Exotic meson candidates from amplitude analyses of B meson decays

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Workshop on Exotic Hadrons

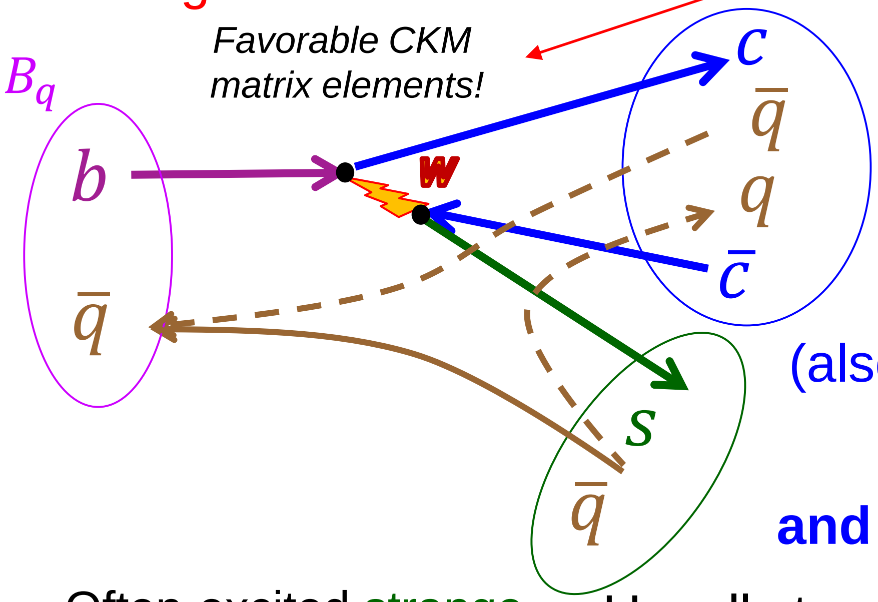
ICNFP2017, **Κολυμβάρι,** Ελλάδα, 21-23 August 2017

Decays of b hadrons as a source of charmonium(-like) states

Weak decay
→ long lifetime

The best trigger gateway at hadronic colliders

Favorable CKM matrix elements!



Source of charmonium states $c\bar{c}$:
$\psi(n^3S), \chi_{cJ}(n^3P), \eta_c(n^1S), h_c(n^1P)$

Easiest to detect: $J/\psi, \psi(2S) \to \mu^+\mu^-, e^+e^-$
then: $\chi_{c1} \to \gamma J/\psi$

(also of charmed meson-antimeson pairs $c\bar{q} + \bar{c}q$)

Dominate the decay rate

and of charmonium-like exotics $c\bar{c}q\bar{q}, \{c\bar{c}qqq\}$:
Usually tagged by decays to charmonium ($\to c\bar{c}$ + light hadrons),
while above the open charm threshold ($\to c\bar{q} + \bar{c}q$)

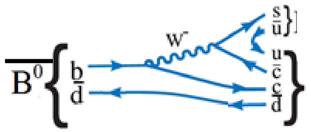
Smaller contributions

Often-excited strange meson {baryon} decaying to
K $\{\Lambda\}$+ light hadrons

Strangeness in the final state helps background suppression, especially at LHCb

Lead to the same final states:
unless the exotic state is super narrow *(the X(3872) is the only case!)*,
difficulty in resolving the conventional and the exotic contributions;
a sophisticated amplitude analysis is necessary!

Discovery of Z(4430)$^+$

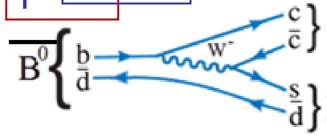


K$^-$

$Z_c^+ \rightarrow \psi' \pi^+$

Z_c^+ K*

$B \rightarrow \psi' \pi^+ K$



ψ'

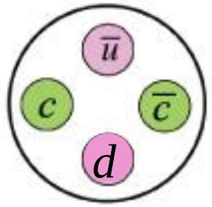
$K^{*0} \rightarrow K^- \pi^+$

Belle 2008

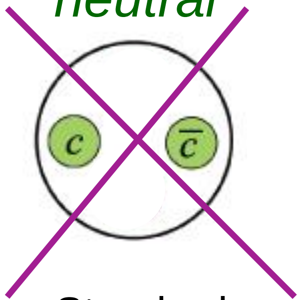
PRL 100, 142001 (2008)

First charged charmonium-like state discovered!

