Observation of the Pentaquark States

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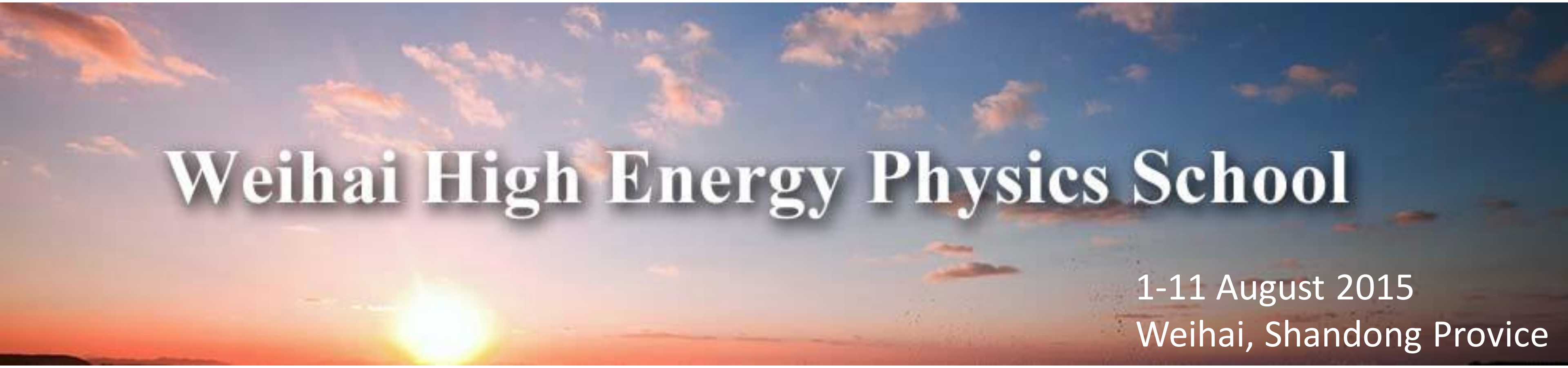
清华大学

2015年8月2日



http://indico.ihep.ac.cn/event/4869/overview

Outline

- Introduction
- $\Lambda_b^0 \to J/\psi p K^-$ & peak structure in $J/\psi p$
- Full amplitude analysis
  - Observation of two $J/\psi p$ resonances
- Summary & prospects

arXiv:1507.03414
Accepted by PRL

Multiquark states have been discussed since the 1st page of the quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

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 $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

http://cds.cern.ch/record/352337/files/CERN-TH-401.pdf

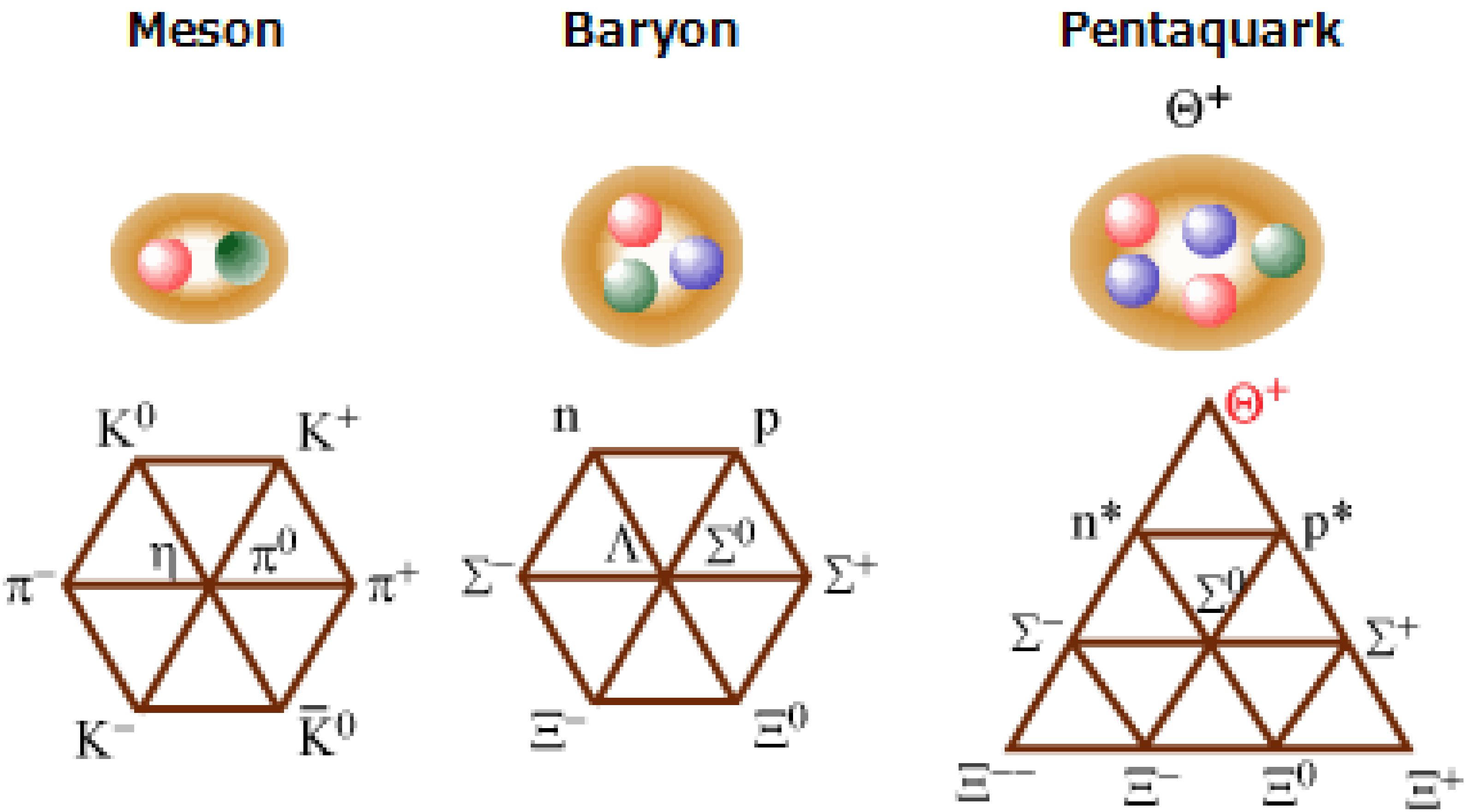
Multiquark states have been discussed since the quark model was proposed

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

8182/TH.401
17 January 1964

Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces break up into an isospin doublet and singlet. Each ace carries baryon number $\frac{1}{3}$ and is consequently fractionally charged. SU_3 (but not the Eightfold Way) is adopted as a higher symmetry for the strong interactions. The breaking of this symmetry is assumed to be universal, being due to mass differences among the aces. Extensive space-time and group theoretic structure is then predicted for both mesons and baryons, in agreement with existing experimental information. An experimental search for the aces is suggested.

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



SU(3) weight diagram for the classification of hadrons

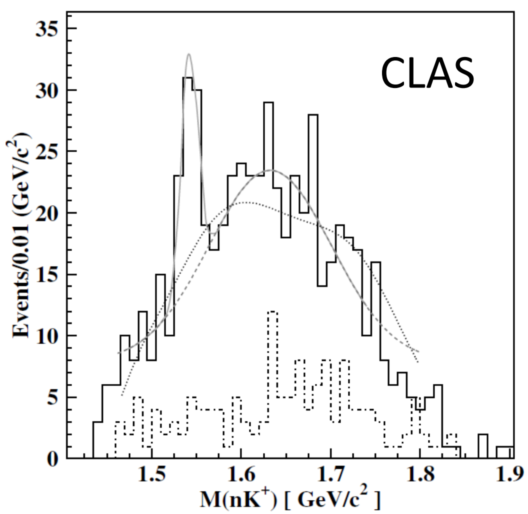
Where are they?

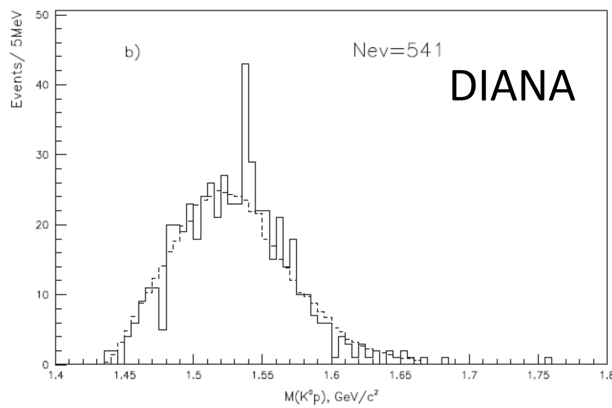
- There is no reason that they should not exist
  - Predicted by M. Gell-Mann(1964), G. Zweig(1964), and other later in context of specific QCD models: Jaffe (1976), Strottman (1979)
- These multi-quark states would be short-lived $\sim 10^{-23}$ s "resonances", whose presences are detected by mass peaks & angular distributions showing the unique J^{PC} quantum numbers
- Pentaquarks are states of matter beyond simple quark picture
  - Could teach us a lot about QCD

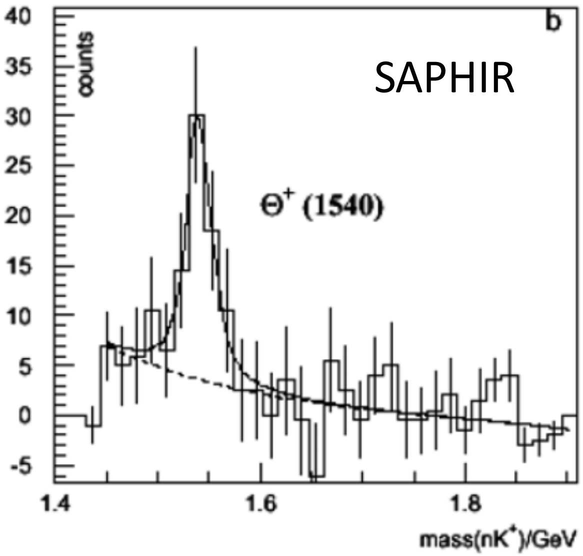
Prejudices

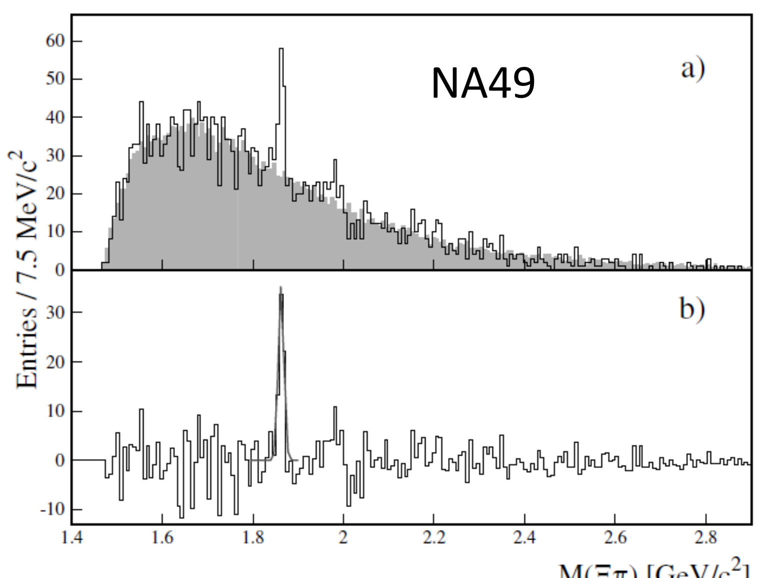
- No convincing states 50 years after Gell-Mann paper proposing $qqqq\bar{q}$ states
- Previous "observations" of several pentaquark states have been refuted
  - $\Theta^+ \to K^0 p, K^+ n, m = 1.54\ \mathrm{GeV}, \Gamma \sim 10\ \mathrm{MeV}$
  - Resonance in $D^{*-}p$ at $3.10\ \mathrm{GeV}, \Gamma = 12\ \mathrm{MeV}$
  - $\Xi^{--} \to \Xi^- \pi^-, m = 1.862\ \mathrm{GeV}, \Gamma < 18\ \mathrm{MeV}$
- Generally they were found/debunked by looking for "bumps" in mass spectra circa 2004

