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Bochum-CNF

Gravitational form factors of the deuteron in nuclear effective field theory and more

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Structure of my talk

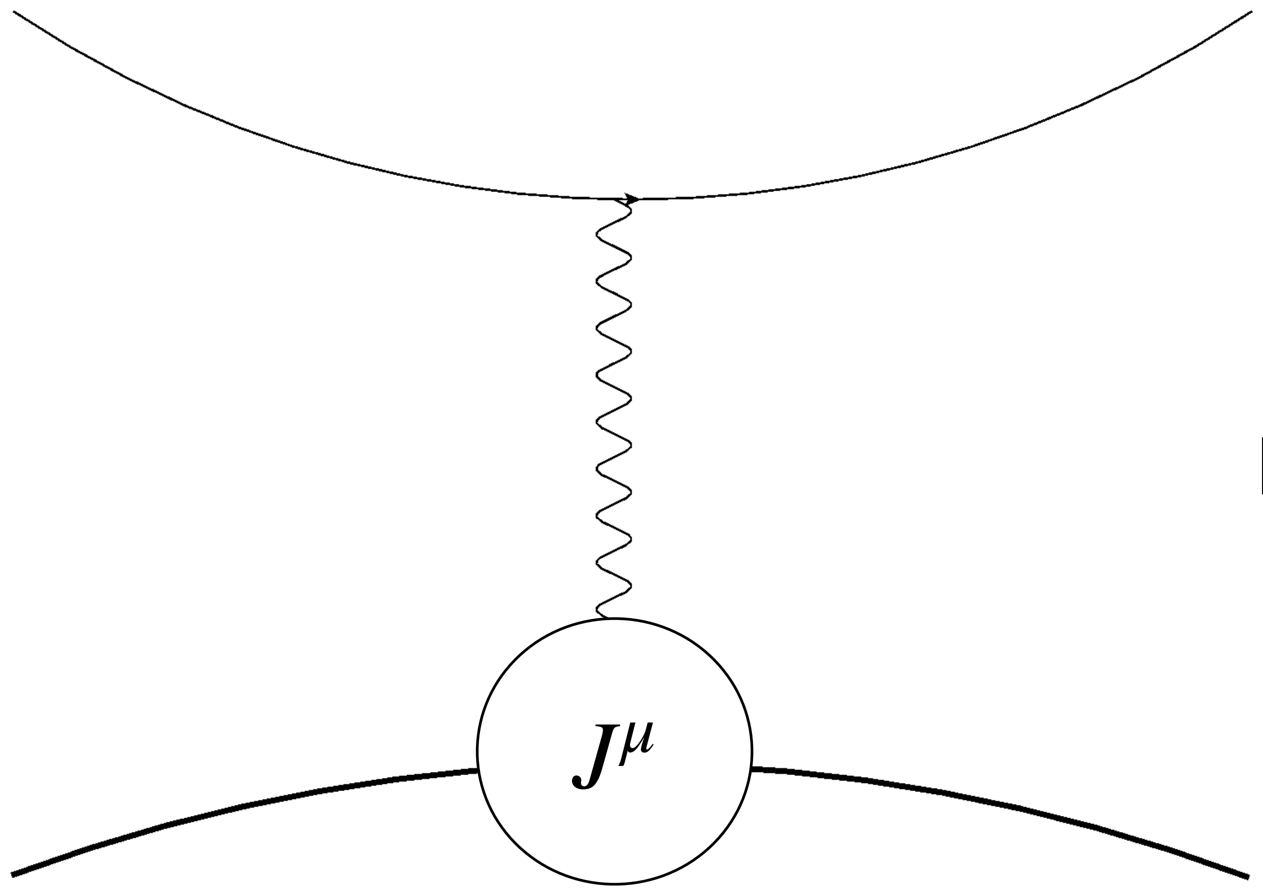
1. Internal gravitational structure of hadronic systems

2. Basics of nuclear EFT

3. Calculation of GFFs of a deuteron in nuclear EFT

* Calculation of the GFFs of a nucleon in Diffusion model

EM structure of a particle



virtual photon

$$d\sigma/d\Omega = \left(d\sigma/d\Omega\right)_{pointlike} \times \left(F_1^2(q^2) + \frac{q^2}{4m^2}(F_2^2(q^2) + \dots) \right)$$

q-dependence —> structure

For spin-1/2

$$\langle p', s' \,|\, \hat{j}^\mu(0) \,|\, p, s \rangle = \bar{u}(p', s') \left[\gamma^\mu F_1(q^2) + \frac{1}{2m} i\sigma^{\mu\nu} q_\nu F_2(q^2) \right] u(p, s)$$

[Rosenbluth, 1950
Hofstadter et al. 1953]

- electric charge

  $F_1(0) = e$

- magnetic moment

  $1/2(F_1(0) + F_2(0)) = \mu$

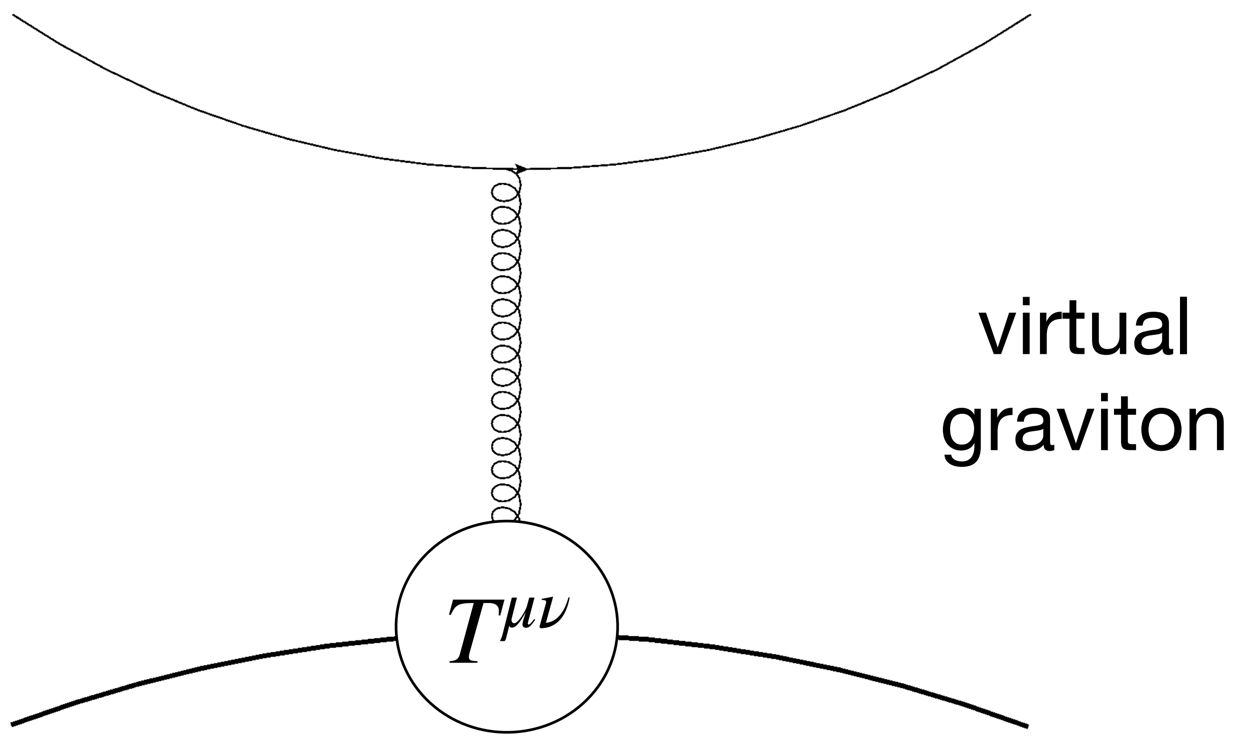
- conserved

  $\partial^\mu j_\mu = 0$

- gauge invariant

Gravitational structure of hadrons

[Kobzarev, Okun (1962)
Pagels (1966)]



For spin-1/2

$$\langle p' | \hat{T}^{\mu\nu}(0) | p \rangle = \bar{u}\left[A(q^2)\frac{P_\mu P_\nu}{m} + iJ(q^2)\frac{(P_\mu \sigma_{\nu\alpha} + P_\nu \sigma_{\mu\alpha})q^\alpha}{4m} + D(q^2)\frac{q_\mu q_\nu - \eta_{\mu\nu}q^2}{4m}\right] u$$

No direct experiment for detection of the matter-graviton interaction

$$T_{\mu\nu}(x) \sim \frac{\delta S_M}{\delta g^{\mu\nu}(x)}\bigg|_{g=\eta}$$

Gravity couples to matter due to EMT

- **mass** $m = \int d^3r\, T_{00}(r)$

  $$A(0) = 1$$

- **spin** $J^i = \epsilon^{ijk} \int d^3r\, r^j\, T_{0k}(r)$

  $$J(0) = 1/2$$

- **anomalous gravitomagnetic moment**

  $$2J(t) = A(t) + B(t) \quad B(0) = 0$$

- symmetric
- conserved

  $$\partial^\mu T_{\mu\nu} = 0$$

- gauge invariant

[Xiang-Dong Ji, Phys.Rev.D 58 (1998)
Xiang-Dong Ji, Phys.Rev.Lett. 78 (1997)]

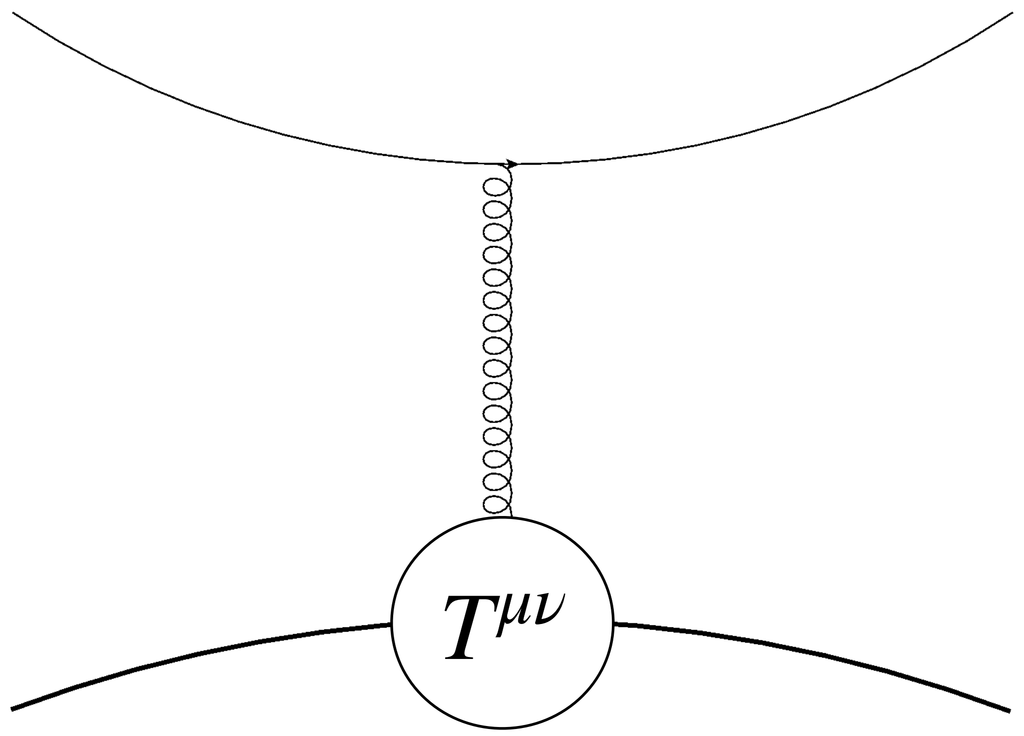
- **D-term:**

$$D = D(0) = -\frac{m}{2}\int d^3r \left(r^i r^j - \frac{1}{3}\delta_{ij}\right) T_{ij}(r)$$

[M.V.Polyakov,
Phys. Lett.B 555, 57 (2003)]

*…D-term as fundamental as mass and spin!
It is necessary connected with the true gravity.*

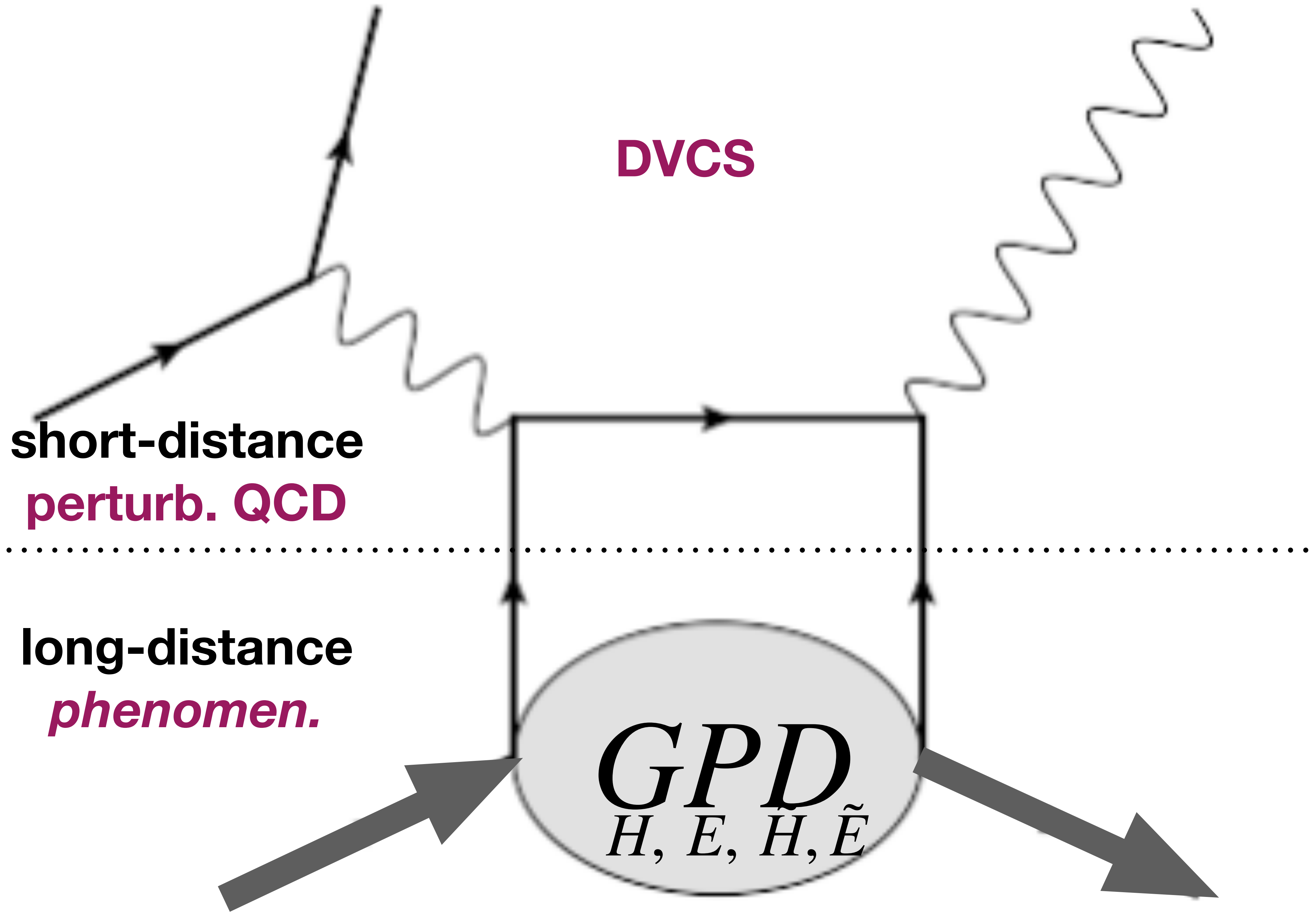
How to measure GFFs?



