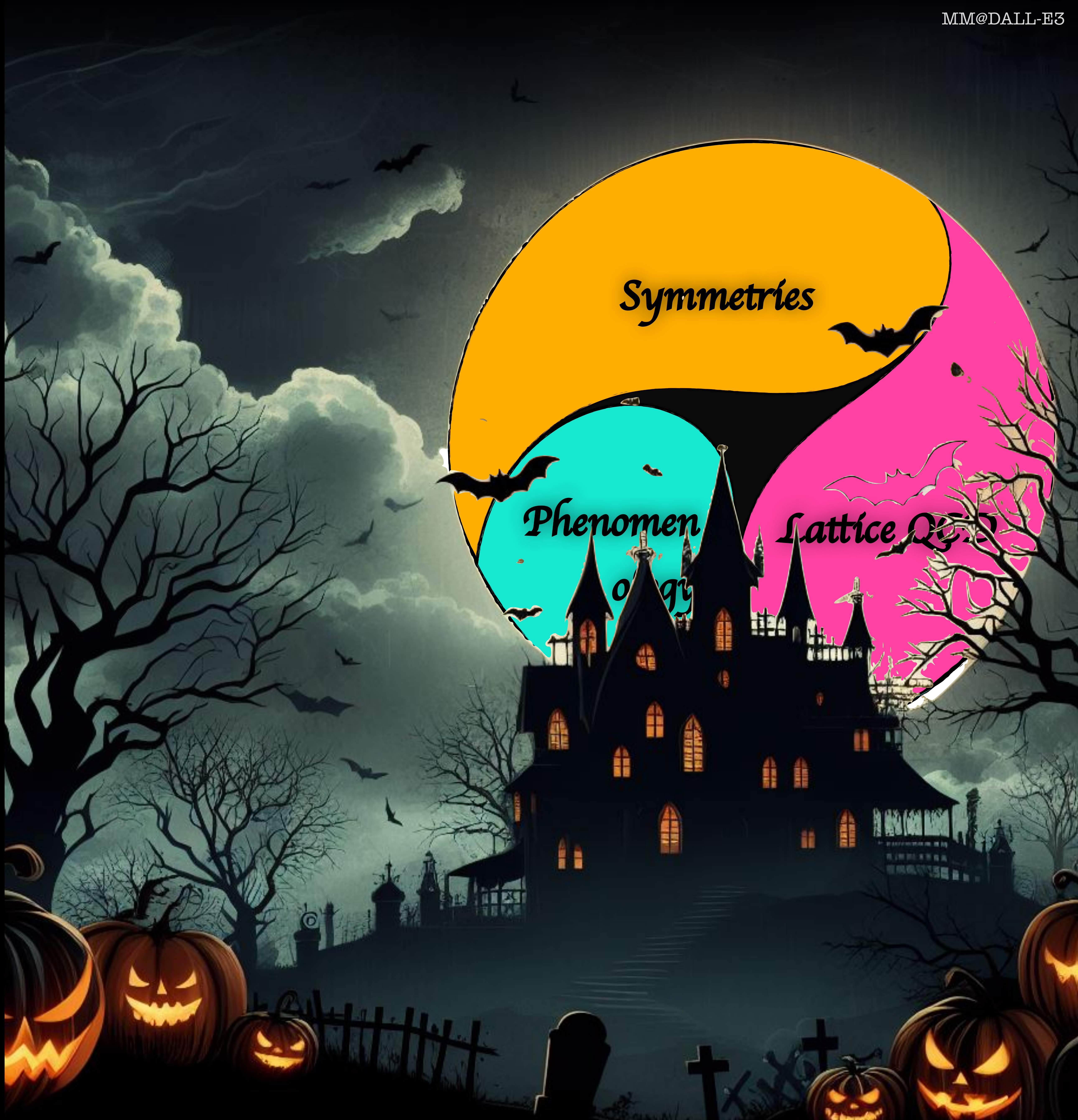
MM@DALL-E3
Symmetries
Phenomen
Lattice

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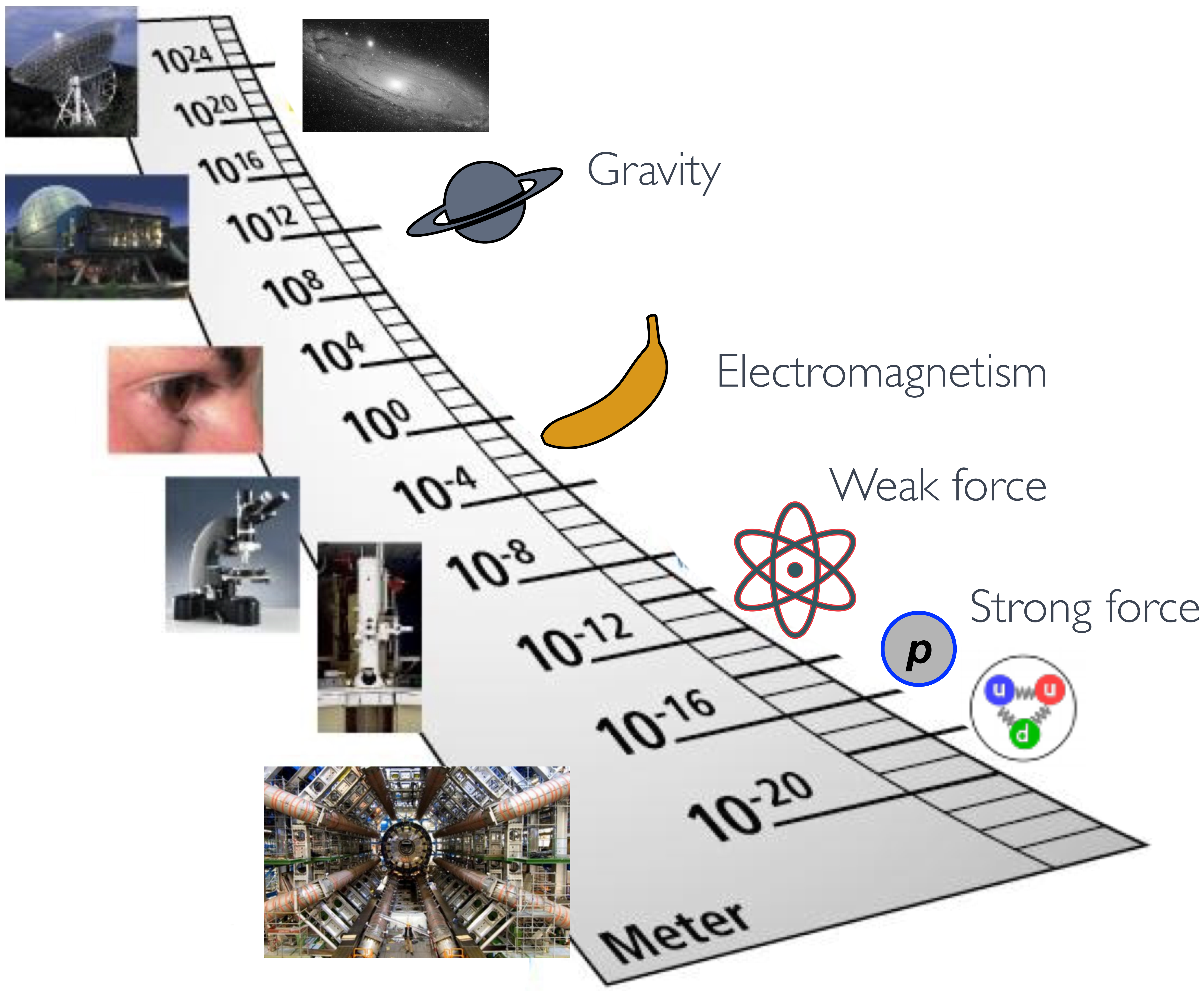
General workflow

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



HISTORICAL EXAMPLE

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

Consciousness causes collapse 1961–1993

Objective-collapse theories 1986–1989

QBism 2010

Many-minds interpretation 1970

Relational interpretation 1994

Consistent histories 1984

Ensemble interpretation 1926

Many-worlds interpretation 1957

Transactional interpretation 1986

Time-symmetric theories 1955

De Broglie–Bohm theory 1927–1952

Copenhagen interpretation 1927

Quantum logic 1936

Quantum mechanics

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

https://en.wikipedia.org/wiki/Interpretations_of_quantum_mechanics

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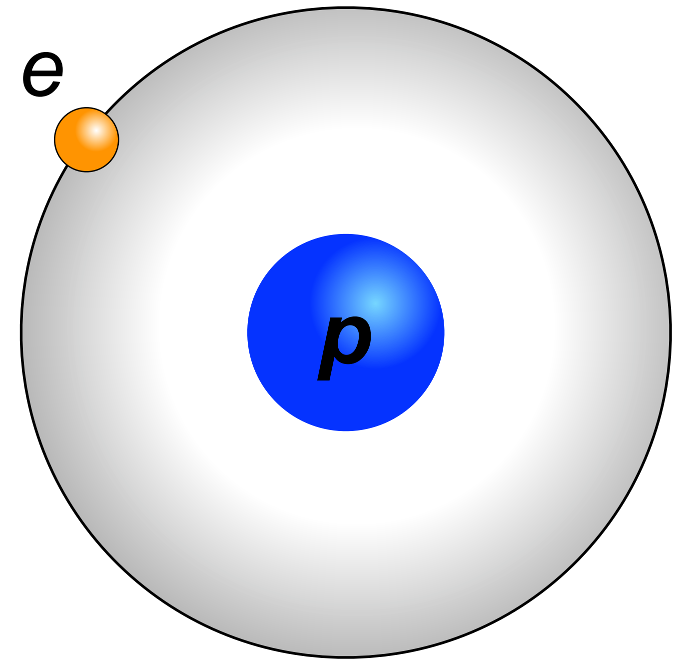
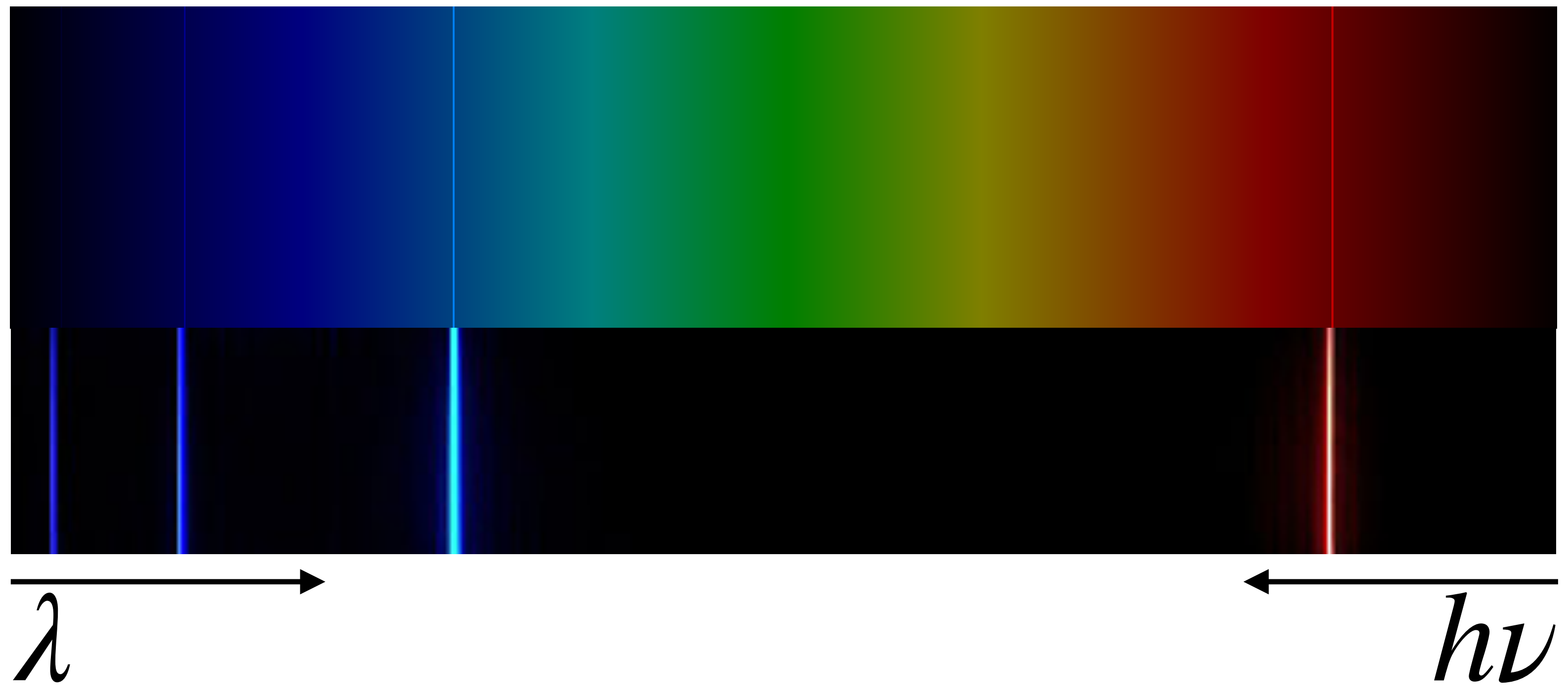
Breakthrough

