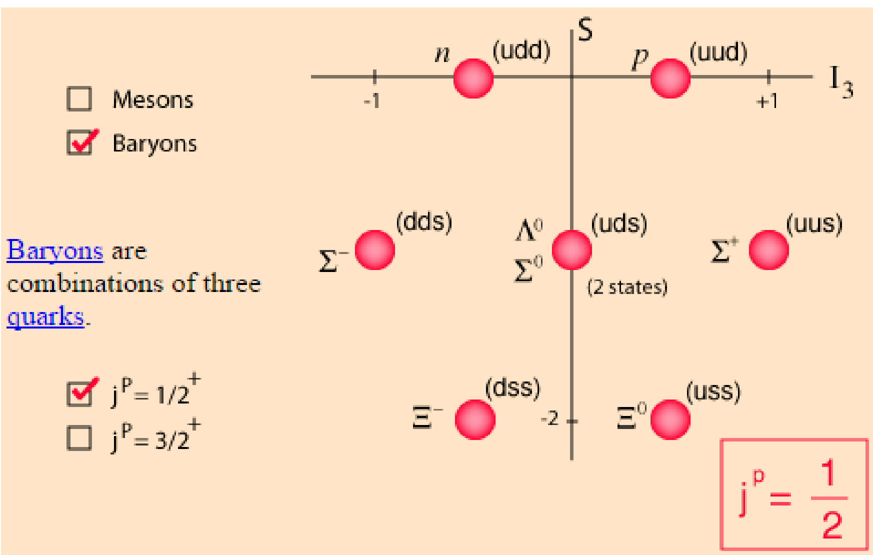
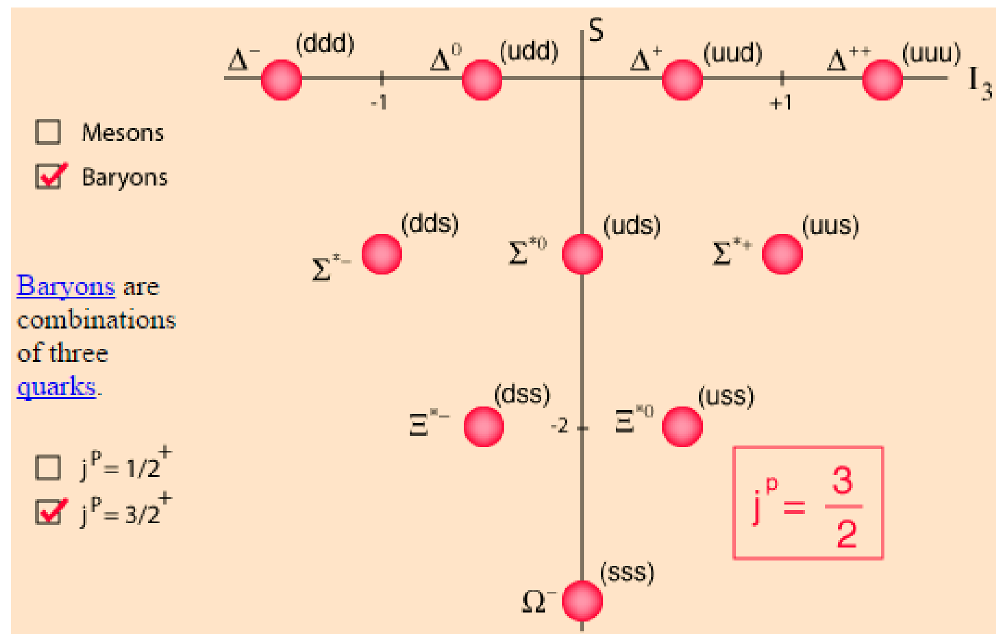
# Searches for New Excited Baryon States


Patrick McCormack April 19, 2014 Physics 290E 

# Baryons

- (Typically) Composed of three quarks of different color
- Fermions, baryon number B=1




Courtesy of http://hyperphysics.phy-astr.gsu.edu/hbase/Particles/haddia.html#c4

# Classification Scheme

- Six types: N (nucleon: p and n), Δ, Λ, Σ, Ξ, Ω

### 8.4. Ordinary (3-quark) baryons

The symbols $N$, $\Delta$, $\Lambda$, $\Sigma$, $\Xi$, and $\Omega$ used for more than 30 years for the baryons made of light quarks ($u$, $d$, and $s$ quarks) tell the isospin and quark content, and the same information is conveyed by the symbols used for the baryons containing one or more heavy quarks ($c$ and $b$ quarks). The rules are:

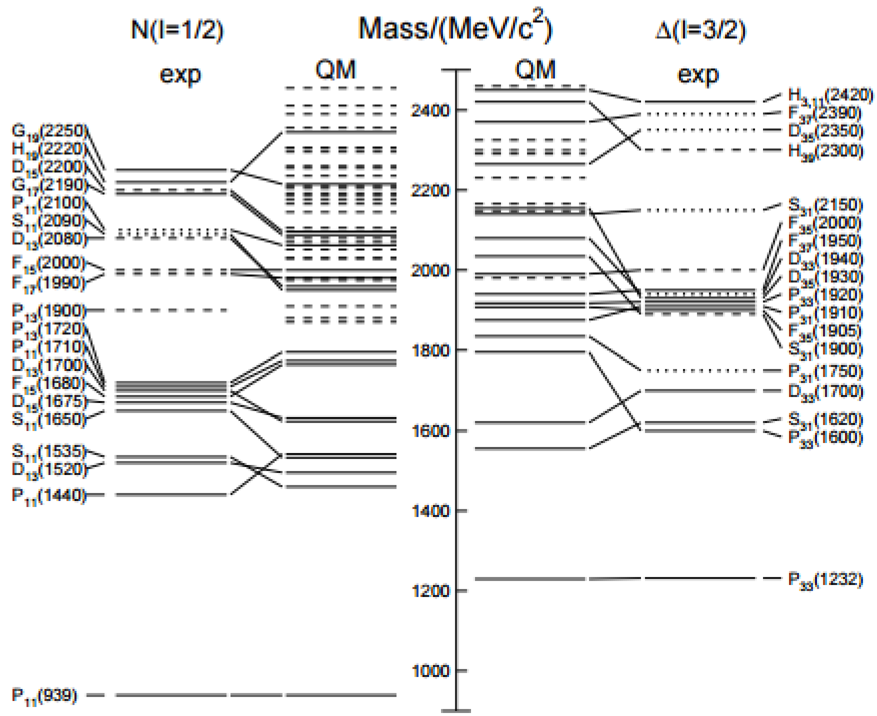
1. Baryons with *three* $u$ and/or $d$ quarks are $N$'s (isospin 1/2) or $\Delta$'s (isospin 3/2).
2. Baryons with *two* $u$ and/or $d$ quarks are $\Lambda$'s (isospin 0) or $\Sigma$'s (isospin 1). If the third quark is a $c$, $b$, or $t$ quark, its identity is given by a subscript.
3. Baryons with *one* $u$ or $d$ quark are $\Xi$'s (isospin 1/2). One or two subscripts are used if one or both of the remaining quarks are heavy: thus $\Xi_c$, $\Xi_{cc}$, $\Xi_b$, *etc.*[*]
4. Baryons with *no* $u$ or $d$ quarks are $\Omega$'s (isospin 0), and subscripts indicate any heavy-quark content.
5. A baryon that decays strongly has its mass as part of its name. Thus $p$, $\Sigma^-$, $\Omega^-$, $\Lambda_c^+$, *etc.*, but $\Delta(1232)^0$, $\Sigma(1385)^-$, $\Xi_c(2645)^+$, *etc.*

