Covariant calculations of Dalitz decays of nucleon resonances and hyperons

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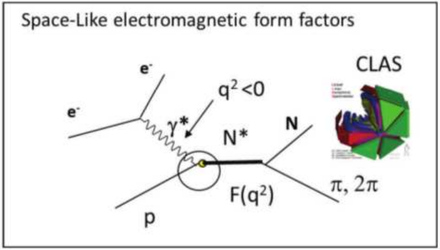
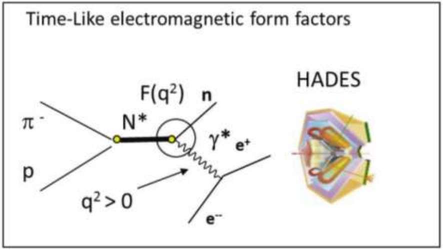
Plan of the talk

- **Introduction**
  Formalism
- **Calculations of Dalitz decays**
  - $N^* \to e^+e^-N$ decays: $N^* = \Delta(1232)\frac{3}{2}^+$, $N(1520)\frac{3}{2}^-$, $N(1535)\frac{1}{2}^-$
  - **Hyperons:** $B' \to e^+e^-B$
    Dalitz decays of decuplet baryons (B') to octet baryons (B)
- **Outlook and Conclusions**

Introduction: Spacelike and Timelike reactions

Figure: B. Ramstein, AIP Conf. Proc. 1735, 080001 (2016) [HADES]





$q^2 \le 0$: CLAS/Jefferson Lab, MAMI, ELSA, JLab-Hall A, MIT-BATES

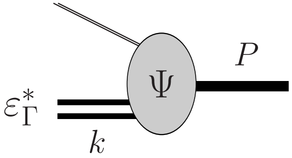
$ep \to e' N(\cdots)$; $\gamma^* N \to N^*$

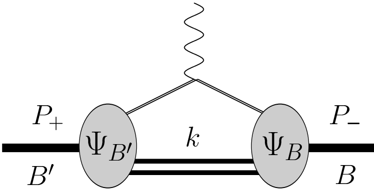
$q^2 > 0$: HADES, ..., PANDA

$\pi^- p \to e^+ e^- n$; $N^* \to \gamma^* N \to e^+ e^- N$

Introduction: Covariant Spectator Quark Model (CSQM) †

- **Covariant Spectator Theory (BARYONS):**
  Active quark off-shell; Spectator particles on-shell
  Stadler, Gross and Frank PRC 56, 2396 (1998); Gross and Agbakpe PRC 73, 015203 (2006)
- Integration into quark pair d.o.f. ← time
  Reduction of system to quark-diquark system
  diquark on-shell Gross, GR and Peña PRC 77, 015202 (2008); PRD 85, 093005 (2012)
- Wave functions: relativistic generalization of $SU_S(2) \otimes SU_F(3) \otimes O(3)$ symmetries
- Radial w.f. ψ_B **determined phenomenologically**
  (Some physical or lattice QCD data)
- Electromagnetic interaction; relativistic impulse approximation **diquark on-shell**
  $J^\mu = 3 \sum_\Gamma \int_k \overline{\Psi}_{B'}(P_+, k) j_q^\mu \Psi_B(P_-, k)$
- Constituent quark current $j_q^\mu(q)$ $(q = u, d, s)$
  Simulate quark dressing (gluons and $q\bar{q}$ effects)





Introduction: CSQM Quark Current ⊕ Transition current †

- **Quark current:**

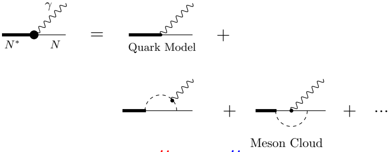
$$j_q^\mu(q) = j_1(q)\gamma^\mu + j_2(q)\frac{i\sigma^{\mu\nu}q_\nu}{2M_N}$$
$$j_i(q) = f_{i+}\lambda_0 + f_{i-}\lambda_3 + f_{i0}\lambda_s$$

λ_l Gell-Mann matrices; $\lambda_s = \mathrm{diag}(0,0,-2)$ [strange quark]

