The scalar and electromagnetic form factors of the nucleon in dispersively improved Chiral EFT

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Jefferson Lab
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Works done in collaboration with C. Weiss
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Introduction

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- Experimental information is available in some limited cases.
- Extend this knowledge to wider kinematic regions.

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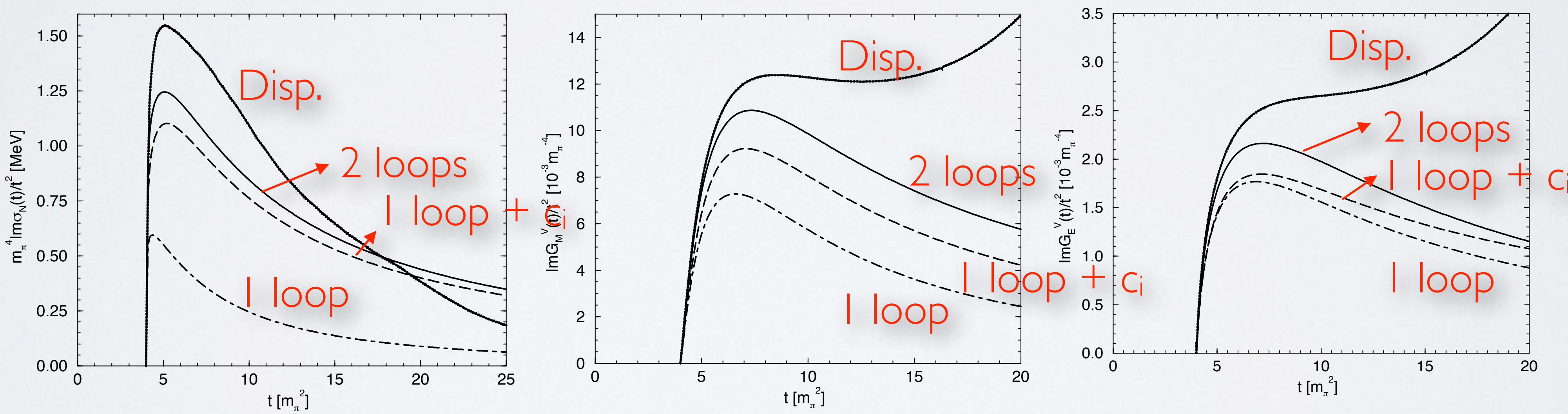

[Kaiser, PRC 68 (2003)]

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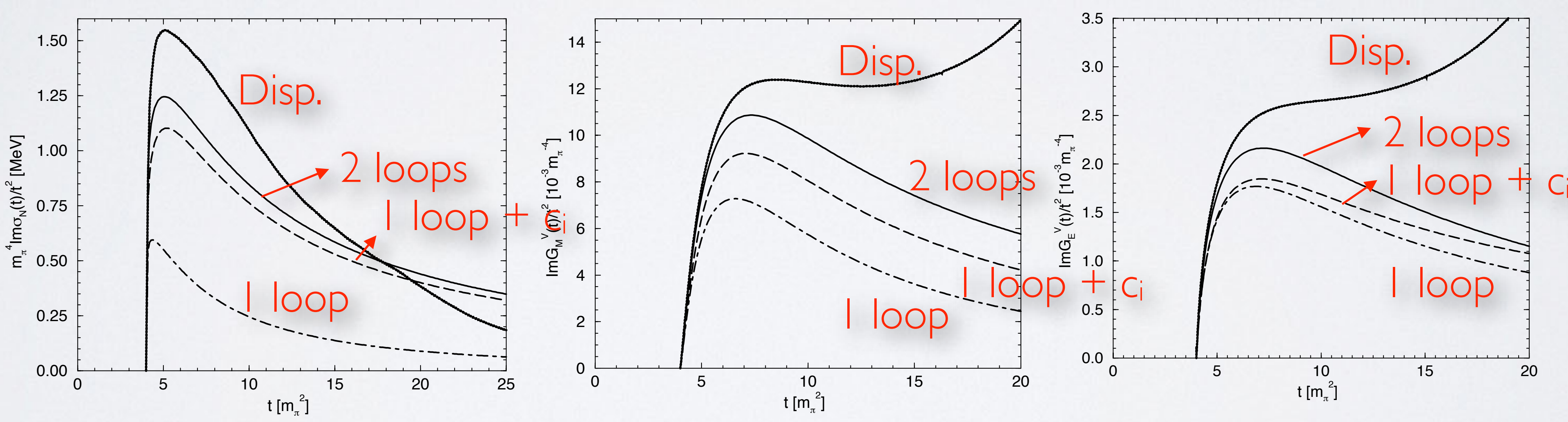

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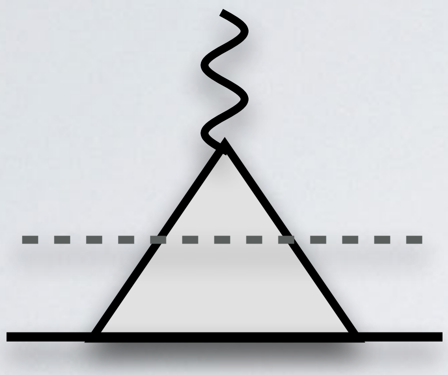
- Higher order calculations are needed (unpractical).

Dispersively Improved χEFT
(DIχEFT)

DIχEFT

- Analytic structure of the FFs.



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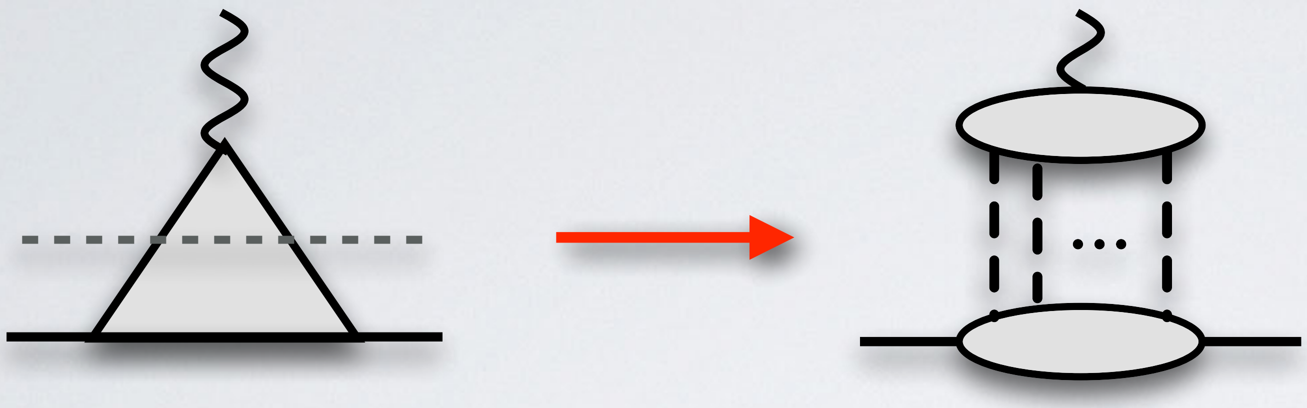

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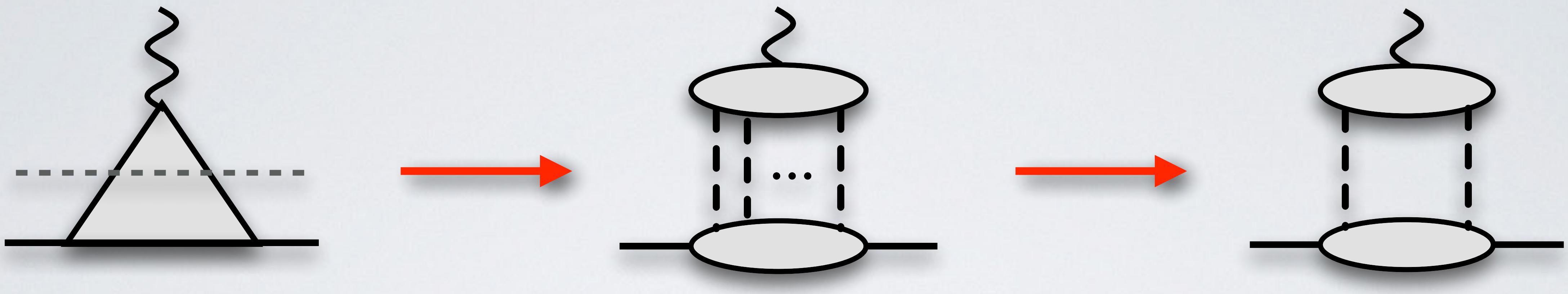

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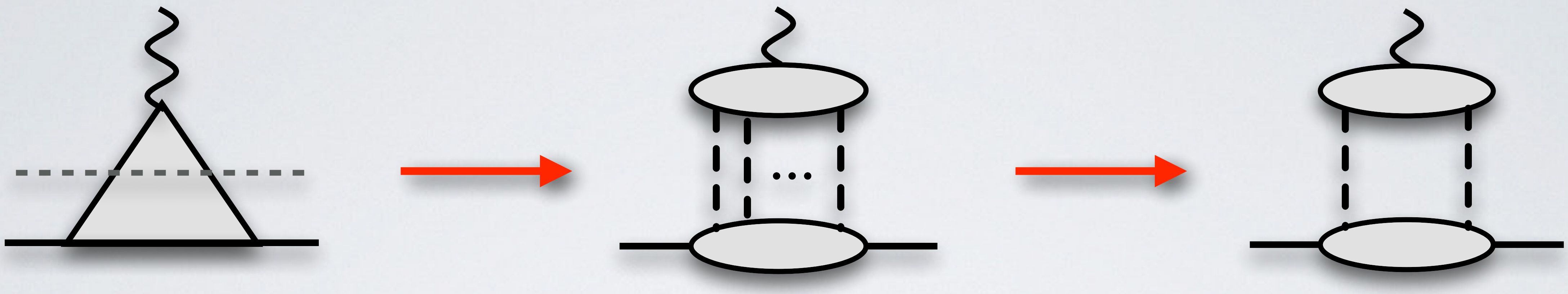

$$\mathrm{Im}\sigma(t) = \frac{3k_{cm}}{4\sqrt{t}(m_N^2 - t/4)}\Gamma_\pi^*(t) f_+^0(t) \qquad \mathrm{Im}G^V_{\{E,M\}}(t) = \frac{k_{cm}^3}{\{m_N, \sqrt{2}\}\sqrt{t}} F_\pi^*(t) f_\pm^1(t)$$

