Covariant quark model calculations of nucleon resonance transition form factors and more

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In collaboration with:
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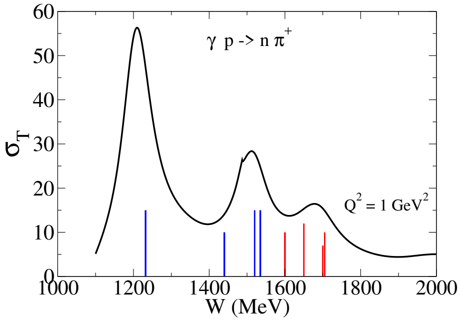
APCTP Workshop on Nuclear Physics 2022:
Physics of Excited Hadrons in the Present and Future Facilities

[1] **OMEG**: **O**rigin of **M**atter and **E**volution of **G**alaxies

Motivation (nucleon resonances)



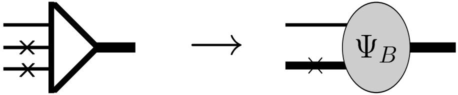
- New accurate data from modern accelerators (JLab, MAMI, ELSA, MIT-Bates ...) associated with N^* states with increasing W (1.4–1.8 GeV) and large Q^2 (2–6 GeV^2)
- $\Rightarrow$ **New challenges**:
  - Interpret the data $\leftrightarrow$ Theory $\leftrightarrow$ relativistic models
  - Make predictions: higher W, higher Q^2 – **JLab-12 GeV–upgrade**

Plan of the talk

- **Theoretical framework**
  Covariant Spectator Quark Model
- **Calculations of N^* transition form factors at large Q^2**
  $\Delta(1232)\frac{3}{2}^+$, $N(1440)\frac{1}{2}^+$, $N(1535)\frac{1}{2}^-$, $N(1520)\frac{3}{2}^-$, $\Delta(1600)\frac{3}{2}^+$
  $N(1650)\frac{1}{2}^-$, $N(1700)\frac{3}{2}^-$, $\Delta(1620)\frac{1}{2}^-$, $\Delta(1700)\frac{3}{2}^-$ **[SQTM]**
  ... some results at low-Q^2
- **Extension of the model** ($SU(3)$ and nuclear medium)
- **Summary and conclusions**

Covariant Spectator Quark Model – Introduction (1)

- Baryon as qqq systems
- Covariant Spectator Theory: wf Ψ_B defined in terms of a 3-quark vertex: system with 2 on-shell quarks and an off-shell quark



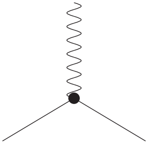
$\Longrightarrow$ qq pair replaced by an *effective* diquark with mass m_D

Gross and Agbakpe PRC 73, 015203 (2006); Gross, GR and Peña PRC 77, 015202 (2008)

- $\Longrightarrow$ reduction to a quark-diquark structure: $\Psi_B(P_B, k)$
  Baryon wave function $\Psi_B(P_B, k)$ free of singularities

  Stadler, Gross and Frank PRC 56, 2396 (1998); Savkli and Gross PRC 63, 035208 (2001)
- Spin-flavor structure ≈ relativistic $SU_F(3) \times SU_S(2)$ structure
- Radial wave function $\psi_B(P_B, k)$ **determined** phenomenologically
  Not a solution of a dynamical wave equation – mass $M_B \equiv M_B^{\rm exp}$
  Shape determined by momentum scale parameters using experimental data or lattice data of some ground state systems

Covariant Spectator Quark Model – Introduction (2)

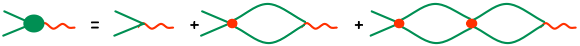


- Quarks with electromagnetic structure (**impulse approximation**)

$$j_q^\mu = \left(\frac{1}{6}f_{1+} + \frac{1}{2}f_{1-}\tau_3\right)\gamma^\mu + \left(\frac{1}{6}f_{2+} + \frac{1}{2}f_{2-}\tau_3\right)\frac{i\sigma^{\mu\nu}q_\nu}{2M_N}$$

form factors $f_{i\pm}$ parametrize dressing of quarks (gluons and $q\bar{q}$) $\kappa_q = f_{2q}(0) \approx 2$

- Vector meson dominance parameterization at quark level:



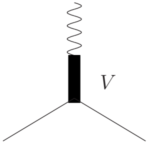
Quark current parametrized in terms of vector meson poles (m_v, M_h)

F Gross, GR, MT Peña, PRC 77, 015202 (2008); GR, MT Peña, JPG 36, 115011 (2009); PRD 80, 013008 (2009); GR, K Tsushima, AW Thomas, JPG 40, 015102 (2013); GR, K Tsushima, F Gross, PRD 80, 033004 (2009)

- 4 parameters determined by the fit to the **nucleon data**

F Gross, GR, MT Peña, PRC 77, 015202 (2008)

Covariant Spectator Quark Model – Introduction (2)



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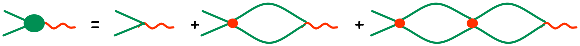

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Covariant Spectator Quark Model – Introduction (3)

Radial wave functions dependent of $(P-k)^2$= (quark momentum)^2

M_B = baryon mass; m_D = diquark mass

$$\chi_B = \frac{(M_B - m_D)^2 - (P-k)^2}{M_B m_D}$$

$$\psi_B(P,k) \propto \frac{N_B}{m_D(\beta_1 + \chi_B)(\beta_2 + \chi_B)}$$

Motivation: obtain correct large-Q^2 falloff in the LO form factors

$$G_i(Q^2) \propto \frac{1}{Q^4} \quad \text{(apart } \log Q^2 \text{ corrections)}$$

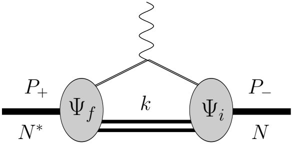
F Gross, GR, MT Peña, PRC 77, 015202 (2008); GR, MT Peña, F Gross, EPJA 36, 329 (2008)

Covariant Spectator Quark Model – Introduction (4)

- Transition current – relativistic impulse approximation

  F Gross, GR, MT Peña, PRC 77, 015202 (2008); EPJA 36, 329 (2008)

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



diquark on-shell

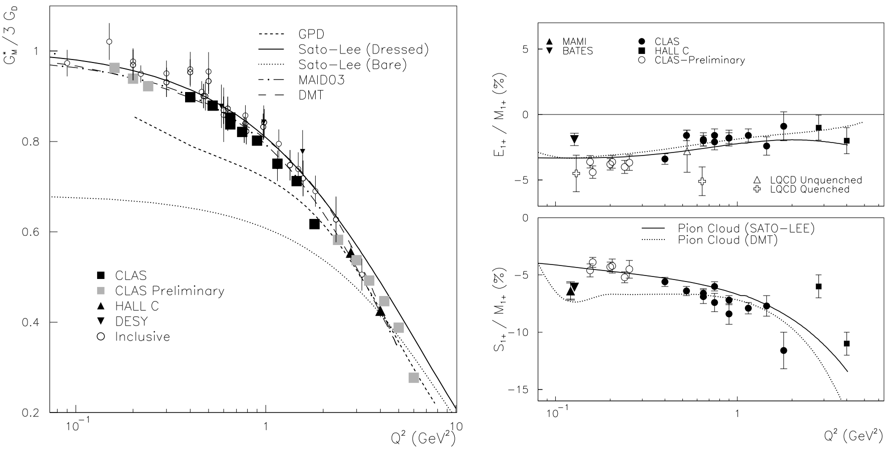
- **Generalization to lattice QCD:**
  - $f_{i\pm}(Q^2; m_\rho, M_N) \to f_{i\pm}(Q^2; m_\rho^{\rm latt}, M_N^{\rm latt})$ – VMD
  - $\psi_B(M_B) \to \psi_B(M_B^{\rm latt})$

