Hadronic Spectroscopy and What We Can Learn About QCD from GlueX

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The College Of WILLIAM & MARY

GlueX
Jefferson Lab
Thomas Jefferson National Accelerator Facility

OUTLINE

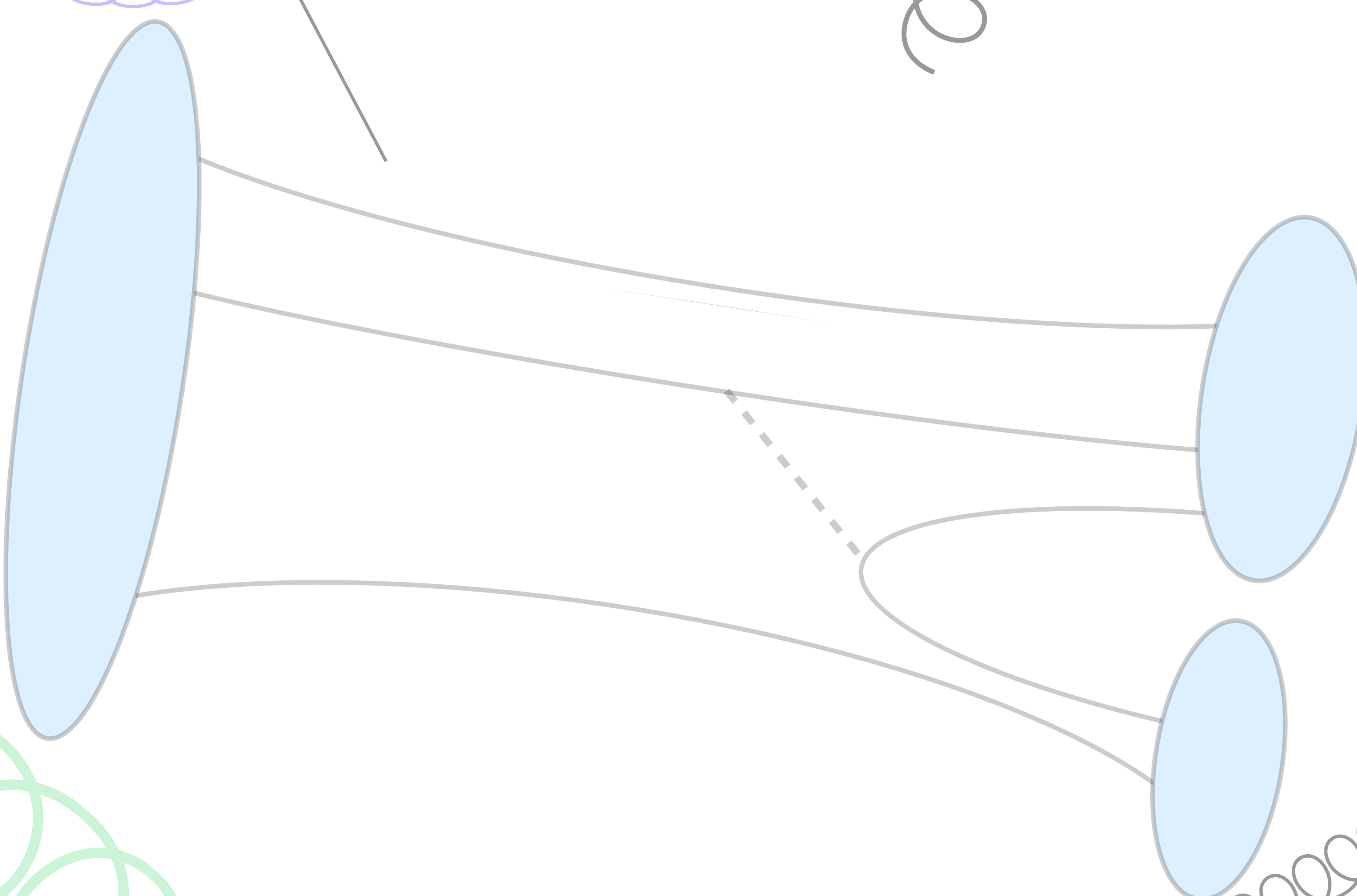
I. Why Study QCD?

II. Hadronic Spectroscopy

III. The GlueX Experiment

IV. The Strangeness Frontier

I. Why Study QCD?



The Standard Model

Standard Model forces		
name	mediator	describes
strong	gluons	nucleons
weak	W/Z bosons	nuclear decay
electromagnetic	photons	chemistry

- Strong force is one of three forces of Standard Model
- Building blocks of the universe we understand so far

What Is QCD?

- Strong force is described by Quantum Chromodynamics (QCD)

- Universally accepted as the correct theory that describes all aspects of the strong force:

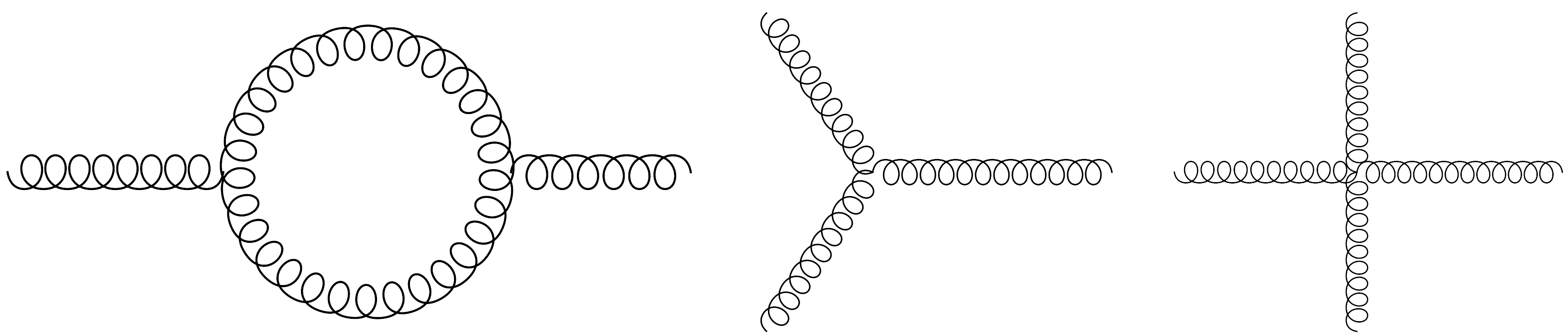
$$\mathcal{L}_{QCD} = \sum \overline{\psi} \left(i \not{D} - m \right) \psi - \frac{1}{4} G_a^{\mu\nu} G^a_{\mu\nu}$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$

- Fundamental constituents are quarks coupled by gluons

QCD - An Overview

- SU(3) gauge theory, one force within Standard Model
- Gluons carry "color" charge - similarities to QED
- Gluons can couple to each other:



- Perturbative calculations possible at high energies
- Can we say we "understand" QCD?
- Is there anything intelligent that we can say about the behavior/dynamics of QCD that is not obvious?

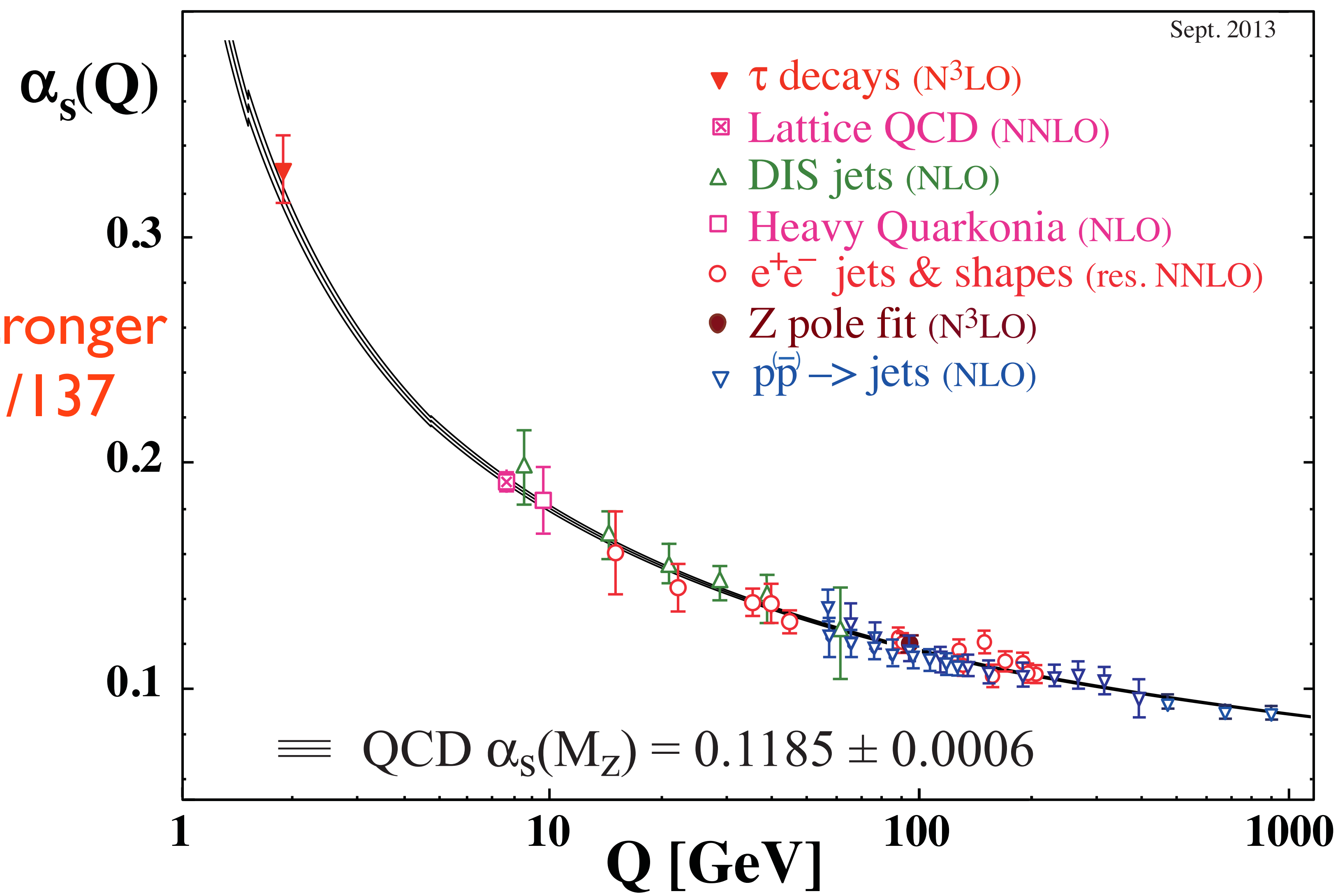
Asymptotic Freedom

- Strength of QCD force weakens at higher energies (shorter distances)

Nobel prize in 2004 to D. Gross, F. Wilczek & D. Politzer

- Different behaviors we see at the keV, MeV, GeV, TeV scales

still much stronger than α_{EM} ~1/137



From PDG review on QCD

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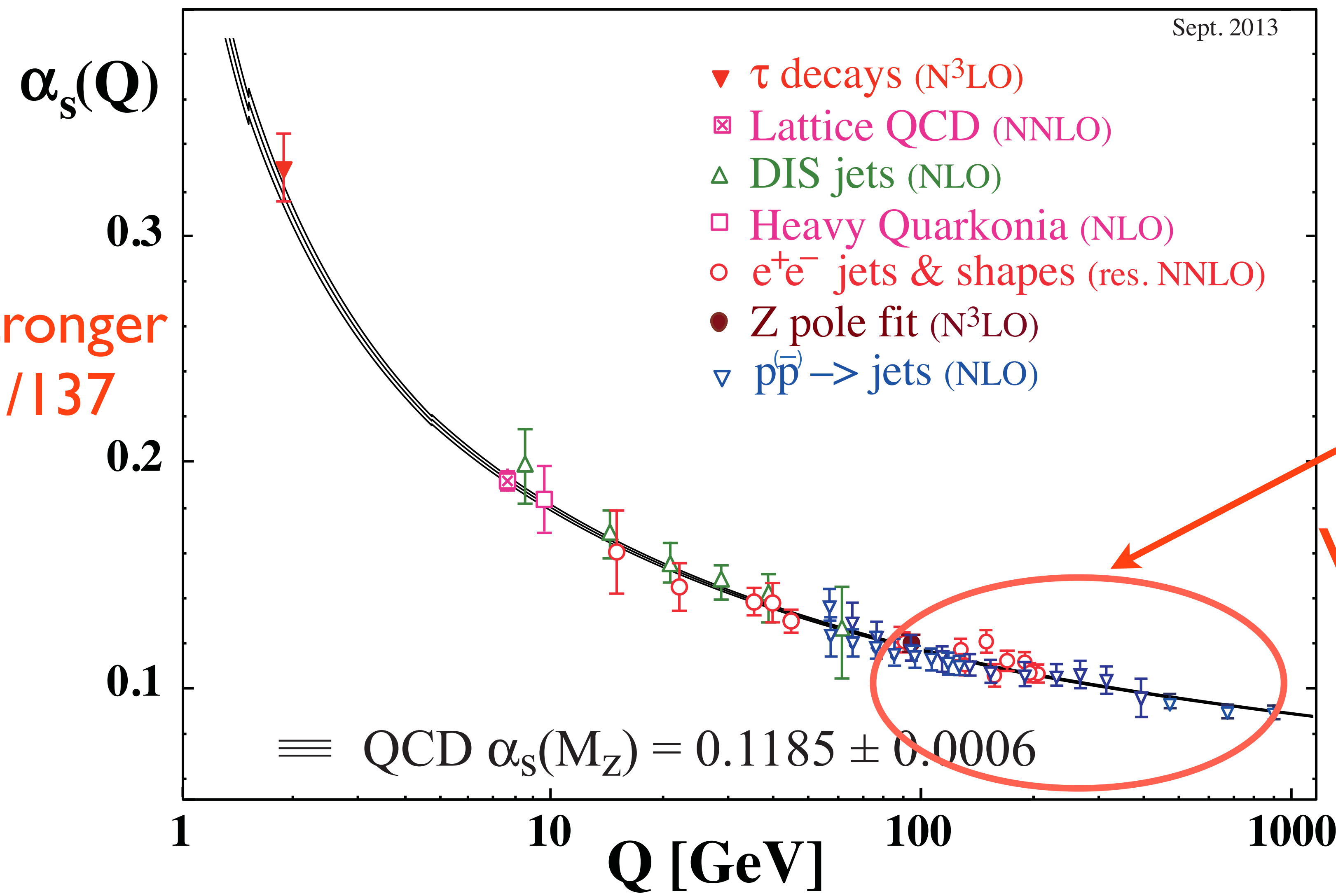

high energies - weaker coupling

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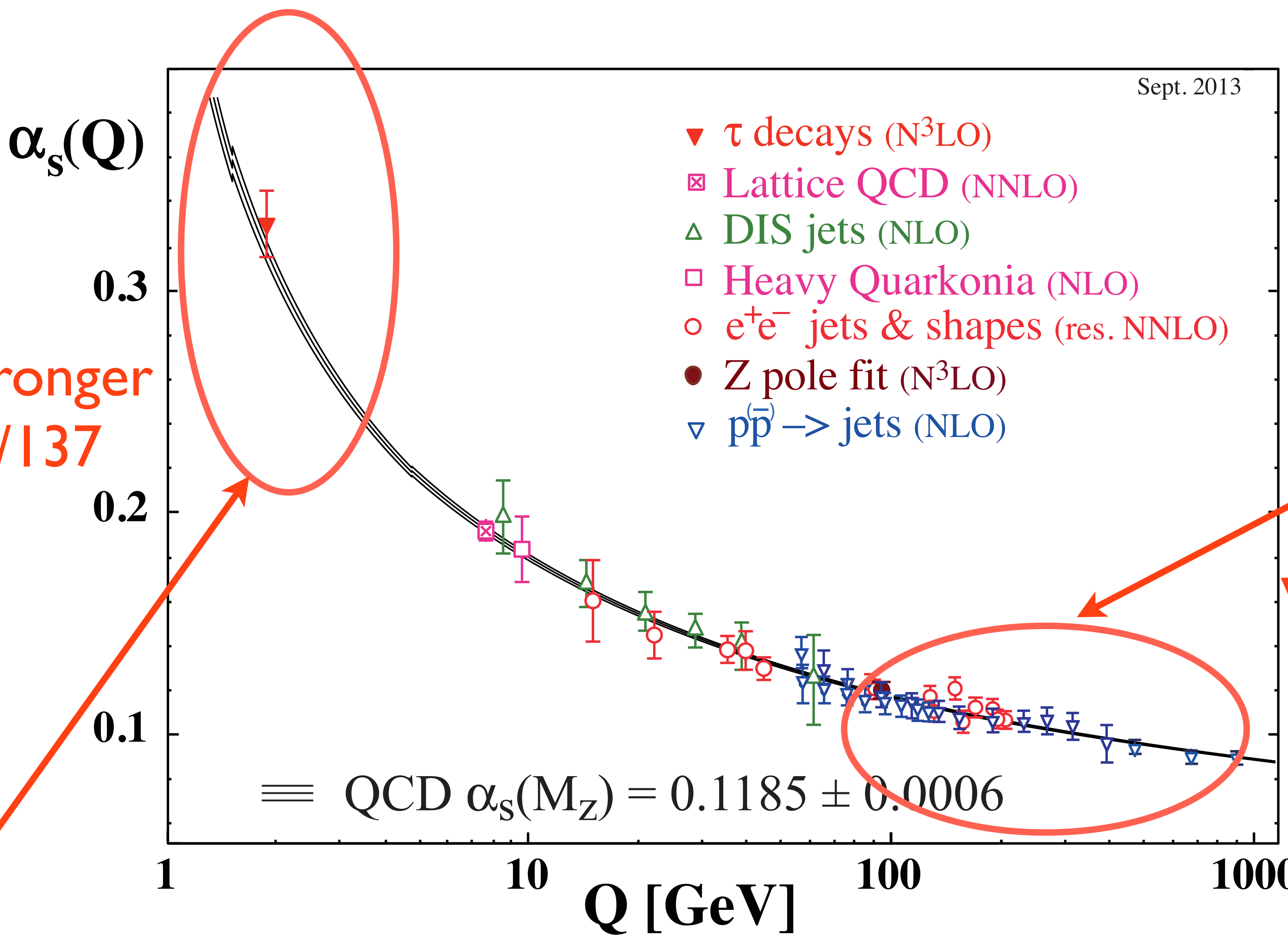


high energies - weaker coupling

From PDG review on QCD

But what about low energies?

QCD at the GeV Scale

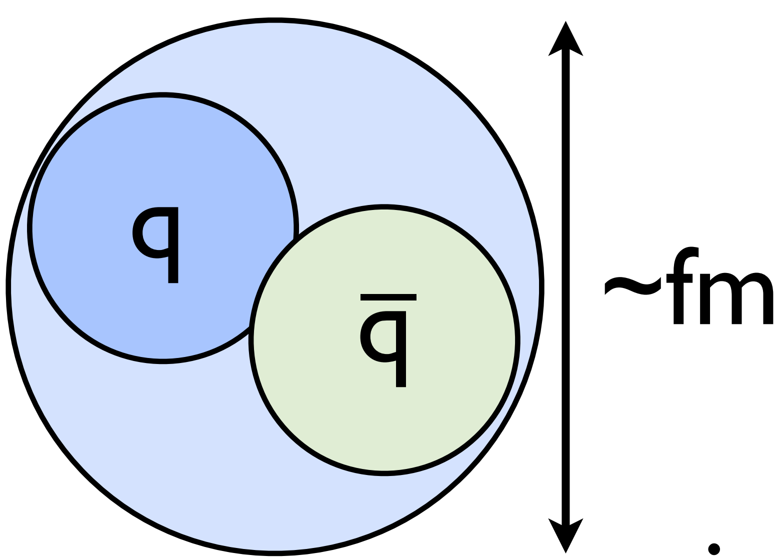
- QCD particles with masses of ~GeV ⇒ creation of new particles, can study interactions
- Particles of the strong force = hadrons account for most of our mass
- Typical interaction energy of GeV - uncertainty principle tells us that

$$\Delta E \Delta t \simeq \hbar$$

- Typical time scale of 10^{-23} s, length scale of 10^{-15} m

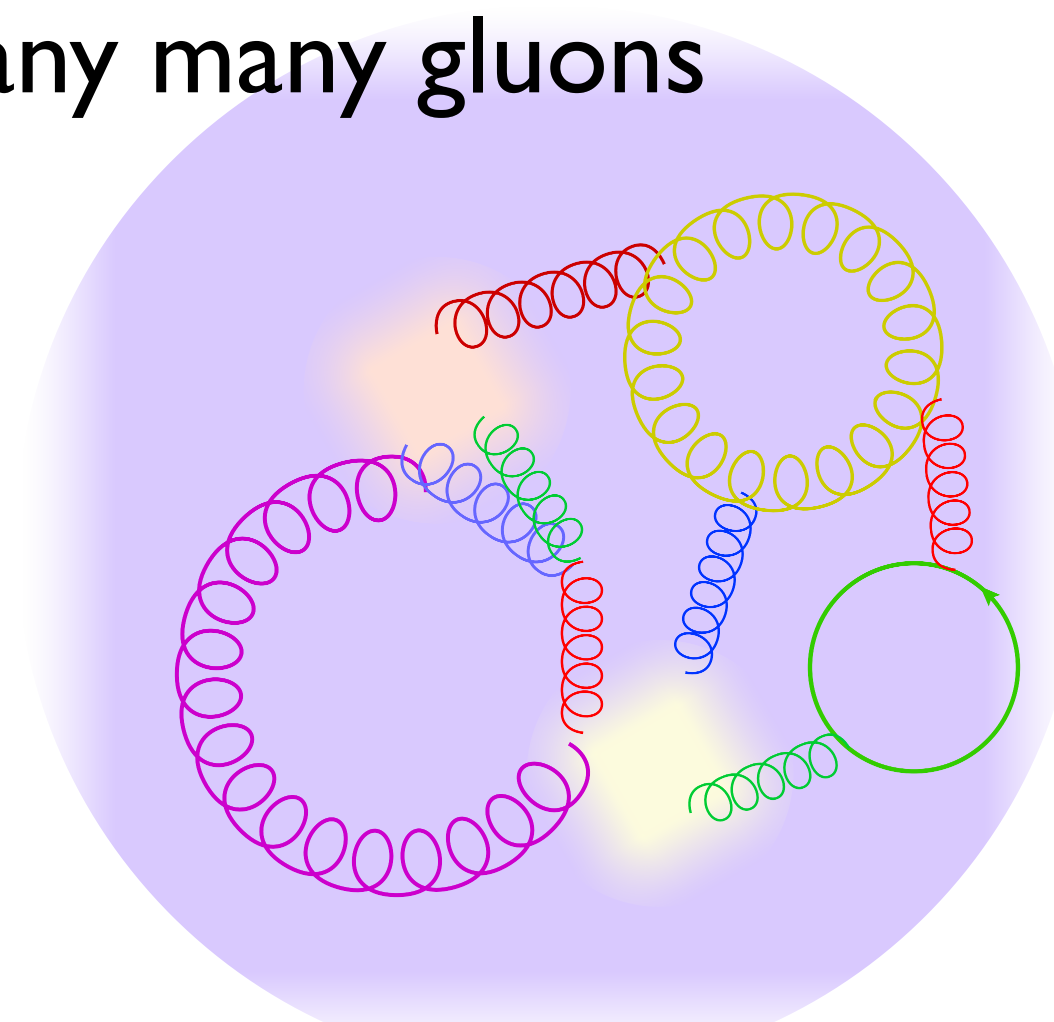
QCD Particles

- "Particles" are bound states of quarks and gluons
- Quarks and gluons are confined within bound states - overall "color neutral"
- "Constituent" quarks give basic properties of states
- Also the "sea" of quarks, and many many gluons coupling!



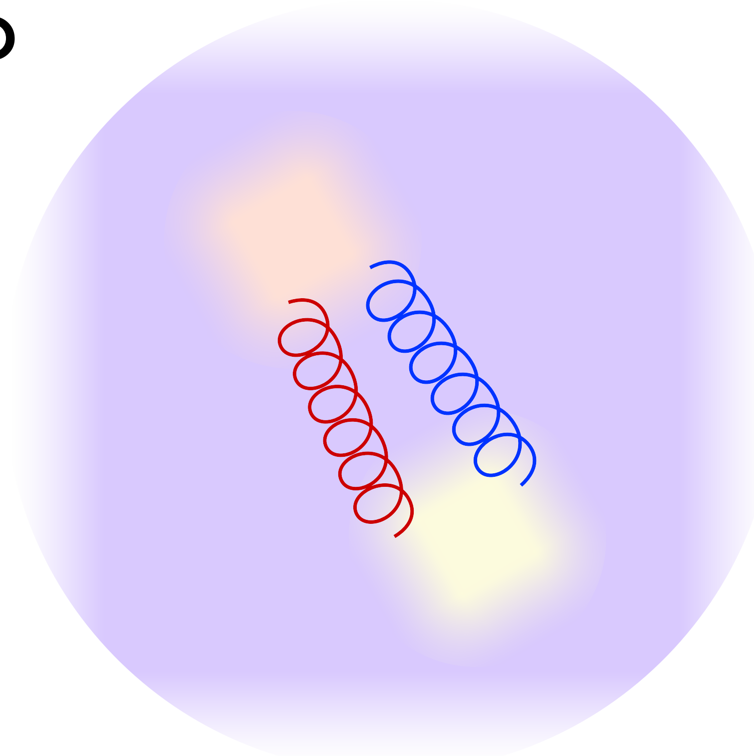
naive picture

reality

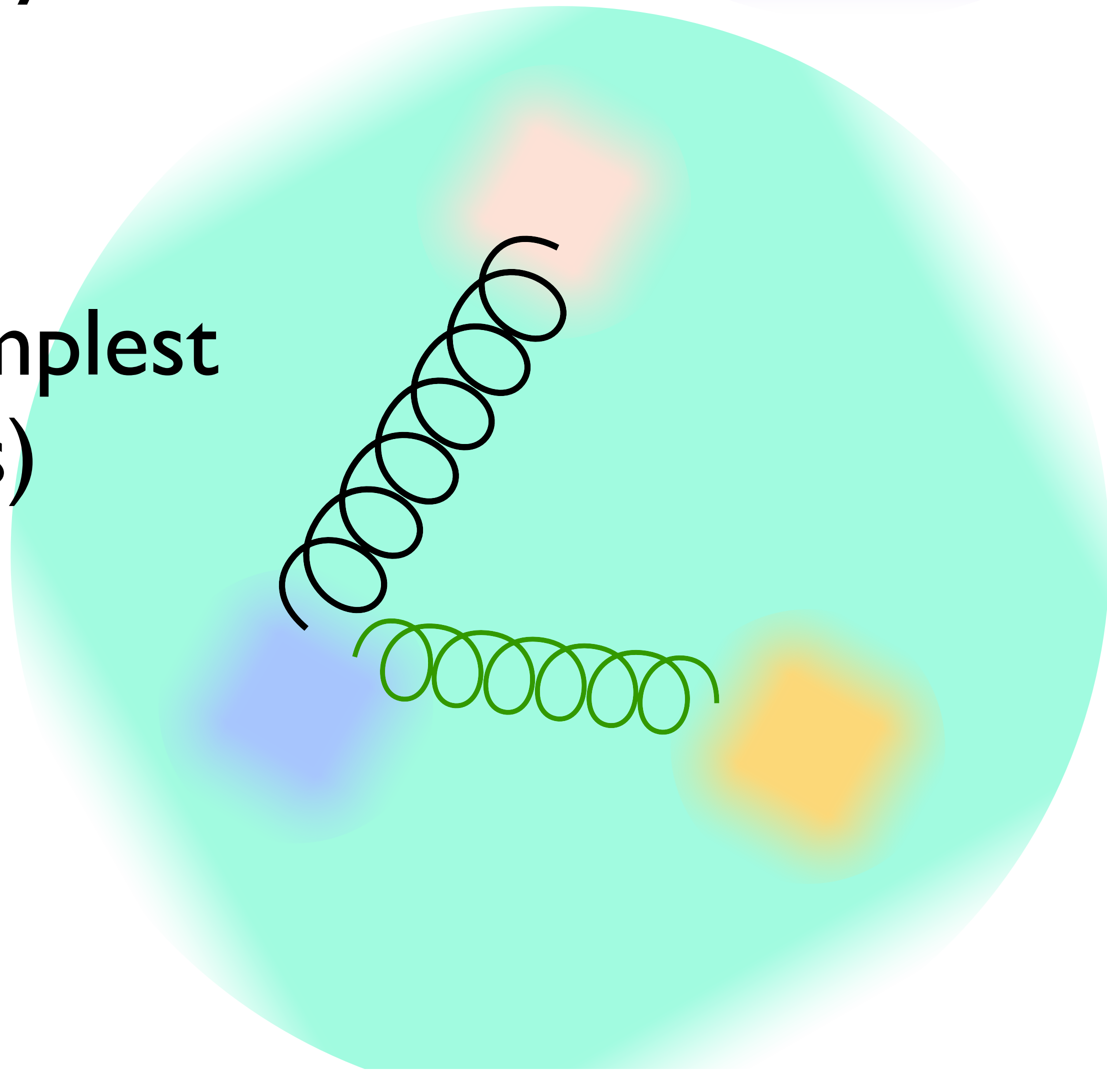


Two Kinds of Hadrons

- Mesons are bosons, typically thought to be a quark and antiquark ($q\bar{q}$)
- pions (π), kaons (K), etc.



