Baryon electromagnetic transition form factors in the Covariant Spectator Theory

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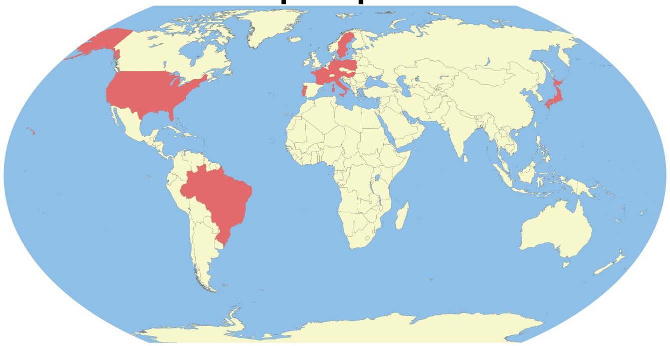
Kandisky "Circles in a circle" (1923)

TÉCNICO LISBOA

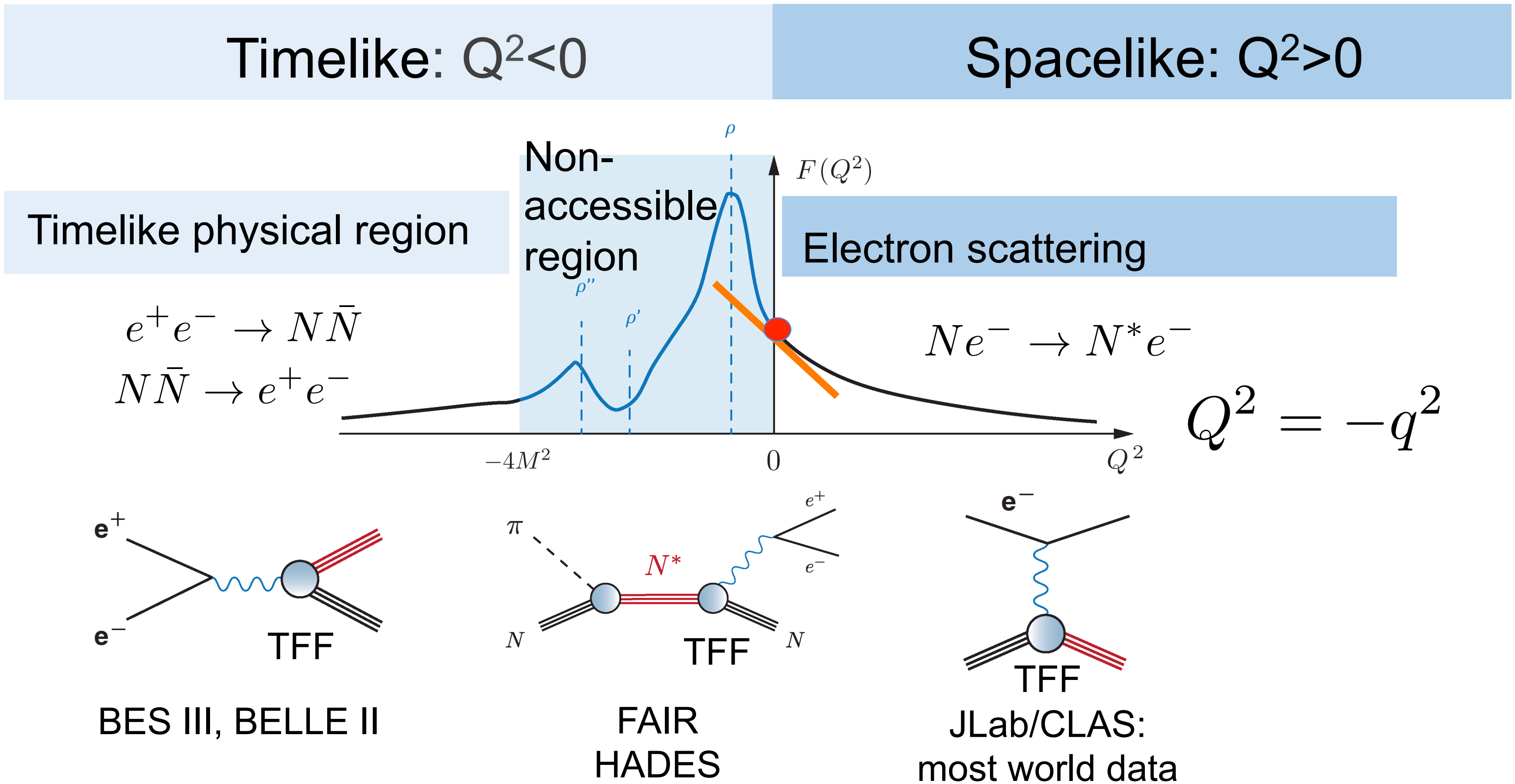
Baryon electromagnetic transition form factors in the Covariant Spectator Theory

Exciting near-future prospects of high-quality data.
Expand our knowledge of the spectrum and structure properties of baryons.

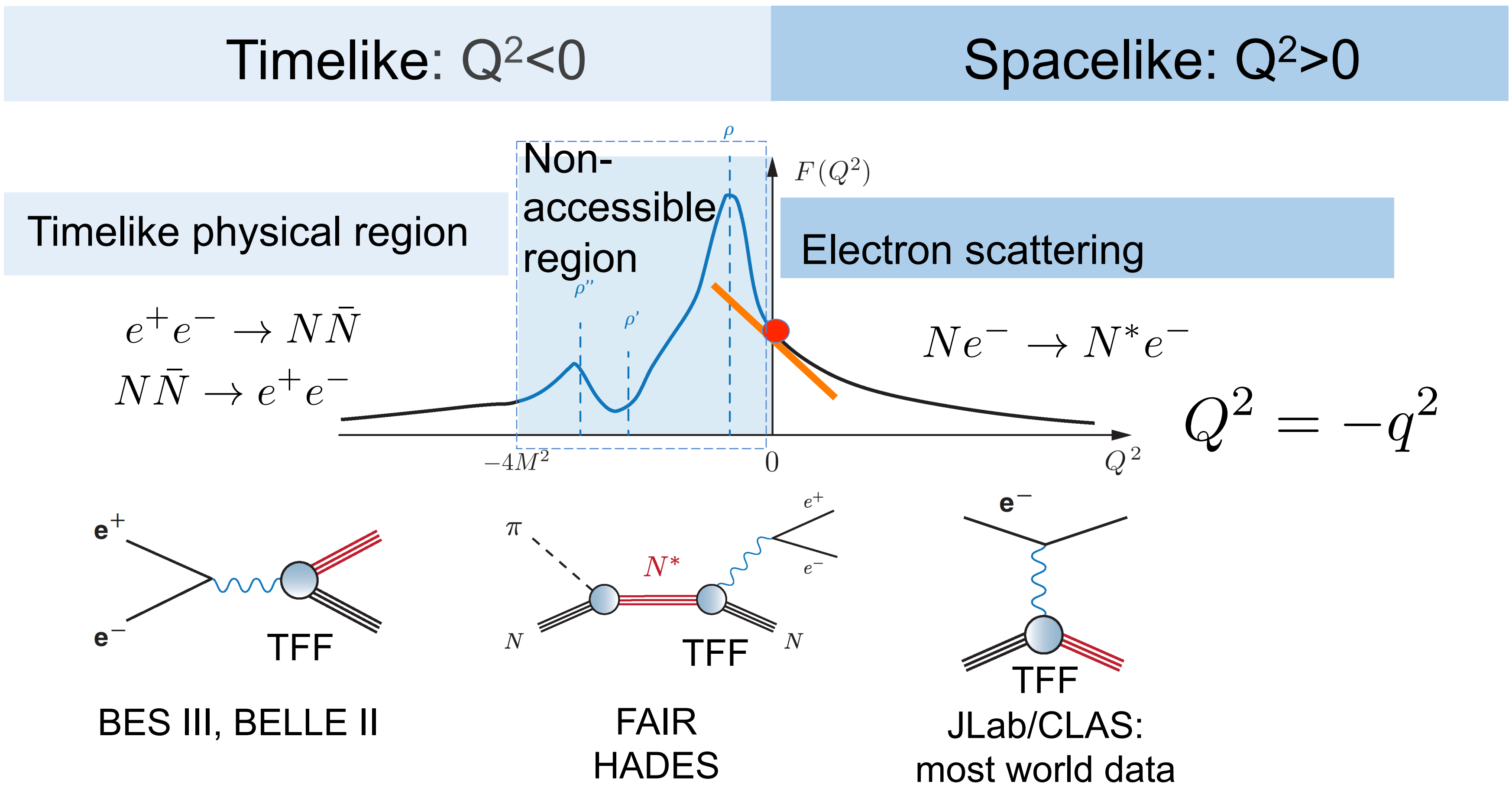


Missing resonances?
Diquark clusters?

Crossing the boundaries to explore baryon resonances

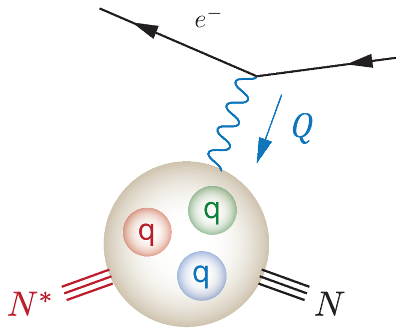


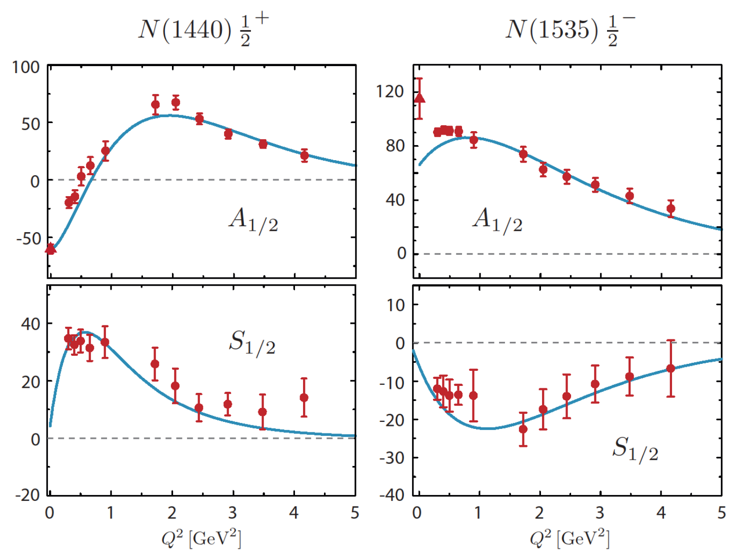
Crossing the boundaries to explore baryon resonances



CLAS/JLab electron scattering data constrain interpretation of HADES dilepton production data. Results have to match at the photon point.

Transition form factors





Baryon resonances
transition form factors

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

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

Spacelike form factors:

- Structure information: shape, qqq excitation vs. hybrid, ...
- Evolution of quark-photon coupling with momentum transfer

Timelike form factors:

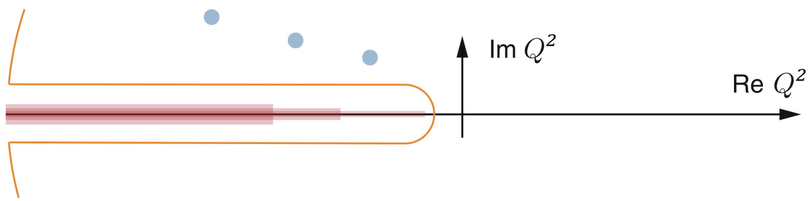
- Particle production channels: vector mesons at small q^2
- Test of vector meson dominance
- In-medium dilepton production

This talk:
Connect Timelike and SpacelikeTransition Form Factors (TFF)
Baryon-photon coupling evolution with momentum transfer

Theoretical toolkits

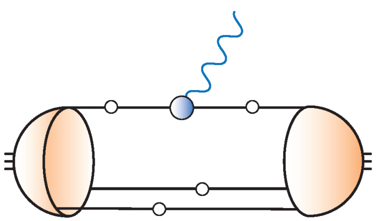
Timelike baryon transition form factors not yet within reach in lattice QCD:
explore alternative methods, estimate theory uncertainty!

- **Analyticity**

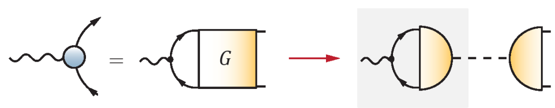


→ Dispersion theory

- **Dynamics**

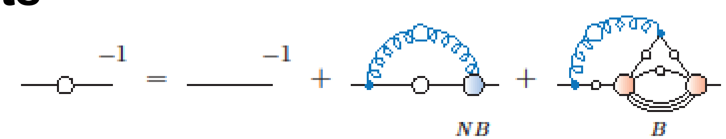


Quark-photon coupling
dynamically generates VM poles!



→ Dyson-Schwinger eqs.
→ Effective Lagrangian models
→ Quark models
→ Vector-meson dominance

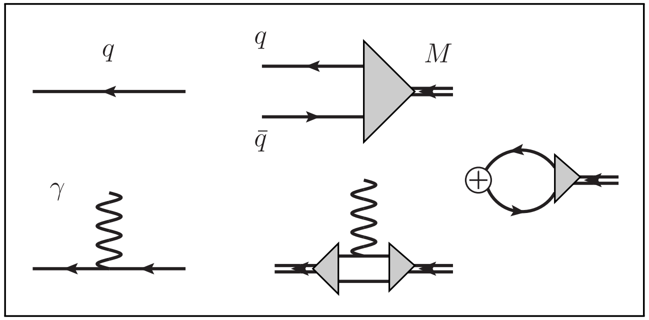
- **Medium effects**



→ In-medium description of resonances!

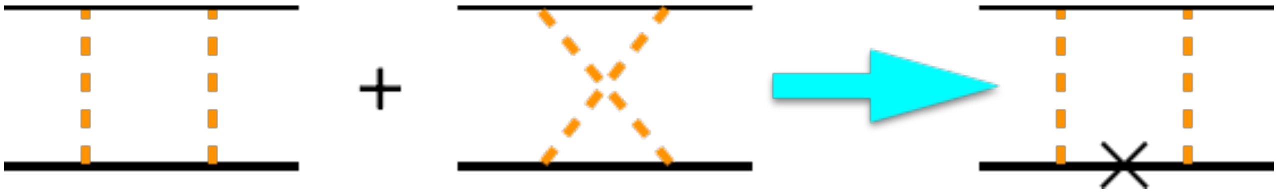
CST©

Covariant Spectator Theory



- Formulation in Minkowski space.