In short, the number of $u$ plus $d$ quarks together with the isospin determine the main symbol, and subscripts indicate any content of heavy quarks. A $\Sigma$ always has isospin 1, an $\Omega$ always has isospin 0, *etc.*

http://pdg.lbl.gov/2014/reviews/rpp2014-rev-naming-scheme-hadrons.pdf

# Quark Model

- Baryons of the ground states are all known and well-predicted
- Excited states are not well understood




http://pdg.lbl.gov/2011/reviews/rpp2011-rev-quark-model.pdf

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

| | | |
|---|---|---|
| $\Delta(1232)$ | $3/2^+$ | **** |
| $\Delta(1600)$ | $3/2^+$ | *** |
| $\Delta(1620)$ | $1/2^-$ | **** |
| $\Delta(1700)$ | $3/2^-$ | **** |
| $\Delta(1750)$ | $1/2^+$ | * |
| $\Delta(1900)$ | $1/2^-$ | ** |
| $\Delta(1905)$ | $5/2^+$ | **** |
| $\Delta(1910)$ | $1/2^+$ | **** |
| $\Delta(1920)$ | $3/2^+$ | *** |
| $\Delta(1930)$ | $5/2^-$ | *** |
| $\Delta(1940)$ | $3/2^-$ | ** |
| $\Delta(1950)$ | $7/2^+$ | **** |
| $\Delta(2000)$ | $5/2^+$ | ** |
| $\Delta(2150)$ | $1/2^-$ | * |
| $\Delta(2200)$ | $7/2^-$ | * |
| $\Delta(2300)$ | $9/2^+$ | ** |
| $\Delta(2350)$ | $5/2^-$ | * |
| $\Delta(2390)$ | $7/2^+$ | * |
| $\Delta(2400)$ | $9/2^-$ | ** |
| $\Delta(2420)$ | $11/2^+$ | **** |
| $\Delta(2750)$ | $13/2^-$ | ** |
| $\Delta(2950)$ | $15/2^+$ | ** |
| | | |
| $\Lambda$ | $1/2^+$ | **** |
| $\Lambda(1405)$ | $1/2^-$ | **** |
| $\Lambda(1520)$ | $3/2^-$ | **** |
| $\Lambda(1600)$ | $1/2^+$ | *** |
| $\Lambda(1670)$ | $1/2^-$ | **** |
| $\Lambda(1690)$ | $3/2^-$ | **** |
| $\Lambda(1710)$ | $1/2^+$ | * |
| $\Lambda(1800)$ | $1/2^-$ | *** |
| $\Lambda(1810)$ | $1/2^+$ | *** |
| $\Lambda(1820)$ | $5/2^+$ | **** |
| $\Lambda(1830)$ | $5/2^-$ | **** |
| $\Lambda(1890)$ | $3/2^+$ | **** |
| $\Lambda(2000)$ | | * |
| $\Lambda(2020)$ | $7/2^+$ | * |
| $\Lambda(2050)$ | $3/2^-$ | * |
| $\Lambda(2100)$ | $7/2^-$ | **** |
| $\Lambda(2110)$ | $5/2^+$ | *** |
| $\Lambda(2325)$ | $3/2^-$ | * |
| $\Lambda(2350)$ | $9/2^+$ | *** |
| $\Lambda(2585)$ | | ** |

| | | |
|---|---|---|
| $\Sigma^+$ | $1/2^+$ | **** |
| $\Sigma^0$ | $1/2^+$ | **** |
| $\Sigma^-$ | $1/2^+$ | **** |
| $\Sigma(1385)$ | $3/2^+$ | **** |
| $\Sigma(1480)$ | | * |
| $\Sigma(1560)$ | | ** |
| $\Sigma(1580)$ | $3/2^-$ | * |
| $\Sigma(1620)$ | $1/2^-$ | * |
| $\Sigma(1660)$ | $1/2^+$ | *** |
| $\Sigma(1670)$ | $3/2^-$ | **** |
| $\Sigma(1690)$ | | ** |
| $\Sigma(1730)$ | $3/2^+$ | * |
| $\Sigma(1750)$ | $1/2^-$ | *** |
| $\Sigma(1770)$ | $1/2^+$ | * |
| $\Sigma(1775)$ | $5/2^-$ | **** |
| $\Sigma(1840)$ | $3/2^+$ | * |
| $\Sigma(1880)$ | $1/2^+$ | ** |
| $\Sigma(1900)$ | $1/2^-$ | * |
| $\Sigma(1915)$ | $5/2^+$ | **** |
| $\Sigma(1940)$ | $3/2^+$ | * |
| $\Sigma(1940)$ | $3/2^-$ | *** |
| $\Sigma(2000)$ | $1/2^-$ | * |
| $\Sigma(2030)$ | $7/2^+$ | **** |
| $\Sigma(2070)$ | $5/2^+$ | * |
| $\Sigma(2080)$ | $3/2^+$ | ** |
| $\Sigma(2100)$ | $7/2^-$ | * |
| $\Sigma(2250)$ | | *** |
| $\Sigma(2455)$ | | ** |
| $\Sigma(2620)$ | | ** |
| $\Sigma(3000)$ | | * |
| $\Sigma(3170)$ | | * |

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

| | | |
|---|---|---|
| $\Lambda_c^+$ | $1/2^+$ | **** |
| $\Lambda_c(2595)^+$ | $1/2^-$ | *** |
| $\Lambda_c(2625)^+$ | $3/2^-$ | *** |
| $\Lambda_c(2765)^+$ | | * |
| $\Lambda_c(2880)^+$ | $5/2^+$ | *** |
| $\Lambda_c(2940)^+$ | | *** |
| $\Sigma_c(2455)$ | $1/2^+$ | **** |
| $\Sigma_c(2520)$ | $3/2^+$ | *** |
| $\Sigma_c(2800)$ | | *** |
| $\Xi_c^+$ | $1/2^+$ | *** |
| $\Xi_c^0$ | $1/2^+$ | *** |
| $\Xi_c^{\prime +}$ | $1/2^+$ | *** |
| $\Xi_c^{\prime 0}$ | $1/2^+$ | *** |
| $\Xi_c(2645)$ | $3/2^+$ | *** |
| $\Xi_c(2790)$ | $1/2^-$ | *** |
| $\Xi_c(2815)$ | $3/2^-$ | *** |
| $\Xi_c(2930)$ | | * |
| $\Xi_c(2980)$ | | *** |
| $\Xi_c(3055)$ | | ** |
| $\Xi_c(3080)$ | | *** |
| $\Xi_c(3123)$ | | * |
| $\Omega_c^0$ | $1/2^+$ | *** |
| $\Omega_c(2770)^0$ | $3/2^+$ | *** |
| | | |
| $\Xi_{cc}^+$ | | * |
| | | |
| $\Lambda_b^0$ | $1/2^+$ | *** |
| $\Lambda_b(5912)^0$ | $1/2^-$ | *** |
| $\Lambda_b(5920)^0$ | $3/2^-$ | *** |
| $\Sigma_b$ | $1/2^+$ | *** |
| $\Sigma_b^*$ | $3/2^+$ | *** |
| $\Xi_b^0, \Xi_b^-$ | $1/2^+$ | *** |
| $\Xi_b(5945)^0$ | $3/2^+$ | *** |
| $\Omega_b^-$ | $1/2^+$ | *** |

