Electromagnetic interactions of light hadrons in covariant chiral perturbation theory

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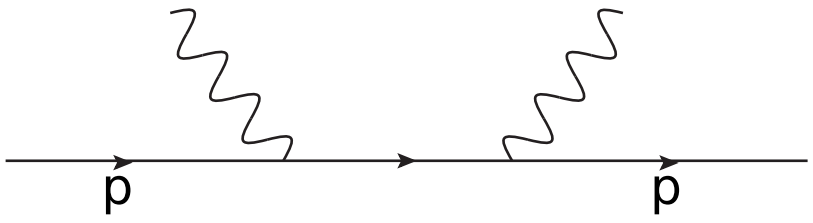
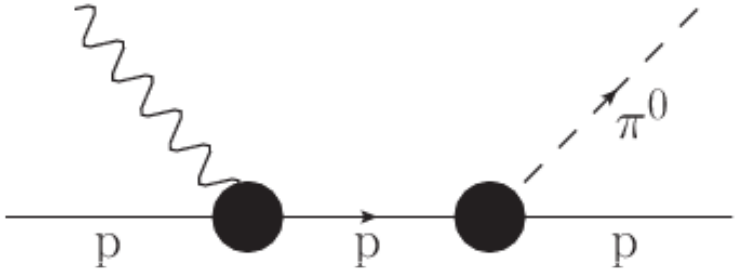
Photon beams

Electromagnetic interactions provide **clean probes** of the hadrons' inner structure

- Low photon energies ($\sim$ 100 MeV): Compton scattering



- Slightly higher ($\gtrsim$ 140 MeV): pion photoproduction



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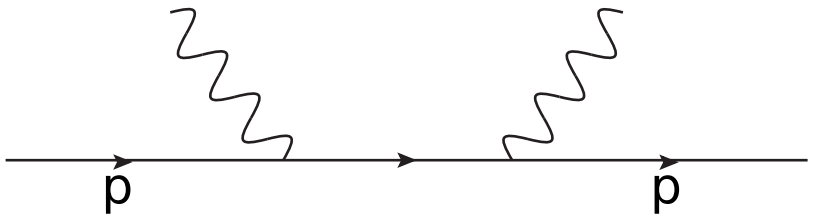
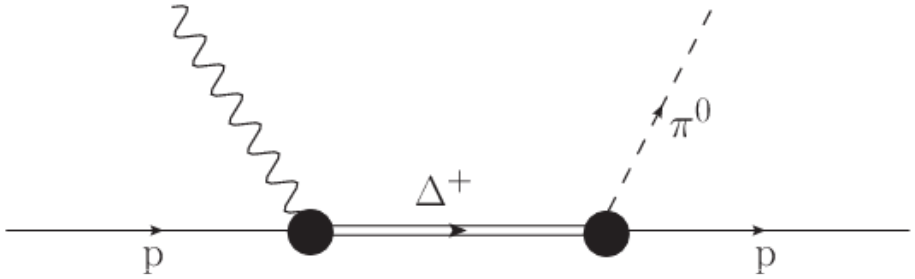
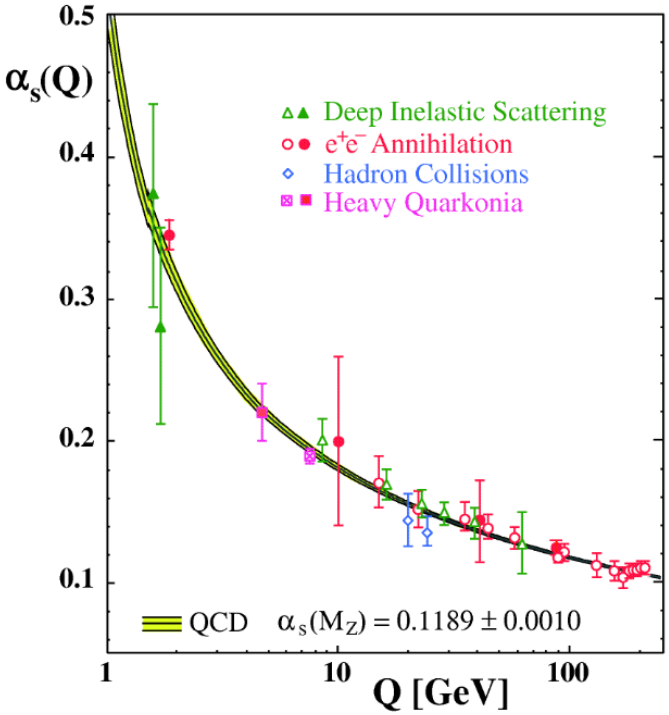


- Even higher: start feeling resonance production



Non-perturbative QCD and chiral perturbation theory

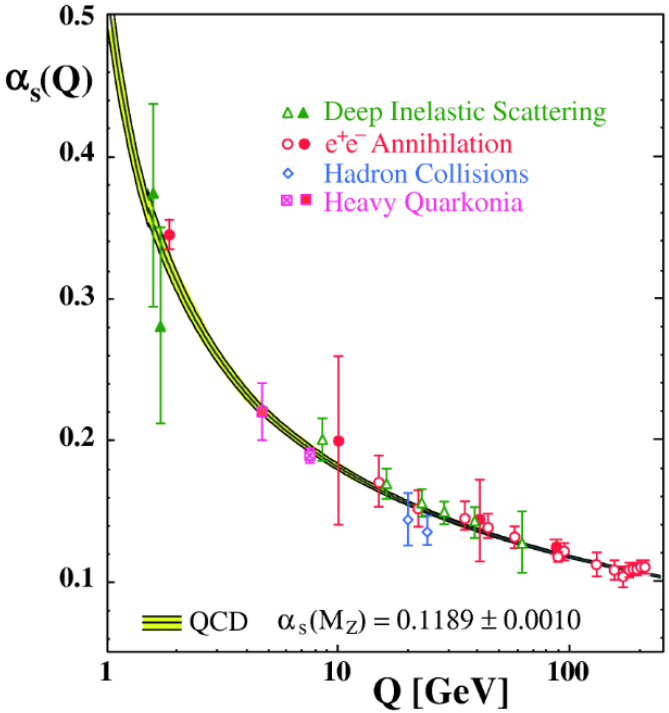


$E_\gamma \approx \mathcal{O}(m_\pi) \Rightarrow \alpha_s = \mathcal{O}(1)$

Perturbative QCD breaks down

$\Longrightarrow$ EFT: expansion around **other parameters**

Non-perturbative QCD and chiral perturbation theory



$E_\gamma \approx \mathcal{O}(m_\pi) \Rightarrow \alpha_s = \mathcal{O}(1)$

Perturbative QCD breaks down

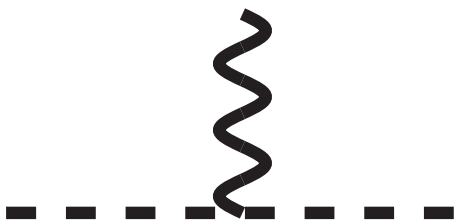
$\Longrightarrow$ EFT: expansion around **other parameters**

Chiral perturbation theory:

- Small masses, momenta ($\frac{m_\pi}{1\ \text{GeV}}, \frac{p_{\text{ext}}}{1\ \text{GeV}} \ll 1$): combined expansion
- New degrees of freedom: ~~quarks and gluons~~ $\Longrightarrow$ mesons and baryons

Lagrangian ordered in terms of chiral parameters

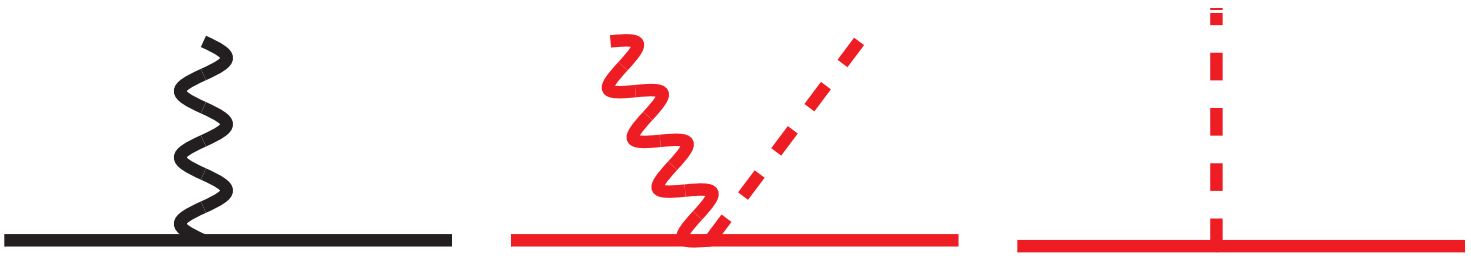
Lowest-order **meson** Lagrangian $\sim p_{\text{ext}}^2,\, m_\pi^2$



$$\mathcal{L}^{(2)}_{\phi\phi\gamma} = \frac{F_0^2}{4}\text{Tr}\left(\nabla_\mu U \nabla^\mu U^\dagger + \chi_+\right)$$

Lowest-order **baryon** Lagrangian $\sim p_{\text{ext}}$

$$\mathcal{L}^{(1)}_{\phi B\gamma} = \text{Tr}\left(\bar{B}(\mathrm{i}\not{D} - m)B\right) + \frac{D}{2}\text{Tr}\left(\bar{B}\gamma^\mu\left\{u_\mu, B\right\}\gamma_5\right) + \frac{F}{2}\text{Tr}\left(\bar{B}\gamma^\mu\left[u_\mu, B\right]\gamma_5\right)$$



Inclusion of the decuplet

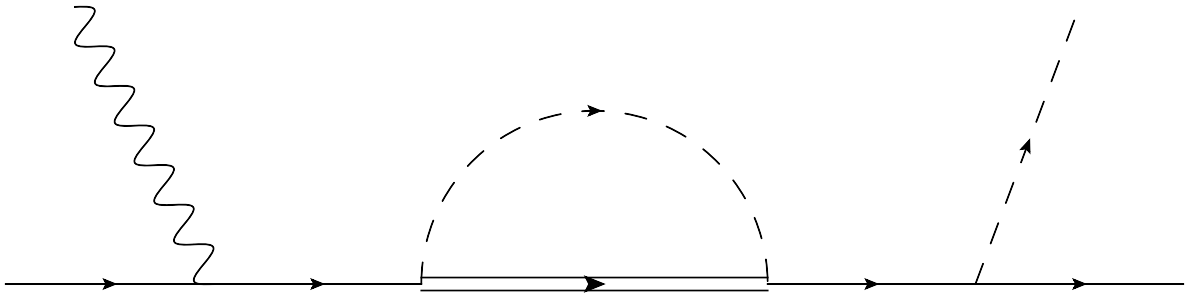
The spin-3/2 states **couple strongly** to the spin-1/2 octet baryons

Geng et al., Phys. Lett. B 676 (2009) 63

$$\mathcal{L}^{(1)}_{\Delta\phi B} = \frac{-\mathrm{i}\sqrt{2}\,\mathcal{C}}{F_0 M_\Delta}\bar{B}^{ab}\varepsilon^{cda}\gamma^{\mu\nu\lambda}(\partial_\mu\Delta_\nu)^{dbe}(\mathrm{D}_\lambda\phi)^{ce} + \text{H.c.}$$

$$\mathcal{L}^{(2)}_{\Delta\gamma B} = -\frac{3\mathrm{i}e\,g_M}{\sqrt{2}m(m+M_\Delta)}\bar{B}^{ab}\varepsilon^{cda}Q^{ce}(\partial_\mu\Delta_\nu)^{dbe}\tilde{F}^{\mu\nu} + \text{H.c.}$$

Matching a diagram to a specific order



$$O = 4L + \sum kV_k - \mathbf{2N_\pi} - \mathbf{N_N} - N_\Delta \cdot \frac{1}{2}$$

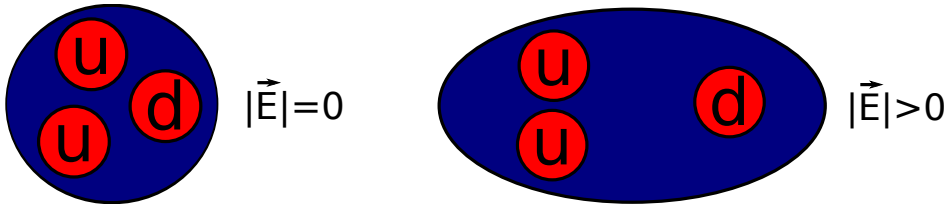
- Propagators: meson $\sim \mathbf{m_\pi^{-2}}$, spin-1/2 baryon $\sim \mathbf{p_{ext}^{-1}}$
- Spin-3/2 baryon: new scale $\delta = M_\Delta - m_N \approx 0.3$ GeV $> m_\pi$
- $(\delta/m_p)^2 \approx (m_\pi/m_p) \Longrightarrow$ far from resonance mass: $\frac{1}{2}$

Pascalutsa and Phillips, Phys. Rev. C 67 (2003) 055202

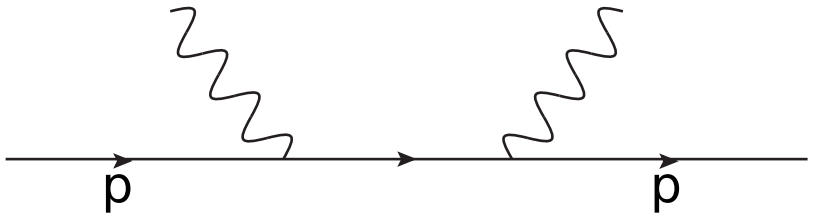
Compton scattering and polarizabilities

Hiller Blin, Gutsche, Ledwig and Lyubovitskij
Phys. Rev. D 92 (2015) 096004
arXiv: 1509.00955 [hep-ph]

Polarizabilities



- In EM field: hadrons deformed due to charged components
- Size of deformation: related to polarizabilities



- Experiment: Compton scattering off hadron targets

Compton scattering and γ_0

- Amplitude expansion **around low photon energy** ω
  - $\mathcal{O}(\omega^0)$: total charge
  - $\mathcal{O}(\omega^1)$: anomalous magnetic moment
  - $\mathcal{O}(\omega^2)$: α_E and β_M
  - $\mathcal{O}(\omega^3)$: spin-dependent polarizabilities γ_i
- Forward spin polarizability γ_0
  - response to deformation relative to **spin axis**
  - photon scattering in **extreme forward direction**
- Theory: Hemmert et al., Phys. Rev. D 57 (1998) 5746

$$\gamma_0 \left[\vec{\sigma} \cdot (\vec{\epsilon} \times \vec{\epsilon}^{\,*})\right] = -\frac{\mathrm{i}}{4\pi} \frac{\partial}{\partial \omega^2} \frac{\epsilon^\mu \mathcal{M}^{\mathrm{SD}}_{\mu\nu} \epsilon^{*\nu}}{\omega} \bigg|_{\omega=0}$$

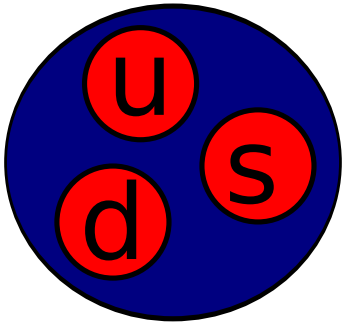
Approaching the experimental results

- Sum rule: Gell-Mann et al., Phys. Rev. 95 (1954) 1612

$$\gamma_0 = -\frac{1}{4\pi^2}\int_{\omega_0}^{\infty} \mathrm{d}\omega \frac{\sigma_{3/2}(\omega) - \sigma_{1/2}(\omega)}{\omega^3}$$