- Two-body CST equation effectively sums ladder and crossed-ladder exchange diagrams, due to cancelations.



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

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

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

- Allows to implement confinement and dynamical chiral symmetry breaking.

Outline

1 Evidence of separation of partonic and hadronic (pion cloud) effects?

2 Space-like e.m. transition FFs & extension to Timelike e.m. transition FFs
Δ(1232) and N*(1520) cases.

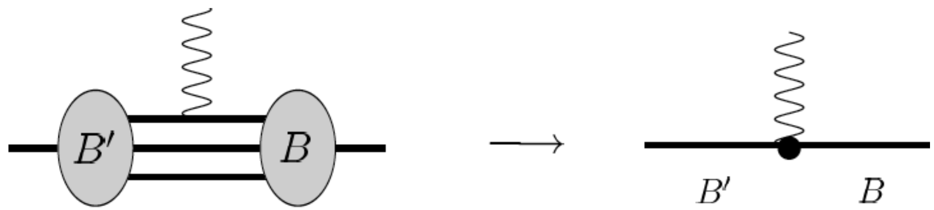
3 Predictions for dilepton mass spectrum and decay widths.

4 Preliminary results for Timelike e.m. FFs of the baryon octet.

This talk: CST phenomenological ansatz for baryon wave functions.

Very recent: Significant progress in
the description of dynamical quark mass generation.
Recent: Good and economical description of
the masses of heavy and heavy-light mesons, including highly excited states.

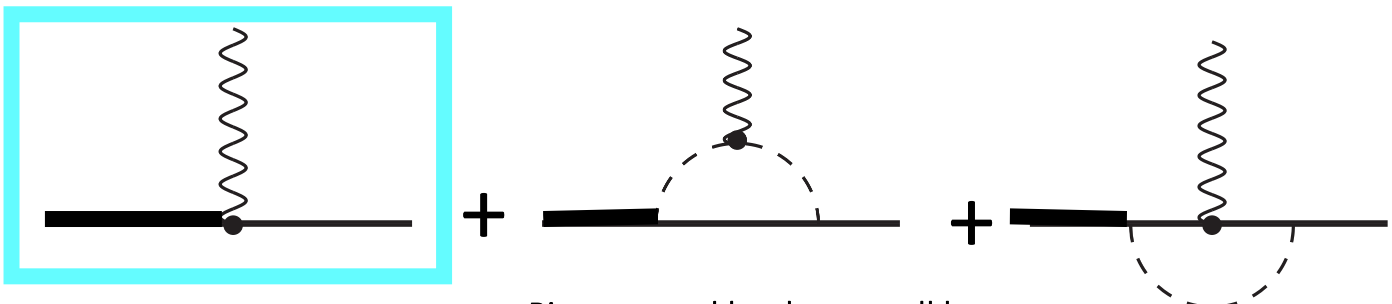
Bare quark and pion cloud components



For low Q^2 : add coupling with pion in flight.

Bare quark component

Pion cloud



$q\bar{q}$ pairs from a single quark included in dressing

Pion created by the overall baryon, not from a single quark

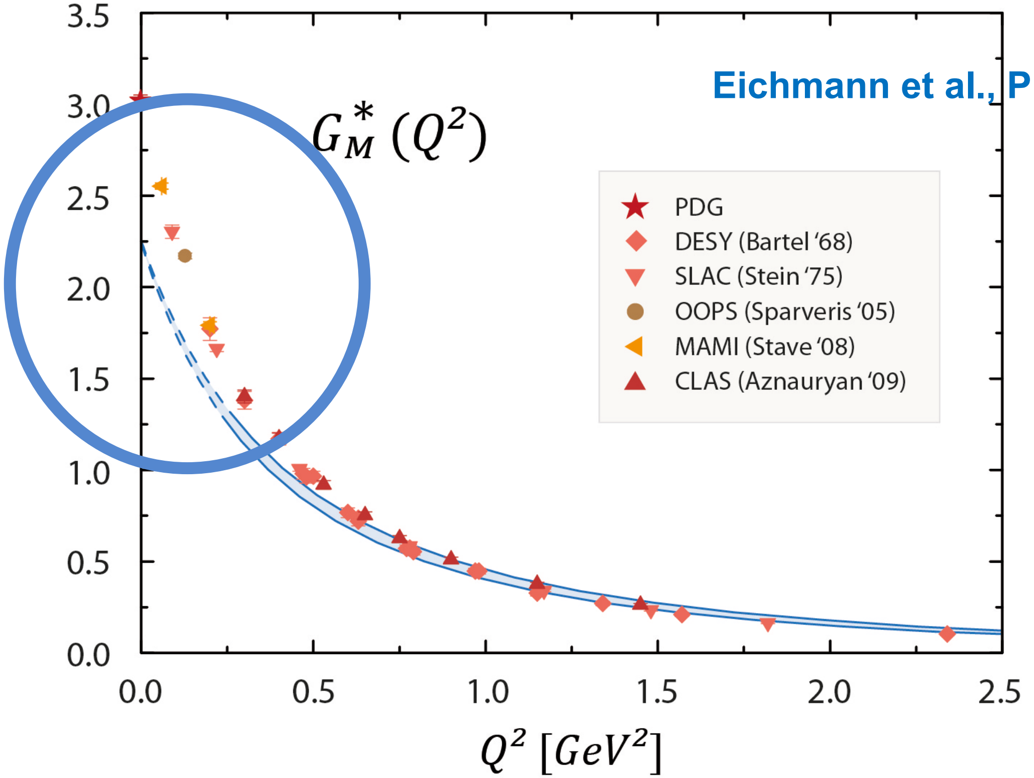
Pion cloud component supressed for high Q^2 $\dfrac{1}{Q^8}$

Model dependence?

Model independent feature

$$\gamma N \to \Delta \qquad\qquad G_M^* = G_M^B + G_M^\pi$$

Separation seems to be supported by experiment.
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)c

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

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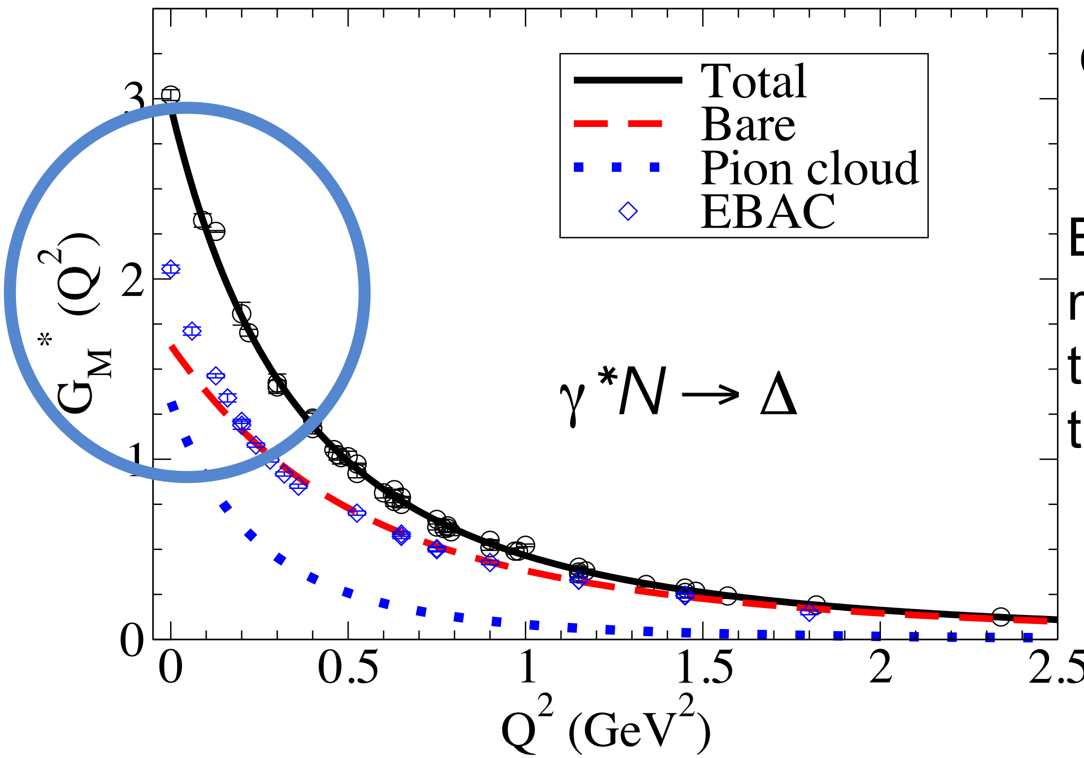


CST 2009

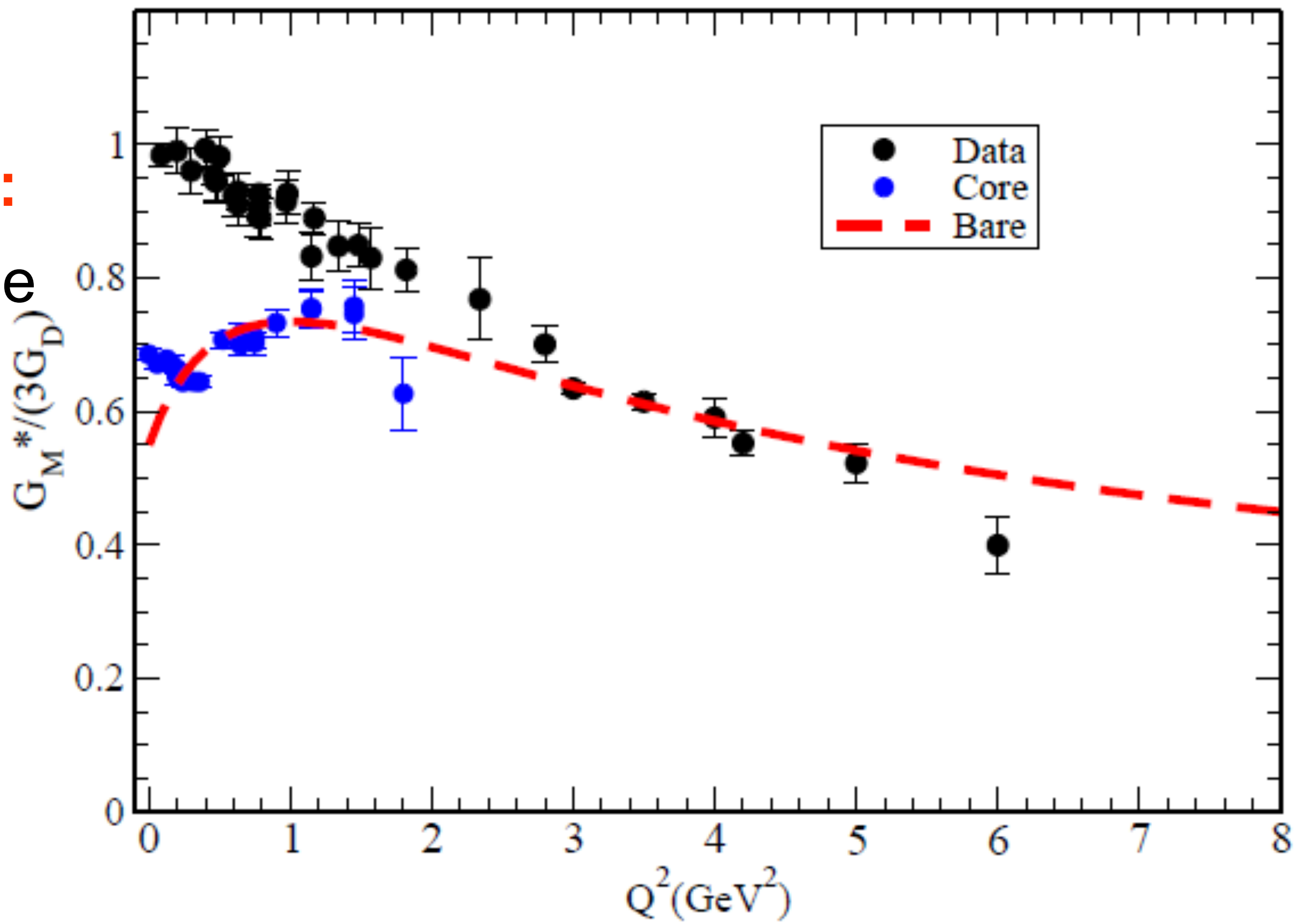
Effect of vicinity of the mass pole of the Delta to the pion-nucleon threshold.

GR and MT Peña PRD 80, 013008 (2009)

CST©

Bare quark core:

- dominates large Q^2 region.
- agrees with EBAC analysis.



