Meson Beams for EIC

(Theory/phenomenology motivation)

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Content

- Baryons
  - Spectroscopy
  - Analysis efforts
  - Meson vs photon-induced reactions
- Mesons
  - Properties of broad mesons
  - Lattice QCD

Several slides by
Maxim Mai
Deborah Roenchen
Moskow Amaryan, …

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National Science Foundation
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Main references

Physics opportunities with meson beams

[Paper link]

William J. Briscoe, Michael Döring, Helmut Haberzettl, D. Mark Manley, Megumi Naruki, Igor I. Strakovsky and Eric S. Swanson

Eur. Phys. J. A (2015) **51**: 129   DOI 10.1140/epja/i2015-15129-5

Physics Opportunities with Meson Beams for EIC

[follow-up] (2021)

Strange Hadron Spectroscopy with Secondary KL Beam in Hall D

KLF Collaboration • Moskov Amaryan (Old Dominion U.) Show All(152)

Aug 18, 2020

[Preprint link]

Light Hadrons accessible with meson beams

$\Delta(1232)3/2^-$
First excited baryon discovered
Standard Breit-Wigner (BW) resonance [Crede]

$\pi_1(1600)$
Isovector exotic (COMPASS/ GlueX,…) [Meyer]

$f_0(500)$ "σ"
Debated whether resonance or not, intricate connection to chiral dynamics; non-BW [Pelaez]

$N(1440)1/2^+$, "Roper"
Enigmatic; absent in many Lattice QCD and quark model calculations; non-BW [Burkert]

$\Lambda(1405)$
Two pole structure complicated production [Mai]

$f_0(980)$
Resonance close to threshold: molecule? Flatté-like, non-BW [Baru]

$a_1(1260)$
Clean production; three-body dynamics

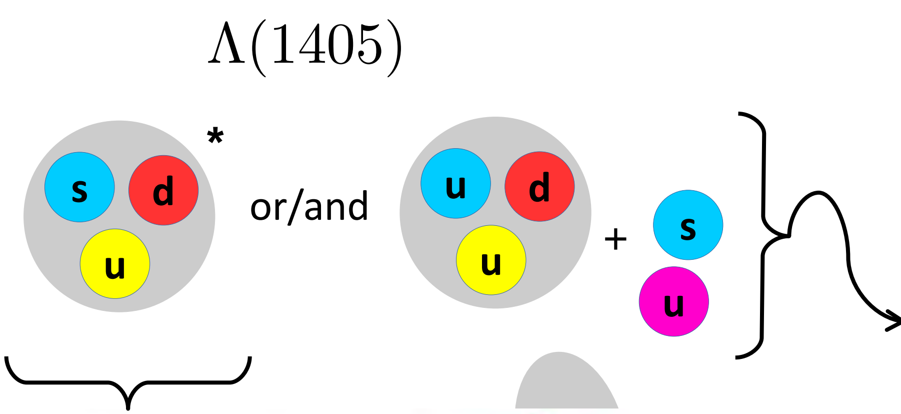
$N(1535)1/2^-$, $N(1650)1/2^-$
Nearby, overlapping resonances with same quantum numbers

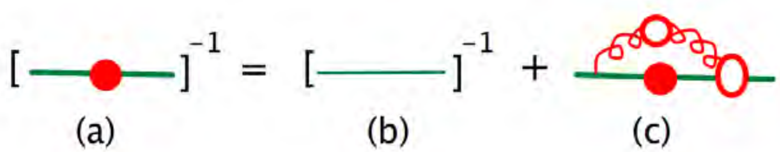
$N(1900)3/2^+$
Recently discovered in large experimental baryon searches for "missing resonance"

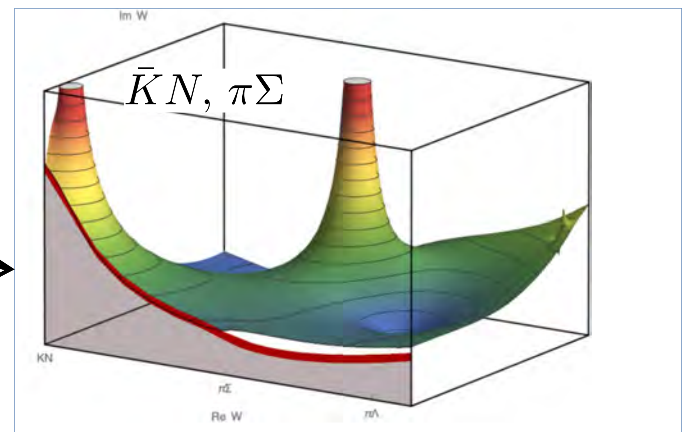
Excited Baryons – Models

How many are there? → missing resonance problem)

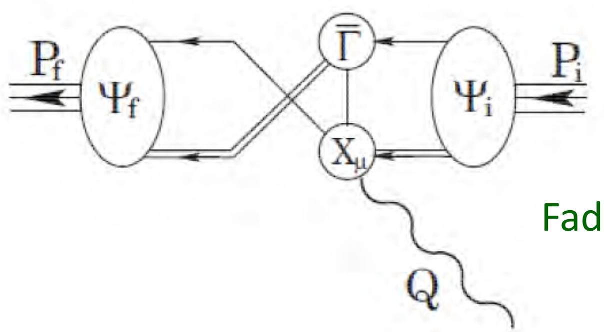
What are they? → 2-quark/3-quark, hadron molecules, …







Hadronic molecule [Mai]



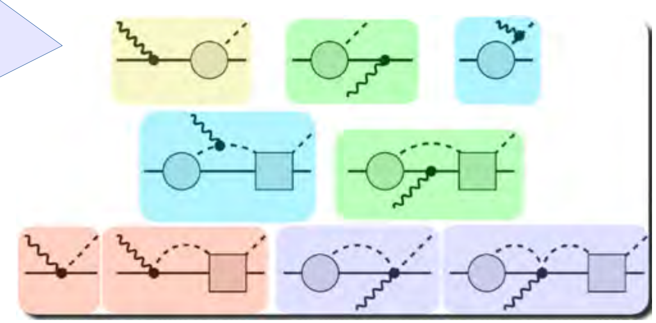
Faddeev Eq. / DSE (Binosi, Cloet, Chang, Roberts)

Using ONLY meson-baryon degrees of freedom (no explicit quark dynamics):

Manifestly gauge invariant approach based on full BSE solution

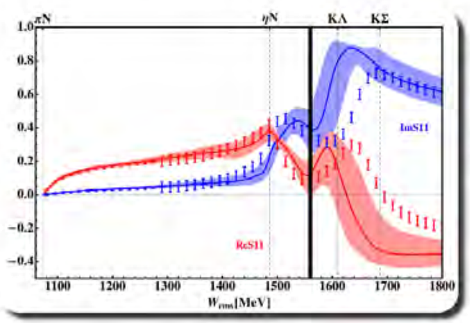
[Ruic, M. Mai, U.-G. Meissner PLB 704 (2011)]

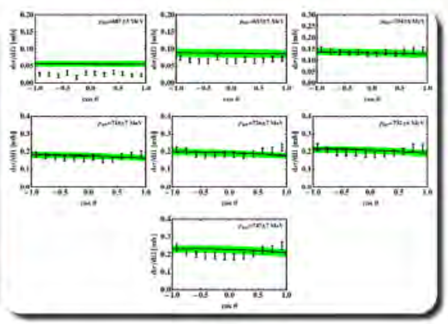
Gauge invariance



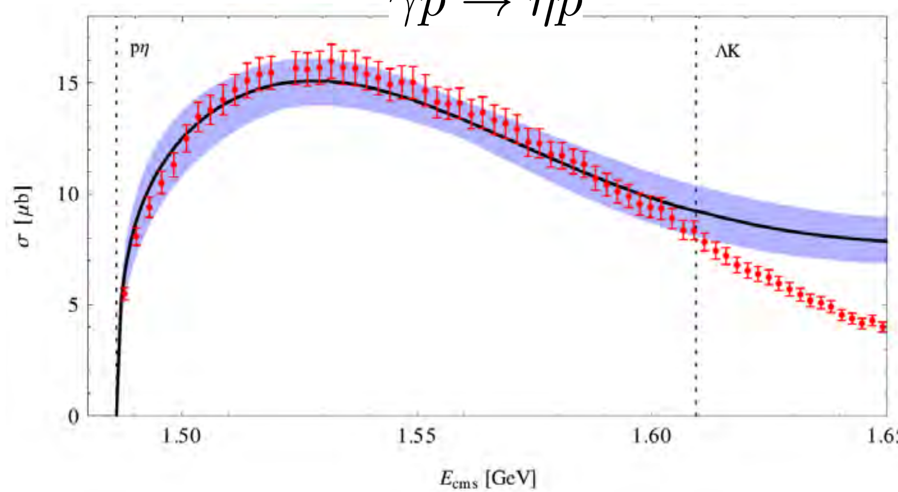
Fit

- Exact unitary meson-baryon scattering amplitude T with parameters, fixed to reproduce:
  - πN-partial wave S_{11} and S_{31} for $\sqrt{s} < 1560$ MeV
    Arndt et al. (2012)
  - $\pi^- p \to \eta n$ differential cross sections
    Prakhov et al. (2005)





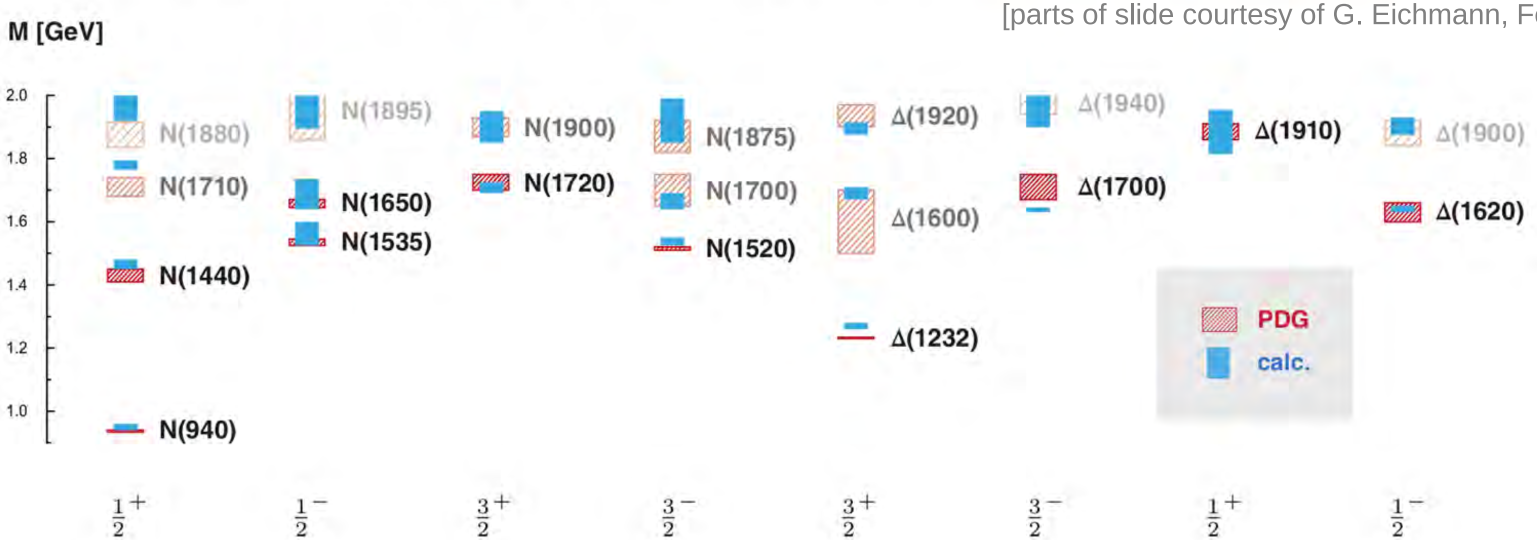
$\gamma p \to \eta p$

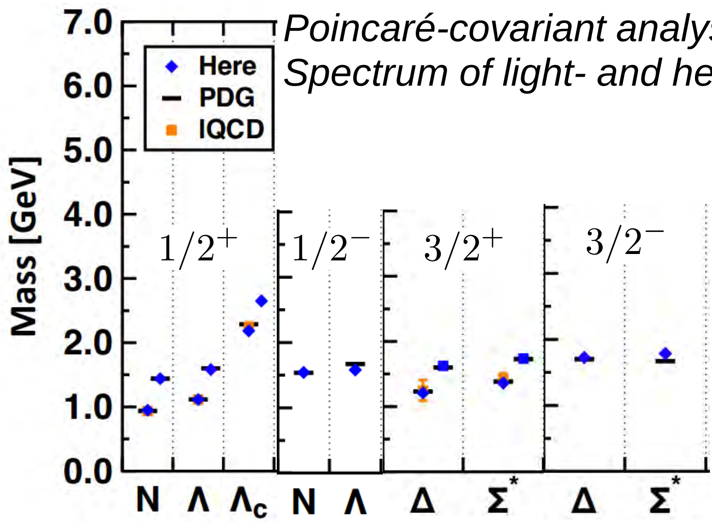


Results in dynamical quark picture

Quark-diquark with reduced pseudoscalar + vector diquarks: GE, Fischer, Sanchis-Alepuz, PRD 94 (2016)

