Exotics as measured at hadron colliders

Sheldon Stone on behalf of LHCb, including results from other collaborations

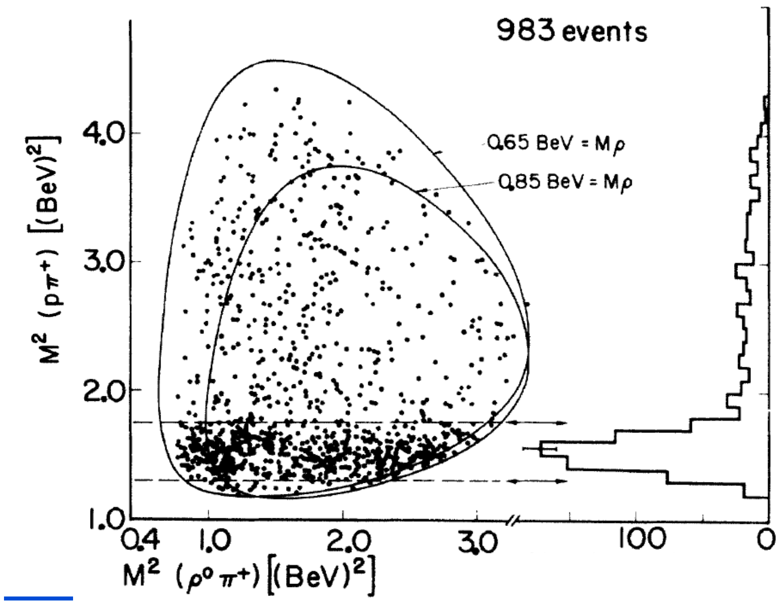
FPCP Naygoya, May 2015

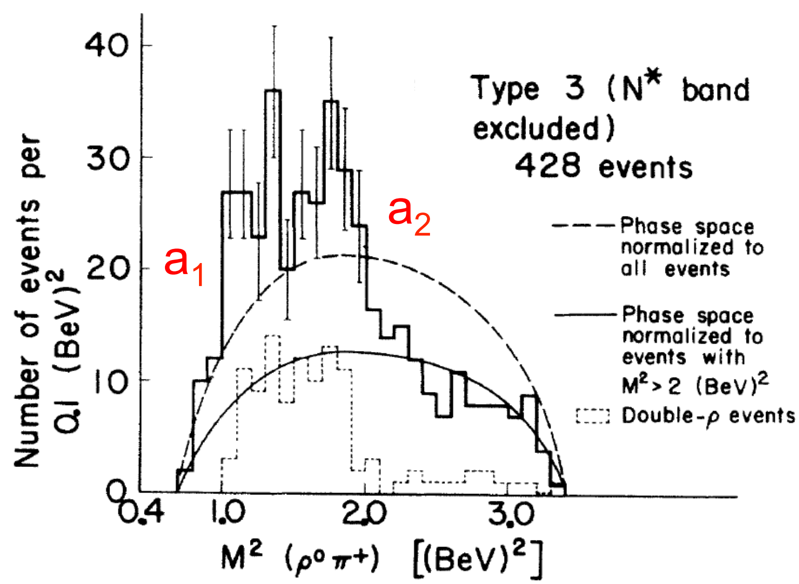
Introduction

- Interest in “exotics” arises from the fact that they would be new states of matter beyond the simple quark picture. Specifically, tetraquark mesons or pentaquark baryons, perhaps glueballs or hybrid states $q\bar{q}g$.
- These would be short-lived ~10^{-23} s “resonances” whose presences is detected by mass peaks and angular distributions showing the presence of unique J^{PC} quantum numbers

Some History: The a_1

- It is also 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)*

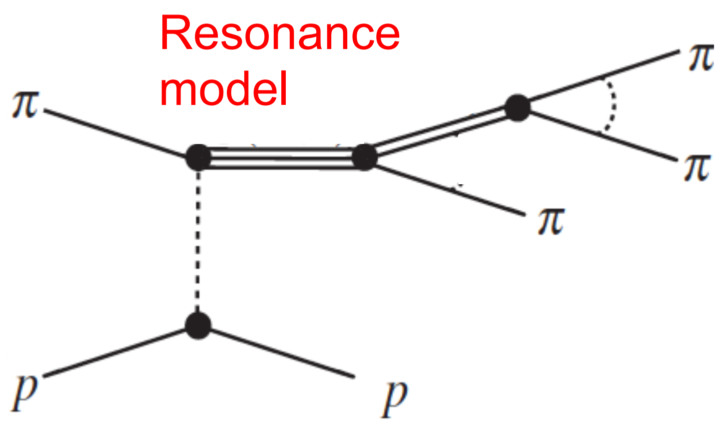


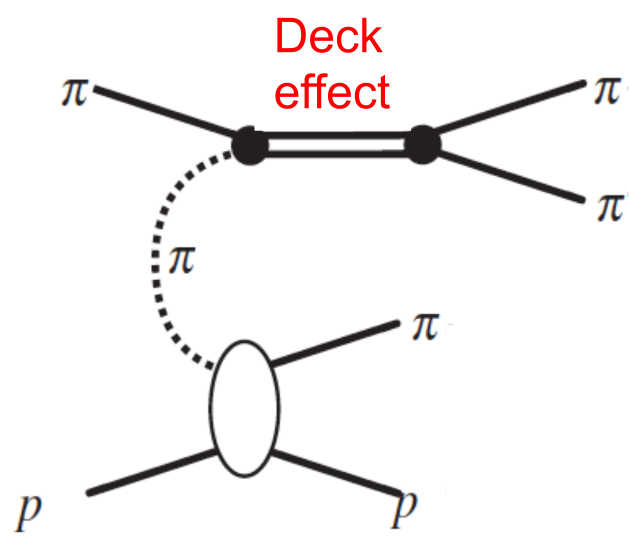


Note BeV≡GeV

"Kinematical" effect

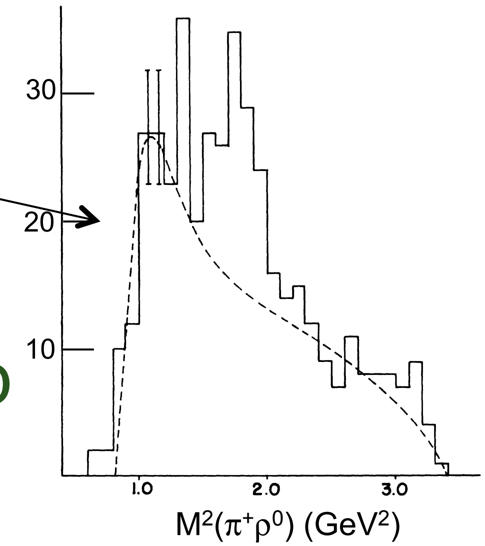
- Clear enhancement near threshold. Is it a new resonance as suggested in original paper?
- Theorists, first Deck, suggest that the threshold enhancement can be due to off shell πp scattering *R.T. Deck, PRL 13, 169 (1964)*





Deck Effect

- Deck's fit to data can provide adequate explanation



- a_1 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
- Lesson: a real state should be seen in several ways. Even though the a_1 is a real state, the Deck effect has to be there to some extent. Likely both are present in hadron production experiments

Scalar meson quandry

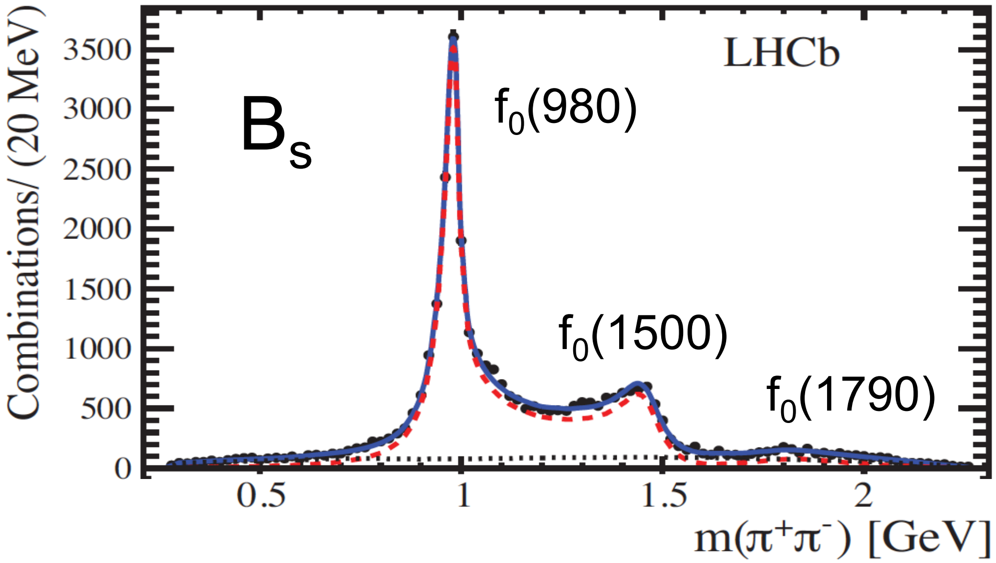
- While 0^- and 1^- mesons follow a simple rule that adding an s-quark increases their mass, the 0^+ mesons are difficult to understand in this context