- Functions $f_{i\ell}$ ($\ell = 0, \pm$) determined by the nucleon and decuplet lattice QCD data
  F Gross, GR and MT Peña PRC 77, 015202 (2008);
  GR, K Tsushima, F Gross, PRD 80, 033004 (2009)
- $f_{i\ell}(q^2)$ parametrized using VMD
  Vector Meson Dominance
  Include terms in m_ω, m_ρ and m_ϕ
- Quark current can be generalized to
  - Lattice QCD regime
  - Nuclear medium
  - Timelike region (decay width Γ_v)
    $m_v \to m_v - i\Gamma_v(q)$

GR and MT Peña, PRD 80, 013008 (2009);
GR, K Tsushima and AW Thomas, JPG 40, 015102 (2013)

Transition current ← time



$$J^\mu = J^\mu_B + J^\mu_{\rm MC}$$

Total current =
[Bare (Valence Quark) current]
+ [Meson Cloud current]

- **Bare current:** quark model
  Use calibration of quark current and radial w.f.
- **Meson cloud current:**
  Educated phenomenological parametrizations

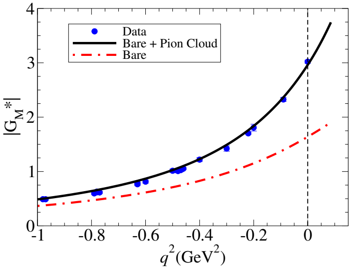
$$G_\ell(q^2) = G_\ell^B(q^2) + G_\ell^{\rm MC}(q^2)$$

Introduction: CSQM – extension to timelike $(Q^2 = -q^2)$

Model extended from $q^2 \leq 0$ to $0 < q^2 \leq (M_{B'} - M_B)^2$

- **Valence quark**
  Extension of quark electromagnetic form factors to $q^2 > 0$ (vector mesons)

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



- **Meson cloud**

$$\left(\frac{\Lambda_D^2}{\Lambda_D^2 - q^2}\right)^n \rightarrow \left(\frac{\Lambda_D^4}{(\Lambda_D^2 - q^2)^2 + \Lambda_D^2\left[\Gamma_D(q^2)\right]^2}\right)^{\frac{n}{2}}$$

Effective decay width; relevant if $\Lambda_D < m_\rho$

Dalitz decay algebra ($B' \to e^+ e^- B$) †

Masses: M_B inital baryon; W = system $\gamma^* B$ ($\approx M_{B'}$); $J^P = \frac{1}{2}^{\pm}, \frac{3}{2}^{\pm}, \ldots$

Magnetic, Electric and Quadrupole Coulomb form factors; $\alpha \equiv \alpha_{\rm em}$

G Wolf et al, NPA 517, 615 (1990); A Faessler et al, PRC 61 (2000);

M I Krivoruchenko et al, Ann. Phys. 296, 299 (2002)

$$\Gamma_{B' \to \gamma^* B}(q, W) = \alpha\, \mathcal{G}(M_B, W, q^2)\, |G_T(q^2, W)|^2 \qquad [|G_T| \textbf{ input}]$$

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

Dalitz decay rate – starting point

$$\Gamma'_{B' \to e^+ e^- B}(q, W) \equiv \frac{d}{dq} \Gamma_{B' \to e^+ e^- B}(q, W) = \alpha \frac{C}{q} \Gamma_{B' \to \gamma^* B}(q, W)$$

$$\Gamma_{B' \to e^+ e^- B}(W) = \int_{2m_e}^{W - M_B} \Gamma'_{B' \to e^+ e^- B}(q, W)\, dq.$$

Radiative decay: $\Gamma_{B' \to \gamma B}(W) = \Gamma_{B' \to \gamma^* B}(0, W)$; $\quad \Gamma_{B' \to \gamma B} \equiv \Gamma_{B' \to \gamma B}(M_{B'})$

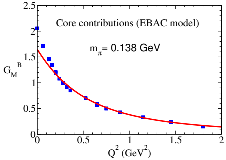
$\gamma^* N \to \Delta(1232)$ transition ($Q^2 = -q^2$)