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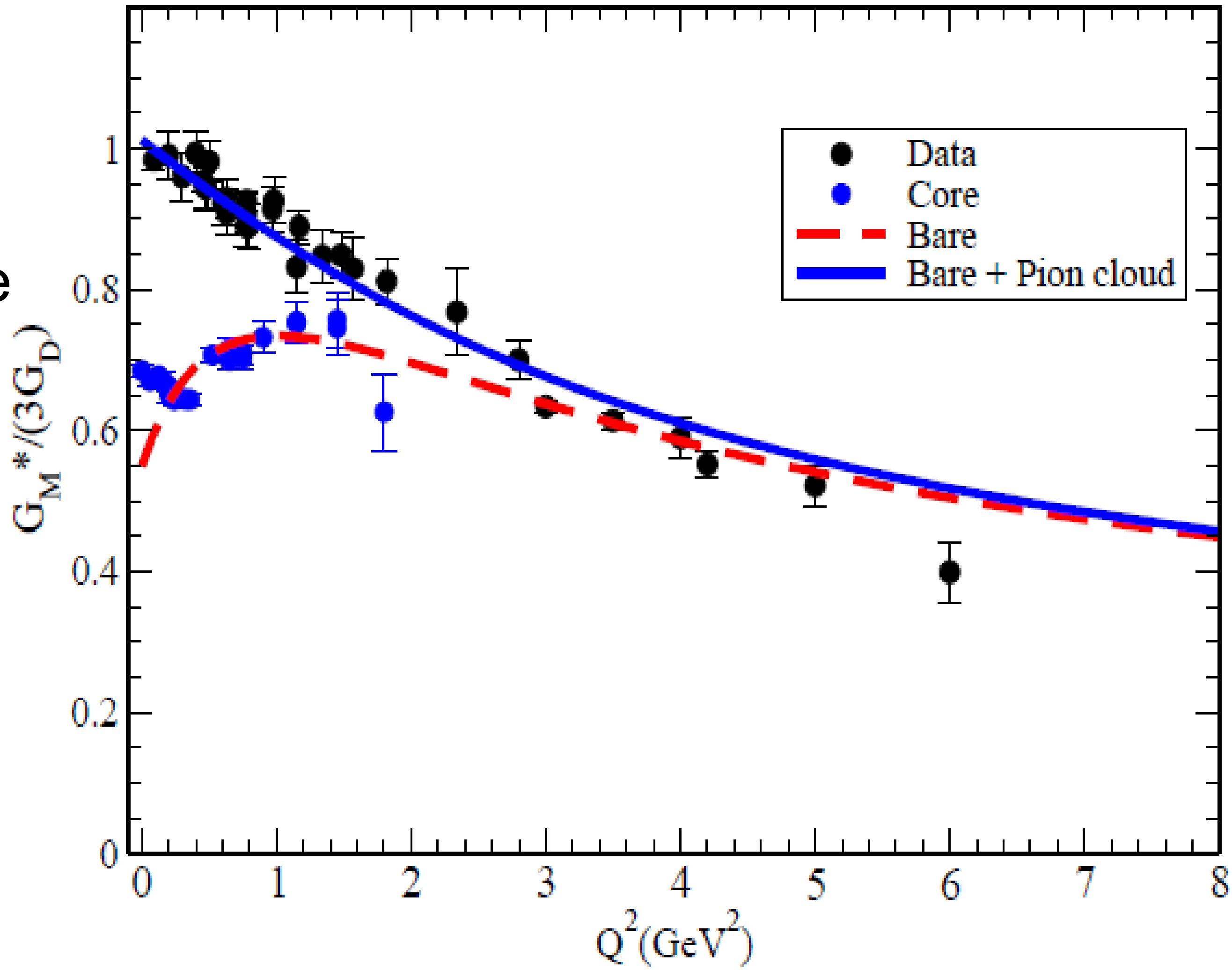
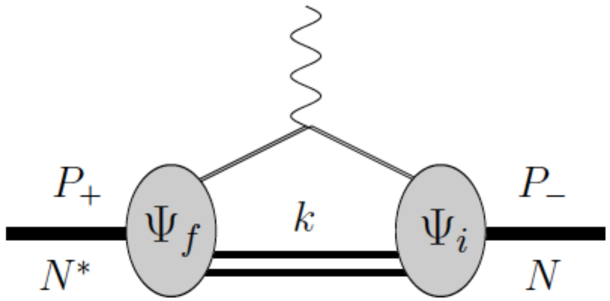
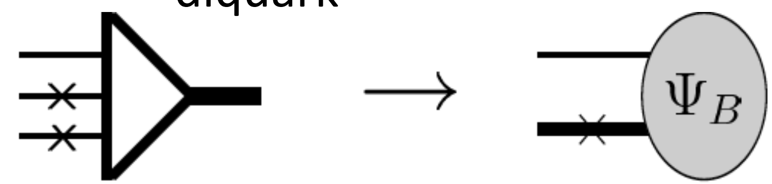


E.M. matrix element



Integrate in the relative momentum of the diquark



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

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

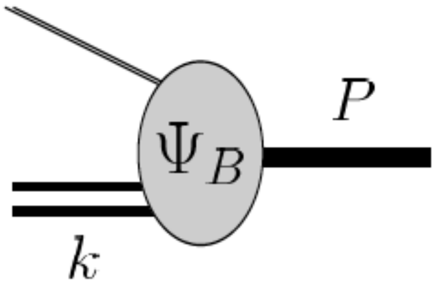
• **Baryon wavefunction** reduced to an effective quark-diquark structure due to the s integration.

• **E.M.** matrix element can be written in terms of an effective baryon composed by an off-mass-shell quark and an on-mass-shell quark pair (diquark) with an average mass.

Wave functions

Nucleon wave function

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



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

Phenomenological function quark-diquark momentum distribution

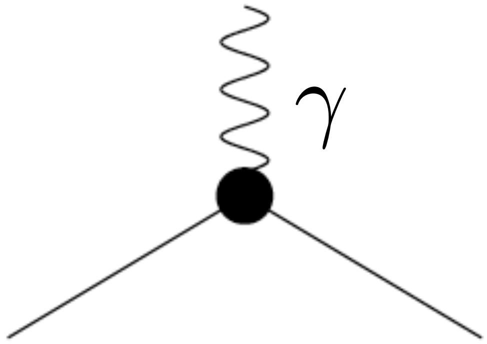
$$U_\alpha(P,\lambda_n) = \frac{1}{\sqrt{3}}\gamma_5\left(\gamma_\alpha - \frac{P_\alpha}{m_H}\right)u_N(P,\lambda_n),$$

Delta wave function

- A quark+ only **axial vector**-diquark term contributes

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

E.M. Current



quark-antiquark

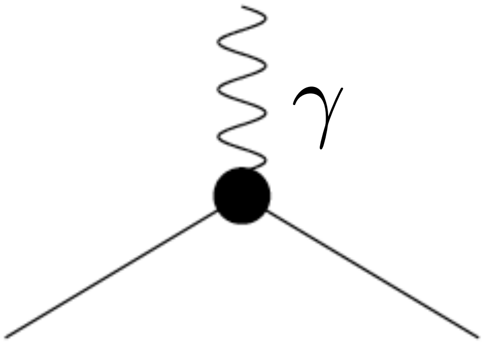
$\oplus$ gluon dressing

Quark form factors f adjusted
to quark charges and
anomalous magnetic moments,
such that experimental magnetic
moments of the nucleons are reproduced.

Constituent quarks (quark form factors)

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

E.M. Current



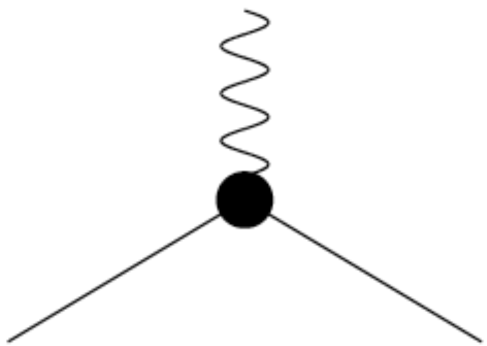
quark-antiquark
$\oplus$ gluon dressing

Processes where pions are
created and absorbed
by the same quark are included in the
constituent quark internal structure,
and thus included in the quark current.

Constituent quarks (quark form factors)

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

E.M. Current



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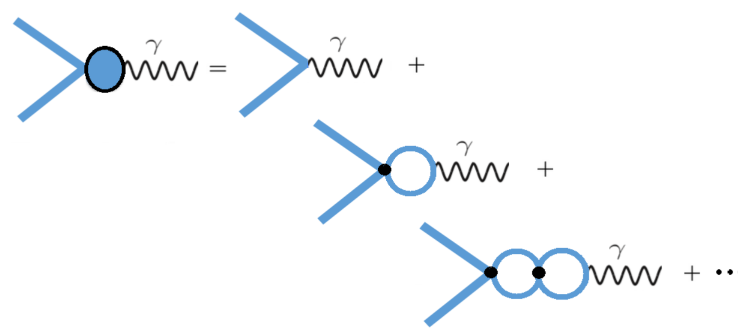
To parametrize the current use **VMD**, a truncation to the ρ pole of the full meson spectrum contribution to the quark-photon coupling.



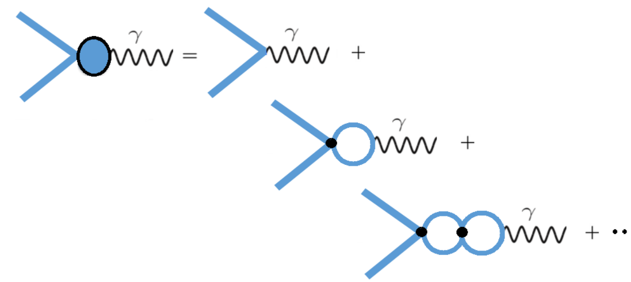
$$\Gamma_\mu(p,Q) = \gamma_\mu + \int \frac{d^4q}{(2\pi)^4} K(p,q,Q) S(q+\eta Q) \Gamma_\mu(q,Q) S(q-\eta Q)$$

4 parameters

Vector meson dominance **2** poles

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

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



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

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

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

Low-energy behavior encodes high-energy behavior: Scale enters in the problem! DIS used to fixed λ

4 parameters

VMD as link to LQCD

- VMD enables link to LQCD:

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**,

and **bare** quark model could be calibrated to the **lattice data.**

- After that, in the limit of the physical pion mass value,

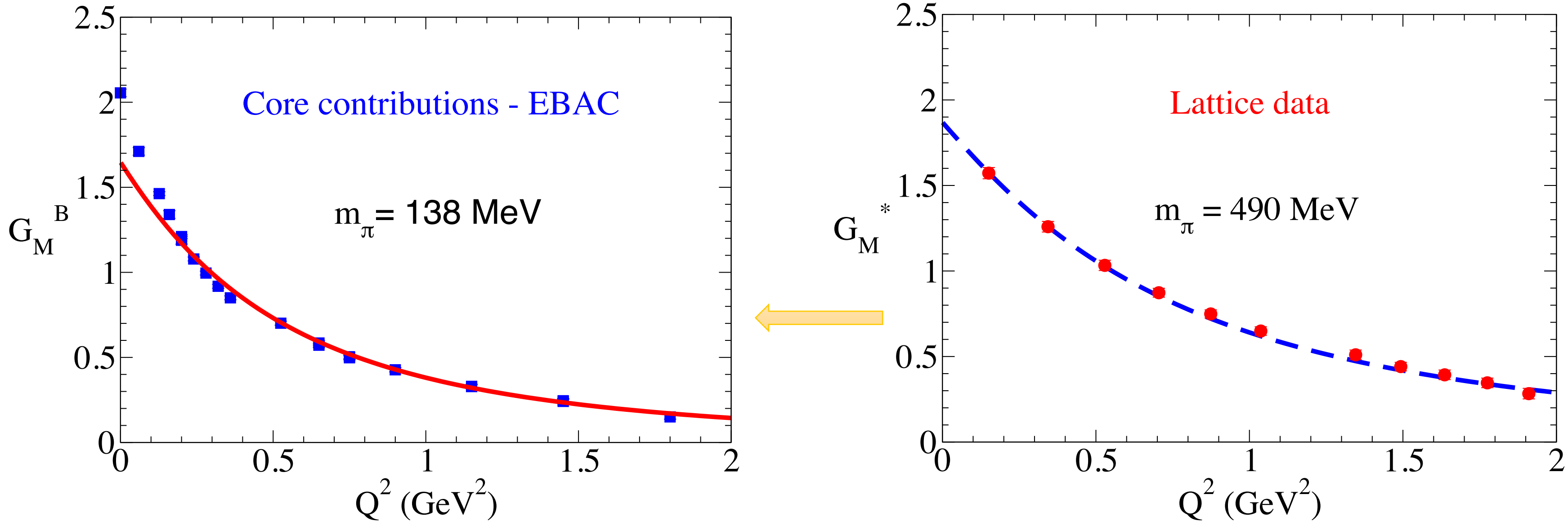
the **experimental data** is well described in the large Q^2 region.

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 at the photon point

$$\gamma N \rightarrow \Delta$$

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

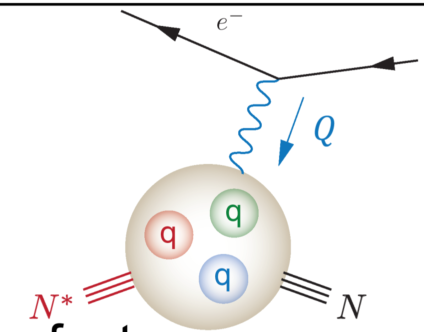
- Only 3 G_i are independent: E.M. Current has to be conserved $\quad q^\mu \Gamma_{\beta\mu} = 0$

$\Rightarrow$ G_M, G_E, G_C Scadron Jones popular choice.

- Only finite G_i are physically acceptable.

Orthogonality between initial and final states necessarily follows from both requirements, giving an important constraint to G_c at $Q^2=0$.

E.M. Current and TFF near the photon point

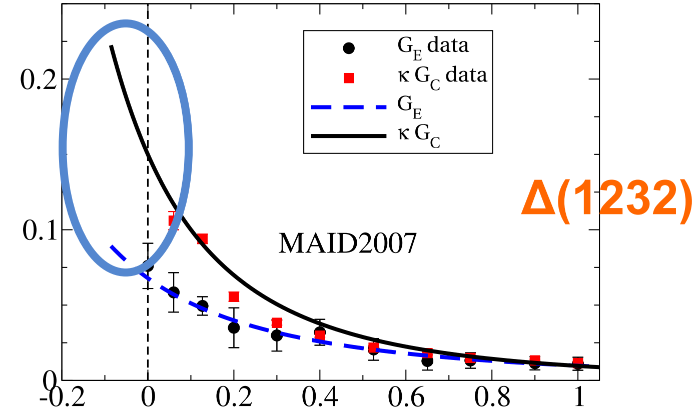


Pseudo Threshold PT $\quad Q_0^2 = -(M_R - M_N)^2 \;\; ; |\vec{Q}| = 0$

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.