  $\sigma_{3/2}(\sigma_{1/2})$: photon and target helicities are (anti)parallel
- Experiment: Pasquini et al., Phys. Lett. B 687 (2004) 160
  $\gamma_0^p = [-1.01 \pm 0.08(\text{stat}) \pm 0.10(\text{syst})] \cdot 10^{-4}\text{fm}^4$
- Dispersion relations: Drechsel et al., Phys. Rept. 378 (2003) 99
  $\gamma_0^p = [-1.1 \pm 0.4] \cdot 10^{-4}\text{fm}^4$ and $\gamma_0^n = [-0.3 \pm 0.2] \cdot 10^{-4}\text{fm}^4$
- **First goal** is to reproduce these values theoretically
- Then extend the theoretical model to **predict** polarizabilities of not yet measured states $\Longrightarrow$ **hyperons**

Hyperons



$$SU(2) \longrightarrow SU(3)$$

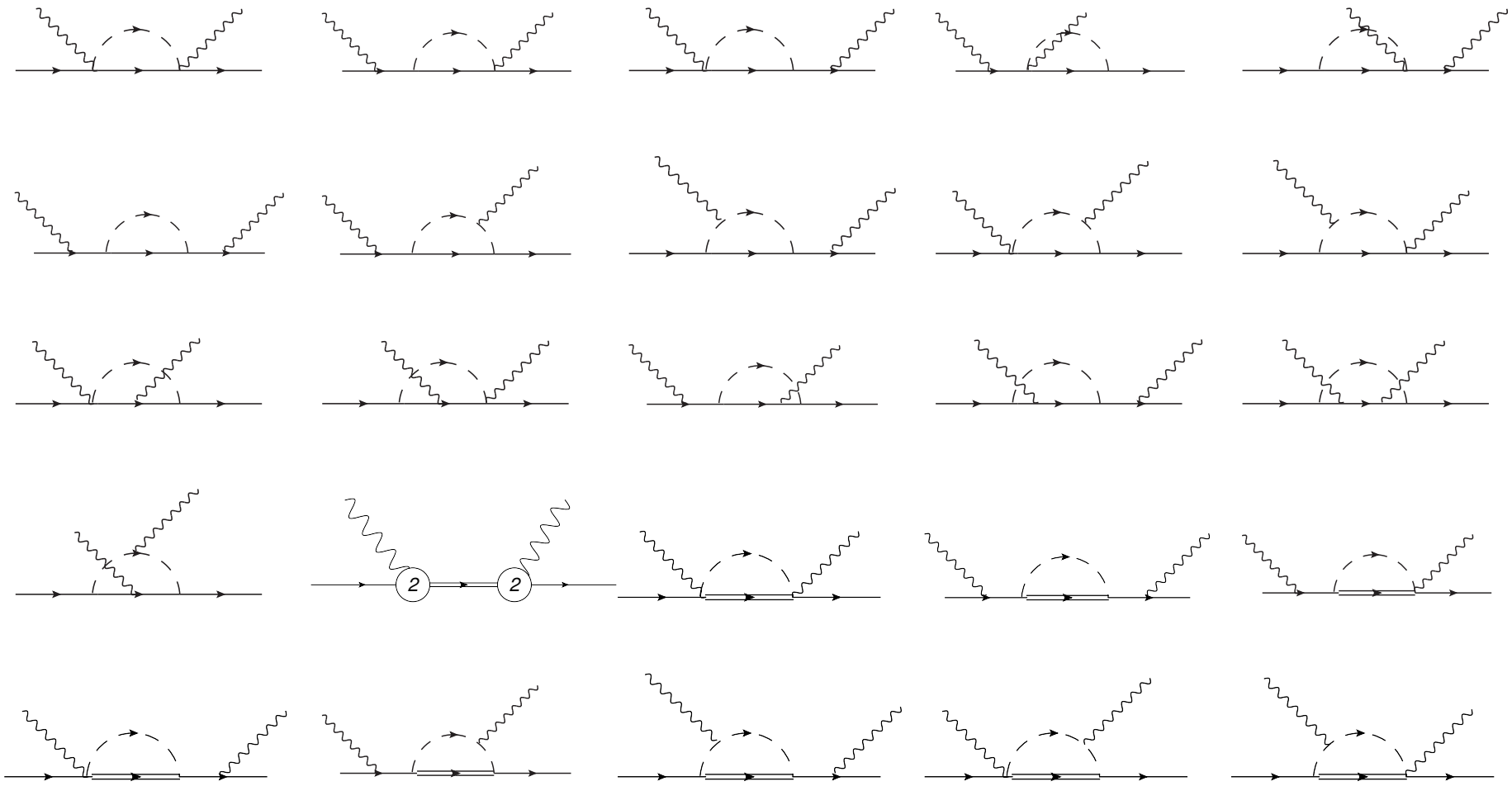
$$\begin{pmatrix} p \\ n \end{pmatrix} \longrightarrow \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}$$

$$\pi^\pm, \pi^0 \longrightarrow \pi^\pm, \pi^0, K^\pm, K^0, \eta$$

$$\Delta(1232) \longrightarrow \Delta^\pm, \Delta^{++}, \Delta^0, \Sigma^{*\pm}, \Sigma^{*0}, \Xi^{*-}, \Xi^{*0}, \Omega$$

- Hyperons: baryons with **strangeness** $\mathcal{S} \neq 0$
- Short lifetimes $\Longrightarrow$ properties computed on the lattice
- Gives space for theoretical predictions

Diagrams contributing to γ_0 up to $\mathcal{O}(p^{7/2})$



Renormalization

- Loop diagrams:
  divergences and **power counting breaking terms**

$$\frac{1}{\epsilon} = \frac{1}{4 - \text{dim}} \quad \text{and} \quad \text{e.g. terms } \propto p^2 \text{ at } \mathcal{O}(p^3)$$

- Fully analytical $\Longrightarrow$ match with **Lagrangian terms**
- **Low-energy constants** of these terms a priori unknwon
- EOMS-renormalization prescription:

  Gegelia and Japaridze, Phys. Rev. D 60 (1999) 114038

  - $\overline{MS}$ absorbs $L = \frac{2}{\epsilon} + \log(4\pi) - \gamma_E$ into LECs
  - Also subtracts PCBT by redefinition of LECs
  - Usually converges faster than other counting schemes (relativistic or not)

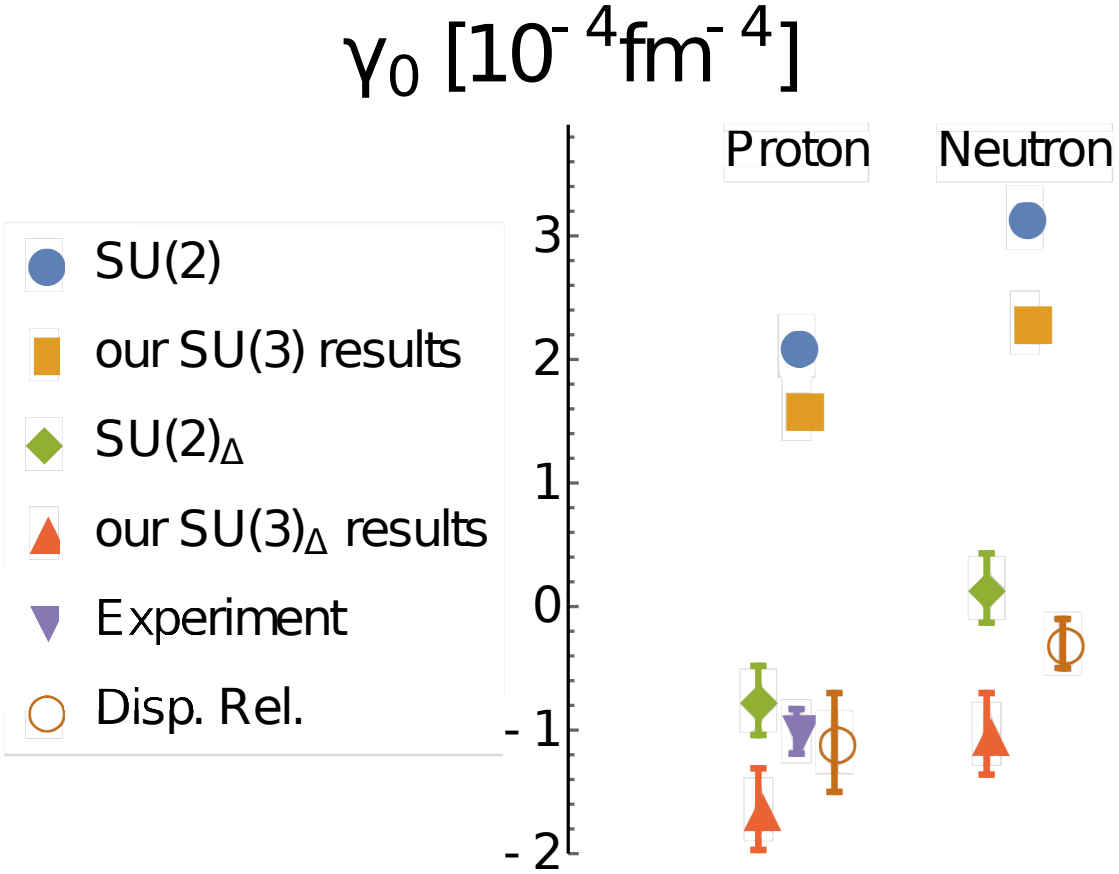
Renormalization

- ∞ and PCBT: **do not** enter pieces $\sim \omega^3$ relevant for γ_0
- Leading order for $\gamma_0 \Longrightarrow$ **no unknwon LECs**
- Results independent of renormalization or unknown LECs

$$\Downarrow$$

pure predictions of ChPT

Results with different covariant ChPT models

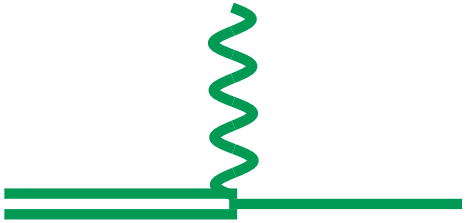


SU(2): Bernard et al., Phys. Rev. D 87 (2013) 054032
SU(2) with Δ: Lensky et al., Eur. Phys. J. C 75 (2015) 604
Experiment: Pasquini et al., Phys. Lett. B 687 (2004) 160
Dispersion relations: Drechsel et al., Phys. Rept. 378 (2003) 99

Results for the hyperons

- Only HBChPT existed: incompatible with exp. (nucleons)

  Vijaya Kumar et al., Phys. Rev. D 84 (2011) 076007

- $\mathbf{g_M}$ not well known
- We estimate it from electromagnetic decay width $\Gamma_{\Delta\to\gamma N}$
-  $g_M = 3.16(16)$

γ_0 [fm^{-4}10^{-4}]	Σ^+	Σ^-	Σ^0	Λ	Ξ^-	Ξ^0
Our full model	-2.30(33)	0.90	0.47(8)	-1.25(25)	0.13	-3.02(33)

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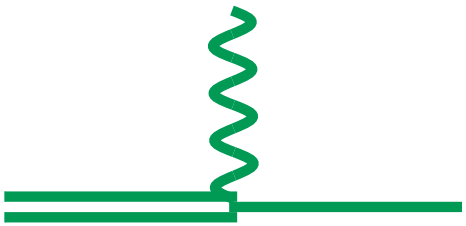
-  $g_M = 3.16(16)$

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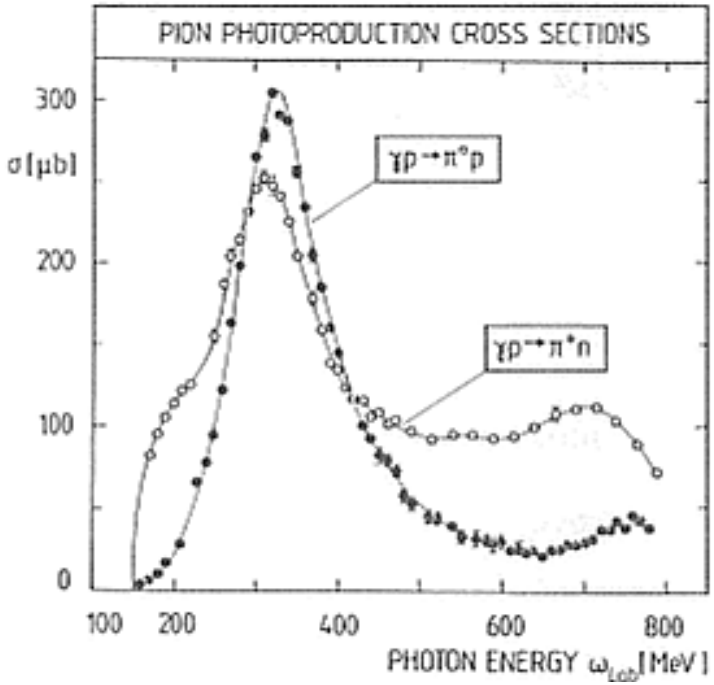
Electromagnetic transition of **negatively charged** hyperons to spin-3/2 partners $SU(3)$ **forbidden** $\Longrightarrow$ no uncertainty from g_M

Neutral pion photoproduction close to threshold

Hiller Blin, Ledwig and Vicente Vacas
Phys. Lett. B 747 (2015) 217, Phys.Rev. D 93 (2016) 094018
arXiv: 1412.4083 [hep-ph], arXiv: 1602.08967 [hep-ph]

Cross sections

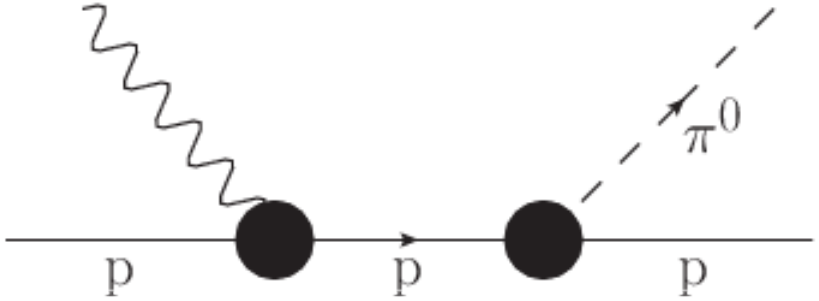
Ericson and Weise (1988) Pions and Nuclei



Reaction	Relative dipole moment
$\gamma p \to \pi^+ n$	1
$\gamma p \to \pi^0 p$	$-\frac{m_\pi}{m_N}$
$\gamma n \to \pi^- p$	$-\left(1+\frac{m_\pi}{m_N}\right)$
$\gamma n \to \pi^0 n$	0

- Close to threshold: charged channels have much larger cross sections than neutral ones
- The charged channels are well described in low-order ChPT. The neutral channel is NOT Bernard et al. (1992) NPB
- Inclusion of the $\Delta(1232)$ spin-$3/2$ resonance is essential Hemmert et al. (1997) PLB

