K-Long Experiment at Jefferson Lab

Igor Strakovsky

伊戈爾·斯特拉科夫斯基

The George Washington University

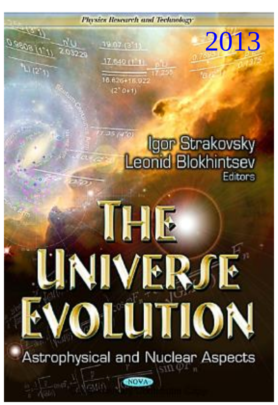
- KLF at Jefferson Lab.
- KLF experiment.
- Aims of KLF project.
- Impact to study Early Universe.
- Hyperon spectroscopy.
- Strange Meson spectroscopy.
- Were we are going
- Summary.

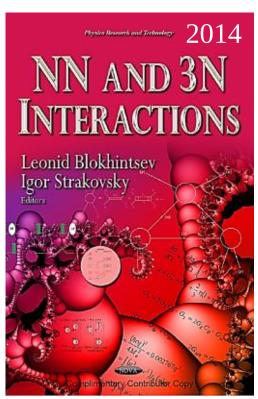
Supported by DE–SC0016583

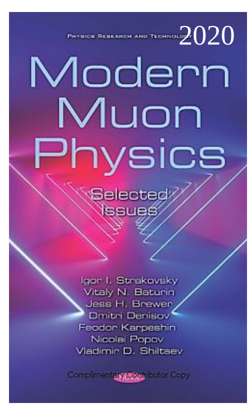
Dr. *Igor Strakovsky* is an experimentalist in fundamental nuclear and particle physics. He received a doctoral degree from the Petersburg Nuclear Physics Institute (PNPI) in 1984 and worked as a research scientist at PNPI before joining the Physics Department at Virginia Tech in 1992 and then the Physics Department at The George Washington University in 1997. He has been a full research professor there since 2009. Since 2022, he is an Honorary Research Fellow of the School of Physics and Astronomy of Glasgow University, UK.

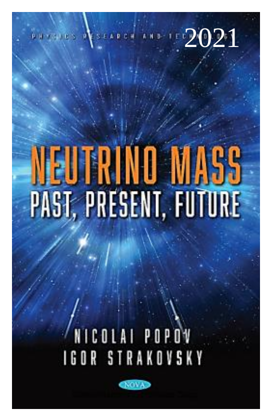
At Virginia Tech, *Igor Strakovsky* was joining the PWA SAID group under the Dick Arndt's leadership. Then he was and is a visiting researcher at TRIUMF, Canada; MAX-lab, Sweden; Juelich FZ and Mainz U., Germany; BNL and JLab, USA. His research is hadronic and electromagnetic physics and nuclear structure. Now his main experimental focus is on Jefferson Lab, in particular, the KLF project where he is a co-spokesperson. KLF has a link to understand the formation of our world in several microseconds after the Big Bang.

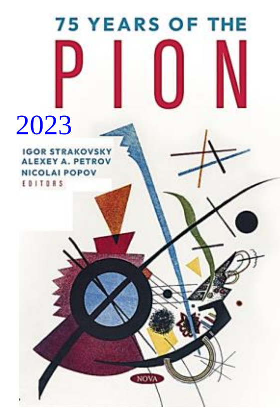
Igor Strakovsky is author of well over **350** published papers in peer-review journals with over **17,000** citations and an h-index of **50**. He authored books, ``*Modern Muon Physics: Selected Issues*'' and ``*Neutrino Mass: Past, Present, and Future*'' and he is a Regional *Award Winner* and one of the **15** national Finalists for The 2008 Inspire Integrity Awards of the National Society of Collegiate Scholars' (NSCS) Inspire Integrity Awards, USA. *Particle Data Group* acknowledges our GWU SAID group activity as the PWA source to go to.







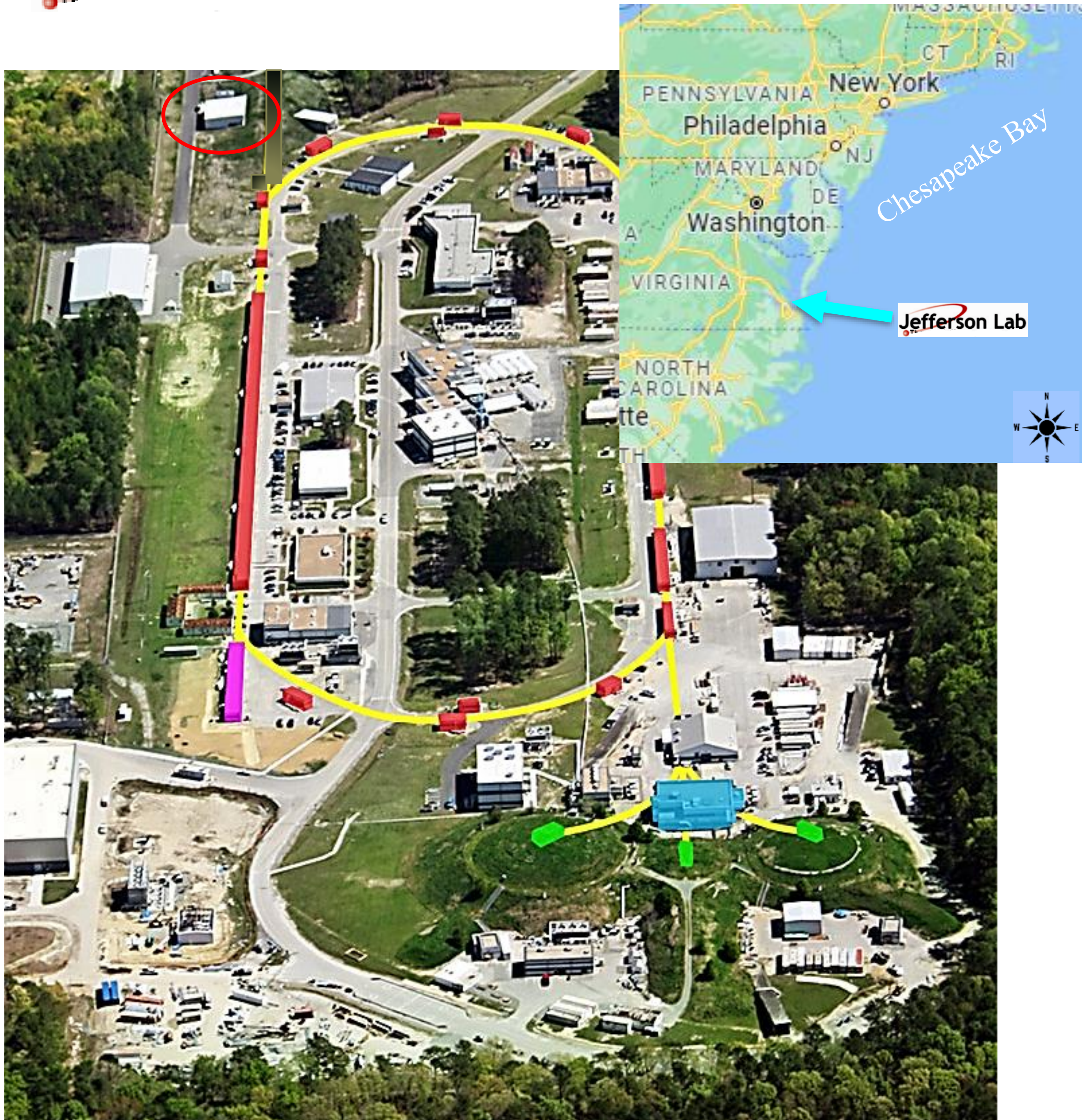




nova science publishers

KLF at Jefferson Laboratory

Jefferson Lab *Continuous Electron Beam Accelerator Facility* *in 2023*



1995 — 2012…

Energy 0.4 — 6.0 GeV

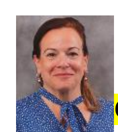
- 200 μA, *Polarization* 85%
- Simultaneous delivery 3 Halls – A, B, C

- 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 — …..

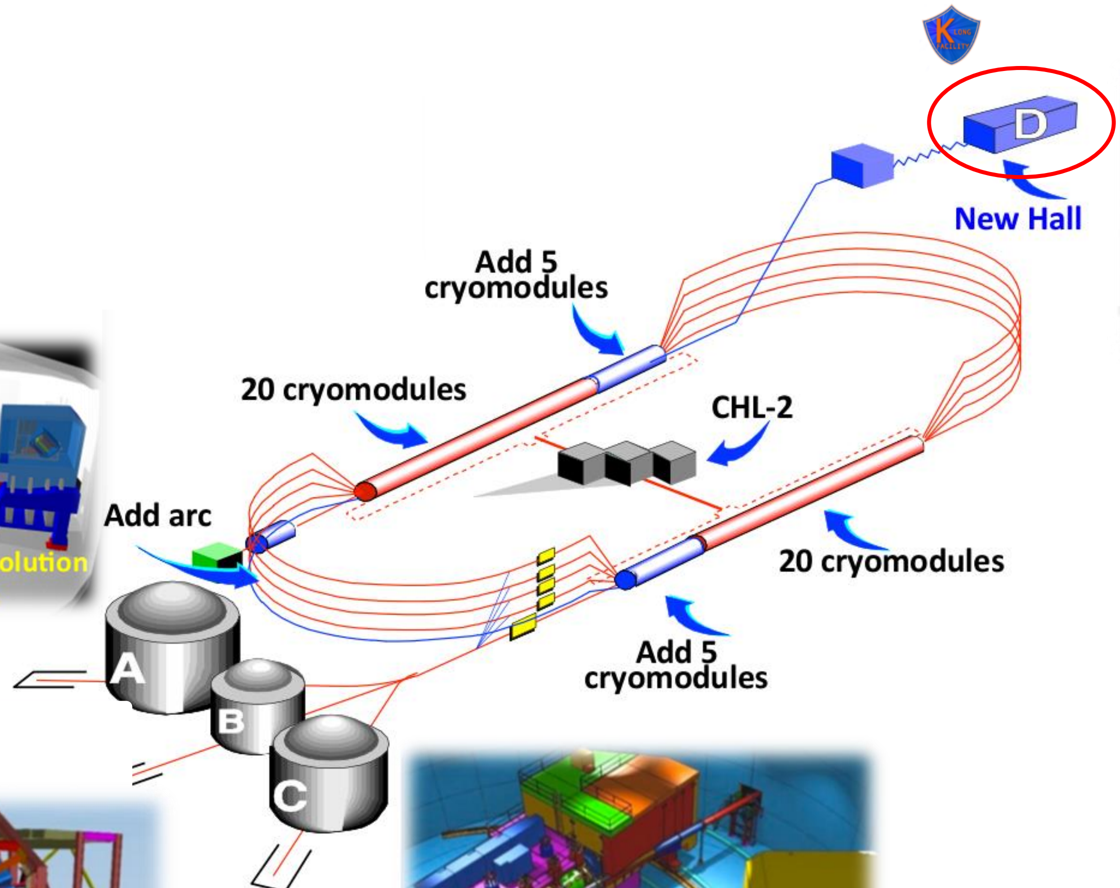
Energy 0.4 — 12.0 GeV

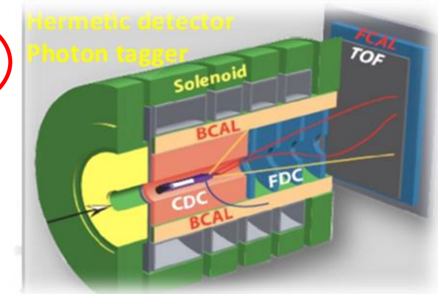
- 150 μA, *Polarization* 85%
- Simultaneous delivery 4 Halls
- FY18: First try simultaneous delivery to **4** Halls — A, B, C, D

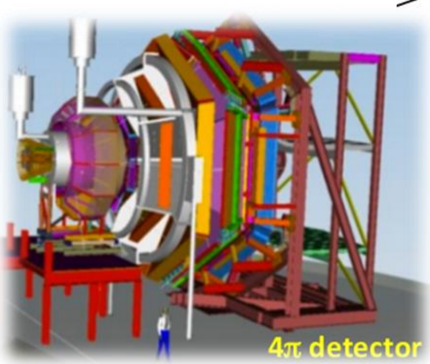


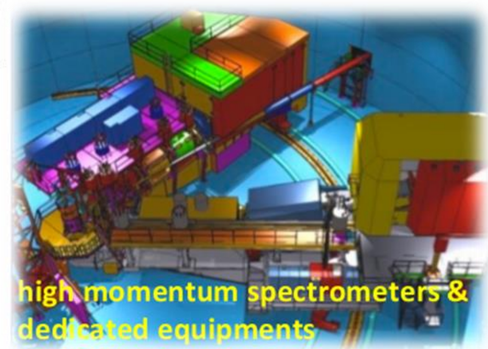
Courtesy of Thia Keppel, **2017**

Jefferson Lab: *What Are We After?*









Beam Power: ***1MW***
Beam Current: ***90 μA***
Max Pass energy: ***2.2 GeV***
Max Enery Hall A-C: ***10.9 GeV***
- ***Max Energy Hall D:*** ***12 GeV***

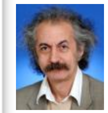
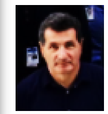
Courtesy of Thia Keppel, 2017

E12-19-001

Strange Hadron Spectroscopy with Secondary K_L Beam in Hall D

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



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Extensive Theoretical Support

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

Jefferson Lab *PAC48 Report*

PAC48 REPORT

Jefferson Lab

48th PROGRAM ADVISORY COMMITTEE (PAC 48)

August 10-14, 2020

September 25, 2020

U.S. DEPARTMENT OF ENERGY

JSA

Prepared for the U.S. Department of Energy under Contract DE-AC05-06OR23177

Recommendations

PAC 48 SUMMARY OF RECOMMENDATIONS

Number	Contact Person	Title	Hall	Days Req'd	Days Awarded	Scientific Rating	PAC Decision	Topic
C12-18-005	M. Boer	Timelike Compton Scattering Off Transversely Polarized Proton	C	50			C2	4
C12-19-001	M. Amarian	Strange Hadron Spectroscopy with Secondary KL Beam in Hall D	D	200	200	A-	Approved	1

C12-19-001

Scientific Rating: A-

Recommendation: Approved

Title: Strange Hadron Spectroscopy with Secondary KL Beam in Hall D

Spokespersons: M. Amaryan (contact), M. Bashkanov, S. Dobbs, J. Ritman, J. Stevens, I. Strakovsky

Motivation: The spectroscopy of strange baryons and mesons, including their fundamental strong interactions, are the focus of this proposal. New and unique data can be obtained with an intense K_L beam aimed at a hydrogen/deuterium target, using the GlueX apparatus to detect final state particles.

Measurement and Feasibility: The proponents have answered all questions outlined in the PAC47 report. Substantial progress has been made on the issues of simulations: details on backgrounds and background reactions have been demonstrated, a demonstration of partial wave analysis for hyperon production was given. The proponents have demonstrated the measuring technique of missing mass reconstruction, allowing them to extend the measuring range both regarding small, four-momentum transfers and isospin decomposition. No show stoppers have been pointed out by the TAC.

Issues: The PAC strongly recommends that the collaboration intensify their cooperation on two issues. (1) Coordinated leadership must be established together with the host laboratory to address the various technical issues connected with the R&D efforts and construction of the K_L beam. (2) Continuous cooperation with JPAC and associated members is recommended for the development of tools to master the challenges connected with the clean extraction of $K\pi$ scattering, the identification of the exchange processes at small momentum transfers, and the amplitude analysis for Δ final states.

