Novel calculation of the nucleon form factors with Dispersively Improved Chiral EFT

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  - Important to understand and solve the "Proton Radius Puzzle".

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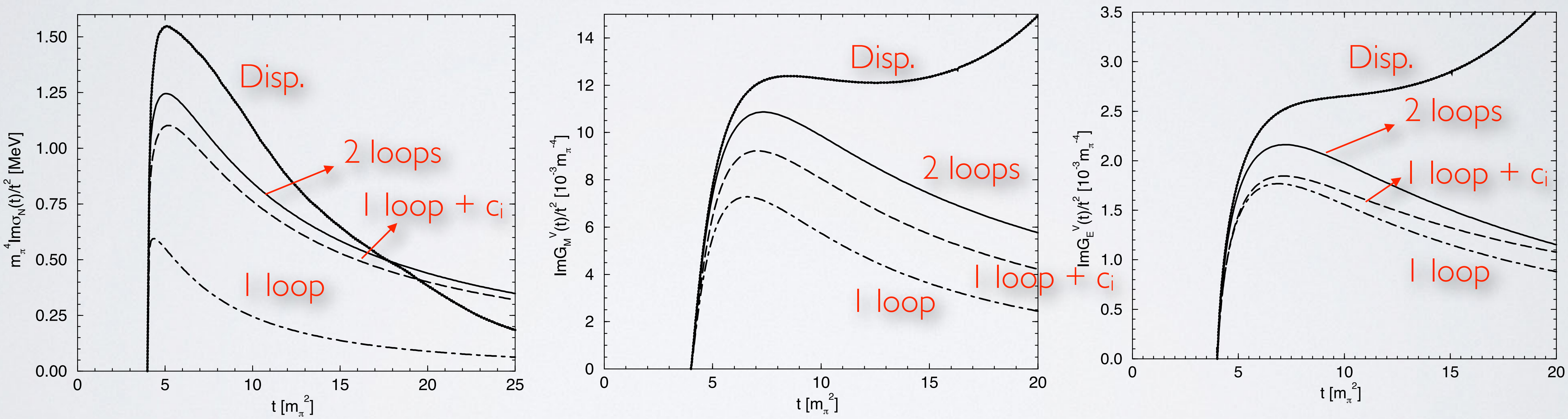

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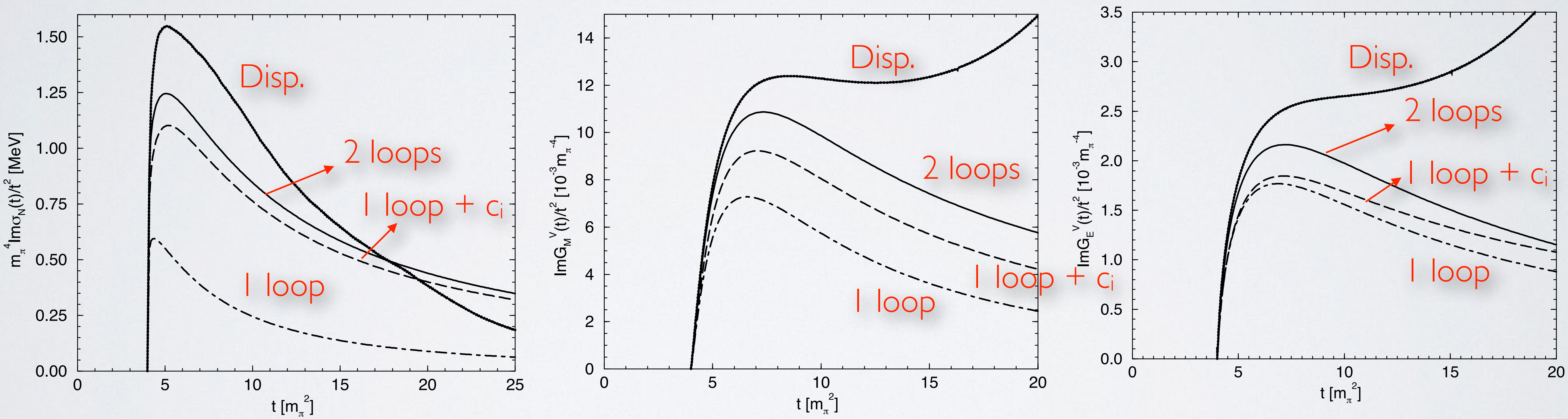

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- Higher order calculations become necessary → Unpractical

Form factors and their analytic structure

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- Definitions.

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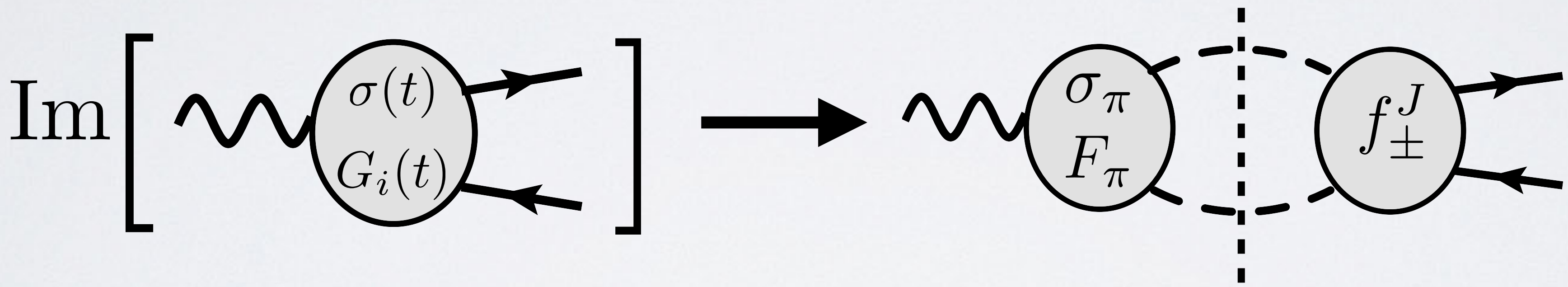

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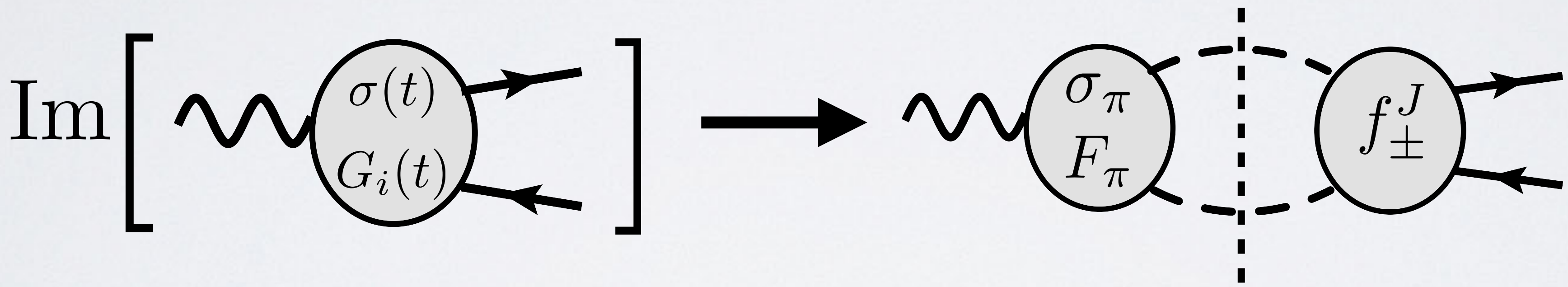

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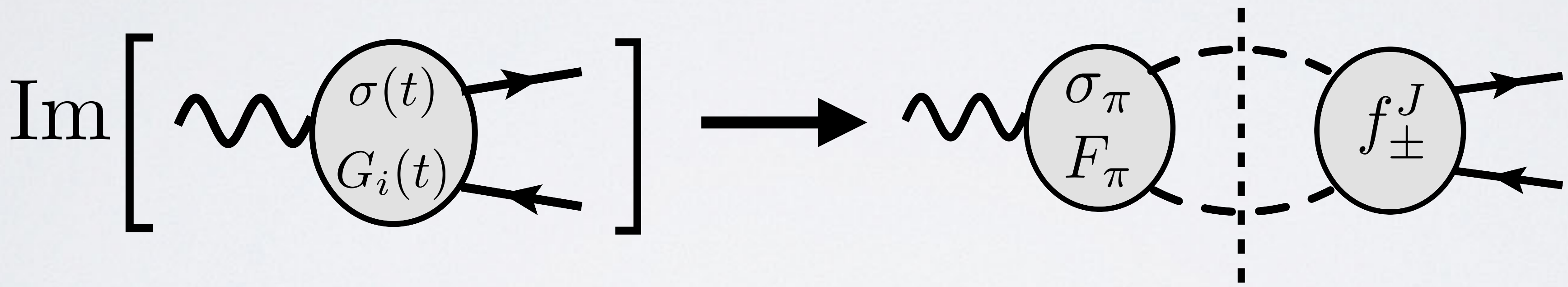

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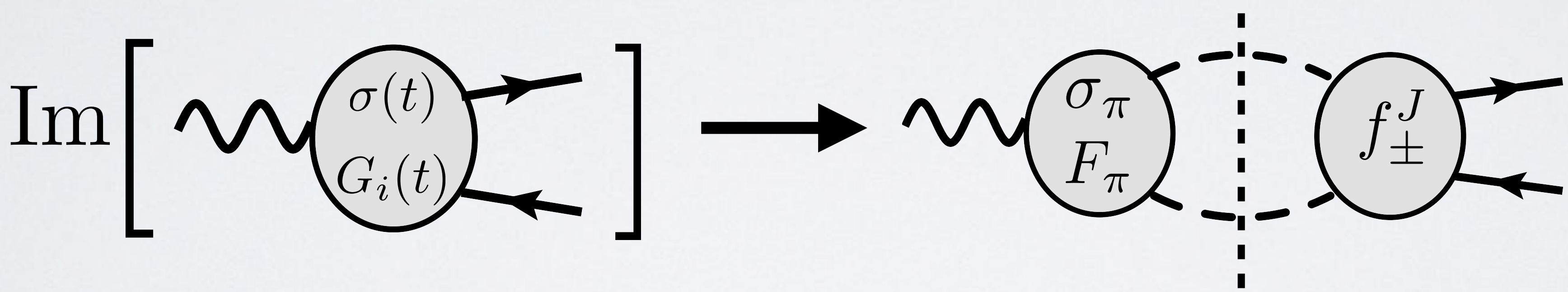

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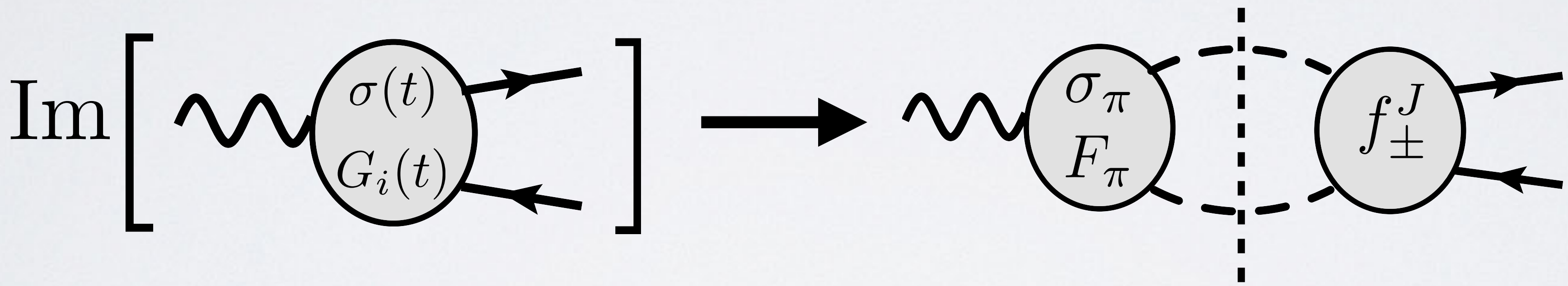

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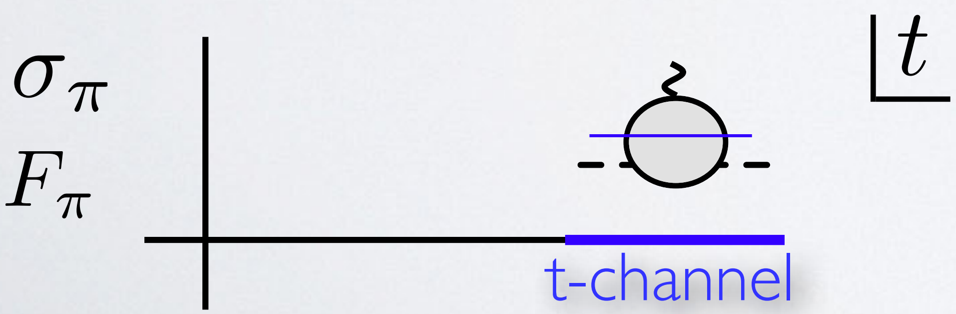

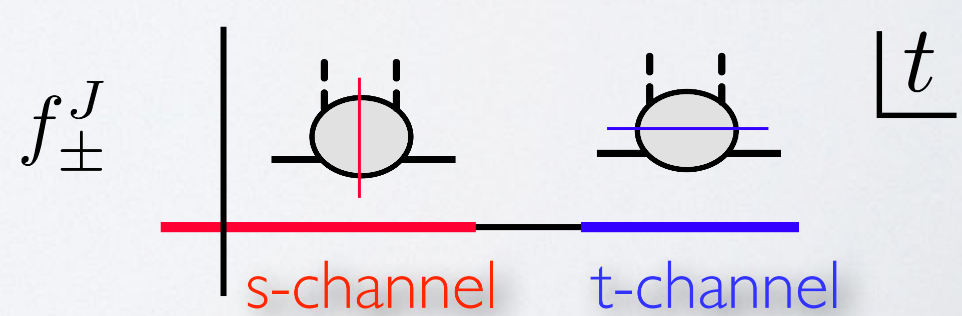

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  - N2LO partially included → One unknown coefficient for each $J_\pm^J$.

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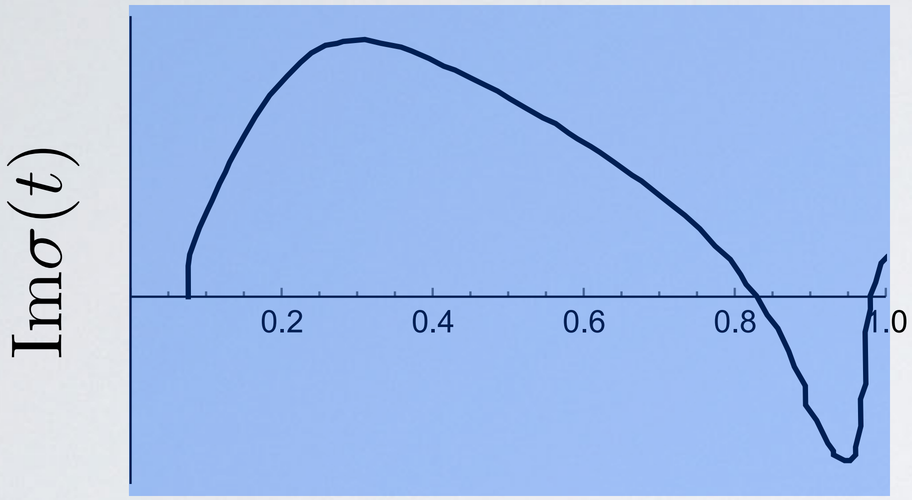

