

Precision Theory for Strong Interaction Physics

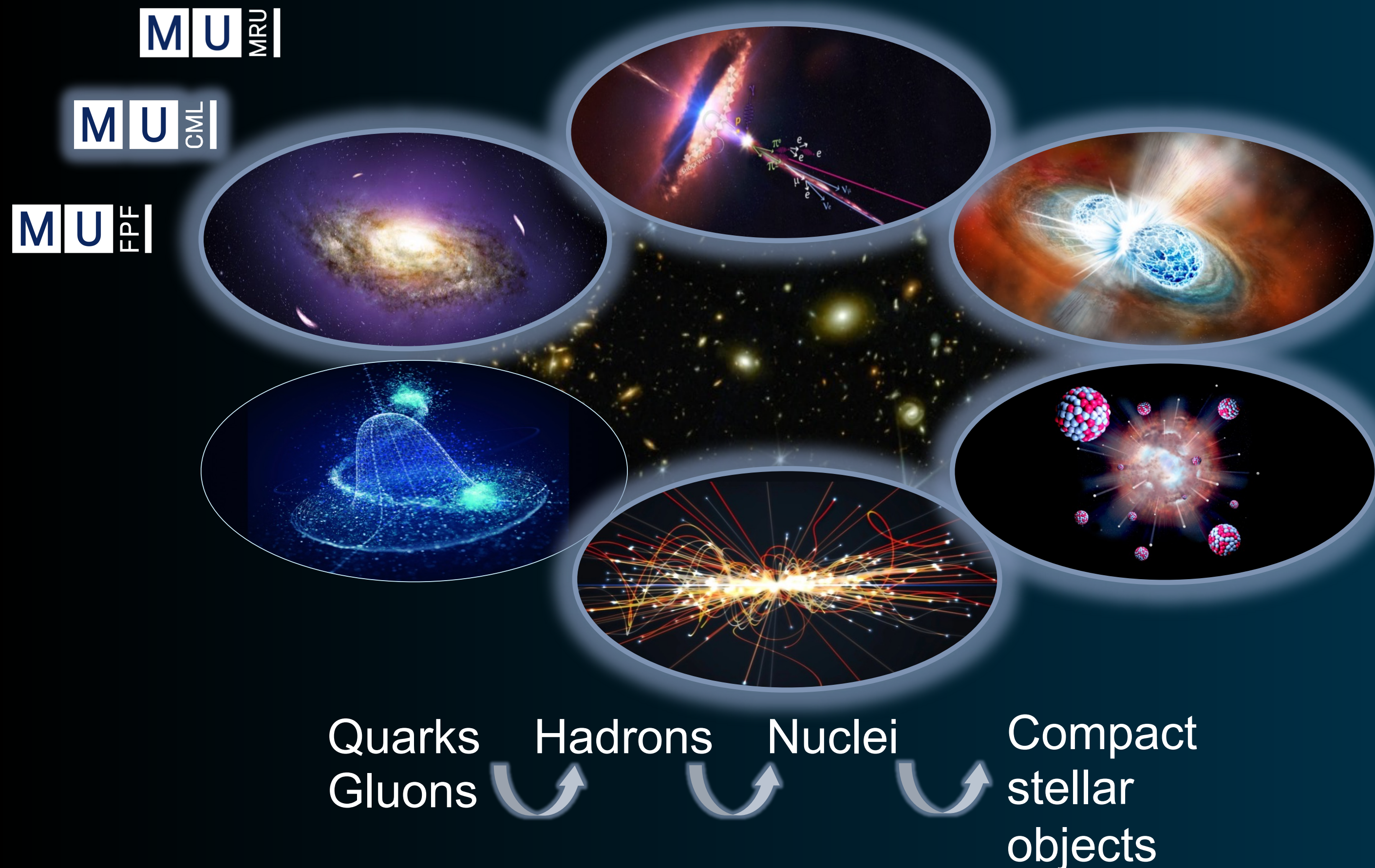
Hartmut Wittig

Helmholtz Institute Mainz and Institute for Nuclear Physics, University of Mainz

MU Days@GSI, 19–20 Oct 2026

CML Mission

“Understand the complex phenomena governed by the strong interaction in the non-perturbative regime of Quantum Chromodynamics (QCD)”

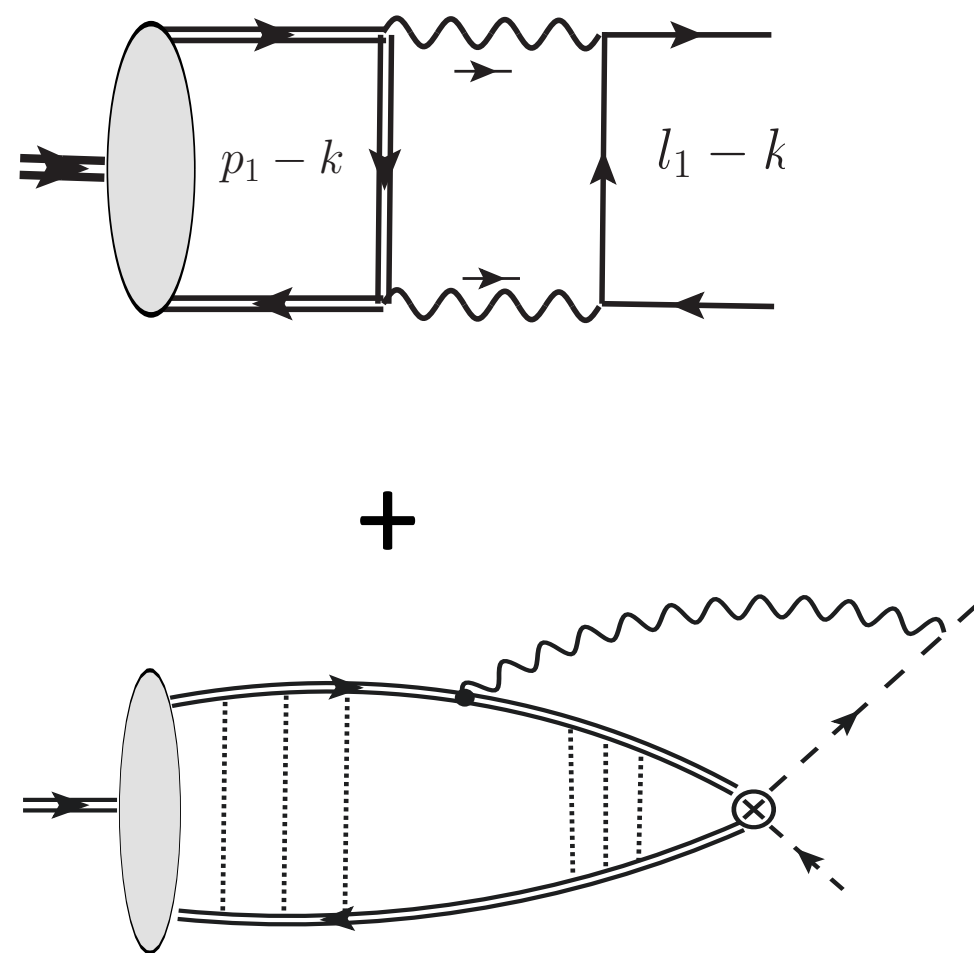


- Understand the **properties of matter** arising from the **strong interaction**
- Explain the **nucleosynthesis of the elements** in the Universe
- Search for physics **beyond the Standard Model** through low-energy precision experiments

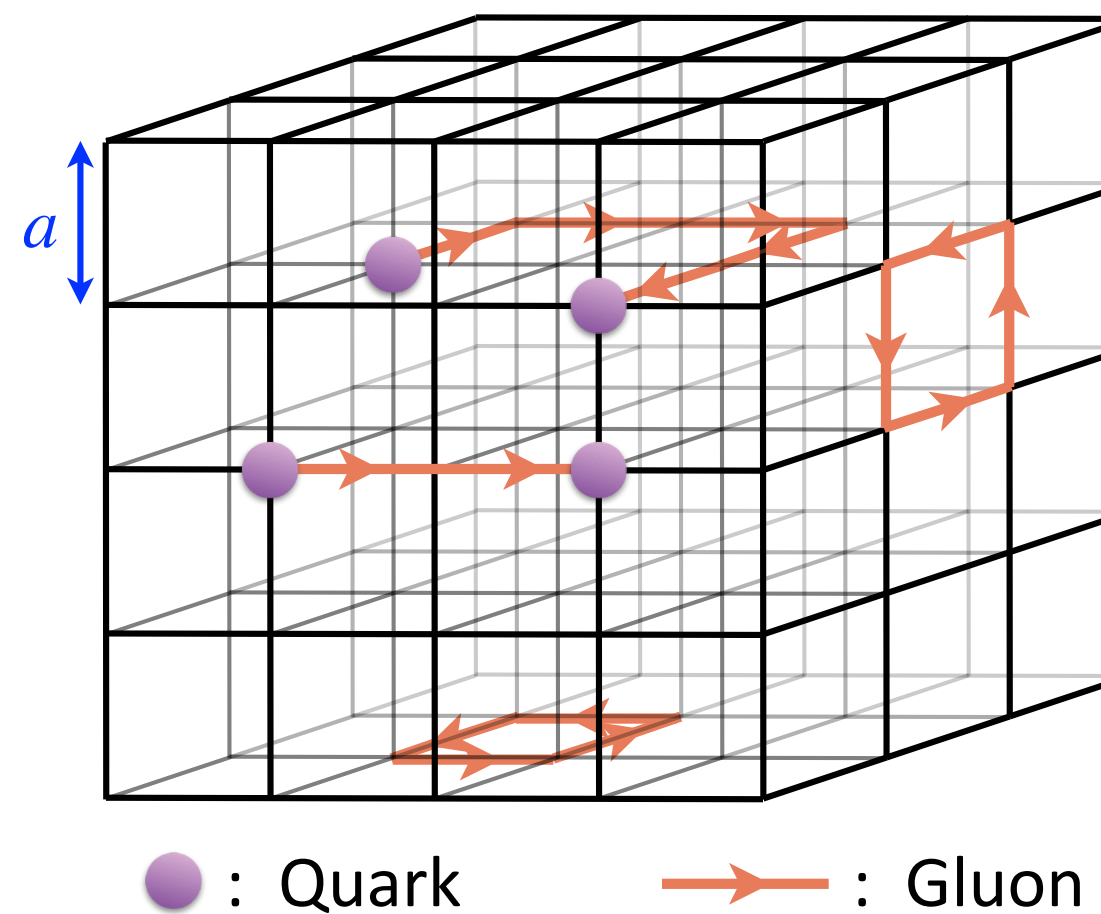
Theoretical framework

Make model-independent predictions for hadronic observables starting from the QCD Lagrangian or its EFT representation

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu} + \sum_{f=u,d,s,\dots} \bar{\psi}_f (i\gamma^\mu D_\mu - m_f) \psi_f, \quad D_\mu = \partial_\mu \mathbf{1} - ig\left(\frac{1}{2}\lambda^a\right)A_\mu^a$$



QCD factorisation



Lattice QCD

NN	3N	4N
X H	—	—
X H K X H	—	—
H K H K	H H H X X	—

Effective Field Theory

This talk

Hadronic contributions to precision observables

- Muon $g - 2$; Running of fine-structure constant and weak mixing angle

Hadron Structure

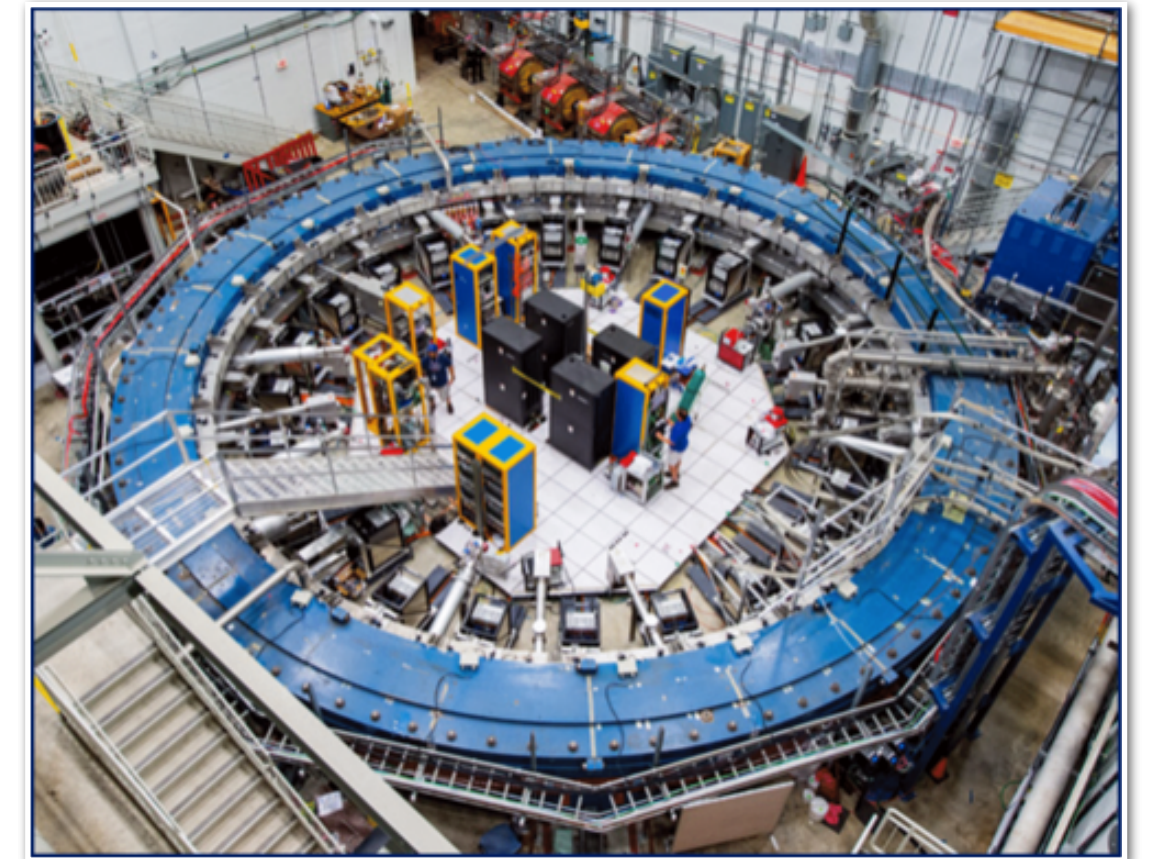
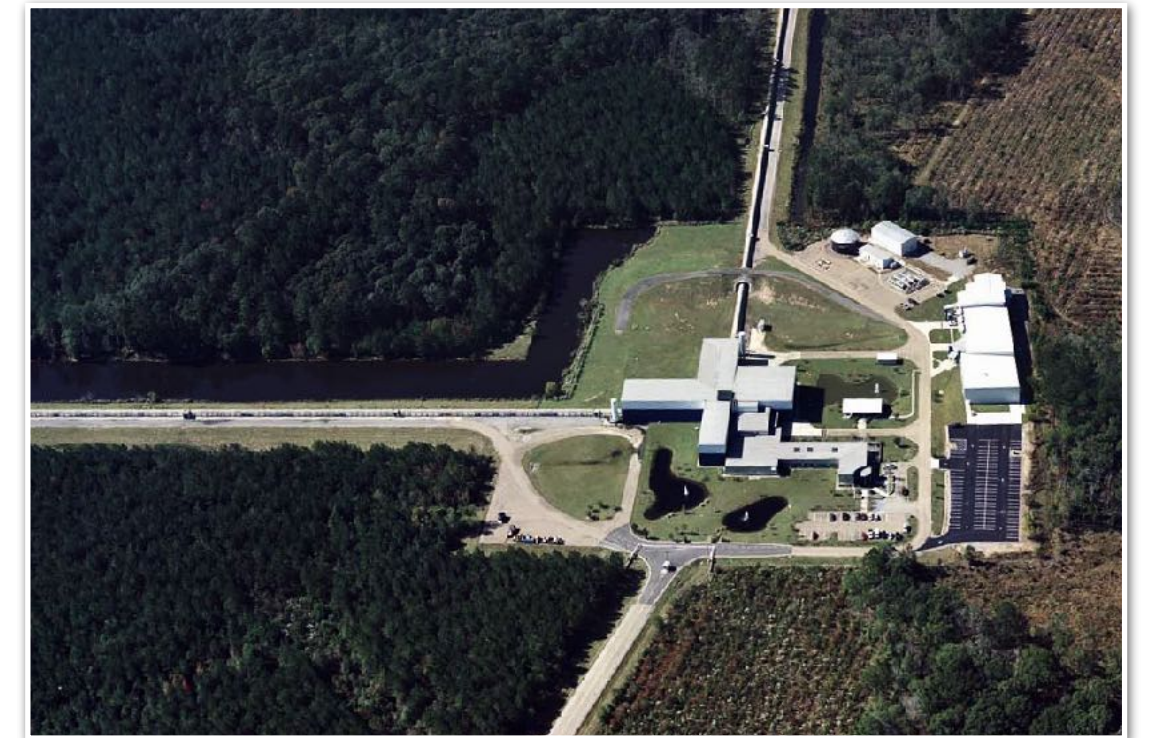
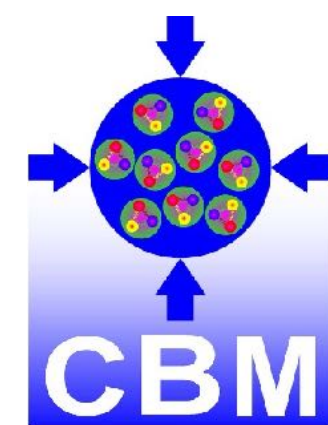
- Form factors; Proton and atomic radii; Nucleon charges and σ -terms

Hadron Spectroscopy

- Baryon-baryon interactions

Nuclear Astrophysics

- Multimessenger signals for neutron star mergers; QCD phase diagram

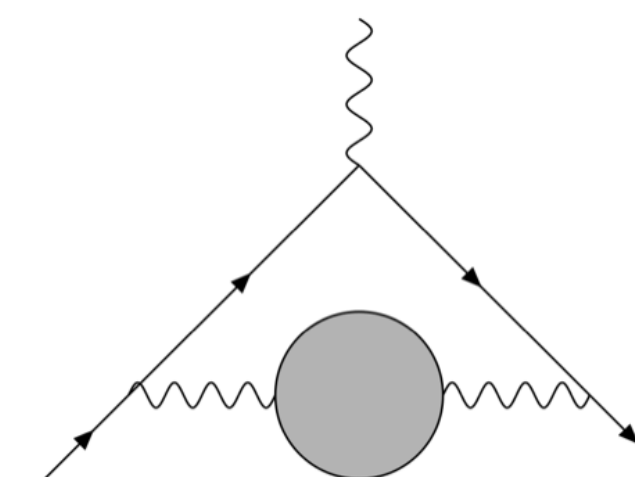


Hadronic contributions to precision observables

Muon $g - 2$: Major activity of theorists and experimentalists at HIM / JGU:

- Measurement of hadronic cross sections at BESIII — data-driven SM prediction
- Lattice QCD calculations: vacuum polarisation and light-by-light scattering
- Direct measurement of $a_\mu = (g - 2)_\mu/2$

$$a_\mu^{\text{LO, hvp}} = \left(\frac{\alpha m_\mu}{3\pi} \right)^2 \int_{m_{\pi^0}^2}^{\infty} ds \frac{R_{\text{had}}(s) \hat{K}(s)}{s^2} = \left(\frac{\alpha}{\pi} \right)^2 \int_0^{\infty} dt \tilde{K}(t) G(t)$$

