

A STORY OF STRANGE(NESS) RESONANCES

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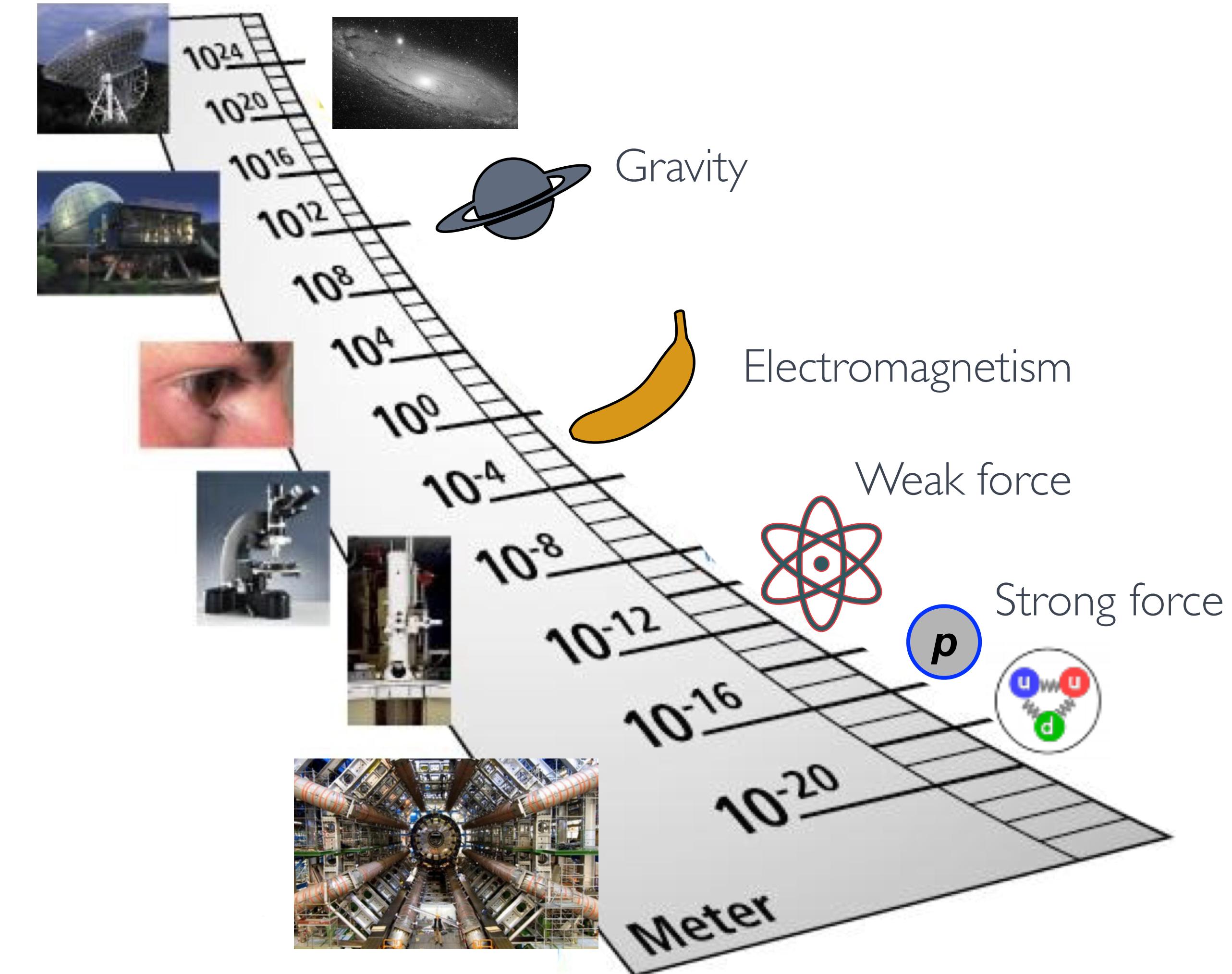
DFG Project ID 196253076 - TRR 110



LEARNING NATURE'S LANGUAGE

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

Quantum mechanics

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

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

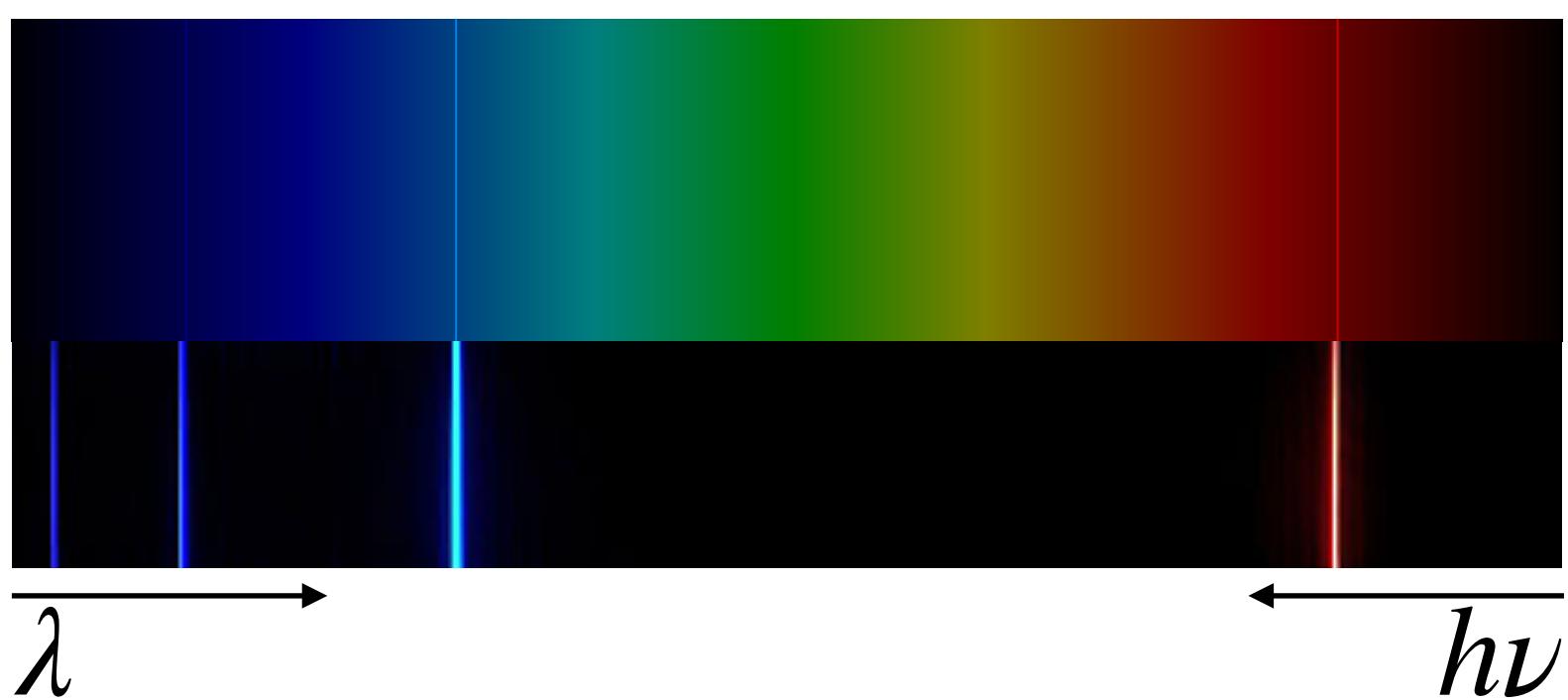
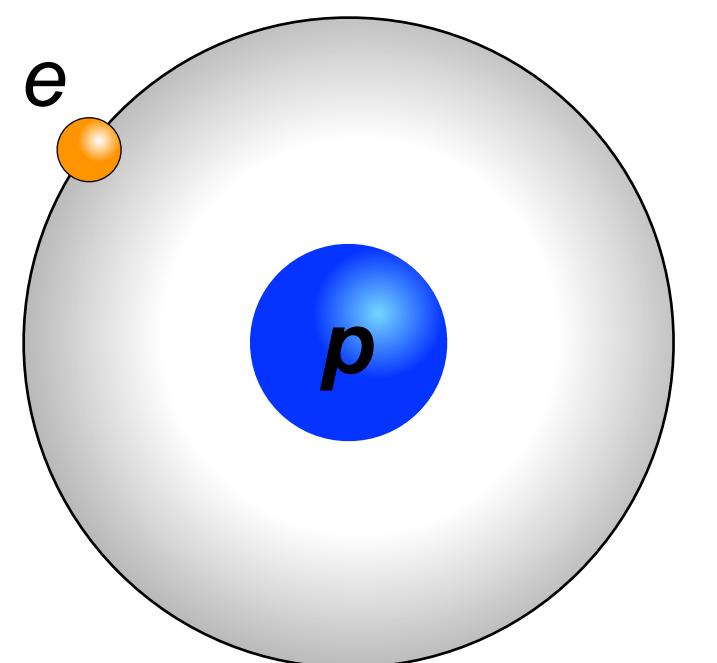
Quantum logic 1936