http://pdg.lbl.gov/2014/tables/rpp2014-qtab-baryons.pdf

# Research Goals

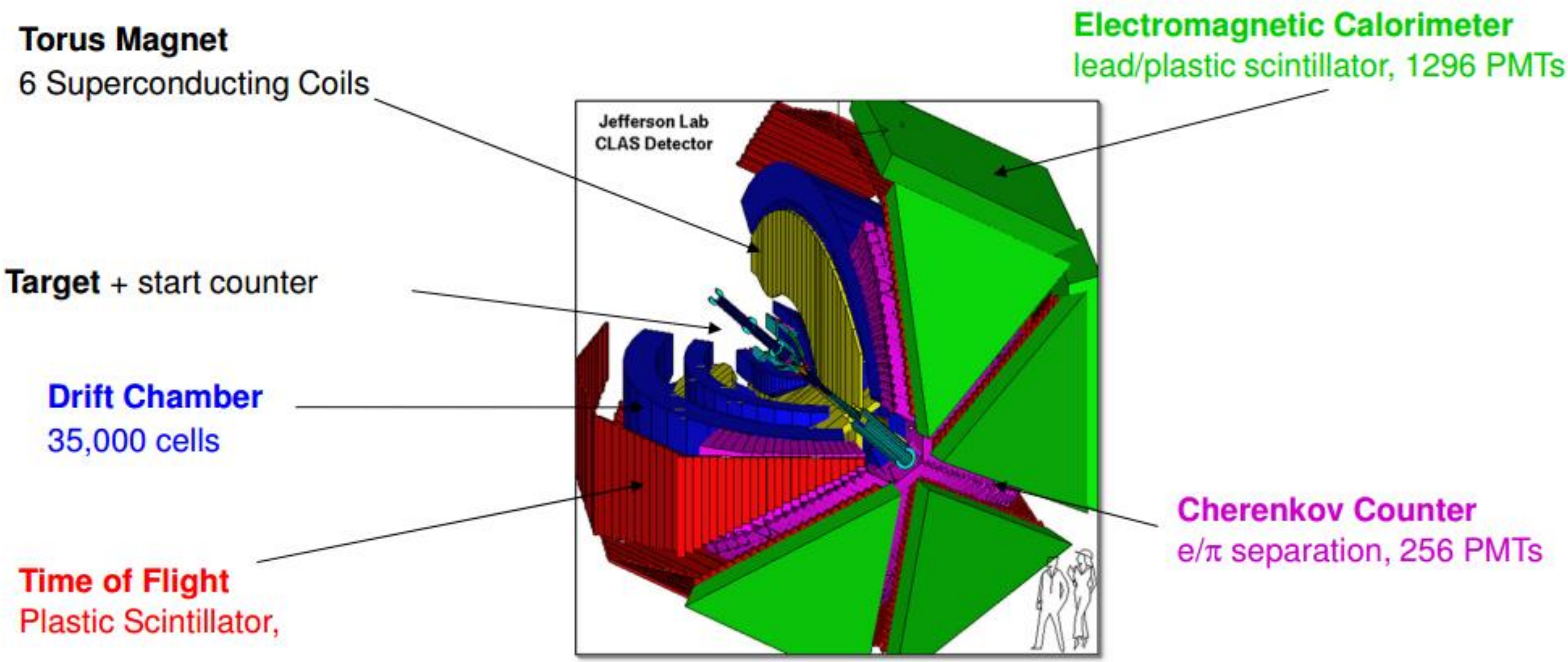
- Obtain resonance structure for light quark flavors
  - Understand strong QCD in light quark sector
- Probe heavy quark baryon sector
- Discover exotic baryon states
- In particular, this is important for understanding hadronization of the early universe

# How do we looks for new baryon states?

- CLAS
  - Electron beam-> Fixed Target
- BELLE and BaBar
  - $e^+e^-$
- CMS and LHCb
  - pp

# CLAS (CEBAF Large Acceptance Spectrometer)

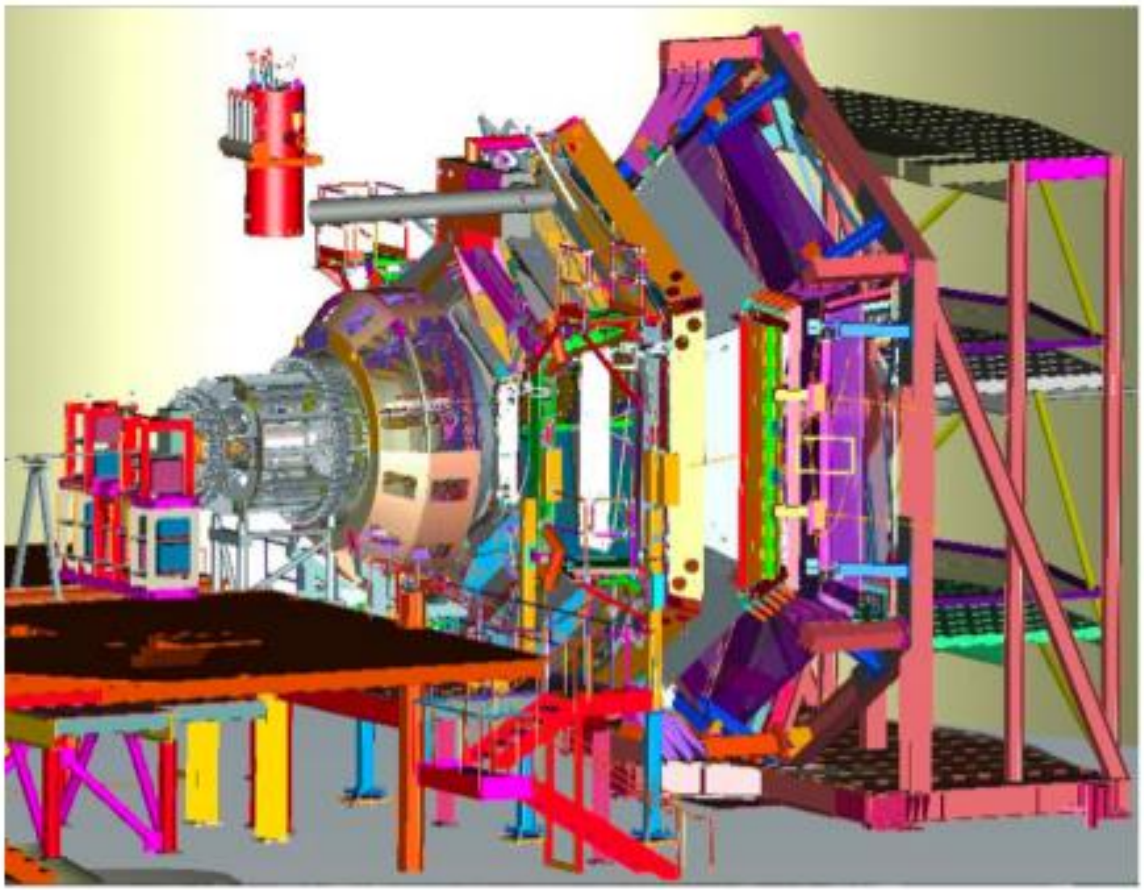
- Currently electron beam reaches 12 GeV