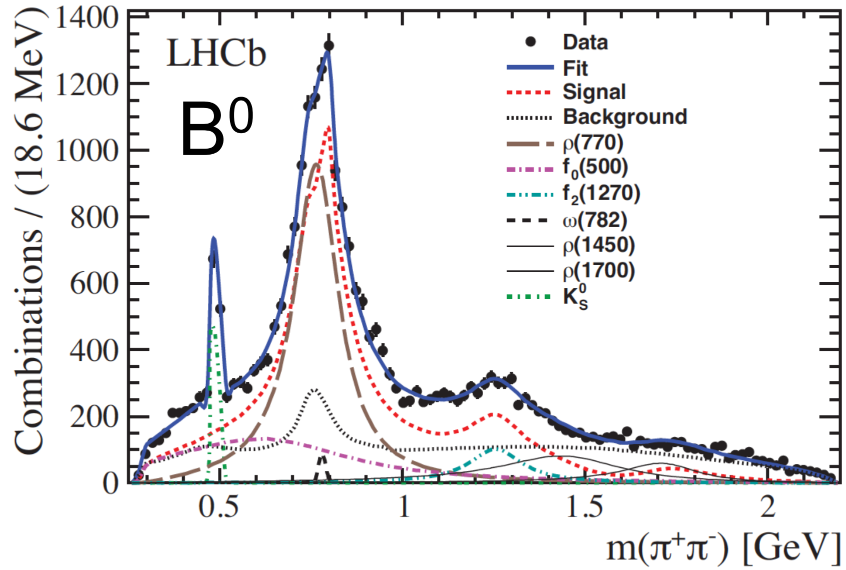
Isospin	1^- state	mass	$q\bar{q}$	0^+ state	mass
1	ρ	776 MeV	$(u\bar{u}+d\bar{d})\sqrt{2}$	$a_0(980)$	980 MeV
0	ω	783 MeV	$(u\bar{u}-d\bar{d})\sqrt{2}$	$f_0(500)$ or **σ**	500 MeV
1/2	K*(892)	892 MeV	(u or d) $\bar{s}$	κ(800)	800 MeV
0	ϕ	1020 MeV	$s\bar{s}$	$f_0(980) \equiv f_0$	980 MeV

- σ & $f_0(980)$ may be mixed by angle ϕ
- Suggestions that scalars are tetraquarks

$B \rightarrow J/\psi \pi^+ \pi^-$ decays

- LHCb data arXiv:1402.6248 arXiv:1404.5673

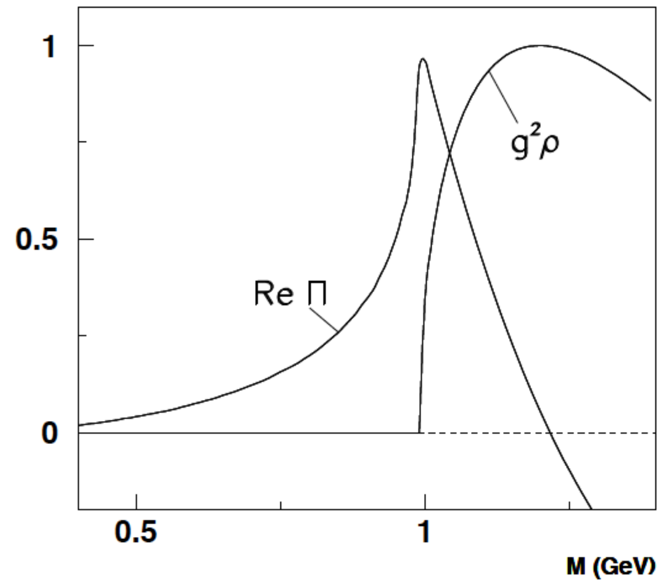




- Note large $f_0(980)$ in B_s & $f_0(500) \equiv \sigma$ in B^0
- Why is $f_0(980)$ so narrow? The mass is very close to threshold for K^+K^-, coupled channel decay into $\pi\pi$ & KK was parameterized by Flatte′

Thresholds & cusps

- In the context of a coupled channel model by Törnqvist, Bugg, arXiv: 0802.0934 has shown that the presence of a threshold can narrow down a resonance. The resonance is real, its structure is not important.



- Others have argued that the thresholds can mimic resonances. (See Swanson arXiv: 1409.3291). Even create a ~90^0 phase shift in Argand plane (Bugg arXiv:1105.5492)

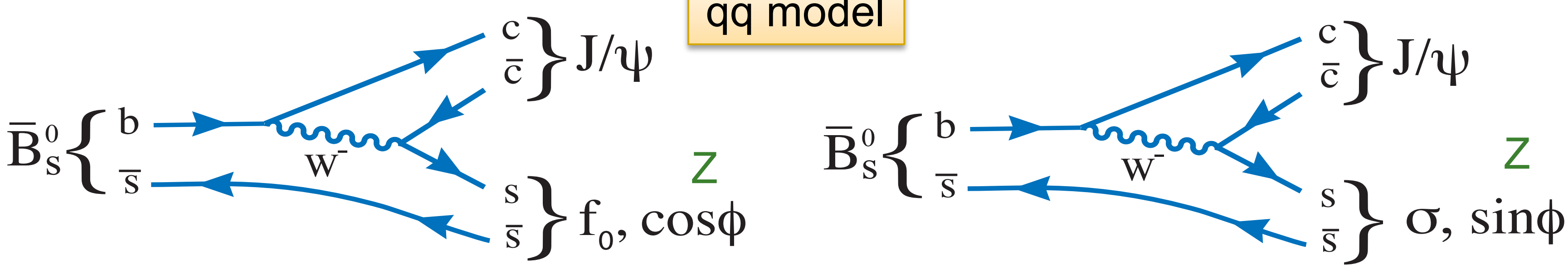
B_s decay diagrams

$$\Gamma(\bar{B}^0_s \to J/\psi f) = C \left| F^f_{B_s}\left(m^2_{J/\psi}\right) \right|^2 \left|V_{cs}\right|^2 \Phi Z^2$$