Copenhagen interpretation 1927

HISTORICAL EXAMPLE

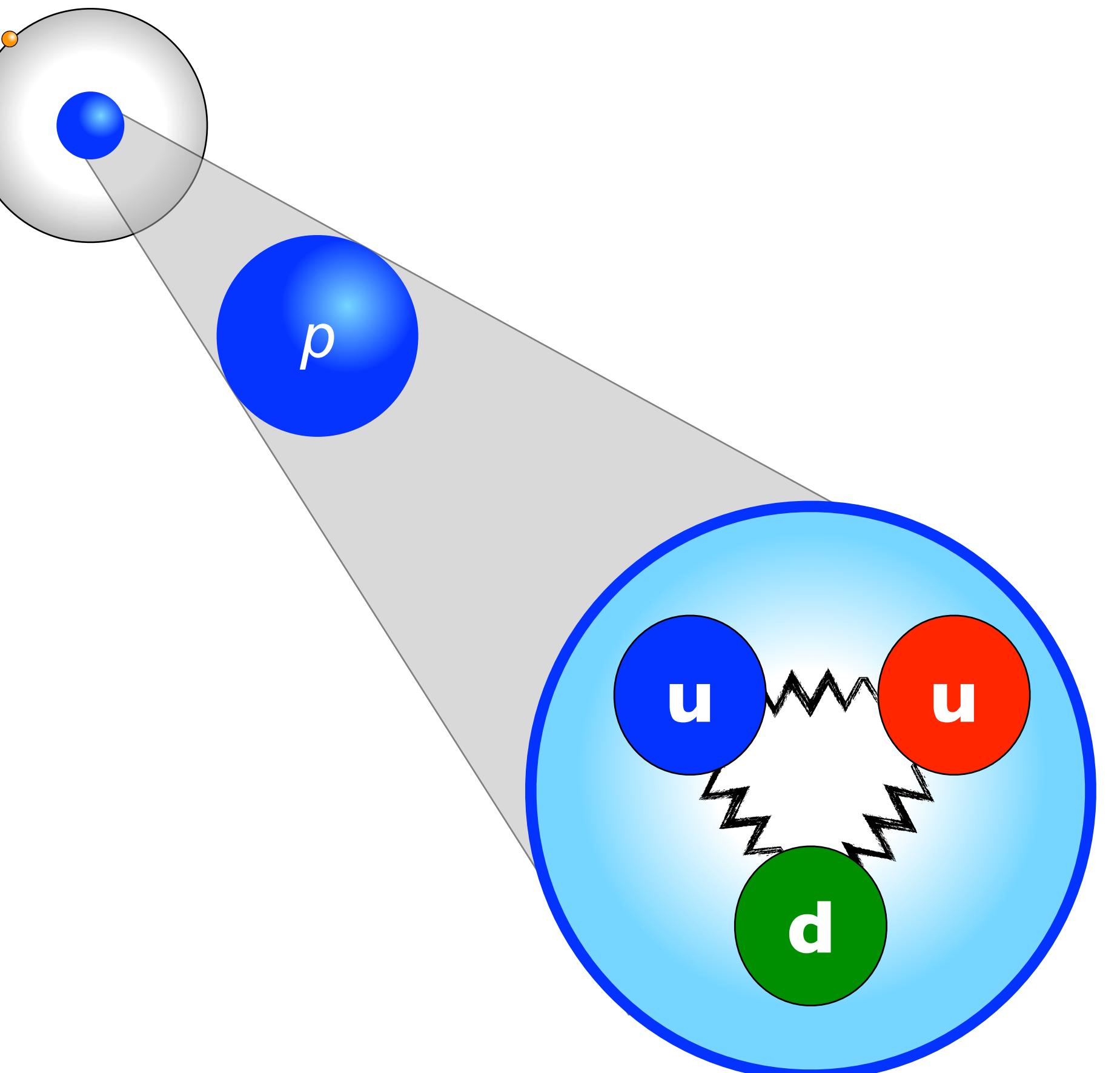
Breakthrough

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



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

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

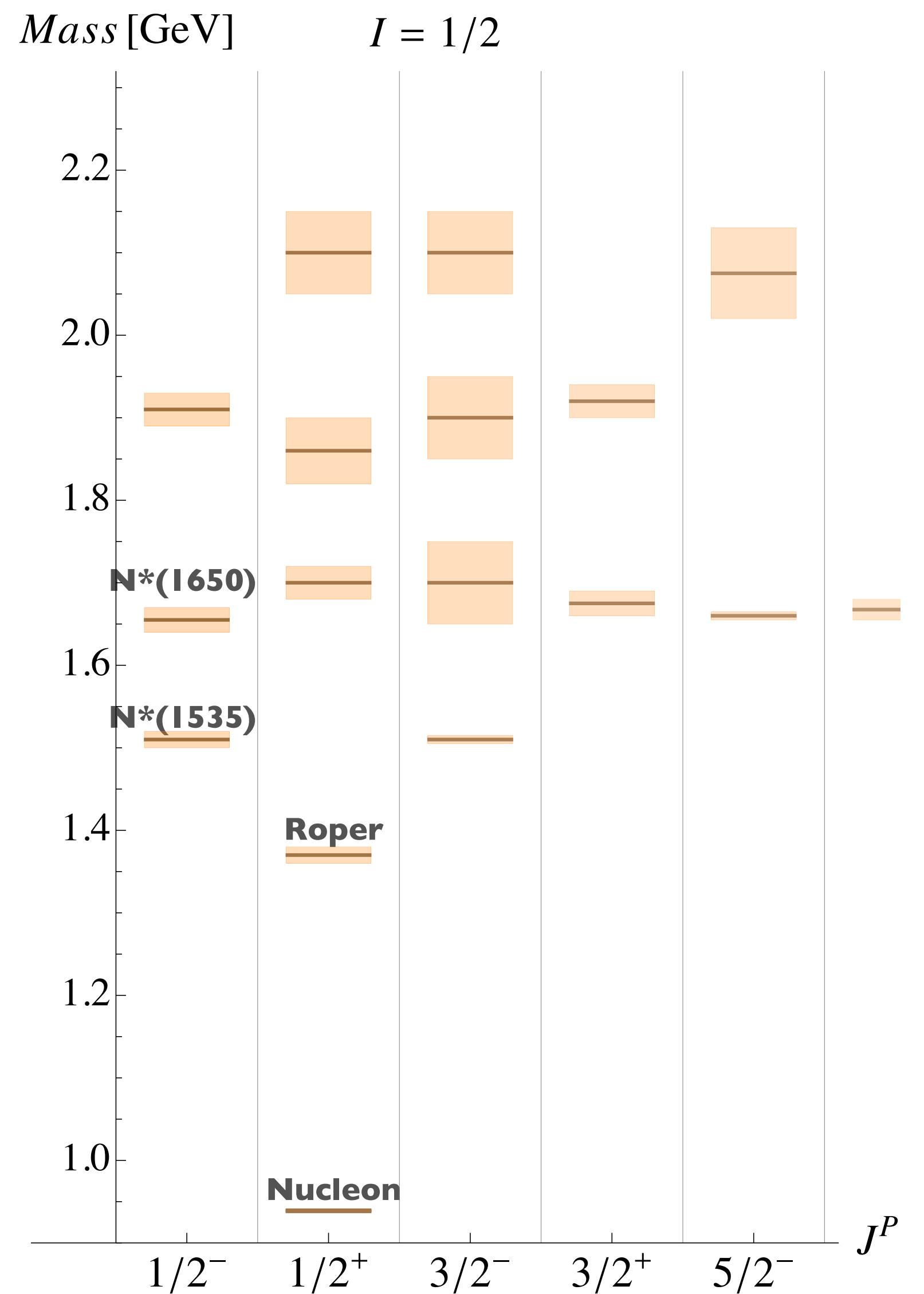
Mostly excited states

≈ 100 mesons & ≈ 50 baryons (*****)

Key questions

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

“do we understand how they are formed?”



QUANTUM CHROMODYNAMICS

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

Color index (3 colors)

Dirac spin algebra

coupling

Minkowski index (0,1,2,3)

quarks == Mass fields (6 flavours)

gluons == force mediators

$$\mathcal{L} = \frac{1}{4g^2} G_{\mu\nu}^a G_{\mu\nu}^a + \sum_j \bar{q}_j (i\gamma^\mu D_\mu + m_j) q_j$$

where $G_{\mu\nu}^a \equiv \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + i f_{bc}^a A_\mu^b A_\nu^c$

and $D_\mu \equiv \partial_\mu + i t^a A_\mu^a$

That's it!

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

QUANTUM CHROMODYNAMICS

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

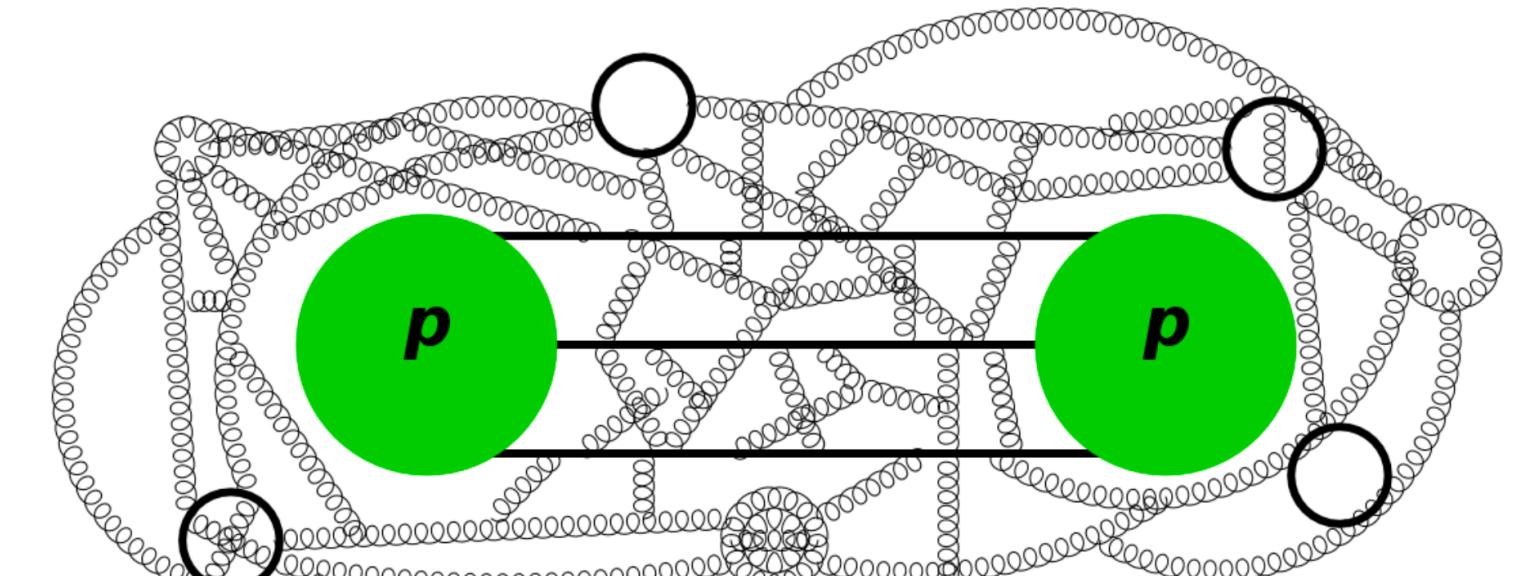
$$\mathcal{L} = \frac{1}{4g^2} G_{\mu\nu}^\alpha G_{\mu\nu}^\alpha + \sum_j g_j (i\gamma^\mu D_\mu + m_j) q_j$$

