$N \to \Delta(1232)$ Resonance Transition Form Factors from Lattice QCD

Srijit Paul
University of Maryland, College Park

In Collaboration: Luka Leskovec, Stefan Meinel, John Negele, Ferenc Pittler, Andrew Pochinsky

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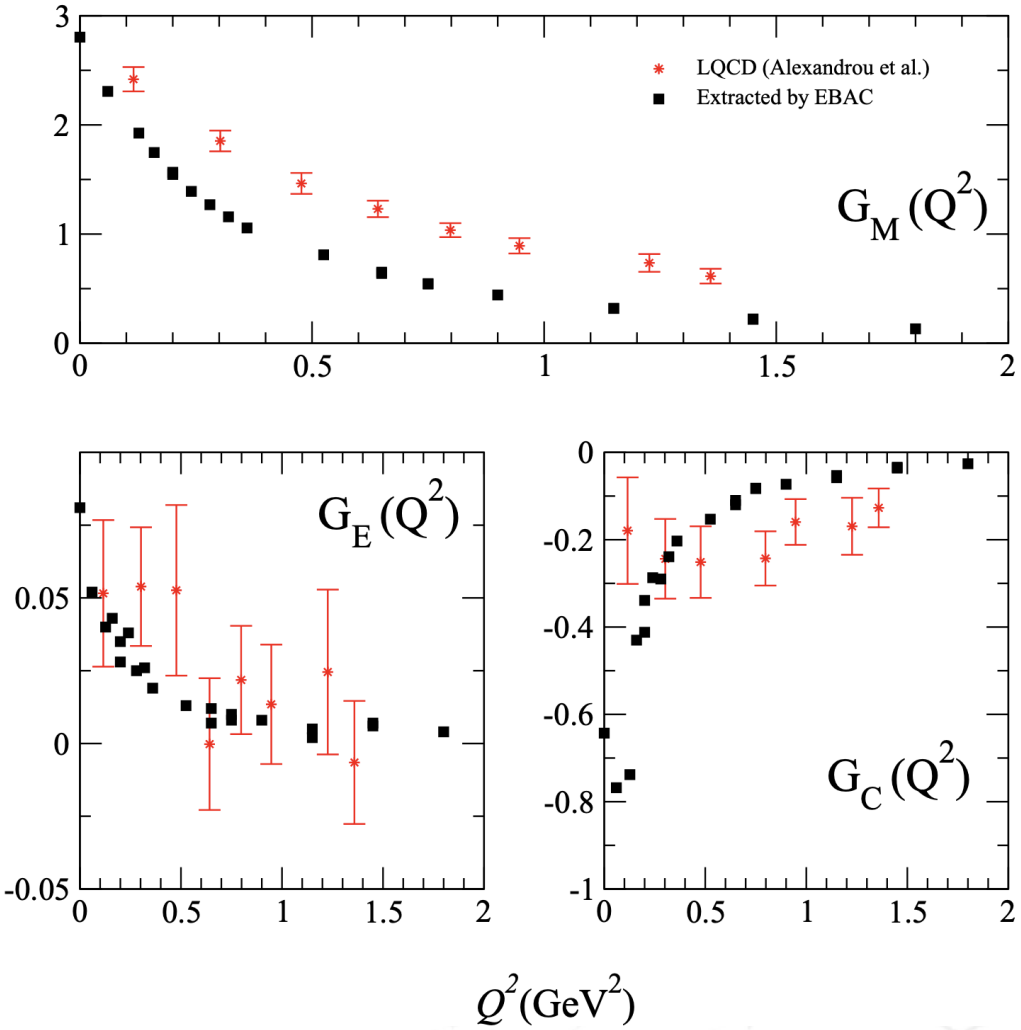
[*www.jlab.org/exp_prog/proposals/09/PR12-09-003.pdf*]



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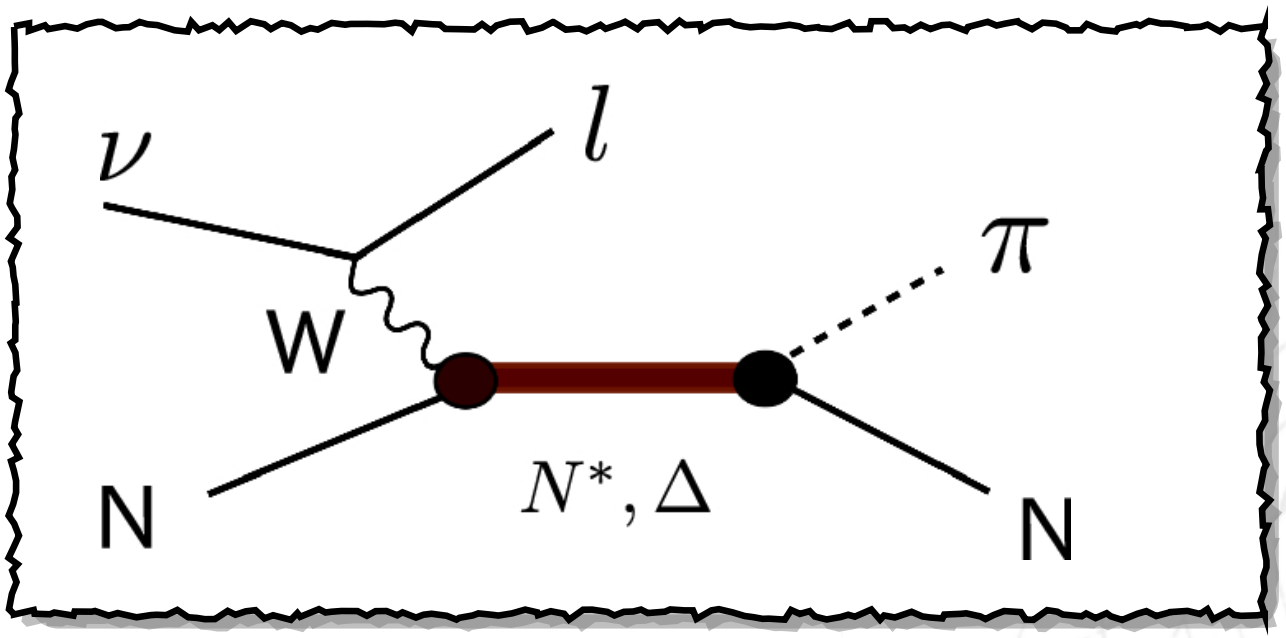

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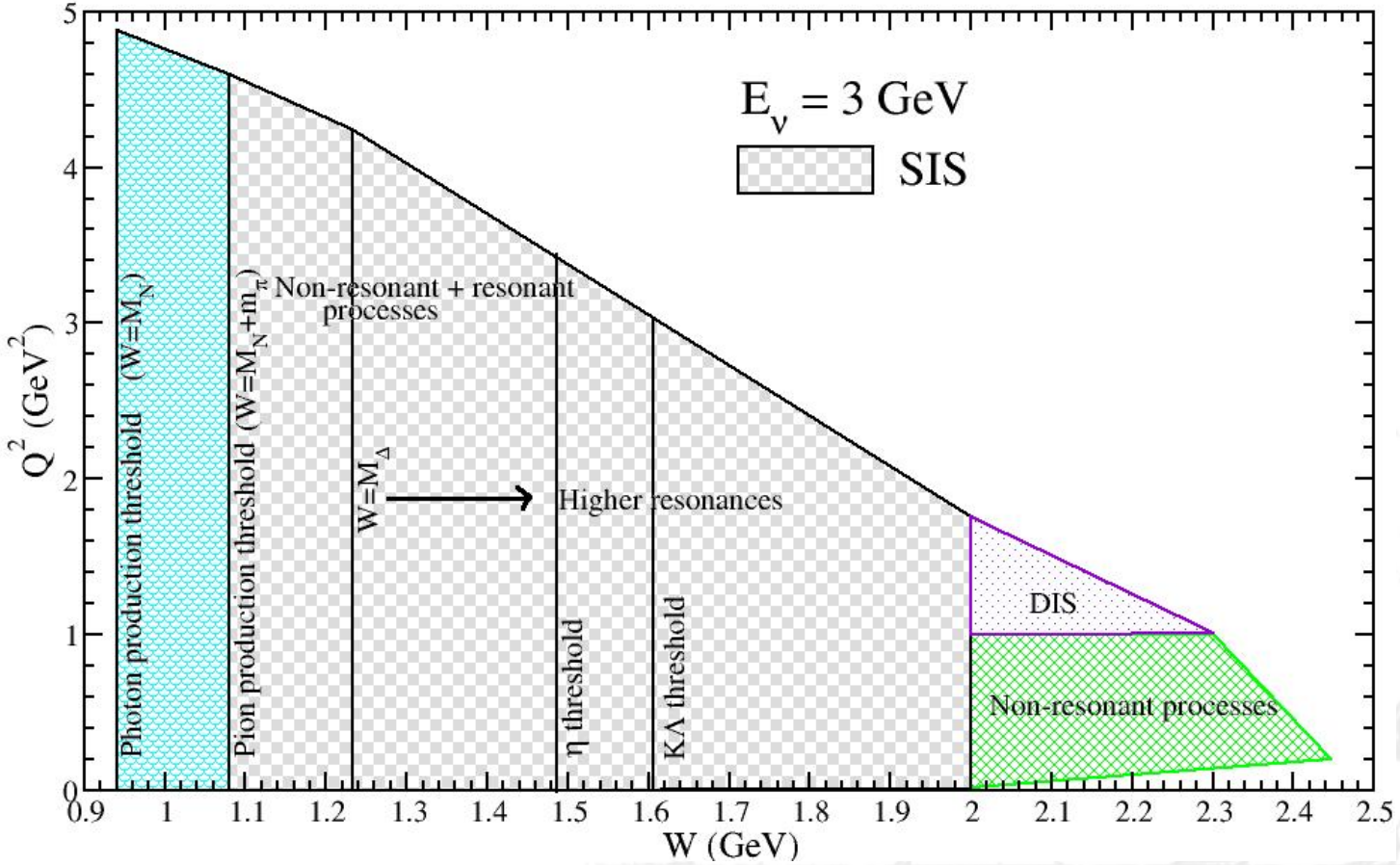

