Highlights for KLF — a personal view

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Introduction

- **What does QCD teach us:**

Lattice QCD		Quark model		Dynamically gen. states
QM states + glueballs and hybrids	$\leftarrow$	not all dynamically generated states are QM states	$\leftrightarrow$	not all QM states are dynamically generated

Is this a change of the quantum mechanical basis?
(qqq versus baryon +meson)

The relation between QM states and dynamically generated states is not understood

QCD inspired models predict states beyond the quark model!

1. Baryons in the quark model

SU(6) relates the spectrum of Λ and Σ hyperons to *N* and Δ:

$$6 \otimes 6 \otimes 6 = 56_{\mathcal{S}} \oplus 70_{\mathcal{M}} \oplus 70_{\mathcal{M}} \oplus 20_{\mathcal{A}}\,.$$

$$56 = {}^{4}10 \oplus {}^{2}8, \quad 70 = {}^{2}10 \oplus {}^{4}8 \oplus {}^{2}8 \oplus {}^{2}1 \quad 20 = {}^{2}8 \oplus {}^{4}1.$$

56	70	20
Δ and *N*	Δ and *N* and Λ	*N*
Σ & Σ, Λ	Σ and Σ, Λ	Σ, Λ and Λ

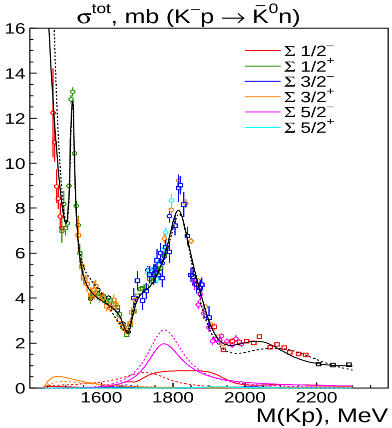
The number of Σ resonances is equal to $n_\Sigma = n_N + n_\Delta$.
The number of Λ resonances is equal to $n_\Lambda = n_N + n_{\Lambda_1}$.

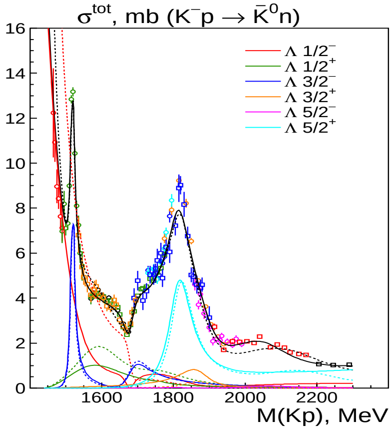
→ The Σ and Λ spectra are very rich!

- What do we know?
- Can we identify singlet, octet and decuplet states?
- There should be spin-quartet Λ singlet states!

1.1 Large number of missing resonances!

More data needed! Prime goal of KLF.





Prominent features: $\Sigma(1775)5/2^-$ $\Lambda(1520)3/2^-$ and $\Lambda(1820)5/2^+$

1.2 Baryons have two oscillators: Understand first and second excitation shell!

The negative-parity states:

(D, L^P_N) S J^P	Singlet	Octet			Decuplet	
	Λ(1380)					
$(70, 1^-_1)$ $\frac{1}{2}$ $\frac{1}{2}^-$	Λ(1405)	N(1535)	Λ(1670) +135	Σ(1620) +85	Δ(1620)	Σ(1900)†
$\frac{3}{2}^-$	Λ(1520)	N(1520)	Λ(1690) +170	Σ(1670) +150	Δ(1700)	Σ(1910)†
$\frac{3}{2}$ $\frac{1}{2}^-$		N(1650)	Λ(1800) +150	Σ(1750) +100		
$\frac{3}{2}^-$		N(1700)	-	-		
$\frac{5}{2}^-$		N(1675)	Λ(1830) +155	Σ(1775) +100	† 1800 and 2050 MeV expected	
		Mean:	+150 MeV	+110 MeV		

1$^{\mathrm{st}}$ excitation shell: single-oscillator excitations!

2$^{\mathrm{nd}}$ excitation shell: 56plet — single-oscillator excitations!

70plet — mixed !

20plet — two-oscillator excitations!

Number of expected and observed resonances that can be assigned to the 2^{nd} excitation shell for $J^P = 1/2^+, .., 7/2^+$. The first number gives the expected number of resonances, followed by the number of observed resonances with 3* and 4*, 1* and 2* (in parentheses).

