Footprints of chiral dynamics: tracing from light to heavy

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Outline

- Introduction
- Recent progress in hadron physics with chiral effective field theory
  - High-order calculation beyond one-loop
  - Interplay with dispersion relations
  - New physics
  - Generalisation to heavy flavored fields
- Summary and outlook

Chiral Perturbation Theory—EFT of QCD at low energies

- **Facets of QCD** — Asymptotic freedom & Color confinement

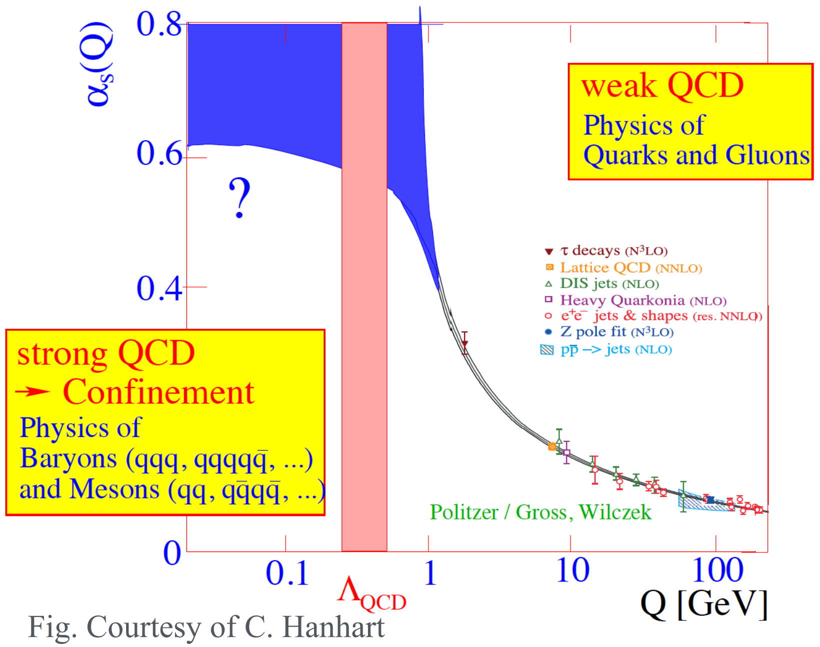
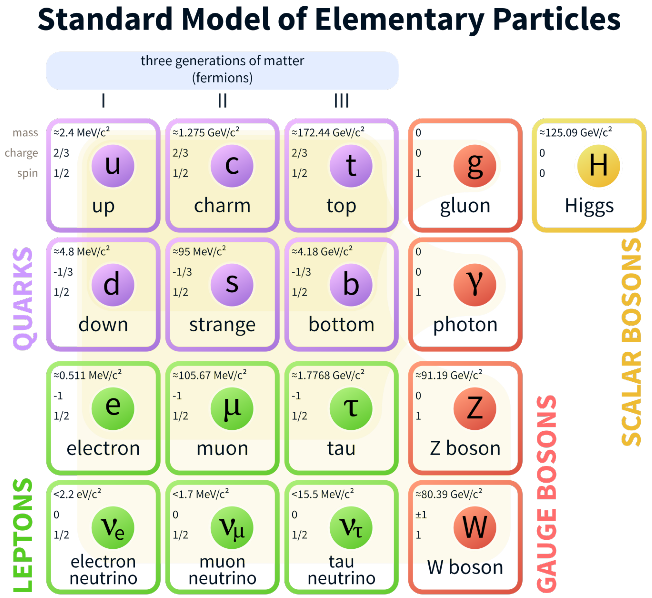
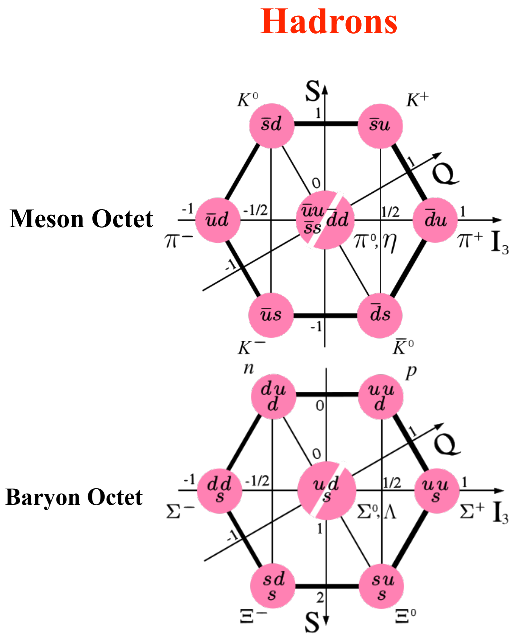


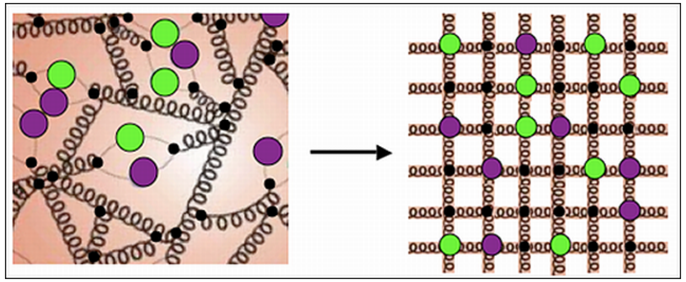
Fig. Courtesy of C. Hanhart





- **Low-energy region** — Quarks are glued together by gluons to form hadrons

Lattice QCD



Phenomenological Models

⇩

- Linear Sigma Model
- Nambu-Jona-Lasinio Model
- Jülich Model
- …

Effective Field Theories

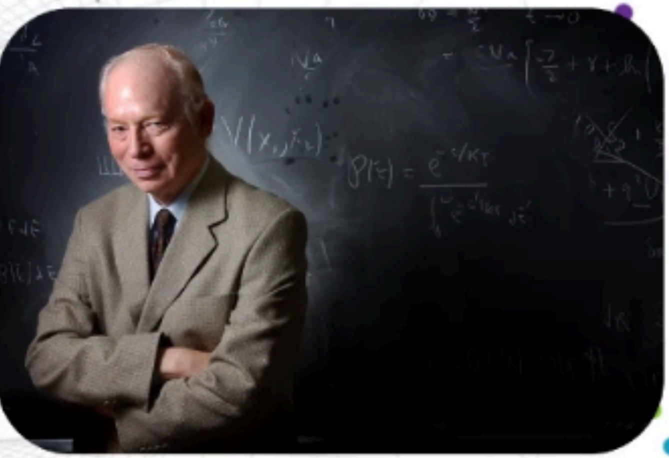
⇩ Chiral Symmetry

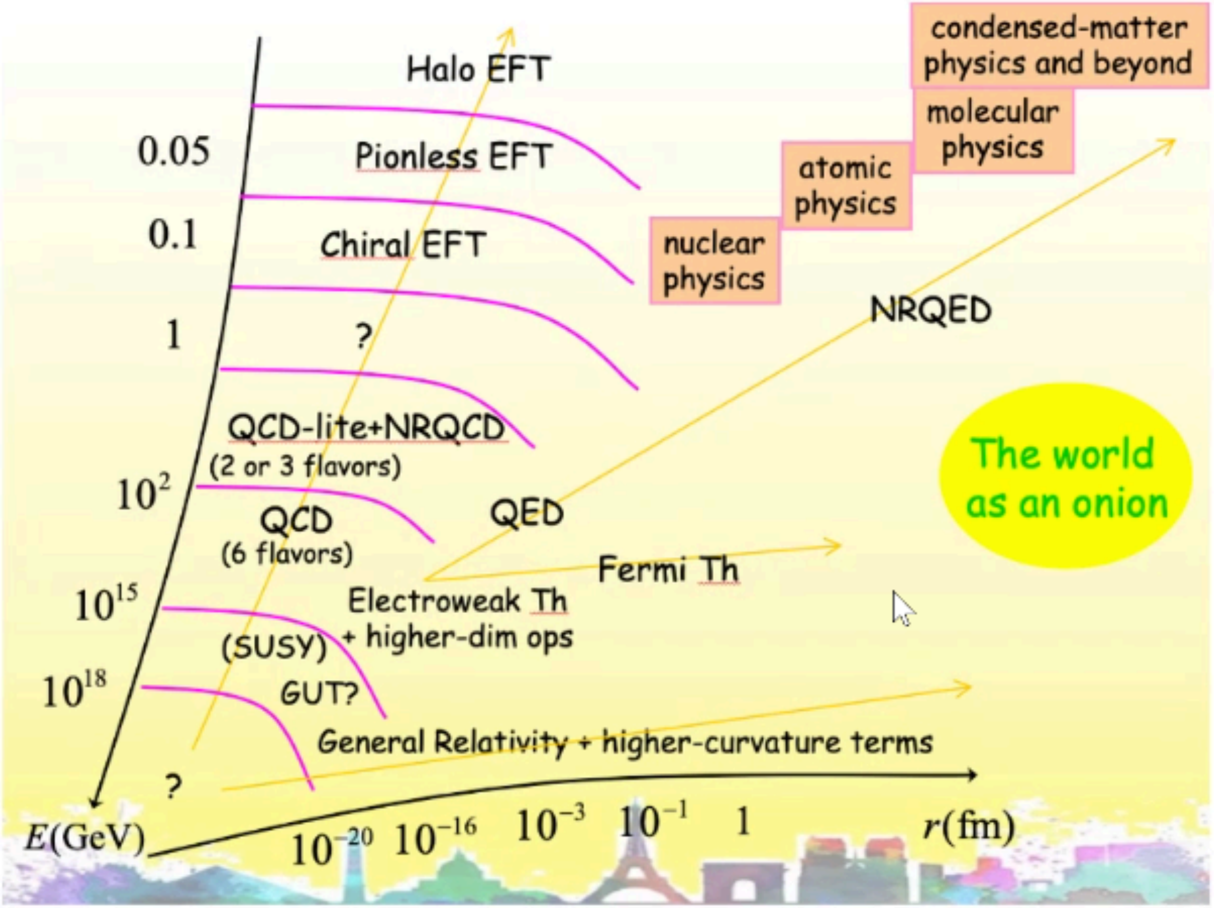
- **Chiral Perturbation theory (ChPT)**

➡ hadron fields as degrees of freedom

➡ Expansion in masses and external momenta

We are entering the era of EFTs





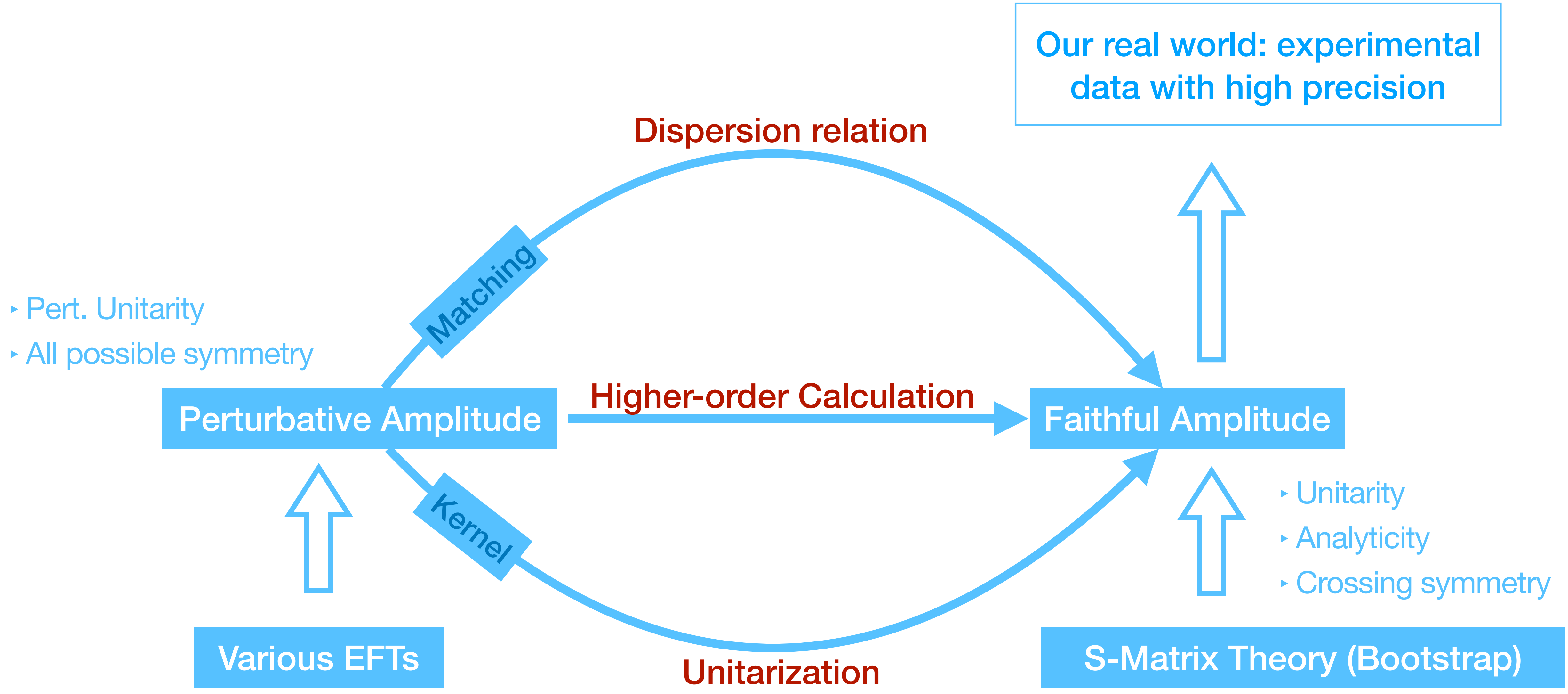
"Now, considering the fact that experiments can probe only a limited range of energies, it seems natural to take EFT as a general framework for analyzing experimental results."

