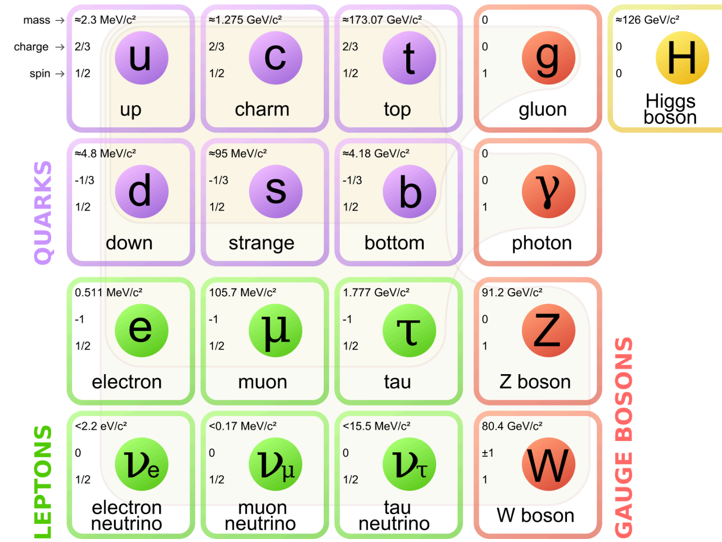
Observation of Pentaquark Candidates at LHCb

Liming Zhang, Tsinghua University

21 March, 2016

What are particles made of?



- Fundamental particles
  - Leptons
  - Quarks
  - Gauge bosons
- Composite particles called hadrons, made of spin=1/2 quarks
  - Baryons normally are composed of 3 quarks. Quarks come in 3 colors, for baryons one of each as r+b+y=white (colorless)
  - Mesons normally are composed of a quark + antiquark, e.g, $r\bar{r}$ or $b\bar{b}$ or $y\bar{y}$

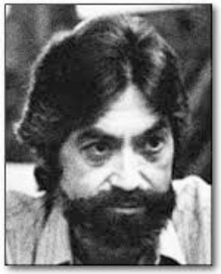
Quark model

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

In the beginning multiquark objects were predicted- now called exotic

G.Zweig *)
CERN - Geneva

8182/TH.401
17 January 1964



A B S T R A C T

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 break-

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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**.

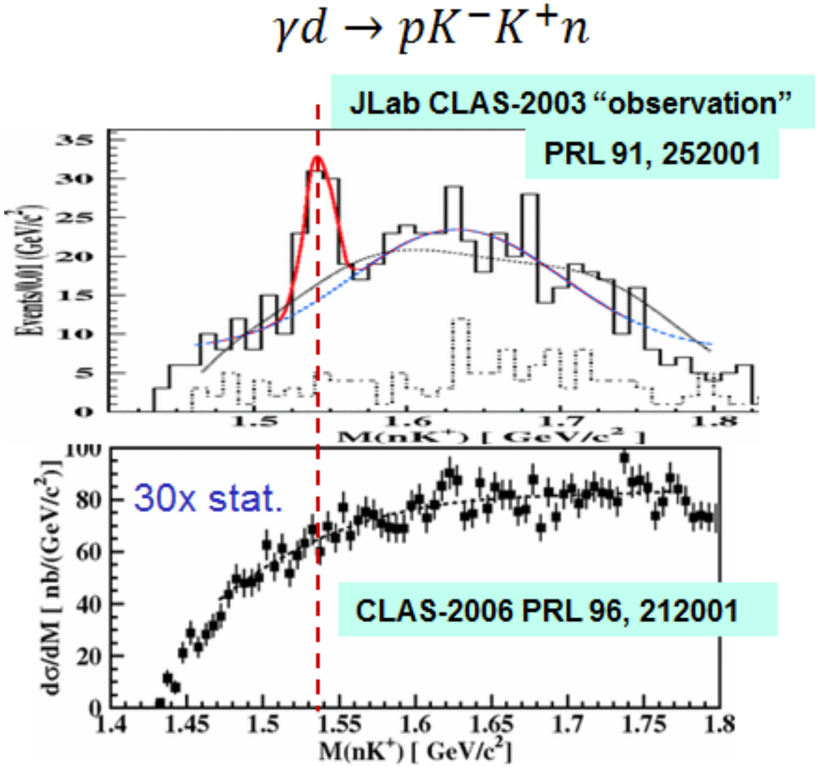
$qqqq\bar{q}$ baryons later called “pentaquarks”; $qq\bar{q}\bar{q}$ meson called “tetraquarks”

Why pentaquarks?

- Interest in pentaquarks arises from the fact that they would be new type of particles beyond the simple quark-model picture. Could teach us a lot about QCD.
- There is no reason they should not exist
  - Predicted by Gell-Mann (64), Zweig (64), others later in context of specific QCD models: Jaffe (76), Högaasen & Sorba (78), Strottman (79)
- These would be short-lived $\sim 10^{-23}$ s "resonances" whose presence is detected by mass peaks & angular distributions showing the presence of unique J^P quantum numbers

Past claimed pentaquark

- No convincing states 50 years after Gell-mann paper proposing qqqq$\bar{q}$ states
- Prediction: Θ^+ ($uudd\bar{s}$) could exist with m ≈1530 MeV
- In 2003,10 experiments reported evidences of narrow peaks of K^0p or K^+n, all >4 σ
- High statistics repeats from JLab showed the original claims were fluctuation



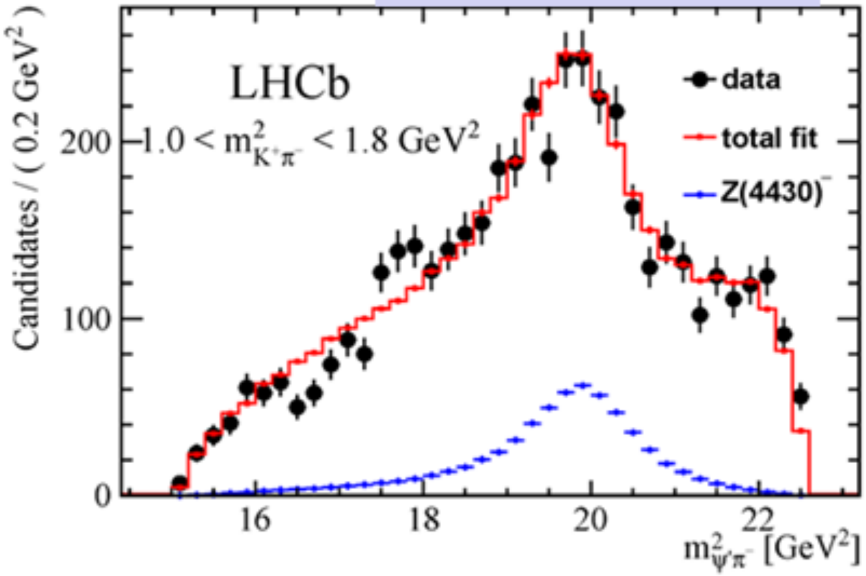
- It was merely a case of "bump hunting"

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

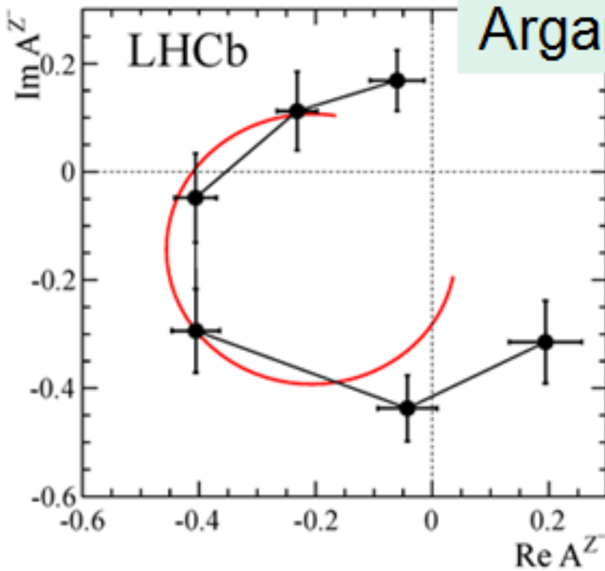
Tetraquark

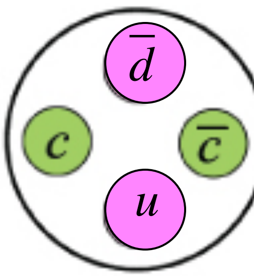
- Experimental evidence started to appear only recently
- $Z(4430)^+ \to \psi' \pi^+$ (Belle, LHCb) from $\overline{B}^0 \to \psi' K^- \pi^+$

[PRL 112, 222002 (2014)]



Argand diagram

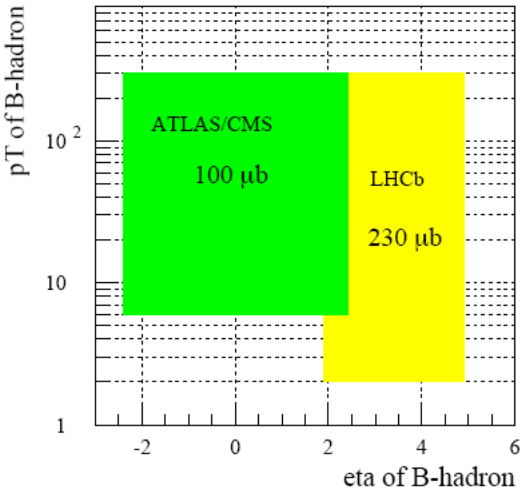


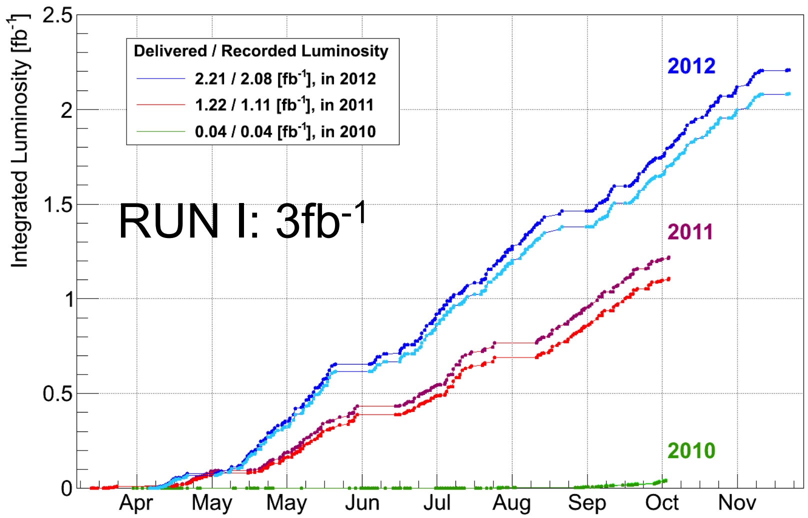


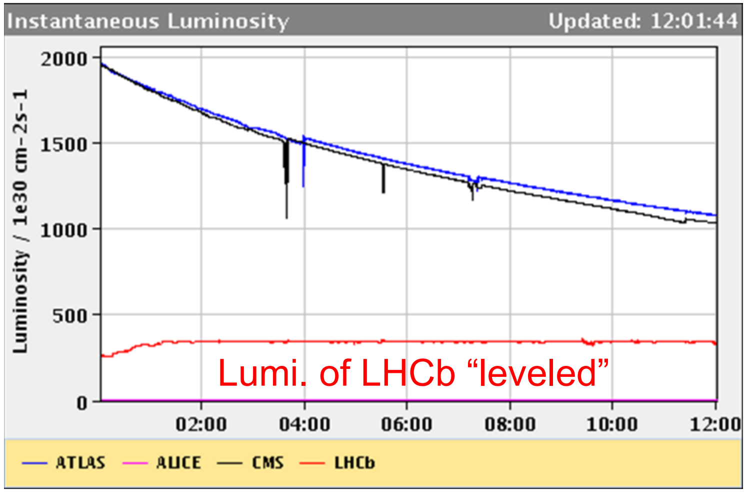
- $Z_c(3900)^+$ and its families (BESIII)
- $Z_b(10610)^+$ and $Z_b(10650)^+$ (Belle)
- These give support to the possibility of pentaquark states

The LHCb Experiment

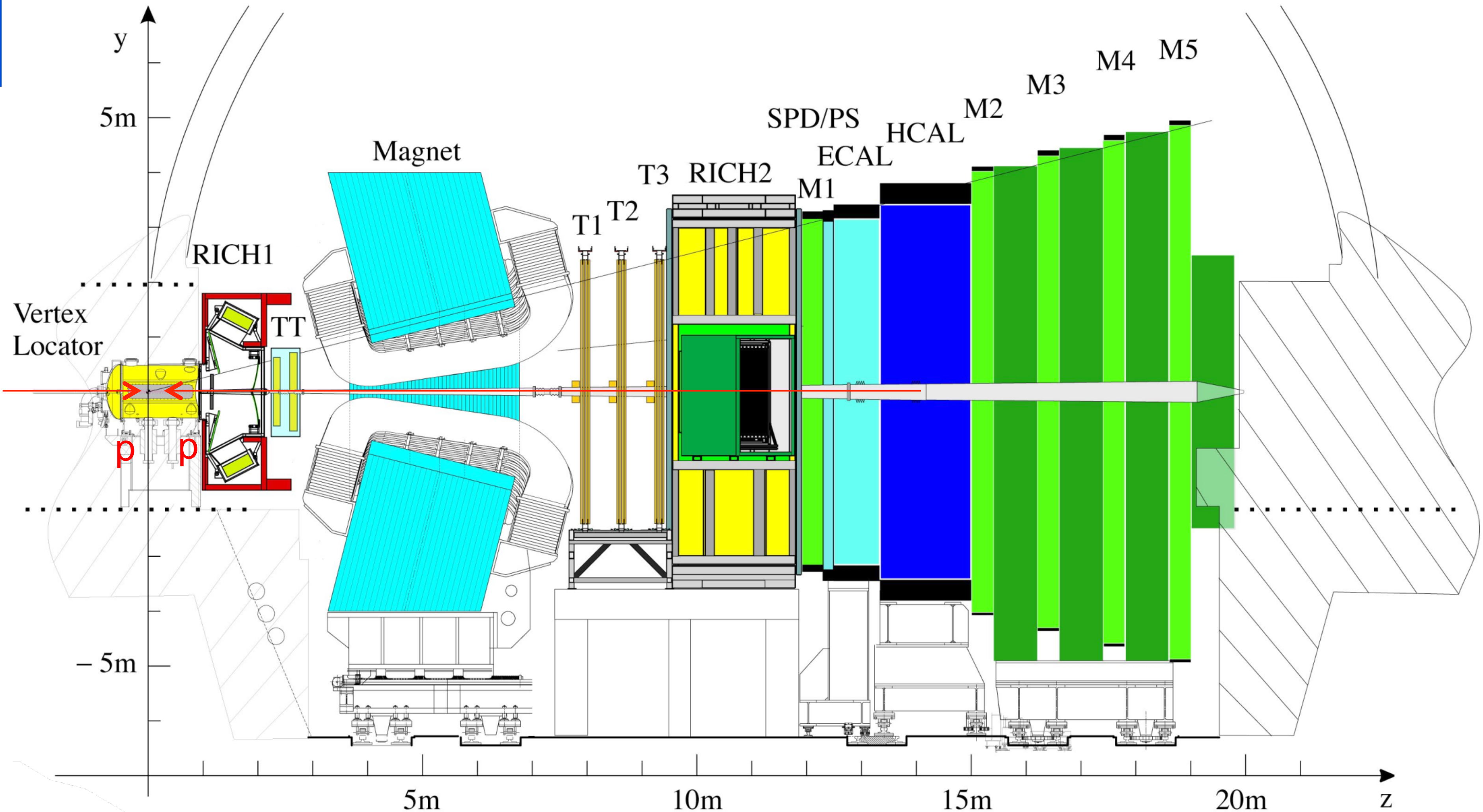
- LHCb is a dedicated B physics experiment at LHC
  - ~1000 × large b production rate than B factory @ Υ(4S)
  - Access to all b-hadrons: B^+, B^0, B_s, B_c, b-baryons
- LHCb acceptance optimised for forward $b\bar{b}$ production: forward single arm spectrometer $1.9<\eta<4.9$
- Luminosity is at ~4×10^{32} $cm^{-2}s^{-1}$ to limit multiple interactions per bunch crossing



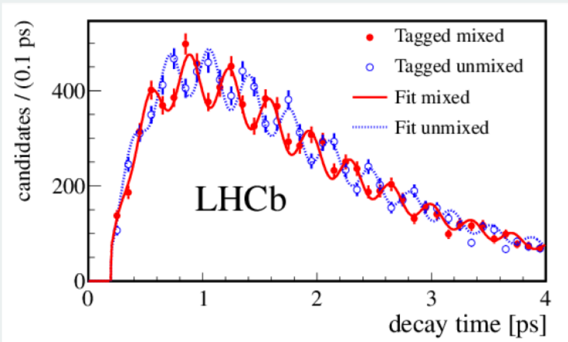
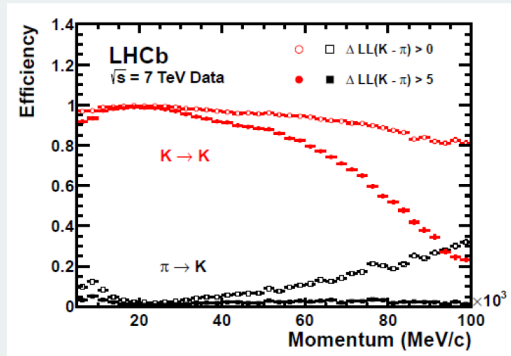
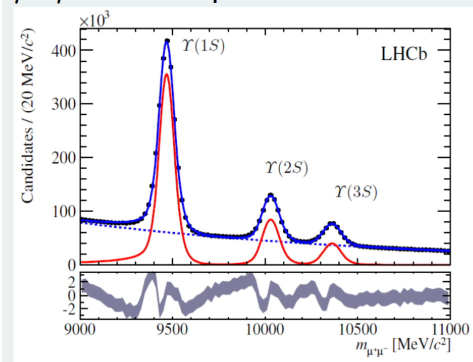




LHCb Detector



Detector performance

Vertexing	PID	Tracking
B_s^0 oscillations with $B_s^0 \to D_s \pi$	K/π ID efficiency and misID rate	$\mu^+\mu^-$ mass spectrum
		
[New J. Phys. 15 (2013) 053021]	[EPJ C73 (2013) 2431]	[PRL 111 (2013) 101805]

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$/c$)

