OBSERVATION OF NEW PENTAQUARK CANDIDATES

Nathan Jurik

University of Oxford

HEP Group Seminar

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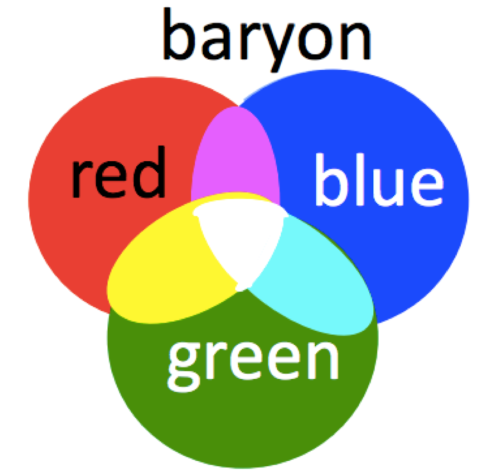
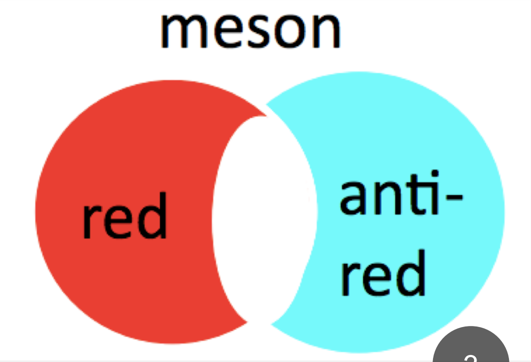
OUTLINE

- Pentaquarks introduction
- Not so brief review of the recent history of pentaquarks in $\Lambda_b^0 \to J/\psi\, pK^-$
  - Observation of $J/\psi\, p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi\, pK^-$ decays [arXiv:1507.03414]
  - Model-independent evidence for $J/\psi\, p$ contributions to $\Lambda_b^0 \to J/\psi\, pK^-$ decays [arXiv:1604.05708]
- New, updated analysis of $\Lambda_b^0 \to J/\psi\, pK^-$ [arXiv:1904.03947]
- Interpretations
- Outlook

HADRONS

- Valence quarks used to classify hadrons and determine quantum numbers.
- Hadrons can be classified according to their number of quarks (n_q) and antiquarks ($n_{\bar{q}}$): $\mathcal{B} = {}^{1}/_{3}\,(n_q - n_{\bar{q}})$
  - "baryons" have $\mathcal{B} = 1$, and "mesons" have $\mathcal{B} = 0$
  - The simplest cases for a meson is $q\bar{q}$, and for a baryon is qqq
  - No known reason other "exotic" hadrons with different quark content ($q\bar{q}q\bar{q}, qqqq\bar{q}$) can't exist!





TETRA- AND PENTA-QUARKS CONCEIVED AT THE BIRTH OF QUARK MODEL

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

...

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while

8419/TH.412
21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

II *)

G. Zweig **)
CERN---Geneva

*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

...

6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $AAAA\bar{A}$, $AAAAA\bar{A}\bar{A}$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $A\bar{A}$, $AA\bar{A}\bar{A}$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $A\bar{A}$ and AAA, that is, "deuces and treys".

- Searches for such states made out of the light quarks (u,d,s) are ~50 years old, but no undisputed experimental evidence has been.

EARLY PENTAQUARK SEARCHES

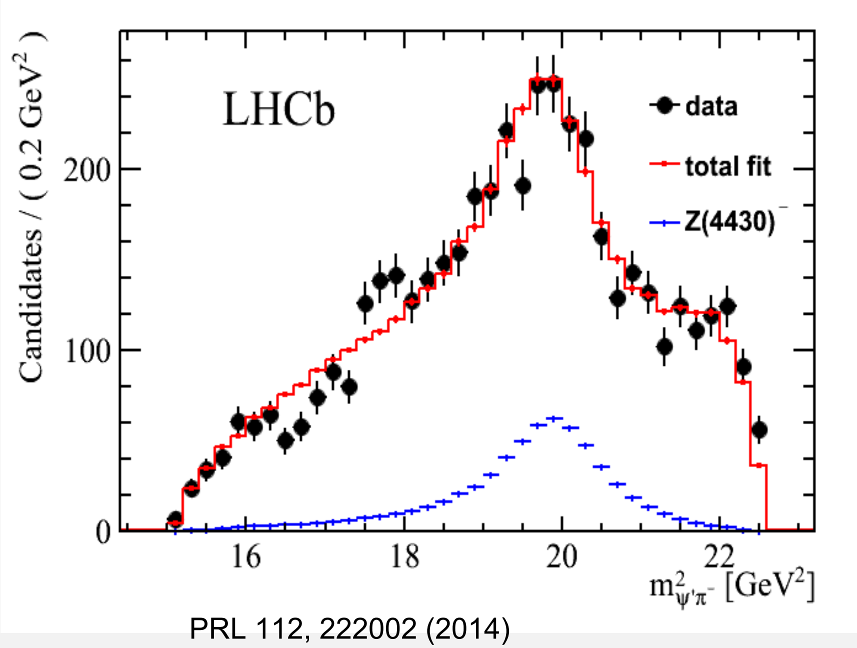
- Most early searches looked for baryons with an $\bar{s}$ quark
  - "Partial-wave" analyses in 70's reported evidence, but were not confirmed.
- In 2003, several experiments reported evidence for a pentaquark candidate, the Θ^+

Experiment	Reaction	Mass (GeV)	Significance
LEPS	$\gamma C \to K^+K^-X$	1.54±0.01	4.6σ
DIANA	$K^+Xe \to K^0_S pX$	1.539±0.002	4.4σ
CLAS	$\gamma d \to K^+K^-pn$	1.542±0.005	$(5.2\pm0.6)\sigma$
SAPHIR	$\gamma p \to K^0_S K^+ n$	1.540±0.004	4.8σ

  - Evidence also shown for other candidates, but none of these would survive further studies with better statistics!
  - The 2006 PDG review said: "The conclusion that pentaquarks in general, and the Θ^+, in particular, do not exist, appears compelling.

TETRAQUARK CANDIDATES: "XYZ STATES"

- Several charmonium and bottomonium-like states observed by several experiments.
  - Don't fit into the conventional quark model and are candidates for tetraquarks.
- Example: Z(4430) is a $c\bar{c}d\bar{u}$ candidate seen by Belle in 2007 and confirmed in 2014 by LHCb.

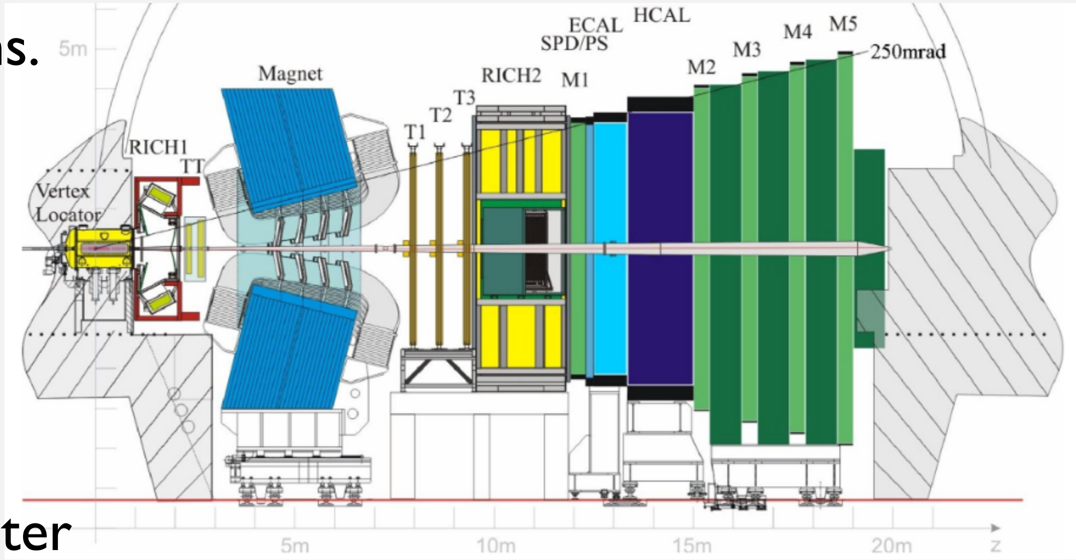


PRL 112, 222002 (2014)

- Perhaps heavy quarks are necessary to help stabilise these states? "Multiquark" states with light quarks are too broad?

LHCB DETECTOR

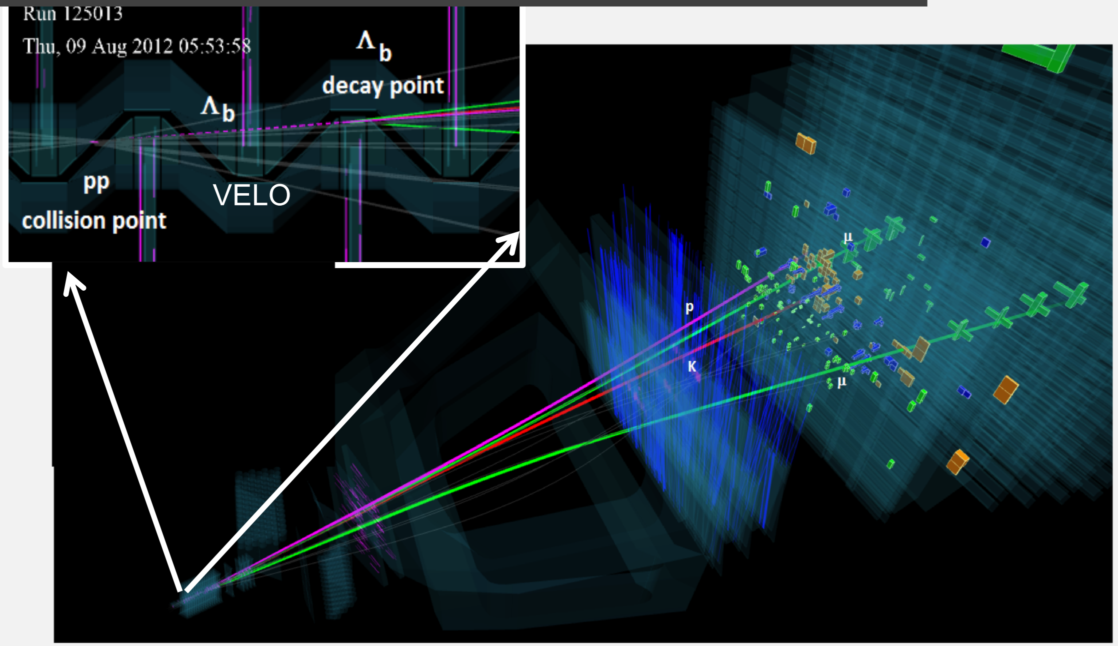
- Forward arm spectrometer designed for precision CP violation measurements and decays of bottom and charm hadrons.
- Rapidity coverage $2.0 < y < 4.5$
- Excellent particle identification:
  - Muons: $\varepsilon{\sim}97\%$ for $1 - 3\%$ $\pi \to \mu$ misidentification
  - Kaons: $\varepsilon{\sim}95\%$ for 5% $\pi \to K$ misidentification
- Very good vertex resolution: $\sigma = 20\mu m$ impact parameter resolution
- Momentum resolution $\Delta p/p = 0.5\%$ at 20GeV to 0.8% at 100 GeV



Int. J. Mod. Phys. A 30 (2015) 1530022

$\Lambda_b^0 \to J/\psi\ pK^-$ SELECTION

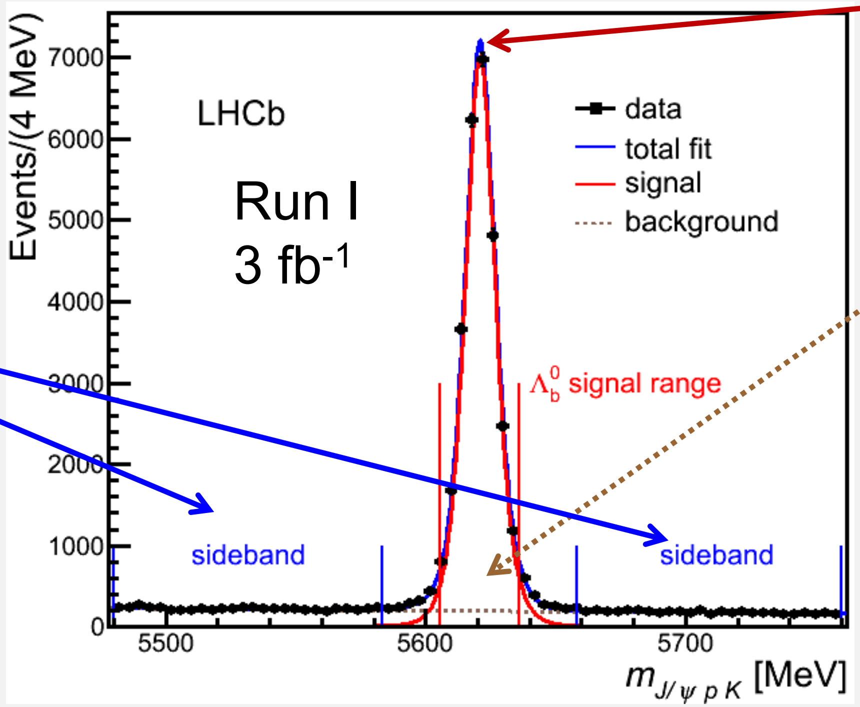
- Candidates have a $(\mu^+\mu^-)Kp$ vertex, with the $(\mu^+\mu^-)$ pair consistent with a J/ψ
- Standard selection to ensure good track and vertex quality,
- Requirements on particle identification, p_T, and separation from the primary vertex.



- Backgrounds from B^0 and B_s decays are vetoed.
- Final background suppression is done with a boosted decision tree.

$\Lambda_b^0 \rightarrow J/\psi\ pK^-$ SIGNAL

The sideband distributions are flat $\rightarrow$ no major reflections from the other b-hadrons after the selection



26,007±166
Λ_b^0 candidates

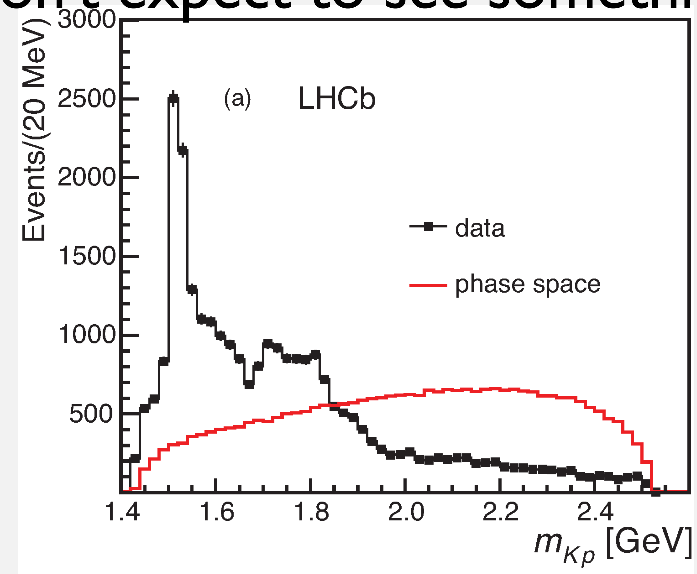
The background is only 5.4% in the signal region!

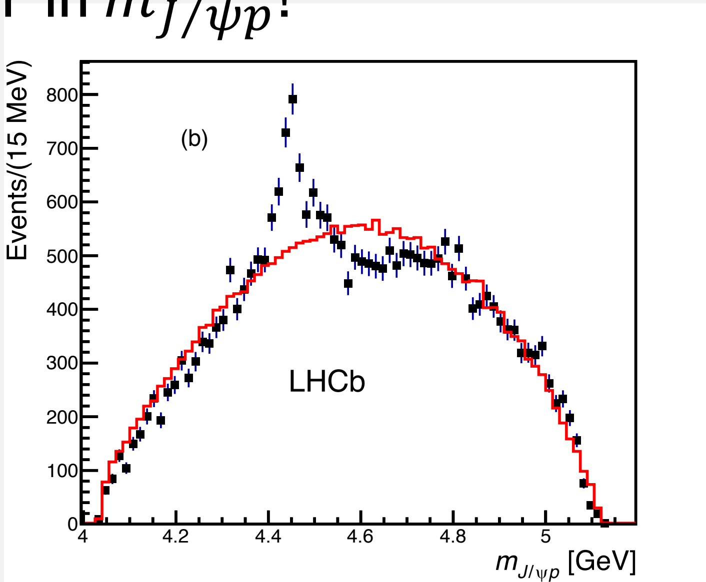
UNEXPECTED STRUCTURE IN $m_{J/\psi p}$

- Decays to $J/\psi\, pK^-$ final state can proceed through intermediate resonances.