  GR, MT Peña, JPG 36, 115011 (2009); PRD 80, 013008 (2009); GR, K Tsushima, F Gross, PRD 80, 033004 (2009); GR, K Tsushima, AW Thomas, JPG 40, 015102 (2013)

  Meson cloud neglegible for large m_π

Calculations of N^* transition form factors at large Q^2

$\gamma^* N \to \Delta(1232)$ – Introduction [Burkert and H Lee, JMP E13, 1035 (2004)]



- Transition dominated by Magnetic Dipole G^*_M: $N(\uparrow\uparrow\downarrow) \longrightarrow \Delta(\uparrow\uparrow\uparrow)$ (spin-flip)
- Small contributions from G^*_E and $\frac{|\mathbf{q}|}{2M_\Delta} G^*_C$; indication of (small) Δ deformation
  GR, MT Peña, A Stadler, PRD 86, 093022 (2012)
- G^*_M usually underestimated by quark models at small Q^2

$\Delta(1232)$ - S-wave model - covariant

$$\Psi_N = \frac{1}{\sqrt{2}} \overbrace{\left(\phi_I^0 \phi_S^0 + \phi_I^1 \phi_S^1\right)}^{SU(6)} \psi_N(P,k) \qquad \Psi_\Delta = -\overbrace{\tilde{\phi}_1^I (\varepsilon_P^*)_\alpha u^\alpha(P)}^{SU(6)} \psi_\Delta(P,k)$$

Radial wave functions: $\psi_N(P,k)$; $\psi_\Delta(P,k)$

$\psi_N(P,k)$: determined by the nucleon data;

$\psi_\Delta(P,k)$: determined by lattice QCD data or **bare core** estimate ($g_{MB_1B_2} = 0$)

Argonne-Osaka dynamical coupled-channel model (previously EBAC/Sato-Lee)

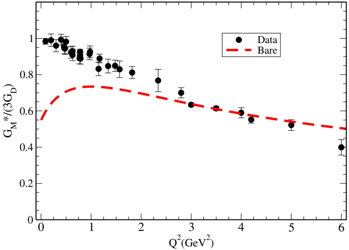
S-wave model

$$G_M^*(Q^2) = \frac{4}{3\sqrt{3}} \frac{M}{M+M_\Delta} \left(f_{1-} + \frac{M_\Delta + M}{2M} f_{2-}\right) \int_k \psi_\Delta \psi_N$$

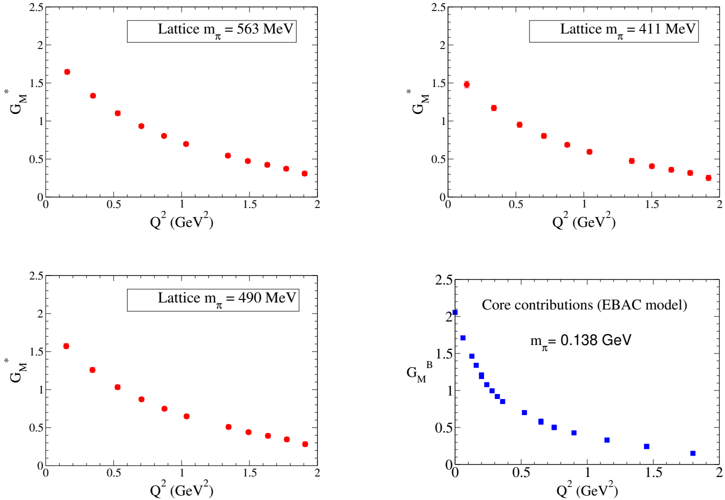
$G_M^*(0) = 2.07 \int_k \psi_\Delta \psi_N \leq 2.07$

Cauchy-Schwarz inequality

Underestimation of $G_M^*(0)|_{\rm exp} \simeq 3$

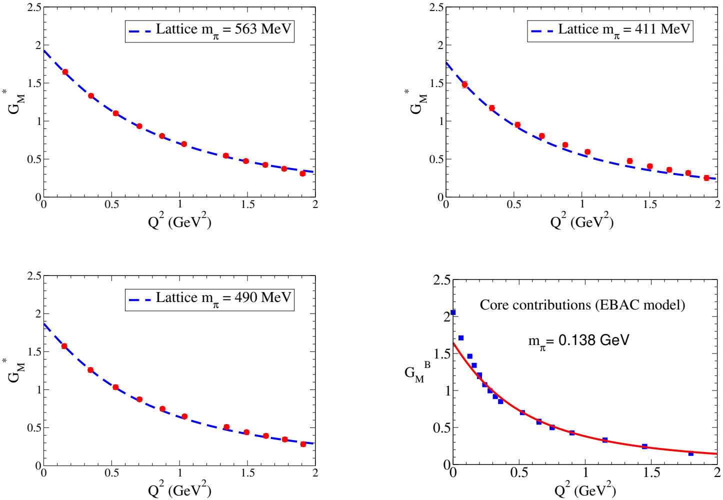


$\gamma^* N \to \Delta$: G_M^* in lattice [GR, MT Peña, PRD 80, 013008 (2009)]



- Lattice: Alexandrou et al, PRD 77, 085012 (2008) $m_\pi = 411 - 563$ MeV
- EBAC estimate: B J-Diaz, TSH Lee, T Sato, L Smith, PRC 75 015205 (2007)

$\gamma^* N \to \Delta$: G_M^* in lattice [GR, MT Peña, PRD 80, 013008 (2009)]



- — Model calibrated by **EBAC bare data**
- - - - Model extended to lattice QCD

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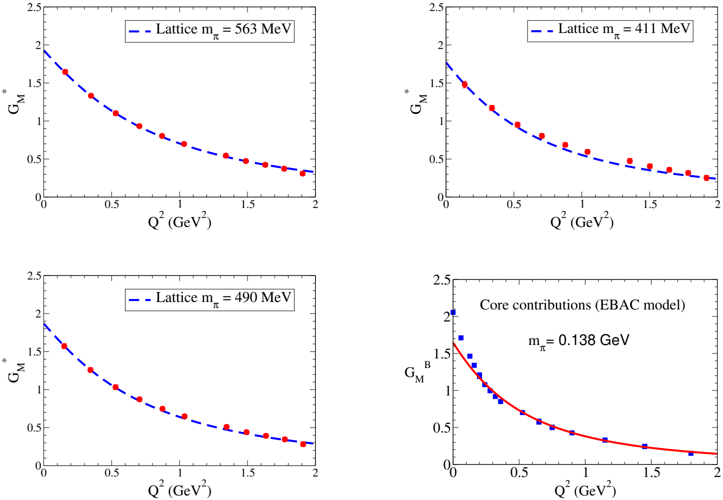
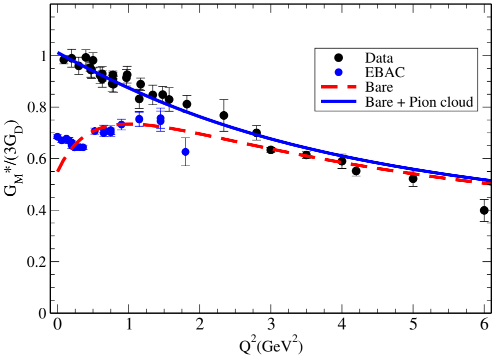


- —— Model calibrated by **EBAC bare data**
- - - - Model extended to lattice QCD **Good description** bare part

$\gamma^* N \to \Delta$: G_M^* (valence + pion cloud)



- Valence quarks insuficient to describe low Q^2 data ($G_M^B \propto 1/Q^4$)
- Include phenomenological pion cloud contribution ($G_M^\pi \propto 1/Q^8$)
  GR, MT Peña J Weil, H van Hees and U Mosel, PRD 93, 033004 (2016)

$\gamma^* N \to \Delta$: How to simulate the pion cloud? [phenomenology]