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

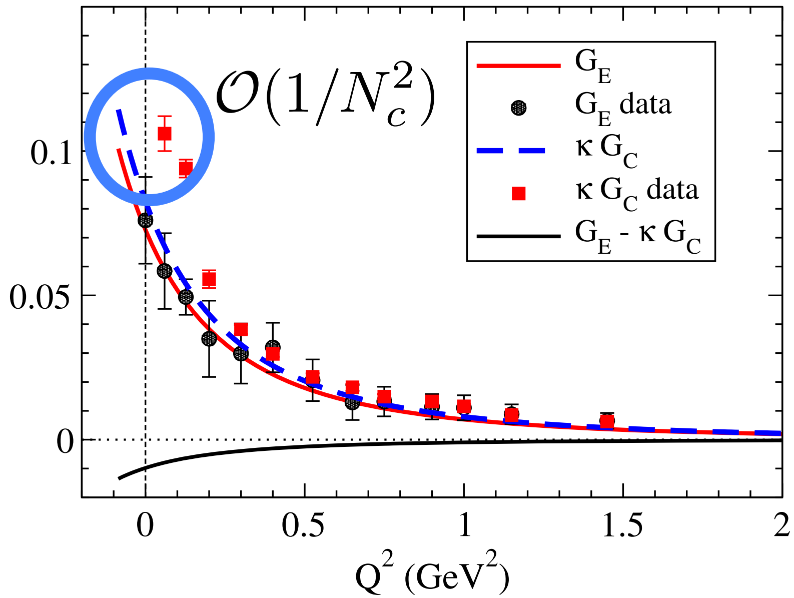
G_E and G_C

$\gamma N \to \Delta$

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.



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- Suggest that pion cloud effects for G_E and G_C
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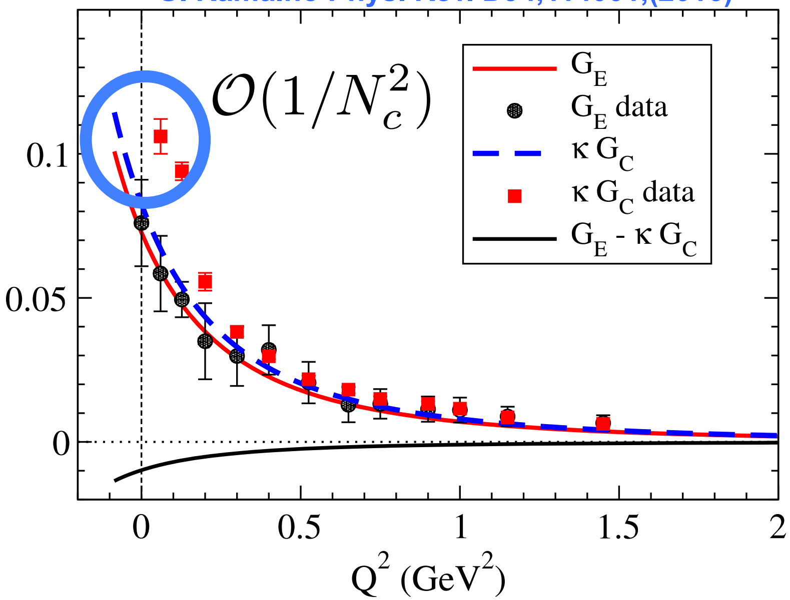
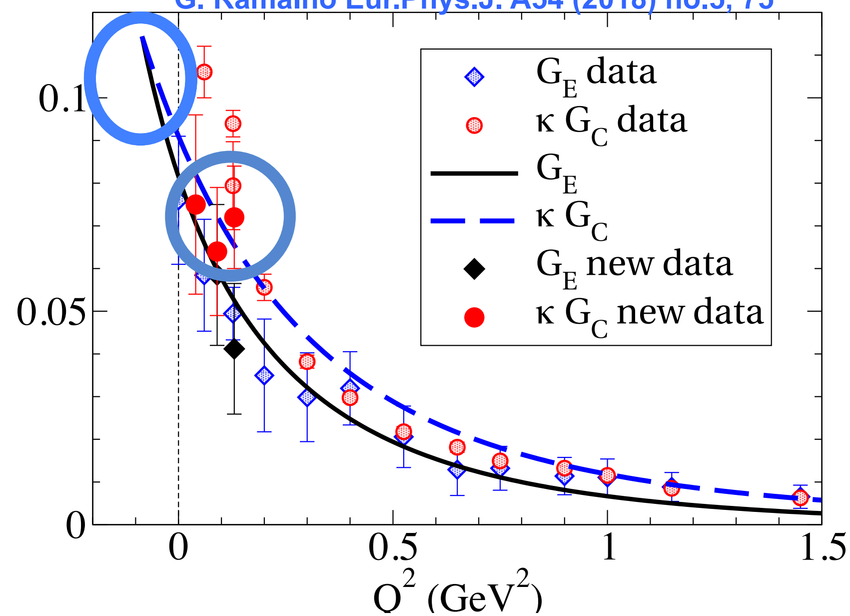
and do not agree to data at low Q^2.

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

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



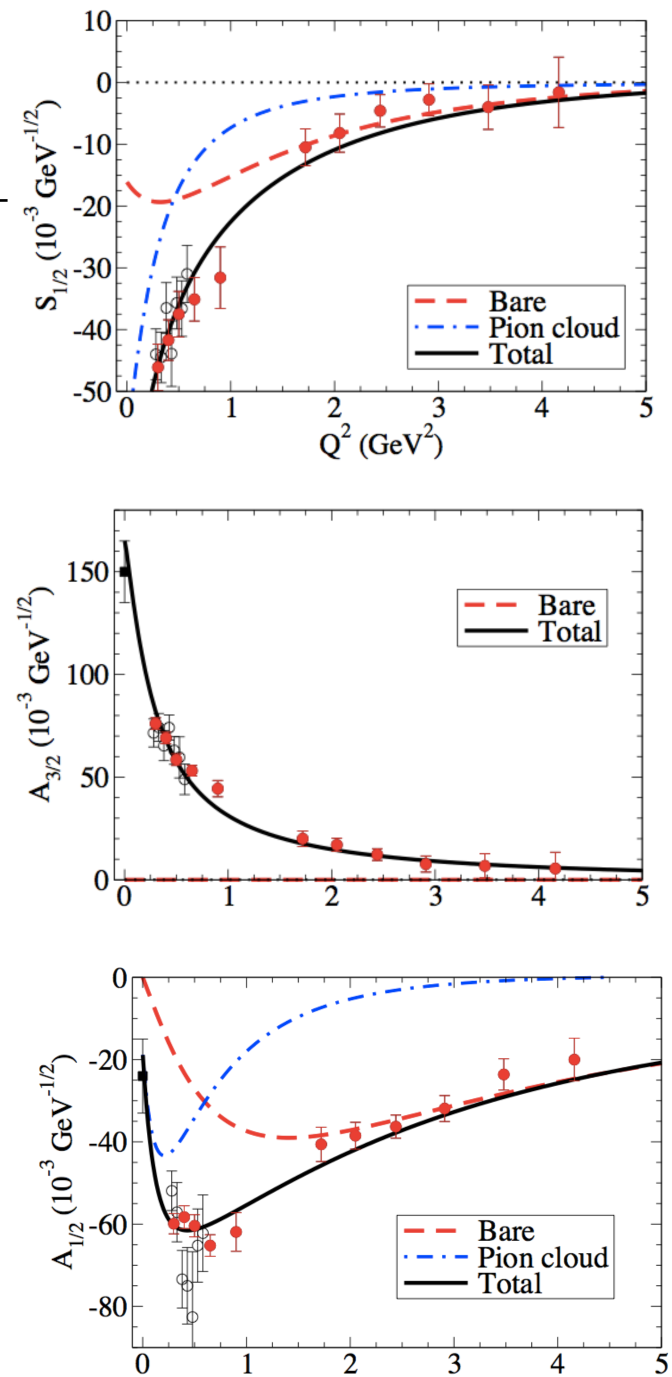
G. Ramalho Eur.Phys.J. A54 (2018) no.5, 75



$N \rightarrow N^*(1520)$ Helicity amplitudes

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

- Bare quark model gives good description of high Q^2 region.



G. Ramalho, M. T. P. , PHYSICAL REVIEW D 85 094016 (2014)

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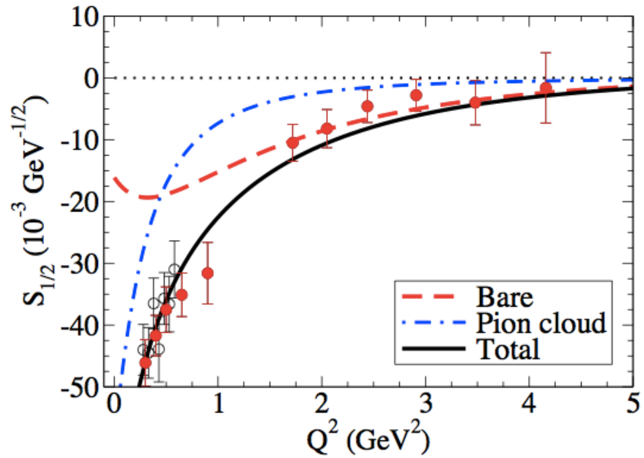

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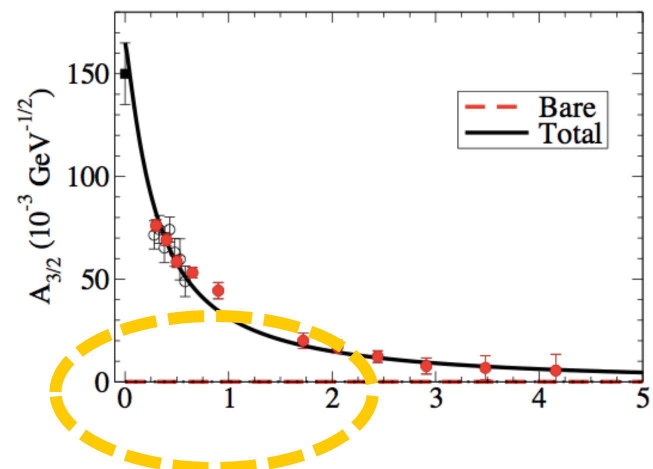
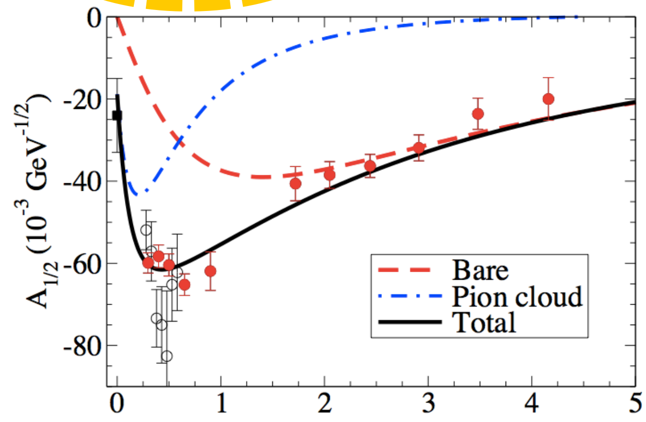


- Bare quark model gives good description of high Q^2 region

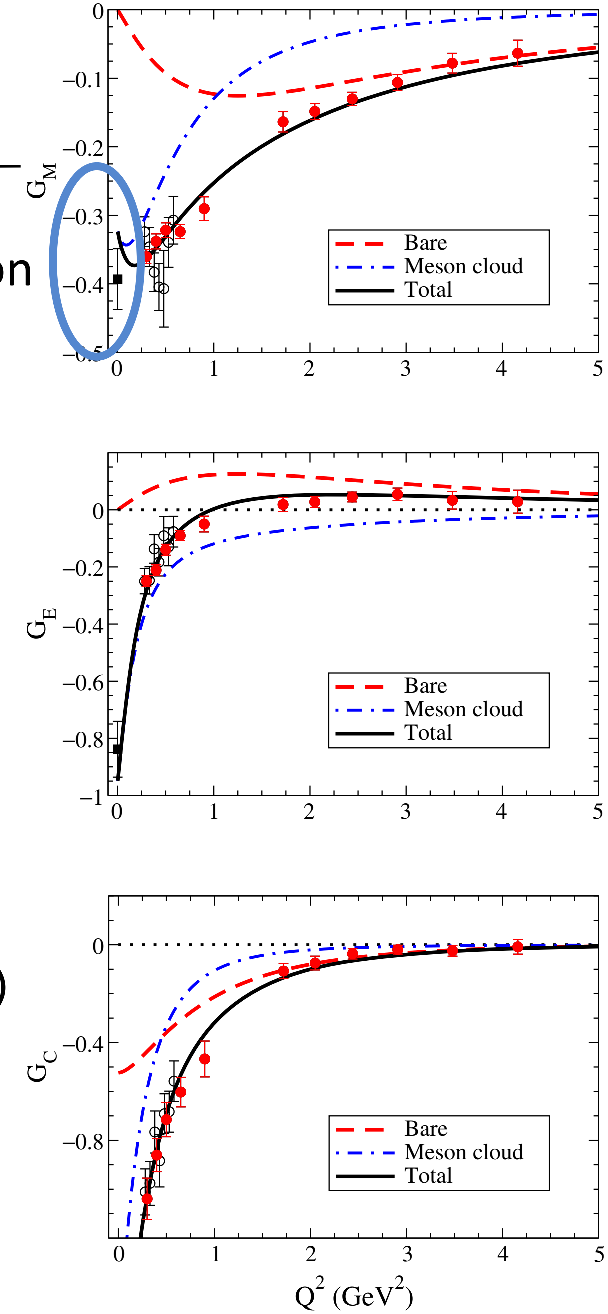
- No bare quark contribution to $A_{3/2}$.



G. Ramalho, M. T. P. , PHYSICAL REVIEW D 85 094016 (2014)

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

Transition Form Factors, Scadron and Jones convention



- Underestimation of G_M close to the photon point due to overall fit.

- Important role of meson cloud;

dominated by the pion due to the πN and $\pi\Delta$ channels branching ratios.

