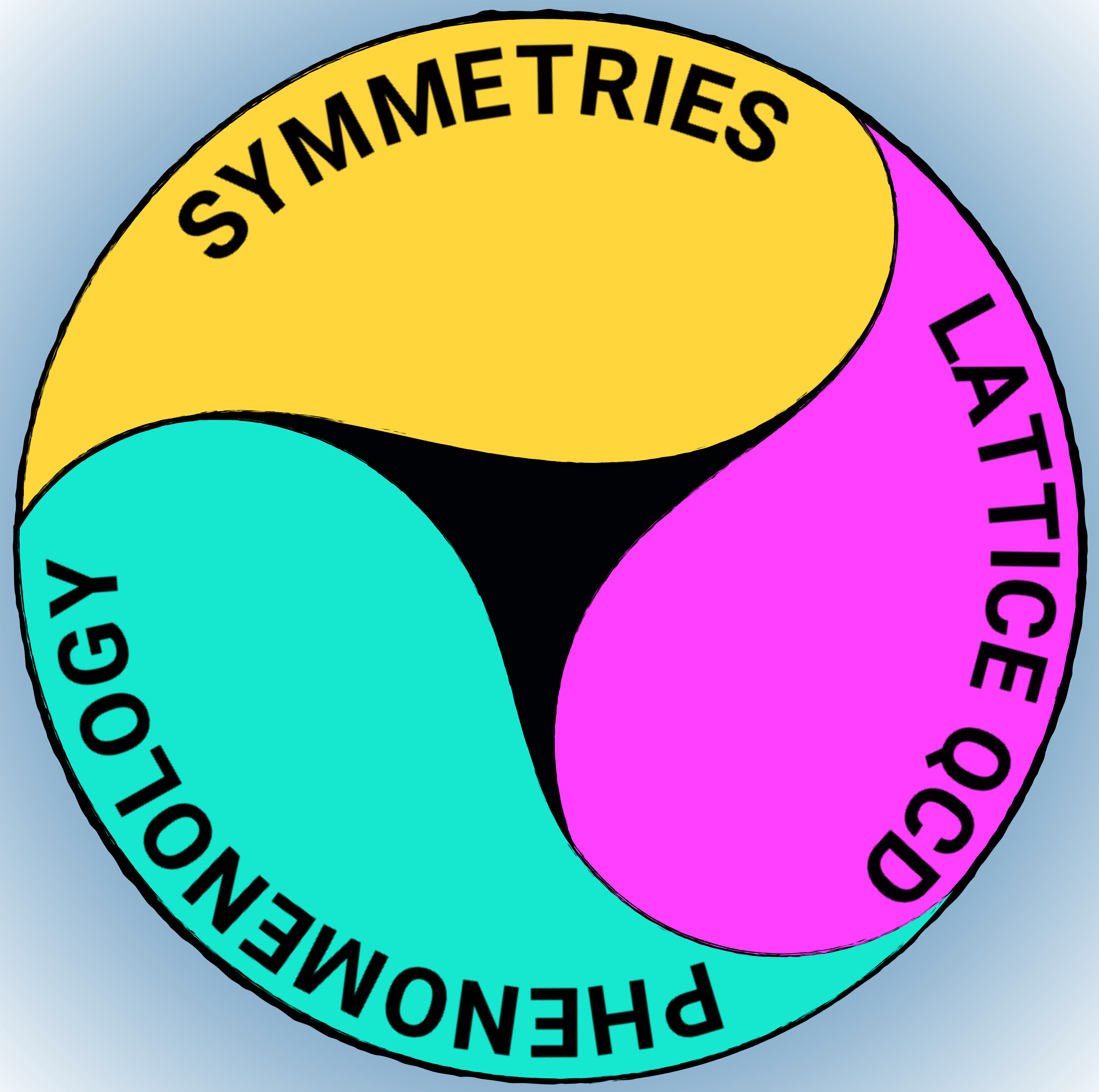
HADRON RESONANCES



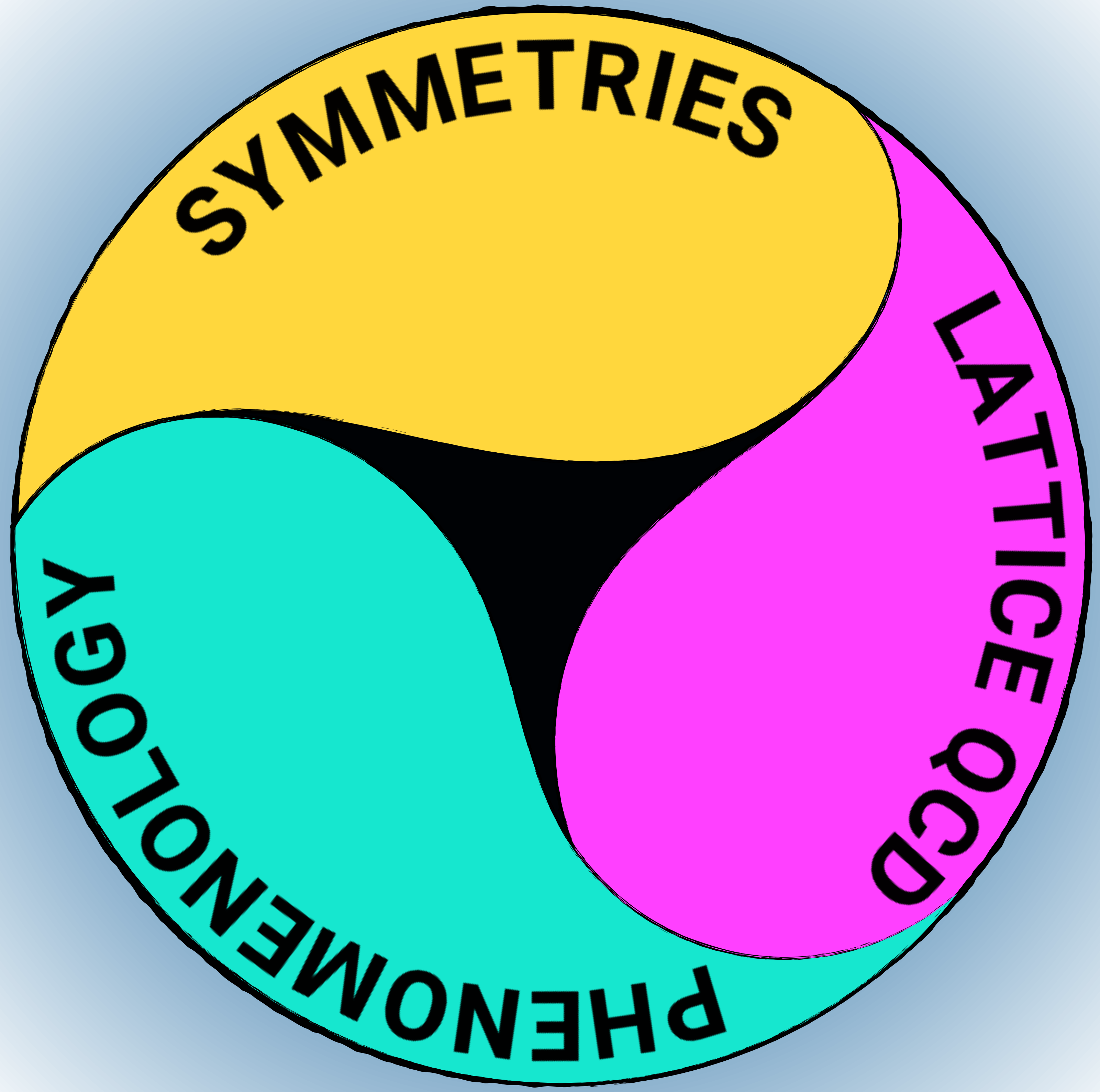
MAXIM MAI

UNIVERSITY OF BERN (MAIN)
THE GEORGE WASHINGTON UNIVERSITY

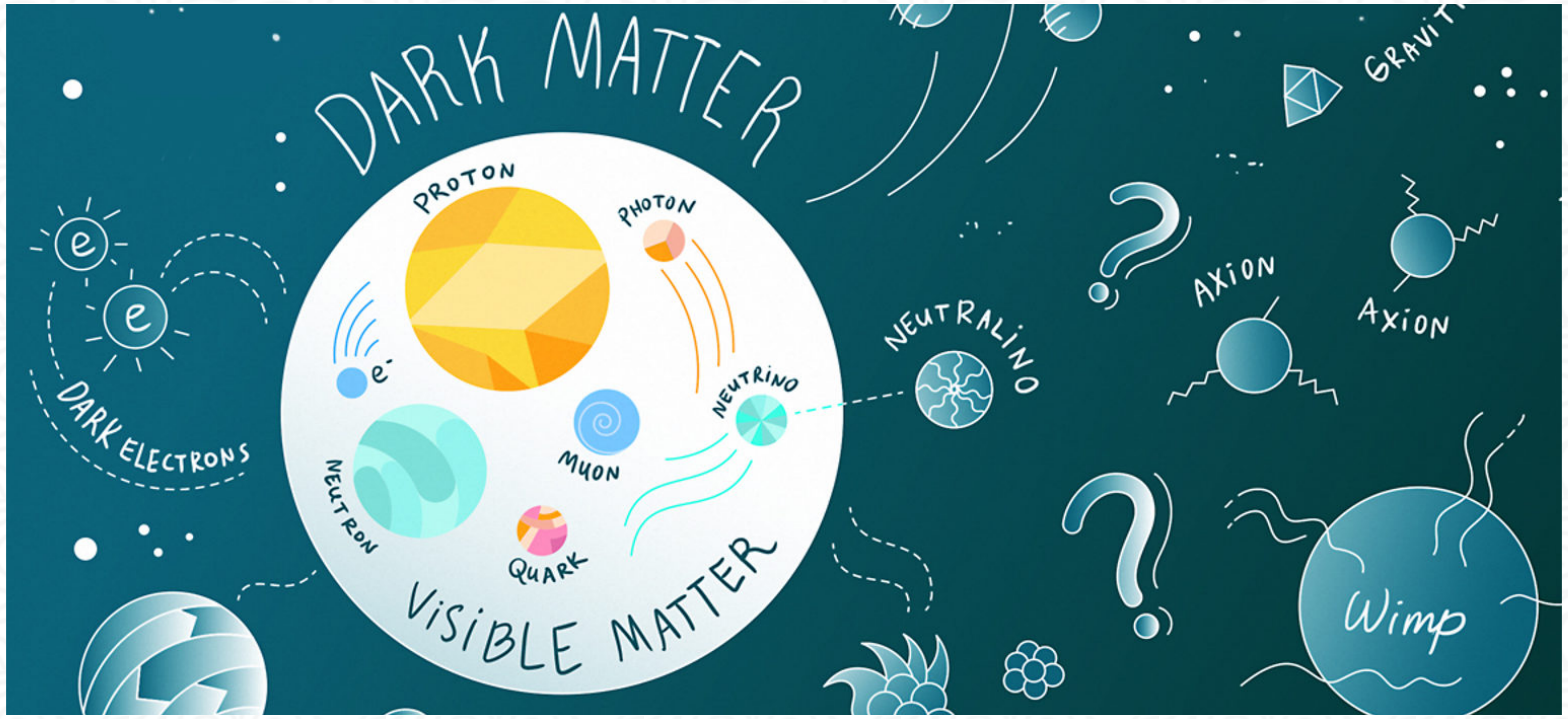
Heisenberg-Programm DFG Deutsche Forschungsgemeinschaft

TRR110: NSFC Grant No. 12070131001, DFG Project-ID 196253076
DOE: DE-SC0016582, DE-AC05-06OR23177, DE-FG02-95ER40907
DFG: Heisenberg Programme (project number: 532635001)
NSF: PHY-2012289

BIG PICTURE



HADRON SPECTRUM

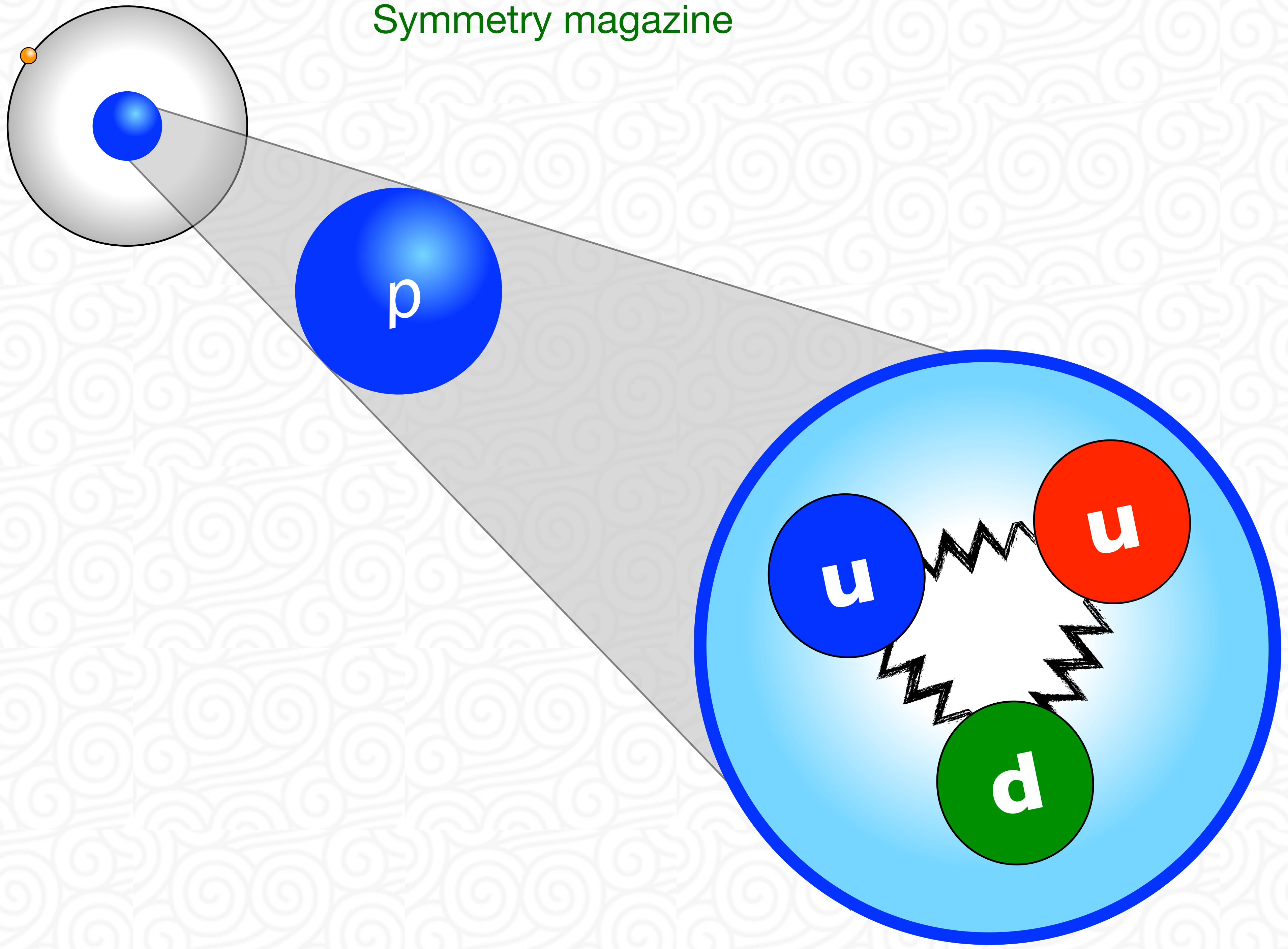


Symmetry magazine

Protons/neutrons

- 99% of the mass of visible matter in the universe
- Building blocks: quarks & gluons (strong force)
- Part of a large class of particles: **hadrons**

what are those?



HADRON SPECTRUM

Many/mostly excited states

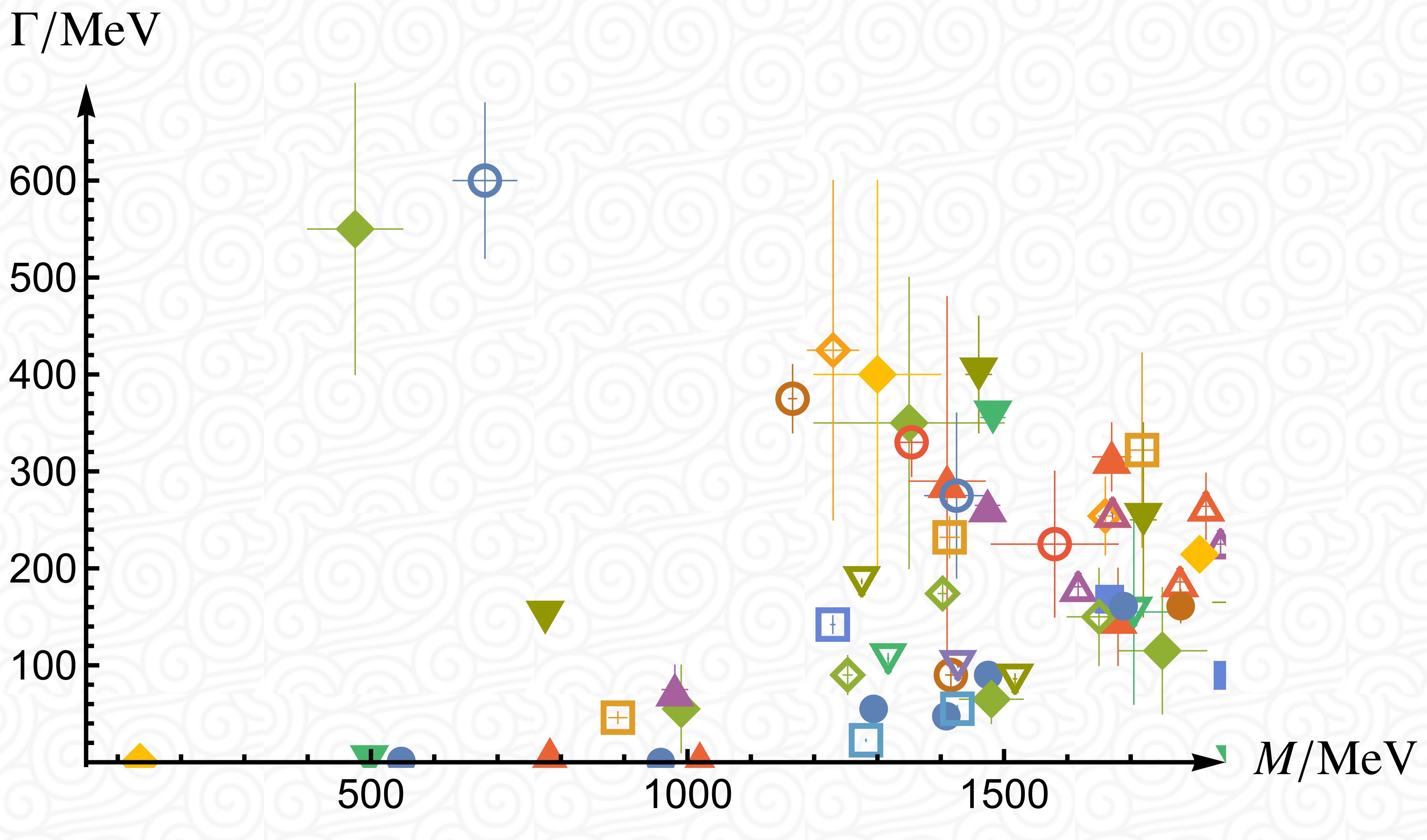
Review: MM/Meißner/Urbach *Phys.Rept.* 1001 (2023) 1-66

≈ 150 mesons

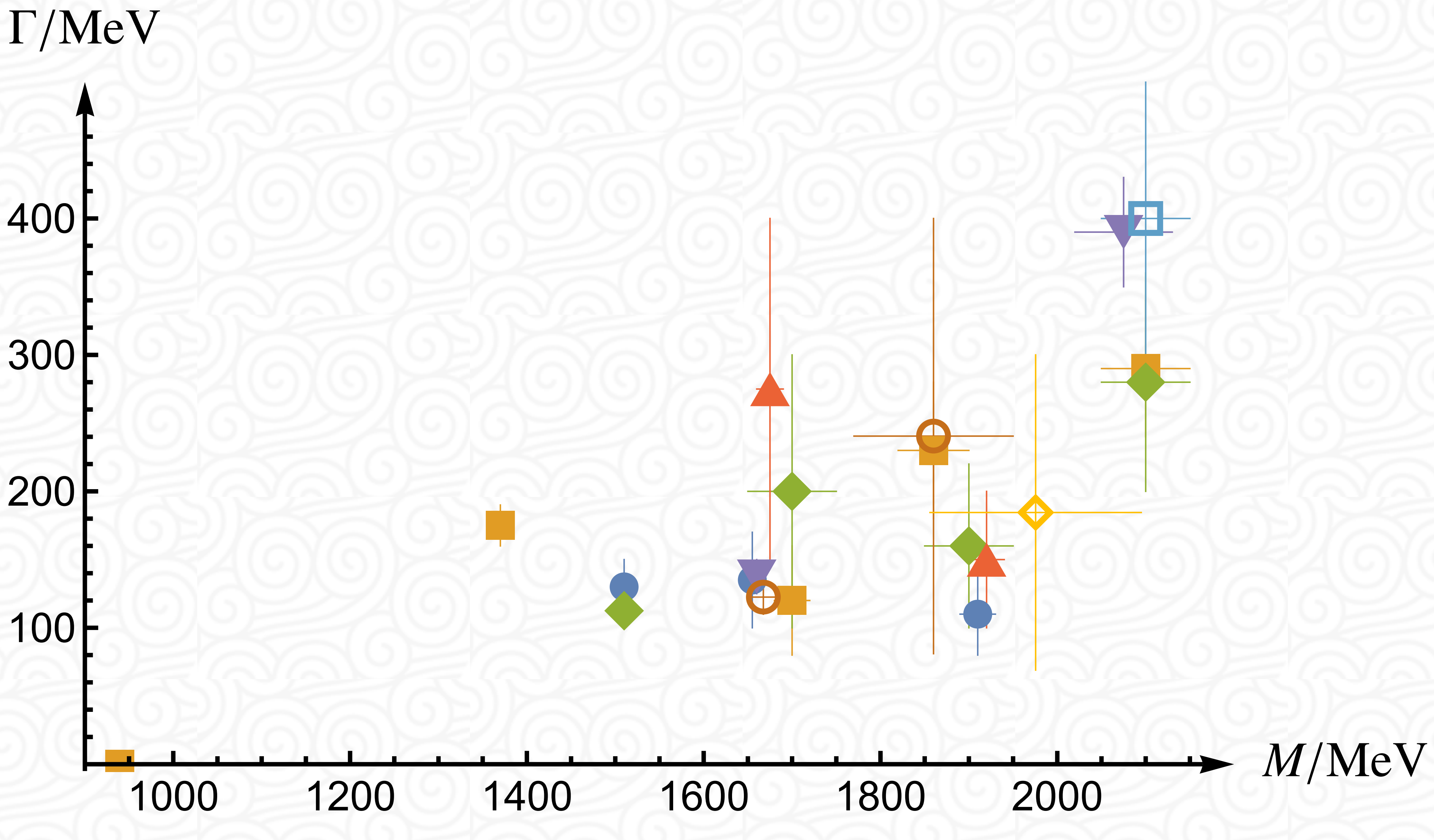
≈ 50 baryons (****)

"If I could remember the names of all these particles, I would have been a botanist."