Recent application – two pion cloud contributions

Motivated by study of the **octet to decuplet transitions**: almost 50% – 50%

GR, K Tsushima, PRD 88, 053002 (2013)

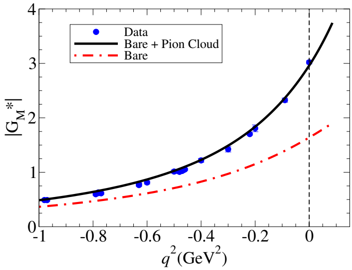
$$G_M^\pi = 3\lambda_\pi^{(a)} \underbrace{F_\pi(q^2)\left(\frac{\Lambda_\pi^2}{\Lambda_\pi^2 - q^2}\right)^2}_{\pi-\text{coupling}} + 3\lambda_\pi^{(b)} \underbrace{\left(\frac{\Lambda_D^2}{(\Lambda_D^2 - q^2)^2 + \Lambda_D^2(\Gamma_D(q^2))^2}\right)^2}_{B'-\text{coupling}}$$

GR, MT Peña J Weil, H van Hees and U Mosel, PRD 93, 033004 (2016)

$F_\pi(q^2)$: phenomenologic electromagnetic pion form factor;

$\Lambda_D^2 = 0.9$ GeV^2; $\Gamma_D(q^2)$ phenomenological width; $\lambda_\pi^{(a)}, \lambda_\pi^{(b)} \simeq 0.448$

$\gamma^* N \to \Delta$: timelike region (1) $q^2_{\max} = (M_\Delta - M_N)^2$



Timelike region $q^2 > 0$ $\uparrow$

$\Delta(1232)$ Dalitz decay

$\Delta \to \gamma^* N \to e^+ e^- N$

$\Gamma \equiv \Gamma_{\Delta \to e^+ e^- N} = \Gamma_{e^+ e^- N}$

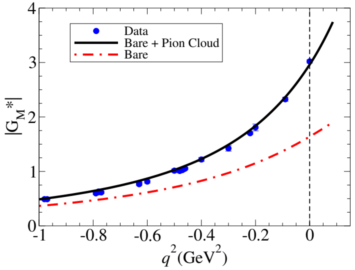
$\frac{d\Gamma}{dq} \equiv \Gamma'(q, W) =$
$A(q^2, W) |G_M(q^2, W)|^2$
(W replace M_Δ)

Delta Dalitz decay width
$\Gamma_{e^+ e^- N} = \int_{2m_e}^{W-M} \Gamma'(q, W) dq$

Model $\Gamma_{e^+ e^- N} = 4.9$ keV

GR, MT Peña J Weil, H van Hees and U Mosel, PRD 93, 033004 (2016)

$\gamma^* N \to \Delta$: timelike region (2)



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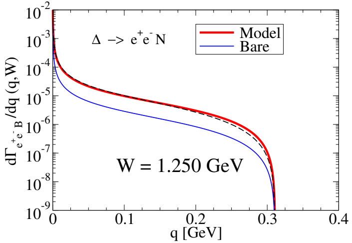

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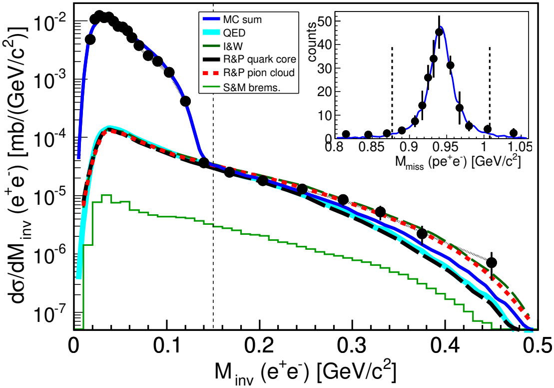
GR, MT Peña J Weil, H van Hees and U Mosel, PRD 93, 033004 (2016)

$\gamma^* N \to \Delta$: timelike region (3)

HADES, PRC 95, 065205 (2017): $pp \to p\Delta^+ \to ppe^+e^-$



Model $\cdots\cdots$ **Data** $\Gamma_{e^+e^-N} = 4.90 \pm 0.83$ keV

$\gamma^* N \to \Delta$: timelike region – Δ Dalitz decay – PDG

$\Delta(1232)$ DECAY MODES

The following branching fractions are our estimates, not fits or averages.

	Mode	Fraction (Γ_i/Γ)
Γ_1	$N\pi$	99.4 %
Γ_2	$N\gamma$	0.55–0.65 %
Γ_3	$N\gamma$, helicity=1/2	0.11–0.13 %
Γ_4	$N\gamma$, helicity=3/2	0.44–0.52 %
Γ_5	pe^+e^-	$(4.2\pm0.7)\times10^{-5}$

$\Gamma(pe^+e^-)/\Gamma_{total}$ **Γ_5/Γ**

VALUE (units 10^{-5})	*DOCUMENT ID*
$4.19\pm0.34\pm0.62$	[1] ADAMCZEW... 17

[1] The systematic uncertainty includes the model dependence.

The obtained Δ Dalitz branching ratio at the pole position is equal to 4.19×10^{-5} when extrapolated with the help of the Ramalho-Peña model [27], which is taken as the reference, since it describes the data better. The branching ratio

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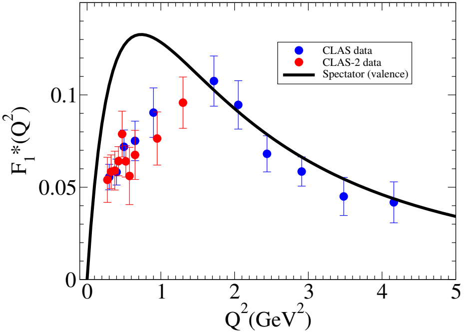
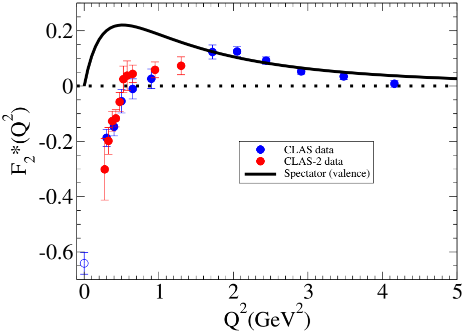
HADES is planning to measure Dalitz decay widths of hyperons

$\Sigma^{*0} \to e^+e^-\Lambda$, $\Sigma^{*+} \to e^+e^-\Sigma^+$, ...

HADES EPJA 57, 139 (2021); GR PRD 102, 054016 (2020)

