Observation of $J/\psi\, p$ resonances consistent with pentaquark states in $\Lambda_b \to J/\psi\, pK^-$ decays

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On behalf of LHCb Collaboration

EMMI Workshop on anti-matter, hyper-matter and exotica production at the LHC

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Contents

- Introduction: Brief pentaquark history
- Selection of $\Lambda_b \to J/\psi\, pK^-$ candidates
- Full amplitude analysis
  - – Observation of two J/ψp resonances
- Conclusion

arXiv:1507.03414
submitted to *PRL*

Multiquark states have been discussed since the quark model was proposed

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

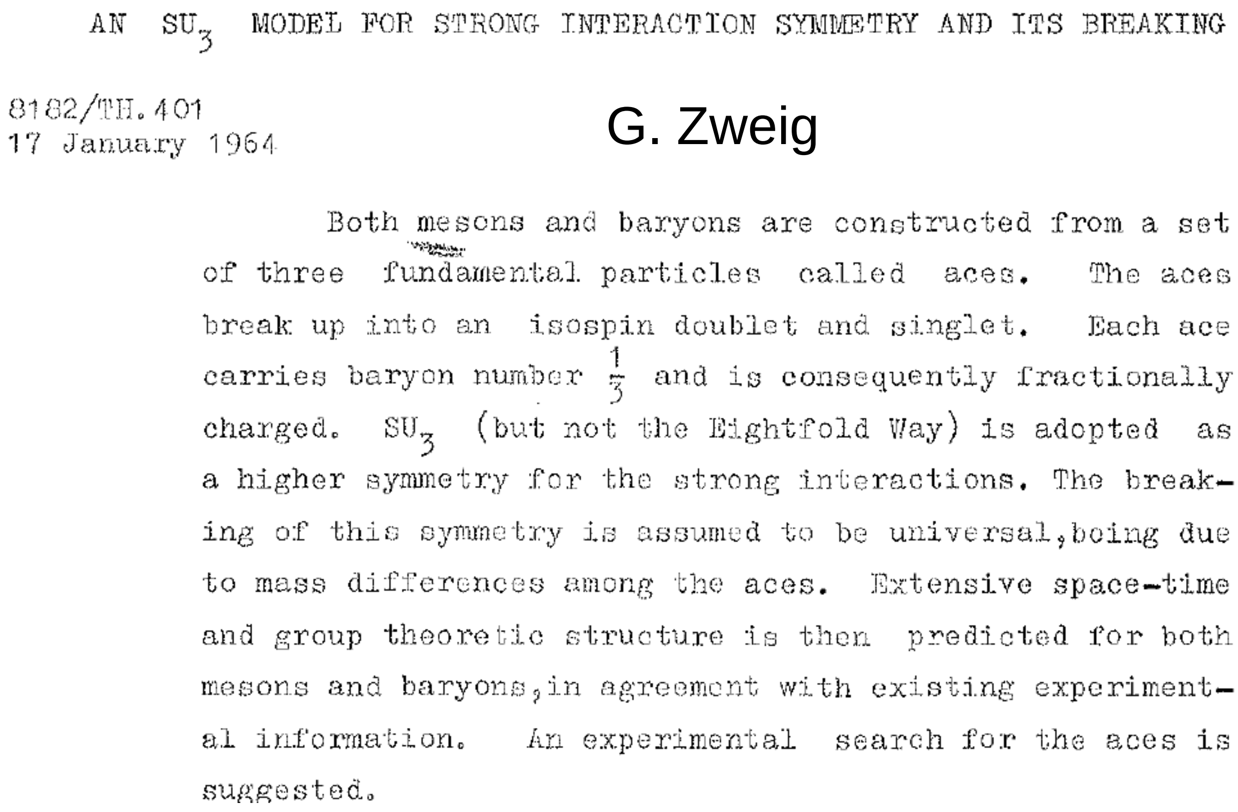
Received 4 January 1964

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 (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 the lowest meson configuration $(q\bar{q})$ similarly gives just **1** and **8**.

Multiquark states have been discussed since the quark model was proposed

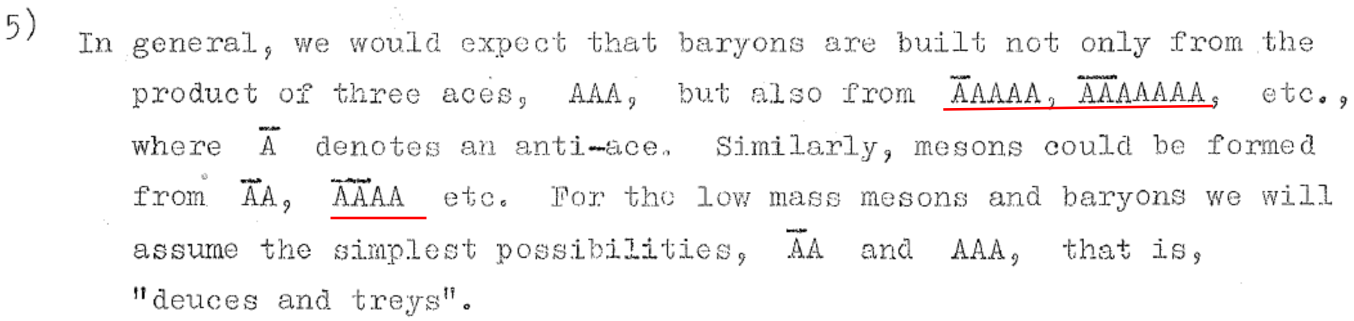


AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

8182/TH.401
17 January 1964

G. Zweig

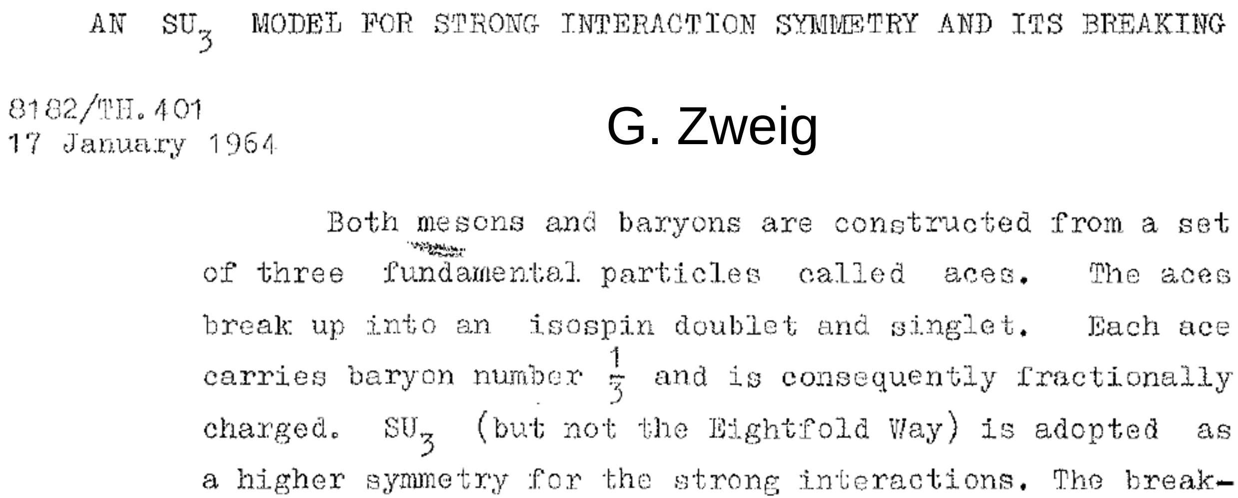
Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces break up into an isospin doublet and singlet. Each ace carries baryon number $\frac{1}{3}$ and is consequently fractionally charged. SU_3 (but not the Eightfold Way) is adopted as a higher symmetry 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".

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

Multiquark states have been discussed since the quark model was proposed



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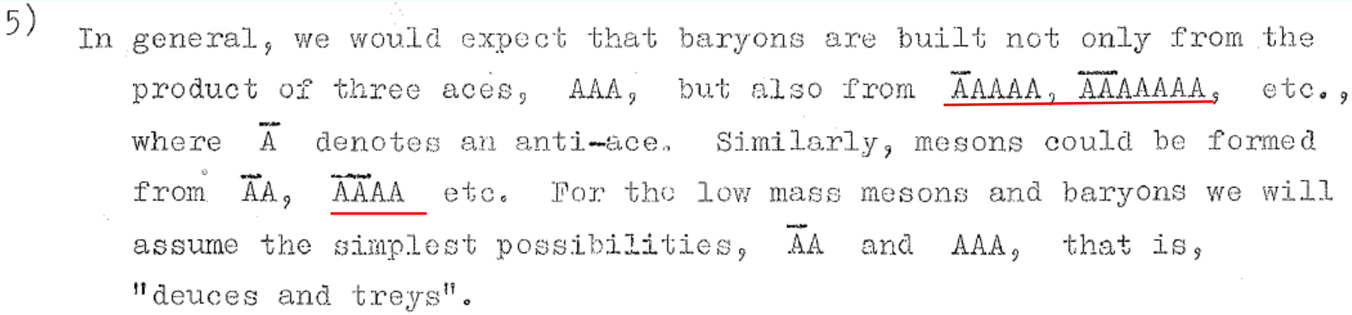
These multiquark states would be short-lived ~10^{-23} s "resonances" whose presences are detected by mass peaks & angular distributions showing the unique J^{PC} quantum numbers



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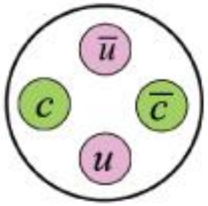
Prejudices against pentaquark

- No convincing states 50 years after Gell-mann paper proposing $qqqq\bar{q}$ states
- Previous “observations” of several pentaquark states have been refuted
- These included
  - $\Theta^+ \to K^0 p$, $K^+ n$, mass=1.54 GeV, $\Gamma \sim 10$ MeV
  - Resonance in $D^{*-}p$ at 3.10 GeV, $\Gamma = 12$ MeV
  - $\Xi^{--} \to \Xi^- \pi^-$, mass=1.862 GeV, $\Gamma < 18$ 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]

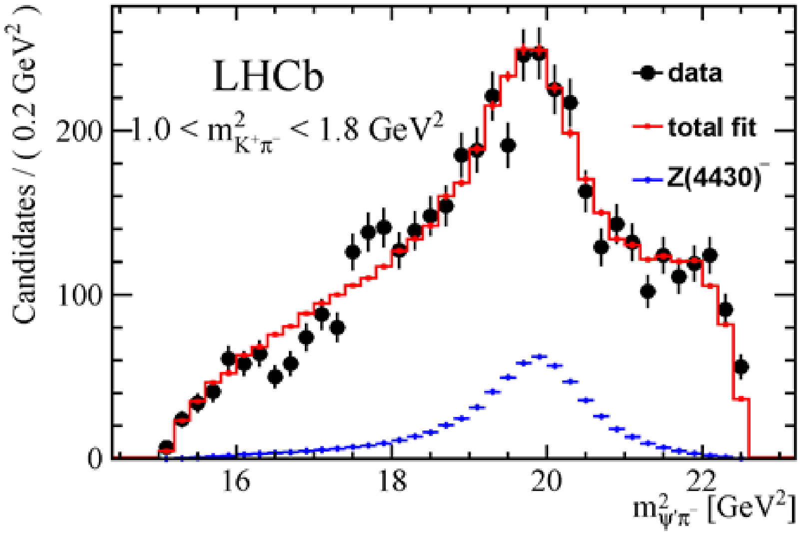
Tetraquark

- $Z(4430)^+$ state is a good candidate for tetraquark

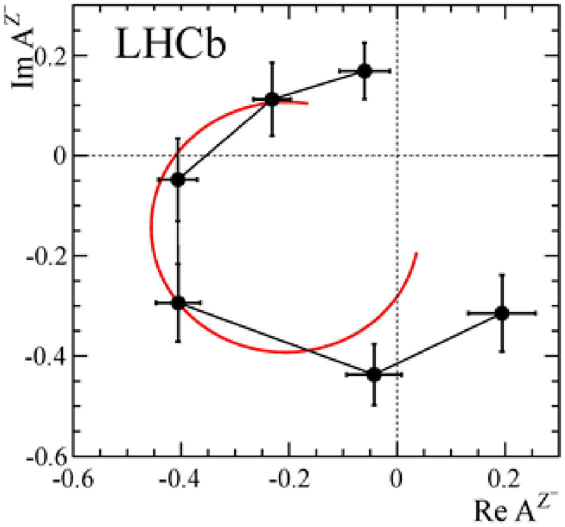


  - $Z(4430)^+ \rightarrow \psi'\pi^+$ observed by Belle in $\bar{B}^0 \rightarrow \psi' K^- \pi^+$
  - Confirmed by LHCb [PRL 112, 222002 (2014)]
  - In both of the analyses, full amplitude fit are performed