Lattice Setup

Budapest-Marseille-Wuppertal simulations $N_f = 2 + 1$
tree-level *clover-improved Wilson fermions* coupled to *doubly HEX smeared links.*

[Durr et.al.,1011.2711]

Label	$N_s^3 \times N_t$	L (fm)	a (fm)	m_π (MeV)	m_N (MeV)	$m_\pi L$
A7	$24^3 \times 48$	2.8	0.1163(4)	255.4(1.6)	1073.3(3.4)	3.61(2)

Table: Parameters of the lattice gauge-field ensembles

Use 48 source positions on $N_{\rm cfg} = 600$ configurations.

Scale setting done using $M_\Omega = 1.672$ GeV.

Smearing parameters optimized for nucleon. $\alpha_{\rm W} = 3.0, N_{\rm W} = 45$.

$Z_v = 0.91939(56)$,

[Green et.al.,1404.4029]

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  pion interpolator:

$$\pi(\vec{p}) = \sum_{\vec{x}} \bar{d}(\vec{x})\gamma_5 u(\vec{x}) e^{i\bar{p}\cdot\vec{x}}$$

  Nucleon interpolators

$$N_\mu^{(1)}(\vec{p}) = \sum_{\vec{x}} \epsilon_{abc} u_a(\vec{x})_\mu \left(u_b^T(\vec{x}) C\gamma_5 d_c(\vec{x})\right) e^{i\vec{p}\cdot\vec{x}}$$

$$N_\mu^{(2)}(\vec{p}) = \sum_{\vec{x}} \epsilon_{abc} u_a(\vec{x})_\mu \left(u_b^T(\vec{x}) C\gamma_0\gamma_5 d_c(\vec{x})\right) e^{i\vec{p}\cdot\vec{x}}$$

  Δ interpolator

$$\Delta^+_{\mu i}(\vec{p}) = \sum_{\vec{x}} \frac{1}{\sqrt{3}} \epsilon_{abc} \left\{2\left[u_a^T C\gamma_i d_b\right] u_{c,\mu} + \left[u_a^T C\gamma_\sigma u_b(\vec{x})\right] d_{c,\mu}\right\}$$

  2-hadron interpolators: $N_\mu^{(1,2)}(\vec{p}_N)\pi(\vec{p}_\pi)$

What are the Resonance Transition Form Factors?

∞-V matrix element $j_\mu^{\text{em}} = \frac{2}{3}\bar{u}\gamma_\mu u - \frac{1}{3}\bar{d}\gamma_\mu d$

$$\left\langle \Delta\left(\mathbf{p}', s'\right) \left| j_\mu^{\text{em}} \right| N(\mathbf{p}, s) \right\rangle = N\ \bar{u}_\sigma\left(\mathbf{p}', s'\right)\ \mathcal{O}_{\sigma\mu}\ u(\mathbf{p}, s)$$

where $N \equiv N(m_\Delta, m_N, E_\Delta(\mathbf{p}'), E_N(\mathbf{p}))$

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Δ as stable$(1 \to 1)$

Rarita-Schwinger Constraints, Lorentz covariance, parity & current cons. $\Longrightarrow$ **3** *[Jones and Scadron, 1973]*

$\mathcal{O}_{\sigma\mu} = G_M^*(q^2)K_{\sigma\mu}^M + G_E^*(q^2)K_{\sigma\mu}^E + G_C^*(q^2)K_{\sigma\mu}^C$

G_M^* :*Magnetic Dipole*,

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Δ as unstable$(1 \to 2)$

Naive helicity counting $= 12$

current cons. & parity $\to 6$,

$N\pi$ projection to $\ell = 1$

Analytically continued to resonance pole $\Longrightarrow$ **3** *[hep-ph/0609004]*

$\mathcal{O}_{\sigma\mu} = F_1^*(q^2)K_{\sigma\mu}^1 + F_2^*(q^2)K_{\sigma\mu}^2 + F_3^*(q^2)K_{\sigma\mu}^3$

F_1^*, F_2^*, F_3^*: *Transition Form Factors*.

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FFs' $\equiv f(Q^2)$.

$N\pi$ threshold above m_Δ.

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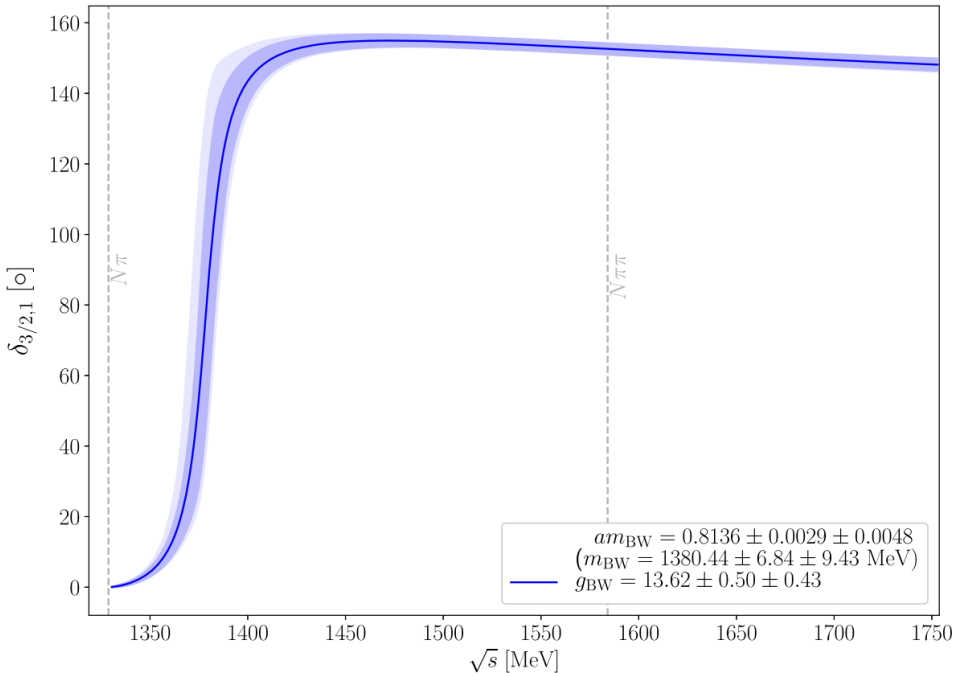
$N\pi = 1328.4$ MeV, $m_\Delta = 1380(11.4)$ MeV $\implies$ **unstable**



[*Silvi, SP.et.al., 2101.00689*]

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Test Signal/Noise : *Single hadron approach*.

- Use 3-quark interpolator for Δ, Near resonance, **dominant overlap**.
- Perform BHWL analysis to extract FFs at $W \approx m_\Delta$.