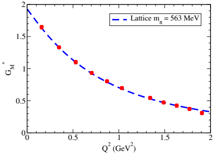
Valence quark contribution

Dominance of magnetic dipole form factor

S-state wave functions $G_M^B \propto 1/Q^4$

$$G_M^B(q^2, W) = \frac{4}{3\sqrt{3}} \left[\frac{2M_N}{M_\Delta + M_N} f_{1-} + f_{2-} \right] \int_k \psi_\Delta \psi_N$$





ψ_Δ determined by EBAC data or lattice data

C Alexandrou et al Phys. Rev. D 77, 085012 (2008);

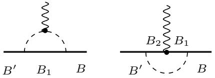
J Diaz et al, PRC 75, 015205 (2007)

Pion (meson) cloud

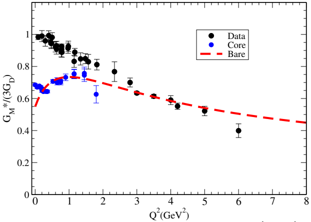
Effective parametrization (λ_π^a, λ_π^b) based on the Cloudy Bag Model & **quark counting rules (pQCD)**

GR and Tsushima, PRD 88, 053002 (2013); GR, Peña Weil, van Hees, Mosel, PRD D 93, 033004 (2016) $G_M^\pi \propto 1/Q^8$

$$G_M^\pi(q^2) = \lambda_\pi^a \left(\frac{\Lambda_\pi^2}{\Lambda_\pi^2 - q^2} \right)^2 F_\pi(q^2) + \lambda_\pi^b \left(\frac{\Lambda_D^2}{\Lambda_D^2 - q^2} \right)^4$$



(a) (b)



Data from DESY, SLAC and CLAS (Jlab)

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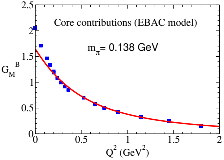

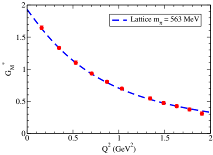

ψ_Δ determined by EBAC data or lattice data

EBAC model: coupled-channel baryon-meson model

$\gamma N \to \pi N$ and $\gamma^* N \to \pi N \Rightarrow$ estimate core contr.

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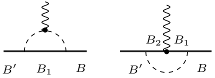

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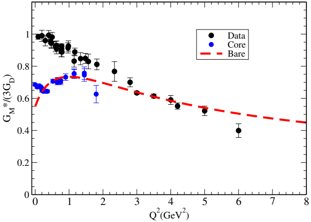

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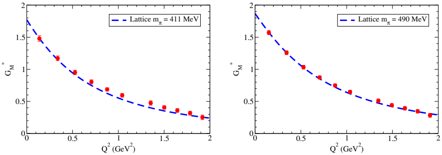

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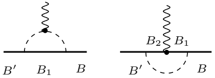

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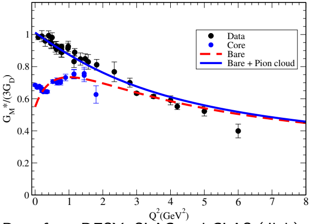


Data from DESY, SLAC and CLAS (Jlab)

$\Delta(1232)$ Dalitz decay

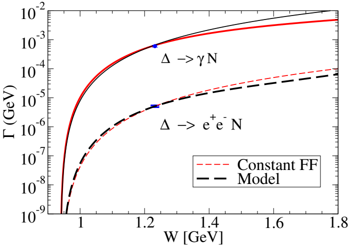
GR, MT Peña, J Weil, H van Hees and U Mosel, PRD 93, 033004 (2016)

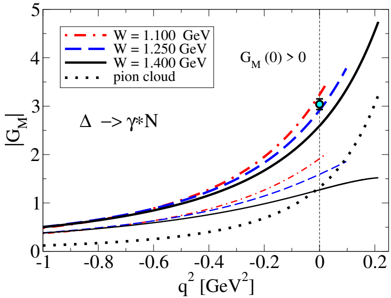
$\Gamma_{N^* \to \gamma^* N}(q, W) \propto$

