Multi-quark exotics by LHCb

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Various Faces of QCD
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LHCb

But which face?

The dark one, I'm affraid ..

F. Wilczek: *The story of the pentaquark shows how poorly we understand QCD*
HADRON05 summary: Heavy quark hadrons and theory, arXiv: hep-ph/0510365 (2005)

Story of strange 5-quarks is rather discouraging but LHCb claims pentaquarks were found in 2015.

Does this mean we do understand QCD better now?

What kind of multi-q exotics?

Colour singlets made up of q, 2q, .., not fitting to standard picture (masses, decay times, quantum numbers)

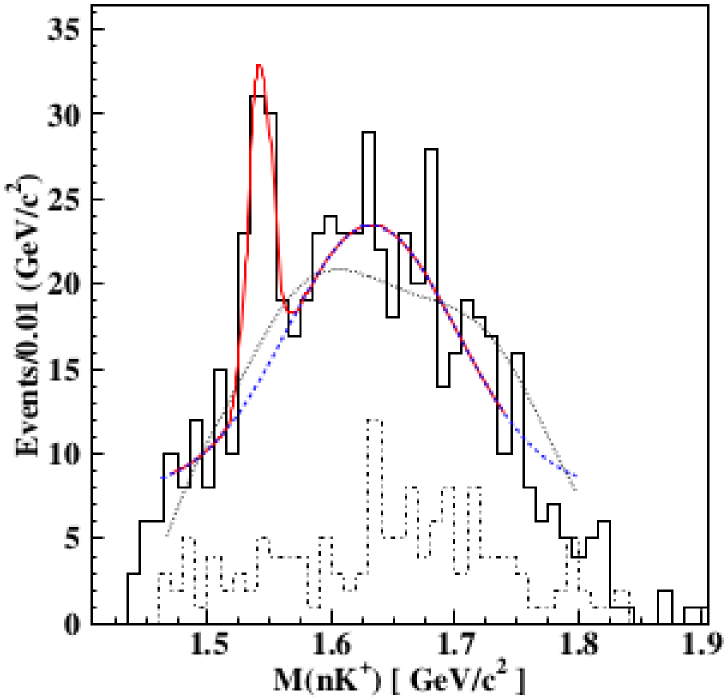
Mostly, recent discoveries of the tetra- and pentaquarks by the LHCb at CERN, but also comparison to the others' findings;

No discussions of hybrids, H-diquarks and glueballs; all those are fascinating subjects but no time ..

Not too much experimental details

Lessons for experimentalists from the past

Do not be satisfied just observing bumps in masses; they could easily be spurious, e.g. 2004 CLAS initial claim at 1.54 GeV was debunked using 20x more events

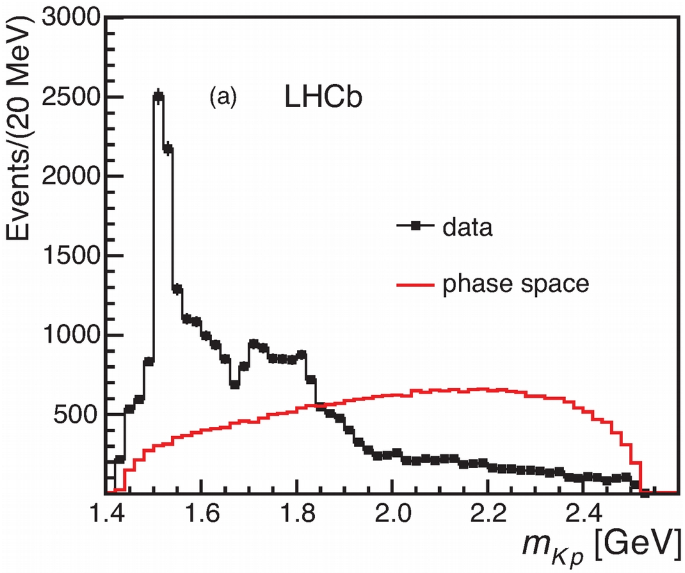


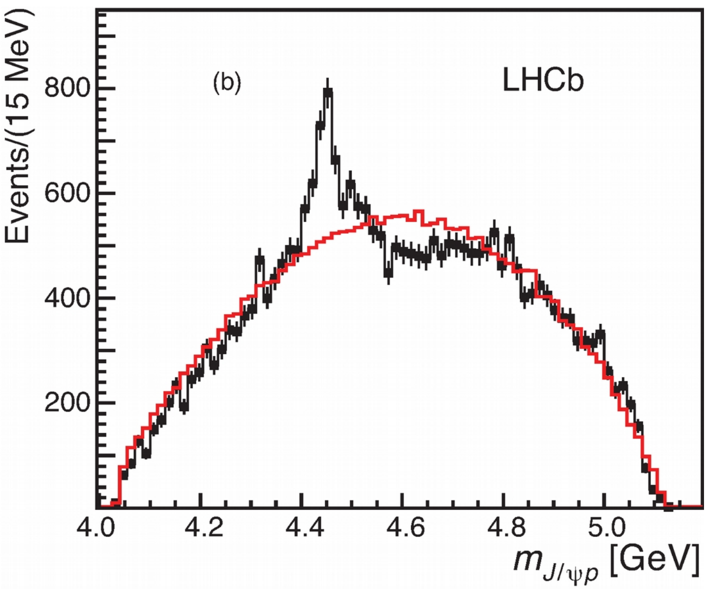
Also, some earlier claims of dibaryons ..

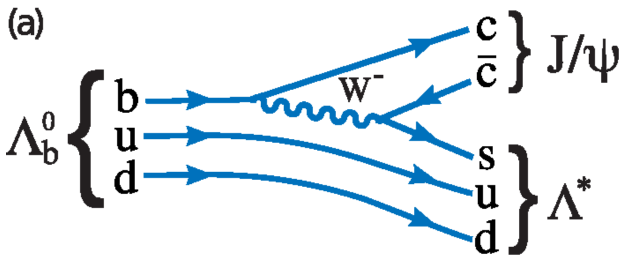
One needs a full-fledged amplitude analysis, esp. in 3-body decays, and observations in different decay modes

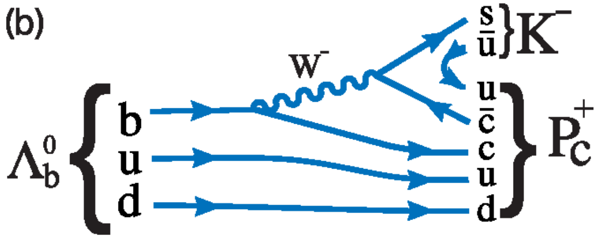
Pentaquarks: LHCb 2015, PRL 115(2015)072001

