Hadronic Spectroscopy and What We Can Learn About QCD from GlueX

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GLUEX
citations
periment

OUTLINE

I. Why Study QCD?

II. Hadronic Spectroscopy

III. The GlueX Experiment

IV. The Strangeness Frontier

PART 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

- The strong force is one of the three forces within the Standard Model of particle physics
- These theories are the building blocks of the universe that we understand so far

What Is QCD?

- The strong force is described by the theory of Quantum Chromodynamics (QCD)

- This is universally accepted as the correct theory that describes all aspects of the strong force:

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

$$G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g f^{abc} A_\mu^b A_\nu^c$$

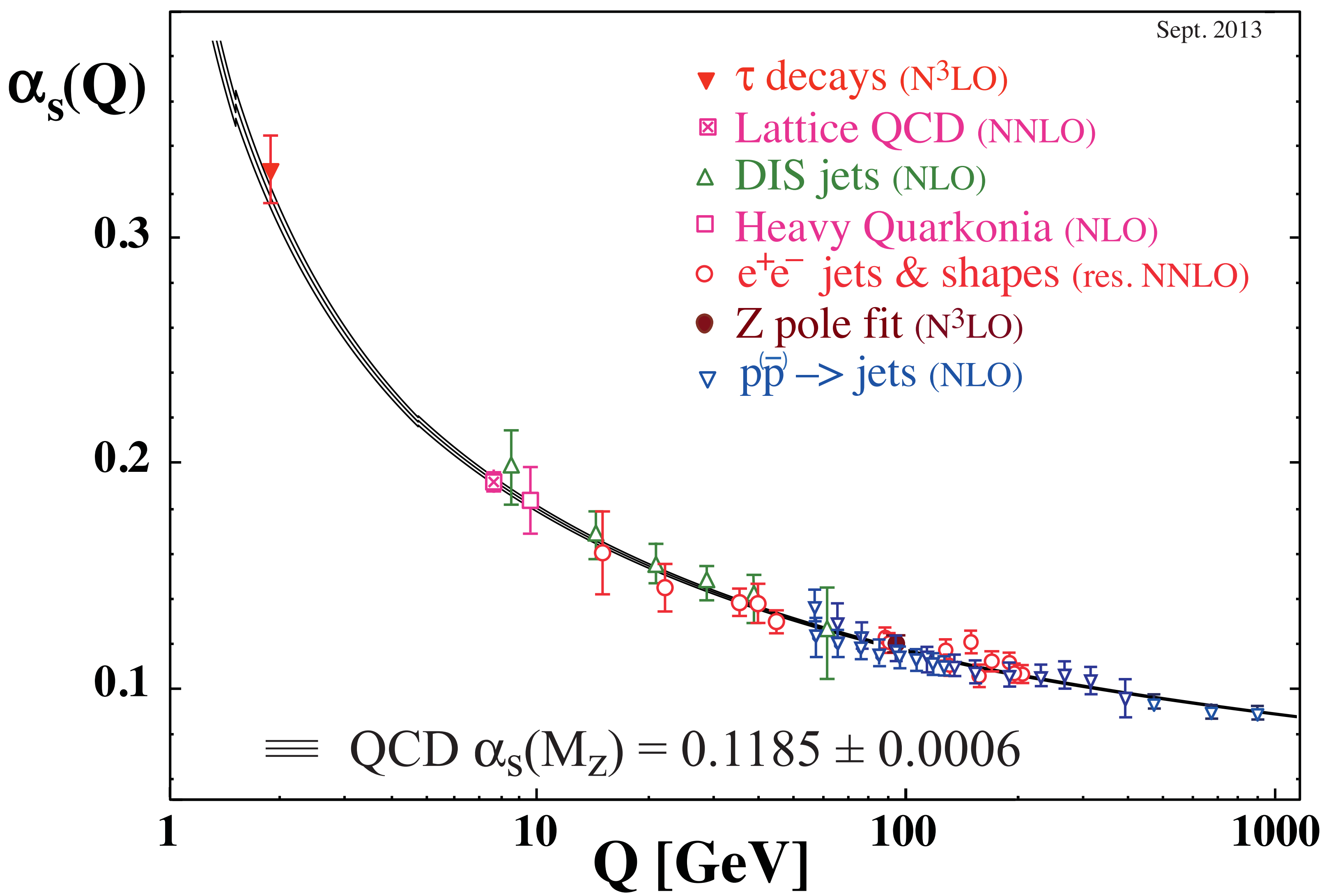
- The fundamental constituents are quarks that are coupled together by gluons

Asymptotic Freedom

- In QCD, the strength of the force weakens as we go to higher energies (shorter distances)

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

- This is responsible for the different behaviors we see at the keV, MeV, GeV, TeV scales



From PDG review on QCD

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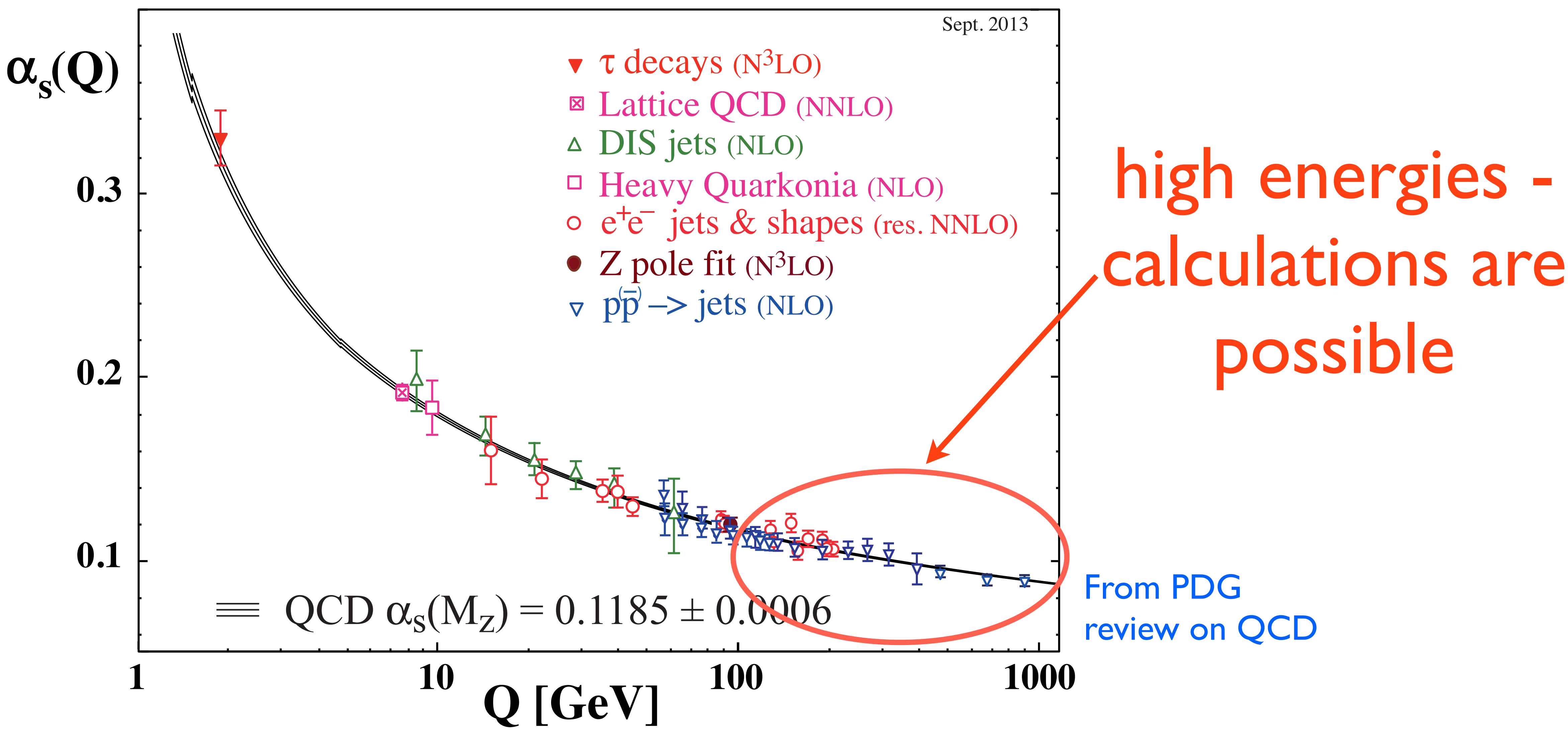

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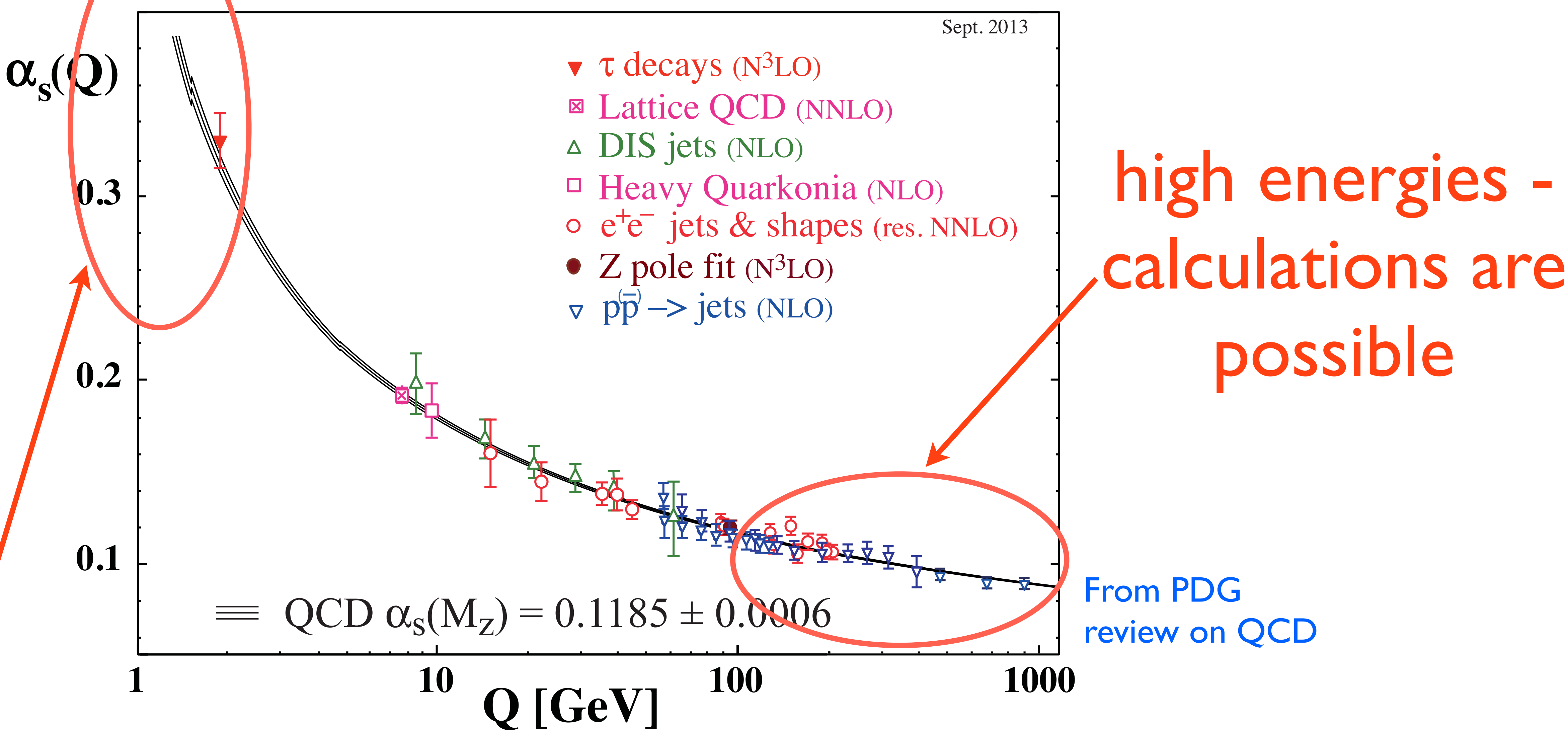


From PDG review on QCD

But what about long distances = low energies?

QCD - An Overview

- QCD is an SU(3) gauge theory and fits together as one component of the Standard Model
- But unlike the electromagnetic force, gluons will couple to each other $\rightarrow$ complicated
- At high energies, perturbative calculations are possible, but not at low energies
- Whether or not we can say we "understand" QCD depends on your definition
- Is there anything intelligent that we can say about the behavior/dynamics of QCD that is not obvious?

QCD at the GeV Scale

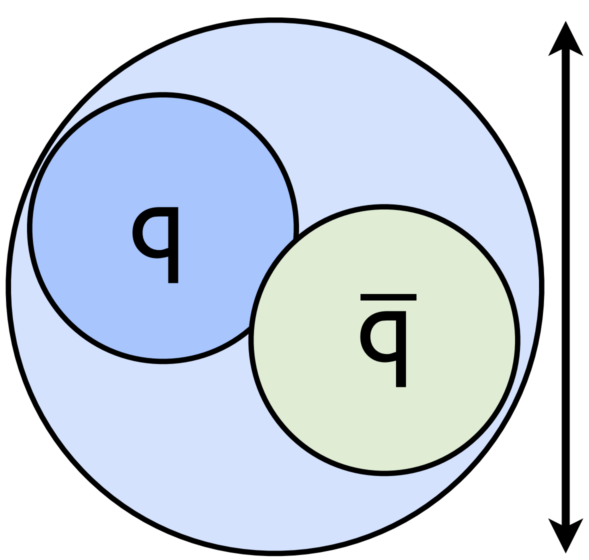
- Energies allow the creation of new particles, which allows us to study the interaction
- Particles of the strong force = hadrons account for most of our mass
- Typical interaction energy of GeV - uncertainty principle tells us that

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

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

QCD Particles

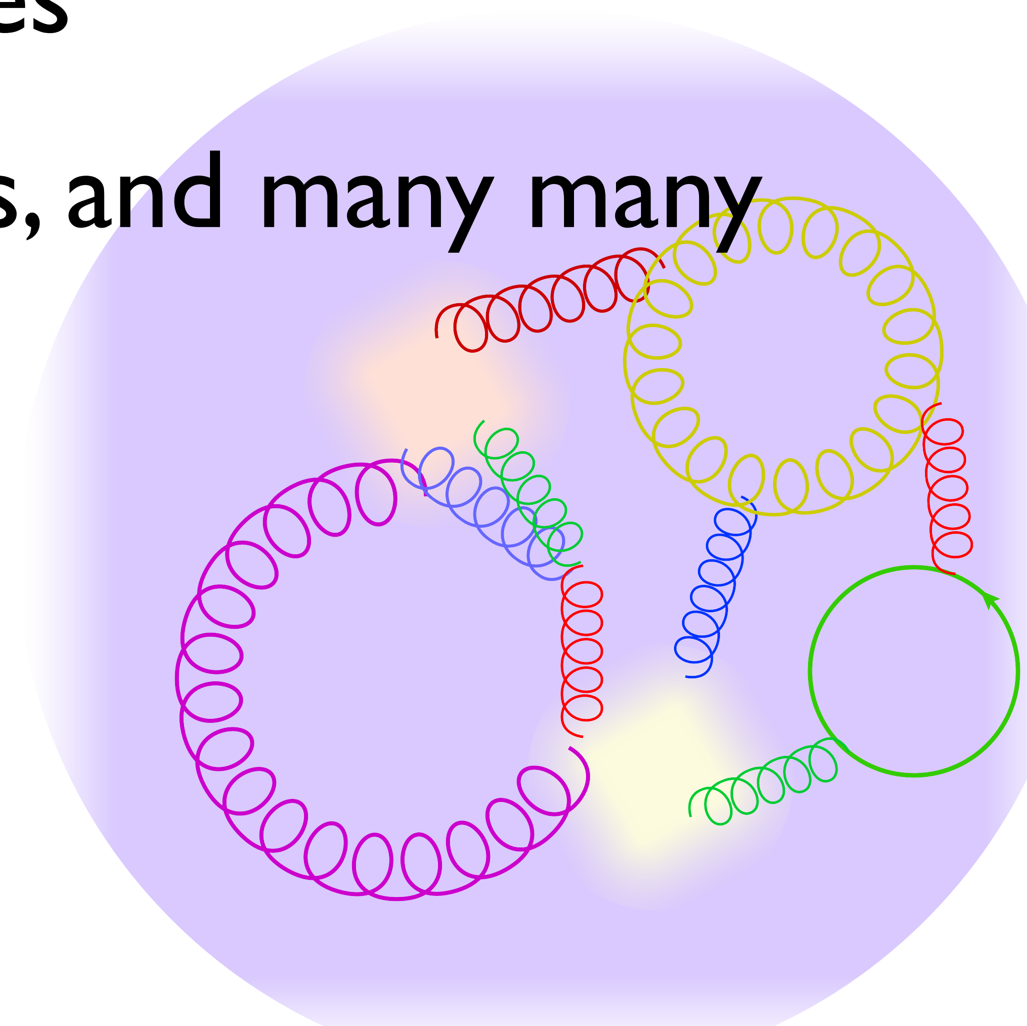
- "Particles" are bound states of quarks and gluons
- The quarks and gluons are confined within the bound states
- There are thought to be "constituent" quarks that give the basic properties of states
- There is also the "sea" of quarks, and many many gluons coupling to all of this!