(as in Aznauryan and Burkert, PRC 85 055202 2012)

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

Crossing the boundaries

N*(1520)

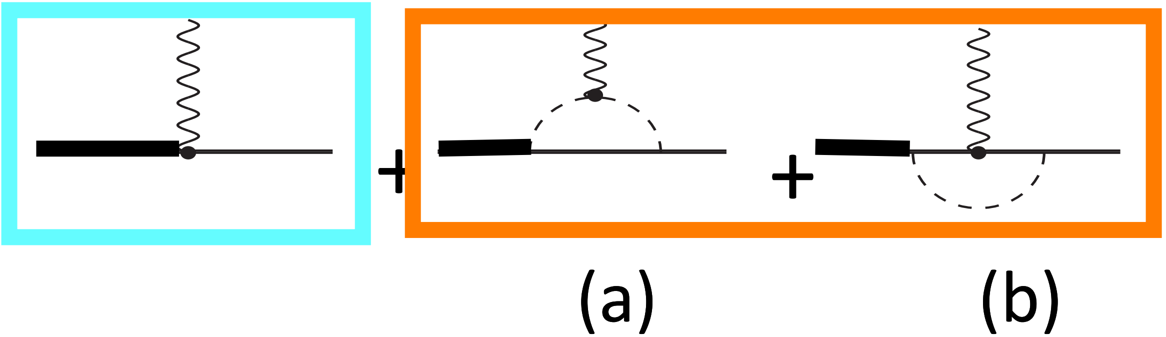
Dominance of iso-vector channel concurs to our model of the meson cloud: pion only

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

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

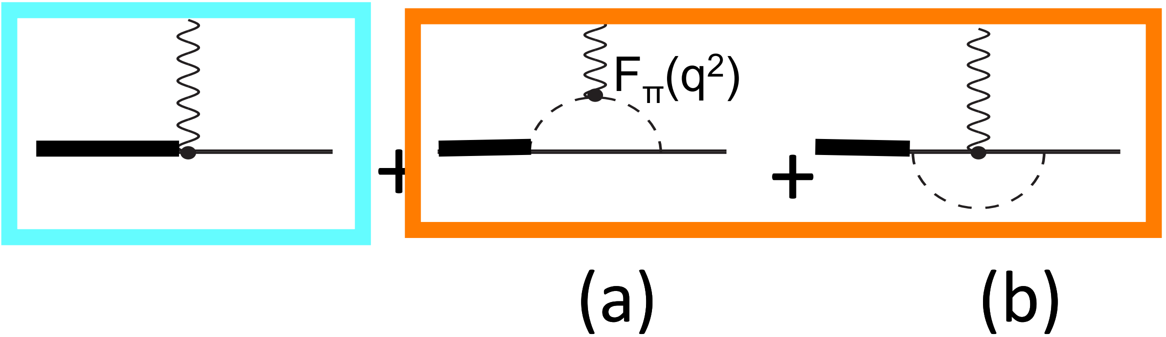
Extension to time like



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

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

Extension to time like



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

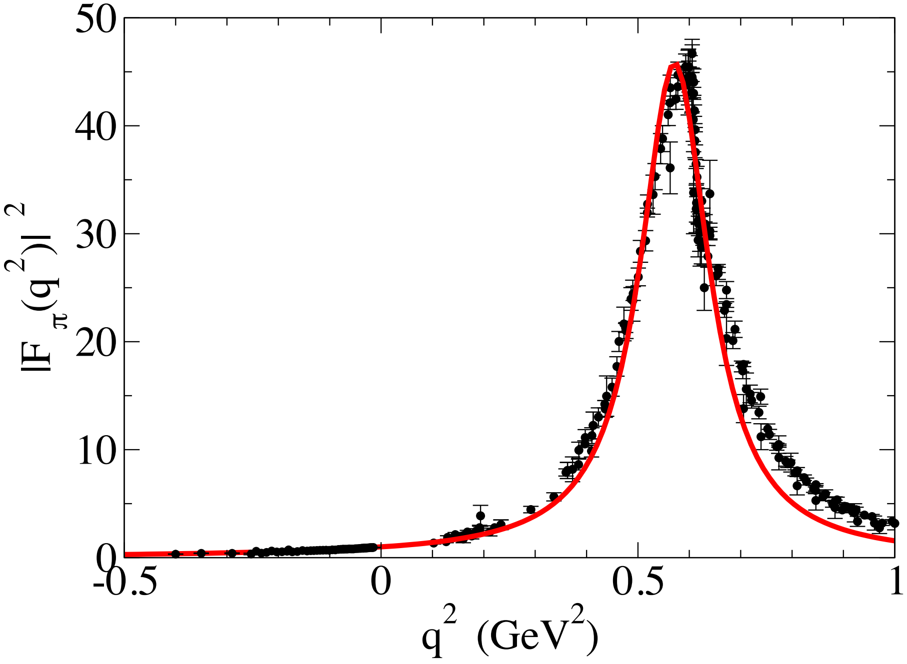
Extension to time like

Parametrization of pion Form Factor

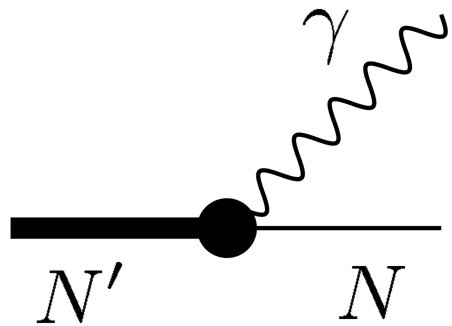
$$F_\pi(q^2) = \frac{\alpha}{\alpha - q^2 - \frac{1}{\pi}\beta q^2 \log \frac{q^2}{m_\pi^2} + i\beta q^2}$$

$\alpha = 0.696\ \mathrm{GeV}^2$

$\beta = 0.178$



Extension to time like



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

$W \geq M$

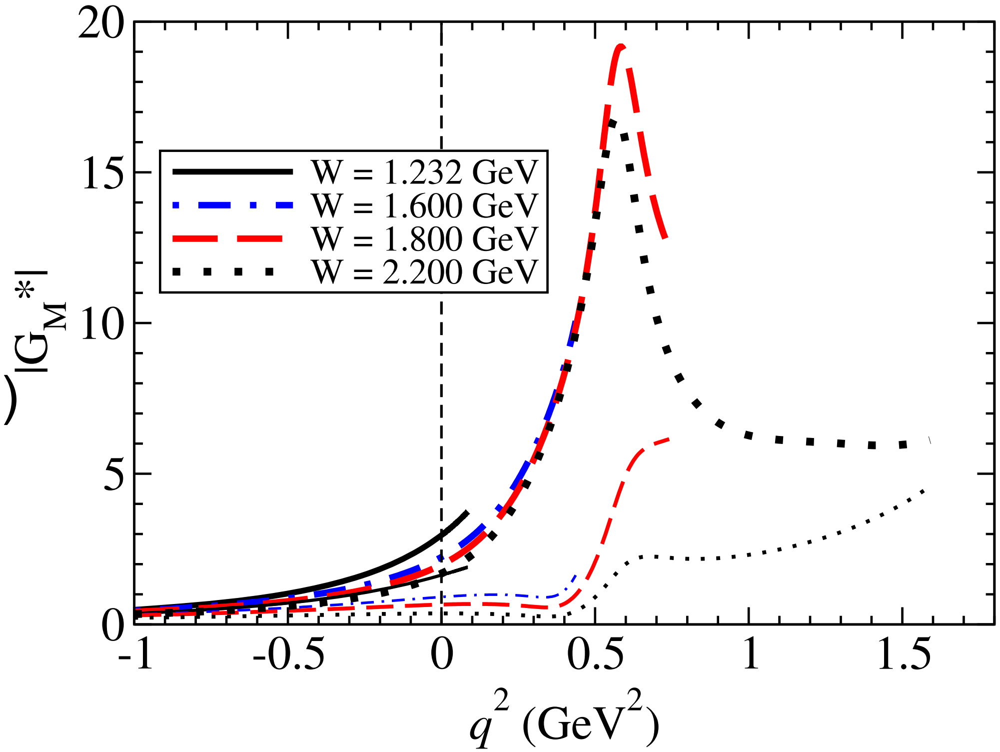
Range of momentum is restricted for each energy W.

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

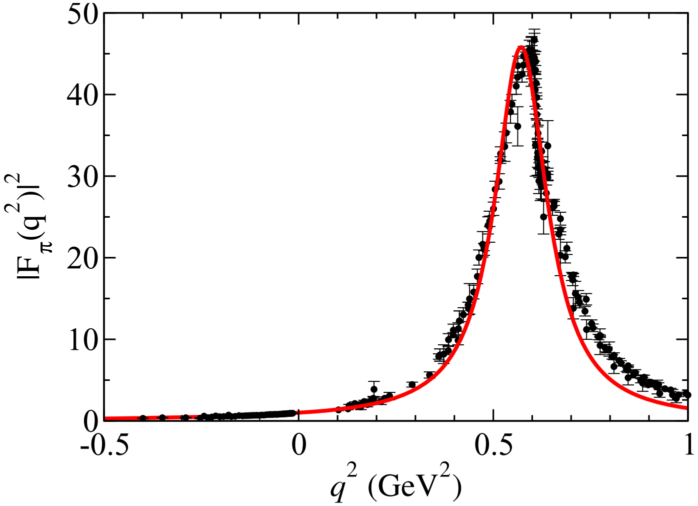
Extension to time like

$$\gamma N \rightarrow \Delta$$

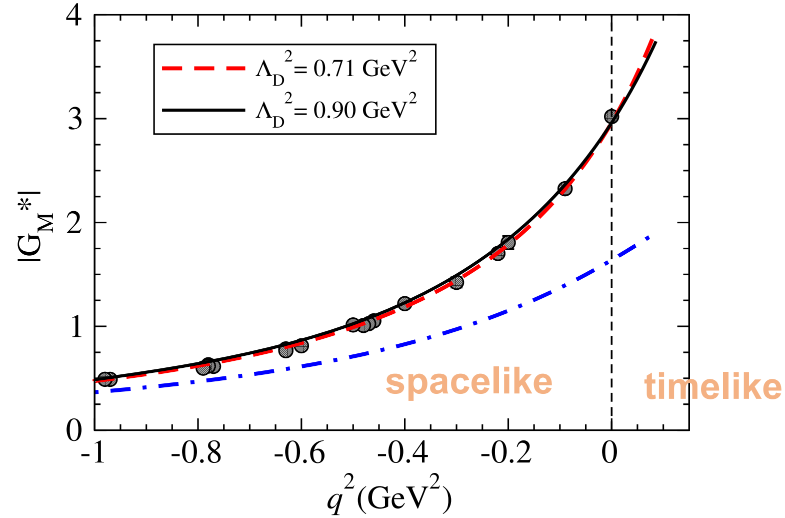
- Extension for higher W shows effect of the rho mass pole
- In that pole region small bare quark contribution (thin lines)



Crossing the boundaries



$$\gamma N \to \Delta$$



Red line : full model

Blue line: Quark core

- Good description of the magnetic dipole physical data ($W = M_\Delta$)

Crossing the boundaries

Δ(1232) Dalitz decay

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

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

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

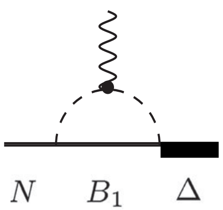
$$\Gamma_{\gamma N}(W) \equiv \Gamma_{\gamma^* N}(0;W)$$

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

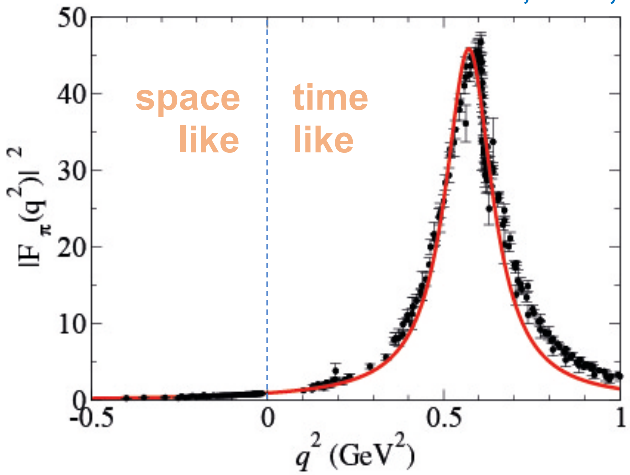
Crossing the boundaries

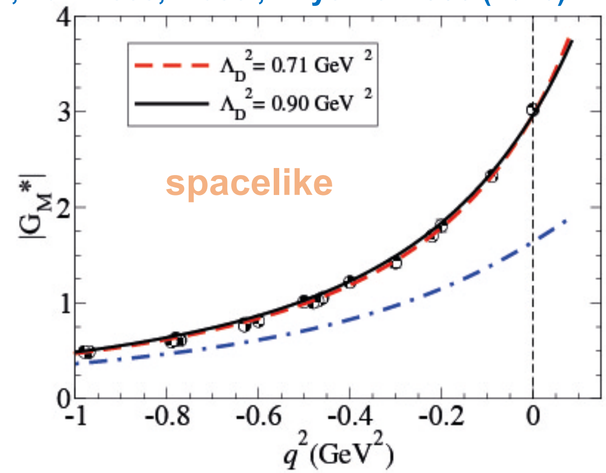
$\Delta(1232)$ Dalitz decay

$\gamma N \to \Delta$

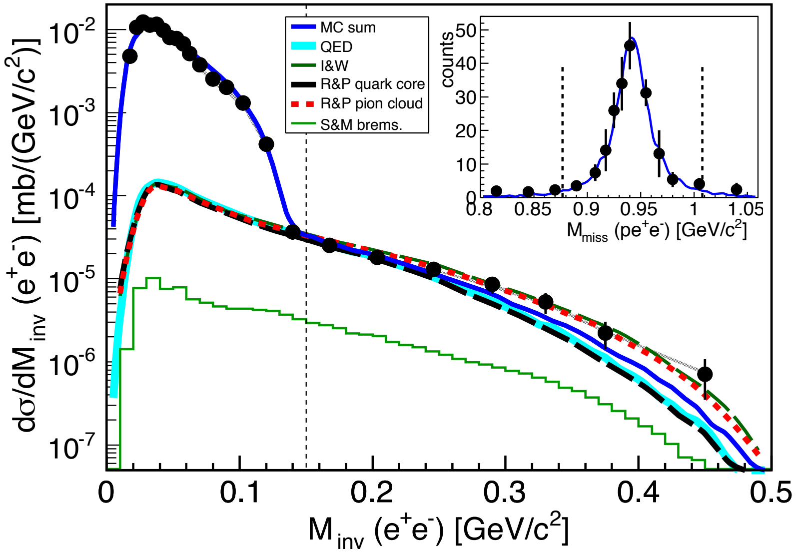


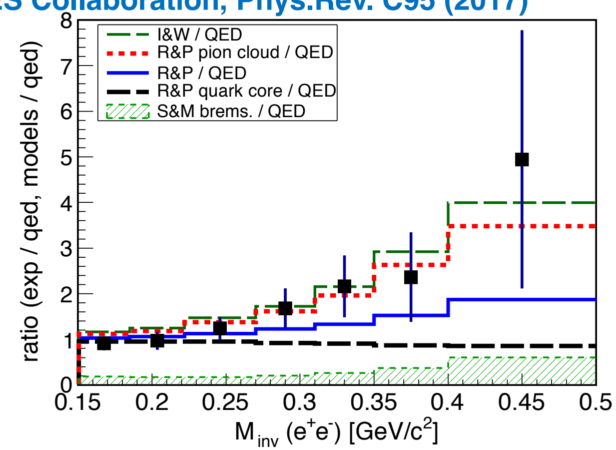
Ramalho, Pena, Weil, Van Hees, Mosel, Phys.Rev. C93 (2016)





