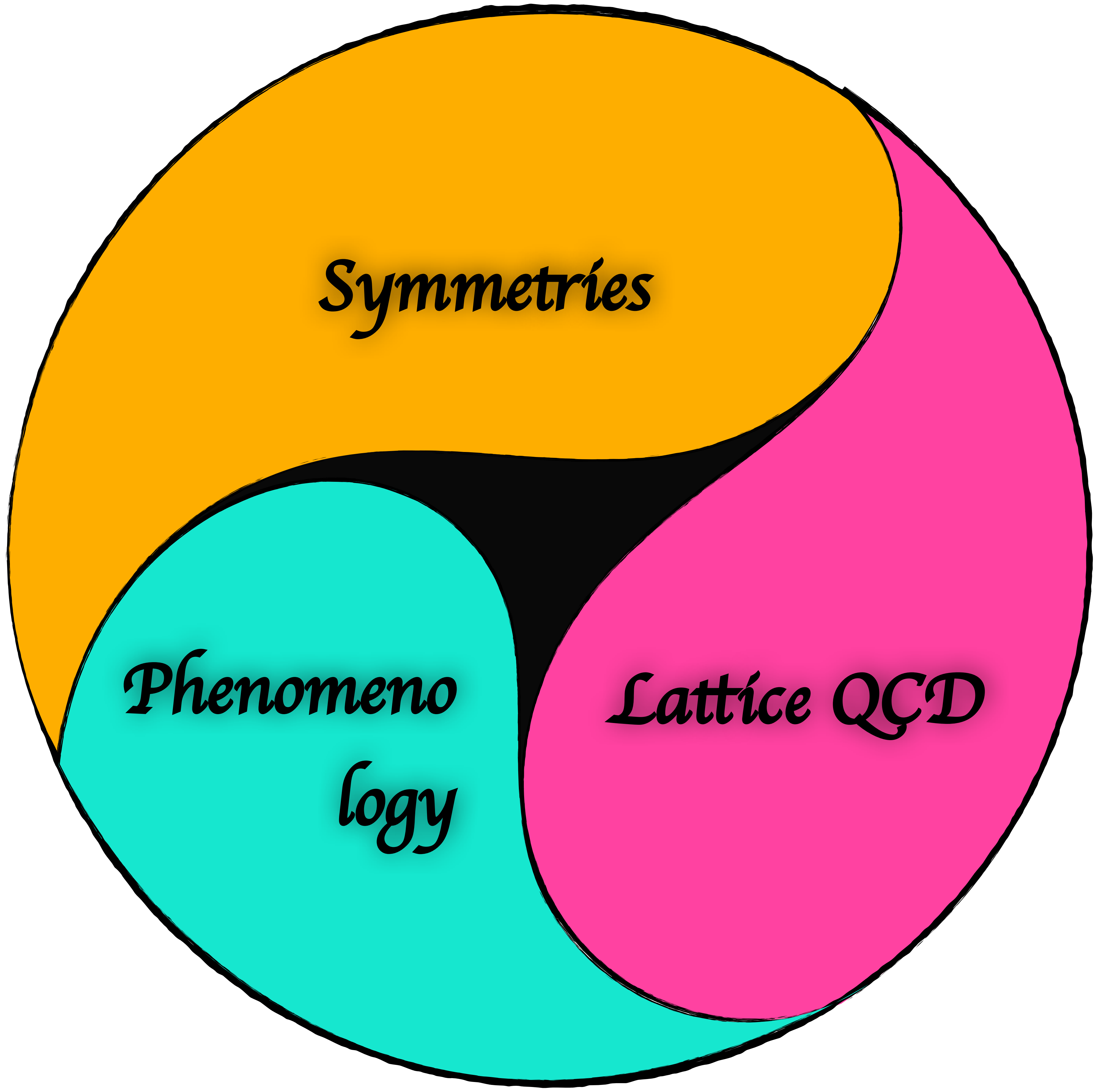
UNIVERSAL PARAMETERS OF EXCITED STATES OF MATTER



Maxim Mai

University of Bonn

The George Washington University

NSF
Deutsche Forschungsgemeinschaft
DFG

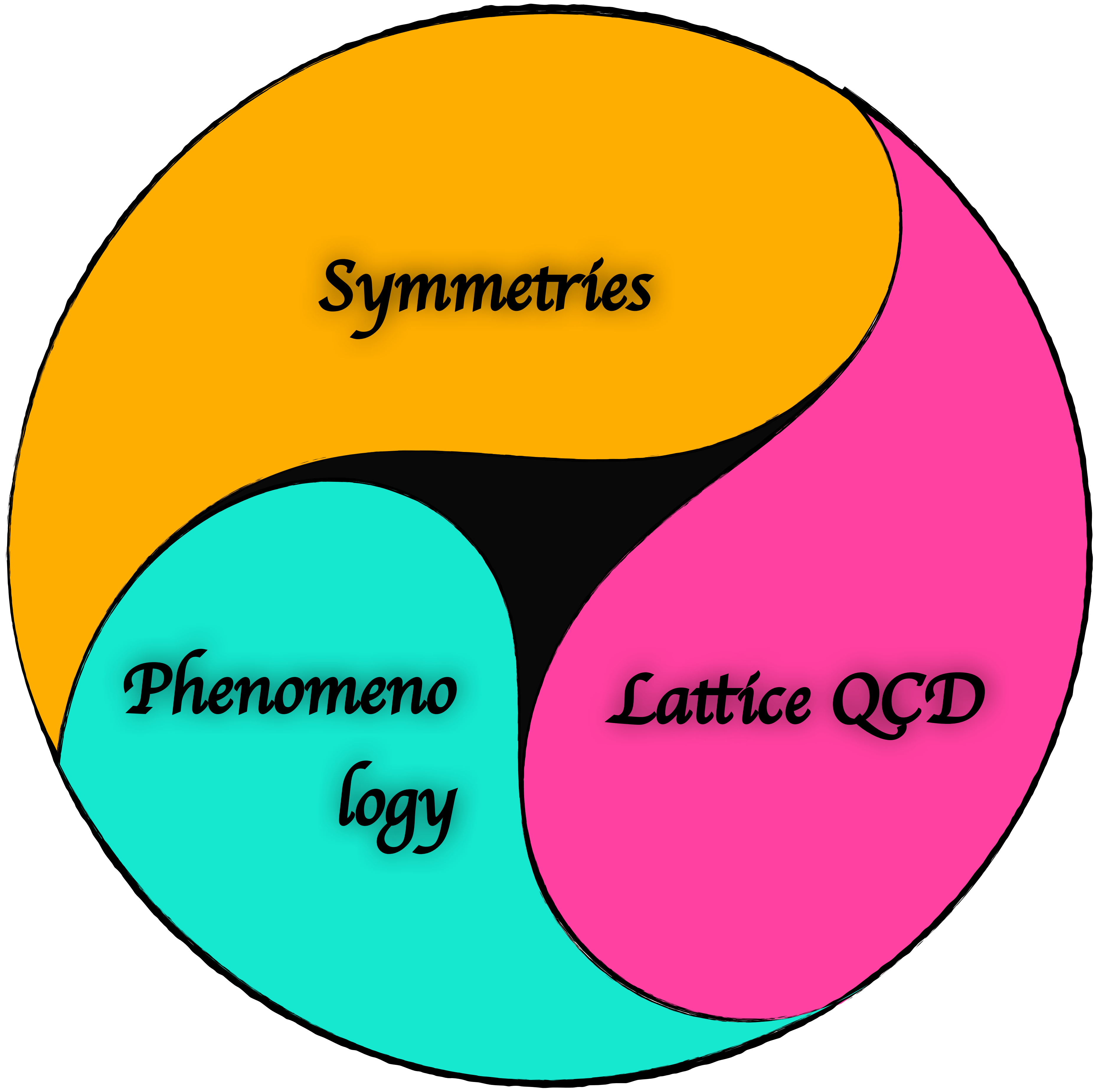
OUTLINE

Big picture

Case #1: Strangeness resonances

Case #2: Three-body resonances

Case #2.1: Three-body resonances from Lattice QCD



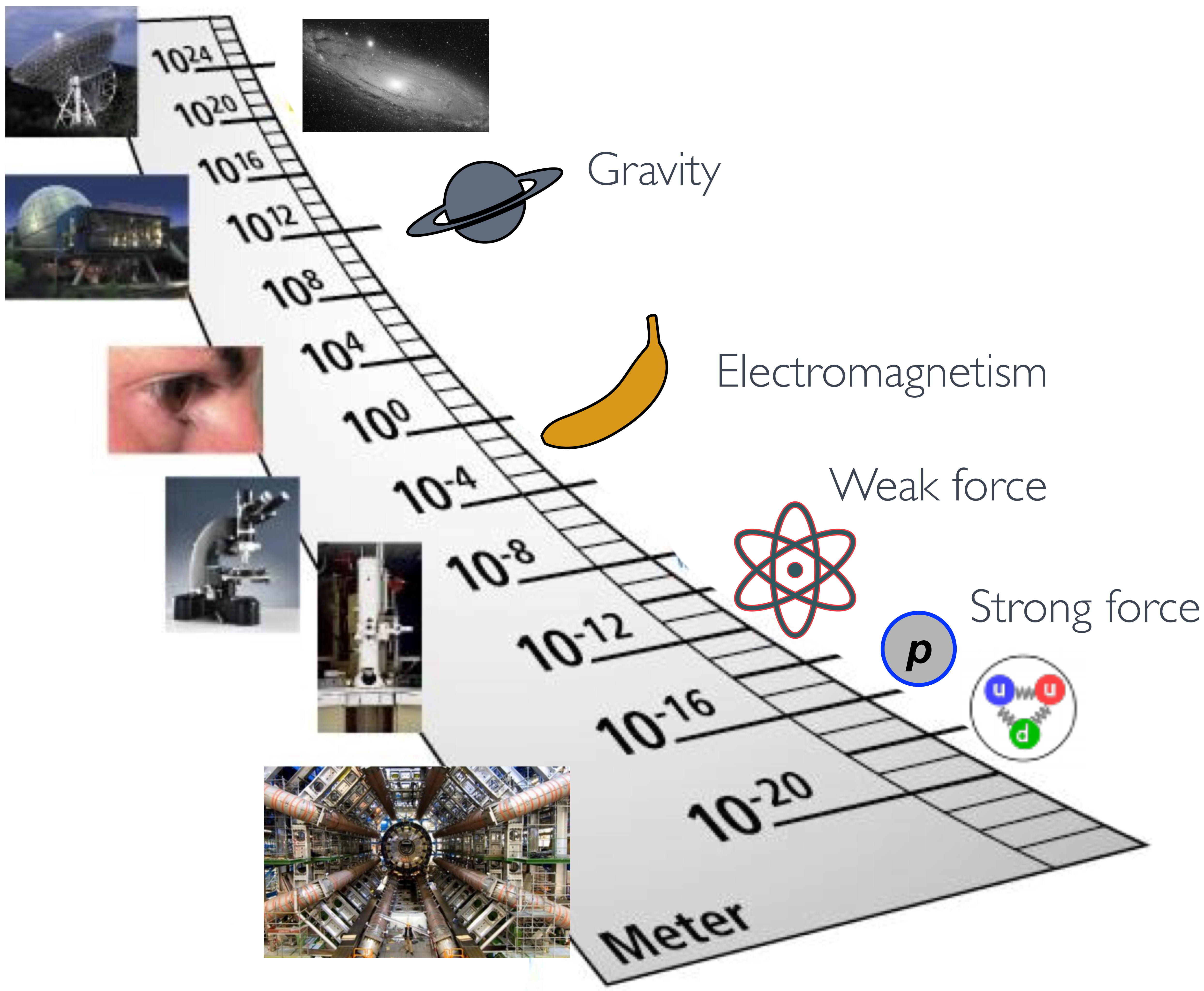
``Towards a theory of hadron resonances" Phys. Rept. 1001 (2023) — MM/Meißner/Urbach

``Multi-particle systems on the lattice and chiral extrapolations: a brief review," Eur. Phys. J. ST 230 (2021) — MM/Döring/Rusetsky

``Review of the Lambda(1405) A curious case of a strangeness resonance," Eur. Phys. J. ST 230 (2021) — MM

Deutsche Forschungsgemeinschaft DFG

LEARNING NATURE'S LANGUAGE



General workflow

- mathematisation (abstract concepts)
- comparison with phenomena (predictions)
- observations, riddles ...

HISTORICAL EXAMPLE

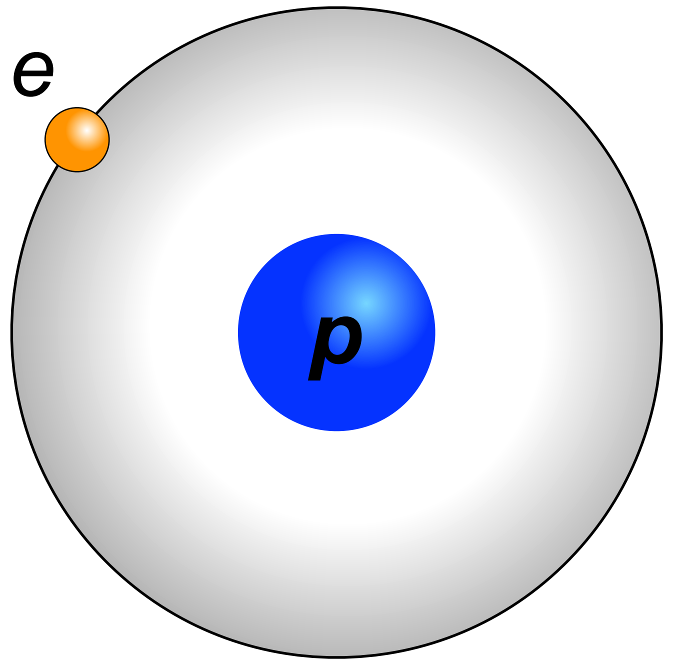
"If you think you understand quantum mechanics then you don't understand quantum mechanics"
R. P. Feynman

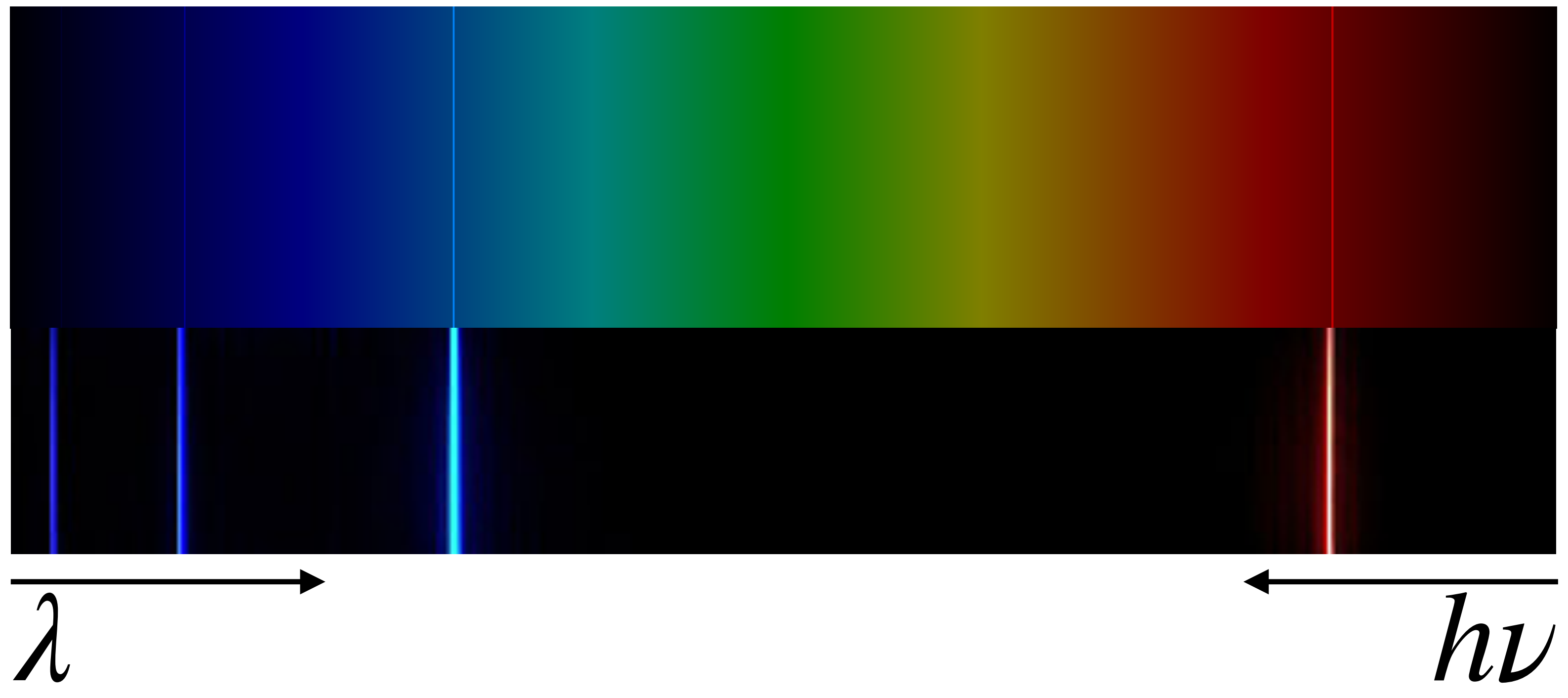
Quantum mechanics

- governs subatomic world
- unconventional language
- many subtleties/interpretations

"… a new perspective on the physical nature of momentum at the quantum level."
U.-J. Wiese
Physics Colloquium Bonn — 12.05.2023

HISTORICAL EXAMPLE





$$\Delta E \sim \frac{1}{n^2} - \frac{1}{m^2}$$

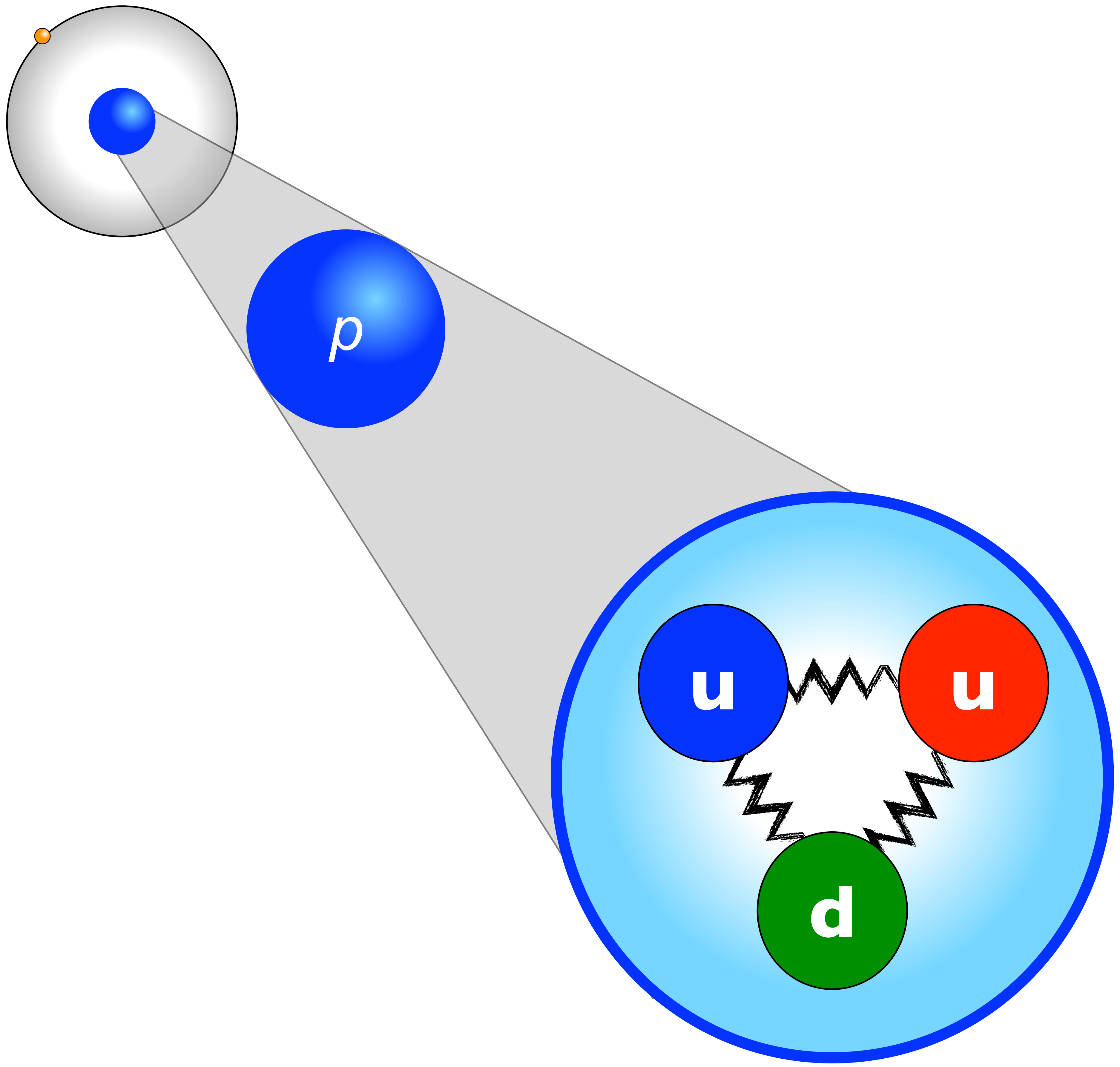
Breakthrough

- explanation of atomic spectra
- discrete excitation energies
- new paradigm of physics

STRONG INTERACTION

Protons/neutrons

- 99% of the mass of visible matter in the universe
- Building blocks: quarks & gluons
- Part of a larger class of particles: **hadrons**



HADRON SPECTROSCOPY

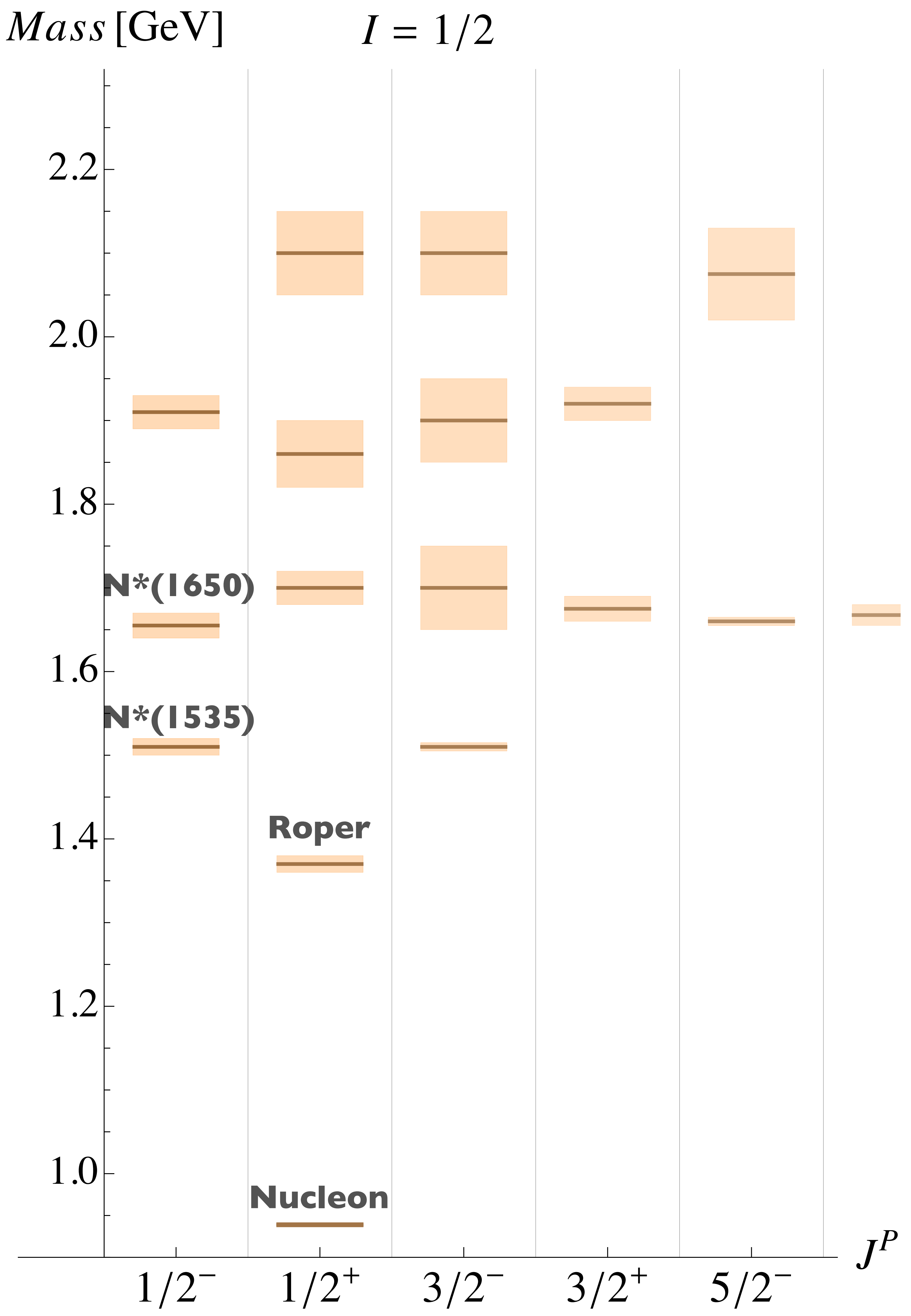
Mostly excited states

≈100 mesons & ≈50 baryons (****)

Key questions

"can we write a law for the pattern of these states?"