[Briceño, Hansen, and Walker-Loud, 1406.5965]

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$$G_{\sigma}^{\Delta j^{\mu} N}\left(t_2, t_1; \vec{p}', \vec{p}; \Gamma\right) =$$

$$\sum_{\vec{x}_2, \vec{x}_1} e^{-i\vec{x}_2 \cdot \vec{p}} \left\langle 0 \left| \Gamma^{\beta\alpha} \Delta_{\alpha,\sigma} \left(\overrightarrow{0}, 0\right) j_{\mu}\left(\vec{x}_1, t_1\right) \bar{N}_{\beta}(\vec{x_2}, t_2) \right| 0 \right\rangle e^{-i\vec{x}_1 \cdot \left(\vec{p}' - \vec{p}\right)},$$

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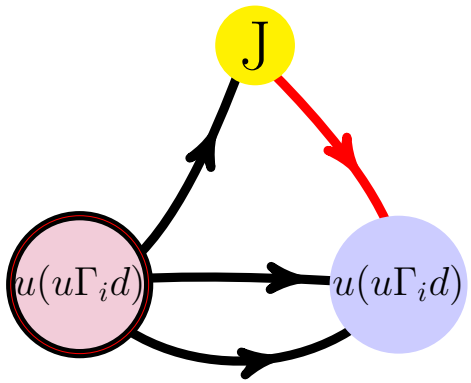
	N
Δ	

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$$R_\sigma\left(t_2,t_1;\mathbf{p}',\mathbf{p};\Gamma;\mu\right)=\left[\frac{\left\langle G_\sigma^{\Delta j^\mu N}\left(t_2,t_1;\mathbf{p}',\mathbf{p};\Gamma\right)\right\rangle\left\langle G_\sigma^{N j^\mu \Delta}\left(t_2,t_1;-\mathbf{p},-\mathbf{p}';\Gamma^\dagger\right)\right\rangle}{\left\langle \delta_{ij}G_{ij}^{\Delta\Delta}\left(t_2,\mathbf{p}';\Gamma_4\right)\right\rangle\left\langle G^{NN}\left(t_2,-\mathbf{p};\Gamma_4\right)\right\rangle}\right]^{1/2},$$

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$$R_\sigma^{sign}\left(t_2,\ t_1;\mathbf{p}',\mathbf{p};\Gamma_\tau;\mu\right)$$

$$=\frac{\left\langle G_\sigma^{\Delta J_\mu N}\left(t_2,t_1;\mathbf{p}',\mathbf{p};\Gamma\right)\right\rangle}{\left\langle G_{ii}^{\Delta\Delta}\left(t_2,\mathbf{p}';\Gamma_4\right)\right\rangle}\left[\frac{\left\langle G_{ii}^{\Delta\Delta}\left(t_2,\mathbf{p}';\Gamma_4\right)\right\rangle}{\left\langle G^{NN}\left(t_2,\mathbf{p};\Gamma_4\right)\right\rangle}\frac{\left\langle G^{NN}\left(t_2-t_1,\mathbf{p};\Gamma_4\right)\right\rangle\left\langle G_{ii}^{\Delta\Delta}\left(t_1,\mathbf{p}';\Gamma_4\right)\right\rangle}{\left\langle G_{ii}^{\Delta\Delta}\left(t_2-t_1,\mathbf{p}';\Gamma_4\right)\right\rangle\left\langle G^{NN}\left(t_1,\mathbf{p};\Gamma_4\right)\right\rangle}\right]^{1/2}$$

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- Fit to extract *form factors*.

Kinematic Combinations for $G_{M1}(\mathbf{q}^2)$

$$\Pi_\sigma\left(\mathbf{0},-\mathbf{q};\Gamma_4;\mu\right)=iA\epsilon^{\sigma 4\mu j}p^j G_{M1}\left(\mathbf{q}^2\right),\ A=\sqrt{\frac{2}{3}}\frac{m_\Delta+m_N}{4m_N E_N}\sqrt{\frac{E_N}{E_N+m_N}}$$

Desired kinematic set-up for G_{M1} extraction

$S_1(\mathbf{q};\mu)=\sum_{\sigma=1}^{3}\Pi_\sigma\left(\mathbf{0},-\mathbf{q};\Gamma_4;\mu\right)$ [*Alexandrou. et.al.1011.3233*]

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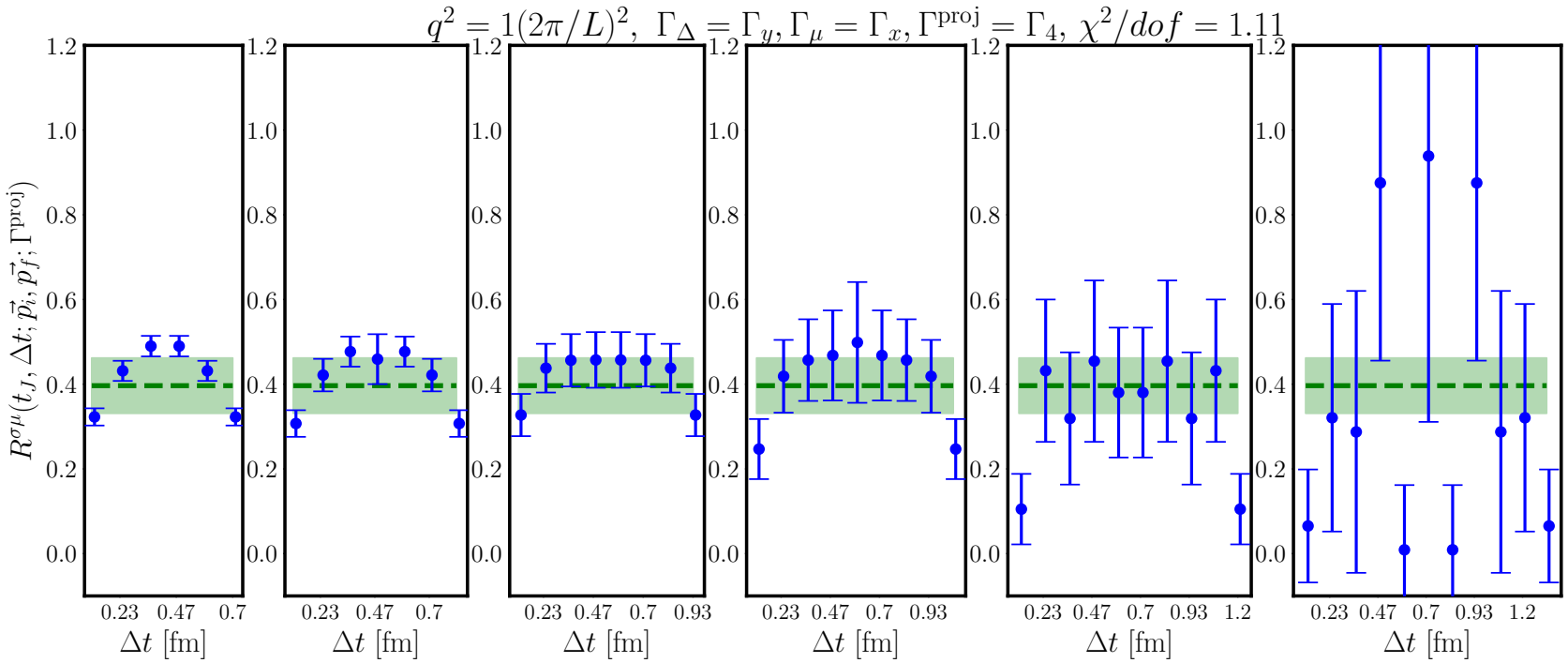

$\vec{p}=(0,0,-1)\frac{2\pi}{L}$ plateau fit to last 3 panels(right)

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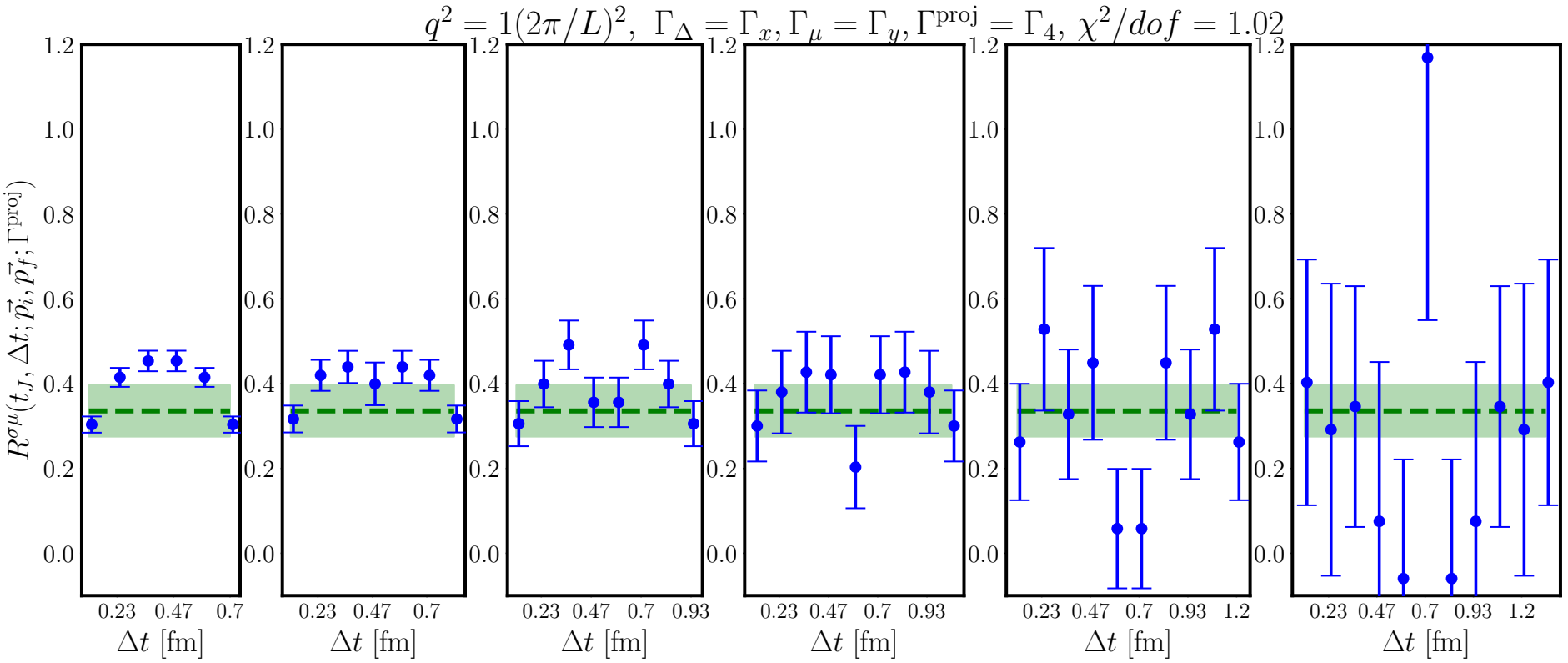