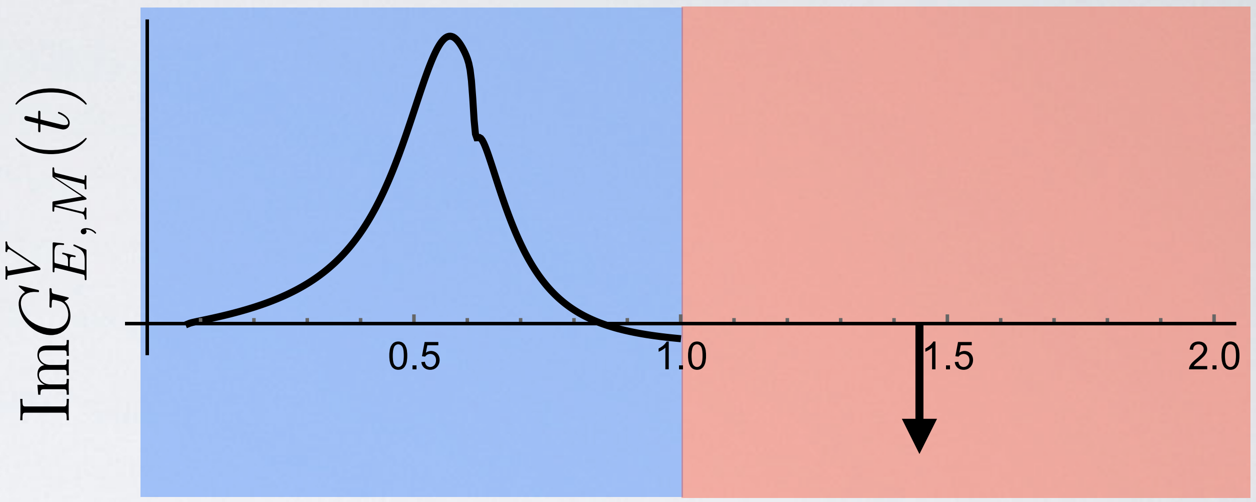

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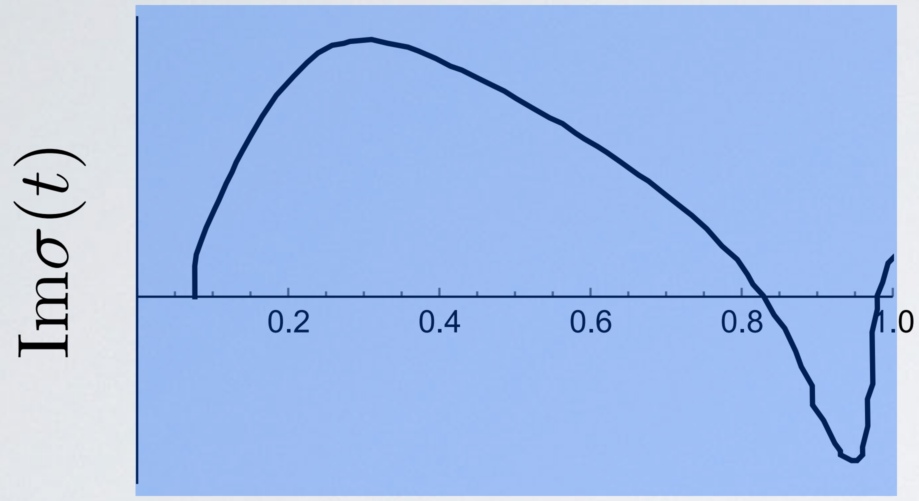

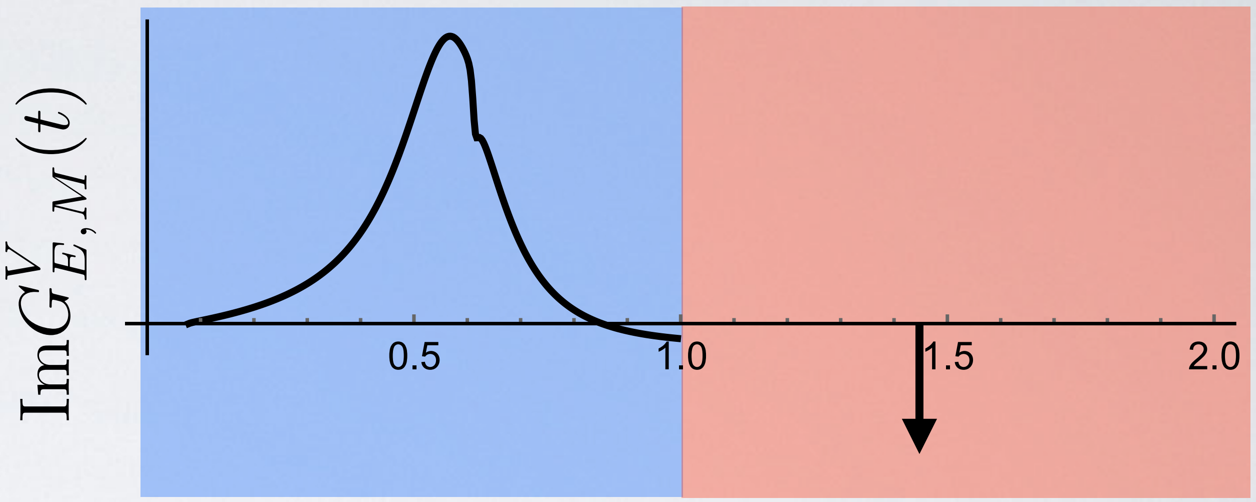

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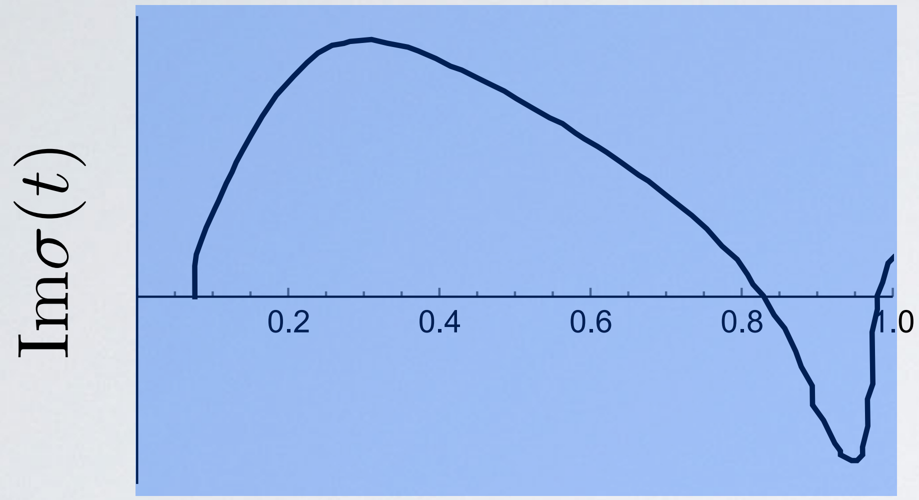

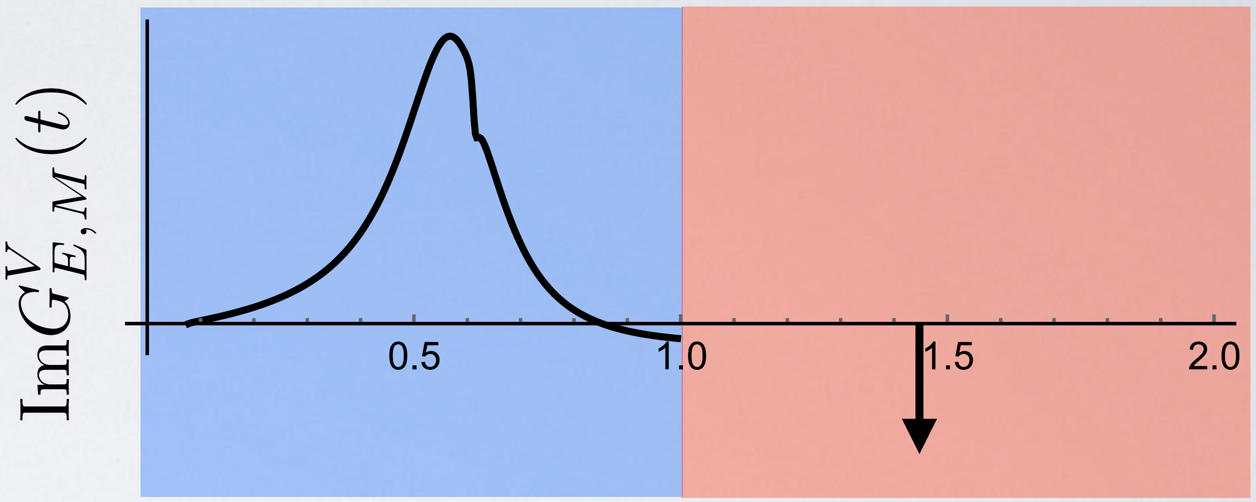

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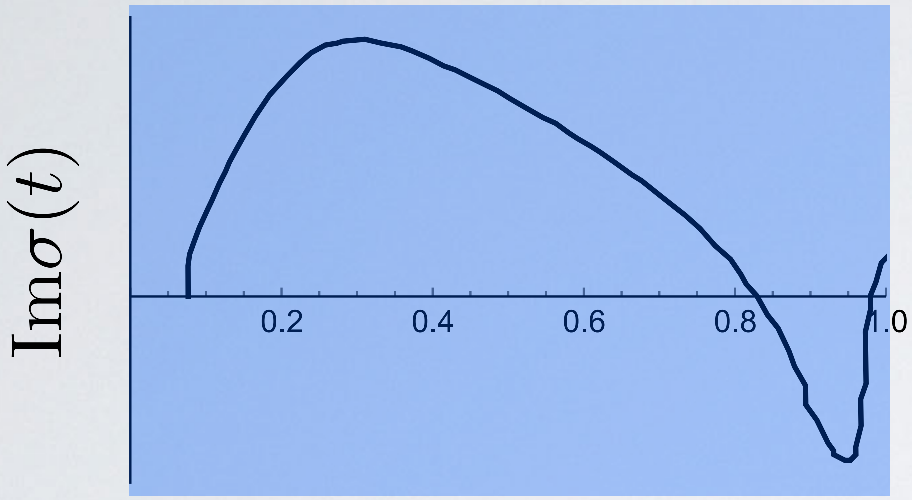

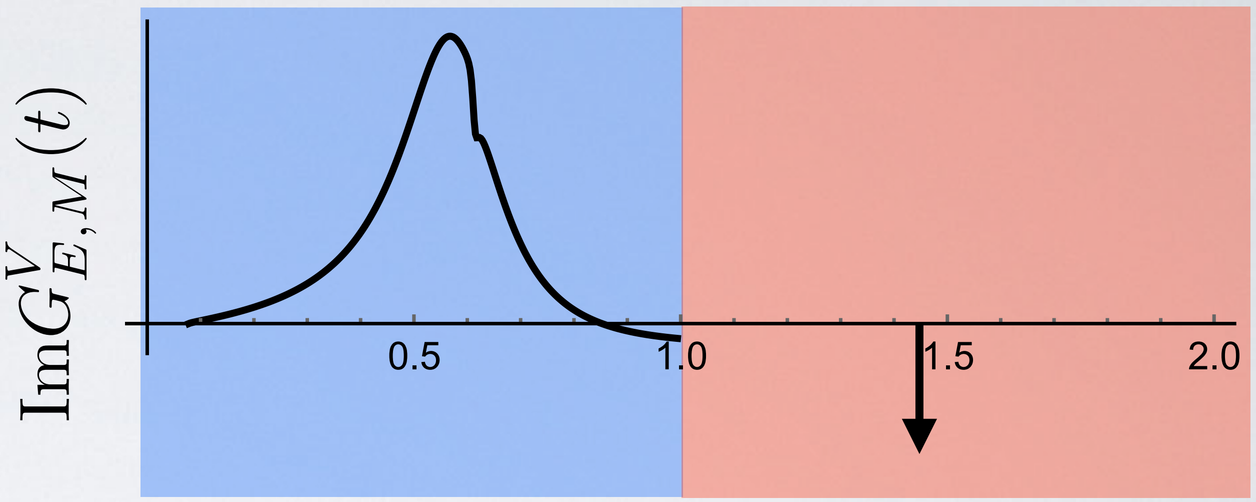

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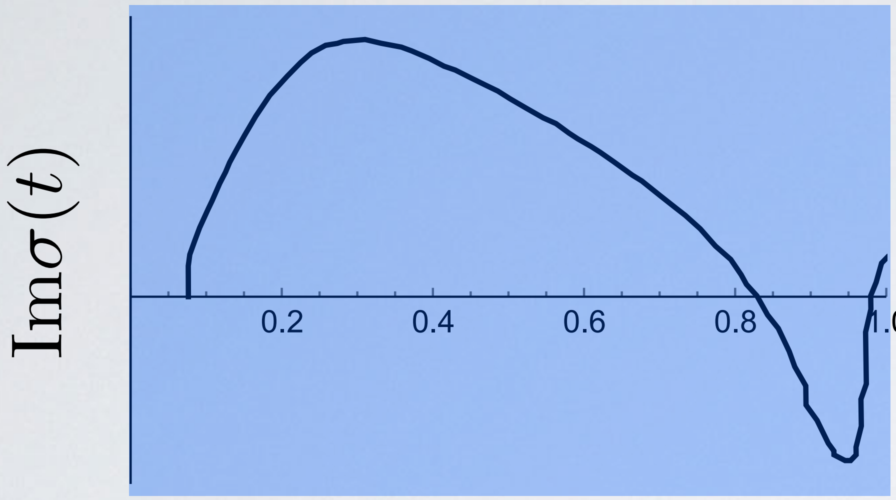

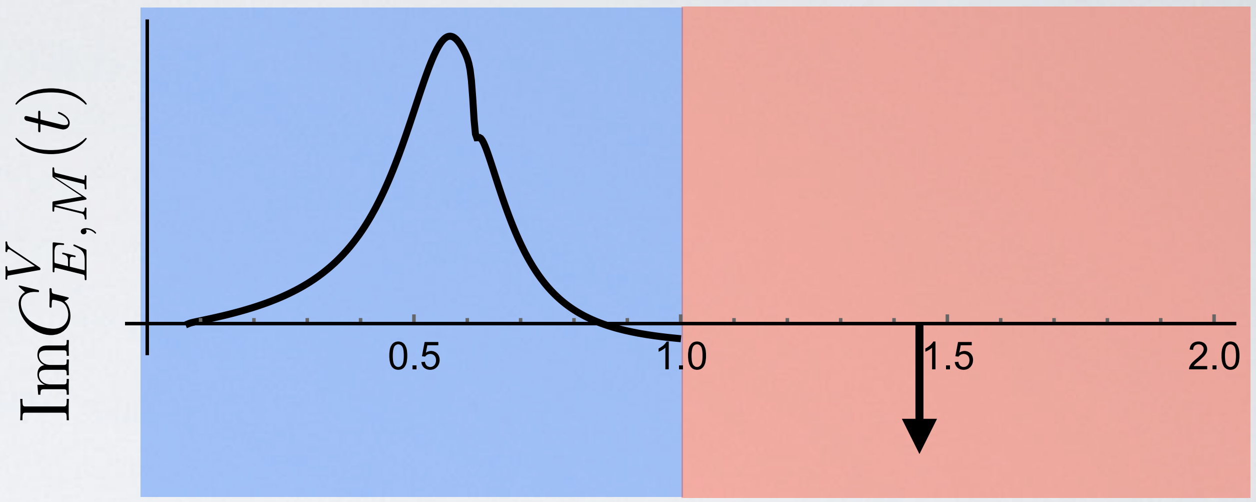

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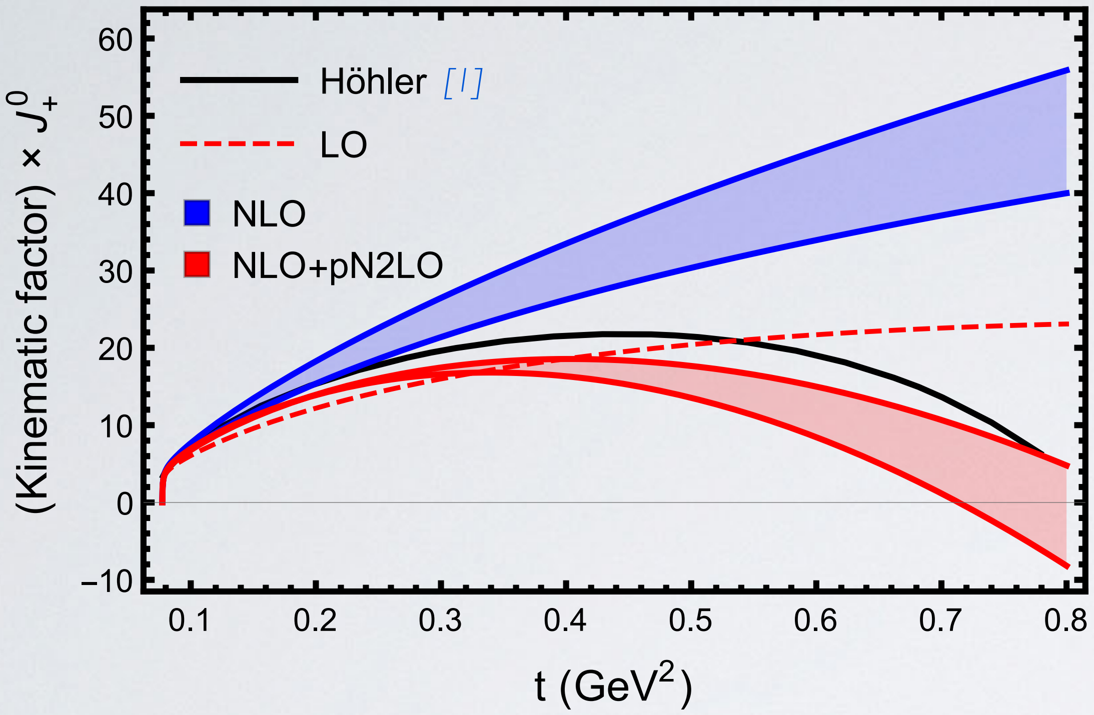
  - Scalar FF $\sigma(0) = \frac{1}{\pi}\int_{4M_\pi^2}^{1\ \mathrm{GeV}^2} dt' \frac{\mathrm{Im}\sigma(t')}{t'}$