$\gamma\ p \to p\ \pi^0$ data

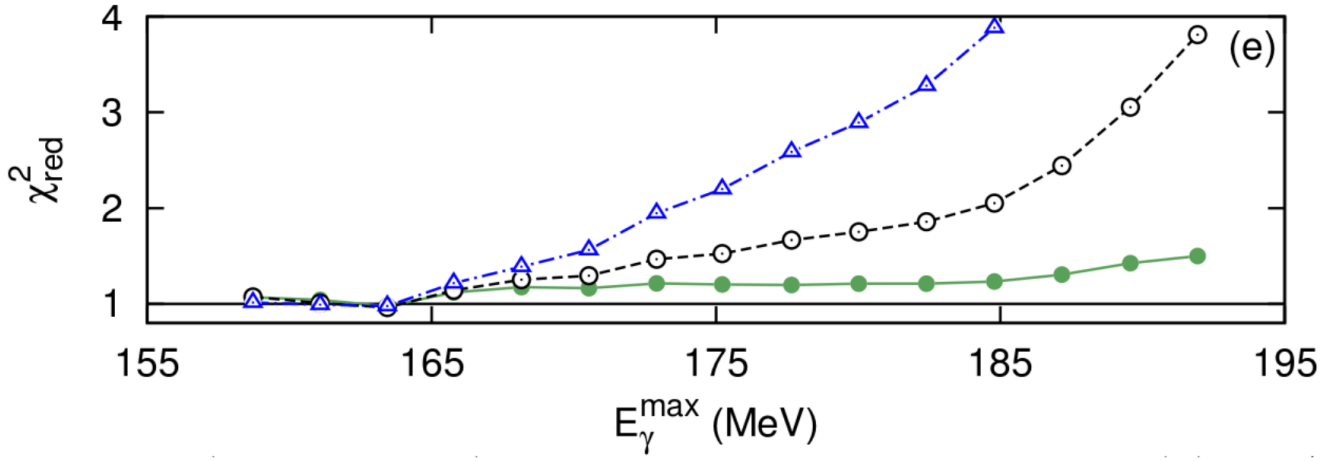


- Very precise data from MAMI Hornidge et al., Phys. Rev. Lett. 111 (2013) 062004
- Can be used to test the convergence of ChPT models
- Measured polarization observables:

$$\frac{d\sigma}{d\Omega} \quad \text{and} \quad \Sigma = \frac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\perp + d\sigma_\parallel}$$

Previous work

$\mathcal{O}(p^4)$ ChPT (terms proportional to m_π^4): Hornidge et al., Phys. Rev. Lett. 111 (2013) 062004

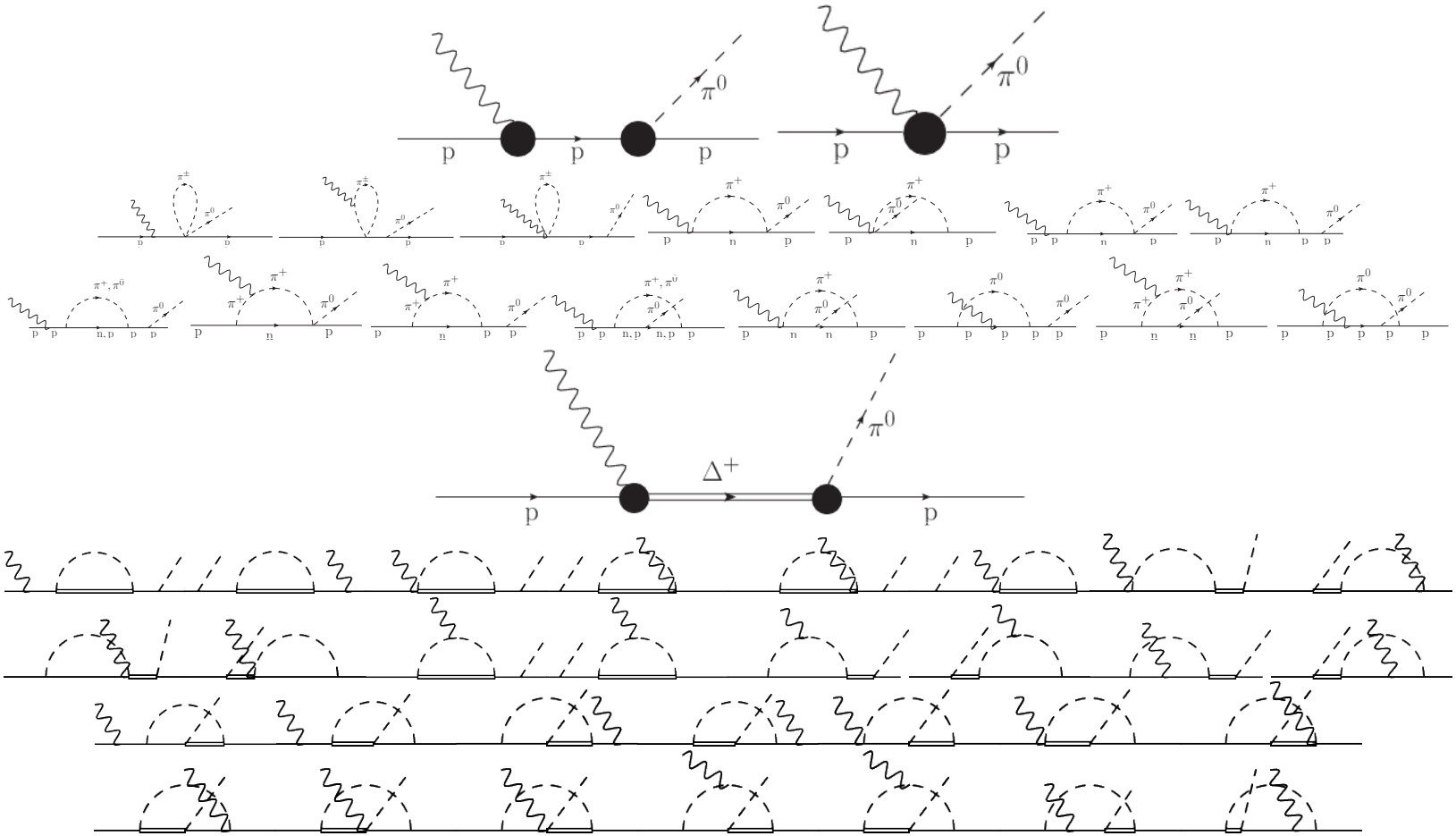


- $\mathcal{O}(p^4)$ relativistic ChPT
- $\mathcal{O}(p^4)$ HBChPT

} Starts failing at 20 MeV above threshold

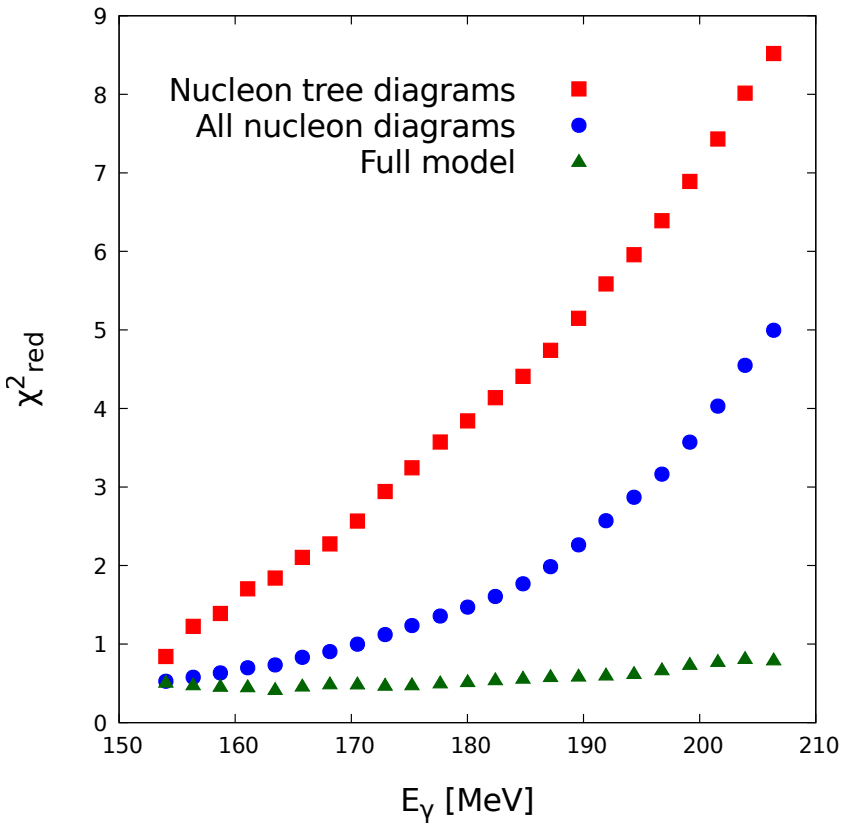
- Empirical fit

Putting all pieces together up to $\mathcal{O}(p^3)$... and $\Delta(1232)$!



First message

What could not be achieved without the $\Delta(1232)$ is now possible, **without the many new fitting constants of** $\mathcal{O}(p^4)$

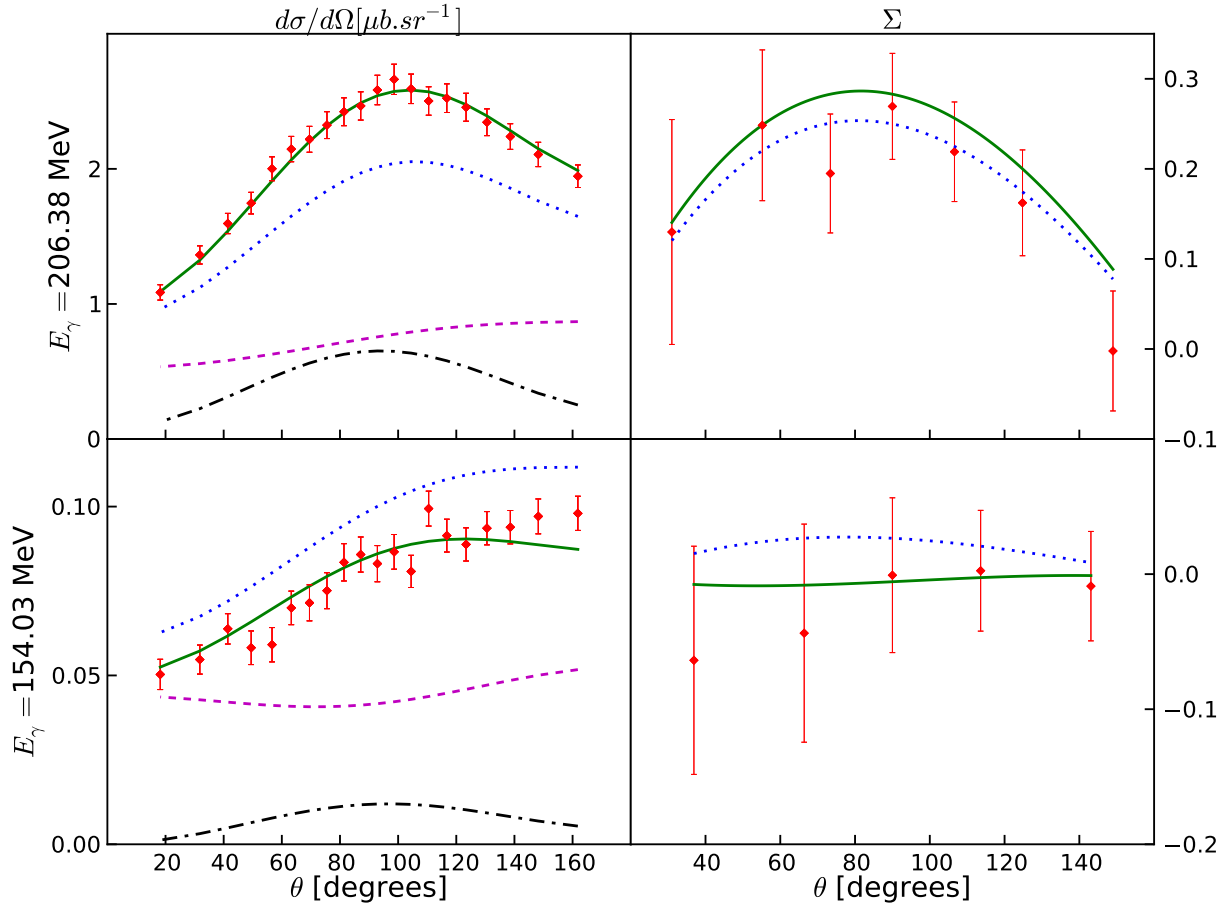


Fit of the low-energy constants

g_0	$\tilde{c}_{67}$	$\tilde{d}_{89} \cdot m_N^2$	$\tilde{d}_{168} \cdot m_N^2$	h_A	g_M	g_E	χ^2/d.o.f.
1.05	**2.45**	1.67	-9.7	**2.85**	2.28	3.30	0.80
1.05	**2.29**	1.17	-10.4	**2.85**	**2.90**	3.53	0.96

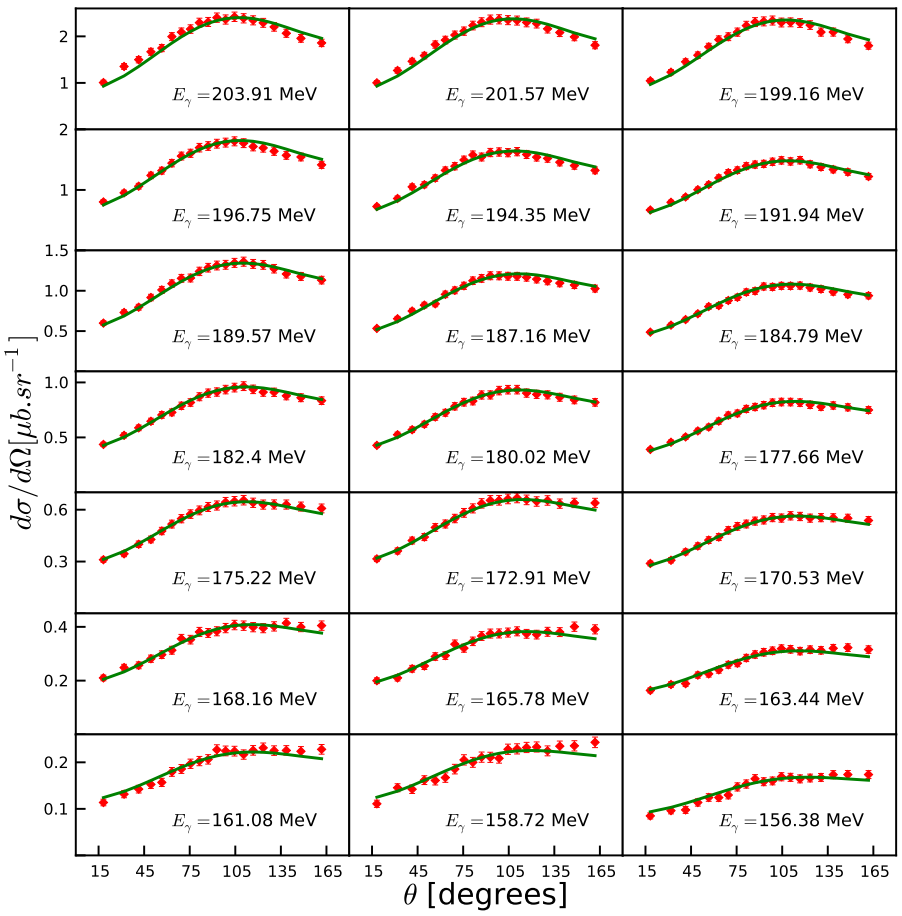
- g_0, $\tilde{c}_{67} = c_6 + c_7$ **converge to the literature values**
  Ledwig et al. (2014) PRD
- $\tilde{d}_{89} = d_8 + d_9$, g_E are of natural size
- d_{18} **is very sensitive to higher-order input.** We fit the combination $\tilde{d}_{168} = 2d_{16} - d_{18}$
- g_M, h_A prefer low values, but **literature value** gives good fit