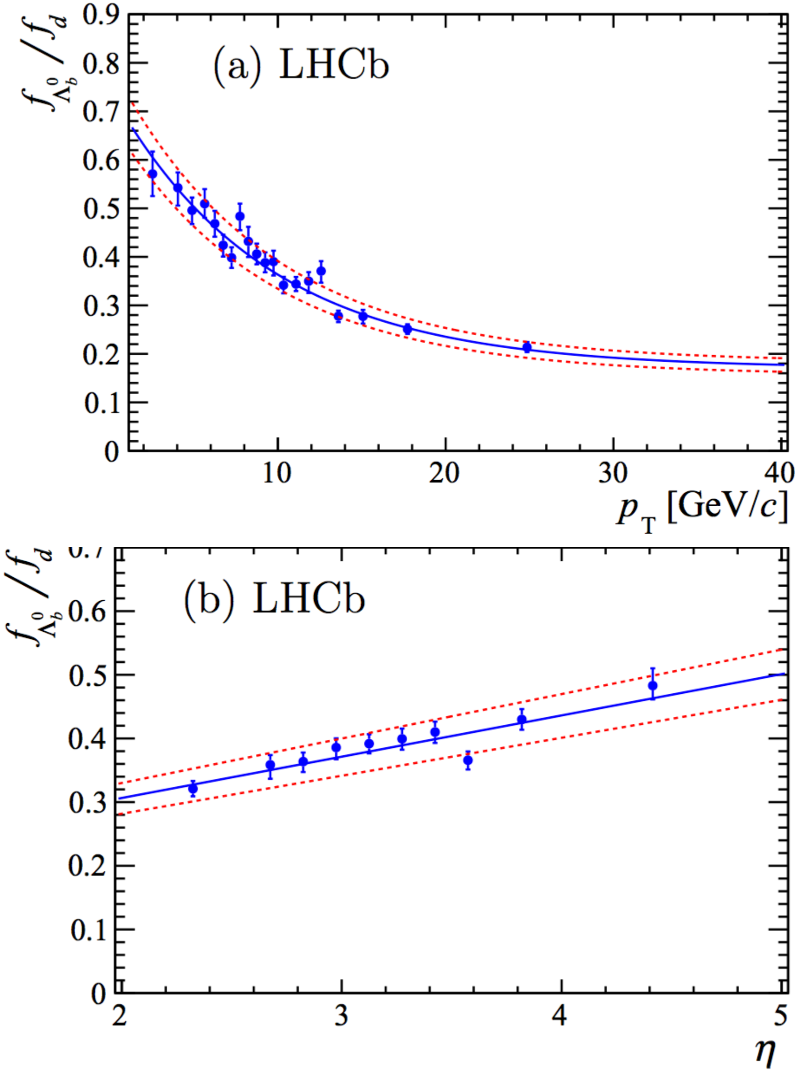
Mass : $\sigma_m = 8$ MeV$/c^2$ for $B \to J/\psi X$ (constrained $m_{J/\psi}$)

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

f_{Λ_b}/f_d

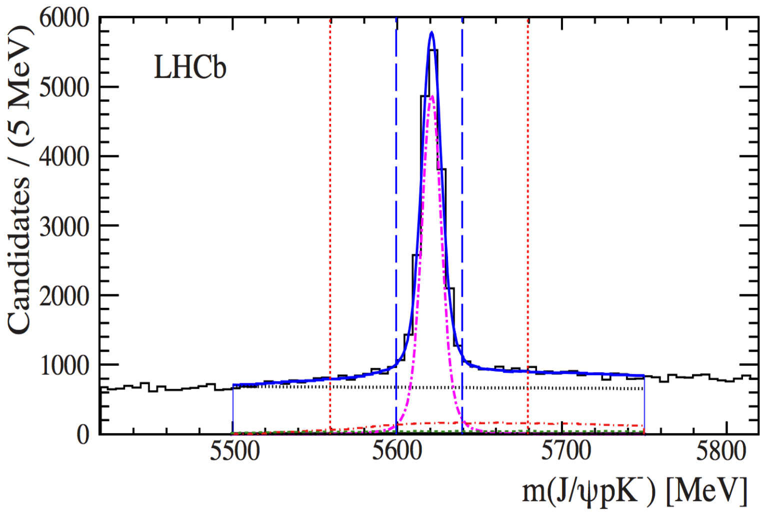


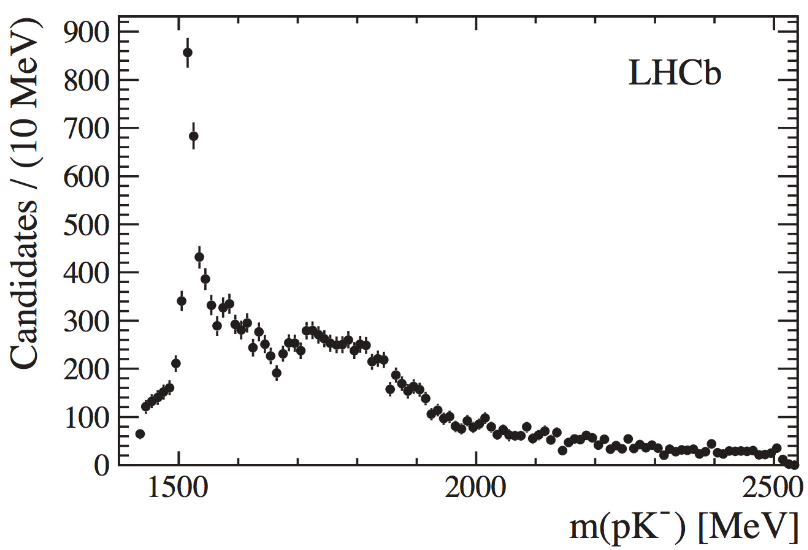
- Determine the p_T and η dependence of f_{Λ_b}/f_d

[LHCb, JHEP 08(2014) 143, arXiv:1405.6842]

- Clear increase of Λ_b at low p_T and large η
  - Many more Λ_b in LHCb than central detectors
- The LHC is a Λ_b factory: 4:2:1 B^0:Λ_b:B_s in LHCb acceptance

$\Lambda_b \to J/\psi K^- p$





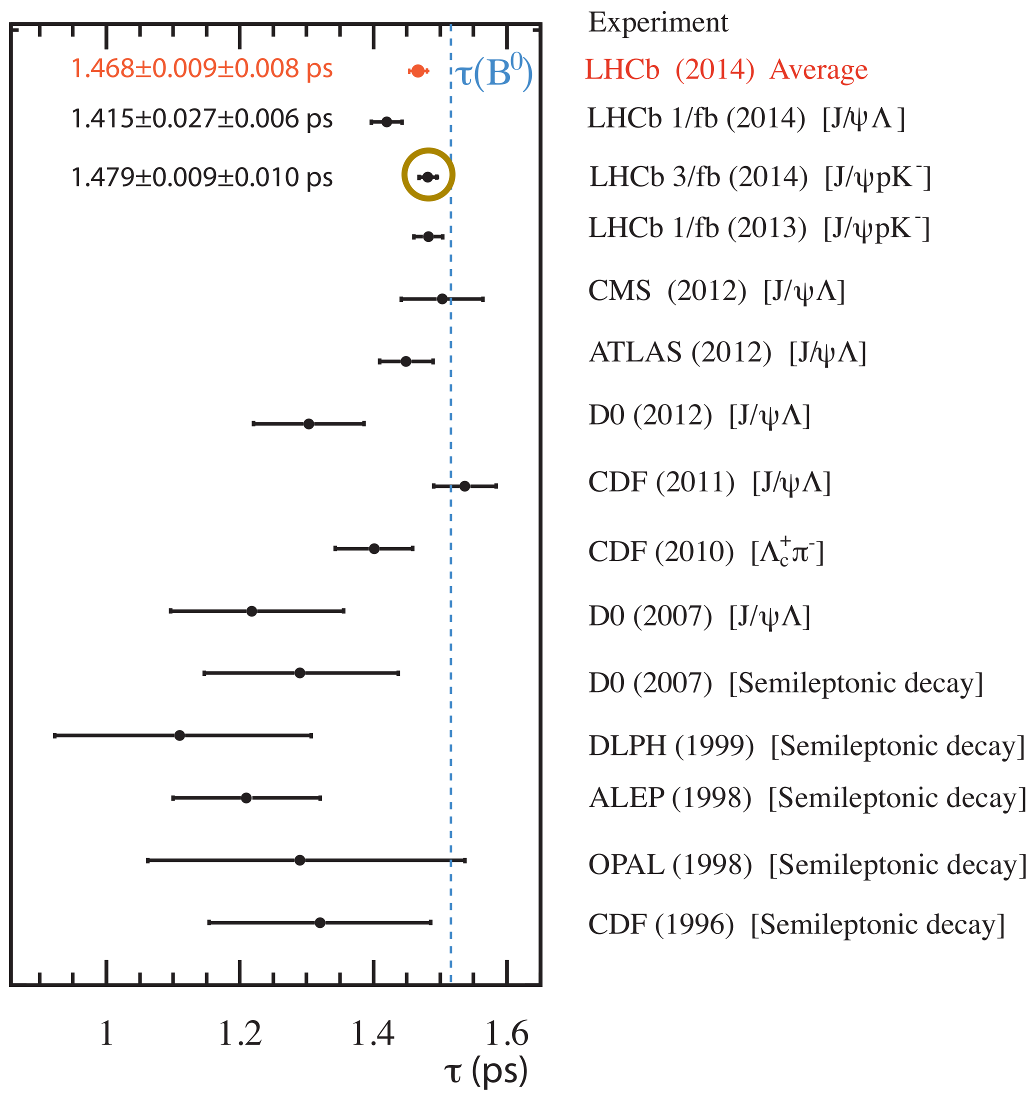
- First observation of the decay with 2011 data
- Unexpected large yield, interesting structure in pK mass
- Used to measure Λ_b lifetime

[LHCb, PRL 111 (2013) 102003, arXiv:1307.2476]

Update with 2011+2012 data
[LHCb, PLB 734 (2014) 122, arXiv:1402.6242]

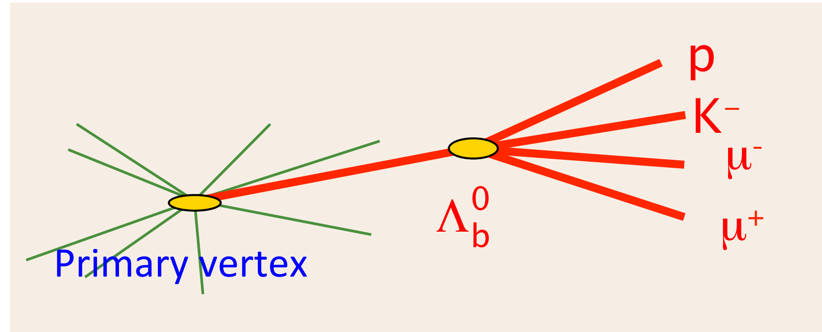
Measurement of Λ_b/B^0 lifetime

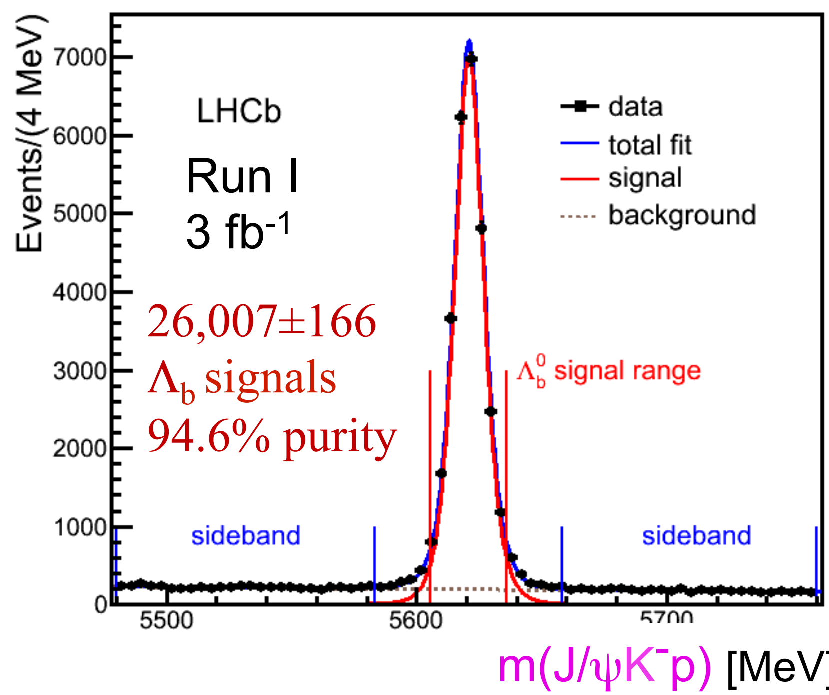
- Long history of a puzzling discrepancy between Λ_b and B lifetime
- Heavy Quark Expansion (HQE) predicts similar lifetime
- With our precision measurements, this story now ends



Data and selection

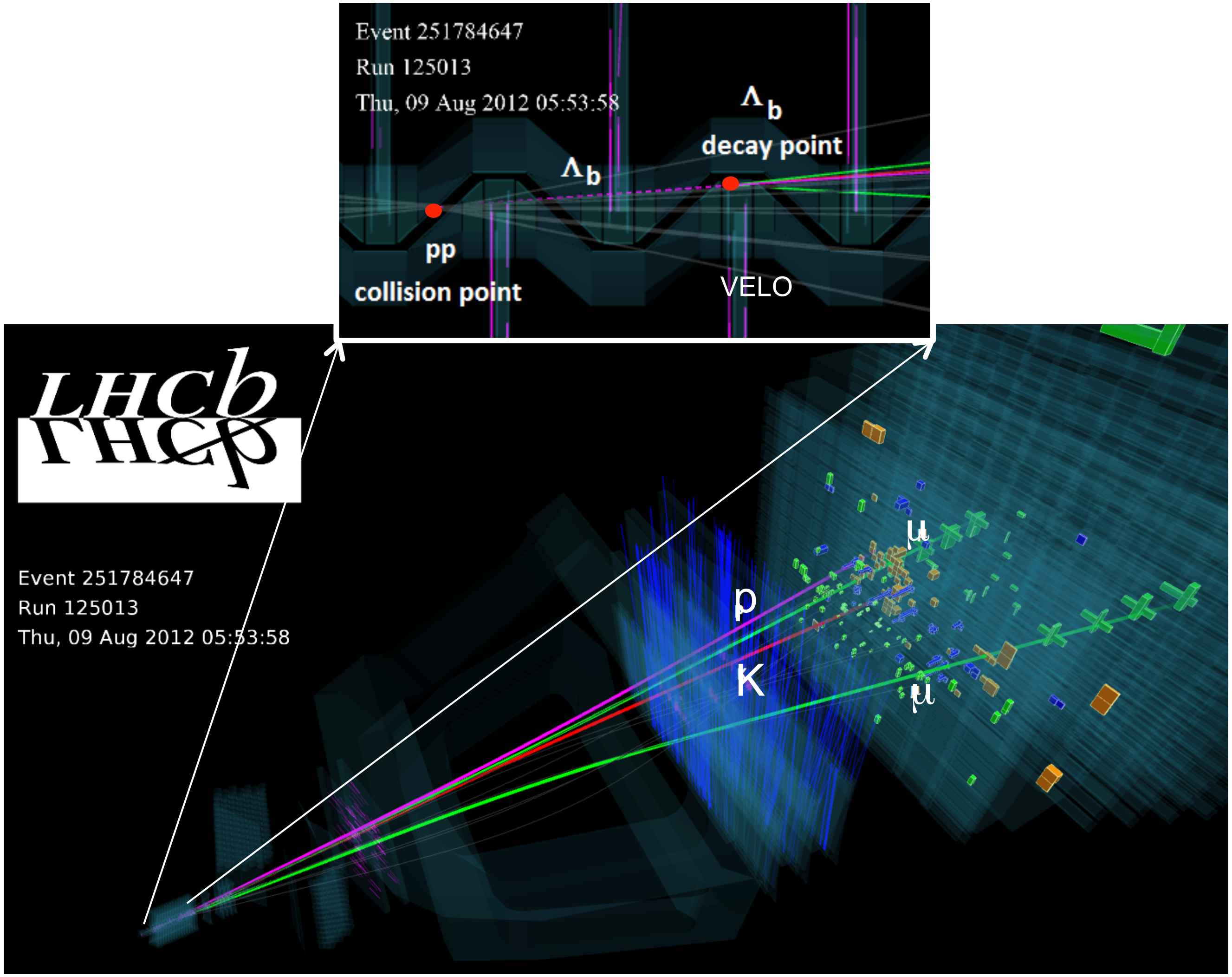
- 2011+2012 3fb^{-1}
- Reoptimized selection
- $B_s \to J/\psi K^- K^+$ & $B^0 \to J/\psi K^- \pi^+$ misID backgrounds are vetoed
- Neural network based selection
- Large and clean Λ_b signals





[PRL 115, 072001 (2015)]

A $\Lambda_b \rightarrow J/\psi K^- p$ candidate



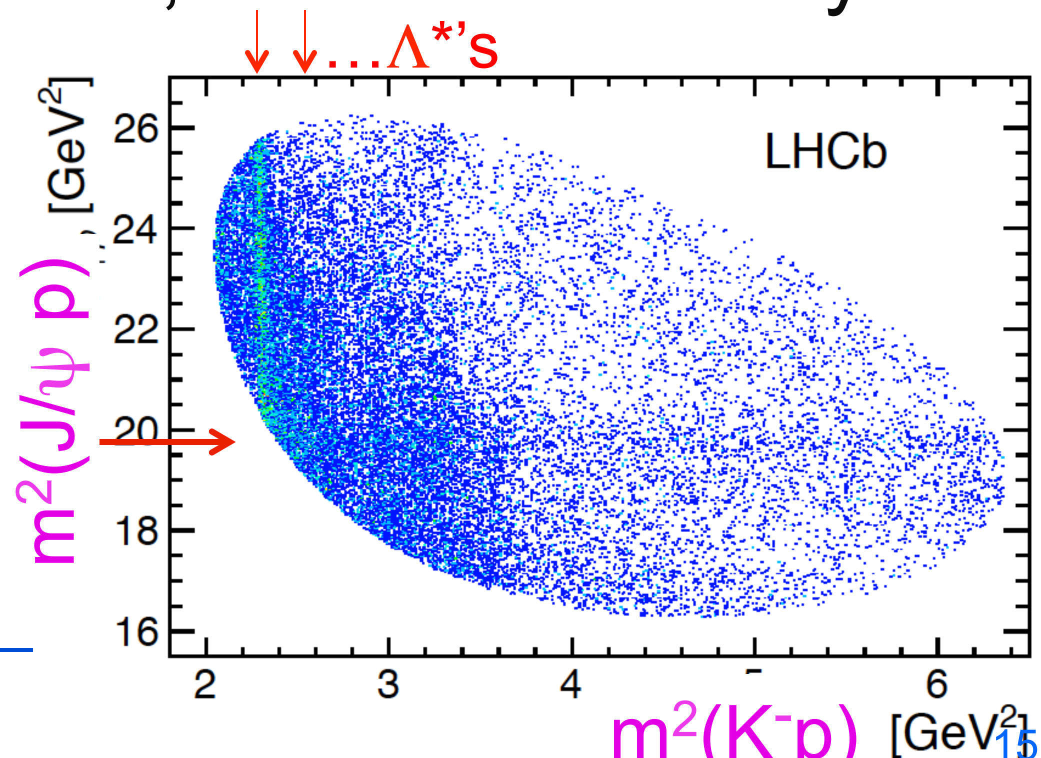
“Dalitz-plot” distribution

- Dalitz-plot generally used for studying 3-body decays
- 3-body decays are often dominated by resonance processes, can be viewed by the distribution