T. Y. Cao

in *Renormalization, From Lorentz to Landau (and Beyond)*, L.M. Brown (ed.), 1993

Importance of EFT

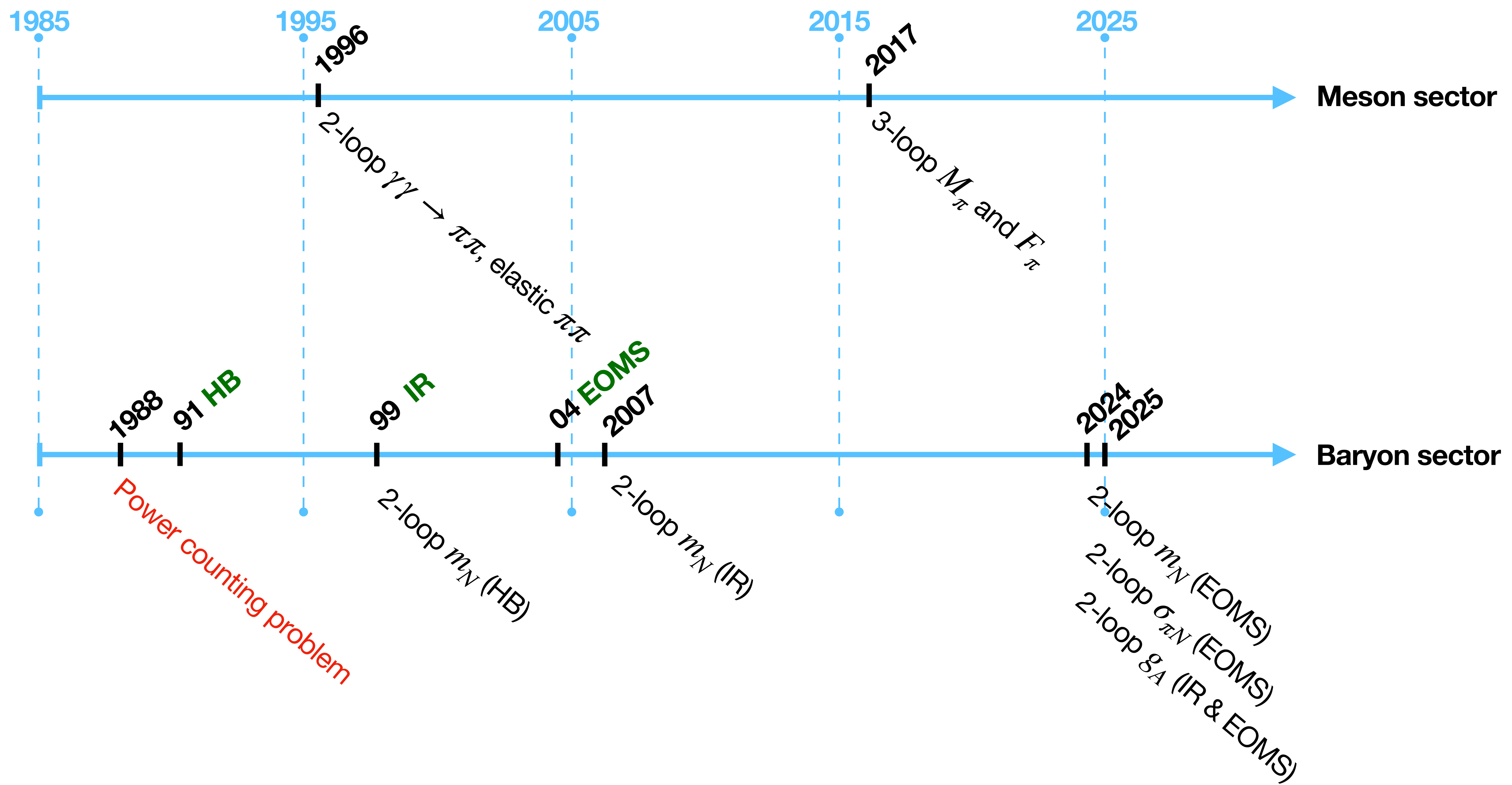
- **Towards faithful scattering amplitudes** [**DLY**, L.-Y. Dai, H.-Q Zheng, and Z.-Y. Zhou, Rept.Prog.Phys. 84 (2021)]



I. High-order calculations beyond one-loop

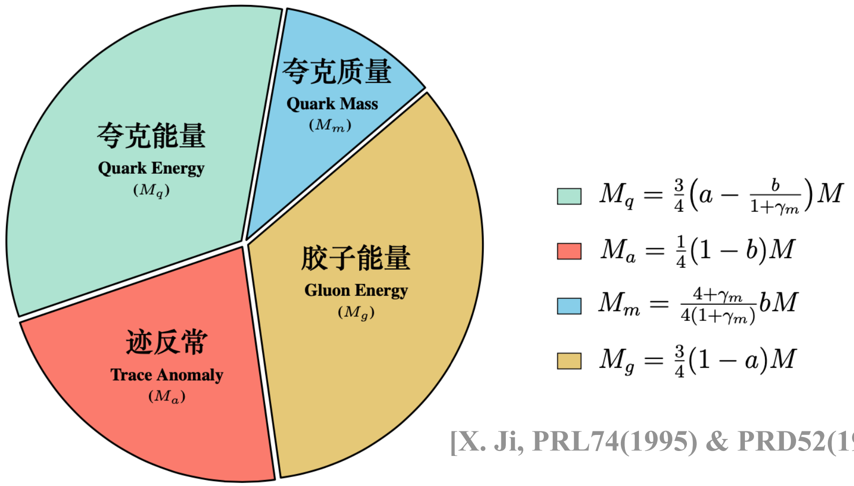
ChPT beyond one-loop

- Time line



Nucleon mass physics

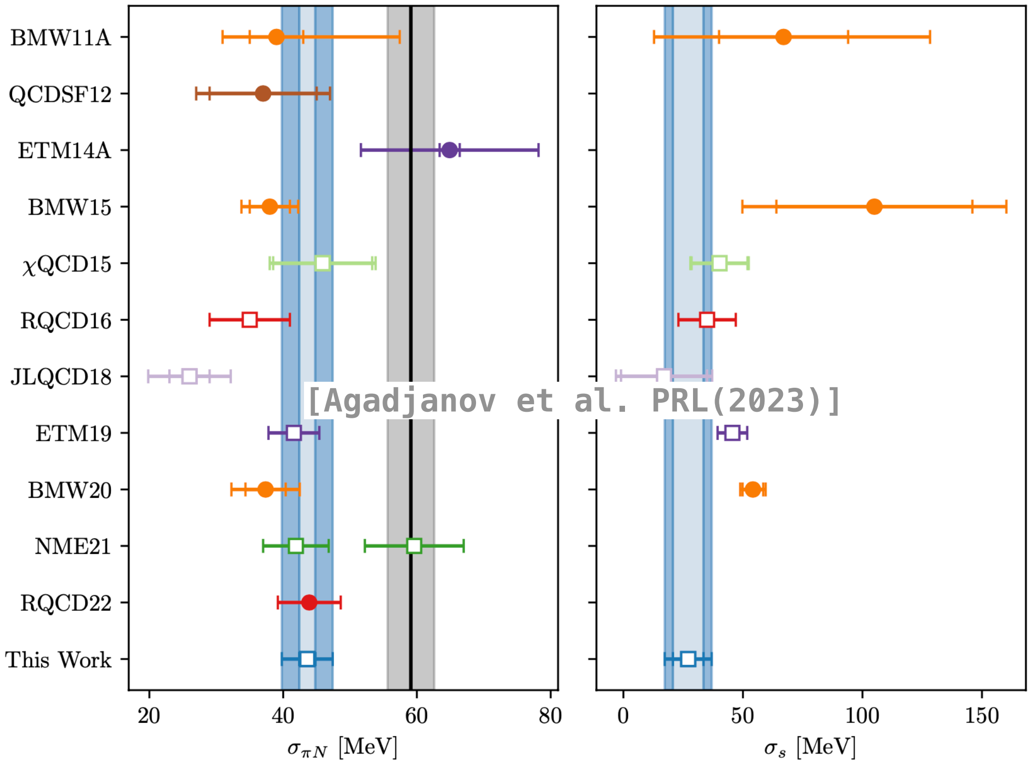
- High precision determination of the nucleon mass
  - The proton mass decomposition
  - Sigma term: tension between lattice QCD and phenomenological results
  - WIMP dark matter: scalar coupling of the nucleon to dark matter
  - …



[X. Ji, PRL74(1995) & PRD52(1995)]

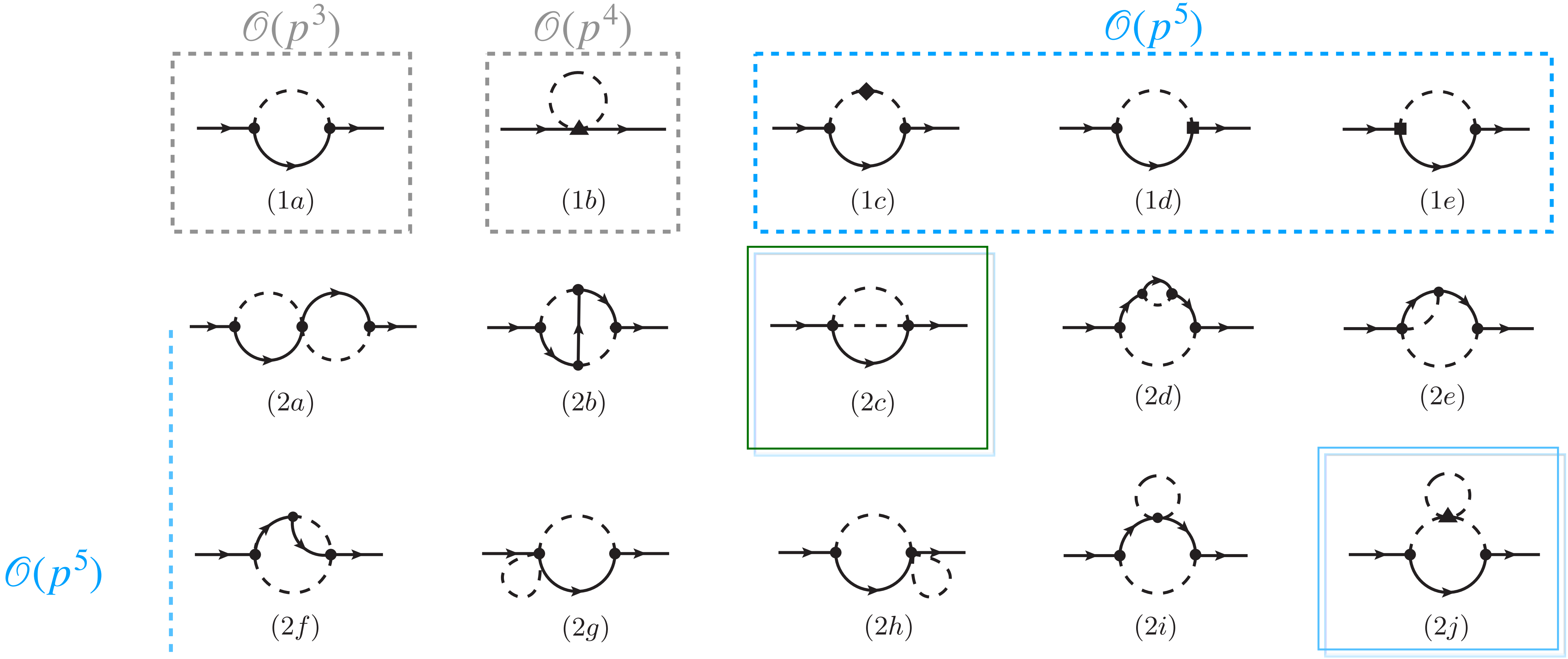
Feynman—Hellmann Theorem

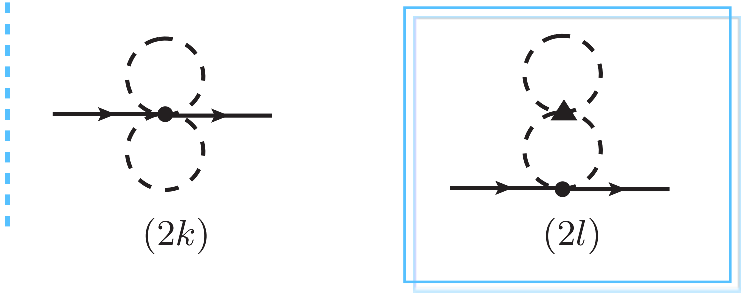
$$\sigma_{\pi N} = \frac{\hat{m}}{2m_N}\langle N|\bar{u}u + \bar{d}d|N\rangle = M_\pi^2 \frac{\partial m_N}{\partial M_\pi^2}$$



[Agadjanov et al. PRL(2023)]

