Status of Λ (1405)

- Maxim Mai -

- The George Washington University -

IMPACT

- **Excited baryon Λ(1405)**

$$I = 0 \quad J^P = 1/2^- \quad S = -1 \quad M = 1405.1^{+1.3}_{-1.0}\ \text{MeV} \quad M = 50.5 \pm 2.0\ \text{MeV}$$

PDG 2019

but only one state quoted… Meißner/Hyodo note in PDG (2015)

- *KbarN interaction is strongly attractive — "dynamical origin?"*

- *twice non-perturbative regime* → *too low for perturbative QCD* / *too high for low-energy EFT*

test of our understanding of QCD

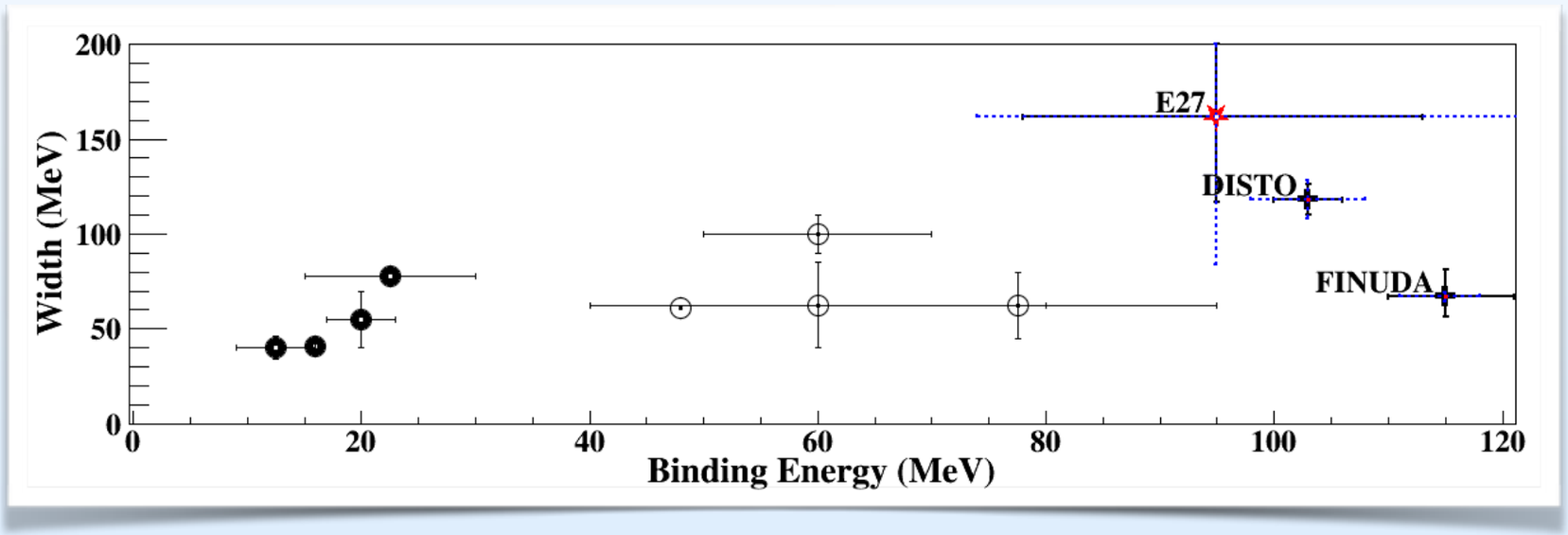
IMPACT

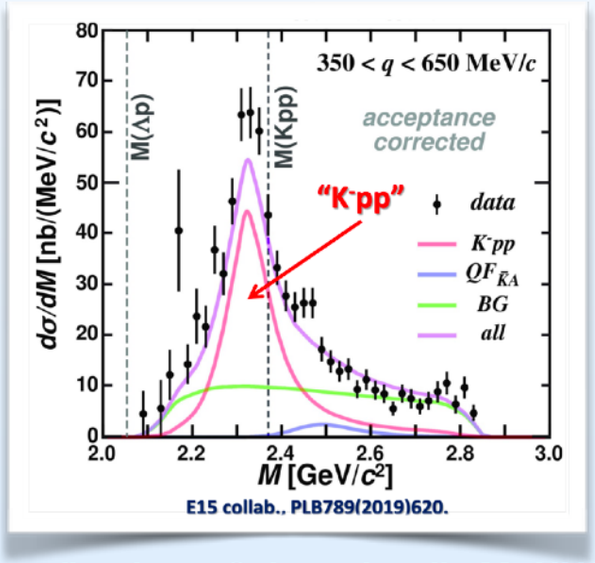
- ***KbarNN & KbarNNN* bound states**

  FINUDA/DISTO/HADES/J-PARC…

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

  see review by Gal/Hungerford/Millener (2016)