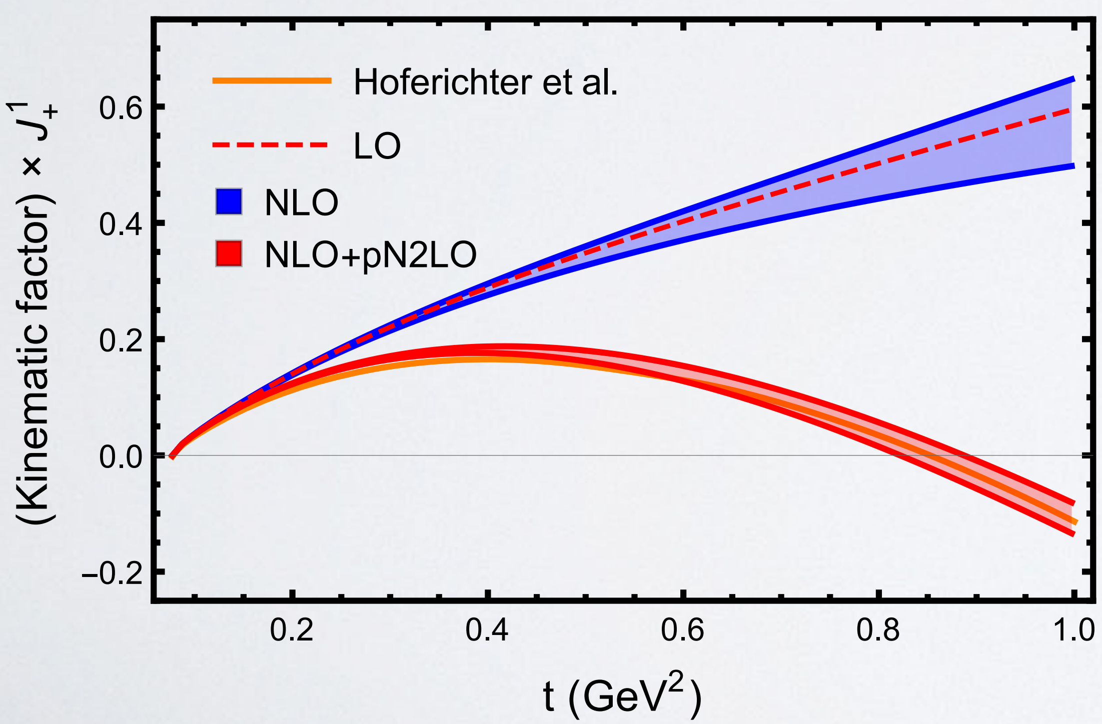
Form factors and their analytic structure

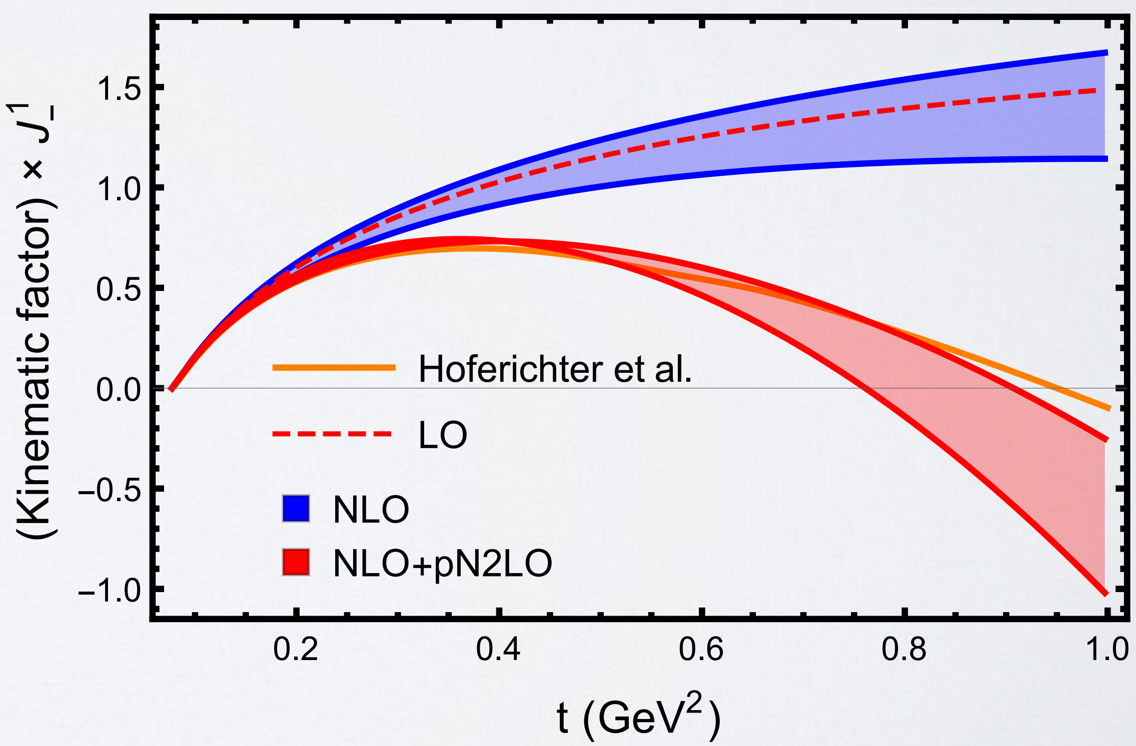
[J. M. Alarcón, C. Weiss, PRC 96 (2017)]



- Higher order corrections are important for t > 0.2 GeV^2.
- Error bands shown correspond to the uncertainties in the LECs.
- Systematic errors are inferred from the difference between NLO and NLO +pN2LO.

[J. M. Alarcón, C. Weiss, 1710.06430; in preparation]





[1] Höhler, in Landolt-Börnstein, 9b2, ed. H. Schopper (Springer, Berlin, 1983)

Form factors and their analytic structure

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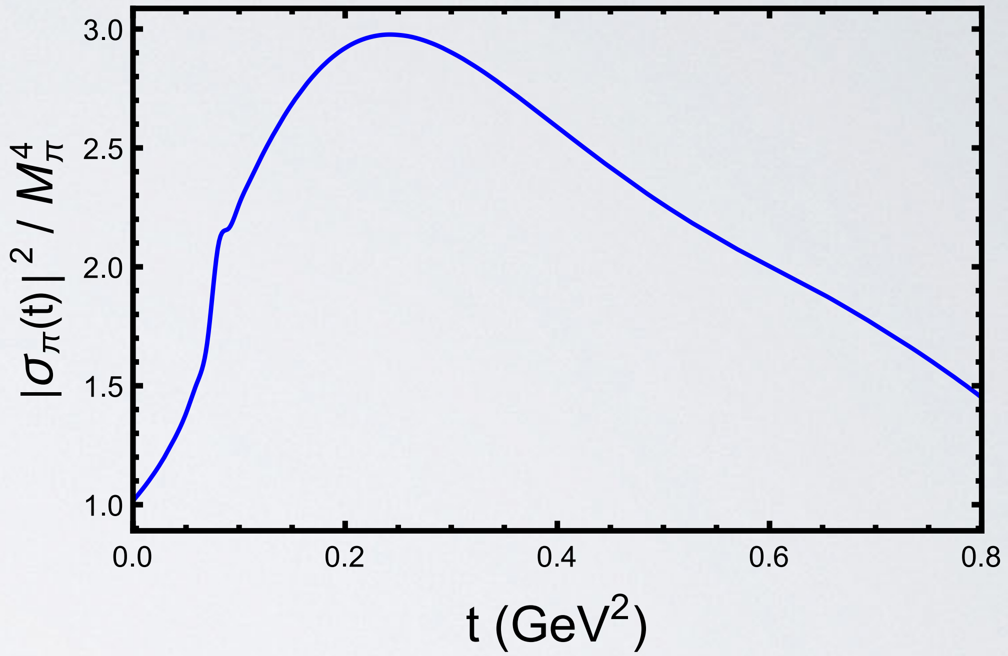

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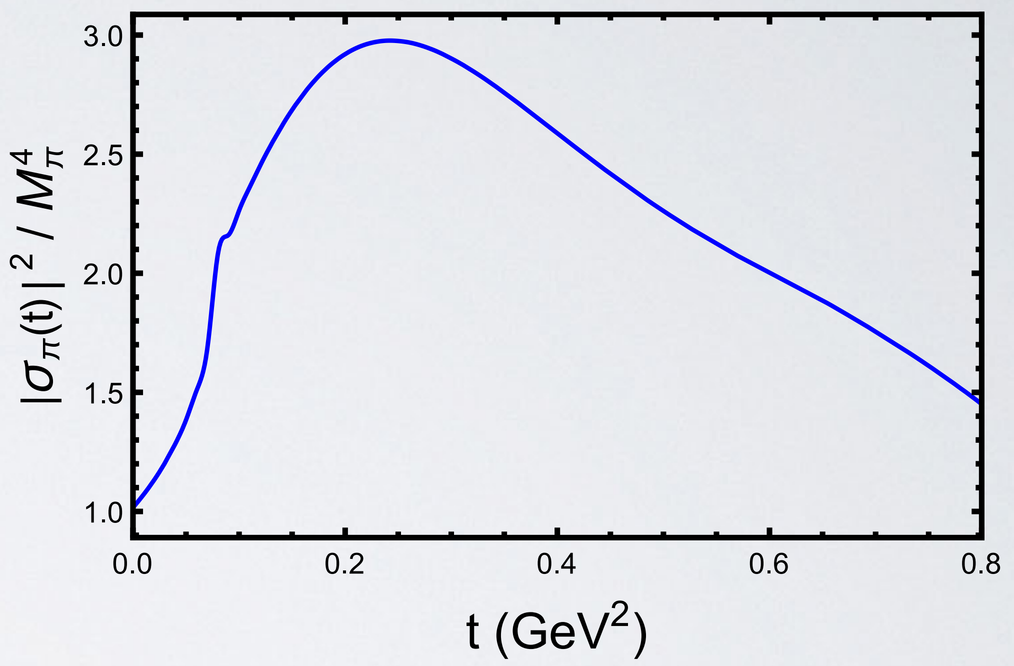

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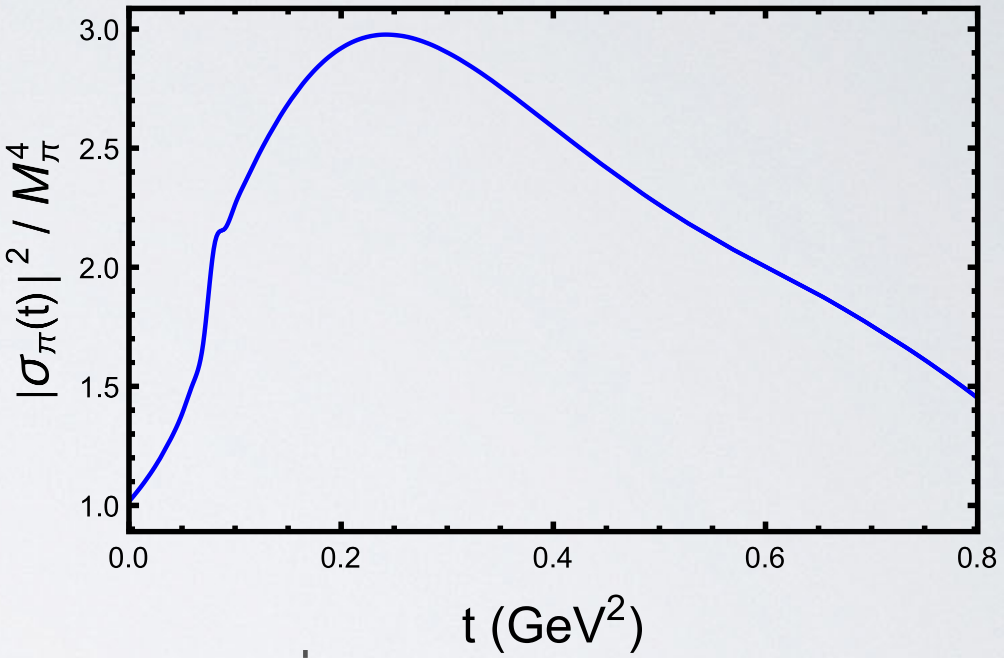

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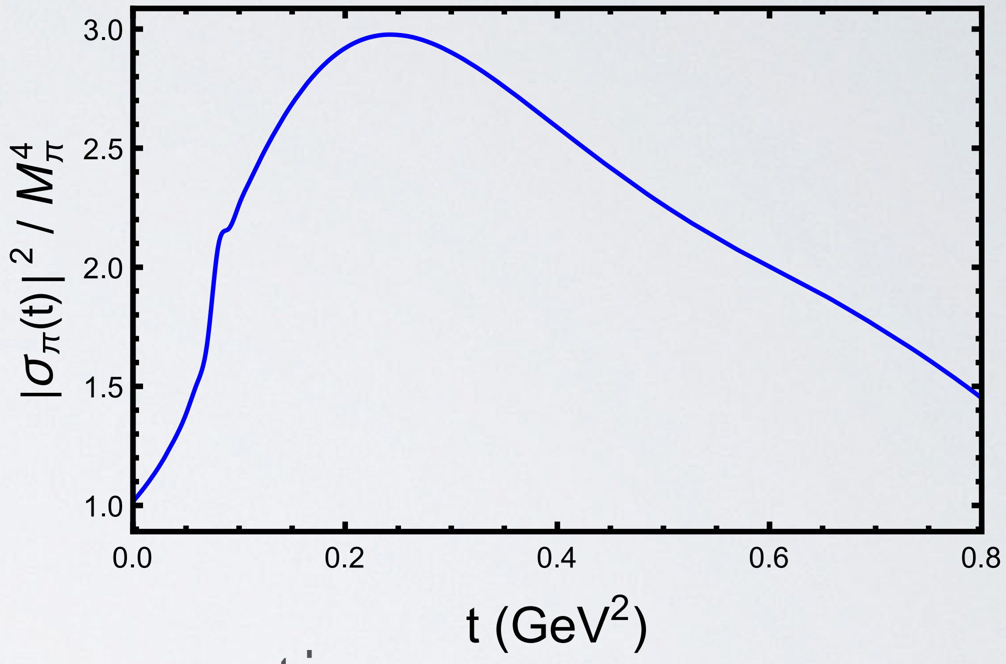