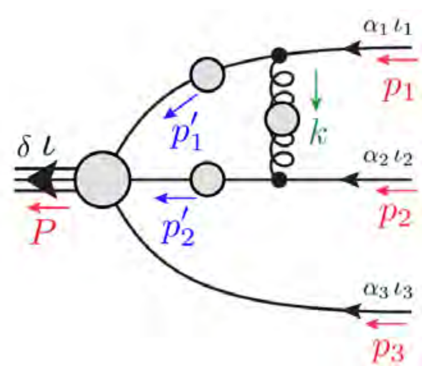
[parts of slide courtesy of G. Eichmann, Few Body 2018]



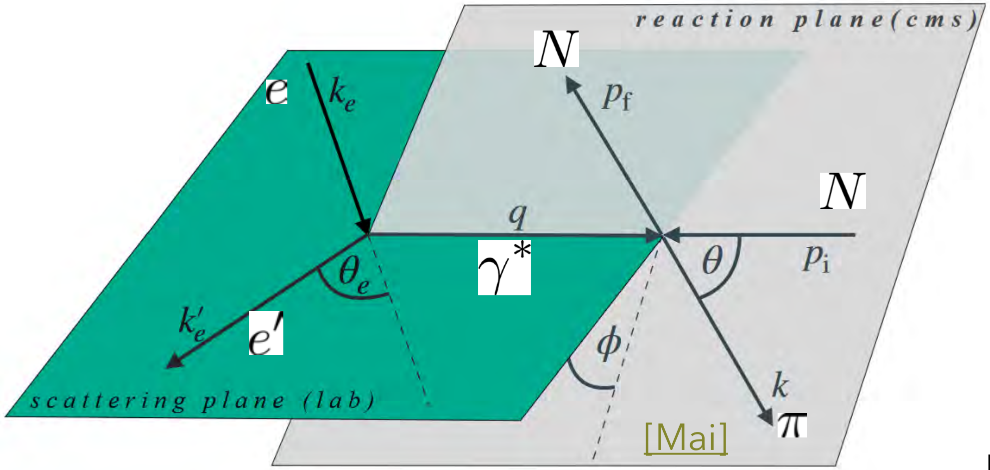


Poincaré-covariant analysis of heavy-quark baryons, Qin, Roberts, Schmidt, PRD (2018)

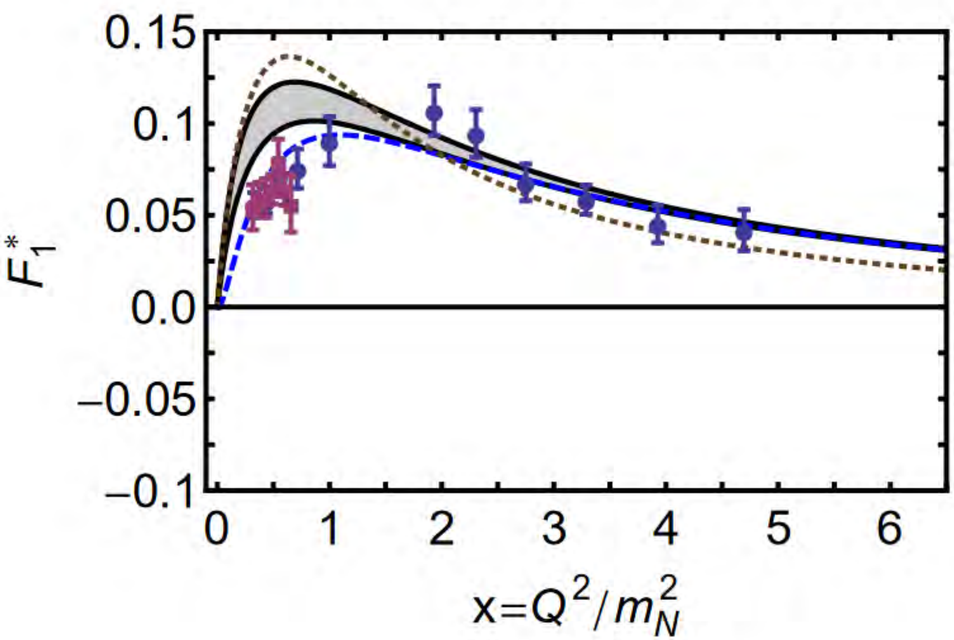
Spectrum of light- and heavy-baryons, Qin, Roberts, Schmidt, Few Body Syst. 60 (2019)



Electroproduction reveals resonance structure

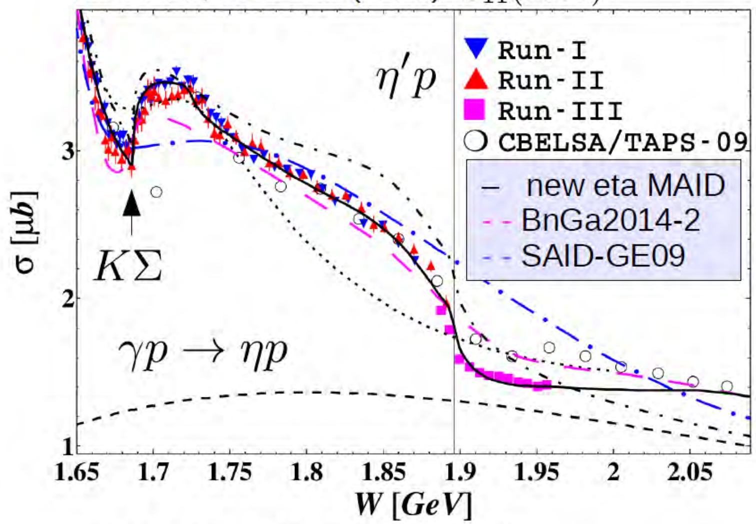


Proton-Roper Transition [Burkert]

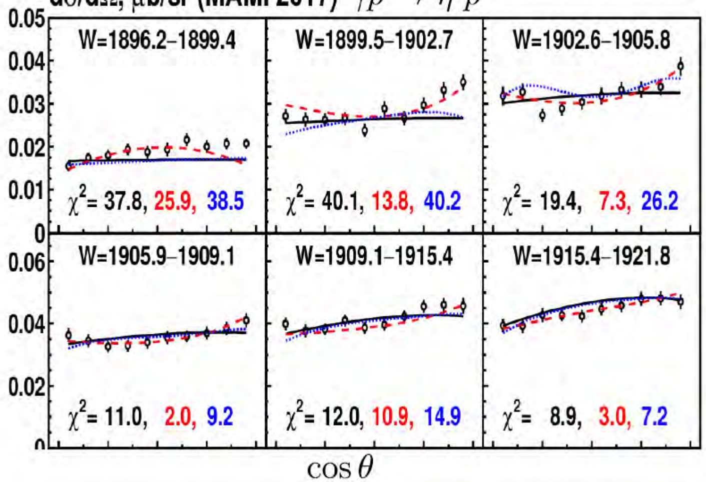


Resonances or not?

A2 MAMI, PRL 118 (2017) $S_{11}(1895)$



dσ/dΩ, μb/sr (MAMI 2017) $\gamma p \to \eta' p$



BnGa
PLB785 (2018):

No narrow resonance

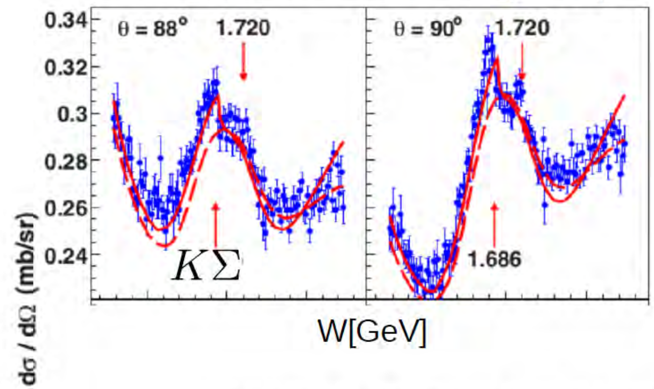
3/2⁻ narrow Resonance

5/2⁻ narrow Resonance

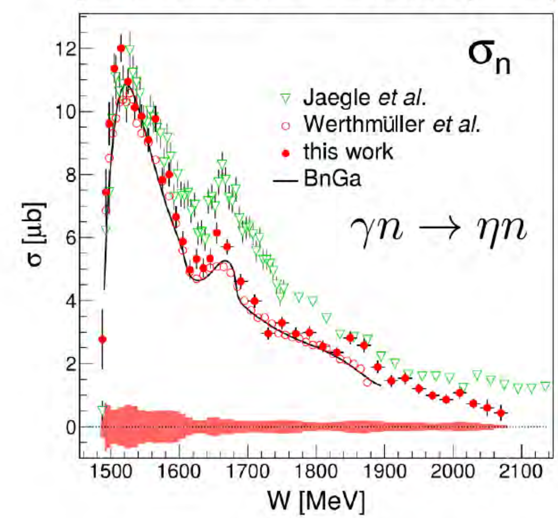
Data: A2.Mami PRL 118 (2017)

$\pi N \to \pi N$

EPECUR/SAID PRC 93 (2016)

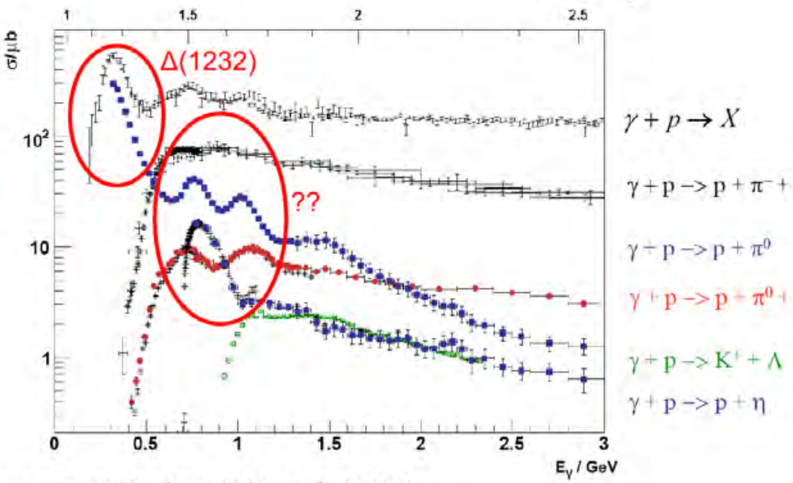


[CBELSA/TAPS EPJA 53 (2017)]



Photoproduction reactions

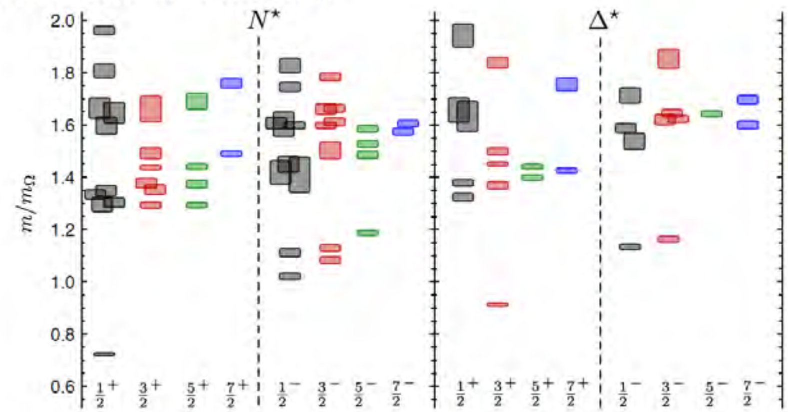
Experimental study of hadronic reactions



source: ELSA; data: ELSA, JLab, MAMI

$\Longleftrightarrow$

Theoretical predictions of excited hadrons
e.g. from lattice calculations:
(with some limitations)