Enrico Fermi



Unflavoured mesons @ PDG 2023



N Baryons @ PDG/2023

...

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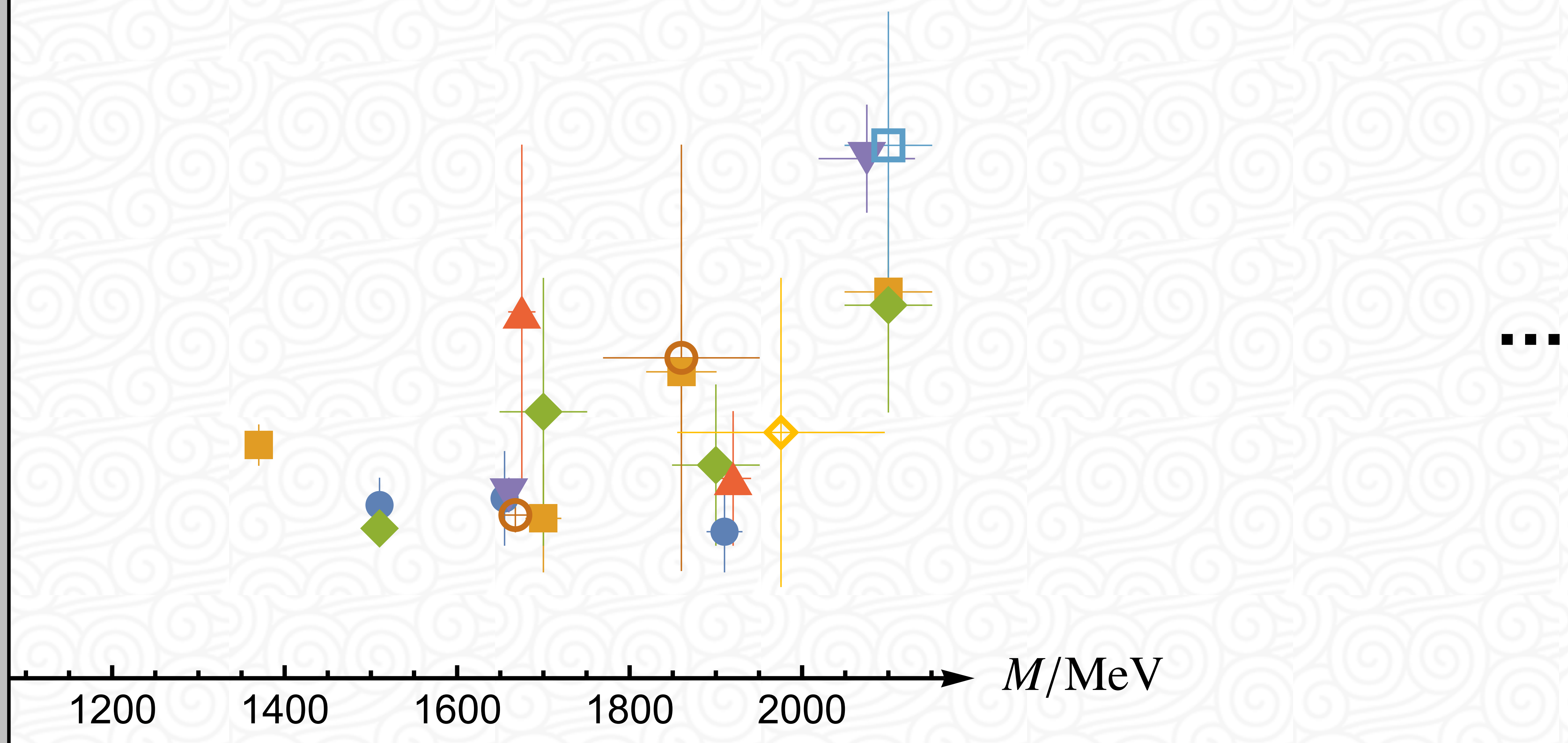
BIRD'S PERSPECTIVE QUESTIONS

- **Are there some patterns?**
- **Minimal spectrum?**

More experiments
Cross-channel models
Statistics/Machine learning tools



N Baryons @ PDG/2023

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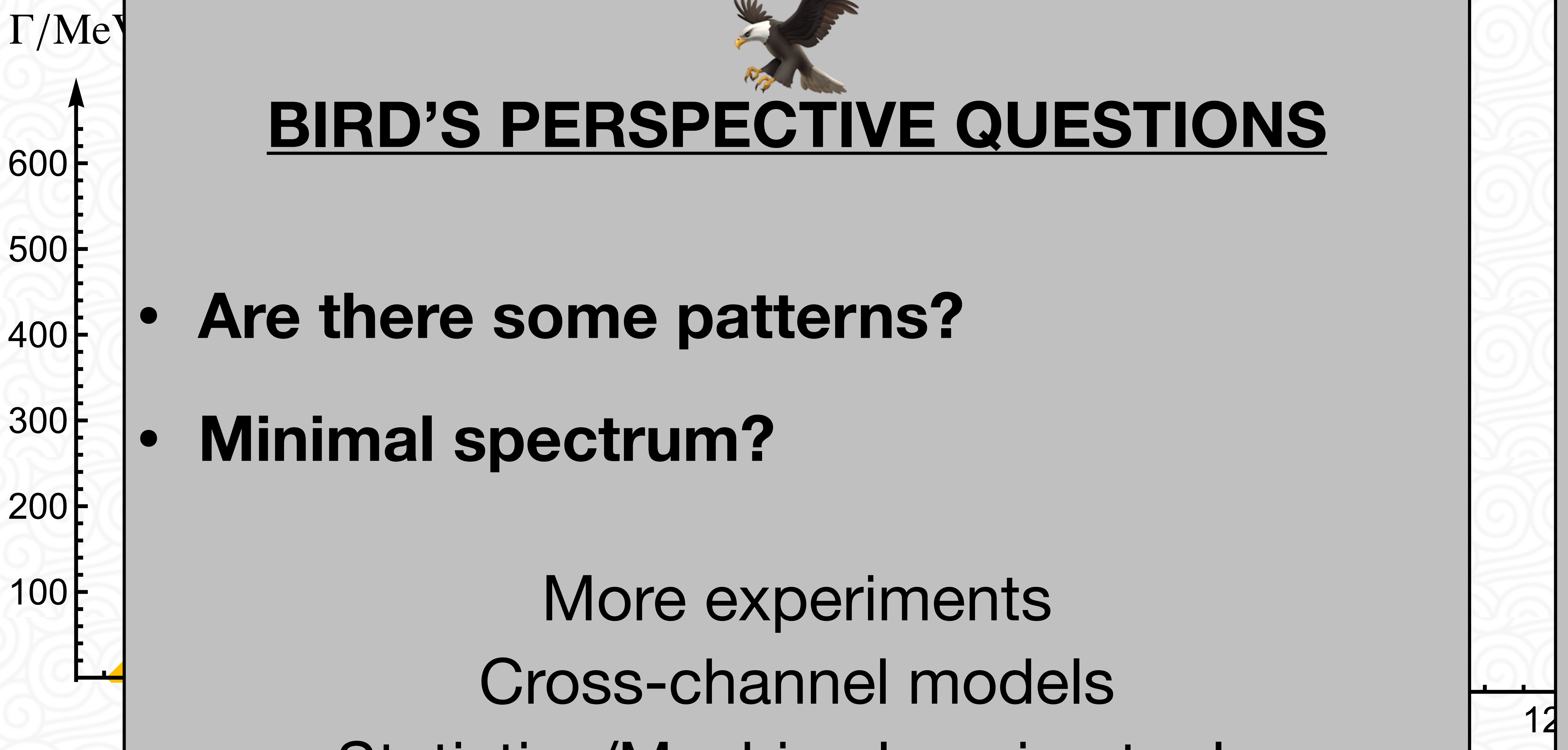


BIRD'S PERSPECTIVE QUESTIONS

- **Are there some patterns?**
- **Minimal spectrum?**

More experiments
Cross-channel models
Statistics/Machine learning tools

Unflavoured mesons @ PDG/2023

FROG'S PERSPECTIVE QUESTIONS

- **How do they form?**
- **What are their reaction mechanisms?**

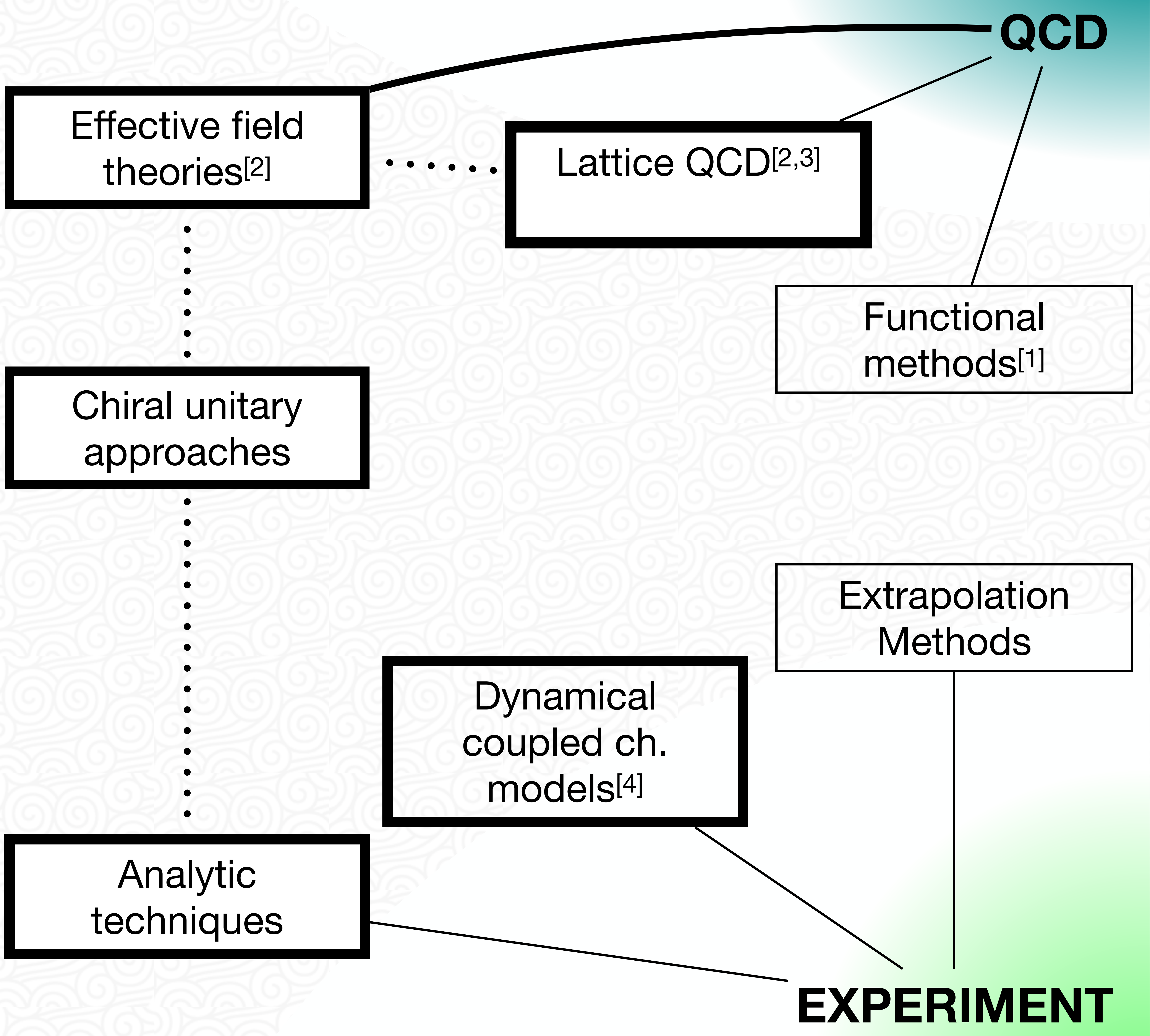
Change reaction probe
Float QCD parameter

N Baryons @ PDG/2023

THEORETICAL APPROACHES

Excited hadrons (double trouble)

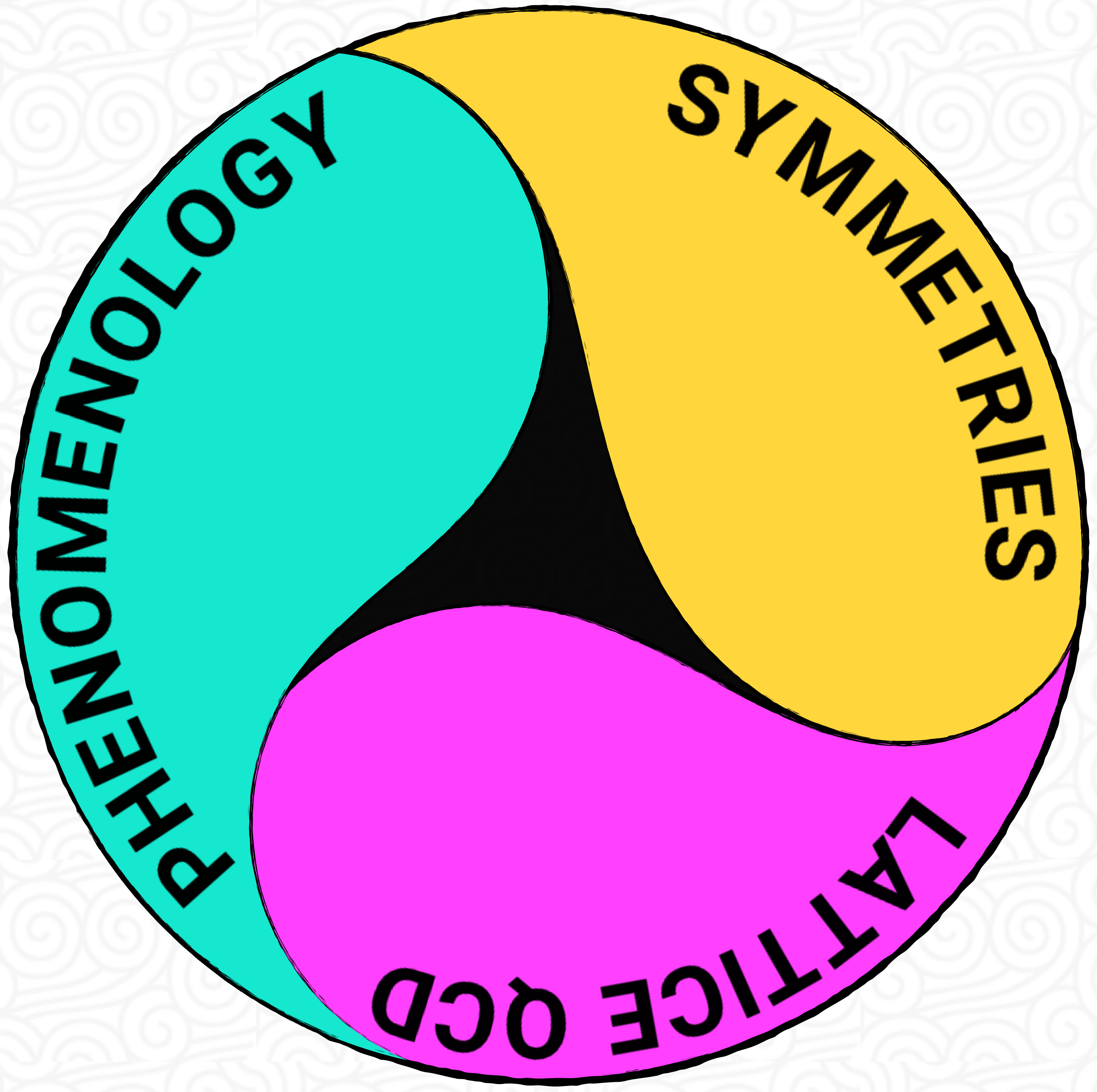
- Non-perturbative regime of QCD
- Non-perturbative phenomena



[1] Review: Eichmann/Sanchis-Alepuz/Alkofer/Fischer Prog.Part.Nucl.Phys. 91 (2016) 1-100
[2] Review: MM/Meißner/Urbach Phys.Rept. 1001 (2023) 1-6
[3] Review: Chen/Chen/Liu/Liu/Zhu Rept.Prog.Phys. 86 (2023) 2
[4] Review: Döring/Haidenbauer/Sato/MM PPNP in progress

STRANGENESS PHYSICS

Testing the limits of Effective field theories
Lattice QCD



REVIEW: MM, *Eur.Phys.J.ST* 230 (2021) 6, 1593-1607

OVERARCHING IMPACT

K^- nuclear (or atomic) states

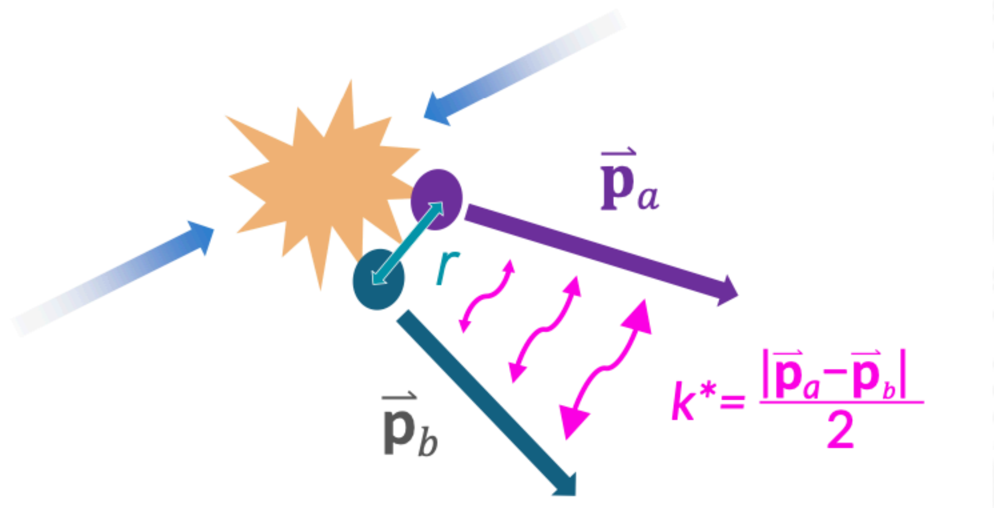
K^- nuclear optical potential

in-medium $\bar{K}N$ amplitudes

$\bar{K}N$ amplitudes in a free space

- Test of our understanding of QCD
- $\bar{K}NN$ & $\bar{K}NNN$ bound states
  Review by Gal/Hungerford/Millener (2016);
- K^- in medium
  Mareš et al. Acta Phys. Polon. B 51, 129 (2020); Hrtánkova et al. Phys.Lett. B 785, 90 (2018)

  ➡ K^--condensate can change NS EoS
- Femtoscopy/Correlations
  Michael Annan Lisa et al, Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402
  L. Fabbietti et al., ARNPS 71 (2021), 377-402