The nucleon mass at two-loop order





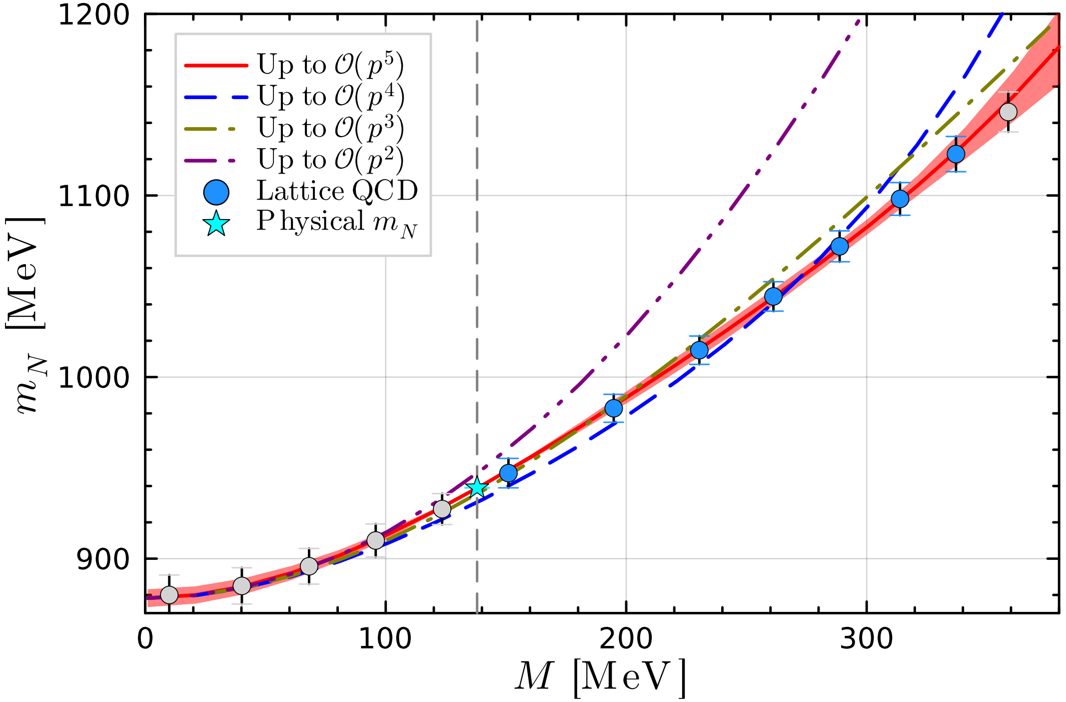
- "t channel": incorporating $\pi\pi$ rescattering effect
- "s channel": incorporating $\pi\pi N$ contribution

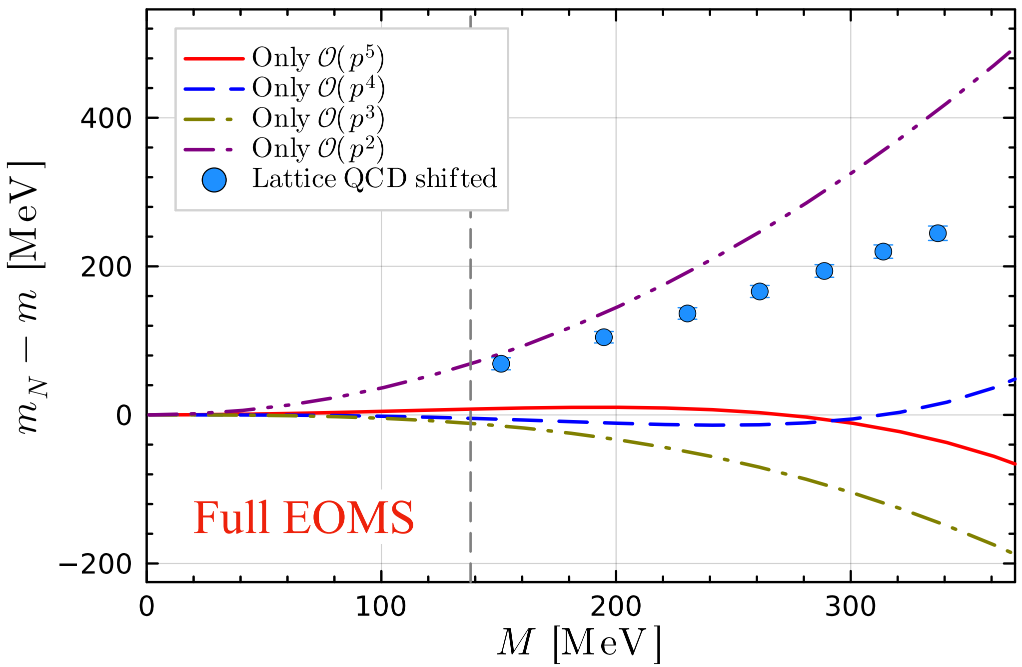
[Liang, Chen, Guo, Guo, and **DLY**, JHEP(2025)]

Two-loop chiral extrapolation

- Assess the convergency of the chiral expansion

[Z.-R. Liang, H.-X. Chen, F.-K. Guo, Z.-H. Guo, and **DLY**, JHEP04 (2025)]



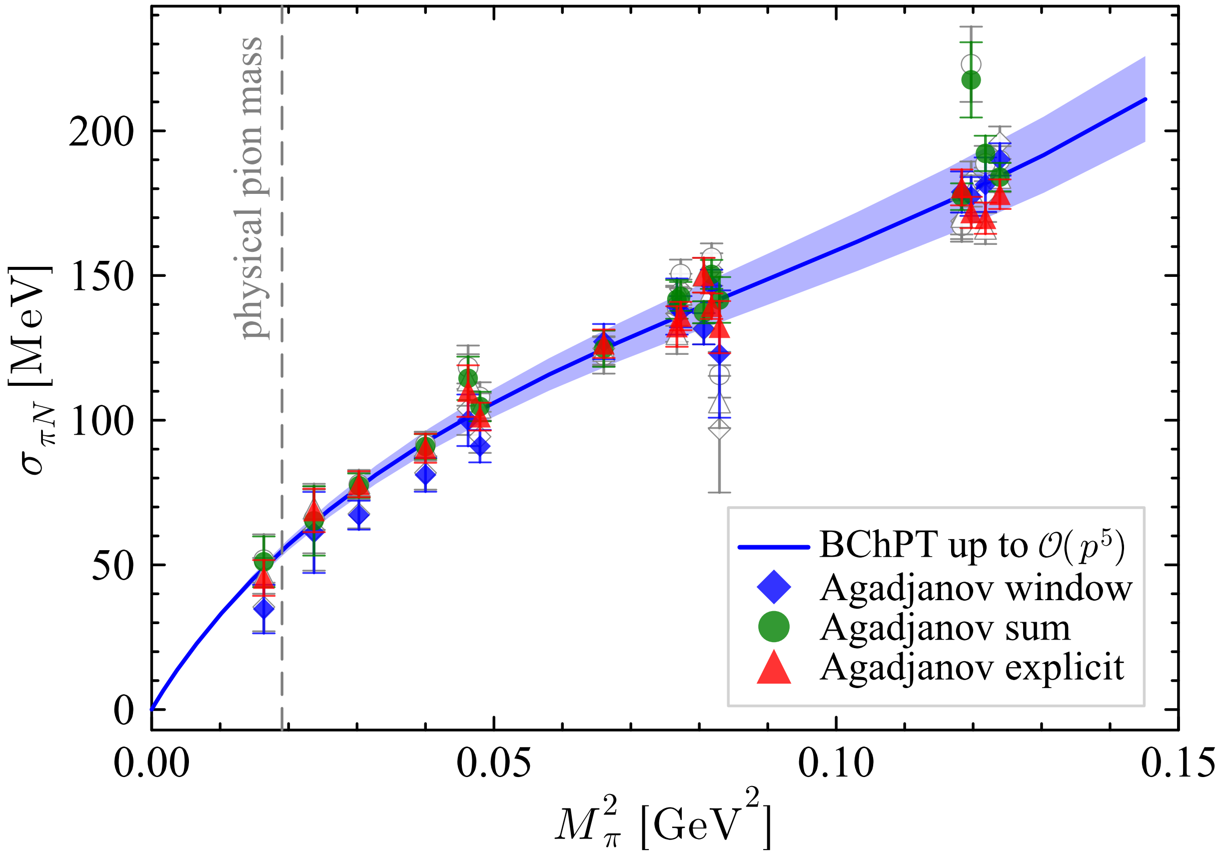


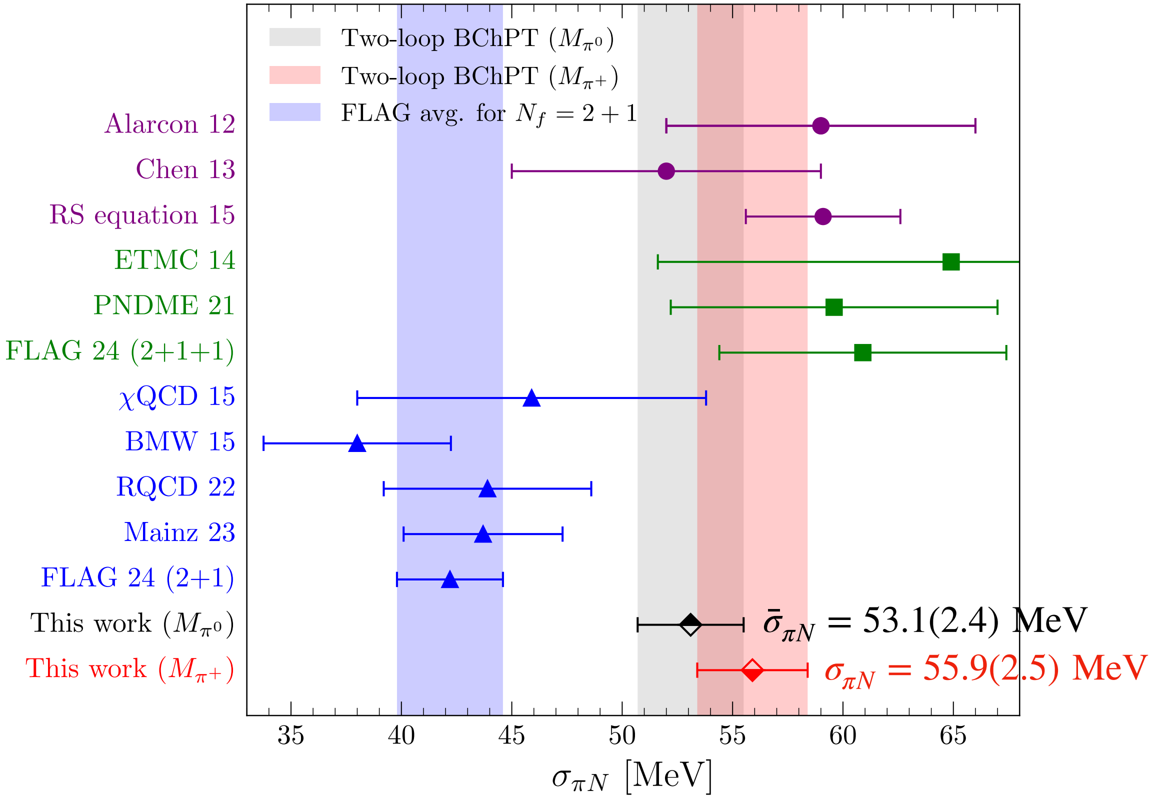
- Two-loop contribution is small, approximately 10 MeV, for pion mass < 300 MeV;

Nucleon sigma term

- Sigma term via Feynman-Hellman theorem

[Z.-R. Liang, H.-X. Chen, F.-K. Guo, Z.-H. Guo, and **DLY**, arXiv:2508.11435 [hep-ph]]





Resolving the tension between lattice QCD and phenomenology!

➡ See talk by 梁泽锐 for more details

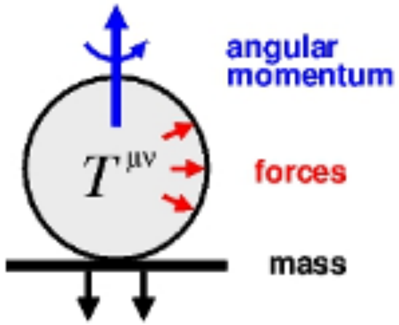
II. Interplay with Dispersion Relations

Gravitational structure of hadrons

- Probes of hadron structure (nucleon as example)

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

Polyakov & Schweitzer, IJMPA (2018) 1830025



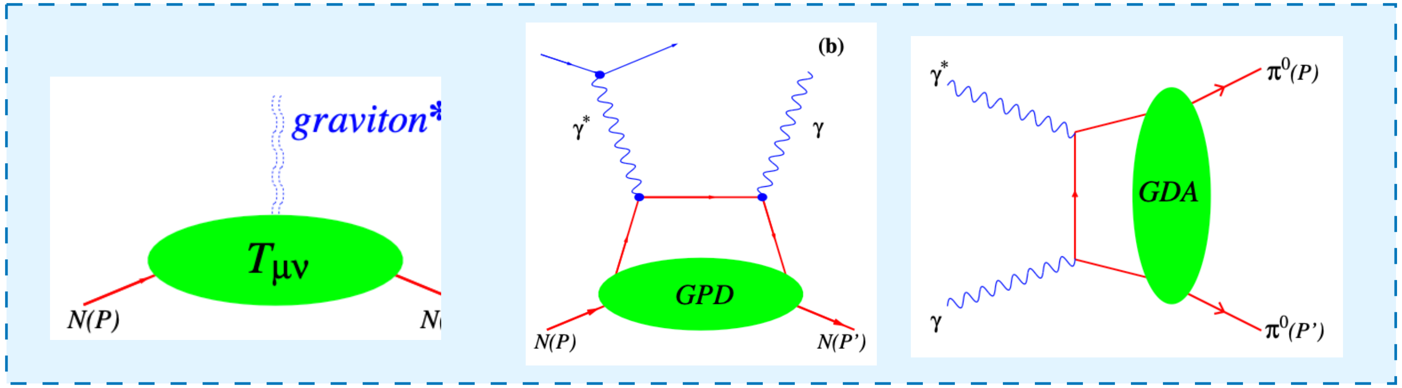
D-term: “Last unknown global property”

