Recent results on pentaquark baryons and selected tetraquark mesons

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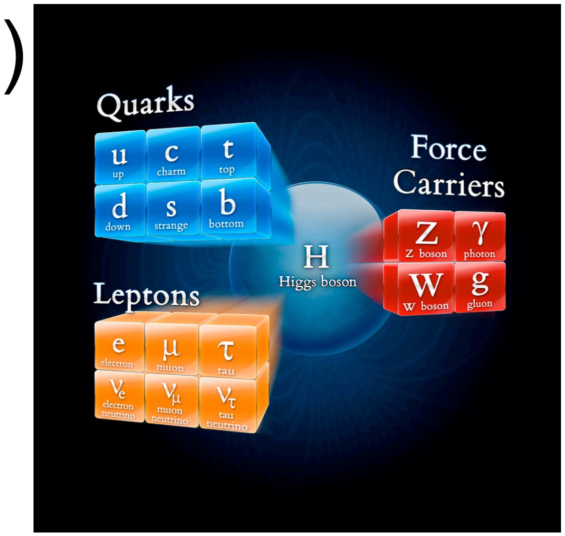
December 14, 2015

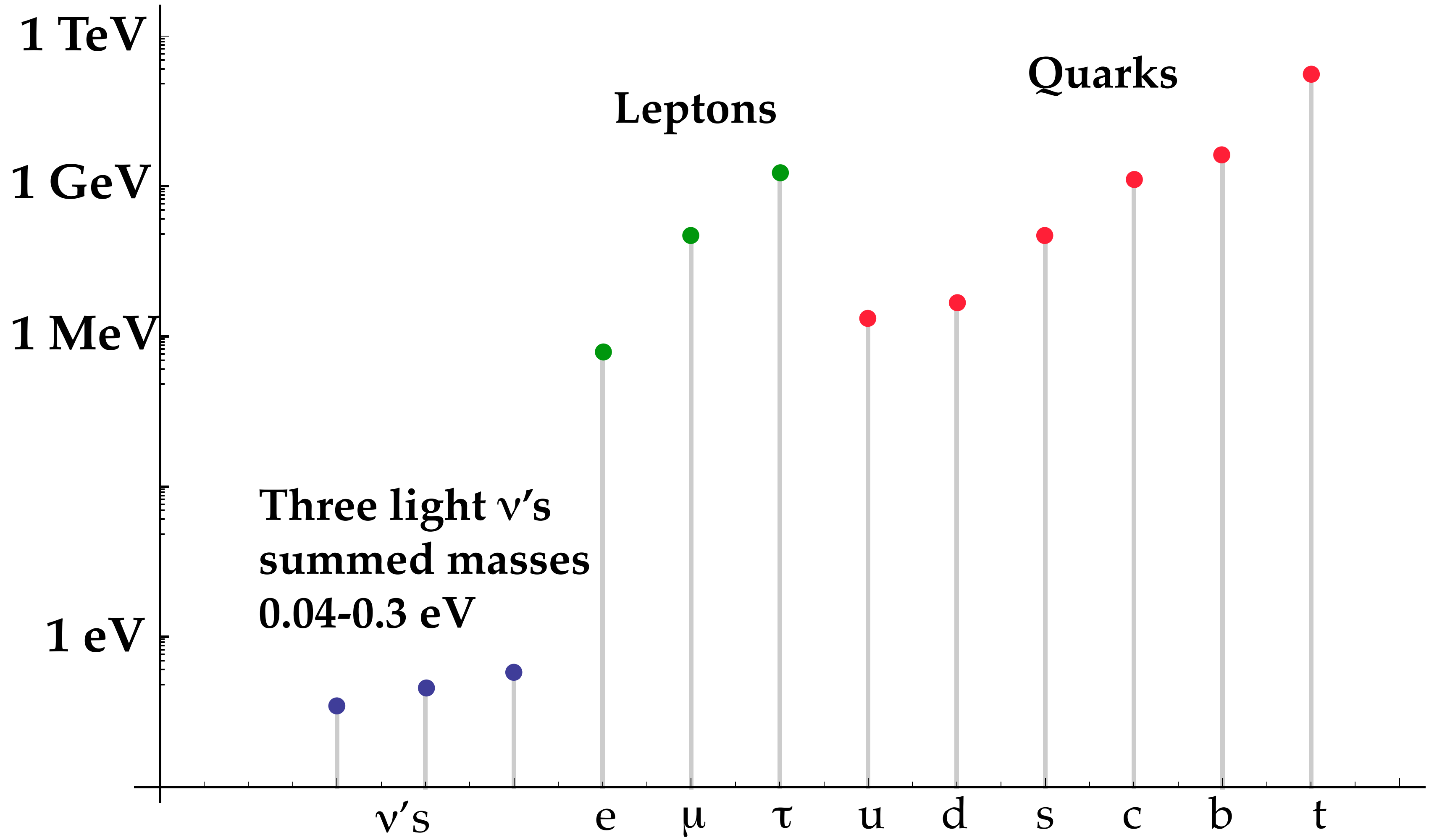
What are particles made of?

- Leptons: e^-, μ^-, τ^-, ν_e, ν_μ, ν_τ elementary point particles (fundamental constituents*)
- Gauge bosons: Z^0, $W^\pm$, H^0
- Hadrons, made of spin=1/2 quarks
- Different quarks have different masses (each one is fundamental*)
  - 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 $y\bar{y}$



*Perhaps substructure?

Masses



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

Quark model

In the beginning multiquark objects were predicted- now called exotic

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)
CERN - Geneva

8182/TH.401
17 January 1964

ABSTRACT

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.

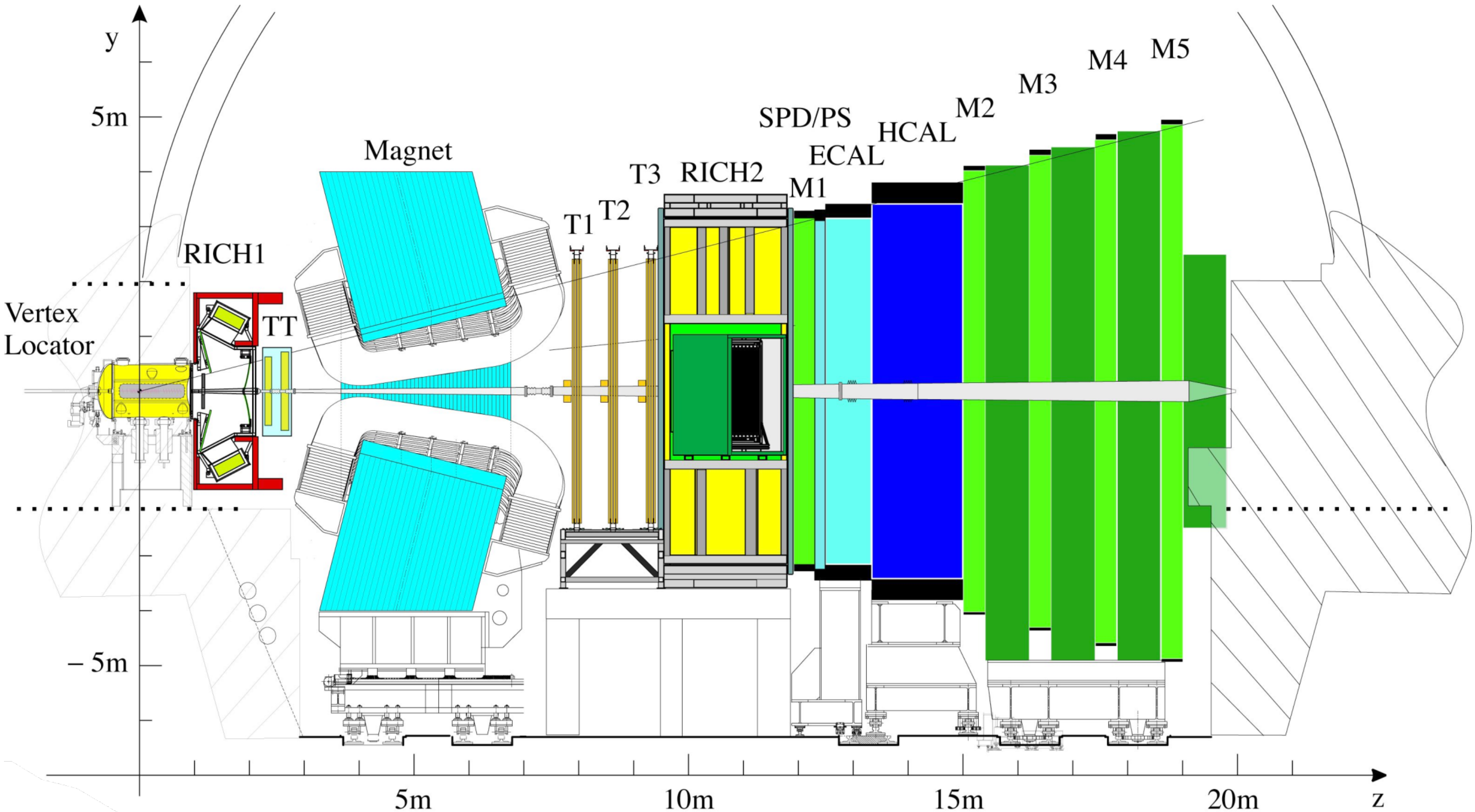
Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

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.

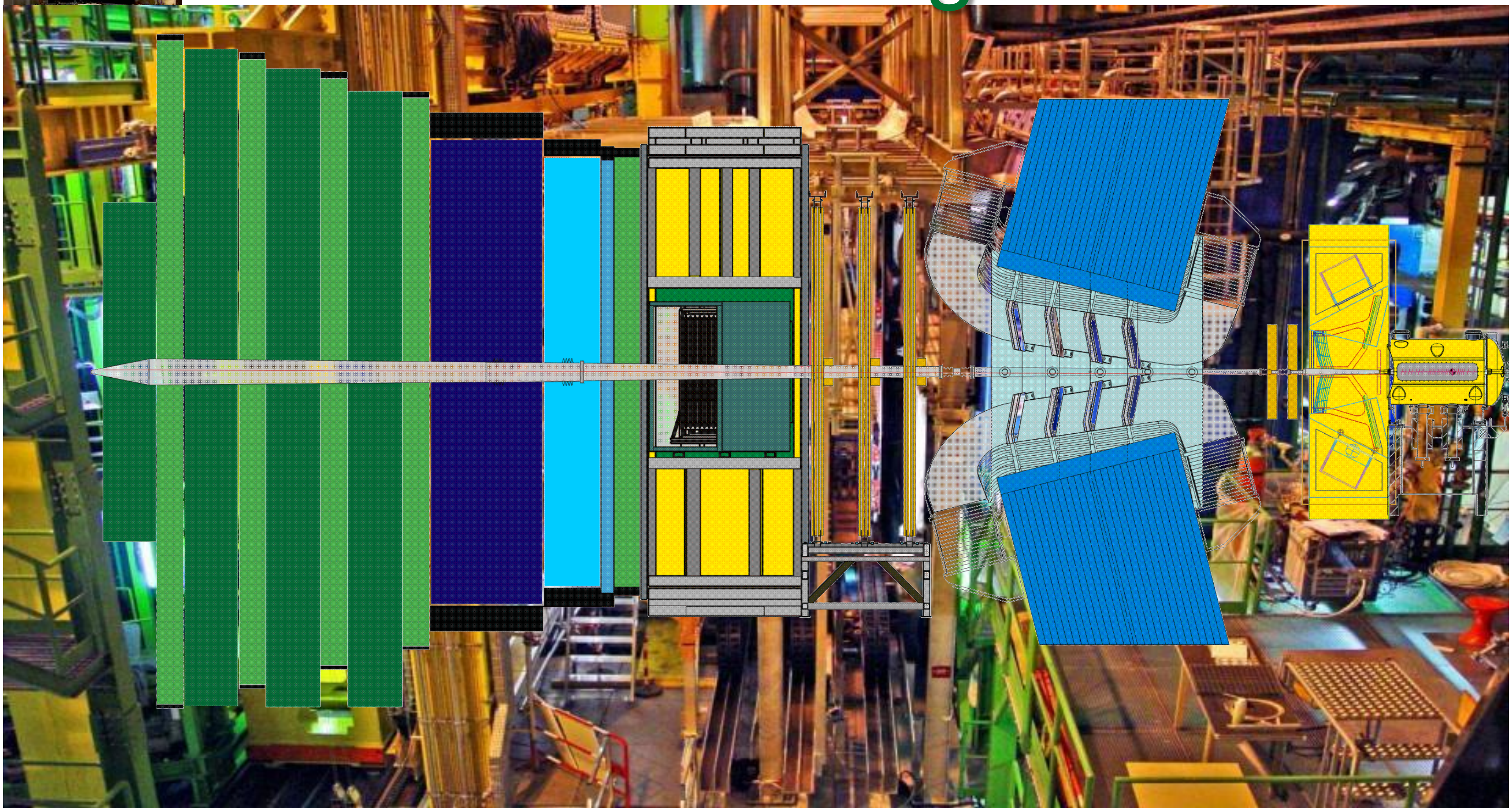
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the 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"

LHCb Detector

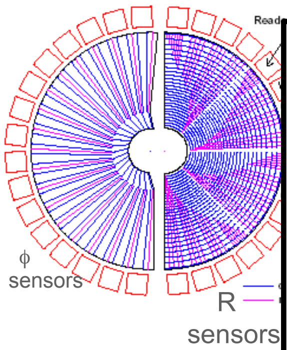


Detector Workings

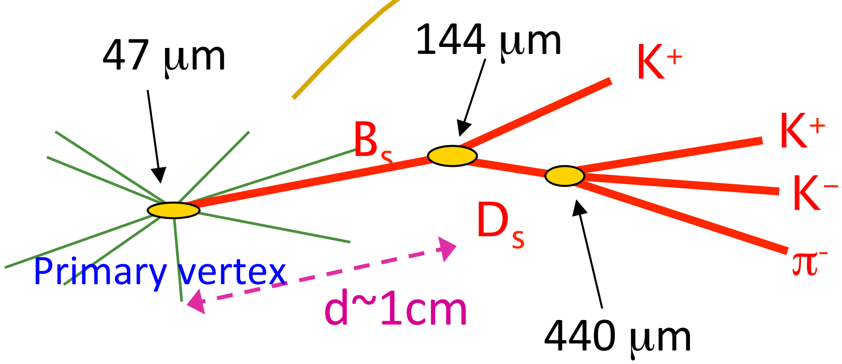


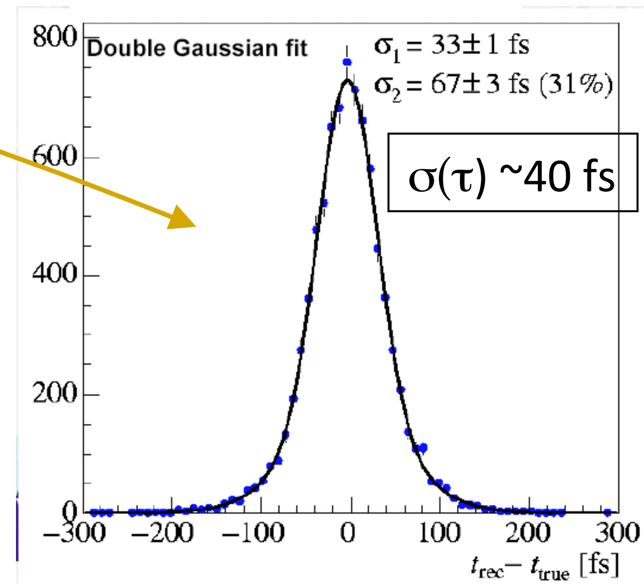
LHCb detector ~ fully installed and commissioned → walk through the detector using the example of a $B_s \rightarrow D_s K$ decay