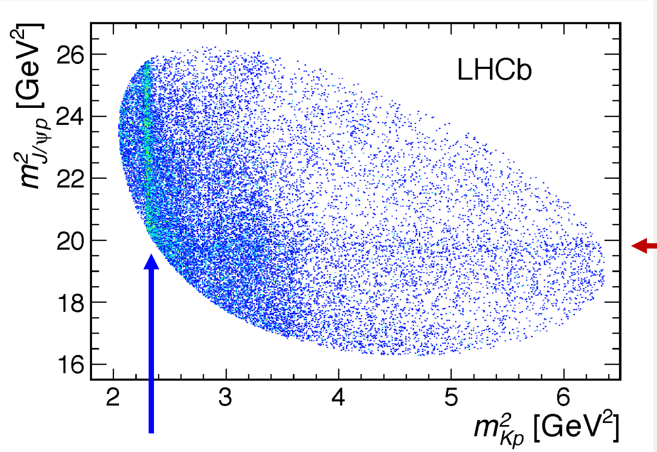
- In Kp system, we expect to see peaking structures in invariant mass, m_{Kp}
  - $\Lambda(1520)$ and other Λ^*'s $\rightarrow$ p K^-

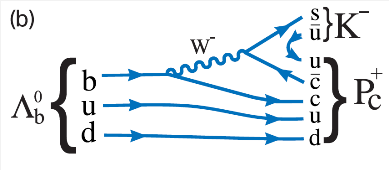
- We don't expect to see something similar in $m_{J/\psi p}$!





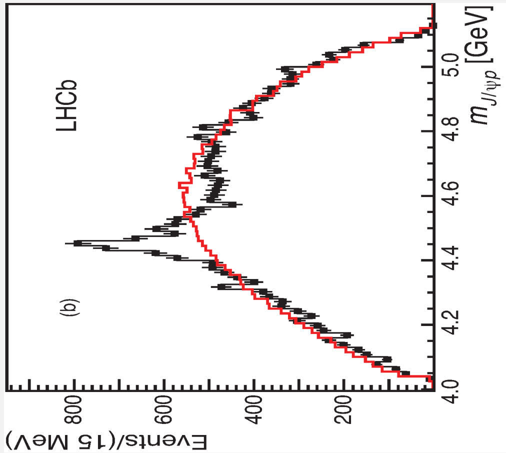
UNEXPECTED STRUCTURE IN $m_{J/\psi p}$



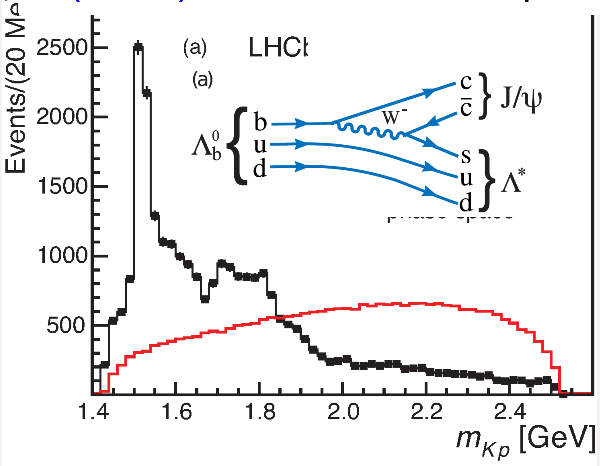


$P_c^+ \to J/\psi\ p$

?



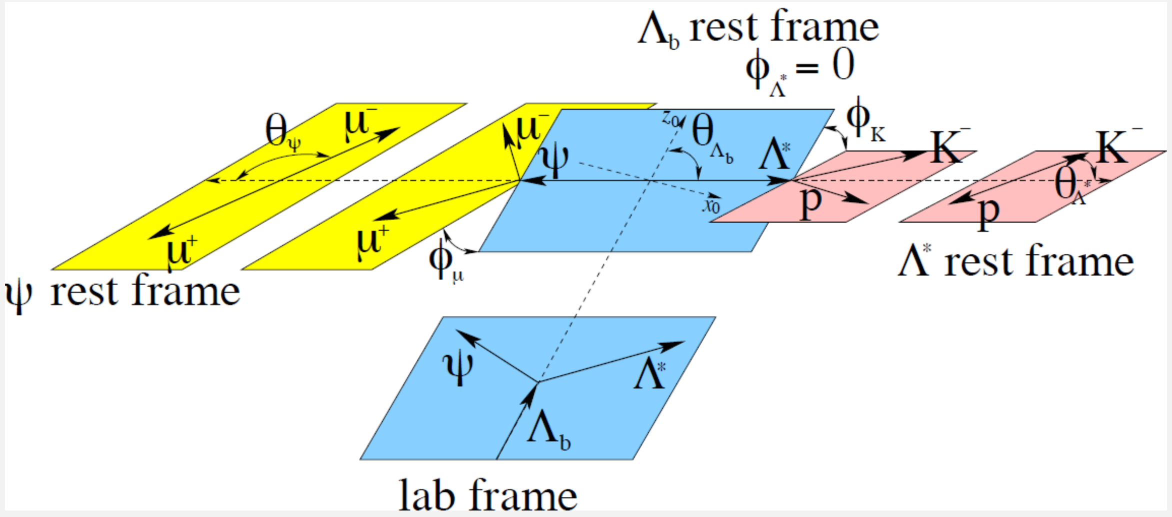
$\Lambda(1520)$ and other Λ^*'s $\to$ p K$^-$



- Thoroughly checked it is not due to some artifact of selection, reconstruction, etc
- Can it be explained as a reflection of interfering Λ^*s ?
- If not how can we learn about its source?

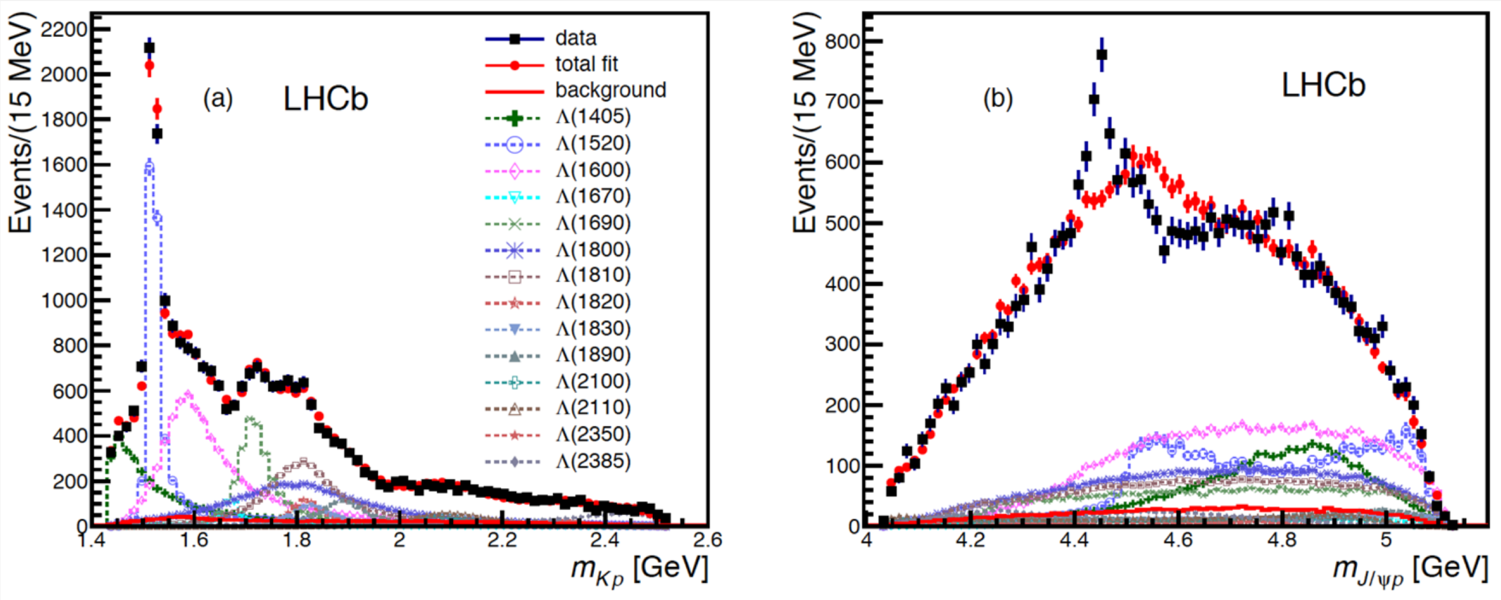
AMPLITUDE ANALYSIS

- Use helicity formalism to write down matrix element describing the full process $\Lambda_b \to \Lambda^* J/\psi$ with $\Lambda^* \to Kp$ and $J/\psi \to \mu\mu$
  - Six-dimensional: use m_{Kp} and 5 decay angles
- Included Breit-Wigner resonances for well-established states in PDG



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

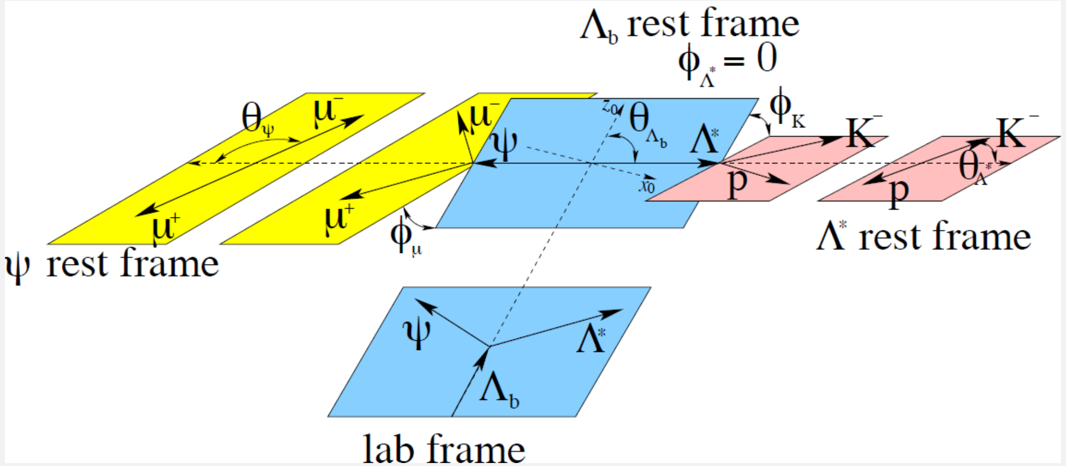
NOT JUST A REFLECTION

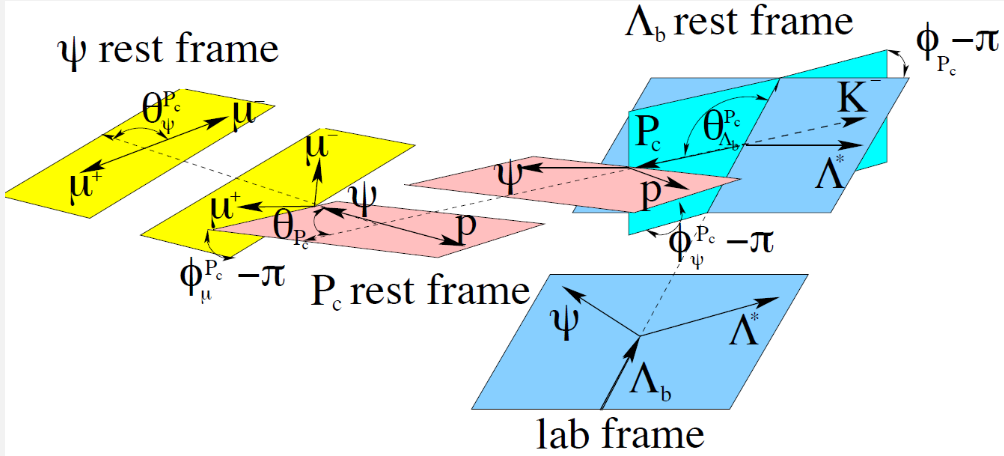


- m_{Kp} is well-described but $m_{J/\psi p}$ looks terrible
- Addition of non-resonant terms, Σ^*'s or extra Λ^*'s doesn't help.
- Not possible to describe the peaking structure with conventional resonances!

INCLUDE P_c CONTRIBUTIONS

- P_c contributions added to the matrix element and allowed to interfere with Λ^*
  - Also modeled with Breit-Wigner resonances

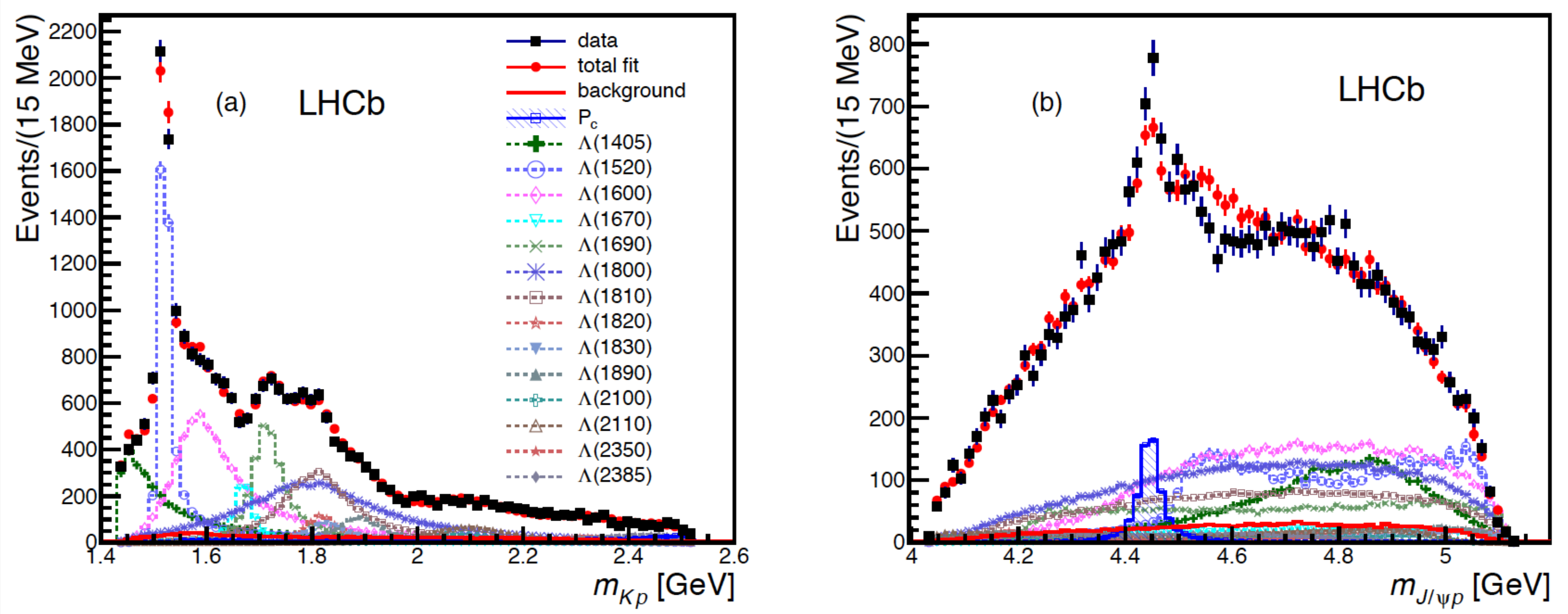




- Angular distributions depends on spin-parity (J^P)
  - Can probe perform different fits to probe quantum numbers.

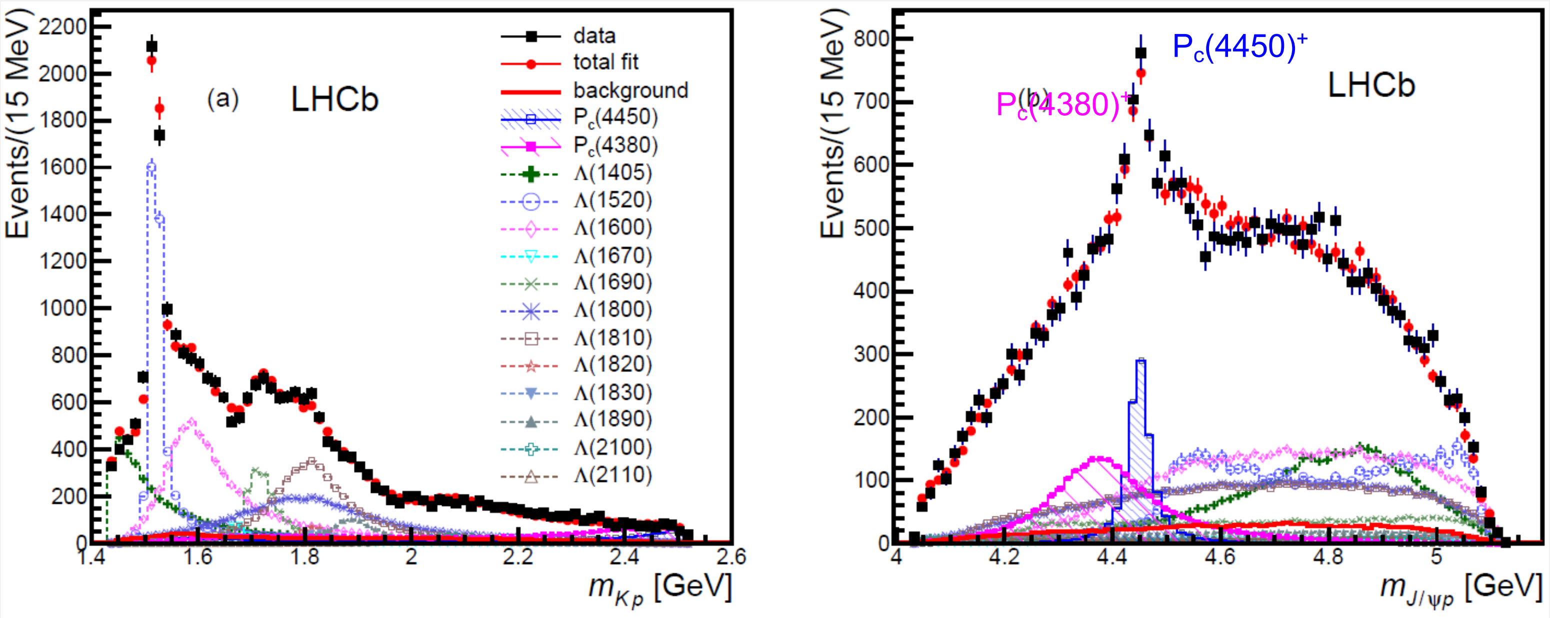
INCLUSION OF A P_c CONTRIBUTION

- Tested all J^P of P_c^+ up to ${}^7/_2{}^{\pm}$
  - Best fits have $J^P = {}^5/_2{}^{\pm}$, but are far from satisfactory



INCLUSION OF TWO P_c CONTRIBUTIONS

- With two P_c resonances we are able to describe the peaking structure!
  - Best fit has $J^P(P_c(4380), P_c(4450))$=(3/2$^-$, 5/2$^+$), but (3/2$^+$, 5/2$^-$) and (5/2$^+$, 3/2$^-$) are comparable.
- Additional P_c resonances did not result in significant improvement in fit quality.