DIχEFT

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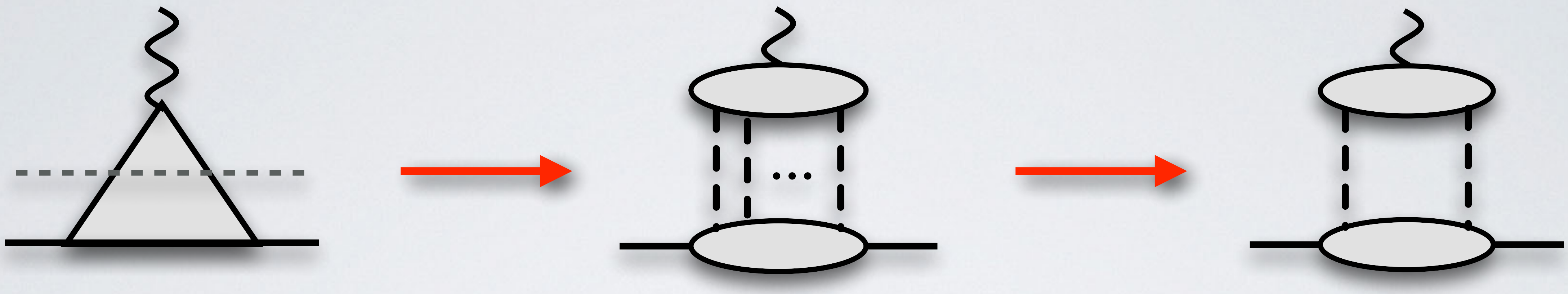

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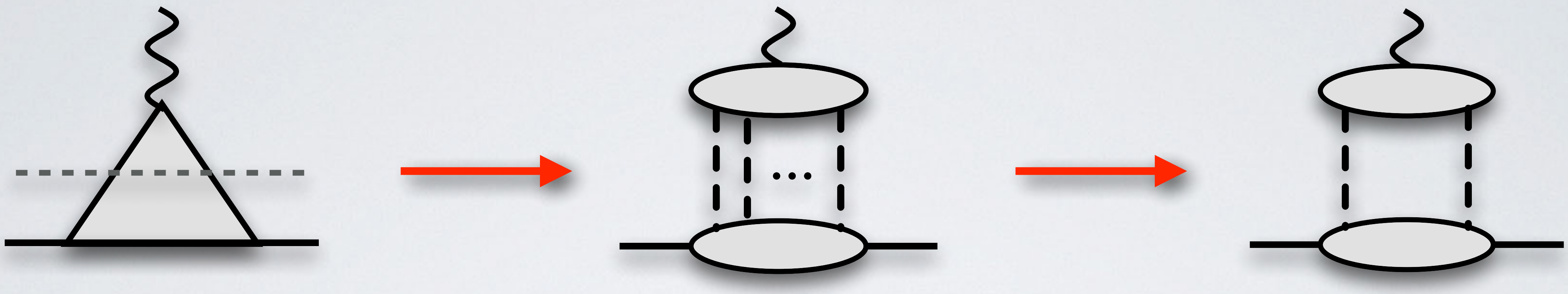

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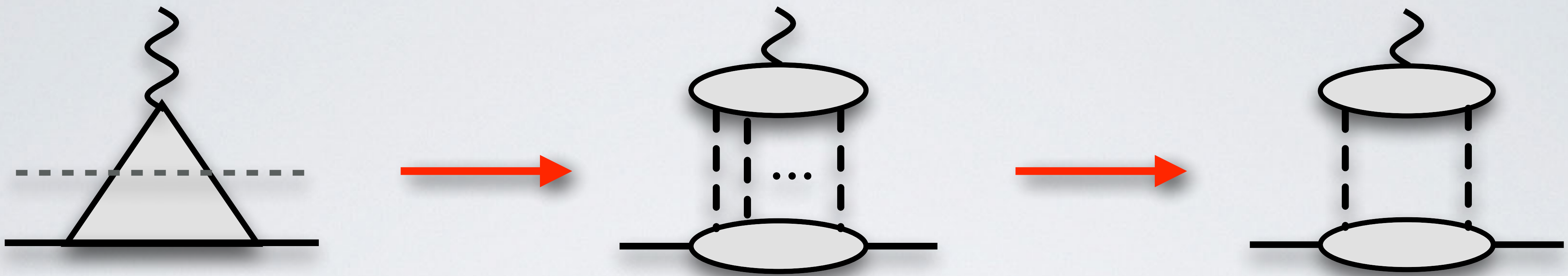

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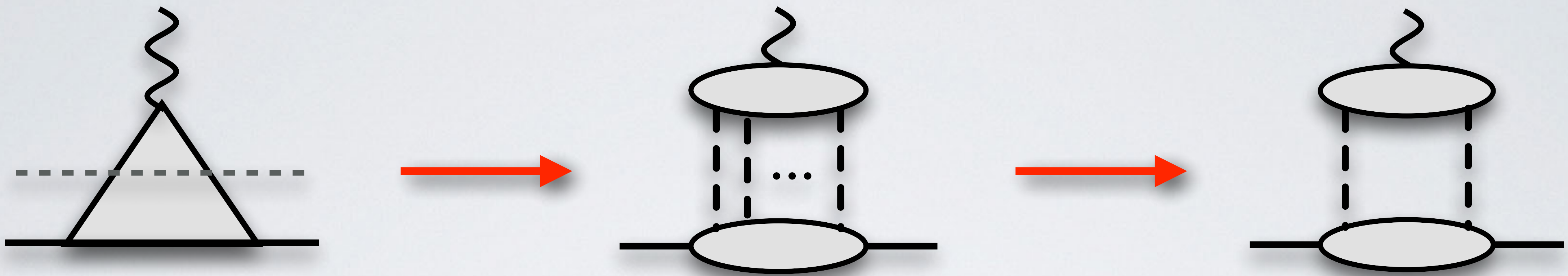

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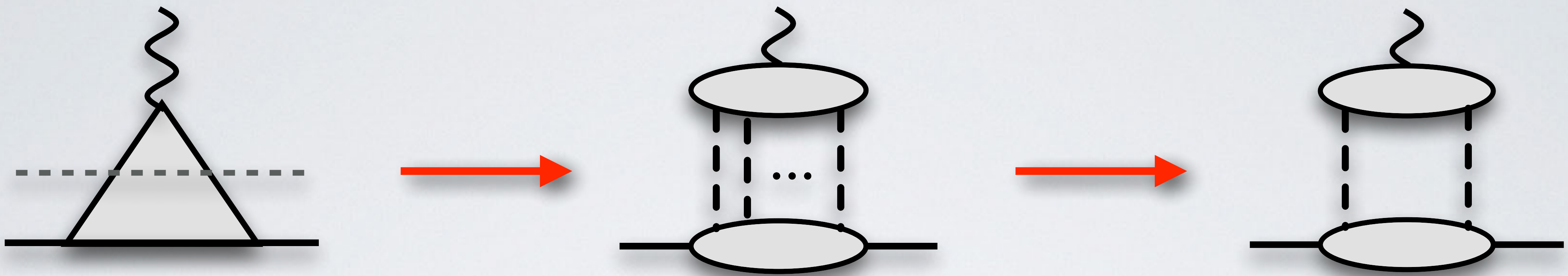

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DIχEFT

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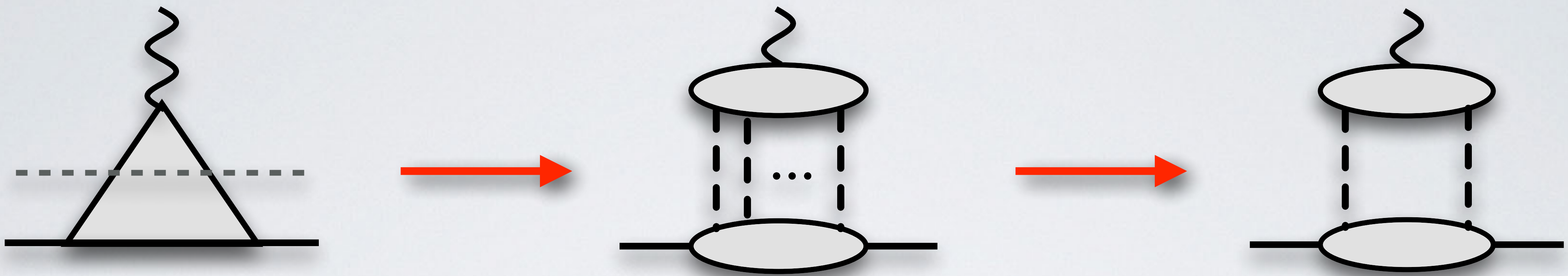

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Data/Dispersion Theory

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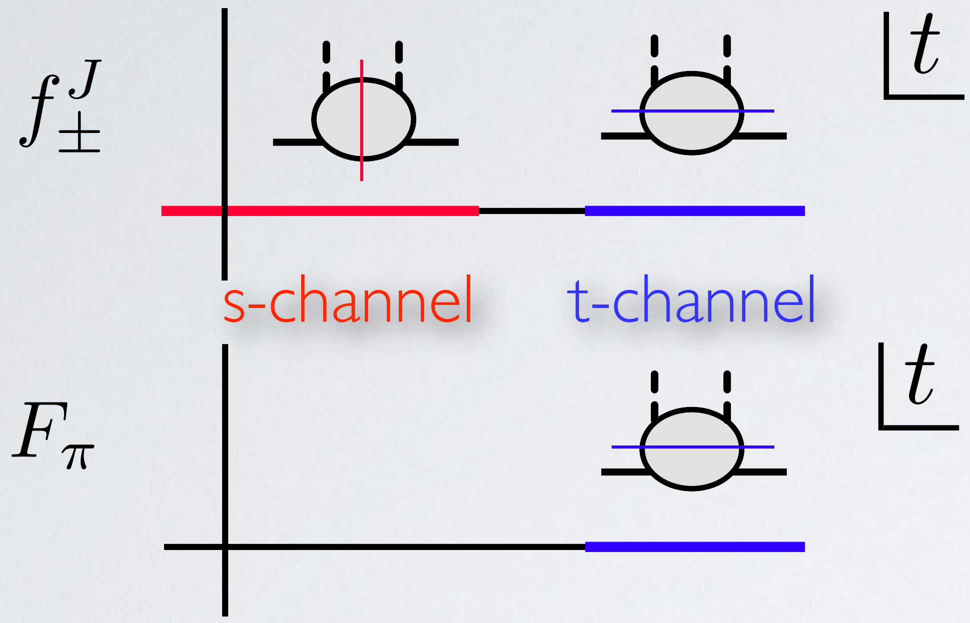

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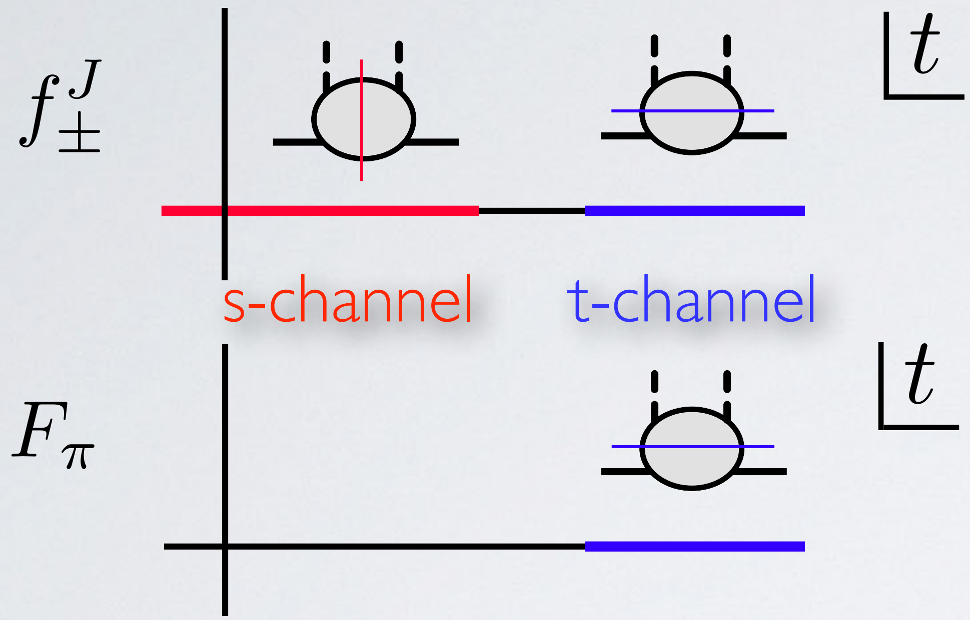