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





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

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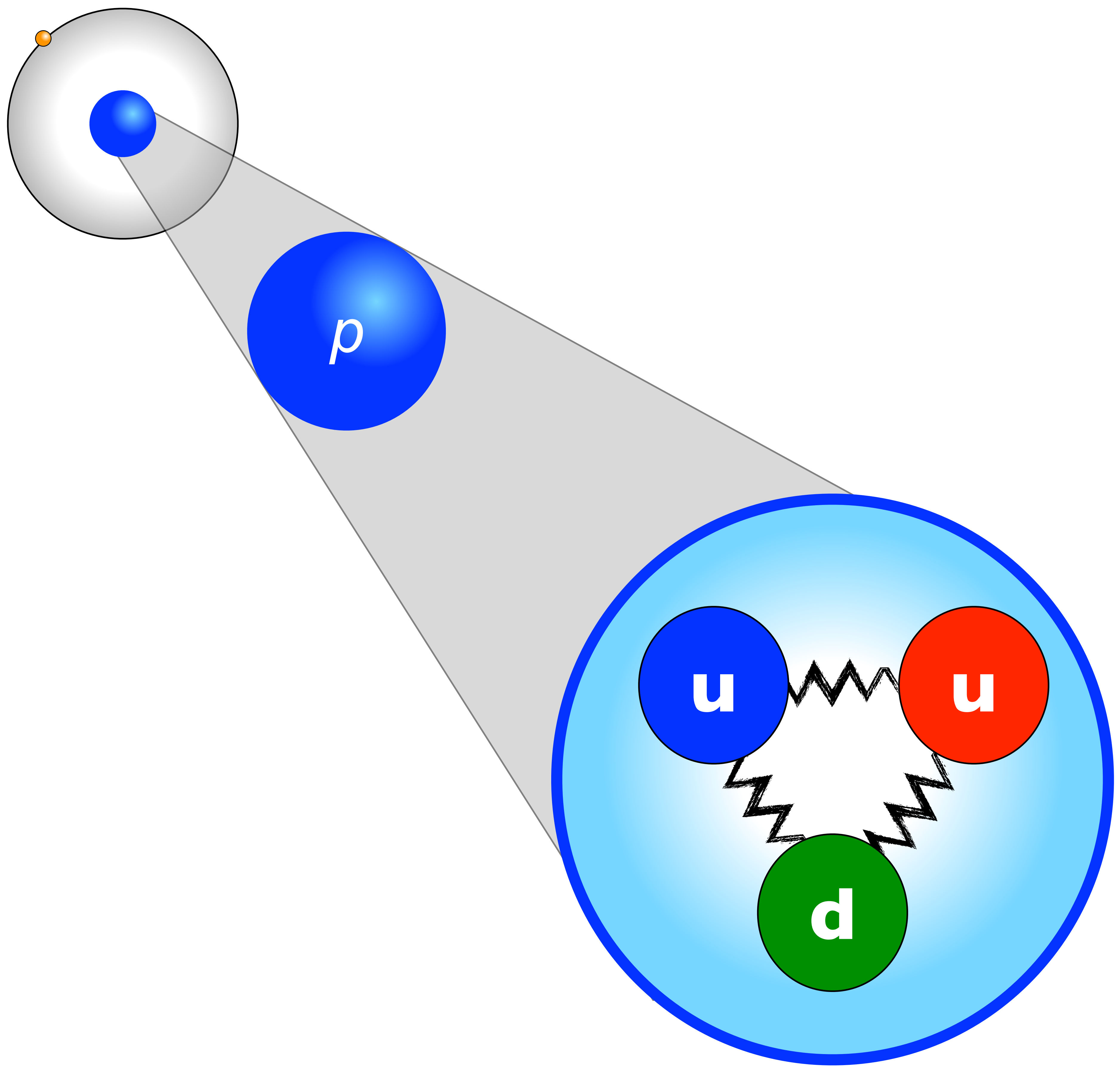

Protons/neutrons

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

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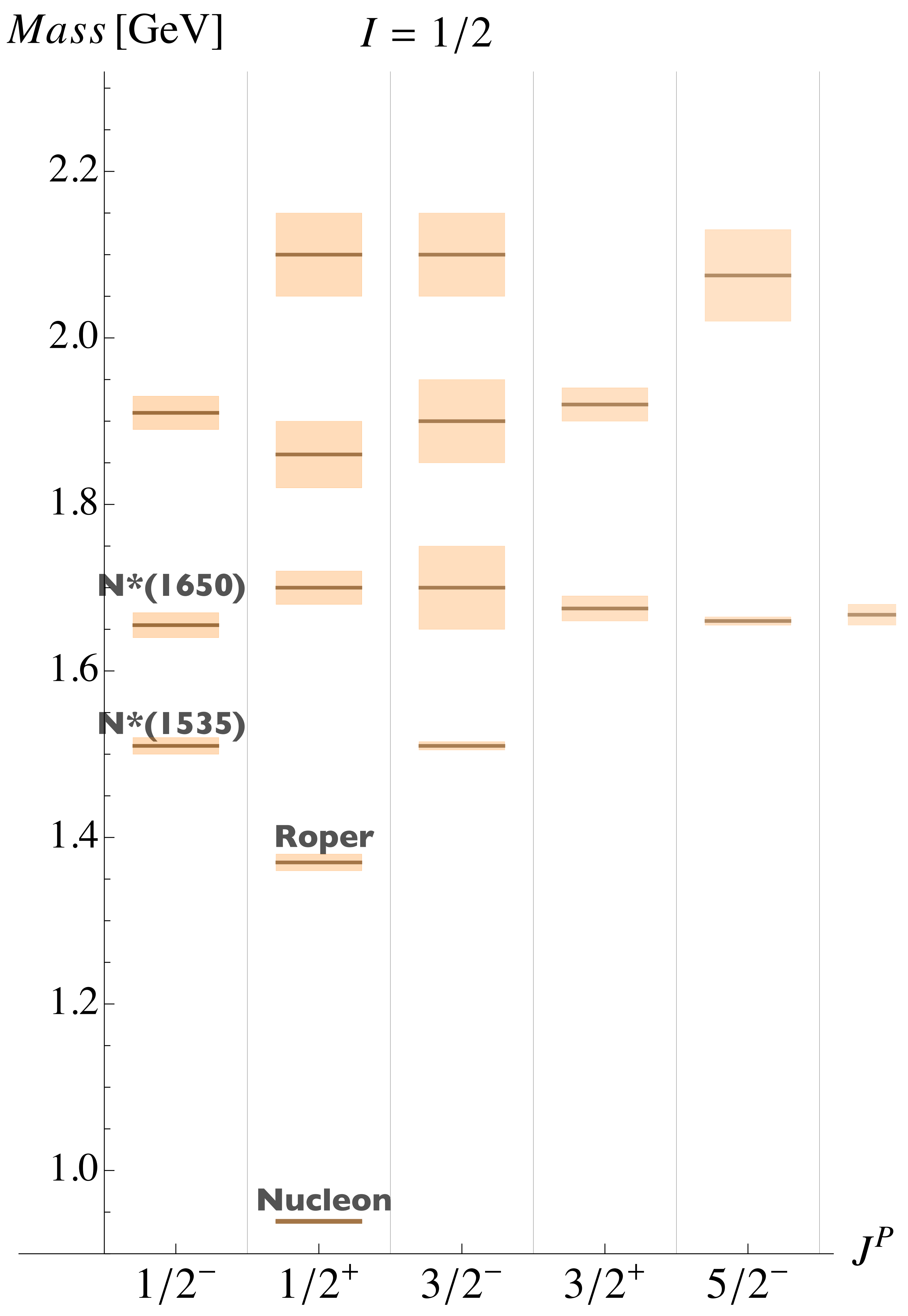
Mostly excited states

≈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)

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

Color index (3 colors)

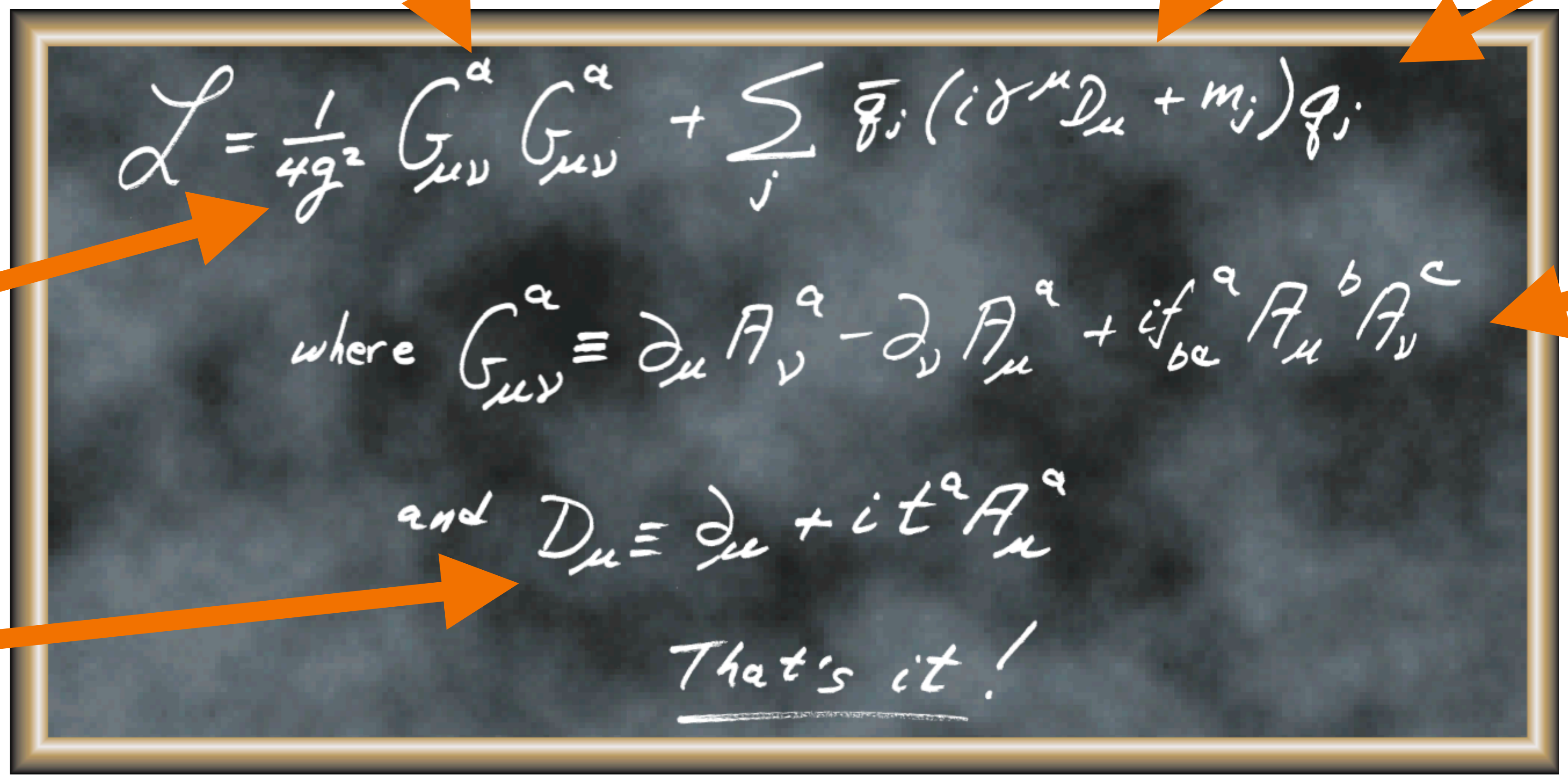
Dirac spin algebra

quarks == Mass fields
(6 flavours)

coupling

gluons == force mediators

Minkowski index
(0,1,2,3)