http://www2.ph.ed.ac.uk/~dwatts1/WattsHSQCD12.pdf

# CLAS12

- Currently undergoing testing



https://www.jlab.org/Hall-B/calcom/cwb-kpp.pdf

# Example Discovery: $N'(1720)\frac{3}{2}^{+}$

- Parameters
  - Invariant CM energy ($W$)
  - Invariant momentum transfer ($Q^2$)
  - Multipole form factors ($G_E, G_M, G_C$)
  - Helicity couplings or photocouplings ($A_{1/2}, A_{3/2}, S_{1/2}$)
- Study $\gamma p \rightarrow \pi^+\pi^- p$ electroproduction cross section and compare to model
- Only existence of both $N'(1720)\frac{3}{2}^{+}$ and conventional $N(1720)\frac{3}{2}^{+}$ states allows good model match to data

# CLAS Results

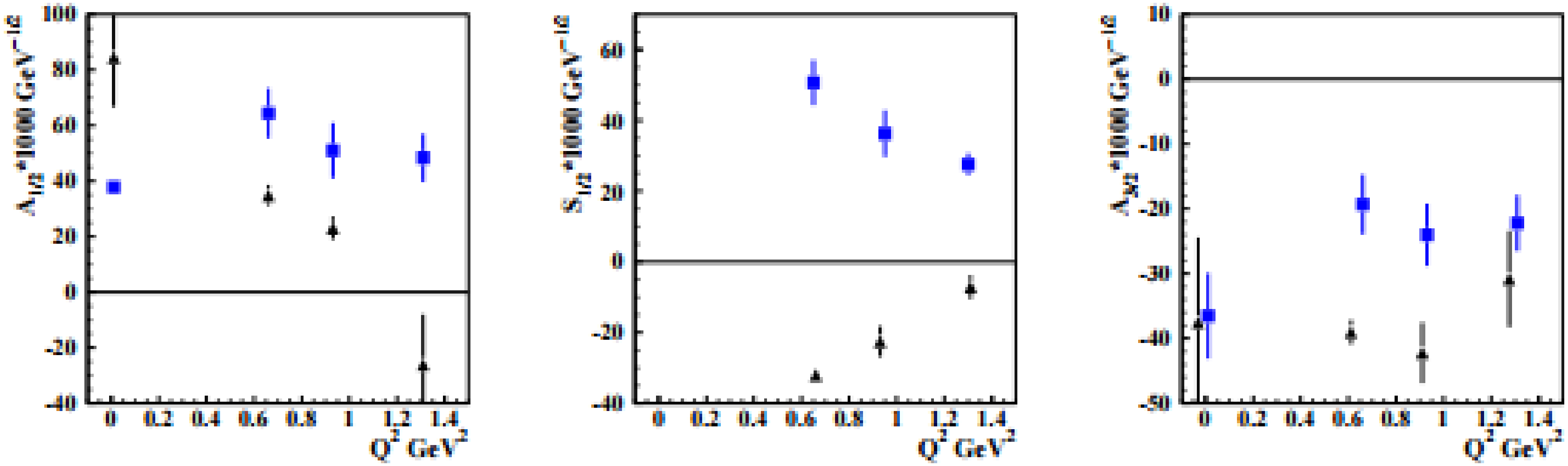
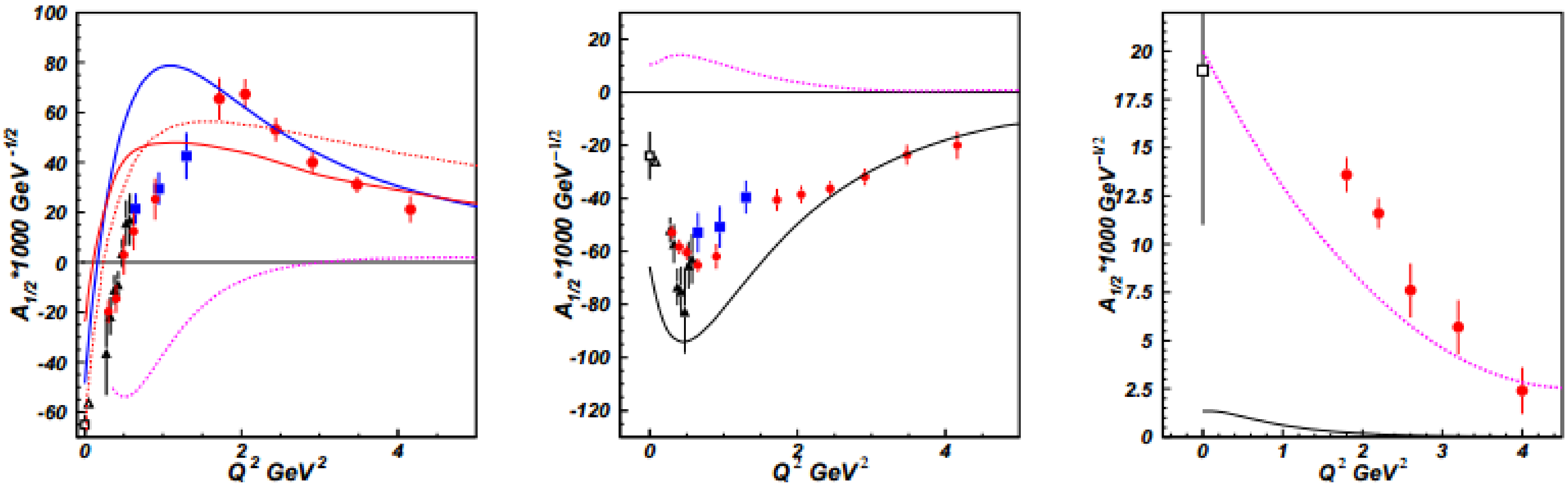



Photo- and electrocouplings of the $N'(1720)\frac{3}{2}^{+}$ (blue) and conventional $N(1720)\frac{3}{2}^{+}$ (black) states as determined from $\gamma p \rightarrow \pi^{+}\pi^{-}p$ and comparison to current models.
“their hadronic decay widths of the πΔ, ρN final states and Q 2 -evolution of their electrocouplings are distinctively different”