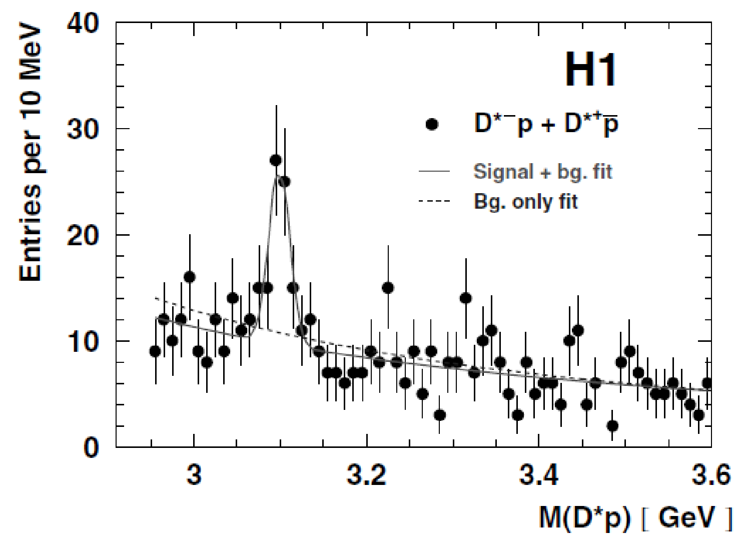
See summary by [K. H. Hicks, Eur. Phys. J. H37 (2012) 1]


CLAS
Events/0.01 (GeV/c²)
M(nK⁺) [GeV/c²]

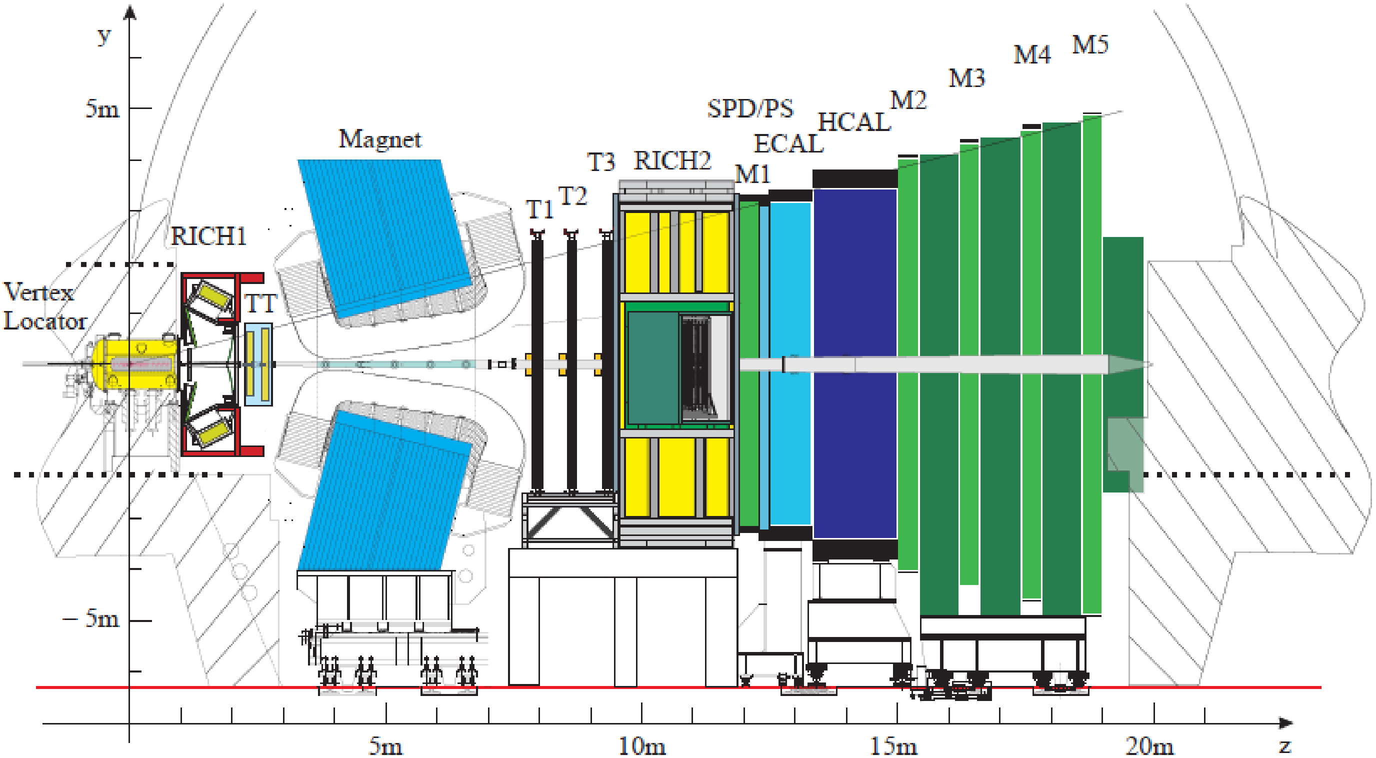

DIANA
b)
Nev=541
Events/ 5MeV
M(K°p), GeV/c²


SAPHIR
b
counts
Θ⁺ (1540)
mass(nK⁺)/GeV


NA49
a)
b)
Entries / 7.5 MeV/c²
M(Ξπ) [GeV/c²]


H1
D*⁻p + D*⁺p̄
Signal + bg. fit
Bg. only fit
Entries per 10 MeV
M(D*p) [GeV]

LHCb detector



Impact parameter: $\sigma_{IP} = 20\ \mu\text{m}$

Proper time: $\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$

Momentum: $\Delta p/p = 0.4 \sim 0.6\%$ $(5 – 100\ \text{GeV}/c)$

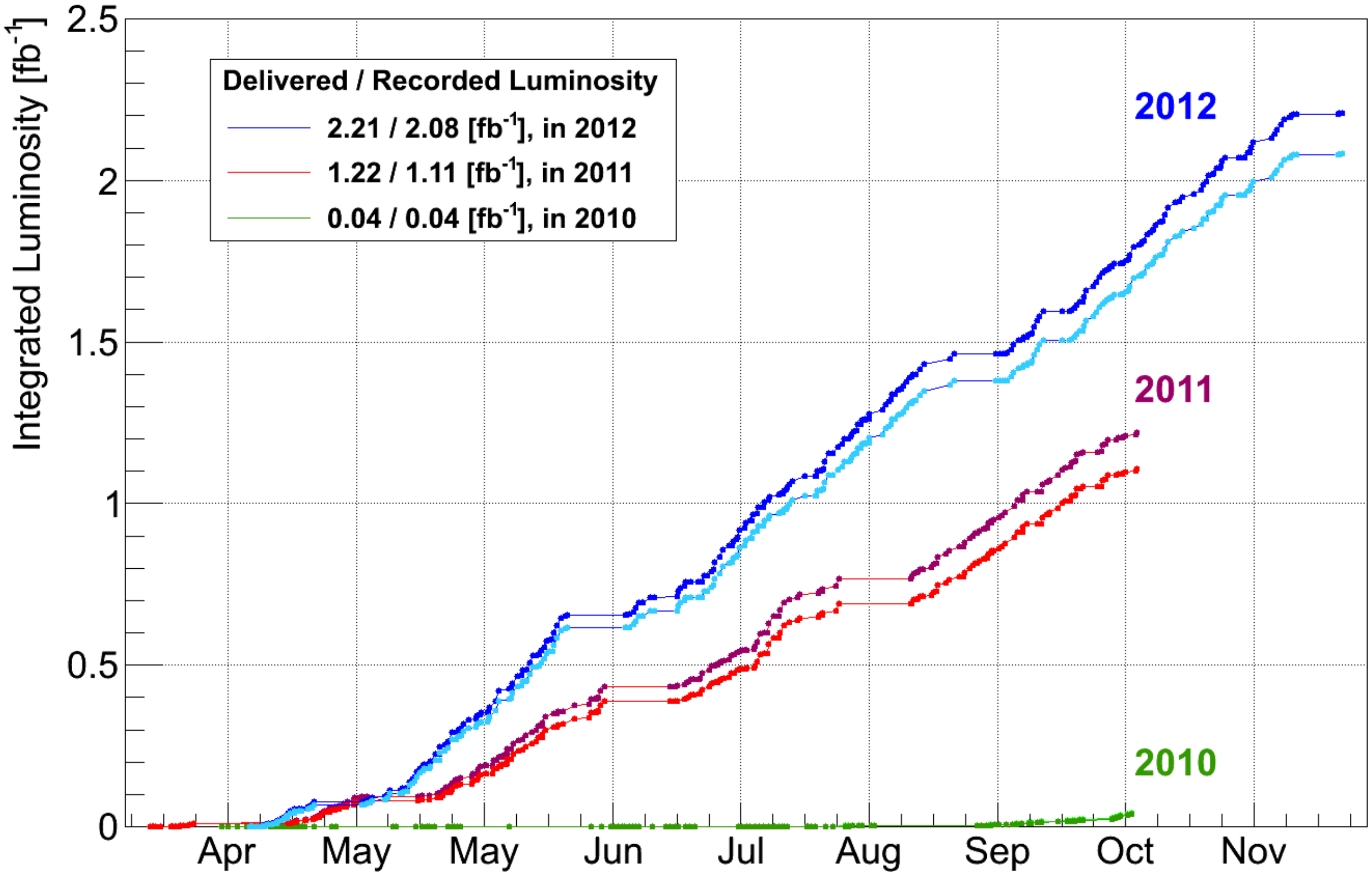
Mass : $\sigma_m = 8\ \text{MeV}/c^2$ for $B \to J/\psi X$ (constrained $\text{m}_{J/\psi}$)

RICH $K - \pi$ separation: $\epsilon(K \to K) \sim 95\%$ mis-ID $\epsilon(\pi \to K) \sim 5\%$

Muon ID: $\epsilon(\mu \to \mu) \sim 97\%$ mis-ID $\epsilon(\pi \to \mu) \sim 1 - 3\%$

ECAL: $\Delta E/E = 1 \oplus 10\%/\sqrt{E(\text{GeV})}$

LHCb data taking



8 TeV
2.1 fb^{-1}

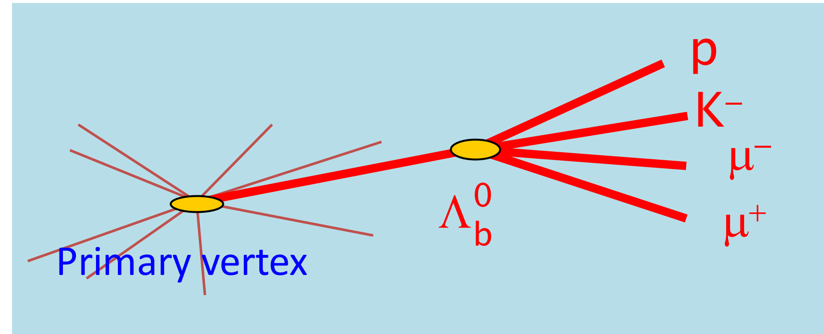
7 TeV
1.1 fb^{-1}

Stable and efficient (> 90%) data taking

This analysis based on 2011 + 2012 data

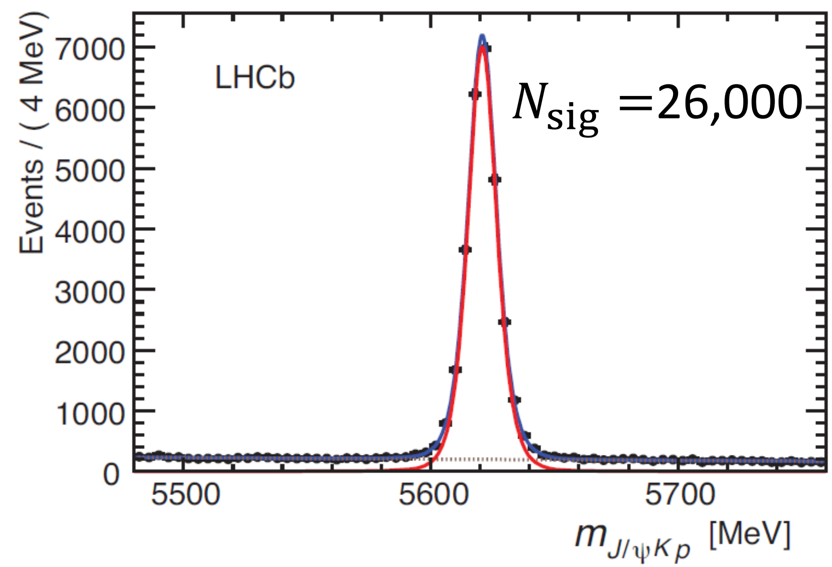
$\Lambda_b^0 \to J/\psi p K^-$ and event selection

