A Physics Case for the K-Long Facility

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Disclaimer: Only a small subset of physics motivations for the Klong facility can be presented. Selection is <u>subjective</u> and <u>incomplete</u>.

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Resources - Experiment

KLF Wiki page: [https://wiki.jlab.org/klproject/index.php/Main_Page]

- Overview of current experimental status: [Sean Dobbs 2022]
  - This talk is not about experimental status of approved KL experiment but provides some physics motivation for it.
  - See Wiki page for talks on experimental status.
- Whitepaper [2020] ; secondary meson beam whitepaper [Briscoe 2015]
- Collaboration meetings [6th Coll. Meeting Nov. 3, 2022]
- Extensive theoretical support:

Alexey Anisovich[5,44], Alexei Bazavov[38], Rene Bellwied[21], Veronique Bernard[42], Gilberto Colangelo[3], Aleš Cieplý[46], Michael Döring[19], Ali Eskanderian[19], Jose Goity[20,49], Helmut Haberzettl[19], Mirza Hadžimehmedović[55], Robert Jaffe[36], Boris Kopeliovich[54], Heinrich Leutwyler[3], Maxim Mai[19], Terry Mart[65], Maxim Matveev[44], Ulf-G. Meißner[5,29], Colin Morningstar[9], Bachir Moussallam[42], Kanzo Nakayama[58], Wolfgang Ochs[37], Youngseok Oh[31], Rifat Omerovic[55], Hedim Osmanović[55], Eulogio Oset[62], Antimo Palano[64], Jose Peláez[34], Alessandro Pilloni[66,67], Maxim Polyakov[48], David Richards[49], Arkaitz Rodas[49,56], Dan-Olof Riska[12], Jacobo Ruiz de Elvira[3], Hui-Young Ryu[45], Elena Santopinto[23], Andrey Sarantsev[5,44], Jugoslav Stahov[55], Alfred Švarc[47], Adam Szczepaniak[22,49], Ronald Workman[19], Bing-Song Zou[4]

Other experiments dedicated to strangeness

- J-PARC (see session on Nuclear Strangeness on Fr. 9/9, 8am)
  - E57, E62 [T. Hashimoto (2019)]
  - E15 [Y. Sada et al. (2016), T. Yamaga (2020)]
  - Many experiments dedicated to the $\bar{K}$-nucleus potential
  - Related to possibility of $\bar{K}NN$ formation [Akaishi 2002];
  - Ongoing debate, e.g., [Magas (2006)]
- Low energies/scattering length: DAΦNE/KLOE/AMADEUS:
  - Siddharta-2/Kaonic deuterium [Miliucci (2021)]
  - Amadeus (new data point of $K^- n \to \Lambda\pi^-$) [K.Piscicchia (2018)]
- CLAS-12: $\gamma p \to K^+(Y^* \to \pi\Sigma, \dots)$
- Panda (mostly ΛN, ...) [Lutz (2009)]
- Belle, Babar, Compass, LHCb,… [Whitepaper 2020]

Klong – the basics

- Klong is a *CP* eigenstate and superposition of strong eigenstates according to

$$K_L^0 = \frac{1}{\sqrt{2}}(K^0 - \overline{K^0}) \qquad K_S^0 = \frac{1}{\sqrt{2}}(K^0 + \overline{K^0})$$

- Weak interaction allows for mixing of strong eigenstates:

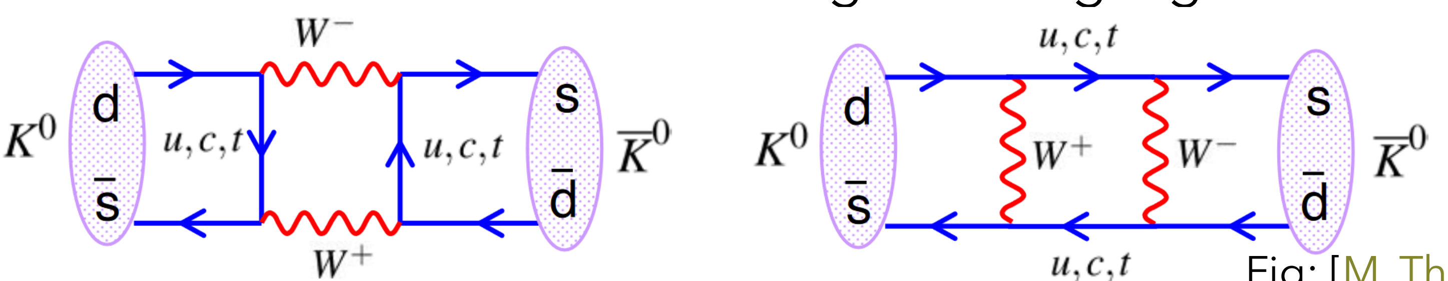


Fig: [M. Thomson/Cam]

- KL produces in general combinations of different isospin and strangeness channels, e.g.:

$$T(K_L^0 p \to K_L^0 p) = \frac{1}{2}\left(\frac{1}{2}T^1(KN \to KN) + \frac{1}{2}T^0(KN \to KN)\right) + \frac{1}{2}T^1(\overline{K}N \to \overline{K}N)$$

$$T(K_L^0 p \to \pi^+\Lambda) \;=\; -\frac{1}{\sqrt{2}}T^1(\overline{K}N \to \pi\Lambda)$$

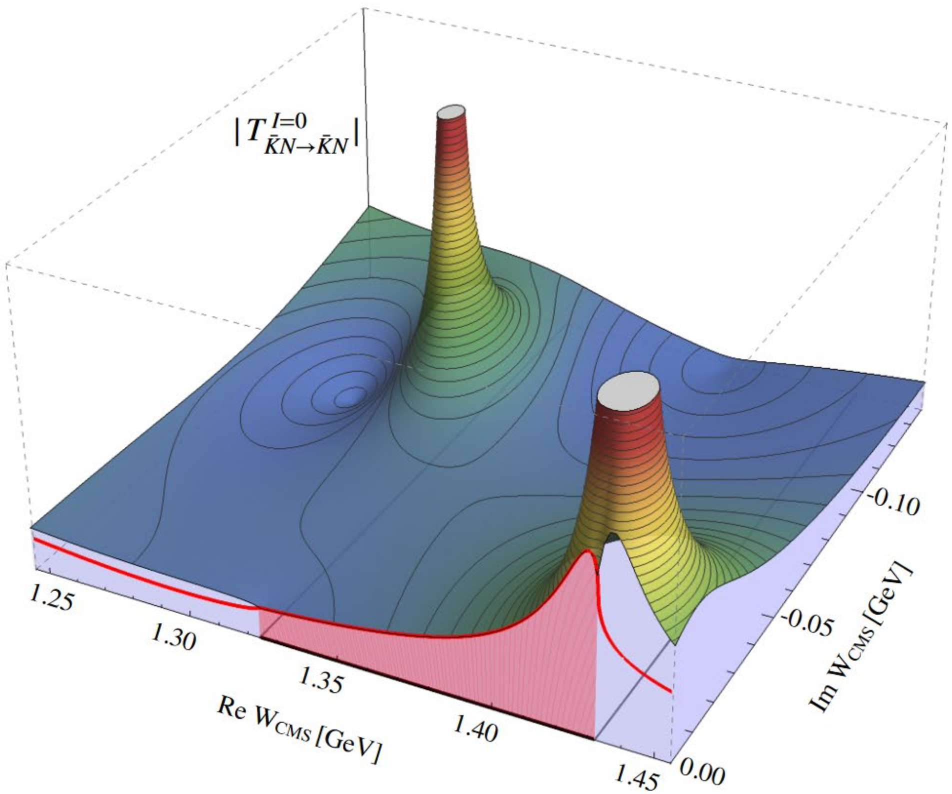
[Manley 2016]

Hyperons at low energies: The $\Lambda(1405)$

Review by [M. Mai (2020)]

The two-pole nature of the $\Lambda(1405)$

- Consequence of coupled-channel $\pi\Sigma, \bar{K}N$ attractive dynamics



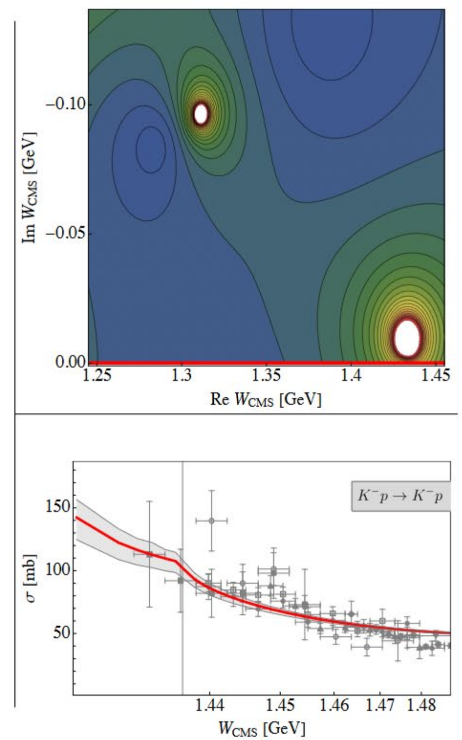


Figure from [M. Mai (2020)]

Decades-long interest in S=-1 low energy

- From Dalitz [PRL 1959] to NNLO treatment connecting all strangeness sectors [J.-Xu Lu (2022)]
- Main question: How does chiral dynamics dictate the low-energy, coupled-channel $\bar{K}N$ interaction?
  - Inherently non-perturbative
  - Expansion of chiral kernels to different chiral orders with subsequent unitarization
- Ten channels in isospin-0 and I=1, usually with mass differences

$$\pi^0\Lambda,\ \pi^-\Sigma^+,\ \pi^0\Sigma^0,\ \pi^+\Sigma^-,\ K^-p,\ \bar{K}^0n,\ \eta\Lambda,\ \eta\Sigma^0,\ K^0\Xi^0,\ K^+\Xi^-$$

