Exotic Spectroscopy

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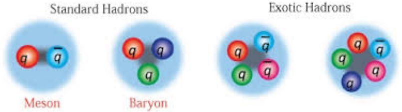
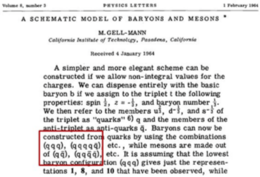
On behalf of the LHCb Collaboration

Lake Louise Winter Institute, 19 – 25 February 2017

The possibility of mesons and baryons with other than $q\bar{q}$ or qqq configurations it was admitted since the introduction of the quark model.





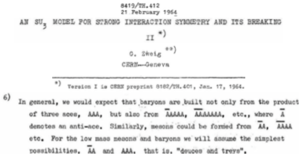
Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

Received 4 January 1964

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while



8419/TH.412
21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

II *)

G. Zweig **)
CERN---Geneva

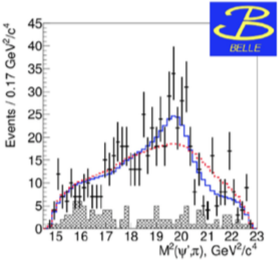
*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

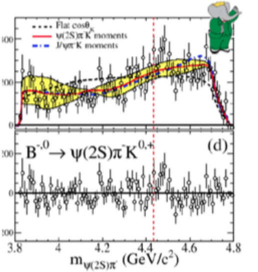
6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons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

- These could be molecular bound states with mesons, tetraquarks, pentaquarks, or hybrids.
- Strong candidates for these exotic hadrons have been observed with contributions from multiple experiments.
- In this talk I will review some of the most relevant results from LHCb.

Tetraquarks studies

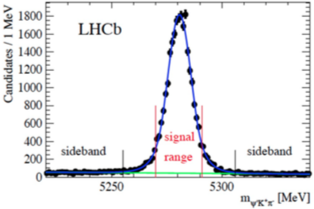
- Exotic signature:
  - Decay to charmonium ($c\bar{c}$ pair content)
  - Electrically charged (needs at least 2 more light quarks)
- Observed by Belle in $\Psi(2S)\pi^+$ in $B^0 \to \Psi(2S)K^+\pi^-$ decays [PRL100, 142001 (2008)]
- Not confirmed by BaBar (but not excluded) [PRD 79, 112001 (2009)]
- Full 4D amplitude analysis by Belle [PRD 88 (2013) 074026]

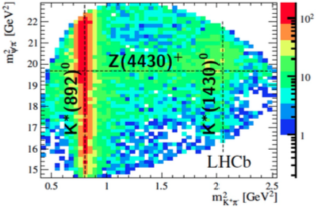


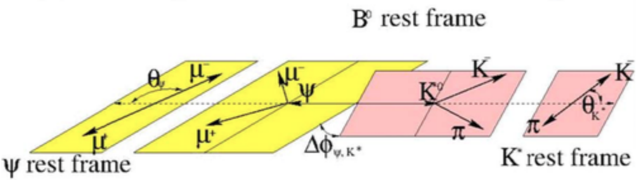


$Z(4430)^-$ confirmation at LHCb [PRL 112 (2014)222002]

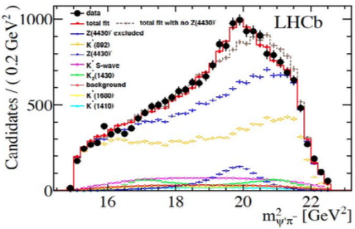
- Sample of $\approx 25k\ B^0 \rightarrow \Psi(2S)K^+\pi^-$ candidates
- $\approx 4\%$ of combinatorial background
- Used 4D amplitude analysis (Isobar approach)