HADES Collaboration, Phys.Rev. C95 (2017)



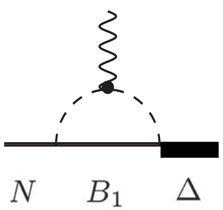


Δ Dalitz decay branching ratio 4.19 x 10^{-5}

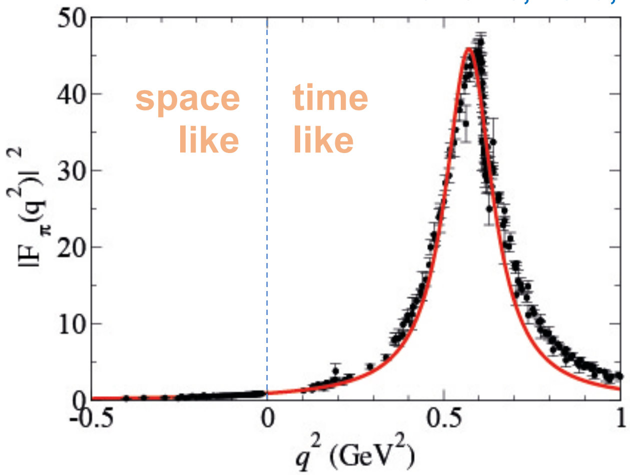
Crossing the boundaries

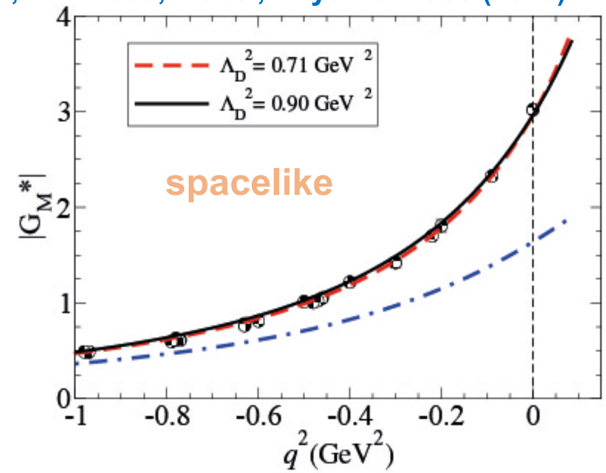
Δ(1232) Dalitz decay

$\gamma N \rightarrow \Delta$

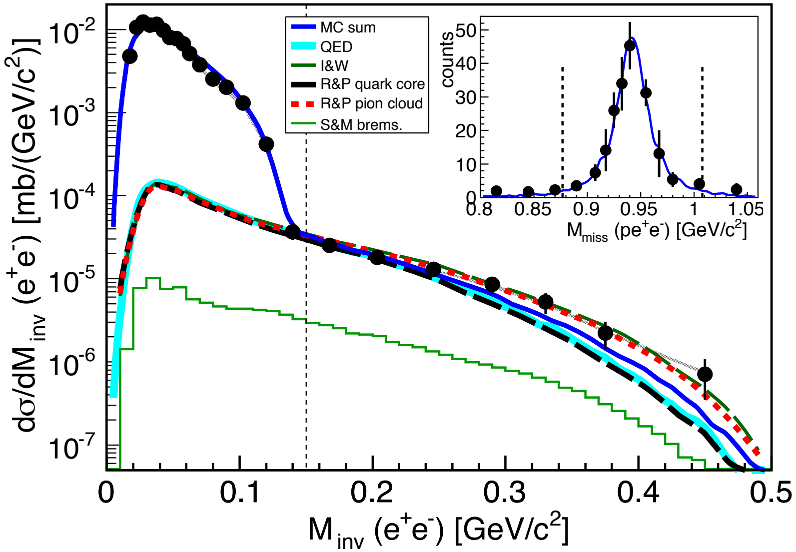


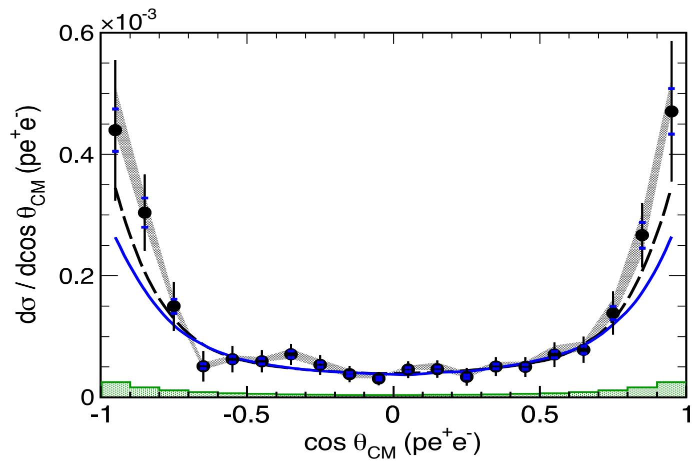
Ramalho, Pena, Weil, Van Hees, Mosel, Phys.Rev. C93 (2016)





HADES Collaboration, Phys.Rev. C95 (2017)





Angular distribution for pe$^+$e$^-$

Crossing the boundaries

N*(1520)

$$\Gamma_{\gamma^* N}(q,W) = \frac{3\alpha}{32}\frac{(W-M)^2}{M^2W^3}\sqrt{y_+y_-}\,y_+|G_T(q^2,W)|^2$$

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

$$|G_T(q^2,W)|^2 = 3|G_M(q^2,W)|^2 + |G_E(q^2,W)|^2 + \frac{q^2}{2W^2}|G_C(q^2,W)|^2.$$

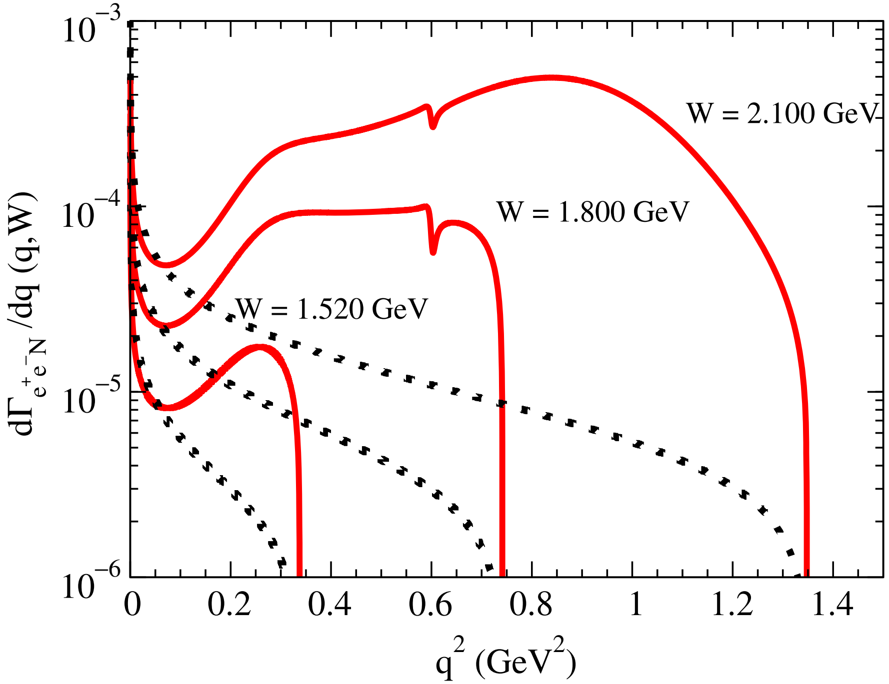
$$\Gamma'_{e^+e^-N}(q,W) \equiv \frac{d\Gamma}{dq}(q,W) = \frac{2\alpha}{3\pi q^3}(2\mu^2+q^2)\sqrt{1-\frac{4\mu^2}{q^2}}\Gamma_{\gamma^* N}(q,W)$$

G. Ramalho, M. T. P. , PHYSICAL REVIEW D 95 0104003 (2017)

Crossing the boundaries

N*(1520)

True prediction

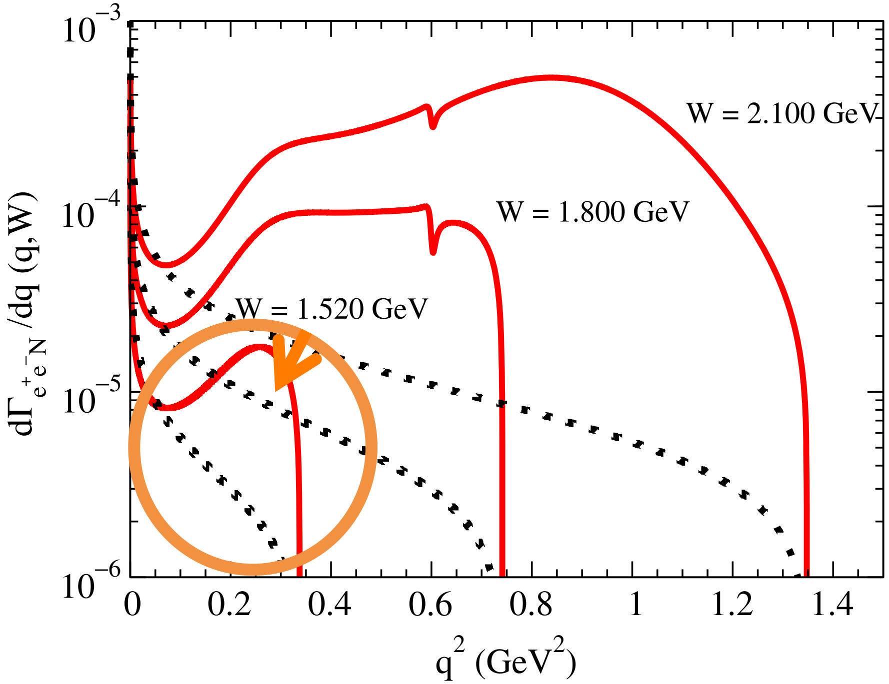


G. Ramalho, M. T. P. , PHYSICAL REVIEW D 95 0104003 (2017)

Crossing the boundaries

N*(1520)

True prediction



G. Ramalho, M. T. P. , PHYSICAL REVIEW D 95 0104003 (2017)

Crossing the boundaries

N*(1520)