- Gravitational structure
  - Gravity couples to matter via QCD energy-momentum tensor (EMT)
  - Impractical probe by scattering off gravitons

✓ Nucleon as targets: accessible by hard-exclusive reactions like DVCS via GPDs

✓ Pions: GPDs →GDAs by crossing

✓ Lattice QCD



Unitarity relation for nucleon GFFs

- Discontinuity

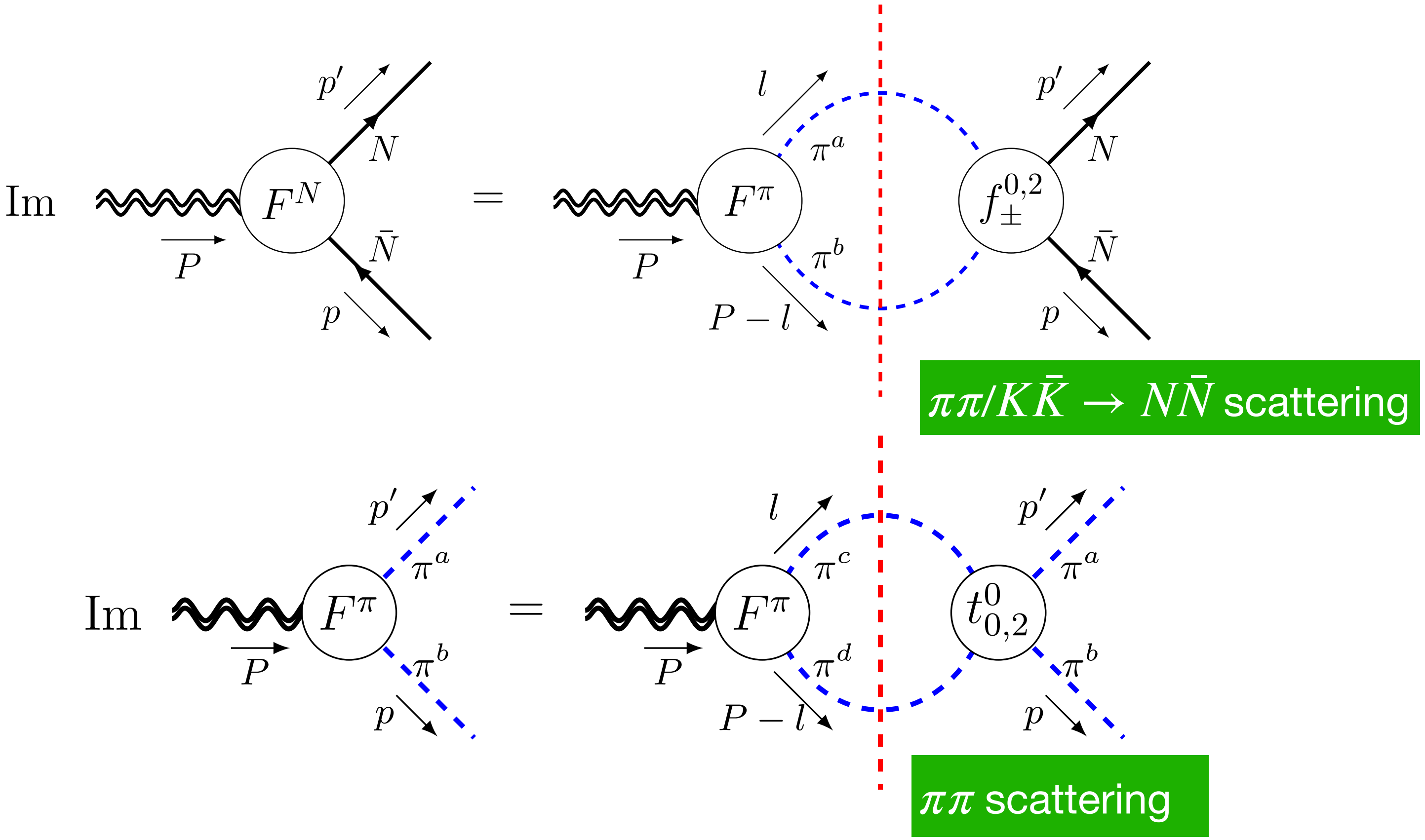
$$\mathrm{Disc}\left\langle N(p')\bar{N}(p)\,|\,\hat{T}^{\mu\nu}(0)\,|\,0\right\rangle \propto \sum_n \left\langle N(p')\bar{N}(p)\,|\,n\right\rangle \left\langle n\,|\,\hat{T}^{\mu\nu}(0)\,|\,0\right\rangle^* \delta^4(p+p'-p_n)$$

- In the region $t \in (t_\pi, 16t_\pi)$, only $\pi\pi$ intermediate state

Dispersion relations：

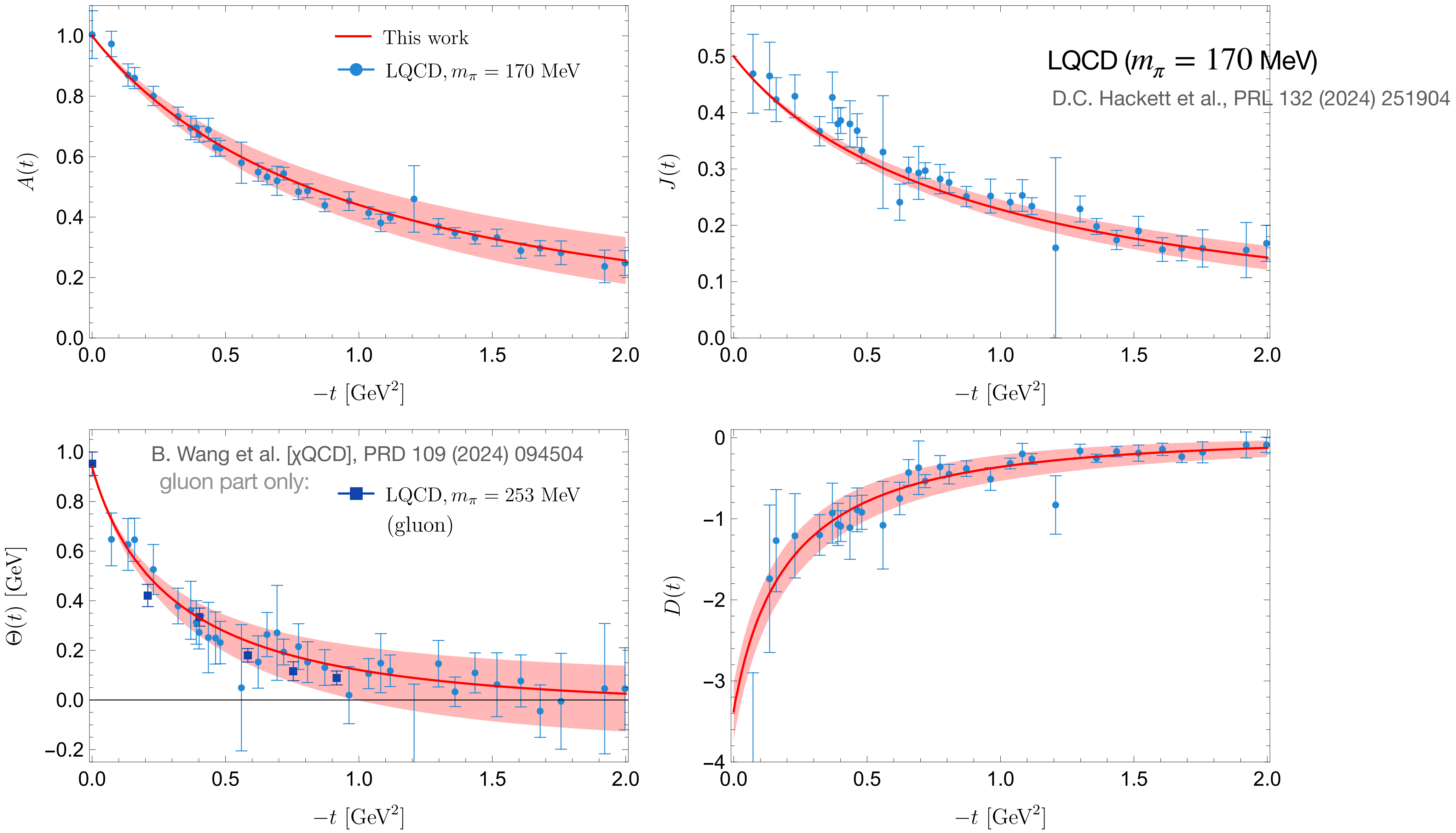
$$(A, J, \Theta)(t) = \frac{1}{\pi}\int_{4m_\pi^2}^{\infty} \mathrm{d}t' \frac{\mathrm{Im}(A, J, \Theta)(t')}{t'-t}$$

$$\frac{1}{\pi}\int_{4m_\pi^2}^{\infty} \mathrm{d}t' \frac{\mathrm{Im}(A, J, \Theta)(t')}{t'} = \left(1, \frac{1}{2}, m_N\right)$$



Nucleon GFFs

Predictions： [X.-H. Cao, F.-K. Guo, Q.-Z. Li and **DLY**, Nature Communications (2025)]



Nucleon GFFs: D-term & radii

[X.-H. Cao, F.-K. Guo, Q.-Z. Li and **DLY**, Nature Communications (2025)]

- *D*-term: $D \equiv D(0)$
- **Various radii in the Breit frame**
  - From the trace FF:
    $$\langle r_\Theta^2 \rangle = 6A'(0) - \frac{9D}{2m_N^2}$$
  - Radius of energy density:
    $$\langle r_{\text{Ener}}^2 \rangle = 6A'(0) - \frac{3D}{2m_N^2}$$
  - Mechanical radius
    $$\langle r_{\text{Mech}}^2 \rangle = \frac{6D}{\int_{-\infty}^{0} \mathrm{d}t\ D(t)}$$
  - Radius of the density $J(t) + \frac{2}{3} t \frac{\mathrm{d}}{\mathrm{d}t} J(t)$
    $$\langle r_J^2 \rangle = 20J'(0)$$

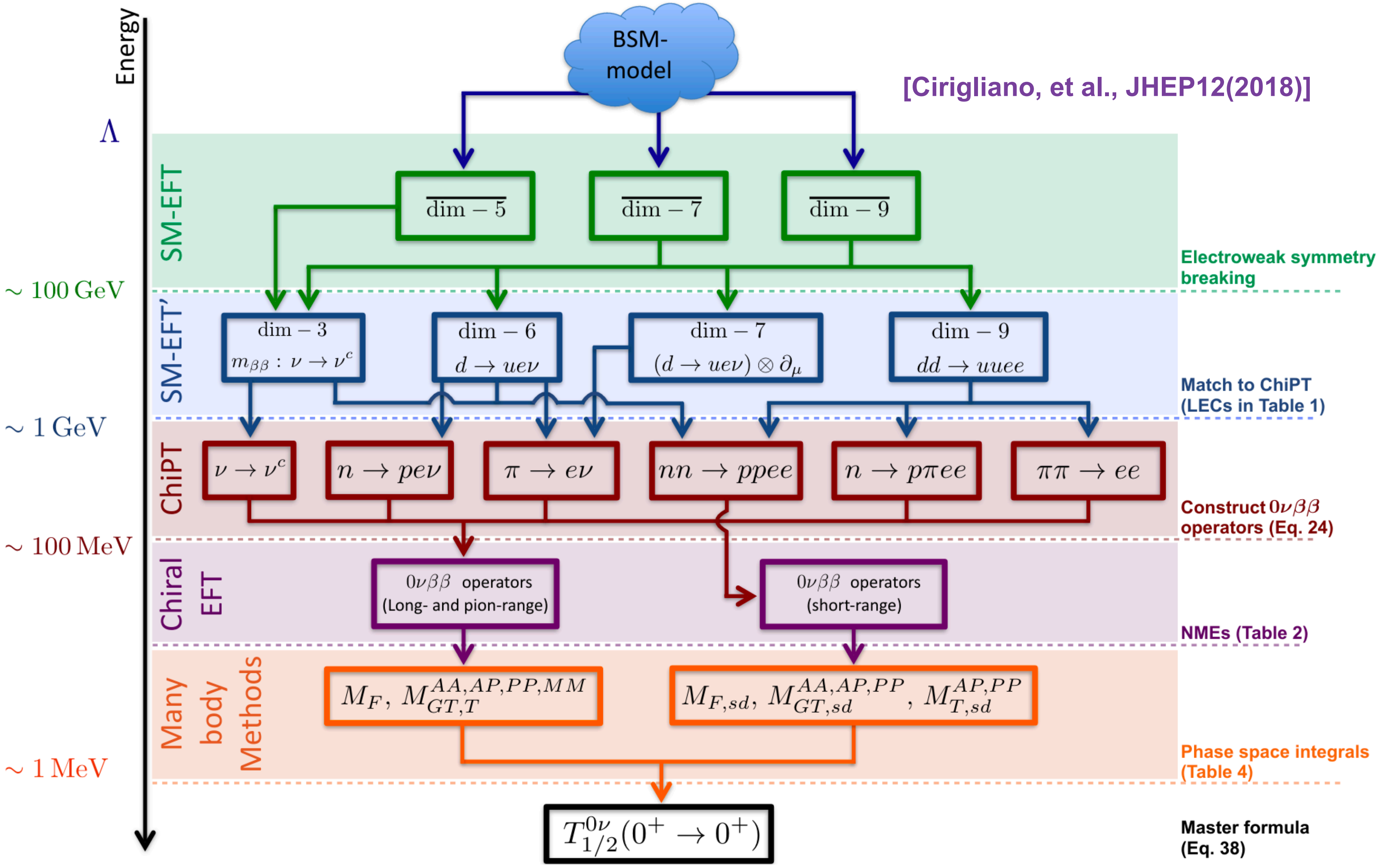
Quantity	Result	Error budget
D-term	$-3.38^{+0.34}_{-0.35}$	+(0.18)ChPT(0.12)PWA(0.26)eff
		-(0.16)ChPT(0.12)PWA(0.29)eff
$\langle r_\Theta^2 \rangle$ [fm]	$0.97^{+0.03}_{-0.03}$	+(0.01)ChPT(0.01)PWA(0.03)eff
		-(0.02)ChPT(0.01)PWA(0.26)eff
$\langle r_{\text{Ener}}^2 \rangle$ [fm]	$0.70^{+0.03}_{-0.04}$	+(0.02)ChPT(0.01)PWA(0.02)eff
		+(0.02)ChPT(0.01)PWA(0.03)eff
$\langle r_{\text{Mech}}^2 \rangle$ [fm]	$0.72^{+0.09}_{-0.08}$	+(0.02)ChPT(0.00)PWA(0.09)eff
		-(0.03)ChPT(0.01)PWA(0.07)eff
$\langle r_J^2 \rangle$ [fm]	$0.70^{+0.02}_{-0.02}$	+(0.01)ChPT(0.01)PWA(0.01)eff
		-(0.01)ChPT(0.00)PWA(0.02)eff