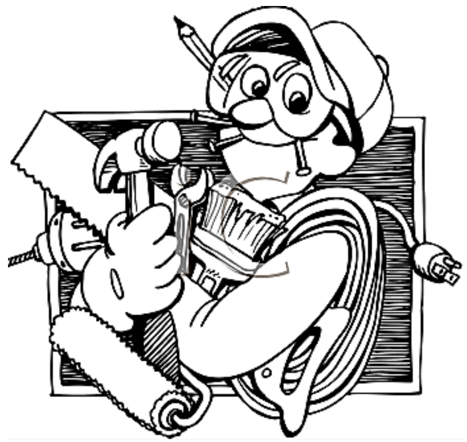
Summary: The future K_L facility will add a new physics reach to JLab, and the PAC is looking forward to see the idea being materialized, in conjunction with the plans for Hall D as spelled out in the 2019 White Paper. The collaboration should now devote all its energy to turn this challenging project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

E12-12-19-001

This Happens because of Strong Support & Dedicated Efforts of Collaboration

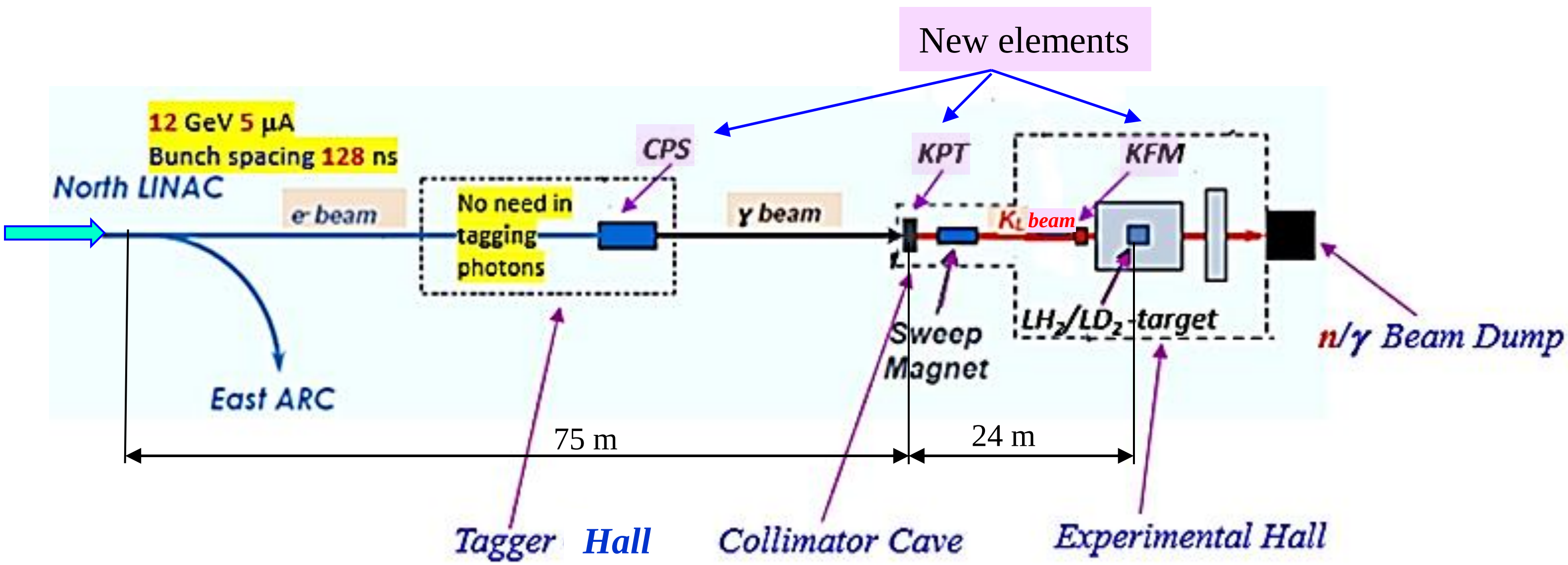
126 experimentalists &
42 theorists
from **74** labs
across **20** countries
worldwide

KLF Experiment

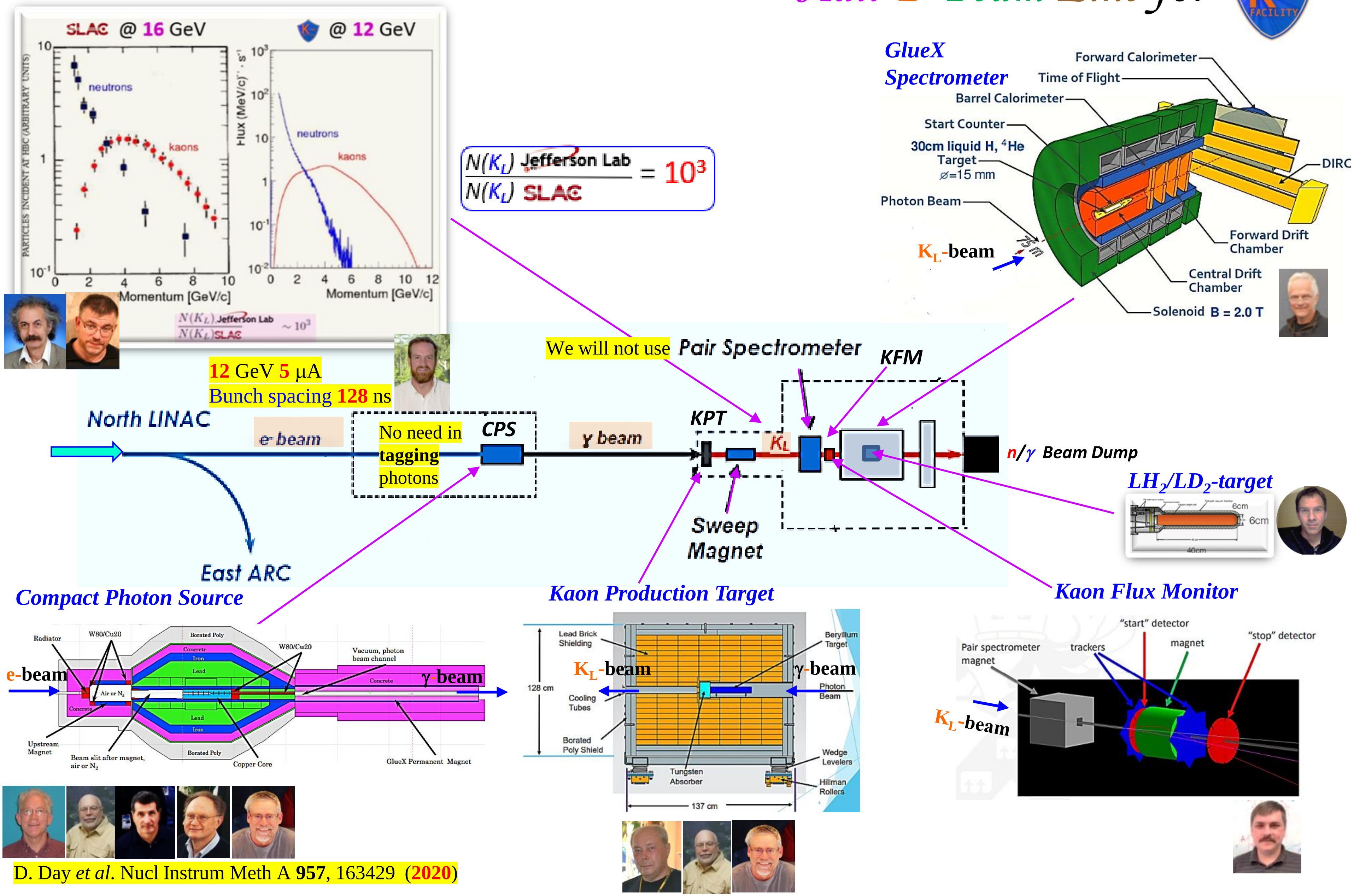


Hall D: Beam Line for K-long

- Electrons (**3.1 x 10^{13}** **e**/sec) are hitting Cu-radiator [10% X_0] @ *CPS* located in *Tagger Hall*.
- Photons (**4.7 x 10^{12}** **γ**/sec, E_γ > 1.5 GeV) are hitting Be-target located in *Collimator Cave*.
- Kaons (**1 x 10^4** K_L/sec) are hitting Cryo target within ***GlueX*** setting.
- Neutrons (**6.6 x 10^5** n/sec) are hitting Cryo target within ***GlueX*** setting.
- Photons (**6.5 x 10^5** **γ**/sec, E_γ > 100 MeV) are hitting Cryo target within ***GlueX*** setting.



Hall D Beam Line for



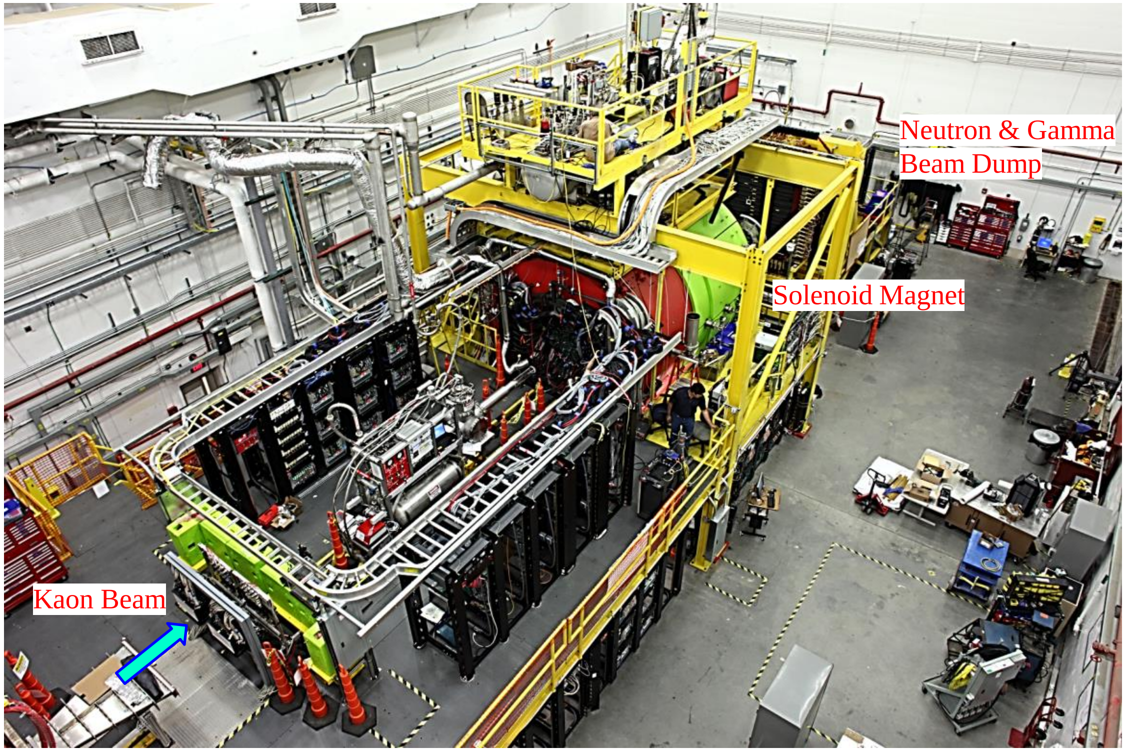
D. Day *et al.* Nucl Instrum Meth A **957**, 163429 (**2020**)

Hall D for KLF

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

- 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.

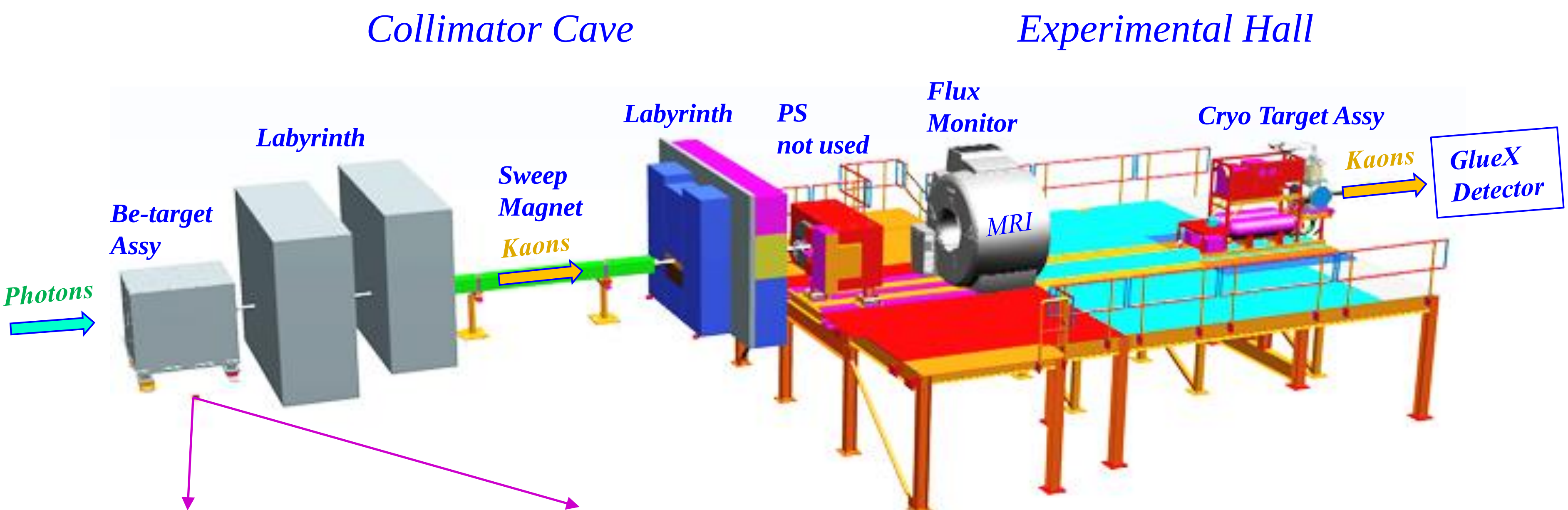
Experimental Hall

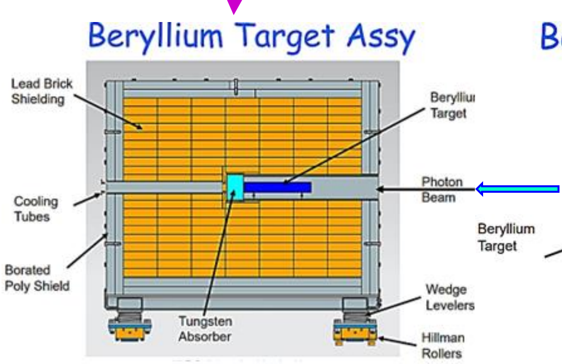


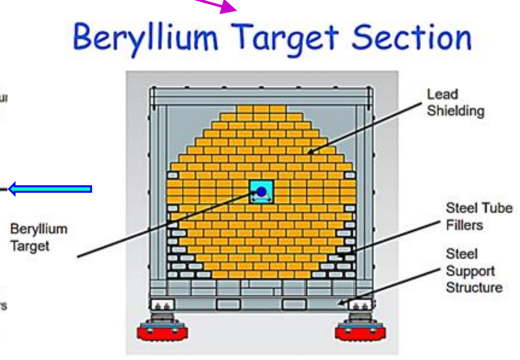
Tagger Hall

Collimator Cave

Hall D Setting [Engineering Design]



