Observation of J/ψ p Resonances Consistent with Pentaquark States in $\Lambda^0_b \rightarrow J/\psi K^- p$ Decays

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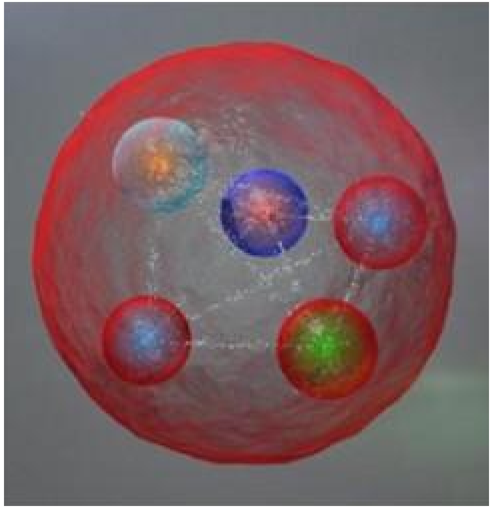

R. Aaij *et al.* (LHCb Collaboration)
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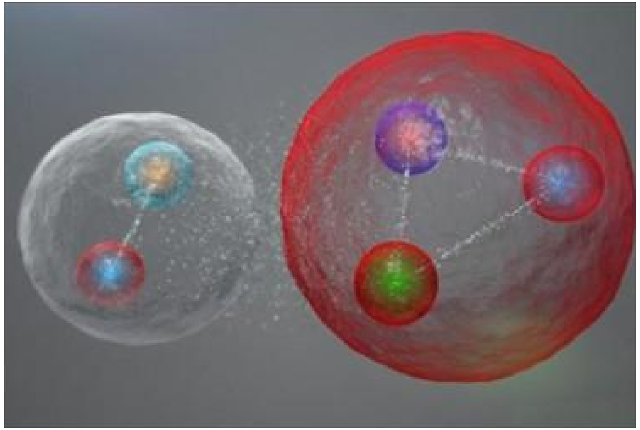
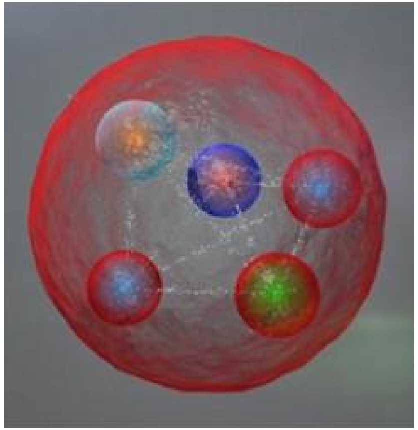


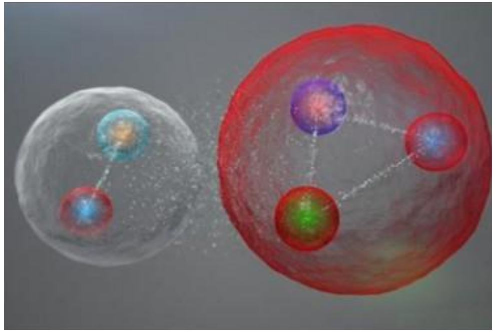
How to Build a Hadron: Color Neutrality

- Hadron recipe: color neutrality
  - Baryons (qqq) such that colors cancel
  - Mesons ($q\bar{q}$) such that colors cancel
- Using this recipe can create hadrons with more than 3 quarks (Gell-Mann)
  - Tetraquark ($q\bar{q}q\bar{q}$)
  - Pentaquark ($qqqq\bar{q}$)



How should we think of pentaquarks?

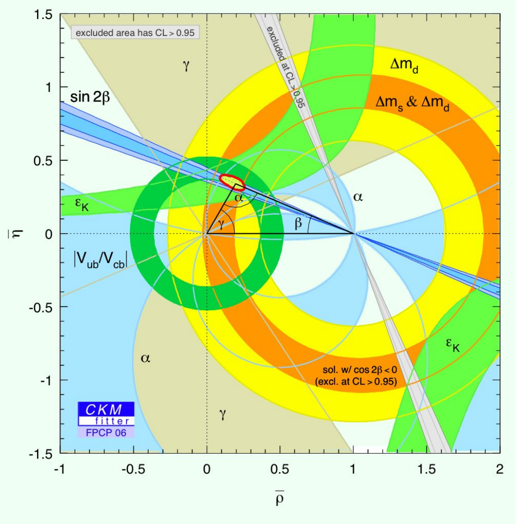
Like this?



Or like this?