- First observed by LHCb as a potential background for
$$B^0 \to J/\psi K^+ K^-$$
- Large signal yield found, used for Λ_b^0 lifetime measurement



Event selection:

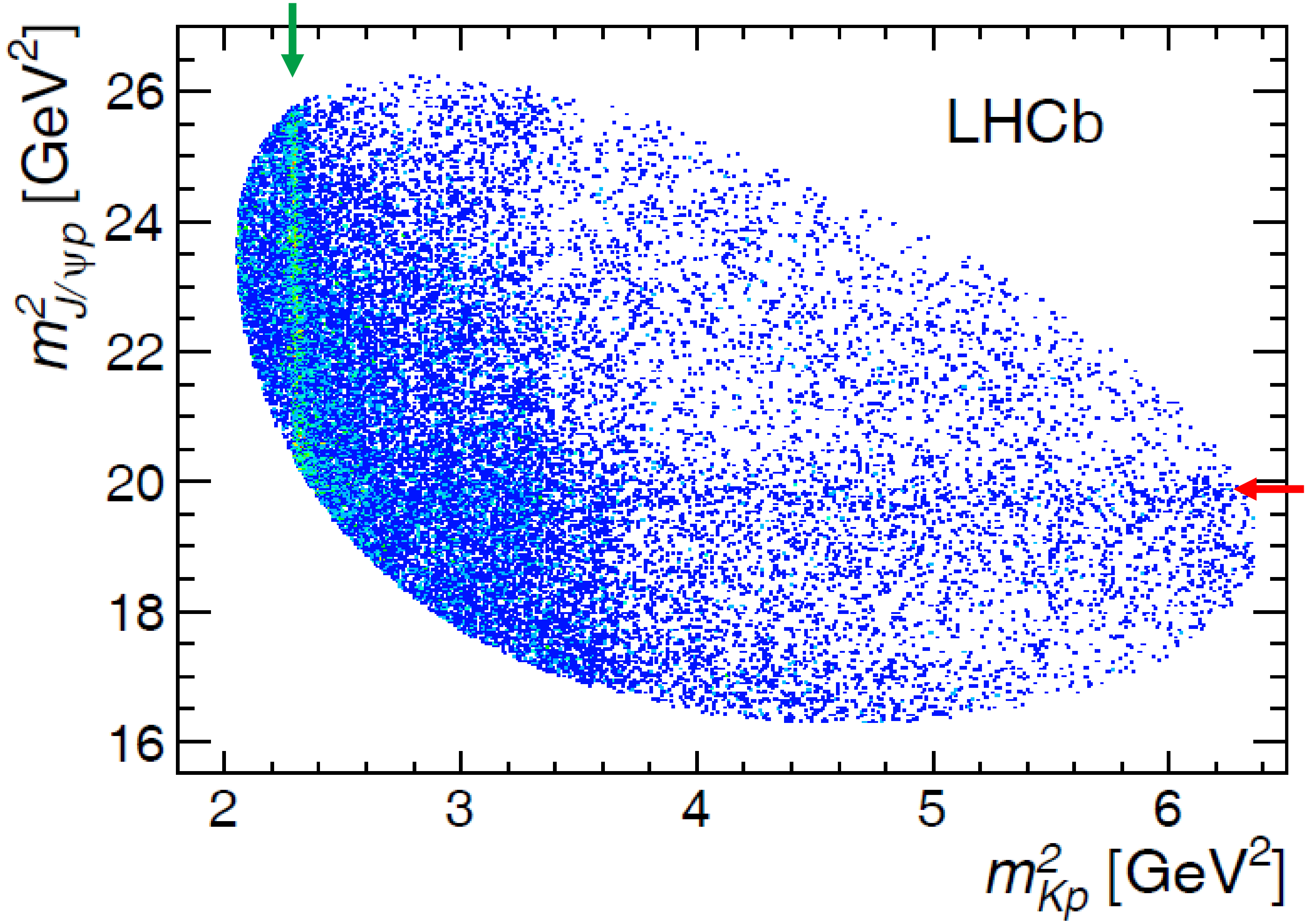
- Standard preselection
- Followed by selection with BDTG
- Veto $B_s^0 \to J/\psi K^+ K^-$ and
$$B^0 \to J/\psi K^+ \pi^-$$
reflections, where K^- and π^- are misidentified as proton



5.4% background in $\pm 2\sigma$

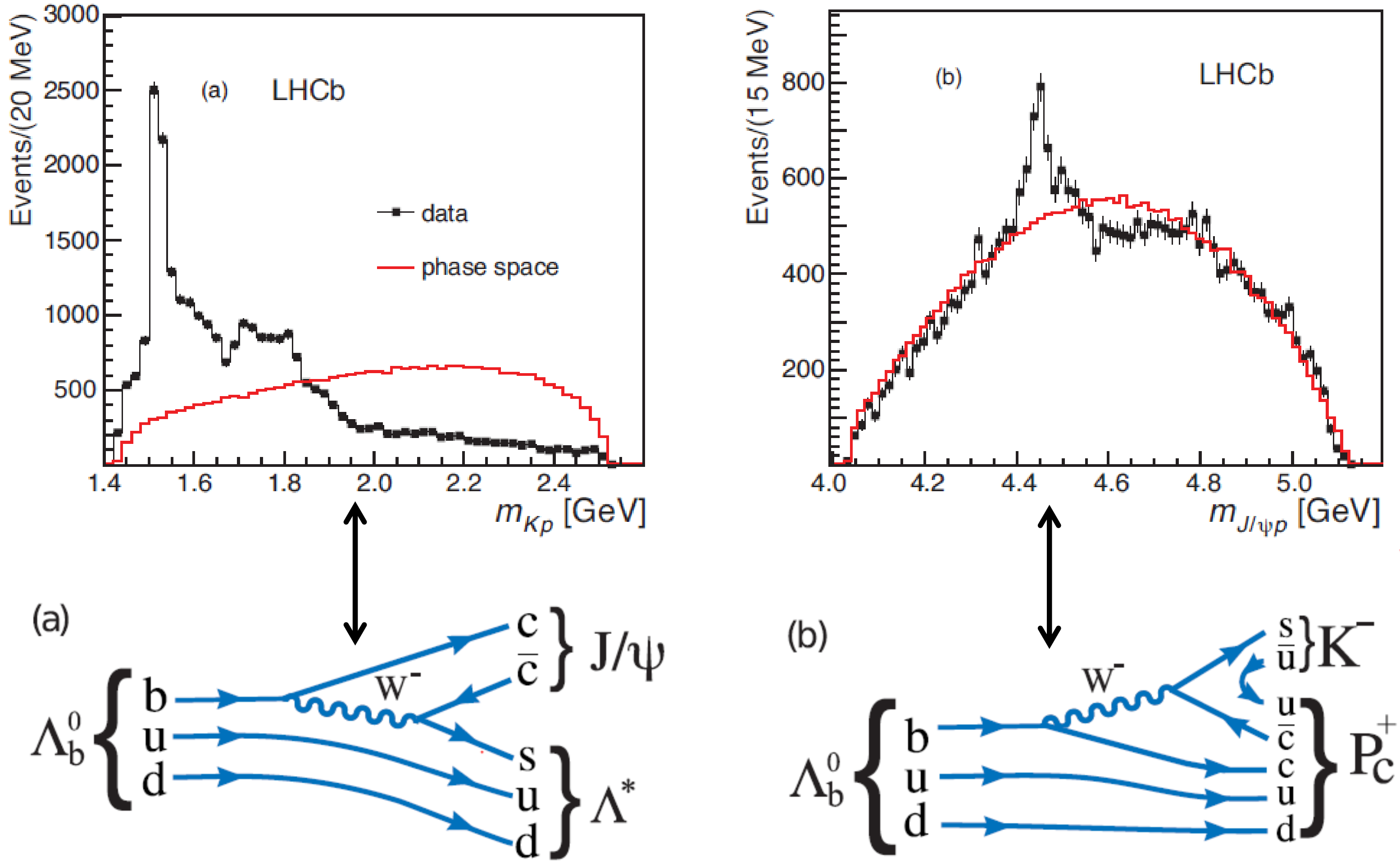
Unusual feature in "Dalitz plot"

$\Lambda(1520) \rightarrow pK^{-}$



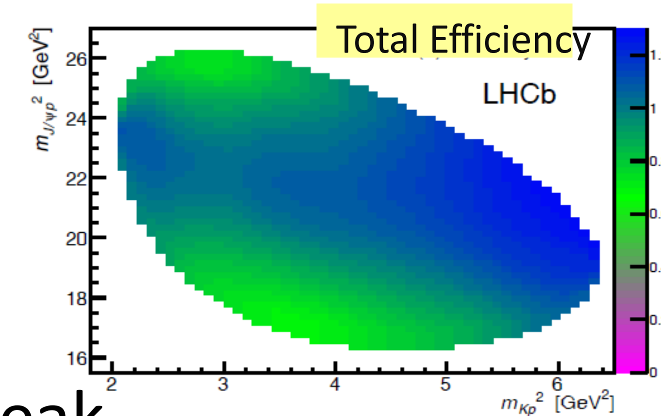
Clear, but what?

Projections



Does this diagram exist?

Is the peak "artifacts"?