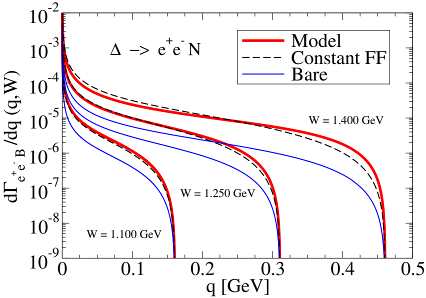
$$\left[|G_M(q^2, W)|^2 + 3|G_E(q^2, W)|^2 + \frac{q^2}{2W^2} |G_C(q^2, W)|^2 \right]$$

Simple estimate:

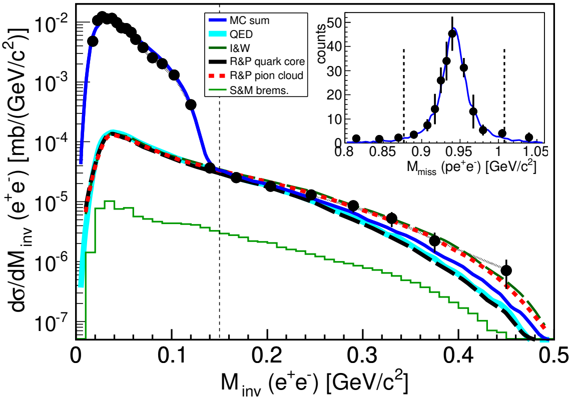
$|G_T(q^2, W)|^2 \simeq |G_M(q^2, W)|^2 + \ldots$ ($\ldots \approx 0.2$–0.6 %)







$\Delta(1232)$ Dalitz decay – HADES ($pp \to p\Delta^+ \to ppe^+e^-$)



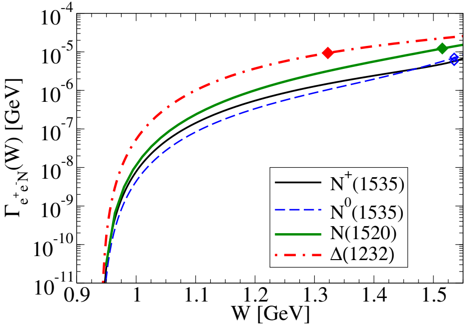
$\Delta(1232)$ Dalitz decay in proton-proton collisions at T = 1.25 GeV HADES, PRC 95, 065205 (2017)

Model $\cdots\cdots$: $\Gamma_{e^+e^-N} = 4.9$ keV HADES: $\Gamma_{e^+e^-N} = 4.9 \pm 0.83$ keV (PDG)

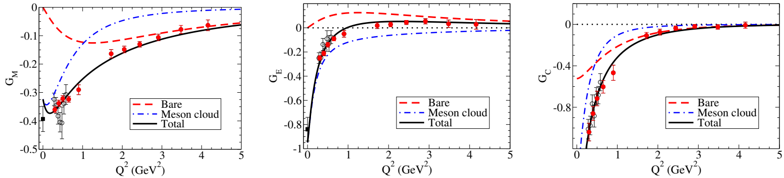
$N(1520)$ and $N(1535)$ Dalitz decay †

GR and MT Peña, PRD 95, 014003 (2017); PRD 101, 114008 (2020)

- Result dependent on isospin channel (n or p excitations)
  $N^+ \to e^+e^-p$ and $N^0 \to e^+e^-n$; TL data – information about the neutron
- Spacelike data dominated by proton data (parametrize Meson Cloud)



$N(1520)$ – radiative decay (MC = Meson Cloud) †

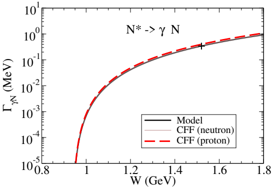


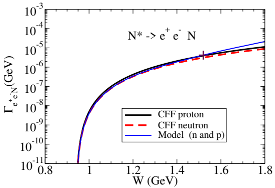
	$\Gamma_{\gamma N}$ (MeV)		
	PDG (FF)	PDG limits	Model
p	**0.43±0.03**	0.31–0.62	**0.34**
n	**0.34±0.03**	0.30–0.64	**0.34**

Model: same result p and n

Dominance of MC (isovec)