~fm

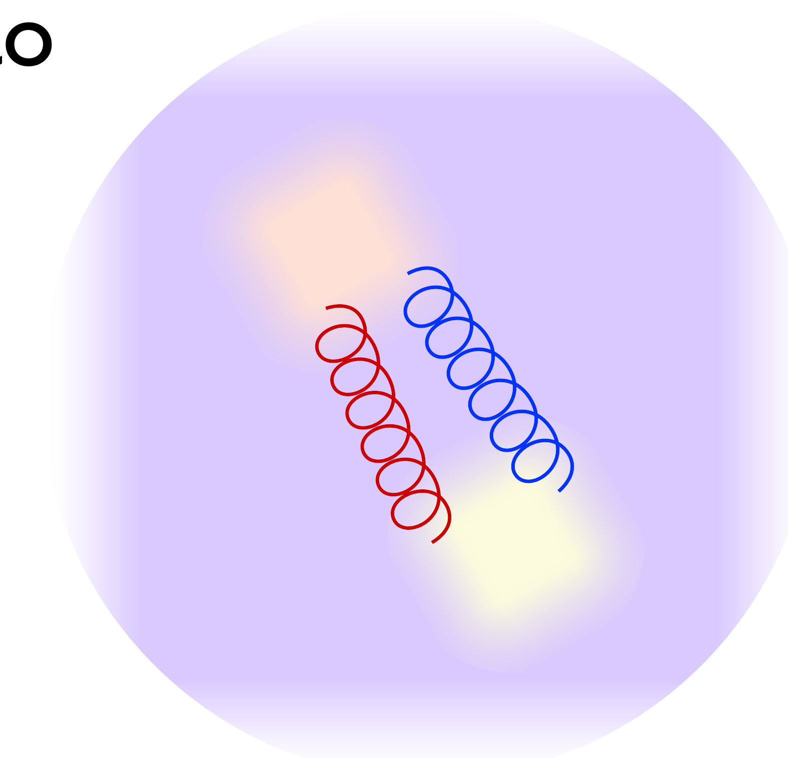
naive picture

reality

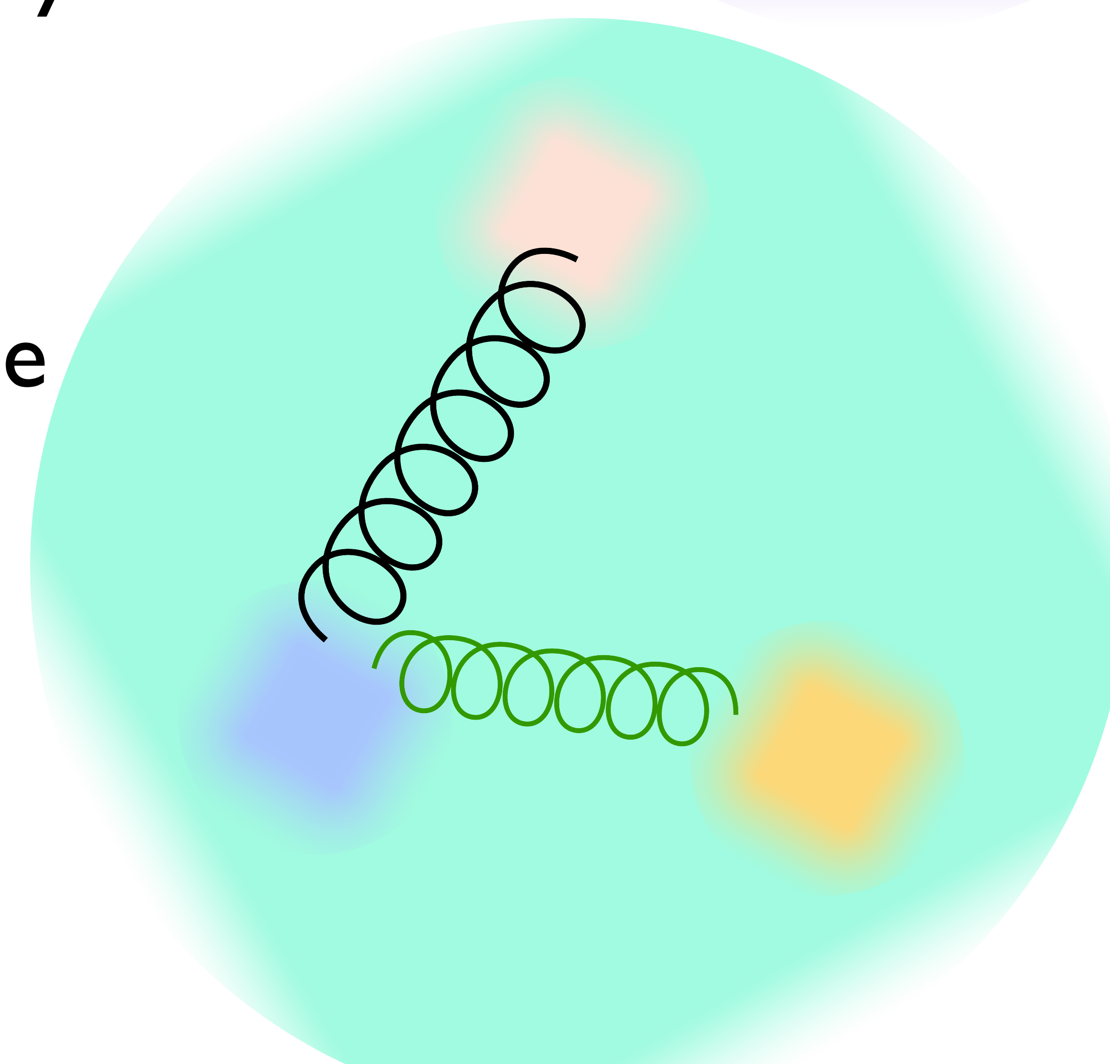


Two Kinds of Hadrons

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

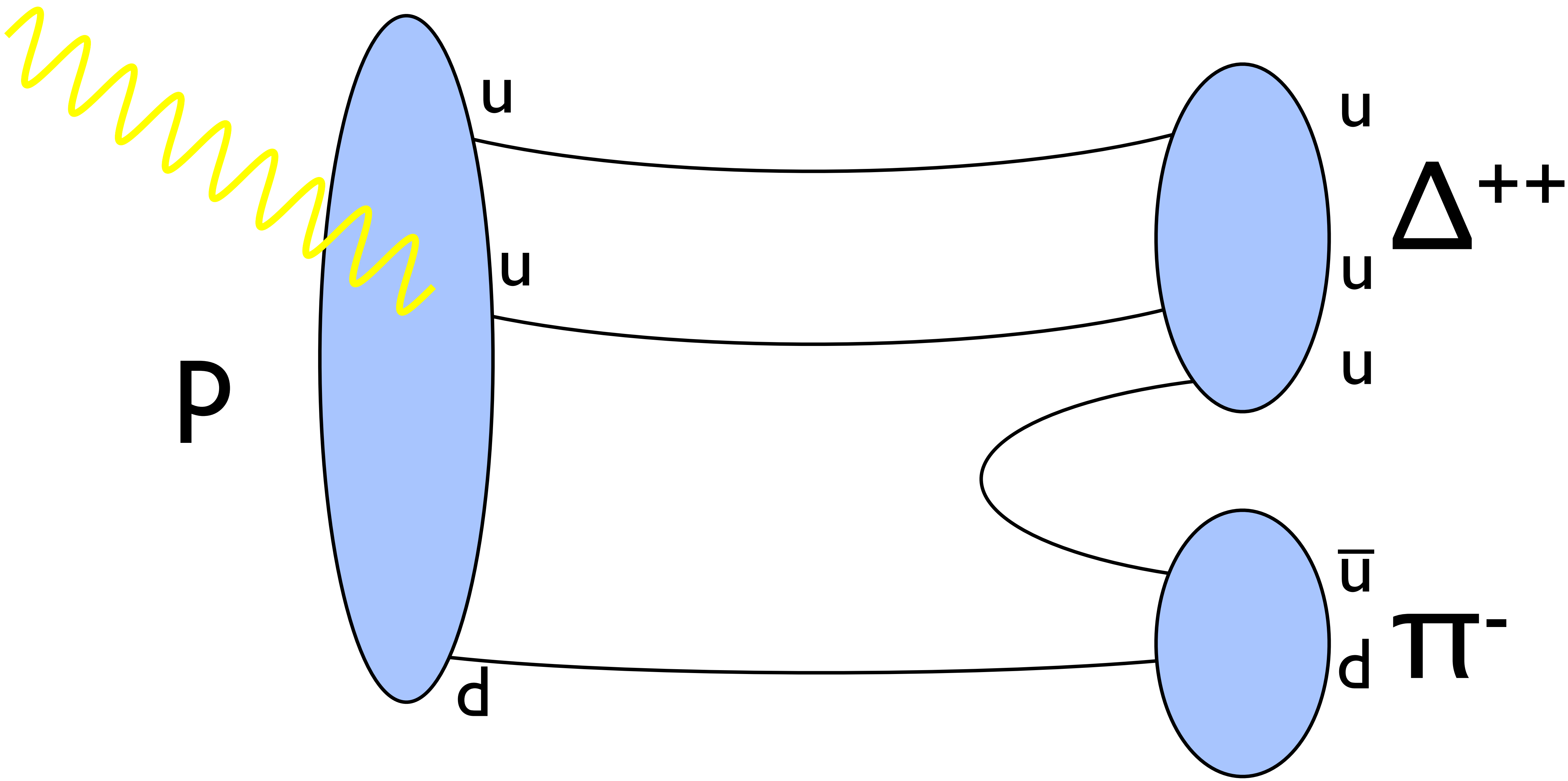


- Baryons are fermions, typically thought to consist of three (anti)quarks (qqq or $\bar{q}\bar{q}\bar{q}$)
- Protons and neutrons are the simplest (and lowest energy examples)



An Experimentalist's View

- We don't know the internal specifics, but from far away, it looks like this:



- Put simply, from the initial and final state, let's try to see what we can say about these bound states of quarks and gluons and understand their interactions

The Known QCD States

mesons

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

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

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 ($C = \pm1$)

	$I(J^P)$
• $D^\pm$	$1/2(0^-)$
• 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 ($B = \pm1$)

	$I(J^P)$
• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B_s^0/b$-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 ($B = \pm1$, $S = \mp1$)

	$I(J^P)$
• 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 ($B = C = \pm1$)

	$I(J^P)$
• $B_c^\pm$	$0(0^-)$

$c\bar{c}$

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

$b\bar{b}$

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

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

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 $4^{++})$
• $f_0(1500)$	$0^+(0^{++})$		
$f_1(1510)$	$0^+(1^{++})$	$\eta(2225)$	$0^+(0^{-+})$
• $f_2'(1525)$	$0^+(2^{++})$	$\rho_3(2250)$	$1^+(3^{--})$
$f_2(1565)$	$0^+(2^{++})$	• $f_2(2300)$	$0^+(2^{++})$
$\rho(1570)$	$1^+(1^{--})$	$f_4(2300)$	$0^+(4^{++})$
$h_1(1595)$	$0^-(1^{+-})$	$f_0(2330)$	$0^+(0^{++})$
• $\pi_1(1600)$	$1^-(1^{-+})$	• $f_2(2340)$	$0^+(2^{++})$
$a_1(1640)$	$1^-(1^{++})$	$\rho_5(2350)$	$1^+(5^{--})$
$f_2(1640)$	$0^+(2^{++})$	$a_6(2450)$	$1^-(6^{++})$
• $\eta_2(1645)$	$0^+(2^{-+})$	$f_6(2510)$	$0^+(6^{++})$
• $\omega(1650)$	$0^-(1^{--})$	OTHER LIGHT	
• $\omega_3(1670)$	$0^-(3^{--})$	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^0_s	$0(0^-)$
• B^*_s	$0(1^-)$
• $B_{s1}(5830)^0$	$0(1^+)$
• $B^*_{s2}(5840)^0$	$0(2^+)$
$B^*_{sJ}(5850)$	$?(?^?)$

BOTTOM, CHARMED ($B = C = \pm1$)	
• $B_c^\pm$	$0(0^-)$

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

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

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^-	$3/2^+$	****
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

Is it all a mess?

From PDG reviews

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

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

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

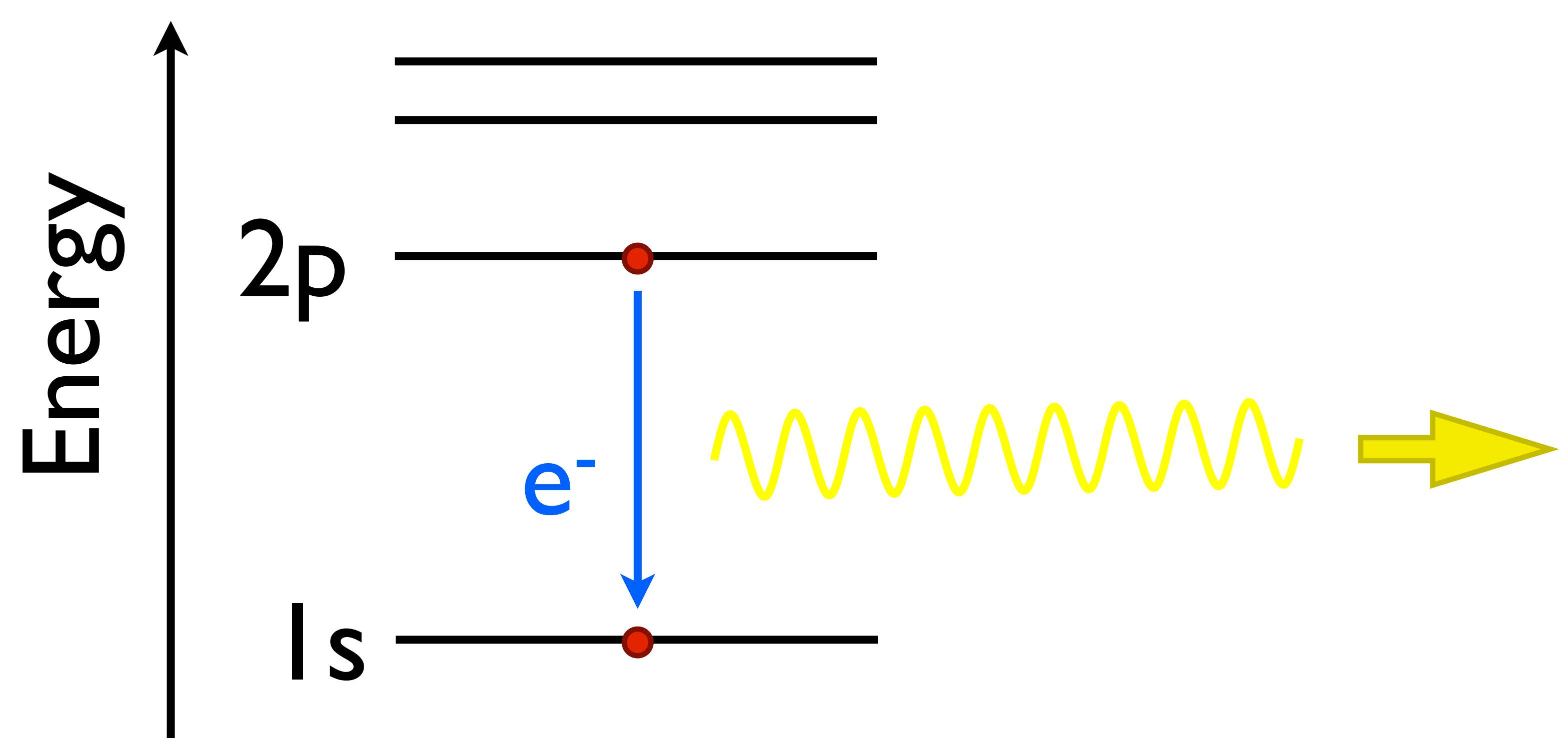
$b\overline{b}$	
$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$

Bringing Order to the Chaos

- Hadron spectroscopy aims to organize the spectrum of hadronic bound states
- Classify hadron states by
  - quantum numbers (J,P,C,S,L,I,...)
  - masses and widths
  - dynamical features
- All of this gives us information on how these states are formed, and how they interact with each other

Atomic Spectroscopy

- Analysis of hydrogen spectrum led to the discovery of quantum mechanics
- Studying the spectrum of atoms allows an understanding of the constituents (electrons/atoms) and forces (electromagnetic)



energy levels of hydrogen

Greater Precision, Greater Knowledge?

- The Bohr model explains the main structures: $$E_n = -\frac{1}{2}\alpha^2 \frac{m_e c^2}{n^2}$$

→ quantum mechanics

Greater Precision, Greater Knowledge?

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- Further experimental, and theoretical investigation leads to the fine, hyperfine structures (spin-orbit, spin-spin) → theory of spin

Greater Precision, Greater Knowledge?

- The Bohr model explains the main structures: $$E_n = -\frac{1}{2}\alpha^2\frac{m_e c^2}{n^2}$$ → quantum mechanics
- Further experimental, and theoretical investigation leads to the fine, hyperfine structures (spin-orbit, spin-spin) → theory of spin
- Even further experimental, and theoretical investigation leads to the Lamb shift (vacuum polarization) → renormalization of QED/QFT

Greater Precision, Greater Knowledge?

- The Bohr model explains the main structures:

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

→ quantum mechanics

- Further experimental, and theoretical investigation leads to the fine, hyperfine structures (spin-orbit, spin-spin)

→ theory of spin

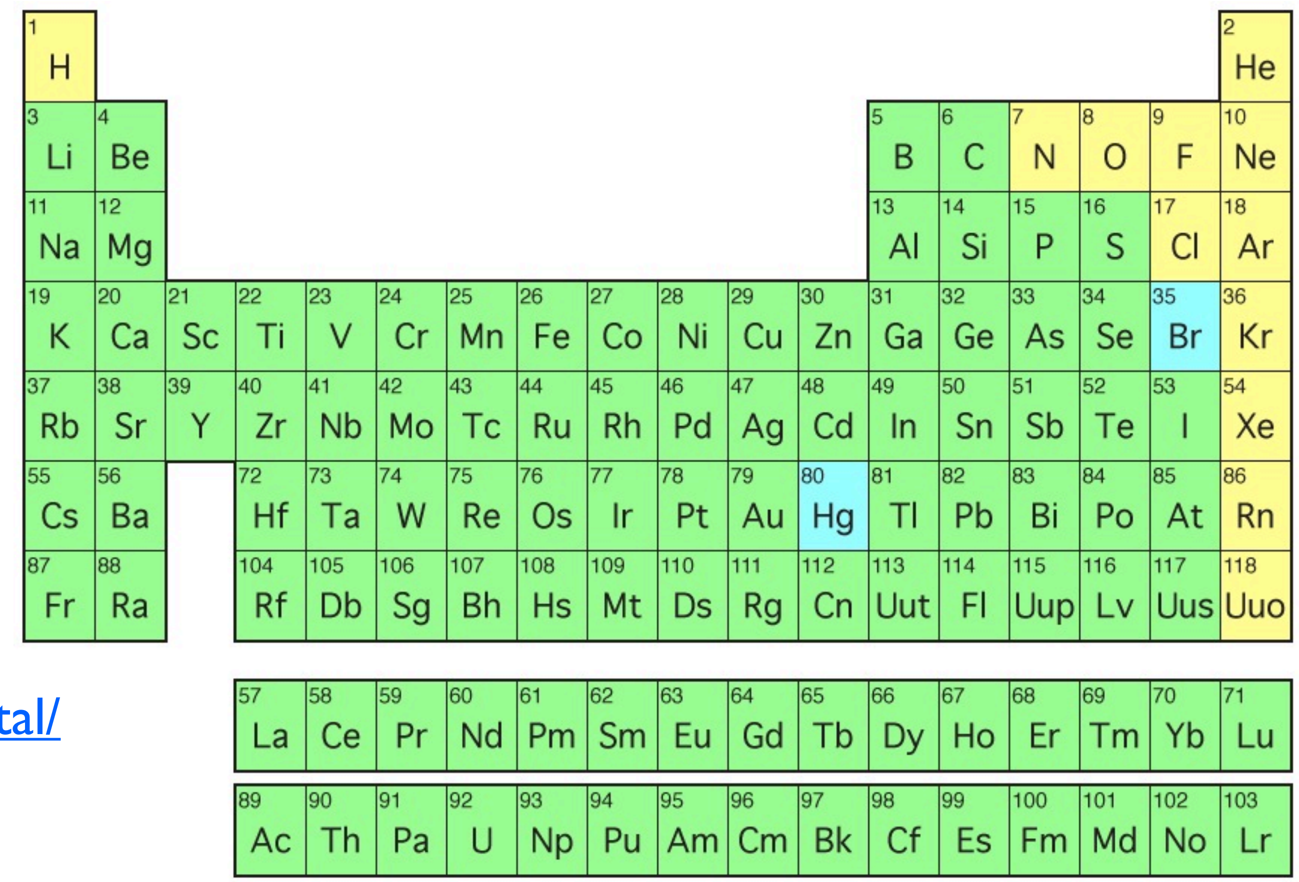
- Even further experimental, and theoretical investigation leads to the Lamb shift (vacuum polarization)

→ renormalization of QED/QFT

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

Spectrum of Hadrons

- All known particles are listed in the PDG
- Need to know how to read and sort this, sort of like the table of elements

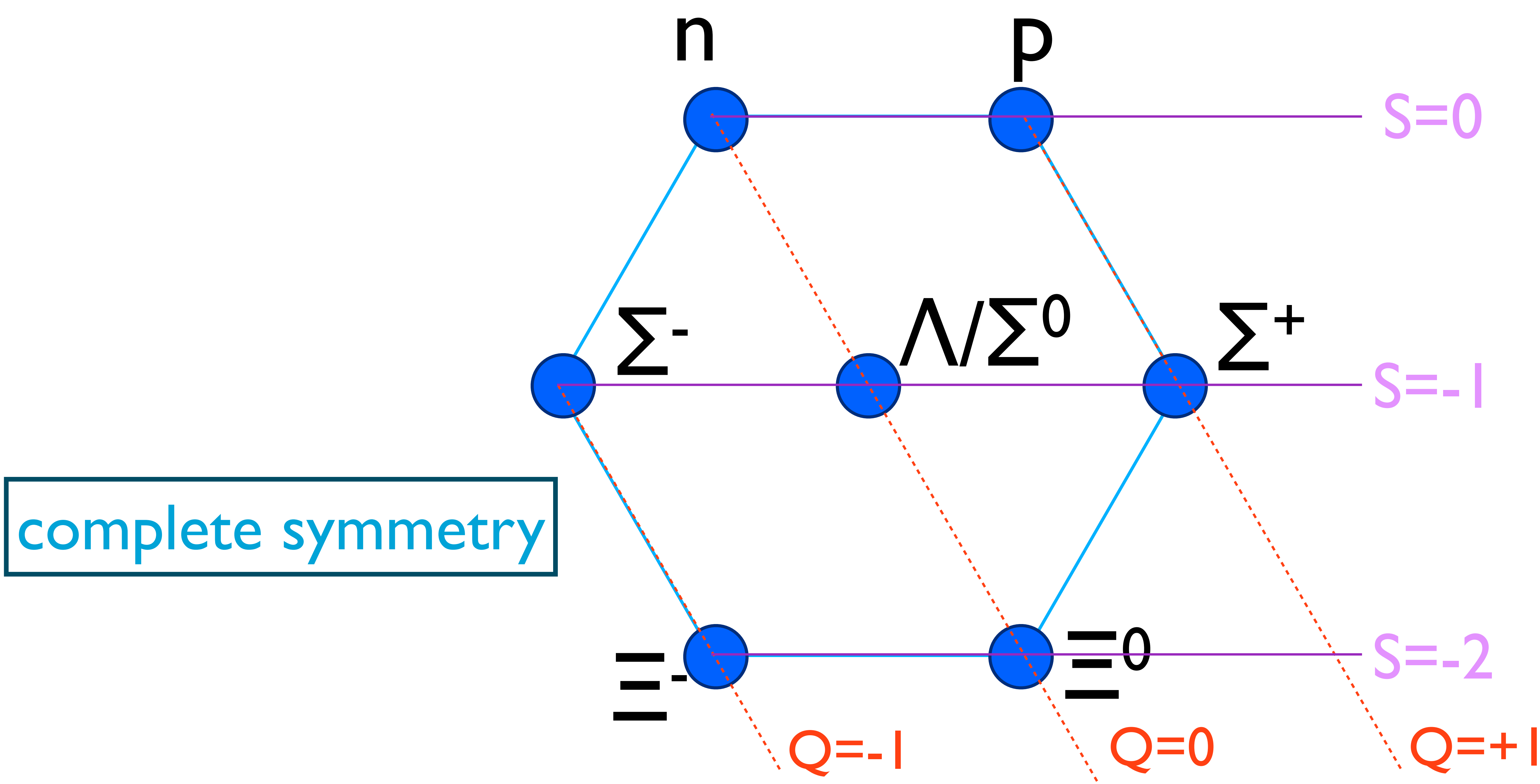


from http://education.jlab.org/itselemental/

- Start with ground states, then excited spectra
- Work with analogies between different families