charged *neutral*



not



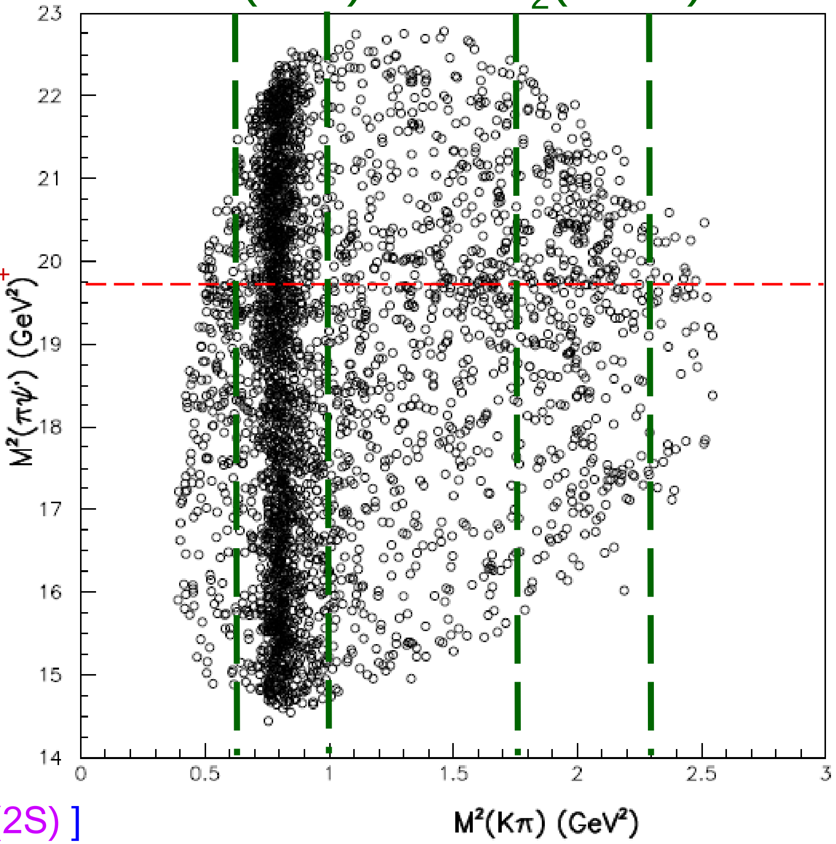
Exotic tetraquark, molecule, …

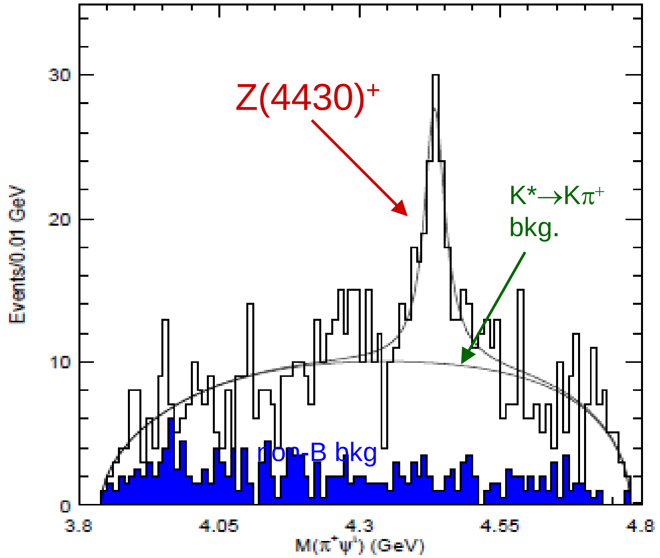
Standard charmonium

1D M(ψ'π⁻) mass fit

"K* veto region": suppress K*(892) and $K^*_2(1430)$

K*(892) $K^*_2(1430)$



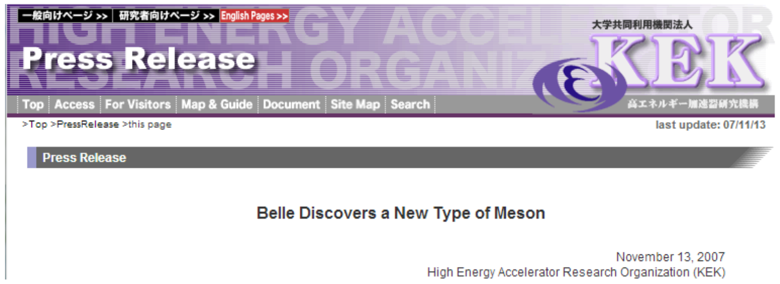


$M(Z) = 4433 \pm 4 \pm 2$ MeV

$\Gamma(Z) = 45^{+18}_{-13}{}^{+30}_{-13}$ MeV

significance 6.5σ

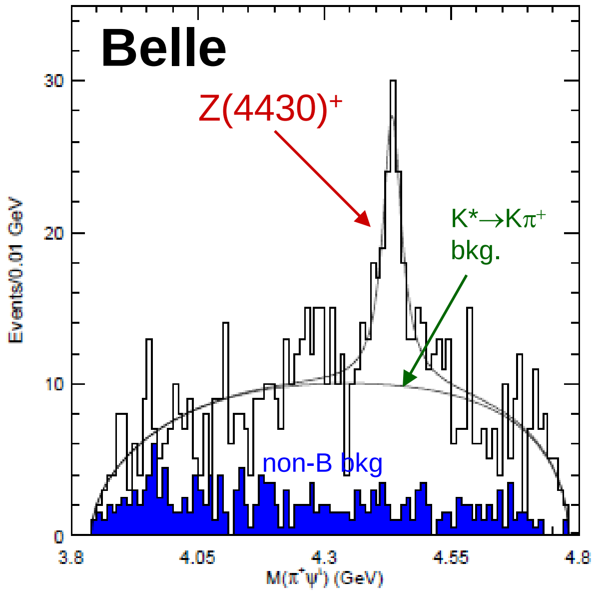
[ψ' ≡ ψ(2S)]



Lesson in importance of doing proper amplitude analysis

2008 1D M(ψ'π⁻) mass fit