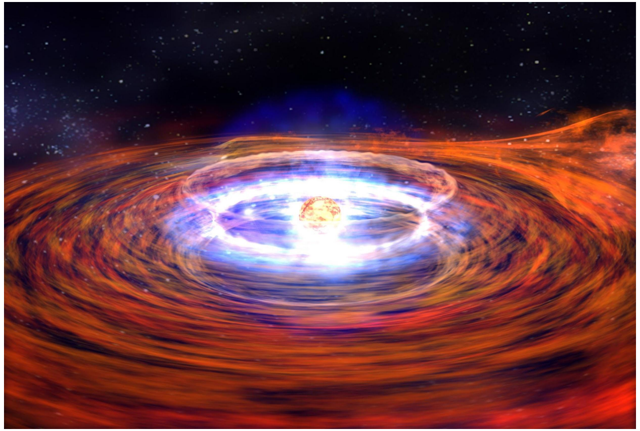
images: http://press.web.cern.ch/press-releases/2015/07/cerns-lhcb-experiment-reports-observation-exotic-pentaquark-particles

Exotic Hadrons Could Provide Insight into Many Areas



These particles provide experimental insight into QCD

Image: www.usqcd.org



Dynamics of seemingly exotic events are relevant to extreme astronomical objects

Image: news.mit.edu

Pentaquark History: Θ^+ (uudd$\bar{s}$) Debacle

- From 2003-2009, 10 different experiments saw 3-5 sigma excess in similar region, with public discovery announcement in 2003
- One-by-one data was retracted (except for LEPS, which still sees excess)
- From 2009 issue of Particle Data Group:

The only advance in particle physics thought worthy of mention in the American Institute of Physics "Physics News in 2003" was a false alarm. The whole story–the discoveries themselves, the tidal wave of papers by theorists and phenomenologists that followed, and the eventual "undiscovery" – is a curious episode in the history of science.

OUCH

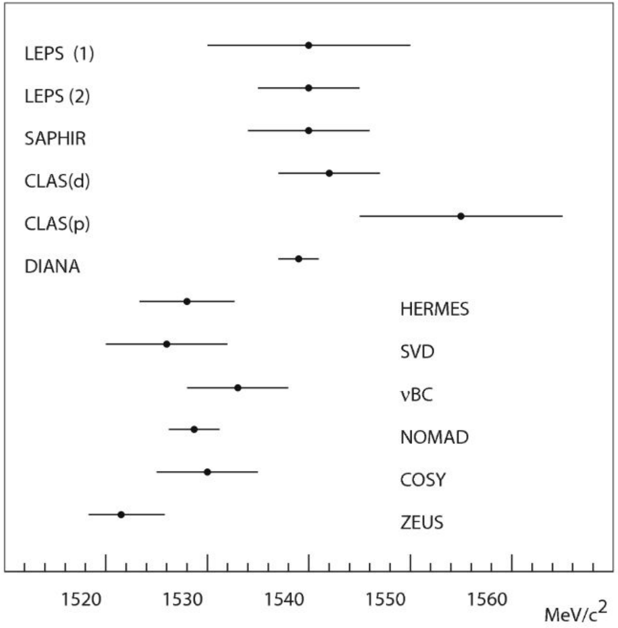
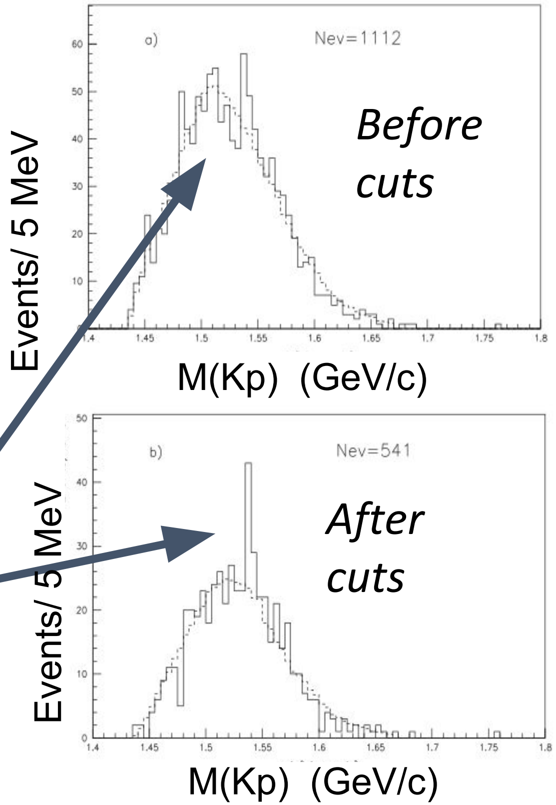


Image: K. H. Hicks, On the conundrum of the pentaquark, Eur. Phys. J. H 37 (2012)

Lessons from Pentaquark Debacle

- Not all 5σ created equal
  - Excess result of 3 parameters:
  - Signal (S), background (B) and variance (V): $S / (\sqrt{B}+V)$
    - Variance especially prone to underestimates if not careful
- Analysis cuts must be justified independent of effect on final mass spectrum