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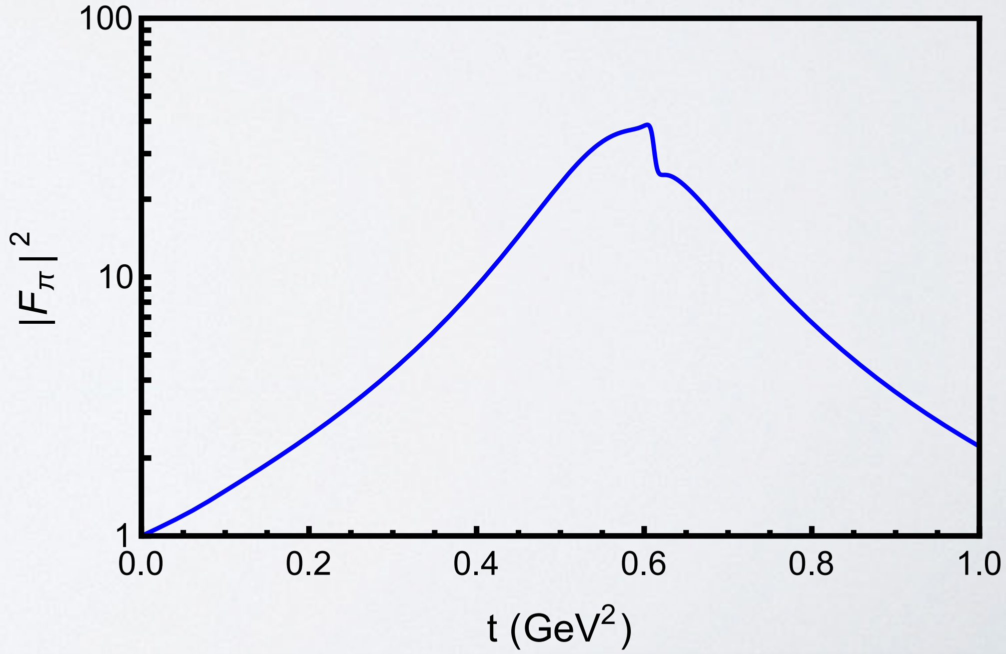
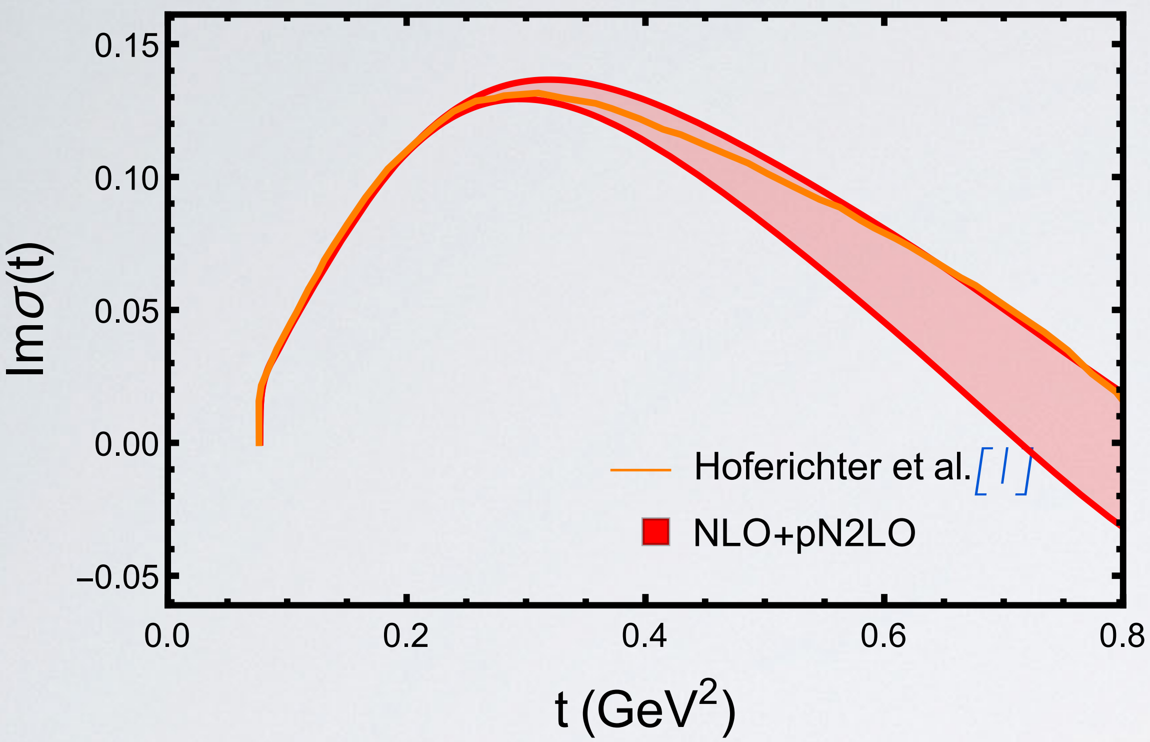


Spectral Functions

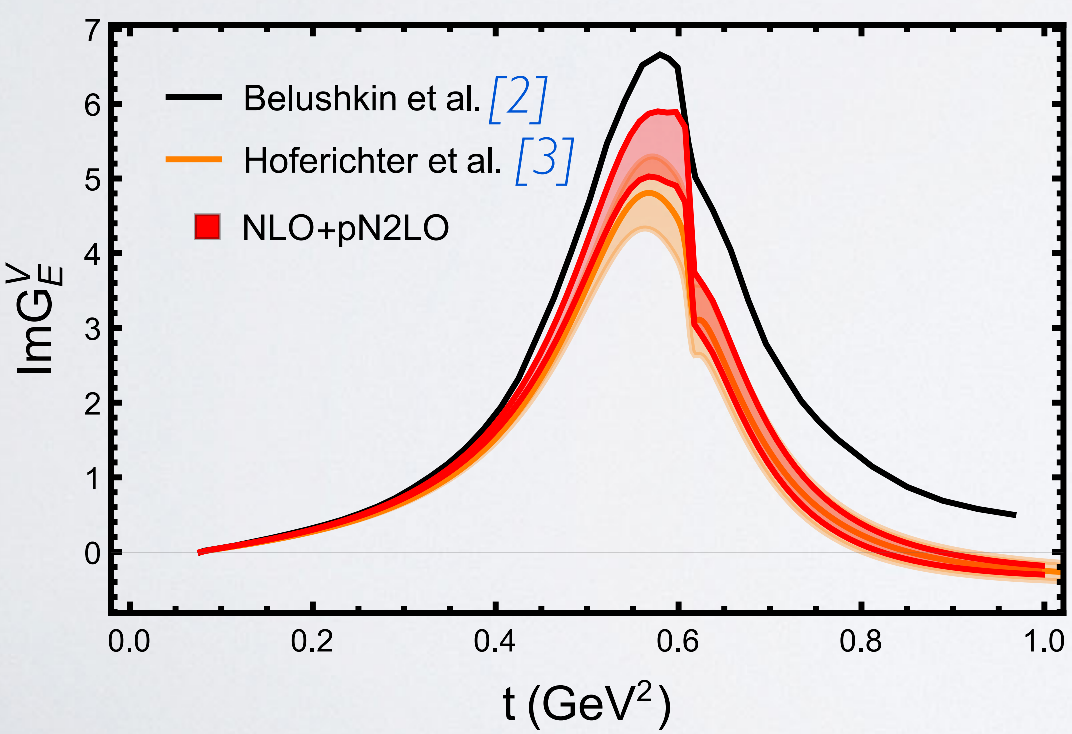
[J. M. Alarcón, C. Weiss, PRC 96 (2017)]

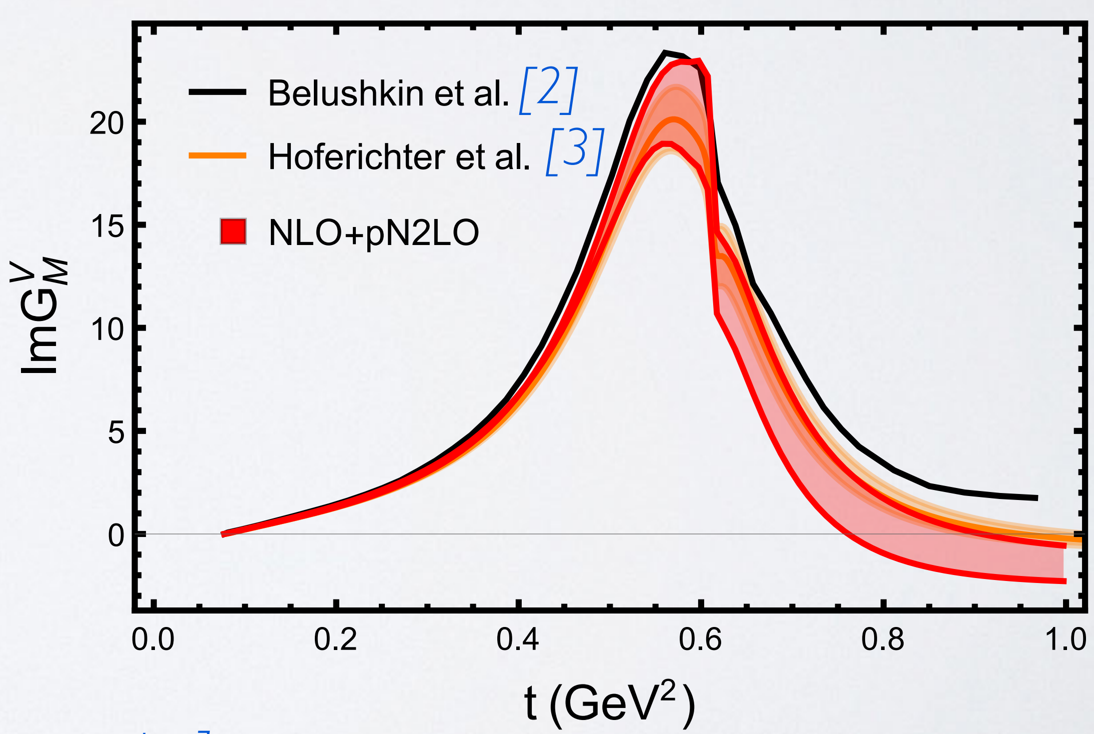


$$\mathrm{Im}\sigma(t) = \frac{3k_{cm}}{4\sqrt{t}(m_N^2 - t/4)}|\Gamma_\pi(t)|^2 J_+^0(t)$$

$$\mathrm{Im}G^V_{\{E,M\}}(t) = \frac{k^3_{cm}}{\{m_N, \sqrt{2}\}\sqrt{t}}|F_\pi(t)|^2 J_\pm^1(t)$$

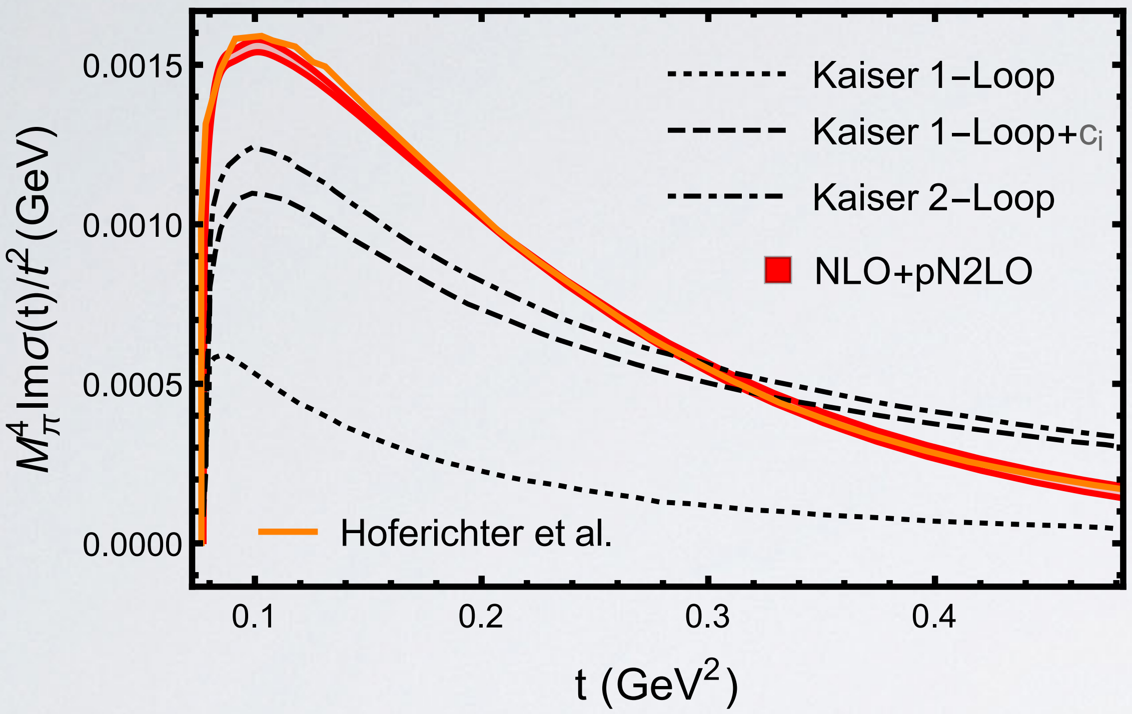
[1] Hoferichter, Ditsche, Kubis, Meißner, JHEP 063 (2012)
[2] Belushkin, Hammer and Meißner, PRC 75 (2007)
[3] Hoferichter, Kubis, Ruiz de Elvira, Hammer, Meißner EPJA 52 (2016)



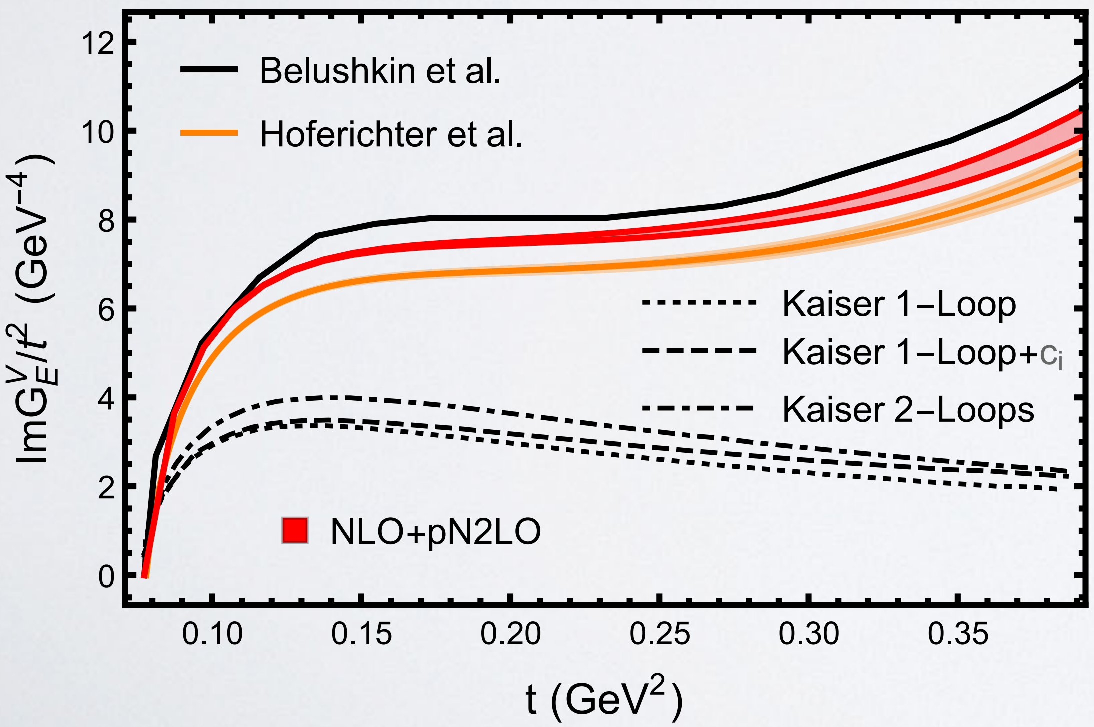


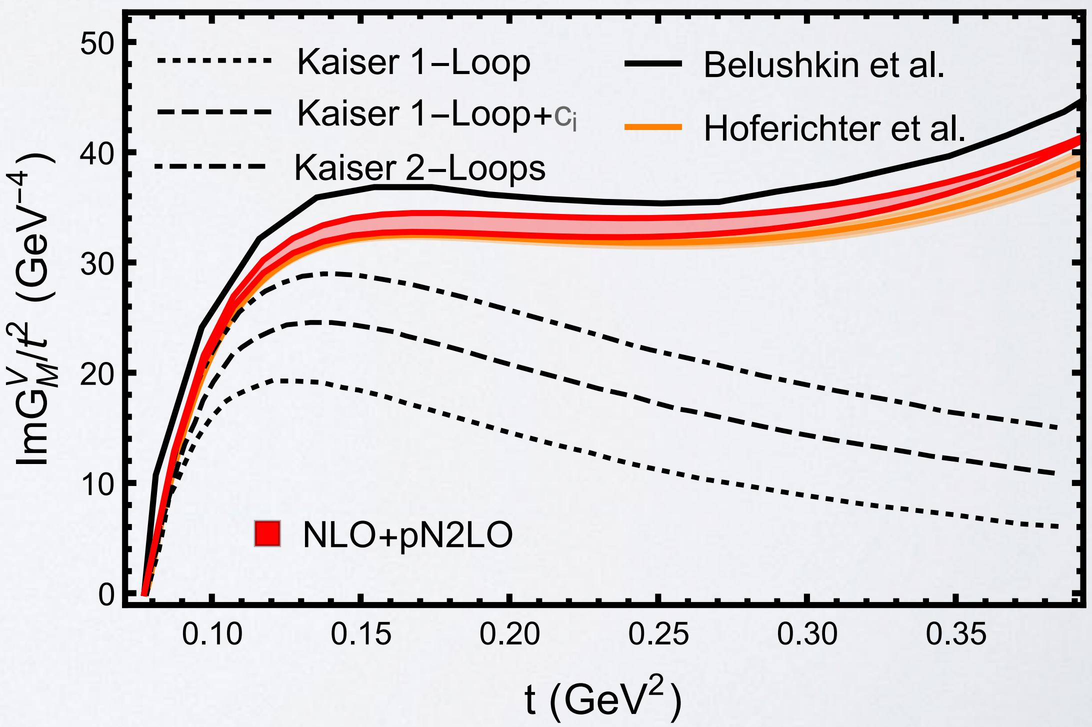
[J. M. Alarcón, C. Weiss, in preparation]