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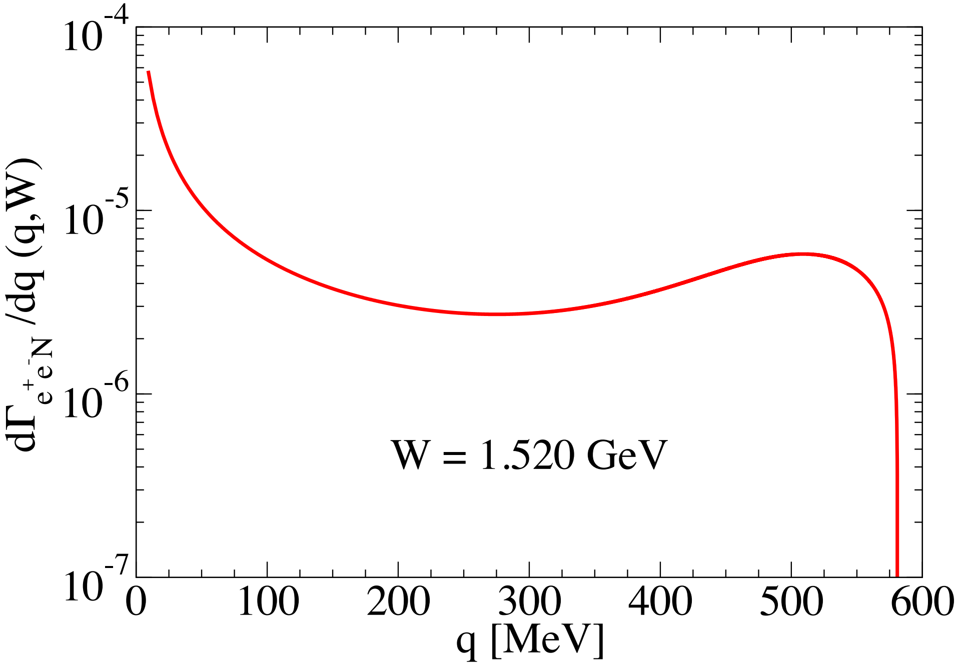
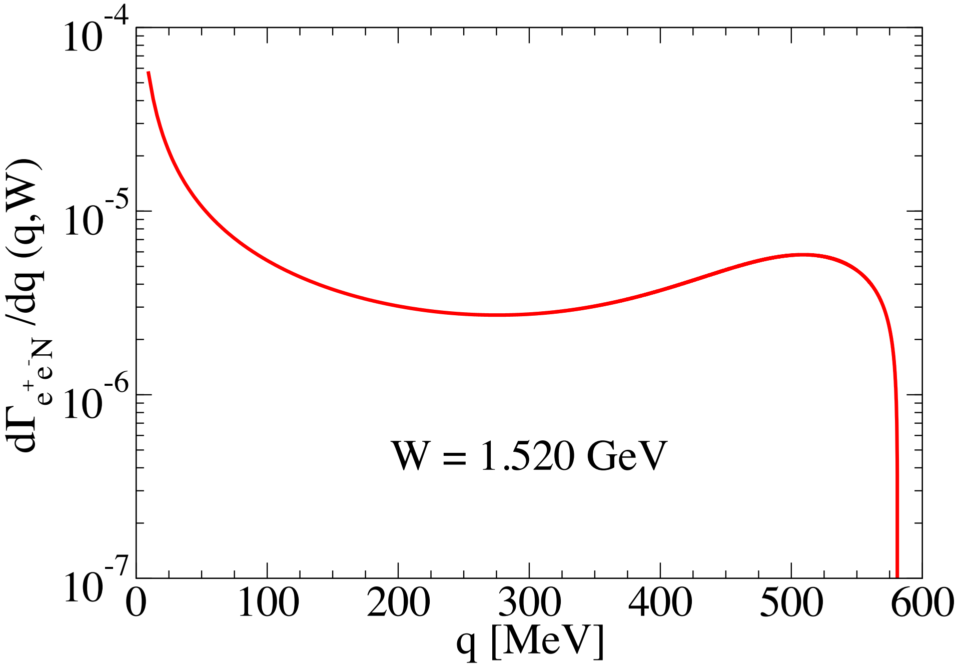
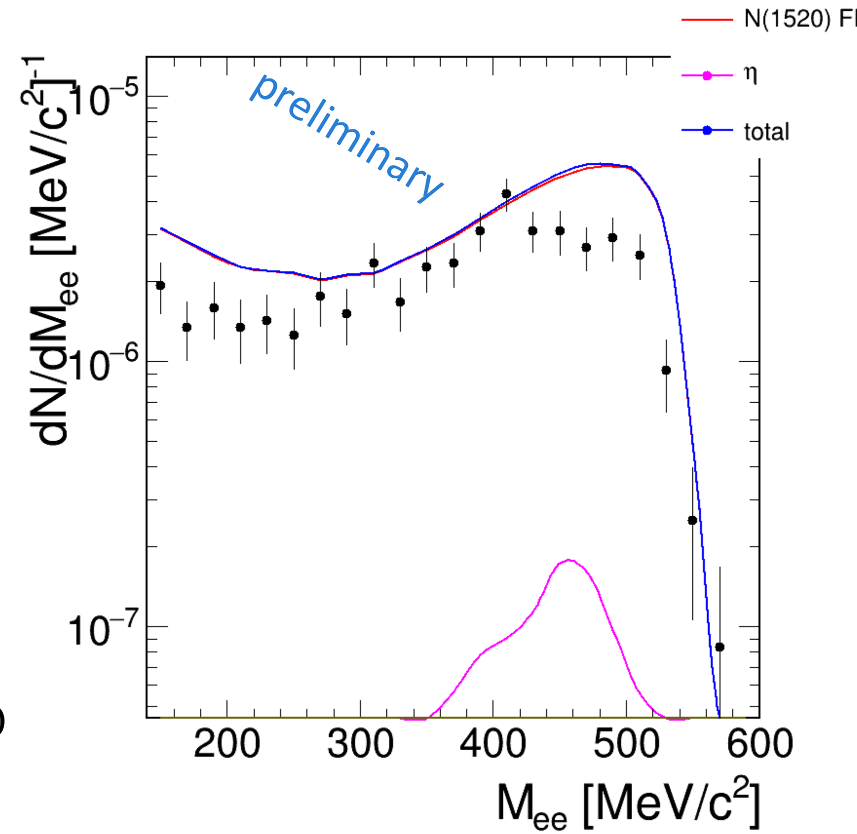


Crossing the boundaries

N*(1520)

True prediction





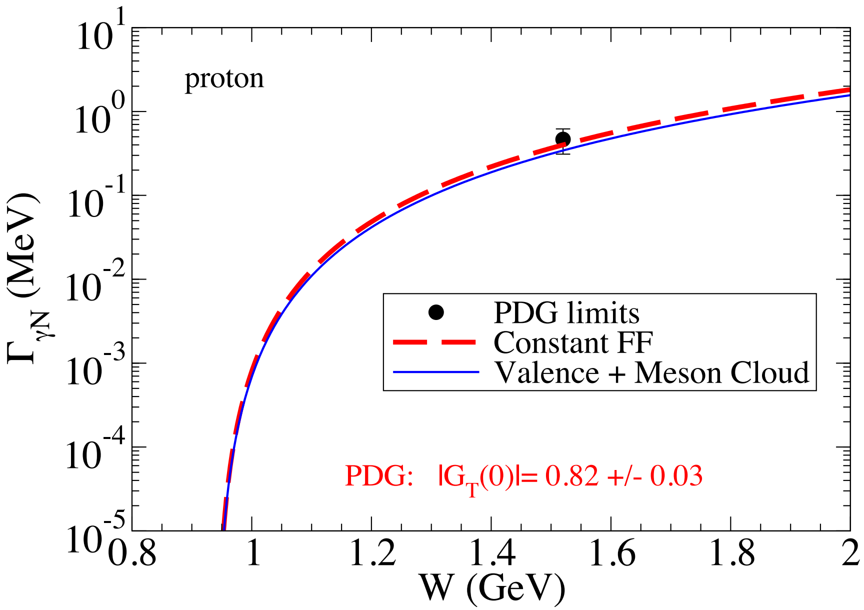
HADES Collaboration

Crossing the boundaries

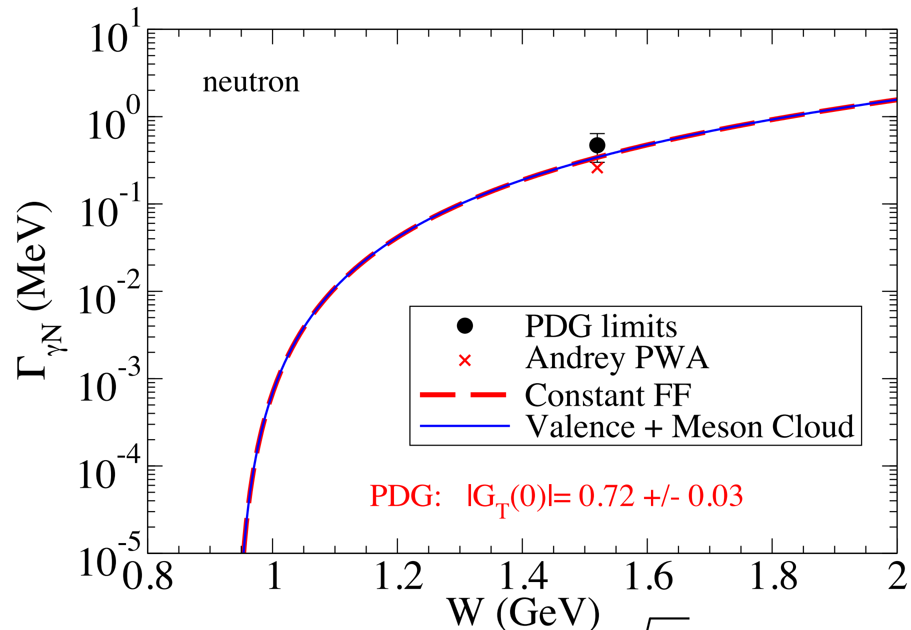
N*(1520)

Update of 2017 results

Proton



Neutron



Devenish (1976) normalization of transition form factors $|G_T| \to \sqrt{\frac{2}{3}}|G_T|$

PDG data:

	$\|G_T(0,M_R)\|^2$	$\Gamma_{\gamma N}$ (MeV) Estimate	PDG limits	Model
p	0.68±0.05	0.43±0.03	0.31–0.62	0.34
n	0.53±0.04	0.34±0.03	0.30–0.64	0.34

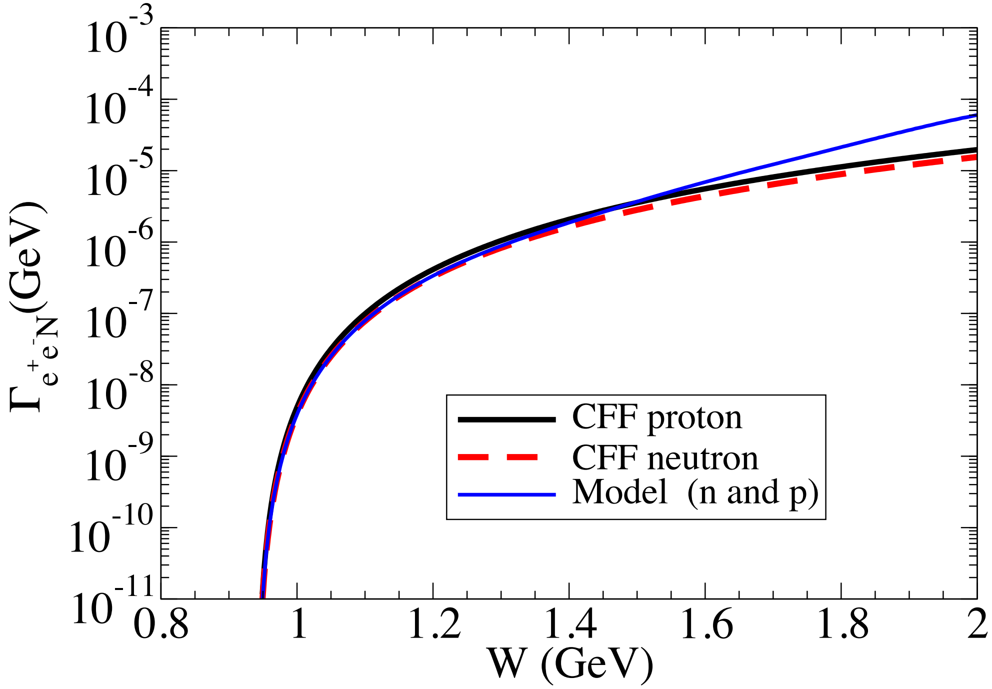
$$G_T^{CST}(0, M_R) = 0.73$$

Consistent with PDG value for γN decay width.

Crossing the boundaries N*(1520)

Update of 2017 results

Neutron and Proton light dilepton decay width



- Similar Proton and neutron results due to iso-vector dominance of meson cloud.

- At higher energies evolution of $G_T(q^2, W)$ with q^2 becomes important.

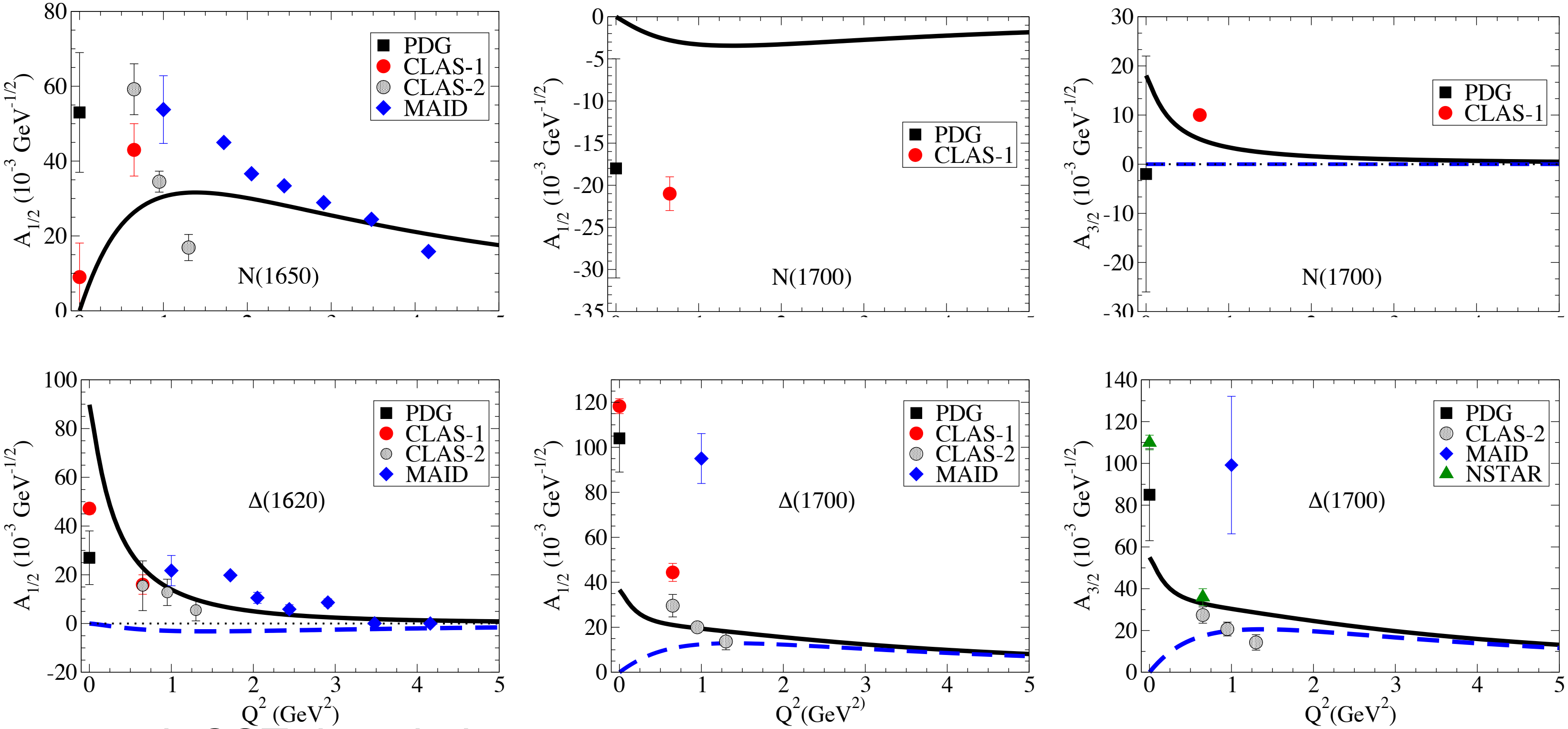
Predictive power:

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)

Summary 1

Covariant **S**pectator quark-diquark model enables description of different resonance states (spin/orbital motion).