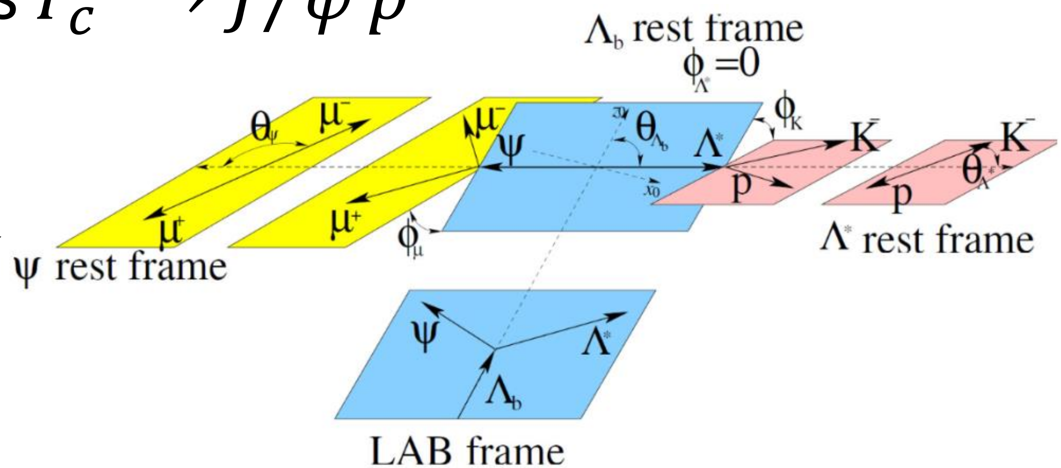


- Many checks done
  - Reflections of B^0 and B_s^0 are vetoed
  - Efficiency doesn't make narrow peak
  - Clones & ghost tracks eliminated
  - Ξ_b decays checked as a source
- Can interference between Λ^* resonances generate a peak in the $J/\psi p$ mass spectrum?
  - A full amplitude analysis is performed using all known Λ^* resonances

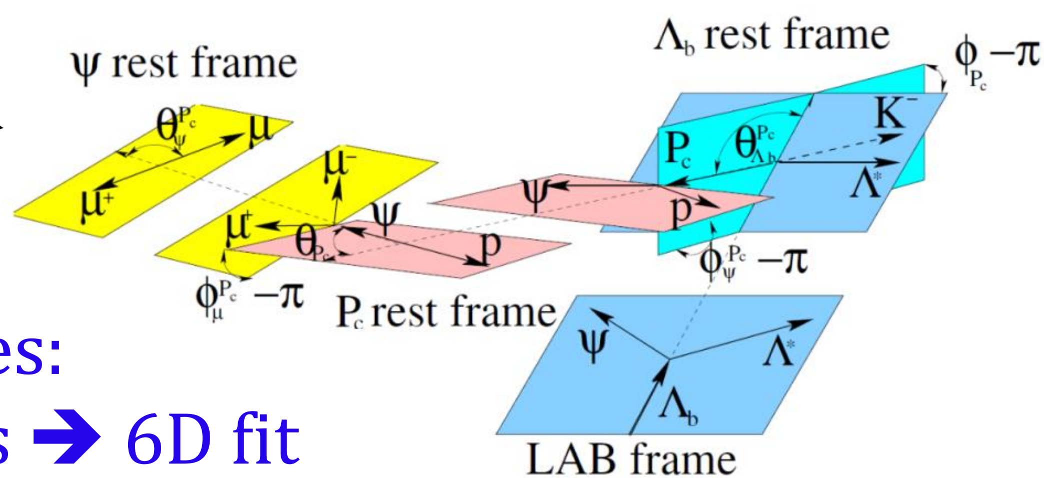
Amplitude analysis

- Allows for $\Lambda^* \to pK^-$ resonances to interfere with pentaquark states $P_c^+ \to J/\psi\, p$

$$\Lambda_b^0 \to J/\psi \Lambda^*,\quad \Lambda^* \to pK^-$$



$$\Lambda_b^0 \to P_c^+ K^-,\quad P_c^+ \to J/\psi p$$



- Independent variables: $m(pK^-)$ and 5 angles ➔ 6D fit

Λ^* resonances

- Each Λ^* resonance: $J = \frac{1}{2}$ ($> \frac{1}{2}$) has 4 (6) complex couplings
- Masses and widths fixed to PDG values
  - Uncertainties are considered as systematics
- Two models: "reduced" and "extended" to test dependence of the Λ^* model

State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# 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

Extended Λ^* model

- The extended model allows all LS couplings of each resonance, and includes poorly motivated states
- First try extended model to describe the data

State	J^p	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
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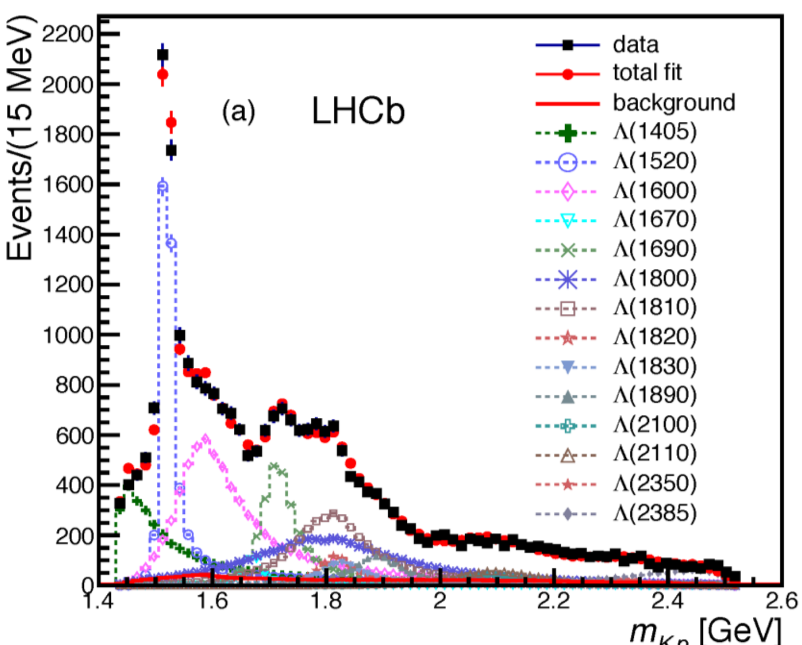
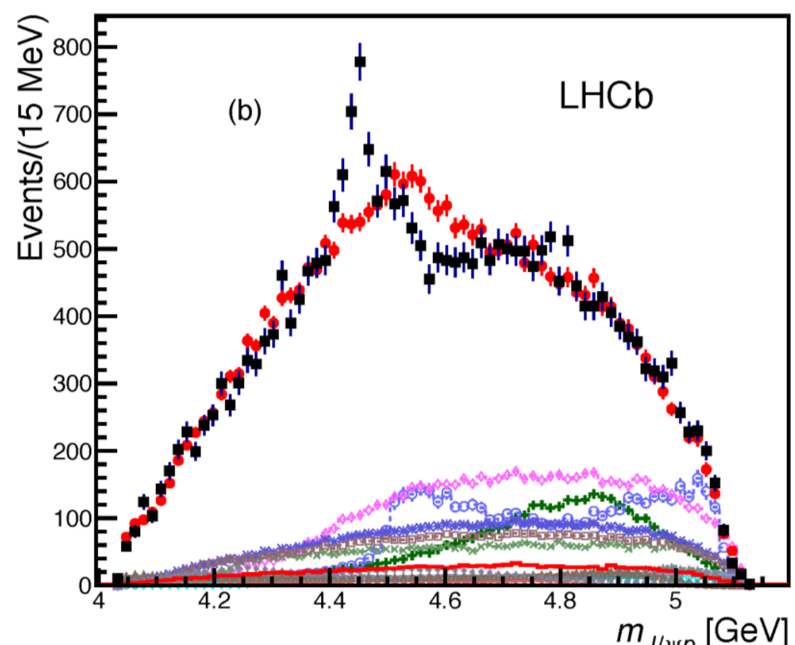
$\Lambda(2350)$	$9/2^+$	2350	150	0	6
$\Lambda(2585)$	?	≈ 2585	200	0	6
Total # of free parameters for Λ^*				64	146

Extended model without P_c^+

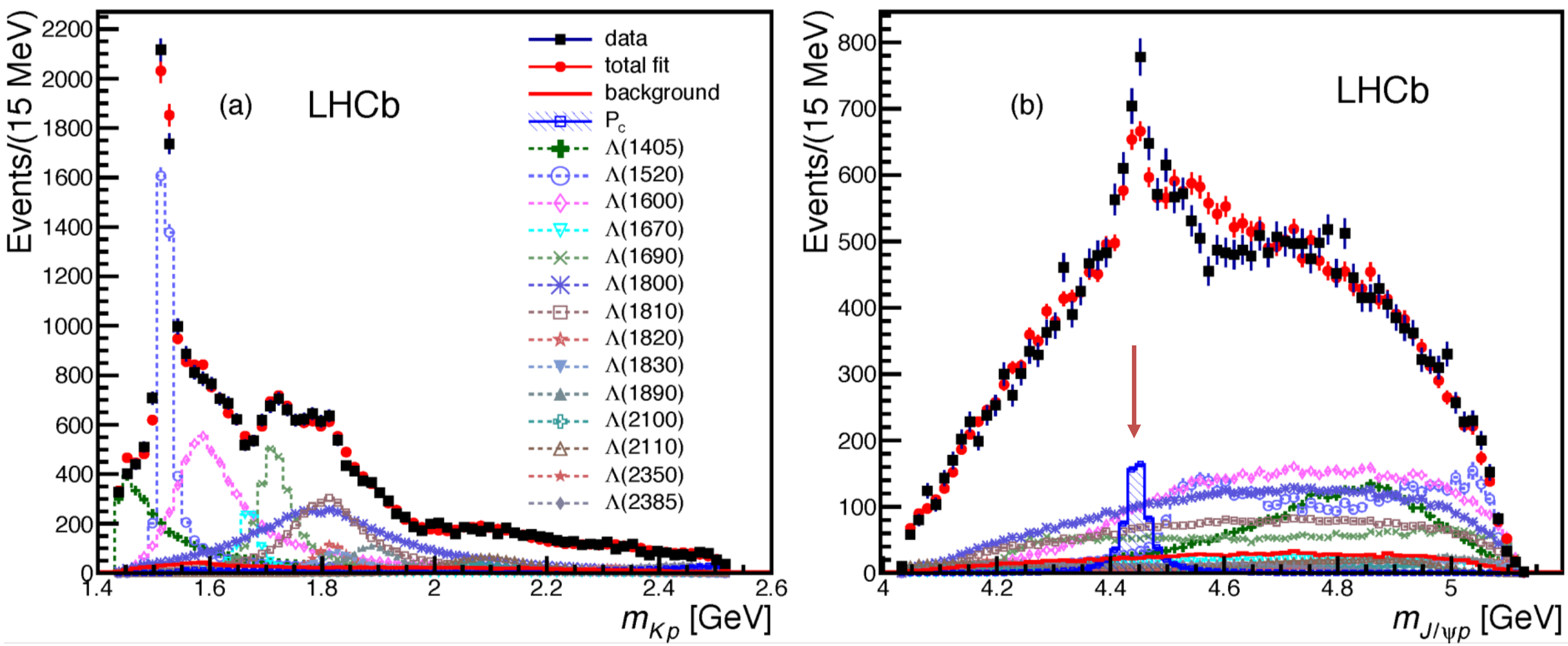
- $m(pK^-)$ looks fine, but not $m(J/\psi p)$
- Other possibilities:
  - All Σ^{*0} $(I = 1)$, isospin violating decay
  - two new Λ^* with free $m\&\Gamma$
  - 4 non-resonant Λ^* with $J^P = \frac{1}{2}^{\pm}$ and $\frac{3}{2}^{\pm}$
- Still fail to describe the data