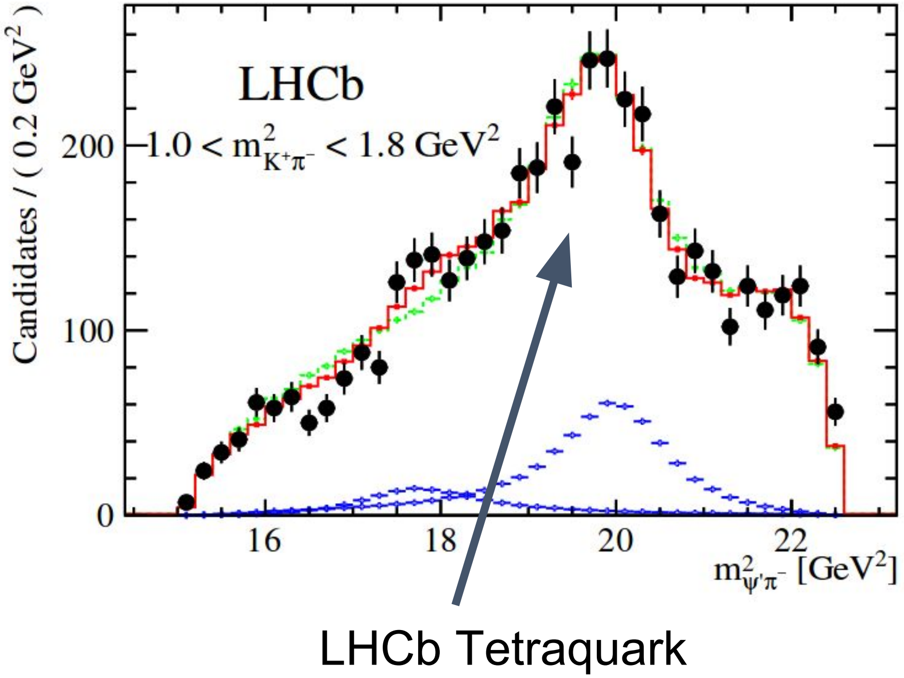


Mass spectrum from DIANA

image: K. H. Hicks, On the conundrum of the pentaquark, Eur. Phys. J. H 37 (2012)

Tetraquarks and Pentaquarks Prior to this Paper

- Pentaquarks:
  - After Θ^+ retraction, nothing definitive before 2015
- Tetraquarks
  - Z(4430) ($c\bar{c}d\bar{u}$) seen by Belle
    - Confirmed at 13 sigma by LHCb in 2012
  - Other potential resonances observed by Belle, DESY, and Fermilab experiments



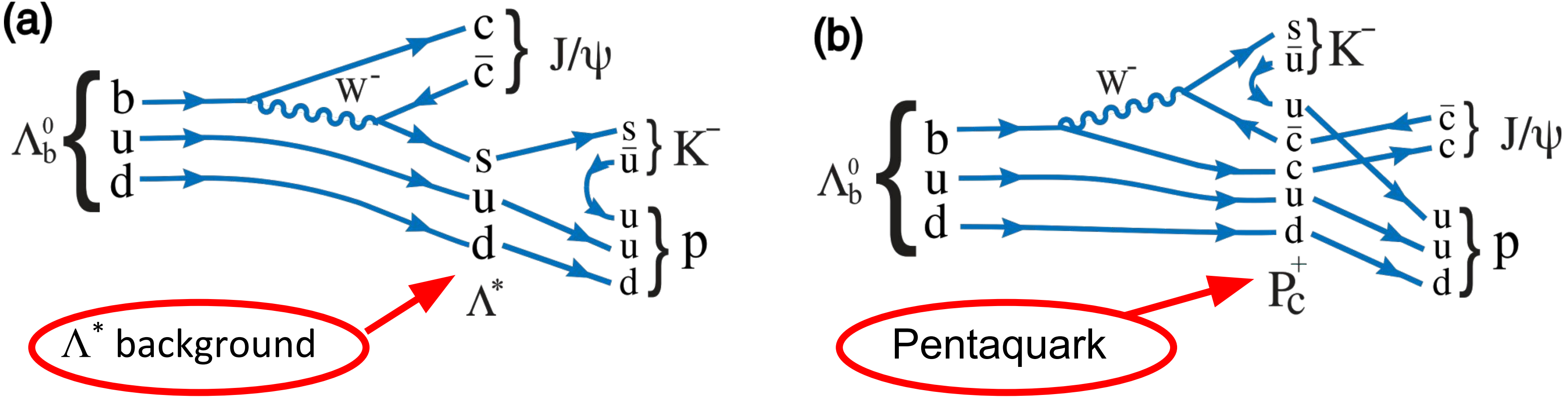
LHCb -- "The LHC Beauty Experiment"