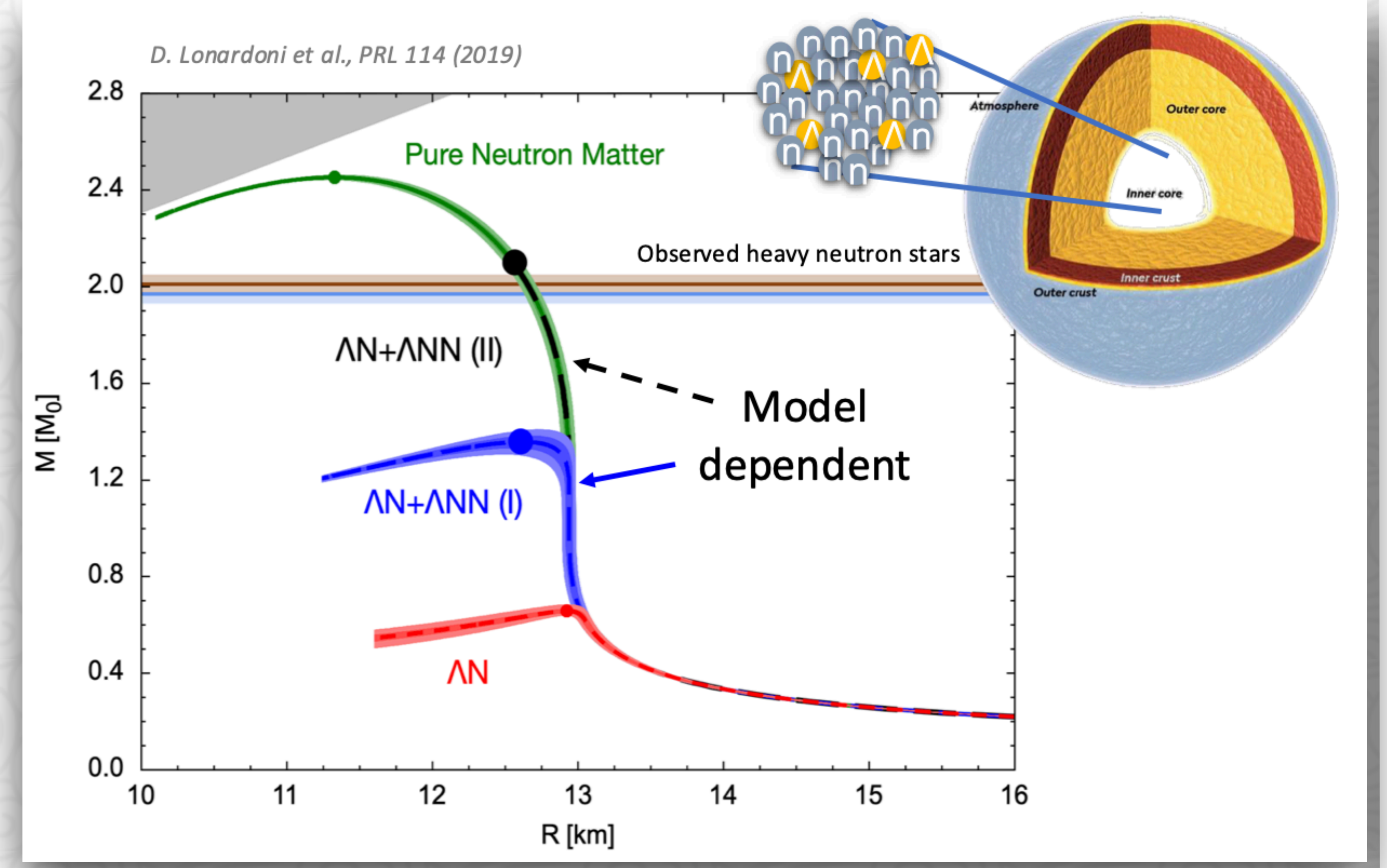
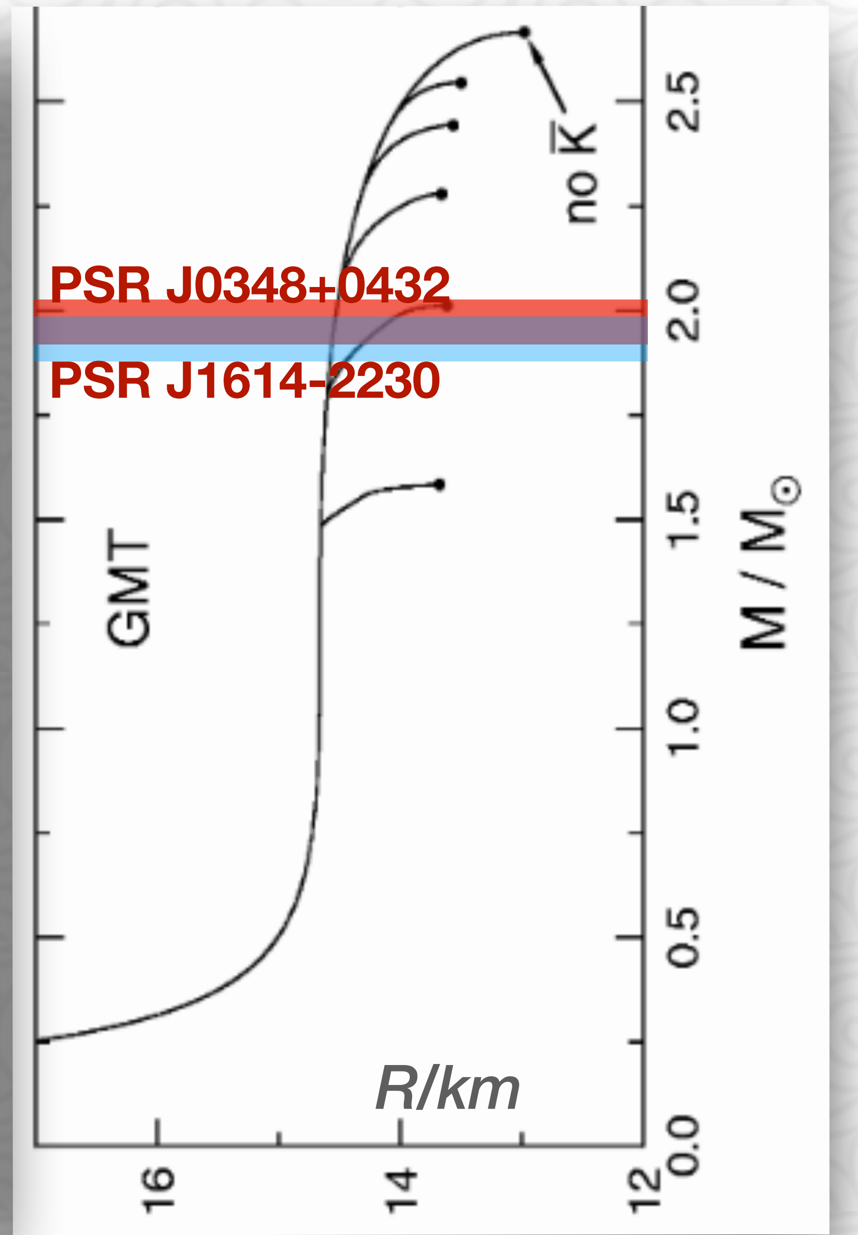


Fig.: Rafaelle Del Grande



Pal et al.,
Nucl. Phys. A 674, 553 (2000)

EXPERIMENT & THEORY

“There is a **large experimental program on production of S particles** by nuclear collisions and by photons, scattering, and interactions of those mesons with nuclei, etc. But just between us theoretical physicists: **What do we do with all these data? We can’t do anything. …**”

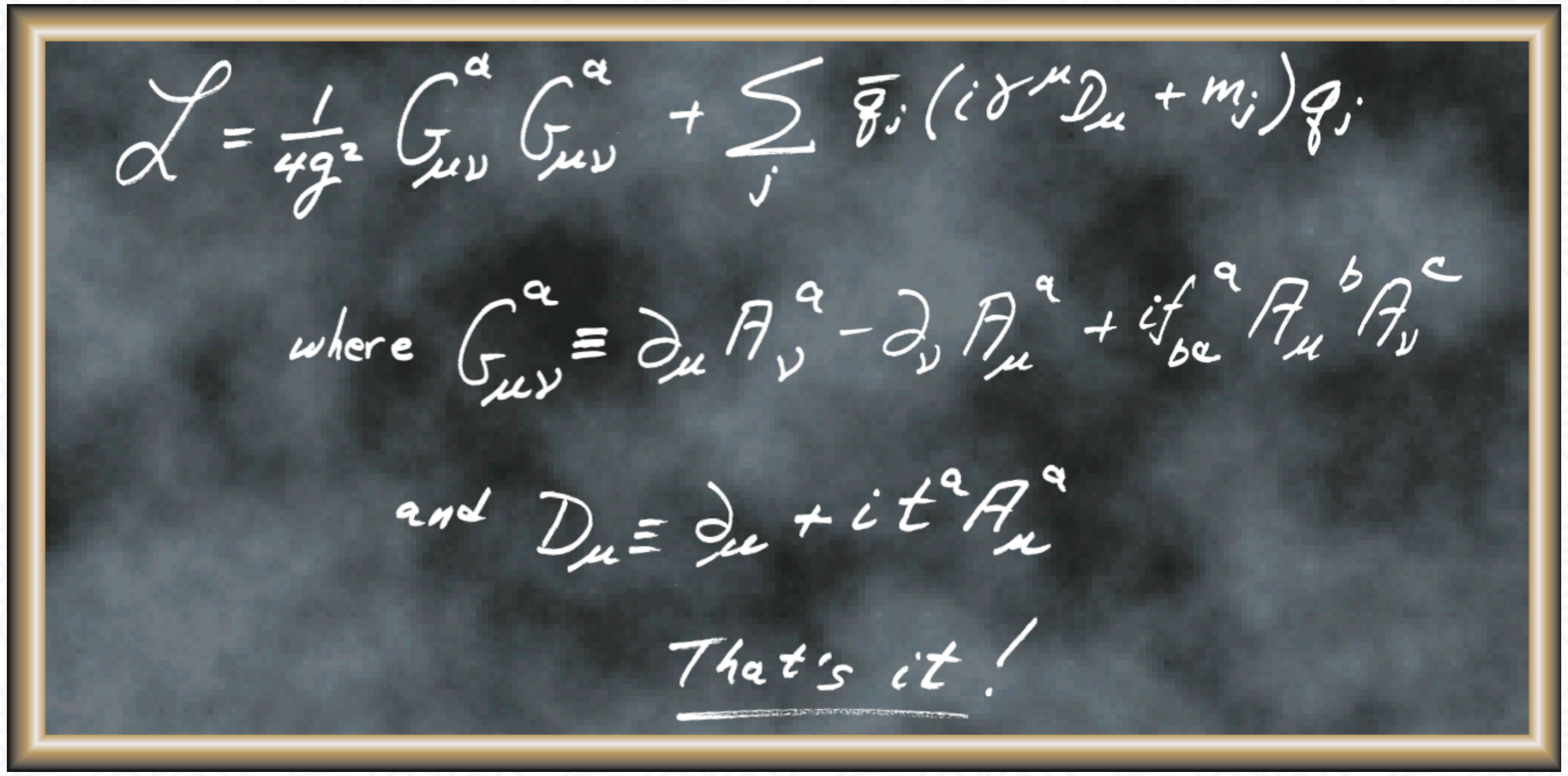
R. P. FEYNMAN

EXCITED HADRONS AND QCD

Directly from QCD? (double trouble)

- small relative momenta
- non-perturbative energy regime

Maybe Effective field theory of QCD?



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

Maybe Effective field theory of QCD?

- Effective/Hadronic degrees of freedom
- Low-energy strong interactions
- Benchmark for many scenarios

Weinberg (1979) Gasser, Leutwyler (1981)

Reviews:

V. Bernard and U.-G. Meißner, Ann. Rev. Nucl. Part. Sci. 57, 33 (2007), arXiv:hep-ph/0611231.119
V. Bernard, Prog. Part. Nucl. Phys. 60, 82 (2008), arXiv:0706.0312 [hep-ph]
S. Scherer, Adv. Nucl. Phys. 27, 277 (2003), arXiv:hep-ph/0210398

$$\mathscr{L}_{\phi B} = \left\langle \bar{B}\left(i\gamma_\mu D^\mu - m\right)B\right\rangle + \frac{D}{2}\left\langle \bar{B}\gamma_\mu\gamma_5\left\{u^\mu, B\right\}\right\rangle + \frac{F}{2}\left\langle \bar{B}\gamma_\mu\gamma_5\left[u^\mu, B\right]\right\rangle$$
$$+b_1\left\langle \bar{B}\left[u_\mu,\left[u^\mu, B\right]\right]\right\rangle + \dots$$
$$+d_4\left\langle \bar{B}\epsilon^{\mu\nu\rho\tau}\gamma^\tau\left[\left[u^\mu, u^\nu\right],\left[u^\rho, B\right]\right]\right\rangle + \dots$$
$$\dots$$

where

$$D_\mu = \partial_\mu + \frac{1}{2}[u^\dagger, \partial_\mu u] \quad u = e^{i\phi/(2F)} \quad u^\mu := iu^\dagger\partial^\mu u - iu\partial^\mu u^\dagger$$

$$\chi_\pm := u^\dagger\chi u^\dagger \pm u\chi^\dagger u \quad \chi := 2B(s - ip)$$

meson/baryon fields:

$$\phi = \sqrt{2}\begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix} \quad B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}$$

Weinberg, Gasser, Leutwyler, Bernard, Tang, Ellis, Bernard, Meißner,…

LOW-ENERGY EFT@QCD

CHPT = EFT of QCD

Weinberg (1979) Gasser, Leutwyler (1981)

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V. Bernard and U.-G. Meißner, Ann. Rev. Nucl. Part. Sci. 57, 33 (2007), arXiv:hep-ph/0611231.119
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- For hadron (strangeness) resonances it fails (perturbatively)!

  Review: MM, Eur.Phys.J.ST 230 (2021) 6, 1593-1607

  - Kaon mass is large → convergence
  - Relevant thresholds are widely separated → convergence
  - Resonance just below $\bar{K}N$ threshold → non-perturbative effect

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$$a^{I=0}_{\bar{K}N} = \Big((+0.53)_{\rm LO} + (+0.97)_{\rm NLO} + (-0.40 + 0.22i)_{\rm NNLO} + \ldots\Big)\ \text{fm}$$

$$a^{I=1}_{\bar{K}N} = \Big((+0.20)_{\rm LO} + (+0.22)_{\rm NLO} + (-0.26 + 0.18i)_{\rm NNLO} + \ldots\Big)\ \text{fm}$$

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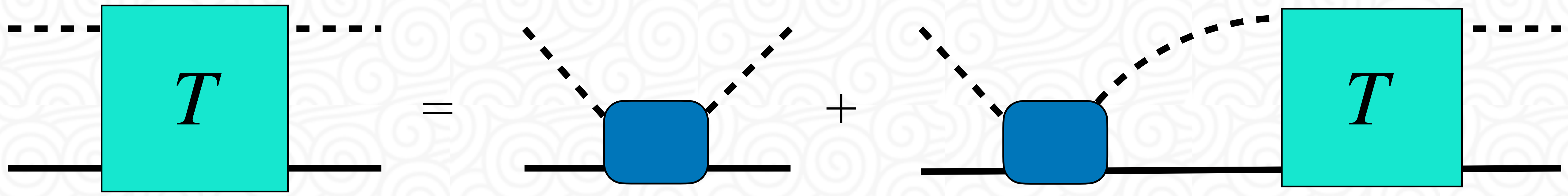
- Extension to higher energies, unitarity restoration — Chiral Unitary Approach (**UCHPT**)

  Weise/Kaiser/Meißner/Lutz/Oset/Oller/Ramos/Hyodo/Borasoy/MM/Bruns/…



CHIRAL UNITARY APPROACH

Good

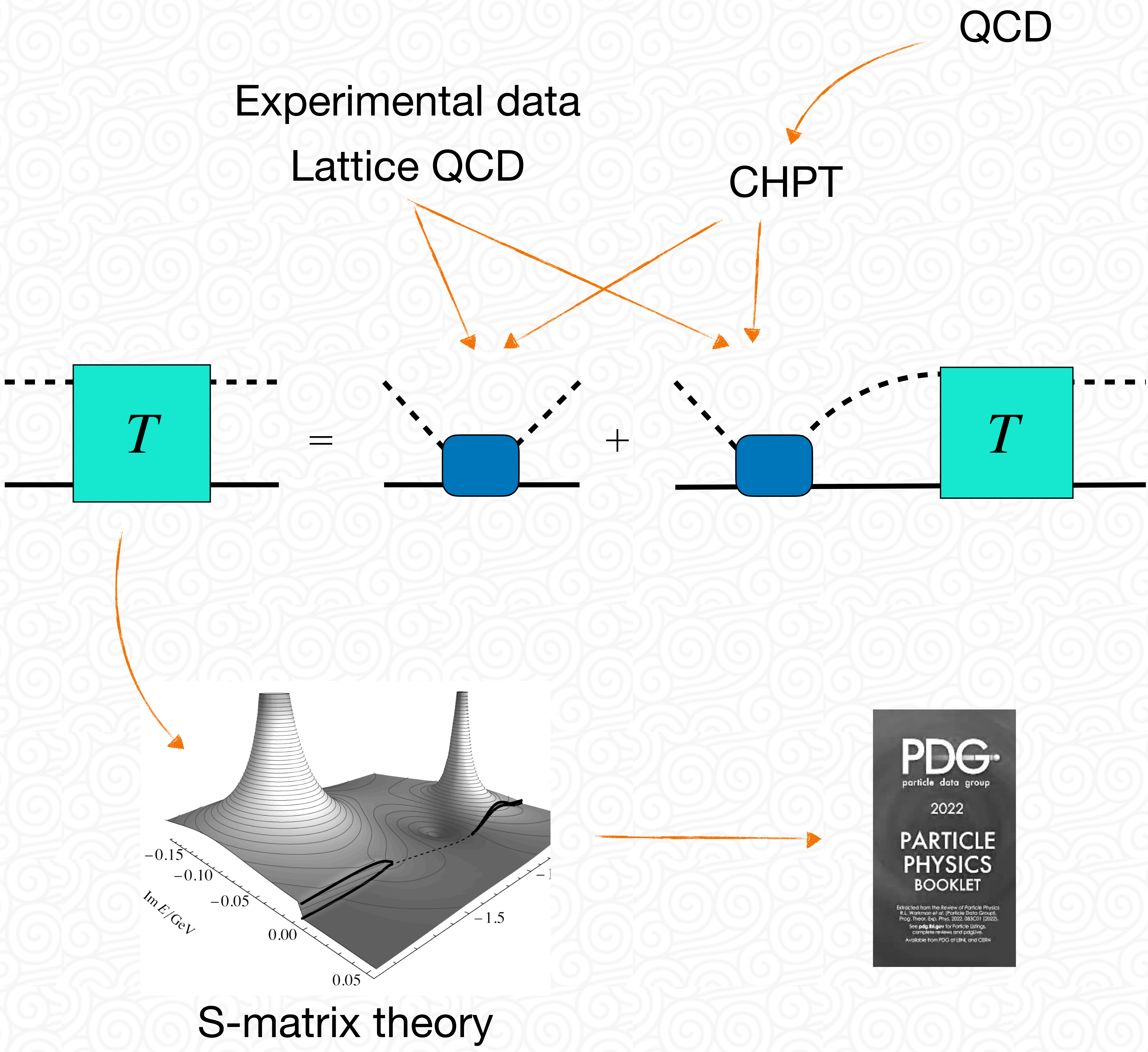
- Non-perturbative scheme
- Record complex pole-positions (*II Riemann Sheet*)
- Often works:
  $N(1535), N(1650), \Lambda(1405), \Lambda(1380), \ldots$

Kaiser/Siegel/Weise Phys.Lett.B 362 (1995)
Lutz/Soyeur Nucl.Phys.A 773 (2006);
MM et al. Phys.Lett.B 697 (2011); …

Attention

- Renormalisation/Crossing symmetry/Power counting only perturbatively
- Choice of interaction kernel

MM et al. Phys.Lett.B 697 (2011); …



EXPERIMENT & THEORY

"There is a **large experimental program on production of S particles** by nuclear collisions and by photons, scattering, and interactions of those mesons with nuclei, etc. But just between us theoretical physicists: **What do we do with all these data? We can't do anything. ...**"