where $G_{\mu\nu}^\alpha \equiv \partial_\mu A_\nu^\alpha - \partial_\nu A_\mu^\alpha + i f_{bc}^\alpha A_\mu^b A_\nu^c$

and $D_\mu \equiv \partial_\mu + i$

That's

* **Gluons** are self interacting – re-create themselves 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

$$\sum_j \bar{g}_j$$

$$A_\nu^a - a$$

$$q_\mu + i\epsilon$$

That's a

Effective Field Theories

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

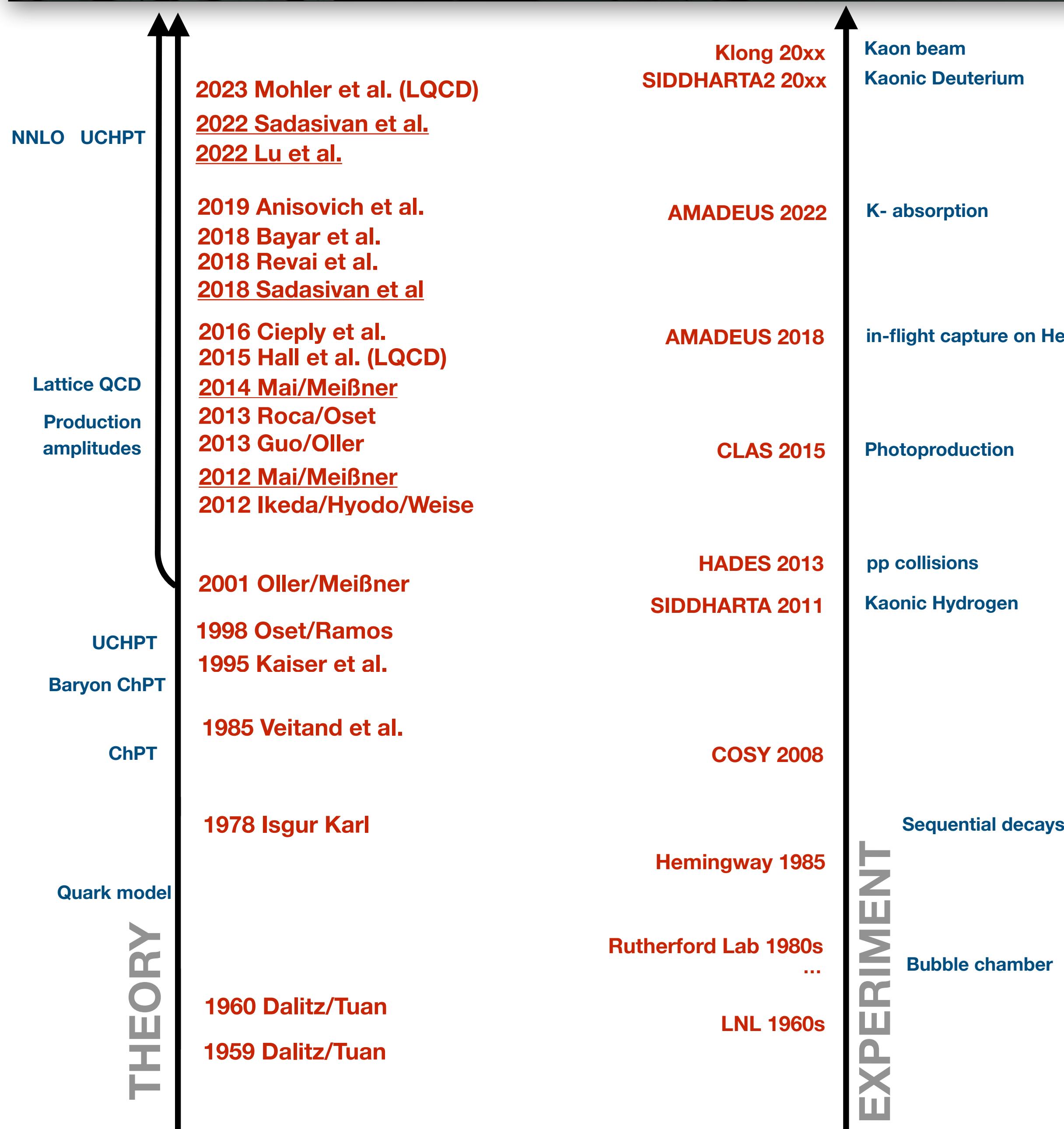
- scale-separation & spontaneous symmetry breaking
- effective degrees of freedom: Goldstone bosons (pseudoscalar mesons)
- Challenges for hadron spectroscopy
 - model-independent but limited to low-energy below resonances
 - extensions to resonance region through S-matrix theory with some model assumptions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

LAMBDA(1405)
THE STORY OF AN UNDEAD
STRANGENESS RESONANCE

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



HISTORY



BROADER IMPACT

Litmus test for theoretical tools

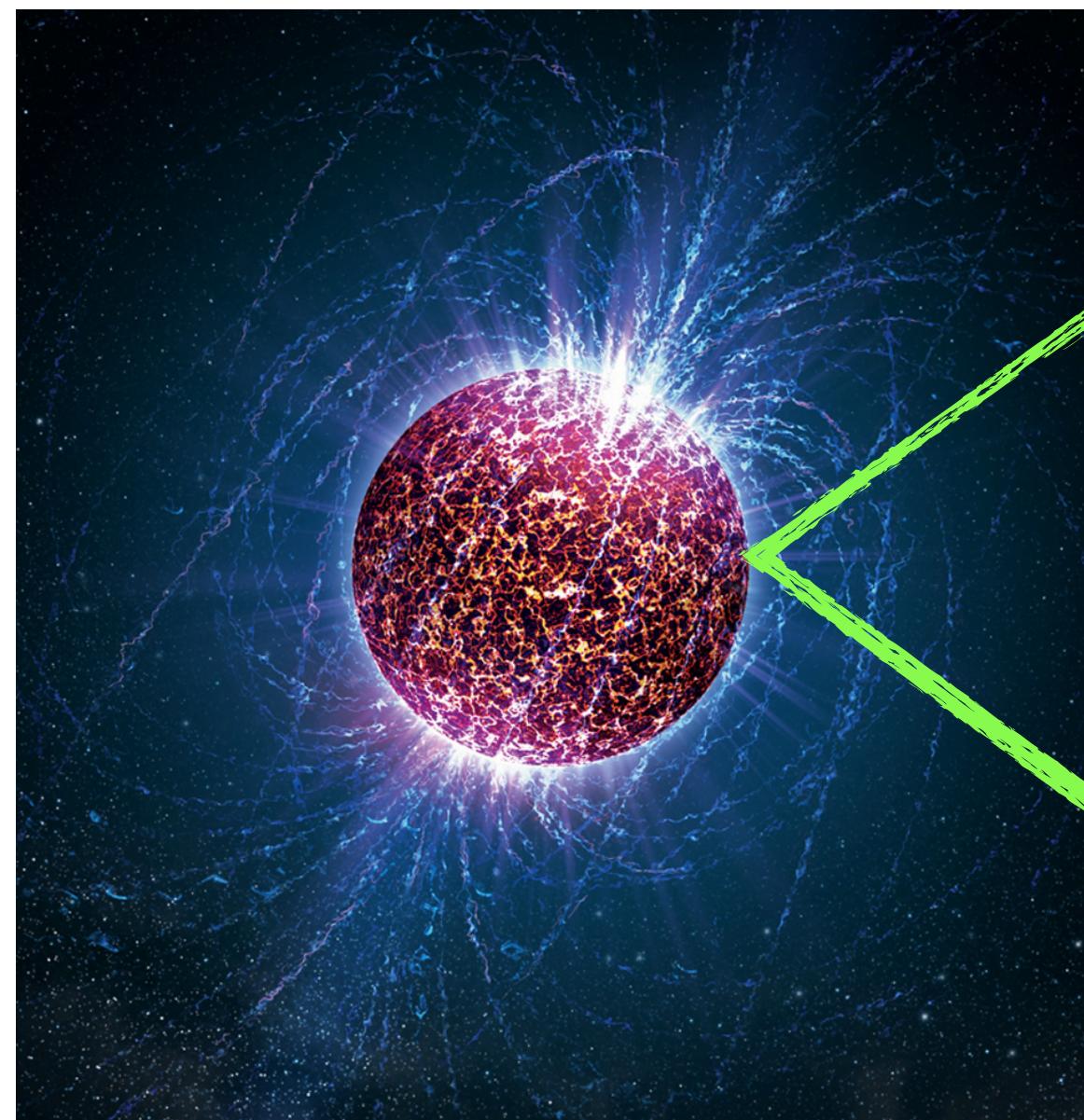
- Twice non-perturbative regime of QCD
 - too low for perturbative QCD
 - too high for low-energy EFT

Reviews:

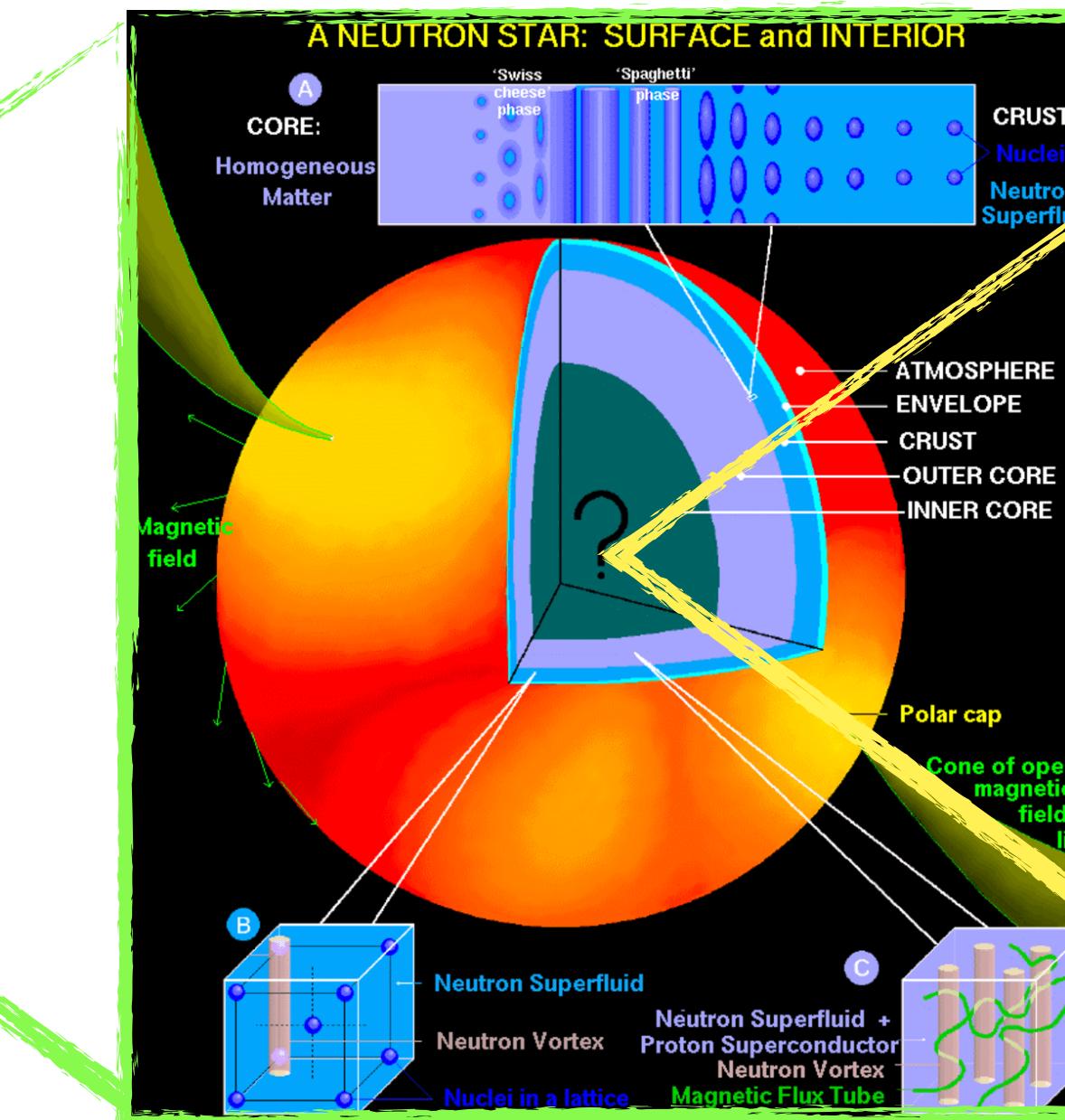
Meißner, Symmetry 12 (2020);
 MM Eur.Phys.J.ST 230 (2021);
 Hyodo/Niiyama Prog.Part.Nucl.Phys. 120 (2021)

Antikaons in nuclear medium

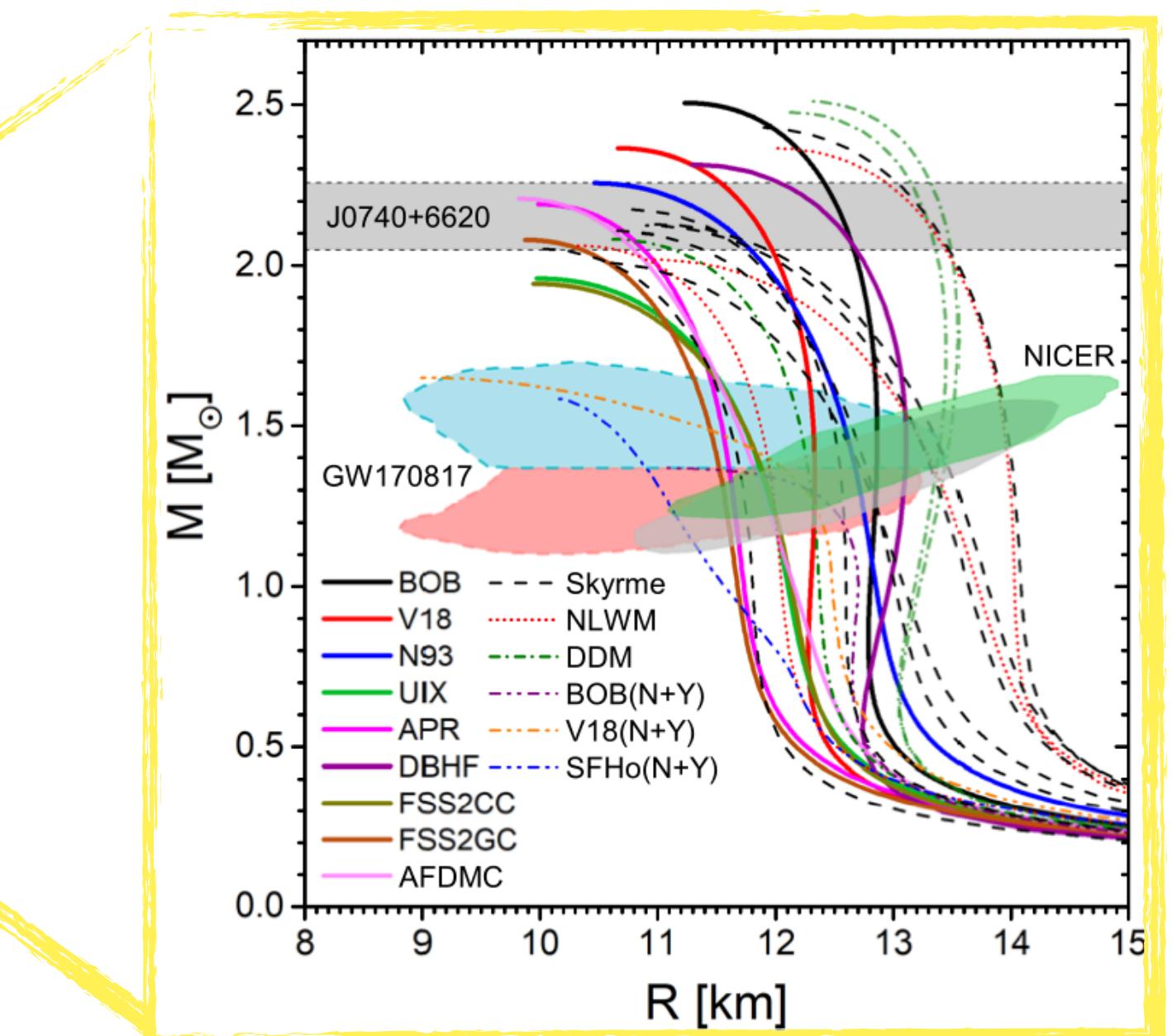
- KbarNN & KbarNNN bound states
 - ...KbarN input is critical for interpretation
- Strangeness in the EoS of neutron stars
 - ...K-condensate can change EoS-stiffness



artist view(Casey Reed)



phys.org Dany P Page

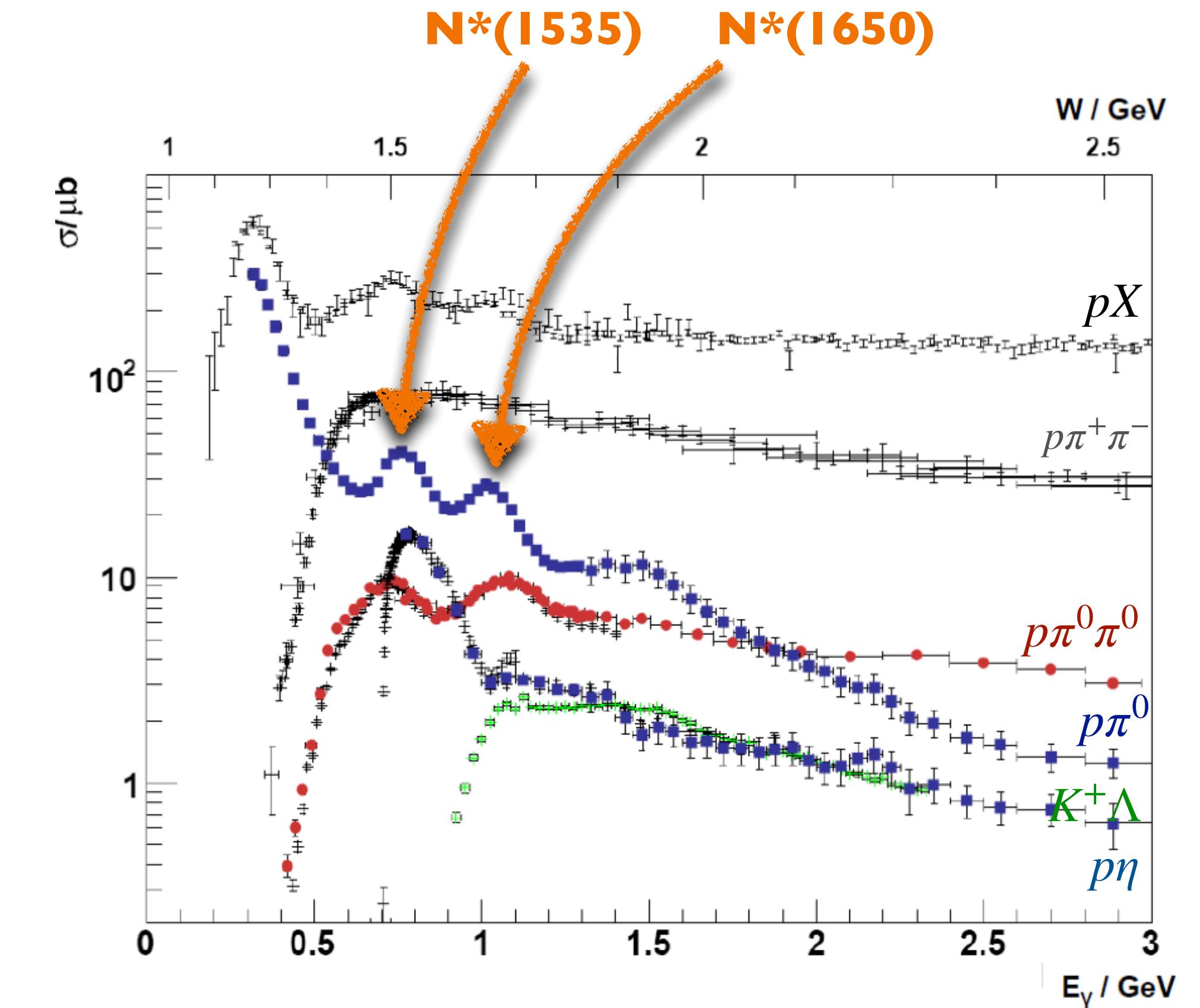
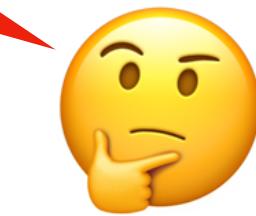


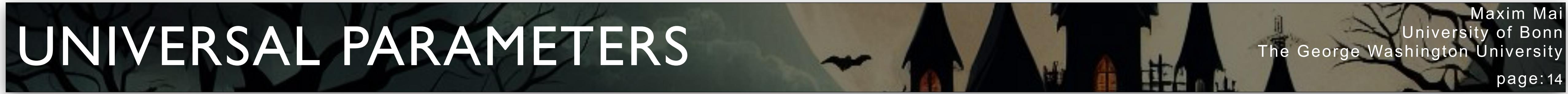
Prog.Part.Nucl.Phys. 120 (2021)

UNIVERSAL PARAMETERS

- Resonances can show up as bumps in experimental data
... depends strongly on reaction, background, etc..