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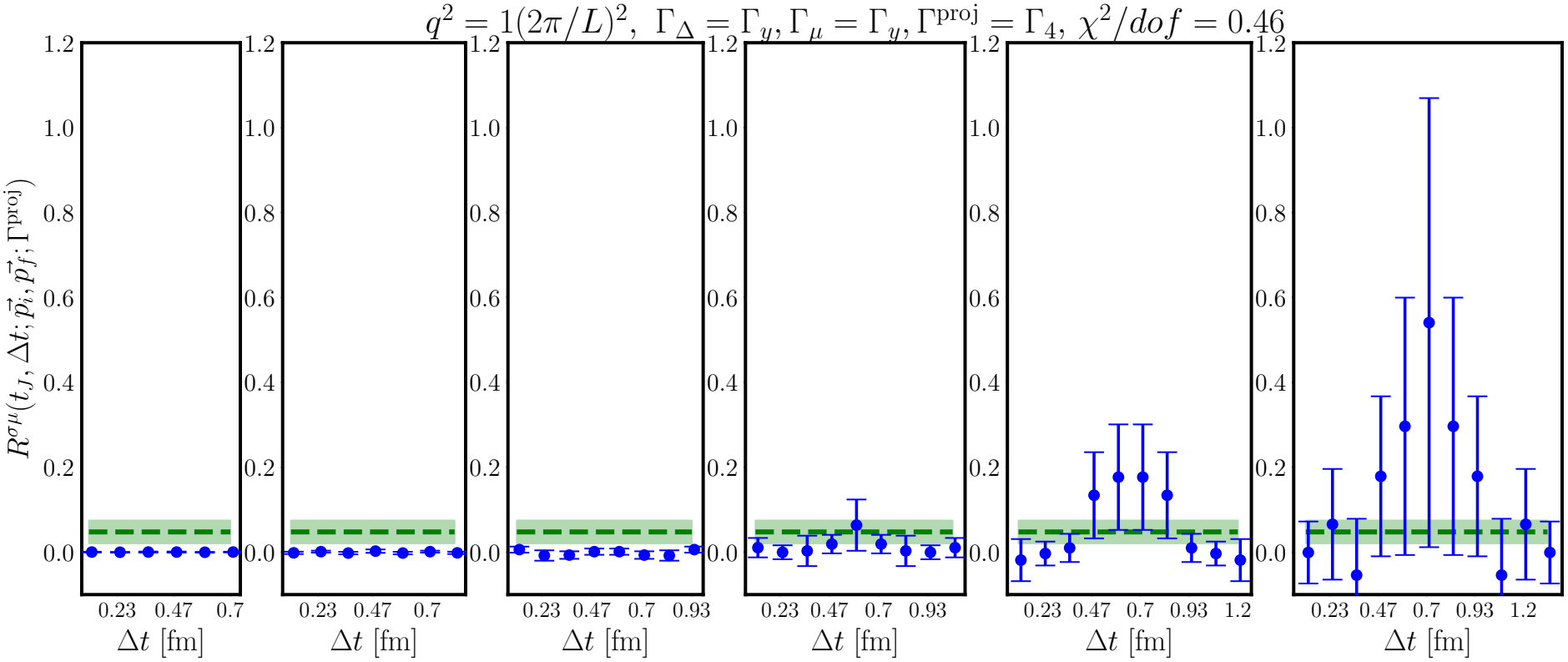

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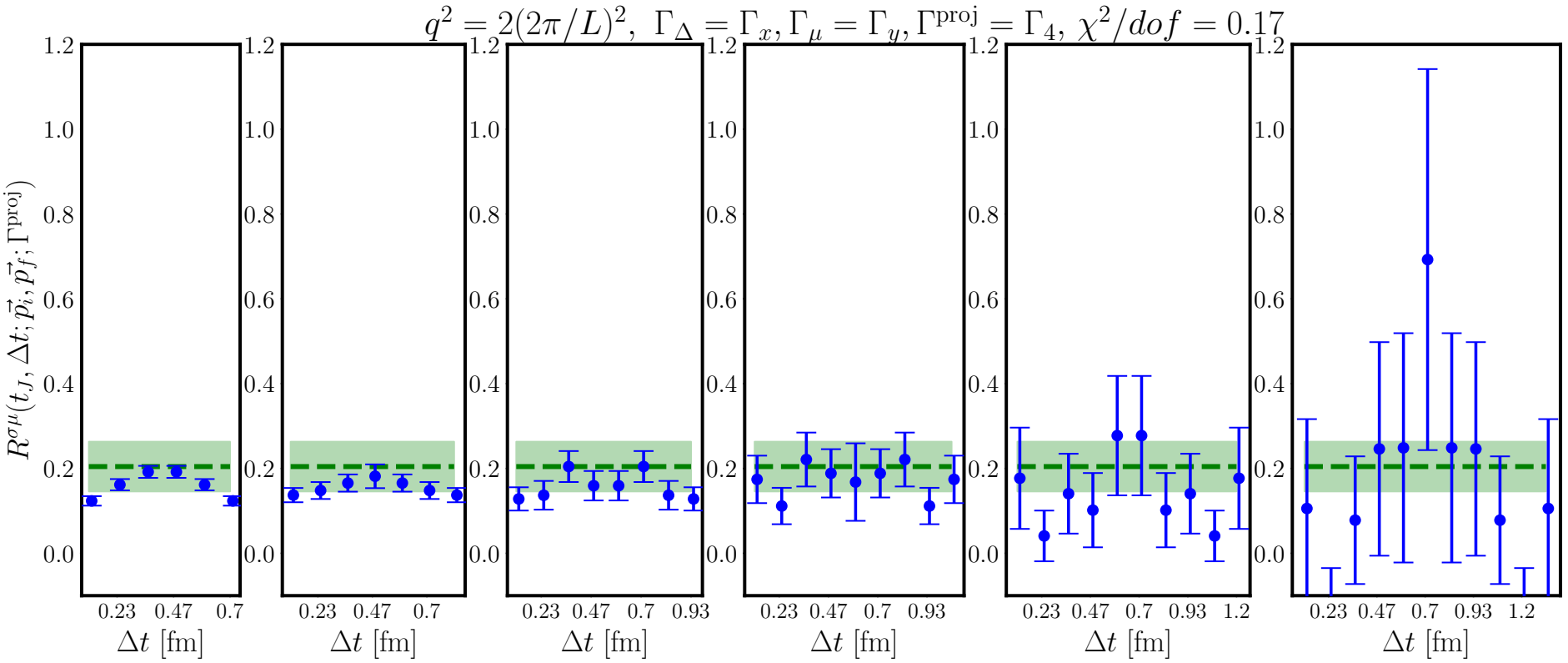