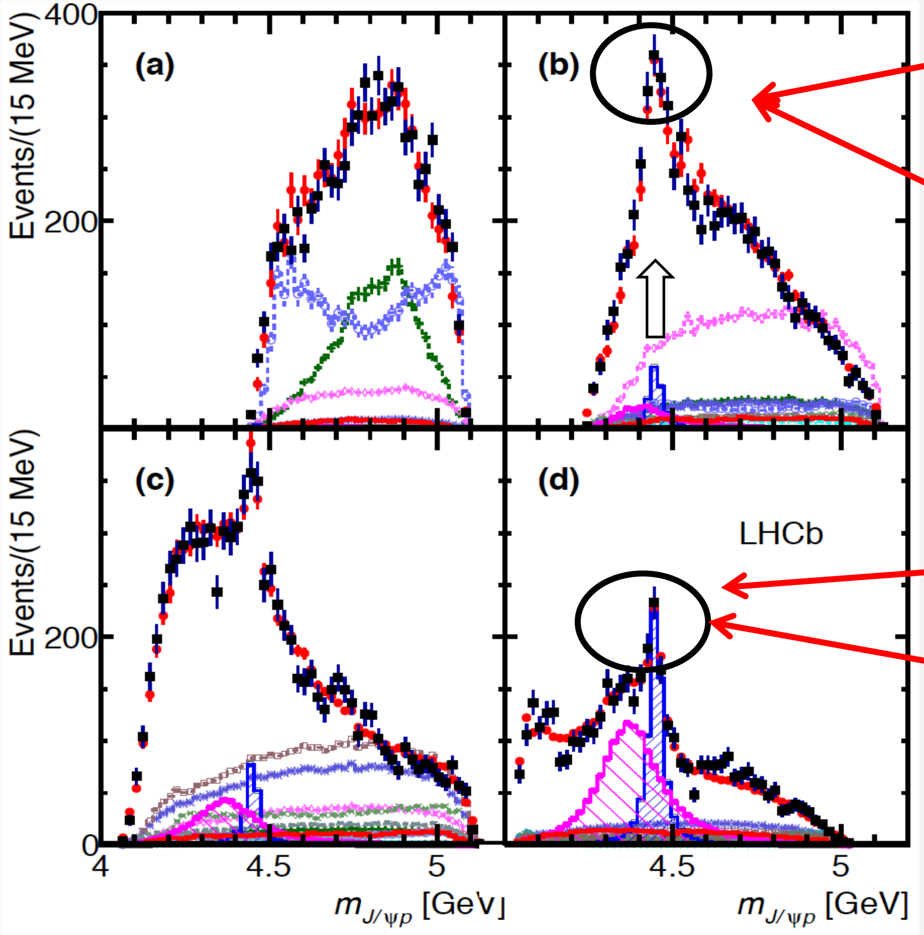


WHY IS MORE THAN ONE RESONANCE NEEDED?

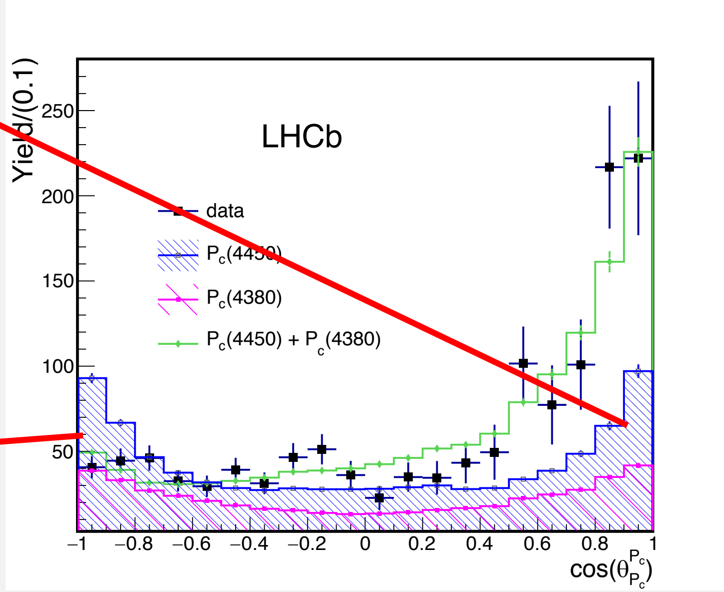
- Informative to examine $m_{J/\psi p}$ in slices of m_{Kp}:

a) m_{Kp}<1.55 GeV
b) 1.55<m_{Kp}<1.70 GeV
c) 1.70<m_{Kp}<2.00 GeV
d) 2.00 GeV<m_{Kp}

- Two opposite parity states necessary to generate this pattern



Positive interference between the P_c states



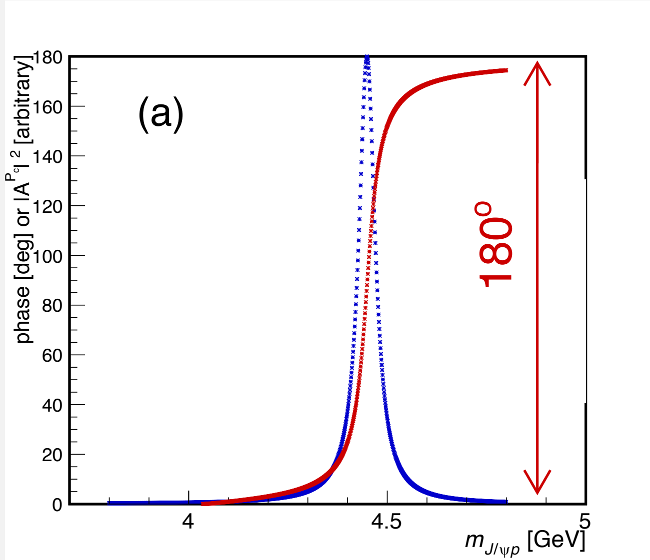
Negative interference between the P_c states

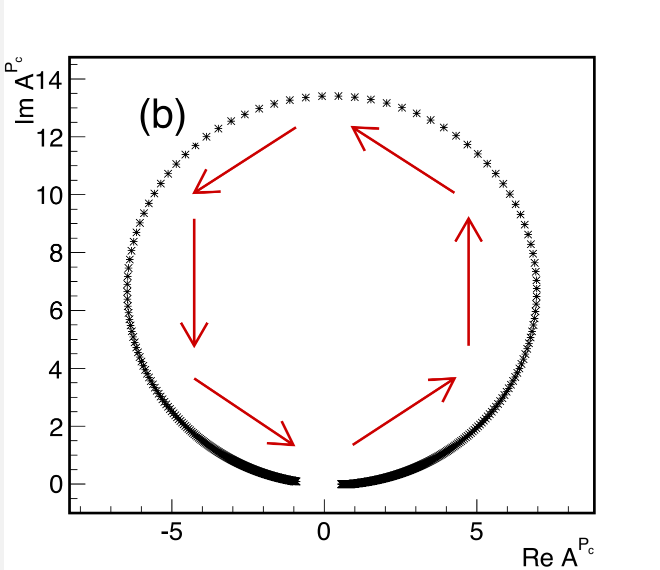
RESONANCE PHASE MOTION

- Relativistic Breit-Wigner function is used to model resonances

$$BW(m|M_0,\Gamma_0) = \frac{1}{M_0^2 - m^2 - iM_0\Gamma(m)}$$

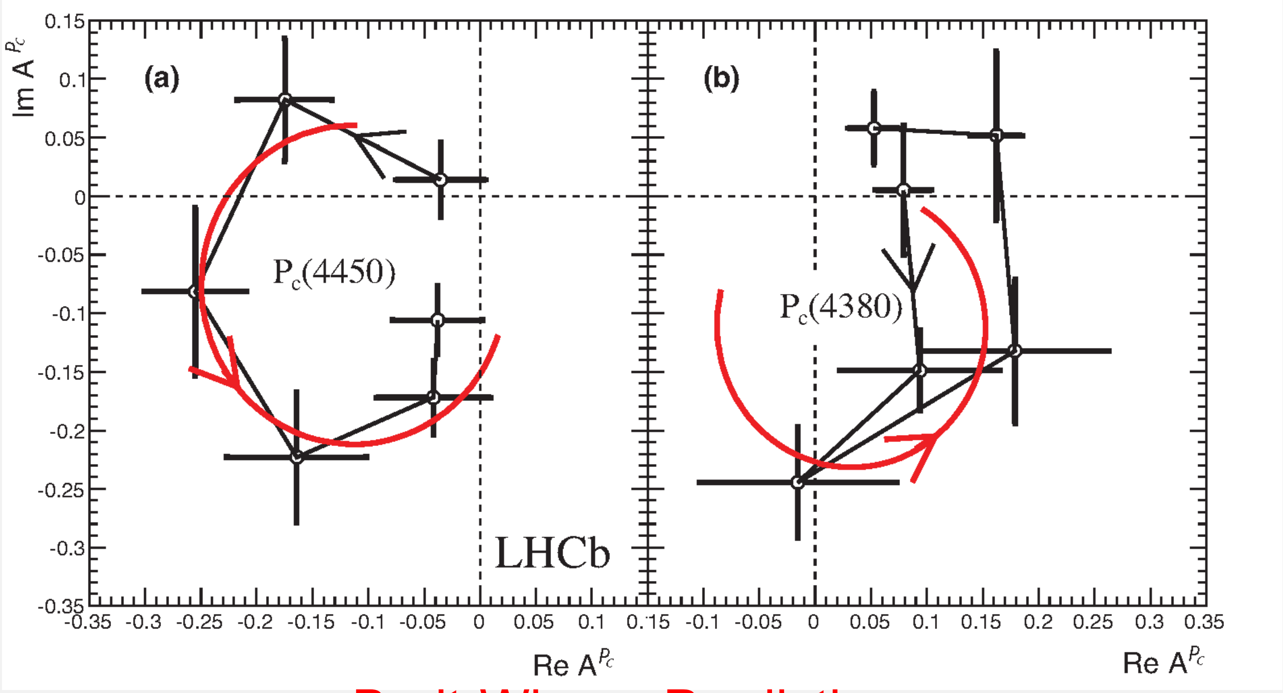
- Exhibits a circular trajectory when displayed in complex plane, with phase change of 180° across pole.





RESONANCE PHASE MOTION

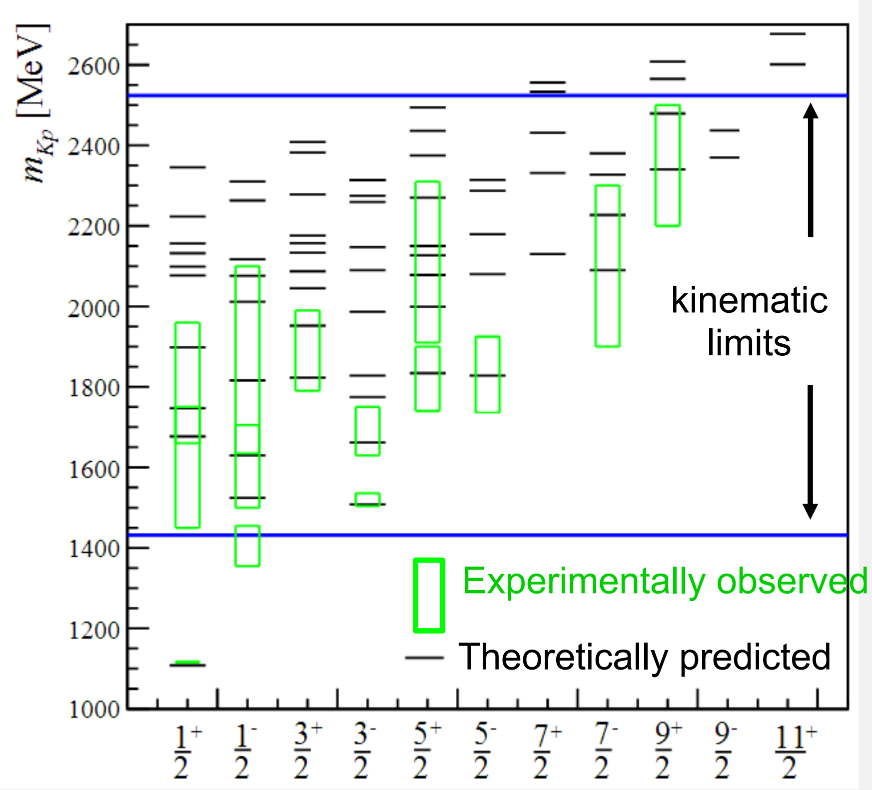
- Study phase motion by replacing the Breit-Wigner shape for individual P_c's with 6 evenly spaced amplitudes in $M_0 \pm \Gamma_0$ range
- Plot fitted values for amplitudes in an Argand diagram
  - $P_c(4450)$: shows a rapid counter-clockwise change of phase across the pole mass
  - $P_c(4380)$: does show large phase change, but much less nice looking.



Breit-Wigner Prediction
Fitted Values

A MODEL-INDEPENDENT CONFIRMATION

- Amplitude analysis used resonances listed in the PDG
  - Also tested that adding additional contributions would not change conclusions.
- Many more states are predicted than are observed.
- A second analysis showed with minimal assumptions that resonances in Kp system alone cannot account for the data.

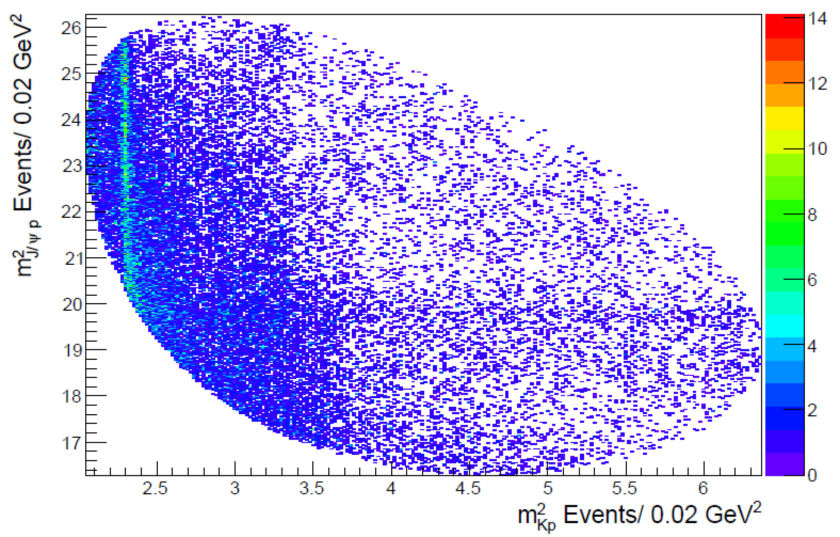


METHOD

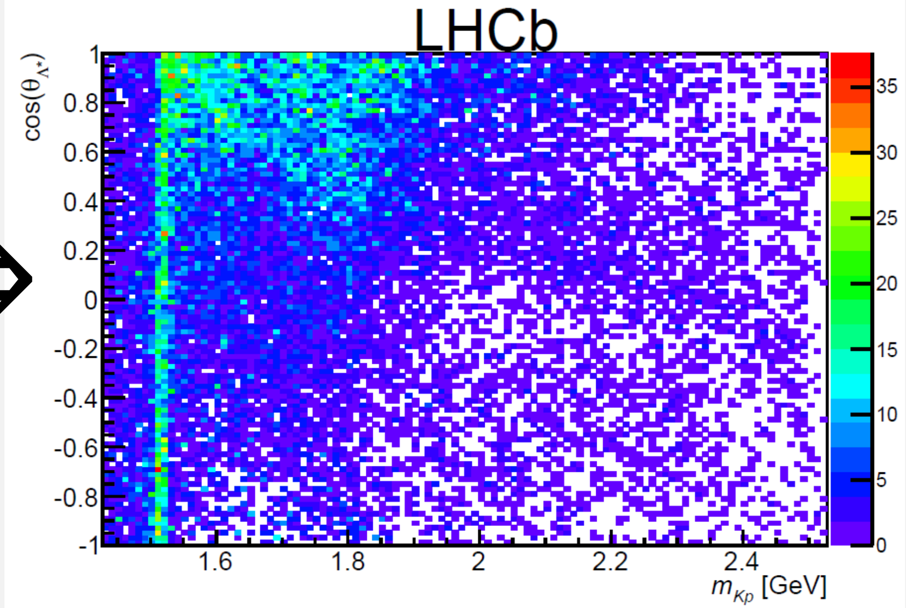
- Demonstrate compatibility/incompatibility of the data with hypothesis only intermediate resonances decaying to Kp are present (H_0).