- Comparison with respect to the old results



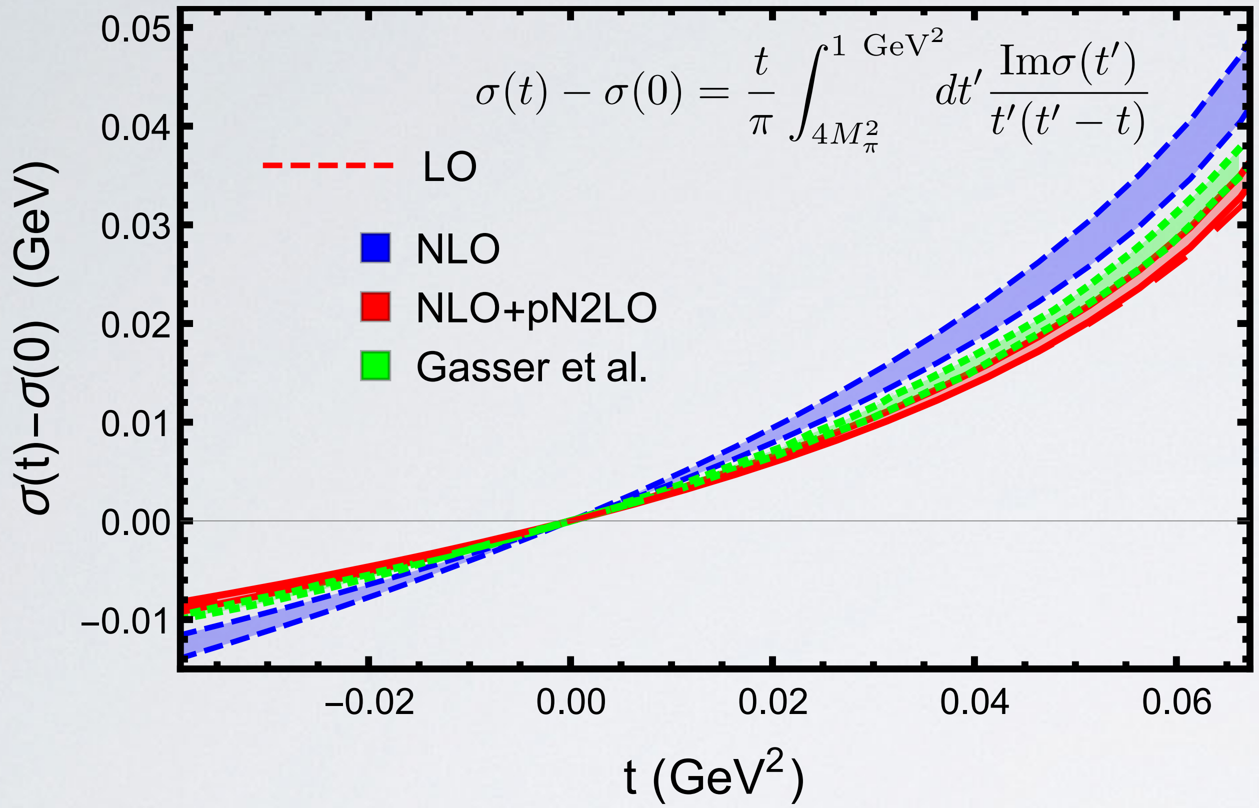
- Conclusions:
  - Brute force calculations are hopeless.
  - Non-perturbative effects are visible in the near-threshold region.
  - Based on unitarity one achieves a factorization suitable for perturbative calculations.

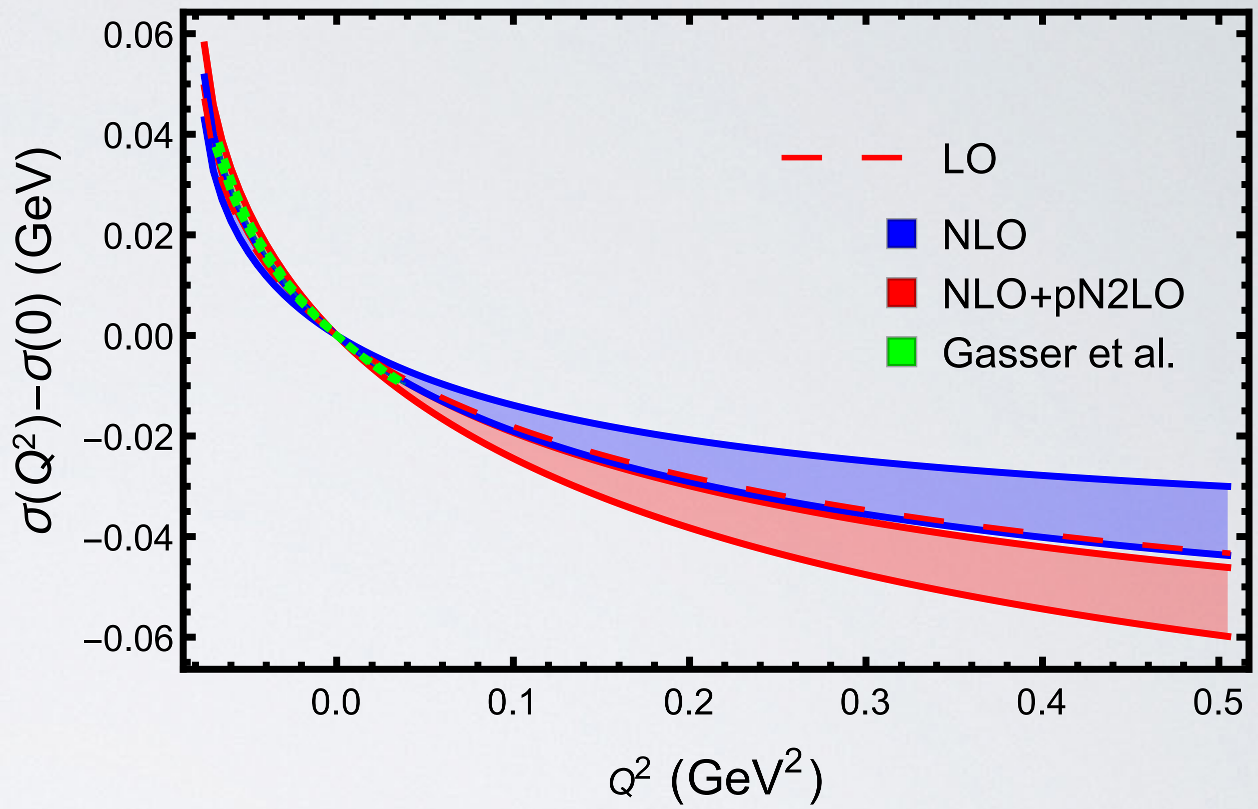




Scalar Form Factor

[J. M. Alarcón, C. Weiss, PRC 96 (2017)]





		LO	NLO	NLO+N2LO	GLS [1]	HKMS[2]
$\langle r^2\rangle_S$ (fm^2)	($\sigma(0)=59$ MeV)	1.06	1.40–1.67	1.03–1.13	–	1.07(4)
	($\sigma(0)=45$ MeV)	1.38	1.83–2.19	1.34–1.49	1.6	–

	LO	NLO	NLO+N2LO	GLS [3]	HDKM [4]	ChPT $\mathcal{O}(p^3)$	ChPT $\mathcal{O}(p^4)$
Δ_σ (MeV)	13.3	17.4 - 20.6	13.3 - 14.5	15.2(4)	13.9(3)	4.6	$14.0+4M_\pi^4\bar{e}_2$

[1] Gasser, Leutwyler, Sainio, PLB 253 260-264, [2] Hoferichter, Klos, Menéndez, Schwenk PRD 94 (2016)
[3] Gasser, Leutwyler, Sainio, PLB 253 252-259, [4] Hoferichter, Ditsche, Kubis, Meißner, JHEP 1206 (2012)

Electromagnetic Form Factor

DIχEFT

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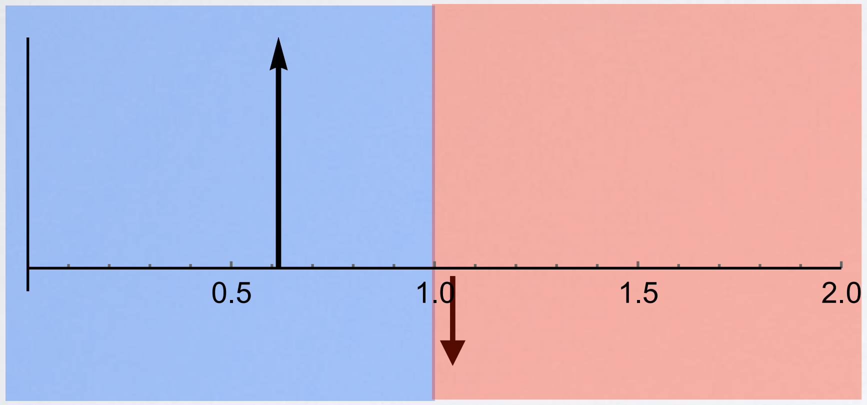

$$\mathrm{Im}G^S_{E,M} = -\pi \sum_{V=\omega,P_S} a_i^{E,M}\delta(t - M_i^2)$$

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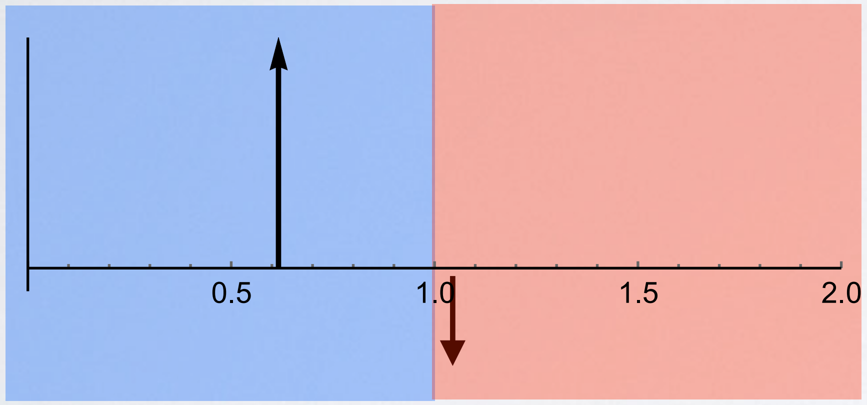

$$\mathrm{Im}G^S_{E,M} = -\pi \sum_{V=\omega,P_S} a_i^{E,M}\delta(t - M_i^2)$$

- We fix the couplings by imposing the charge and radii sum rules:

$$G^S_{E,M}(0) = \frac{1}{\pi}\int_{4M_\pi^2}^{\infty} dt' \frac{\mathrm{Im}G_i^S(t')}{t'} \qquad \langle r^2_{E,M}\rangle^S = \frac{6}{\pi}\int_{4M_\pi^2}^{\infty} dt' \frac{\mathrm{Im}G^S_{E,M}(t')}{t'^2}$$

DIχEFT

- Reconstructing the form factors with $G_{E,M}^{p,n}(t) = \frac{1}{\pi}\int_{4M_\pi^2}^{\infty} dt' \frac{\mathrm{Im}G_{E,M}^{p,n}(t')}{t'-t-i0^+}$

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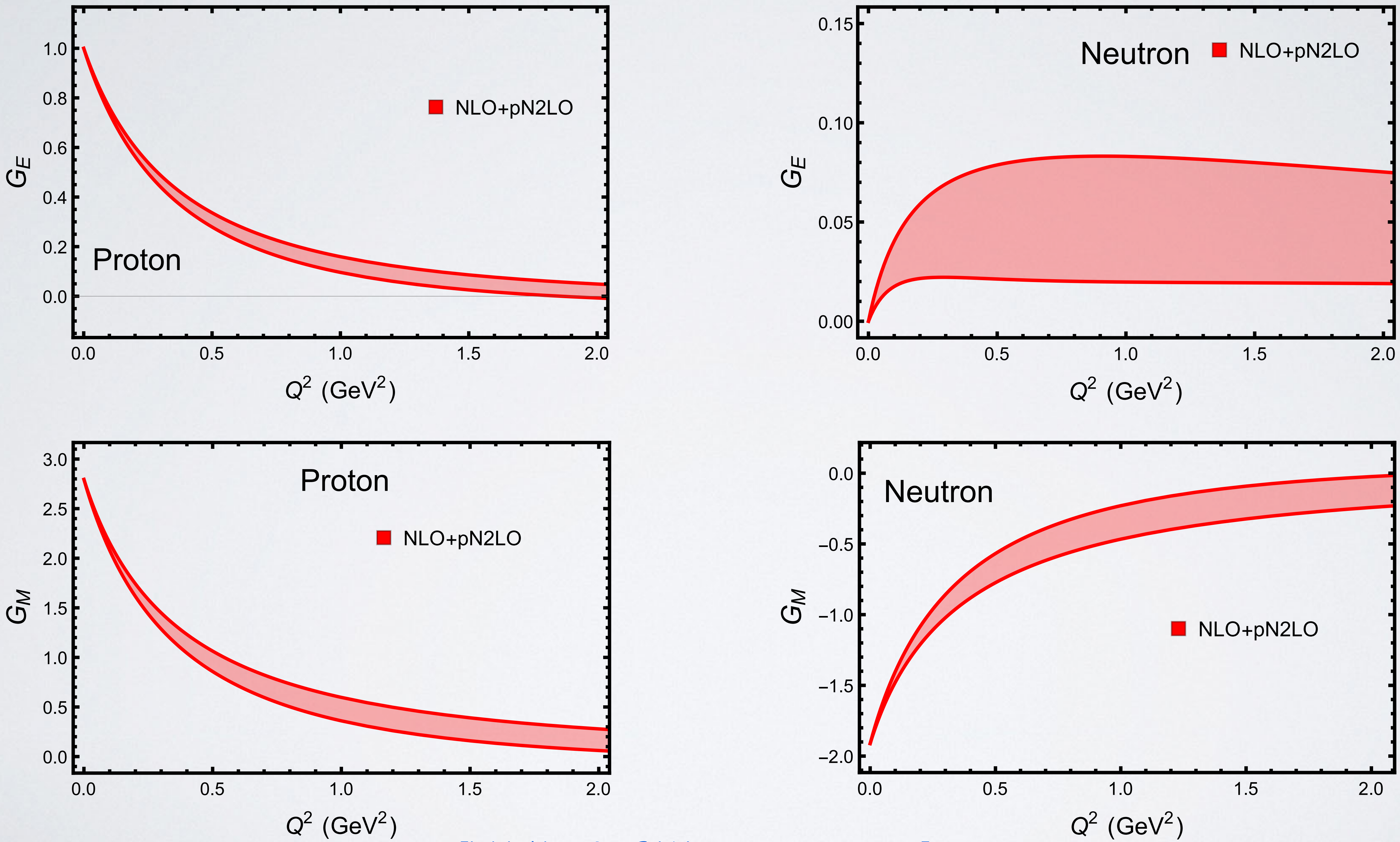

[J. M. Alarcón, C. Weiss, in preparation]