- Baryons are fermions, typically thought to consist of three (anti)quarks (qqq or $\bar{q}\bar{q}\bar{q}$)
- Protons and neutrons are simplest (and lowest energy examples)



The Known QCD States

mesons

LIGHT UNFLAVORED ($S = C = B = 0$)

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $f_0(500)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	$a_2(1700)$	$1^-(2^{++})$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $\phi(1020)$	$0^-(1^{--})$	$X(1835)$	$?^?(?^{-+})$
• $h_1(1170)$	$0^-(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $b_1(1235)$	$1^+(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $a_1(1260)$	$1^-(1^{++})$	• $\pi_2(1880)$	$1^-(2^{-+})$
• $f_2(1270)$	$0^+(2^{++})$	$\rho(1900)$	$1^+(1^{--})$
• $f_1(1285)$	$0^+(1^{++})$	$f_2(1910)$	$0^+(2^{++})$
• $\eta(1295)$	$0^+(0^{-+})$	• $f_2(1950)$	$0^+(2^{++})$
• $\pi(1300)$	$1^-(0^{-+})$	$\rho_3(1990)$	$1^+(3^{--})$
• $a_2(1320)$	$1^-(2^{++})$	• $f_2(2010)$	$0^+(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$	$f_0(2020)$	$0^+(0^{++})$
$h_1(1380)$	$?^-(1^{+-})$	• $a_4(2040)$	$1^-(4^{++})$
• $\pi_1(1400)$	$1^-(1^{-+})$	• $f_4(2050)$	$0^+(4^{++})$
• $\eta(1405)$	$0^+(0^{-+})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $f_1(1420)$	$0^+(1^{++})$	$f_0(2100)$	$0^+(0^{++})$
• $\omega(1420)$	$0^-(1^{--})$	$f_2(2150)$	$0^+(2^{++})$
$f_2(1430)$	$0^+(2^{++})$	$\rho(2150)$	$1^+(1^{--})$
• $a_0(1450)$	$1^-(0^{++})$	• $\phi(2170)$	$0^-(1^{--})$
• $\rho(1450)$	$1^+(1^{--})$	$f_0(2200)$	$0^+(0^{++})$
• $\eta(1475)$	$0^+(0^{-+})$	$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
• $f_0(1500)$	$0^+(0^{++})$		
$f_1(1510)$	$0^+(1^{++})$	$\eta(2225)$	$0^+(0^{-+})$
• $f_2'(1525)$	$0^+(2^{++})$	$\rho_3(2250)$	$1^+(3^{--})$
$f_2(1565)$	$0^+(2^{++})$	• $f_2(2300)$	$0^+(2^{++})$
$\rho(1570)$	$1^+(1^{--})$	$f_4(2300)$	$0^+(4^{++})$
$h_1(1595)$	$0^-(1^{+-})$	$f_0(2330)$	$0^+(0^{++})$
• $\pi_1(1600)$	$1^-(1^{-+})$	• $f_2(2340)$	$0^+(2^{++})$
$a_1(1640)$	$1^-(1^{++})$	$\rho_5(2350)$	$1^+(5^{--})$
$f_2(1640)$	$0^+(2^{++})$	$a_6(2450)$	$1^-(6^{++})$
• $\eta_2(1645)$	$0^+(2^{-+})$	$f_6(2510)$	$0^+(6^{++})$
• $\omega(1650)$	$0^-(1^{--})$		
• $\omega_3(1670)$	$0^-(3^{--})$		

OTHER LIGHT

Further States

STRANGE ($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K^0_S	$1/2(0^-)$
• K^0_L	$1/2(0^-)$
$K_0^*(800)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K_0^*(1430)$	$1/2(0^+)$
• $K_2^*(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K_3^*(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K_0^*(1950)$	$1/2(0^+)$
$K_2^*(1980)$	$1/2(2^+)$
• $K_4^*(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K_5^*(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED ($C = \pm1$)

• $D^\pm$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
• $D_0^*(2400)^0$	$1/2(0^+)$
$D_0^*(2400)^\pm$	$1/2(0^+)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^\pm$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)^0$	$1/2(2^+)$
• $D_2^*(2460)^\pm$	$1/2(2^+)$
$D(2550)^0$	$1/2(0^-)$
$D(2600)$	$1/2(?^?)$
$D^*(2640)^\pm$	$1/2(?^?)$
$D(2750)$	$1/2(?^?)$

CHARMED, STRANGE ($C = S = \pm1$)

	$I(J^P)$
• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}(2573)$	$0(?^?)$
• $D_{s1}^*(2700)^\pm$	$0(1^-)$
$D_{sJ}^*(2860)^\pm$	$0(?^?)$
$D_{sJ}(3040)^\pm$	$0(?^?)$

BOTTOM ($B = \pm1$)

• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B^0_s/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
$B_J^*(5732)$	$?(?^?)$
• $B_1(5721)^0$	$1/2(1^+)$
• $B_2^*(5747)^0$	$1/2(2^+)$

BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$)

• B_s^0	$0(0^-)$
• B_s^*	$0(1^-)$
• $B_{s1}(5830)^0$	$0(1^+)$
• $B_{s2}^*(5840)^0$	$0(2^+)$
$B_{sJ}^*(5850)$	$?(?^?)$

BOTTOM, CHARMED ($B = C = \pm1$)

• $B_c^\pm$	$0(0^-)$

$c\bar{c}$

	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$?^?(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $X(3872)$	$0^+(1^{++})$
• $\chi_{c0}(2P)$	$0^+(0^{++})$
• $\chi_{c2}(2P)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
• $\psi(4040)$	$0^-(1^{--})$
$X(4050)^\pm$	$?(?^?)$
$X(4140)$	$0^+(?^{?+})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
$X(4250)^\pm$	$?(?^?)$
• $X(4260)$	$?^?(1^{--})$
$X(4350)$	$0^+(?^{?+})$
• $X(4360)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
$X(4430)^\pm$	$?(?^?)$
• $X(4660)$	$?^?(1^{--})$

$b\bar{b}$

$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $h_b(1P)$	$?^?(1^{+-})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
$\eta_b(2S)$	$0^+(0^{-+})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\Upsilon(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
$h_b(2P)$	$?^?(1^{+-})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\chi_b(3P)$	$?^?(?^{?+})$
• $\Upsilon(4S)$	$0^-(1^{--})$
$X(10610)^\pm$	$?^+(1^+)$
$X(10650)^\pm$	$?^+(1^+)$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

baryons

p	$1/2^+$	****
n	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1685)$		*
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	***
$N(1720)$	$3/2^+$	****
$N(1860)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***
$N(1880)$	$1/2^+$	**
$N(1895)$	$1/2^-$	**
$N(1900)$	$3/2^+$	***
$N(1990)$	$7/2^+$	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	**
$N(2100)$	$1/2^+$	*
$N(2120)$	$3/2^-$	**
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2300)$	$1/2^+$	**
$N(2570)$	$5/2^-$	**
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**

$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	***
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	**
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(1920)$	$3/2^+$	***
$\Delta(1930)$	$5/2^-$	***
$\Delta(1940)$	$3/2^-$	**
$\Delta(1950)$	$7/2^+$	****
$\Delta(2000)$	$5/2^+$	**
$\Delta(2150)$	$1/2^-$	*
$\Delta(2200)$	$7/2^-$	*
$\Delta(2300)$	$9/2^+$	**
$\Delta(2350)$	$5/2^-$	*
$\Delta(2390)$	$7/2^+$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
$\Delta(2750)$	$13/2^-$	**
$\Delta(2950)$	$15/2^+$	**

Λ	$1/2^+$	****
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	***
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	$3/2^-$	****
$\Lambda(1800)$	$1/2^-$	***
$\Lambda(1810)$	$1/2^+$	***
$\Lambda(1820)$	$5/2^+$	****
$\Lambda(1830)$	$5/2^-$	****
$\Lambda(1890)$	$3/2^+$	****
$\Lambda(2000)$		*
$\Lambda(2020)$	$7/2^+$	*
$\Lambda(2100)$	$7/2^-$	****
$\Lambda(2110)$	$5/2^+$	***
$\Lambda(2325)$	$3/2^-$	*
$\Lambda(2350)$	$9/2^+$	***
$\Lambda(2585)$		**

Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
$\Sigma(1385)$	$3/2^+$	****
$\Sigma(1480)$		*
$\Sigma(1560)$		**
$\Sigma(1580)$	$3/2^-$	*
$\Sigma(1620)$	$1/2^-$	*
$\Sigma(1660)$	$1/2^+$	***
$\Sigma(1670)$	$3/2^-$	****
$\Sigma(1690)$		**
$\Sigma(1750)$	$1/2^-$	***
$\Sigma(1770)$	$1/2^+$	*
$\Sigma(1775)$	$5/2^-$	****
$\Sigma(1840)$	$3/2^+$	*
$\Sigma(1880)$	$1/2^+$	**
$\Sigma(1915)$	$5/2^+$	****
$\Sigma(1940)$	$3/2^-$	***
$\Sigma(2000)$	$1/2^-$	*
$\Sigma(2030)$	$7/2^+$	****
$\Sigma(2070)$	$5/2^+$	*
$\Sigma(2080)$	$3/2^+$	**
$\Sigma(2100)$	$7/2^-$	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(1530)$	$3/2^+$	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	$3/2^-$	***
$\Xi(1950)$		***
$\Xi(2030)$	$\geq \frac{5}{2}^?$	***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-	$3/2^+$	****
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

From PDG reviews

The Known QCD States

mesons

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$\pi^\pm$	$1^-(0^-)$	$\pi_2(1670)$	$1^-(2^{-+})$
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η	$0^+(0^{-+})$	$\rho_3(1690)$	$1^+(3^{--})$
$f_0(500)$	$0^+(0^{++})$	$\rho(1700)$	$1^+(1^{--})$
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$f_0(980)$	$0^+(0^{++})$	$\pi(1800)$	$1^-(0^{-+})$
$a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
$\phi(1020)$	$0^-(1^{--})$	$X(1835)$	$?^?(?^{-+})$
$h_1(1170)$	$0^-(1^{+-})$	$\phi_3(1850)$	$0^-(3^{--})$
$b_1(1235)$	$1^+(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$
$a_1(1260)$	$1^-(1^{++})$	$\pi_2(1880)$	$1^-(2^{-+})$
$f_2(1270)$	$0^+(2^{++})$	$\rho(1900)$	$1^+(1^{--})$
$f_1(1285)$	$0^+(1^{++})$	$f_2(1910)$	$0^+(2^{++})$
$\eta(1295)$	$0^+(0^{-+})$	$f_2(1950)$	$0^+(2^{++})$
$\pi(1300)$	$1^-(0^{-+})$	$\rho_3(1990)$	$1^+(3^{--})$
$a_2(1320)$	$1^-(2^{++})$	$f_2(2010)$	$0^+(2^{++})$
$f_0(1370)$	$0^+(0^{++})$	$f_0(2020)$	$0^+(0^{++})$
$h_1(1380)$	$?^-(1^{+-})$	$a_4(2040)$	$1^-(4^{++})$
$\pi_1(1400)$	$1^-(1^{-+})$	$f_4(2050)$	$0^+(4^{++})$
$\eta(1405)$	$0^+(0^{-+})$	$\pi_2(2100)$	$1^-(2^{-+})$
$f_1(1420)$	$0^+(1^{++})$	$f_0(2100)$	$0^+(0^{++})$
$\omega(1420)$	$0^-(1^{--})$	$f_2(2150)$	$0^+(2^{++})$
$f_2(1430)$	$0^+(2^{++})$	$\rho(2150)$	$1^+(1^{--})$
$a_0(1450)$	$1^-(0^{++})$	$\phi(2170)$	$0^-(1^{--})$
$\rho(1450)$	$1^+(1^{--})$	$f_0(2200)$	$0^+(0^{++})$
$\eta(1475)$	$0^+(0^{-+})$	$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
$f_0(1500)$	$0^+(0^{++})$	$\eta(2225)$	$0^+(0^{-+})$
$f_1(1510)$	$0^+(1^{++})$	$\rho_3(2250)$	$1^+(3^{--})$
$f_2'(1525)$	$0^+(2^{++})$	$f_2(2300)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$	$f_4(2300)$	$0^+(4^{++})$
$\rho(1570)$	$1^+(1^{--})$	$f_0(2330)$	$0^+(0^{++})$
$h_1(1595)$	$0^-(1^{+-})$	$f_2(2340)$	$0^+(2^{++})$
$\pi_1(1600)$	$1^-(1^{-+})$	$\rho_5(2350)$	$1^+(5^{--})$
$a_1(1640)$	$1^-(1^{++})$	$a_6(2450)$	$1^-(6^{++})$
$f_2(1640)$	$0^+(2^{++})$	$f_6(2510)$	$0^+(6^{++})$
$\eta_2(1645)$	$0^+(2^{-+})$	OTHER LIGHT	
$\omega(1650)$	$0^-(1^{--})$	Further States	
$\omega_3(1670)$	$0^-(3^{--})$		

STRANGE ($S=\pm1$, $C=B=0$)	$I(J^P)$
$K^\pm$	$1/2(0^-)$
K^0	$1/2(0^-)$
K^0_S	$1/2(0^-)$
K^0_L	$1/2(0^-)$
$K_0^*(800)$	$1/2(0^+)$
$K^*(892)$	$1/2(1^-)$
$K_1(1270)$	$1/2(1^+)$
$K_1(1400)$	$1/2(1^+)$
$K^*(1410)$	$1/2(1^-)$
$K_0^*(1430)$	$1/2(0^+)$
$K_2^*(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
$K^*(1680)$	$1/2(1^-)$
$K_2(1770)$	$1/2(2^-)$
$K_3^*(1780)$	$1/2(3^-)$
$K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K_0^*(1950)$	$1/2(0^+)$
$K_2^*(1980)$	$1/2(2^+)$
$K_4^*(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K_5^*(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^?)$
CHARMED ($C=\pm1$)	
$D^\pm$	$1/2(0^-)$
D^0	$1/2(0^-)$
$D^*(2007)^0$	$1/2(1^-)$
$D^*(2010)^\pm$	$1/2(1^-)$
$D_0^*(2400)^0$	$1/2(0^+)$
$D_0^*(2400)^\pm$	$1/2(0^+)$
$D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^\pm$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
$D_2^*(2460)^0$	$1/2(2^+)$
$D_2^*(2460)^\pm$	$1/2(2^+)$
$D(2550)^0$	$1/2(0^-)$
$D(2600)$	$1/2(?^?)$
$D^*(2640)^\pm$	$1/2(?^?)$
$D(2750)$	$1/2(?^?)$

CHARMED, STRANGE ($C=S=\pm1$)	$I(J^P)$
$D_s^\pm$	$0(0^-)$
$D_s^{*\pm}$	$0(?^?)$
$D_{s0}^*(2317)^\pm$	$0(0^+)$
$D_{s1}(2460)^\pm$	$0(1^+)$
$D_{s1}(2536)^\pm$	$0(1^+)$
$D_{s2}(2573)$	$0(?^?)$
$D_{s1}^*(2700)^\pm$	$0(1^-)$
$D_{sJ}^*(2860)^\pm$	$0(?^?)$
$D_{sJ}(3040)^\pm$	$0(?^?)$
BOTTOM ($B=\pm1$)	
$B^\pm$	$1/2(0^-)$
B^0	$1/2(0^-)$
$B^\pm/B^0$ ADMIXTURE	
$B^\pm/B^0/B^0_s/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
B^*	$1/2(1^-)$
$B_J^*(5732)$	$?(?^?)$
$B_1(5721)^0$	$1/2(1^+)$
$B_2^*(5747)^0$	$1/2(2^+)$
BOTTOM, STRANGE ($B=\pm1$, $S=\mp1$)	
B_s^0	$0(0^-)$
B_s^*	$0(1^-)$
$B_{s1}(5830)^0$	$0(1^+)$
$B_{s2}^*(5840)^0$	$0(2^+)$
$B_{sJ}^*(5850)$	$?(?^?)$
BOTTOM, CHARMED ($B=C=\pm1$)	
$B_c^\pm$	$0(0^-)$

$c\bar{c}$	$I^G(J^{PC})$
$\eta_c(1S)$	$0^+(0^{-+})$
$J/\psi(1S)$	$0^-(1^{--})$
$\chi_{c0}(1P)$	$0^+(0^{++})$
$\chi_{c1}(1P)$	$0^+(1^{++})$
$h_c(1P)$	$?^?(1^{+-})$
$\chi_{c2}(1P)$	$0^+(2^{++})$
$\eta_c(2S)$	$0^+(0^{-+})$
$\psi(2S)$	$0^-(1^{--})$
$\psi(3770)$	$0^-(1^{--})$
$X(3872)$	$0^+(1^{++})$
$\chi_{c0}(2P)$	$0^+(0^{++})$
$\chi_{c2}(2P)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
$\psi(4040)$	$0^-(1^{--})$
$X(4050)^\pm$	$?(?^?)$
$X(4140)$	$0^+(?^{?+})$
$\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
$X(4250)^\pm$	$?(?^?)$
$X(4260)$	$?^?(1^{--})$
$X(4350)$	$0^+(?^{?+})$
$X(4360)$	$?^?(1^{--})$
$\psi(4415)$	$0^-(1^{--})$
$X(4430)^\pm$	$?(?^?)$
$X(4660)$	$?^?(1^{--})$
$b\bar{b}$	
$\eta_b(1S)$	$0^+(0^{-+})$
$\Upsilon(1S)$	$0^-(1^{--})$
$\chi_{b0}(1P)$	$0^+(0^{++})$
$\chi_{b1}(1P)$	$0^+(1^{++})$
$h_b(1P)$	$?^?(1^{+-})$
$\chi_{b2}(1P)$	$0^+(2^{++})$
$\eta_b(2S)$	$0^+(0^{-+})$
$\Upsilon(2S)$	$0^-(1^{--})$
$\Upsilon(1D)$	$0^-(2^{--})$
$\chi_{b0}(2P)$	$0^+(0^{++})$
$\chi_{b1}(2P)$	$0^+(1^{++})$
$h_b(2P)$	$?^?(1^{+-})$
$\chi_{b2}(2P)$	$0^+(2^{++})$
$\Upsilon(3S)$	$0^-(1^{--})$
$\chi_b(3P)$	$?^?(?^{?+})$
$\Upsilon(4S)$	$0^-(1^{--})$
$X(10610)^\pm$	$?^+(1^+)$
$X(10650)^\pm$	$?^+(1^+)$
$\Upsilon(10860)$	$0^-(1^{--})$
$\Upsilon(11020)$	$0^-(1^{--})$

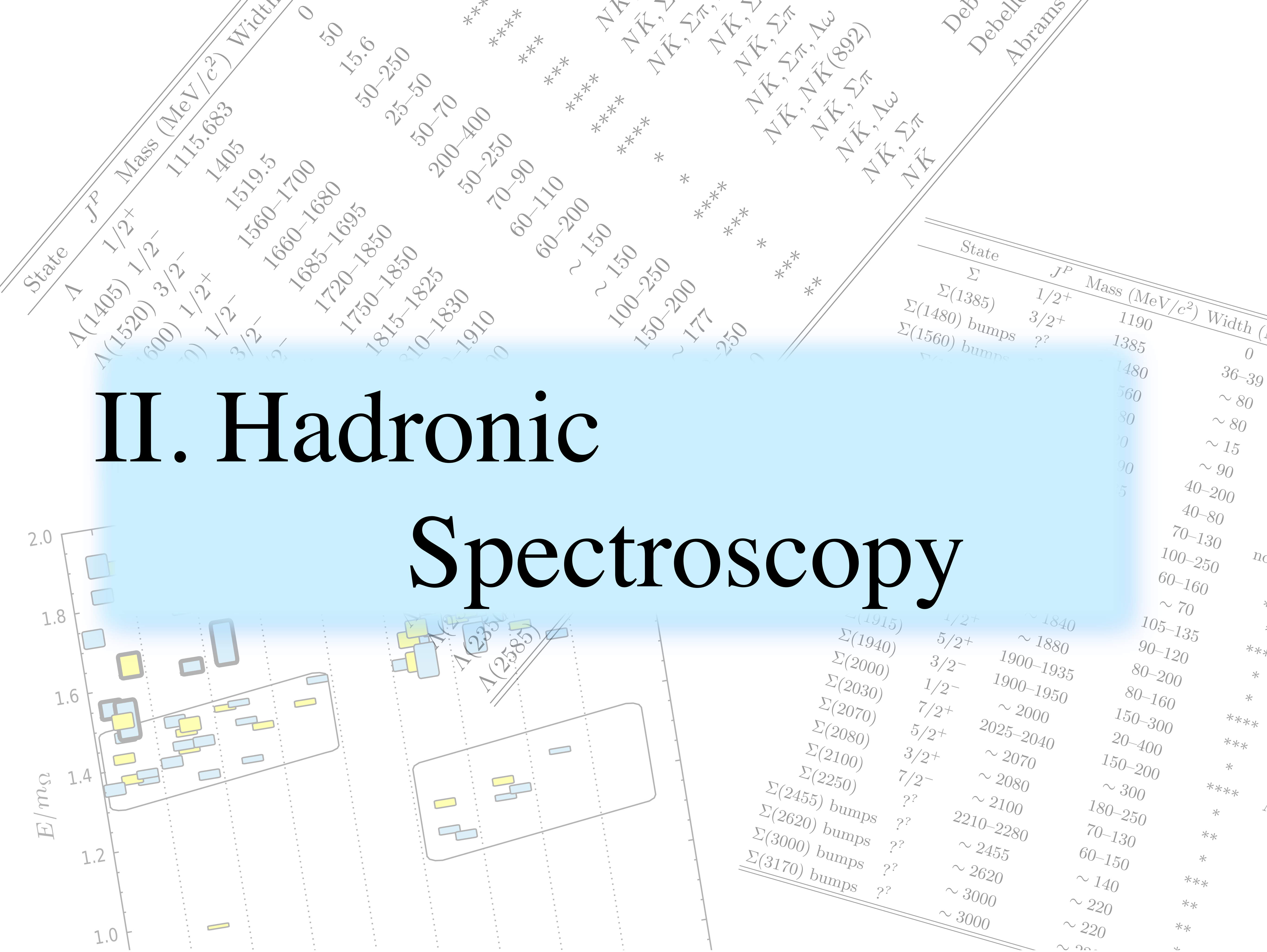
baryons

p	$1/2^+$	****	$\Delta(1232)$	$3/2^+$	****
n	$1/2^+$	****	$\Delta(1600)$	$3/2^+$	***
$N(1440)$	$1/2^+$	****	$\Delta(1620)$	$1/2^-$	****
$N(1520)$	$3/2^-$	****	$\Delta(1700)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****	$\Delta(1750)$	$1/2^+$	*
$N(1650)$	$1/2^-$	****	$\Delta(1900)$	$1/2^-$	**
$N(1675)$	$5/2^-$	****	$\Delta(1905)$	$5/2^+$	****
$N(1680)$	$5/2^+$	****	$\Delta(1910)$	$1/2^+$	****
$N(1685)$		*	$\Delta(1920)$	$3/2^+$	***
$N(1700)$	$3/2^-$	***	$\Delta(1930)$	$5/2^-$	***
$N(1710)$	$1/2^+$	***	$\Delta(1940)$	$3/2^-$	**
$N(1720)$	$3/2^+$	****	$\Delta(1950)$	$7/2^+$	****
$N(1860)$	$5/2^+$	**	$\Delta(2000)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***	$\Delta(2150)$	$1/2^-$	*
$N(1880)$	$1/2^+$	**	$\Delta(2200)$	$7/2^-$	*
$N(1895)$	$1/2^-$	**	$\Delta(2300)$	$9/2^+$	**
$N(1900)$	$3/2^+$	***	$\Delta(2350)$	$5/2^-$	*
$N(1990)$	$7/2^+$	**	$\Delta(2390)$	$7/2^+$	*
$N(2000)$	$5/2^+$	**	$\Delta(2400)$	$9/2^-$	**
$N(2040)$	$3/2^+$	*	$\Delta(2420)$	$11/2^+$	****
$N(2060)$	$5/2^-$	**	$\Delta(2750)$	$13/2^-$	**
$N(2100)$	$1/2^+$	*	$\Delta(2950)$	$15/2^+$	**
$N(2120)$	$3/2^-$	**			
$N(2190)$	$7/2^-$	****	Λ	$1/2^+$	****
$N(2220)$	$9/2^+$	****	$\Lambda(1405)$	$1/2^-$	****
$N(2250)$	$9/2^-$	****	$\Lambda(1520)$	$3/2^-$	****
$N(2300)$	$1/2^+$	**	$\Lambda(1600)$	$1/2^+$	***
$N(2570)$	$5/2^-$	**	$\Lambda(1670)$	$1/2^-$	****
$N(2600)$	$11/2^-$	***	$\Lambda(1690)$	$3/2^-$	****
$N(2700)$	$13/2^+$	**	$\Lambda(1800)$	$1/2^-$	***
			$\Lambda(1810)$	$1/2^+$	***
			$\Lambda(1820)$	$5/2^+$	****
			$\Lambda(1830)$	$5/2^-$	****
			$\Lambda(1890)$	$3/2^+$	****
			$\Lambda(2000)$		*
			$\Lambda(2020)$	$7/2^+$	*
			$\Lambda(2100)$	$7/2^-$	****
			$\Lambda(2110)$	$5/2^+$	***
			$\Lambda(2325)$	$3/2^-$	*
			$\Lambda(2350)$	$9/2^+$	***
			$\Lambda(2585)$		**

Σ^+	$1/2^+$	****	Ξ^0	$1/2^+$	****
Σ^0	$1/2^+$	****	Ξ^-	$1/2^+$	****
Σ^-	$1/2^+$	****	$\Xi(1530)$	$3/2^+$	****
$\Sigma(1385)$	$3/2^+$	****	$\Xi(1620)$		*
$\Sigma(1480)$		*	$\Xi(1690)$		***
$\Sigma(1560)$		**	$\Xi(1820)$	$3/2^-$	***
$\Sigma(1580)$	$3/2^-$	*	$\Xi(1950)$		***
$\Sigma(1620)$	$1/2^-$	*	$\Xi(2030)$	$\geq \frac{5}{2}^?$	***
$\Sigma(1660)$	$1/2^+$	***	$\Xi(2120)$		*
$\Sigma(1670)$	$3/2^-$	****	$\Xi(2250)$		**
$\Sigma(1690)$		**	$\Xi(2370)$		**
$\Sigma(1750)$	$1/2^-$	***	$\Xi(2500)$		*
$\Sigma(1770)$	$1/2^+$	*			
$\Sigma(1775)$	$5/2^-$	****	Ω^-	$3/2^+$	****
$\Sigma(1840)$	$3/2^+$	*	$\Omega(2250)^-$		***
$\Sigma(1880)$	$1/2^+$	**	$\Omega(2380)^-$		**
$\Sigma(1915)$	$5/2^+$	****	$\Omega(2470)^-$		**
$\Sigma(1940)$	$3/2^-$	***			
$\Sigma(2000)$	$1/2^-$	*			
$\Sigma(2030)$	$7/2^+$	****			
$\Sigma(2070)$	$5/2^+$	*			
$\Sigma(2080)$	$3/2^+$	**			
$\Sigma(2100)$	$7/2^-$	*			
$\Sigma(2250)$		***			
$\Sigma(2455)$		**			
$\Sigma(2620)$		**			
$\Sigma(3000)$		*			
$\Sigma(3170)$		*			

How do we understand this?

From PDG reviews



II. Hadronic Spectroscopy

Bringing Order to the Chaos

LIGHT UNFLAVORED ($S = C = B = 0$)	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $f_0(500)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	$a_2(1700)$	$1^-(2^{++})$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $\phi(1020)$	$0^-(1^{--})$	$X(1835)$	$?^?(?^{-+})$
• $h_1(1170)$	$0^-(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $b_1(1235)$	$1^+(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $a_1(1260)$	$1^-(1^{++})$	• $\pi_2(1880)$	$1^-(2^{-+})$
• $f_2(1270)$	$0^+(2^{++})$	$\rho(1900)$	$1^+(1^{--})$
• $f_1(1285)$	$0^+(1^{++})$	$f_2(1910)$	$0^+(2^{++})$
• $\eta(1295)$	$0^+(0^{-+})$	• $f_2(1950)$	$0^+(2^{++})$
• $\pi(1300)$	$1^-(0^{-+})$	$\rho_3(1990)$	$1^+(3^{--})$
• $a_2(1320)$	$1^-(2^{++})$	• $f_2(2010)$	$0^+(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$	$f_0(2020)$	$0^+(0^{++})$
$h_1(1380)$	$?^-(1^{+-})$	• $a_4(2040)$	$1^-(4^{++})$
• $\pi_1(1400)$	$1^-(1^{-+})$	• $f_4(2050)$	$0^+(4^{++})$
• $\eta(1405)$	$0^+(0^{-+})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $f_1(1420)$	$0^+(1^{++})$	$f_0(2100)$	$0^+(0^{++})$
• $\omega(1420)$	$0^-(1^{--})$	$f_2(2150)$	$0^+(2^{++})$
$f_2(1430)$	$0^+(2^{++})$	$\rho(2150)$	$1^+(1^{--})$
• $a_0(1450)$	$1^-(0^{++})$	• $\phi(2170)$	$0^-(1^{--})$
• $\rho(1450)$	$1^+(1^{--})$	$f_0(2200)$	$0^+(0^{++})$
• $\eta(1475)$	$0^+(0^{-+})$	$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
• $f_0(1500)$	$0^+(0^{++})$		
$f_1(1510)$	$0^+(1^{++})$	$\eta(2225)$	$0^+(0^{-+})$

STRANGE ($S = \pm1, C = B = 0$)	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K^0_S	$1/2(0^-)$
• K^0_L	$1/2(0^-)$
$K^*_0(800)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K^*_0(1430)$	$1/2(0^+)$
• $K^*_2(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K^*_3(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K^*_0(1950)$	$1/2(0^+)$
$K^*_2(1980)$	$1/2(2^+)$
• $K^*_4(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K^*_5(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED

CHARMED, STRANGE ($C = S = \pm1$)	$I(J^P)$
• $D^\pm_s$	$0(0^-)$
• $D^{*\pm}_s$	$0(?^?)$
• $D^*_{s0}(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}(2573)$	$0(?^?)$
• $D^*_{s1}(2700)^\pm$	$0(1^-)$
$D^*_{sJ}(2860)^\pm$	$0(?^?)$
$D_{sJ}(3040)^\pm$	$0(?^?)$

BOTTOM ($B = \pm1$)	
• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B^0_s/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
$B^*_J(5732)$	$?(?^?)$
• $B_1(5721)^0$	$1/2(1^+)$
• $B^*_2(5747)^0$	$1/2(2^+)$

BOTTOM, STRANGE ($B = \pm1, S = \mp1$)	
• B^0_s	$0(0^-)$
• B^*_s	$0(1^-)$
• $B_{s1}(5830)^0$	$0(1^+)$
• $B^*_{s2}(5840)^0$	$0(2^+)$
$B^*_{sJ}(5850)$	$?(?^?)$

$c\overline{c}$	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$?^?(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $X(3872)$	$0^+(1^{++})$
• $\chi_{c0}(2P)$	$0^+(0^{++})$
• $\chi_{c2}(2P)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
• $\psi(4040)$	$0^-(1^{--})$
$X(4050)^\pm$	$?(?^?)$
$X(4140)$	$0^+(?^{?+})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
$X(4250)^\pm$	$?(?^?)$
• $X(4260)$	$?^?(1^{--})$
$X(4350)$	$0^+(?^{?+})$
• $X(4360)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
$X(4430)^\pm$	$?(?^?)$
• $X(4660)$	$?^?(1^{--})$

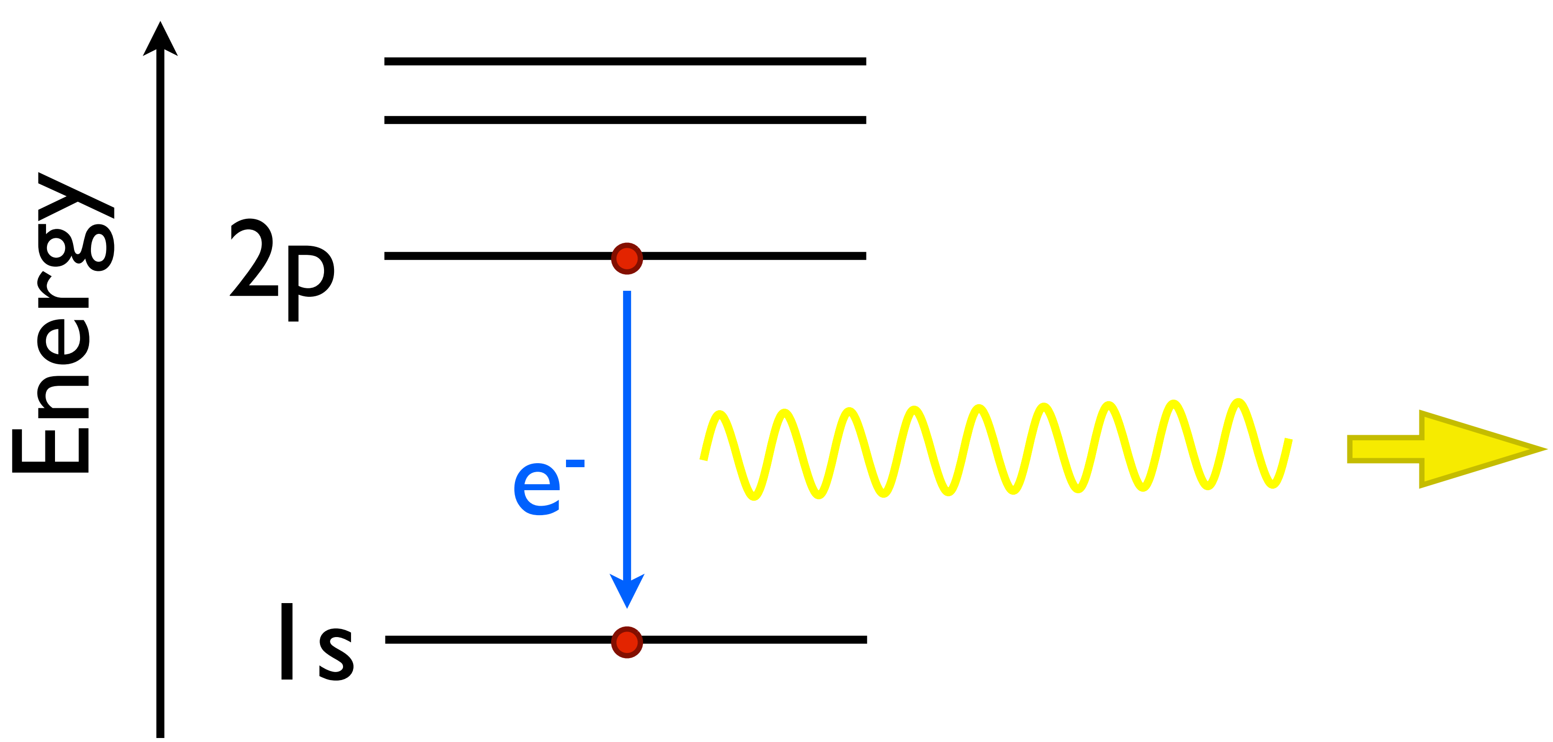
$b\overline{b}$	
$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$

Bringing Order to the Chaos

- Hadronic spectroscopy → organize the spectrum of hadronic bound states
- Classify hadron states by
  - quantum numbers (J,P,C,S,L,I,...)
  - masses and widths
  - dynamical features
- How are these states are formed, and how do they interact with each other?

