Electromagnetic Baryon Transition Form Factors

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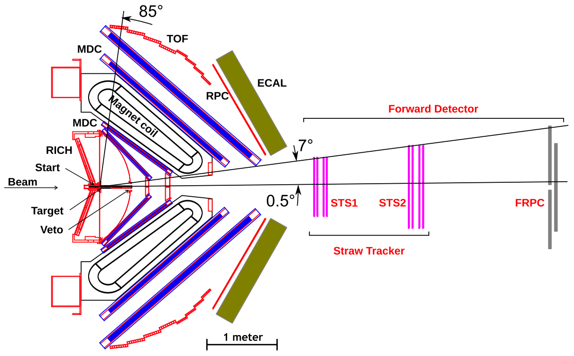
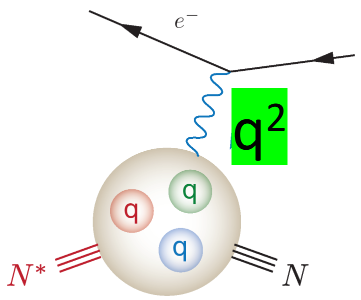
In Collaboration with Gilberto Ramalho,
Gernot Eichmann, André Torcato, Ana Arriaga

✓ HADES collaboration

Enables studies in the few GeV region; probes electromagnetic couplings with short-lived QCD systems.



Electromagnetic Transition form factors (TFF‘s)



Baryon resonances **transition form factors**

CLAS: Aznauryan et al.,
Phys. Rev. C 80 (2009)

MAID: Drechsel, Kamalov, Tiator,
EPJ A 34 (2009)

Gernot Eichmann and Gilberto Ramalho
Phys. Rev. D 98, 093007 (2018)

G. Ramalho, M. T. P. ,
Prog. Part. Nucl. Phys., (2023)

$q^2<0$

Spacelike form factors:

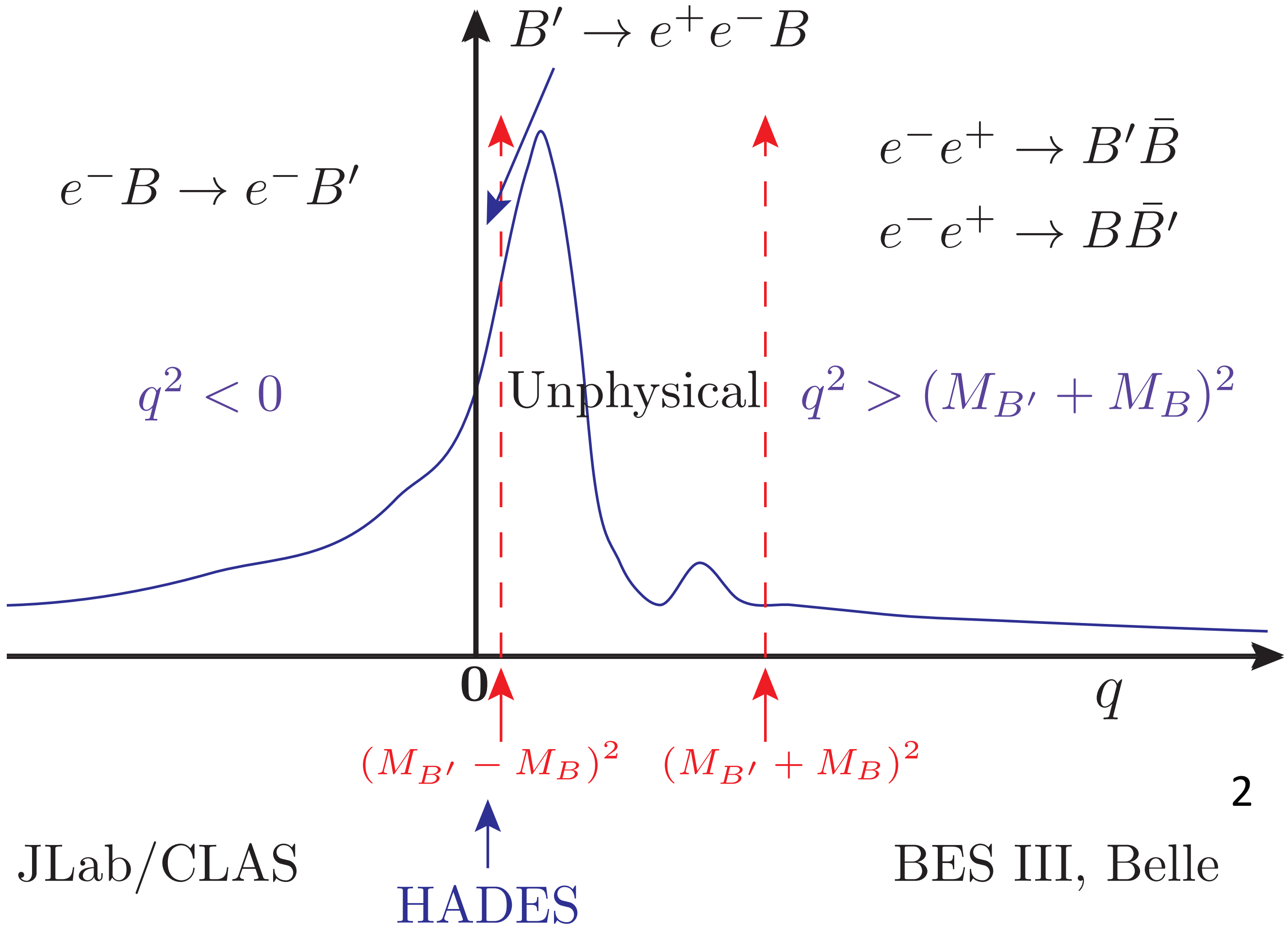
- Structure information: shape, qqq excitation vs. hybrid, ...

$q^2>0$

Timelike form factors:

- Particle production channels, spectroscopy

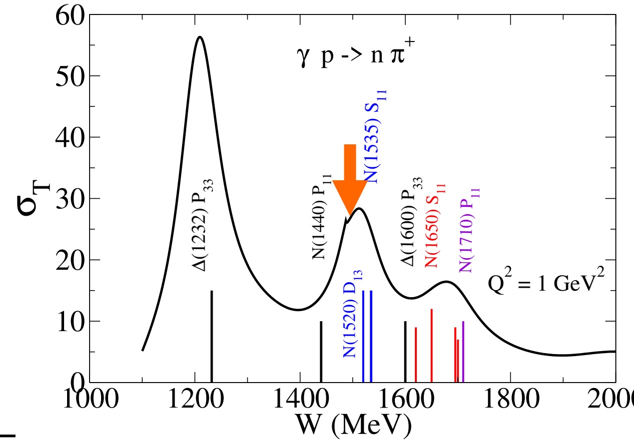
This talk: our experience
Connect Timelike and SpacelikeTransition Form Factors (TFF)
Obtain Baryon-Photon coupling evolution with 4 momentum transfer



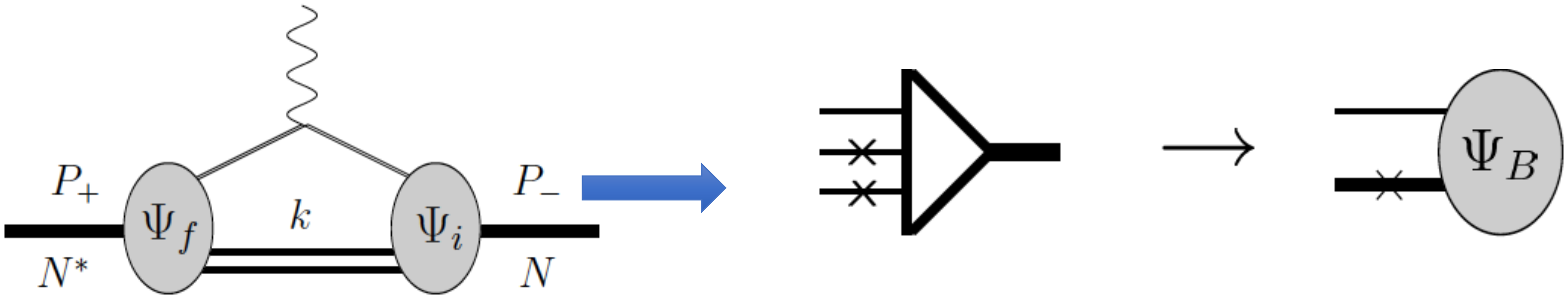
$B' \to e^+e^-B$
$e^-B \to e^-B'$
$e^-e^+ \to B'\bar{B}$
$e^-e^+ \to B\bar{B}'$
$q^2 < 0$
Unphysical
$q^2 > (M_{B'} + M_B)^2$
0
q
$(M_{B'} - M_B)^2$
$(M_{B'} + M_B)^2$
2
JLab/CLAS
HADES
BES III, Belle

Baryon resonances S=0 PDG

I	S	$J^P = \frac{1}{2}^+$	$\frac{3}{2}^+$	$\frac{5}{2}^+$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{5}{2}^-$
$\frac{1}{2}$	0	**N(940)** **N(1440)** $N(1710)$ $N(1880)$	**N(1720)** $N(1900)$	**N(1680)** $N(1860)$	**N(1535)** **N(1650)** $N(1895)$	**N(1520)** $N(1700)$ $N(1875)$	**N(1675)**
$\frac{3}{2}$	0	**Δ(1910)**	**Δ(1232)** Δ(1600) Δ(1920)	**Δ(1905)**	**Δ(1620)** Δ(1900)	**Δ(1700)** Δ(1940)	Δ(1930)



E.M. matrix element



$$\int_{k_1k_2} \equiv \int \frac{d^4k_1 d^4k_2}{(2\pi)^6}\delta_+(m_1^2 - k_1^2)\delta_+(m_2^2 - k_2^2) = \int \frac{d^3k_1 d^3k_2}{(2\pi)^6 4E_1E_2},$$

$$\int_{sk} = \underbrace{\int \frac{d\Omega_{\hat{\mathbf{r}}}}{4(2\pi)^3}\int_{4m_q^2}^{\infty} ds\sqrt{\frac{s-4m_q^2}{s}}}_{\int_s}\underbrace{\int \frac{d^3k}{(2\pi)^3 2E_s}}_{\int_k},$$

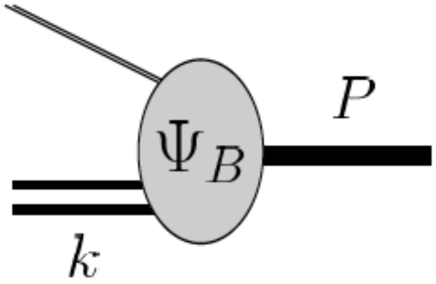
- **For the E.M. matrix element calculation,** the Baryon vertex is integrated over the spectator quarks variables. (Covariant Spectator Model, **CST**)

- **A reduced quark - diquark Baryon** wave function is all that is needed; it is phenomenologically constructed.

- ✓ The wf is symmetry based only; not dynamically generated
- ✓ The Diquark is not pointlike; it encloses structure

Eg. S-wave

- **Nucleon** wavefunction



- A quark + **scalar**-diquark component
- A quark+ **axial vector**-diquark component

$$\Psi^S_{N\lambda_n}(P,k) = \frac{1}{\sqrt{2}}[\phi^0_I u_N(P,\lambda_n) - \phi^1_I \varepsilon^{\alpha *}_{\lambda P} U_\alpha(P,\lambda_n)] \times \psi^S_N(P,k)$$

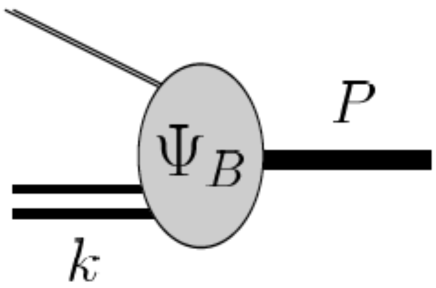
$$U_\alpha(P,\lambda_n) = \frac{1}{\sqrt{3}}\gamma_5\Big(\gamma_\alpha - \frac{P_\alpha}{m_H}\Big)u_N(P,\lambda_n),$$

Phenomenological functions ψ

- ✓ The wf is symmetry based only; not dynamically generated
- ✓ The Diquark is not pointlike; it encloses structure

Eg. S-wave

- **Nucleon** wavefunction



  - A quark + **scalar**-diquark component
  - A quark+ **axial vector**-diquark component

$$\Psi^S_{N\lambda_n}(P,k) = \frac{1}{\sqrt{2}}[\phi^0_I u_N(P,\lambda_n) - \phi^1_I \varepsilon^{\alpha *}_{\lambda P} U_\alpha(P,\lambda_n)] \times \boxed{\psi^S_N(P,k)}$$

$$U_\alpha(P,\lambda_n) = \frac{1}{\sqrt{3}}\gamma_5\left(\gamma_\alpha - \frac{P_\alpha}{m_H}\right)u_N(P,\lambda_n),$$

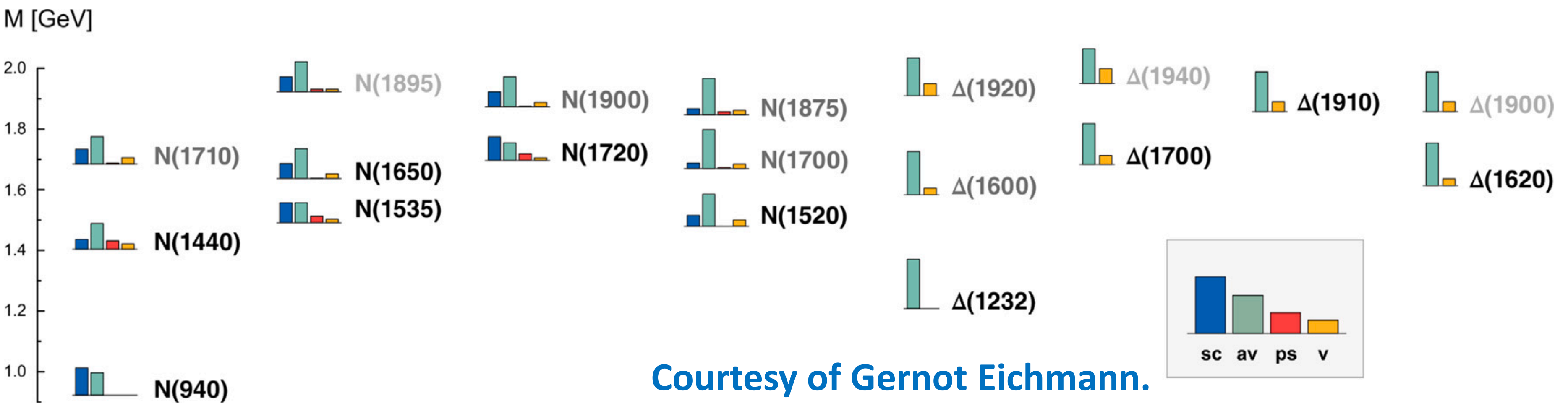
- **Delta (1232)** "wavefunction"
  - Only quark + **axial vector**-diquark term contributes