- One of four large experiments at LHC
- Data from p-p collisions at 7-8 TeV, representing ~3 fb^{-1} integrated luminosity
- Primarily a spectrometer, designed to study the bottom quark and its decay products at a few angles

Image: Maximilien Brice (CERN), https://commons.wikimedia.org/wiki/File:CERN_Aerial_View.jpg

Decay of the Λ^0_b May Produce a Pentaquark

- Possible decays of the Λ^0_b baryon are shown below
- Decay may produce a pentaquark consisting of u,u,d,c,$\bar{c}$ quarks
- Add J/ψ and p masses, peaks correspond to pentaquark (P^+_c) states
- Pentaquark must be filtered from background Λ^*

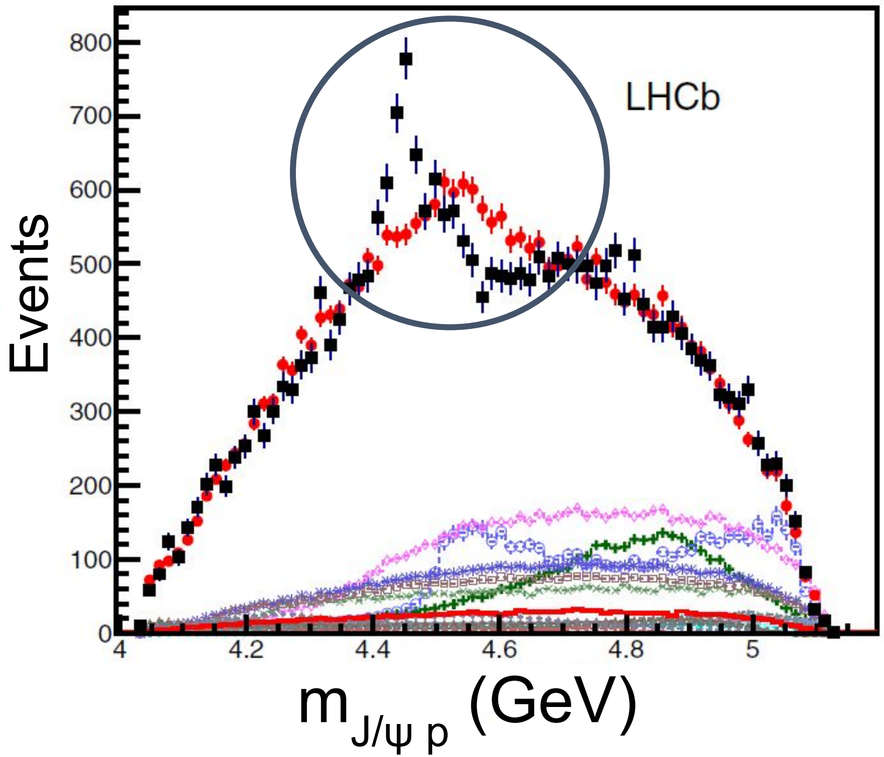


Event Selection: Needles in a Haystack

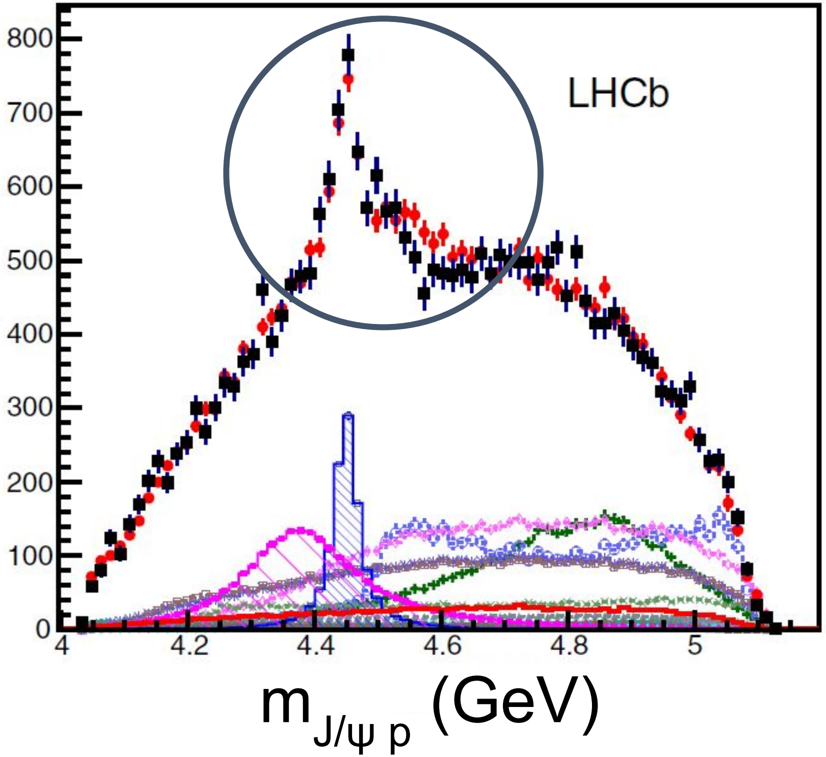
- Events must contain:
  - Each of the particles in the final state: μ^+, μ^-, p, K^-
  - Muon masses must add to J/ψ
  - A Λ^0_b candidate of the correct mass and lifetime
- A boosted decision tree (BDT) selects events
  - Simulate many events with all the desired particles
  - Use simulations as a guide to select similar events in the data
- Result: ~26K events of the desired type with only ~5% contamination