figs from Sakuma's talk MENU2019

IMPACT

◉ *KbarNN & KbarNNN* bound states

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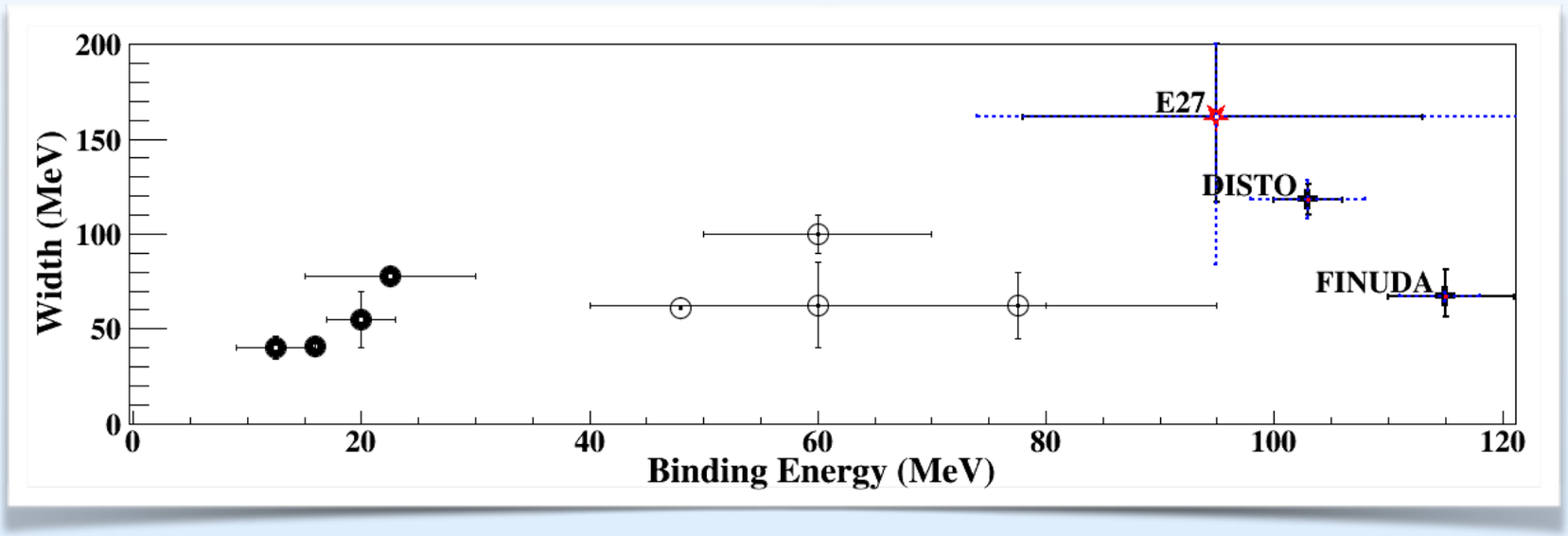
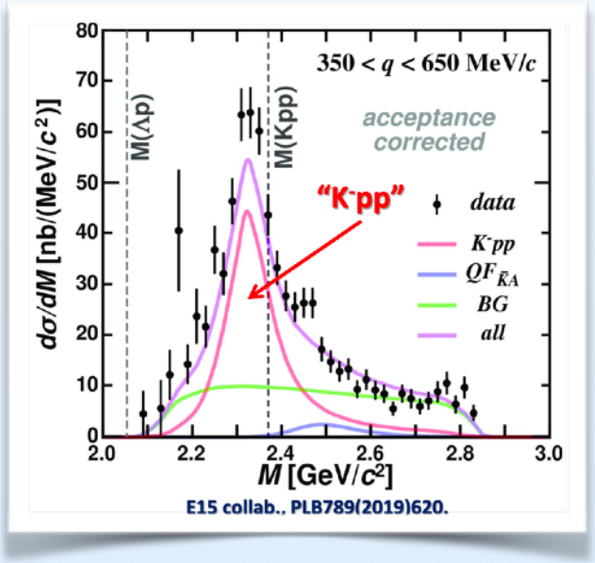




figs from Sakuma's talk MENU2019

◉ K^- in nuclear medium

Cieply et al. (2011)
…

K^- nuclear (or atomic) states

K^- nuclear optical potential

in-mediumK^-N amplitudes

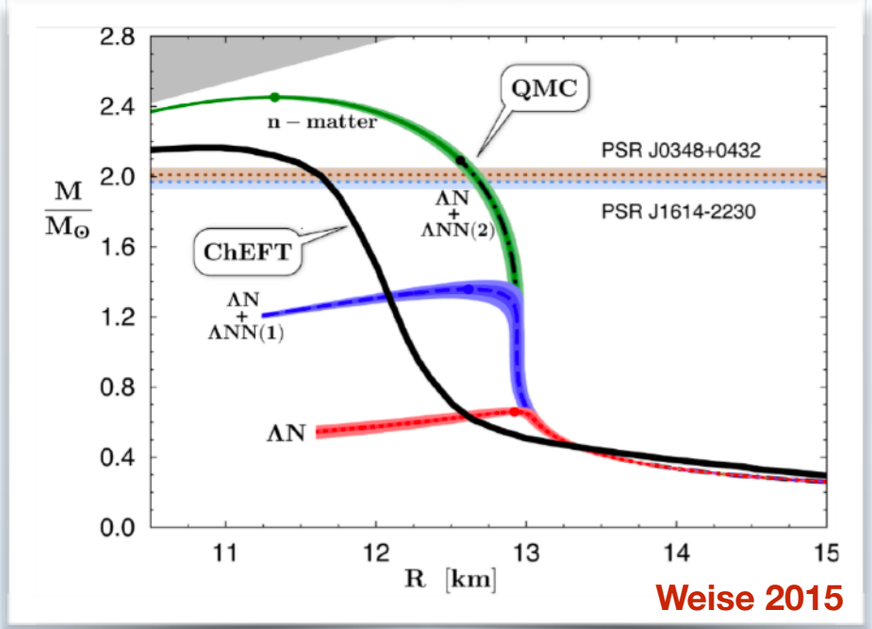
K^-N amplitudes in a free space

IMPACT

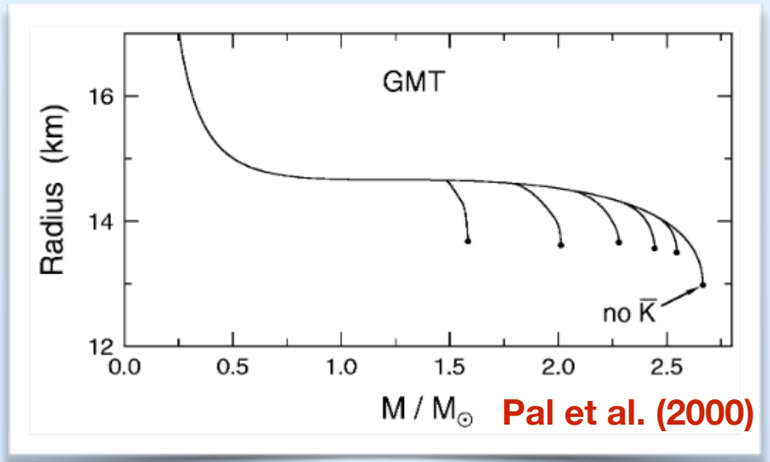
◉ **Observation of ~$2M_\odot$ neutron stars**

Demorest et al. (Nature 2010)

- *challenges our understanding of the EoS of NS*



Weise 2015



Pal et al. (2000)

- *K-condensate can change EoS-stiffness* Pal et al. (2000)

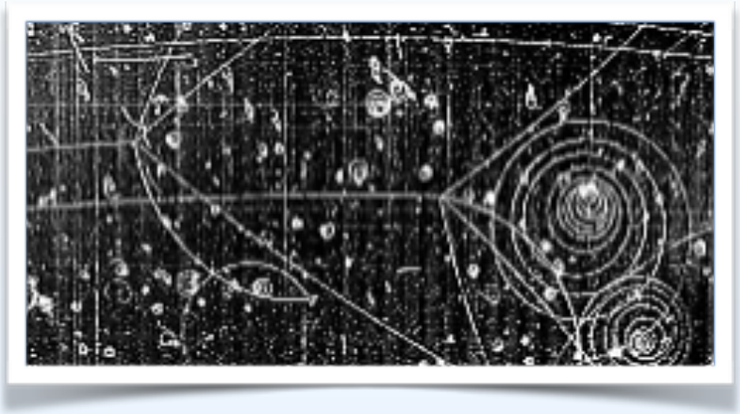
***but**: hyperons become more relevant at higher densities & internal structure of NS neglected* Gal et al. (2016)

EXPERIMENTAL & LATTICE QCD INPUT

EXPERIMENTAL INPUT

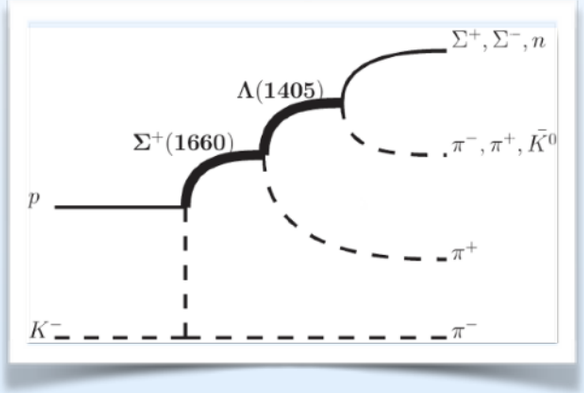
- **Cross sections** LNL (1960s), Rutherford Lab(1980s), ...