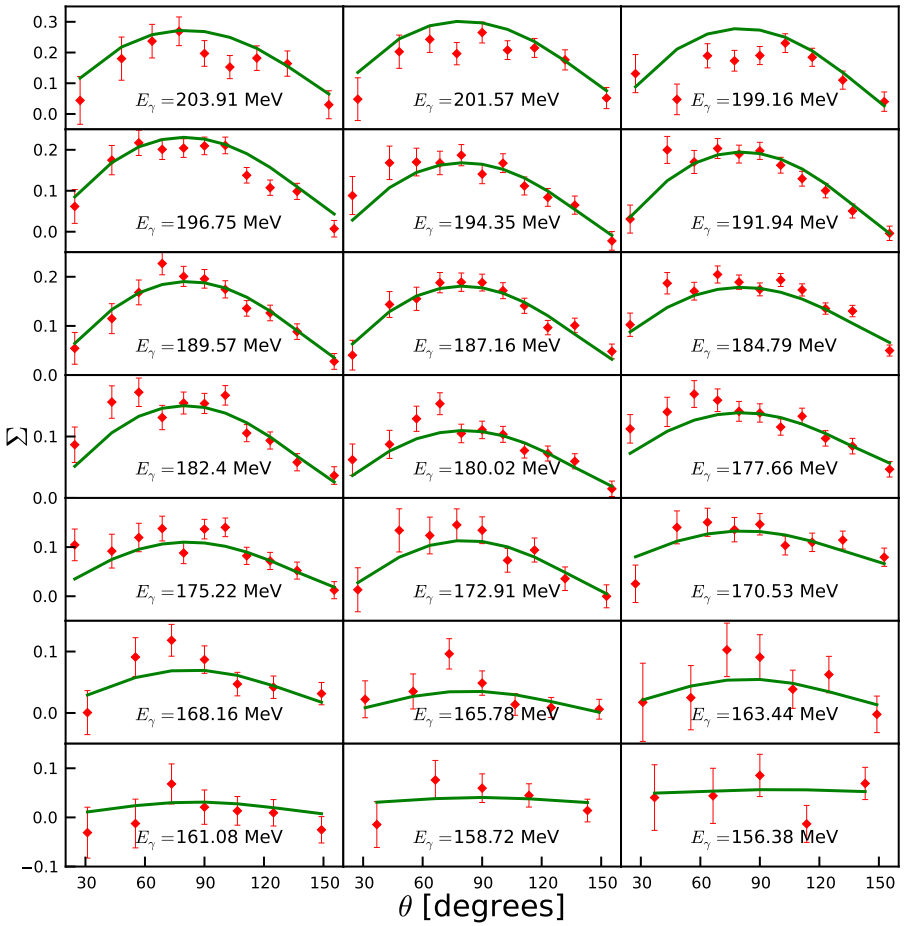
Comparing theoretical curves with data



- MAMI $\gamma p \to p\pi^0$ data
  Hornidge et al., Phys. Rev. Lett. 111 (2013) 062004
- $\mathcal{O}(p^3)$ nucleonic model
  Unable to reproduce the energy dependence
- $\mathcal{O}(p^{7/2})$ with $\Delta(1232)$
  Good reproduction for all 800 data points
- Only $\Delta(1232)$ contribution
- Only nucleonic contribution

All data points for $d\sigma/d\Omega$ and Σ





$\sim$ 800 data points

Summary I

Framework

- Electromagnetic probes of light baryons in $SU(3)$ ChPT
- Explicit inclusion of the $\Delta(1232)$ resonance
- Covariant renormalization scheme: EOMS

Hyperon polarizabilities

- We **reproduce the nucleon γ_0** for the first time in $SU(3)$
- **Predictive** results for **hyperon** polarizabilities at $\mathcal{O}(p^{7/2})$
- Σ^- and Ξ^- do not depend on uncertainties from LECs

Summary II

Neutral pion photoproduction

- High-quality description of $\gamma p \to p\pi^0$ threshold data: **cross sections and polarization observables** match experimental data at $E_\gamma > 180$ MeV **for the first time**
- $\mathcal{O}(p^{7/2})$ better than Δ-less $\mathcal{O}(p^4)$ HB or covariant ChPT
- Strong constraints of previously unknown LECs

Outlook

- **Compton scattering:**
  Magnetic moments, spin independent, photon virtuality, ...
- **Pion photoproduction:**
  Cusp effect, charge production, photon virtuality, ...

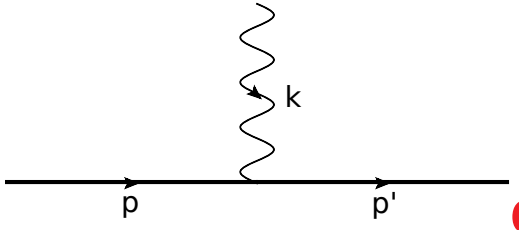
Additional material

Higher orders of the nucleonic Lagrangian

$$\mathcal{L}_N = \bar{\Psi}\Big\{ \frac{1}{8m}\left(\mathbf{c_6} f^+_{\mu\nu} + \mathbf{c_7}\,\mathrm{Tr}\left[f^+_{\mu\nu}\right]\right)\sigma^{\mu\nu}$$
$$+ \frac{\mathrm{i}}{2m}\varepsilon^{\mu\nu\alpha\beta}\left(\mathbf{d_8}\,\mathrm{Tr}\left[\tilde{f}^+_{\mu\nu}u_\alpha\right] + \mathbf{d_9}\,\mathrm{Tr}\left[f^+_{\mu\nu}\right]u_\alpha + \mathrm{H.c.}\right)\mathrm{D}_\beta$$
$$+ \frac{\gamma^\mu\gamma_5}{2}\left(\mathbf{d_{16}}\,\mathrm{Tr}\left[\chi_+\right]u_\mu + \mathrm{i}\,\mathbf{d_{18}}[\mathrm{D}_\mu, \chi_-]\right)\Big\}\Psi + \ldots$$

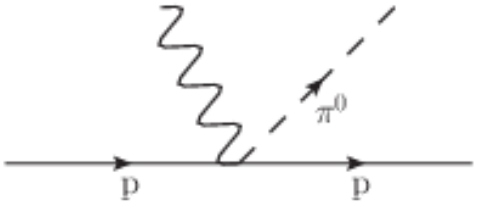
Fettes et al., Ann. Phys. 283 (2000) 273

$\mathcal{O}(\mathbf{p^2})$

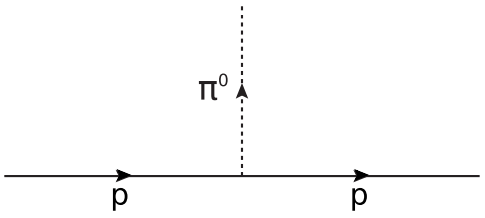


$\mathbf{c_6}$, $\mathbf{c_7}$

$\mathcal{O}(\mathbf{p^3})$

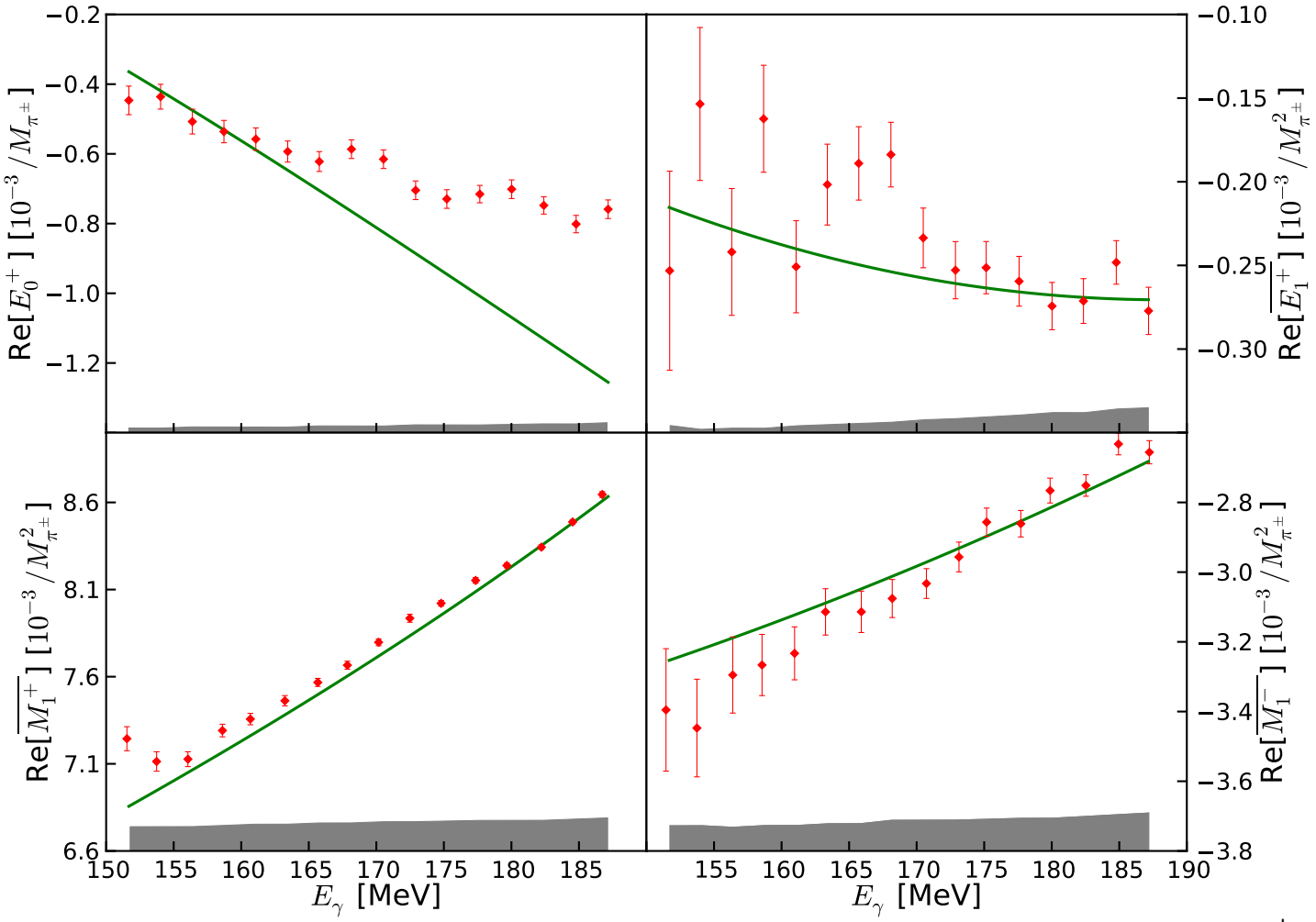


$\mathbf{d_8}$, $\mathbf{d_9}$



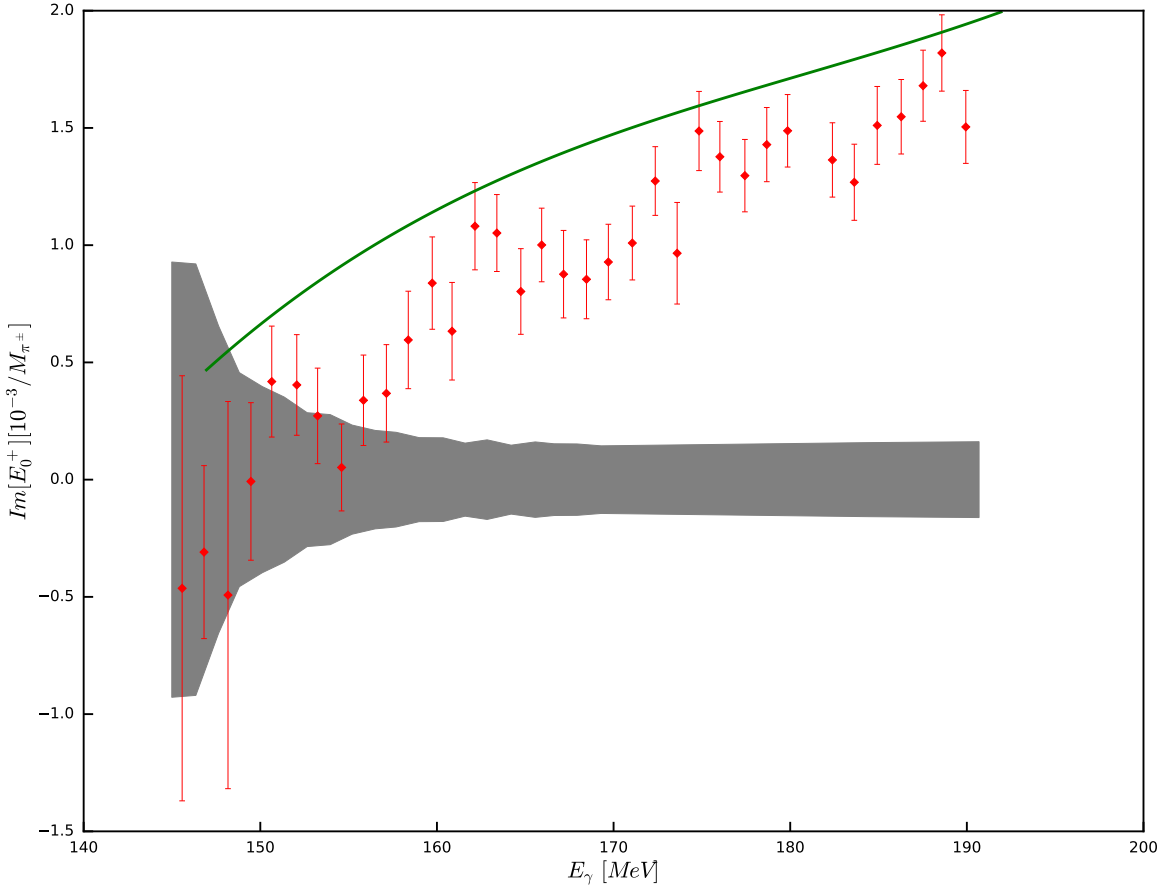
$\mathbf{d_{16}}$, $\mathbf{d_{18}}$

Multipoles — the real part



The explicit inclusion of Δ is essential to reproduce M_1^+

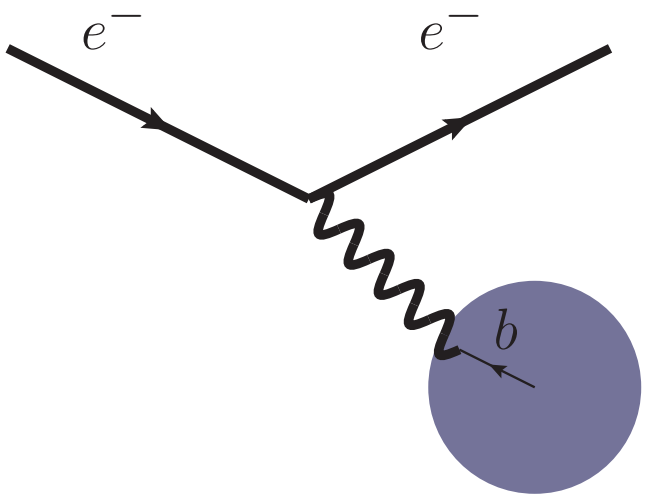
E_0^+ — the imaginary part



The contribution of *D*-waves needs to be taken into account in order to get the correct behavior for E_0^+

Schumann et al. (2015) PLB

Electron-scattering form factors



Matrix decomposition of the amplitude:

$$\gamma^\mu F_1(Q^2) + \frac{\mathrm{i}\sigma^{\mu\nu} q_\nu}{2m} F_2(Q^2) \boxed{+\frac{\mathrm{i}\sigma^{\mu\nu}\gamma_5 q_\nu}{2m} F_{\mathrm{EDM}}(Q^2)}$$

***CP* violating**

CP violation

Origin and consequences of *CP* violation:

- Standard model complex phases in quark mixing matrix: **confirmed experimentally** (electroweak), very **small**
- Not yet seen in the strong interaction sector, but possible
- Would lead to a permanent EDM of the neutron (nEDM)
- In the SM this EDM would only be of $\sim 10^{-32} e\ cm$

Connection with matter–antimatter asymmetry

Postulated principles to explain **matter-antimatter asymmetry**:

Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5 (1967) 32

- Baryon number conservation: **violated**
- Processes take place **out of** thermal equilibrium
- *C* and *CP* symmetries: **violated**

CP violation from CKM matrix not enough for asymmetry
$\Longrightarrow$ **physics beyond the standard model?**