Phenomenological functions ψ

$$\Psi^S_\Delta(P,k) = -\boxed{\psi^S_\Delta(P,k)\tilde{\phi}^1_I}\varepsilon^{\beta *}_{\lambda P} w_\beta(P,\lambda_\Delta)$$

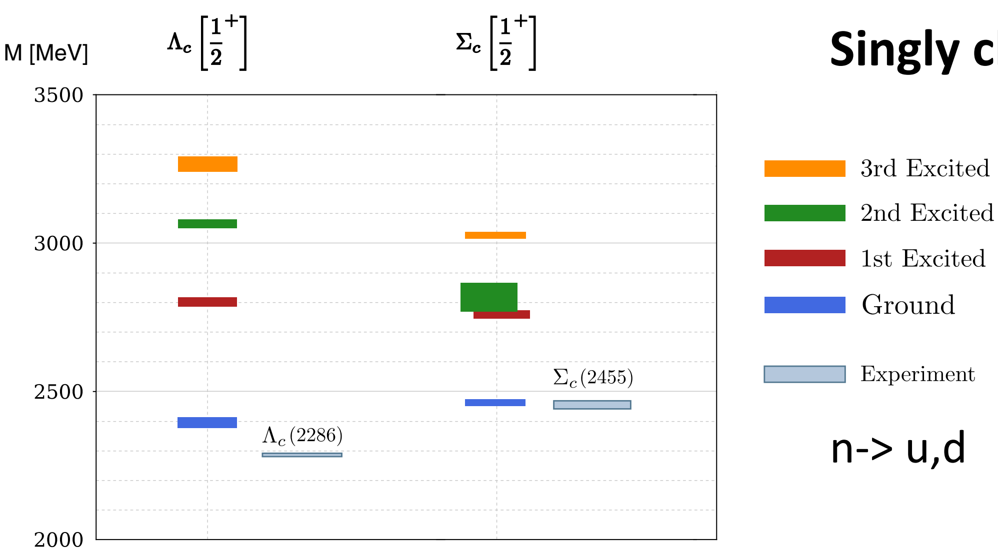
Dyson–Schwinger methods deciphered puzzle of the low mass of the parity + $N(1440)$ state relatively to the parity - $N(1535)$ and N(1650) states.

The combination of different diquark correlations in baryon structure explained it.

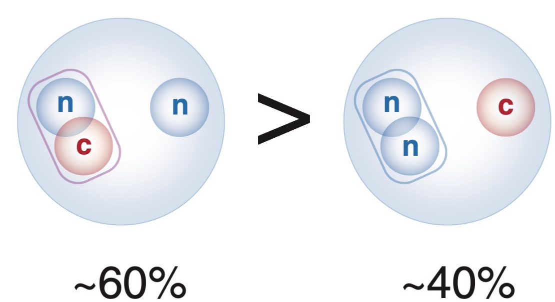


Courtesy of Gernot Eichmann.

Singly charmed Baryons

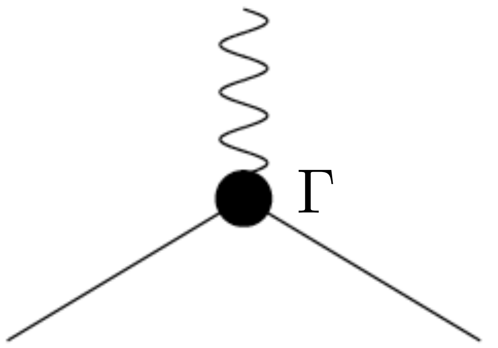


n-> u,d



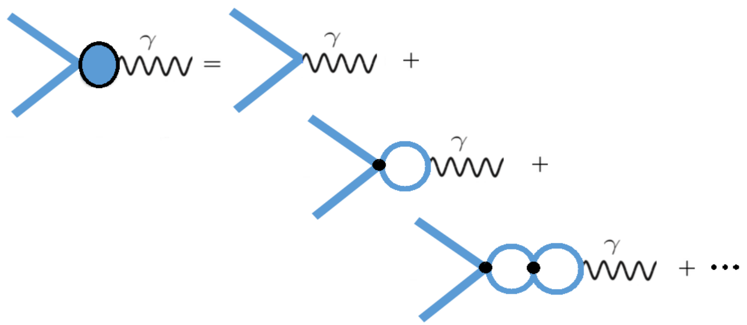
A. Torcato, A. Arriaga, G. Eichmann, M. T. P. Few Body Syst. 64 3, 45 (2023)

Quark E.M. Current



quark-antiquark
⊕ gluon dressing

Quark-photon vertex



$$\Gamma_\mu(p,Q) = \gamma_\mu + \int \frac{d^4q}{(2\pi)^4} K(p,q,Q) S(q+\eta Q)\Gamma_\mu(q,Q)S(q-\eta Q)$$

Meson Spectrum is tied to this vertex

Constituent quarks (quark form factors)

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

To parametrize the current we use Vector Meson Dominance at the quark level, a truncation to the rho and omega poles of the full meson spectrum contribution to the quark-photon coupling.

4 parameters

VMD as link to LQCD

experimental data well described in the large Q^2 region.

VMD

In the current the **vector meson** mass is taken as a function of the running pion mass.

Pion cloud contribution negligible for **large pion masses**

quark model calibrated to the **lattice data**

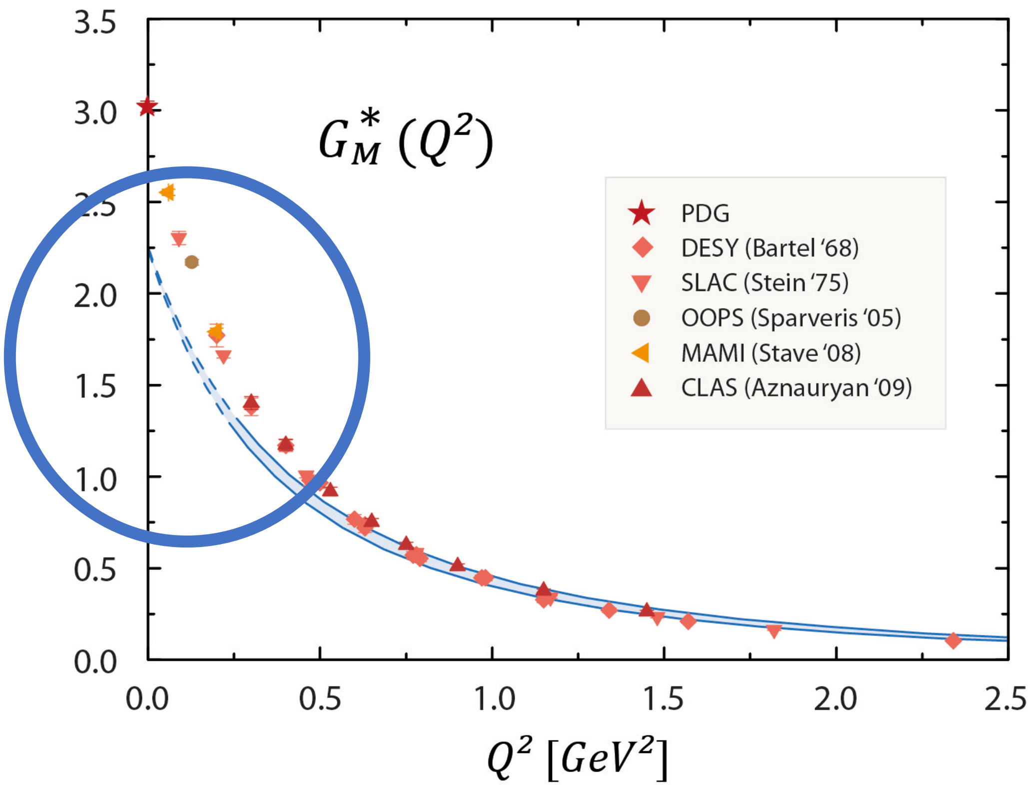
Take the limit of the physical pion mass value

Model independent feature

$$\gamma N \rightarrow \Delta$$

Missing strength of G_M at the origin is an universal feature, even in dynamical quark calculations.

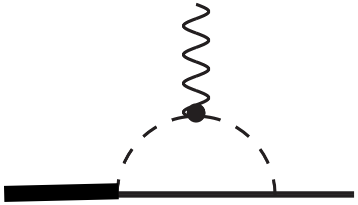
Eichmann et al., Prog. Part. Nucl. Phys. 91 (2016)



Effect of vicinity of the mass of the Delta to the pion-nucleon threshold.

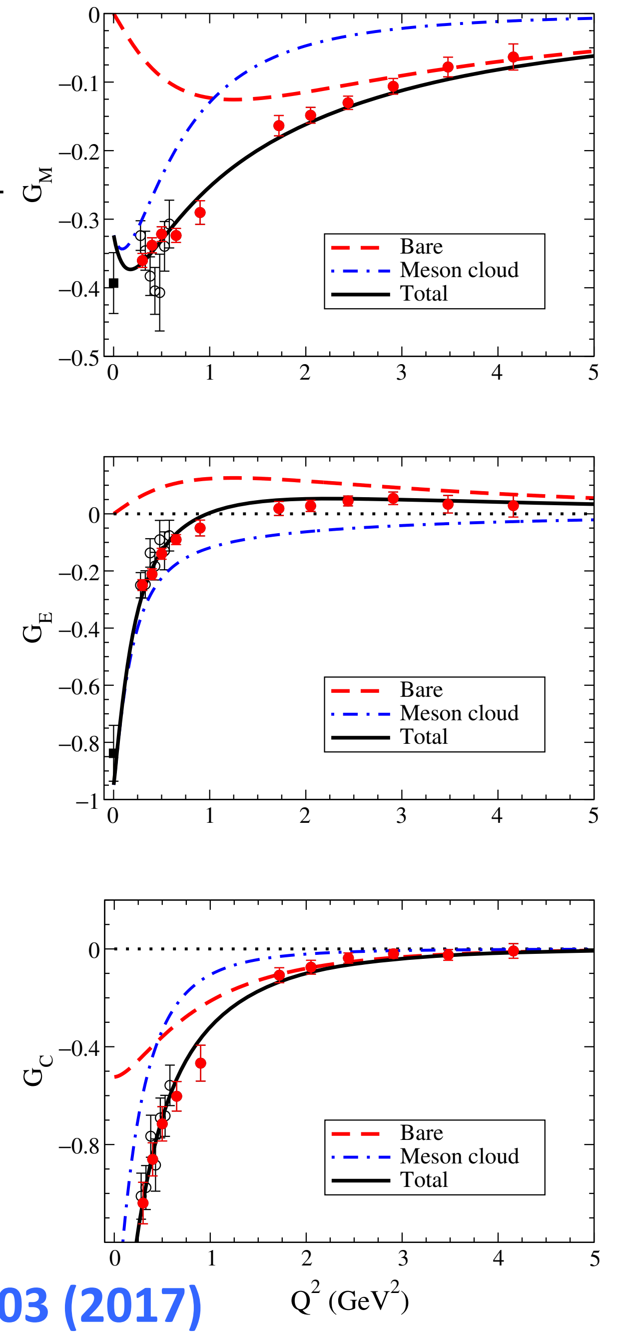
Pion loop effects suppressed for high Q^2

$$\frac{1}{Q^8}$$



$N \rightarrow N^*(1520)$ **TFFs**

$J^P=3/2^-$ $I=1/2$
60% decay πN
30% decay to $\pi\Delta$



- Bare quark model gives good description in the high momentum transfer region.

- For low Q^2, failure of description hints to meson effects.

Consistent with Aznauryan and Burkert, PRC 85 055202 2012 and PDG

G. Ramalho, M. T. P. , PHYSICAL REVIEW D 95 014003 (2017)

$N \to N^*(1520)$

PDG data at the photon point:

	$A_{1/2}$	$A_{3/2}$	$\lvert A\rvert^2$
p	-0.025 ± 0.005	0.140 ± 0.005	20.2 ± 1.4
n	-0.050 ± 0.005	-0.120 ± 0.005	15.7 ± 1.3

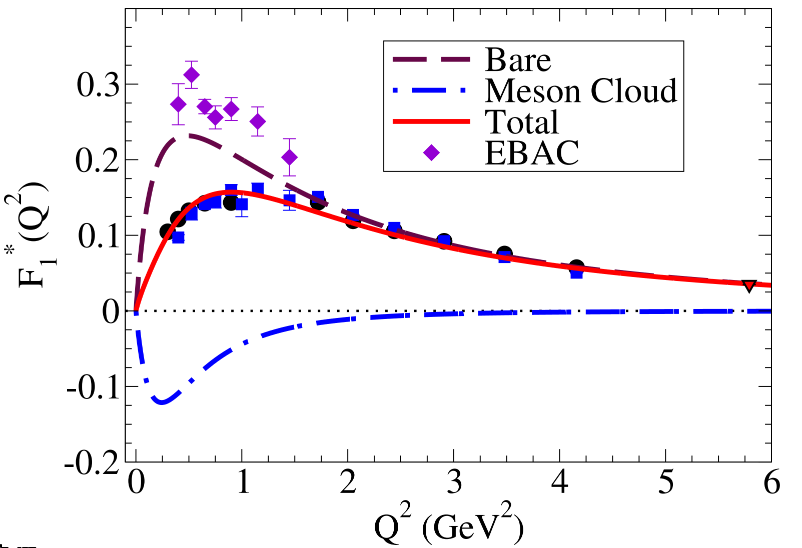
$$A^V_{3/2} \approx 0.13\ ;\ A^S_{3/2} \approx 0.01\,(GeV^{-1/2})$$

Dominance of iso-vector channel concurs
to the interpretation of low Q^2 effects as "pion cloud effects"

$N \to N^*(1535)$ TFFs

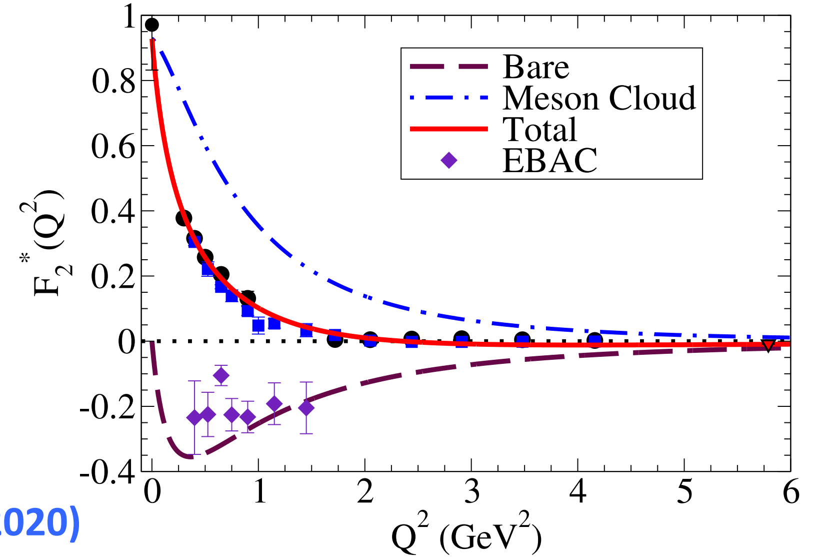
J^P=1/2$^-$ I=1/2
~50% decay to πN
~50% decay to ηN

$$J^\mu = \bar{u}_R \left[F_1^* \left(\gamma^\mu - \frac{\not{q} q^\mu}{q^2} \right) + F_2^* \frac{i\sigma^{\mu\nu} q_\nu}{M_N + M_R} \right] \gamma_5 u_N$$



- Again good agreement of bare quark core with data in the large Q^2 region.
- It dominates F_1^* for large Q^2
- Meson effects in F_2^* extend to high Q^2 region.