The Simplest Case

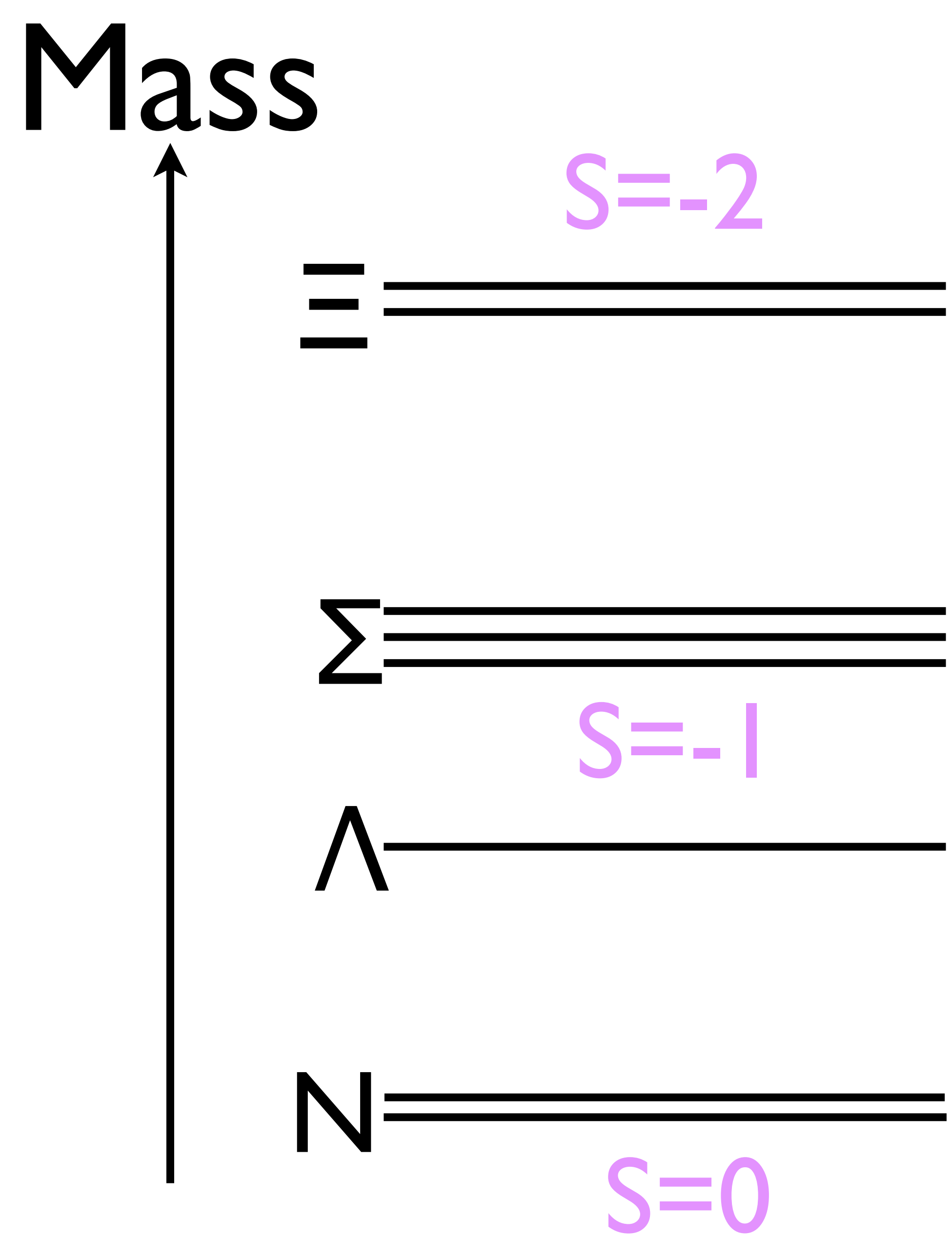
- Ground state octet baryons
- Made of up, down, strange quarks
- Flavor SU(3) → lowest baryon states will form an octet



The Simplest Case

- Ground state octet baryons
- Flavor SU(3) → lowest baryon states will form an octet
- Hierarchy of splittings, similar for ground state mesons

broken symmetry



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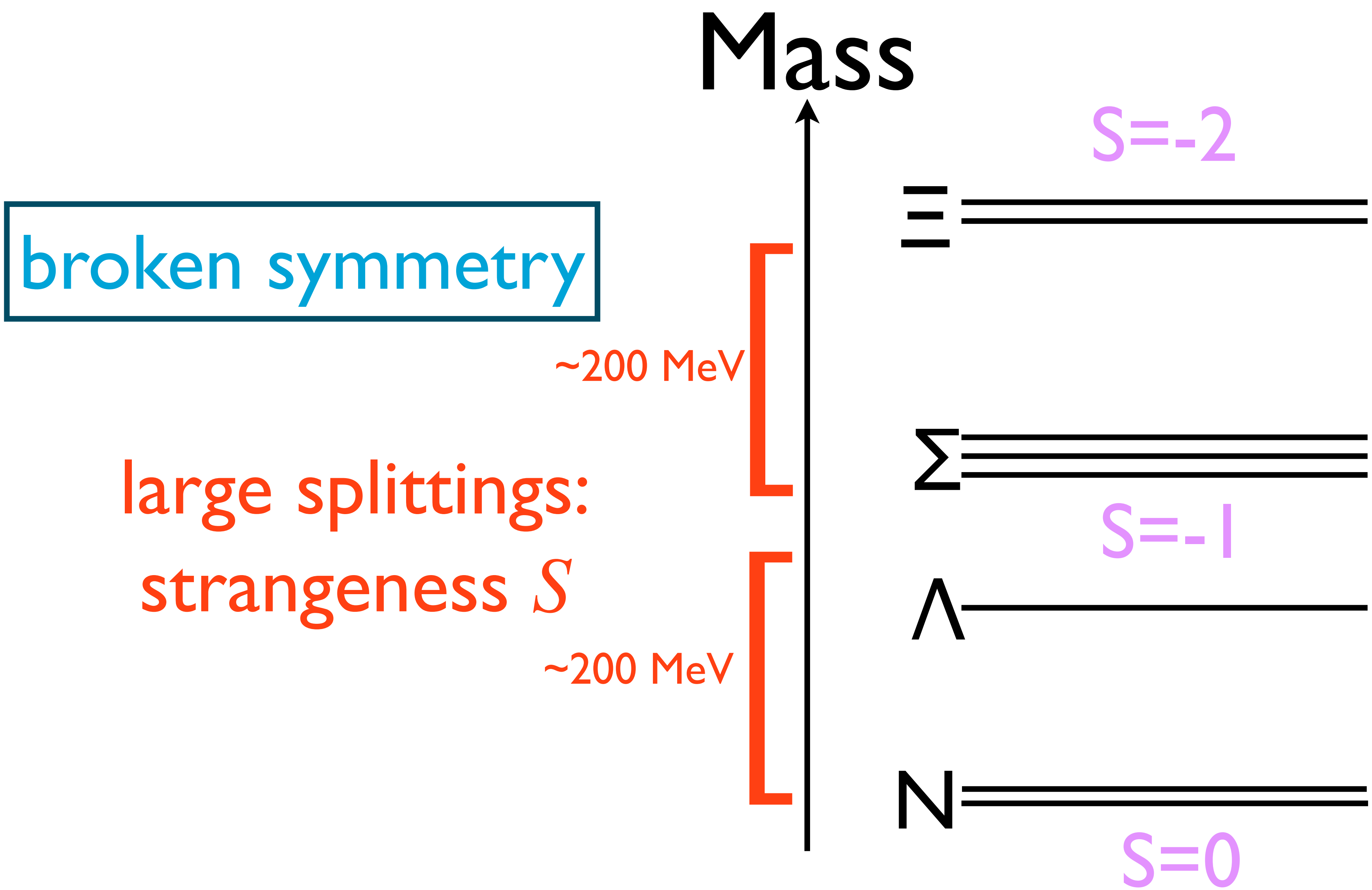

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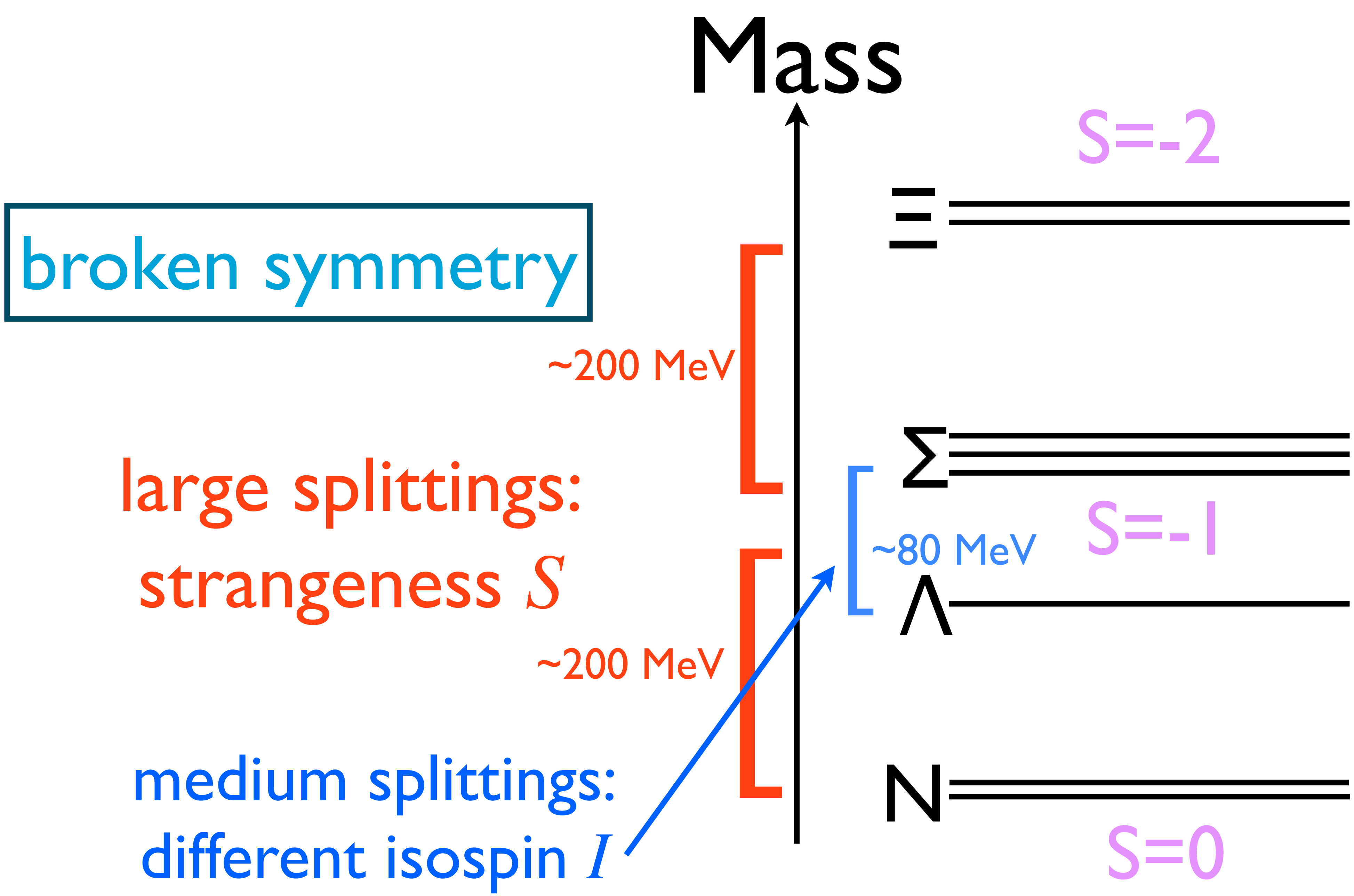

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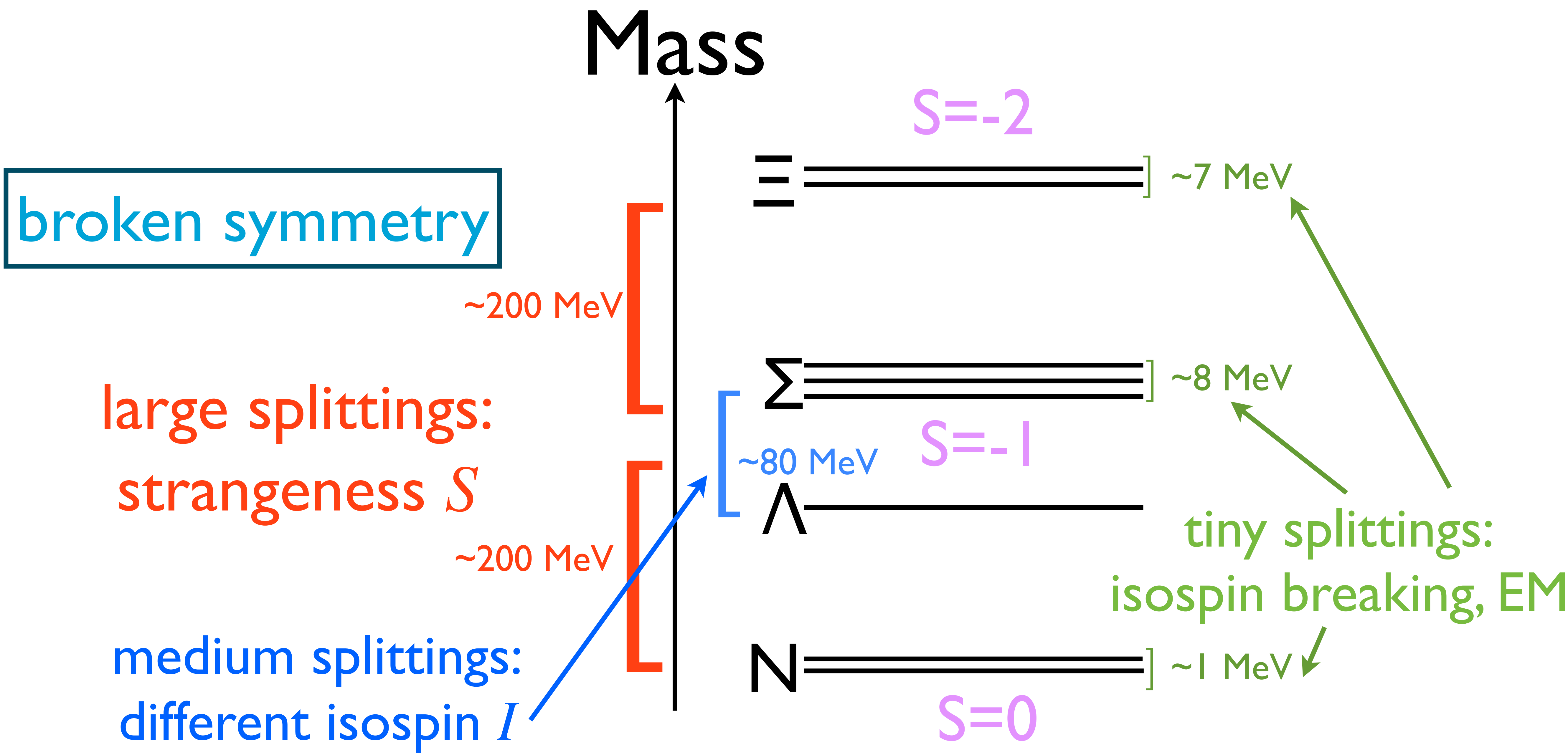

Difficulties at Higher Masses

- 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

figure of overlapping resonances

Theory and Models

- Experiment has the final say, but that's not all
- We rely on theory for
  - guidance, predictions
  - organization of known results
- Theories are usually based on QCD, but need empirical modeling
- How do we tie all of the experimental data with the underlying theory of QCD?

The Constituent Quark Model

- Successful theory describing many of low-energy states
- The "Standard Model" of low energy QCD - any theory will be compared against it
- However, it is an empirical theory - how far can we go beyond it?

The Constituent Quark Model

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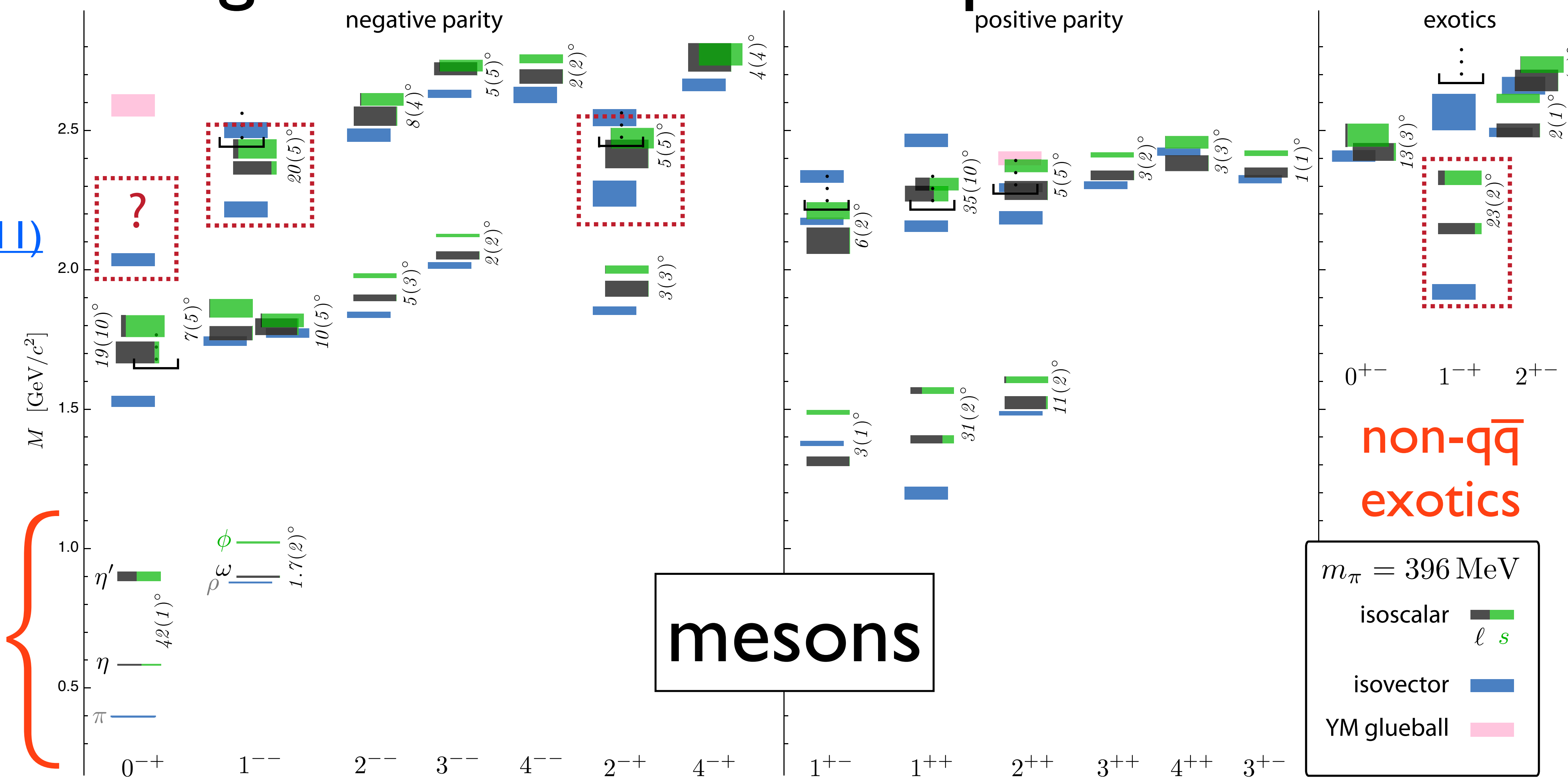
- The "Standard Model" of low energy QCD - any theory will be compared against it
- However, it is an empirical theory - how far can we go beyond it?