"do we understand how they are formed?"

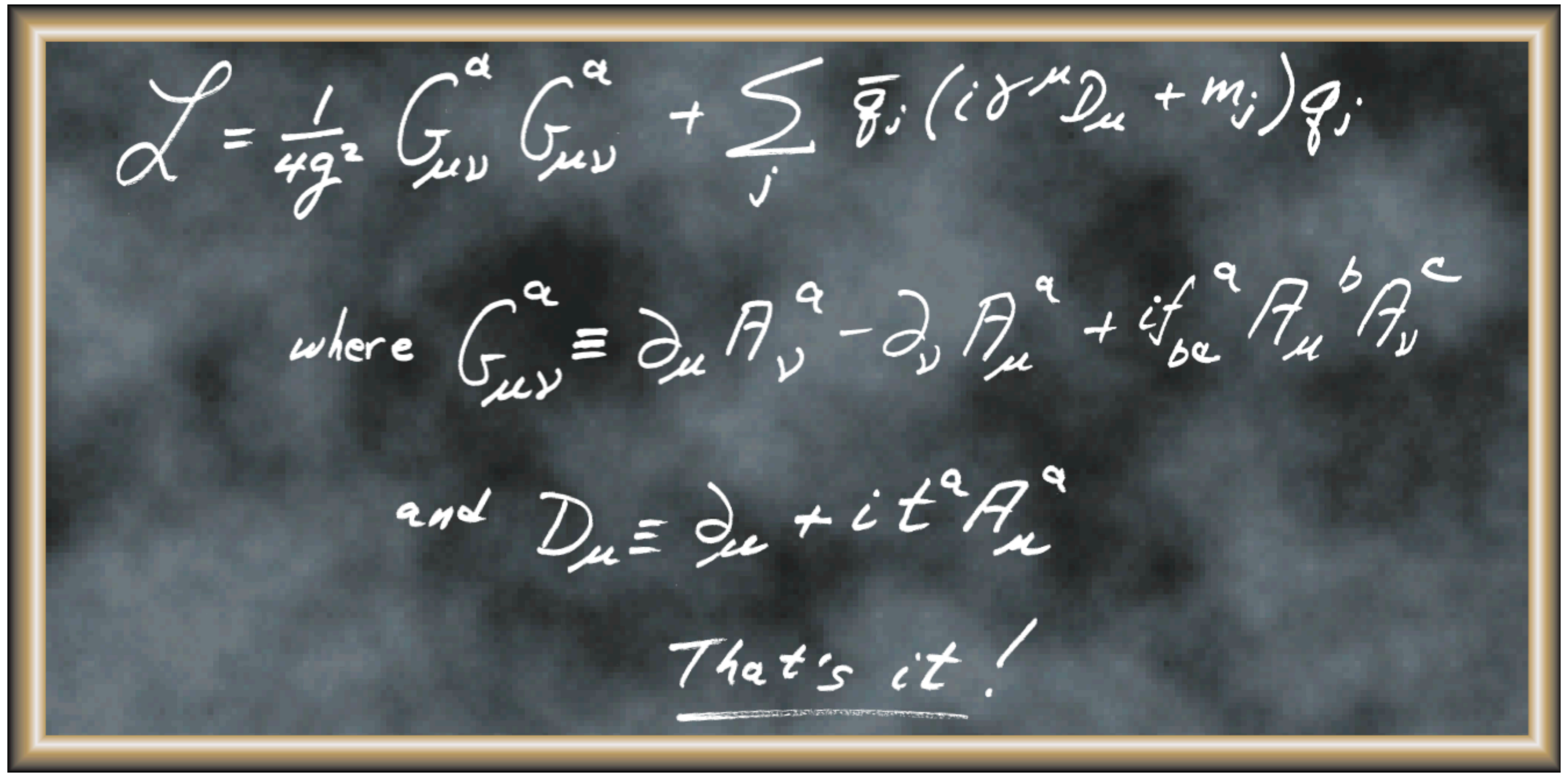


R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

QUANTUM CHROMODYNAMICS

- Compact form + passed all tests so far
- Non-perturbative at low energies

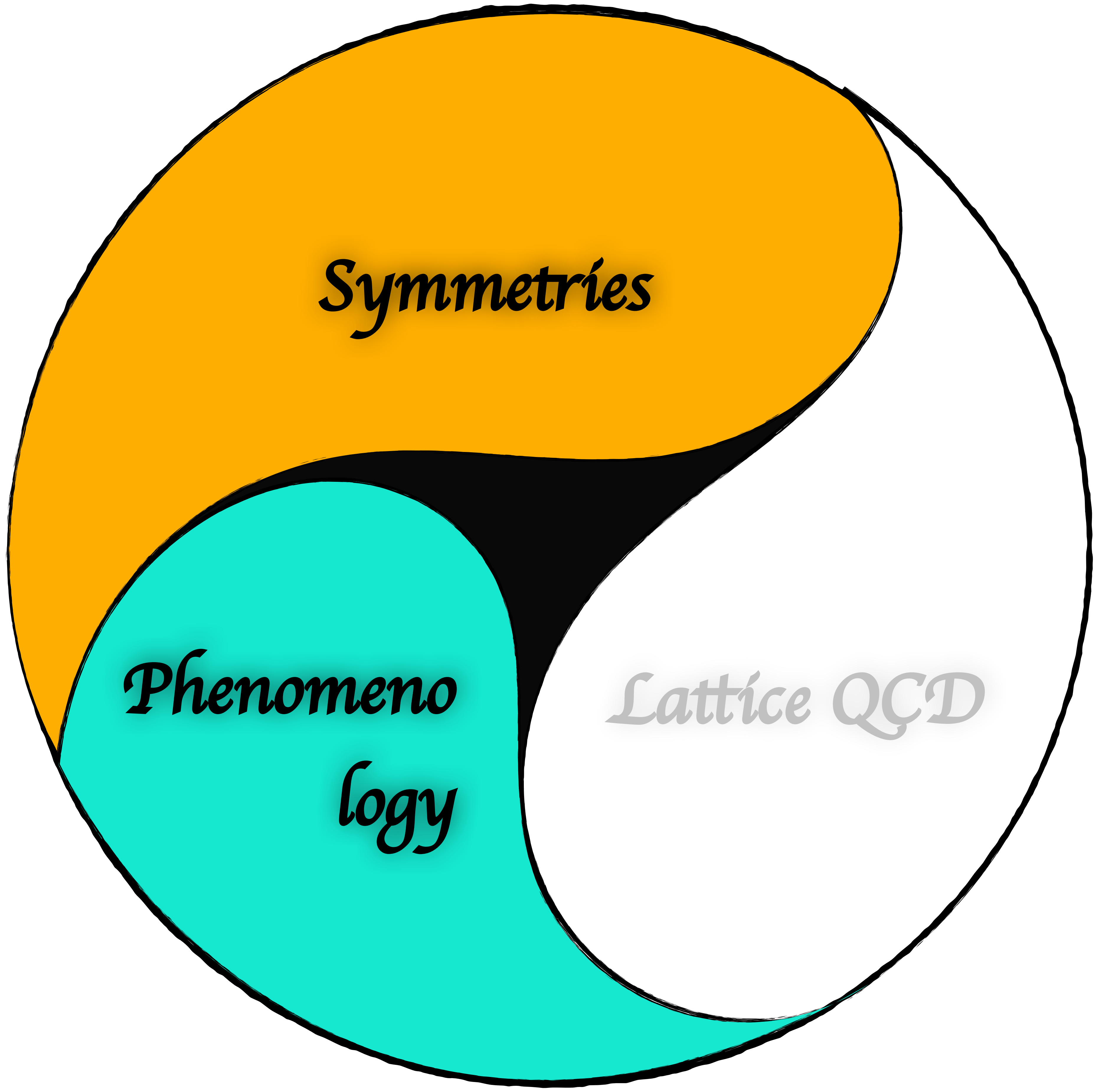
- Additional tools needed for hadron spectroscopy
  - ☞ *Effective field theories*
  - ☞ *Lattice QCD*



http://frankwilczek.com/Wilczek_Easy_Pieces/298_QCD_Made_Simple.pdf

CASE #1

LAMBDA(1405) — A CURIOUS CASE OF A STRANGENESS RESONANCE



BROADER IMPACT

Twice non-perturbative regime of QCD

- too low for perturbative QCD
- too high for low-energy EFT

KbarNN & KbarNNN bound states

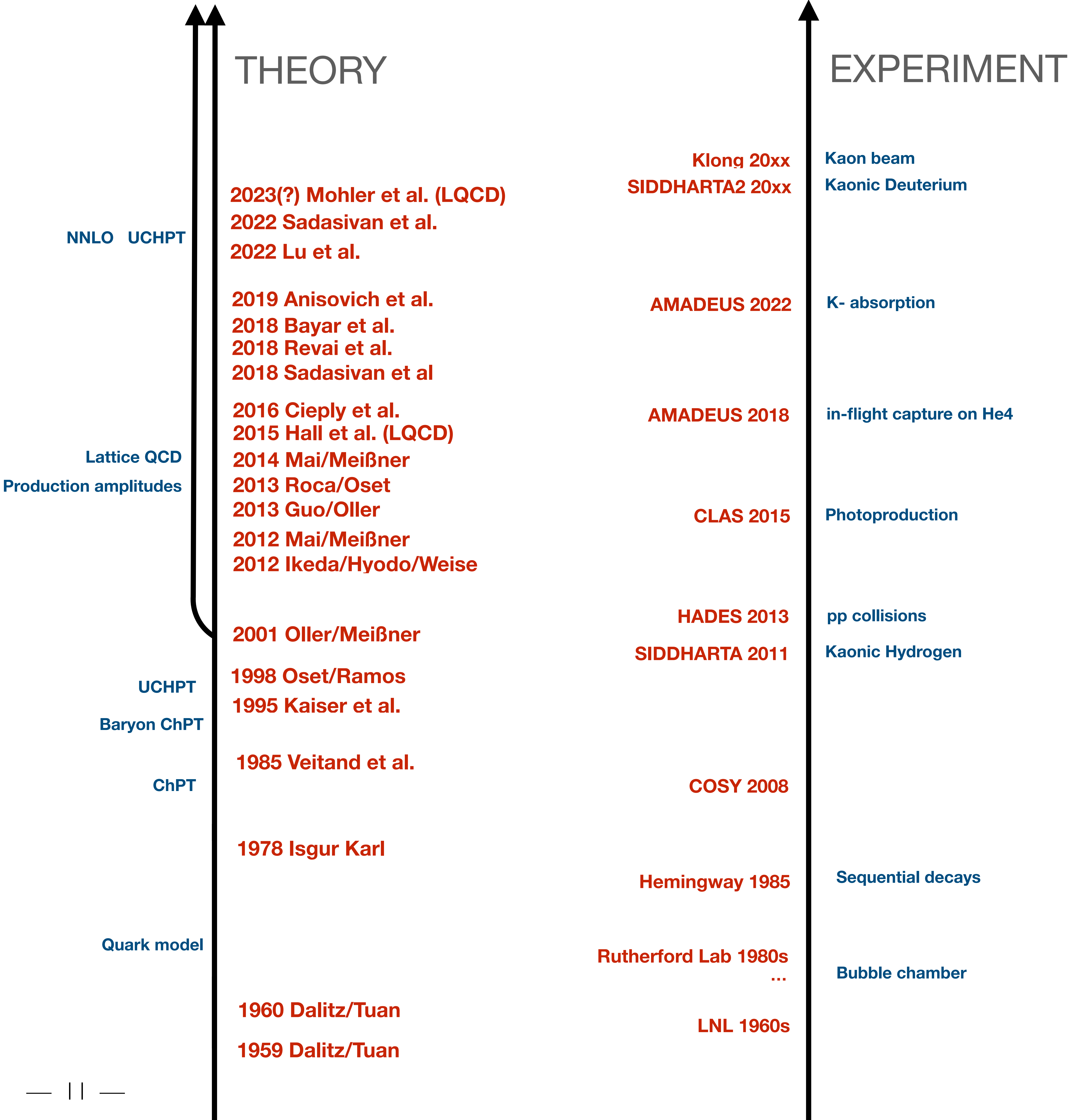
- dominated by KbarN interaction
- KbarN input is critical for interpretation

Antikaons in nuclear medium

- Strangeness in the EoS of neutron stars
- *K*-condensate can change EoS-stiffness

DEVELOPMENTS AND OUTLOOK

- Predicted in late 1950's
- Long history of experimental and theoretical efforts[1]



1) Reviews: Meißner, *Symmetry* 12 (2020); MM Eur.Phys.J.ST 230 (2021); Hyodo/Niiyama Prog.Part.Nucl.Phys. 120 (2021)

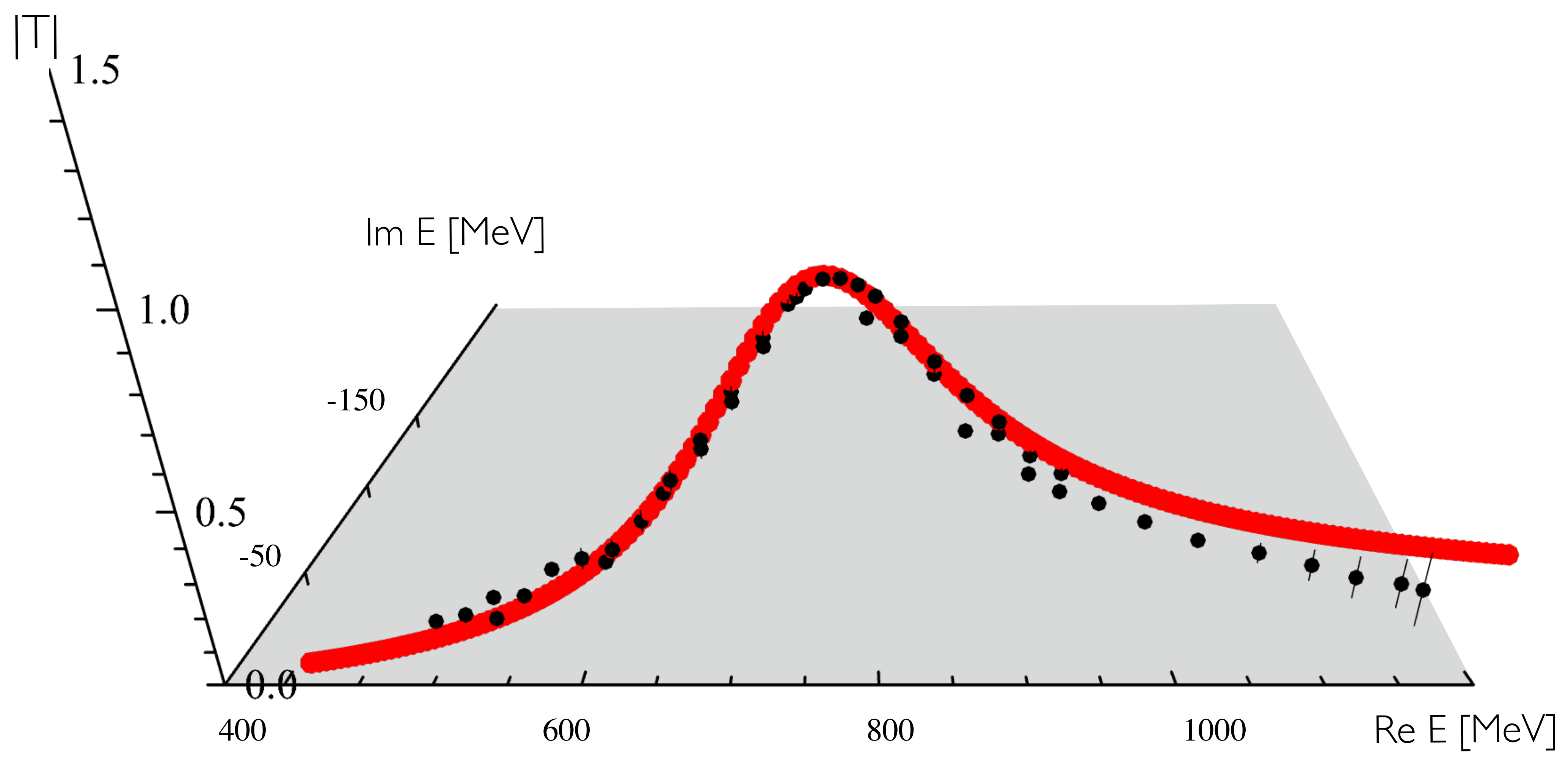
UNIVERSAL PARAMETERS

- Resonances can show up as bumps in experimental data

… depends strongly on reaction, background, etc..

- Reaction-independent (universal) parameters:

pole positions on unphysical Riemann Sheets



Data: Estabrooks et al. Nucl.Phys.B 79; Protopopescu et al. Phys.Rev.D 7;

UNIVERSAL PARAMETERS

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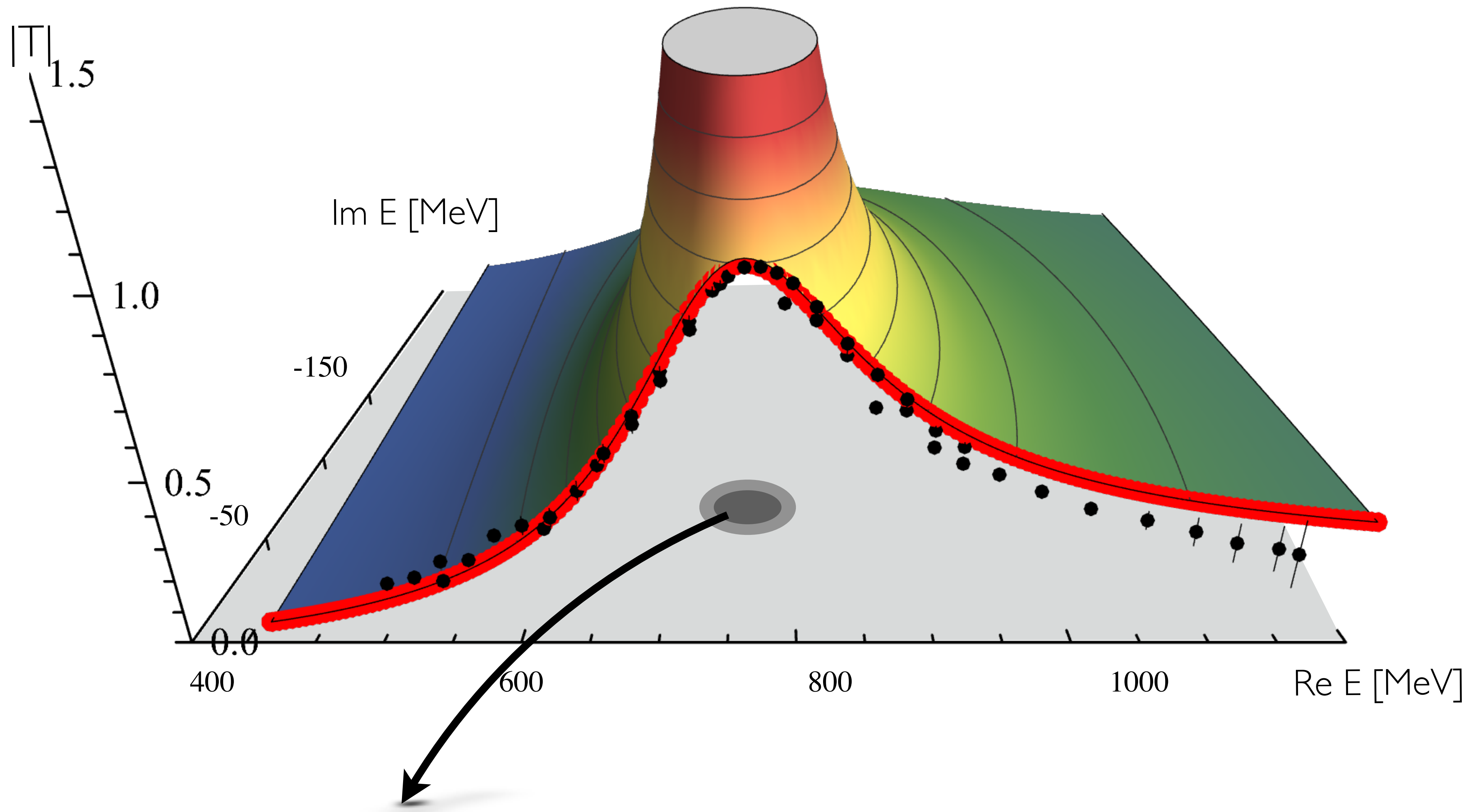


$M^* = (750 - i60)$ MeV

Universal property of the ρ – meson

Data: Estabrooks et al. Nucl.Phys.B 79; Protopopescu et al. Phys.Rev.D 7;