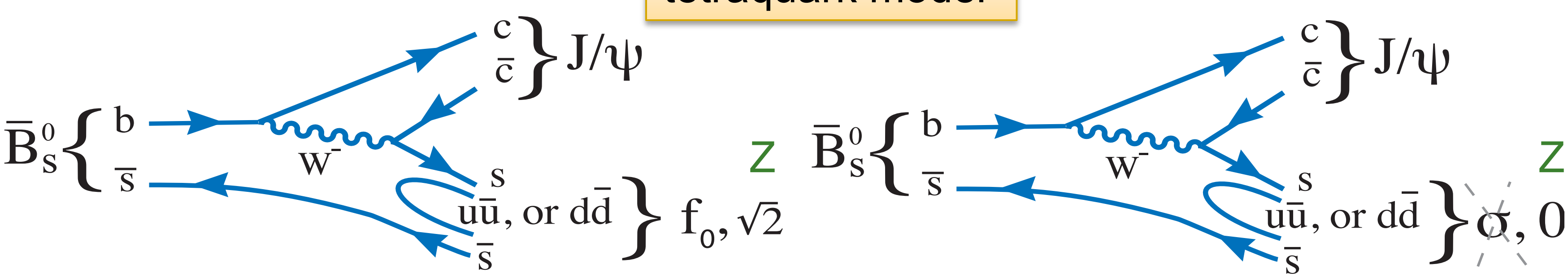
form factor — phase space — coupling

Stone & Zhang arXiv:1305.6554

qq̄ model



tetraquark model

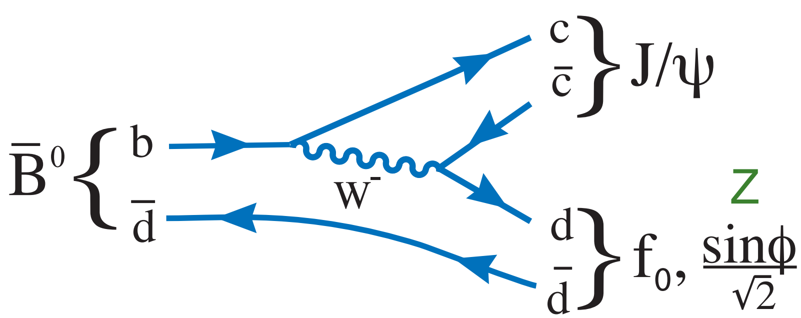


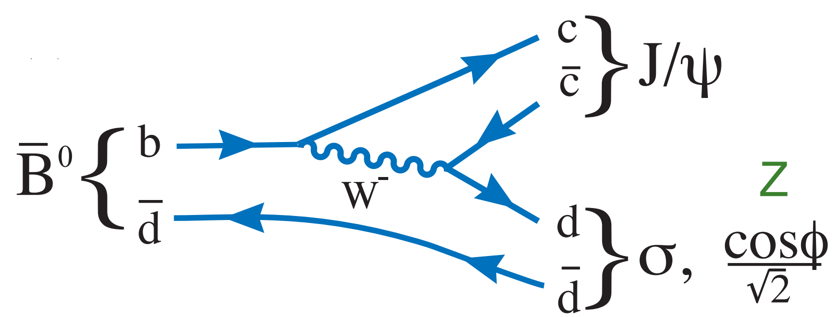
First prediction: If σ is a tetraquark it will not be seen in $B_s \to J/\psi\sigma$

B^0 decay diagrams

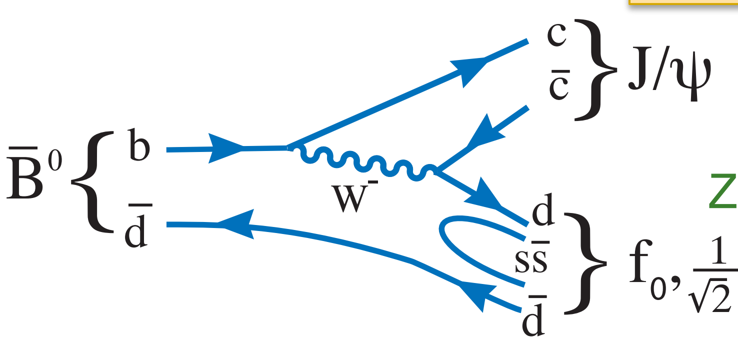
$$\Gamma(\bar{B}^0 \to J/\psi f) = C\left|F^f_{B^0}\left(m^2_{J/\psi}\right)\right|^2 \left|V_{cd}\right|^2 \Phi Z^2$$

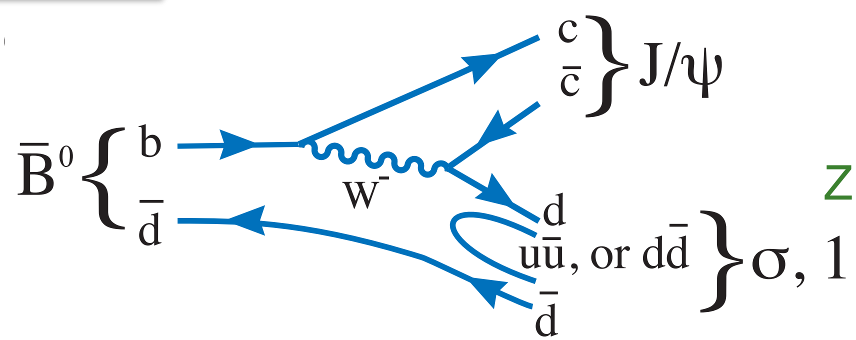
qq̄ model





tetraquark model





Rate ratios

Label	Mode ratio	Rate ratio	$\mathcal{Z}^2$ $q\bar{q}$	$\mathcal{Z}^2$ tetraquark
$r^{0f_0}_{sf_0}$	$\frac{\Gamma(\bar{B}^0 \to J/\psi\, f_0)}{\Gamma(\bar{B}^0_s \to J/\psi\, f_0)}$	$= \frac{\lvert F^{f_0}_{B^0}(m^2_{J/\psi})\rvert^2}{\lvert F^{f_0}_{B^0_s}(m^2_{J/\psi})\rvert^2} \frac{\lvert V_{cd}\rvert^2 \Phi^{f_0}_{B^0}}{\lvert V_{cs}\rvert^2 \Phi^{f_0}_{B^0_s}}$	$\frac{1}{2}\tan^2\phi$	$\frac{1}{4}$
$r^{0f_0}_{0\sigma}$	$\frac{\Gamma(\bar{B}^0 \to J/\psi\, f_0)}{\Gamma(\bar{B}^0 \to J/\psi\, \sigma)}$	$= \frac{\lvert F^{f_0}_{B^0}(m^2_{J/\psi})\rvert^2}{\lvert F^{\sigma}_{B^0}(m^2_{J/\psi})\rvert^2} \frac{\Phi^{f_0}_{B^0}}{\Phi^{\sigma}_{B^0}}$	$\tan^2\phi$	$\frac{1}{2}$
$r^{s\sigma}_{sf_0}$	$\frac{\Gamma(\bar{B}^0_s \to J/\psi\, \sigma)}{\Gamma(\bar{B}^0_s \to J/\psi\, f_0)}$	$= \frac{\lvert F^{\sigma}_{B^0_s}(m^2_{J/\psi})\rvert^2}{\lvert F^{f_0}_{B^0_s}(m^2_{J/\psi})\rvert^2} \frac{\Phi^{\sigma}_{B^0_s}}{\Phi^{f_0}_{B^0_s}}$	$\tan^2\phi$	0
$r^{sf_0}_{0\sigma}$	$\frac{\Gamma(\bar{B}^0_s \to J/\psi\, f_0)}{\Gamma(\bar{B}^0 \to J/\psi\, \sigma)}$	$= \frac{\lvert F^{f_0}_{B^0_s}(m^2_{J/\psi})\rvert^2}{\lvert F^{\sigma}_{B^0}(m^2_{J/\psi})\rvert^2} \frac{\lvert V_{cs}\rvert^2 \Phi^{f_0}_{B^0_s}}{\lvert V_{cd}\rvert^2 \Phi^{\sigma}_{B^0}}$	2	2