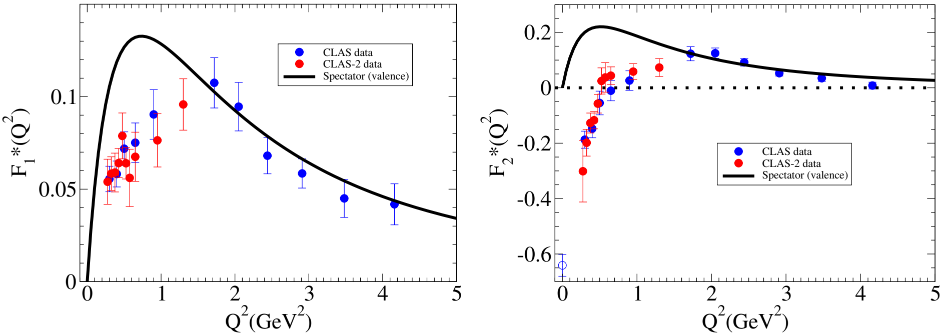
$\gamma^* N \to N(1440)$ – Introduction





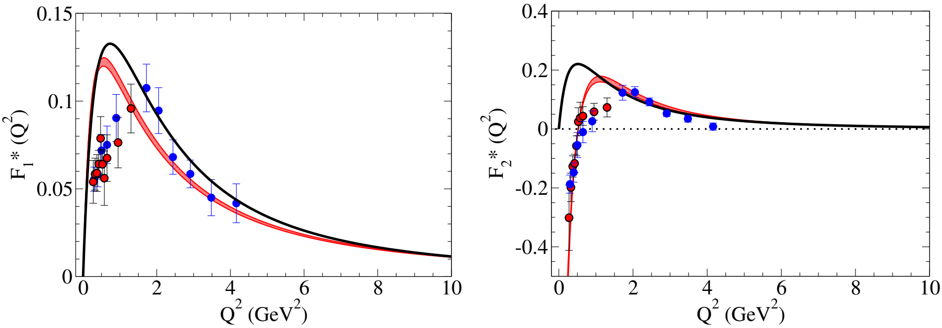
- **CSQM:** Roper defined as the **1st radial** excitation of the nucleon
  Same spin/flavor structure as the nucleon
  Radial wave function defined by the orthogonality with nucleon state
  GR and K Tsushima, PRD 81, 074020 (2010); PRD 89, 073010 (2014)
- No adjustable parameters; **No** meson cloud components included
- **CLAS data:** IG Aznauryan et al., PRC 80, 055203 (2009);
  VI Mokeev et al., PRC 86, 035203 (2012); PRC 93, 025206 (2016)

$\gamma^* N \to N(1440)$ – Results



- **Good results** for $Q^2 > 1.5$ GeV^2 – valence quark dominance
  Support **Roper** as **1st radial** excitation of the nucleon
- Failure for $Q^2 < 1.5$ GeV^2 – meson cloud ?
  GR and K Tsushima, AIP Conf.Proc. 1374, 353 (2011)

$\gamma^* N \to N(1440)$ – Comparing results



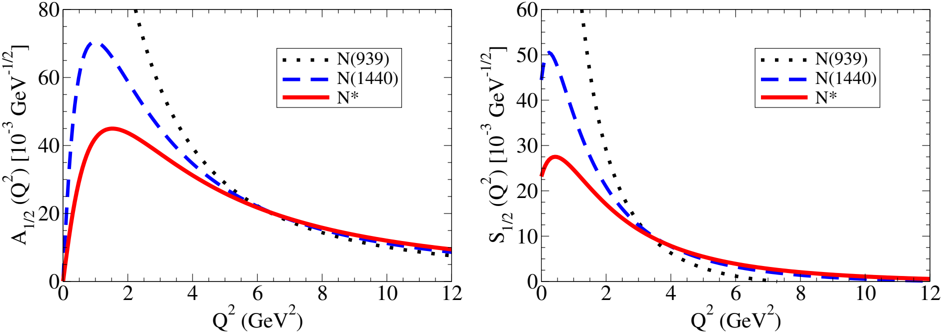
— CSQM === Holography

Holographic calculation

GR, D Melnikov, PRD 97, 034037 (2018); GR, PRD 96, 054021 (2017)

Very different formalisms; Very similar results at large Q^2

$\gamma^* N \to N^*$ – 2nd radial excitation of the nucleon



N^* is identified as $N(1880)$

Comparison with Roper and Nucleon ($A_{1/2} \propto G_M$; $S_{1/2} \propto G_E$)

Similar result for large Q^2 (same short range structure)

$\gamma^* N \to \Delta(1600)$ [GR and K Tsushima, PRD 82, 073007 (2010)]

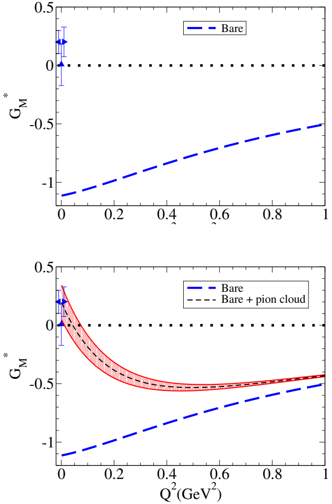
$\Delta(1600)$ as the 1st radial excitation
of $\Delta(1232)$ EPJA, 36, 329 (2008) [S-state]
$G_E^* \equiv 0$, $G_C^* \equiv 0$

Bare : $G_M^B(0) = -1.113$

Valence quarks **insuficient** to explain data

π cloud effects: rough estimate - - -

Final result consistent with $Q^2 = 0$ data
Predictions for large Q^2



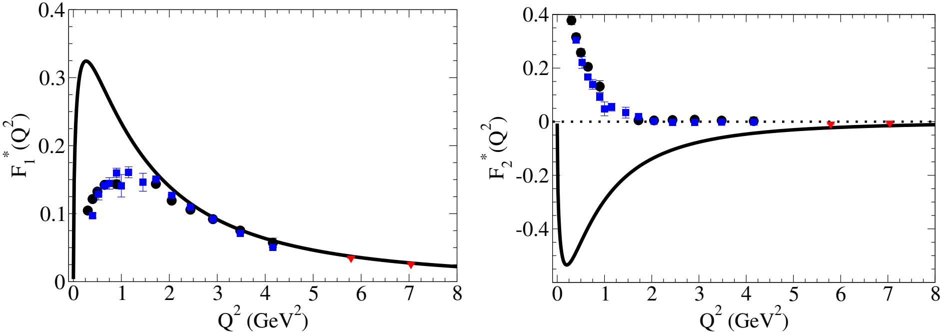
$\gamma^* N \to N(1535)\frac{1}{2}^-$ and $\gamma N^* \to N(1520)\frac{3}{2}^-$

- Negative parity states
- Valence quark contributions estimated within the CSQM framework
  Radial wave functions determined using $\neq$ prescriptions
  - $N(1525)$: GR and MT Peña, PRD 84, 033007 (2011)
    GR and MT Peña, PRD 101, 114008 (2020) – $N(1535)$ Dalitz decay
  - $N(1520)$: GR and MT Peña, PRD 89, 094016 (2014);
    GR and MT Peña, PRD 95, 014003 (2017) – $N(1520)$ Dalitz decay

Recent development – **Semirelativistic approximation**
GR, PRD 95, 054008 (2017)

- Mass difference (M_R and M_N) neglected in a first approximation
- Radial wave function determined by ψ_N (nucleon)
  Orthogonality ensured; **Non-relativistic properties;** Covariant expressions
- Form factors determined without **any** adjustable parameter
  Model parameters determined by **Nucleon** system

$\gamma^* N \to N(1535)$ – SR approx – Results



- 2 form factors; Data from **CLAS**, MAID and Jlab/Hall C
- Good results for F_1^* ($Q^2 > 1.5$ GeV^2); consequence of meson cloud !
- F_2^* wrong sign; $(F_2^*)_{\rm exp} \approx 0$ for $Q^2 > 1.5$ GeV^2
  Interpretation: Cancellation between valence and meson cloud

Implications of $F_2^* = 0$?