- ChPT: NLO ChPT inputs
- paw: $\pi\pi/K\bar{K} \to N\bar{N}$
- eff: effective poles m_S, m_D

III. New physics

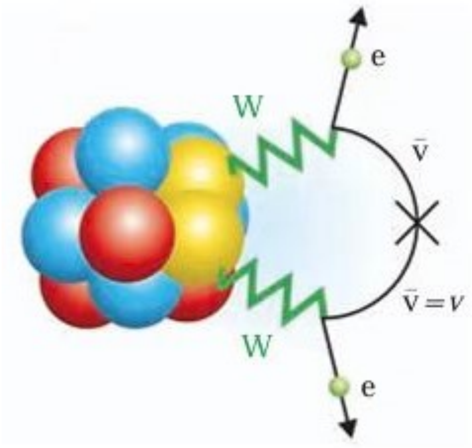
ChEFT and BSM physics

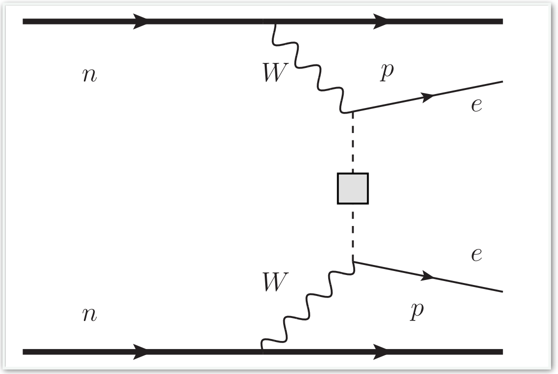
- EFT at various scalars (e.g. Lepton number violation)



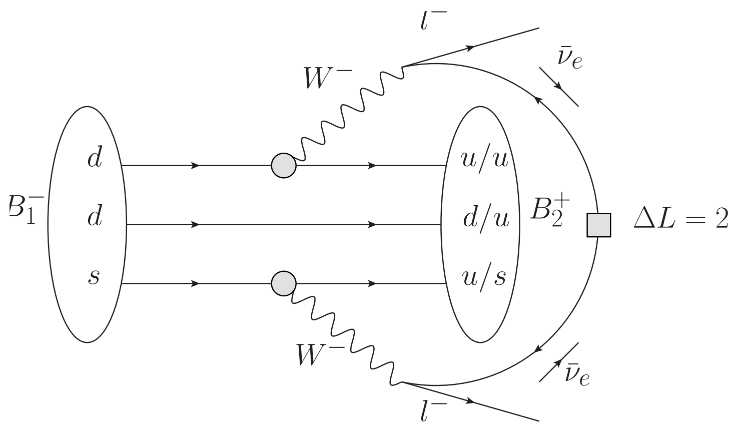
Hadronic neutrinoless double beta decay

- **Nuclear $0\nu 2\beta$**





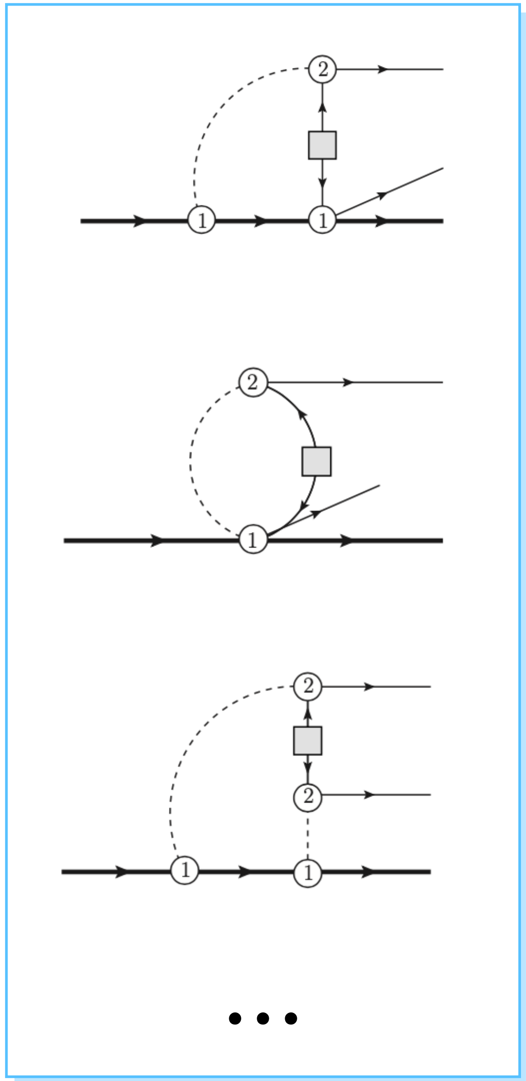
- **Hadronic $0\nu 2\beta$?**
  - Kaons: $K^{\pm} \to \pi^{\mp} l_{\alpha}^{\pm} l_{\beta}^{\pm}$ [Liao, Ma and Wang, JHEP03(2020)]
  - Hyperons

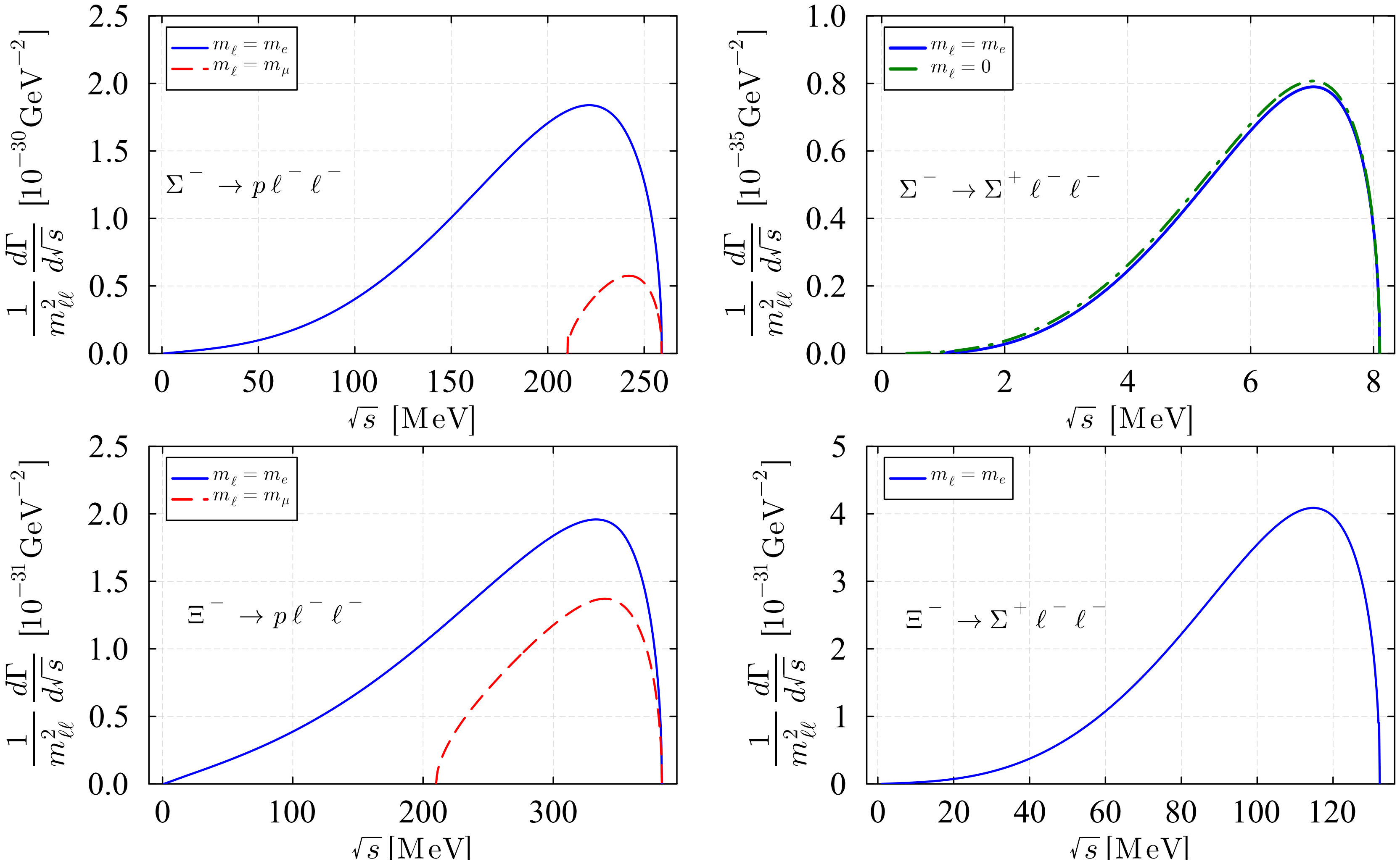


- $\Delta S = 0$: $\Sigma^-[dds] \to \Sigma^+[uus]e^-e^-$;
- $\Delta S = 1$: $\Sigma^-[dds] \to p[duu]\ell^-\ell^-$,$\Xi^-[dss] \to \Sigma^+[uus]e^-e^-$;
- $\Delta S = 2$: $\Xi^-[dss] \to p[duu]\ell^-\ell^-$.

Hadronic neutrinoless double beta decay

- **Hyperon $0\nu 2\beta$ in BChPT** [Z.-Y. Zhao, Z.-R. Liang, F.-K. Guo, L.-P. He and **DLY**, arXiv:2602.08453 [hep-ph]]





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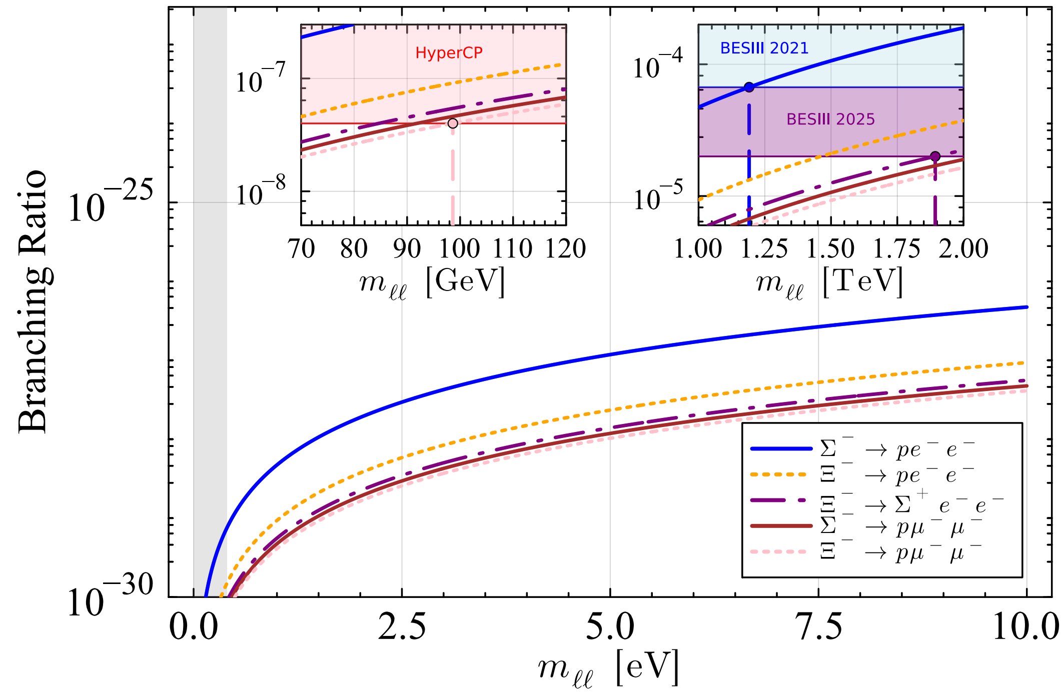
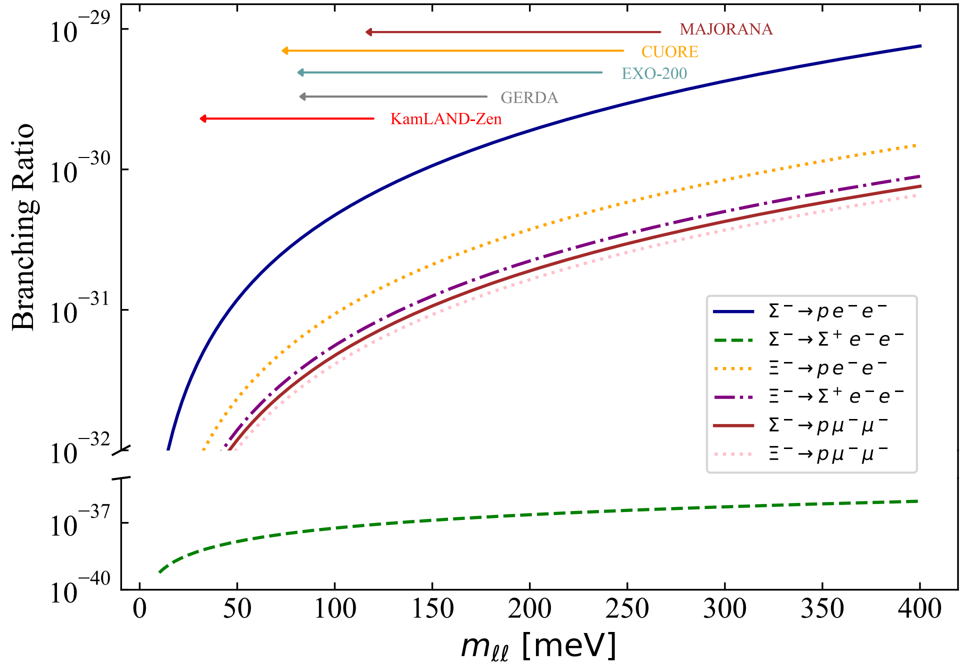