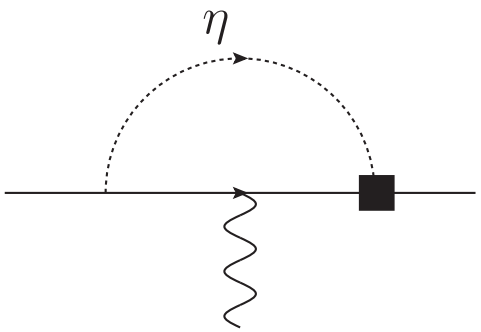
Generating a neutron EDM

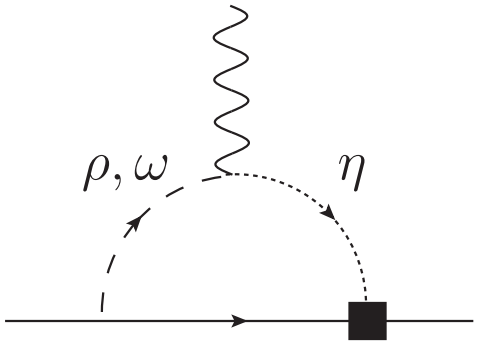
Precision EDM measurements: **neutral and stable** neutron

Current experimental upper limit for neutron EDM:

Review of Particle Physics $\qquad$ $\text{nEDM} < 2.9 \cdot 10^{-26} e\,\text{cm}$

We explore one possibility to generate the nEDM from the theoretical perspective:





Need: *CP*-violating couplings ■ of the η, η' to the nucleons

CP-violating $\eta, \eta' \to \pi\pi$ decays

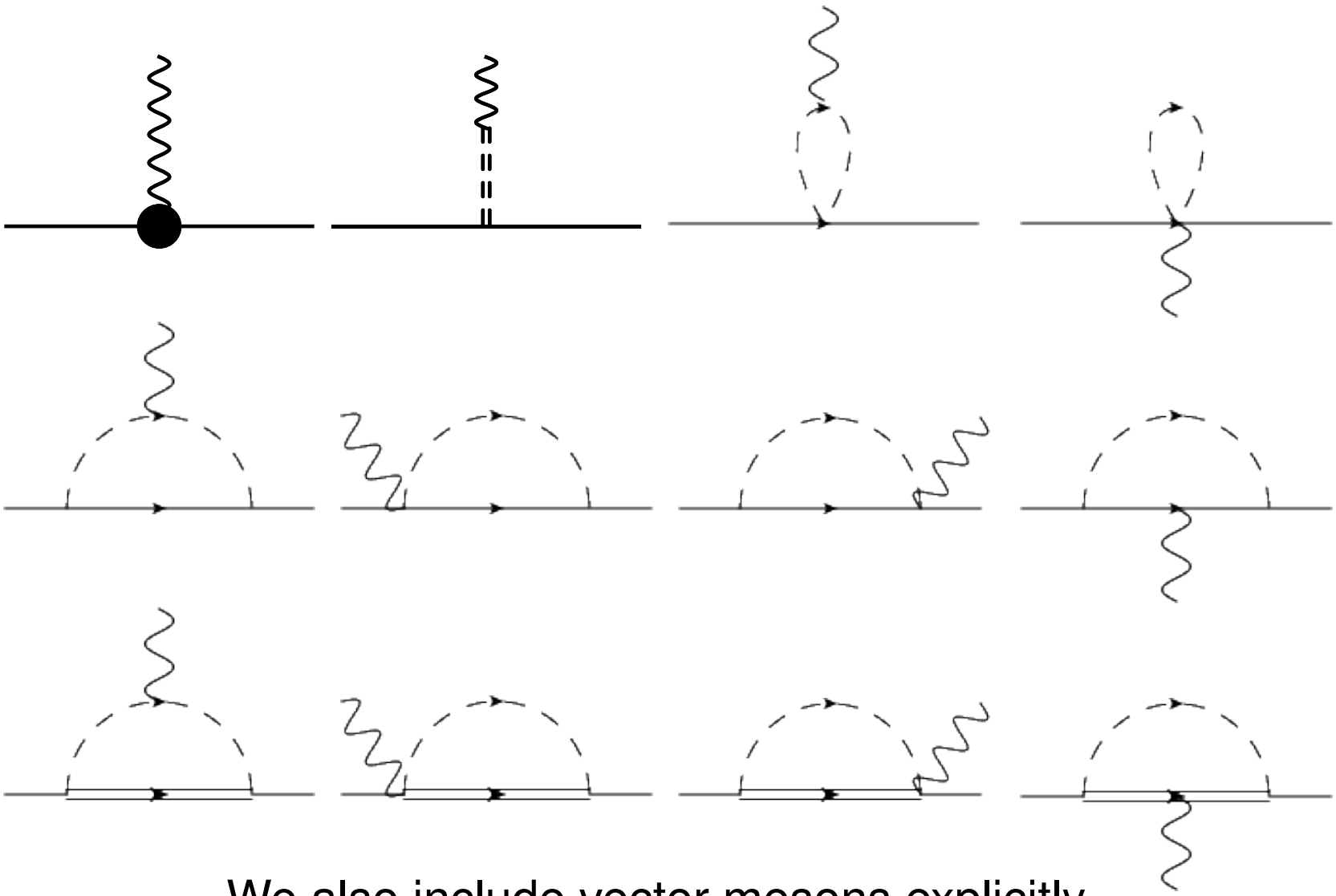
We extract the *CP*-violating η, η' **coupling to the nucleon** from the *CP*-violating η, η' **couplings to two pions**:

Tight constraint on *CP*-violating decays

From the experiment:

- $$\frac{\Gamma(\eta \to \pi\pi)}{\Gamma_\eta^{\text{full}}} < \begin{cases} 1.3 \times 10^{-5} \text{ for } \pi^+\pi^- \\ 3.5 \times 10^{-4} \text{ for } \pi^0\pi^0 \end{cases}$$
  $$\Longrightarrow \text{generates nEDM}_{\text{theo}} < 10^{-18} e \text{ cm}$$
- $\text{nEDM}_{\text{exp}} < 2.9 \cdot 10^{-26} e$ cm
- *CP*-violating branching ratio should be reduced by further **eight orders of magnitude**
- Relevant for the rare $\eta(\eta')$-decay measurements by the GlueX and LHCb experiments

Contributions to form factors up to $\mathcal{O}(p^3)$



We also include vector mesons explicitly

Octet-baryon electromagnetic form factors

- Calculated all octet-baryon electromagnetic form factors

$$G_E(q^2) = F_1(q^2) + \frac{q^2}{4m_{B0}^2} F_2(q^2)$$

$$= 1 + q^2 \frac{\langle r_E^2 \rangle}{6} + \frac{q^4}{2} \frac{\mathrm{d}^2}{(\mathrm{d}q^2)^2} G_E(q^2) \mid_{q^2=0} + \mathcal{O}(q^6)$$

Octet-baryon electromagnetic form factors

- Calculated all octet-baryon electromagnetic form factors

$$G_E(q^2) = F_1(q^2) + \frac{q^2}{4m_{B0}^2} F_2(q^2) \quad \textbf{Predictive}$$

$$= 1 + q^2 \frac{\langle r_E^2 \rangle}{6} + \frac{q^4}{2} \boxed{\frac{\mathrm{d}^2}{(\mathrm{d}\mathbf{q}^2)^2} \mathbf{G_E}(\mathbf{q}^2)} |_{q^2=0} + \mathcal{O}(q^6)$$

- Here: compare predictive higher-order piece with available proton data (**polynomial fits**)
- Relevant for fits to constrain better r_E: proton radius puzzle
- Might help to understand discrepancies between data from electron–proton scattering and muonic Lamb shift

Electric form factor and charge radius

Experiment: **11.7 – 16.6** GeV^{-4} Higinbotham et al., PRC 93 (2016) 055207

SU(2) theory: Ledwig et al., Phys. Rev. D 85 (2012) 034013 + our work

$\frac{d^2}{(dq^2)^2} G_E(q^2)\|_{q^2=0}$ [GeV^{-4}]	Octet	Decuplet	Vector	Total
Our results $SU(2)$	4.9	0.6	12.0	17.5
Our results $SU(3)$	3.9	-0.1	10.7	**14.5**

Another predictive quantity: peripheral transverse baryon electromagnetic densities

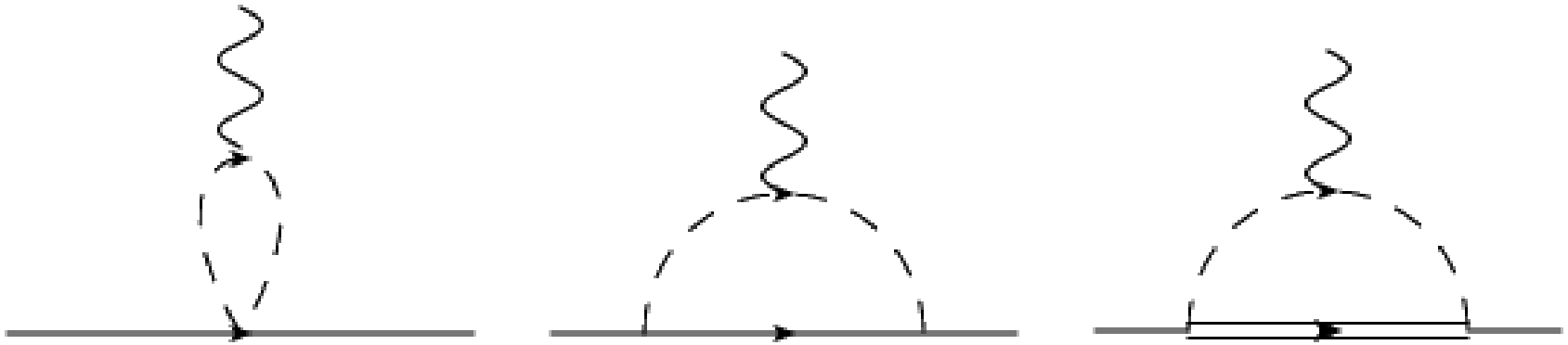
Dispersive representation of electromagnetic densities

$$\rho_{1,2}(b) = \int_{4m_\pi^2}^{\infty} \frac{dt}{2\pi} K_0(\sqrt{t}b) \frac{\mathrm{Im}\, F_{1,2}(t)}{\pi}$$

Bessel function $K_0 \sim e^{-b\sqrt{t}}$ suppression at large t

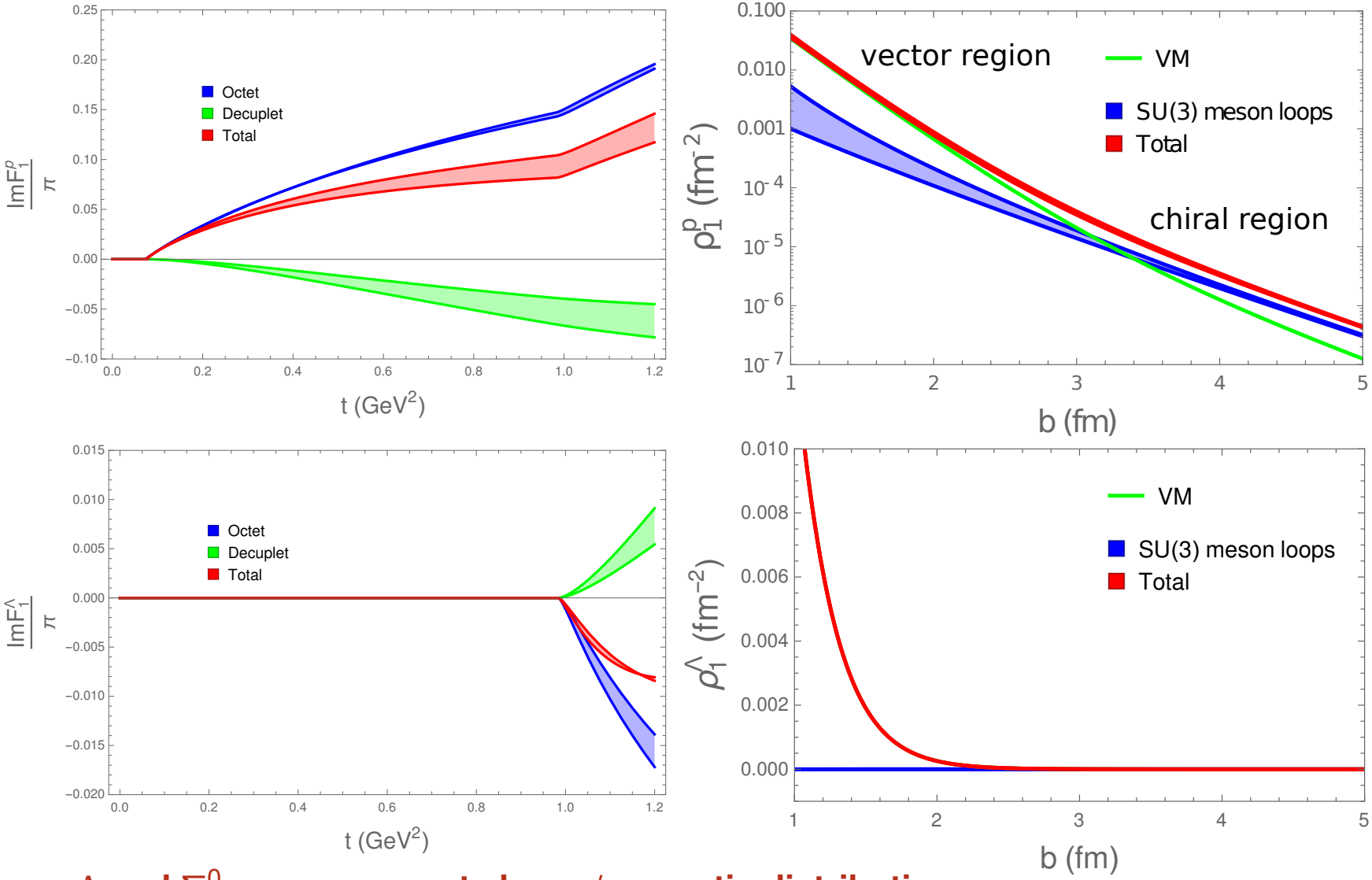
$\Longrightarrow$ Distance b is a filter of masses $\sqrt{t} \sim 1/b$