No direct experiment to measure GFFs

$$H, E \sim d\sigma/d\Omega$$

Details in
M.V.Polyakov, PLB 555 (2003)
Anikin, Teryaev, PRD76 (2007)
Diehl and Ivanov, EPJC52 (2007)
Radyushkin, PRD83, 076006 (2011)
Bertone et al., PRD 103 (2021)



However, it is possible with 2 photons

Second Mellin moments of GPDs

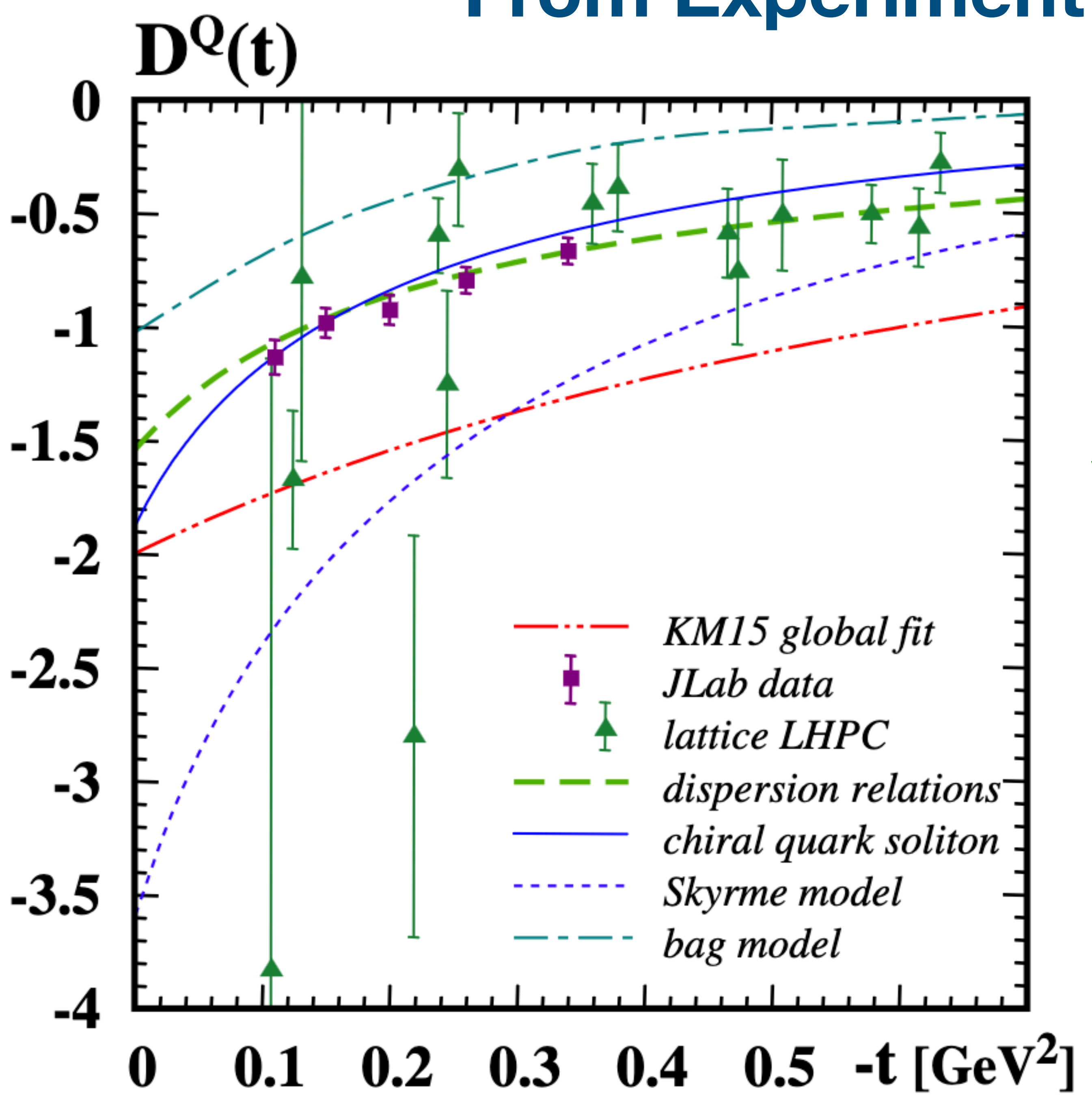
$$\int_{-1}^{1} dx\ xH(x, \xi, t) = A(t) + \xi^2 D(t)$$

$$\int_{-1}^{1} dx\ xE(x, \xi, t) = B(t) - \xi^2\ D(t)$$

Details in
[D. Müller et al., F.Phys. 42,1994,
X. Ji, PRL 78, 610, 1997
A. Radyushkin, PLB 380, 1996]

Results for GFFs

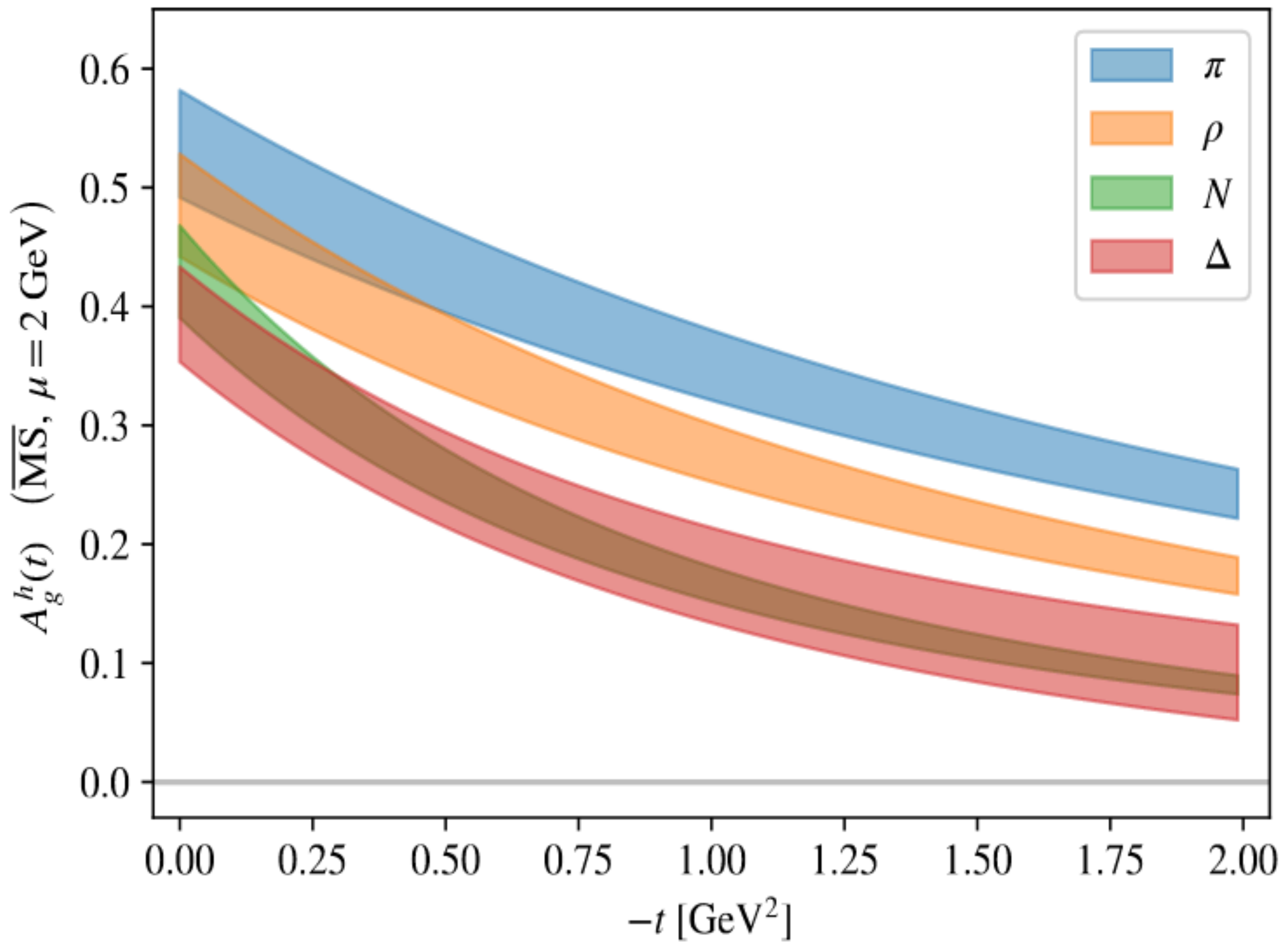
From Experiment



Comparison of first experimental data with lattice data and model calculations
[M.V. Polyakov, P. Schweitzer, Int.J.Mod.Phys.A 33 (2018)]

Details in
[Burkert et al., Nature 557 (2018)
Kumeticki, Nature 570 (2019)
Dutrieux et al., Eur.Phys.J C 81
V.Burkert, L. Elouadrhiri, F.X.Girod, C. Lorce, P. Schweitzer
[Rev. Mod. Phys. 95, (2023)]

From lattice



Gluon contribution to GFF A(t) for various hadrons from lattice QCD study
with pion mass mπ = 450(5) MeV
[Pefkou et all. *Phys.Rev.D* 105 (2022)]

Details in
[Detmold et al. Phys.Rev.Lett. 126 (2021)
Alexandrou et al., Phys.Rev.D 105 (2022)
Hacket et al., arXiv:2310.08484v1 (2023)]

From ChPT

Details in
[Alharazin, Djukanovic, Gegelia, Polyakov, *Phys.Rev.D* 102 (2020)
Epelbaum, Gegelia, Meißner, Polyakov*, Phys.Rev.D* 105 (2022)
Alharazin, Epelbaum, Gegelia, Meißner, Sun, *Eur.Phys.J.C* 82 (2022)
Alharazin, *Phys.Rev.D 109 (2024)*]

How to use FFs?

for non-relativistic (heavy) systems

[Hofstadter et. all,
Rev. Mod. Phys. 30, 482 (1958)]

$$F(Q^2) = \int d^3 r \rho(\mathbf{r}) e^{i\vec{Q}\cdot\vec{r}}$$

charge density
of proton

[Sachs,
Phys. Rev.126, 2256-2260 (1962)]

Breit frame
$Q^2 = -\vec{q}^{\,2}$

$$\rho(r) \equiv \int \frac{d^3Q}{(2\pi)^3} G_E(Q^2) e^{-i\vec{Q}\cdot\vec{r}}$$

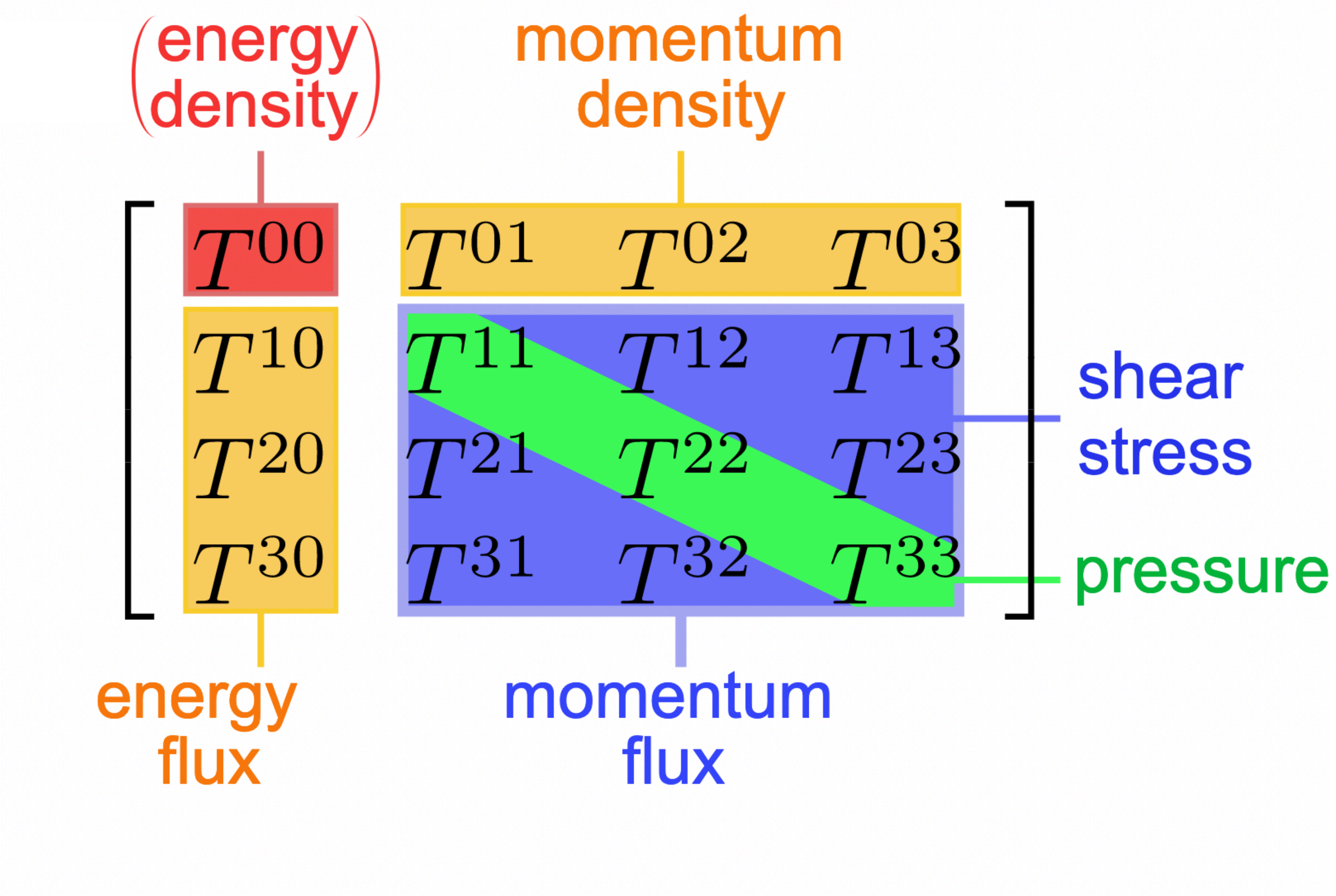
[M.V.Polyakov,
Phys. Lett.B 555, 57 (2003)]

$$T_{\mu\nu}(\mathbf{r}, s) = \frac{1}{2E}\int \frac{d^3Q}{(2\pi)^3} e^{i\vec{Q}\cdot\vec{r}} \langle p', s' | \hat{T}_{\mu\nu}(0) | p, s \rangle$$

em:	$\partial_\mu J^\mu_{\text{em}} = 0$	$\langle N' \vert J^\mu_{\text{em}} \vert N \rangle$	$\longrightarrow$	$Q = 1.602176487(40) \times 10^{-19}\text{C}$ $\mu = 2.792847356(23)\mu_N$
weak:	PCAC	$\langle N' \vert J^\mu_{\text{weak}} \vert N \rangle$	$\longrightarrow$	$g_A = 1.2694(28)$ $g_p = 8.06(55)$
gravity:	$\partial_\mu T^{\mu\nu}_{\text{grav}} = 0$	$\langle N' \vert T^{\mu\nu}_{\text{grav}} \vert N \rangle$	$\longrightarrow$	$m = 938.272013(23)\,\text{MeV}/c^2$ $J = \frac{1}{2}$ $\boldsymbol{D} = \boldsymbol{?}$

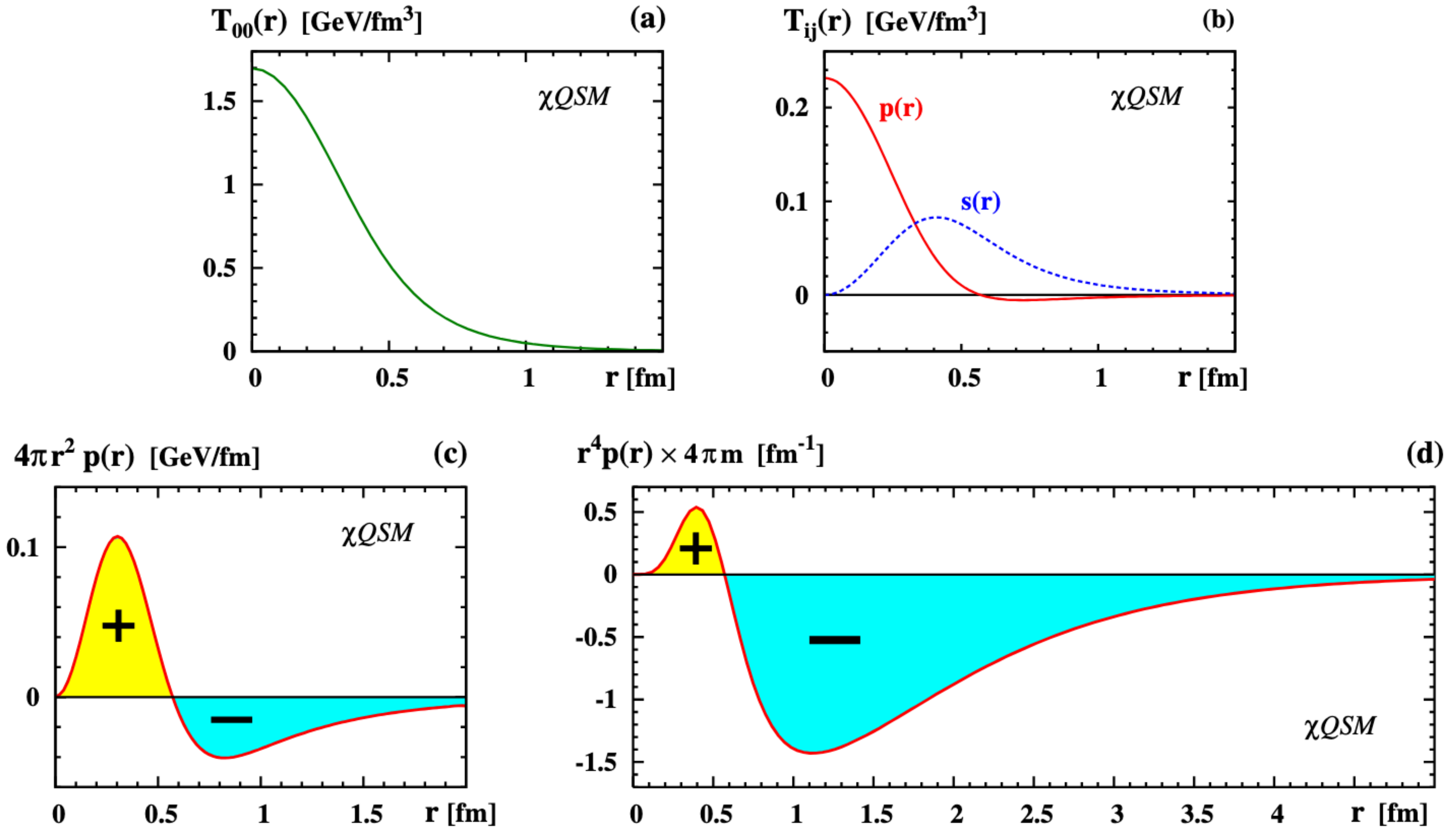
Last global unknown property

Mechanical properties



total energy

$$m = \int d^3 r T_{00}(r)$$



M.V. Polyakov, P. Schweizer [Int. J. Mod. Phys. A 33] (2018)

pressure **shear force**

$$T^{ij}(r) = \delta^{ij} p(r) + \left(\frac{r^i r^j}{r^2} - \frac{1}{3}\delta^{ij} \right) s(r)$$

$$\partial_i T_{ij}(r) = 0$$

$$\int d^3r\; p(r) = 0$$

the von Laue stability condition

[Laue, Ann. Phys. 340, 524 (1911)]

$$\frac{2}{3}s'(r) + p'(r) + \frac{2}{r}s(r) = 0$$

equilibrium equation

$$F^i(r) = T^{ij}(r)dS\, n^j = \left(\frac{2}{3}s(r) + p(r)\right) dS^i$$

the normal forces

$$\frac{2}{3}s(r) + p(r) > 0$$

local stability condition

$$D < 0$$

[Perevalova, Polyakov, Schweitzer,
Phys. Rev. D 94, 054024 (2016)]

D-term via the static approximation

$$D \equiv D(0) = -\frac{m}{2}\int d^3r \left(r^i r^j - \frac{1}{3}\delta_{ij}\right) T_{ij}(r) = m\int d^3r r^2 p(r) = -\frac{4}{15}m\int d^3r r^2 s(r)$$

[M.V.Polyakov,
Phys. Lett.B 555, 57 (2003)]

Why deuteron?

