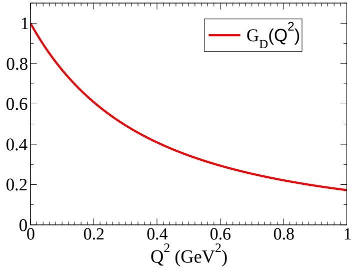

- Unphysical singularity on G_D

- Alternative function: ρ-propagator with pion cloud
  F. Iachello and Q. Wan, PRC 69, 055204 (2004) for $q^2 \gg 4m_\pi^2$:

$$F_\rho(Q^2) = \frac{m_\rho^2}{m_\rho^2 + Q^2 + \frac{1}{\pi}\frac{\Gamma_\rho^0}{m_\pi} Q^2 \log \frac{Q^2}{m_\pi^2}}$$

$\Gamma_\rho^0 = \Gamma_\rho(m_\rho^2)$ decay constant

Timelike: Extension for timelike (3)

- Alternative function: ρ-propagator with pion cloud
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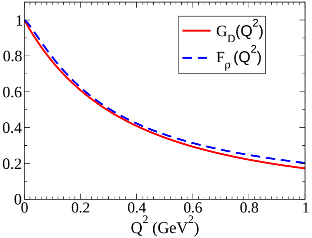
  $\Gamma_\rho^0 = \Gamma_\rho(m_\rho^2)$ decay constant
- F_ρ provide an **extra** falloff for $q^2 < 0$



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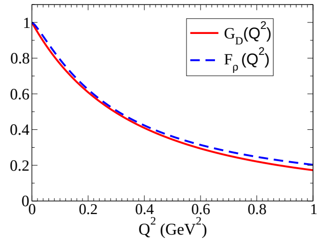

- **Include explicit effect of pion cloud dressing**

Timelike: Extension for timelike (4) - Model 2

- Model 2: ($\simeq$ Model 1 in SL)

$$G_M^{\pi}(q^2) = \lambda_\pi (3F_\rho) \left(\frac{\Lambda_\pi^2}{\Lambda_\pi^2 - q^2} \right)^2$$

- Model 2: ($\simeq$ Model 1 in SL)

$$G_M^\pi(q^2) = \lambda_\pi (3F_\rho) \left(\frac{\Lambda_\pi^2}{\Lambda_\pi^2 - q^2} \right)^2$$

- For $q^2 > 0$

$$F_\rho(q^2) = \frac{m_\rho^2}{m_\rho^2 - q^2 - \frac{1}{\pi} \frac{\Gamma_\rho^0}{m_\pi} q^2 \log \frac{q^2}{m_\pi^2} + i \frac{\Gamma_\rho^0}{m_\pi} q^2}$$

Timelike: Extension for timelike (4) - Model 2

- Model 2: ($\simeq$ Model 1 in SL)

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- Simulates pion cloud dressing (include in F_ρ)

Timelike: Extension for timelike (4) - Model 2

- Model 2: ($\simeq$ Model 1 in SL)

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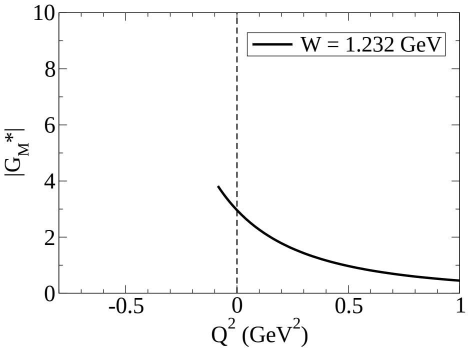
- Simulates pion cloud dressing (include in F_ρ)
- No unphysical singularities

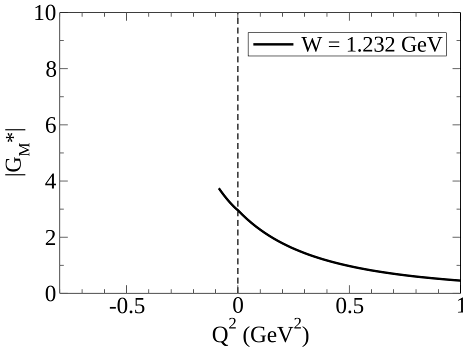
Timelike: $|G_M^*|$ [PRD 85, 113014 (2012)]

Models defined only for $Q^2 \geq -(W-M)^2$

Model 1

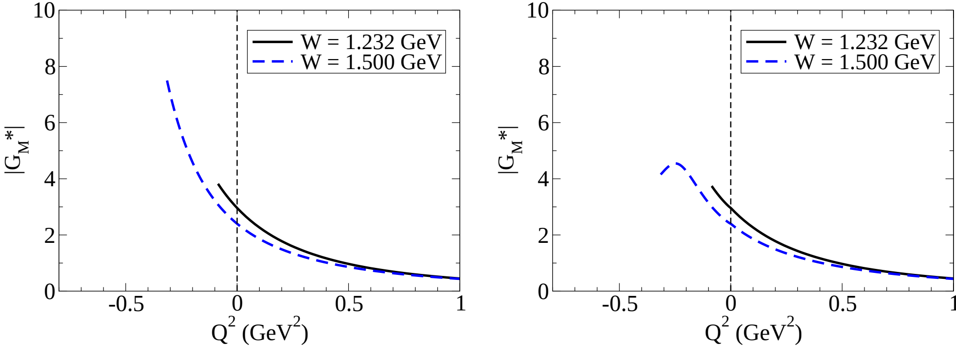


Model 2



Models defined only for $Q^2 \geq -(W-M)^2$

Model 1 | Model 2



Timelike: $|G_M^*|$ [PRD 85, 113014 (2012)]