Atomic Spectroscopy

- Hydrogen spectrum led to quantum mechanics
- Spectrum of atoms shows interactions of constituents (electrons/nuclei) and forces (electromagnetic)



energy levels of hydrogen

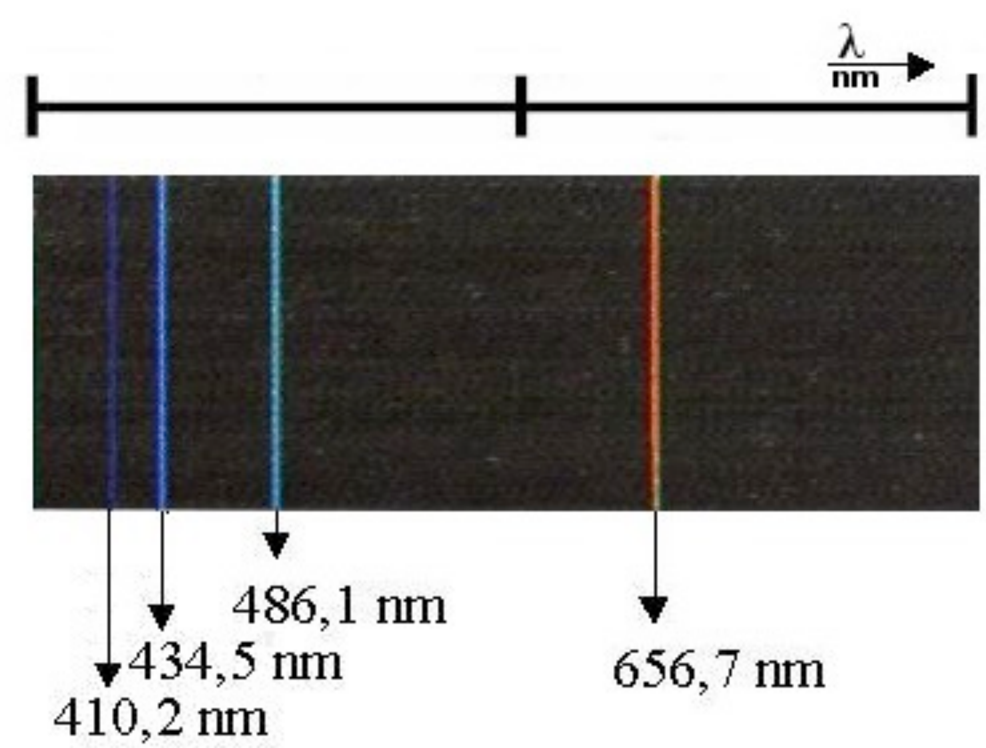


Figure from Winston Roberts (FSU) webpage:
http://www.physics.fsu.edu/users/roberts/roberts_hadrons.html

Greater Precision, Greater Knowledge?

- Main features given by Bohr model:

$$E_n = -\frac{1}{2}\alpha^2 \frac{m_e c^2}{n^2}$$

→ quantum mechanics

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- Further details by fine, hyperfine structures (spin-orbit, spin-spin)

→ theory of spin

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→ renormalization of QED/QFT

Greater Precision, Greater Knowledge?

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- Further details by fine, hyperfine structures (spin-orbit, spin-spin)

→ theory of spin

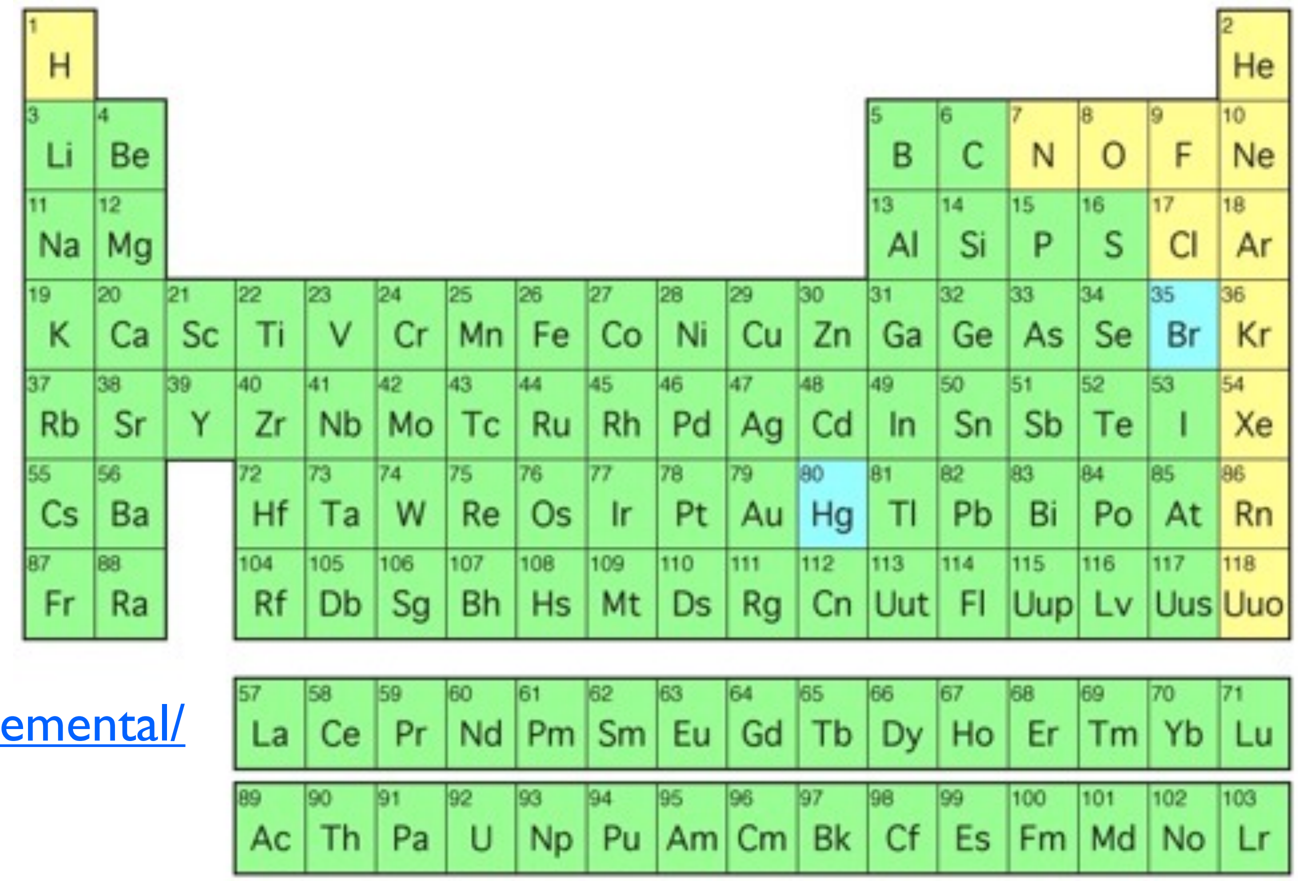
- Even further description by Lamb shift (vacuum polarization)

→ renormalization of QED/QFT

Precision studies lead to a better understanding, new discoveries!!

Spectrum of Hadrons

- Many many particles listed in PDG: http://pdg.lbl.gov
- Require sorting tools, like the table of elements



from http://education.jlab.org/itselemental/

- Use available symmetries, known facts
- Start with ground states, work towards excited spectra

Symmetries of the Quarks

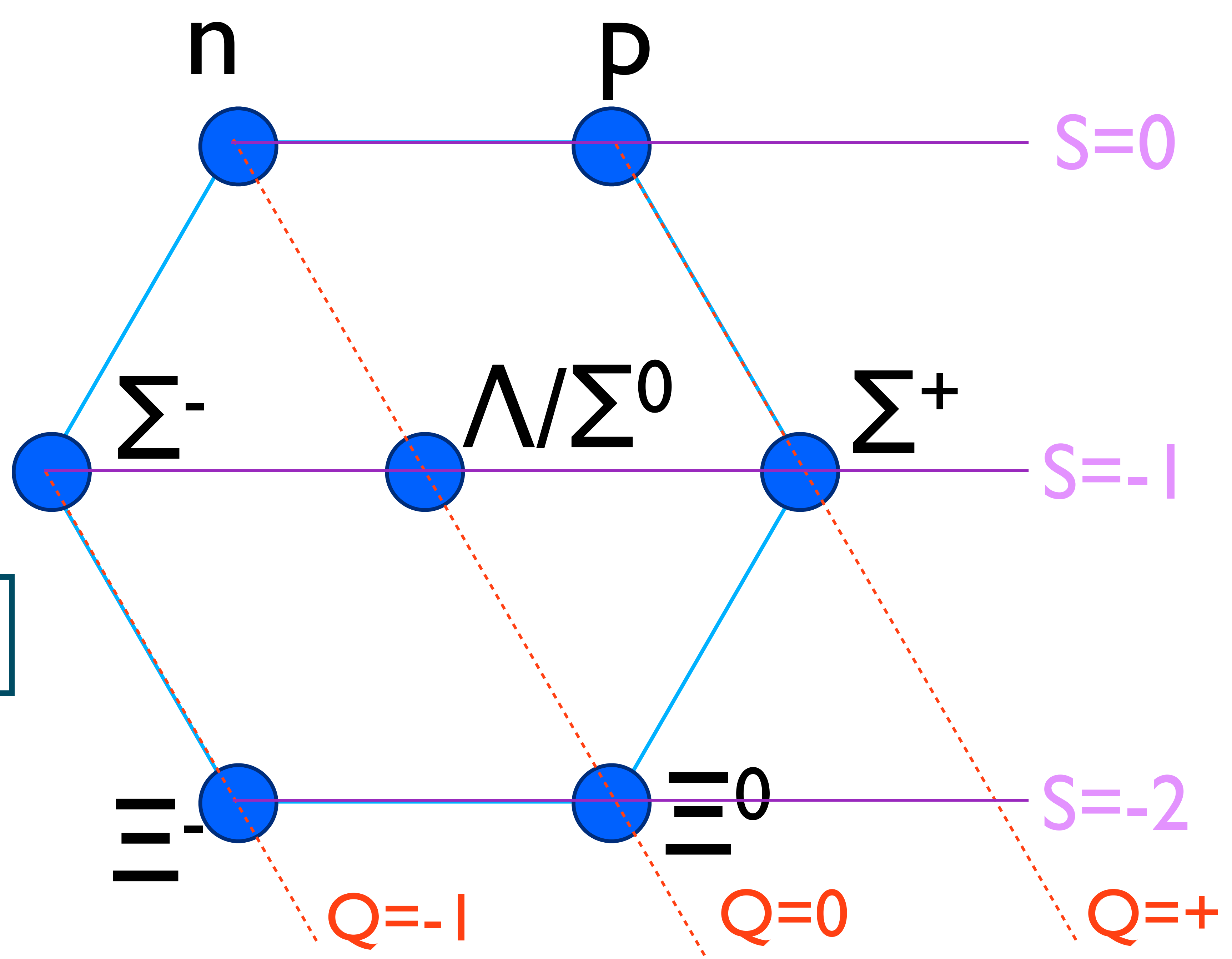
- Lightest quarks: up, down, strange
- Light masses, how QCD couples leads to approximate symmetry - broken by mass differences, E&M effects
- Group representation of states: flavor SU(3)
- Symmetry between up, down quarks - rather precise, “isospin”: SU(2), same as usual spin
- Masses of proton (uud), neutron (udd):

$$m_p = 938.272 \mathrm{MeV/c^2}$$
$$m_n = 939.565 \mathrm{MeV/c^2}$$

- Symmetry between strange and up/down more broken

The Simplest Case

- Ground state baryons - made of three u, d, s quarks
- Flavor SU(3) → lowest baryon states will form an octet



complete symmetry

The Simplest Case

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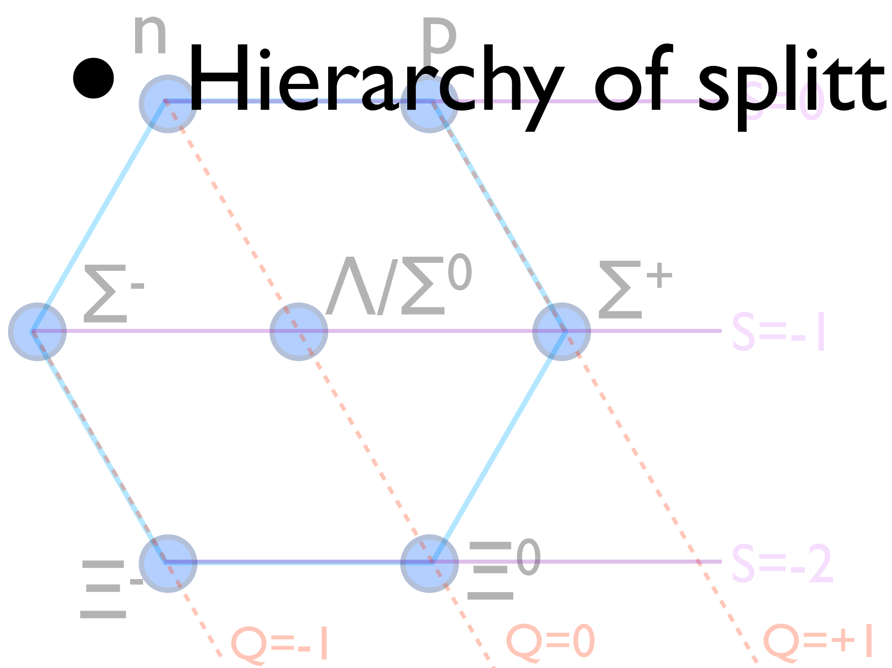
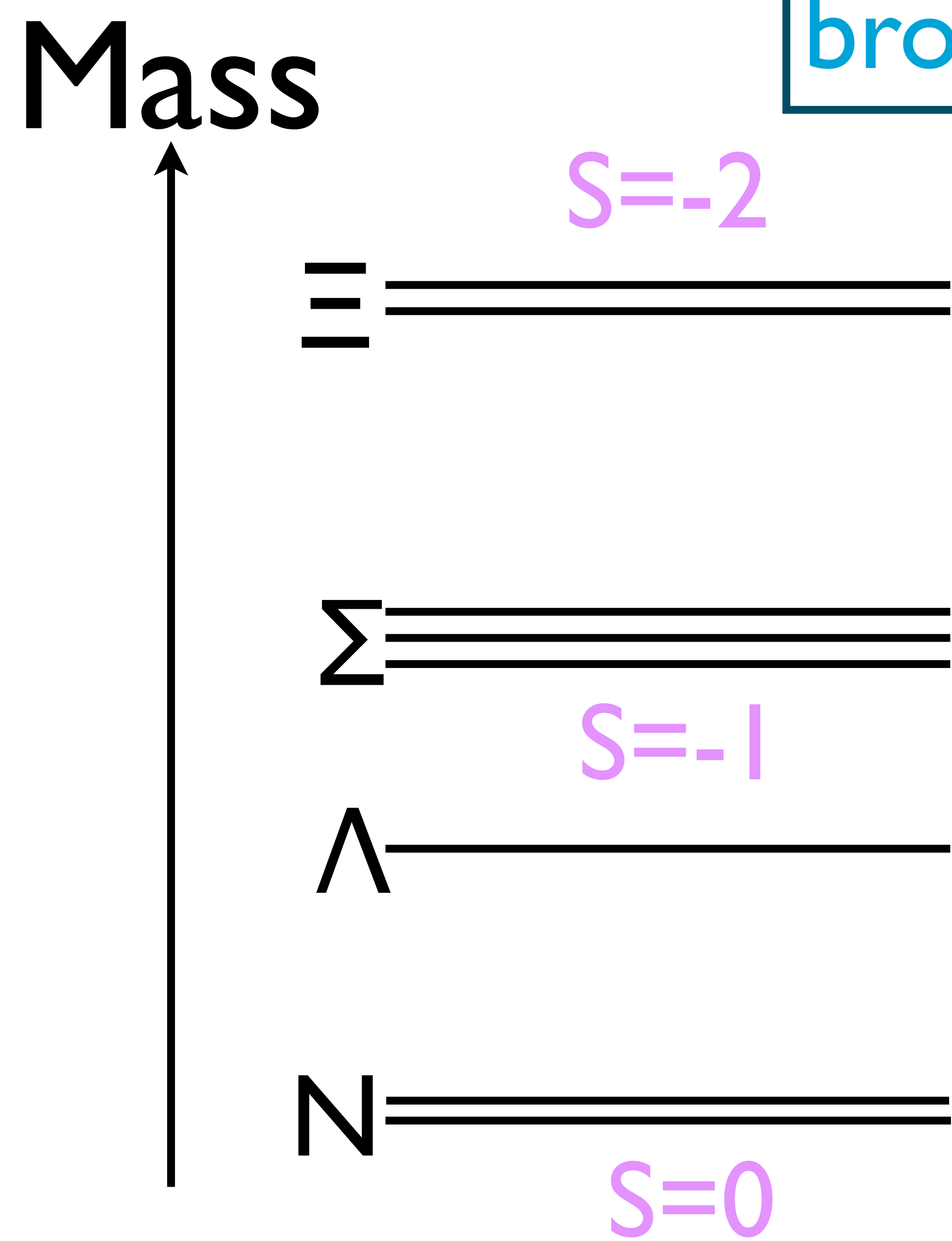
- Hierarchy of splittings, similar for ground state mesons



broken symmetry



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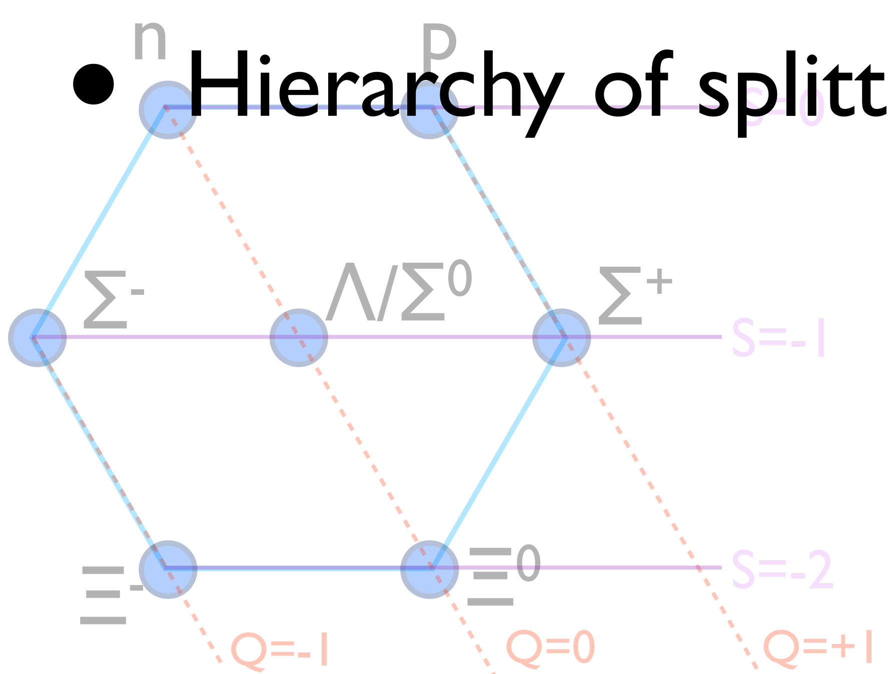
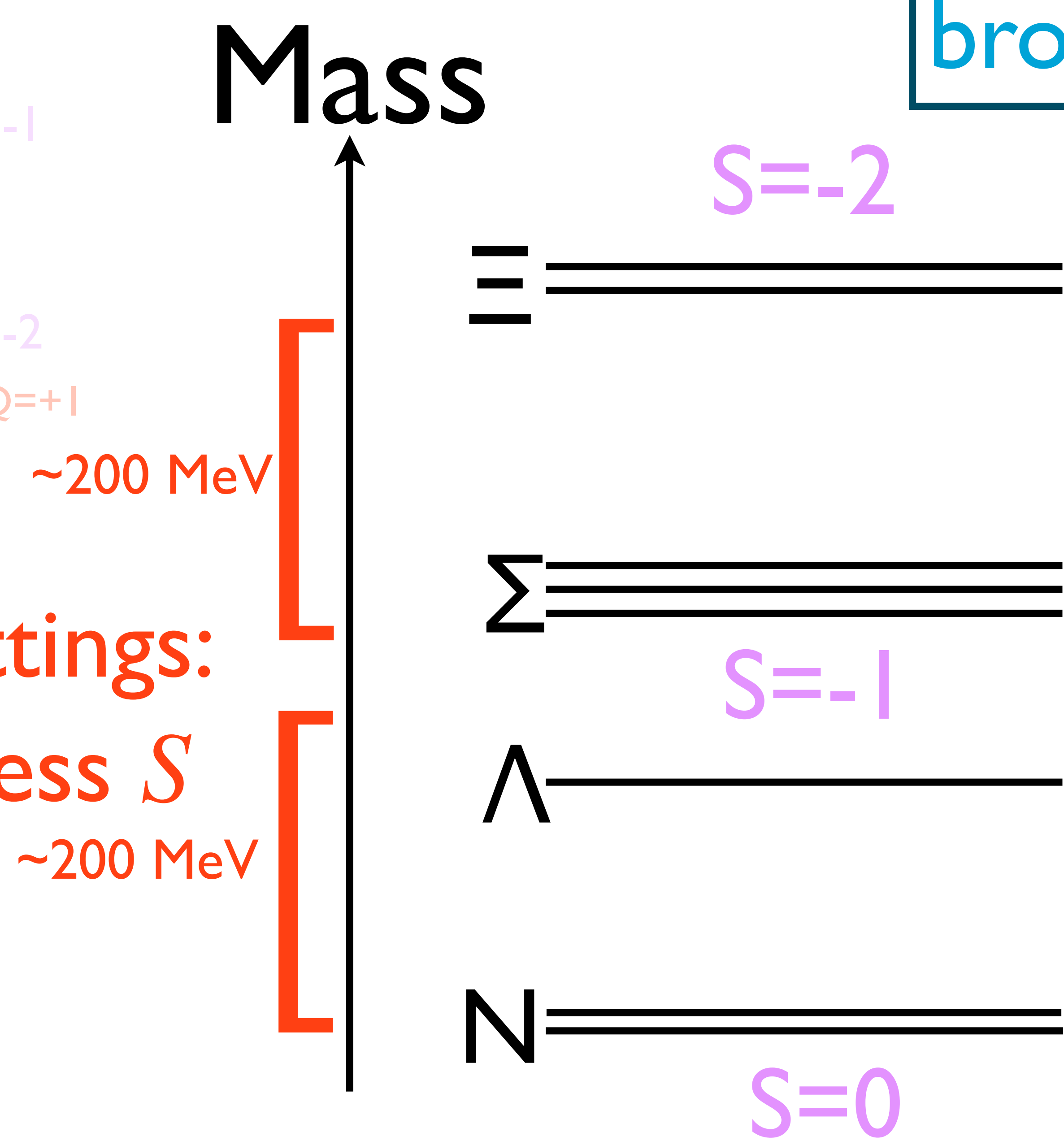


broken symmetry



large splittings:
strangeness S

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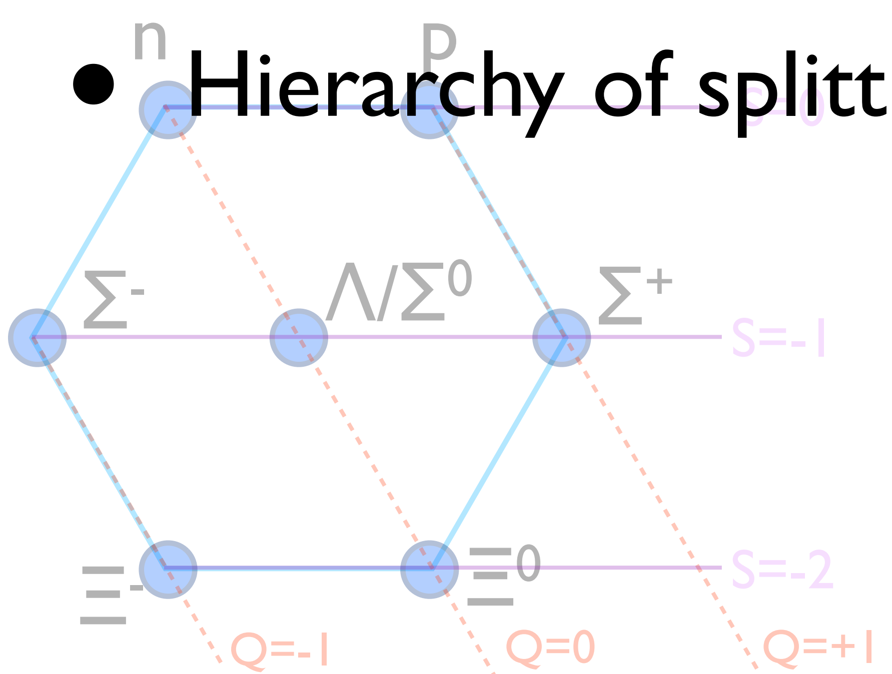
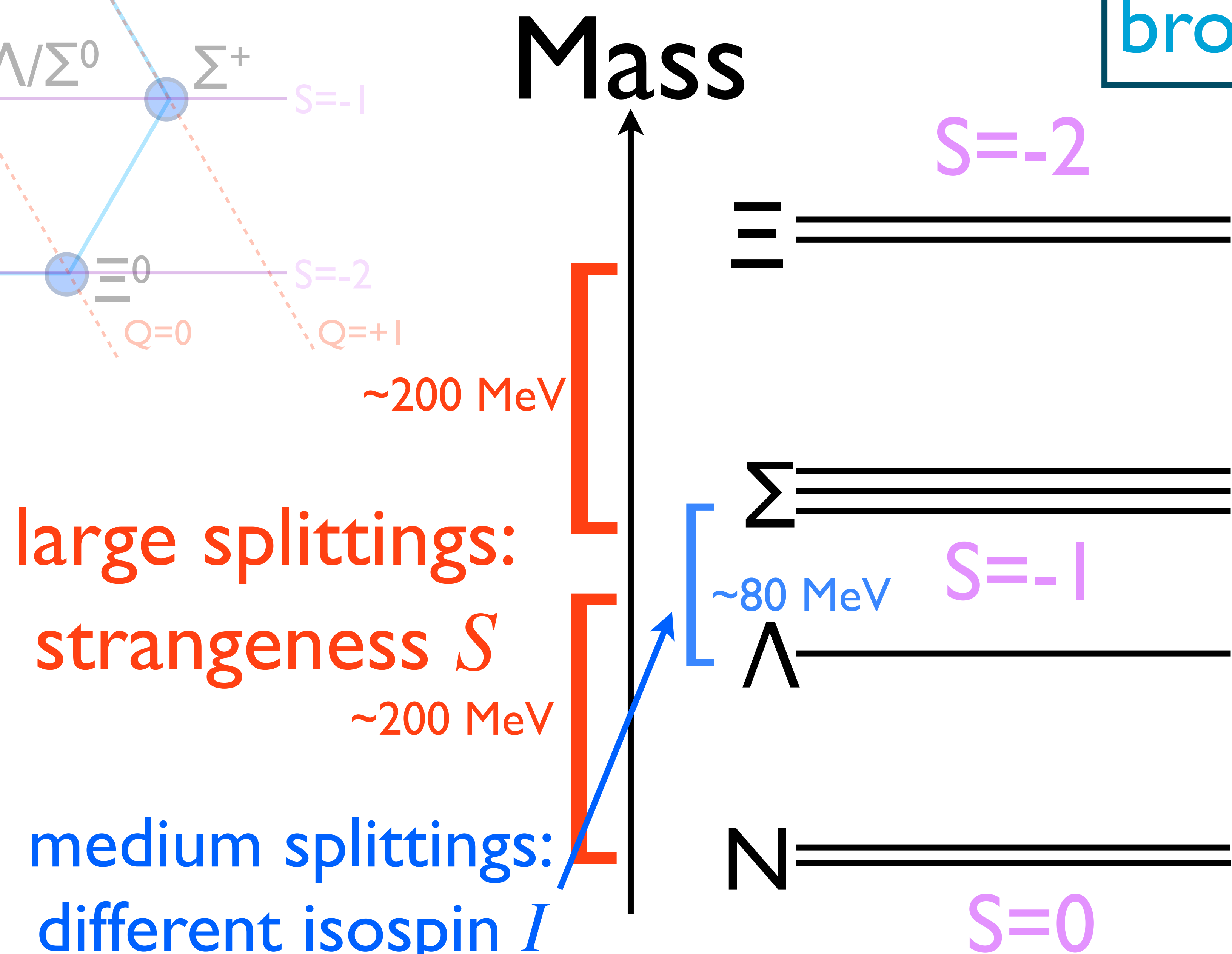