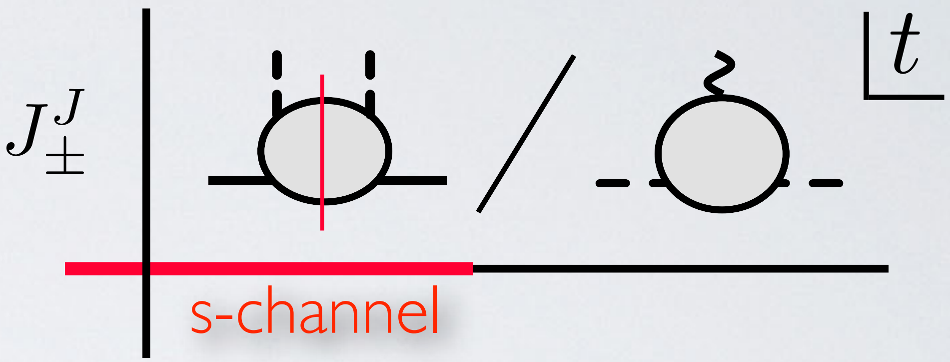

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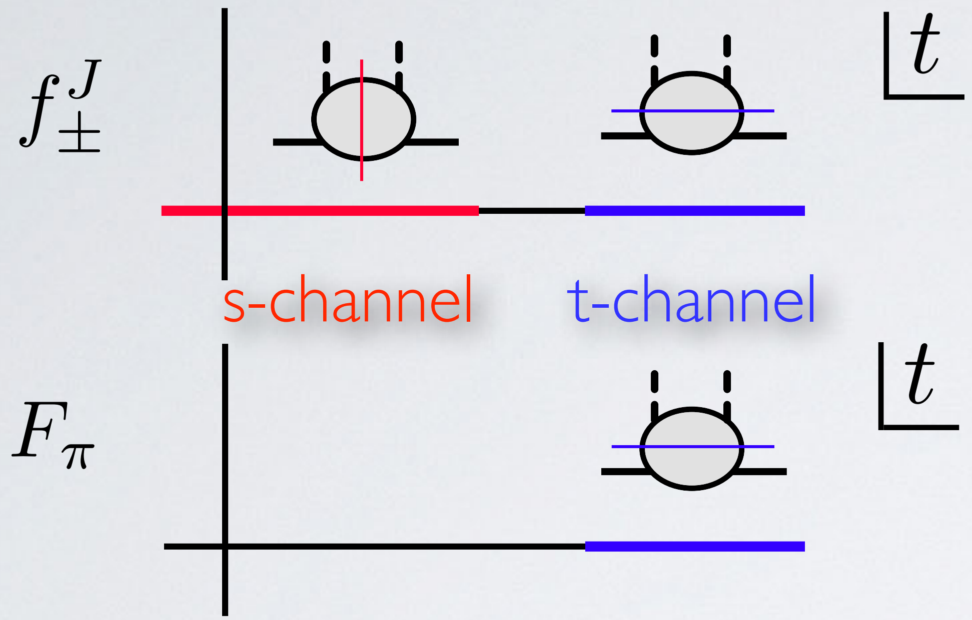

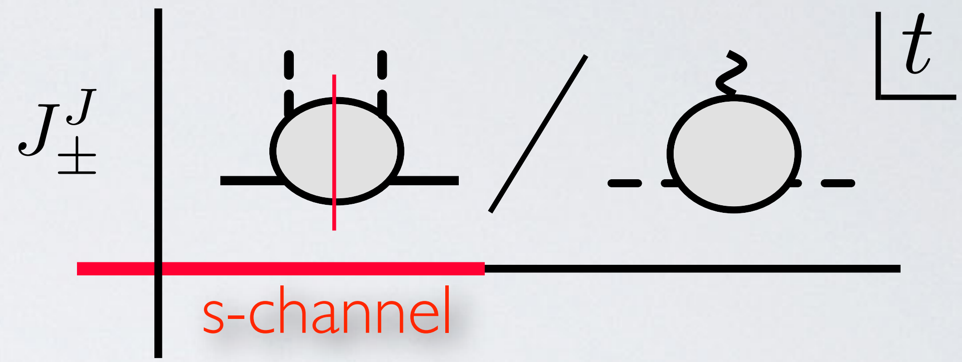

No RHC (Watson's Theorem)
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DIχEFT

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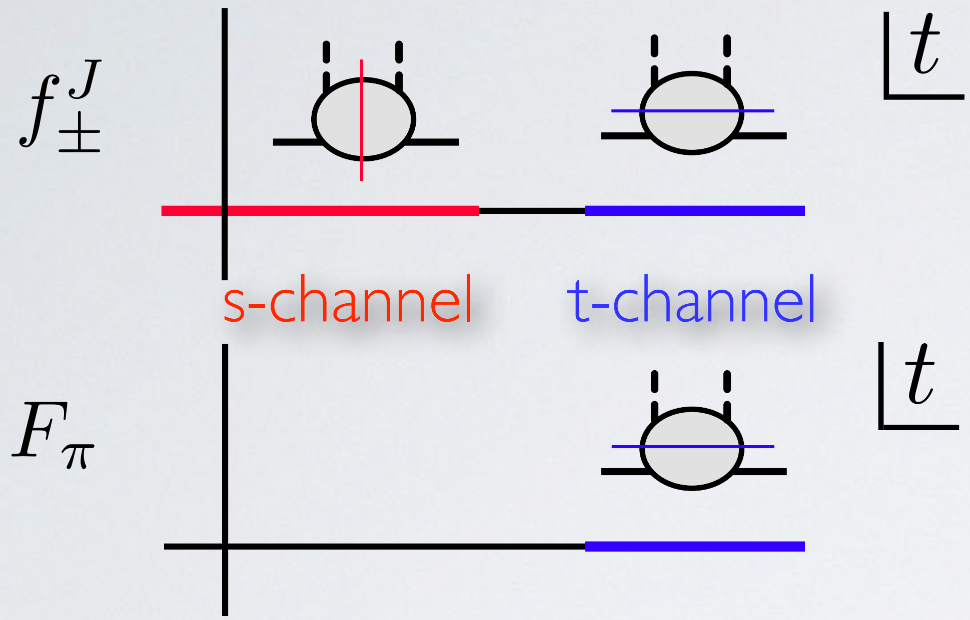

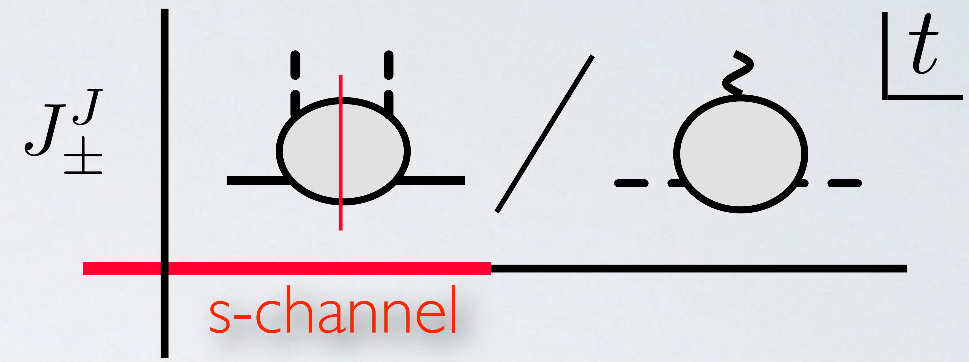

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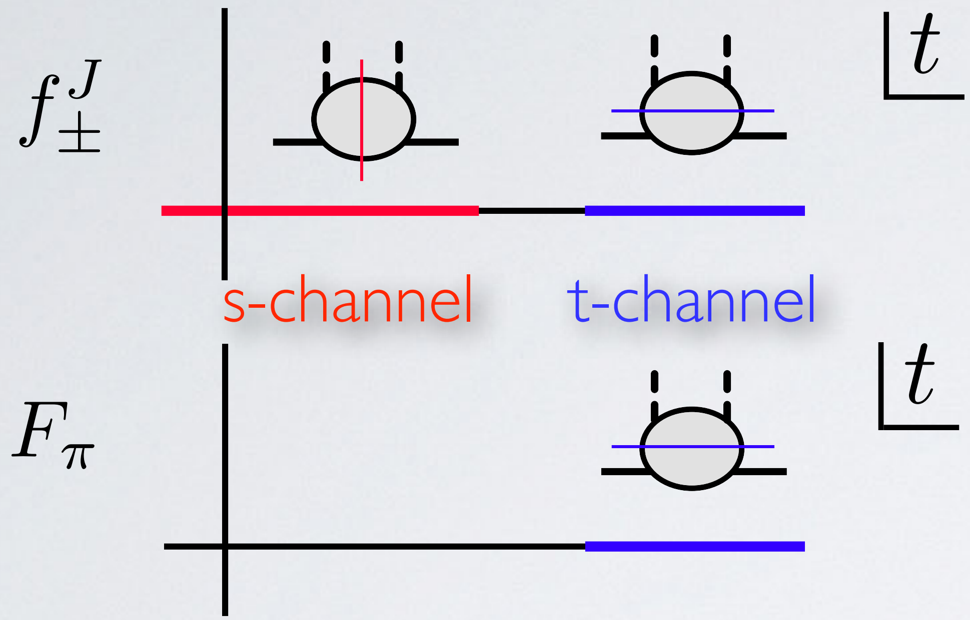