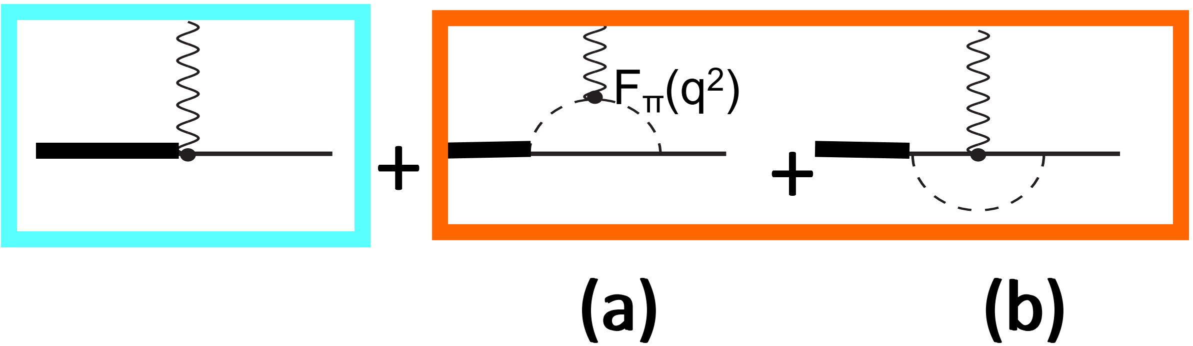
$$A^V_{1/2}(0) = 0.090 \pm 0.013 \text{ GeV}^{-1/2}$$
$$A^S_{1/2}(0) = 0.015 \pm 0.013 \text{ GeV}^{-1/2}$$



Effect from the ηN together with πN channel

G. Ramalho, M. T. P. , PHYSICAL REVIEW D 101 114008 (2020)

Extension to the Timelike region



The residue of the pion from factor $F_\pi(q^2)$ at the timelike ρ pole is proportional to the $\rho \longrightarrow \pi\pi$ decay

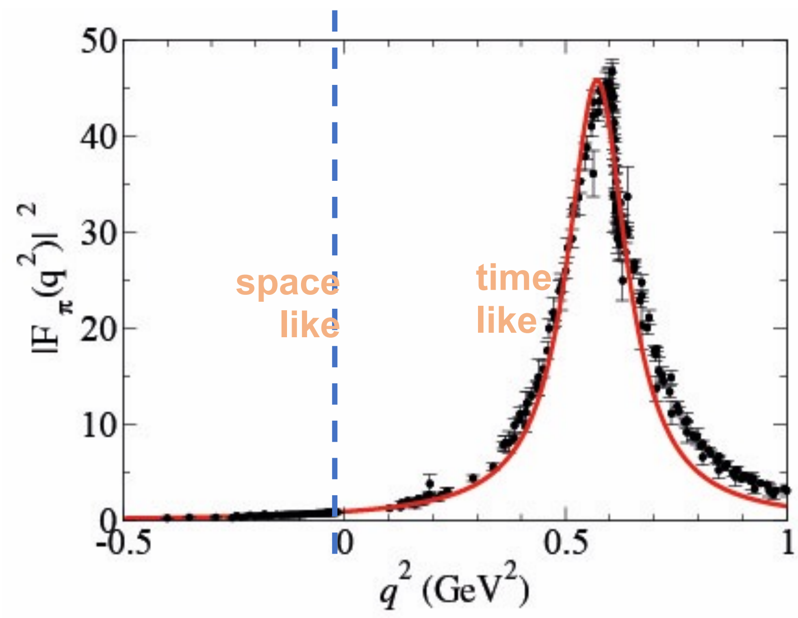
Diagram (a) related with pion electromagnetic form factor $F_\pi(q^2)$

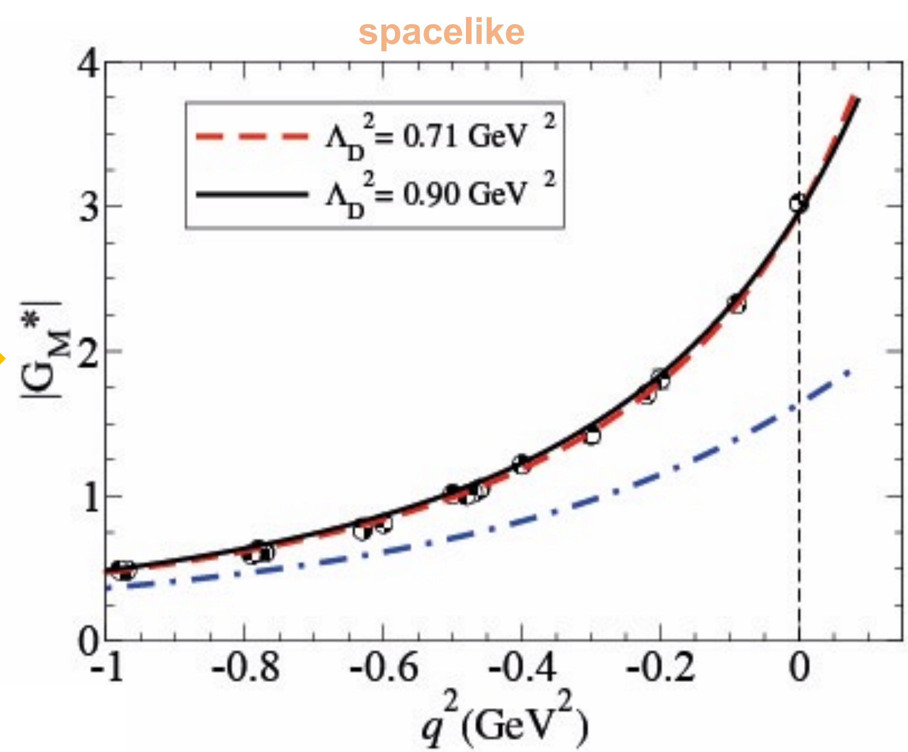
Extension to the Timelike region

$\Delta(1232)$ Dalitz decay

Ramalho, Pena, Weil, Van Hees, Mosel, Phys.Rev. C93 033004 (2016)

$\gamma N \to \Delta$





Parametrization of pion Form Factor

$$F_\pi(q^2) = \frac{\alpha}{\alpha - q^2 - \frac{1}{\pi}\beta q^2 \log\frac{q^2}{m_\pi^2} + i\beta q^2}$$

$\alpha = 0.696$ GeV^2

$\beta = 0.178$

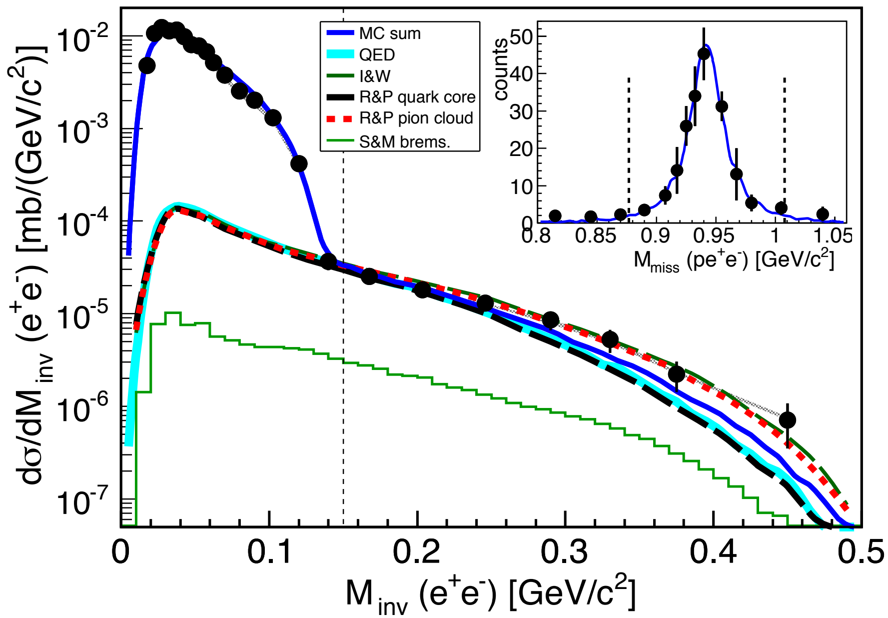
TFF restricted to the kinematic region that depends on the resonance mass W.

Dilepton mass spectrum   Δ(1232) Dalitz decay

HADES Collaboration, Phys.Rev. C95 0652205 (2017)

proton-proton collisions @1.25 GeV

True CST prediction:
Red line



Signature of adequate TFF form factor q^2 dependence

Δ Dalitz decay branching ratio extracted 4.19×10^{-5}

Entry in PDG

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

VALUE (units 10^{-5})	*DOCUMENT ID*
4.19±0.34±0.62	[1] ADAMCZEW... 17

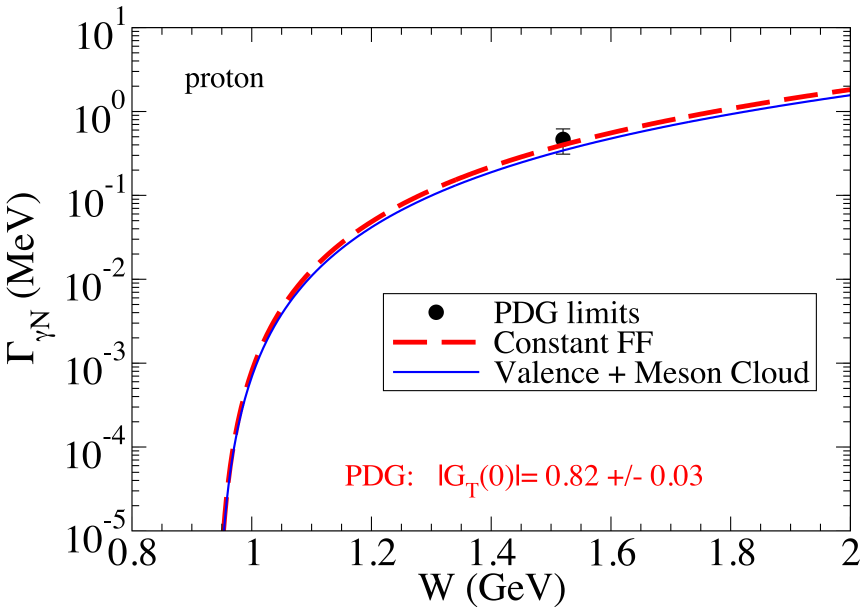
[1] The systematic uncertainty includes the model dependence.

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

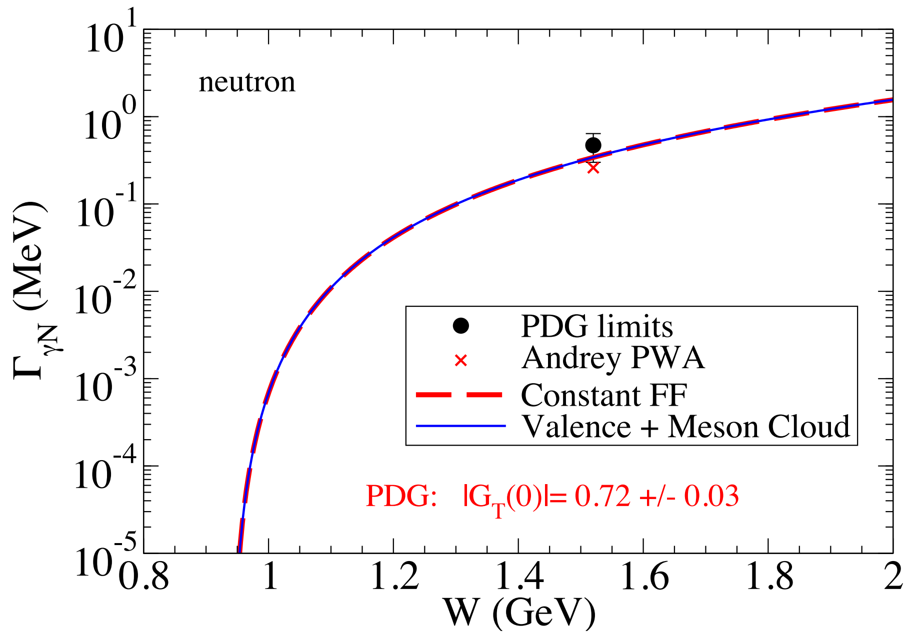
Radiative decay widths

N*(1520) $J^P=3/2^-$ I=1/2
60% decay πN
30% decay to $\pi\Delta$

Proton



Neutron

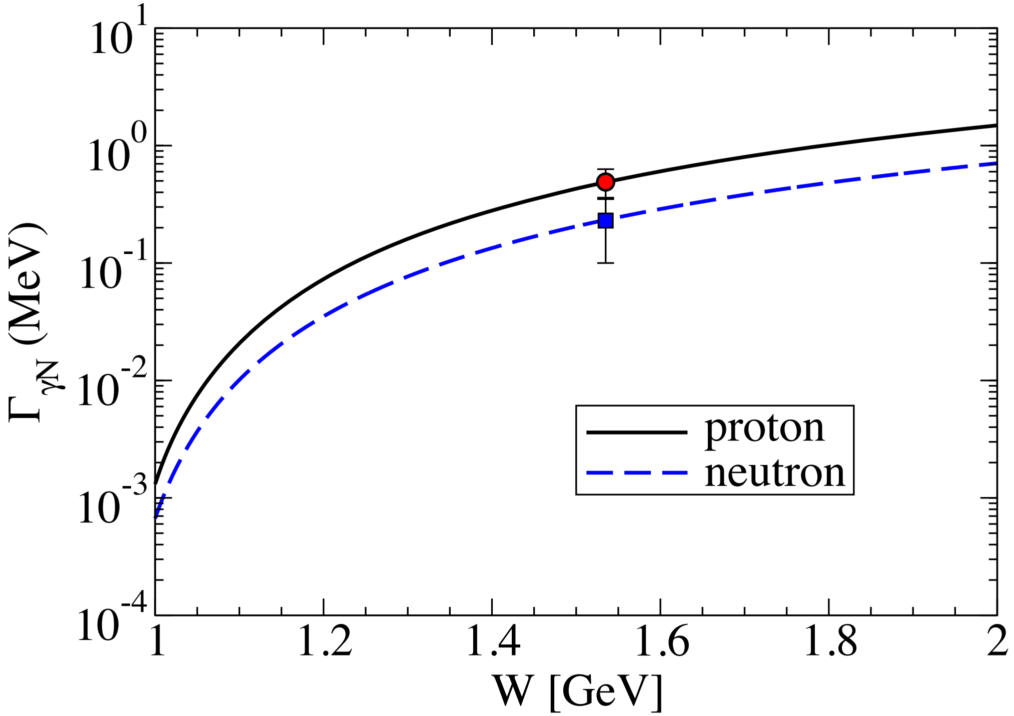


G. Ramalho and M.T. P. Phys. Rev. D 95, 014003 (2017)

Result Consistent with PDG value for γN decay width.