- Their interaction to
  - LO [Kaiser (1995), Oset (1998), Oller (2001), Jido (2003); ~700 citations each],
  - NLO [Mai (2014), Z. H. Guo (2012)],
  - NNLO [J.-Xu Lu (2022)]
- Full Bethe-Salpeter equation in [Mai (2014)]

$$T(\not{q}_2,\not{q}_1;p) = V(\not{q}_2,\not{q}_1;p) + i\int \frac{d^d\ell}{(2\pi)^d}\frac{V(\not{q}_2,\not{\ell};p)}{\ell^2-M^2+i\epsilon}\frac{1}{\not{p}-\not{\ell}-m+i\epsilon}T(\not{\ell},\not{q}_1;p), \quad (1)$$

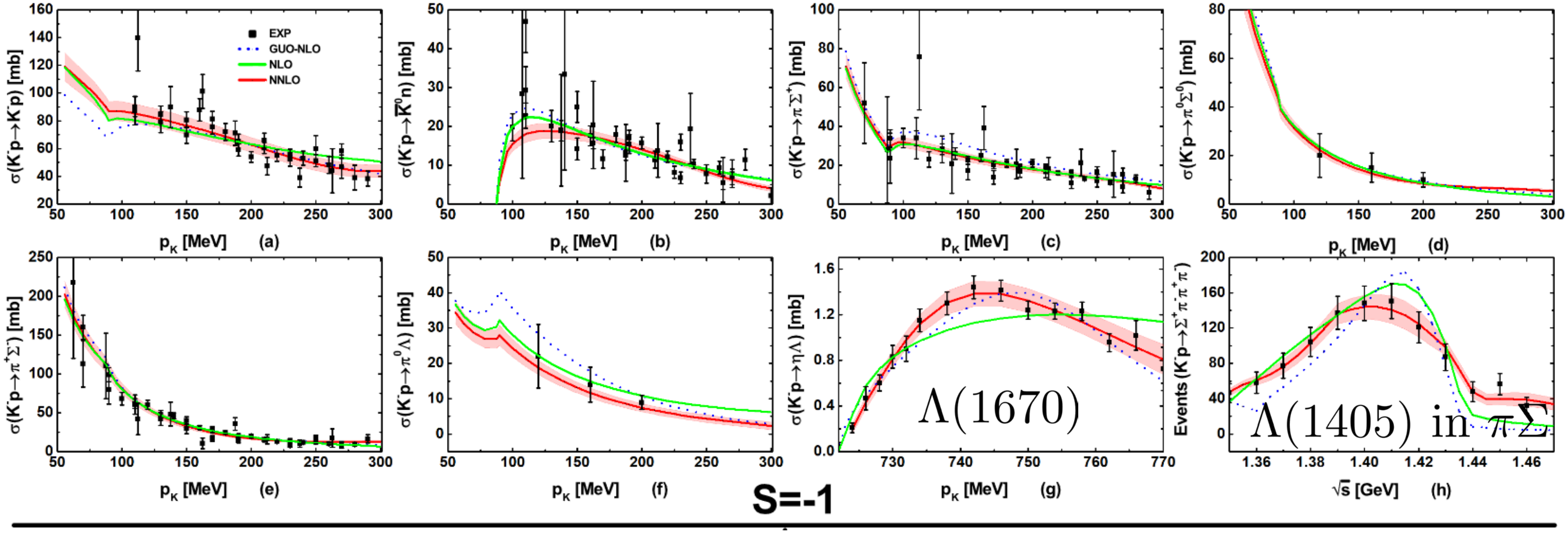
Interconnecting meson-baryon strangeness sectors at NNLO [J.-Xu Lu, L.S. Geng, MD, Mai 2022]

- First simultaneous study of meson-baryon interaction of
  - Strangeness S=0: (πN) Perturbative [SAID WI08 phases]
  - S=+1 (KN) Perturbative [SAID SP92]
  - S=-1: $(\bar{K}N$ in 10 chann.) Unitarized exp. data
- Chiral convergence poor for S=0:
  - One really needs NNLO for a global analysis
  - extended-on-mass-shell (EOMS) formulation of BCHPT improves convergence in $SU(3)_f$
- NNLO has more parameters (33) than NLO (20),
  - but interconnection of data sectors (for 1^{st} time) leads to **smaller** uncertainties than NLO due to much larger, “orthogonal” data base.
- Smaller uncertainties than NLO analyses of individual sectors
- Estimation of truncation error of chiral expansion (for 1^{st} time in meson baryon)
  - largest source of uncertainties [see talk by L.S. Geng on Monday, 9/5 on this topic]

Results – Data description in S=-1

[J.-Xu Lu 2022]

- Strangeness sector:
  - $x^2/dof = 1.56$ at NNLO with constraints from strangeness S=0 and S=+1
  - compare: x^2/dof =2 at NLO [Z. H. Guo (2012)] without add. constraints

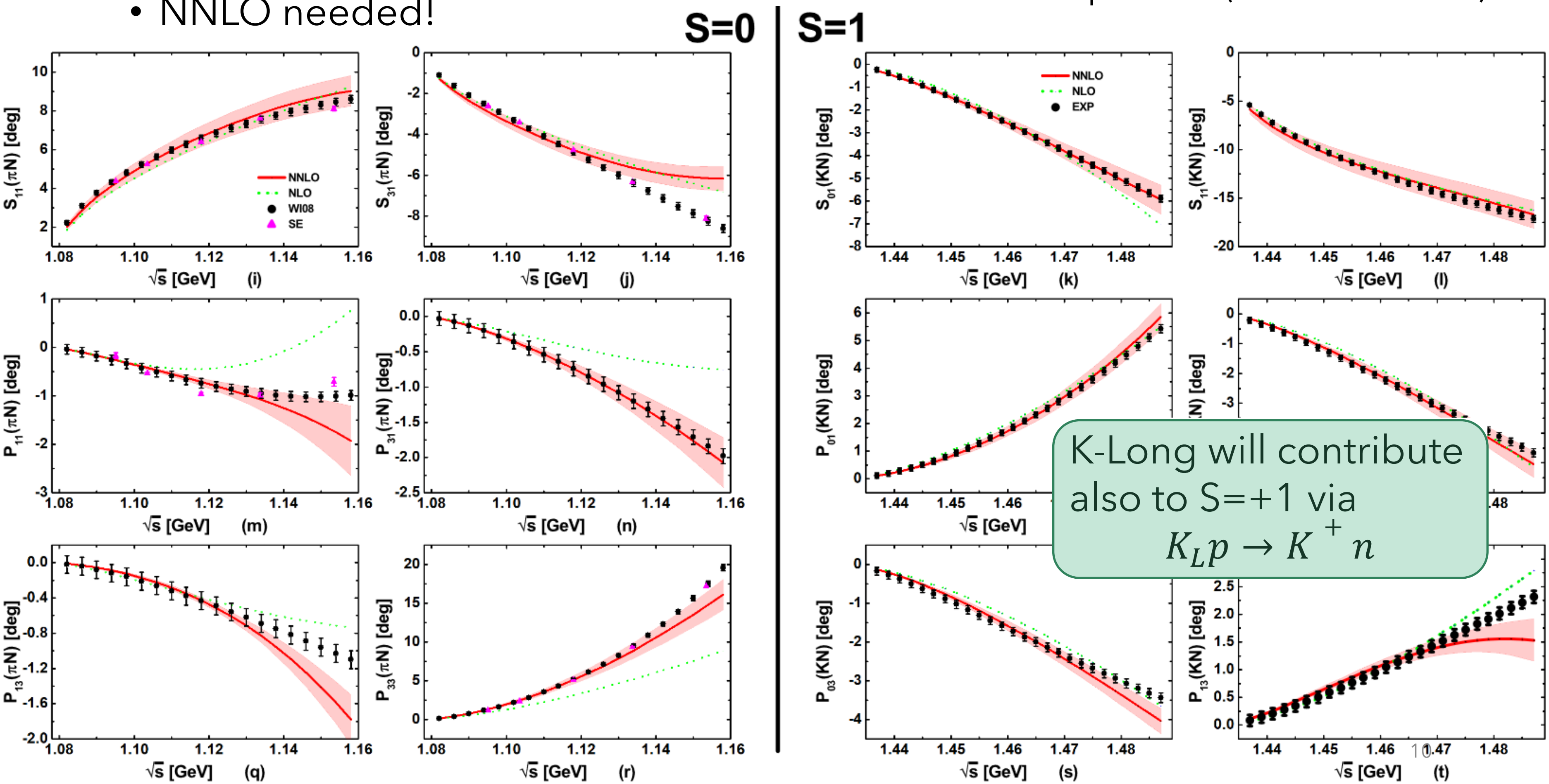


(and threshold quantities/not shown)

Results – PW description in S=0, +1

[J.-Xu Lu 2022]

- Compare NLO and NNLO
  - NNLO needed!
- Uncertainty bands from truncation of chiral expansion (dominant error)