- A PDF representing this hypothesis is constructed from the data as

$$\mathcal{F}(m_{Kp}, \cos\theta_{\Lambda^*} | H_0) = \mathcal{F}(m_{Kp})\mathcal{F}(\cos\theta_{\Lambda^*} | H_0, m_{Kp})$$

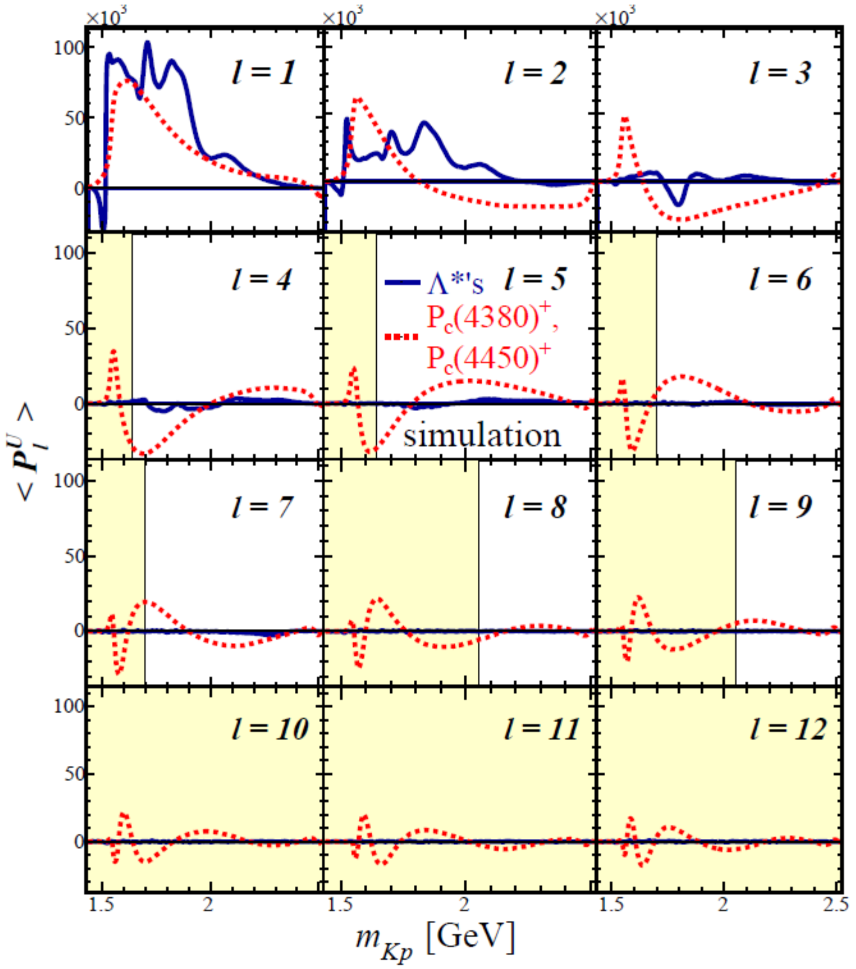


$\Leftrightarrow$



THE PDF'S

- The $\mathcal{F}(m_{Kp})$ comes directly from observed data.
- The angular distribution can be expanded in terms of Legendre polynomials P_l in bins of m_{Kp}
  $$dN/d\cos\theta_{\Lambda^*} = \sum_{l=0}^{l_{max}} \langle P_l^U \rangle P_l(\cos\theta_{\Lambda^*})$$
  where $< P_l^U >$ is the unnormalized Legendre moment of rank l
- In presence of Kp resonances with spin up to J_{max} moments above $l_{max} = 2J_{max}$, correspond to statistical fluctuations or additional sources.
  - Allows for creation of H_0 hypothesis PDF
  - l_{max} chosen conservatively based off observed data & quark model expectations

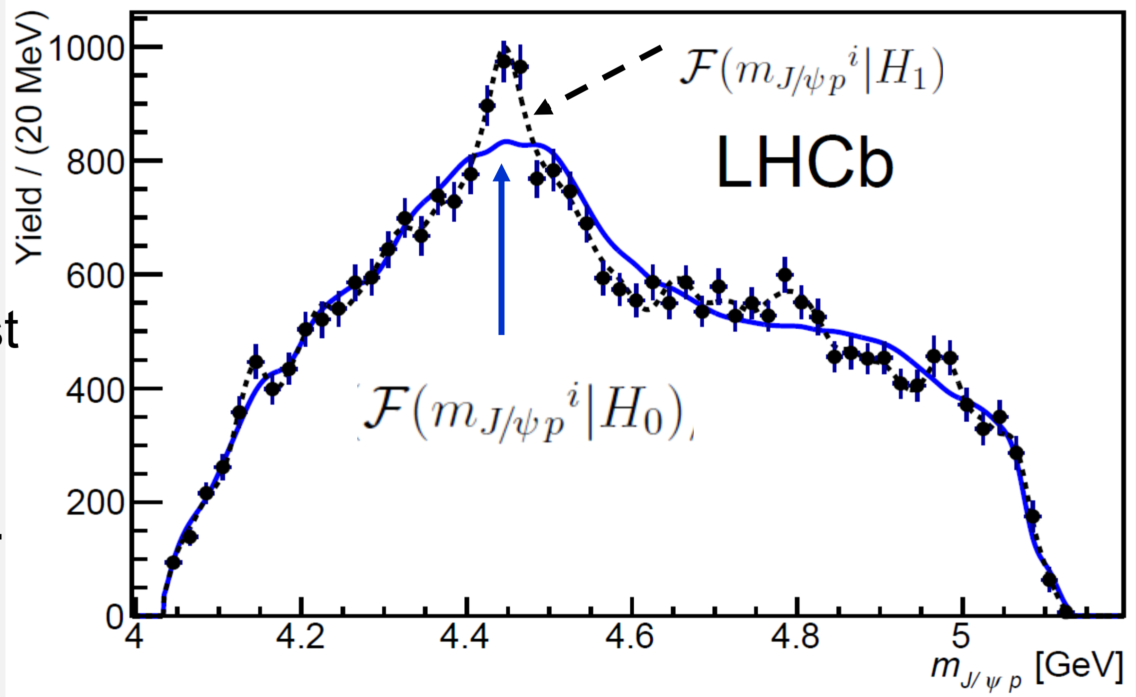


COMPATIBILITY WITH $m_{J/\psi p}$

- The 2D PDF is projected onto $m_{J/\psi p}$ and compared to the data
  - Clearly fails to reproduce the data!

- Compatibility is probed via log-likelihood ratio test with H_1 hypothesis.
  - Includes high enough order Legendre moments to reproduce structures in the data.

- Toys used to get test variable distribution under H_0 hypothesis



- The hypothesis that only Kp contributions are present in the data can be ruled out at over 9σ confidence level.

CONCLUSIONS FROM MODEL INDEPENDENT ANALYSIS

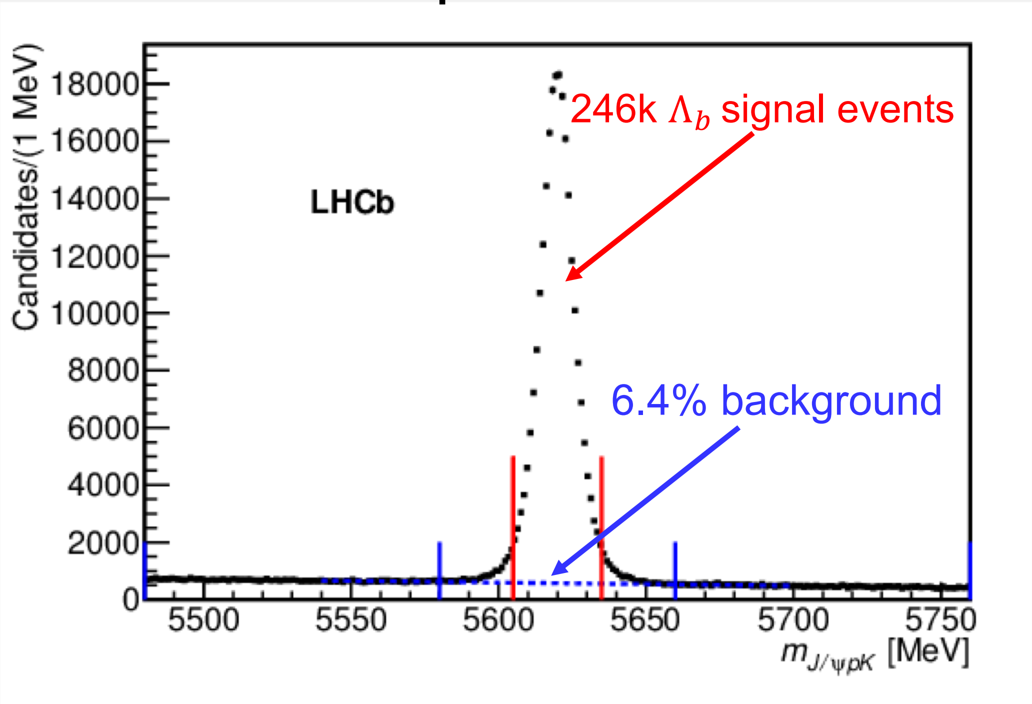
- The hypothesis that the data can be accounted for with only resonances in Kp system rejected at over 9σ

- A powerful conclusion, but really the only one that can be made.
  - Useful reference for stating narrow structures in $m_{J/\psi p}$ be attributed to Kp resonances.

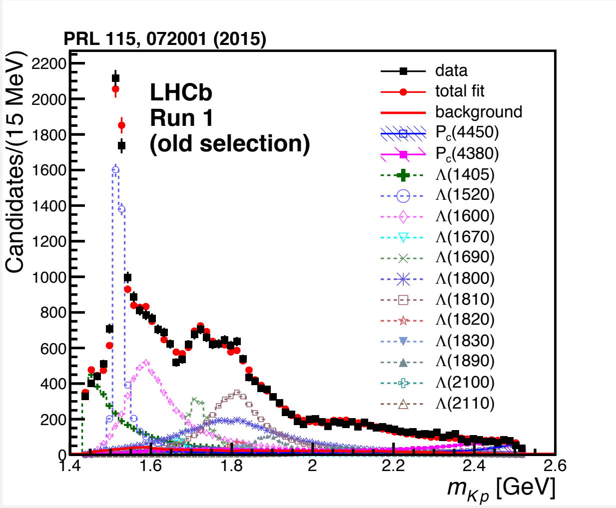
- Formally not able to say anything about the source of these higher moments.
  - Peak in $m_{J/\psi p}$ is rather telling, though.

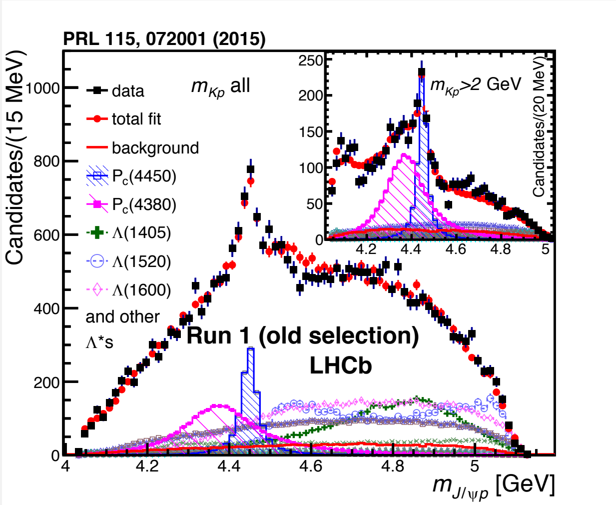
FULL RUN 1 + RUN 2 DATASET

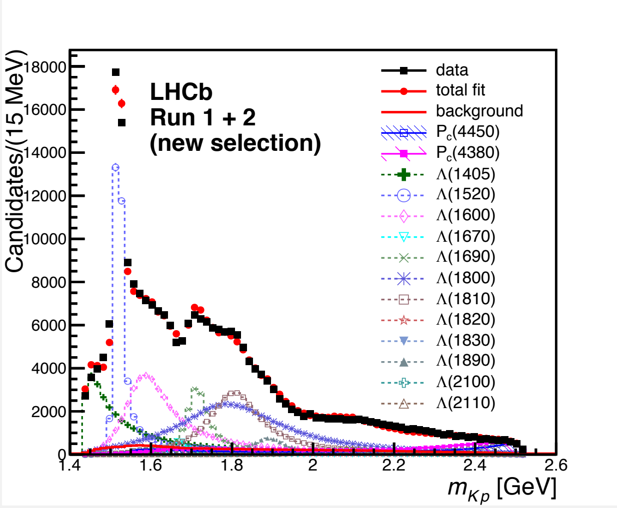
- New analysis boosted from improvements in the data selection, integrated luminosity, and cross-section ($\sqrt{s}$ = 13 TeV vs 7-8 TeV)
  - 9x more statistics than in previous studies.

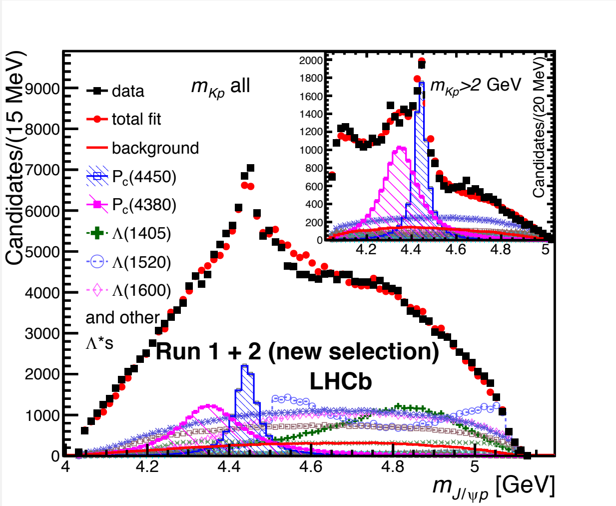


DATA CONSISTENCY CHECK



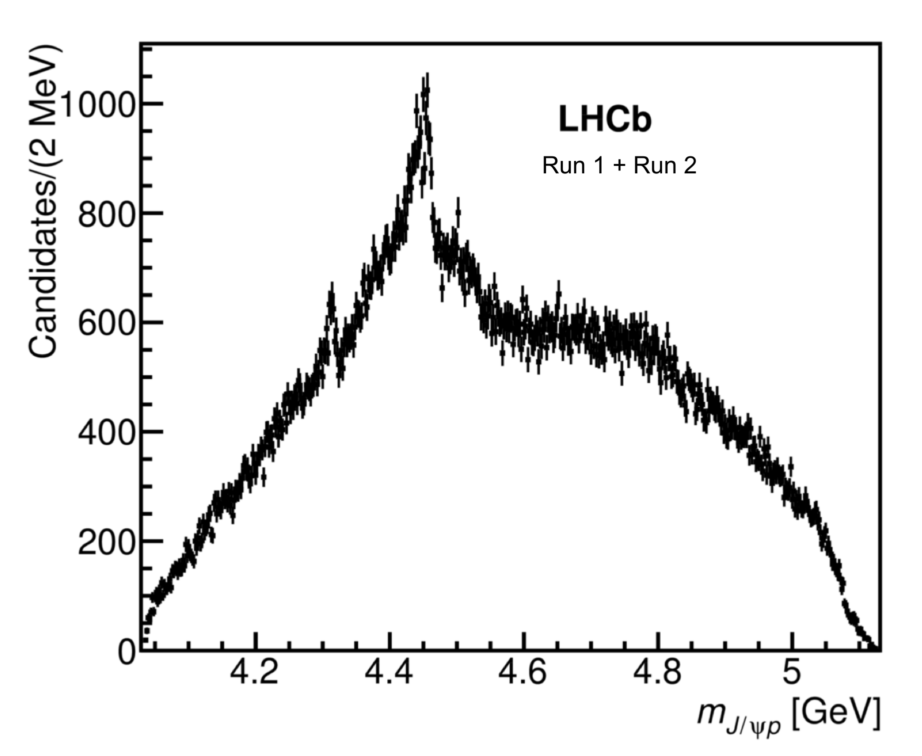






- The 6D amplitude model fit to masses and decay angles was repeated.
- Resulting $P_c(4450)^+$ and $P_c(4380)^+$ parameters consistent with the 2015 results
- However…