LHCb observes large yields of $\Lambda_b(5620) \to J/\Psi\, p\, K^-$





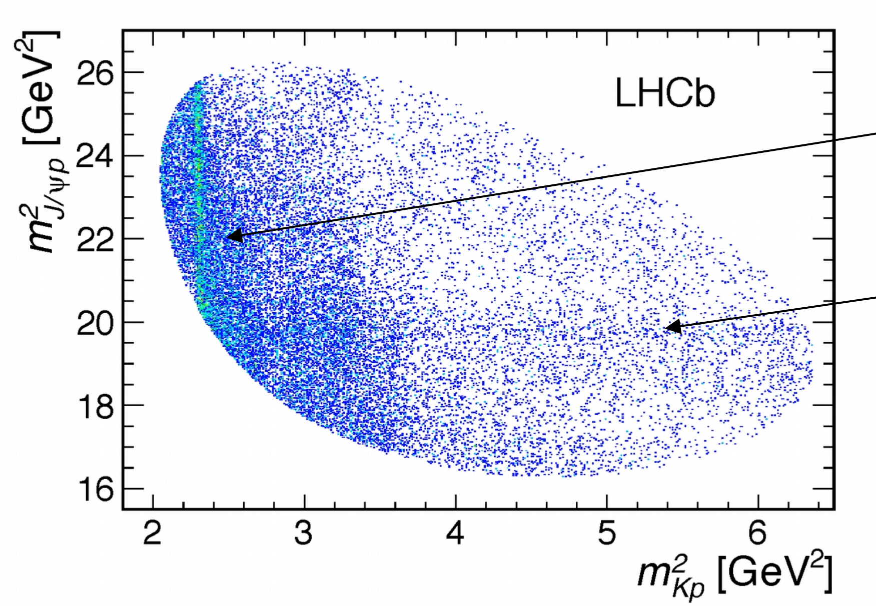




$\Lambda^* \to K^- p$

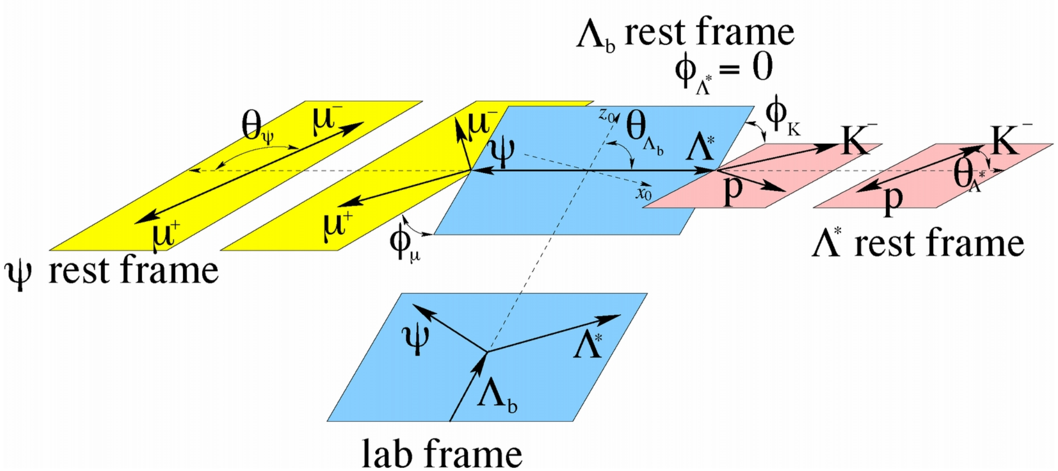
$P_c^+ \to J/\Psi\, p$

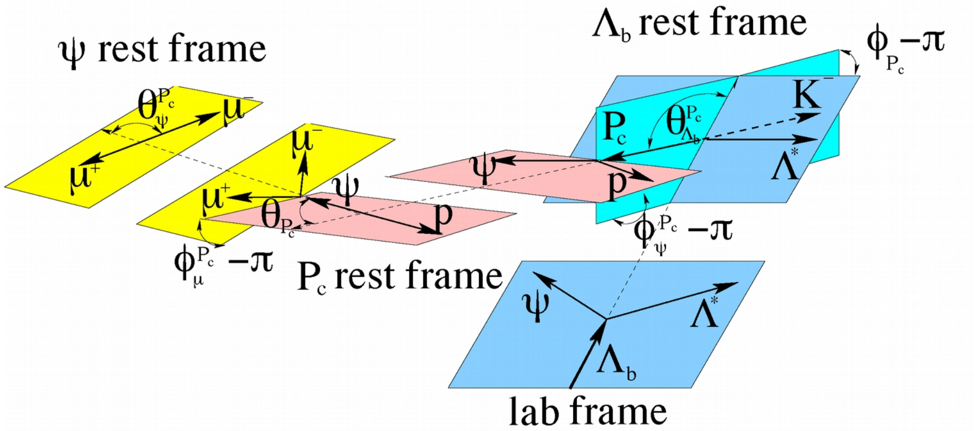
Dalitz plots and amplitude analysis



$m^2 = 2.3\ \text{GeV}^2$ $\Lambda(1520)$

$m^2 = 19.5\ \text{GeV}^2$





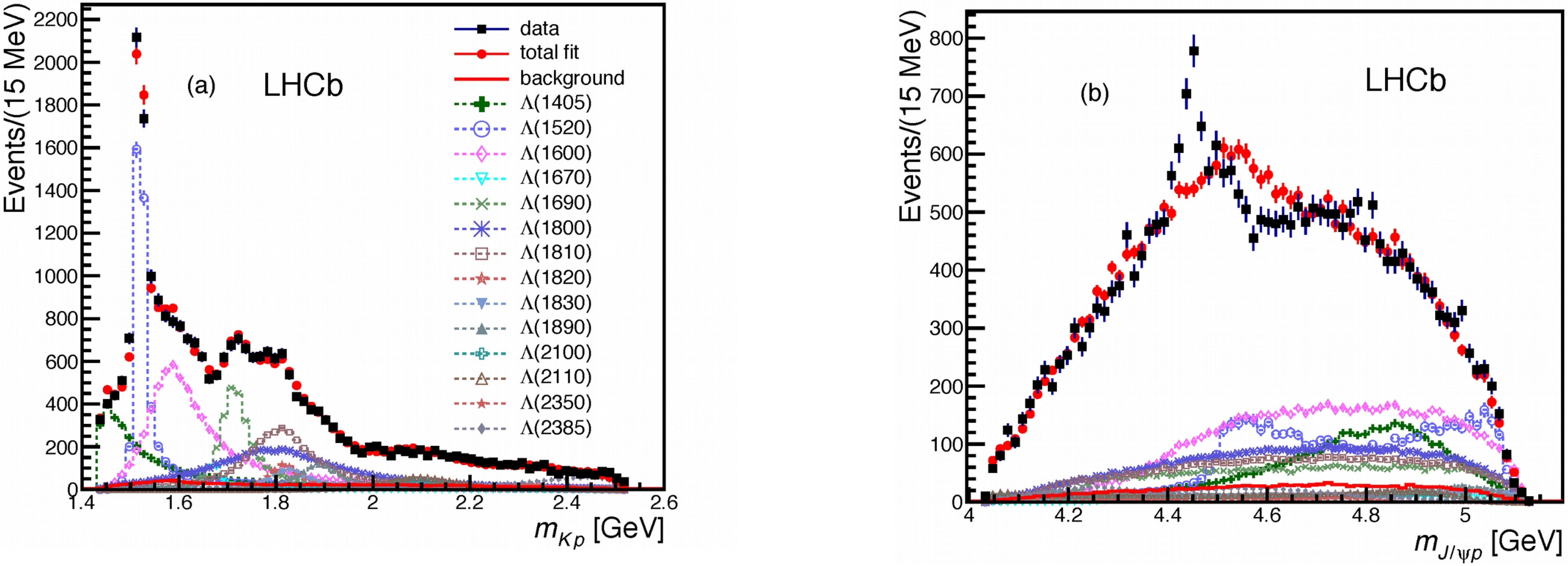
Λ^* decay chain

P_c^+ decay chain

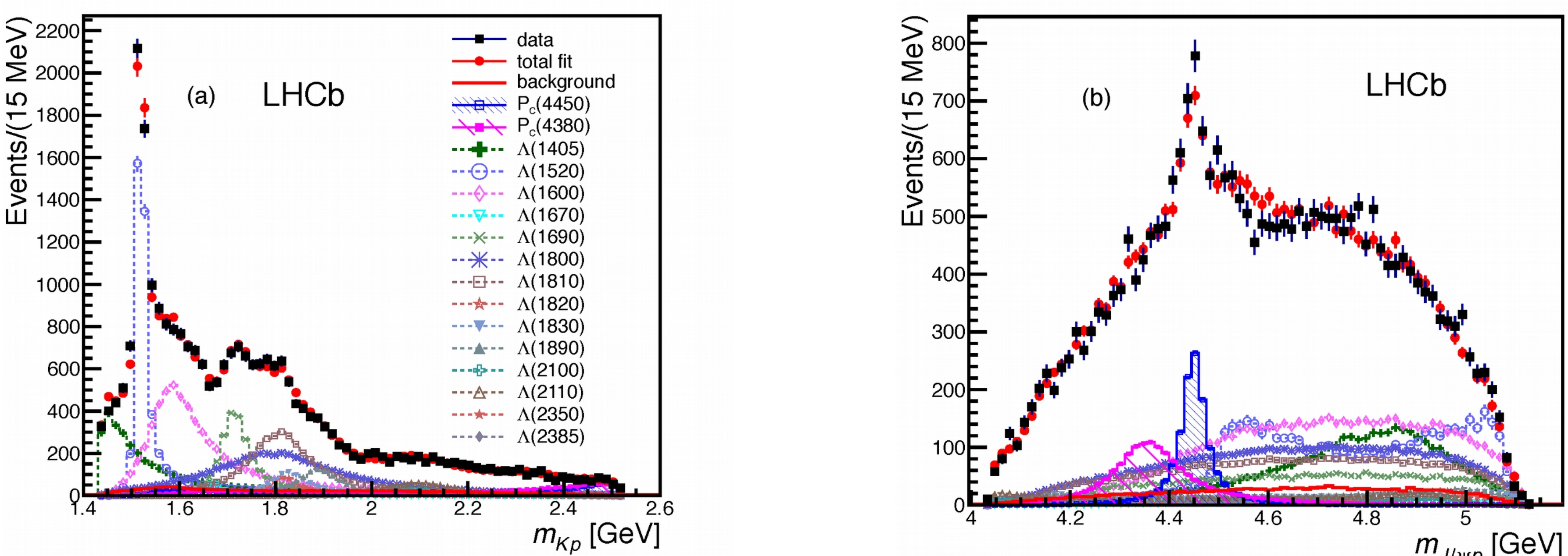
Outline of the amplitude analysis procedure

- For each two-body decay, mass and angular variables are used
- For mass shapes – Breit-Wigner or Flatte (close to KP threshold)
- Each sequential decay contributes to amplitude a term depending on helicity-dependent couplings and mass terms
- Amplitudes summed-up over helicities and Λ resonances, then squared
- Then multiplied by phase space and efficiencies → signal probabilities; further used to construct likelihoods and fits of signals and backgrounds
- Max-likelihood fits performed:
    - 6 dimesions: m(Kp) and 5 angles
    - 4-6 helicity-dependent couplings per Λ resonance