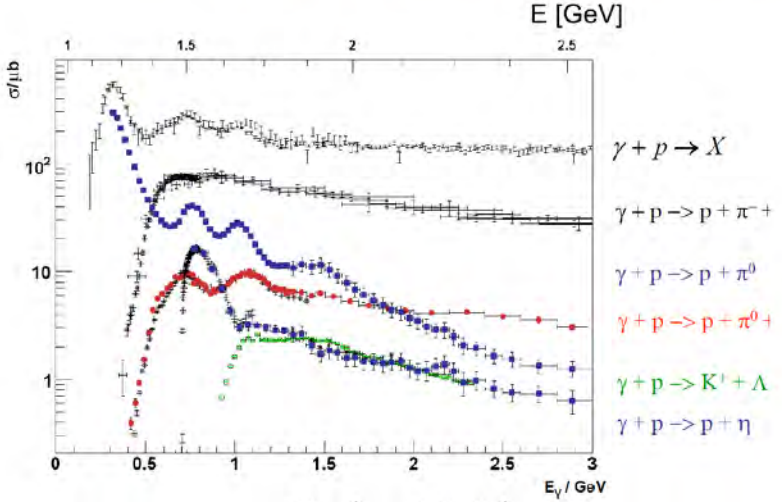


$m_\pi = 396$ MeV [Edwards *et al.*, Phys.Rev. D84 (2011)]

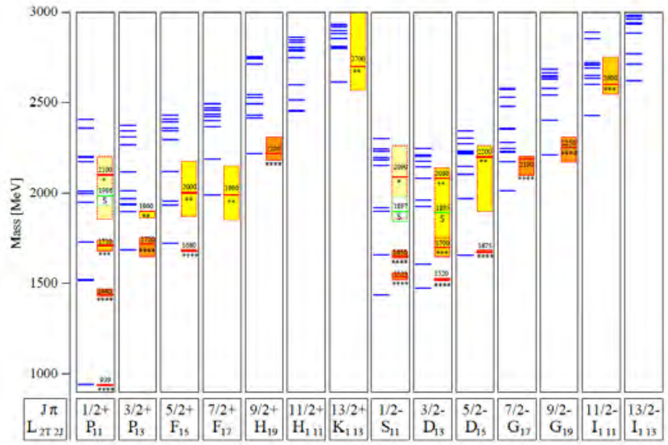
$$\gamma^{(*)}N \to \begin{cases} \pi N \\ \eta N,\ K\Lambda,\ K\Sigma, \omega N, \phi N, \ldots \\ \pi\pi N, \pi\eta N, \ldots \end{cases}$$

SAID Data Base @ GW:
https://gwdac.phys.gwu.edu/
New:
https://jbw.phys.gwu.edu/

From experimental data to the resonance spectrum



source: ELSA; data: ELSA, JLab, MAMI



Löring *et al.* EPJ A 10, 395 (2001), experimental spectrum: PDG 2000

Different modern analyses frameworks:

- **unitary isobar models:** unitary amplitudes + Breit-Wigner resonances
  MAID, Yerevan/JLab, KSU
- **(multi-channel) K-matrix:** GWU/SAID, BnGa (phenomenological),
  Gießen (microscopic Bgd)
- **dynamical coupled-channel (DCC):** 3d scattering eq., off-shell intermediate states
  ANL-Osaka (EBAC), Dubna-Mainz-Taipeh, Jülich-Bonn
- **other groups:** JPAC (high energies), Mainz-Tuzla-Zagreb PWA (MAID + fixed-t
  dispersion relations, L+P), Gent, truncated PWA

PDG Changes

- Changes from one PDG edition to another
- New states in red
- Upgrade existing states
- Removal older & lower rated states
- All changes come from Partial-wave analysis (PWA) of photon-induced reactions.

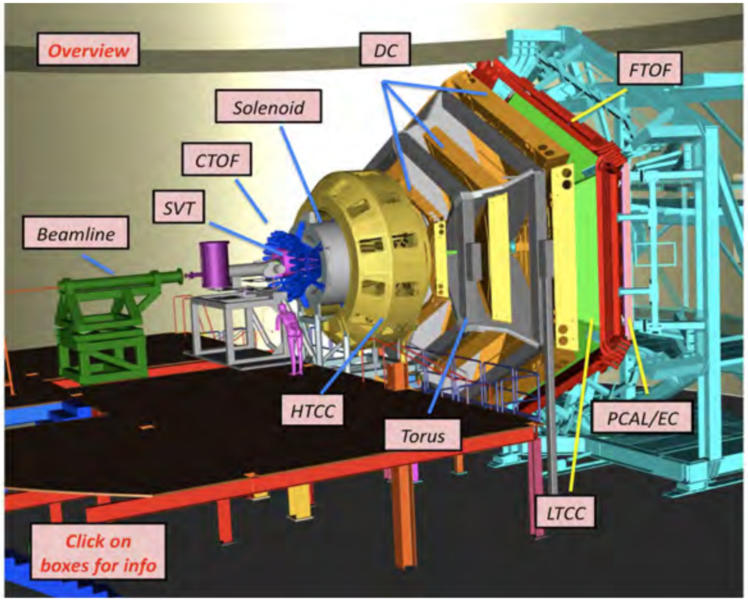
Table from [Crede]

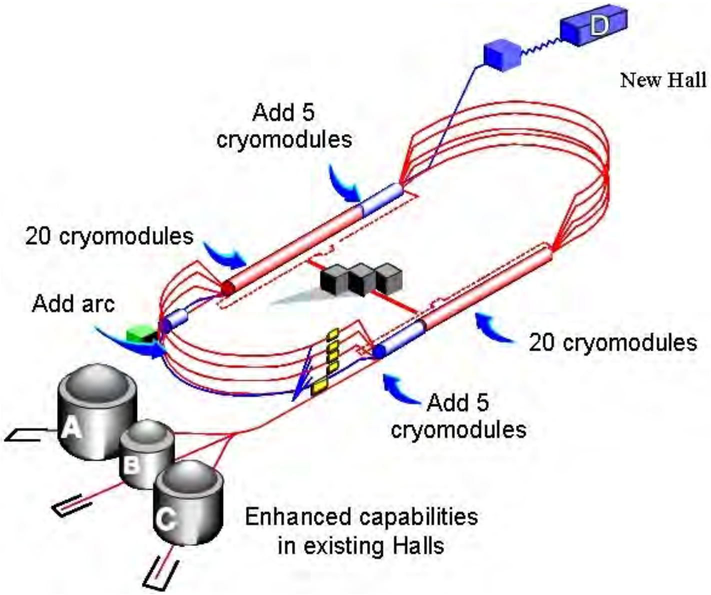
Table 9. (Colour online) Baryon Summary Table for N^* and Δ resonances including recent changes from PDG 2010 [2] to PDG 2012 [1].

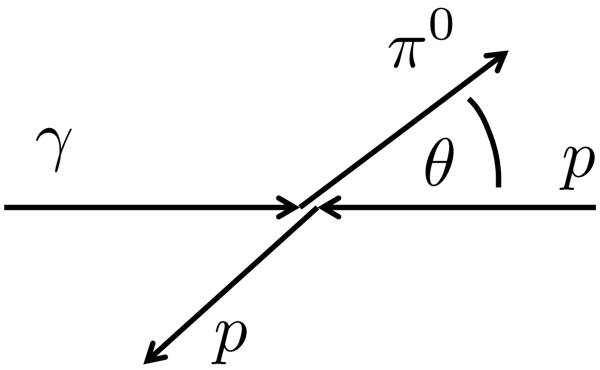
N^*	J^P $(L_{2I,2J})$	2010	2012	Δ	J^P $(L_{2I,2J})$	2010	2012
p	$1/2^+$ (P_{11})	****	****	$\Delta(1232)$	$3/2^+$ (P_{33})	****	****
n	$1/2^+$ (P_{11})	****	****	$\Delta(1600)$	$3/2^+$ (P_{33})	***	***
$N(1440)$	$1/2^+$ (P_{11})	****	****	$\Delta(1620)$	$1/2^-$ (S_{31})	****	****
$N(1520)$	$3/2^-$ (D_{13})	****	****	$\Delta(1700)$	$3/2^-$ (D_{33})	****	****
$N(1535)$	$1/2^-$ (S_{11})	****	****	$\Delta(1750)$	$1/2^+$ (P_{31})	*	*
$N(1650)$	$1/2^-$ (S_{11})	****	****	$\Delta(1900)$	$1/2^-$ (S_{31})	**	**
$N(1675)$	$5/2^-$ (D_{15})	****	****	$\Delta(1905)$	$5/2^+$ (F_{35})	****	****
$N(1680)$	$5/2^+$ (F_{15})	****	****	$\Delta(1910)$	$1/2^+$ (P_{31})	****	****
$N(1685)$			*				
$N(1700)$	$3/2^-$ (D_{13})	***	***	$\Delta(1920)$	$3/2^+$ (P_{33})	***	***
$N(1710)$	$1/2^+$ (P_{11})	***	***	$\Delta(1930)$	$5/2^-$ (D_{35})	***	***
$N(1720)$	$3/2^+$ (P_{13})	****	****	$\Delta(1940)$	$3/2^-$ (D_{33})	*	**
$N(1860)$	$5/2^+$		**				
$N(1875)$	$3/2^-$		***				
$N(1880)$	$1/2^+$		**				
$N(1895)$	$1/2^-$		**				
$N(1900)$	$3/2^+$ (P_{13})	**	***	$\Delta(1950)$	$7/2^+$ (F_{37})	****	****
$N(1990)$	$7/2^+$ (F_{17})	**	**	$\Delta(2000)$	$5/2^+$ (F_{35})	**	**
$N(2000)$	$5/2^+$ (F_{15})	**	**	$\Delta(2150)$	$1/2^-$ (S_{31})	*	*
~~$N(2080)$~~	D_{13}	**		$\Delta(2200)$	$7/2^-$ (G_{37})	*	*
~~$N(2090)$~~	S_{11}	*		$\Delta(2300)$	$9/2^+$ (H_{39})	**	**
$N(2040)$	$3/2^+$		*				
$N(2060)$	$5/2^-$		**				
$N(2100)$	$1/2^+$ (P_{11})	*	*	$\Delta(2350)$	$5/2^-$ (D_{35})	*	*
$N(2120)$	$3/2^-$		**				
$N(2190)$	$7/2^-$ (G_{17})	****	****	$\Delta(2390)$	$7/2^+$ (F_{37})	*	*
~~$N(2200)$~~	D_{15}	**		$\Delta(2400)$	$9/2^-$ (G_{39})	**	**
$N(2220)$	$9/2^+$ (H_{19})	****	****	$\Delta(2420)$	$11/2^+$ $(H_{3,11})$	****	****
$N(2250)$	$9/2^-$ (G_{19})	****	****	$\Delta(2750)$	$13/2^-$ $(I_{3,13})$	**	**
$N(2600)$	$11/2^-$ $(I_{1,11})$	***	***	$\Delta(2950)$	$15/2^+$ $(K_{3,15})$	**	**
$N(2700)$	$13/2^+$ $(K_{1,13})$	**	**				

Photoproduction experiments

(Jlab, Mami, Elsa,…)







The role of meson beams in baryon spectroscopy

(Non-strange, light baryon sector)

- Pion-induced reactions

$$\pi N \to \begin{cases} \pi N \\ \eta N,\ K\Lambda,\ K\Sigma \\ \pi\pi N, \pi\eta N, \ldots \end{cases}$$

- **Two** complex amplitudes (g,h)

Data!