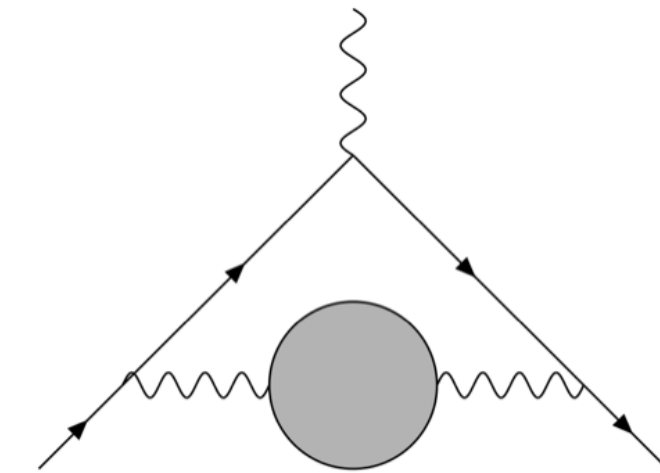


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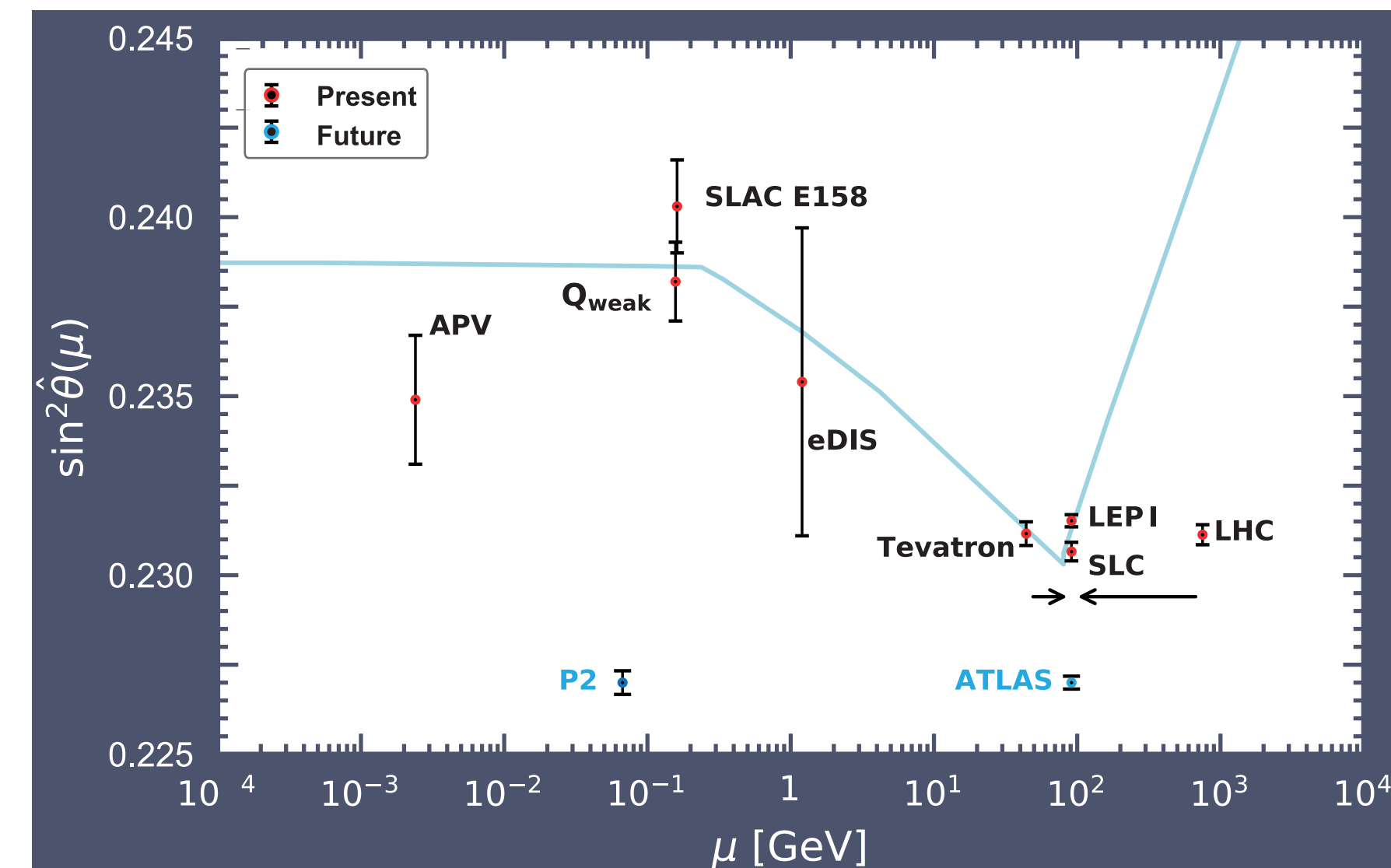
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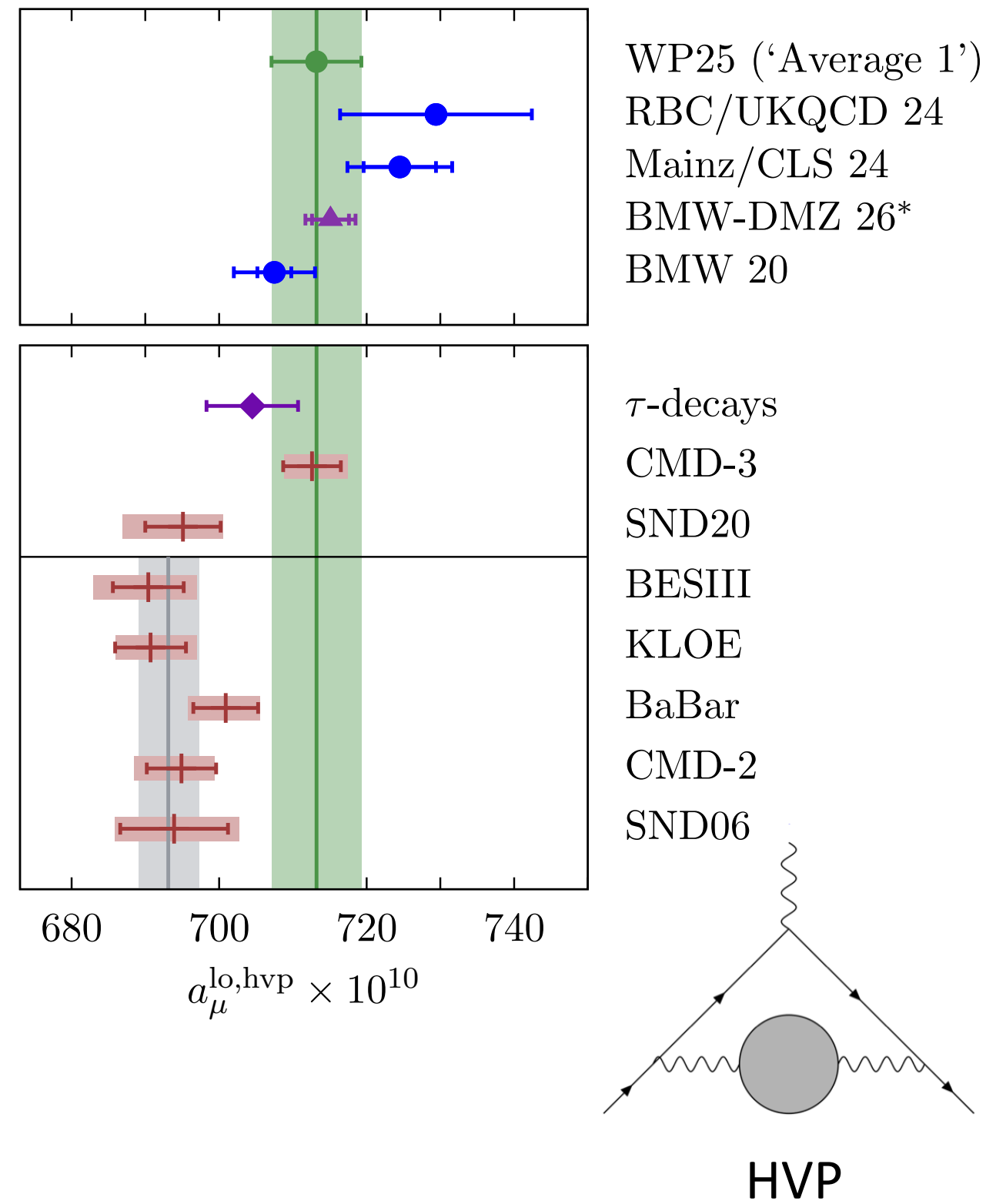
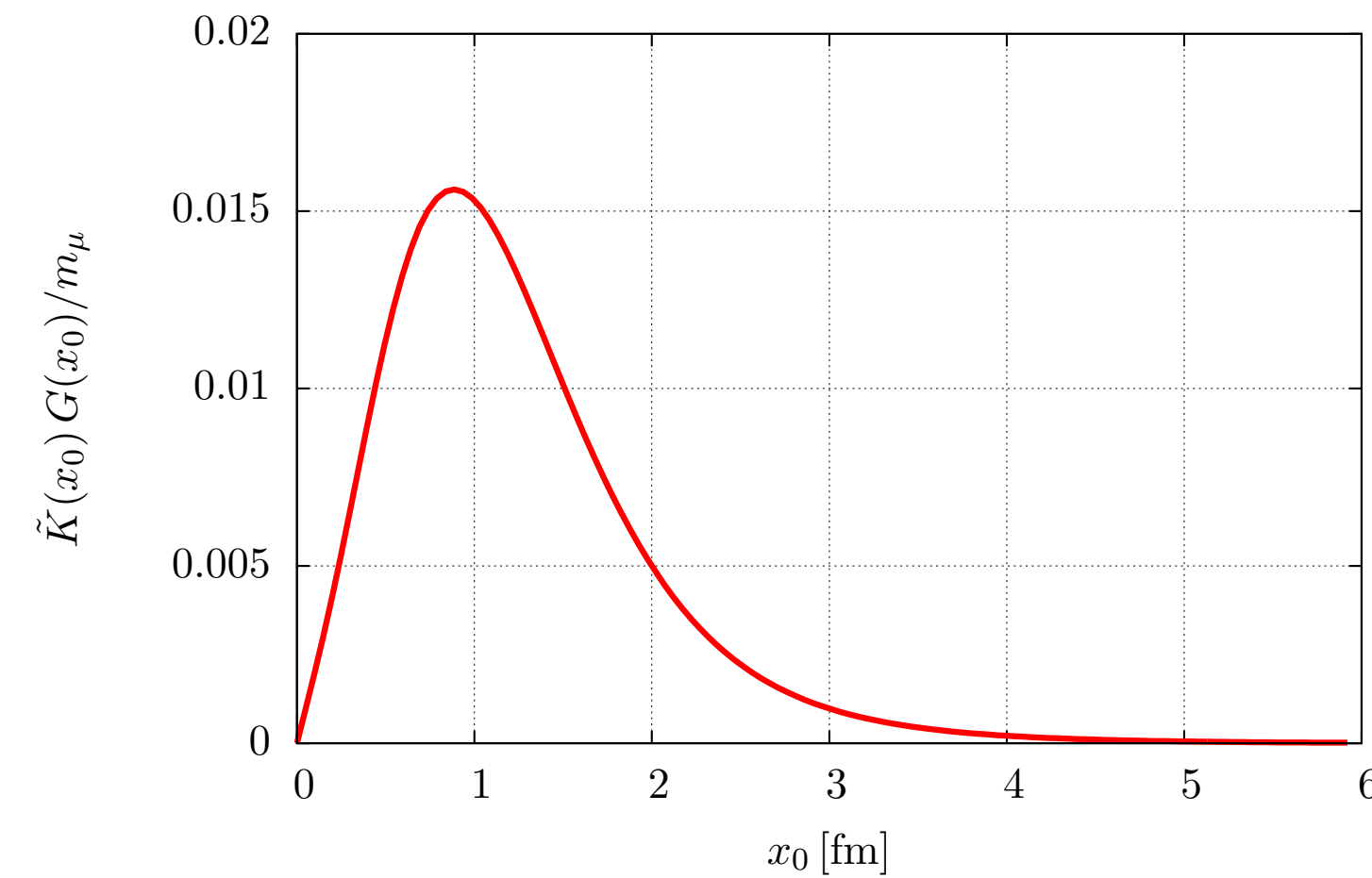
Running of electromagnetic and electroweak mixing angle

- $\alpha(M_Z^2)$: crucial input parameter for FCC-ee
- $\Delta_{\text{had}} \sin^2 \theta_W$: allows for precision test of SM; complements experimental programme at P2@MESA