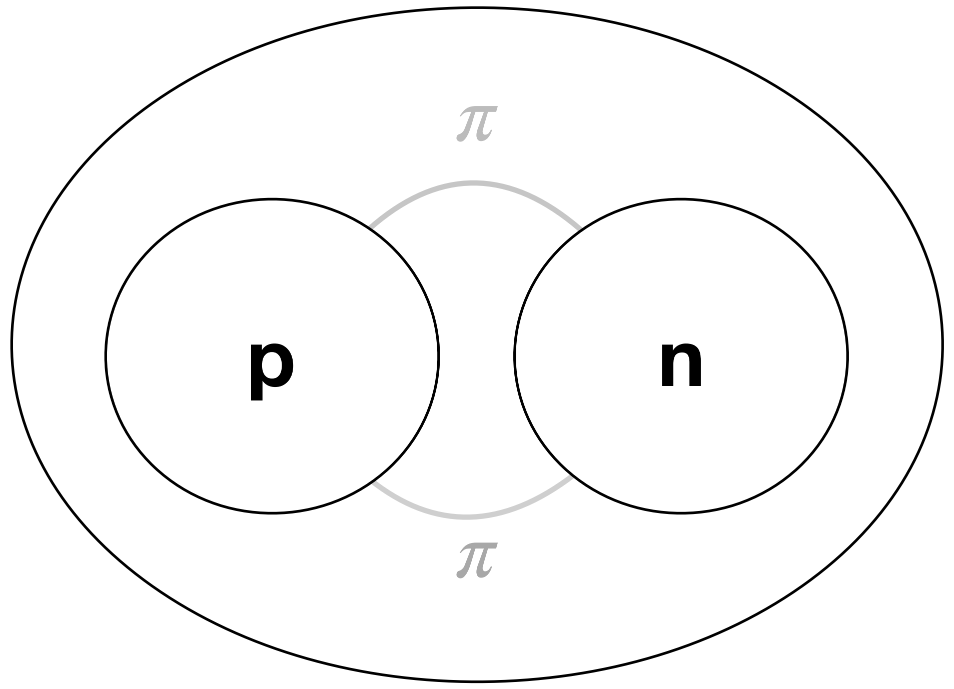
GFFs in ChPT

Nucleon
Alharazin, Djukanovic, Gegelia, Polyakov, *Phys.Rev.D* 102 (2020)

ρ-meson
*Epel*baum, Gegelia, Meißner, Polyakov, *Phys.Rev.D* 105 (2022)

Δ-resonances
Alharazin, Epelbaum, Gegelia, Meißner, Sun, *Eur.Phys.J.C* 82 (2022)

Deuteron is a bound state of one proton and one neutron



S=1, I=0

binding energy

$$E_b = 2.2\ \text{MeV}$$

very loosely bound system

quadrupole moment

$$Q_d \simeq 0.29\ \text{fm}^2$$

the deuteron is not spherical

EFT ✔

Chiral Effective Field Theory

EFT $\approx$ QCD at a low-energy

Low-energy means $q \ll \Lambda$

$E_{\text{kin}} \sim 15$ MeV, $\Lambda \sim 1$ GeV

1. For nuclear physics at momenta $q \sim m_\pi$
chiral EFT
with **nucleons and pions as explicit degrees of freedom**

EFT provides a systematic, model-independent framework:

1. Identify the relevant **degrees of freedom** at the energy scale of interest
2. Write the **most general Lagrangian** consistent with the symmetries of QCD
3. Organise the infinite number of terms by a **power counting** scheme
4. Compute observables **order by order**, with each order providing a systematically improvable approximation

2. Leading order Lagrangian in NN sector

$$
\begin{array}{c|c}
\hat{\hat{O}}_1 & \left(\bar{\psi}\psi\right)\left(\bar{\psi}\psi\right) \\
\hat{\hat{O}}_2 & \left(\bar{\psi}\gamma^\mu\psi\right)\left(\bar{\psi}\gamma_\mu\psi\right) \\
\hat{\hat{O}}_3 & \left(\bar{\psi}\gamma_5\gamma^\mu\psi\right)\left(\bar{\psi}\gamma_5\gamma_\mu\psi\right) \\
\hat{\hat{O}}_4 & \left(\bar{\psi}\sigma^{\mu\nu}\psi\right)\left(\bar{\psi}\sigma_{\mu\nu}\psi\right)
\end{array}
$$

3. Weinberg's power counting:

To identify systematically the importance of terms **in the Lagrangian**

$$m_N \sim O\left(\frac{1}{\varepsilon}\right), \; p \sim O(\varepsilon)$$

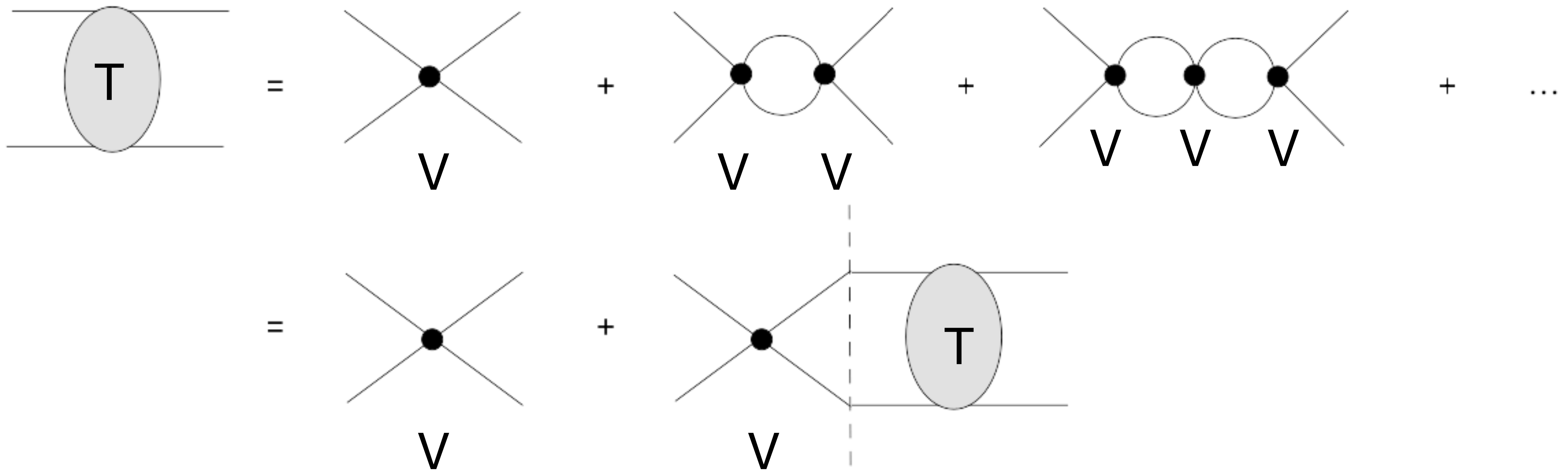
4.

$$F(q^2) = 1 - c_1\frac{q^2}{\Lambda^2} + c_2\left(\frac{q^2}{\Lambda^2}\right)^2 + \ldots$$

LO *NLO* *NNLO*

The NN Amplitude and Non-Perturbative Resummation

The NN amplitude



Kinematics

incoming nucleons $p_1 = (E_p, \mathbf{p}),\, p_3 = (E_p, -\mathbf{p})$

outgoing nucleons $p_2 = (E_{p'}, \mathbf{p}'),\, p_4 = (E_{p'}, -\mathbf{p}')$

Bethe-Salpeter equation

$$T_{ac,bd}(p_1, p_3; p_2, p_4) = V_{ac,bd}(p_1, p_3; p_2, p_4) + \int \frac{d^4k}{(2\pi)^4} V_{ac,m_1n_1}(p_1, p_3; k, p_1 + p_3 - k)$$
$$\times \Delta^{m_1m_2}(k)\Delta^{n_1n_2}(p_1 + p_3 - k)\; T_{m_2n_2,bd}(k, p_1 + p_3 - k; p_2, p_4),$$

Lippmann-Schwinger equation in non-relativistic case

$$t_0(\mathbf{p}, \mathbf{p}')^{ac,bd} = v_0(\mathbf{p}, \mathbf{p}')^{ac,bd} - m^2 \int \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{v_0^{ac,km}(\mathbf{p}, \mathbf{k}) t_0^{km,bd}(\mathbf{k}, \mathbf{p}')}{\omega_k^2(E - 2\omega_k + i\epsilon)}, \qquad \omega_k = \sqrt{\mathbf{k}^2 + m^2},\; E = 2\sqrt{\mathbf{p}^2 + m^2}$$

Gravitational Form Factors of Deuteron

[M.V. Polyakov, B.-D. Sun, *Phys.Rev.D* 100 (2019)]

Parameterisation of matrix element of EMT for spin-1 system:

$$P = \frac{p+p'}{2}$$

$$q = p' - p$$

$$\langle p',\sigma' | \hat{T}_{\mu\nu}(\mathbf{x},0) | p,\sigma\rangle = e^{-i\mathbf{q}\cdot\mathbf{x}}\Bigg[\frac{1}{2}\left(q_\mu q_\nu - g_{\mu\nu}q^2\right)\left(\epsilon'\cdot\epsilon D_0(q^2) + \frac{P\cdot\epsilon' P\cdot\epsilon}{M^2}D_1(q^2)\right)$$

$$+2P_\mu P_\nu\left(-\epsilon'\cdot\epsilon A_0(q^2) + \frac{P\cdot\epsilon' P\cdot\epsilon}{M^2}A_1(q^2)\right) + 2\left(P_\mu\left[\epsilon'_\nu P\cdot\epsilon + \epsilon_\nu P\cdot\epsilon'\right] + P_\nu[\epsilon'_\mu P\cdot\epsilon + \epsilon_\mu P\cdot\epsilon']\right)J(q^2)$$

$$+\left[\frac{1}{2}q^2(\epsilon_\mu\epsilon'_\nu + \epsilon'_\mu\epsilon_\nu) - (\epsilon'_\nu q_\mu + \epsilon'_\mu q_\nu)\epsilon\cdot P + (\epsilon_\nu q_\mu + \epsilon_\mu q_\nu)\epsilon'\cdot P - 4g_{\mu\nu}P\cdot\epsilon' P\cdot\epsilon\right]E(q^2)$$

6 GFFs

A_0, A_1, J, E, D_0, D_1

In static approximation:

$$\langle p',\sigma' | \hat{T}_{00} | p,\sigma\rangle = 2m_D^2\left[\delta_{\sigma'\sigma}\left(\mathscr{E}_0(-\mathbf{q}^2) + \frac{\mathbf{q}^2}{3m_D^2}\mathscr{E}_2(-\mathbf{q}^2)\right) - \frac{q^{\sigma'}q^{\sigma}}{m_D^2}\mathscr{E}_2(-\mathbf{q}^2)\right]$$

$$\langle p',\sigma' | \hat{T}_{0i} | p,\sigma\rangle = -m_D\mathscr{J}(-\mathbf{q}^2)\left(\delta_{i\sigma'}q^{\sigma} - \delta_{i\sigma}q^{\sigma'}\right)$$

$$\langle p',\sigma' | \hat{T}_{ij} | p,\sigma\rangle = 2\Big[\mathscr{D}_2(-\mathbf{q}^2)\left(\delta_{ij}q^{\sigma}q^{\sigma'} - \frac{1}{2}q^i(q^{\sigma}\delta_{j\sigma'} + q^{\sigma'}\delta_{j\sigma}) - \frac{1}{2}q^j(q^{\sigma}\delta_{i\sigma'} + q^{\sigma'}\delta_{i\sigma}) + \frac{\mathbf{q}^2}{2}(\delta_{i\sigma}\delta_{j\sigma'} + \delta_{i\sigma'}\delta_{j\sigma})\right)$$

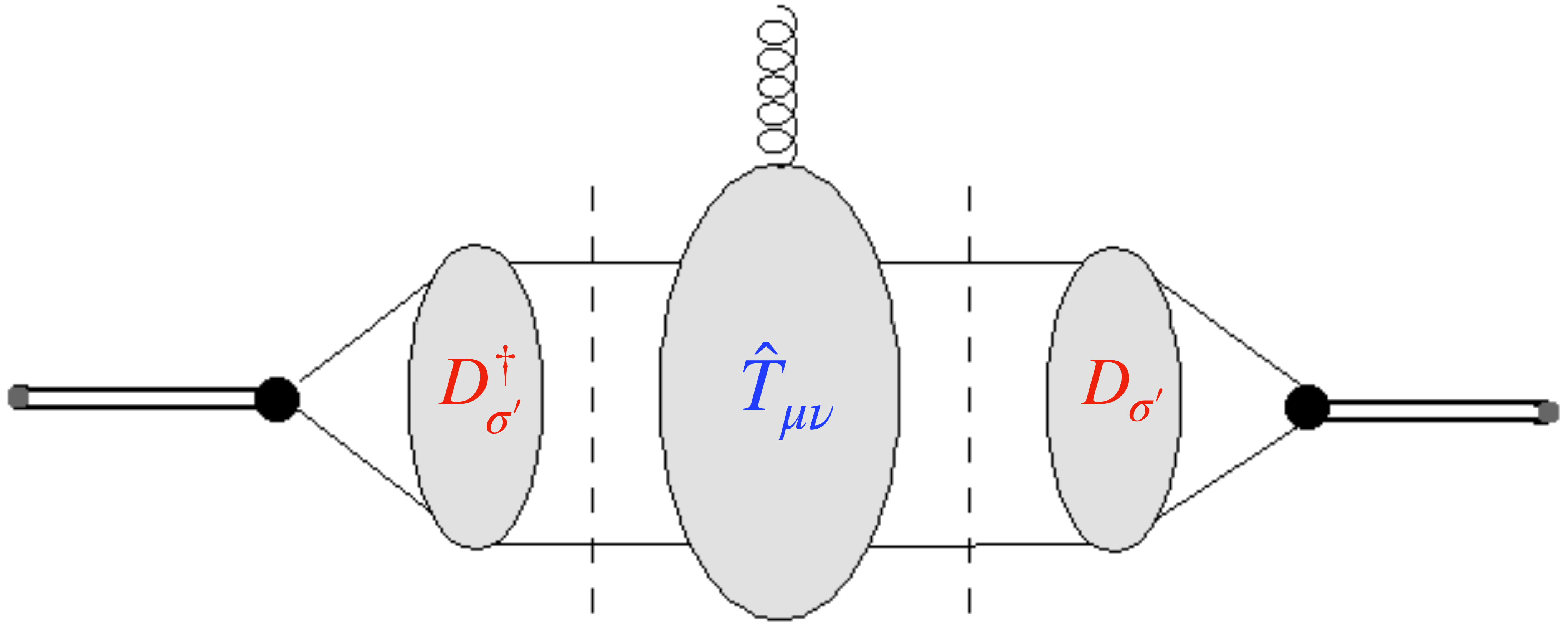
$$+\left(\mathbf{q}^2\delta_{ij} - q_i q_j\right)\left\{\delta_{\sigma'\sigma}\left(\mathscr{D}_0(-\mathbf{q}^2) - \frac{2}{3}\mathscr{D}_2(-\mathbf{q}^2) + \frac{\mathbf{q}^2}{3m_D^2}\mathscr{D}_3(-\mathbf{q}^2)\right) - \frac{q^{\sigma'}q^{\sigma}}{m_D^2}\mathscr{D}_3(-\mathbf{q}^2)\right\}\Big]$$