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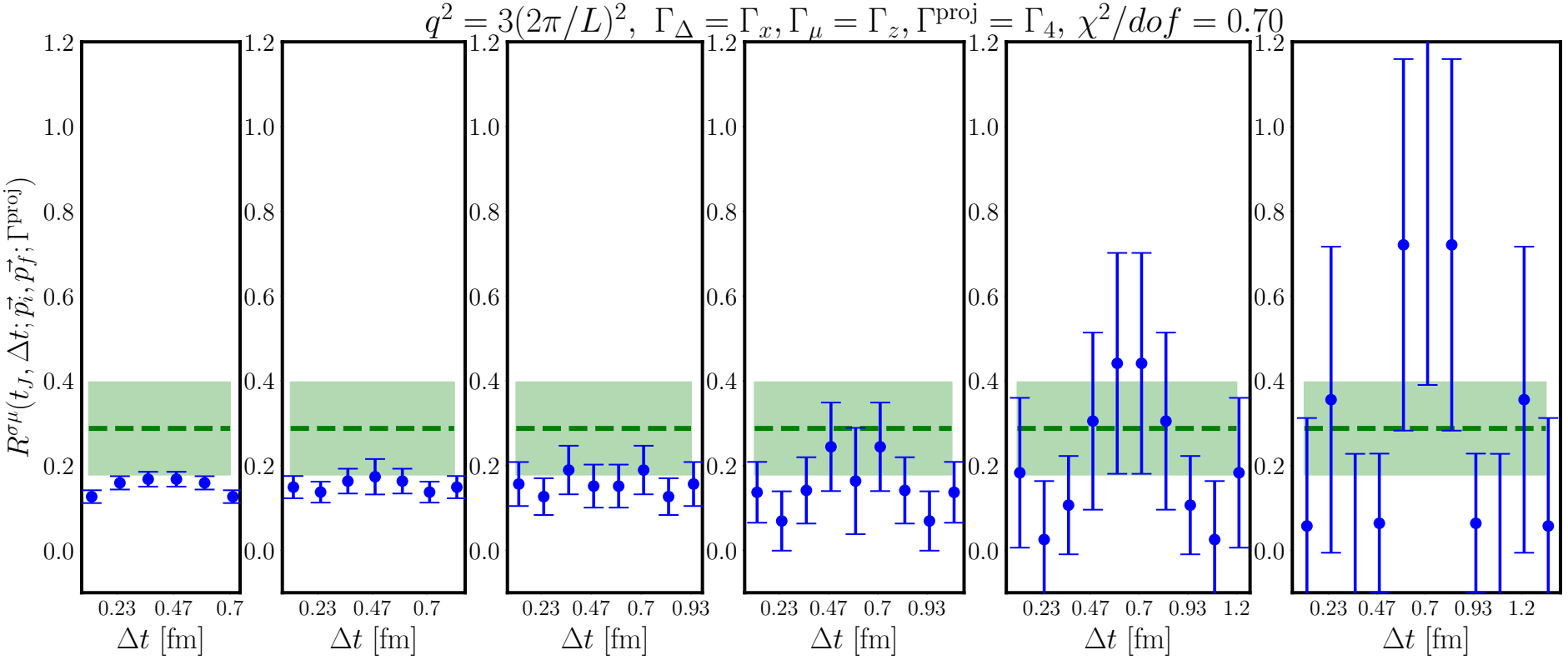

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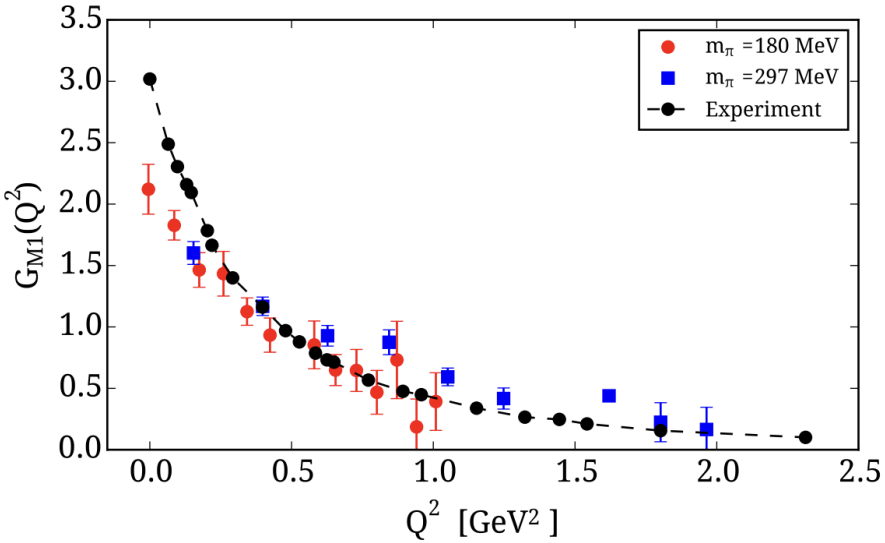
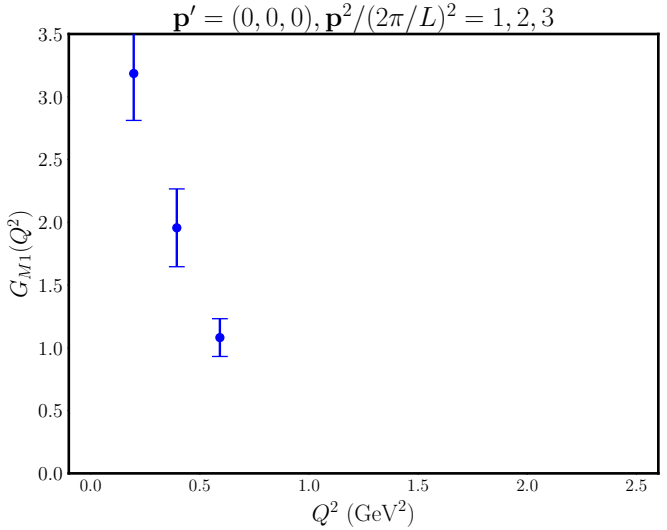
$G_{M1}(q^2)$ Preliminary Results

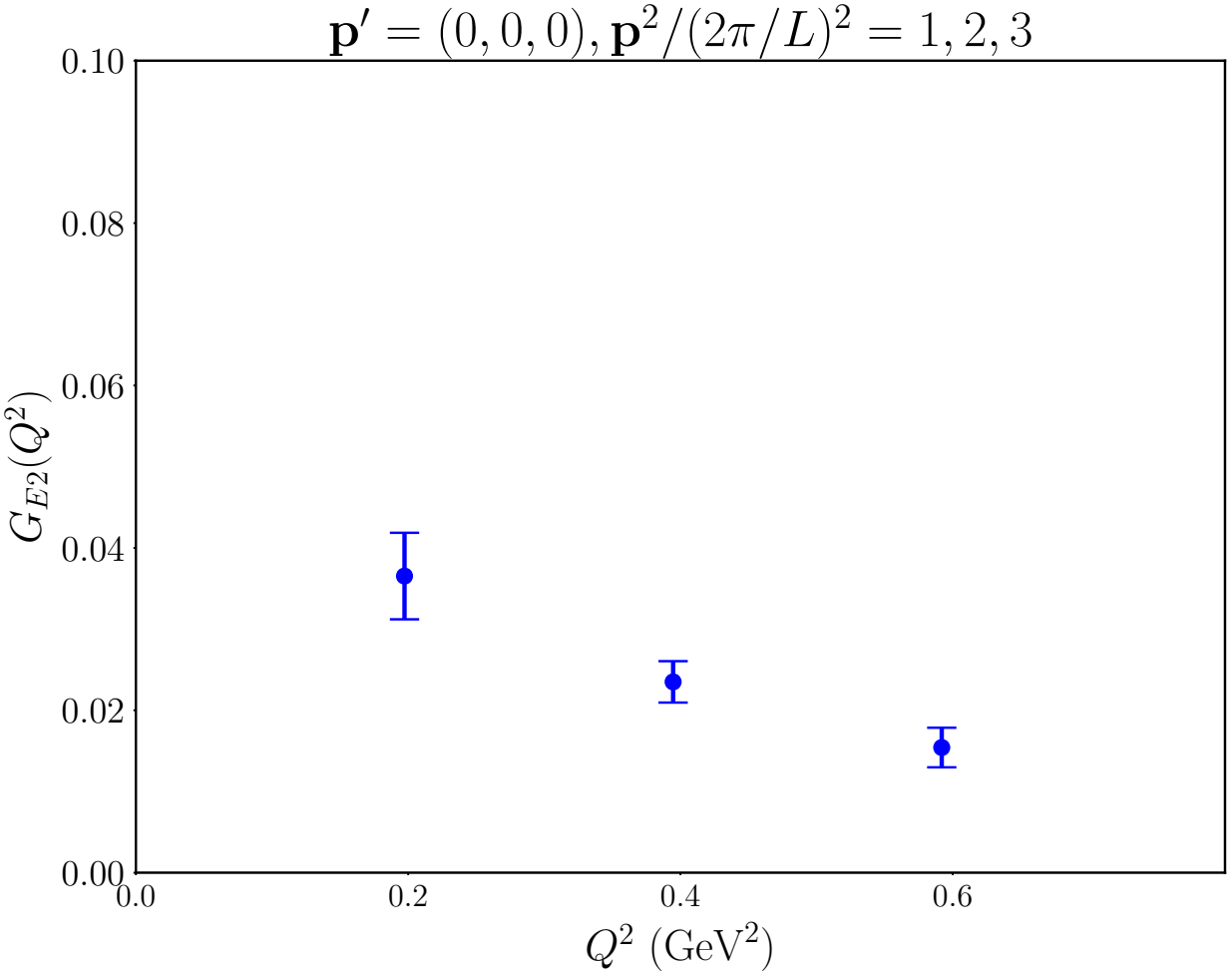
[*Alexandrou. et.al., 1011.3233*]