  - *$K^-p \to K^-p, \bar{K}0n, \ldots$*
  - *bubble chamber experiments*
  - *huge error bars*



- **πΣ mass distribution** Hemingway (1985)

  - *(2m) bubble chamber @ CERN*
  - *low energy resolution*
  - *multi-step production mechanism*



- **SIDDHARTA** Bazzi et al.(2011)

  - *Strong energy shift and width in $\bar{K}H$*
  - *Very precise, but only determines K^-p scattering length*

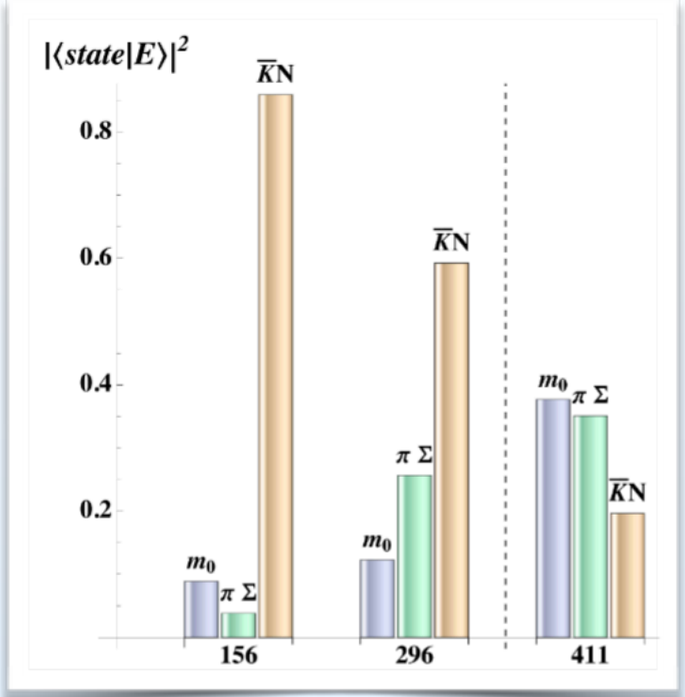
Meißner, Raha, Rusetsky (2004)

- **pp collisions** COSY (2008) HADES (2013)

  - *high quality data, but theoretical analysis very intricate*

LATTICE QCD

- **Magnetic form factor of s-quark vanishes** Hall et al. (2015)
  - *Λ(1405) is dominated by a molecular KbarN state*
  - *statistics/operator basis is small*
  - *contribution of the second pole neglected* Molina/Doring (2015)



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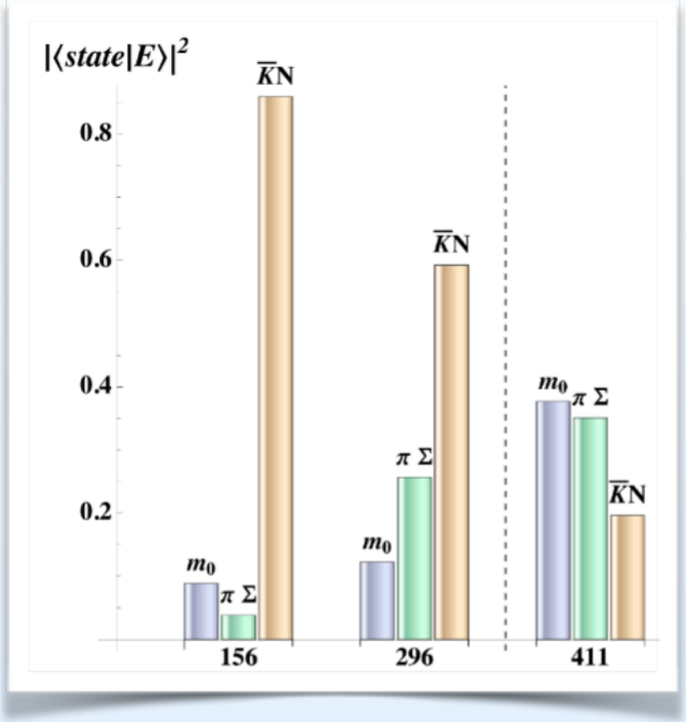
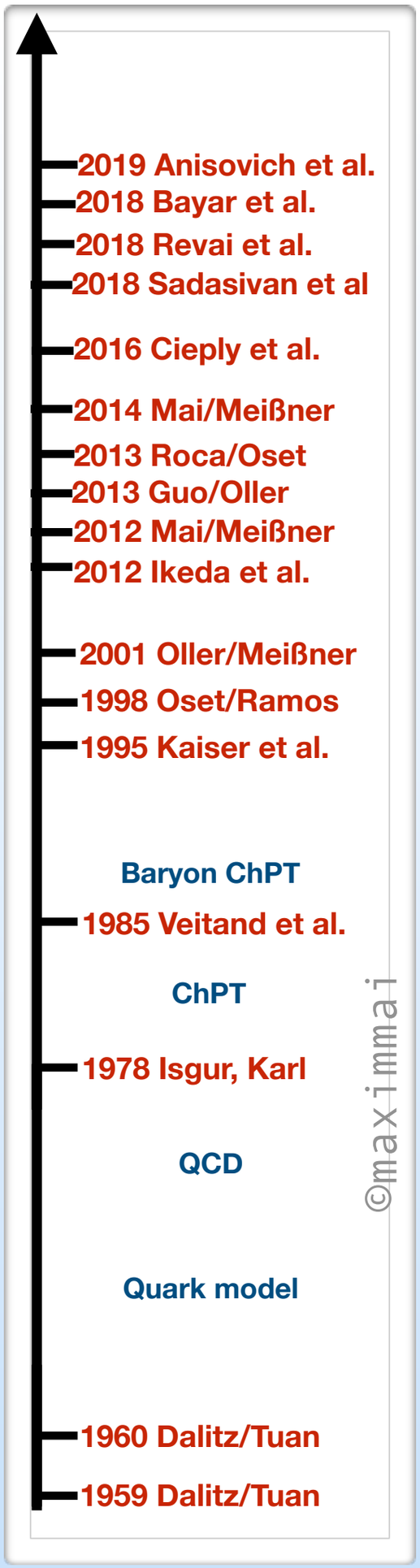


- **Ongoing efforts**

  - *Λ(1405)→Σπ finite volume spectrum @ 280 MeV* Hörz et al. (20??)