Models defined only for $Q^2 \geq -(W-M)^2$

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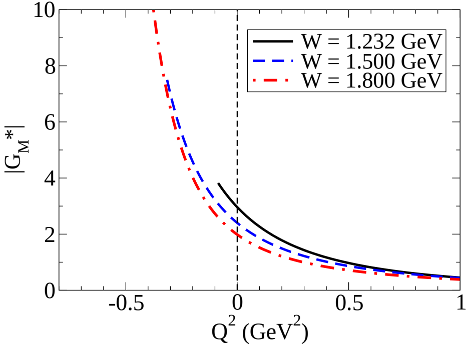
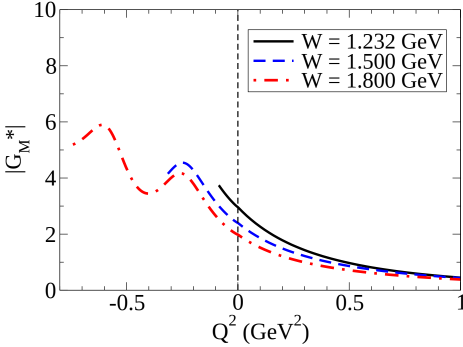
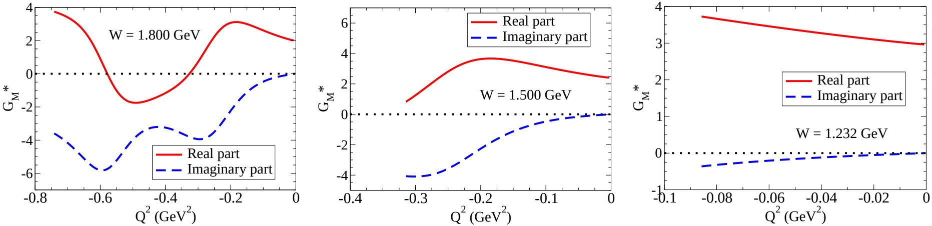


Model 2



Model for $Q^2 \geq -(W-M)^2$ GR and M. T. Peña, PRD 85, 113014 (2012)

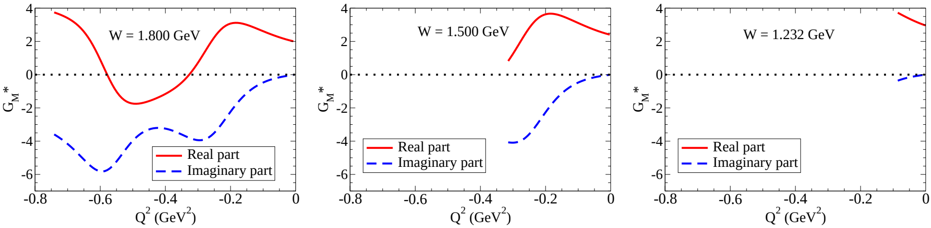


$$G_M^*(Q^2;W) = \underbrace{G_M^B(Q^2;W)}_{\text{VMD}} + \underbrace{G_M^\pi(Q^2)}_{\propto F_\rho}$$

$$G_M^B(Q^2;W) = \frac{8}{3\sqrt{3}}\frac{M}{M+W} f_v \int_k \psi_\Delta \psi_N, \qquad G_M^\pi(Q^2) = 3\lambda_\pi F_\rho \left(\frac{\Lambda_\pi^2}{\Lambda_\pi^2 - q^2}\right)^2$$

Timelike: Form factors G_M^* - Model 2 (2)

Model for $Q^2 \geq -(W-M)^2$ GR and M. T. Peña, PRD 85, 113014 (2012)



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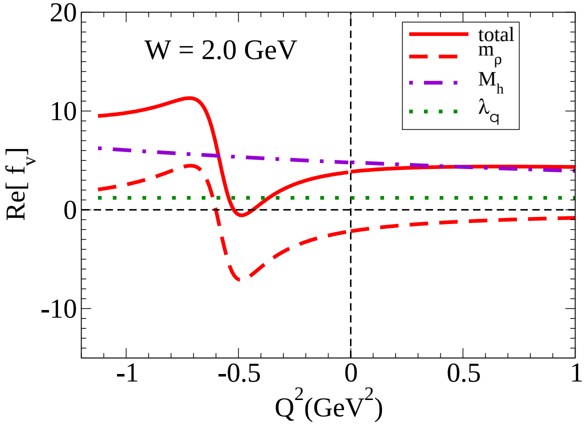
Timelike: VMD structure; f_v

$$G_M^B(Q^2) = \frac{8}{3\sqrt{3}} \frac{M}{M+W} f_v \int_k \psi_\Delta \psi_N \qquad f_v = f_{1-} + \frac{W+M}{2M} f_{2-}$$



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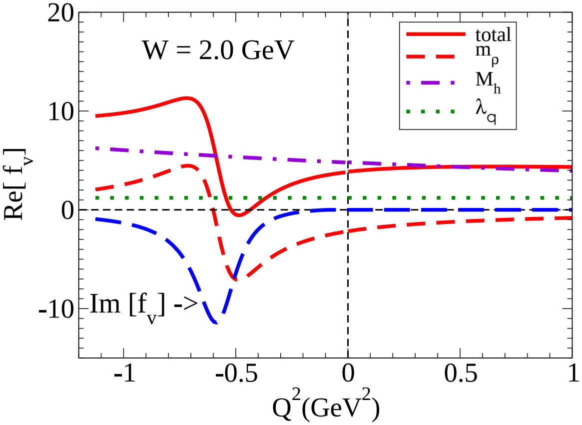
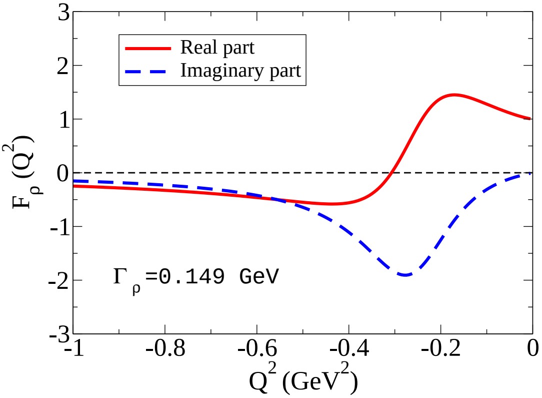