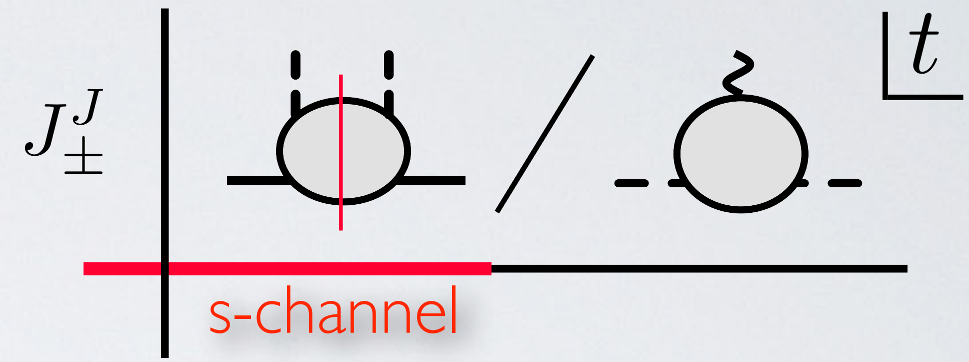

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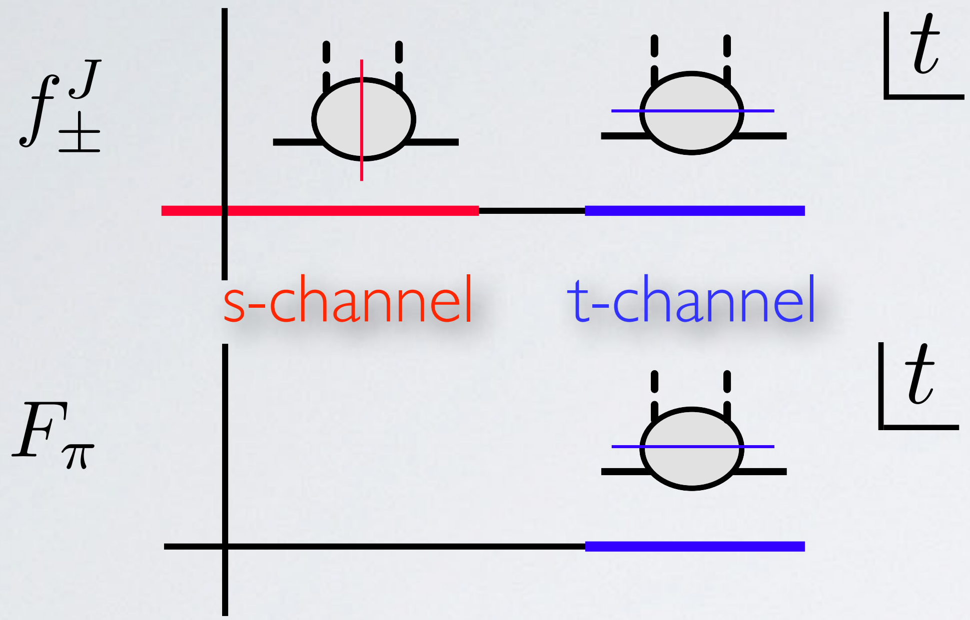

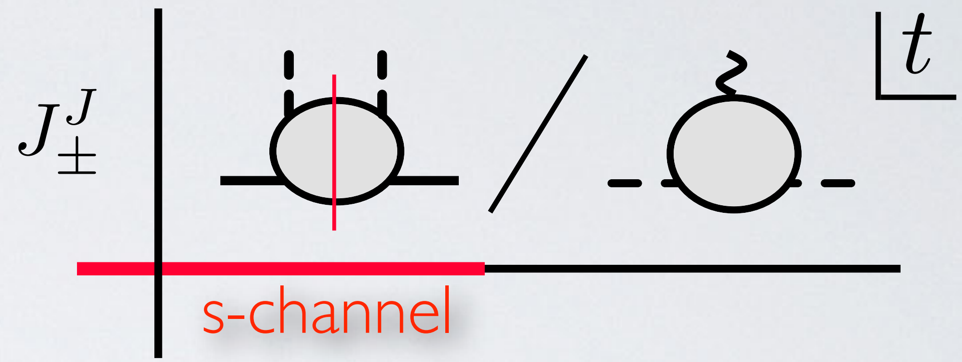

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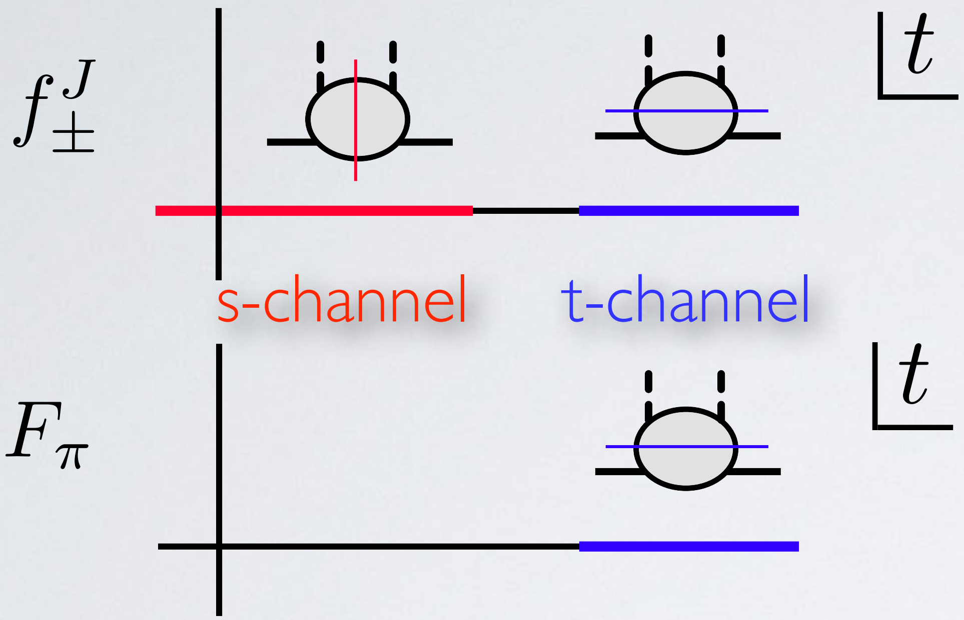

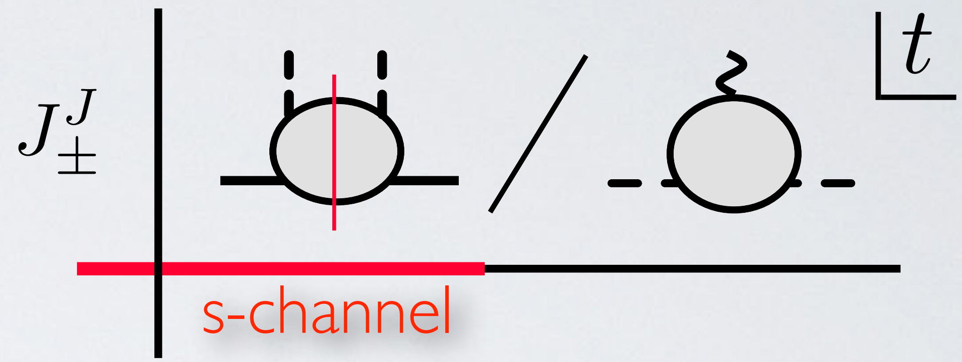

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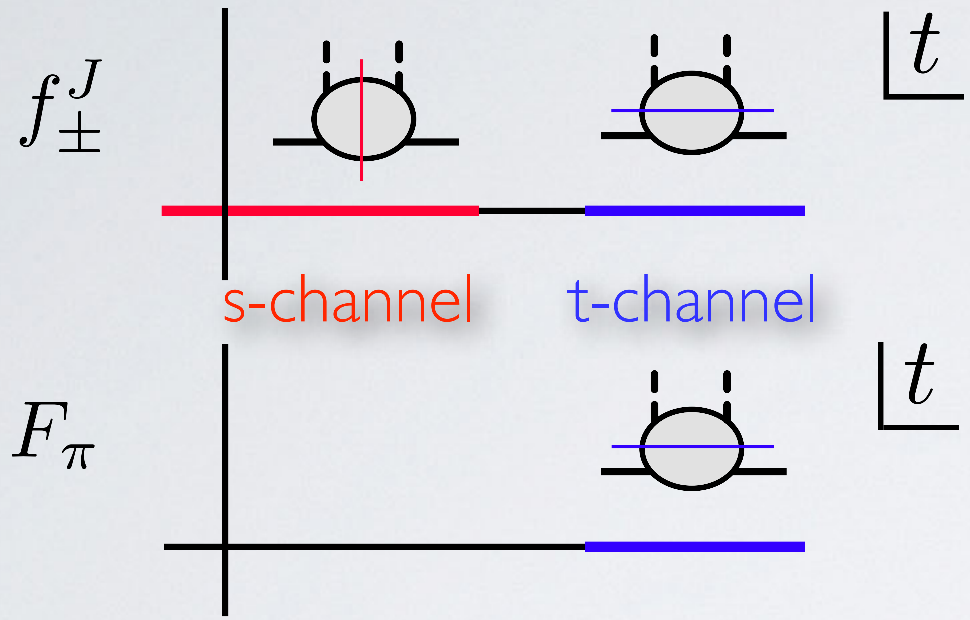

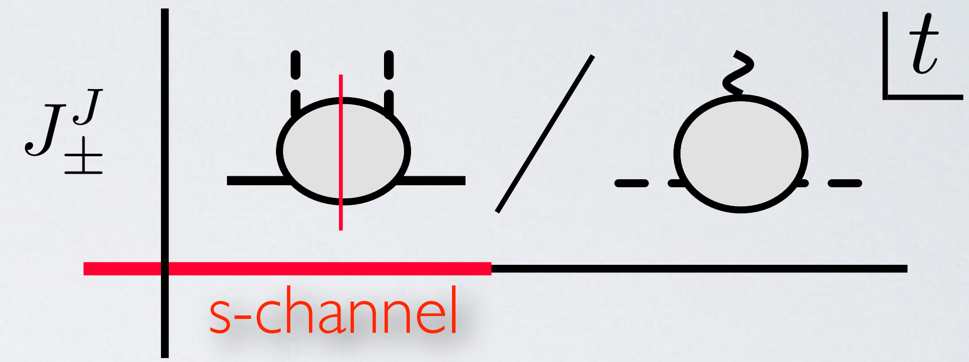

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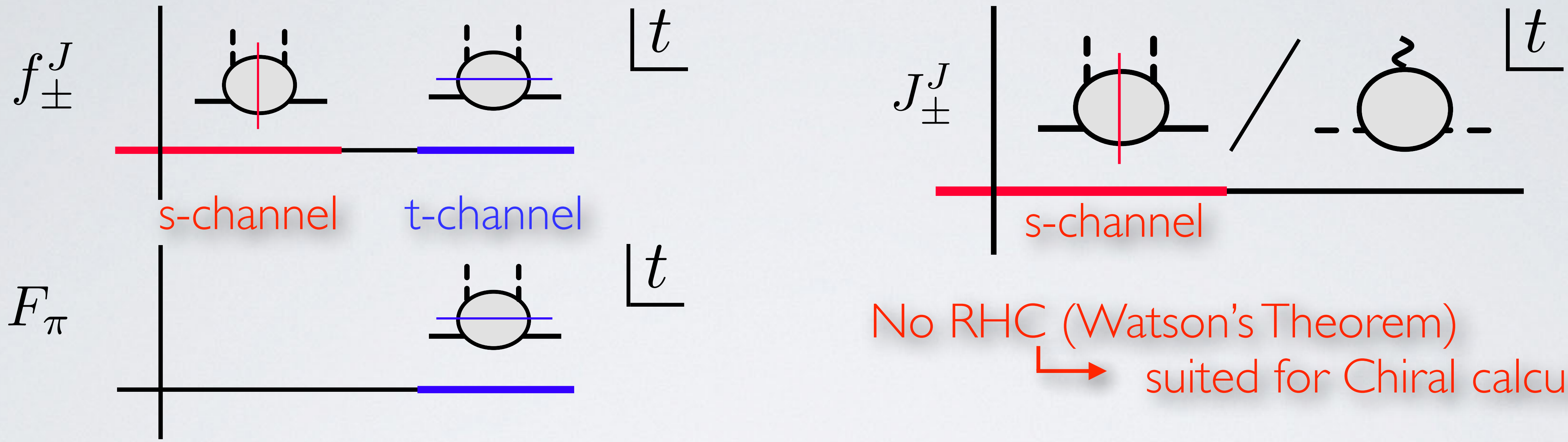