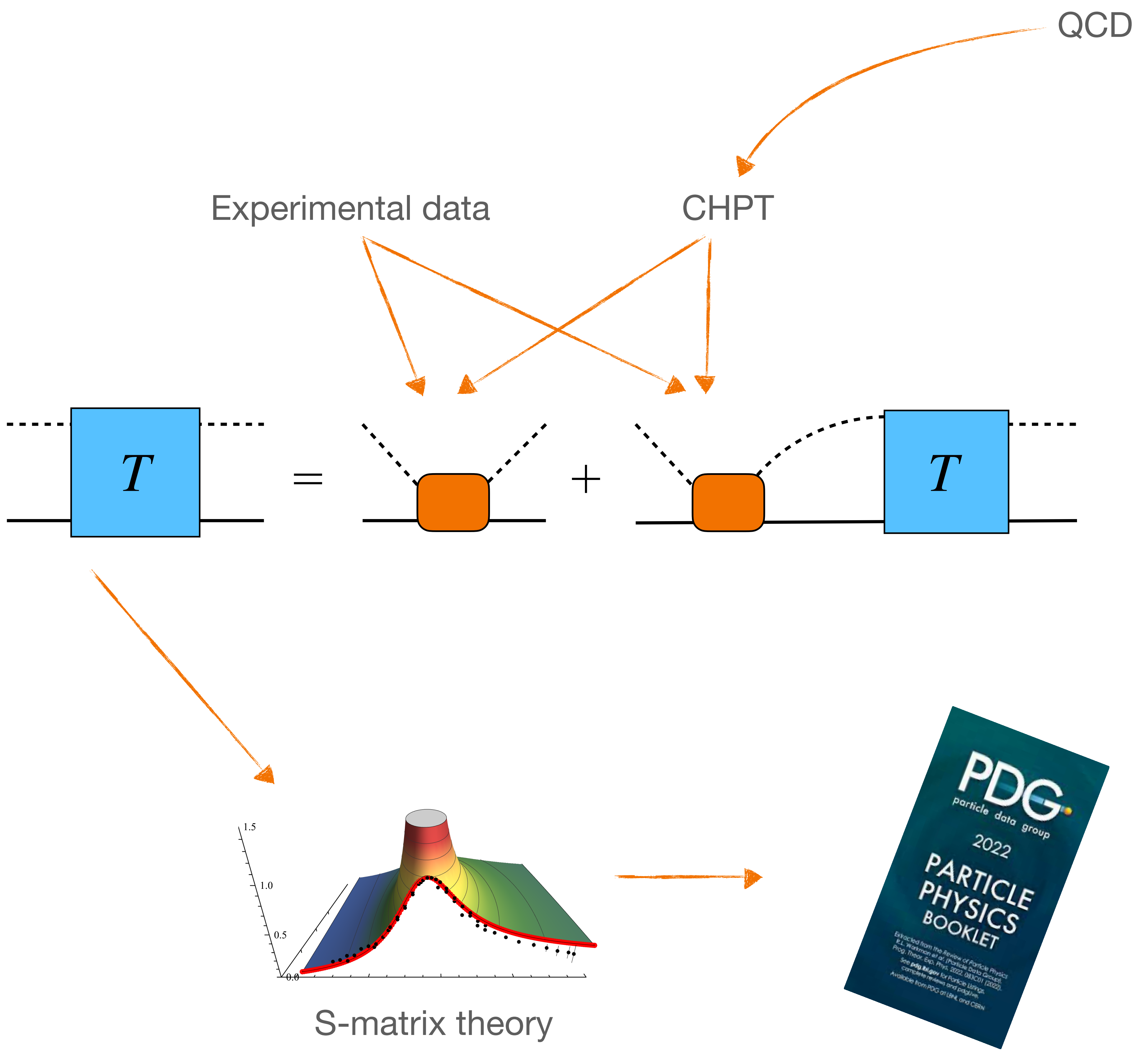
TRANSITION AMPLITUDE

One way:

- Chiral Perturbation Theory (#QCD#EFT) dictates the form of the interaction at low energies
- Unitary scattering amplitude from the Bethe-Salpeter equation

Fit: free parameters to experimental data / LQCD

Extract: Complex pole positions for complex energies

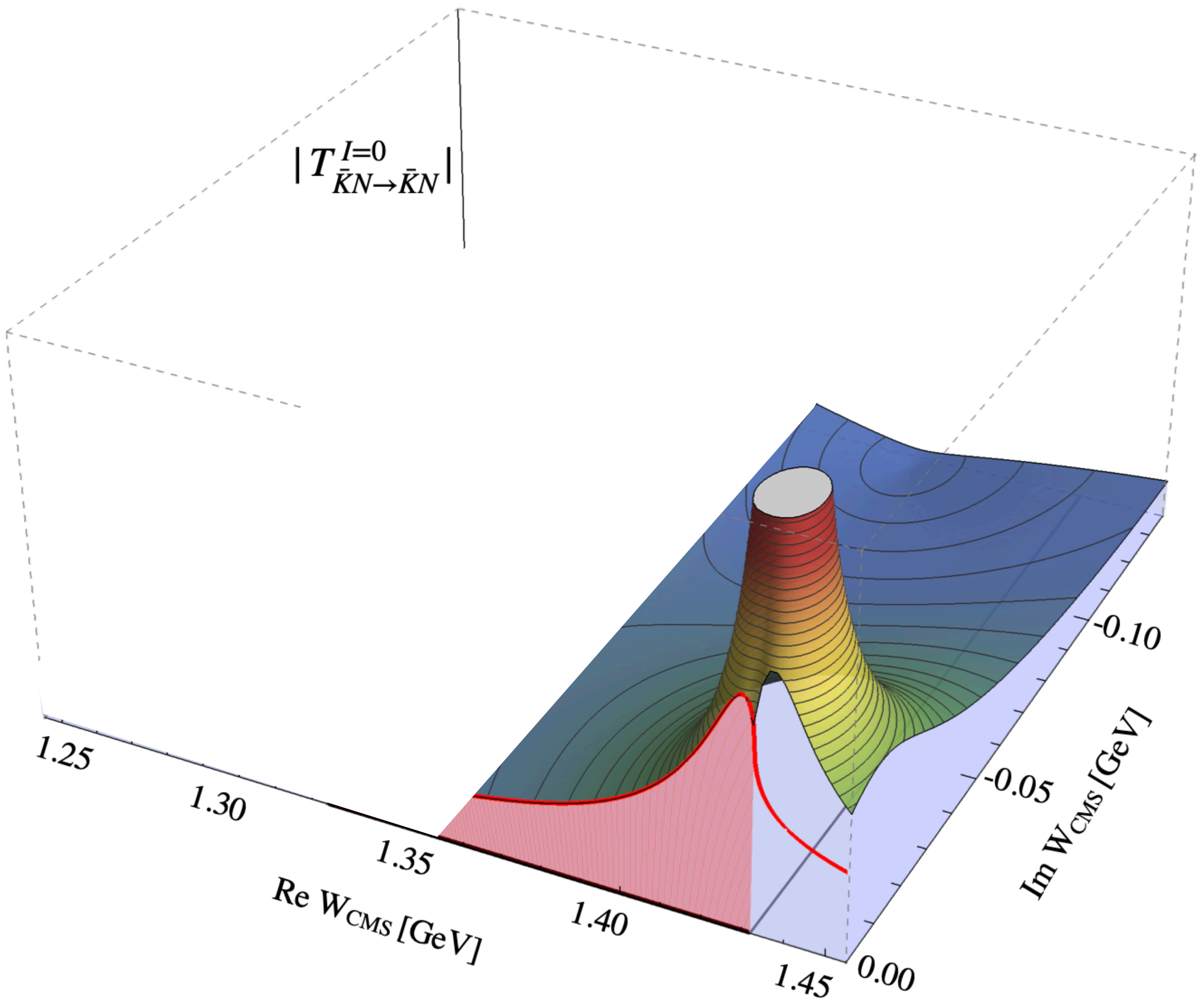


RESONANCE POLE(S)

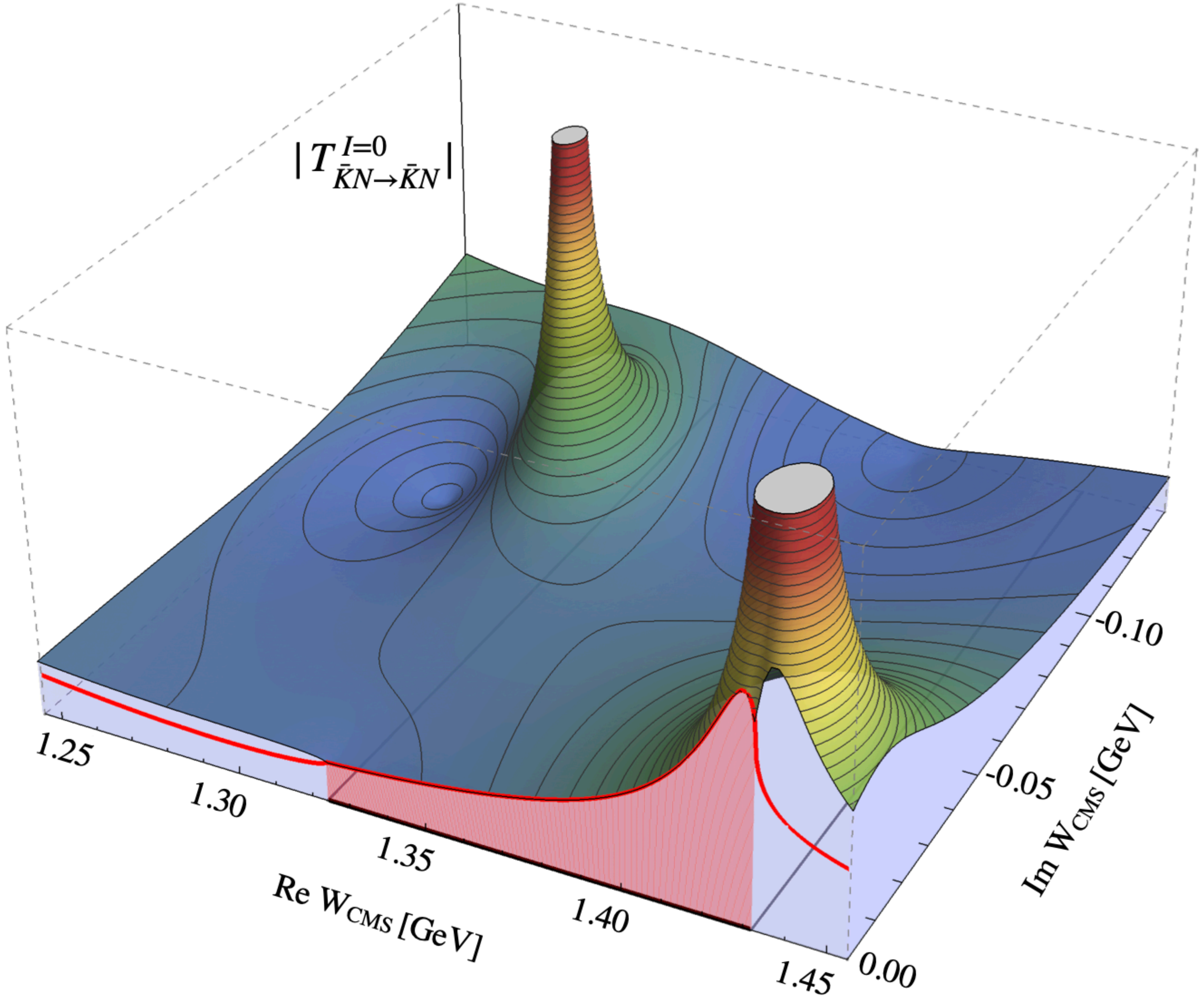
- Narrow pole below KbarN threshold

  W= (1421…1429)-i(10…25) MeV*

  → systematical and statistical uncertainties shrinking



RESONANCE POLE(S)



- Inclusion of chiral symmetry constants demands a second state[1]:

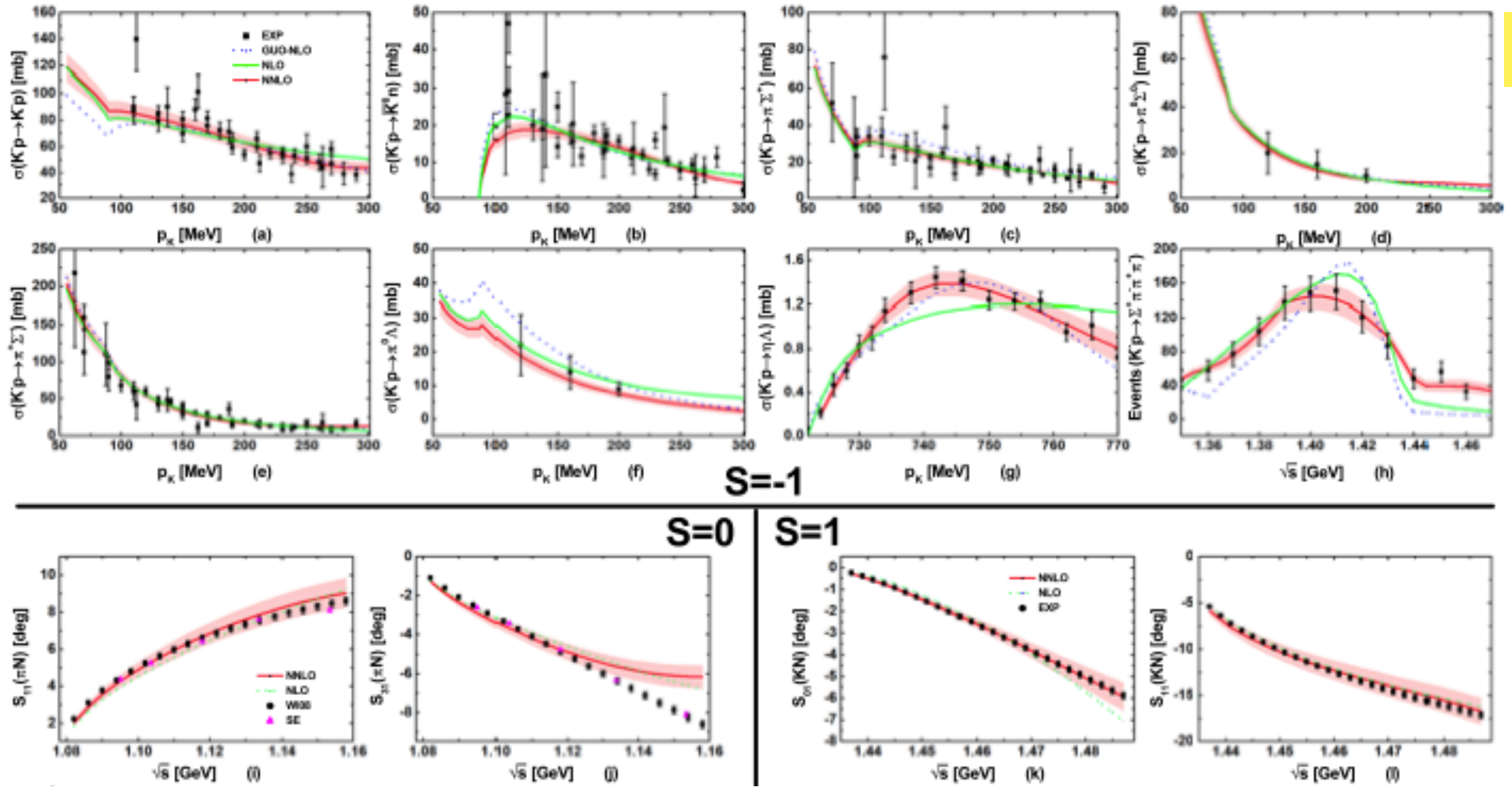
  W= (1325…1381)-i(56…114) MeV*

→ Common phenomenon in hadron physics[2]

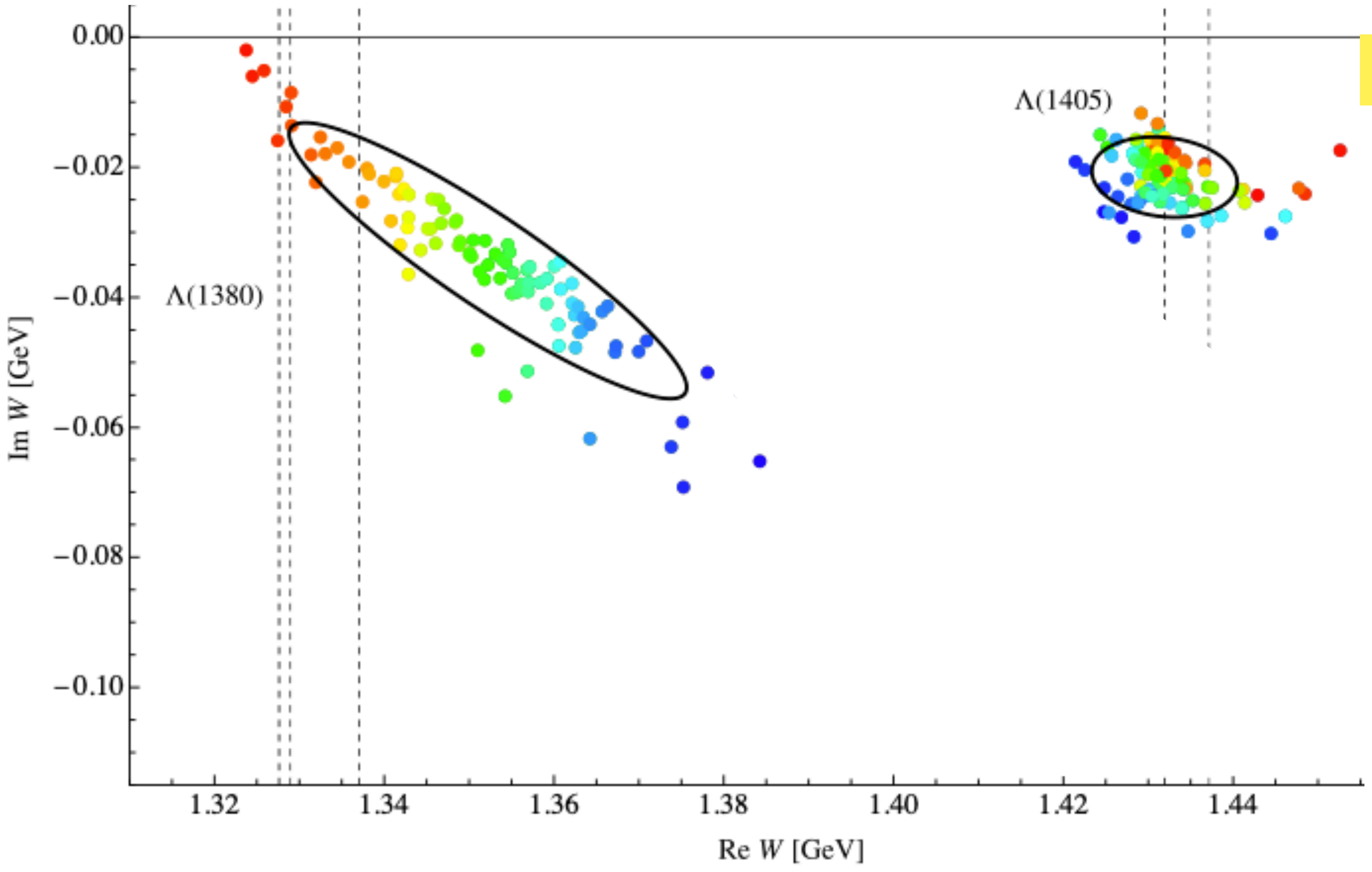
1) Oller/Meißner (2001); Ikeda/Hyodo/Weise(2011); MM/Meißner(2012); Guo/Oller(2012),…
2) Meißner, *Symmetry* 12 (2020) 6, 981

CURRENT FRONTIER

- many tests:
  - → K⁺**Σπ** photo-production constraints[1]
  - → Theory update: NNLO UCHPT[2]
  - → K- absorption data[3]
- Two pole structure from Lattice QCD[4]



2)

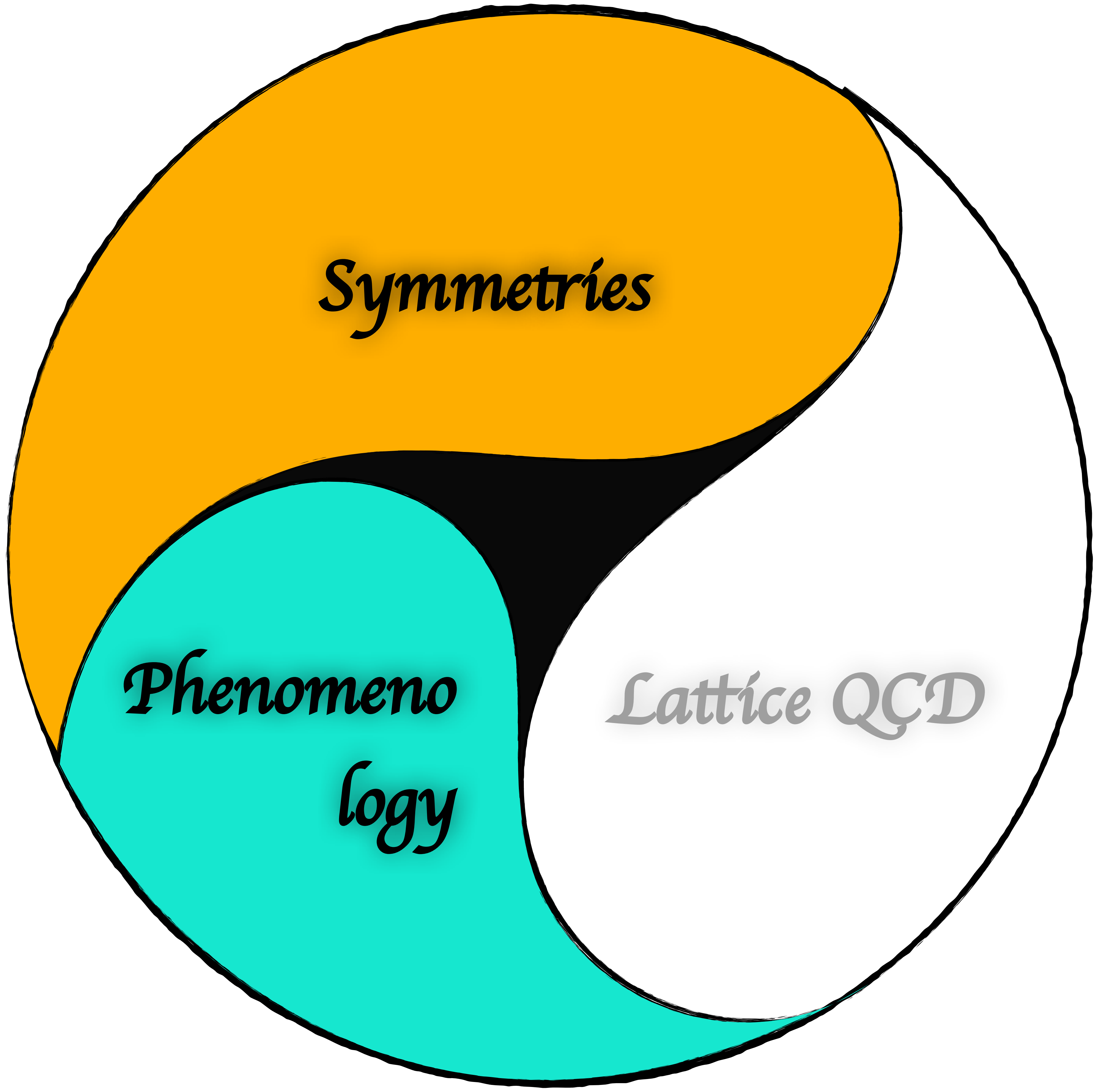


3)