Hadronic contributions to muon $g - 2$ from Lattice QCD

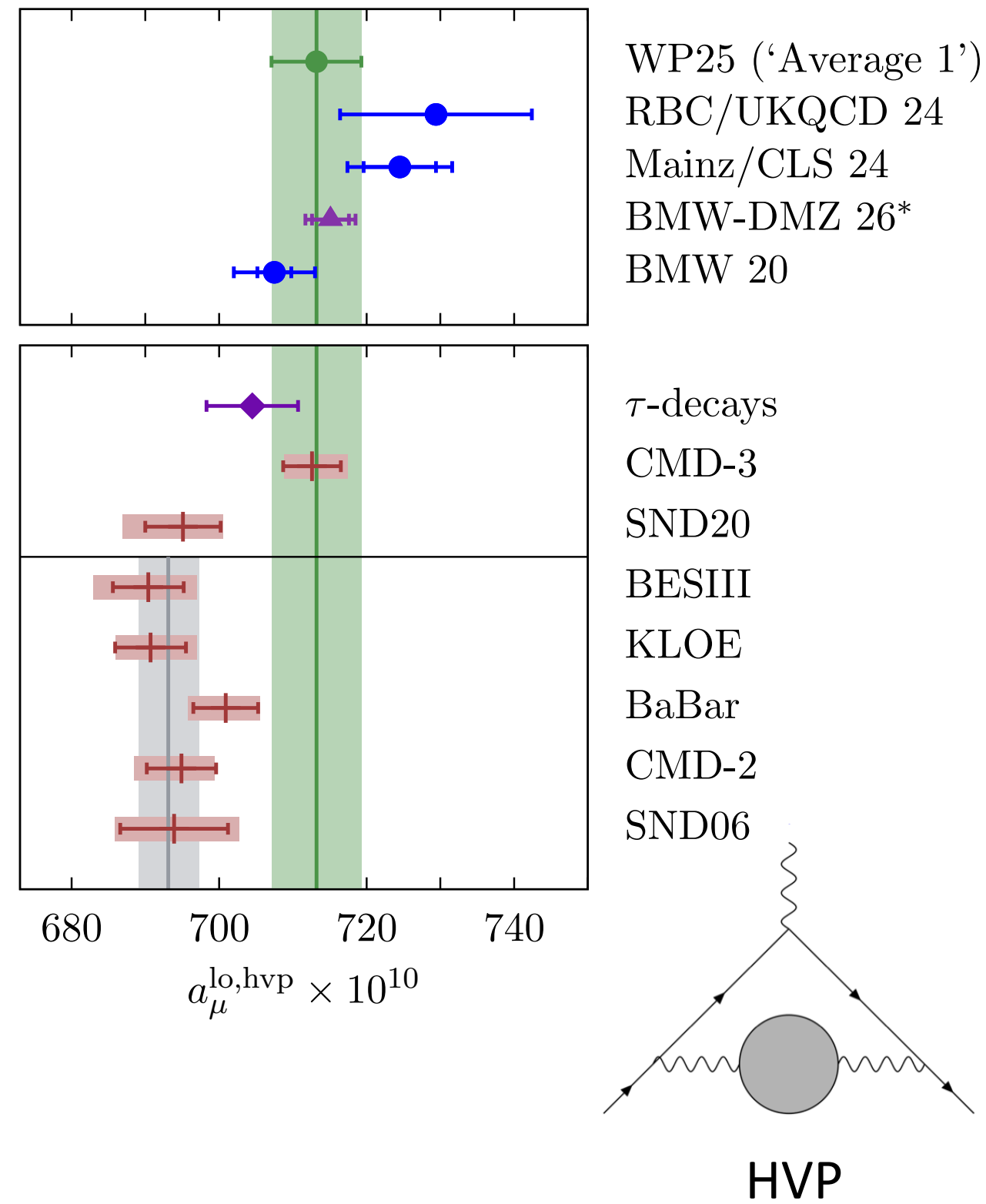
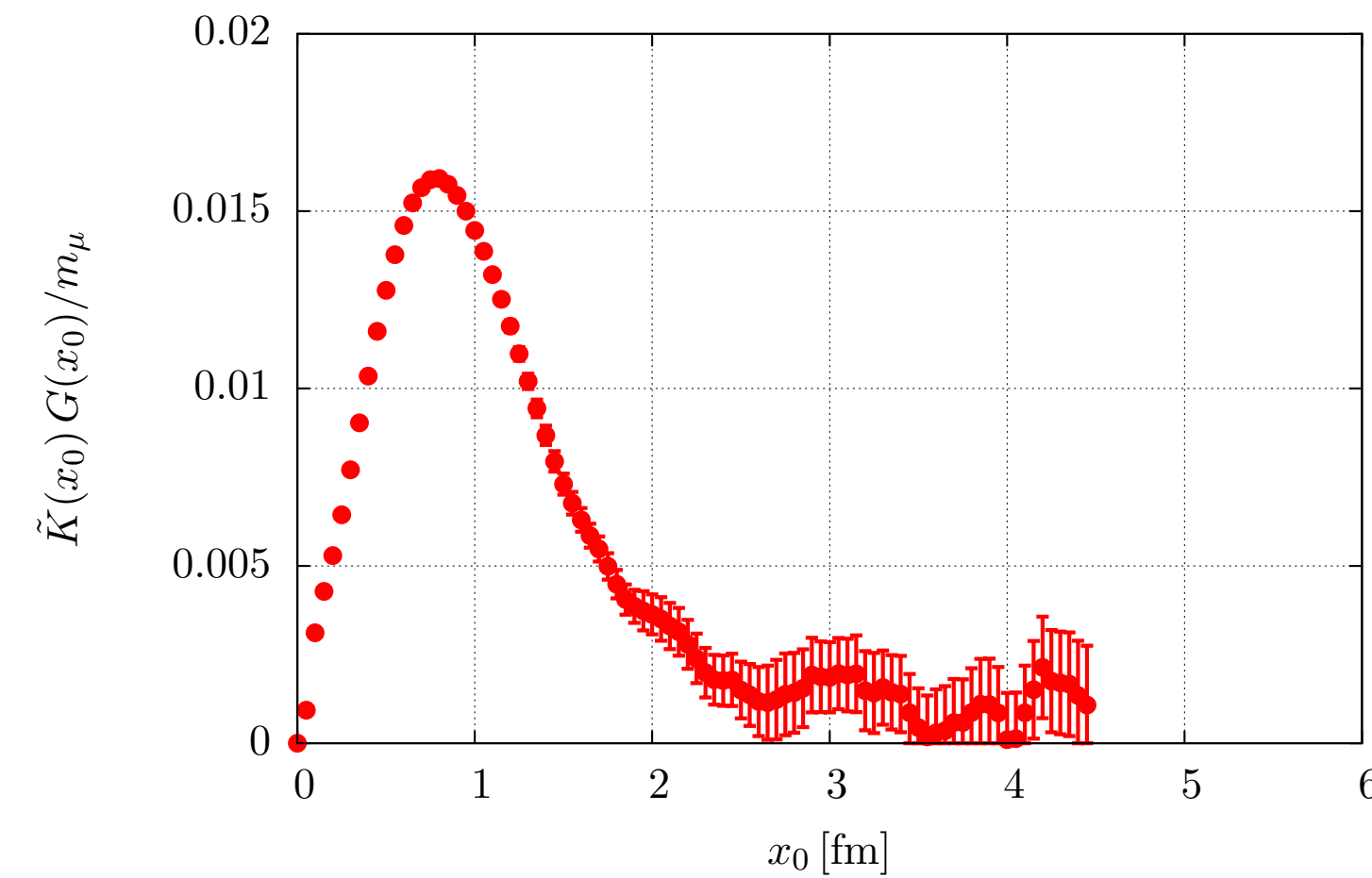
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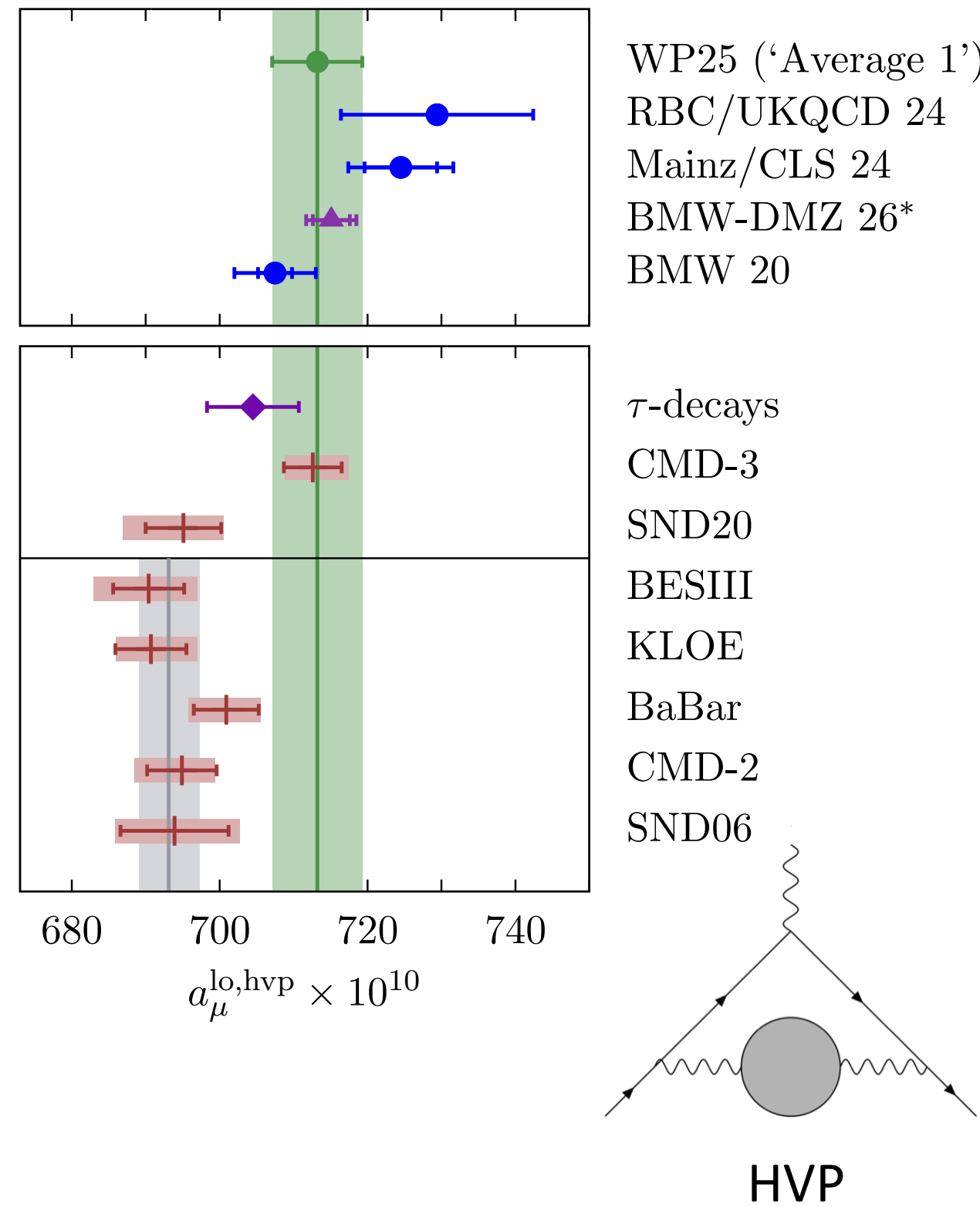
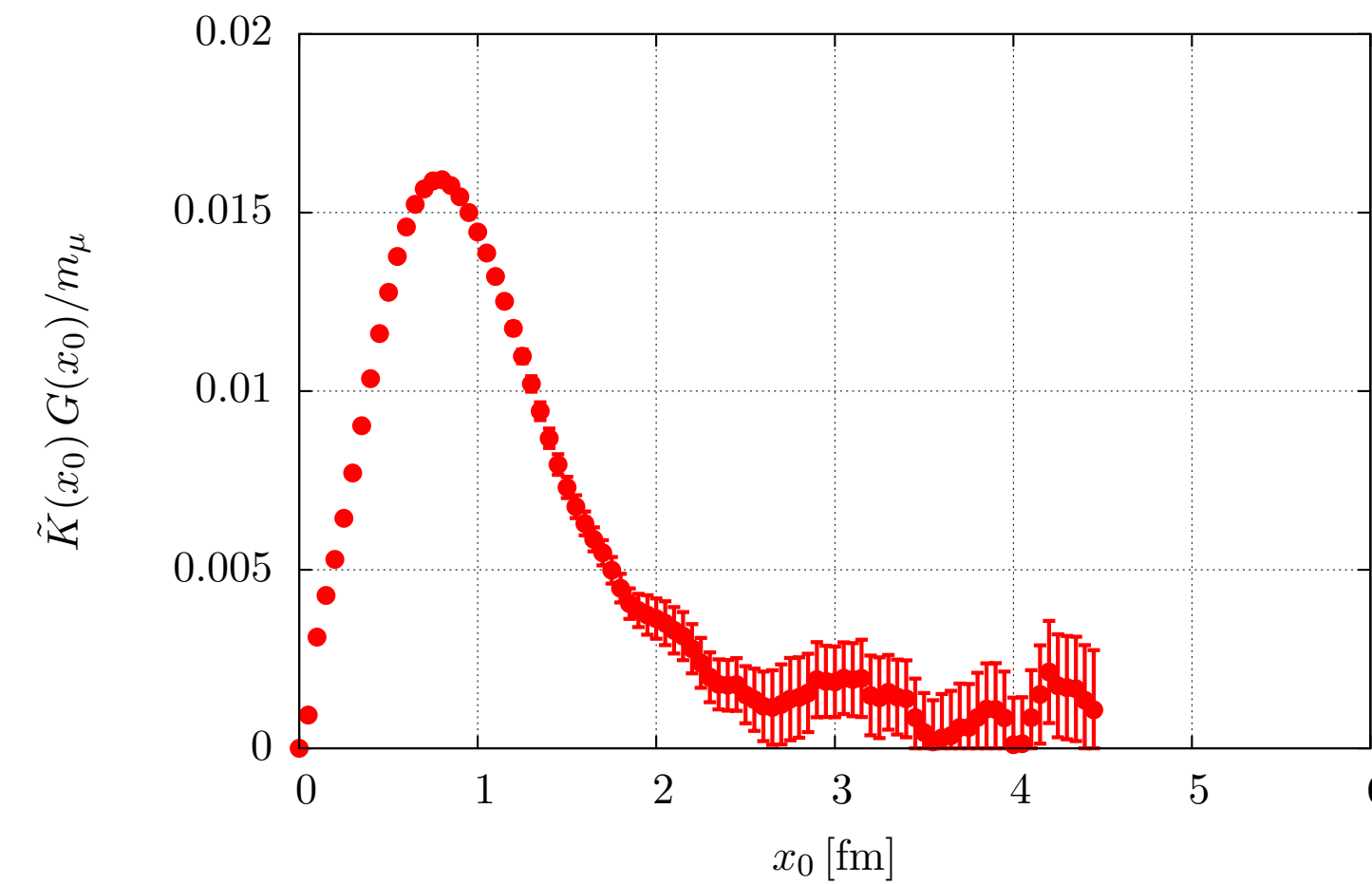
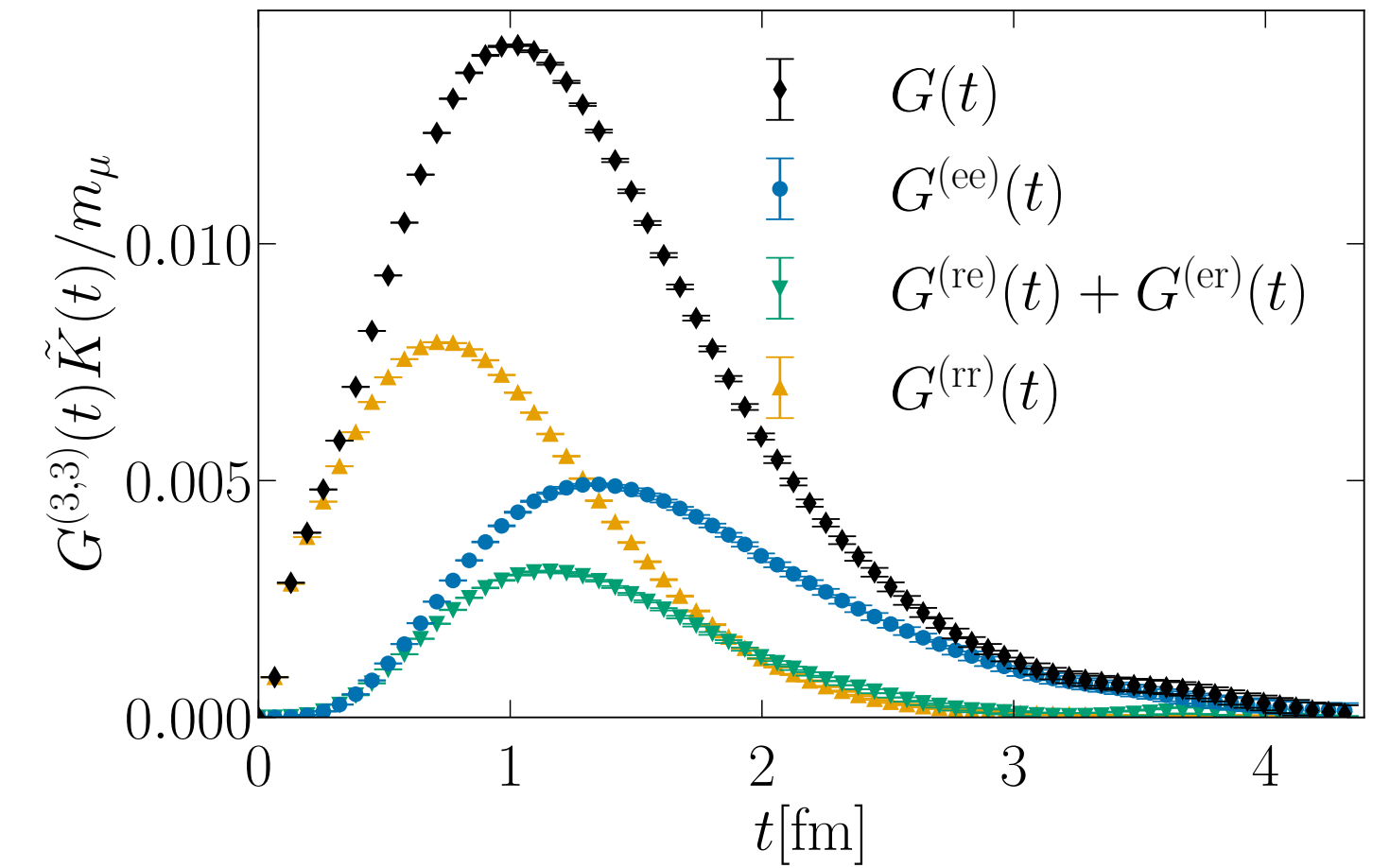
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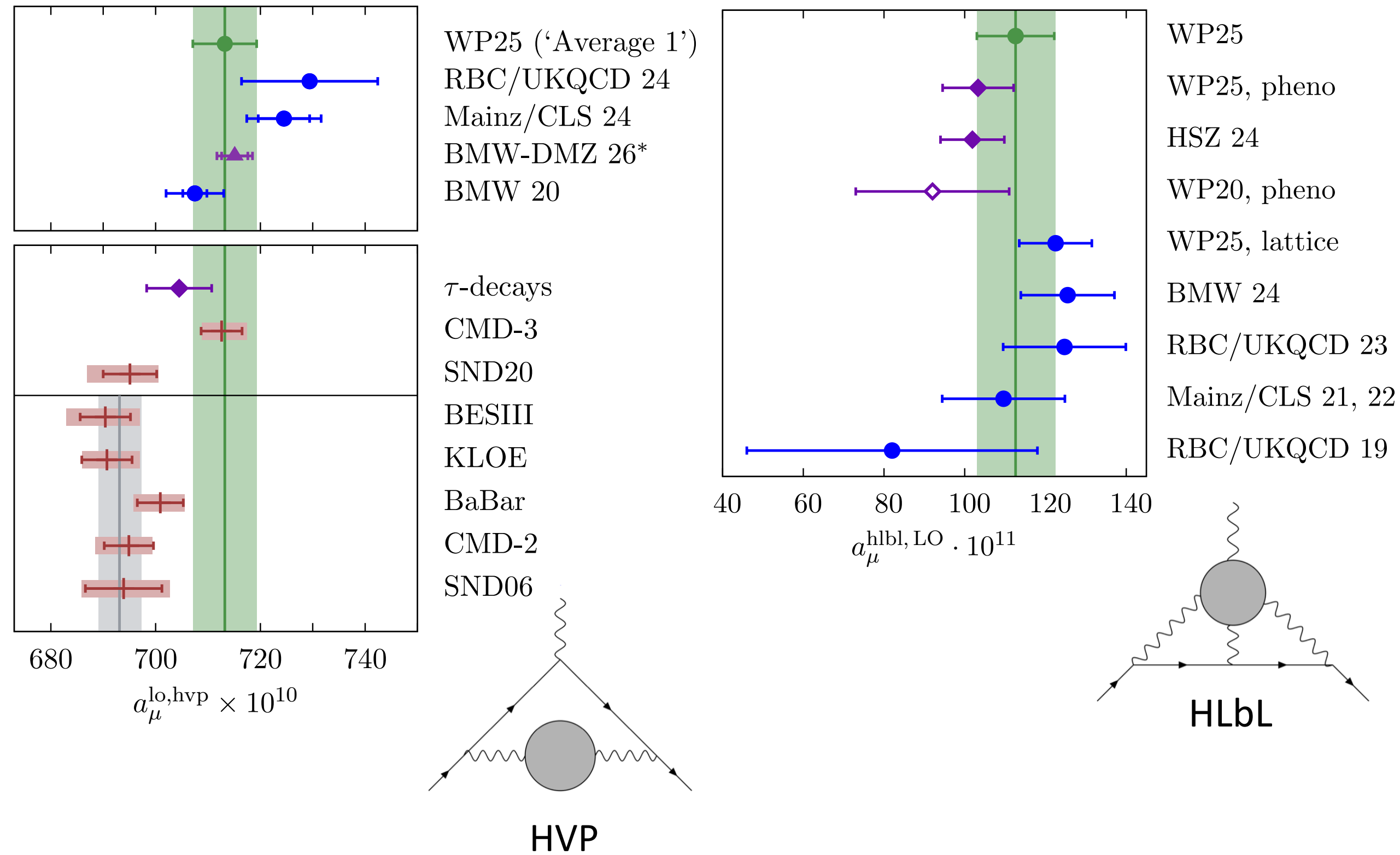
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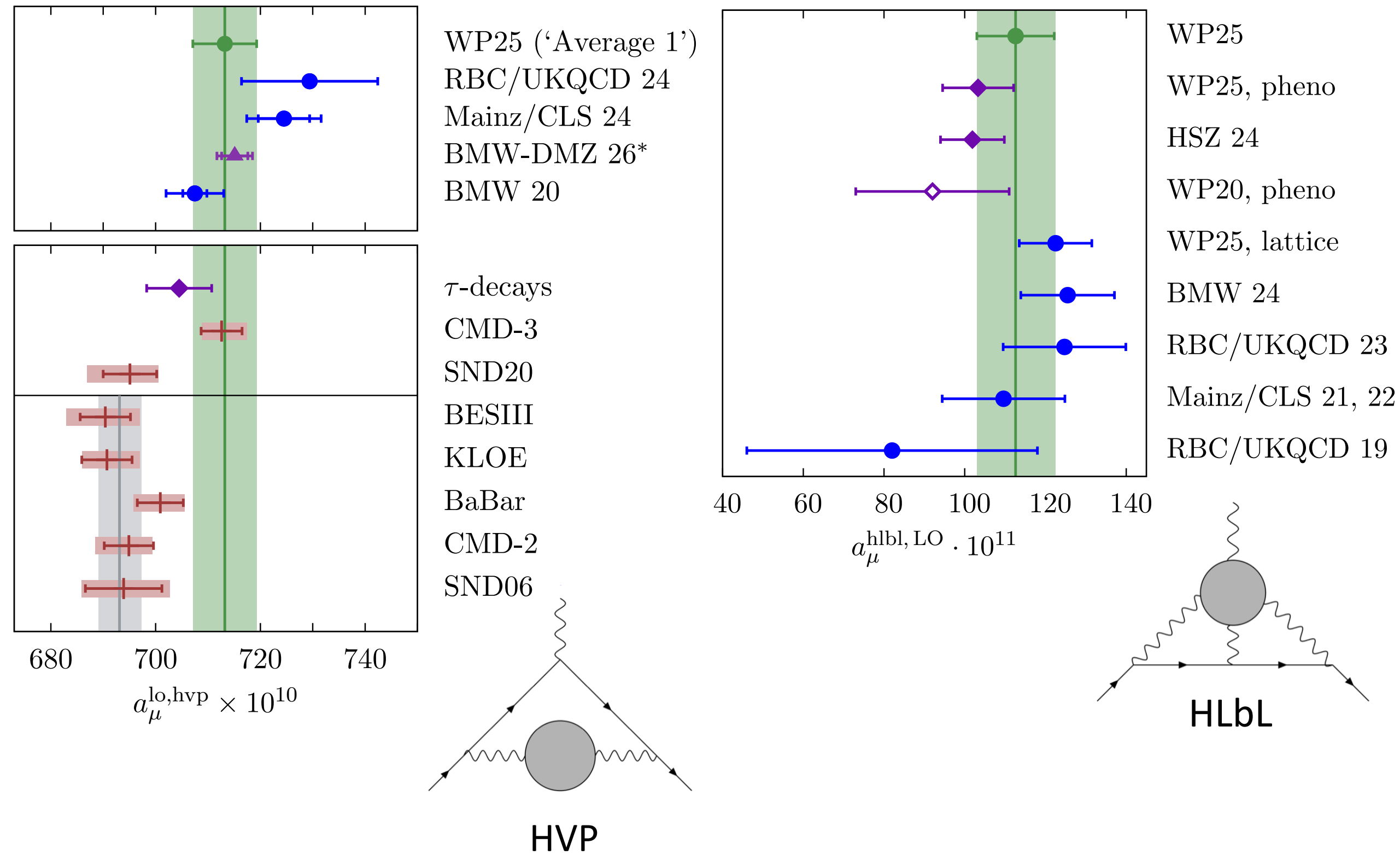
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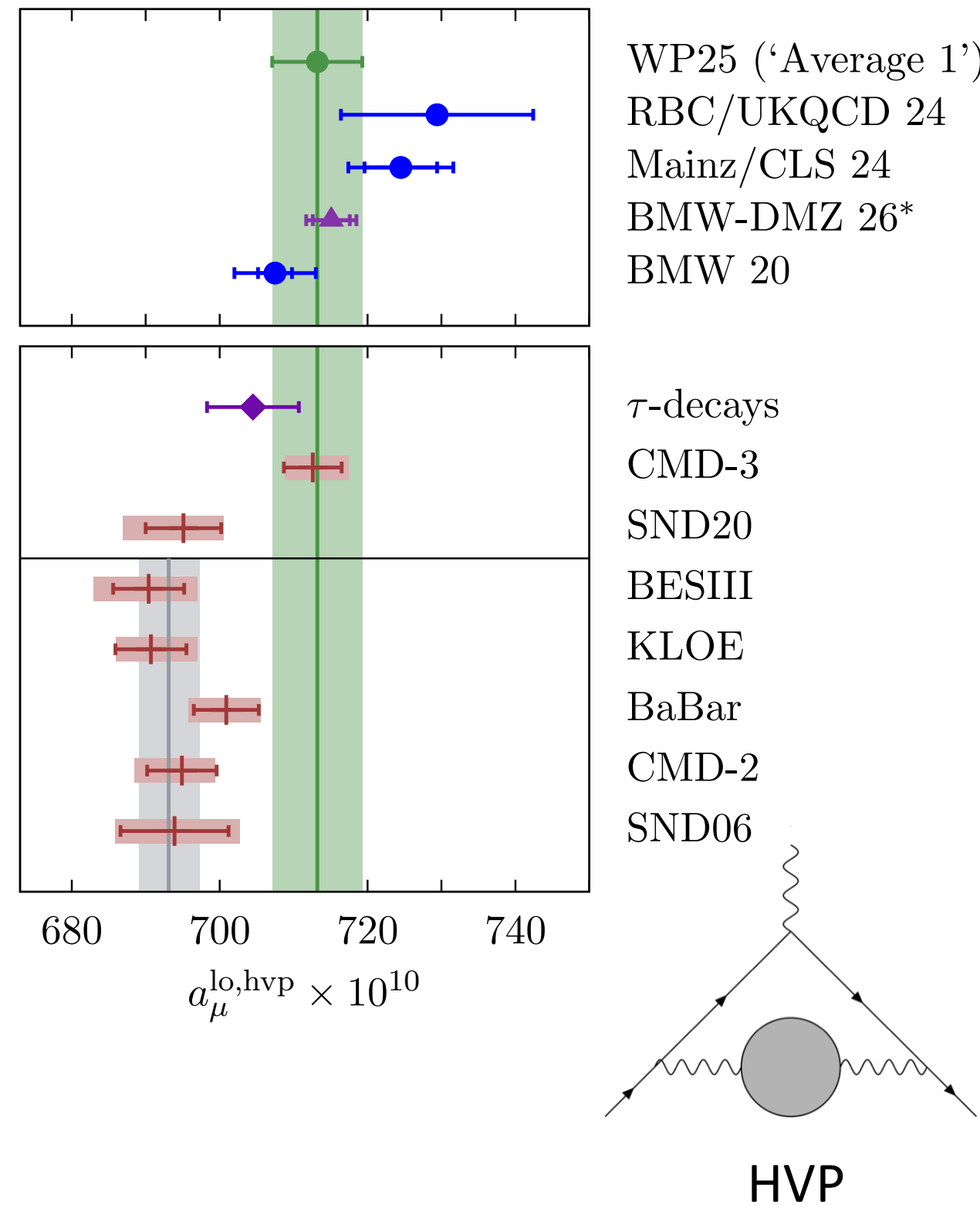
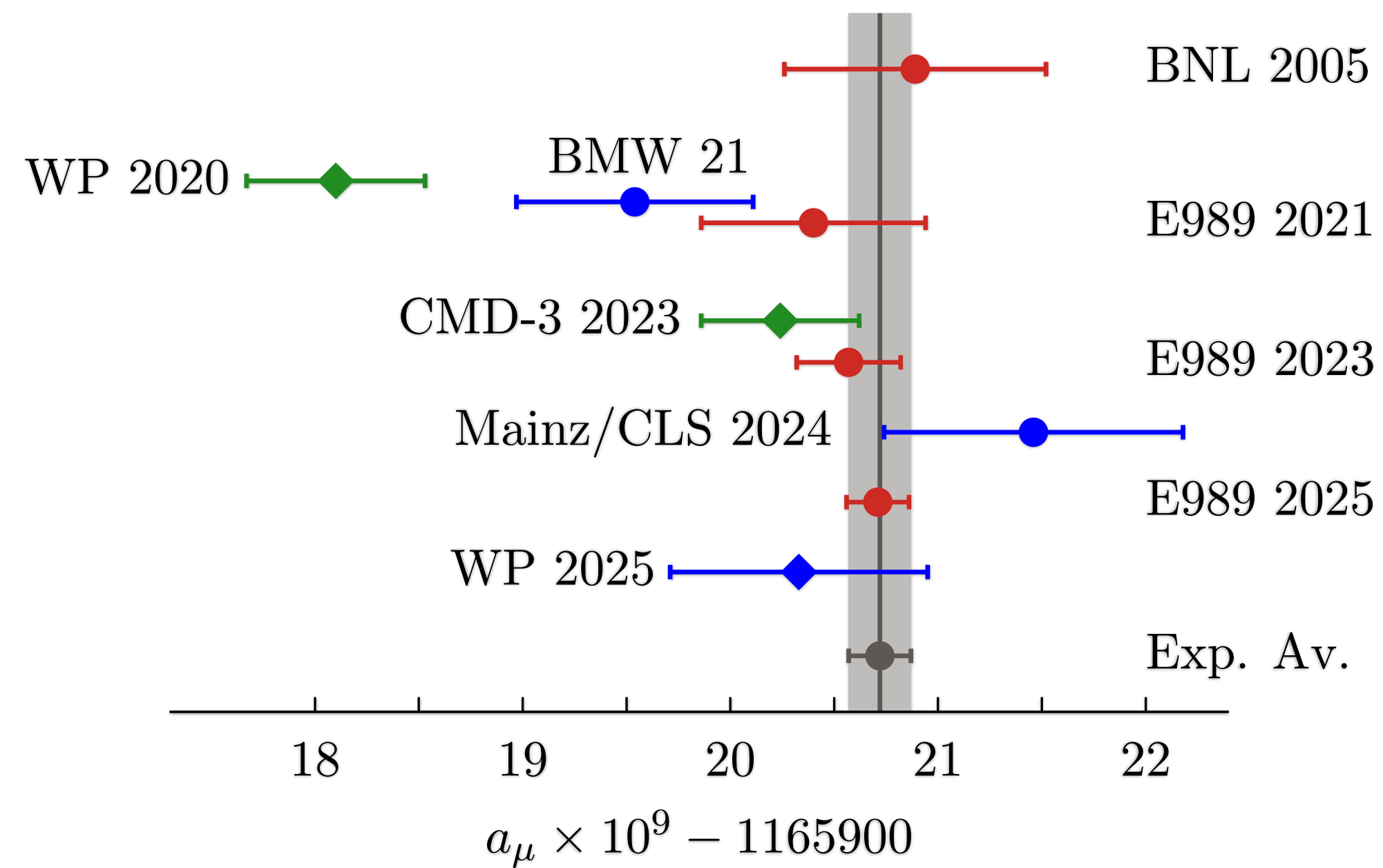
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- Significant tension with data-driven method at comparable precision
- Lattice QCD estimate for HVP confirms validity of SM: $a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (38 \pm 63) \cdot 10^{-11}$