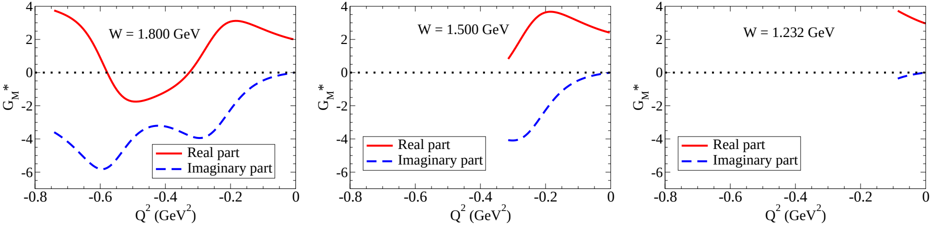
Timelike: Pion cloud structure; F_ρ

$$G_M^\pi(Q^2) = 3\lambda_\pi F_\rho \left(\frac{\Lambda_\pi^2}{\Lambda_\pi^2 - q^2} \right)^2 \qquad F_\rho(q^2) = \frac{m_\rho^2}{m_\rho^2 - q^2 - \frac{1}{\pi}\frac{\Gamma_\rho^0}{m_\pi} q^2 \log \frac{q^2}{m_\pi^2} + i \frac{\Gamma_\rho^0}{m_\pi} q^2}$$



Timelike: Form factors G_M^* - Model 2

GR and M. T. Peña, PRD 85, 113014 (2012)



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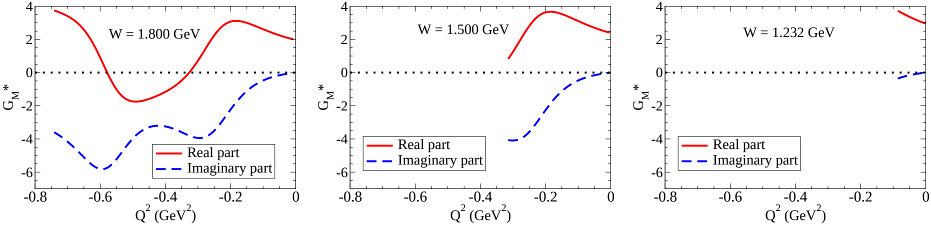

- Dominance of $Re(G_M^*)$ for small q^2

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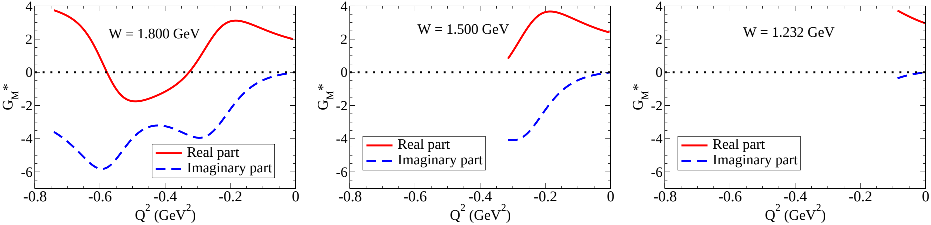
GR and M. T. Peña, PRD 85, 113014 (2012)



- Dominance of $Re(G_M^*)$ for small q^2
- Peak for $Im(G_M^*)$ near $q^2 \simeq 0.3$ GeV^2 (pion cloud)

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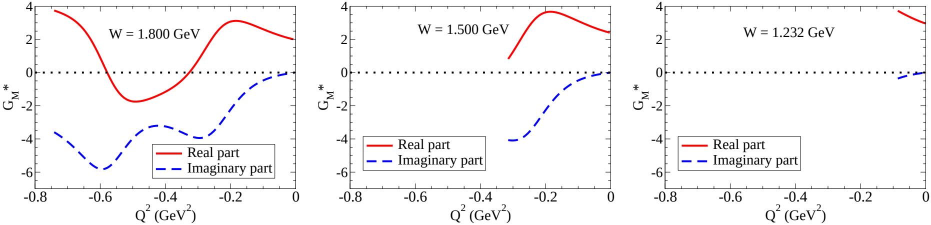

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- Peak for $Im(G_M^*)$ near $q^2 \simeq m_\rho^2$ (valence quark)

Dalitz decay: $g_\Delta(W)$ and $\Gamma(W)$

G. Wolf et al., NPA 517, 615 (1990)

- Calculation of **Breit-Wigner** mass distribution of $\Delta(1232)$

$$g_\Delta(W) = A \frac{W^2 \Gamma_{tot}(W)}{(W^2 - M_\Delta^2)^2 + W^2 [\Gamma_{tot}(W)]^2}$$

$$\Gamma_{tot}(W) = \Gamma_{\pi N}(W) + \Gamma_{\gamma N}(W) + \Gamma_{e^+e^- N}(W)$$

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- Dominant process $\Delta \to \pi N$ $\left[\nu(W) = \frac{\beta^2}{\beta^2 + q_\pi^2(W)}\right]$

$$\Gamma_{\pi N}(W) = \frac{M_\Delta}{W} \left(\frac{q_\pi(W)}{q_\pi(M_\Delta)} \right)^3 \left(\frac{\nu(W)}{\nu(M_\Delta)} \right)^2 \Gamma_{\pi N}^0$$