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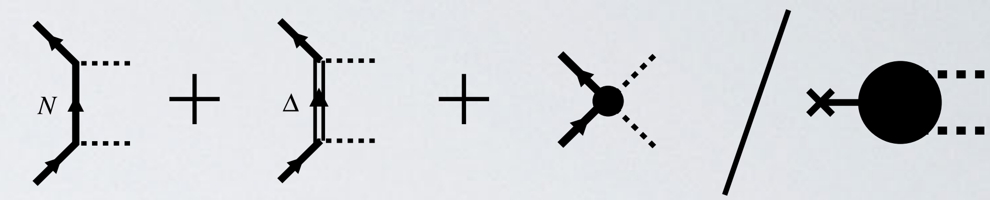
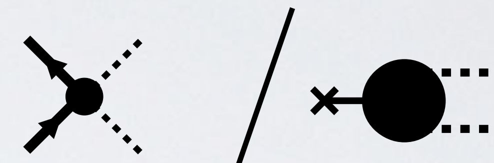
  - N2LO → Estimation

DIχEFT

- $J_\pm^J \equiv f_\pm^J / F_\pi$ smooth → suited for ChEFT.
- LO:



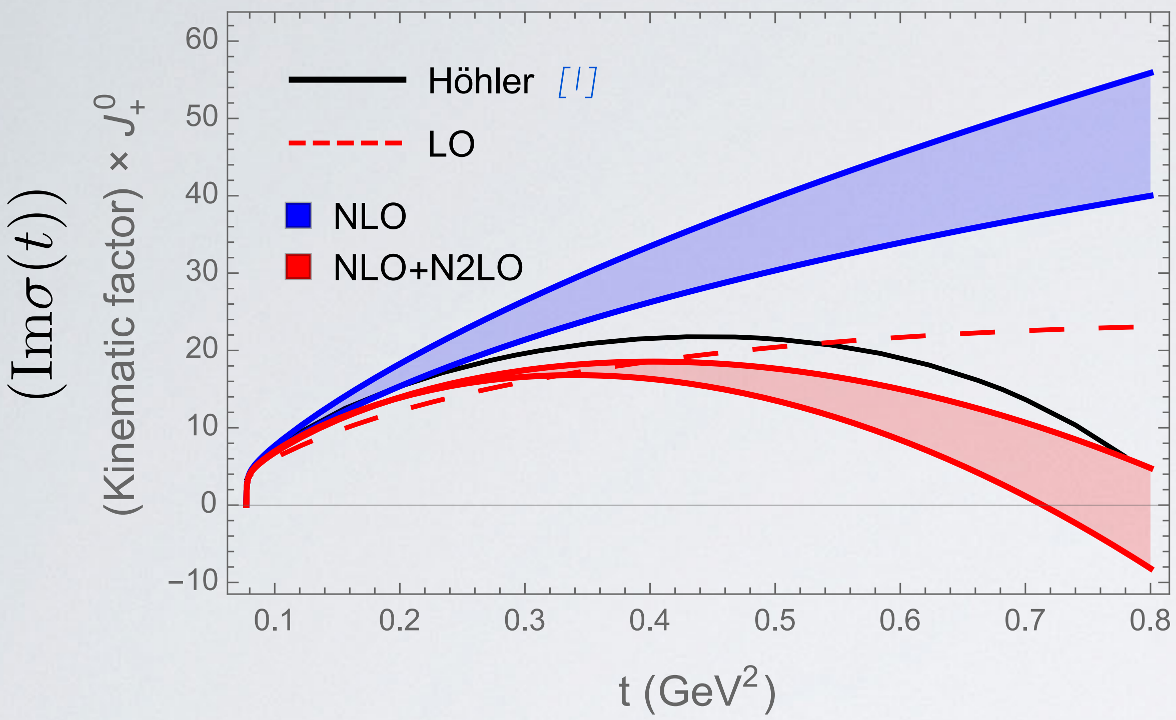
- NLO:

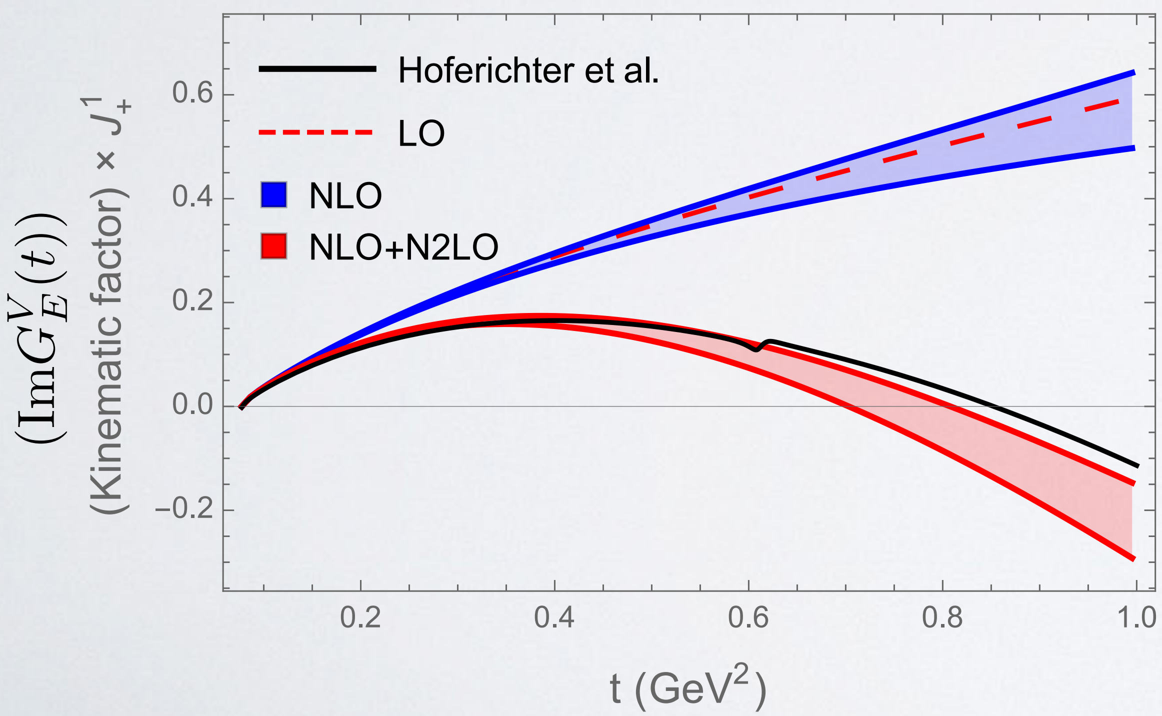


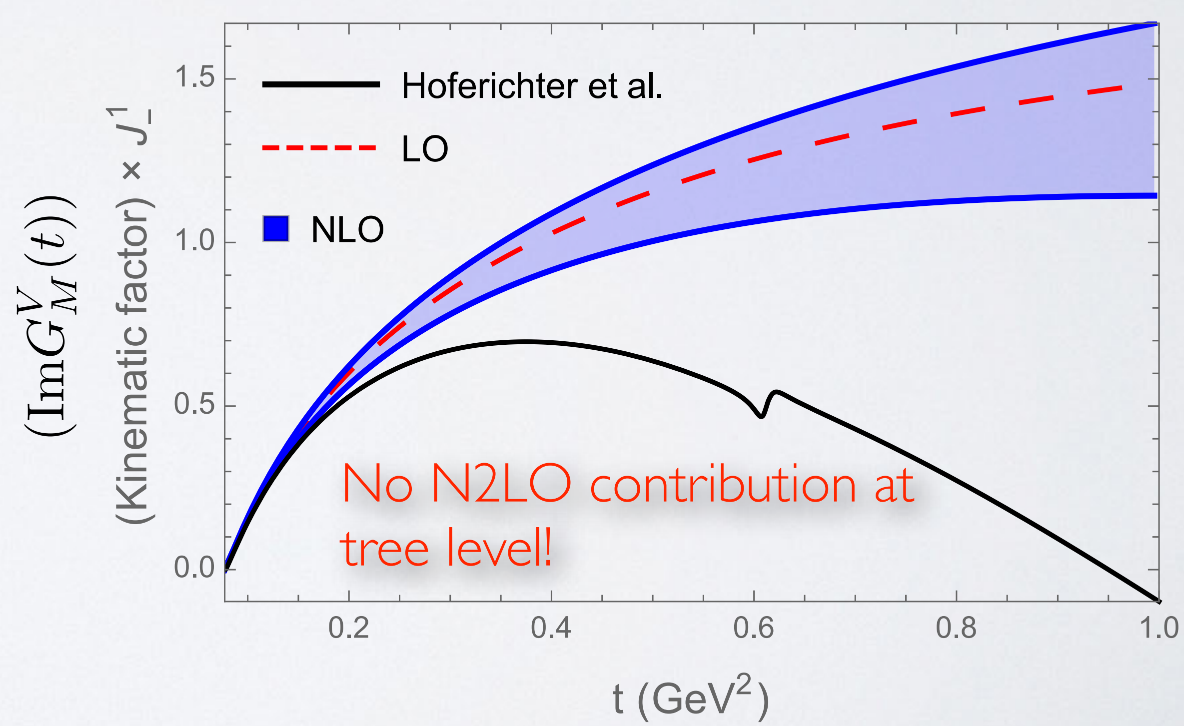
c_1, c_2, c_3, c_4

- NLO+N2LO :