Two P^+_c States are Required to Reproduce Curve

Fit **without** pentaquark states



Fit **with** pentaquark states



Results: New States “Consistent with” Pentaquark

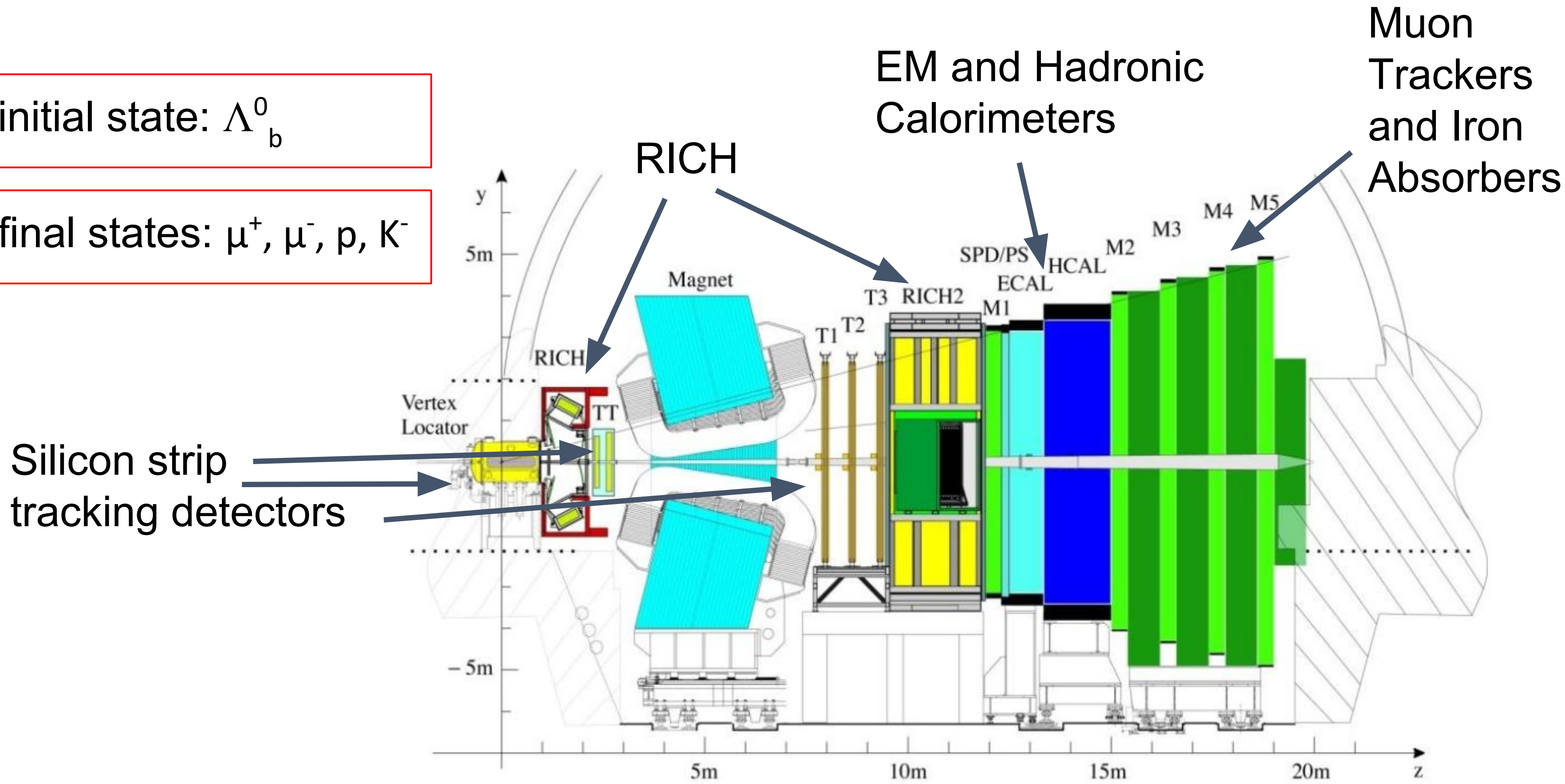
- Excess is consistent with two new pentaquark states
  - Mass distribution is fit best when two P^+_c states are added, at 4380 and 4450 MeV
  - Mass and width of the two states determined to 9σ and 12σ respectively
- Caveats:
  - No independent verification yet
  - Binding mechanism unknown