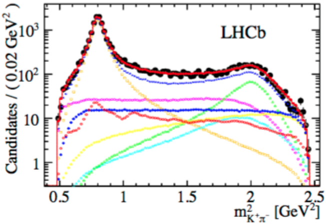




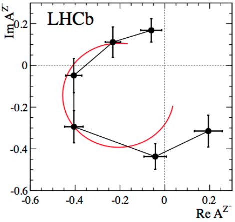


- The Z(4430) it has a BW shape in m($\Psi(2S)\pi^-$) mass, but is basically flat in m($K^+\pi^-$).
- Poor fit with only K^* resonances (brown dashed line)
- Including Z(4430) clearly improves the fit





- M: 4475$\pm$7 MeV
- Γ: 172$\pm$13 MeV
- $J^P = 1^+$
- Argand diagram shows a behavior characteristic of a resonance.



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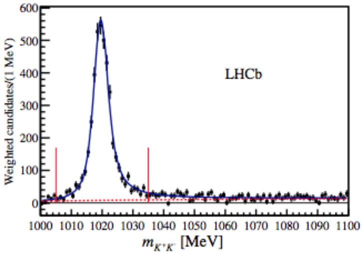
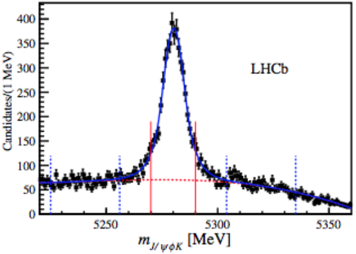
- Reported by CDF (2008 & 20011), Belle (2009), D0 (2013), CMS (2013), BaBar (2013) & LHCb (2011)
- X(4140) structure could be molecular, tetraquark, hybrid state or rescattering effect
- Run1 sample: Nsignal $= 4289 \pm 151$ ($23 \pm 6\%$ background)





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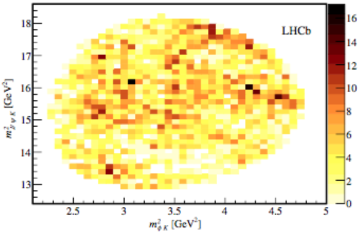

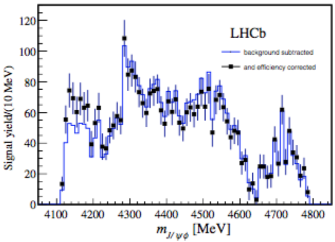

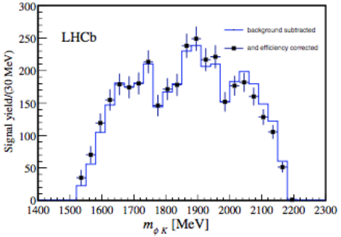

- All previous results based in 1-D projections
- LHCb performed Amplitude Analysis for the first time

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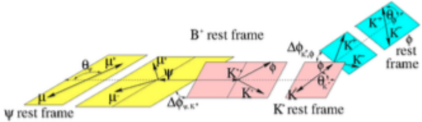
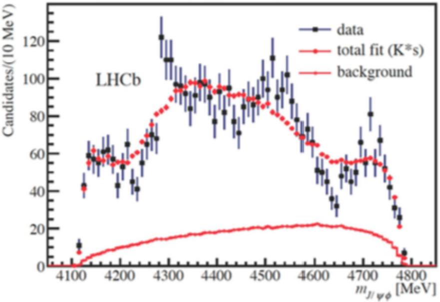
- 6D fit including K^* resonances + NR background



Masses and widths not constrained

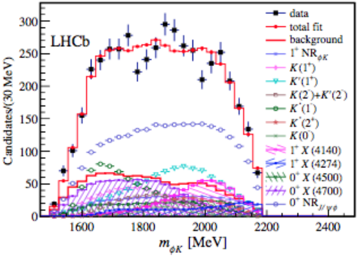
- K^* resonances alone don't describe well the data