- Photon-induced reactions

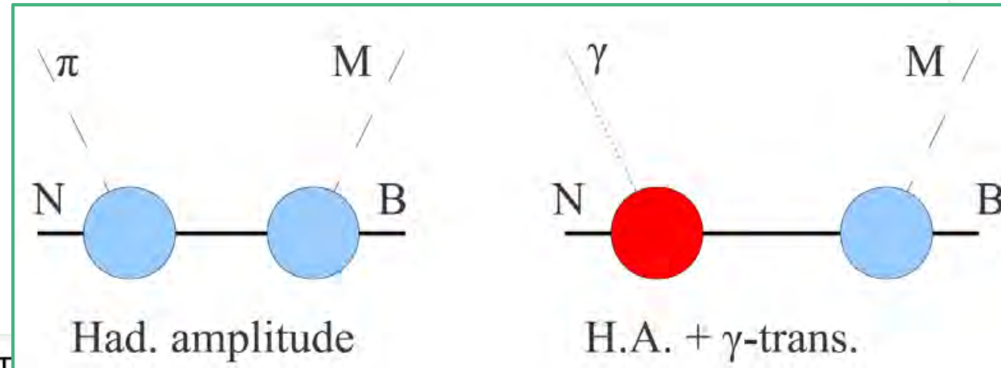
$$\gamma^{(*)} N \to \begin{cases} \pi N \\ \eta N,\ K\Lambda,\ K\Sigma \\ \pi\pi N, \pi\eta N, \ldots \end{cases}$$

$$\begin{cases} \pi N \\ \eta N,\ K\Lambda,\ K\Sigma \\ \pi\pi N, \pi\eta N, \ldots \end{cases} \leftrightarrow \begin{cases} \pi N \\ \eta N,\ K\Lambda,\ K\Sigma \\ \pi\pi N, \pi\eta N, \ldots \end{cases}$$

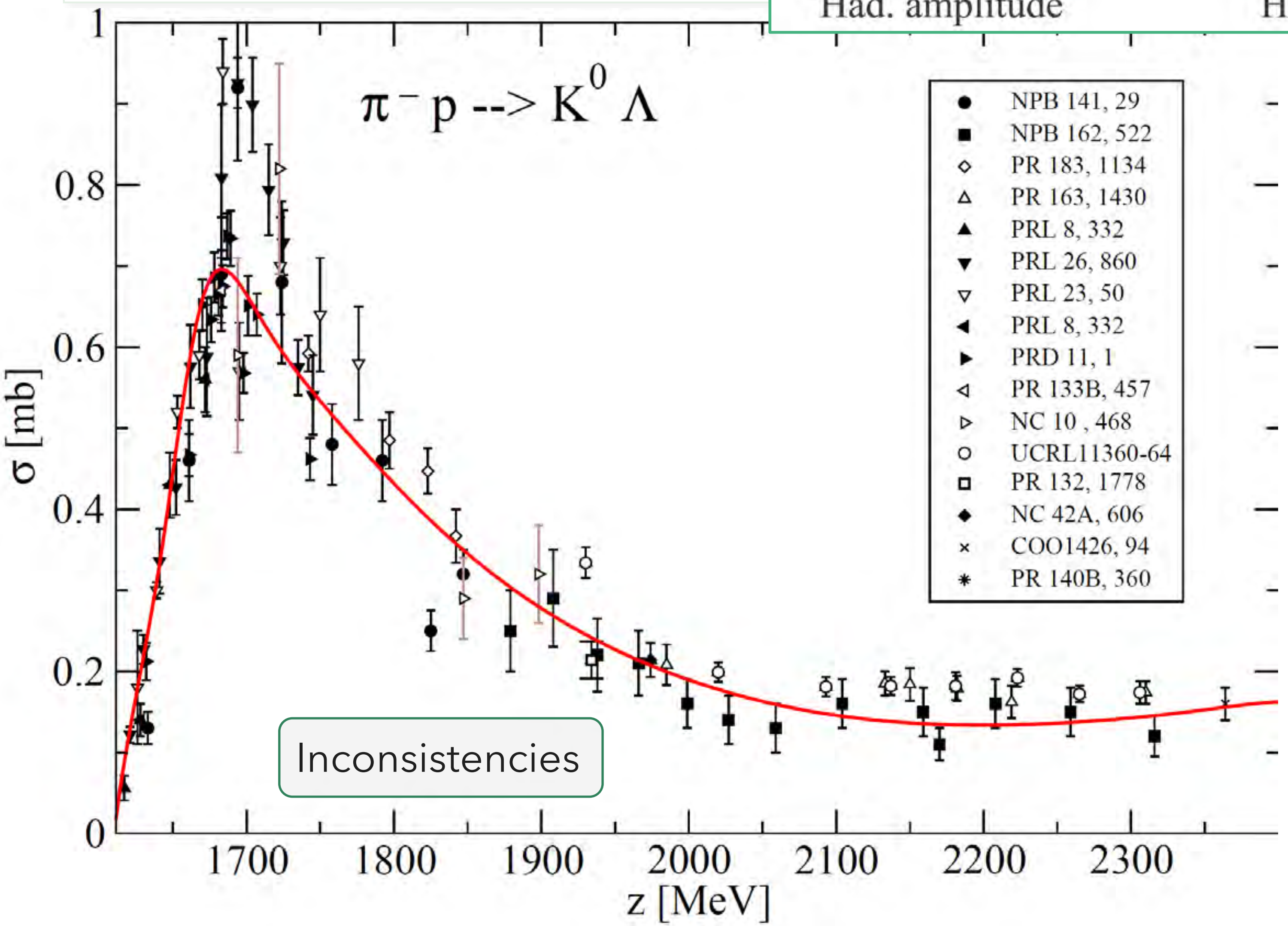
- Final-state interaction as sub-process
- **Four** (photo) or **six** (electro) complex amplitudes (CGNL, ...)

Photon-induced reactions have more dof and their analysis depends on meson-induced reaction data (except complete experiment).

Data

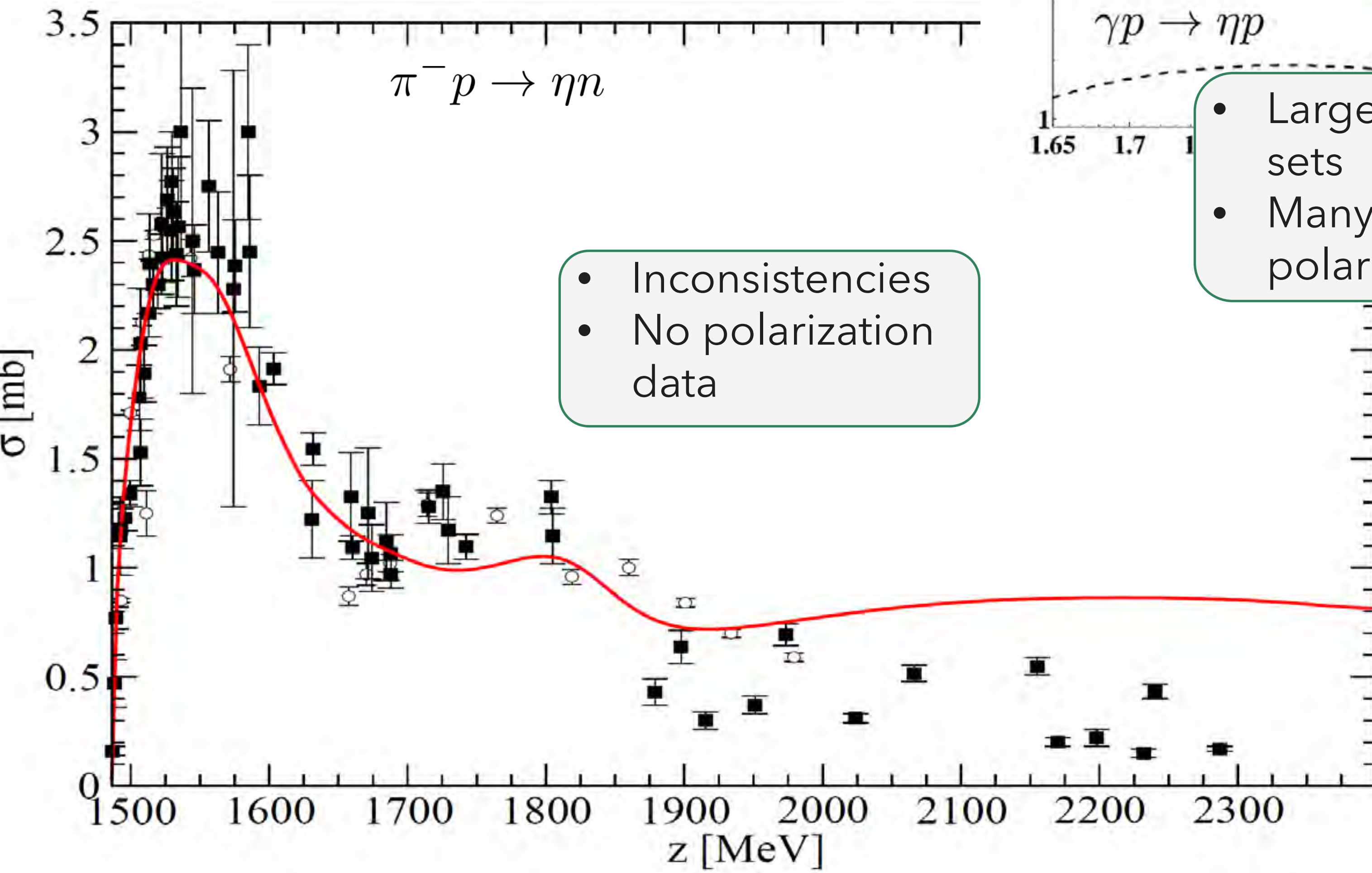


π
M
γ
M
N
B
N
B
Had. amplitude
H.A. + γ-trans.

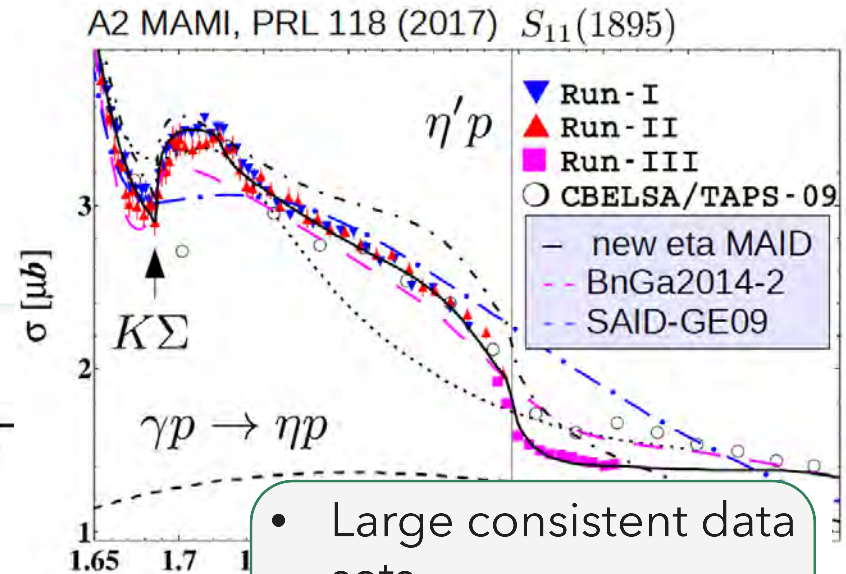


π⁻ p --> K⁰ Λ
σ [mb]
z [MeV]
0
0.2
0.4
0.6
0.8
1
1700
1800
1900
2000
2100
2200
2300
NPB 141, 29
NPB 162, 522
PR 183, 1134
PR 163, 1430
PRL 8, 332
PRL 26, 860
PRL 23, 50
PRL 8, 332
PRD 11, 1
PR 133B, 457
NC 10 , 468
UCRL11360-64
PR 132, 1778
NC 42A, 606
COO1426, 94
PR 140B, 360
Inconsistencies

Data: eta



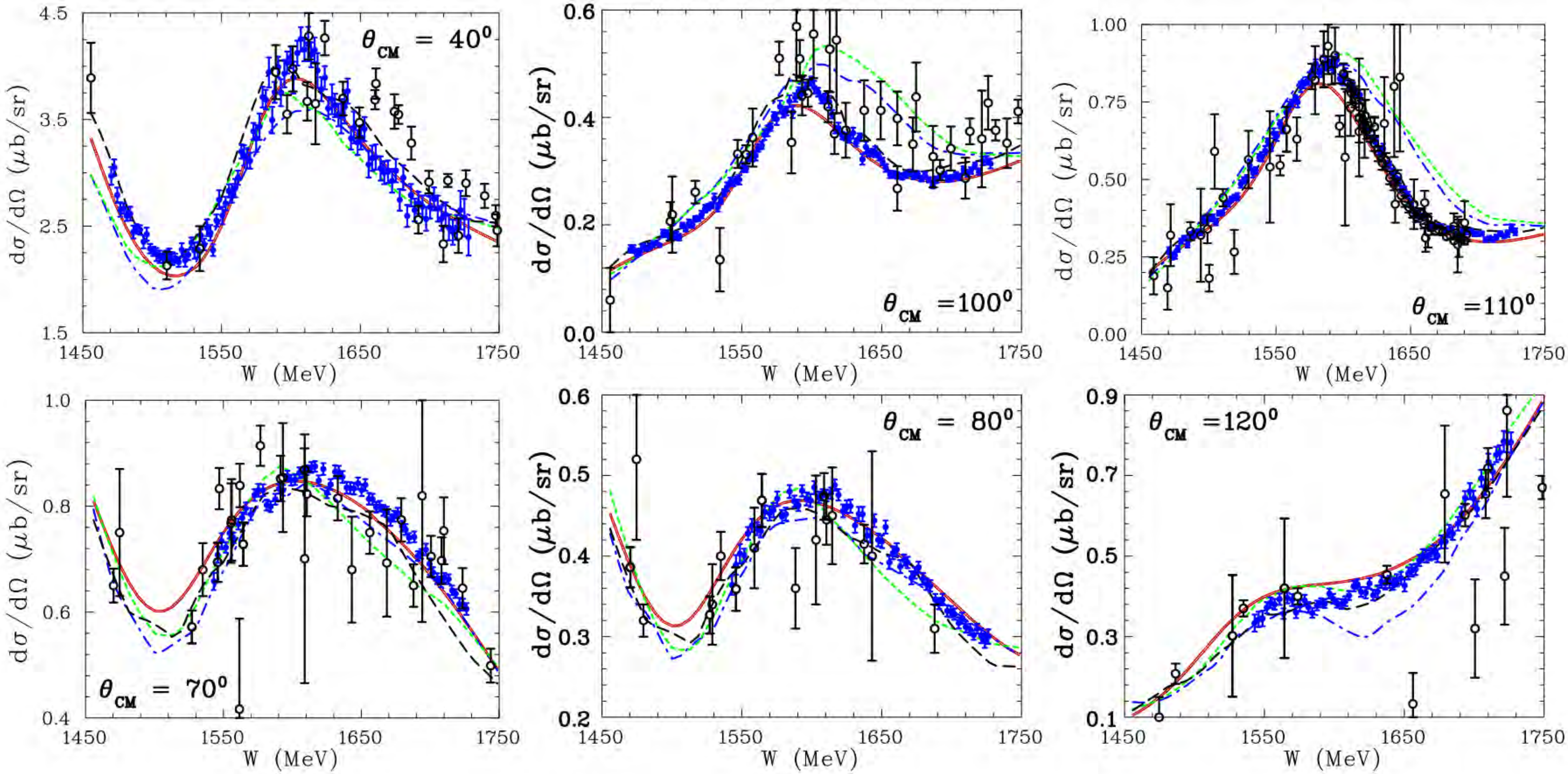
- Inconsistencies
- No polarization data