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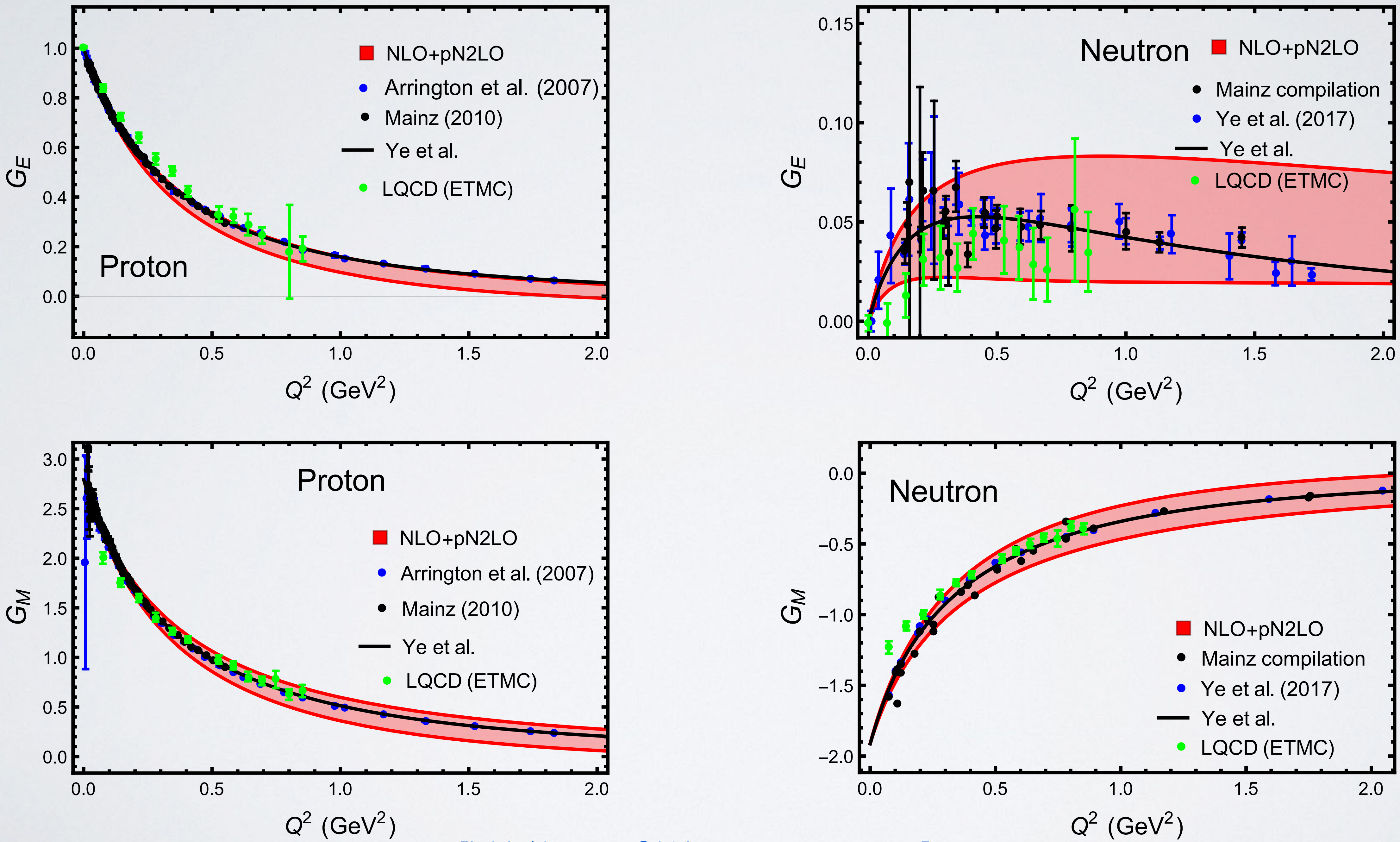

[J. M. Alarcón, C. Weiss, in preparation]

DIχEFT

- Moments

$$G_E(Q^2) = 1 - \frac{\langle r_E^2 \rangle}{3!} Q^2 + \frac{\langle r_E^4 \rangle}{5!} Q^4 - \frac{\langle r_E^6 \rangle}{7!} Q^6 + \frac{\langle r_E^8 \rangle}{9!} Q^8 + \dots$$

$$\frac{G_M(Q^2)}{\mu_N} = 1 - \frac{\langle r_M^2 \rangle}{3!} Q^2 + \frac{\langle r_M^4 \rangle}{5!} Q^4 - \frac{\langle r_M^6 \rangle}{7!} Q^6 + \frac{\langle r_M^8 \rangle}{9!} Q^8 + \dots$$

[J. M. Alarcón, C. Weiss, 1710.06430]

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	G_E^p	G_E^n	G_M^p	G_M^n
$\langle r^2\rangle$ (fm^2)	(0.70059, 0.767638)	(-0.079362, -0.14641)	(0.688927, 0.764926)	(0.740108, 0.775516)
$\langle r^4\rangle$ (fm^4)	(1.47274, 1.6019)	(-0.635304, -0.506146)	(1.67591, 1.78208)	(2.04528, 2.04238)
$\langle r^6\rangle$ (fm^6)	(8.51876, 8.96183)	(-6.10983, -5.66675)	(11.525, 11.5793)	(15.2307,15.6446)
$\langle r^8\rangle$ (10^2 fm^8)	(1.26893, 1.29627)	(-1.1587 , -1.13137)	(1.83446, 1.8822)	(2.59672, 2.69128)
$\langle r^{10}\rangle$ (10^3 fm^{10})	(3.93325, 3.96482)	(-3.86593, -3.83435)	(5.70736, 5.90496)	(8.27382, 8.58060)
$\langle r^{12}\rangle$ (10^5 fm^{12})	(2.04126, 2.04851)	(-2.03856, -2.03131)	(2.90303, 3.00426)	(4.23250, 4.38216)
$\langle r^{14}\rangle$ (10^7 fm^{14})	(1.55741,1.56055)	(-1.55921, -1.55608)	(2.15788, 2.2296)	(3.14973, 3.2547)
$\langle r^{16}\rangle$ (10^9 fm^{16})	(1.62407, 1.62627)	(-1.62604, -1.62384)	(2.19083, 2.25977)	(3.19849, 3.2992)
$\langle r^{18}\rangle$ (10^{11} fm^{18})	(2.20993, 2.21213)	(-2.21208, -2.20988)	(2.90451, 2.99138)	(4.24059, 4.36742)
$\langle r^{20}\rangle$ (10^{13} fm^{20})	(3.79638, 3.79932)	(-3.79931, -3.79637)	(4.86668, 5.00572)	(7.1054, 7.30839)

[J. M. Alarcón, C. Weiss, 1710.06430]

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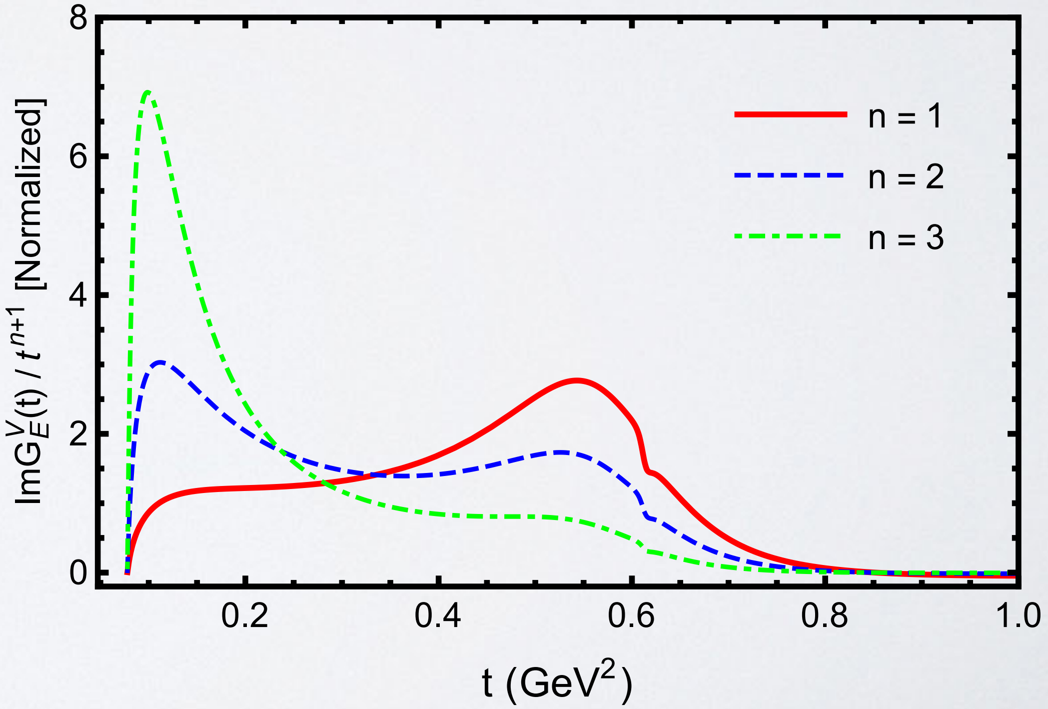
$\langle r^{12} \rangle$ (10^5 fm^{12})	(2.04126, 2.04851)	(-2.03856, -2.03131)	(2.90303, 3.00426)	(4.23250, 4.38216)
$\langle r^{14} \rangle$ (10^7 fm^{14})	(1.55741,1.56055)	(-1.55921, -1.55608)	(2.15788, 2.2296)	(3.14973, 3.2547)
$\langle r^{16} \rangle$ (10^9 fm^{16})	(1.62407, 1.62627)	(-1.62604, -1.62384)	(2.19083, 2.25977)	(3.19849, 3.2992)
$\langle r^{18} \rangle$ (10^{11} fm^{18})	(2.20993, 2.21213)	(-2.21208, -2.20988)	(2.90451, 2.99138)	(4.24059, 4.36742)
$\langle r^{20} \rangle$ (10^{13} fm^{20})	(3.79638, 3.79932)	(-3.79931, -3.79637)	(4.86668, 5.00572)	(7.1054, 7.30839)

- Higher order moments governed by the near-threshold region

$$\langle r^{2n} \rangle = \frac{(2n+1)!}{\pi} \int_{4M_\pi^2}^{\infty} dt' \frac{\mathrm{Im}G(t')}{t'^{n+1}}$$



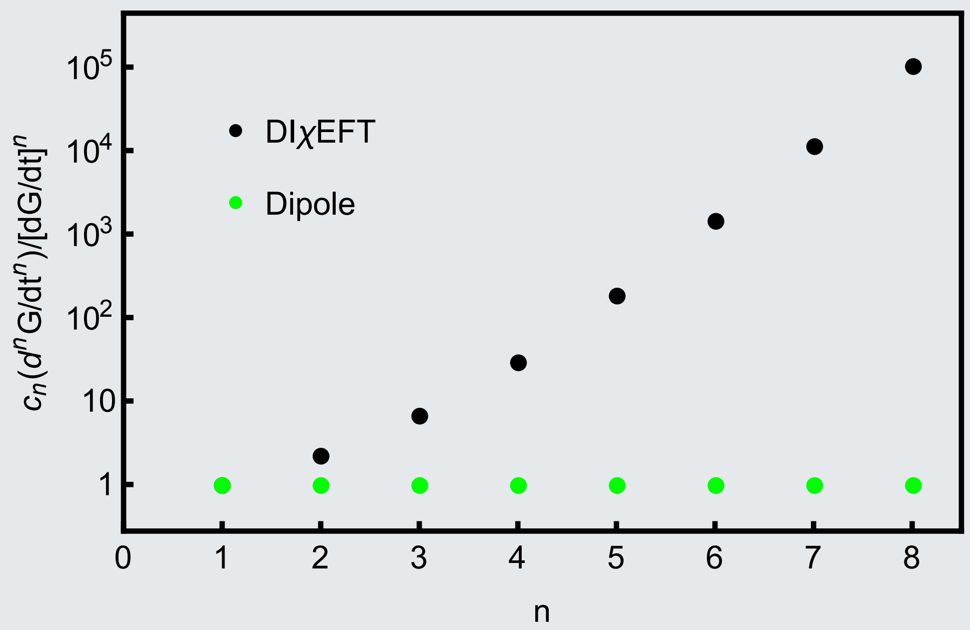
[J. M. Alarcón, C. Weiss, 1710.06430]

- Moments

$$G_E(Q^2) = 1 - \frac{\langle r_E^2 \rangle}{3!} Q^2 + \frac{\langle r_E^4 \rangle}{5!} Q^4 - \frac{\langle r_E^6 \rangle}{7!} Q^6 + \frac{\langle r_E^8 \rangle}{9!} Q^8 + \ldots$$

$$\frac{G_M(Q^2)}{\mu_N} = 1 - \frac{\langle r_M^2 \rangle}{3!} Q^2 + \frac{\langle r_M^4 \rangle}{5!} Q^4 - \frac{\langle r_M^6 \rangle}{7!} Q^6 + \frac{\langle r_M^8 \rangle}{9!} Q^8 + \ldots$$

	G_E^p
$\langle r^2 \rangle$ (fm^2)	(0.70059, 0.767638)
$\langle r^4 \rangle$ (fm^4)	(1.47274, 1.6019)
$\langle r^6 \rangle$ (fm^6)	(8.51876, 8.96183)
$\langle r^8 \rangle$ (10^2 fm^8)	(1.26893, 1.29627)
$\langle r^{10} \rangle$ (10^3 fm^{10})	(3.93325, 3.96482)
$\langle r^{12} \rangle$ (10^5 fm^{12})	(2.04126, 2.04851)
$\langle r^{14} \rangle$ (10^7 fm^{14})	(1.55741,1.56055)
$\langle r^{16} \rangle$ (10^9 fm^{16})	(1.62407, 1.62627)
$\langle r^{18} \rangle$ (10^{11} fm^{18})	(2.20993, 2.21213)
$\langle r^{20} \rangle$ (10^{13} fm^{20})	(3.79638, 3.79932)



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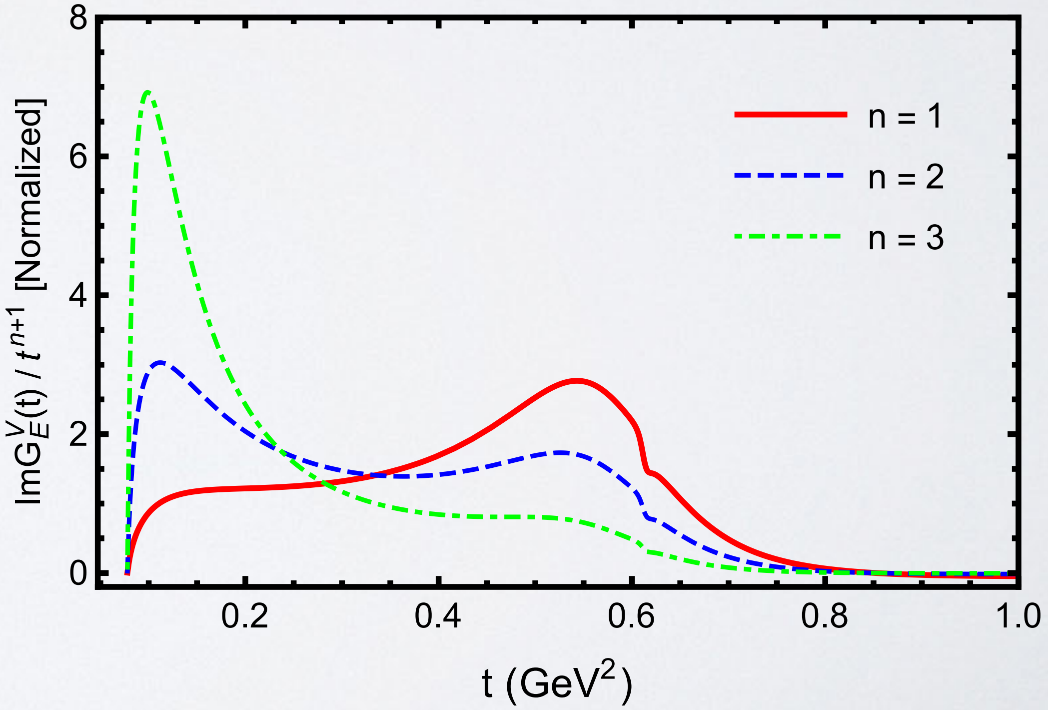

[J. M. Alarcón, C. Weiss, 1710.06430]

Nucleon Densities

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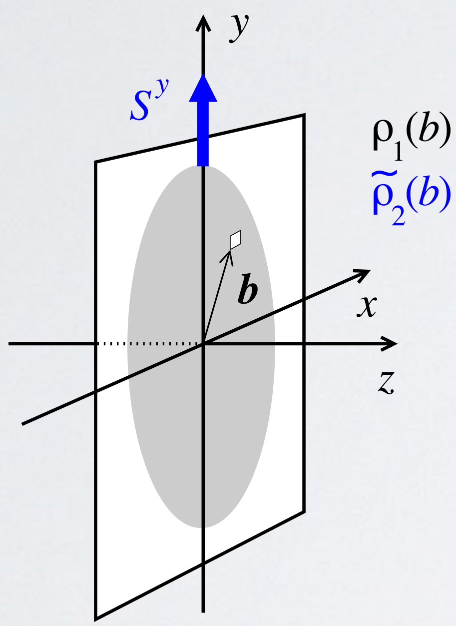

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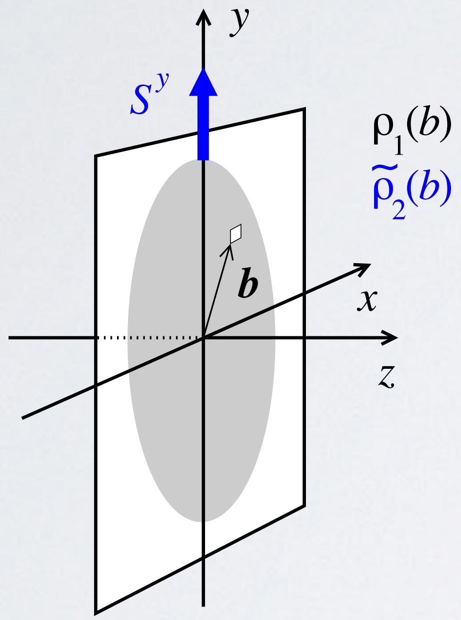