$\tau = \frac{Q^2}{(M_R+M_N)^2}$ $Q^2 > 1.5$ GeV^2

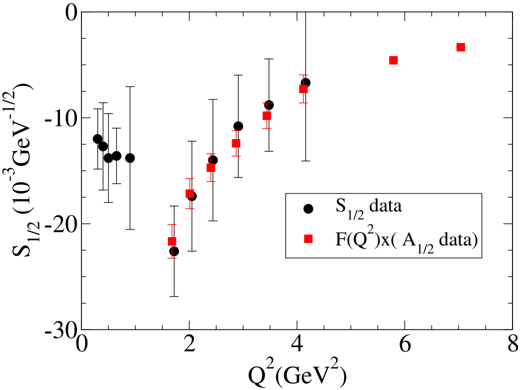
$$S_{1/2} \simeq -\frac{\sqrt{1+\tau}}{\sqrt{2}} \frac{M_R^2 - M_N^2}{2 M_R Q} A_{1/2}$$

GR, K Tsushima,
PRD 84, 051301 (2011)

GR, D Jido, K Tsushima,

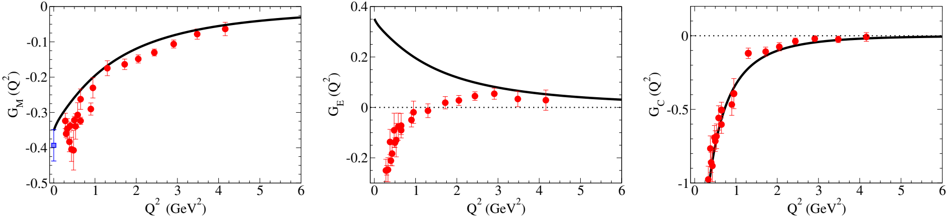
PRD 85, 093014 (2012)

Cancellation between
valence and meson cloud



More data are welcome

$\gamma^* N \to N(1520)$ – SR approx – Results

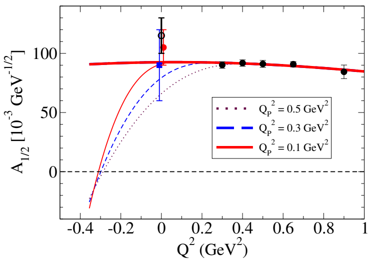


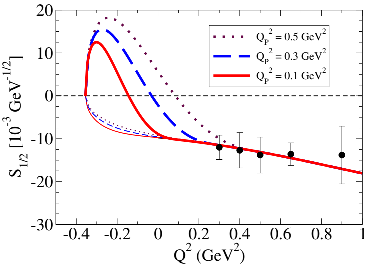
- 3 independent form factors: G_M, G_E, G_C
- —- SemiRelativistic approach (**SR**); data from **CLAS**
- **SR** very good description of the data – Except for G_E
  Explanation: amplitude $A_{3/2} \propto (G_E + G_M)$ dominated by meson cloud
  CSQM (no meson cloud): $A_{3/2} \equiv 0$, $G_E \equiv -G_M$
- **Describe well valence quark degress of freedom** (apart $G_E + G_M$)

Ambiguity about $S_{1/2}$ near $Q^2 = 0$

Siegert's theorem: at PT $A_{1/2} = \sqrt{2}(M_R - M_N)\frac{S_{1/2}}{|\mathbf{q}|}$

GR, PLB 759, 126 (2016); PRD 100, 114014 (2019), Devenish et al, PRD 14, 3063 (1976)





Data: PDG 2012, **PDG 2016**, PDG 2020

- Case 1 (**Thick lines**): $A_{1/2}$ smooth: $A_{1/2} > 0 \Rightarrow S_{1/2}$ **must** change sign
- Case 2 (Thin lines): $S_{1/2}$ smooth: $S_{1/2} < 0 \Rightarrow A_{1/2}$ **must** change sign

$N(1535)$ helicity amplitudes at low Q^2

Ambiguity about $S_{1/2}$ near $Q^2 = 0$

Siegert's theorem: at PT $A_{1/2} = \sqrt{2}(M_R - M_N)\frac{S_{1/2}}{|\mathbf{q}|}$

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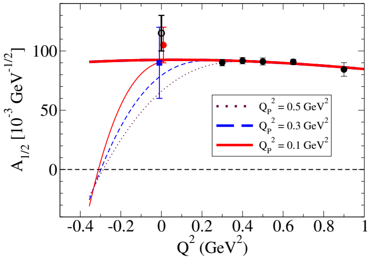

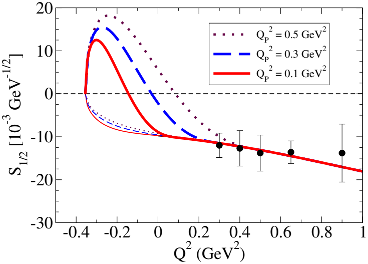

Data: PDG 2012, **PDG 2016**, PDG 2020

More data needed below 0.3 GeV^2

- Case 1 (**Thick lines**): $A_{1/2}$ smooth: $A_{1/2} > 0 \Rightarrow S_{1/2}$ **must** change sign
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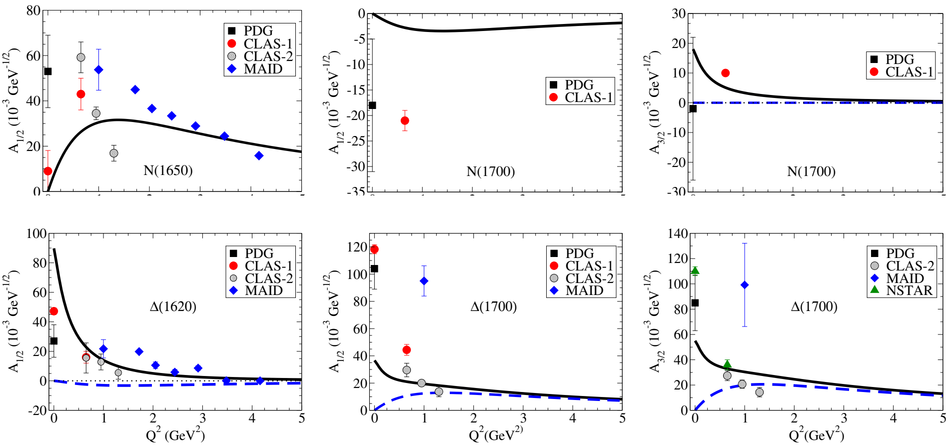
Combination with SQTM

Single Quark Transition Model $\oplus$ CSQM
Hey and Weyers, PL 48B, 69(1974); Cottingham and Dunbar, ZPC 2, 41 (1979);
Burkert et al, PRC 67, 035204 (2003)

- Models applied to $[70, 1^-]$ multiplet
- Use CSQM results for $N(1535)\frac{1}{2}^-$, $N(1520)\frac{3}{2}^-$
- Predict amplitudes for
  $N(1650)\frac{1}{2}^-$, $N(1700)\frac{3}{2}^-$, $\Delta(1620)\frac{1}{2}^-$, $\Delta(1700)\frac{3}{2}^-$
  GR, PRD 90, 033010 (2014)

Estimates compared with data from **CLAS, MAID** and **PDG**

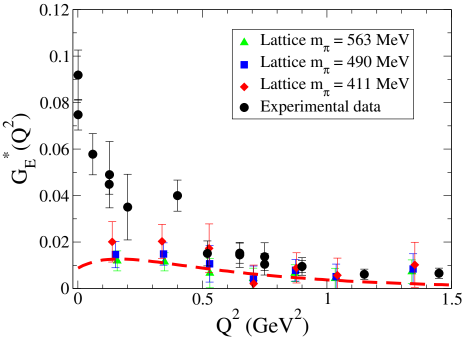
Multiplet $[70, 1^-]$ GR PRD 90, 033010 (2014)

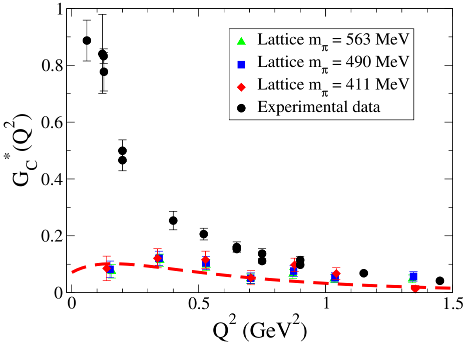


- Model compares well with $N(1650)$ and $\Delta(1620)$
- **More large Q^2 data are necessary** to test the calculations

Some calculations of N^* transition form factors at low Q^2

$\gamma^* N \to \Delta$: $G_E^*(Q^2)$, $G_C^*(Q^2)$ [GR, MT Peña, PRD 80, 013008 (2009)]





- Bare contributions (QM) determined by fit to lattice Alexandrou, PRD 77, 085012 (2008)