- Large consistent data sets
- Many different polarization data

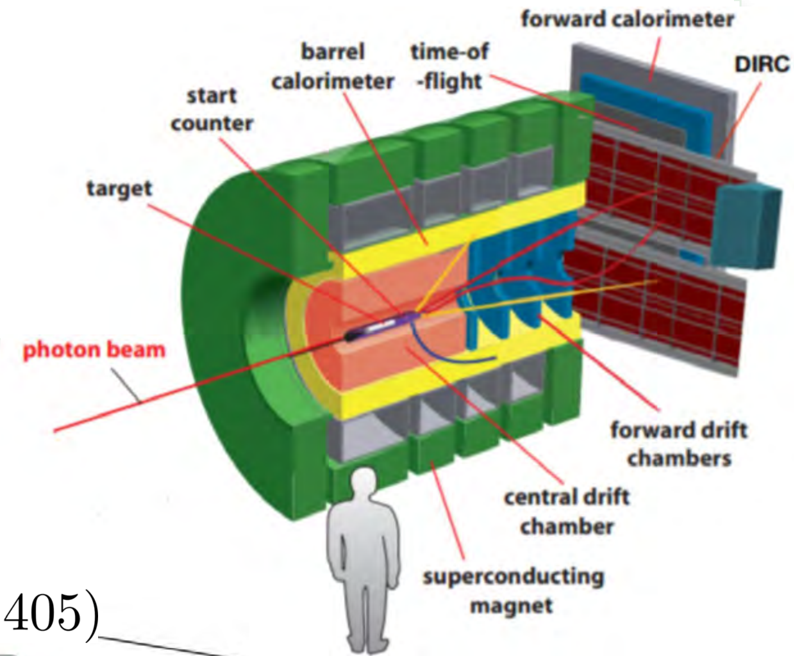
Example of recent improvements

Goal: Reduction of systematic uncertainties/ large body of consistent data

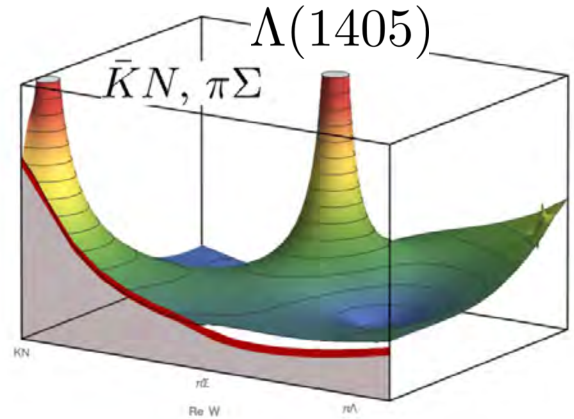


EPECUR experiment [Alekseev 2015] (**blue**) compared to previous measurements (**black**)

K-Long Facility



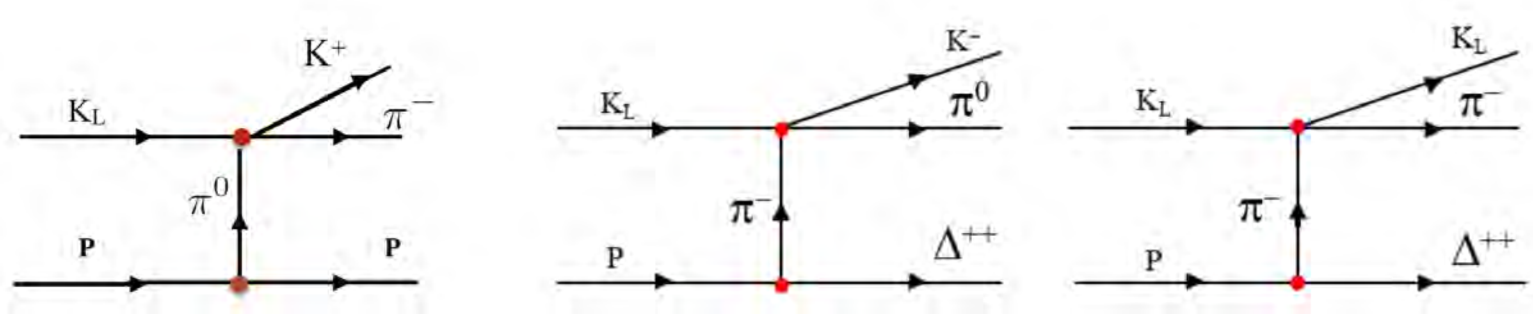
- Hyperon spectroscopy: Increased activity and analyses by
  - Kent state group,
  - JPAC,
  - Bonn-Gatchina,
  - ANL-Osaka,…



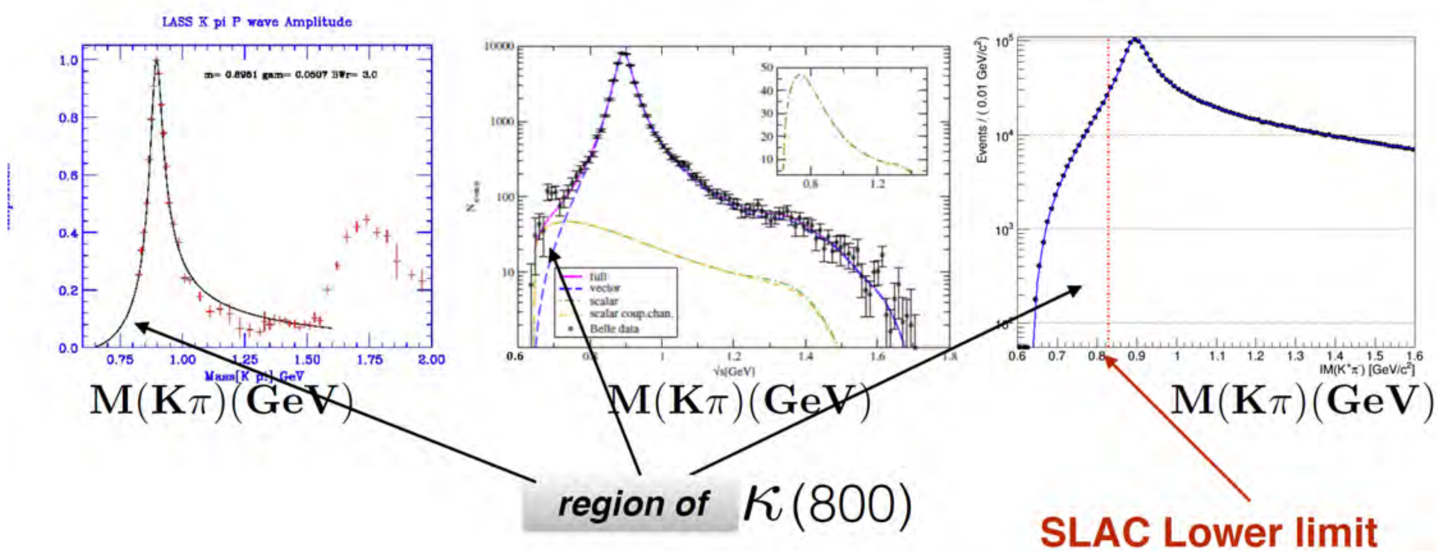
From: [Mai]

- Strange meson spectroscopy
  - Broader physics scope [Proposal]
- To accomplish physics program 200 days running is approved

Example: Broad scalar resonances

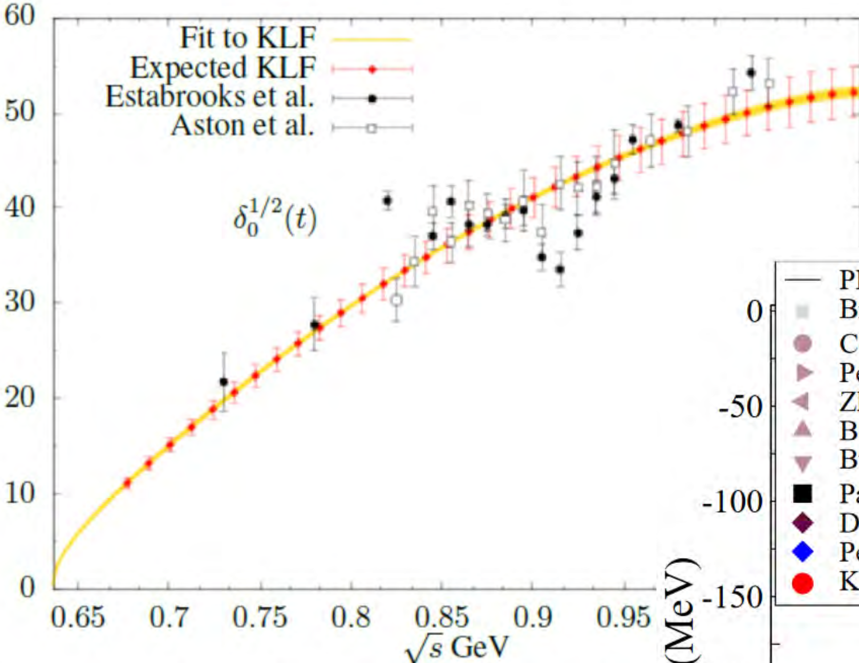


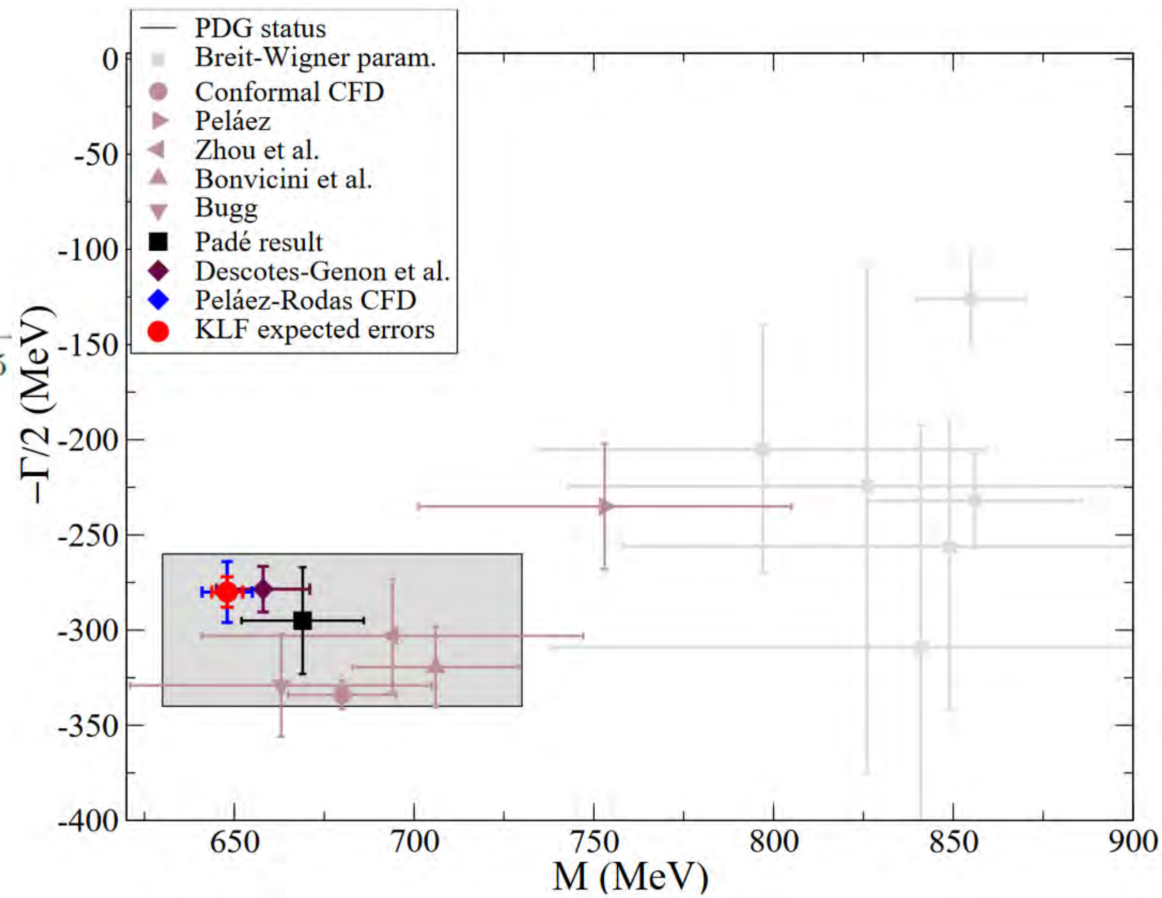
SLAC	Belle	KLF
$K^-\pi^+ \to K^-\pi^+$	$\tau \to K\pi\nu_\tau$	$K_L\pi^0 \to K^+\pi^-$