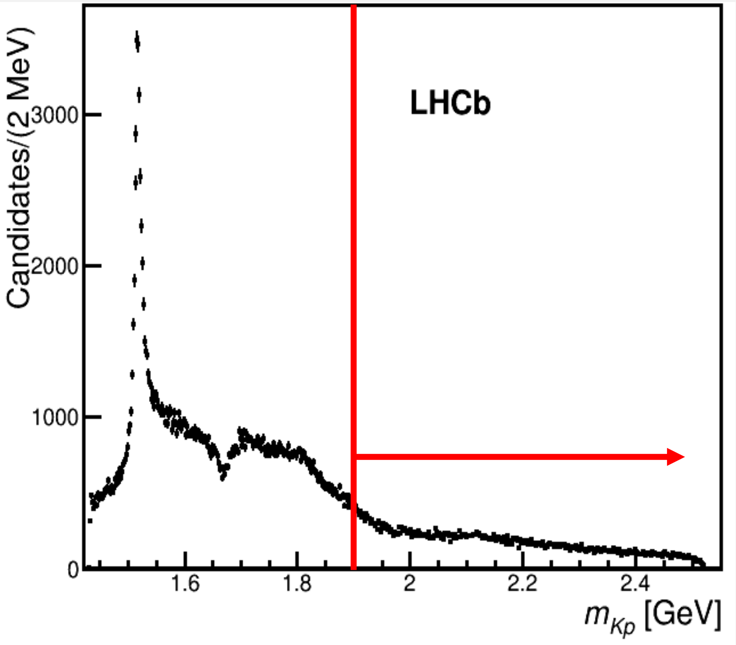
A CLOSER LOOK

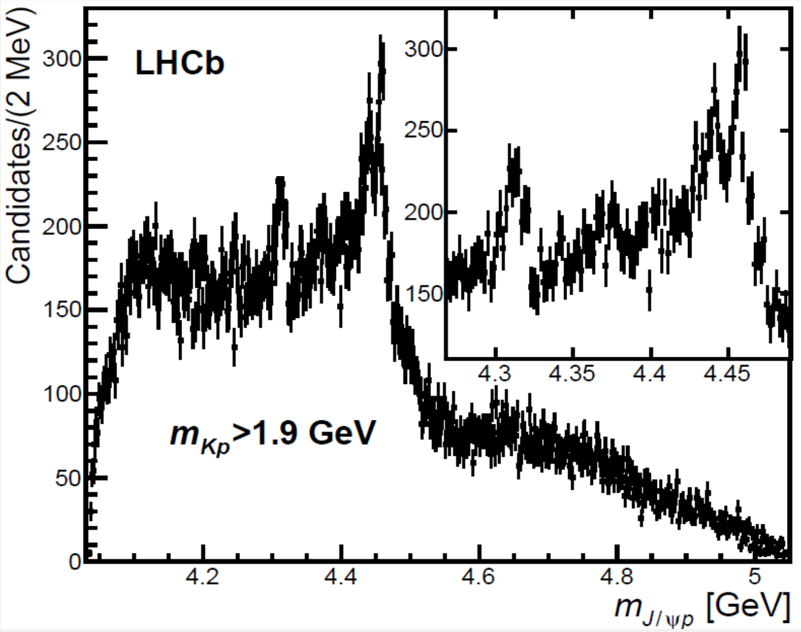


- With 9x more statistics, and a finer binning
  - Appearance of narrow peak at 4312 MeV
  - $P_c(4450)$ splitting into two peaks?
- Mass resolution is 2.3-2.7 MeV in 4.3-4.6 GeV region
  - Thanks to excellent momentum resolution, vertexing and J/ψ and Λ_b mass constraints
- Widths comparable to resolution!

SUPPRESSION OF Λ^* CONTRIBUTIONS

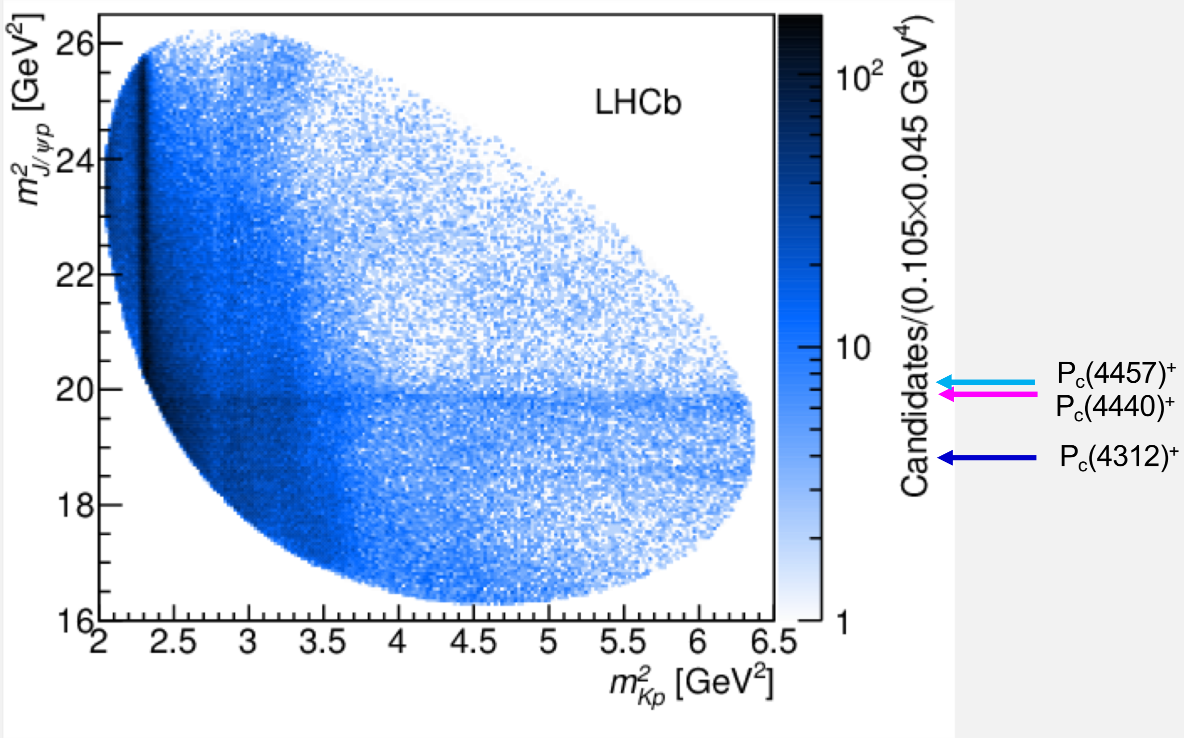
- Can Eliminate 80% of $\Lambda^* \to Kp$ backgrounds by cutting on $m_{K\pi}$>1.9 GeV
- Can clearly see three peaks!
  - Henceforth referred to as $P_c(4312), P_c(4440), P_c(4457)$





DALITZ PLOT

- New $P_c(4312)$ band clearly visible across Dalitz plane.

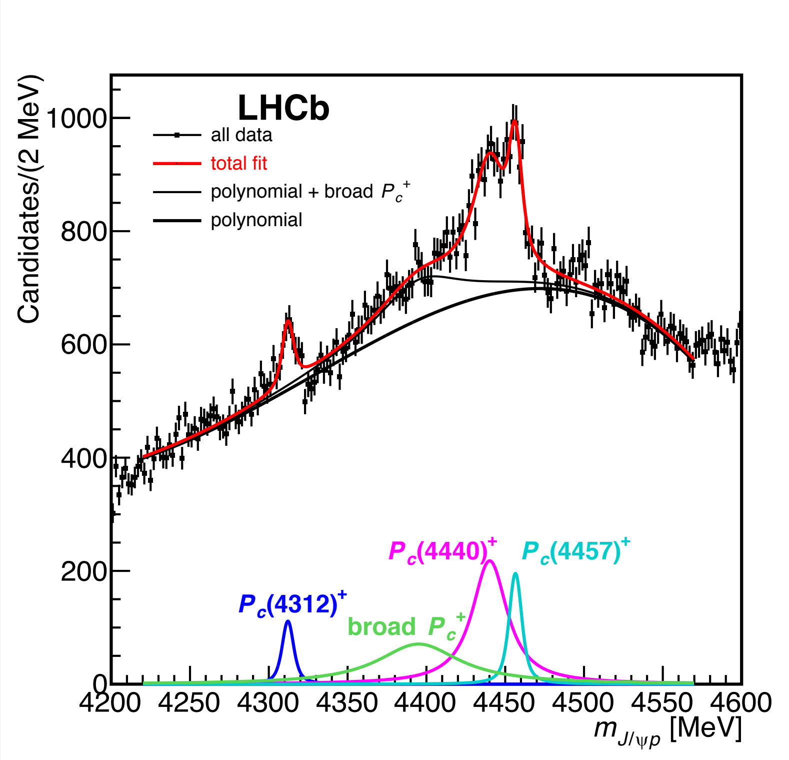


ANALYSIS STRATEGY

- Many challenges to overcome for an amplitude analysis
  - Could be years before converging on results.
- But… no need for amplitude analysis to prove that narrow $J/\psi p$ peaks are not Λ^* reflections
- Perform one-dimensional fits to $m_{J/\psi p}$ to characterize the narrow peaks.
  - Measure mass, width, and rates.
  - Can't hope to measure quantum numbers or to be sensitive to broad $J/\psi p$ contributions like $P_c(4380)$.

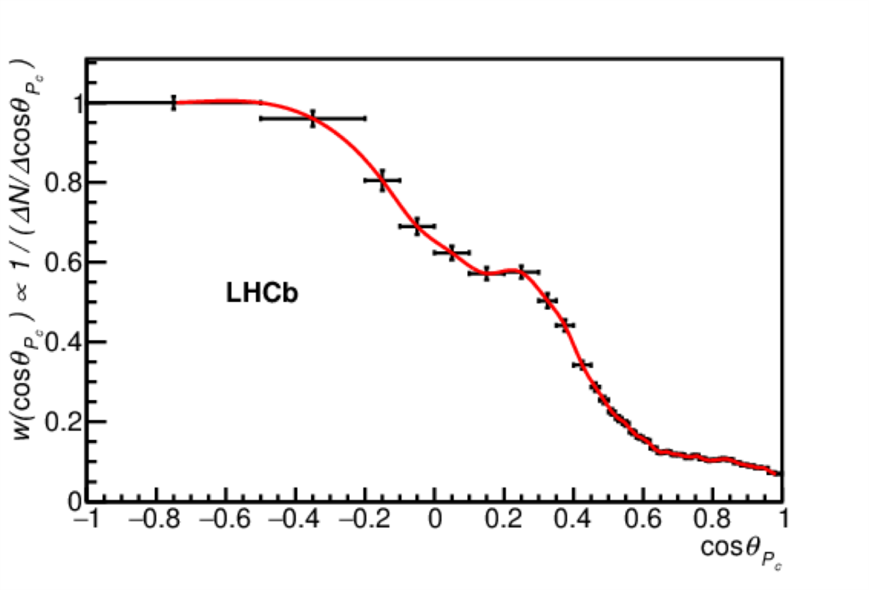
FIT MODEL

- Signal modelled using relativistic Breit-Wigner
  - Convolved with detector resolution (2-3 MeV)
  - Added incoherently, as interference effects can't be disentangled from only $m_{J/\psi p}$
  - Several interference configurations tested as part of systematic uncertainty.
- Background modelled with Chebychev polynomial
  - Polynomial degree varied as part of systematic uncertainty studies.
  - Additional fits done with possible broad Breit-Wigner P_c contributions.



A BETTER Λ^* SUPPRESSION

- Rather than cut away events, weight them according to expected background contribution
- As $\bar{x} = \sum_i^N x_i/N$ is not best estimator if errors $\sigma_i(x)$ are not equal, it's not optimal to average all events with equal weights.
- P_c rates are small relative to Λ^* backgrounds.
  - Statistical errors on P_c parameters driven by background fluctuations.
- Λ^* contributions mostly populate $\cos\theta_{P_c} > 0$
  - Use inverse of distribution as weight.



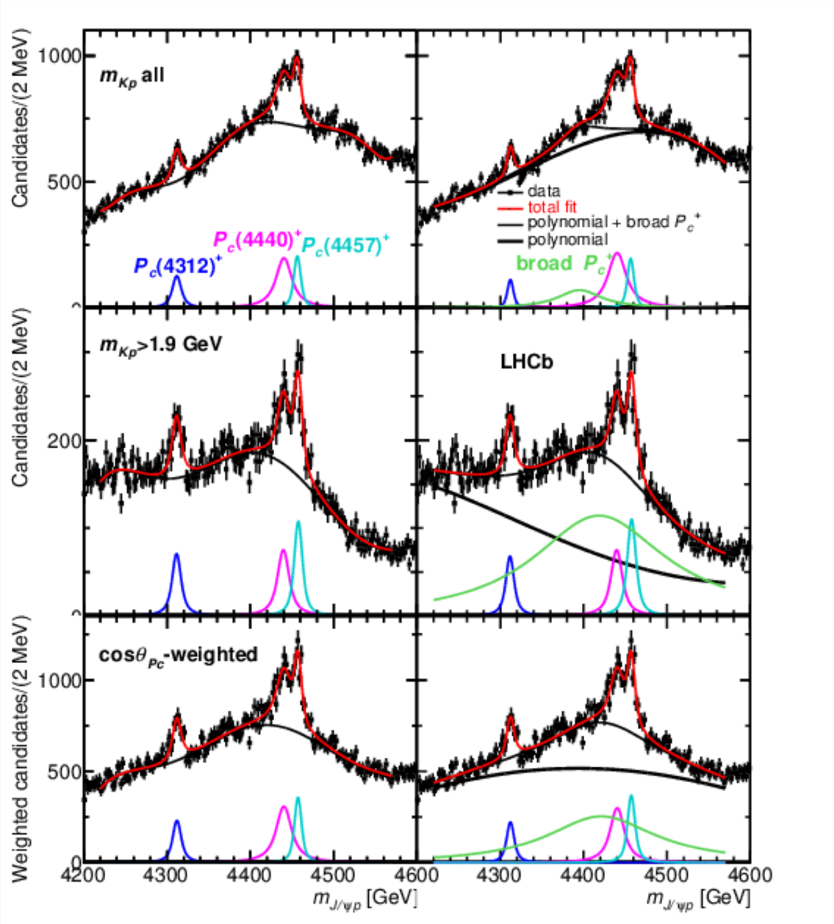
high m_{Kp} low m_{Kp}

FITS TO $J/\psi p$ MASS DISTRIBUTIONS

Full data

$m_{K\pi}$>1.9 GeV

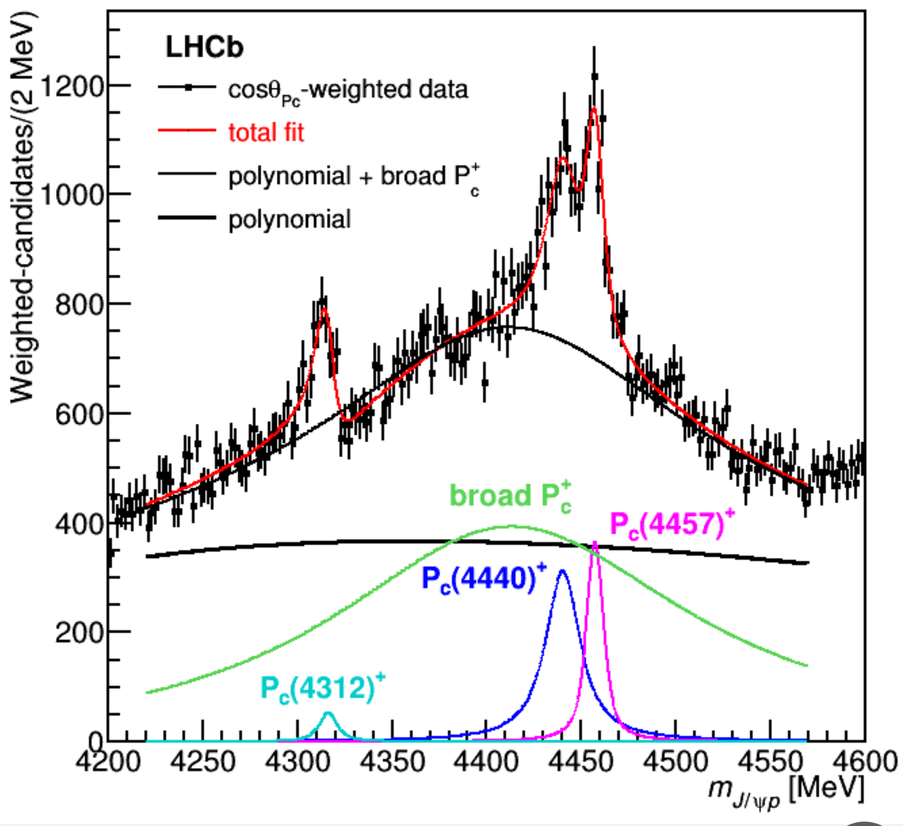
Full data, weighted



- Fits are performed with three methods.
- The $\cos\theta_{P_c}$-weighted data is most sensitive, and is used as default approach for measuring masses and widths.
  - Different approaches have different Λ^* compositions and help probe systematic uncertainties.
- To determine the relative production rates, must fit full data set after efficiency correction.