PRL 100, 142001 (2008)
("K* veto region")



$M(Z) = 4433 \pm 4 \pm 2$ MeV

$\Gamma(Z) = 45^{+18\ +30}_{-13\ -13}$ MeV

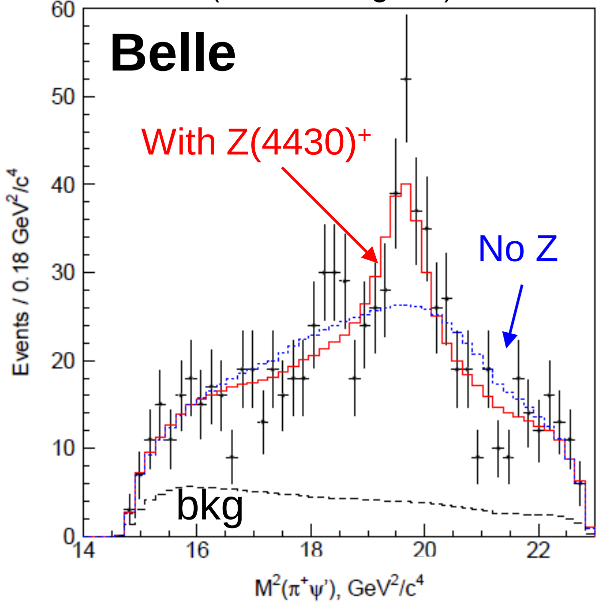
significance 6.5σ

Ad hoc assumption about $K^* \to K\pi^+$ background shape.

2009 2D amplitude ("Dalitz") fit

(same data)

PRD 80, 031104 (2009)
("K* veto region")



$M(Z) = 4443^{+15\ +19}_{-12\ -13}$ MeV

$\Gamma(Z) = 107^{+86\ +74}_{-43\ -56}$ MeV

significance 6.4σ

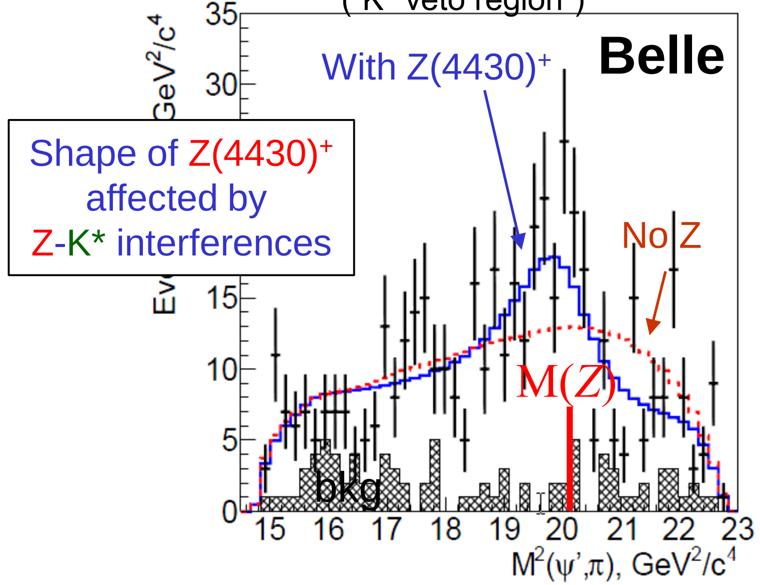
Proper model of $K^* \to K\pi^+$ resonances.