Slide: [M. Amaryan]

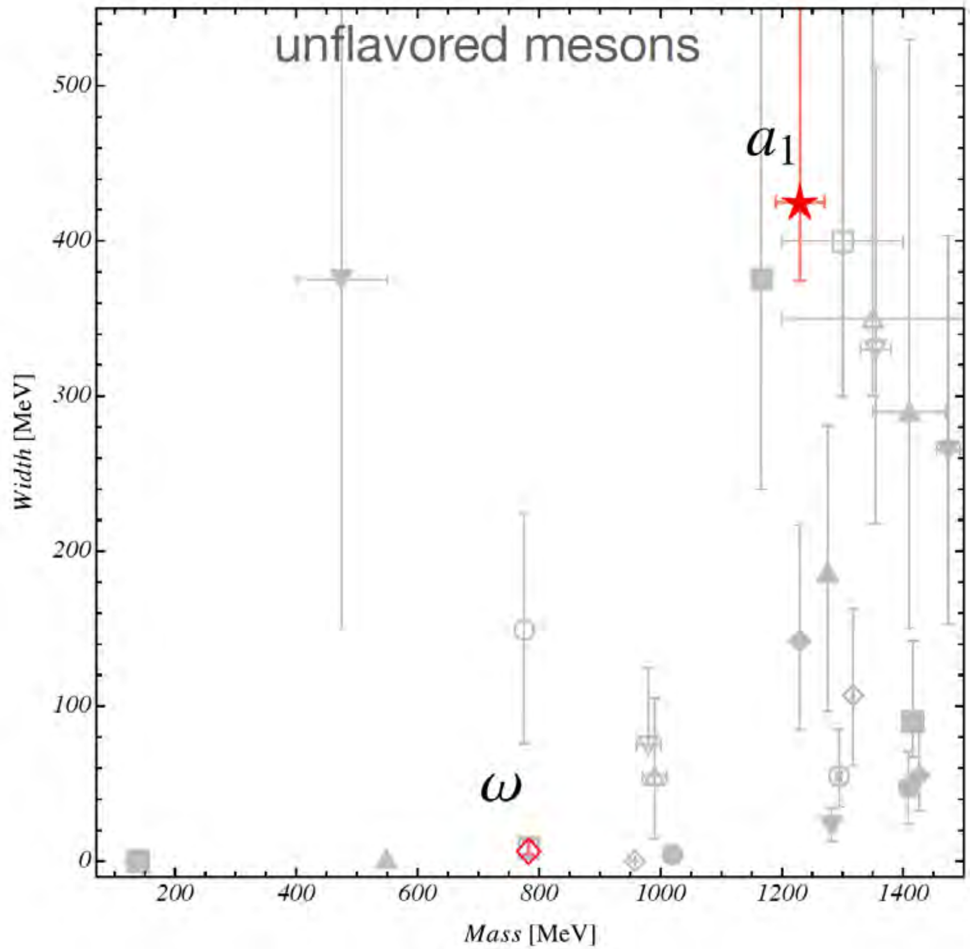
(KLF:) Projected precision





Adhikari, Amaryan,
[Analysis note]

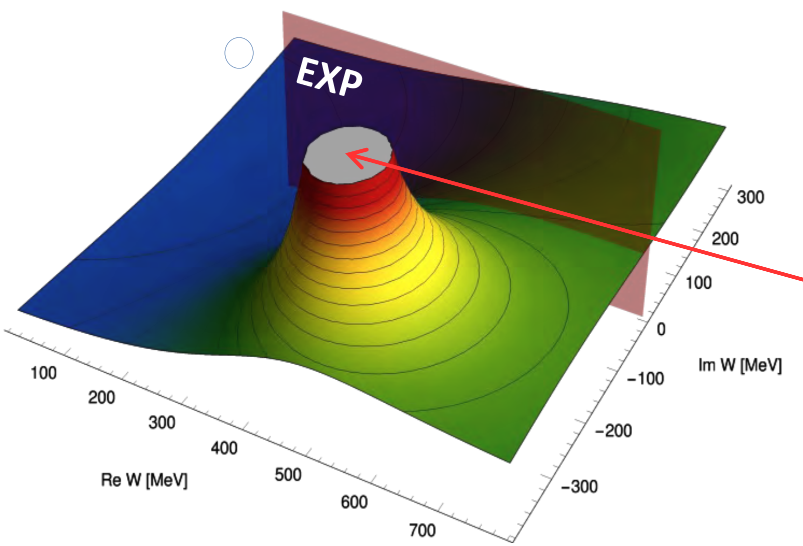
Light unflavored mesons- lattice QCD

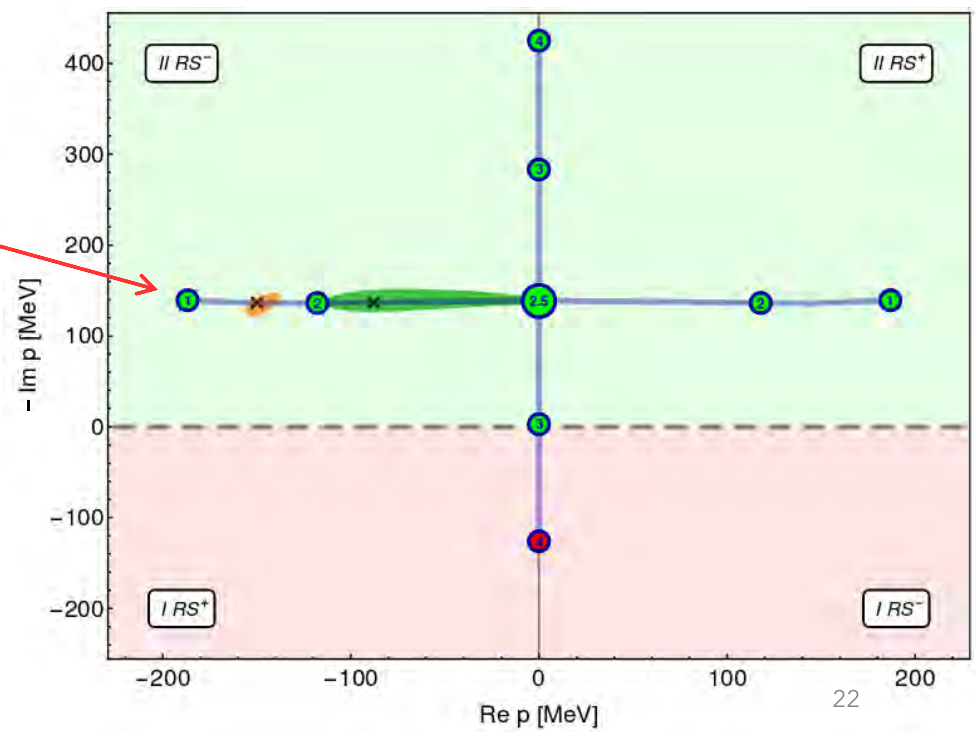


- Extensive work on 2-body coupled channel resonances from lattice QCD (**HadSpec** collaboration, **BGR** group, **Bonn** group, …) [Briceno]
- Calculations on three-body systems starting to emerge [Hansen] [Mai]

Chiral trajectories in lattice QCD

- A lattice calculation at M_π=227 MeV and 315 MeV [GWQCD, 1803.02897]
- σ becomes a (virtual) bound state @ M_π = (345) 415 MeV

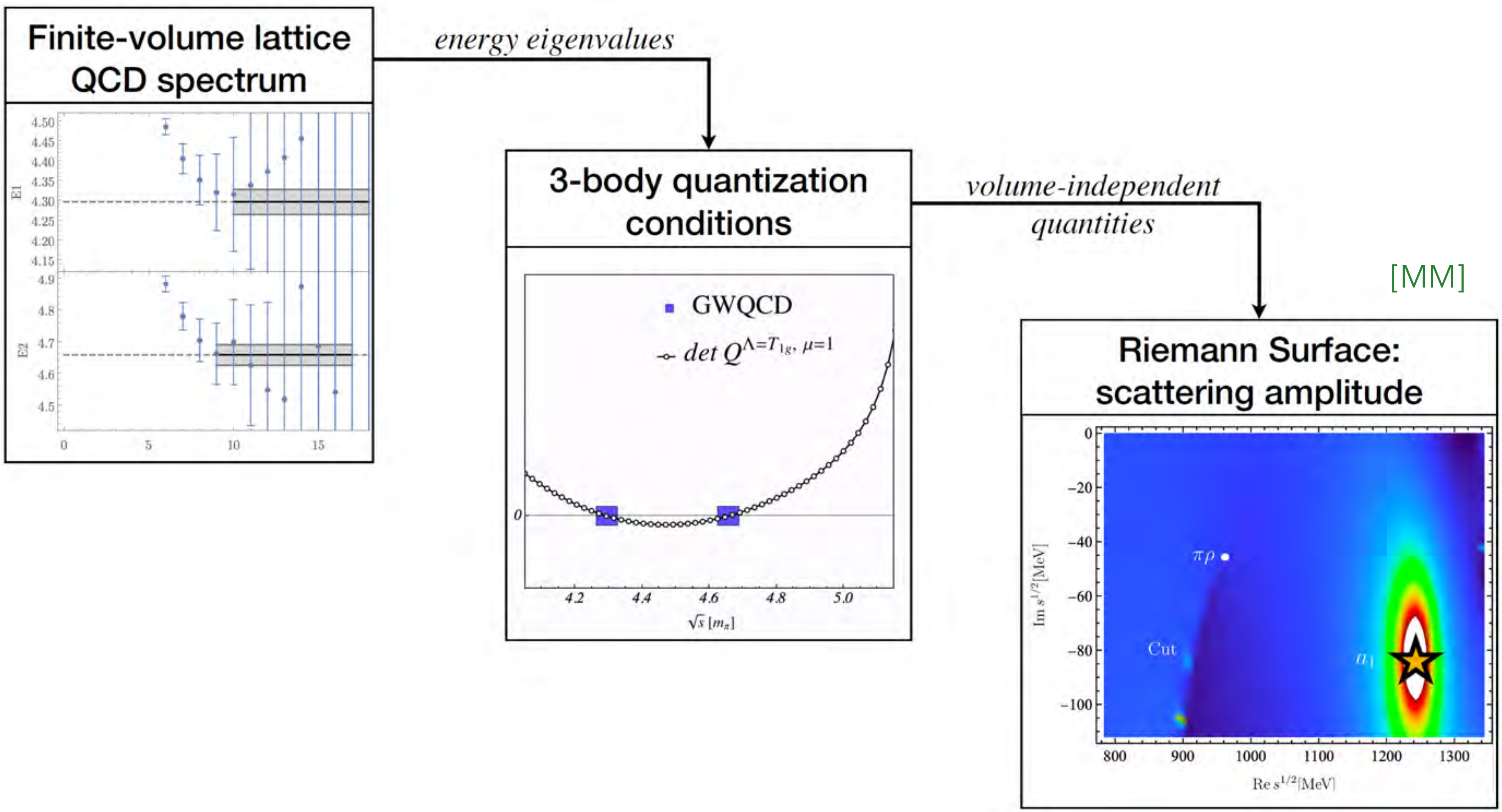




Extraction of $a_1(1260)$ from lattice QCD

[Mai/GWQCD]

• First-ever three-body resonance from 1st principles (with explicit three-body dynamics).