Dalitz decay: $g_\Delta(W)$ and $\Gamma(W)$

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- $\Gamma_{\gamma N}$ and $\Gamma_{e^+e^- N}$ calculated using the model for $\Delta \to \gamma^* N$

Dalitz decay: $\Gamma_{\gamma N}(W)$ and $\Gamma_{e^+e^-N}(W)$

- Width function $\Gamma_{\gamma^* N}(q;W)$ with $q = \sqrt{q^2}$
  $y_\pm = (W \pm M)^2 - q^2$
  F. Dohrmann et al, EPJA 45, 401 (2010) $\alpha \simeq 1/137$

$$\Gamma_{\gamma^* N}(q;W) = \frac{\alpha}{16} \frac{(W+M)^2}{M^2 W^3} \sqrt{y_+ y_-} y_- |G_T(q^2,W)|^2$$

$$|G_T(q^2;M_\Delta)|^2 = |G_M^*(q^2;W)|^2 + 3|G_E^*(q^2;W)|^2 + \frac{q^2}{2W^2}|G_C^*(q^2;W)|^2$$

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- Then

$$\Gamma_{\gamma N}(W) \equiv \Gamma_{\gamma^* N}(0;W)$$

$$\Gamma_{e^+e^-N}(W) = \frac{2\alpha}{3\pi}\int_{2m_e}^{W-M}\Gamma_{\gamma^* N}(q;W)\frac{dq}{q}$$

threshold: $2m_e$ ($\gamma^* \to e^+e^-$); upper limit $q^2=(W-M)^2$

Dalitz decay: $\Gamma_{\gamma N}(W)$ and $\Gamma_{e^+e^-N}(W)$

- Width function $\Gamma_{\gamma^* N}(q;W)$ with $q = \sqrt{q^2}$
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- Then

$$\Gamma_{\gamma N}(W) \equiv \Gamma_{\gamma^* N}(0;W)$$

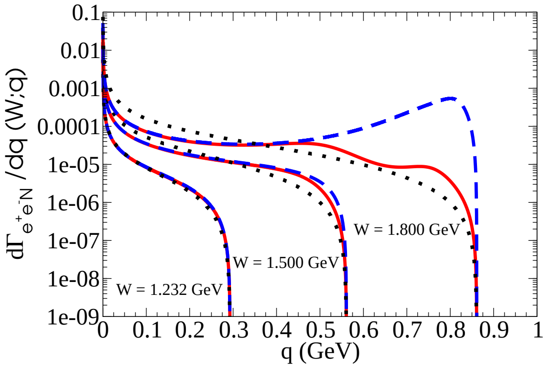
$$\Gamma_{e^+e^-N}(W) = \frac{2\alpha}{3\pi}\int_{2m_e}^{W-M} \Gamma_{\gamma^* N}(q;W)\frac{dq}{q}$$

  threshold: $2m_e$ ($\gamma^* \to e^+e^-$); upper limit $q^2 = (W-M)^2$

- $|G_M^*|^2$ model $\Rightarrow$ model for $\Gamma_{\gamma N}$ and $\Gamma_{e^+e^-N}$

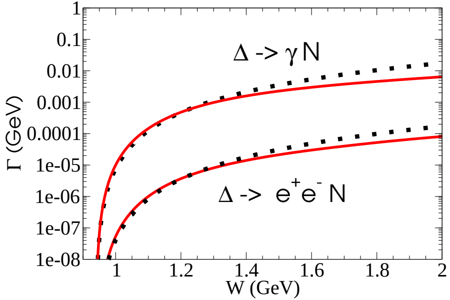
Dalitz decay: models

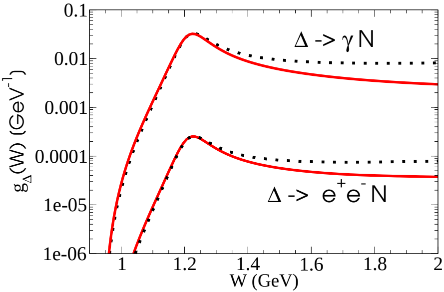
- Constant form factor model: $G_M^*(q^2; W) \equiv G_M^*(0, M_\Delta)$
  M. Zetenyi and G. Wolf, PRC 67, 044002 (2003);
  F. Dohrmann et al, EPJA 45, 401 (2010)
- Two-component quark model (core/pion cloud decomposition)
  F. Iachello and Q. Wan, PRC 69, 055204 (2004);
  R. Bijker and F. Iachello, PRC 69, 068201 (2004);
  F. Dohrmann et al, EPJA 45, 401 (2010)
- Vector meson dominance
  M. I. Krivoruchenko, et at., Annals Phys. 296, 299 (2002)
- **Spectator quark model**



· · · const; — — — Model 1; —— Model 2

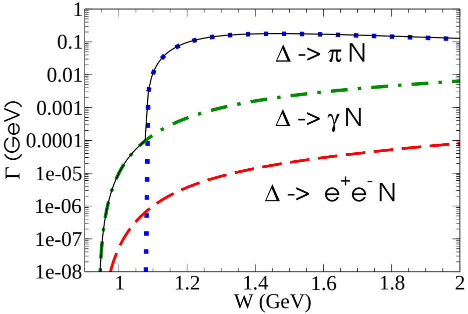
Dalitz decay: $\Gamma(W)$, $g_\Delta(W)$