$d_{14} - d_{15}, d_1 + d_2$

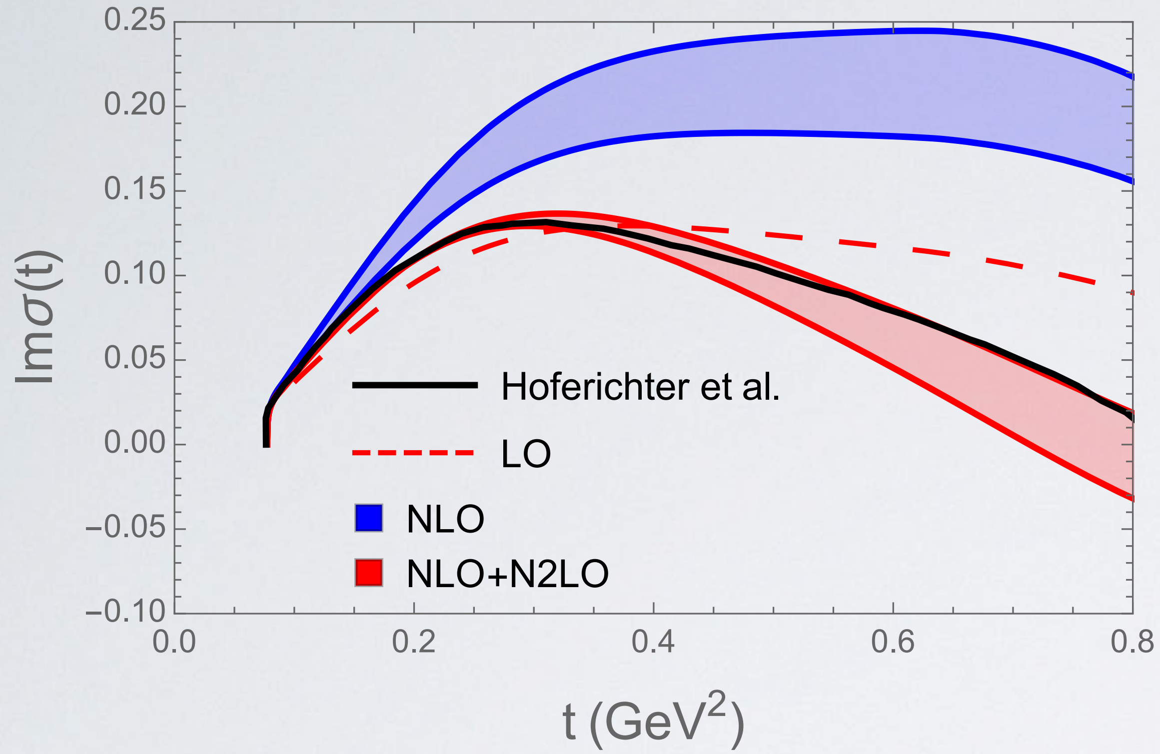






[1] Höhler, in Landolt-Börnstein, 9b2, ed. H. Schopper (Springer, Berlin, 1983)

DIχEFT



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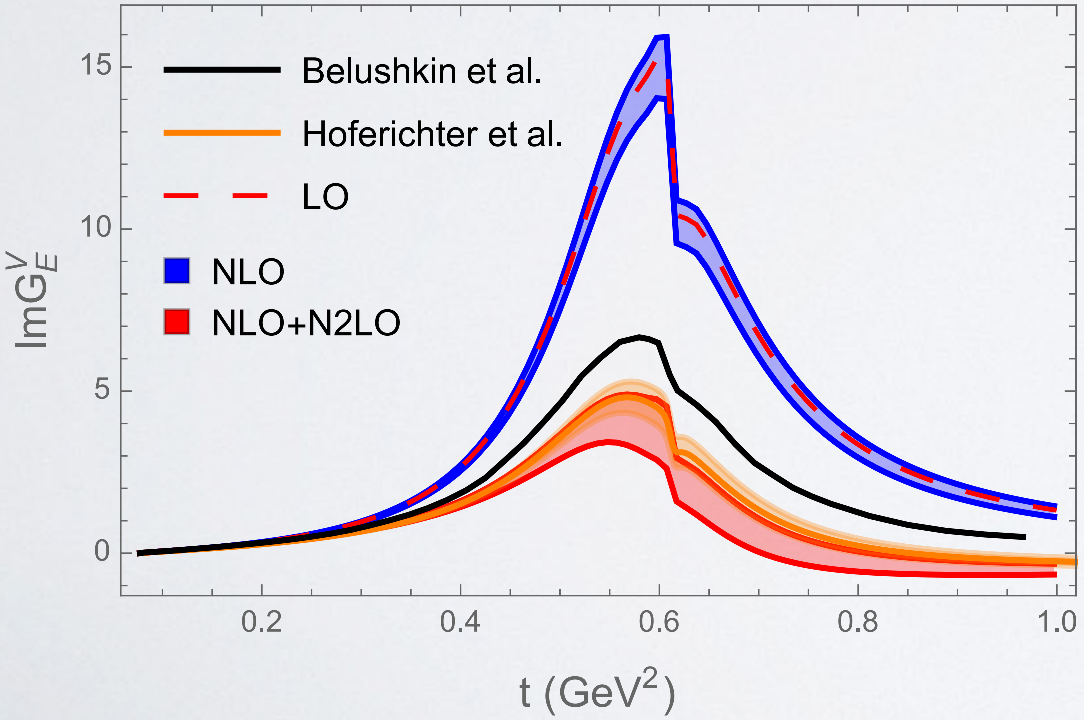
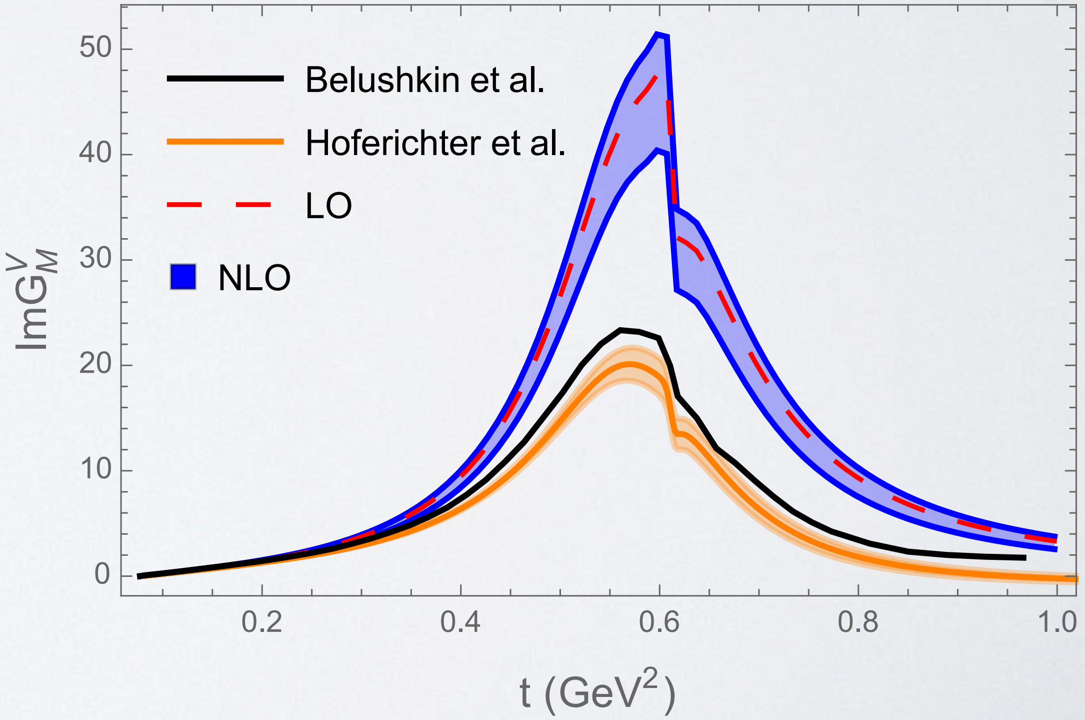
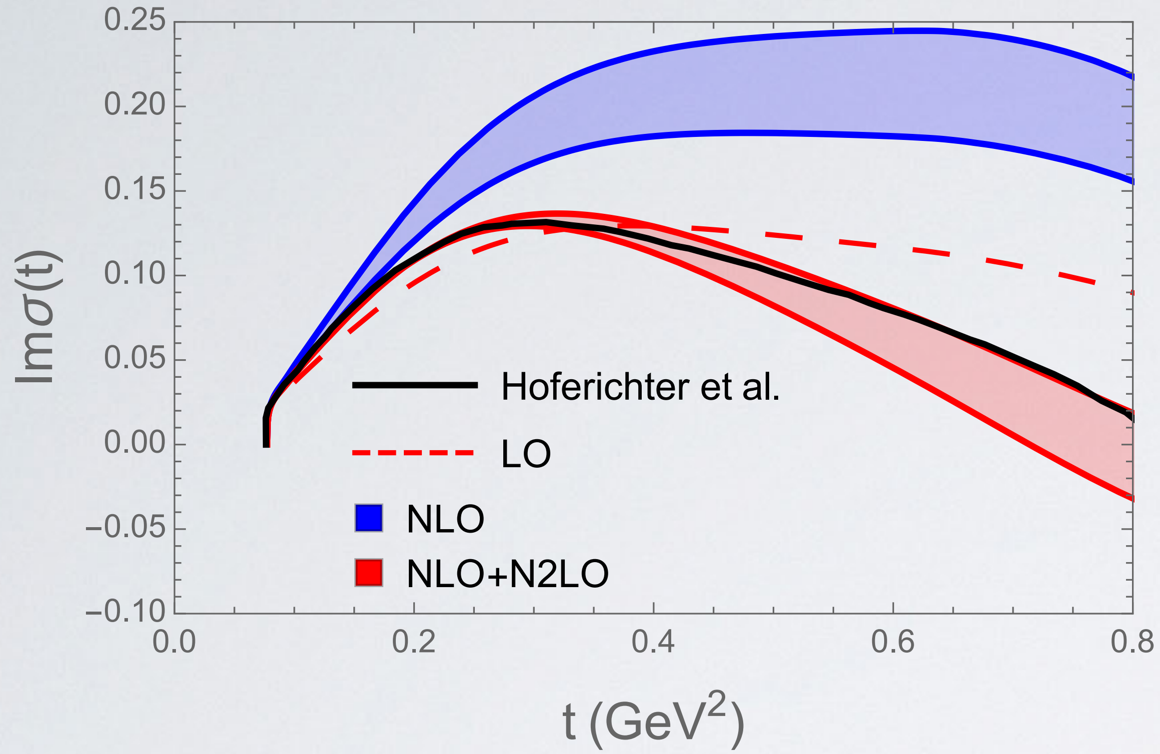
[1] Hoferichter, Ditsche, Kubis, Meißner, JHEP 063 (2012)
[2] Belushkin, Hammer and Meißner, PRC 75 (2007)
[3] Hoferichter, Kubis, Ruiz de Elvira, Hammer, Meißner EPJA 52 (2016)