Neglect interplay of resonance interferences

2013 4D amplitude fit

(subsample with $\psi' \to l^+l^-$)

PRD 88, 074026 (2013)
$0.996\ GeV/c^2 < M(K,\pi) < 1.332\ GeV/c^2$
("K* veto region")



$M(Z) = 4485^{+22\ +28}_{-22\ -11}$ MeV

$\Gamma(Z) = 200^{+41\ +26}_{-46\ -35}$ MeV

significance 6.4σ (5.6σ with sys.)

$J^P=1^+$ preferred by $>3.4\sigma$

Interferences properly implemented

Naïve mass fits can lead to biased central values and severely underestimated errors!

BaBar puts Z(4430)$^+$ in limbo

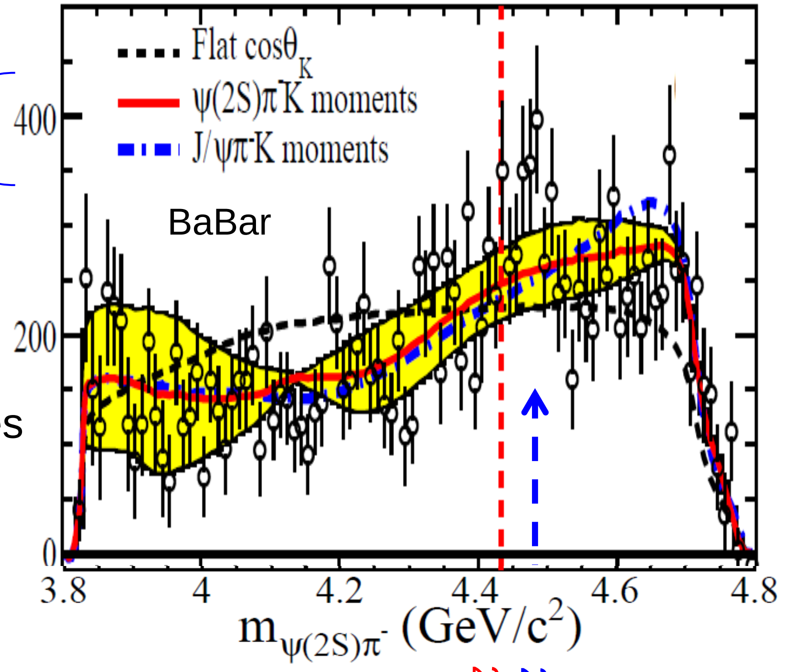
BaBar PRD 79, 112001 (2009)

Data sample comparable to Belle (18% smaller)

"Attributable" to K*s

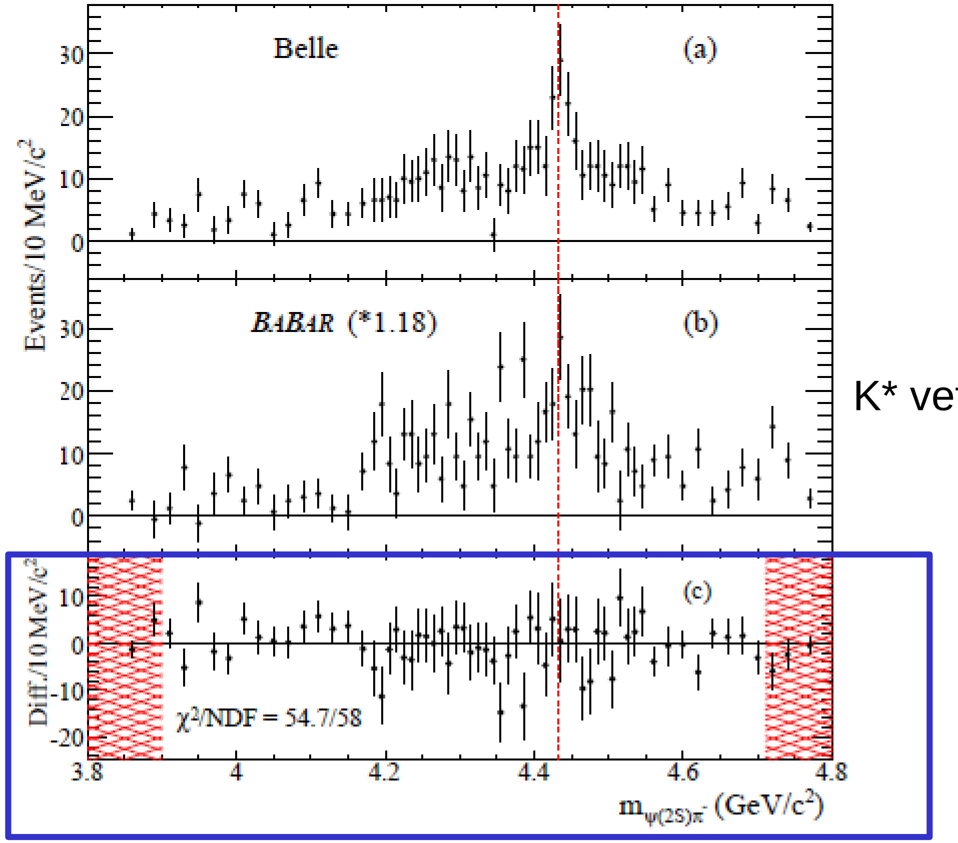
Some part of it actually comes from Z(4430)$^+$!

