K-Long Facility at *Jefferson Lab*

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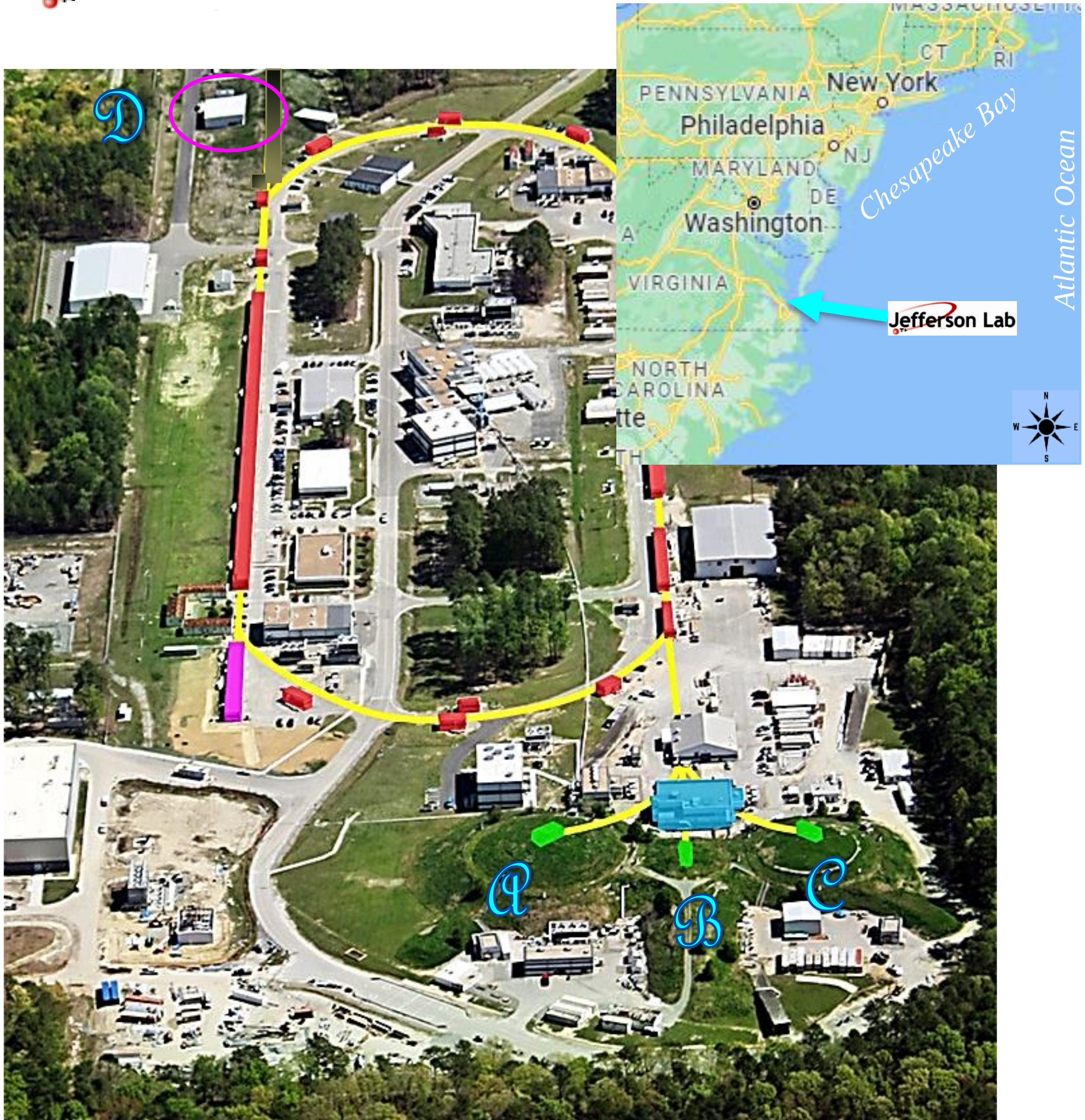
The George Washington University

- *KLF at Jefferson Lab.*
- *KLF experiment.*
- Aims *of KLF* project.
- *Impact for Early Universe.*
- *Hyperon spectroscopy.*
- *Exotics*
- *Strange Meson spectroscopy.*
- *Where are we now & Where will be in future?*
- *Summary.*
- *A bit of history.*

Supported by DE−SC0016583

KLF @ Jefferson Laboratory

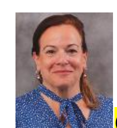
Jefferson Lab *Continuous Electron Beam Accelerator Facility* in 2025



1995 — 2012…
Energy 0.4 — 6.0 GeV
- 200 μA, *Polarization* 85%
- Simultaneous delivery 3 Halls – A, B, C

- 500+ PhDs completed
- On average 22 US Ph.Ds per year, roughly 25–30% of US Ph.Ds in nuclear physics
- 1530 users in FY16, ~1/3 international from 37 countries

…2016 — …
Energy 0.4 — 12.0 GeV
- 150 μA, *Polarization* 85%
- Simultaneous delivery 4 Halls
- FY18: First try simultaneous delivery to **4** Halls — A, B, C, D



Courtesy of Thia Keppel, 2017

E12-12-19-001

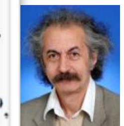
This Happens because of Strong Support & Dedicated Efforts of KLONG Collaboration

E12-19-001

Strange Hadron Spectroscopy with Secondary K_L Beam in Hall D

arXiv:2008.08215v2 [nucl-ex] 14 Sep 2020

KLF Analysis Coordinator



KLF Spokesperson

Experimental Support:

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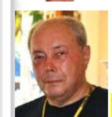

KLF PC chair

Extensive Theoretical Support

Theoretical Support:

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Jefferson Lab *PAC48 Report*, **2020**

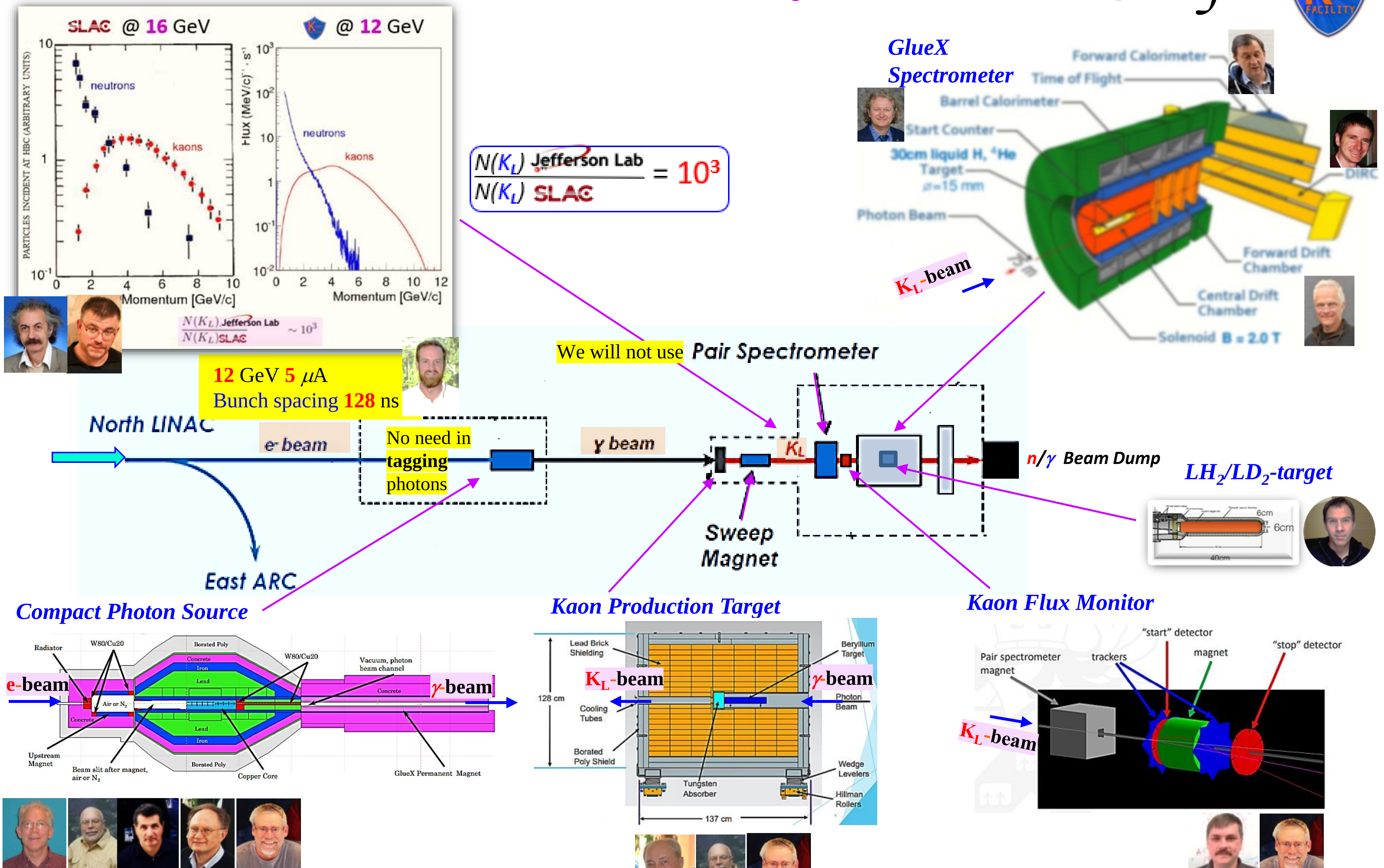
Summary: The future K_L facility will add a new physics reach to JLab, and the PAC is looking forward to see the idea being materialized, in conjunction with the plans for Hall D as spelled out in the 2019 White Paper. The collaboration should now devote all its energy to turn this challenging project into an experimental facility and in parallel prepare for a successful data analysis.

e-Print: 2008.08215 [nucl-ex]

https://wiki.jlab.org/klproject/index.php/Main_Page

KLF Experiment

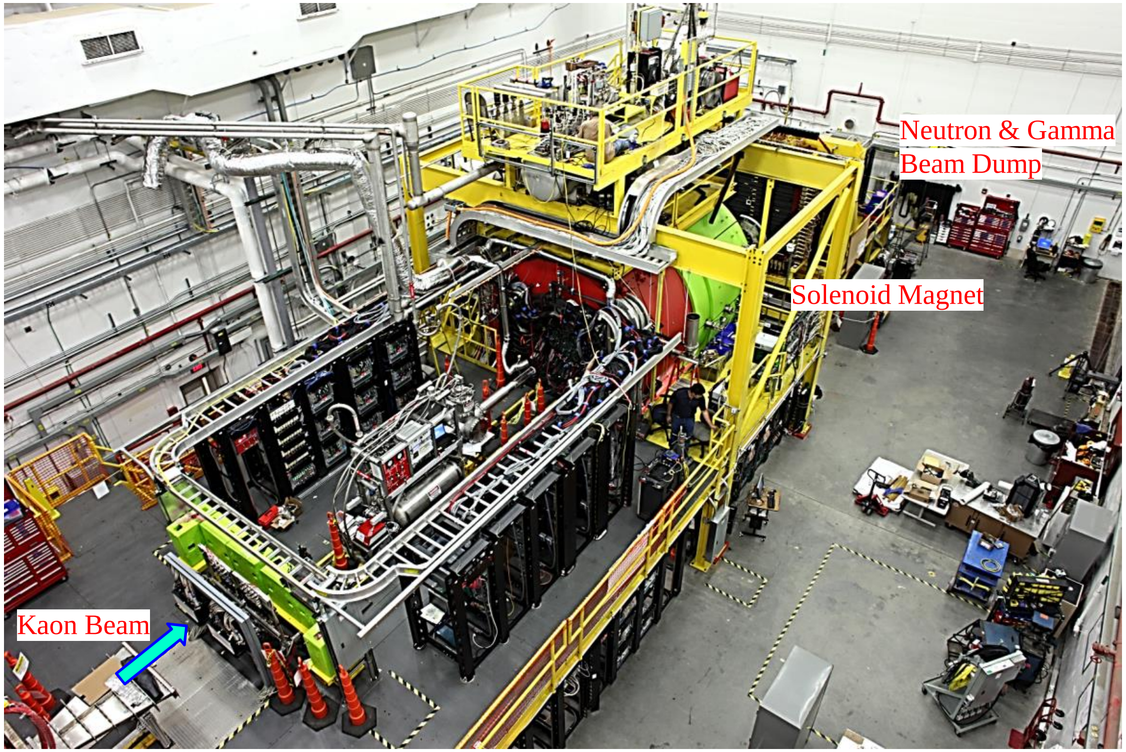
Hall D Beam Line for



D. Day *et al*. Nucl Instrum Meth A **957**, 163429 (2020)

- Superior ***CEBAF*** electron beam will enable flux on order of ***10^4 K_L/sec***, which exceeds flux of that previously attained @ SLAC by *three orders* of magnitude.

Experimental Hall [***GlueX Spectrometer***, ***KFM***, ***SC***, ***Cryo Target***]



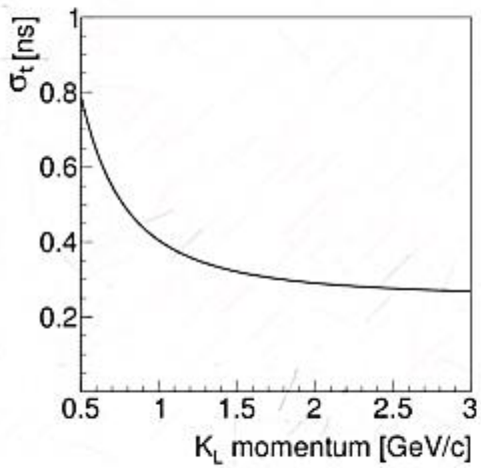
S. Adhikari *et al*, Nucl Inst Meth A **987**, 164807 (2021)

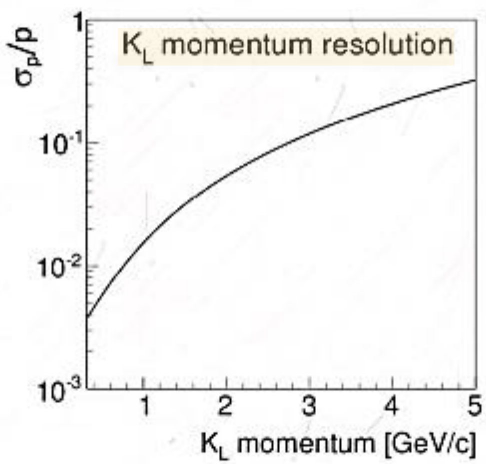
Tagger Hall [***CPS***]

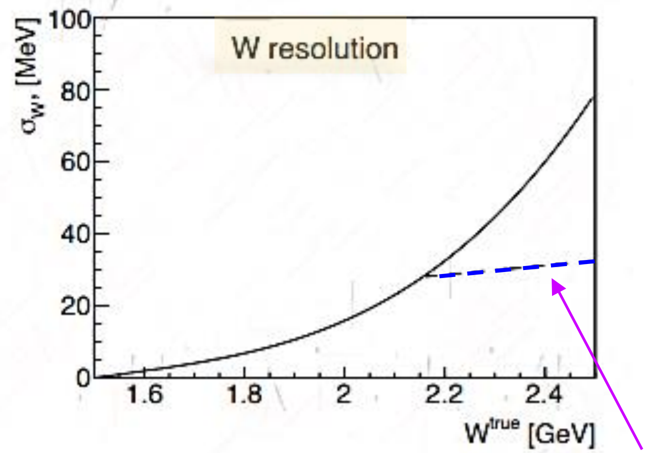
Collimator Cave [***KPT***]

K_L Momentum Determination & Beam Resolution

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







Reconstruction of final-state particles

- Momentum measured with *TOF* between *SC* (surrounded *LH_2*/*LD_2*) & *RF* from *CEBAF*.

- ***Mean lifetime*** of $\mathbf{K_L}$ is 51.16 nsec ($c\tau$ = 15.3 m) whereas
  Mean lifetime of $\mathbf{K^-}$ is 12.38 nsec ($c\tau$ = 3.7 m).
- For this reason, it is much easier to perform measurements of K_Lp scattering @ low beam energies compared with K^-p scattering.

Aims of KLF Project

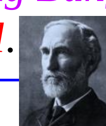
- project has firmly to setup secondary K_L beamline @ Jefferson Lab, with *flux* of *three order of magnitude higher* than SLAC had, for scattering experiments on both *proton* & *neutron* (*first* time !) targets.