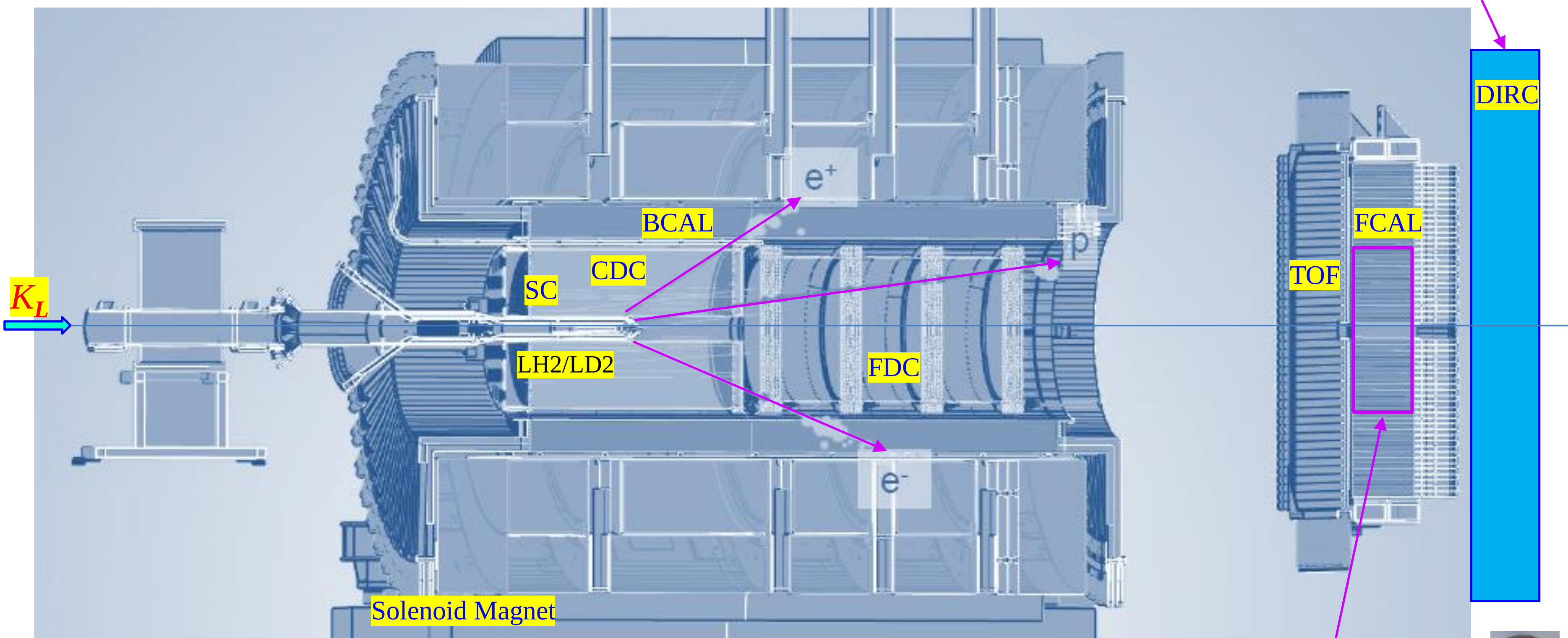




GlueX Spectrometer for KLF

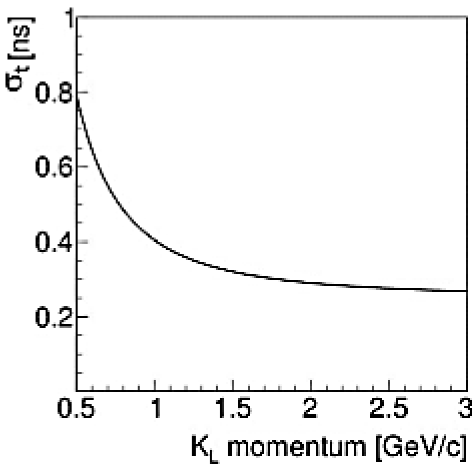
S. Adhikari *et al*, Nucl Inst Meth **987**, 164807 (**2021**)

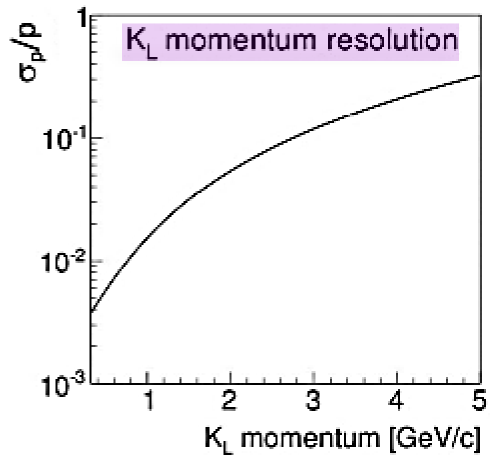
- **DIRC** is new . it came recently

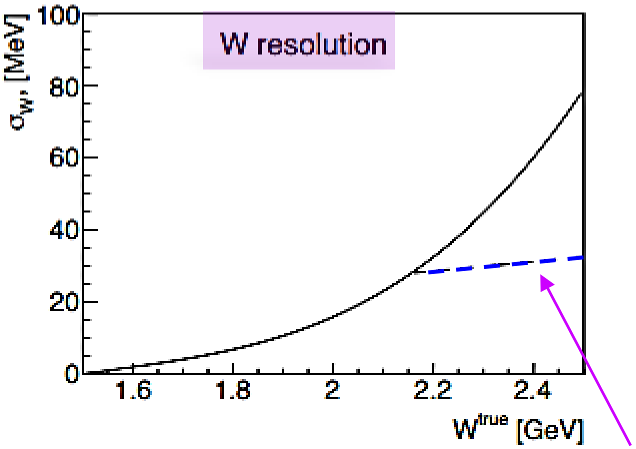


- **FCAL II** is coming with **1,600** $PbWO_4$ crystals using GW help.

KL Momentum Determination & Beam Resolution



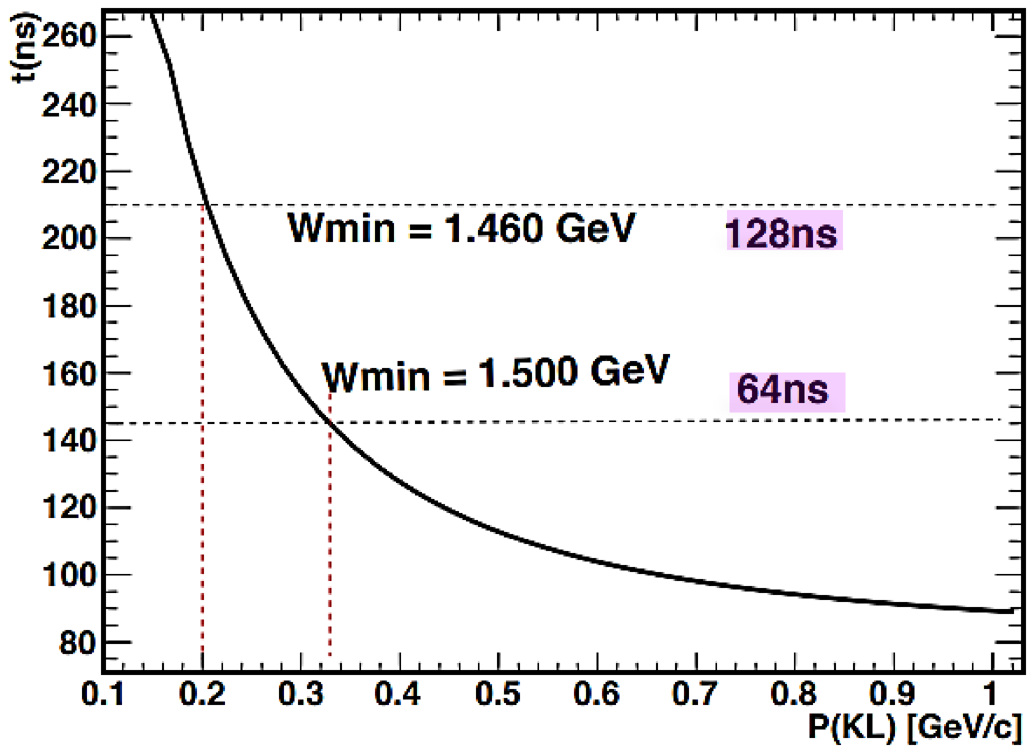




- Momentum measured with *TOF* between *SC* (surrounded LH_2/LD_2) & *RF* from *CEBAF*.
- ***Mean lifetime*** of **KL** is 51.16 nsec (**cτ** = 15.3 m) whereas the mean lifetime of **K⁻** is 12.38 nsec (**cτ** = 3.7 m).
- For this reason, it is much easier to perform measurements of KL-p scattering @ low beam energies compared with K-p scattering.

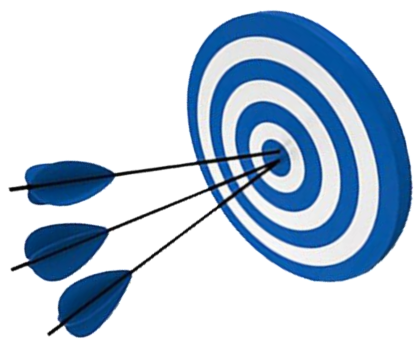
Electron Beam Parameters

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



- 128 ns confirmed feasible

Aims of KLF Project



We Can Do It, but Why?

- Why to use *kaon beam*? What is advantage compared to *electrons* or *photons* **?**
- What is so special about *K-long* compared to *charged kaon* beam **?** Complimentary to J-PARC.
- What is advantage of producing secondary kaon beam with *EM* probe, compared to *proton* beam **?**
- How much Jefferson Lab accelerator could make breakthrough compared to previous results @SLAC**?**
- Why to do this KLF experiment, what are we going to learn **?**
- How will it affect our knowledge on *Hyperon Spectroscopy* **?**
- What are we going to learn about strange *Meson Spectroscopy* **?**
- Is this KLF experiment about "*stamp collection*" or what **?**
- There are many more *questions* - some constructive & some less so
  - answers to which shaped approved KLF experiment.

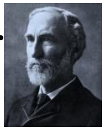
- project has firmly to setup secondary K_L beamline @ Jefferson Lab, with *flux* of *three order of magnitude higher* than SLAC had, for scattering experiments on both *proton* & *neutron* (*first* time !) targets.

- *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^* .

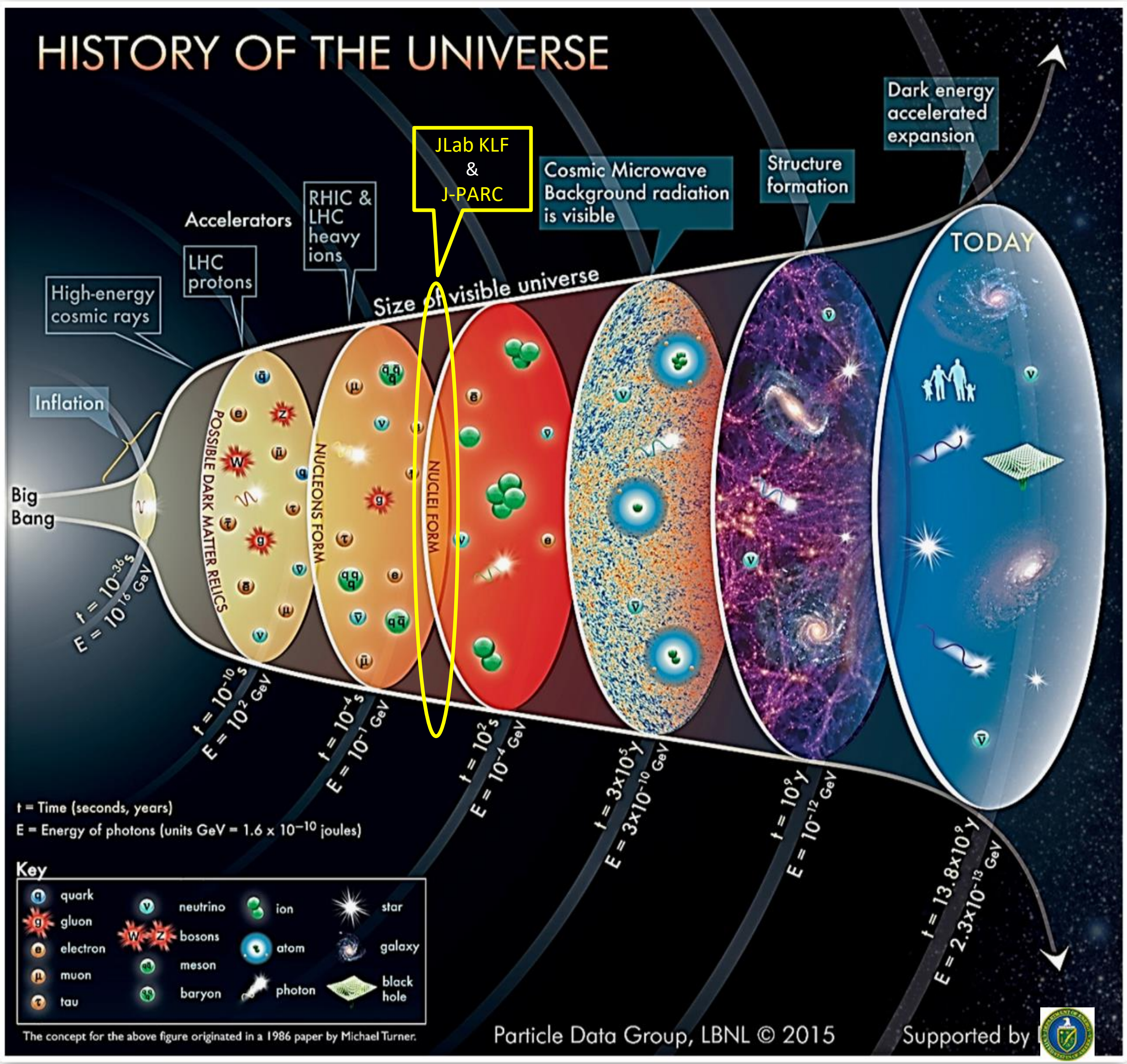
- We intend to do *strange meson spectroscopy* by studies of π-K interaction to locate *pole* positions in I = 1/2 & 3/2 channels.

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



Impact to Study 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*.

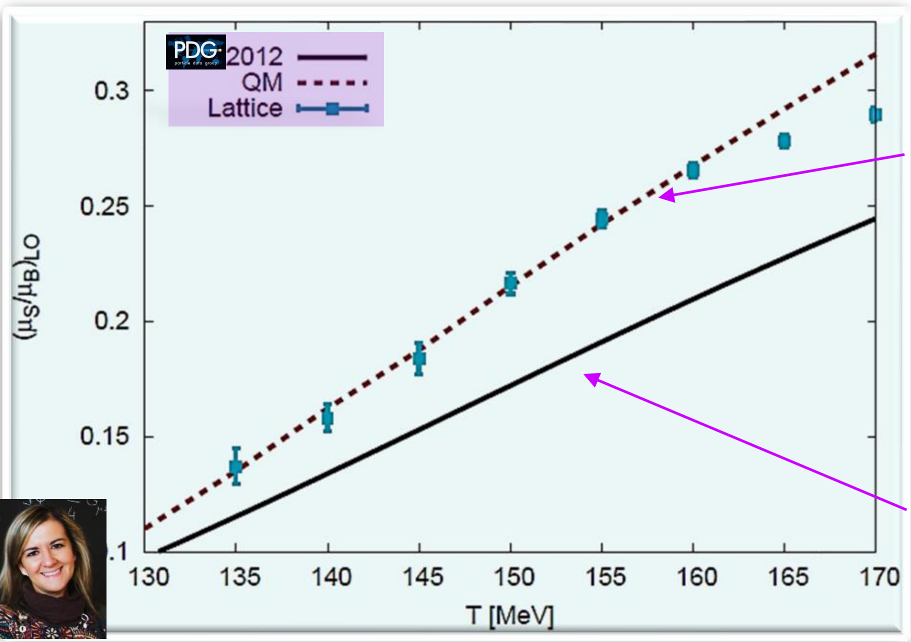
- For that reason, advancing our understanding of formation of *baryons* from ***quarks*** & ***gluons*** requires new experiments to search for any *missing hyperon* resonances.