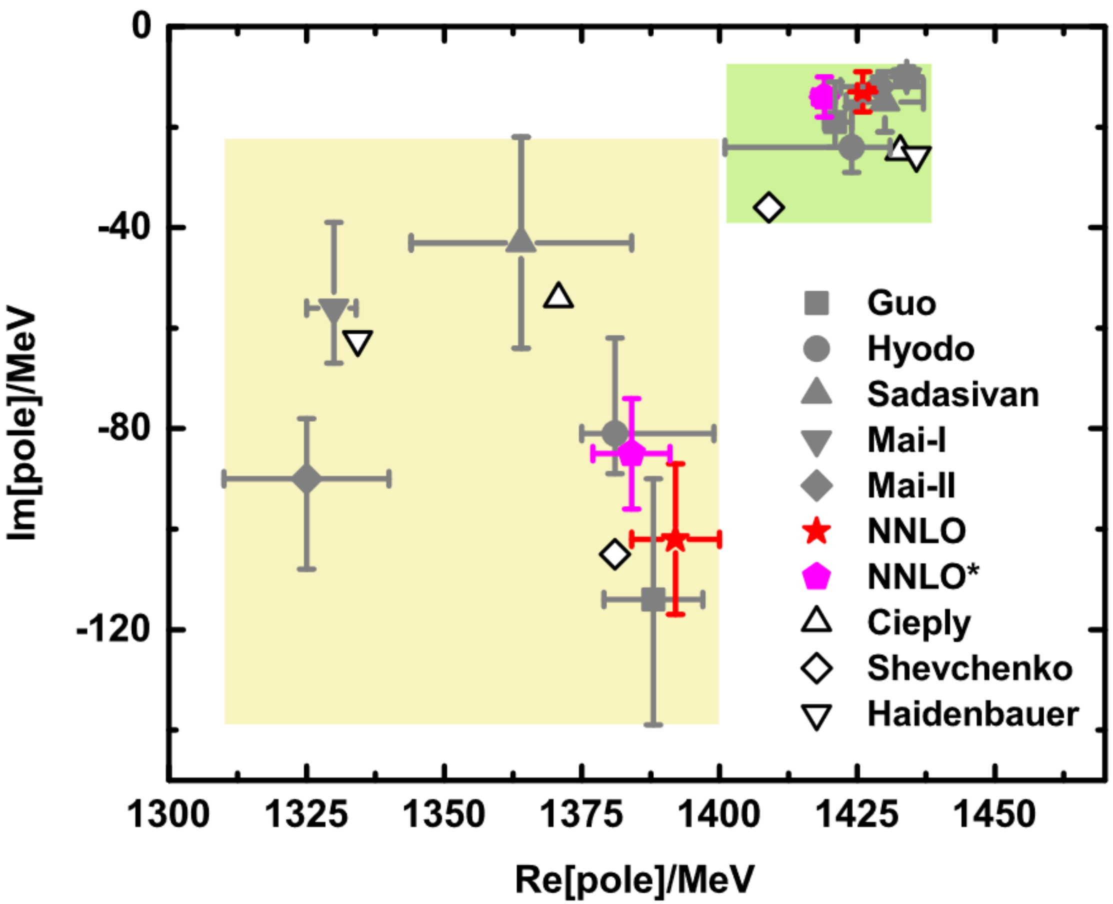


K-Long will contribute also to S=+1 via
$K_L p \to K^+ n$

Two-pole structure of $\Lambda(1405)$ confirmed

[J.-Xu Lu 2022]

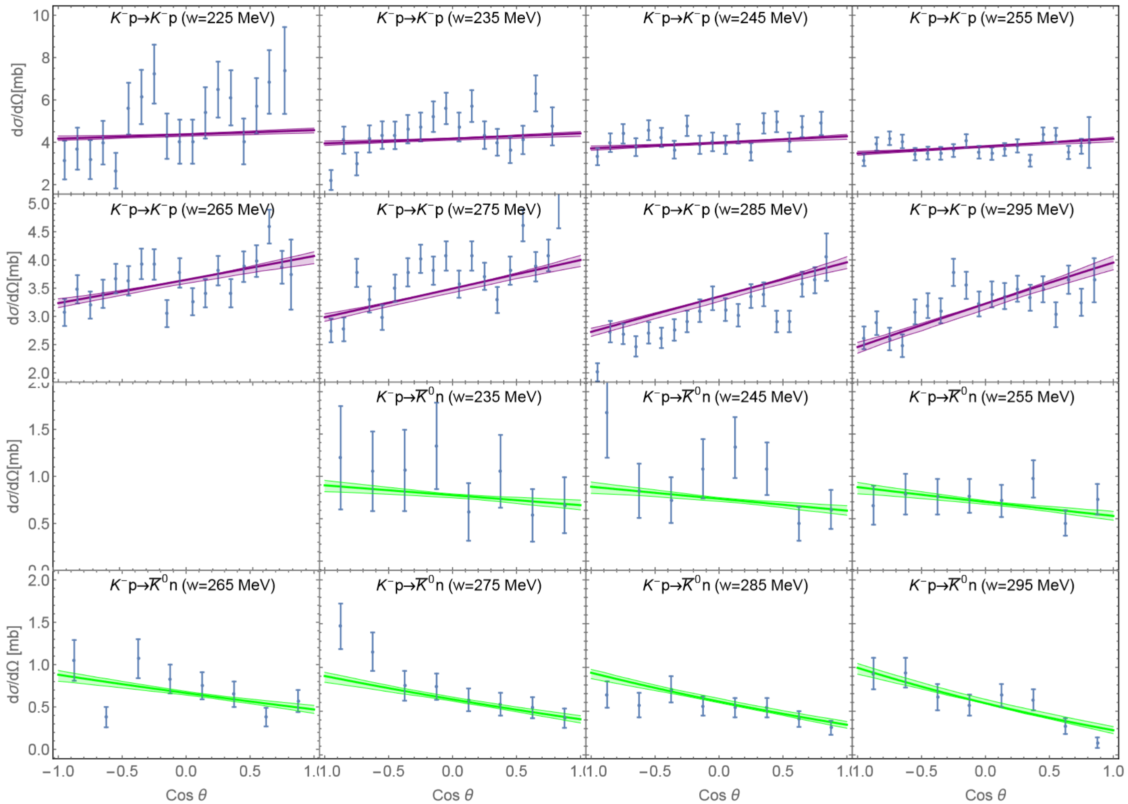
- with smaller uncertainties than at NLO, due to global data analysis.



- **NNLO**: Main result
- **NNLO***: Fit without constraints from baryon masses

Klong will improve low-energy data situation

- The **only** low-energy differential cross section available:



Data: [Mast 1976]
NLO: [Sadasivan 2018]

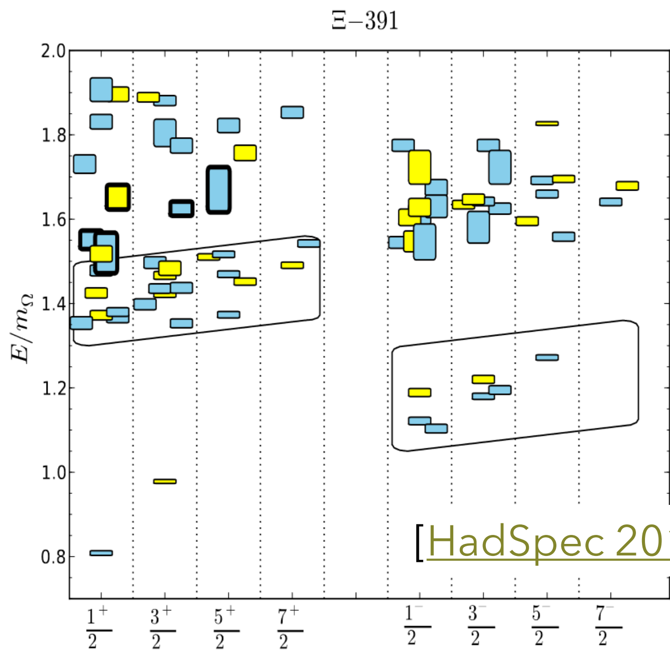
- P-wave important for NLO and NNLO chiral approaches
  → Not everything is S-wave… !

Hyperon spectroscopy

Why Klong will not “just” add more data

Klong for cascade baryons

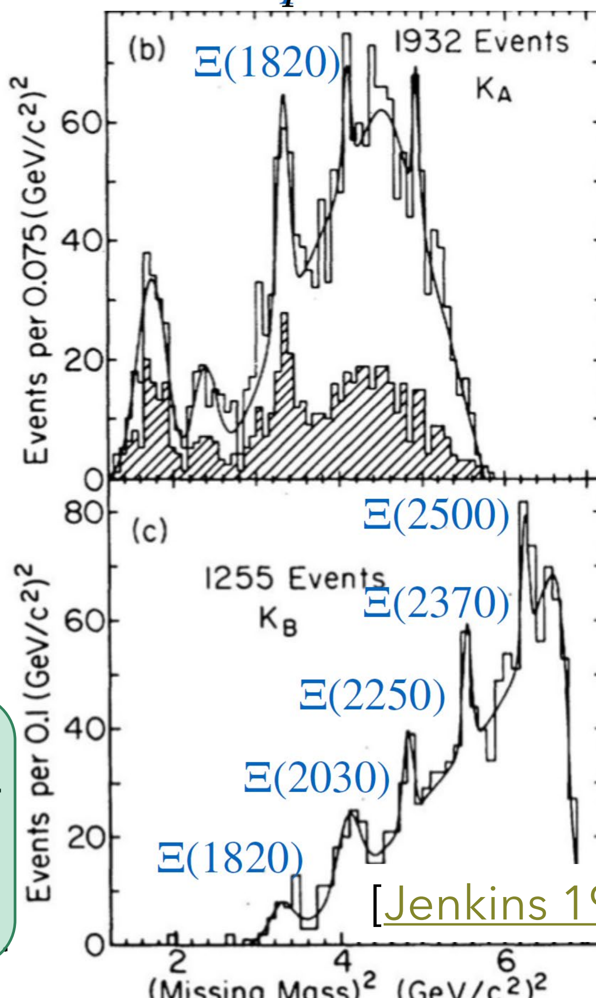
- Most of our knowledge of cascade comes from beam experiments in the 60s–80s, with little new until recently.