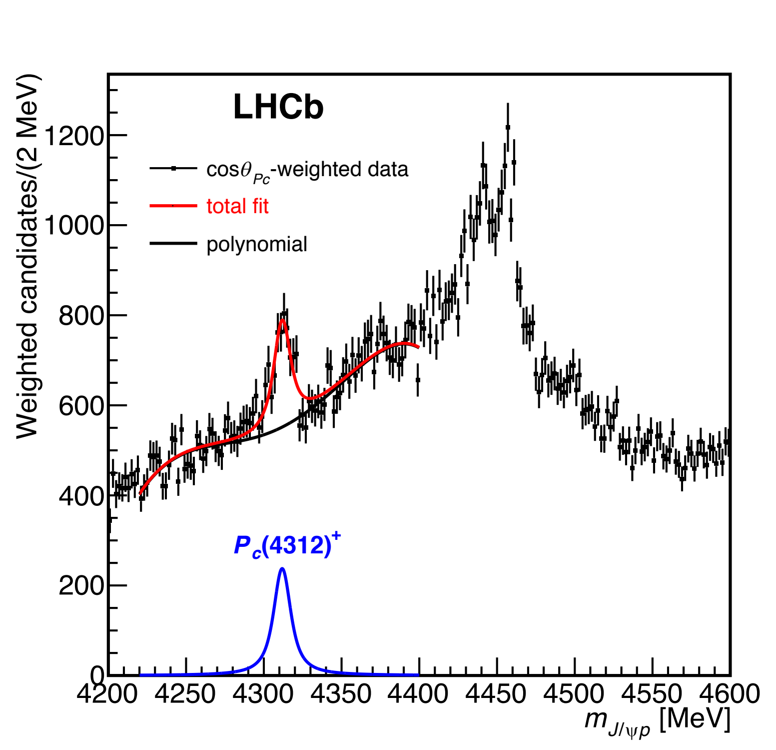
FITS WITH INTERFERENCES

- Also perform fits with coherent sum between various Breit-Wigner amplitudes
  - Include additional phase to control interference
  - Including broad P_c^+ contribution.
  - Example of a fit with interference: $P_c(4312)^+$ interfering with a broad P_c^+
- No significant evidence for interferences
- Largest source of systematic uncertainty.



SYSTEMATIC UNCERTAINTIES

- In addition to Λ^* compositions in different fit samples, different interference configurations, and different combinations of polynomial and broad Breit-Wigner components.
- Fit in narrower mass ranges.
- Mass resolution is also varied within uncertainties.
- Removal of BDT from selection
- Nominal fits assume S-wave (no angular momentum) production and decay
  - Inclusion of P-wave factors is tested



RESULTS

- Mass, width, and relative rates are reported

State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

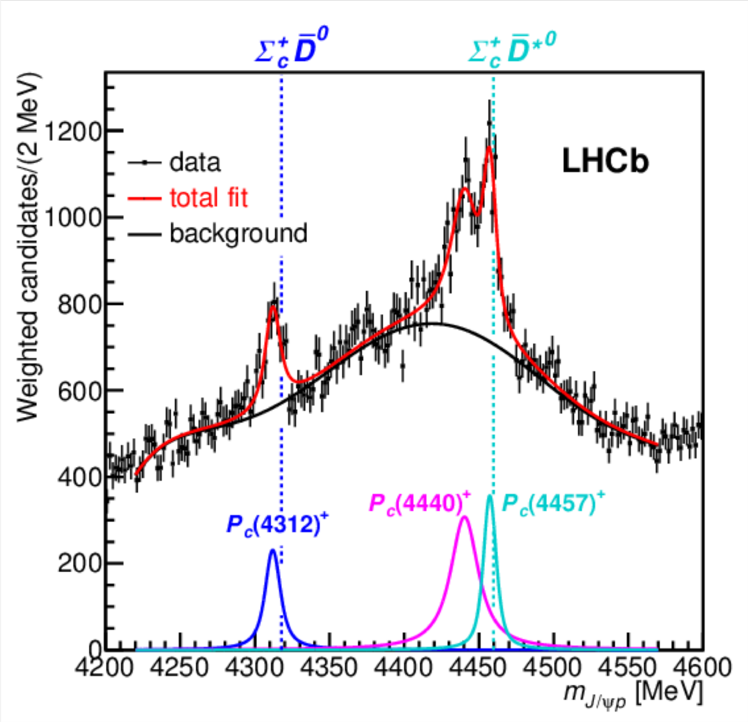
- All widths are consistent with resolution, so upper limits set.
- Relative rates are defined as

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi\, p)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, p K^-)}$$

and should be interpreted with care as they include effects of interference with other resonances.

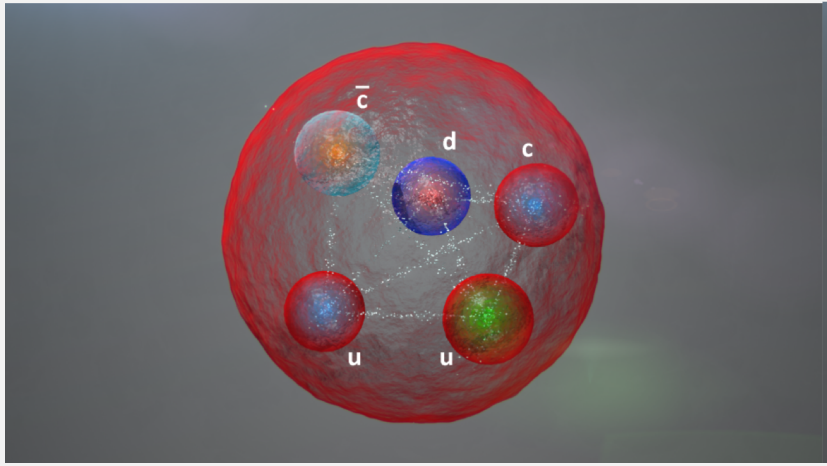
SIGNIFICANCES

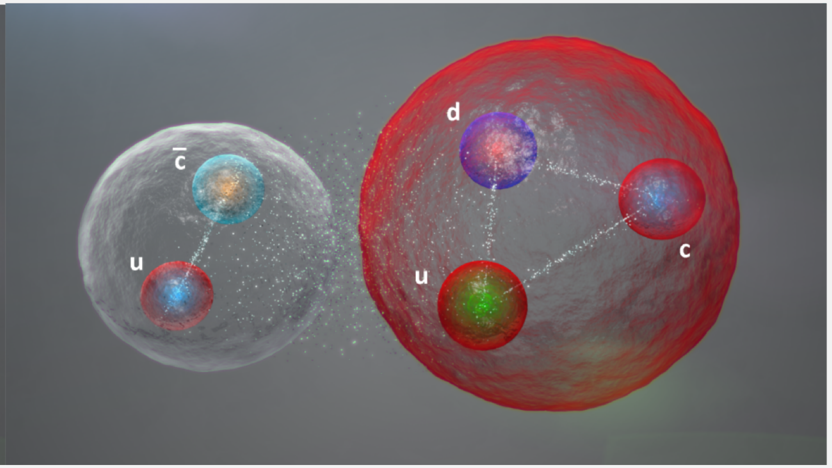
- Significance of $P_c(4312)$ determined from $\Delta\chi^2$ with and without including it
  - Distribution under null hypothesis obtained from large sample of pseudo-experiments taking into account look-elsewhere effect
  - Significance of 7.3σ (8.2σ) for the $m_{K\pi}$>1.9 GeV ($\cos\theta_{P_c}$-weighted) fits
- Two peak structure also tested against null hypothesis of one Breit-Wigner
  - Significance of 5.4σ (6.2σ) for the $m_{K\pi}$>1.9 GeV ($\cos\theta_{P_c}$-weighted) fits

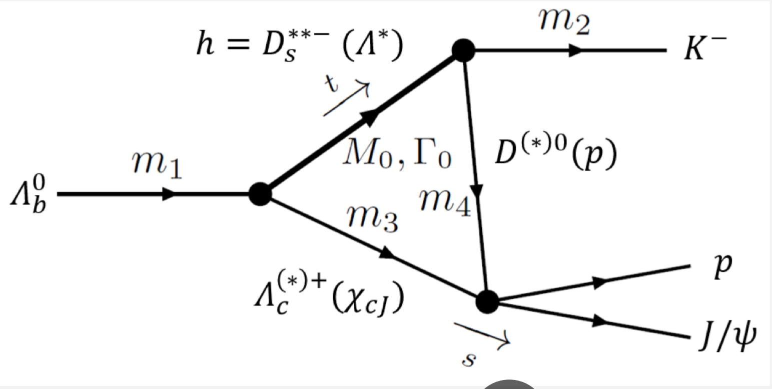


THEORETICAL INTERPRETATIONS

- Tightly-bound pentaquarks: all quarks in same colour-confinement volume
- "Molecular" pentaquarks: weakly bound meson+baryon
- Rescattering: triangle-diagram processes known to peak when all three hadrons nearly on mass shells

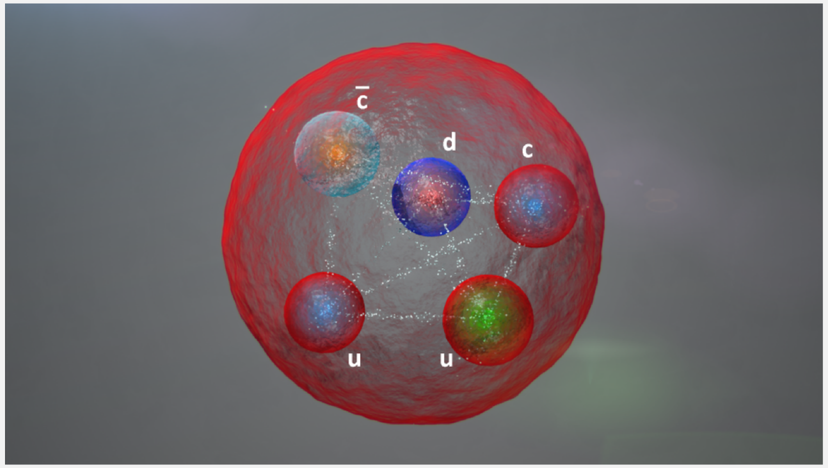






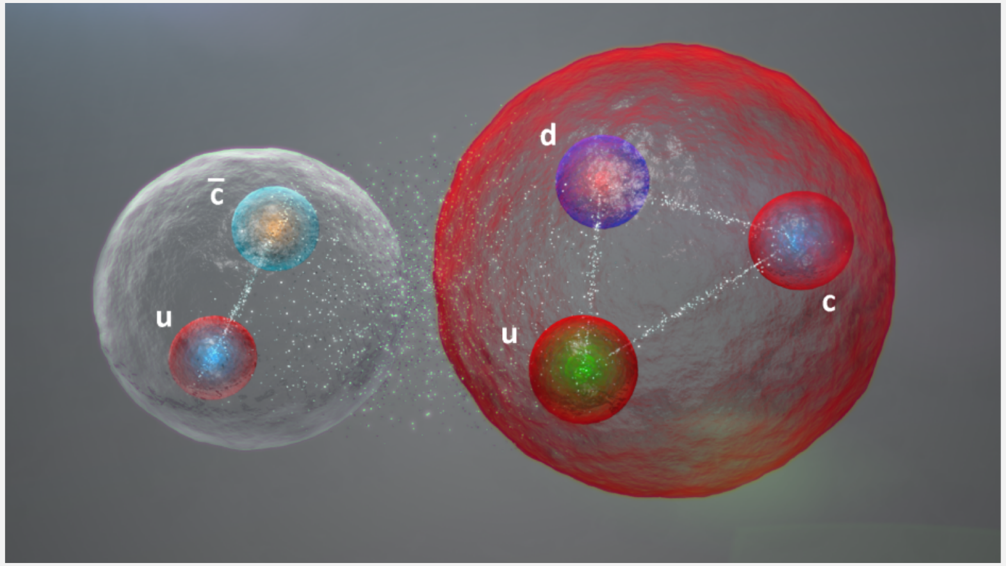
TIGHTLY-BOUND PENTAQUARKS

- Tend to use diquarks as building blocks
  - diquark+diquark+anti-quark
- These models predict many states
  - Proponents of these models will be happy to see more states.
- They have trouble explaining the widths.
  - Decay by fall-apart, would expect wider states
- Need something to slow down decay to make them narrow,
  - Angular momentum between diquarks?

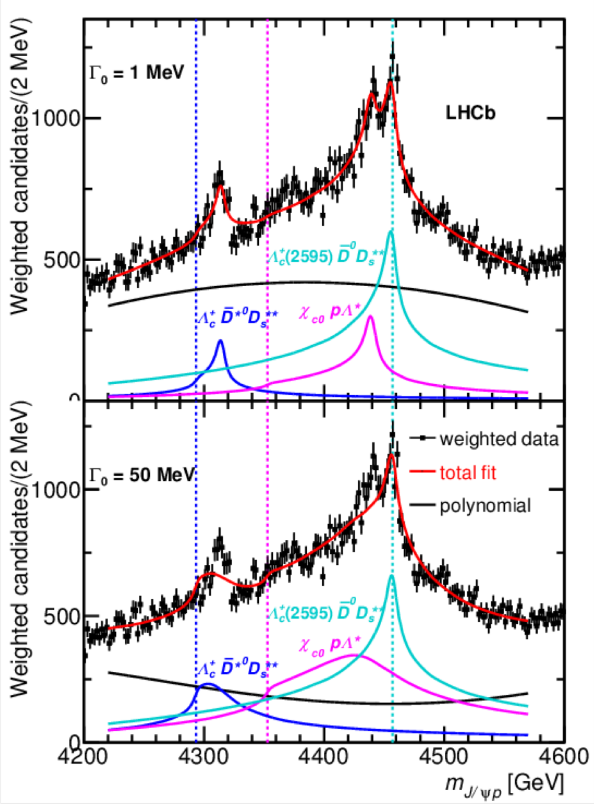


MOLECULAR PENTAQUARKS

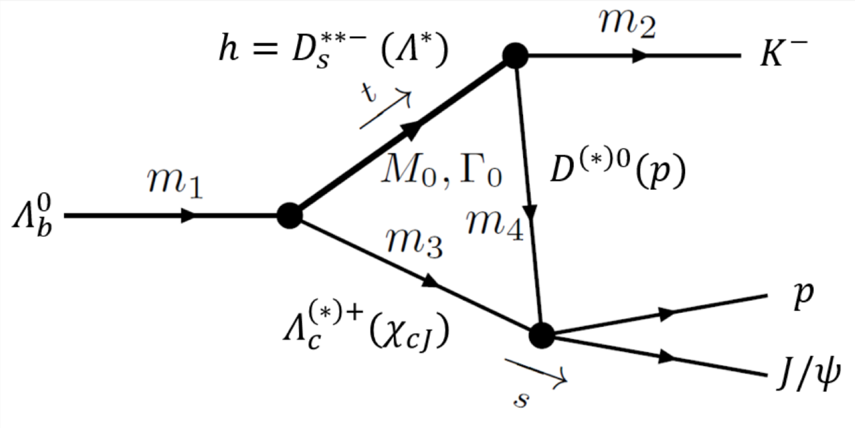
- Weakly bound meson+baryon system
- Shallow potential well, n=0,L=0 between hadrons
  - Very few states expected (S)
  - Weak binding expected: masses a few MeV below the related baryon-meson thresholds
- Decay by heavy quarks changing confinement partners, then fall-apart:
  - All states naturally narrow



HADRON RESCATTERING VIA TRIANGLE DIAGRAMS

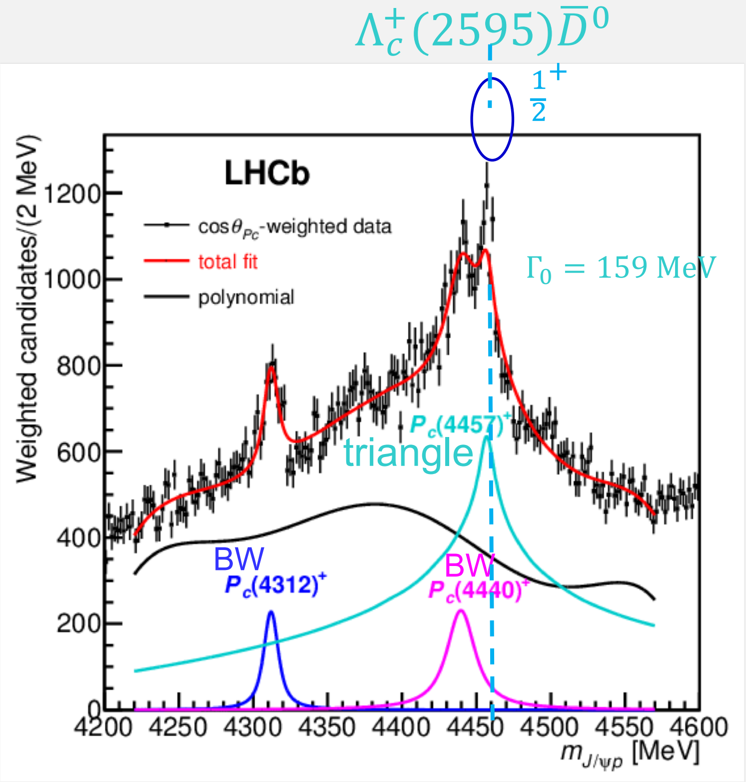


- Can peak above a threshold given by the sum of the masses of the rescattering hadrons (m3 + m4)

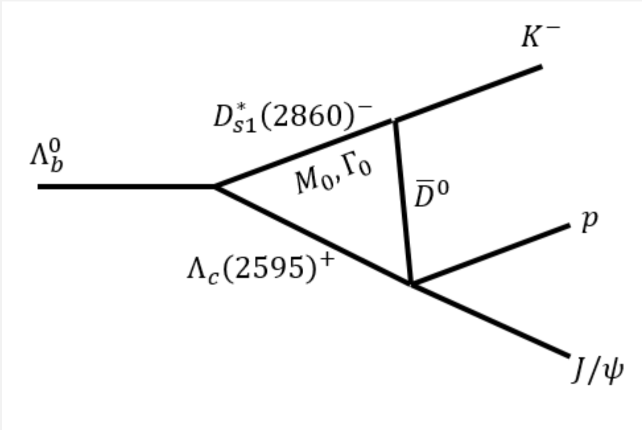


- Decent fits obtainable when assuming unrealistic Γ_0 for the excited D_s or Λ(top)
- When using realistic widths (bottom), clear that $P_c(4312)^+$, $P_c(4440)^+$ are too far from any rescattering thresholds to be triangle diagram peaks.