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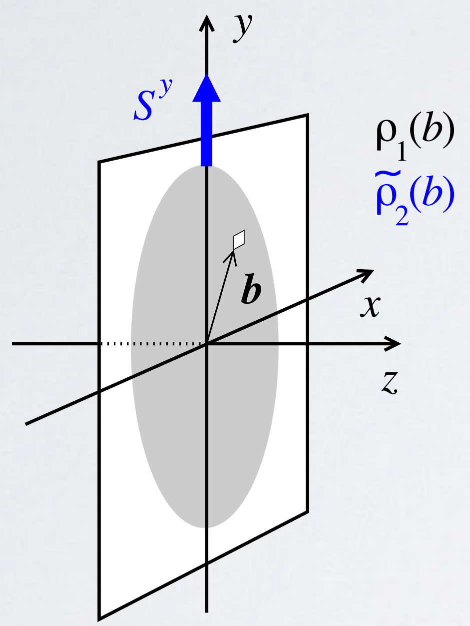

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$$\rho_1(b) = \int_0^\infty d\Delta_T \frac{\Delta_T J_0(\Delta_T b)}{2\pi} F_1^B(t=-\Delta_T^2) = \int_{t_{\rm thr}}^\infty dt \frac{K_0(\sqrt{t}b)}{2\pi}\frac{{\rm Im}F_1^B(t)}{\pi}$$

$$\tilde{\rho}_2(b) = \int_0^\infty d\Delta_T \frac{-\Delta_T^2 J_1(\Delta_T b)}{4\pi m_B} F_2^B(t=-\Delta_T^2) = \int_{t_{\rm thr}}^\infty dt \frac{-\sqrt{t}K_1(\sqrt{t}b)}{4\pi m_B}\frac{{\rm Im}F_2^B(t)}{\pi}$$

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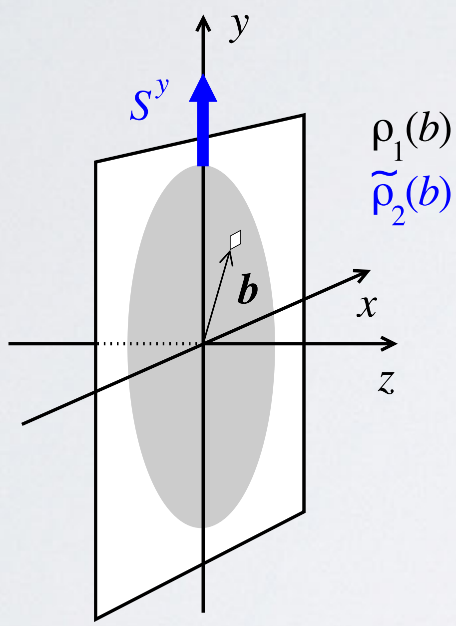

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- The input necessary to compute the densities can be taken from experimental data (parametrizations) or theory.

Nucleon Densities

- Densities are more sensitive to near-threshold contributions for b>1 fm:

$$K_{0,1}(\sqrt{t}b) \sim \frac{e^{-\sqrt{t}b}}{(\sqrt{t}b)^{1/2}} \qquad (\sqrt{t}b \gg 1)$$

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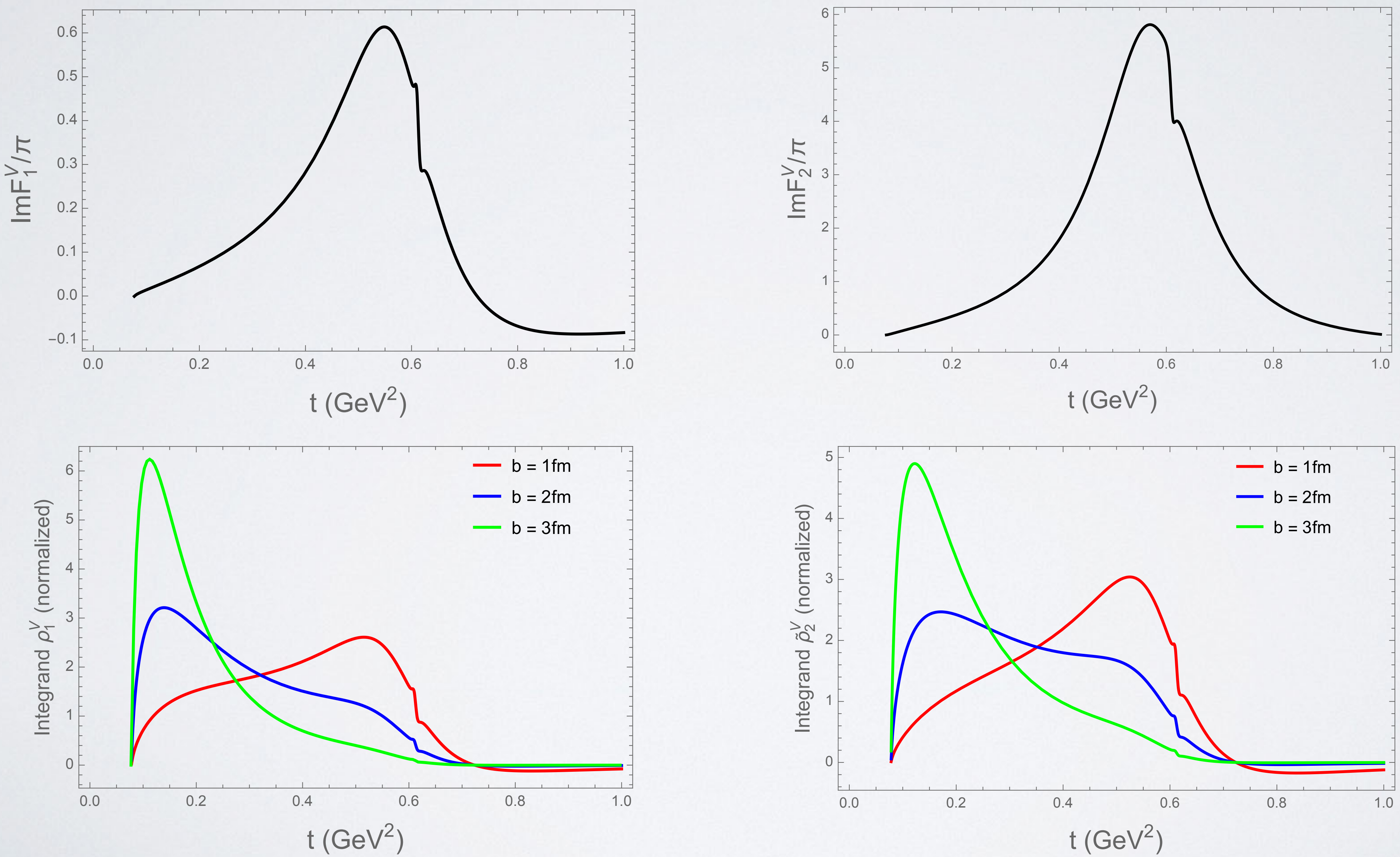
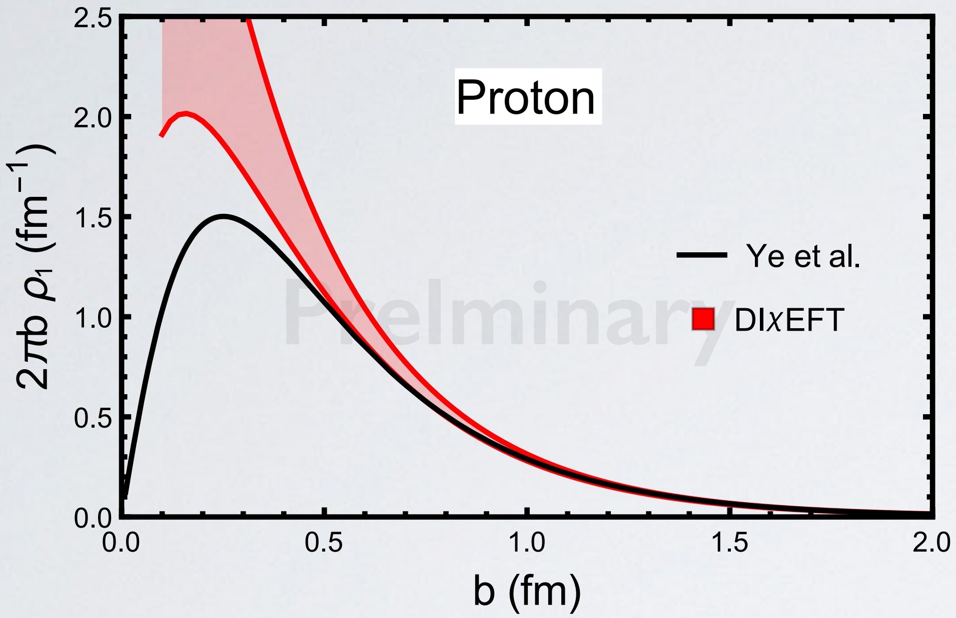
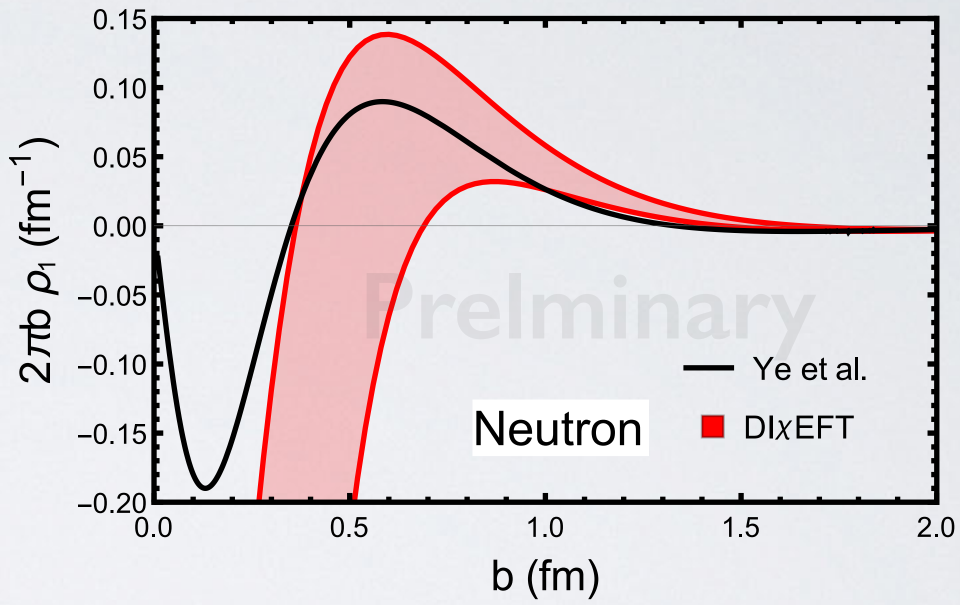


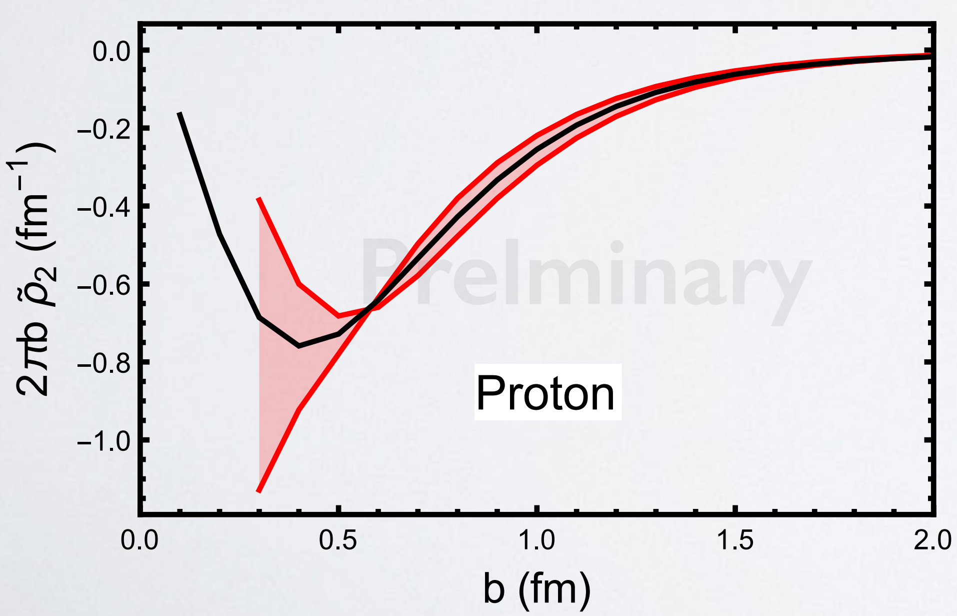
Nucleon Densities

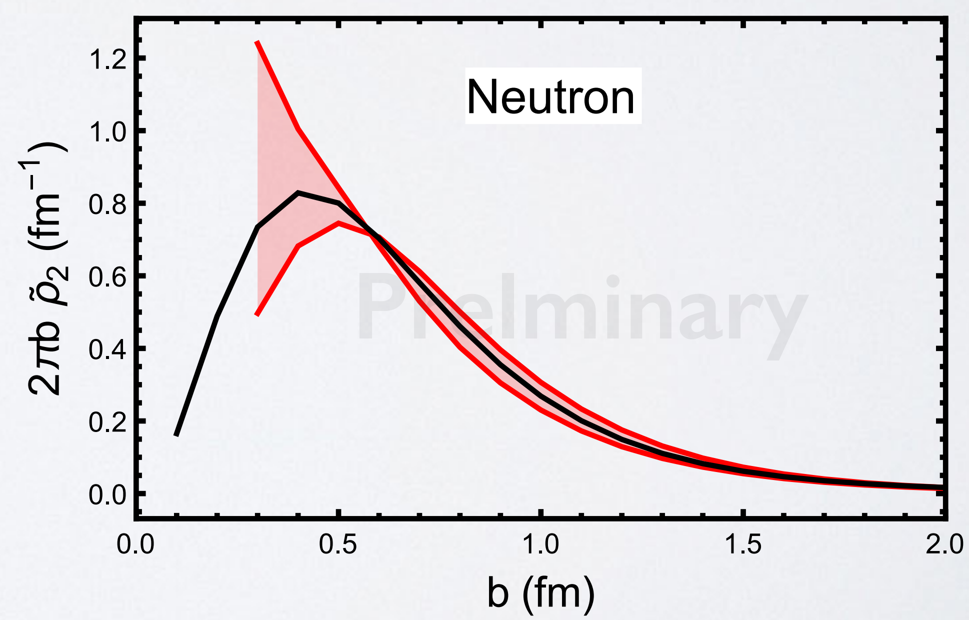
- Charge Densities





- Magnetization Densities





[J. M. Alarcón, C. Weiss, in preparation]