B-Vertex Measurement

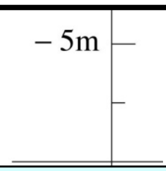


Example: $B_s \rightarrow D_s K$





Decay time resolution = 40 fs

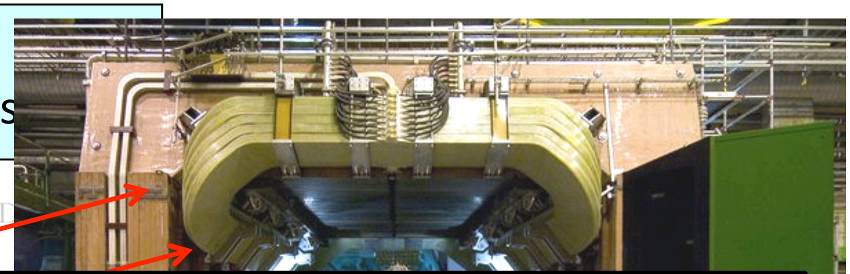


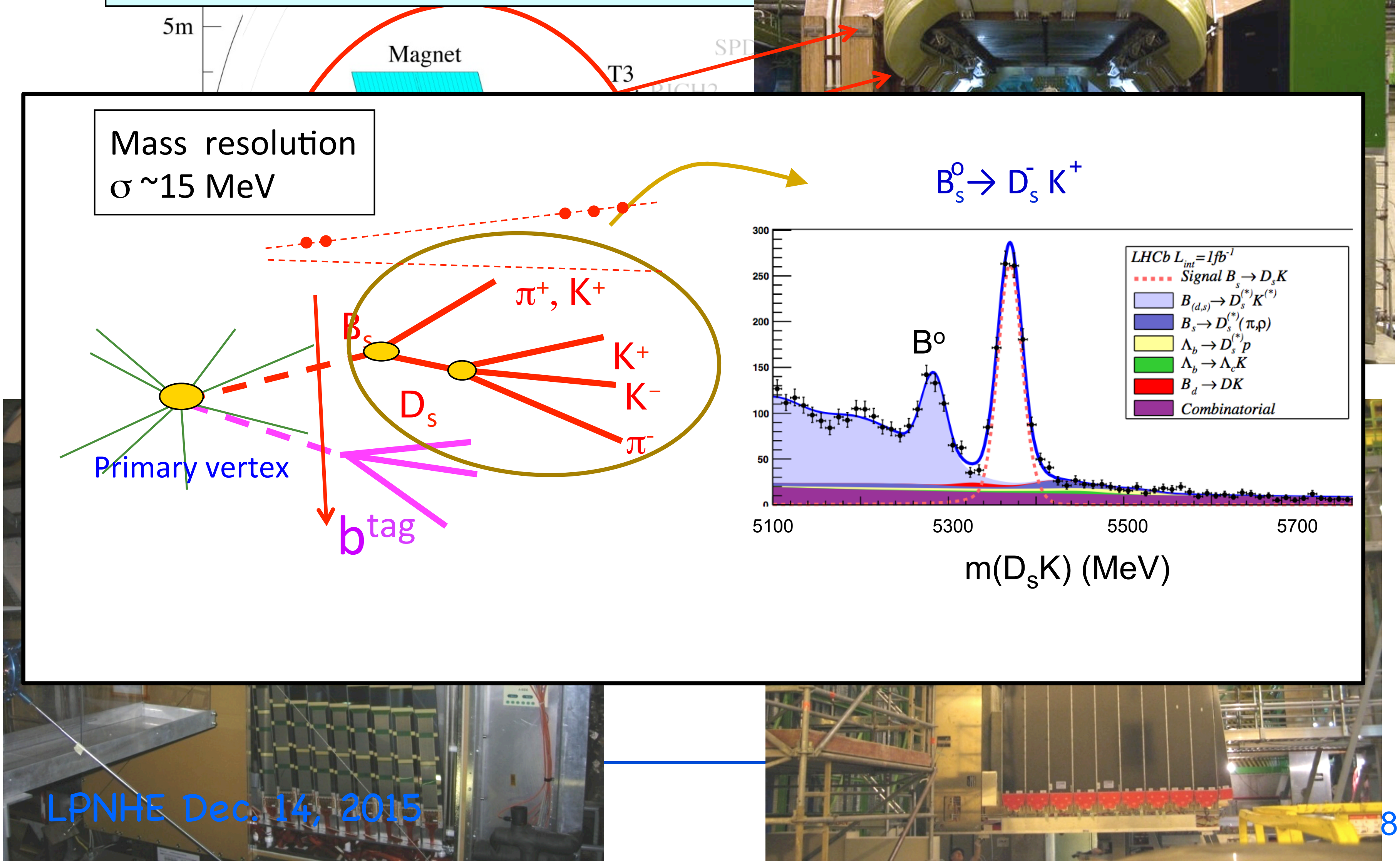
Vertex Locator (Velo)
Silicon strip detector with
~ 5 μm hit resolution
→ 30 μm IP resolution

Vertexing:
- trigger on impact parameter
- measurement of decay distance & decay time=d/v=md/p

Momentum and Mass measurement

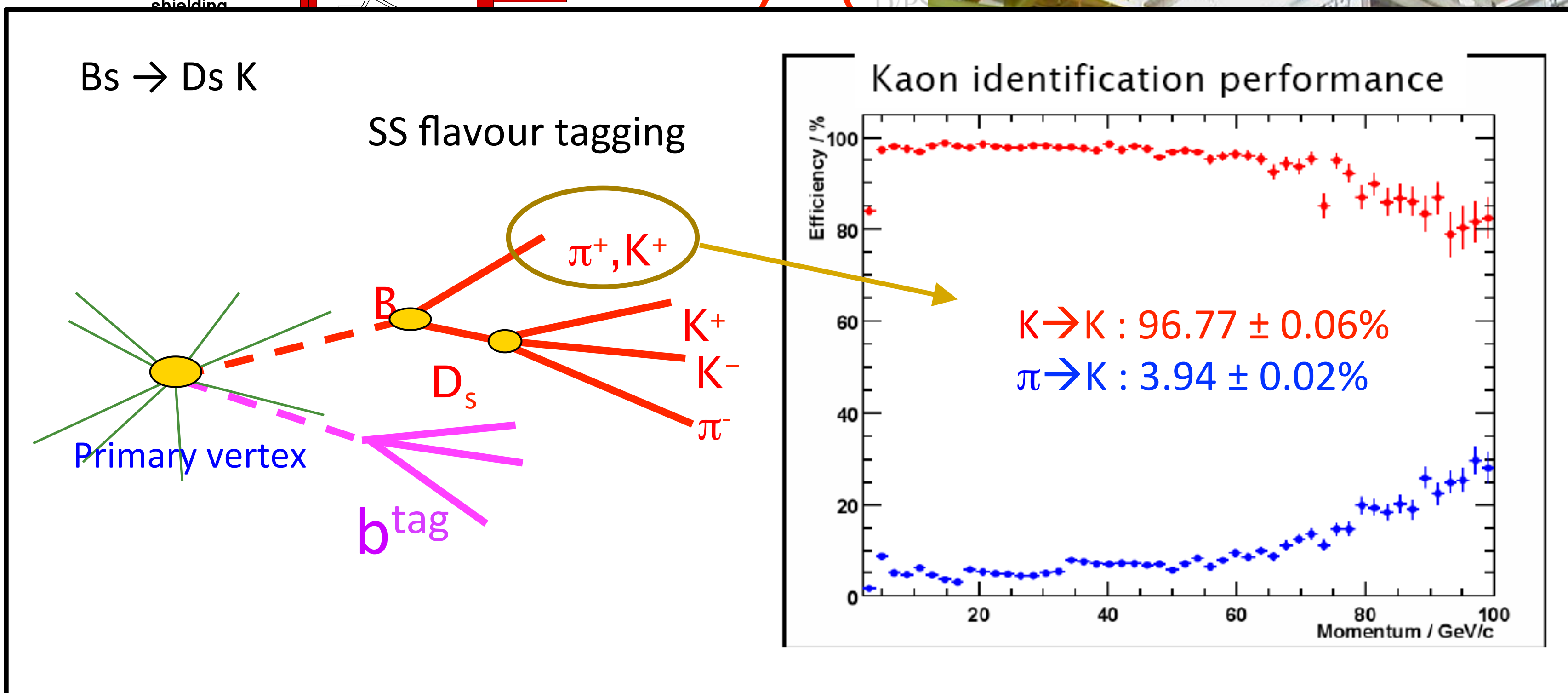
Momentum meas. + direction (VELO):
Mass resolution for background suppres





Hadron Identification

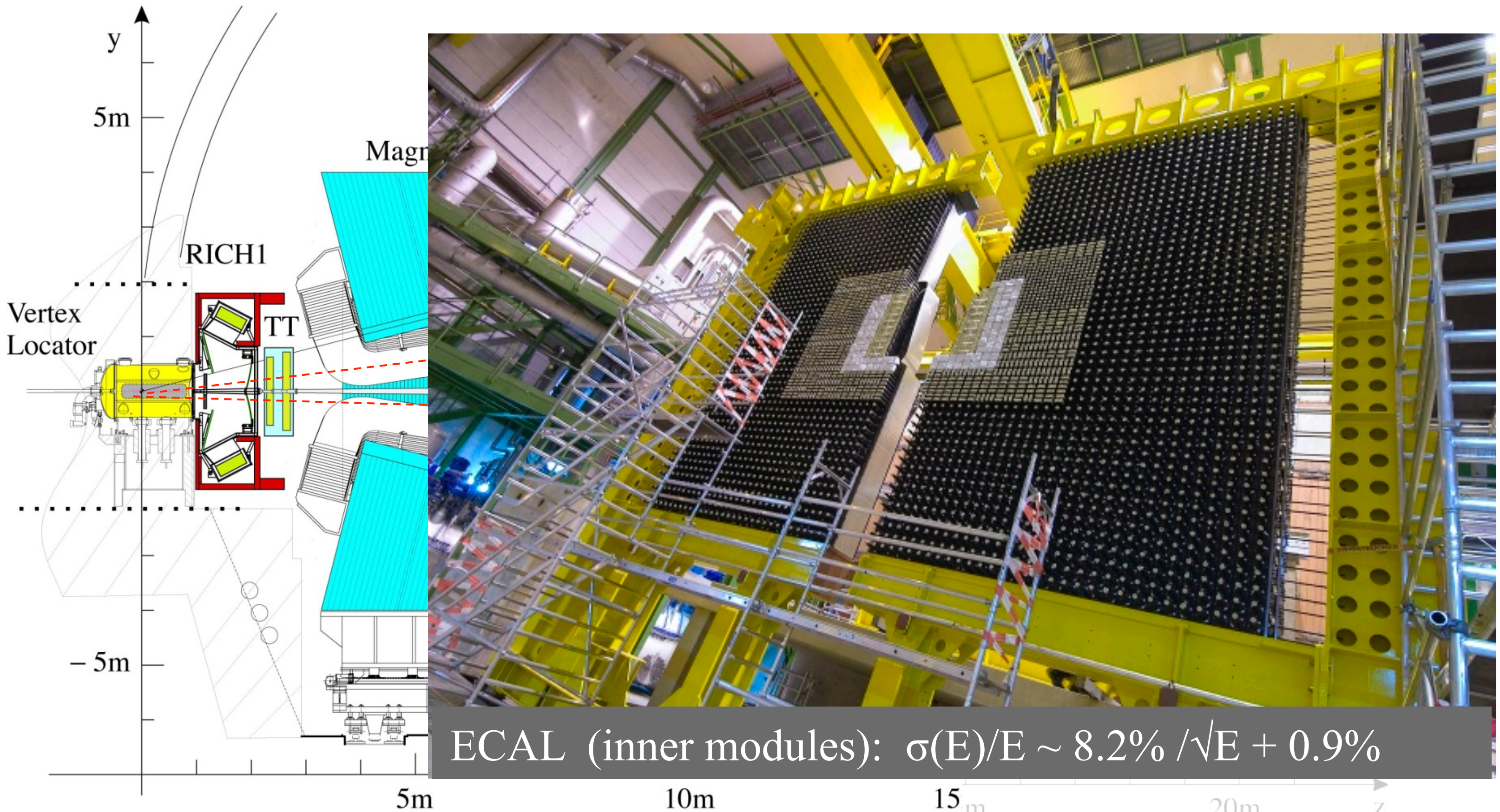
RICH: K/π identification using Cherenkov light emission angle



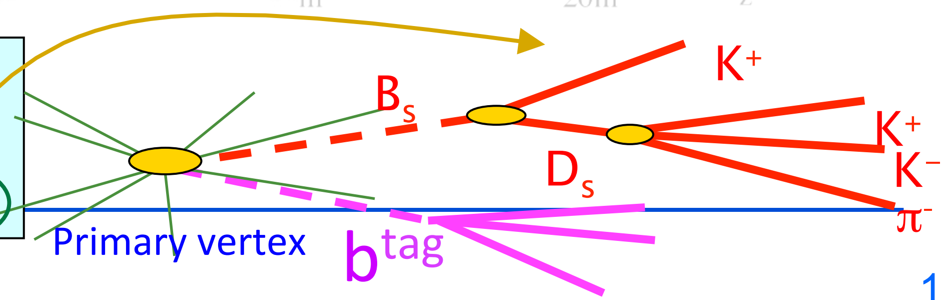
RICH1: 4 m^3 C_4F_{10} n=1.0014

RICH2: 100 m3 CF_4 n=1.0005

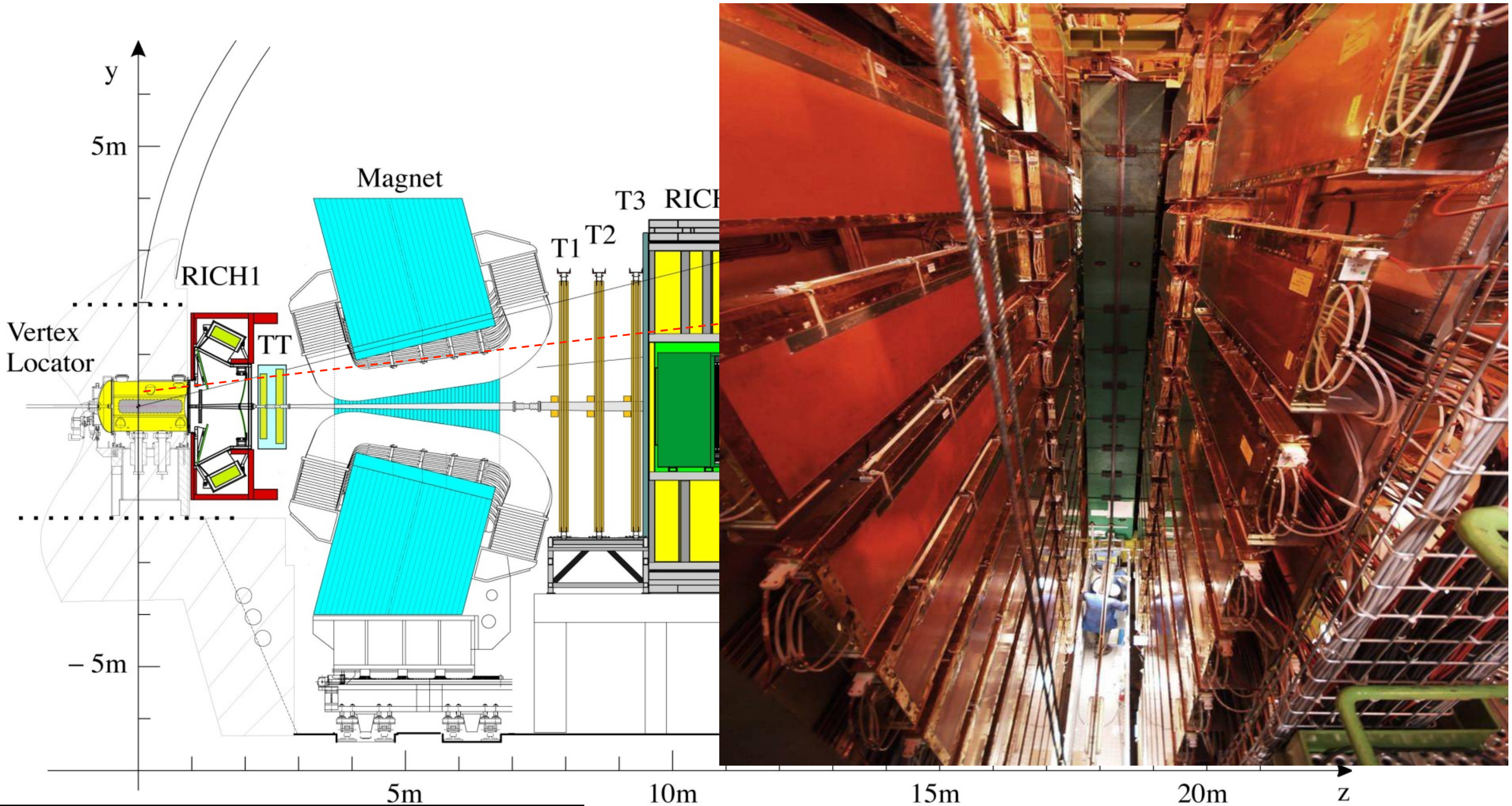
Calorimetry and L0 trigger



Calorimeter system :
- Identify electrons, hadrons, π^0 ,γ
- Level 0 trigger: high E_T electron and hadron