- 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, YSTAR**2016**

Chemical Potential

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

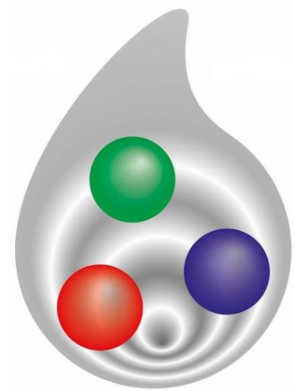
- \+ ``*Missing*" *Resonances* (*CQM*/*LQCD* calculations).

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

- Contribution from *observed Resonances*. PDG

- The *Early Universe* was *Strange*.

Hyperon Spectroscopy

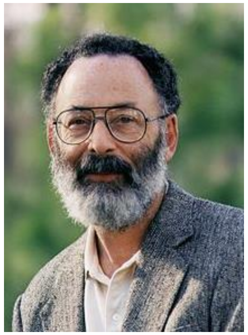


It is clear that we still need much more information about the existence and parameters of many baryon states, especially in the N=2 mass region, before this question of non-minimal SU(6) x O(3) super-multiplet can be settled.

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.

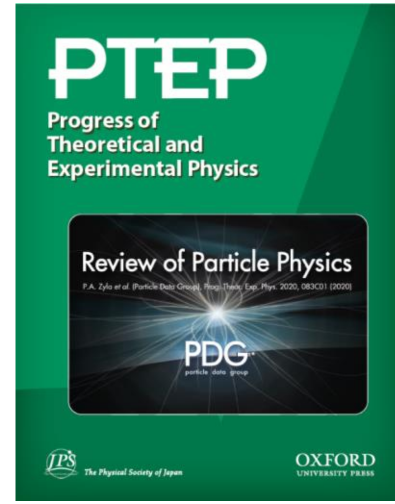
Gerhard Höhler, 1987



*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 @ PDG2022



GW Contribution

R.L. Workman *et al*, Prog Theor Exp Phys **2022**, 083C01 (**2022**)

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])	$3/2^-$	[illegible]
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)	$13/2^+$	**

Δ(1232)	$3/2^+$	****
Δ(1600)	$3/2^+$	***
Δ(1620)	$1/2^-$	****
Δ(1700)	$3/2^-$	****
Δ(1750)	$1/2^+$	*
Δ(1900)	$1/2^-$	**
Δ(1905)	$5/2^+$	****
Δ(1910)	$1/2^+$	[illegible]
Δ(1920)	3/[illegible]	[illegible]
Δ(1930)	[illegible]$/2^-$	[illegible]
Δ(1940)	$3/2^-$	[illegible]
Δ(1950)	$7/2^+$	[illegible]
Δ(20[illegible]0)	$5/2^+$	[illegible]
Δ([illegible])	[illegible]	[illegible]
Δ(2200)	$7/2^-$	*
Δ(2300)	$9/2^+$	**
Δ(2350)	$5/2^-$	*
Δ(2390)	$7/2^+$	*
Δ(2400)	$9/2^-$	**
Δ(2420)	$11/2^+$	****
Δ(2750)	$13/2^-$	**
Δ(2950)	$15/2^+$	**

Λ	$1/2^+$	****
Λ(1405)	$1/2^-$	****
Λ(1520)	$3/2^-$	****
Λ(1600)	$1/2^+$	***
Λ(1670)	$1/2^-$	****
Λ(1690)	$3/2^-$	****
Λ(1800)	$1/2^-$	***
Λ(1810)	1/[illegible]	***
Λ(1820)	[illegible]$/2^+$	****
Λ(1830)	$5/2^-$	****
Λ(1890)	$3/2^+$	****
Λ(200[illegible])	[illegible]	[illegible]
Λ([illegible])	$7/2^+$	[illegible]
Λ(2100)	$7/2^-$	****
Λ(2110)	$5/2^+$	***
Λ(2325)	$3/2^-$	*
Λ(2350)	$9/2^+$	***
Λ(2585)		**

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

Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
Ξ(153[illegible])	[illegible]	[illegible]
Ξ(162[illegible])		*
Ξ(1690)		***
Ξ(182[illegible])	[illegible]	***
Ξ(19[illegible])		***
Ξ(2030)	[illegible]	***
[illegible]		*
Ξ(2250)		**
Ξ(2370)		**
Ξ(2500)		*
Ω^-	$3/2^+$	[illegible]
Ω(2[illegible])⁻		[illegible]
Ω([illegible]0)⁻		[illegible]
Ω([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 been made *only* in **2010**.

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

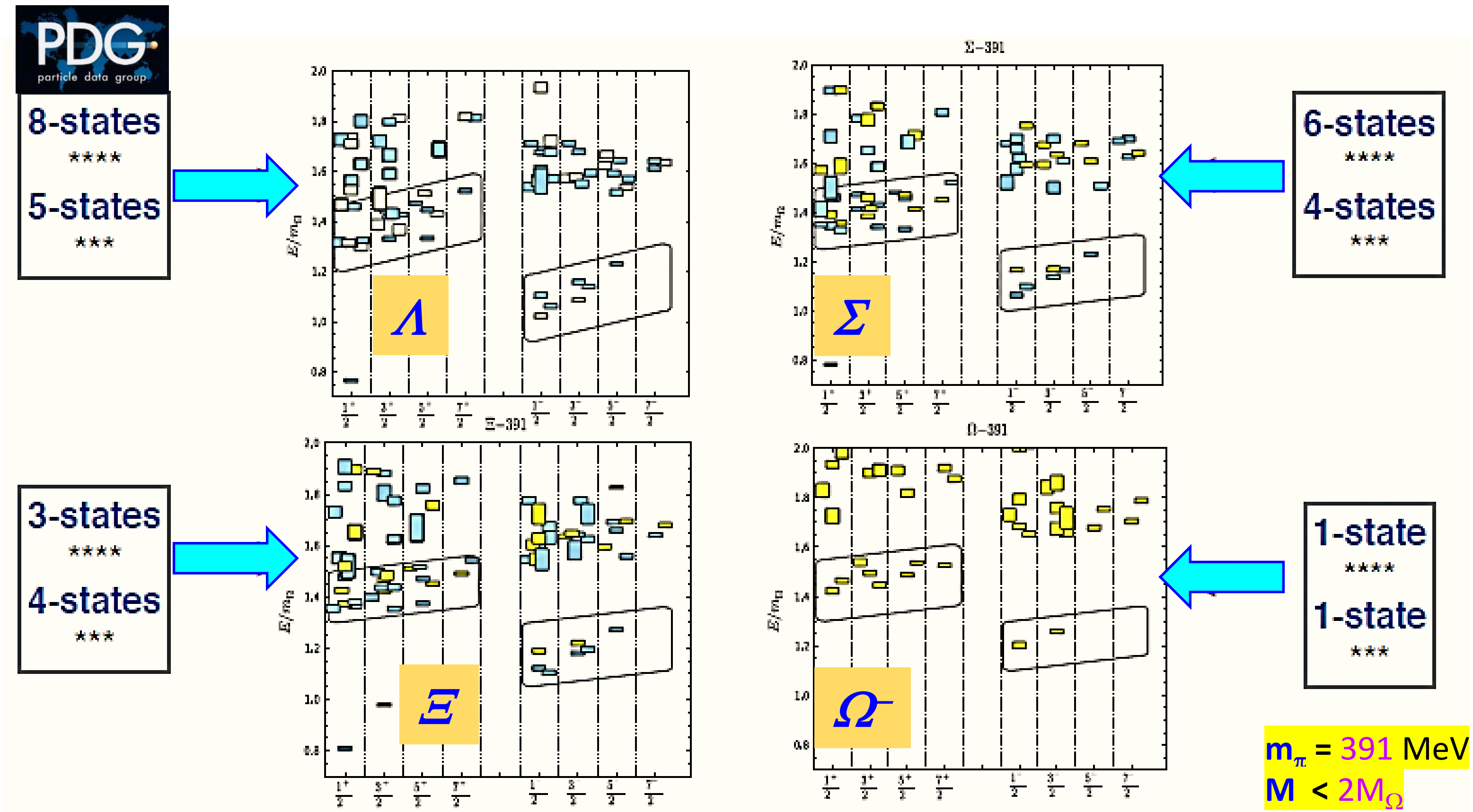
Jefferson Lab

- PDG2022 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**)

LQCD for Hyperon Spectroscopy

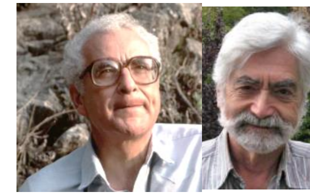


m_π = 391 MeV
$M < 2M_\Omega$

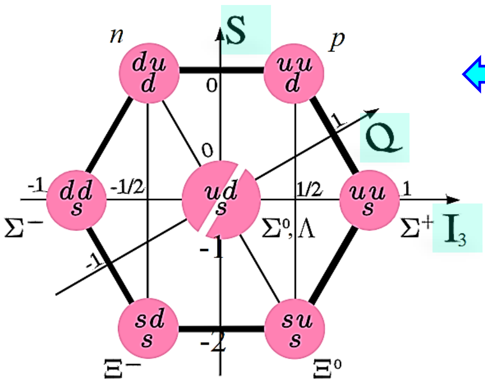
- According to *LQCD*, there are should be more than 400 states including *hybrids* (thick bordered).

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

Baryon Multiplets of Eight-fold Way

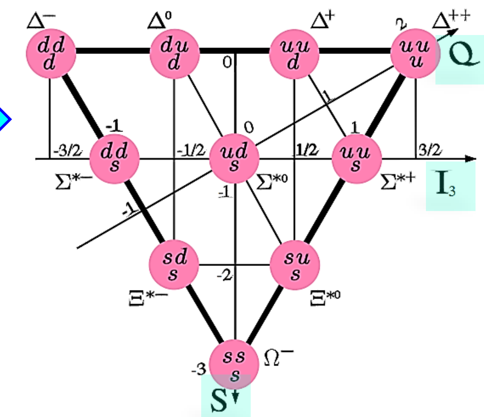


- **Three light quarks** can be arranged in 6 baryonic families, N*, Δ*, Λ*, Σ*, Ξ*, & Ω*.
- Number of members in family that can exist is not arbitrary.
- If $SU(3)_F$ symmetry of *QCD* is controlling, then:



Spin 1/2 baryon octet: N^*, Λ^*, Σ^*, Ξ^*

Spin 3/2 baryon decuplet: Δ^*, Σ^*, Ξ^*, Ω^*



had/spec PDG

Resonance	LQCD	Observed
N*	62	36
Δ*	38	29
Λ*	71	23
Σ*	66	28
Ξ*	73	12
Ω*	36	5

R. G. Edwards *et al*, Phys Rev D **87**, 054506 (2013): $M < 2M_\Omega$

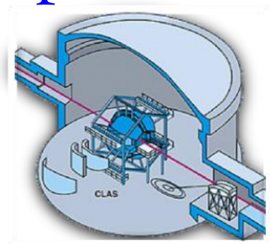
- Seriousness of "*missing-states*" problem is obvious from these numbers.
- One needs to *complete* $SU(3)_F$ multiplets.

B.M.K. Nefkens, πN Newsletter, **14**, 150 (1997)

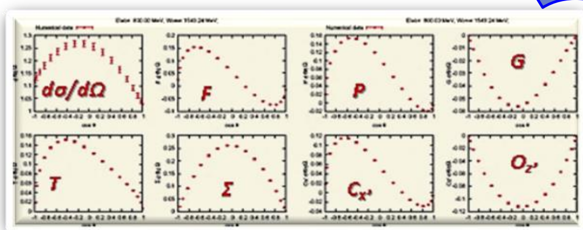
Road Map to Baryon Spectroscopy

Facility

Experiment

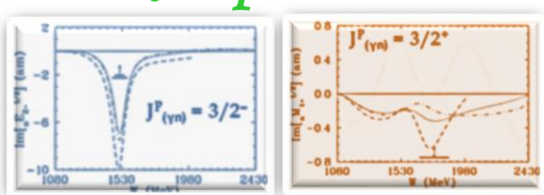


Data



PWA

Amplitudes

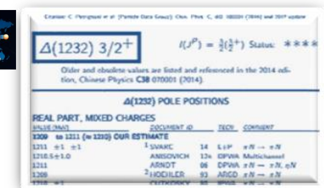


- *That is not hunting for bumps*

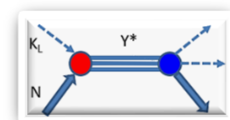
QCD

LQCD

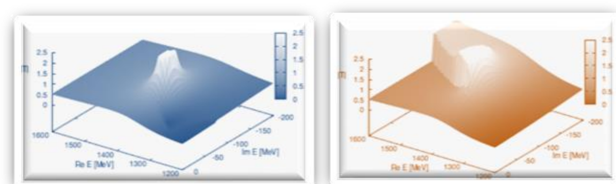
PDG particle data group



PWA



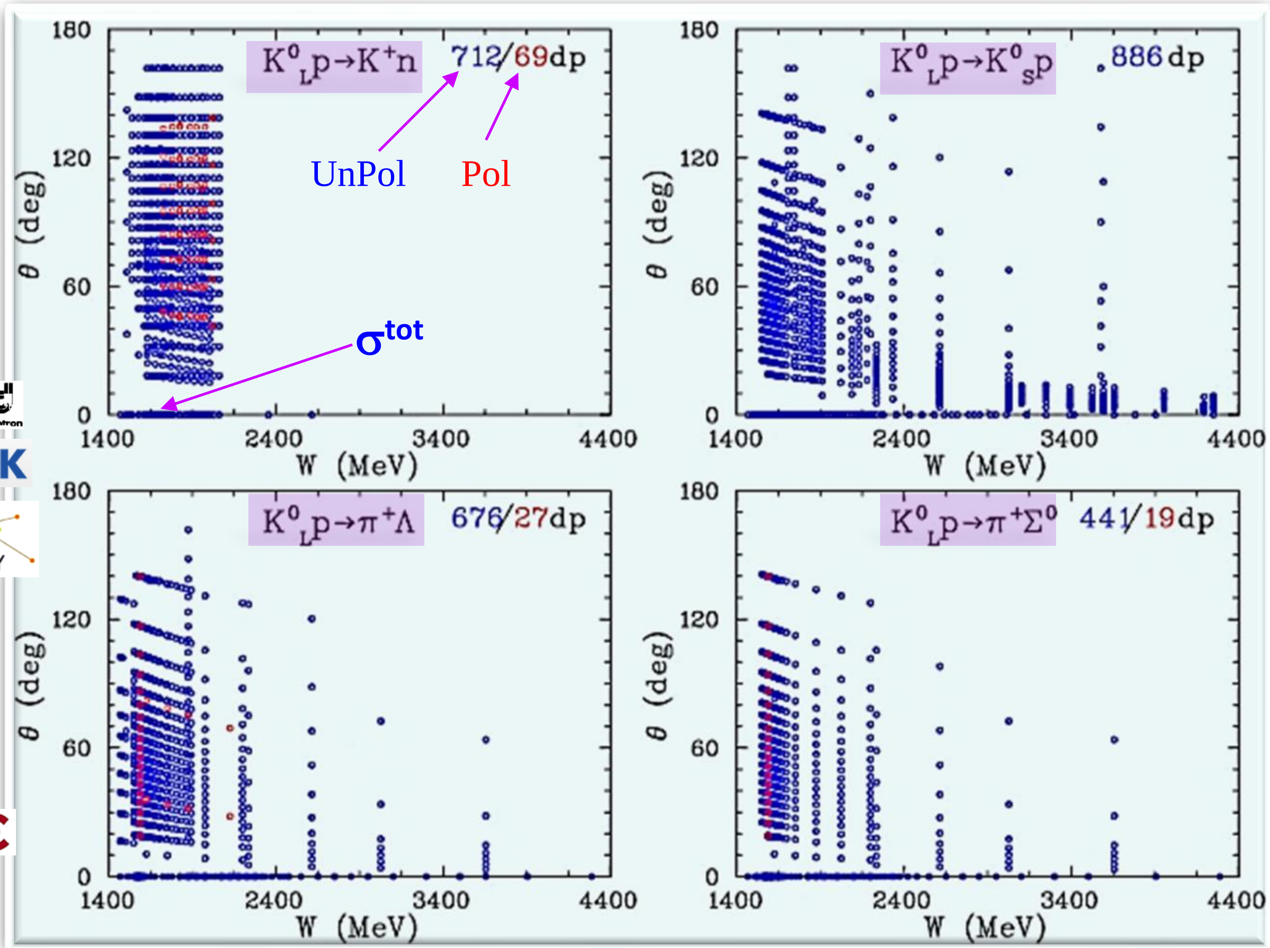
Resonances



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.