[HadSpec 2013]

Mismatch: Severe "missing resonance" problem

$K^- p \to K^+ X$



[Jenkins 1983]

KLF will search for cascades:

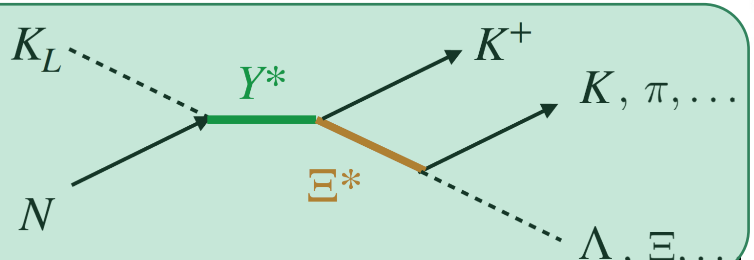
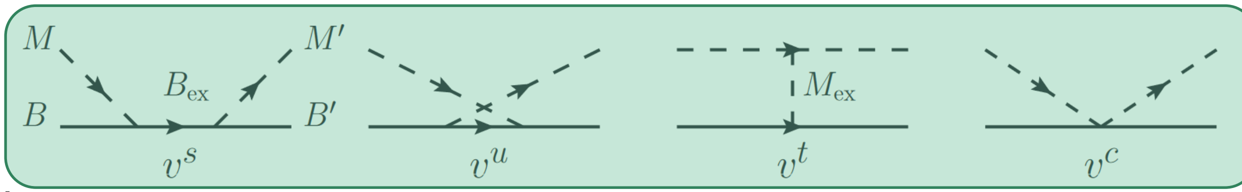


Diagram: S. Dobbs, Hadron 2021

Phenomenological interest in kaon-induced reactions: hyperon spectrum

Almost all major analysis groups have turned to perform partial-wave analyses of the strangeness -1 sector

- Kent state group/Manley [Zhang 2013]
- ANL/Osaka [Kamano 2014]



- Joint Physics Analysis Center (JPAC) [Fernandez 2016]
- Bonn-Gatchina (BnGa) group [Matveev 2019]
  - Notably, includes analys of K^-p → quasi-two-body states [Matveev 2019]
  - $K^-p \to \pi\Lambda(1520),\ \bar{K}\Delta(1232),\ \pi\Sigma(1385),\ \bar{K}^*N,$ and $\omega\Lambda.$
- Juelich-Bonn group [Roenchen, in preparation] building on
  - Previous Juelich model [Haidenbauer 2010]

Changes of hyperon spectrum by BnGa

[Matveev 2019]

	[43]	[17]		[43]	[17]
$\Lambda(1405)1/2^-$	****	****	$\Sigma(1580)3/2^-$	*	-
$\Lambda(1520)3/2^-$	****	****	$\Sigma(1620)1/2^-$	*	(*)
$\Lambda(1600)1/2^+$	***	****	$\Sigma(1660)1/2^+$	***	***
$\Lambda(1670)1/2^-$	****	****	$\Sigma(1670)3/2^-$	****	****
$\Lambda(1690)3/2^-$	****	****	$\Sigma(1730)3/2^+$	*	-
$\Lambda(1710)1/2^+$	*	-	$\Sigma(1750)1/2^-$	***	****
$\Lambda(1800)1/2^-$	***	***	$\Sigma(1770)1/2^+$	*	-
$\Lambda(1810)1/2^+$	***	(*)	$\Sigma(1775)5/2^-$	****	****
$\Lambda(1820)5/2^+$	****	****	$\Sigma(1840)3/2^+$	*	-
$\Lambda(1830)5/2^-$	****	***	$\Sigma(1880)1/2^+$	**	-
$\Lambda(1890)3/2^+$	****	****	$\Sigma(1900)1/2^-$	*	**
$\Lambda(2000)$	*	-	$\Sigma(1915)5/2^+$	****	****
$\Lambda(2020)7/2^+$	*	-	$\Sigma(1940)3/2^+$	*	-
$\Lambda(2050)3/2^-$	*	-	$\Sigma(1940)3/2^-$	***	***
$\Lambda(2070)3/2^+$	-	*	$\Sigma(2000)1/2^-$	*	-
$\Lambda(2080)5/2^-$	-	*	$\Sigma(2000)3/2^-$	-	*
$\Lambda(2100)7/2^-$	****	****	$\Sigma(2030)7/2^+$	****	****
$\Lambda(2110)5/2^+$	***	**	$\Sigma(2070)5/2^+$	*	-
			$\Sigma(2080)3/2^+$	**	-
			$\Sigma(2100)7/2^-$	*	*
			$\Sigma(2160)1/2^-$	-	*

[43]: RPP 2018
[17]: BnGa 2019

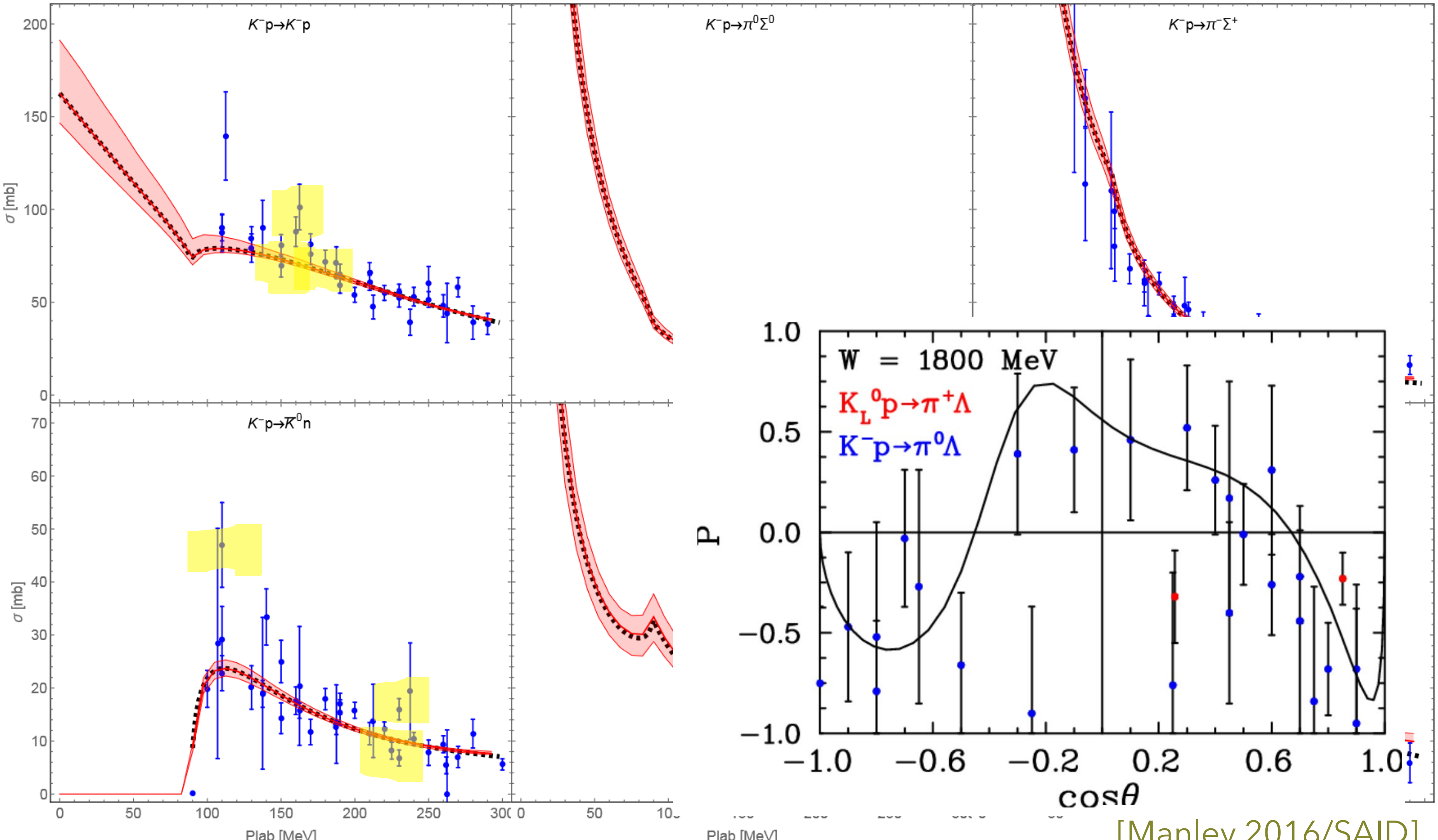
The Σ "bumps" at 1480 (*), 1560 (**), 1690 (**) MeV and the claims at 1620 and 1670 MeV from production experiments are also not seen.