1) Roca/Oset Phys.Rev.C 87 (2013); MM/Meißner Eur.Phys.J.A 51 (2015); Sarantsev et al. Eur.Phys.J.A 55 (2019); Bruns/Cieply/MM *Phys.Rev.D* 106 (2022)
2) Lu/Geng/Döring/MM Phys.Rev.Lett. 130 (2023)
3) AMADEUS Phys. Lett. B 782 (2018); Sadasivan et al Front.Phys. 11 (2023)
4) Daniel Mohler's Talk at the INT workshop 2023

CASE #2

THREE-BODY RESONANCES



HADRONIC 3-BODY PROBLEM: IMPACT

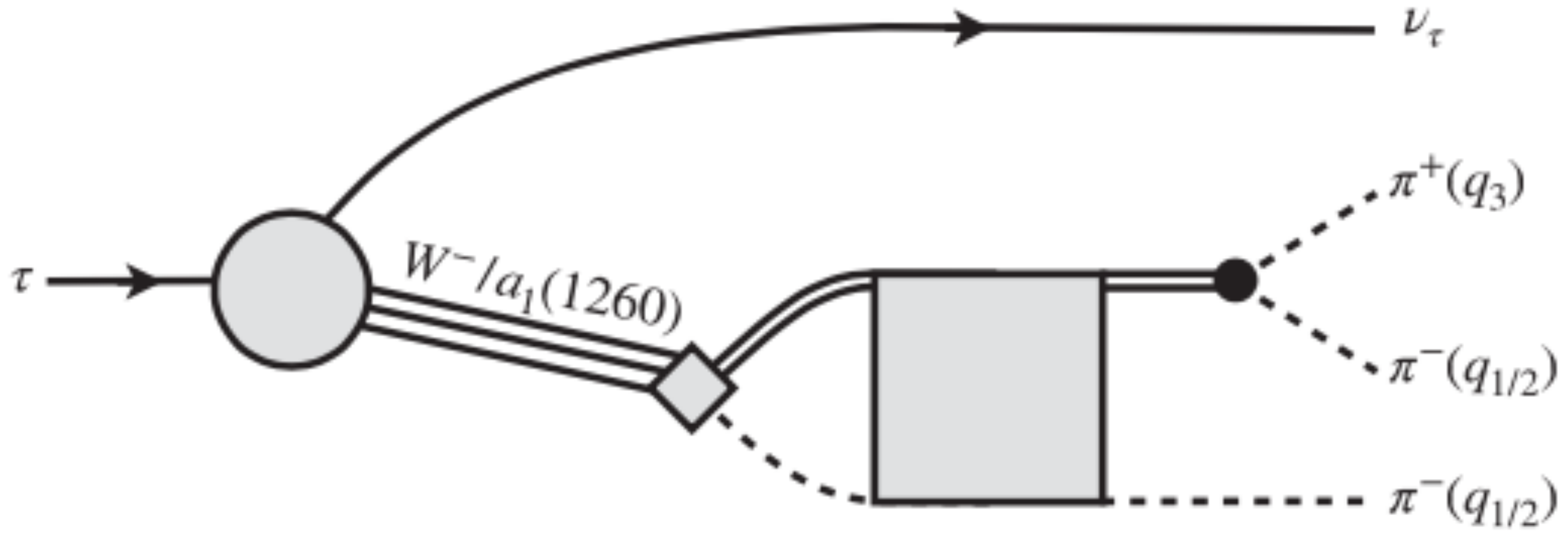
Intricate kinematics/dynamics

- 8 variables
- 2-body sub-channel dynamics

Hadron spectroscopy riddles

- Roper(1440) → $\pi\pi$N [first FV evaluations[1]]
- X(3872) → **DbarDπ**
- a_1(1260) → $\pi\pi\pi$
- …

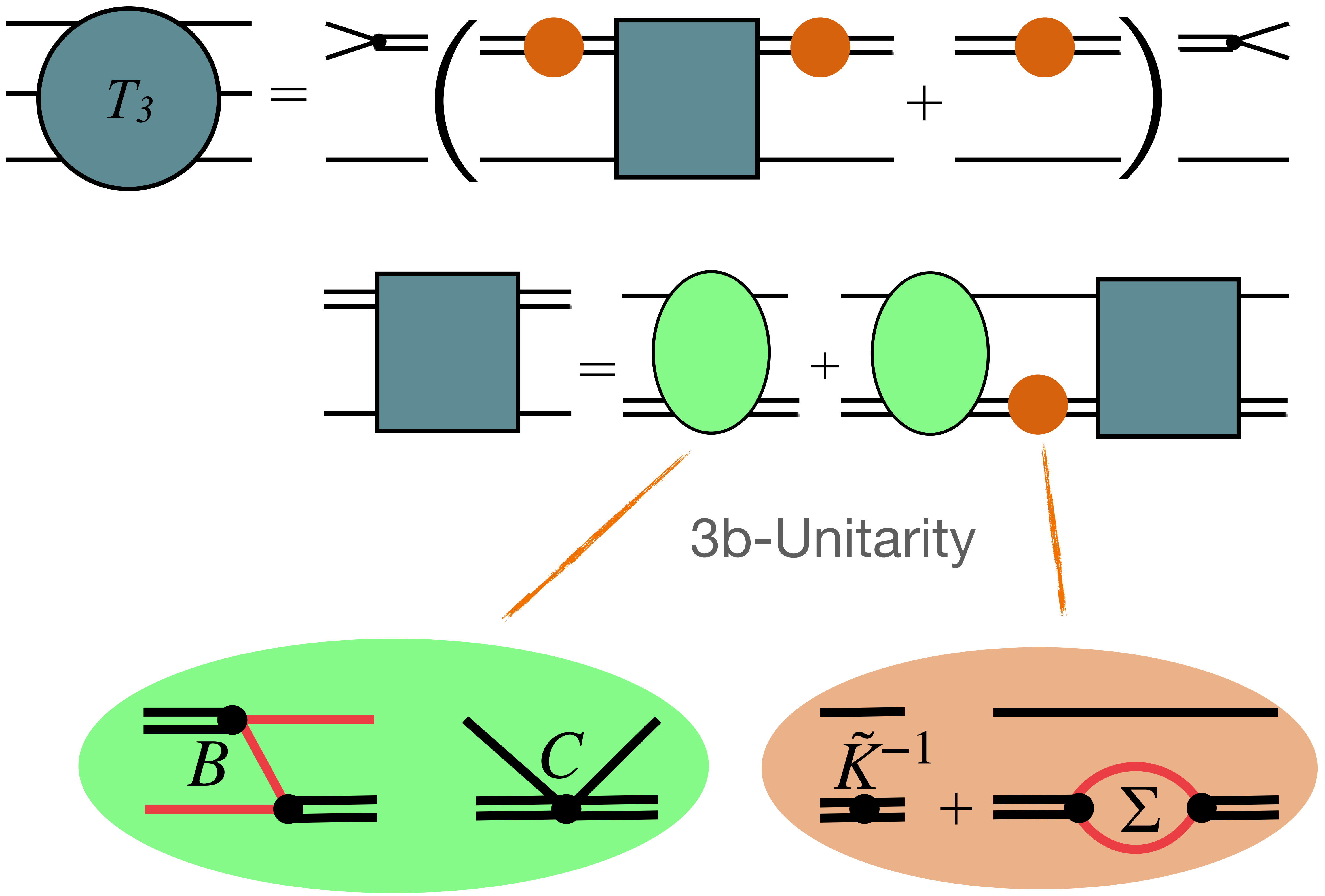
- Beyond Standard Model: τ-EDM



- Precision physics: rare hadronic W-decays[2]
- Exotic states of matter[3]

1) Severt/MM/Meißner JHEP04(2023) >>> PHD talk on Friday
2) Sirunyan et al. [CMS@CERN] PRL122
3) Experimental programs: GlueX@JLAB; COMPASS@CERN;

SCATTERING AMPLITUDE

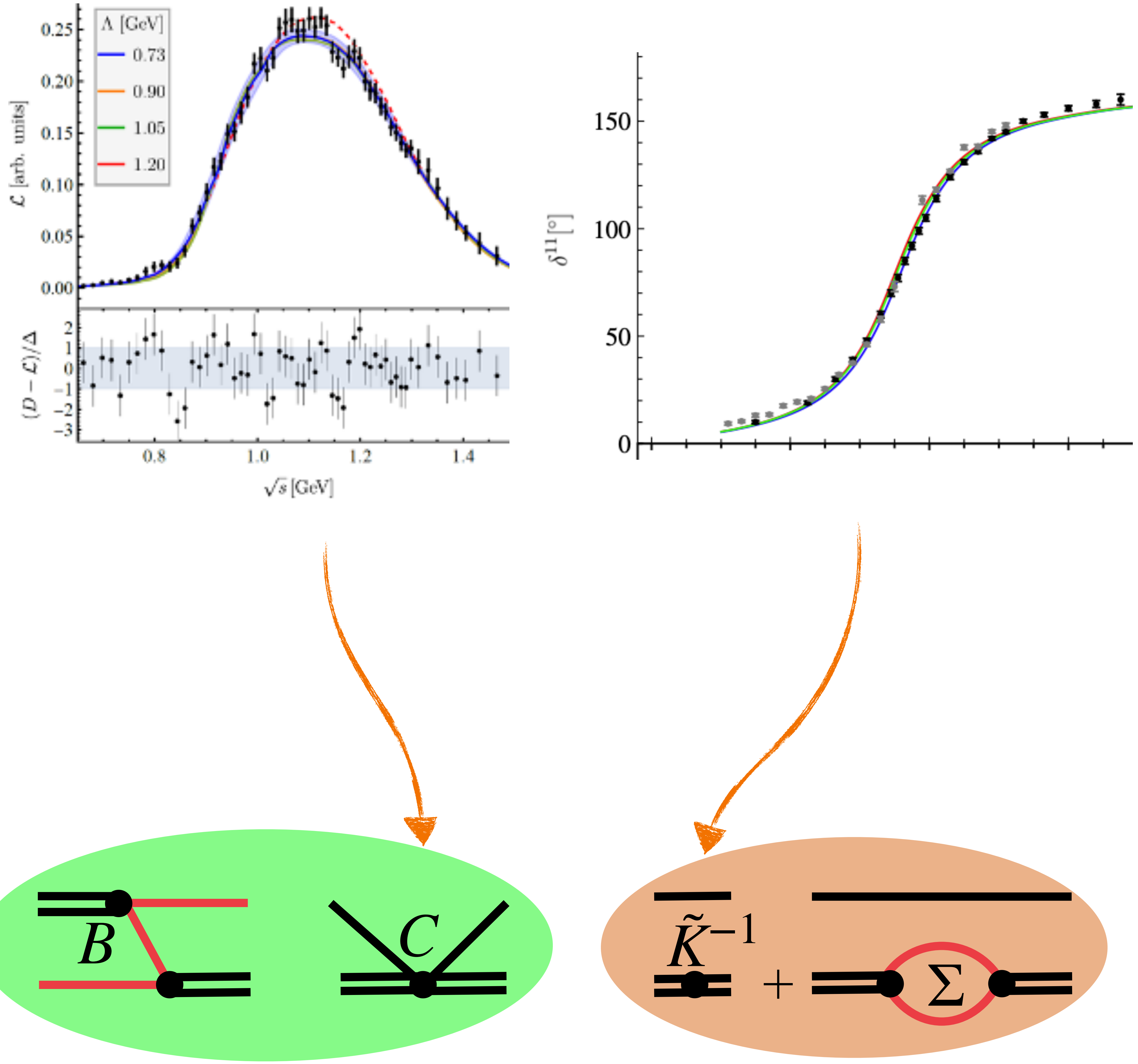


Three-body scattering amplitude[1,2]

- constructed from unitarity
- novel result from the S-matrix theory

1) MM/Hu/Döring/Pilloni/Szczepaniak Eur.Phys.J.A 53 (2017)
2) related approaches: Wunderlich et al. JHEP 08 (2019); Jackura et al. Eur.Phys.J.C 79 (2019);

$a_1(1260)$ PHENOMENOLOGY

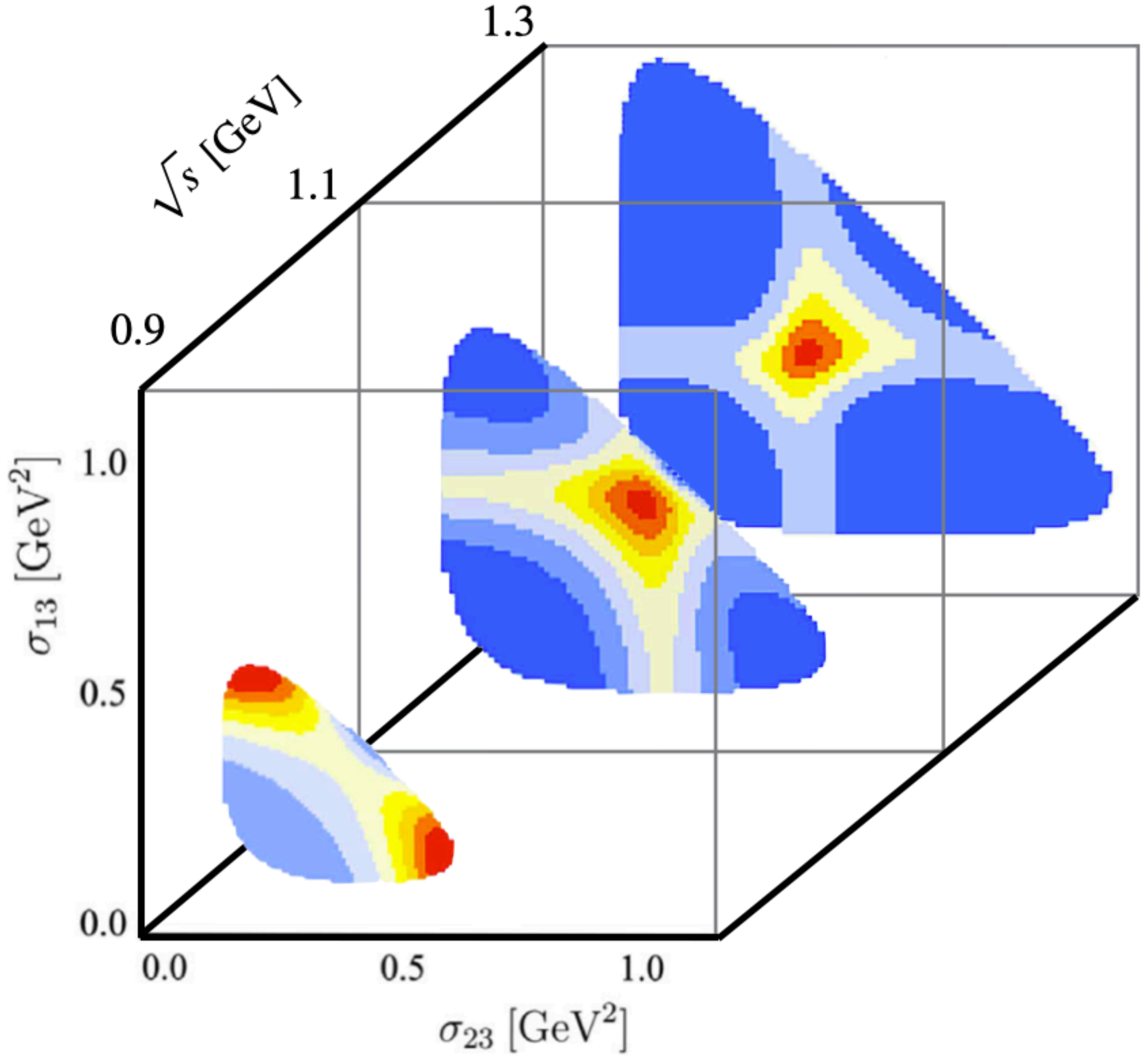


- Fix quantum numbers to **a_1(1260) → $\pi\pi\pi$**
- solution via complex spectator momentum
- unknown parameter from fits[1] to data

1) Sadasivan/MM/Döring/Alexandru/Culver/Lee Phys.Rev.D 101 (2020)

Data: Schael [ALEPH] Phys.Rept. 421 (2005); Estabrooks et al. Nucl.Phys.B 79; Protopopescu et al. Phys.Rev.D 7;

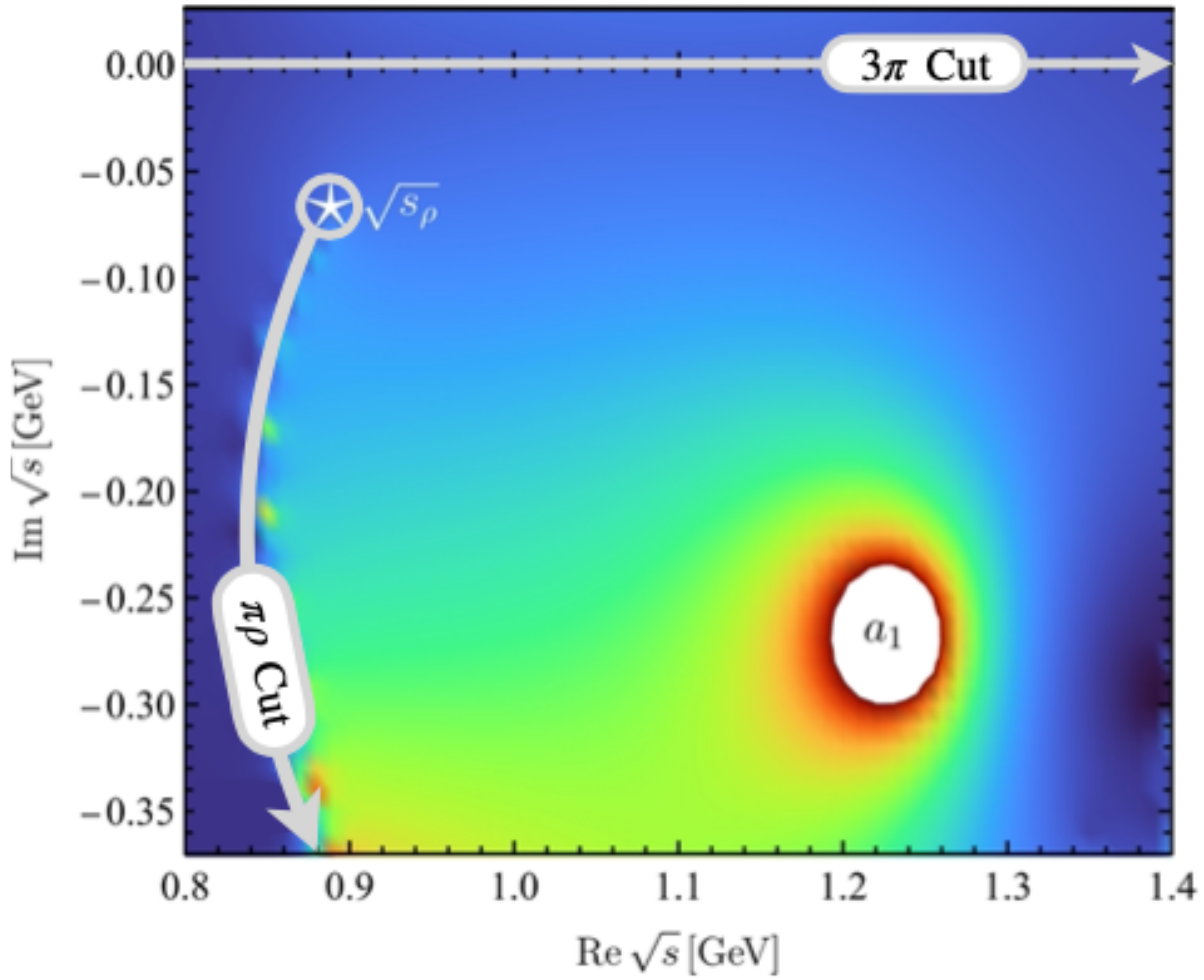
a₁(1260) PHENOMENOLOGY



Dalitz plot

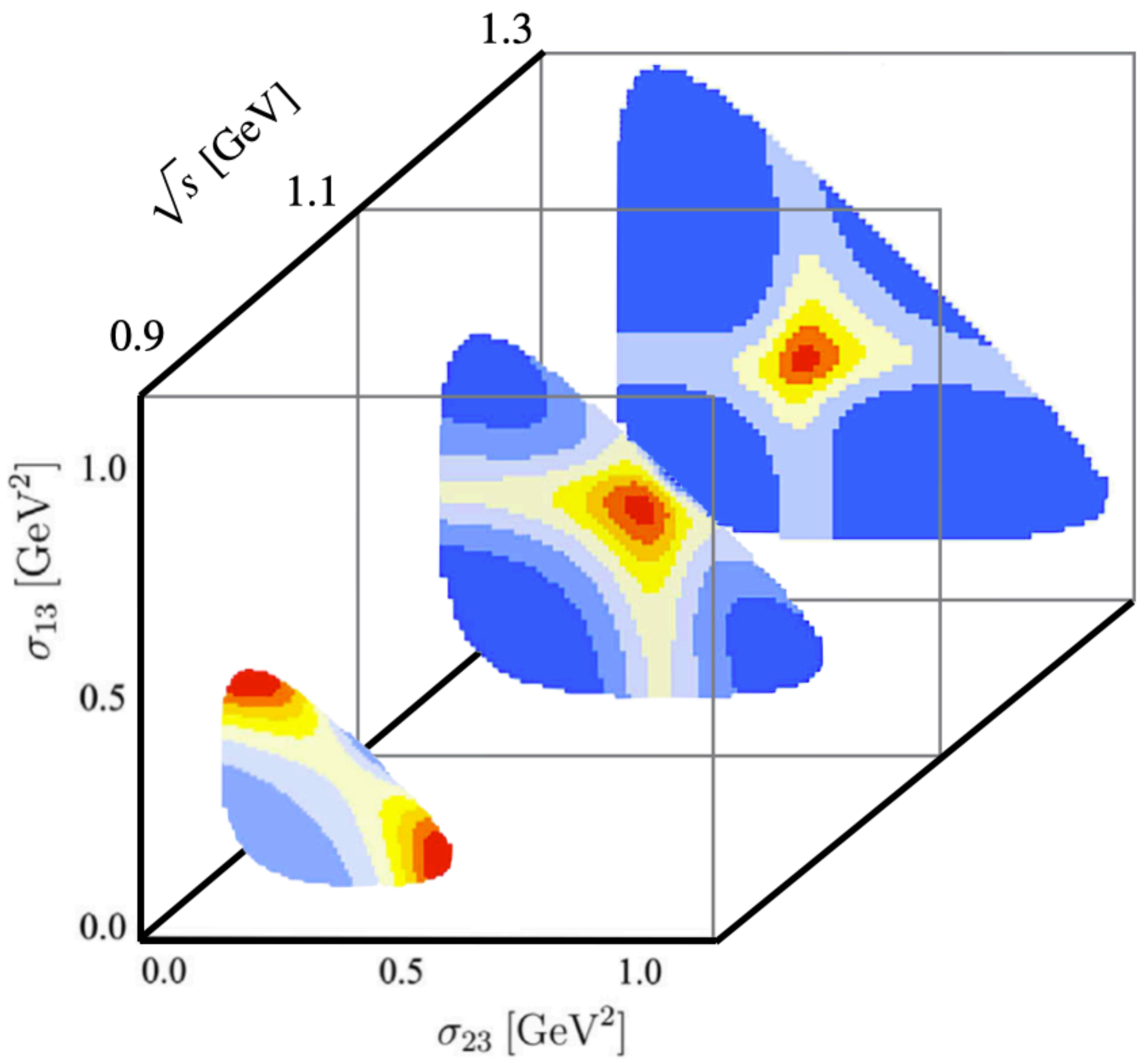
- Predictions[1]:
  - generalized kinematics: Dalitz Plot
  - universal parameters of a_1(1260)