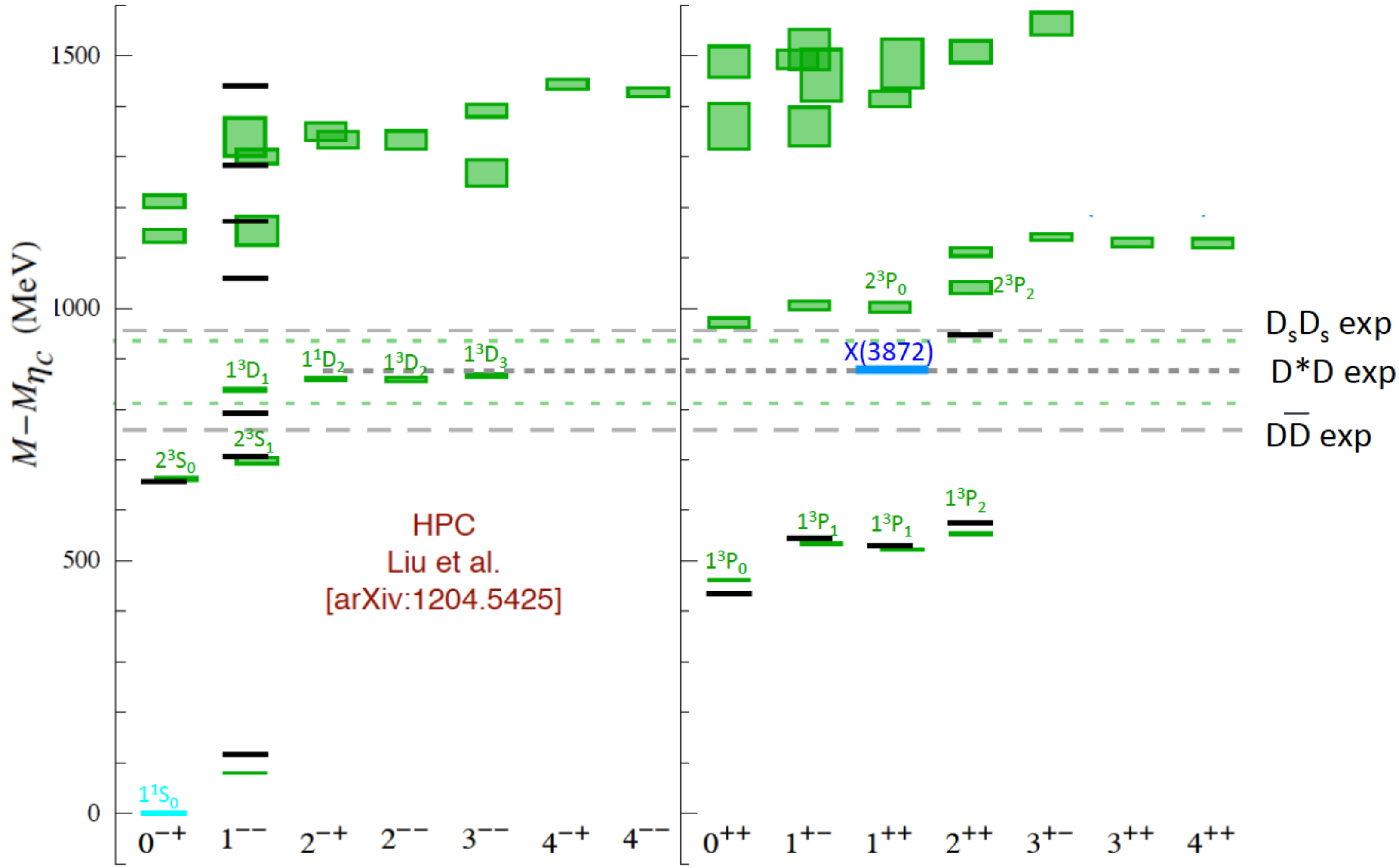
Last ratio is independent of model, allows measurement of form factor ratio of $0.99^{+0.13}_{-0.04}$

LHCb results

- $r_{0\sigma}^{0f_0}$<0.098 @ 90% cl, should be ½ for tetraquark, suggests the f_0 & σ are $q\bar{q}$ states
- Possible deviations caused by tetraquark mixing, isospin violation, etc…
- If $q\bar{q}$, mixing angle $|\phi|$ <17^o at 90% cl arXiv: 1404.5673

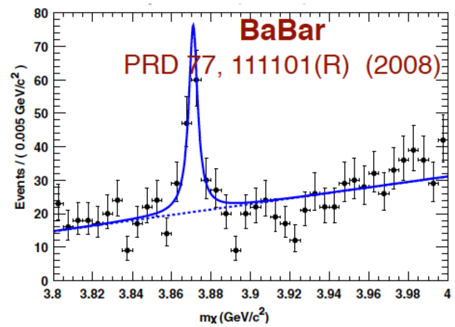
Charmonium like exotics

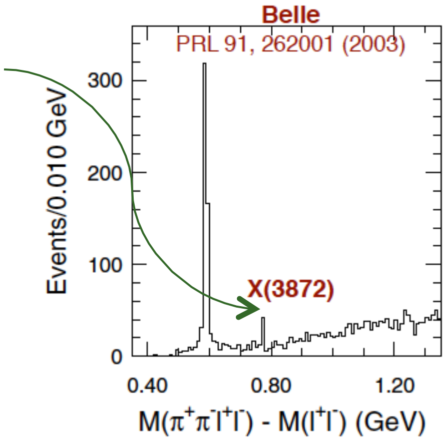
Predicted states and measurements



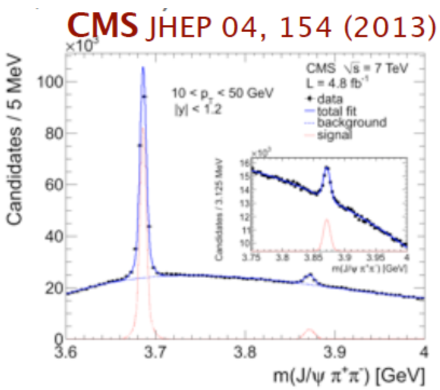
X(3872)

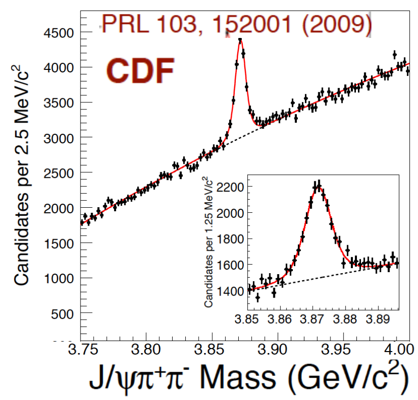
- First seen by Belle using B→$(J/\psi\pi^+\pi^-)K$

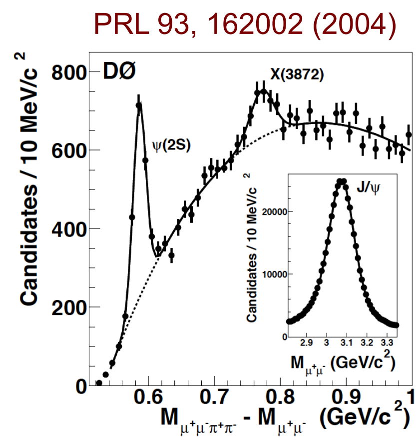




- Confirmed by BaBar
- Observed in direct production by CDF, D0 CMS, & LHCb







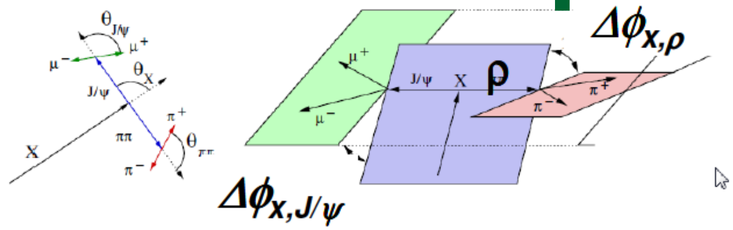
- At $D^{*0}D^0$ threshold: Δm=-0.17±0.26 MeV

Properties

- Decay modes: $J/\psi\pi^+\pi^-$ dominated by ρ^0, also seen in $J/\psi\gamma$, $\psi'\gamma$, which implies C=+, $D^{*0}D^0$ where the mass appears to be higher and the width larger (For other modes Γ<1.2 MeV, but here $\Gamma = 3.4^{+1.7}_{-1.2}$ MeV)
- What is its internal structure? $q\bar{q}$ charmonium state, tetraquark state, molecular state binding D^{*0} & D^0 but would have large size due to weak binding 0.17±0.26 MeV
- J^{PC} measured by CDF to be 1^{++} or 2^{-+} [hep-ex/0612053]. New measurements by LHCb

LHCb full amplitude analysis

$B^+ \to X(3872) K^+$, $X(3872) \to J/\psi\, \pi^+\pi^-$, $J/\psi \to \mu^+\mu^-$



5 independent angles describing the decay in helicity formalism

$$|\mathcal{M}(\Omega|J_X)|^2 = \sum_{\Delta\lambda_\mu=-1,+1} \Big| \sum_{\lambda_{J/\psi},\lambda_\rho=-1,0,+1} A_{\lambda_{J/\psi},\lambda_\rho} \times D^{J_X}_{0,\lambda_{J/\psi}-\lambda_\rho}(0,\theta_X,0)^* \times D^1_{\lambda_\rho,0}(\Delta\phi_{X,\rho},\theta_\rho,0)^* \times D^1_{\lambda_{J/\psi},\Delta\lambda_\mu}(\Delta\phi_{X,J/\psi},\theta_{J/\psi},0)^* \Big|^2$$