		$1/2^+$	$3/2^+$	$5/2^+$	$7/2^+$	Sum
N	expected (4*3*, 2*1*):	4 (4,0)	5 (3,1)	3 (1,2)	1 (1,0)	13 (9,3)
Δ		2 (1,1)	3 (2,0)	2 (1,0)	1 (1,0)	8 (5,1)
Λ		6 (2,1)	7 (1,1)	5 (2,0)	1 (0,1)	19 (5,3)
Σ		6 (1,1)	8 (0,4)	5 (1,1)	2 (1,0)	21 (3,6)
Ξ		6 (0,0)	8 (0,0)	5 (0,0)	2 (0,0)	21 (0,0)
Ω		2 (0,0)	3 (0,0)	2 (0,0)	1 (0,0)	8 (0,0)

In the spectra of Λ and Σ resonances, 40 resonances are expected in the second excitation shell. Only 8 are known with 3 or 4 stars in RPP notation.

That is too little!

(D, L_N^P)	S	J^P	Singlet	Octet			Decuplet	
$(56, 0_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$		$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$		
	$\frac{3}{2}$	$\frac{3}{2}^+$					$\Delta(1600)$	$\Sigma(1780)$
$(70, 0_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$\Lambda(1710)$	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Delta(1750)$	-
	$\frac{3}{2}$	$\frac{3}{2}^+$		-	-	-		
$(56, 2_2^+)$	$\frac{1}{2}$	$\frac{3}{2}^+$		$N(1720)$	$\Lambda(1890)$	$\Sigma(1940)$		
	$\frac{1}{2}$	$\frac{5}{2}^+$		$N(1680)$	$\Lambda(1820)$	$\Sigma(1915)$		
	$\frac{3}{2}$	$\frac{1}{2}^+$					$\Delta(1910)$	-
	$\frac{3}{2}$	$\frac{3}{2}^+$					$\Delta(1920)$	$\Sigma(2080)$
	$\frac{3}{2}$	$\frac{5}{2}^+$					$\Delta(1905)$	$\Sigma(2070)$
	$\frac{3}{2}$	$\frac{7}{2}^+$					$\Delta(1950)$	$\Sigma(2030)$
$(70, 2_2^+)$	$\frac{1}{2}$	$\frac{3}{2}^+$	$\Lambda(2070)$	-	-	-	-	-
		$\frac{5}{2}^+$	$\Lambda(2110)$	$N(1860)$	-	-	$\Delta(2000)$	-
	$\frac{3}{2}$	$\frac{1}{2}^+$		$N(1880)$	-	-		
		$\frac{3}{2}^+$		$N(1900)$	-	-		
		$\frac{5}{2}^+$	(all 1*	$N(2000)$	-	-		
		$\frac{7}{2}^+$	in RPP)	$N(1990)$	$\Lambda(2085)$	-		
$(20, 1_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	-	-	-	-	Not yet any	
		$\frac{3}{2}^+$	-	-	-	-	two-oscillator	
		$\frac{5}{2}^+$	-				excitation	

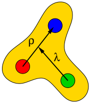
1.3 Search for the 20plet:

$\Lambda(2099)1/2^+$, $\Lambda(2176)3/2^+$, $\Lambda(2150)5/2^+$

U. Löring, B. C. Metsch and H. R. Petry, Eur. Phys. J. A 10 447 (2001).

The multiplets 70, 56, and 20 arise from the combination of the three light quarks u, d, s having spin 1/2:

$$6 \otimes 6 \otimes 6 = 56_S \oplus 70_M + 20_A$$



Classical orbits:

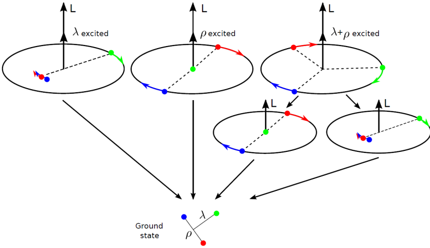
2^{nd} excitation shell:

$$\mathcal{S} = \frac{1}{\sqrt{2}} \left\{ \left[\phi_{0s}(\vec{\rho}) \times \phi_{0d}(\vec{\lambda})\right] + \left[\phi_{0d}(\vec{\rho}) \times \phi_{0s}(\vec{\lambda})\right] \right\}^{(L=2)},$$

$$\mathcal{M}_S = \frac{1}{\sqrt{2}} \left\{ \left[\phi_{0s}(\vec{\rho}) \times \phi_{0d}(\vec{\lambda})\right] - \left[\phi_{0d}(\vec{\rho}) \times \phi_{0s}(\vec{\lambda})\right] \right\}^{(L=2)}$$

$$\mathcal{M}_A = \left[\phi_{0p}(\vec{\rho}) \times \phi_{0p}(\vec{\lambda})\right]^{(L=2)},$$

$$\mathcal{A} = \left[\phi_{0p}(\vec{\rho}) \times \phi_{0p}(\vec{\lambda})\right]^{(L=1)}.$$



Baryons in the 20plet can neither decay nor be produced in a single step!