Two-pion cut: low-mass states $\rightarrow$ **peripheral transverse** ρ



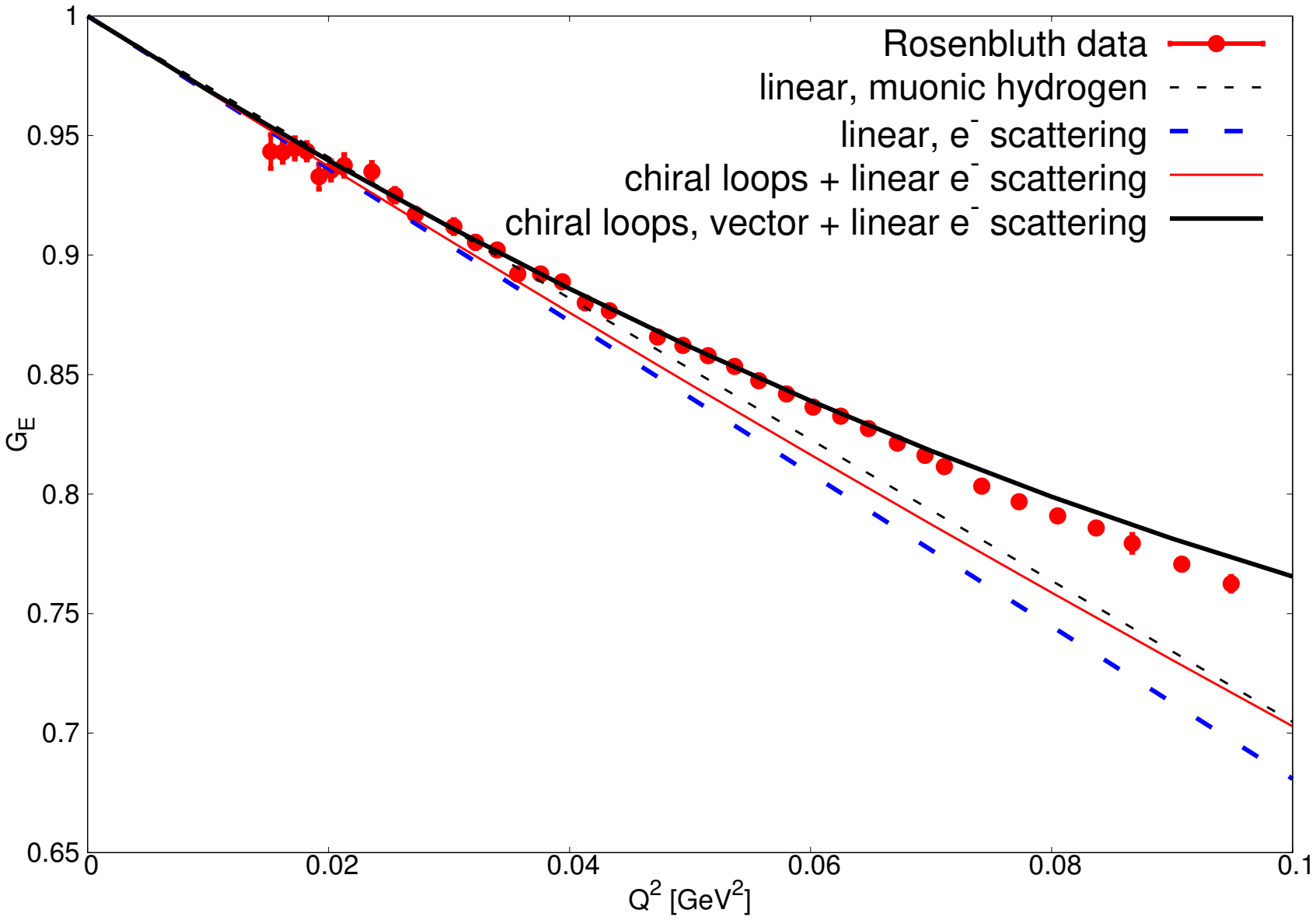
Only these diagrams have **imaginary parts** at this cut