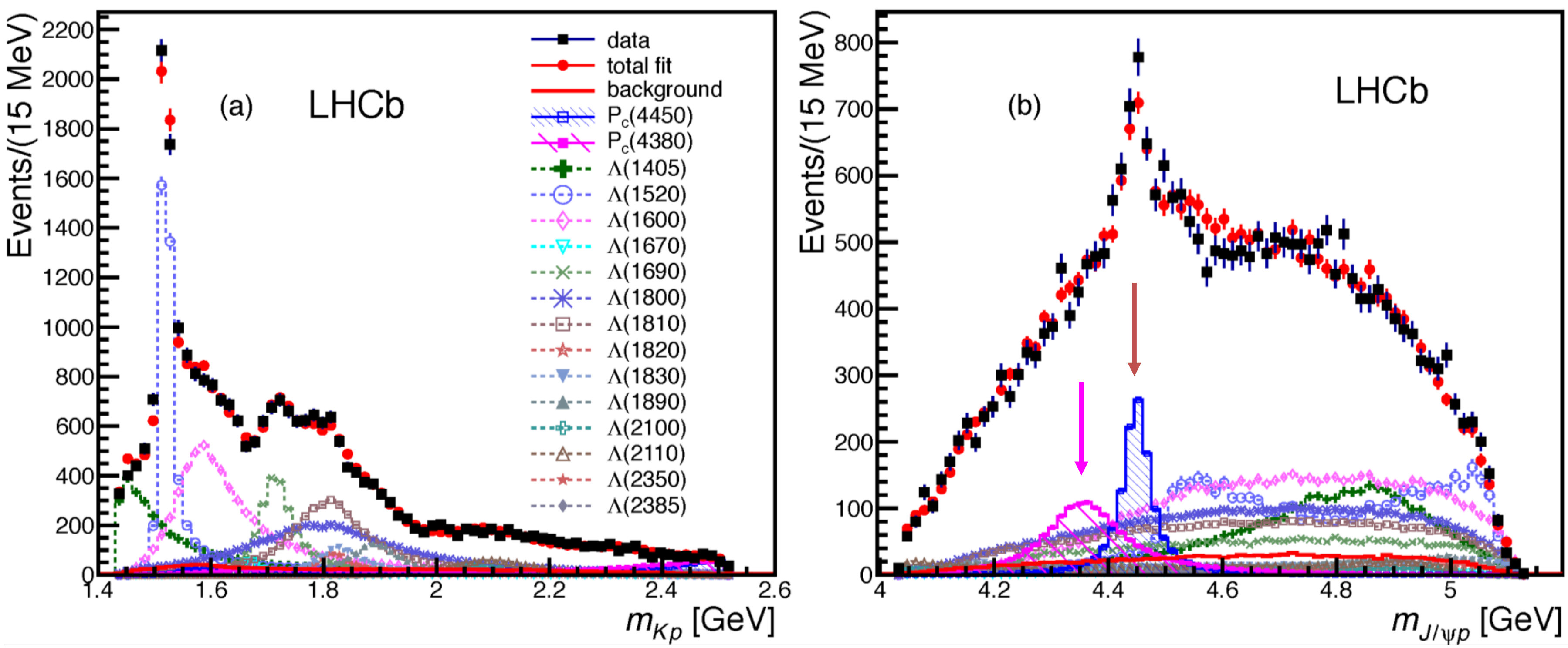
Extended model with one P_c^+

- Try all J^P up to $\frac{7}{2}^{\pm}$. Neither gives good fit
  - 8 (10) free parameters for a P_c^+ of $J = \frac{1}{2}\left(> \frac{1}{2}\right)$
  - Best fit has $J^P = \frac{5}{2}^{\pm}$



Extended model with two P_c^+'s

- Leads to a good fit
  - The 2nd broad P_c^+ visible in other projections (shown later)
  - It also modifies the narrow P_c^+'s decay angular distribution via interference to match the data



Reduced Λ^* model

- Too many free parameters in extended model
  - Some high mass states with high L not likely present in data
- Use only well motivated contributions for final results

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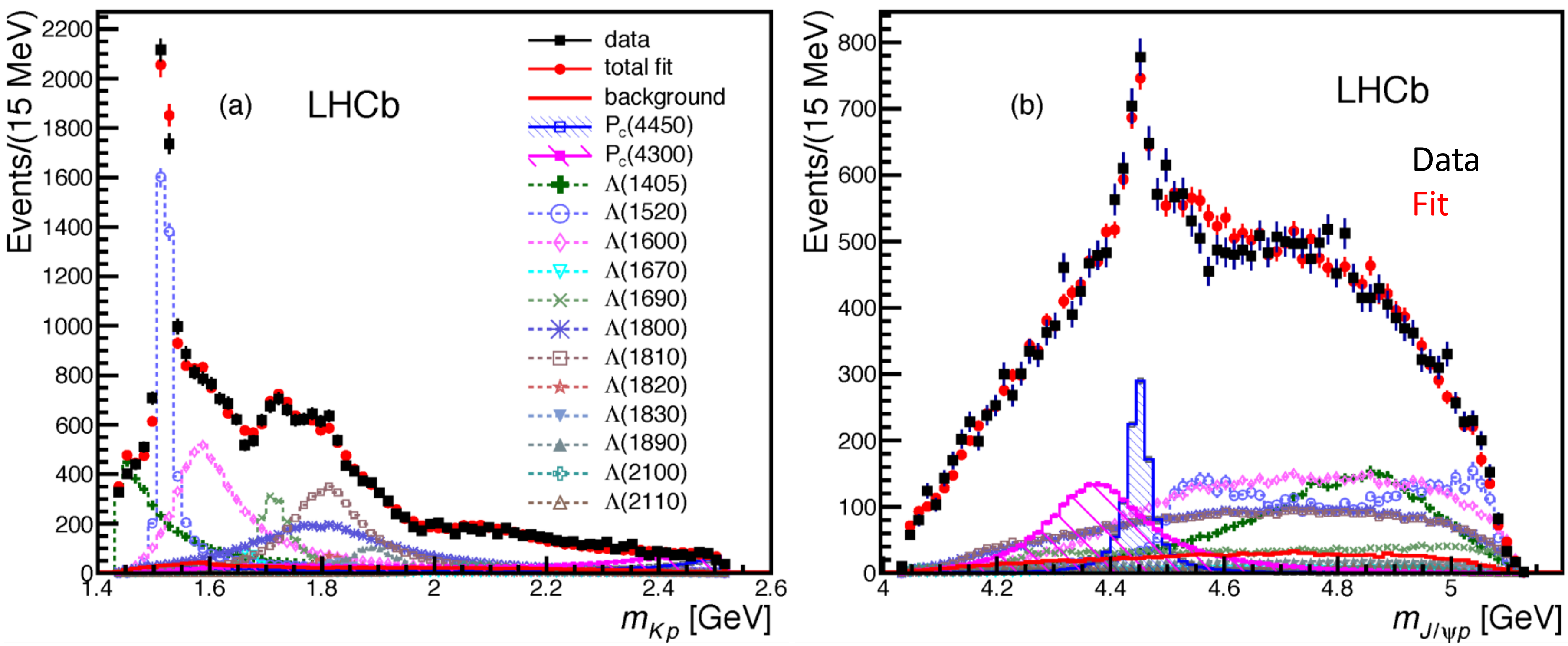
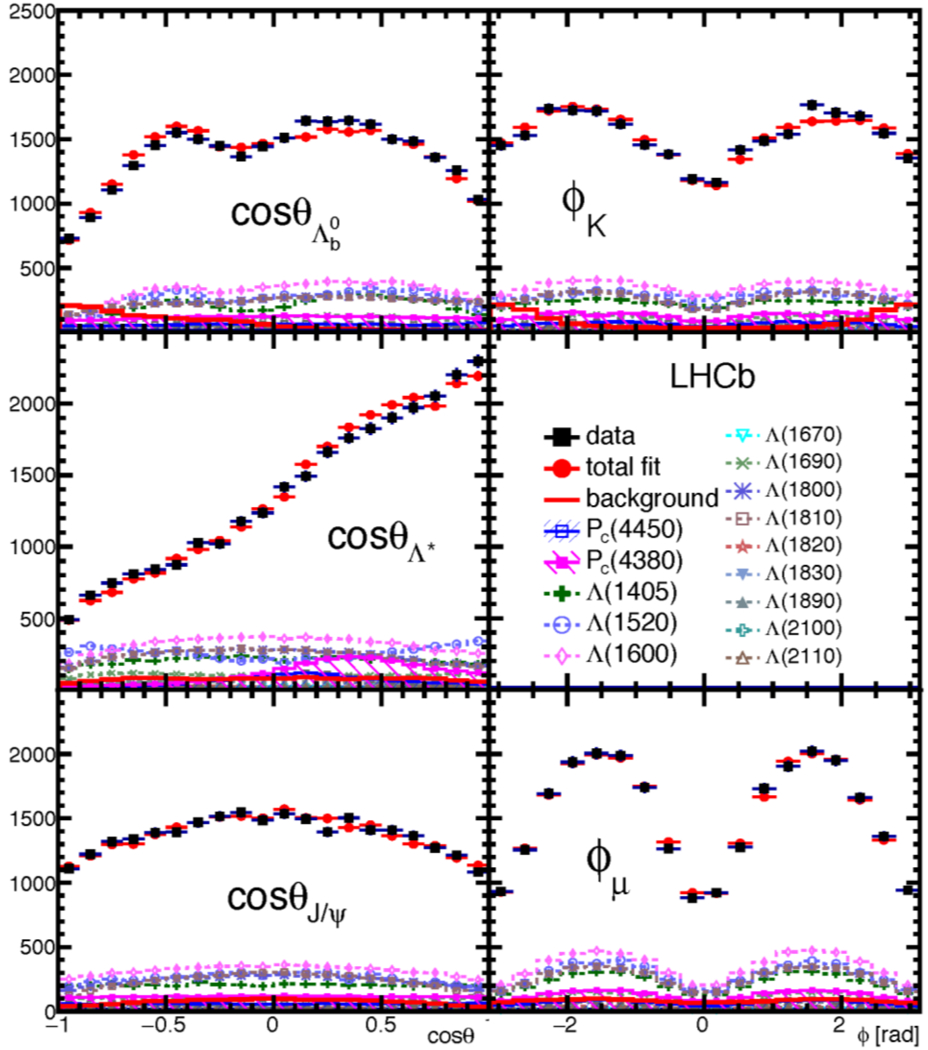
$\Lambda(2350)$	$9/2^+$	2350	150	0	6
$\Lambda(2585)$	?	$\approx$2585	200	0	6
Total # of free parameters for Λ^*				64	146

Reduced model with two P_c^+'s

- Fits are good in all 6 dimensions (see next slide)!

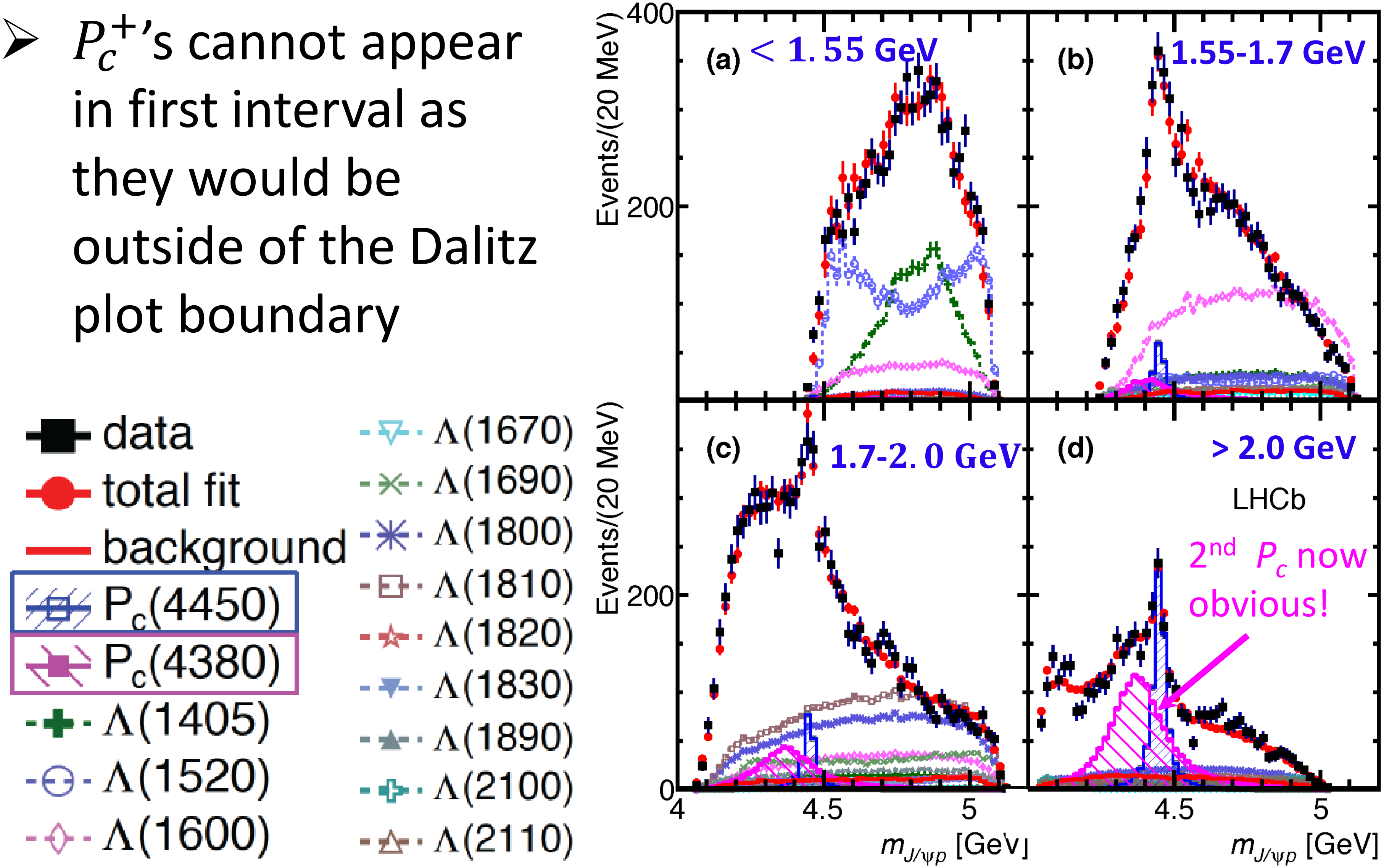


Angular distributions



$M(J/\psi\, p)$ in $M(Kp)$ Slices

- P_c^+'s cannot appear in first interval as they would be outside of the Dalitz plot boundary