6 GFFs

$\mathscr{E}_0, \mathscr{E}_2, \mathscr{J}, \mathscr{D}_0, \mathscr{D}_2, \mathscr{D}_3$

[J.P., Epelbaum et al., *JHEP* 07 237 (2023)]

Three-point function of the EMT operator



Three-point function of the EMT operator

$$G^{\sigma'\sigma}_{\mu\nu}(p', p) = \int d^4x d^4y \, e^{-ip'y} e^{ipx} \langle 0 | T \left[\mathscr{D}^{\dagger}_{\sigma}(x) \hat{T}_{\mu\nu}(0) \, \mathscr{D}_{\sigma'}(y) \right] | 0 \rangle$$

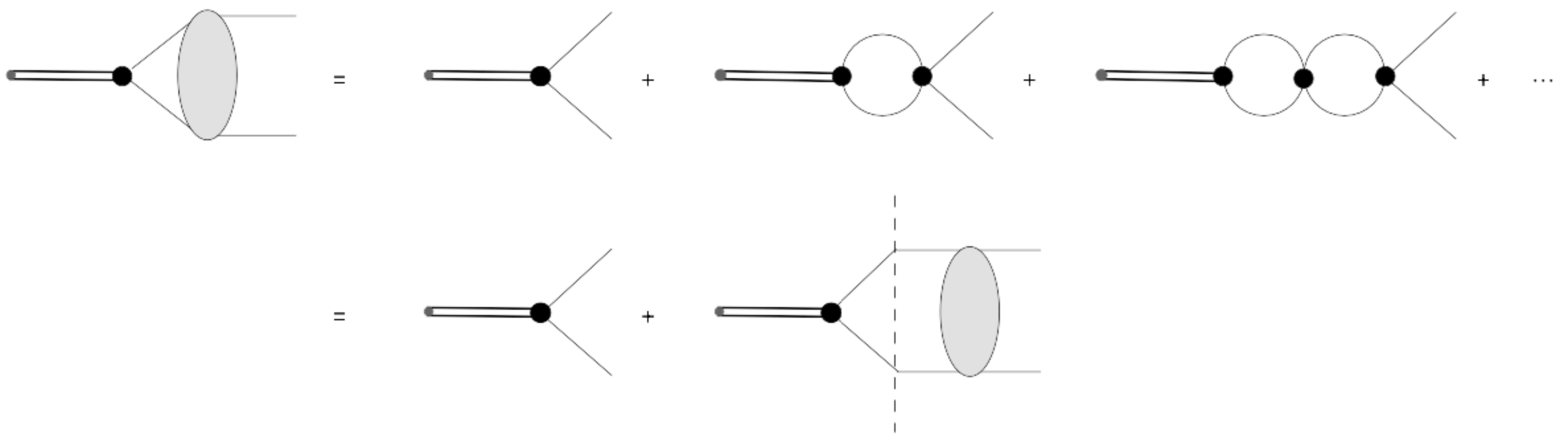
The Lehmann-Symanzik-Zimmermann (LSZ) reduction formula

$$\langle p', \sigma' | \hat{T}_{\mu\nu} | p, \sigma \rangle = -\frac{2m_D}{Z} \left[\left(p^2 - m_D^2\right) \left(p'^2 - m_D^2\right) G^{\sigma'\sigma}_{\mu\nu}(p', p) \right]_{p^2, p'^2 \to m_D^2}$$

$\mathscr{E}_0, \mathscr{E}_2, \mathscr{J}$, etc.

$m_D = 2m_N - E_b$, Z - the residue of the deuteron propagator

Lippmann-Schwinger equation on deuteron amplitude:



After integrating over zero-component:

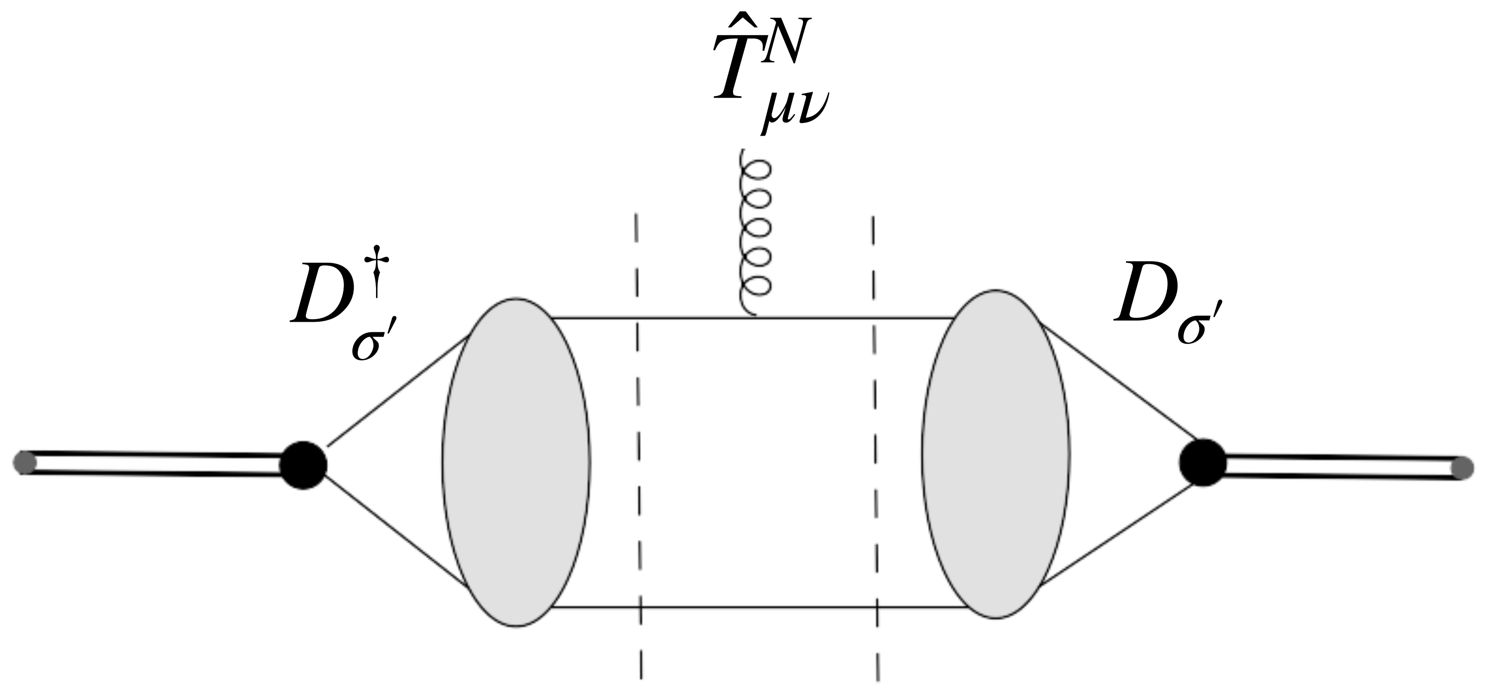
$$D^{ab}_i(\mathbf{p}) = P^{ab}_i + m_N^2 \int \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{V^{ab,cd}(\mathbf{k}, \mathbf{p}) D^{cd}_i(\mathbf{k})}{\omega_k^2 (E - 2\omega_k + i\epsilon)}$$

$$\omega_k = \sqrt{\mathbf{k}^2 + m^2}, \; E = 2\sqrt{\mathbf{p}^2 + m^2}$$

[Epelbaum, Gasparyan, Gegelia, Schindler,
Eur. Phys. J. A **50** (2014)
J.P., Epelbaum at al., Acta Phys.Polon.B 56 (2025),
J.P. , doi:10.13154/294-12206 (2024)]

Lorentz-invariant EMT and Lagrangian

$$T_{\mu\nu} = \frac{2}{\sqrt{-g}} \frac{\delta S}{\delta g^{\mu\nu}}\Bigg|_{g_{\mu\nu}=\eta_{\mu\nu}} \qquad \mathcal{L} = \frac{1}{2}\bar{\psi} i\gamma^\mu \overleftrightarrow{\partial}_\mu \psi - m_N \bar{\psi}\psi$$



Three-point function of the EMT operator at leading order

Leading order contribution to the EMT operator

$$\hat{T}^N_{\mu\nu} = \eta_{\mu\nu} m_N (\bar{\psi}\psi) - \frac{1}{2}\eta_{\mu\nu}(\bar{\psi} i \overleftrightarrow{\partial}_\alpha \gamma^\alpha \psi) + \frac{1}{4}(\bar{\psi} i \overleftrightarrow{\partial}_\mu \gamma_\nu \psi) + \frac{1}{4}(\bar{\psi} i \overleftrightarrow{\partial}_\nu \gamma_\mu \psi)$$

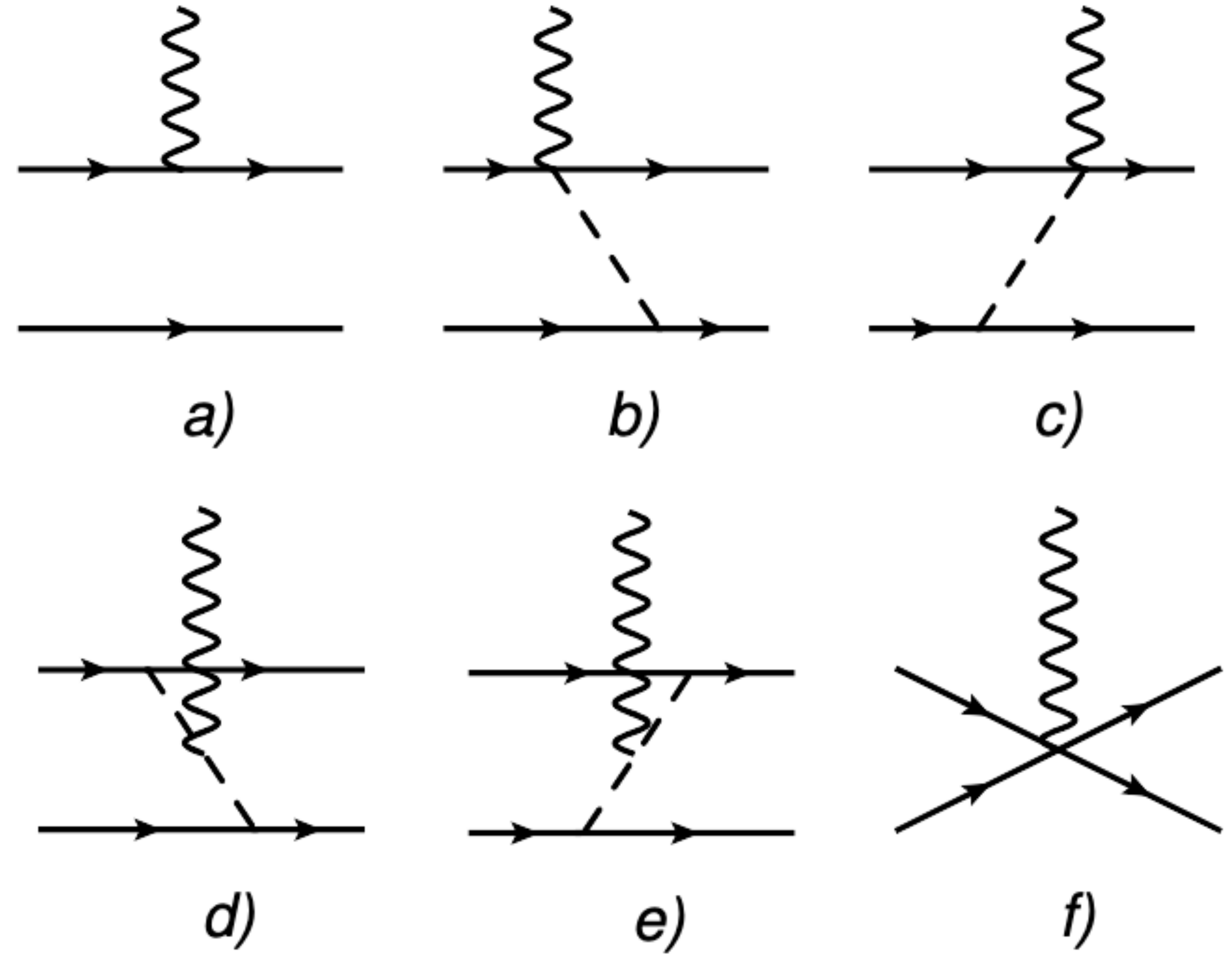
Heavy baryon reduction

$$\hat{T}^N_{00}(\mathbf{k}-\mathbf{q}/2, \mathbf{k}+\mathbf{q}/2) = m_N + \frac{\mathbf{k}^2}{2m_N} - \frac{i\epsilon_{lmn}\sigma^l \mathbf{k}^m \mathbf{q}^n}{4m_N} + \mathcal{O}(\epsilon^7),$$

$$\hat{T}^N_{0i}(\mathbf{k}-\mathbf{q}/2, \mathbf{k}+\mathbf{q}/2) = \mathbf{k}_i + \frac{1}{4} i\epsilon_{ilm}\sigma^l \mathbf{q}^m + \mathcal{O}(\epsilon^4),$$

$$\hat{T}^N_{ij}(\mathbf{k}-\mathbf{q}/2, \mathbf{k}+\mathbf{q}/2) = \frac{\mathbf{k}_i\mathbf{k}_j}{m_N} + \frac{i\sigma^k \mathbf{q}^m}{4m_N}(\mathbf{k}_i\epsilon_{jkm} + \mathbf{k}_j\epsilon_{ikm}) + \mathcal{O}(\epsilon^7).$$

$$m_N \sim O\left(\frac{1}{\varepsilon}\right) \qquad p \sim O(\varepsilon)$$



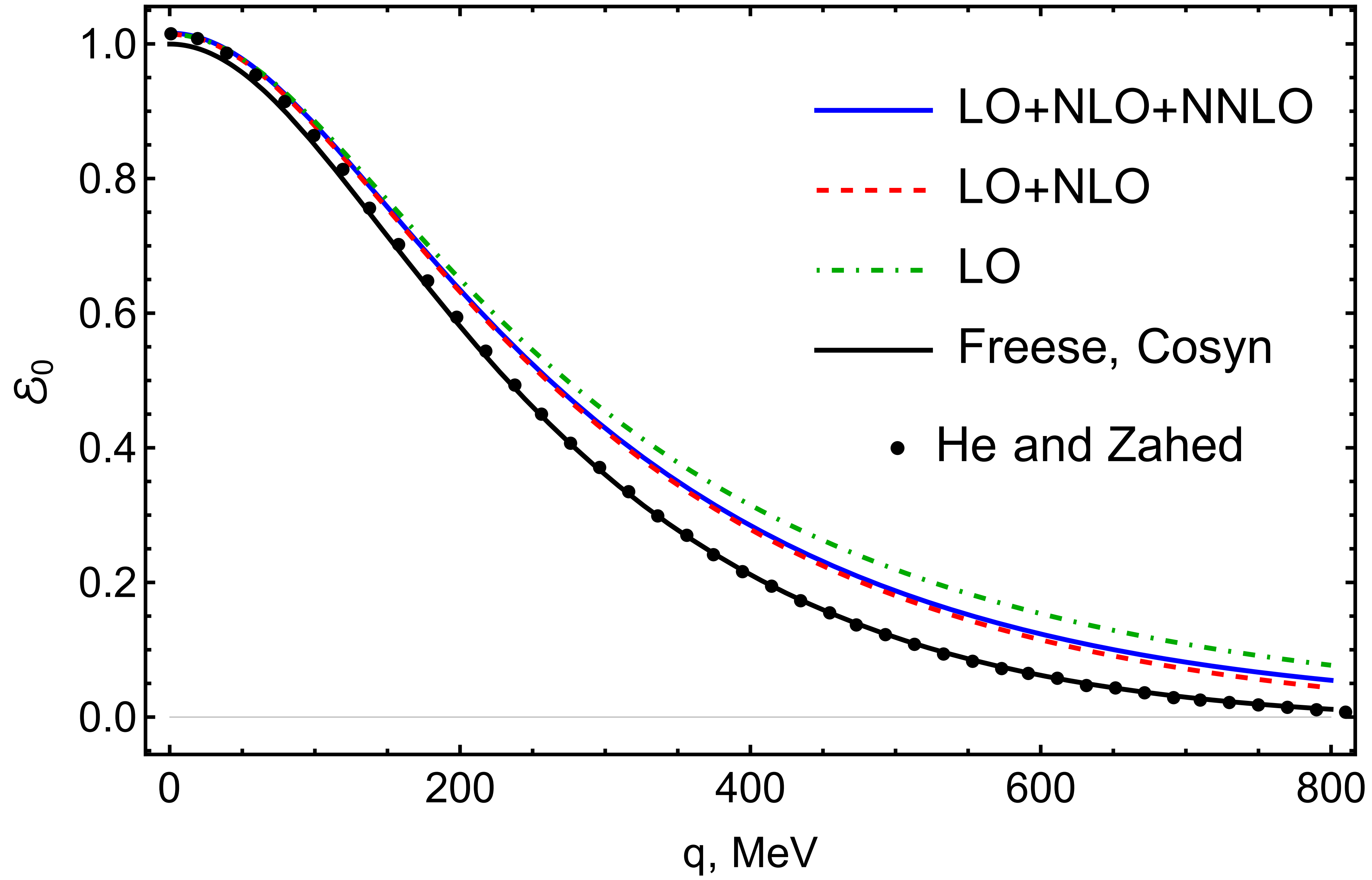
Tree-level time-ordered diagrams

Three-point function of the EMT operator

$$G^{\sigma\sigma',N}_{\mu\nu}(-\mathbf{q}/2,\mathbf{q}/2) = 4m_N^2 \int \frac{d^3k}{(2\pi)^3} \frac{D^{\dagger ab}_\sigma(\mathbf{k}-\mathbf{q}/4)\hat{T}^{N,ca}_{\mu\nu}(\mathbf{k}+\mathbf{q}/2,\mathbf{k}-\mathbf{q}/2)D^{cb}_{\sigma'}(\mathbf{k}+\mathbf{q}/4)}{((\mathbf{k}+\mathbf{q}/4)^2+B)((\mathbf{k}-\mathbf{q}/4)^2+B)}$$