Data consistency – the problem

- All these analysis would greatly benefit from new data
  - Better constraints on baryon masses, widths and branching ratios
  - Better constraints on the existence of new states
- Typical x^2/dof~1.5 in best case: This is a bad value!
  - It indicates that the fit is highly improbably given the data
  - …Under the assumption the data are *consistent*. Which they are not.
- High values of x^2 make quantitative statements of likeliness of existence of resonances impossible
- Data base dominated by systematic uncertainties
  - Many different experiments, from different decades, using different techniques.
  - Data from those experiments are sometimes not overlapping in kinematics – no way to uniquely rule out data
  - Gross mismatch of size of data sets from different observables

A closer look at the problem

[Sadasivan 2018]



[Manley 2016/SAID]

Contributions from K-Long

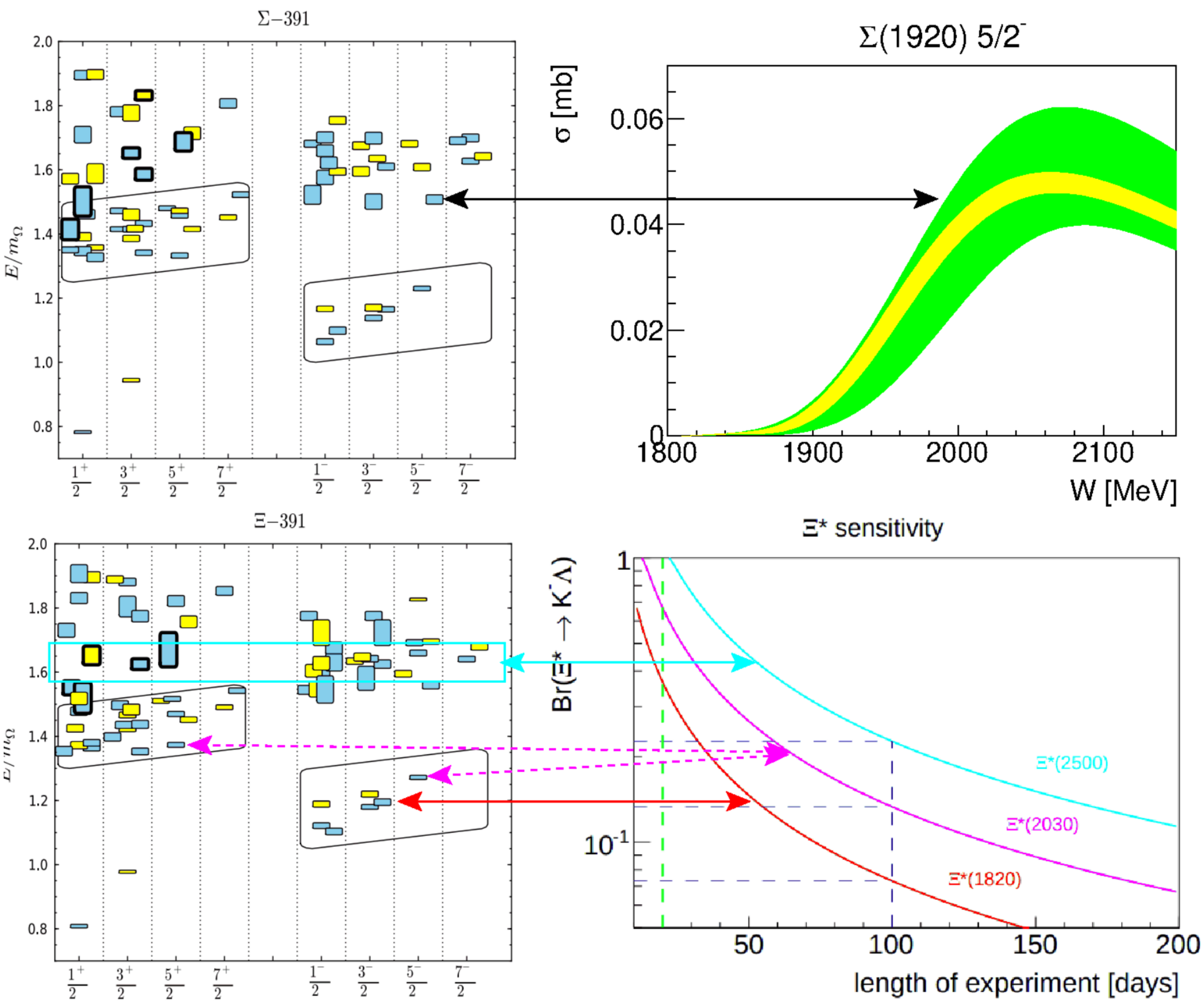
- K-Long will not only increase the data base
- It will provide a large ***consistent*** data base
- Will provide realistic chance to control systematic error by standard methods (data "floating" not performed by any analysis, so far → See SAID and Juelich-Bonn-Washington/JBW analysis)
- Will provide a chance to realistically model the systematic error:
  - Additive?
  - Multiplicative?
  - How distributed?
  - What prior is best (model distribution of uncertainty)
- Quantitative statements on resonance properties & existence might become possible
- Similar situation challenge in πN sector [Briscoe 2015]

Klong: two-body reactions

- Proton target: only Σ*
  - $K_L p \rightarrow K_S p$
  - $K_L p \rightarrow \pi^+ \Lambda$
  - $K_L p \rightarrow K^+ \Xi^0$
  - $K_L p \rightarrow \pi^0 \Sigma^+$
  - $K_L p \rightarrow \eta \Sigma^+$
  - $K_L p \rightarrow \omega \Sigma^+$
- Neutron target: Λ* and Σ*
- Observables:
  - Differential cross section
  - Self-polarization from hyperon decay
  - … depends on $\alpha\_$ which has changed [BESIII (2019), Ireland 2019]

From: S. Dobbs, Hadron 2021

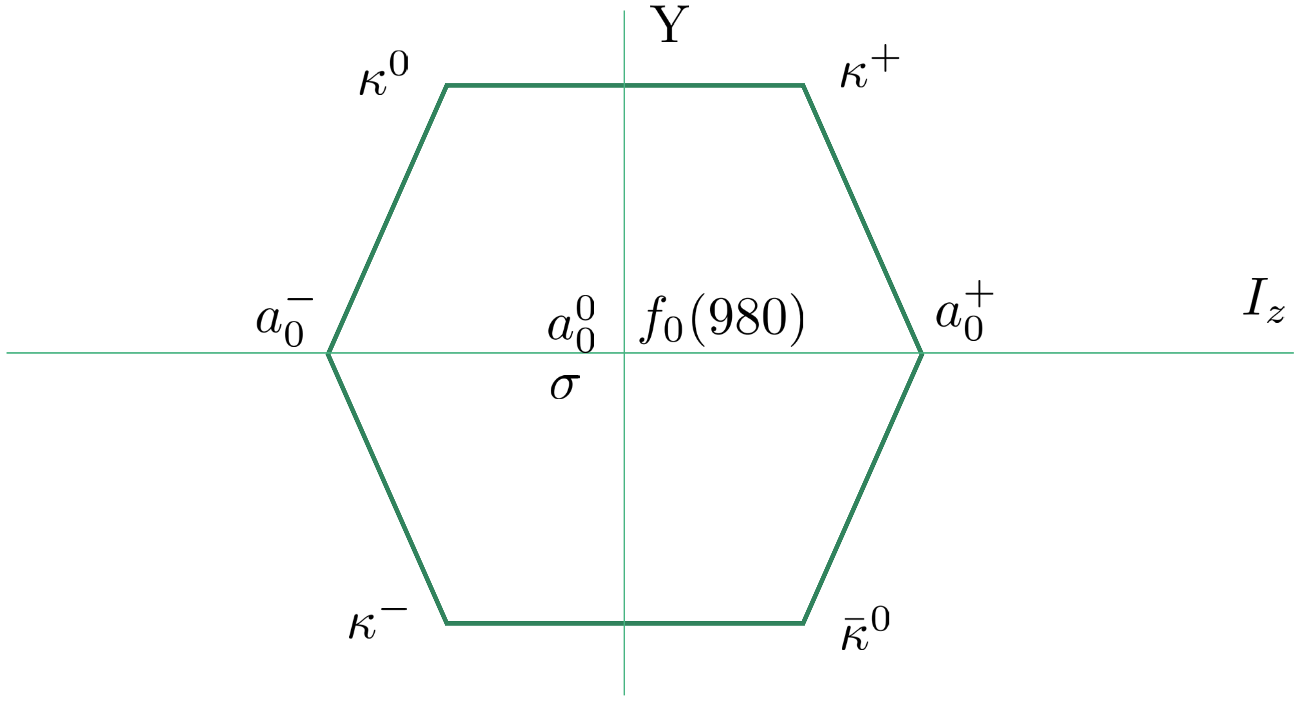
Discovery potential & projected sensitivity



- **Left**: Lattice prediction [HadSpec 2013]
- **Upper right**: Simulated cross section for resonance assuming 20 and 100 days of run time (using BnGa)
- **Lower right**: Estimate of minimal measurable branching ratios of some resonances
- With 100 days of run time, resonances with BR >4% seem to be accessible
- Irregular shapes require potentially more.