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

Roger Cotes

Sir Ronald Aylmer Fisher

- 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 < 500 MeV) & possessing not too small BR (BR > 4%).
  - ⇒ Tends (by construction) to miss narrow Resonances with Γ < 20 MeV.

PWA Formalism for πN Elastic Scattering

G. Höhler, *Pion-Nucleon Scattering*, Landoldt-Boernstein Vol. **I/9b2**, edited by H. Schopper (Springer, **1983**)

- Differential cross section & polarization for πp elastic scattering:

$$\frac{d\sigma}{d\Omega} = \lambda\!\!\!^{-2}(|f|^2 + |g|^2)$$

$$P\frac{d\sigma}{d\Omega} = 2\lambda\!\!\!^{-2}\,\mathrm{Im}(fg^*)$$

$\lambda\!\!\!^{-} = \hbar/k$ & k is momentum of incoming pion in CM.

$f(W,\theta)$ is non-spin-flip
$g(W,\theta)$ is spin-flip
amplitudes @ W & θ.

- In terms of partial waves, $f(W,\theta)$ & $g(W,\theta)$ can be expanded as

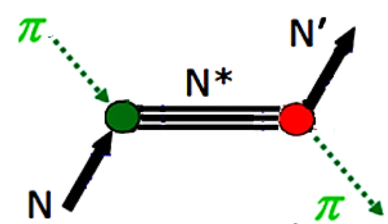
$$f(W,\theta) = \sum_{l=0}^{\infty}[(l+1)T_{l+} + lT_{l-}]P_l(\cos\theta)$$

$$g(W,\theta) = \sum_{l=1}^{\infty}[T_{l+} - T_{l-}]P_l^1(\cos\theta)$$

l is initial *orbital* angular momentum:
$P_l(\cos\theta)$ is Legendre polynomial.
$P_l'(\cos\theta)$ is associated Legendre function.

J is total *angular* momentum:
for T_{l+} is $J = l + 1/2$,
for T_{l-} is $J = l - 1/2$.

- **πN** elastic scattering data allowed establishment of **4**-star resonances ⇒

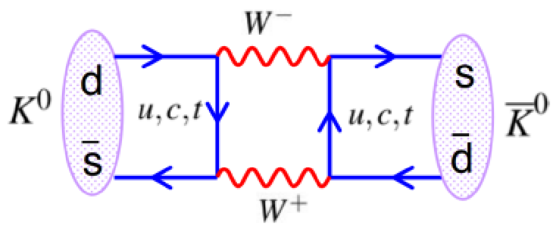


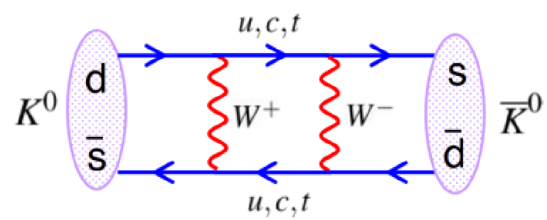
- K-Long is CP *eigenstate* & superposition of strong *eigenstates* according to

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

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

- *Weak* interaction allows for mixing of strong *eigenstates*:





- K-Long produces in general combinations of different *isospin* & *strangeness* channels, *e.g.*:

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

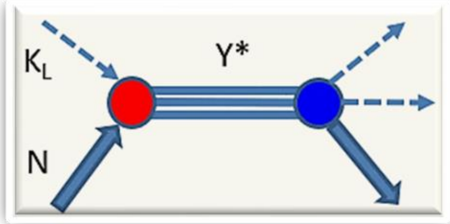
$$T(K_L^0 p \to \pi^+\Lambda) \;=\; -\frac{1}{\sqrt{2}}T^1(\overline{K}N \to \pi\Lambda)$$

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 $S = -2$	$K_L p \to K^+ \Sigma^0$ $K_L p \to K^+ \Sigma^{0*}$	$K_L n \to K^0 \Sigma^0$ $K_L n \to K^0 \Sigma^{0*}$
Three-body with $S = -2$	$K_L p \to \pi^+ K^+ \Sigma^-$ $K_L p \to \pi^+ K^+ \Sigma^{-*}$	$K_L n \to \pi^+ K^- \Sigma^0$ $K_L n \to \pi^+ K^- \Sigma^{0*}$
Three-body with $S = -3$	$K_L p \to K^+ K^+ \Omega^-$ $K_L p \to K^+ K^+ \Omega^{-*}$	$K_L n \to K^+ K^0 \Omega^-$ $K_L n \to K^+ K^0 \Omega^{-*}$

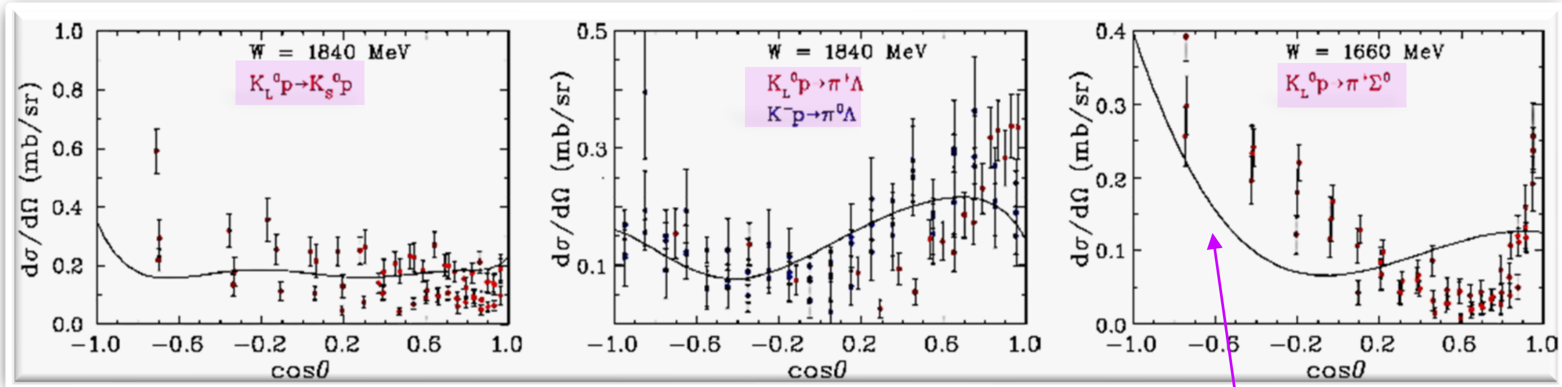
- To search for ``*missing*'' hyperons, we need measurements of production reactions:

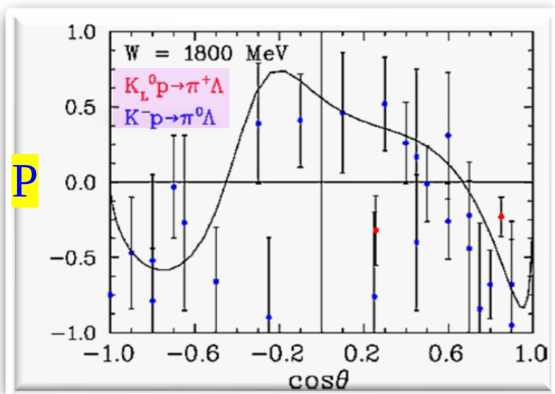
Σ^*:	$K_L^0 p \to \pi \Sigma^* \to \pi\pi\Lambda$
Λ^*:	$K_L^0 p \to \pi \Lambda^* \to \pi\pi\Sigma$
Ξ^*:	$K_L^0 p \to K \Xi^*,\ \pi K \Xi^*$
Ω^*:	$K_L^0 p \to K^+ K^+ \Omega^*$



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.

Expected Cross Sections vs Bubble Chamber Data

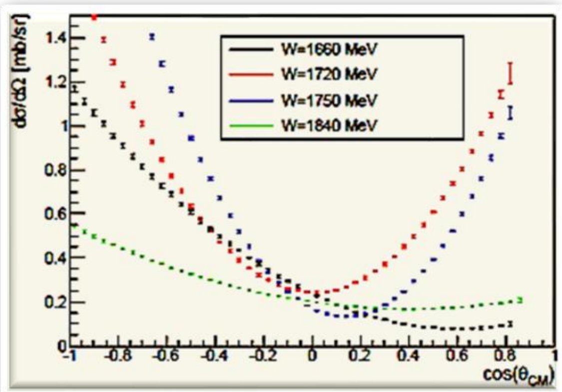
- measurements will span *cos θ* from *–0.95* to *0.85* in CM above W = *1490* MeV.

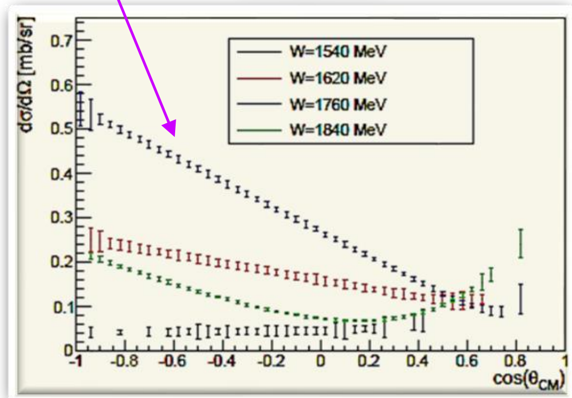
- Uncertainties (statistics only) correspond to *100* days of running time for:

$K_Lp \to K_Sp$

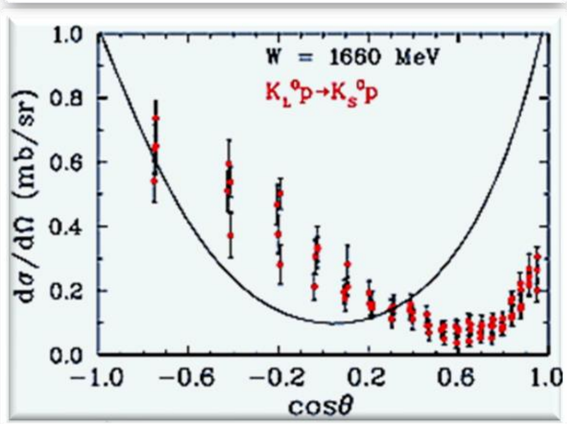
$K_Lp \to \pi^+\Lambda$

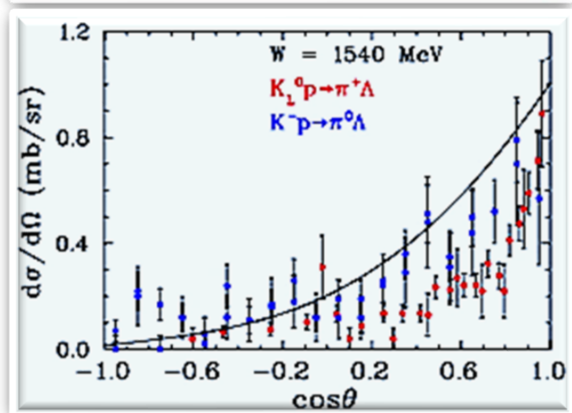
GEANT4



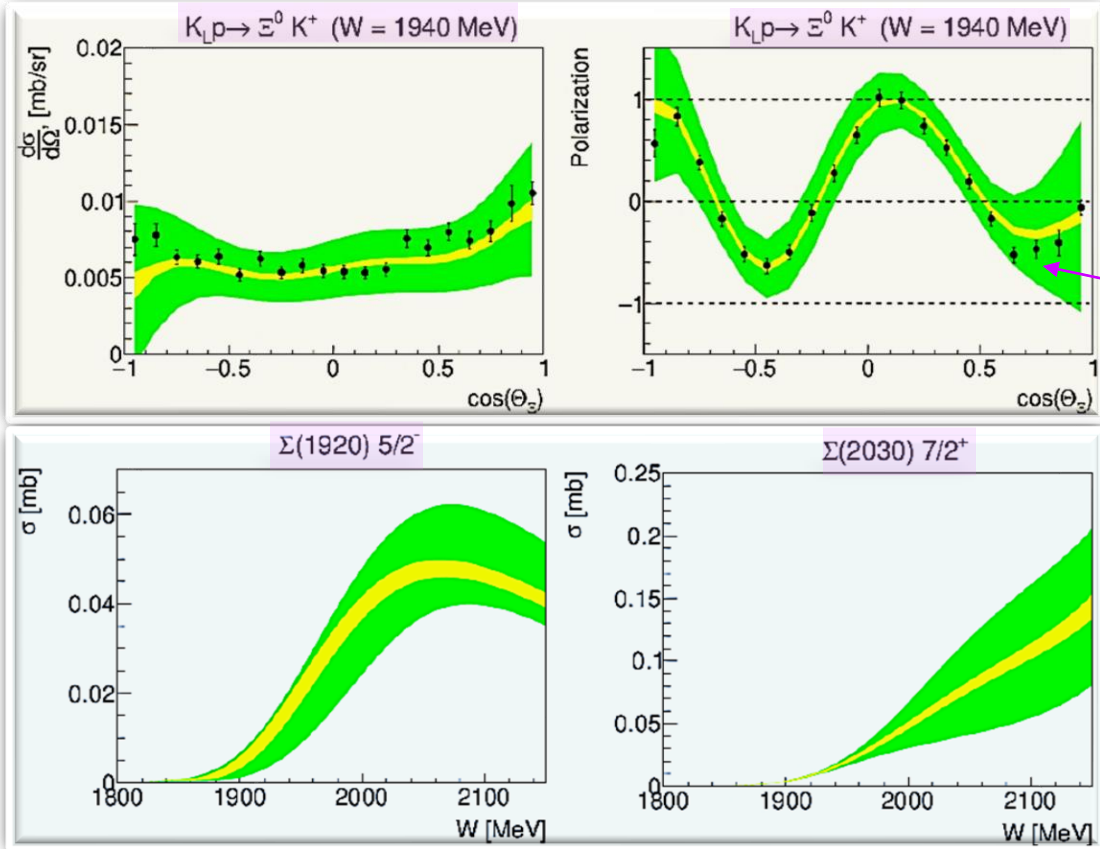


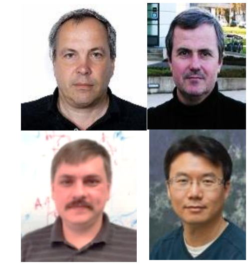
Expected Data





BC Data





Quasi-data using ***GlueX*** detector properties

GEANT4

100 days

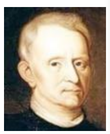
20 days

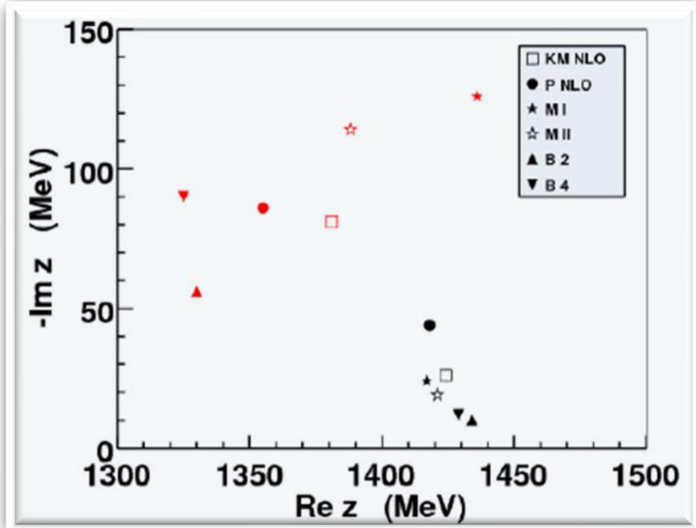
- At least **100** days needed to get *precise* solution.