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

QUANTUM CHROMODYNAMICS

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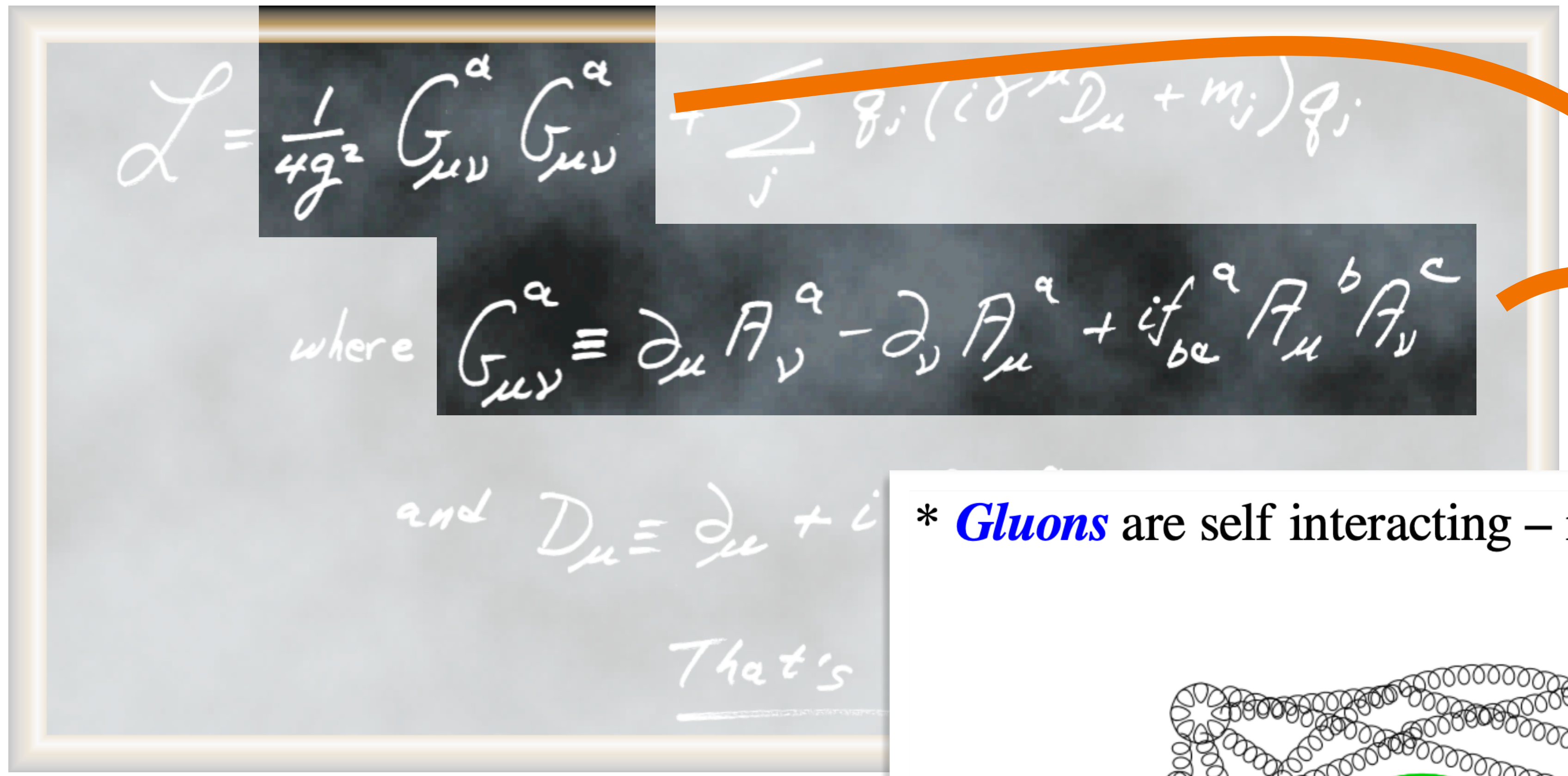
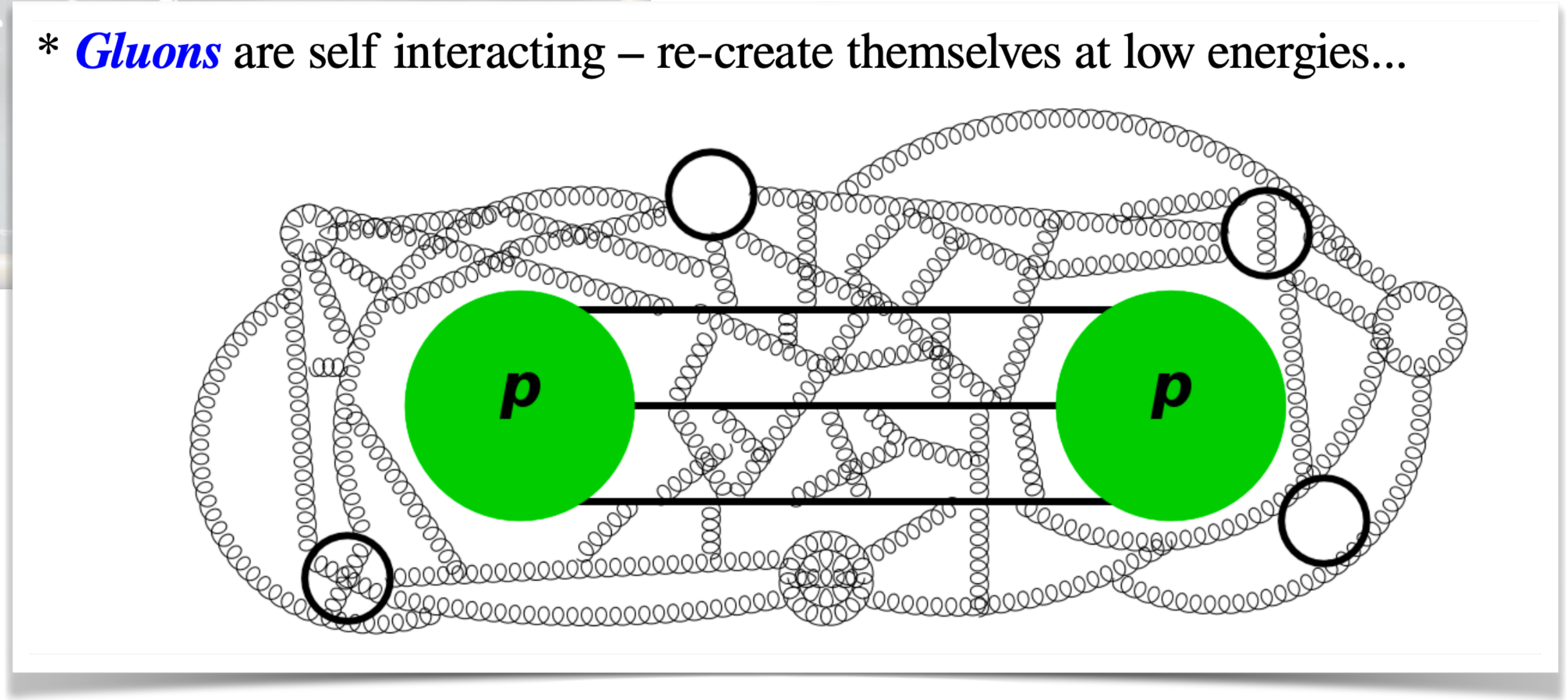
- Compact form, passed all tests so far
- Non-perturbative at low energies





QUANTUM CHROMODYNAMICS

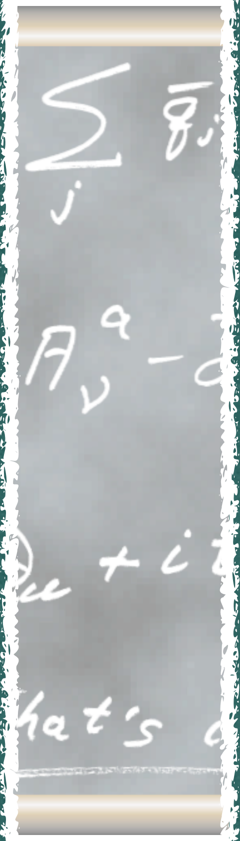
- Compact form, passed all tests so far
- Non-perturbative at low energies
- Systematic approaches to hadron spectroscopy

Lattice QCD

[Wilson (1974) …]

- **ab-initio** numerical calculations of QCD correlation functions through path-integral formalism
- Challenges for comparison to real-world quantities:
  - discretised Euclidean space-time
  - finite volume
  - unphysical quark masses

recall recent seminar talk by M. Döring



Effective Field Theories

[Weinberg (1979) Gasser, Leutwyler (1984) …]

- scale-separation & spontaneous symmetry breaking
- effective degrees of freedom: Goldstone bosons (pseudoscalar mesons)
- Challenges for hadron spectroscopy
  - model-independent but limited to low-energy below resonances
  - extensions to resonance region through S-matrix theory with some model assumptions …

… this talk

LAMBDA(1405)
THE STORY OF AN UNDEAD STRANGENESS RESONANCE

MM Eur.Phys.J.ST 230 (2021)

MM@DALL-E3[10.2023]

HISTORY

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THEORY

NNLO UCHPT
- 2023 Mohler et al. (LQCD)
- 2022 Sadasivan et al.
- 2022 Lu et al.
- 2019 Anisovich et al.
- 2018 Bayar et al.
- 2018 Revai et al.
- 2018 Sadasivan et al

Lattice QCD

Production amplitudes
- 2016 Cieply et al.
- 2015 Hall et al. (LQCD)
- 2014 Mai/Meißner
- 2013 Roca/Oset
- 2013 Guo/Oller
- 2012 Mai/Meißner
- 2012 Ikeda/Hyodo/Weise
- 2001 Oller/Meißner

UCHPT
- 1998 Oset/Ramos

Baryon ChPT
- 1995 Kaiser et al.

ChPT
- 1985 Veitand et al.