Radiative decay widths N*(1535)

$J^P = 1/2^-$ I=1/2
~50% decay to π N
~50% decay to η N



G. Ramalho and M.T. P. Phys.Rev.D 101 (2020) 11, 114008, (2020)

Different results for proton and neutron electromagnetic widths due to iso-scalar term in the eta meson cloud.

Timelike results give information on the neutron.

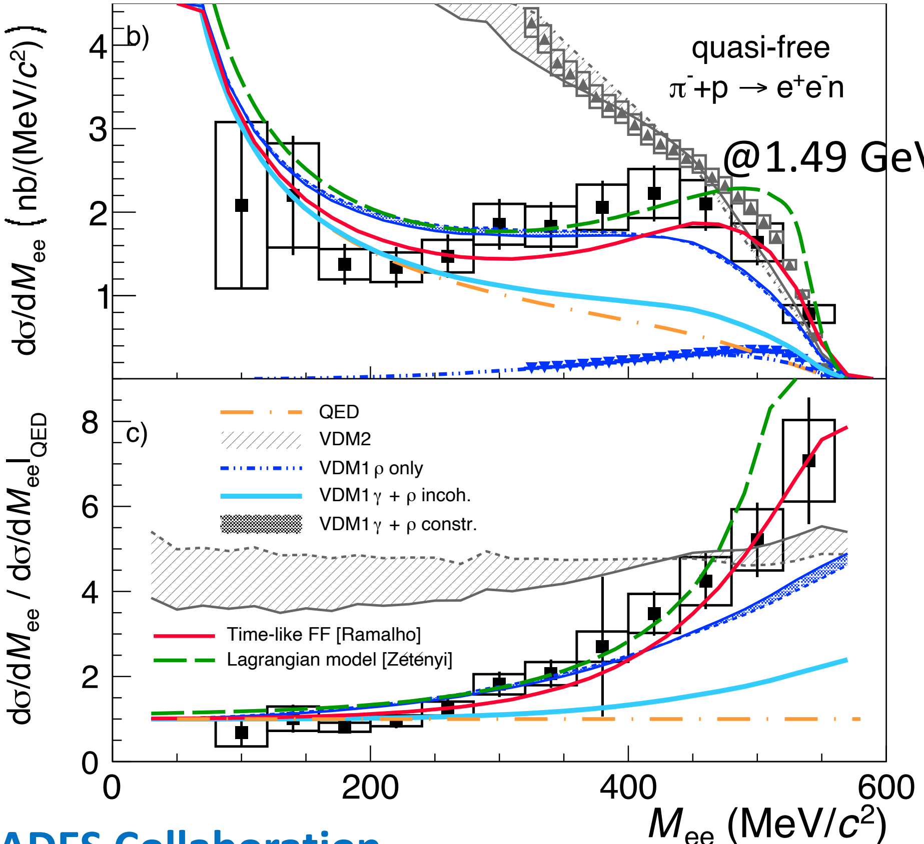
	$A_{1/2}(0)$ [$\mathrm{GeV}^{-1/2}$]		$\Gamma_{\gamma N}$ [MeV]		
	Data	Model	Estimate	PDG limits	Model
p	0.105 ± 0.015	0.101	0.49 ± 0.14	0.19–0.53	0.503
n	-0.075 ± 0.020	-0.074	0.25 ± 0.13	0.013–0.44	0.240

Dilepton mass spectrum

N*(1520) + N*(1535)

Dalitz decay

True CST prediction: Red line



Simulations based on the CST model (**red line**) for these resonances also give a satisfactory description of the data.

Below 200 MeV/c^2 , data agrees with a pointlike baryon-photon vertex (QED orange line) .

At larger invariant masses, data is more than 5 times larger than the pointlike result, showing a strong effect of the transition form factor evolution.

HADES Collaboration

"First measurement of massive virtual photon emission from N* baryon resonances" e-Prints: 2205.15914 [nucl-ex], 2022 + 2309.13357 [nucl-ex], 2023

Extension to the Strange Baryon Sector

Extend the parametrization of the e.m. current to the valence quark d.o.f of the **whole** baryon octet.

$$j_i = \frac{1}{6} f_{i+} \lambda_0 + \frac{1}{2} f_{i-} \lambda_3 + \frac{1}{6} f_{i0} \lambda_s$$

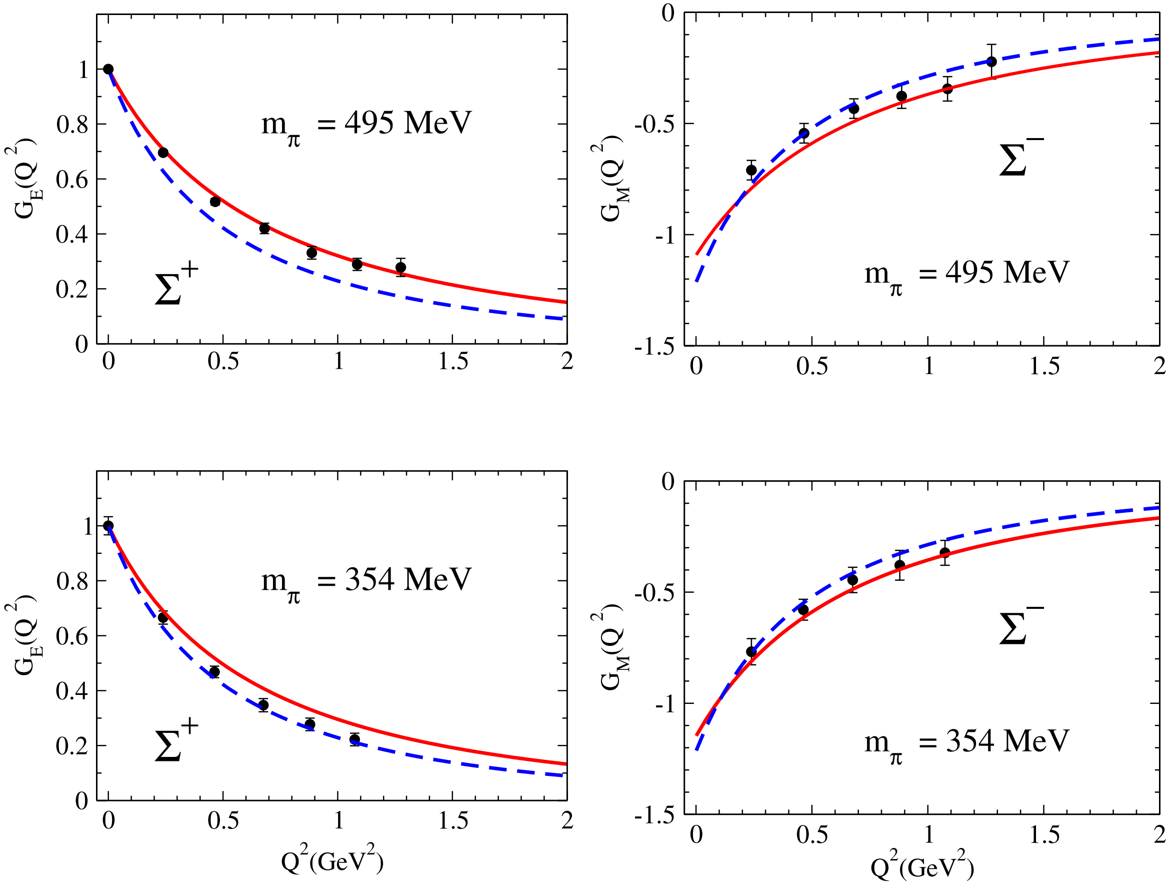
$$\lambda_0 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \qquad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\lambda_s \equiv \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

Two examples:

Red line: lattice

Blue line: physical regime



Parameters determined by
a **global fit** to
octet baryon lattice data for the
e.m. form factors
and physical magnetic moments.

Lattice data:
H.W. Lin and K. Orginos,
Phys. Rev. D 79, 074507 (2009).

G. Ramalho and K.Tsushima, PRD 84, 054014 (2011)

Post 2020 Hyperon data evolution

	G	$\frac{G_E}{G_M}$	$\Delta\Phi$	Experiment	q^2 range (GeV^2)
Λ	$\surd$			BESIII23 [13]	5.0–8.7
	$\surd$			BESIII21 [16]	12.3–21.2
	$\surd$			BaBar06 [8], CLEO [31, 32]	
		$\surd$	$\surd$	BESIII22 [15]	14.2
		$\surd$	$\surd$	BESIII23 [14]	13.8 †
	$\surd$	$\surd$	$\surd$	BESIII19 [22]	5.7
	$\surd$	$\surd$		BaBar07 [9]	
Σ^+	$\surd$	$\surd$	$\surd$	BESIII23 [10]	5.7–8.4
	$\surd$	$\surd$		BESIII21 [19]	5.7–9.1
	$\surd$			CLEO [31, 32]	
Ξ^-	$\surd$			BESIII23 [11]	9.6–23.5
	$\surd$			BESIII20 [21]	16.1–21.2

CST compared to Recent Hyperon FF data

Use S.Pacetti, R. Baldini Ferroli and E. Tomasi-Gustafsson, Phys. Rept. 550-551,1 (2015):

Unitarity and Analyticity demand that for $q^2 \to \infty$

$$G_M(q^2) \simeq G_M^{\rm SL}(-q^2),$$
$$G_E(q^2) \simeq G_E^{\rm SL}(-q^2).$$

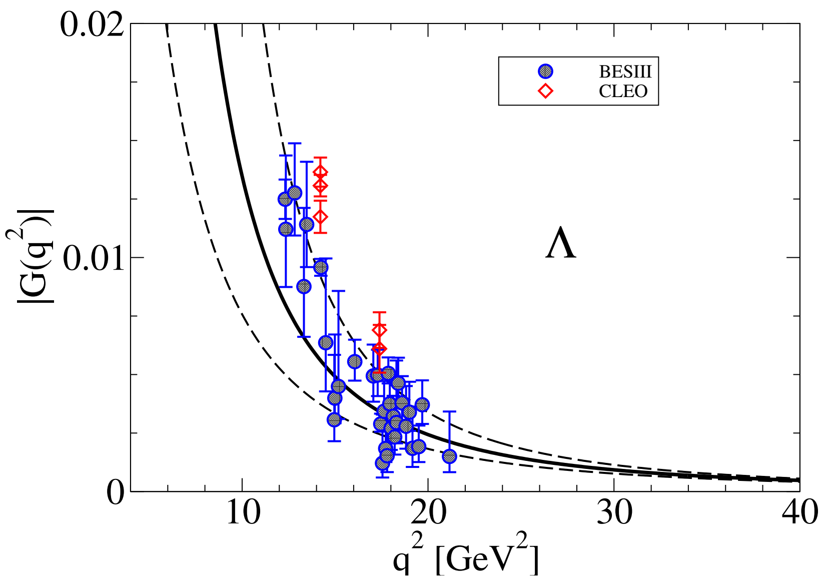
Guidance for determination of onset of "reflection" symmetry

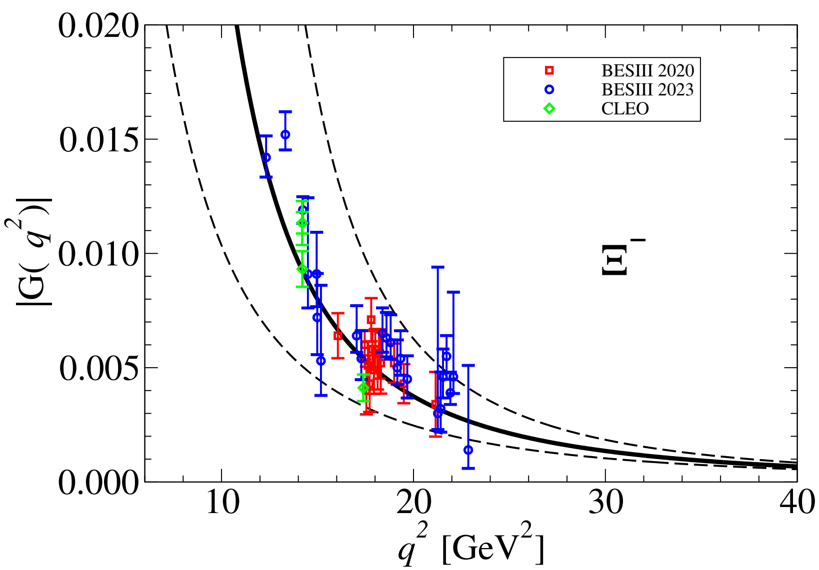
Uncertainty:

Full line: $G(q^2) = G(2M^2 - q^2)$

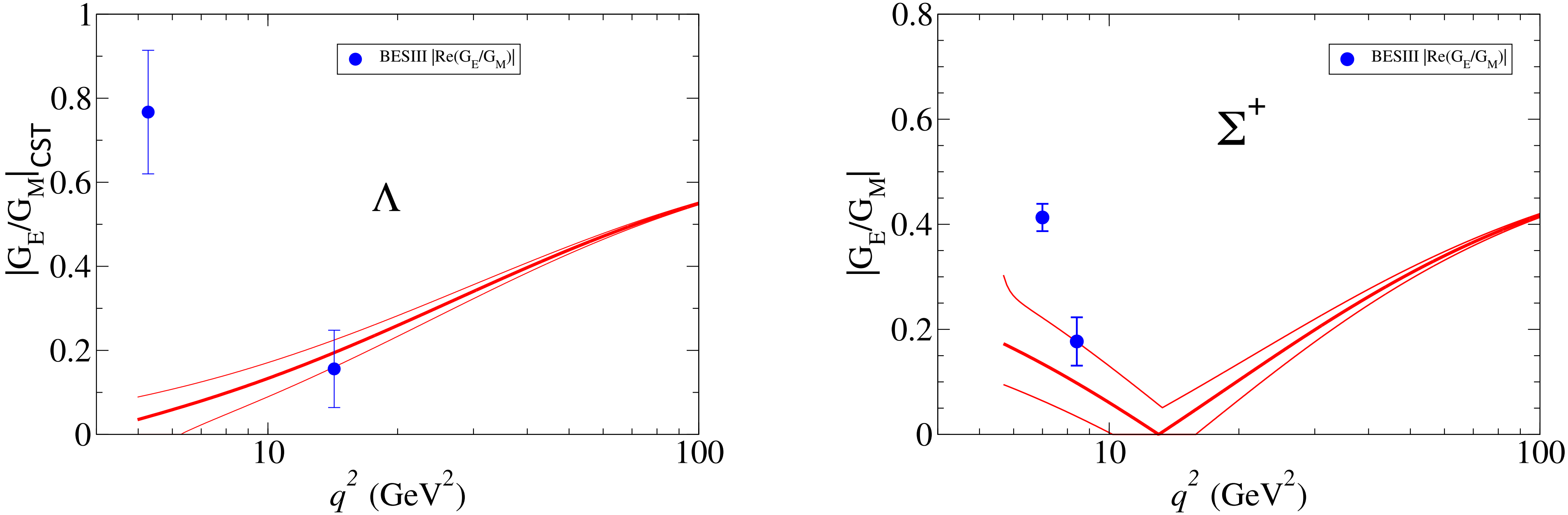
Dashed lines: $G(q^2) = G(4M^2 - q^2)$

$G(q^2) = G(-q^2)$





$$\left|\mathrm{Re}\left(\frac{G_E}{G_M}\right)\right| = \frac{|G_E|}{|G_M|}\,|\cos(\Delta\Phi)|,$$



Summary

CST phenomenological ansatz for the baryon wave functions describes

different excited states of the nucleon, with a variety of spin and orbital motion.