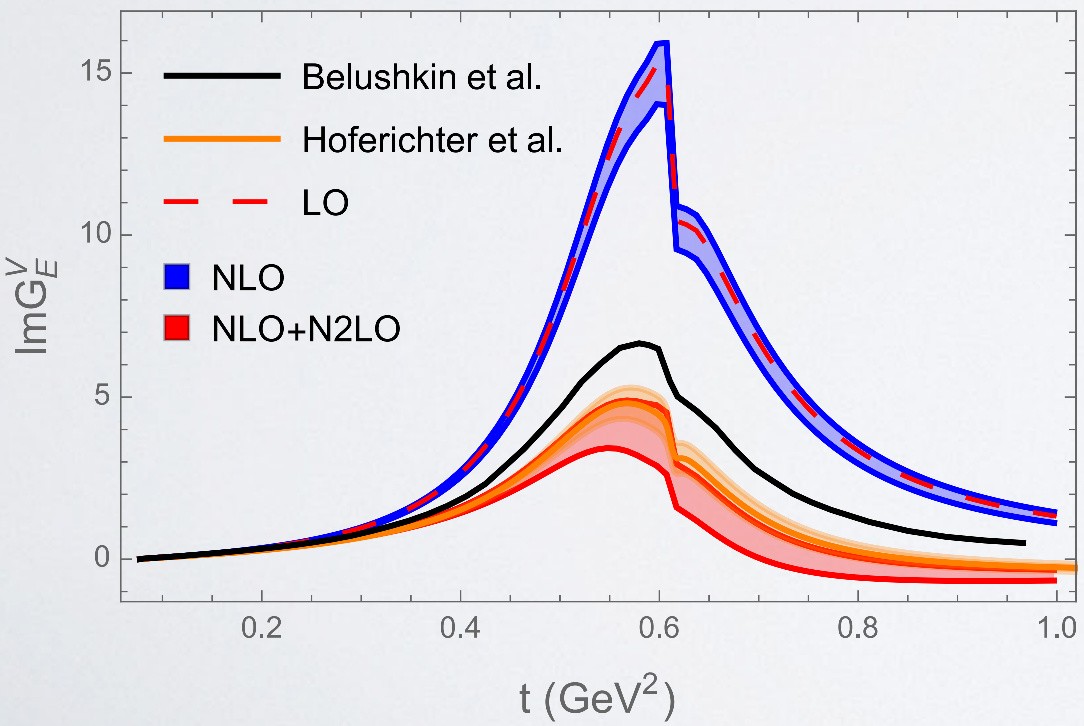
DIχEFT

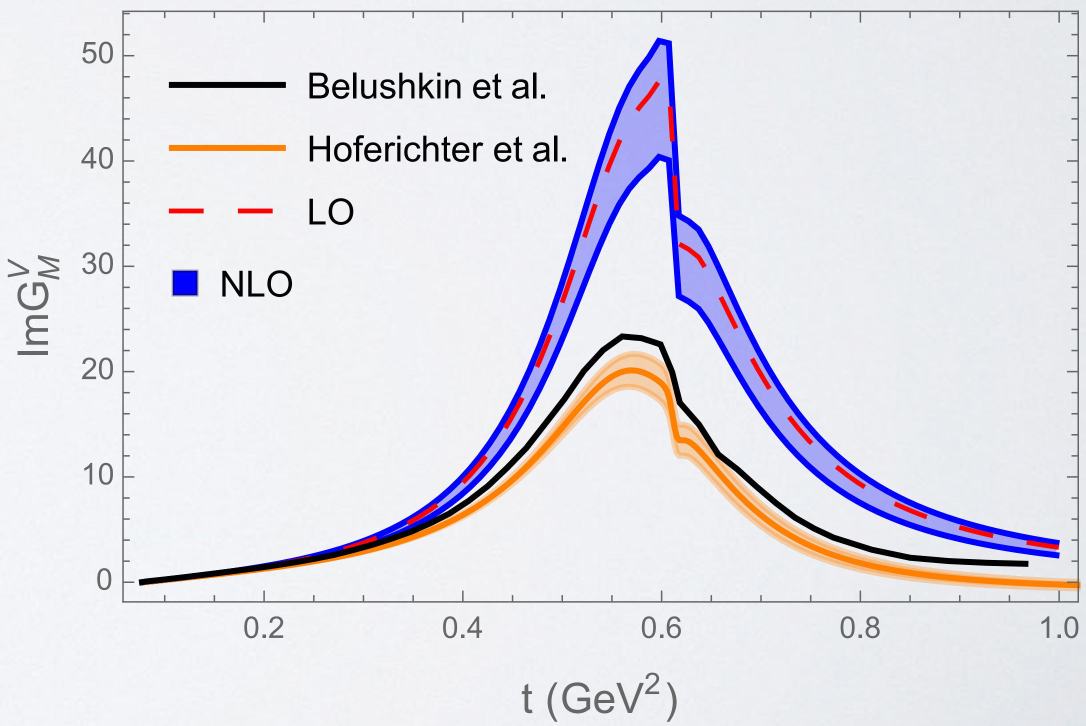


$$\mathrm{Im}\sigma(t) = \frac{3k_{cm}}{4\sqrt{t}(m_N^2 - t/4)}|\Gamma_\pi(t)|^2 J_+^0(t)$$

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

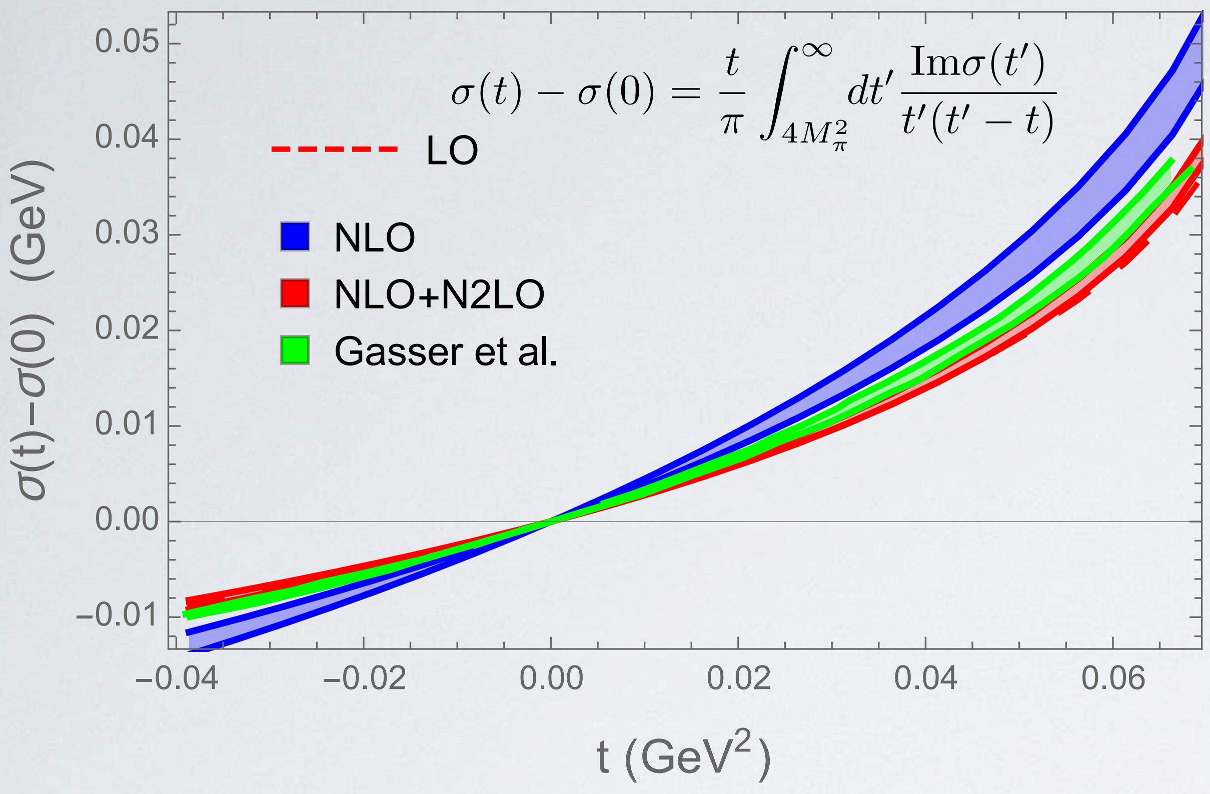
[1] Hoferichter, Ditsche, Kubis, Meißner, JHEP 063 (2012)
[2] Belushkin, Hammer and Meißner, PRC 75 (2007)
[3] Hoferichter, Kubis, Ruiz de Elvira, Hammer, Meißner EPJA 52 (2016)