broken symmetry



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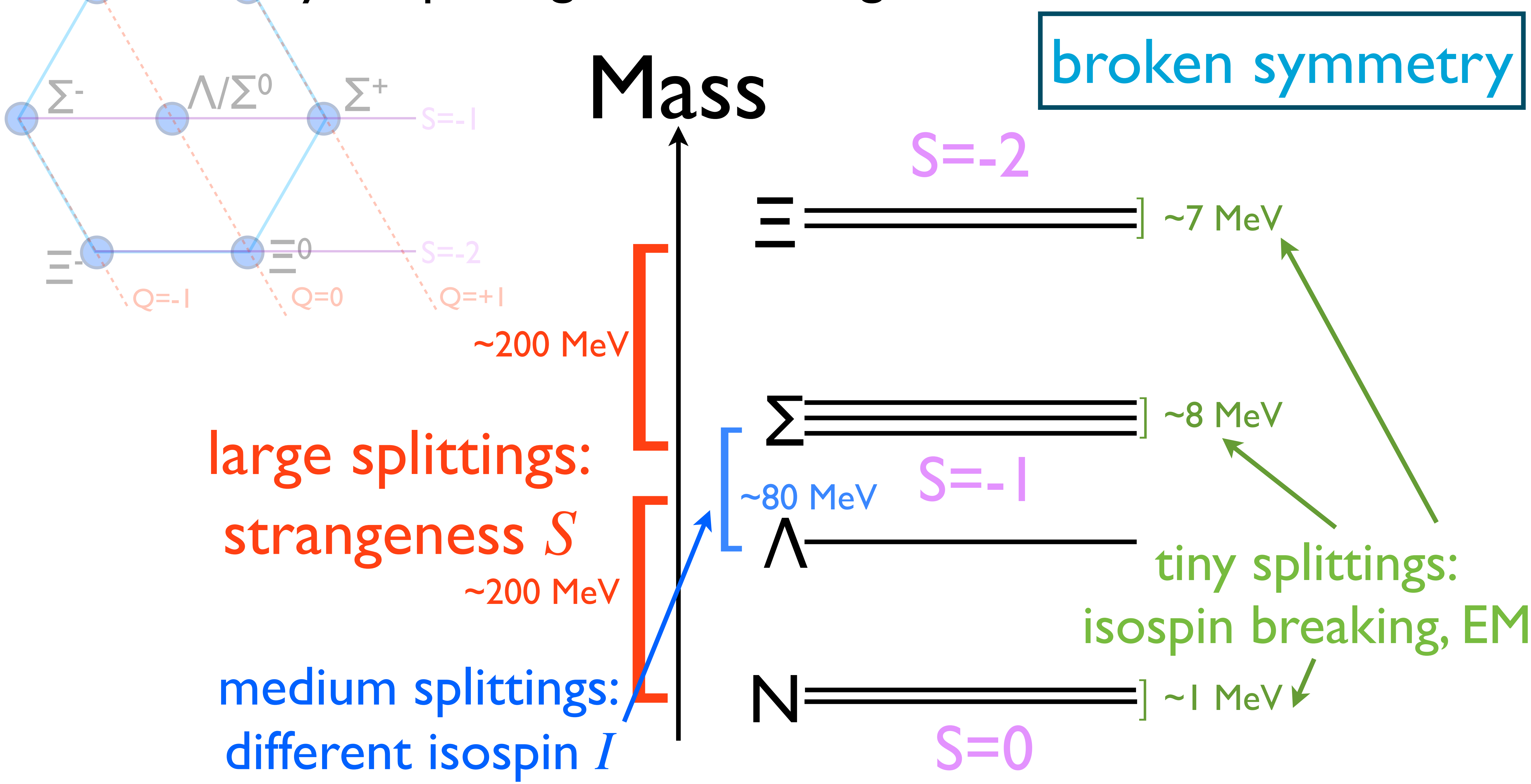
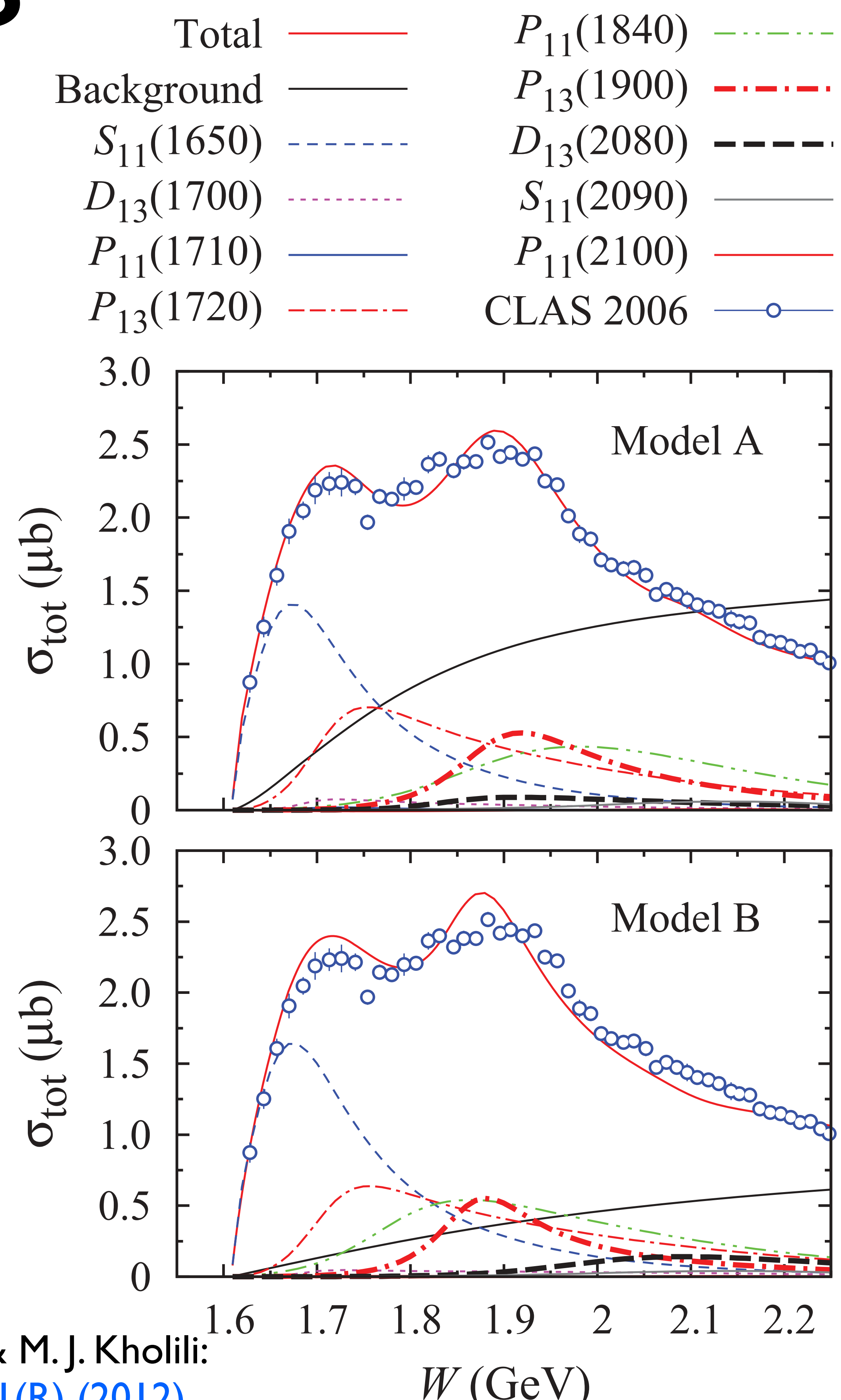


Difficulties at Higher Masses

- At higher energies (masses), the states have much larger widths, resulting in overlaps
- Also, dynamical considerations (multiple decay channels, cascading decays) complicate the picture
- Leads to difficulty in unambiguous interpretation
- Example: γ + p (→ N*) → K^+ Λ: N* states are produced which decay to K^+ Λ - but which ones?



From T. Mart & M. J. Kholili: PRC86, 022201(R) (2012)

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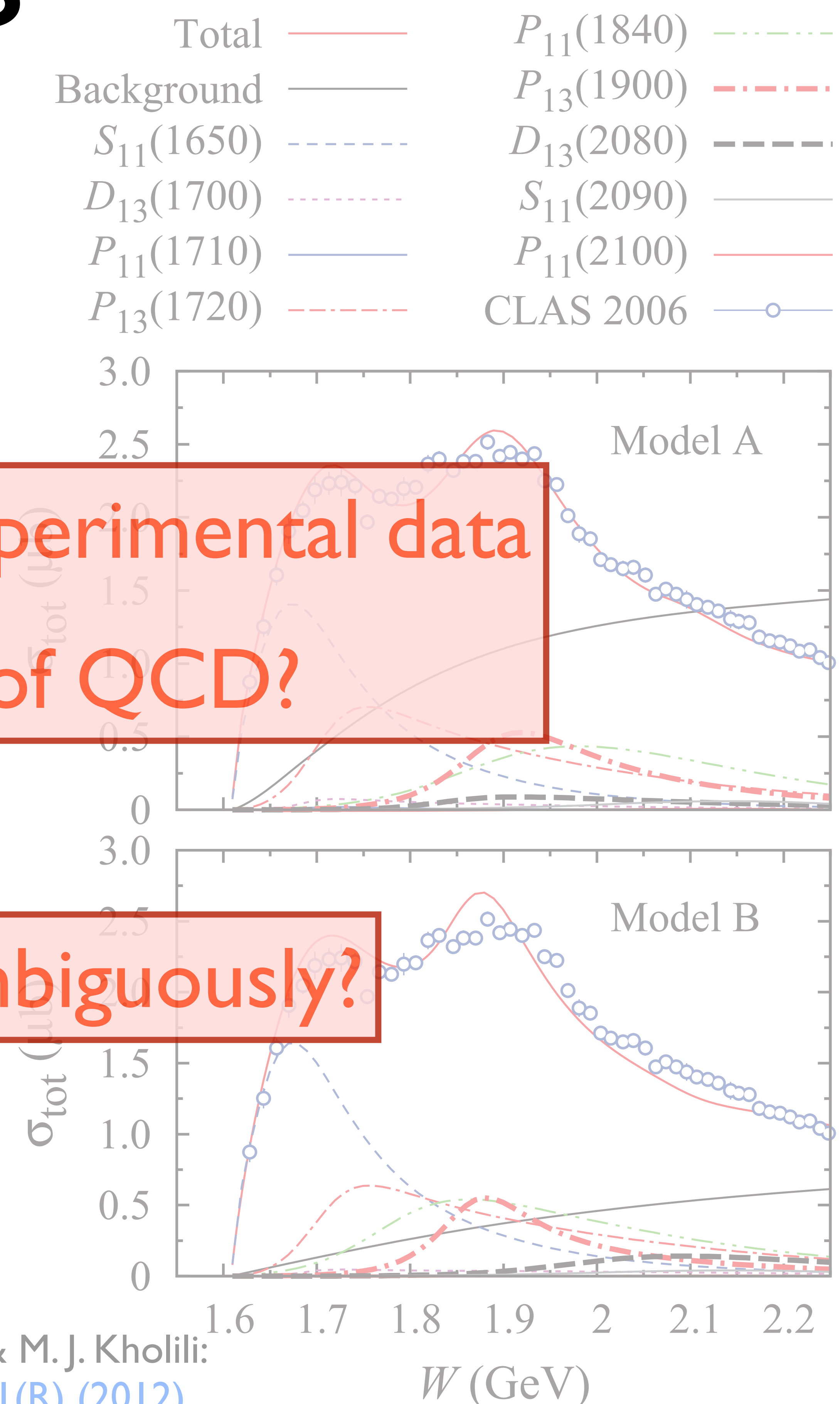
- Example: $\gamma + p\ (\rightarrow N^*) \rightarrow K^+ \Lambda$: N^* states are produced which decay to $K^+ \Lambda$ - but which ones?

How do we tie all of the experimental data with the underlying theory of QCD?

Can we do this unambiguously?



From T. Mart & M. J. Kholili: [PRC86, 022201(R) (2012)]

III. The GlueX Experiment

Jefferson Lab

- Located in Newport News, VA
- Currently upgrading electron accelerator: 6 → 12 GeV
- Provides e^- bunch every 2 ns
- Upgrades to Halls A, B, C

https://www.jlab.org

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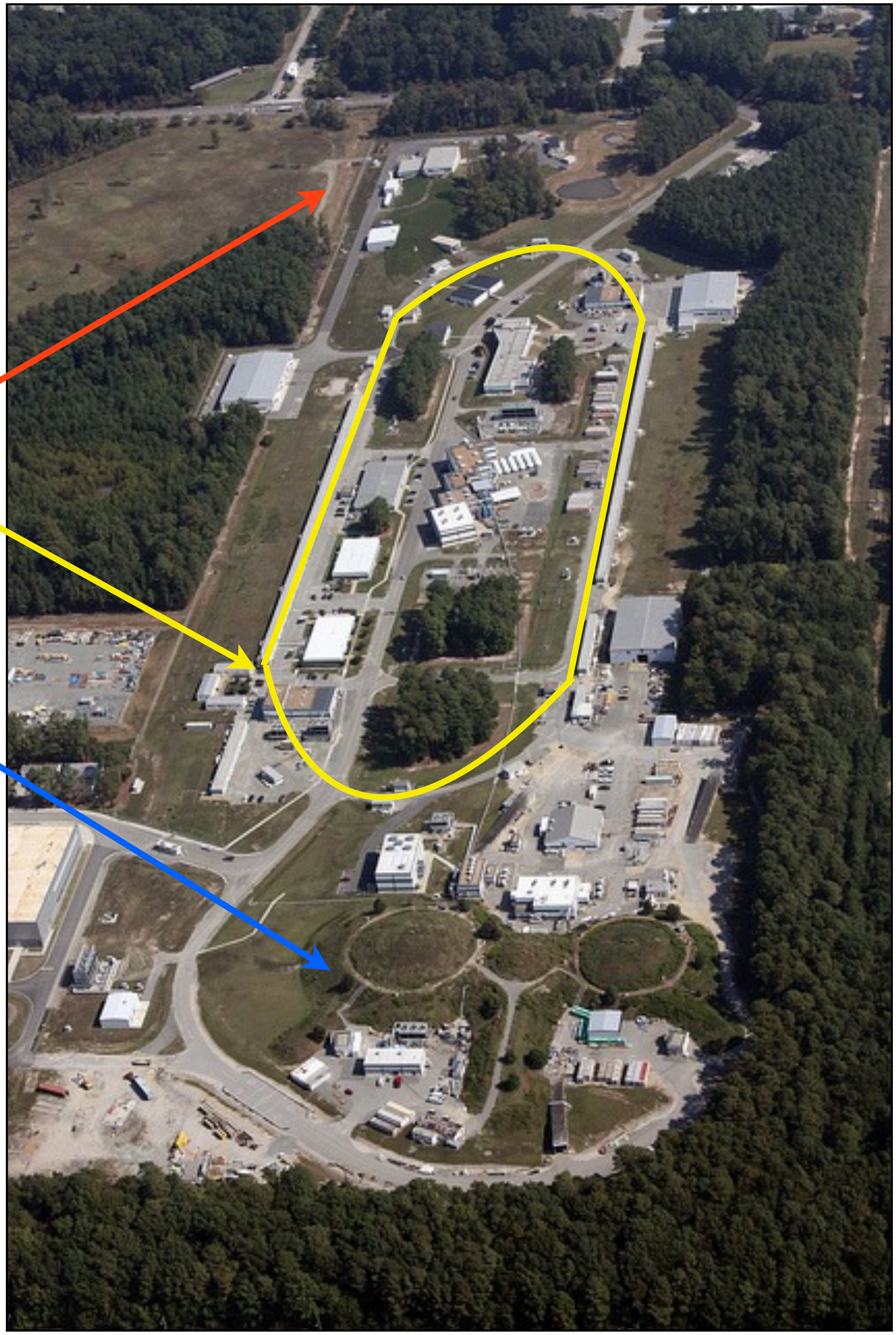
- Upgrades to Halls A, B, C
- New Hall D

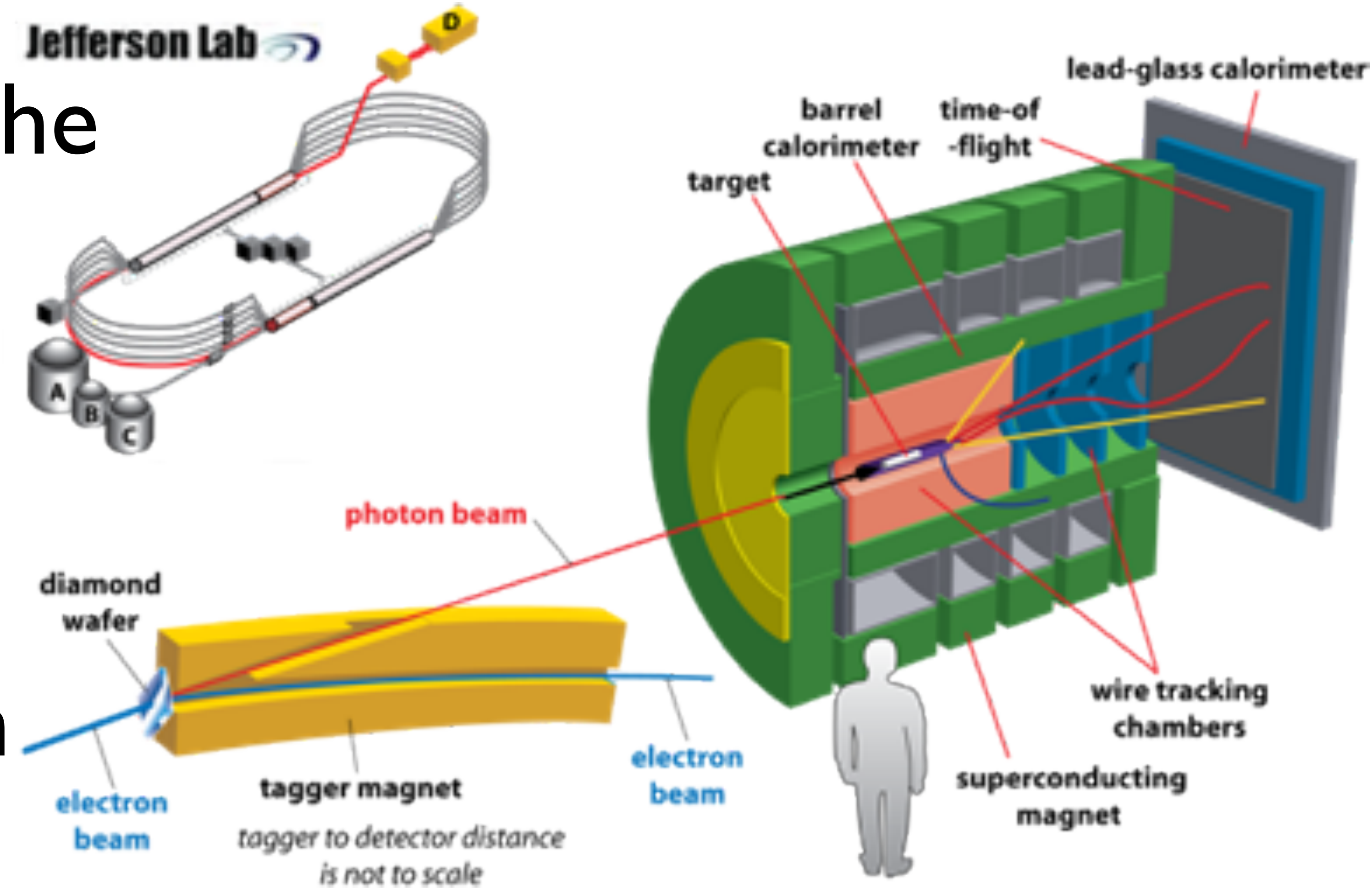


https://www.jlab.org

The GlueX Experiment

- Main experiment in Hall D
- Flagship experiment of the JLab 12 GeV era

http://www.gluex.org

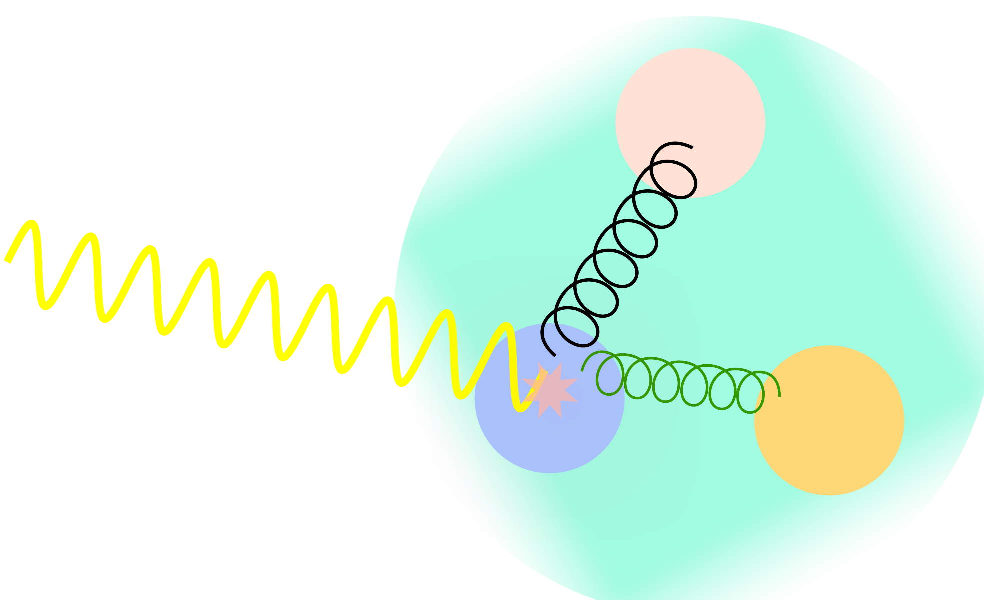


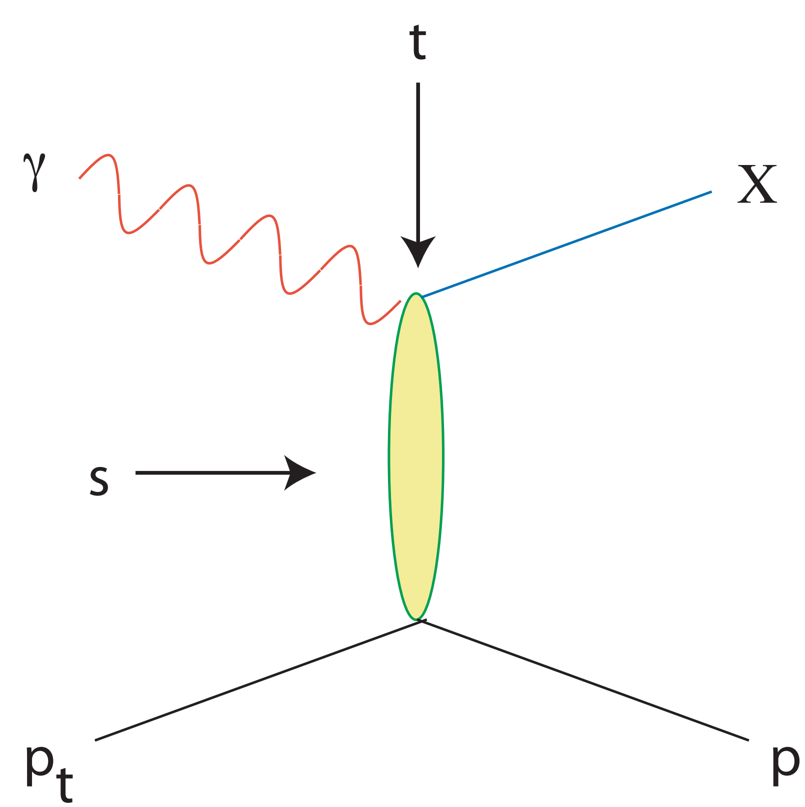
- Photon beam on proton target
- Main goal is hadronic spectroscopy - both mesons and baryons

Other experiments such as pion polarizability are also planned. See JLAB PAC report: http://www.jlab.org/exp_prog/PACpage/PAC40/PAC40_Final_Report.pdf

Photoproduction

- We know what photon is → Use a well-known object to probe something less well-known
- Photoproduction has not been studied at these energies in as much detail as a hadroproduction (hadron beam) → new discoveries?

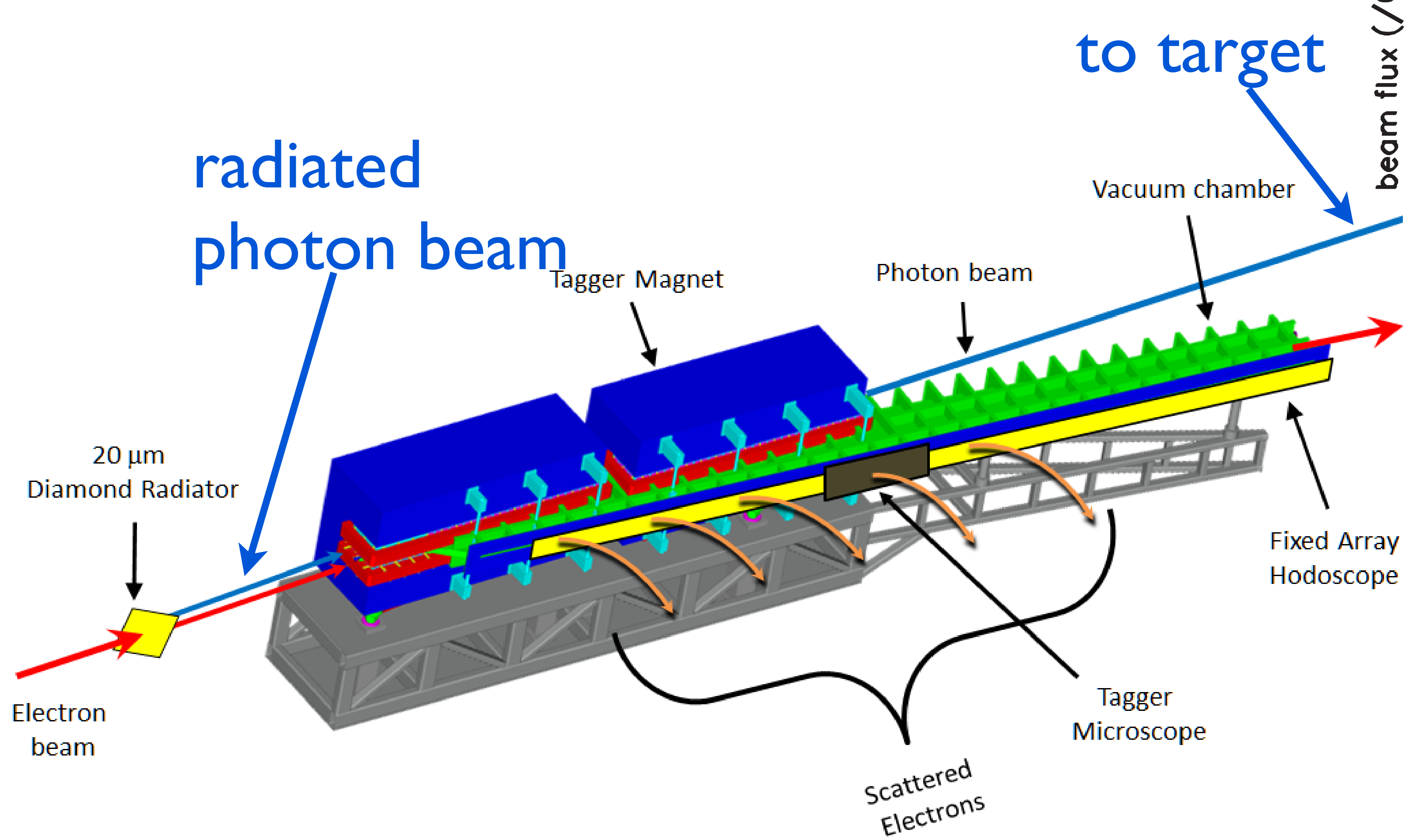


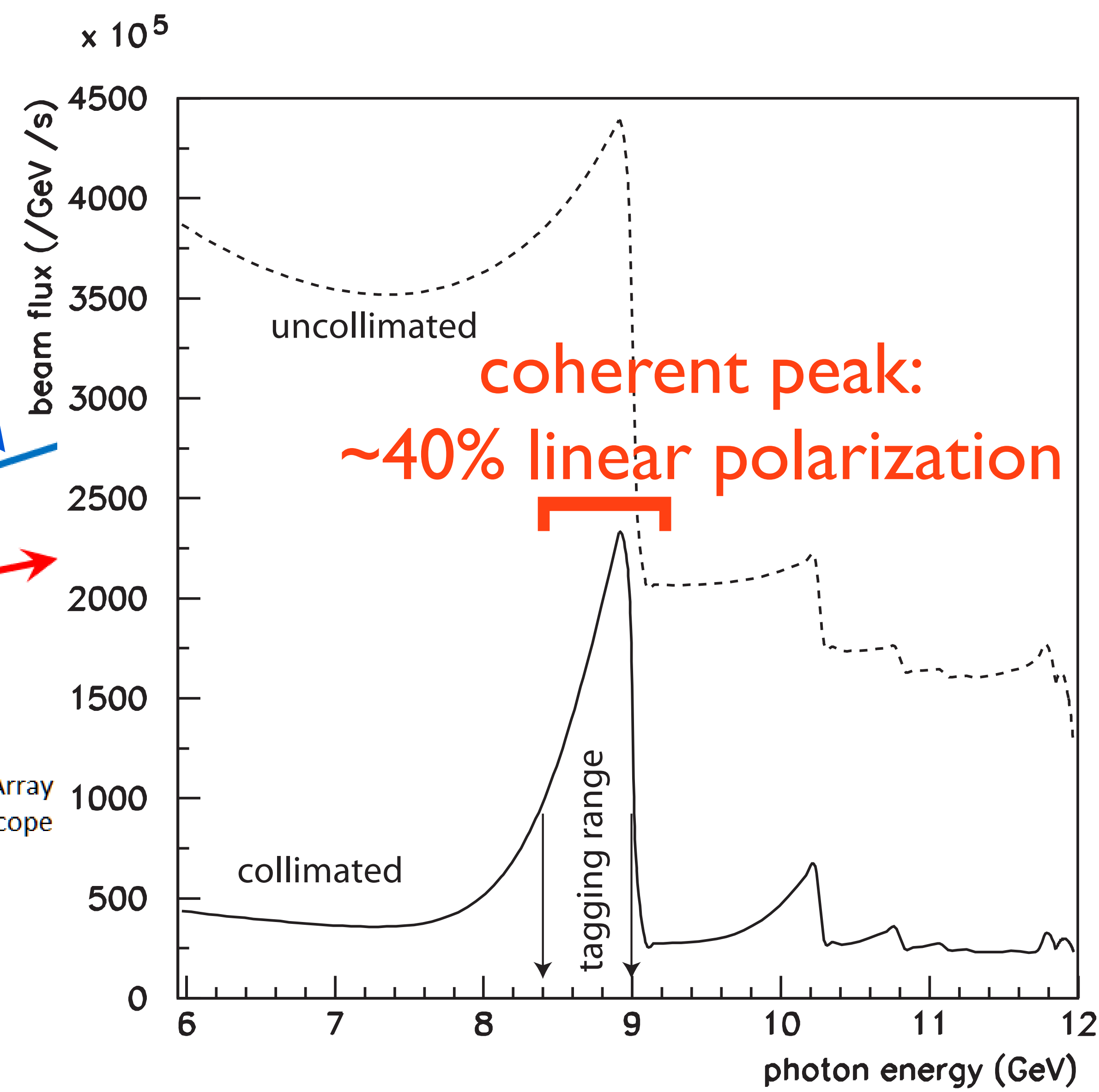


Why 12 GeV Beam?