1 Descriptions consistent with experimental data at high Q^2=-q^2.

2 Model made consistent with LQCD in the large pion mass regime (through VMD).

3 Spacelike e.m. transition FFs for:
N*(1440), N*(1520), N*(1535), ..., baryon octet, etc.

4 Extension to timelike e.m. transition FFs for dilepton mass spectrum and decay widths, and hyperon form factors; predictive power demonstrated.

5 Investigate low q^2 momentum transfer region:
Determine timelike form factors of higher mass states for knowledge of proton and the neutron electromagnetic couplings (q2=0) in the transitions.

Our approach is phenomenological,
in the best tradition of the beginnings of Hadron Physics

"Murray looked at two pieces of paper, looked at me and said
'***In our field it is costumary to put theory and experiment on the same piece of paper***'."

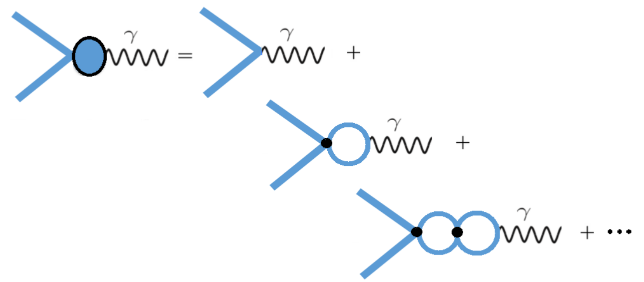
Memories of Murray and the Quark Model
George Zweig, Int.J.Mod.Phys.A25:3863-3877,2010

Zweig quark or the constituent quark

Back up slides

$$f(Q^2) = e + gB(Q^2)e + gB(Q^2)gB(Q^2)e + \cdots = e + \frac{gB(Q^2)e}{1 - gB(Q^2)}$$

if $gB(Q^2) = \frac{\lambda^2}{\Lambda^2 + Q^2}$, then $f(Q^2) = e + \frac{\lambda^2 e}{\Lambda^2 - \lambda^2 + Q^2}$



$$f_{1+} = \lambda + \frac{1-\lambda}{1 + Q_0^2/m_v^2} + \frac{c_\pm Q_0^2/M_h^2}{\left(1 + Q_0^2/M_h^2\right)^2}$$

$$f_{2\pm} = \kappa_\pm \left(\frac{d_\pm}{1 + Q_0^2/m_v^2} + \frac{(1 - d_\pm)}{1 + Q_0^2/M_h^2} \right)$$

$$\Gamma_\mu(p,Q) = \gamma_\mu + \int \frac{d^4q}{(2\pi)^4} K(p,q,Q) S(q+\eta Q) \Gamma_\mu(q,Q) S(q-\eta Q)$$

To parametrize the current use Vector Meson Dominance at the quark level a truncation to the rho and omega poles of the full meson spectrum contribution to the quark-photon coupling.

4 parameters

$$\frac{m_v^2}{m_v^2 - q^2} \rightarrow \frac{m_v^2}{m_v^2 - q^2 - i m_v \Gamma_v(q^2)},$$

$$\Gamma_\rho(q^2) = \Gamma_\rho^0 \frac{m_\rho^2}{q^2}\left(\frac{q^2-4m_\pi^2}{m_\rho^2-4m_\pi^2}\right)^{\frac{3}{2}} \theta(q^2-4m_\pi^2), \quad (4.7)$$

where $\Gamma_\rho^0 = 0.149$ GeV.

For the application in this paper, however, we also have to include the ω pole. To this end, the function $\Gamma_\omega(q^2)$ will include the decays $\omega \to 2\pi$ (function $\Gamma_{2\pi}$) and $\omega \to 3\pi$ (function $\Gamma_{3\pi}$). The case $\omega \to 3\pi$ can be interpreted as the process $\omega \to \rho\pi \to 3\pi$, and therefore we decomposed $\Gamma_\omega(q^2)$ into [44]

$$\Gamma_\omega(q^2) = \Gamma_{2\pi}(q^2) + \Gamma_{3\pi}(q^2), \quad (4.8)$$

$$\Gamma_{2\pi}(q^2) = \Gamma_{2\pi}^0 \frac{m_\omega^2}{q^2}\left(\frac{q^2-4m_\pi^2}{m_\omega^2-4m_\pi^2}\right)^{\frac{3}{2}} \theta(q^2-4m_\pi^2), \quad (4.9)$$

where $\Gamma_{2\pi}^0 = 1.428 \times 10^{-4}$ GeV. Note that $\Gamma_{2\pi}$ is similar to the function Γ_ρ except for the constant $\Gamma_{2\pi}^0$ (about 10^3 smaller) and the mass. For the function $\Gamma_{3\pi}$ we use the result from Ref. [44]

$$\Gamma_{3\pi}(q^2) = \int_{9m_\pi^2}^{(q-m_\pi)^2} ds\, \mathcal{A}_\rho(s)\bar{\Gamma}_{\omega\to\rho\pi}(q^2,s), \quad (4.10)$$

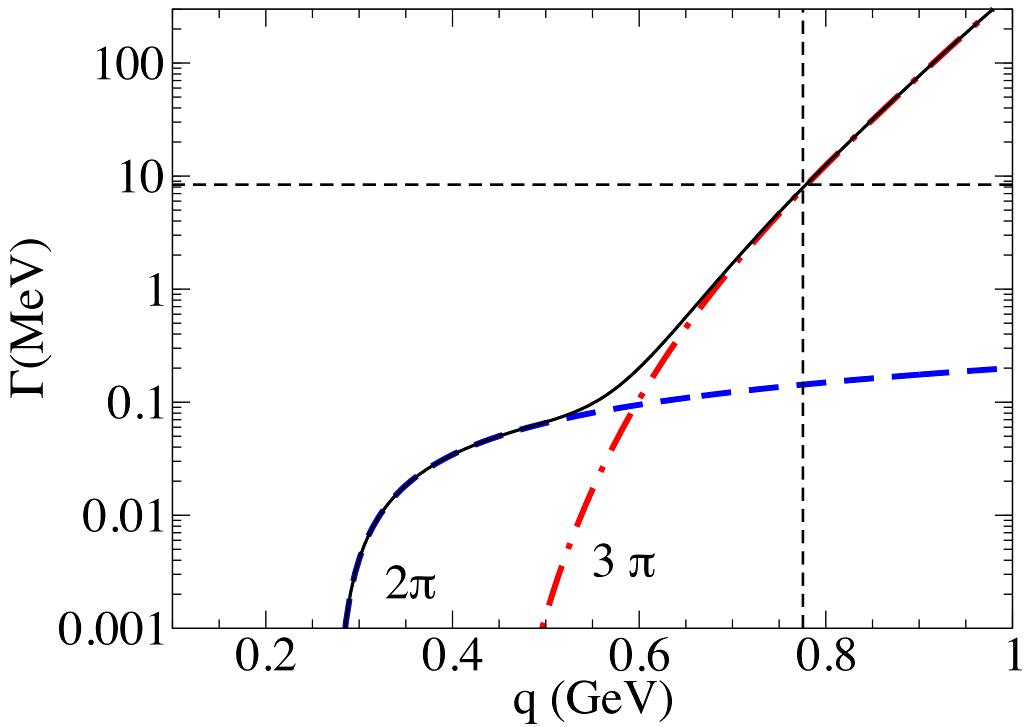


FIG. 1: Γ_ω as a function of q. The 2π, 3π channels are indicated by the long-dashed and dotted-dashed lines respectively. The solid line represents the sum of the two channels. The short-dashed vertical and horizontal lines indicate the ω mass point and the ω-physical width (8.4 MeV).

Extension to Strangeness in the timelike region

CST seems to work well at large Q^2.

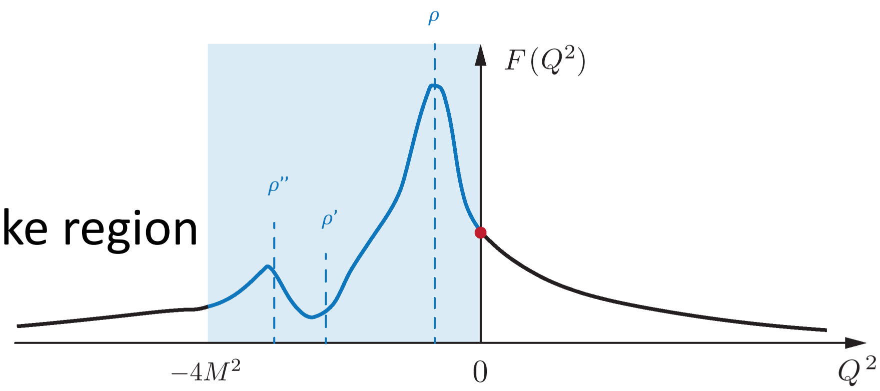
$$e^+e^- \to \gamma^* \to B\bar{B}$$

Use S.Pacetti, R. Baldini Ferroli and E. Tomasi-Gustafsson, Phys. Rept. 550-551,1 (2015).

Unitarity and Analyticity demand that for $q^2 \to \infty$

Reflection symmetry sets in, implying real form factor as in the space like region

$$G_M(q^2) \simeq G_M^{\rm SL}(-q^2),$$
$$G_E(q^2) \simeq G_E^{\rm SL}(-q^2).$$



Effective Form factor that gives the integrated cross section

$$|G(q^2)|^2 = \left(1+\frac{1}{2\tau}\right)^{-1}\left[|G_M(q^2)|^2+\frac{1}{2\tau}|G_E(q^2)|^2\right] = \frac{2\tau|G_M(q^2)|^2+|G_E(q^2)|^2}{2\tau+1}.$$

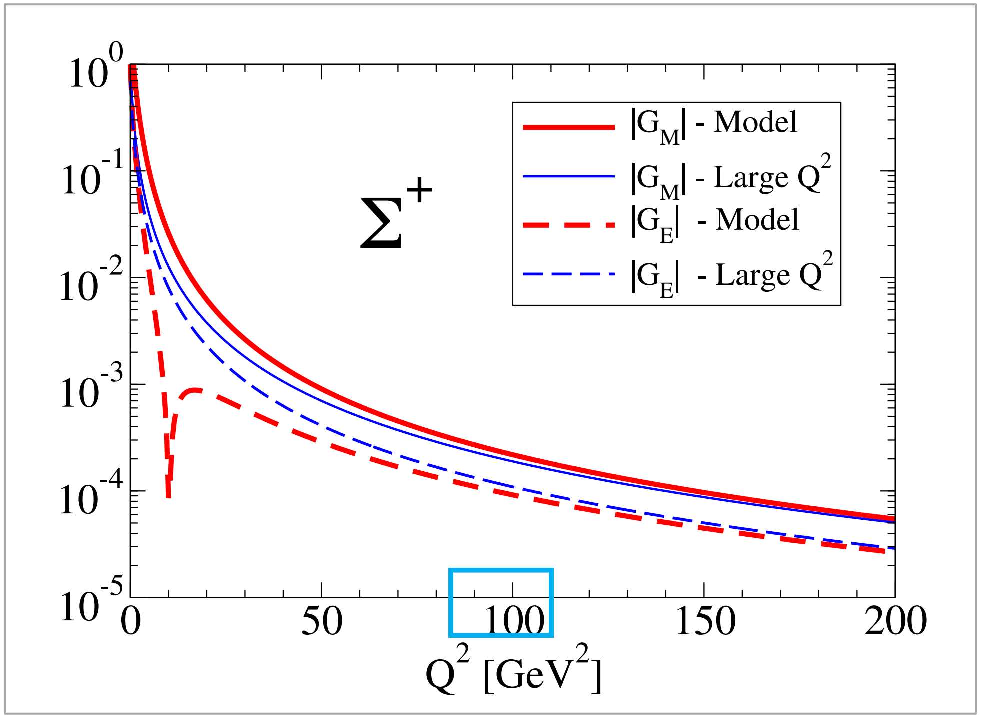
$$\tau = \frac{q^2}{4M_B^2}$$

Asymptotic behavior reached at energies higher than reflection property

$$e^+e^- \to \gamma^* \to B\bar{B}$$

Guidance for determination of onset of perturbative QCD falloffs:

$G_M \propto 1/q^4$ and $G_E \propto 1/q^4$.