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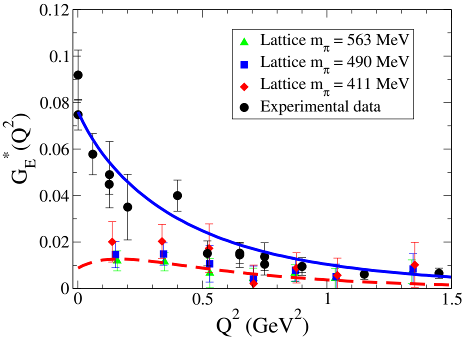
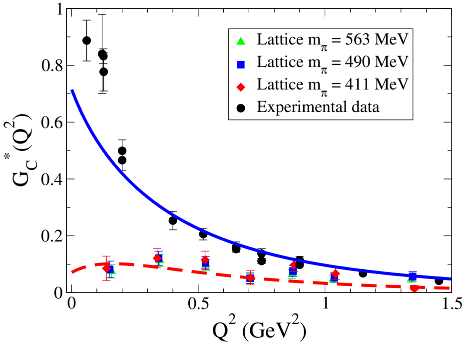
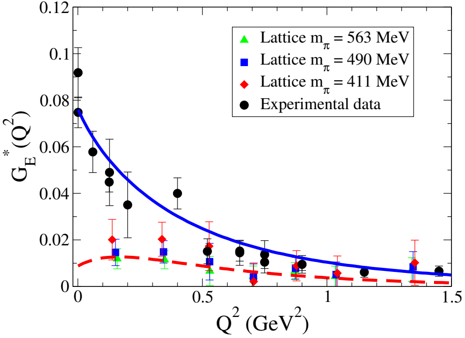


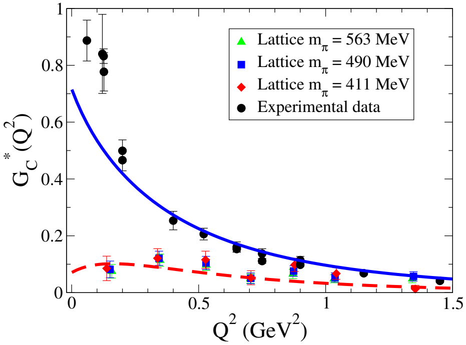


- Bare contributions (QM) determined by fit to lattice Alexandrou, PRD 77, 085012 (2008)
- Pion cloud: large N_c relations $\propto \tilde{G}_{En} = \frac{G_{En}}{Q^2}$; **No extra parameters**

Pascalutsa and Vanderhaeghen, PRD 76, 111501 (2007); Buchmann PRD 66, 056002 (2002)

$\gamma^* N \to \Delta$: $G_E^*(Q^2)$, $G_C^*(Q^2)$ [GR, MT Peña, PRD 80, 013008 (2009)]





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  Pascalutsa and Vanderhaeghen, PRD 76, 111501 (2007); Buchmann PRD 66, 056002 (2002)
- Bare (QM) $\oplus$ pion cloud (th) contributions $\approx$ **data** [CLAS, MAMI, MIT, PDG]

$\gamma^* N \to \Delta$: quadrupoles – Siegert's theorem

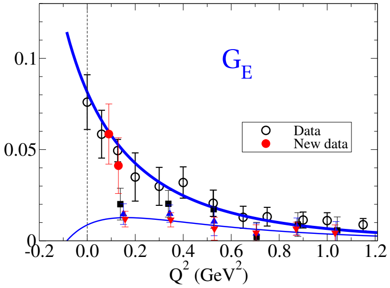
The previous parametrizations **are not** consistent with Siegert's theorem $\kappa = \frac{M_\Delta - M}{2M_\Delta}$

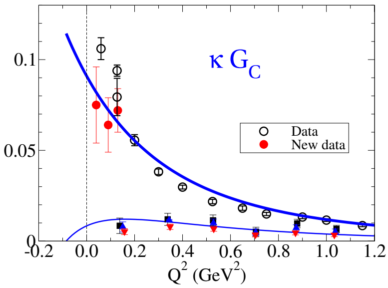
Siegert's theorem: at pseudothreshold $|\mathbf{q}| = 0$; $Q^2 = -(M_\Delta - M)^2$; $G_E^* = \kappa G_C^*$

Improved Large-N_c: GR, EPJA 54, 75 (2018) $\alpha = \frac{Q^2}{2M_\Delta(M_\Delta - M)} = \mathcal{O}\left(\frac{1}{N_c^2}\right)$

$$G_E^\pi = \left(\frac{M}{M_\Delta}\right)^{3/2} \frac{M_\Delta^2 - M^2}{2\sqrt{2}} \frac{\tilde{G}_{En}}{1+\alpha}, \qquad G_C^\pi = \left(\frac{M}{M_\Delta}\right)^{1/2} \sqrt{2} M M_\Delta \tilde{G}_{En}$$

Siegert's theorem valid   New data JLab/Hall A: A Blomberg, PLB 760, 267 (2016)





Extension of the model to $SU_F(3)$ and nuclear medium

Extension to $SU_F(3)$ and nuclear medium EMFF (1)

- $SU_F(3)$ **quark current:**

$$j_q^\mu = j_1 \gamma^\mu + j_2 \frac{i\sigma^{\mu\nu} q_\nu}{2M_N}, \quad j_i = f_{i+}\lambda_0 + f_{i-}\lambda_3 + \overbrace{f_{i0}\lambda_s}^{\text{quark } s}$$

λ_a **Gell-Mann matrices;**
radial wave functions defined for systems with **strange quarks**

- **Baryons with strange quarks:** octet, decuplet, octet to decuplet, ...

PRD 88, 053002 (2013); PRD 87, 093011 (2013); PRD 86, 114030 (2012); PRD 84, 054014 (2011); GR, Jido, Tsushima, PRD 85, 093014 (2012); GR, Peña, PRD 83, 054011 (2011); Gross, GR, Tsushima, PLB 690, 183 (2010); GR, Tsushima, Gross, PRD 80, 033004 (2009)

Octet baryon EM form factors:

$$G_{EB} = Z_B \left[G_{EB}^{\mathrm{B}} + G_{EB}^{\pi} \right], \quad G_{MB} = Z_B \left[G_{MB}^{\mathrm{B}} + G_{MB}^{\pi} \right]$$

Z_B: normalization; $G_{\alpha B}^{\mathrm{B}}$ bare contribution;
$G_{\alpha B}^{\pi}$ phenomenological pion cloud contribution $\propto g_{\pi BB'}^2$

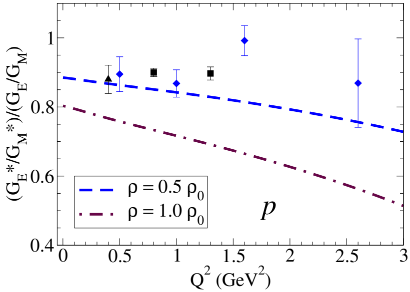
Extension to $SU_F(3)$ and nuclear medium EMFF (2)

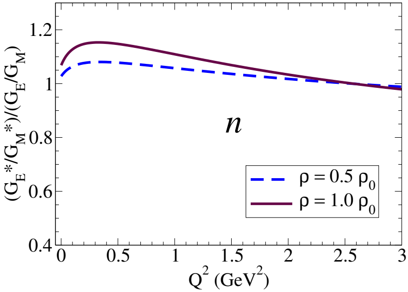
- Calibration of model in **vacuum** by **Lattice QCD data** (radial wave functions) – bare part & **Physical data** (N form factors, magnetic moments, baryon radii) – pion cloud part GR, Tsushima, Thomas, JPG 40, 015102 (2013)
- **Generalize** model to the **nuclear medium** ($*$) for a density ρ
  Medium propertites estimated by **Quark-Meson-Coupling Model**
  Saito, Tsushima and Thomas, Prog. Part. Nucl. Phys. 58, 1 (2007)
  $m_h \to m_h^*$; $g_{MBB'} \to g_{MBB'}^*$
  Use **VMD** character of the **CSQM** in the extension