  Possible pitfalls towards physical results:

    - *2-dimensional chiral trajectory*
    - *multichannel Lüscher's formalism*



THEORETICAL PROGRESS

— personal re-collection —

THEORETICAL PROGRESS

- 2019 Anisovich et al.
- 2018 Bayar et al.
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Baryon ChPT

- 1985 Veitand et al.

ChPT

- 1978 Isgur, Karl

QCD

Quark model

- 1960 Dalitz/Tuan
- 1959 Dalitz/Tuan

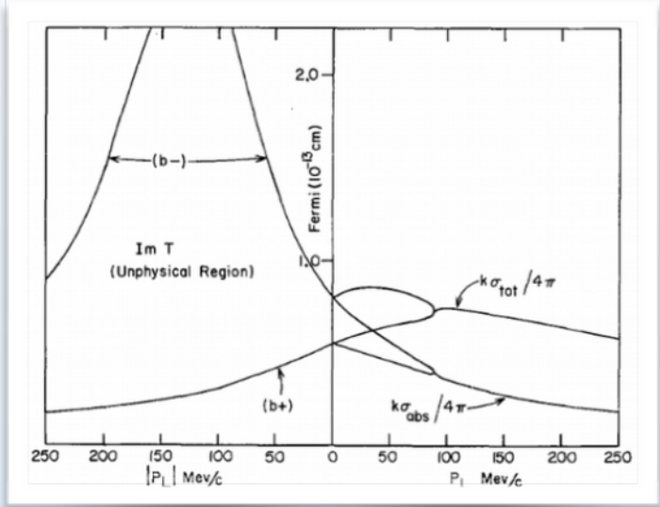
◉ Beginning

ANNALS OF PHYSICS: 8, 100–118 (1959)

The Energy Dependence of Low Energy K^--Proton Processes*

R. H. DALITZ AND S. F. TUAN

persion relations. Four sets of scattering amplitudes are obtained consistent with all the present data on K^--proton interactions and the possibilities for discrimination between them are discussed. Two of these amplitudes are found to correspond to a resonance-like behavior just within the unphysical region.



- *Λ(1405) due to strong attraction between K^- and p* — 1959 Dalitz/Tuan
- *K-matrix approach* — 1960 Dalitz/Tuan

"Archetype" of a dynamically generated state

quasi-bound KbarN state in πΣ continuum

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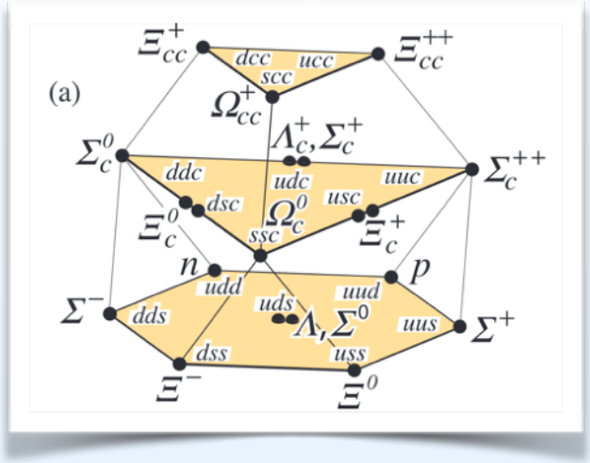
◉ **Quark Model explains many features of the hadron spectrum**

- *What is about Λ(1405)?*



as a qqq state:

- *Λ(1405) mass-degenerate to Λ(1520)*
- *possible extensions: active glue, hybrids, …*

1978 Isgur, Karl

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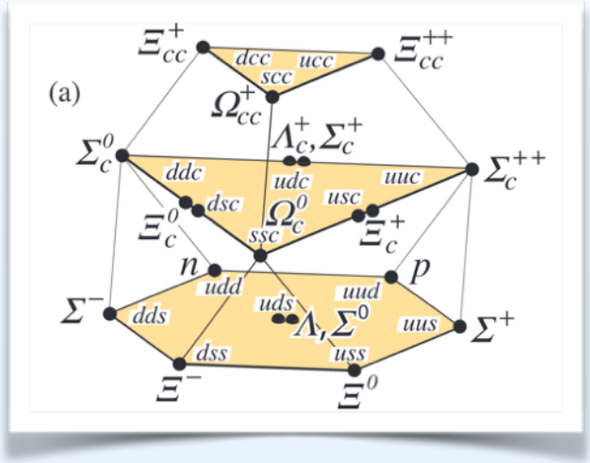

as a qqq state:

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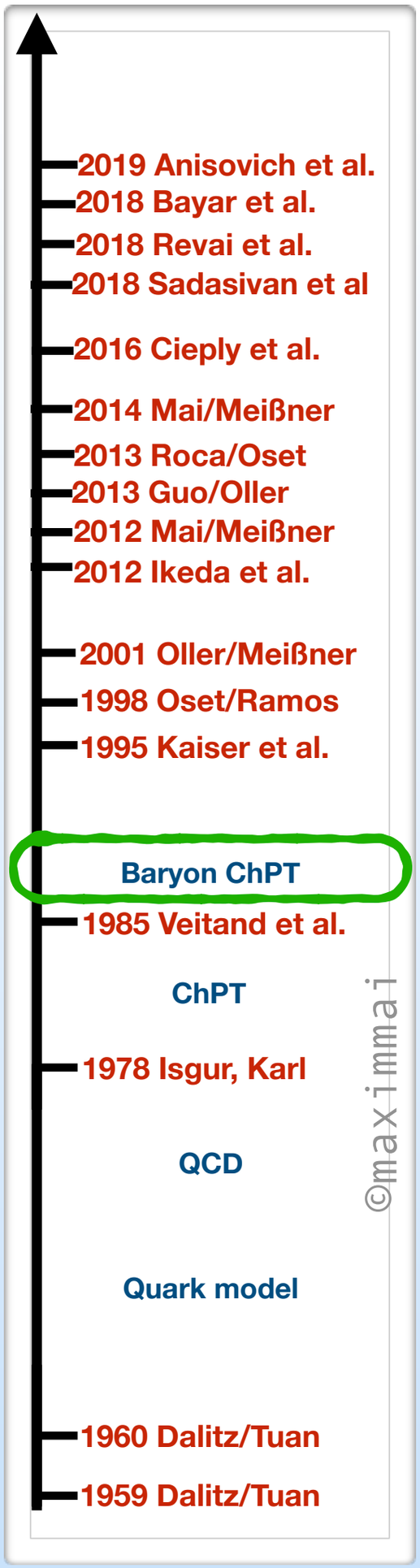
1978 Isgur, Karl

- **SU(3) cloudy bag model**

Veitand et al (1985)

> In the controversy over the nature of the $\Lambda^*(1405)$, the present model comes down firmly on the side of the $\Lambda^*(1405)$ being primarily a $\bar{K}N$ bound state.[25] This indicates that the $\Lambda^*(1405)$ should not be included as one of the states fit in simple quark-model descriptions of baryon resonances.