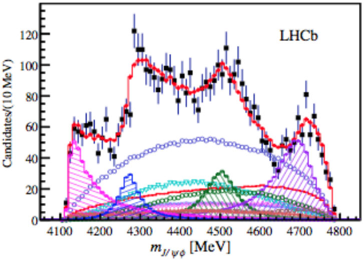


X(4140) in $B^+ \to J/\Psi\phi K^+$ [PRL 118 (2017) 022003] & [PRD 95 (2017) 012002]

- Fits including exotics
- Add X and Z^+ components with various quantum numbers
- Z^+ components improve fit marginally
- Found Two 1^{++} and two 0^{++} states with large significance

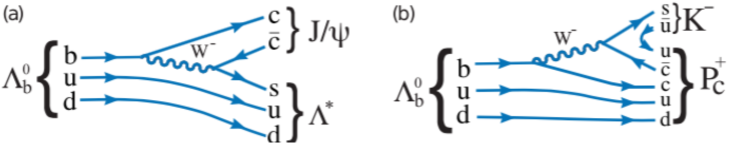
Contribution	Sign. or Ref.	Fit results M_0 [MeV]	Γ_0 [MeV]	FF %
All $X(1^+)$				$16\pm3\,^{+\ 6}_{-\ 2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\,^{+4.6}_{-2.8}$	$83\pm21\,^{+21}_{-14}$	$13.0\pm3.2\,^{+4.7}_{-2.0}$
ave.	Table 1	4147.1 ± 2.4	15.7 ± 6.3	
$X(4274)$	6.0σ	$4273.3\pm8.3\,^{+17.2}_{-\ 3.6}$	$56\pm11\,^{+\ 8}_{-11}$	$7.1\pm2.5\,^{+3.5}_{-2.4}$
CDF	[26]	$4274.4\,^{+8.4}_{-6.7}\pm1.9$	$32\,^{+22}_{-15}\pm8$	
CMS	[23]	$4313.8\pm5.3\pm7.3$	$38\,^{+30}_{-15}\pm16$	
All $X(0^+)$				$28\pm\ 5\pm\ 7$
$NR_{J/\psi\,\phi}$	6.4σ			$46\pm11\,^{+11}_{-21}$
$X(4500)$	6.1σ	$4506\pm11\,^{+12}_{-15}$	$92\pm21\,^{+21}_{-20}$	$6.6\pm2.4\,^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704\pm10\,^{+14}_{-24}$	$120\pm31\,^{+42}_{-33}$	$12\pm\ 5\,^{+\ 9}_{-\ 5}$





Pentaquarks studies

- Decay mode, not observed before, found to have large rates and low background
- Diagram a) expected to be dominated by $\Lambda^* \to K^- p$
- It could also have exotic contributions, as indicated by the diagram b)



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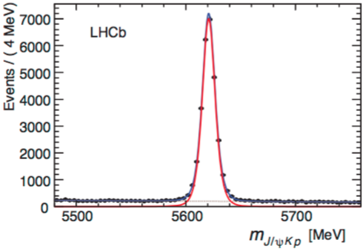
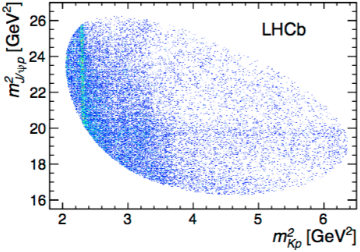
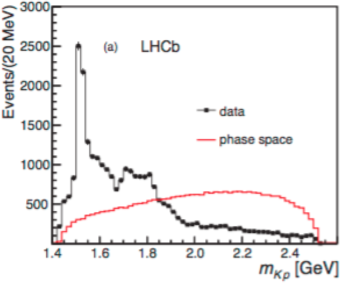
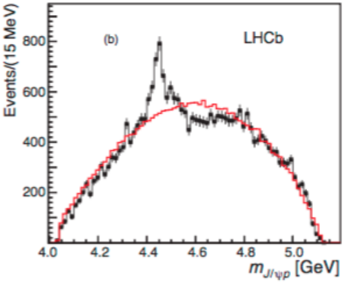
Clean signal of 26k candidates with 5.4% background ($\pm 2\sigma$) in Run1 data sample (3 fb^{-1})