[J.P., Epelbaum at al., Acta Phys.Polon.B 56 (2025), J.P. , doi:10.13154/294-12206 (2024)]

Results



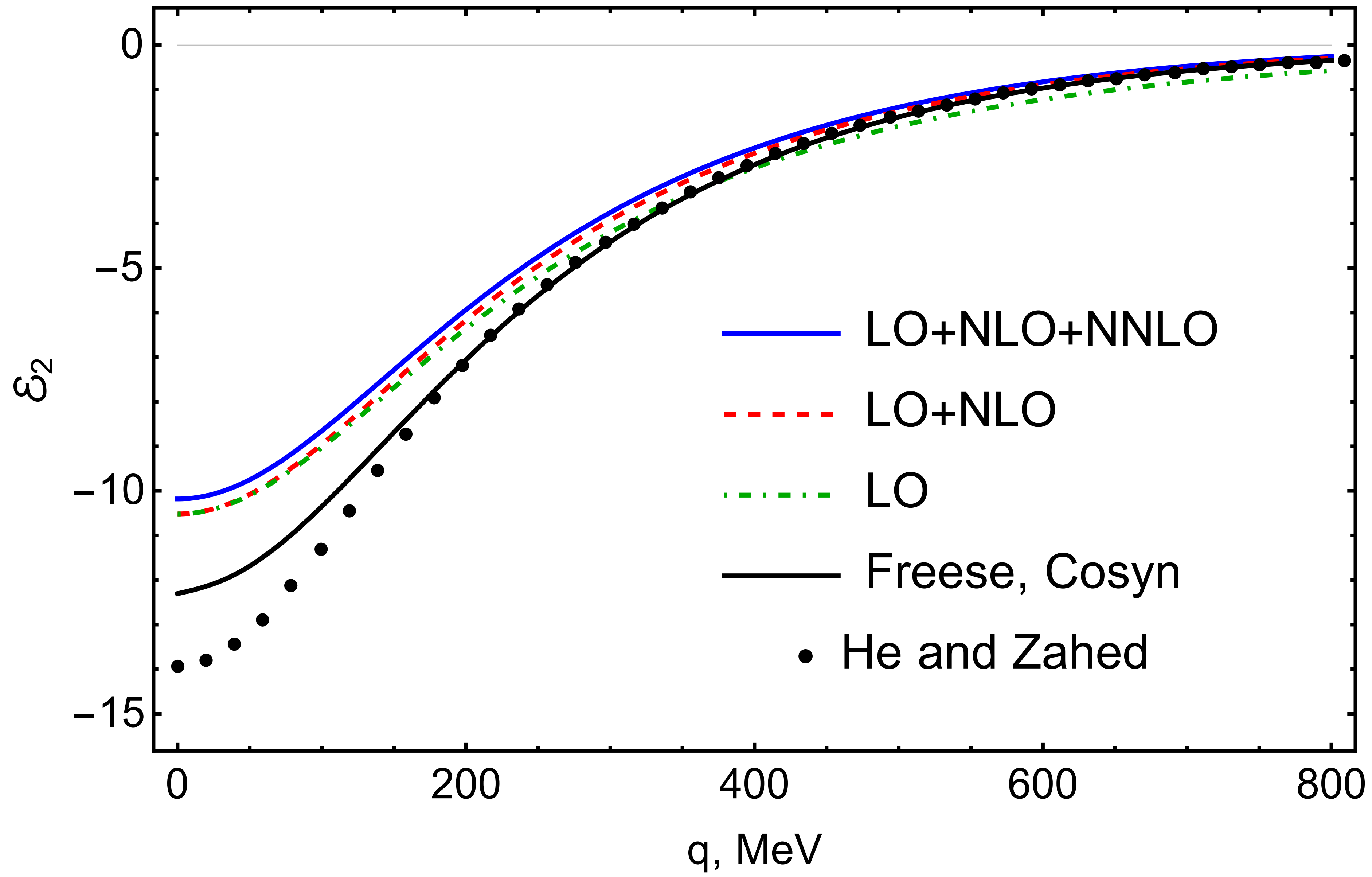
[J.P., Epelbaum at al., Acta Phys.Polon.B 56 (2025),
J.P. , doi:10.13154/294-12206 (2024),
F. He and I. Zahed, Phys. Rev. C 110 (2024),
A. Freese and W. Cousin, *Phys.Rev.D* 106 (2022),
A. Freese and W. Cosyn ,2602.18298 (2026)]

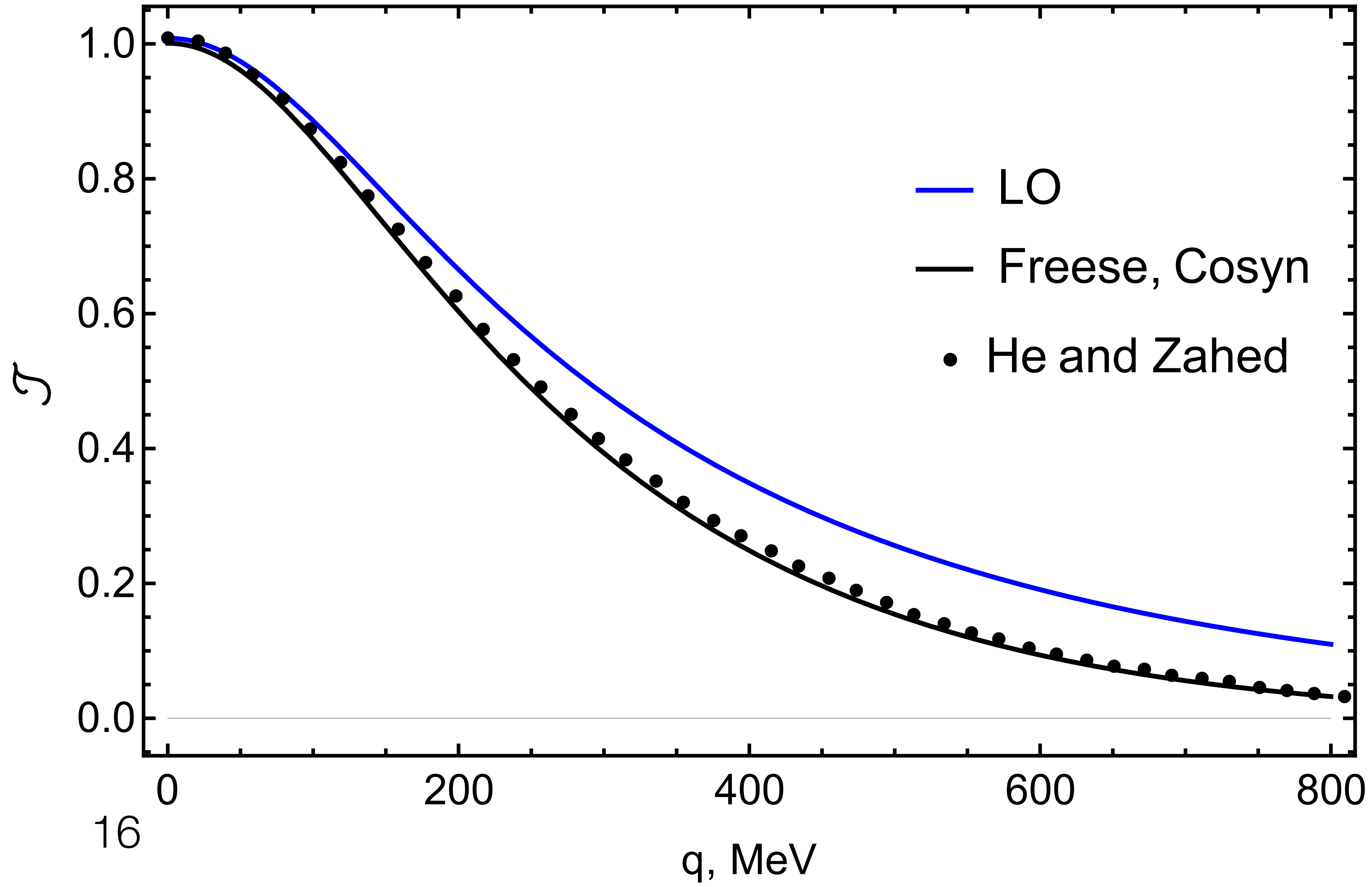
$C_T + C_S$ is fixed by E_b

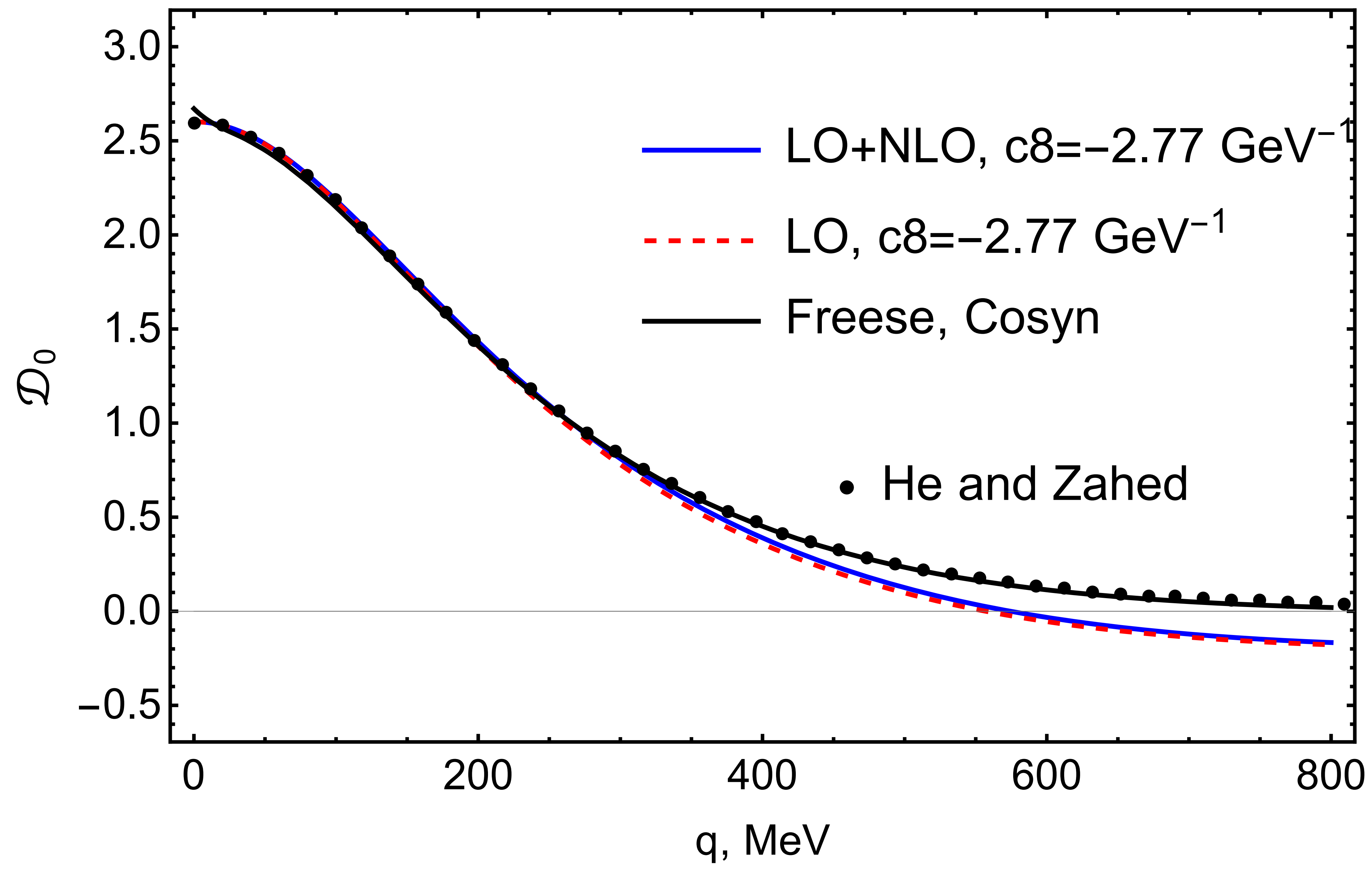
Smooth cutoff $\Lambda = 500$ MeV

Our EMT is not conserved,
however the effect is small for $\Lambda = 400 - 600$ MeV

NNLO is not complete!
Relativistic corrections to the three-point function are needed







[J.P., Epelbaum at al., Acta Phys.Polon.B 56 (2025),
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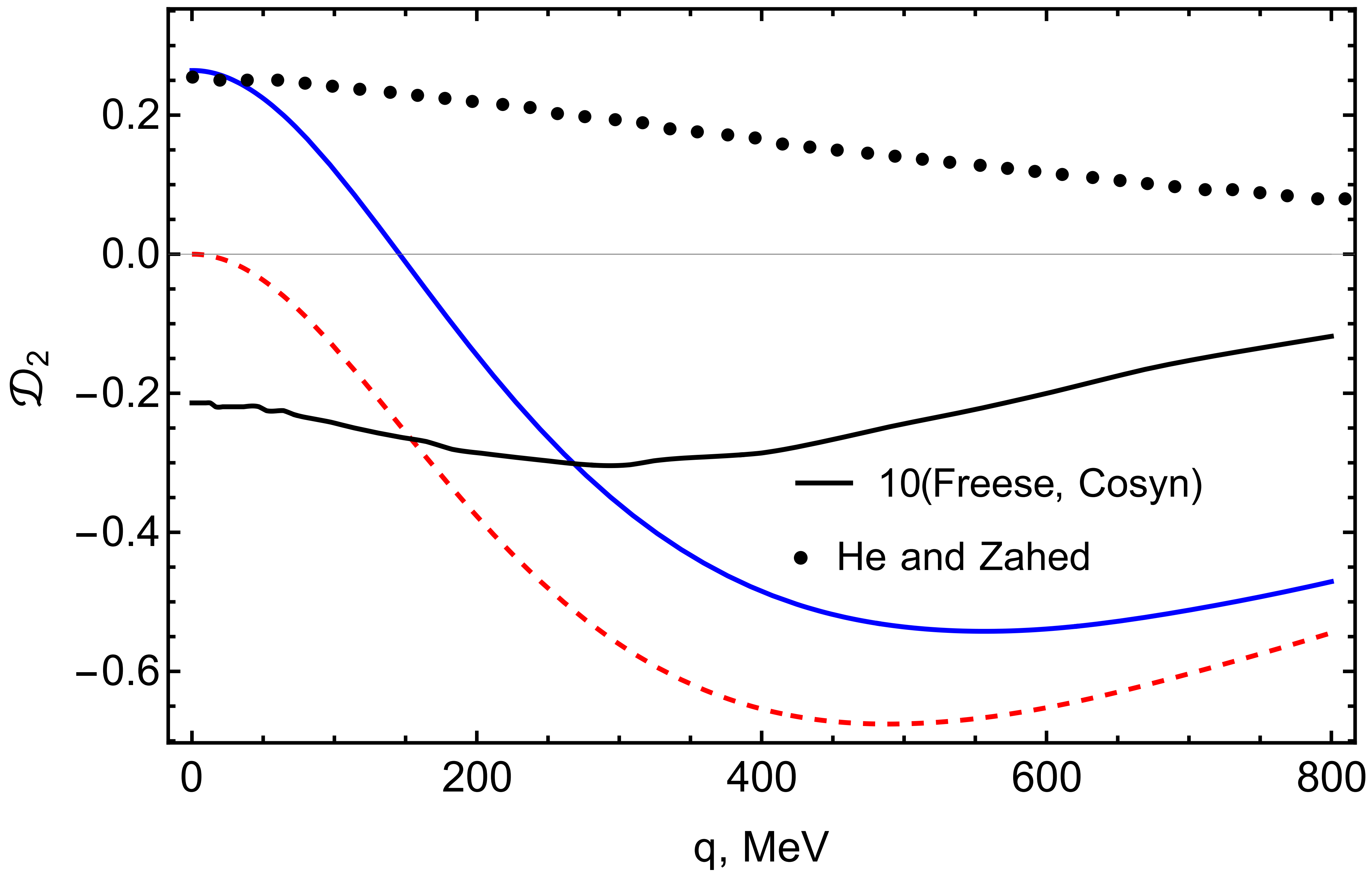
A. Freese and W. Cosyn, *Phys.Rev.D* 106 (2022),
A. Freese and W. Cosyn ,2602.18298 (2026)]