[Belle, PRL 100 142001 (2008)]
[Belle, PRD 88, 074026 (2013)]

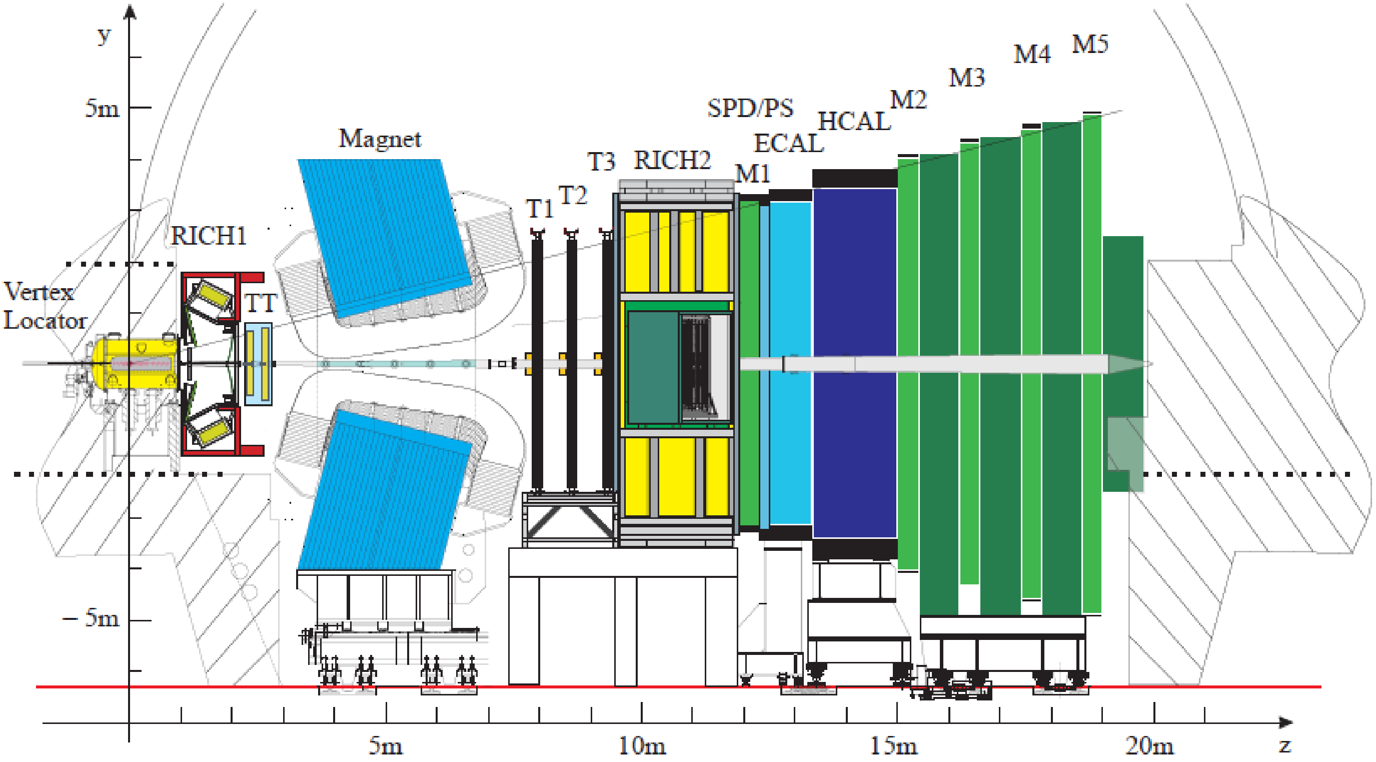


Argand diagram



- This gives support to the possibility of pentaquark states

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 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 $\epsilon(\pi \to K) \sim 5\%$

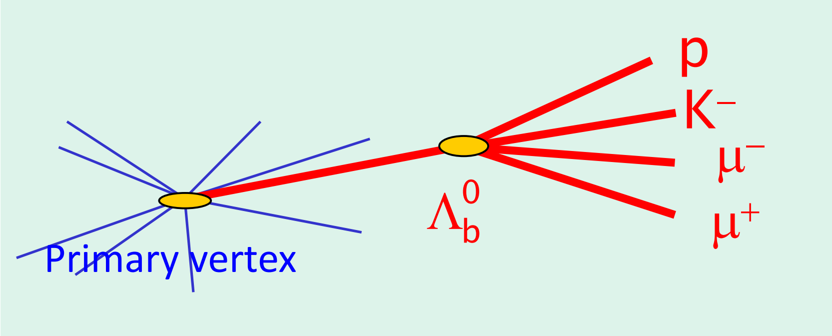
Muon ID: $\epsilon(\mu \to \mu) \sim 97\%$ mis-ID $\epsilon(\pi \to \mu) \sim 1-3\%$

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

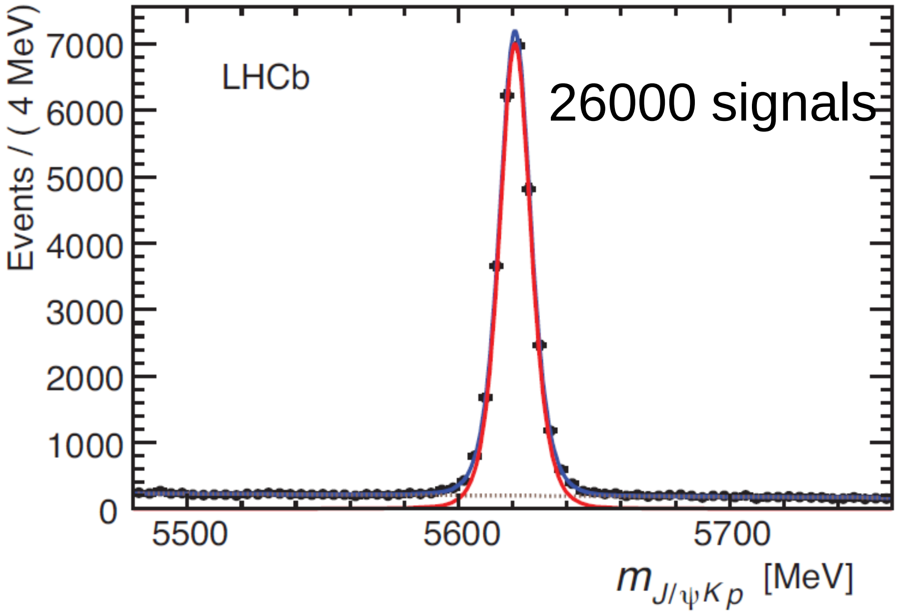
Data and selection of $\Lambda_b \to J/\psi\, pK^-$

- $\Lambda_b \to J/\psi\, pK^-$ was first observed by LHCb and used to measure the Λ_b lifetime

[PRL 111, 102003 (2013)]

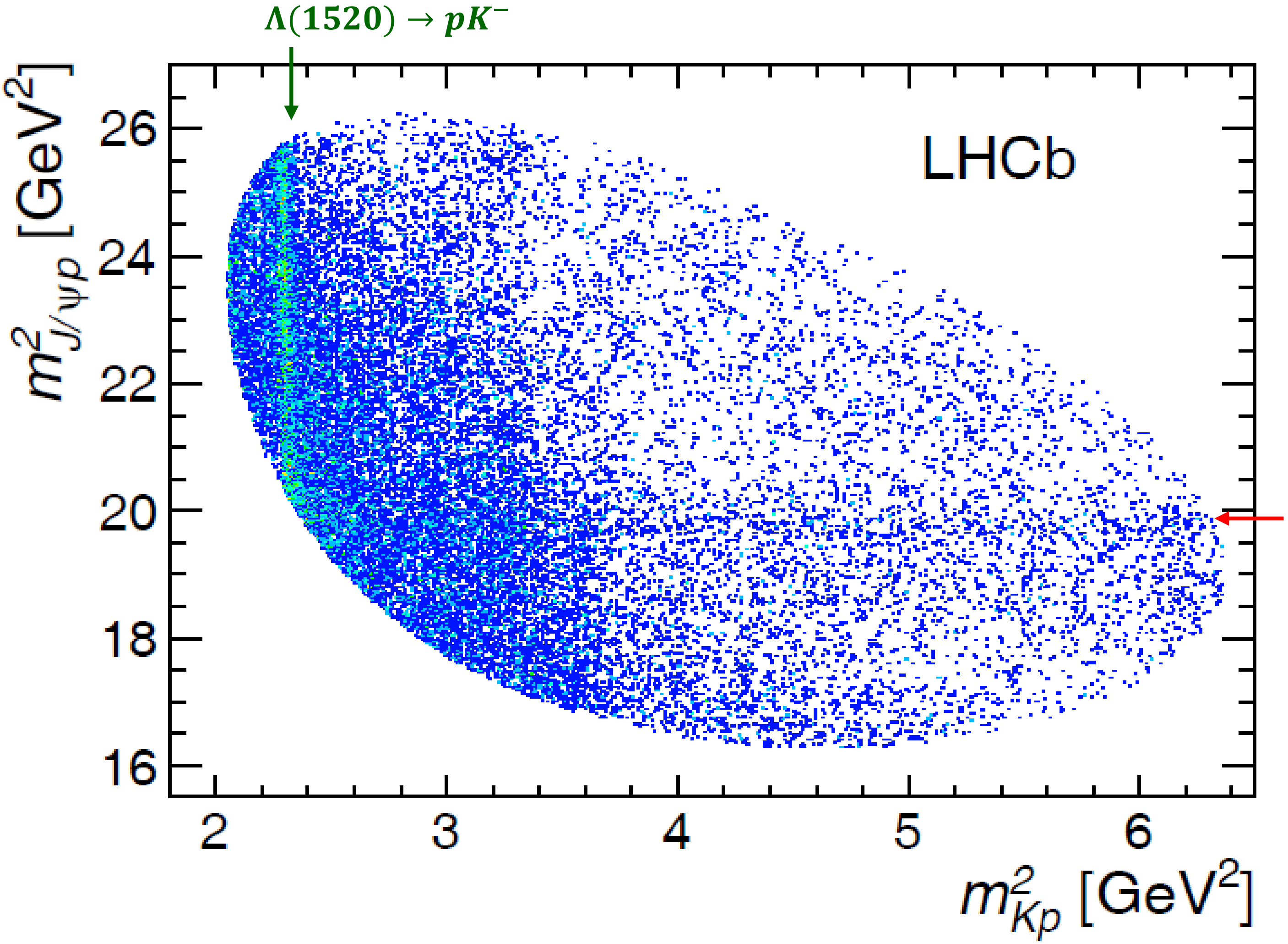


- LHCb Run I Data 3fb^{-1}
- Standard preselection
- Followed by selection with BDTG (gradient Boosted Decision) technique using 8 variables
- Veto $B_s^0 \to J/\psi K^+K^-$and $B^0 \to J/\psi K^+\pi^-$ reflections where $K^-$and π^- are misID as proton