Modern experiments with large statistics could make significant contributions to our understanding

Lattice QCD

- Discretize space-time, full QCD calculations on this lattice
- No empirical assumptions, but takes tremendous computing power
- Now at the stage where it can make predictions

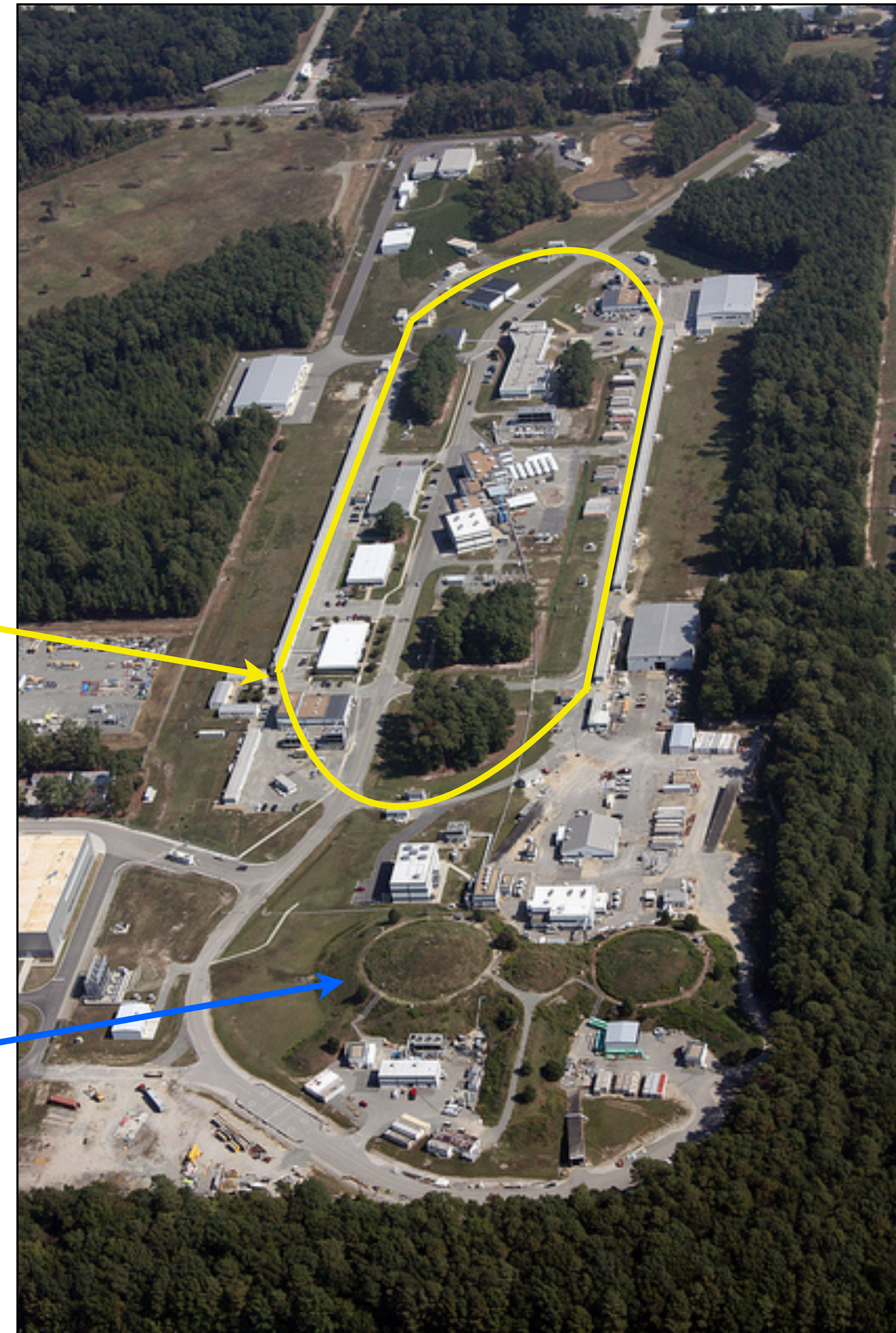
from PRD83, 111502(R) (2011)



PART III.
The GlueX Experiment

Jefferson Lab

- Located in Newport News, VA
- Currently upgrading electron accelerator from 6 GeV to 12 GeV
- CEBAF accelerator provides e^- bunch every 2ns
- Upgrades to the three existing experimental Halls A, B, C

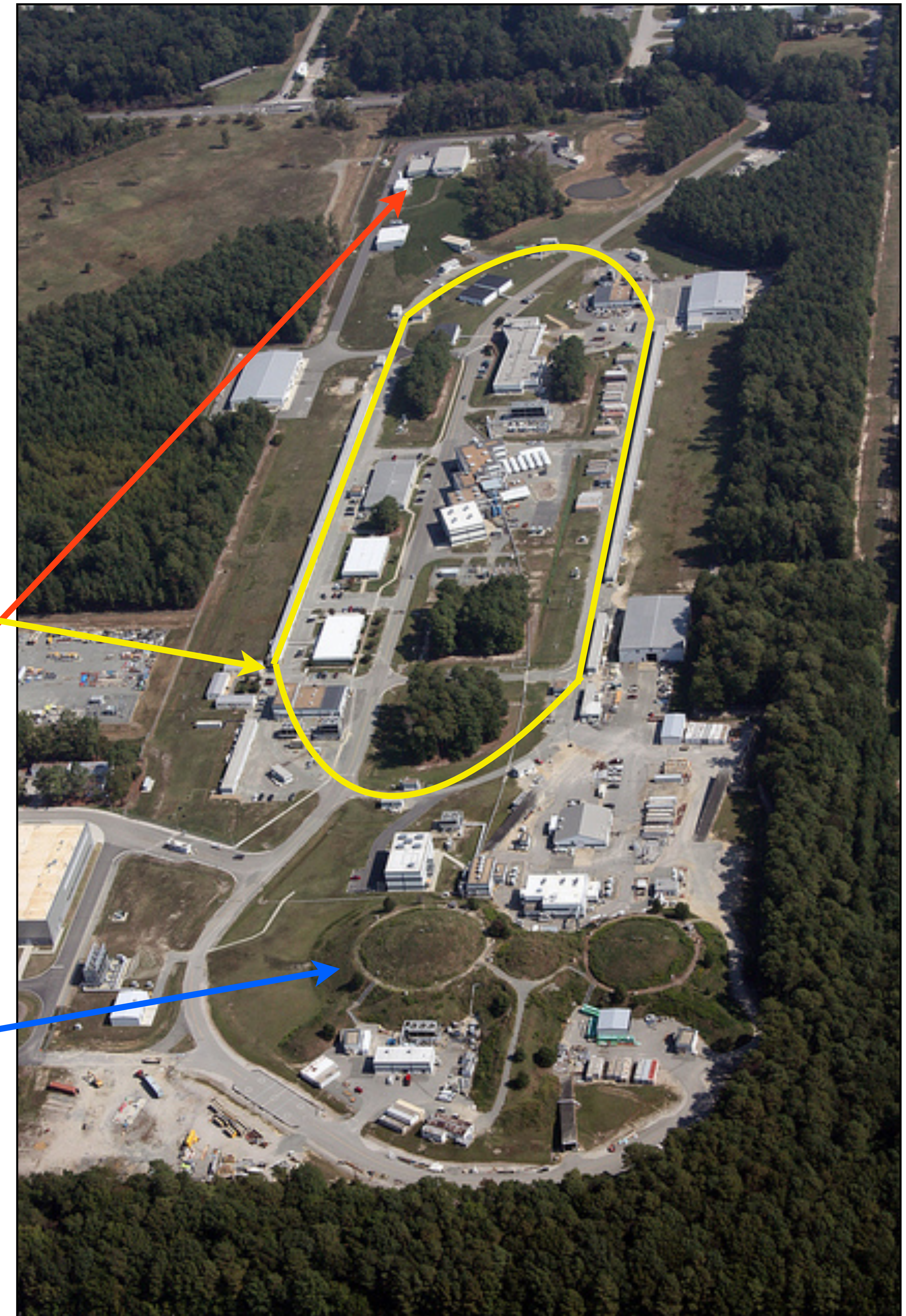


https://www.jlab.org

Jefferson Lab

- Located in Newport News, VA
- Currently upgrading electron accelerator from 6 GeV to 12 GeV
- CEBAF accelerator provides e$^-$ bunch every 2ns
- Upgrades to the three existing experimental Halls A, B, C
- New Hall D

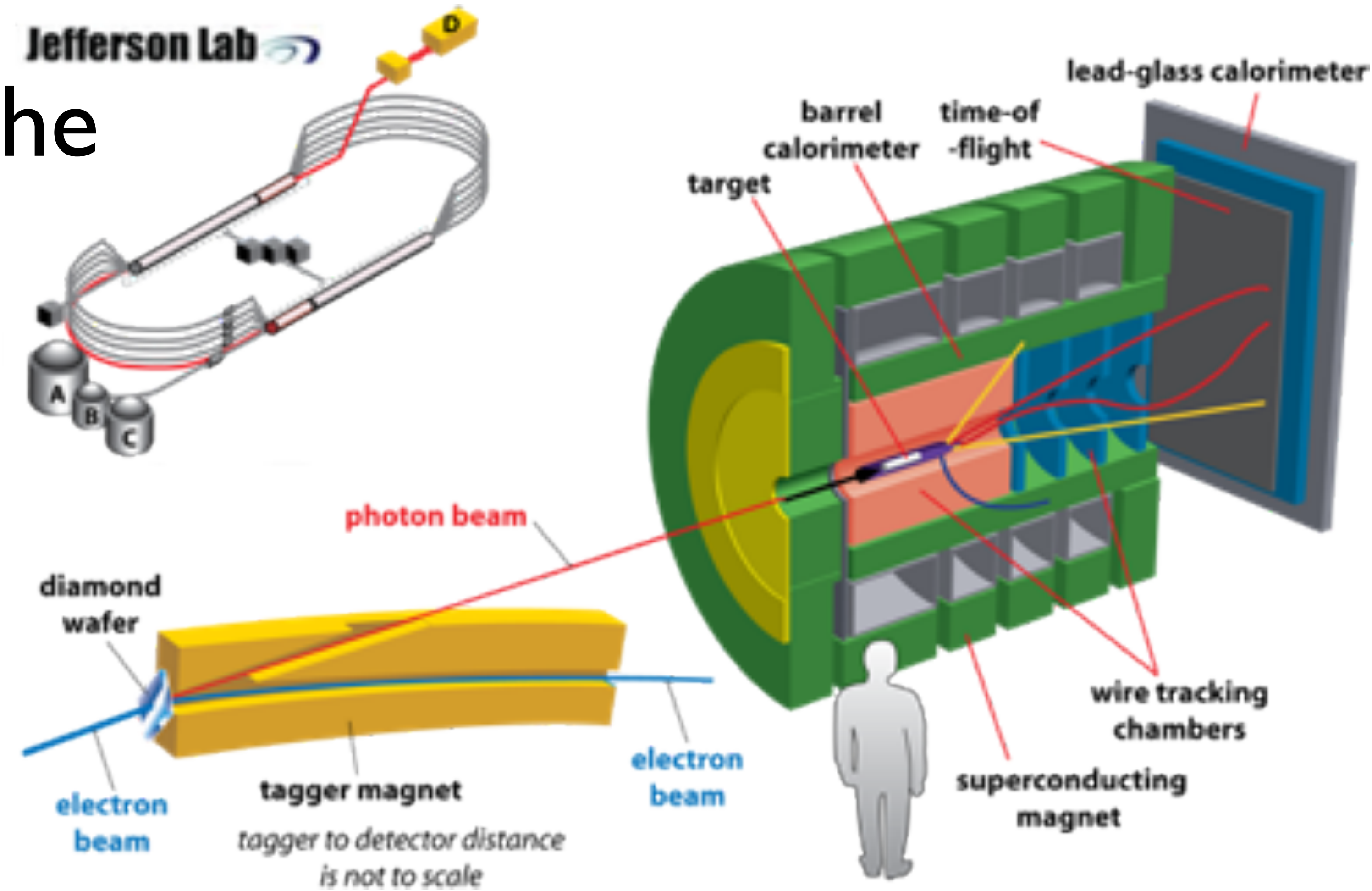
https://www.jlab.org



The GlueX Experiment

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

http://www.gluex.org

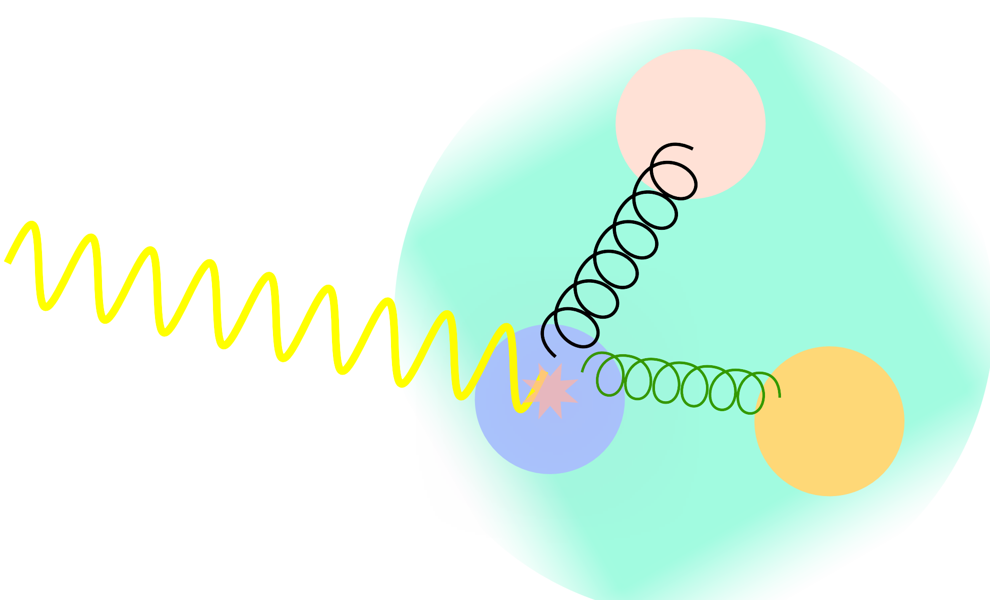


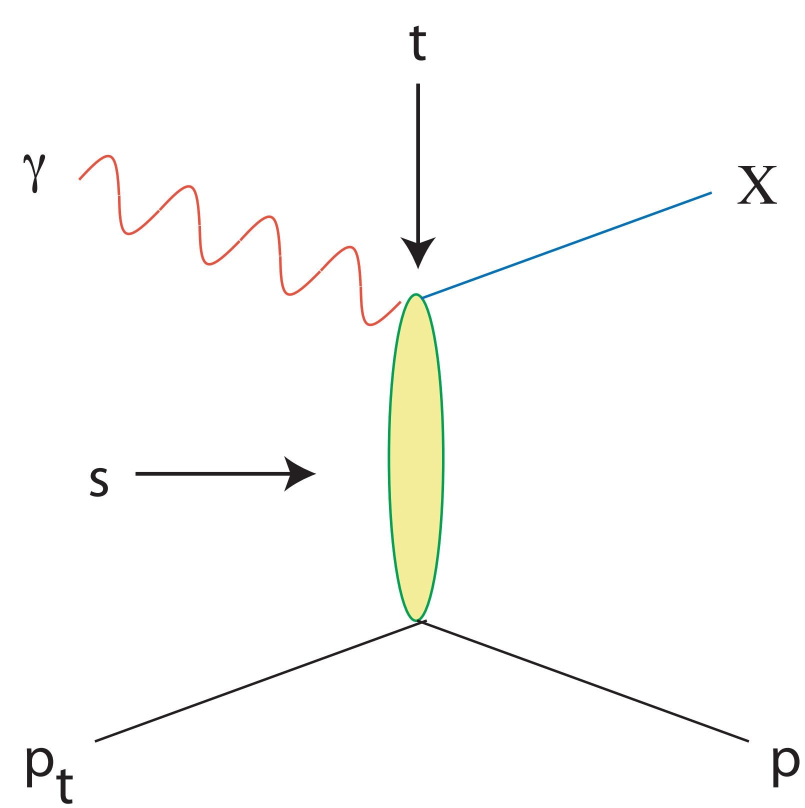
- Will use a photon beam on a proton target
- Main goal is hadronic spectroscopy - both mesons and baryons

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

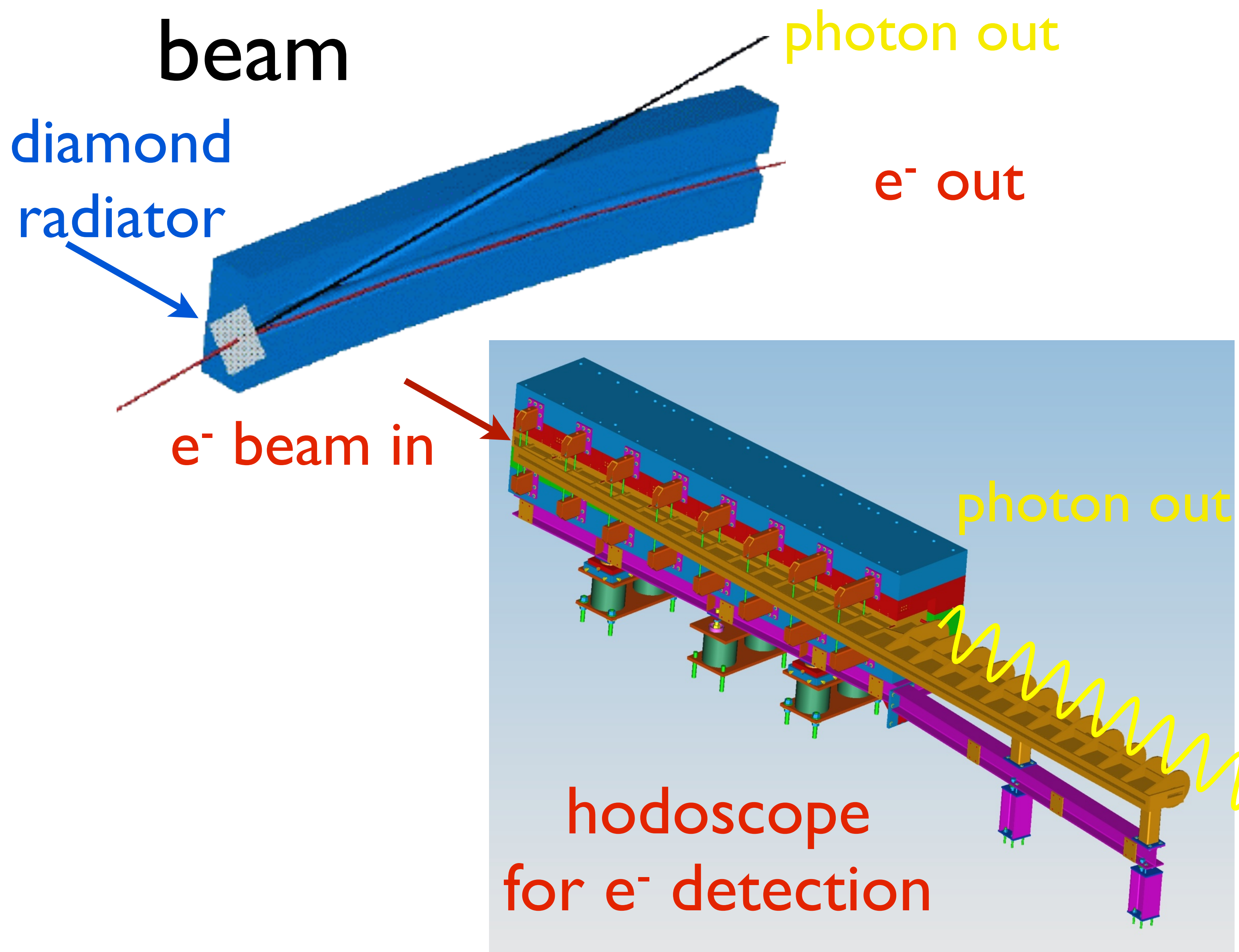
- The photon is something we completely understand → Use a well-known object to probe something less well-known
- Not studied at these energies in as much detail as a hadron probe (π or p), may lead to new discoveries