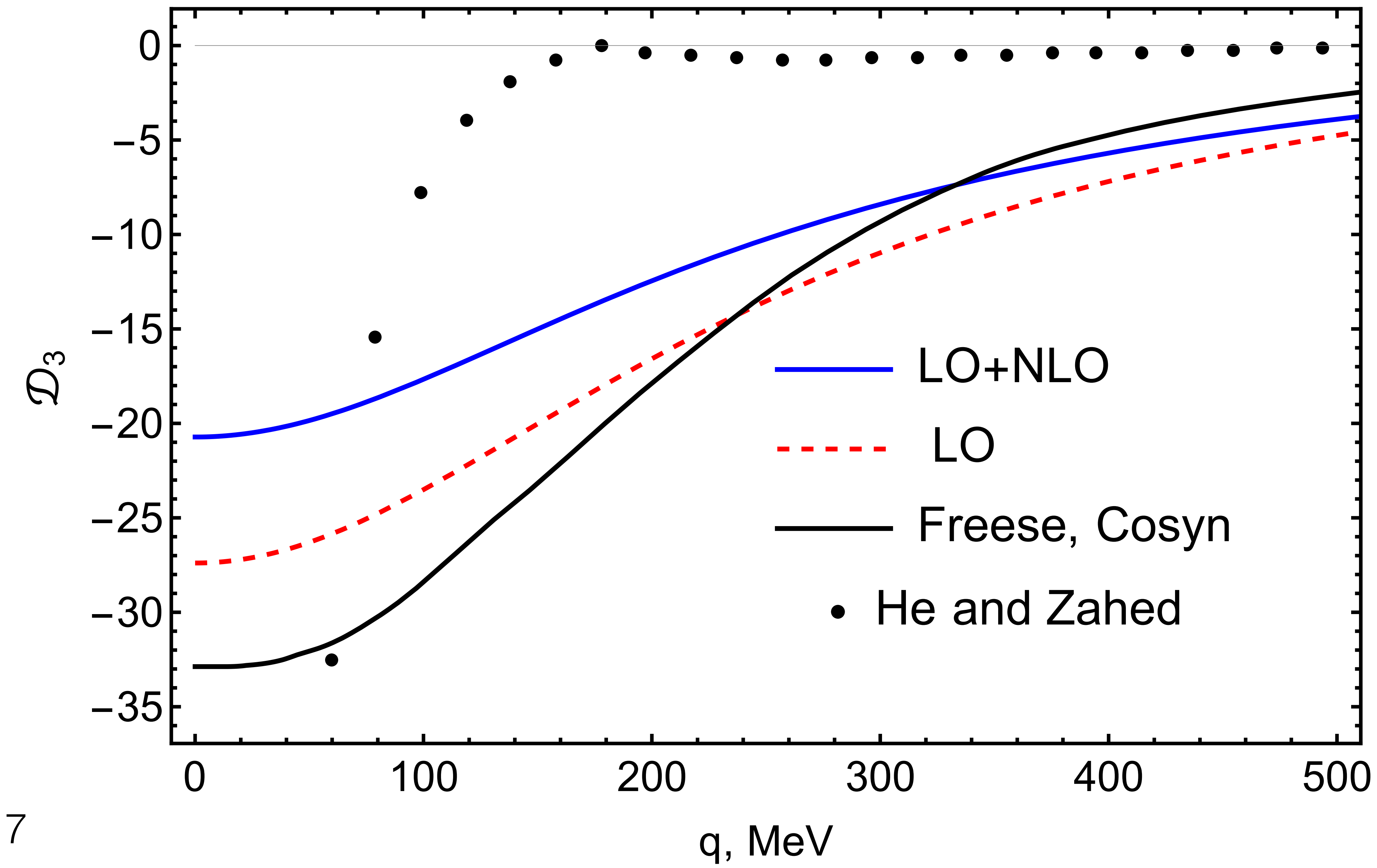
We fix $c_8 = -2.77\ \mathrm{GeV}^{-1}$

$c_8 = -4.28 \pm 0.37\ \mathrm{GeV}^{-1}$
[Cao at al.,
arXiv:2507.05375]

NLO is not complete!

NLO Lagrangian of the NN contact interaction is needed



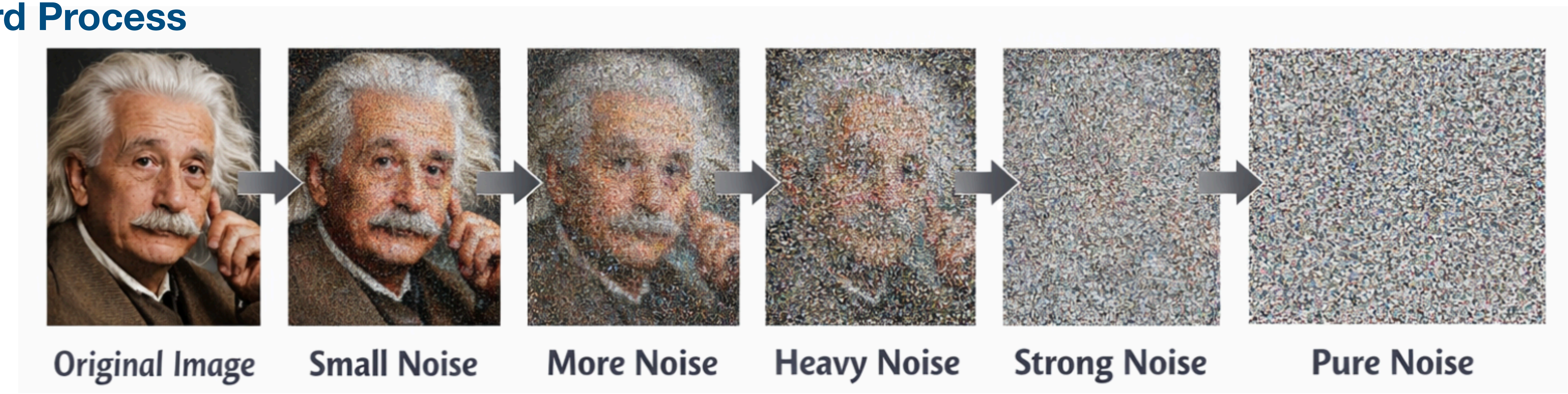


Reconstruction of the GFFs using Generative Mashing Learning

Diffusion Model

Forward Process

x_0

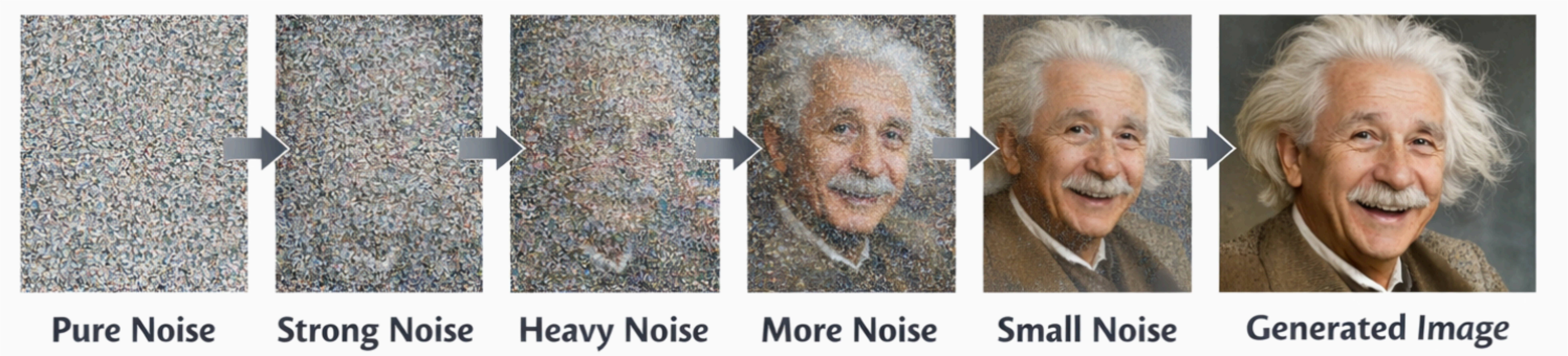


x_T

The neural Network learns to correctly identify what noise was added at each step

Reverse Sampling

x_T



$\hat{x}_0$

Pipeline Overview

From physics-motivated functions to generated form factors with uncertainties

1 — Define Base Functions

$$\frac{\mathrm{GF}(0)}{(1 - t/M^2)^n}$$

$$\vdots$$

$$\mathrm{GF}(0)\,\frac{3j_1(R\sqrt{-t})}{R\sqrt{-t}}\,e^{-\beta(-t)}$$

with random coefficients

$N_t = 200$ in

$0 \leq -t \leq 2\ \mathrm{GeV}^2$

→

2 — Generate Training Data

(Synthetic FFs)

6×10^4

curves per class

In total:

6×10^5

training samples

6×10^3

validation samples

Normalised on: $\mu = 0,\ \sigma = 1$

→

3 — Train the Model

The network:

f_θ

ResNet-Attention Hybrid

Input:

1. FFs
2. Noise
3. Conditions

Output:

19×10^6

learned parameters

→

4 — Generation

Input:

1. Pure noise
2. Conditions

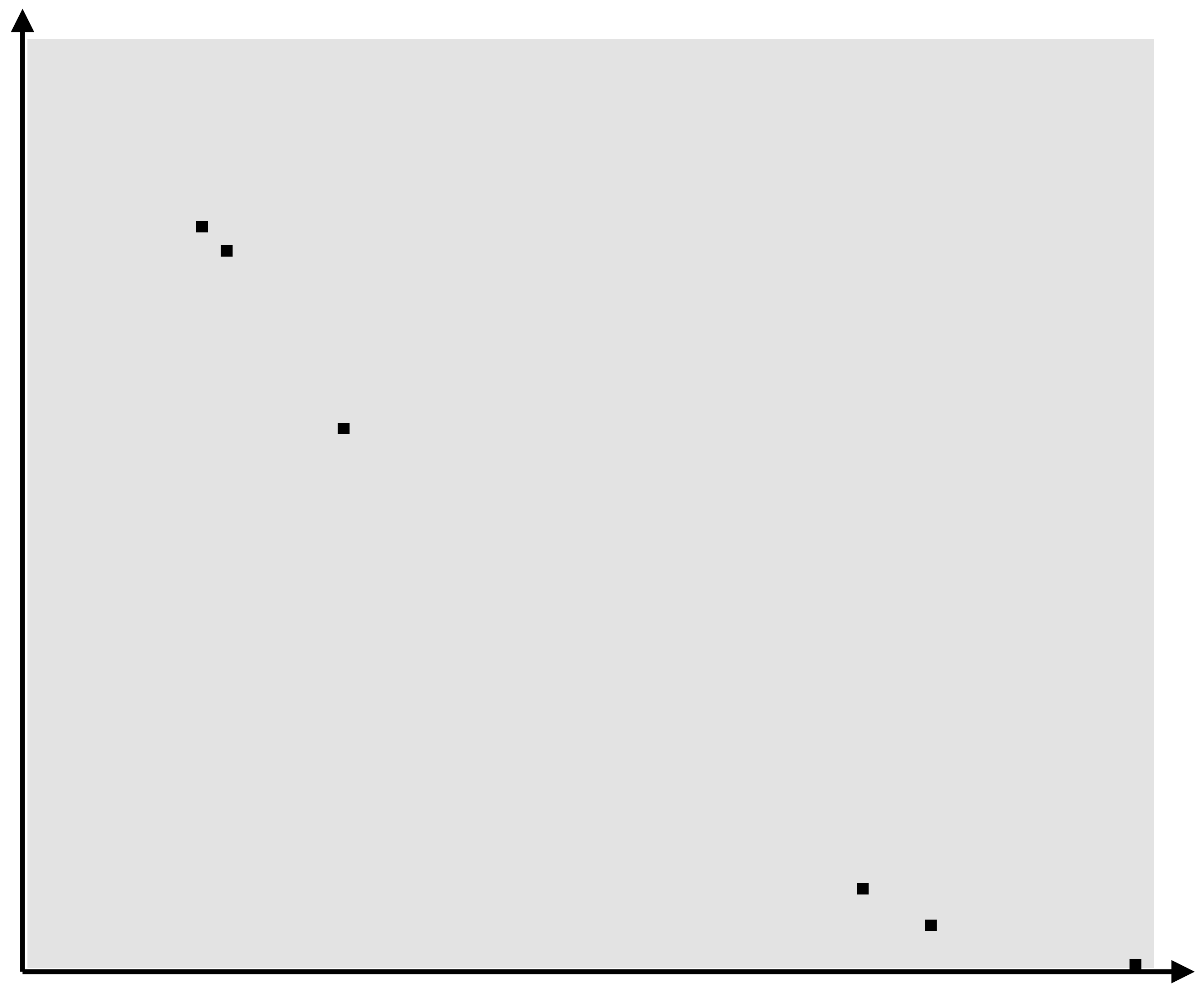
Output:

The predicted FFs

with uncertainties

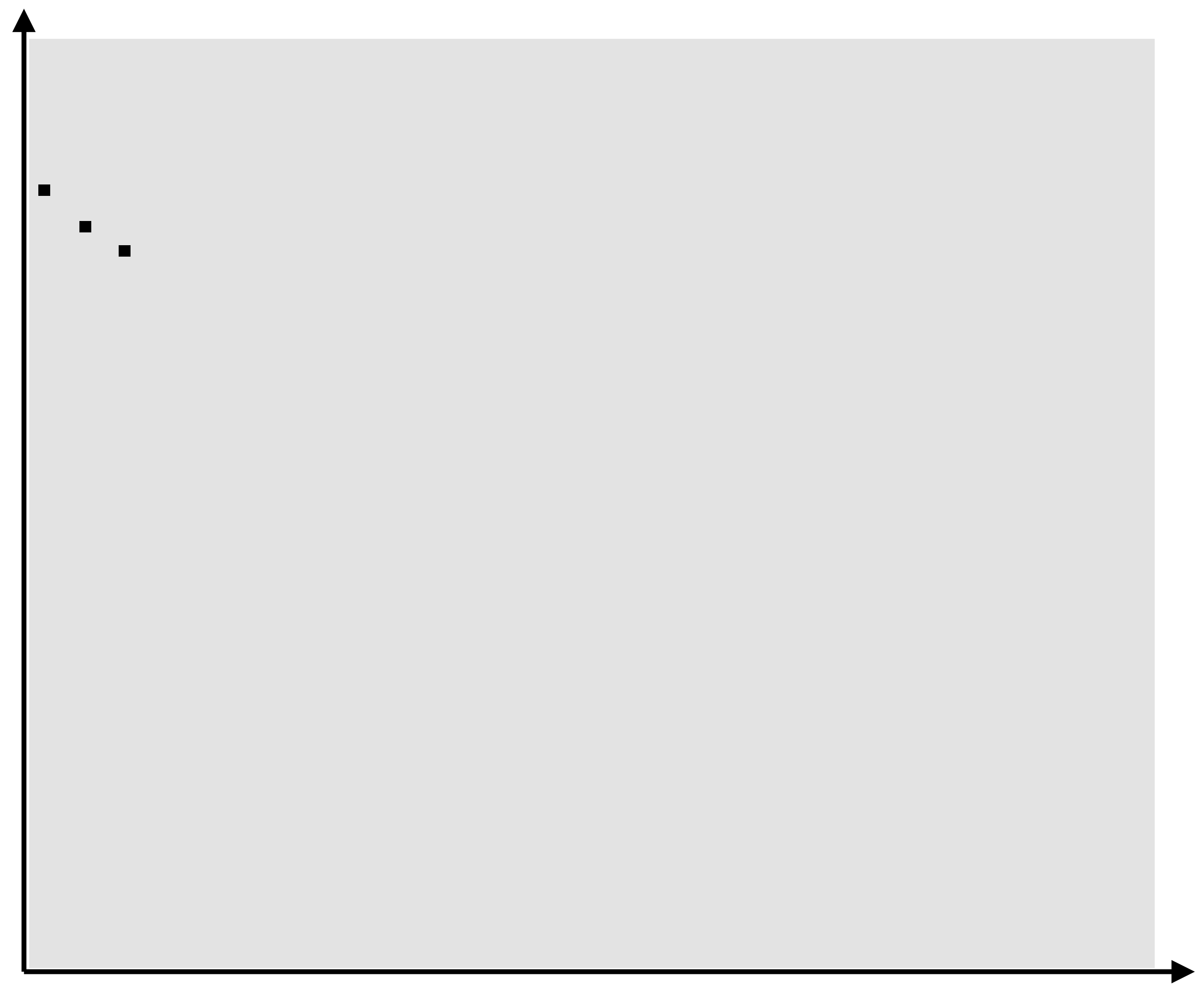
Conditioning Strategies

Random mask



- 50 % of training data
- keep 5–30 randomly chosen points **across the full curve** as clean values