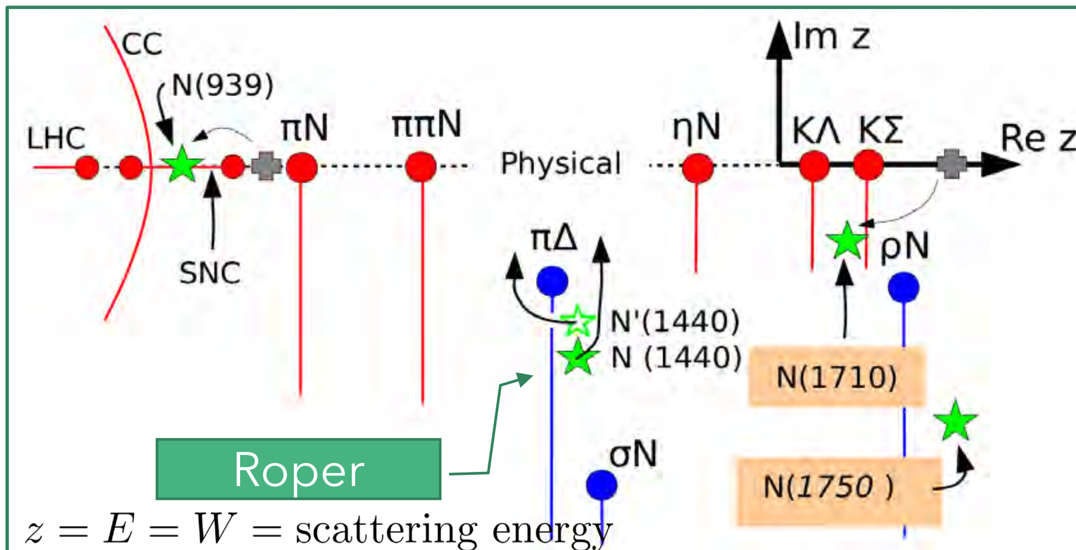
Summary of phenomenological aspects

- Meson beams benefit baryon spectroscopy:
  - Directly: they induce the most elementary reactions
  - Indirectly: they are needed for the final-state interaction of photo-induced reactions
  - Non-strange & Hyperon spectroscopy: complementary to photon-induced reactions
- Meson beams benefit spectroscopy and amplitude analysis of light mesons
- Many more aspects (not discussed):
  - Low-energy precision pion-nucleon physics
  - Inverse pion electroproduction
  - Glueballs,…
- Implementation at EIC: Initial ideas exist, see references in [preprint]

Spare slides

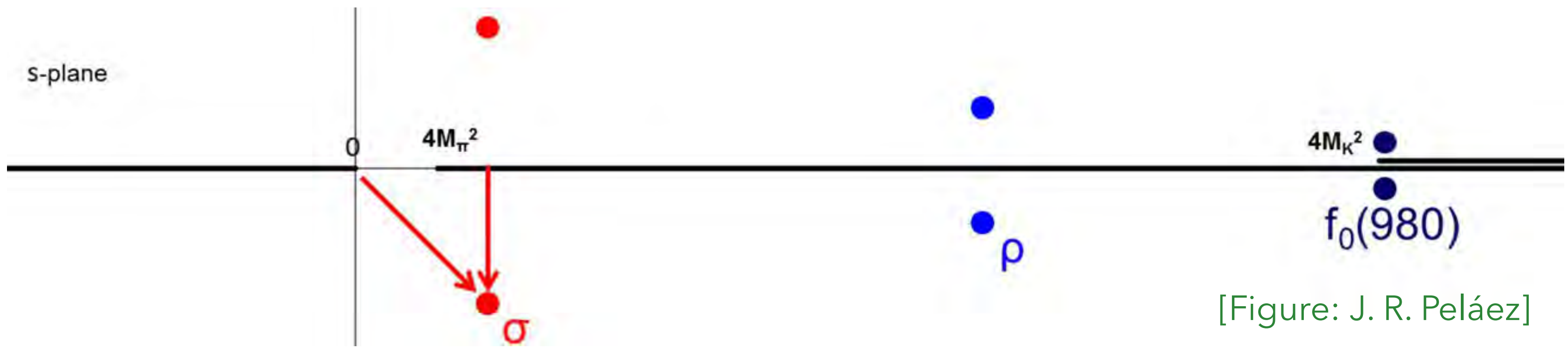
Hadronic resonances as poles

- Defining resonances as poles in amplitudes at complex energies provides meaningful definition
  - Real part of pole position ⟺ Mass
  - 2x Imaginary part of pole position ⟺ Width
  - Pole residue ⟺ Branching ratio into different channels because amplitudes factorize at poles
  - Analytic structure
    - Red: Real thresholds
    - Blue: sub-channel thres.
    - Why is Roper double?
    - What happens below threshold?



Right-hand and left-hand cuts

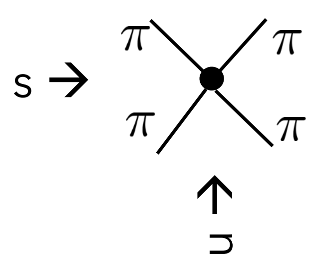
- Pole positions of wide resonances might be distorted if "left-hand cut" is not taken properly into account (and: analyticity in *s*, not $\sqrt{s}$)



[Figure: J. R. Peláez]

- Build in crossing symmetry manifestly through Roy-(like equations)

[Peláez]

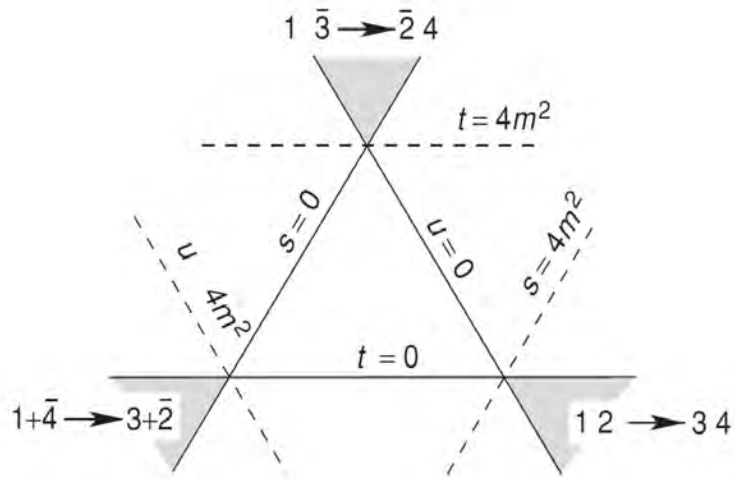


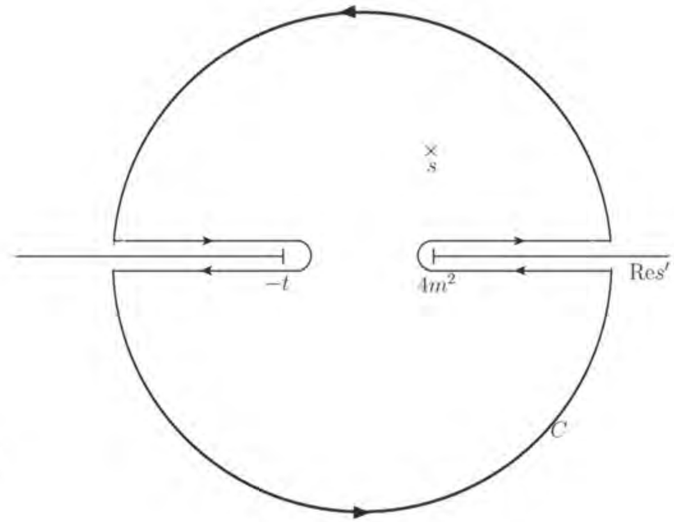
Advantage: $\pi\pi$ scattering in u-channel is still $\pi\pi$

πN: [Hoferichter]

Roy(-like) equations

[Figure & formulas: J. R. Peláez] [Gribov]





$$T(s,t,u) = \frac{1}{\pi}\int_{4m^2}^{\infty} ds' \frac{\mathrm{Im}T(s',t,u')}{s'-s} + \frac{1}{\pi}\int_{-\infty}^{-t} ds' \frac{\mathrm{Im}T(s',t,u')}{s'-s}$$

Unphysical region

Subtraction

$$T^{(I)}(s,t) = T^{(I)}(0,t) + \frac{s}{\pi}\int_{4M_\pi^2}^{\infty} ds' \left[\frac{\mathrm{Im}\,T^{(I)}(s',t)}{s'(s'-s)} - \frac{\mathrm{Im}\,T^{(I)}(u',t)}{u'(u'-s)}\right]$$

Crossing relations:

$$T^{(I)}(u',t,s') = \sum_{I'} C_{su}^{II'} T^{(I')}(s',t,u'), \quad T^{(I)}(0,t) = \sum_{I''} C_{st}^{II''} T^{(I'')}(t,0)$$

$s \leftrightarrow u$ crossing

Only physical Region!

Partial-wave expansion

Roy-Eq.: $$t_\ell^{(I)}(s) = \overline{ST}_\ell^I(s) + \sum_{I'=0}^{2}\sum_{\ell'=0}^{\ell_{max}} \int_{4M_\pi^2}^{s_{max}} ds' \overline{K}_{\ell\ell'}^{II'}(s,s')\mathrm{Im}\, t_{\ell'}^{I'}(s') + \overline{DT}_\ell^I(s)$$

Coupled partial waves

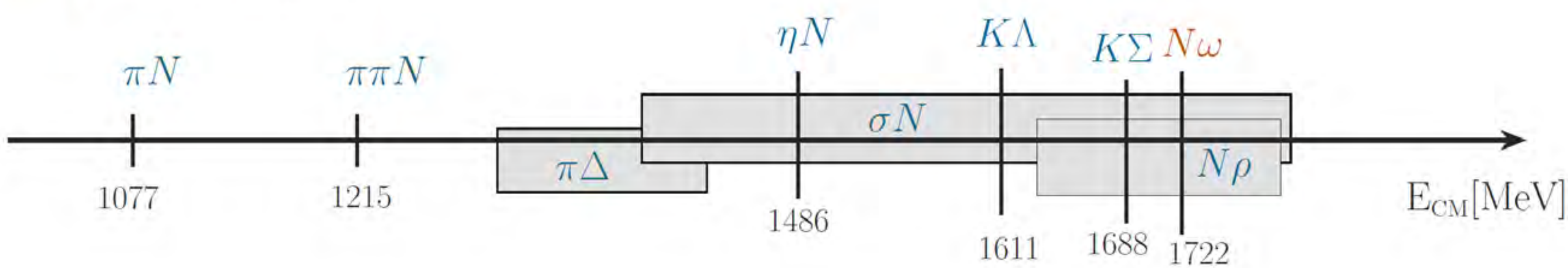
JBW DCC approach (Jülich-Bonn-Washington)

Dynamical coupled-channels (DCC): **simultaneous** analysis of different reactions

The scattering equation in partial-wave basis

$$\langle L'S'p'|T^{IJ}_{\mu\nu}|LSp\rangle = \langle L'S'p'|V^{IJ}_{\mu\nu}|LSp\rangle + \sum_{\gamma,L''S''}\int_0^\infty dq \quad q^2 \quad \langle L'S'p'|V^{IJ}_{\mu\gamma}|L''S''q\rangle \frac{1}{E - E_\gamma(q) + i\epsilon} \langle L''S''q|T^{IJ}_{\gamma\nu}|LSp\rangle$$

- channels ν, μ, γ:



JBW DCC approach (Jülich-Bonn-Washington)

The scattering equation in partial-wave basis

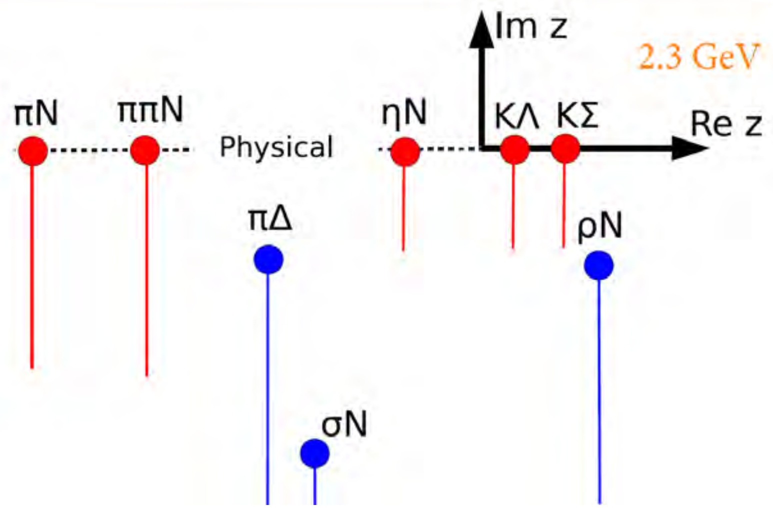
$$\langle L'S'p'|T^{IJ}_{\mu\nu}|LSp\rangle = \langle L'S'p'|V^{IJ}_{\mu\nu}|LSp\rangle + \sum_{\gamma,L''S''}\int_0^\infty dq \quad q^2 \quad \langle L'S'p'|V^{IJ}_{\mu\gamma}|L''S''q\rangle \frac{1}{E-E_\gamma(q)+i\epsilon}\langle L''S''q|T^{IJ}_{\gamma\nu}|LSp\rangle$$