# CLAS N* Spectrum and Structure

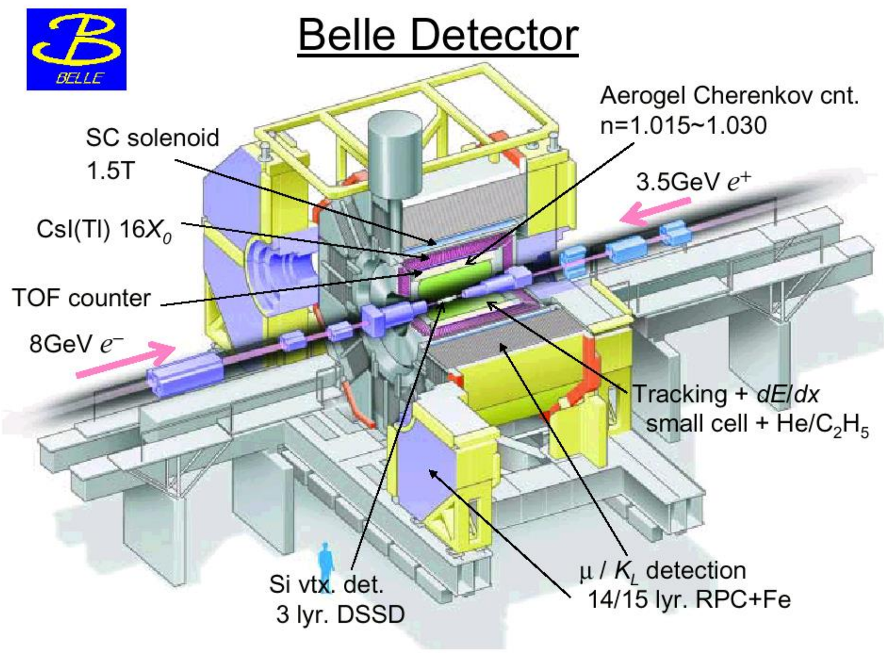
- CLAS has provided the majority of current information on the properties of $N(1440)\frac{1}{2}^{+}$, $N(1520)\frac{3}{2}^{-}$, $\Delta(1232)\frac{3}{2}^{+}$, $N(1535)\frac{1}{2}^{-}$ nucleon resonances, which are the most well understood
- They have also studied electrocouplings for $N(1675)\frac{5}{2}^{-}$, $N(1680)\frac{5}{2}^{+}$, and $N(1710)\frac{1}{2}^{+}$
- Data comes from $\gamma p \rightarrow \pi^{+}\pi^{-}p$ and $\gamma p \rightarrow N\pi$ channels

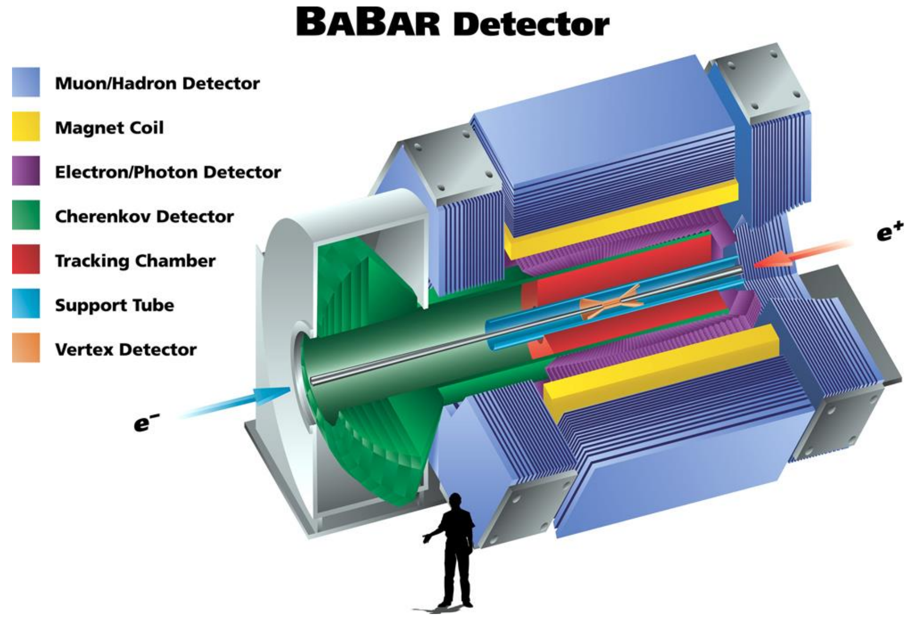
# CLAS Results




Electrocouplings of $N(1440)\frac{1}{2}^{+}$(left), $N(1520)\frac{3}{2}^{-}$ (center), $N(1675)\frac{5}{2}^{-}$ (right) resonances

# BELLE and BaBar




The Belle Detector from at Kek and the BaBar detector at SLAC.