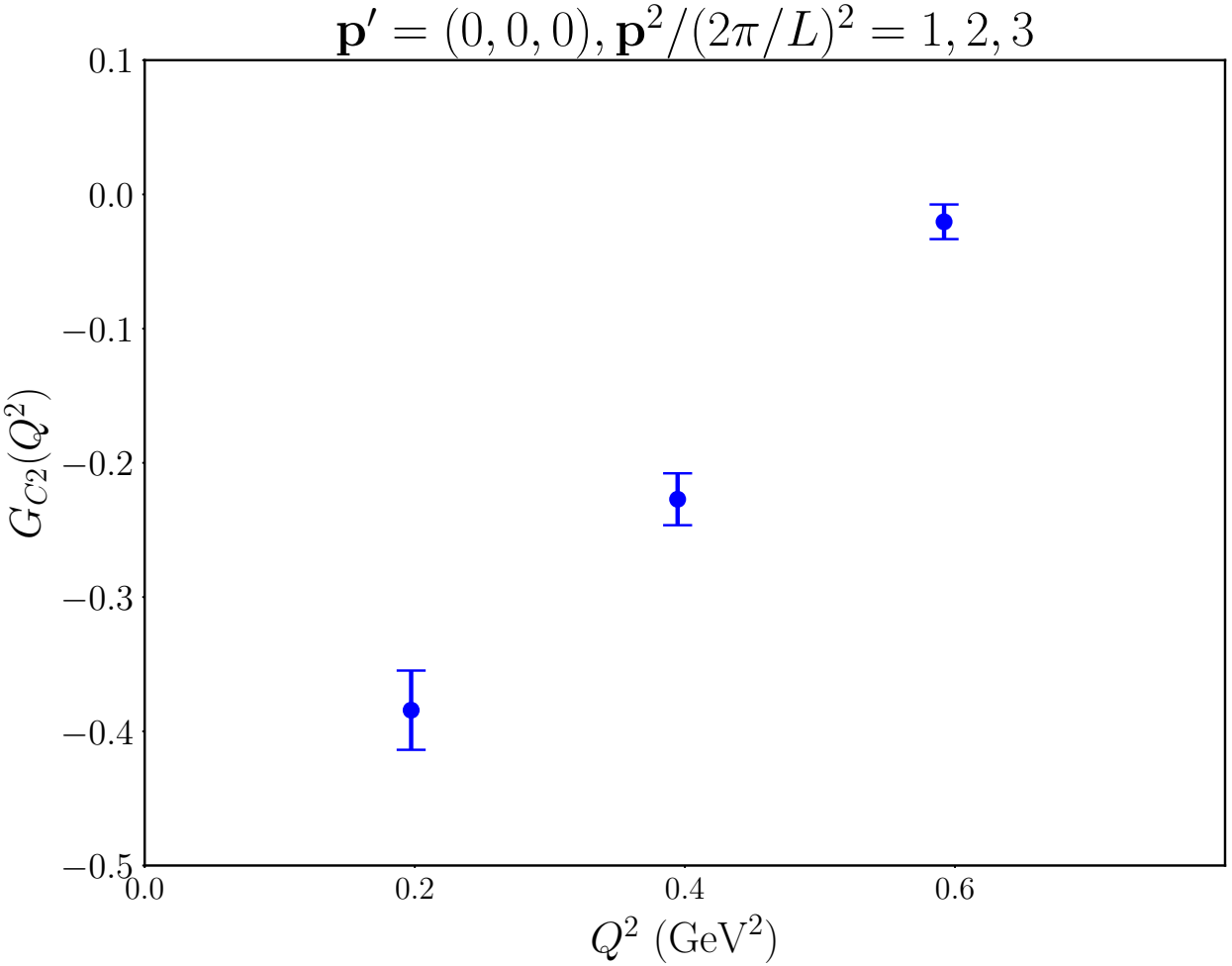


Qualitative agreement with experiment. $\Longrightarrow$
Multihadron analysis viable.

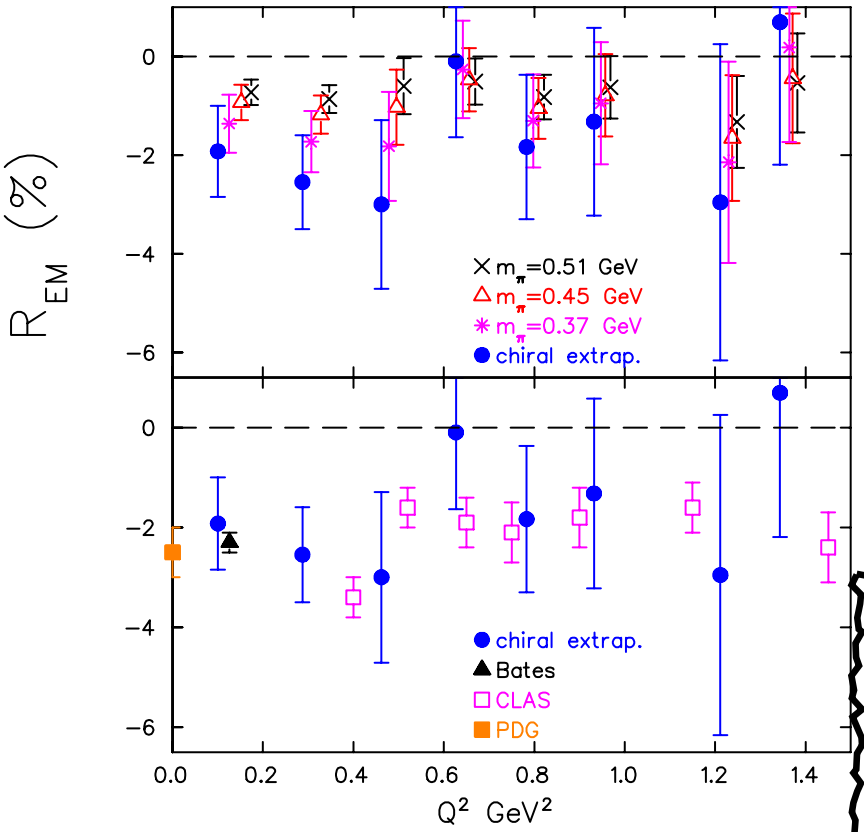
$G_{E2}(\mathbf{q}^2)$ Preliminary Results