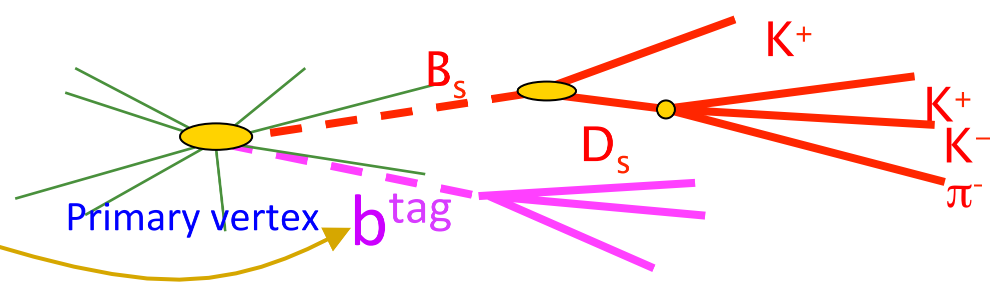


Muon identification and L0 trigger



Muon system:

- Level 0 trigger: High P_t muons
- OS flavour tagging

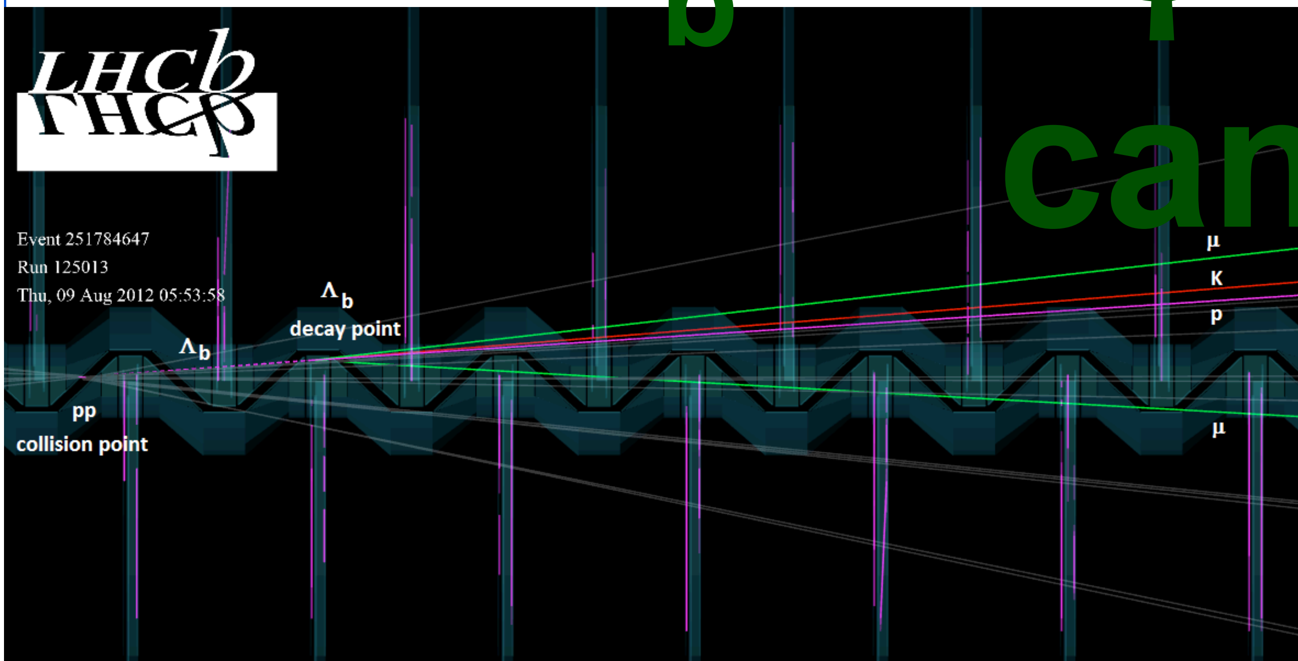


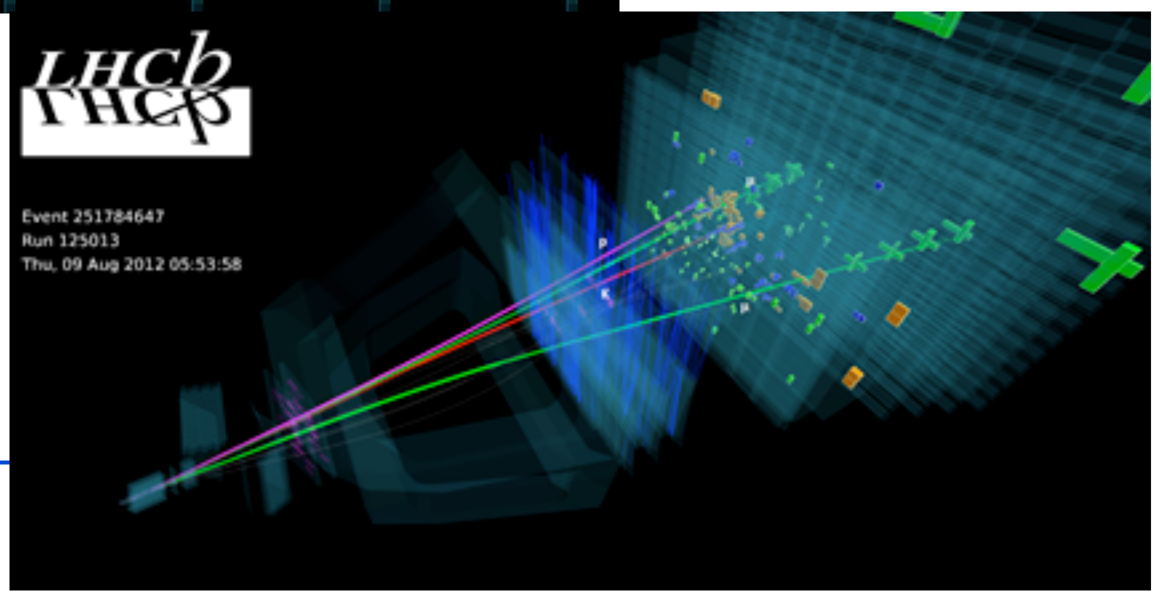
LHCb goals

- 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 ∠'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
  - Study of $B^0\rightarrow J/\psi K^+K^-$, turned not to be that interesting [arXiv:1308.5916] but $\Lambda_b\rightarrow J/\psi K^-p$ was suggested as a potential background

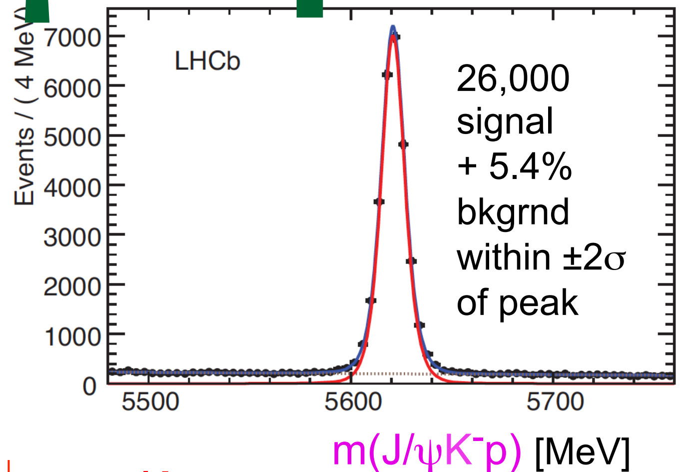
A $\Lambda_b \to J/\psi K^- p$ candidate





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

- This decay had not been seen before
- Large signal found, used for Λ_b lifetime measurement [arXiv:1402.6242]

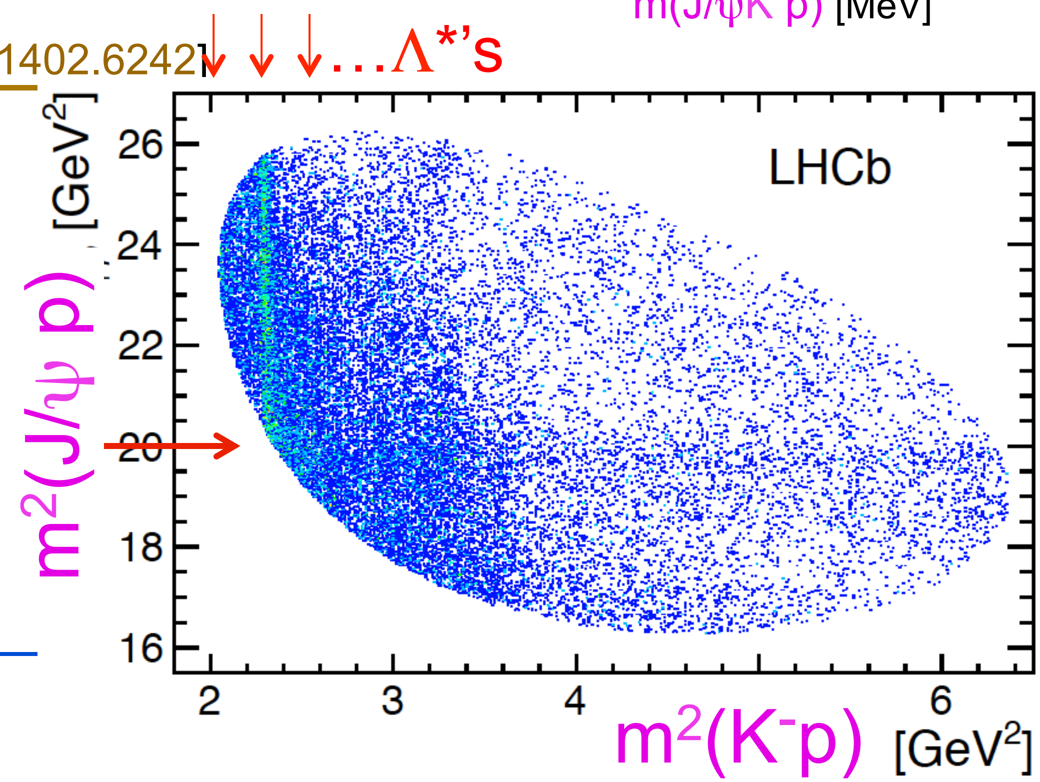


- 3 body decay,

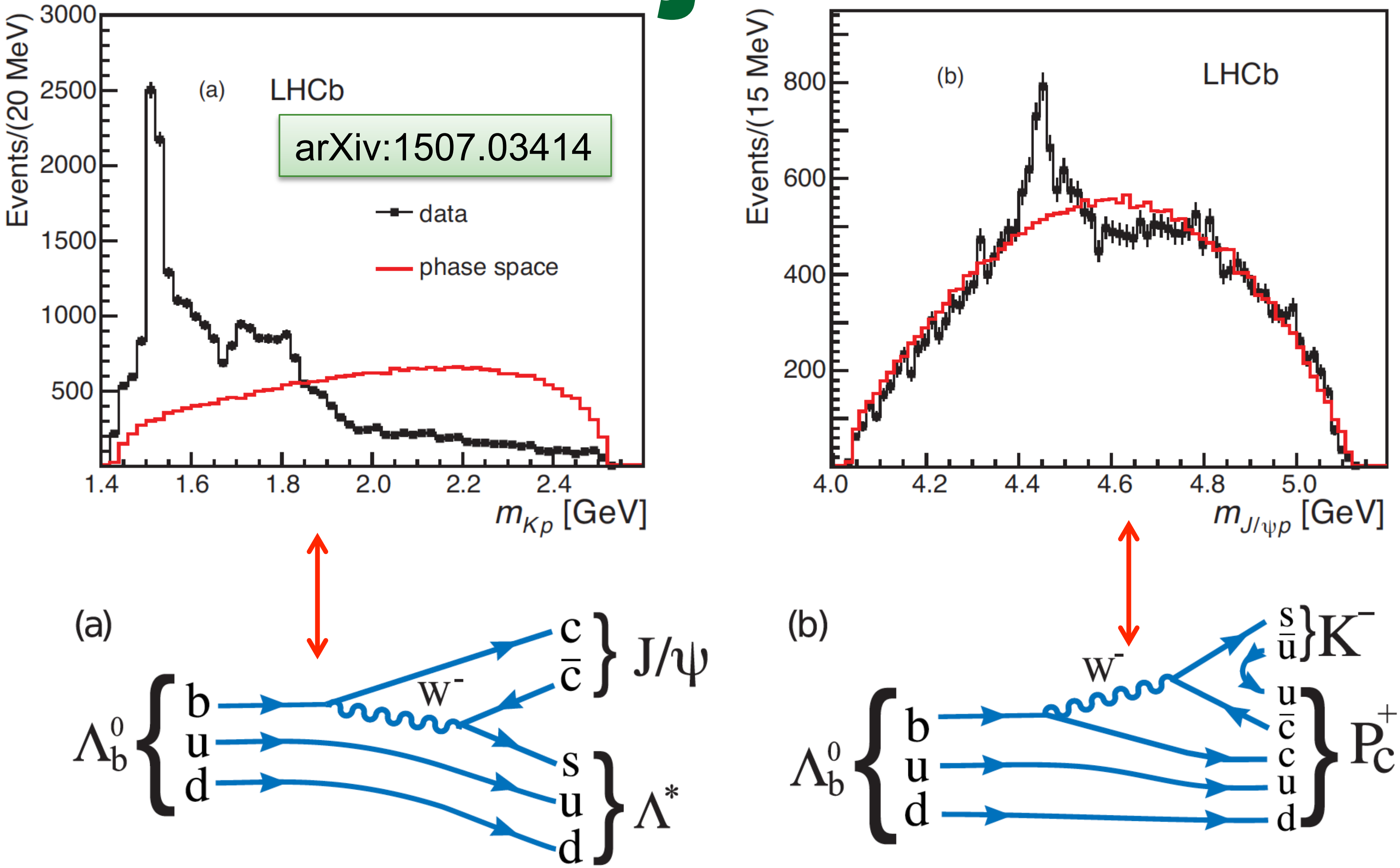
Make a Dalitz plot.

Showed an unusual feature

[arXiv:1507.03414]



Projections



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

Why pentaquarks?

- Interest in pentaquarks arises from the fact that they would be new states of matter 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 ~10^{-23} s "resonances" whose presence is detected by mass peaks & angular distributions showing the presence of unique J^P quantum numbers

Prejudices

- No convincing states 51 years after Gell-mann & Zweig proposed qqq and $qqqq\bar{q}$ baryonic states
- Previous "observations" of several pentaquark states have been refuted
- These included
  - $\Theta^+ \to K^0 p$, $K^+ n$, mass=1.54 GeV, Γ~10 MeV
  - Resonance in $D^{*-}p$ at 3.10 GeV, Γ=12 MeV
  - $\Xi^{--} \to \Xi^- \pi^-$, mass=1.862 GeV, Γ<18 MeV
- Generally they were found/debunked by looking for "bumps" in mass spectra circa 2004 [see Hicks Eur. Phys. J. H37 (2012) 1.]