Underestimate CFF for p

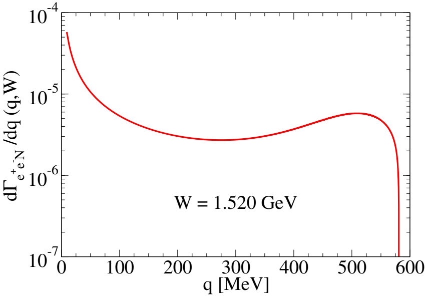


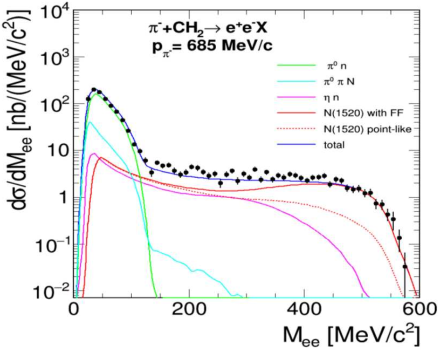


SL: Valence quark contributions (Bare) dominate at large Q^2

TL ($N^* \to e^+e^- N$): Model prediction larger than CFF estimates (n and p); $\Gamma_{e^+e^-B} = 4.2$ keV

$N(1520)$ Dalitz decay – HADES





Calculation: Dalitz decay rate

GR and MT Peña, PRD 95, 014003 (2017)

HADES πp W=1.49 GeV,

Witold Przygoda presentation

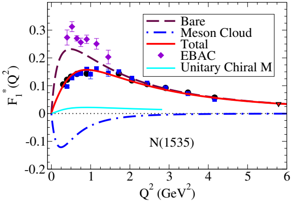
—— N(1520) with FF

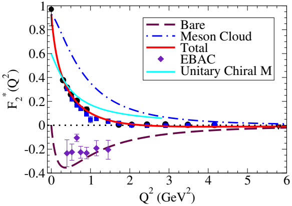
Much larger than pointlike

Signature of q^2-deppendence of form factors $G_T(q^2, W)$

Dalitz decay measurement deppend on the range of W

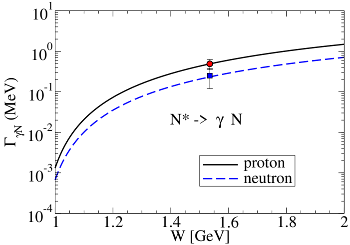
$N(1535)$ – radiative decay (MC = Meson Cloud) †

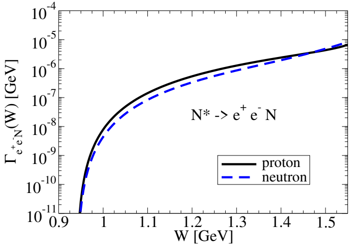




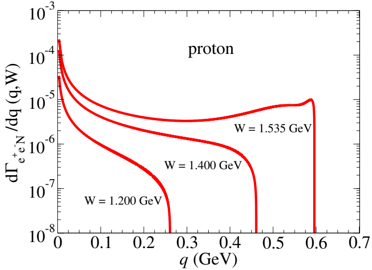
← Proton data

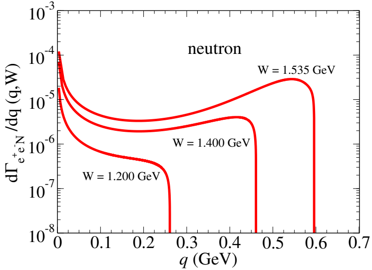
	$A_{1/2}(0)$ [GeV$^{-1/2}$] Data	$\Gamma_{\gamma N}$ [MeV] PDG (FF)	PDG limits	Model
p	0.105±0.015	0.49±0.14	0.19–0.53	**0.503**
n	−0.075±0.020	0.25±0.13	0.013–0.44	**0.240**





$N(1535)$ Dalitz decay – HADES





⇑ Calculation: Dalitz decay rate

GR and MT Peña, PRD 101, 114008 (2020)