Quark model
- 1978 Isgur Karl
- 1960 Dalitz/Tuan
- 1959 Dalitz/Tuan

EXPERIMENT

- Klong 20xx — Kaon beam
- SIDDHARTA2 20xx — Kaonic Deuterium
- AMADEUS 2022 — K- absorption
- AMADEUS 2018 — in-flight capture on He4
- CLAS 2015 — Photoproduction
- HADES 2013 — pp collisions
- SIDDHARTA 2011 — Kaonic Hydrogen
- COSY 2008
- Hemingway 1985 — Sequential decays
- Rutherford Lab 1980s
- ...
- LNL 1960s — Bubble chamber

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BROADER IMPACT

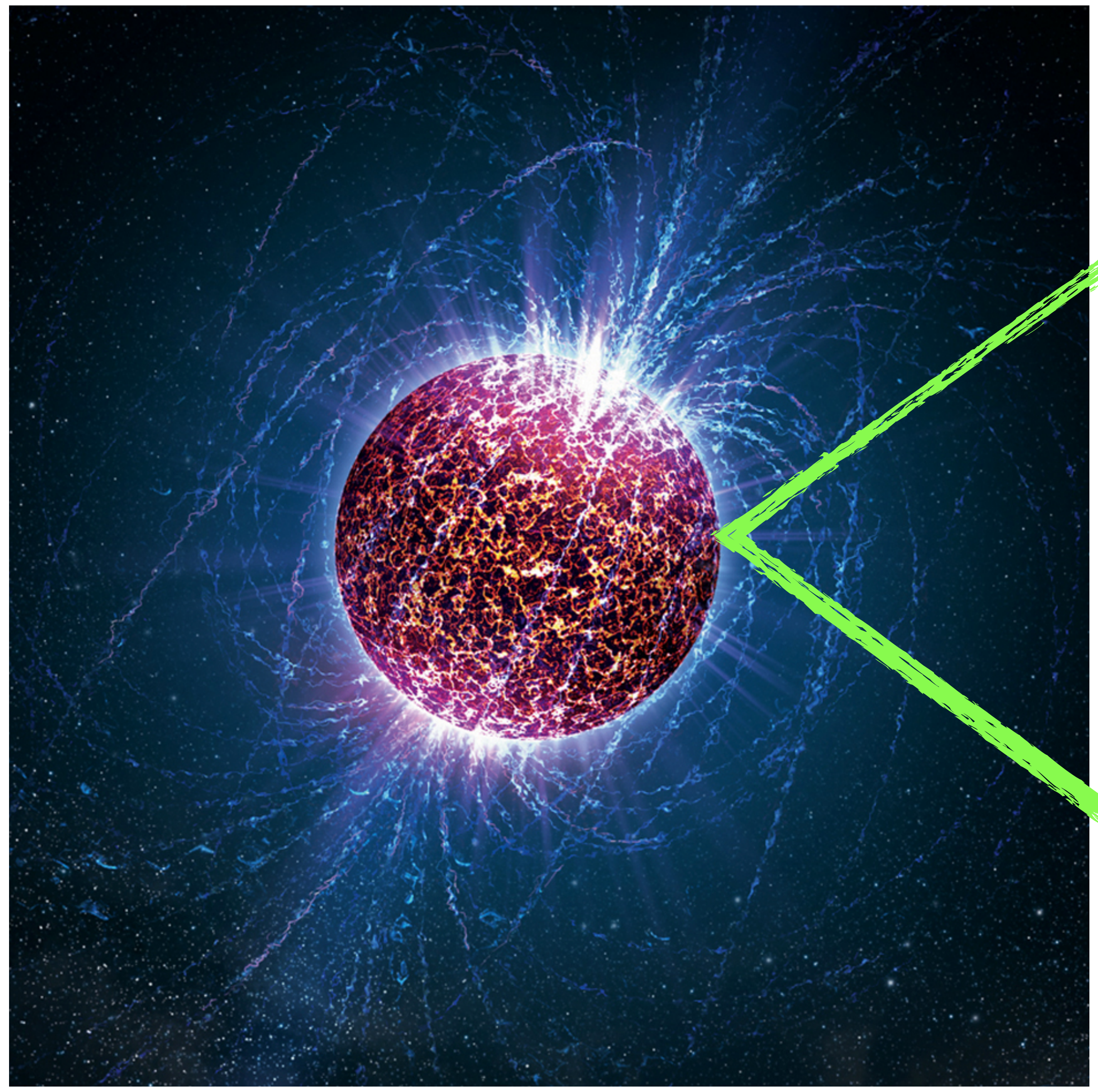
Litmus test for theoretical tools

- Twice non-perturbative regime of QCD
  - too low for perturbative QCD
  - too high for low-energy EFT

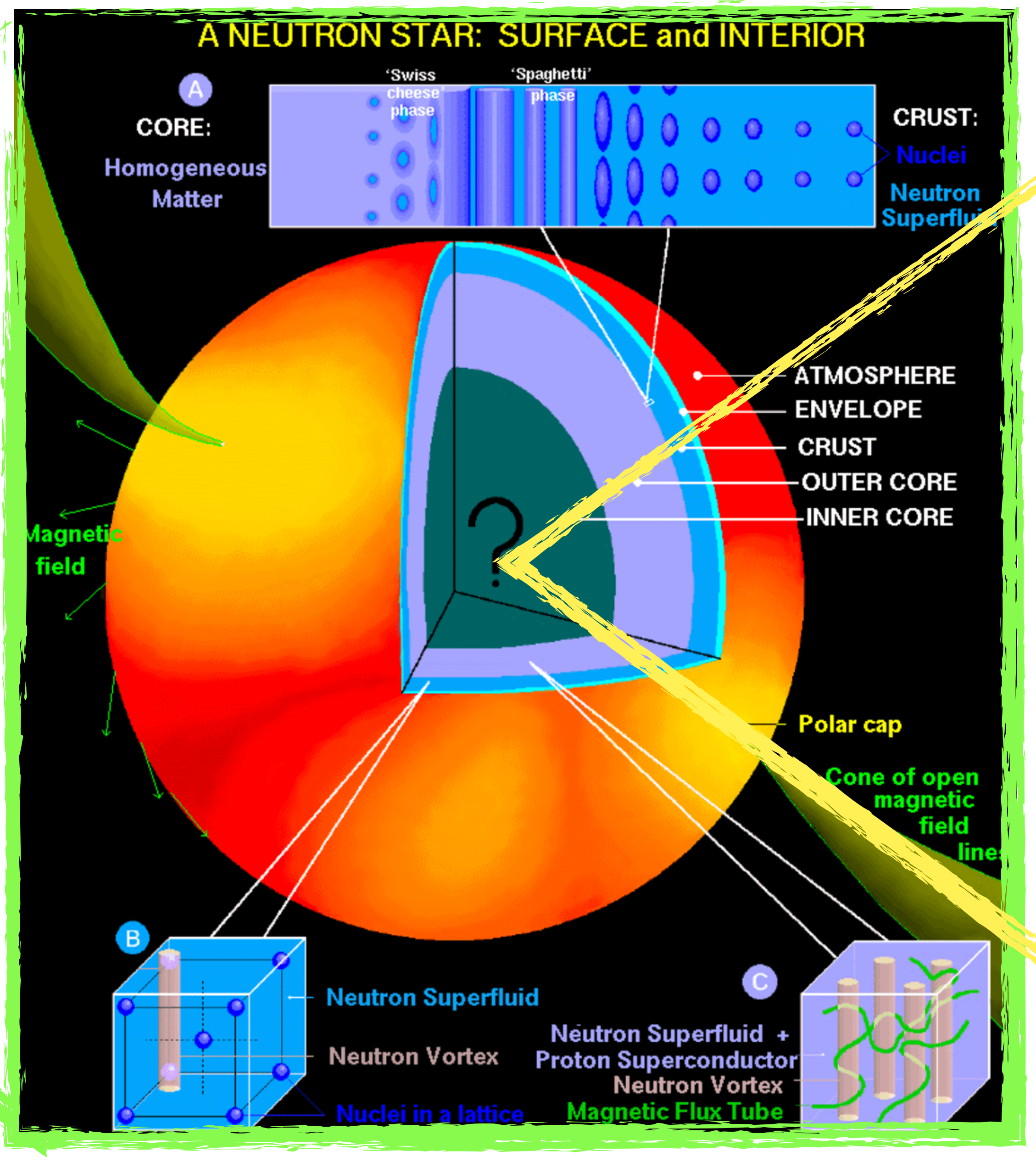
Reviews:
Meißner, Symmetry 12 (2020);
MM Eur.Phys.J.ST 230 (2021);
Hyodo/Niiyama Prog.Part.Nucl.Phys. 120 (2021)

Antikaons in nuclear medium

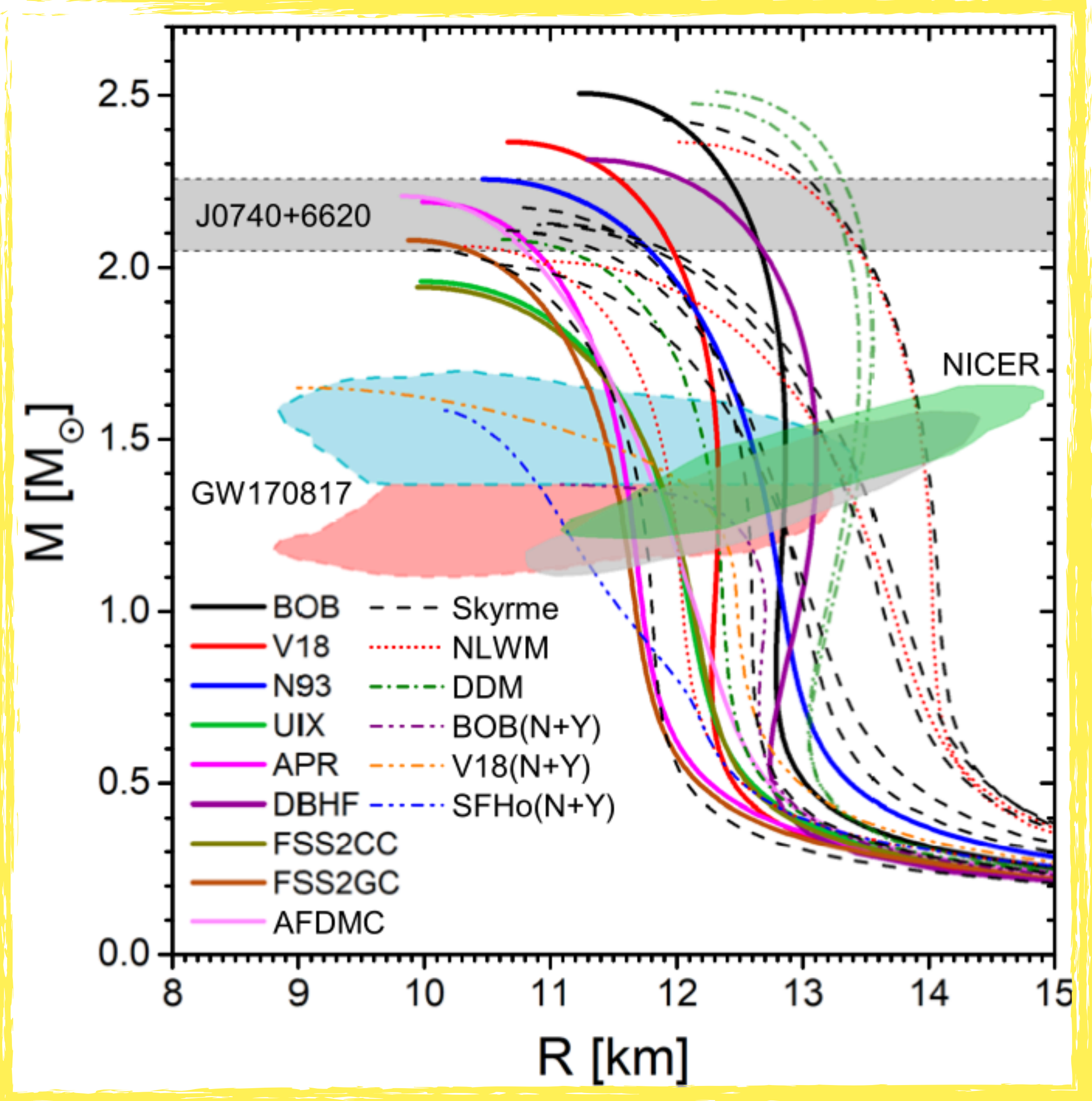
- KbarNN & KbarNNN bound states
  …KbarN input is critical for interpretation
- Strangeness in the EoS of neutron stars
  …*K*-condensate can change EoS-stiffness



artist view(Casey Reed)



phys.org Dany P Page



Prog.Part.Nucl.Phys. 120 (2021)