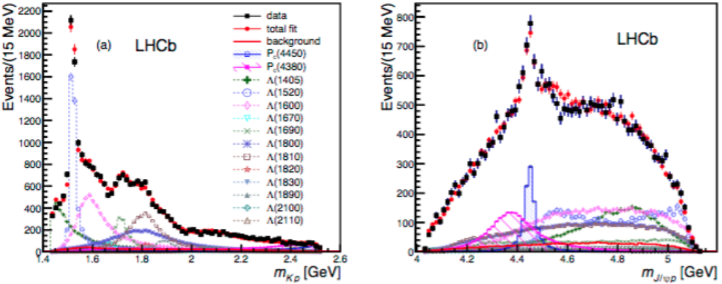






Amplitude model:

- 6-D amplitude fit
- two exotic states required to obtain an adequate fit

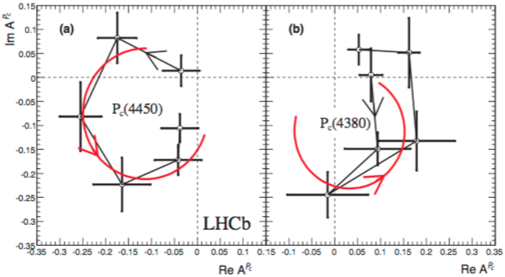


- Interference between two P_c of opposite parity required to explain the P_c decay angular distribution

	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass [MeV/c^2]	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width [MeV/c^2]	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Fit fraction [%]	$8.4 \pm 0.7 \pm 4.2$	$4.1 \pm 0.5 \pm 1.1$
Significance	9σ	12σ

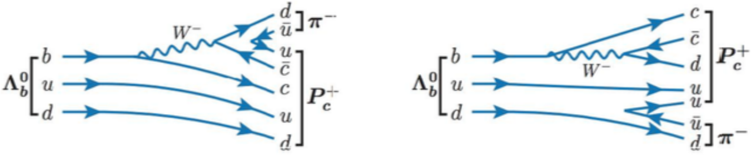
Combined significance $> 15\sigma$

Real and imaginary part of the amplitude determined independently in 6 bins between $M \pm \Gamma$

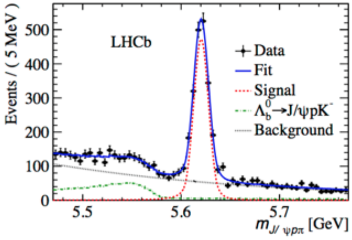


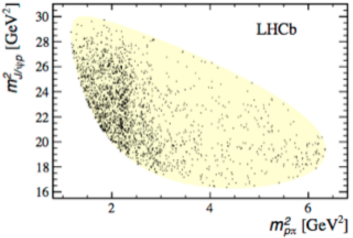
- The $P_c(4450)$ amplitude shows a phase variation consistent with what expected for a Breit-Wigner resonance
- Not conclusive for $P_c(4380)$ (more statistics needed)

Cabibbo-suppressed Λ_b^0 (observed by LHCb [JHEP 1407 (2014) 103]) decays to baryonic exotic resonances



Observing the same P_c^+ states in a different decay mode could indicate they are really resonances and not some kinematical effects [arXiv:1512.01959]





$N_s = 1885 \pm 50$

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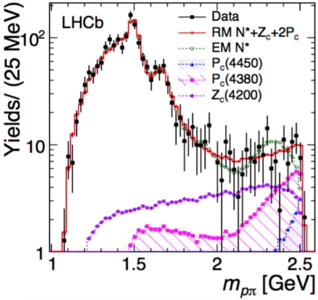
Perform 6-D amplitude analysis fit to interfering amplitudes