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





UNIVERSAL PARAMETERS

Reaction-independent parameters

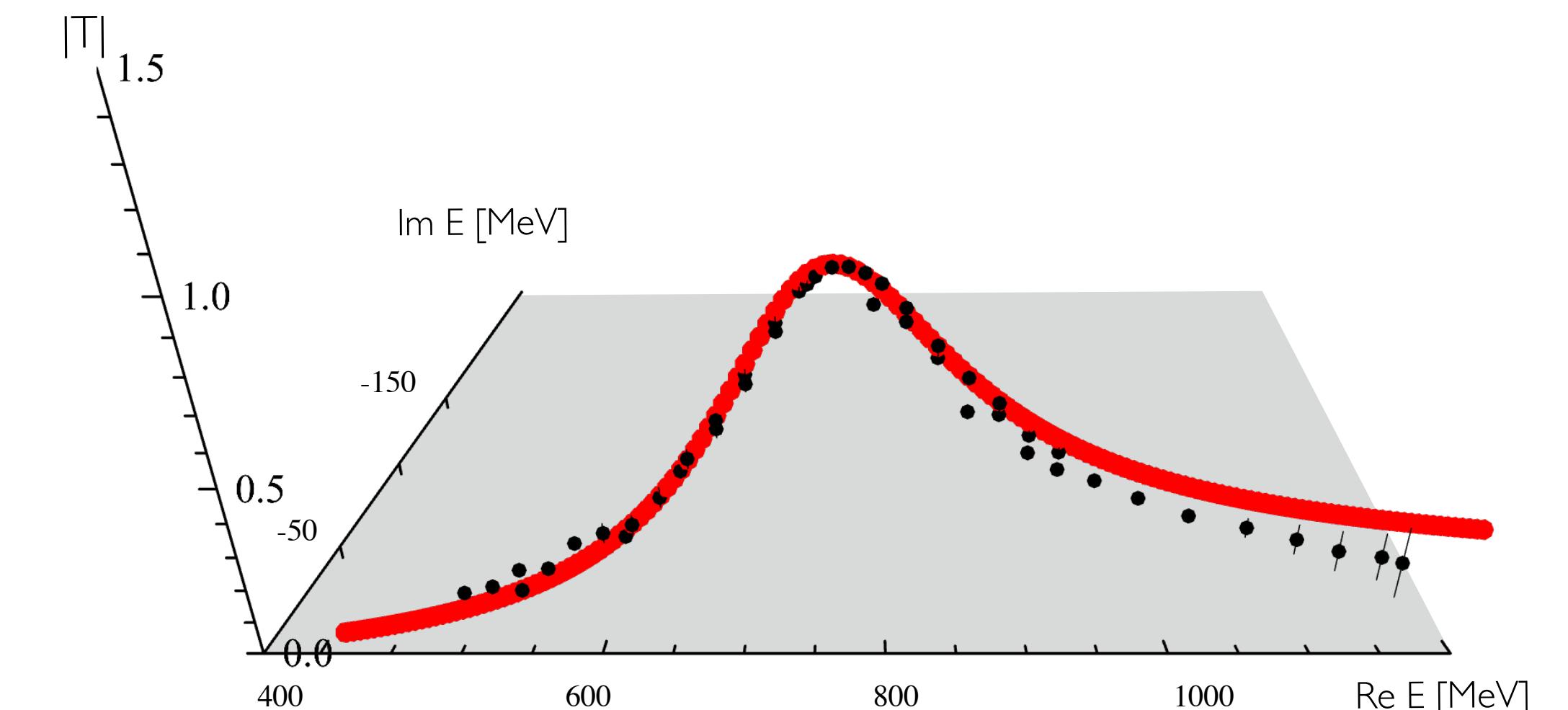
pole positions on unphysical Riemann Sheets

KEY QUANTITY — Transition amplitudes

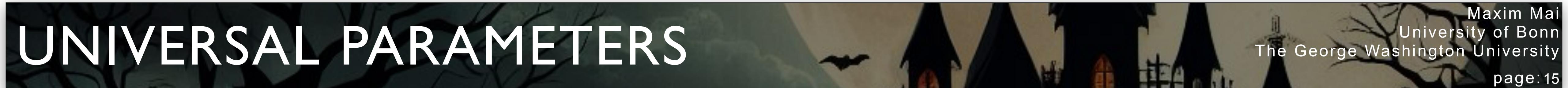
Constrained by Unitarity/Analyticity/Crossing

Constrained by CHPT/LatticeQCD

Constrained by Observations



UNIVERSAL PARAMETERS



Reaction-independent parameters

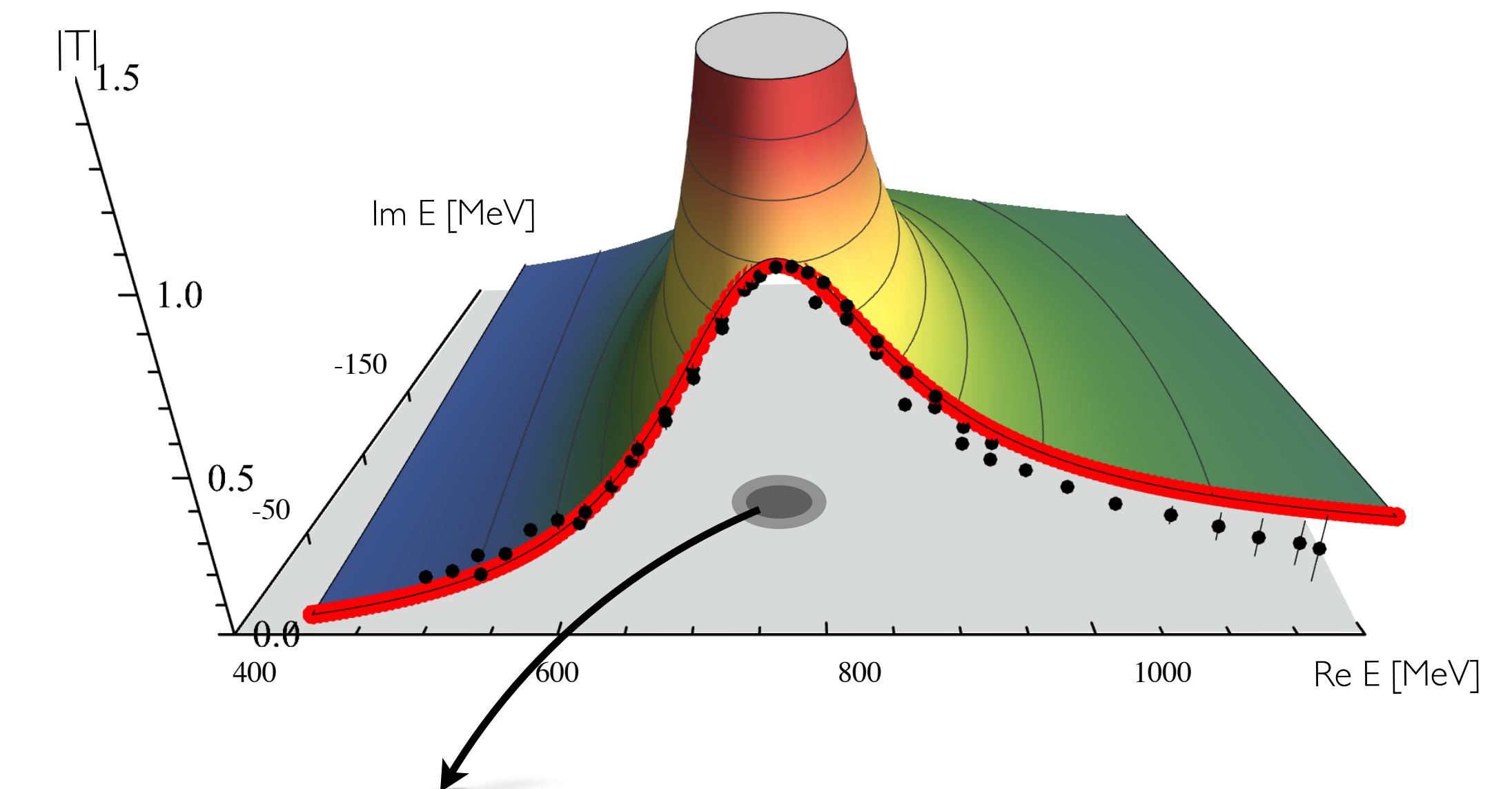
pole positions on unphysical Riemann Sheets