Universal parameters



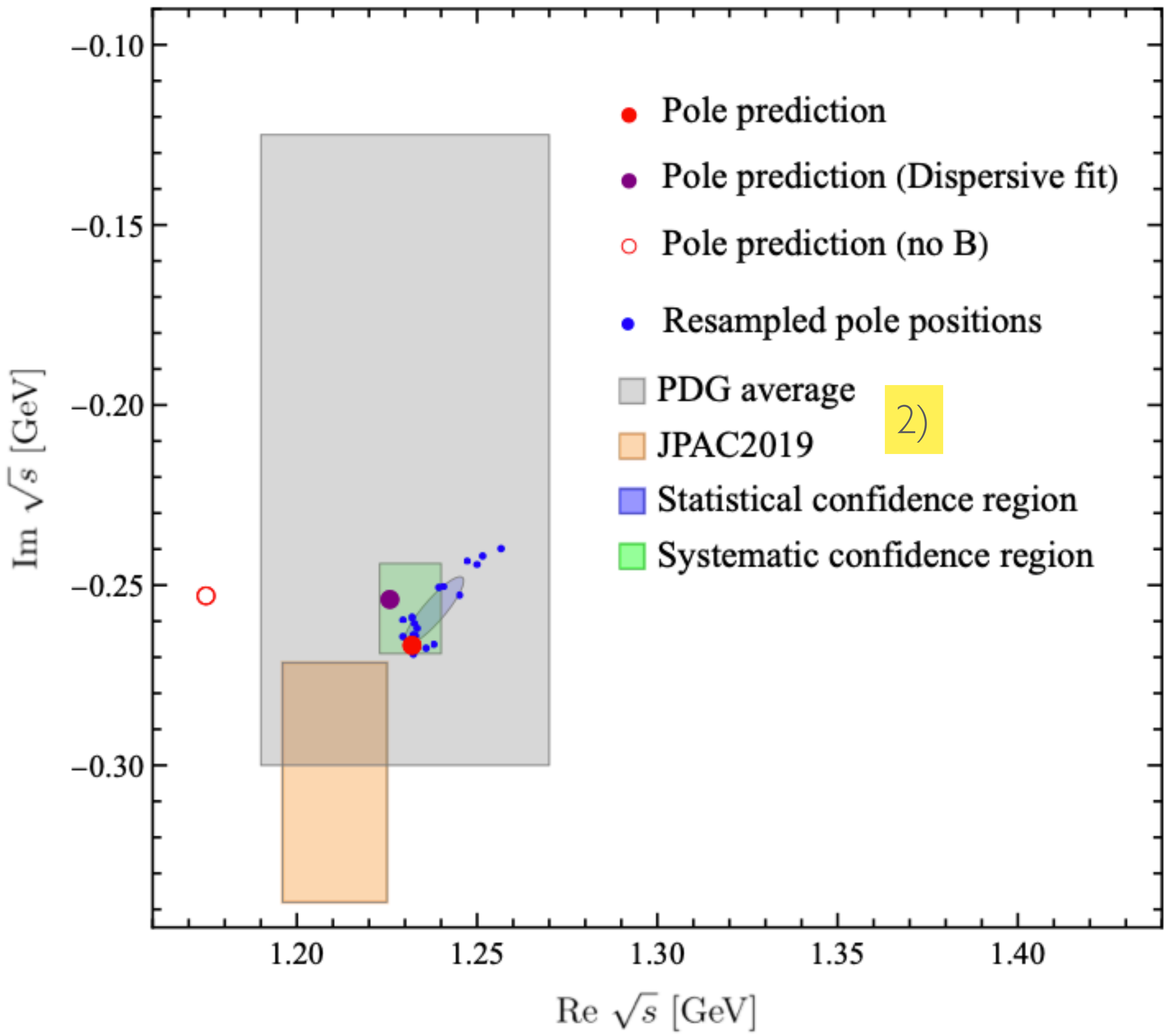
1) Sadasivan/MM/Döring/Alexandru/Culver/Lee Phys.Rev.D 101 (2020)

a₁(1260) PHENOMENOLOGY



Dalitz plot

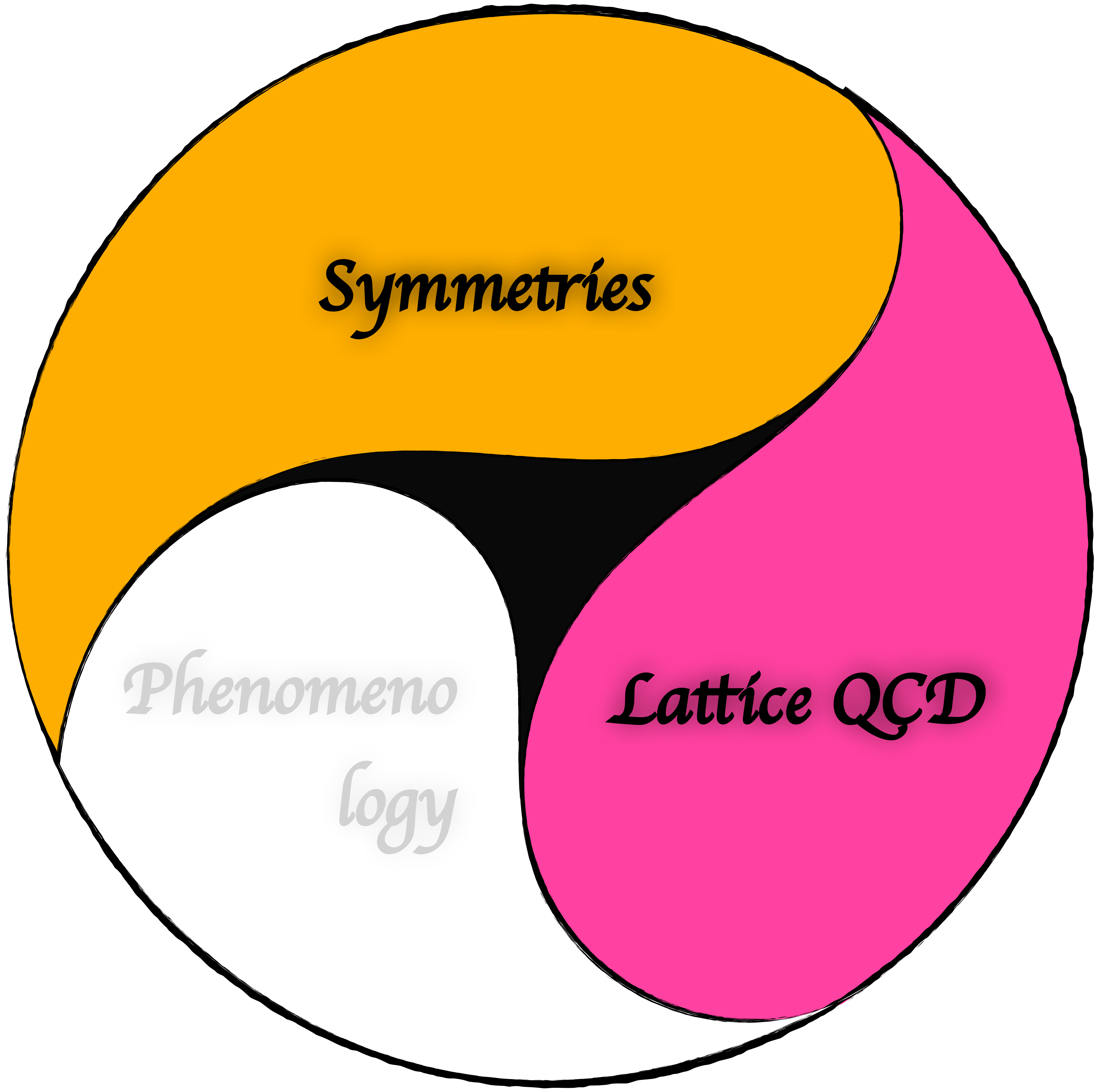
- Predictions[1]:
  - generalized kinematics: Dalitz Plot
  - universal parameters of $a_1(1260)$



1) Sadasivan/MM/Döring/Alexandru/Culver/Lee Phys.Rev.D 101 (2020)
2) [PDG]Workman et al. (2022); Mikhasenko et al. Phys.Rev.D 98 (2018)

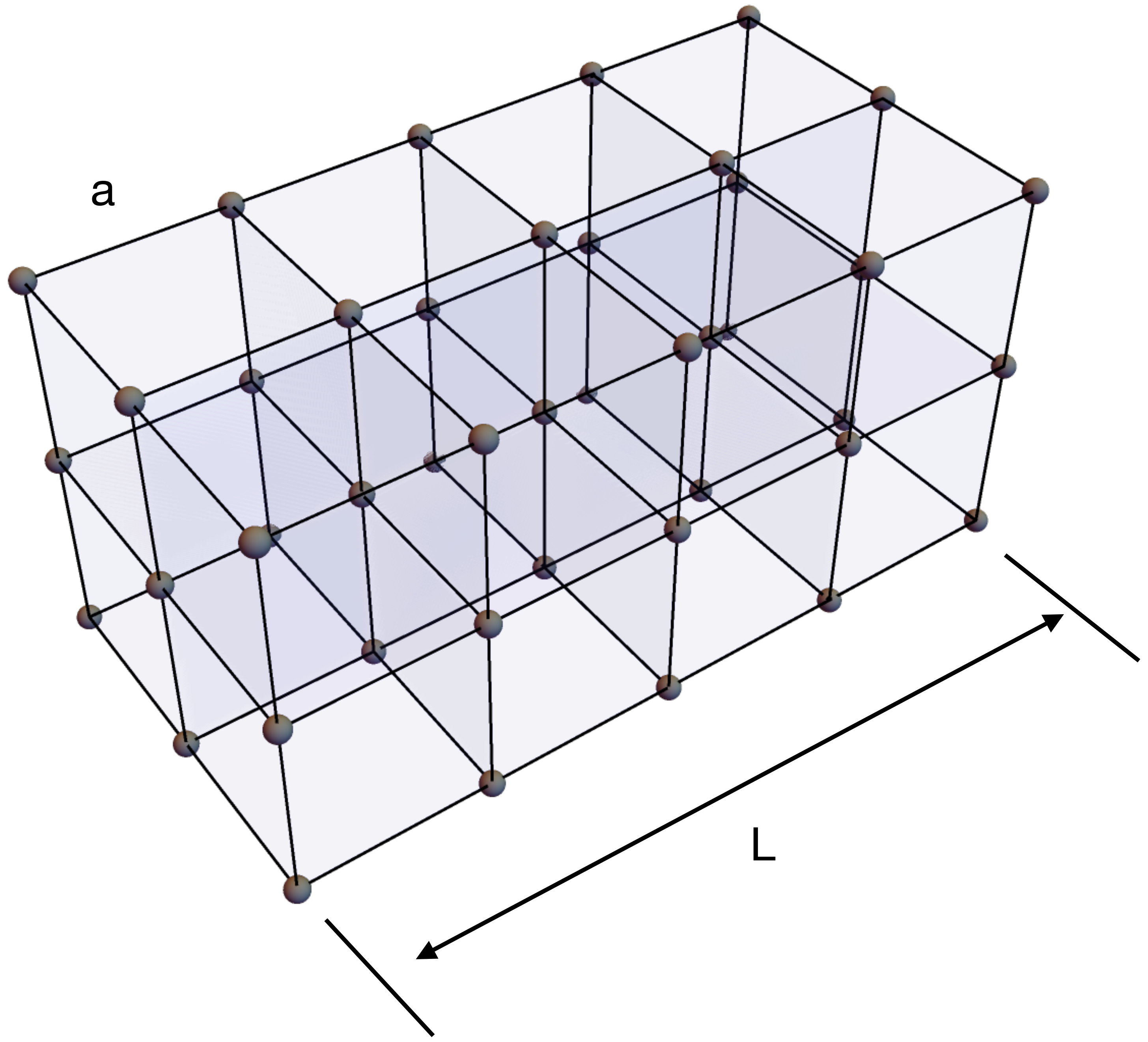
CASE #2.1

THREE-BODY RESONANCES FROM LATTICE QCD



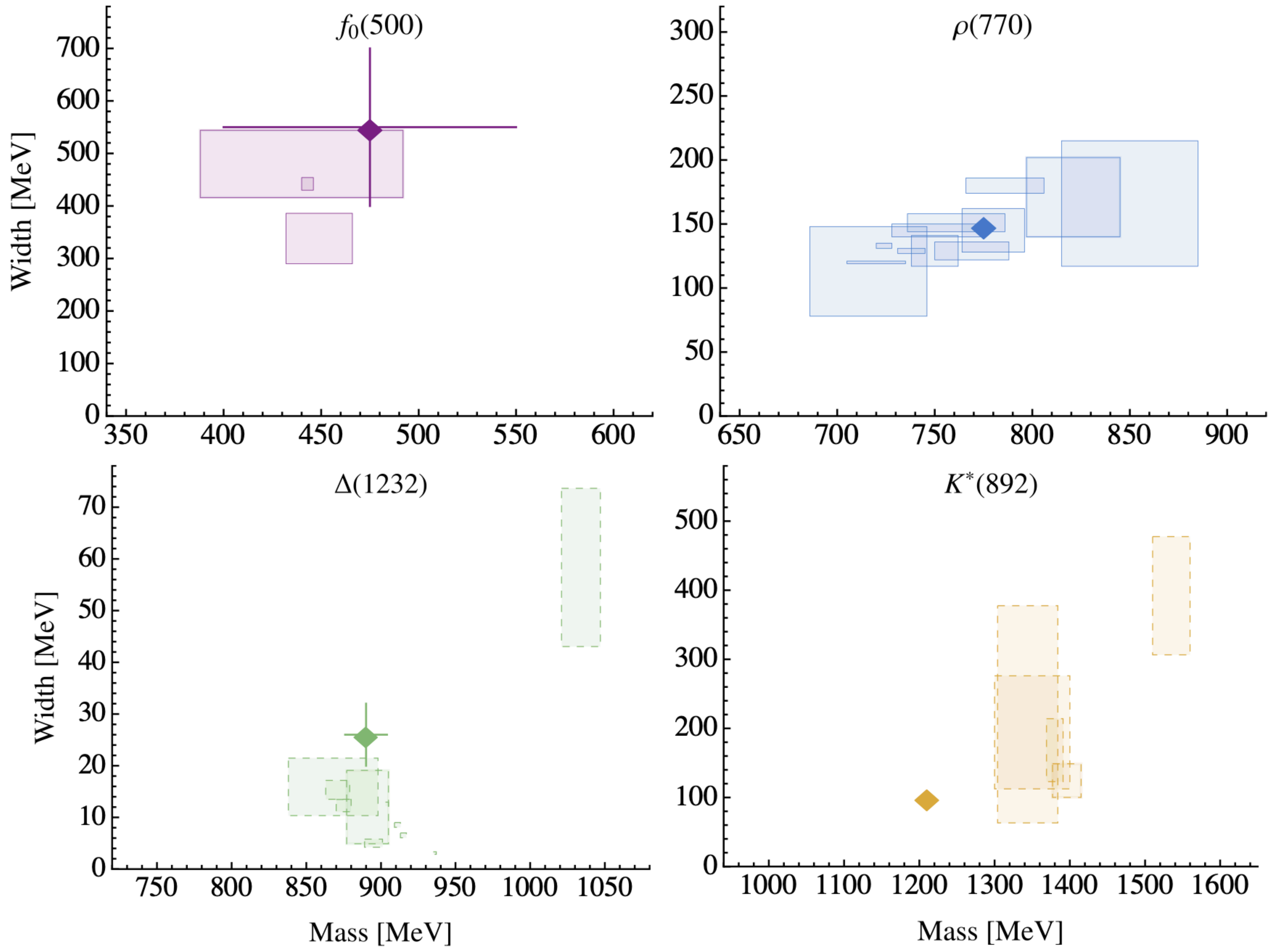
LATTICE HADRON SPECTROSCOPY

$$\mathcal{L}_{QCD} = \sum \bar{q}^a_f \left(i \not{D}_{ab} - m_f \delta_{ab} \right) q^b_f - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$



- Numerical evaluation of QCD Green's functions

LATTICE HADRON SPECTROSCOPY



MM/Meißner/Urbach 2206.01477 Phys.Rept. 1001 (2023)

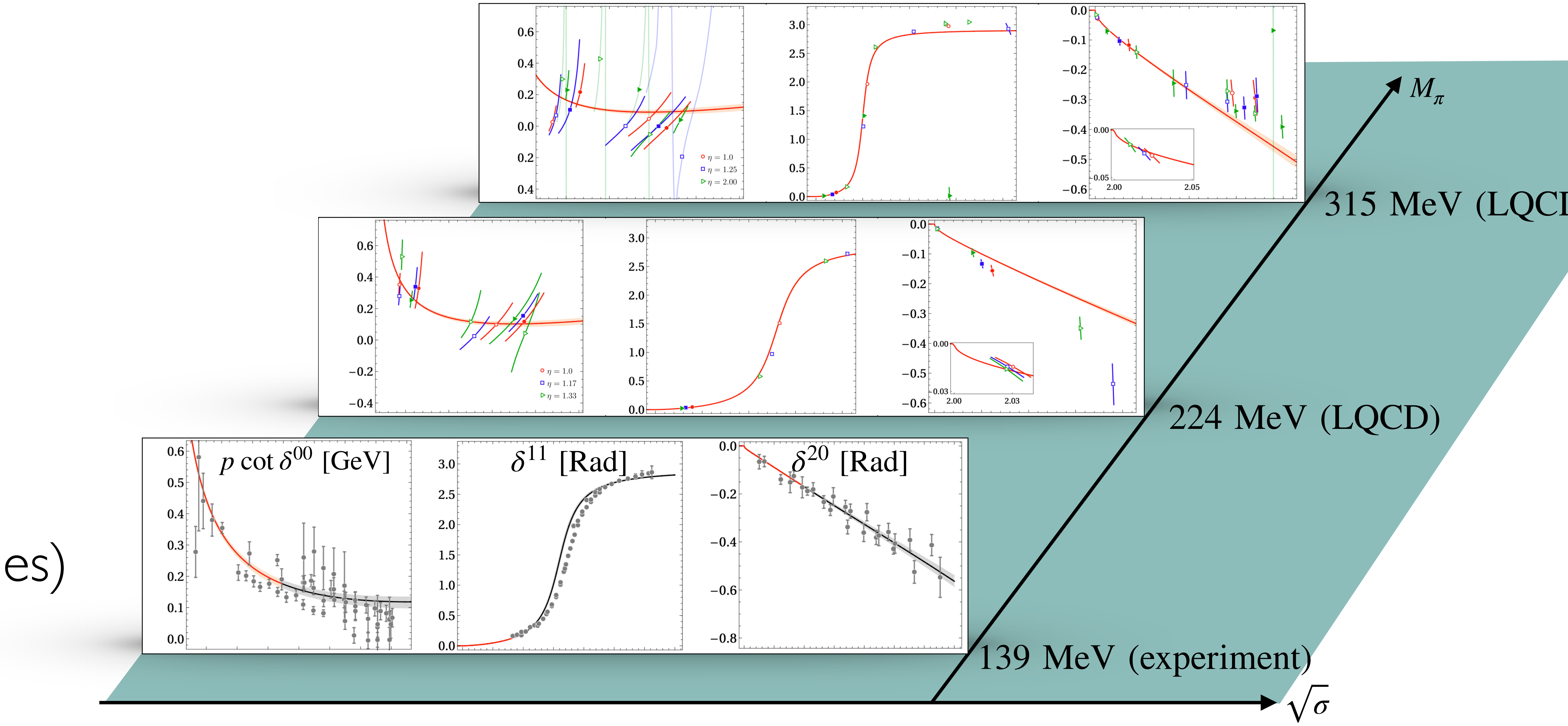
- Many studies of 2-body systems[1]

1) [NPLQCD], [RQCD], [ETMC], [HadSpec], ...
2) Reviews: Briceño/Dudek/Young Rev.Mod.Phys. 90 (2018); MM/Meißner/Urbach Phys.Rept. 1001 (2023)

LATTICE HADRON SPECTROSCOPY

- Experimentally inaccessible scenarios:
  → Unconventional quantum numbers
  → Three-body scattering
  → Unphysical pion mass (chiral trajectories)

  …



MM/Culver/Brett/Alexandru/Döring/Lee *Phys.Rev.D* 100 (2019)

Review: MM/Döring/Rusetsky EPJ ST (2021)