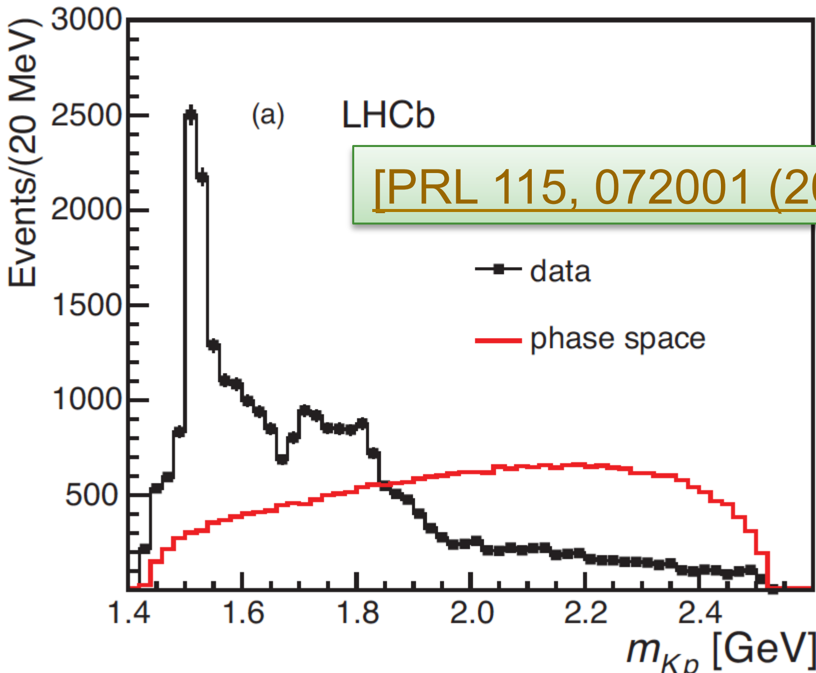
Make a Dalitz plot.

Showed an ______________ unusual feature

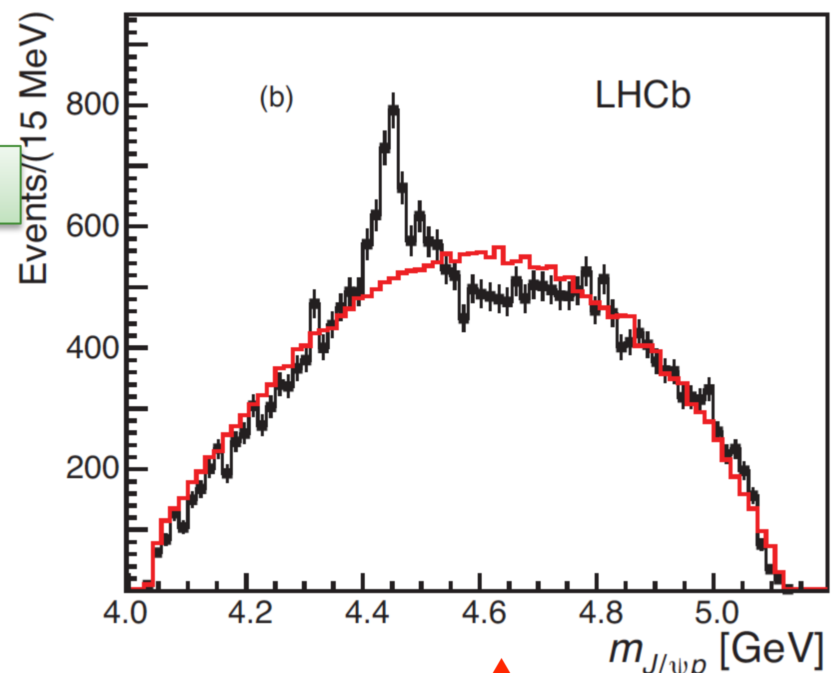
[PRL 115, 072001 (2015)]

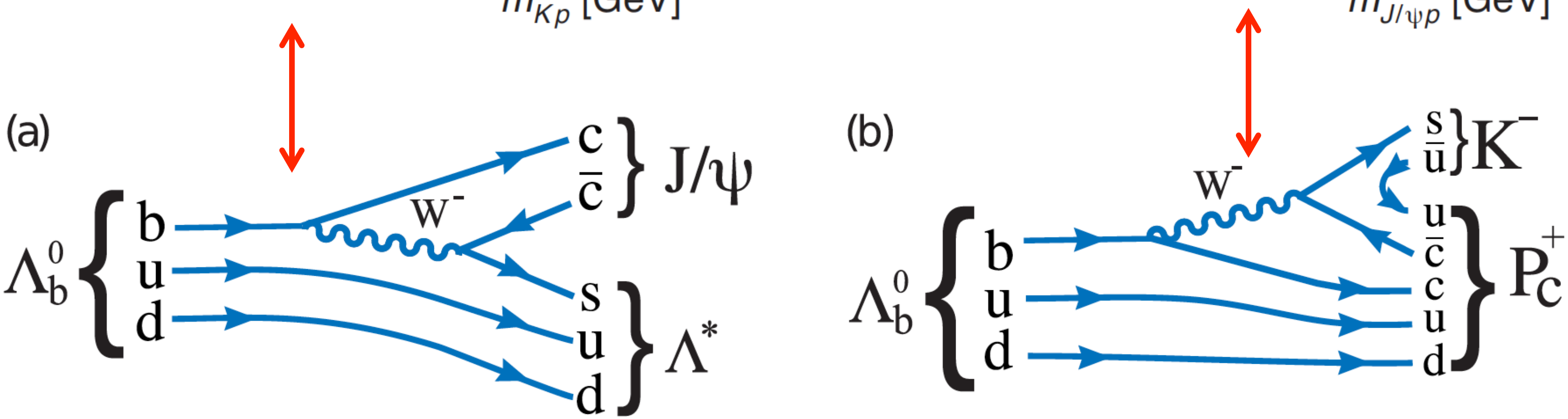


Projections



[PRL 115, 072001 (2015)]

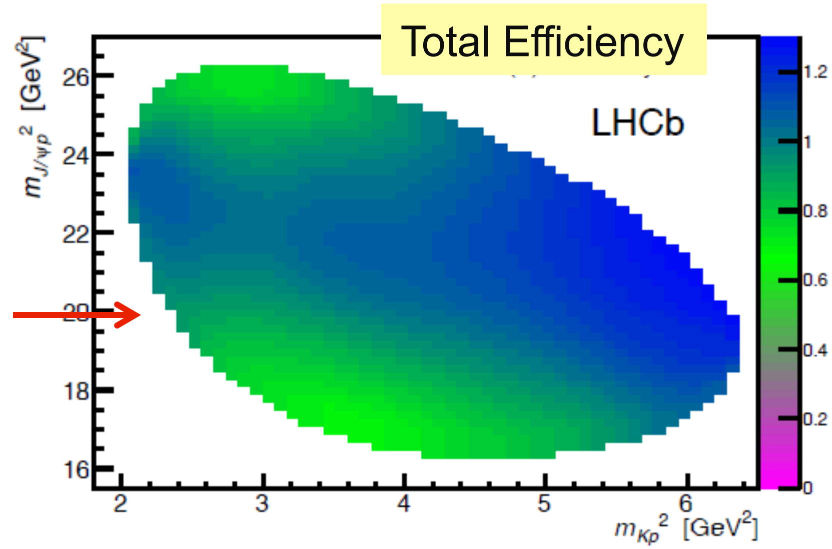




Does a 4 quark +$\bar{q}$ state exist?

Is the peak "an artifact"?

- Many checks done: this is not be the case:
  - MisID background of B^0 and B_s are vetoed
  - Ξ_b decays checked
  - Efficiency doesn't make narrow peak
  - No peaking sideband bkg
  - Clones & ghost tracks eliminated

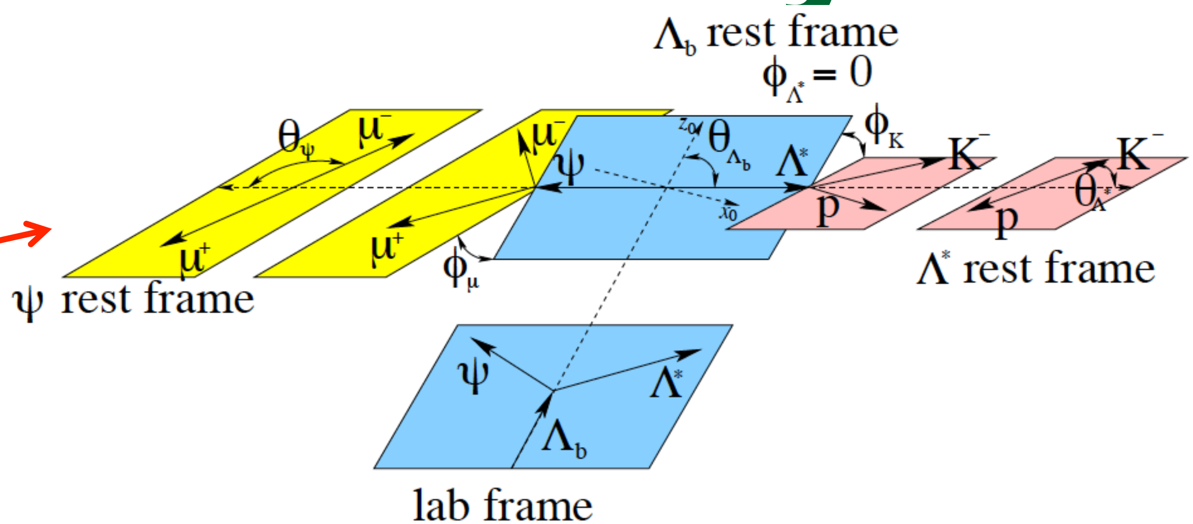


- Can interference between Λ^* resonances generate a peak in the J/ψp mass spectrum?
  - A full amplitude analysis is performed using all known Λ^* resonances

Amplitude analysis

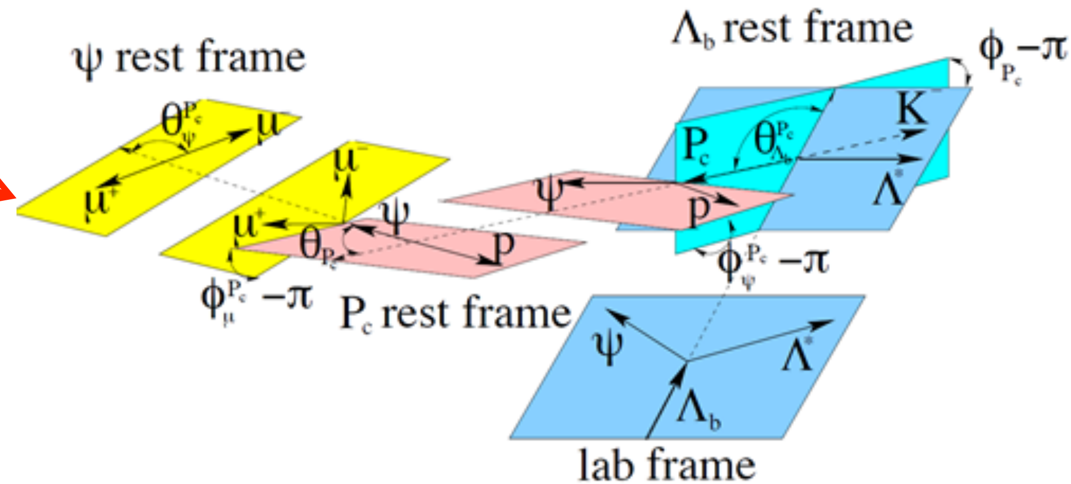
- Two interfering channels:

$\Lambda_b \rightarrow J/\psi \Lambda^*$, $\Lambda^* \rightarrow K^- p$



&

$\Lambda_b \rightarrow P_c^+ K^-$, $P_c^+ \rightarrow J/\psi\ p$



- Use m(K⁻p) & 5 decay ∠'s as fit parameters

Amplitude Analysis

- 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:

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

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

Amplitude Analysis

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

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

$$\mathcal{H}^{\Lambda_n^*\to Kp}_{\lambda_p,\,0} D^{J_{\Lambda_n^*}}_{\lambda_{\Lambda^*},\,\lambda_p}(\phi_K,\theta_{\Lambda^*},0)^* R_n(m_{Kp})\, D^{1}_{\lambda_\psi,\,\Delta\lambda_\mu}(\phi_\mu,\theta_\psi,0)^*$$

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$$\mathcal{H}^{P_{cj}\to\psi p}_{\lambda_\psi^{P_c},\lambda_p^{P_c}} D^{J_{P_{cj}}}_{\lambda_{P_c},\,\lambda_\psi^{P_c}-\lambda_p^{P_c}}(\phi_\psi,\theta_{P_c},0)^* R_j(m_{\psi p})\ \ D^{1}_{\lambda_\psi^{P_c},\,\Delta\lambda_\mu^{P_c}}(\phi_\mu^{P_c},\theta_\psi^{P_c},0)^*$$

- *R*(*m*) are resonance parametrizations, generally are described by Breit-Wigner, Flatte´ amplitude

Amplitude Analysis

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$$\mathcal{H}^{\Lambda_n^*\to Kp}_{\lambda_p,0} D^{J_{\Lambda_n^*}}_{\lambda_{\Lambda^*},\lambda_p}(\phi_K,\theta_{\Lambda^*},0)^* R_n(m_{Kp}) D^{1}_{\lambda_\psi,\Delta\lambda_\mu}(\phi_\mu,\theta_\psi,0)^*$$

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$$\mathcal{H}^{P_{cj}\to\psi p}_{\lambda_\psi^{P_c},\lambda_p^{P_c}} D^{J_{P_{cj}}}_{\lambda_{P_c},\lambda_\psi^{P_c}-\lambda_p^{P_c}}(\phi_\psi,\theta_{P_c},0)^* R_j(m_{\psi p})\ D^{1}_{\lambda_\psi^{P_c},\Delta\lambda_\mu^{P_c}}(\phi_\mu^{P_c},\theta_\psi^{P_c},0)^*$$

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

Amplitude Analysis

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

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$$\mathcal{H}^{\Lambda_n^*\to Kp}_{\lambda_p,\,0} D^{J_{\Lambda_n^*}}_{\lambda_{\Lambda^*},\,\lambda_p}(\phi_K,\theta_{\Lambda^*},0)^* R_n(m_{Kp})\, D^{1}_{\lambda_\psi,\,\Delta\lambda_\mu}(\phi_\mu,\theta_\psi,0)^*$$

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$$\mathcal{H}^{P_{cj}\to\psi p}_{\lambda_\psi^{P_c},\lambda_p^{P_c}} D^{J_{P_{cj}}}_{\lambda_{P_c},\,\lambda_\psi^{P_c}-\lambda_p^{P_c}}(\phi_\psi,\theta_{P_c},0)^* R_j(m_{\psi p})\;\; D^{1}_{\lambda_\psi^{P_c},\,\Delta\lambda_\mu^{P_c}}(\phi_\mu^{P_c},\theta_\psi^{P_c},0)^*$$

- Add together coherently to allow them interfering

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

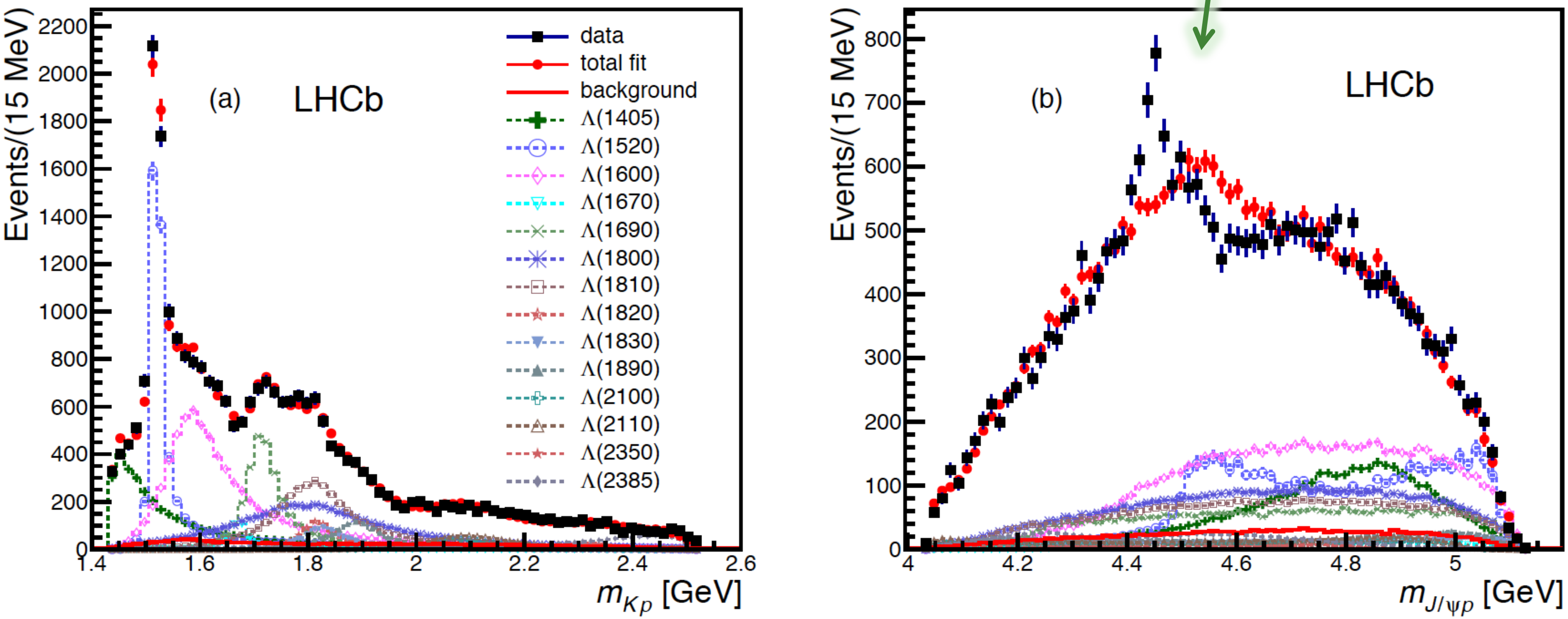
Models: extended & reduced

- Consider all Λ* states & all allowed L values

	State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
Flatte´	$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
BW ↓	$\Lambda(1520)$	$3/2^-$	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
				# parameters	64	146