THEORETICAL PROGRESS



- **ChPT allows to access non-perturbative regime of QCD**

  Weinberg (1979) Gasser, Leutwyler (1983)

  - *Extension to SU(3) and baryons*

    Gasser, Leutwyler (1985)
    Jenkins, Manohar (1990)
    Bernard, Kaiser, Meißner (1995)
    ...

  - ***Low Energy Effective Field Theory:***

    expansion of QCD Greens functions in m_q and p

    low-energy constants — integrated out QCD dof

    renormalizable order-by-order

  - *Benchmark for many low-energy processes, but*

    for non-resonant systems at threshold only…

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◉ Unitarization / Re-summation

Kaiser/Siegel/Weise (1995) Oset/Ramos (1998)

- *Lippmann-Schwinger equation for $K^-p, \Sigma\pi, \Lambda\pi$*
- *Potential from Chiral Lagrangian*

> *"Thus, a potential derived from chiral dynamics with interaction ranges commensurate with the meson-baryon system necessarily produces a quasi-bound state or resonance below or near the K^-p threshold"*

Oller/Meißner (2001)

- *Relativistic re-summation of chiral potential*
- *Two-poles on II Riemann Sheet* → **Now part of PDG**

Borasoy/Nissler/Weise (2005) ....

- *Exploration of systematics, surprises etc..*

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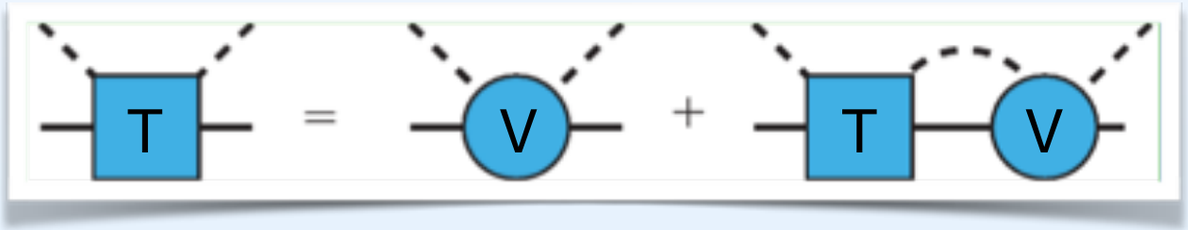
◉ Current state of the art

Ikeda/Hyodo/Weise(2012)
Mai/Meißner(2013)
Guo/Oller (2013)

- *Bethe-Salpeter equation*



- *NLO chiral potential*

$$V(\not{q}_2, \not{q}_1; p) = A_{WT}(\not{q}_1 + \not{q}_2) + Born(s) + Born(u) + A_{14}(q_1 \cdot q_2) + A_{57}[\not{q}_1, \not{q}_2] + A_M + A_{811}\Big(\not{q}_2(q_1 \cdot p) + \not{q}_1(q_2 \cdot p)\Big)$$

- *Free parameters fixed to the experimental data*
- *Off-shell effects are moderate*

Mai/Meißner(2013)

more details in D. Sadasivan's talk

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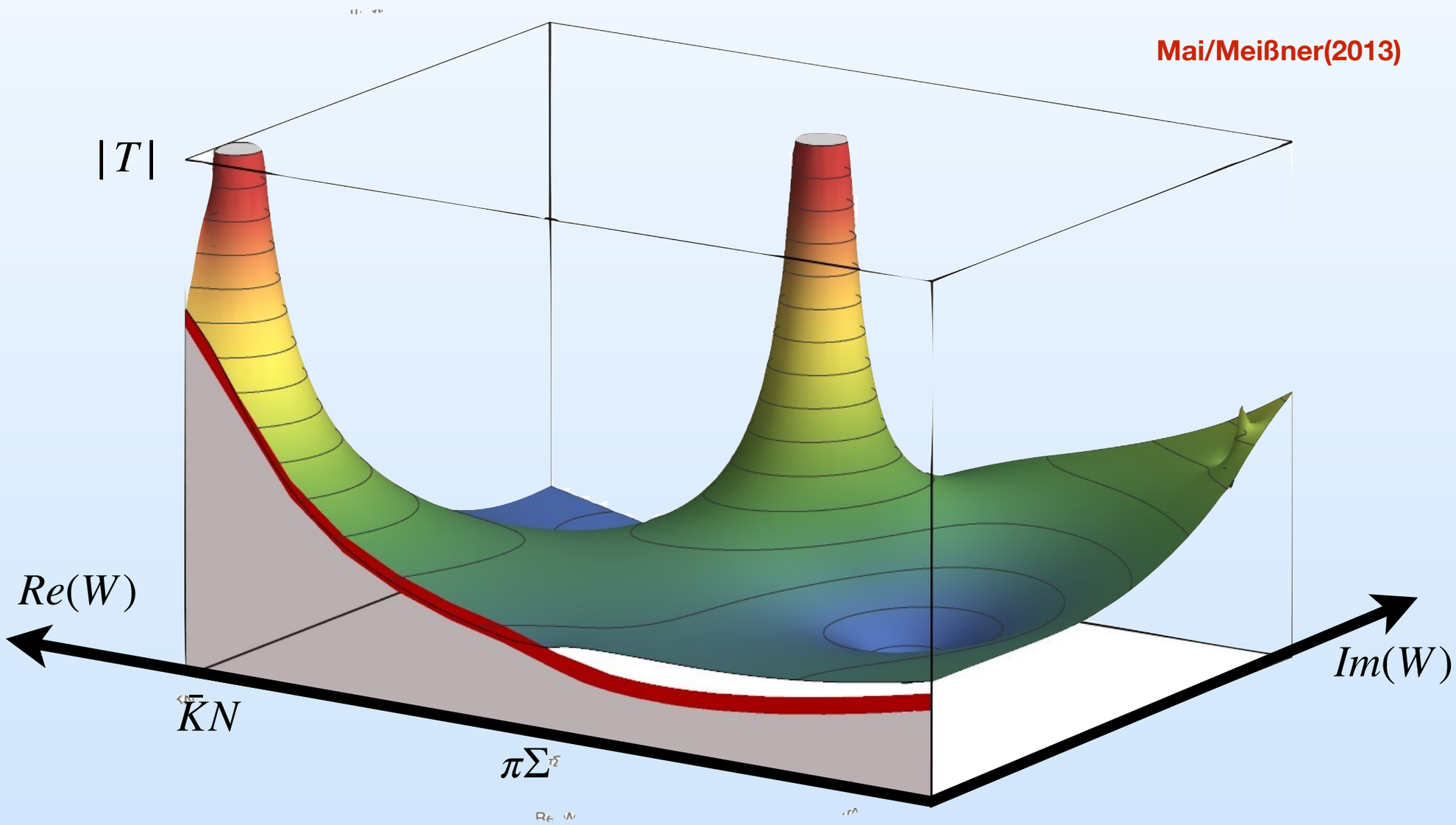
Common feature:

Narrow pole (1410 MeV) & broad pole (~1350MeV)



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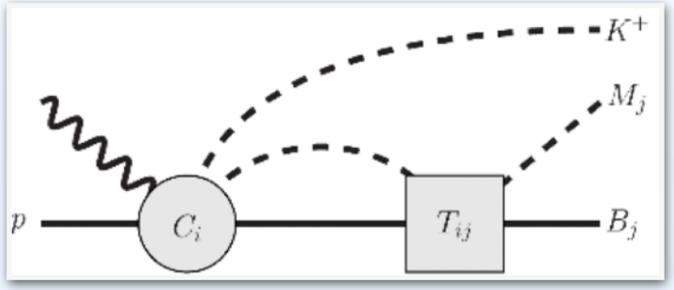
◉ **Inclusion of $\gamma p \to K^+\pi\Sigma$ data** — Mai/Meißner (2015)

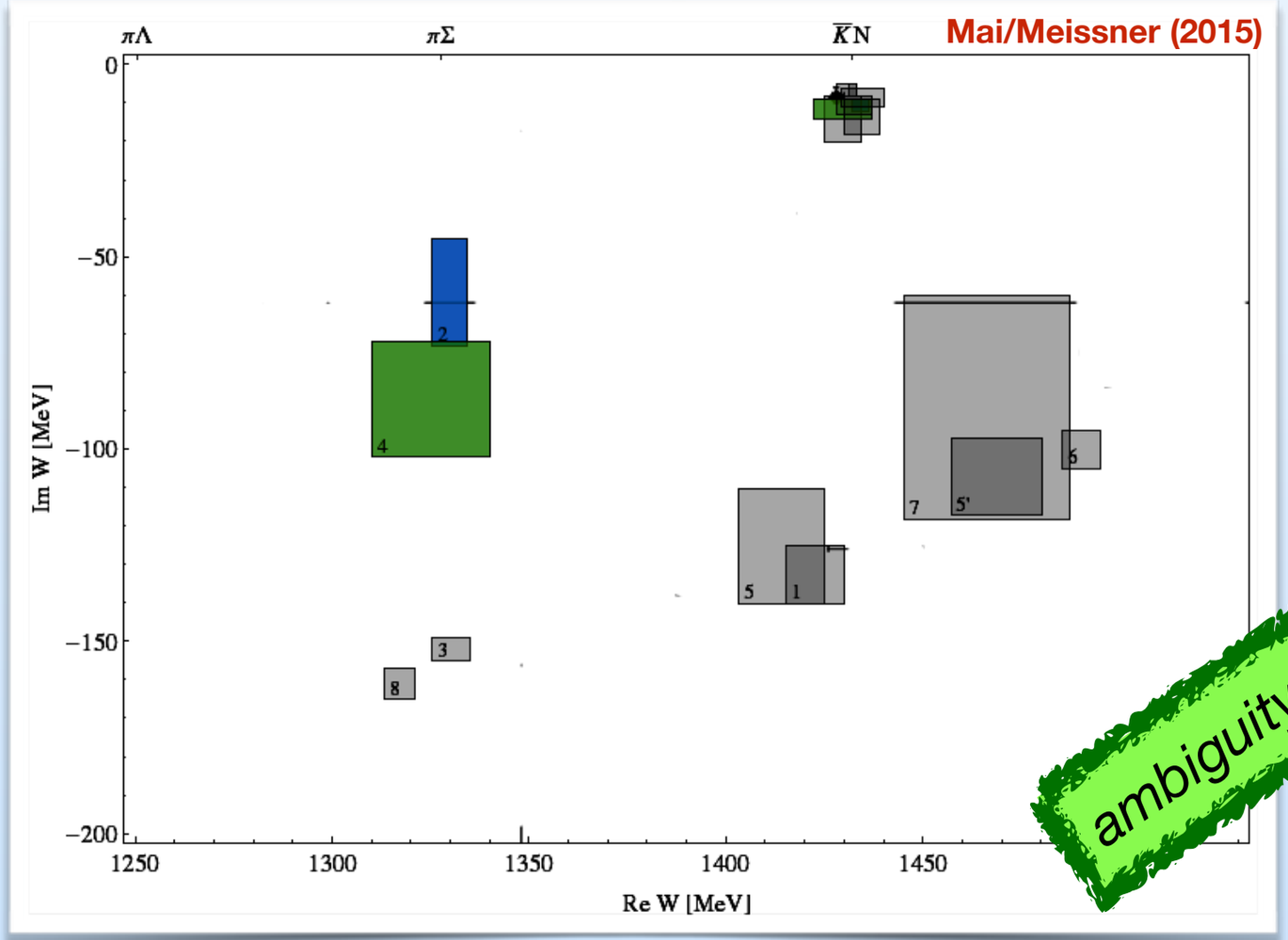
- *high precision data from* ***CLAS@JLAB*** — Moryia et al. (2013)

- *two-meson photo-production mechanism?*

MM/Meißner(2014) Roca/Oset (2013)



Mai/Meissner (2015)