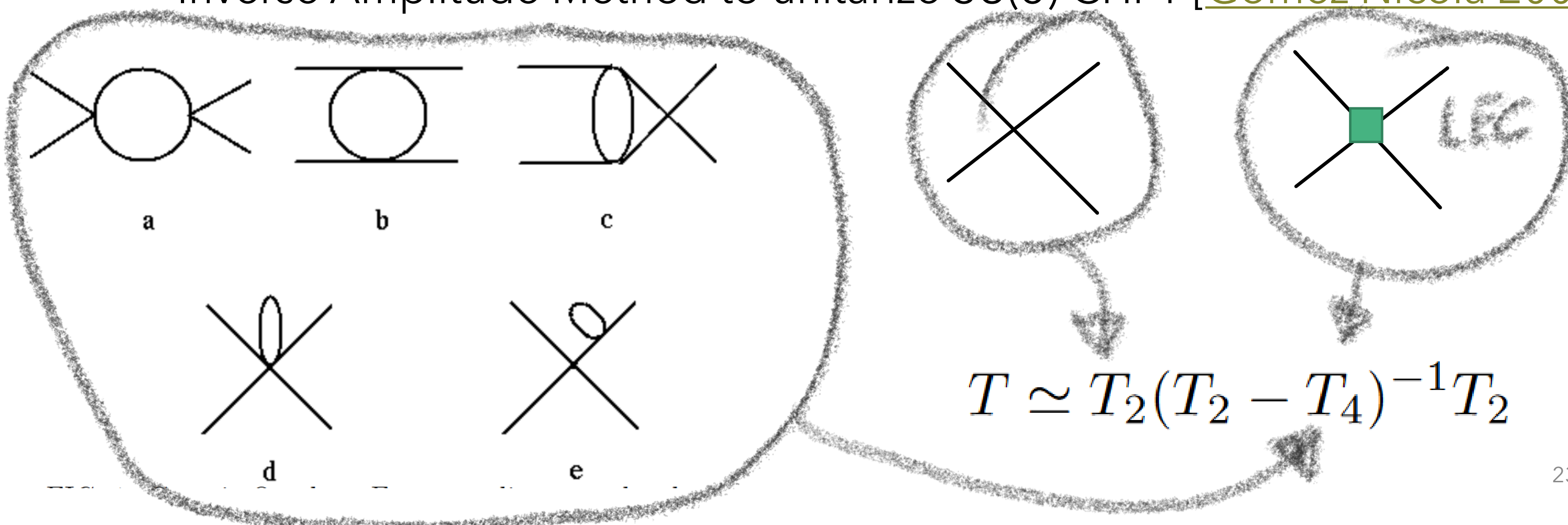
Meson spectroscopy

The κ resonance and other enigmatic states



Kaon-pion scattering

- One of the prime subjects of CHPT
- How does CHPT converge for $SU(3)_f$ compared to $\pi\pi$?
  - Worse convergence
- CHPT calculations to one [Bernard 1991] and two loops [Bijnens 2004]
- Not necessarily low energies only:
  - Inverse Amplitude Method to unitarize SU(3) CHPT [Gomez Nicola 2004]

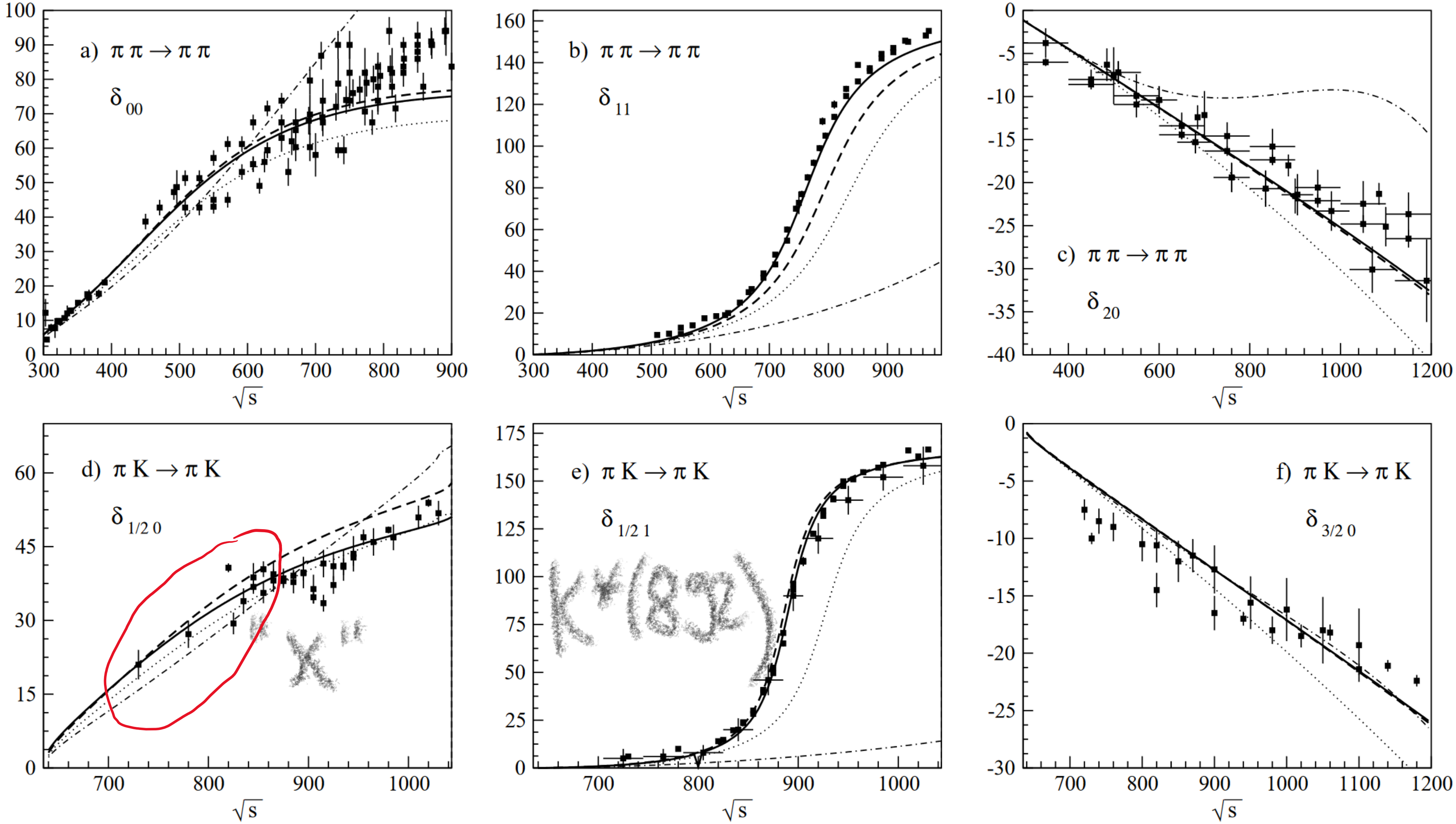


$$T \simeq T_2 (T_2 - T_4)^{-1} T_2$$

IAM and data

[Nebreda 2010]

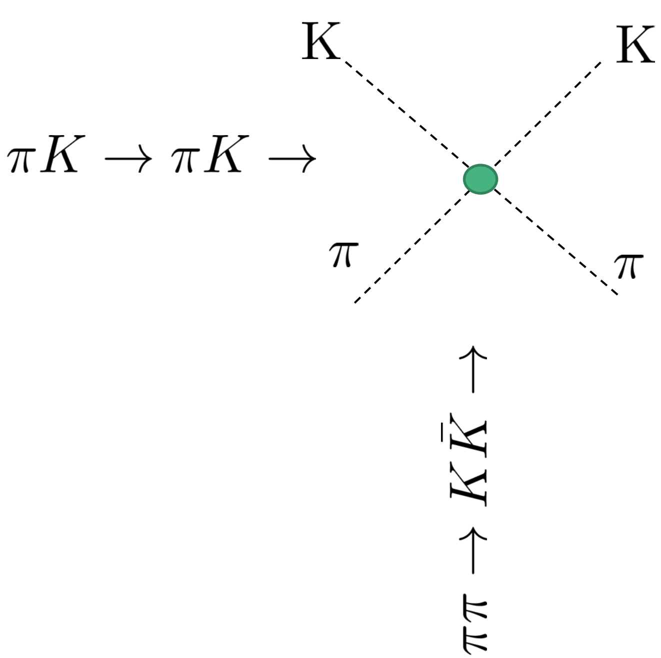
Large body of theory references!

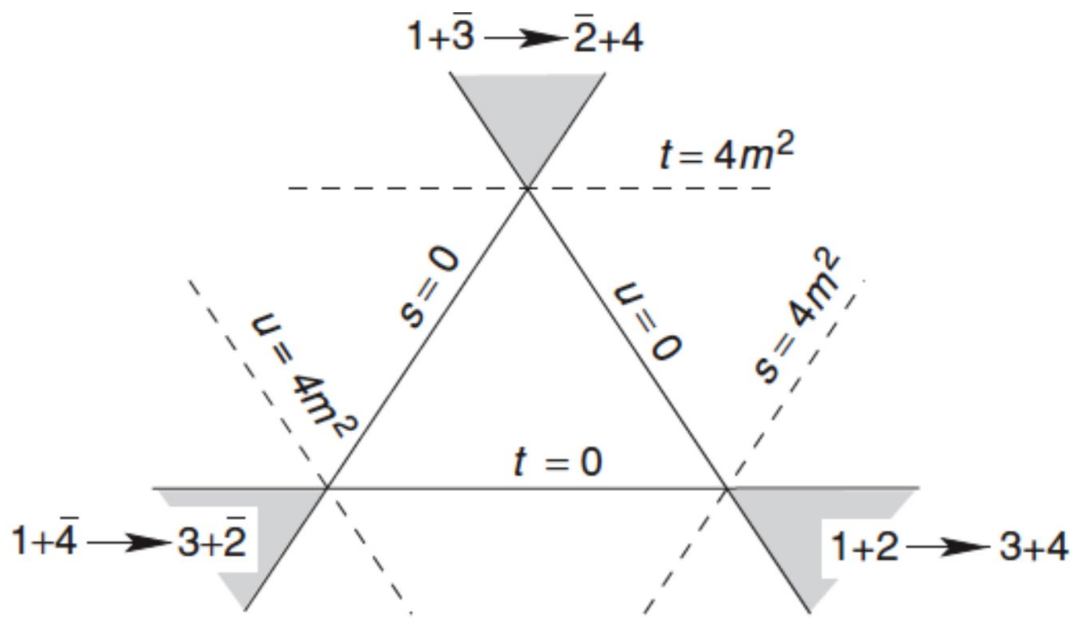


Dispersive approaches

E.g.: [Buettiker 2004]/dispersive etc.