Spectral functions and densities

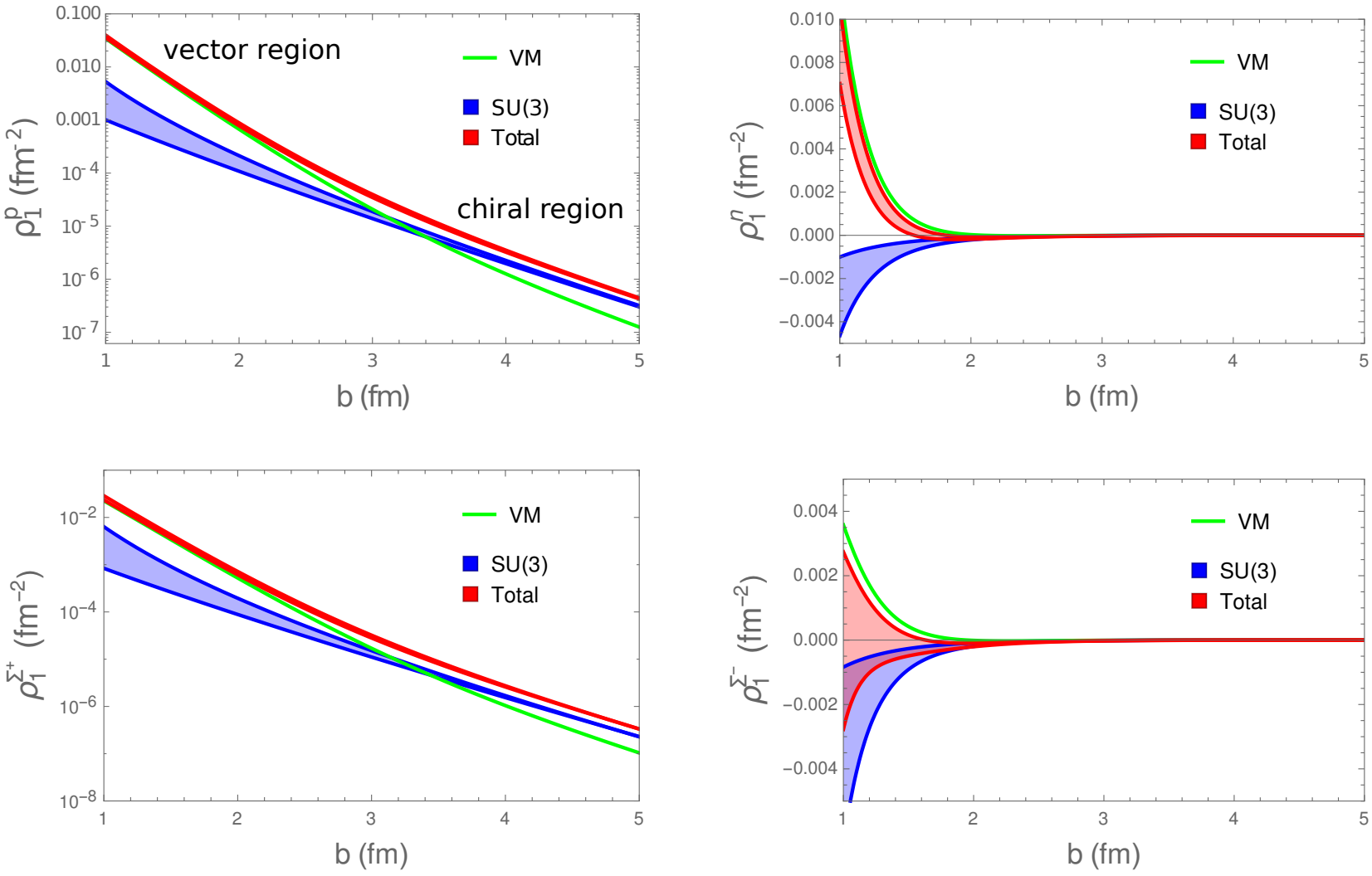


Λ and Σ^0: very compact charge/magnetic distributions

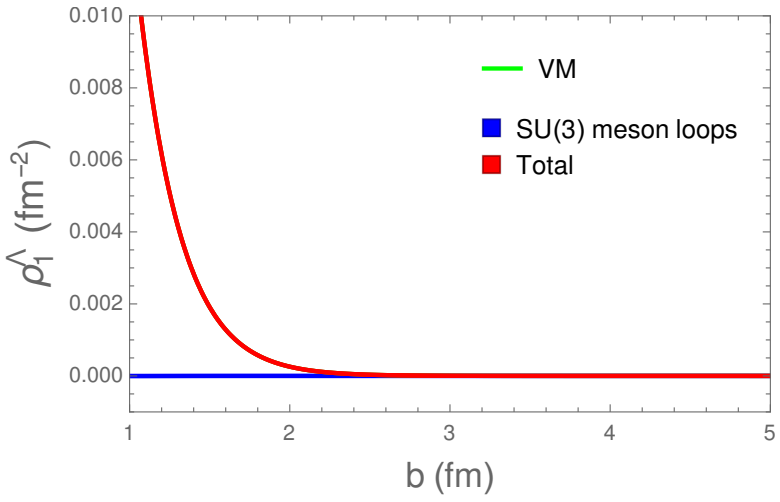
Rosenbluth data and charge radius

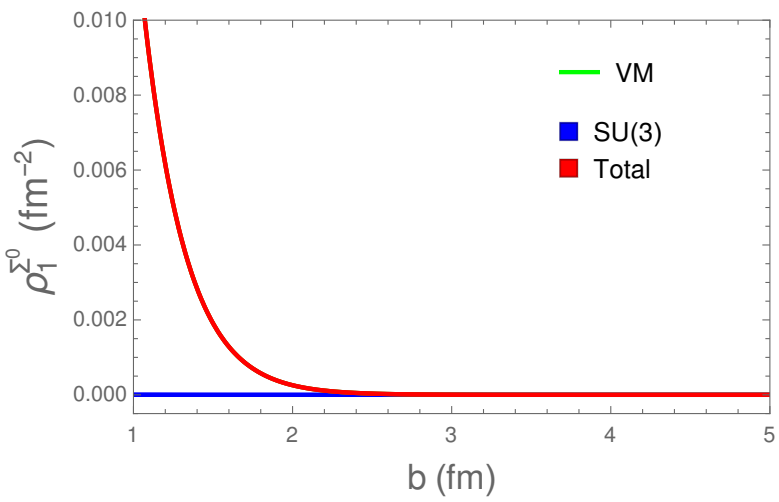


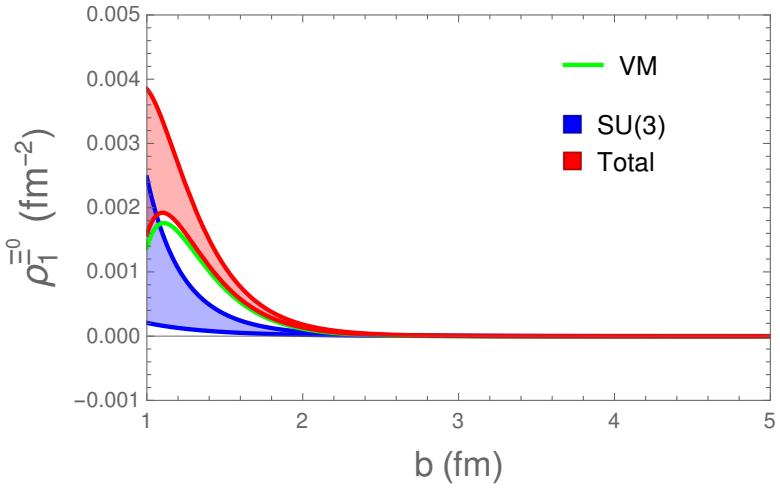
Octet charge densities

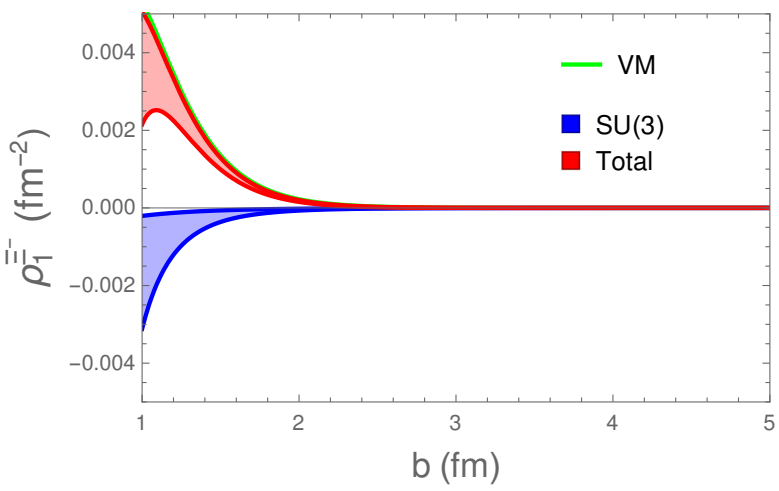


Octet charge densities

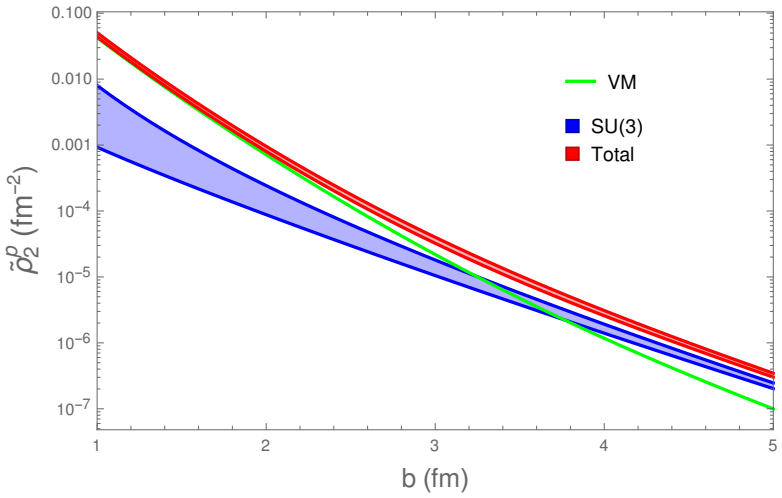


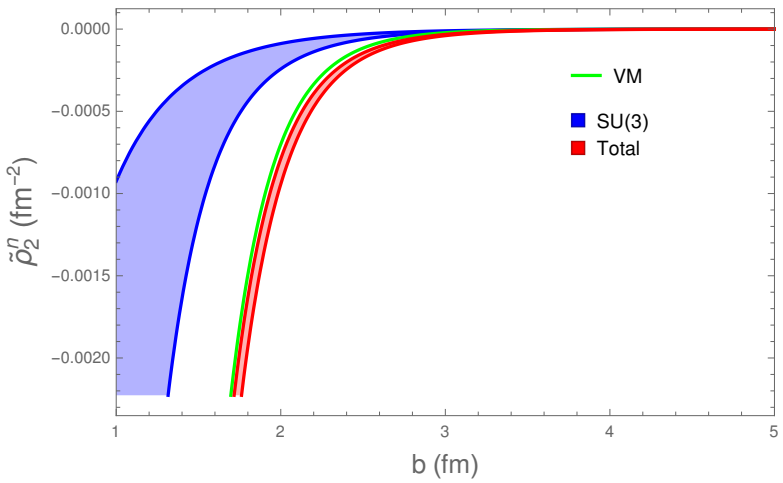


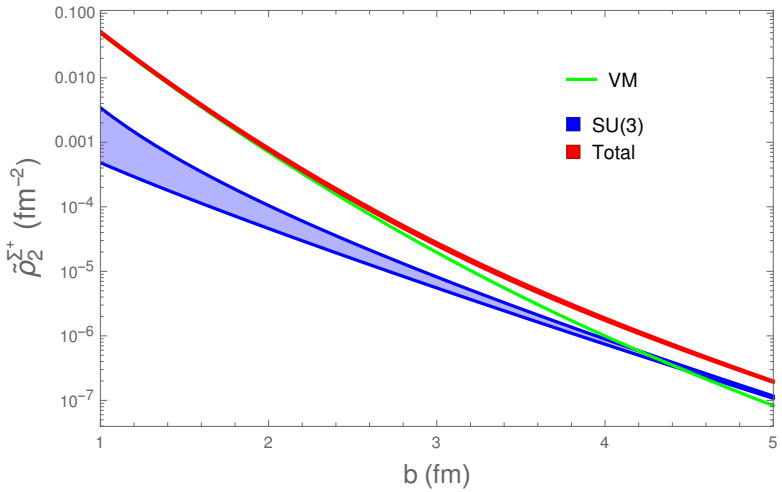


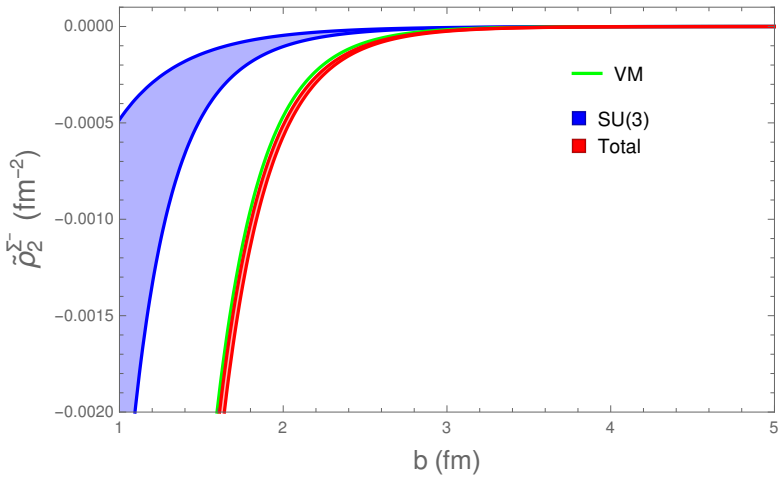


Octet magnetic densities

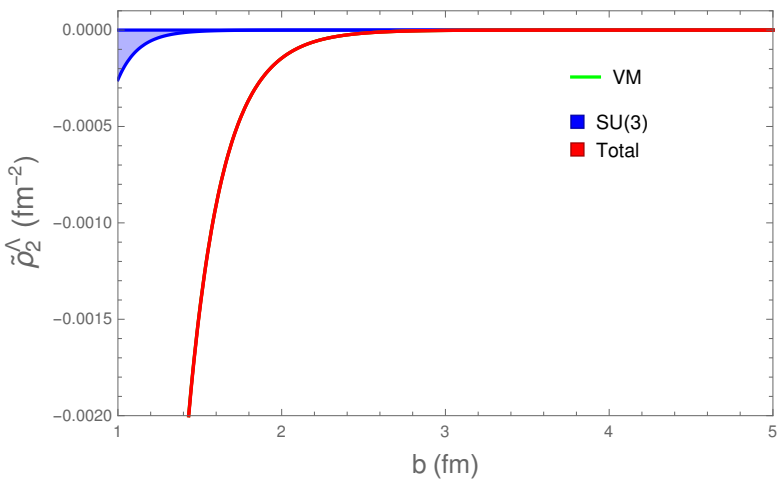


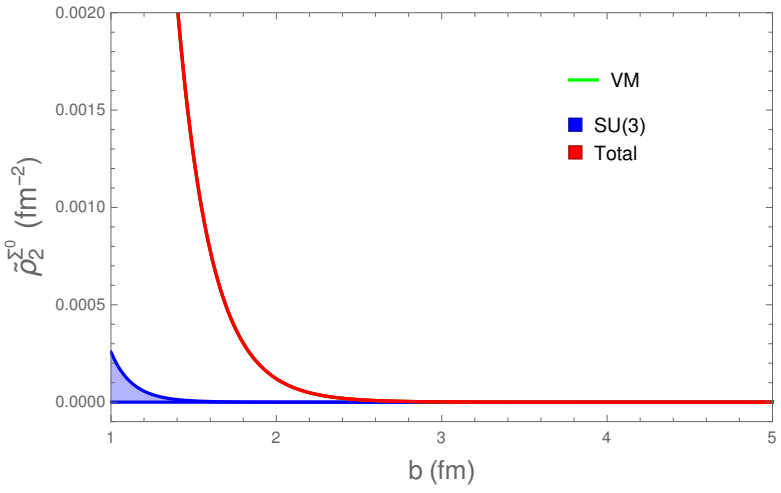


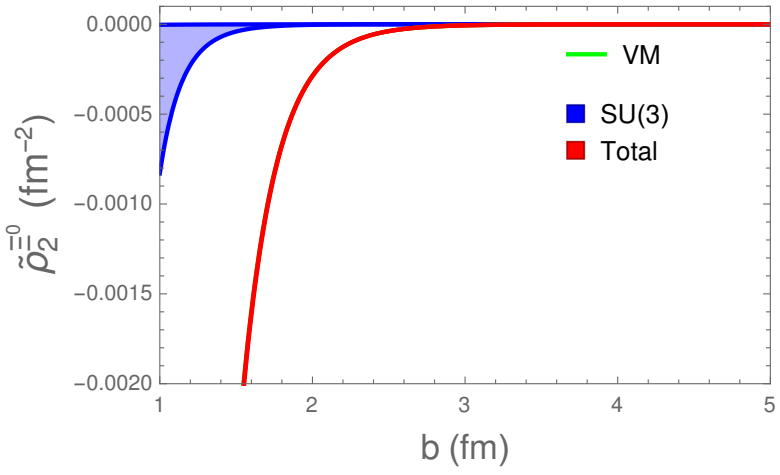


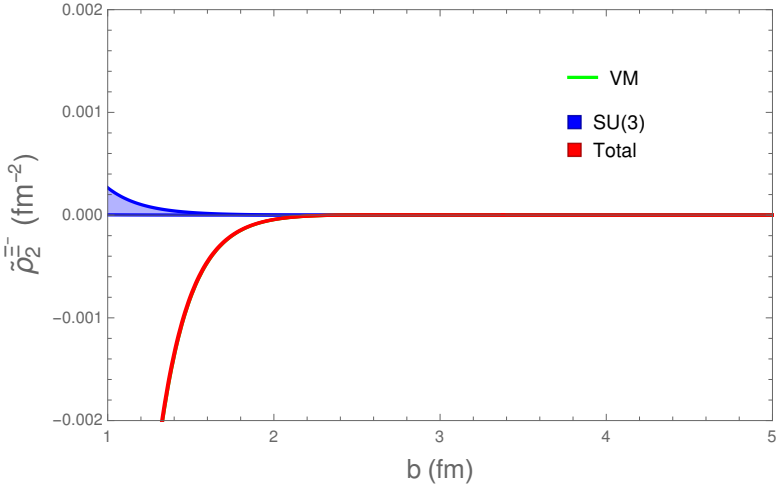


Octet magnetic densities

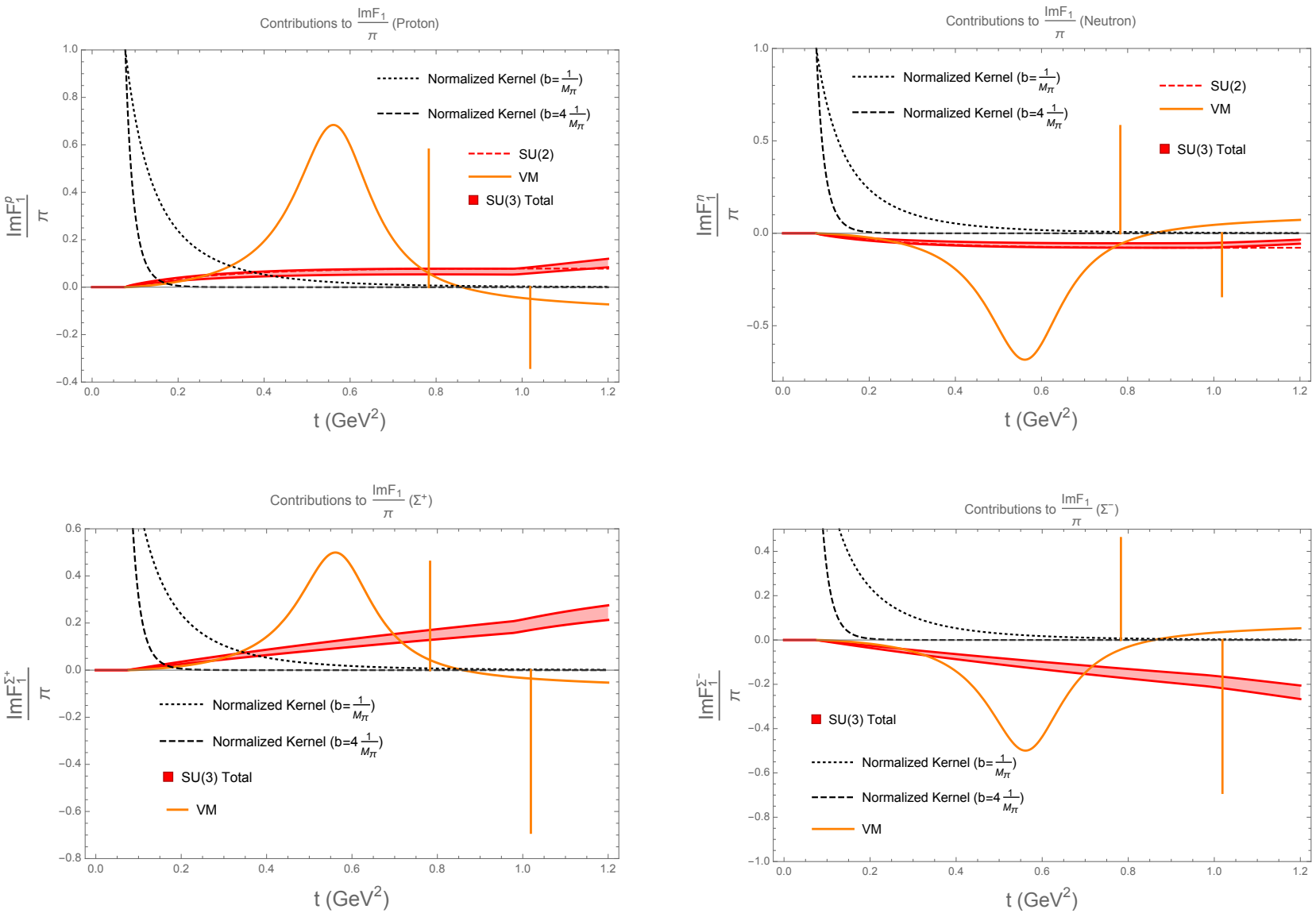




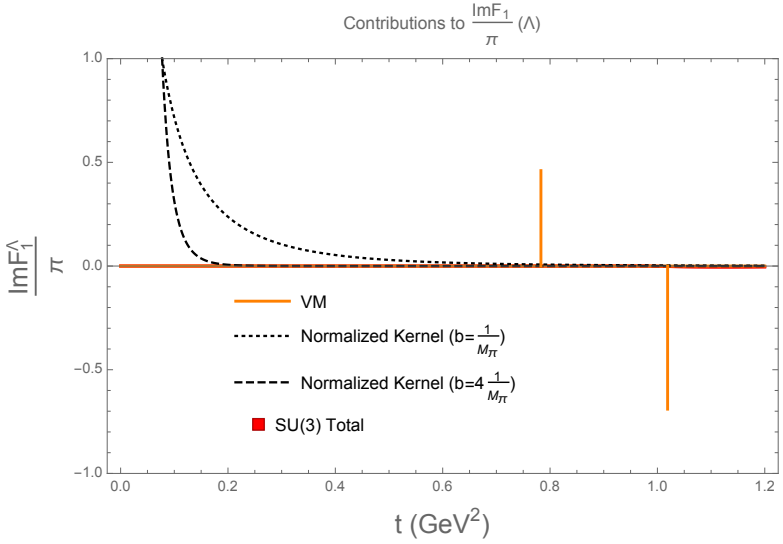


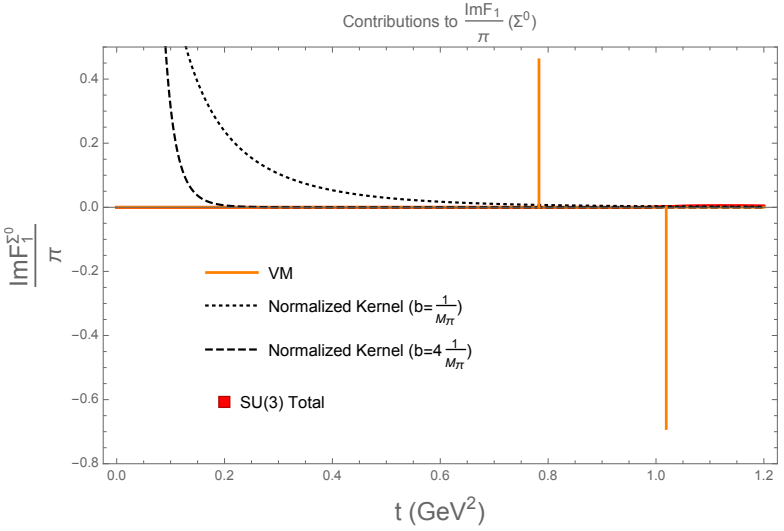


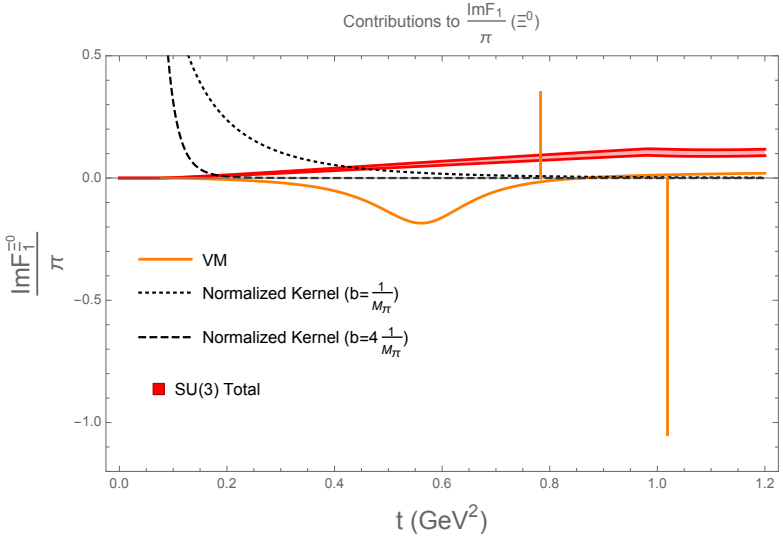
Octet Im(F_1)

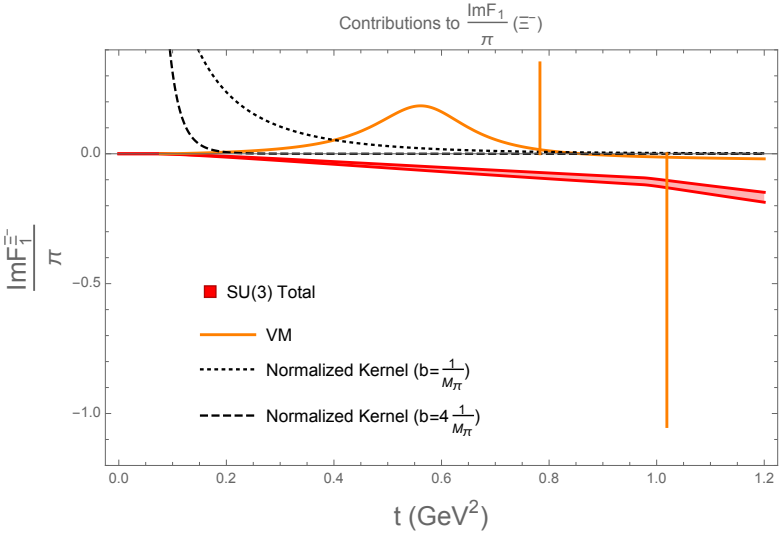

Contributions to $\frac{\mathrm{ImF_1}}{\pi}$ (Proton)
Normalized Kernel (b=$\frac{1}{M_\pi}$)
Normalized Kernel (b=4$\frac{1}{M_\pi}$)
SU(2)
VM
SU(3) Total
$\frac{\mathrm{ImF_1^p}}{\pi}$
t (GeV^2)
Contributions to $\frac{\mathrm{ImF_1}}{\pi}$ (Neutron)
Normalized Kernel (b=$\frac{1}{M_\pi}$)
Normalized Kernel (b=4$\frac{1}{M_\pi}$)
SU(2)
VM
SU(3) Total
$\frac{\mathrm{ImF_1^n}}{\pi}$
t (GeV^2)
Contributions to $\frac{\mathrm{ImF_1}}{\pi}$ (Σ^+)
Normalized Kernel (b=$\frac{1}{M_\pi}$)
Normalized Kernel (b=4$\frac{1}{M_\pi}$)
SU(3) Total
VM
$\frac{\mathrm{ImF_1^{\Sigma^+}}}{\pi}$
t (GeV^2)
Contributions to $\frac{\mathrm{ImF_1}}{\pi}$ (Σ^-)
SU(3) Total
Normalized Kernel (b=$\frac{1}{M_\pi}$)
Normalized Kernel (b=4$\frac{1}{M_\pi}$)
VM
$\frac{\mathrm{ImF_1^{\Sigma^-}}}{\pi}$
t (GeV^2)