- *CEBAF* will remain ***prime facility*** for fixed target electron scattering @ luminosity ***frontier***. *First hadronic facility* @ Jefferson Lab.

- We will determine differential cross sections & self-polarization of *hyperons* with ***GlueX*** detector to enable precise *PWA* in order to determine ***all*** *resonances* up to 2500 MeV in spectra of Λ^*, Σ^*, Ξ^*, & Ω^*. To complete ***SU(3)$_F$*** *multiplets*, one needs no less than 48 Λ^*, 38 Σ^*, 61 Ξ^*, & 31 Ω^*.

- We intend to do *strange meson spectroscopy* by studies of π-K interaction to locate *pole* positions in I = 1/2 & 3/2 channels.

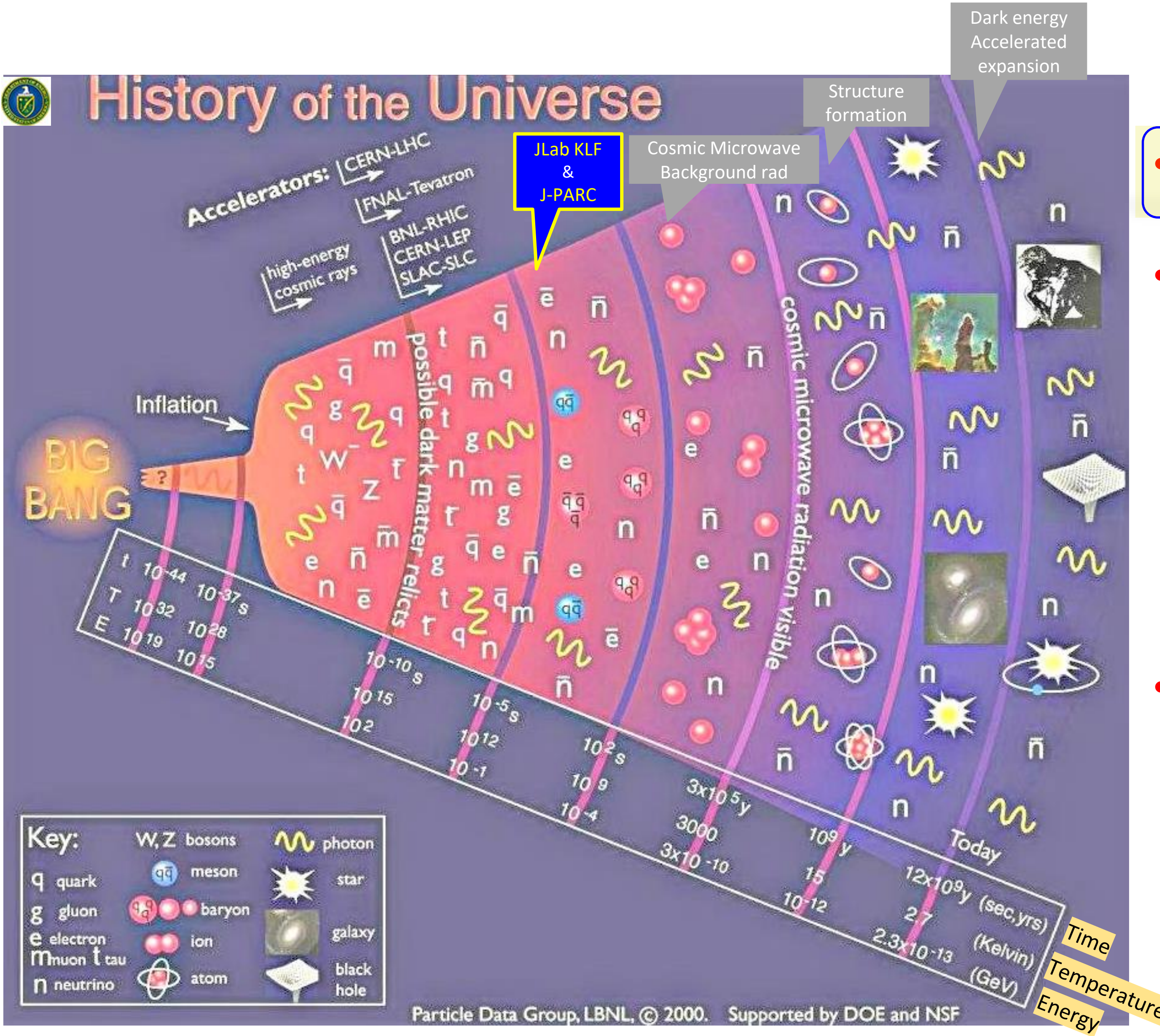
- has link to *ion-ion high energy* facilities such as CERN & [logo] & will allow understand formation of our world in *several microseconds* after *Big Bang*. *Hyperons* are playing ***leading*** role to reproduce *Chemical Potential*.



Josiah Willard Gibbs

Impact for Early Universe

History of the Universe



- is *Home* of *Hot Big Bang Theory*.

- Omission of any ``*missing hyperon states*" in *Standard Model* will negatively impact our understanding of *QCD freeze-out* in heavy-ion & hadron collisions, *hadron spectroscopy*, & *thermodynamics* of *Early Universe*.

- For that reason, advancing our understanding of formation of *baryons* from *quarks* & *gluons* requires new experiments to search for any *missing hyperon* resonances.

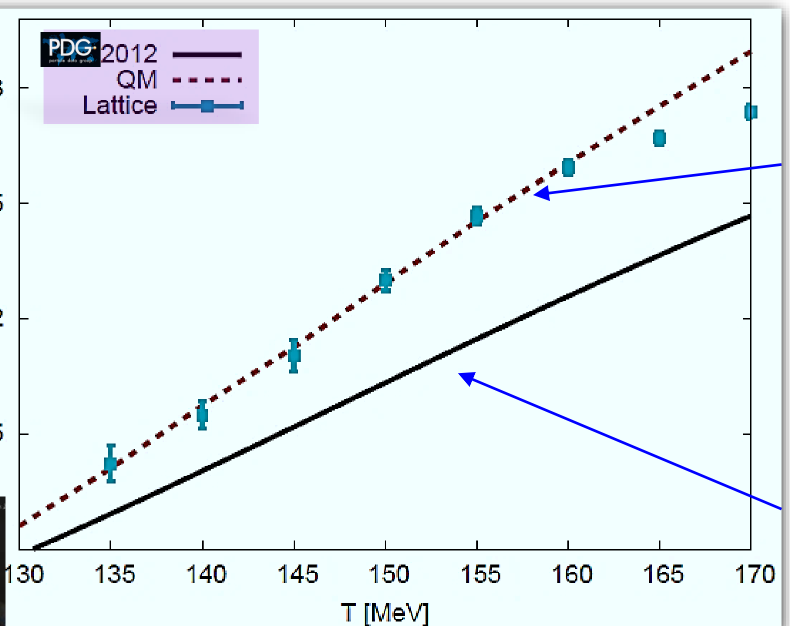
Thermodynamics @ *Freeze-Out*

- In *thermodynamics*, *chemical potential* of *species* is *energy* that can be absorbed or released due to change of particle number of given species, *e.g.*, in chemical reaction or phase transition.
- *Chemical potential* of species in mixture is defined as rate of change of free energy of thermodynamic system with respect to change in number of atoms of species that are added to system.
- @ *chemical equilibrium* or in *phase equilibrium*, total sum of product of *chemical potentials* & stoichiometric coefficients is zero, as free energy is @ minimum.


Josiah Willard Gibbs

- Recent studies that compare *LQCD* calculations of *thermodynamic*, statistical *Hadron Resonance Gas* models, & ratios between measured yields of different hadron species in heavy ion collisions provide indirect evidence for presence of ”*missing*” resonances in all these contexts.


Rolf Hagedorn



Courtesy of Claudia Ratti, YSTAR2016

Chemical Potential

$$\left(\frac{\mu_S}{\mu_B}\right)_{LO} = -\frac{\chi_{11}^{BS}}{\chi_2^S} - \frac{\chi_{11}^{QS}}{\chi_2^S}\frac{\mu_Q}{\mu_B}$$

- **+** ``*Missing*” *Resonances* (*CQM*/*LQCD* calculations).

Contribution order:
- ***Hyperons***
- Non-strange ***Baryons***
- ***Mesons***
- Light ***Nuclei***

- Contribution from *observed Resonances* PDG

- The *Early Universe* was *Strange*.

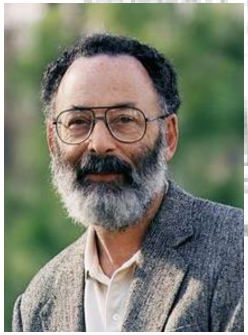
Hyperon Spectroscopy

It is clear that we still need much more information about the existence and parameters of many baryon states, especially in the N=2 mass region, before this question of non-minimal SU(6) x O(3) super-multiplet can be settled.

Dick Dalitz, **1976**

The first problem is the notion of a resonance is not well defined. The ideal case is a narrow resonance far away from the thresholds, superimposed on slowly varying background. It can be described by a Breit-Wigner formula and is characterized by a pole in the analytic continuation of the partial wave amplitude into the low half of energy plane.

Gerhard Höhler, 1987



*Why N*s are important – The first is that nucleons are the stuff of which our world is made. My second reason is that they are simplest system in which the quintessentially non-Abelian character of QCD is manifest. The third reason is that history has taught us that, while relatively simple, Baryons are sufficiently complex to reveal physics hidden from us in the mesons.*

Nathan Isgur, **2000**

Baryon Sector @ PDG2024

GW Contribution

S. Navas *et al*, Phys Rev D **110**, 030001 (**2024**)

p	$1/2^+$	****
n	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1685)$		*
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	***
$N(17$[illegible]$)$	$3/2^+$	[illegible]
$N(18$[illegible]$)$	$5/2^+$	[illegible]
$N(1$[illegible]$)$	$3/2^-$	***
$N(1$[illegible]$0)$	[illegible]$/2^+$	**
$N($[illegible]$5)$	[illegible]$/2^-$	**
$N($[illegible]$00)$	[illegible]	***
$N($[illegible]$90)$	$7/$[illegible]	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	**
$N(2100)$	$1/2^+$	*
$N(2120)$	$3/2^-$	**
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**

$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	***
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	**
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(1920)$	$3/$[illegible]	***
$\Delta(1930)$	[illegible]$/2^-$	***
$\Delta(1940)$	$3/2^-$	[illegible]
$\Delta(1950)$	$7/2^+$	****
$\Delta(20$[illegible]$0)$	$5/2^+$	[illegible]
$\Delta($[illegible]$)$	[illegible]	[illegible]
$\Delta(2200)$	$7/2^-$	*
$\Delta(2300)$	$9/2^+$	**
$\Delta(2350)$	$5/2^-$	*
$\Delta(2390)$	$7/2^+$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
$\Delta(2750)$	$13/2^-$	**
$\Delta(2950)$	$15/2^+$	**
Λ	$1/2^+$	****
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	***
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	$3/2^-$	****
$\Lambda(1800)$	$1/2^-$	***
$\Lambda(1810)$	$1/$[illegible]	***
$\Lambda(1820)$	[illegible]$/2^+$	****
$\Lambda(1830)$	$5/2^-$	****
$\Lambda(1890)$	$3/2^+$	****
$\Lambda(200$[illegible]$)$	[illegible]	[illegible]
$\Lambda($[illegible]$)$	$7/2^+$	[illegible]
$\Lambda(2100)$	$7/2^-$	****
$\Lambda(2110)$	$5/2^+$	***
$\Lambda(2325)$	$3/2^-$	*
$\Lambda(2350)$	$9/2^+$	***
$\Lambda(2585)$		**

Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
$\Sigma(1385)$	$3/2^+$	****
$\Sigma(1480)$		*
$\Sigma(1560)$		**
$\Sigma(1580)$	$3/2^-$	*
$\Sigma(1620)$	$1/2^-$	**
$\Sigma(1660)$	$1/2^+$	***
$\Sigma(1670)$	$3/2^-$	****
$\Sigma(1690)$		**
$\Sigma(1750)$	[illegible]	[illegible]
$\Sigma(1770)$	[illegible]$/2^+$	*
$\Sigma(1775)$	[illegible]$^-$	****
$\Sigma(1840)$	3[illegible]$^+$	*
$\Sigma(1880)$	$1/2^+$	**
$\Sigma(191$[illegible]$)$	$5/2^+$	[illegible]
$\Sigma($[illegible]$)$	[illegible]	***
$\Sigma(2000)$	$1/2^-$	*
$\Sigma(2030)$	$7/2^+$	****
$\Sigma(2070)$	$5/2^+$	*
$\Sigma(2080)$	$3/2^+$	**
$\Sigma(2100)$	$7/2^-$	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(153$[illegible]$)$	[illegible]	[illegible]
$\Xi(162$[illegible]$)$		*
$\Xi(1690)$		***
$\Xi(182$[illegible]$)$	[illegible]$/2^-$	***
$\Xi(19$[illegible]$)$		***
$\Xi(2030)$	$\geq \frac{5}{2}?$	***
[illegible]		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-	$3/2^+$	[illegible]
$\Omega(2$[illegible]$)^-$		***
$\Omega($[illegible]$0)^-$		**
$\Omega($[illegible]$70)^-$		[illegible]

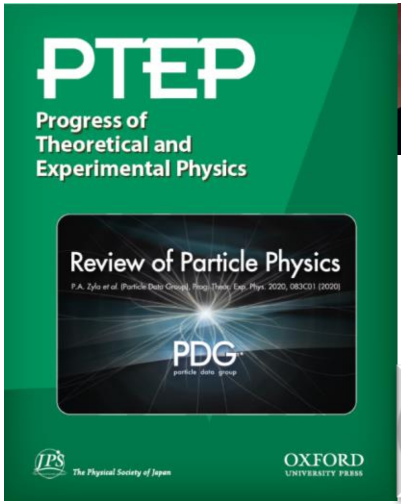
Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$		***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	***
$\Xi_c^{\prime +}$	$1/2^+$	***
$\Xi_c^{\prime 0}$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2930)$		*
$\Xi_c(2980)$		***
$\Xi_c(3055)$		**
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
Ξ_{cc}^+		*
Λ_b^0	$1/2^+$	***
Σ_b	$1/2^+$	***
Σ_b^*	$3/2^+$	***
Ξ_b^0, Ξ_b^-	$1/2^+$	***
Ω_b^-	$1/2^+$	***

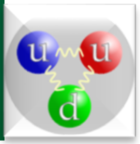
- First *hyperon* was discovered in **1950**.

V.D. Hopper & S. Biswas, Phys Rev **80**, 1099 (**1950**)

- Pole position in complex energy plane for *hyperons* has made *only* in **2010**.