Matrix element

$$A_{\lambda_{J/\psi},\lambda_\rho} = \sum_L \sum_S B_{LS} \times \begin{pmatrix} J_{J/\psi} & J_\rho \\ \lambda_{J/\psi} & -\lambda_\rho \end{pmatrix}\Bigg| \begin{matrix} S \\ \lambda_{J/\psi}-\lambda_\rho \end{matrix} \Bigg) \times \Bigg(\begin{matrix} L & S \\ 0 & \lambda_{J/\psi}-\lambda_\rho \end{matrix} \Bigg| \begin{matrix} J_X \\ \lambda_{J/\psi}-\lambda_\rho \end{matrix} \Bigg)$$

Relation of the helicity couplings to LS amplitudes

$$P_X = P_{J/\psi}\, P_\rho\, (-1)^L = (-1)^L$$

Parity conservation

J^{PC}	B_{LS} all L	B_{LS} minimal L
0^{-+}	B_{11}	B_{11}
0^{++}	B_{00}, B_{22}	B_{00}
1^{-+}	$B_{10}, B_{11}, B_{12}, B_{32}$	B_{10}, B_{11}, B_{12}
1^{++}	B_{01}, B_{21}, B_{22}	B_{01}
2^{-+}	$B_{11}, B_{12}, B_{31}, B_{32}$	B_{11}, B_{12}
2^{++}	$B_{02}, B_{20}, B_{21}, B_{22}, B_{42}$	B_{02}
3^{-+}	$B_{12}, B_{30}, B_{31}, B_{32}, B_{52}$	B_{12}
3^{++}	$B_{21}, B_{22}, B_{41}, B_{42}$	B_{21}, B_{22}
4^{-+}	$B_{31}, B_{32}, B_{51}, B_{52}$	B_{31}, B_{32}
4^{++}	$B_{22}, B_{40}, B_{41}, B_{42}, B_{62}$	B_{22}

LHCb 2015 (all L) — Many more amplitudes to fit

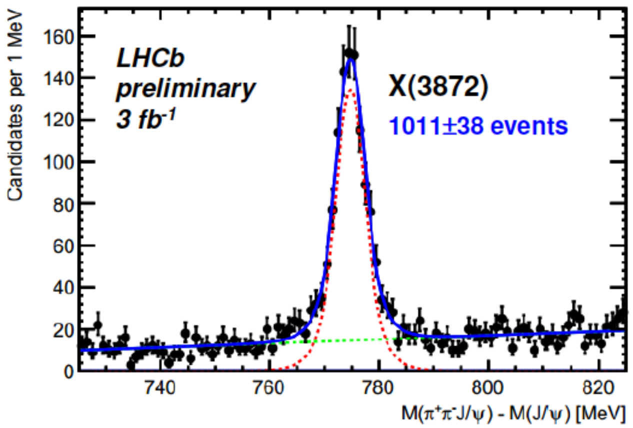
CDF 2007 (minimal L, 0^{-+} to 3^{-+})

LHCb 2013 (1^{++}, 2^{-+} minimal L)

LS amplitudes to be determined from the data

J^{PC}

- LHCb data (3/fb)



- State is only 1^{++} with mainly S-wave decay

arXiv:1504.06339

Results

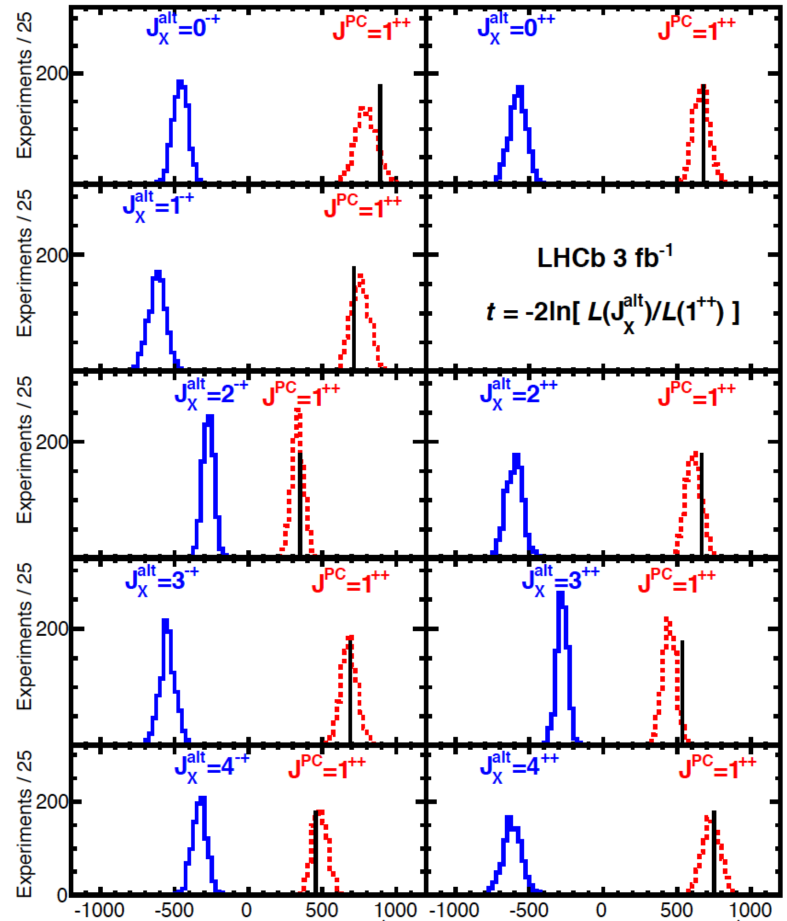
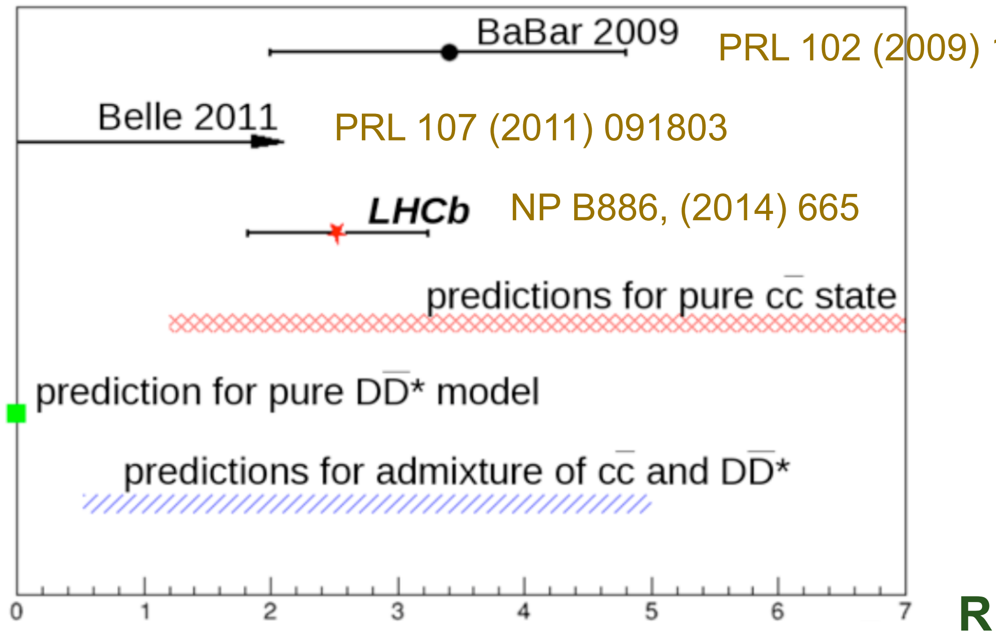
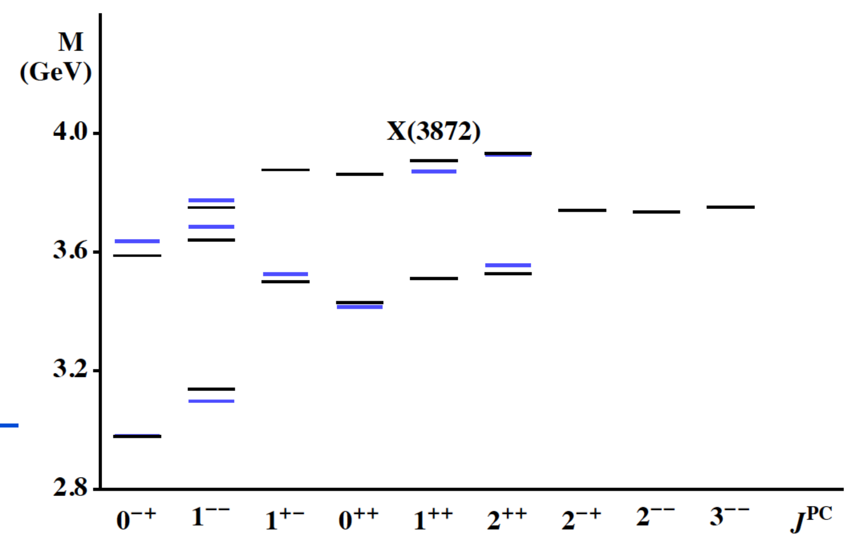