UNIVERSAL PARAMETERS

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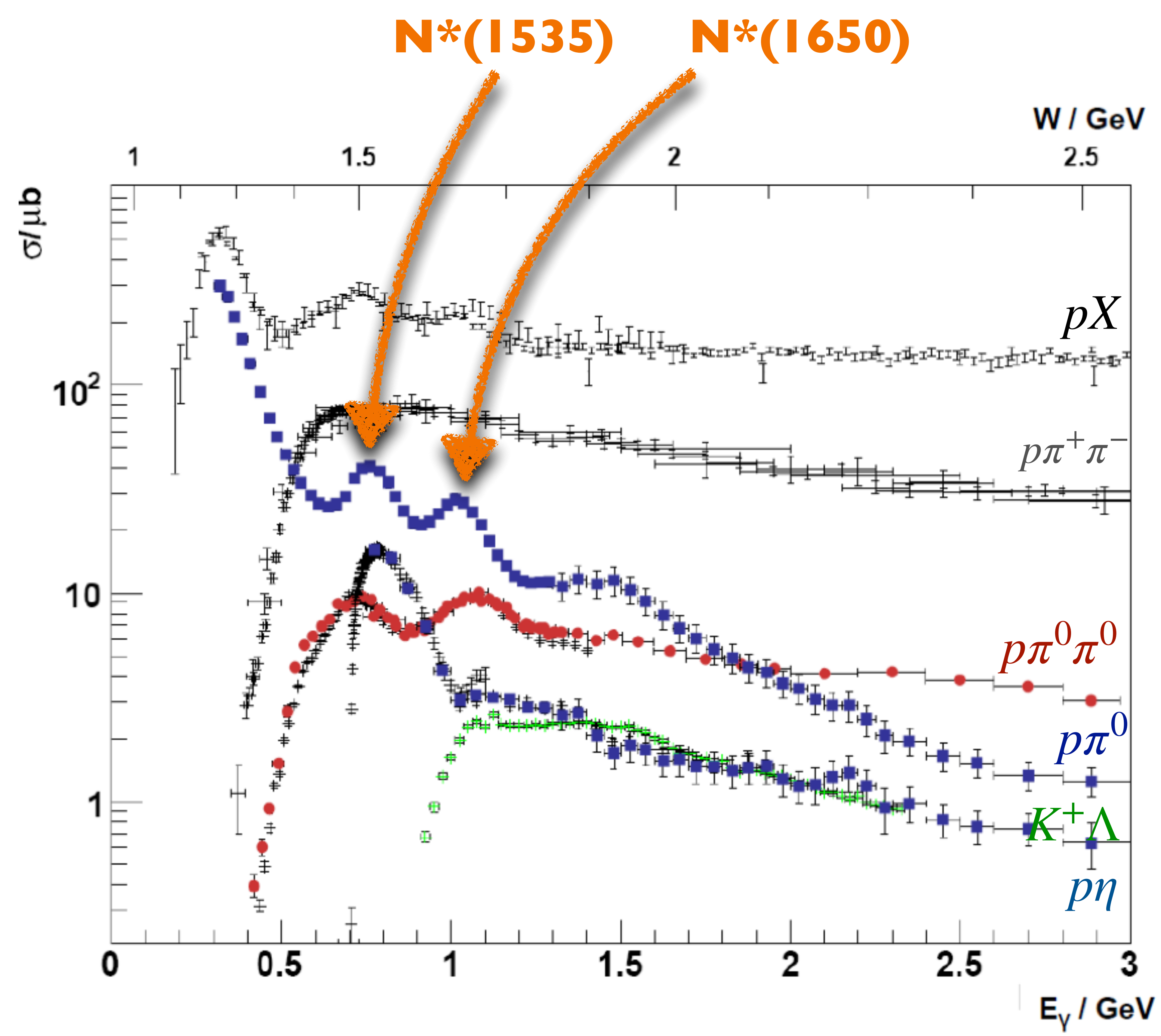
- Resonances can show up as bumps in experimental data

… depends strongly on reaction, background, etc..

can one ever obtain reaction-independent (universal) parameters?



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

UNIVERSAL PARAMETERS

Reaction-independent parameters

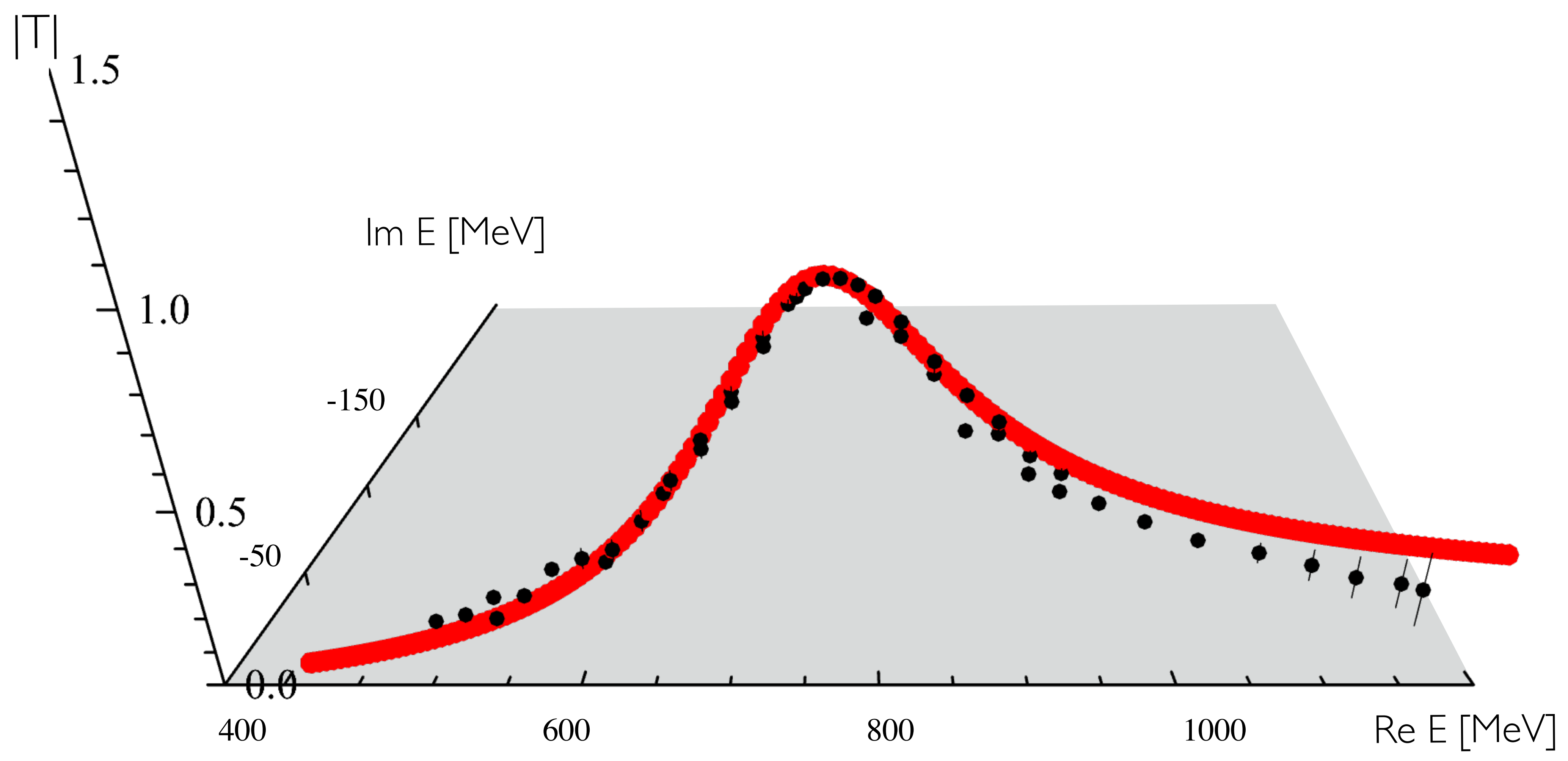
pole positions on unphysical Riemann Sheets

KEY QUANTITY — Transition amplitudes

Constrained by Unitarity/Analyticity/Crossing

Constrained by CHPT/LatticeQCD

Constrained by Observations



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

Reaction-independent parameters

pole positions on unphysical Riemann Sheets

KEY QUANTITY — Transition amplitudes

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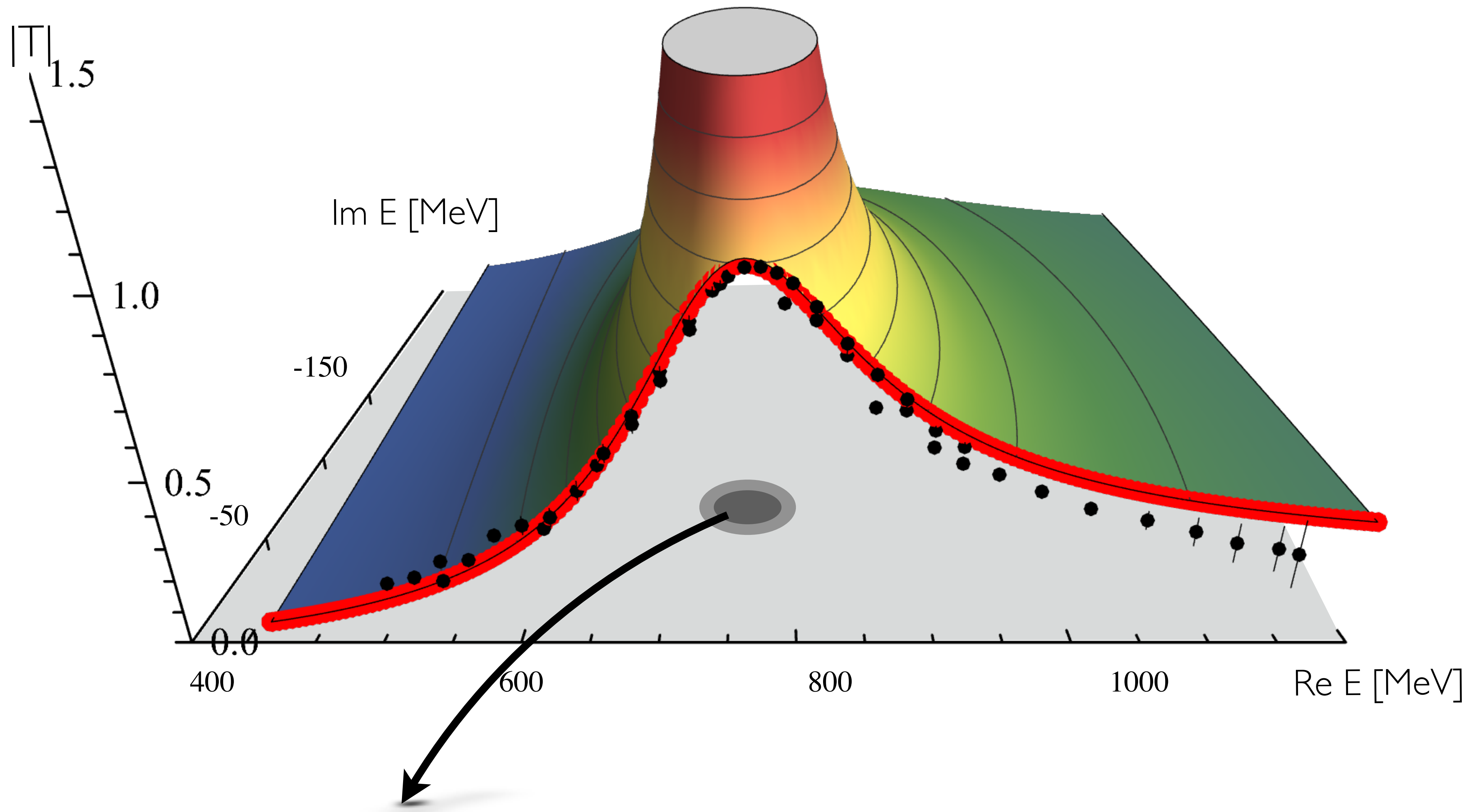