Y. Qung *et al*, Phys Lett B **694**, 123 (**2010**)





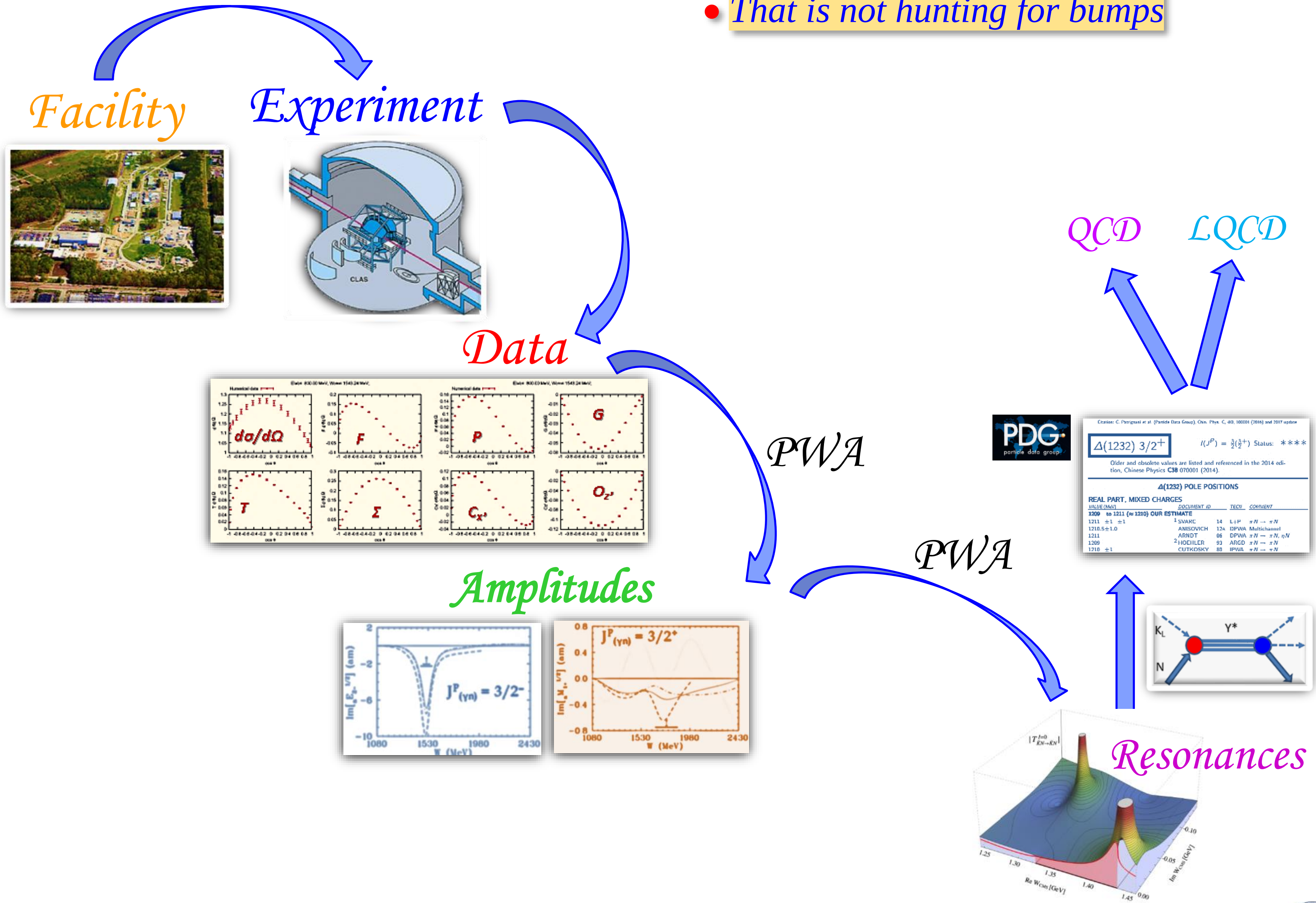
- PDG2024 has 133 Baryon Resonances (69 of them are 4* & 3*).
- In case of SU(6) x O(3), 434 states would be present if all revealed multiplets were fleshed out (*three* **70** & *four* **56**).

- LQCD results are similar.

R. Koniuk & N. Isgur, Phys Rev Lett **44**, 845 (**1980**)

Road Map to Baryon Spectroscopy

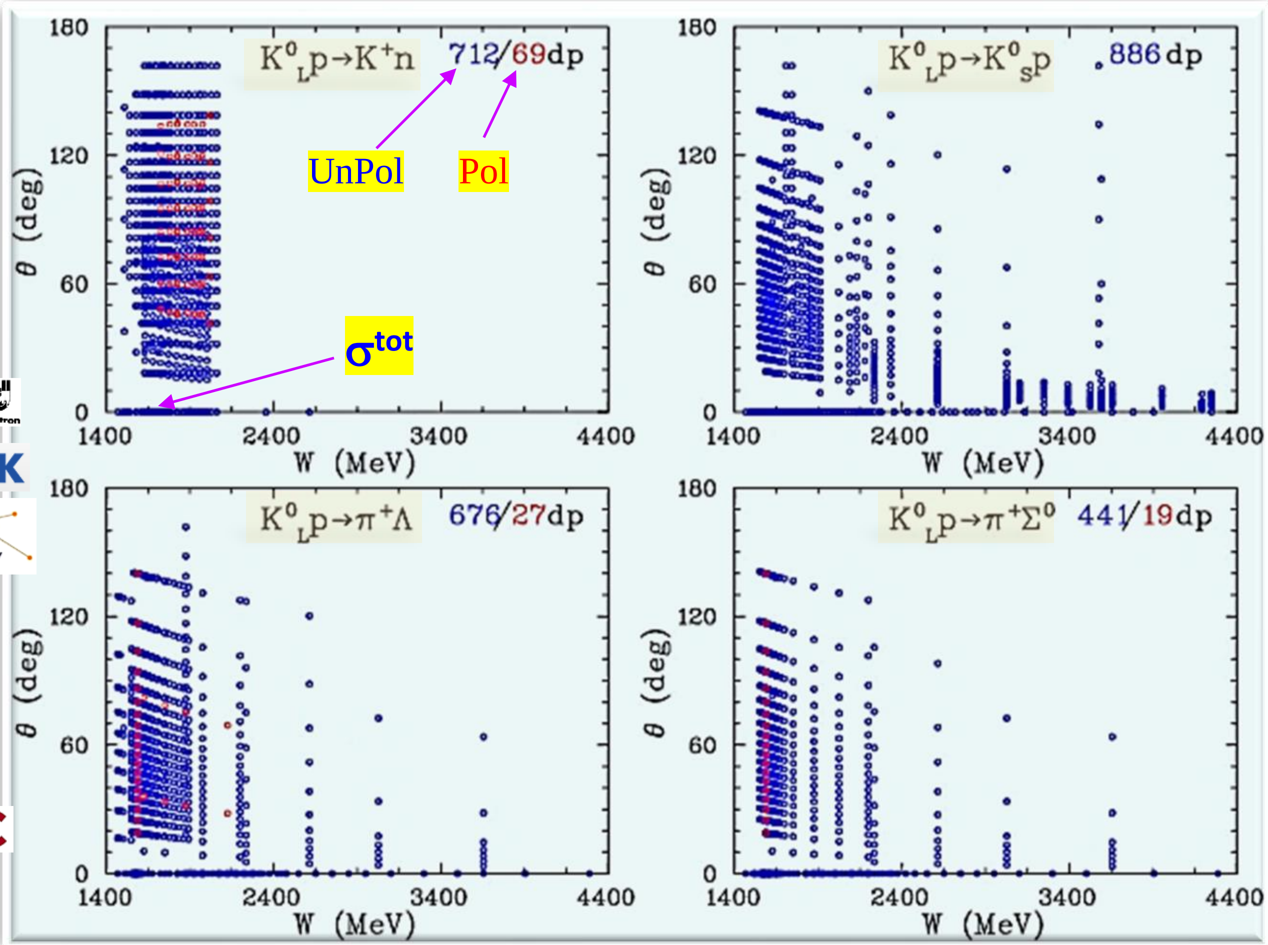
- *That is not hunting for bumps*



World K–long Data – Ground for Hyperon Phenomenology

SAID: http://gwdac.phys.gwu.edu/

- Limited number of K_L induced measurements (1961 – 1982) 2426 $d\sigma/d\Omega$, 348 σ^{tot}, & 115 P observables do not allow today to *feel comfortable* with *Hyperon Spectroscopy* results.



W = 1.45 – 5.05 GeV

- Limited number of K_L observables in *hyperon spectroscopy* @ present poorly constrain phenomenological analyses.
- *Overall systematics* of previous experiments varies between 15% & 35%. *Energy binning* is much broader than hyperon widths.
- There were **no** measurements using *polarized target*. It means that there are no *double polarized* observables which are critical for *complete experiment* program.
- We are not aware of any data on ***neutron*** target.

What Can Be Learned with K_L Beam ?

Target ⟹	Proton	Neutron [*first* measurements]
Elastic & Charge-Exchange	$K_L p \to K_S p$ $K_L p \to K^+ n$	$K_L n \to K_S n$ $K_L n \to K^- p$
Two-body with **S** = –1	$K_L p \to \pi^+ \Lambda$ $K_L p \to \pi^+ \Sigma^0$	$K_L n \to \pi^0 \Lambda$ $K_L n \to \pi^0 \Sigma^0$
Two-body with **S** = –2	$K_L p \to K^+ \Xi^0$ $K_L p \to K^+ \Xi^{0*}$	$K_L n \to K^0 \Xi^0$ $K_L n \to K^0 \Xi^{0*}$
Three-body with **S** = –2	$K_L p \to \pi^+ K^+ \Xi^-$ $K_L p \to \pi^+ K^+ \Xi^{-*}$	$K_L n \to \pi^+ K^- \Xi^0$ $K_L n \to \pi^+ K^- \Xi^{0*}$
Three-body with **S** = –3	$K_L p \to K^+ K^+ \Omega^-$ $K_L p \to K^+ K^+ \Omega^{-*}$	$K_L n \to K^+ K^0 \Omega^-$ $K_L n \to K^+ K^0 \Omega^{-*}$

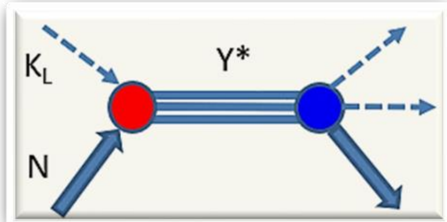
- To search for ``*missing*'' hyperons, we need measurements of production reactions:

Σ^*: $K^0_L p \to \pi\Sigma^* \to \pi\pi\Lambda$

Λ^*: $K^0_L p \to \pi\Lambda^* \to \pi\pi\Sigma$

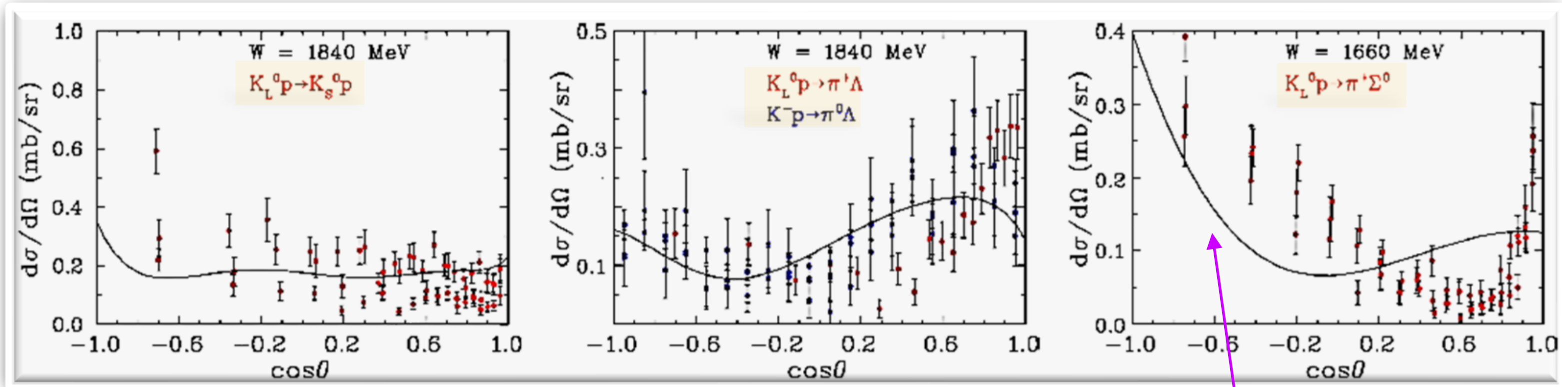
Ξ^*: $K^0_L p \to K\Xi^*, \pi K\Xi^*$

Ω^*: $K^0_L p \to K^+K^+\Omega^*$

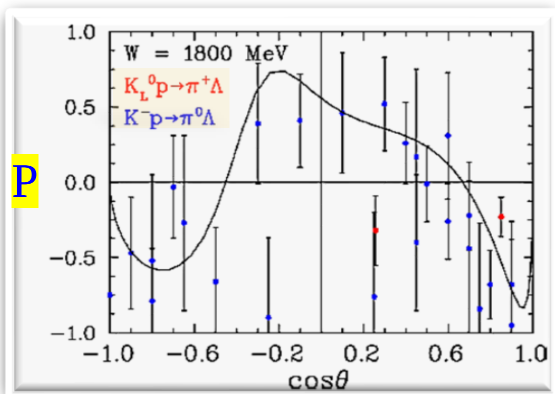


Samples of PWA Results for Current DB

H. Zhang *et al* Phys Rev C **88**, 035204 (**2013**)
H. Zhang *et al* Phys Rev C **88**, 035205 (**2013**)

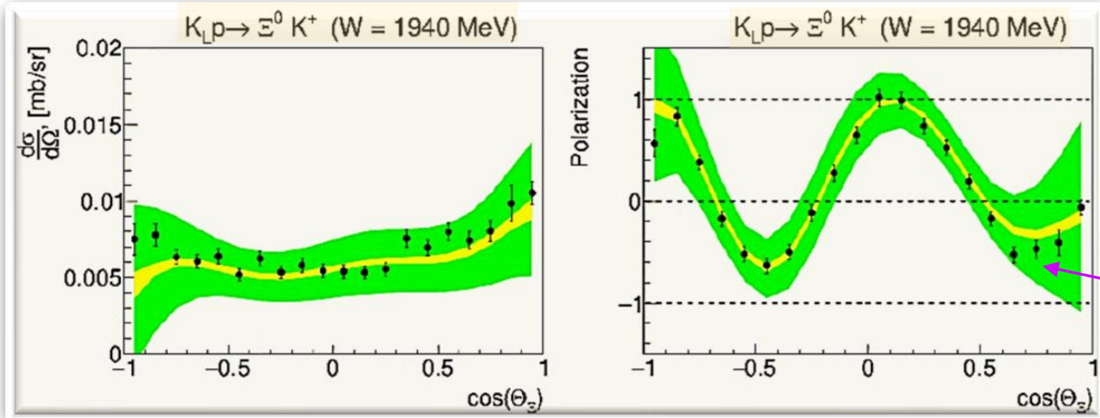


- *PWA* (&) predictions at lower & higher energies have poorer agreement for ***S ≠ 0*** data than for ***S = 0*** data.



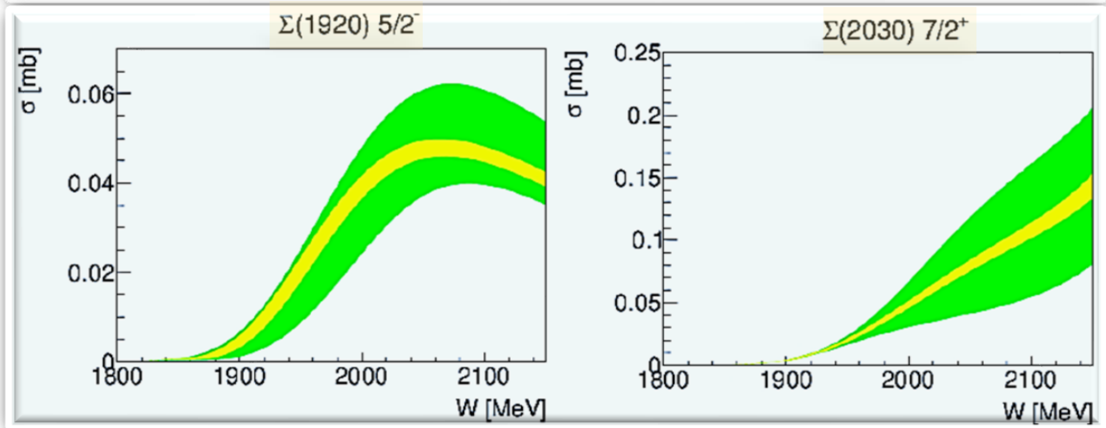
- Polarized measurements are *tolerable* for any *PWA* solutions.

Impact Proposed Data using PWA



Quasi-data using *GlueX* detector properties

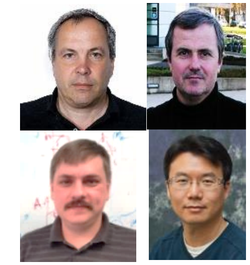
GEANT4



100 days

20 days

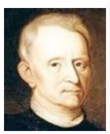
- At least **100** days needed to get *precise* solution.