Figure 3: Distributions of the test statistic $t \equiv -2\ln[\mathcal{L}(J_X^{\rm alt}))/\mathcal{L}(1^{++})]$, for the simulated experiments under the $J^{PC} = J_X^{\rm alt}$ hypothesis (blue solid histograms) and under the $J^{PC} = 1^{++}$ hypothesis (red dashed histograms). The values of the test statistics for the data, $t_{\rm data}$, are shown by the solid vertical lines.

$R \equiv \Gamma(X \to \psi' \gamma)/\Gamma(X \to J/\psi)$

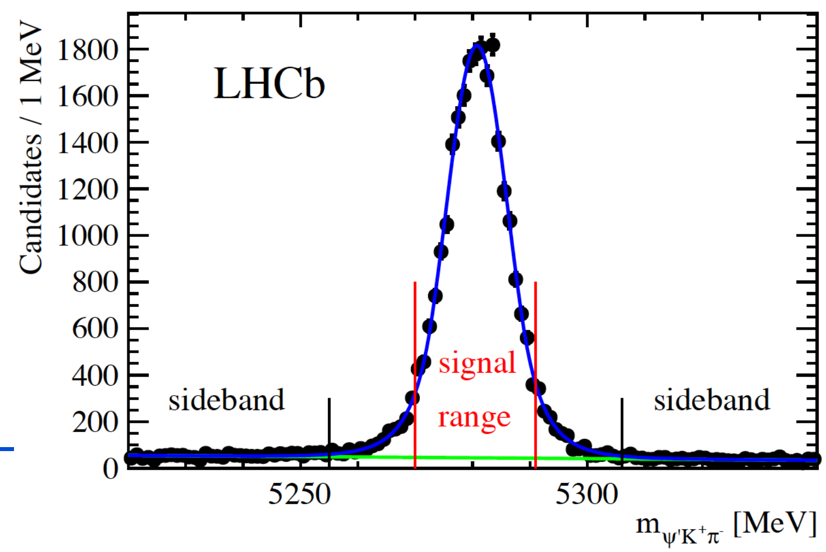
- Rules out molecular interpretation
- Consistent with $c\bar{c}$ state where the presence of the threshold has lowered the mass & width





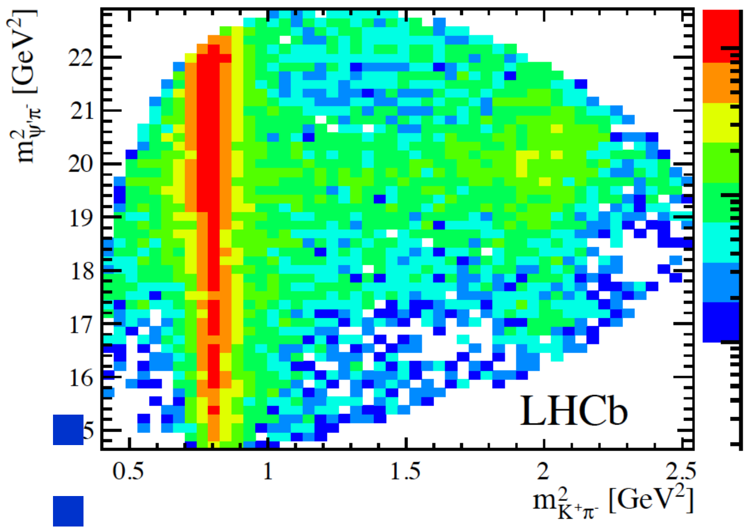
$Z_c(4430)$, M=4479 MeV

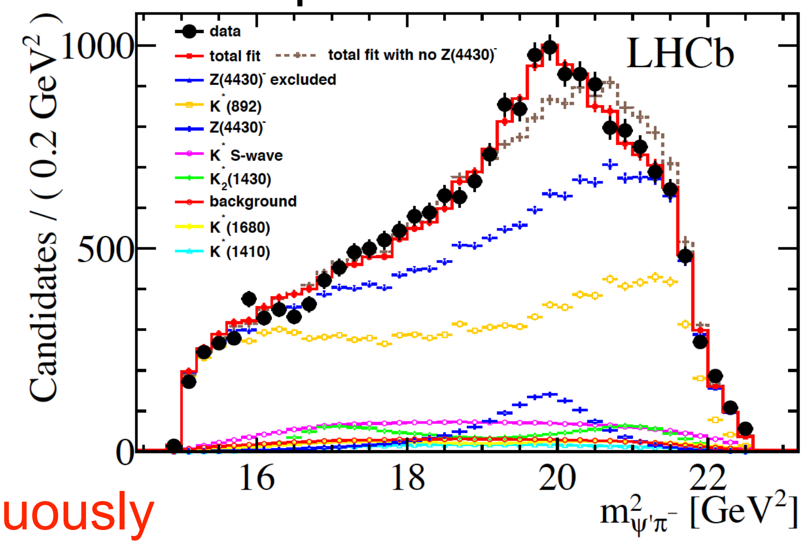
- $B^0 \to \psi' \pi^- K^+$, peak in $m(J/\psi\pi^-)$, charged charmonium state must be exotic, not $q\bar{q}$
  - First observed by Belle M=4433±5 MeV, Γ=45 MeV
  - Debunked by Babar: explanation in terms of K*'s
  - Belle reanalysis using full amplitude fit: M= $4485 \pm 22^{+28}_{-11}$ MeV, Γ=200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



LHCb Amplitude analysis

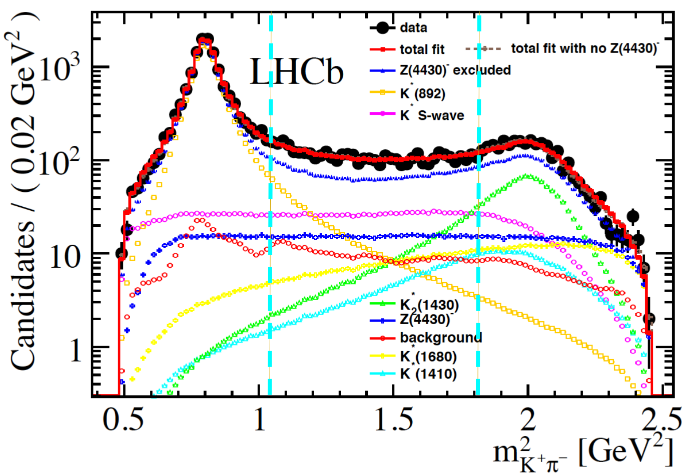
- Full 4D fit to both $K^* \to K^- \pi^+$ & $Z \to \psi' \pi^-$ states