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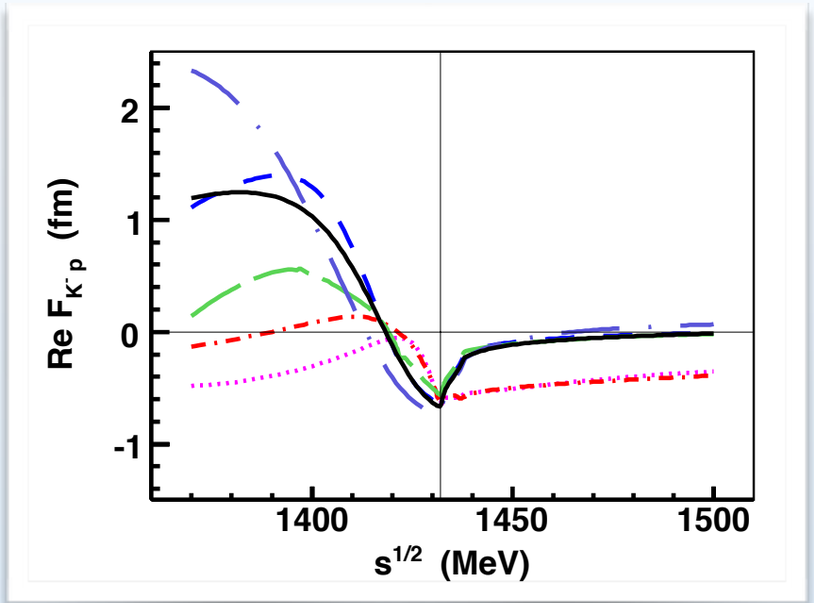
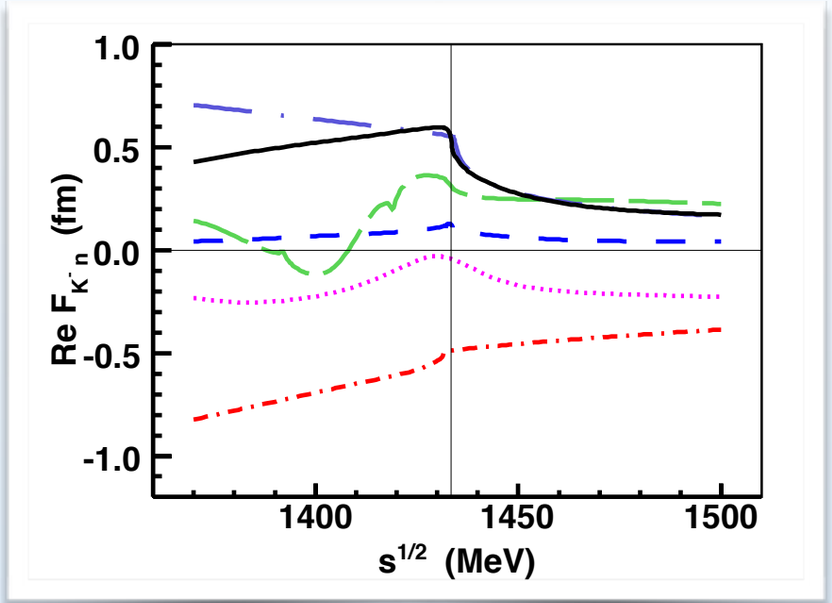
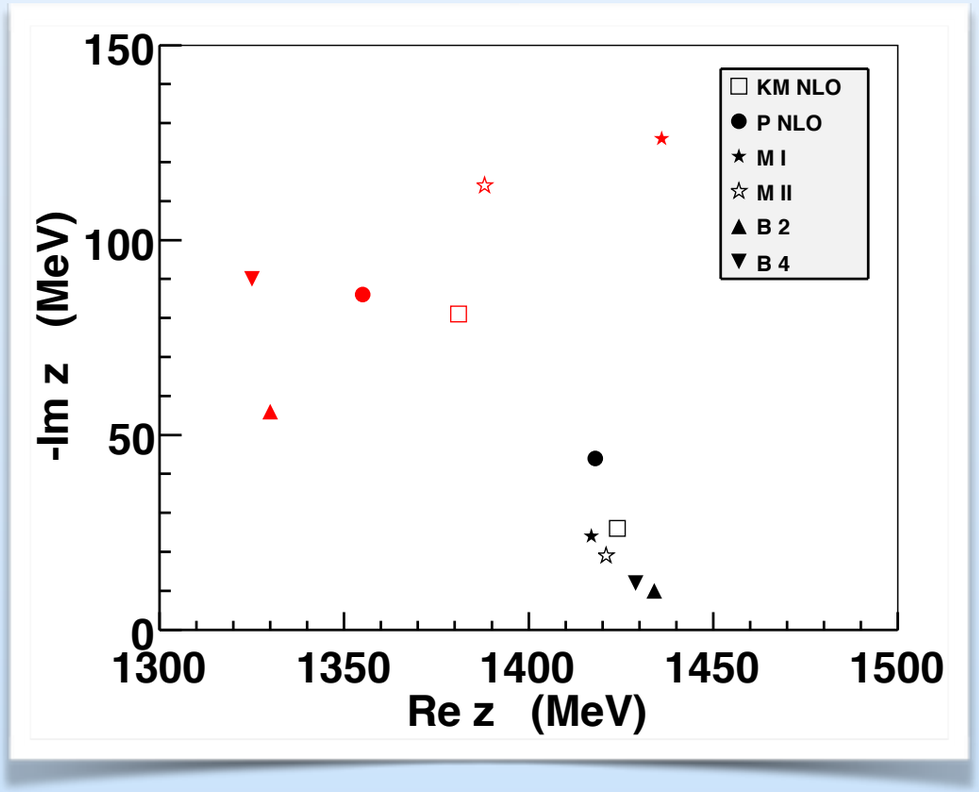
Compare different models

Cieply, MM, Meißner, Smejkal (2016)





- *K^-p amplitude is fixed around threshold*
- *Broad pole & K^-n amplitude not determined precisely*



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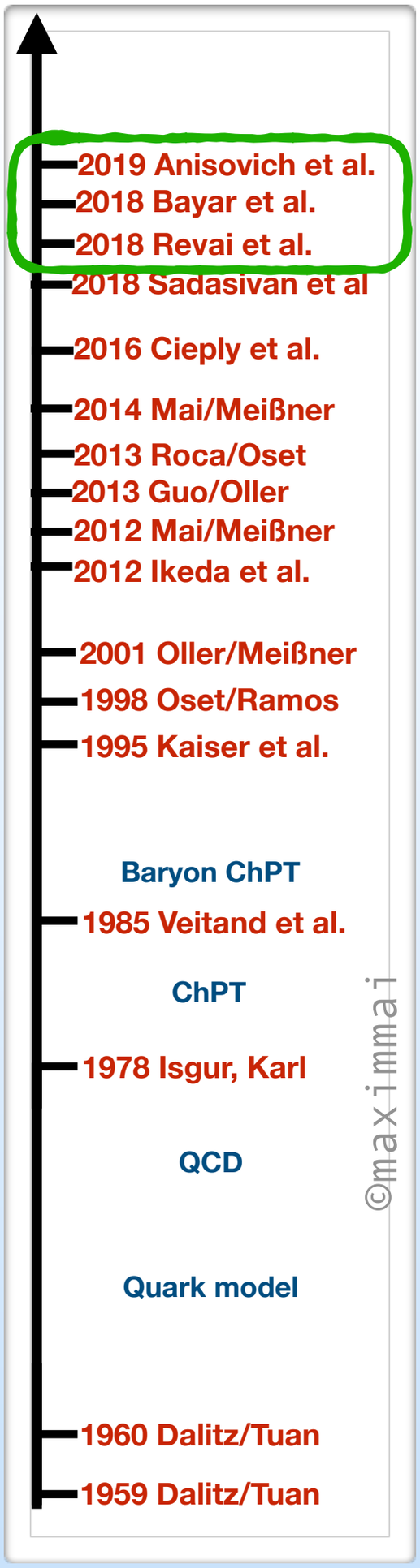