Hadronic running of electromagnetic coupling

[Conigli et al., Phys Rev Lett 137 (2026) 071901; Phys Rev D 114 (2026) 034508]

Value of fine-structure constant is energy-dependent

$$\alpha(q^2) = \frac{\alpha}{1 - \Delta\alpha(q^2)} \quad \alpha^{-1}(M_Z^2) = 127.951 \pm 0.009$$

- Crucial input quantity for future colliders;
Precision limited by hadronic contributions
- Employ combination of lattice and perturbative QCD
("Euclidean split technique")

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$$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2) = \Delta\alpha_{\text{had}}^{(5)}(-Q_0^2) \leftarrow \text{lattice QCD}$$

$$+[\Delta\alpha_{\text{had}}^{(5)}(-M_Z^2) - \Delta\alpha_{\text{had}}^{(5)}(-Q_0^2)] \leftarrow \text{pQCD}$$

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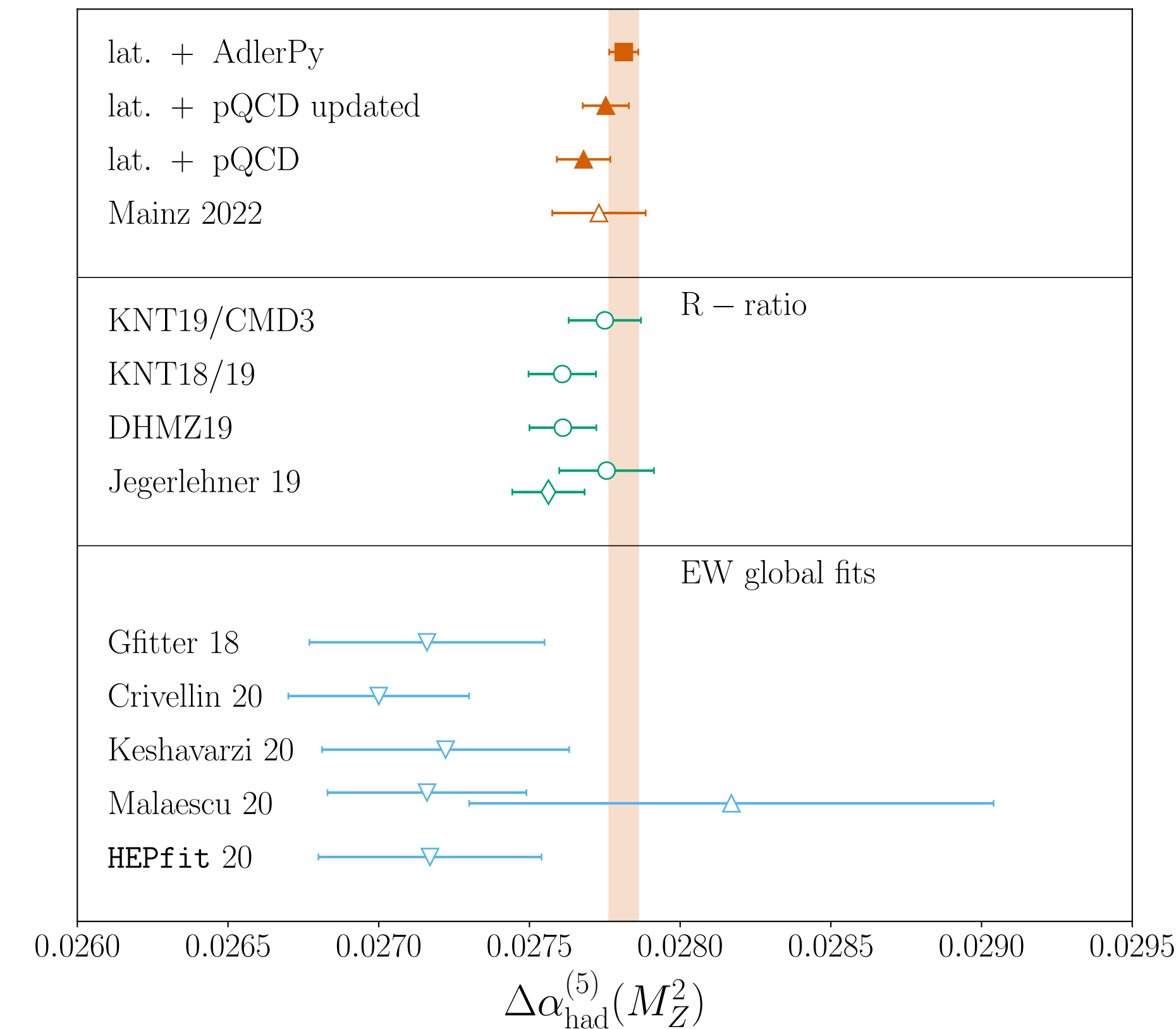
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$$\Rightarrow \Delta\alpha_{\text{had}}^{(5)}(M_Z^2) = 0.027\,821(34)_{\text{lat}}(35)_{\text{pQCD}} \quad [0.17\%]$$



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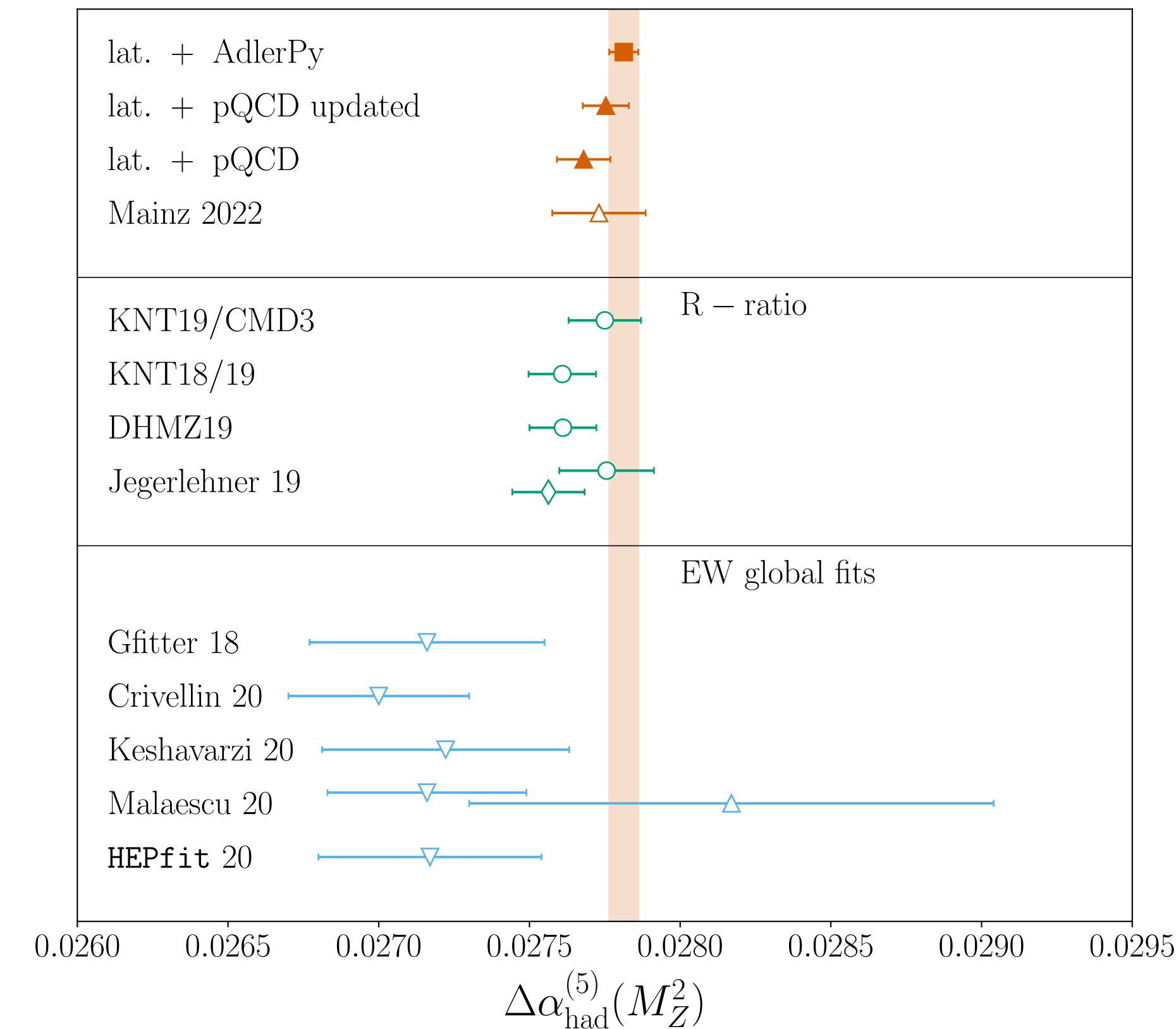
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- Two times more precise than phenomenological estimates
- Tension with data-driven evaluations; mild tension with global electroweak fits
- Improve precision further to meet requirements of FCC-ee

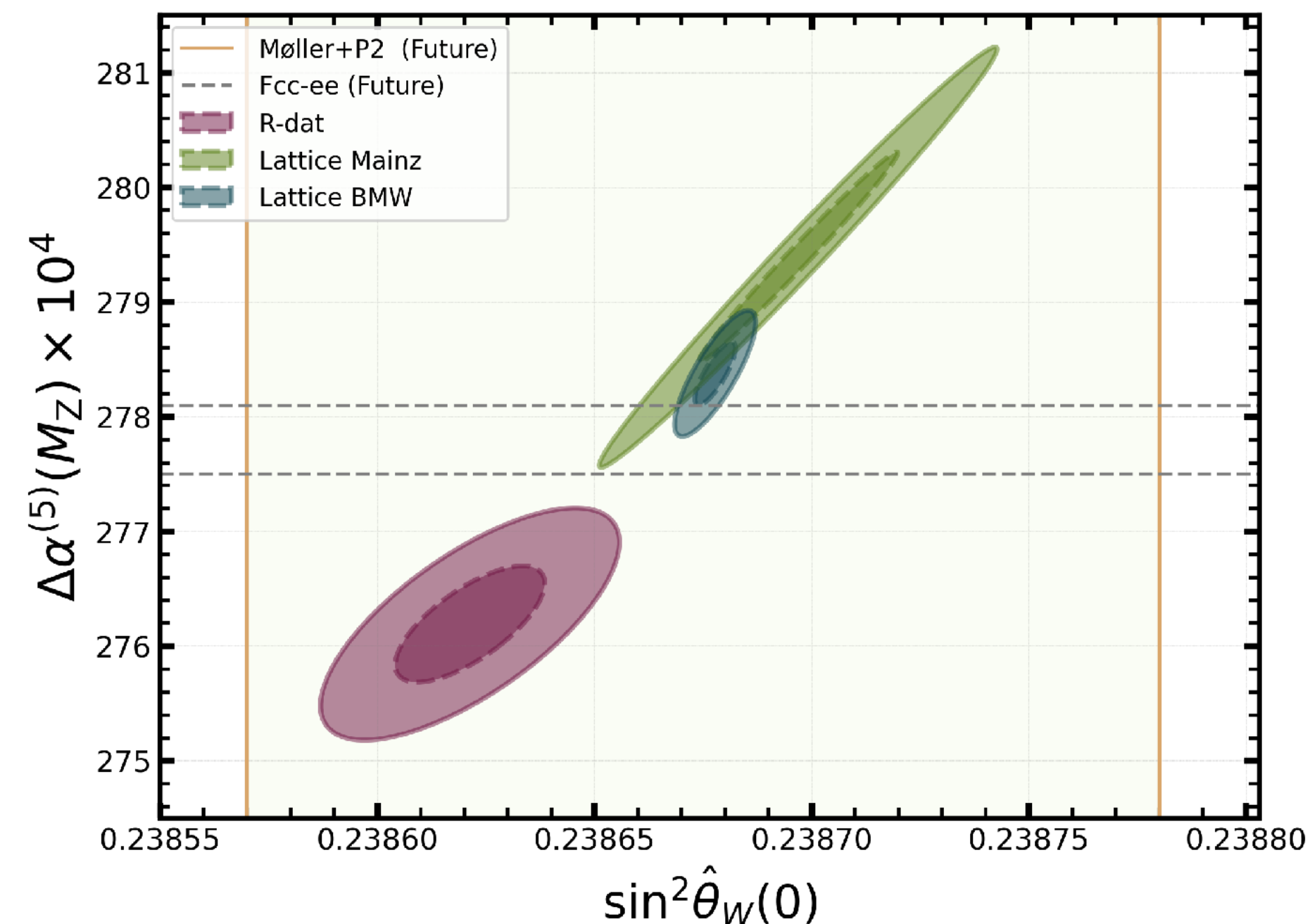
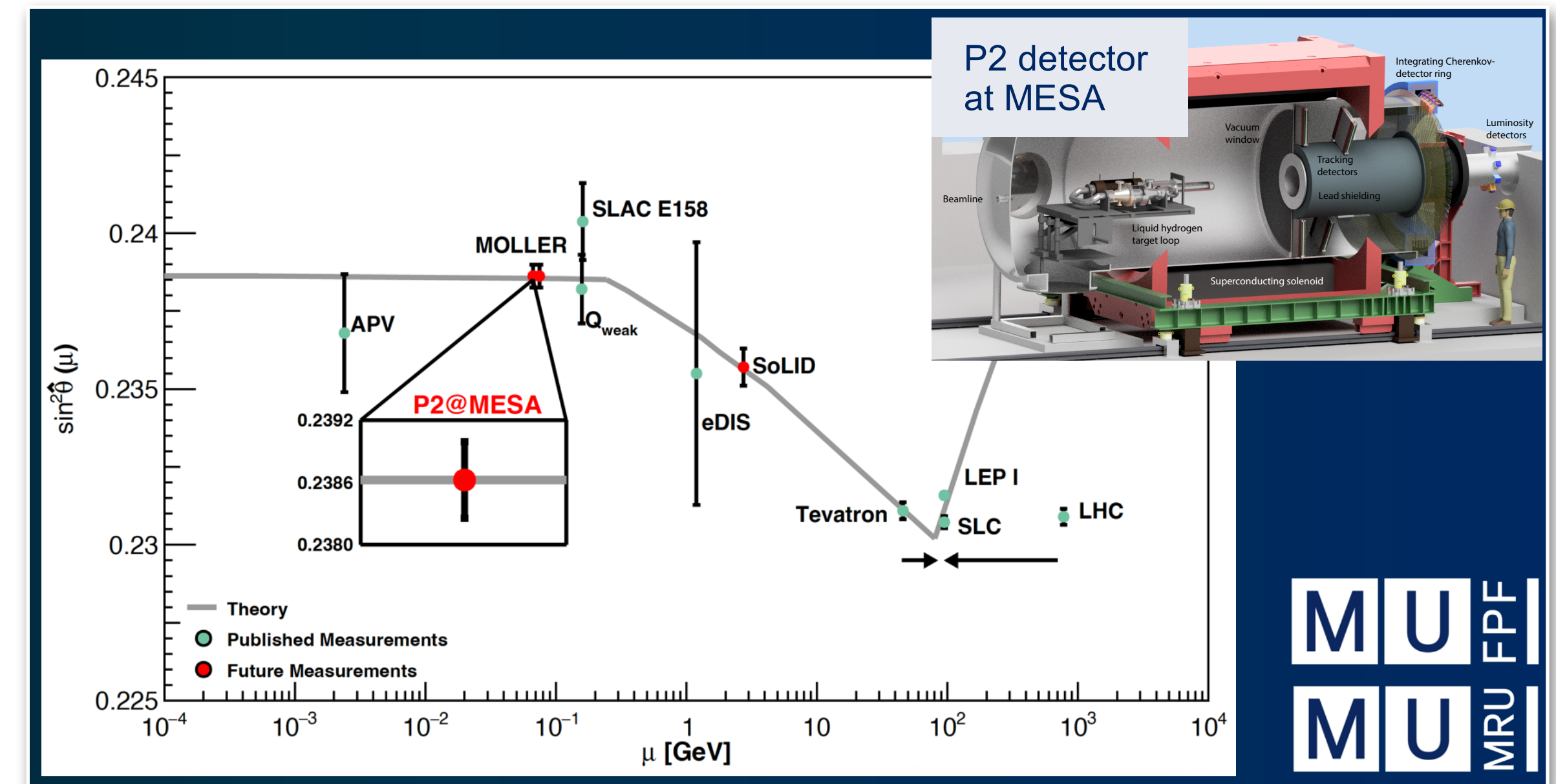


Hadronic running of electroweak mixing angle

[Erler, Ferro-Hernandez, Kuberski, Phys Rev Lett 133 (2024) 171801]

Employ combination of perturbative QCD and lattice simulations to determine the hadronic running of $\sin^2 \theta_W$ free from experimental ambiguities

Sensitivity of Standard Model test:



Hadronic uncertainties much smaller than present and future experimental error on $\sin^2 \theta_W$

Form factors: electromagnetic, axial, strange,...

- Proton radius and nuclear radii
- Hadronic background in precision experiments
- Input for long-baseline neutrino experiments

Nucleon charges and matrix elements

- Constrain / characterise BSM interactions: g_S , g_T , $\sigma_{\pi N}$
- Provide information on nucleon structure: $\langle x \rangle_{u-d}$, $\langle x \rangle_{\Delta u - \Delta d}$, $\langle x \rangle_{\delta u - \delta d}$
→ input for LHC, EIC

Methodology: Effective Field Theory; Lattice QCD

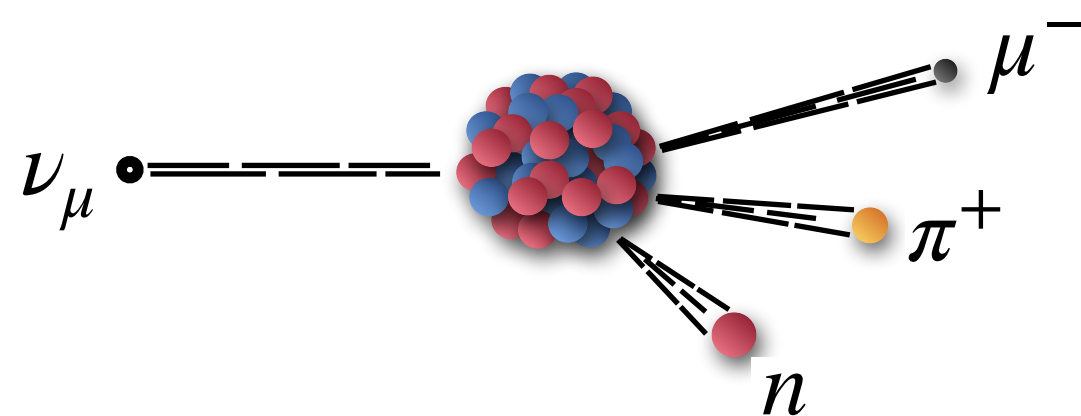
Neutrino-nucleus cross sections from nuclear EFT

[Sobczyk, Bacca et al., Phys Rev C 106 (2022) 034310; Phys Rev C 109 (2023) 044314]

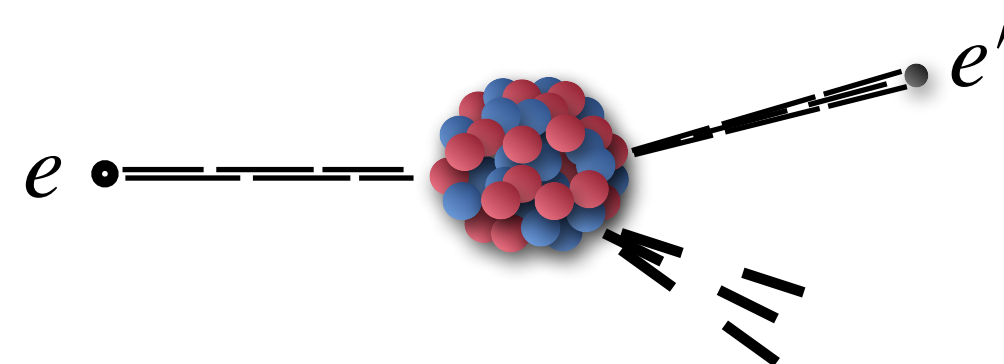
DUNE, T2HK: Knowledge of neutrino-nucleus cross sections for energy transfers $\sim 100 \text{ MeV} - \text{GeV}$ required

- Compute lepton-nucleus cross sections within *ab-initio* EFT framework
- First step for modelling this process at higher energy transfers

Goal:

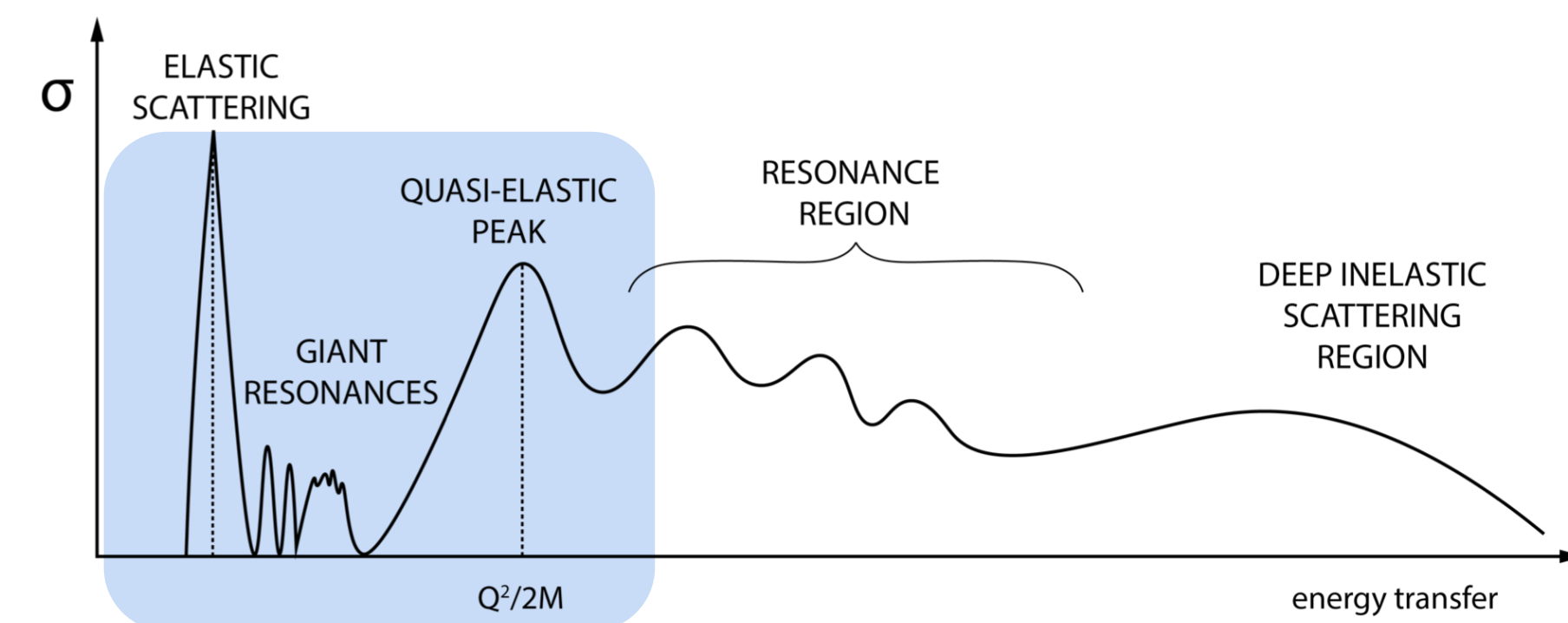
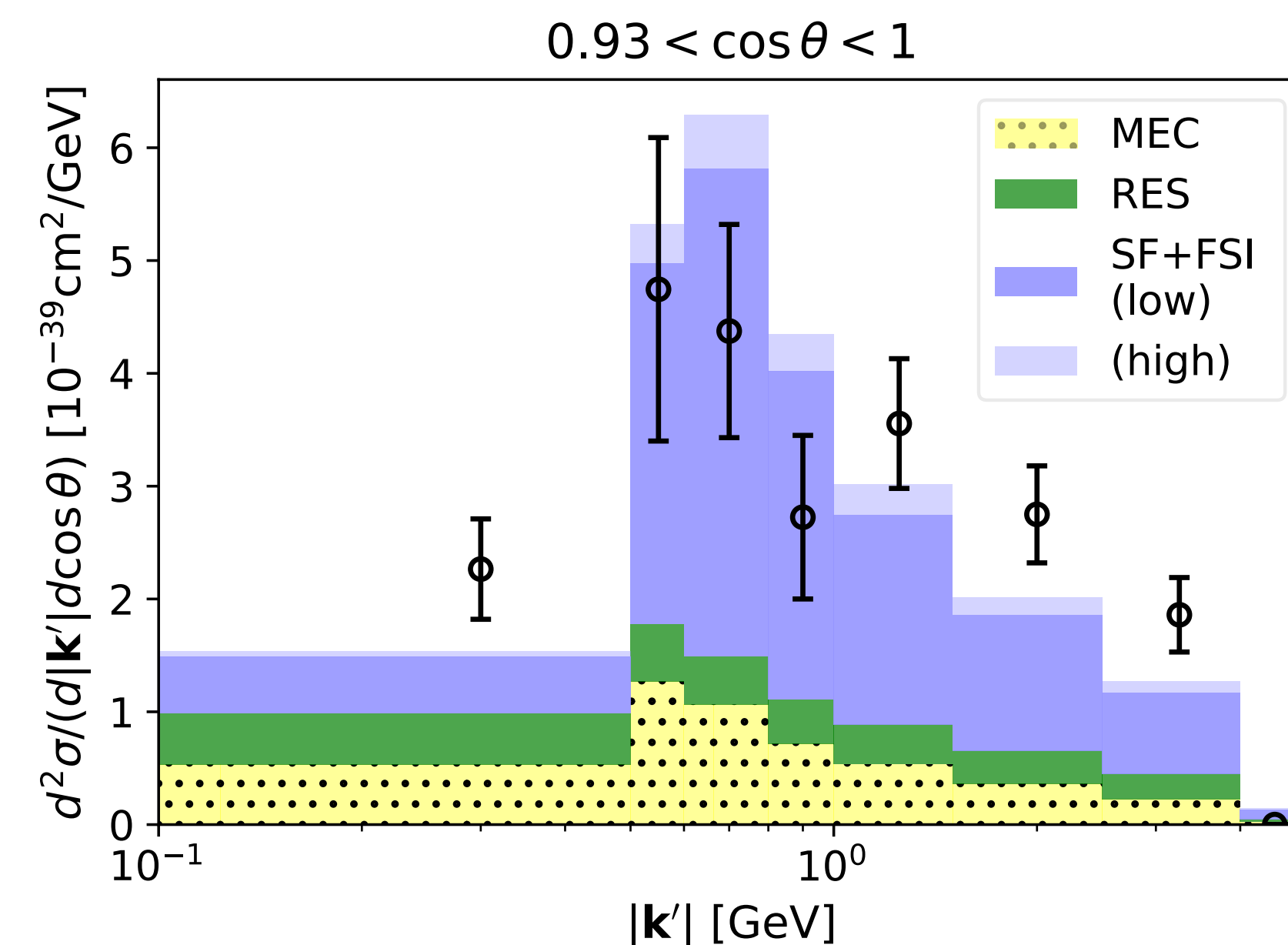


Intermediate step:



Spectral function for electron scattering on ^{16}O via coupled-cluster theory with expansion of integral transforms

Good agreement with measured cross section data for $\nu_\mu + ^{16}\text{O} \rightarrow \mu^- + X$ (T2K)



Axial form factors of the nucleon in lattice QCD

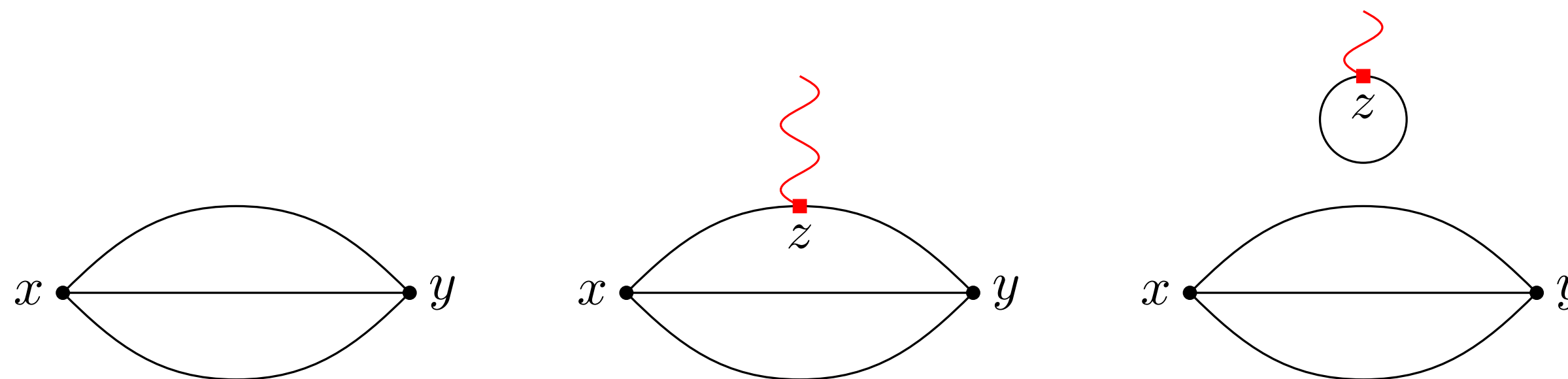
[Barone et al., Phys Rev D 112 (2025) 1; Phys Rev D 114 (2026) 034520;
Djukanovic et al., Phys Rev D 106 (2022) 074503]

Goal: complete decomposition of nucleon axial form factors in SU(3)-flavour basis

G_A^{u-d} (isovector): sensitive to W -boson exchange → T2HK, DUNE

G_A^{u+d-2s} (isoscalar octet): Z -boson exchange — background in measurement of $\sin^2 \theta_W$ with P2@MESA

G_A^{u+d+s}, G_A^s (singlet): relevant for cross section in various dark matter models



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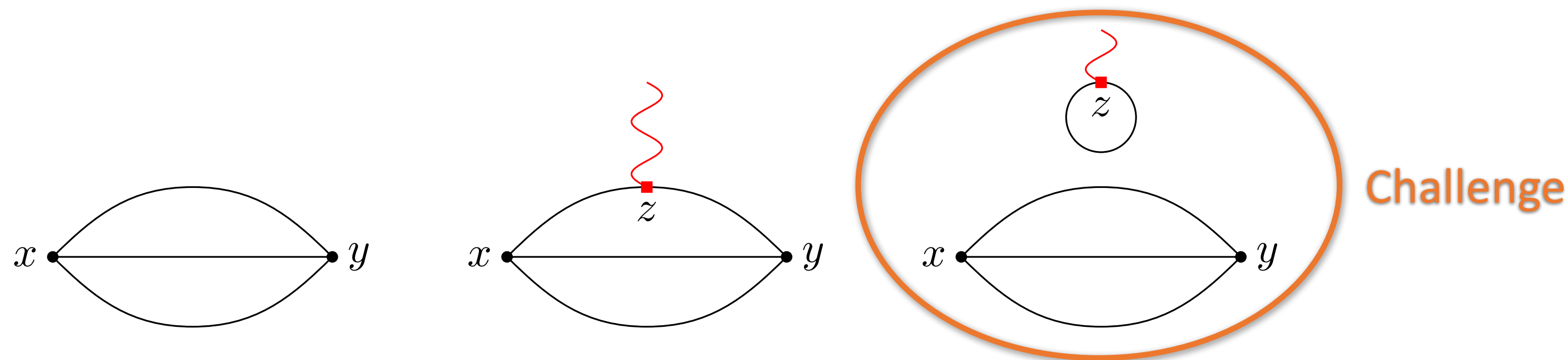
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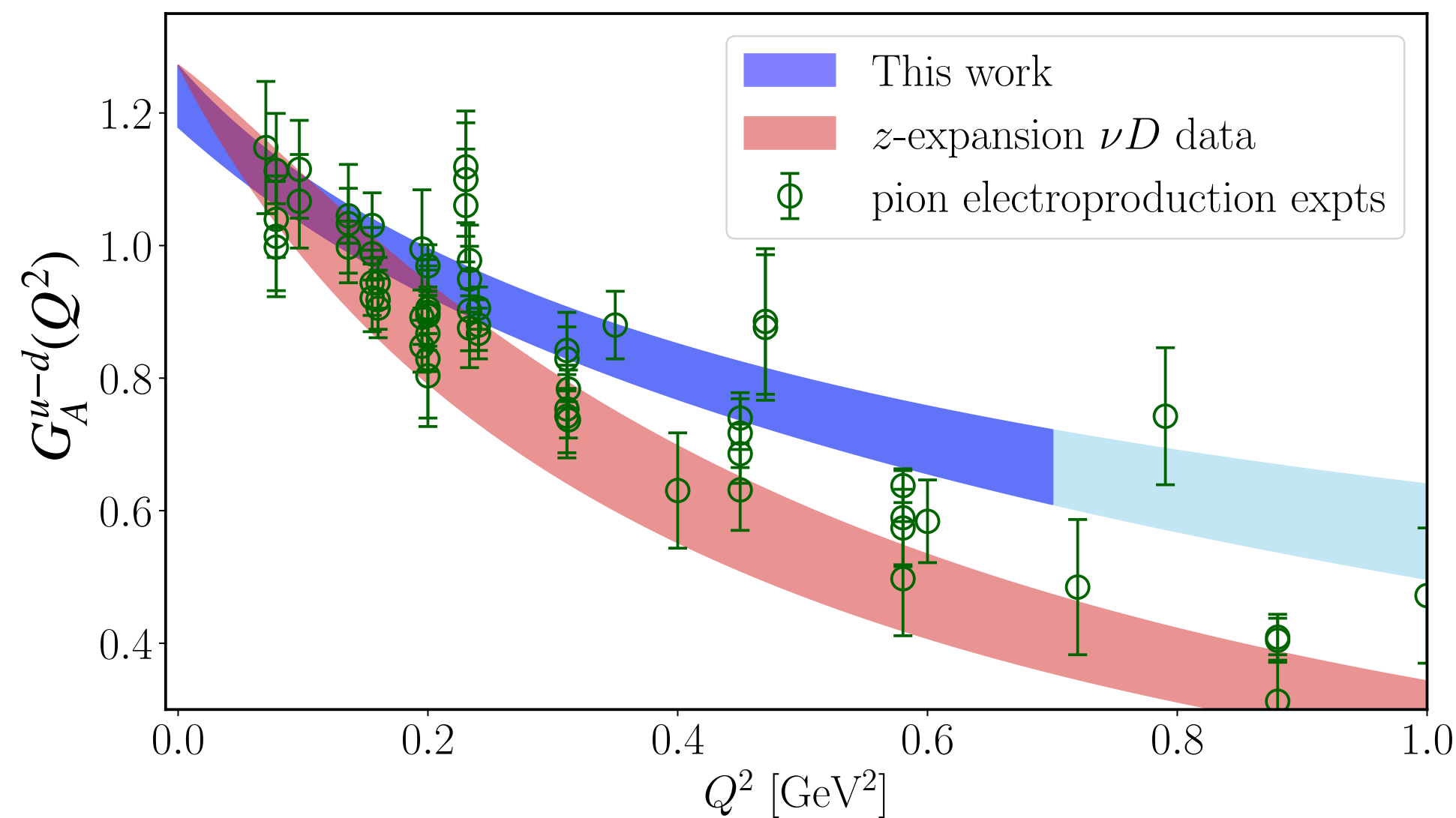
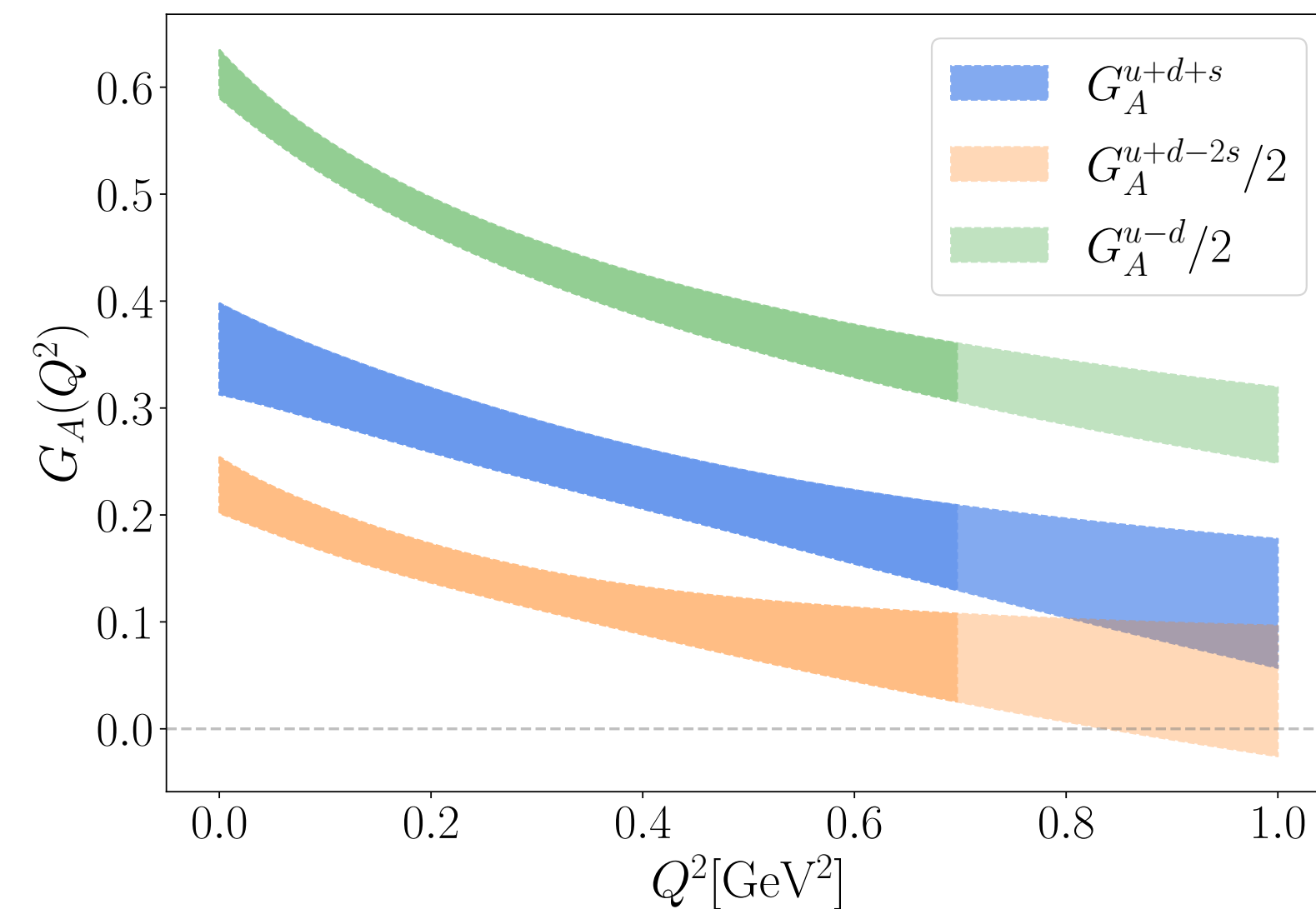
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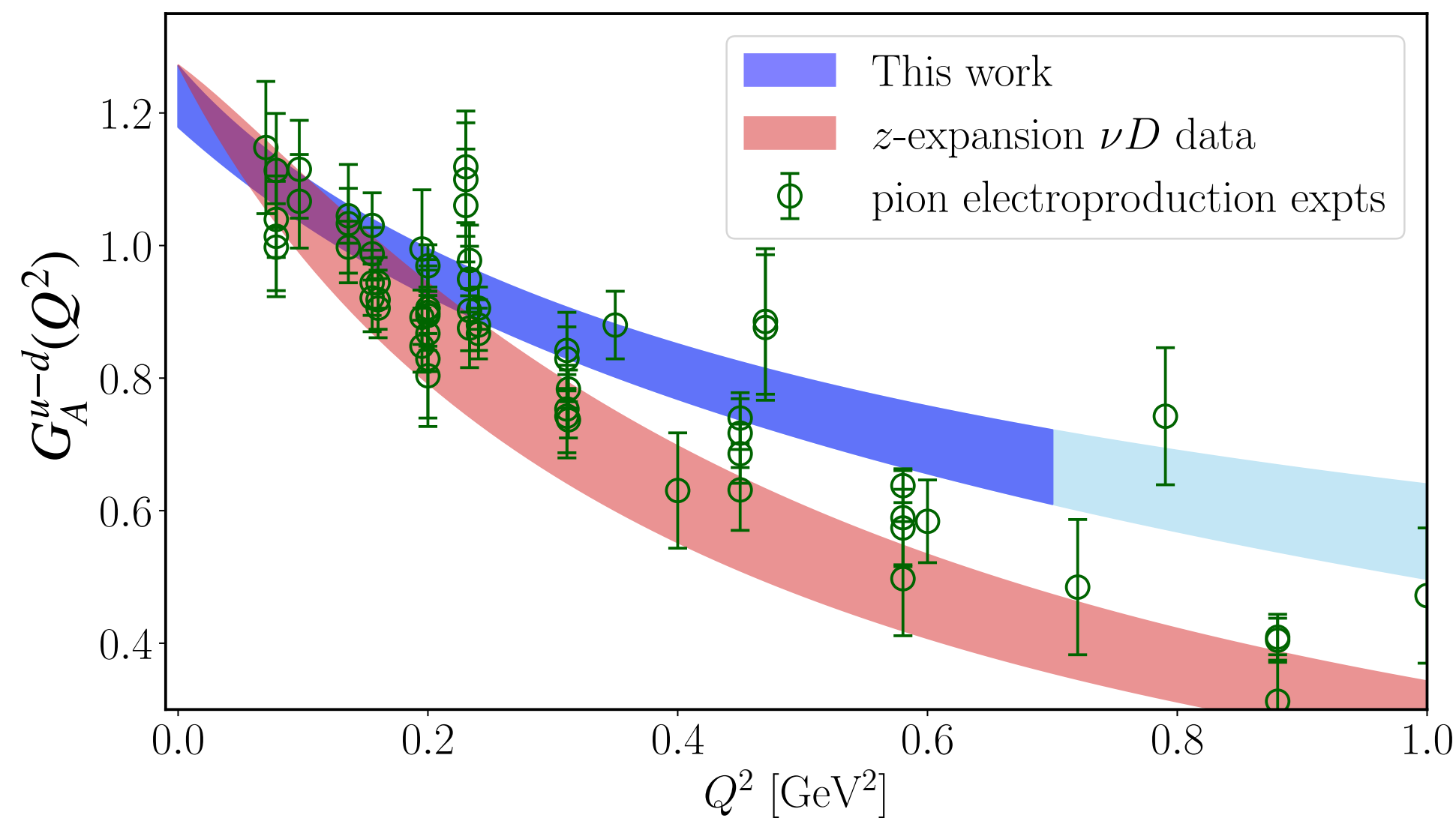
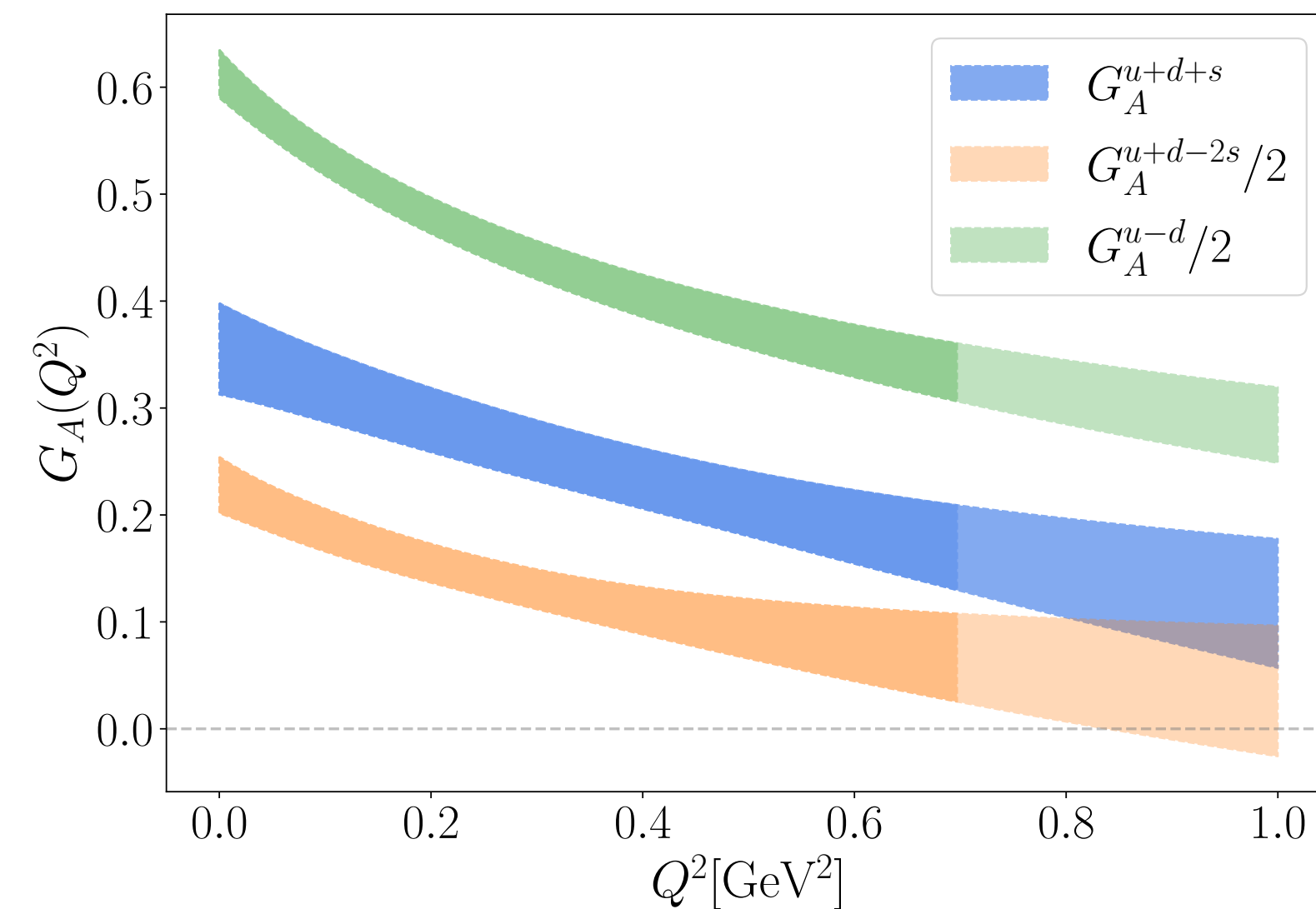
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- Mild tension with νD experimental data