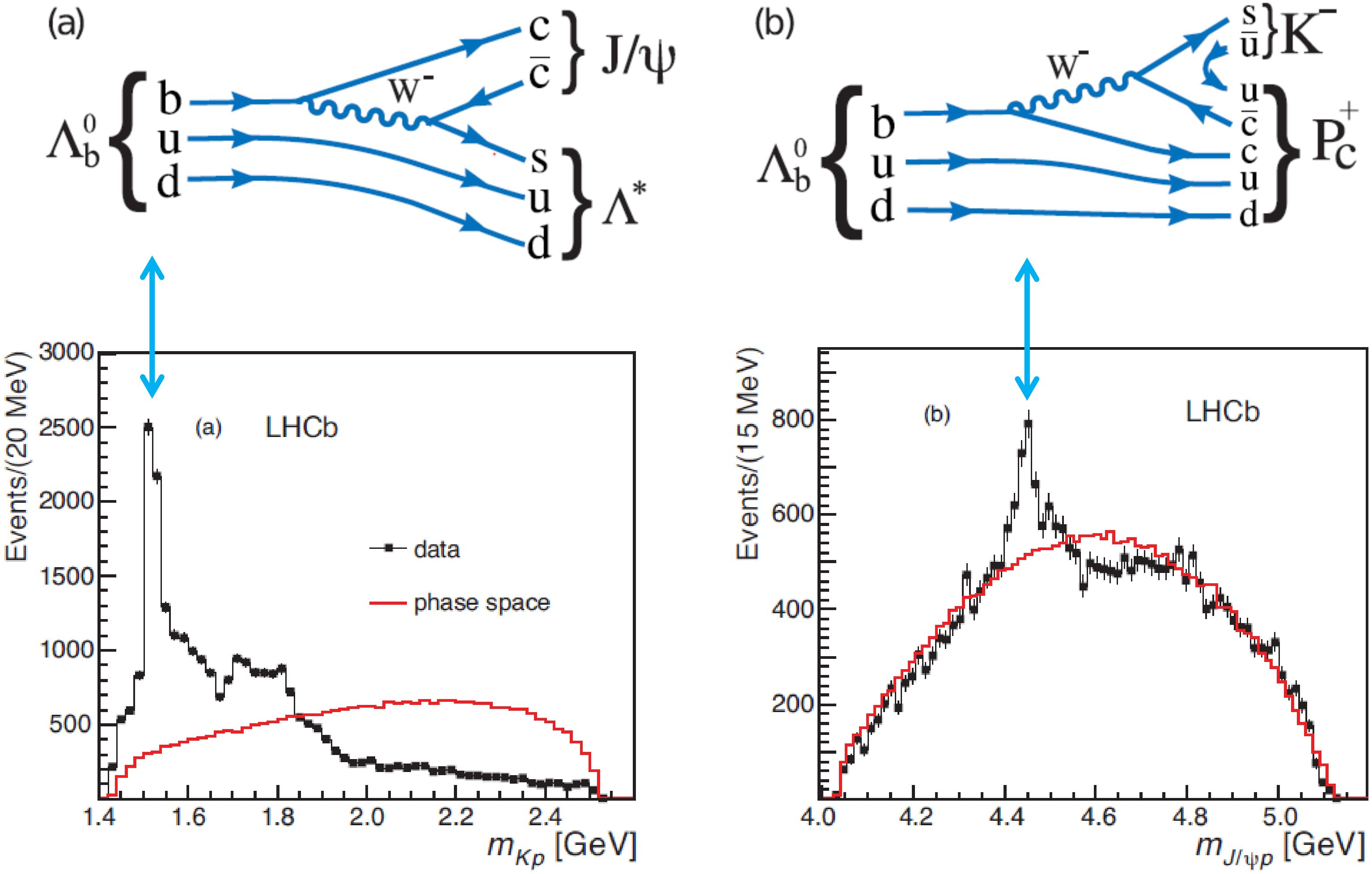
5.4% background in ±2σ

“Dalitz-plot”



A clear but unusual feature

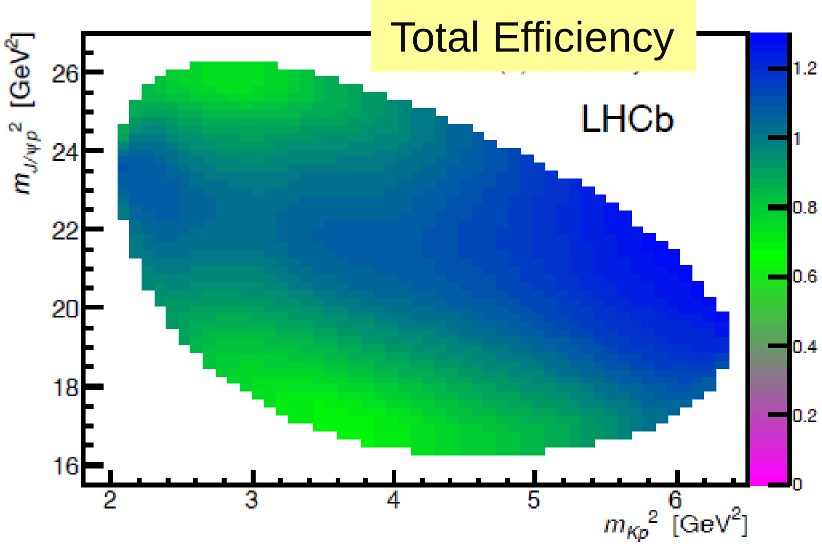
Projections of “Dalitz-plot”



Does this diagram exist?

Is the peak “an artifact”?

- Many checks done that shows this is not be the case:
  - Reflections of B^0 and B_s are vetoed
  - Ξ_b decays checked
  - Efficiency doesn’t make narrow peak
  - Sideband background doesn’t peak
  - Clones & ghost tracks eliminated


Total Efficiency

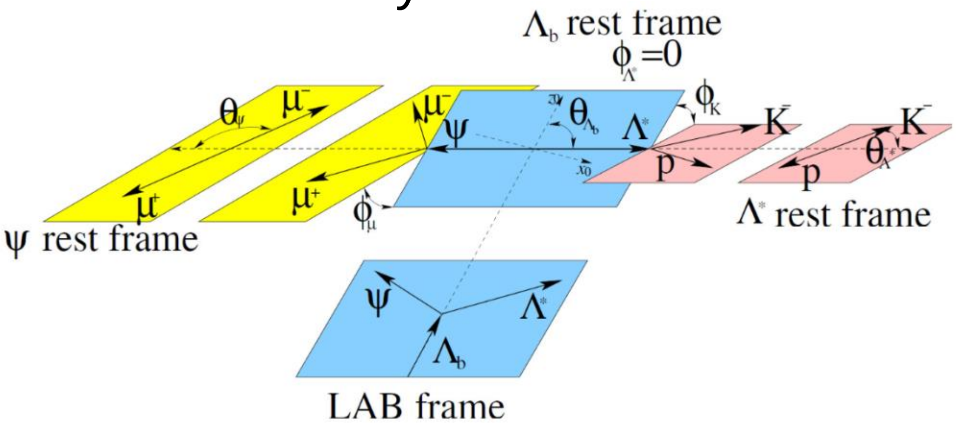
- Can interference between Λ^* resonances generate a peak in the J/ψp mass spectrum?
  - A full amplitude analysis is performed using all known Λ^* resonances

Amplitude Analysis Formalism

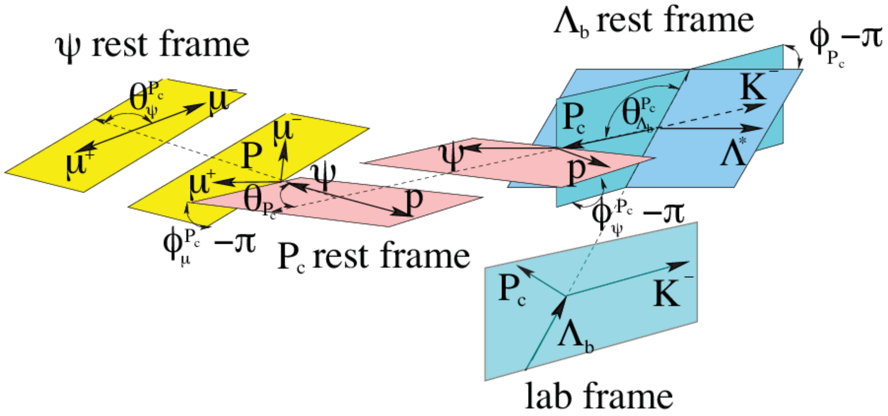
- Helicity formalism
  - Allows for the conventional $\Lambda^* \rightarrow pK$ resonances to interfere with pentaquark states $P_c^+ \rightarrow J/\psi\, p$
  - Use m(K⁻p) & 5 decay angles as fit parameters.

So 6D fit

Λ^* Decay Chain

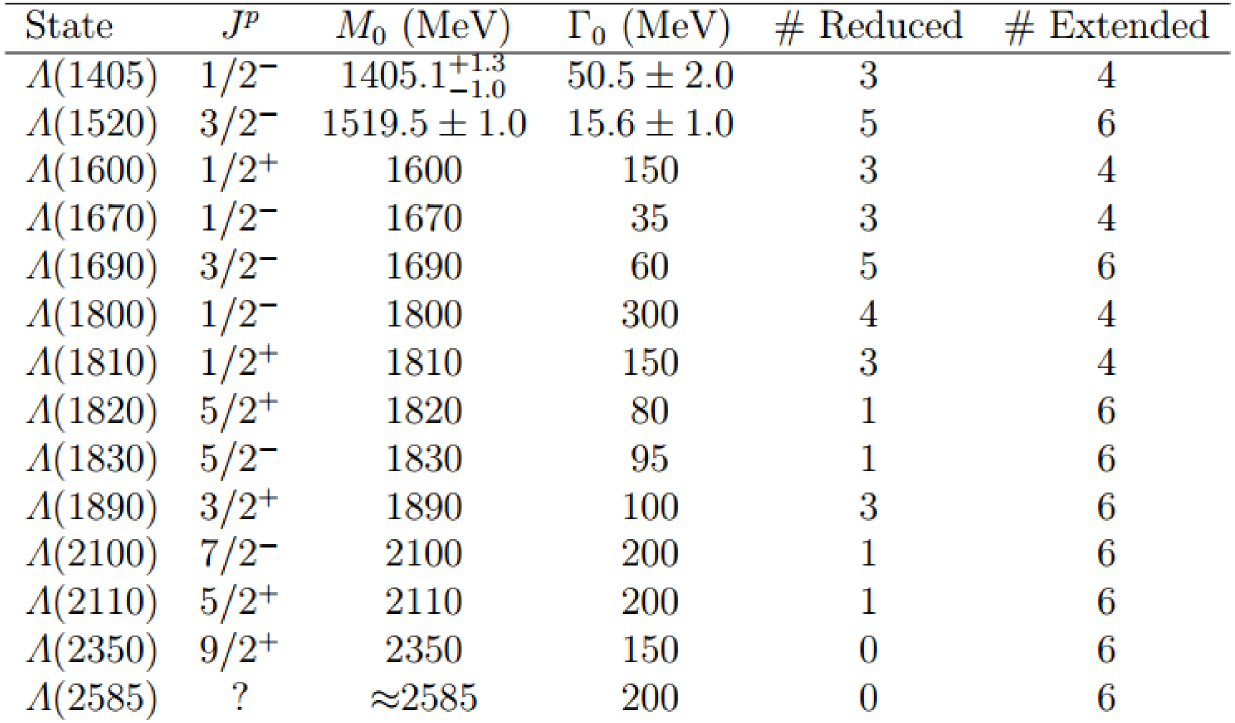


P_c^+ Decay Chain



Λ^* Resonances

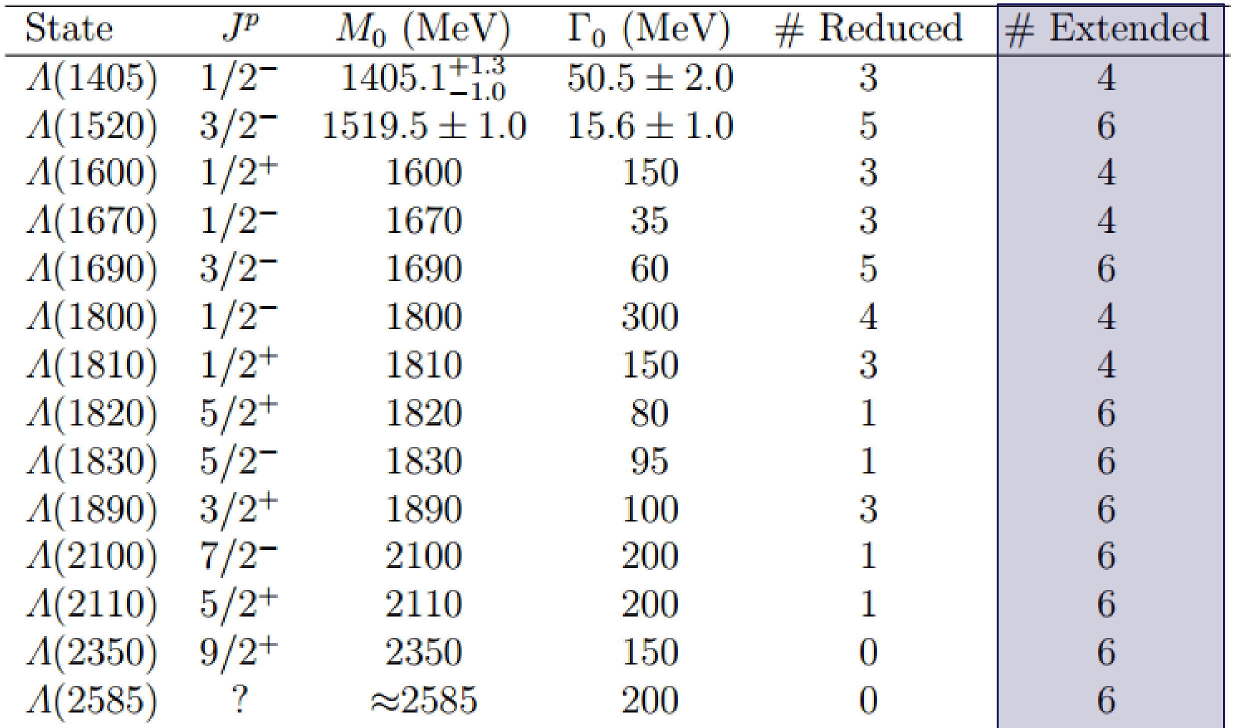
- Each Λ^* resonance: J=1/2 (>1/2) has 4 (6) complex couplings
- Masses and widths are fixed to the PDG values, uncertainties are considered as systematics
- Two models: “reduced” and “extended” to test on the dependence of the Λ^* model