No pentaquark hypothesis



With two pentaquark states $(3/2)^-$ and $(5/2)^+$, clear significance of 15σ

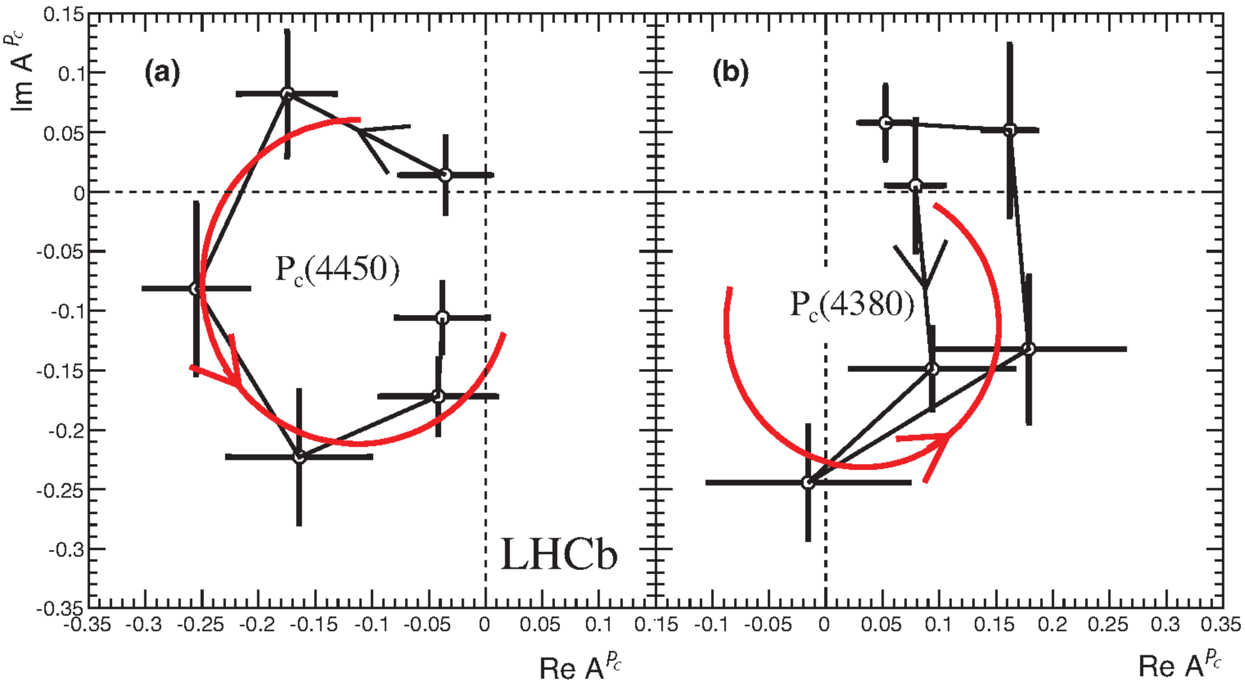


Argand plots analysis

$$f_l(k) = \frac{i}{2}(1 - \eta_l(k)e^{2i\delta_l(k)})$$ plotted parametrically as function of mass

Elastic scattering unitarity circle $\frac{1}{2}|\delta_l(k) - \frac{i}{2}|$

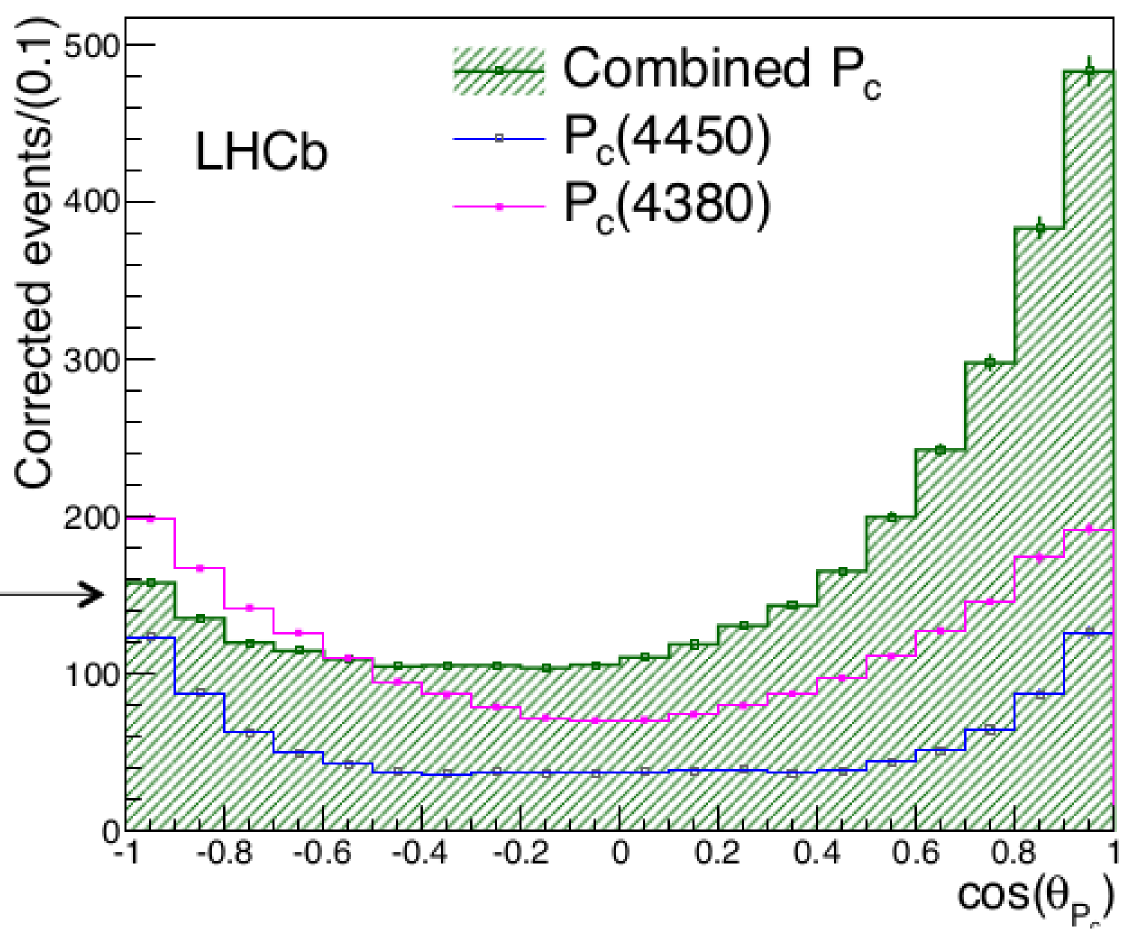
Resonance – rapid, counterclockwise increase of phase by ~2π; no background phase – peak at $\delta_l = \pi/2$
Background alters the shape



Clear resonance evidence for P(4450); inconclusive for P(4380)

Interference between opposite-parity pentaquark states needed to explain decay angle distributions

Large m_{Kp}
Negative interference

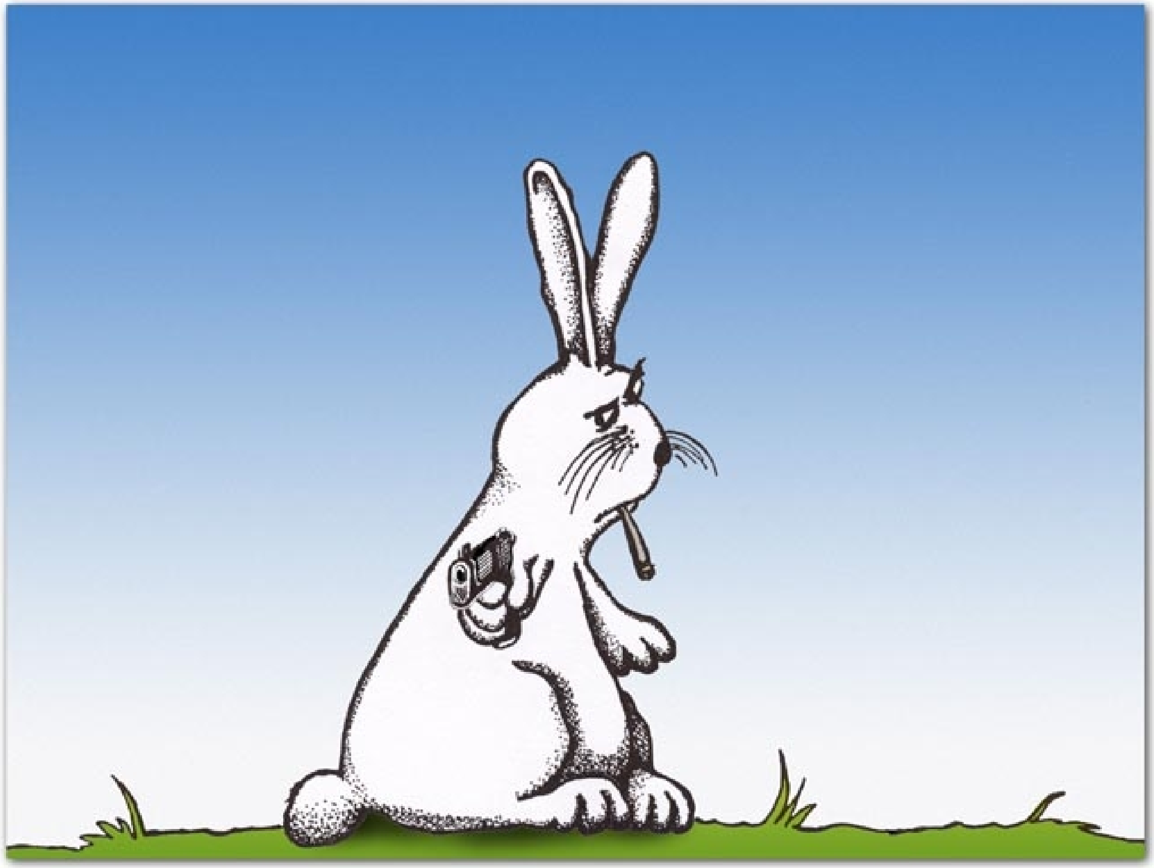


Small m_{Kp}
Positive interference

Best fit results (MeV, %)

P(3/2-)	m=4380±8±29	Γ=205±18±86	f=8.4±0.7±4.2
P(5/2+)	m=4450±2±3	Γ=39±5±19	f=4.1±0.5±1.1

Intriguing results, **demand for analysis using a different method**



When Alice turned around, the rabbit had drawn a 9 mm Beretta automatic. *"Curiouser and curiouser,"* said Alice.