Dependence on the isospin

q^2-dependence related with range of W

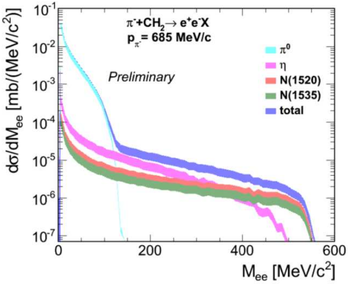
Proton: $\Gamma_{e+e-N} = 5.7$ keV

Neutron: $\Gamma_{e+e-N} = 7.2$ keV

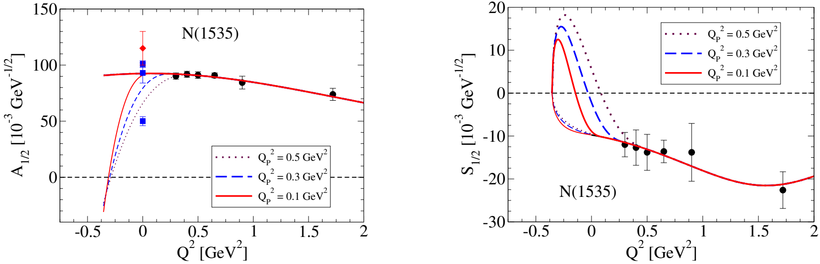
HADES, B. Ramstein, ⟹

Proceedings of NSTAR2019

EPJ Web of Conf. 241, 01012 (2020)



About the $N(1535)$ data at low Q^2 (optional)



GR, PLB 759, 126 (2016); PRD 100, 114014 (2019), Devenish et al, PRD 14, 3063 (1976) — Siegert's theorem

Extension to timelike extremely sensitive to the low-Q^2 data

Ambiguities about the $\gamma^* N \to N(1535)$ data near $Q^2 = 0$ $[A_{1/2}(0) = ?,\ S_{1/2}(0) = ?]$

Estimates may change with new data

Hyperon Dalitz decays $B' \to e^+e^- B$

Extension of $\gamma^* N \to \Delta(1232)$ to **octet baryons** transitions to **decuplet baryons**

GR and K Tsushima, in preparation; GR, PRD 102, 054016 (2020); GR and K Tsushima, PRD 88, 053002 (2013)

Include also kaon cloud F_K kaon physical FF

Parameters estimated ($\Lambda^2_{K\text{a}}$, $\Lambda^2_{K\text{b}}$,) by CBM expansion $G_M^{K\ell}(q^2) = G_M^{K\ell}(0) + G_M^{K\ell(1)} q^2$

$$G_M^K(q^2) = G_M^{K\text{a}}(0) \left(\frac{\Lambda^2_{K\text{a}}}{\Lambda^2_{K\text{a}} - q^2} \right)^3 F_K(q^2) + G_M^{K\text{b}}(0) \left(\frac{\Lambda^4_{K\text{b}}}{(\Lambda^2_{K\text{b}} - q^2)^2 + \Lambda^2_{K\text{b}} \Gamma^2_{K\text{b}}} \right)^2$$

	$G_M^\pi(0)$	$G_M^{K\text{a}}(0)$	$G_M^{K\text{b}}(0)$	$G_M^K(0)$	$G_M^{\text{B}}(0, M_{B'})$	$\alpha_\pi(\%)$	$\alpha_K(\%)$
$\Delta \to \gamma^* N$	1.323	0.0167	0.0367	0.0534	1.633	44.0	1.8
$\Sigma^{*0} \to \gamma^* \Lambda$	1.027	0.0670	0.2768	0.3438	1.683	36.0	11.3
$\Sigma^{*+} \to \gamma^* \Sigma^+$	0.663	0.1527	0.2640	0.4167	2.094	20.9	13.1
$\Sigma^{*0} \to \gamma^* \Sigma^0$	0.270	0.1019	0.1001	0.2020	0.969	18.7	14.0
$\Sigma^{*-} \to \gamma^* \Sigma^-$	−0.124	0.0510	−0.0638	−0.0128	−0.156	42.3	4.4
$\Xi^{*0} \to \gamma^* \Xi^0$	0.308	0.1850	0.5126	0.6976	2.191	9.6	21.8
$\Xi^{*-} \to \gamma^* \Xi^-$	−0.138	0.0370	−0.1070	−0.0700	−0.168	36.7	18.6

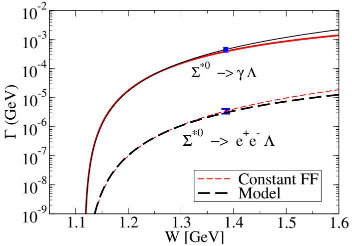
GR and K Tsushima, PRD 84, 054014 (2011); PRD 86, 114030 (2012); PRD 87, 093011 (2013);