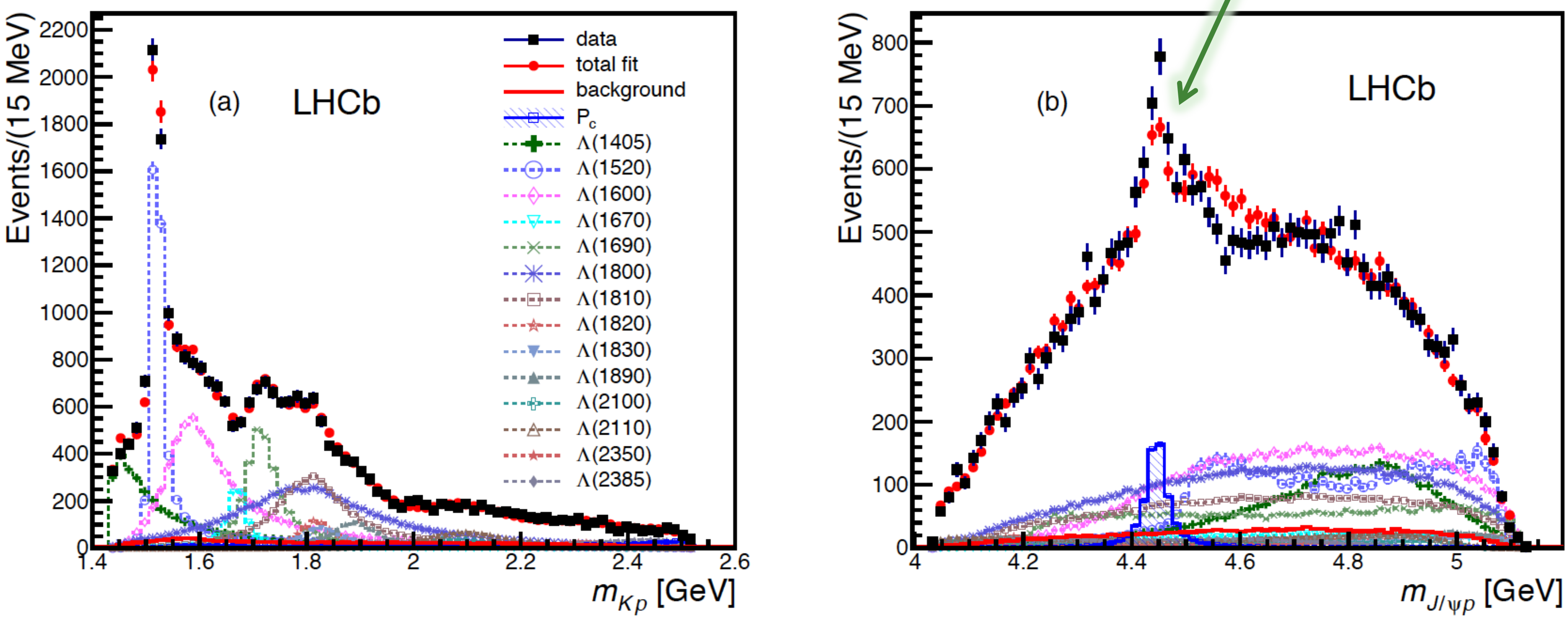
Results without P_c states

- Use extended model, so all possible known Λ^* amplitudes. m_{Kp} looks fine, but not $m_{J/\psi p}$
- Additions of non-resonant, extra Λ^*, all Σ^* (isospin violating process) don't help



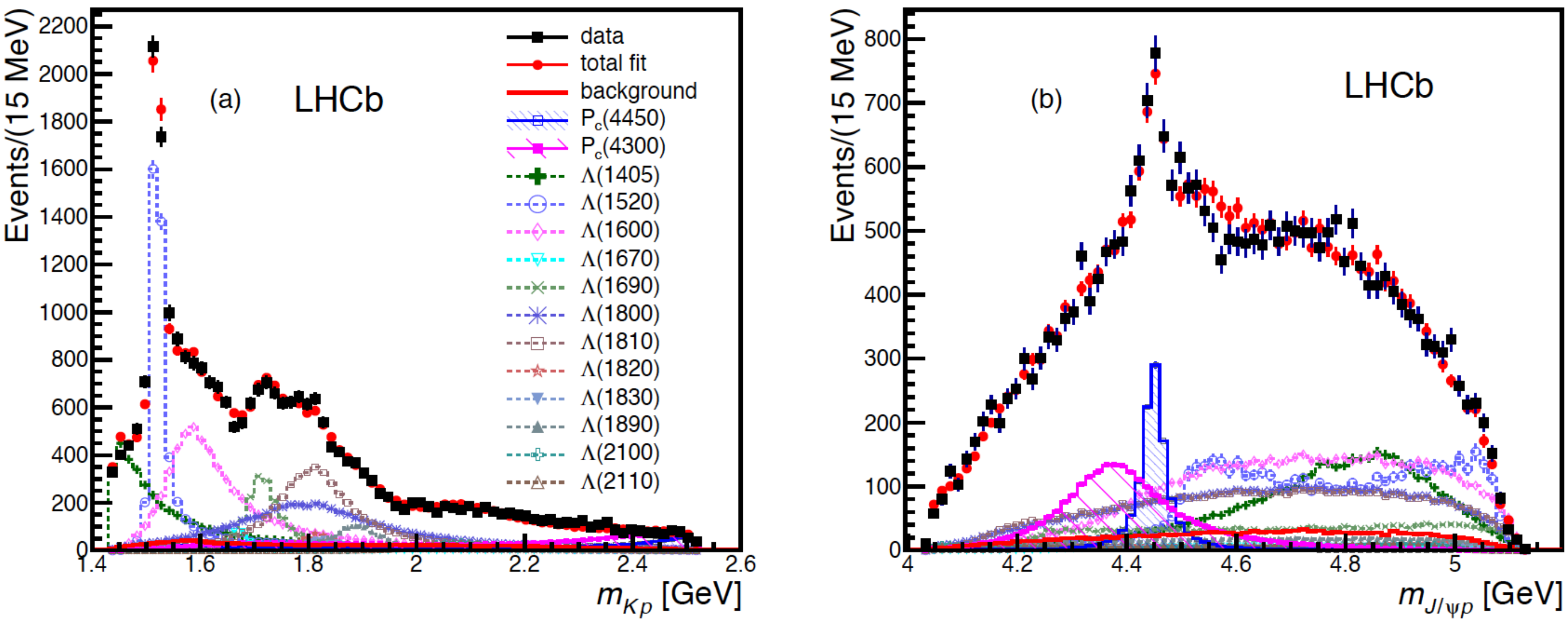
Extended model with 1 P_c

- Try all J^P up to $7/2^{\pm}$
- Best fit has $J^P = 5/2^{\pm}$. Still not a good fit



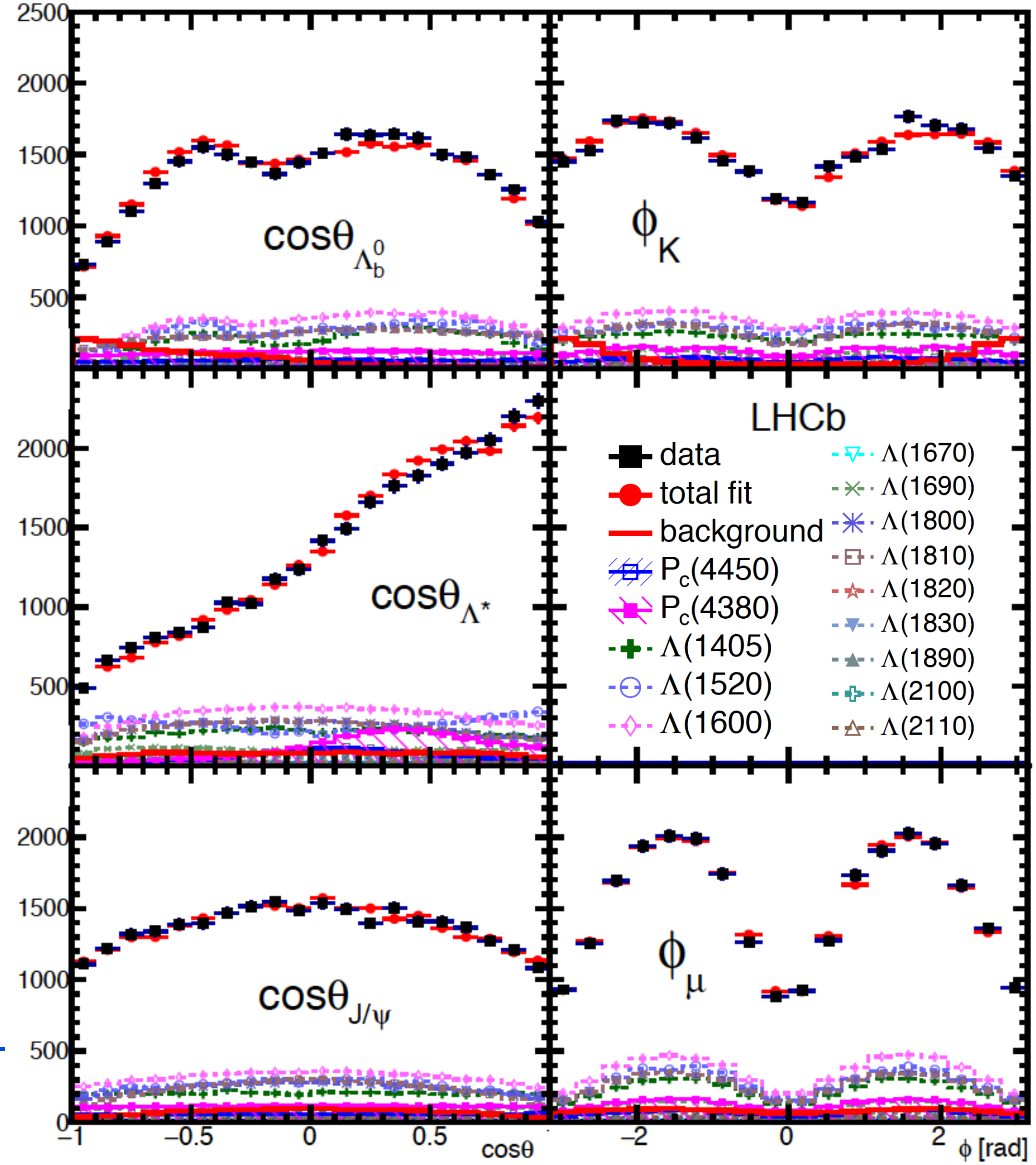
Reduced model with 2 P_c's

- Best fit has $J^P=(3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ are preferred