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



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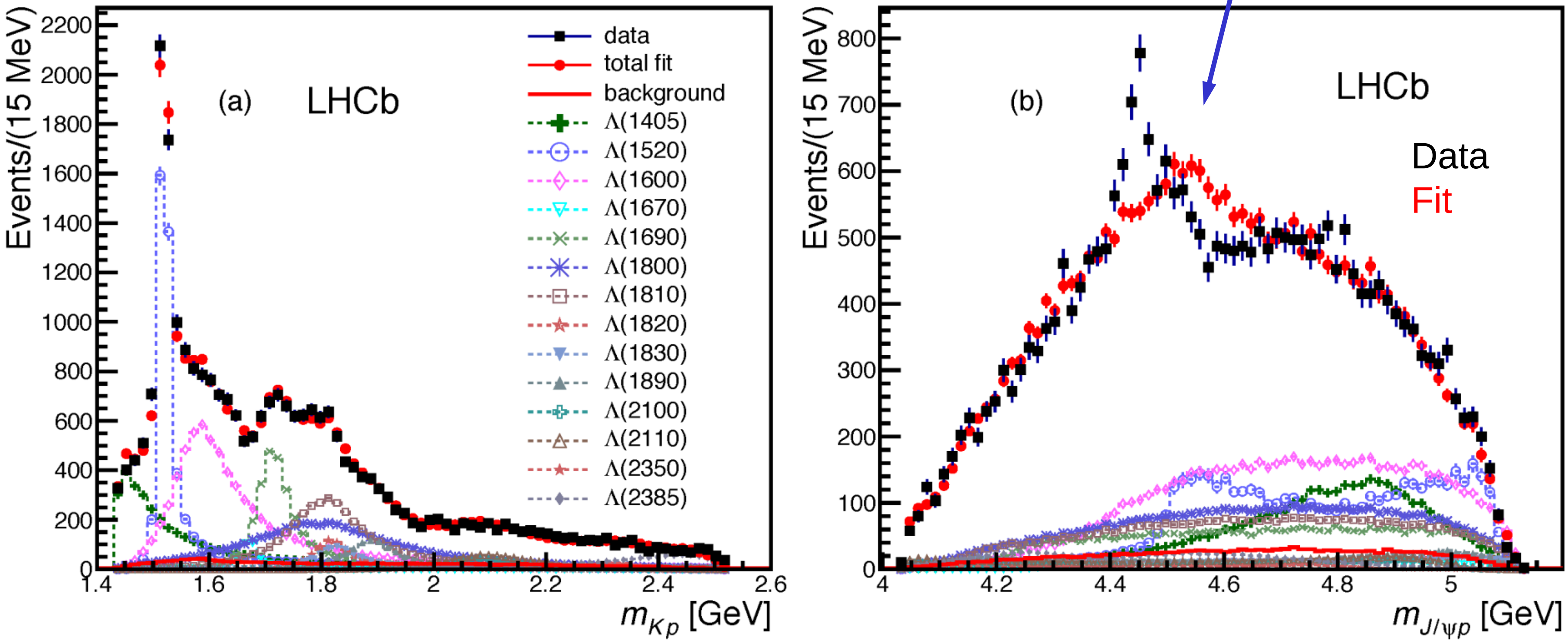
$\Lambda(2585)$	?	≈ 2585	200	0	6
Total # of free parameters for Λ^*				64	146

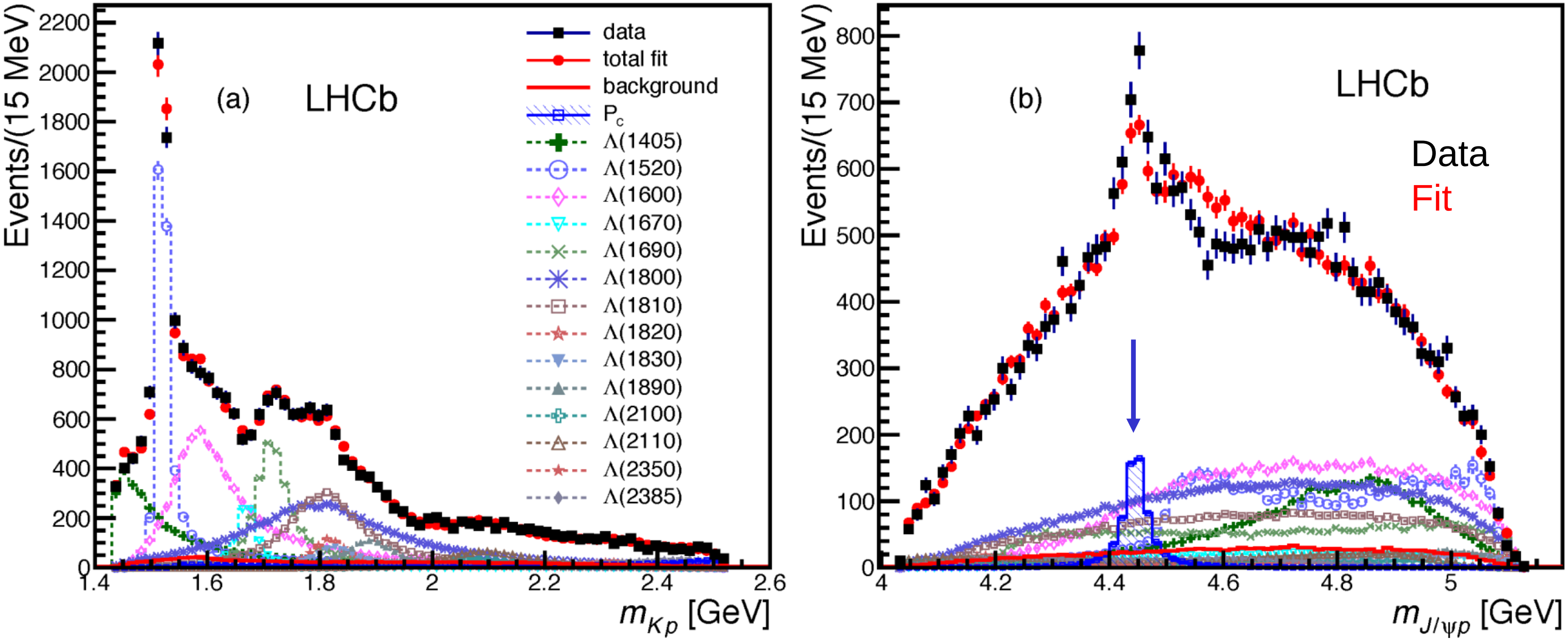
Extended model fits with only Λ^*

- Fails to reproduce the $M(J/\psi\, p)$ peaking structures!
- Other possibilities:
  - All Σ^{*0} (I=1), isospin violating decay
  - two new Λ^* with free m&Γ
  - 4 non-resonant Λ^* with $J^P = 1/2^{\pm}$ and $3/2^{\pm}$
- Still fail to describe the data



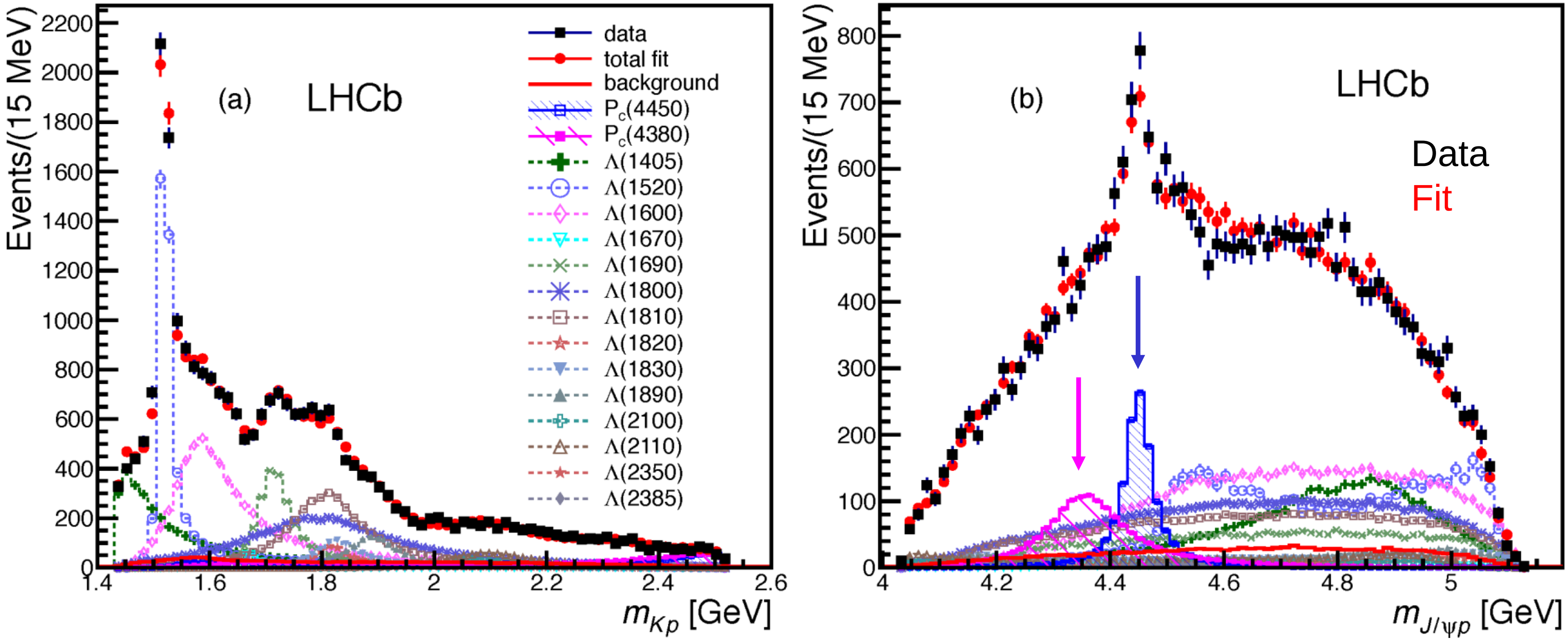
Extended model fits with 1 P_c^+

- Try all J^P up to $7/2^{\pm}$. All don't give good fit
    - 8/10 free parameters for a P_c^+ of J=1/2 or >1/2