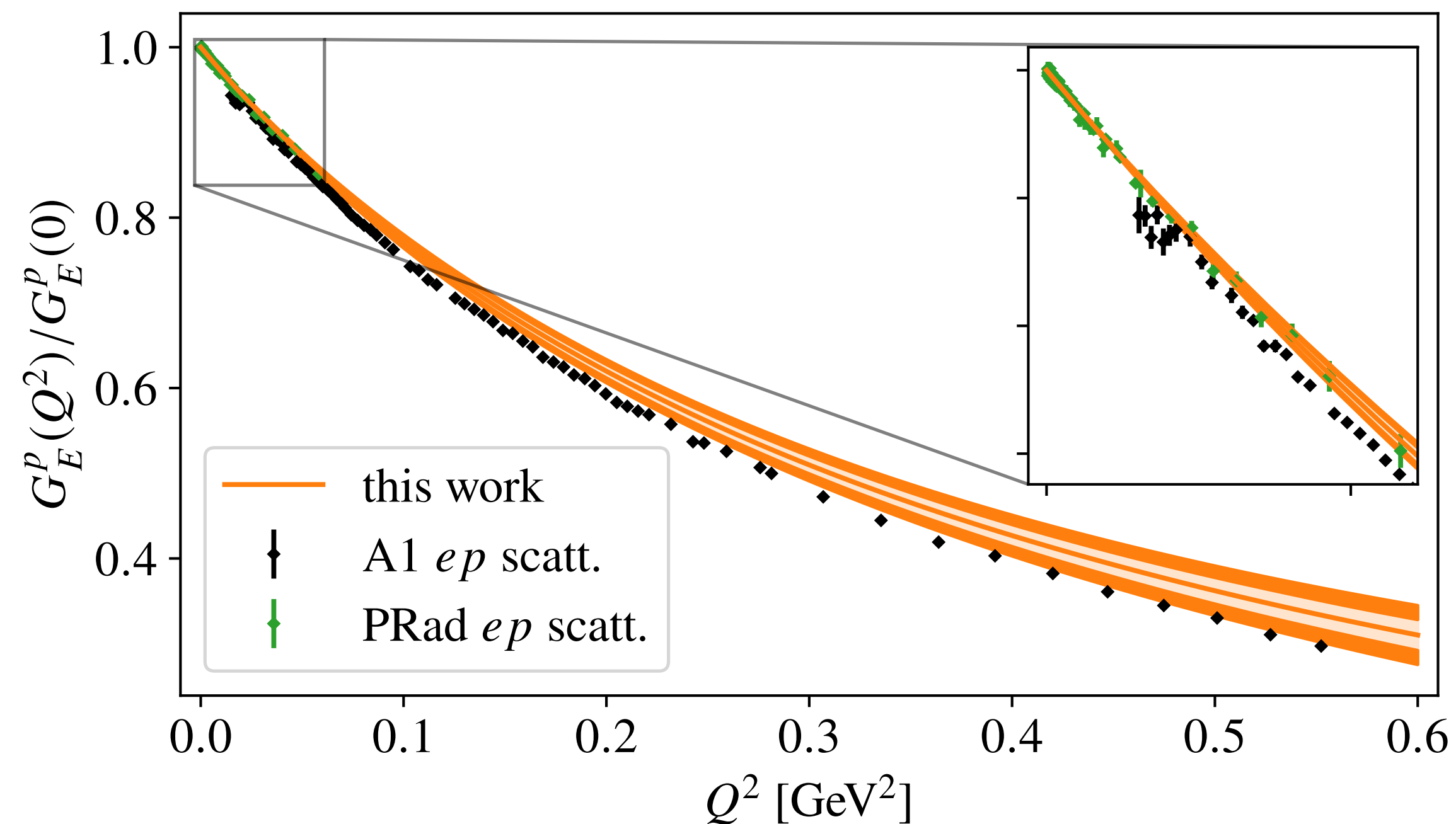
Proton radius puzzle

[Djukanovic et al., Phys Rev Lett 132 (2024) 21; Phys Rev D 109 (2024) 9]

First lattice calculation of electromagnetic form factors of proton and neutron with complete error budget

Precision at small momentum transfers competitive or better than *ep* scattering

Low value of the electric charge radius preferred – impact on the proton radius puzzle



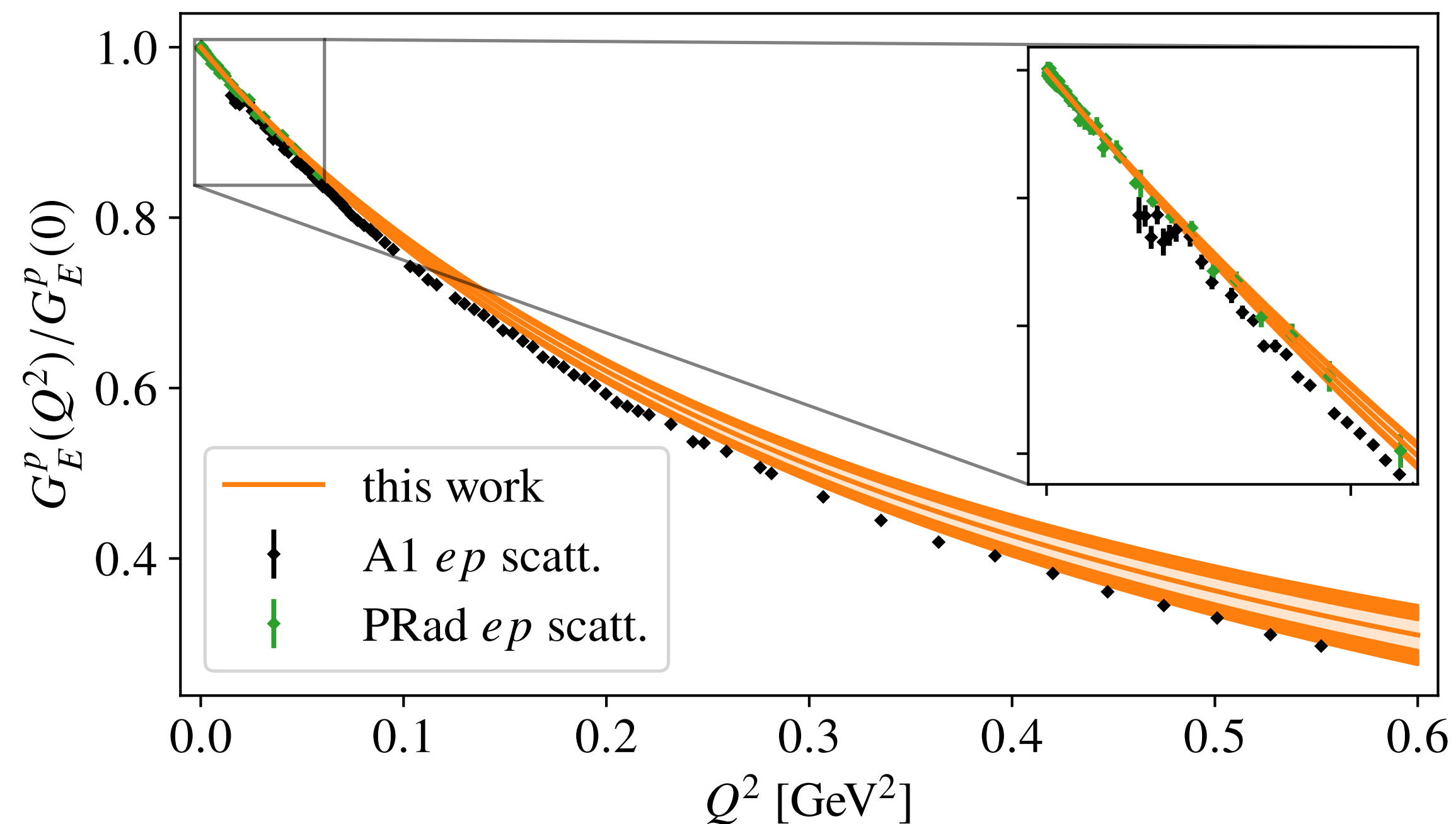
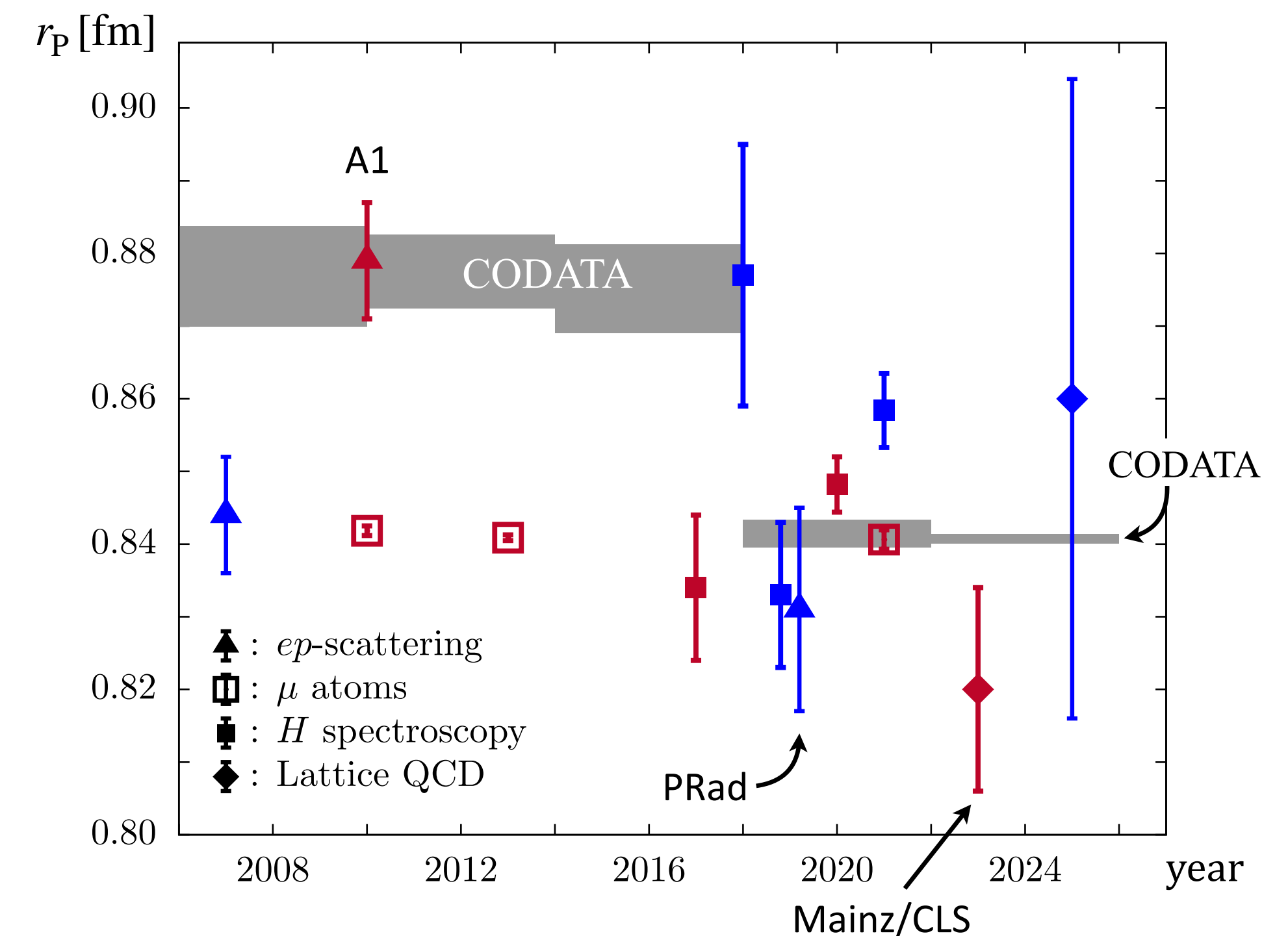
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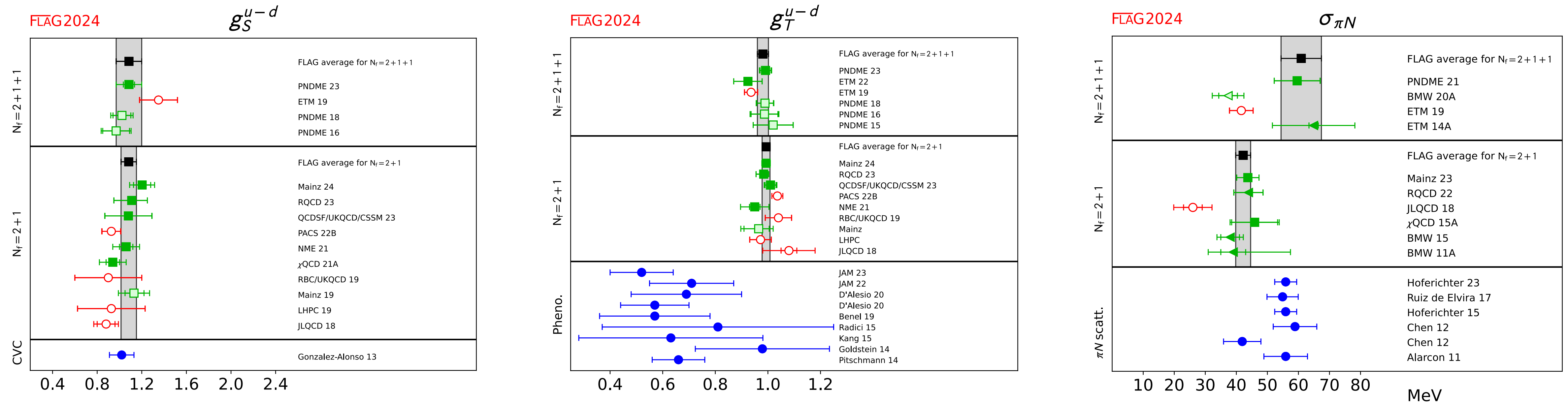


Nucleon charges and sigma-terms

[Djukanovic et al., Phys Rev Lett 131 (2023) 26; Phys Rev D 109 (2024) 074507;
Lutz et al., EPJC 83 (2023) 440]

BSM models contain additional scalar and tensor interactions — constrained by nucleon charges g_S, g_T

Pion-nucleon sigma-term $\sigma_{\pi N}$ characterises coupling of dark matter particles to nucleon



- Consistent and precise lattice results for g_S and g_T
- $\sigma_{\pi N}$: Mild tension between lattice results and πN scattering
- Detailed analysis of lattice data within EFT framework consistent with dispersion theory

Finite-volume quantisation (aka “Lüscher formalism”)

- First-principles approach to study hadronic interactions and resonances in QCD

$$\det \left[F(E, \mathbf{P}, L) + \mathcal{K}(E_{\text{cm}})^{-1} \right] = 0, \quad E_{\text{cm}} = \sqrt{E^2 - \mathbf{P}^2}$$

 lattice input

$$\text{S-wave: } \left[\mathcal{K}^{-1} \right]_{0,0}^{s^+} = \frac{p \cot \delta_0^I}{8\pi E_{\text{cm}}}$$

- Applied to baryon-baryon, baryon-meson (e.g. $\Lambda(1405)$) and meson-meson (e.g. ρ , T_{cc} , ...) interactions
- Extension to three-particle interactions

Complementary to phenomenology / dispersion theory

The H Dibaryon in Lattice QCD

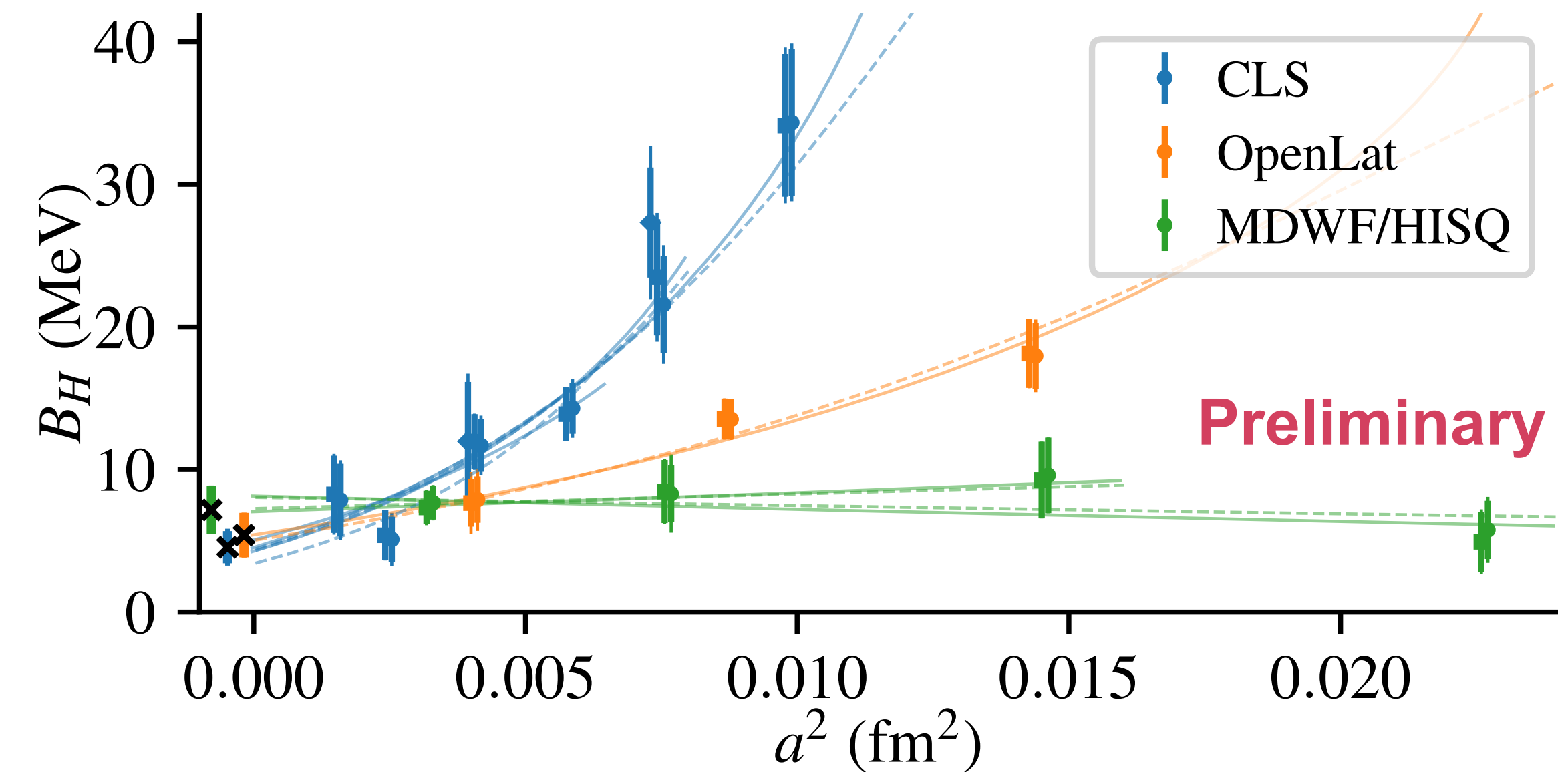
[Green et al., Phys Rev Lett 127 (2021) 242003; BaSc Collab., in prep.]