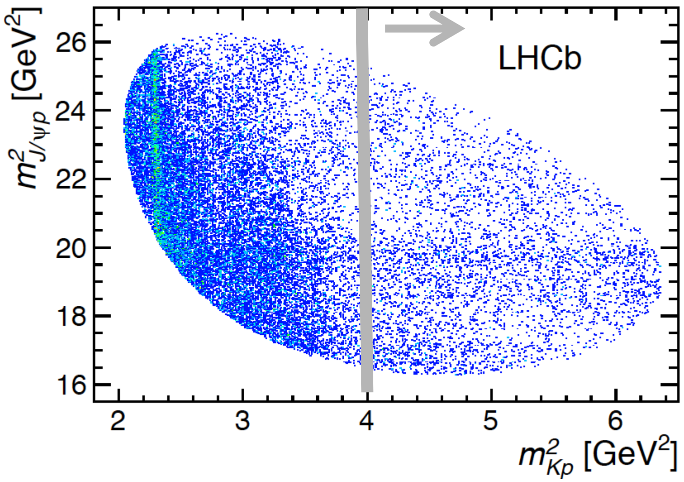


Angular distributions

Good fits in the angular variables



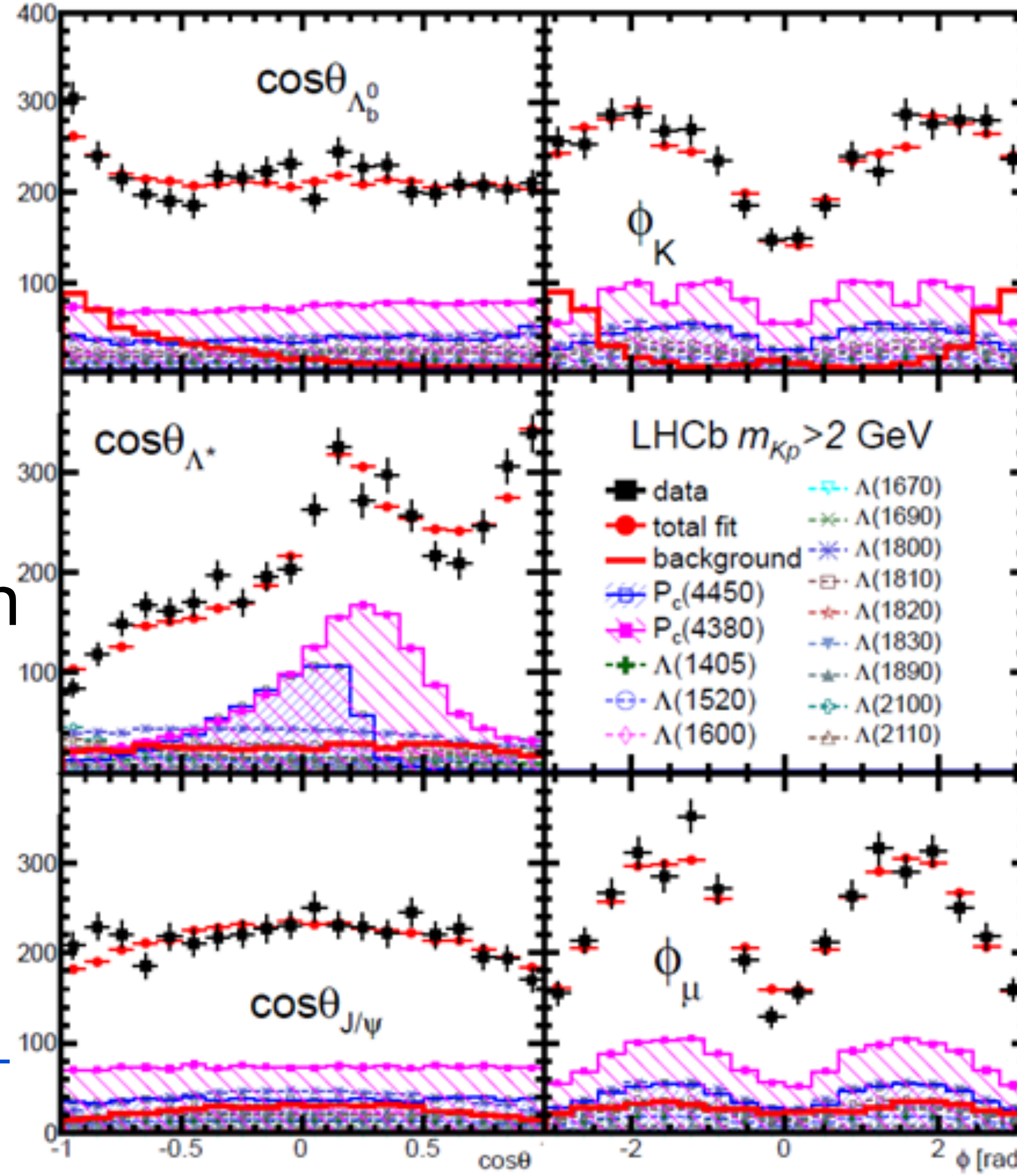
Better View



- Cut m_{Kp}>2GeV to enhance P_c^+ fraction

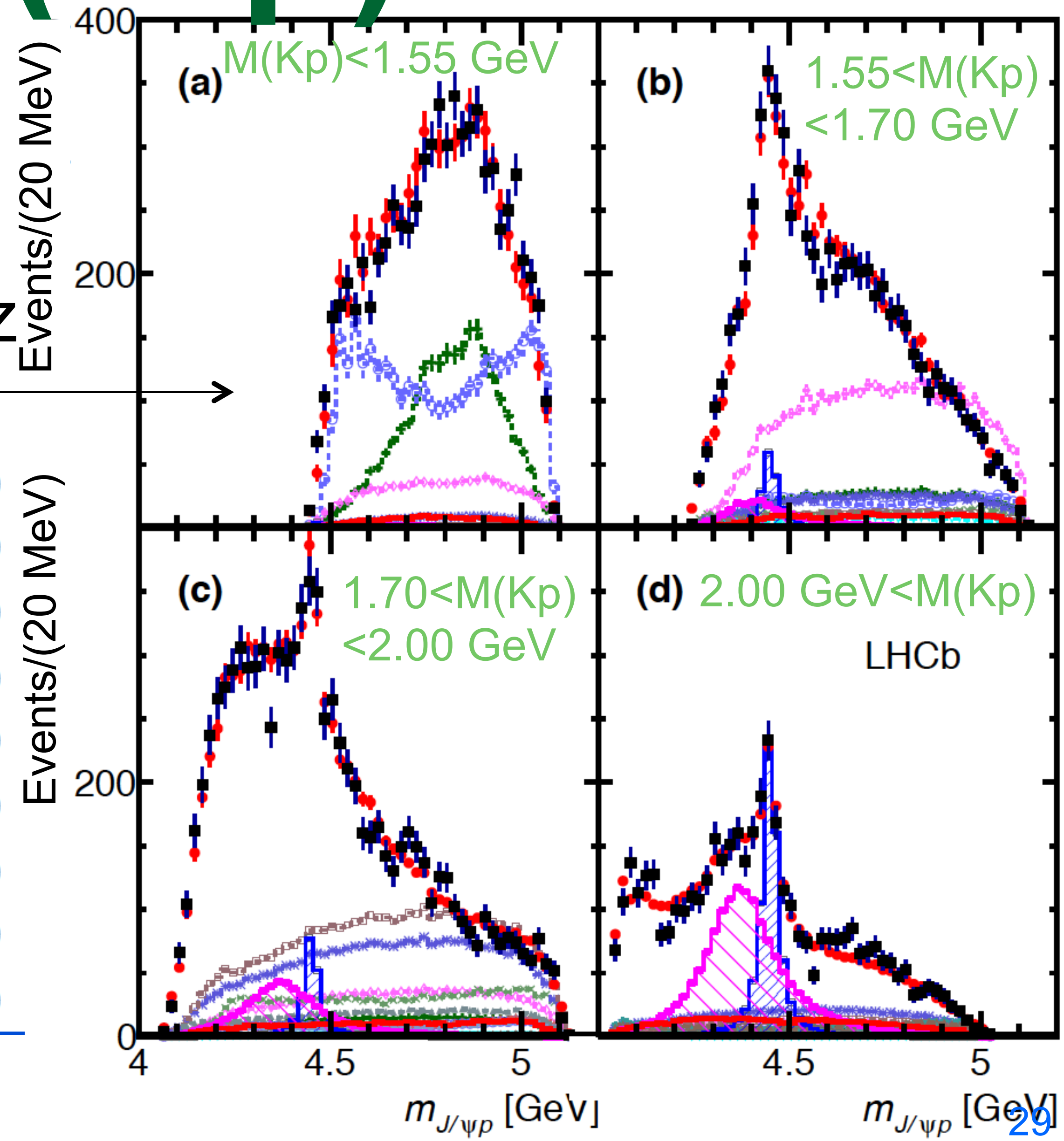
→

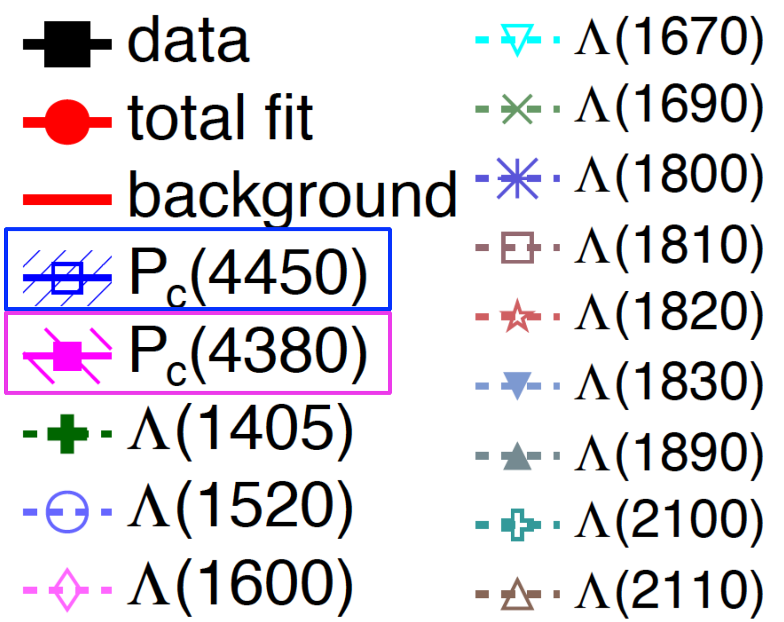
Should be visible by other LHC experiments



In m(K⁻p) slices

Pc's cannot appear in first interval as they would be outside of the Dalitz plot boundary

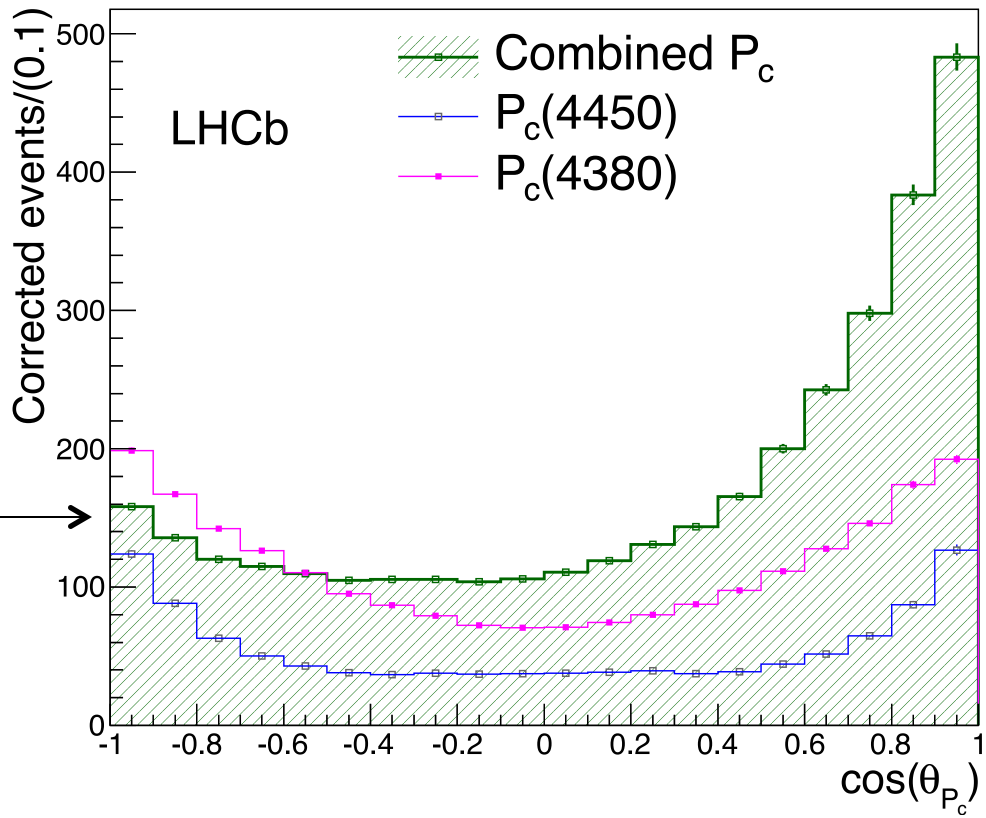




Data demands 2 states

- Interference between opposite parity states needed to explain P_c decay angle distribution
- Fit projections

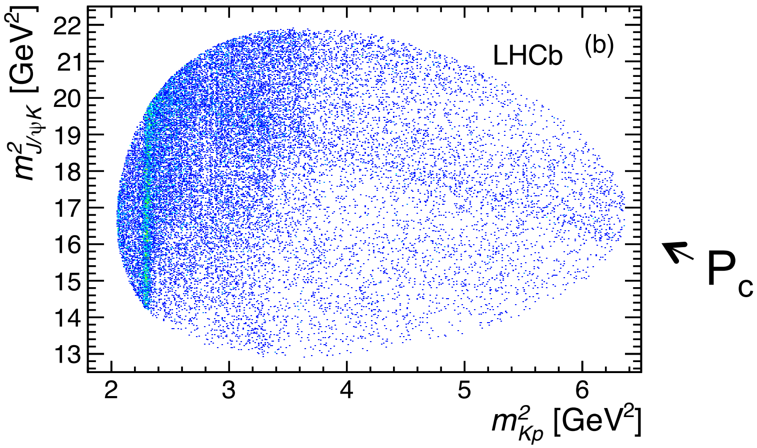
Large m(Kp) region negative interference

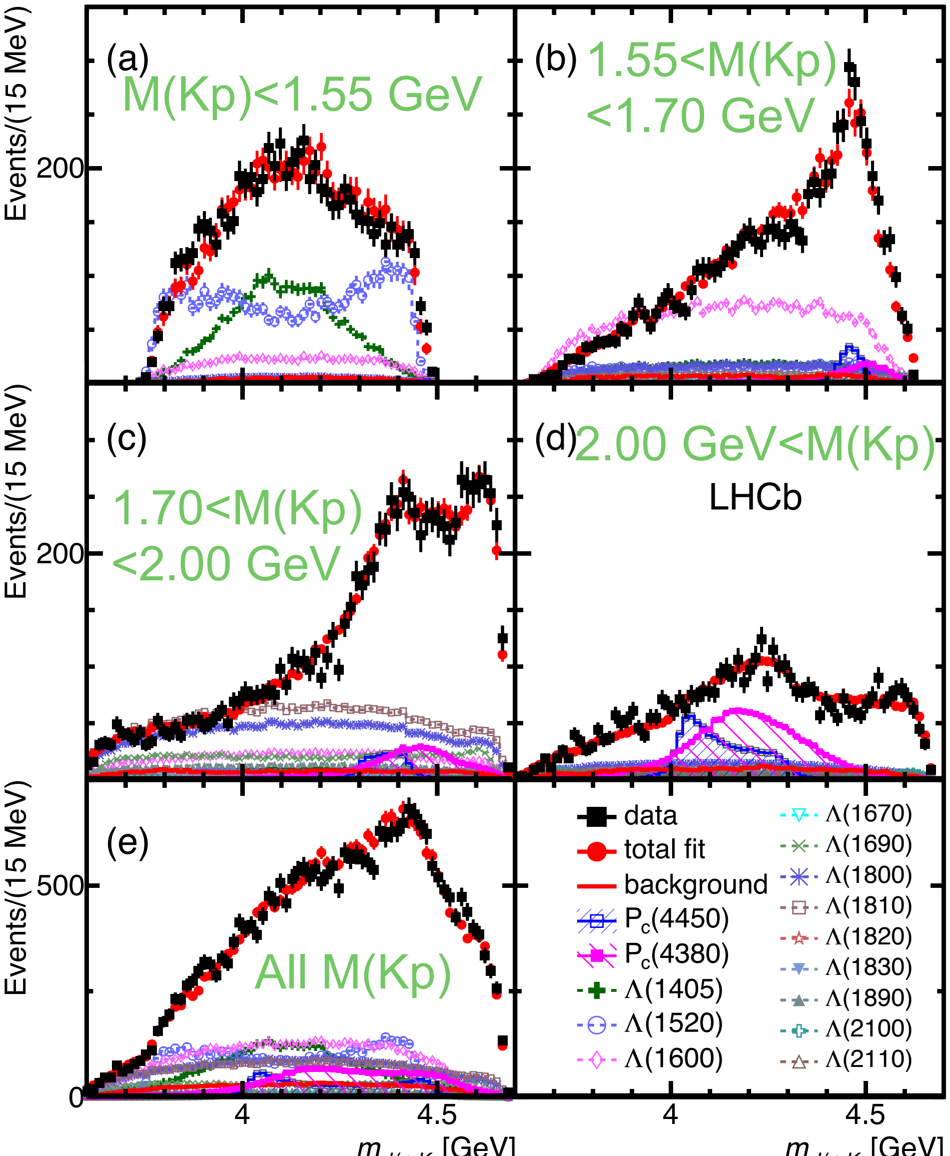


Small m(Kp) region positive interference

m(J/ψ K⁻)

- Our fit explains m(J/ψ K⁻)





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

Significances

- To include systematic uncertainty, the extended model fits are used
- Fit improves greatly, for 1 P_c $\Delta(-2\ln\mathcal{L})=14.7^2$, adding the 2^{nd} P_c improves by 11.6^2, for adding both together $\Delta(-2\ln\mathcal{L})=18.7^2$
- Toy MCs are used to obtain significances based on $\Delta(-2\ln\mathcal{L})$
- Significances:
  - 1^{st} $P_c(4450)^+$: 12σ
  - 2^{st} $P_c(4380)^+$: $9\ \sigma$
  - Total : 15σ

Fit results

	$P_c(4380)^+$	$P_c(4450)^+$
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
$\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-; P_c^+ \to J/\psi p)$	$(2.56 \pm 0.22 \pm 1.28^{+0.46}_{-0.36}) \times 10^{-5}$	$(1.25 \pm 0.15 \pm 0.33^{+0.22}_{-0.18}) \times 10^{-5}$

Branching ratio results are accepted Chin. Phys. C (arXiv:1509.00292)

Ref: $\mathcal{B}(B^0 \to Z^-(4430)K^+; Z^- \to \psi(2S)\pi^-) = (3.4 \pm 0.5^{+0.9}_{-1.9} \pm 0.2) \times 10^{-5}$

Cross-checks

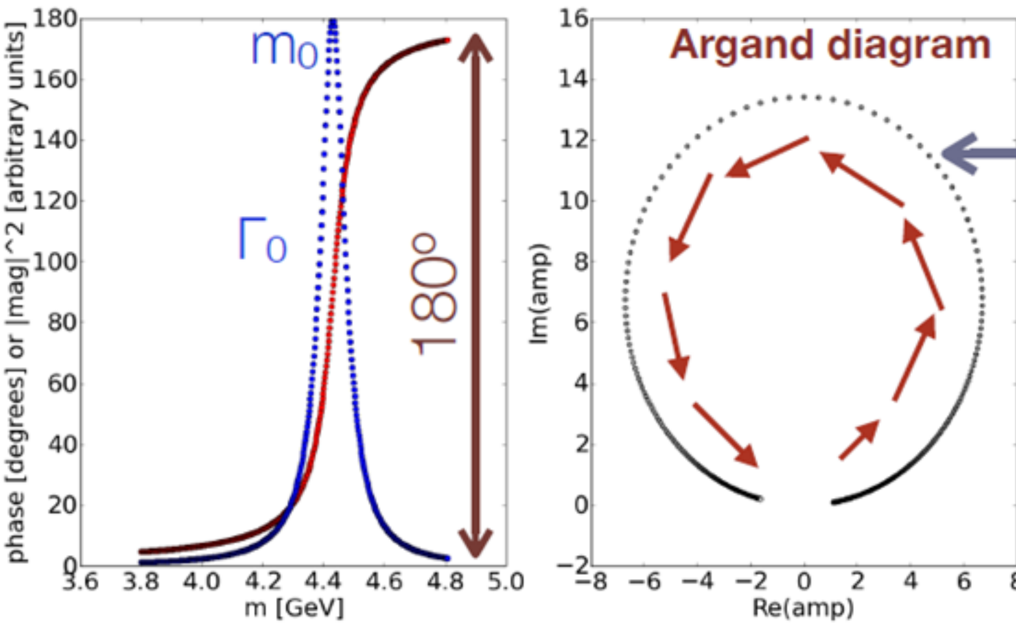
- Many done, some listed here:
- Signal found using different selections by others
- Two independently coded fitters using different background subtractions (sFit & cFit)
- Split data shows consistency: 2011/2012, magnet up/down, $\overline{\Lambda}_b/\Lambda_b$, $\Lambda_b(p_T\ \text{low})/\Lambda_b(p_T\ \text{high})$
- Selection varied
  - BDTG>0.5 instead of 0.9 (default)
  - B^0 and B_s misID background modeled in the fit instead of veto

Breit-Wigner amplitude

- Often a relativistic Breit-Wigner amplitude is used to model resonance
- Function has Re & Im parts

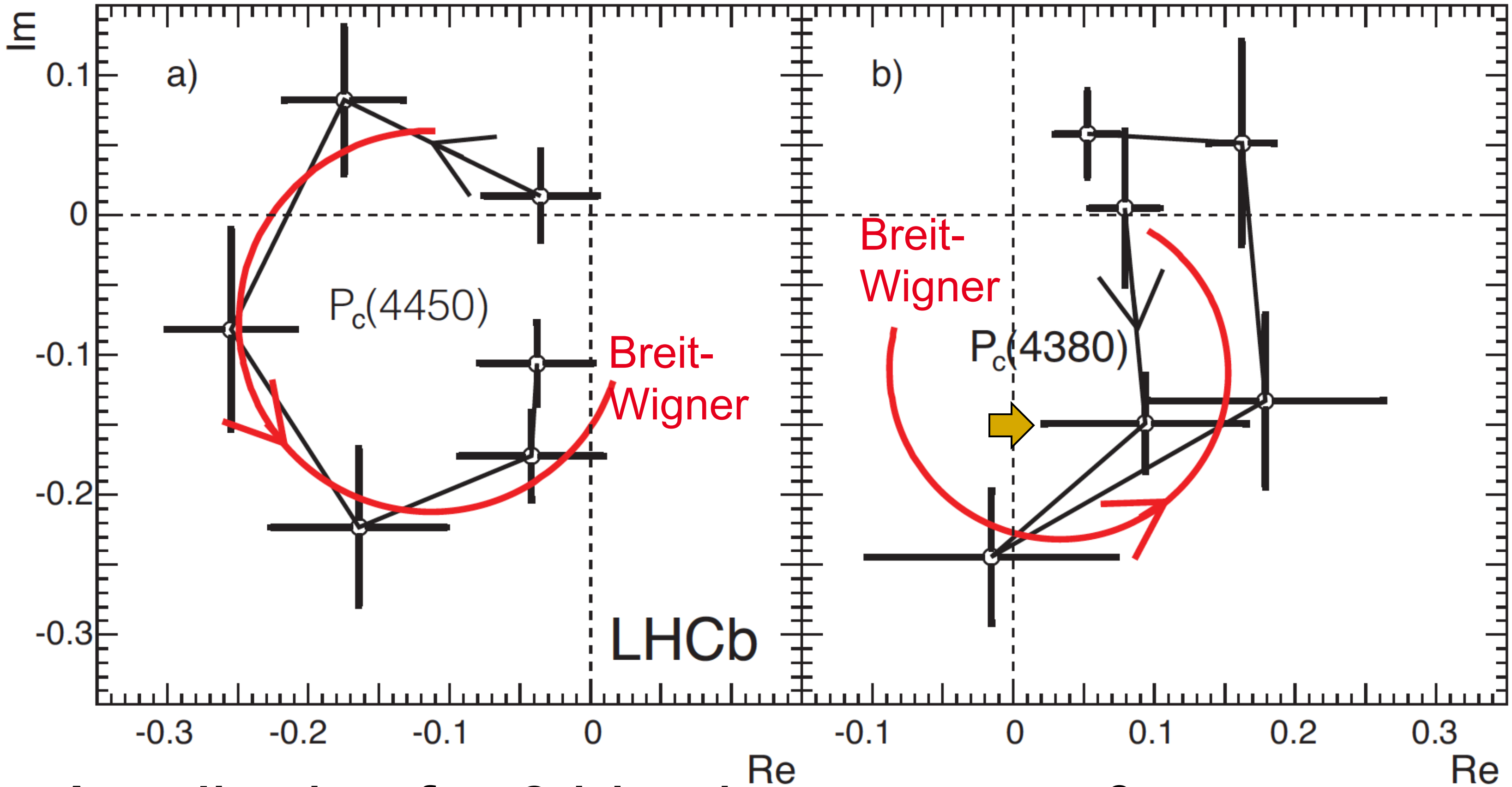
$$BW(m|M_0,\Gamma_0) = \frac{1}{M_0^2 - m^2 - iM_0\Gamma(m)}$$