$M^* = (750 - i60)$ MeV

Universal property of the ρ – meson

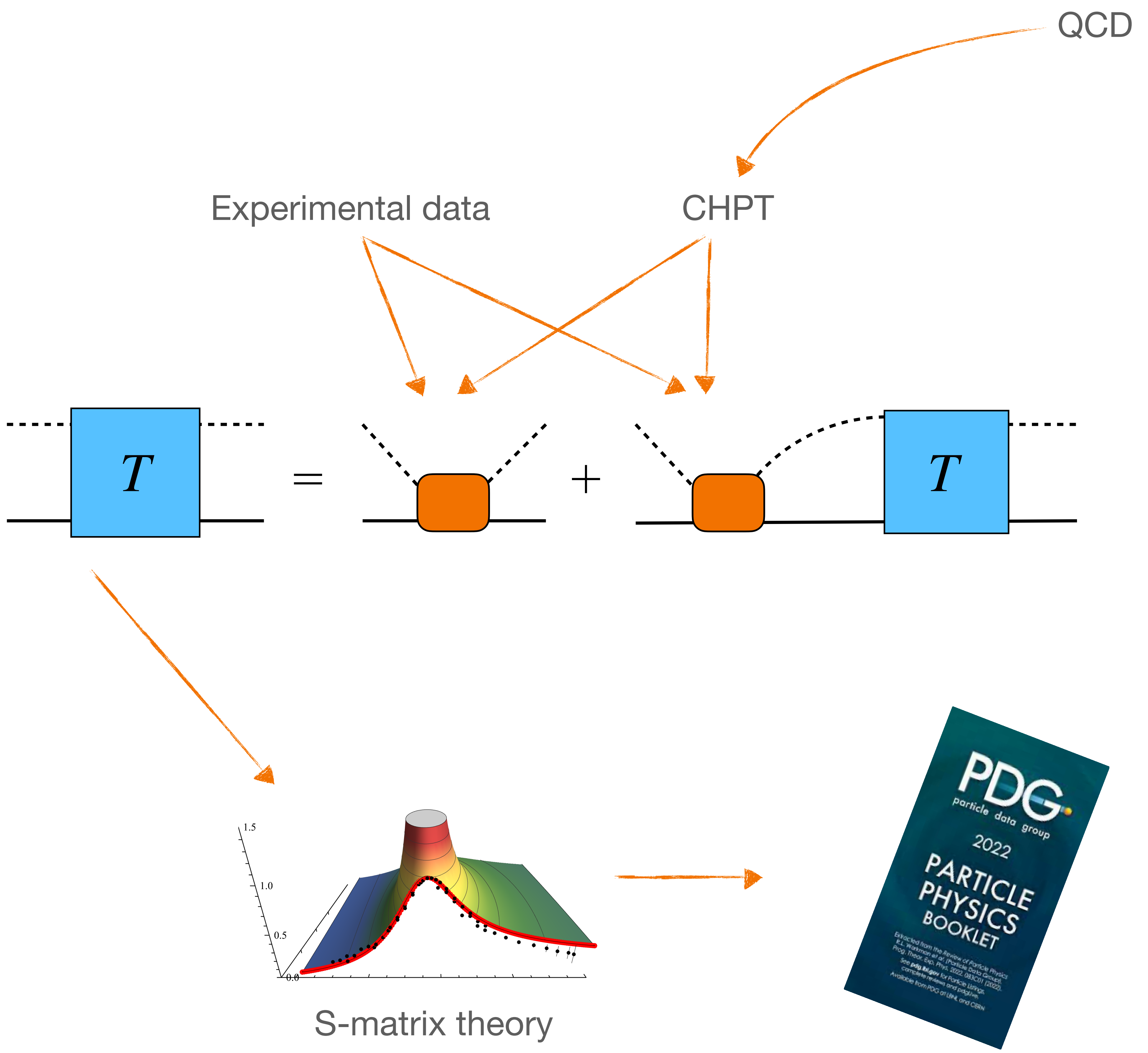
Data: Estabrooks et al. Nucl.Phys.B 79; Protopopescu et al. Phys.Rev.D 7;

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)

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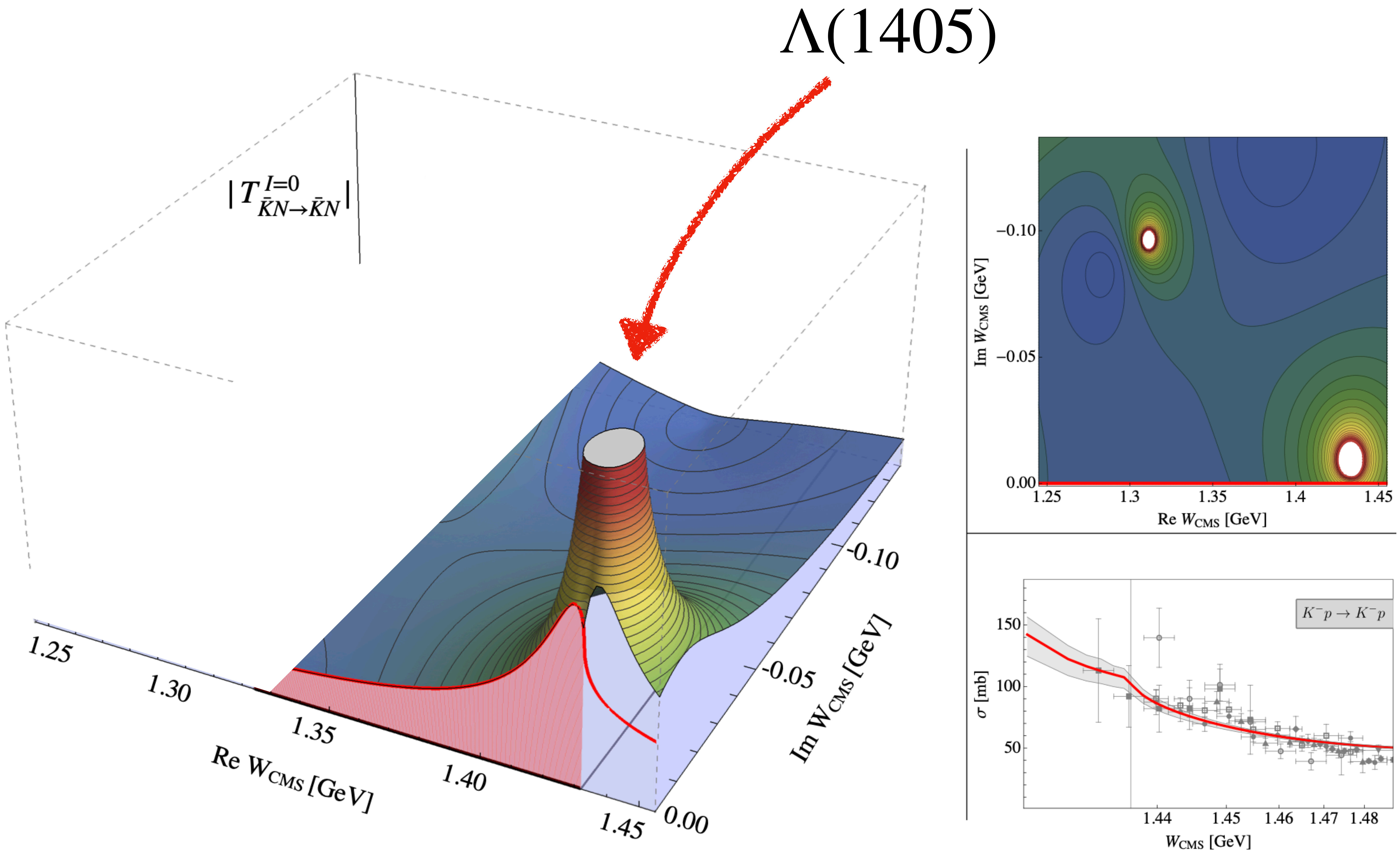
- Narrow pole below KbarN threshold

  W= (1421…1429)-i(10…25) MeV*

… well estimated

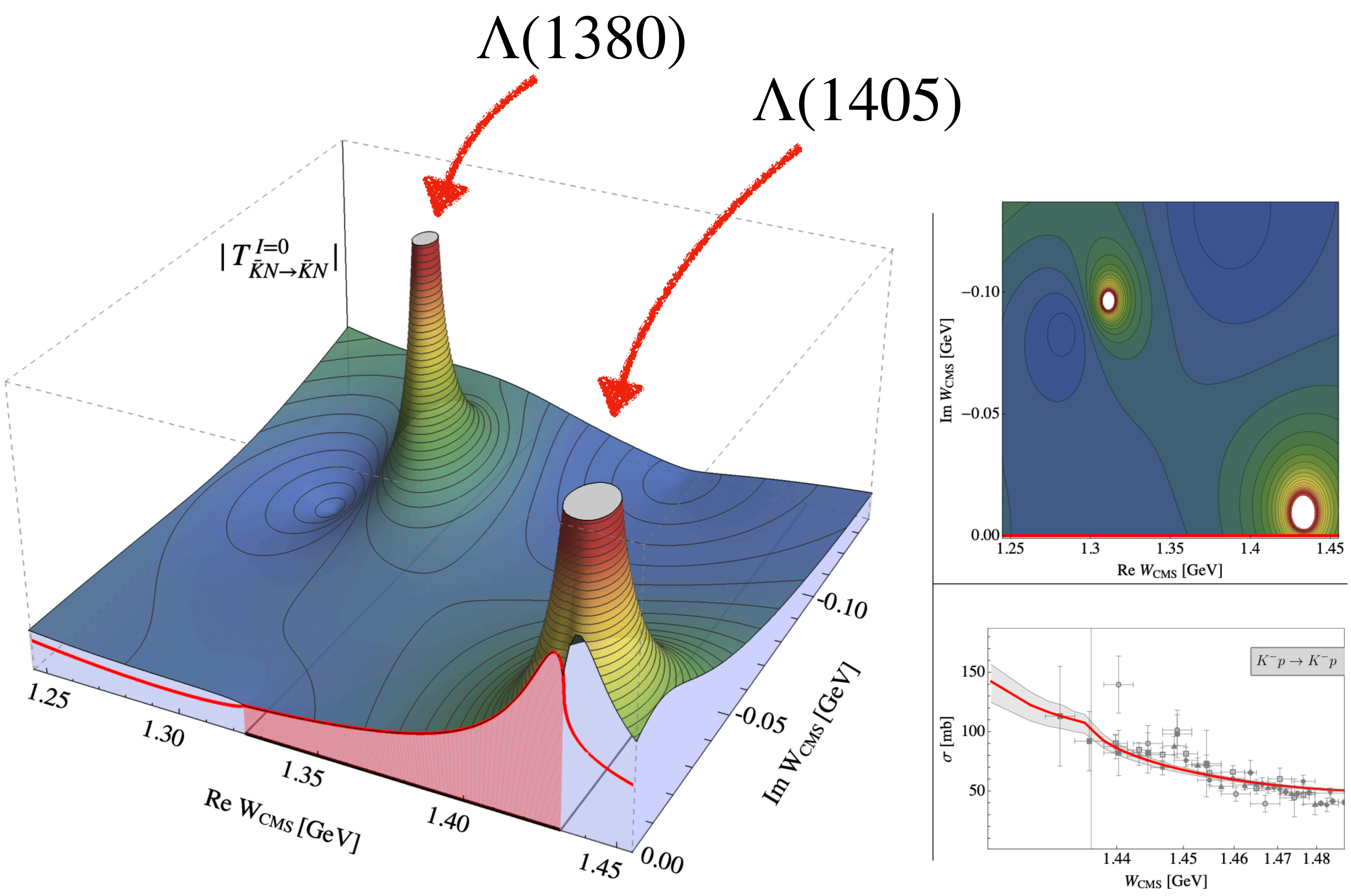


RESONANCE POLE(S)