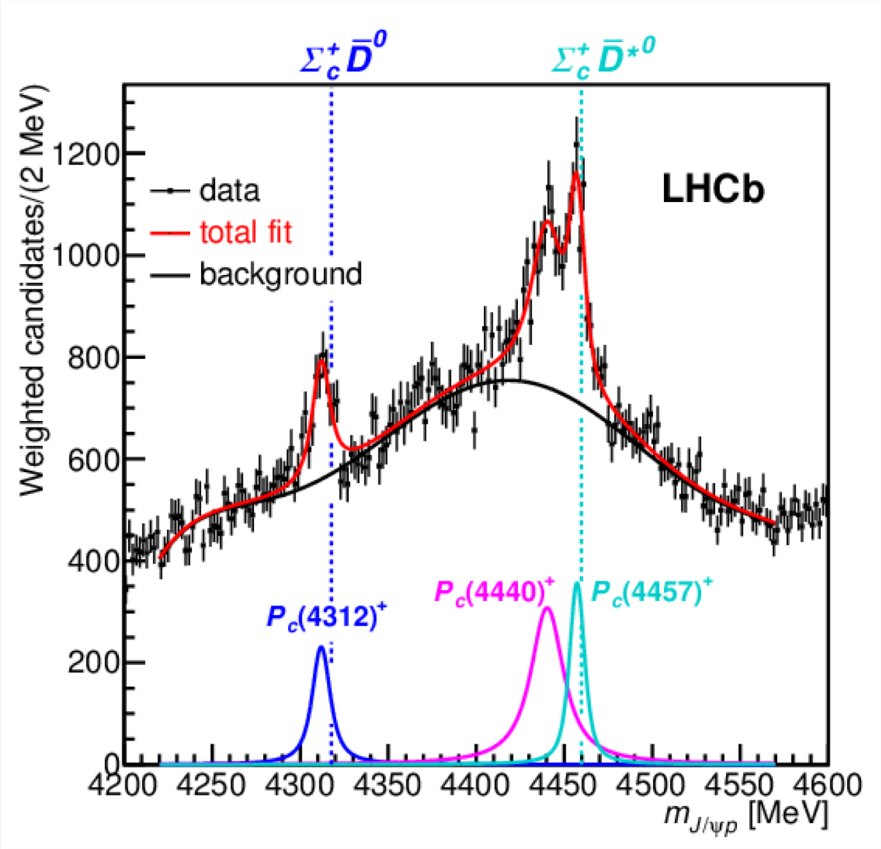
HADRON RESCATTERING VIA TRIANGLE DIAGRAMS



- $\mathrm{P_c(4457)^+}$ is right at the $\Lambda_c^+(2595)\bar{D}^0$ threshold
  - Triangle diagram more plausible.
- PDG value used for $D_{s1}^*(2860)^-$ width
- Fit quality decent, but not as good as BW amplitude
- Amplitude analysis will be more enlightening
  - Interference effects may even change things.



MOLECULAR VS TIGHTLY BOUND



- All candidates are narrow, below relevant thresholds with plausible binding energies.
  - $P_c(4440)$ ~20 MeV lower than $\Sigma_c^+ \bar{D}^{*0}$, but some models predict $^1/_2{}^-$ and $^3/_2{}^-$
  - Favours "molecular" pentaquarks with meson-baryon substructure

- Diquark model takes nearness to.thresholds as chance and must provide some mechanism to create narrow widths, e.g. separated by a potential barrier

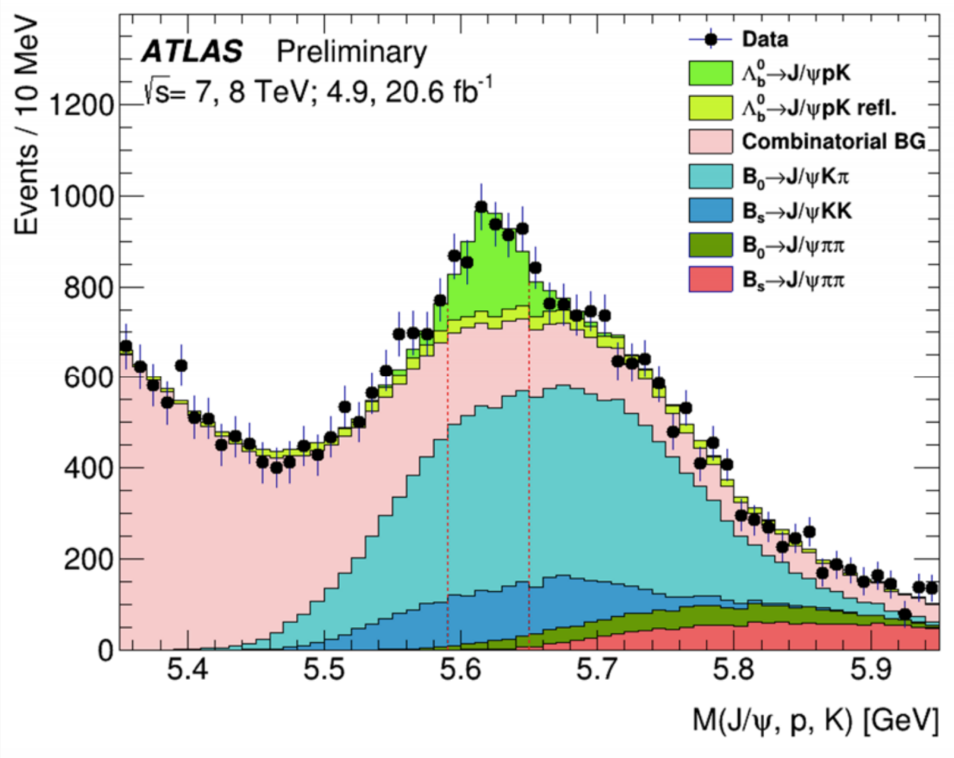
- No hypothesis can be ruled out at this point.

FUTURE PROSPECTS

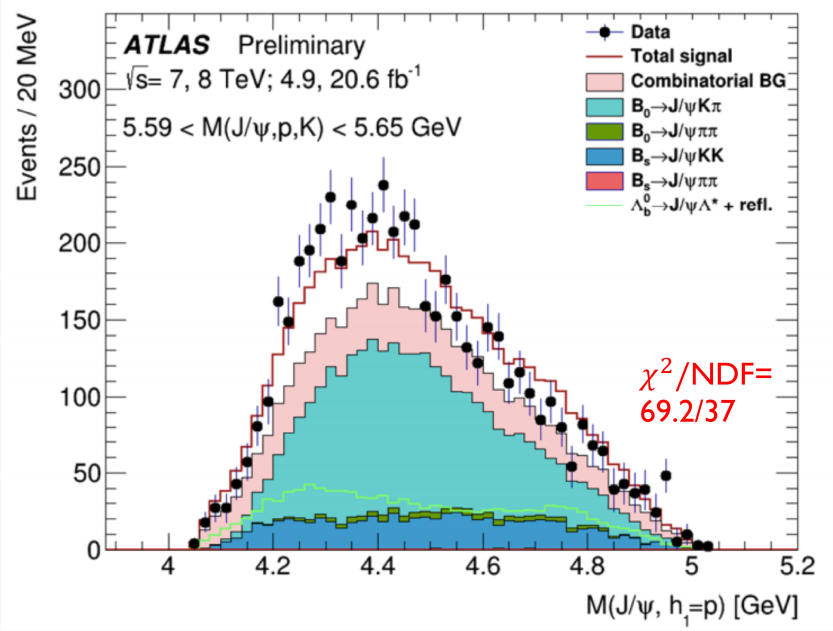
- Several avenues to pursue in trying to figure out mechanism responsible for these peaks.
  - Could even be complicated interplay between several effects!
- More studies with $\Lambda_b^0 \to J/\psi\, pK^-$
  - Amplitude analysis has several challenges, but will be critical.
  - More data: will additional peaks appear in upgrade?
- Look for the P_c states in other decay modes and production mechanisms.
- Of course, look for other pentaquarks too.

NEWS FROM ATLAS

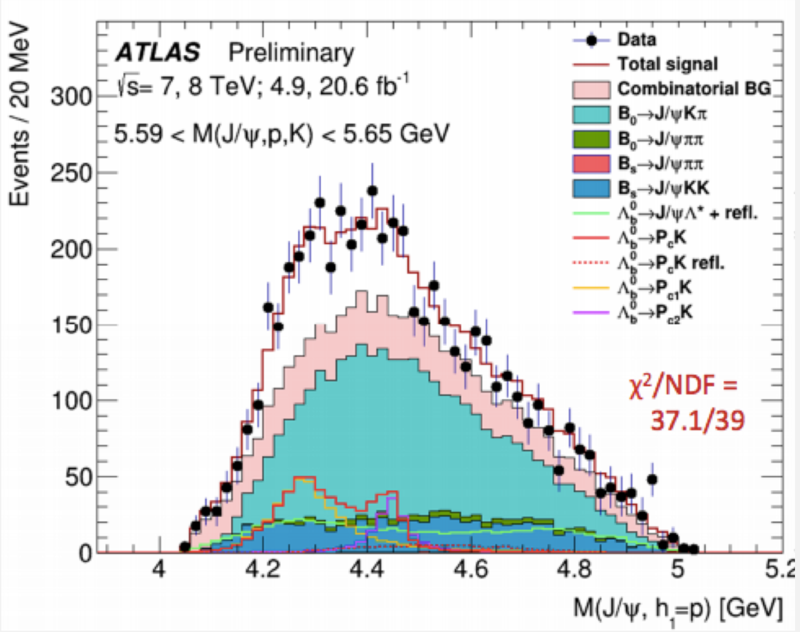
- Presented at Beauty conference: [link]
- Lack of charged hadron identification makes for more complicated analysis
- Must also analyse several other b-hadron decay modes with non-trivial decay dynamics.
- Analysis of Run 1 data yields 2270 ± 300 signal candidates
    - Less than 1/10 of LHCb Run 1 analysis



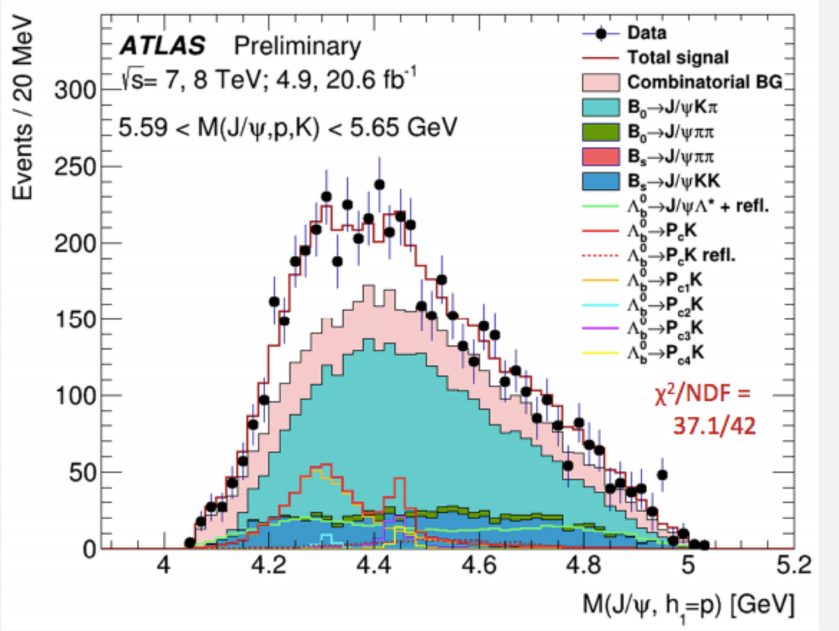
NEWS FROM ATLAS



No P_c



2 P_c

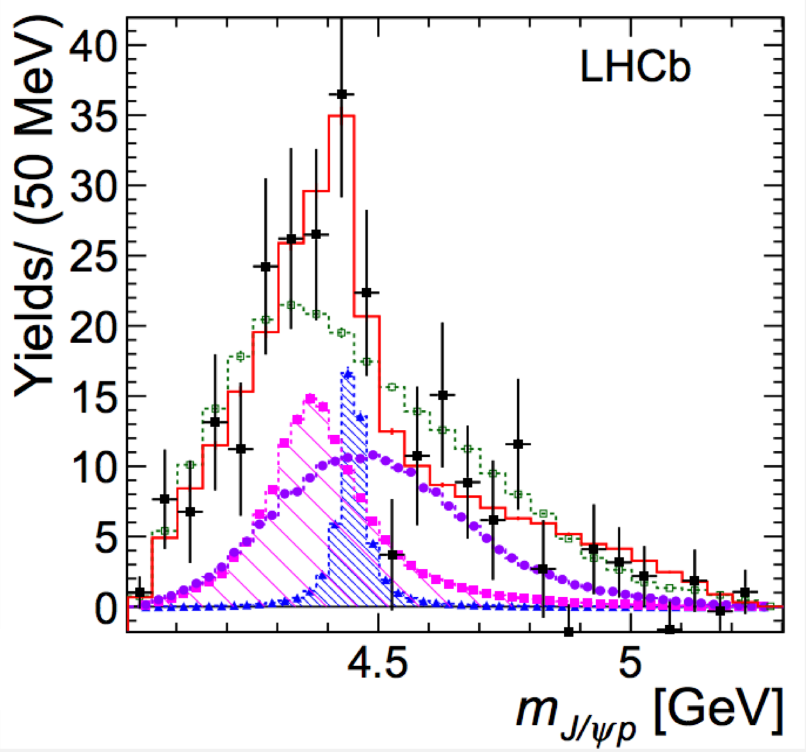


4 P_c

- Description of data is poor with no P_c fit, though this model not completely excluded
- Update planned with full data sample.