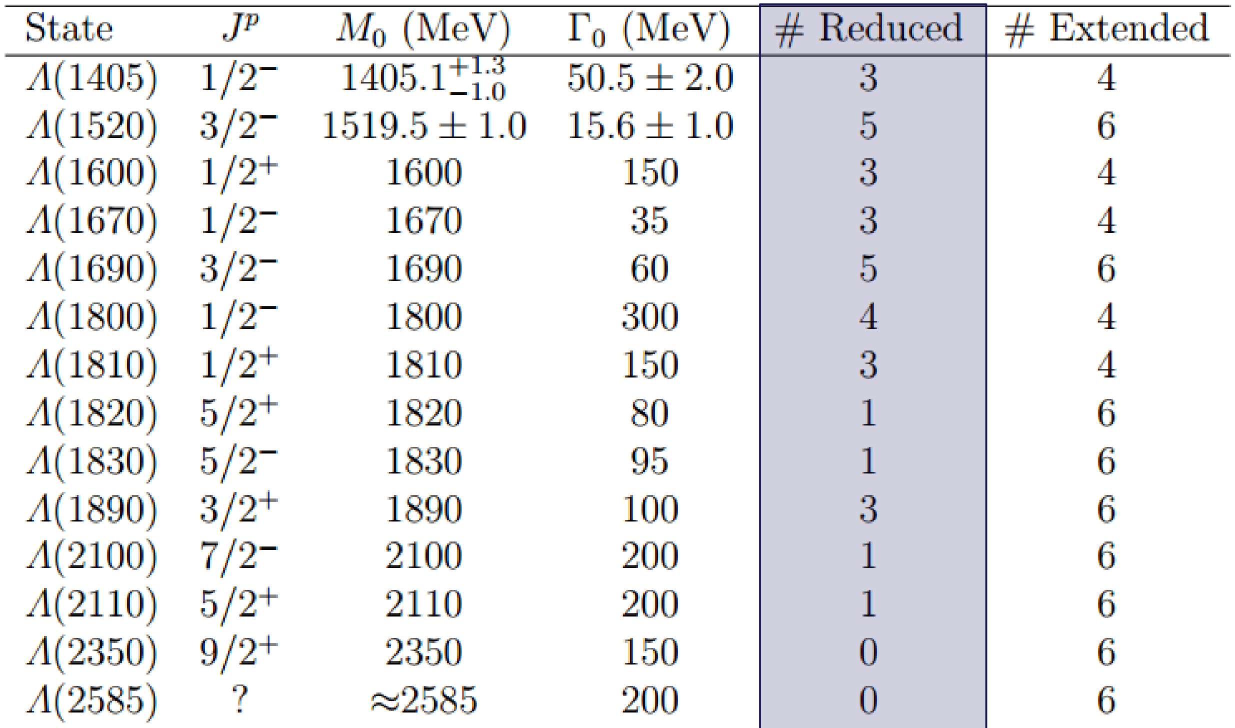
Extended model fits with 2 P_c^+

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



Reduced Λ^* model: default model

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



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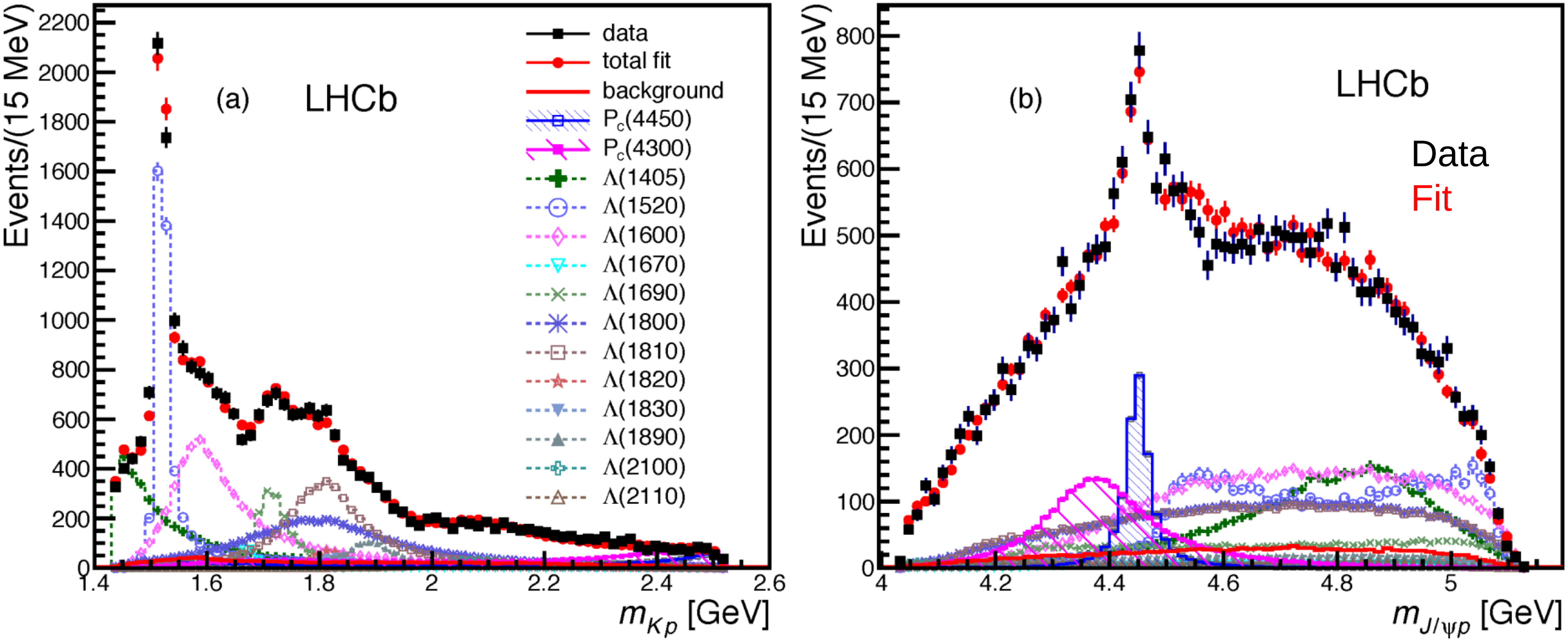
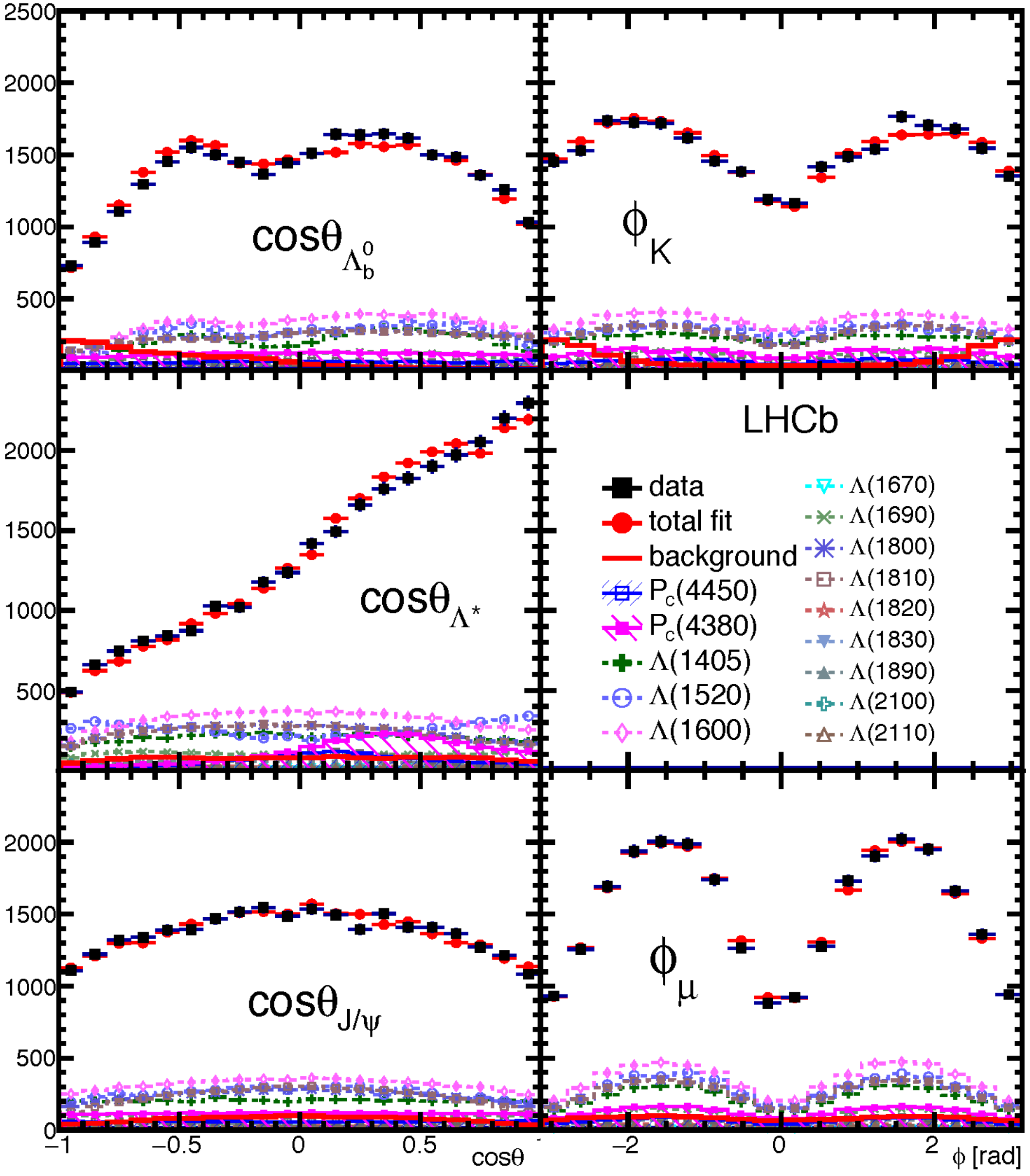
$\Lambda(2585)$	?	$\approx$2585	200	0	6
Total # of free parameters for Λ^*				64	146

2 P_c^+ fit in reduced model

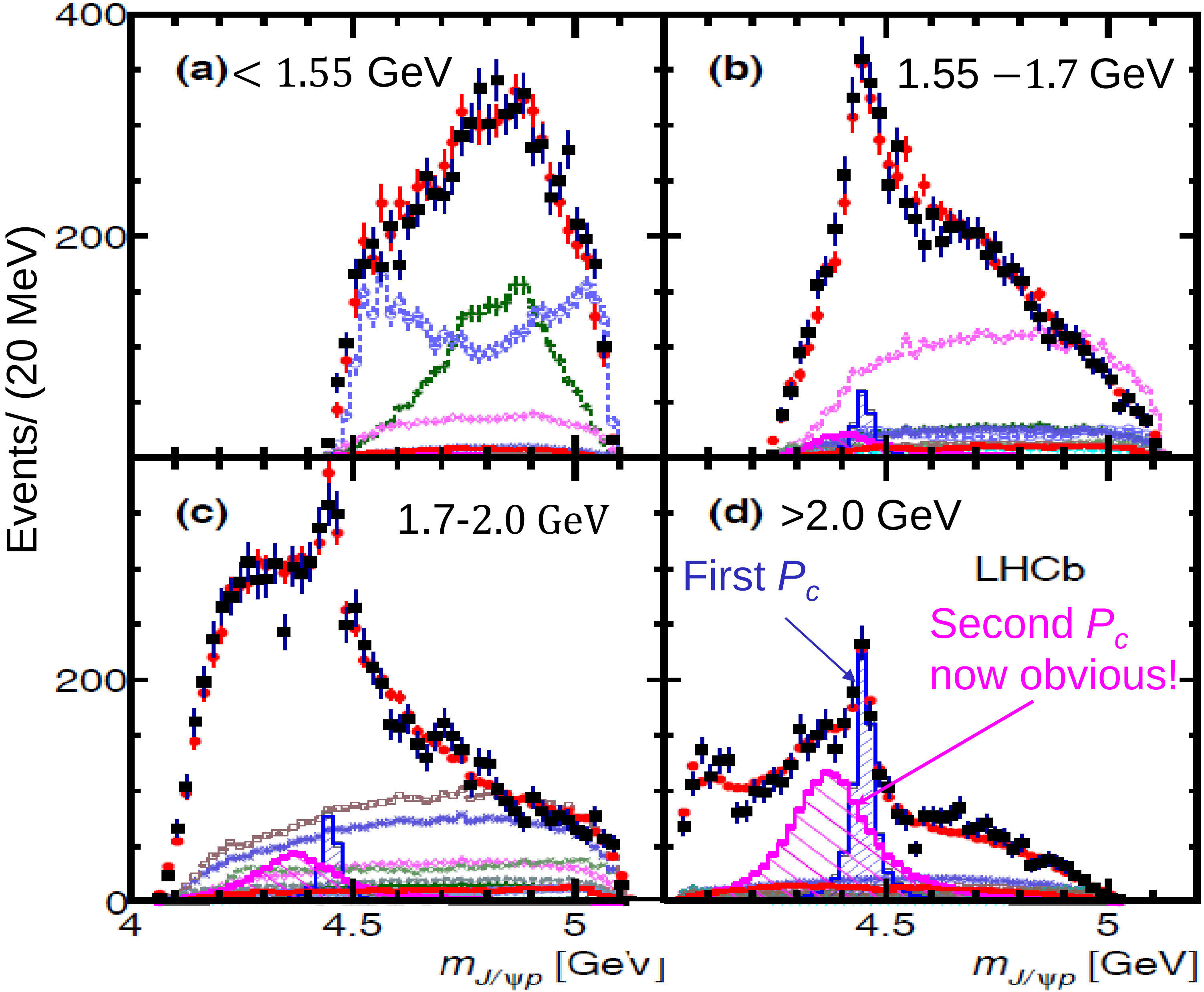
- Fits are good in all 6 dimensions (see next slide)!