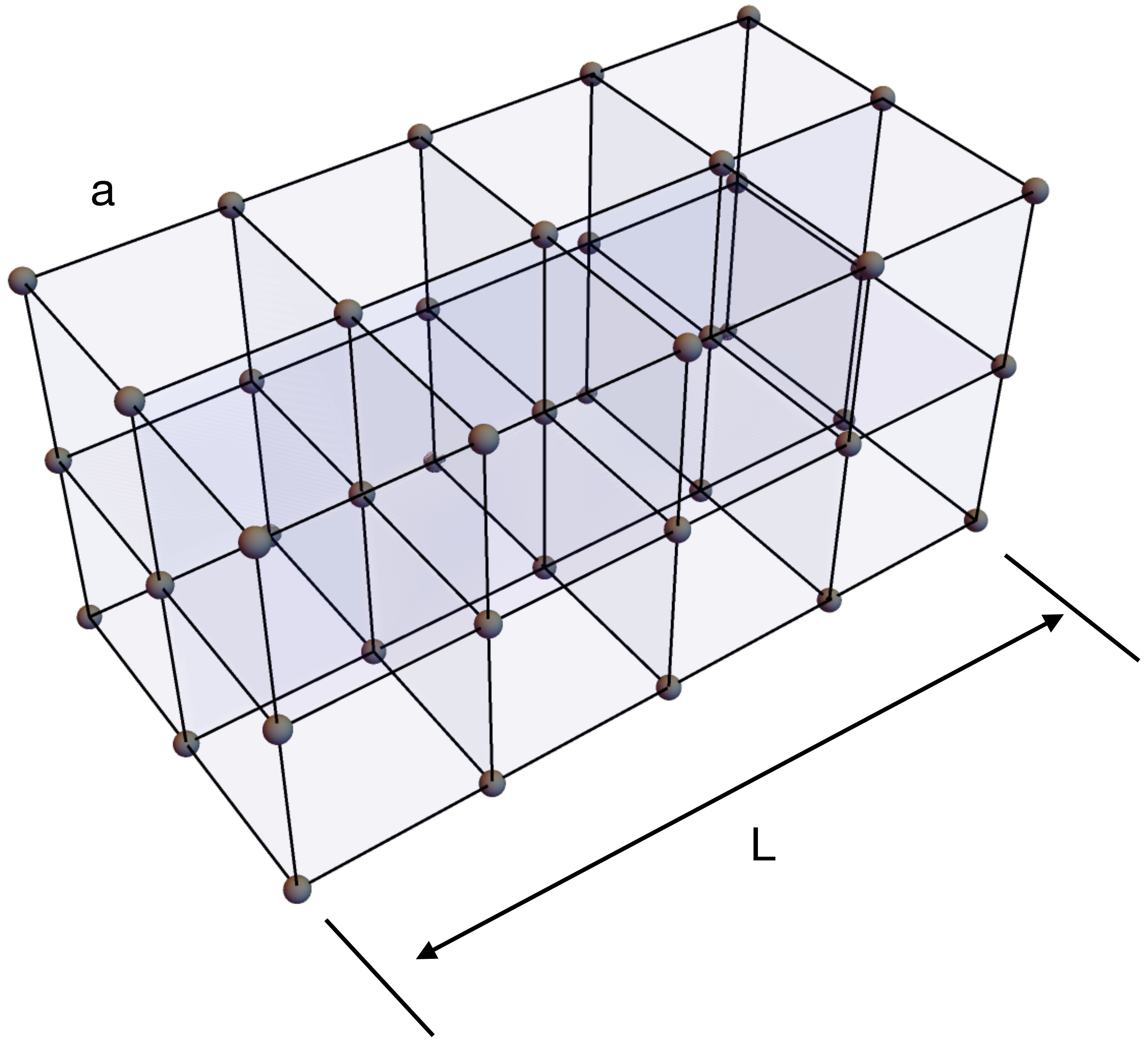
1) [NPLQCD], [RQCD], [ETMC], [HadSpec], ...
2) Reviews: Briceño/Dudek/Young Rev.Mod.Phys. 90 (2018); MM/Meißner/Urbach Phys.Rept. 1001 (2023)

LATTICE QCD

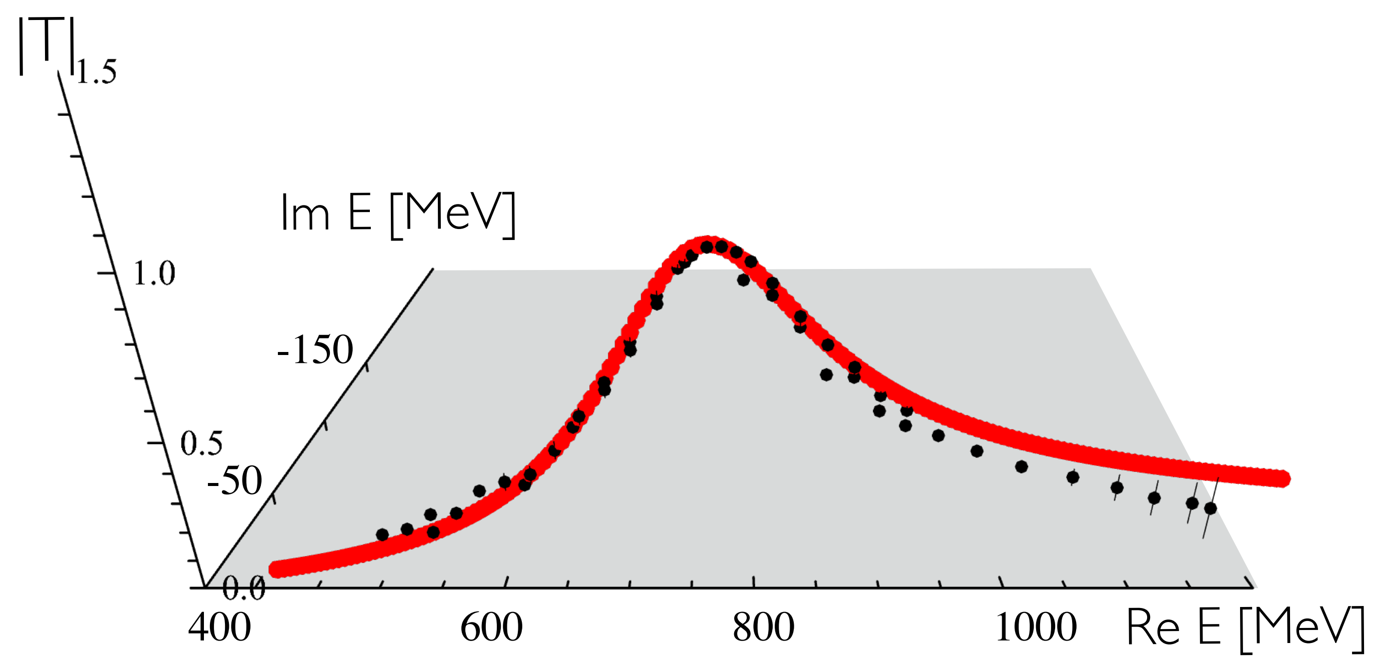
$$\mathcal{L}_{\mathrm{QCD}} = \sum \bar{q}_f^a \left(i \not{D}_{ab} - m_f \delta_{ab}\right) q_f^b - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu}$$

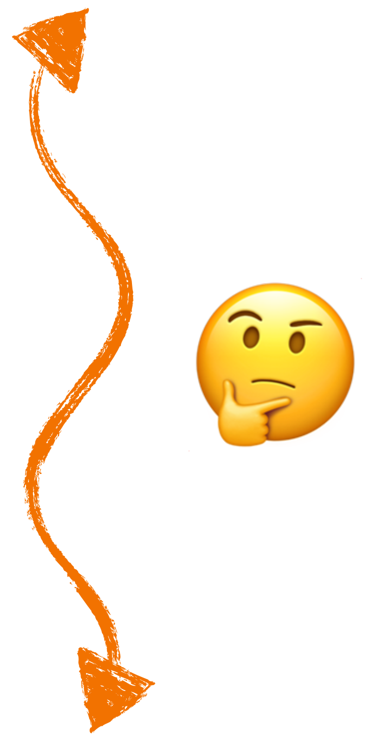
Lattice QCD: numerical evaluation of QCD Green's functions. But…

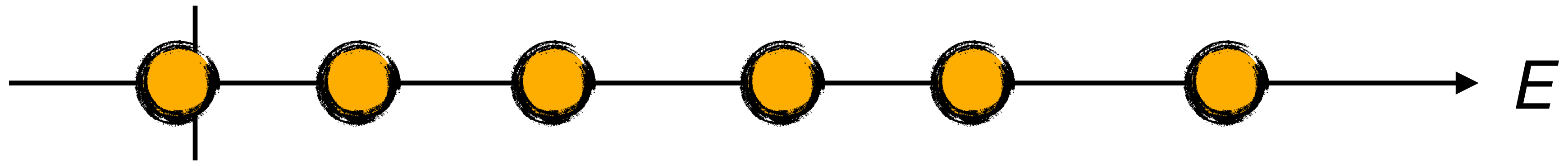
- discretized Euclidean space time (***a>0***)
- in finite volume (***L<oo***)



HADRONS IN A BOX





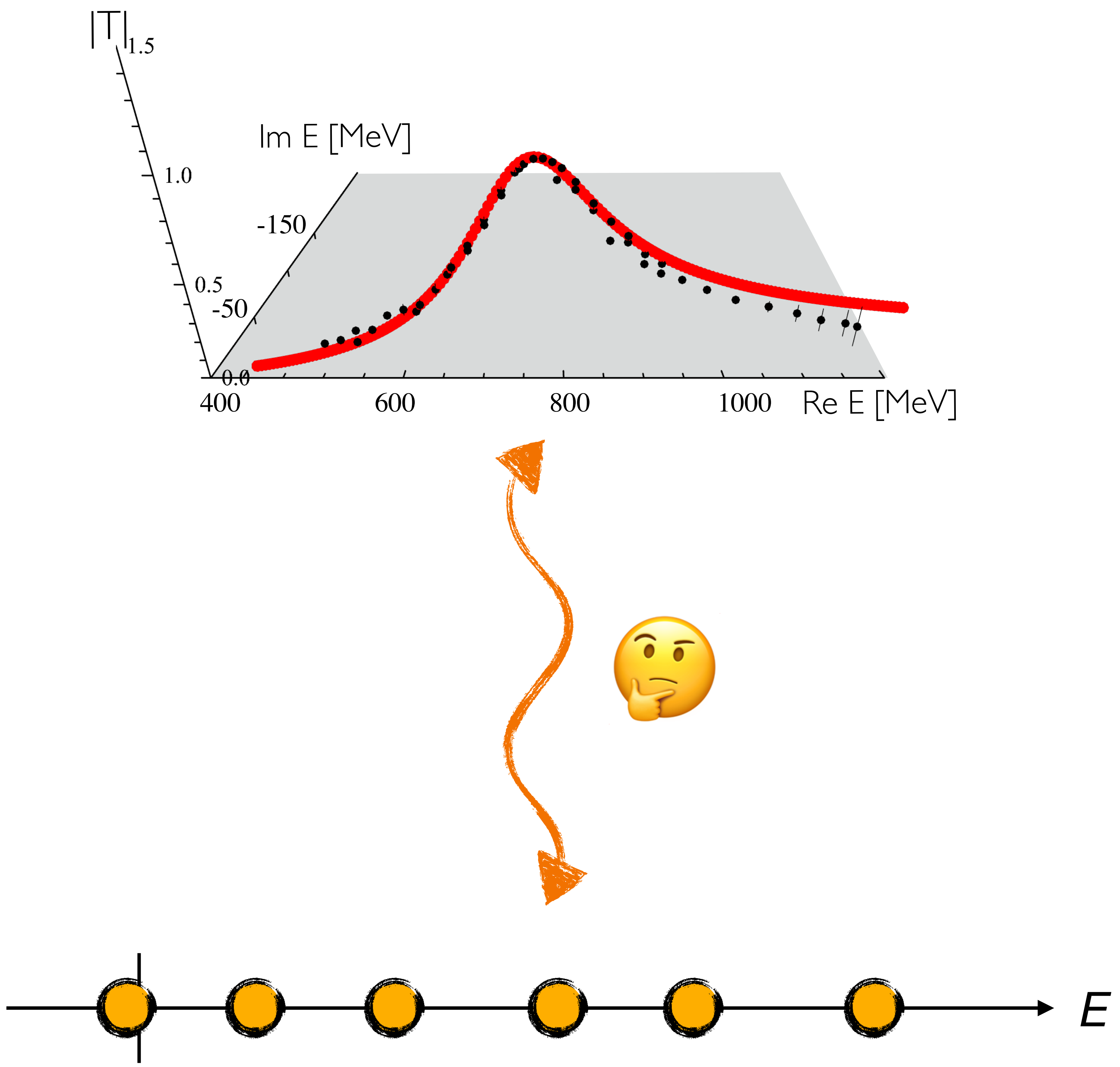


Finite-volume spectrum is real and discrete!

... requires mapping: **Quantization condition**[1,2]

1) Lüscher, Gottlieb, Rummukainen, Feng, Li, Döring, Briceño, Meißner, Rusetsky, Hansen, MM, Blanton, ...
2) Reviews: Hansen/Sharpe Ann.Rev.Nucl.Part.Sci. 69 (2019); MM/Döring/Rusetsky Eur.Phys.J.ST 230 (2021);

HADRONS IN A BOX



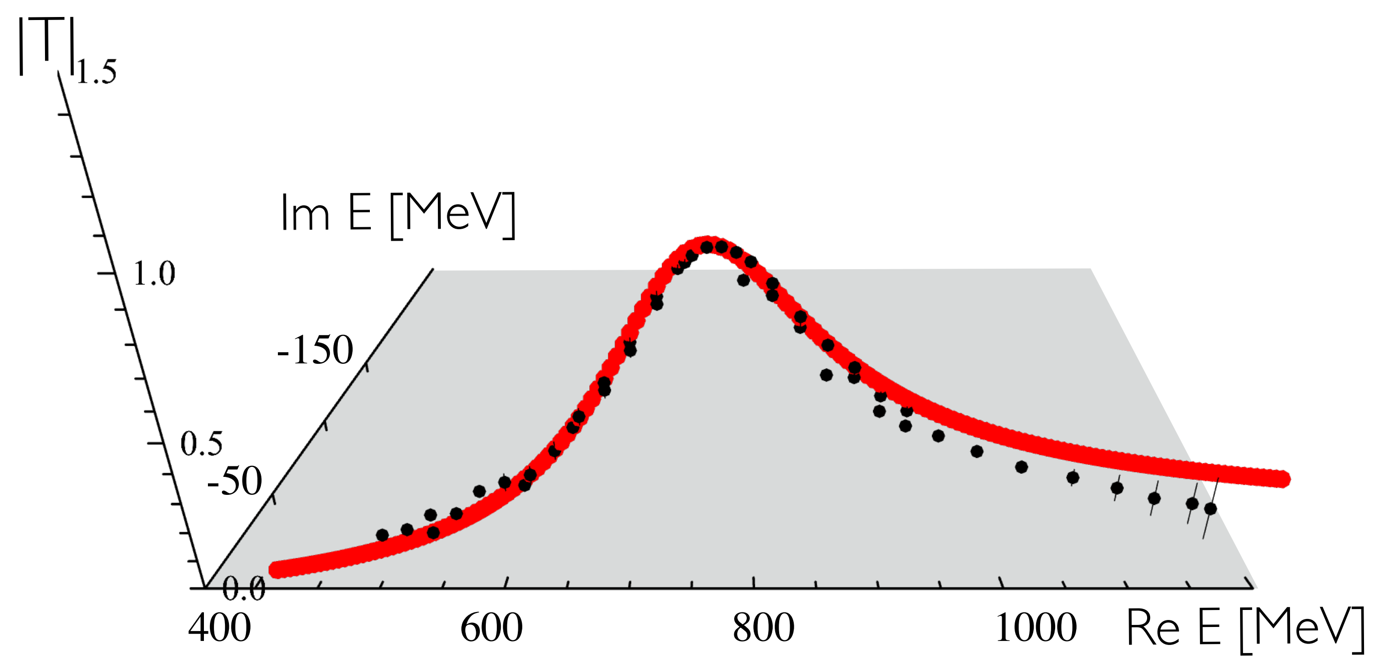
🤗 Heavily simplified:

on-shell particle-configurations: $\Delta E \sim mL$

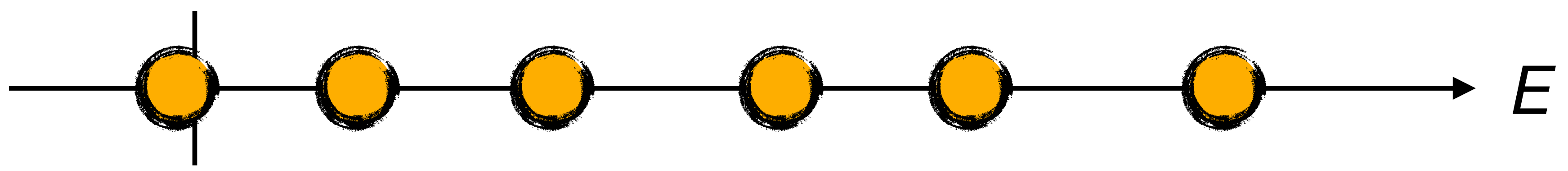
off-shell particle-configurations: $\Delta E \sim e^{-mL}$

1) Lüscher, Gottlieb, Rummukainen, Feng, Li, Döring, Briceño, Meißner, Rusetsky, Hansen, MM, Blanton, ...
2) Reviews: Hansen/Sharpe Ann.Rev.Nucl.Part.Sci. 69 (2019); MM/Döring/Rusetsky Eur.Phys.J.ST 230 (2021);

HADRONS IN A BOX



🤩 *A unitary "T-matrix" accounts for all O(mL) effects!*



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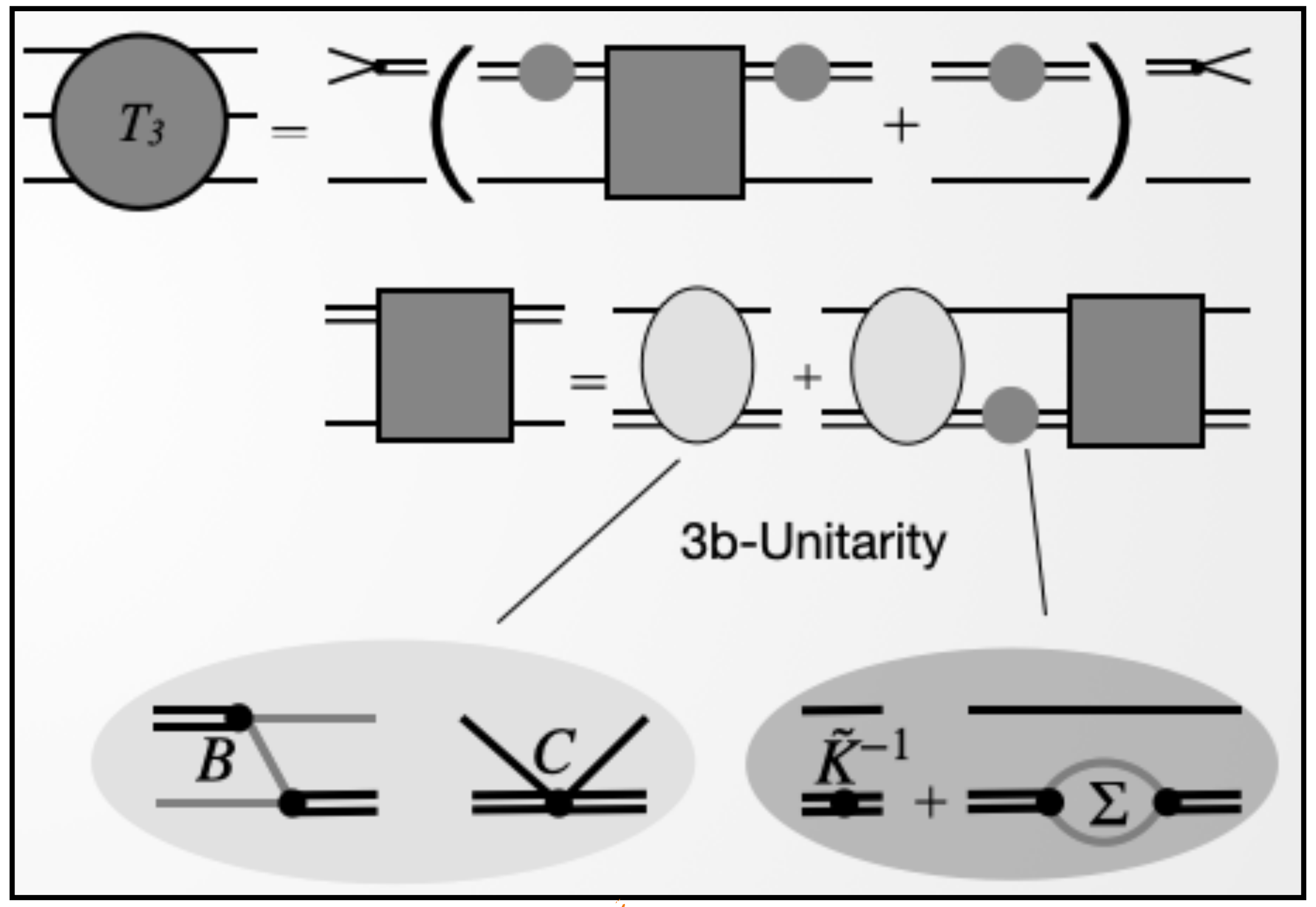
2) Reviews: Hansen/Sharpe Ann.Rev.Nucl.Part.Sci. 69 (2019); MM/Döring/Rusetsky Eur.Phys.J.ST 230 (2021);

3-BODY QUANTISATION CONDITION



Reminder

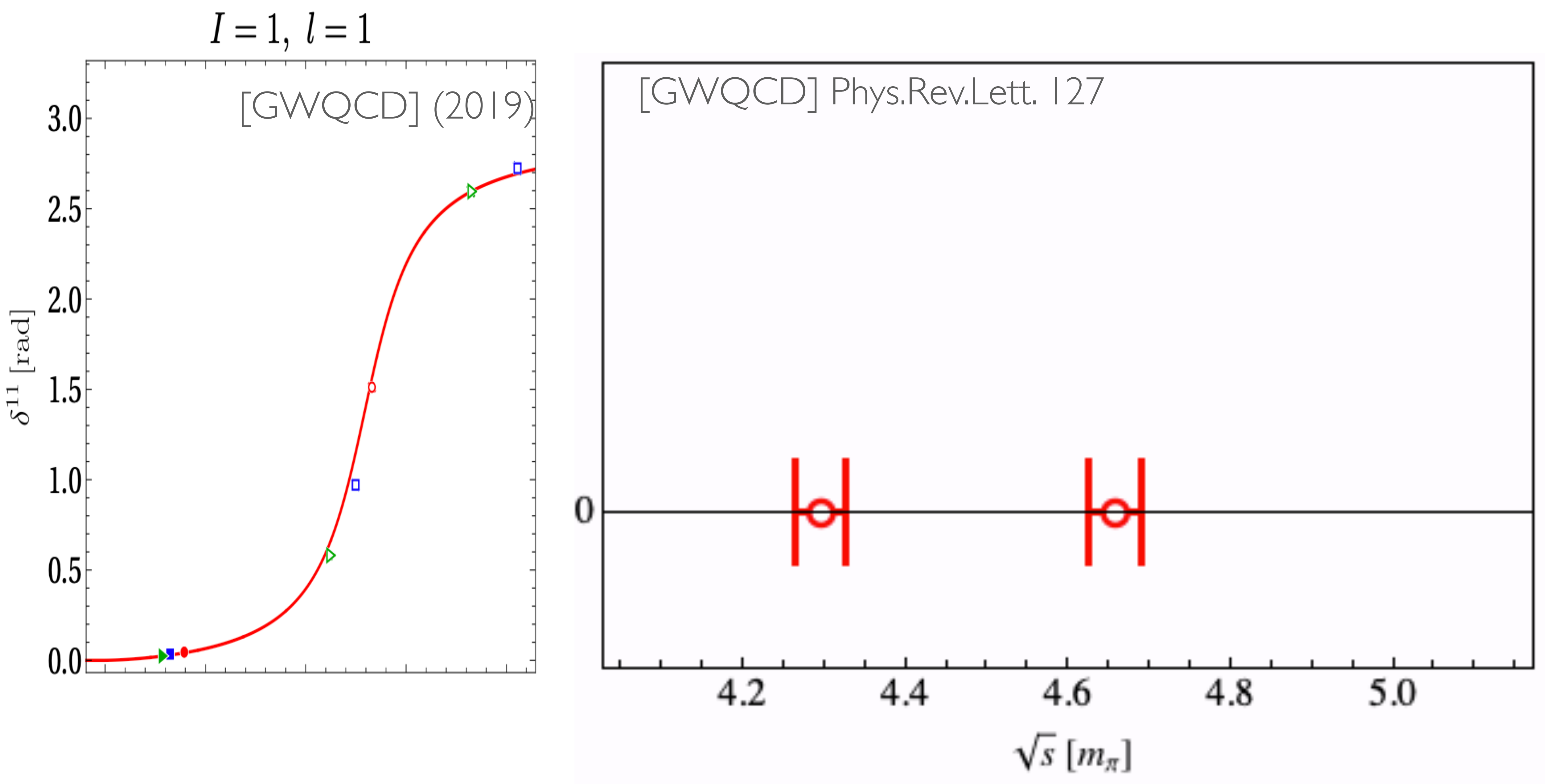
Finite-volume unitarity (FVU)[1,2]