Quantum numbers

- Tested all J^P combinations up to spin $\frac{7}{2}$
- **Best fit has $\boldsymbol{J^P = \left[\frac{3}{2}^- \text{(low)}, \frac{5}{2}^+ \text{(high)}\right]}$**
  - Plots shown correspond to this combination
- $\left[\frac{3}{2}^+ \text{(low)}, \ \frac{5}{2}^- \text{(high)}\right]$ & $\left[\frac{5}{2}^+ \text{(low)}, \frac{3}{2}^- \text{(high)}\right]$ are also possible: $\Delta(-2\ln\mathcal{L}) < 3^2$
- All others are ruled out: $\Delta(-2\ln\mathcal{L}) > 5.9^2$

Fit results

Resonance	Mass (MeV)	Width (MeV)	Fit fraction (%)
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$8.4 \pm 0.7 \pm 4.2$
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$4.1 \pm 0.5 \pm 1.1$
$\Lambda(1405)$			$15 \pm 1 \pm 6$
$\Lambda(1520)$			$19 \pm 1 \pm 4$

Systematic uncertainty discussed in next slide

Significances

- Fit improves greatly, for 1 P_c^+ $\Delta(-2\ln L)=14.7^2$
  adding the 2nd P_c^+ **additionally** improves by 11.6^2
  ➔ Adding both P_c^+'s improves 18.7^2

- Toy MCs are used to obtain significances based on $\Delta(-2\ln L)$

- To include systematic uncertainty, the extended model fits are used:
  - 1st $P_c(4450)^+$: 12σ
  - 2st $P_c(4380)^+$: $9\ \sigma$

Systematic Uncertainties

Source	M_0 (MeV)		Γ_0 (MeV)		Fit fractions (%)			
	low	high	low	high	low	high	$\Lambda(1405)$	$\Lambda(1520)$
Extended vs. reduced	21	0.2	54	10	3.14	0.32	1.37	0.15
Λ^* masses & widths	7	0.7	20	4	0.58	0.37	2.49	2.45
Proton ID	2	0.3	1	2	0.27	0.14	0.20	0.05
$10 < p_p < 100$ GeV	0	1.2	1	1	0.09	0.03	0.31	0.01
Nonresonant	3	0.3	34	2	2.35	0.13	3.28	0.39
Separate sidebands	0	0	5	0	0.24	0.14	0.02	0.03
J^P $(3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$	10	1.2	34	10	0.76	0.44		
$d = 1.5 - 4.5$ GeV^{-1}	9	0.6	19	3	0.29	0.42	0.36	1.91
$L_{\Lambda_b^0}^{P_c}$ $\Lambda_b^0 \to P_c^+$ (low/high)K^-	6	0.7	4	8	0.37	0.16		
L_{P_c} P_c^+ (low/high) $\to J/\psi\, p$	4	0.4	31	7	0.63	0.37		
$L_{\Lambda_b^0}^{\Lambda_n^*}$ $\Lambda_b^0 \to J/\psi\, \Lambda^*$	11	0.3	20	2	0.81	0.53	3.34	2.31
Efficiencies	1	0.4	4	0	0.13	0.02	0.26	0.23
Change $\Lambda(1405)$ coupling	0	0	0	0	0	0	1.90	0
Overall	29	2.5	86	19	4.21	1.05	5.82	3.89
sFit/cFit cross check	5	1.0	11	3	0.46	0.01	0.45	0.13

Λ^* modelling contributes the largest

Systematic uncertainties

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Alternate J^P fits give sizeable uncertainty

Systematic uncertainties

Source	M_0 (MeV)		Γ_0 (MeV)		Fit fractions (%)			
	low	high	low	high	low	high	$\Lambda(1405)$	$\Lambda(1520)$
Extended vs. reduced	21	0.2	54	10	3.14	0.32	1.37	0.15
Λ^* masses & widths	7	0.7	20	4	0.58	0.37	2.49	2.45
Proton ID	2	0.3	1	2	0.27	0.14	0.20	0.05
$10 < p_p < 100$ GeV	0	1.2	1	1	0.09	0.03	0.31	0.01
Nonresonant	3	0.3	34	2	2.35	0.13	3.28	0.39
Separate sidebands	0	0	5	0	0.24	0.14	0.02	0.03
J^P $(3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$	10	1.2	34	10	0.76	0.44		
$d = 1.5 - 4.5$ GeV^{-1}	9	0.6	19	3	0.29	0.42	0.36	1.91
$L^{P_c}_{\Lambda_b^0}$ $\Lambda_b^0 \to P_c^+$ (low/high)K^-	6	0.7	4	8	0.37	0.16		
L_{P_c} P_c^+ (low/high) $\to J/\psi\, p$	4	0.4	31	7	0.63	0.37		
$L^{\Lambda^*_n}_{\Lambda_b^0}$ $\Lambda_b^0 \to J/\psi\, \Lambda^*$	11	0.3	20	2	0.81	0.53	3.34	2.31
Efficiencies	1	0.4	4	0	0.13	0.02	0.26	0.23
Change $\Lambda(1405)$ coupling	0	0	0	0	0	0	1.90	0
Overall	29	2.5	86	19	4.21	1.05	5.82	3.89
sFit/cFit cross check	5	1.0	11	3	0.46	0.01	0.45	0.13

Varying choices in mass depend function also give sizeable uncertainty

Systematic uncertainties

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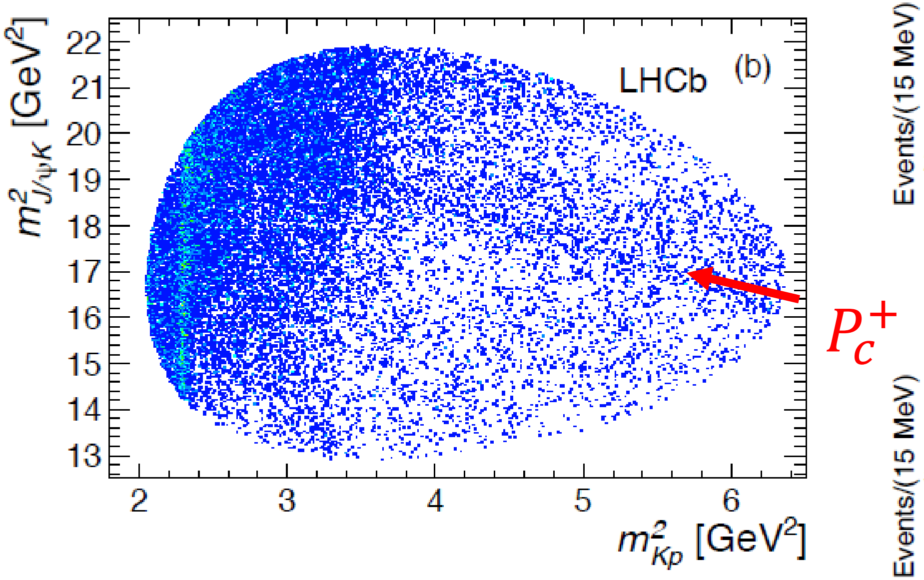
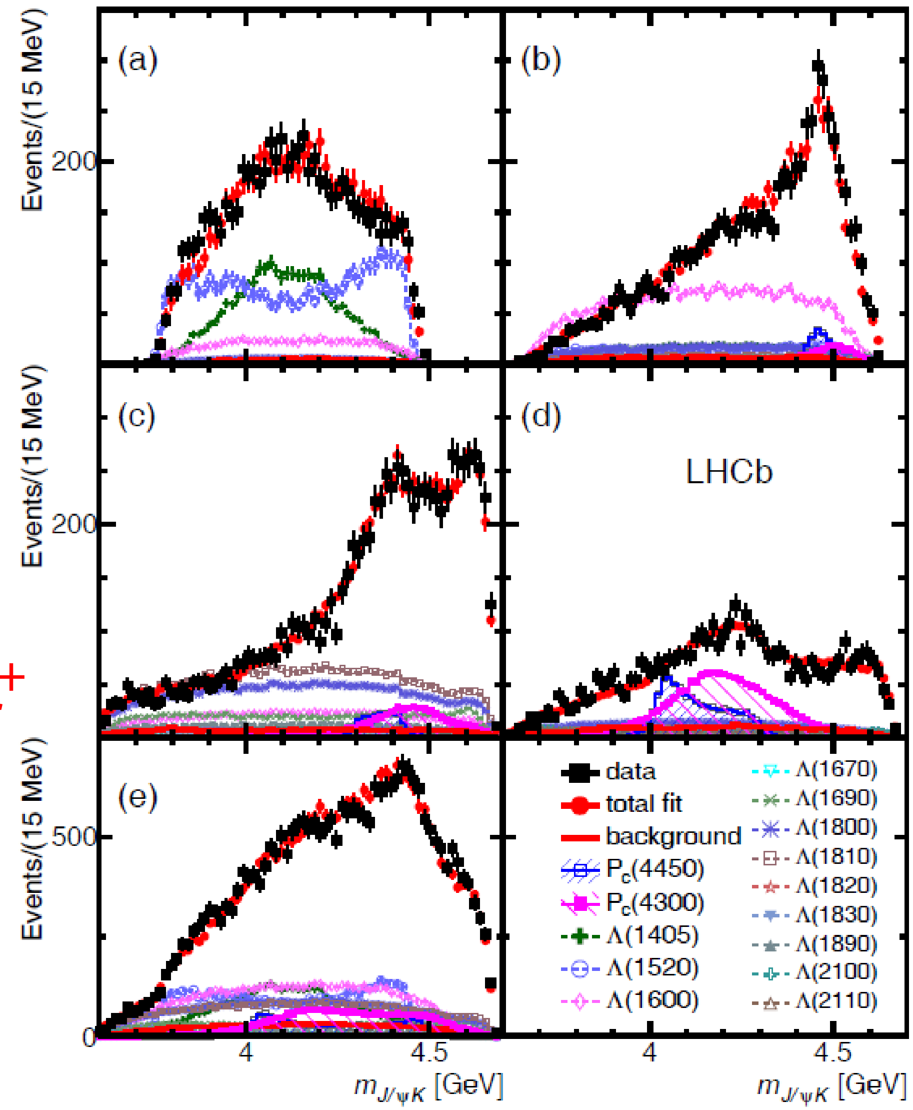
sFit/cFit give consistent results