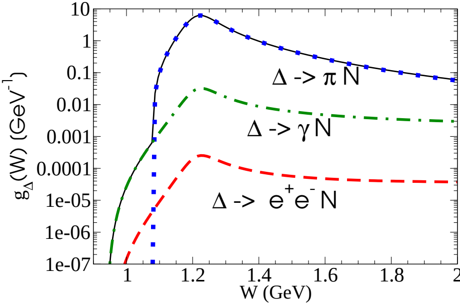




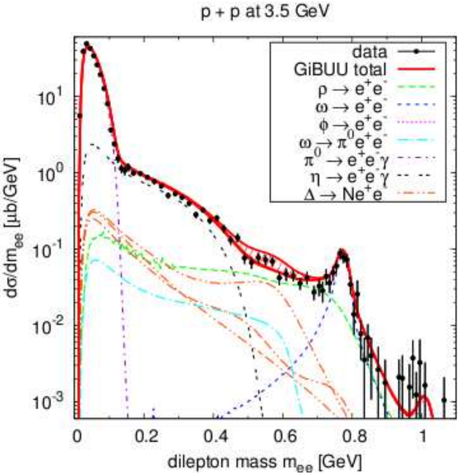
$\cdots$ const; —— Model 2

Dalitz decay: $\Gamma(W)$, $g_\Delta(W)$ - Model 2 (with πN) †





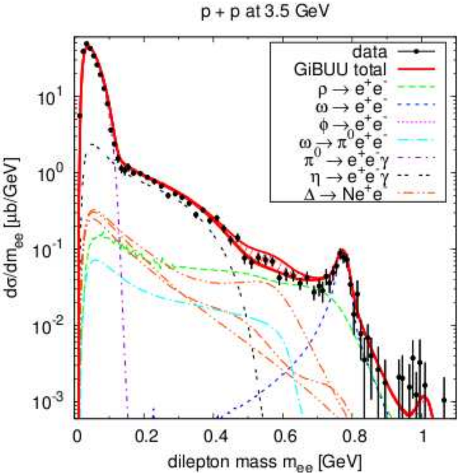
Dalitz decay: cross-section (GiBUU model)



Courtesy of Janus Weil

Model from J. Weil, H. van Hees and U. Mosel, EPJA 48, 111 (2012)

Dalitz decay: cross-section (GiBUU model)



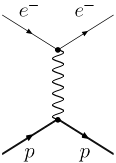
$\Delta \to \gamma^* N$ models very important for 0.4 GeV $< q = m_{ee} <$ 0.7 GeV

Model from J. Weil, H. van Hees and U. Mosel, EPJA 48, 111 (2012)

Nucleon form factors (1)

$$J^\mu = F_1(Q^2)\gamma^\mu + F_2(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M}$$

Spacelike

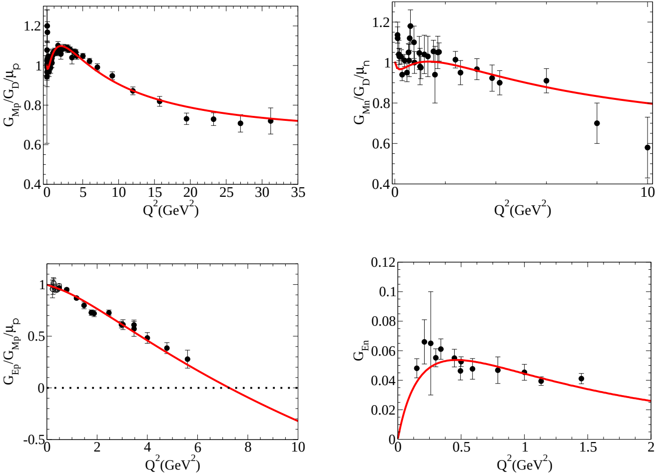


$q^2 \leq 0$

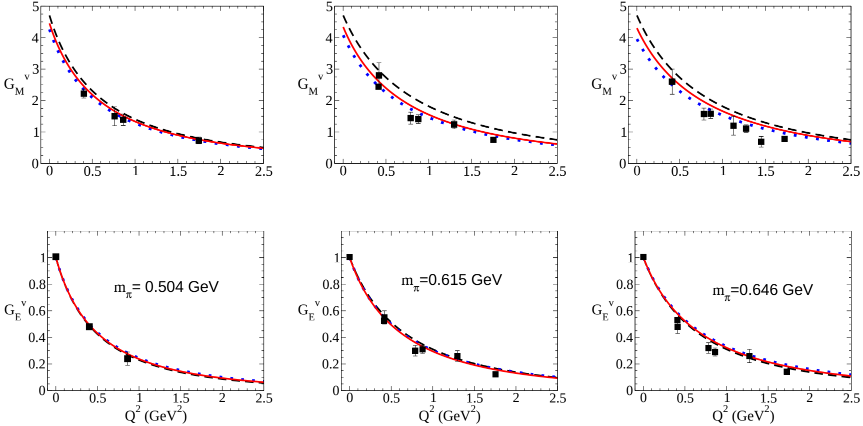
Nucleon SL form factors

F Gross, GR and MT Peña, PRC 77, 015202 (2008) – model II – **No pion cloud**

Nucleon form factors: $G_E = F_1 - \tau F_2$, $G_M = F_1 + F_2$; $\tau = \frac{Q^2}{4M_N^2}$