- separates volume dependent terms
- volume independent terms connect infinite/finite-volume spectra

$$0 = \det\left[2L^3E\left(\tilde{K}_n^{-1} - \Sigma\right) - B - C\right]_{\mathbf{p}'\mathbf{p}}$$

1) Lüscher, Gottlieb, Rummukainen, Feng, Li, Döring, Briceño, Meißner, Rusetsky, Hansen, MM, Blanton, ...
2) Reviews: Hansen/Sharpe Ann.Rev.Nucl.Part.Sci. 69 (2019); MM/Döring/Rusetsky Eur.Phys.J.ST 230 (2021);

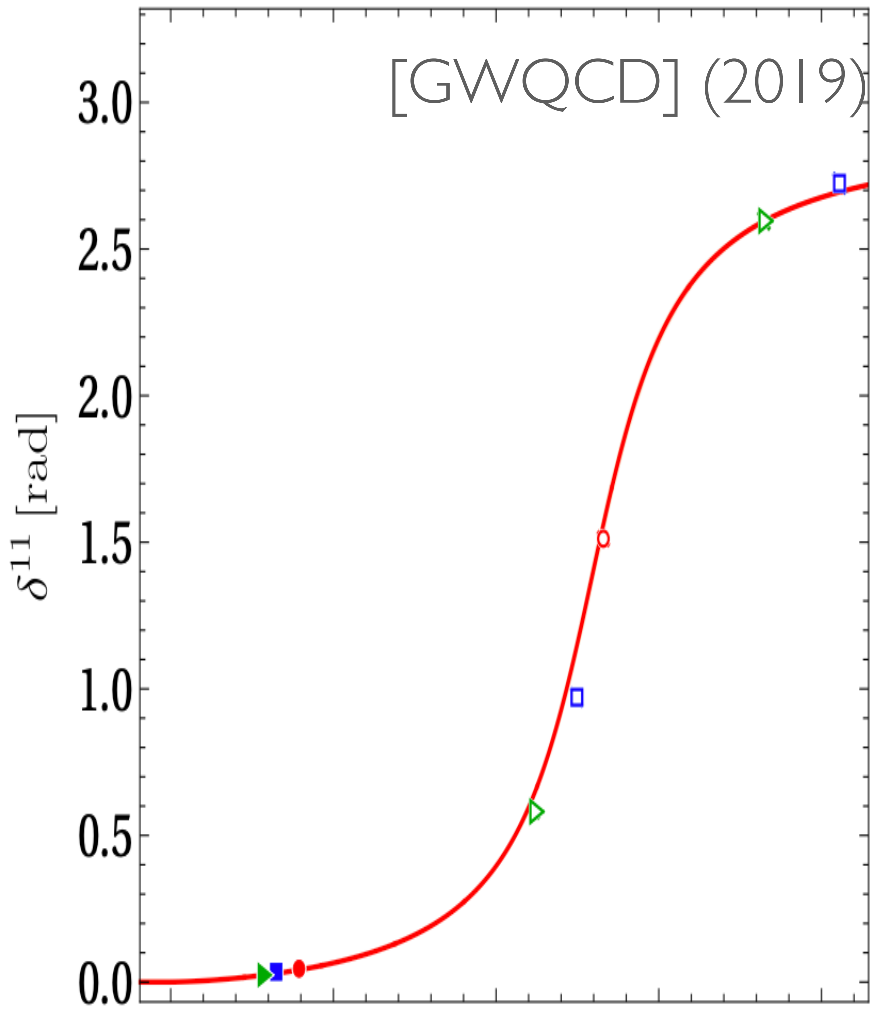
- First LQCD calculation[1] of a resonant 3b system
  - $N_f = 2$ dynamical fermions
  - LapH smearing
  - $\boldsymbol{P}$=(0,0,0)
  - m_π=**224** MeV, $m_\pi L$=3.3
  - *GEVP with one-/two-/three-meson operators*

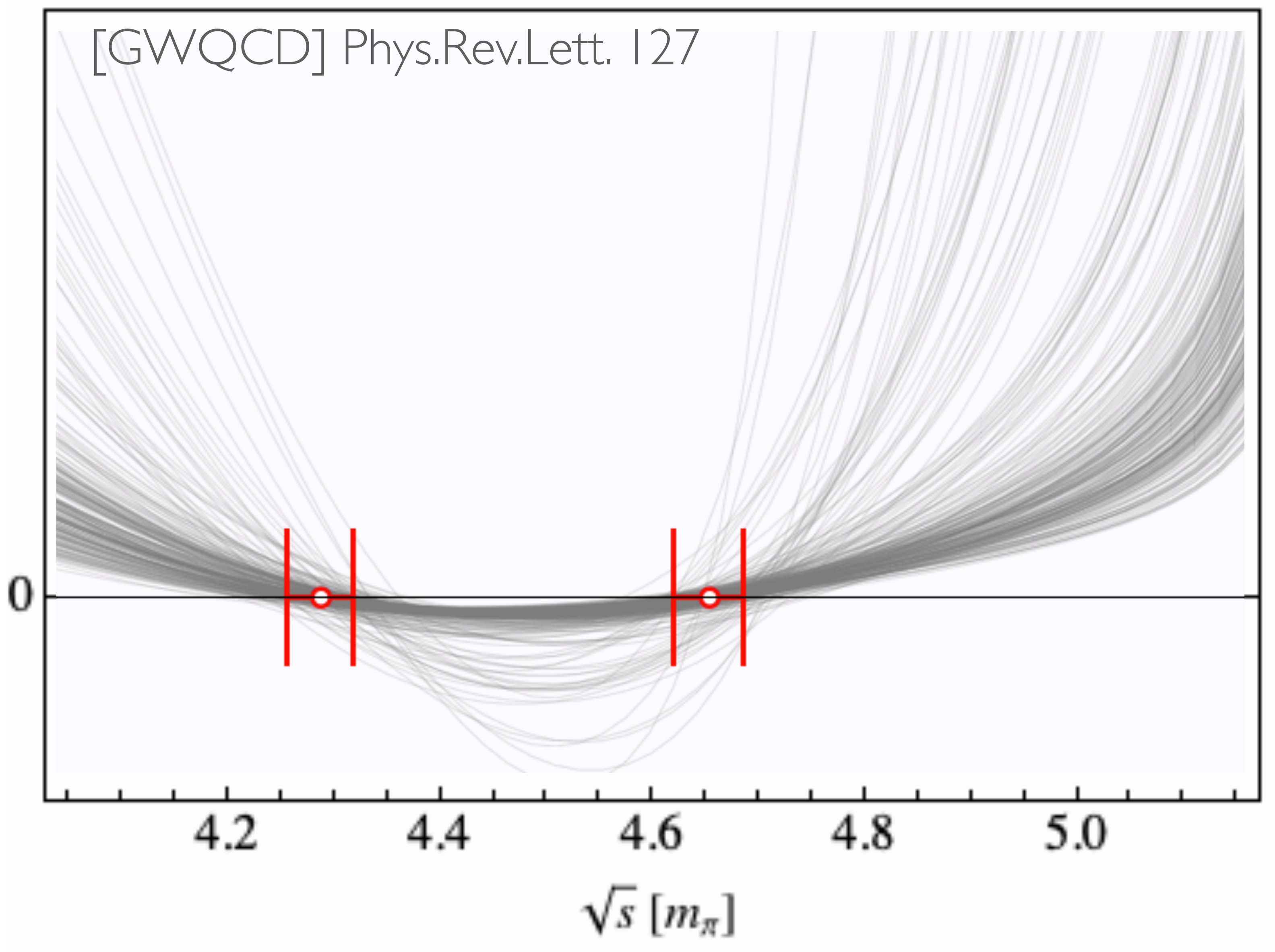


1) MM/Culver/Döring/Alexandru/Lee/Brett/Sadasivan [GWQCD] Phys.Rev.Lett. 127

$$0 = \det\left[2L^3E\left(\tilde{K}_n^{-1} - \Sigma\right) - B - C\right]_{\mathbf{p}'\mathbf{p}}$$

$I=1,\ l=1$



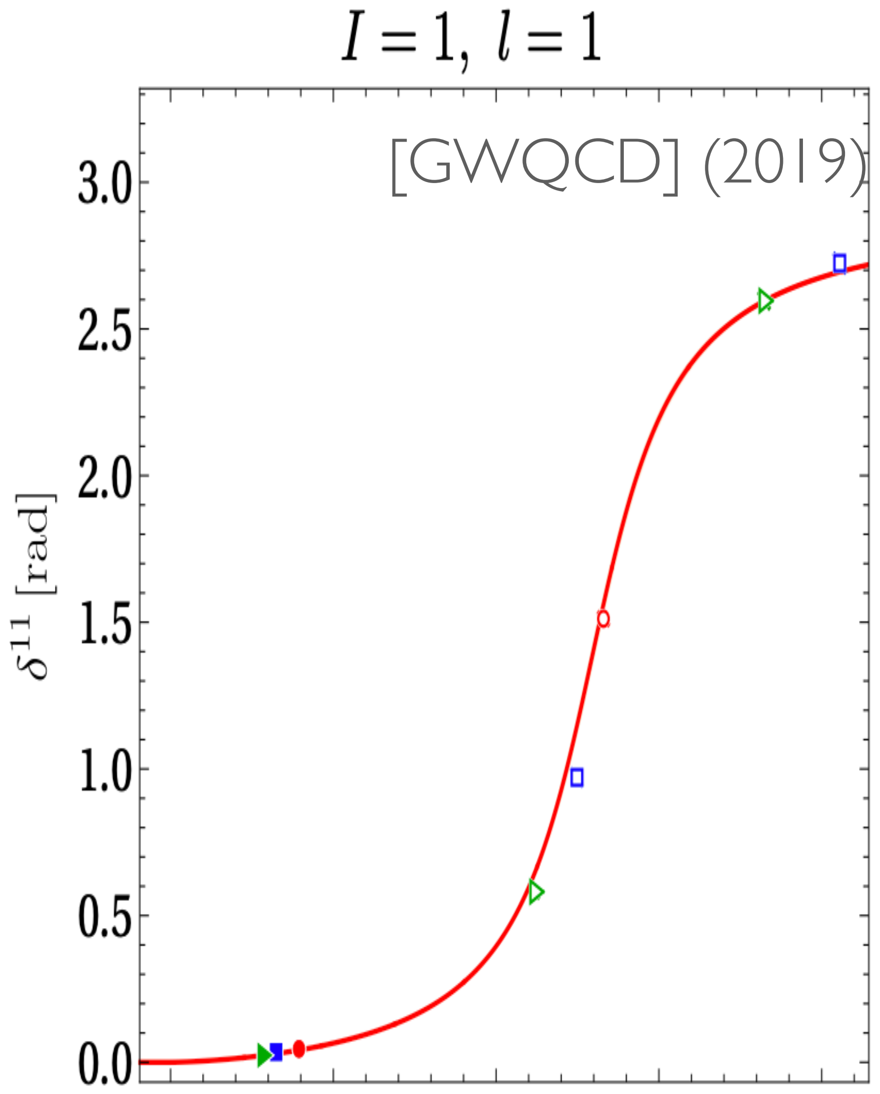


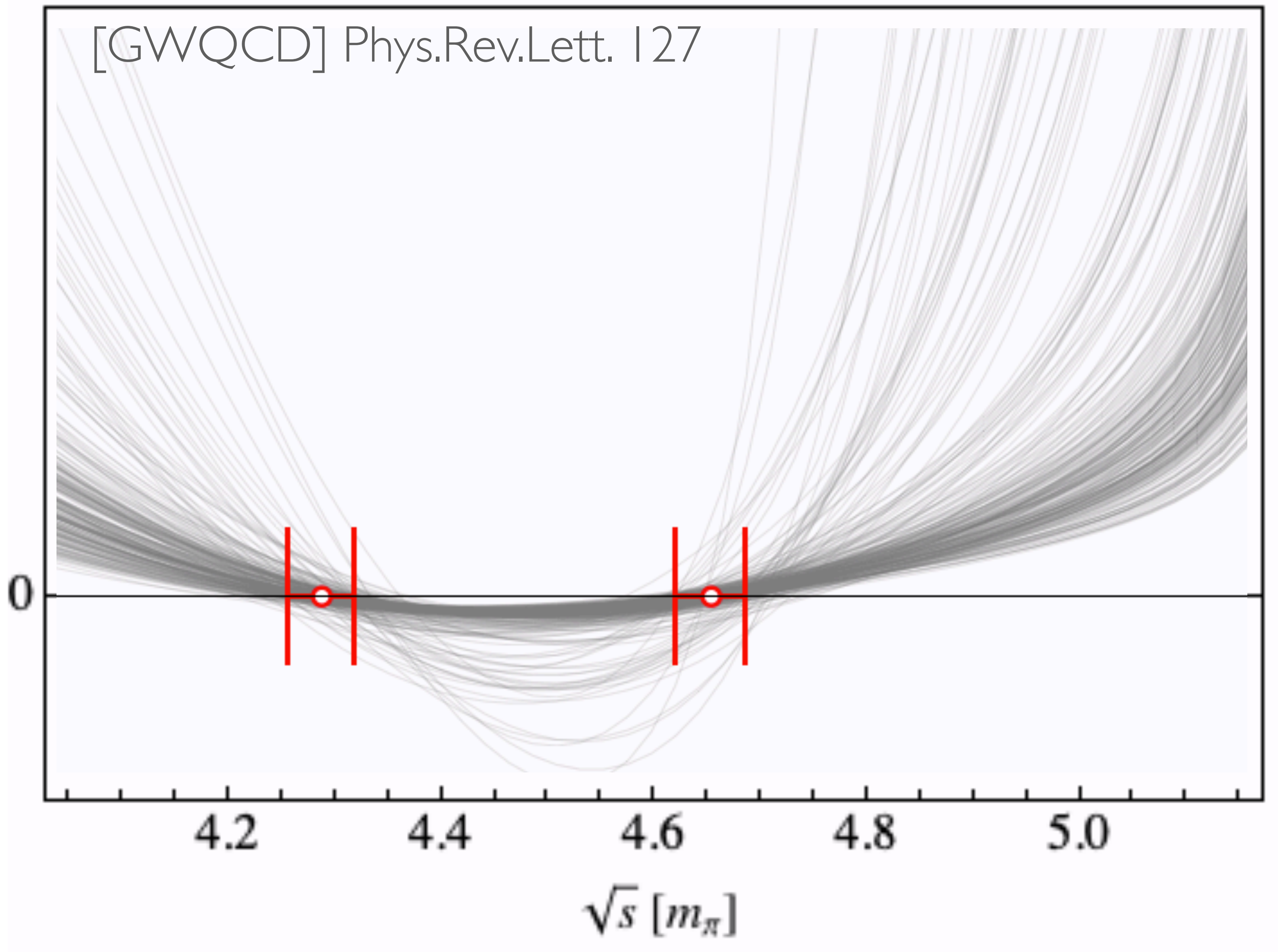
1) MM/Culver/Döring/Alexandru/Lee/Brett/Sadasivan [GWQCD] Phys.Rev.Lett. 127

"Heavier Universe"

$$0 = \det\left[2L^3E\left(\tilde{K}_n^{-1} - \Sigma\right) - B - C\right]_{\mathbf{p}'\mathbf{p}}$$

$$T^c = B + C + \int \frac{d^3\ell}{(2\pi)^3} \frac{(B+C)}{2E_l} \frac{1}{\tilde{K}_n^{-1} - \Sigma_n} T^c$$