Model independent analysis: LHCb, PRL 117(2016)082002

Assess validity of null hypothesis: $\Lambda_b \to J/\Psi\, p\, K^-$ proceeds via $\Lambda_b \to J/\Psi \Lambda^*$, $\Lambda^* \to pK^-$
Λ^* refering to Λ or (believed to be small) non-resonant background or Σ.

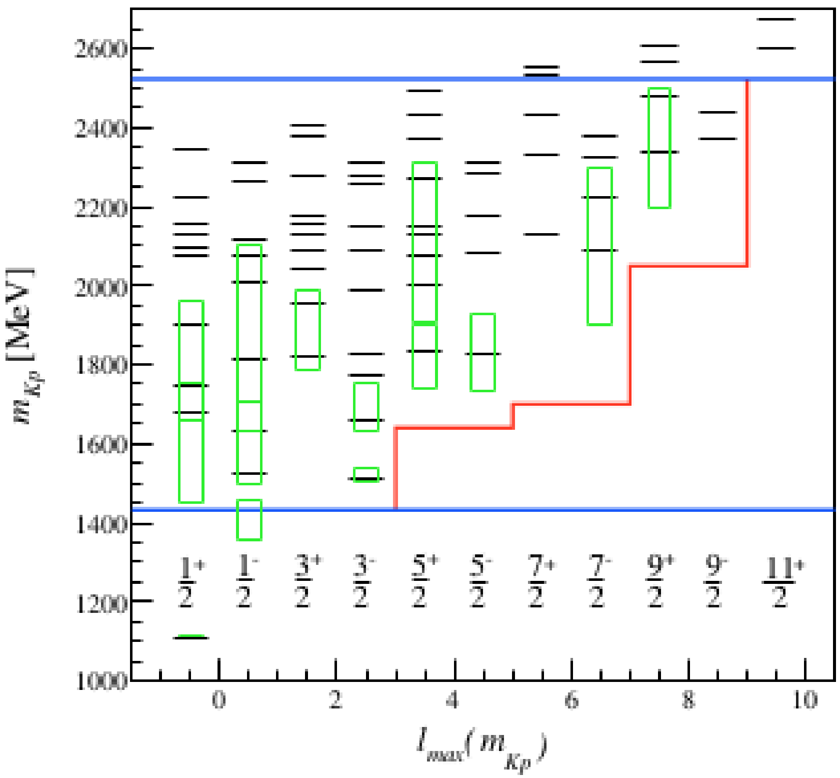
Analysis in plane $(\mathrm{m}_{Kp}, \cos\theta_{\Lambda^*})$

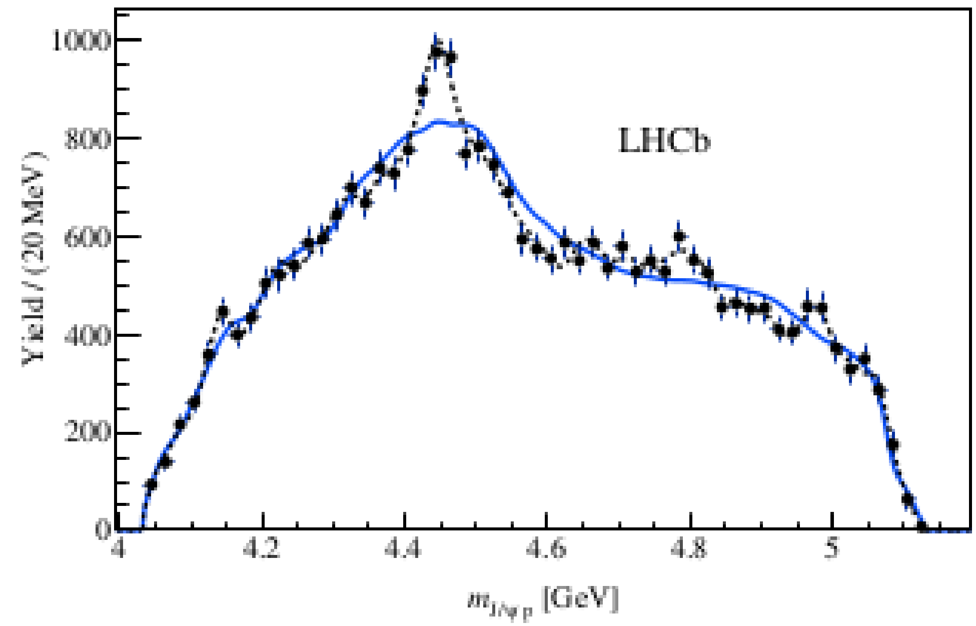
$$\frac{dN}{d\cos\theta} = \sum_{l=0}^{l_{max}} \langle P_l^U \rangle P_l(\cos\theta)$$

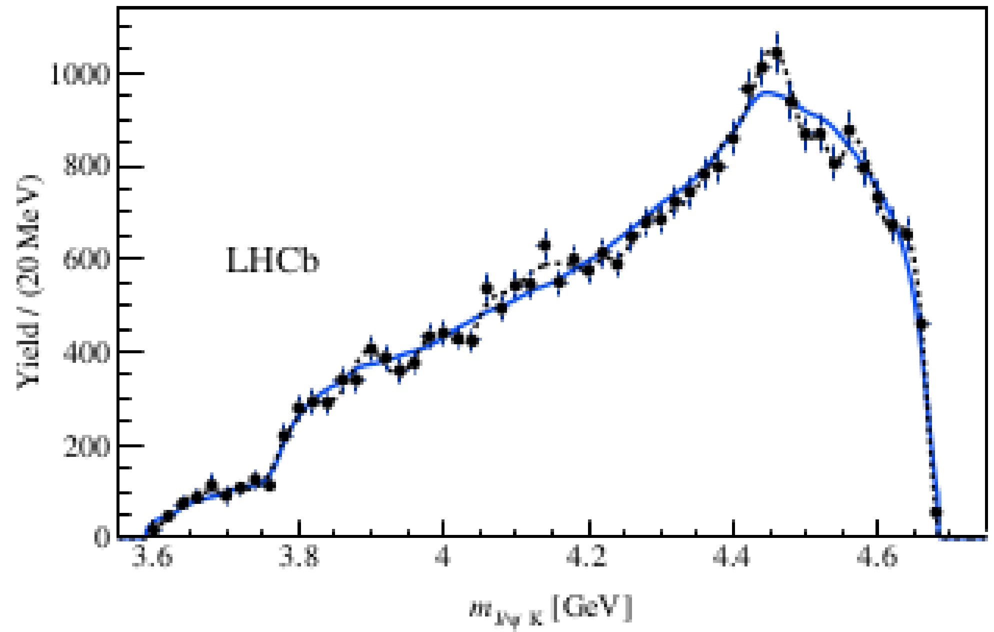
$$\langle P_l^U \rangle = \int_{-1}^{1} d\cos\theta\, P_l^U(\cos\theta) \frac{dN}{d\cos\theta}$$