KEY QUANTITY — Transition amplitudes

Constrained by Unitarity/Analyticity/Crossing

Constrained by CHPT/LatticeQCD

Constrained by Observations



$$M^* = (750 - i60) \text{ MeV}$$

Universal property of the ρ – meson

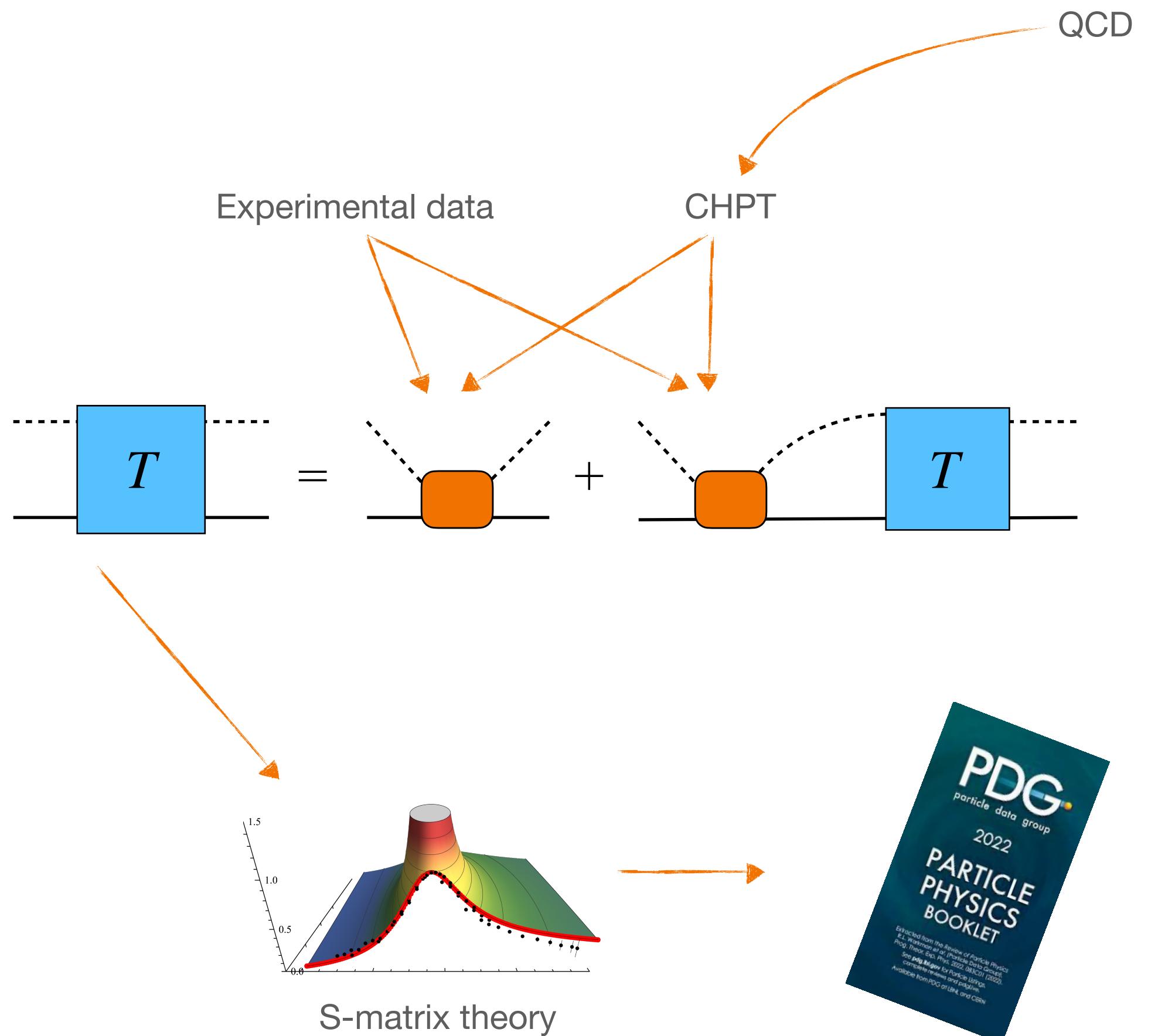
TRANSITION AMPLITUDE (UCHPT)

One way:

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

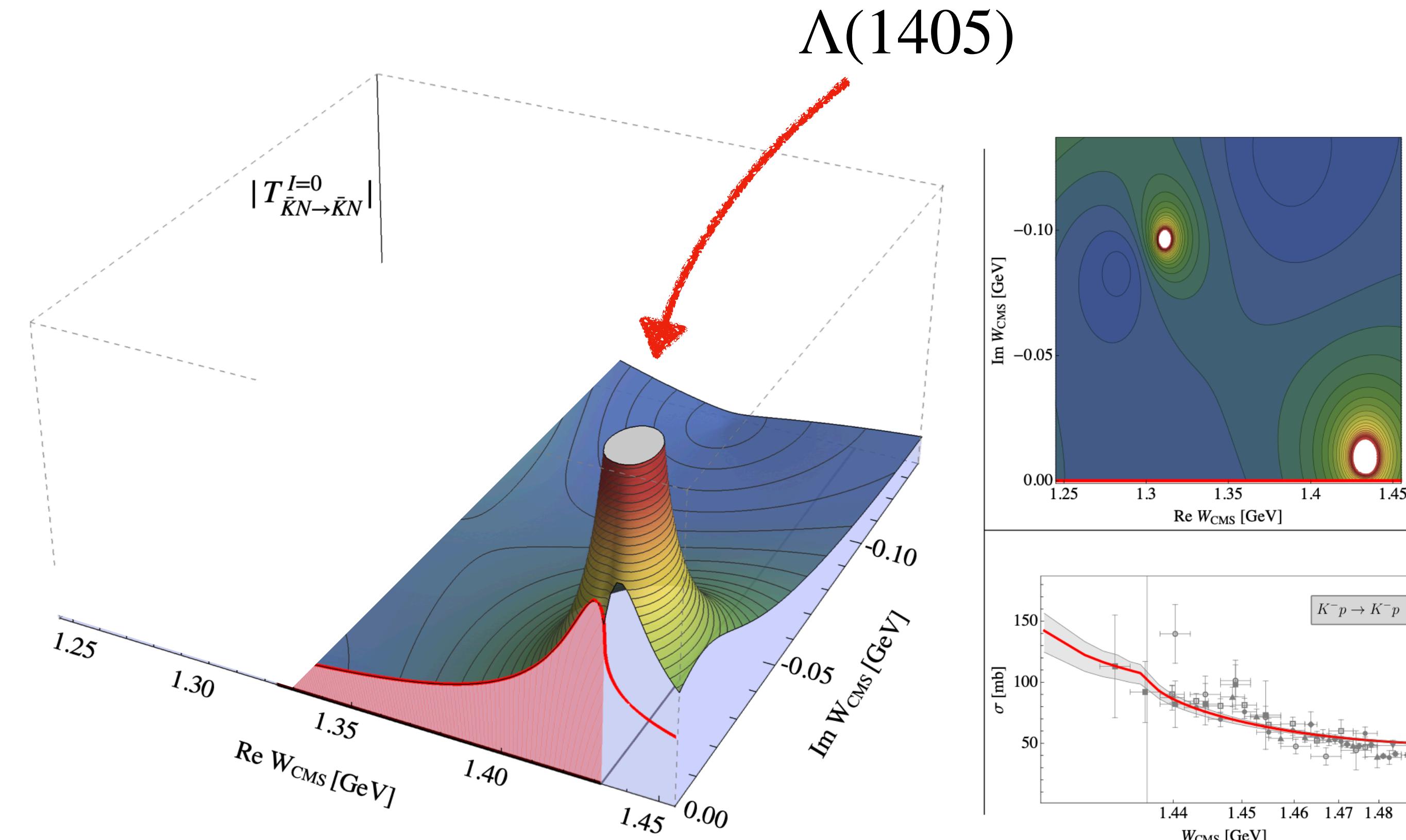
Fit: free parameters to experimental data / LQCD

Extract: Complex pole positions for complex energies



RESONANCE POLE(S)

- Narrow pole below KbarN threshold
 $W^* = (1421 \dots 1429) - i(10 \dots 25) \text{ MeV}$
... well estimated

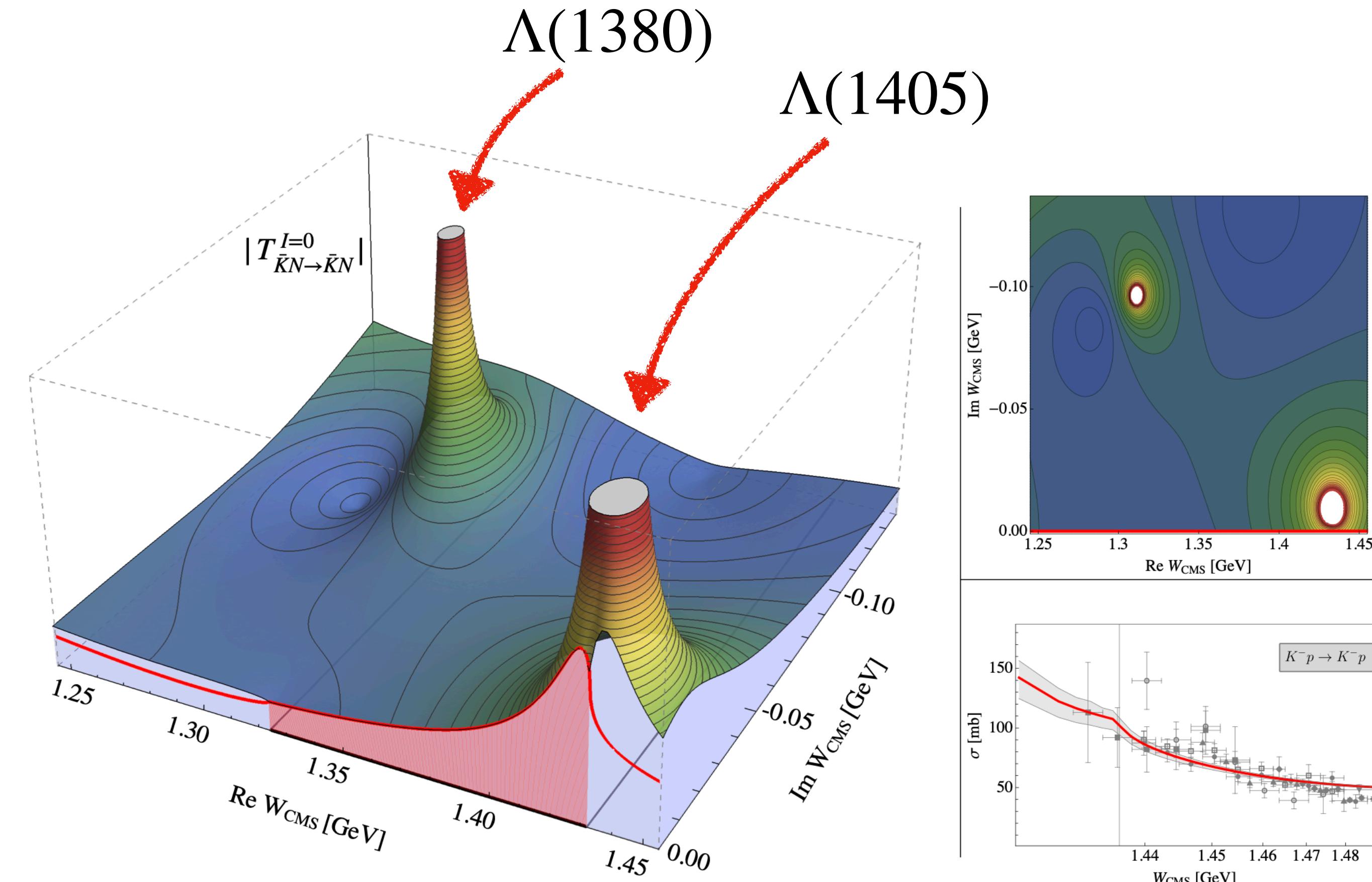


RESONANCE POLE(S)