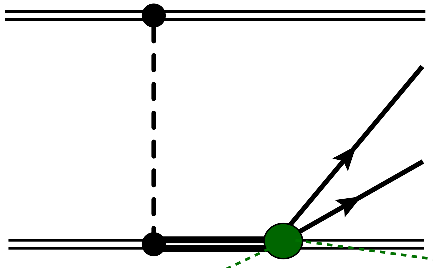
- Complementary to nuclear $0\nu2\beta$
- Future hyperon factory

Process	$\frac{\Gamma_{0\nu}}{m_{\ell\ell}^2}$ [sec^{-1}/MeV^2]	$\mathcal{B}(B_1 \to B_2 \ell^- \ell^-)$	
		This work	Experiments
$\Sigma^- \to p\, e^- e^-$	3.194×10^{-7}	4.7×10^{-31}	$< 6.7 \times 10^{-5}$ [26]
$\Sigma^- \to \Sigma^+ e^- e^-$	3.925×10^{-14}	5.8×10^{-38}	-
$\Sigma^- \to p\, \mu^- \mu^-$	3.202×10^{-8}	4.7×10^{-28}	-
$\Xi^- \to \Sigma^+ e^- e^-$	3.404×10^{-8}	5.6×10^{-32}	$< 2.0 \times 10^{-5}$ [27]
$\Xi^- \to p\, e^- e^-$	5.706×10^{-8}	9.4×10^{-32}	-
$\Xi^- \to p\, \mu^- \mu^-$	2.509×10^{-8}	4.1×10^{-28}	$< 4.0 \times 10^{-8}$ [25]

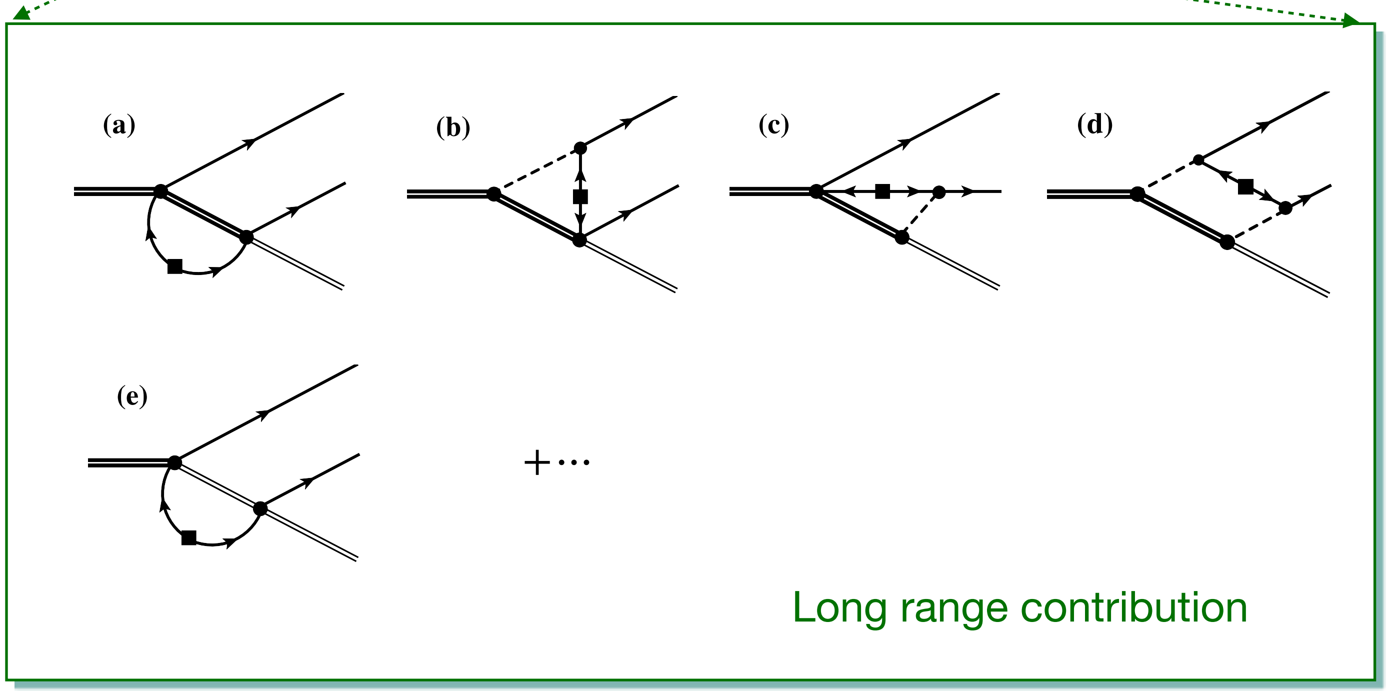
Hadronic neutrinoless double beta decay

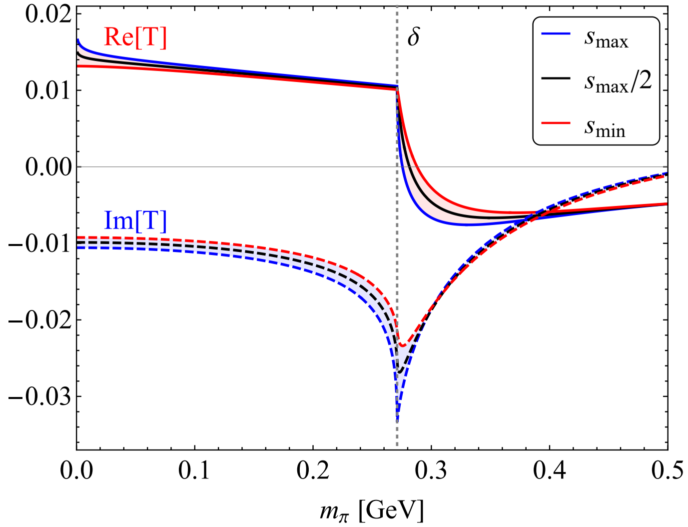
- **Delta $0\nu 2\beta$ in BChPT**

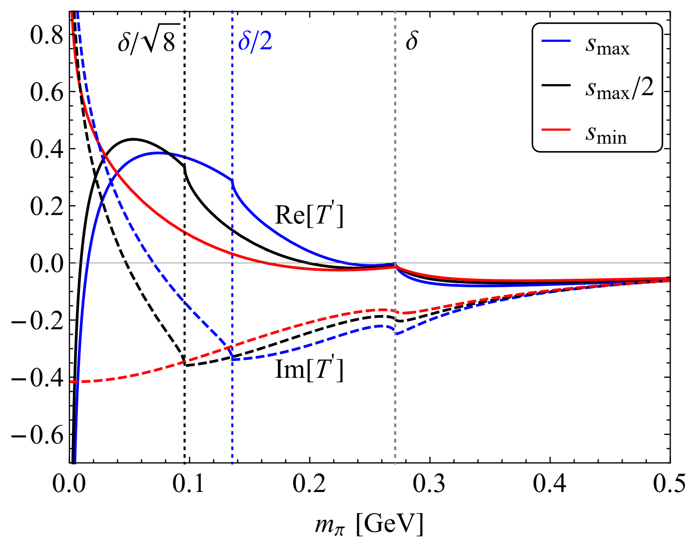
[He, Guo, Meissner, **DLY**, Zhang & Zhang, arXiv:2604.12535 [hep-ph]]



- Towards a deltafull description of $nn \to ppee$
- Pion mass dependence



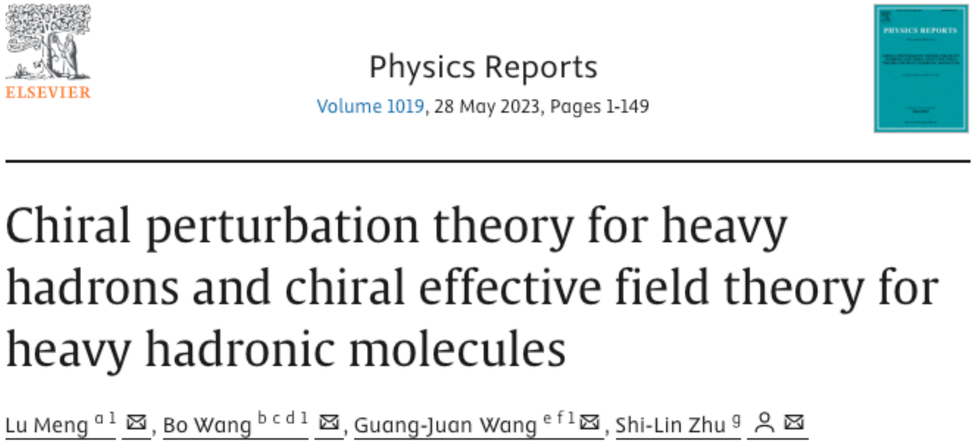




IV. Generalisation to heavy matter fields

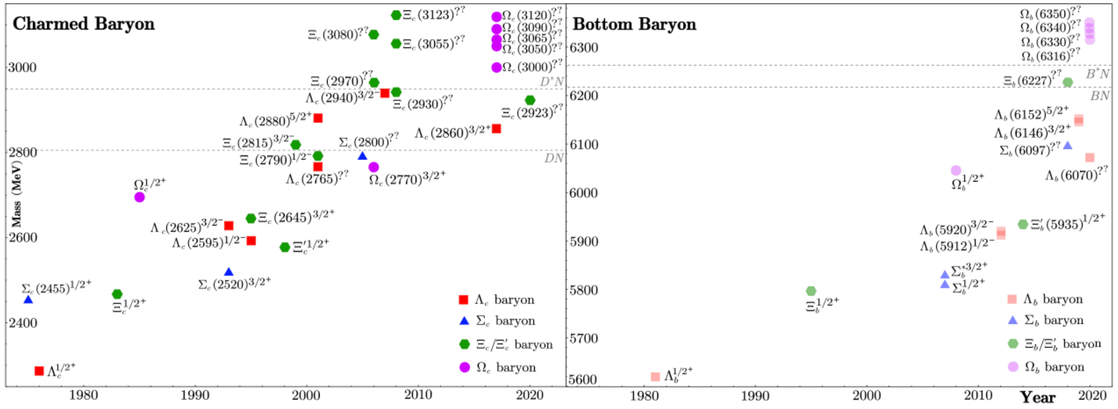
Generalisation to heavy matter fields

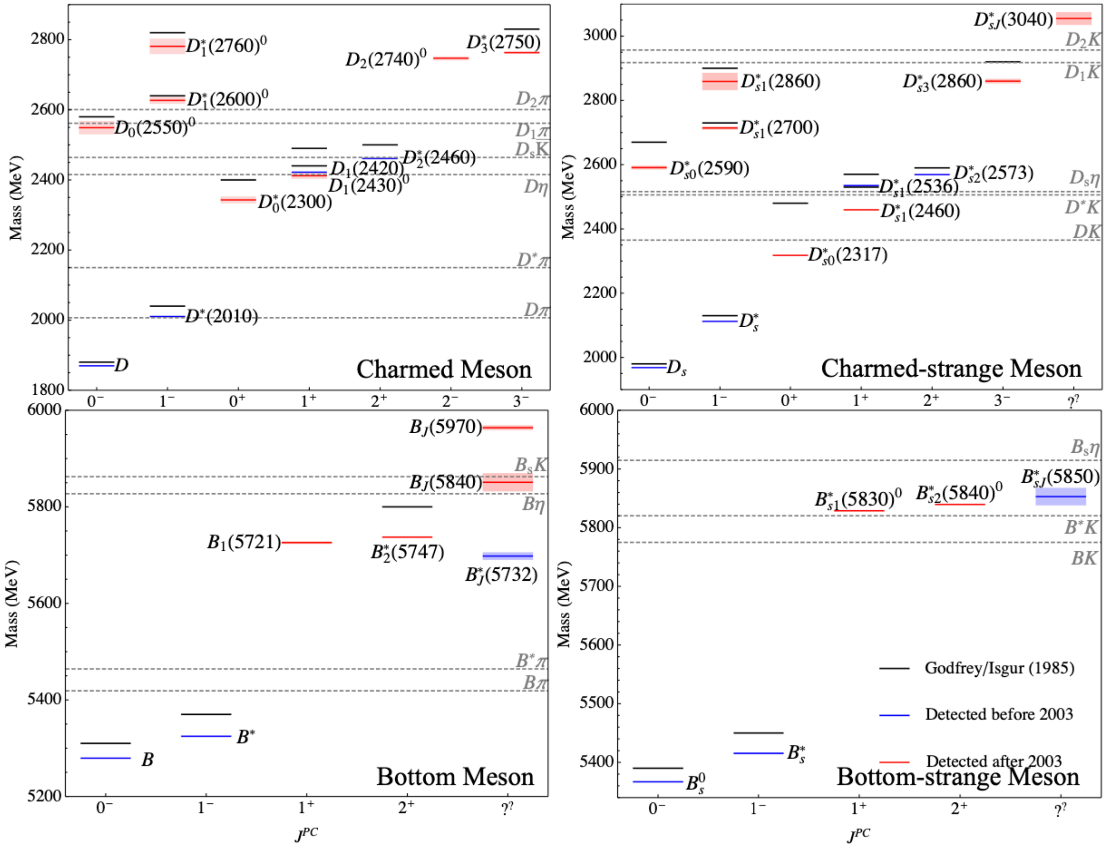
- Heavy matter fields: D/B mesons, Charmed baryons, …