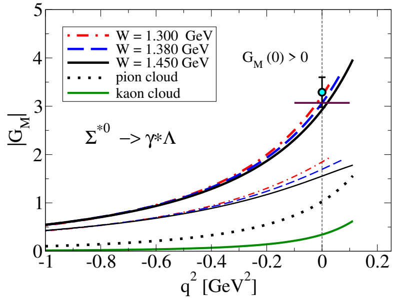
GR, K Tsushima and AW Thomas, JPG 40, 015102 (2013)

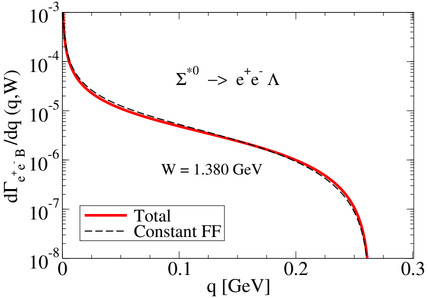
Interesting cases: $\Sigma^{*0} \to \gamma^* \Lambda$ and $\Sigma^{*+} \to \gamma^* \Sigma^+$ ($\approx \Xi^{*0} \to \gamma^* \Xi^0$)

$\Sigma^{*0} \to e^+e^-\Lambda$ – Dalitz decay (preliminary)

- K increase $|G_M|$
- $|G_M(0)|_{\rm mod} \lesssim |G_M(0)|_{\rm exp}$
- Model $\approx$ CFF

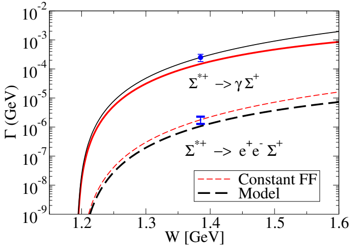


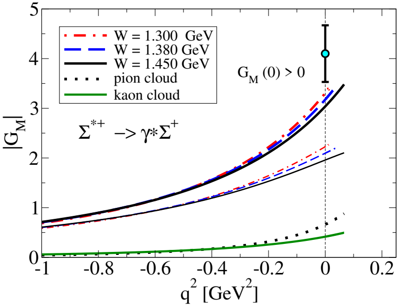


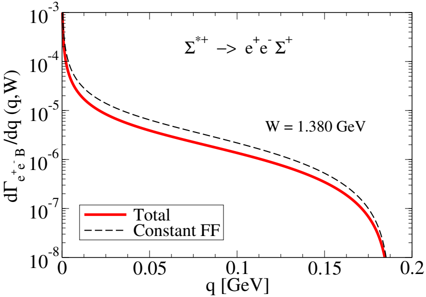


$\Sigma^{*+} \to e^+e^-\Sigma^+$ – Dalitz decay (preliminary)

- K increase $|G_M|$
- $|G_M(0)|_{\text{mod}} < |G_M(0)|_{\text{exp}}$
- Model $<$ CFF







Decuplet baryon decays $B' \to \gamma^* B$ $\dagger$

Decay widths in keV $\Sigma^{*0,-}$, $\Xi^{*0,-}$ **decays – equivalence to CFF**

Decay	$\Gamma_{\gamma B}$ No K	**Model**	Exp		$\Gamma_{e^+e^-B}$ CFF	**Model** (No K)	
$\Delta \to \gamma^* N$	621	644	660±47				
$\Sigma^{*0} \to \gamma^* \Lambda$	314	392	452±86		3.47±0.65	3.04 (2.4)	5.04±0.70 ■
$\Sigma^{*+} \to \gamma^* \Sigma^+$	116	149	250±70		1.78±0.50	1.07 (0.81)	
$\Sigma^{*0} \to \gamma^* \Sigma^0$	24	31	< 1750 $\dagger$	$\simeq \frac{1}{4}\Gamma_{\gamma\Sigma^+}$	**0.220**	0.220 (0.16)	
$\Sigma^{*-} \to \gamma^* \Sigma^-$	1.3	1.3	< 9.5 #		**0.0090**	0.0091 (0.0083)	
$\Xi^{*0} \to \gamma^* \Xi^0$	111	172	$\dagger$		**1.253**	1.265 (0.76)	
$\Xi^{*-} \to \gamma^* \Xi^-$	1.6	2.4	< 366		**0.0173**	0.0175 (0.012)	