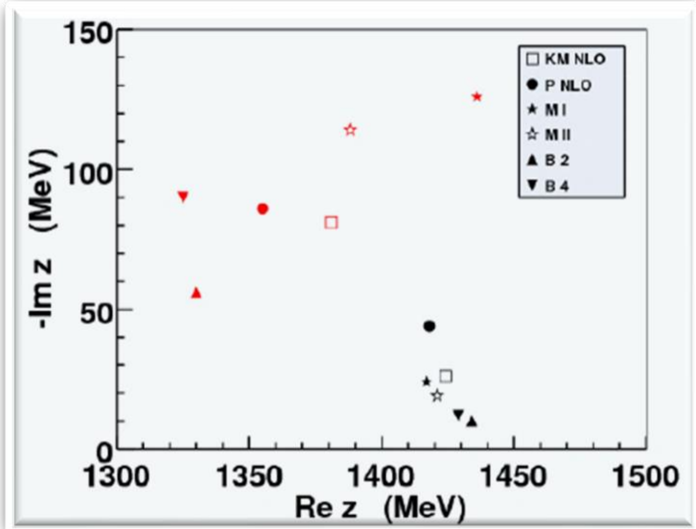


Resonance	20 days: M, Γ	100 days: M, Γ	PDG: M, Γ	hadspec M
Σ(1920)5/2⁻	1977±21±25 327±25±25	1923±10±10 321±10±10	?	2027 2487 2659 2781
Σ(2030)7/2⁺	1981±30±30 350±80	1930±20±30 400±40	2030±10 180±30	2686 2709 2793 2806

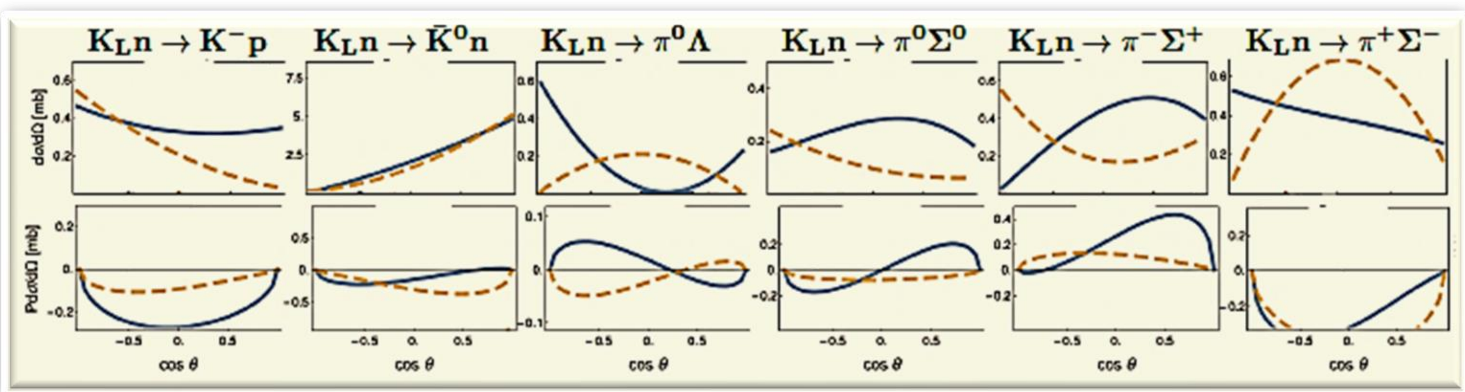
R.G. Edwards *et al*, Phys Rev D **87**, 054506 (**2013**)

Theory for "Neutron" Target Measurements





- There are **6** different models.
- *Pole* positions of *Λ(1405)* in chiral unitary approaches.
- Each symbol represents position of 1st (black) & 2nd (red) pole in each model.

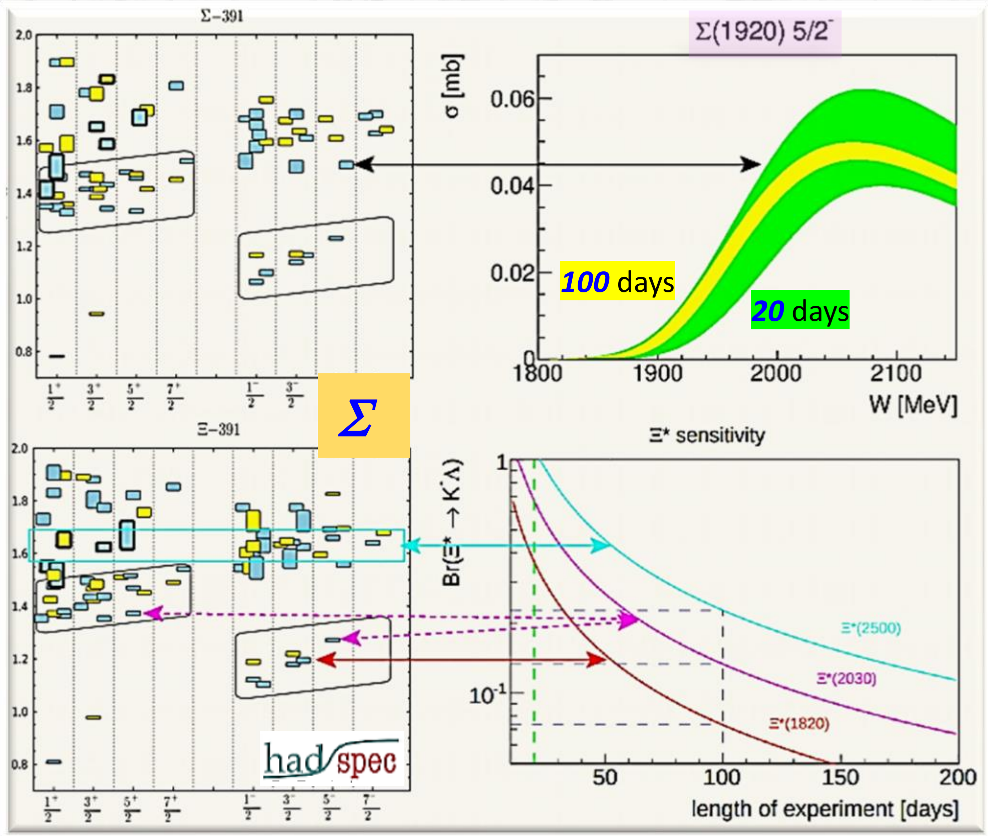


- *P* = **300** MeV/c

Courtesy of Maxim Mai, **2019**

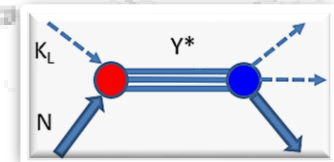
Summary of Hyperon Spectroscopy

Money Plot



- We showed that KLF sensitivity with *100 days* of running will allow to discovery many *hyperons* with good precision.

- *Why should it be done with KL beam ?*
  This is only realizable way to observe ***s***-channel resonances having ***all momenta*** of K_L @ once (``*tagged*'' *kaons*).



- *Why should it be done* @ Jefferson Lab ?
  Because nowhere else in existing facilities this can be done.

- *Why should we care that there are dozens of missing states ?*

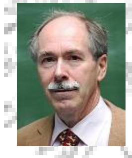
…The new capabilities of the 12-GeV era facilitate a detailed study of baryons containing two and three strange quarks. Knowledge of the spectrum of these states will further enhance our understanding of the manifestation of QCD in the three-quark arena.

2015 Long Range Plan for Nuclear Science

Exotics

Anyone can ask Big Questions, but it is not easy to ask questions that would suggest new pathways leading to real progress of our understanding.

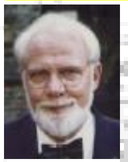
Courtesy of Gerard 't Hooft, 2022

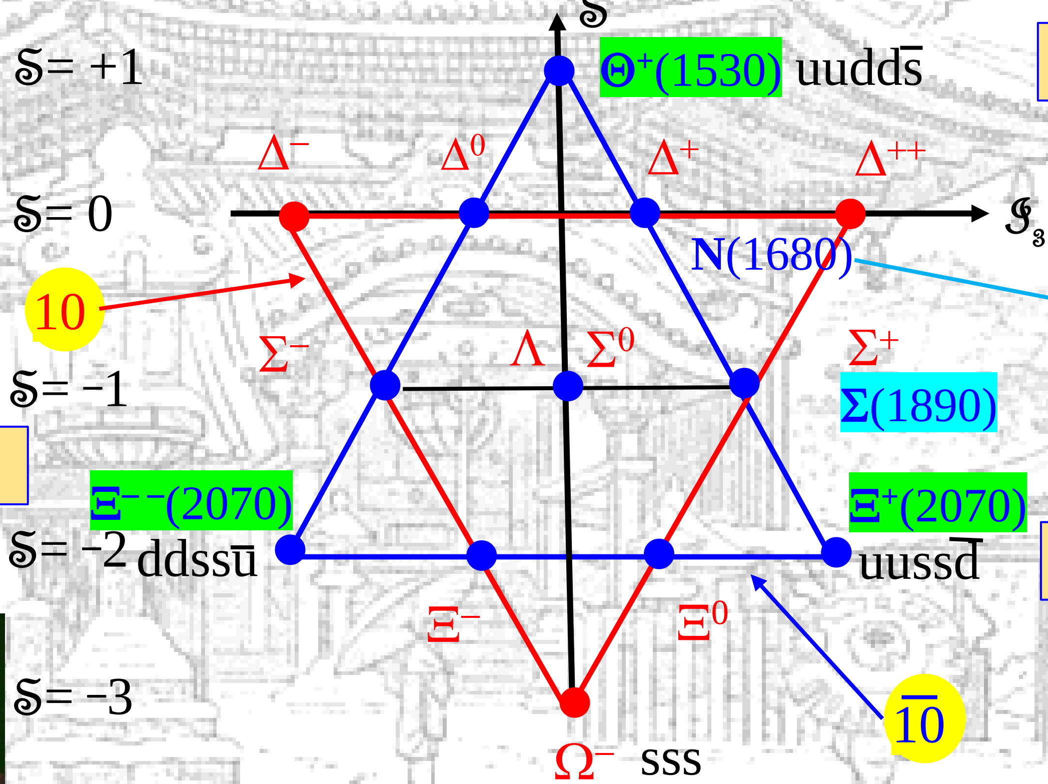


What Else ?

10 & $\overline{10}$ – P wave Multiplets

J.J. de Swart, Rev Mod Phys **35**, 916 (1963)





$K_L p \rightarrow K^+ n$

Not N(1710)

R.A. Arndt *et al*.
Phys Rev C **69**, 035208 (2004)

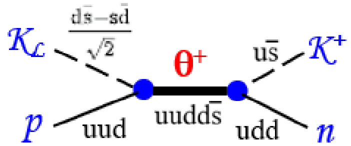
$K_L p \rightarrow K^+K^+K^+\Xi^{--}$

$K_L p \rightarrow K_S \Xi^+$

- In addition to ordinary hyperon states made of qqq, experiment may observe exotic Θ^+ pentaquark lying in apex of $\overline{10}$ it will also be sensitive to observe exotic Ξ^+ lying in ***right corner*** of $\overline{10}$ in reaction $K_L p \rightarrow K_S \Xi^+$ & to observe another exotic state Ξ^{--} lying in ***left corner*** of $\overline{10}$ in reaction $K_L p \rightarrow K^+K^+K^+\Xi^{--}$

D. Diakonov, V. Petrov, & M.V. Polyakov, Z. Phys. A **359**, 305 (1997)

What One Can Expect for $K_L p \to \Theta^+ \to K^+ n$ from KLF ?



$P_{01}(J^P = ½^+)$

M. Amaryan, S. Hirama, D. Jido, & IIS, Mod Phys Lett A **39**, 2450063 (2024)

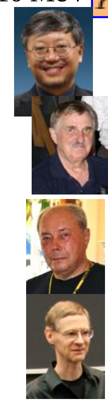
V.V. Barmin *et al* Phys Rev C **89**, 045204 (2014): M = **1538**±2 MeV → p_{KL} = **440** MeV/c → k = **0.26**8 GeV/c & **Γ** = **0.34**±0.10 MeV

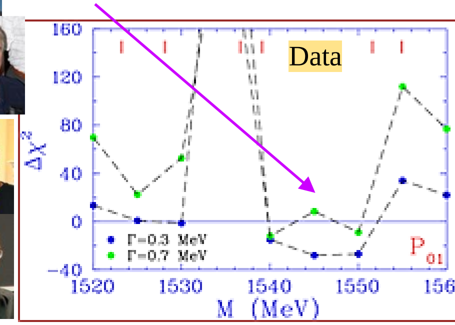
$K^+Xe \to K^0 pXe$

Ghil-Seok Yang & Hyun-Chul Kim, PTEP **2013**, 013D01 (2013) ChSA: **Γ** = **0.5**±0.1 MeV

R.A. Arndt, IIS, & R.L. Workman, Phys Rev C **68**, 042201(R) (2003): Modified **KN PWA** gave: **Γ** < **0.5** MeV @ **M** ~ **1545** MeV

Assuming θ^+ width Γ = 0.4 MeV



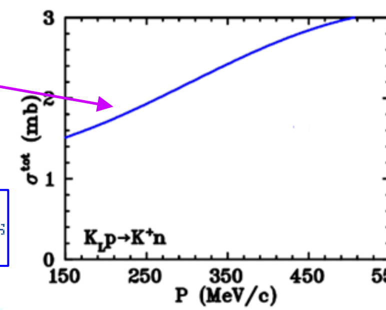


R.N. Cahn & G.H. Trilling, Phys Rev D **69**, 011501(R) (2004):

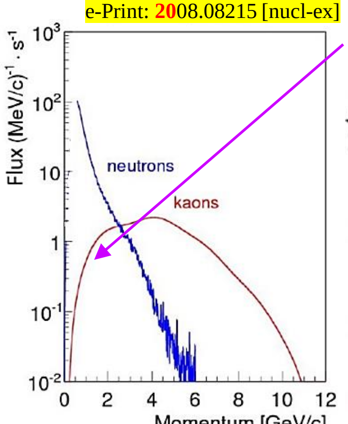
$$\sigma_0 = \frac{2J+1}{(2s_{K_L}+1)(2s_p+1)}\frac{4\pi}{k^2} = 68 \text{ mb}$$

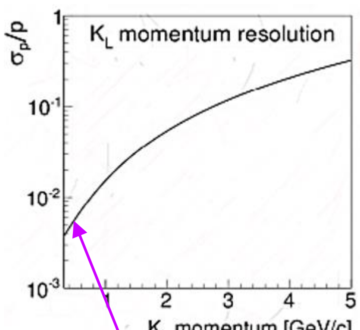
Y. Iizawa, D. Jido, & S. Huebsch, [arXiv:2308.09397 [hep-ph]]: Assuming bkgd Xsec @ 440 MeV/c

σ_0 = **3** mb



e-Print: 2008.08215 [nucl-ex] @ 1 MeV/c bin & flux = 0.1 (MeV/c s)$^{-1}$.
It means - we will have **~10^6 K_L/100** days.

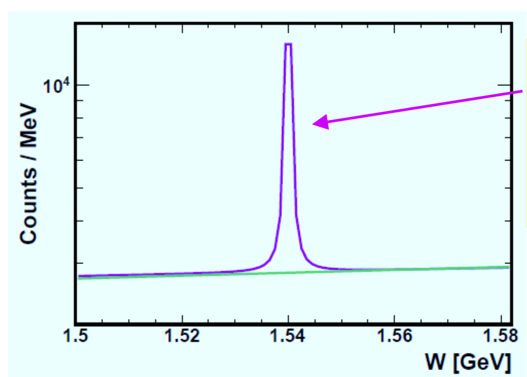




σ_p/p = **6 × 10^{-3}**

10,000

$$N_{peak} = \frac{\Gamma(\Theta^+)\,\pi\sigma_0\,N_{bkgd}\,B_i B_f}{2\sigma_{bkgd}\,\Delta m_0} = 18,000 \text{ events}$$



10k events in peak in **100** days.
Taking into account
- acceptance &
- efficiency of kaon registration,

One can expect **100** events per day.

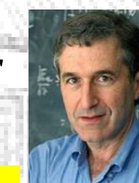
$R = S/B = 4/1$

If Θ^+ does not Survive, `Damned' Questions Revive:

- *Why are there no strongly bound exotic states…, like those of two quarks and two antiquarks or four quarks and one antiquark?*

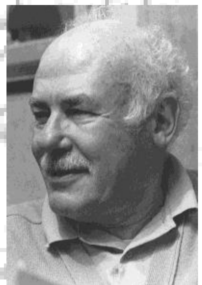
H. Lipkin, Phys Lett **45B**, 267 (1973)

- *…either these states will be found by experimentalists, or our confined, quark-gluon theory of hadrons is as yet lacking in some fundamental, dynamical ingredient which will forbid the existence of these states or elevate them to much higher masses.*



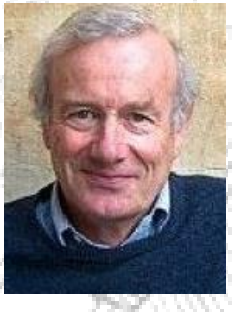
R. Jaffe & K. Johnson, Phys Lett **60B**, 201 (1976)

Strange Meson Spectroscopy



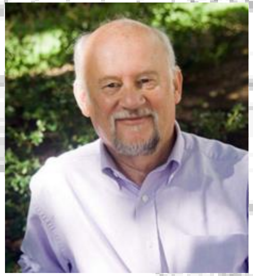
The di-quark or meson-baryon puzzle: Why is the quark-quark interaction just enough weaker than the quark-anti-quark interaction so that di-quarks near the meson mass are not observed, but three-quark systems have masses comparable to those of mesons?