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

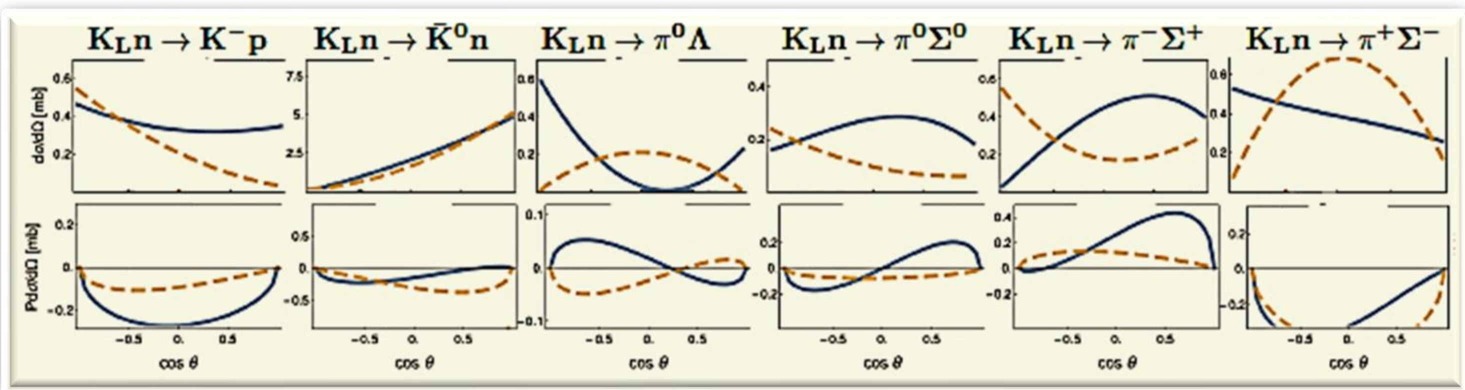
Resonance	20 days: M, Γ	100 days: M, Γ	PDG: M, Γ	hadspec M
Σ(1920)5/2⁻	1977±21±25 327±25±25	1923±10±10 321±10±10	?	2027 2487 2659 2781
Σ(2030)7/2⁺	1981±30±30 350±80	1930±20±30 400±40	2030±10 180±30	2686 2709 2793 2806

Theory for "Neutron" Target Measurements





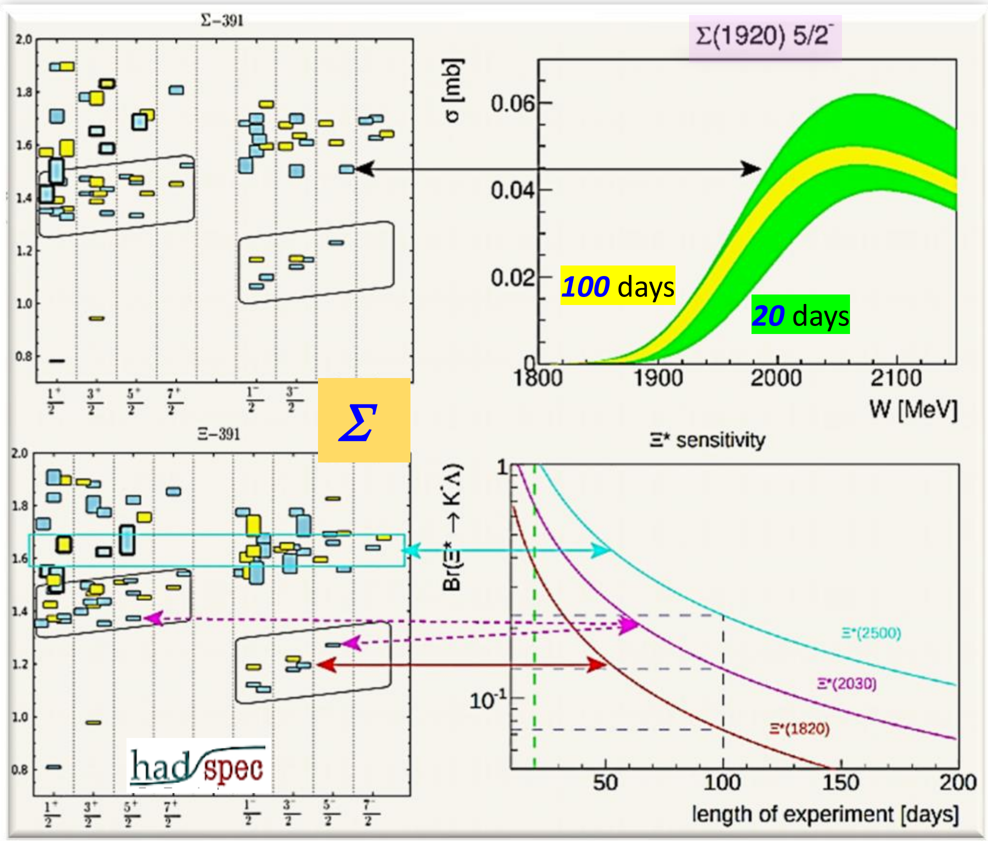
- There are **6** different models.
- *Pole* positions of *Λ(1405)* in chiral unitary approaches.
- Each symbol represents position of 1st (black) & 2nd (red) pole in each model.



- *P* = 300 MeV/c

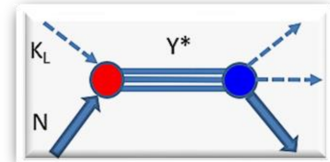
Courtesy of Maxim Mai, **2019**

Summary of Hyperon Spectroscopy



- We showed that KL 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 *KL* @ once (``*tagged*'' *kaons*) .



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

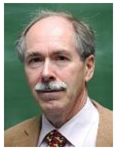
- *Why should we care that there are dozens of missing states* ?

…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

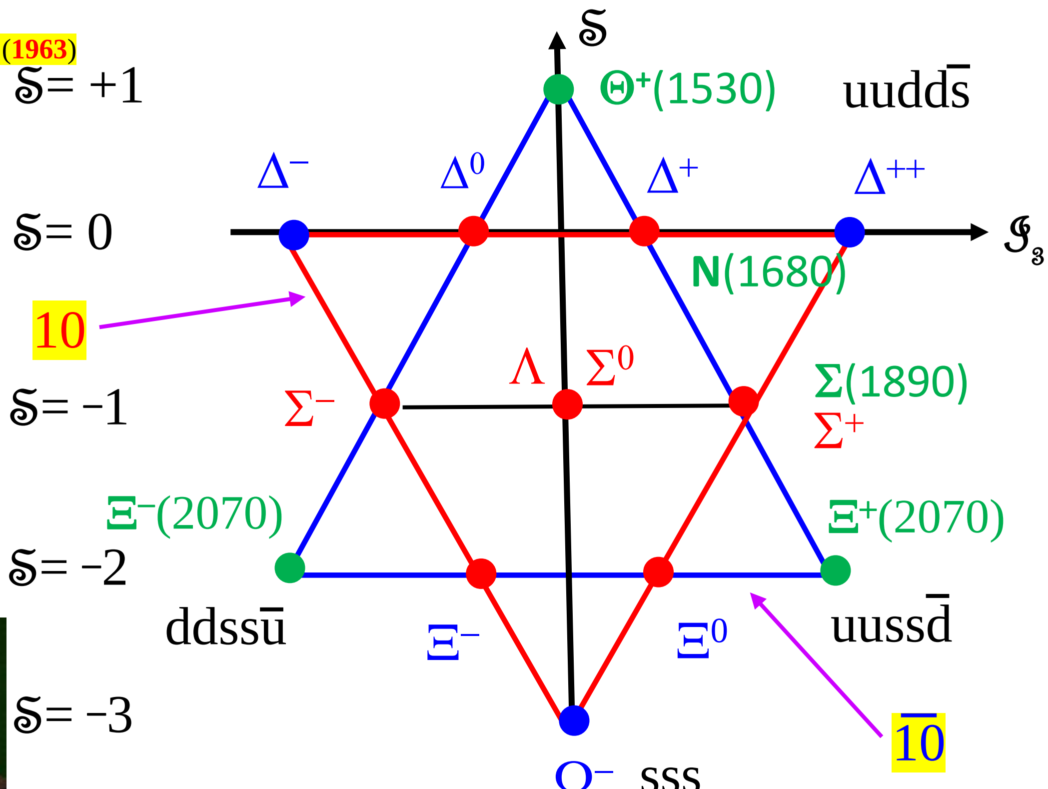
Anyone can ask Big Questions, but it is not easy to ask questions that would suggest new pathways leading to real progress of our understanding. Courtesy of Gerard 't Hooft, **2022**

What Else ?



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

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



$K_L p \rightarrow K^+ n$

$K_L p \rightarrow K_S \Xi^+$

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

- ***Big Question***: if there is *no exotics* then **WHY ?**

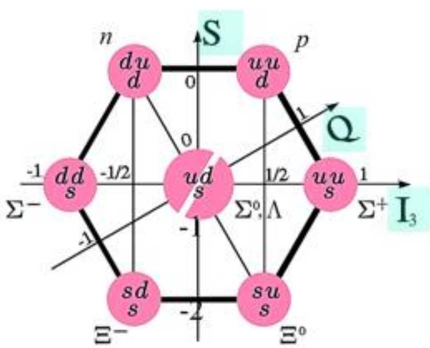
Unitarity Partners (?)

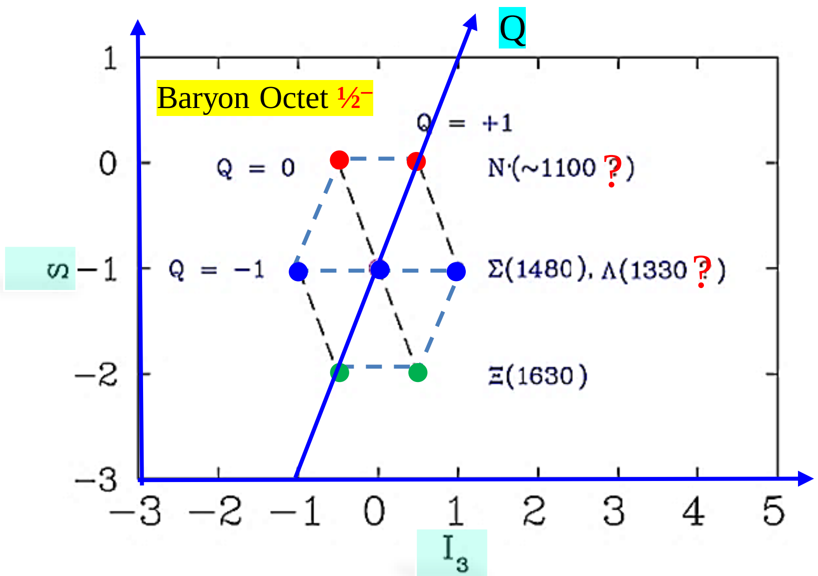
Ya. Azimov, R. Arndt, IIS, R. Workman, Phys Rev C **68**, 045204 (**2003**)

8 – S wave Multiplets

- If $\overline{10}$ is predicted to be $1/2^+$ (P-wave)
  Where is ground (S-wave) state ($1/2^-$) ?
- If this state is analogue to $\overline{10}$,
  then its intrinsic structure must be different,
  & its flavor structure must be different as well
  could be 8.
- There is no prediction of $1/2^-$ in ChSA
  (no predictions for negative parity @ all).

Baryon Octet $½^+$

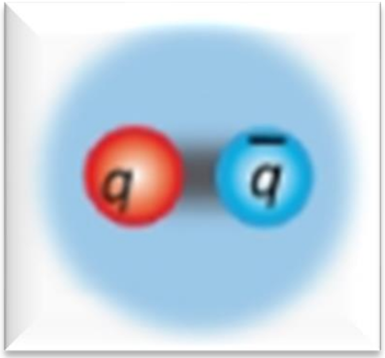




$$M = a_0 + a_1 Y + a_2 \left[I(I+1) - \frac{1}{4} Y^2 \right]$$

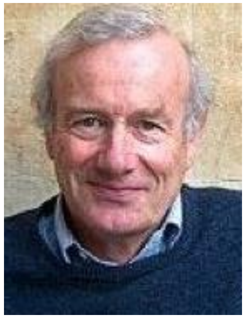
- Mixing be able to shift some masses for Gell-Mann-Okubo mass formula.

Strange Meson Spectroscopy



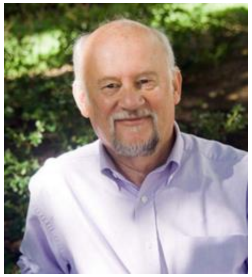
The di-quark or meson-baryon puzzle: Why is the quark-quark interaction just enough weaker than the quark-anti-quark interaction so that di-quarks near the meson mass are not observed, but three-quark systems have masses comparable to those of mesons?

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 qq–anti-q-anti-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.