Angular Projections



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



First P_c

Second P_c now obvious!

Quantum Numbers

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

Fit Results

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

Systematic uncertainty discussed in next slide

Significances

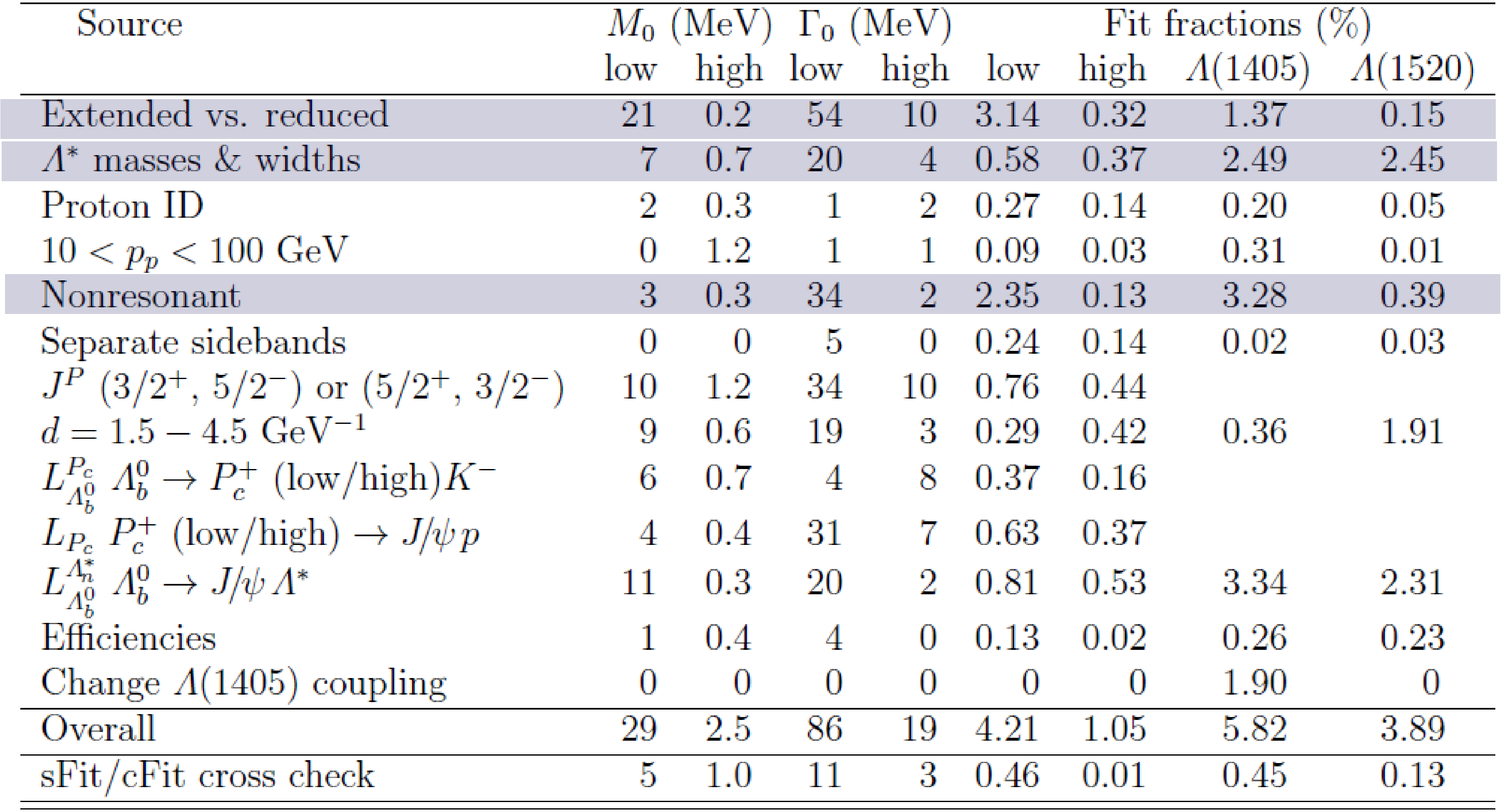
- To include systematic uncertainty, the extended model fits are used.

- Fit improves greatly, for 1 P_c^+ Δ(-2ln$L$)=216=14.7^2, adding the 2nd P_c^+ improves by 135=11.6^2

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

- Significances:
  - 1^{st} $P_c(4450)^+$: 12σ
  - 2^{st} $P_c(4380)^+$: 9 σ

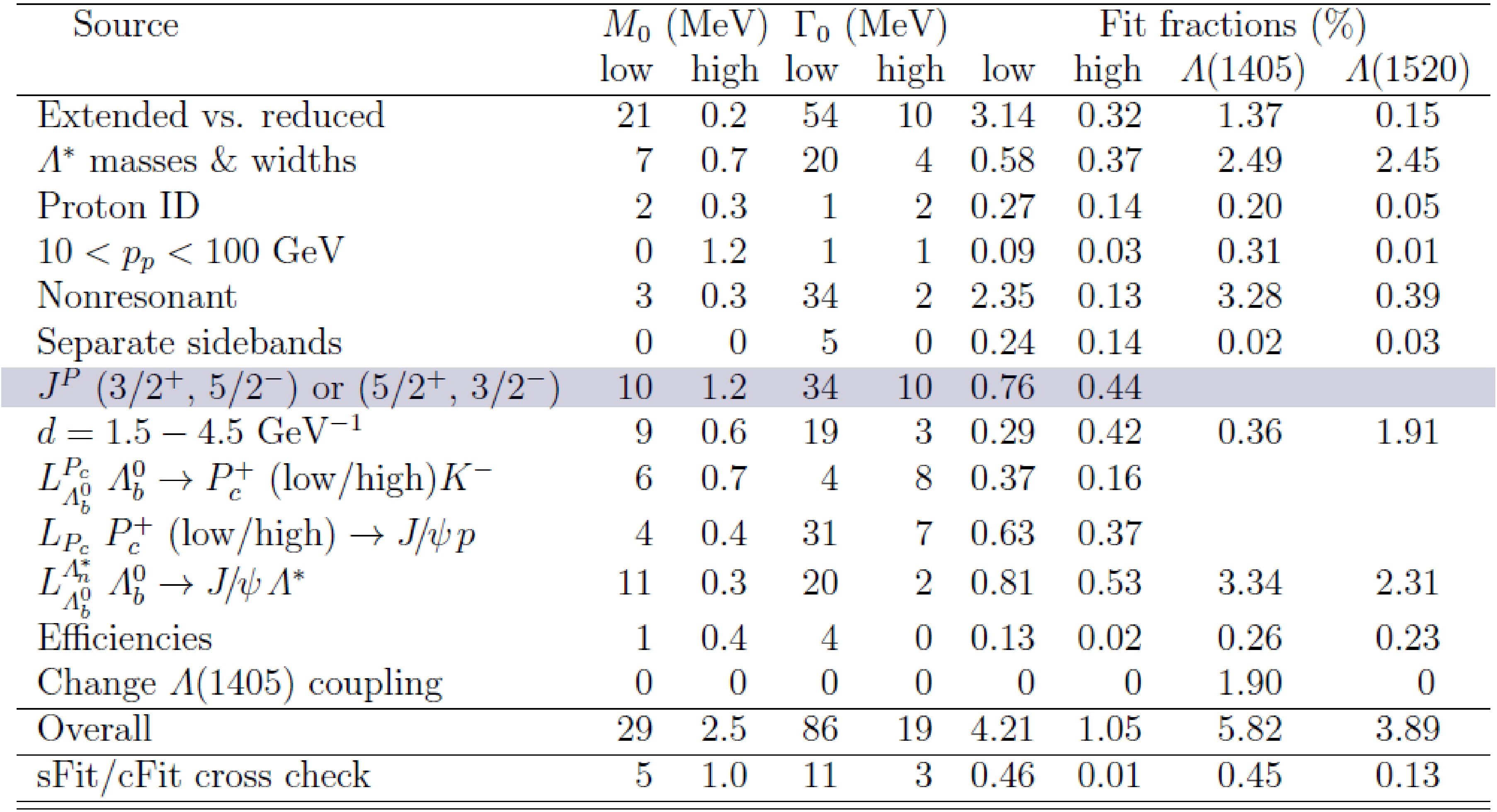
Systematic Uncertainties



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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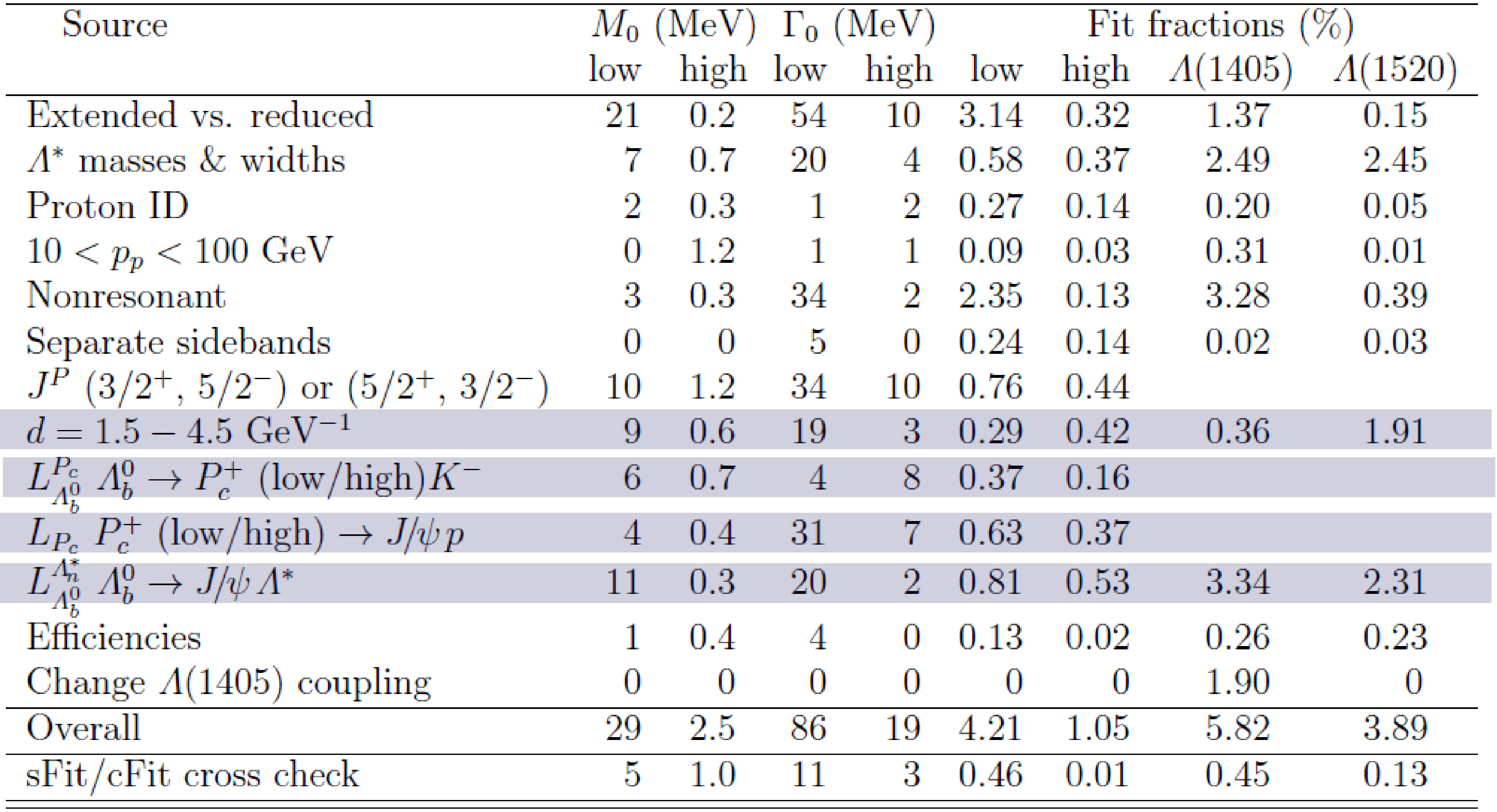
J^P $(3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$	10	1.2	34	10	0.76	0.44		
$d = 1.5 - 4.5$ GeV^{-1}	9	0.6	19	3	0.29	0.42	0.36	1.91
$L^{P_c}_{\Lambda^0_b}$ $\Lambda^0_b \to P_c^+$ (low/high)K^-	6	0.7	4	8	0.37	0.16		
L_{P_c} P_c^+ (low/high) $\to J/\psi\, p$	4	0.4	31	7	0.63	0.37		
$L^{\Lambda^*_n}_{\Lambda^0_b}$ $\Lambda^0_b \to J/\psi\, \Lambda^*$	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