Harry Lipkin, 1973



For the region below 1 GeV, the debate centers on whether the phenomena are truly resonant or driven by attractive t-channel exchanges, and if the former, whether they are molecules or $\bar{q}q\bar{q}q$.

Frank Close, 2007



QCD predicts there should be a far richer spectrum, with states made predominantly of glue, we call glueballs, tetra-quark states made of two quarks and two anti-quarks... For almost forty years we have been searching for these additional states. Indeed, we may well have observed some of these, but there is little certainty of what has been found.

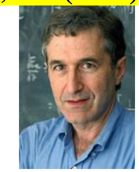
Michael Pennington, 2015

A simple picture for both mesons and baryons is inconsistent with any version of relativistic field theory, where one can not exclude presence of an arbitrary number of virtual $\bar{q}q$ *pairs and/or gluons. Therefore, adequate description of any hadron should use a Fock column, where lines correspond to particular configurations (but with the same ``global'' quantum numbers, like I, J, P, C, and so on).*

Yakov Azimov, 2015

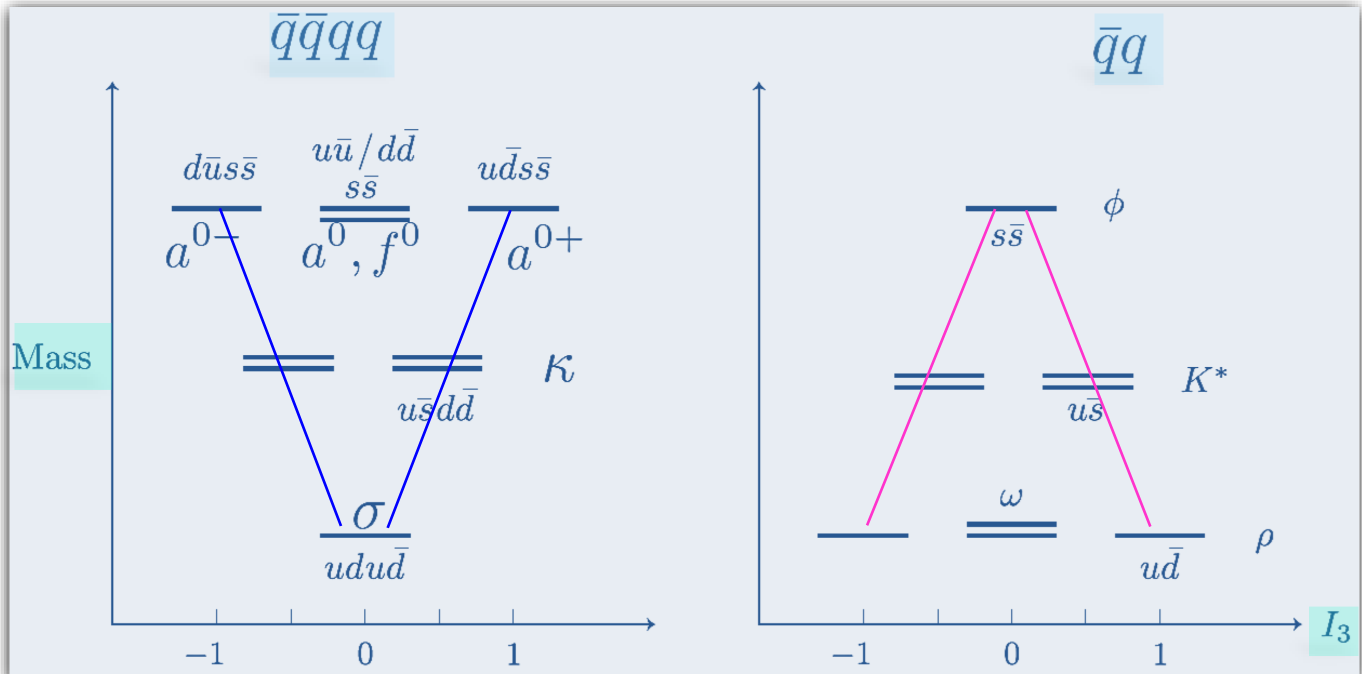
Scalars vs Vectors or Eyewitness of 4q Exotics ?

R.J. Jaffe, Phys Rev D **15**, 267 (**1977**)
arXiv: **0001**123 [hep-ph]
Prog Theor Phys Suppl **168**, 127 (**2007**)



Inverted mass hierarchy tetraquarks
Scalar Mesons

Ordinary meson states
Vector Mesons



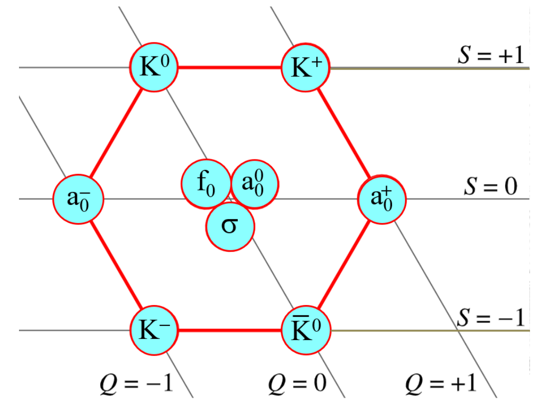
- Very different mass *hierarchy*.
- Possibly suggesting *4q tetraquark*.
- Structure of ***scalar*** mesons.

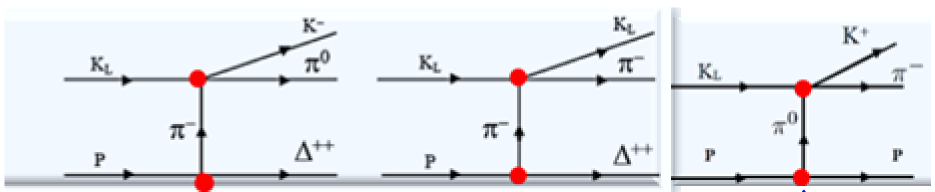
- *Certainly, there is no clear distinction between 4q & ``meson molecule'' categories.*

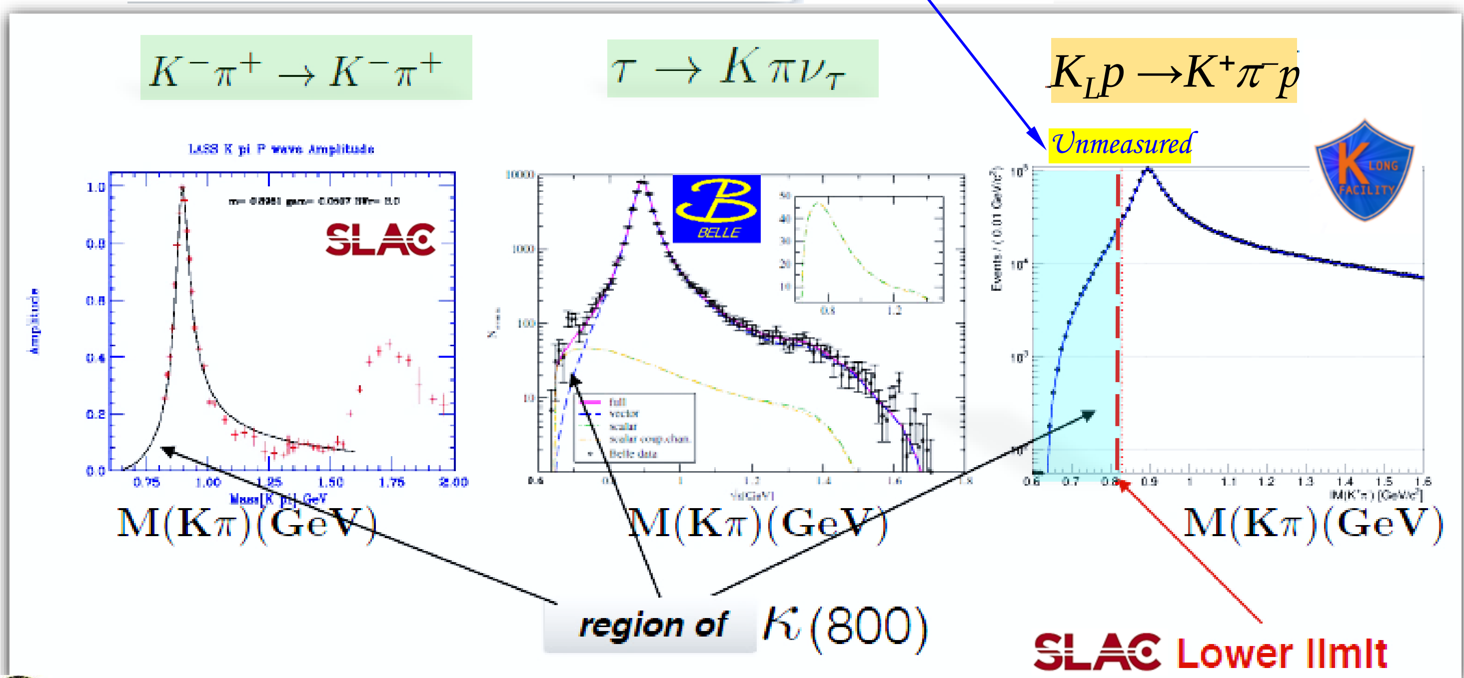
"I like the conclusion that the a_0 is a multi quark state." Courtesy of Bob Jaffe, **2022**

Proposed Measurements for $K\pi$ Scattering

- ***Four*** states called *κ(700)*.
- PDG : *still need further confirmation.*
- allows determination of all *four* states.

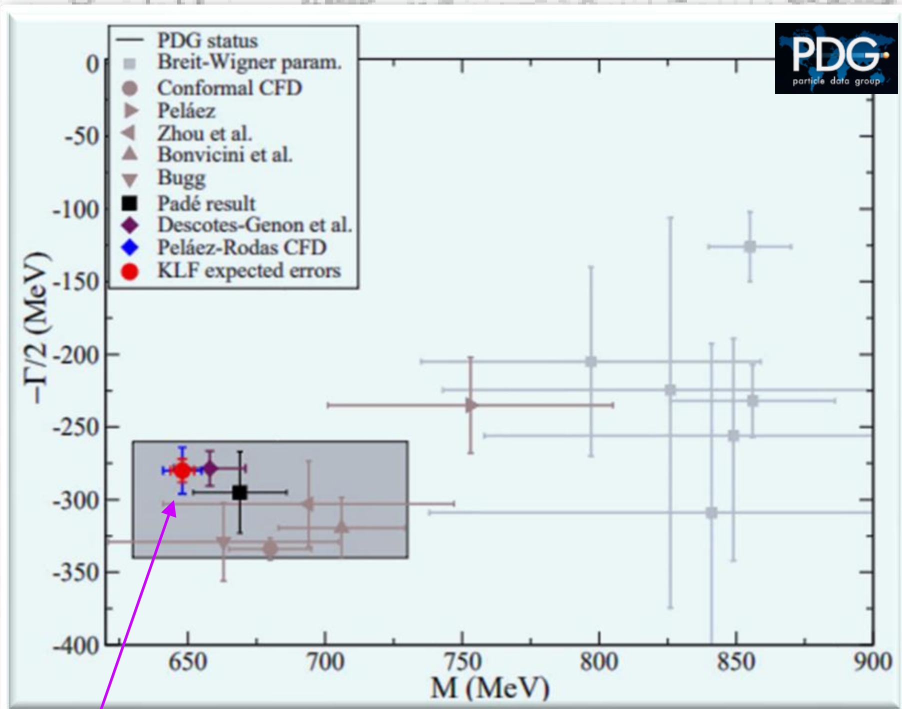






Summary of $K\pi$ Spectroscopy

Money Plot



- [KLF logo] will have very significant *impact* on our knowledge on *$K\pi$ scattering amplitudes*.
- It will certainly improve still conflictive determination of *heavy K*'s parameters*.
- It will help to settle tension between phenomenological determination of *scattering lengths* from data vs *ChPT* & *LQCD*.
- For *K*(700)*, it will reduce:
  - *uncertainties* in *mass* by factor of *two* &
  - *uncertainties* in *width* by factor of *five*.
- It will help to clarify debated of its *existence*, &, therefore, long standing problem of existence of *scalar* meson *nonet*.

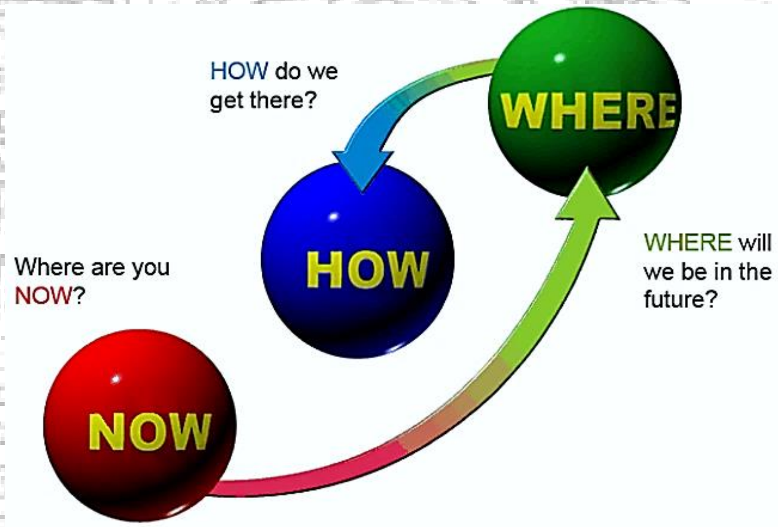
100 days

- **Roy-Steiner** dispersion approach
  $M - i\Gamma/2 = (648 \pm 4) - i(280 \pm 8)$ MeV

Simon Eidelman Prize 2025

J.R. Pelaez *et al* Phys Rev D **93**, 074025 (**2016**)

Where are We Now &
Where will be in Future?