- Dynamics evolve with energy
  → want to observe behavior with energy

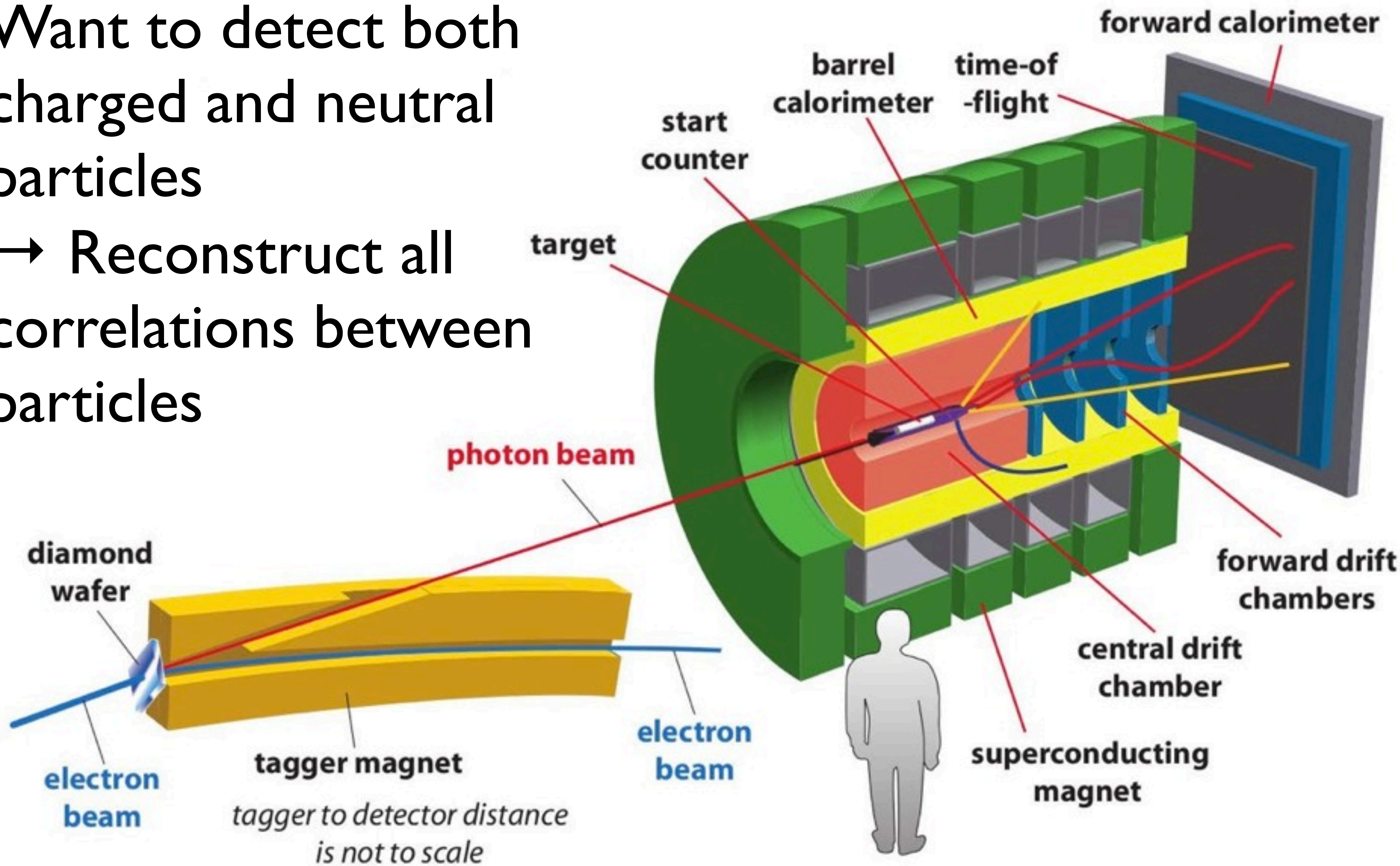
- Bremsstrahlung beam - radiate photons from electron beam



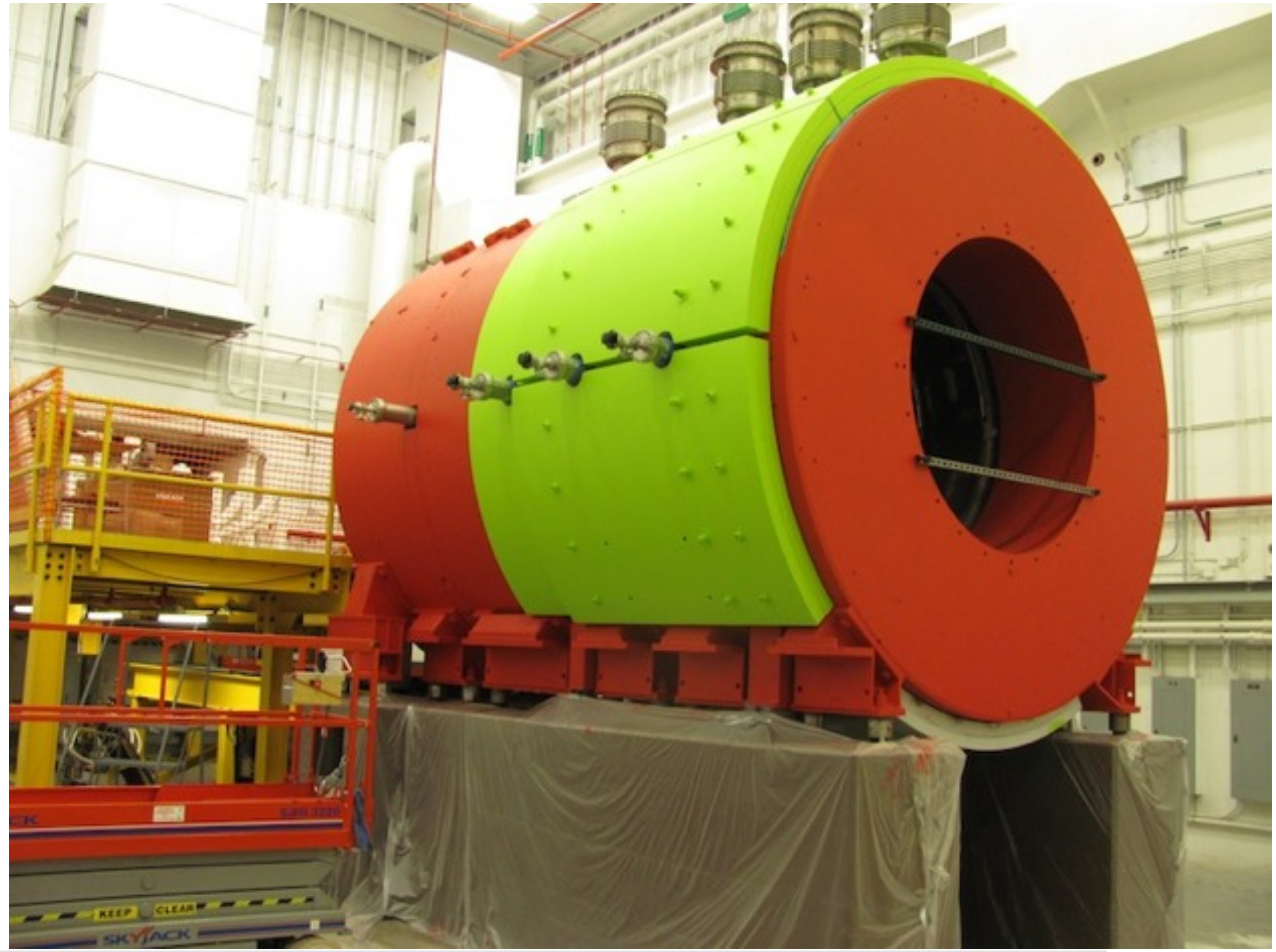


GlueX Detectors

- Cover the most area reasonably possible
- Want to detect both charged and neutral particles
  → Reconstruct all correlations between particles



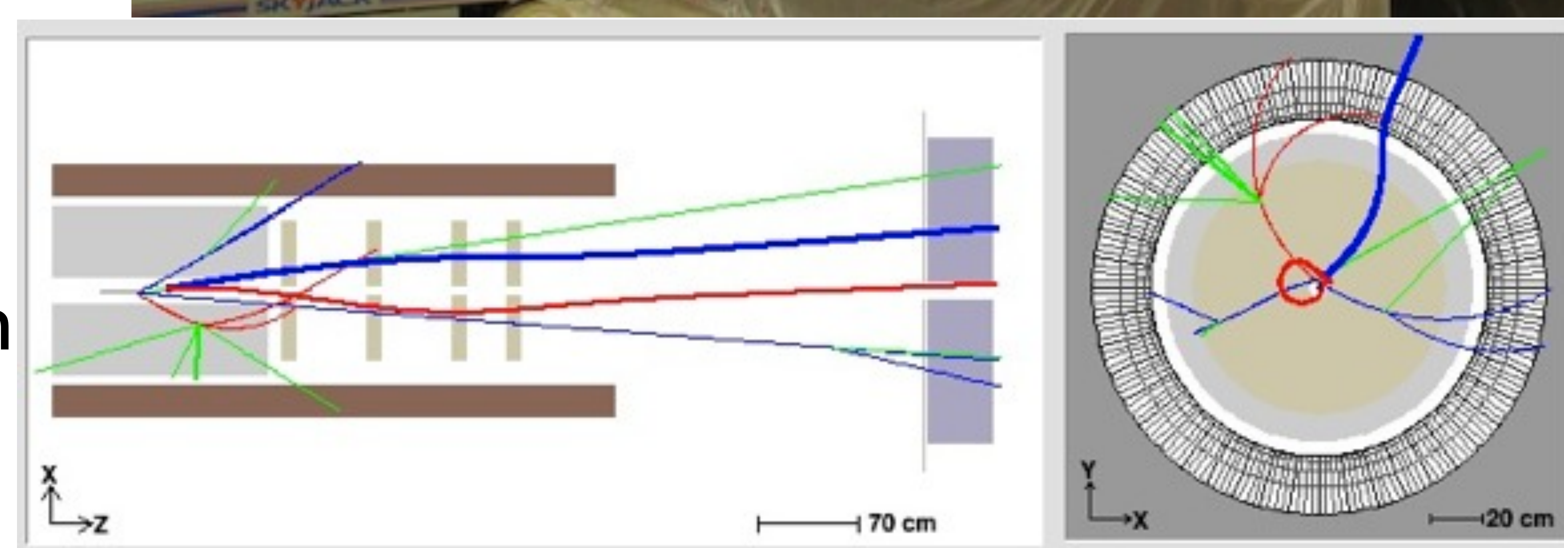
GlueX Detectors



Tracking

- Solenoid magnet provides 2.2T field, bends trajectory of charged particles

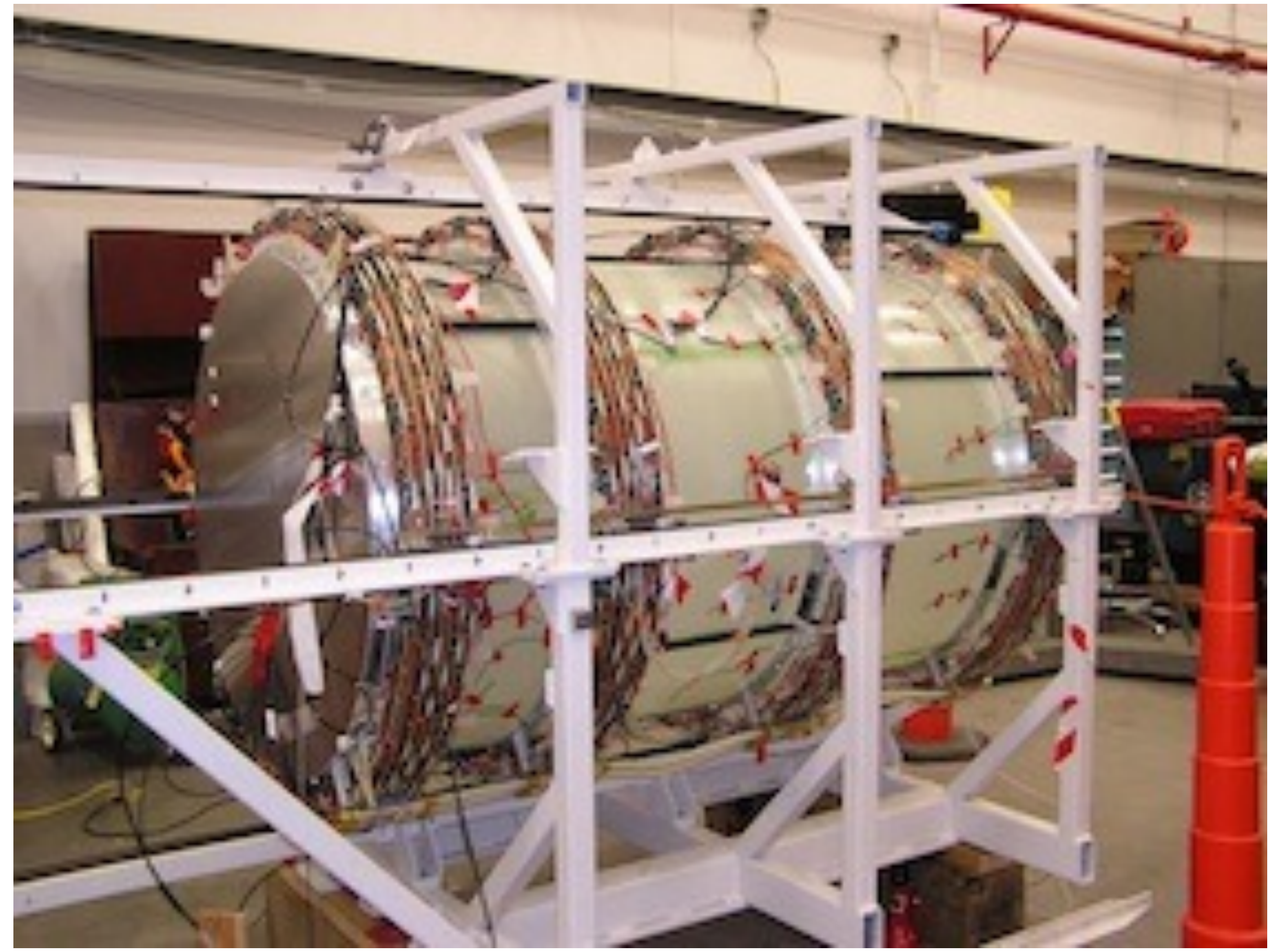
Charged tracks (red and blue) spiraling in magnetic field



GlueX Detectors

Tracking

- Central Drift Chamber (CDC) and Forward Drift Chamber (FDC) provide charged particle hit information



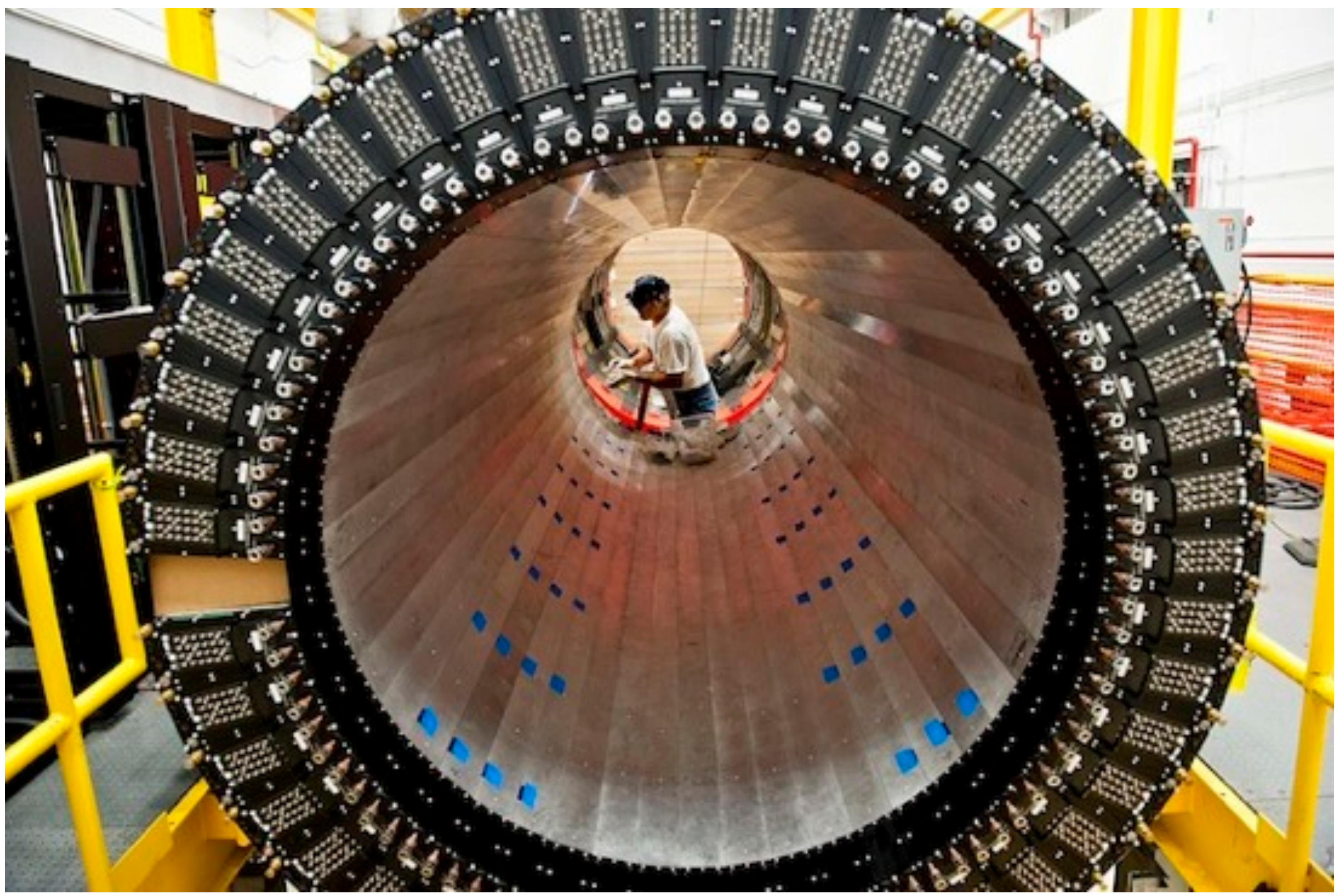
completed FDC

building of CDC

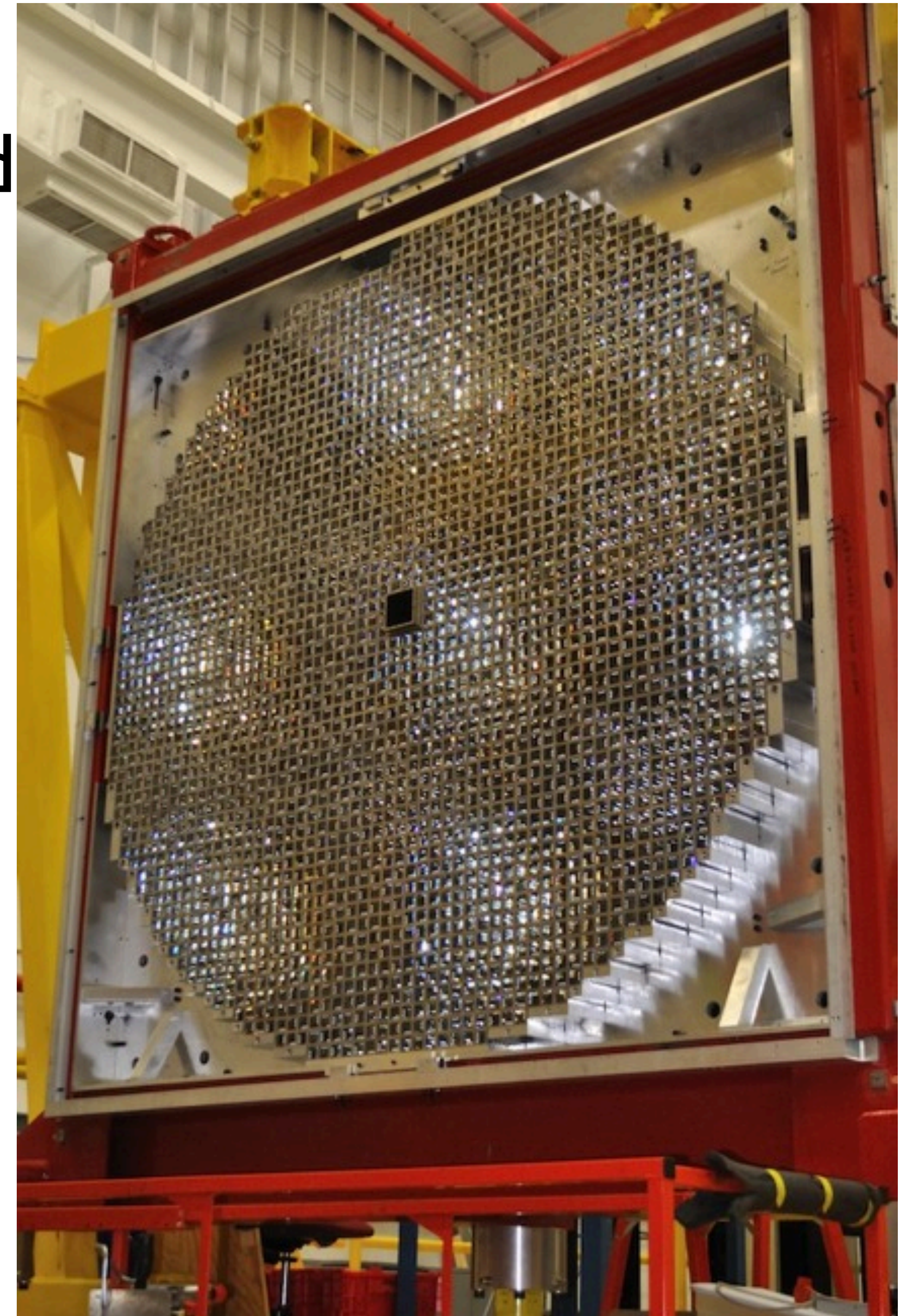
GlueX Detectors

Calorimetry

- Barrel Calorimeter (BCAL) and Forward Calorimeter (FCAL) provide photon reconstruction



installation of BCAL

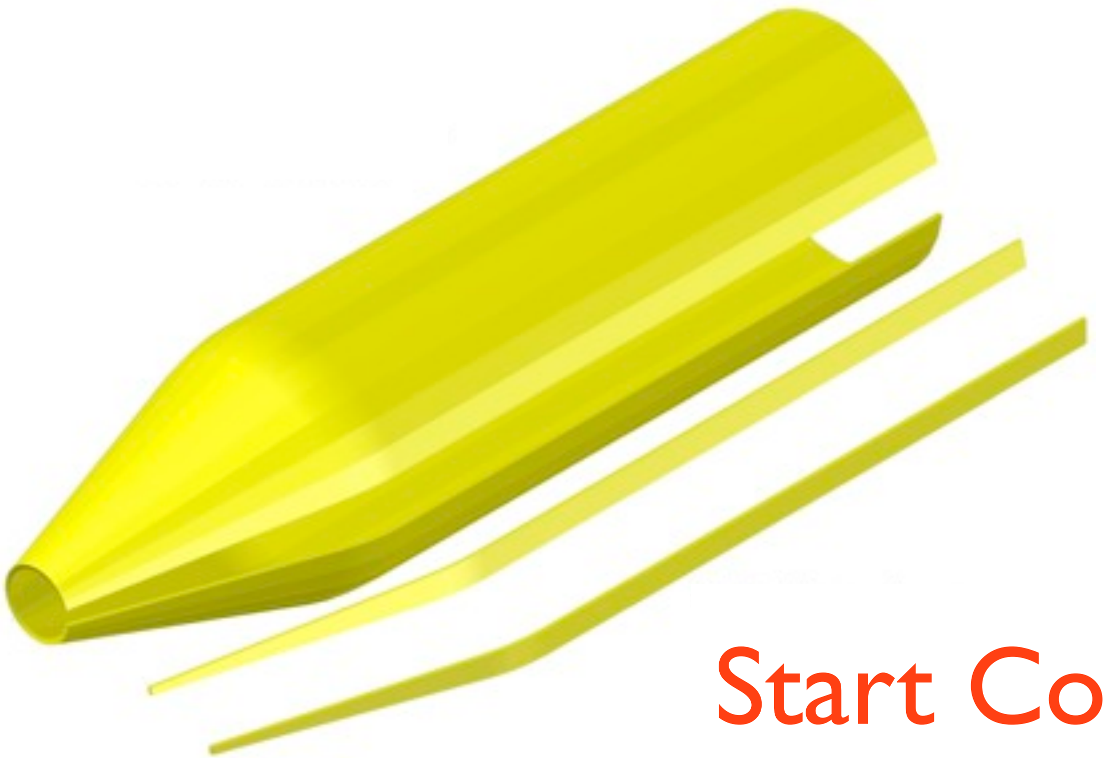


fully stacked FCAL

GlueX Detectors

Particle Identification

- Time-of-flight wall (TOF) and Start Counter provide timing, identity of charged particles
- Further upgrades with DIRC are being planned

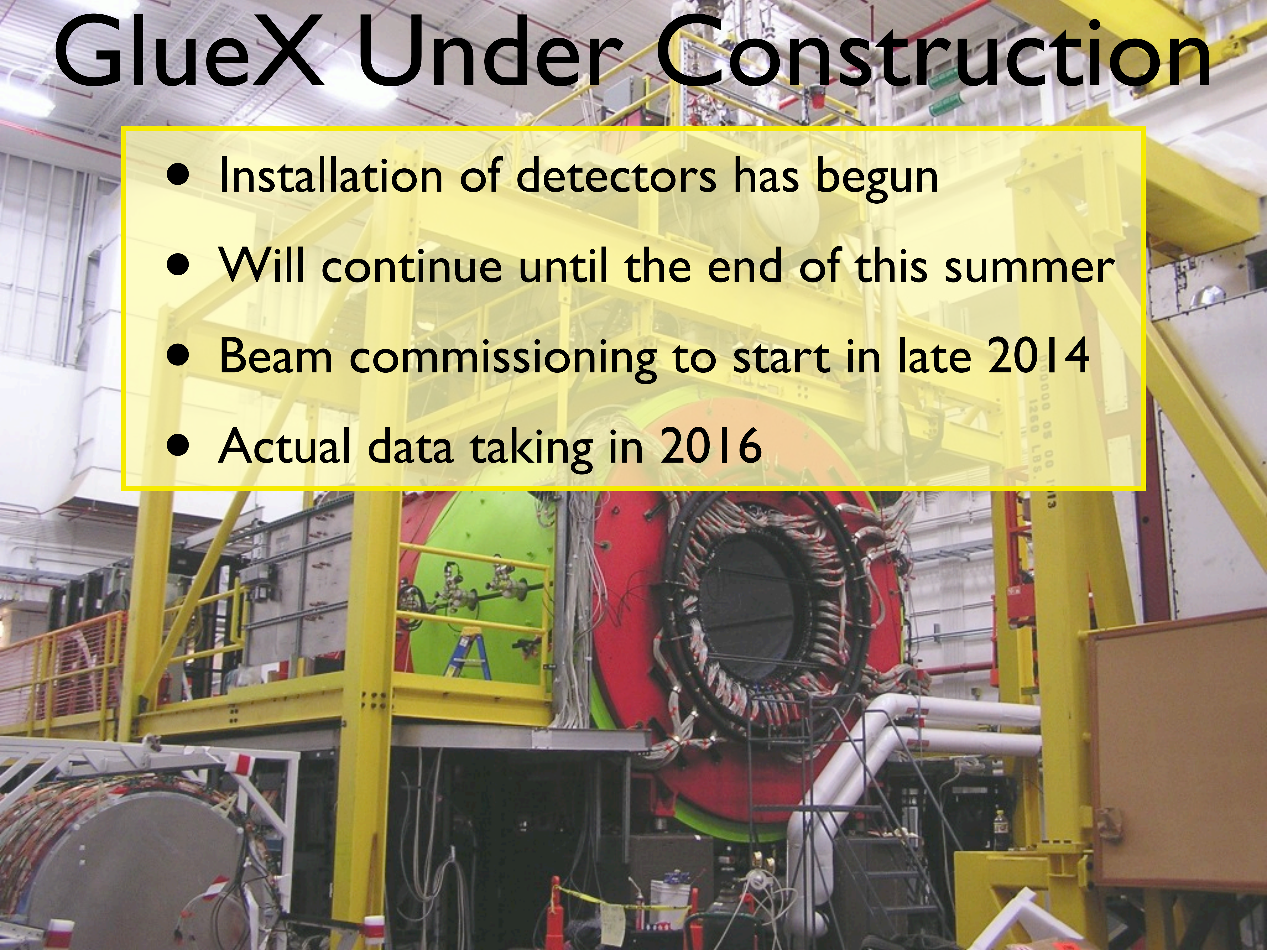


Start Counter

TOF modules

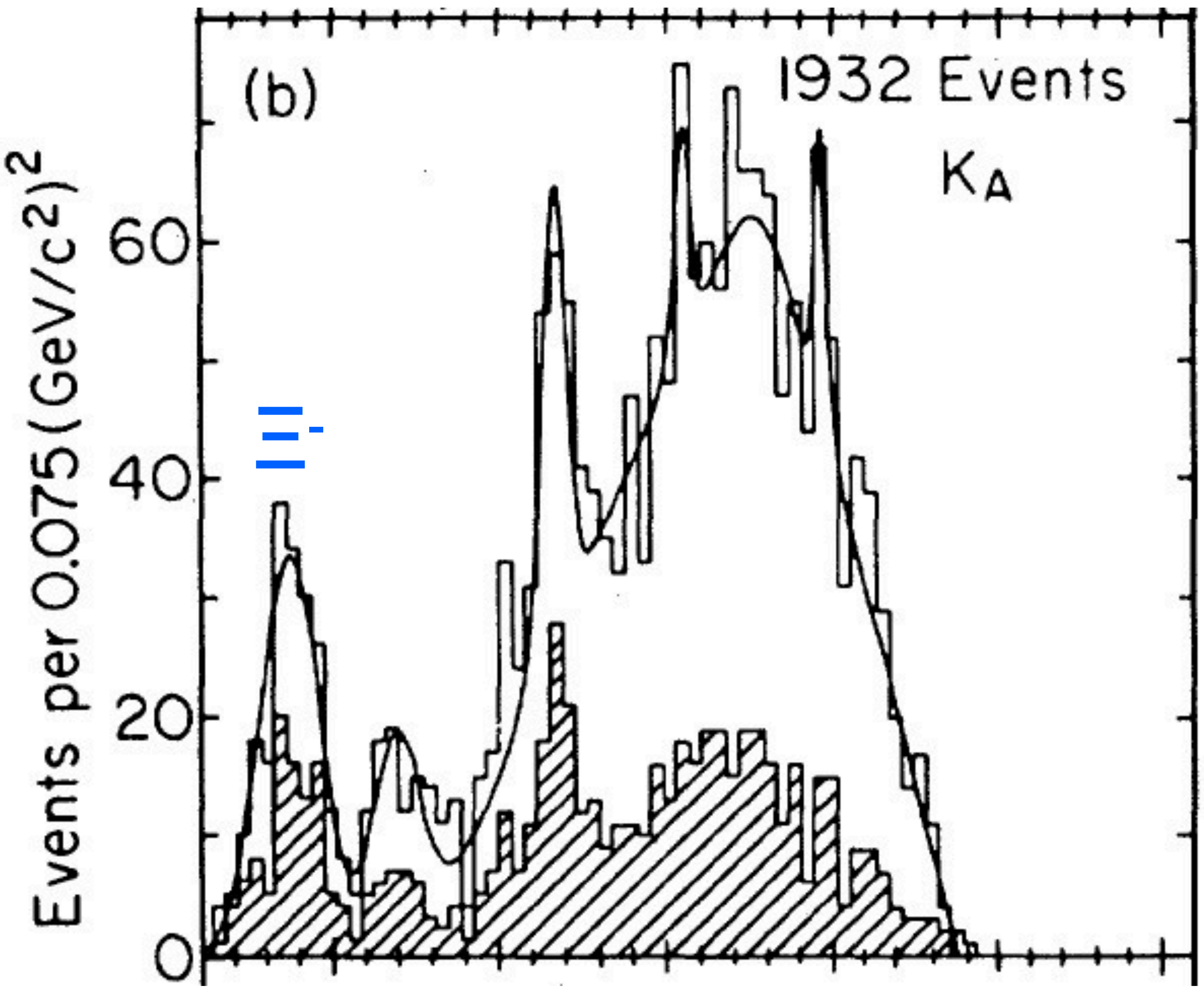
GlueX Under Construction

- Installation of detectors has begun
- Will continue until the end of this summer
- Beam commissioning to start in late 2014
- Actual data taking in 2016