$J/\psi K^-$ system

- $J/\psi\, K$ system is well described by the Λ^* and P_c reflections



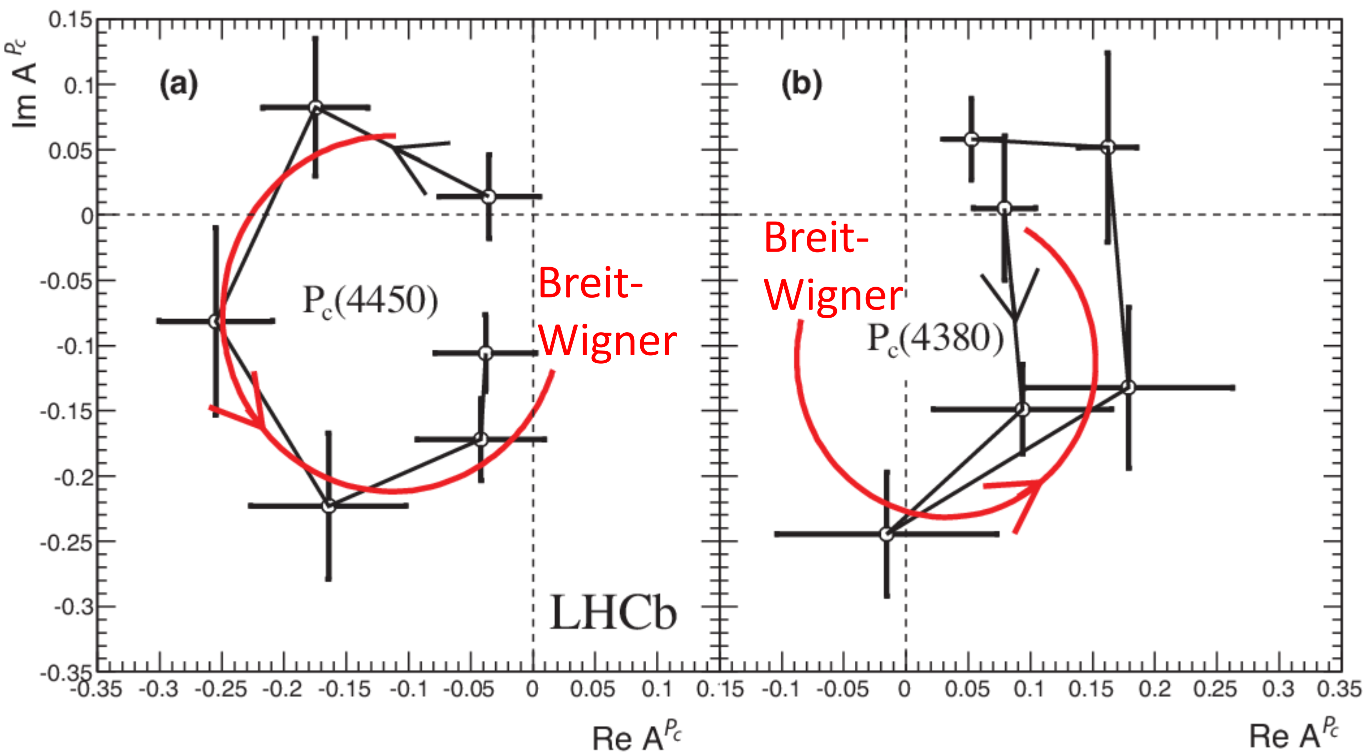


Cross-checks

- Two independently coded fitters using different background subtractions (sFit & cFit)
- Split data show consistency:
  - 2011/2012
  - magnet up/down
  - $\Lambda_b^0/\overline{\Lambda}_b^0$
  - $\Lambda_b^0(\mathrm{low}\ p_\mathrm{T})/\Lambda_b^0(\mathrm{high}\ p_\mathrm{T})$
- Selection varied
  - BDTG>0.5 instead of 0.9 (default)
  - B^0 and B_s^0 reflections modelled in the fit instead of veto

Argand diagram

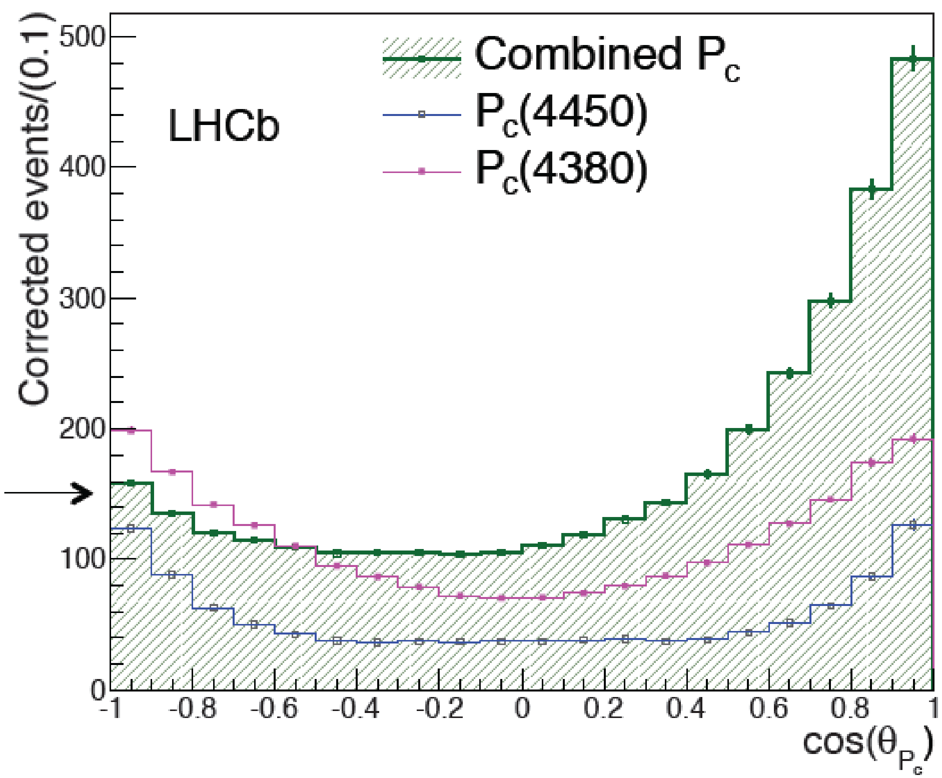
- Replace the Breit-Wigner amplitude for either one P_c^+ by 6 independent amplitudes in range of $\pm\Gamma_0$ around M_0
- $P_c(4450)^+$ shows resonance behavior: a rapid contour-clockwise change of phase when cross pole mass
- $P_c(4380)^+$ does show large phase change, but is not conclusive



Why the 2nd state is needed?

- It is demanded by the data
- Interference between opposite parity states is needed to explain the P_c^+ decay angle distribution

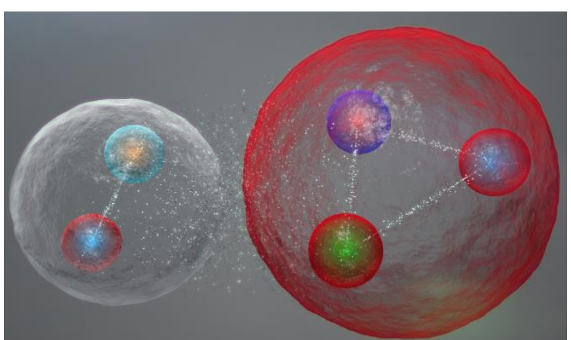
Large $m(Kp)$ region: negative interference

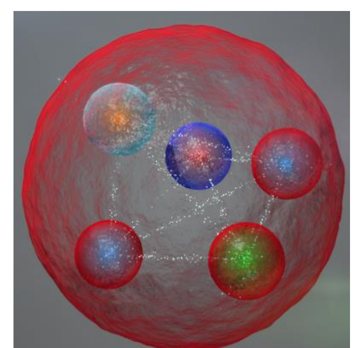


small $m(Kp)$ region: positive interference

Intepretation

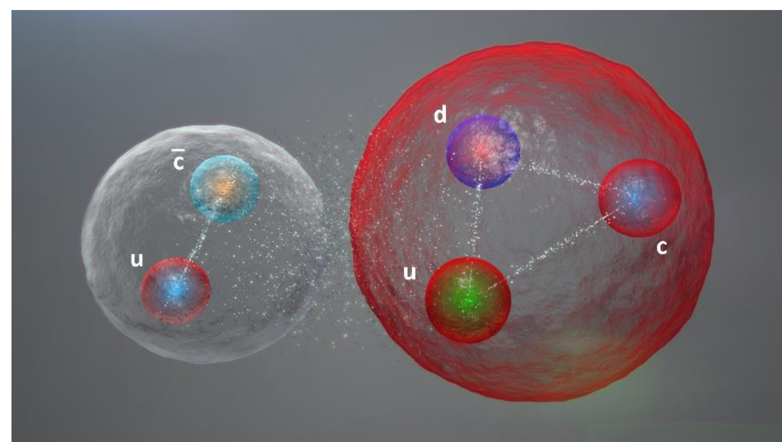
- Different binding mechanisms are possible
  - Tightly-bound
    - ✓ Two colored diquarks + one anti-quark [PRD20 (1979) 748; arXiv:1507.04980]
    - ✓ Colored diquark + colored triquark [arXiv:1507.05867]
    - ✓ Bag model [NPB123 (1977) 507]
  - Weakly bound “molecules” of baryon-meson
- All models must explain J^P of two states not just one
- They should also predict other properties: mass, width





Molecular models & rescattering

- Molecular models, generally with meson exchange for binding
- π-exchange models usually predict only one state, mainly $J^P = 1/2^+$, but could also include ρ exchange…
- $\Sigma_c D^{(*)}$ components?
- $\chi_{c1} p$ rescattering?



Summary

- Full amplitude analysis performed for $\Lambda_b^0 \to J/\psi\, pK^-$
- Two Breit-Wigner shaped resonances in $J/\psi p$ mass observed, with minimal quark content of $c\bar{c}uud$, therefore called pentaquark-charmonium states: $P_c(4380)^+$, $P_c(4450)^+$
  - The preferred J^P are of opposite parity, with one state having $J = \frac{3}{2}$ and the other $J = \frac{5}{2}$
- Determination their internal binding mechanism will require more study
- A lattice QCD calculation will be most welcome
- We look forward to establishing the structure of many other states or other decay modes

Outlook

- Determination their internal binding mechanism will require more study

- We look forward to establishing the structure of many other states or other decay modes

- Run II data provides good opportunities

Thank you!