Perturbative QCD limit is way above the region
where reflection symmetry starts to be valid **(100 GeV^2 versus 10 GeV^2)**

G. Ramalho and M.T.P. Phys.Rev.D 101 (2020) 1, 014014, (2020)

Timelike region

$\Delta(1232)$ Dalitz decay

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

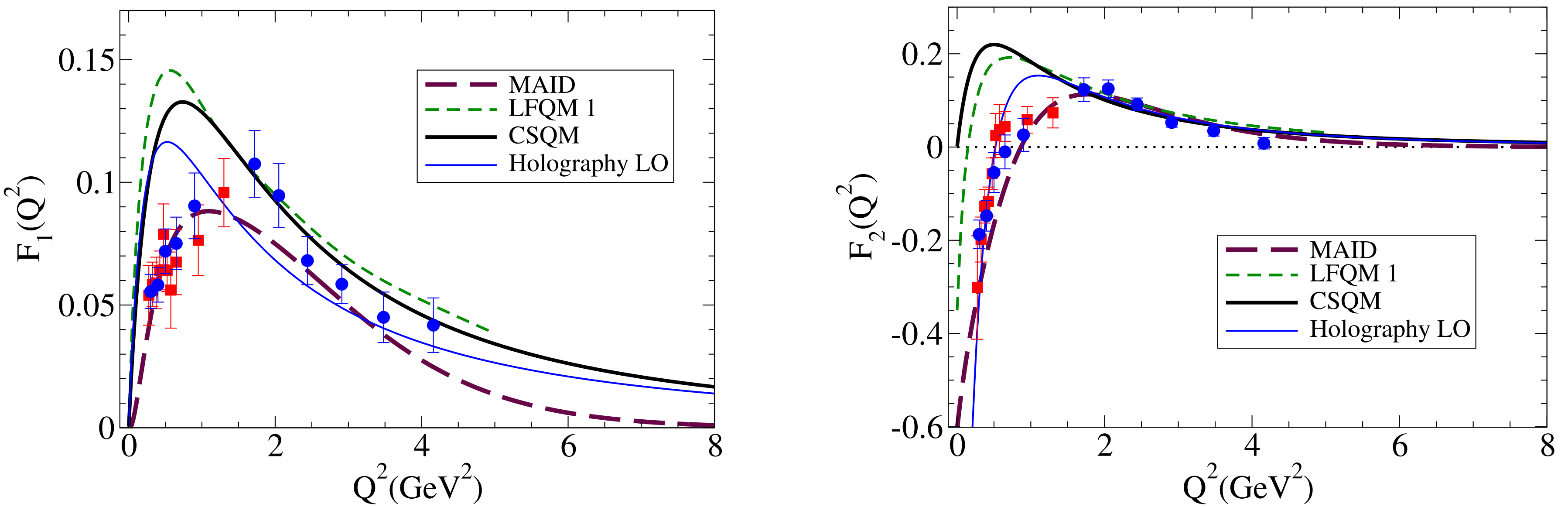
$$|G_T(q^2;M_\Delta)|^2 = |G_M^*(q^2;W)|^2 + 3|G_E^*(q^2;W)|^2 + \frac{q^2}{2W^2}|G_C^*(q^2;W)|^2$$

$$y_\pm = (W \pm M)^2 - q^2$$

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

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

$N \to N^*(1440)$ **TFFs** J^P=1/2$^+$ I=1/2



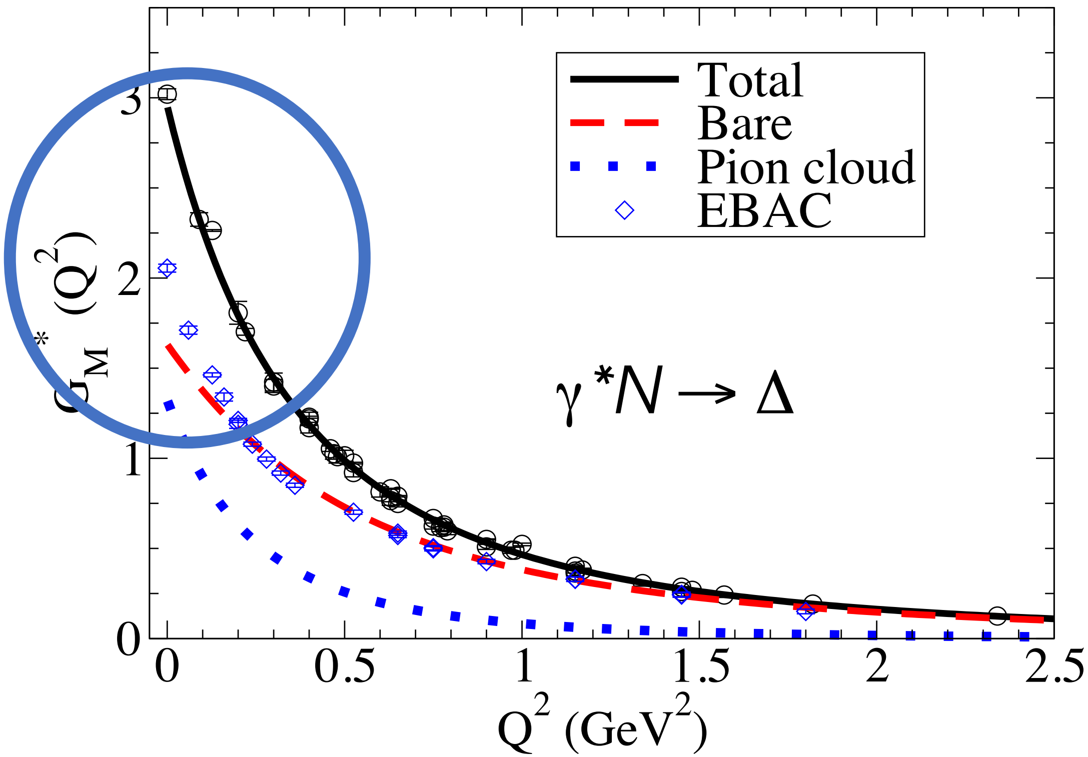
G. Ramalho, M. T. P. , Prog. Part. Nucl. Phys., 2023

Model independent feature (Covariant Spectator Theory)

$$\gamma N \to \Delta$$

Missing strength of of G_M at the origin.
Separation between quark core and pion cloud seems to be supported by experiment.

$$G^*_M = G^B_M + G^\pi_M$$



CST© 2009

Bare quark core:

- dominates in the large Q^2 region.
- agrees with other calculations ("EBAC") with pion couplings switched off.

Transition E.M. Current

$$\gamma N \longrightarrow \Delta$$

$$\Gamma^{\beta\mu}(P,q) = \left[G_1 q^\beta \gamma^\mu + G_2 q^\beta P^\mu + G_3 q^\beta q^\mu - G_4 g^{\beta\mu}\right]\gamma_5$$

- Only 3 G_i are independent:
  E.M. Current has to be conserved

$$q^\mu \Gamma_{\beta\mu} = 0 \quad \Longrightarrow$$

G_M, G_E, G_C Scadron-Jones popular choice.

Transition E.M. Current

$$\gamma N \rightarrow \Delta$$

$$\Gamma^{\beta\mu}(P,q) = \left[G_1 q^\beta \gamma^\mu + G_2 q^\beta P^\mu + G_3 q^\beta q^\mu - G_4 g^{\beta\mu}\right]\gamma_5$$

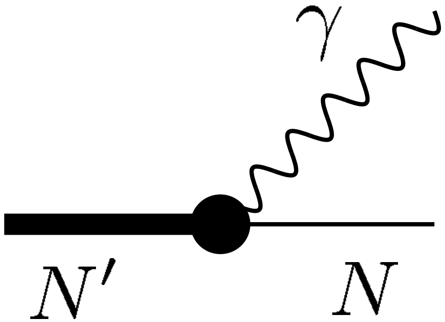
- Only 3 G_i are independent:
  E.M. Current has to be conserved

$$q^\mu \Gamma_{\beta\mu} = 0$$ ➡

G_M, G_E, G_C Scadron-Jones popular choice.

- Only finite G_i are physically acceptable.

Extension to Timelike



R rest frame

$$P_R = (W, 0, 0, 0); \qquad P_N = (E_N, 0, 0, -|\mathbf{q}|); \qquad q = (\omega, 0, 0, |\mathbf{q}|)$$

Timelike $q^2 > 0$

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

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

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

Spacelike $-q^2 = Q^2 > 0$

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

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

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

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

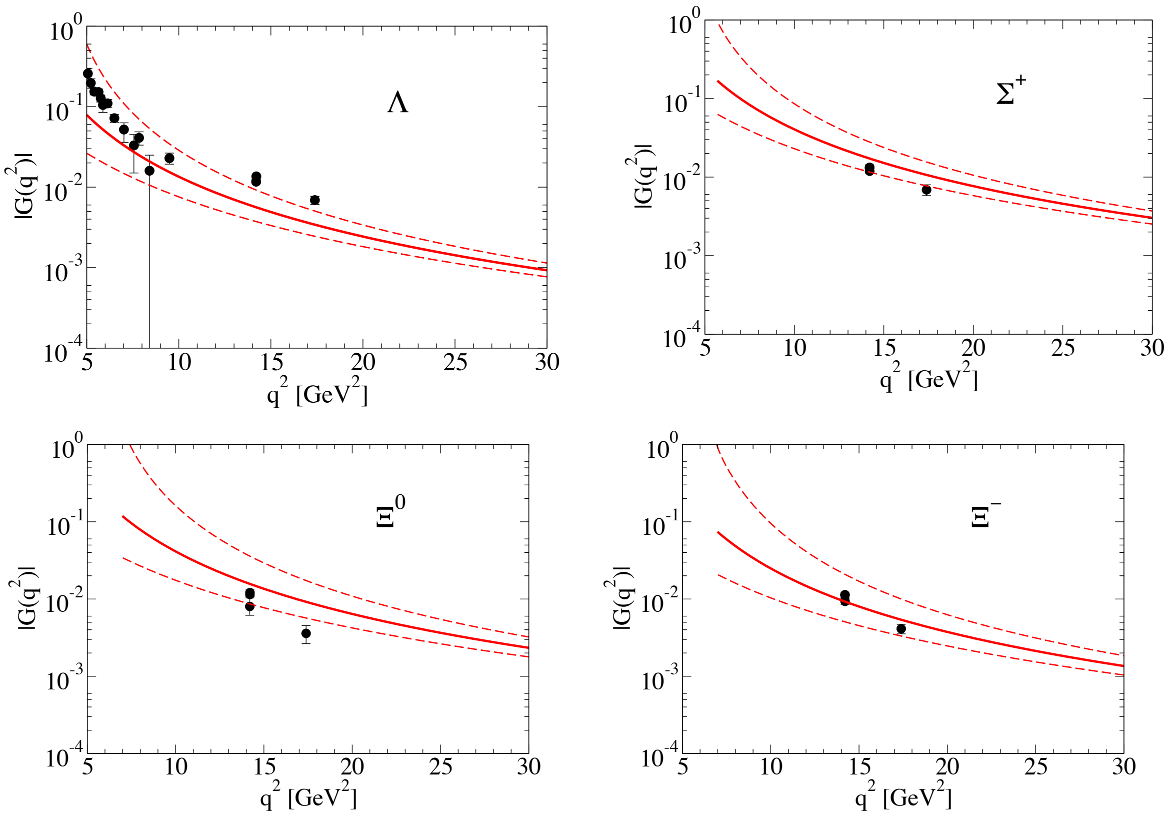
$W \geq M$

Transition form factors in the timelike region are restricted to a given kinematic region that depends on the varying resonance mass W.

Extension to Strangeness in the timelike region

$e^+e^- \to \gamma^* \to B\bar{B}$

Data from Babar, CLEO,BESIII



$$G_M(q^2) \simeq G_M^{\rm SL}(-q^2),$$
$$G_E(q^2) \simeq G_E^{\rm SL}(-q^2).$$

Uncertainty bar:

Full line: $G(q^2) = G(2M^2 - q^2)$

Dashed lines: $G(q^2) = G(4M^2 - q^2)$

$G(q^2) = G(-q^2)$

Guidance for determination of onset of ”reflection” symmetry

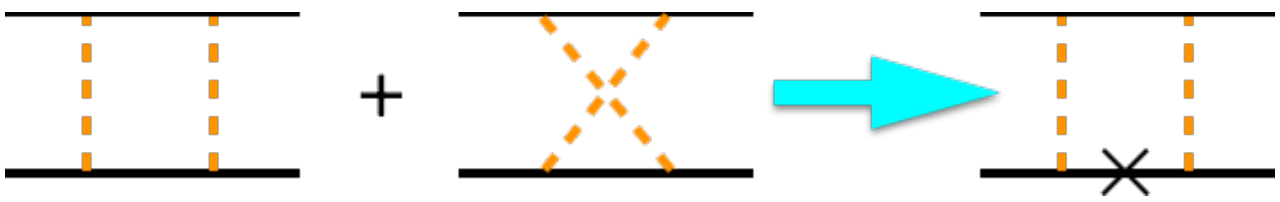
G. Ramalho and M.T.P. Phys.Rev.D 101 (2020) 1, 014014, (2020)

	G	$\frac{G_E}{G_M}$	$\Delta\Phi$	Experiment	q^2 range (GeV^2)
Λ	$\surd$			BESIII23 [13]	5.0–8.7
	$\surd$			BESIII21 [16]	12.3–21.2
	$\surd$			BaBar06 [8], CLEO [31, 32]	
		$\surd$	$\surd$	BESIII22 [15]	14.2
		$\surd$	$\surd$	BESIII23 [14]	13.8 †
	$\surd$	$\surd$	$\surd$	BESIII19 [22]	5.7
	$\surd$	$\surd$		BaBar07 [9]	
Σ^0	$\surd$			BaBar06 [8]	
Σ^+	$\surd$	$\surd$	$\surd$	BESIII23 [10]	5.7–8.4
	$\surd$	$\surd$		BESIII21 [19]	5.7–9.1
	$\surd$			CLEO [31, 32]	
Σ^-	$\surd$			BESIII21 [19]	5.7–9.1

CST© Covariant Spectator Theory

- Formulation in Minkowski space.

- Motivation is partial cancellation



- Manifestly covariant, although only three-dimensional loop integrations.

$$\int_k = \int \frac{d^3\mathbf{k}}{2E_D(2\pi)^3}$$

- Provides wave functions from covariant vertex with simple transformation properties under Lorentz boosts, appropriate angular momentum structures and smooth non-relativistic limit.