GlueX Data Counts

- Data volume - the more the merrier



Jenkins et al.,
PRL 51, 951 (1983)

several dozen counts

GlueX Data Counts

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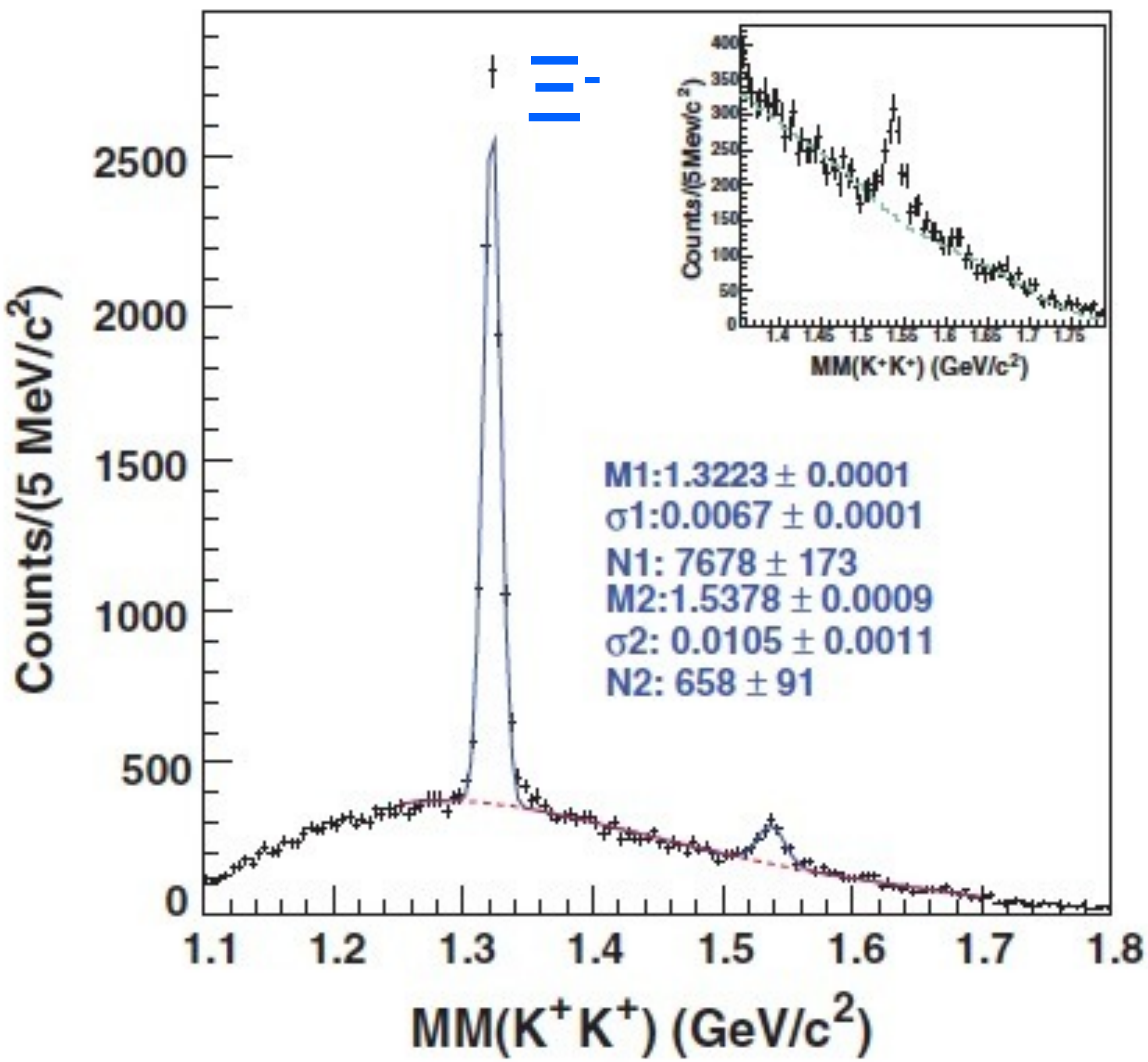

Guo et al., [CLAS] PRC76, 025208 (2007)

~7700 counts

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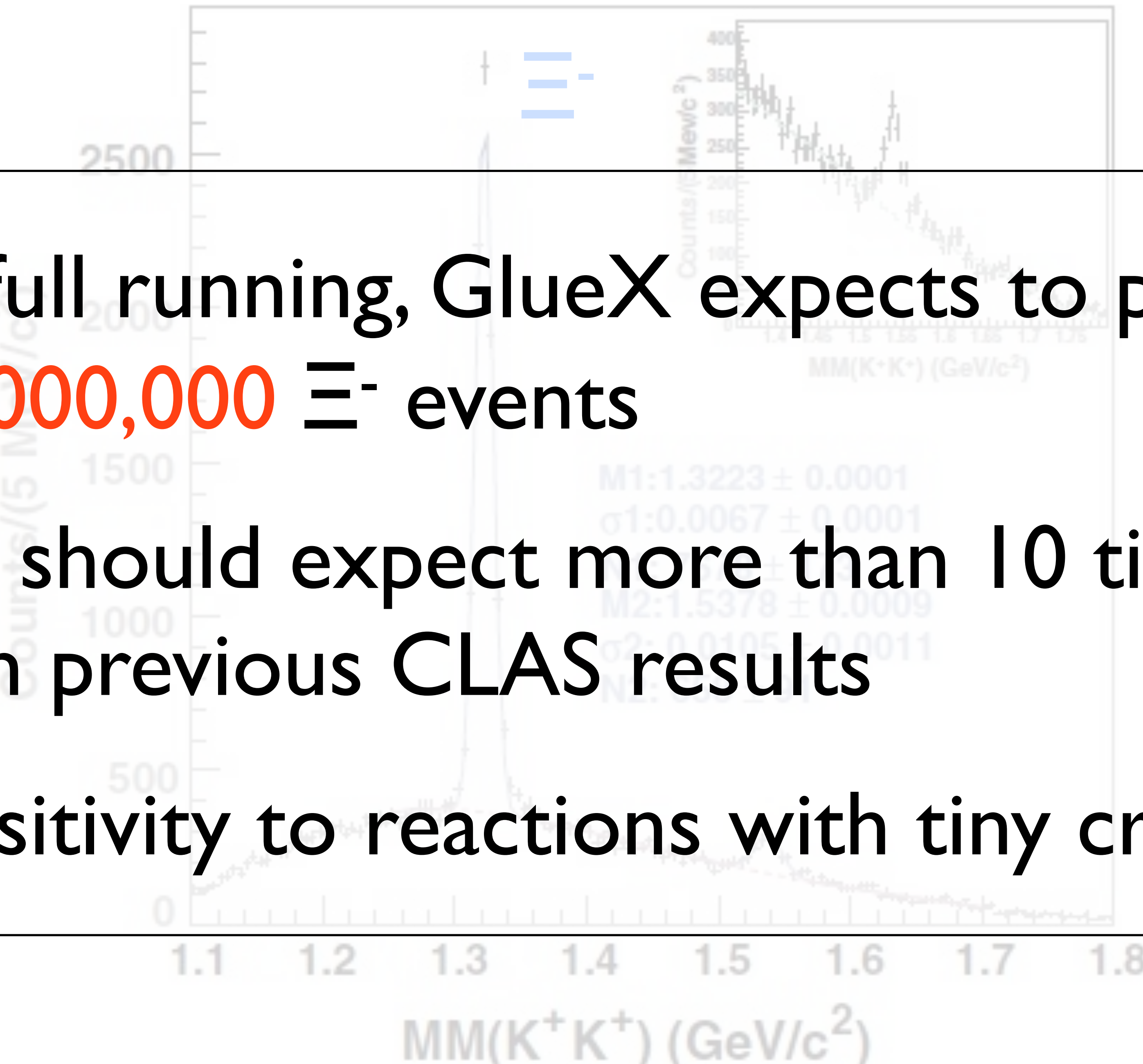
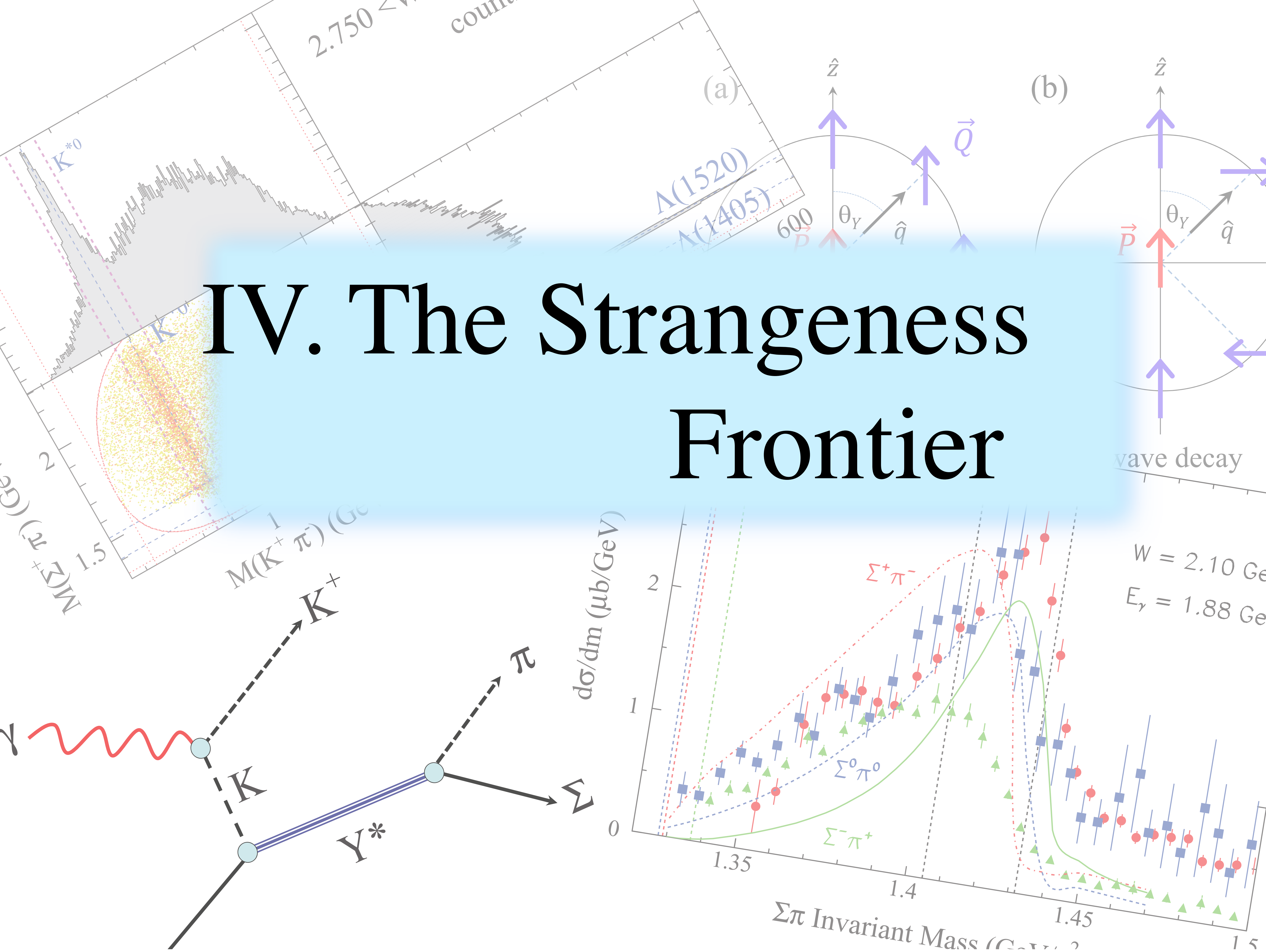


Guo et al., [CLAS]
PRC76, 025208 (2007)

~7700 counts

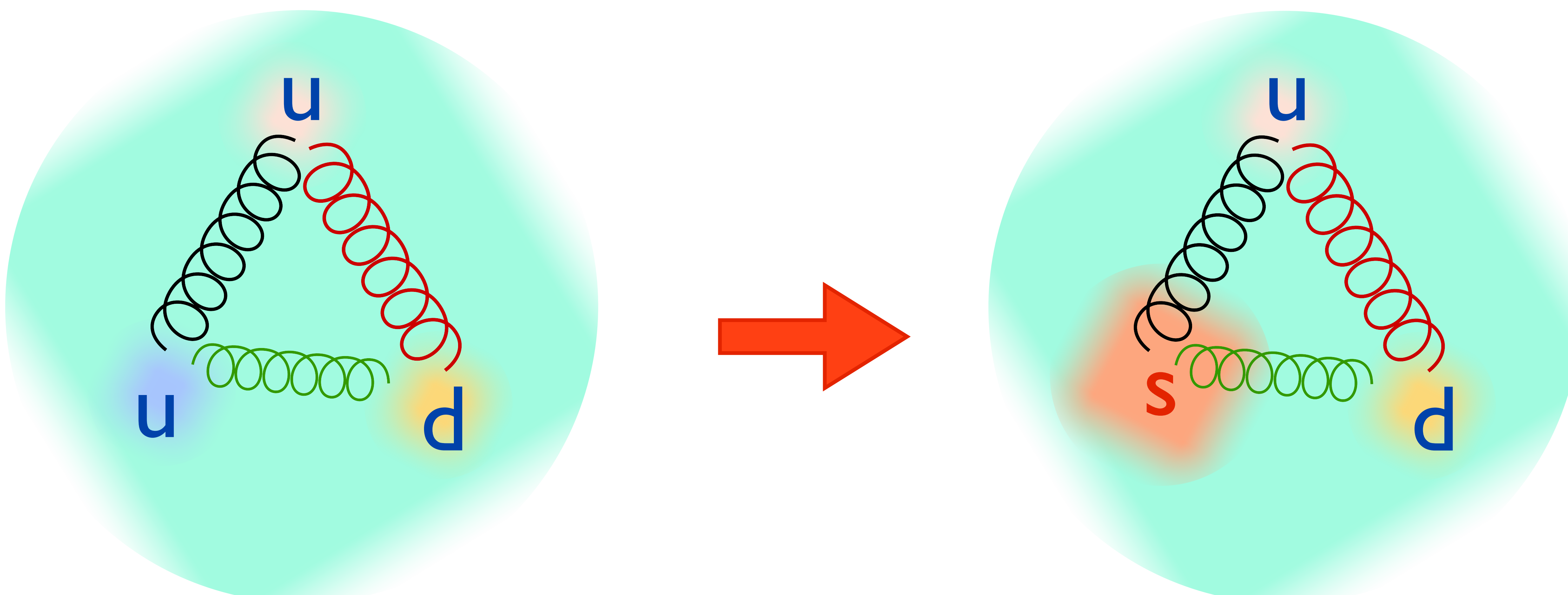
- At full running, GlueX expects to produce ~9,000,000 Ξ^- events
- We should expect more than 10 times more statistics than previous CLAS results
- Sensitivity to reactions with tiny cross sections



IV. The Strangeness Frontier

What is Strangeness?

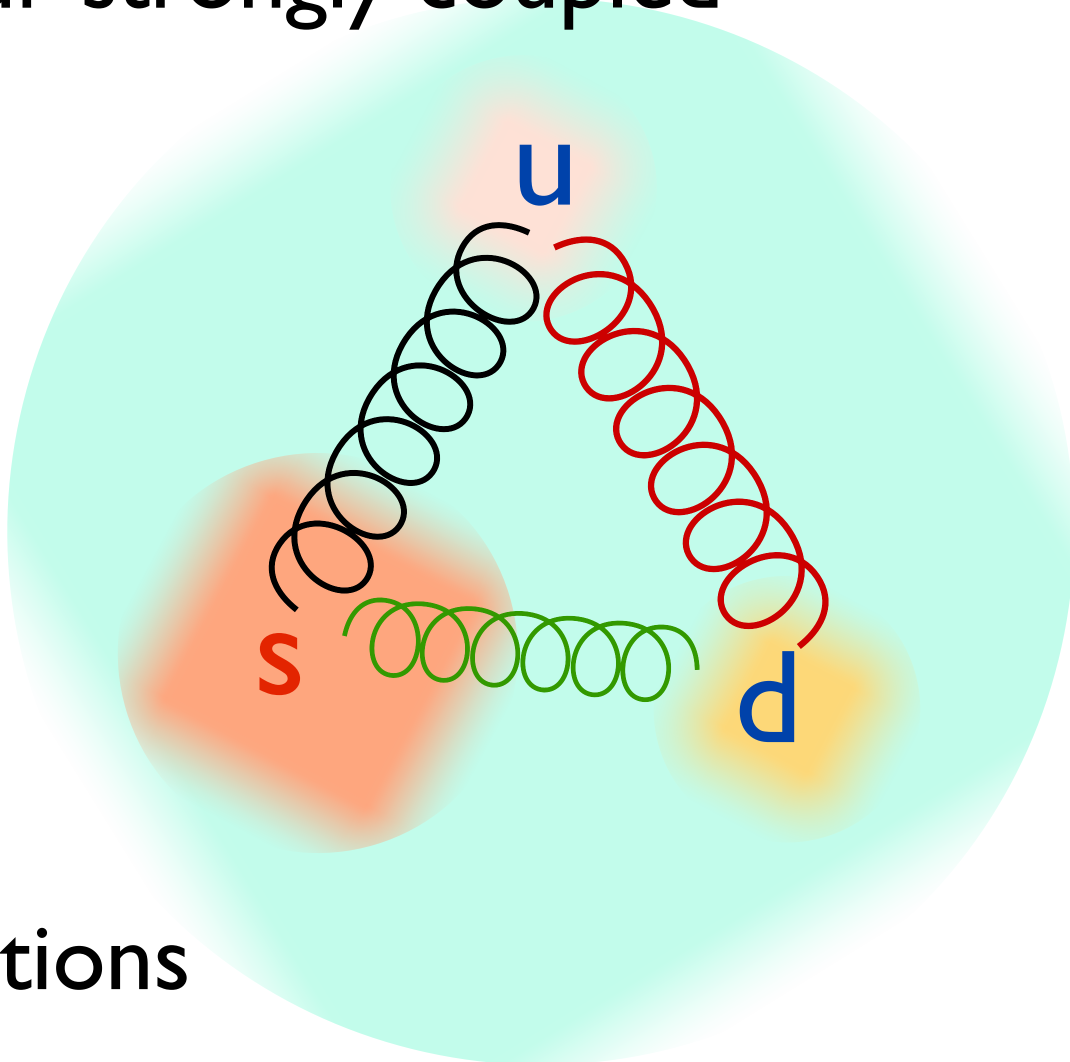
- Quarks "flavors" = different types
- Strange quarks produced/annihilated in pairs



- Once s and $\bar{s}$ quark separate to different hadrons, they can only decay via the weak force
- "Strange" because they live "forever" - time scale of ns = 10^{15} times longer than strong scale! → detectable signal!

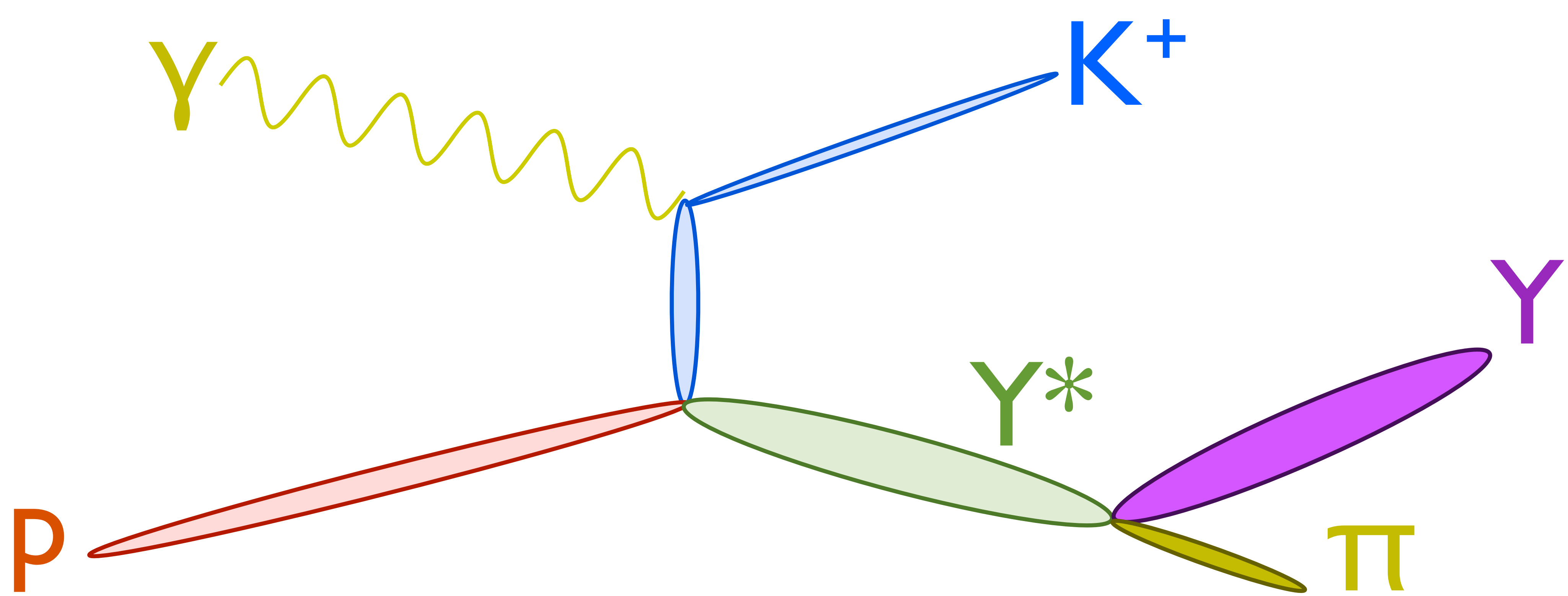
The Gift of Strangeness

- s quarks heavier than u and d quarks → a little more energy to create - but still easily accessible in our strongly coupled energy regime
- Strange particles have given us:
  - parity violation (θτ puzzle)
  - CP violation (neutral kaons)
  - concept of flavor, SU(3)
  - distinction of strong/weak interactions
  - insights into weak decays
  - searches for beyond SM physics



Studying Strange Baryons

- Non-strange baryons (N and Δ): well-studied
- Large overlap of N and Δ states → difficult to study
- Spectrum of strange baryons: much less known
- Generally (much) smaller widths
- Strange baryons: produced in association with kaon(s) to conserve strangeness → complicates analysis somewhat



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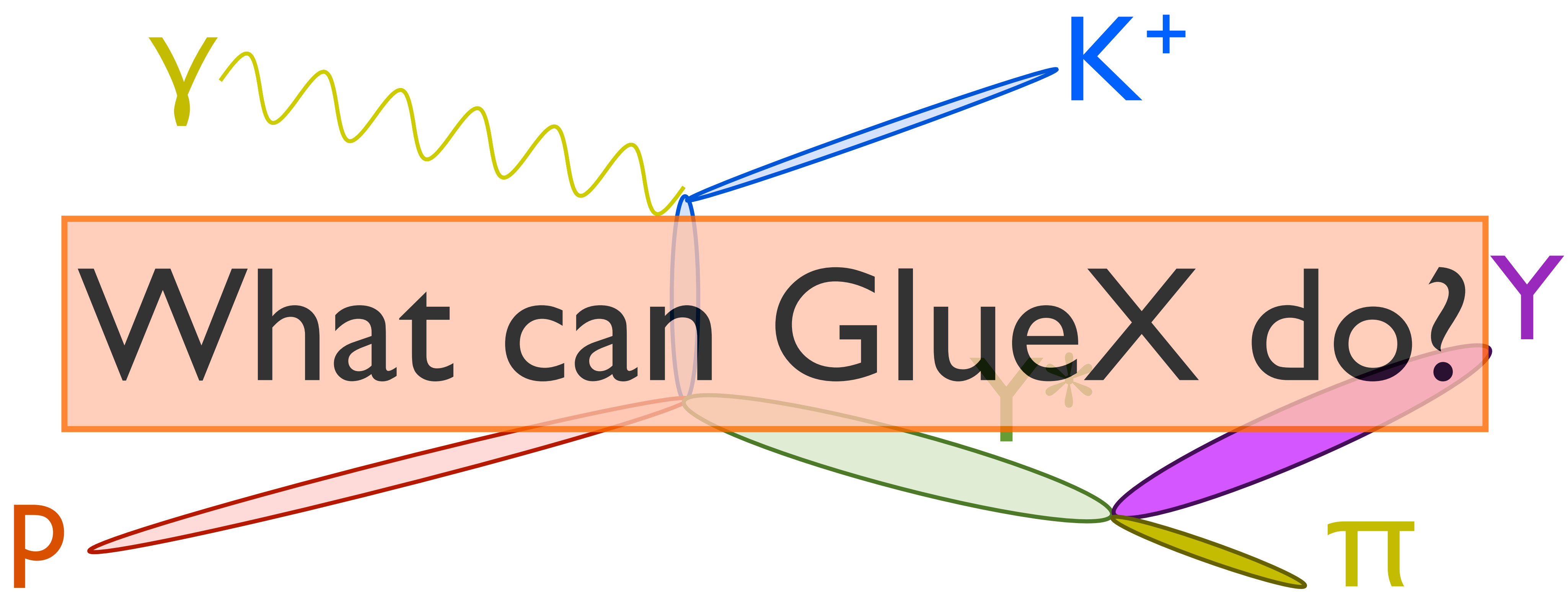
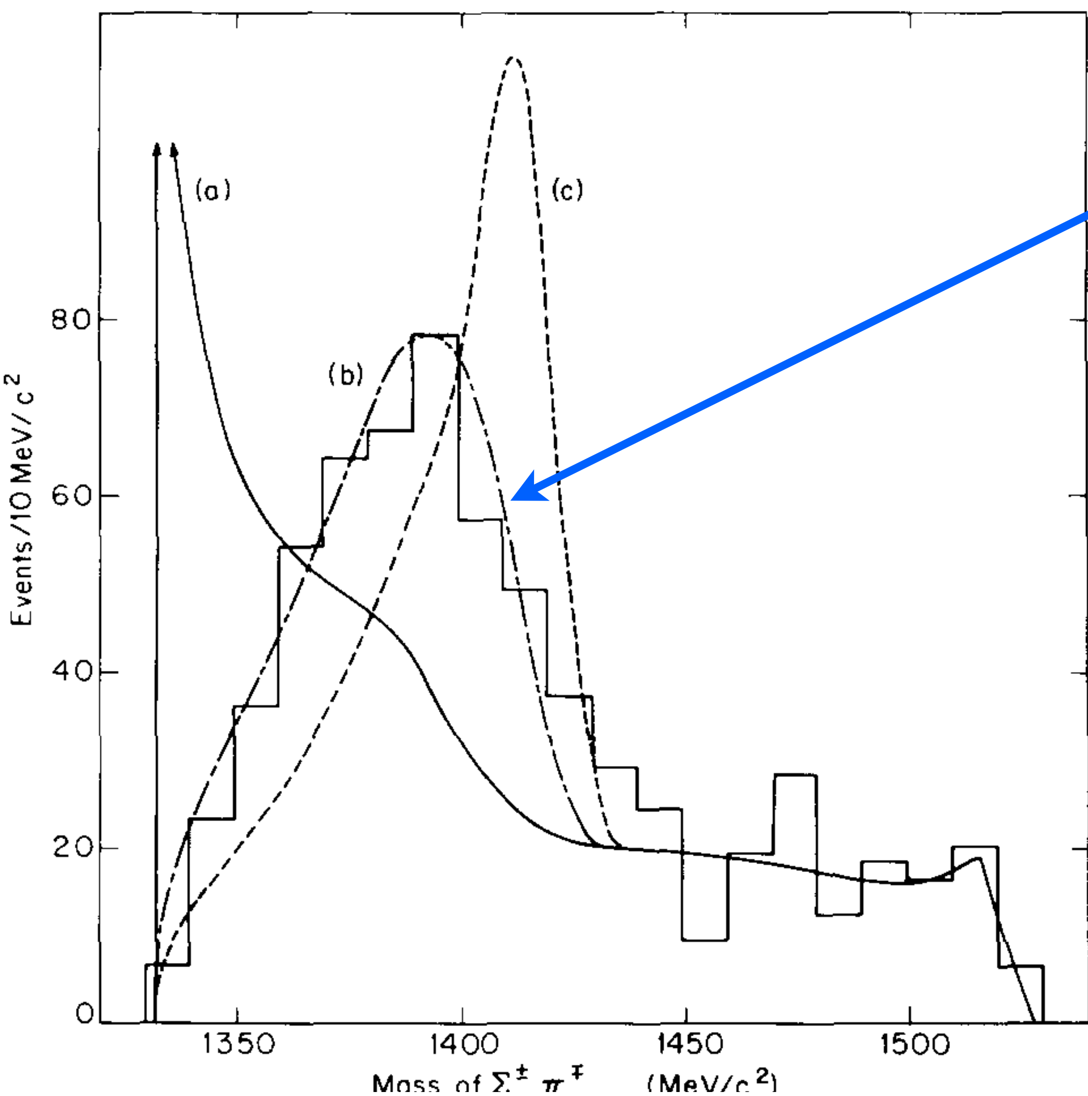
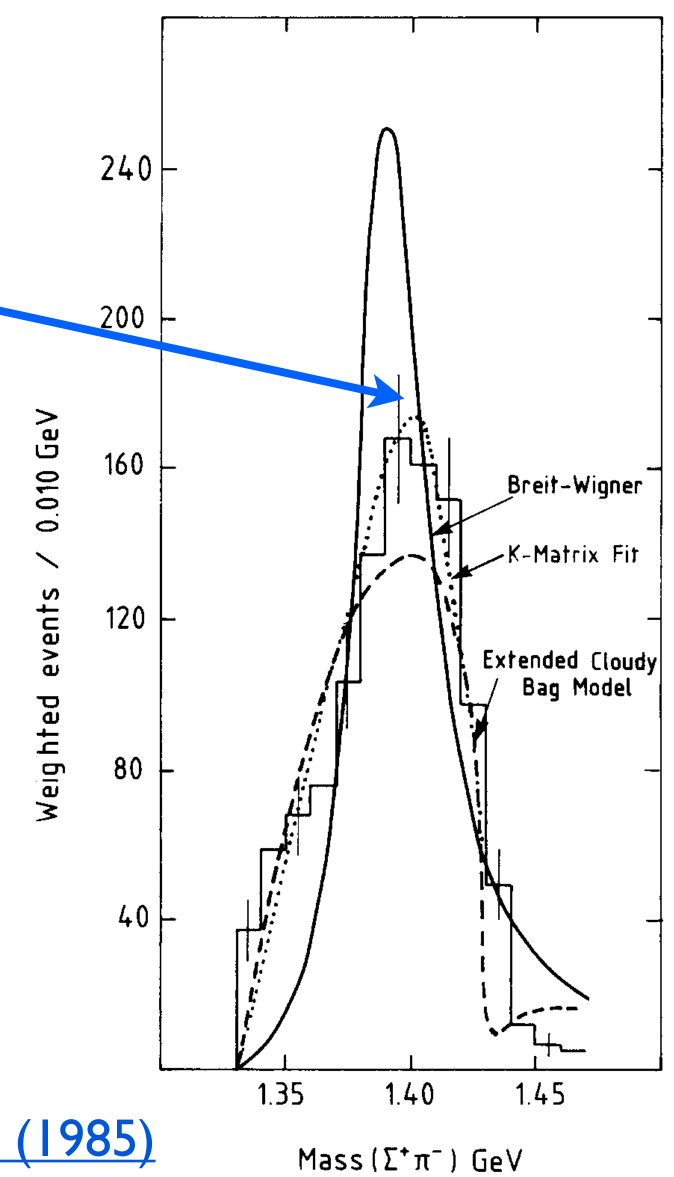