- Relating s-channel and t-channel processes at constant b=us to a tower of coupled equations of partial waves:

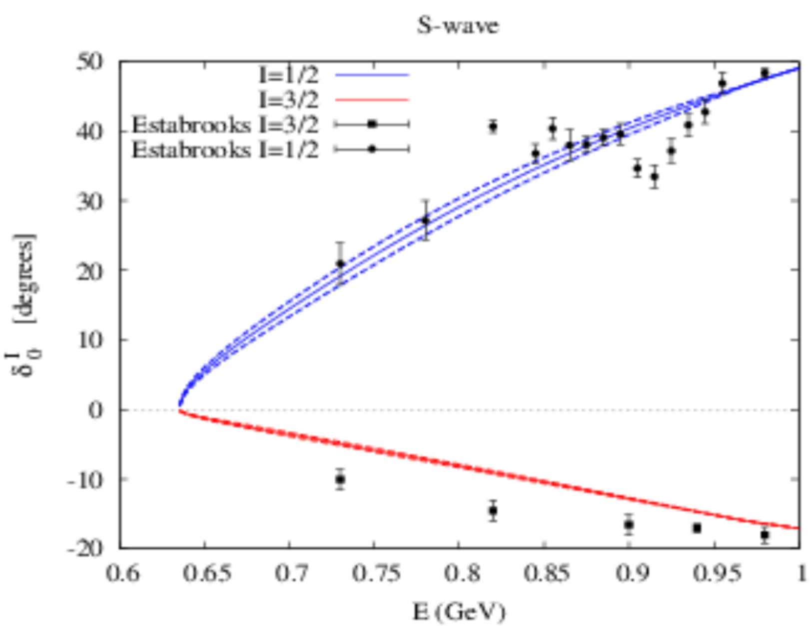


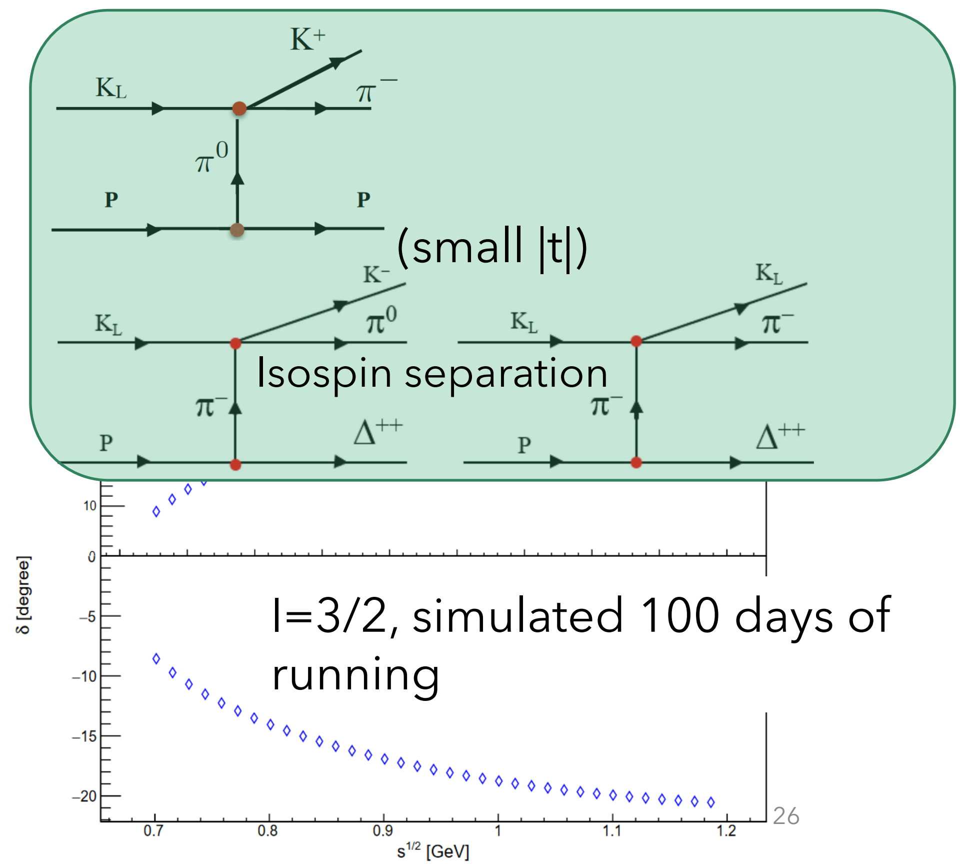


Mandelstam plane

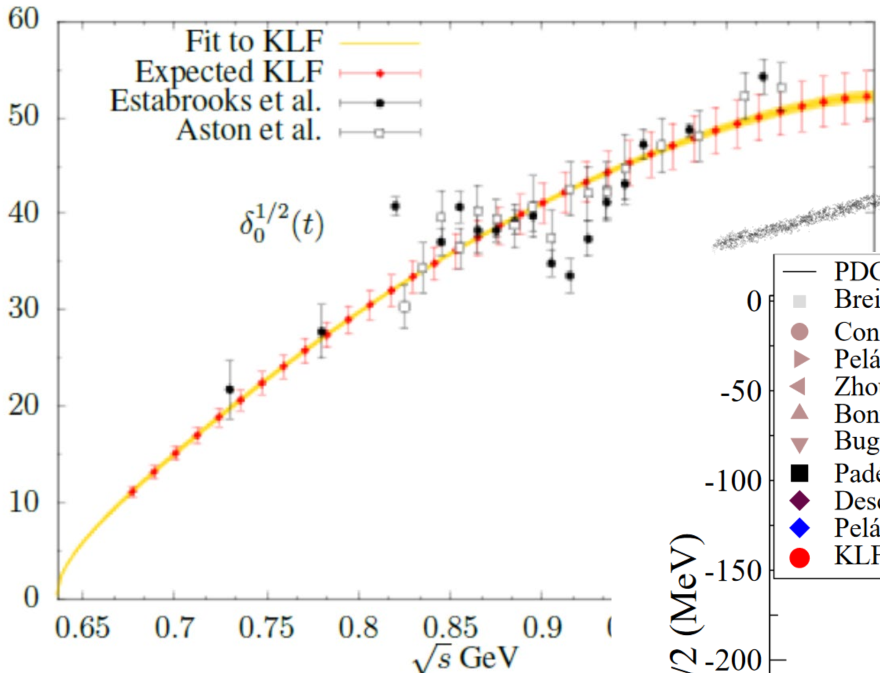
How K-Long can improve data situation

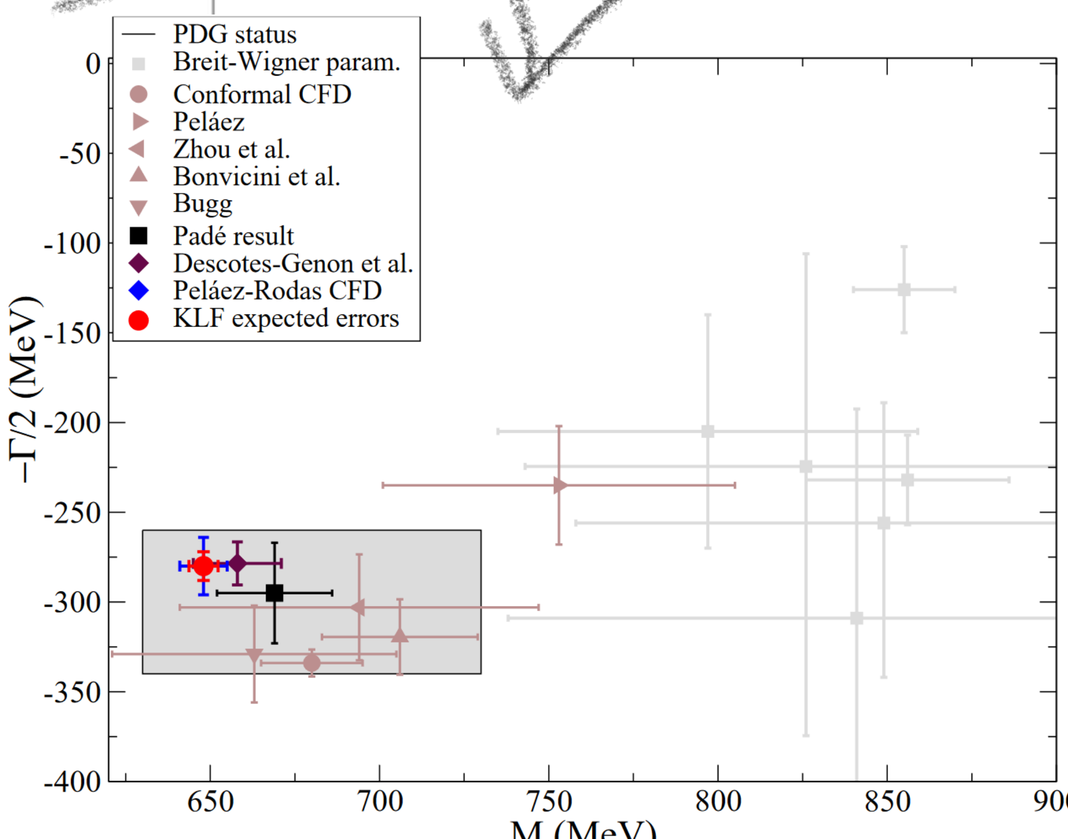
- Very inferior $\pi K \to \pi K$ low-energy scattering data to date
- Sizable tension between scattering lengths from dispersive analyses and lattice QCD data
- K-Long will specifically improve the low-energy situation