- 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

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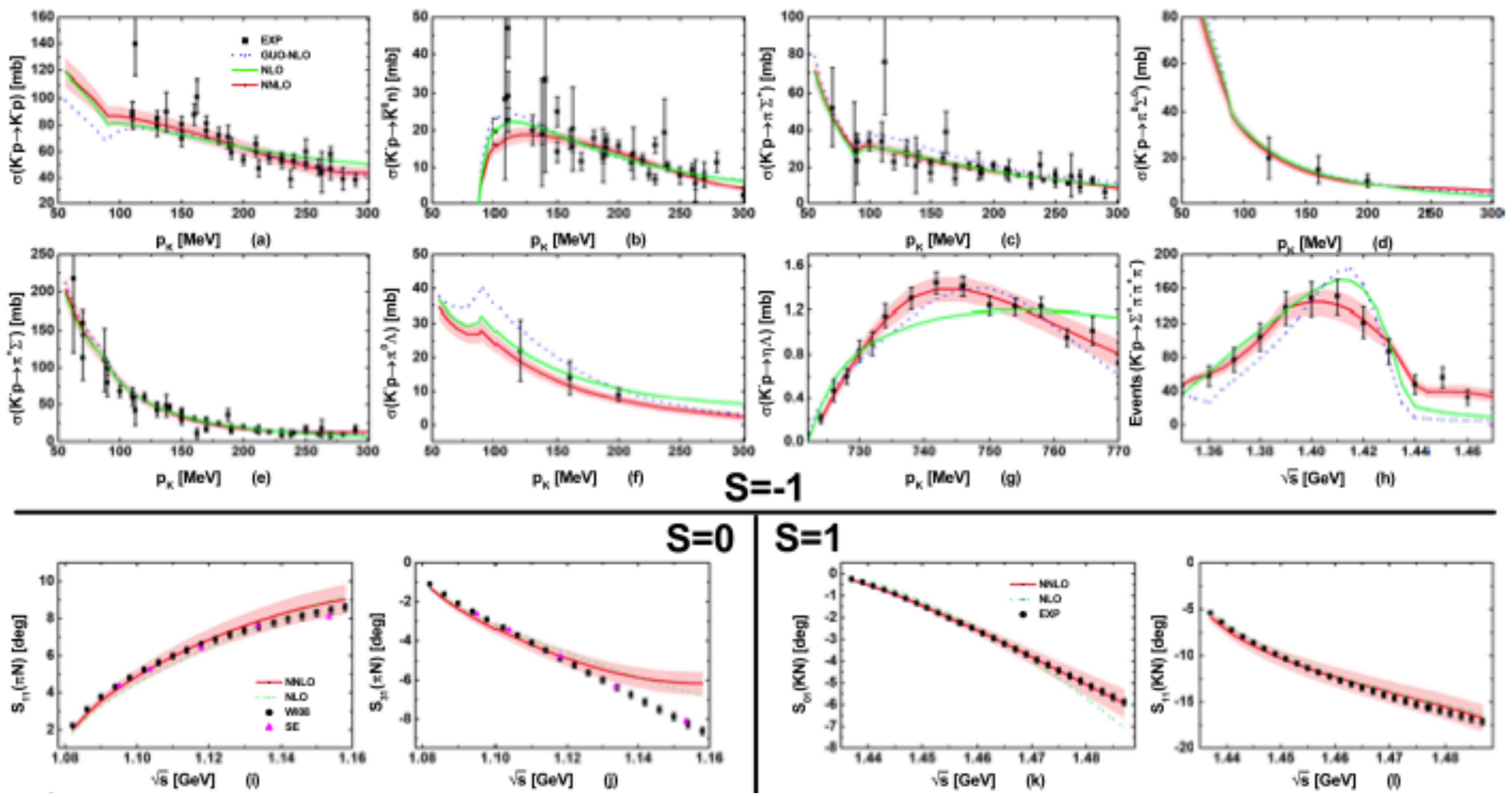
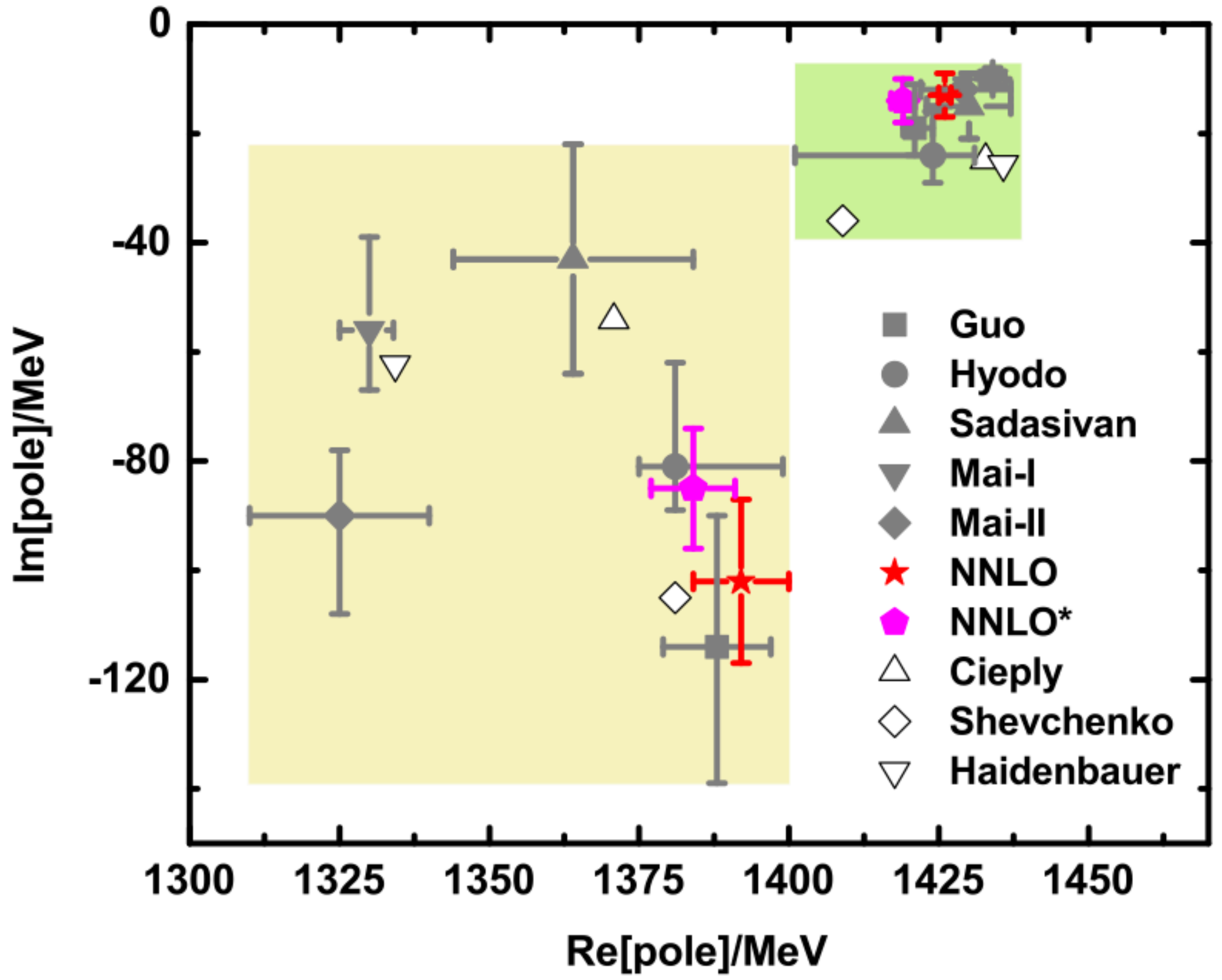


Many tests:

- K+**Σπ** photo-production constraints[1]
- Theory update: NNLO UCHPT[2]

➡ ***two-pole structure prevails***



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)