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



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

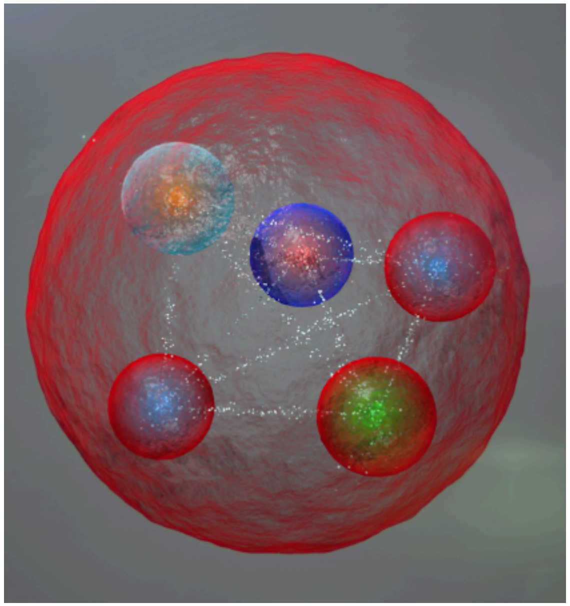
Argand diagrams

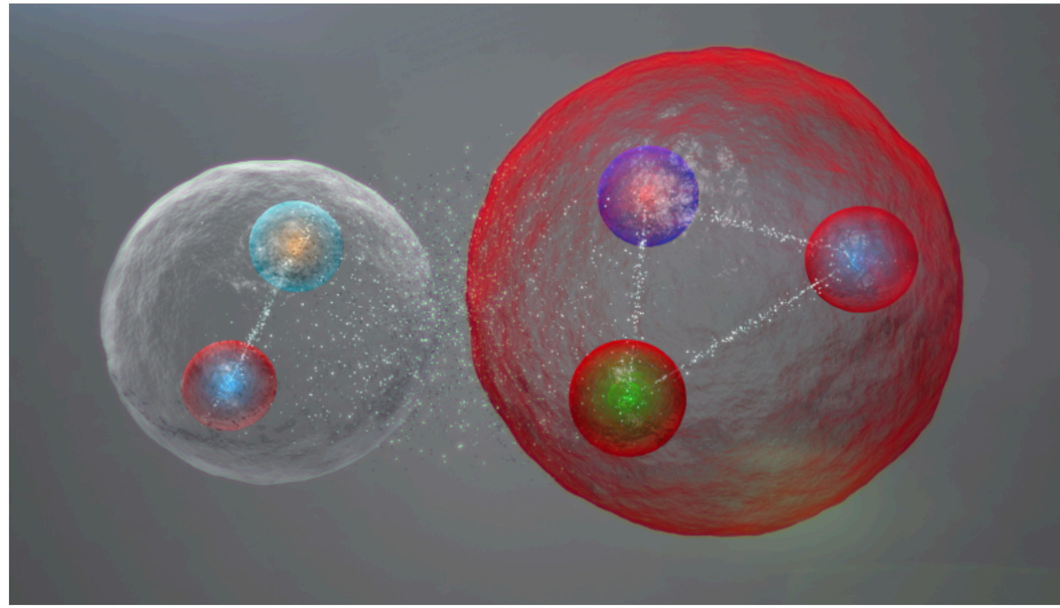


- Amplitudes for 6 bins between $+\Gamma$ & $-\Gamma$
- Left: too good, Right: one point 2σ away from expectation

What's a pentaquark

Popular explanations



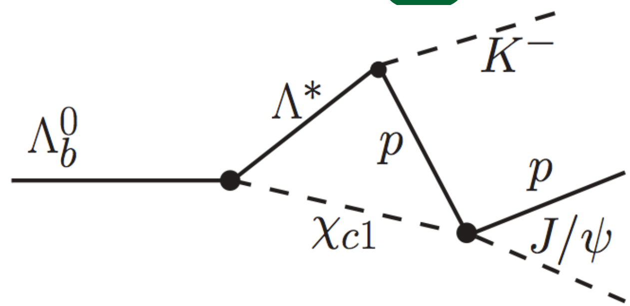


tightly bonded quarks

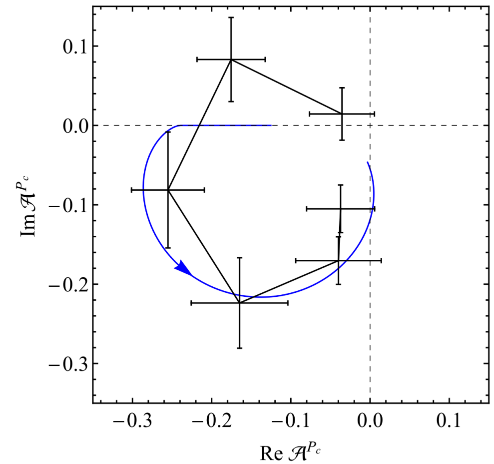
Weakly bound “molecules” of baryon-meson

Already >150 papers citing our result, with many possible interpretations

Rescattering



- As $m(\chi_{c1}p)=m(P_c(4450))$, $P_c(4450)$ is explained as $\chi_{c1}p \to J/\psi p$
- Can explain phase motion
- No predict the size of the rescattering amplitude
- Also difficult to predict two states…



[Guo et. al. arXiv:1507.04950]

- Experimental test: Could be killed if seeing $P_c(4450) \to \chi_{c1}p$ from $\Lambda_b \to \chi_{c1}pK^-$

Other P_c channels

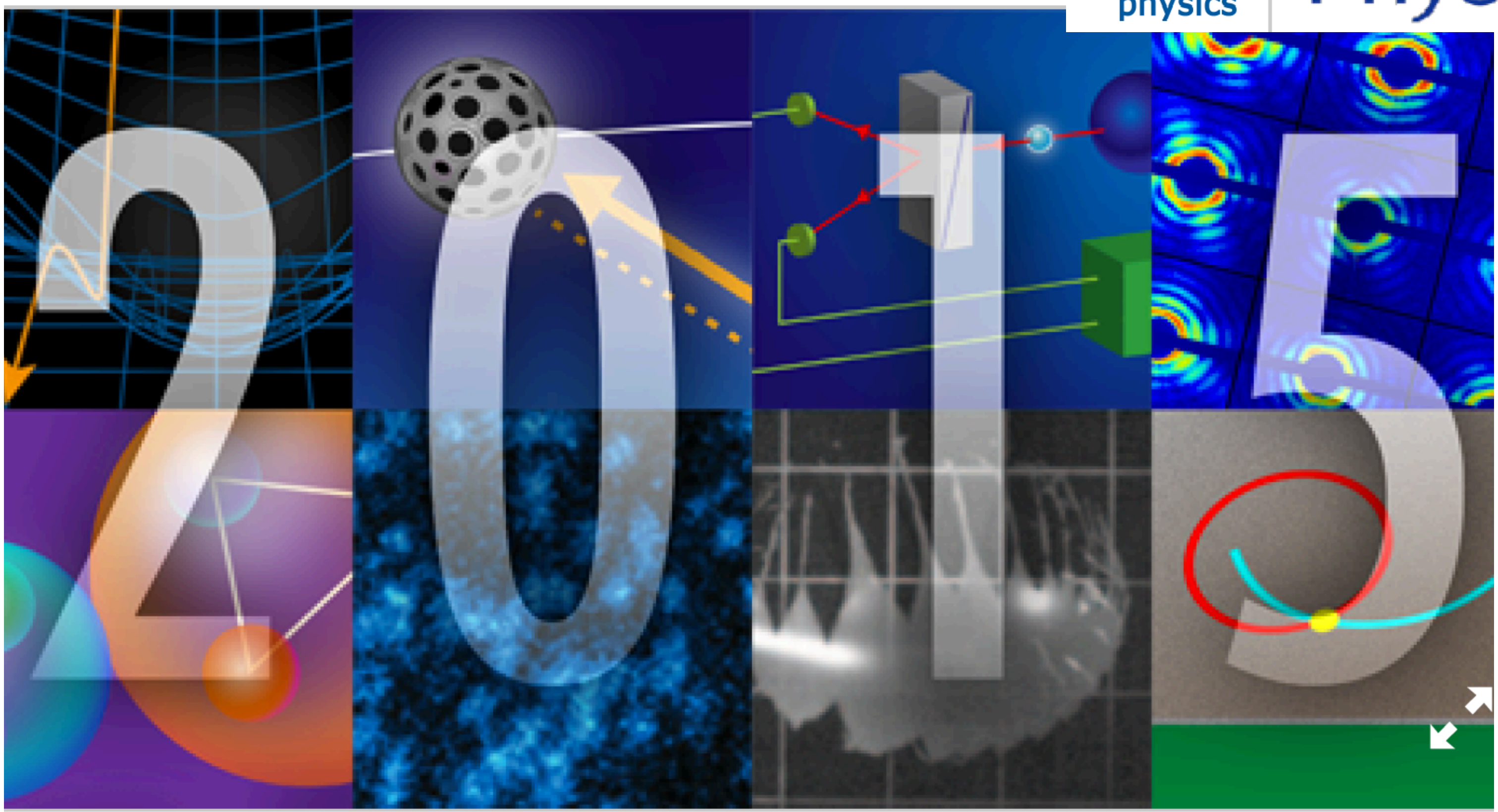
- B-Baryon decays:
  - $\Lambda_b \to J/\psi p \pi^-$: Cabibbo-suppressed
  - Hadronic: $\Lambda_b \to \Lambda_c^+ \bar{D}^0 K^-$
  - Other charmonium: $\eta_c p$, $\chi_{c1} p$ from Λ_b decays
- Direct production: background is high in low p_T, other LHC experiment can do it in high p_T?
- From non-hadron collider experiment:
  - Photon production: $\gamma p \to J/\psi p$ could be done at JLab
  - $e^+e^- \to J/\psi p\bar{p}$
- Generic pentaquarks: $[\bar{b}udud]$ and $[\bar{b}buud]$

Yields: at least 1/10 smaller than ideal mode $J/\psi p$

Conclusions

- LHCb has found two resonances decaying into J/ψp with pentaquark content of uudc$\bar{c}$. [PRL 115, 072001 (2015)]
- They have spin 3/2 & 5/2 & opposite Parity
- Determination of their internal binding, the "color chemistry" will require more study.
- Other exotic states have appeared containing $c\bar{c}$ (or $b\bar{b}$) quarks: the $Z^+(4430)\rightarrow\psi'\pi^+$ appears to be a tetraquark with $J^P=1^+$. Is binding stronger for c & b?
- We look forward to further searches for exotics
- We encourage our LHC colleagues to testify our results

Highlights of the Year

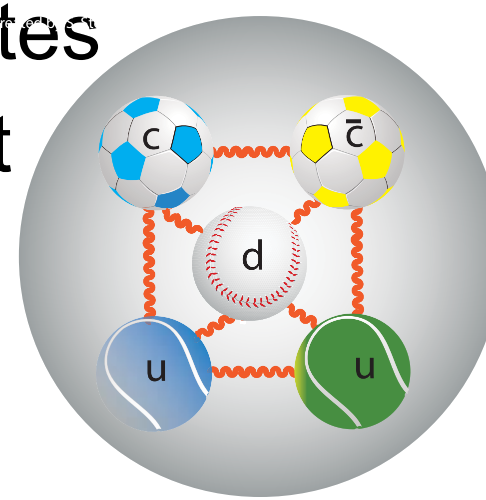


"The new pattern of quarks presents a unique opportunity to test models of the complex forces that bind quarks together"

The End

Pentaquark models

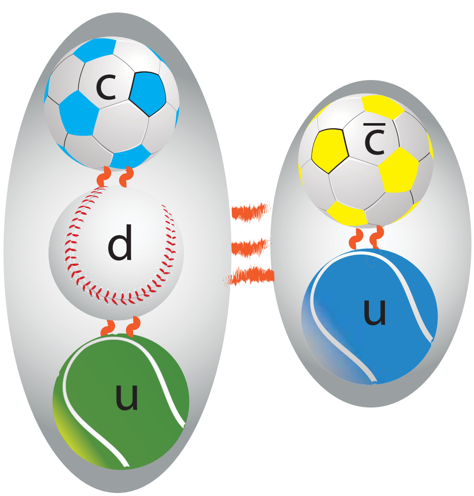
- All models must explain J^P of two states not just one. They also should predict properties of other states: masses, widths, J^P.



- Many models: Lets start with **tightly bound quarks** ala′ Jaffe
  - Two colored diquarks plus the anti-quark, L.Maiani, et. al, [arXiv:1507.04980]
  - Colored diquark + colored triquark, R. Lebed [arXiv :1507.05867]

Molecular models

- Molecular models, generally with meson exchange for binding
- Inspired by proximity of baryon-meson mass sums to P_c masses



Possible decay modes

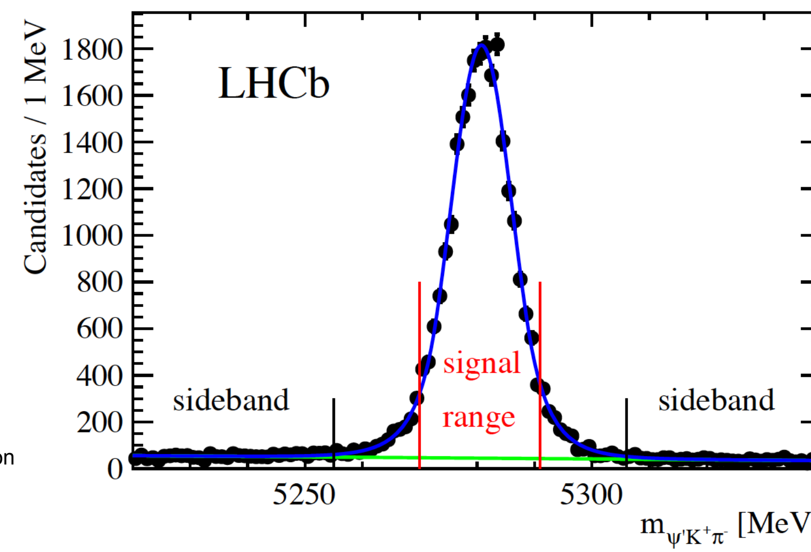
composition→	$P_c(4450)$				$P_c(4380)$	
	$\chi_{c1}p$	$\Sigma_c\bar{D}^*$	$\Lambda_c^*\bar{D}$	$J/\psi N^*$	$\Sigma_c^*\bar{D}$	$J/\psi N^*$
$J/\psi N$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$	$\checkmark$
$\eta_c N$	$\times$	$\times$	$\checkmark$	$\times$	$\times$	$\times$
$J/\psi\Delta$	$\times$	$\checkmark$	$\times$	$\times$	$\checkmark$	$\times$
$\eta_c\Delta$	$\times$	$\checkmark$	$\times$	$\times$	$\checkmark$	$\times$
$\Lambda_c\bar{D}$	$\checkmark$	$[\times]$	$[\checkmark]$	$\times$	$[\times]$	$\times$
$\Lambda_c\bar{D}^*$	$\checkmark$	$\checkmark$	$[\checkmark]$	$\checkmark$	$\checkmark$	$\checkmark$
$\Sigma_c\bar{D}$	$\checkmark$	$[\times]$	$\checkmark$	$\times$	$[\times]$	$\times$
$\Sigma_c^*\bar{D}$	$\checkmark$	$\checkmark$	$[\times]$	$\checkmark$		
$J/\psi N\pi$	$\times$	$\checkmark$	$\times$	$\checkmark$	$\checkmark$	$\checkmark$
$\Lambda_c\bar{D}\pi$	$\times$	$\times$	$\times$	$\times$	$\checkmark$	$\times$
$\Lambda_c\bar{D}^*\pi$	$\times$	$\checkmark$	$\times$	$\times$		
$\Sigma_c^+\bar{D}^0\pi^0$	$\times$	$\checkmark$	$\checkmark$	$\times$		

[Burns arXiv:1509.02460]

Z(4430)$^+$ tetraquark

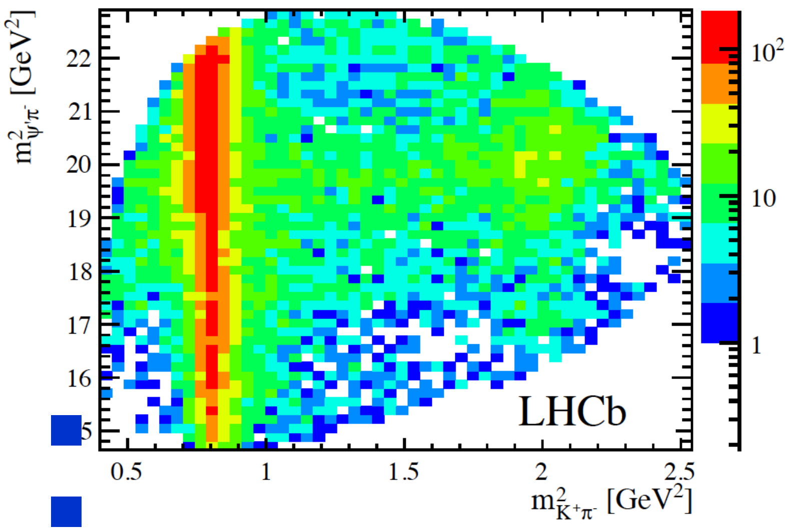
- $B^0 \rightarrow \psi' \pi^- K^+$, peak in $m(\psi'\pi^-)$, charged charmonium state must be exotic, not $q\bar{q}$
  - First observed by Belle M=4433±5 MeV, Γ=45 MeV
  - Challenged by BaBar: explanation in terms of K*'s
  - Belle reanalysis using full amplitude fit: M=$4485 \pm 22^{+28}_{-11}$ MeV, Γ=200 MeV, 1^+ preferred but 0^- & 1^- not excluded [arXiv:1306.4894]
- LHCb analysis also uses full amplitude fit
  - M= $4475 \pm 7^{+15}_{-25}$ MeV
  - Γ=172 MeV [arXiv:1404.1903]