R. P. FEYNMAN

THE ENIGMA OF THE $\Lambda(1405)$

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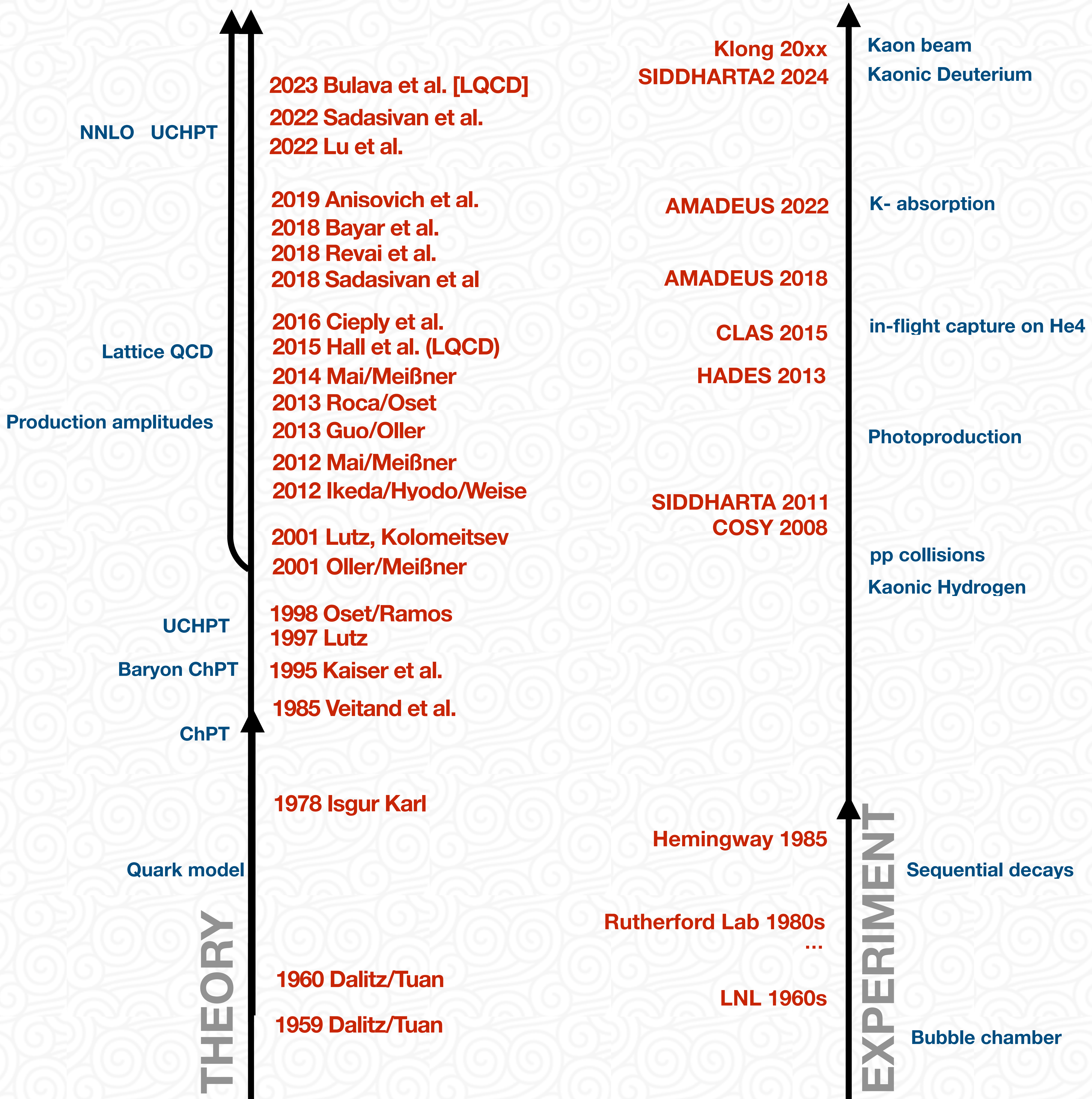
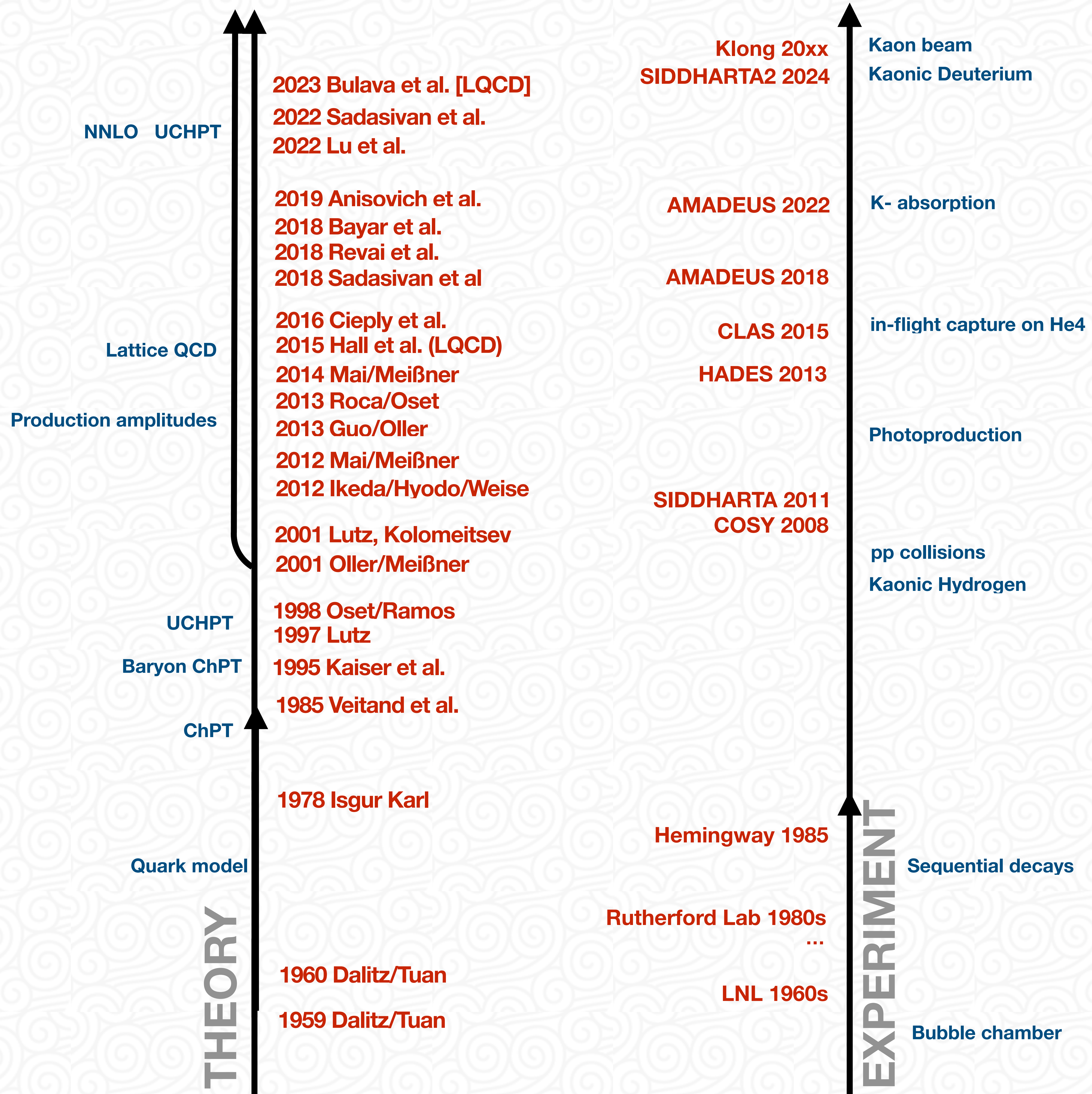


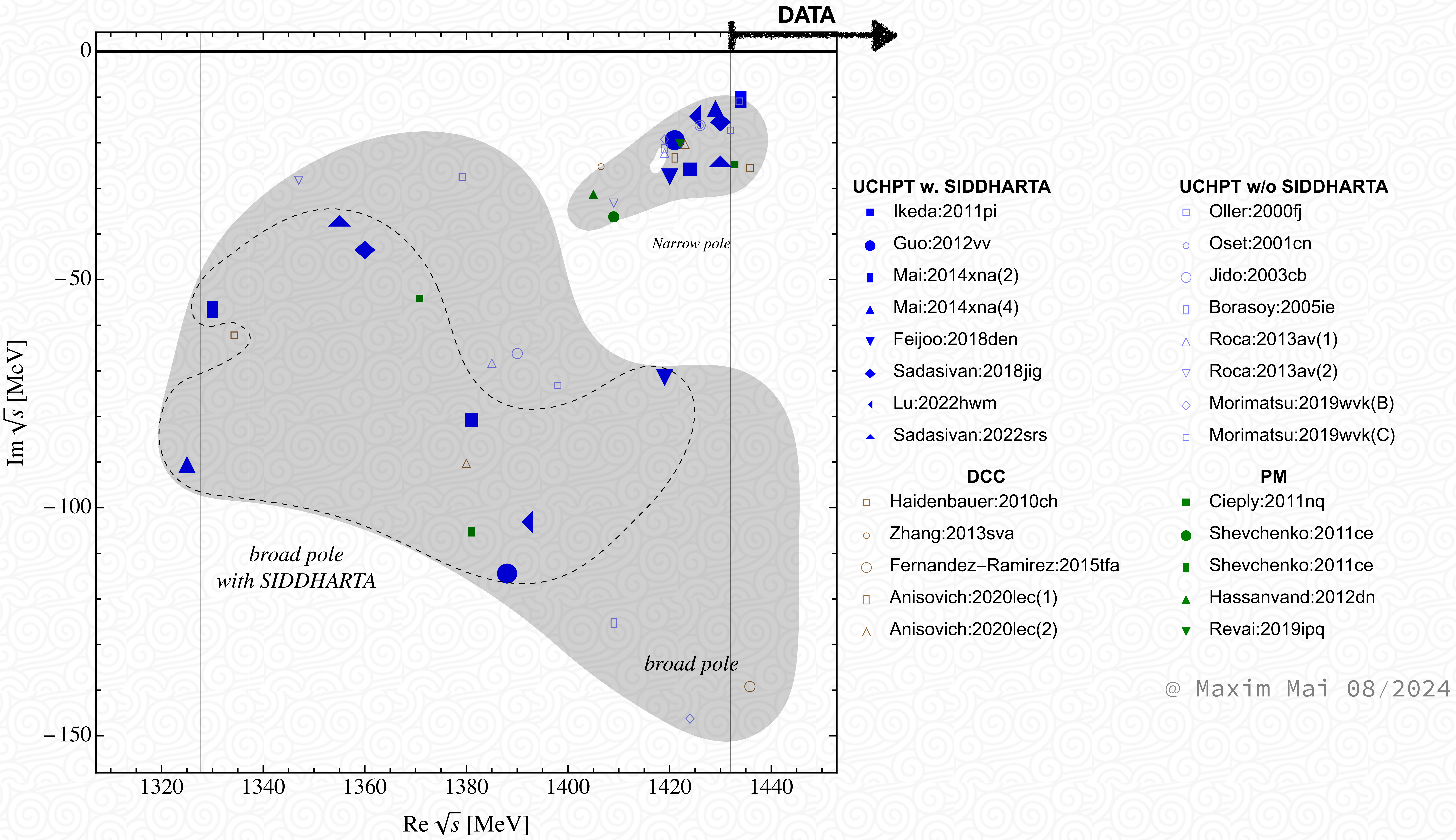
THE ENIGMA OF THE $\Lambda(1405)$

Long history of experimental and theoretical efforts

- Sub-($\bar{K}N$)-threshold $\Lambda(1405)$ resonance
- second state $\Lambda(1380)$ predicted from UCHPT
- no direct experimental verification
- confirmed by many critical tests & LQCD



CURRENT STATUS OF THE $\Lambda(1405)$



UNPHYSICAL QUARK MASSES

CHPT encodes quark mass dependence

- SU(3) limit provides a simpler resonance structure

  Jido et al. Nucl.Phys.A 725 (2003); Garcia-Recio/Lutz/Nieves Phys.Lett.B 582 (2004) 49-54;

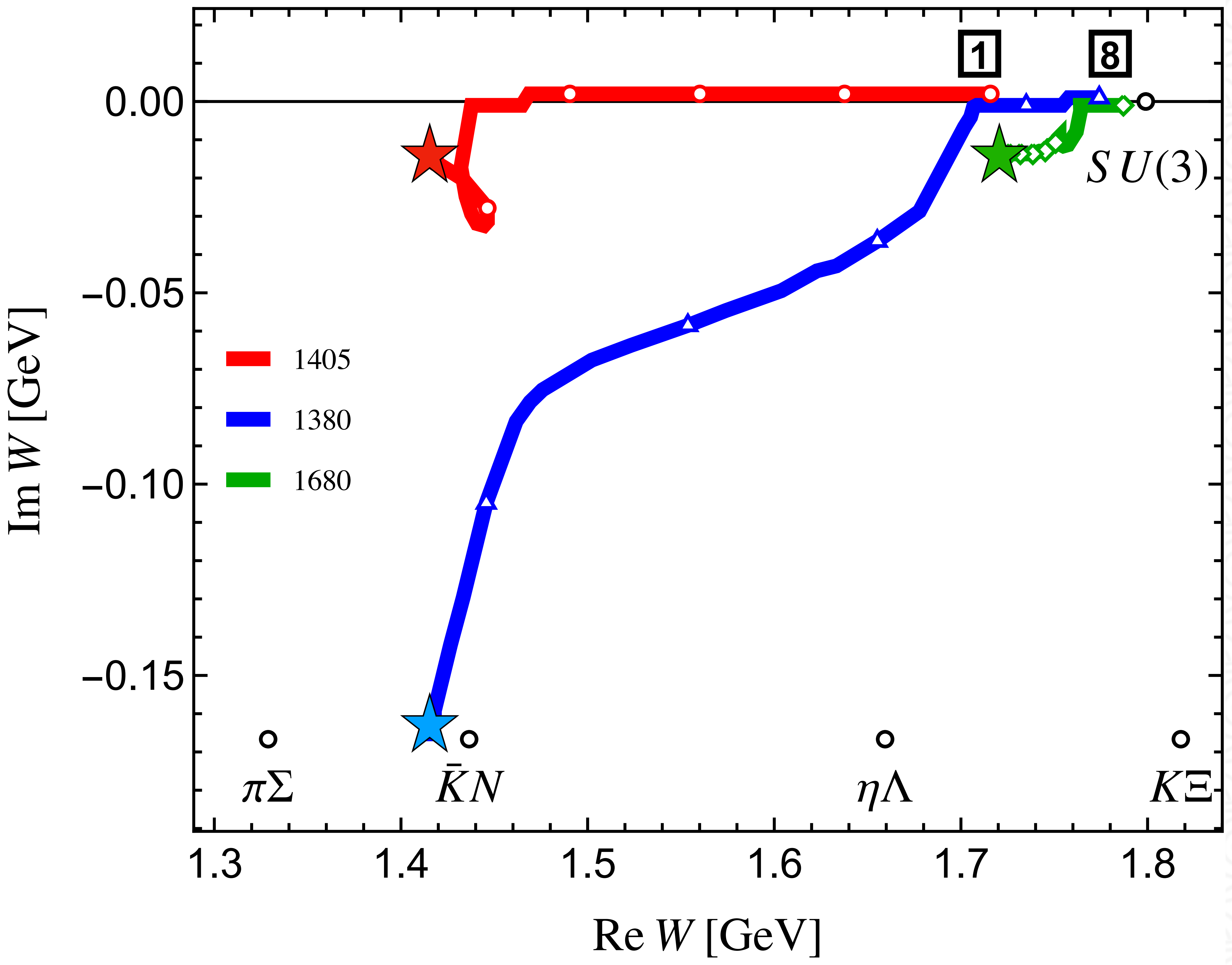
  → 1 singlet + 2 octet poles

  → LO/NLO "tracks" differ

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

- Resonance ↔ virtual bound state ↔ bound state

  (?) Lattice QCD



LATTICE HADRON SPECTROSCOPY

Numerical evaluation of QCD Green's functions

- Euclidean discretised (UV) space-time, finite volume (IR)

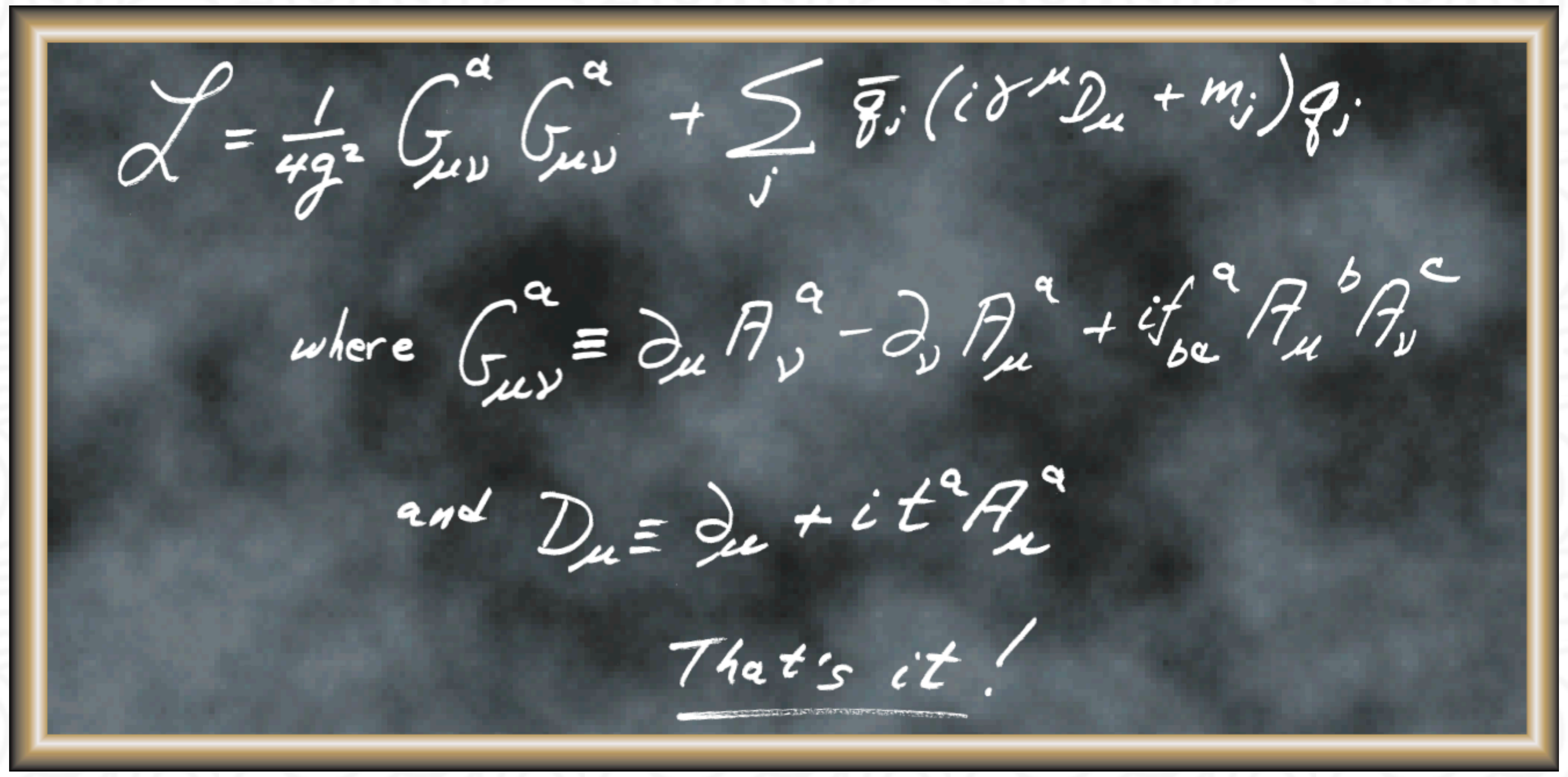
Experimentally inaccessible scenarios:

→ Unconventional quantum numbers

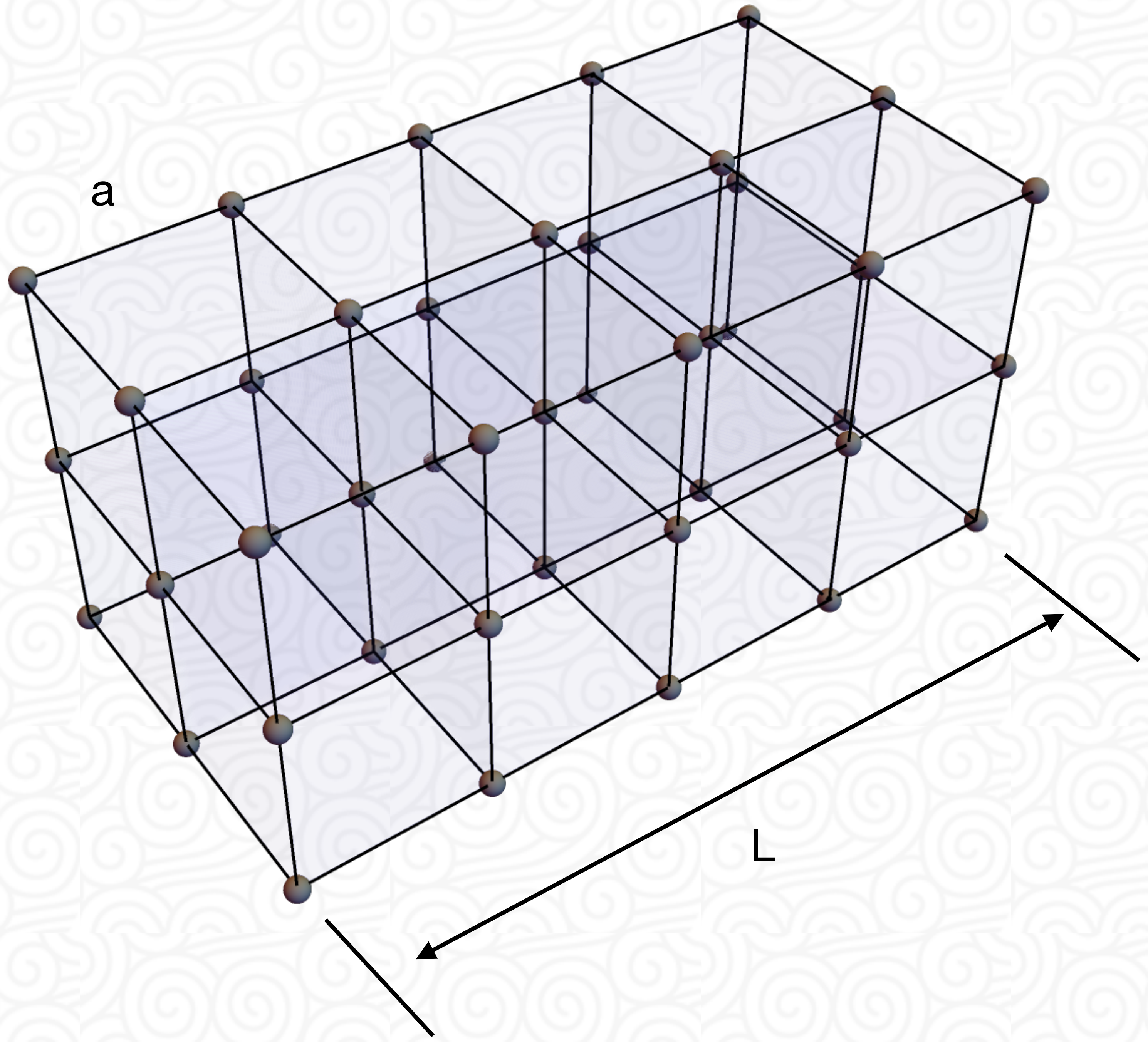
→ Three-body scattering

→ Unphysical pion mass (chiral trajectories)

…

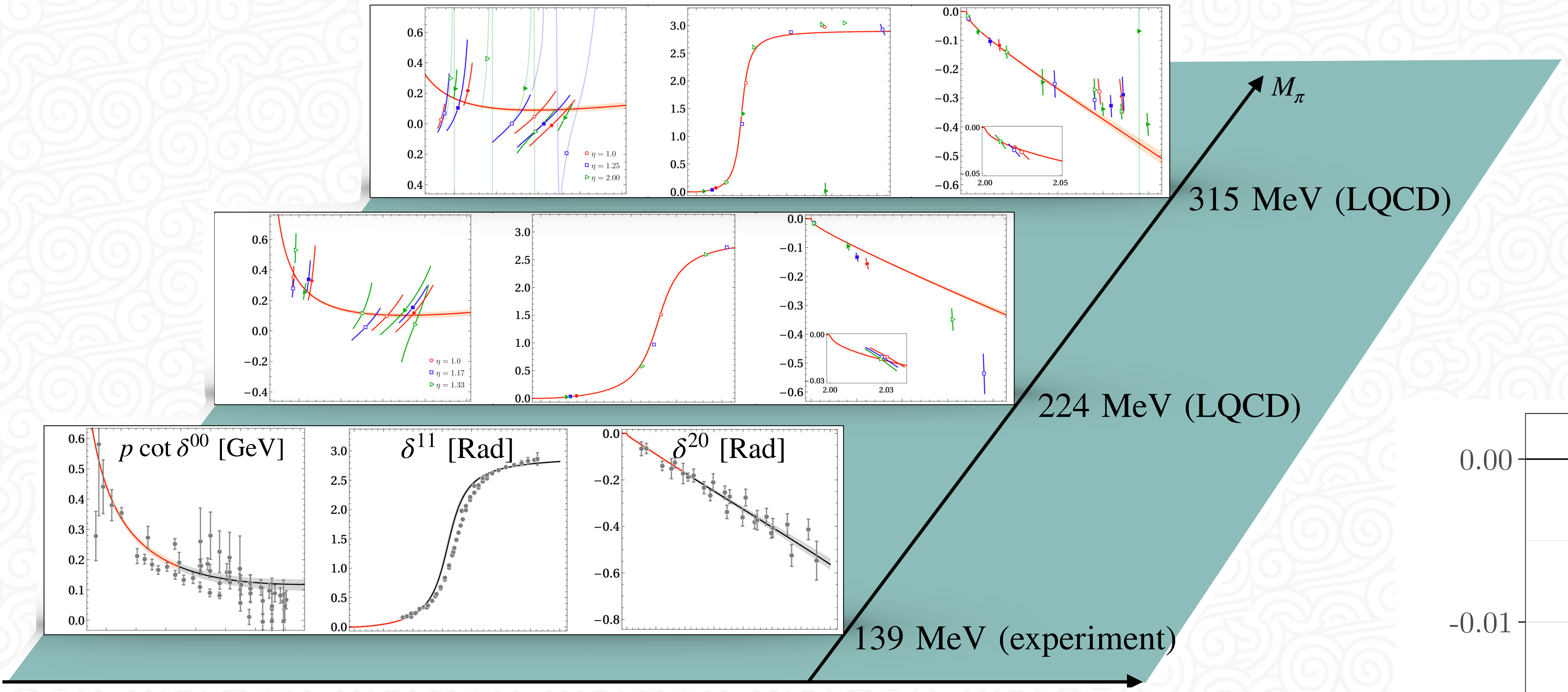


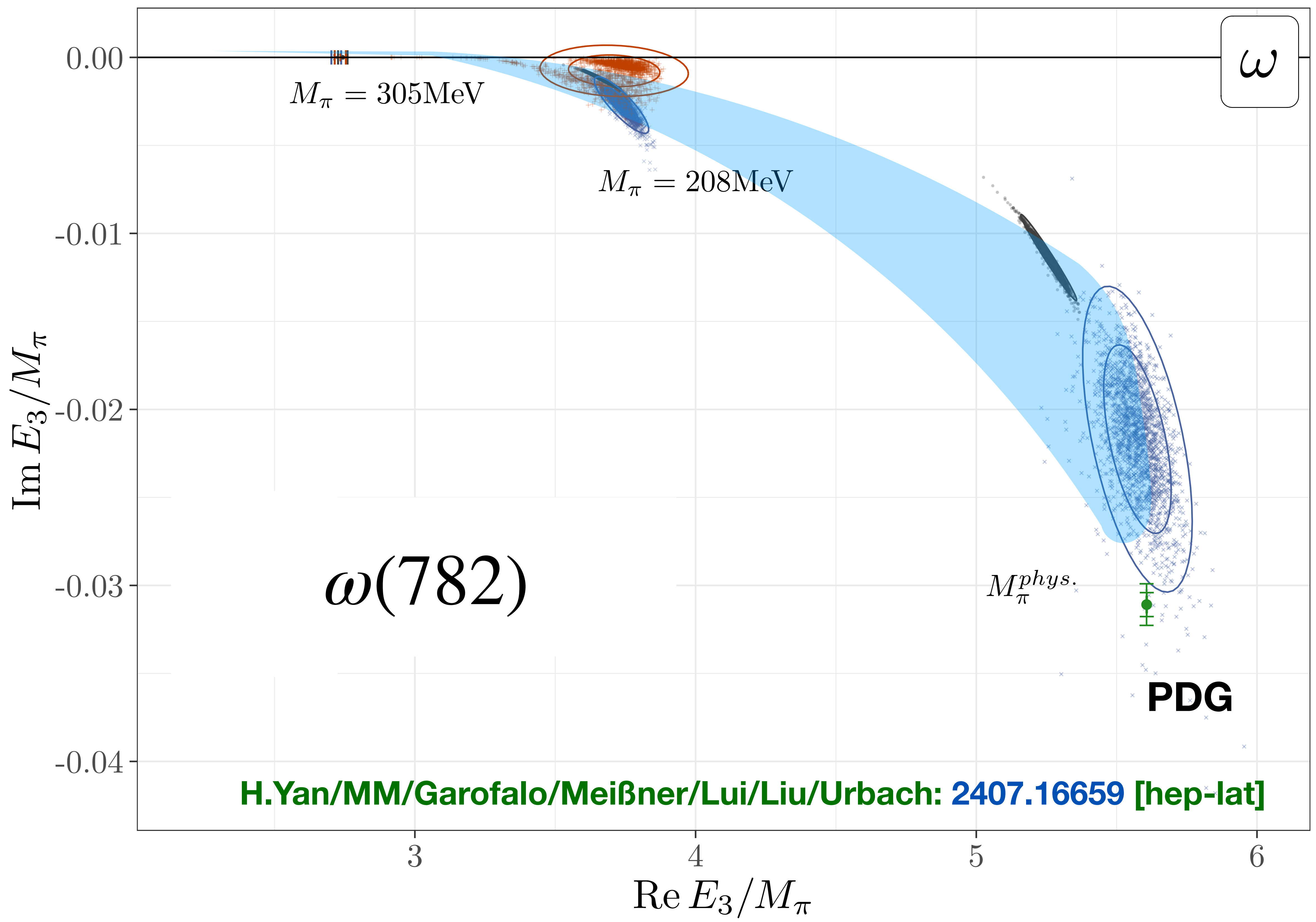
http://frankwilczek.com/Wilczek_Easy_Pieces/298_QCD_Made_Simple.pdf



LATTICE HADRON SPECTROSCOPY

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





H.Yan/MM/Garofalo/Meißner/Lui/Liu/Urbach: 2407.16659 [hep-lat]

Current frontier: three-body resonances from LQCD

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

UNPHYSICAL QUARK MASSES

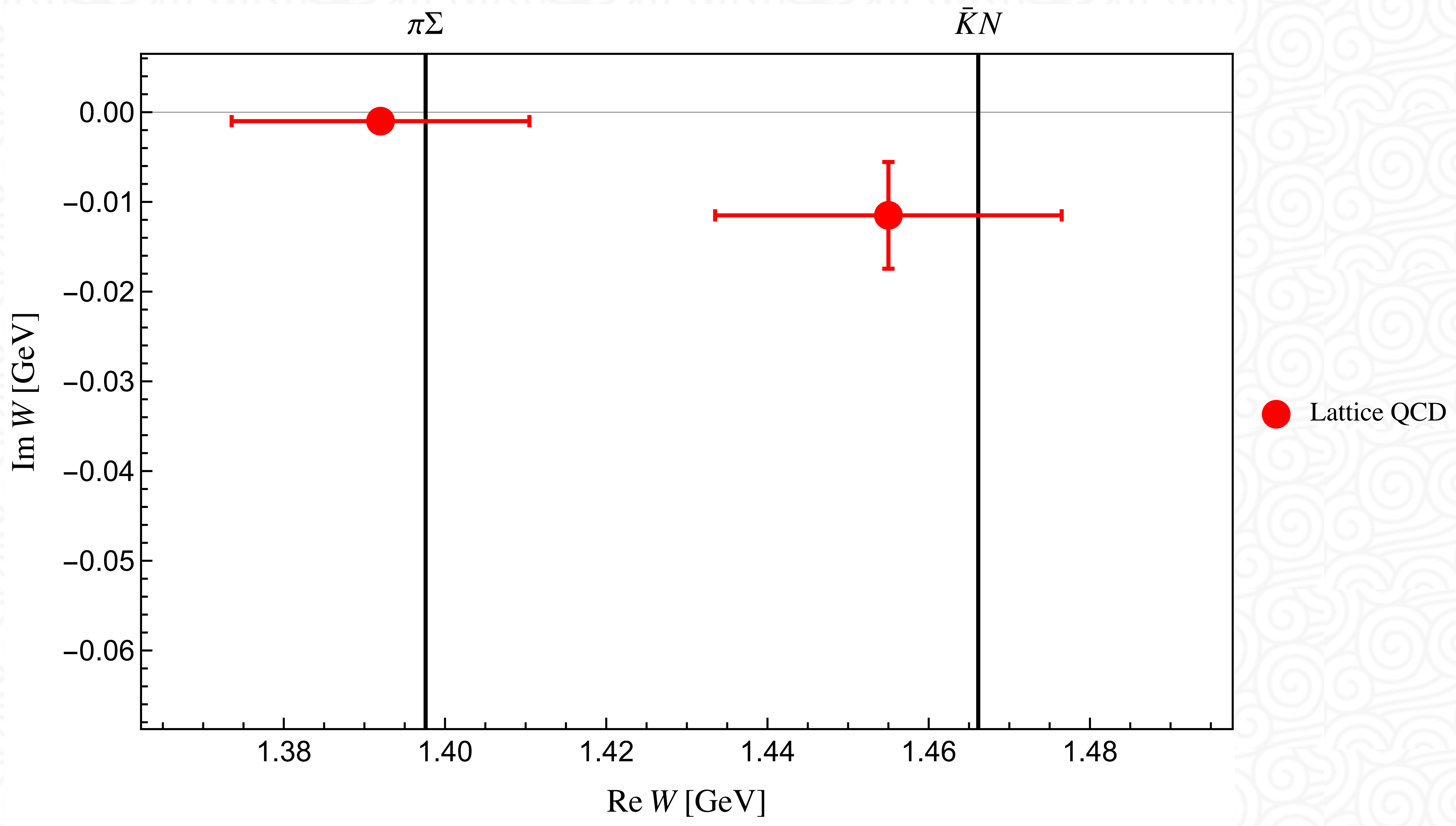
CHPT encodes quark mass dependence

- Available Lattice spectrum

[BaSc] Bulava et al. Phys.Rev.Lett. 132 (2024) 5; 2307.13471

$M_\pi \approx 200\,\mathrm{MeV}\ \ M_K \approx 487\,\mathrm{MeV}$

$M_\pi L = 4.181(16)\quad a = 0.0633(4)(6)\,\mathrm{fm}$



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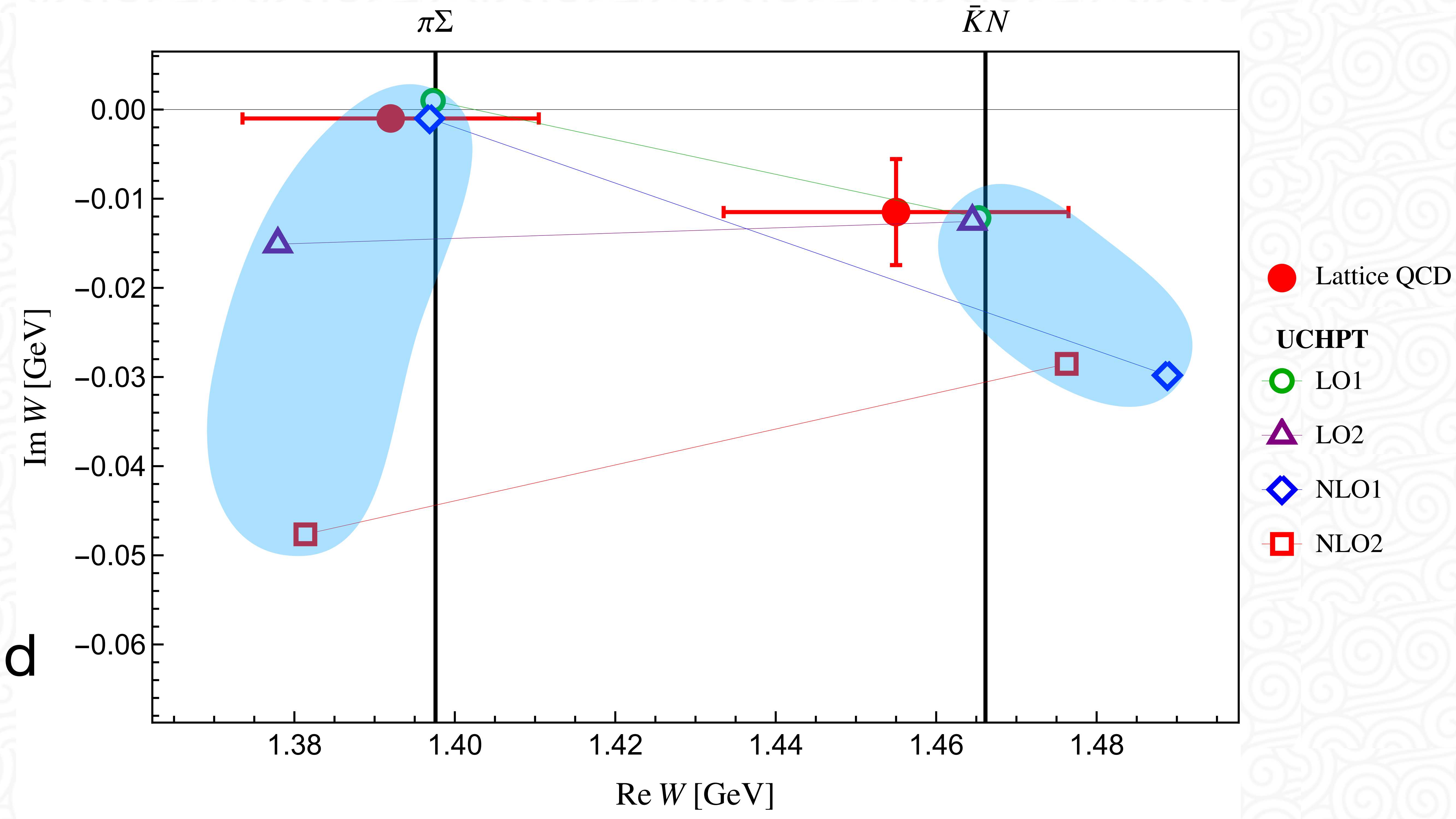
$M_\pi L = 4.181(16)$ $a = 0.0633(4)(6)\,\mathrm{fm}$

Compare to prediction of UHPT

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

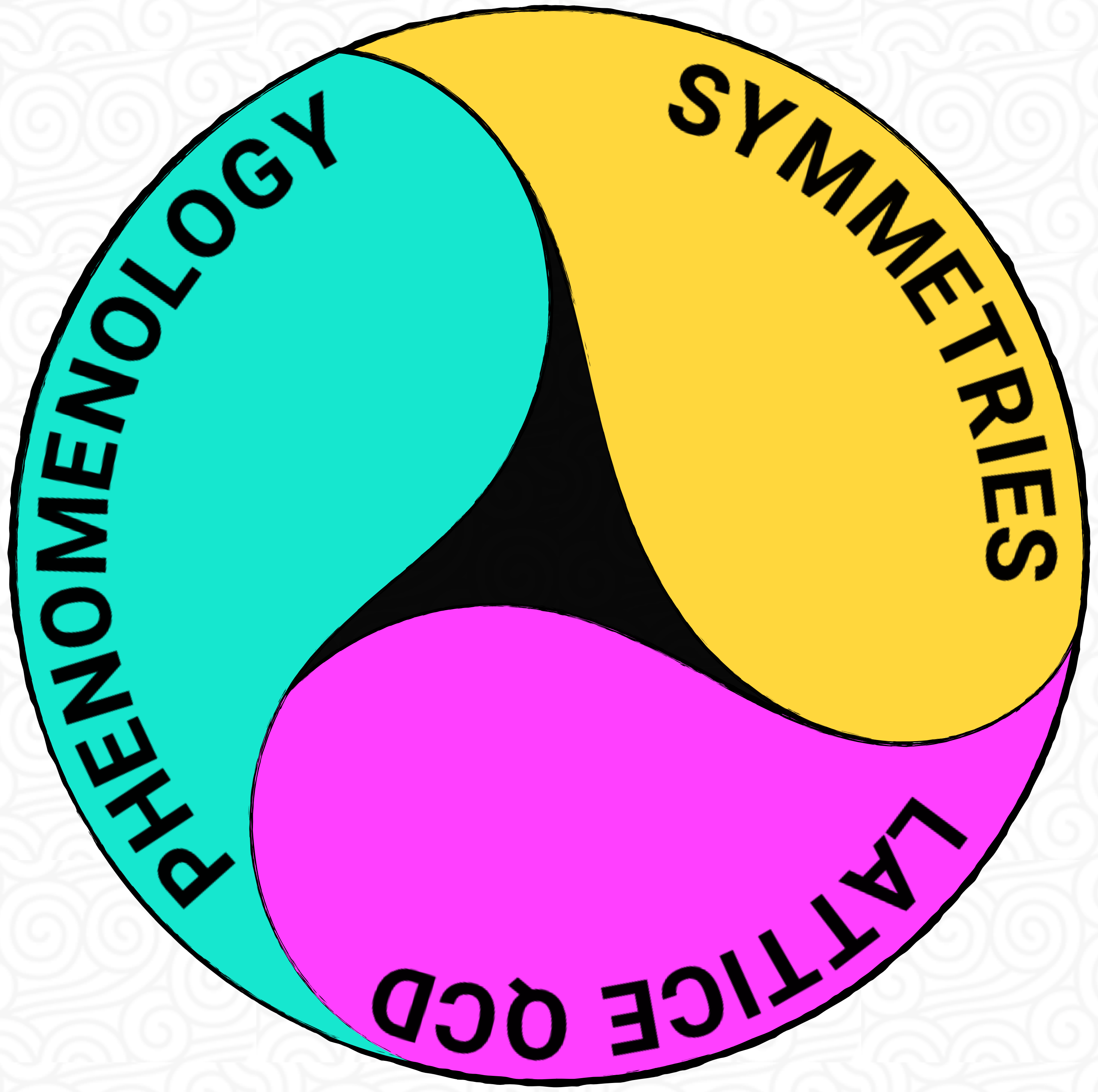
- mostly ok but not always
- possible disagreement between old $K^- p$ data and LQCD

>> experiment/theory update needed.