Decay amplitude analysis

- Are there "artifacts" that can produce a peak?
  - Many checks done that shows this is not the case: e.g. changing p to K, or π to K allows us to veto misidentified $B_s \rightarrow J/\psi K^- K^+$ & $B^0 \rightarrow J/\psi K^- \pi^+$
  - Clones & ghost tracks eliminated
  - Ξ_b decays checked as a source
- Can interferences between Λ^* resonances generate a peak in the $J/\psi p$ mass spectra?
  - Implemented a decay amplitude analysis that incorporates both decay sequences:

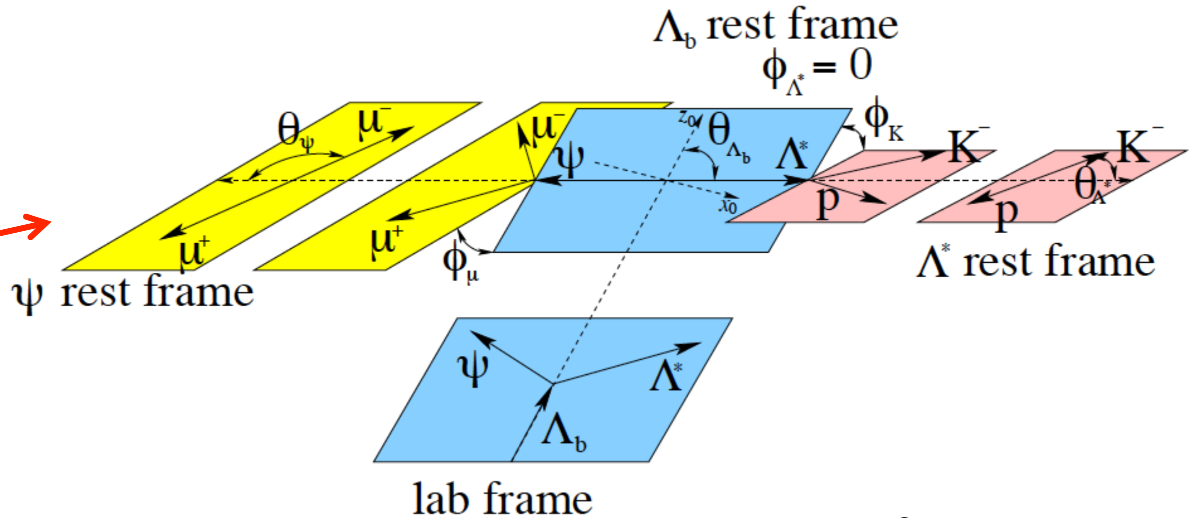
Matrix Element

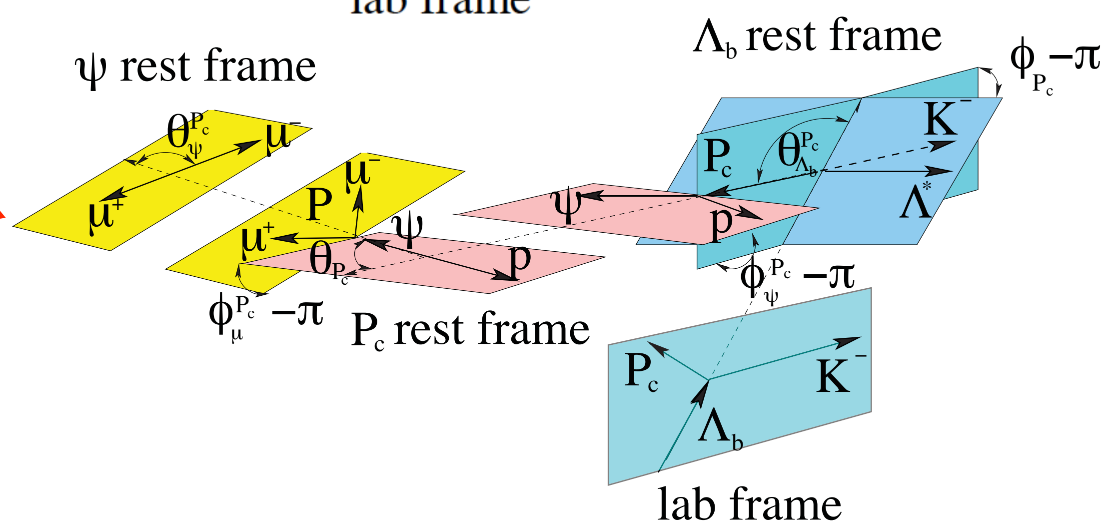
- Two interfering channels:

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

&

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





- Use $m(K^-p)$ & 5 decay ∠'s as fit parameters
- Resonance mass shapes: Breit-Wigner or Flatte´

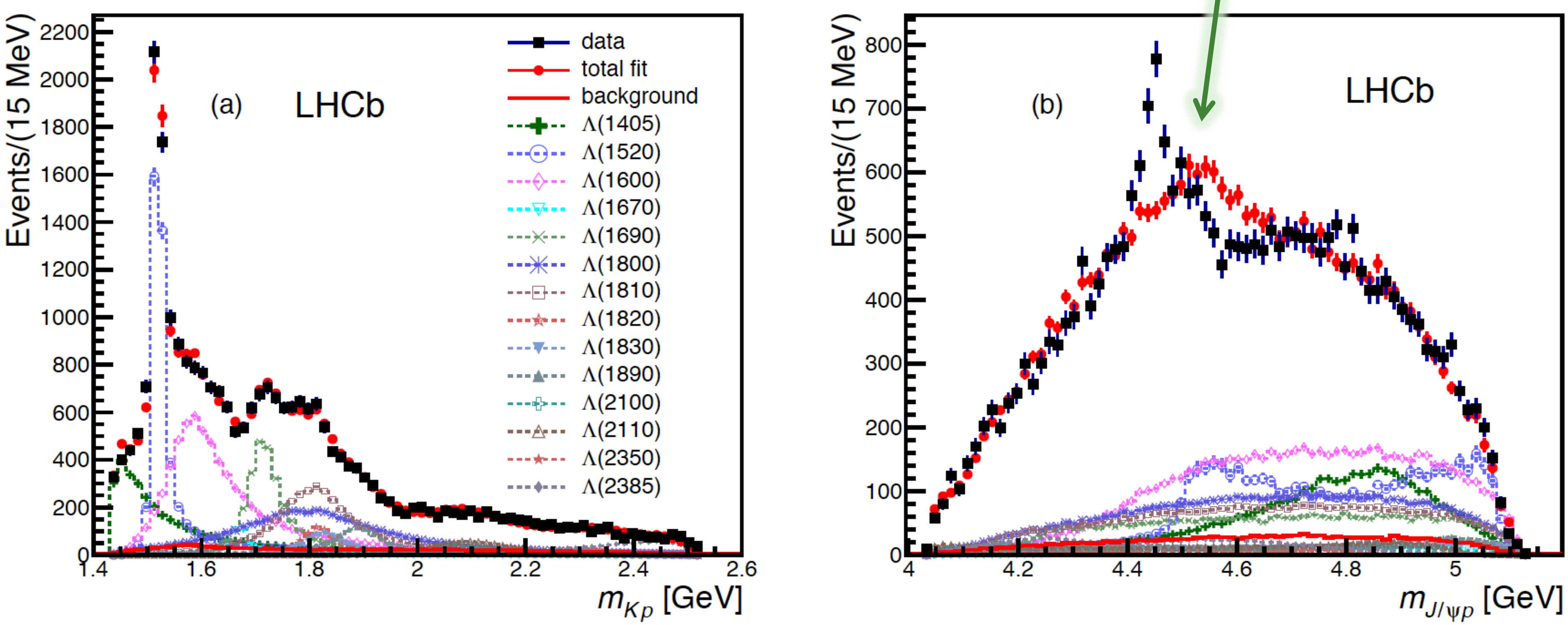
Models: extended & reduced

- 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
	$\Lambda(2585)$	?	$\approx$2585	200	0	6
				# parameters	64	146