■ HADES feasibility study EPJA 57, 30 (2021)

$\dagger$ To be measured soon? Increase strangeness production

Close to experimental limit $|G_M(0)|_{\rm mod} \simeq 0.3$; $|G_M(0)|_{\rm exp} < 0.8$

$$\Gamma_{\gamma B} = \frac{\alpha}{16} \frac{(M_{B'}^2 - M_B^2)^3}{M_{B'}^3 M_B^2} |G_M(0, M_{B'})|^2$$

$$\Gamma_{e^+e^-B} = \int \Gamma'_{e^+e^-B}(q, M_{B'}) dq$$

Outlook and Conclusions

Dalitz decays:

- Calculation based on **Covariant Spectator Quark Model** (Bare + Meson Cloud)
  [Parametrizations sensitive to SL data ($N(1535)$) – p targets; TL data – n targets]
- Calculations with W-dependence are important to compare with data: $\Gamma_{e^+e^-B}(W)$
- **Nucleon resonances** (N^*)
  - $\Delta(1232)$ result consistent with **first Dalitz decay measurement** (HADES)
  - $\Delta(1232)$, $N(1520)$: show effects of dependence on q^2; $N(1535)$ under study
- **Hyperon decays** (decuplet baryons decays into octet baryons)
  - Expected: measurements of $\Sigma^0(1385)$, $\Sigma^-(1385)$, $\Xi^0(1533)$
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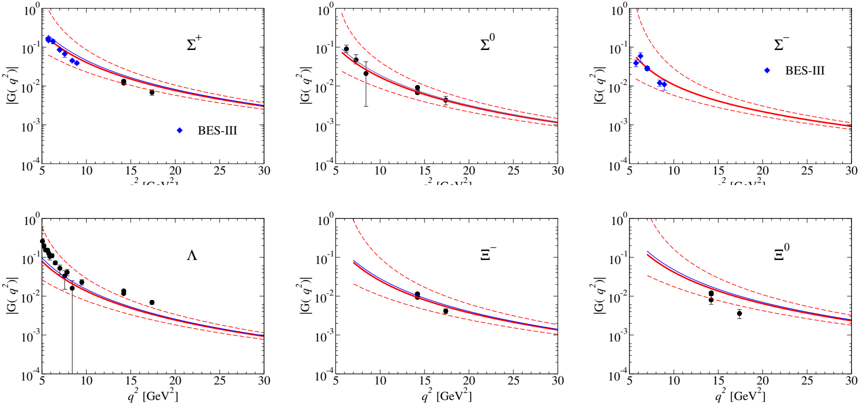
Hyperon elastic form factors at large q^2 [Octet (Λ, Σ, Ξ), Ω^-]

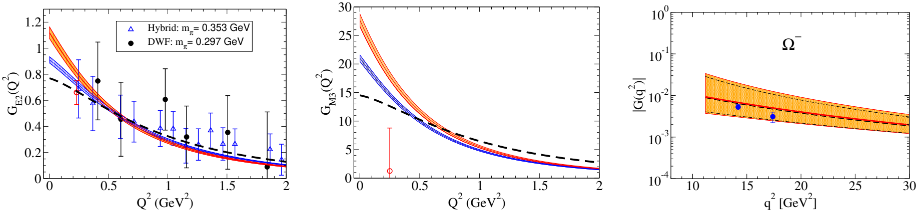
Hyperon elastic form factors **at large** q^2 $(e^+e^-, p\bar{p} \to B\bar{B})$



GR, MT Peña and K Tsushima PRD 101, 014014 (2020) — Data from CLEO, BaBar, BES-III (new data Σ^-)

Ω^- elastic form factors **at large** q^2

GR, PRD 103, 074018 (2021)



C Alexandrou et al, PRD 82, 034504 (2010) [lattice]; S Dobbs, et al, PRD 96, 092004 (2017) [TL data]

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Thank you 🙂 gilberto.ramalho2013@gmail.com