Suspected P^+_c	Angular momentum	Mass	Width
P^+_c (4380)	$3/2^-$	(4380 ± 8 ± 29) MeV	(205 ± 18 ± 86) MeV
P^+_c (4450)	$5/2^+$	(4449.8 ± 1.7 ± 2.5) MeV	(39 ± 5 ± 19) MeV

How LHCb Detects a Pentaquark

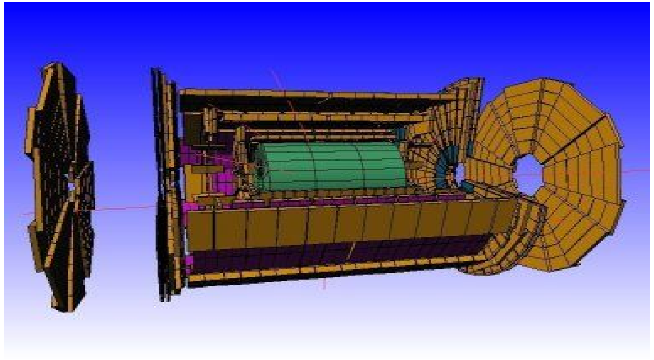
P^+_c initial state: Λ^0_b

P^+_c final states: μ^+, μ^-, p, K^-



Simulations - Physics' Modern Friend

- Simulations used to 'train' the Gradient Boosted Decision Tree (BDTG)
- PYTHIA used to generate hadrons
  - Has been used for a long time, recently converted from Fortran to C++
- Geant4 used to model hadron interactions
  - Used by LHC, MINOS, and T2K
- $2x10^6$ $\Lambda^0_b \rightarrow J/\psi\ K^- p$ events generated
  - 10% efficiency with trigger/reconstruction
  - Specifically removed events with reconstructed mass within 30 MeV of B-meson



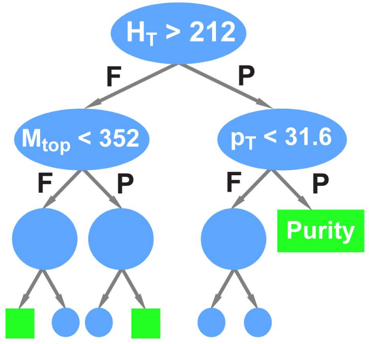
top: Pythia logo   bottom: ATLAS collaboration geometry using Geant4

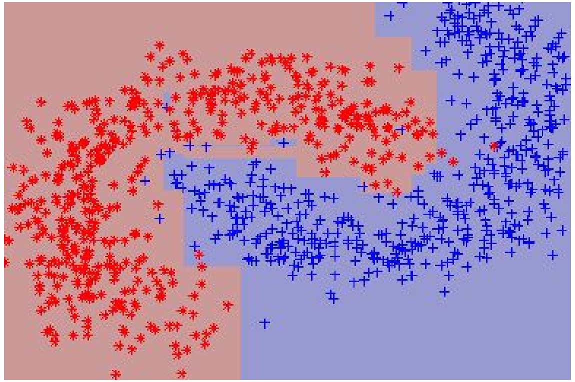
Simulations - A Cut Above the Rest

- Simulations can only do what they are programmed to do
  - Fine for processes we understand well
- If a program has an error and we don't witness it, is it wrong?
  - Software has been used for many years, and is well vetted
  - CERN developed the Geant software, and has a lot of data to check for validation
- No human could do the calculations in one lifetime, how can we check?
  - Trust in the algorithm, and the computer will make very few algebra mistakes
  - Computers are essential to the operation of large-scale projects like LHCb

Boosted Decision Trees: Digital Bloodhounds

- Used to classify information
  - "Learning" stage based on simulated data
  - Determines properties by which the signal and background data differ
- Pitfalls:
  - Overtraining can exclude available signal
  - Signal recovered may be biased





Images: D∅, Perclass
http://www-d0.fnal.gov/Run2Physics/top/singletop_observation/
http://perclass.com/index.php/html/blog_comments/support_for_decision_trees/

Matrix Elements from Helicity Coupling

$$\mathcal{H}_{\lambda_p}^{\Lambda_n^* \to Kp} \; D_{\lambda_{\Lambda^*}, \lambda_p}^{J_{\Lambda_n^*}}(\phi_K, \theta_{\Lambda^*}, 0)^* \; R_{\Lambda_n^*}(m_{Kp}).$$

complex number, will be a fitting parameter

rotation matrix from Λ*'s frame into K^- p frame

a Λ* resonance, related to the invariant mass in the K^- p system

Changing frames makes the math simpler!