Physics Reports
Volume 1019, 28 May 2023, Pages 1-149

Chiral perturbation theory for heavy hadrons and chiral effective field theory for heavy hadronic molecules

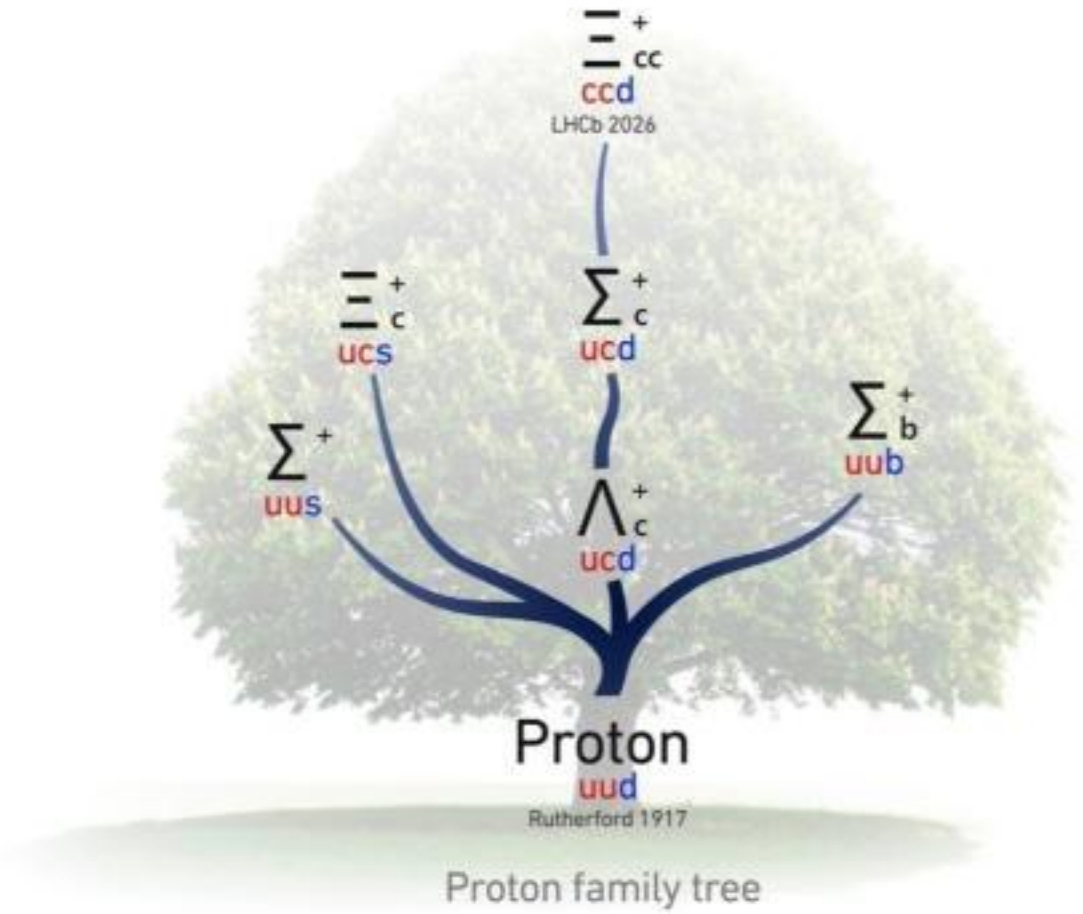
Lu Meng [a 1], Bo Wang [b c d 1], Guang-Juan Wang [e f 1], Shi-Lin Zhu [g]



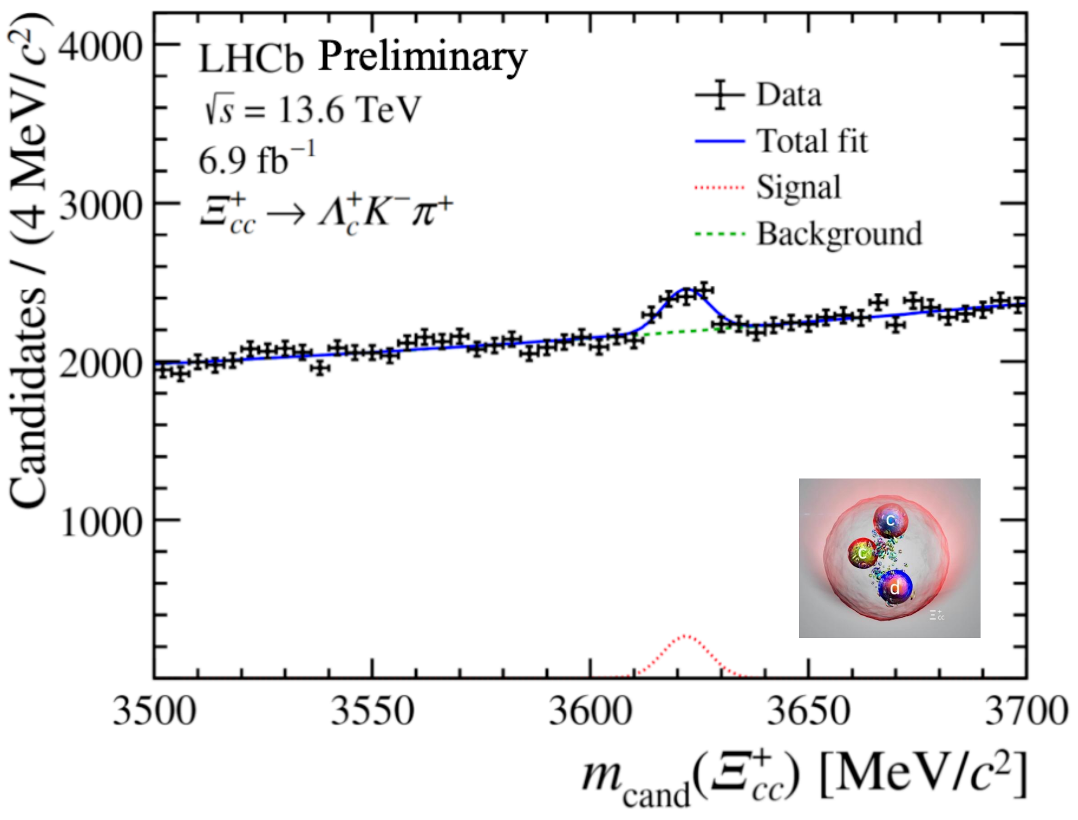


Generalisation to heavy matter fields

- The doubly charmed baryons



- Very recent observation of Ξ^+_{cc} by LHCb
- Mass: 3619.97 ± 0.83(stat) $\pm\ 0.26$(syst)$^{+1.90}_{-1.30}$(life time)

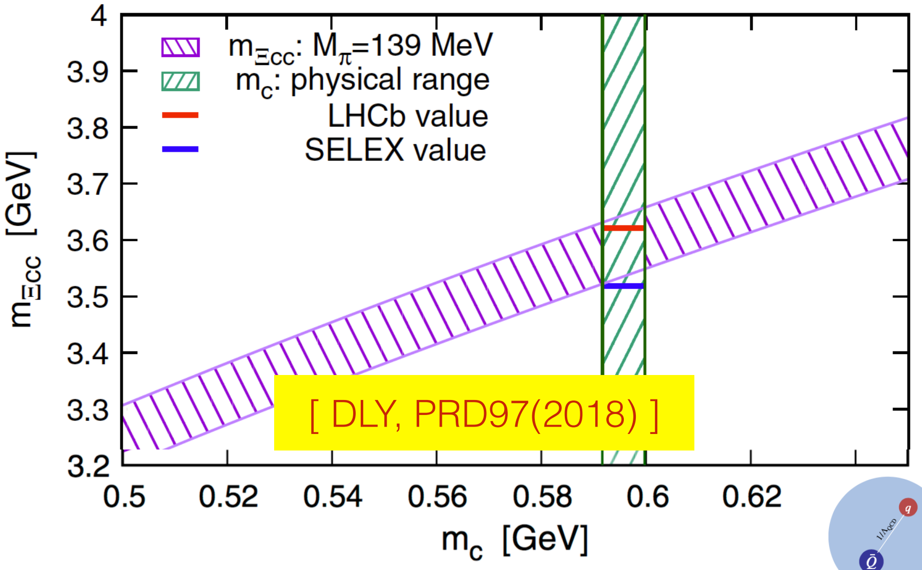


Towards a new paradigm for negative-parity doubly charmed baryons?

➡ **Interactions between Goldstone Bosons and DCB**

DCB in ChPT

- Interactions between Goldstone Bosons and DCB

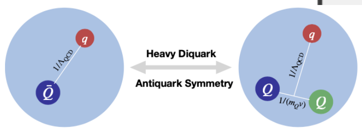


[DLY, PRD97(2018)]

$$\mathcal{L}_{M\psi} = \bar{\psi}\Big\{\Big[(i\not{D} - m) + \frac{g_A}{2}\not{u}\gamma_5\Big] + \sum_{i=1}^{8} b_i \mathcal{O}_i^{(2)} + \sum_{j=1}^{32} c_j \mathcal{O}_j^{(3)} + \sum_{k=1}^{218} d_k \mathcal{O}_k^{(4)} + \cdots\Big\}\psi$$

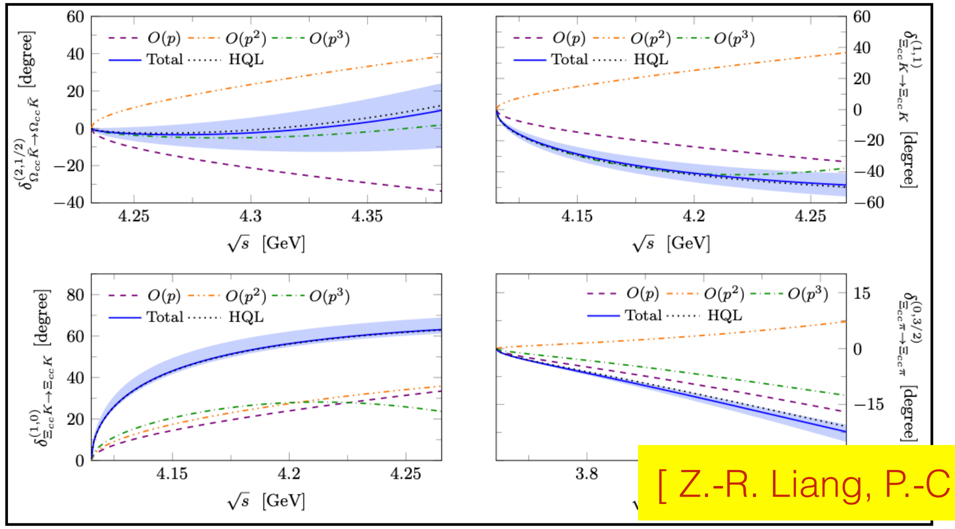
		Relativistic	Non-relativistic
$O(p^2)$	1	$\langle \chi_+ \rangle$	$\langle \chi_+ \rangle$
	2	$\widetilde{\chi}_+$	$\widetilde{\chi}_+$
	3	u^2	u^2
	4	$\langle u^2 \rangle$	$\langle u^2 \rangle$
	5	$\{u^\mu, u^\nu\} D_{\mu\nu} + h.c.$	$-8m^2 (v \cdot u)^2$
	6	$\langle u^\mu u^\nu \rangle D_{\mu\nu} + h.c.$	$-4m^2 \langle (v \cdot u)^2 \rangle$
	[illegible]	[illegible]	[illegible]

[P.-C. Qiu & DLY, PRD103(2021)]