- **Very recent developments**

1) Are the chiral based $\bar{K}N$ potentials really energy-dependent? — Revai (2018)

- *"with off-shell effects only **one pole**"*

however:

a) not relativistic treatment → two poles are back otherwise — Cieply/Bruns in preparation

b) off shell effects are already studied — MM/Meißner (2012)

2) Hyperon I: Study of the $\Lambda(1405)$ — Anisovich et al. (2019) → **next talk**

- *BnGa based phenomenological approach*
- *fit to large set of data ➡ **one pole***

however:

a) data on $\pi^- p \to K^0 \pi\Sigma$ & $pp \to pK^+\pi\Sigma$ — Bayar et al. (2018)

require second pole (not included)

b) kaonic atoms (not tested) — Gal/Friedman

THEORETICAL PROGRESS

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QCD

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1960 Dalitz/Tuan
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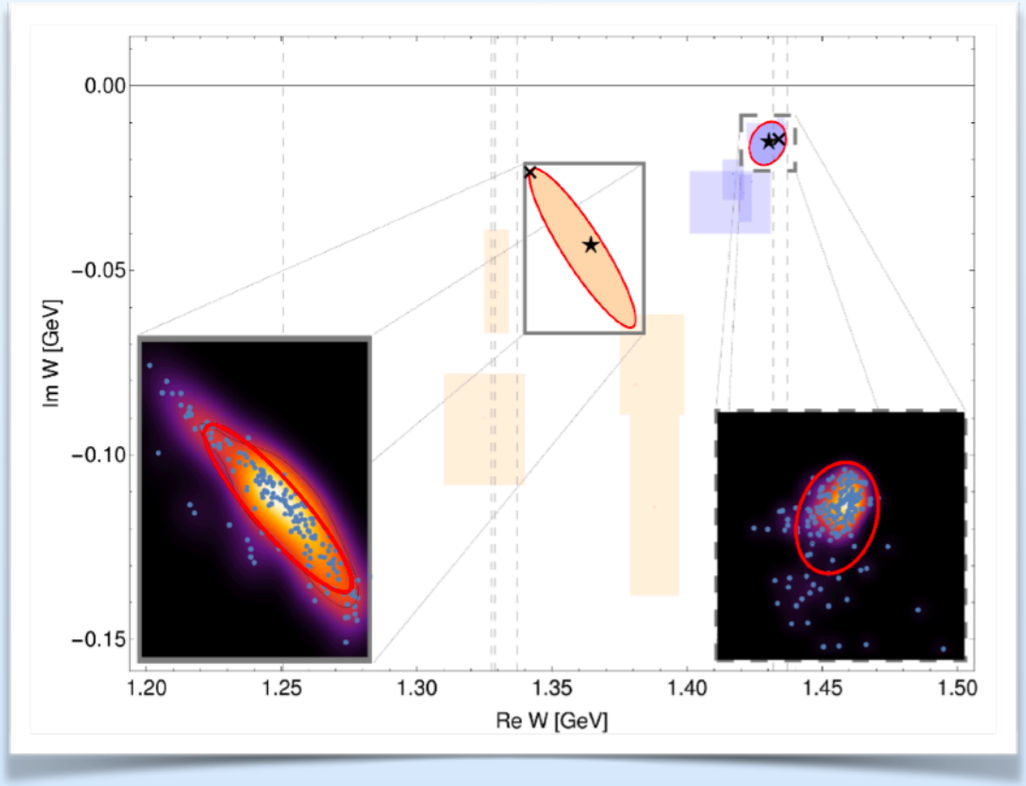
- **Very recent developments**
  - *Coupled-channel chiral unitary approach*
  - *simultaneous s- and p-wave analysis*

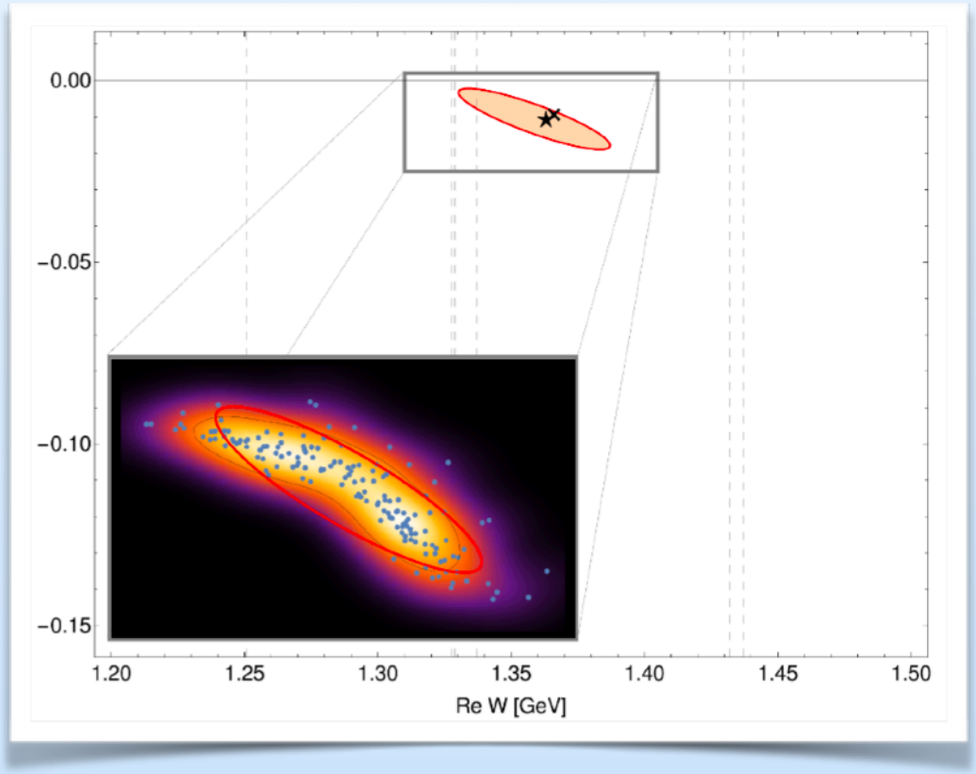
Sadasivan/MM/Doring (2018)

more details in D. Sadasivan's talk

$I(J^P) = 0(1/2^-)$



$I(J^P) = 1(1/2^+)$



SUMMARY

- **Λ(1405) is becoming this year 60y old …**

  … has often been declared as resolved

- ***Dynamical character is non-trivial (multiple channels, attractive interaction,…)***

- ***Several ansatzes have been tested:***

  Quark Model → *fails*

  K-Matrix → *fails*

  Dynamical models → *new approaches keep appearing* → *more tests needed*

  Chiral Unitary app. → *tested/developed over 24 years*

  Λ(1405) = "Archetype" of a dynamically generated resonance

  the only way for chiral extrapolation (LQCD)

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THERE'S LIFE IN THE OLD DOG YET.