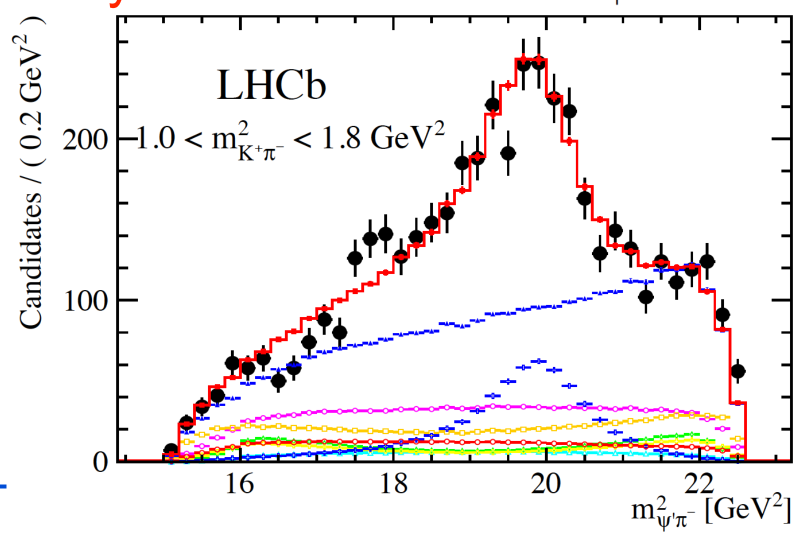




$J^P=1^+$

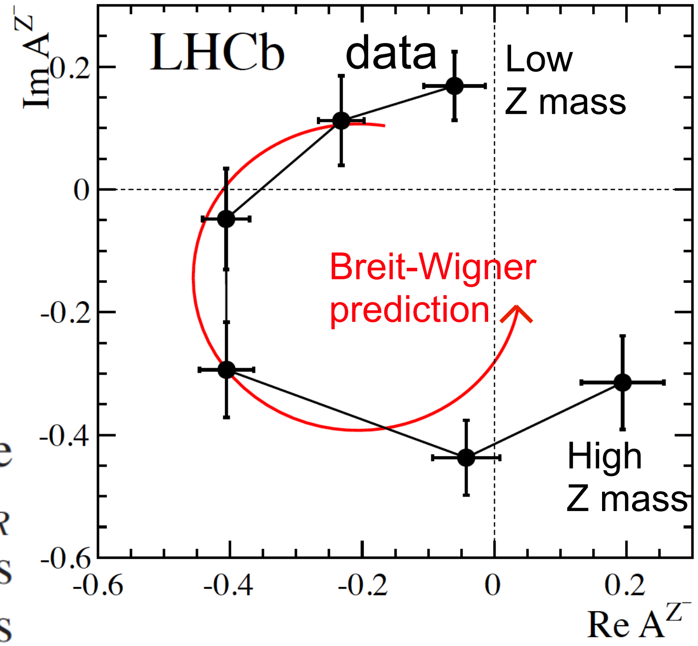
Unambiguously





Is it a resonance?

- LHCb produces Argand plot that shows a clear & large change in phase
- Problem with quoted mass



In the default fit, we follow the approach of Belle that uses a running mass M_R in the $(p_R/M_R)^{L_R}$ term, where M_R is the invariant mass of two daughters of the R resonance; p_R is the daughter's momentum in the rest frame of R and L_R is the orbital angular momentum of the decay. The more conventional formulation PDG is to use $p_R^{L_R}$ (equivalent to a fixed M_R mass). This changes the Z_1^- parameters via the K^* terms in the amplitude model: $M_{Z_1^-}$ varies by -22 MeV, $\Gamma_{Z_1^-}$ by $+29$ MeV,

← From LHCb paper

Believe now that old formula is wrong: m_Z=4456 MeV, Belle – LHCb average

Other Explanations

- Molecule:

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

T. Barnes et.al, [arXiv:1409.6651

- Same scattering phase

as Breit-Wigner

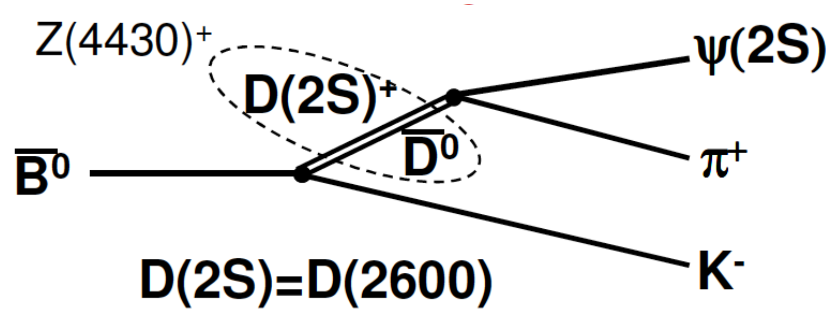
- Rescattering:

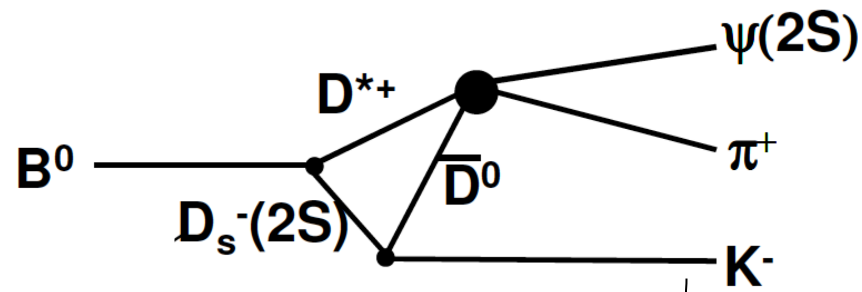
P. Pakhov & T. Uglov

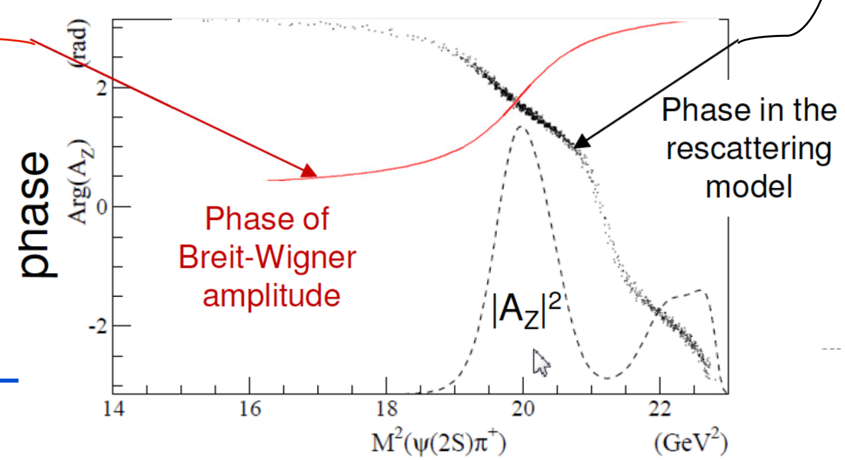
[arXiv:1408:5295]

- Opposite phase
- Ruled out by LHCb

Argand diagram

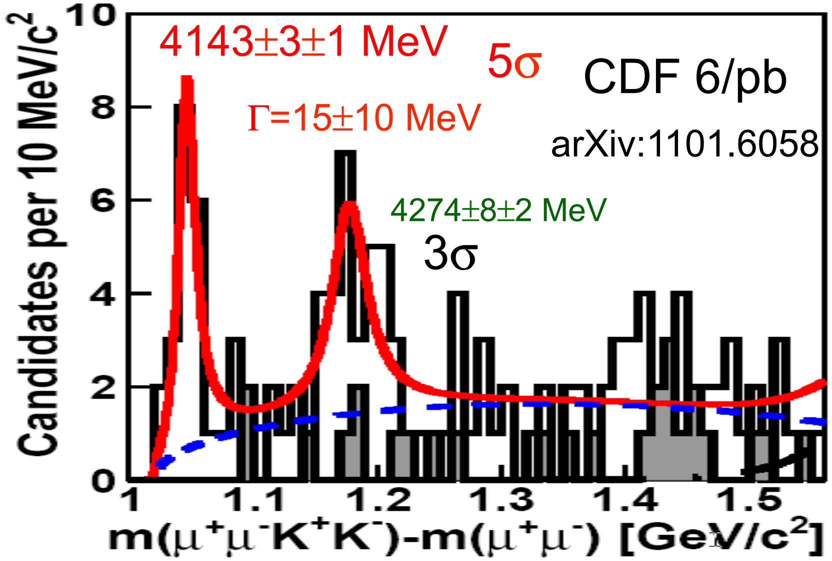


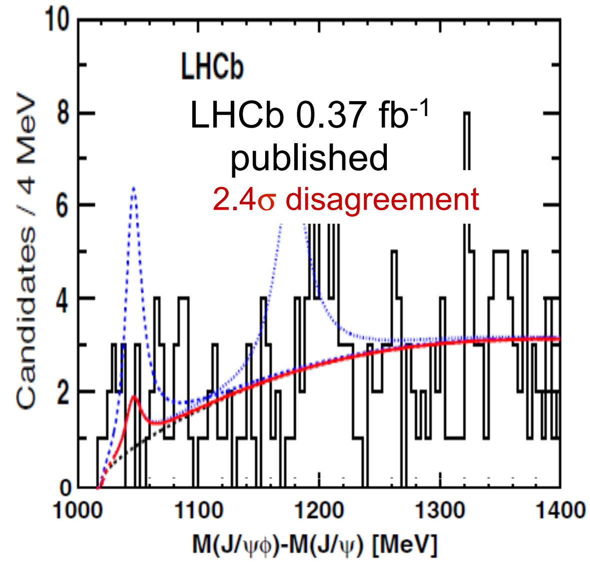




X(4140)