Heavy Diquark-Antiquark Symmetry

(S, I)	Processes	$\mathcal{O}(p^1)$	$\mathcal{O}(p^2)$	$\mathcal{O}(p^3)$ Tree	$\mathcal{O}(p^3)$ Loop	Total-EOMS	HB
$(-2, \frac{1}{2})$	$\Omega_{cc}\bar{K} \to \Omega_{cc}\bar{K}$	-0.27	0.29	-0.11	-0.001	$-0.09^{+0.12}_{-0.13}$	$-0.20(1)$
$(1, 1)$	$\Xi_{cc}K \to \Xi_{cc}K$	-0.27	0.27	-0.13	-0.47	-0.60 ± 0.13	$-0.25(1)$
$(1, 0)$	$\Xi_{cc}K \to \Xi_{cc}K$	0.27	0.34	0.13	0.30	1.03 ± 0.19	$0.92(2)$
$(0, \frac{3}{2})$	$\Xi_{cc}\pi \to \Xi_{cc}\pi$	-0.12	0.04	-0.01	-0.06	-0.16 ± 0.02	$-0.10(2)$
$(-1, 0)$	$\Xi_{cc}\bar{K} \to \Xi_{cc}\bar{K}$	0.54	0.24	0.25	0.16	$1.19^{+0.22}_{-0.21}$	$2.15(11)$
	$\Omega_{cc}\eta \to \Omega_{cc}\eta$	-0.001	0.37	0.0	$0.05 + 0.55i$	$0.42^{+0.18}_{-0.19} + 0.55i$	$0.57(3) + 0.21i$
$(-1, 1)$	$\Omega_{cc}\pi \to \Omega_{cc}\pi$	0.0	0.04	0.0	-0.04	-0.01 ± 0.02	$-0.002(1)$
	$\Xi_{cc}\bar{K} \to \Xi_{cc}\bar{K}$	0.0	0.31	0.0	$-0.04 + 0.10i$	$0.27^{+0.13}_{-0.13} + 0.10i$	$0.26(1) + 0.19i$
$(0, \frac{1}{2})$	$\Xi_{cc}\pi \to \Xi_{cc}\pi$	0.25	0.04	0.01	0.04	0.34 ± 0.02	$0.36(1)$
[illegible]	[illegible]	[illegible]01	0.32	0.0	-0.26	$0.06^{+0.14}_{-0.15}$	$0.34(1) + 0.10i$
[illegible]	[illegible]	[illegible]7	0.29	0.11	$-0.01 + 0.55i$	$0.66^{+0.13}_{-0.13} + 0.55i$	$1.18(6) + 0.29i$

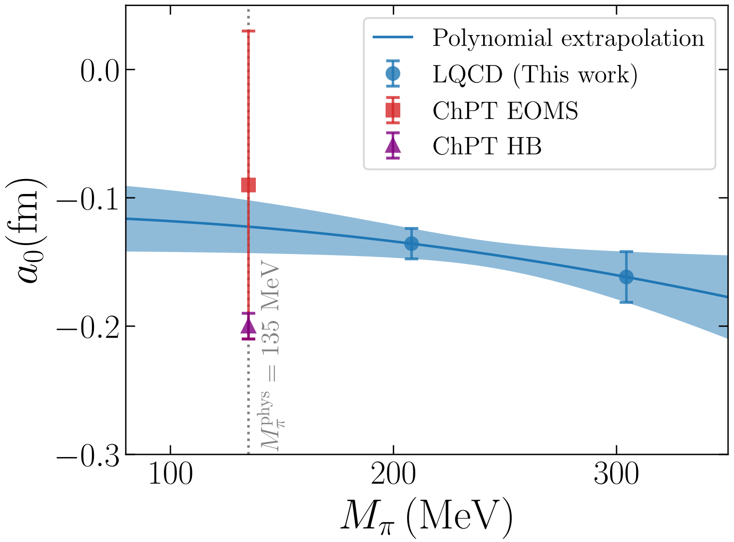


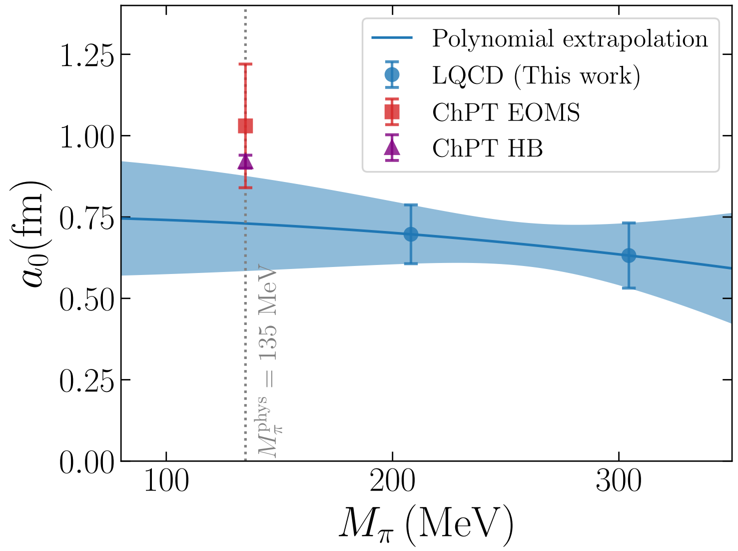
[Z.-R. Liang, P.-C. Qiu & DLY, JHEP07(2023)]

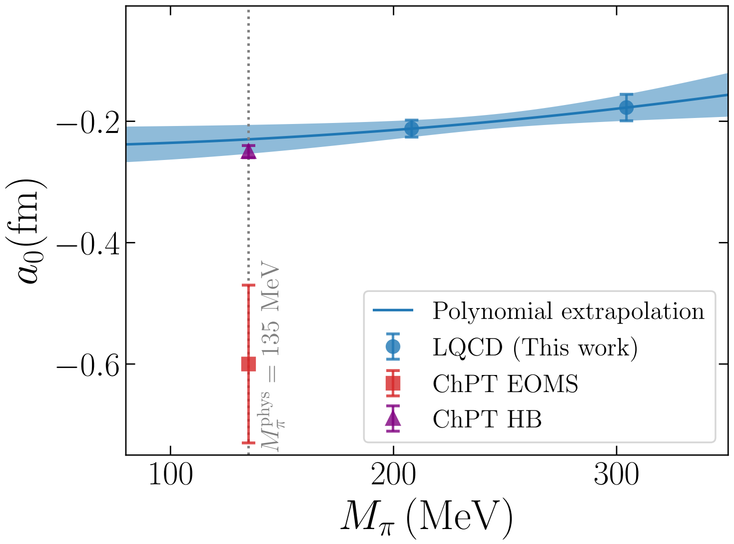
DCB in ChPT and lattice QCD

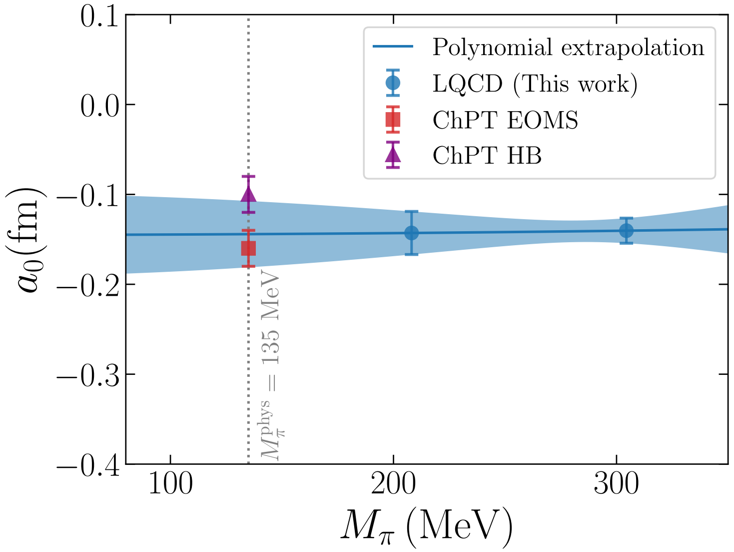
- Chiral extrapolation

[J.-Y. Yi, Z.-R. Liang, L. Liu & **DLY**, JHEP03(2026)]









- Single channels: Good agreement using LECs estimated by HADS

(S,I)	Process	EOMS	HB
$(-2,\frac{1}{2})$	$\Omega_{cc}\bar{K}\to\Omega_{cc}\bar{K}$	$-0.09^{+0.12}_{-0.13}$	$-0.20(1)$
$(0,\frac{3}{2})$	$\Xi_{cc}\pi\to\Xi_{cc}\pi$	-0.16 ± 0.02	$-0.10(2)$
$(1,1)$	$\Xi_{cc}K\to\Xi_{cc}K$	1.03 ± 0.19	$0.92(2)$
$(1,0)$	$\Xi_{cc}K\to\Xi_{cc}K$	-0.60 ± 0.13	$-0.25(1)$

- Coupled channels: new DCB states with negative parity

First observation of a negative-parity doubly charmed baryon on lattice

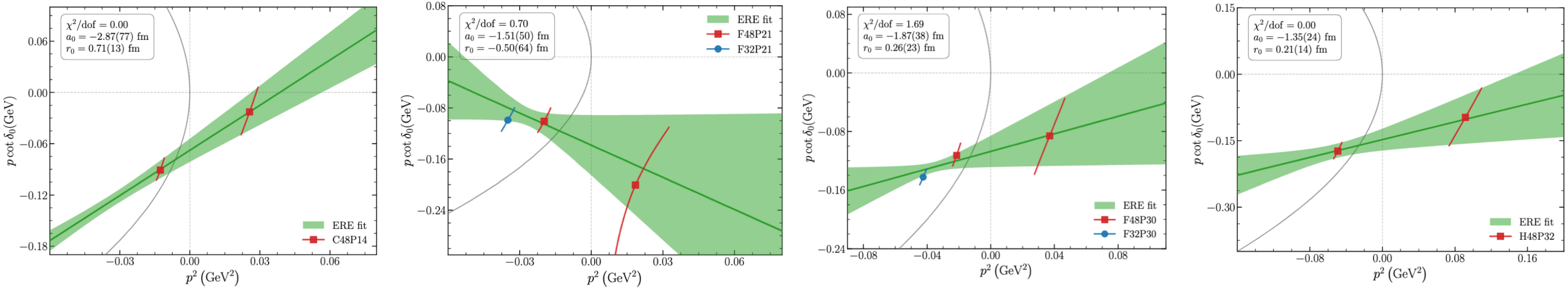
- A new pentaquark state?

[J.-Y. Yi, Z.-R. Liang, L. Liu & **DLY**, 2026, In preparation]

$$p \cot \delta_0 = \frac{1}{a_0} + \frac{1}{2} r_0 p^2 + \mathcal{O}(p^4) \qquad t_l^{(J)} \sim \frac{1}{p \cot \delta_l^{(J)} - ip}$$

$(-1, 0)$	$\Xi_{cc}\bar{K} \to \Xi_{cc}\bar{K}$ $\Omega_{cc}\eta \to \Omega_{cc}\eta$ $\Xi_{cc}\bar{K} \to \Omega_{cc}\eta$

Ensemble Group	a_0 (fm)	r_0 (fm)	p_B^2 (GeV^2)	E_B (MeV)
$M_\pi \approx 140$ MeV, $a = 0.105$ fm $(L = 48)$	$-2.87(77)$	$0.71(13)$	$-0.0064(23)$	$7.3(2.6)$
$M_\pi \approx 210$ MeV, $a = 0.077$ fm $(L = 32, 48)$	$-1.51(50)$	$-0.50(64)$	$-0.0131(38)$	$15.4(4.5)$
$M_\pi \approx 300$ MeV, $a = 0.077$ fm $(L = 32, 48)$	$-1.87(38)$	$0.26(23)$	$-0.0130(36)$	$14.4(4.0)$
$M_\pi \approx 320$ MeV, $a = 0.052$ fm $(L = 48)$	$-1.35(24)$	$0.21(14)$	-0.0256(65)	$27.7(7.1)$



(a) $M_\pi \approx 140$ MeV, $a = 0.105$ fm $(L = 48)$

(b) $M_\pi \approx 210$ MeV, $a = 0.077$ fm $(L = 32, 48)$

(c) $M_\pi \approx 300$ MeV, $a = 0.077$ fm $(L = 32, 48)$

(d) $M_\pi \approx 320$ MeV, $a = 0.052$ fm $(L = 48)$

Summary

- The nucleon mass and sigma term with two-loop accuracy:
  - Resolving the long-standing tension between lattice QCD and dispersive determinations

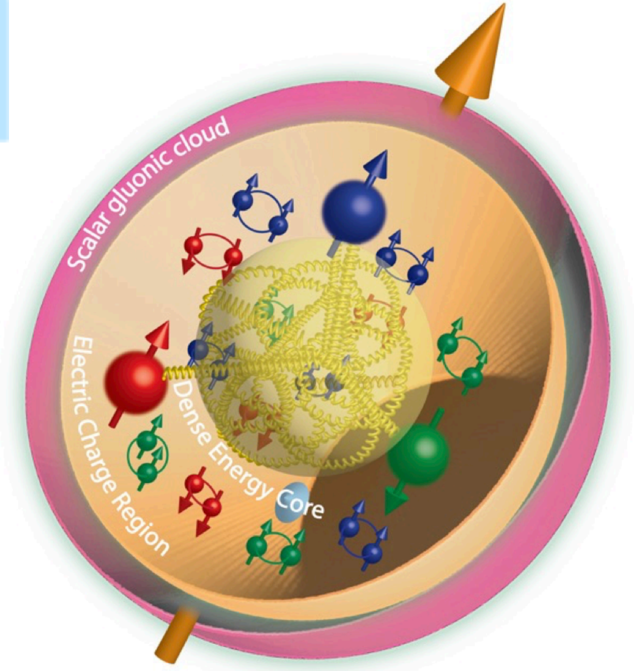
$$\sigma_{\pi N} = 55.9(2.5)\ \text{MeV} \quad \text{vs} \quad \sigma_{\pi N}^{\text{RS}} = 59.1(3.5)\ \text{MeV}$$

- Nucleon static properties:
  - Precise determination of D term: $D^N = -3.38^{+0.34}_{-0.35}$
  - Suggesting a modern structural view of the nucleon:

$$\sqrt{\langle r_\Theta^2 \rangle} = 0.97^{+0.03}_{-0.03}\ \text{fm} \quad > \sqrt{\langle r_{E,p}^2 \rangle} \simeq 0.84\ \text{fm} > \quad \sqrt{\langle r_{\text{Ener}}^2 \rangle} = 0.70^{+0.03}_{-0.04}\ \text{fm}$$

proton electric charge

- Others:
  - New physics: neutrinoless double beta decays, CP violations, …
  - Heavy flavour physics, exotic states,….



Courtesy of Meziani

Thank you very much!