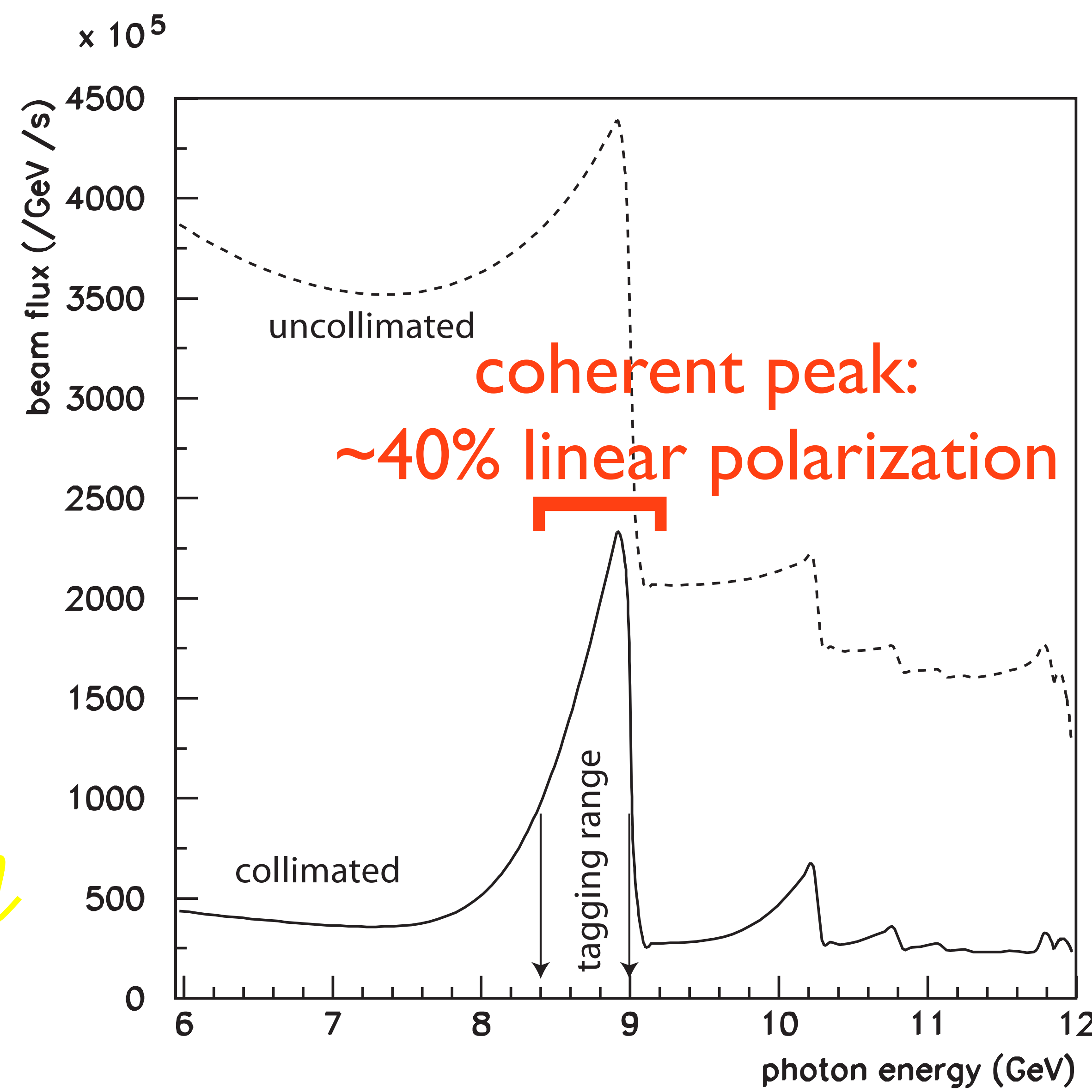




Why 12 GeV Beam?

- For QCD, this is the energy scale where the interesting things happen, and you want to observe the behavior as a function of energy
- Bremsstrahlung beam - radiate photons from electron beam



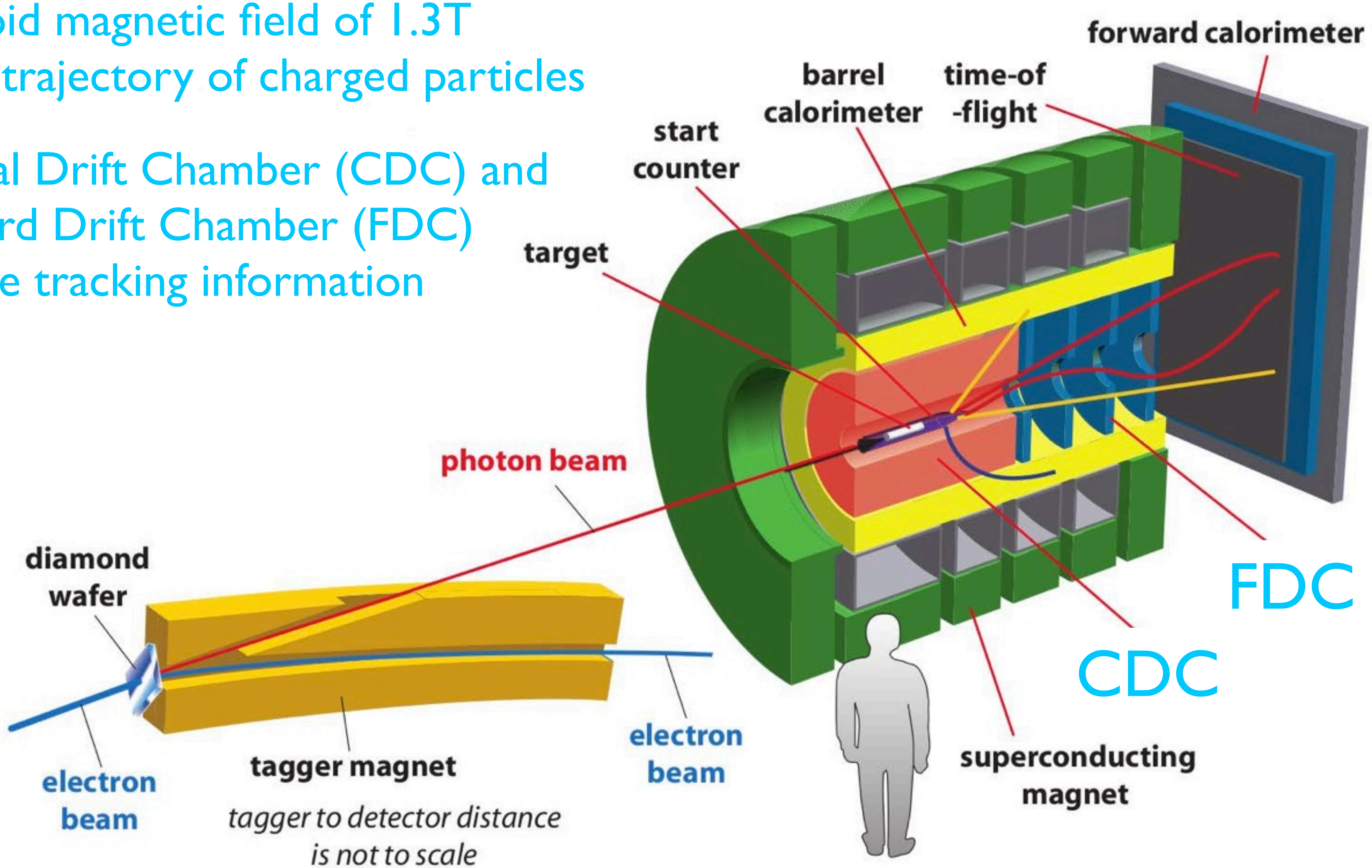


GlueX Detectors

- We need to cover the most area reasonably possible

Tracking

- Solenoid magnetic field of 1.3T bends trajectory of charged particles
- Central Drift Chamber (CDC) and Forward Drift Chamber (FDC) provide tracking information

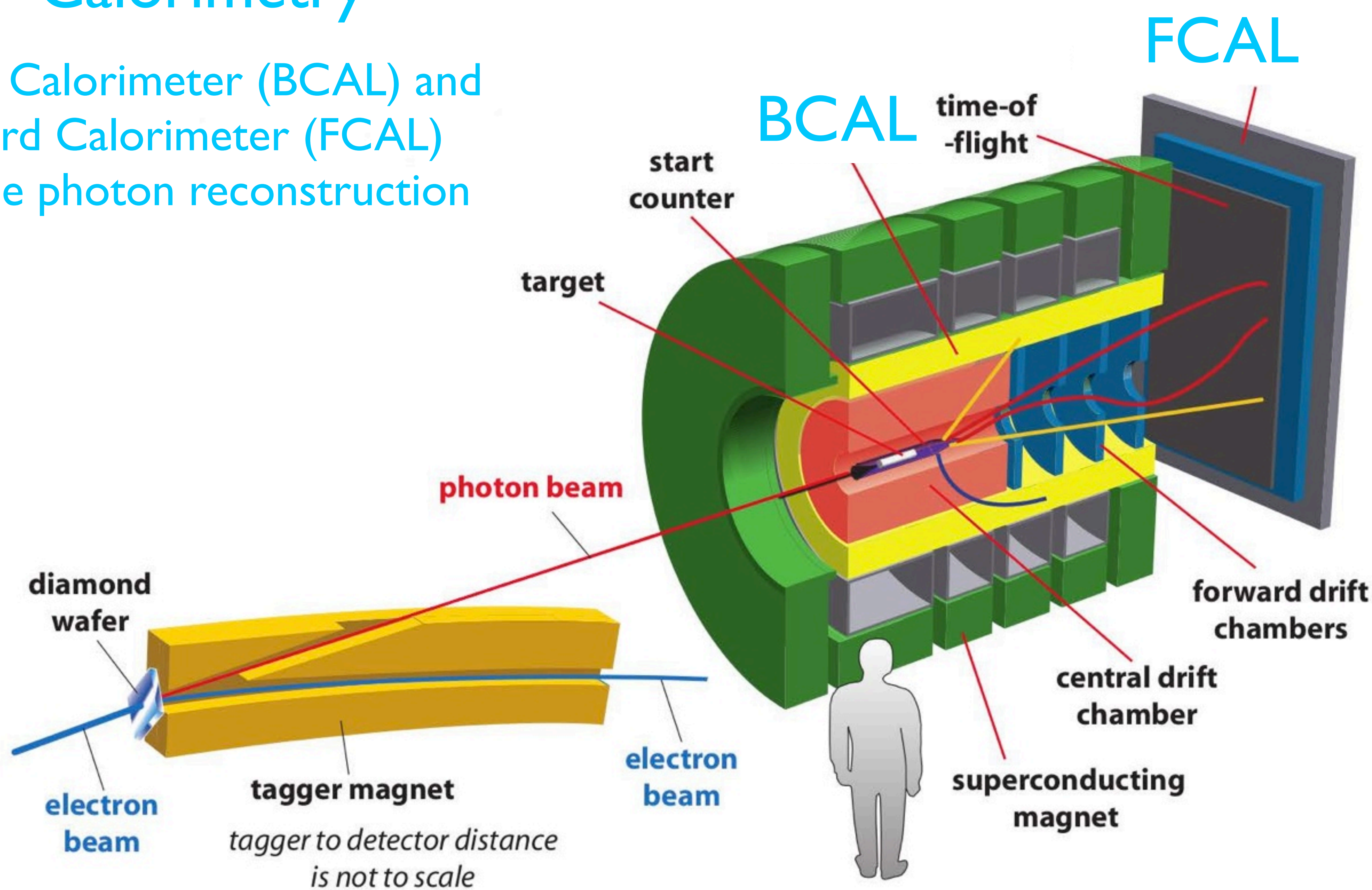


GlueX Detectors

- We need to cover the most area reasonably possible

Calorimetry

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

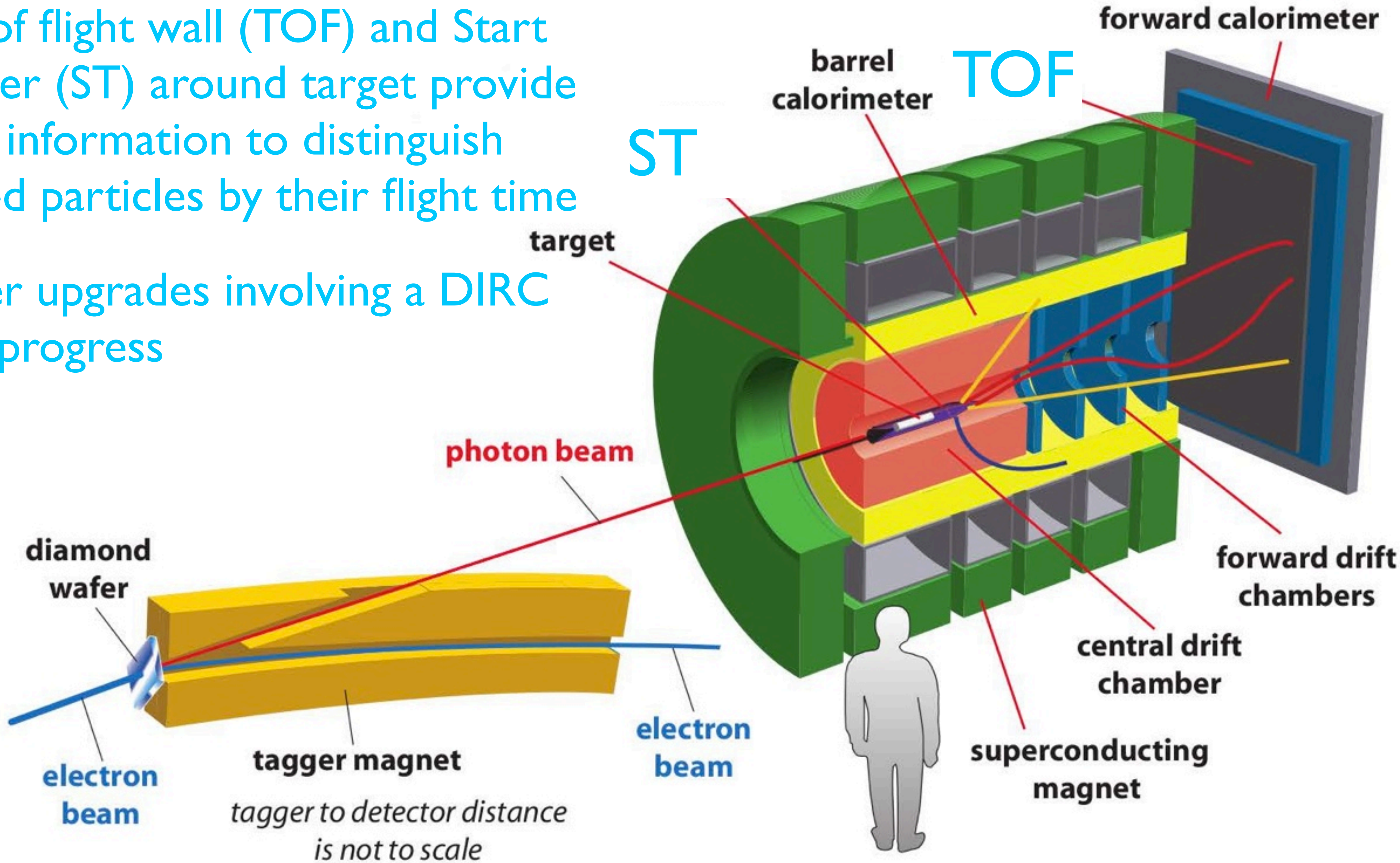


GlueX Detectors

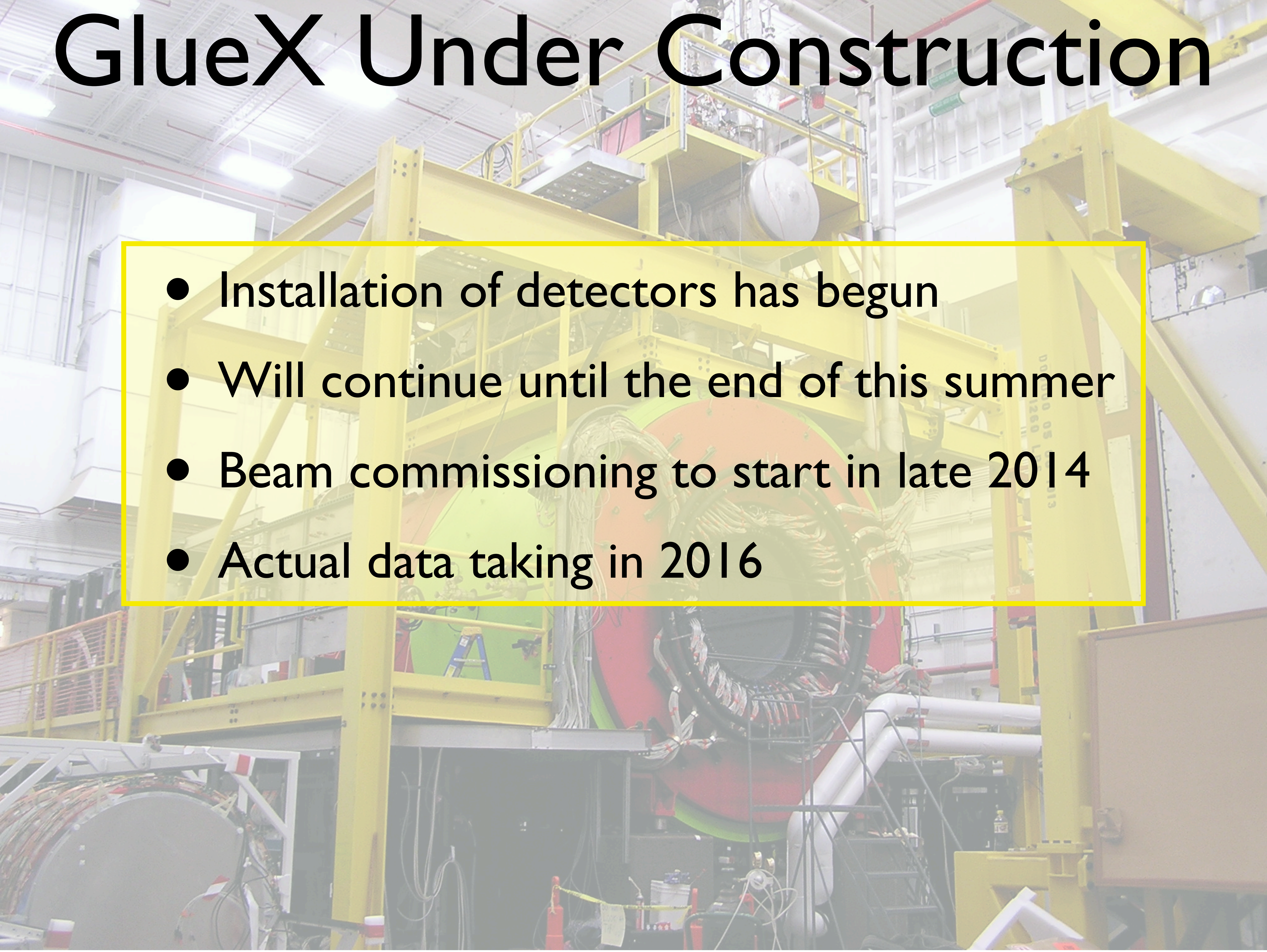
- We need to cover the most area reasonably possible

Particle Identification

- Time of flight wall (TOF) and Start Counter (ST) around target provide timing information to distinguish charged particles by their flight time
- Further upgrades involving a DIRC are in progress