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		
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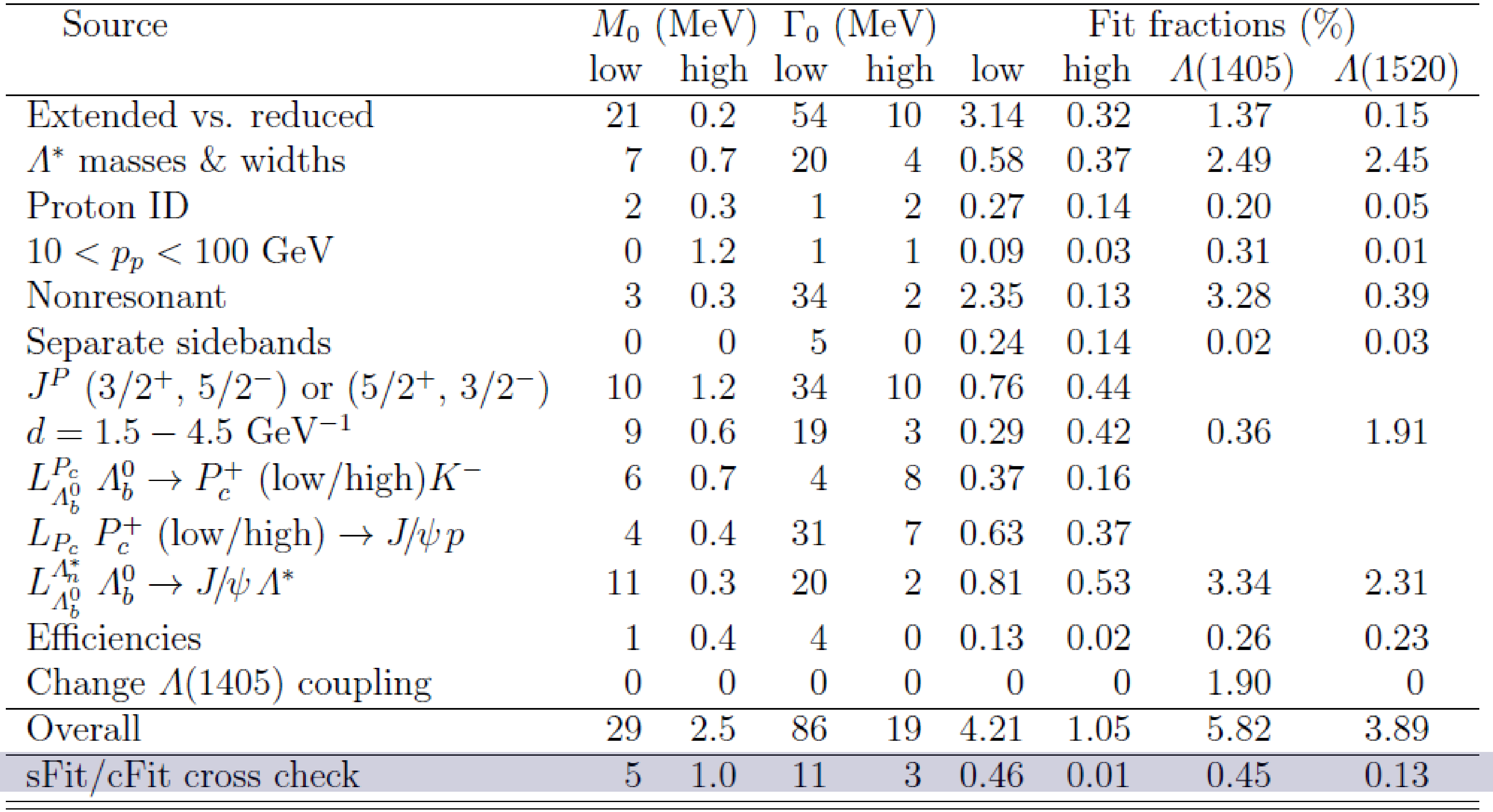
Varying choices in mass depend function also give sizeable uncertainty

Systematic Uncertainties



Source	M_0 (MeV) low	M_0 (MeV) high	Γ_0 (MeV) low	Γ_0 (MeV) high	Fit fractions (%) low	Fit fractions (%) high	Fit fractions (%) $\Lambda(1405)$	Fit fractions (%) $\Lambda(1520)$
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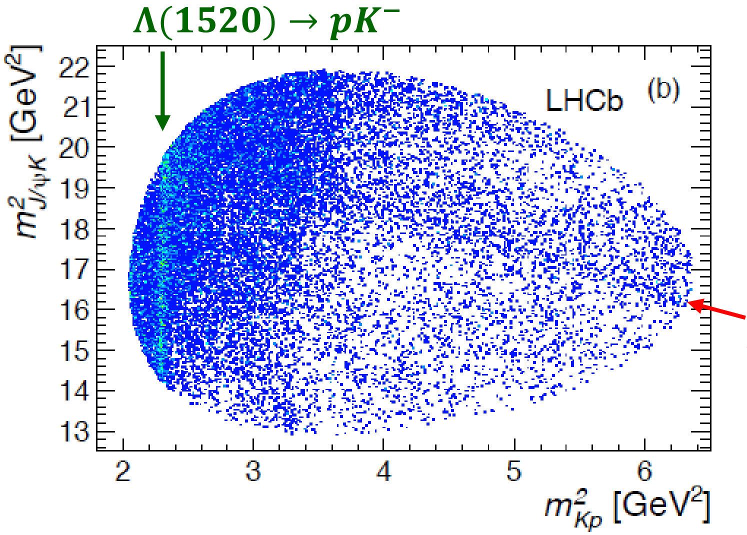
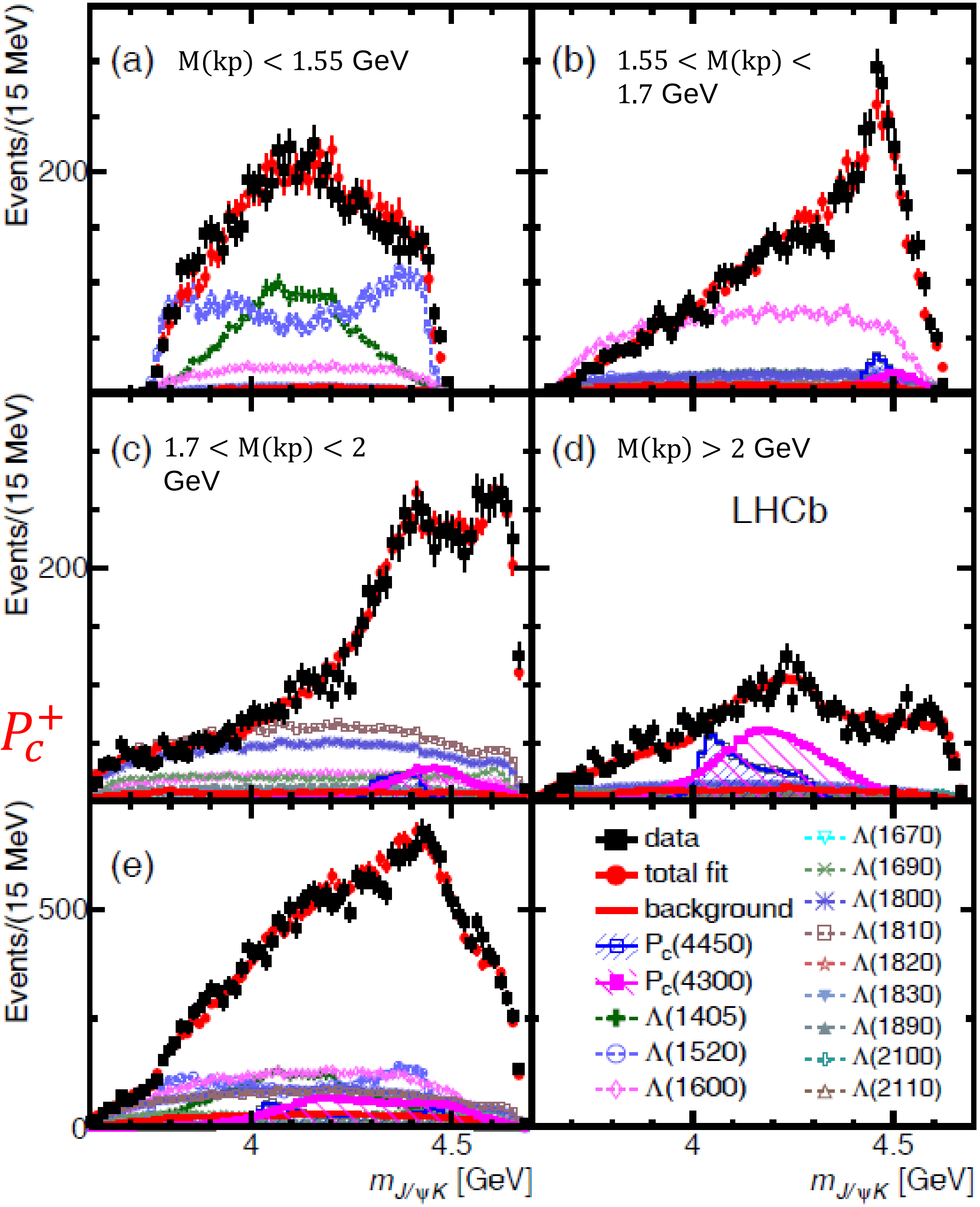
sFit/cFit give consistent results

$J/\psi\, K$ 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)

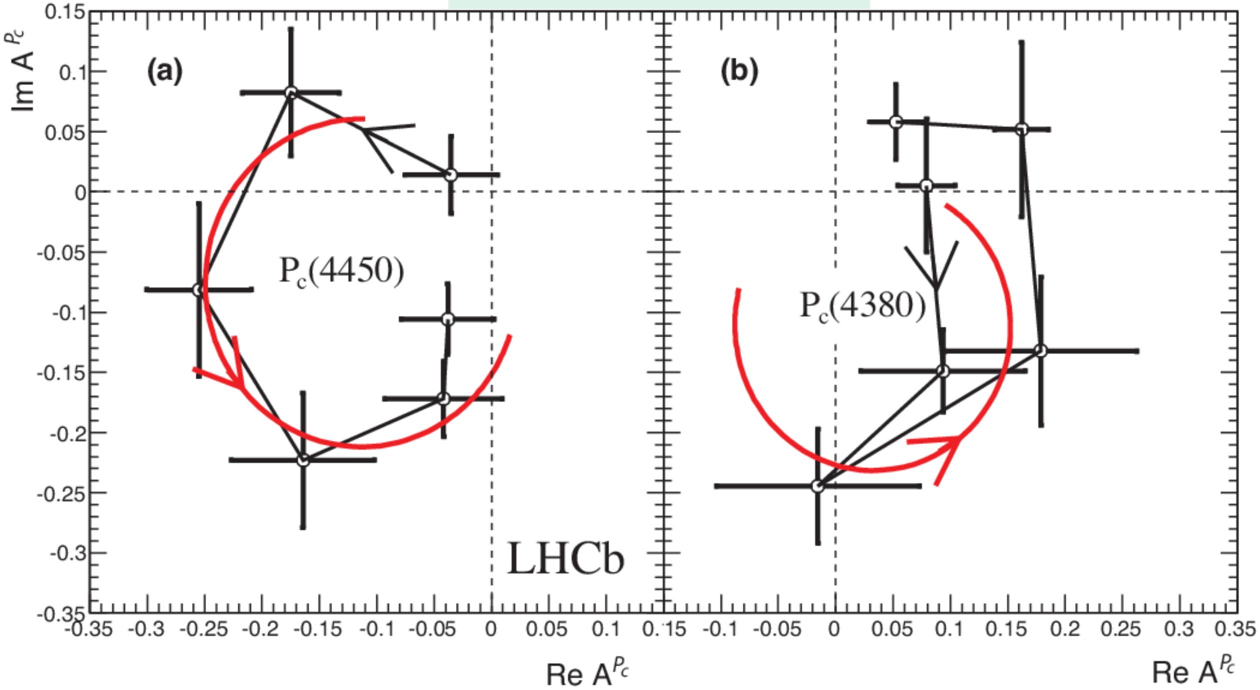
- Split data show consistency 2011/2012, magnet up/down, $\Lambda_b^0/\overline{\Lambda}_b^0$, two Λ_b^0 p_T bins