A. Thiel *et al.* [CBELSA/TAPS], Phys. Rev. Lett. 114 091803 (2015).

Search for 20plet-Λ resonances in a cascade process:

$\Sigma^+(\mathrm{highmass}) \to \Lambda(2099)1/2^+ + \pi^+$

to singlet component of η only

$\searrow \to \Lambda(1520)3/2^- + \eta,\ L = 0$

$\searrow \to \Sigma + \pi,\ N\bar{K}$

$\Sigma^+(\mathrm{highmass}) \to \Lambda(2176)3/2^+ + \pi^+$

$\searrow \to \Lambda(1820)5/2^+ + \pi,\ L = 0$

$\searrow \to \Sigma + \pi,\ N\bar{K}$

$\Sigma^+(\mathrm{highmass}) \to \Lambda(2150)5/2^+ + \pi^+$

to singlet component of η only

$\searrow \to \Lambda(1520)3/2^- + \eta,\ L = 0$

$\searrow \to \Sigma + \pi,\ N\bar{K}$

Small cross section expected! Questionable due to low expected rate,

but clear proof of three-body dynamics in baryons

2. Dynamically generated resonances beyond the q.m.

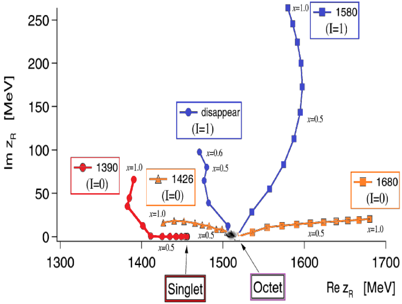
2.1 DGR from EFTs

Effective field theories generate in $\bar{K}N - \Sigma\pi$ coupled channel dynamics two poles in the Λ(1405) region!

I=0: (1379.2 - i 27.6) MeV

(1433.7 - i 11.0) MeV

J. A. Oller and U. G. Meissner, Phys. Lett. B 500, 263 (2001), D. Jido, J. A. Oller, E. Oset, A. Ramos, U. G. Meissner, Nucl. Phys. A 725, 181 (2003).



In the quark model (and so far on the lattice[1]), only one singlet pole is expected at this mass!

	N	QM	EFT
singlet		Λ(1405)	Λ(1380)
octet	N(1535)	Λ(1670)	Λ(1405)
octet	N(1650)	Λ(1800)	Λ(1670)

[1]: R. Pavao, P. Gubler, P. Fernandez-Soler, J. Nieves, M. Oka and T. T. Takahashi, [arXiv:2010.01270 [hep-lat]].

Is Λ(1405) a SU(3) singlet or octet state?

2.2 SU(3) nature of $\Lambda(1405)$ from its decays

SU(3) coupling constants for hyperon decays and the SU(6) predictions for the coefficient α in decays of octet hyperons.

V. Guzey and M. V. Polyakov, [arXiv:hep-ph/0512355 [hep-ph]].

RPP

$8_1 \to 8 \otimes 8$

$$\begin{pmatrix} N \\ \Sigma \\ \Lambda \\ \Xi \end{pmatrix} \to \begin{pmatrix} N\pi & N\eta & \Sigma K & \Lambda K & \\ N\bar{K} & \Sigma\pi & \Lambda\pi & \Sigma\eta & \Xi K \\ N\bar{K} & \Sigma\pi & \Lambda\eta & \Xi K & \\ \Sigma\bar{K} & \Lambda\bar{K} & \Xi\pi & \Xi\eta & \end{pmatrix} = \frac{1}{\sqrt{20}} \begin{pmatrix} 9 & -1 & -9 & -1 & \\ -6 & 0 & 4 & 4 & -6 \\ 2 & -12 & -4 & -2 & \\ 9 & -1 & -9 & -1 & \end{pmatrix}^{1/2}$$