ELECTROPRODUCTION

Probing the structure of resonances



PHOTON-INDUCED EXCITATION

Nature of states

- Momentum transfer dependence
  $Q^2 = -q_0^2 + |\vec{q}|^2$

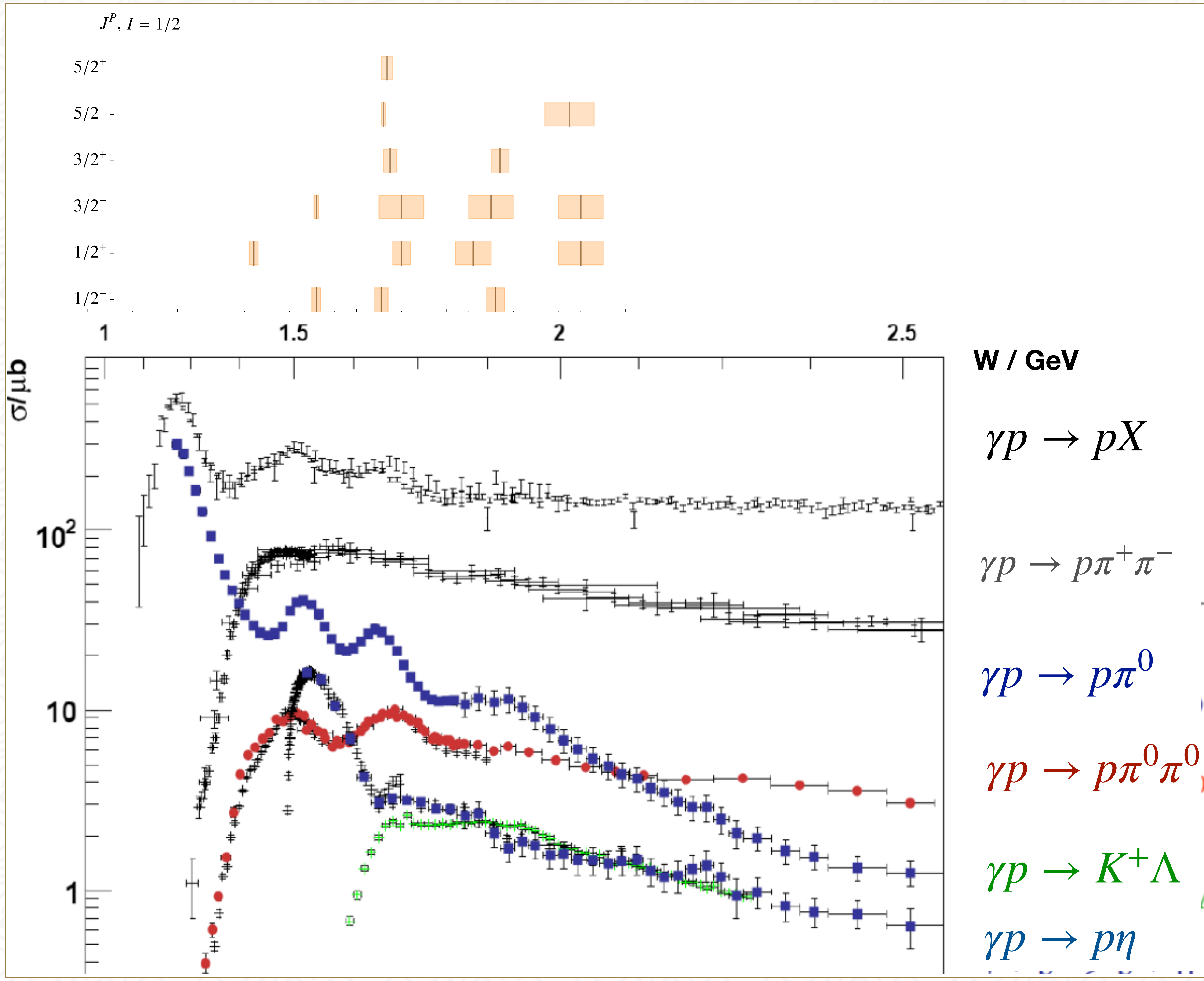
- Compositeness(?)

Experimental accessibility

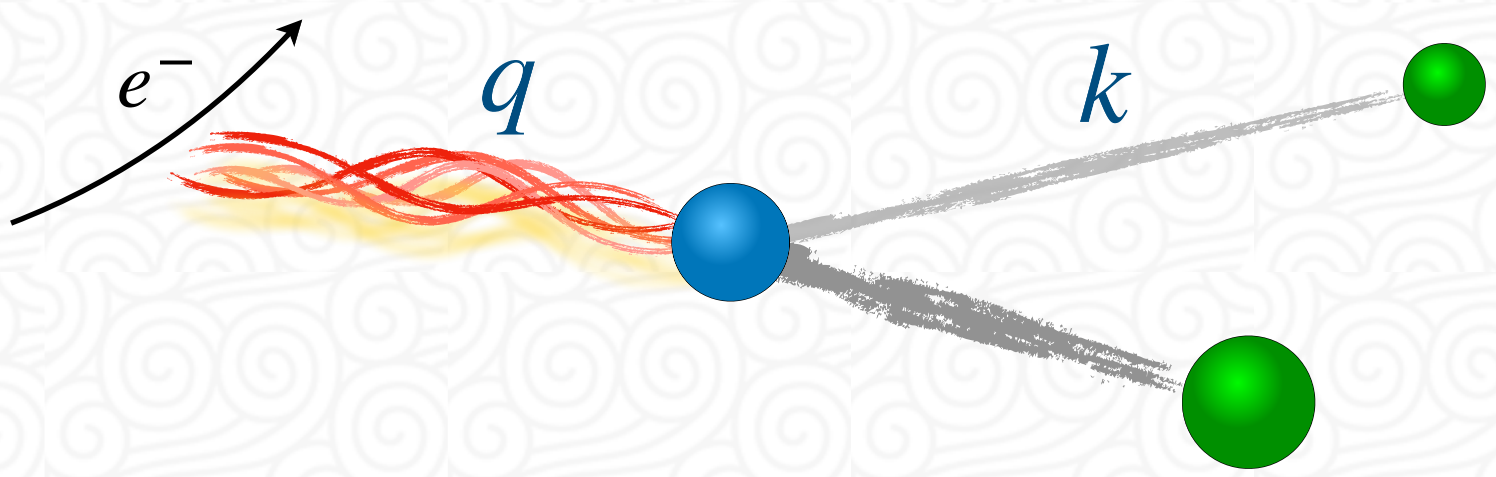
- Large amount of data $(\sim 10^5)$

- more data coming up from, e.g., JLab
  $Q^2 = 5 - 12\,\mathrm{GeV}^2$

Carman, Joo, Mokeev, Few Body Syst. 61, 29 (2020) ... ; [CLAS] Phys.Rev.C 105 (2022) 065201; ...



KINEMATICAL VARIABLES

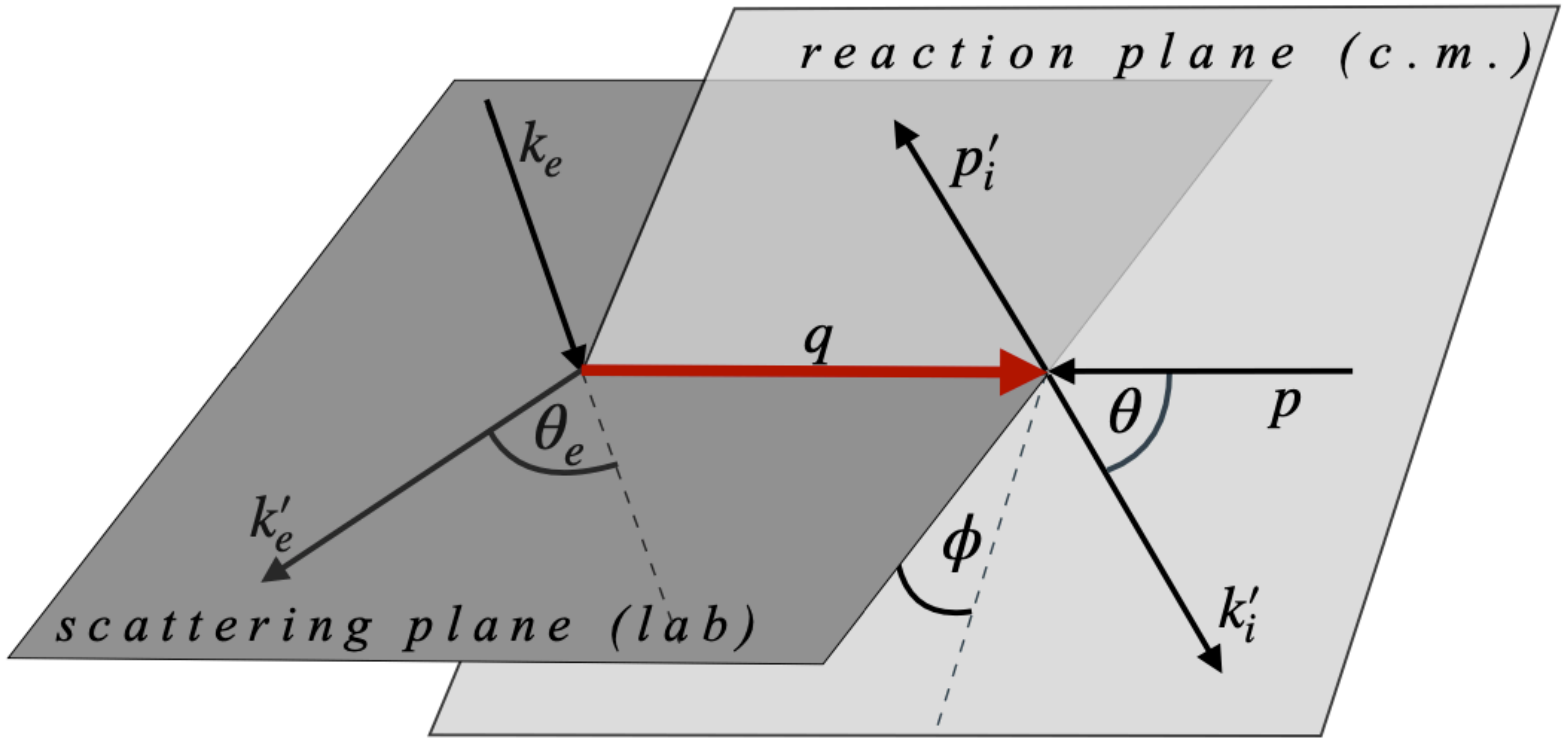


Five kinematical variables (3*(2+3)-10=5)

1. total energy: W
2. photon virtuality: Q^2
3. transverse photon polarisation:

$$\epsilon = 1 + 2\frac{q_L^2}{Q^2}\tan^2\frac{\theta_e}{2}$$

4. production angles: θ, φ



MULTIPOLES — OBSERVABLES

Observable (e.g. cross section) $\frac{d\sigma^v}{d\Omega}\left(W,Q^2,\epsilon,\theta,\phi\right) = \sigma_T + \epsilon\sigma_L + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi + \ldots$

↑

Structure functions $\sigma_T\left(W,Q^2,\theta\right) = k/q_\gamma\left(|H_1|^2+|H_2|^2+|H_3|^2+|H_4|^2\right)/2\,,\ldots$

↑

Helicity amplitudes $H_1\left(W,Q^2,\theta\right) = \sin\theta\cos\theta/2(-\mathcal{F}_3-\mathcal{F}_4)/\sqrt{2}\,,\ldots$

↑

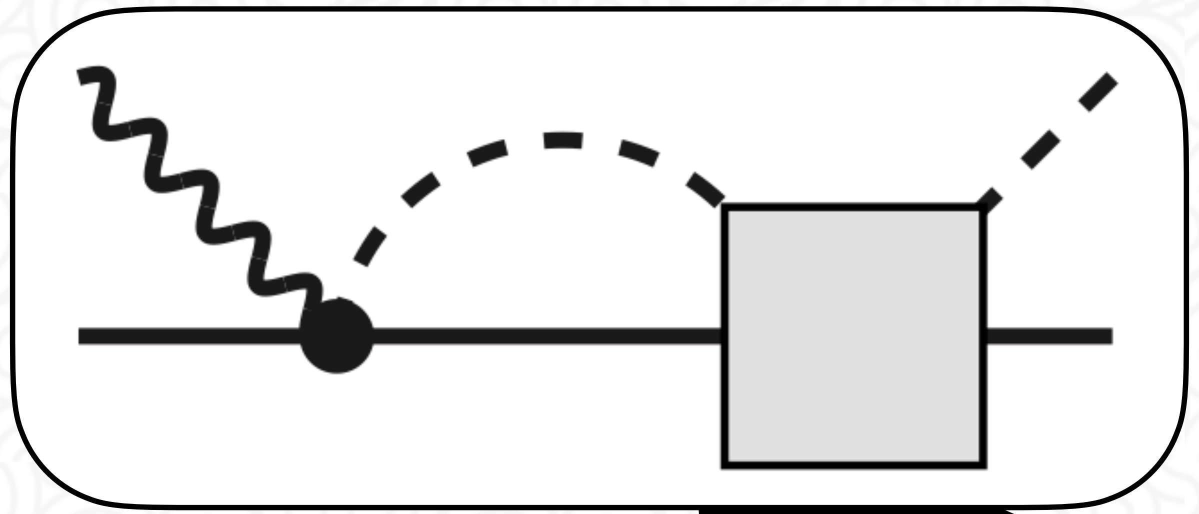
CGLN amplitudes $\mathcal{F}_1\left(W,Q^2,\theta\right) = \sum_{\ell\geq 0}\ell M_{\ell+}(W,Q^2)P'_{\ell+1}(\cos\theta) + \ldots$

↑

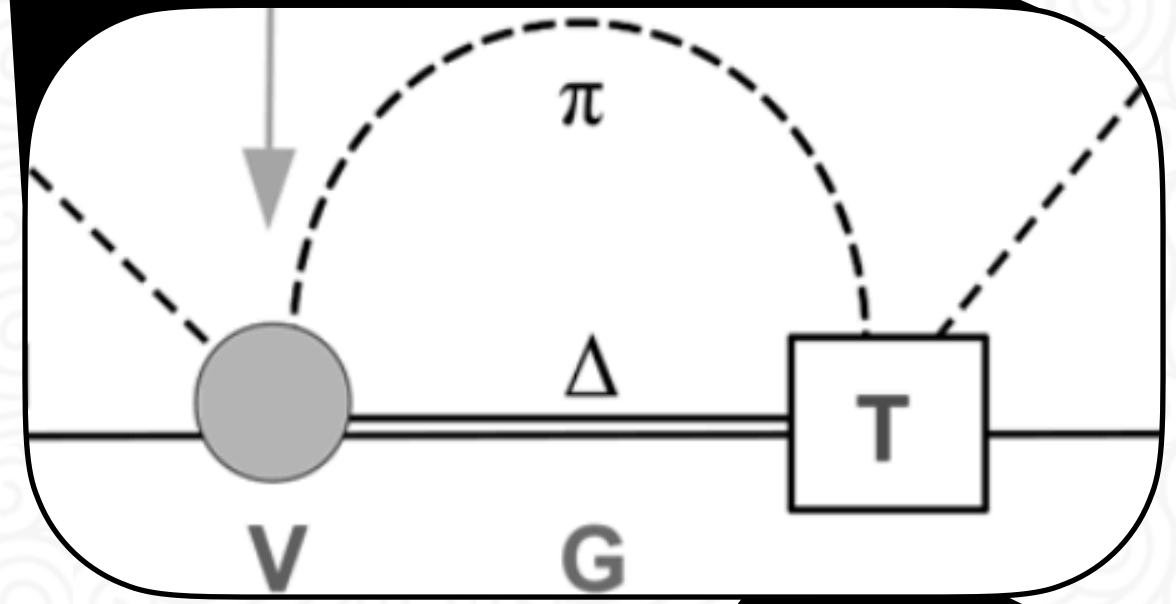
Multipoles $\{E_{\ell\pm}(W,Q^2), L_{\ell\pm}(W,Q^2), M_{\ell\pm}(W,Q^2)\}$

Chew et al. Phys.Rev. 106 (1957); Dennery Phys.Rev. 124 (1961); Berends et al. Nucl.Phys.B 4 (1967); ... (for explicit formulas) MM et al. Phys.Rev.C 103 (2021)

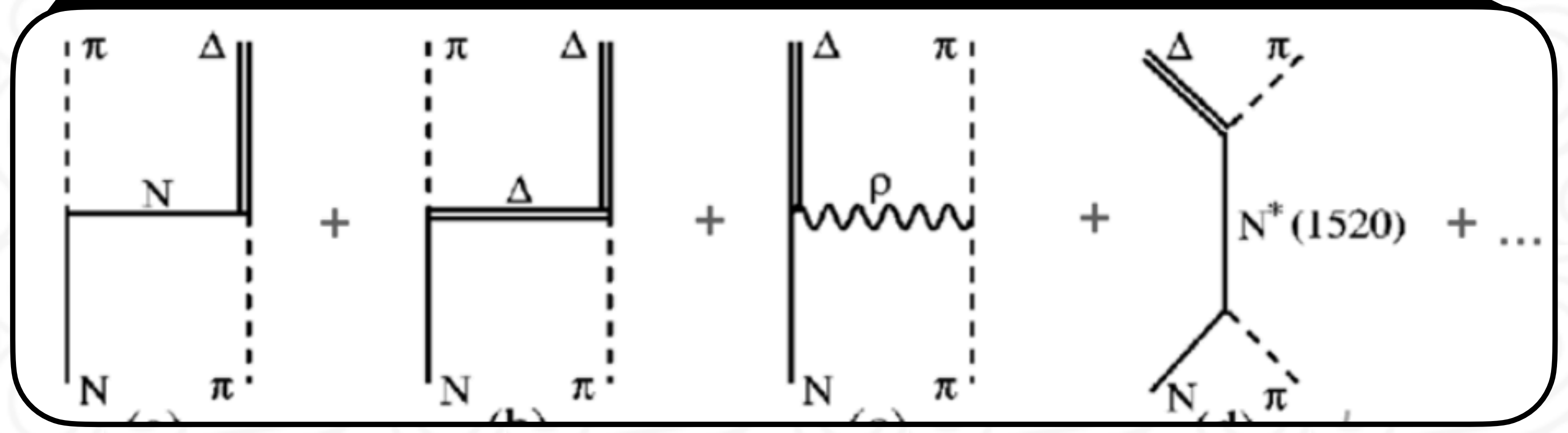
JÜLICH-BONN WASHINGTON



- Gauge invariance (CGLN constraints)
  Chew et al. Phys.Rev. 106 (1957); Dennery Phys.Rev. 124 (1961); Berends et al. Nucl.Phys.B 4 (1967);
- Siegert's theorem — low wavelength limit
  A. J. F. Siegert, Phys. Rev. 52, 787 (1937) L. Tiator, Few Body Syst. 57, 1087 (2016).
- Photon virtuality dependence



- Lippmann-Schwinger equation
- **Final-state unitarity**
- Coupled channel dynamics



- Phenomenological Lagrangians
- Meson/Baryon exchange parametrisation

MM, M. Döring, C. Granados, H. Haberzettl, Ulf-G. Meißner, D. Rönchen, I. Strakovsky, R. Workman Published in: Phys.Rev.C 103 (2021) 6, 065204 e-Print: 2104.07312 [nucl-th]
D. Rönchen, M. Döring, F. Huang, H. Haberzettl, J. Haidenbauer, C. Hanhart, S. Krewald, U.-G. Meißner, and K. Nakayama, Eur. Phys. J. A 50, 101 (2014), [Erratum: Eur.Phys.J.A 51, 63 (2015)], arXiv:1401.0634 [nucl-th].
...