Several applications: **Δ(1232)**, N*(1440), N*(1535)**, N*(1520),...,** dilepton mass spectrum.

Consistent with experimental data at high Q^2.

Consistent with LQCD in the large pion mass regime informing on “pion cloud” effects.

VMD and “pion cloud” sustained extension to the timelike region of the TFF of the **Δ(1232) and N*(1520).**

Outlook

LQCD simulations below the N* threshold will help too refine interpretation provided by theoretical quark models.

New experimental data at large Q^2 and even more precise data in all ranges can improve interpretation of empirical results.

Dynamical calculations of diquark vertices within CST to be done, to support quark-diquark picture for baryons, seen within Dyson-Schwinger approach for dynamical quarks.

Extension to Strangeness

Timelike transitions appear as a
unique opportunity to explore hyperon structure.
N. Cabibbo and R. Gatto,
Phys. Rev. Lett. 4, 313 (1960);
Phys. Rev. 124, 1577 (1961).

They are new windows for the role of
diquarks in baryons, deduced from how form factors vary
with quark composition.
S. Dobbs, A. Tomaradze, T. Xiao,
K. K. Seth and G. Bonvicini,
Phys. Lett. B 739, 90 (2014)

Extension to strangeness in the Spacelike region with a global fit to lattice data and physical magnetic moments

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

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

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

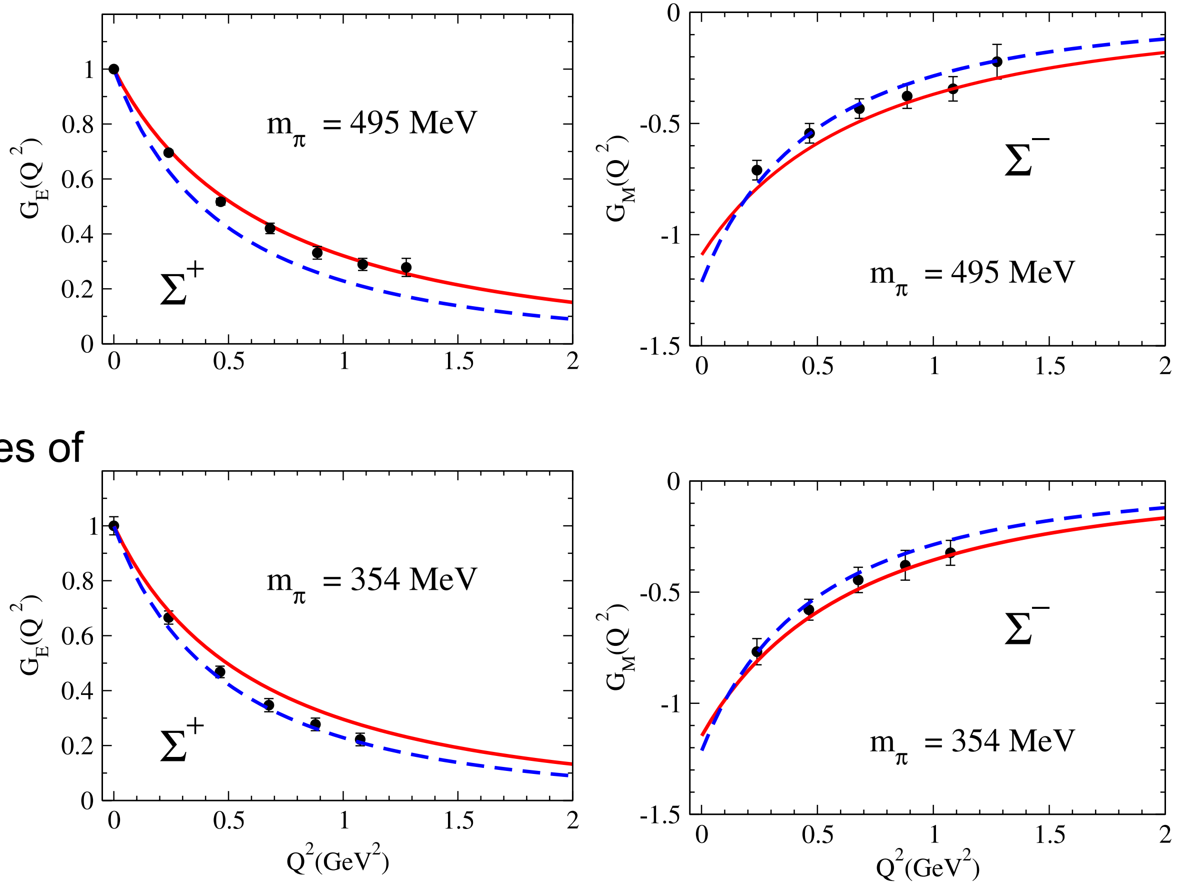
$$\lambda_s \equiv \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

Parameters for valence quark degrees of freedom and the pion cloud dressing determined by a **global fit** to octet baryon lattice data for the e.m. form factors and physical magnetic moments.

Two examples:

Red line: lattice

Blue line: physical regime



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

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

Extension to Strangeness in the timelike region

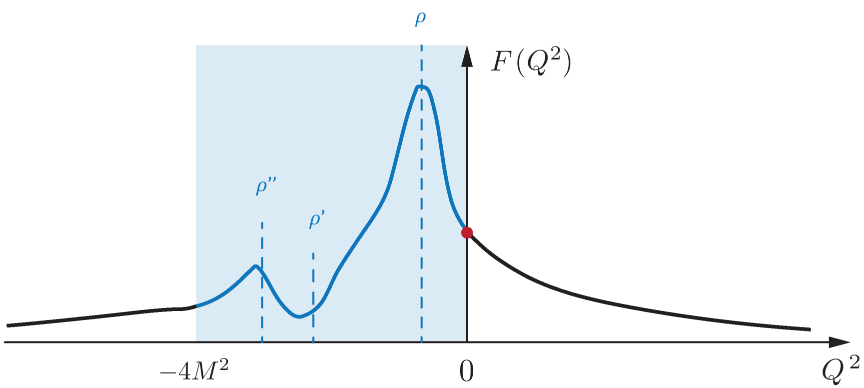
$$e^+e^- \to \gamma^* \to B\bar{B}$$

$$|G(q^2)|^2 = \left(1 + \frac{1}{2\tau}\right)^{-1} \left[|G_M(q^2)|^2 + \frac{1}{2\tau}|G_E(q^2)|^2\right.$$
$$= \frac{2\tau|G_M(q^2)|^2 + |G_E(q^2)|^2}{2\tau + 1}. \qquad \tau = \frac{q^2}{4M_B^2}$$

Effective Form factor that gives the integrated cross section

Analiticity demands that for $q^2 \to \infty$

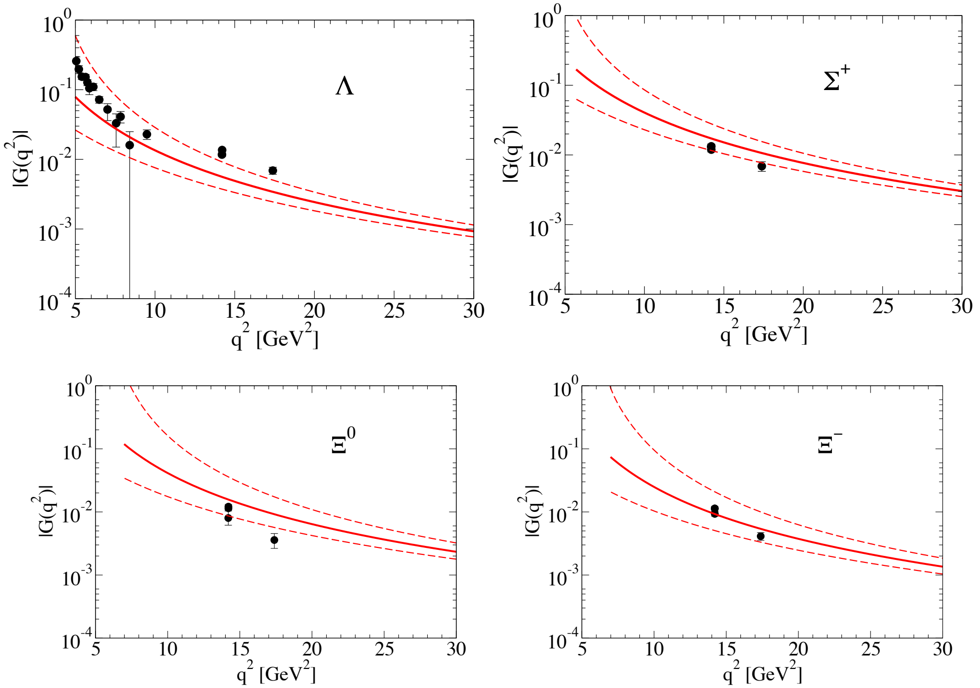
$$G_M(q^2) \simeq G_M^{\mathrm{SL}}(-q^2),$$
$$G_E(q^2) \simeq G_E^{\mathrm{SL}}(-q^2).$$



Extension to Strangeness in the timelike region

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

Preliminary

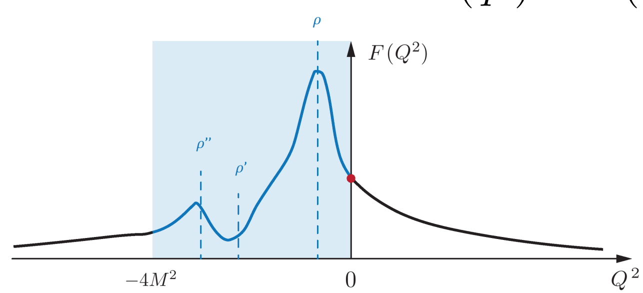


Full line: $G(q^2) = G(2M^2 - q^2)$

Dashed lines:

$$G(q^2) = G(4M^2 - q^2)$$
$$G(q^2) = G(-q^2)$$

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



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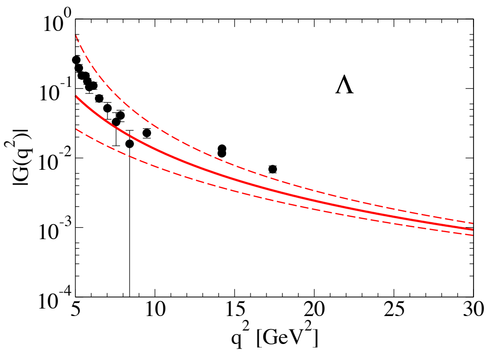

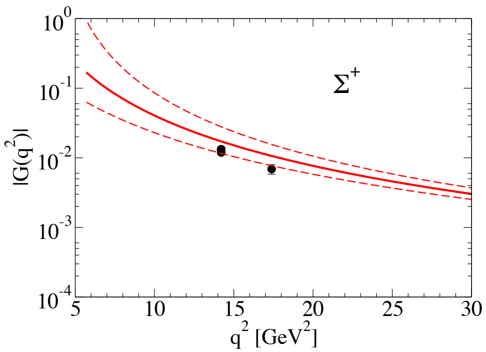

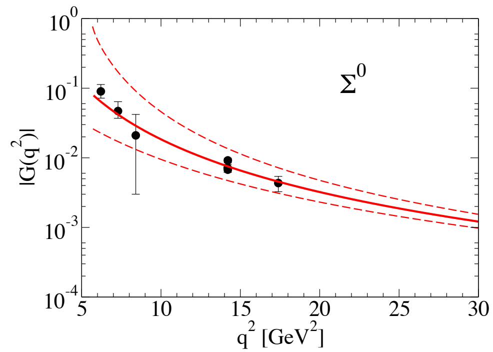

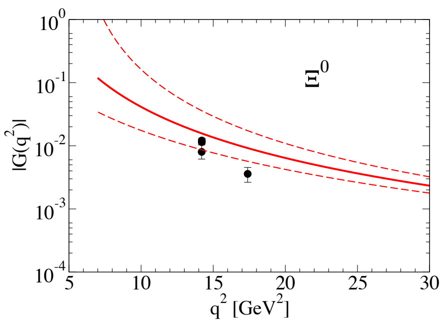

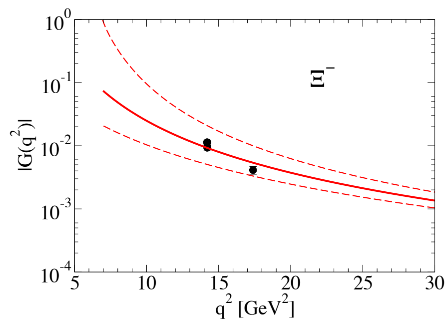

Full line: $G(q^2) = G(2M^2 - q^2)$

Dashed lines:

$$G(q^2) = G(4M^2 - q^2)$$

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

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

This enables:

- Predictions for future experiments
- Guide determination of onset of

-scaling effects

-perturbative QCD falloffs : $G_M \propto 1/q^4$ and $G_E \propto 1/q^4$.

Summary 2

Covariant **S**pectator quark-diquark model enables description of different resonance states (spin/orbital motion).

Several applications: **Δ(1232)**, N*(1440), N*(1535)**, N*(1520)**,baryon octet, octet to decuplet transitions, DIS, dilepton mass spectrum.

Consistent with experimental data at high Q^2.

Consistent with LQCD in the large pion mass regime informing on “pion cloud” effects, and **high q^2 behavior of time-like hyperon FFs**.

VMD and “pion cloud” sustained extension to the timelike region of the TFF of the **Δ(1232) and N*(1520).**

Outlook

LQCD simulations below the N* threshold will help too refine interpretation provided by theoretical quark models.

LQCD data on the baryon octet e.m. FF’s precious source of information, due to scarcity of experimental information.

New experimental data at large Q^2 and even more precise data in all ranges can improve interpretation of empirical results.

Dynamical calculations of diquark vertices within CST to be done, to support quark-diquark picture for baryons, seen within Dyson-Schwinger approach for dynamical quarks.

Thank you!

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Gernot Eichmann (IST-Ulisboa)

Sofia Leitão (IST-Ulisboa)

Franz Gross (JLAB)

TÉCNICO LISBOA

Crossing the boundaries to explore baryon resonances