Clustered mask

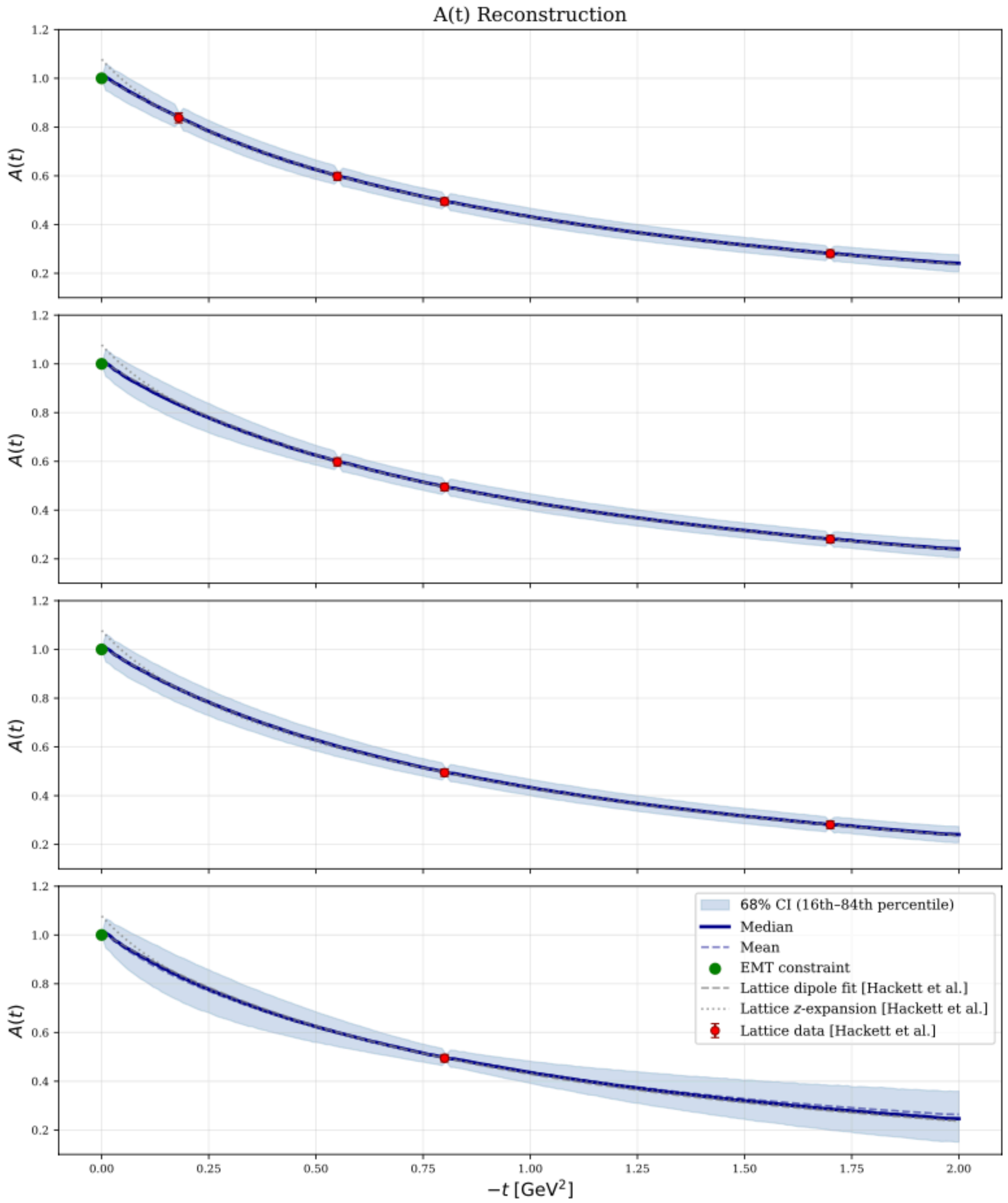


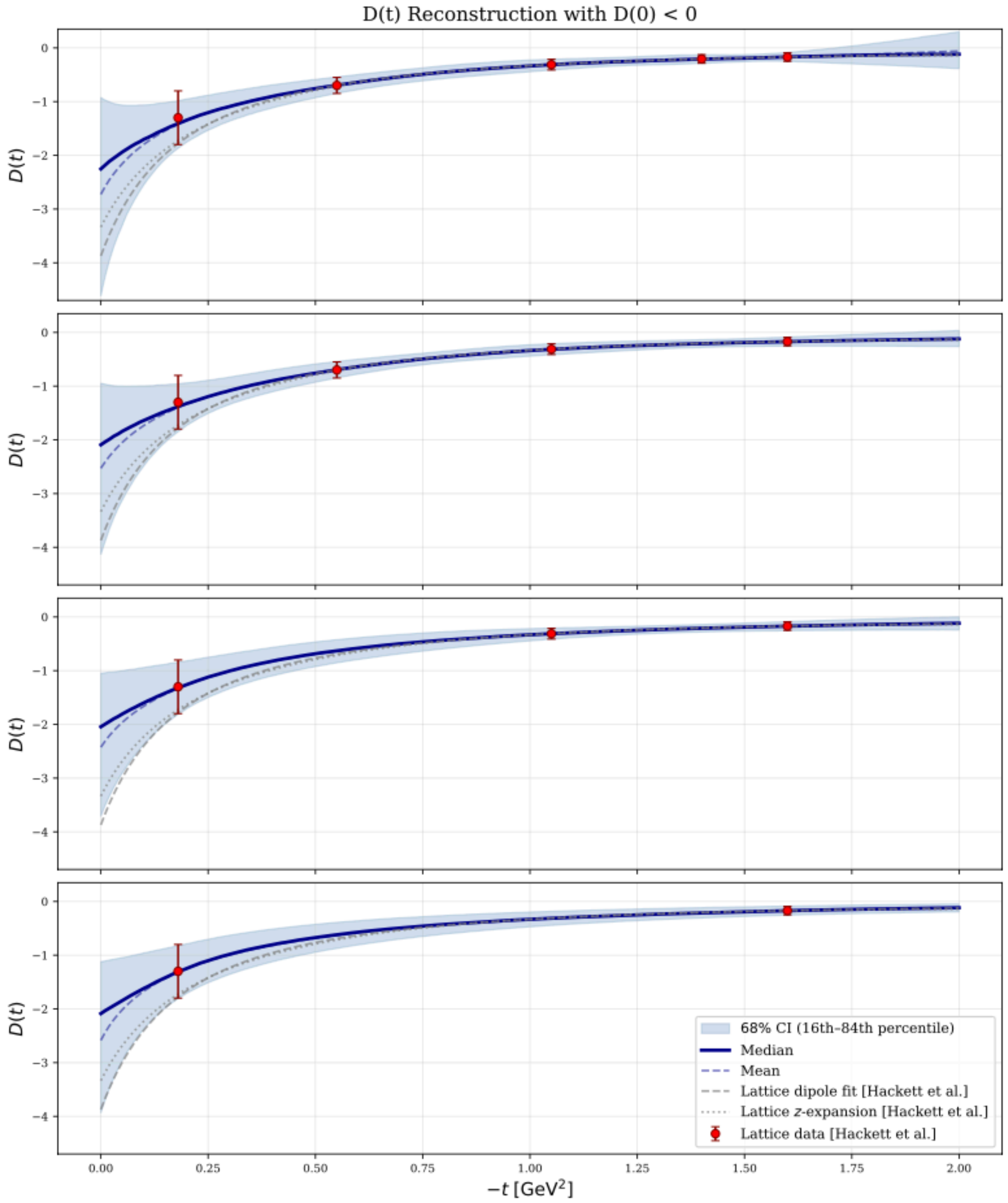
- 30 % of training data
- clean values at 5–15 random positions from the **first 30% of the grid**
- **low-energy region**

Unconditional

- 20 % of training data
- no conditioning at all
- prevents from becoming over-reliant on conditioning

[H. Alharazin and J.P., arXiv:2602.19267 (2026)]





Extraction of c_8 and c_9

[Cao at al., arXiv:2507.05375]

[H. Alharazin and J.P., arXiv:2602.19267 (2026)]

the ChPT expressions

$$c_8 = -4.28 \pm 0.37\ \mathrm{GeV}^{-1}$$
$$c_9 = -0.68 \pm 0.05\ \mathrm{GeV}^{-1}$$

$$c_8 = -4.6 \pm 0.8\ \mathrm{GeV}^{-1}$$
$$c_9 = -0.61 \pm 0.19\ \mathrm{GeV}^{-1}$$

$$\begin{aligned} A(t) &= 1 + s_A t + \mathcal{O}(t^2)\,, \\ J(t) &= \frac{1}{2} + s_J t + \mathcal{O}(t^2)\,, \\ D(t) &= D(0) + s_D t + \mathcal{O}(t^2)\,. \end{aligned}$$

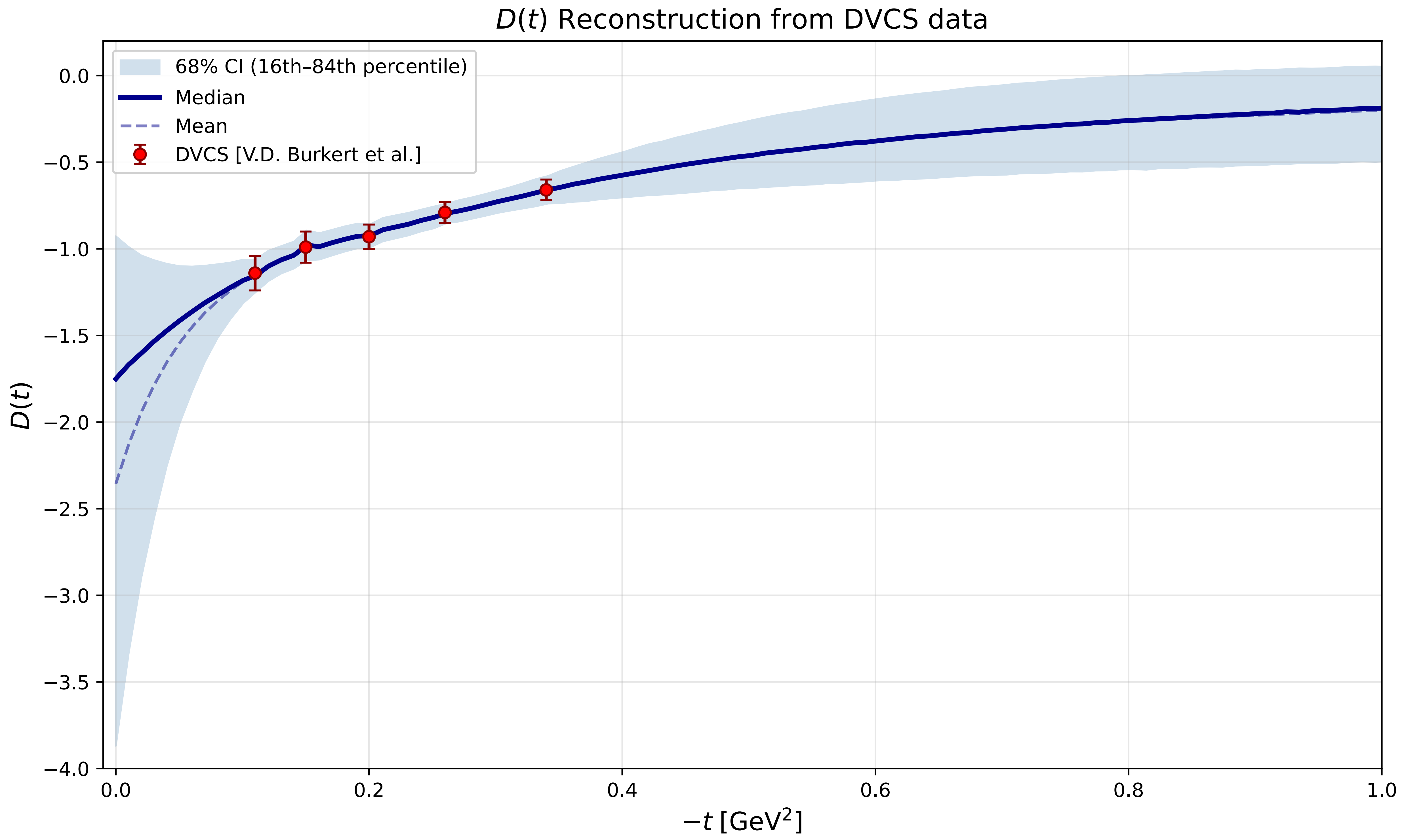
$$\begin{aligned} s_A &= -\frac{7g_A^2}{128\pi F^2 m_N} M_\pi + \frac{\left(c_2 m_N - 4g_A^2\right)}{16\pi^2 F^2 m_N^2} M_\pi^2 \ln\left(\frac{M_\pi}{m_N}\right) - \frac{3g_A^2\left(2c_9 m_N + 1\right)}{32\pi^2 F^2 m_N^2} M_\pi^2 + \mathcal{O}(M_\pi^3)\,, \\ s_J &= -\frac{g_A^2}{32\pi^2 F^2} \ln\left(\frac{M_\pi}{m_N}\right) + \frac{g_A^2\left(4c_9 m_N - 5\right)}{64\pi^2 F^2} + \frac{7g_A^2}{128\pi F^2 m_N} M_\pi + \mathcal{O}(M_\pi^2)\,, \\ s_D &= -\frac{g_A^2 m_N}{40\pi F^2}\frac{1}{M_\pi} - \frac{\left(5g_A^2 + 4\left(c_2 + 5c_3\right) m_N\right)}{80\pi^2 F^2} \ln\left(\frac{M_\pi}{m_N}\right) + \frac{g_A^2\left(24 + (15c_8 + 40c_9) m_N\right)}{480\pi^2 F^2} \\ &+ \frac{\left(4c_1 - c_2 - 7c_3\right) m_N}{40\pi^2 F^2} + \mathcal{O}(M_\pi)\,. \end{aligned}$$

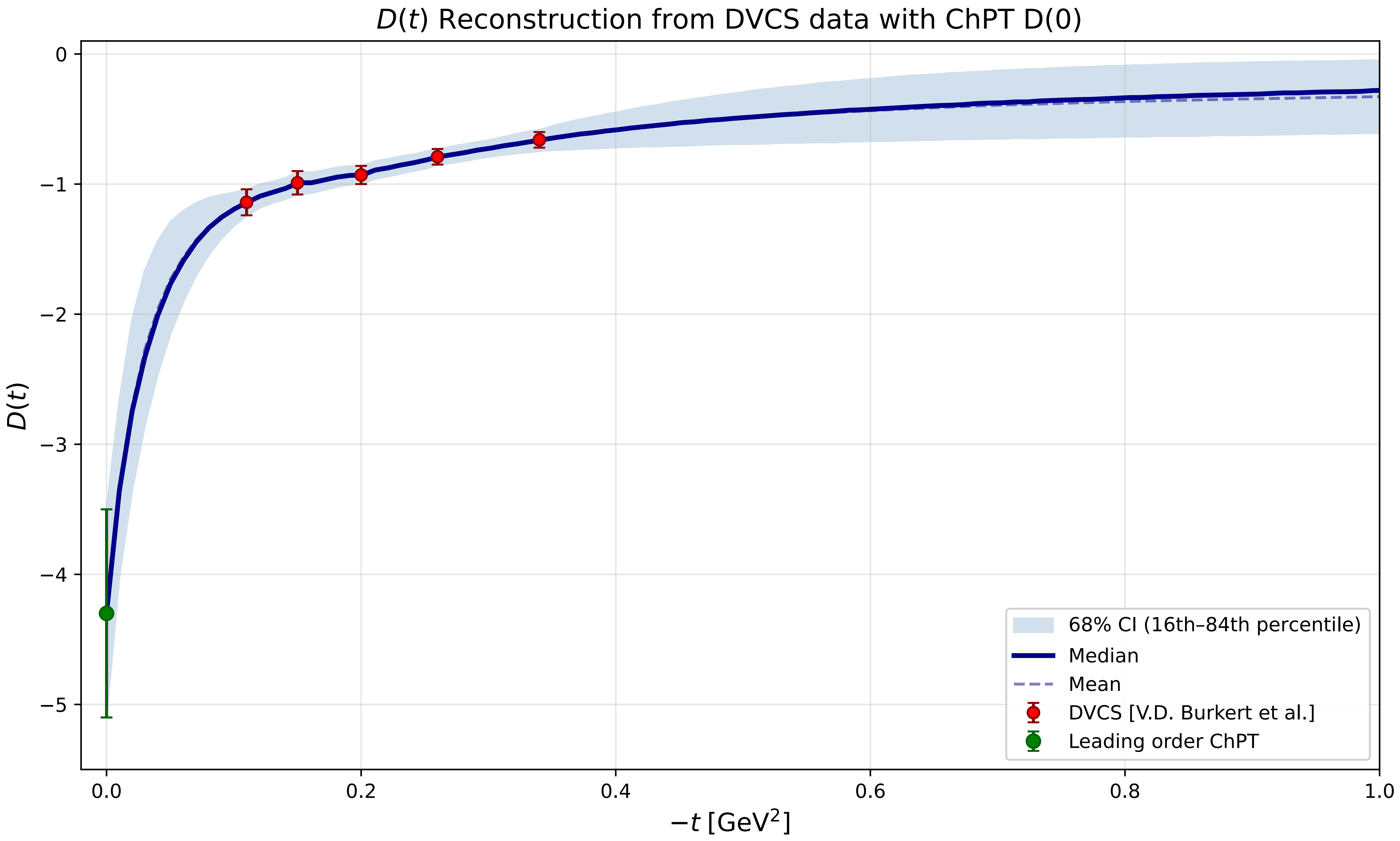
$$-t \in [0,\ 100]\ \mathrm{MeV}^2$$

[H. Alharazin et al., *Phys.Rev.D* 102 (2020) 7]