Backup slides

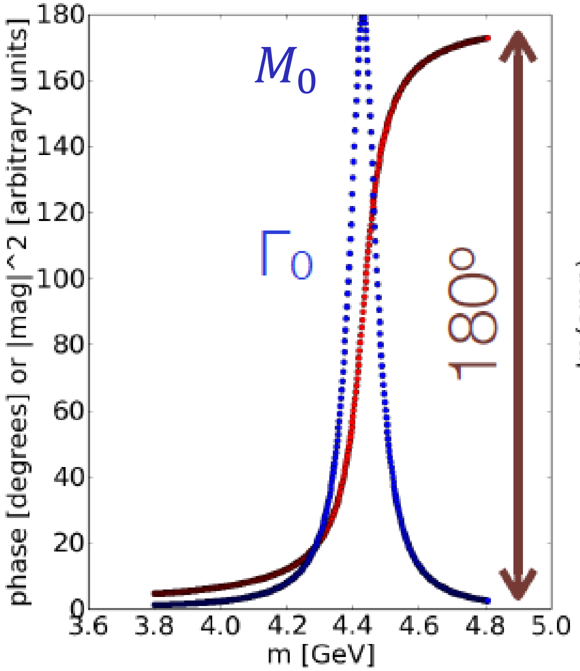
Breit-Wigner amplitude

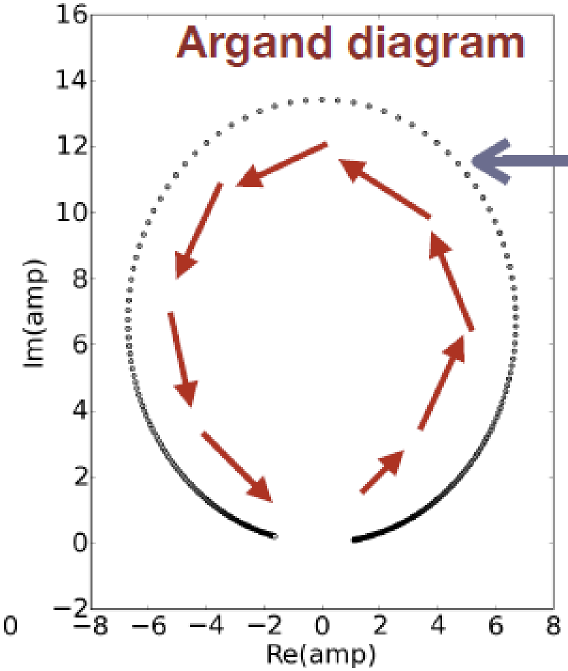
- Often a relativistic Breig-Wigner function is used to model resonance
- q is daughter momentum in the resonance rest frame

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

$$\Gamma(m) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2L+1} \frac{M_0}{m} B_L'(q,q_0,d)^2$$

Blatt-Weisskopf function for orbital angular momentum (*L*) barrier factors





- Circular trajectory in complex plane is characteristic of resonance
- Circle can be rotated by arbitrary phase
- Phase change of 180° across the pole

sFit

- Signal PDF

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

$\vec{\omega}$: fitting parameters
Φ : phase-space = pq
ϵ: efficiency

$$I(\vec{\omega}) \propto \sum_{j}^{N_{\text{MC}}} w_j^{\text{MC}}\,|\mathcal{M}(m_{Kp\,j},\Omega_j|\vec{\omega})|^2$$

- Normalization calculated using simulated PHSP MC ($\Phi\epsilon$ included)
- w^{MC} discuss later

- sFit minimizes

$$-2\ln\mathcal{L}(\vec{\omega}) = -2s_W\sum_i W_i \ln\mathcal{P}_{\text{sig}}(m_{Kp\;i},\Omega_i|\vec{\omega})$$
$$= -2s_W\sum_i W_i\ln|\mathcal{M}(m_{Kp\;i},\Omega_i|\vec{\omega})|^2 + 2s_W\,\ln I(\vec{\omega})\sum_i W_i$$
$$\boxed{-2s_W\sum_i W_i\ln[\Phi(m_{Kp\;i})\epsilon(m_{Kp\;i},\Omega_i)].}$$

W_i is sWeighs from m(J/ψKp) fits
$s_W = \Sigma_i W_i \,/\, \Sigma_i W_i^2$ constant factor to correct uncertainty

Constant (invariant of $\vec{\omega}$), is dropped
No need to know $\Phi\varepsilon$ paramerizaiton

cFit

- cFit uses events in ±2σ window (σ=7.52MeV)
- Total PDF $\mathcal{P}(m_{Kp}, \Omega | \overrightarrow{\omega}) = (1-\beta)\,\mathcal{P}_{\rm sig}(m_{Kp}, \Omega | \overrightarrow{\omega}) + \beta\,\mathcal{P}_{\rm bkg}(m_{Kp}, \Omega)$
- Background is described by sidebands 5σ-13.5σ
- cFit minimizes

Background fraction β=5.4%

$$-\ln \mathcal{L}(\overrightarrow{\omega}) = \sum_i \ln \left[|\mathcal{M}(m_{Kp\ i}, \Omega_i | \overrightarrow{\omega})|^2 + \frac{\beta\, I(\overrightarrow{\omega})}{(1-\beta) I_{\rm bkg}} \frac{\mathcal{P}^u_{\rm bkg}(m_{Kp\ i}, \Omega_i)}{\Phi(m_{Kp\ i})\epsilon(m_{Kp\ i}, \Omega_i)} \right] + N \ln I(\overrightarrow{\omega}) + \text{constant},$$

$$I_{\rm bkg} \propto \sum_j w_j^{\rm MC} \frac{\mathcal{P}^u_{\rm bkg}(m_{Kp\ j}, \Omega_j)}{\Phi(m_{Kp\ i})\epsilon(m_{Kp\ j}, \Omega_j)}$$

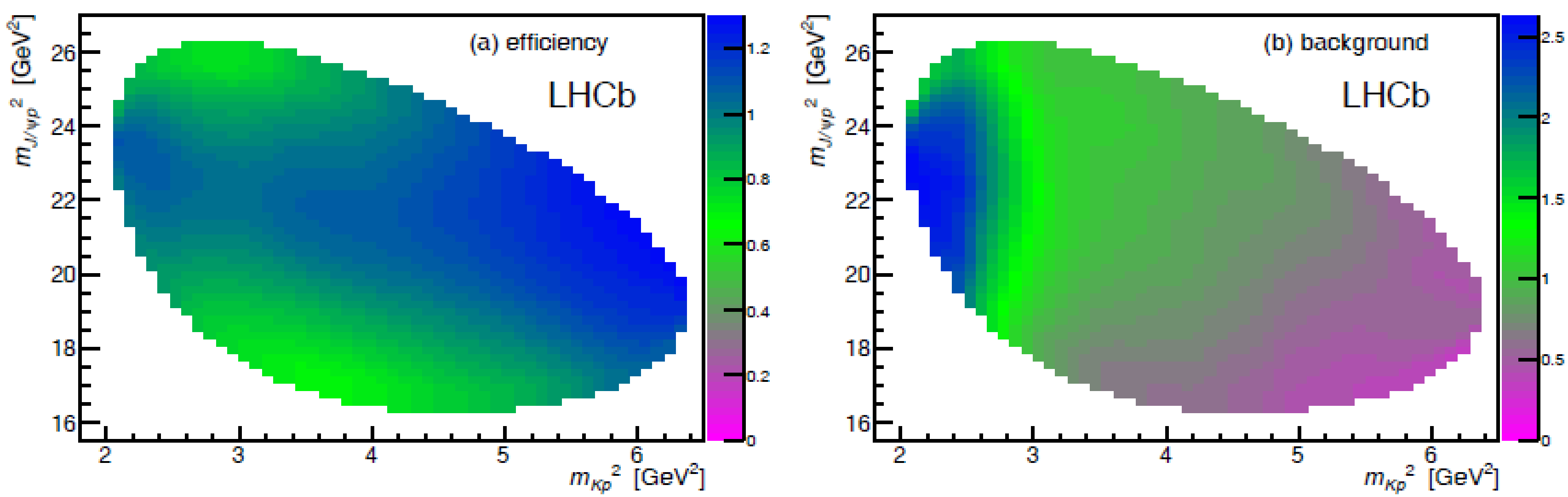
Signal efficiency parameterization becomes part of background parameterization,
effects only a tiny part of total PDF because of small β

cFit efficiency and background parameterizations

- Both use similar ways

$$\epsilon(m_{Kp},\Omega) = \epsilon_1(m_{Kp},\cos\theta_\Lambda)\cdot\epsilon_2(\cos\theta_{\Lambda_b^0}|m_{Kp})\cdot\epsilon_3(\cos\theta_{J/\psi}|m_{Kp})\cdot\epsilon_4(\phi_K|m_{Kp})\cdot\epsilon_5(\phi_\mu|m_{Kp})$$

$$\frac{\mathcal{P}^u_{\rm bkg}(m_{Kp},\Omega)}{\Phi(m_{Kp})} = P_{{\rm bkg}_1}(m_{Kp},\cos\theta_\Lambda)\cdot P_{{\rm bkg}_2}(\cos\theta_{\Lambda_b^0}|m_{Kp}) \cdot P_{{\rm bkg}_3}(\cos\theta_{J/\psi}|m_{Kp})\cdot P_{{\rm bkg}_4}(\phi_K|m_{Kp})\cdot P_{{\rm bkg}_5}(\phi_\mu|m_{Kp}).$$



Amplitude Analysis Formalism II

- The matrix element for the Λ^* decay is:

$$\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\,\lambda_p,\,\Delta\lambda_\mu} \equiv \sum_n \sum_{\lambda_{\Lambda^*}} \sum_{\lambda_\psi} \mathcal{H}^{\Lambda_b^0\to\Lambda_n^*\psi}_{\lambda_{\Lambda^*},\,\lambda_\psi} D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\,\lambda_{\Lambda^*}-\lambda_\psi}(0,\theta_{\Lambda_b^0},0)^* \\ \mathcal{H}^{\Lambda_n^*\to Kp}_{\lambda_p,\,0} D^{J_{\Lambda_n^*}}_{\lambda_{\Lambda^*},\,\lambda_p}(\phi_K,\theta_{\Lambda^*},0)^* R_n(m_{Kp})\, D^{1}_{\lambda_\psi,\,\Delta\lambda_\mu}(\phi_\mu,\theta_\psi,0)^*$$

- And for the P_c:

$$\mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\,\lambda_p^{P_c},\,\Delta\lambda_\mu^{P_c}} \equiv \sum_j \sum_{\lambda_{P_c}} \sum_{\lambda_\psi^{P_c}} \mathcal{H}^{\Lambda_b^0\to P_{cj}K}_{\lambda_{P_c},\,0} D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\,\lambda_{P_c}}(\phi_{P_c},\theta^{P_c}_{\Lambda_b^0},0)^* \\ \mathcal{H}^{P_{cj}\to\psi p}_{\lambda_\psi^{P_c},\lambda_p^{P_c}} D^{J_{P_{cj}}}_{\lambda_{P_c},\,\lambda_\psi^{P_c}-\lambda_p^{P_c}}(\phi_\psi,\theta_{P_c},0)^* R_j(m_{\psi p})\;\; D^{1}_{\lambda_\psi^{P_c},\,\Delta\lambda_\mu^{P_c}}(\phi_\mu^{P_c},\theta_\psi^{P_c},0)^*$$

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- $R(m)$ are resonance parametrizations, generally are described by Breit-Wigner amplitude

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- $\mathcal{H}$ are complex helicity couplings determined from the fit

Amplitude Analysis Formalism II

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- Wigner D-matrix arguments are Euler angles corresponding to the fitted angles.

Amplitude Analysis Formalism III

- They are added together as:

$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b^0}} \sum_{\lambda_p} \sum_{\Delta\lambda_\mu} \left| \mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} + e^{i\,\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p^{P_c}} d^{\frac{1}{2}}_{\lambda_p^{P_c},\lambda_p}(\theta_p)\, \mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\lambda_p^{P_c},\Delta\lambda_\mu} \right|^2$$

- α_μ and θ_p are rotation angles to align the final state helicity axes of the μ and p, as helicity frames used are different for the two decay chains.

- Helicity couplings $\mathcal{H} \Rightarrow$ LS amplitudes *B* via:

$$\mathcal{H}^{A\to B\,C}_{\lambda_B,\lambda_C} = \sum_L \sum_S \sqrt{\frac{2L+1}{2J_A+1}} B_{L,S} \left(\begin{array}{cc|c} J_B & J_C & S \\ \lambda_B & -\lambda_C & \lambda_B - \lambda_C \end{array} \right) \times \left(\begin{array}{cc|c} L & S & J_A \\ 0 & \lambda_B - \lambda_C & \lambda_B - \lambda_C \end{array} \right)$$

  - Convenient way to enforce parity conservation in the strong decays via: $P_A = P_B P_C (-1)^L$

Curious history of pentaquark Θ^+ search

See summary by [K. H. Hicks, Eur. Phys. J. H37 (2012) 1]

- Prediction: $\Theta^+(uudd\bar{s})$ could exist with m ≈1530 MeV, $\Gamma \leq$ 10 MeV
- In 2003-2004,10 experiments reported seeing narrow peaks of $K^0 p$ or $K^+ n$, mass from 1522 to 1555 MeV, all >4 σ
- Couldn't be confirmed by high-statistics experiments
- High statistics repeats from JLab showed the original claims were fluctuation

JLab CLAS-2006 PRL 96, 212001

$\gamma d \rightarrow p K^- K^+ n$