in bins of m_{Kp}

Upper l_{max} determined from well established resonances decaying to Kp



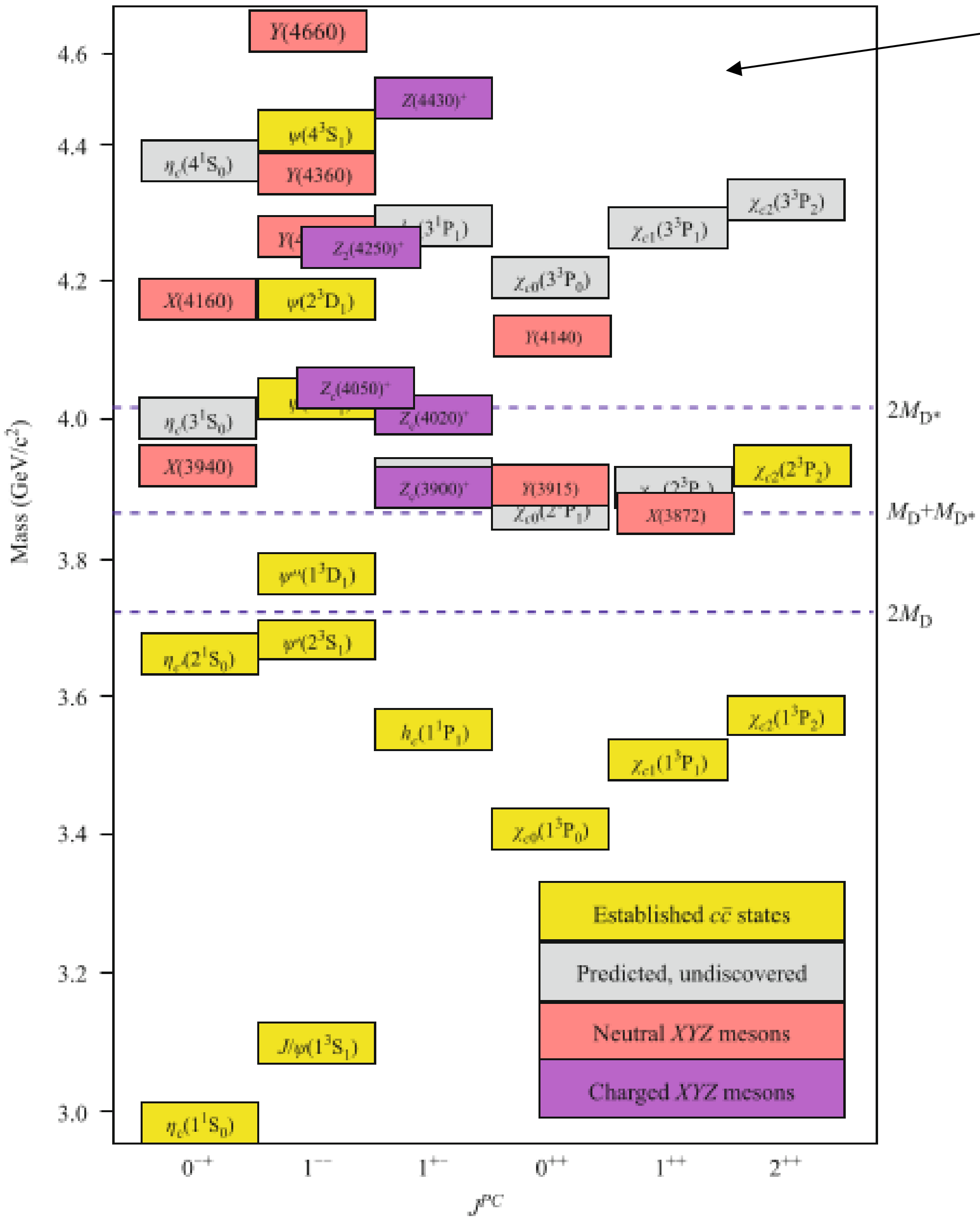


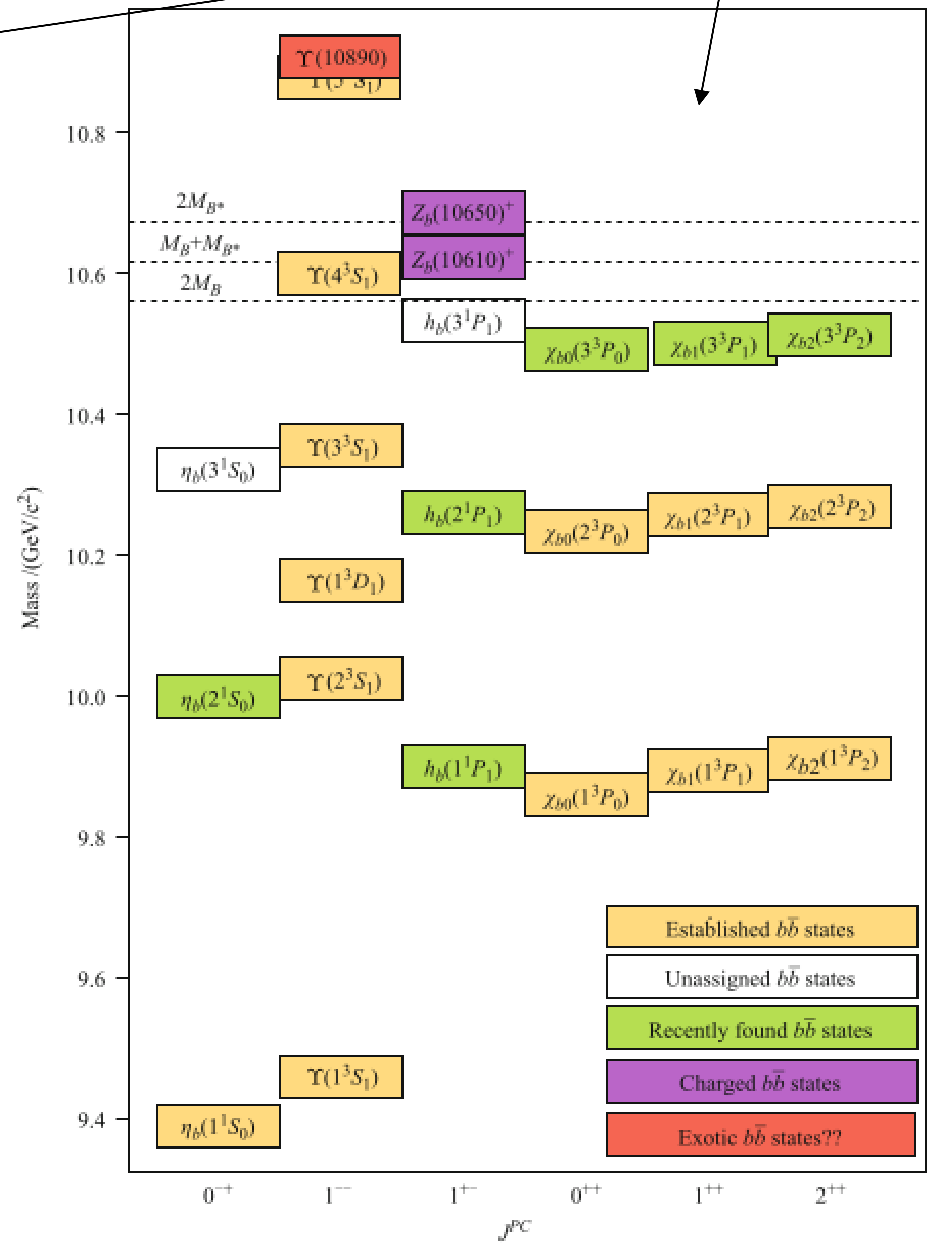


Null hypothesis rejected at 9σ

XYZ exotics: tetraquarks

Mesons seen to decay heavy q q-bar but not accomodated into known quarkonia





Example: $Z(4430)^-$ tetraquark

Some history

Belle 2007 found peak at M=4433±5 MeV, Γ≈45 MeV in $\Psi(2S)\pi^-$ from $B^0 \to \Psi(2S)\pi^- K^+$

Being $\Psi(2S)\pi^-$ resonance it cannot comprise only 2 quarks and must be a tetraquark

This finding was disputed by BaBar 2008; each mass distribution well described by reflections

Belle 2013, with higher statistics of 2000 signal events and full amplitude analysis with interferences reconfirmed the state