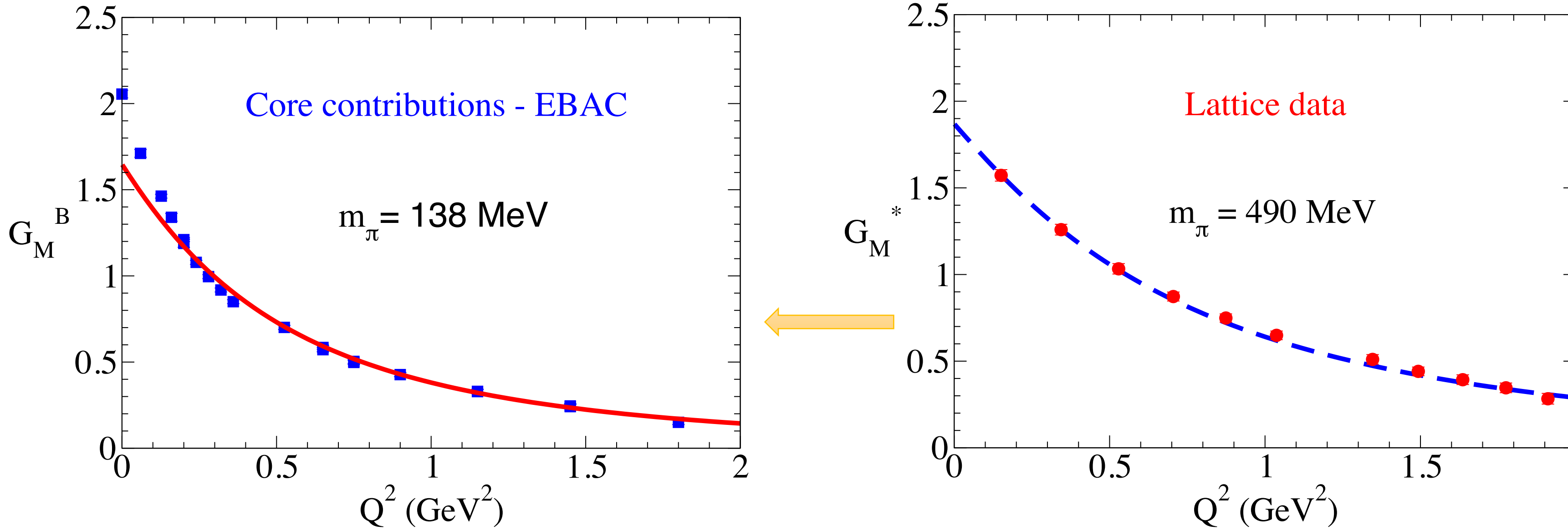
$\gamma N \rightarrow \Delta$

Connection to Lattice QCD

To control model dependence:

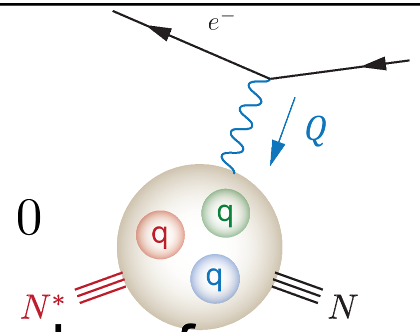
CST model and LQCD data are made **compatible.**

G. Ramalho and M. T. Peña, Phys. Rev. D 80, 013008 (2009)



Model (no pion cloud) valid for lattice pion mass regime.
No refit of wave function scale parameters for the physical pion mass limit.

E.M. Current and TFF near the photon point

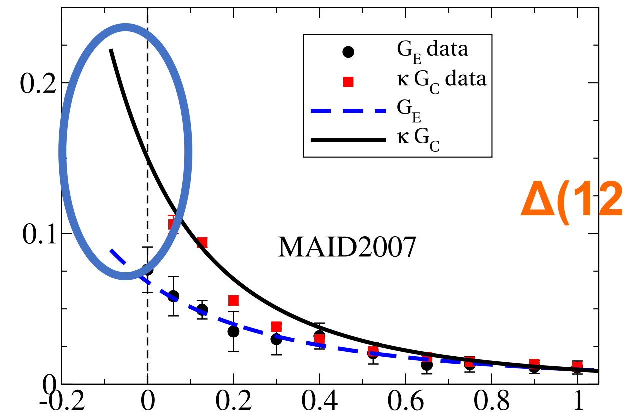


Pseudo Threshold PT $Q_0^2 = -(M_R - M_N)^2 \ ; |\vec{Q}| = 0$

An accident of the definition of the Jones and Scadron form factors:

$$G_E(PT) = \frac{M_R - M}{2M_R} G_C(PT)$$

A form of the "Siegert condition"!
This is implied by orthogonality of states.
If data analysis proceed through helicity amplitudes this behavior may be missed.



Δ(1232)

G.Ramalho Phys. Lett. B 759 (2016) 126

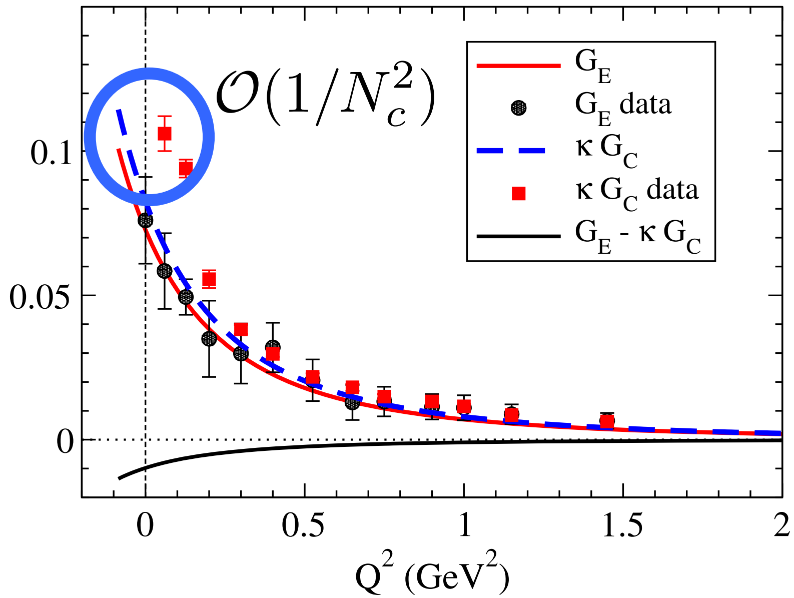
G_E and G_C

$\gamma N \to \Delta$

Large N_C limit and SU(6) quark models:

- Suggest that pion cloud effects for G_E and G_C

generate deviations from the Siegert condition of the order $\mathcal{O}(1/N_c^2)$ and do not agree to data at low Q^2.



G_E and G_C

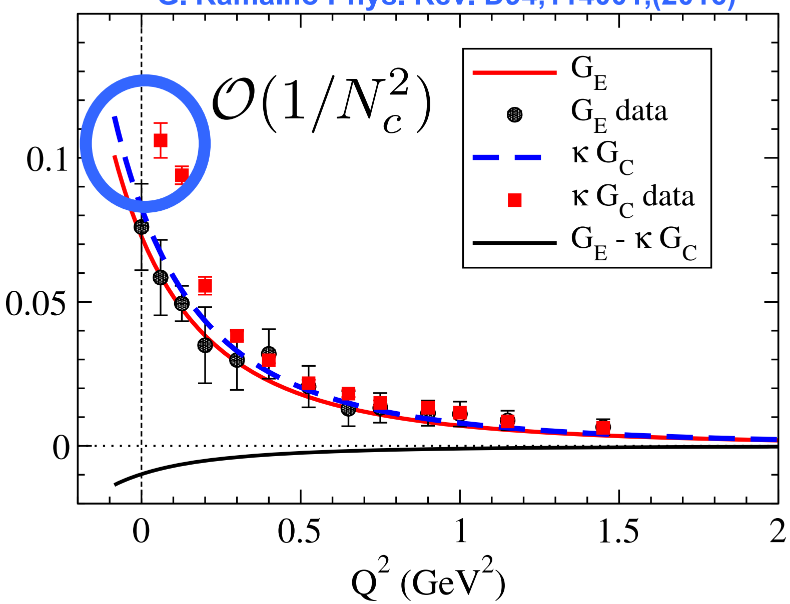
$\gamma N \to \Delta$

Large N_C limit and SU(6) quark models:

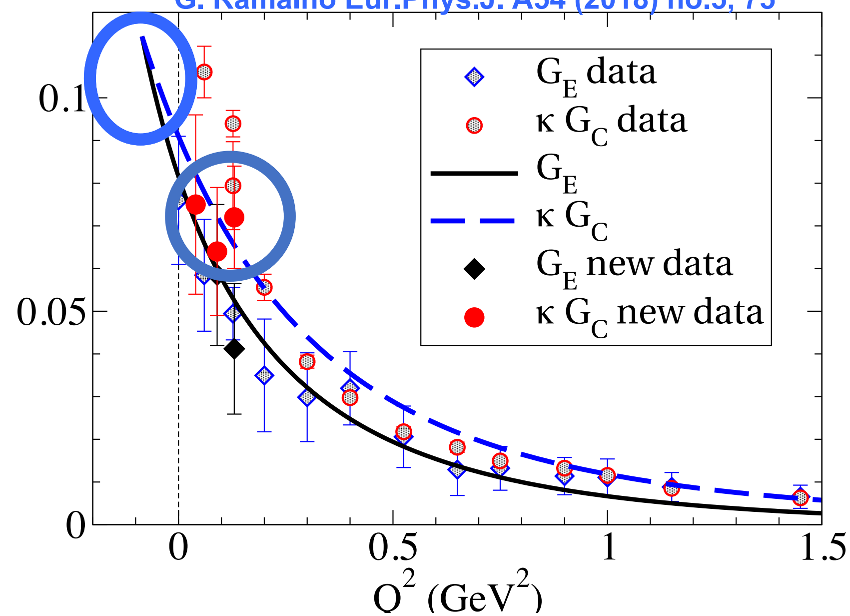
- Suggest that pion cloud effects for G_E and G_C generate deviations from the Siegert condition of the order $\mathcal{O}(1/N_c^2)$ and do not agree to data at low Q^2.

Corrected parametrization with deviations $\mathcal{O}(1/N_c^4)$ generated agreement with 2017 JLAB data

G. Ramalho Phys. Rev. D94,114001,(2016)



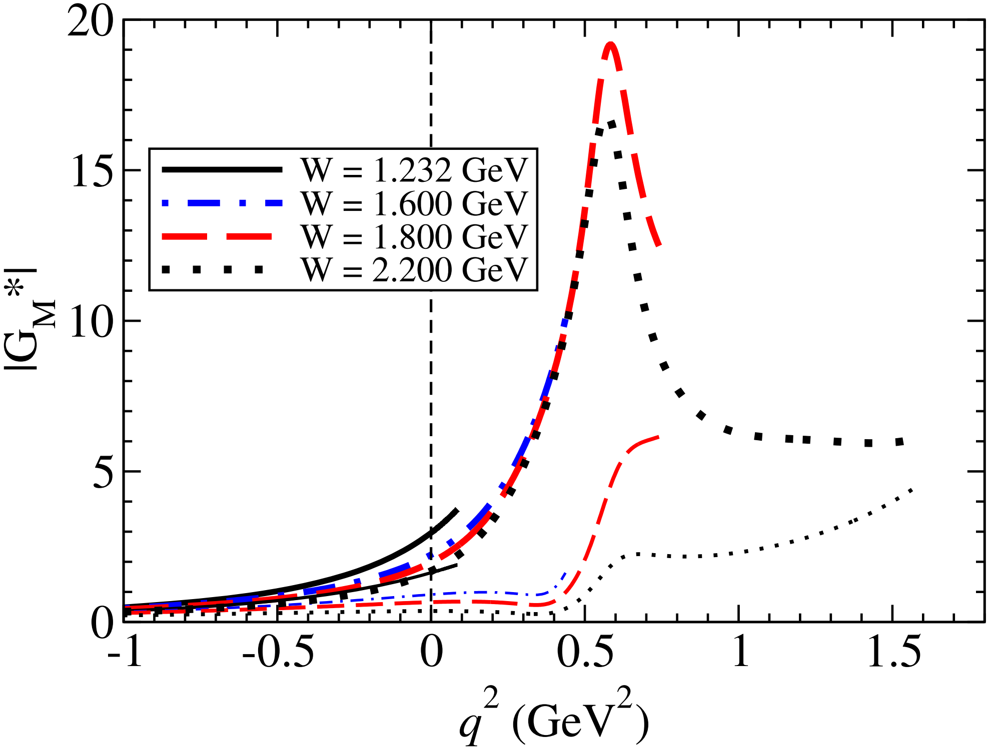
G. Ramalho Eur.Phys.J. A54 (2018) no.5, 75



Extension to Timelike

$$\gamma N \rightarrow \Delta$$

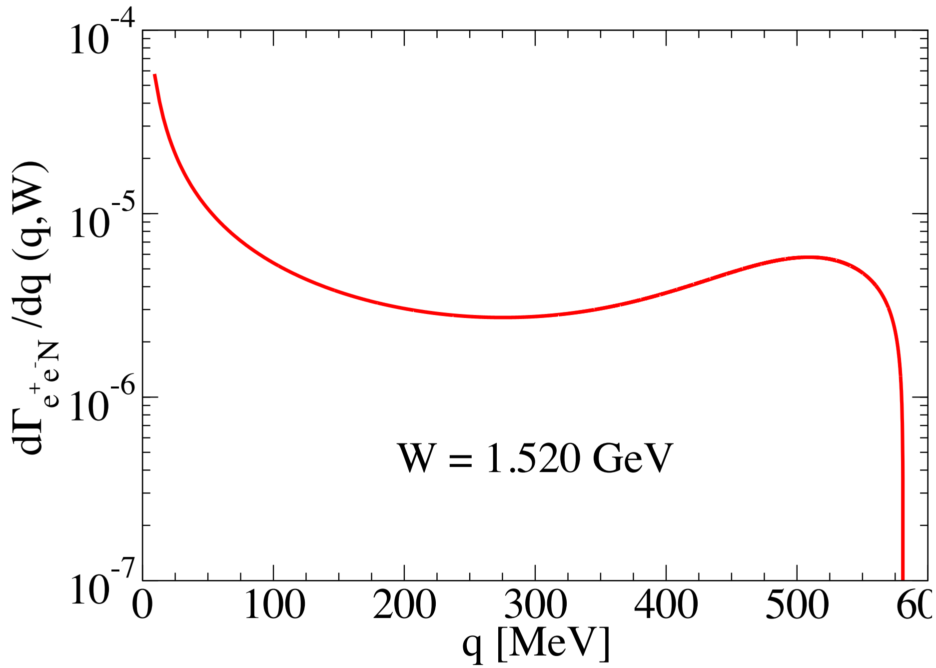
- Extension to higher W shows effect of the rho mass pole
- In that pole region small bare quark contribution (thin lines)