Octet Im(F_1)

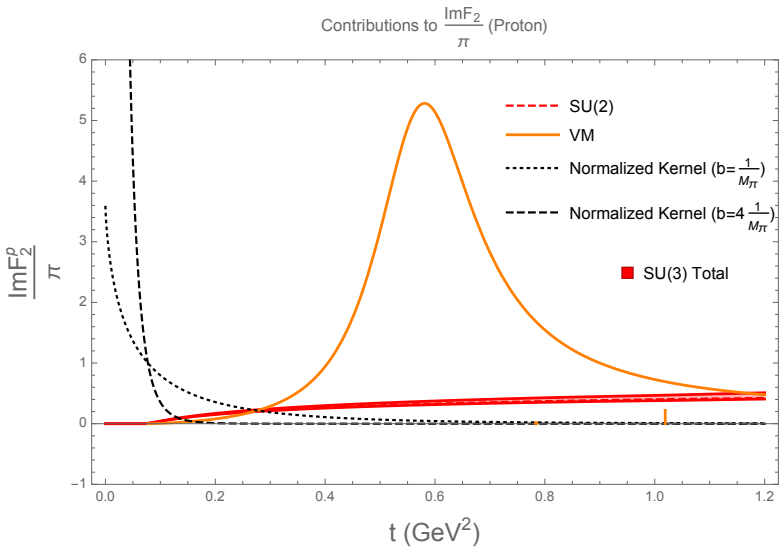

Contributions to $\frac{\mathrm{ImF_1}}{\pi}$ (Λ)
$\frac{\mathrm{ImF_1^{\Lambda}}}{\pi}$
VM
Normalized Kernel (b=$\frac{1}{M_\pi}$)
Normalized Kernel (b=4$\frac{1}{M_\pi}$)
SU(3) Total
t (GeV^2)

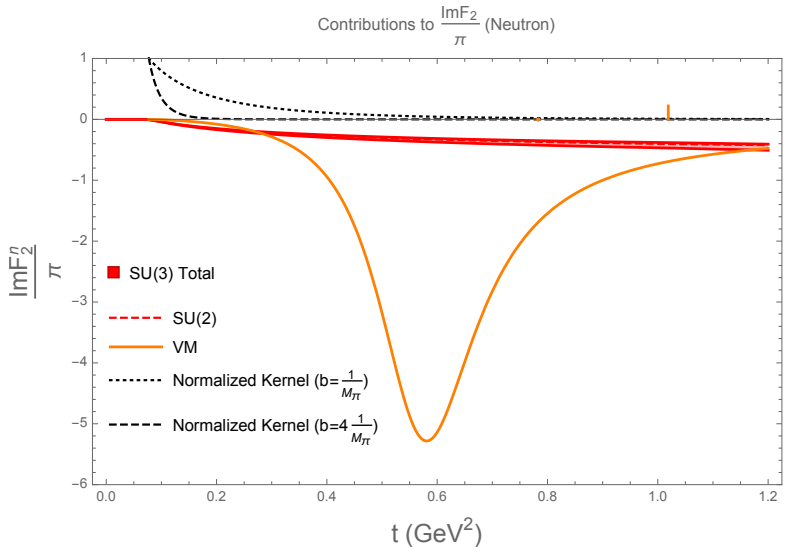

Contributions to $\frac{\mathrm{ImF_1}}{\pi}$ (Σ^0)
$\frac{\mathrm{ImF_1^{\Sigma^0}}}{\pi}$
VM
Normalized Kernel (b=$\frac{1}{M_\pi}$)
Normalized Kernel (b=4$\frac{1}{M_\pi}$)
SU(3) Total
t (GeV^2)

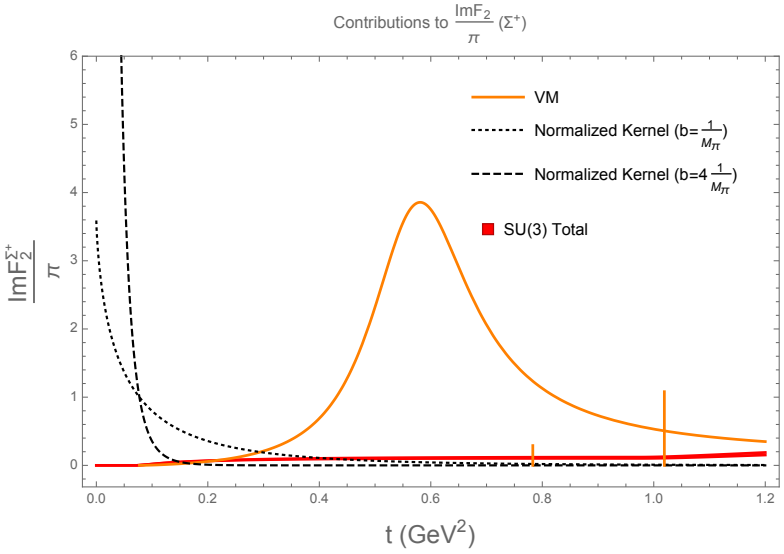

Contributions to $\frac{\mathrm{ImF_1}}{\pi}$ (Ξ^0)
$\frac{\mathrm{ImF_1^{\Xi^0}}}{\pi}$
VM
Normalized Kernel (b=$\frac{1}{M_\pi}$)
Normalized Kernel (b=4$\frac{1}{M_\pi}$)
SU(3) Total
t (GeV^2)

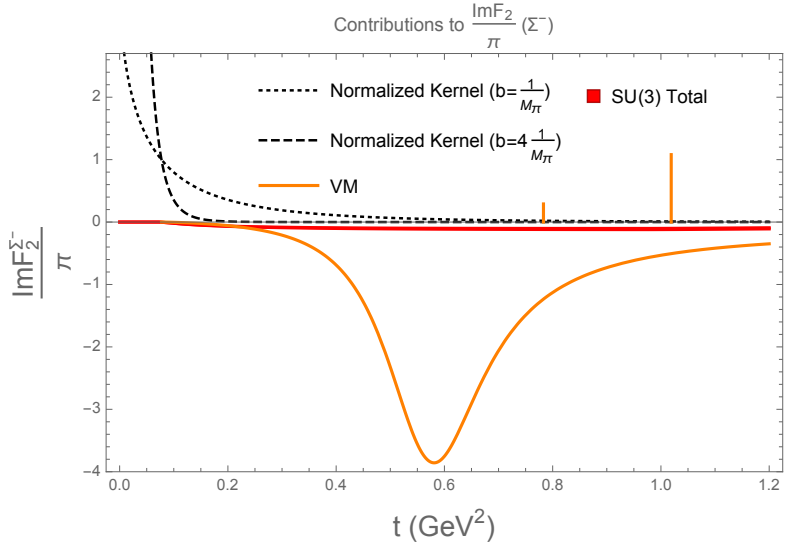

Contributions to $\frac{\mathrm{ImF_1}}{\pi}$ (Ξ^-)
$\frac{\mathrm{ImF_1^{\Xi^-}}}{\pi}$
SU(3) Total
VM
Normalized Kernel (b=$\frac{1}{M_\pi}$)
Normalized Kernel (b=4$\frac{1}{M_\pi}$)
t (GeV^2)

Octet Im(F_2)

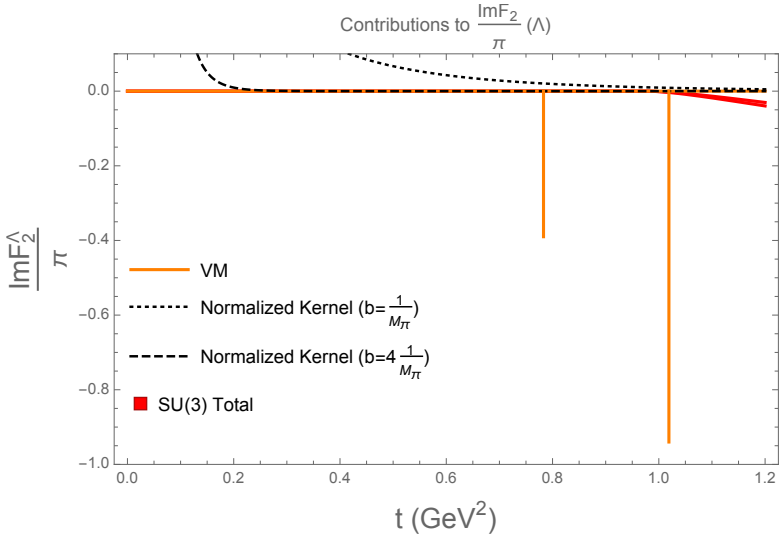

Contributions to $\frac{\mathrm{ImF_2}}{\pi}$ (Proton)
SU(2)
VM
Normalized Kernel (b=$\frac{1}{M_\pi}$)
Normalized Kernel (b=4$\frac{1}{M_\pi}$)
SU(3) Total
$\frac{\mathrm{ImF_2^p}}{\pi}$
t (GeV^2)

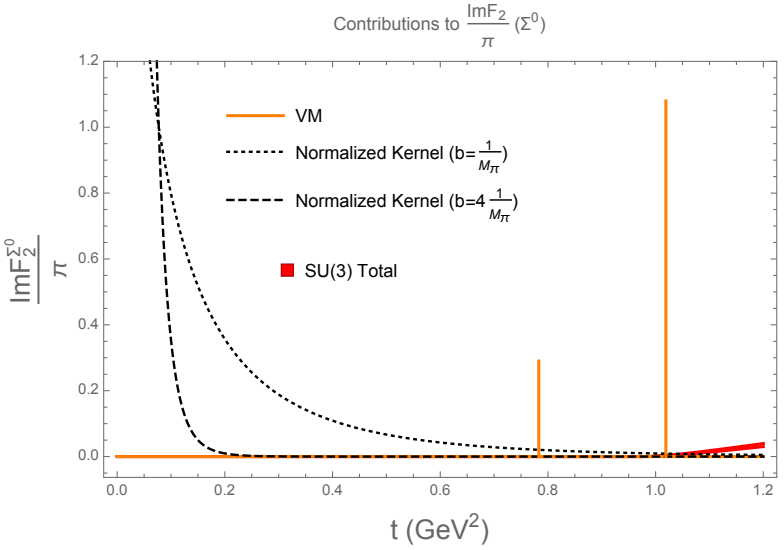

Contributions to $\frac{\mathrm{ImF_2}}{\pi}$ (Neutron)
SU(3) Total
SU(2)
VM
Normalized Kernel (b=$\frac{1}{M_\pi}$)
Normalized Kernel (b=4$\frac{1}{M_\pi}$)
$\frac{\mathrm{ImF_2^n}}{\pi}$
t (GeV^2)

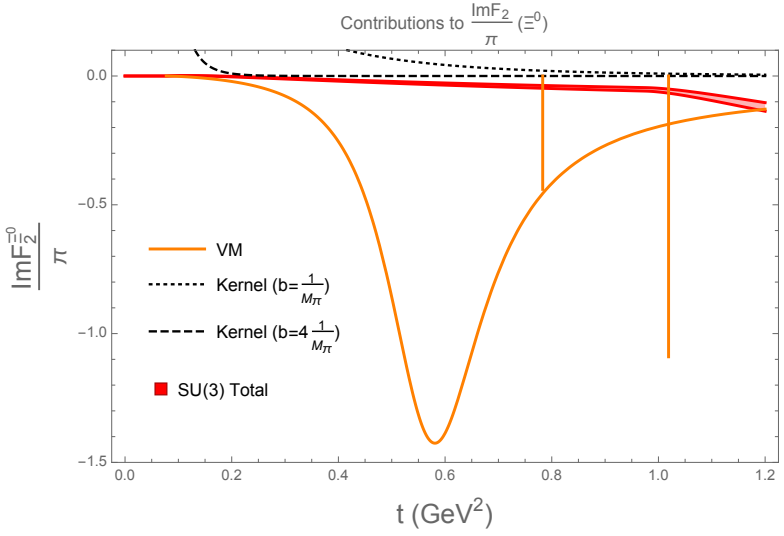

Contributions to $\frac{\mathrm{ImF_2}}{\pi}$ (Σ^+)
VM
Normalized Kernel (b=$\frac{1}{M_\pi}$)
Normalized Kernel (b=4$\frac{1}{M_\pi}$)
SU(3) Total
$\frac{\mathrm{ImF_2^{\Sigma^+}}}{\pi}$
t (GeV^2)

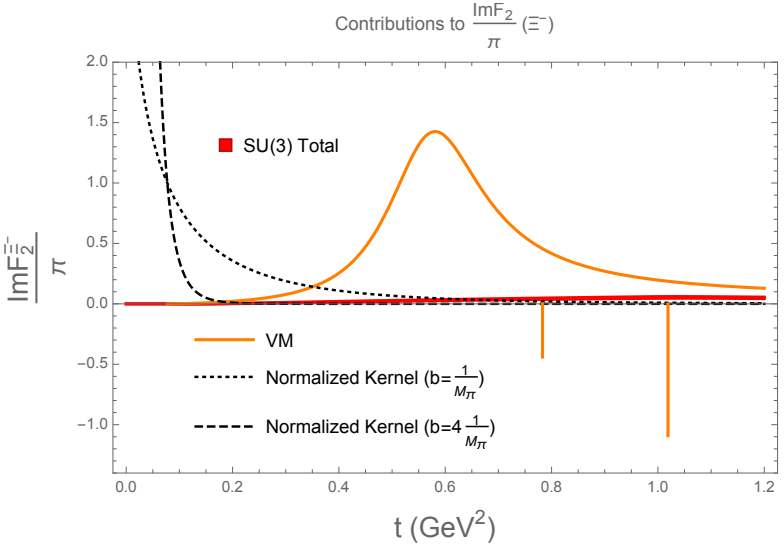

Contributions to $\frac{\mathrm{ImF_2}}{\pi}$ (Σ^-)
Normalized Kernel (b=$\frac{1}{M_\pi}$)
SU(3) Total
Normalized Kernel (b=4$\frac{1}{M_\pi}$)
VM
$\frac{\mathrm{ImF_2^{\Sigma^-}}}{\pi}$
t (GeV^2)

Octet Im(F_2)


Contributions to $\frac{\mathrm{ImF_2}}{\pi}$ (Λ)
$\frac{\mathrm{ImF_2^{\Lambda}}}{\pi}$
VM
Normalized Kernel (b=$\frac{1}{M_\pi}$)
Normalized Kernel (b=4$\frac{1}{M_\pi}$)
SU(3) Total
t (GeV^2)


Contributions to $\frac{\mathrm{ImF_2}}{\pi}$ (Σ^0)
$\frac{\mathrm{ImF_2^{\Sigma^0}}}{\pi}$
VM
Normalized Kernel (b=$\frac{1}{M_\pi}$)
Normalized Kernel (b=4$\frac{1}{M_\pi}$)
SU(3) Total
t (GeV^2)


Contributions to $\frac{\mathrm{ImF_2}}{\pi}$ (Ξ^0)
$\frac{\mathrm{ImF_2^{\Xi^0}}}{\pi}$
VM
Kernel (b=$\frac{1}{M_\pi}$)
Kernel (b=4$\frac{1}{M_\pi}$)
SU(3) Total
t (GeV^2)


Contributions to $\frac{\mathrm{ImF_2}}{\pi}$ (Ξ^-)
$\frac{\mathrm{ImF_2^{\Xi^-}}}{\pi}$
SU(3) Total
VM
Normalized Kernel (b=$\frac{1}{M_\pi}$)
Normalized Kernel (b=4$\frac{1}{M_\pi}$)
t (GeV^2)