DATA VALIDATION

Experimental data

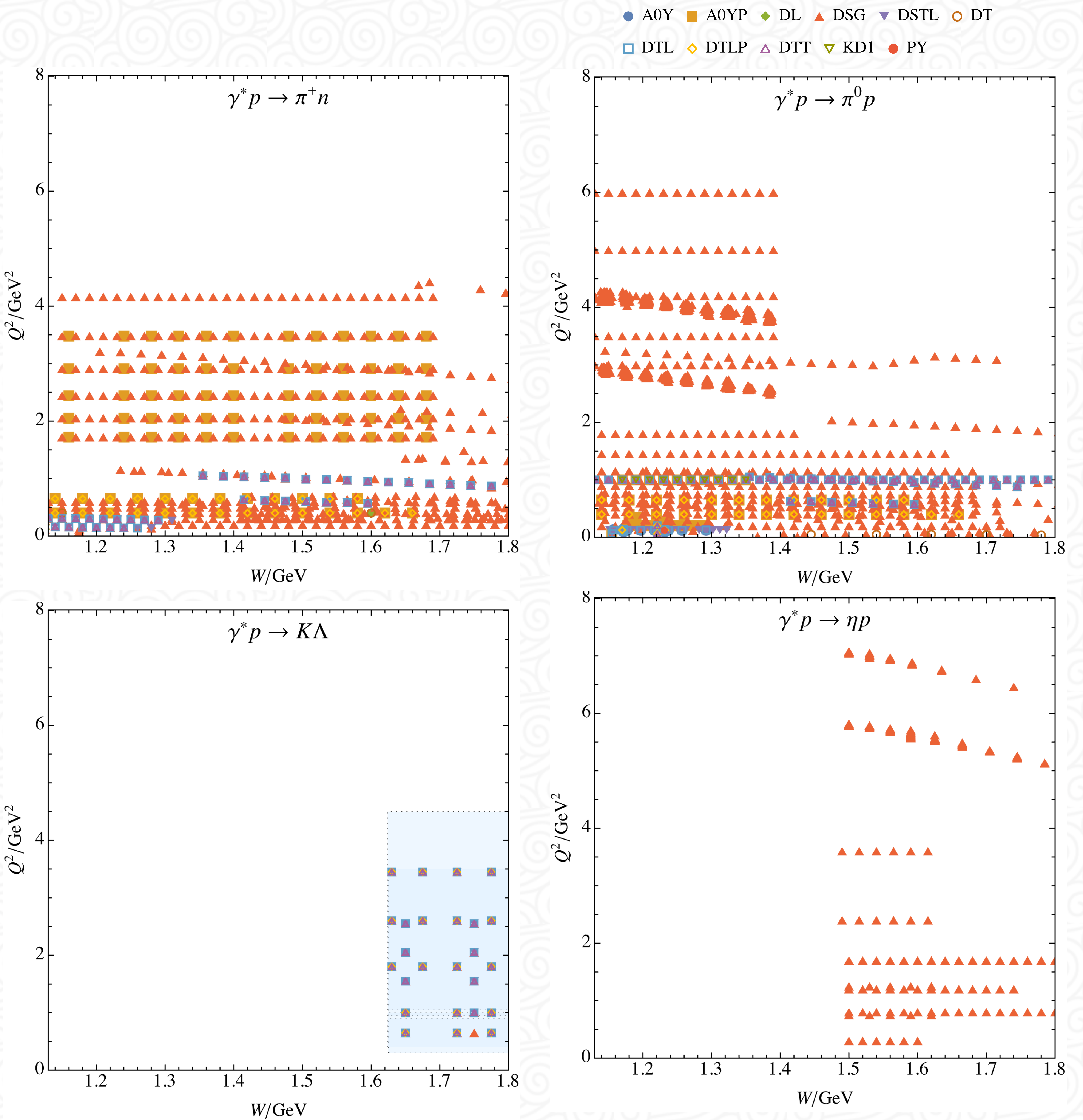
$1.13 < W/\mathrm{GeV} < 1.80\,,\;\; Q^2/\mathrm{GeV}^2 < 8$

~110k data points

~ 90 observable types

Parametrization

- S/P/D/F waves ~500 parameters
- DOF~109k (is this good?)



DATA VALIDATION

Experimental data

$1.13 < W/\text{GeV} < 1.80\,, \quad Q^2/\text{GeV}^2 < 8$

~110k data points

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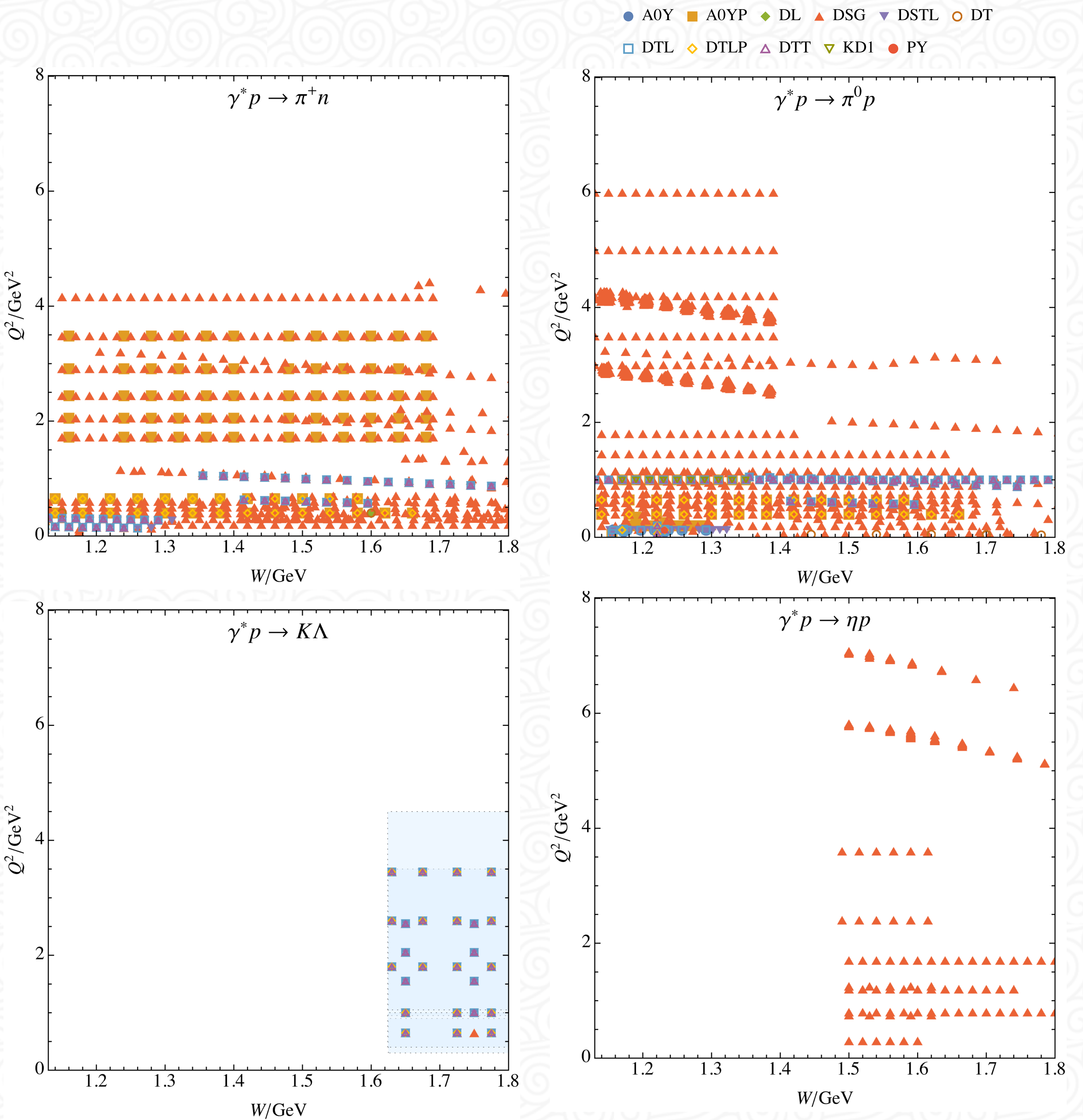
Parametrisation dependence due to incomplete data

- even for a truncated complete electroproduction experiment
  L. Tiator, R. L. Workman, Y. Wunderlich, and H. Haberzettl, Phys. Rev. C 96, 025210 (2017), arXiv:1702.08375 [nucl-th].
- in future: Bias-variance tradeoff with statistical criteria
  J. Landay, MM, M. Doring, H. Haberzettl, and K. Nakayama, Phys. Rev. D 99, 016001 (2019) arXiv:1810.00075 [nucl-th].



DATA DESCRIPTION/FITS

πN[1]

Fit	$\chi^2_{\rm dof}$
$\mathfrak{F}_1$	1.77
$\mathfrak{F}_2$	1.69
$\mathfrak{F}_3$	1.81
$\mathfrak{F}_4$	1.78
$\mathfrak{F}_5$	1.81
$\mathfrak{F}_6$	1.78

$\pi N/\eta N$[2]

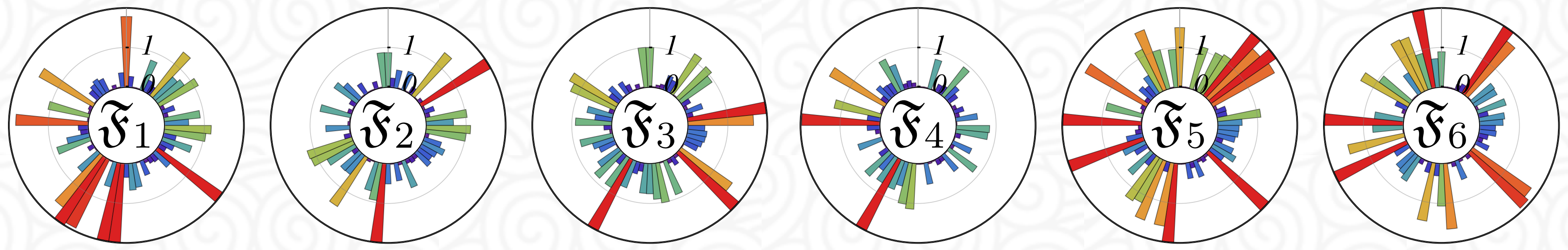
	χ^2/dof
$\mathfrak{F}_1^{\rm reg}$	1.66
$\mathfrak{F}_1^{\rm reg}$	1.73
$\mathfrak{F}_1^{\rm reg}$	1.69
$\mathfrak{F}_1^{\rm reg}$	1.69
$\mathfrak{F}_1^{\rm wt}$	1.54
$\mathfrak{F}_1^{\rm wt}$	1.63
$\mathfrak{F}_1^{\rm wt}$	1.58
$\mathfrak{F}_1^{\rm wt}$	1.58

$\pi N, \eta N, K\Lambda$[3]

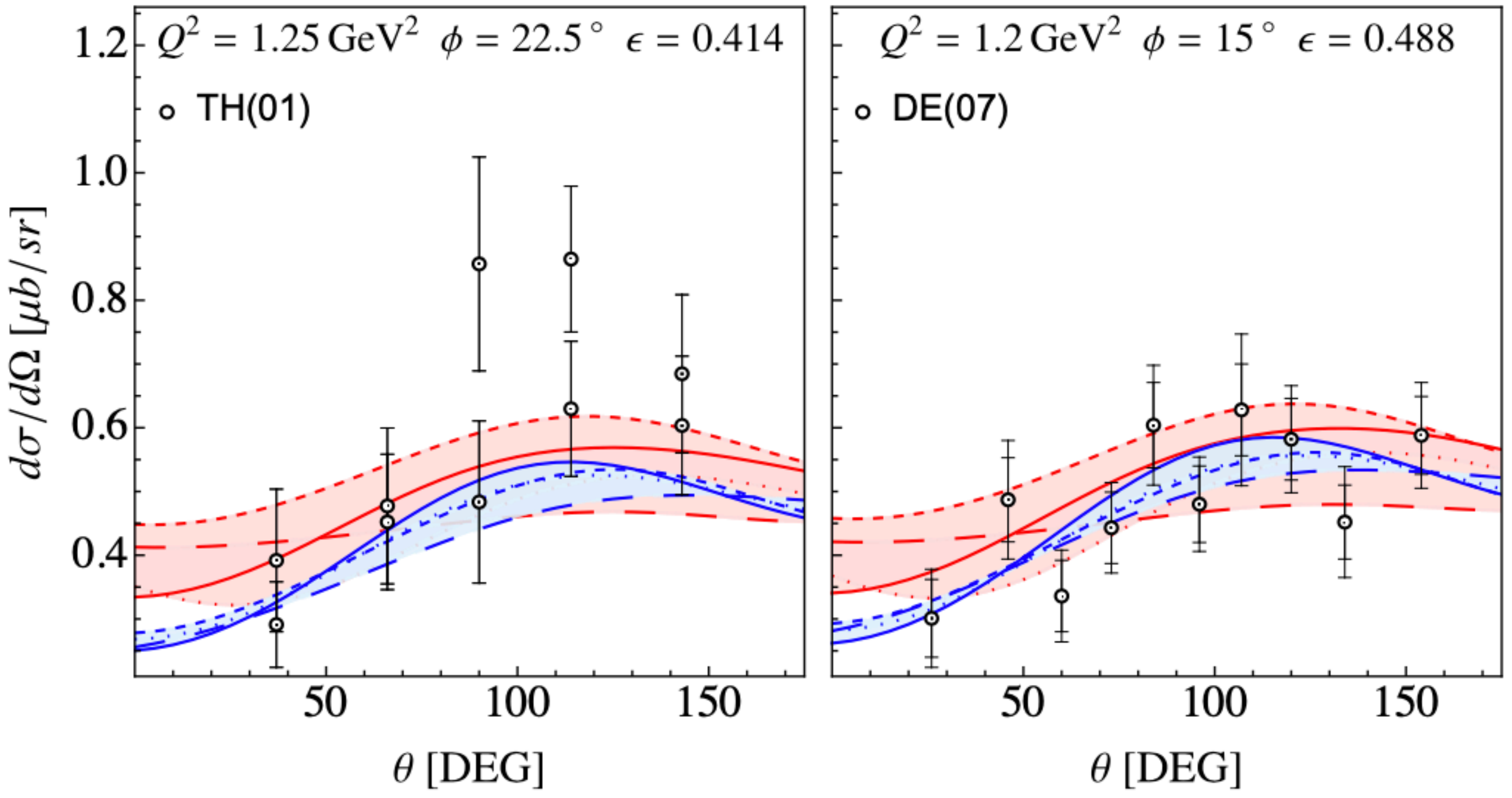
	$\chi^2_{\rm dof}$
FIT$_1$	1.42
FIT$_2$	1.35
	$\chi^2_{\rm wt,dof}$
FIT$_3$	1.12
FIT$_4$	1.06

Uncertainties:

- systematical: due to different fitting strategies studied

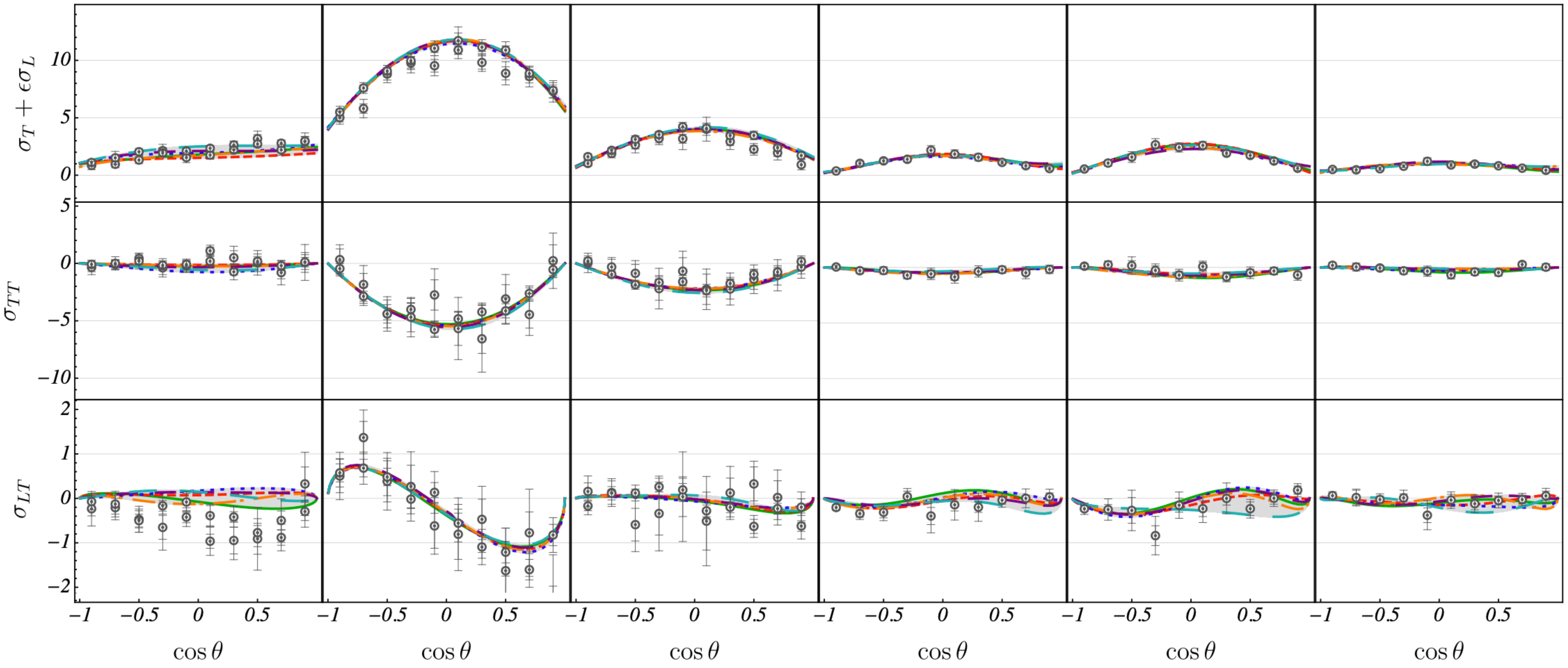


- statistical: need more data base cleaning, model selection…



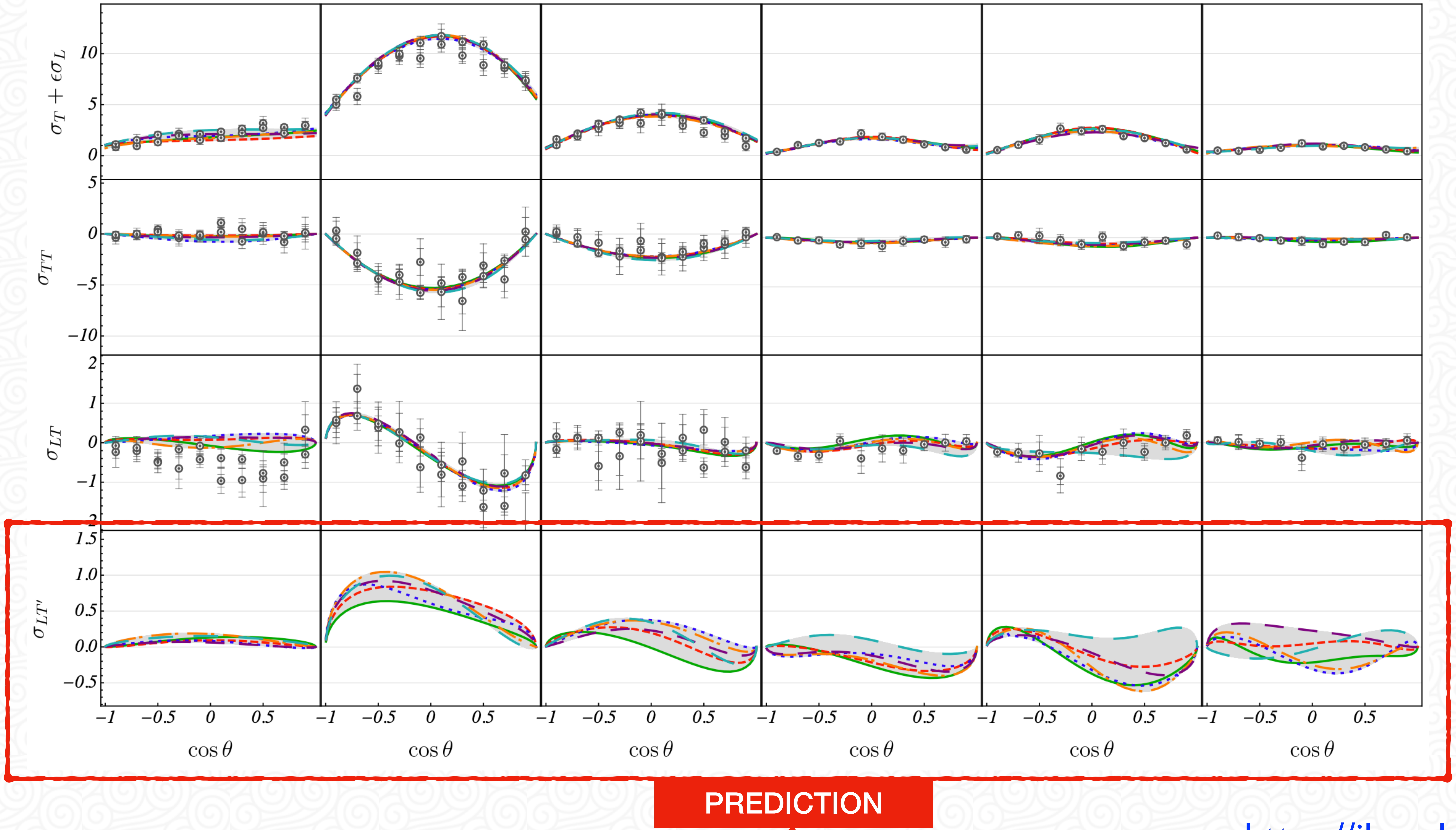
[1] Phys.Rev.C 103 (2021) 6
[2] Phys.Rev.C 106 (2022) 1
[3] Eur.Phys.J.A 59 (2023) 12