- Selection varied
  - – BDTG>0.5 instead of 0.9 (default)
  - – B^0 and B_s reflections modelled in the fit instead of veto

Resonance behavior

- 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

Argand diagram

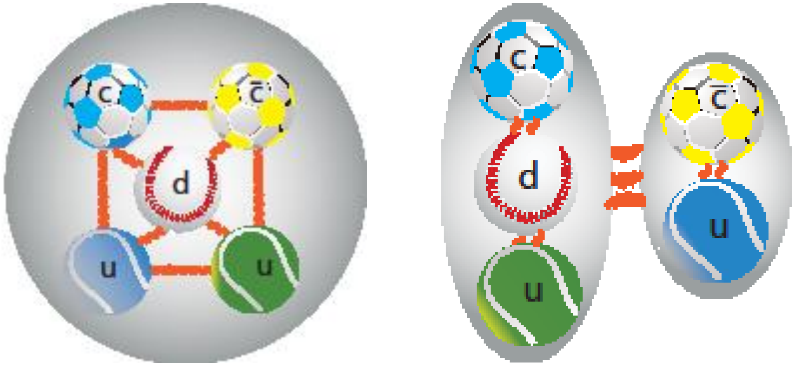


Breit-Wigner expectation
Fitted values

Interpretation

- Threshold ("cusps") [Swanson arXiv:1504.07952, 1409.3291, Bugg 1105.5492] has obvious difficulties
  - The closest threshold 4457.1 ± 0.3 MeV ($\Lambda_c(2595)D^0$) is somehow above the measured mass
  - And it would give $J^P = 1/2^+$, disfavored by our data
  - No threshold close to the low state

- Different binding mechanisms of pentaquark are possible
  - Tightly-bound
  - Weakly bound "molecules" of baryon-meson



Conclusions

- Have performed a full amplitude fit to $\Lambda_b \to J/\psi\, pK^-$
- Two Breit-Wigner shaped resonances in $J/\psi\, p$ mass are observed, with minimal quark content of $c\bar{c}uud$, therefore called pentaquark-charmonium states
  - The preferred J^P are of opposite parity, with one state having J=3/2 and the other 5/2

	$P_c(4380)^+$	$P_c(4450)^+$
Significance	9σ	12σ
Mass (MeV)	4380 ± 8 ± 29	4449.8 ± 1.7 ± 2.5
Width (MeV)	205 ± 18 ± 86	39 ± 5 ± 19
Fit fraction(%)	8.4 ± 0.7 ± 4.2	4.1 ± 0.5 ± 1.1

- Paper arXiv:1507.03414 submitted to *PRL*

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

Backup

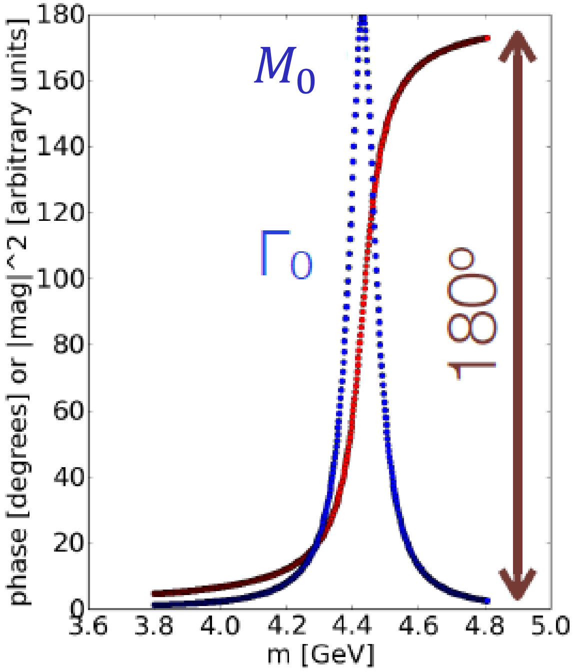
Breit-Wigner amplitude

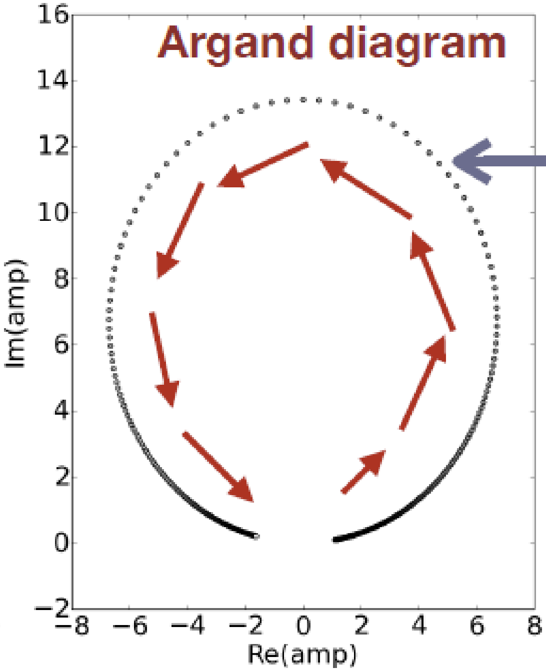
- Often a relativistic Breig-Wigner function is used to model resonance
- q is daughter momentum in the resonance rest frame

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

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

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

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

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

$$I(\vec{\omega}) \propto \sum_j^{N_{\rm MC}} w_j^{\rm MC} \left|\mathcal{M}(m_{Kp\,j},\Omega_j|\vec{\omega})\right|^2$$

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

- sFit minimizes

$$-2\ln\mathcal{L}(\vec{\omega}) = -2s_W\sum_i W_i \ln\mathcal{P}_{\rm sig}(m_{Kp\ i},\Omega_i|\vec{\omega})$$

$$= -2s_W\sum_i W_i \ln\left|\mathcal{M}(m_{Kp\ i},\Omega_i|\vec{\omega})\right|^2 + 2s_W\ \ln I(\vec{\omega})\sum_i W_i$$

$$\boxed{-2s_W\sum_i W_i \ln[\Phi(m_{Kp\ i})\epsilon(m_{Kp\ i},\Omega_i)].}$$

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 $\mathcal{P}(m_{Kp},\Omega|\vec{\omega}) = (1-\beta)\,\mathcal{P}_{\rm sig}(m_{Kp},\Omega|\vec{\omega}) + \beta\,\mathcal{P}_{\rm bkg}(m_{Kp},\Omega)$
- Background is described by sidebands 5σ-13.5σ
- cFit minimizes

Background fraction β=5.4%

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

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

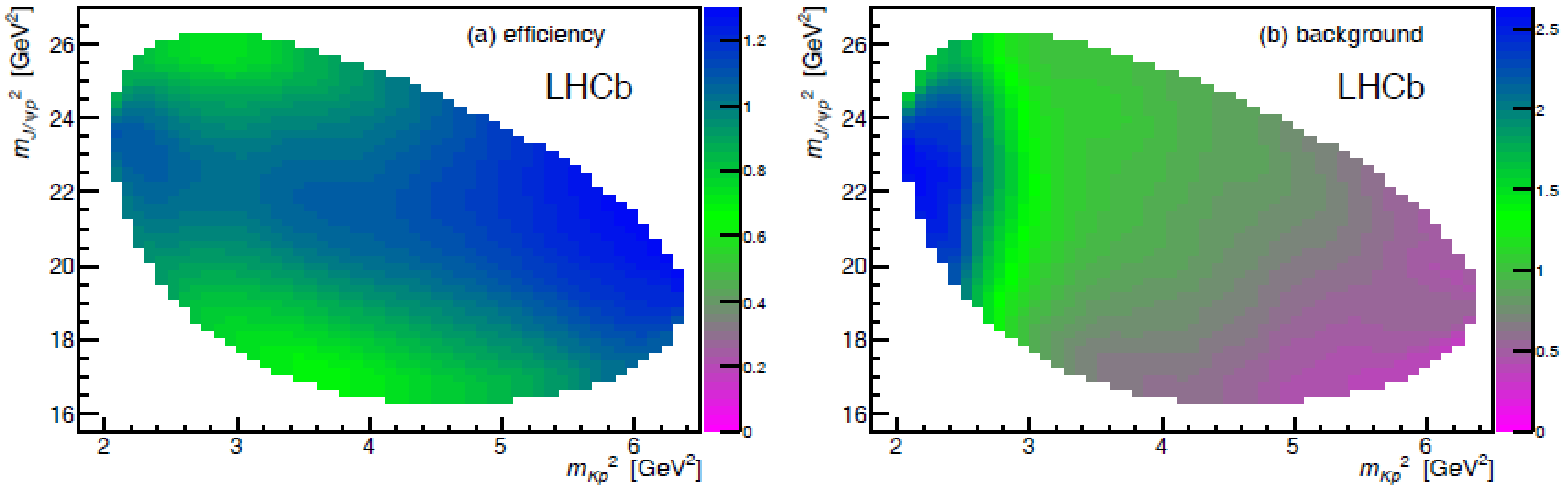
Signal efficiency parameterization becomes part of background parameterization,
effects only a tiny part of total PDF because of small β

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

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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:

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

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

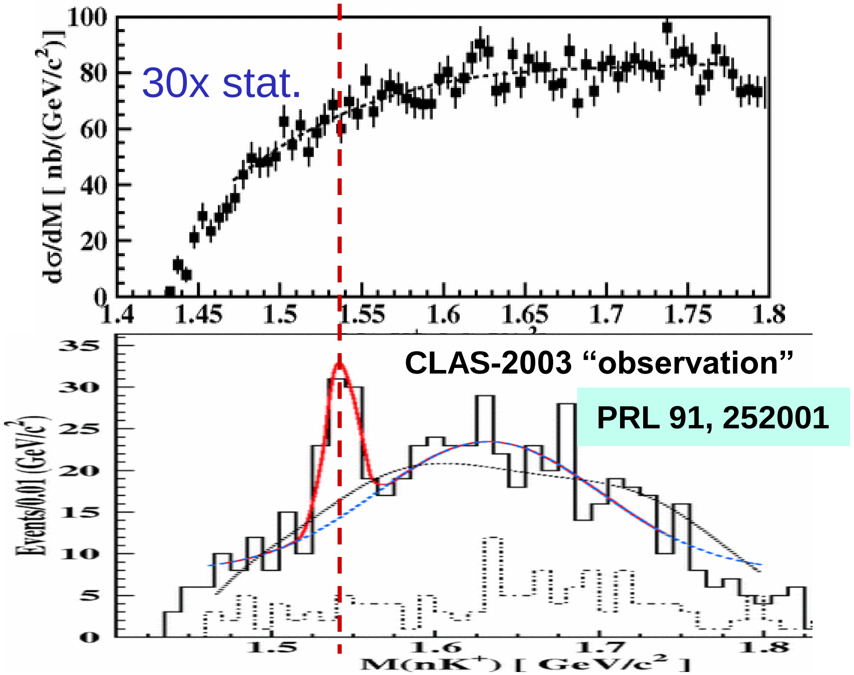
Curious history of pentaquark Θ^+search

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

- Prediction: $\Theta^+(uud d\bar{s})$ could exist with m ≈1530 MeV, $\Gamma \leq 10$ MeV
- In 2003-2004,10 experiments reported seeing narrow peaks of K^0p 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

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



30x stat.

CLAS-2003 “observation”

PRL 91, 252001