Beam Time Approved by PAC48

- Expected cornucopia of differential cross sections of different reactions with LH_2 & below W = *2.5* GeV for *100* days of beam time:

For $d\sigma/d\Omega$

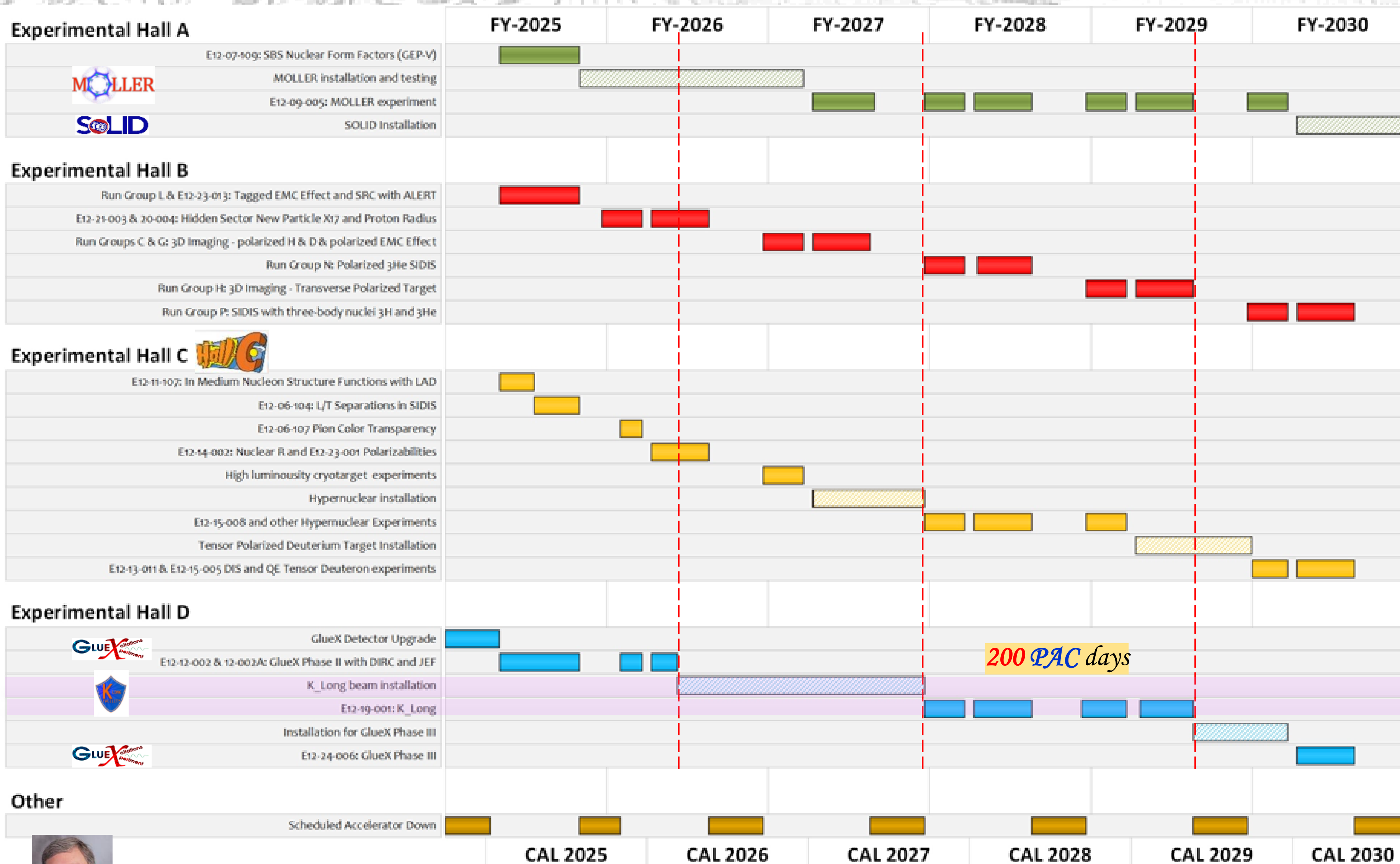
Reaction	Statistics (events)
$K_L p \to K_S p$	2.7M
$K_L p \to \pi^+ \Lambda$	7M
$K_L p \to K^+ \Xi^0$	2M
$K_L p \to K^+ n$	60M
$K_L p \to K^- \pi^+ p$	7M

For ***P*****,** statistics is 0.2M

- There are no data on ``*neutron*" targets &, for this reason, it is hard to make realistic estimate of statistics for $K_L n$ reactions.
  If we assume similar statistics as on ``*proton*" target, full program will be completed after running *100* days with LH_2 & *100* days with LD_2 *cryo* targets.

- Expected systematics for dσ/dΩ is ***5***–***10***%.

Jefferson Lab *Tentative Long-Term Schedule*



Courtesy of David Dean, Nov 2024

- goal is
  - To setup *KL Facility* @ Jefferson Lab
  - To measure & bring *new physics*.

07/2010: PAC43 LoI
09/2020: PAC48 approved C12-19-001, A-
08/2023: ERR-I approved
08/2024: IERR approved
07/2025: PAC53 Jeopardy is coming
08/2025: ERR-II will come
10/2025: ERR-III will come

- Jefferson Lab would advance *Hyperon Spectroscopy* & study of *strangeness* in nuclear & hadronic physics.
  We may have cornucopia of many missing/new strange states.
  To complete ***SU(3)$_F$*** *multiplets*, one needs no less than 48 Λ^*, 38 Σ^*, 61 Ξ^*, & 31 Ω^*.

- Discovering of ``*missing*'' *hyperon states* would assist in advance our understanding of formation of ***baryons*** & ***mesons*** from *quarks* & *gluons* *microseconds* (**!**) after *Big Bang*.

  Our expectation is to get **1** missed/new *hyperon* per **1** day.

- In *Strange Meson Spectroscopy*, ***PWA*** will allow to determine excited *K** states including *scalar K*(700)* states.

- proves to be exceptional ``*playground*'' for advancing our understanding of QCD & Nuclear Matter.
- We appreciate *Alex Dzierba* who allows to build up Hall D with GlueX spectrometer @ Jefferson Lab

桜が近づいてきました

ありがとうございました。

質問を歓迎します

igor@gwu.edu


BACKUP

A Bit of History

PHYSICAL REVIEW VOLUME 138, NUMBER 5B 7 JUNE 1965

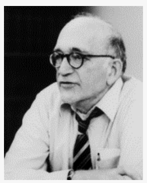
First paper on subject

Photoproduction of Neutral K Mesons*

CP-violation (1964) *Hot topic*!

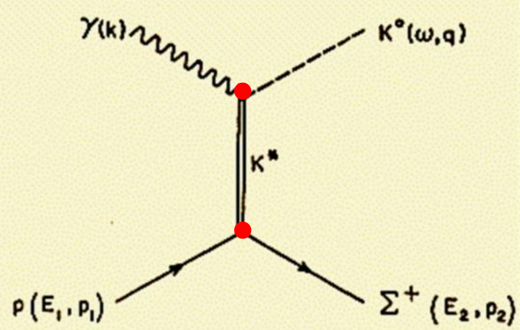
S. D. DRELL AND M. JACOB†
Stanford Linear Accelerator Center, Stanford University, Stanford, California

(Received 6 January 1965)



Photoproduction of a neutral K-meson beam at high energies from hydrogen is computed in terms of a K^* vector-meson exchange mechanism corrected for final-state interactions. The results are very encouraging for the intensity of high-energy K_2 beams at high-energy electron accelerators. A typical magnitude is 20 μb/sr for a lower limit of the K^0 photoproduction differential cross section, at a laboratory peak angle of 2°, for 15-BeV incident photons.

FIG. 1. K^* exchange in photoproduction.



Our motivation in carrying out this calculation is to emphasize the strong suggestion that an intense "healthy" K_2 beam will emerge from high-energy electron accelerators (SLAC in particular) and will be available for detailed experimental studies.

50 μb/sr

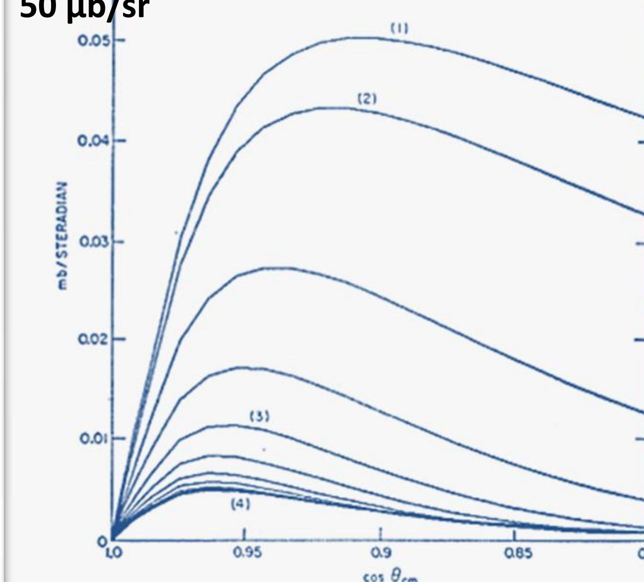


FIG. 3. Center-of-mass differential cross section at 10 BeV. Curve (1) gives the Born approximation. Curve (2) is obtained after subtraction of the $j=\frac{1}{2}$ partial wave. Curves (3) and (4) are respectively obtained after the $j=\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \frac{7}{2}$, and all partial waves have been corrected for absorption in final state. The results shown as directly obtained from the drawn by the computer.

Courtesy of Mike Albrow, KL2016

A bit of History

The possibility that useful K_L beam could be made @ electron synchrotron by photoproduction was being considered, & *1965* prediction for SLAC by Drell & Jacob was optimistic.

Sci-Tech DARESBURY

From: **Mike Albrow** **Aug 29, 2020**
To: Igor Strakovsky
*Dear **Igor**, That is excellent news, thank you for letting me know.*
*In one of those strange coincidences, my professor at Manchester who had the idea for our K0 photoproduction experiments and led the program, **Paul Murphy** (Manchester Univ.) died on Wednesday **Aug 26**. He was **89**.*
*I had told him about your plans, he was still interested. He would have been happy to know that **50** years later you are benefitting from his idea.*
*Best, **Mike** (I am doing well, thank you)*
*PS: If your proposal was accepted on **Aug 26**th let me know, it would be **strange synchronicity**!*

8.B.5
8.B.6
Nuclear Physics B23 (1970) 509-524. North-Holland Publishing Company

PHOTOPRODUCTION OF K^0 MESONS FROM PROTONS AND FROM COMPLEX NUCLEI

M. G. ALBROW ‡, D. ASTON, D. P. BARBER, L. BIRD ‡‡, R. J. ELLISON, C. HALLIWELL, A. E. HARCKHAM ‡‡‡, F. K. LOEBINGER, P. G. MURPHY, J. WALTERS ‡‡ and A. J. WYNROE
Schuster Laboratories, The University of Manchester, Manchester M13 9PL
R. F. TEMPLEMAN
Daresbury Nuclear Physics Laboratory, Daresbury, Near Warrington, Lancs.

Received 16 July 1970

Study photoproduction as means of making clean K0 beams & their decays & later, interactions.

VOLUME 22, NUMBER 18 PHYSICAL REVIEW LETTERS 5 MAY 1969

PRODUCTION OF K_2^0 MESONS AND NEUTRONS BY 10- AND 16-GeV ELECTRONS ON BERYLLIUM*

A. D. Brody, W. B. Johnson, D. W. G. S. Leith, G. Loew, J. S. Loos, G. Luste, R. Miller, K. Moriyasu, B. C. Shen, W. M. Smart, and R. Yamartino
SLAC
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 13 March 1969)

Systematics of particle-anti-particle processes through intrinsic property of K-longs.

QCD & Hadron Spectrum

- QCD gives rise to *hadron spectrum*.

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

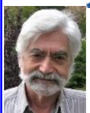
A SCHEMATIC MODEL OF BARYONS AND MESONS

M. GELL-MANN

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" ... Baryons can now be constructed from quarks by using the combinations (q q q), (q q q q $\bar{q}$), etc., while mesons are made out of (q $\bar{q}$), (q q $\bar{q}$ $\bar{q}$), etc.

CERN-TH-412 (Feb 21, 1964)

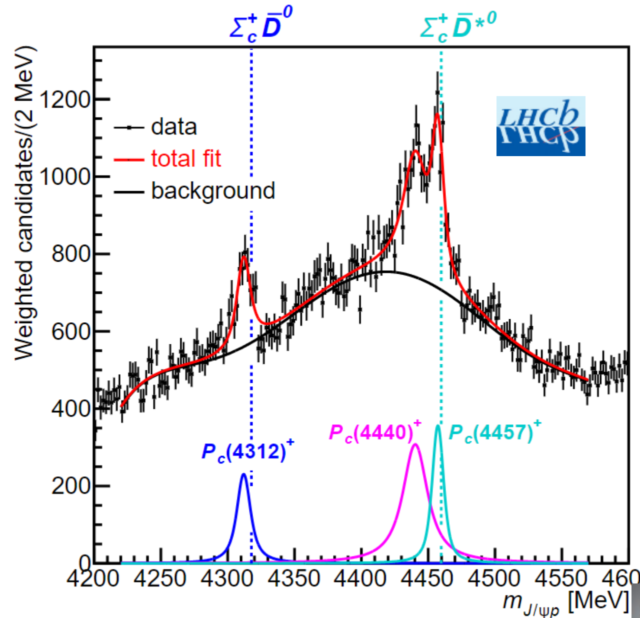
AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING



G. Zweig *)

CERN – Geneva

Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces break up into an isospin doublet and singlet. Each ace carries baryon number $\frac{1}{3}$ and is consequently fractionally charged. SU_3 (but not the Eightfold Way) is adopted as a higher symmetry for the strong interactions. The breaking of this symmetry is assumed to be universal, being due to mass differences among the aces. Extensive space-time and group theoretic structure is then predicted for both mesons and baryons, in agreement with existing experimental information. An experimental search for the aces is suggested.



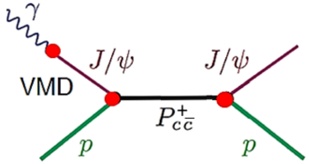
R. Aaij *et al*, Phys Rev Lett **122**, 222001 (2019)
R. Aaij *et al*, Phys Rev Lett **115**, 072001 (2015)

- LHCb claims *evidence* for ***four*** *hidden-charm* $qqq\bar{q}q$ *states* near *open-charm* decay thresholds for $\Sigma_c^+\bar{D}^0$ & $\Sigma_c^+\bar{D}^{*0}$ in $\Lambda_b^0 \to P_{c\bar{c}}^+ K^- \to (J/\psi\, p) K^-$ decays.

- Many $\bar{q}q$ & *qqq* states have been *observed*.

PDG 220 & 100.

- $\bar{q}q\bar{q}q$, $qqq\bar{q}q$, … *are not forbidden* or we *do not know* it yet.



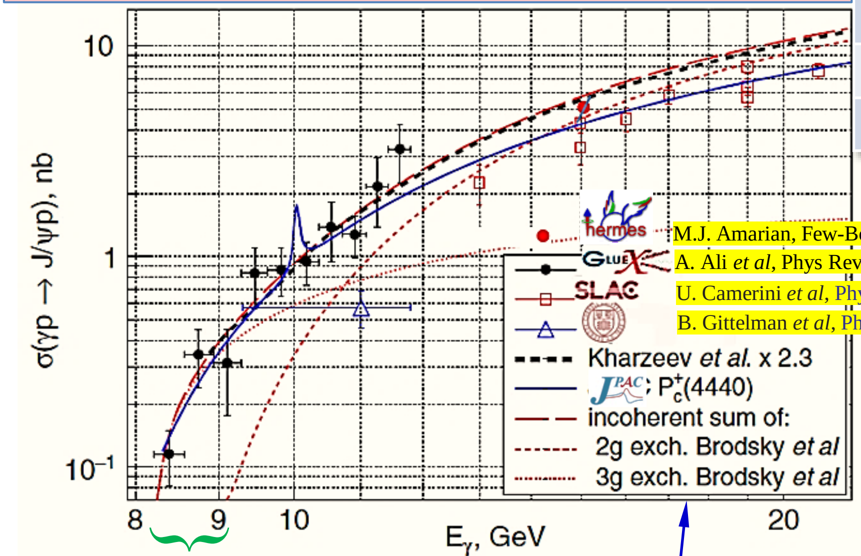
How Bump Hunting works in GlueX data?