Reconstruction from the DVCS data and ChPT

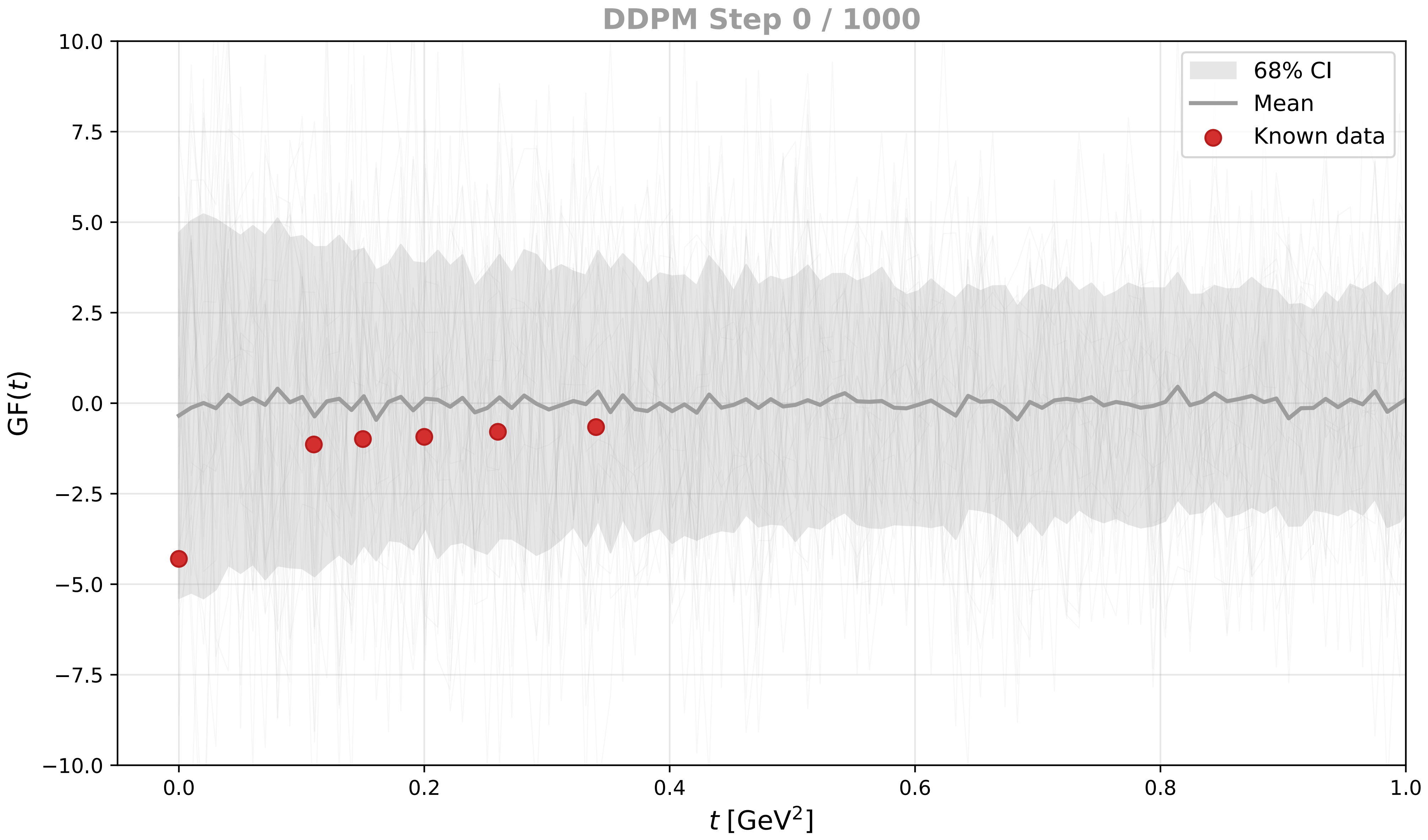
[H. Alharazin and J.P., arXiv:2602.19267 (2026)]

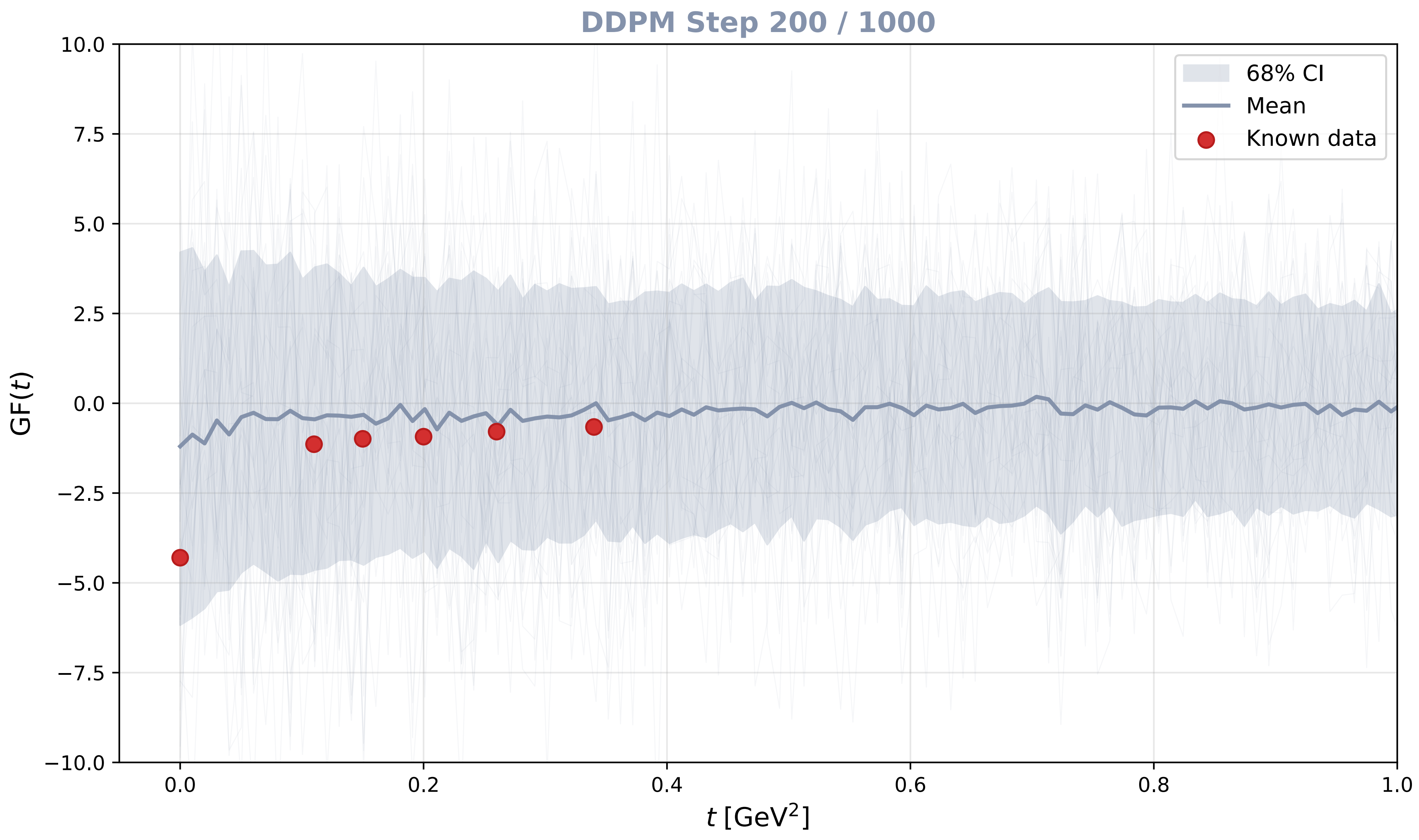


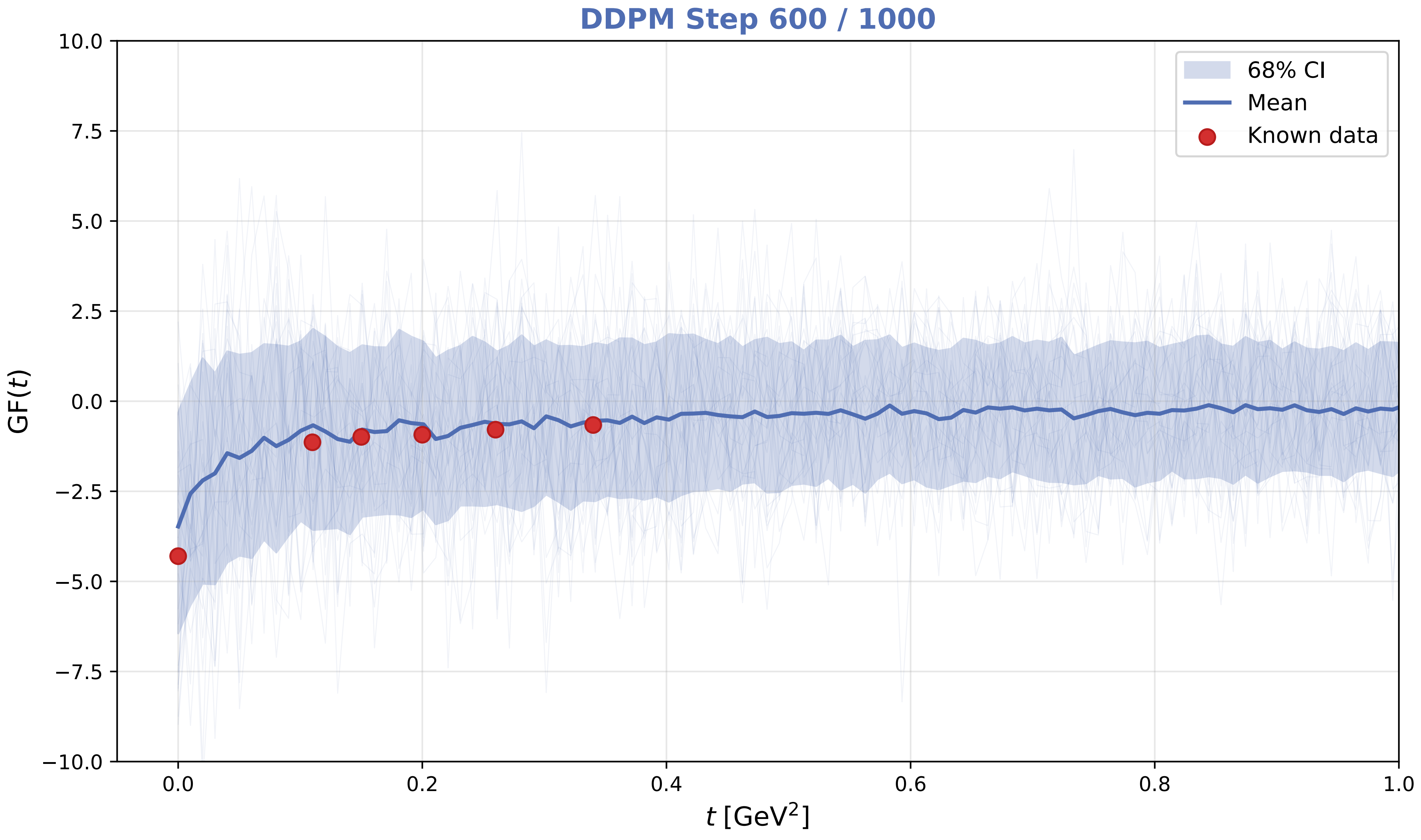


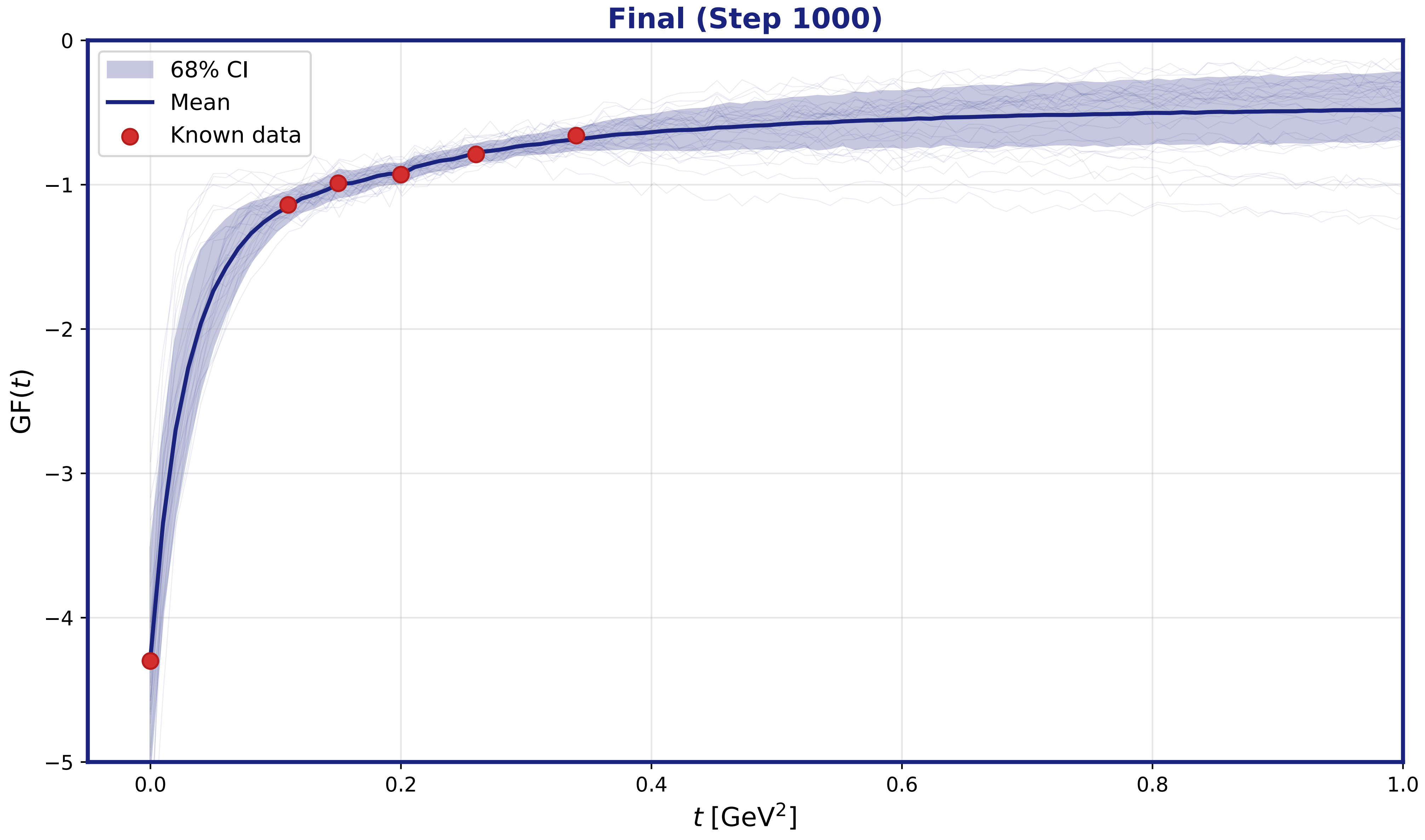
[V. D. Burkert et al., arXiv:2104.02031 (2021)]

Link: Reconstruction live









Summary and Outlook

- First part: why gravitational form factors are interesting and important to study

- Second part: I discussed the calculation of the GFFs of the deuteron within chiral EFT
  - $\mathscr{E}_0$, $\mathscr{J}$, and $\mathscr{D}_0$ are consistent with existing model calculations
  - $\mathscr{D}_2$ and $\mathscr{D}_3$ form factors need to be improved by including NLO contributions to the NN contact interaction
  - we need to apply the symmetry preserving cutoff

- Last part: I presented a new approach for reconstructing GFFs using AI
  - this method can also be applied to other hadrons, including the deuteron
  - the reconstruction of GPDs using this approach

- We look forward to the results and to feedback from the scientific community

Thank you for your attention!