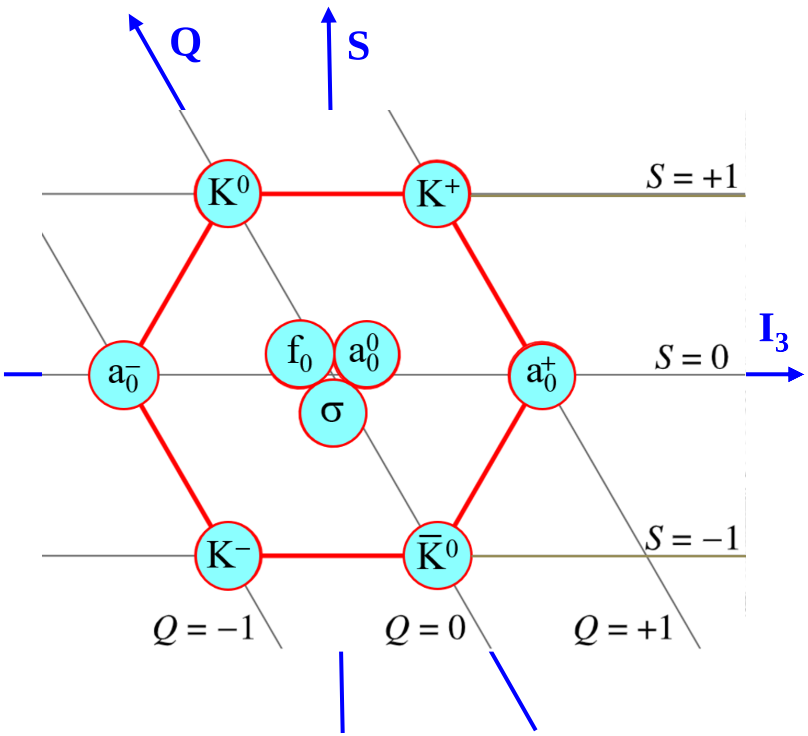
Michael Pennington, **2015**

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 quark-anti-quark 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**

Scalar Meson Nonet

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

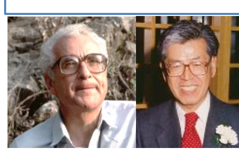


- ***Four*** states called *κ(700).*
- PDG: *still need further confirmation*.
- K-Long Facility allows determination of all *four* states.

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

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

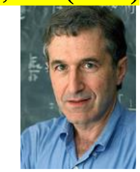
- This phenomenological formula works with accuracy of 5%.



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

Scalars vs Vectors or Eyewitness of 4q Exotics ?

R.J. Jaffe, Phys Rev D **15**, 267 (1977)
arXiv: 0001123 [hep-ph]
Prog Theor Phys Suppl **168**, 127 (**2007**)

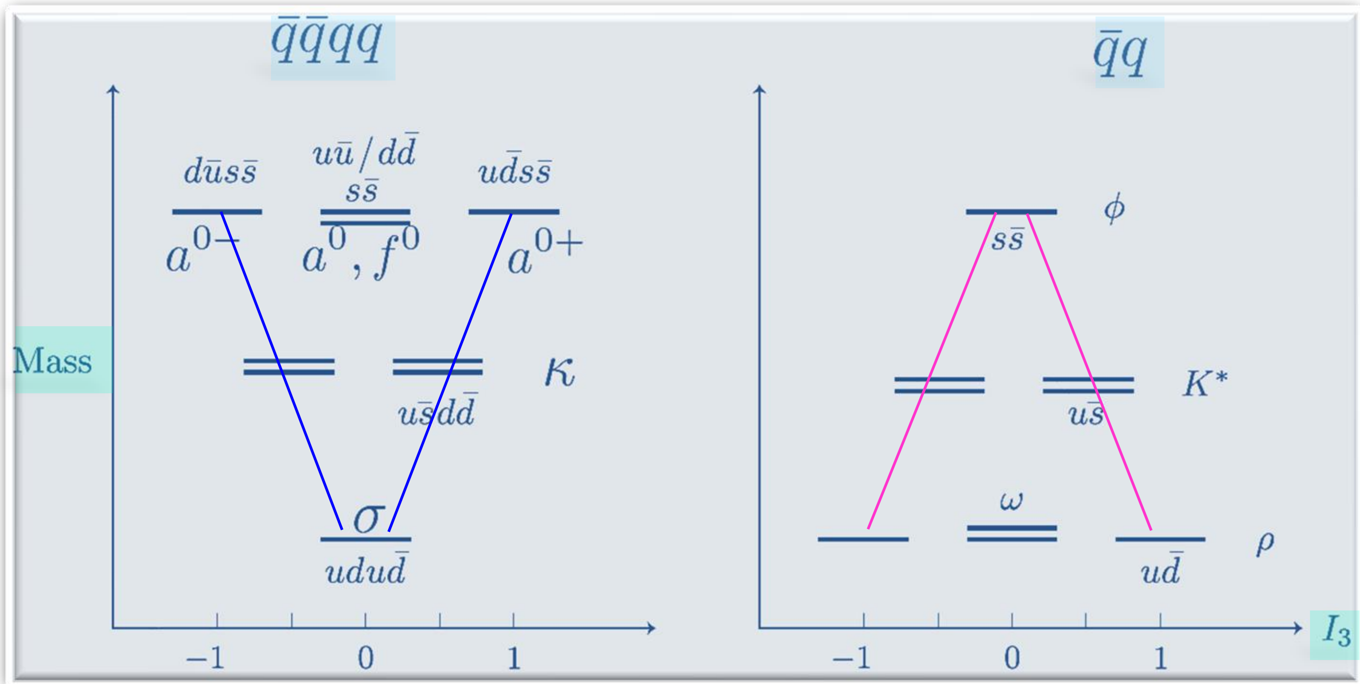


Inverted mass hierarchy tetraquarks

Scalar Mesons

Ordinary meson states

Vector Mesons



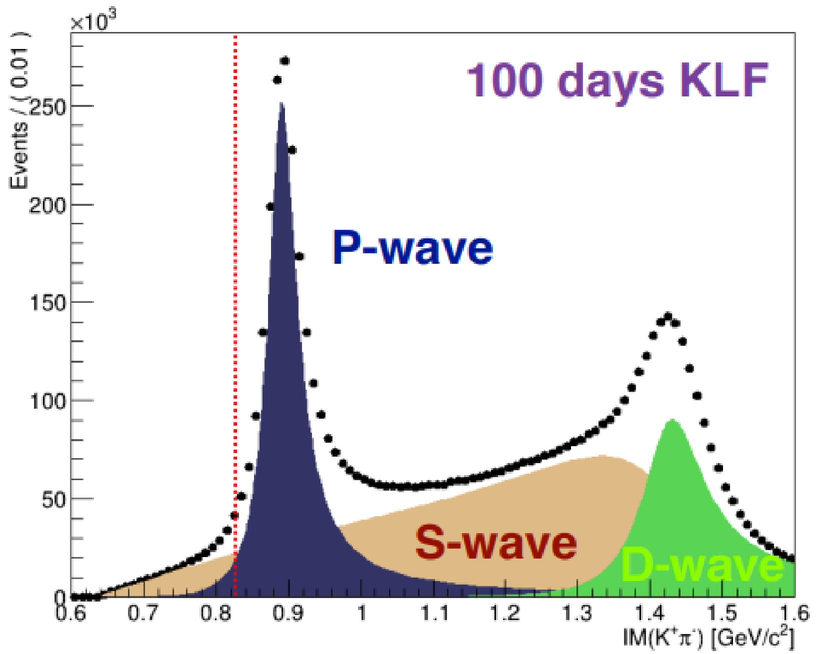
- Very different mass *hierarchy*.
- Possibly suggesting *4q tetraquark*.
- Structure of ***scalar*** mesons.

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

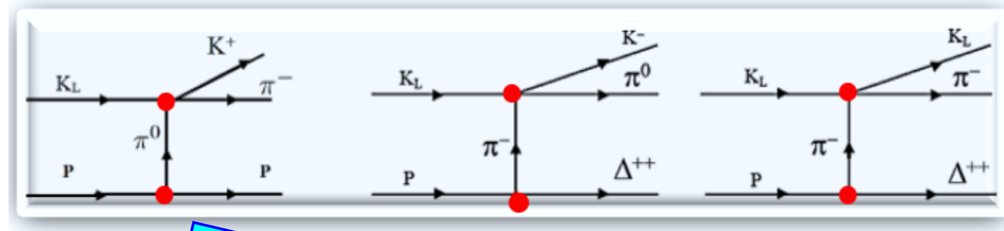
"I like the conclusion that the a_0 is a multi quark state." Courtesy of Bob Jaffe, **2022**

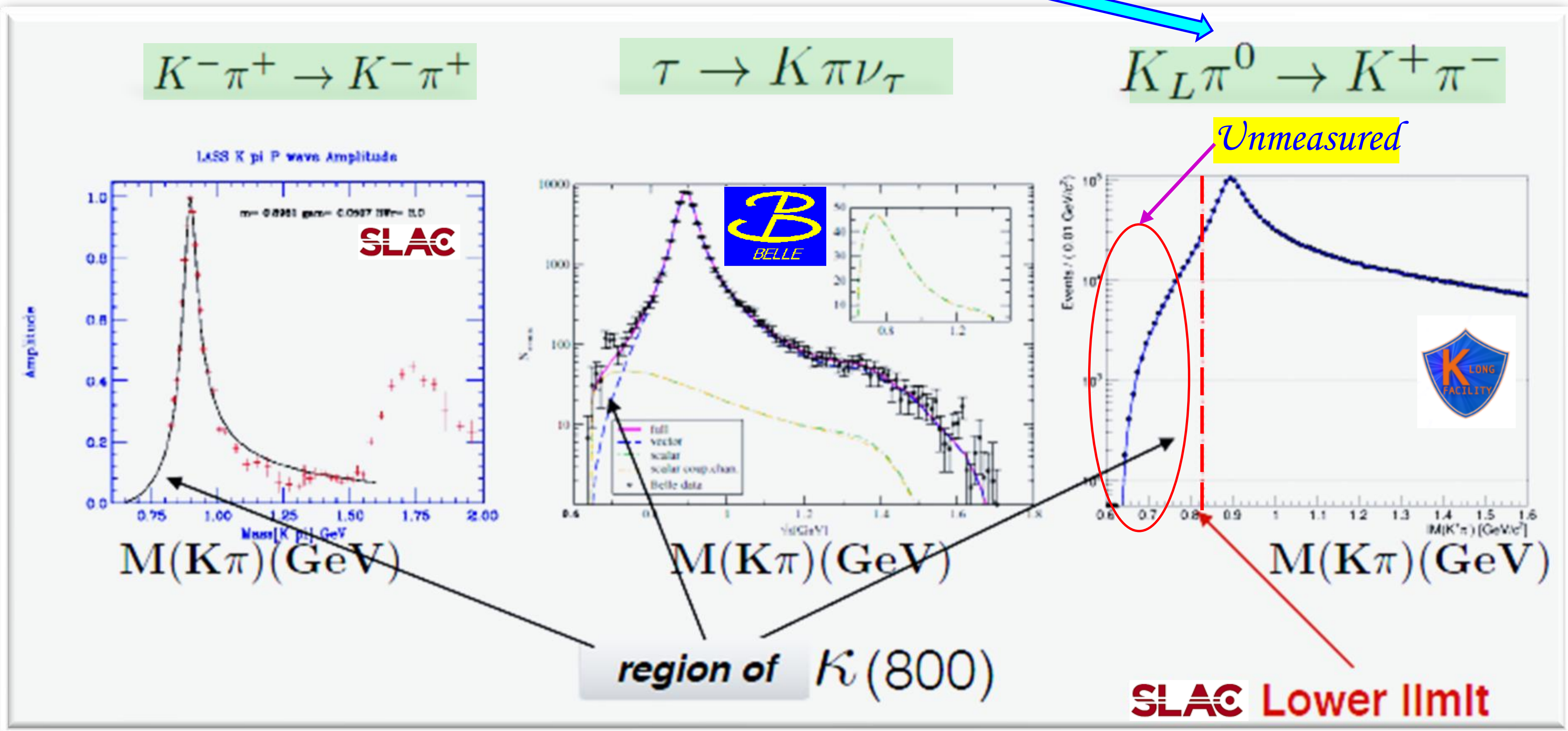
- Most knowledge of kaon spectrum comes from *older* kaon beam experiments.
    - More recent insight from, *e.g.*, *PWA* of decays from *charm* quark hadrons.
- High-statistics KLF data gives additional insight.
    - Unique access to high mass/spin states.
    - Study of scalar $K\pi$ system.

$$K_L p \to K^{\pm}\pi^{\mp}p$$

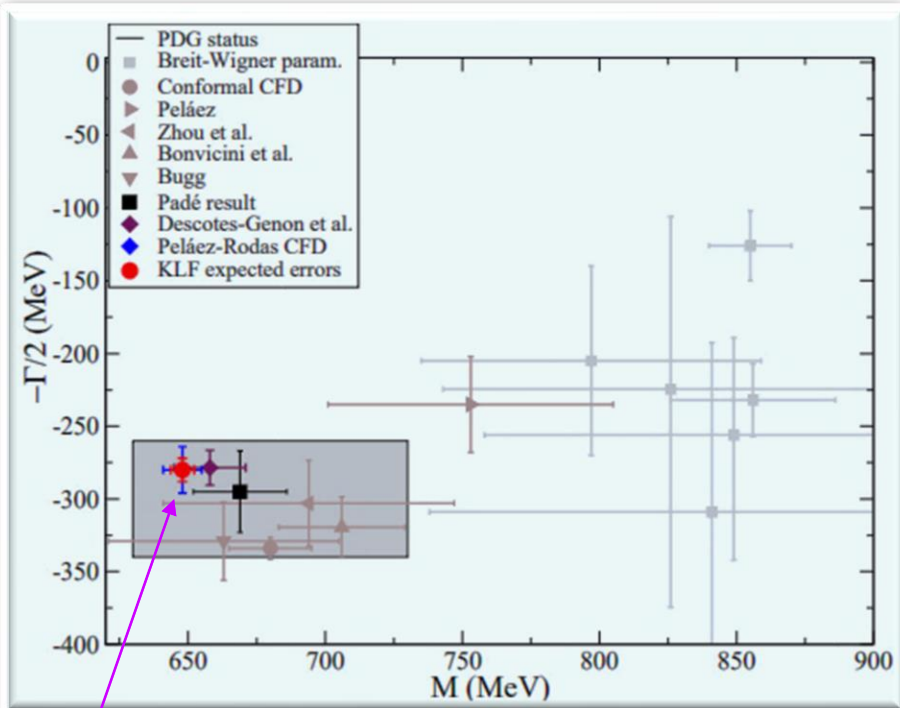


Proposed Measurements for $K\pi$ Scattering



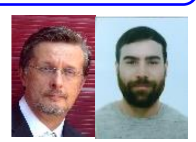


Summary of $K\pi$ Spectroscopy



100 days

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



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

- 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*.