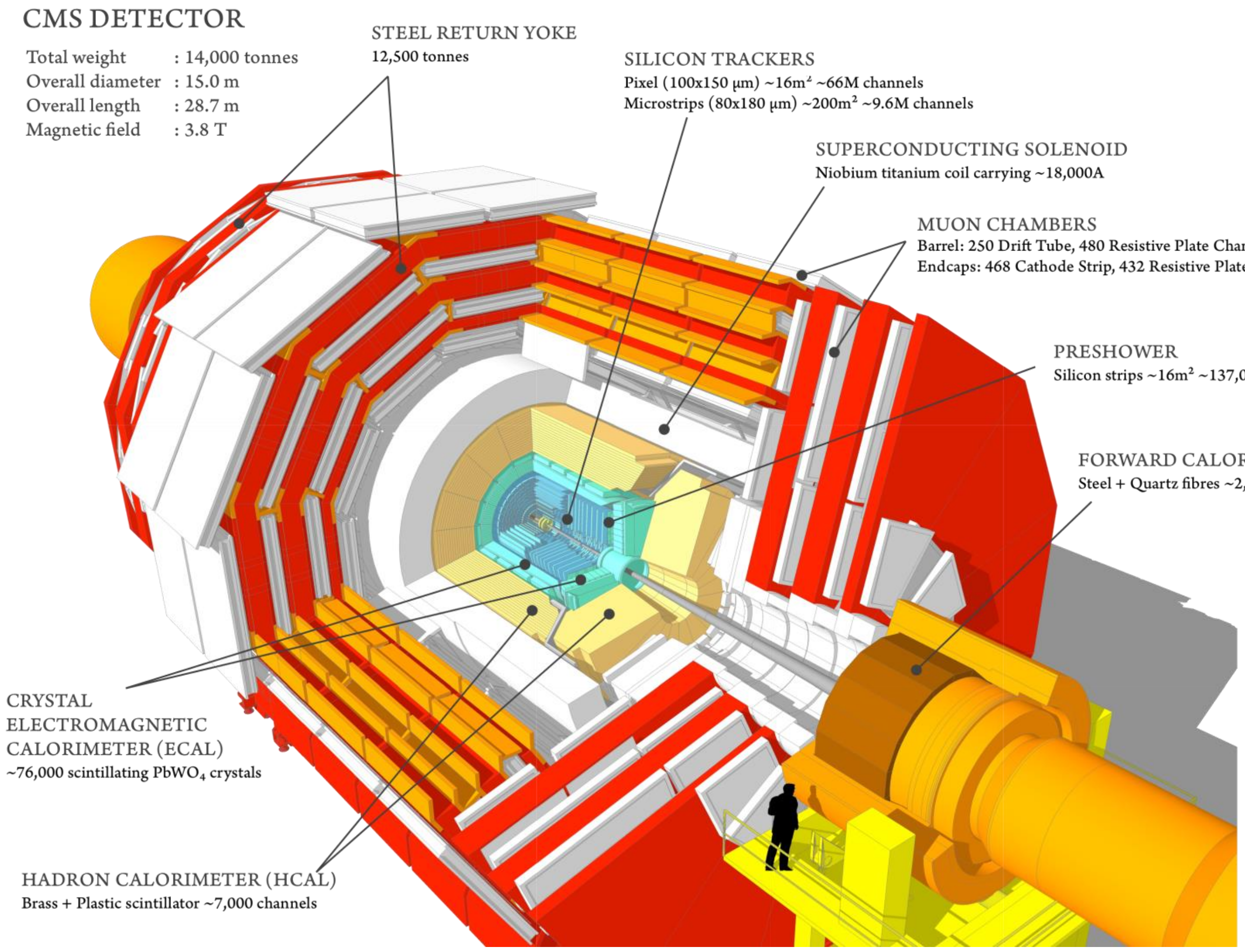
# BELLE and BaBar

- Designed to study CP violation in the B meson system
- ~10 GeV electron-positron collisions
- B mesons can decay baryonically
  - $\bar{B}^{o} \rightarrow \Lambda_c^+ \bar{p}$
  - $B^- \rightarrow \Lambda_c^+ \bar{p} \pi^-$

# BELLE and BaBar Baryon Resonances

- $B^- \to \Lambda_c^+ \bar{p} \pi^-$ system has resonances
  - $B^- \to \Sigma_c(2455)^o \bar{p}$
    - Branching ratio of ~.12
  - $B^- \to \Sigma_c(2800)^o \bar{p}$
    - Branching ratio of ~.12
  - Expected resonance $B^- \to \Sigma_c(2520)^o \bar{p}$ not observed
- First measurement of $\Sigma_c(2455)^o$ spin is ½ as predicted by quark model, but $\Sigma_c(2800)^o$ mass disagrees with PDG?