LHCb, PRD 92(2015)112009, full amplitude analysis

25 000 signal events $B^0 \to \Psi(2S)\pi^- K^+$

Unambiguously determined $J^P = 1^+$ m=4475±7$_{-25}^{+15}$ MeV

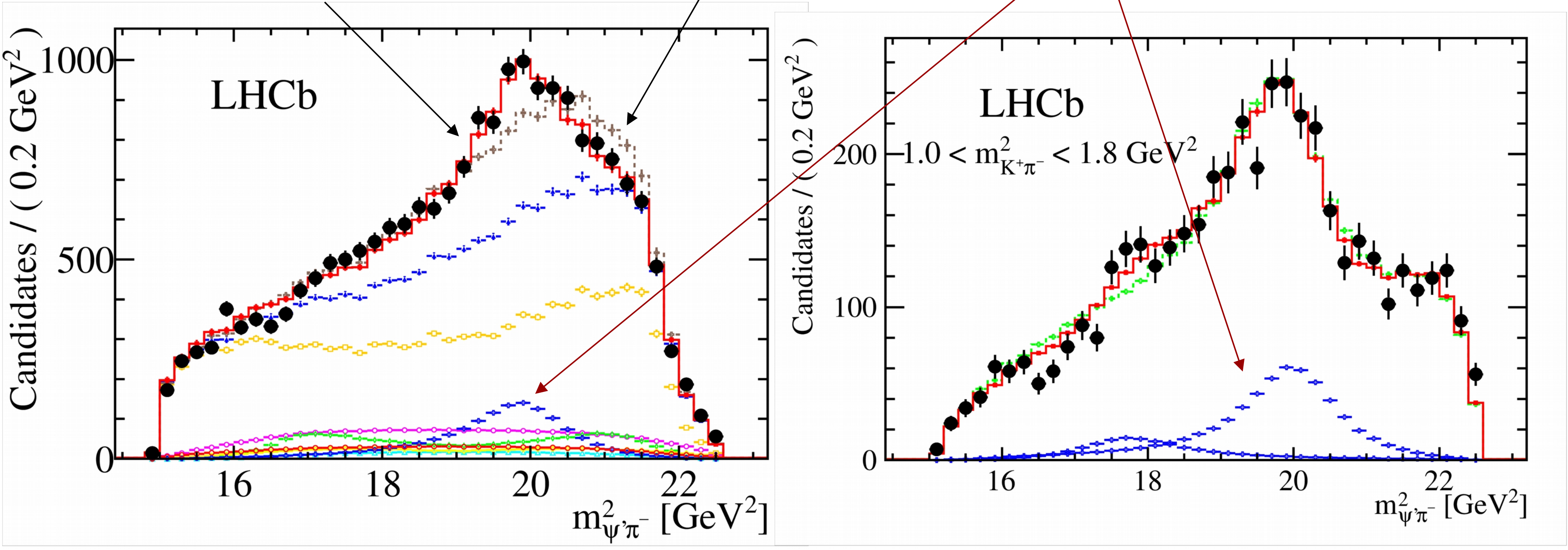
Γ=172±13$_{-34}^{+37}$ MeV

Its updated mass is now 4475 MeV, but we keep the old name

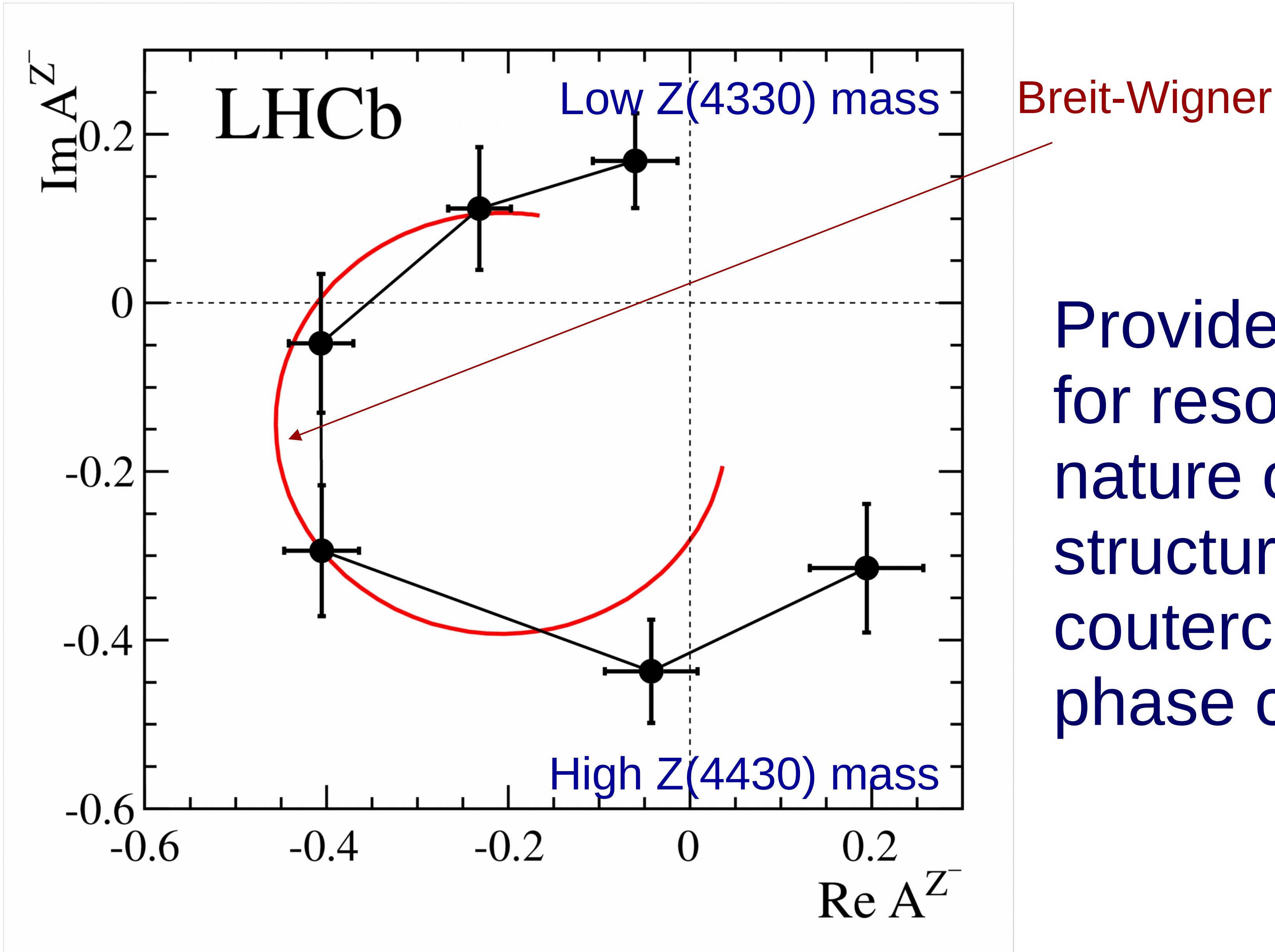
Total fit with Z(4430)

Total fit no Z(4330)

Z(4430)$^-$



Argand plot for Z(4430)$^-$



Provides evidence for resonant nature of the structure: large, couterclockwise phase change

Other recent LHCb searches for exotic states

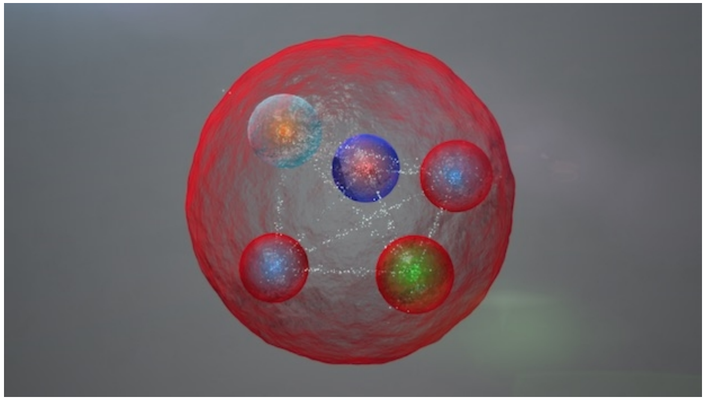
Confirmation of Belle and D0 findings: $X(3872) \rightarrow J/\Psi\ \pi\pi$ from $B^+ \rightarrow K^+ J/\Psi\ \pi\pi$

Confirmation of Belle and D0: $X(4140,4274) \rightarrow J/\Psi\ \Phi$ from $B^+ \rightarrow J/\Psi\ \Phi\ K^+$
and discovery of two new states: $X(4500)$ and $X(4700)$

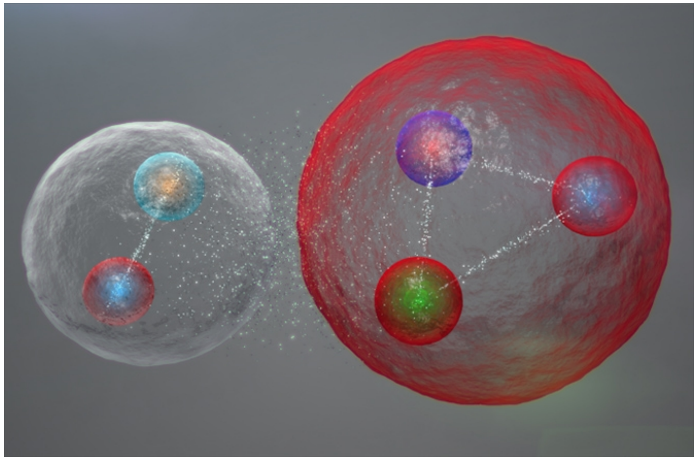
Non-confirmation of D0's: $pp \rightarrow X(5568)^+ \rightarrow B_s \pi^+$

New findings: $D^*(2760) \rightarrow \pi^- D^+$ and $D^*(3000) \rightarrow \pi^- D^+$ from $B^- \rightarrow \pi^- \pi^- D^+$

Interpretations: truly multiquark exotics or trivial hadronic resonance?



Compact: five (four) tightly bound quarks contained in compact volume?



Molecular: a meson weakly bound to a proton (another meson)?
Shall one call it rather a molecule?

Are hadrons bound strong enough such that they overlap and a multiquark component to the wave function is necessary?

Molecular hypothesis J/Ψ + proton
Light meson (no valence charm) exchanges strongly suppressed by Zweig rule

Such interaction should be dominated by gluon exchange, dipole etc.

But light OBE is conceivable for a system with the same overal valence quark contents but differently arranged, e.g.