$8_2 \to 8 \otimes 8$

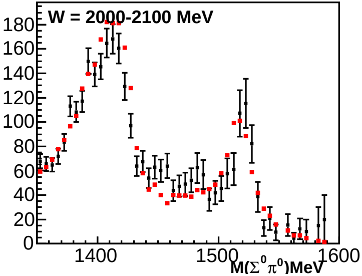
$$\begin{pmatrix} N \\ \Sigma \\ \Lambda \\ \Xi \end{pmatrix} \to \begin{pmatrix} N\pi & N\eta & \Sigma K & \Lambda K & \\ N\bar{K} & \Sigma\pi & \Lambda\pi & \Sigma\eta & \Xi K \\ N\bar{K} & \Sigma\pi & \Lambda\eta & \Xi K & \\ \Sigma\bar{K} & \Lambda\bar{K} & \Xi\pi & \Xi\eta & \end{pmatrix} = \frac{1}{\sqrt{12}} \begin{pmatrix} 3 & 3 & 3 & -3 & \\ 2 & 8 & 0 & 0 & -2 \\ 6 & 0 & 0 & 6 & \\ 3 & 3 & 3 & -3 & \end{pmatrix}^{1/2}$$

Decay mode	$8 \to 8+8$	$1 \to 8+8$	
$\Lambda \to N\bar{K}$	$\sqrt{\frac{2}{3}}(2\alpha+1)A_8$	$\frac{1}{2}A_1$	
$\Lambda \to \Sigma\pi$	$2(\alpha-1)A_8$	$\sqrt{\frac{3}{2}}A_1$	
	$^2 8[56]$	$^2 8[70]$	$^4 8[70]$
α	$\frac{2}{5}$	$\frac{5}{8}$	$-\frac{1}{2}$

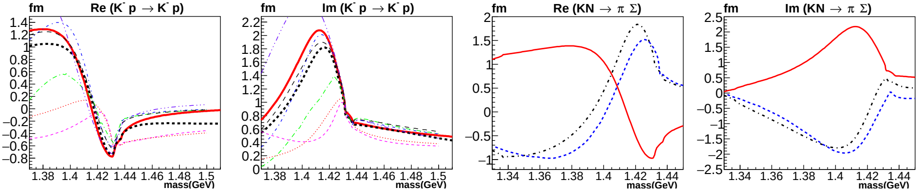
	$^2 1[70]$	$^2 8[56]$	$^2 8[70]$	$^4 8[70]$
$\frac{A(\Lambda\to N\bar{K})}{A(\Lambda\to\Sigma\pi)}$	$\sqrt{\frac{1}{6}}$	$-\sqrt{\frac{3}{2}}$	$-\sqrt{6}$	0
Sign	$\oplus$	$-$	$\ominus$	

2.3 BnGa fit to a large data set

- $K^- N$ scattering
- $\Delta E + i\frac{\Gamma}{2}$ of $\pi^- p$ atom
- CLAS data on $\gamma p \to K^+(\Sigma^\pm \pi^\mp)$
- CLAS data on $(\Sigma^0 \pi^0)$ predicted!

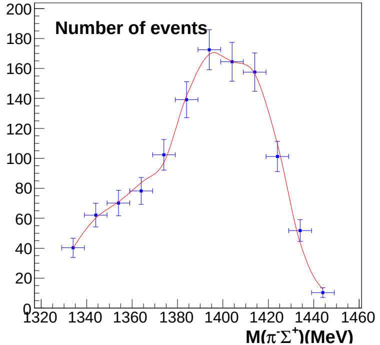


Fit with one pole at 1405 MeV:



Fit with one pole: $\Lambda(1405)$ is SU(3) singlet. Fit with two poles: $\bar{K}N$ amplitude flips sign: $\Lambda(1405)$ become SU(3) octet!

3.4 KLF determines SU(3) structure of Λ(1405)



$\Sigma^+\pi^-$ mass from $K^-p \to \pi^-\pi^+\pi^\mp\Sigma^\pm$ for events with $M_{\pi^+\pi^\pm\Sigma^\mp}$ compatible with $\Sigma(1670)3/2^-$. Number of events /10 MeV.