Strangeness -1 Dynamics

- Example: Λ(1405) - Longstanding problem as first excited Λ state: Line shape is distorted
- Dynamics of coupling of $N\bar{K}$ and Σπ states that it couples to



rapid drop in intensity at $N\bar{K}$ threshold



Thomas et. al, [Nucl. Phys. B56, 15 (1973)]

Hemingway, [Nucl. Phys. B253, 742 (1985)]

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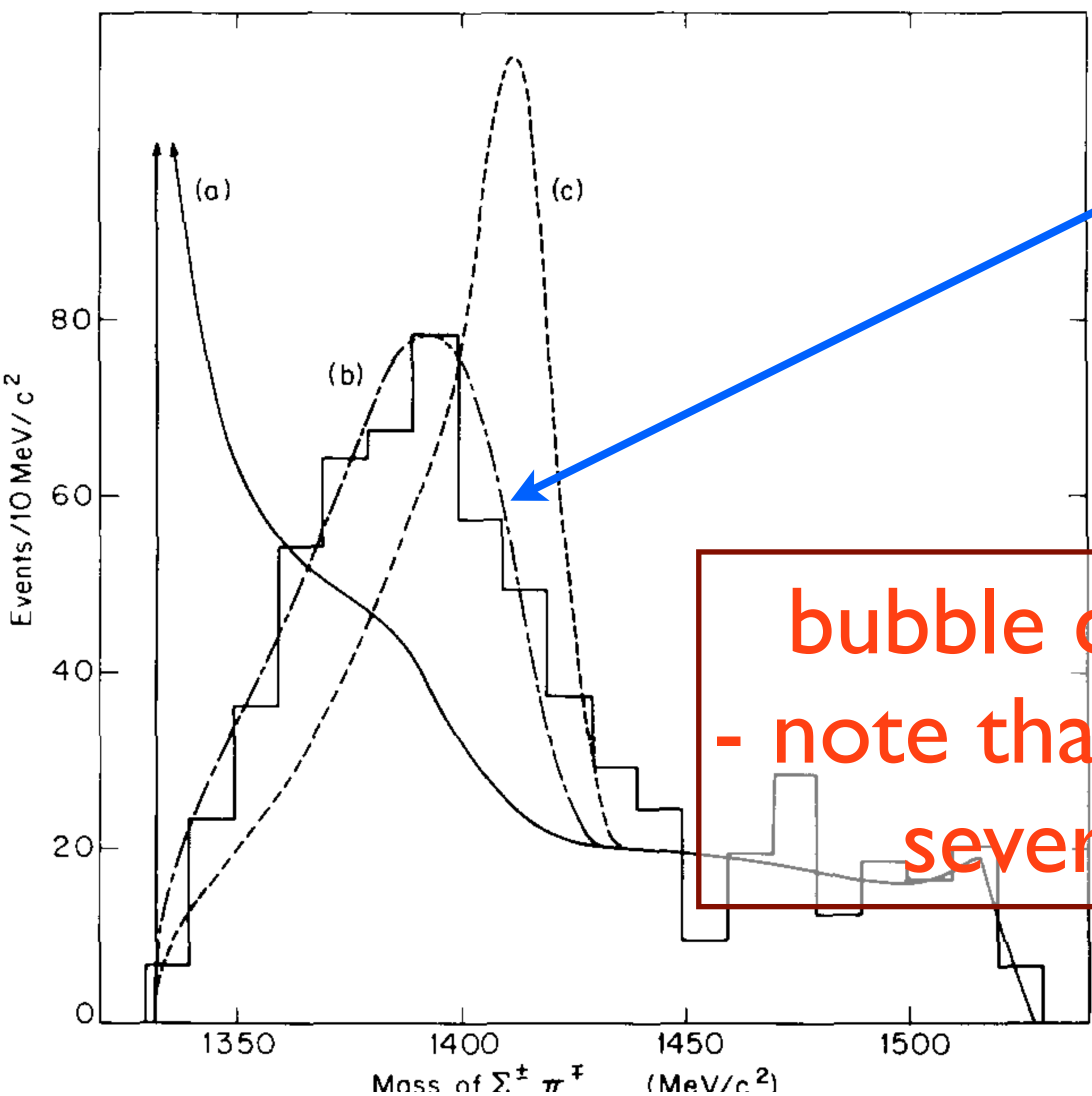
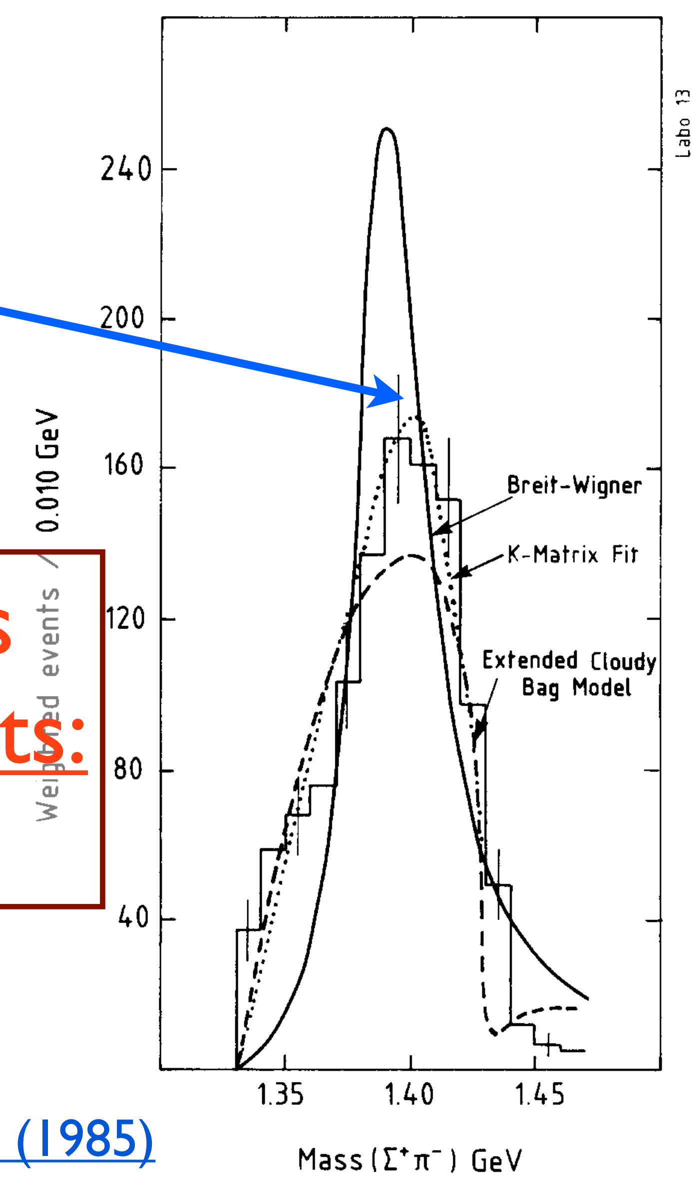


Thomas et. al, Nucl. Phys. B56, 15 (1973)

rapid drop in intensity at $N\bar{K}$ threshold

bubble chamber experiments - note that these are <u>raw counts</u>: several hundred counts



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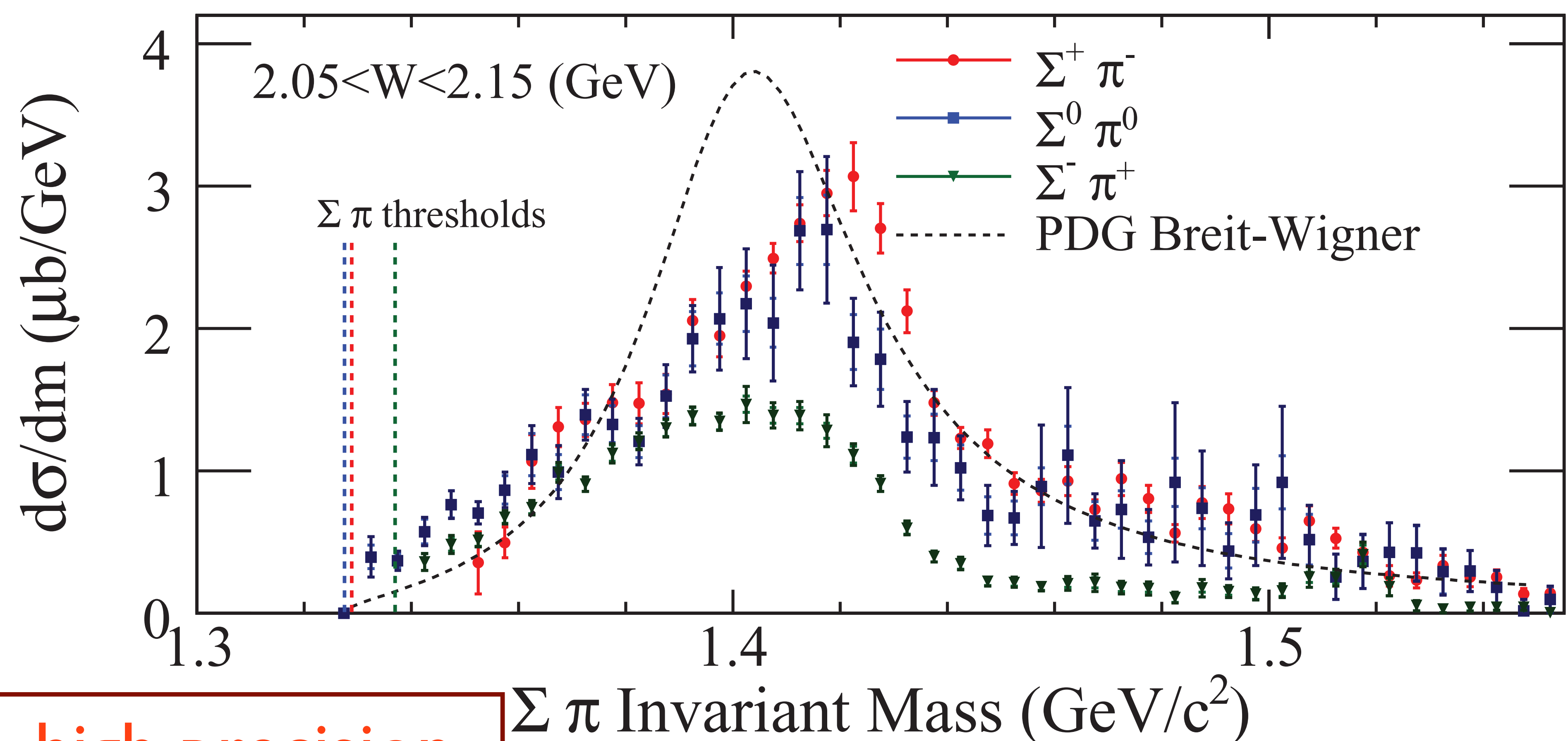
Strangeness -1 Dynamics

- CLAS produced the $\Lambda(1405)$ with high statistics (~10^5 events in each decay mode)
- New finding - Dynamics of final states, together with small isospin 1 amplitude cause line shapes to be different for different $\Sigma\pi$ decay channels



modern experiments - high precision, normalized cross sections

Moriya et al. (CLAS), PRC 87, 035206 (2013)

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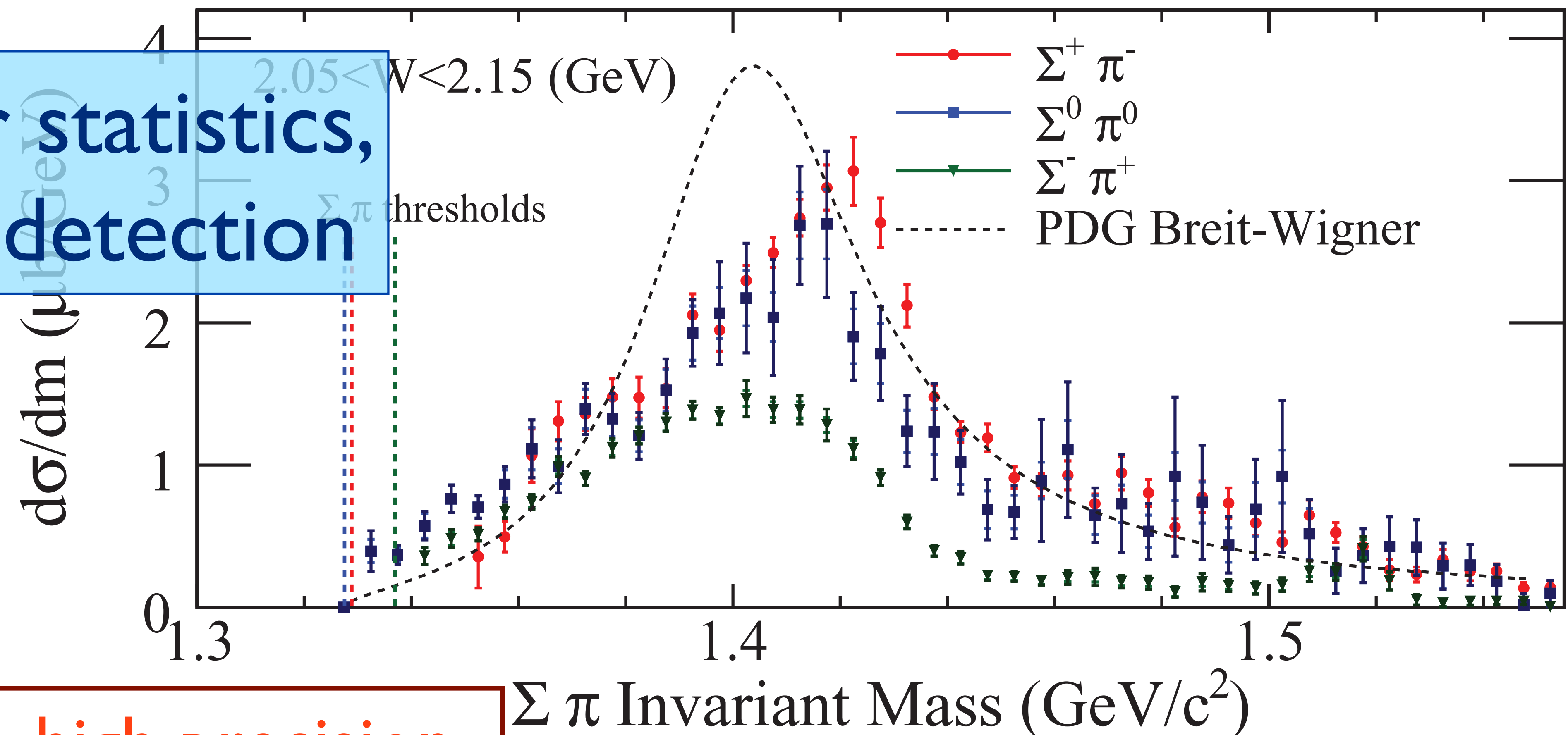
GlueX → higher statistics, neutral particle detection



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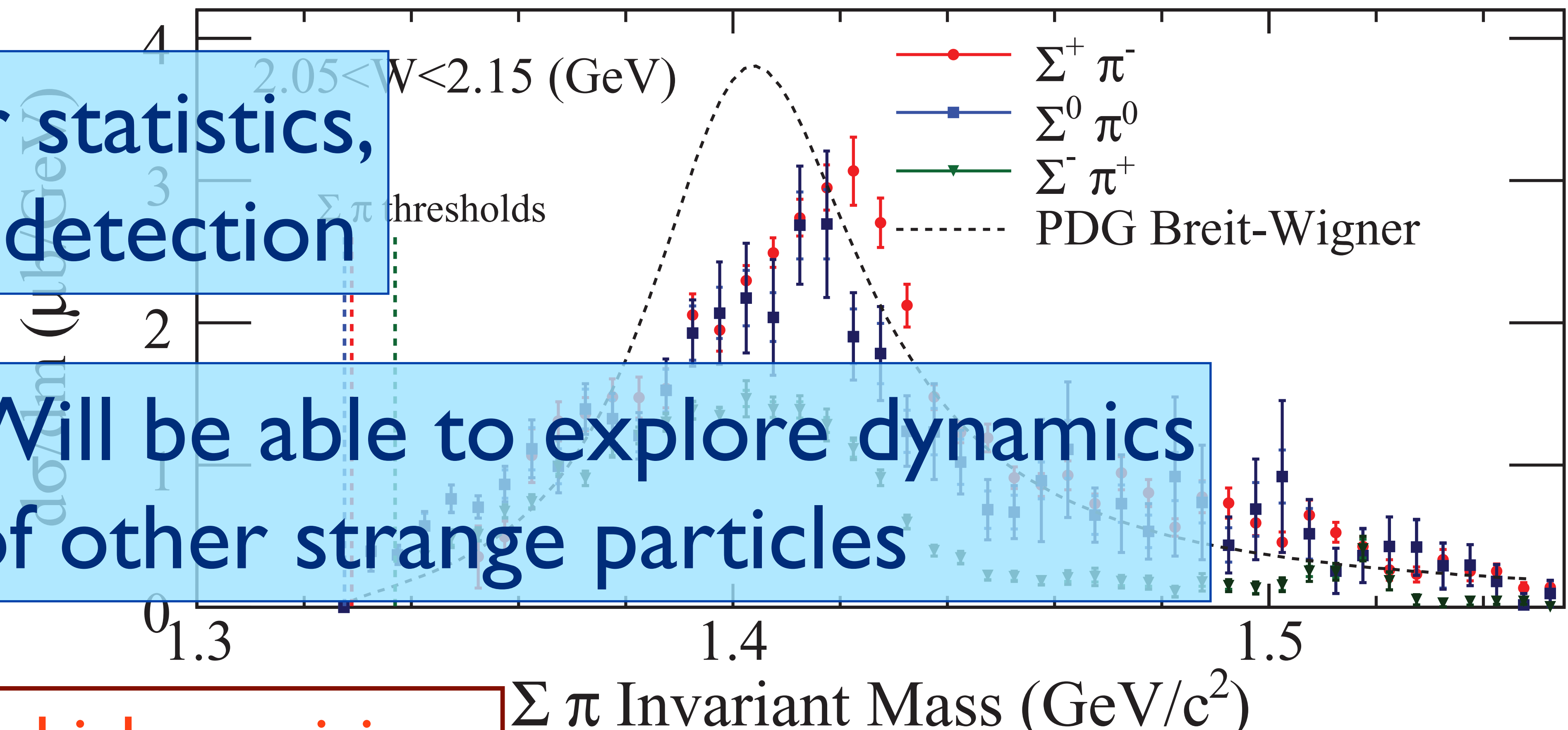


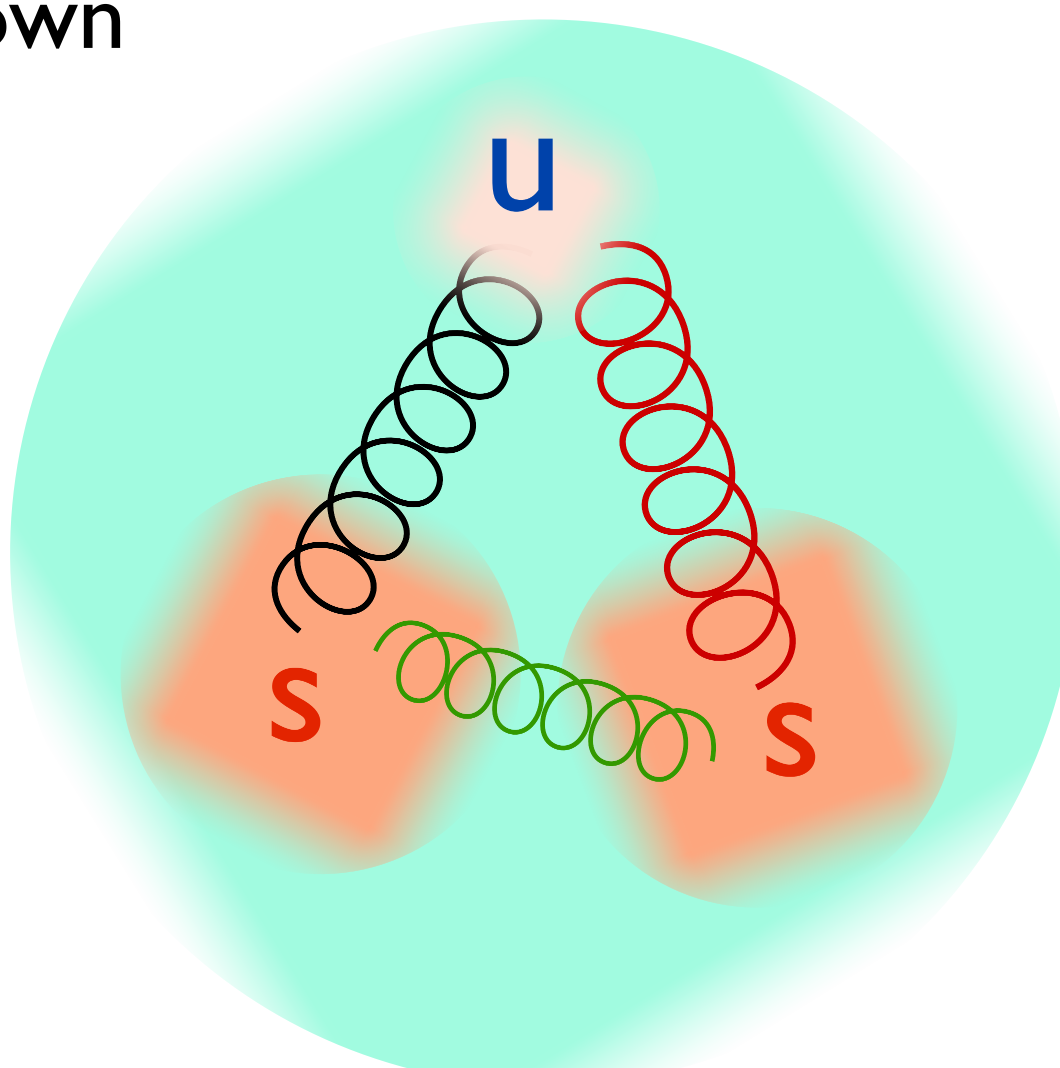
Will be able to explore dynamics of other strange particles

modern experiments - high precision, normalized cross sections

Moriya et al. (CLAS), PRC 87, 035206 (2013)

Even Stranger - The Ξ States

- Replace TWO quarks in a 3-quark system to make Ξ (Cascade) states
- To produce these states we need TWO S=+1 particles (kaons) created in association
- Has been studied with K^- beam (S=-1) and bubble chambers, but excited spectrum is not well known



The Known Ξ Spectrum

State	Status	J^P	Width (MeV)
Ξ	****	$1/2^+$	0
$\Xi(1530)$	****	$3/2^+$	9
$\Xi(1620)$	*	$?^?$	22
$\Xi(1690)$	***	$?^?$	< 30
$\Xi(1820)$	***	$3/2^-$	24
$\Xi(1950)$	***	$?^?$	60 ± 20
$\Xi(2030)$	***	$\geq 5/2^?$	20^{+15}_{-5}
$\Xi(2120)$	*	$?^?$	< 20
$\Xi(2250)$	**	$?^?$	< 30
$\Xi(2370)$	**	$?^?$	80
$\Xi(2500)$	*	$?^?$	150

- Ξ and Ξ(1530) are well-known octet and decuplet states

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GlueX could make a <u>very large</u> contribution to our knowledge of Ξ states → comparison to other baryons

- Ξ and Ξ(1530) are well-known octet and decuplet states
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GlueX Study of $\Xi^-(1820)$

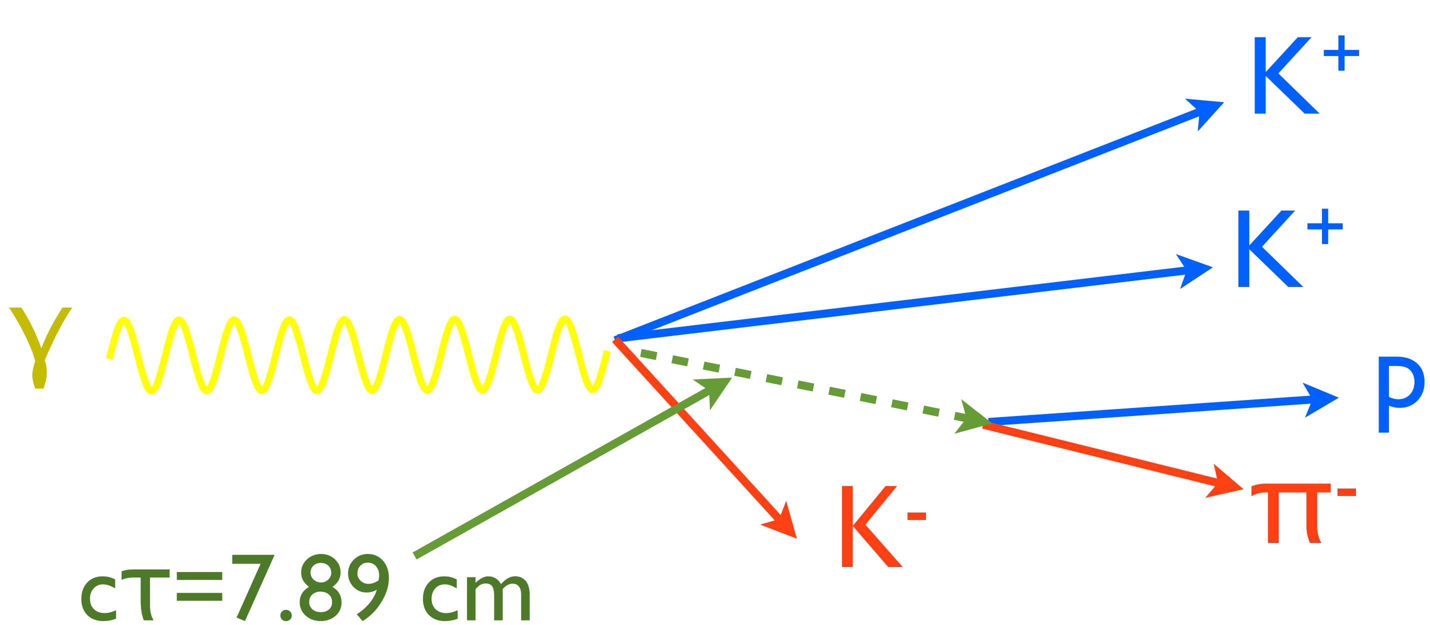
- Use simulated data to study

$$\gamma + p \rightarrow \underline{K^+} + \underline{K^+} + \Xi^-(1820)$$
$$\Xi^-(1820) \rightarrow \Lambda + \underline{K^-}$$
$$\Lambda \rightarrow \underline{p} + \underline{\pi^-}$$