Used Maximum Likelihood to Fit Mass Distributions

$$\mathcal{P}_{\mathrm{sig}}(m_{Kp}, \Omega|\overrightarrow{\omega}) = \frac{1}{I(\overrightarrow{\omega})}\left|\mathcal{M}(m_{Kp}, \Omega|\overrightarrow{\omega})\right|^2 \Phi(m_{Kp})\epsilon(m_{Kp}, \Omega)$$

Decay amplitude

Selection efficiency

Two independent methods for removing background were used: explicit (cFit) and implicit (sFit)

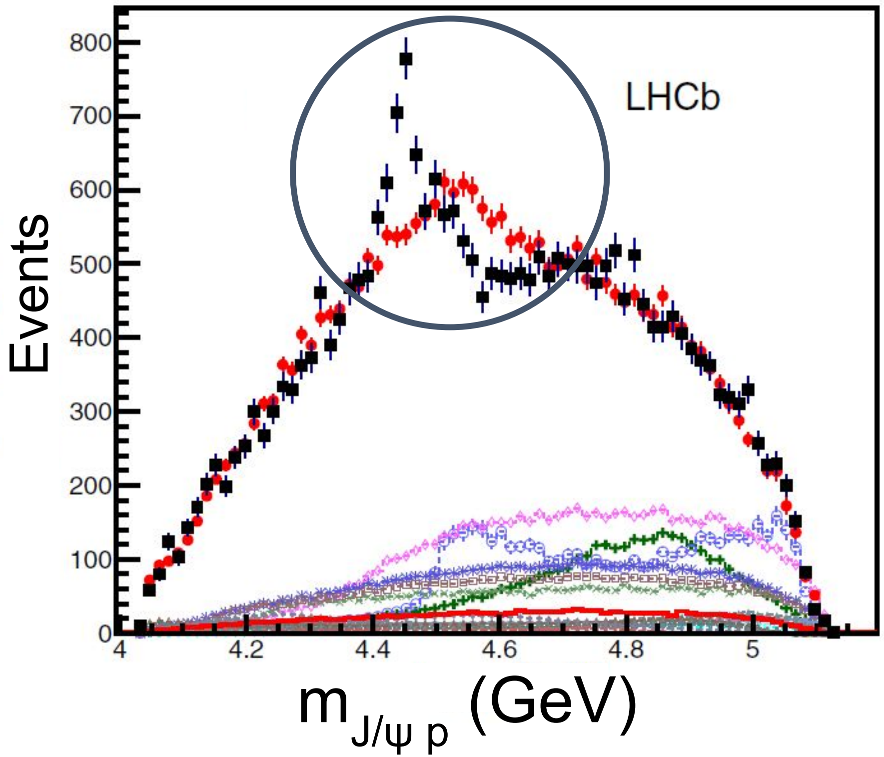
Note: selection efficiencies based on simulated production and selection rates

Considered Both Likely and Unlikely Λ^* Events

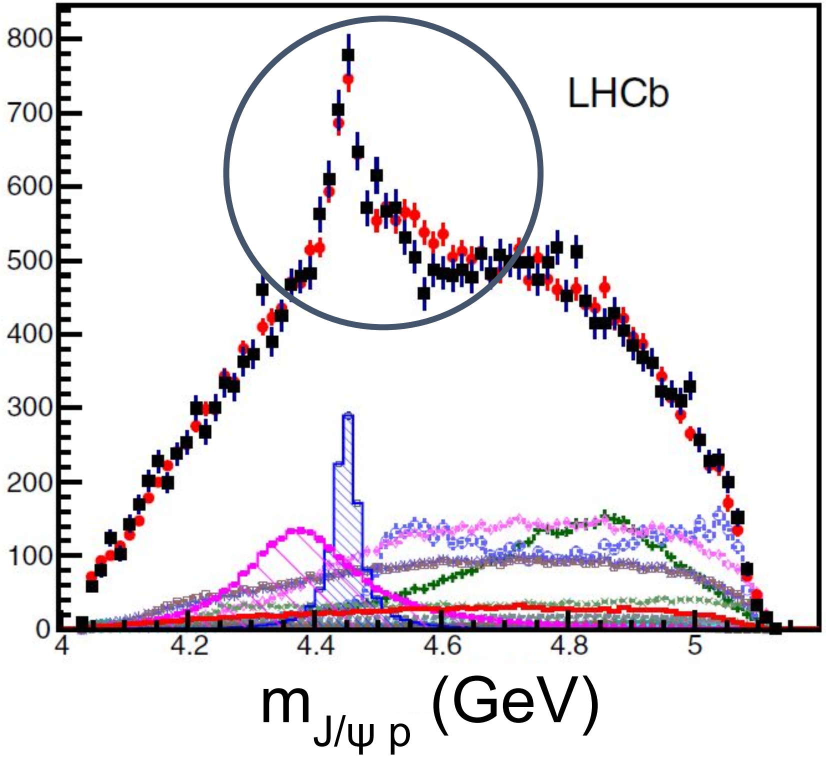
State	J^P	M_0 (MeV)	Γ_0 (MeV)	Number Reduced	Number Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	1890	100	3	6
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150	0	6
$\Lambda(2585)$	?	≈ 2585	200	0	6