$\Sigma_c^+ \bar{D}^{*0}, \quad \Lambda_c^+ \bar{D}^{*0}$

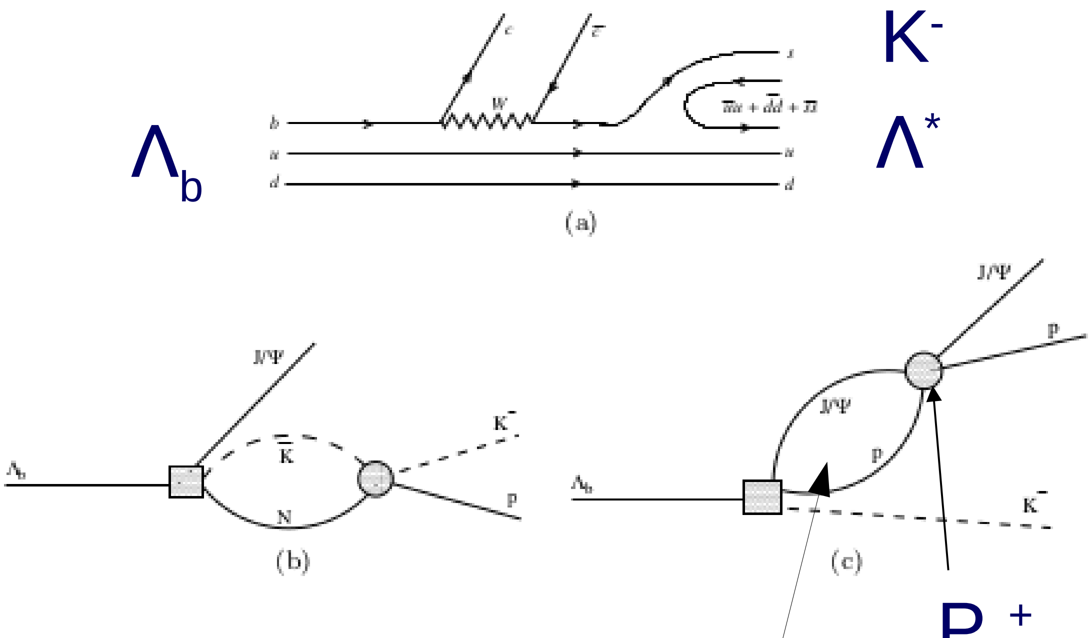
Back to pentaquarks: rescattering in the final state
Roca, Nieves, Oset, PRD 92(2015)094003

J/Ψ

K^-

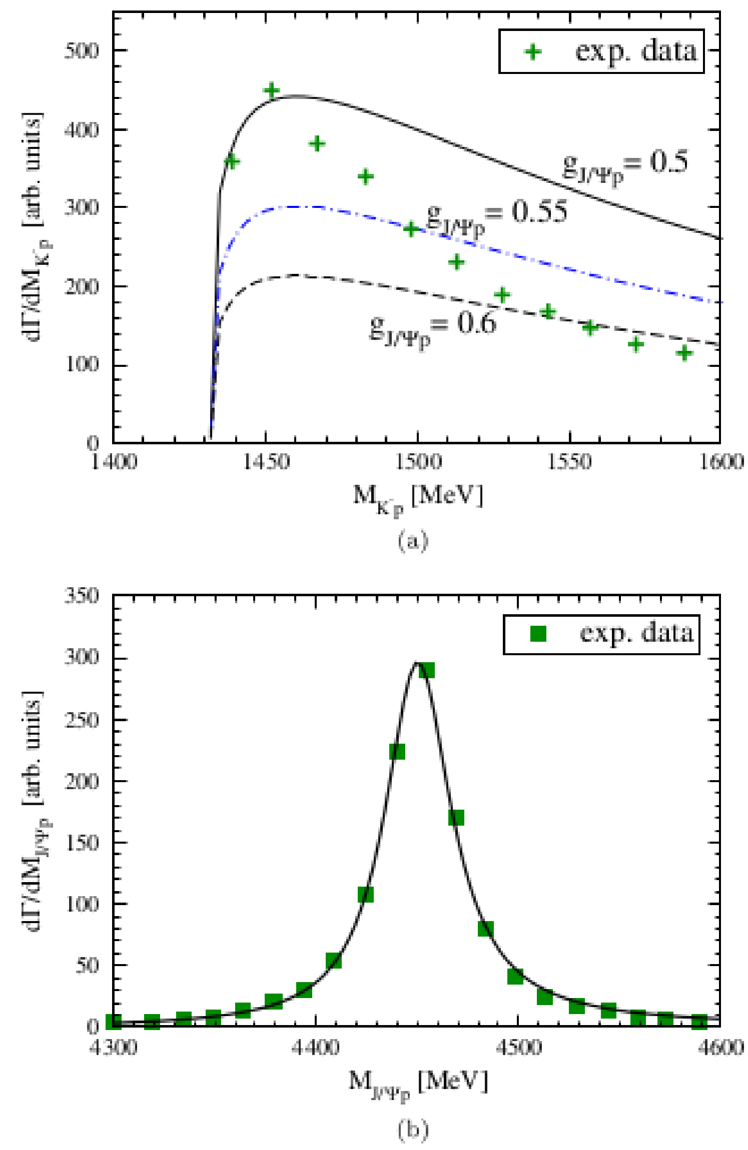
Λ_b

Λ^*



P_c^+

May be also ΣD



Data points: LHCb,
only Λ(1405) accounted for

Likely explanation for $P_c^+(4450)$; close to threshold for channels $\Sigma_c^+ \bar{D}^{*0}$, $\Lambda_c^+ \bar{D}^{*0}$

Rescattering mechanism resulting in molecular state seems unlikely for $P_c^+(4380)$; deep binding, above 80 MeV below threshold for ΣD, amounting to 4462 MeV.

Would likely be a kind of compact pentaquark, for which both large binding and width are natural.

In a sense, true nature of P(4380) is more intriguing.

Final remarks

- Lots of data on XYZ (wide spectrum of mass 3-10 GeV)
- Only LHCb evidence signals of two P and wave of interest
- Experiments: always perform full amplitude analysis, do not be content with bumps in mass
- Need for independent experimental measurements of pentaquark signals
- Need for theory, lattice QCD warmly welcome but results do not yet exist
- Why strange pentaquarks do not show up? Higher mass make them more stable?

Consider Λ states

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

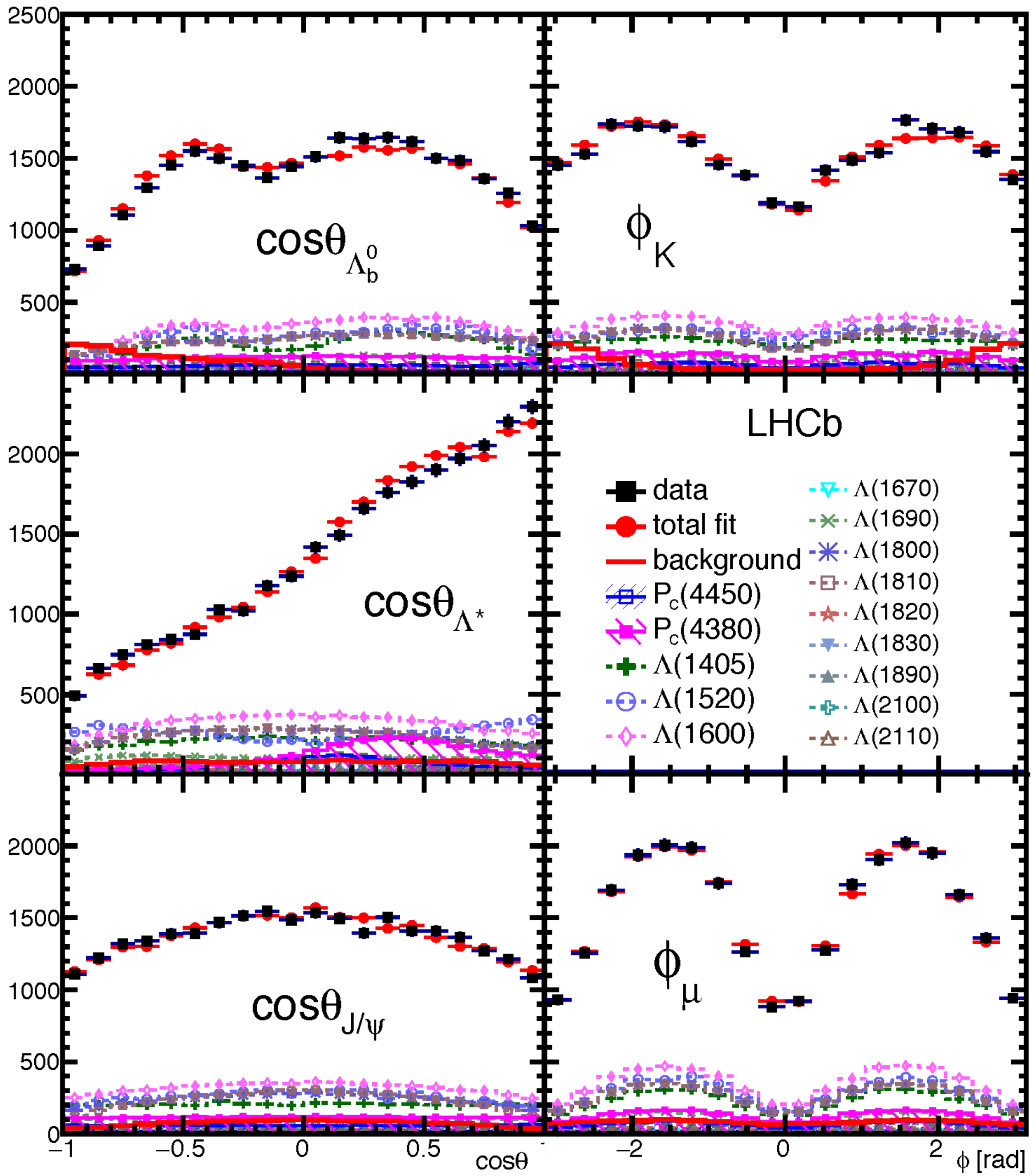
Reduced model: only 14 well-established Λs (64 fit parameters)