A. Ali *et al*, Phys Rev Lett **123**, 072001 (**2019**)
S. Adhikari *et al*, Phys Rev C **108**, 025201 (**2023**)

- GlueX sees *no evidence* for LHCb P_{cc}s Upper limits @ 90% CL

2016–2017 data: **469**±22 $\gamma p \to J/\psi p \to e^+e^- p$ & **68** pb^{-1}

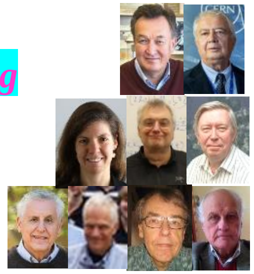
State	Upper Limit
$P_c(4312)$	**4.6** %
$P_c(4440)$	**2.3** %
$P_c(4457)$	**3.8** %



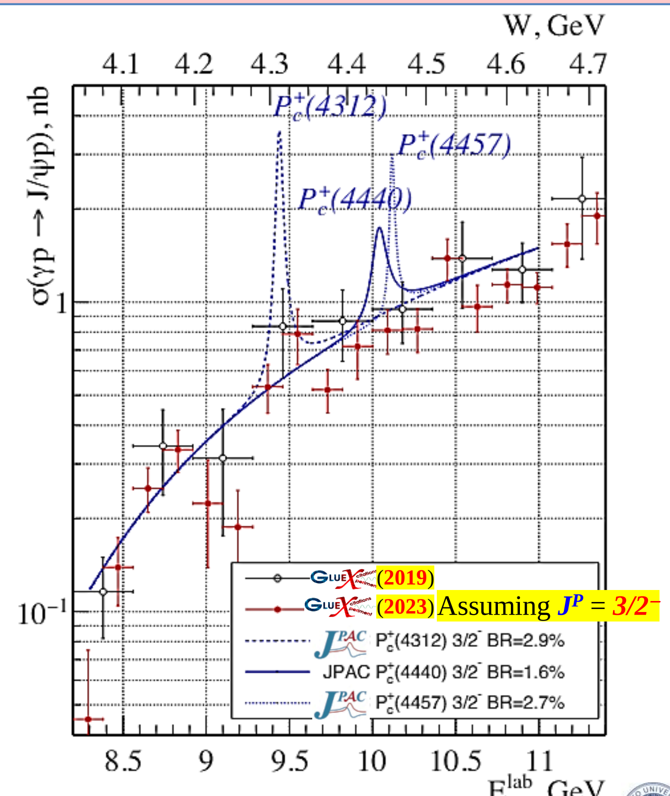
M.J. Amarian, Few-Body Syst Suppl. **11**, 359 (**1999**)
A. Ali *et al*, Phys Rev Lett **123**, 072001 (**2019**)
U. Camerini *et al*, Phys Rev Lett **35**, 483 (**1975**)
B. Gittelman *et al*, Phys Rev Lett **35**, 1616 (**1975**)

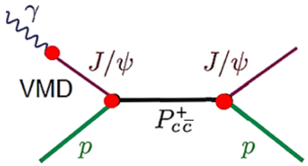
D. Kharzeev, H. Satz, A. Syamtomov, & G. Zinovjev, Nucl Phys A **661**, 568 (**1999**)
JPAC A.N. Hiller Blin *et al*, Phys Rev D **94**, 034002 (**2016**)
S. Brodsky, E. Chudakov, P. Hoyer, & J.M. Laget, Phys Lett B **498**, 23 (**2001**)

- Near *threshold*, ***3g*** works better than *2g*



2016–2018 data: **2270**±58 $\gamma p \to J/\psi p \to e^+e^- p$ & **320** pb^{-1}





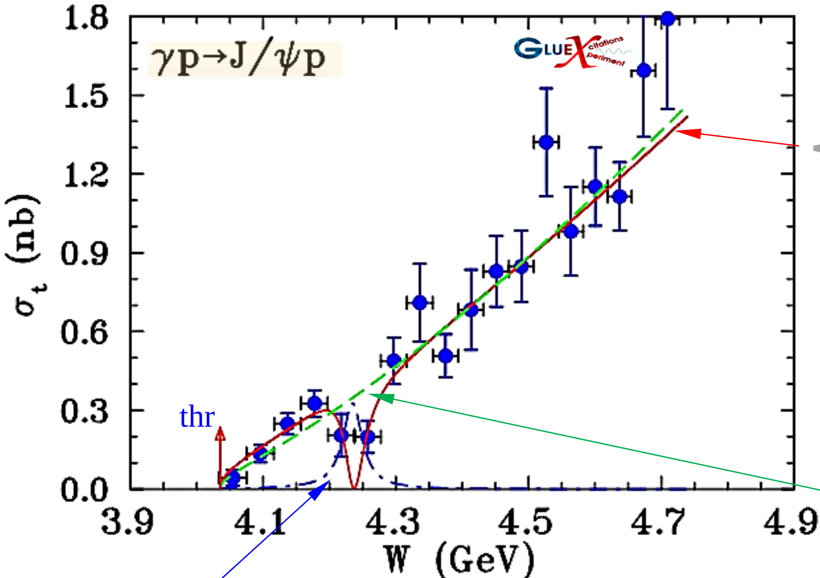
Alternative Solution for GlueX Data

IIS, W.J. Briscoe, E. Chudakov, I. Larin, L. Pentchev, A. Schmidt, R.L. Workman,

Phys Rev C **108**, 015202 (**2023**)

- We suggested to apply *rearrangement interference* for revealing *faint* resonance signals (***amplification*** by *interference* with *strong* background signal).
- Relative *phase* α leads to *constructive* (***bump***) or *destructive* (***dip***) *interference* for particular **PW**.

$$f = b + R \cdot \exp(2i\alpha)$$



Resonance: χ^2/ndf=11.99/12=1.00

M= 4235 ±8 MeV
Γ= 35.4±8.2 MeV
X= 0.023±0.005
α= 40.8±5.7 deg

Resolution ~6 MeV

Background:
A= 0.00251±0.00046 nb GeV/c
B= 0.00688±0.00083 nb/GeV/c

No Resonance: χ^2/ndf=19.74/16=1.23
A= 0.00183±0.00040 nb GeV/c
B= 0.00766±0.00077 nb/GeV/c

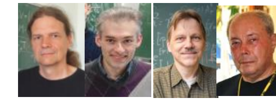
- *Dip position* does not correspond to *real mass* of **P_c(4312)$^+$.**
- It may depend on reaction *mechanism* (including *cusps* (*open charm*)) & background choices.

- If "*bump*" is imposed on GlueX data "*by hand*" (consider 7th - 9th energy values up from threshold), qualitative description of data up to **W** = **4.35** GeV is possible, but with higher χ^2, if our fit form is used.

- Obtained mass in our analysis is almost **77** MeV below LHCb determination, but it cannot exclude that this is $P_c(4312)^+$.

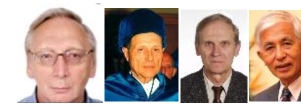
Deciphering Mechanism of Near-Threshold J/ψ Photoproduction

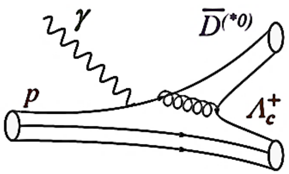
Meng-Lin Du, V. Baru, Feng-Kun Guo, Ch. Hanhart, U.-G. Meissner, A. Nefediev, & IIS, Eur Phys J C **80**, 1053 (2020)

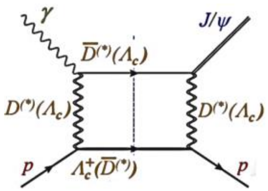


- It was shown that *fluctuation* of *photon* into ***open charm*** $\gamma p \to \Lambda_c \bar{D}$.
  is preferable than into *Charmonium J/ψ*.

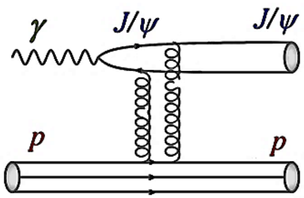
K. Boreskov, A. Capella, A. Kaidalov, & J. Tran Than Van, Phys Rev D **47**, 919 (1993)





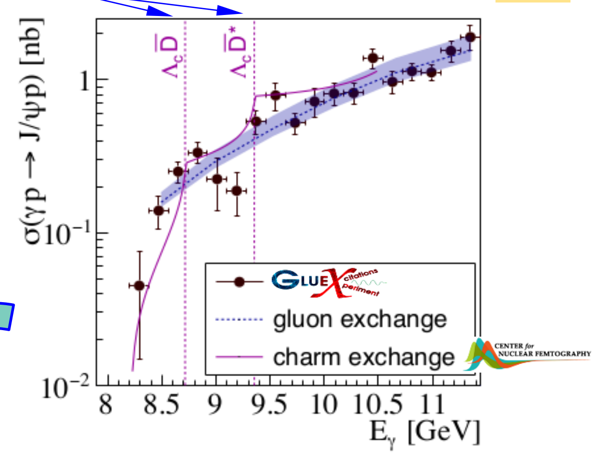


- $c\bar{c}$ *pair* is produced by ***1g*** & interacts with *proton*.

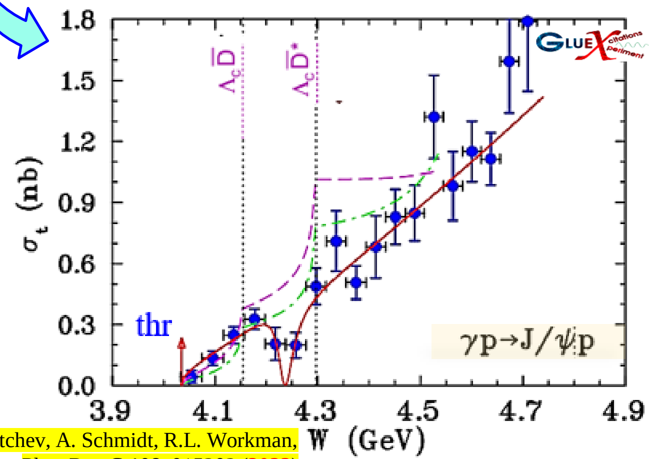


- $c\bar{c}$ *pair* is produced by ***photon*** via *VMD* & interacts with ***proton*** through ***2g*** exchange.

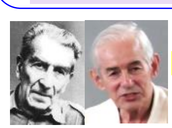
- *Cusp* effect is visible & in agreement with GlueX



- These *two mechanisms* act simultaneously.
  Assuming there is only *first* one,
  then key consequence: *threshold cusps* !
- There is no fit to GlueX data.



- One should study *two-component* problem accounting for *interference* between these *two components*.
- Effect of *charm* exchange is smaller than *gluon* exchange.
- *Gluon* contribution can be strongly *suppressed* due to "*young*" effect.



E.L. Feinberg, Sov Phys Usp, **23**, 629 (1980)
Courtesy of Misha Ryskin, July 2020

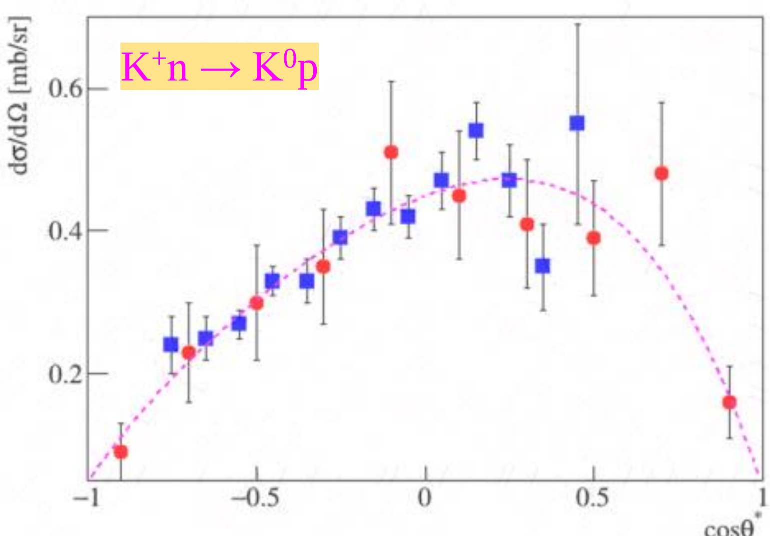
IIS, W.J. Briscoe, E. Chudakov, I. Larin, L. Pentchev, A. Schmidt, R.L. Workman, Phys Rev C **108**, 015202 (2023)

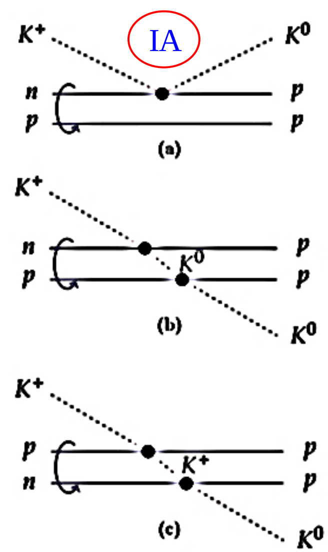
$K^+d \to \Theta^+p \to K^0pp$ for J-PARC

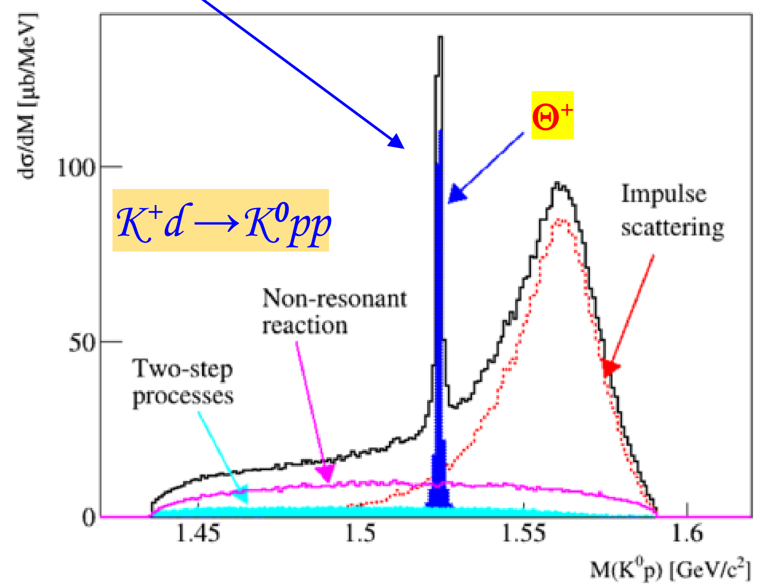
J.K. Ahn & S.H. Kim, J. Korean Phys. Soc. **82**, 579 (2023).
S.H. Kim *et al*. LoI for J-PARC PAC38, 2024


We propose to search for Θ^+ in $K^+d \to K^0pp$ reaction at p_{K^+}=0.5 GeV/c at J-PARC. A large acceptance Hyperon Spectrometer, which consists mainly of a time projection chamber and a 1-T superconducting magnet, will exclusively measure the decay products of Θ^+, such that $\Theta^+ \to K^0p$, followed by $K^0 \to \pi^+\pi^-$, with a mass resolution of 1 MeV at M_Θ. We investigated the feasibility of the proposed experiment using a Monte Carlo simulation. As a result, we expect to collect five orders of magnitude Θ^+ events, assuming a cross section of 300 μb in 15-day beam time at J-PARC.

Theoretical estimation







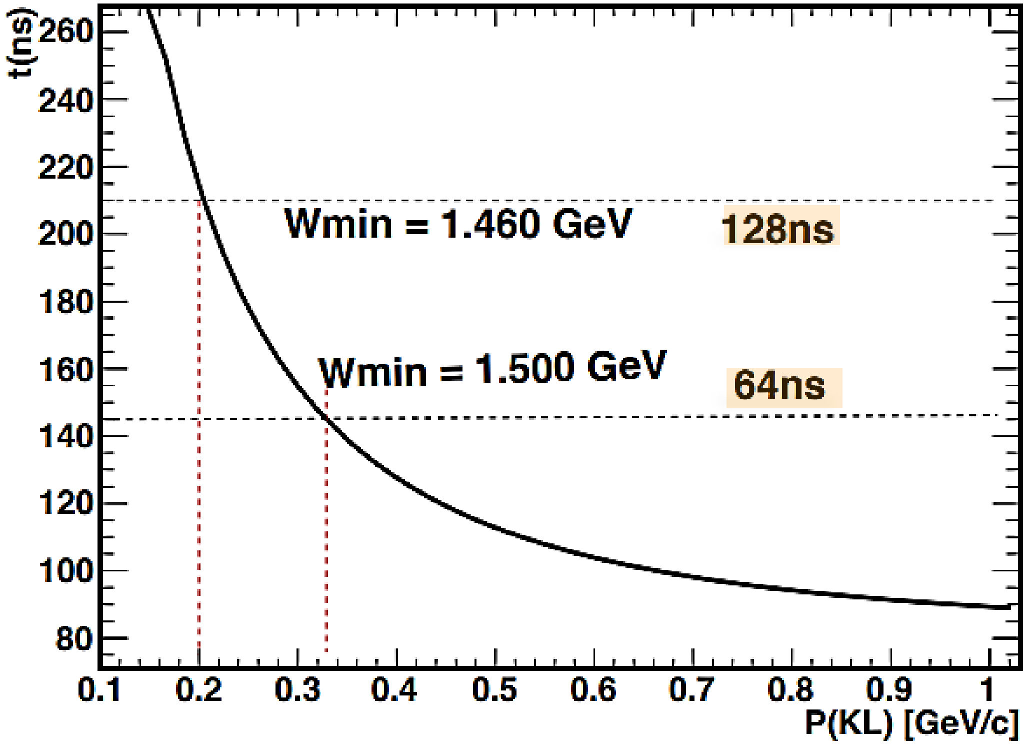
■ @ 0.434 GeV/c C.J.S. Damerell et al, Nucl Phys B **94**, 374 (1975)

● @ 0.470 GeV/c R.G. Glasser et al., Phys. Rev. D **15**, 1200 (1977)

- Expectation is 137,000 Θ^+ events

Electron Beam Parameters

- E_e = 12 GeV   I = 5 μA
- Bunch spacing 64 *vs* 128 ns



- 128 ns confirmed feasible

Narrow Resonances in PWA

R.A. Arndt, Y.I. Azimov, M.V. Polyakov, IIS, & R.L. Workman, Phys Rev. C **69**, 035208 (**2004**)