R. J. Hemingway, Nucl. Phys. B 253, 742 (1985).

BnGa fit: 75% $\Lambda(1405)1/2^-$;
25% $\Sigma(1385)3/2^+$

The signs of the SU(6) amplitudes for

$\Sigma^+(1670)3/2^- \to \pi^+\Lambda(1405)$;
$\Lambda(1405) \to \Sigma^\pm\pi^\mp$ and

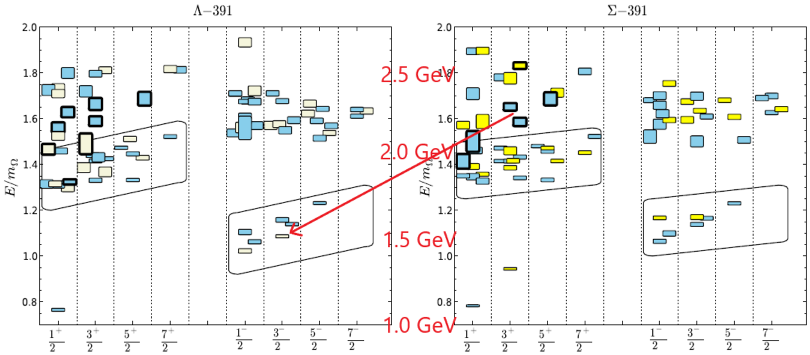
$\Sigma^+(1670)3/2^- \to \pi^+\Sigma(1385)$;
$\Sigma(1385) \to \Sigma^\pm\pi^\mp$.

		Λ(1405) SU(3) structure:	1	8
$\Sigma^+(1670)3/2^-$	$\to$	$\Lambda(1405)\pi^+$	+	+
		$\hookrightarrow \Sigma^\pm\pi^\mp$	+	-
Sign of transition amplitude at pole:			⊕	⊖
$\Sigma^+(1670)3/2^-$	$\to$	$\Sigma^0(1385)\pi^+$	+	+
		$\hookrightarrow \Sigma^\pm\pi^\mp$	+	+
Sign of transition amplitude at pole:			⊕	⊕

3. Hybrids and glueballs

3.1 Σ hybrids at KLF

No exotic quantum numbers!



Most promising:

- **Spring breaking leads to orbital angular momentum in the final state**
- **$\Lambda(1520)3/2^-$ dominant structure**
- **$\Sigma_h^+(2250)3/2^+ \to \Lambda(1520)3/2^- + \pi^+$ *S*-wave decay**
- **Two $\Sigma_h^+(2250)3/2^+$ and $\Sigma_h^+(2350)3/2^+$ isolated (lattice prediction)**

On hybrid decays

The spring breaking of a hybrid is supposed to lead to orbital angular momentum in one of the outgoing particles. The best choice for a start seems to be the decay into $\Lambda(1520)\pi$. But other decay modes like $\Lambda(1520)\eta$, $\Lambda(1405)\pi$, $\Lambda(1820)\pi$ are also valuable. Mesons with internal orbital angular momentum can also be used: $\Lambda\sigma$, $\Lambda f_0(980)$. (These are in a $^3P_0$ state, i.e. $L = 1$). I call the ratio for a hyperon to go into one of these final states $R(L = 1)$ and “normal” decays like $\Sigma\pi$ where both particles are in the S-state, $R(L = 0)$. The ratio

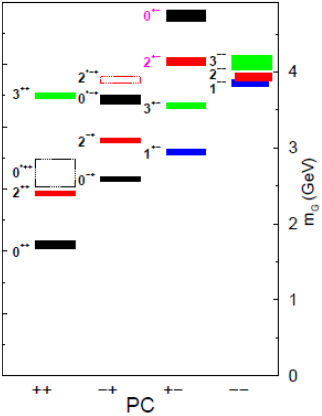
$$r = \sum R_i(L = 1) / \sum R_i(L = 0)$$

gives information about the internal structure:

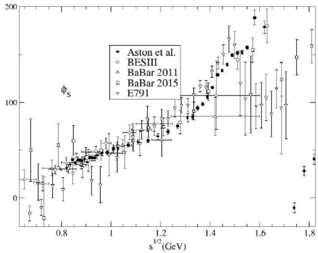
- $r = 0$: Hyperon belongs to a 56plet
- $0.2 < r < 1$: Hyperon belongs to a 70plet
- $1 < r$: Hyperon is a hybrid

The actual numbers are estimates. I expect classes of hybrids for which r falls into separated ranges of values.