H dibaryon: Conjectured bound state of two Λ -hyperons — double hyper-nucleus

Large discretisation effects in the binding energy

Lattice artefacts enhance strength of $\Lambda\Lambda$ -interactions

Cross-check using different discretisations of the quark action:



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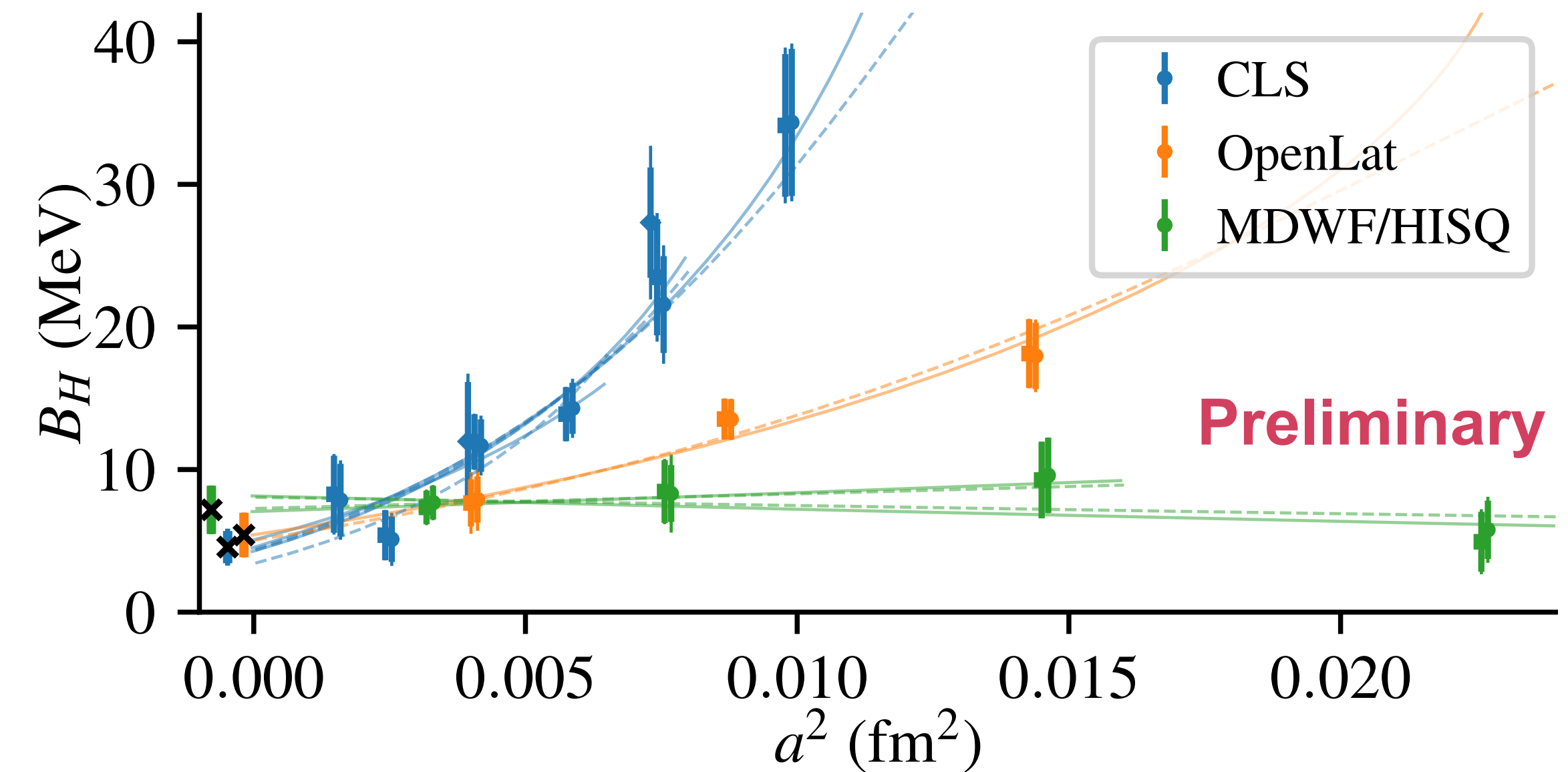
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$$B_H^{N_f=3} = \begin{cases} 4.56 \pm 1.13 \pm 0.63 \text{ MeV} & \text{CLS} \\ 5.41 \pm 1.56 \pm 0.24 \text{ MeV} & \text{OpenLat} \\ 7.2 \pm 1.7 \text{ MeV} & \text{MDWF/HISQ} \end{cases}$$

(SU(3)-flavour symmetric point)



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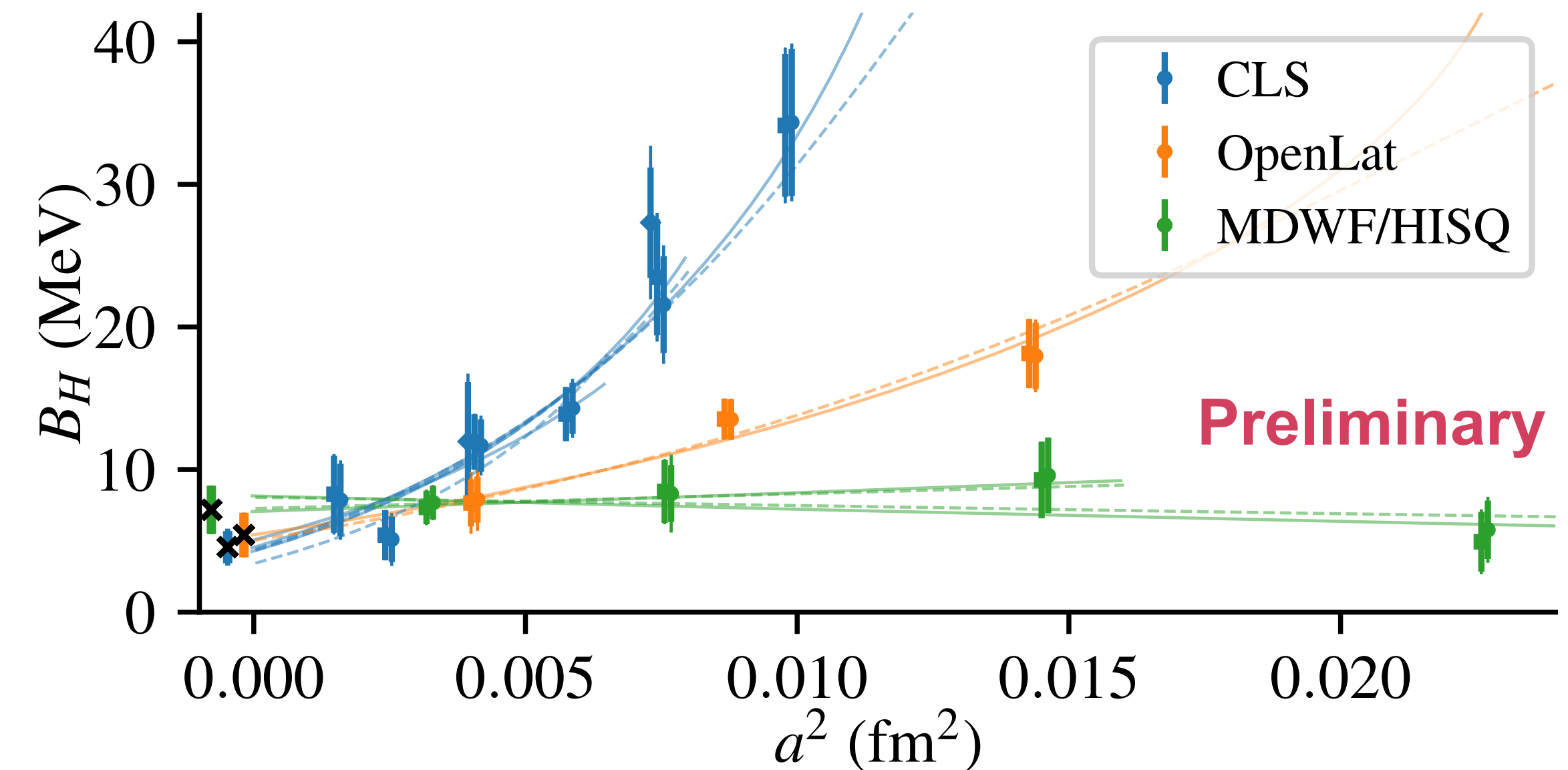
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- Weakly bound H dibaryon confirmed for a broad variety of discretisations; consistent with findings by ALICE determined using “femtoscopy”
- No deeply bound six-quark state observed as required for dark matter scenario

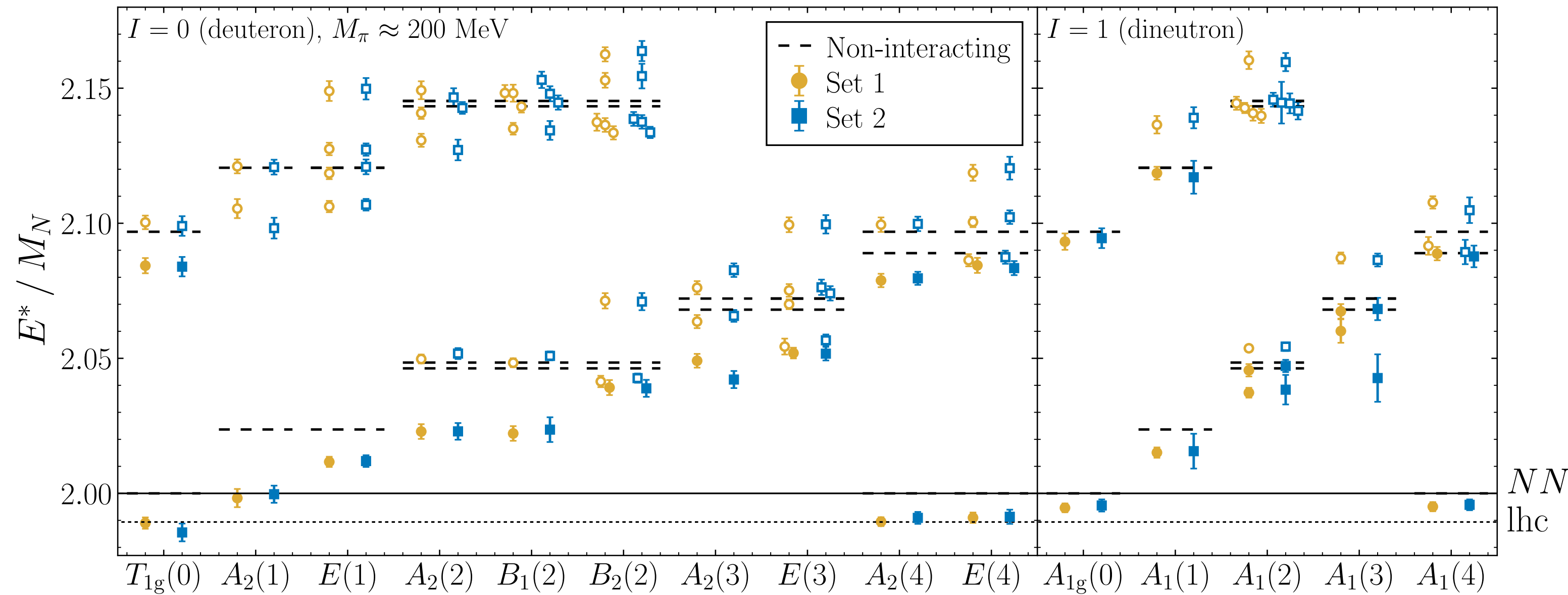
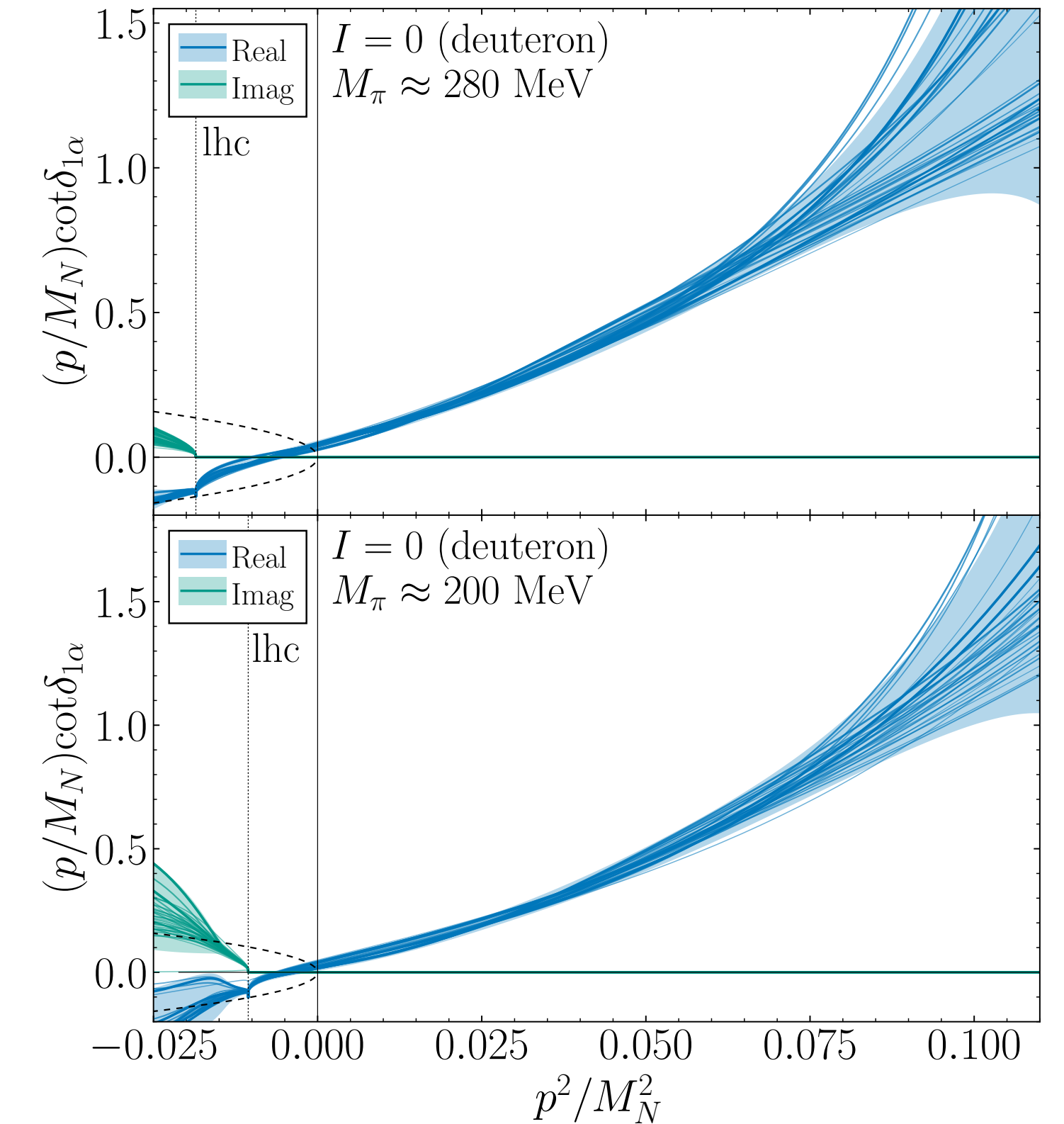


Nucleon-nucleon interactions

[Baeza-Ballesteros et al., arXiv:2610:23332]

Disagreement over existence of NN -bound states at heavier-than-physical pion mass

- Study pion-mass dependence of NN scattering amplitudes in the $I = 0$ (deuteron) and $I = 1$ (dineutron) channels

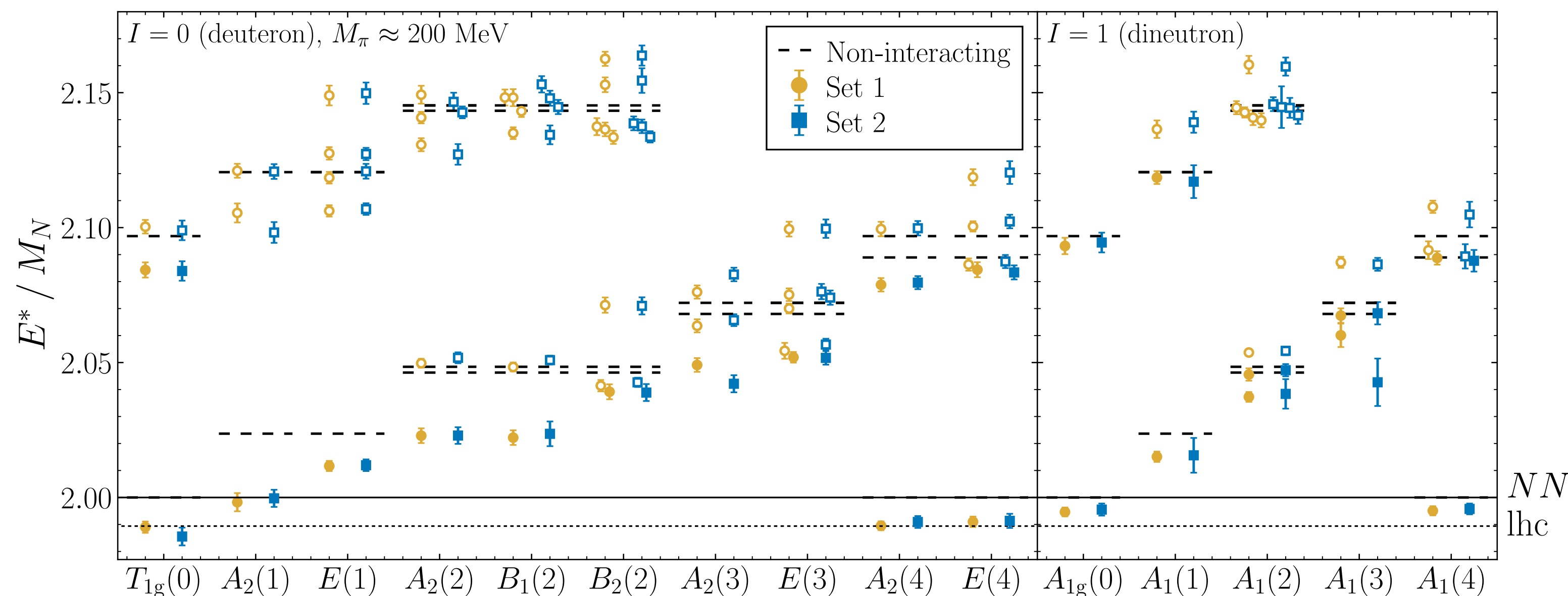
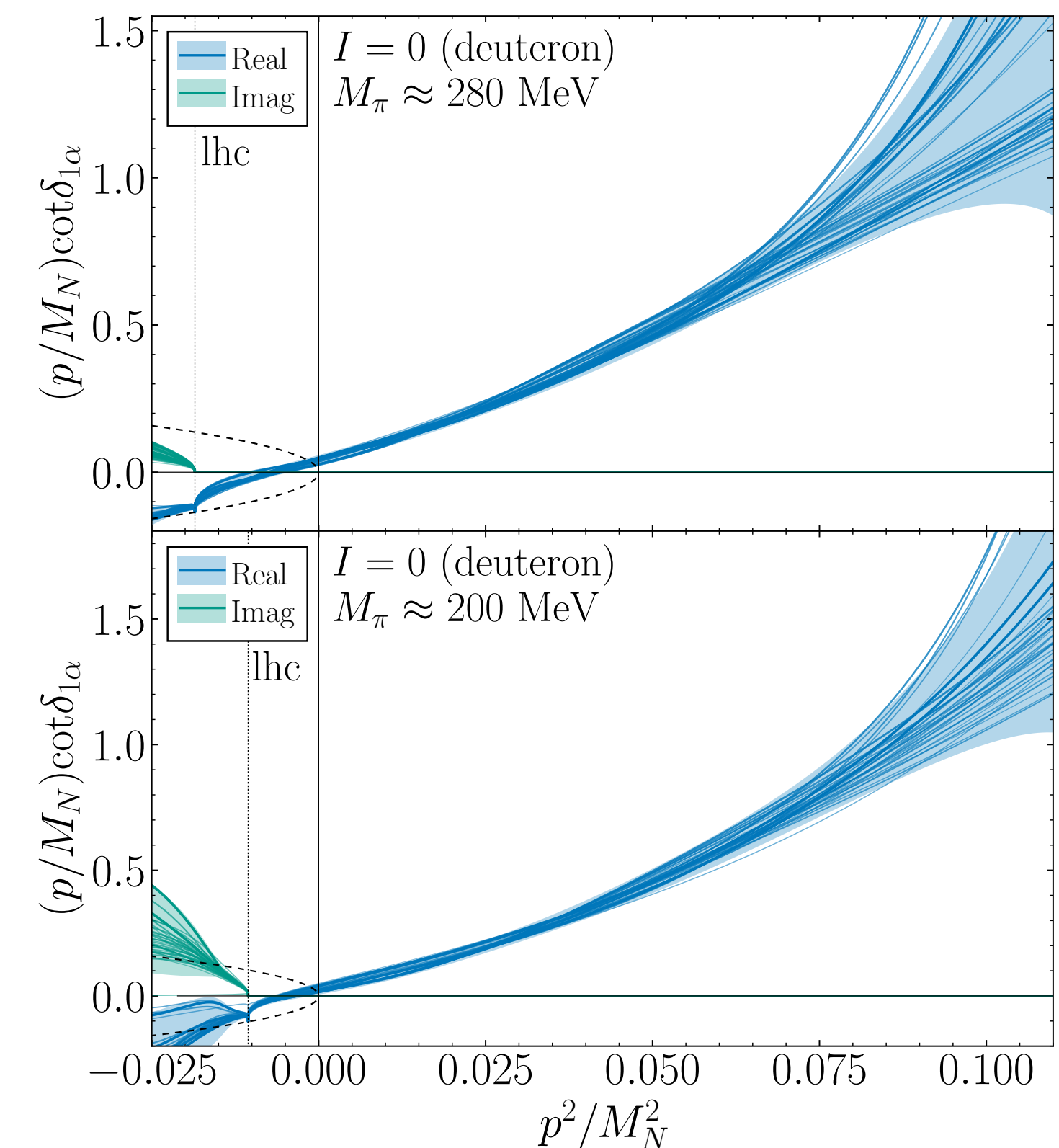