CI=150

- Because PWA (by construction) tends to *miss narrow* Res with Γ_R < **20** MeV
- We assume existence of Res & **refit** over whole DB

- Insertion of *narrow* Res in PWA for

  Elastic case: $e^{2i\delta} \Rightarrow e^{2i\delta}{}_R \, e^{2i\delta}{}_B$

  $$e^{2i\delta}{}_R = (M_R - W + i\,\Gamma_R/2) / (M_R - W - i\,\Gamma_R/2)$$

  Inelastic case: $\eta\, e^{2i\delta} \Rightarrow \langle a|S|a\rangle = r_a A(W)\, e^{2i\delta}{}_R + (1 - r_a)\, B(W)$

  $$r_a = BR(R \to a) \qquad |A(M_R)| = 1 \qquad \Sigma r_a = 1$$

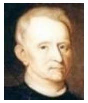
  $\eta \le 1 \Rightarrow \quad r_a |A(W)| + (1 - r_a) |B(W)| \le 1$

- Refitting
  - *Worse description*
    - $\Rightarrow$ Res with corresponding M_R & Γ_R is not supported
  - *Better description*
    - $\Rightarrow$ Res may exist
    - $\Rightarrow$ Effect can be due to various corrections (*eg*, *thresholds*)
    - $\Rightarrow$ Both possibilities can contribute

  Some additional checks are necessary
- True Res should provide effect only in particular PW
- While Non-Res source may show similar effects in various PWs

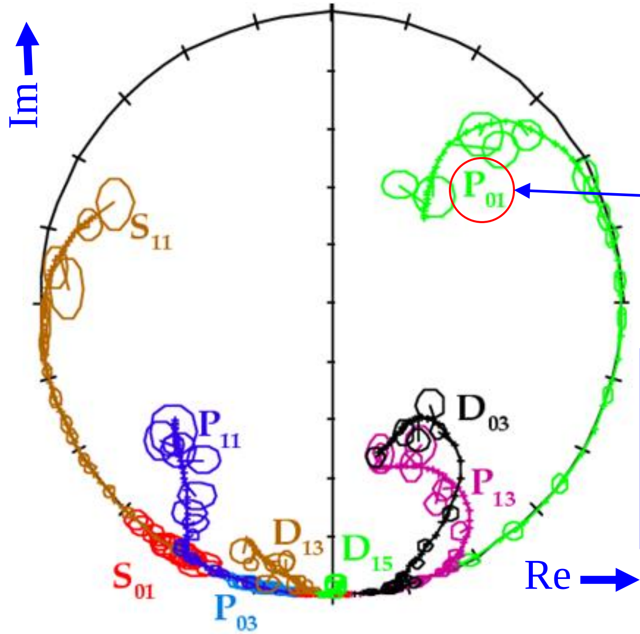
Standard KN PWA

J.S. Hyslop, R.A. Arndt, L.D. Roper, & R.L. Workman, Phys Rev D **46**, 961 (1992)



CI=163

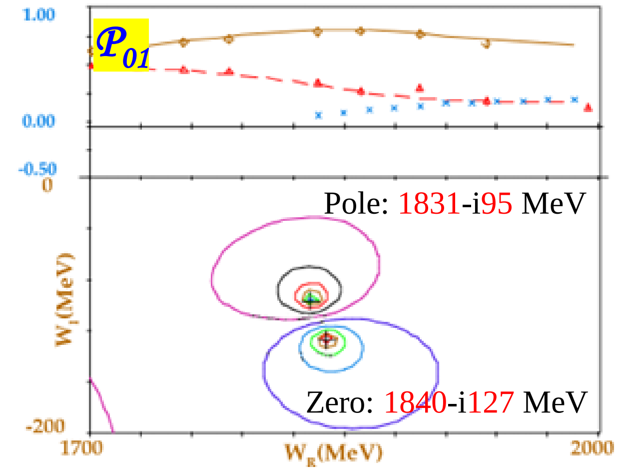
T = 0 [20] 1100 MeV

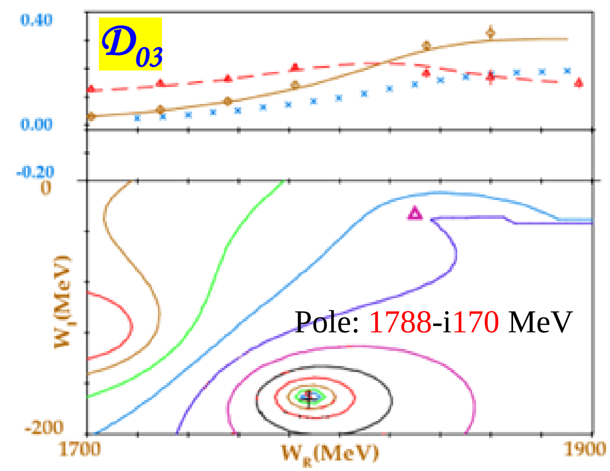


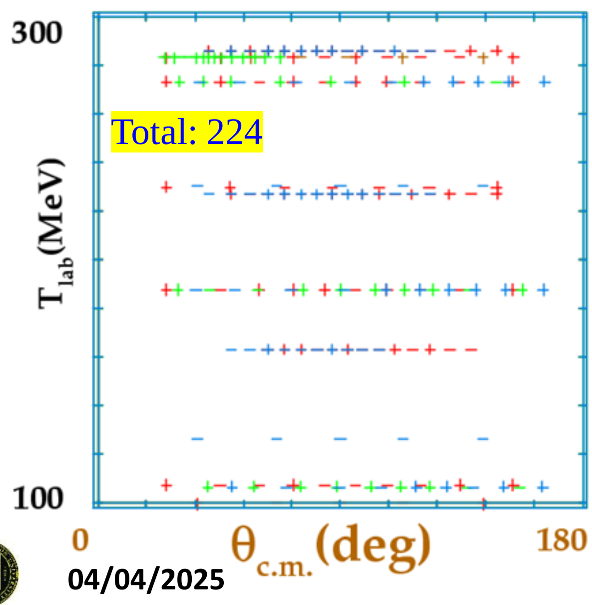
- Pole Positions:

I	Ampl	ReW (MeV)	-ImW (MeV)
0	P_{01}	1831	95
	D_{03}	1788	170
1	P_{13}	1811	118
	D_{15}	2074	253

- All Res in *standard* PWA are too *heavier* & too *broader* than Θ^+.







$K^+n \rightarrow K^+n$ – 98
$K^+n \rightarrow K^0p$ – 6
$K^+d \rightarrow K^0pp$ – 77
$K^+d \rightarrow K^+np$ – 43

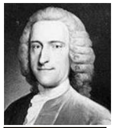
Modified KN PWA for Θ(1540)
R.A. Arndt, IIS, & R.L. Workman, Phys Rev C **68**, 042201(R) (2003)

PWA for Baryons

- Originally PWA arose as technology to determine amplitude of reaction via fitting scattering data.

  ⇒ That is *non-trivial mathematical problem* – looking for solution of ill-posed problem following to Hadamard & Tikhonov.
  [number of equations less than number of unknown quantities]

  ⇒ There are two main technologies to look for solution:
  (i) *least-squares minimization* of functions which are linear in unknown parameters, χ^2 &
  (ii) *likelihood measures goodness* of fit of statistical model.
  [*Minimizing* χ^2 is equivalent to *maximizing* (log) likelihood just case not small statistics]



Roger Cotes

Sir Ronald Aylmer Fisher

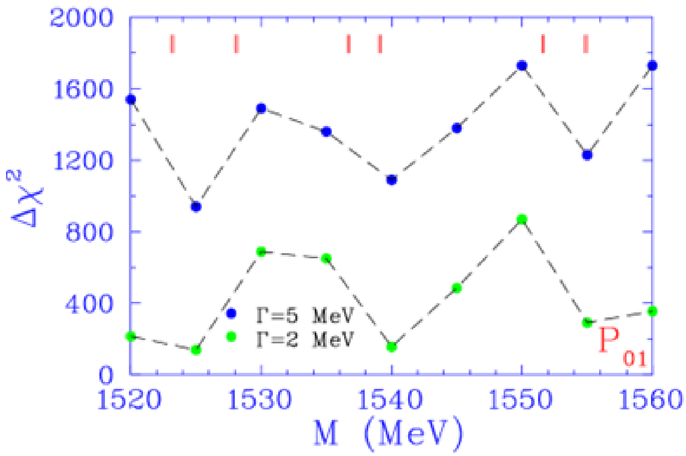
  ⇒ Model *independent* treatment or data *driven* treatment.

- Resonances appeared as by-product
  [bound states objects with definite quantum numbers, mass, lifetime, & so on].

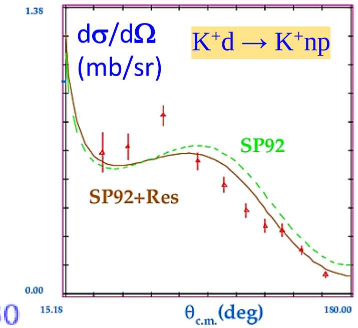
- Standard PWA
  ⇒ Reveals only wide Resonances, but not too wide (Γ_R < 500 MeV) & possessing not too small BR (BR > 4%).
  ⇒ Tends (by construction) to miss narrow Resonances with Γ_R < 20 MeV.

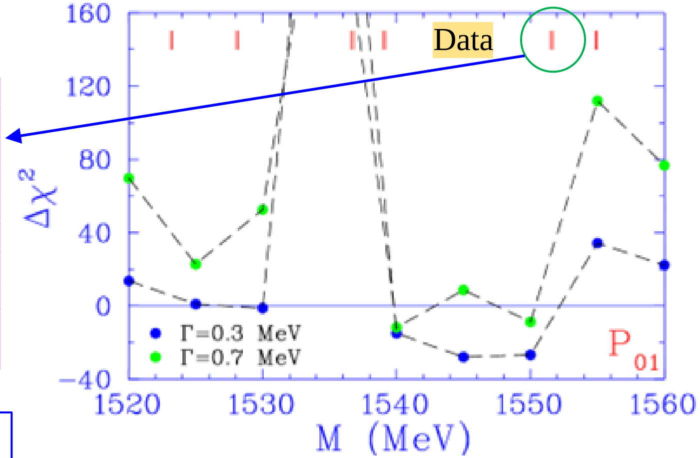
$\Delta\chi^2$ *due to Insertion of Res into Different Waves*

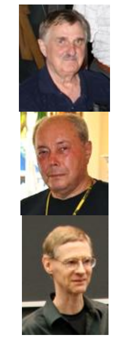
R.A. Arndt, IIS, & R.L. Workman, Phys Rev C **68**, 042201(R) (**2003**)



P_{01} ($J^P = ½^+$)

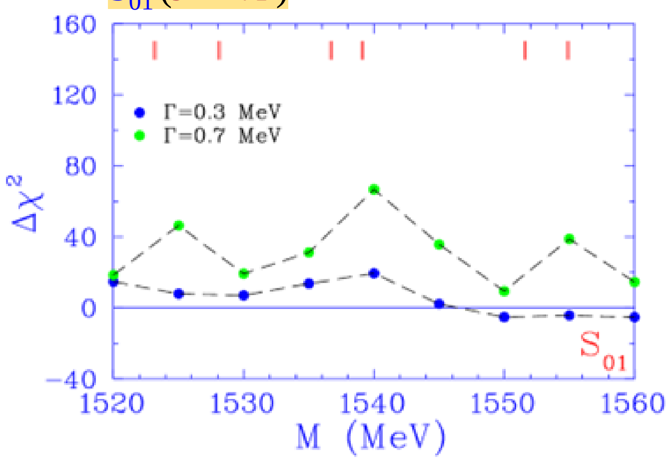




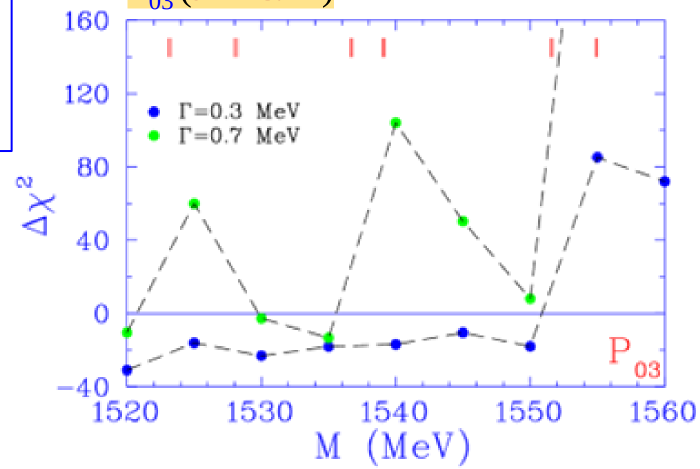


- Res contributes
  $\sim \Gamma_{el} / (M_R - W)$
  @ $|M_R - W| >> \Gamma_R$
- For
  M_R ~ 1545 MeV
  Γ_R < 0.5 MeV

S_{01} ($J^P = ½^-$)



P_{03} ($J^P = 3/2^+$)

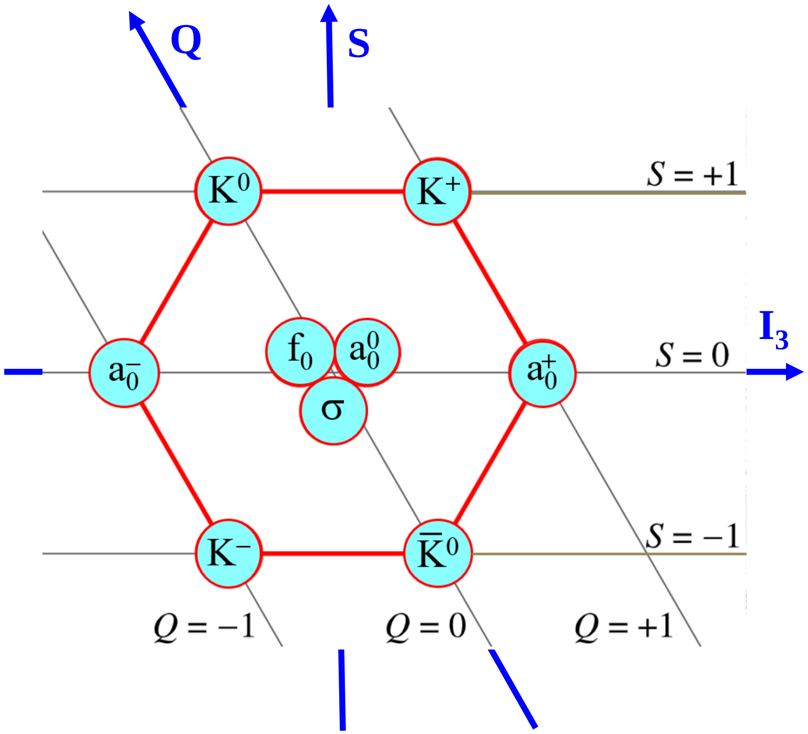


For I = 0:

- Only one partial wave (P_{01}) admits effect near 1545 MeV: resonance, **Γ** < **0.5** MeV
- Other partial waves (S_{01} & P_{03}) may have the effect only by accompanied by other corrections

Scalar Meson Nonet

SU(3): $J^{PC} = 0^{++}$ *Nonet*



- ***Four*** states called *κ(700).*
- PDG: *still need further confirmation*.
- allows determination of all *four* states.

$$M = a_0 + a_1 Y + a_2 \left[I(I+1) - \frac{1}{4} Y^2 \right]$$

I *– isospin,* ***Y*** *– strangeness* (*hypercharge*), $\boldsymbol{a_i}$ *– free prmts.*

- This phenomenological formula works with accuracy of 5%.

- Mixing be able to shift some masses for *Gell-Mann-Okubo mass* formula.


ARCTIC OCEAN
ARCTIC OCEAN
Greenland Sea
GREENLAND
CANADA
NORTH AMERICA
UNITED STATES
PACIFIC OCEAN
MEXICO
ATLANTIC OCEAN
RUSSIA
ASIA
KAZAKHSTAN
CHINA
IRAN
INDIA
PACIFIC OCEAN
AFRICA
BRAZIL
SOUTH AMERICA
PACIFIC OCEAN
ATLANTIC OCEAN
INDIAN OCEAN
AUSTRALIA
142 experimentalists &
43 theorists
from 74 labs
across 18 countries
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