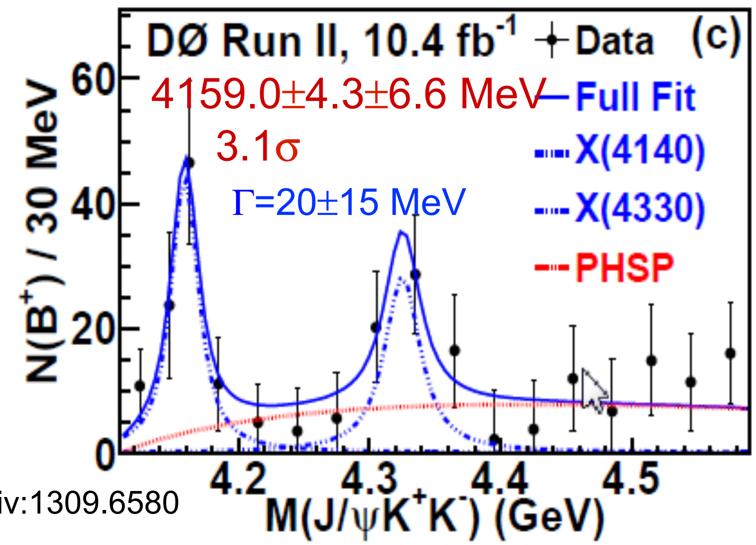
- $B^+ \to J/\psi\phi K^+$ peaks 1st seen by CDF



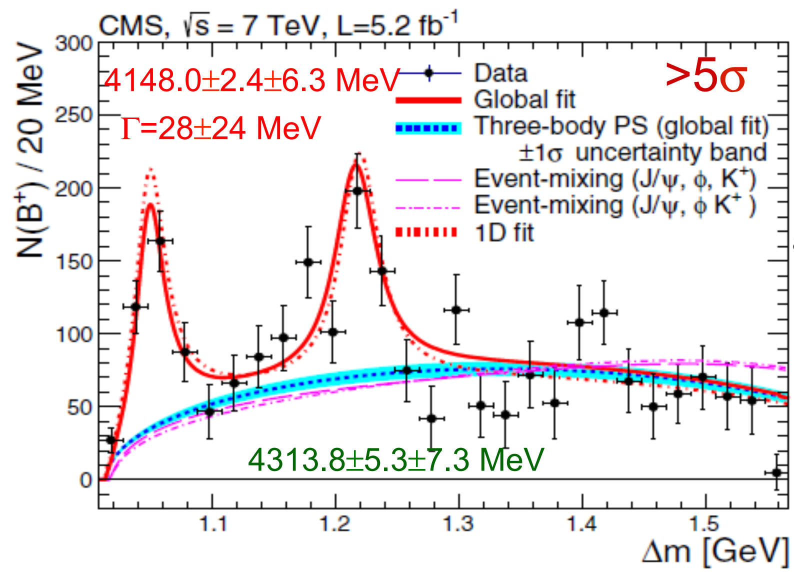


arXiv:1202.5087

Waiting for full amplitude Analysis!



arXiv:1309.6580

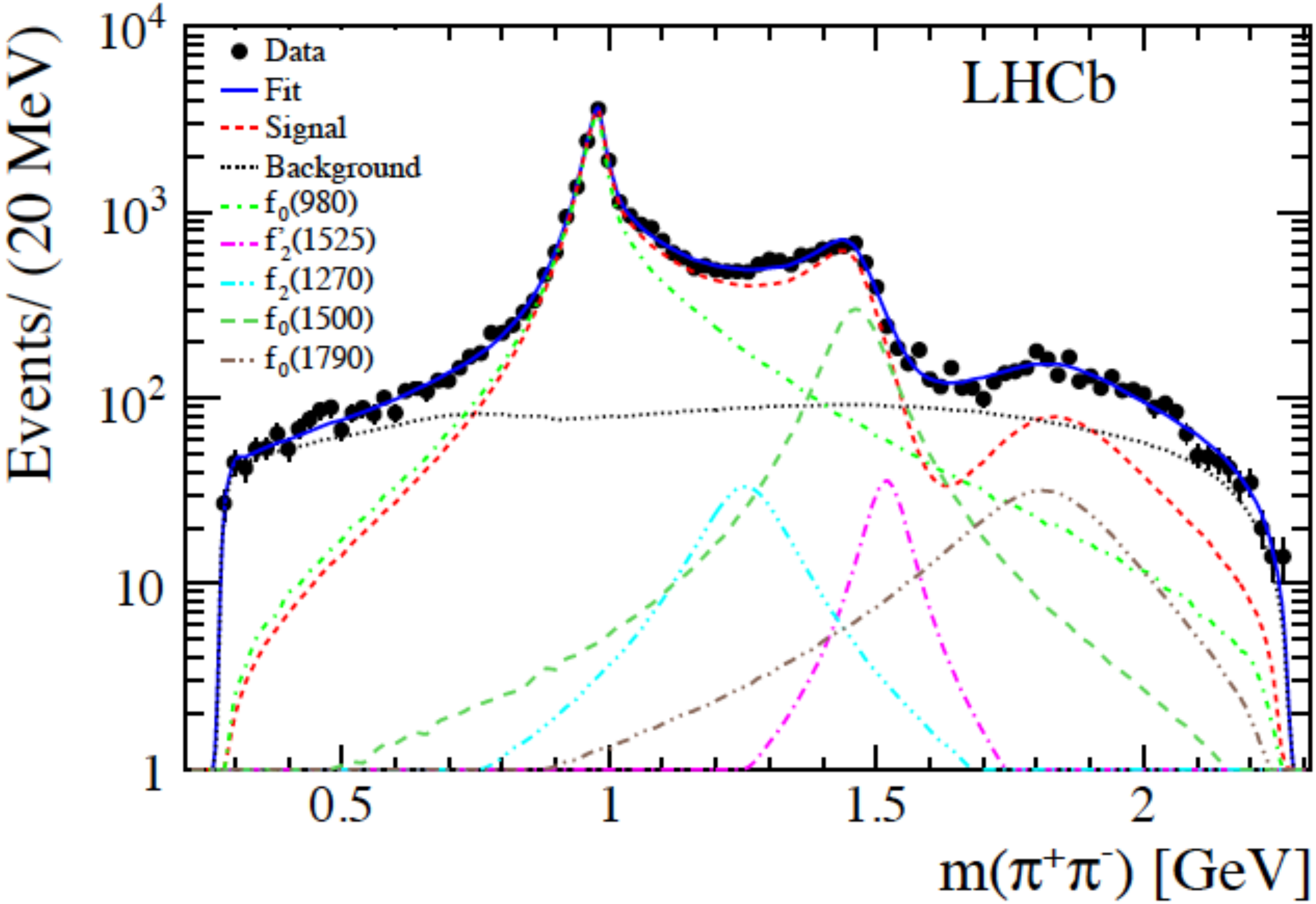


arXiv:1309.6920

Conclusions

- Many new effects seen in data by all heavy flavor experiments that are exotic meson candidates
- Different interpretations offered. Some involve threshold "cusps" that produce effects in the $f_0(980)$ & X(3872), though both of these are likely to be $q\bar{q}$ states
- The $Z^+(4430)$ appears to be a viable exotic
- We look forward to establishing the structure of many other states

The End



FPCP Nagoya, May 2015