INTERPOLATOR OR EXTRAPOLATOR



[1] MODEL: [JBW] MM et al. Phys.Rev.C 103 (2021) 6; Phys.Rev.C 106 (2022) 015201
[2] DATA: Joo et al. [CLAS] PRC (2003), PRL (2002)

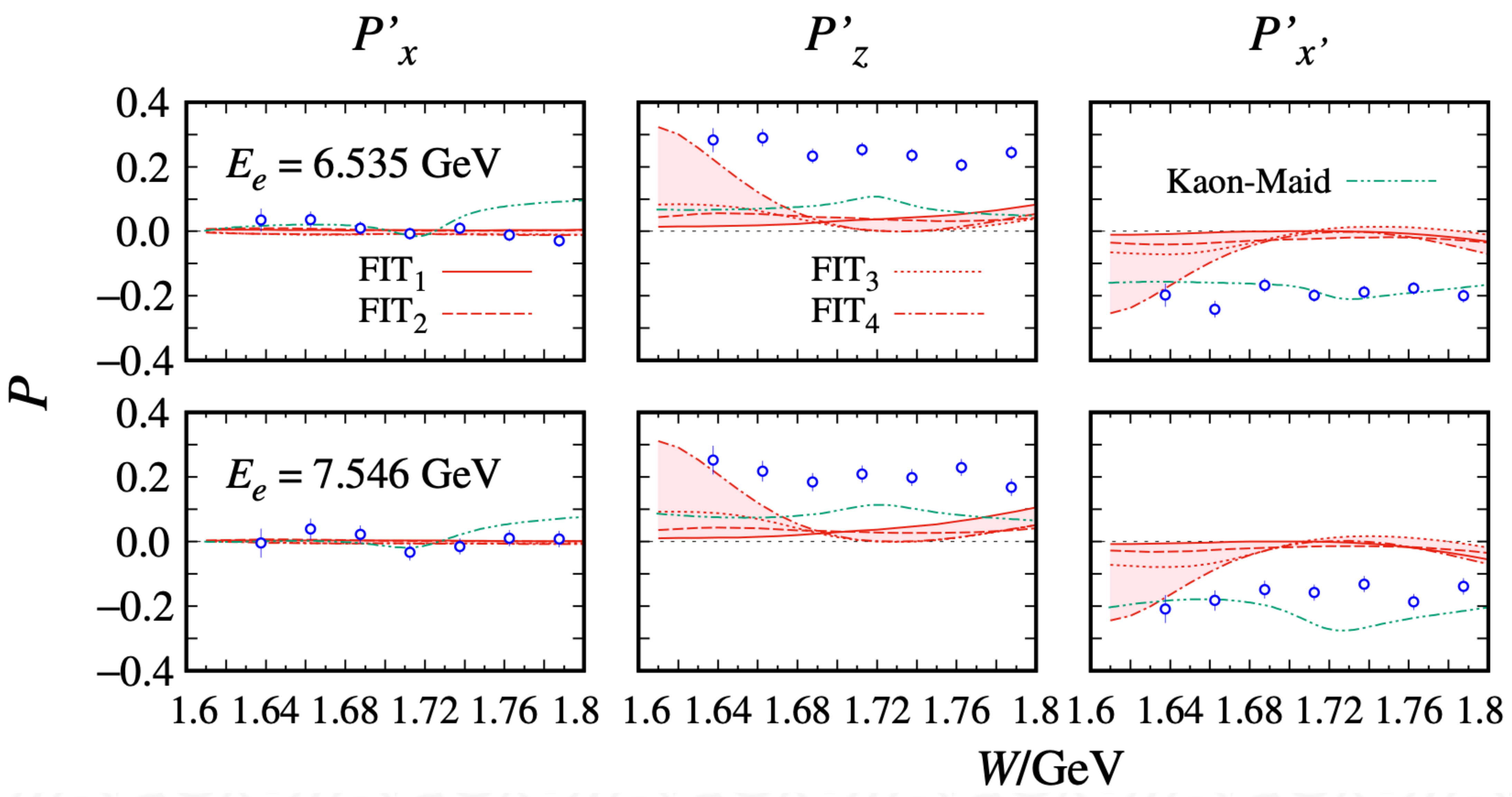
INTERPOLATOR OR EXTRAPOLATOR



https://jbw.phys.gwu.edu/

[1] MODEL: [JBW] MM et al. Phys.Rev.C 103 (2021) 6; Phys.Rev.C 106 (2022) 015201
[2] DATA: Joo et al. [CLAS] PRC (2003), PRL (2002)

NEW L-SENSITIVE DATA



Beam-recoil transferred polarisation[1]

- compare to our prediction (no fit) for integrated kinematics

➥ large drop-off in Q^2 due to L-multipoles

➥ fits to new data[2] will be instrumental

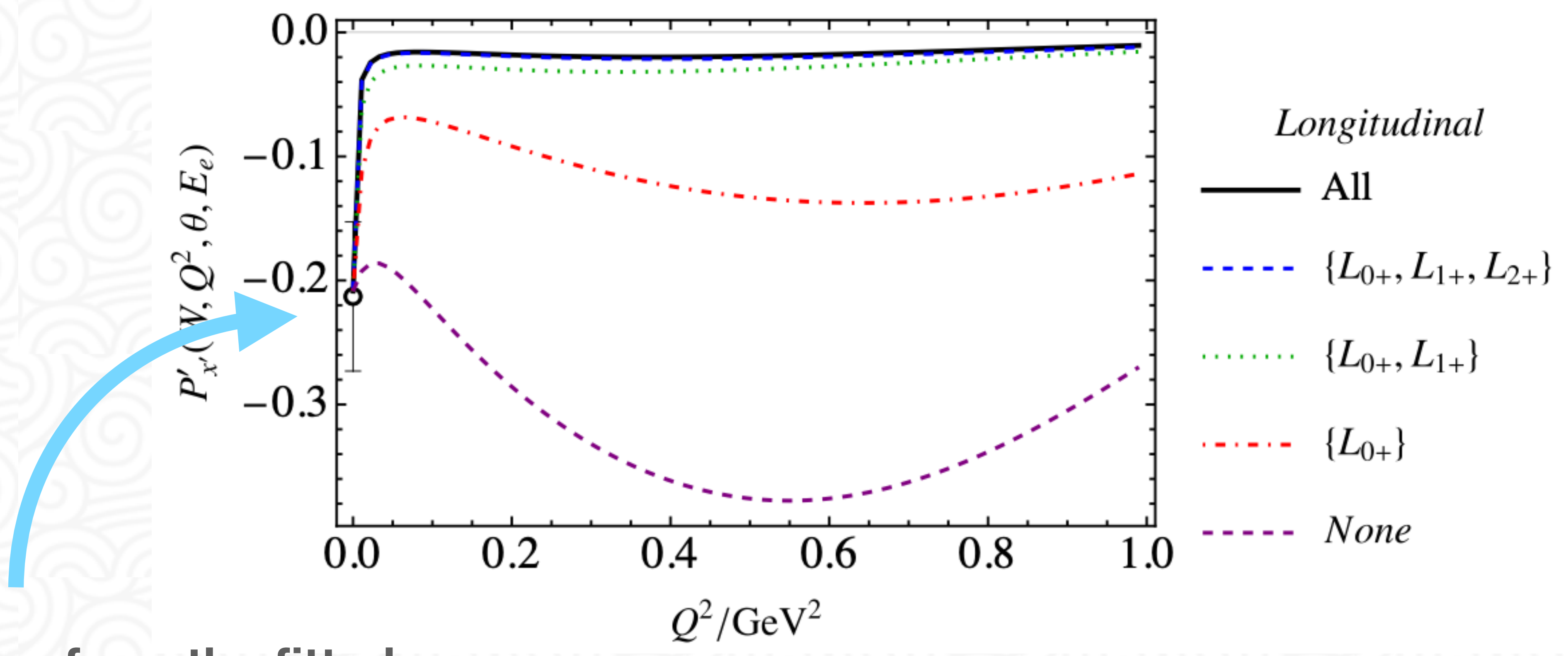


Photo-production datum form the fitted data base

[1] Carman et al. Phys. Rev. C 105, 065201 (2022), arXiv:2202.03398 [nucl-ex]
[2] running analysis at JLAB — unintegrated data

TRANSITION FORM FACTORS

Hadron structure probe[1]

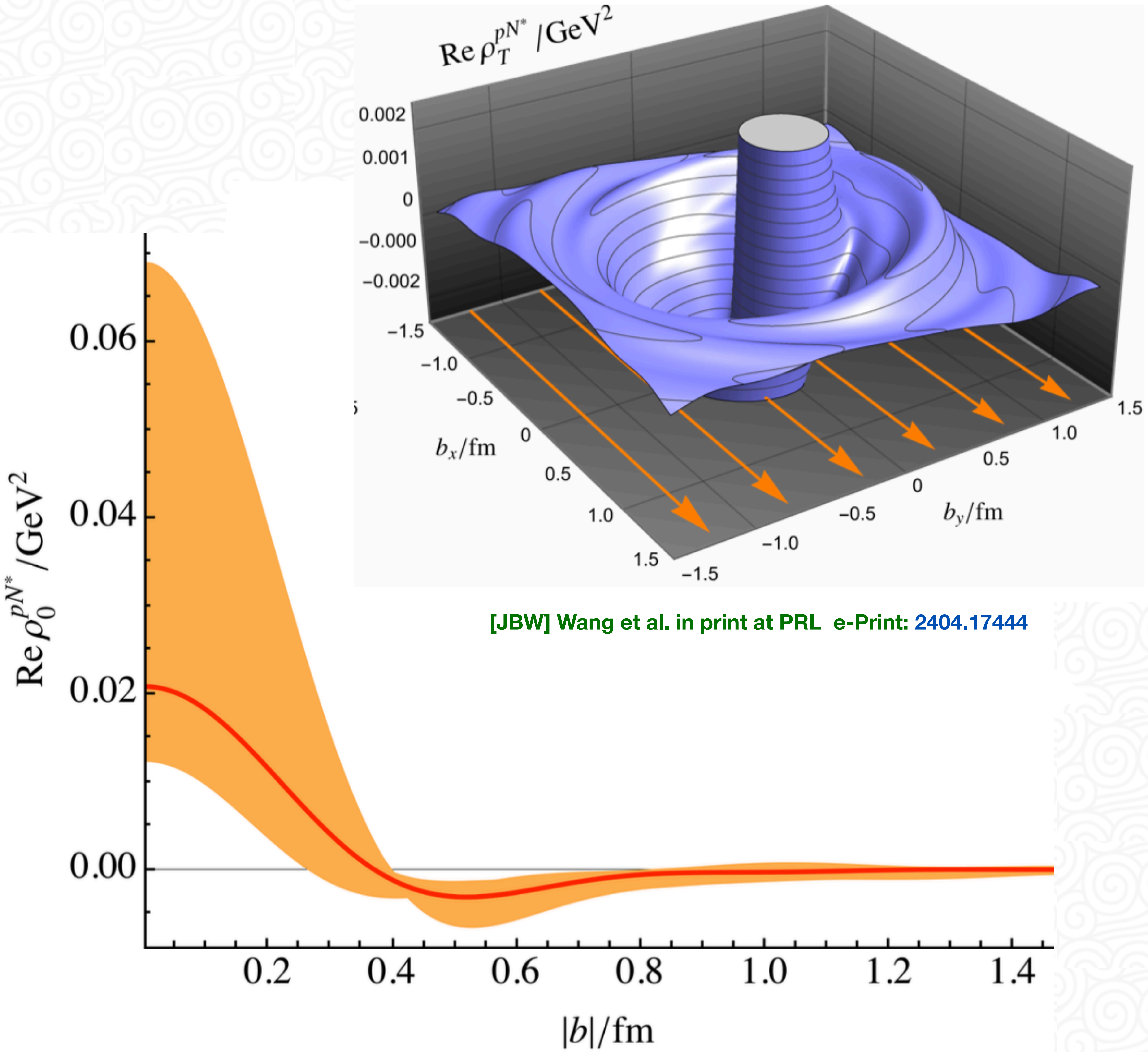
- transition between excited and ground state baryons[2]

$$H_h^{l\pm,I}(Q^2) = C_I \sqrt{\frac{p_{\pi N}}{\omega_0} \frac{2\pi(2J+1)z_p}{m_N \widetilde{R}^{l\pm,I}}} \widetilde{\mathcal{H}}_h^{l\pm,I}(Q^2)\,,$$

- 12 N/Δ states are determined

- Charge distribution in light front RF[3]

$$\rho_0^{NN^*}(\vec{b}) = \int_0^\infty \frac{dQ}{2\pi} Q\, J_0(bQ) F_1^{NN^*}(Q^2),$$



[JBW] Wang et al. in print at PRL e-Print: 2404.17444

[1] Aznauryan and V. D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012), arXiv:1109.1720 [hep-ph];
G. Ramalho and M. T. Peña, Prog. Part. Nucl. Phys. 136, 104097 (2024), arXiv:2306.13900 [hep-ph].
[2] Workman, L. Tiator, and A. Sarantsev, Phys. Rev. C 87, 068201 (2013), arXiv:1304.4029 [nucl-th].
[3] Tiator et al. CPC(HEP & NP), 2009, 33(X)

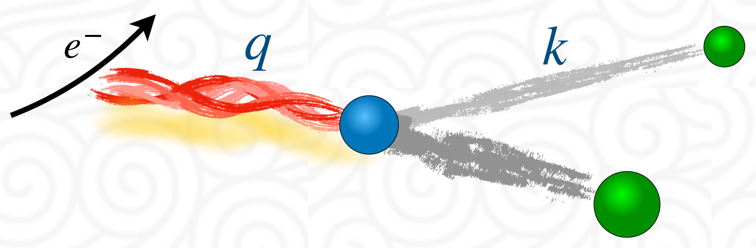
Synergetic approach to hadron spectrum

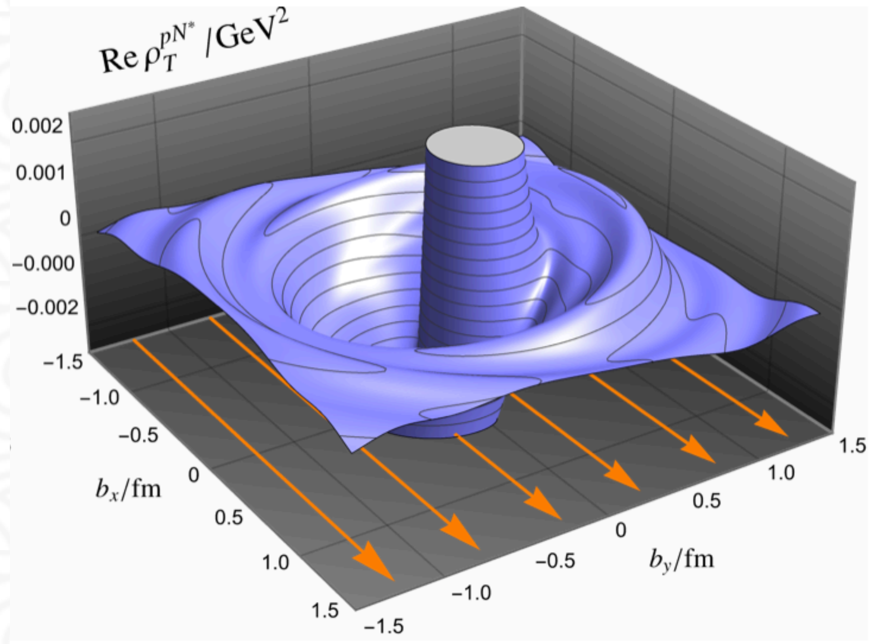
Lattice QCD: ab-initio QCD calculations + **Effective field theories:** quark-mass dependence, symmetries

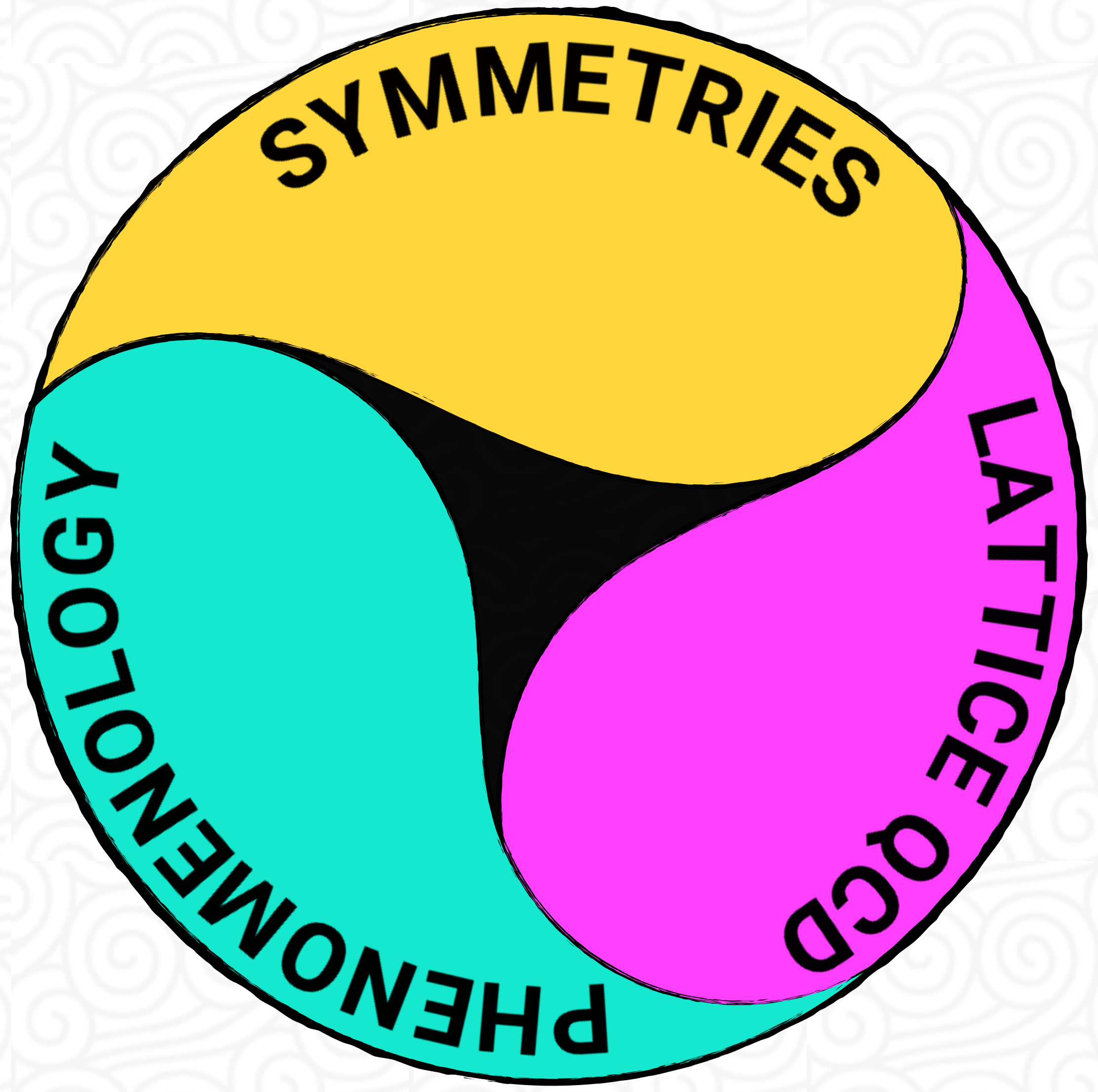
+ **S-matrix :** 3-body Quantization condition

Photon probe (CLAS/GlueX experiments)

- Transition form factors of resonances
- Charge distribution of excited states (POLE)

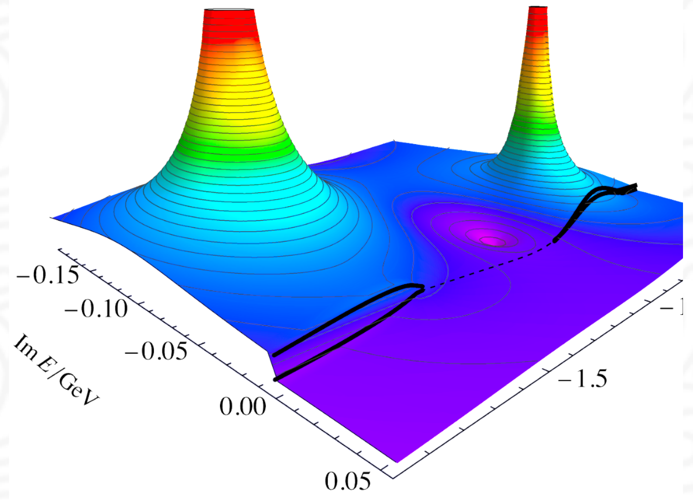






Hadronic degrees of freedom

- Many resonances generated through hadron interaction
- S-matrix+EFT guidance



Lattice QCD

- First calculations of three-body resonances from QCD
- Quark mass dependence