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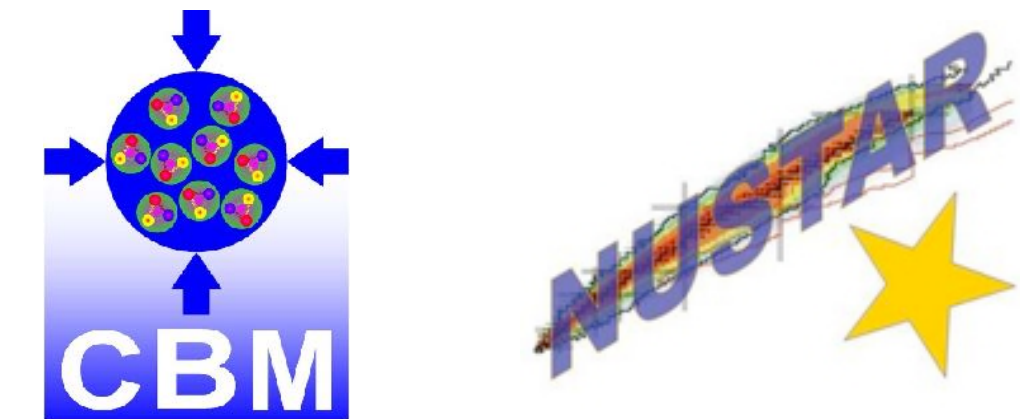
- Study pion-mass dependence of NN scattering amplitudes in the $I = 0$ (deuteron) and $I = 1$ (dineutron) channels



- Find virtual bound state in the deuteron and dineutron channels at $m_\pi = 280$ and 200 MeV
- Nucleon-nucleon interaction increases as pion mass is lowered

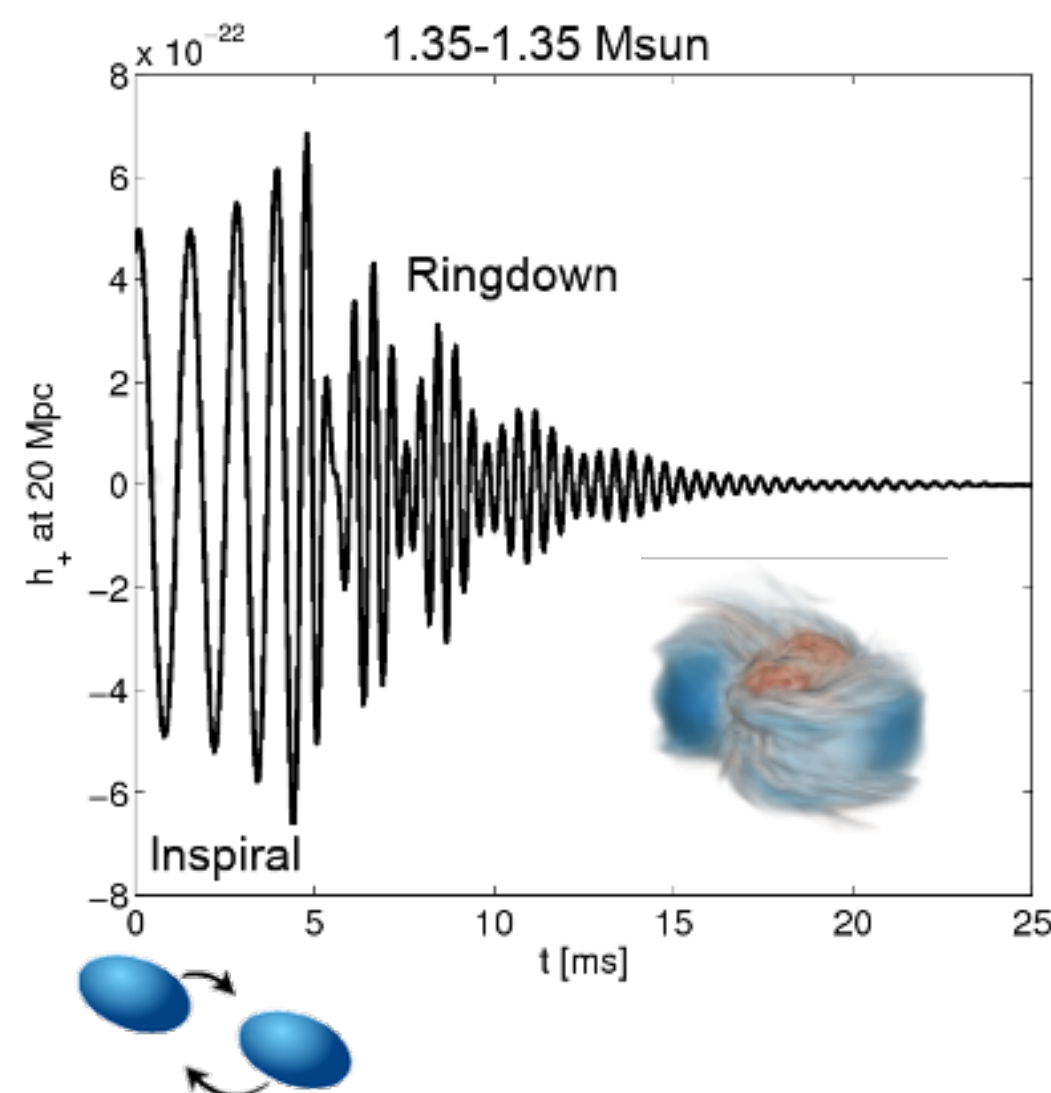
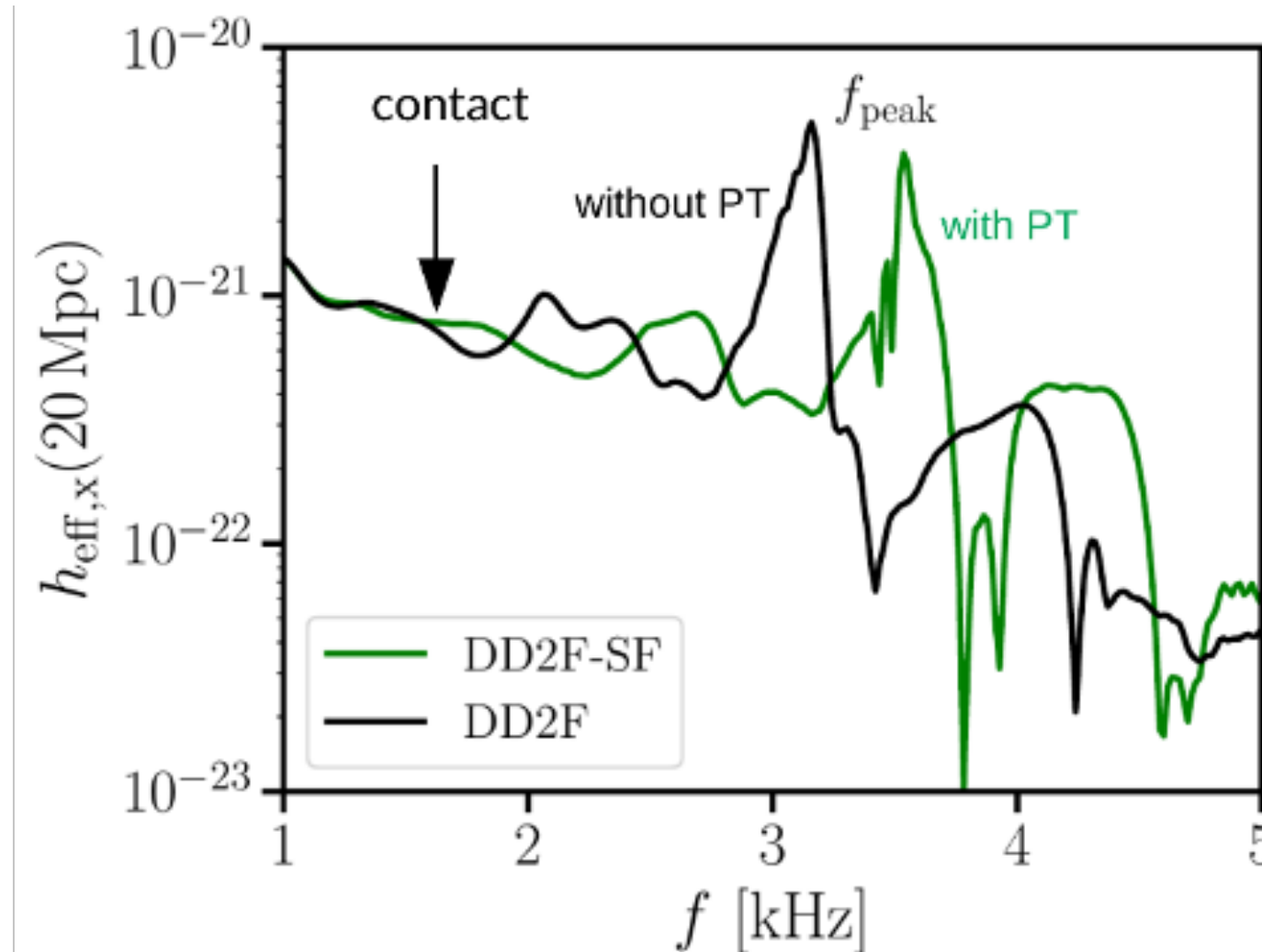
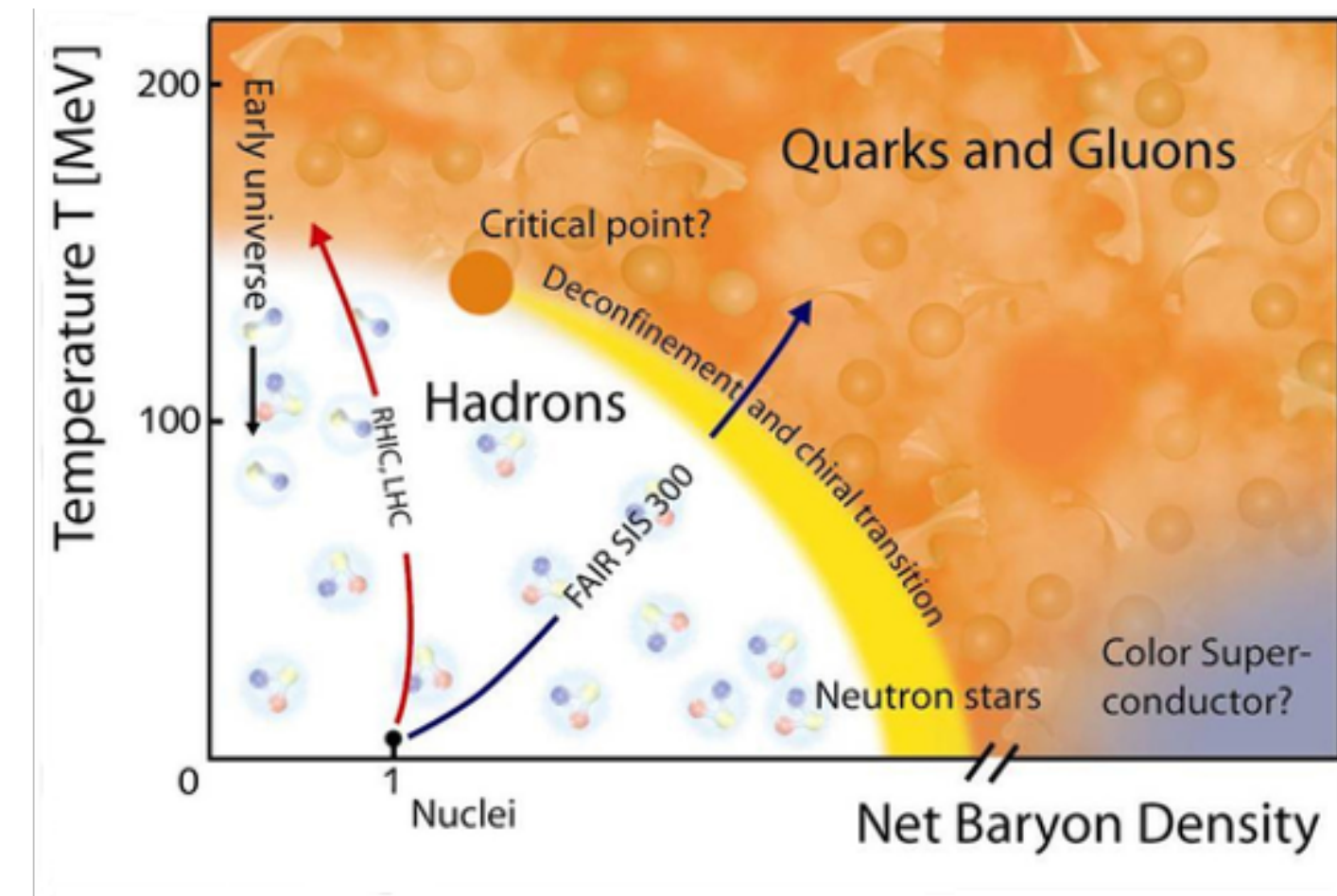
Experimental programme at GSI/FAIR

- High-density matter probed by CBM / HADES and NuSTAR
- Structure and reactions of neutron-rich nuclei studied at NuSTAR



Gravitational waves and multi-messenger astrophysics

- Search for a critical endpoint in the QCD phase diagram
- Signature of first-order transition contained in post-merger signal

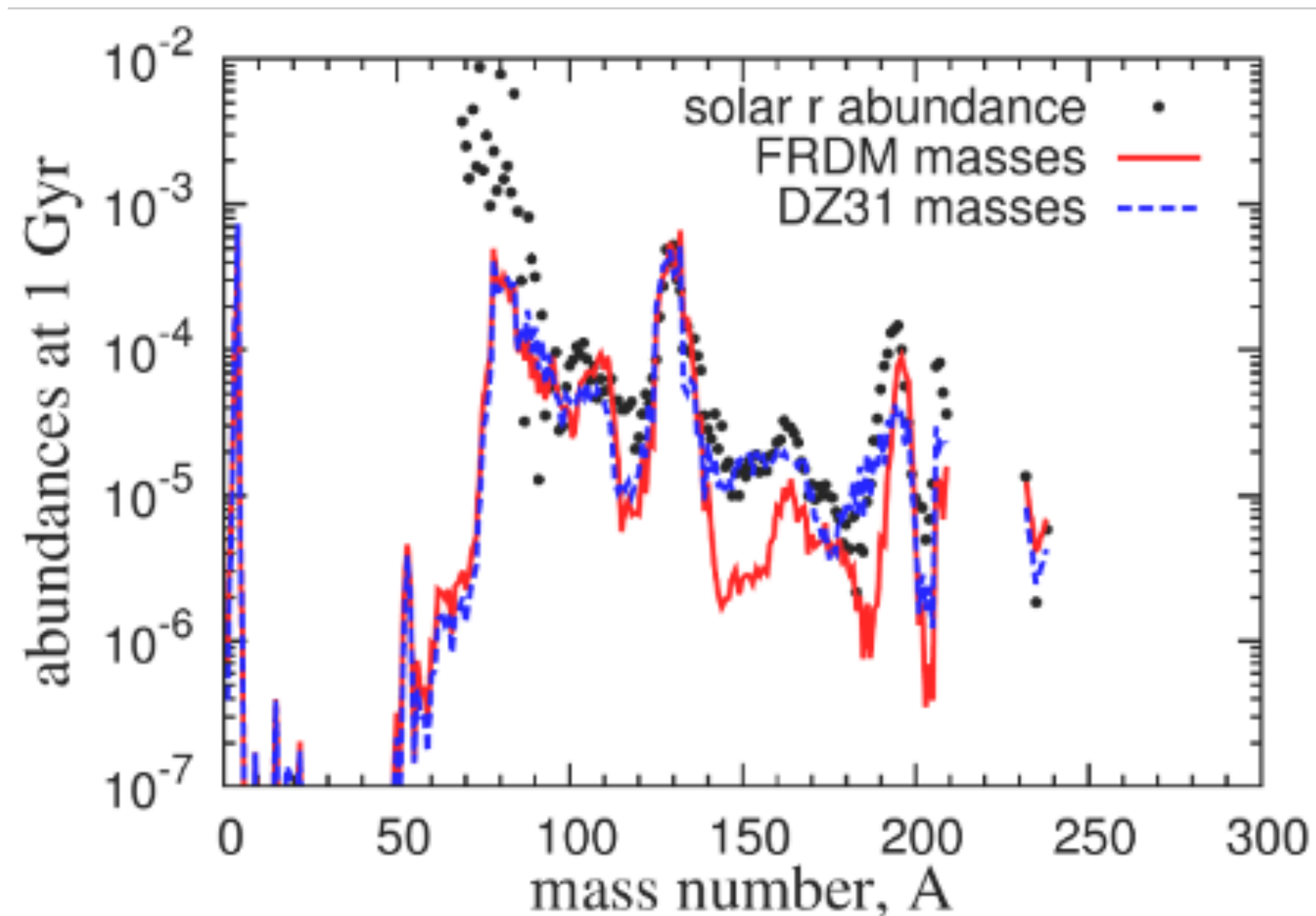
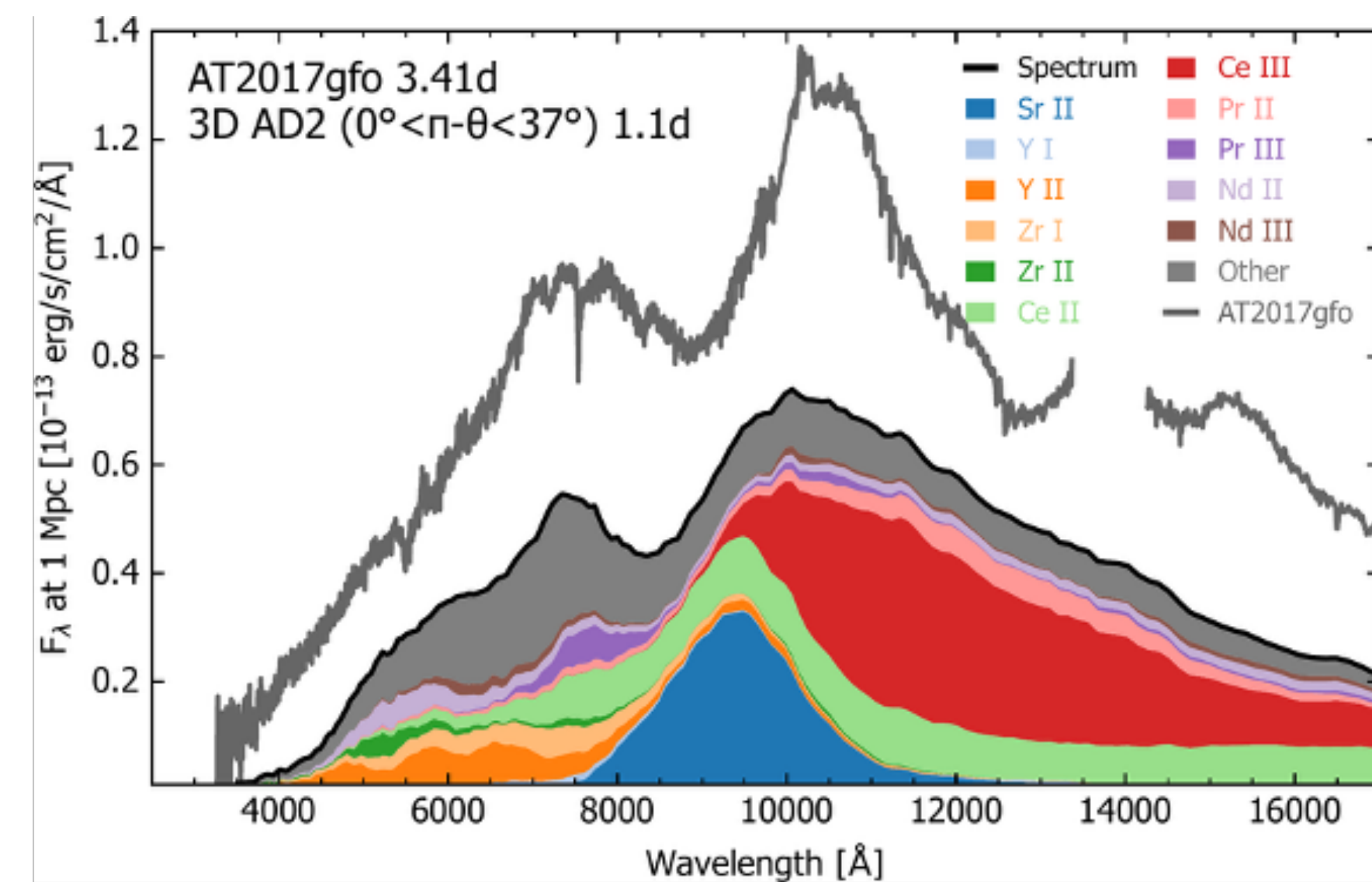


Electromagnetic signals for r -process

[Shingles et al., *Astrophys J Lett* 954 (2023) 2, L41]

NuSTAR will provide data for masses and beta-decays for exotic nuclei

- Reduce uncertainties in predicting abundances for nucleosynthesis
- Predict electromagnetic spectra based on merger simulations, nucleosynthesis network calculations and radiative transfer simulations



- Identify individual elements in ejecta of kilonovas

Broad and vigorous programme in theoretical particle, hadron and nuclear physics

Hadron physics has entered the precision stage:

- Model-independent predictions that have direct impact on experiment
- Understanding of fundamental processes in term of QCD
- Tensions between different theoretical approaches remain to be understood

Nuclear astrophysics calculations crucial for interpretation of FAIR data

Availability of sufficient computing resources crucial

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Thank you

...and may the strong force be with you...