- Inclusion of chiral symmetry constants demands a second state¹:

$$W^* = (1325 \dots 1381) - i(56 \dots 114) \text{ MeV}$$

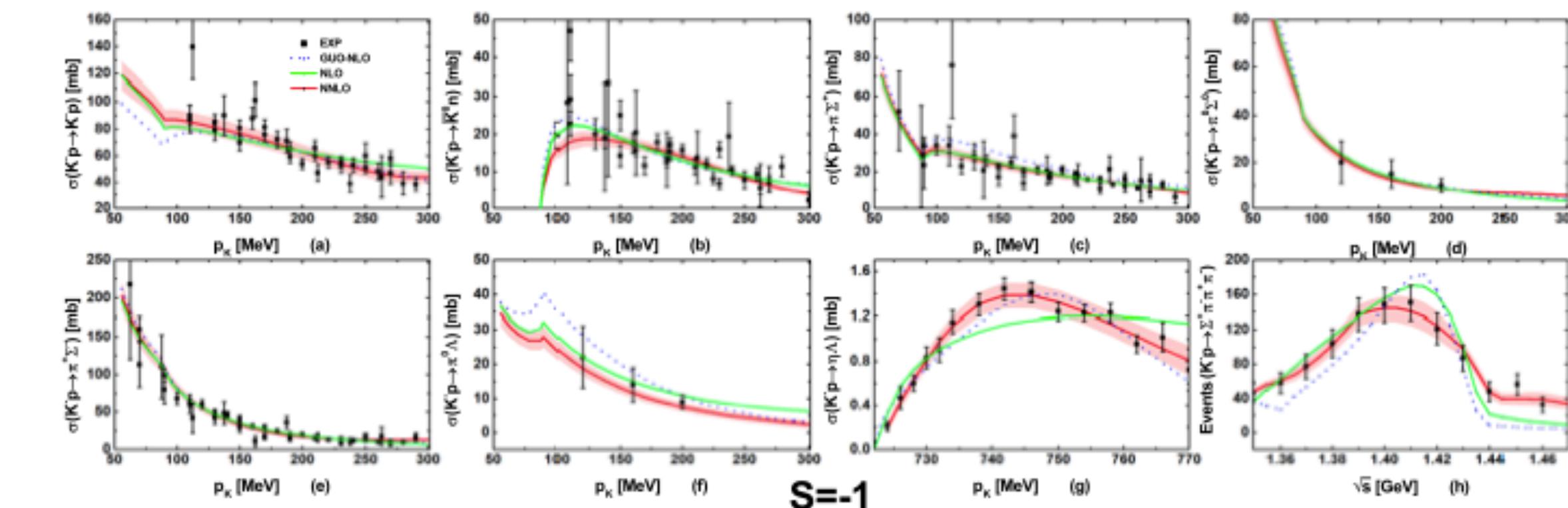
... Common phenomenon in hadron physics²



1) Oller/Meißner (2001); Ikeda/Hyodo/Weise(2011); MM/Meißner(2012); Guo/Oller(2012),...

2) Meißner, Symmetry 12 (2020) 6, 981

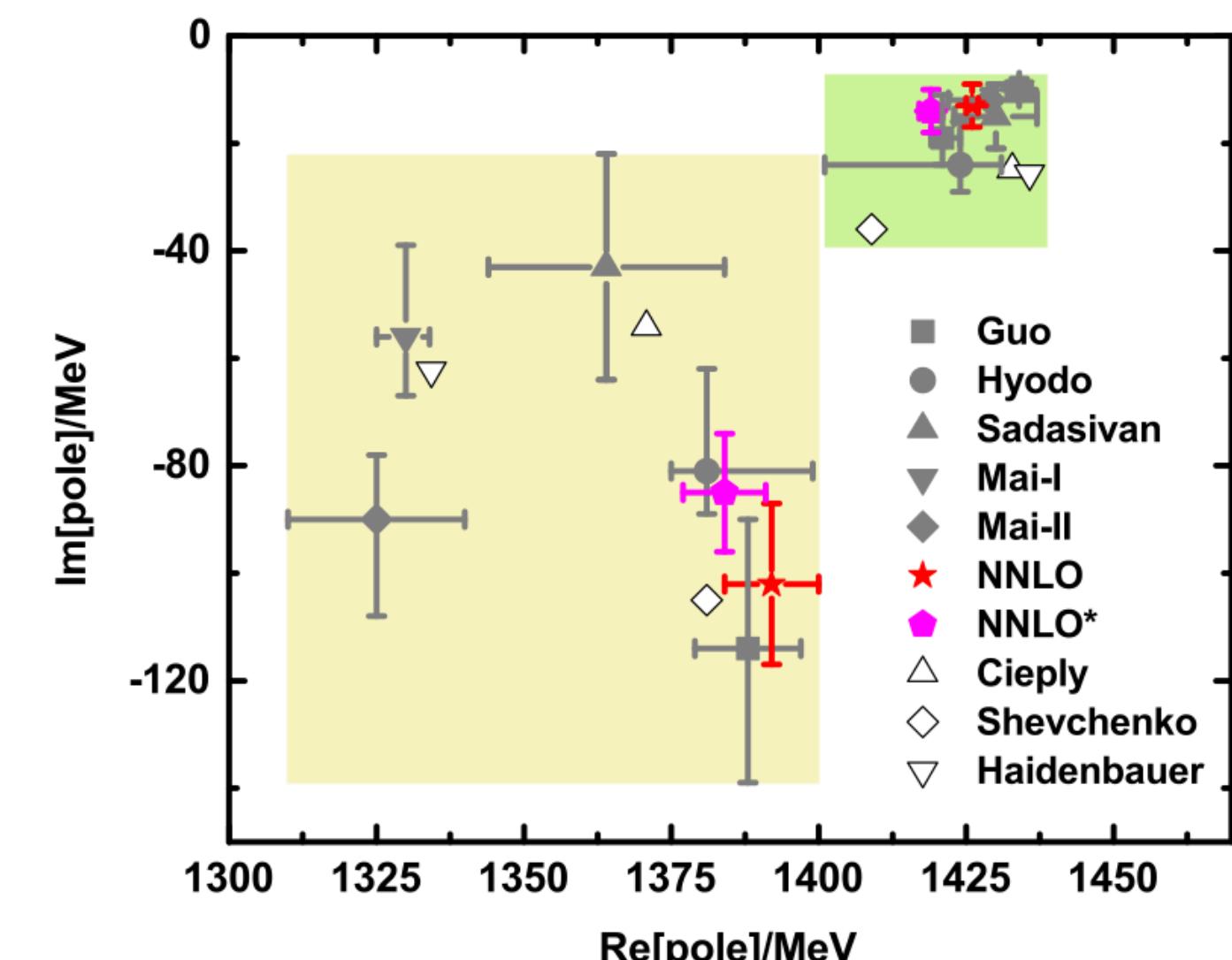
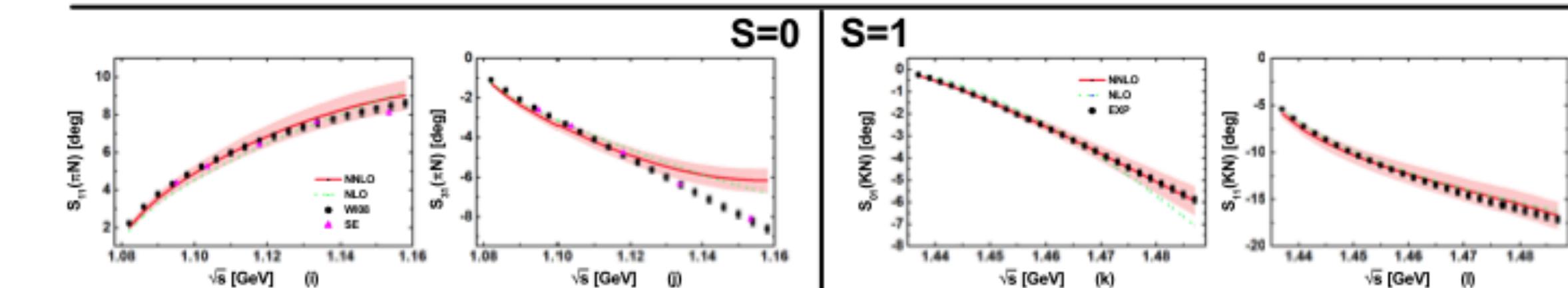
CURRENT FRONTIER #1



Many tests:

- $K^+\Sigma\pi$ photo-production constraints¹
- Theory update: NNLO UCHPT²

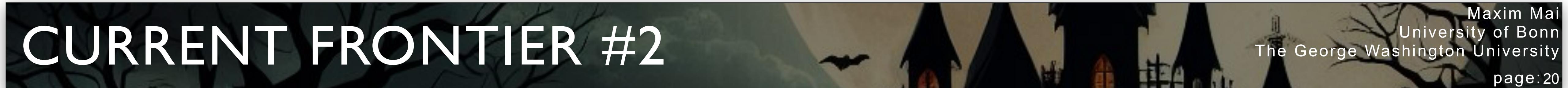
→ **two-pole structure prevails**



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)