P_c STATES IN $\Lambda_b^0 \to J/\psi\ p\pi^-$

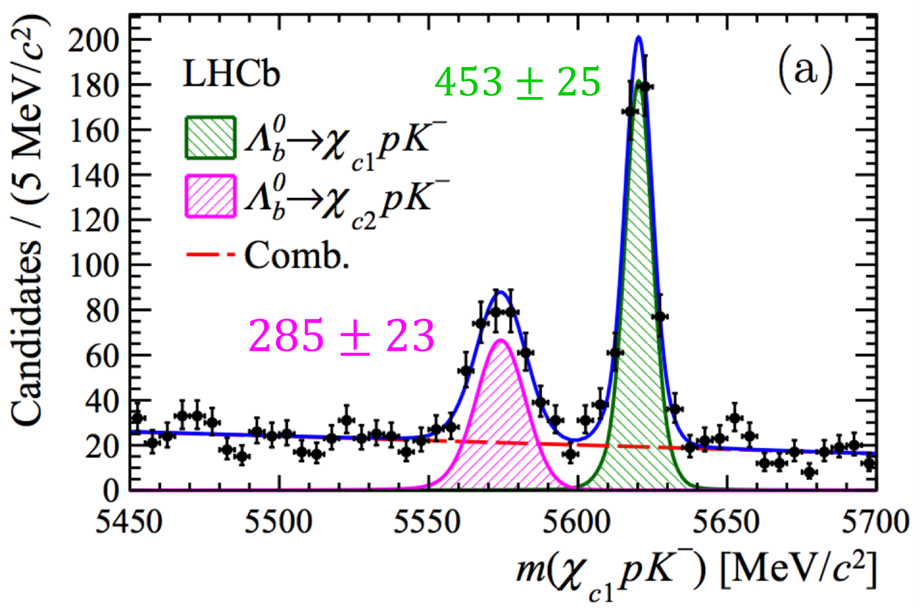
- Lower stats due to Cabibbo suppression
- Dominated by excited nucleon contributions
- Also possible contribution from $Z_c \to J/\psi\,\pi^-$
  - Three interfering decay chains
- Exotic contributions have a significance of 3.1σ
  - Not able to make conclusive statements.
- With full Run 1+2 statistics, should have bit less than statistics of original $\Lambda_b^0 \to J/\psi\, pK^-$ analysis



[arXiv:1606.06999]

P_c STATES IN $\Lambda_b^0 \to \chi_{c1,2}\, pK^-$

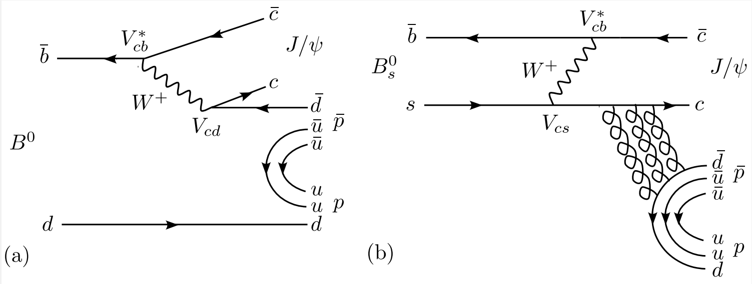
- Can look for $P_c(4457)$ just above threshold
  - Of course other P_c states as well
- Made difficult because requires reconstruction of photon
  - Lower efficiency, higher background
- Observation of the decay modes was done with Run 1 data
  - Amplitude analysis planned with full data set



[arXiv:1704.07900]

P_c STATES IN $B^0_{(s)} \to J/\psi\, p\bar{p}$

- First observation made of the suppressed $B^0_{(s)} \to J/\psi\, p\bar{p}$ decay modes

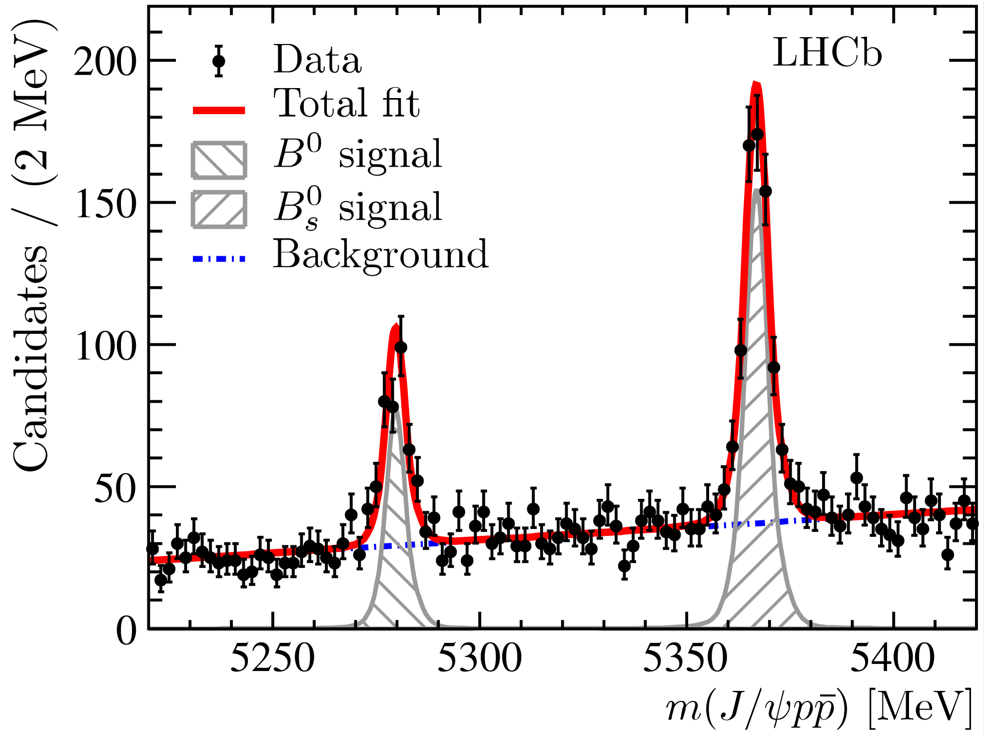


- Suppression may be lifted from exotic contributions.

$$\mathcal{B}(B^0 \to J/\psi p\bar{p}) = (4.51 \pm 0.40\ (\text{stat}) \pm 0.44\ (\text{syst})) \times 10^{-7}$$
$$\mathcal{B}(B^0_s \to J/\psi p\bar{p}) = (3.58 \pm 0.19\ (\text{stat}) \pm 0.39\ (\text{syst})) \times 10^{-6}$$

- Branching fractions higher than expected.
- Amplitude analysis with full Run1+2 data sets under way

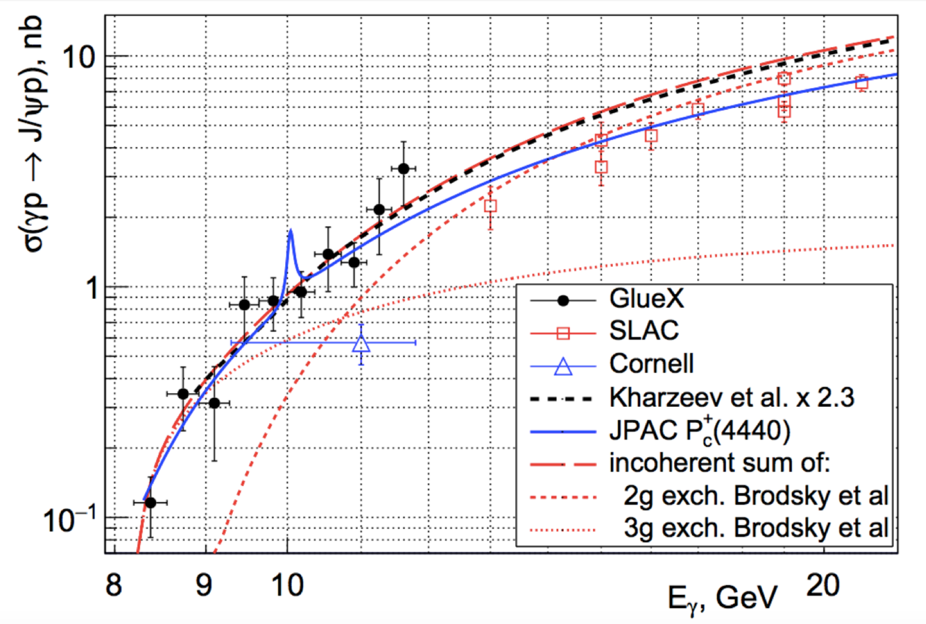
[arXiv:1902.05588]

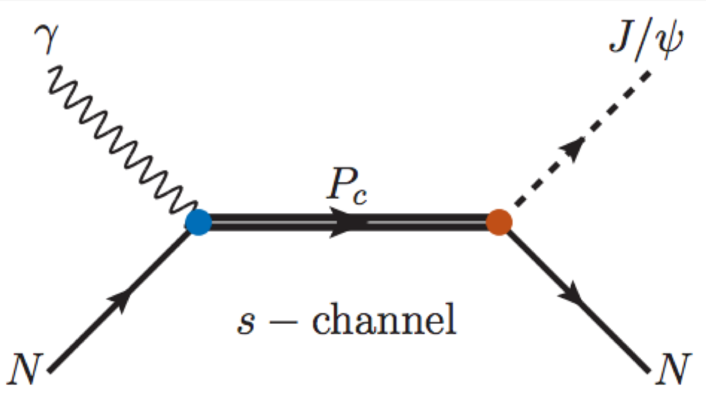


DIRECT PRODUCTION

- Tricky to look for from pp collisions
  - Short-lived, so swamped by backgrounds.
  - Not clear that would be significant production if molecular picture is right!
- Studies underway to look for them in photoproduction at JLAB
  - Results already from GlueX, more to come

[arXiv:1905.10811]

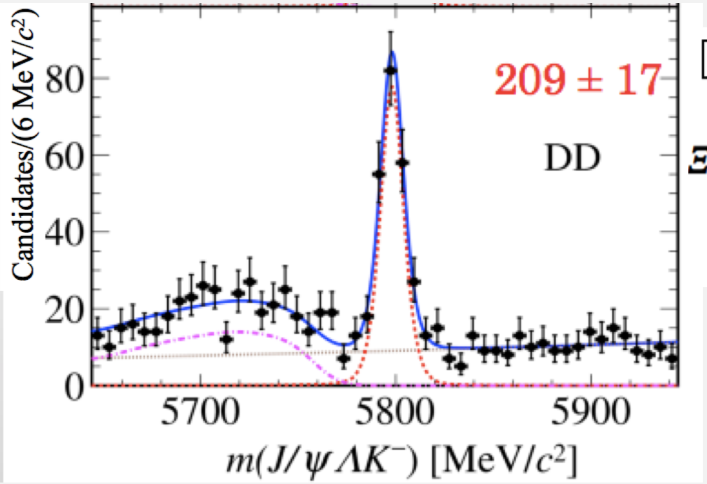


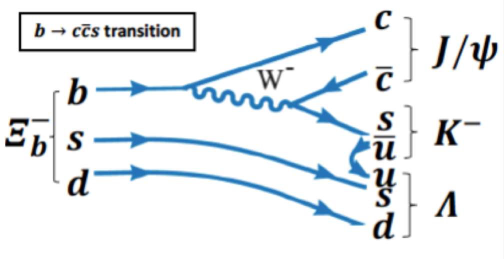


OTHER PENTAQUARKS

- Discovery of further states is crucial for shedding light on internal bindings and the nature of these states.
  - Pentaquarks with different charge, spin-parity, isospin
- Weakly decaying pentaquarks which are too light to decay strongly
  - $P^+_{B^0p} \to J/\psi\, K^+\pi^-p$ and $P^+_{B_sp} \to J/\psi\, \phi p$ limits set [arXiv:1712.08086]

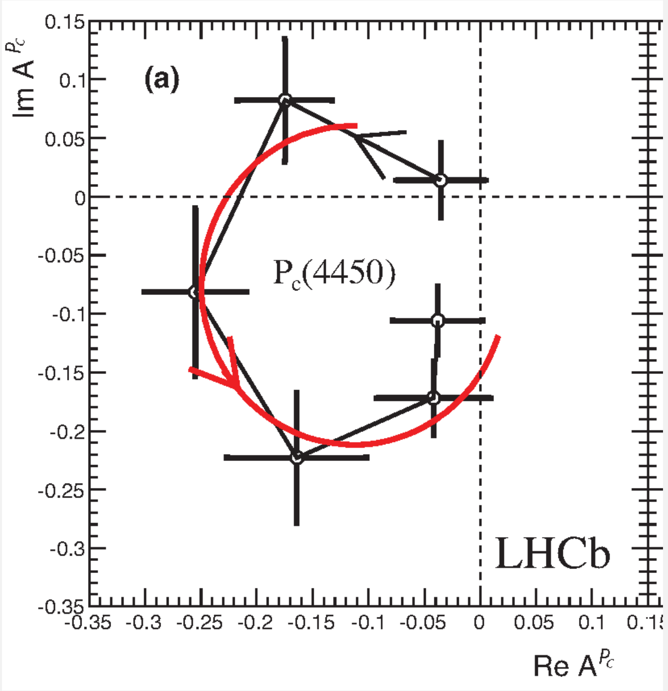
- A systematic search should be done, as we also learn from non-observations
- Several searches underway, such as $\Lambda_b^0 \to J/\psi\Lambda K^-$ with Run I data [arXiv:1701.05274]





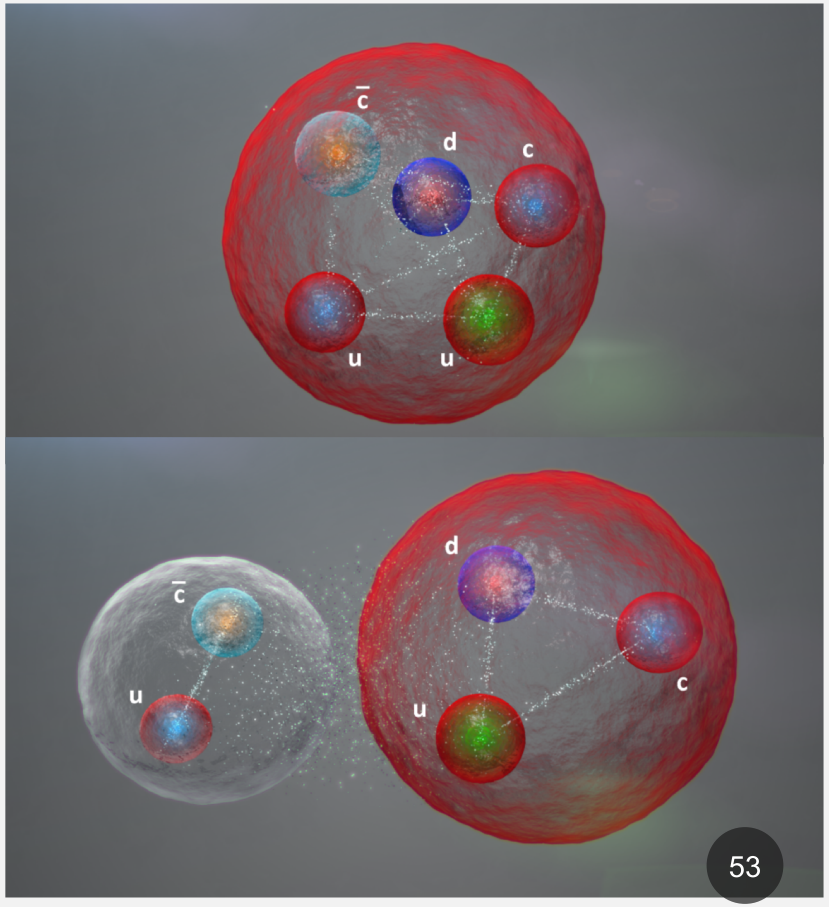
REFLECTIONS ON PREVIOUS AMPLITUDE ANALYSIS

- With an order of magnitude more data, not surprising the data has new things to tell
- $P_c(4312)$ was not significant, nor was splitting of $P_c(4450)$ into two resonances.
    - Unaccounted for contributions explain difficulty in determining J^P
    - Certain features of the amplitude analysis still surprising though, e.g. how nice the Argand diagram looked.
- Ultimately, we will have to await new amplitude analysis for more answers.



SUMMARY

- The narrow $P_c(4312)$ is discovered, and previously reported $P_c(4450)^+$ structure resolved into two narrow states: the $P_c(4440)^+$ and $P_c(4457)^+$
- These results shed more light on binding mechanism, but still require further elucidation.
- Towards this effort we continue to fully utilize the Run 1+2 data, and have increased statistics on the way.
- We look forward to more input from theory and other experiments!

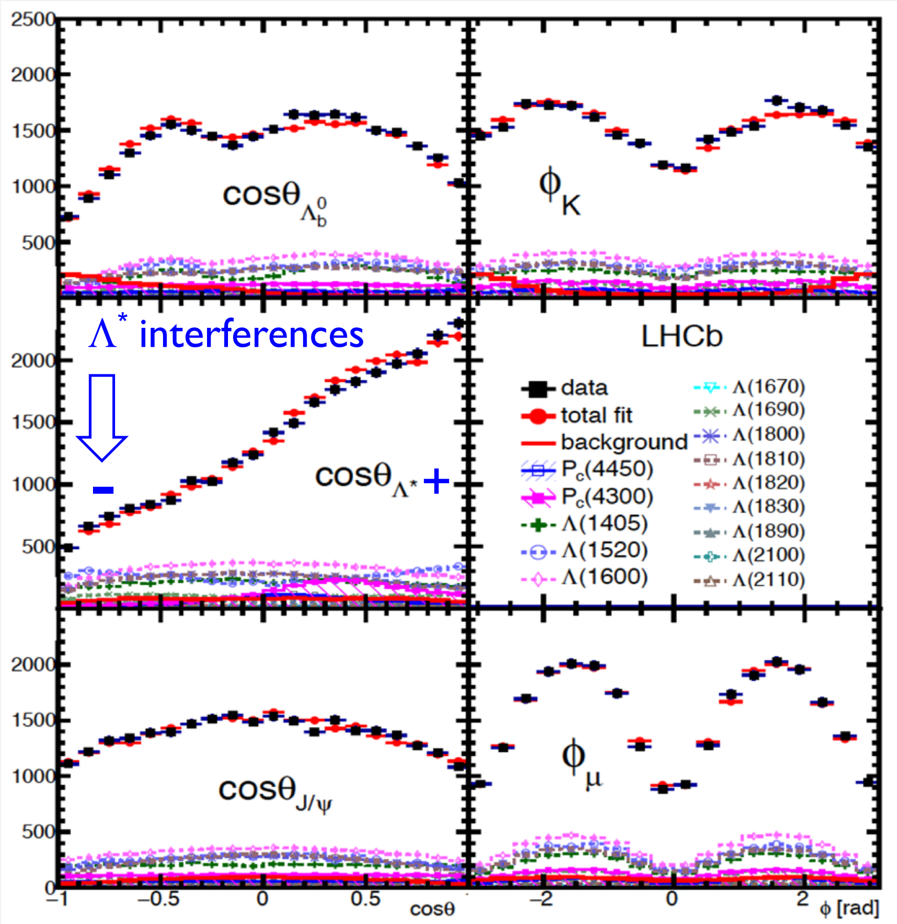


BACK UP

ANGULAR DISTRIBUTIONS

- Good description of the data in all 6 dimensions.

All data



P_c enriched region