3.2 No glueballs at KLF , but scalar K_0^*



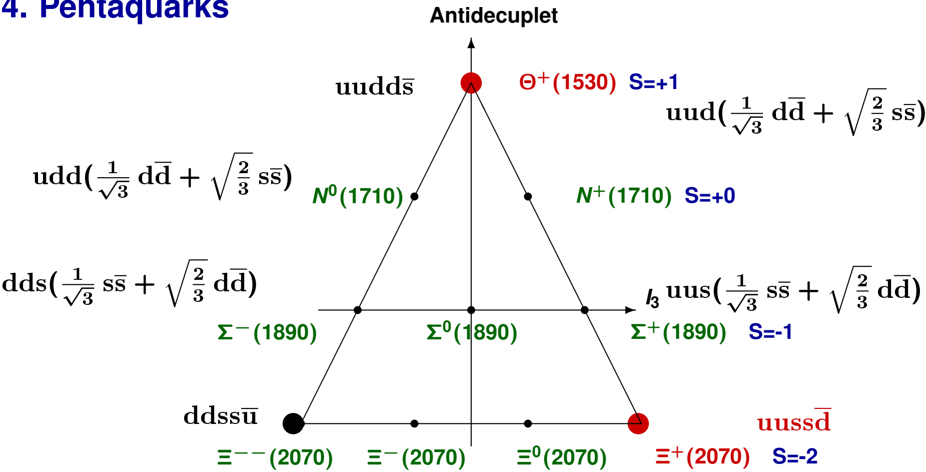
$f_0(980)$	$a_0(980)$	$K_0^*(700)$
$f_0(1500)$	$a_0(1450)$	$K_0^*(1450)$
$f_0(1710)$		?
$f_0(2100)$	$a_0(2020)$	$K_0^*(1950)$



Scalar mesons with strangeness, K_0^* series very important.

Existence or not of a $K_0^*(1680)$ helps to decide if $f_0(1710)$ is a glueball!

4. Pentaquarks



The antidecuplet and its quark model decomposition. The antidecuplet predicted by the chiral soliton model describes nucleons in terms of the pion field and not by the number of quarks. The three corner-states are incompatible with a *qqq* assignment.

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

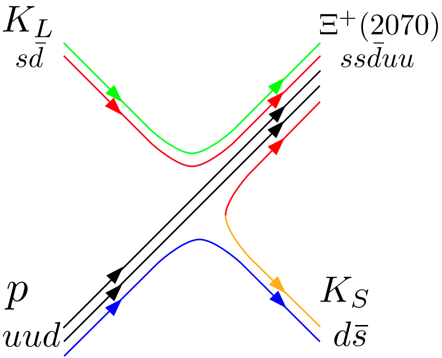
Study reactions:

$K_L\, p \to \Theta^+(1530) \to K^+\, n$ charge exchange (phase shift!)

$K_L\, p \to K_S\, \Xi^+(2070)$

$\searrow \to \Xi^0 \pi^+$ ($\approx$ 30% predicted, $c\tau = 8.7$ cm)

$\searrow \to \Lambda \pi^0$ (100%, $c\tau = 7.9$ cm)



Baryon exchange in *t*-channel

Meson-baryon exchange in *s*-channel

$\Xi^+(2070)$ reconstruction

The path, energy and momentum of the primary K_L needs to be known. The $\Xi^+(2070)$ is short-lived. It decay point is the interaction point. The π^+ is measured; its path intersects with the K_L path. From energy and momentum conservation, direction and (missing) momentum of the Ξ^0 can be constructed. Along this path, the Λ decays into p and π^+. The Λ decay vertex can be reconstructed (and the path of the Ξ^0 constrained). The two photons of the π^0 decay stem from intersection point of the π^+ with the direction of the missing momentum of the Ξ^0.

Summary

My own expectation

KLF offers a wide range of opportunities:

1. **Baryons in the quark model**
   - 1.1 **Missing resonances** — **Several new resonances will be found and/or upgraded**
   - 1.2 **Two oscillators**
   - 1.3 **Λ resonances in the 20plet** — **Unlikely, not sufficient statistics**
2. **Dynamically generated resonances beyond the q.m.**
   - 2.1 **DGR from EFTs**
   - 2.2 **SU(3) nature of Λ(1405)**
   - 2.3 **The BnGa fit**
   - 2.4 **KLF and the Λ(1405)** — **KLF will contribute to clarification**
3. **Glueballs and hybrids**
   - 3.1 **Σ hybrids at KLF** — **"Candidates" will be discussed**
   - 3.2 **No glueballs at KLF but scalar K_0^*** — **Better K_0^*(700), K_0^*(1450), ... ?**
4. **Pentaquarks** — **Good new upper limits**