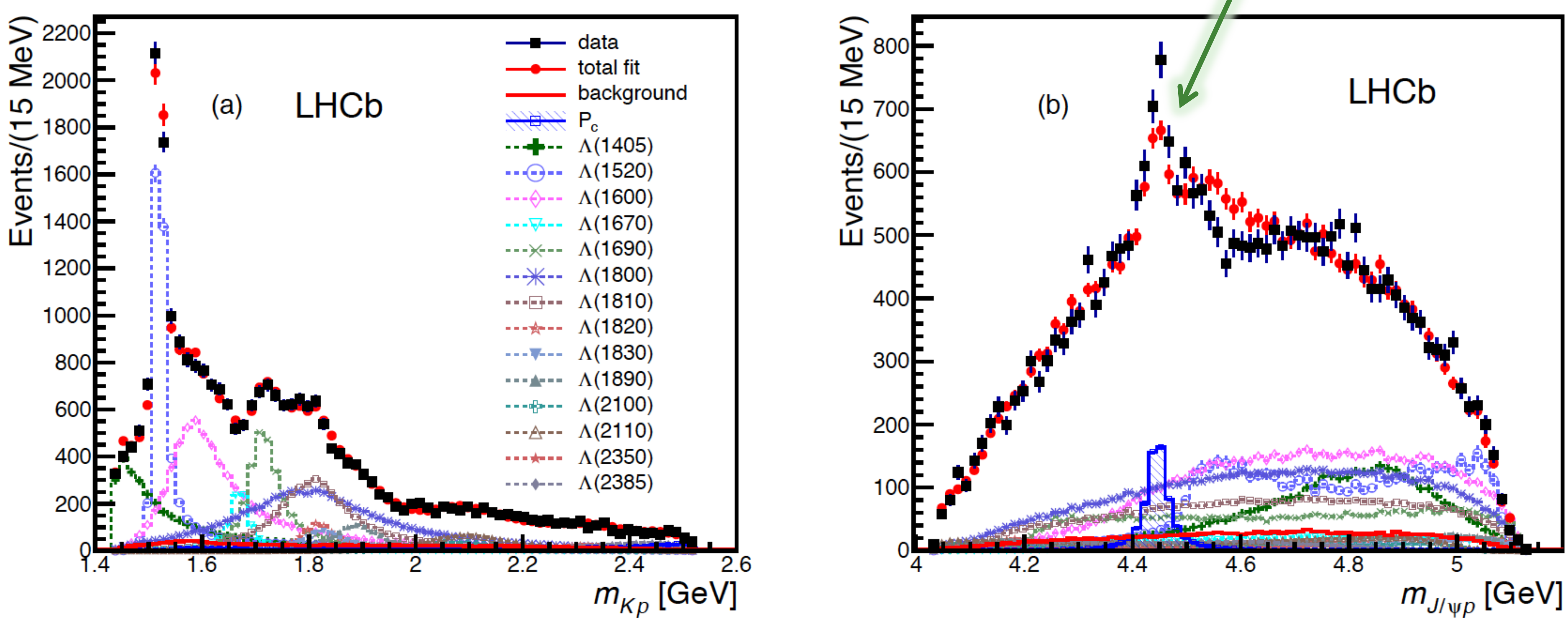
Results without P_c states

- 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^*'s doesn't help



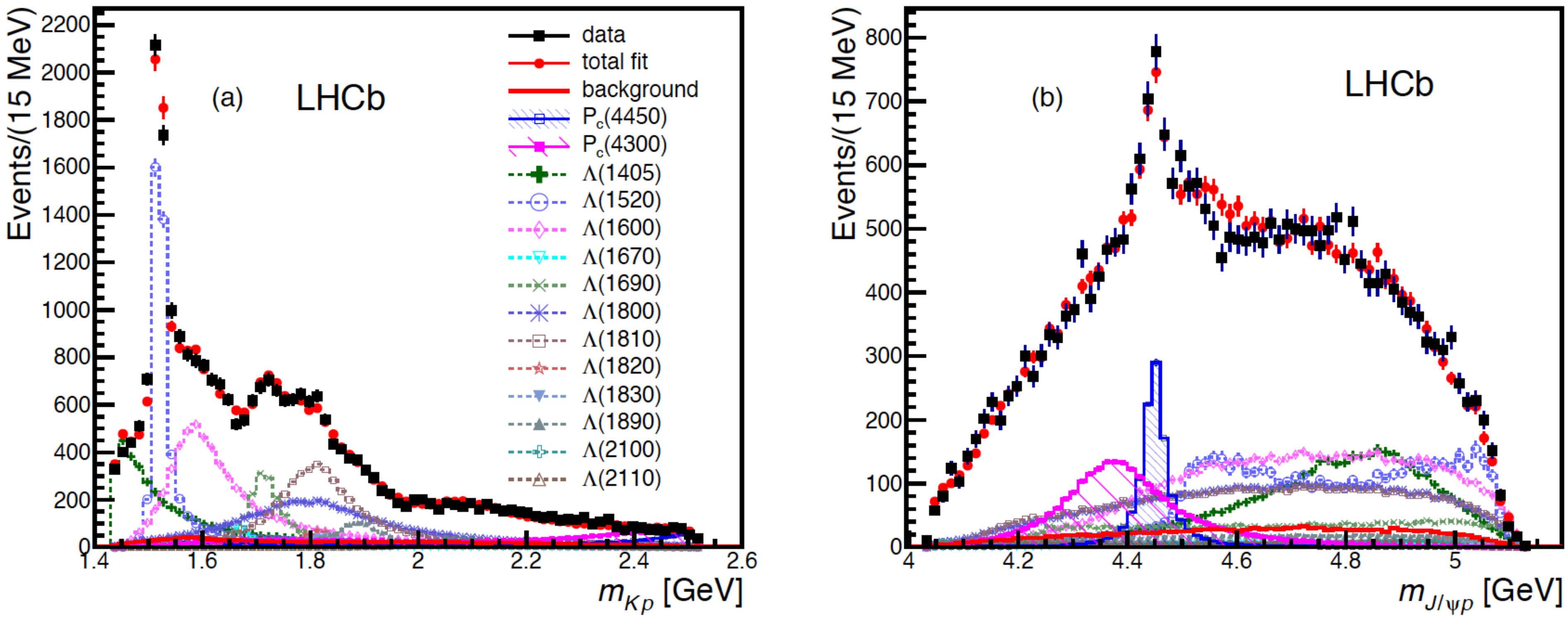
Extended model with 1 P_c

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



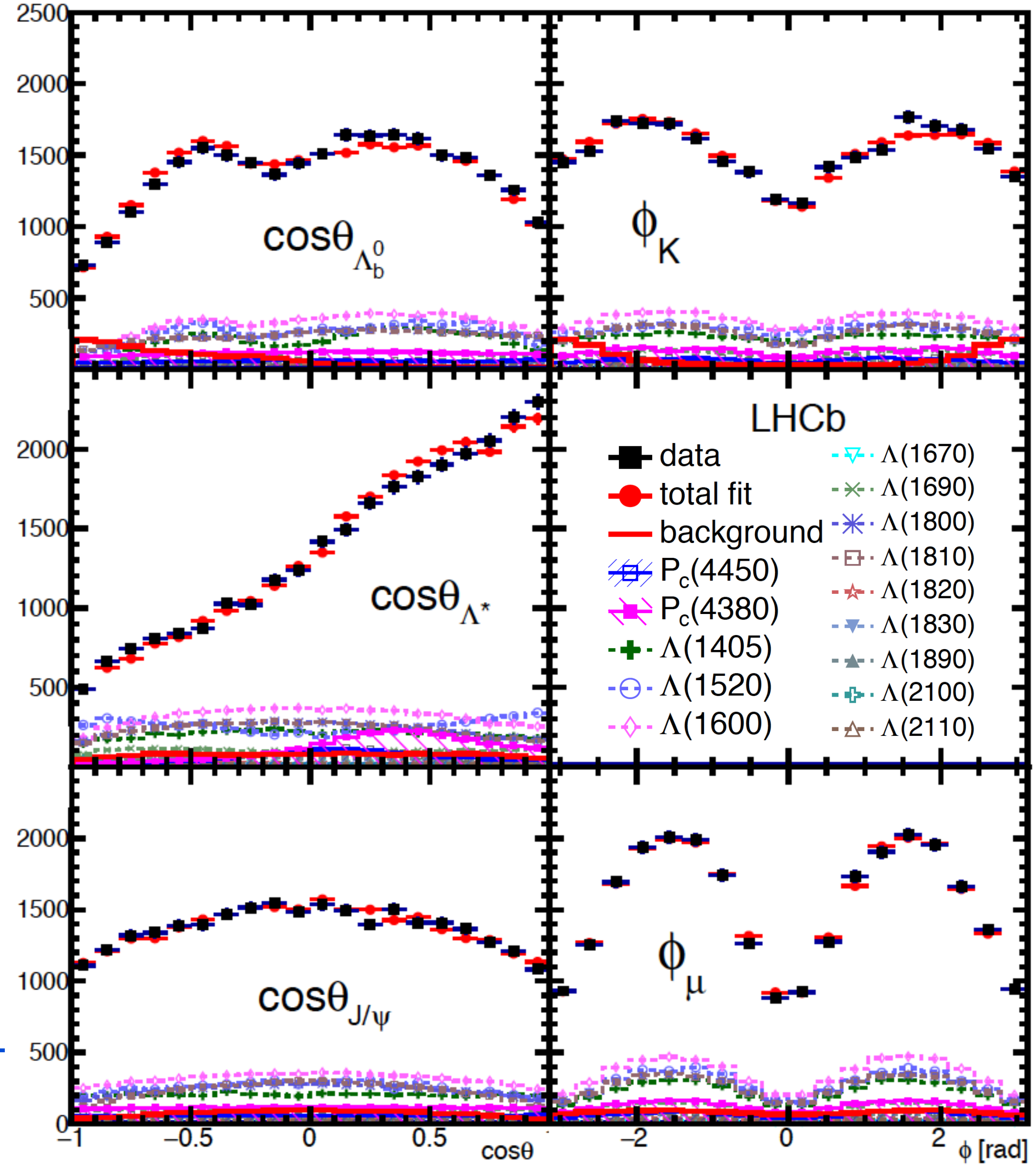
Reduced model with 2 P_c's

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



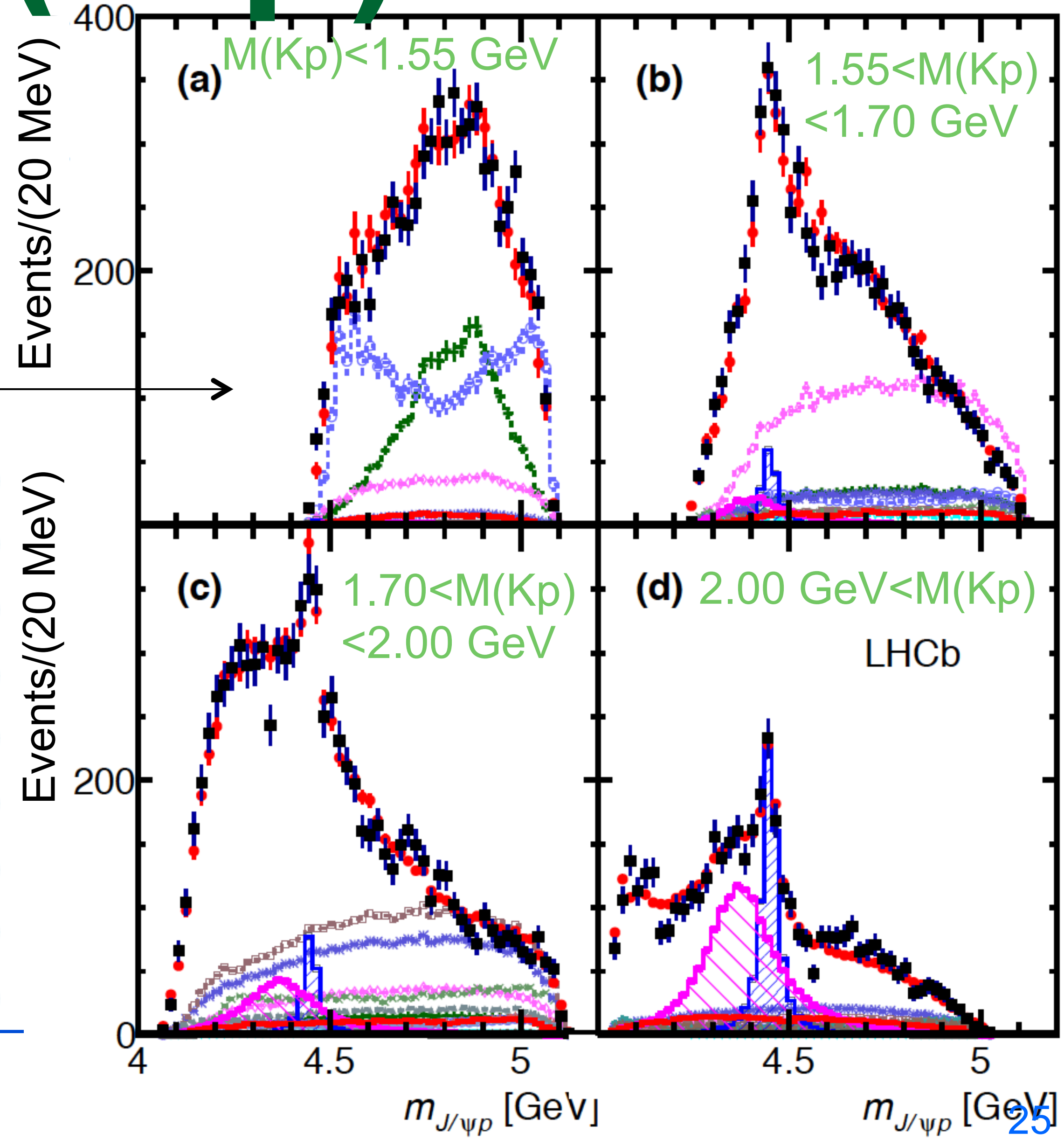
Angular distributions

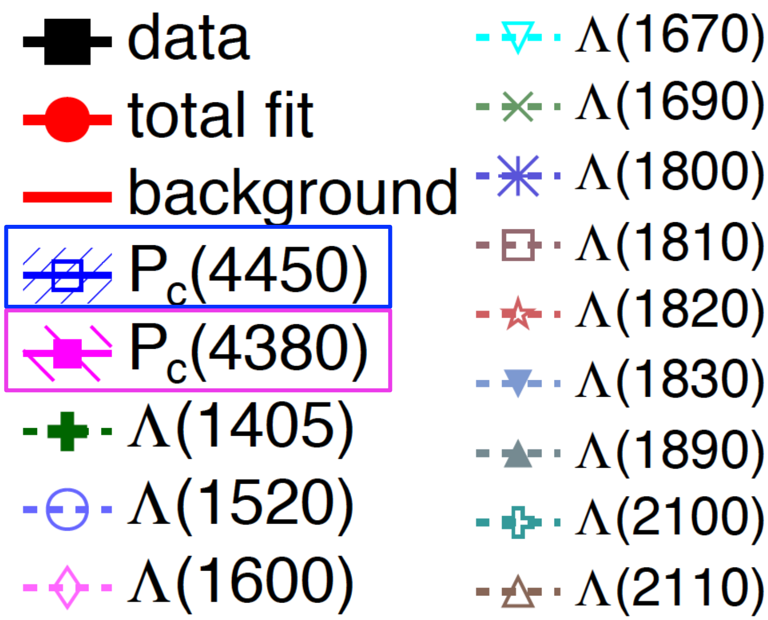
Good fits in the angular variables



In m(K^-p) slices

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

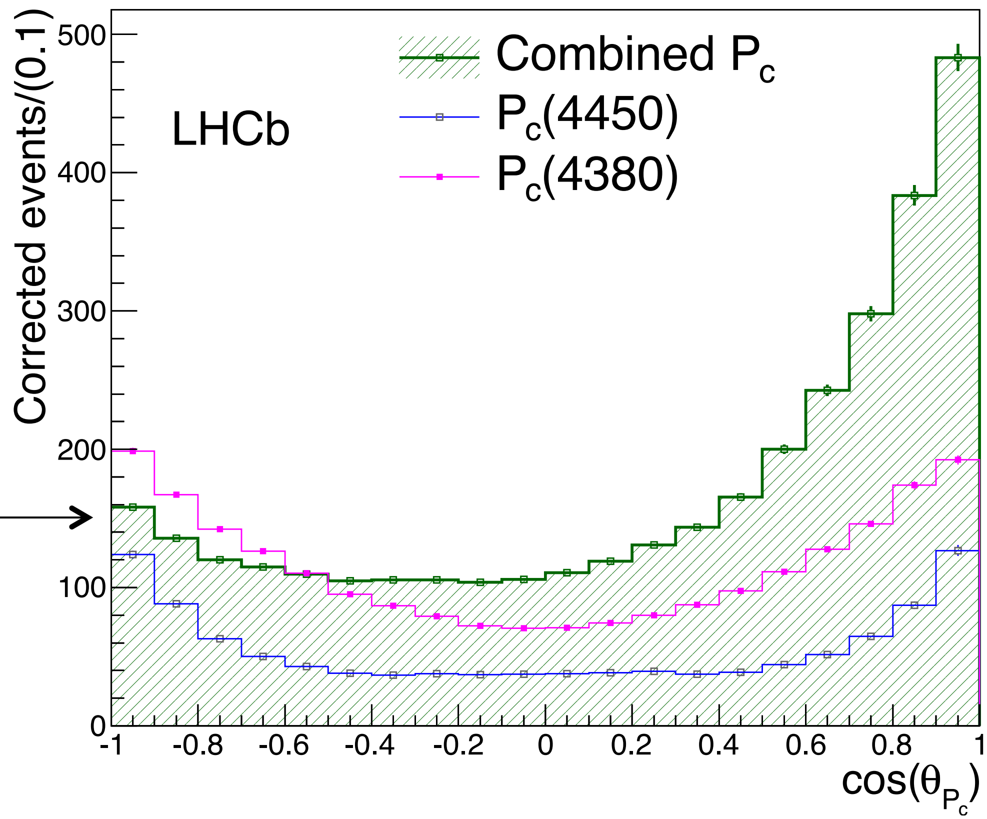




Data demands 2 states

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

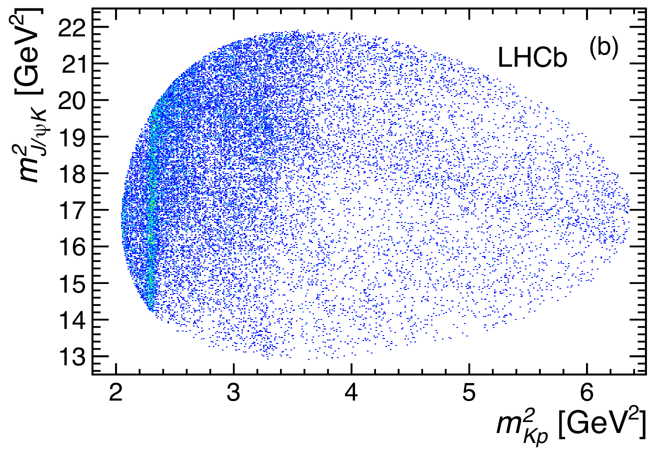
Large m(Kp) region negative interference

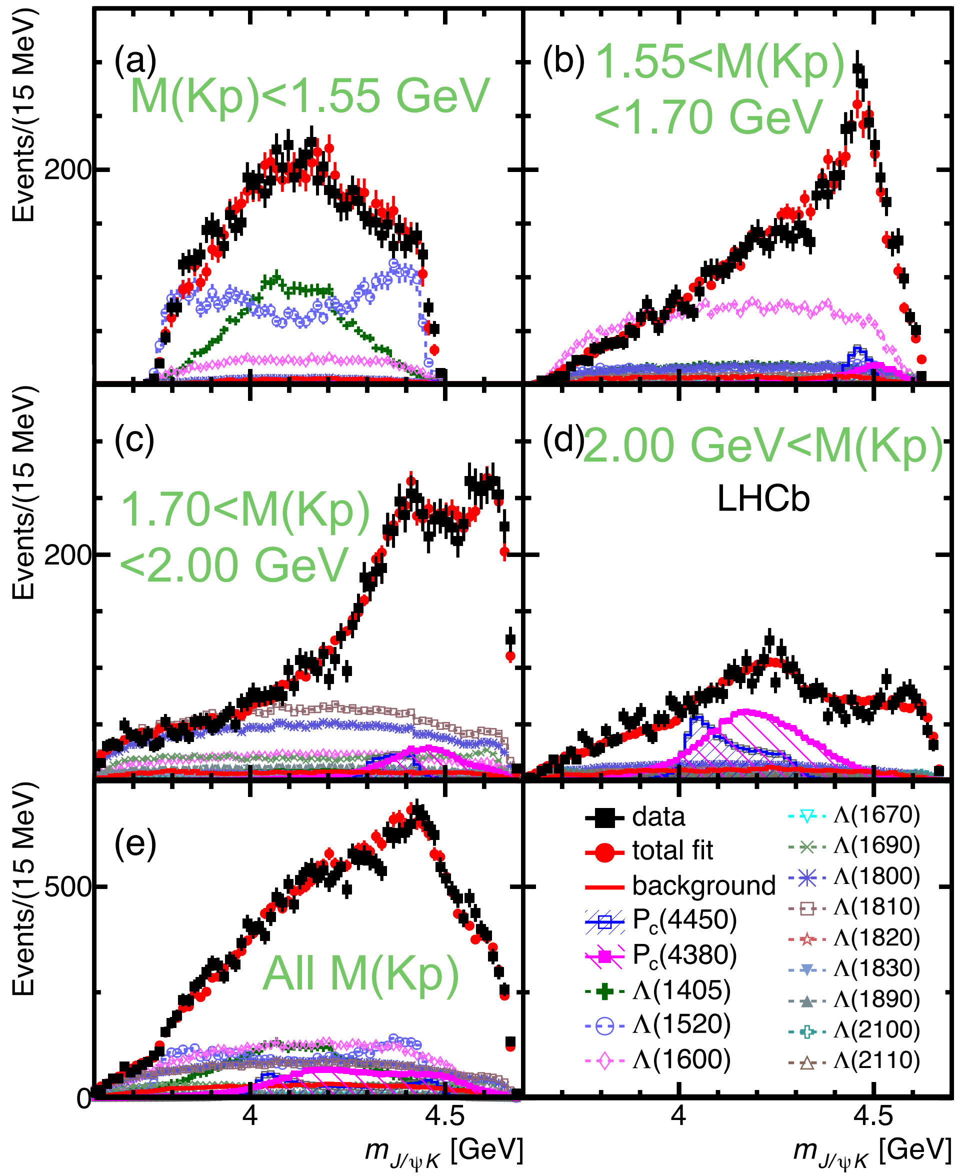


Small m(Kp) region positive interference

m(J/ψ K⁻)

- Our fit explains m(J/ψ K⁻)





Significances

- Fit improves greatly, for 1 P_c $\Delta(-2\ln\mathcal{L})=14.7^2$, adding the 2nd P_c improves by 11.6^2, for adding both together $\Delta(-2\ln\mathcal{L})=18.7^2$
- Using toy simulations 1st state has significance of 9σ & 2nd state 12σ, including systematic uncertainties, coming from difference between extended & reduced model results.