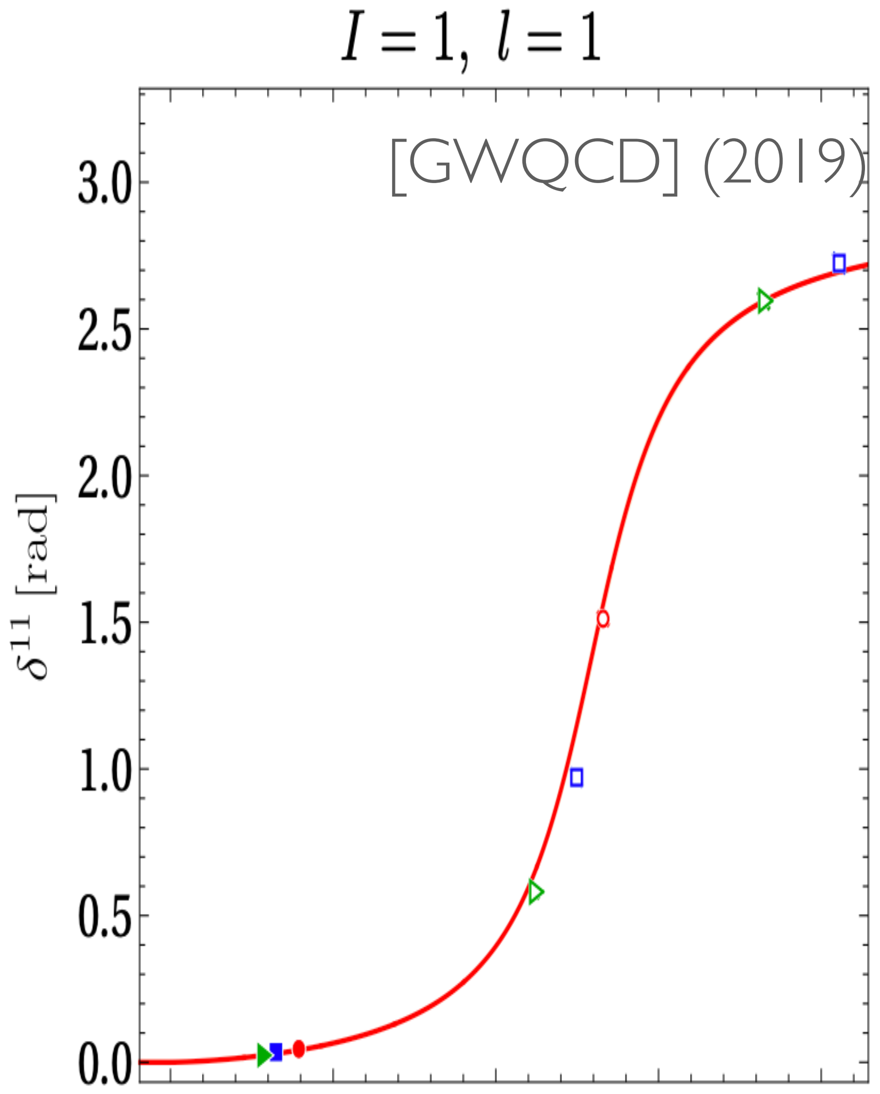


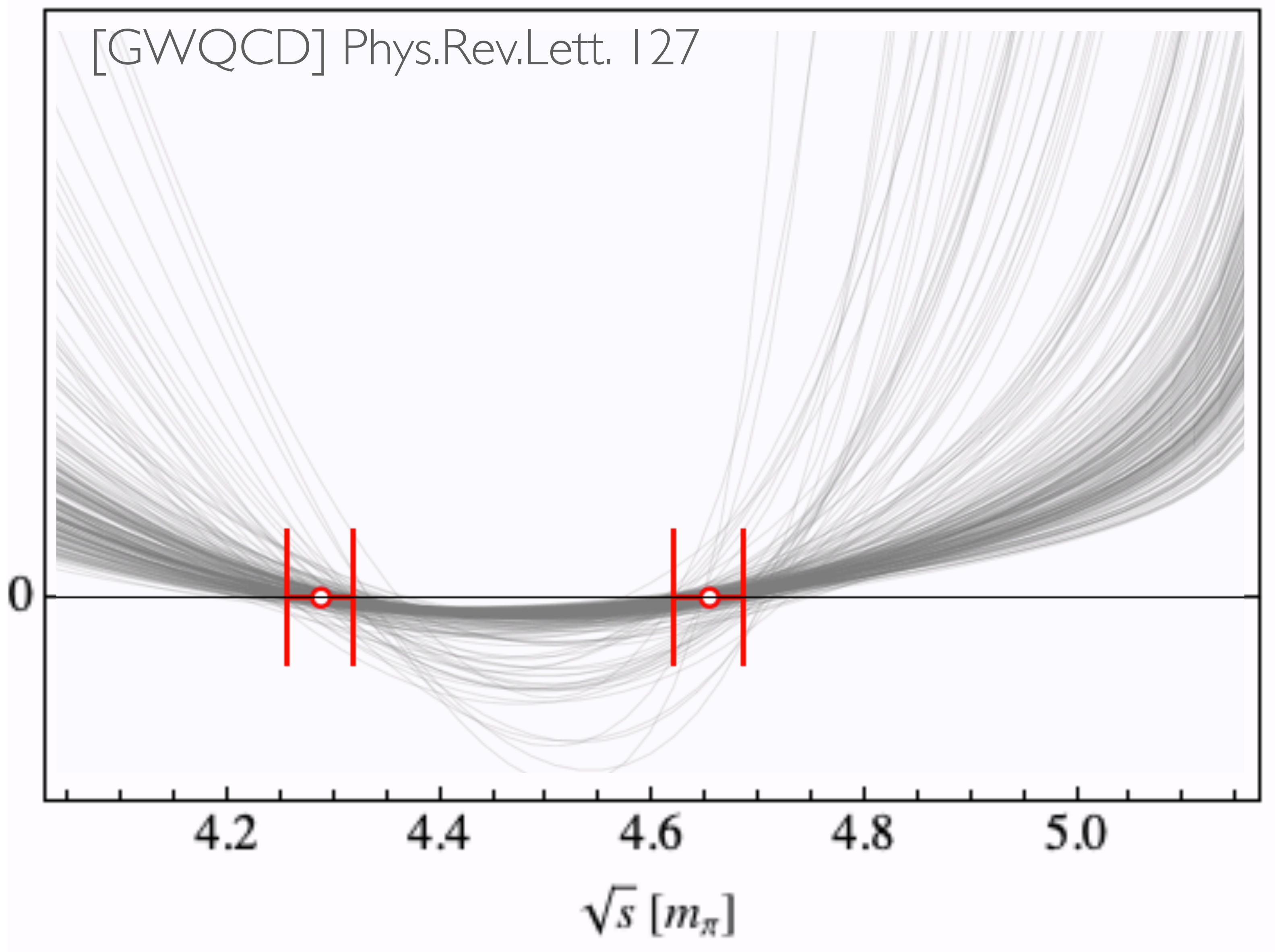


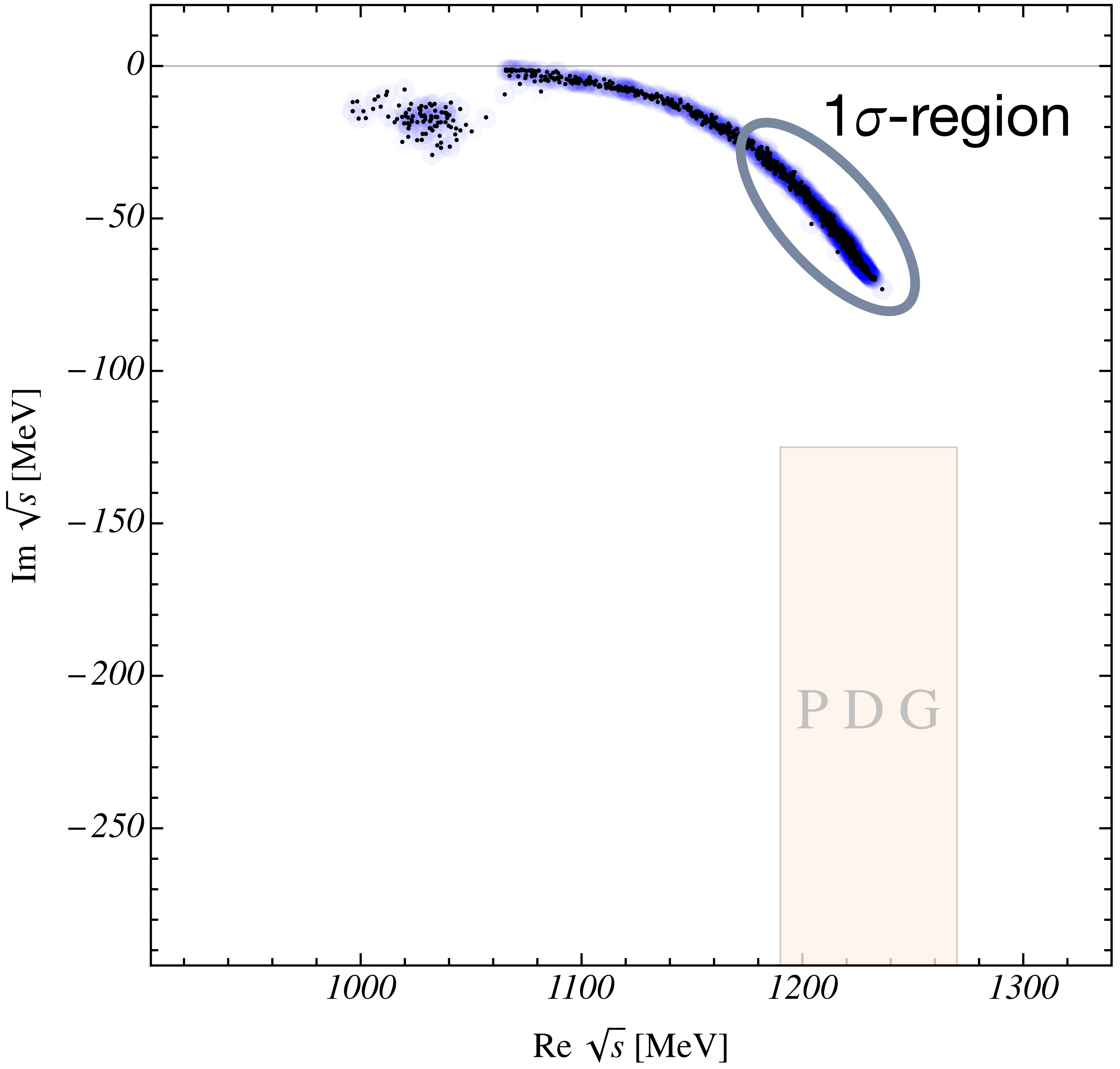
1) MM/Culver/Döring/Alexandru/Lee/Brett/Sadasivan [GWQCD] Phys.Rev.Lett. 127

$$0 = \det\left[2L^3E\left(\tilde{K}_n^{-1} - \Sigma\right) - B - C\right]_{\mathbf{p'p}}$$

$$T^c = B + C + \int \frac{d^3\ell}{(2\pi)^3}\frac{(B+C)}{2E_l}\frac{1}{\tilde{K}_n^{-1}-\Sigma_n}T^c$$







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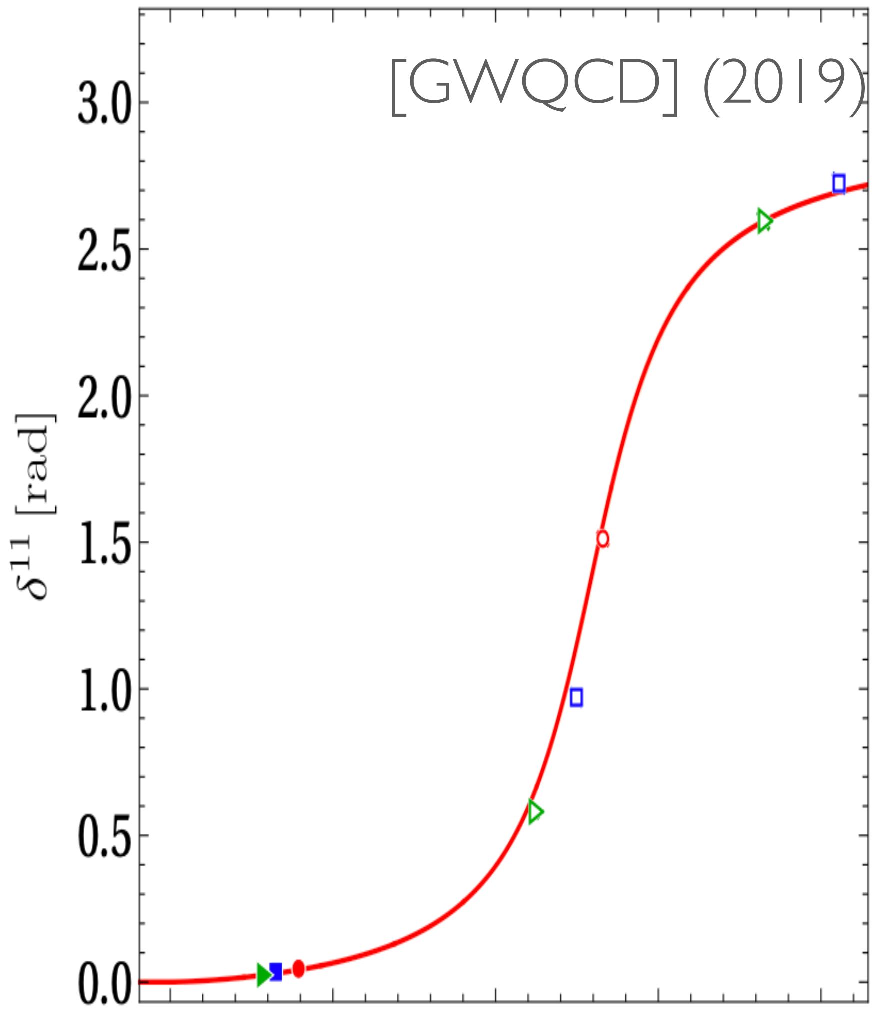
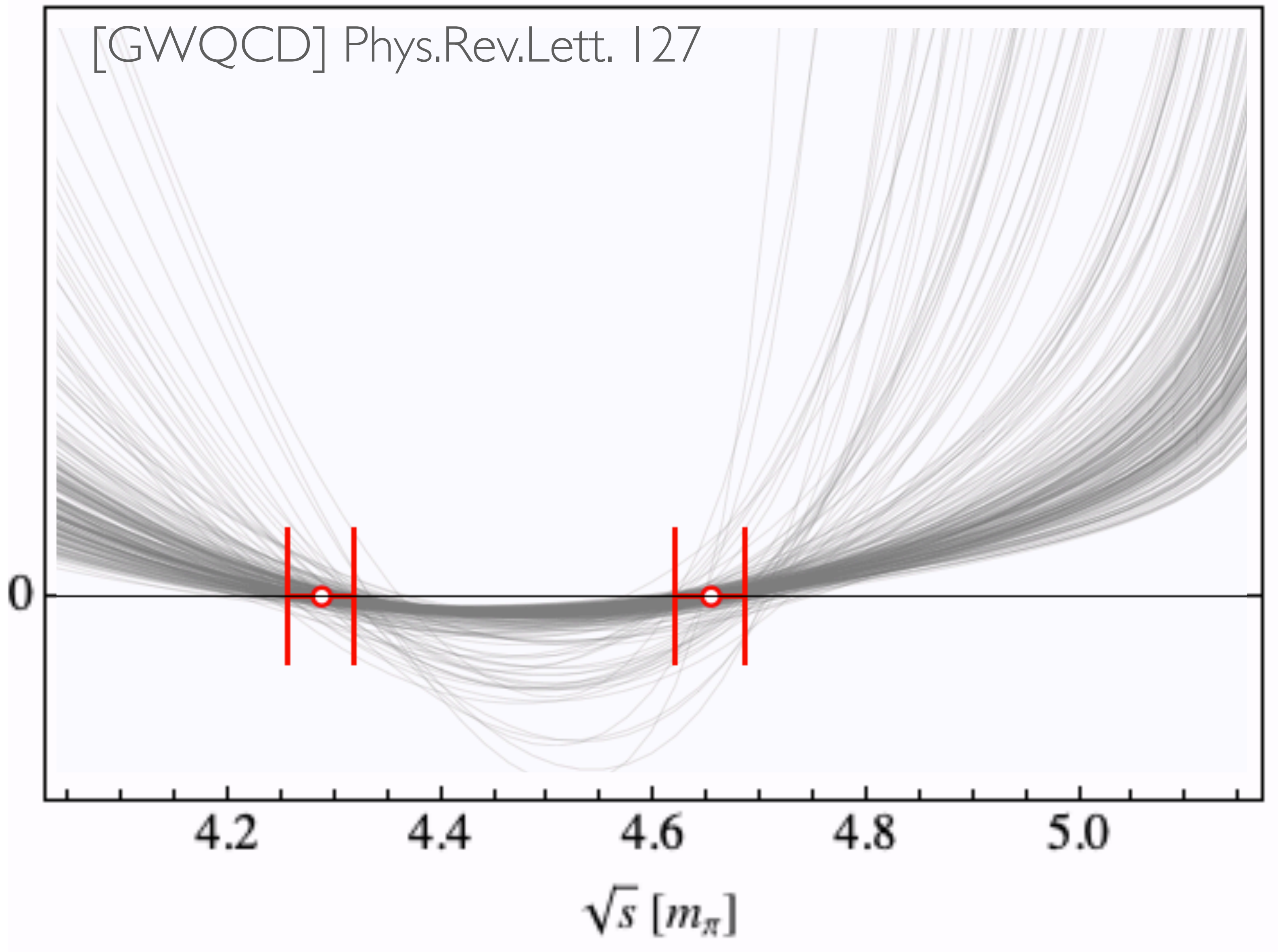
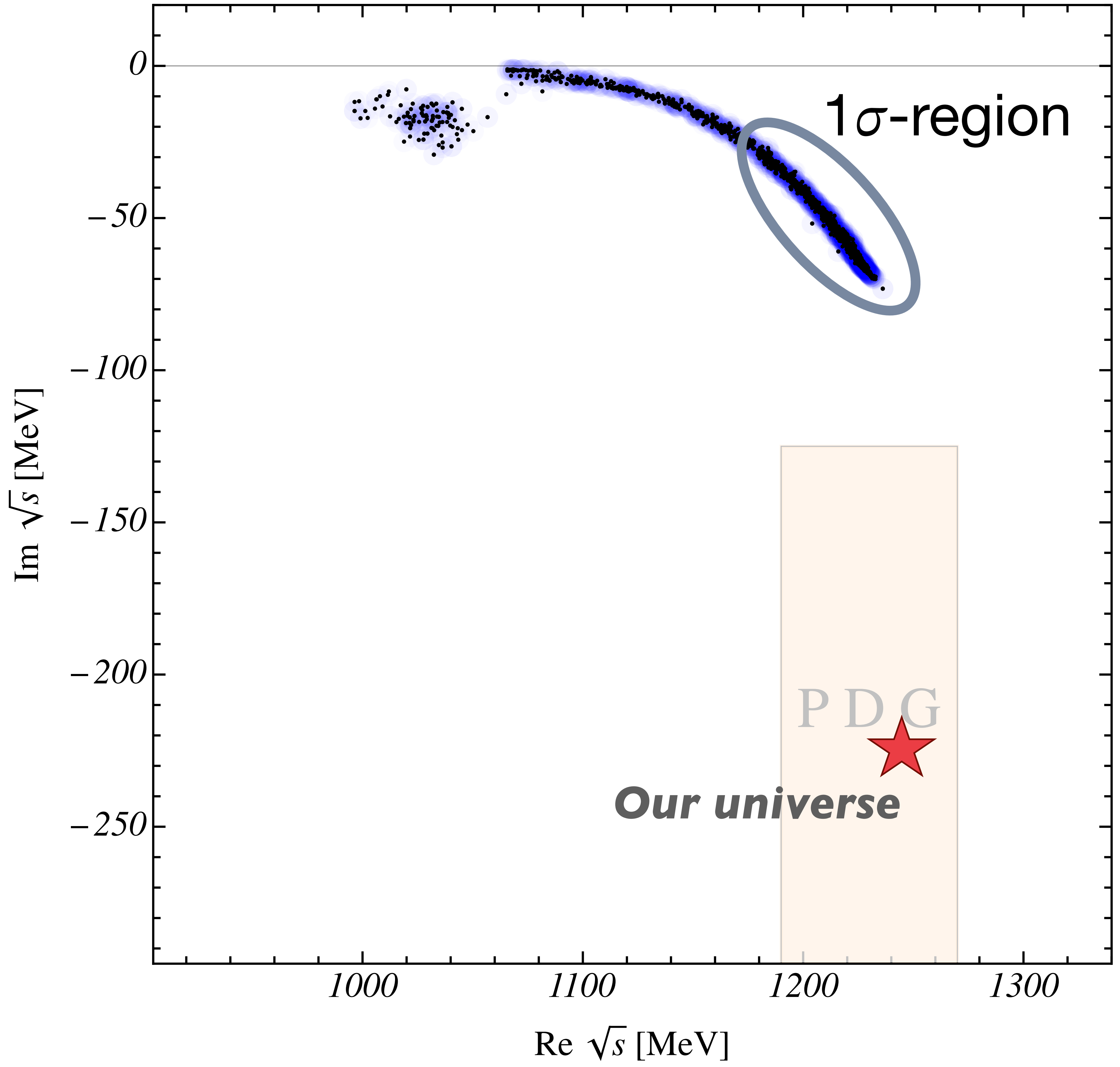
$I = 1,\ l = 1$







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SUMMARY

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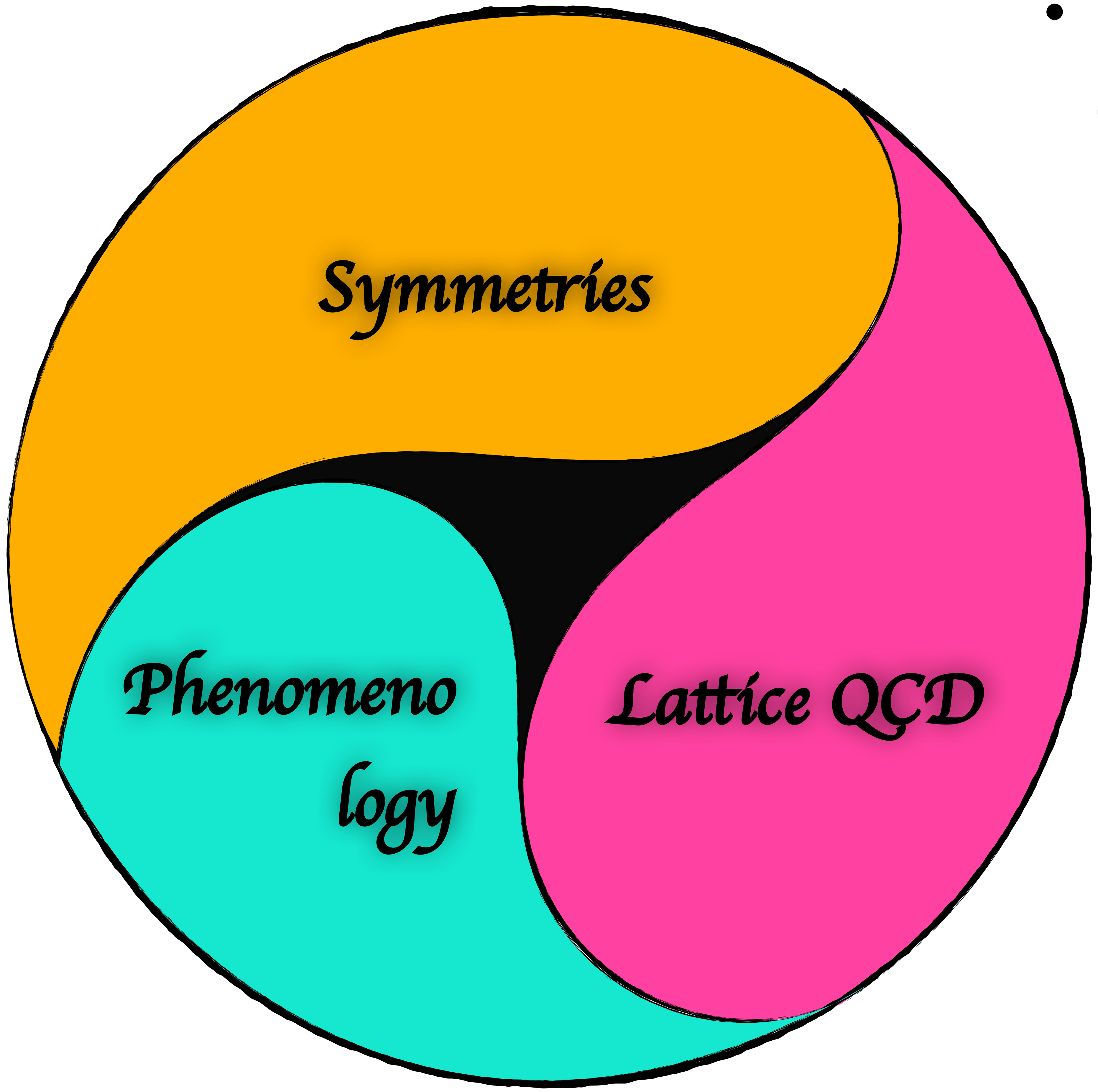

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  - → QCD symmetries constraints to hadron-hadron dynamics
  - → Strong predictive power

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  - → Effective field theories and S-matrix theory provide a bridge to real world physics

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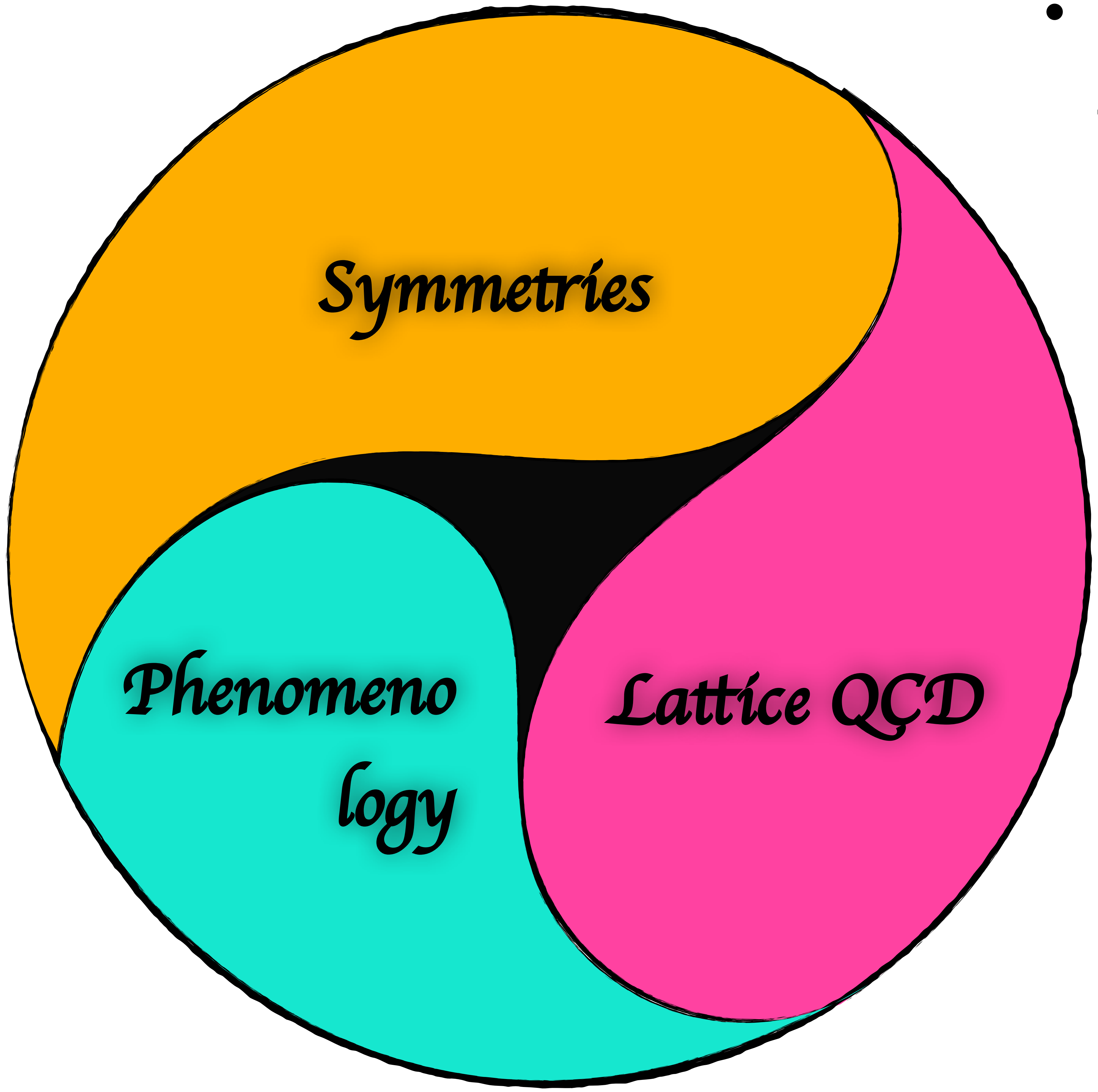

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THANK YOU