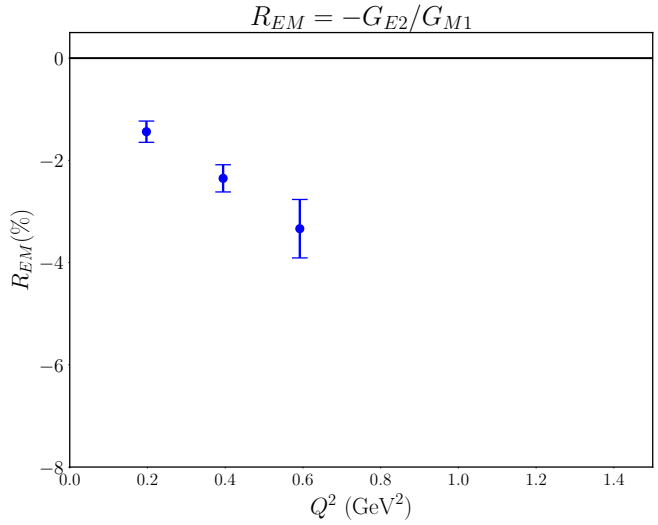


$G_{C2}(Q^2)$ Preliminary Results



R_{EM} Ratio

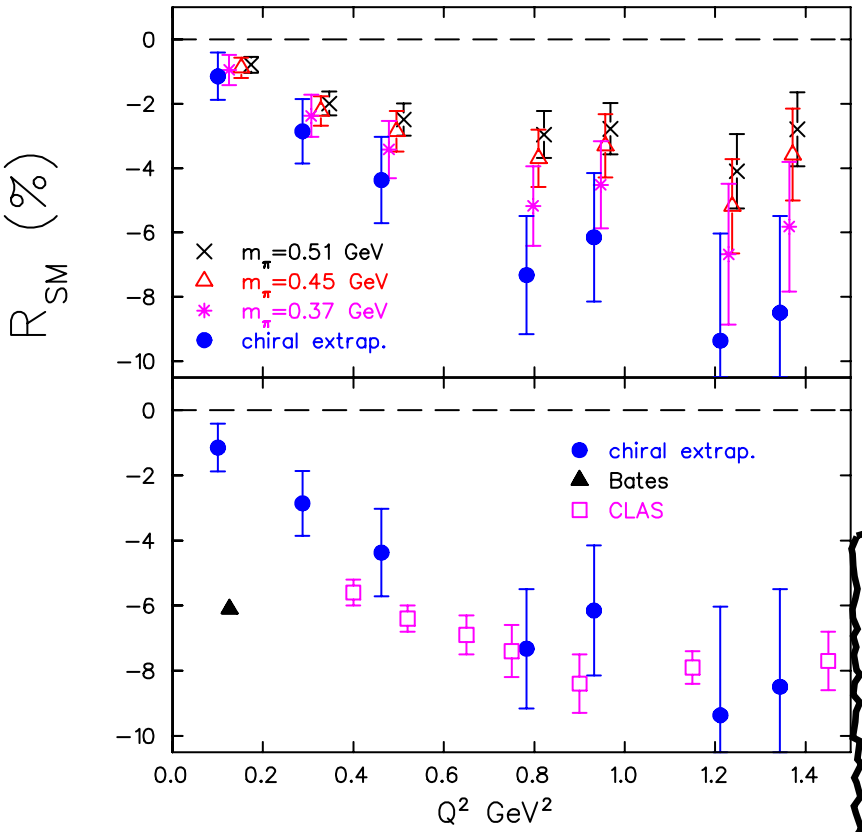


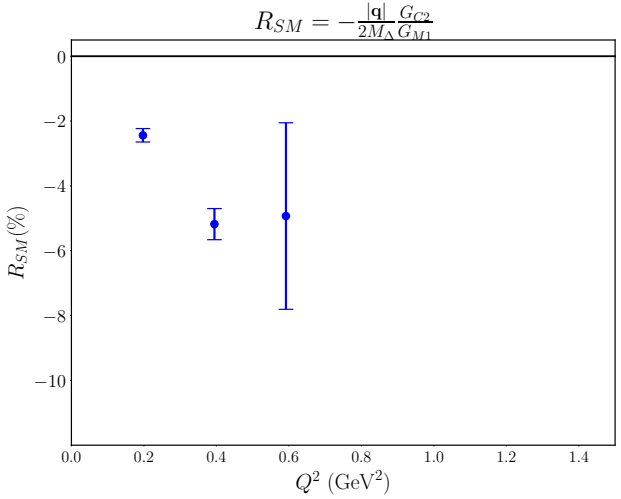


$$R_{\mathrm{EM}} = -\frac{G_{E2}\left(q^2\right)}{G_{M1}(q^2)}$$

Reasonably small statistical uncertainties. $\Longrightarrow$ Multihadron analysis viable.

R_{SM} Ratio





$$R_{\rm SM} = -\frac{|\vec{q}|}{2m_\Delta}\frac{G_{C2}\left(q^2\right)}{G_{M1}(q^2)}.$$

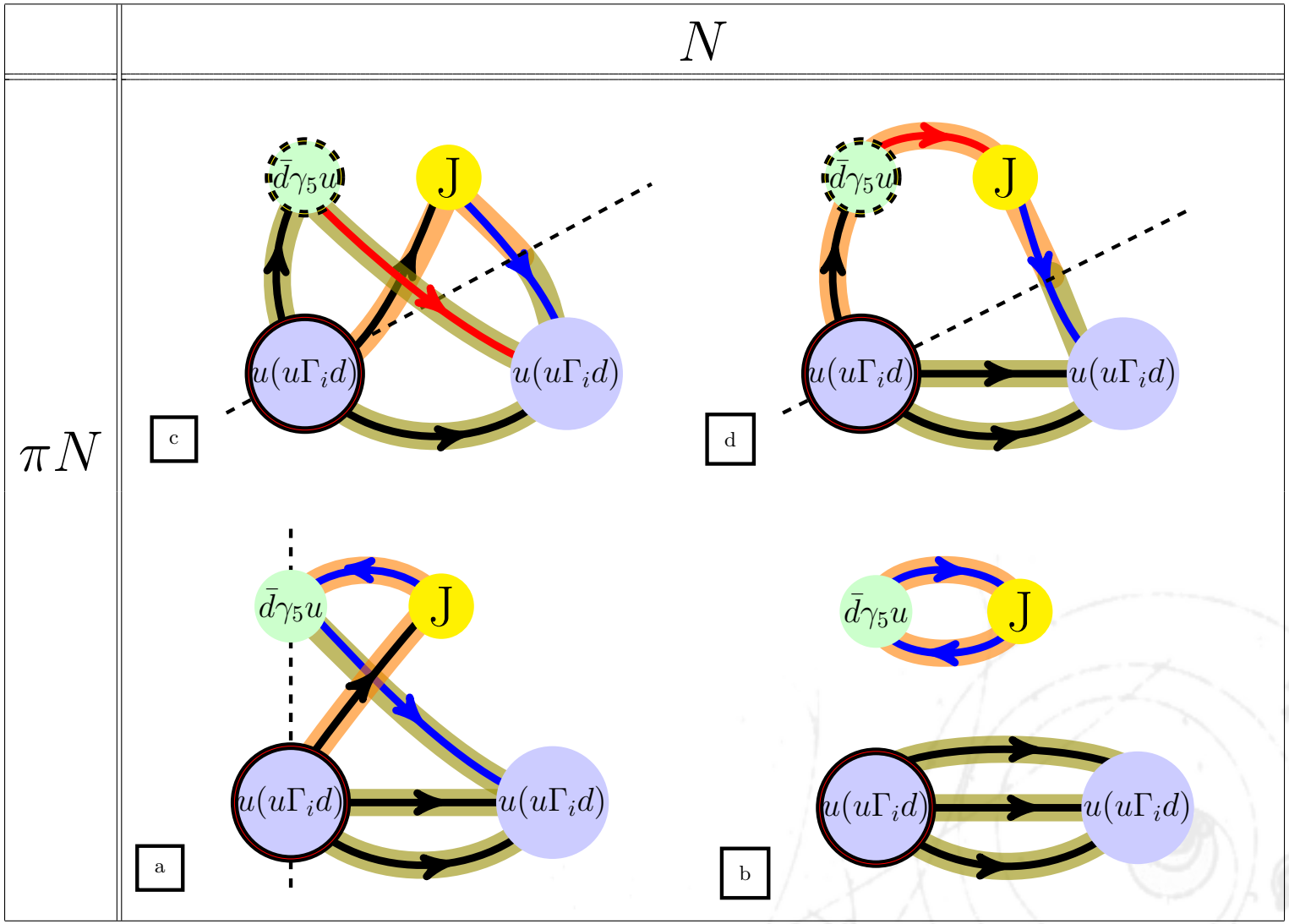
Reasonably small statistical uncertainties. $\Longrightarrow$ Multihadron analysis viable.

Summary

- Viability of undertaking a multihadron analysis of $\Delta(1232)$ resonance transition form factors using *BHWL formalism*.
- Preliminary results of G_{M1}, G_{E2}, G_{C2} form factors and R_{EM}, R_{SM} ratios at $m_\pi = 255$ MeV.
- Qualitative agreement with experimental data.

Outlook

- $\langle N\pi|J|N\rangle$ matrix elements using *bilocal $N\pi$ interpolators*.



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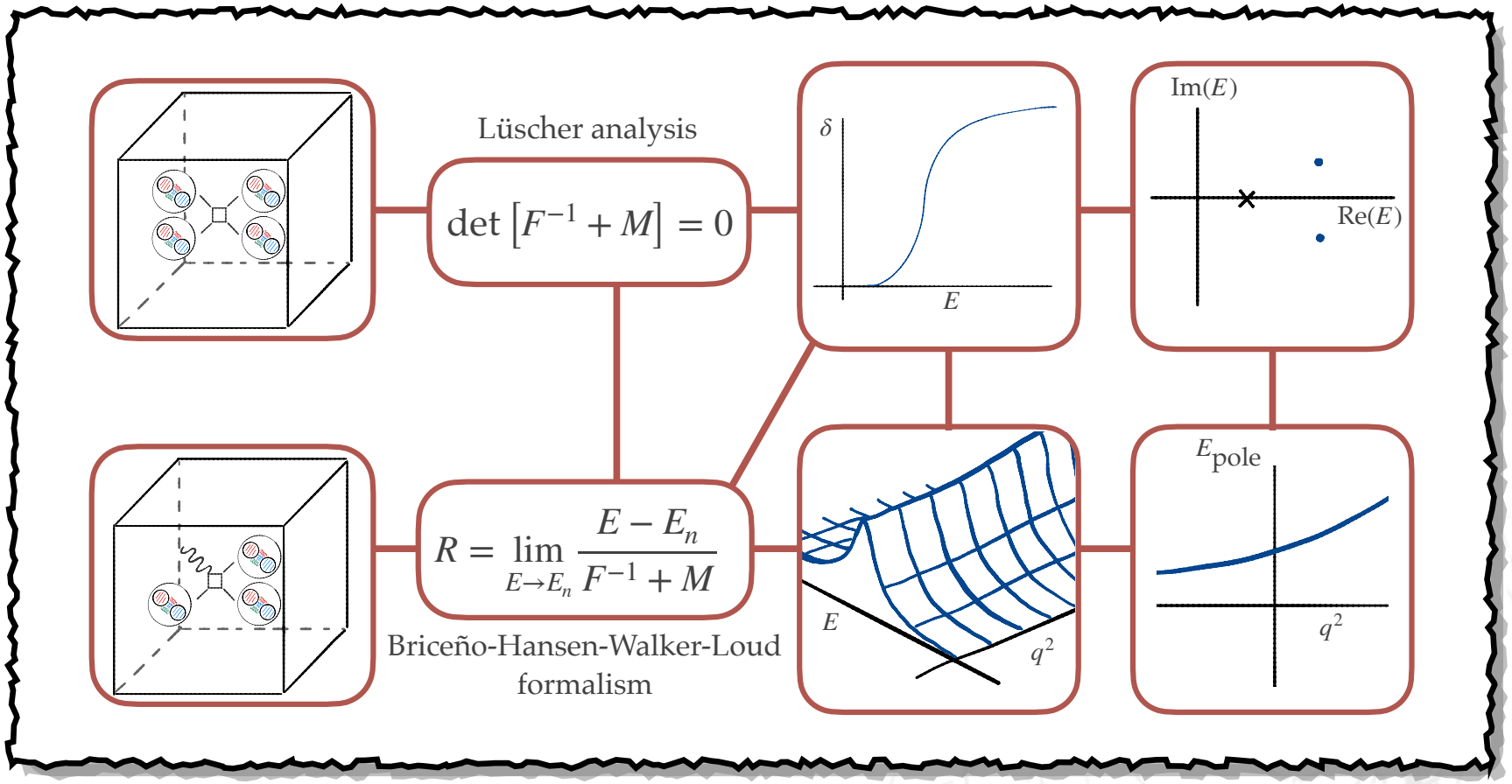