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
Λ(1405)		15±1±6
Λ(1520)		19±1±4

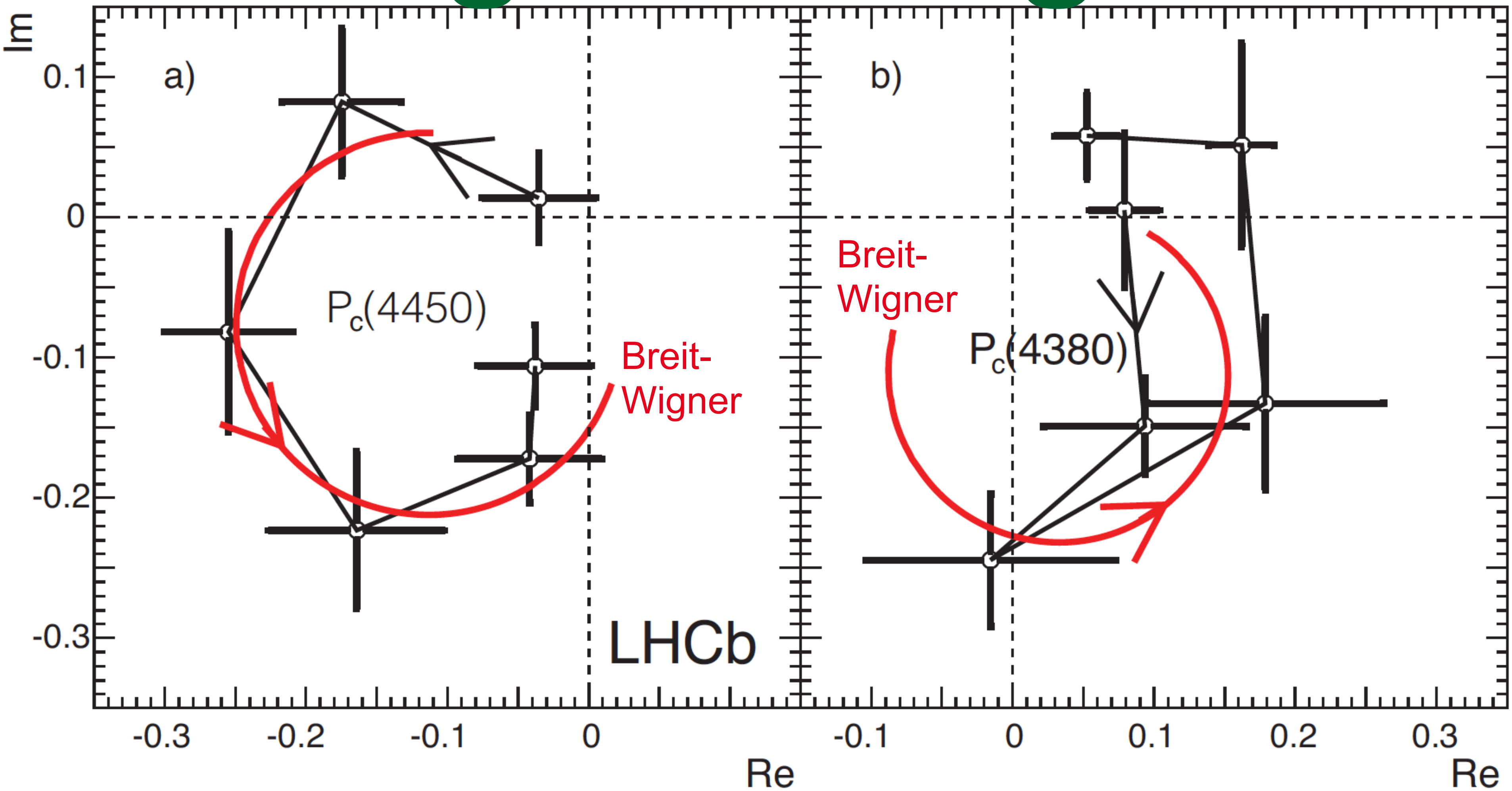
Systematic uncertainties

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

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, $\overline{\Lambda}_b/\Lambda_b$, $\Lambda_b(p_T\text{ low})/\Lambda_b(p_T\text{ high})$
- Extended model fits tried without P_c states, but two additional high mass Λ^* resonances allowing masses & widths to vary, or 4 non-resonant terms of J up to 3/2

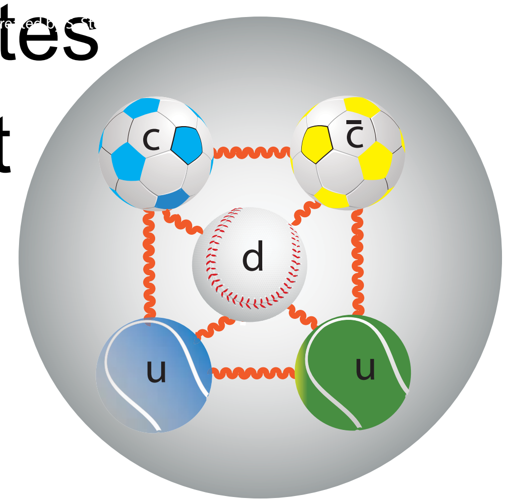
Argand diagrams



- Amplitudes for 6 bins between +Γ & -Γ

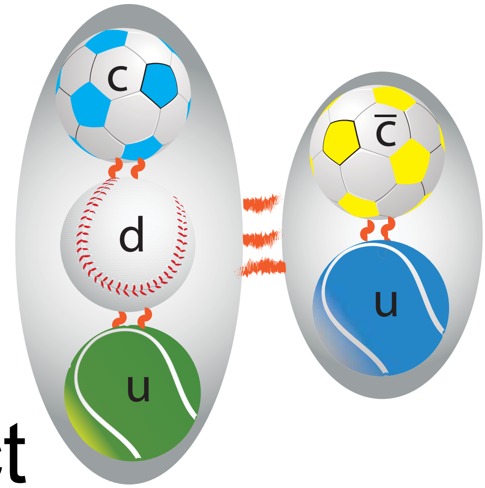
Pentaquark models

- 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], ibid [PRD20(1979) 748]
  - Colored diquark + colored triquark, R. Lebed [arXiv: 1507.05867]
  - Bag model, Jaffe; Strings, Rossi & Veneziano [Nucl. Phys. B123 (1977) 507]

Molecular models



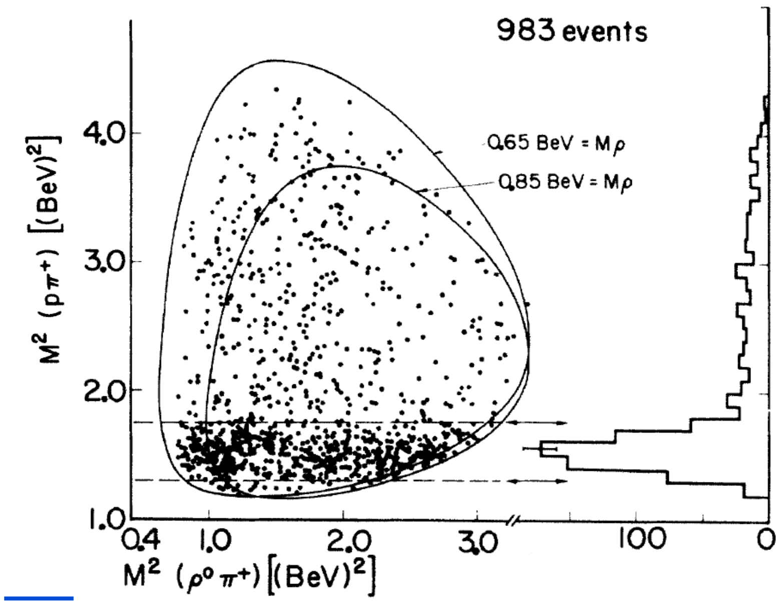
- Molecular models, generally with meson exchange for binding
- Ala' Törnqvist [Z. Phys. C61 (1994) 525]
- π exchange models usually predict only one state, mainly $J^P=1/2^+$, but could also include ρ exchange…
- Several authors consider $\Sigma_c\, D^{(*)}$ components (most of these are postdictions)

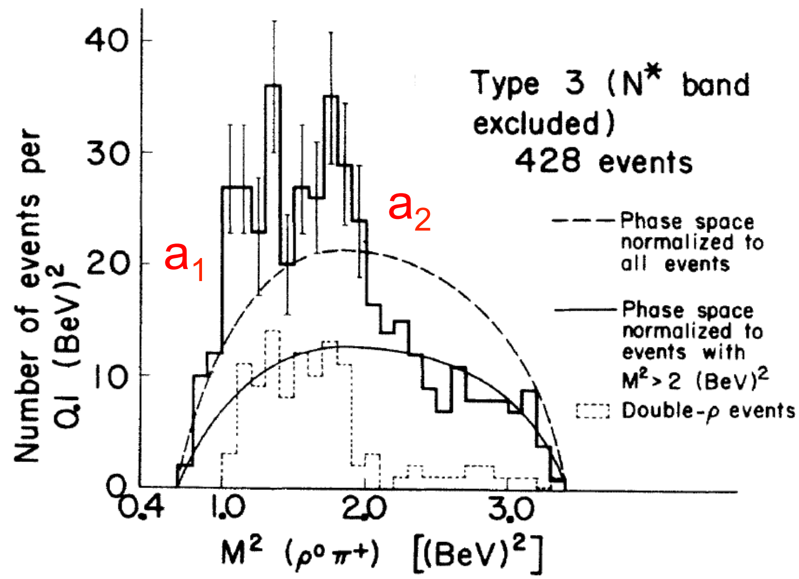
Rescattering

- These are all postdictions
- They construct non-BW amplitude that must mimic mass shape & phase variation of a BW
- eg. $\Lambda_b \to XY(Z) \to J/\psi p K^-$, especially when $m(XY)=m(P_c)$, hence the word "cusp"
- These models have so far not predicted the size of the rescattering amplitude
- Also difficult to predict two states…

Some History: The a_1

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

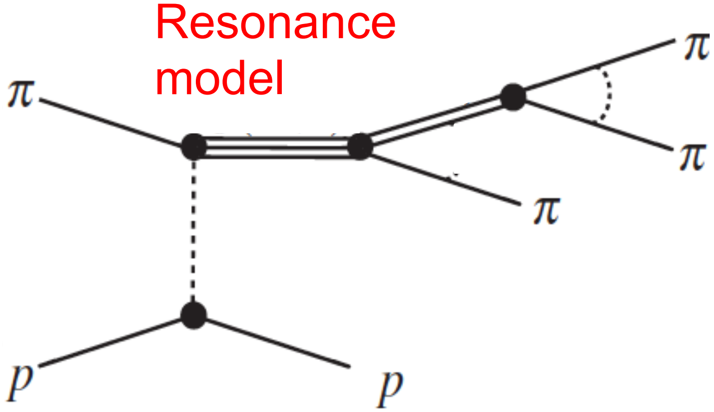


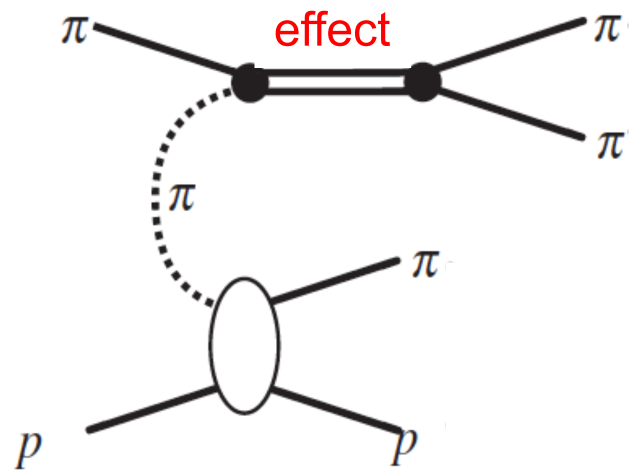


Note BeV≡GeV

"Kinematical" effect

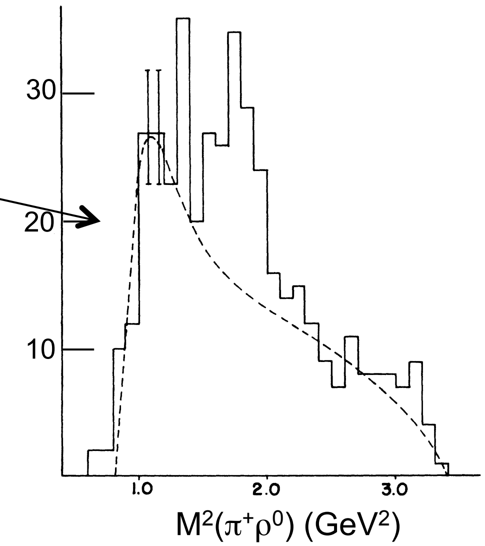
- Clear enhancement near threshold. Is it a new resonance as suggested in original paper?
- Theorists, first Deck, suggest that the threshold enhancement can be due to off shell πp scattering *R.T. Deck, PRL 13, 169 (1964)*





Deck Effect

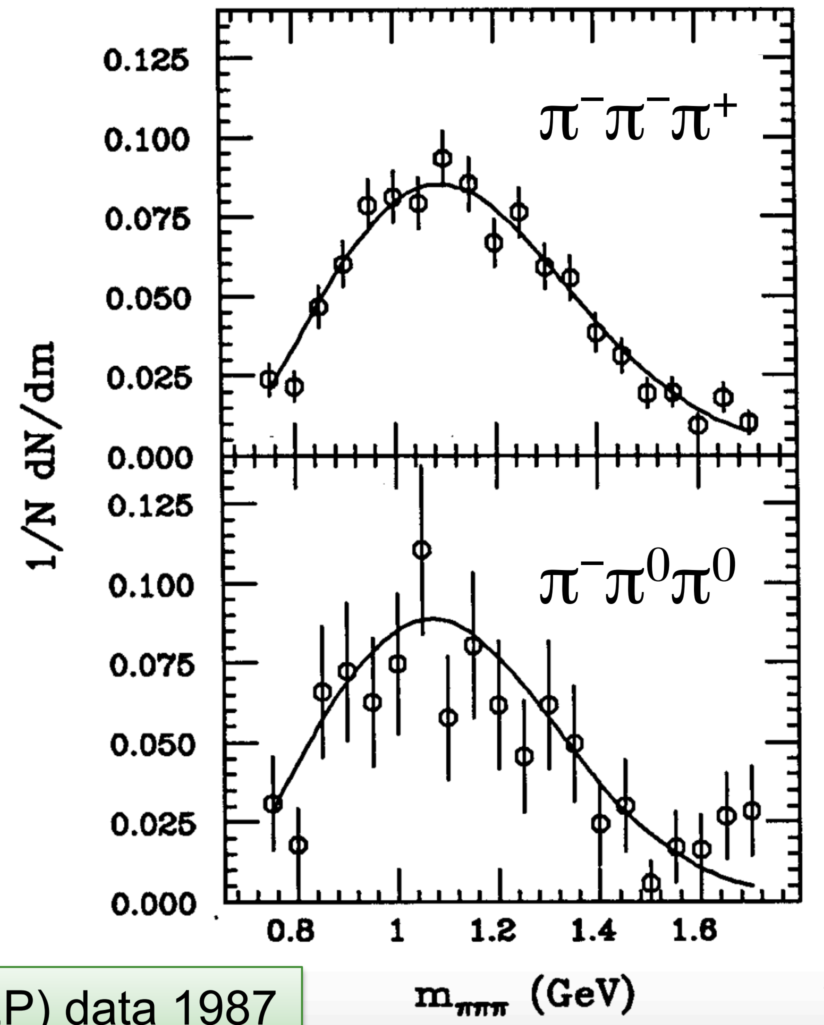
- Deck's fit to data can provide adequate explanation



- a_1 then seen in different charge states & different channels, e.g. $K^+p \rightarrow K^+\pi^+\pi^-\pi^0\ p$
- Many more sophisticated theory papers
- Controversy continued until observation of a_1 in $\tau^- \rightarrow \pi^+\pi^-\pi^-\nu$ decays, ~1977

$\tau^{-} \rightarrow (\pi\pi\pi)^{-}\nu$

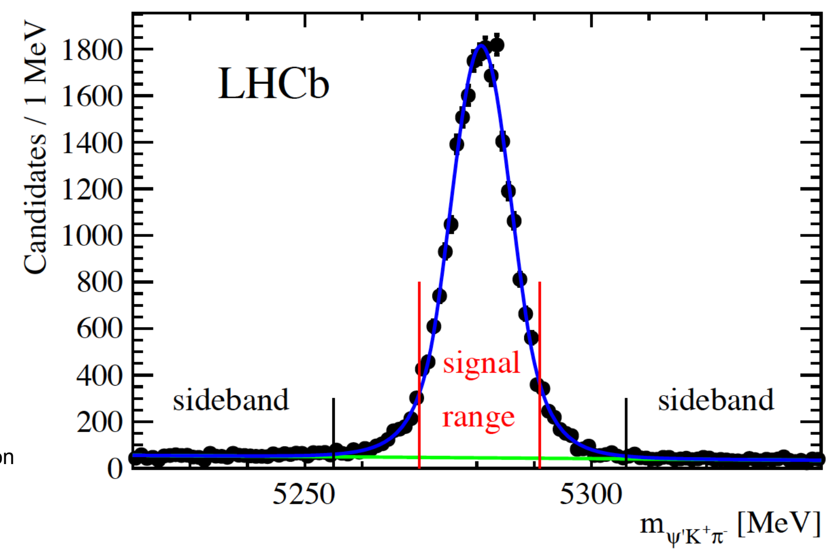
Surmises: a full amplitude analysis may have proved the resonant nature of the a_1 earlier. Important to see resonant states in several ways. There never was an unambiguous demonstration of the Deck effect.