Octet baryon G_E/G_M in vacuum and in medium
GR, Melo, Tsushima, PRD 100, 014030 (2019)

Extension to $SU_F(3)$ and nuclear medium EMFF (3)

Proton and neutron double ratio: $\mathcal{R}_N = \frac{G_E^*/G_M^*}{G_E/G_M}$





GR, Melo, Tsushima, PRD 100, 014030 (2019); GR, Tsushima, Thomas, JPG 40, 015102 (2013)

Data ^{4}He$(\vec{e}, e'\vec{p})^3$H, JLab, MAMI $\rho_0 =$ normal nuclear density

Dieterich, PLB 500 (2001); Strauch, EPJA 19 S1 (2004); Paolone, PRL 105 (2010)

Octet baryon axial-vector form factors in vacuum

[GR and K Tsushima PRD 94, 014001 (2016)] Generalization of nucleon to octet baryon

$$(J_5^\mu)_a = \bar{u}(P_+)\left[G_A(Q^2)\gamma^\mu + G_P(Q^2)\frac{q^\mu}{2M}\right]\gamma_5 u(P_-)\,\frac{\lambda_a}{2},$$

- Extend octet model to the axial-vector transition; P-state mixture

$$j_{Aq}^\mu = \left(g_A^q\gamma^\mu + g_P^q\frac{q^\mu}{2M}\right)\gamma_5\frac{\tau_a}{2}, \qquad \Psi_N = \sqrt{1-n_P^2}\,\Psi_S + n_P\Psi_P$$

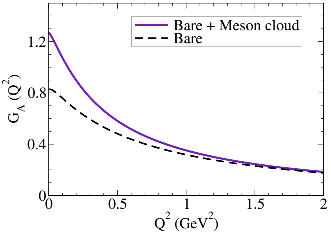
- $g_A^q \equiv f_{1-}$ (isovector); g_P^q fit to the lattice QCD data for nucleon

$$G_A = G_A^B + G_A^{MC}, \qquad G_P = G_P^{\rm pole} + G_P^B + G_P^{MC}, \qquad G_P^{\rm pole} = \frac{4M^2}{\mu^2+Q^2}G_A^B$$

- $\mu = m_\pi$ ($\Delta S = 0$), $\mu = m_K$ ($\Delta S = 1$)
  G_A^{MC}: $SU(3)$ effective model (D, $F \sim g_{\pi NN}^2$)

- Bare: lattice data, $SU(6)$; Meson-Cloud: nucleon and $G_A^{B,B'}(0)$ data

Octet baryon: axial-vector transitions



Nucleon: fix current

$\Delta S = 0$ $(d \to u)$

$n \to p$

$\Sigma^- \to \Lambda$

$\Sigma^- \to \Sigma^0$

$\Sigma^0 \to \Sigma^+$

$\Sigma^+ \to \Lambda$ $(u \to d)$

$\Xi^- \to \Xi^0$

$\Delta S = 1$ $(s \to u)$

$\Sigma^- \to n$

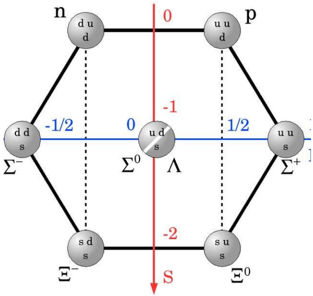
$\Sigma^0 \to p$

$\Lambda \to p$

$\Xi^- \to \Sigma^0$

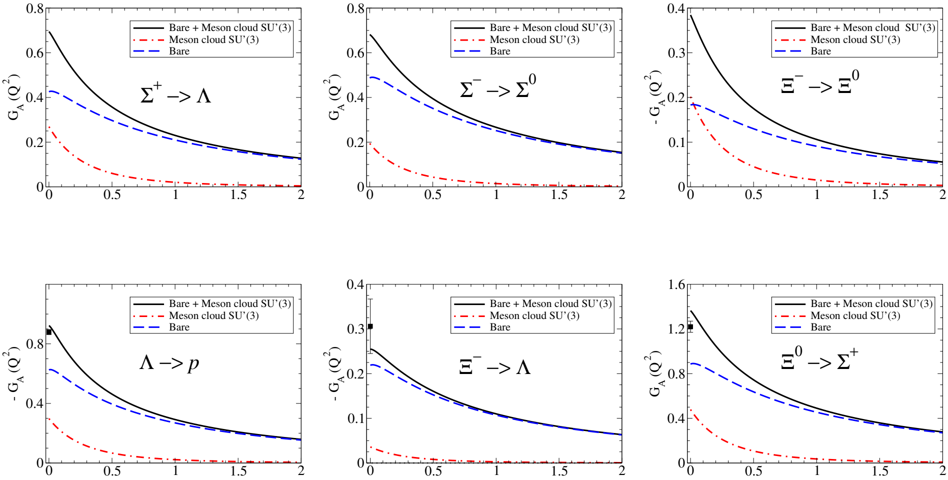
$\Xi^- \to \Lambda$

$\Xi^0 \to \Sigma^+$

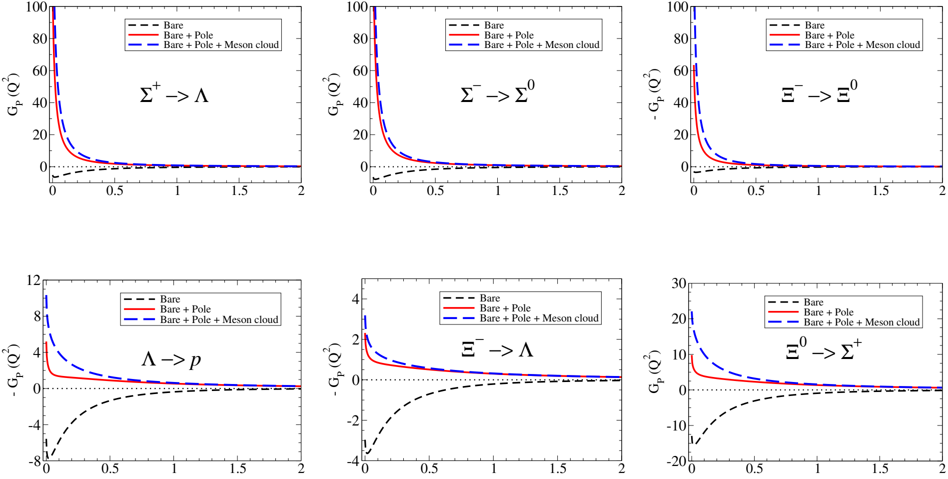


Study Q^2-dependence of form factors

Axial-vector form factor G_A: $\Delta S = 0$, $\Delta S = 1$



Axial-vector form factor G_P: $\Delta S = 0$, $\Delta S = 1$

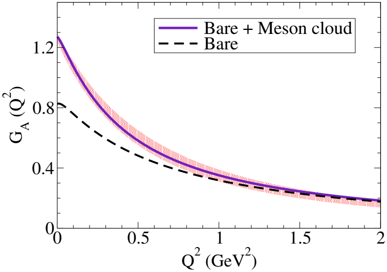


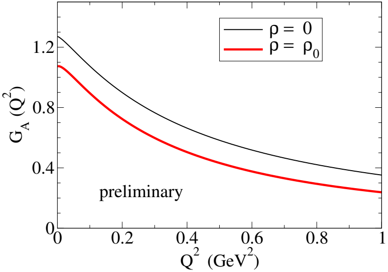
Extension to the nuclear medium $G_A(n \to p)$ $[\rho = 0, \rho_0]$