# CMS

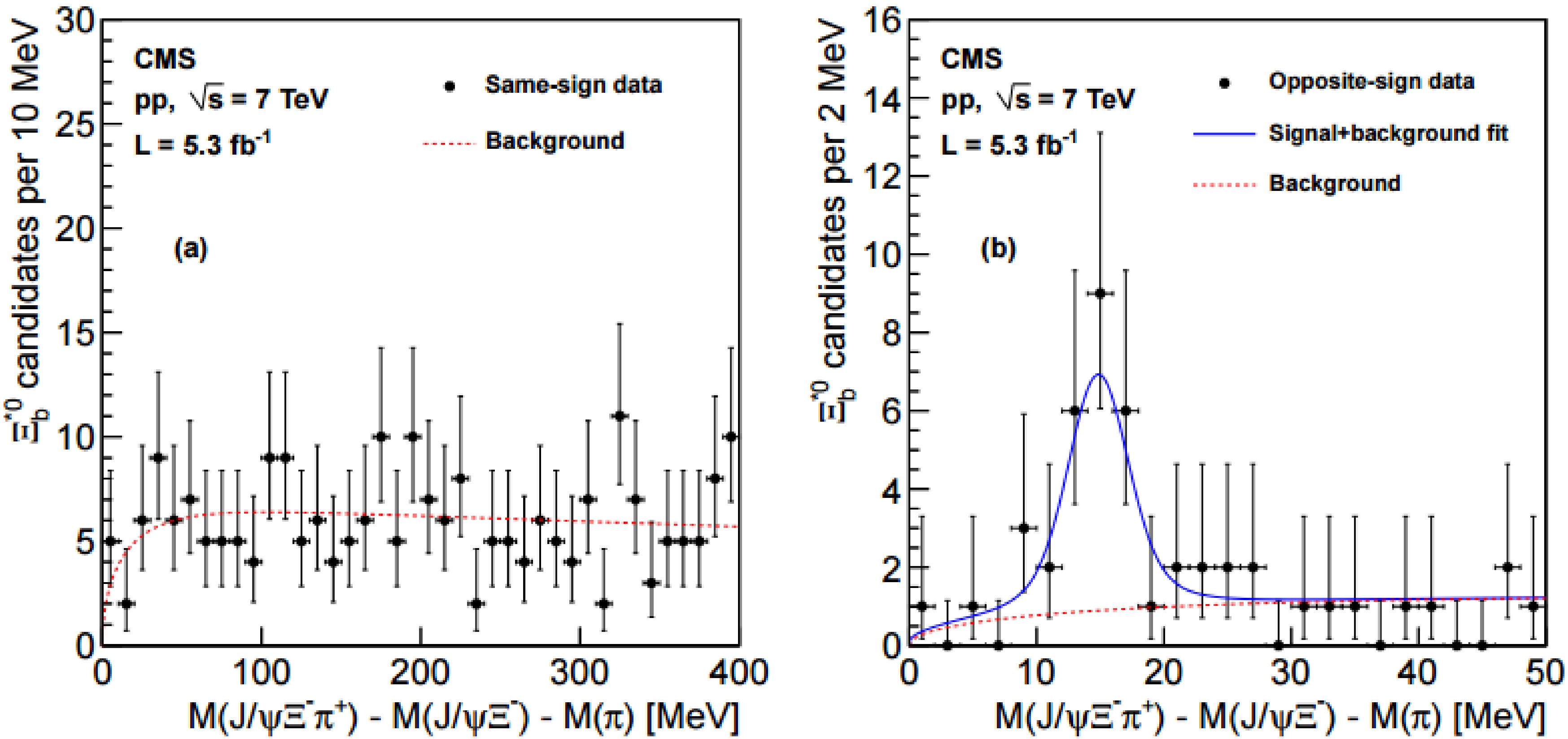


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

# CMS Observations

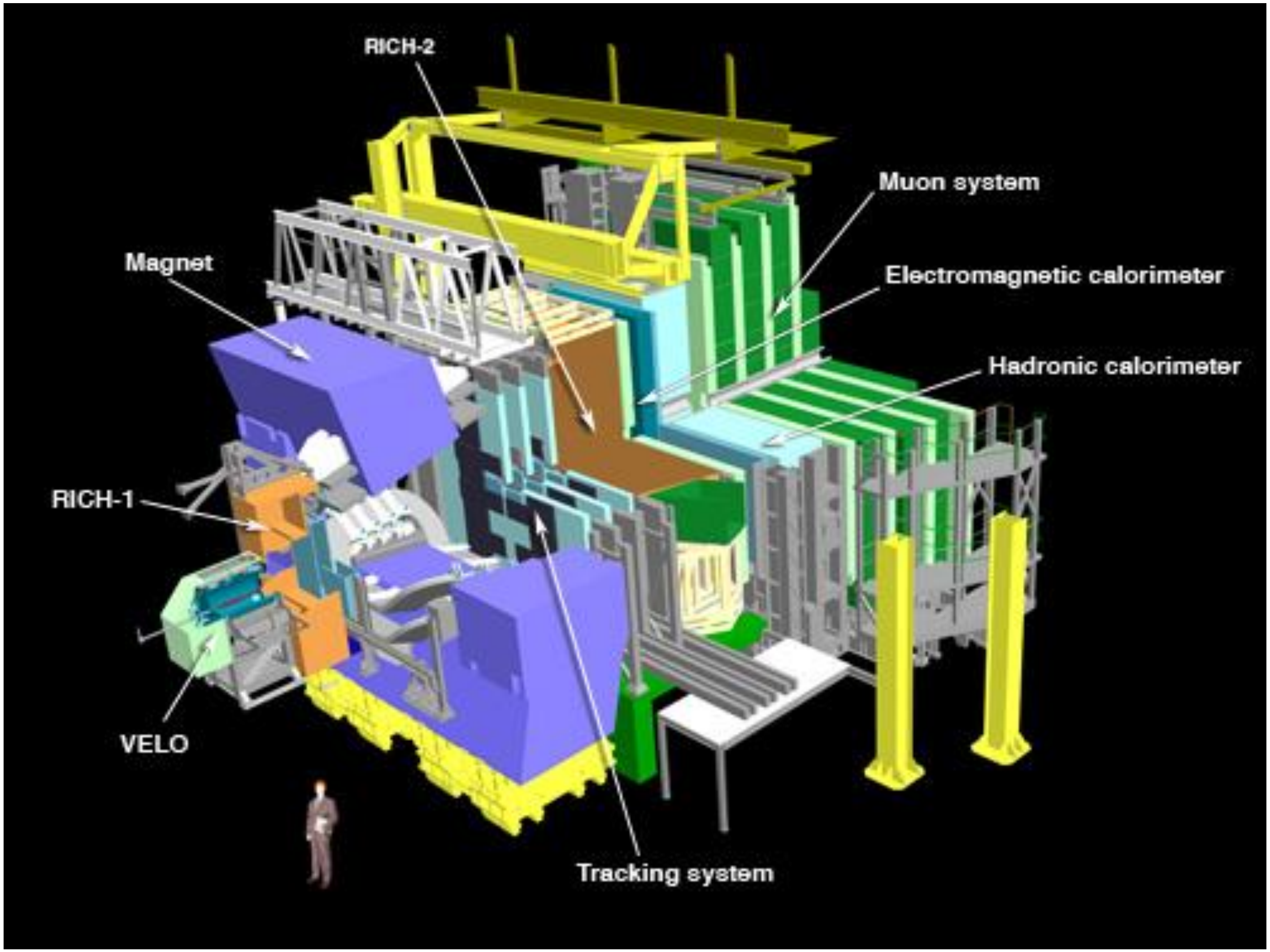
- High energy pp collisions $\sqrt{s} = 7\ TeV$
- A resonance beauty-valence Ξ baryon with $J^P = \frac{3}{2}^+$ and L=0 was observed
- Decay chain
  - $\Xi_b^{*o} \rightarrow \Xi_b^- \pi^+, \Xi_b^- \rightarrow J/\Psi \Xi^-, J/\Psi \rightarrow \mu^+ \mu^-,$
    $\Xi^- \rightarrow \Lambda^o \pi^-, \Lambda^0 \rightarrow p \pi^-$

# CMS Results




A baryon of mass 5945 MeV is observed with significance around $7\sigma$.
Given its decay modes, it is identified as the $\Xi_b^{*o}$.

# LHCb



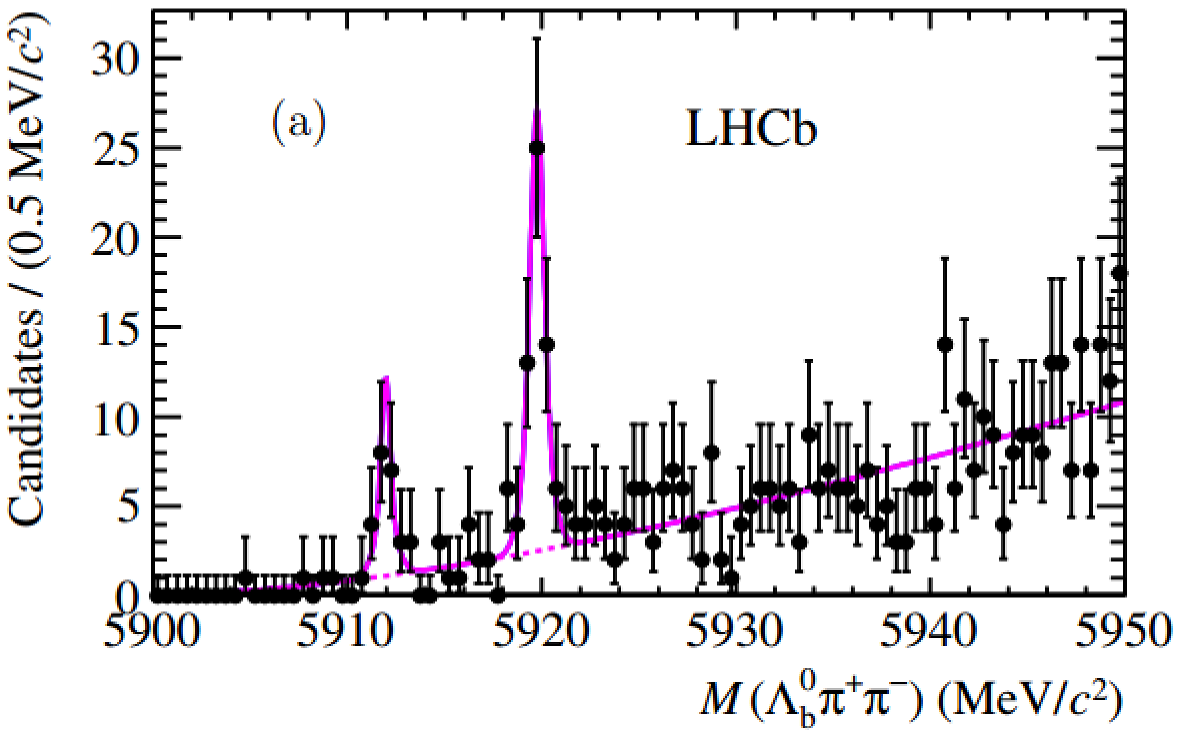
RICH-2
Muon system
Magnet
Electromagnetic calorimeter
Hadronic calorimeter
RICH-1
VELO
Tracking system

# LHCb

- Actually a specialized b-physics experiment designed to measure CP violation in b-hadrons
- Also based on the LHC, studying high energy pp collisions
- LHCb detector is a single-arm forward spectrometer