Where We are Going

Beam Time Approved

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

For $d\sigma/d\Omega$

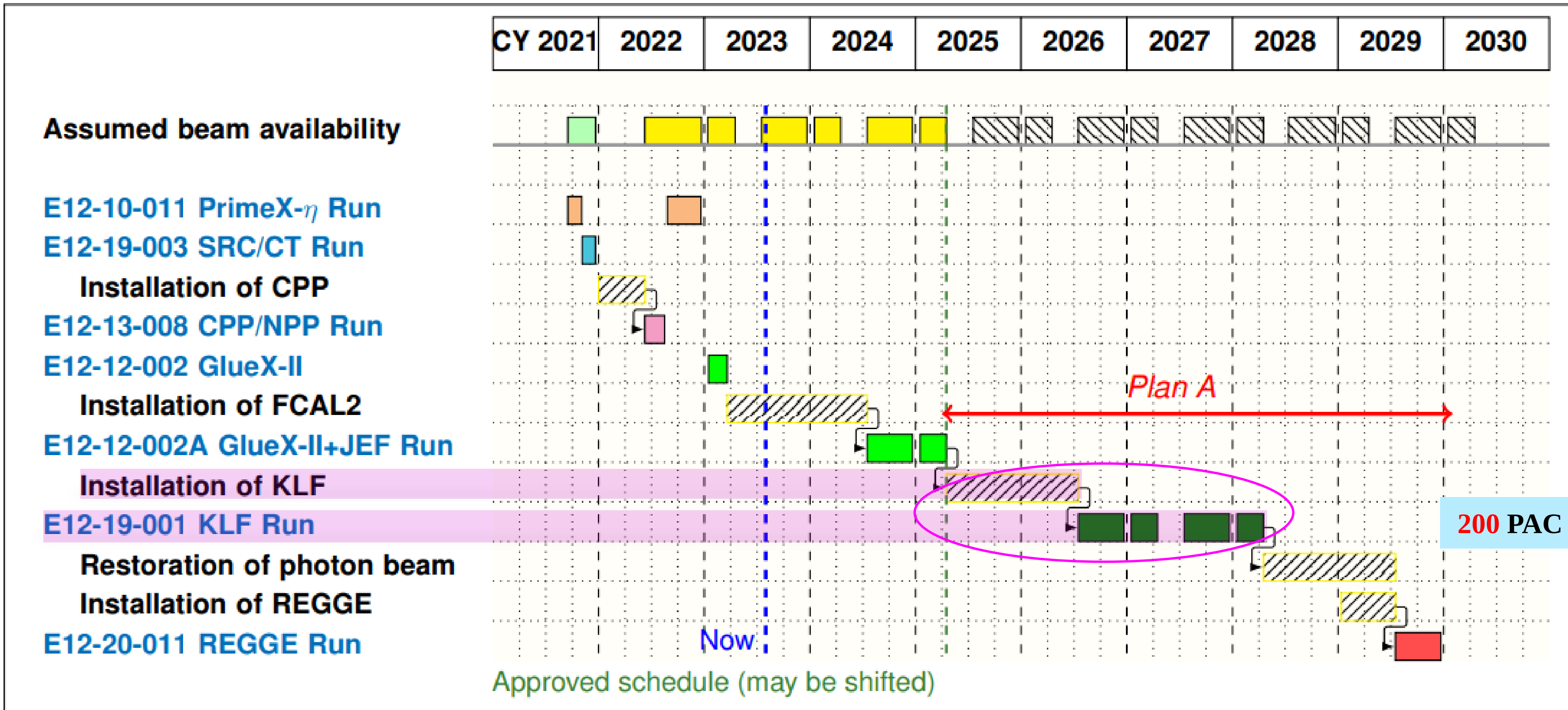
Reaction	Statistics (events)
$K_Lp \to K_Sp$	2.7M
$K_Lp \to \pi^+\Lambda$	7M
$K_Lp \to K^+\Xi^0$	2M
$K_Lp \to K^+n$	60M
$K_Lp \to K^-\pi^+p$	7M

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_Ln 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 is *10*% or less.

Hall D running schedule: outlook



- Assuming 31 weeks/year for Hall D running in 2024/07-2025/03 and 30 weeks afterwards
- Assuming KLF compatibility with MOLLER, and timing budgeting for KLF and REGGE
- Assuming timely construction of JEF,KLF,REGGE

7th Collaboration Meeting @ Jefferson Lab

https://wiki.jlab.org/klproject/index.php/September_19th,_2023

TENTATIVE AGENDA [edit]

Tuesday, September 19, 2023 [edit]

- 8:00-8:20 (20') Coffee
- 8:20-15.40 (440') Session I --- Project Status (JLab F113 or L102 and virtually on Zoom). Chair: *Sean Dobbs*
  - 8:20-8:35 (10+5') *Cynthia Keppel*, [Welcome Remarks].
  - 8:35-9:05 (20+10') *Douglas Higinbotham*, [ERR Results and JLab Beam Schedule].
  - 9:05-9.25 (15+5') *Eugene Chudakov*, [Hall D Status Report].
  - 9:25-9:45 (15+5') *Mikhail Bashkanov*, [Excited Omega Baryon States at KLF].
  - 9:45-10:10 (20+5') *Arkaitz Rodas*, [The Quest for Strange Resonances at KLF].
- 10:10-10:30 (20') Coffee
  - 10:30-10:55 (20+5') *Andrey Sarantsev*, [Search for Lambda and Sigma Hyperons in the Experiments with Polarized Target].
  - 10:55-11:15 (15+5') *Mariangela Bondì*, [The Muon Missing Momentum Experiment @ JLab-KLF].
  - 11:15-11:40 (20+5') *Boris Grube*, [Kaon spectroscopy at COMPASS].
  - 11:40-12:05 (20+5') *Dominik Stamen*, [gamma K to K pi Dispersion Analysis of the Primakoff Reaction].
- 12:05-12:50 (45') Lunch, on your own.
  - 12:50-13:10 (15+5') *Sean Dobbs*, [Software for KLF].
  - 13:10-13:30 (15+5') *Tim Whitlatch*, [K-Long Engineering Update].
  - 13:30-13:50 (15+5') *Hovanes Egiyan*, [Conceptual Design of CPS].
  - 13:50-14:10 (15+5') *Igor Strakovsky*, [The Kaon Production Target - Final Design].
  - 14:10-14:30 (15+5') *Mikhail Bashkanov*, [The Flux Monitor - Final Design].
  - 14:30-14:45 (10+5') *Richard Jones*, [Design of a Fast Photon Beam Position Monitor for the KLF Beamline].
  - 14:45-15:05 (15+5') *Sunil Pokharel*, [Effects of Spin-Flipper on the CEBAF Injector for K-Long Bunch Charge at 200 kV].
  - 15:05-15:25 (15+5') *Shukui Zhang*, [Status of the CEBAF Photo-Injector Drive Laser System for KL Beam].
  - 15:25-15:40 (10+5') *Edy Nissen*, [Electron Beam Characteristics and Beam Diagnostics].
- 15:40-16:00 (20') Coffee
- 16:00-17:10 (70') Session II --- Seminar (JLab F113 or L102 and virtually on Zoom). Chair: *TBD*
  - Separate Zoom link for Seminar:
  - 16:00-17:10 (60+10') [TBD] --- *TBD* ....

歡迎
請進來

KLF Experiment was approved in **08/20**.
ERR-I was approved in **08/23**,

- Our goal is
  - To setup *KL Facility* @ Jefferson Lab
  - To do measurements which bring *new physics*.

- Jefferson Lab KLF would advance *Hyperon Spectroscopy* & study of *strangeness* in nuclear & hadronic physics.
  We may have cornucopia of many missing 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* from *quarks* & *gluons* *microseconds* (**!**) after *Big Bang*.
  Our expectation is to get **1** messed/new *hyperon* per **1** day.

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

非常感謝

歡迎提問

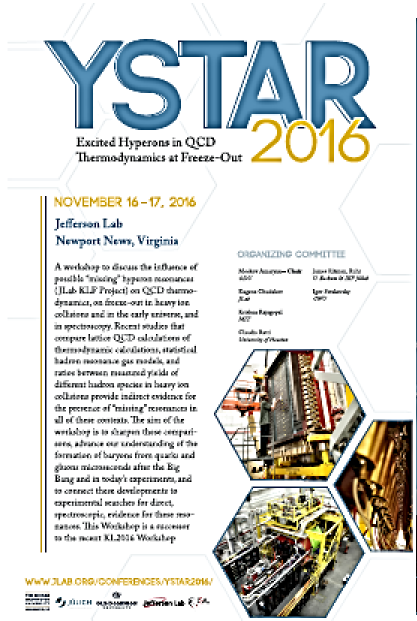
igor@gwu.edu
Igor Strakovsky

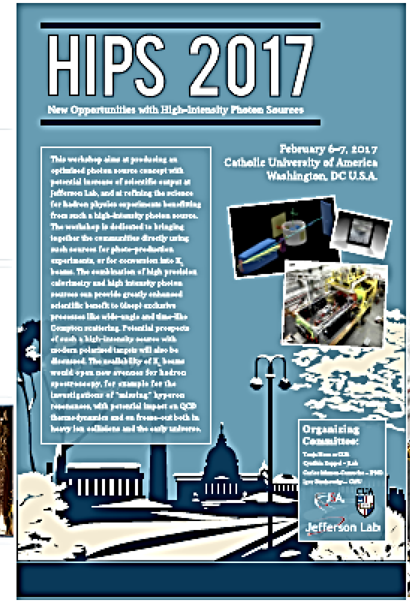
Other Experiments Dedicated to Strangeness

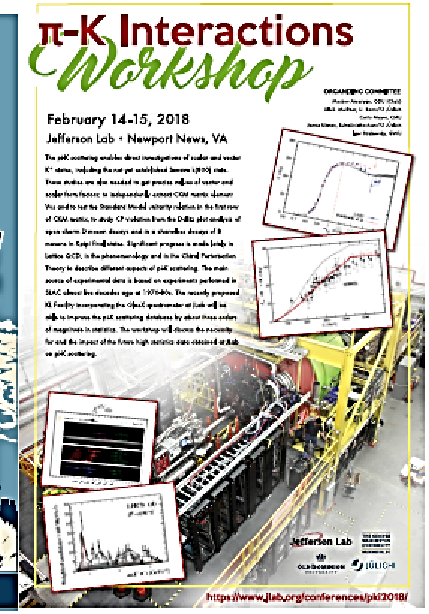
- J-PARC
  - E57, E62 [T. Hashimoto (2019)]
  - E15 [Y. Sada et al. (2016), T. Yamaga (2020)]
  - Many experiments dedicated to the $\bar{K}$-nucleus potential
  - Related to possibility of $\bar{K}NN$ formation [Akaishi 2002];
  - Ongoing debate, e.g., [Magas (2006)]
- Low energies/scattering length: DAFNE AMADEUS
  - Siddharta-2/Kaonic deuterium [Miliucci (2021)]
  - Amadeus (new data point of $K^- n \to \Lambda\pi^-$) [K.Piscicchia (2018)]
- CLAS12, GlueX $\gamma p \to K^+(Y^* \to \pi\Sigma, \dots)$
- (mostly ΛN, ...) [Lutz (2009)]
- BELLE, , COMPASS 25 years 1997 – 2022, LHCb [Whitepaper 2020]


BACKUP

Four International Workshops Supported KLF Program







KL2016
[60 people from 10 countries, 30 talks] https://www.jlab.org/conferences/kl2016/
OC: M. Amaryan, E. Chudakov, C. Meyer, M. Pennington, J. Ritman, & I. Strakovsky

YSTAR2016
[71 people from 11 countries, 27 talks] https://www.jlab.org/conferences/YSTAR2016/
OC: M. Amaryan, E. Chudakov, K. Rajagopal, C. Ratti, J. Ritman, & I. Strakovsky

HIPS2017
[43 people from 4 countries, 19 talks] https://www.jlab.org/conferences/HIPS2017/
OC: T. Horn, C. Keppel, C. Munoz-Camacho, & I. Strakovsky

PKI2018
[48 people from 9 countries, 27 talks] http://www.jlab.org/conferences/pki2018/
OC: M. Amaryan, U.-G. Meissner, C. Meyer, J. Ritman, & I. Strakovsky

In total: 222 participants & 103 talks

A Bit of History

PHYSICAL REVIEW VOLUME 138, NUMBER 5B 7 JUNE 1965

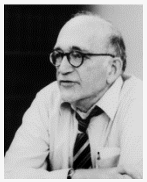
First paper on subject

Photoproduction of Neutral *K* Mesons*

CP-violation (1964)
Hot topic!

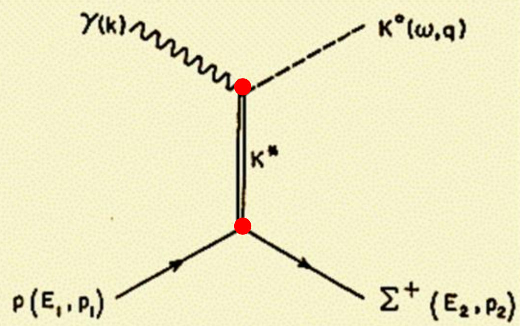
S. D. Drell and M. Jacob†
Stanford Linear Accelerator Center, Stanford University, Stanford, California

(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.

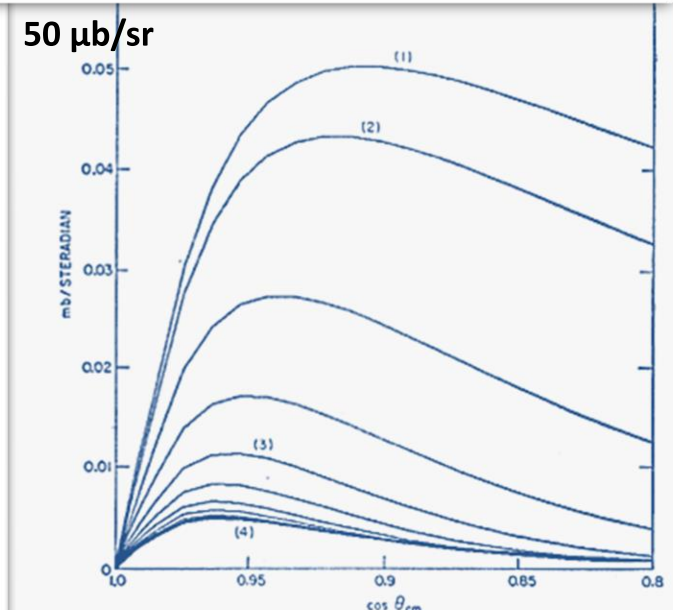


Fig. 3. Center-of-mass differential cross section at 10 BeV. Curve (1) gives the Born approximation. Curve (2) is obtained after subtraction of the $j=\frac{1}{2}$ partial wave. Curves (3) and (4) are respectively obtained after the $j=\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \frac{7}{2}$, and all partial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

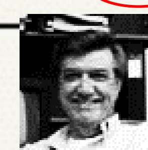
PHOTOPRODUCTION OF K^0 MESONS FROM PROTONS AND FROM COMPLEX NUCLEI

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*

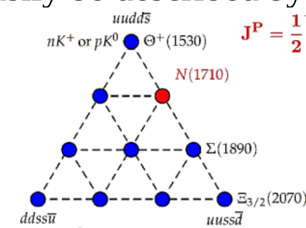
A. D. Brody, W. B. Johnson, D. W. G. S. Leith, G. Loew, J. S. Loos, G. Luste, R. Miller, K. Moriyasu, B. C. Shen, W. M. Smart, and R. Yamartino
SLAC
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 13 March 1969)

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

KLF Potential

- For complete experiment, one can use *FROST* hydrogen/deuterium *polarized* target.

- Further potential exists to search for possible *exotic* baryonic states, ***5q***, that cannot easily be described by usual three-valence-quark structure.



- Similarly, scattering of kaons from nuclear targets could be favorable method to measure matter form factor (&, therefore, *neutron skin*) of heavy nuclei, with different & potentially smaller systematics than other probes.

- High quality *neutron beam* will allow to study $np \to K^+X$ & $np \to \pi^+X$.

- *Short Range Correlation* (***SRC***) experiments are doable as well.

- Study *Primakoff* reaction using *KL* probe & nuclear targets is possible via *K^{*0}(892)* decay into $K^0\gamma$,
BR = 0.25 ± 0.20%.

- Physics potential connected with studies of ***CP***-violating decays of *KL* as, *e.g*, $K_L^0 \to \pi^0\nu\bar{\nu}$ is very appealing.

- High flux *KL* beam allows first measurement of *KL β-decay*, $K_L^0 \to K^+e^-\bar{\nu}_e$
SM postulated to preserve conservation laws in *β*-decay
Pauli: ``*I created a monster*.”

BR ~ 4×10^{-9}