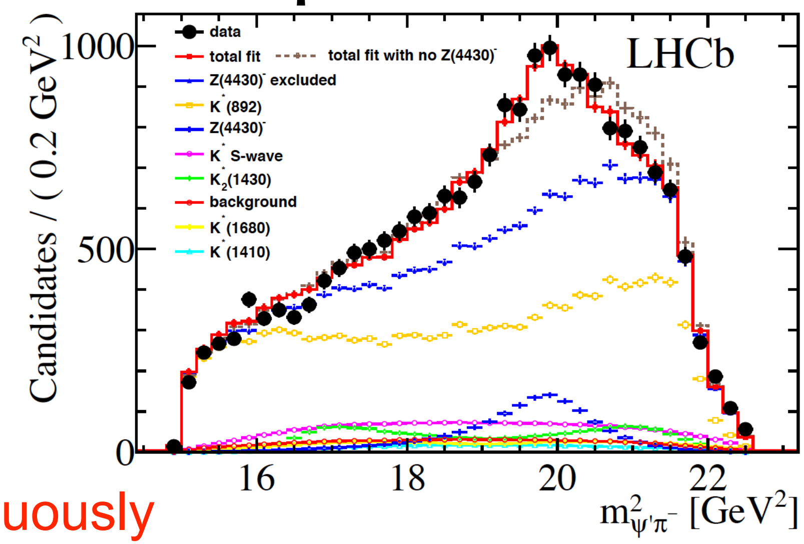
see also , LHCb-PAPER-2015-038 in preparation



LHCb Amplitude analysis

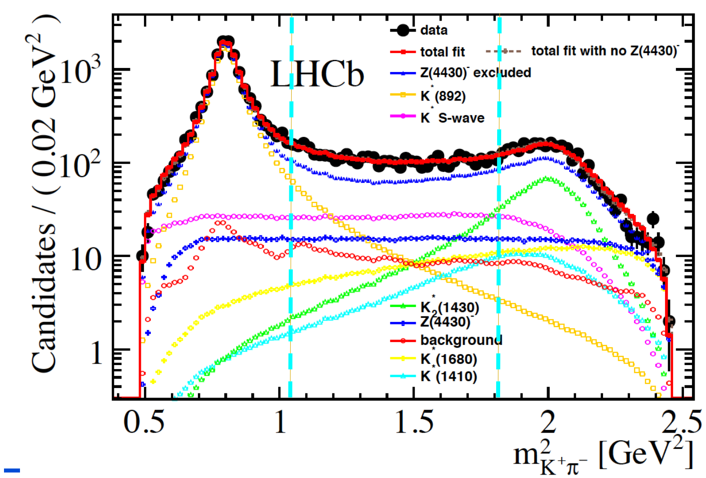
- Full 4D fit to both K*→K⁻π⁺ & Z→ψ′π⁻ states

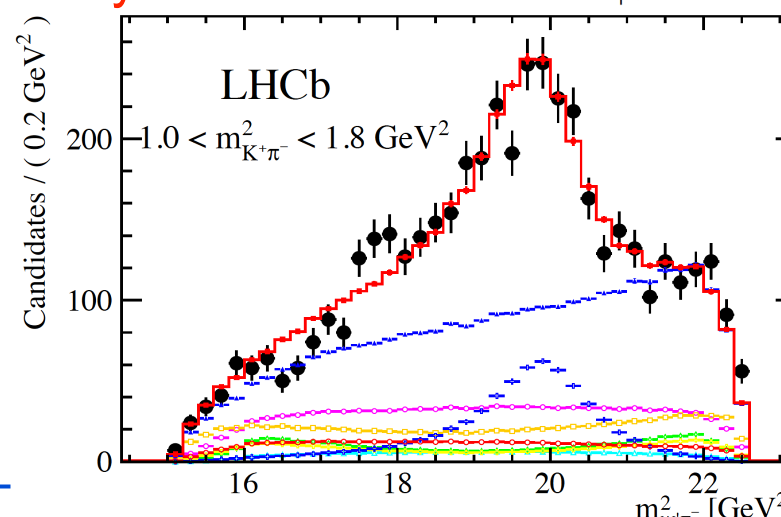




$J^P=1^+$

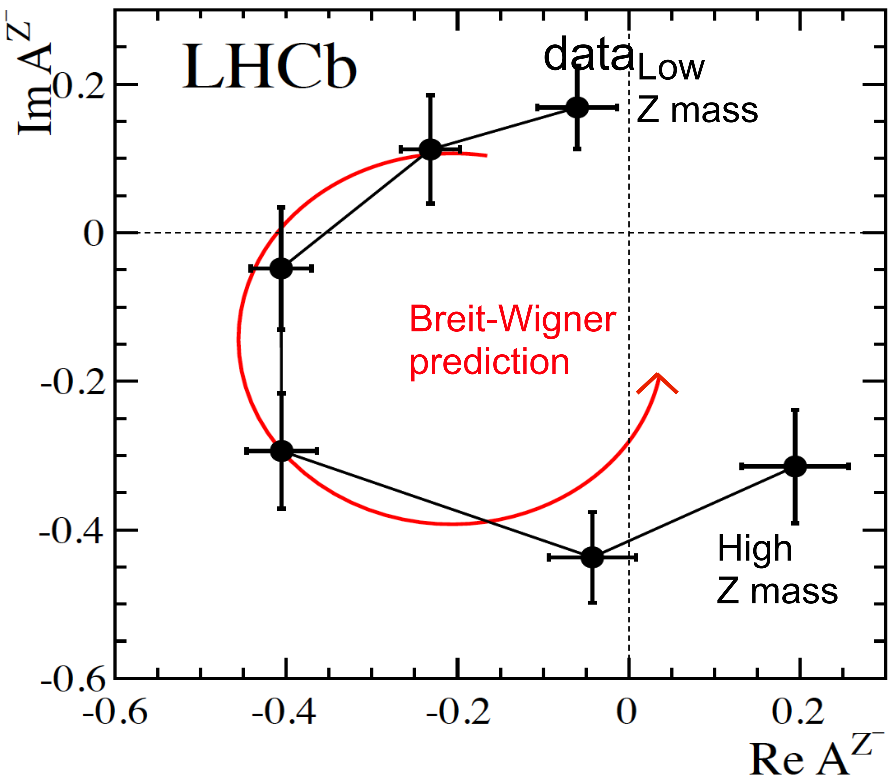
Unambiguously





Is it a resonance?

- LHCb produced an Argand plot that shows a clear & large phase change
- There are also attempts at rescattering explanations



Other Explanations

- **Molecule:**

L. Ma et.al, [arXiv:1404.3450]

T. Barnes et.al, [arXiv:1409.6651

- Same scattering phase

as Breit-Wigner

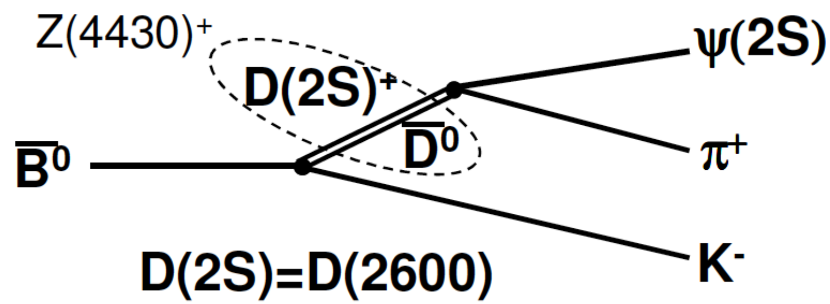
- Rescattering:

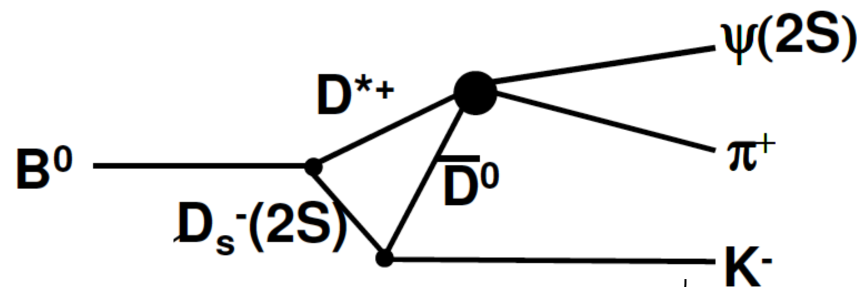
P. Pakhov & T. Uglov

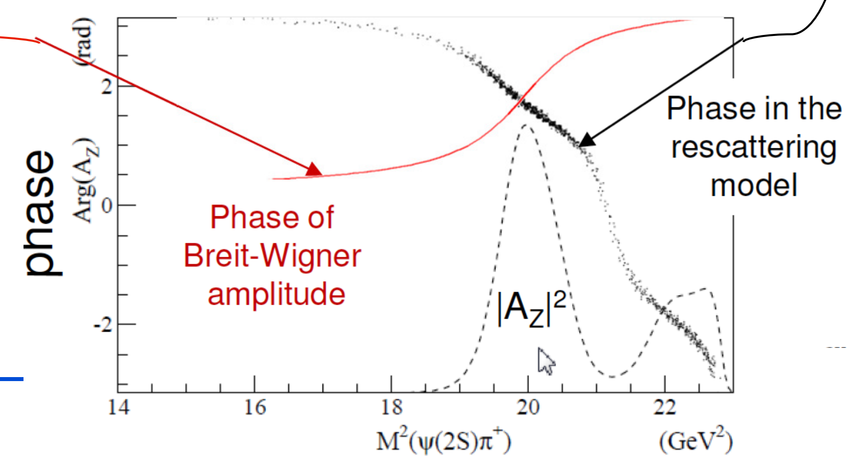
[arXiv:1408:5295]

- Opposite phase
- Ruled out by LHCb

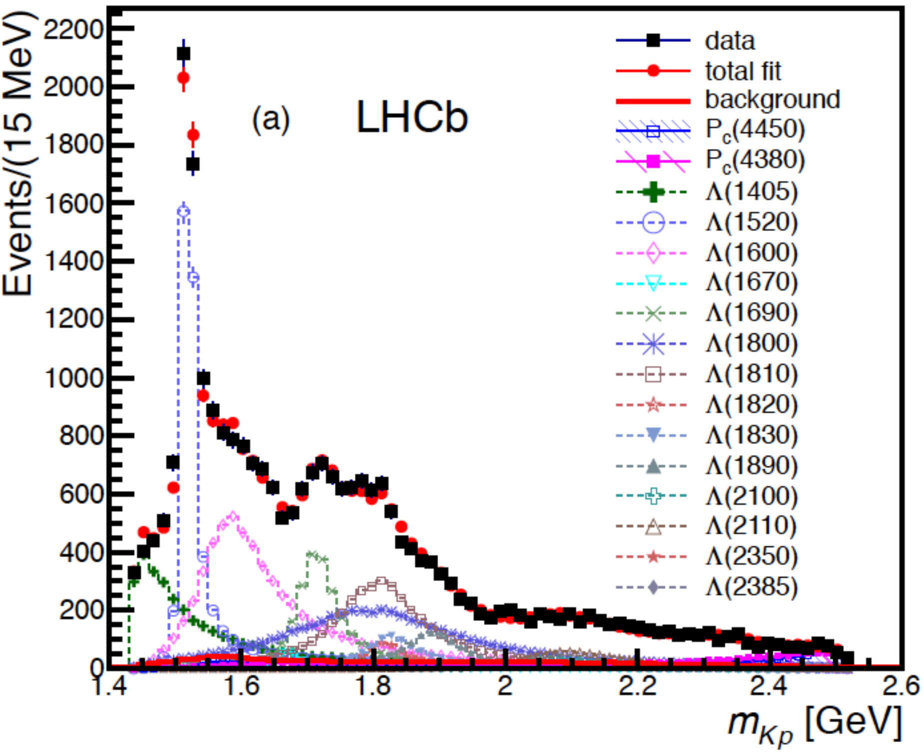
Argand diagram

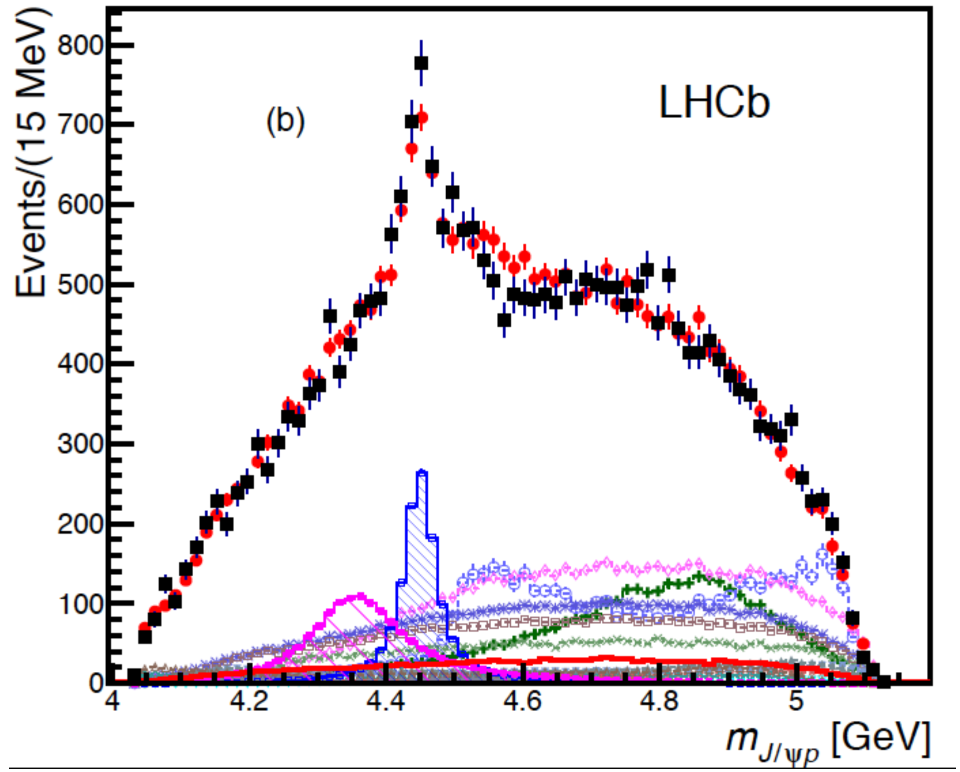






Extended model with 2 P_c's





Amplitude formalism

- The amplitude for the Λ^* decay sequence is given by

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

- For the P_c:

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

Amplitude formalism II

- The amplitude for the Λ^* decay sequence is given by

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

- For the P_c:

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

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

Amplitude formalism III

- The amplitude for the Λ^* decay sequence is given by

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

$$\mathcal{H}^{\Lambda_n^*\to Kp}_{\lambda_p,0} D^{J_{\Lambda_n^*}}_{\lambda_{\Lambda^*},\lambda_p}(\phi_K,\theta_{\Lambda^*},0)^* R_n(m_{Kp})\, D^{1}_{\lambda_\psi,\Delta\lambda_\mu}(\phi_\mu,\theta_\psi,0)^*$$

- For the P_c

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

$$\mathcal{H}^{P_{cj}\to\psi p}_{\lambda_\psi^{P_c},\lambda_p^{P_c}} D^{J_{P_{cj}}}_{\lambda_{P_c},\lambda_\psi^{P_c}-\lambda_p^{P_c}}(\phi_\psi,\theta_{P_c},0)^* R_j(m_{\psi p})\;\; D^{1}_{\lambda_\psi^{P_c},\Delta\lambda_\mu^{P_c}}(\phi_\mu^{P_c},\theta_\psi^{P_c},0)^*$$

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

Amplitude formalism IV

- Λ^* decay sequence is given by

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

- For the P_c

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

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

Amplitude formalism V

- They are summed as:

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

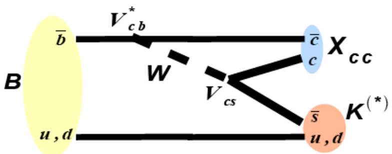
- α_μ & θ_p are rotation angles needed to align the final state helicity axes of the μ & p, as the initial helicity frames are different for the two decay chains

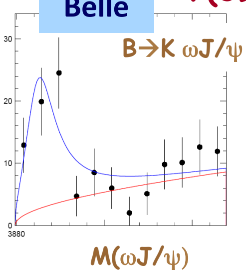
- Helicity couplings $\mathcal{H} \Rightarrow$ LS amplitudes *B* via:

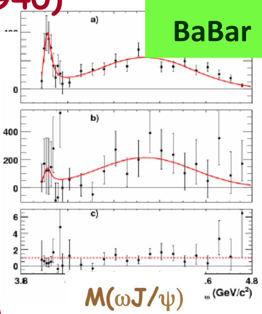
$$\mathcal{H}^{A\to B\,C}_{\lambda_B,\lambda_C} = \sum_L \sum_S \sqrt{\tfrac{2L+1}{2J_A+1}} B_{L,S} \left(\begin{array}{cc|c} J_B & J_C & S \\ \lambda_B & -\lambda_C & \lambda_B - \lambda_C \end{array} \right) \times \left(\begin{array}{cc|c} L & S & J_A \\ 0 & \lambda_B - \lambda_C & \lambda_B - \lambda_C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

  - Convenient way to enforce parity conservation in the strong decays via: P_A

Other tetraquark candidates



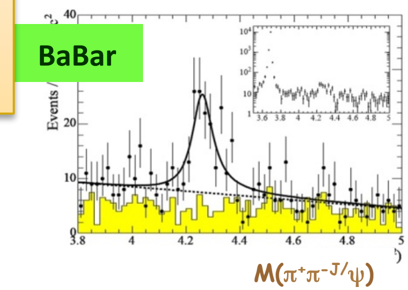


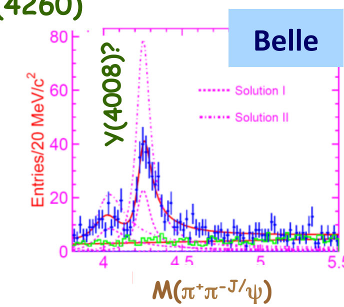


Z(4430)

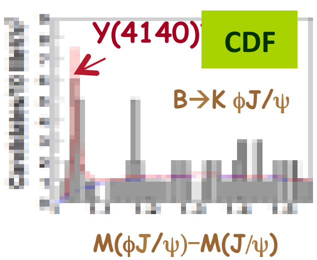
Thus far, no amplitude analyses for these states

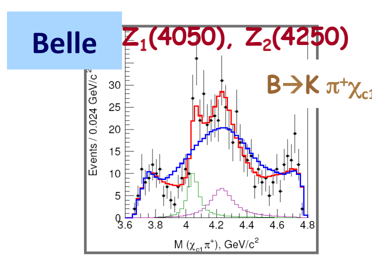
Y(4260)