Summary and Conclusions

Summary and Conclusions

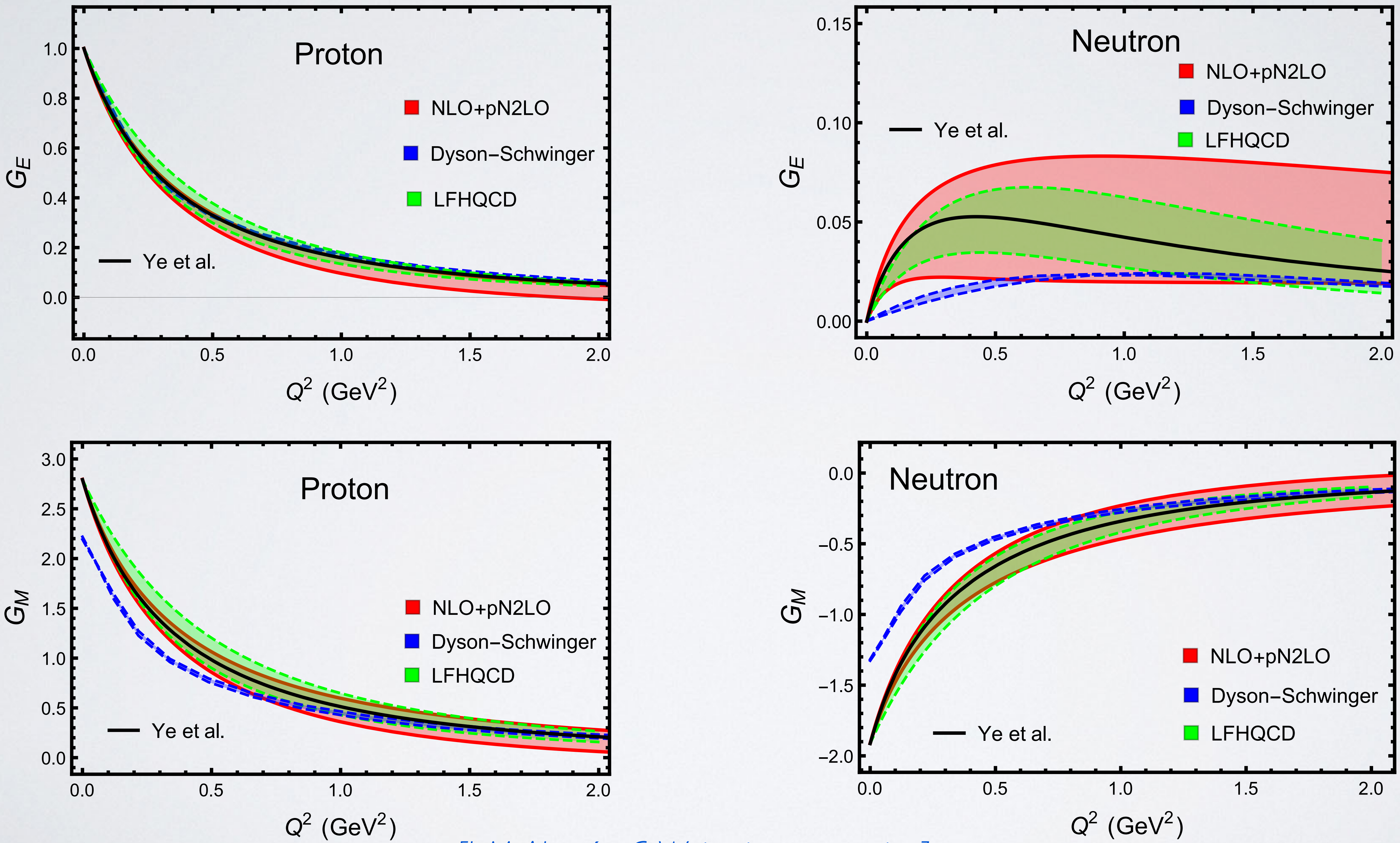
- Through unitarity, it is possible to find a representation suited for ChEFT → **Predictions** of the Nucleon Form factors.
- The results improve previous ChEFT calculations and are competitive with dispersion theory calculations.
- EM FFs have a much complex structure that what it seems.
- DIχEFT implements the constrains that allow to reconstruct the FFs with its full complexity:
  - Analyses of FF data.
  - Two photon exchange corrections to $e^{-}p$ scattering.
- Results used to understand "Proton Radius Puzzle" (PRad).
- Learn about the partonic structure of the nucleon.
- New promising method to compute nucleon matrix elements from first principles (EM tensor, D-term, extension to G-parity odd, ...).

FIN

Spares

DIχEFT

- Reconstructing the form factors with $G^{p,n}_{E,M}(t) = \frac{1}{\pi}\int_{4M_\pi^2}^{\infty} dt' \frac{\mathrm{Im}G^{p,n}_{E,M}(t')}{t' - t - i0^+}$

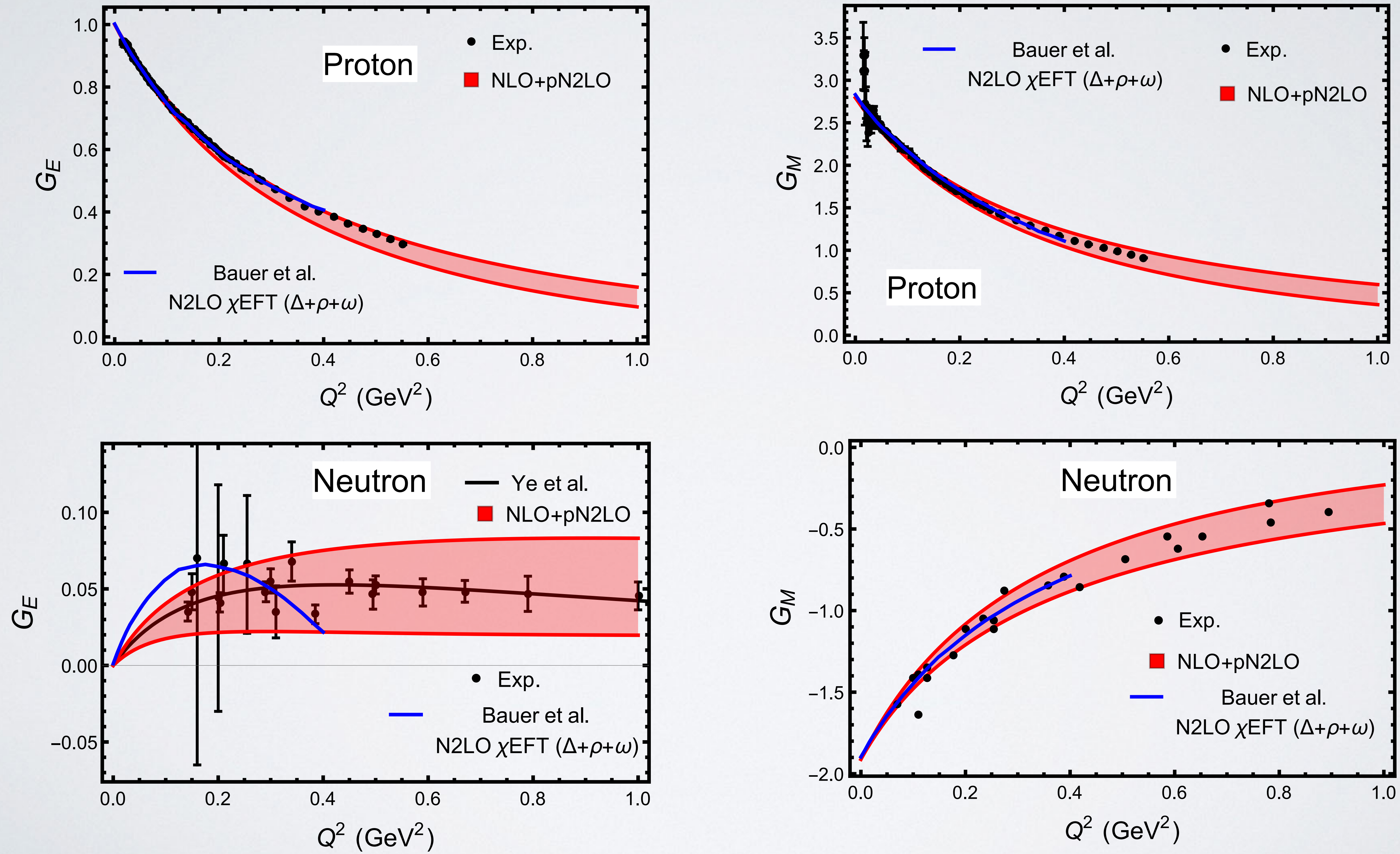


[J. M. Alarcón, C. Weiss, in preparation]

DIχEFT

- Comparison with respect to the old results

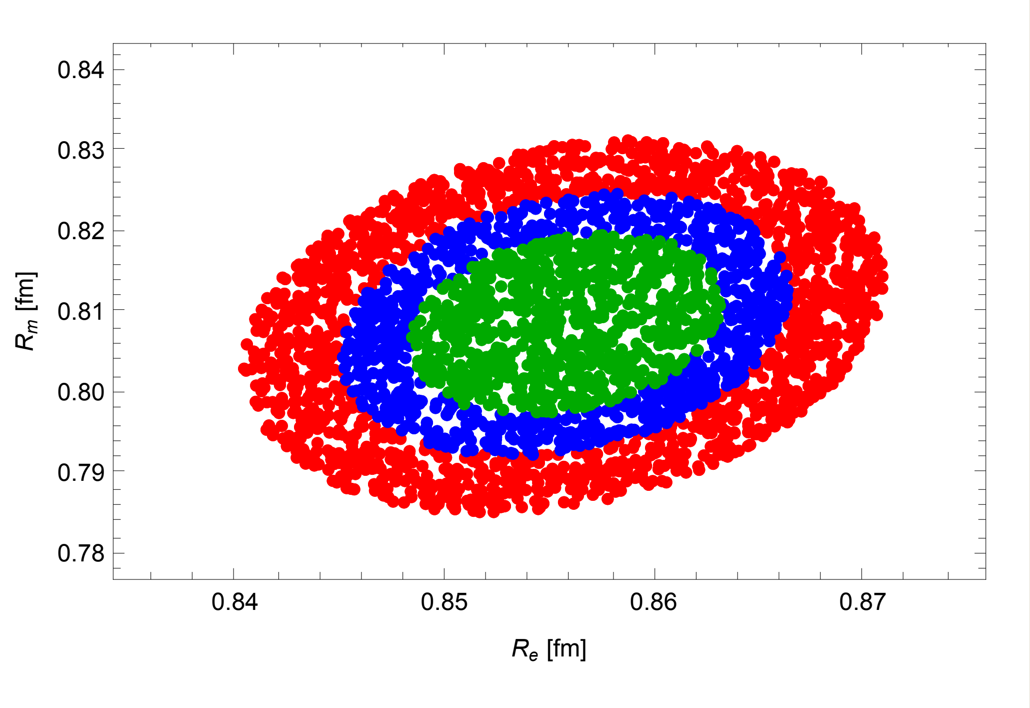
[T. Bauer, J. Bernauer, S. Scherer, PRC 86 (2012)]

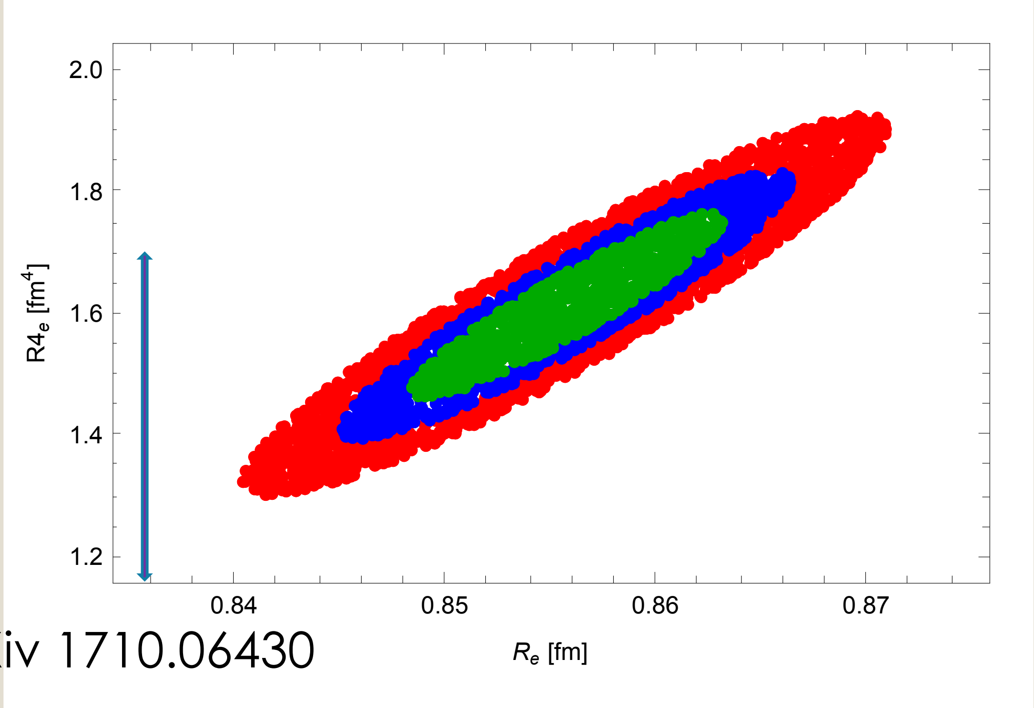


DIχEFT

Talk by Marko Horbatsch (JLab, 12/8/2017)

($Q^2_{max} = 0.2$ GeV^2) χ_{red}^2 : green<1.08, blue<1.10,red<1.14





J.A & C.W arXiv 1710.06430

Is lowest reduced chi-squared χ_{red}^2 the answer?

If not, why not?

Are there systematic problems with the MAMI data?

Clearly: P&P prediction 0.6(3) = No Go

I. Sick & D. Trautmann: 2.01(5) PRC 2017
M. Distler: 2.6 fm^4

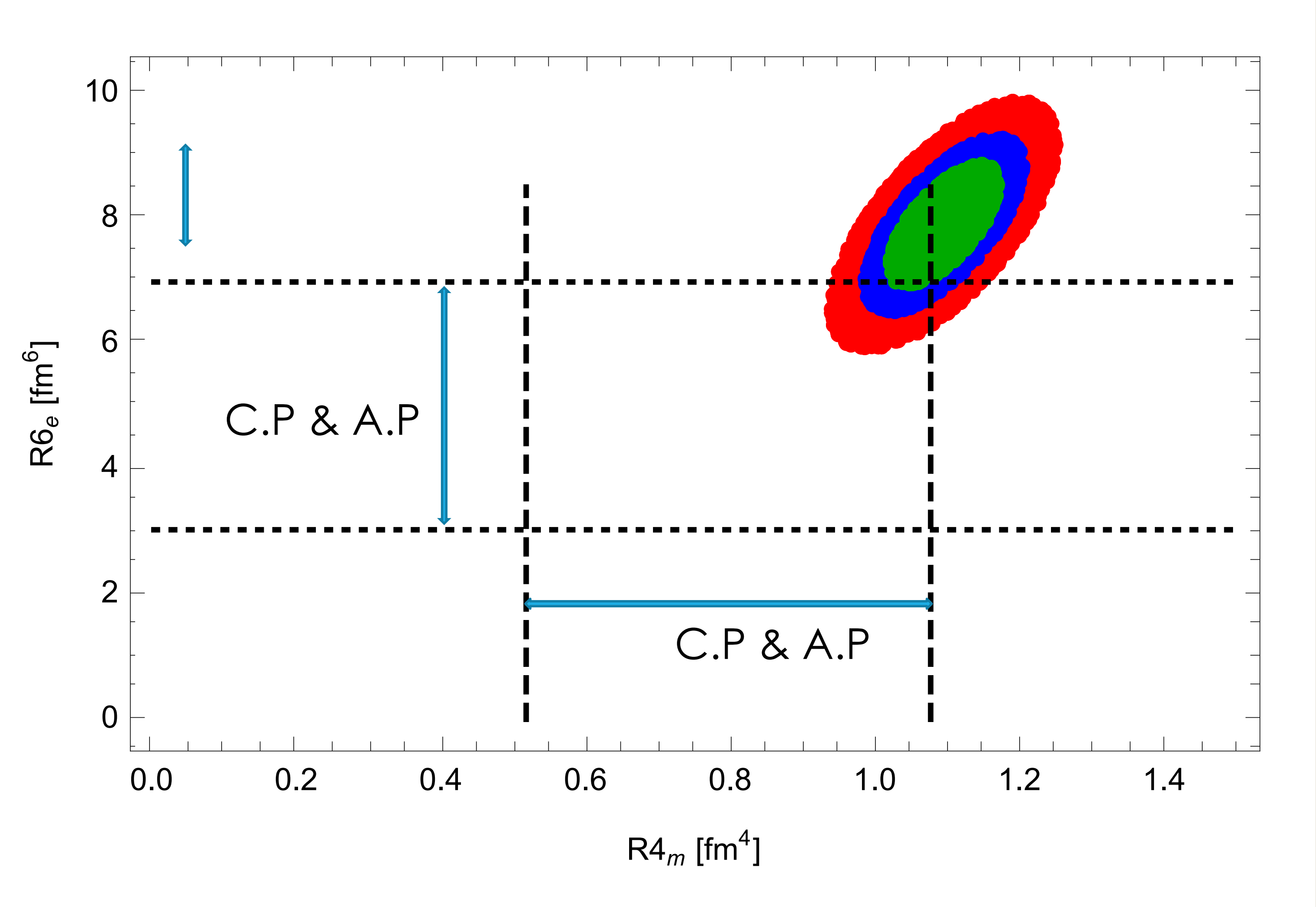
Note the R_e vs $\langle r^4 \rangle_e$ correlation !!

(Courtesy of Marko Horbatsch)

Talk by Marko Horbatsch (JLab, 12/8/2017)

Is it consistent for the higher moments ?

J.A & C.W arXiv 1710.06430



(Courtesy of Marko Horbatsch)

DIχEFT

- We study the naturalness of the isovector moments by defining:

$$a_n = \frac{\langle r^{2n}\rangle^V}{(2n+1)!} = \frac{1}{\pi}\int_{4M_\pi^2}^{\infty} dt' \frac{\mathrm{Im}G^V(t')}{t'^{n+1}}$$

- If the integral were dominated by a certain region t', the ratio $\frac{a_{n+1}}{a_n}$ would be given by the average of $1/t'$ over this region.