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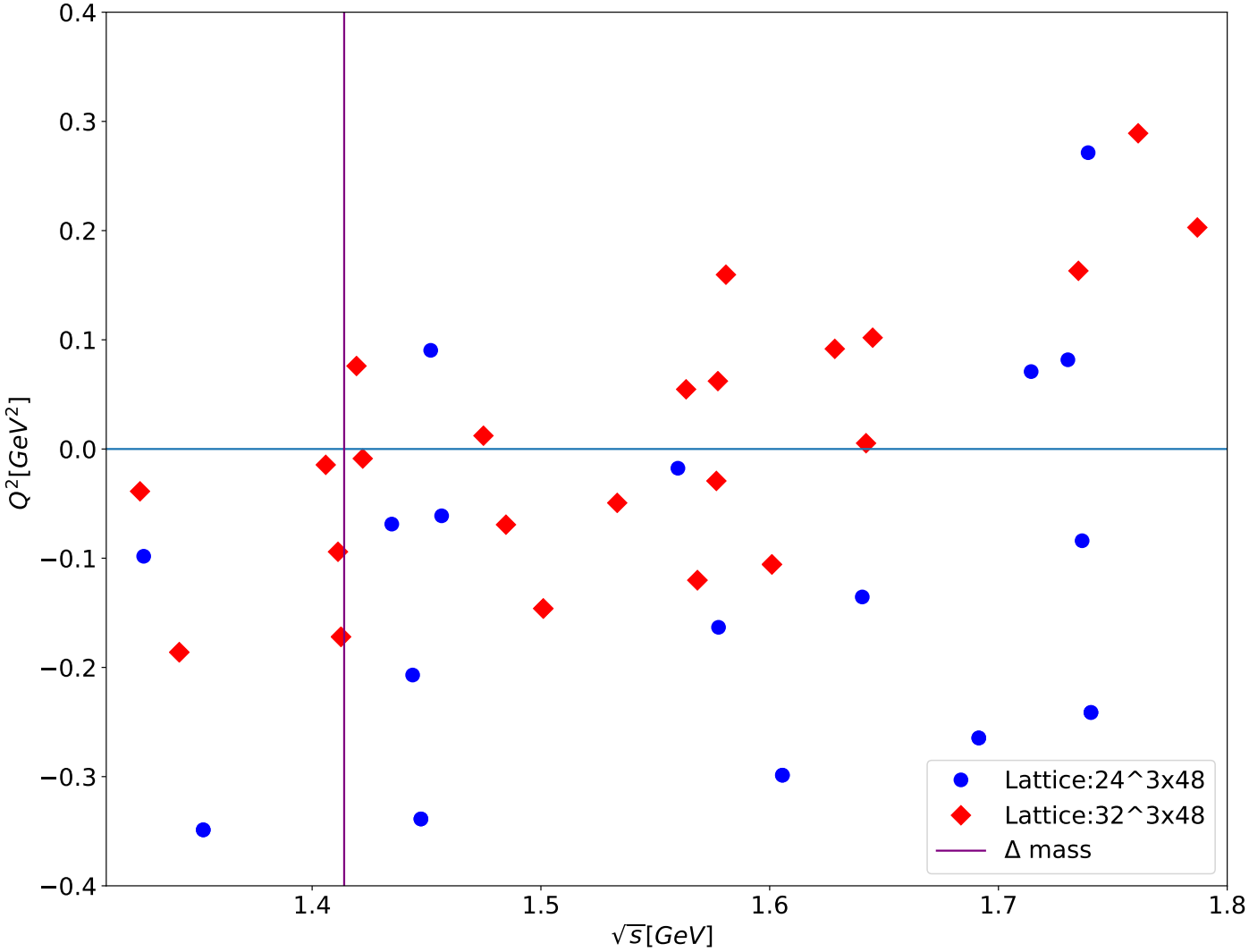
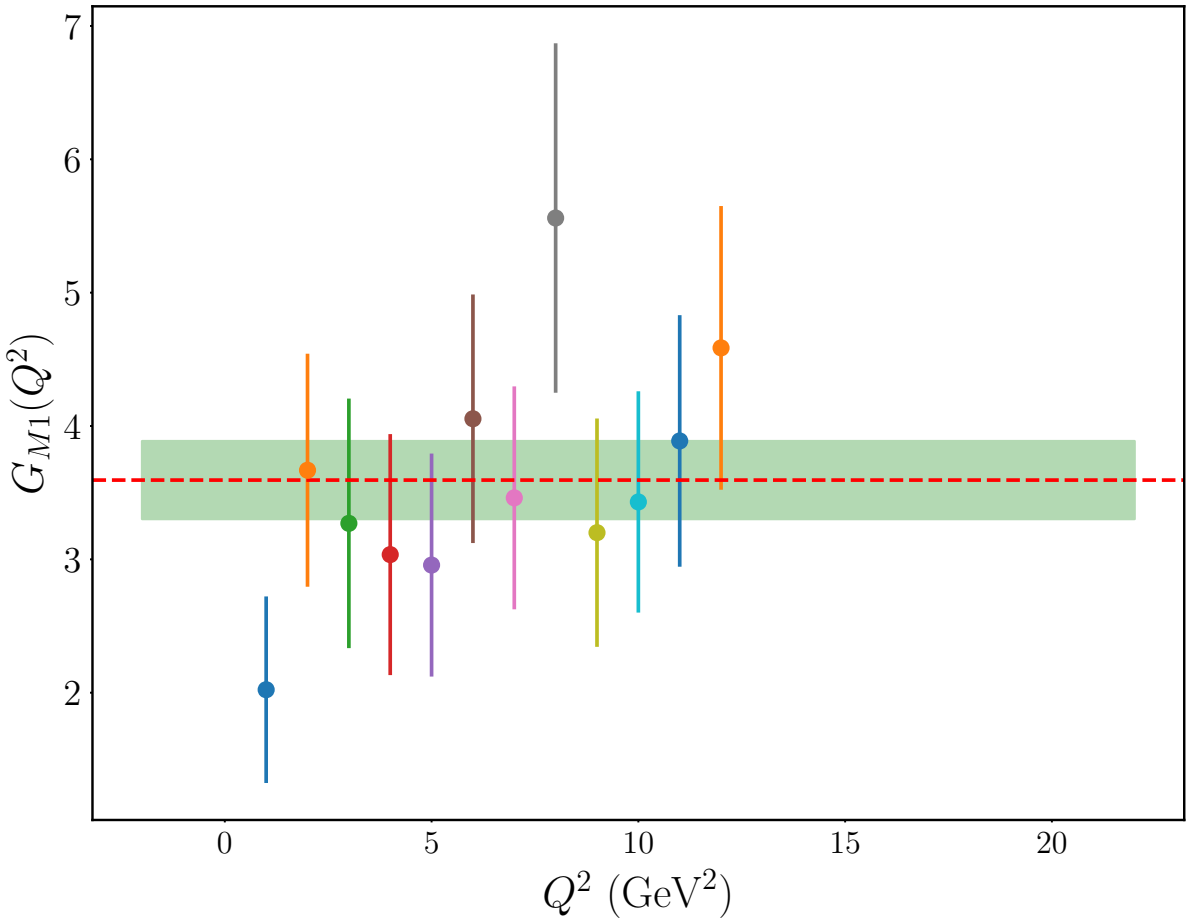


Thank You!

Backup Slides



for $G_{M1}(Q^2)$