CURRENT FRONTIER #2

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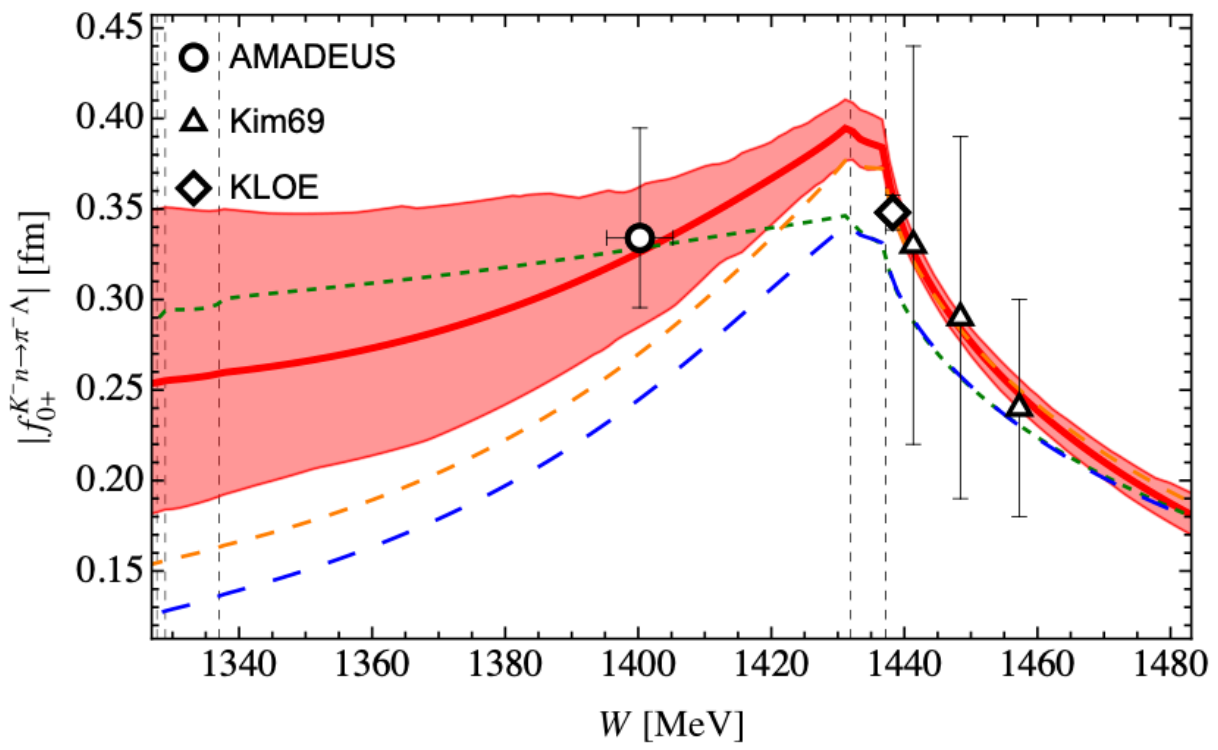
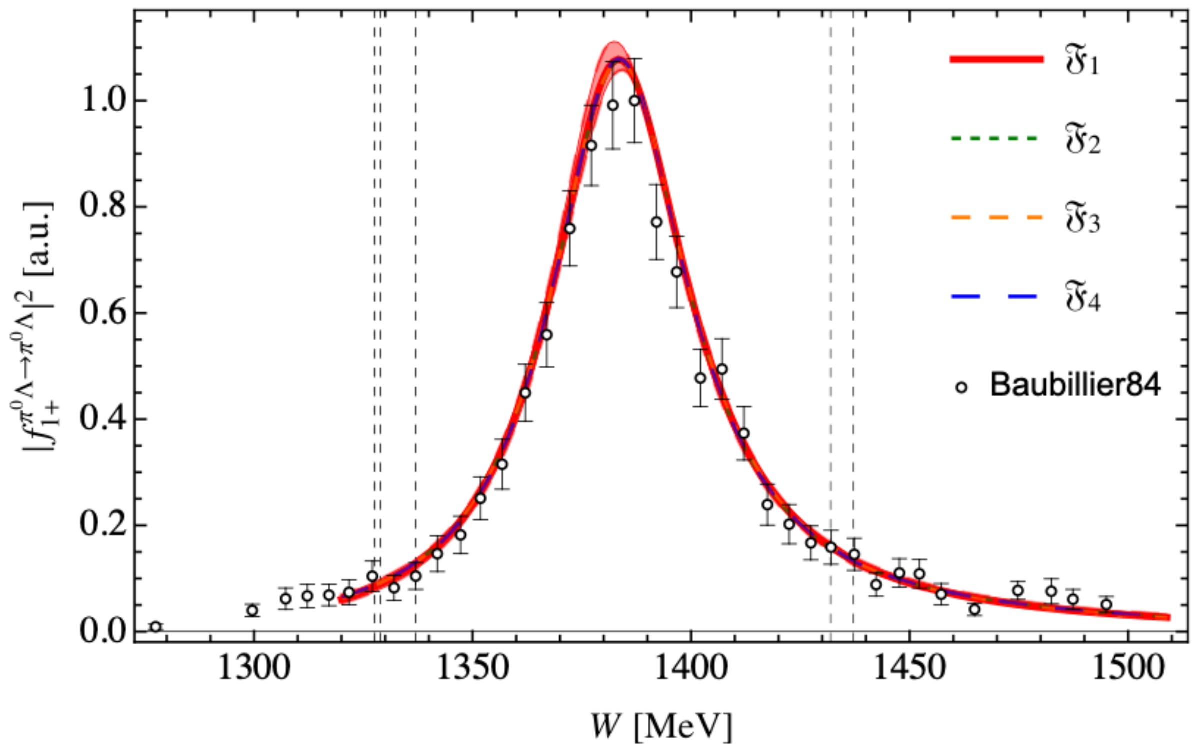


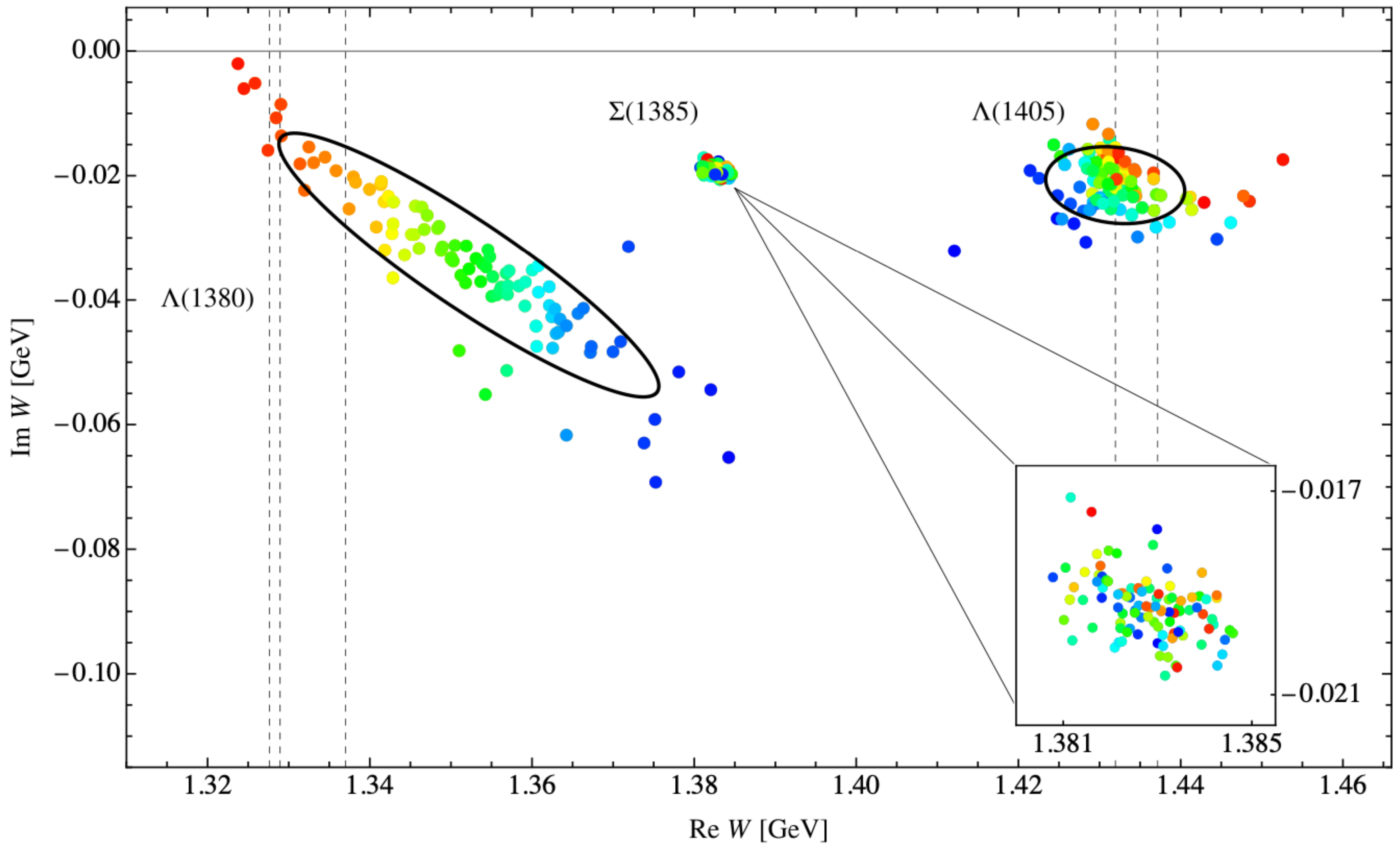


Many tests:

- new data sources[1]
- Higher-partial waves inclusion[2]

➡ ***two-pole structure prevails***

➡ ***cross-correlations uncovered***



1)AMADEUS Phys. Lett. B 782 (2018);
2)Sadasivan et al Front.Phys. 11 (2023)

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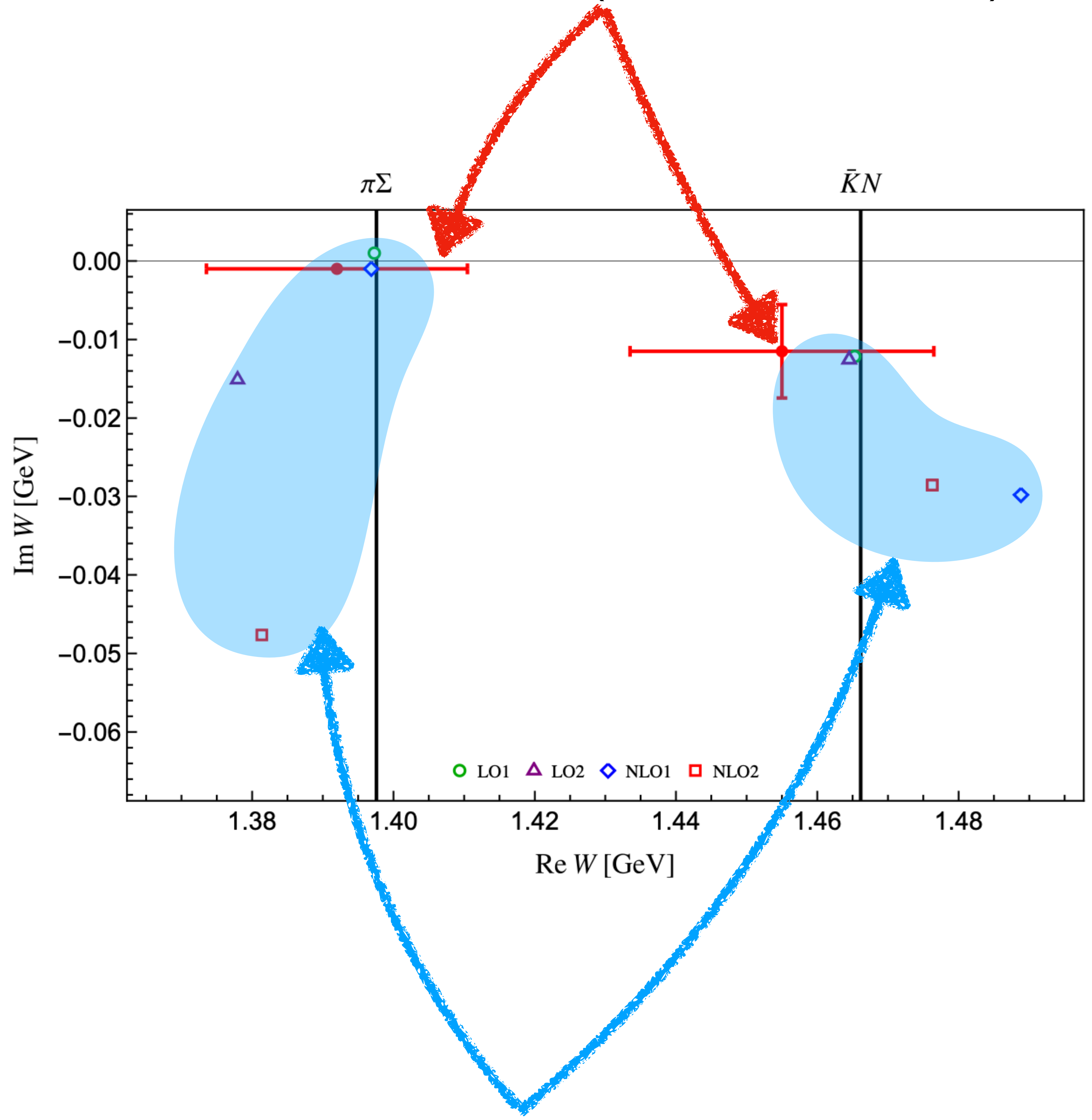
Lattice QCD (M_π=200 MeV)



UCHPT (M_π=200 MeV)

Theoretical limits[1]

- Explore SU(3) limit (m_u=m_d=m_s)
- unphysical mass regimes vs Lattice QCD[2]

➡ ***two-pole structure prevails***

1) Guo/Kamyia/MM/Meißner Phys.Lett.B 846 (2023) 138264
2) Bulava et al. 2307.10413 [hep-lat]

SUMMARY

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- Spectrum of hadrons holds the key to understanding of the strong interaction (#QCD)
- QCD is non-perturbative at low energies (#Lattice QCD, #Effective Field Theories)
- EFT+Unitarity provide a model (#UCHPT) for complex states such as

  Lambda(1405) + a new Lambda(1380)

  - Many theoretical investigations
  - Experimental progress
  - Lattice QCD

  agree with it so far…

$\Lambda(1380)$ $\Lambda(1405)$