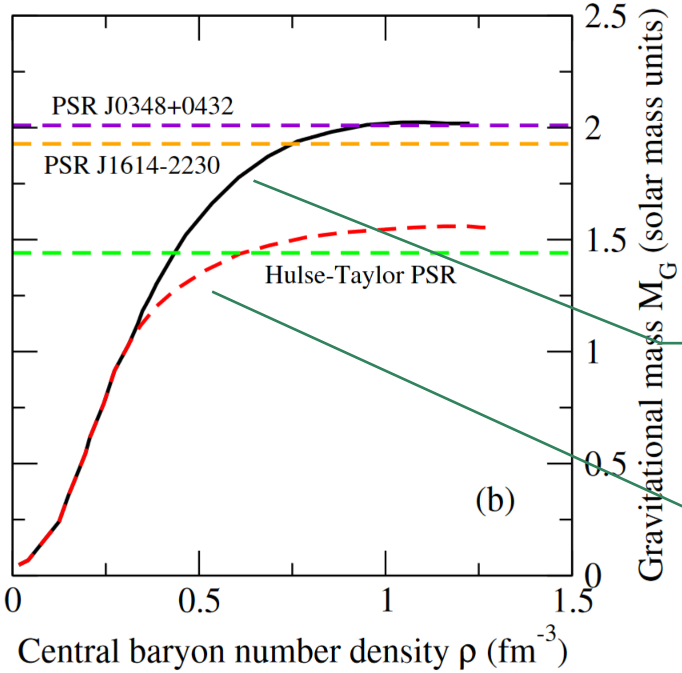
How the κ pole position will improve





More aspects of strangeness physics

- K-induced production of a_0, f_0
- Neutron-induced reactions: Elastic *np* scattering
- The YN interaction for neutron stars and hypernuclei
- (Semileptonic decays of Λ)



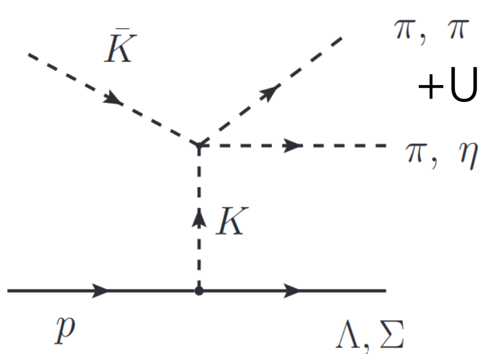
Without hyperons

With hyperons: softer EOS/ smaller max. mass

$$K_L p \to \pi^+ \Lambda/\Sigma \Rightarrow YN \to YN$$

Kaon-induced two-meson production

- $a_0(980)$ and $f_0(980)$ are enigmatic S-wave resonances
  - Dynamically generated [Oller 1999]
  - Hadronic molecules [Baru 2004] [Guo 2018]
  - Both couple strongly to $\bar{K}K$
  - a_0-f_0 mixing through isospin breaking [BesIII] [Tarasov 2013]
- K-Long "specific" reactions $K^-p \to \Lambda\pi^+\pi^-,\ \Sigma^0\pi^+\pi^-,\ \Lambda\pi^0\eta,\ \Sigma^0\pi^0\eta,\ \Sigma^+\pi^-\eta$
  - Similarly: $\overline{K^0}p$ → [...]   [J.-J. Xie 2016]



+Unitarization

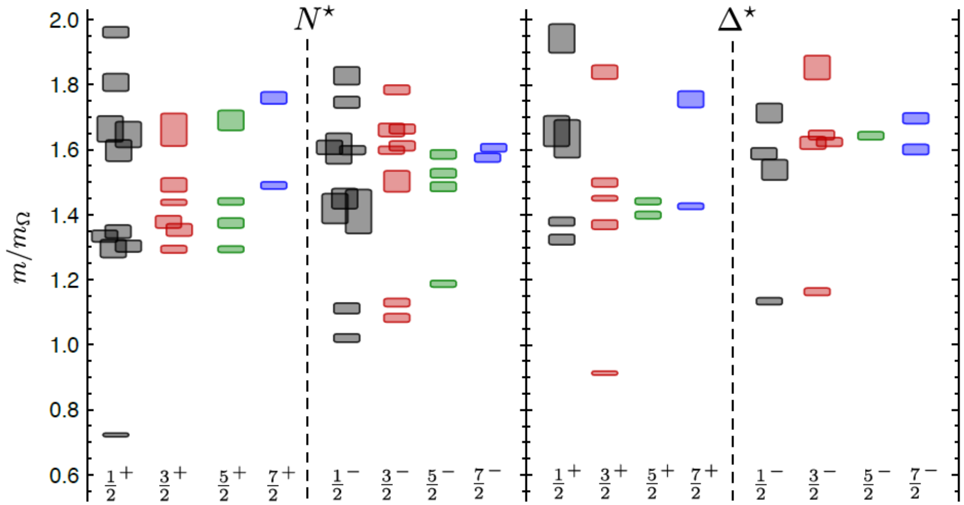
- Opportunity to study couplings of these resonances to $\pi\pi, K\overline{K}, \pi\eta$
- E.g.: *f_0(500)* weak coupling to $K\overline{K}$, but *f_0(980)* strong coupling

Summary

- Hyperons and Cascades: Significant theoretical interest in spectrum of excited states through
  - Lattice QCD predictions – *missing resonance problem* clearly revealed for *S*=-*1*, but even more strikingly for *S*=-*2* baryons.
  - (Unitarized) CHPT – continuous activity to understand low-energy QCD dynamics
  - Phenomenological analysis groups – almost all groups analyzed strangeness sector in recent years. Analysis pipeline established.
- Meson spectroscopy
  - Symmetries and scalar multiplets require a light scalar with strangeness: the κ.
  - Continuous theory interest by lattice, (unitarized) CHPT, dispersive methods/Roy-Steiner equations
- Klong will make crucial contributions to these questions and help resolve decades-old problems related to inconsistent, sparse data bases theory relies on.

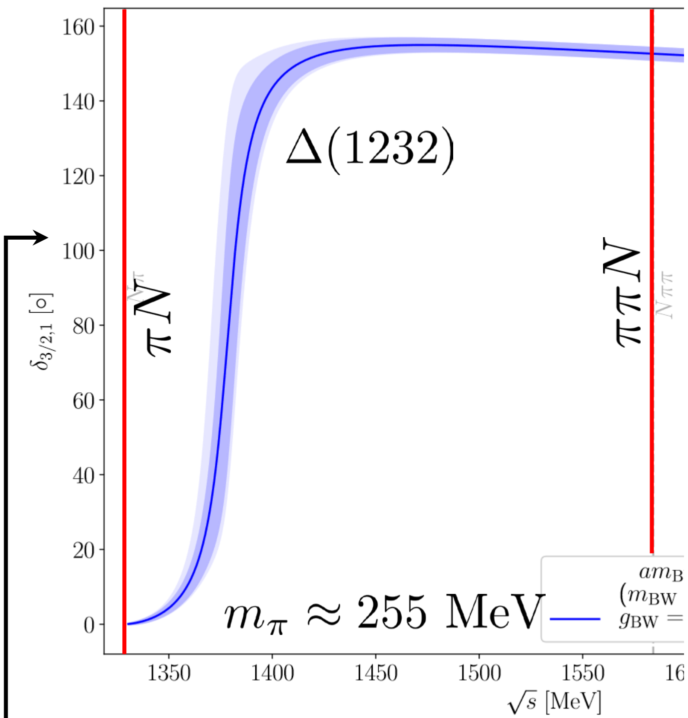
(spare slides)

Lattice QCD for excited baryons: S=0



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

- Pioneering spectroscopic calculations, but
- Information on existence, width & properties of resonances requires
  - Meson-baryon interpolating operators
  - Detailed finite-volume analysis



[G. Silvi et. al., arXiv: 2101.00689]

See also: Bulava et al., [2208.03867]

Determination of α_- from CLAS data

[D.G. Ireland/ JBW, PRL (2019)]

- Fierz identities for polarization observables

$$O_x^2+O_z^2+C_x^2+C_z^2+\Sigma^2-T^2+P^2=1$$
$$\Sigma P - C_x O_z + C_z O_x - T = 0\ .$$

$$a\ (= \alpha_-^{\rm old}/\alpha_-)$$

$$\mathcal{F}_i^{(1)} = a^2 l^2\left(\mathcal{O}_{x,i}^2+\mathcal{O}_{z,i}^2-\mathcal{T}_i^2\right) + a^2c^2\left(\mathcal{C}_{x,i}^2+\mathcal{C}_{z,i}^2\right)+l^2\Sigma_i^2+a^2\mathcal{P}_i^2\ ,$$
$$\mathcal{F}_i^{(2)} = al\left[\Sigma_i\mathcal{P}_i-\mathcal{T}_i-ac(\mathcal{C}_{x,i}\mathcal{O}_{z,i}-\mathcal{C}_{z,i}\mathcal{O}_{x,i})\right]$$

- Leads to a new value for asymmetry α_-
- Implications for CP violation
- change of data base for most measured pol. observables