# LHCb Example Discovery: $\Lambda_b^{*o}(5912), \Lambda_b^{*o}(5920)$

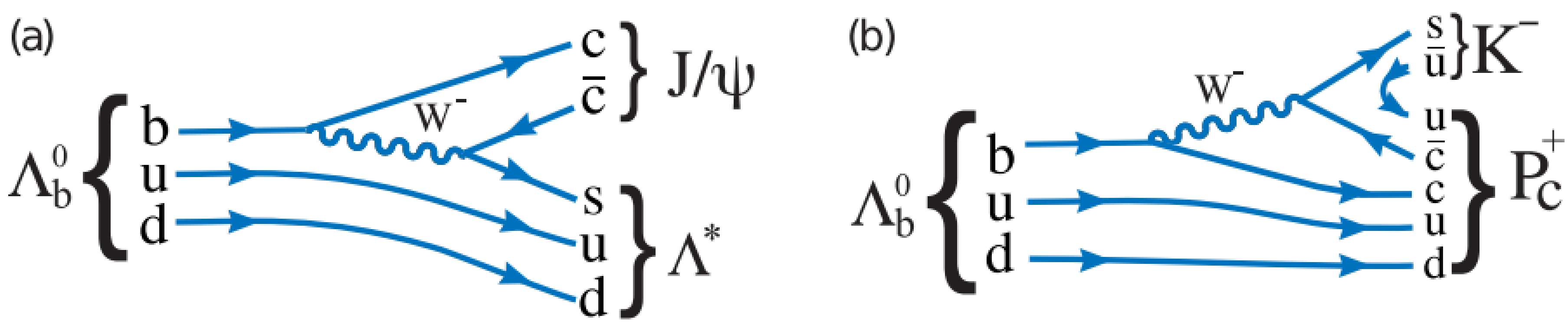
- Decay chain:
  - $\Lambda_b^{*o} \rightarrow \Lambda_b^o \pi^+ \pi^-, \Lambda_b^o \rightarrow \Lambda_c^+ \pi^-, \Lambda_c^+ \rightarrow p K^- \pi^+$




Invariant mass spectrum of $\Lambda_b^o \pi^+ \pi^-$

# What about Pentaquarks?

- Pentaquarks have three quarks and a quark-antiquark pairs, thus they are fermions with B=1 and can be considered baryons
- LHCb found a pentaquark in their data
  - An “accidental  discovery”



# The Analysis

- Decay under study: $\Lambda_b^o \rightarrow J/\Psi \mathrm{K}^{-}\mathrm{p}$
- Data could not be explained without two resonances in the $J/\Psi p$ mass distribution
- Two particles $P_c(4380)^+$ ($9\sigma$) and $P_c(4450)^+$ ($12\sigma$)
  - Quark content: $c\bar{c}uud$
  - Opposite parities and spins of 3/2 and 5/2

# LHCb results

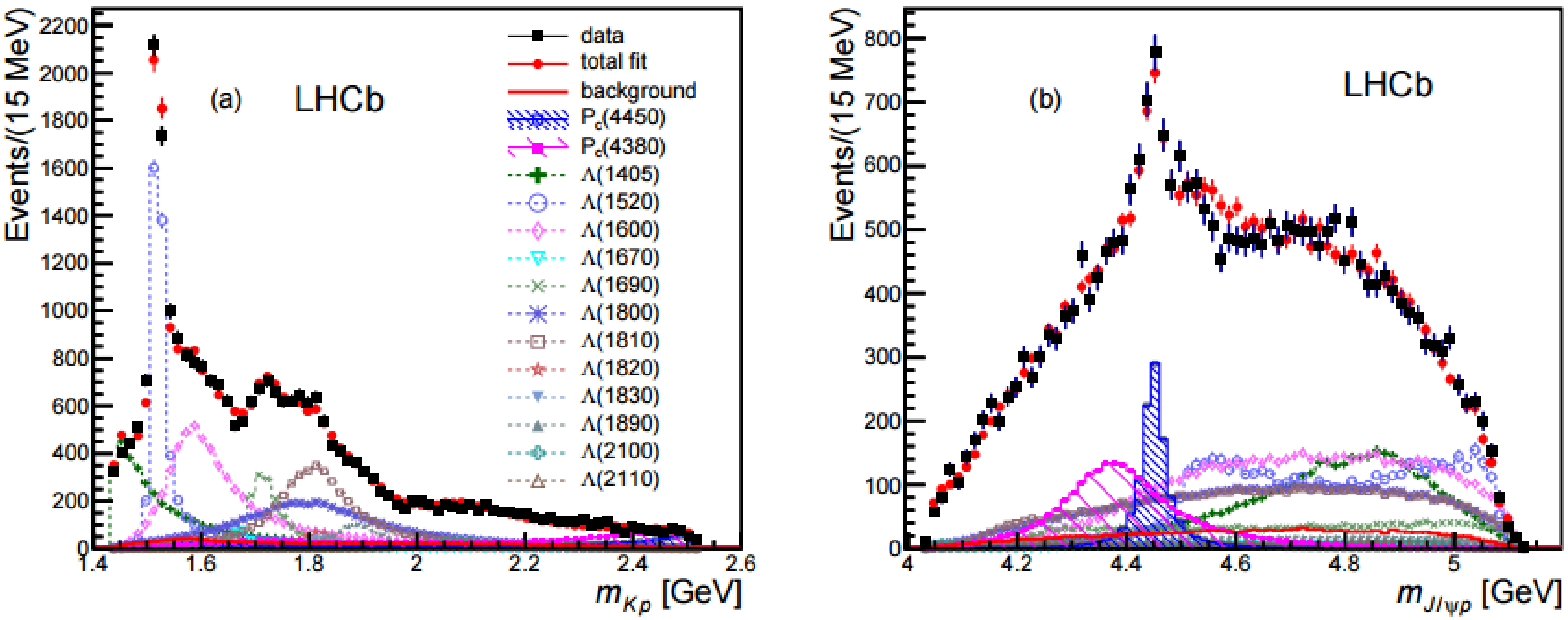



Figure 3: Fit projections for (a) $m_{Kp}$ and (b) $m_{J/\psi p}$ for the reduced $\Lambda^*$ model with two $P_c^+$ states (see Table 1). The data are shown as solid (black) squares, while the solid (red) points show the results of the fit. The solid (red) histogram shows the background distribution. The (blue) open squares with the shaded histogram represent the $P_c(4450)^+$ state, and the shaded histogram topped with (purple) filled squares represents the $P_c(4380)^+$ state. Each $\Lambda^*$ component is also shown. The error bars on the points showing the fit results are due to simulation statistics.

# Sources

- Particle Data Group
  - http://pdg.lbl.gov/2014/tables/contents_tables_baryons.html
  - http://pdg.lbl.gov/2011/reviews/rpp2011-rev-quark-model.pdf
  - http://pdg.lbl.gov/2014/reviews/rpp2014-rev-naming-scheme-hadrons.pdf
- https://www.jlab.org/Hall-B/clas-web/
- Spectrum and Structure of Excited Baryons with CLAS, CLAS Collaboration (https://arxiv.org/pdf/1610.00400.pdf)
- Recent results on the nucleon resonance spectrum and structure from the CLAS detector, CLAS Collaboration (https://arxiv.org/pdf/1508.04088.pdf)
- BARYONIC B MESON DECAYS AT BELLE AND BABAR, Y. W. Chang (https://arxiv.org/pdf/0906.0173.pdf)
- Observation of a new $\Xi_b$ baryon, CMS Collaboration (https://arxiv.org/pdf/1204.5955.pdf)
- Observation of excited $\Lambda_b^o$ baryons, LHCb Collaboration (https://arxiv.org/pdf/1205.3452.pdf)
- Observation of $J/\Psi\ p$ resonances consistent with pentaquark states in $\Lambda_b^o \rightarrow J/\Psi\ K^-\ p$ decays, LHCb Collaboration (https://arxiv.org/pdf/1507.03414.pdf)