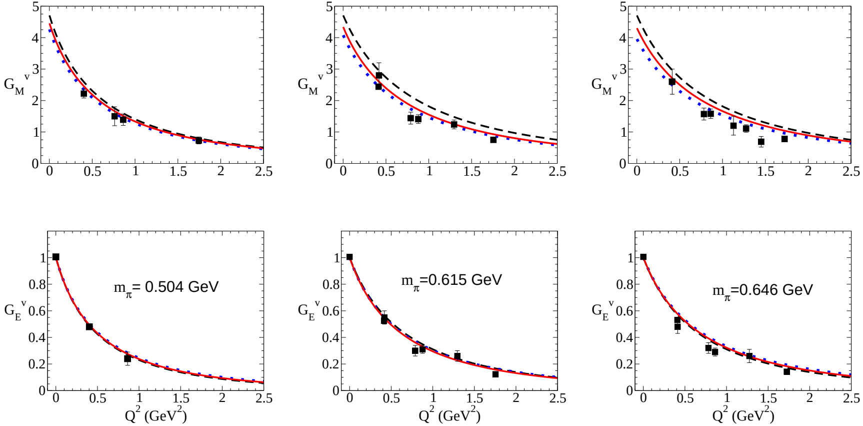
Nucleon SL form factors in lattice G_E^v, G_M^v



- - - - GR and M. T. Peña, JPG 36, 15011 (2009)

Data: Göckeler et al, PRD 71, 034508 (2005)

Nucleon SL form factors in lattice G_E^v, G_M^v



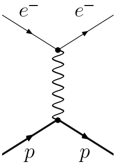
- - - - Description of lattice data (no refit)

Model valid for **physical** and **lattice** regimes (no pion cloud)

Nucleon form factors (2)

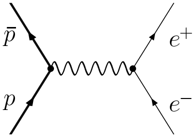
$$J^\mu = F_1(Q^2)\gamma^\mu + F_2(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M}$$

Spacelike



$q^2 \leq 0$

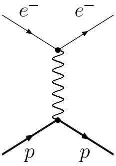
Timelike



$q^2 \geq 4M^2$

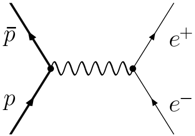
$$J^\mu = F_1(Q^2)\gamma^\mu + F_2(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M}$$

Spacelike



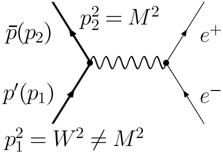
$q^2 \le 0$

Timelike



$q^2 \ge 4M^2$

Unphysical



$4m_e^2 \le q^2 \le 4M^2$

Nucleon form factors in timelike region $[0 < q^2 < 4M^2]$

Unphysical form factors: $4m_e^2 < q^2 < 4M^2$ can be accessed by:

- $\gamma N \to e^+ e^- N$, $\pi N \to e^+ e^- N$
  Schäfer, Dönges and Mosel, PLB 342, 13 (1995);
  Dieperink and Nagorny, PLB 397, 20 (1997)
- $NN \to e^+ e^- NN$
  Schäfer, Dönges, Engel and Mosel, NPA 575, 429 (1994)
- $\bar{N}N \to e^+ e^- \pi$
  Gakh, Gustafsson, Dbeyssi and Gakh, PRC 86, 025204 (2012)

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Comments:

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Comments:

- It is necessary to define **off-shell** form factors (extra parameters ...)
- Nucleon form factors contributions are mixed with other processes
  (Bethe-Heitler mechanism, Virtual Compton Scattering, higher resonances, ...)
- Two-photon exchange effects negleted in 1st approximation

Models:

- **Vector meson dominance:** (FF as combination of VM poles)

  Iachello, Jackson and Landé, PLB 43, 191 (1973); Gari and Krümpelmann PLB 274, 159 (1992); Lomon, PRC 64, 035204 (2001); Gustafsson, Lacroix, Duterte and Gakh EPJA 24, 419 (2005); Krivorunchenko and Martemyanov, Ann. Phys. 296, 299 (2002)

  Analytical extension for $q^2 \geq 4M^2$; Interpolation for $0 < q^2 < 4M^2$

- **Dispersion Analysis** (using Dispersion Relations)

  Frazer and Fulco PR 117, 1609 (1960); Mergell, Meißner and Drechsel, NPA 596 (1996); Hammer and Meißner, EPJA 20, 469 (2004)

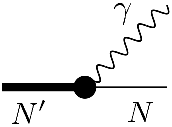
$$F_i(q^2) = \frac{1}{\pi} \int_{t_0}^{\infty} dq' \frac{\mathrm{Im} F_i(q'^2)}{q'^2 - q^2}$$

t_0 threshold deppendent of the channel (isoscalar/isovector)

Spectral function $\mathrm{Im}(F_i)$ for $q^2 > 0$ (TL) $\Leftrightarrow$ FF for $q^2 < 0$ (SL)

Alternative Model:

- N' **as a** qqq **system with mass** W **(on-shell)**



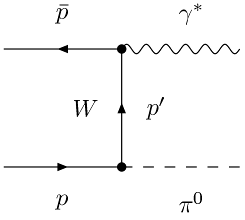
$0 \leq q^2 \leq (W - M)^2$

analytical continuation of **baryon wave functions** and **quark currents** (follow extension to lattice regime)

- **Calculate of form factors:**
  $G_E(Q^2; W)$, $G_M(Q^2; W)$ for the region $0 \leq q^2 \leq (W - M)^2$
  (analogous to the $\gamma^* N \to \Delta$ calculations)

Unphysical nucleon form factors $[0 < q^2 \leq (W - M)^2]$

Reaction $\bar{p}p \to \pi^0 \gamma^*$



Intermediate p with mass W (vertex $p' \to p\gamma^*$)