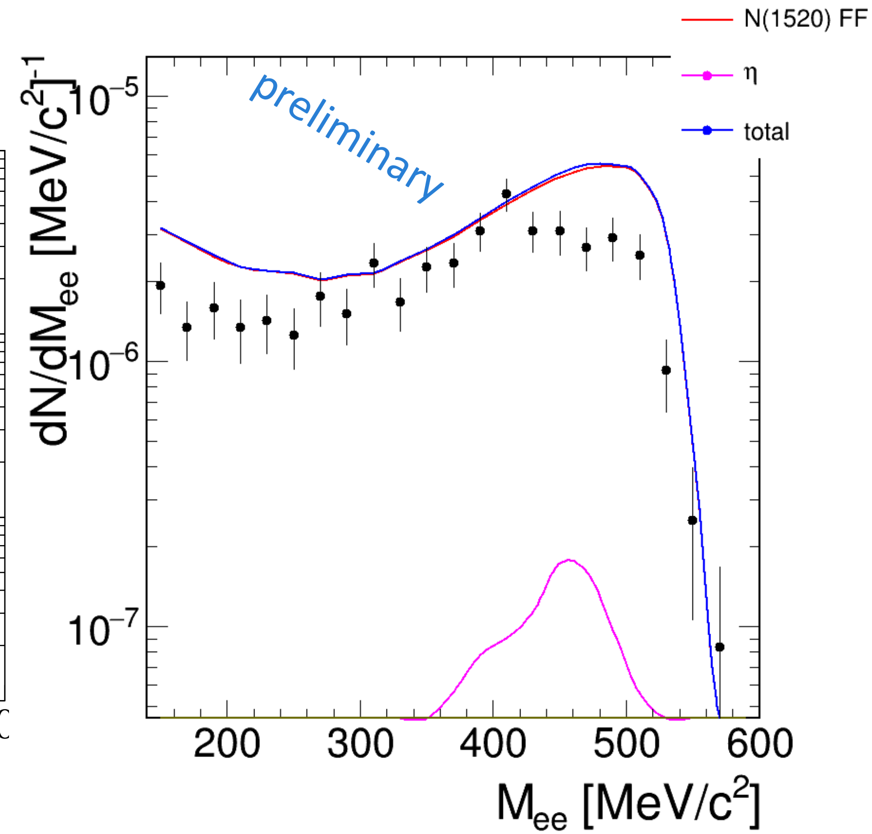


Crossing the boundaries

N*(1520) Dalitz decay

True prediction



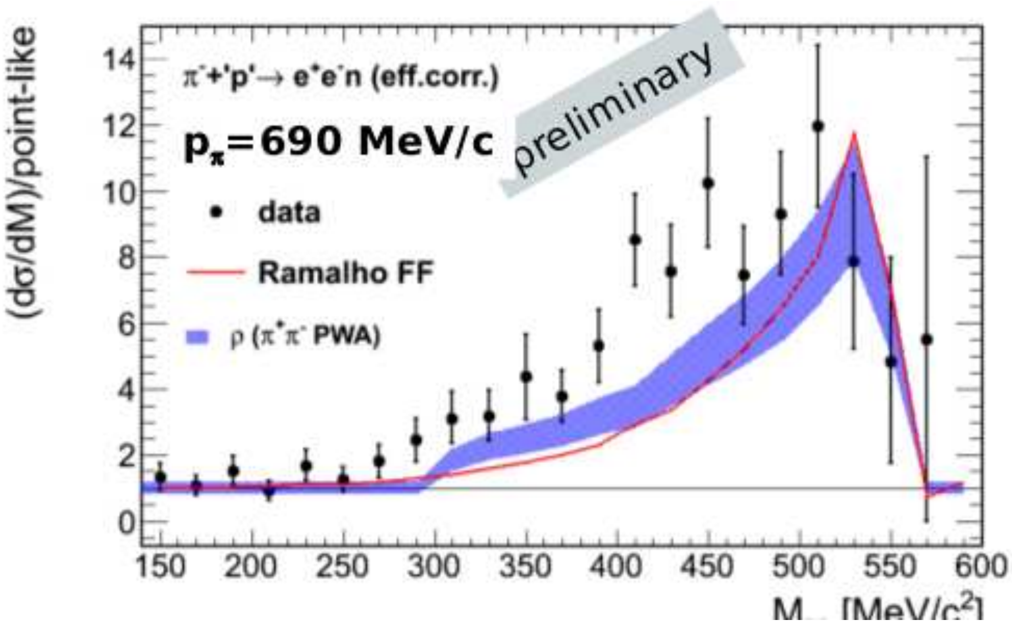


HADES Collaboration
2018

Crossing the boundaries

N*(1520) Dalitz decay

Effect of dependence of e.m. coupling with W   True prediction



B. Ramstein, NSTAR2019   HADES Collaboration

Ratio to pointlike case

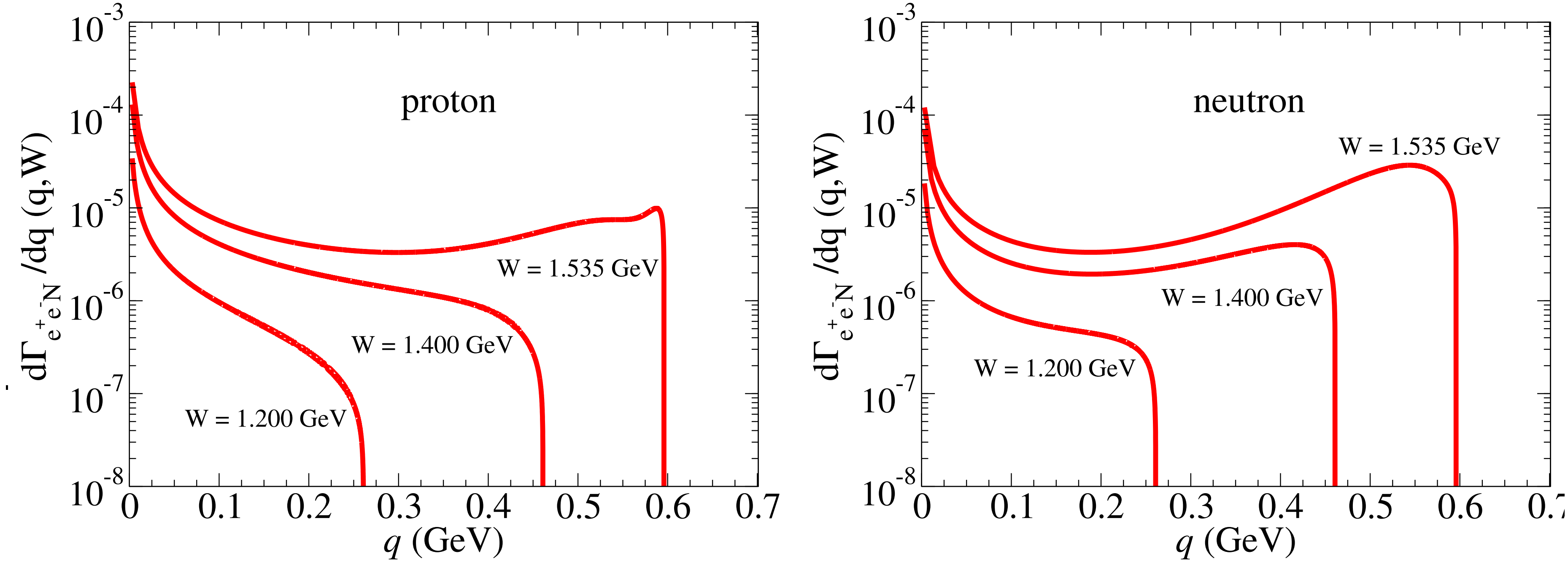
Crossing the boundaries

N*(1535) Dalitz decay

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

$$|G_T(q^2,W)|^2 = |G_E(q^2,W)|^2 + \frac{q^2}{2W^2}|G_C(q^2,W)|^2$$

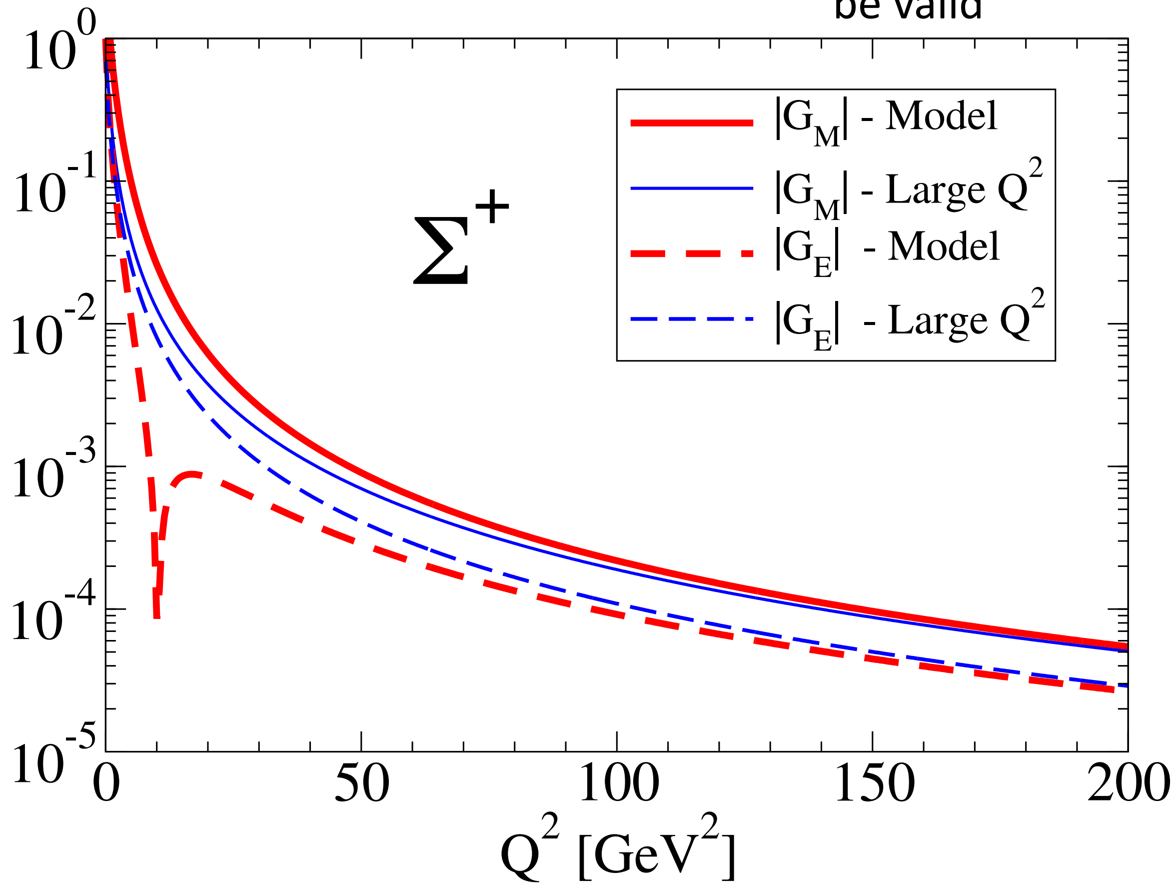
$$\frac{d\Gamma_{e+e-N}}{dq}(q,W) = \frac{2\alpha}{3\pi q^3}(2\mu^2+q^2)\sqrt{1-\frac{4\mu^2}{q^2}}\,\Gamma_{\gamma^* N}(q,W),$$



Asymptotic behavior

$$e^+e^- \to \gamma^* \to B\bar{B}$$

Perturbative QCD limit is way above the region where refletion symmetry starts to be valid



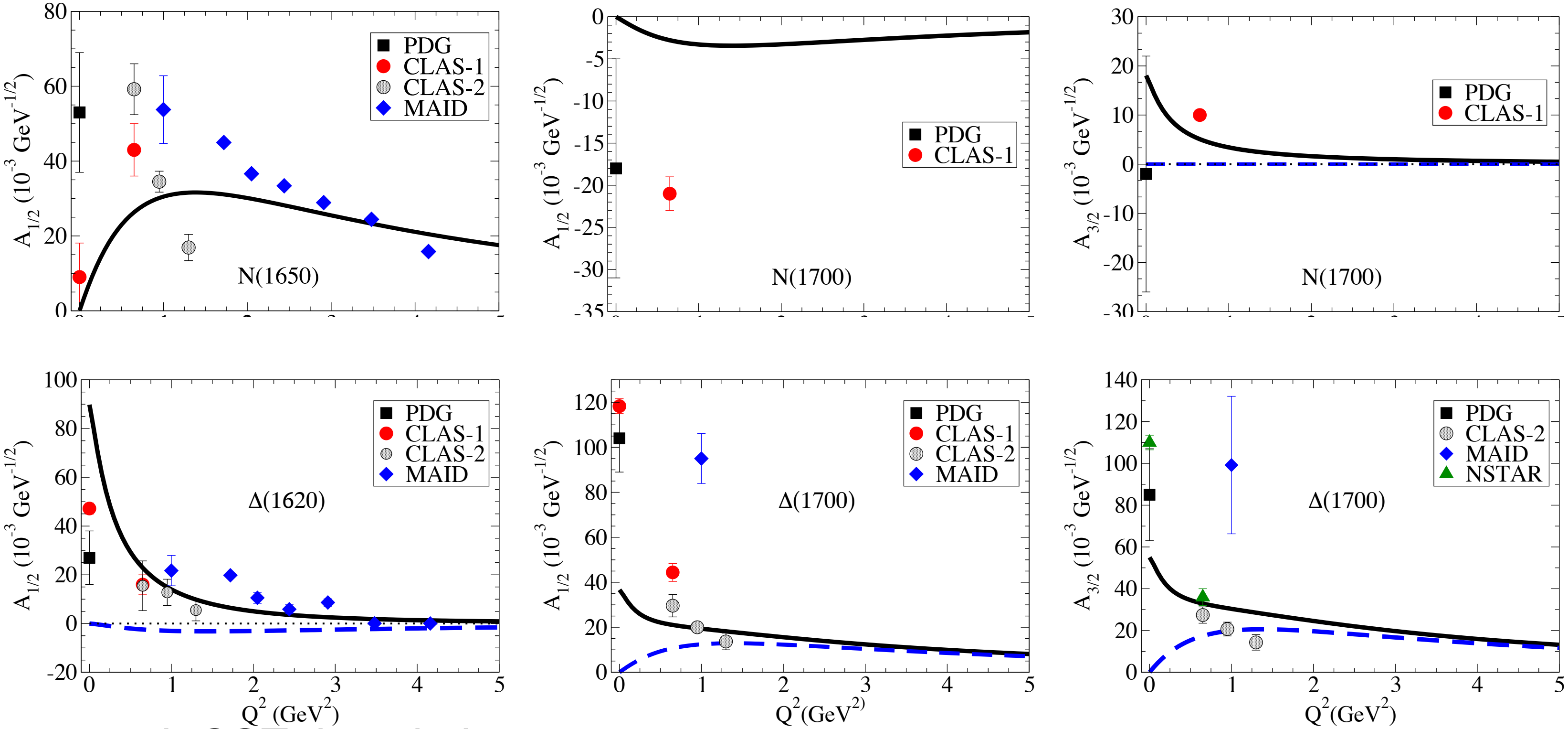
Predictive power:

D13(J=3/2-)   **S11**(J=1/2-)   (I=1/2)   are part of a large supermultiplet (SU(6) spin-flavor with O(3) symmetry)

S. Capstick and W. Roberts, Prog. Part. Nucl. Phys. 45, S241 (2000); V. D. Burkert et al. Phys. Rev. C 67, 035204 (2003).

Input: $N(1520), N(1535)$; **Output:** $N(1650), N(1700), \Delta(1620), \Delta(1700)$

D13   **S11**   **S11**   D13   **S31**   D33



Bare quark CST description expected to work well in high Q^2 region!

G. Ramalho , PRD 90, 033010 (2014)