Even Extended Model Fails Without P_c^+

Extended, without pentaquark states



Reduced, with pentaquark states



Citation Analysis

Three types of citations:

- Further analysis by LHCb
  - What is the spin quantum number?
- Theoretical models of the pentaquark
  - How is the pentaquark bound?
- Springboard into future research
  - Where do we go from here?

- ❑ Total citations: 55 on Google Scholar, 6 on Scopus
- ❑ Article published in August 2015

Areas of Future Research

- Search for ‘doubly-heavy’ hadron molecules
- Does the P^+_c have a strange analogue?
- Does the LHCb data support more than 2 pentaquarks?

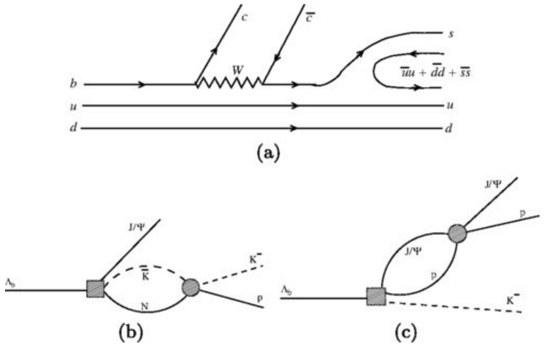
How is the Pentaquark Bound?

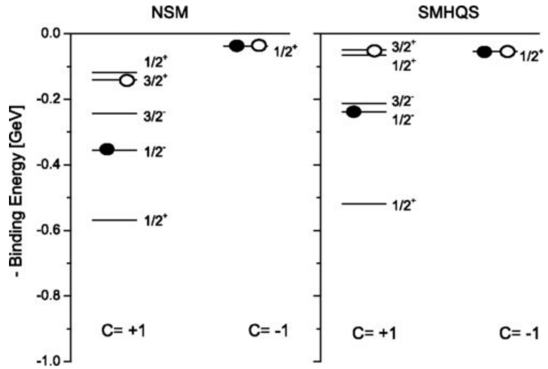
- A molecular state of a meson and a baryon
- Baryons as topological solitons
- Triple string flip-flop and QCD

Backup Slides

Theoretical Explanations

- Baryons as topological solitons
  - http://journals.aps.org/prd/abstract/10.1103/PhysRevD.92.051501 (2)
- Triple string flip-flop and QCD
  - http://arxiv.org/pdf/1509.04943v1.pdf
- A molecular state of a meson and a baryon
  - http://journals.aps.org/prd/abstract/10.1103/PhysRevD.92.094003 (1)





top: other pentaquark Feynman diagrams (1)
bottom: energy levels for soliton charmed mesons (2)

Springboard

- Search for ‘doubly-heavy’ hadron molecules
    - http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.115.122001

- Does the P_c have a strange analogue?
    - http://arxiv.org/abs/1510.06648

- Does the LHCb data support more than 2 pentaquarks?
    - http://www.sciencedirect.com/science/article/pii/S0370269315008631

The Channel-Specific Term

$$R_{\Lambda_n^*}(m_{Kp}) = B'_{L_{\Lambda_b^0}^{\Lambda_n^*}}(p, p_0, d) \left(\frac{p}{M_{\Lambda_b^0}}\right)^{L_{\Lambda_b^0}^{\Lambda_n^*}} \mathrm{BW}(m_{Kp}|M_0^{\Lambda_n^*}, \Gamma_0^{\Lambda_n^*})\, B'_{L_{\Lambda_n^*}}(q, q_0, d) \left(\frac{q}{M_0^{\Lambda_n^*}}\right)^{L_{\Lambda_n^*}}$$

$B'_L(p, p_o, d)$: Blatt-Weisskopf functions, where p is the momentum, p_o is the momentum on the mass shell, d is a constant. if $p = p_o$, $B'_L = 1$. Here, p, p_o are the proton momenta; q, q_o are the K^- momenta.

BW is the relativistic Breit-Wigner Amplitude

L is the orbital angular momentum between the Λ* and the J/ψ