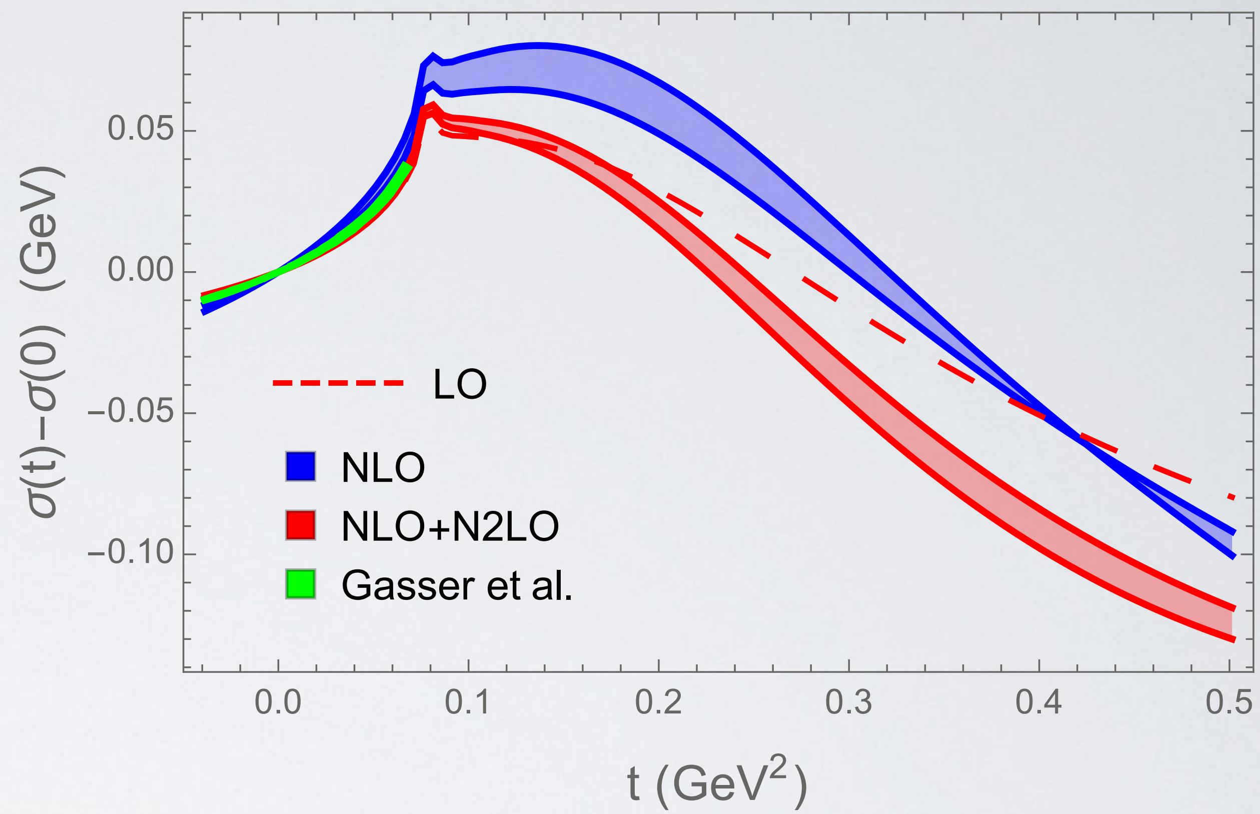




Scalar Form Factor

DIχEFT





		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	–

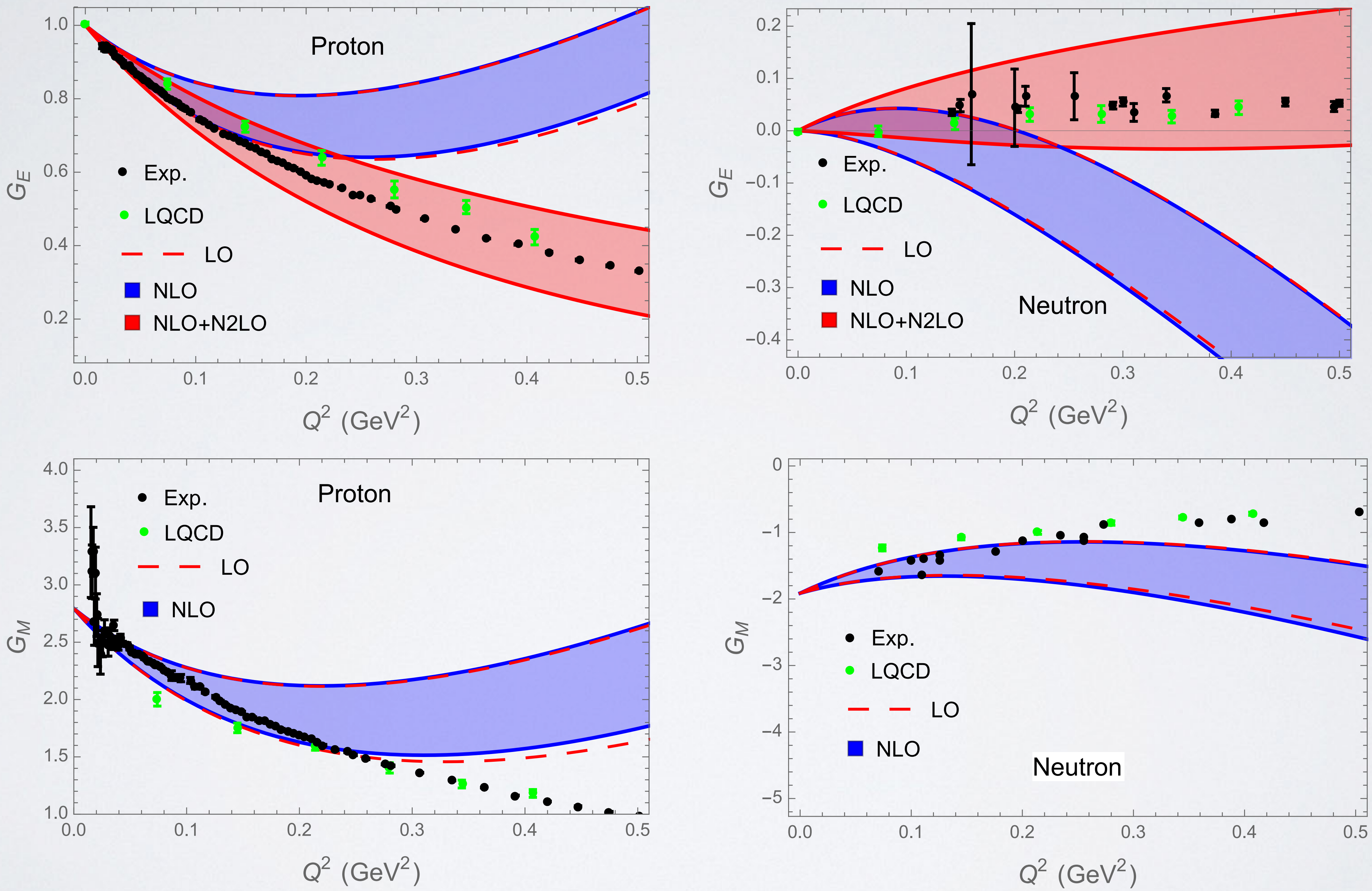
	LO	NLO	NLO+N2LO	GLS [3]	HDKM [4]	ChPT $\mathcal{O}(p^3)$	ChPT $\mathcal{O}(p^4)$
Δ_σ (MeV)	13.3	17.4 - 20.6	13.3 - 14.5	15.2(4)	13.9(3)	4.6	$14.0 + 4M_\pi^4\bar{e}_2$

[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 Factors

DIχEFT

$$G^{p,n}_{E,M}(Q^2) = G^{p,n}_{E,M}(0) \mp \frac{\langle r_{E,M}\rangle^V}{6} Q^2 \pm \frac{Q^4}{\pi}\int_{4M_\pi^2}^{\infty} dt' \frac{\mathrm{Im}G^V_{E,M}(t')}{t'^2(t'+Q^2)} - \frac{Q^2}{\pi}\int_{4M_\pi^2}^{\infty} dt' \frac{\mathrm{Im}G^S_{E,M}(t')}{t'(t'+Q^2)}$$



● *A1 Collaboration* ● *ETM Collaboration, 1706.00469 (2017)*

DIχEFT

- Radii

	LO	NLO	NLO+N2LO	Exp.
$\langle r_E^2\rangle^p$ (fm^2)	(1.11, 1.49)	(1.05, 1.52)	(0.46, 0.94)	(0.71 , 0.77)
$\langle r_M^2\rangle^p$ (fm^2)	(1.19, 1.46)	(1.04, 1.54)	–	(0.60 , 0.76)
$\langle r_E^2\rangle^n$ (fm^2)	(-0.84, -0.47)	(-0.88, -0.40)	(-0.29, 0.18)	-0.12
$\langle r_M^2\rangle^n$ (fm^2)	(1.29 , 1.64)	(1.08, 1.81)	–	(0.77, 0.79)

DIχEFT

- Radii

	LO	NLO	NLO+N2LO	Exp.
$\langle r_E^2 \rangle^p$ (fm^2)	(1.11, 1.49)	(1.05, 1.52)	(0.46, 0.94)	(0.71 , 0.77)
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$\langle r_E^2 \rangle^n$ (fm^2)	(-0.84, -0.47)	(-0.88, -0.40)	(-0.29, 0.18)	-0.12
$\langle r_M^2 \rangle^n$ (fm^2)	(1.29 , 1.64)	(1.08, 1.81)	–	(0.77, 0.79)

- Higher moments

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

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

DIχEFT

- Radii

	LO	NLO	NLO+N2LO	Exp.
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$\langle r_M^2\rangle^p$ (fm^2)	(1.19, 1.46)	(1.04, 1.54)	–	(0.60 , 0.76)
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G_E^p

	LO	NLO	NLO+N2LO
$\langle r^4\rangle$(fm^4)	(2.09, 2.48)	(2.00, 2.53)	(1.16, 1.70)
$\langle r^6\rangle$(fm^6)	(10.77, 11.70)	(10.46, 11.86)	(7.59, 9.00)
$\langle r^8\rangle$(fm^8)	(144.35, 148.22)	(142.04, 149.46)	(121.32, 128.74)

G_E^n

	LO	NLO	NLO+N2LO
$\langle r^4\rangle$(fm^4)	(-1.53, -1.13)	(-1.58, -1.04)	(-0.74, -0.20)
$\langle r^6\rangle$(fm^6)	(-8.94, -8.02)	(-9.11, -7.71)	(-6.24, -4.84)
$\langle r^8\rangle$(fm^8)	(-135.09, -131.21)	(-136.32, -128.91)	(-115.60, -108.18)

G_M^p

	LO	NLO
$\langle r^4\rangle$(fm^4)	(2.38, 2.68)	(2.14, 2.81)
$\langle r^6\rangle$(fm^6)	(13.91, 14.61)	(12.86, 15.17)
$\langle r^8\rangle$(fm^8)	(204.60, 207.57)	(193.78, 213.38)

G_M^n

	LO	NLO
$\langle r^4\rangle$(fm^4)	(3.30, 2.87)	(3.49, 2.51)
$\langle r^6\rangle$(fm^6)	(19.62, 18.60)	(20.44, 17.07)
$\langle r^8\rangle$(fm^8)	(295.06, 290.72)	(303.54, 274.93)

Summary and Conclusions

Summary and Conclusions

- Chiral EFT can be combined with dispersion theory improve calculation of Form Factors.
- Studying the analytic structure of the matrix element allows us to separate the perturbative vs the non-perturbative part:
  - t-channel → non-perturbative → $|F_\pi|^2$ (data, lattice, dispersion theory)
  - s-channel → perturbative → ChEFT → Prediction from πN scattering.
- *DIχEFT* achieves good **predictions** for the spectral functions up to t~0.3 GeV^2 and potentially up to 1 GeV^2.
- Direct application to $G = +1$ operators → Scalar and EM FFs
  - EFT of DM detection (scalar FF).
  - Proton Radius Puzzle (higher order derivatives).
- Promising new approach to unveil the structure of the nucleon from first principles.

FIN

Spares

DIχEFT

- We estimate the size of the N2LO corrections by considering only the tree level contributions.
  - Born Terms are accounted for though $g_A \to g_A - 2d_{18}M_\pi^2$
  - Contact terms depend on d_i
    - Scalar

$$A^+ = -\frac{4\nu^2 m_N}{f_\pi^2}(d_{14} - d_{15}) \qquad B^+ = \frac{4\nu m_N}{f_\pi^2}(d_{14} - d_{15})$$

    - Vector

$$A^- = \frac{2\nu}{f_\pi^2}\left[2(d_1 + d_2 + 2d_5)M_\pi^2 - (d_1 + d_2)t + 2d_3\nu^2\right] \qquad B^- = 0$$

Dominant

- Estimate the value of $d_1 + d_2$ and $d_{14} - d_{15}$ by imposing the charge sum rules

1 GeV^2 1 GeV^2

$$\sigma(0) = \frac{1}{\pi}\int_{4M_\pi^2}^{\Lambda} dt' \frac{\mathrm{Im}\sigma(t')}{t'} \qquad G_{E,M}(0) = \frac{1}{\pi}\int_{4M_\pi^2}^{\Lambda} dt' \frac{\mathrm{Im}G_{E,M}(t')}{t'}$$

DIχEFT

- To reconstruct the EM form factors, we need the isoscalar component as well.
- One cannot apply the same approach as in the isovector case.
- In the isospin limit, only odd number of pions contribute ($G = -1$)
- The isocalar component is dominated by the ω and ϕ exchanges.
- We model the isoscalar spectral functions through the exchange of these VM in the narrow width approximation.

$$\mathrm{Im} F_i^S = \pi \sum_{V=\omega,\phi} a_i^V \, \delta(t - M_V^2) \qquad (i = 1, 2)$$

a_1^ω	a_1^ϕ	a_2^ω	a_2^ϕ
$(0.58, 0.85)$	$(-0.49, 0.26)$	$(-0.13, 0.38)$	$(-0.23, 0.28)$

- We use SU(3) symmetry, some assumptions about the F/D ratio and empirical $g_{\omega NN}$ couplings from [Machleidt PRC 63 (2001)] [Belushkin et al., PRC 75 (2007)]