Study Q^2-dependence of form factors **in medium**

== experimental data in vacuum

Preliminary calculation for $\rho = \rho_0$





Model can be used to calculate $B' \to e^- \bar{\nu} B, e^+ \nu B$,
and reactions with (anti-)neutrinos in **nuclear medium**
$\nu B \leftrightarrow e^- B'$, $\bar{\nu} B \leftrightarrow e^+ B'$, $\nu B \to \nu B$, $\bar{\nu} B \to \bar{\nu} B$

Summary and conclusions

- We present **covariant** calculations of the electromagnetic transition form factors for several N^* states at large Q^2
  $\Delta(1232)$, $N(1440)$, $N(1520)$, $N(1535)$, $\Delta(1600)$, ...
  $N(1650)$, $N(1700)$, $\Delta(1620)$, $\Delta(1700)$

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  Dominance of valence quark effects for large Q^2 ($Q^2 \gtrsim 2$ GeV^2)
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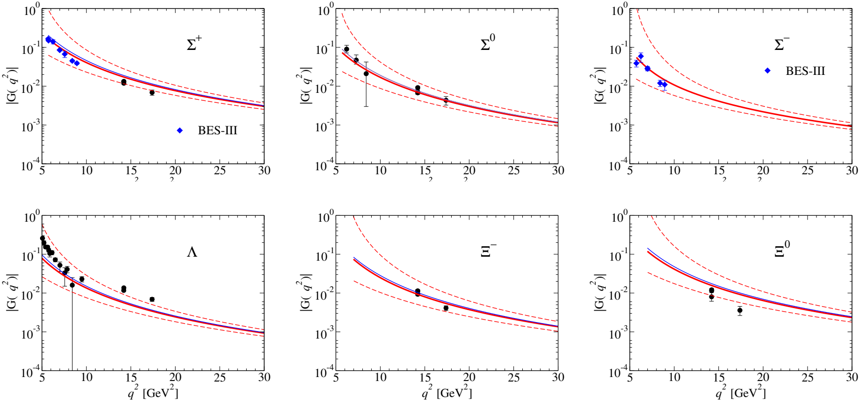
  - Nuclear medium: electromagnetic and axial-vector transitions
    Applications to astrophysics (OMEG)
  - Timelike region ...

Hyperon elastic form factors **at large** q^2



GR, MT Peña and K Tsushima PRD 101, 014014 (2020); GR, PRD 103, 074018 (2021)

Data from CLEO, BaBar, BES-III

Summary and conclusions **Thank you**

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More information

Other applications

- Electromagnetic form factors of hyperons **at large** q^2 †

  GR, Tsushima, Peña, PRD 101, 014014 (2020); GR, PRD 103, 074018 (2021)

  Babar, BES-III, CLEO, ...

- Baryons with strange quarks: octet, decuplet, octet to decuplet, ...

  PRD 88, 053002 (2013); PRD 87, 093011 (2013); PRD 86, 114030 (2012); PRD 84, 054014 (2011); GR, Jido, Tsushima, PRD 85, 093014 (2012); GR, Peña, PRD 83, 054011 (2011); Gross, GR, Tsushima, PLB 690, 183 (2010); GR, Tsushima, Gross, PRD 80, 033004 (2009)

- Deep inelastic stattering – nucleon

  Gross, GR, Peña, PRD 85, 093006 (2012); PRD 85, 093005 (2012); PRC 77, 015202 (2008)

- Transition form factors in the timelike region – HADES
  Dalitz decays ($N^* \to e^+ e^- N$, $B' \to e^+ e^- N$) hyperons
  GR, Peña, PRD 85, 113014 (2012); PRD 95, 014003 (2017); GR, Peña, Weil, Hees, Mosel, PRD 93, 033004 (2016); GR, Peña, PRD 101, 114008 (2020); GR, PRD 102, 054016 (2020)

- Structure of baryons in the nuclear medium

  GR, Melo, Tsushima, PRD 100, 014030 (2019); GR, Tsushima, Thomas, JPG 40, 015102 (2013)

- Axial structure of octet baryon (in vacuum)

  GR, Tsushima, PRD 94, 014001 (2016)

Dynamical Coupled-Channel – EBAC model

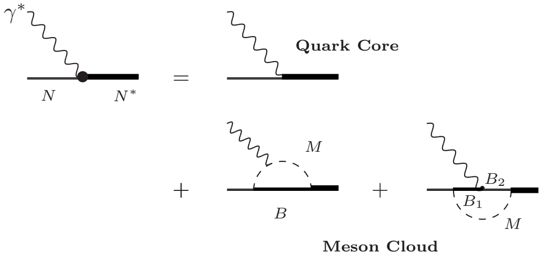
EBAC = Excited Baryon Analysis Center @ Jefferson Lab

`https://ebac-theory.jlab.org` → Argonne-Osaka DCC model

$\gamma^* B \to MB'$ and $MB \to M'B'$ transitions

Include intermediate baryon resonances B^* ($B^* \to MB$, $B^* \to \gamma B$)

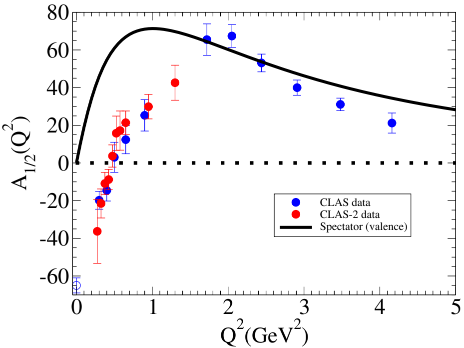
$$G_l = G_l^{\rm bare} + G_l^{\rm MC}$$

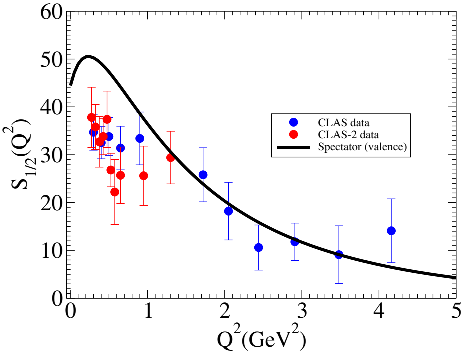


Turn off meson coupling ($g_{MBB'} = 0$): $G_l \to G_l^{\rm bare}$

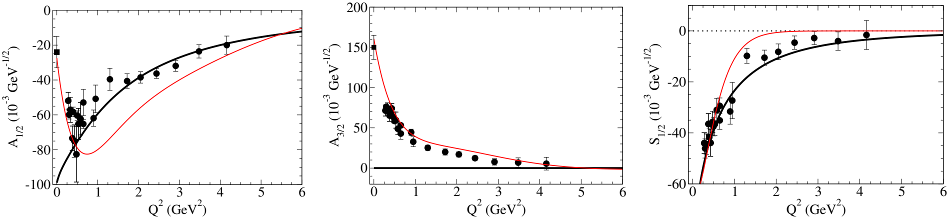
B J-Diaz, TSH Lee, T Sato, L Smith, PRC 75 015205 (2007)

$\gamma N \to N(1440)$ – Helicity amplitudes (optional)





$\gamma^* N \to N(1520)$ – SR app – Amplitudes (optional)



- 3 independent helicity amplitudes
- —- SemiRelativistic approach (**SR**); data from **CLAS**, include MAID fit
- **SR** very good description of the $Q^2 > 1.5$ GeV^2 data
  Except for $A_{3/2}$ (CSQM: $A_{3/2} \equiv 0$) – $A_{3/2} \leftarrow$ dominated by meson cloud ?
- **Describe well valence quark degress of freedom** ($(A_{3/2})_{\rm bare} \approx 0$)

Semirelativistic approximation – Summary

GR, PRD 95, 054008 (2017)

- **SR approach** gives a good description of form factor/ helicity amplitude data in the region $Q^2 > 1.5$ GeV^2
  Deviations (low Q^2) may be the result of the missing meson cloud
- **No parameters adjusted** ($\psi_R \equiv \psi_N$) – Predictions