State	J^P	Mass (MeV)	Width (MeV)	RM	EM
NR $p\pi$	$1/2^-$	-	-	4	4
$N(1440)$	$1/2^+$	1430	350	3	4
$N(1520)$	$3/2^-$	1515	115	3	3
$N(1535)$	$1/2^-$	1535	150	4	4
$N(1650)$	$1/2^-$	1655	140	1	4
$N(1675)$	$5/2^-$	1675	150	3	5
$N(1680)$	$5/2^+$	1685	130	-	3
$N(1700)$	$3/2^-$	1700	150	-	3
$N(1710)$	$1/2^+$	1710	100	-	4
$N(1720)$	$3/2^+$	1720	250	3	5
$N(1875)$	$3/2^-$	1875	250	-	3
$N(1900)$	$3/2^+$	1900	200	-	3
$N(2190)$	$7/2^-$	2190	500	-	3
$N(2300)$	$1/2^+$	2300	340	-	3
$N(2570)$	$5/2^-$	2570	250	-	3
Free parameters				40	106

Include in the fit:

- All known N^* (Extended)
- Only well motivated (Reduced)
- Sample size limited: fix P_c and Z_c parameters when testing if their amplitudes are required
- The m($p\pi^-$) projection is adequately described by fits with N^* only
- Exotic components seem not required



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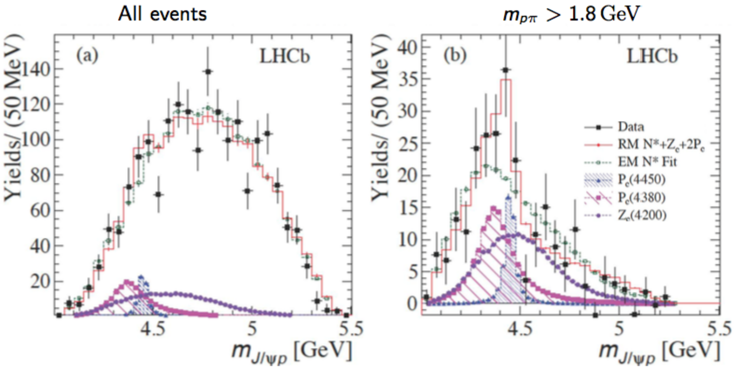
Fits including exotics



Exotic components are required for an acceptable fit in all regions of variable space

States	Fit fraction (%)
$P_c(4380)^+$	$5.1 \pm 1.5^{+2.1}_{-1.6}$
$P_c(4450)^+$	$1.6^{+0.8+0.6}_{-0.6-0.5}$
$Z_c(4200)^-$	$7.7 \pm 2.8^{+3.4}_{-4.0}$

None has individually large significance (AA limited by sample size)

I have reviewed a few selected recent results on spectroscopy of exotic states:

- Tetraquarks
  - Observation of exotic X & Z states
- Pentaquarks
  - Observation of $P_c(4450)^{\pm}$ and $P_c(4380)^{\pm} \to J/\Psi p$ in $\Lambda_b^0 \to J/\Psi p K^-$
  - Evidence for exotic hadrons in $\Lambda_b^0 \to J/\Psi p \pi^-$
    - Limited by statistics
- LHCb is providing a wealth of results on hadron physics (still a lot to understand)
- Still a lot of new data to be analized!

Greetings from Honduras!!!

Come visit us!!!

El Zamorano

Honduras is at the heart of America and El Zamorano University is at the heart of Honduras

Zamorano is an international university that offers young people from different countries and backgrounds the opportunity to become professionals - leaders - with skills and values, capable of transforming companies and organizations that respond to current challenges in Latin America and the world.