- Final state is 5 charged particles, K^+, K^+, K^-, p, π^-

- Want to know efficiency to reconstruct the state, and mass resolution

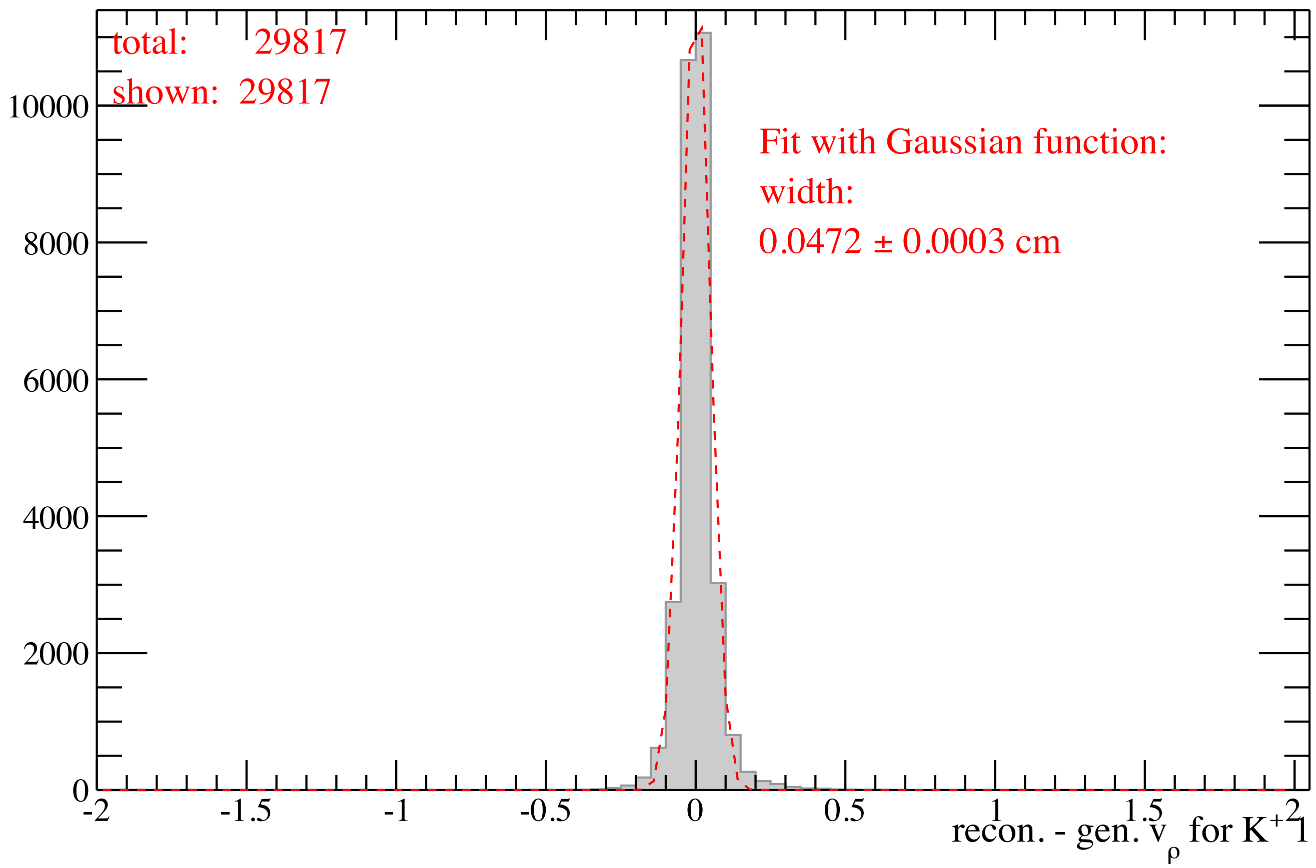
- Use mass M = 1820 MeV/c^2, width Γ = 24 MeV as input



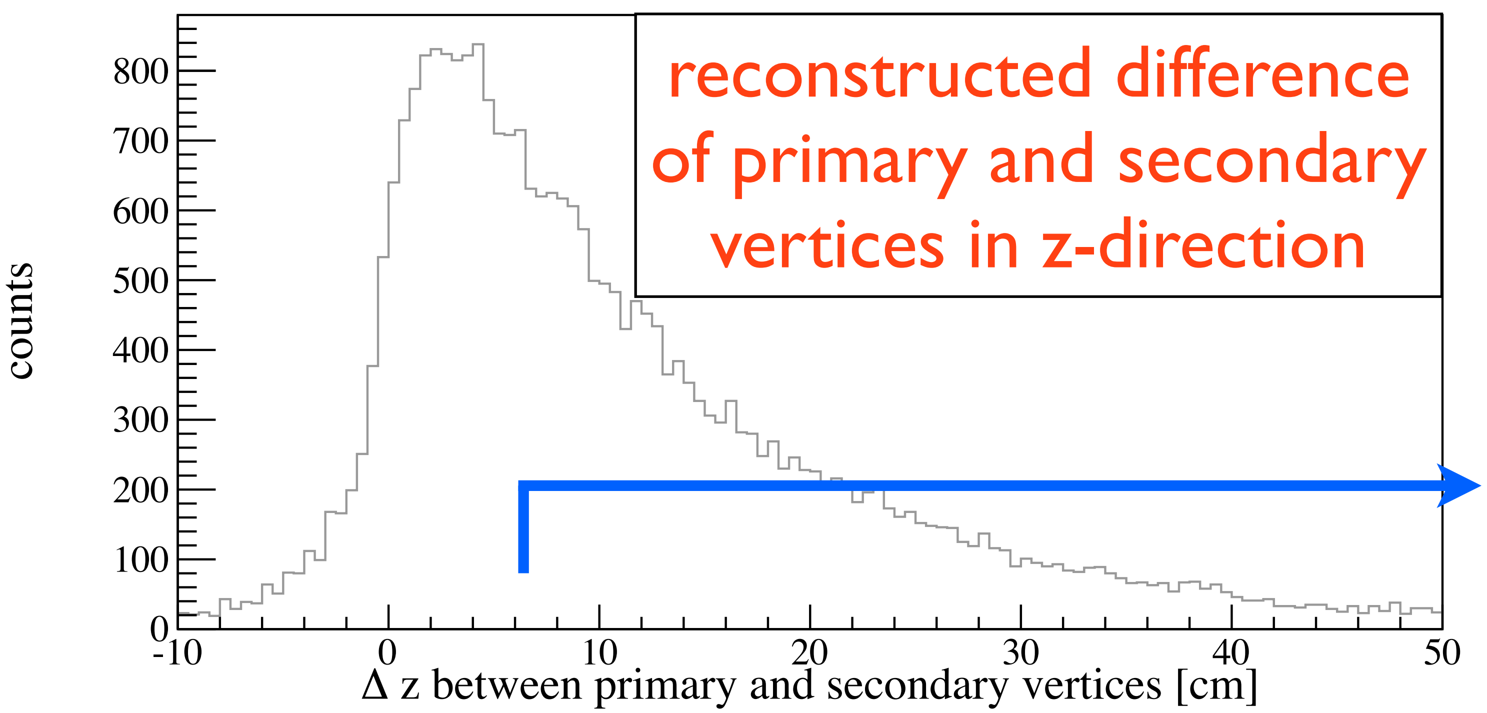
- Primary vertex of K^+, K^+, K^-
- Secondary vertex of p, π^-

Simulated Vertex of $\Xi^-(1820)$

- Primary vertex resolution: ~0.05 cm in xy plane



difference of reconstructed and generated radii



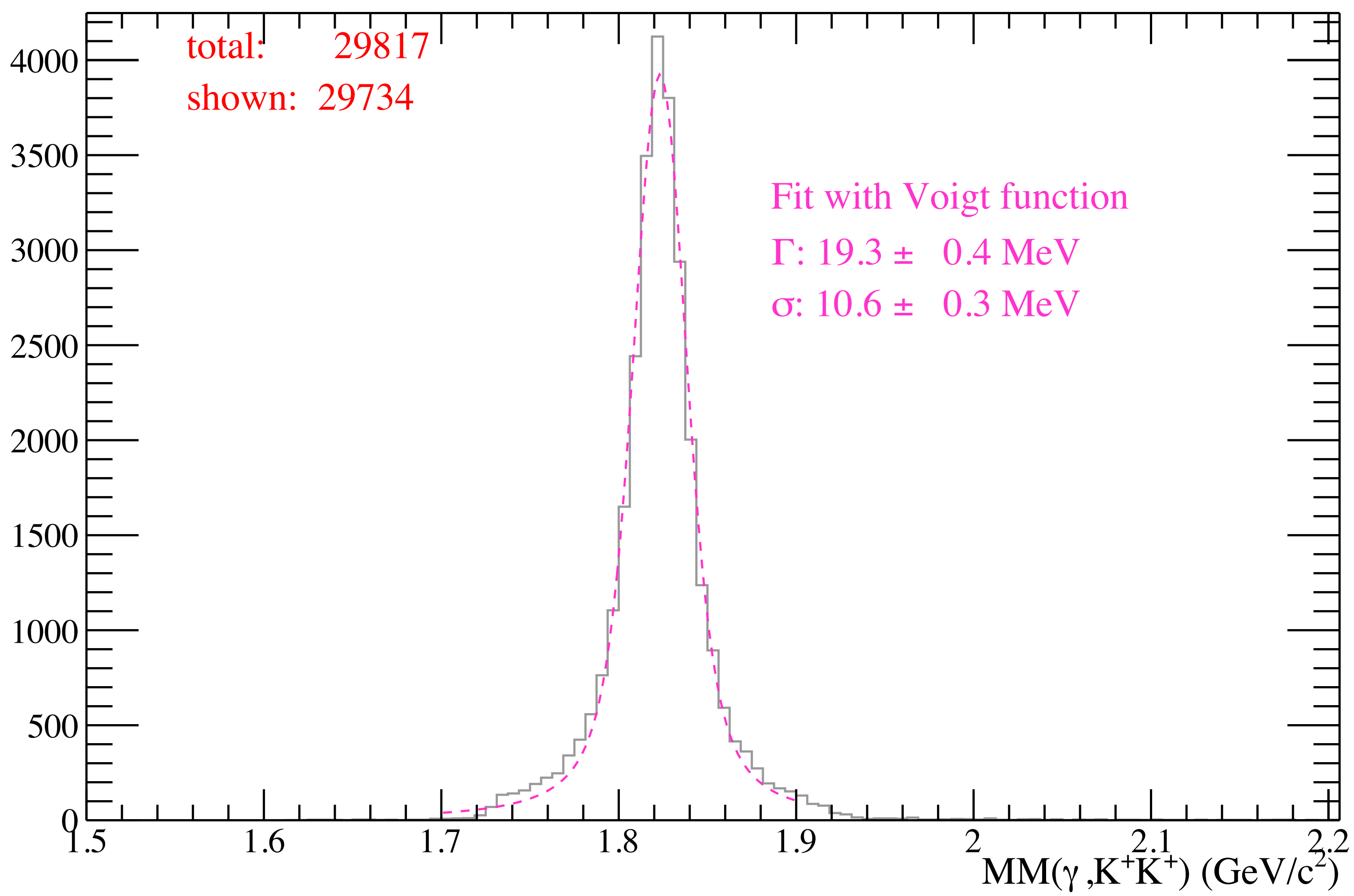
reconstructed difference of primary and secondary vertices in z-direction

large reconstructed vertex difference

- Secondary (and in some cases tertiary) vertices expected to be a strong discriminator against non-strange reactions

Simulated Mass of $\Xi^-(1820)$

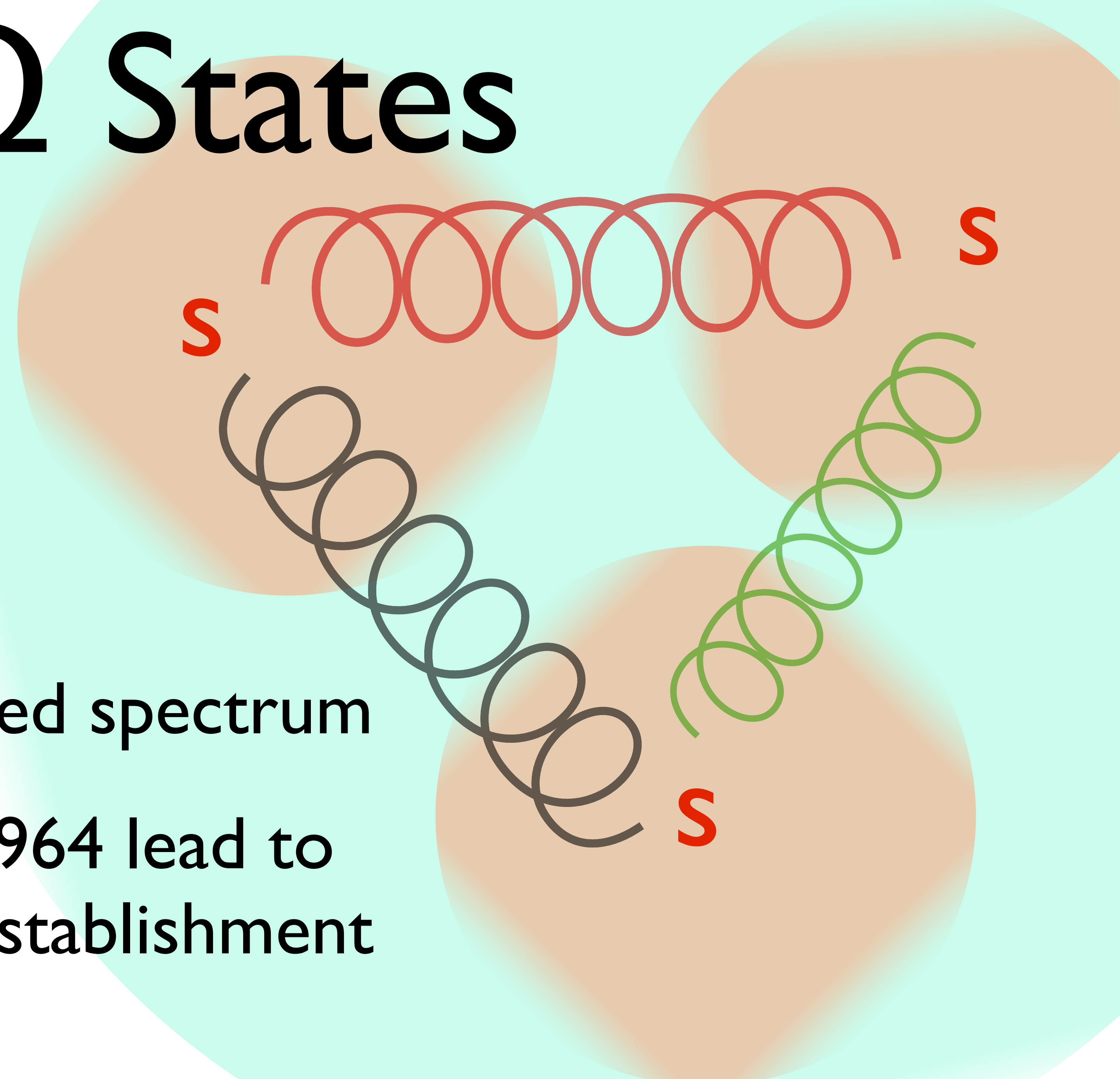
- Reconstruction rate: ~1.6% (exclusive)
- Mass resolution of $\Xi^-(1820)$ is 10 MeV
- Expect at least ~6k events to be reconstructed in full dataset, assuming 1 nb cross section



reconstruction software still under development, further progress expected

- In reality, expect a spectrum of such states
- Can we determine the features of these states?

Maximum Strangeness - The Ω States



- Strangeness S=-3, Ω^- states
- Very little known about excited spectrum
- Prediction and discovery in 1964 lead to acceptance of quark model, establishment of flavor SU(3)
- GlueX could make contributions to our understanding of these states - Ω has never been detected in photoproduction

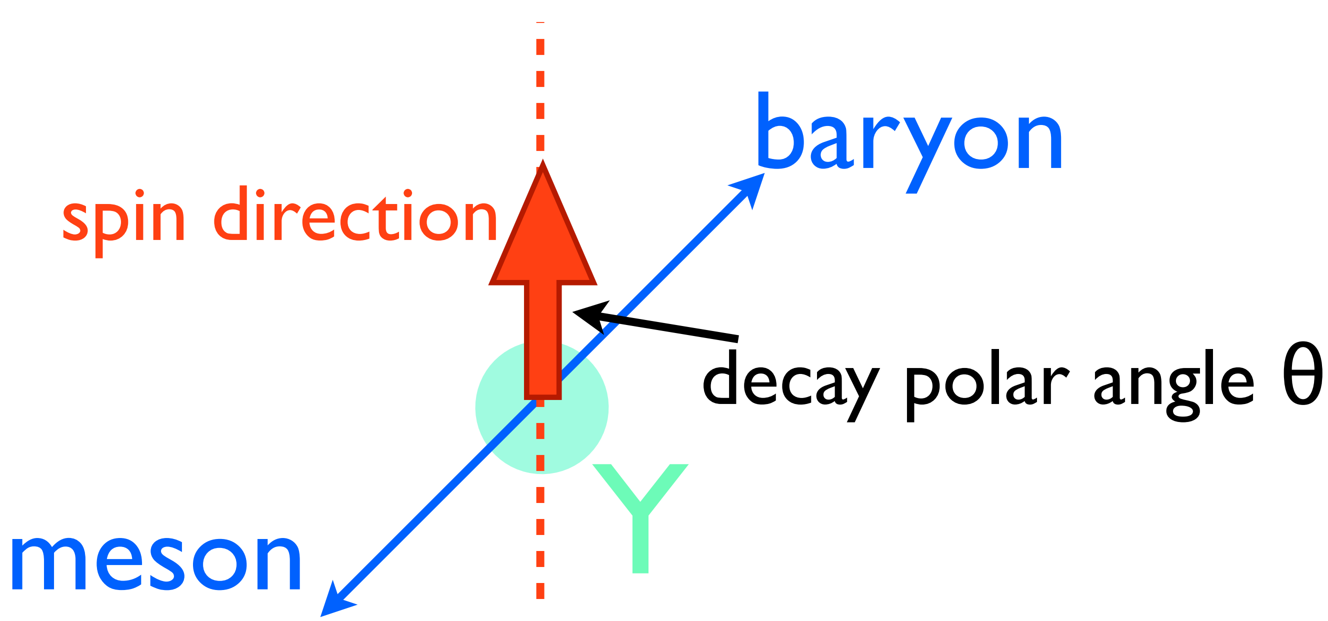
Conclusions

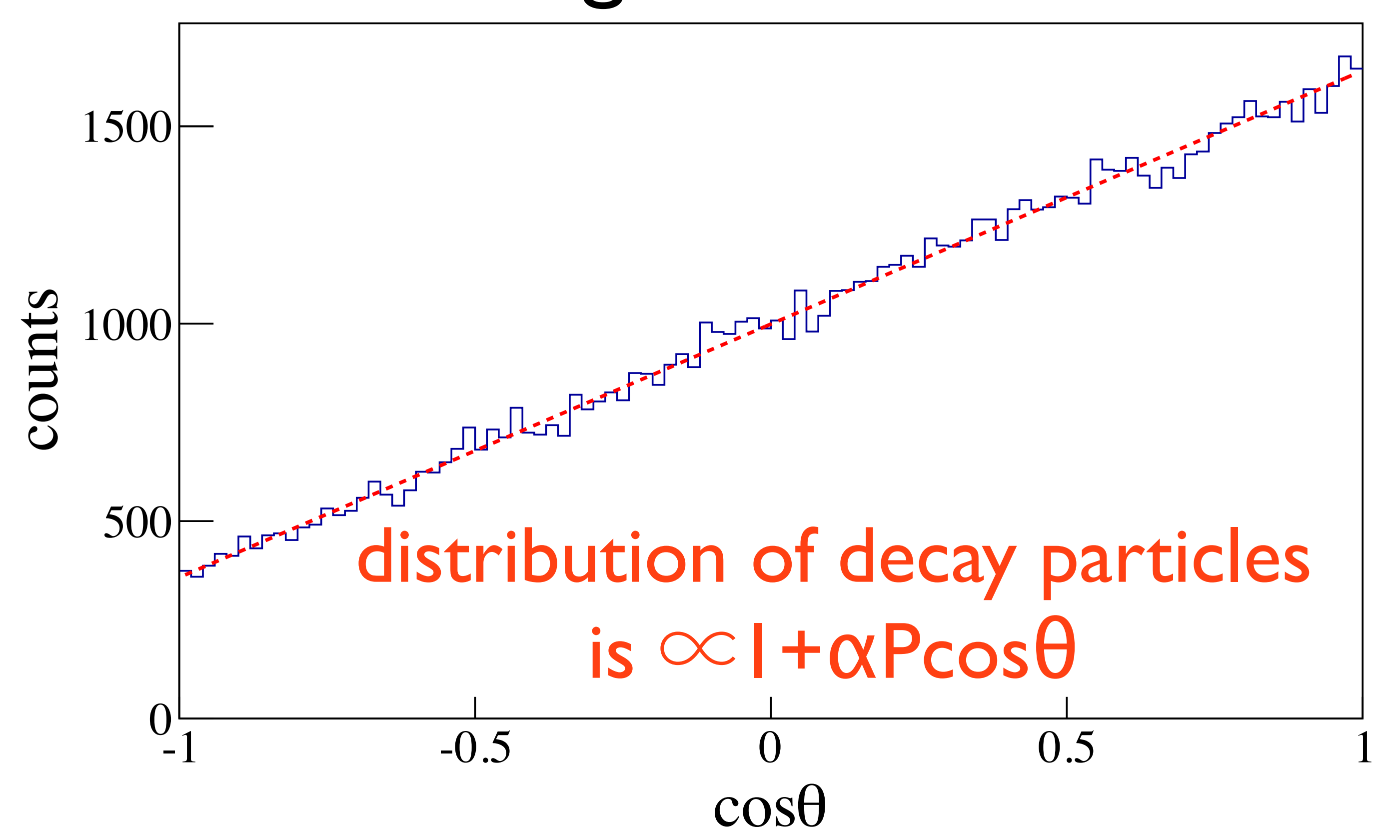
- QCD at the GeV scale is strongly coupled... and messy at first glance
- Need to use all of the information possible - experiment, theory, lattice - to construct a coherent picture of how this theory behaves
- Can we bring structure to the chaos, and connect experiment to QCD?
- GlueX will take enormous amounts of data → explore hadron spectrum for mesons and baryons
- The "strangeness frontier" will be exciting!

Backup Slides

Polarization of Strange Baryons

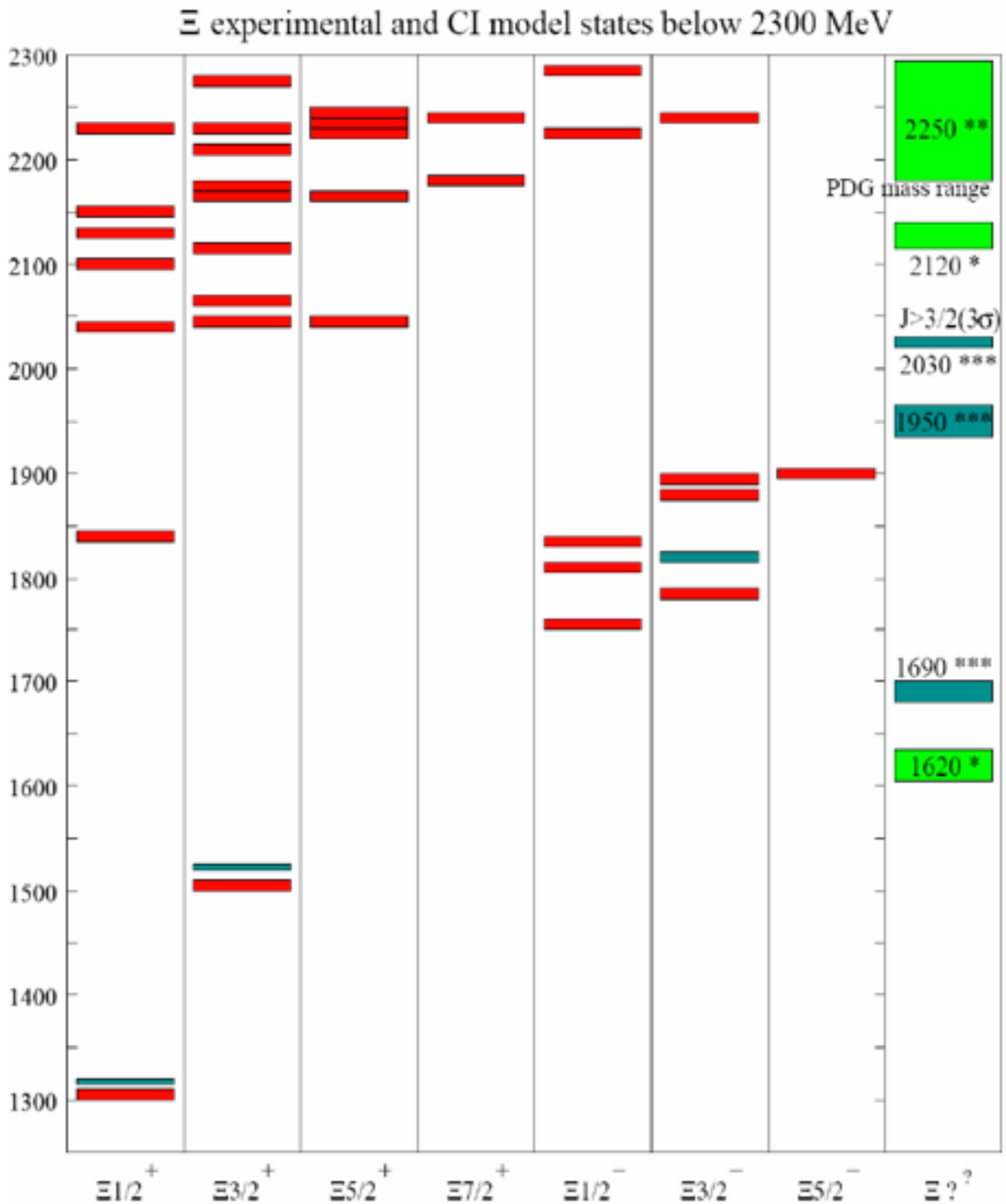
- Ground state strange baryon decays → interference between S-wave and P-wave decay amplitudes (weak force)
- Asymmetry in decay distribution, "self-analyzes" polarization of particles → Polarizations are measurable! (more difficult for non-strange baryons)
- More measurable observables → More strength to resolve ambiguities, explore dynamics





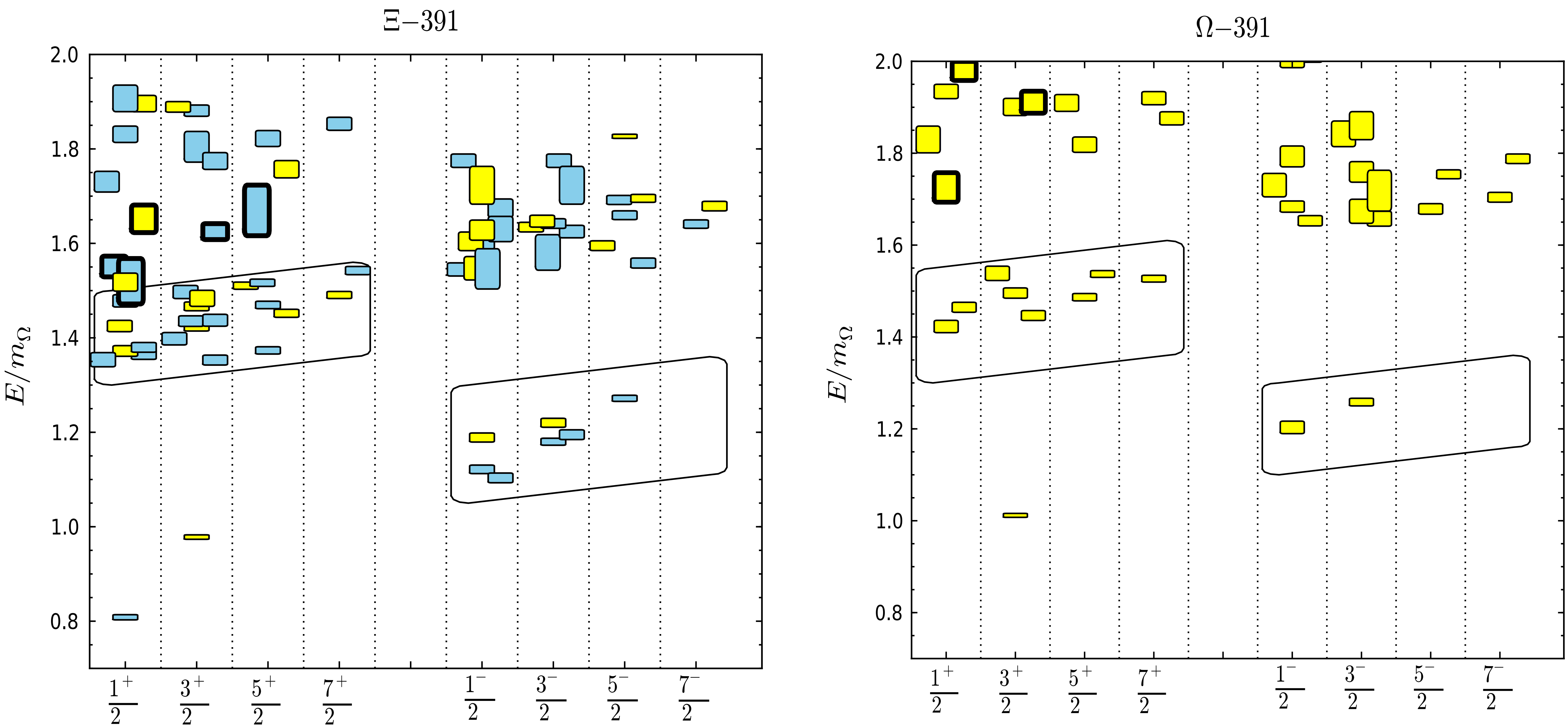
α: constant P: polarization

Theory Predictions for Ξ



Based on *Chao, Isgur, Karl.*, [PRD23, 155 (1981)](#)
figure from Simon Capstick

Lattice QCD Predictions for Ξ, Ω



R. G. Edwards *et al.*, PRD87, 054506 (2013)

Spectrum of Ω States

State	J^P	Mass (MeV/c^2)	Width (MeV)	Status	Primary decay modes	Last reported
Ω^-	$3/2^+$	1672.45	0[a]	****	$\Lambda K^-, \Xi^0\pi^-, \Xi^-\pi^0, \Xi^-\pi^+\pi^-, \Xi^0 e^-\nu_e$	Kamaev (2010)
$\Omega(2250)$	$?^?$	2252 ± 9	55 ± 18	***	$\Xi^-\pi^+K^-, \Xi(1530)^0 K^-$	Aston (1987)
$\Omega(2380)$	$?^?$	~ 2380	26 ± 23	**	$\Omega\pi$	Hassall (1981)
$\Omega(2470)$	$?^?$	2474 ± 12	72 ± 33	**	$\Omega^-\pi^+\pi^-$	Aston (1988)

[a] $\tau = 8.21$ ns

- Ground state and <u>three</u> excited states reported
- Ground state decays to ΛK^- (67.8%), $\Xi^0\pi^-$ (23.6%), $\Xi^-\pi^-$ (8.6%)
- No spin-parity information for excited states
- Decay modes will be $\Omega\pi$, $\Omega\pi\pi$, $\Xi\overline{K}$, $\Xi\overline{K}\pi$