3-body $\pi\pi N$ channel:

- parameterized effectively as $\pi\Delta$, σN, ρN
- $\pi N/\pi\pi$ subsystems fit the respective phase shifts

↳ branch points move into complex plane

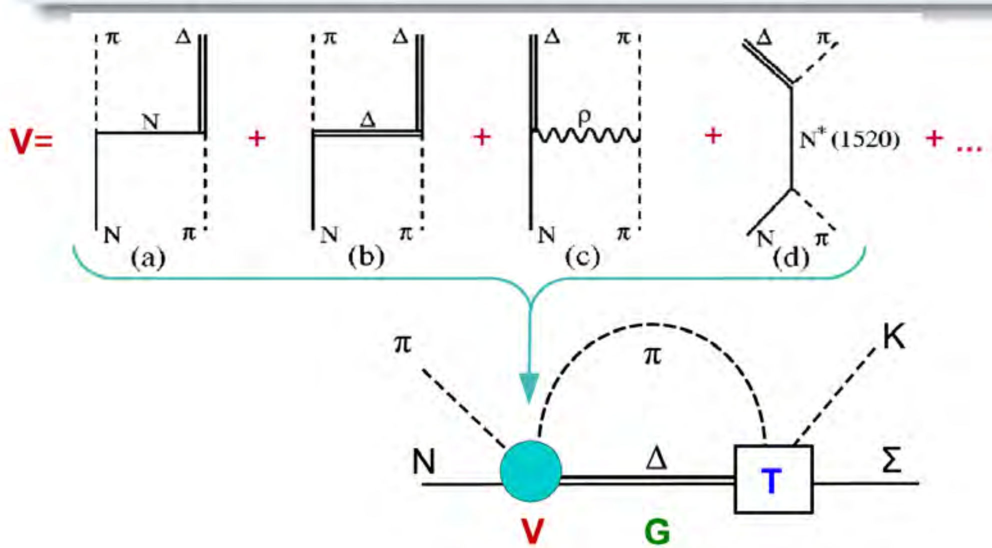
Inclusion of branch points important to avoid false resonance signal!



JBW DCC approach (Jülich-Bonn-Washington)

The scattering equation in partial-wave basis

$$\langle L'S'p'|T^{IJ}_{\mu\nu}|LSp\rangle = \langle L'S'p'|V^{IJ}_{\mu\nu}|LSp\rangle + \sum_{\gamma,L''S''}\int_0^\infty dq \quad q^2 \quad \langle L'S'p'|V^{IJ}_{\mu\gamma}|L''S''q\rangle \frac{1}{E-E_\gamma(q)+i\epsilon}\langle L''S''q|T^{IJ}_{\gamma\nu}|LSp\rangle$$

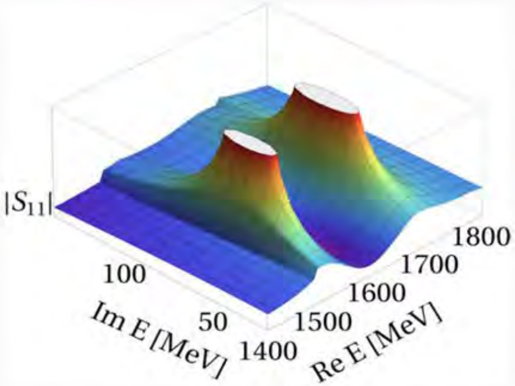


- potentials V constructed from effective $\mathcal{L}$
- s-channel diagrams: T^P
  genuine resonance states
- t- and u-channel: T^{NP}
  dynamical generation of poles
  partial waves strongly correlated
- contact terms

Workflow: Resonance Couplings

Resonance states: **Poles in the T-matrix** on the 2^{nd} Riemann sheet

[D. Roenchen, M. D., U.-G. Meißner, EPJ A 54, 110 (2018)



- Re(E_0) = "mass", -2Im(E_0) = "width"
- elastic πN residue ($|r_{\pi N}|, \theta_{\pi N \to \pi N}$), normalized residues for inelastic channels ($\sqrt{\Gamma_{\pi N}\Gamma_\mu}/\Gamma_{tot}, \theta_{\pi N \to \mu}$)
- photocouplings at the pole: $\tilde{A}^h_{pole} = A^h_{pole} e^{i\vartheta^h}$, $h = 1/2,\ 3/2$

Inclusion of $\gamma p \to K^+\Lambda$ in JüBo ("JuBo2017-1"): 3 additional states

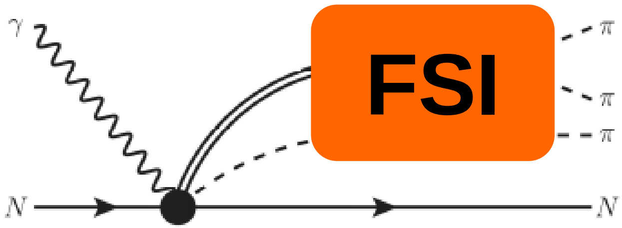
	z_0 [MeV]	$\frac{\Gamma_{\pi N}}{\Gamma_{tot}}$	$\frac{\Gamma_{\eta N}}{\Gamma_{tot}}$	$\frac{\Gamma_{K\Lambda}}{\Gamma_{tot}}$
N(1900)3/2$^+$	$1923 - i\,108.4$	1.5 %	0.78 %	2.99 %
N(2060)5/2$^-$	$1924 - i\,100.4$	0.35 %	0.15 %	13.47 %
Δ(*2190*)1/2$^+$	$2191 - i\,103.0$	33.12 %		

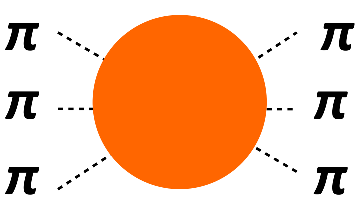
- N(1900)3/2$^+$: s-channel resonances, seen in many other analyses of kaon photoproduction (BnGa), 3 stars in PDG
- N(2060)5/2$^-$: dynamically generated, 2 stars in PDG, seen e.g. by BnGa
- Δ(*2190* 1 2$^+$: dyn. gen., no equivalent PDG state

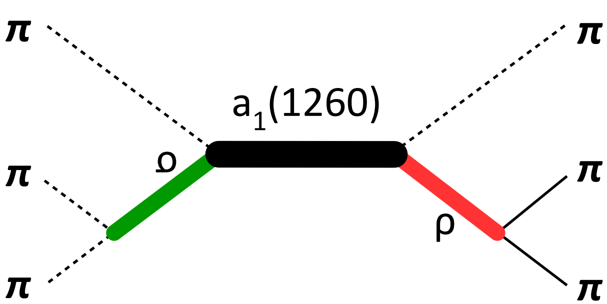
3. Three-body systems

Light mesons

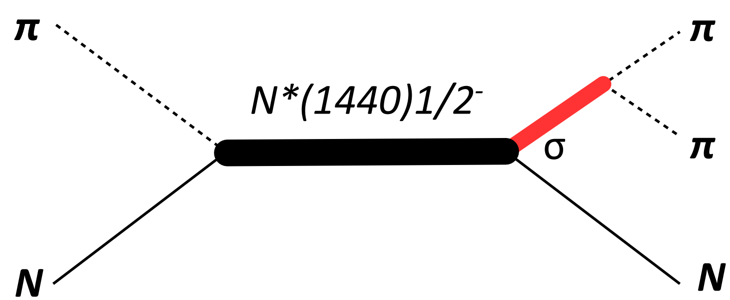
- Important channel in GlueX @ Jlab: hybrids and exotics
- Finite volume spectrum from lattice QCD:
  Lang (2014), Woss [HadronSpectrum] (2018) Hörz (2019), Culver (2020), Fischer (2020), Hansen (2020),...







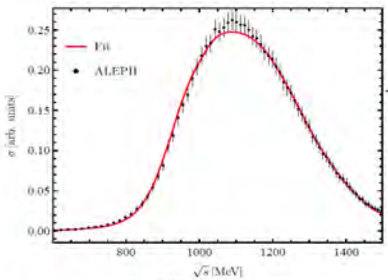
Light baryons



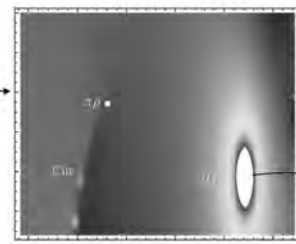
- Roper resonance is debated for ~50 years in experiment. Can only be seen in PWA.
- 1st calculation w. meson-baryon operators on the lattice: **Lang et al. (2017)**

Extraction of $a_1(1260)$ from lQCD

[Mai/GWQCD]

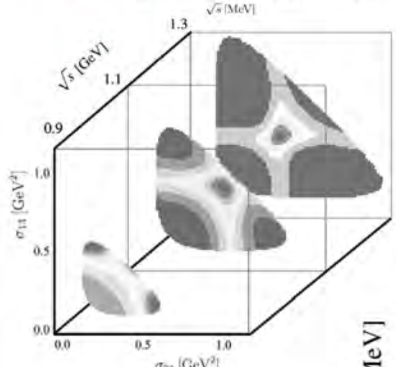


C

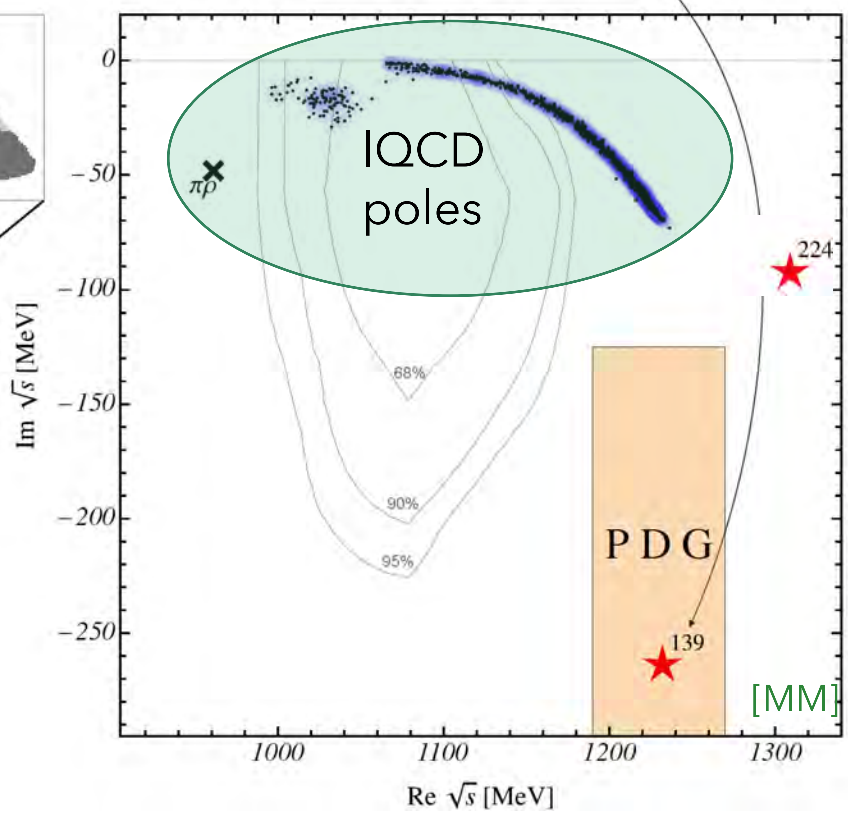


What does phenomenology says?

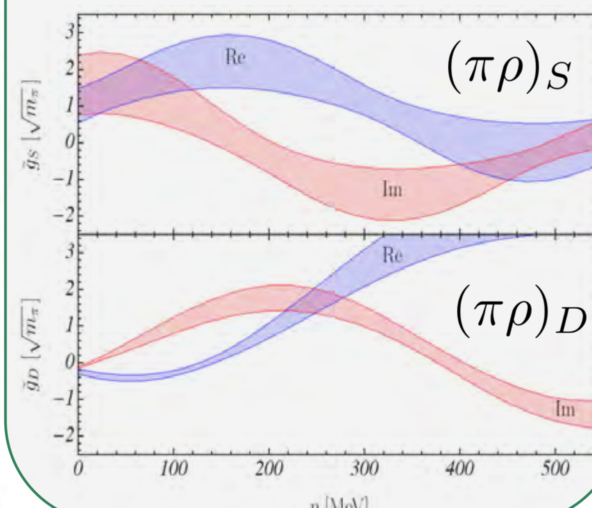
- $\tau \to (\pi\pi\pi)\nu_\tau$ from ALEPH@CERN
- fit to line shape to fix C



[Sadasivan]



"**Branching ratios**" in 3B decays are momentum – dependent, complex pole residues



Review 2B-lattice: [Briceno]
Reviews 3B-lattice: [Hansen] [Mai]