MAC (PEP) data 1987

$Z(4430)^+$ tetraquark

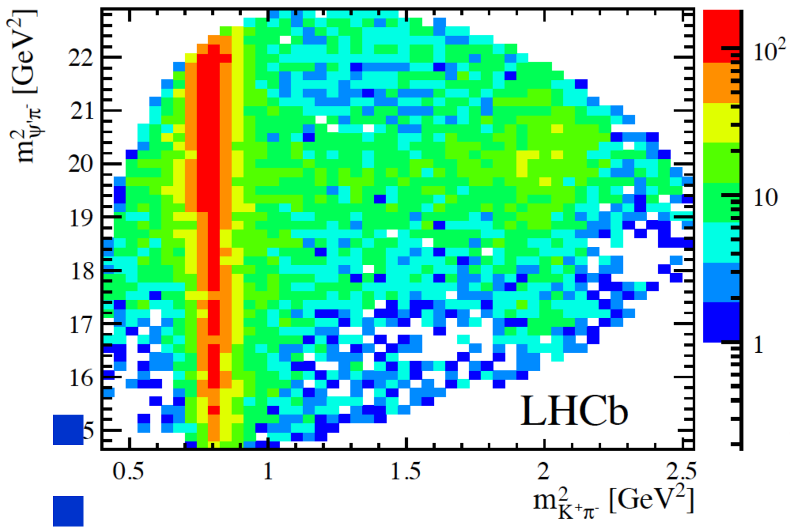
- $B^0 \to \psi' \pi^- K^+$, peak in $m(\psi' \pi^-)$, charged charmonium state must be exotic, not $q\bar{q}$
  - First observed by Belle M=4433±5 MeV, Γ=45 MeV
  - Challenged by BaBar: explanation in terms of K*'s
  - Belle reanalysis using full amplitude fit: M= $4485 \pm 22^{+28}_{-11}$ MeV, Γ=200 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

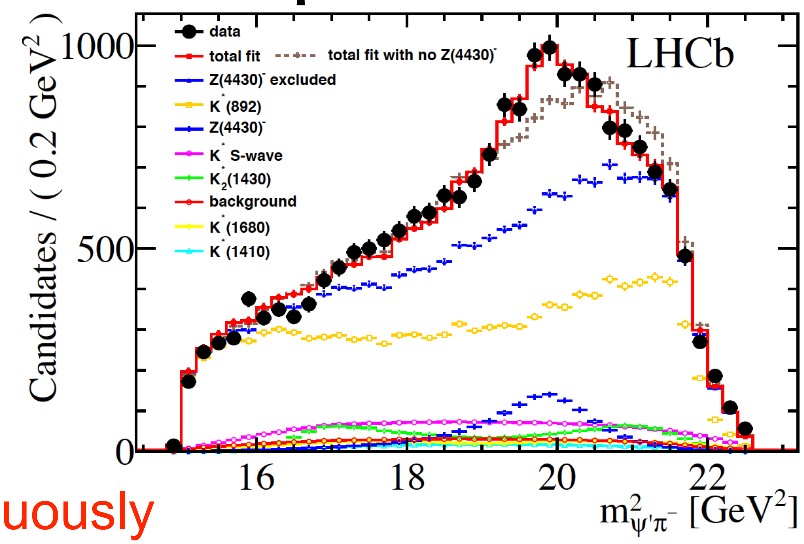
LHCb Amplitude analysis

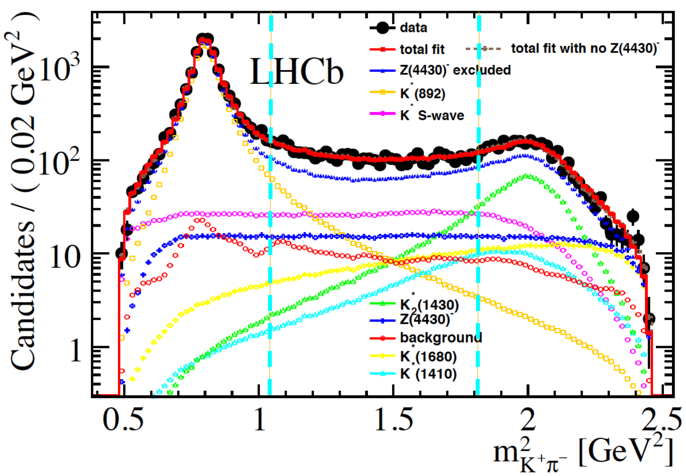
- Full 4D fit to both $K^* \to K^-\pi^+$ & $Z \to \psi'\pi^-$ states

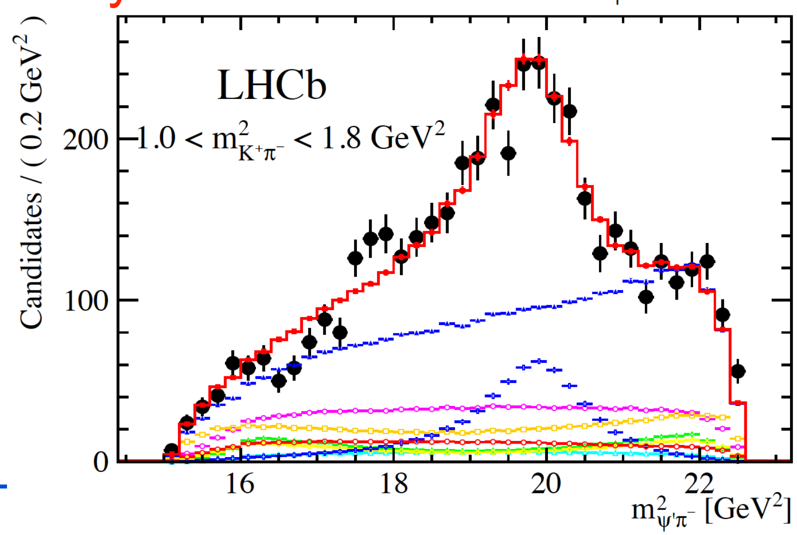


$J^P=1^+$

Unambiguously

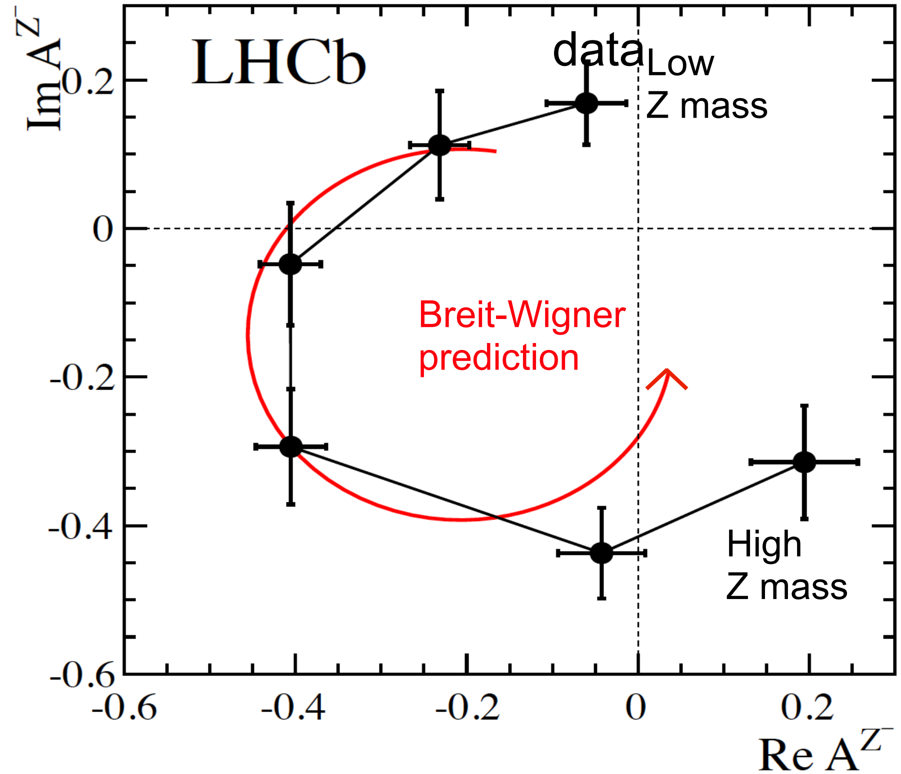






Is it a resonance?

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



Other Explanations

- Molecule:

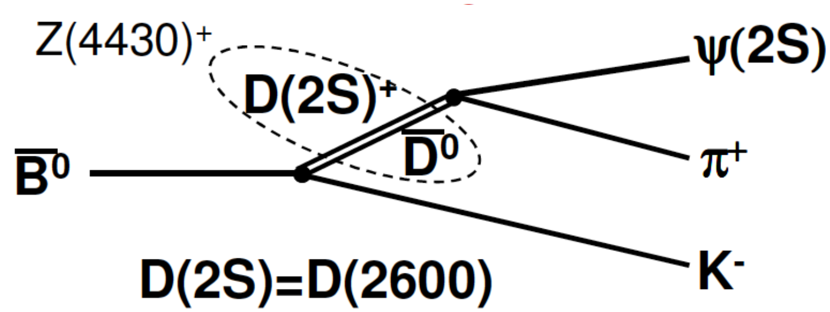
L. Ma et.al, [arXiv:1404.3450]

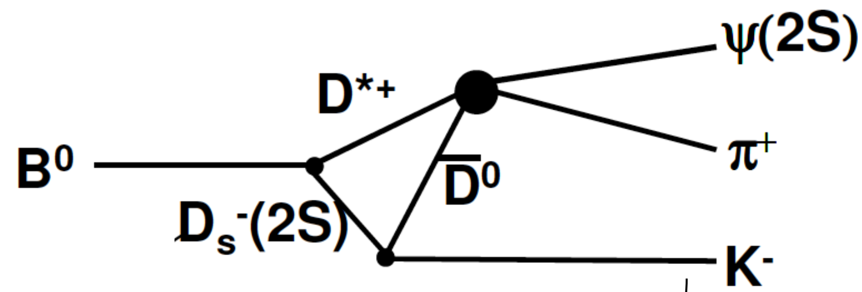
T. Barnes et.al, [arXiv:1409.6651

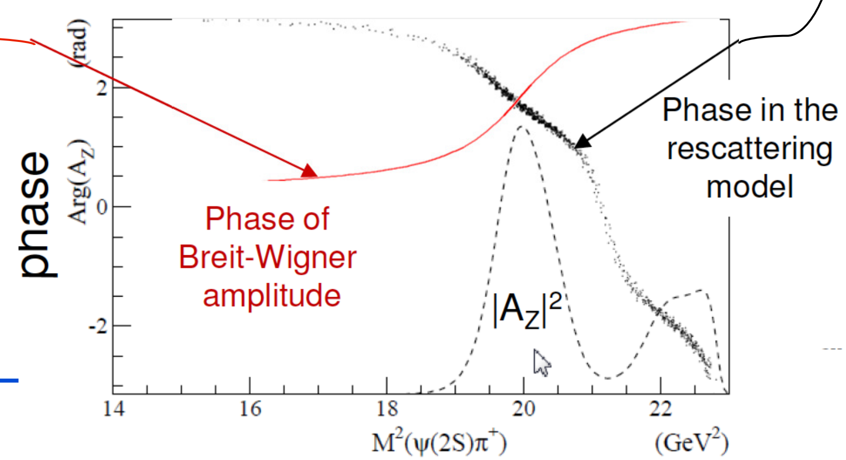
- Same scattering phase as Breit-Wigner
- Rescattering:

P. Pakhov & T. Uglov [arXiv:1408:5295]

- Opposite phase
- Ruled out by LHCb Argand diagram

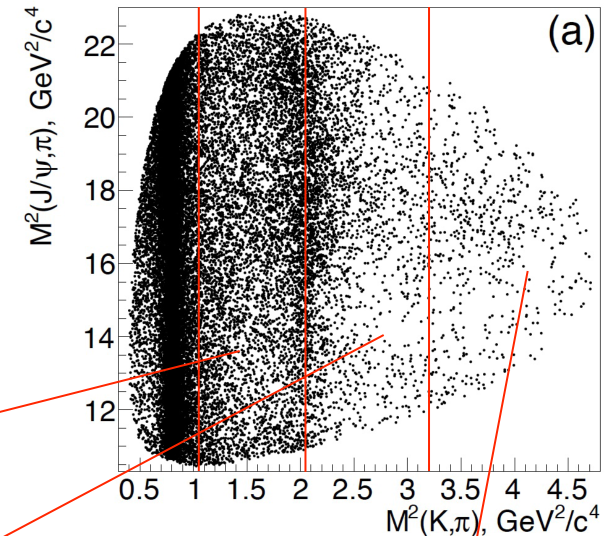


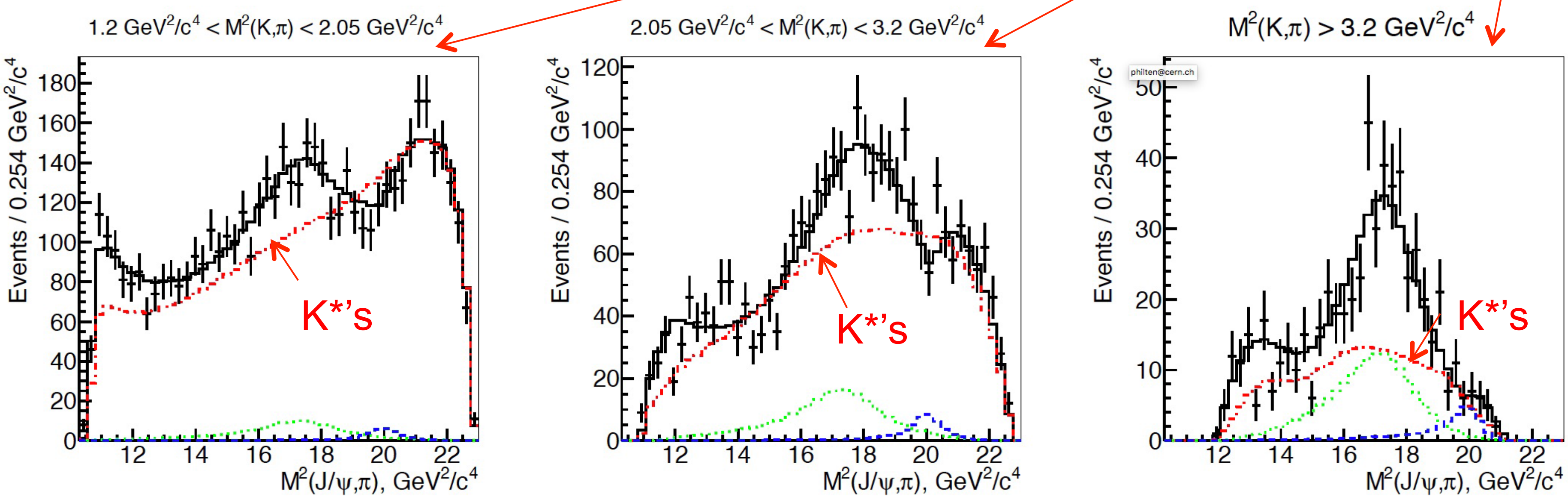




$B^0 \rightarrow J/\psi\ \pi^- K^+$

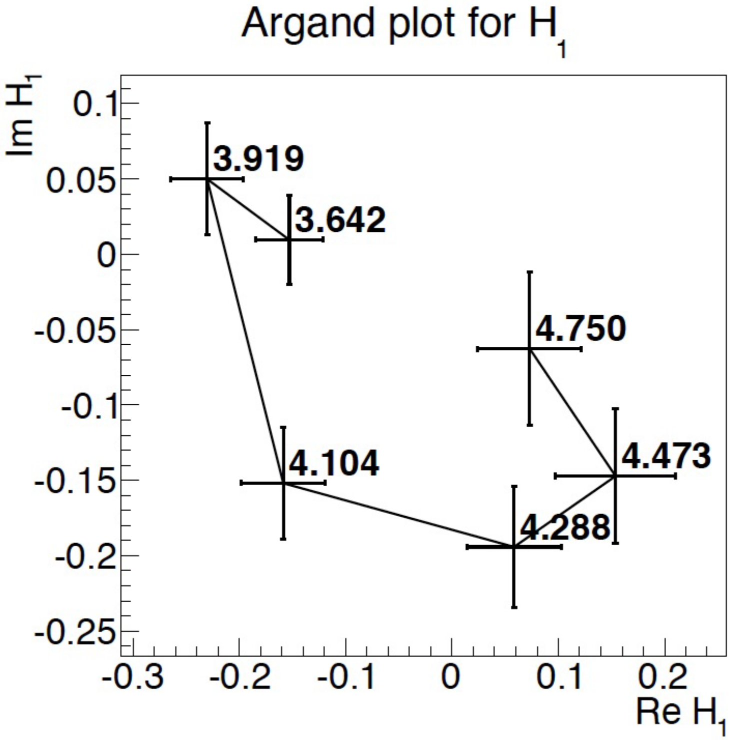
- Bells again does a full amplitude analysis [arXiv:1408.6457]
- Sees $Z_c(4430) \rightarrow J/\psi\ \pi^-$, at 4σ level with $B(Z_c \rightarrow J/\psi\ \pi^-) / B(Z_c \rightarrow \psi' \pi^-) \sim 0.1$
- Plus a new state $Z_c(4200)$, $\Gamma \sim 370$ MeV