Extended model: all Λs (146 fit parameters)

Systematic uncertainties, summary

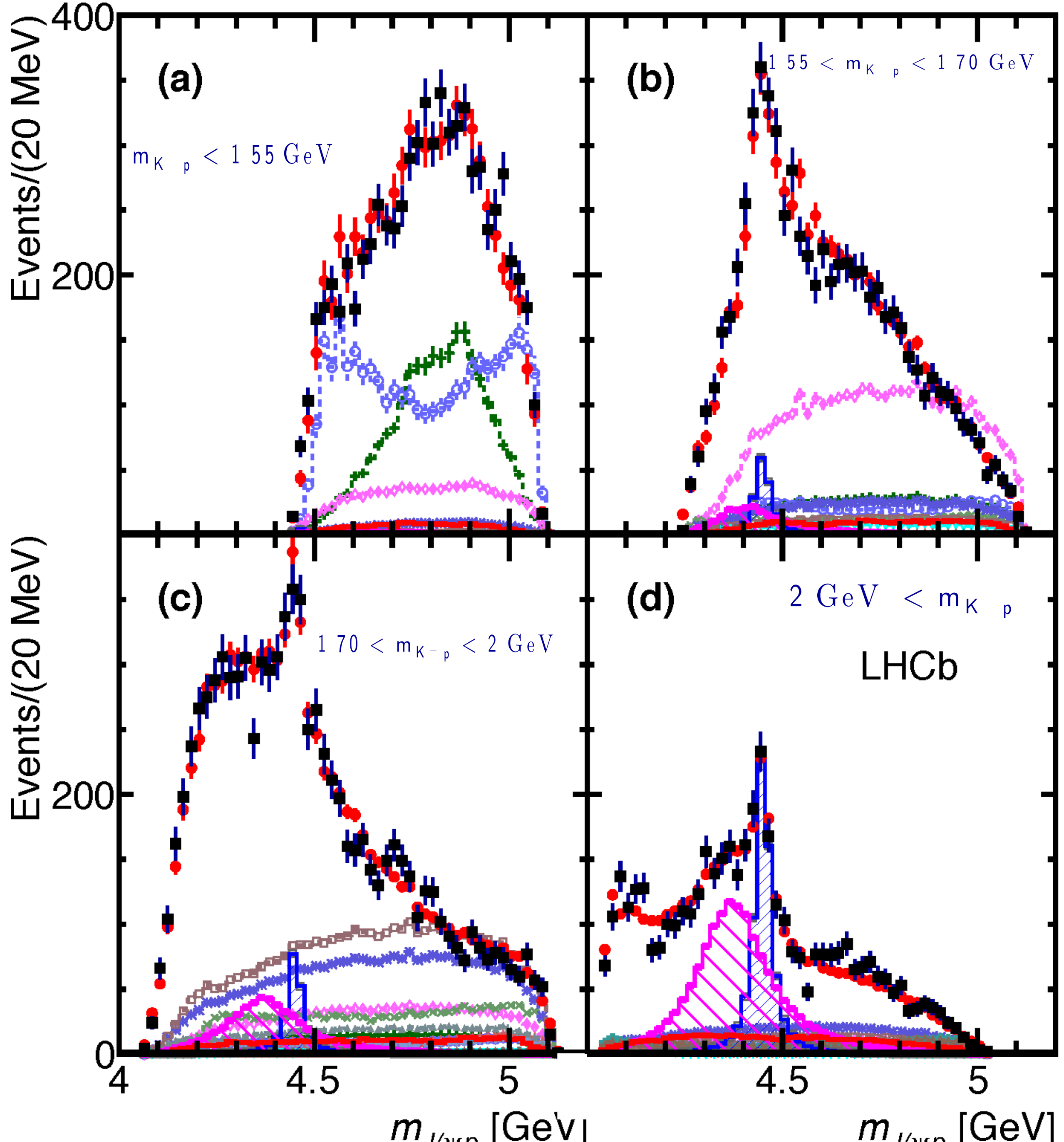
Source	M_0 (MeV)		Γ_0 (MeV)		Fit fractions (%)			
	low	high	low	high	low	high	$\Lambda(1405)$	$\Lambda(1520)$
Extended vs. reduced	21	0.2	54	10	3.14	0.32	1.37	0.15
Λ^* masses & widths	7	0.7	20	4	0.58	0.37	2.49	2.45
Proton ID	2	0.3	1	2	0.27	0.14	0.20	0.05
$10 < p_p < 100$ GeV	0	1.2	1	1	0.09	0.03	0.31	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
$L^{P_c}_{\Lambda^0_b}$ $\Lambda^0_b \to P_c^+$ (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

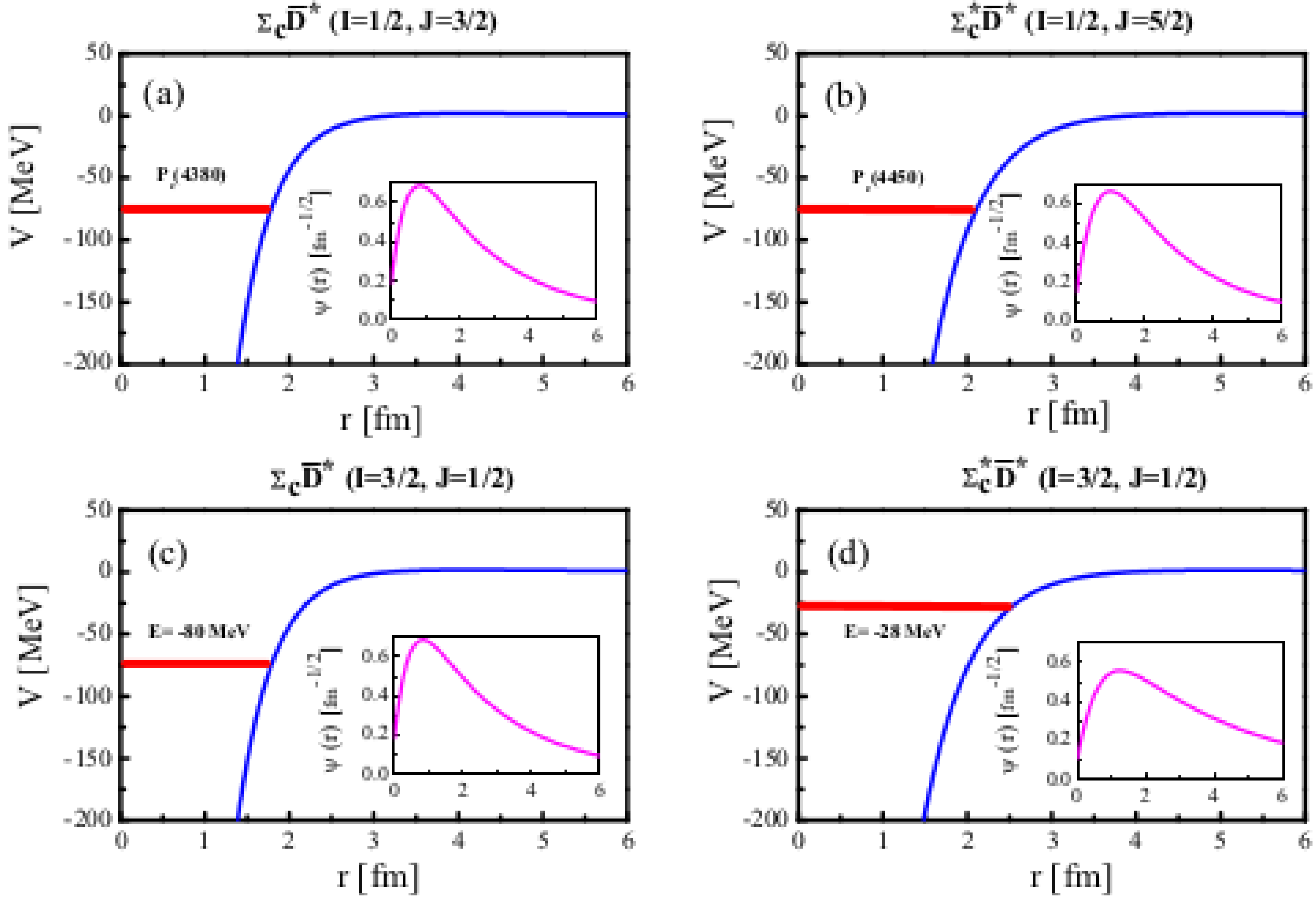
Fits to the angular distributions



Fits in mass slices

P's cannot appear in the first slice for kinematical reasons





Hua-Xing Chen et al.
Phys. Rep. 636(2016)1