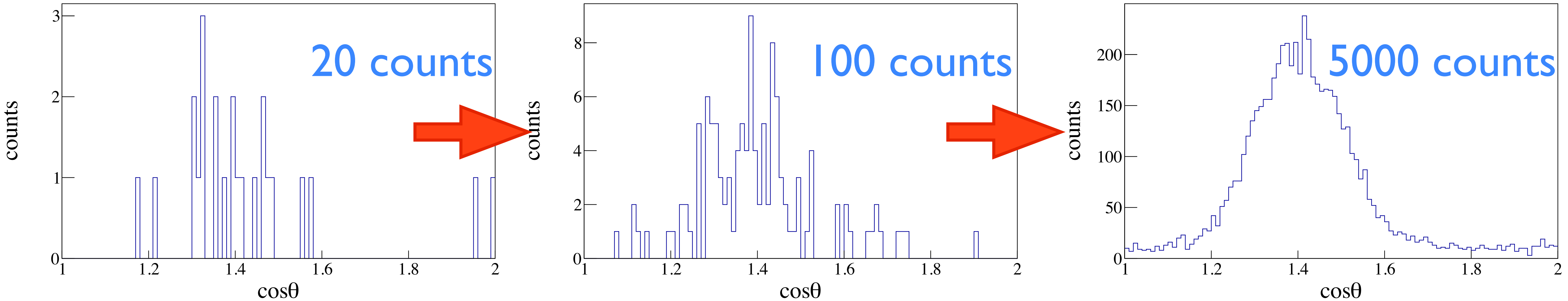
GlueX Under Construction



- 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 Volumes

- Data volume - the more the merrier



all with 20% backgrounds

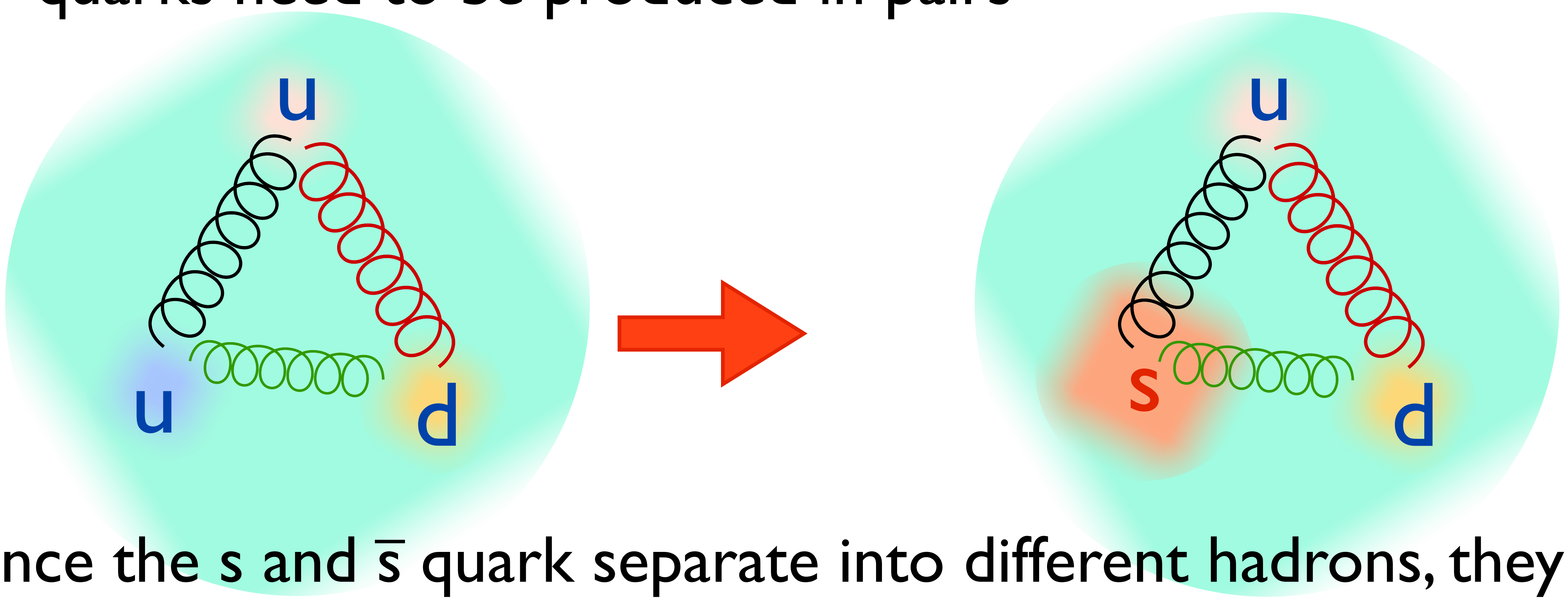
- At full running, GlueX will take 5×10^7 γ/s within the coherent peak
- Need to write 1GB/s, 3.2PB of raw data to tape/year!!
- Even more needed for simulated backgrounds, analyses, etc.

Truly benefiting from advances in technology

PART IV.
The Strangeness Frontier

What is Strangeness?

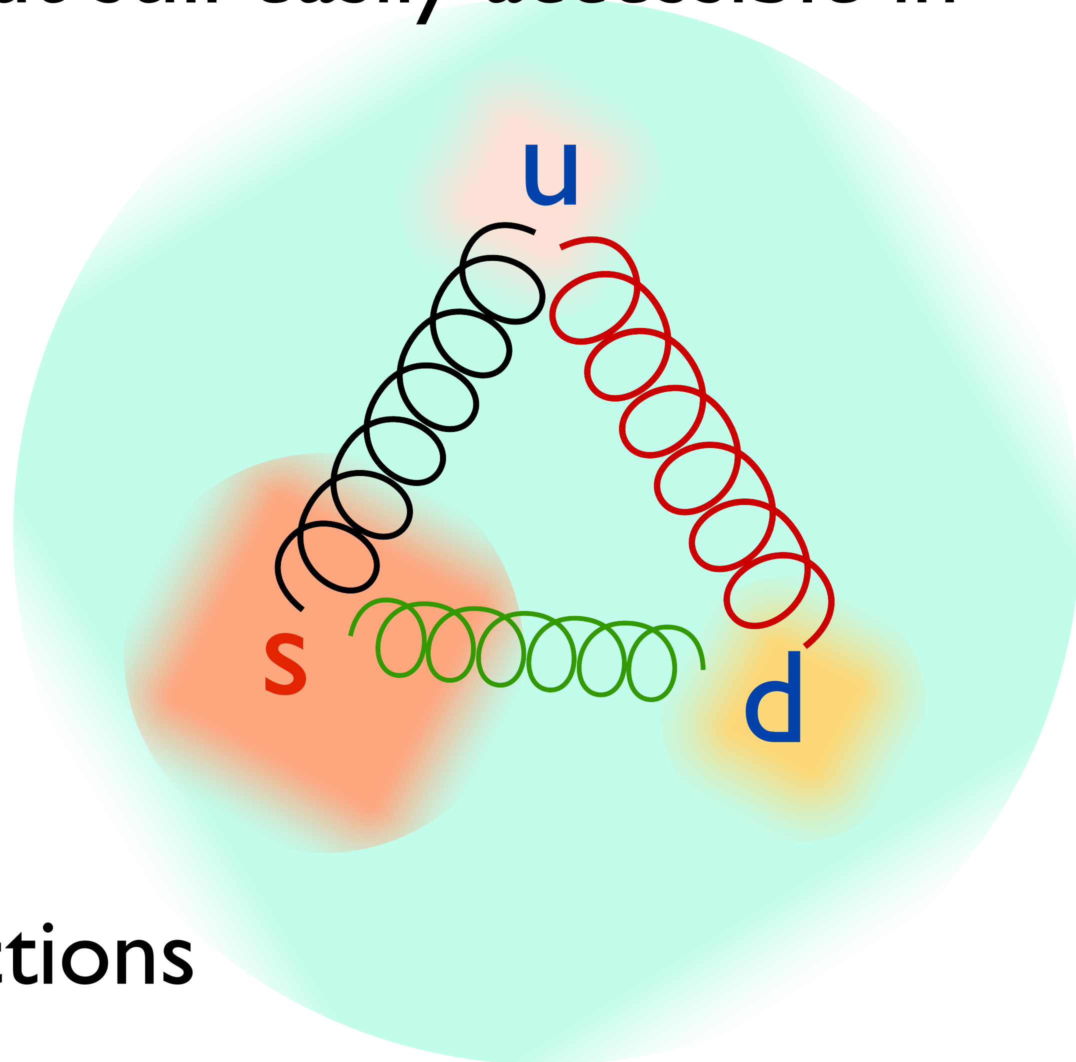
- Quarks come in different "flavors", i.e., different types
- Replace the usual "up" "down" quark by "strange" quark
- The strong force conserves quark flavor, so that strange quarks need to be produced in pairs



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

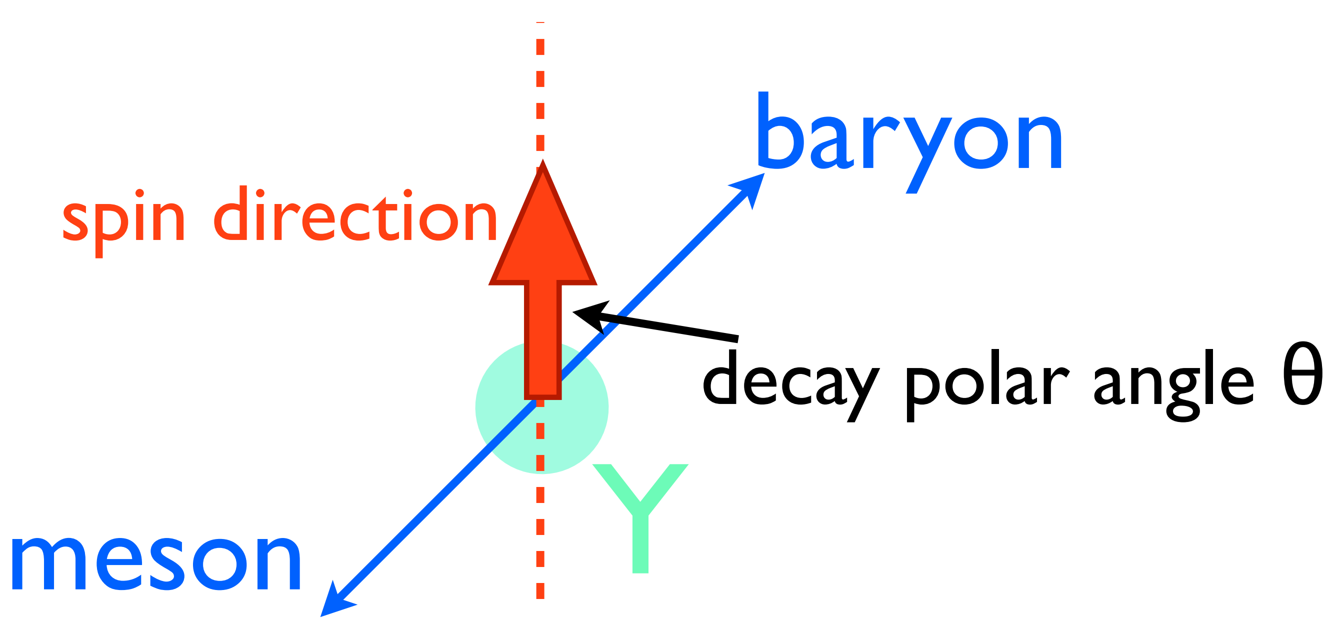
The Gift of Strangeness

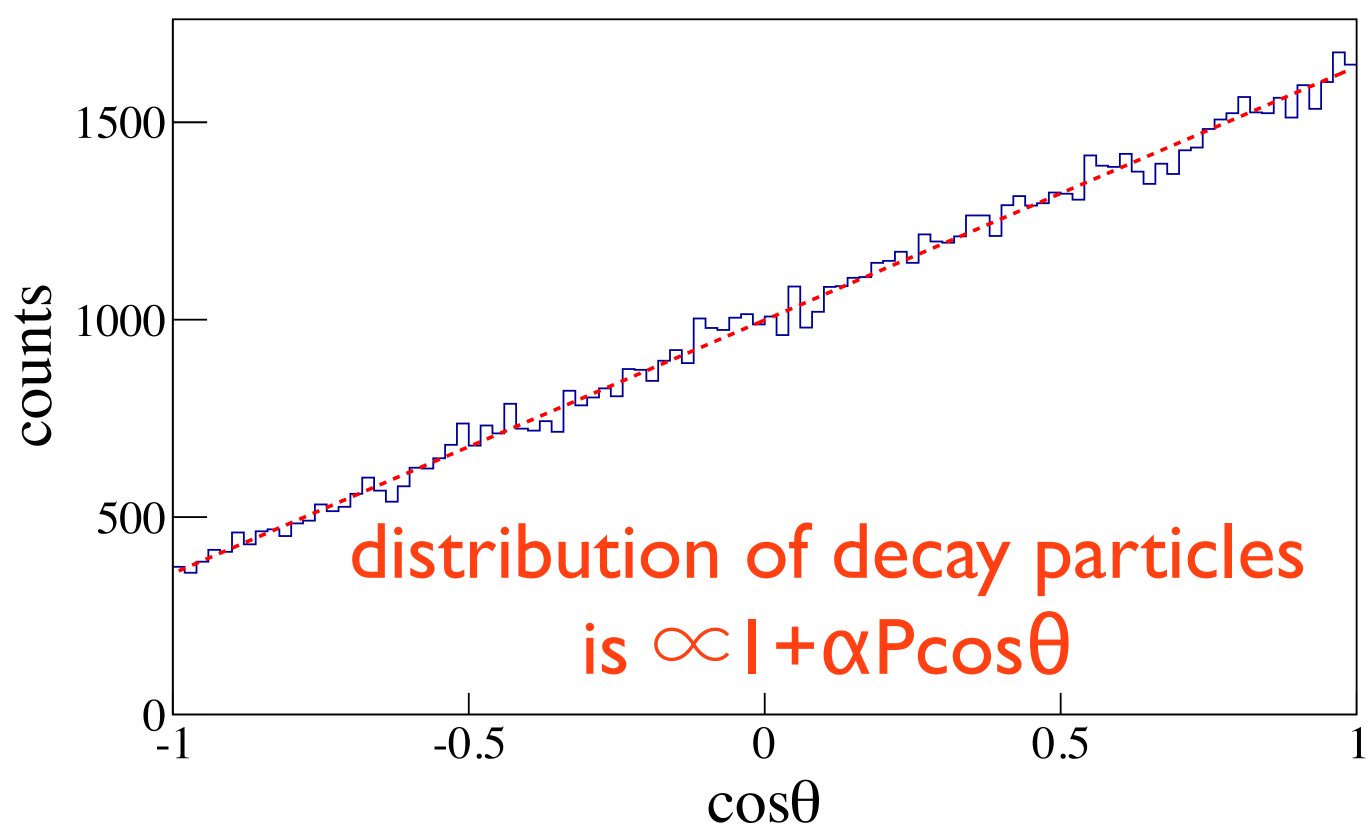
- s quarks are heavier than u and d quarks, so it takes more energy to create strange particles - but still easily accessible in our strongly coupled energy regime
- Strange particles have given us:
  - parity violation (θτ puzzle)
  - CP violation (neutral kaons)
  - concept of flavor, SU(3)
  - distinction of strong/weak interactions
  - insights into weak decays
  - searches for beyond SM physics
- Astrophysical interest too, can there be "strange matter"?



Polarization of Strange Baryons

- When a ground state strange baryon decays via the weak force, there is interference between the S-wave and P-wave decay amplitudes
- Leads to asymmetry in decay distribution, "self-analyzes" polarization of particles → Polarizations are measurable! (a lot more difficult to measure for non-strange baryons)
- More measurable observables ambiguities, explore dynamics

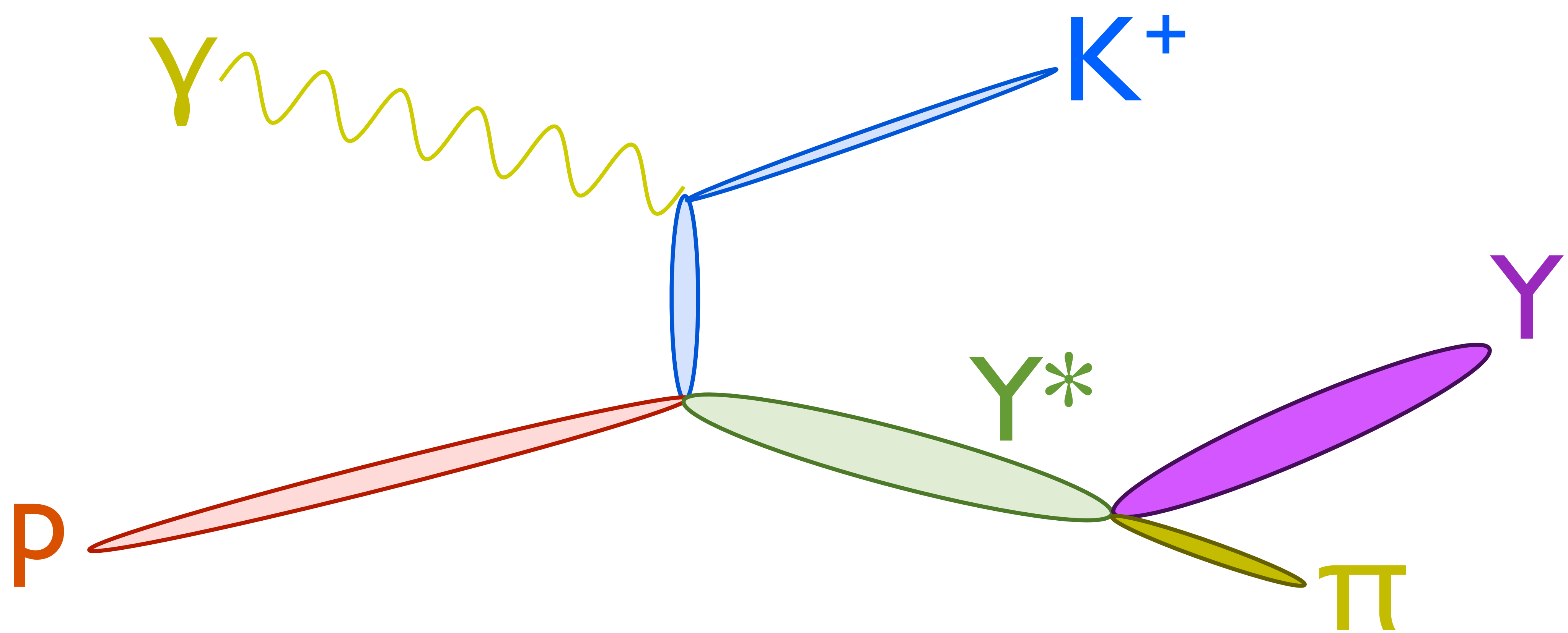




α: constant P: polarization

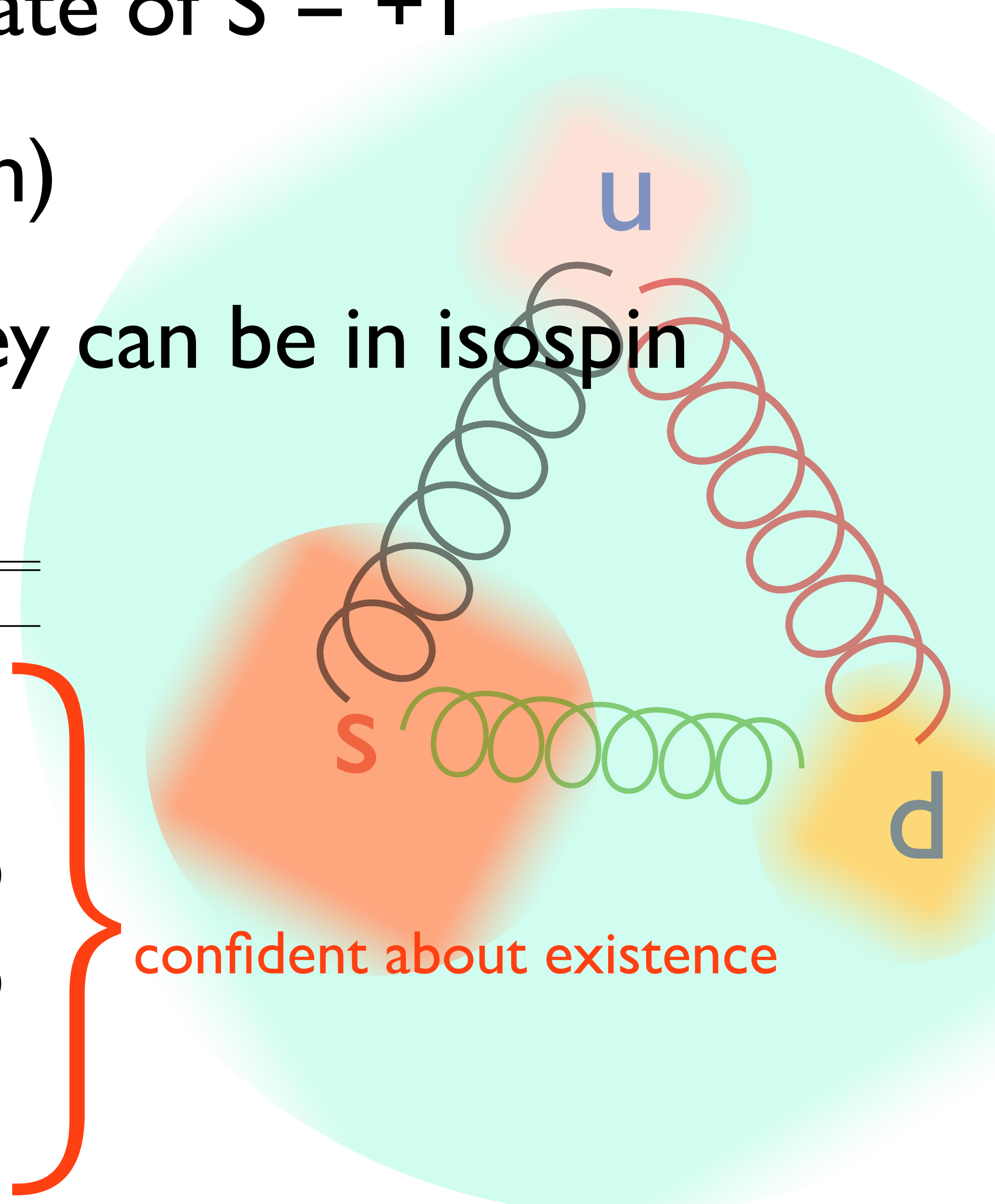
Studying Strange Baryons

- Non-strange baryon spectrum (N and Δ) have been studied in past with π beam
- Large overlap of states make it difficult to identify states
- In general strange states have (much) smaller widths
- Strange baryons must be produced in association with kaon(s) to conserve strangeness → complicates analysis somewhat