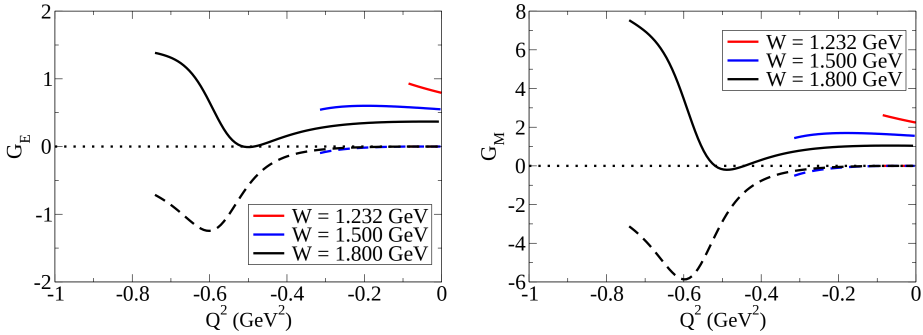
$$J^\mu = F_1^*(Q^2)\left(\gamma^\mu - \frac{\not{q} q^\mu}{q^2}\right) + F_2^*(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{M + W}$$

$$G_+(Q^2) \equiv \left\langle N', +\frac{1}{2}\middle| \epsilon^{(+)} \cdot J \middle| N, -\frac{1}{2}\right\rangle \propto \overbrace{F_1^*(Q^2) + F_2^*(Q^2)}^{G_M}$$

$$G_0(Q^2) \equiv \left\langle N', +\frac{1}{2}\middle| \epsilon^{(0)} \cdot J \middle| N, +\frac{1}{2}\right\rangle \propto \underbrace{F_1^*(Q^2) - \frac{Q^2}{(M+W)^2}F_2^*(Q^2)}_{G_E}$$

Nucleon timelike form factors (preliminary)

Proton Extension of Model II/ PRC77 015202 (2008)

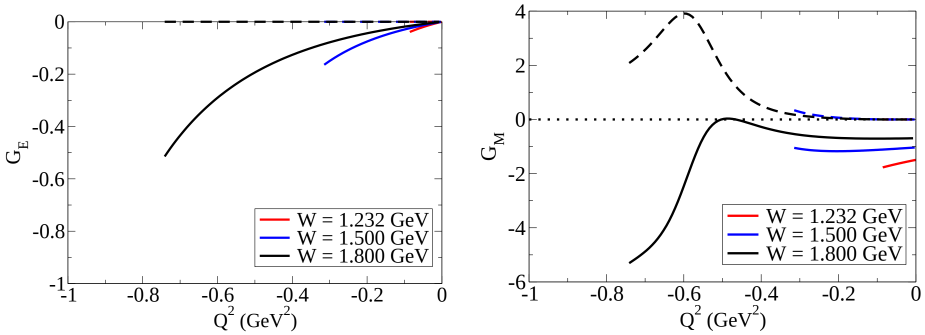


Real (solid); Imaginary (dashed)

Model with **no pion cloud**

Nucleon timelike form factors (preliminary)

Neutron Extension of Model II/ PRC77 015202 (2008)



Real (solid); Imaginary (dashed)

Model with **no pion cloud**

Conclusions

- **Spectator QM**: valence quark model $\oplus$ **effective** meson cloud
  Model applied to the study of $\gamma^* N \to R$ in the timelike region $q^2 > 0$
  Nucleon and R as qqq on-shell systems

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  - very rich structure in TL regime
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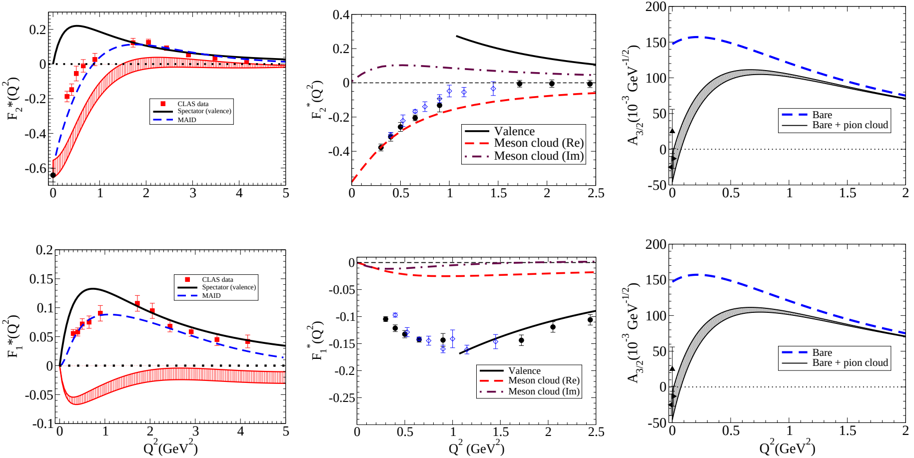
- Possible extension to the nucleon unphysical form factors
  $\gamma^* N \to N'$ (on-shell mass W)
- Formalism can be extended to other resonances:
  $N^*(1440), N^*(1535), \Delta(1600)$,
  depending of the pion cloud component
  [$\Delta(1232)$ system very well constrained]

$N^*(1440), N^*(1535), \Delta(1600)$ form factors

$N^*(1440)$ $\qquad$ $N^*(1535)$ $\qquad$ $\Delta(1600)$



Selected bibliography (part 1)

- **Timelike $\gamma^* N \to \Delta$ form factors and Delta Dalitz decay**,
  G. Ramalho and M. T. Pena, Phys. Rev. D **85**, 113014 (2012)
  [arXiv:1205.2575 [hep-ph]].
- **A pure S-wave covariant model for the nucleon**,
  F. Gross, G. Ramalho and M. T. Peña, Phys. Rev. C **77**, 015202 (2008)
  [arXiv:nucl-th/0606029].
- **A covariant formalism for the N^* electroproduction at high momentum transfer**,
  G. Ramalho, F. Gross, M. T. Peña and K. Tsushima,
  Exclusive Reactions and High Momentum Transfer IV, 287 (2011)
  [arXiv:1008.0371 [hep-ph]].
- **A Covariant model for the nucleon and the Δ**,
  G. Ramalho, M. T. Peña and F. Gross, Eur. Phys. J. A **36**, 329 (2008)
  [arXiv:0803.3034 [hep-ph]].