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mersi
kia ora
barka
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Backup

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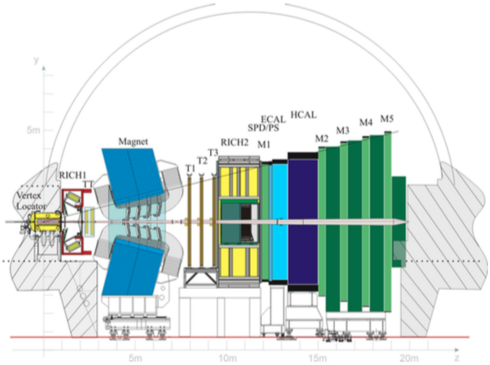
A one-arm spectrometer detecting *B*- and *D*-mesons after $p - p$ collisions [Int.J.Mod.Phys. A30 (2015) no.07, 1530022]



- ☐ Flavor Physics
- ☐ Rare decays
- ☐ (Exotic) spectroscopy

LHCb Detectors:

1. VELO
2. TT Stations
3. Magnet
4. RICH
5. Calorimeters
6. Muon Station

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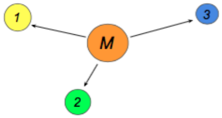


$M \to 1 + 2 + 3$

Invariants:

- $\vec{p}_i$: 9 observables
- 4–momentum $(E, \vec{p})$ conservation $P = \sum_{i=1}^{3} p_i$
- spinless particles: isotropy
- 2 variables to describe the decay

Invariants:

- $s = P^2 = M^2$
- $s_{12} = (p_1 + p_2)^2$
- $s_{23} = (p_2 + p_3)^2$
- $s_{13} = (p_3 + p_1)^2$

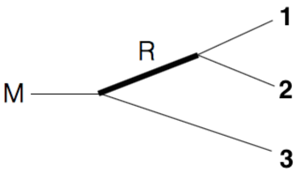
$$B^0 \to \Psi(2S)\pi^+K^- \Longrightarrow (s_{12}, s_{13})$$

Isobar Model in $B^0 \to \Psi(2S)\pi^+ K^-$: coherent sum of interfering resonances

$$\mathcal{M} = a_{NR} e^{i\delta_{NR}} + \sum_i a_i e^{i\delta_i} \mathcal{A}_i(s_{12}, s_{13})$$

$$\mathcal{A}_i = \underbrace{F_D F_{R_i}}_{form\ factors} \times \underbrace{\mathcal{M}_i^J}_{angular\ fuction} \times \underbrace{\mathcal{BW}_i}_{lineshape-propagator}$$

a_{NR}, δ_{NR} assumed to be constant



- Example $B^0 \to \Psi(2S)\pi^- K^+$:
  - $B^0 \to \Psi(2S)\ K^{*0}$, $K^{*0} \to K^+\pi^-$

Isobar Model formalism (Breit-Wigner)

J	$F^J_{R,D}(p^*,p^*_0)$
0	1
1	$\sqrt{\frac{1+z_0}{1+z}}$
2	$\sqrt{\frac{(z_0-3)^2+9z_0}{(z-3)^2+9z}}$

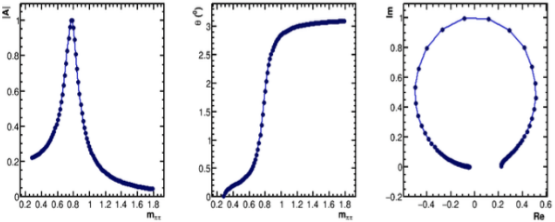
$$\mathcal{BW}_i = \frac{1}{m_r^2 - s_{12} - i m_r \Gamma(\sqrt{s_{12}})}$$

$$\Gamma(\sqrt{s_{12}}) = \Gamma_r \left(\frac{p^*}{p^*_0}\right)^{2J+1} \frac{m_r}{\sqrt{s_{12}}} \left(\frac{F^J_{R,D}(z)}{F^J_{R,D}(z_0)}\right)^2$$

$z = (p^* d)^2$ and $z_0 = (p^*_0 d)^2$,

p^*: decay momentum in **12** rest frame.

p^*_0: p^* calculated at m_r.



Circular trajectory in complex plane & phase change of 180^0 across the pole is characteristic of resonance