Strangeness -1 Baryons

- The strong interaction conserves strangeness so we must produce them in association with a state of S = +1
- Easiest way is to create a meson (kaon)
- We have two light quarks (u or d), they can be in isospin configurations of 0 (Λ) or 1 (Σ)



State	J^P	Mass (MeV/c^2)	Width (MeV)	Status	Primary decay modes	Last reported
Λ	$1/2^+$	1115.683	0	****	$p\pi^-$, $n\pi^0$	—
$\Lambda(1405)$	$1/2^-$	1405	50	****	$\Sigma\pi$	CLAS (2013)
$\Lambda(1520)$	$3/2^-$	1519.5	15.6	****	$N\bar{K}, \Sigma\pi, \Lambda\pi\pi$	CLAS (2013)
$\Lambda(1600)$	$1/2^+$	1560–1700	50–250	***	$N\bar{K}, \Sigma\pi$	Gopal (1980)
$\Lambda(1670)$	$1/2^-$	1660–1680	25–50	****	$N\bar{K}, \Sigma\pi, \Lambda\eta$	Manley (2002)
$\Lambda(1690)$	$3/2^-$	1685–1695	50–70	****	$N\bar{K}, \Sigma\pi, \Lambda\pi\pi, \Sigma\pi\pi$	Koiso (1985)
$\Lambda(1800)$	$1/2^-$	1720–1850	200–400	***	$N\bar{K}, \Sigma\pi$	Manley (2002)
$\Lambda(1810)$	$1/2^+$	1750–1850	50–250	***	$N\bar{K}, \Sigma\pi, N\bar{K}(892)$	Gopal (1980)
$\Lambda(1820)$	$5/2^+$	1815–1825	70–90	****	$N\bar{K}, \Sigma\pi, \Sigma(1385)\pi$	Gopal (1980)
$\Lambda(1830)$	$5/2^-$	1810–1830	60–110	****	$N\bar{K}, \Sigma\pi, \Sigma(1385)\pi$	Gopal (1980)
$\Lambda(1890)$	$3/2^+$	1850–1910	60–200	****	$N\bar{K}, \Sigma\pi$	Gopal (1980)
$\Lambda(2000)$	$?^?$	~ 2000	~ 150	*	$N\bar{K}, \Sigma\pi$	Cameron (1978)
$\Lambda(2020)$	$7/2^+$	~ 2020	~ 150	*	$N\bar{K}, \Sigma\pi, \Lambda\omega$	Gopal (1980)
$\Lambda(2100)$	$7/2^-$	2090–2110	100–250	****	$N\bar{K}, N\bar{K}(892)$	Gopal (1980)
$\Lambda(2110)$	$5/2^+$	2090–2140	150–200	***	$N\bar{K}, \Sigma\pi$	Gopal (1980)
$\Lambda(2325)$	$3/2^-$	~ 2325	~ 177	*	$N\bar{K}, \Lambda\omega$	Debellefon (1978)
$\Lambda(2350)$	$9/2^+$	2340–2370	100–250	***	$N\bar{K}, \Sigma\pi$	Debellefon (1978)
$\Lambda(2585)$	$?^?$	~ 2585	~ 300	**	$N\bar{K}$	Abrams (1970)

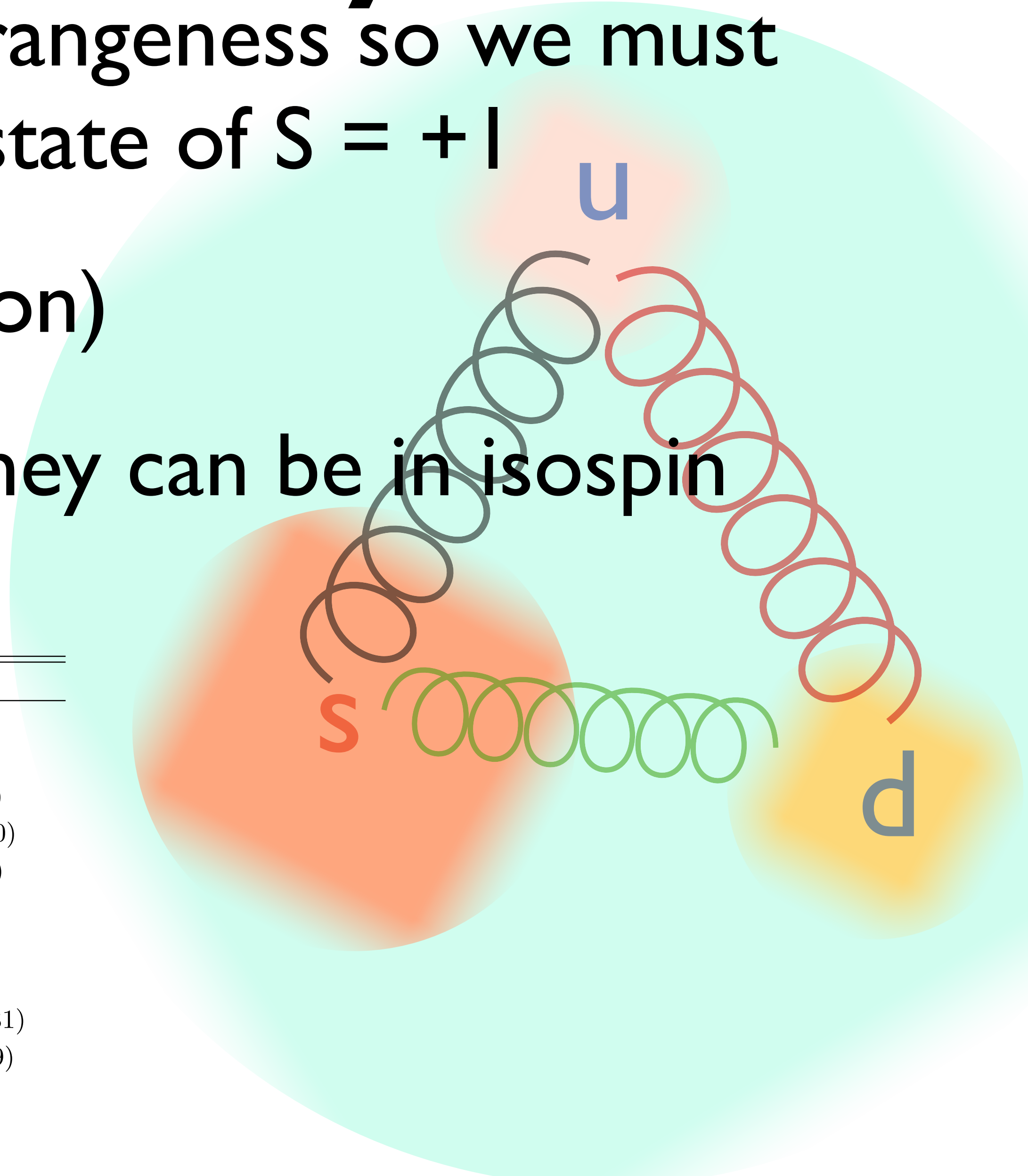
confident about existence

not so much

based on PDG summary

Strangeness -1 Baryons

- The strong interaction conserves strangeness so we must produce them in association with a state of S = +1
- Easiest way is to create a meson (kaon)
- We have two light quarks (u or d), they can be in isospin configurations of 0 (Λ) or 1 (Σ)



State	J^P	Mass (MeV/c^2)	Width (MeV)	Status	Primary decay modes	Last reported
Σ	$1/2^+$	1190	0	****	weak or E&M decay	—
$\Sigma(1385)$	$3/2^+$	1385	36–39	****	$\Lambda\pi, \Sigma\pi$	CLAS (2013)
$\Sigma(1480)$ bumps	$?^?$	~ 1480	~ 80	*	$N\bar{K}, \Lambda\pi\Sigma\pi$	Zychor (2006)
$\Sigma(1560)$ bumps	$?^?$	~ 1560	~ 80	**	$\Lambda\pi, \Sigma\pi$	Meadows (1980)
$\Sigma(1580)$	$3/2^-$	~ 1580	~ 15	*	$N\bar{K}, \Lambda\pi, \Sigma\pi$	Carroll (1976)
$\Sigma(1620)$	$1/2^-$	~ 1620	~ 90	*	$N\bar{K}, \Lambda\pi, \Sigma\pi$	Morris (1978)
$\Sigma(1660)$	$1/2^+$	1630–1690	40–200	***	$N\bar{K}, \Lambda\pi, \Sigma\pi$	Gao (2011)
$\Sigma(1670)$	$3/2^-$	1665–1685	40–80	****	$N\bar{K}, \Lambda\pi, \Sigma\pi$	Gao (2011)
$\Sigma(1670)$ bumps	$?^?$	~ 1670	70–130	not listed	$N\bar{K}, \Lambda\pi, \Sigma\pi$	Ferrersoria (1981)
$\Sigma(1690)$ bumps	$?^?$	~ 1690	100–250	**	$N\bar{K}, \Lambda\pi, \Sigma\pi$	Goddard (1979)
$\Sigma(1750)$	$1/2^-$	1730–1800	60–160	***	$N\bar{K}, \Sigma\eta$	Gopal (1980)
$\Sigma(1770)$	$1/2^+$	~ 1770	~ 70	*	$N\bar{K}, \Lambda\pi, \Sigma\pi$	Gopal (1980)
$\Sigma(1775)$	$5/2^-$	1770–1780	105–135	****	$N\bar{K}, \Lambda\pi, \Sigma\pi, \Sigma(1385)\pi, \Lambda(1520)\pi$	Gopal (1980)
$\Sigma(1840)$	$3/2^+$	~ 1840	90–120	*	$N\bar{K}, \Lambda\pi, \Sigma\pi$	Gopal (1980)
$\Sigma(1880)$	$1/2^+$	~ 1880	80–200	*	$N\bar{K}, \Lambda\pi, \Sigma\pi$	Gopal (1980)
$\Sigma(1915)$	$5/2^+$	1900–1935	80–160	****	$N\bar{K}, \Lambda\pi, \Sigma\pi$	Gopal (1980)
$\Sigma(1940)$	$3/2^-$	1900–1950	150–300	***	$N\bar{K}$	Gopal (1980)
$\Sigma(2000)$	$1/2^-$	~ 2000	20–400	*	$N\bar{K}, \Lambda\pi, \Sigma\pi$	Gopal (1980)
$\Sigma(2030)$	$7/2^+$	2025–2040	150–200	****	$N\bar{K}, \Lambda\pi, \Sigma\pi, \Sigma(1385)\pi, \Lambda(1520)\pi, \Delta(1232)\bar{K}$	Gopal (1980)
$\Sigma(2070)$	$5/2^+$	~ 2070	~ 300	*	$N\bar{K}, \Sigma\pi$	Gopal (1980)
$\Sigma(2080)$	$3/2^+$	~ 2080	180–250	**	$N\bar{K}, \Lambda\pi$	Corden (1976)
$\Sigma(2100)$	$7/2^-$	~ 2100	70–130	*	$N\bar{K}, \Lambda\pi, \Sigma\pi$	Barbaro-Galtieri (1970)
$\Sigma(2250)$	$?^?$	2210–2280	60–150	***	$N\bar{K}, \Lambda\pi$	Debellefon (1978)
$\Sigma(2455)$ bumps	$?^?$	~ 2455	~ 140	**	$N\bar{K}$	Abrams (1970)
$\Sigma(2620)$ bumps	$?^?$	~ 2620	~ 220	**	$N\bar{K}$	Dibianca (1975)
$\Sigma(3000)$ bumps	$?^?$	~ 3000	~ 220	*	$N\bar{K}, \Lambda\pi$	Ehrlich (1966)
$\Sigma(3170)$ bumps	$?^?$	~ 3000	~ 220	*	$\Lambda K\bar{K}\pi, \Sigma K\bar{K}\pi, \Xi K\pi$	Aston (1985)

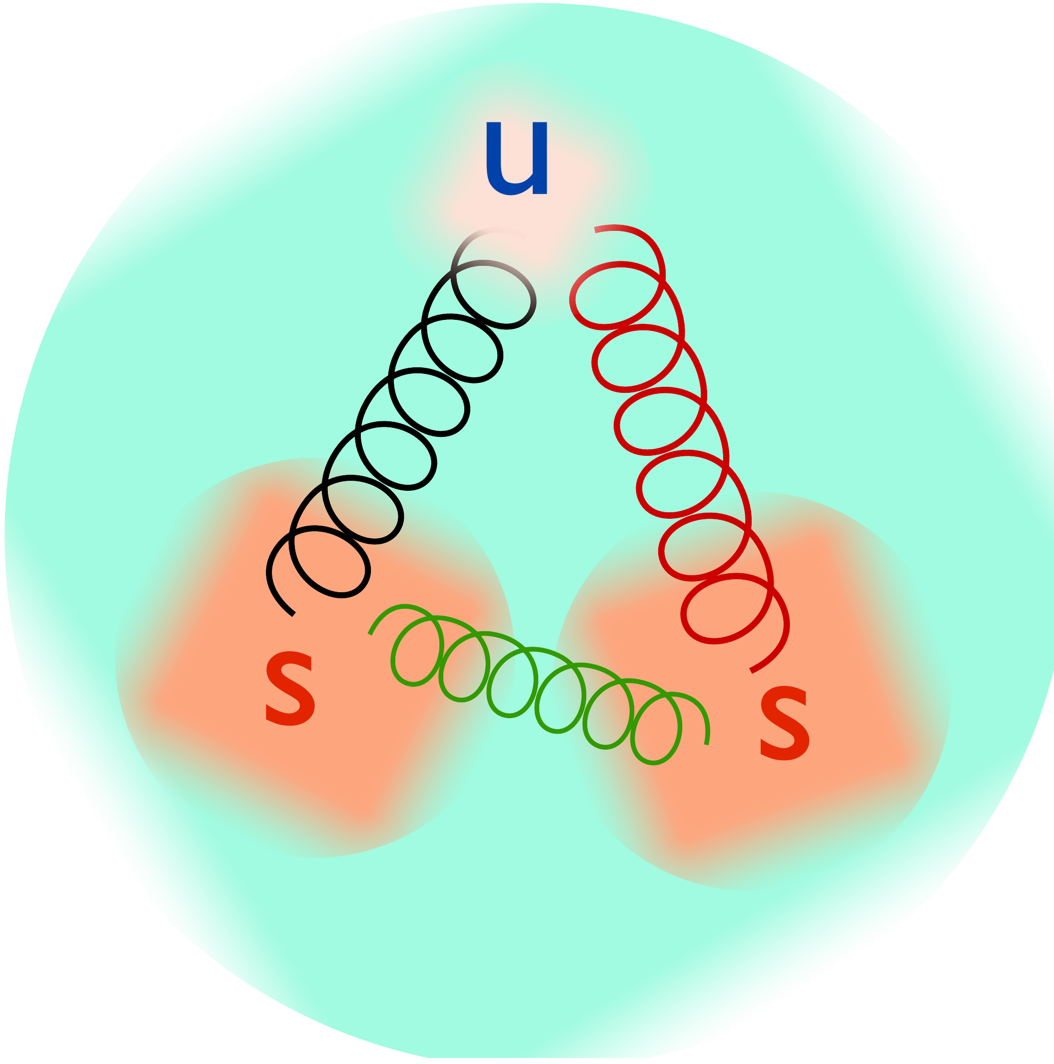
only a few scattered states that we are confident about

mysterious "bumps" appear even at low masses

based on PDG summary

Even Stranger - The Ξ States

- We can replace TWO quarks in a 3-quark system to make Ξ (Cascade) states
- To produce these states now we need TWO S=+1 particles (kaons) created in association
- Has been studied using K^- beam, but the excited spectrum is not known well



The Known Ξ Spectrum

State	J^P	Mass (MeV/c^2)	Width (MeV)	Status	Primary decay modes	Last reported
Ξ	$1/2^+$	1320	0	****	$\Lambda\pi$	—
$\Xi(1530)$	$3/2^+$	1530	9	****	$\Xi\pi$	BaBar (2008)
$\Xi(1620)$	$?^?$	~ 1620	22	*	$\Xi\pi$	Hassall (1981)
$\Xi(1690)$	$?^?$	1690	< 30	***	$\Lambda\bar{K}, \Sigma\bar{K}, \Xi\pi$	BaBar (2008)
$\Xi(1820)$	$3/2^-$	1823	24	***	$\Lambda\bar{K}$	Anisovich (2012)
$\Xi(1950)$	$?^?$	1950 ± 15	60 ± 20	***	$\Lambda\bar{K}, \Xi\pi$	Adamovich (1999)
$\Xi(2030)$	$\geq 5/2^?$	2025 ± 5	20^{+15}_{-5}	***	$\Sigma\bar{K}, \Lambda\bar{K}$	Jenkins (1983)
$\Xi(2120)$	$?^?$	~ 2120	< 20	*	$\Lambda\bar{K}$	Chliapnikov (1979)
$\Xi(2250)$	$?^?$	~ 2250	< 30	**	$\Xi\pi\pi, \Lambda\bar{K}\pi, \Sigma\bar{K}\pi$	Biagi (1987)
$\Xi(2370)$	$?^?$	~ 2370	80	**	$\Lambda\bar{K}\pi, \Sigma\bar{K}\pi$	Jenkins (1983)
$\Xi(2500)$	$?^?$	~ 2500	150	*	$\Xi\pi, \Lambda\bar{K}, \Sigma\bar{K}, \Xi\pi\pi$	Jenkins (1983)