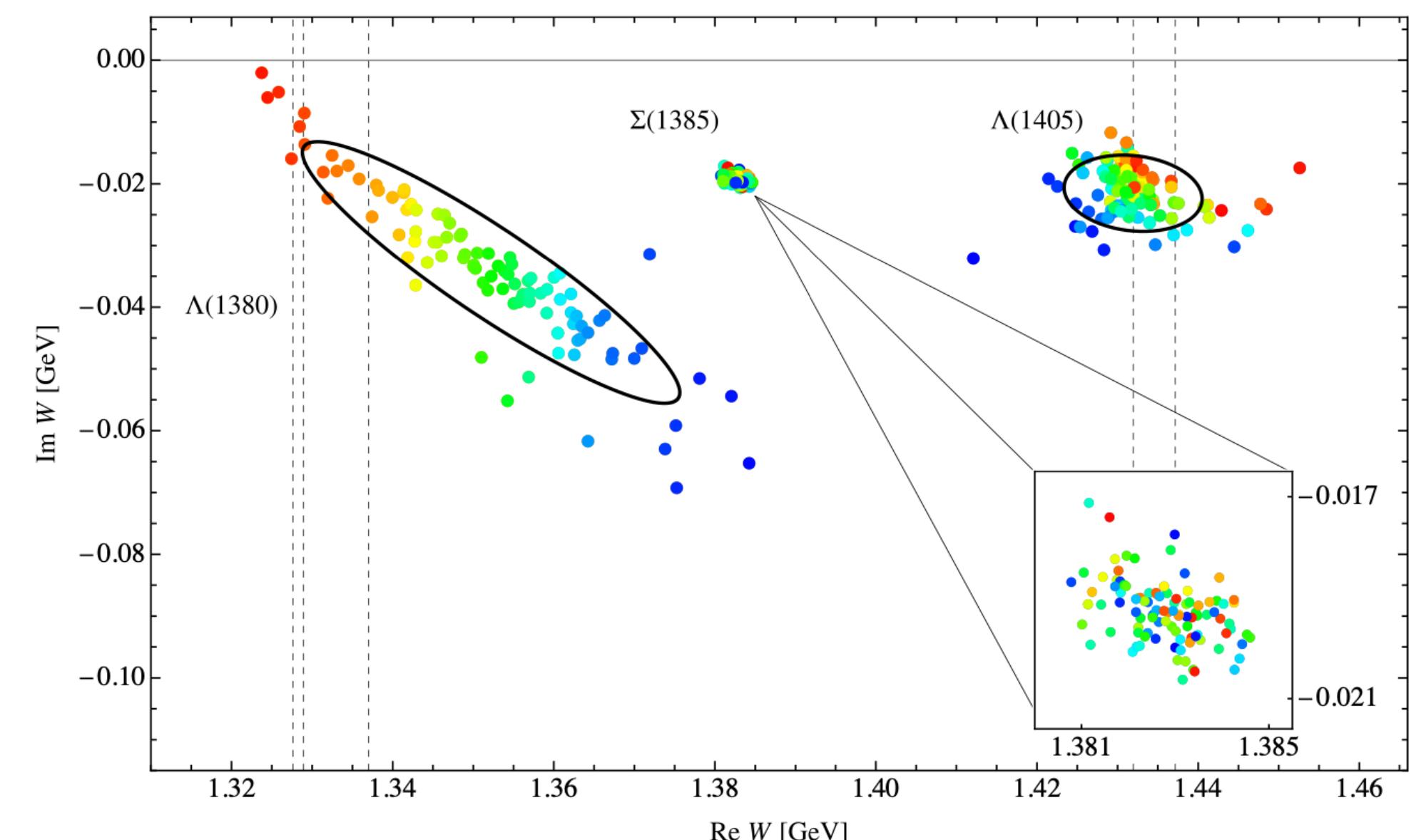
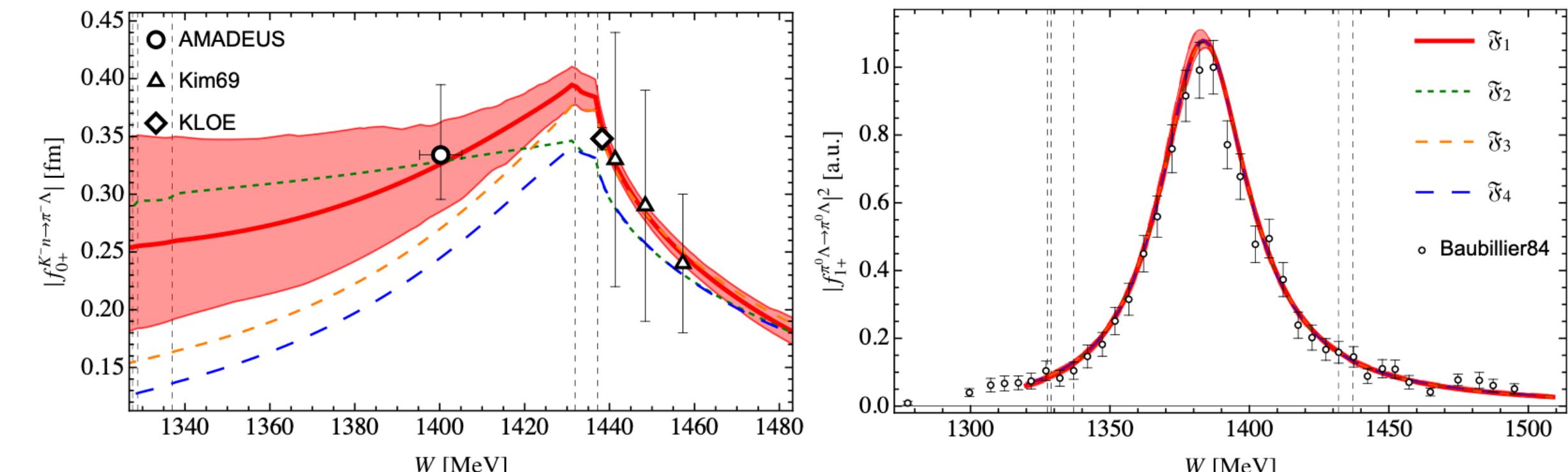
2) Lu/Geng/Döring/MM Phys.Rev.Lett. 130 (2023)

CURRENT FRONTIER #2



Many tests:

- new data sources¹
- Higher-partial waves inclusion²
- **two-pole structure prevails**
- **cross-correlations uncovered**



1)AMADEUS Phys. Lett. B 782 (2018);

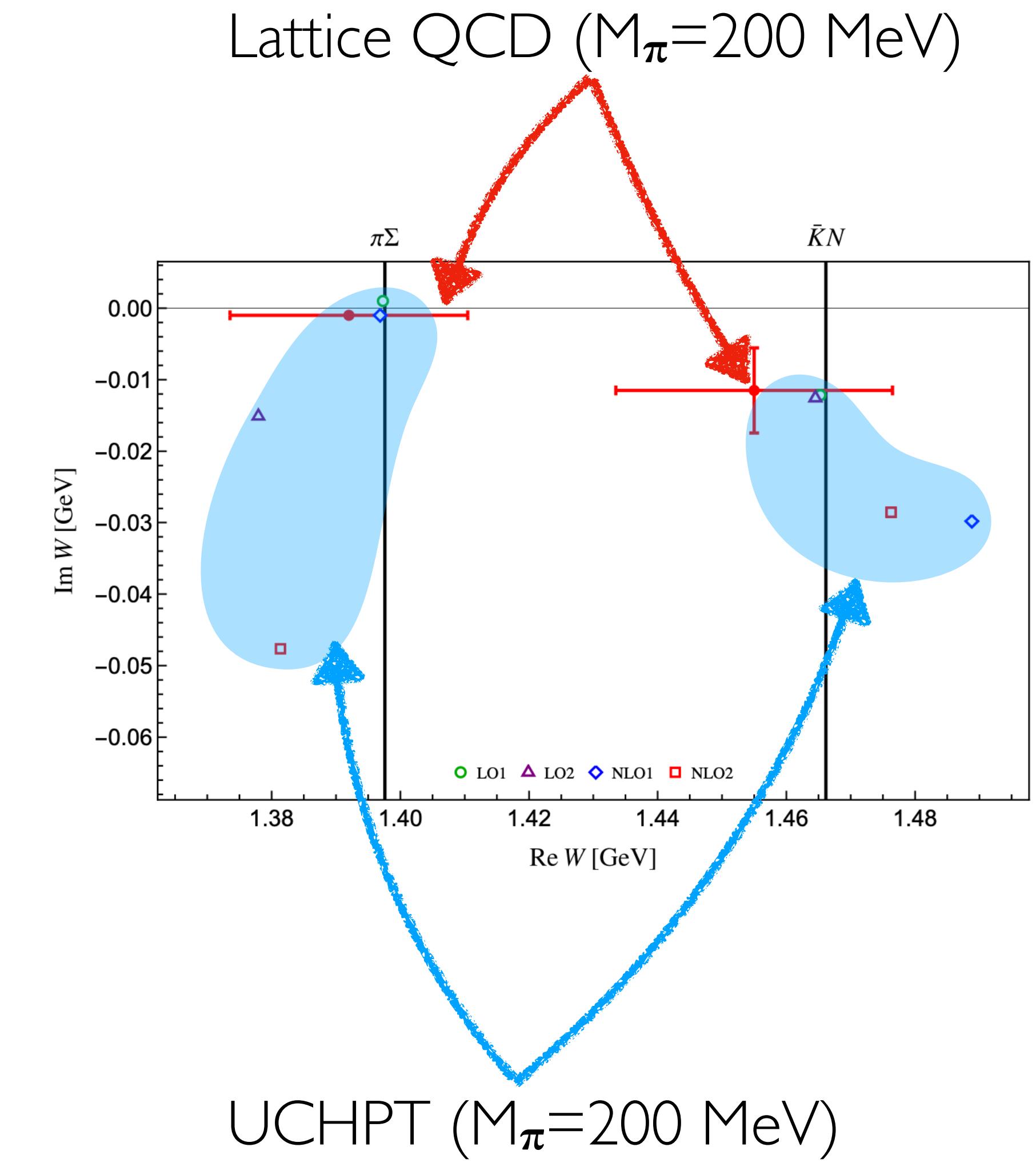
2)Sadasivan et al Front.Phys. 11 (2023)

CURRENT FRONTIER #2

Theoretical limits¹

- Explore SU(3) limit ($m_u=m_d=m_s$)
- unphysical mass regimes vs Lattice QCD²

→ **two-pole structure prevails**



1) Guo/Kamyia/MM/Meißner Phys.Lett.B 846 (2023) 138264

2) Bulava et al. 2307.10413 [hep-lat]

SUMMARY

- 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...