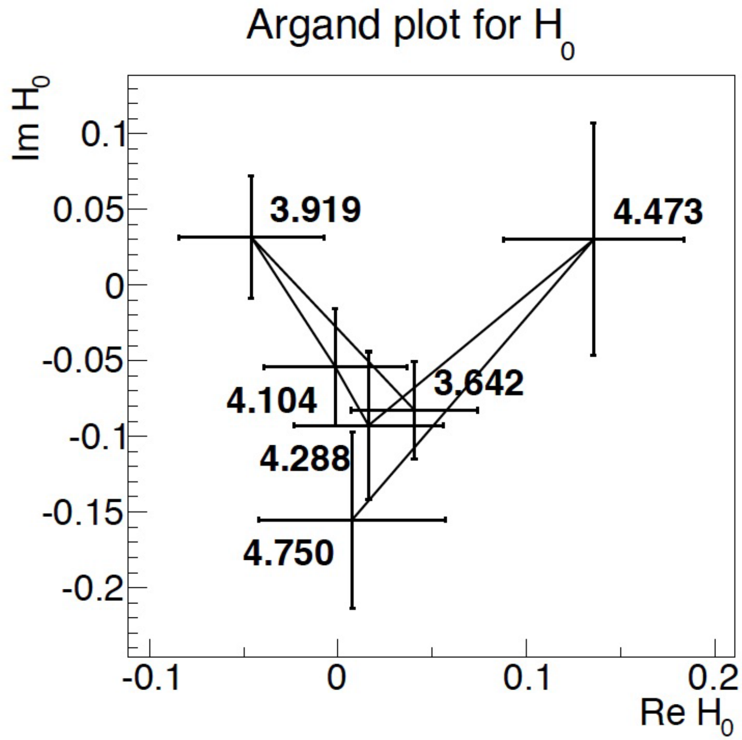




$Z_c(4200)$

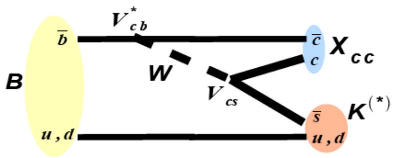
- Also provides Argand plots for the two different helicity amplitudes in the decay





- Needs confirmation from another experiment

Other tetraquark candidates

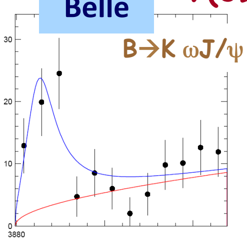


Thus far, no amplitude analyses for these states

Y(3940)

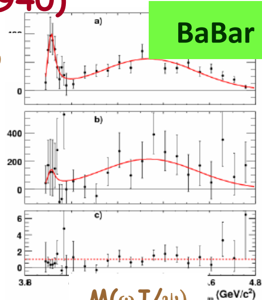
Belle

B→K ωJ/ψ



M(ωJ/ψ)

BaBar

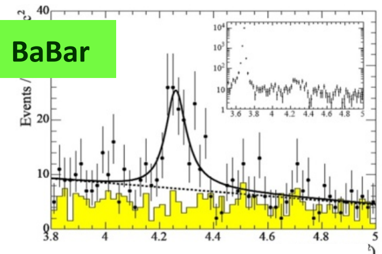


M(ωJ/ψ)

Z(4430)

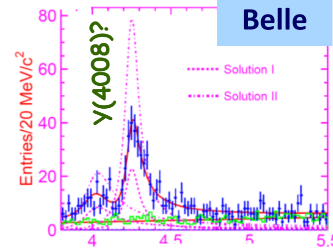
Y(4260)

BaBar



M($\pi^+\pi^-$J/ψ)

Belle



Y(4008)?

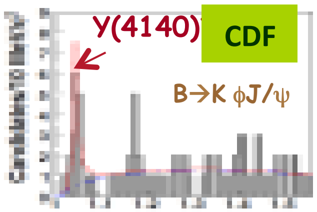
M($\pi^+\pi^-$J/ψ)

Y(4350) & Y(4660)

Y(4140)

CDF

B→K φJ/ψ

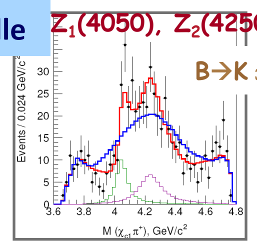


M(φJ/ψ)−M(J/ψ)

Belle

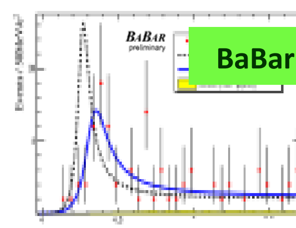
Z_1(4050), Z_2(4250)

B→K $\pi^+\chi_{c1}$



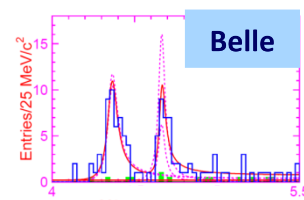
M($\pi^\pm\chi_{c1}$)

BaBar



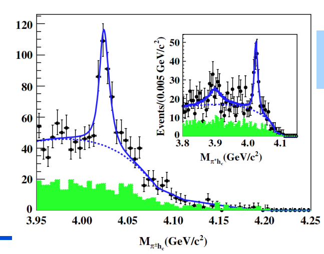
M($\pi^+\pi^-\psi'$)

Belle



M($\pi^+\pi^-\psi'$)

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



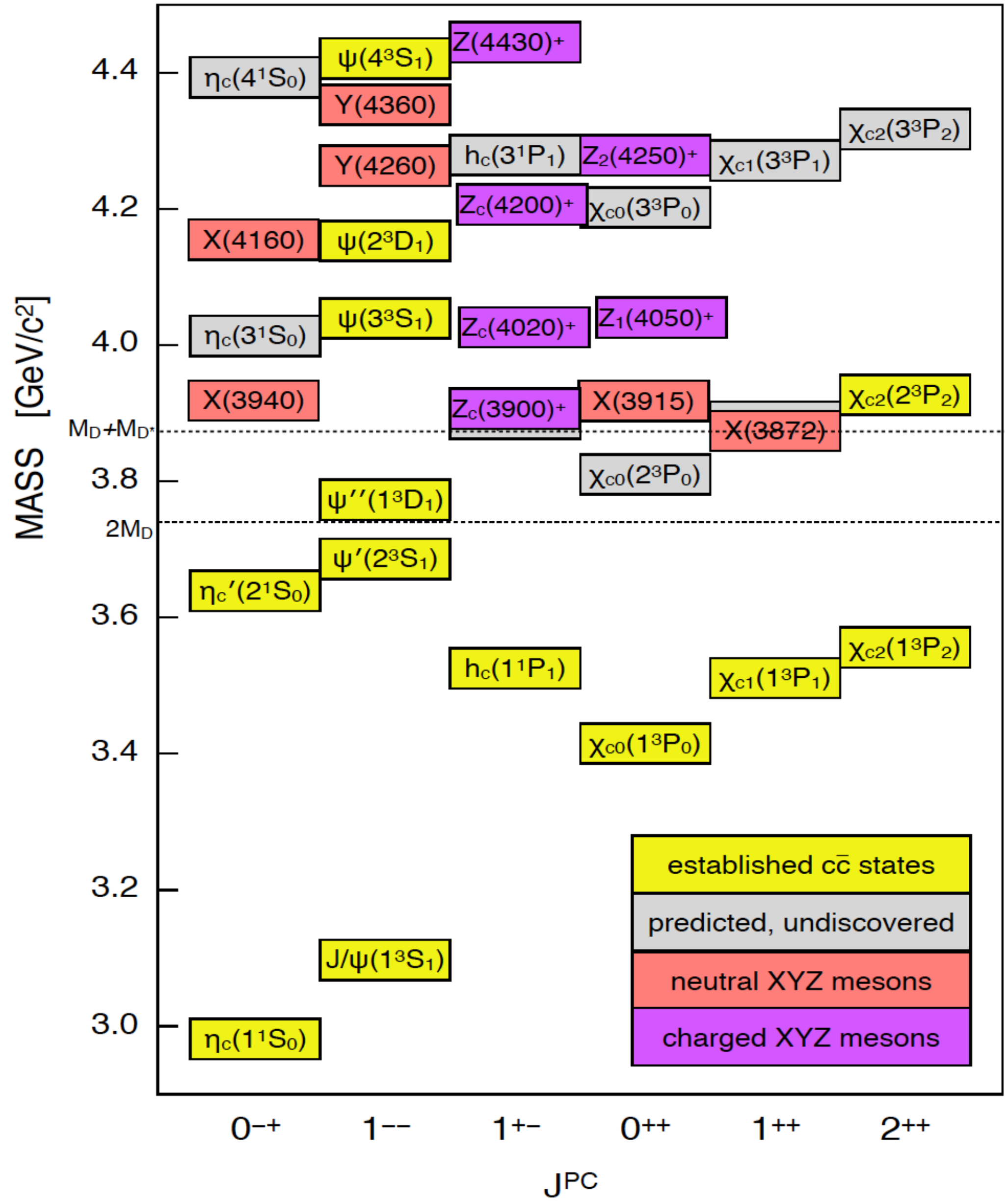
M($\pi^\pm h_c$)

BES

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

Tetraquark summary

- Predicted neutral charmonium states compared with found cc states, & both neutral & charged exotic candidates



- From Olsen [arXiv:1511.01589]

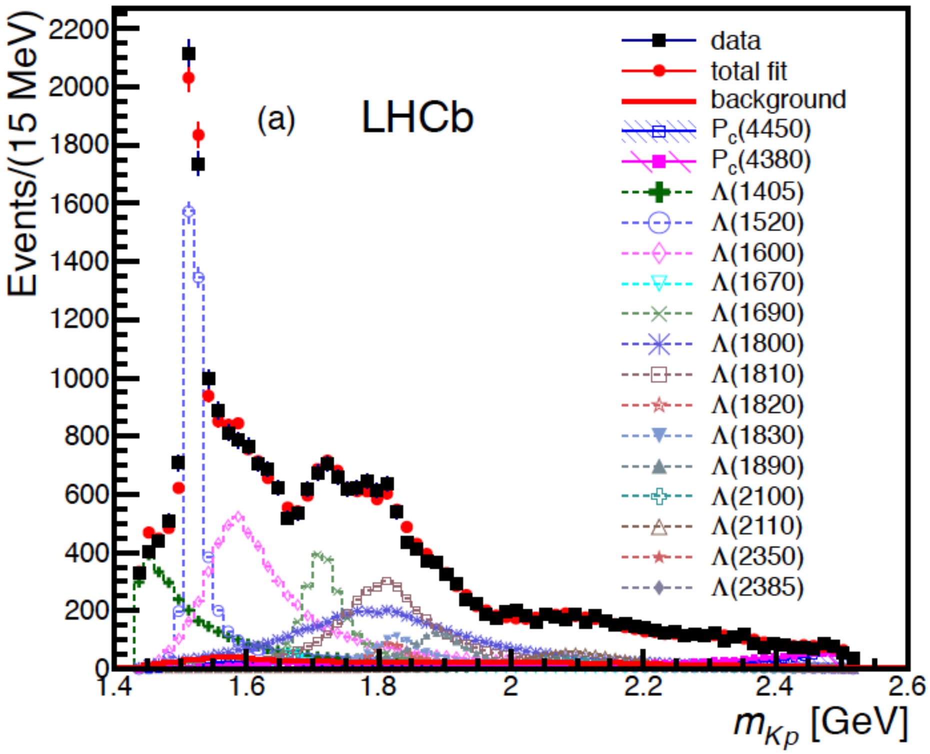
Conclusions

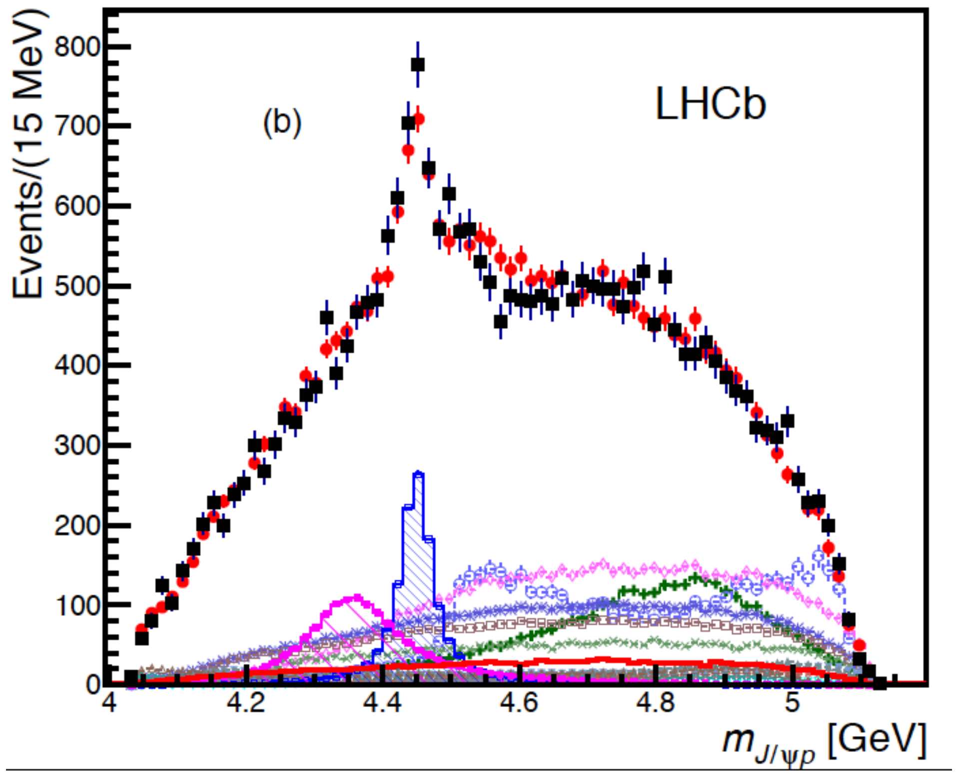
- LHCb has found two resonances decaying into $J/\psi p$ with pentaquark content of $uudc\bar{c}$ arXiv:1507.03414.
- They have spin 3/2 & 5/2 & opposite Parity
- Determination of their internal binding, the "color chemistry" will require more study.
- Other exotic states have appeared containing $c\bar{c}$ (or $b\bar{b}$) quarks: the $Z^{+}(4430)\rightarrow\psi' K^{-}\pi^{+}$ appears to be a tetraquark with $J^{P}=1^{+}$. Is binding stronger for c & b?
- Lattice QCD calculations providing masses would be most welcome
- We look forward to further searches for exotics

The End

US LHCb groups gratefully acknowledge support from the NSF

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:

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

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