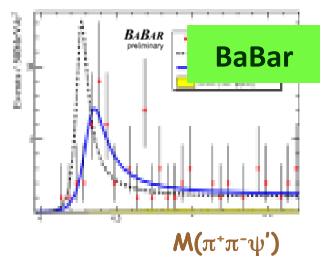


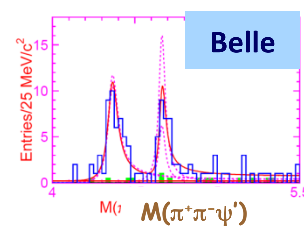
Y(4350) & Y(4660)



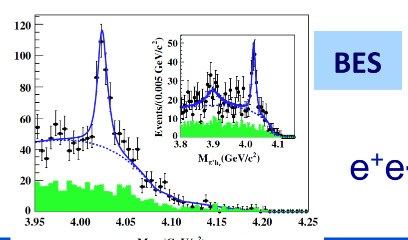


$M(\pi^{\pm}\chi_{c1})$





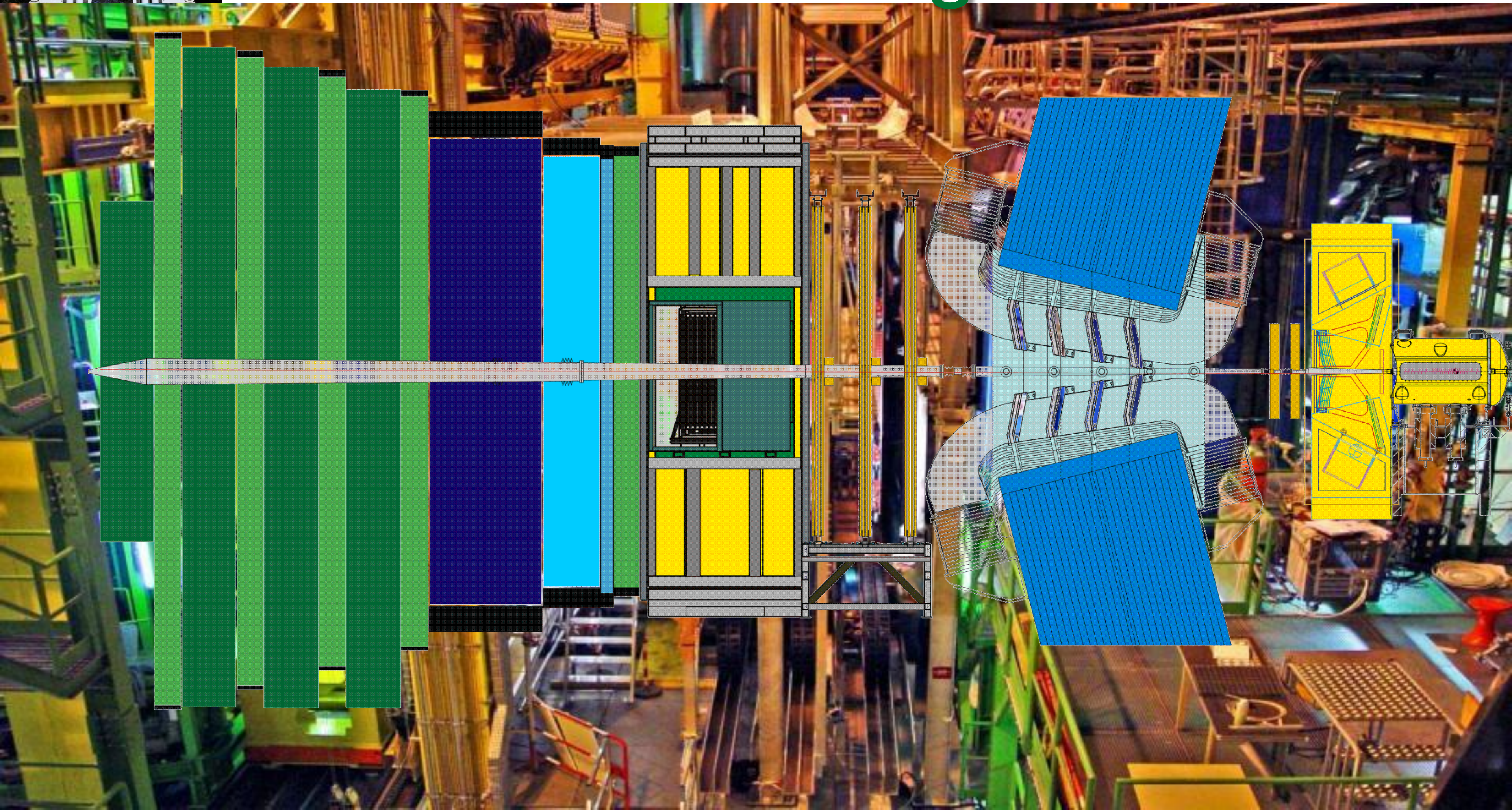
All current candidates contain a $c\bar{c}$ or $b\bar{b}$



$M(\pi^{\pm}h_c)$

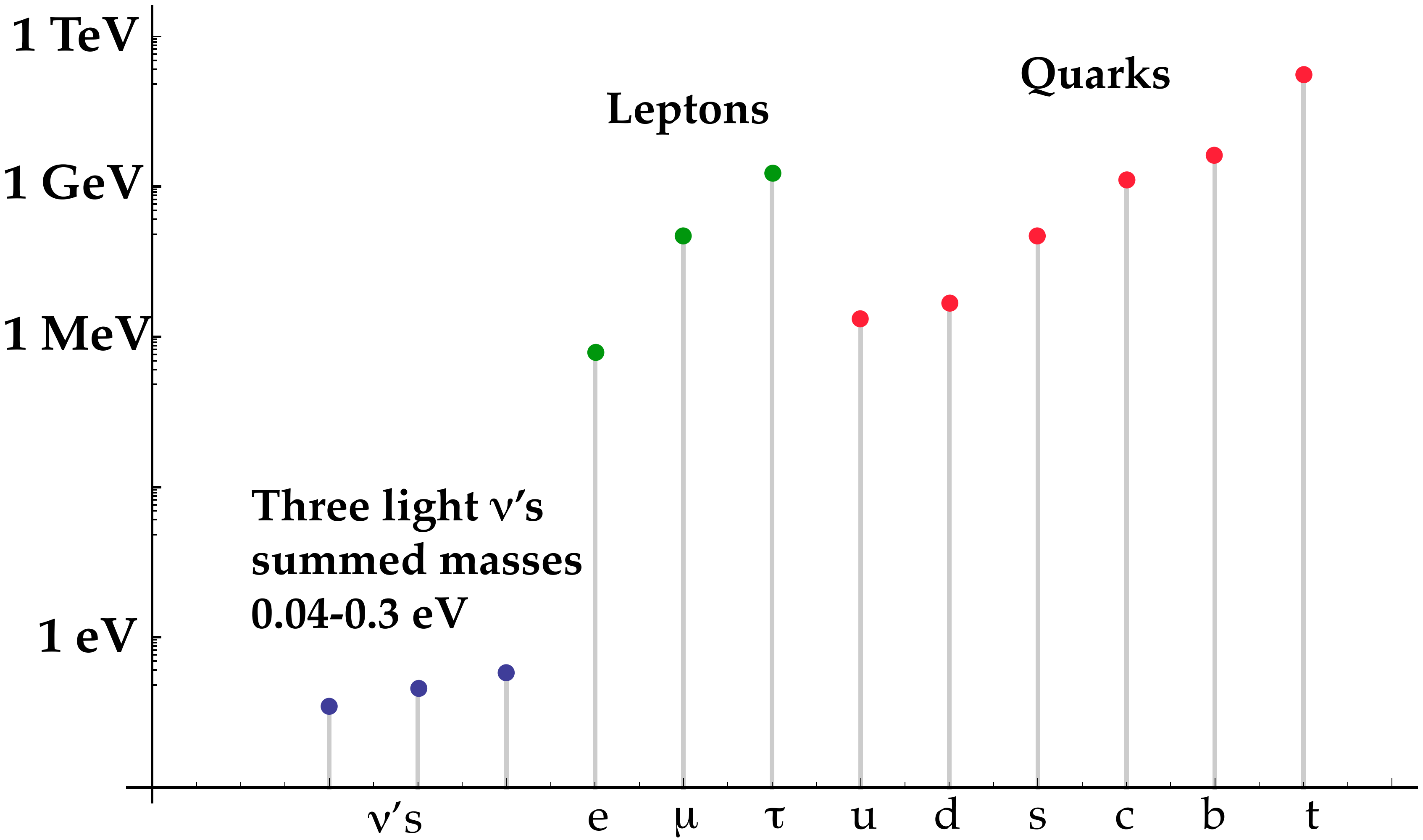
$e^+e^- \to Y(4260) \to \pi^+ Z_c(4020)^- \to \pi^- h_c$

Detector Workings



LHCb detector ~ fully installed and commissioned → walk through the detector using the example of a $B_s \rightarrow D_s K$ decay

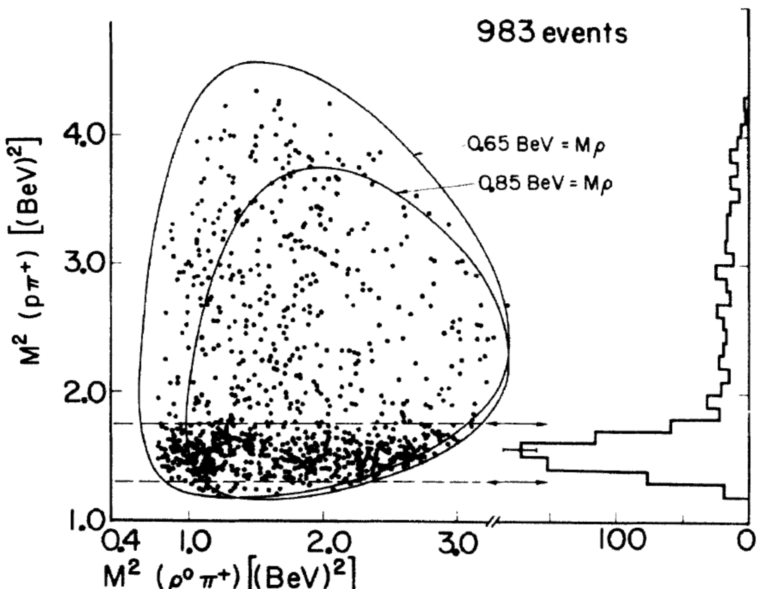
Masses

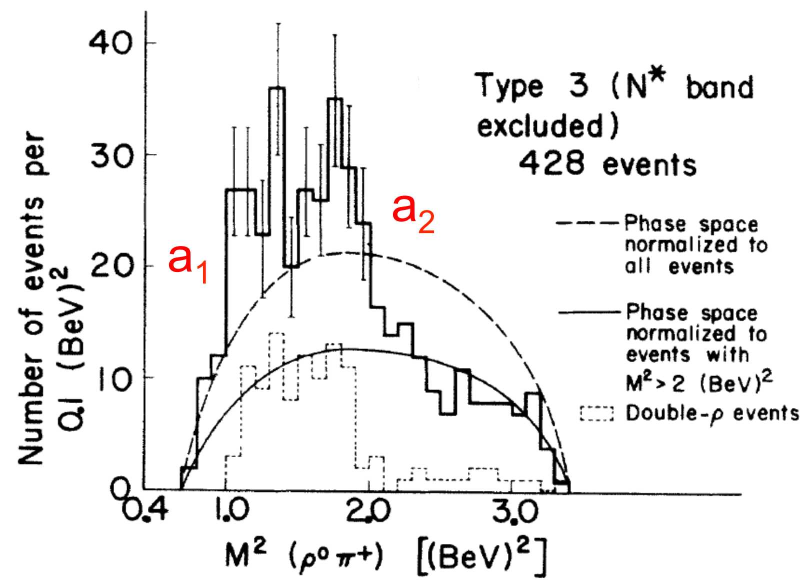


12 orders of magnitude differences not explained; t quark as heavy as Tungsten

Some History: The a_1

- Is it possible for other processes to mimic resonant effects?
- Example: The Deck effect, a lesson in confusion: $\pi^+ p \to \pi^+ \rho^0 p$, $\rho^0 \to \pi^+ \pi^-$, using a 3.65 GeV π^+ beam, *G. Goldhaber et. al, PRL 12, 336 (1964)*

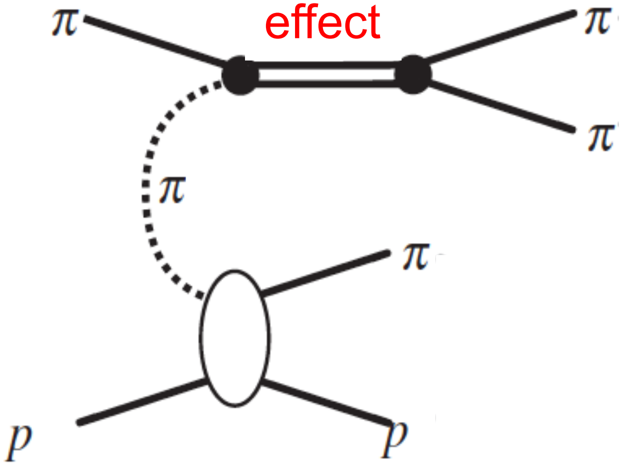




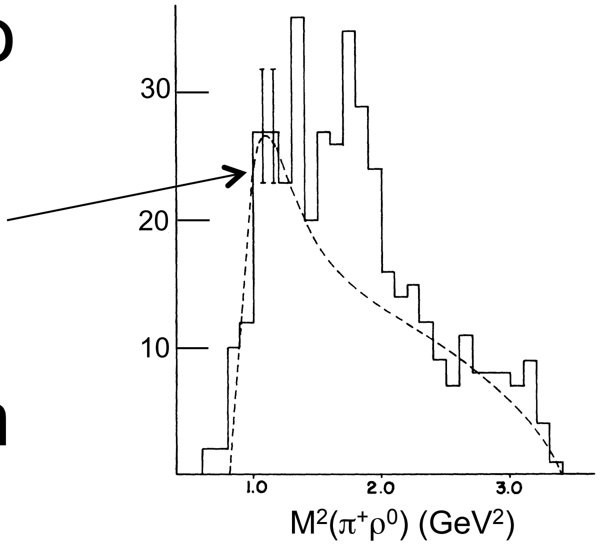
Note BeV≡GeV

"Kinematical" effect

- Clear enhancement near threshold. Is it a new resonance as suggested in original paper?
- Theorists, first Deck, suggest that the threshold enhancement can be due to off shell πp scattering *R.T. Deck, PRL 13, 169 (1964)*

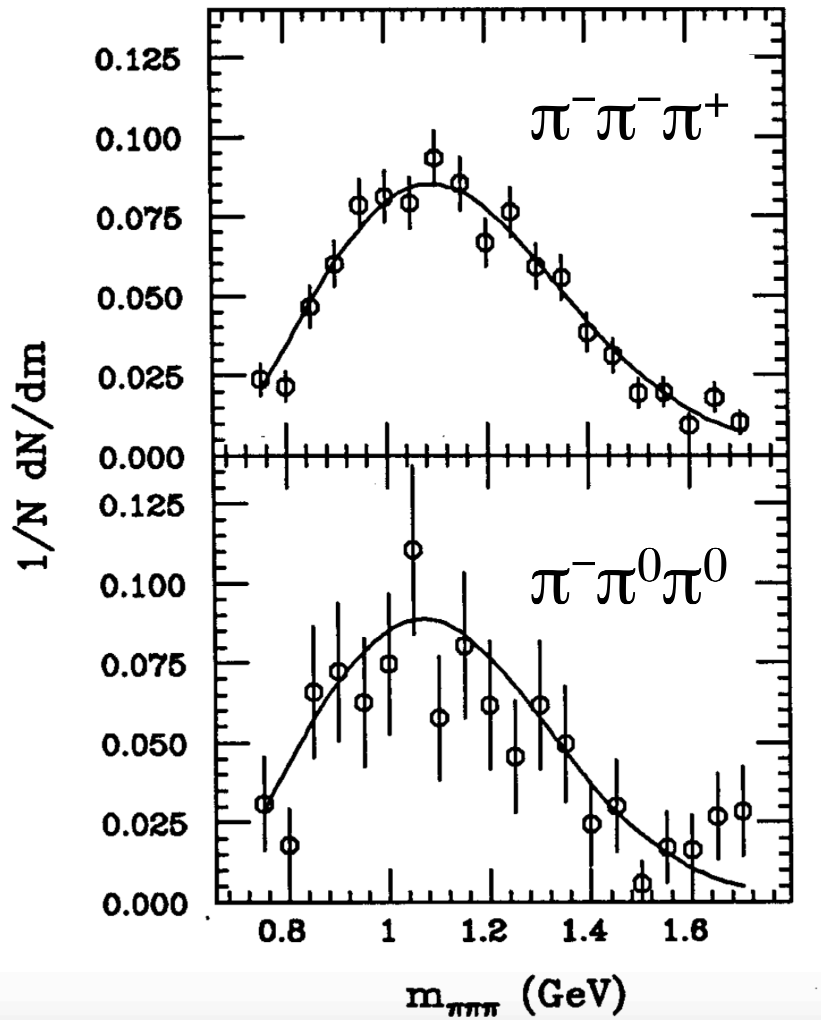


- Deck's fit to data can provide adequate explanation



$\tau^- \to (\pi\pi\pi)^- \nu$

- Controversy continued until observation of a_1 in $\tau^- \to \pi^+\pi^-\pi^-\nu$ decays, ~1977
- Surmises: a full amplitude analysis may have proved the resonant nature of the a_1 earlier. Important to see resonant states in several ways. There never was an unambiguous demonstration of the “Deck” effect.



MAC (PEP) data 1987

LHCb goals

- Find or establish limits on physics beyond the standard model using CP violating & rare beauty & charm decays

- Rare: $B_{(s)}\rightarrow\mu^+\mu^-$, $B^0\rightarrow K^*\mu^+\mu^-$, $B^-\rightarrow K e^+e^-/K\mu^+\mu^-$
- CP violation: determine $\angle$'s: γ, β, ϕ_s
  - γ measured with $B^-\rightarrow D^0 K^-$ decays
  - ϕ_s measured with $B_s\rightarrow J/\psi\phi$ & $J/\psi\pi^+\pi^-$ decays
  - All $B\rightarrow J/\psi\ \pi^+\pi^-$ & $J/\psi K^+K^-$ studied
  - In study of $B^0\rightarrow J/\psi K^+K^-$ [arXiv:1308.5916], $\Lambda_b\rightarrow J/\psi K^- p$ was suggested as a potential background

Fit results

Mass (MeV)	Width (MeV)	Fit fraction (%)
4380±8±29	205±18±86	8.4±0.7±4.2
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