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

The Known Ξ Spectrum

State	J^P	Mass (MeV/c^2)	Width (MeV)	Status	Primary decay modes	Last reported
Ξ	$1/2^+$	1320	0	****	$\Lambda\pi$	—
$\Xi(1530)$	$3/2^+$	1530	9	****	$\Xi\pi$	BaBar (2008)
$\Xi(1620)$	$?^?$	~ 1620	22	*	$\Xi\pi$	Hassall (1981)
$\Xi(1690)$	$?^?$	1690	< 30	***	$\Lambda\bar{K}, \Sigma\bar{K}, \Xi\pi$	BaBar (2008)
$\Xi(1820)$	$3/2^-$	1823	24	***	$\Lambda\bar{K}$	Anisovich (2012)
$\Xi(1950)$	$?^?$	1950 ± 15	60 ± 20	***	$\Lambda\bar{K}, \Xi\pi$	Adamovich (1999)
$\Xi(2030)$	$\geq 5/2^?$	2025 ± 5	20^{+15}_{-5}	***	$\Sigma\bar{K}, \Lambda\bar{K}$	Jenkins (1983)
$\Xi(2120)$	$?^?$	~ 2120	< 20	*	$\Lambda\bar{K}$	Chliapnikov (1979)
$\Xi(2250)$	$?^?$	~ 2250	< 30	**	$\Xi\pi\pi, \Lambda\bar{K}\pi, \Sigma\bar{K}\pi$	Biagi (1987)
$\Xi(2370)$	$?^?$	~ 2370	80	**	$\Lambda\bar{K}\pi, \Sigma\bar{K}\pi$	Jenkins (1983)
$\Xi(2500)$	$?^?$	~ 2500	150	*	$\Xi\pi, \Lambda\bar{K}, \Sigma\bar{K}, \Xi\pi\pi$	Jenkins (1983)

- Ξ and Ξ(1530) are well-known octet and decuplet states
- Beyond these, almost everything is a mystery, including existences

The Known Ξ Spectrum

State	J^P	Mass (MeV/c^2)	Width (MeV)	Status	Primary decay modes	Last reported
Ξ	$1/2^+$	1320	0	****	$\Lambda\pi$	—
$\Xi(1530)$	$3/2^+$	1530	9	****	$\Xi\pi$	BaBar (2008)
$\Xi(1620)$	$?^?$	~ 1620	22	*	$\Xi\pi$	Hassall (1981)
$\Xi(1690)$	$?^?$	1690	< 30	***	$\Lambda\bar{K}, \Sigma\bar{K}, \Xi\pi$	BaBar (2008)
$\Xi(1820)$	$3/2^-$	1823	24	***	$\Lambda\bar{K}$	Anisovich (2012)
$\Xi(1950)$	$?^?$	1950 ± 15	60 ± 20	***	$\Lambda\bar{K}, \Xi\pi$	Adamovich (1999)
$\Xi(2030)$	$\geq 5/2^?$	2025 ± 5	20^{+15}_{-5}	***	$\Sigma\bar{K}, \Lambda\bar{K}$	Jenkins (1983)
$\Xi(2120)$	$?^?$	~ 2120	< 20	*	$\Lambda\bar{K}$	Chliapnikov (1979)
$\Xi(2250)$	$?^?$	~ 2250	< 30	**	$\Xi\pi\pi, \Lambda\bar{K}\pi, \Sigma\bar{K}\pi$	Biagi (1987)
$\Xi(2370)$	$?^?$	~ 2370	80	**	$\Lambda\bar{K}\pi, \Sigma\bar{K}\pi$	Jenkins (1983)
$\Xi(2500)$	$?^?$	~ 2500	150	*	$\Xi\pi, \Lambda\bar{K}, \Sigma\bar{K}, \Xi\pi\pi$	Jenkins (1983)

- Ξ and Ξ(1530) are well-known octet and decuplet states
- Beyond these, almost everything is a mystery, including existences
- Most states do not even have spin or parity information

The Known Ξ Spectrum

State	J^P	Mass (MeV/c^2)	Width (MeV)	Status	Primary decay modes	Last reported
Ξ	$1/2^+$	1320	0	****	$\Lambda\pi$	—
$\Xi(1530)$	$3/2^+$	1530	9	****	$\Xi\pi$	BaBar (2008)
$\Xi(1620)$	$?^?$	~ 1620	22	*	$\Xi\pi$	Hassall (1981)
$\Xi(1690)$	$?^?$	1690	< 30	***	$\Lambda\bar{K}, \Sigma\bar{K}, \Xi\pi$	BaBar (2008)
$\Xi(1820)$	$3/2^-$	1823	24	***	$\Lambda\bar{K}$	Anisovich (2012)
$\Xi(1950)$	$?^?$	1950 ± 15	60 ± 20	***	$\Lambda\bar{K}, \Xi\pi$	Adamovich (1999)
$\Xi(2030)$	$\geq 5/2^?$	2025 ± 5	20^{+15}_{-5}	***	$\Sigma\bar{K}, \Lambda\bar{K}$	Jenkins (1983)
$\Xi(2120)$	$?^?$	~ 2120	< 20	*	$\Lambda\bar{K}$	Chliapnikov (1979)
$\Xi(2250)$	$?^?$	~ 2250	< 30	**	$\Xi\pi\pi, \Lambda\bar{K}\pi, \Sigma\bar{K}\pi$	Biagi (1987)
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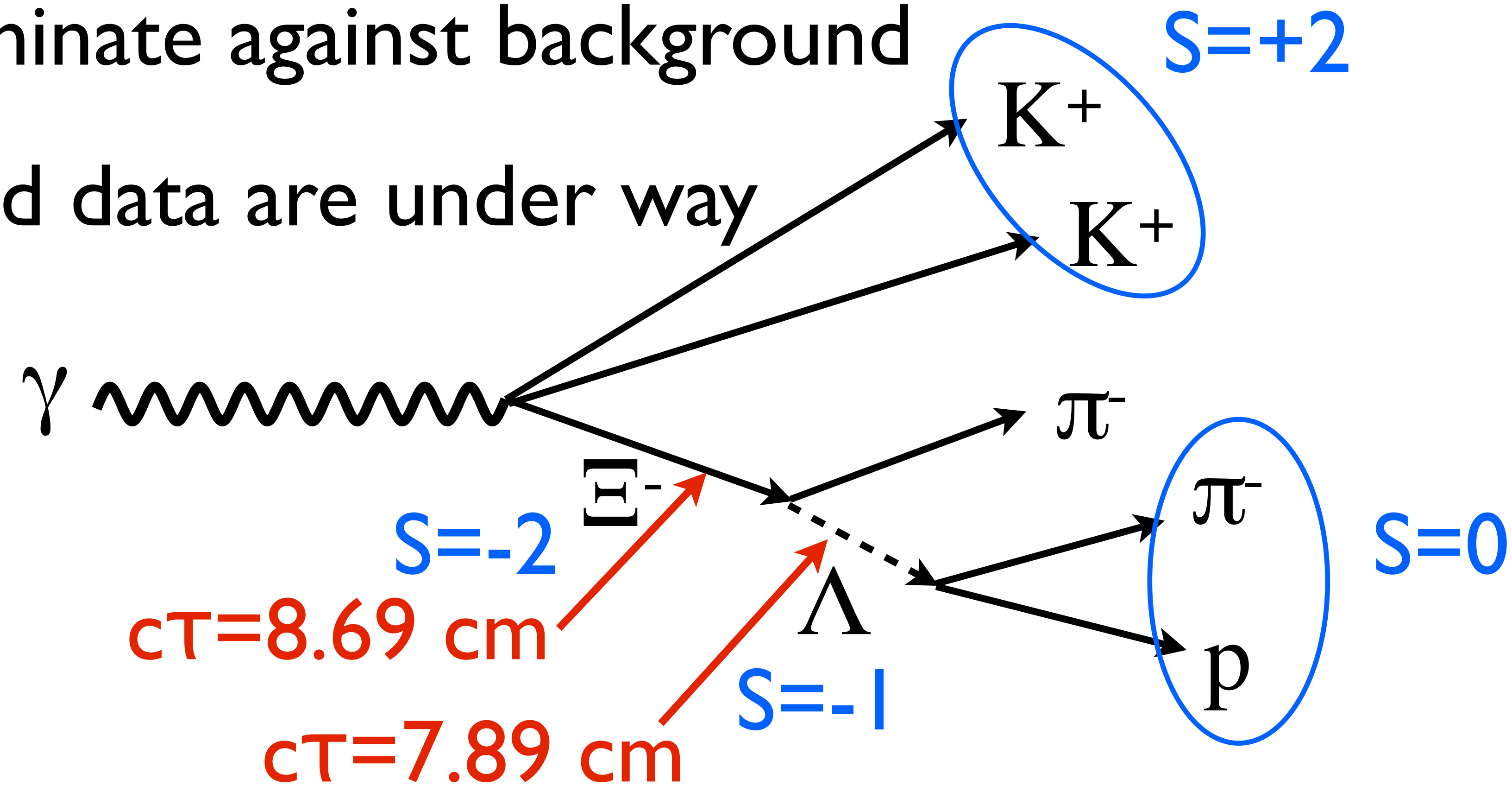
$\Xi(2500)$	$?^?$	~ 2500	150	*	$\Xi\pi, \Lambda\bar{K}, \Sigma\bar{K}, \Xi\pi\pi$	Jenkins (1983)

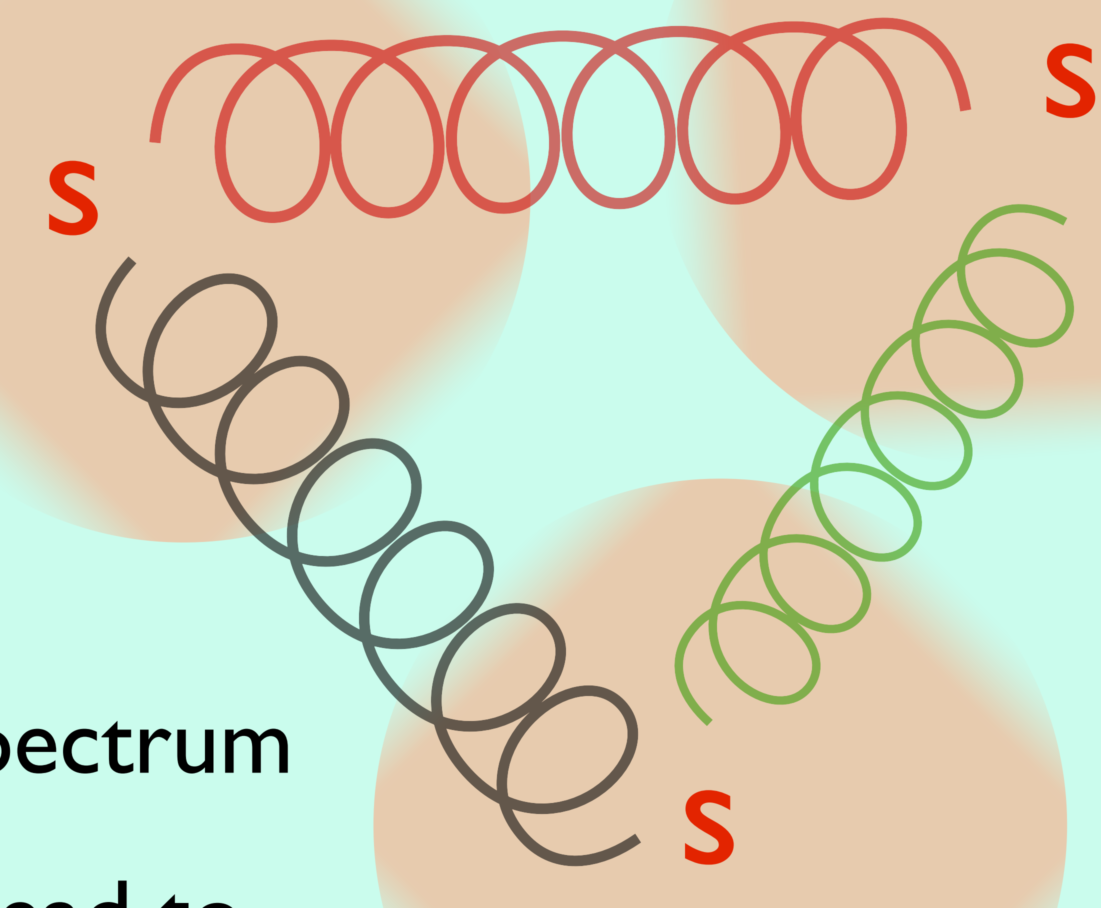
- Ξ and Ξ(1530) are well-known octet and decuplet states
- Beyond these, almost everything is a mystery, including existences
- Most states do not even have spin or parity information
- Widths are small, detection may not be difficult

GlueX and Ξ States

- GlueX could make a very large contribution to our knowledge of Ξ states, enable a comparison to spectrum of other baryons
- Note that when Ξ states decay, they will first live for "a very long time" to weakly decay to Λπ (total strangeness -1), then the Λ again lives for "a very long time"
- The vertex information can be exploited to detect the Ξ states and also discriminate against background
- Studies using simulated data are under way



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

Conclusions

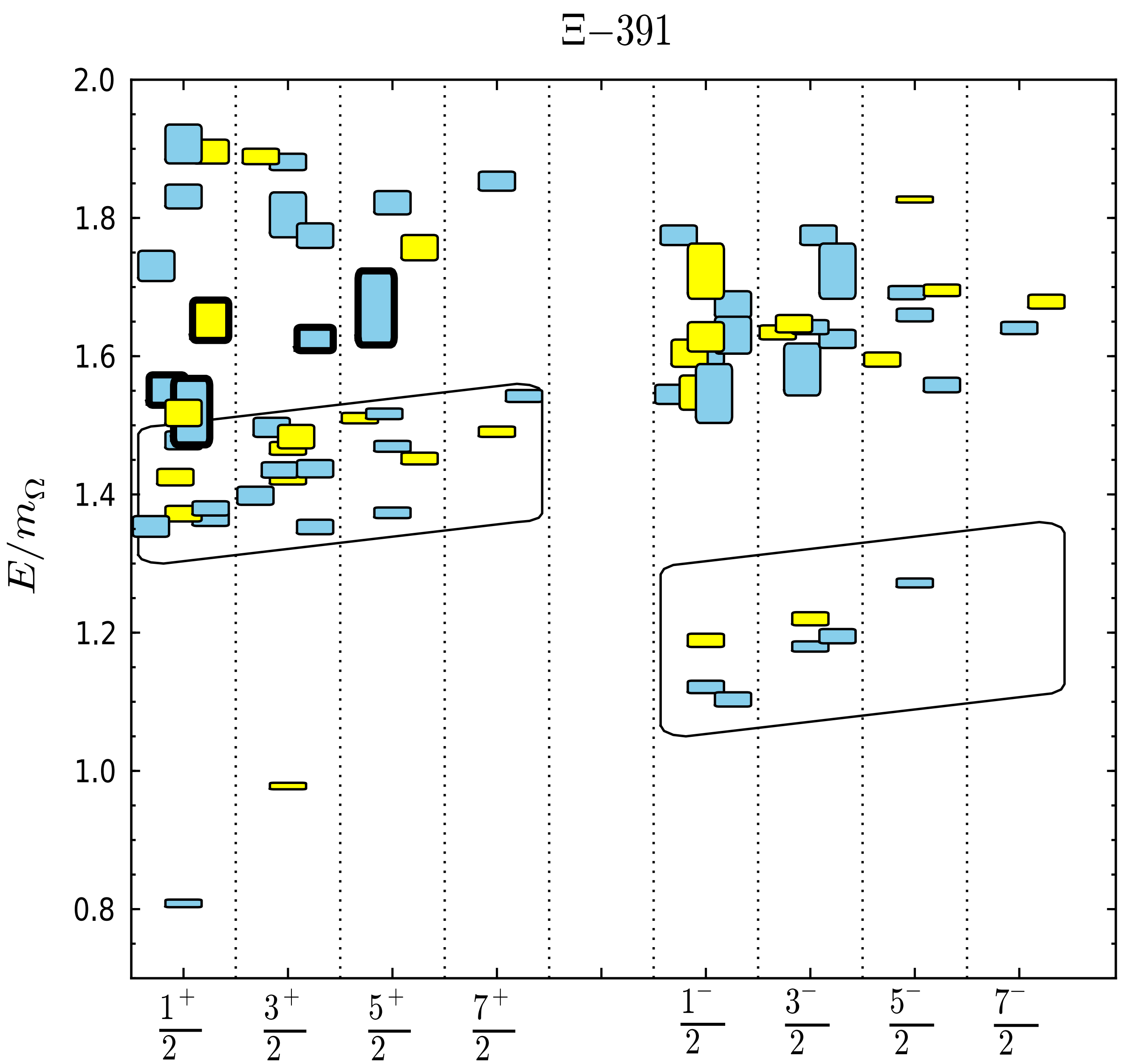
- QCD at the GeV scale is strongly coupled... and messy at first glance
- We need to use all of the information possible - experiment, theory, lattice - to construct a coherent picture of how this theory behaves
- The challenge is: can we bring structure to the chaos?
- GlueX will take enormous amounts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

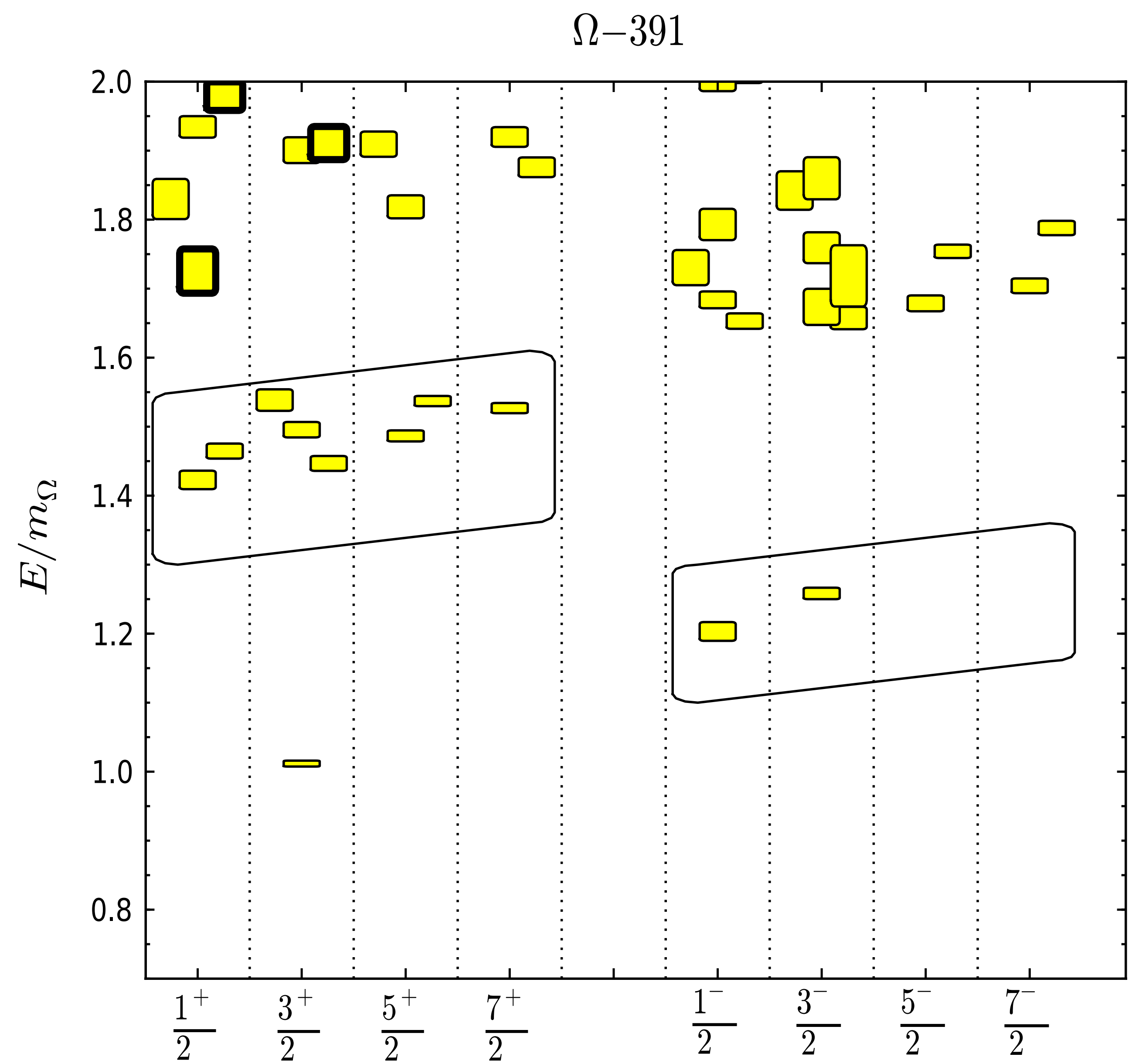
Backup Slides

How is spectroscopy done?

Determination of Spin and Parity

Lattice QCD Predictions for Ξ, Ω





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

Ξ Studies

- Ξ production, reconstruction in GlueX

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	***	$\Xi^-\pi^+K^-, \Xi(1530)^0K^-$	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 three excited states
- 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 $\Omega\pi$, $\Omega\pi\pi$, $\Xi\overline{K}$, $\Xi\overline{K}\pi$