Selected bibliography (part 2)

- **D-state effects in the electromagnetic $N\Delta$ transition**, G. Ramalho, M. T. Peña and F. Gross, Phys. Rev. D **78**, 114017 (2008) [arXiv:0810.4126 [hep-ph]].
- **Nucleon and $\gamma N \to \Delta$ lattice form factors in a constituent quark model**, G. Ramalho and M. T. Peña, J. Phys. G **36**, 115011 (2009) [arXiv:0812.0187 [hep-ph]].
- **Valence quark contribution for the $\gamma N \to \Delta$ quadrupole transition extracted from lattice QCD**, G. Ramalho and M. T. Peña, Phys. Rev. D **80**, 013008 (2009) [arXiv:0901.4310 [hep-ph]].
- **Electromagnetic form factors of the Δ with D-waves**, G. Ramalho, M. T. Pena and F. Gross, Phys. Rev. D **81**, 113011 (2010) [arXiv:1002.4170 [hep-ph]].

Selected bibliography (part 3)

- **Valence quark contributions for the $\gamma N \to P_{11}(1440)$ form factors**,
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  [arXiv:1002.3386 [hep-ph]].
- **A model for the $\Delta(1600)$ resonance and $\gamma N \to \Delta(1600)$ transition**,
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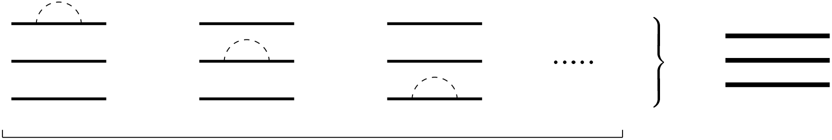
  [arXiv:1008.3822 [hep-ph]].
- **A covariant model for the $\gamma N \to N(1535)$ transition at high momentum transfer**,
  G. Ramalho and M. T. Pena, Phys. Rev. D **84**, 033007 (2011)
  [arXiv:1105.2223 [hep-ph]].
- **Valence quark and meson cloud contributions for the $\gamma^* \Lambda \to \Lambda^*$ and $\gamma^* \Sigma^0 \to \Lambda^*$ reactions**,
  G. Ramalho, D. Jido and K. Tsushima, Phys. Rev. D **85**, 093014 (2012)
  [arXiv:1202.2299 [hep-ph]].

Selected bibliography (part 4)

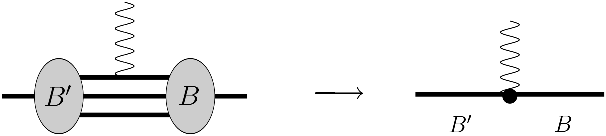
- **Octet baryon electromagnetic form factors in a relativistic quark model**
  G. Ramalho and K. Tsushima, Phys. Rev. D **84**, 054014 (2011) [arXiv:1107.1791 [hep-ph]].
- **Octet baryon electromagnetic form factors in nuclear medium**, G. Ramalho, K. Tsushima and A. W. Thomas, arXiv:1206.2207 [hep-ph].
- **Covariant nucleon wave function with S, D, and P-state components**, F. Gross, G. Ramalho and M. T. Pena, Phys. Rev. D **85**, 093005 (2012) [arXiv:1201.6336 [hep-ph]].

More ...

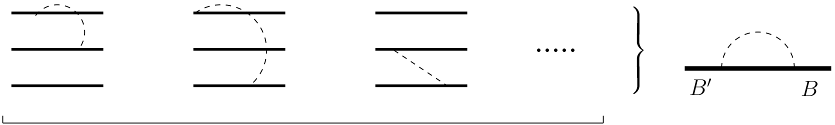
Backup slides



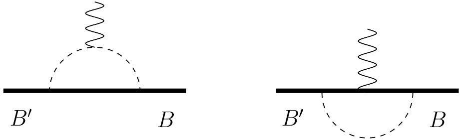
γ coupling:



Quark structure and electromagnetic interaction (II)



γ coupling:



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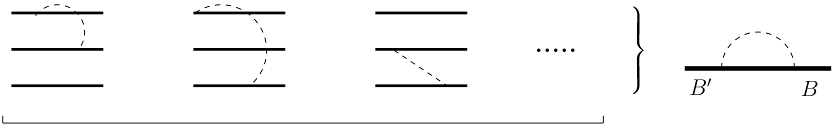

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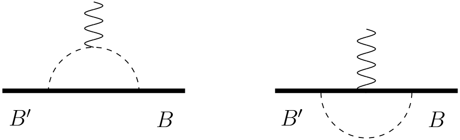
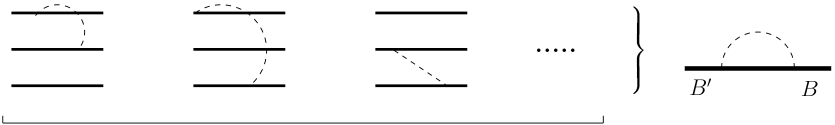


- Not important at high Q^2 [pQCD: supression $1/Q^4$],
  Very important at low Q^2



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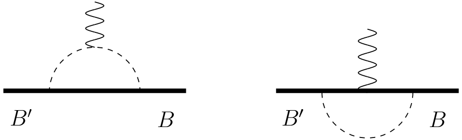

- Not important at high Q^2 [pQCD: supression $1/Q^4$],
  Very important at low Q^2
- Assume NO interference with quark dressing processes

$$F = F^B + F^{mc}$$

(bare $\oplus$ meson cloud)