all K* masses



2008 Z$^+$ mass

2013 Z$^+$ mass



K* veto region

Kπ helicity angle moments analysis cannot possibly deal with Z-K* interferences, thus any upper limits from this method are at best questionable!

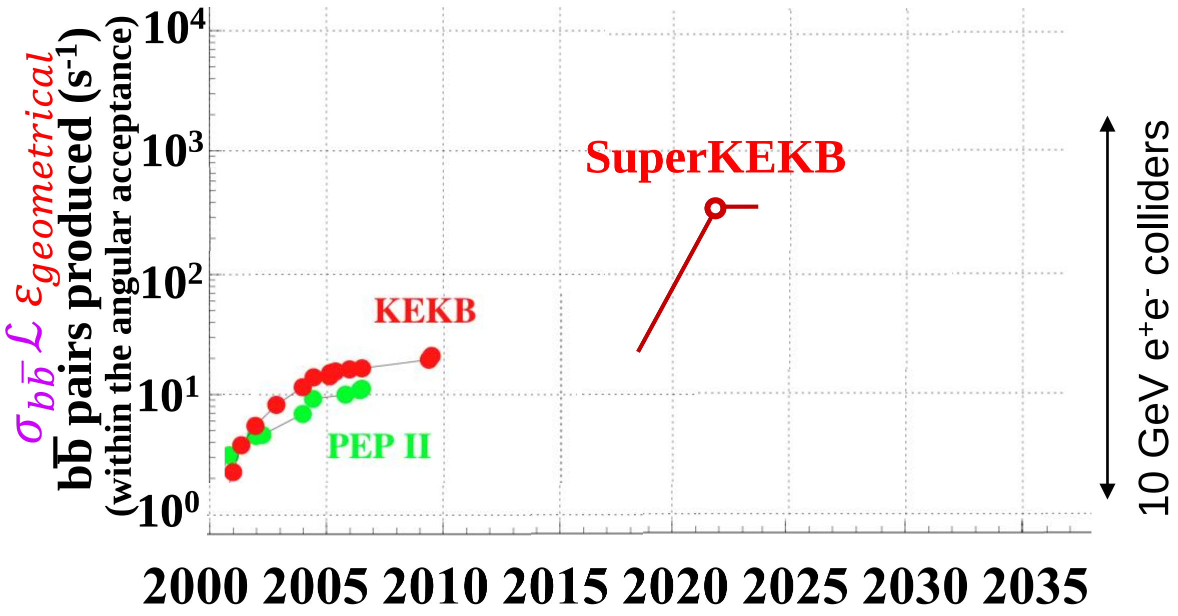
We see no significant evidence for a $Z(4430)^-$ signal for any of the processes investigated, neither in the total $J/\psi\pi^-$ or $\psi(2S)\pi^-$ mass distribution, nor in the corresponding distributions for the regions of $K\pi^-$ mass for which observation of the $Z(4430)^-$ signal was reported. We obtain branching-fraction upper limits $\mathcal{B}(B^- \to Z^-\bar{K}^0, Z^- \to J/\psi\pi^-) < 1.5 \times 10^{-5}$, $\mathcal{B}(B^0 \to Z^-K^+, Z^- \to J/\psi\pi^-) < 0.4 \times 10^{-5}$, $\mathcal{B}(B^- \to Z^-\bar{K}^0, Z^- \to \psi(2S)\pi^-) < 4.7 \times 10^{-5}$, and $\mathcal{B}(B^0 \to Z^-K^+, Z^- \to \psi(2S)\pi^-) < 3.1 \times 10^{-5}$ at 95% confidence level, where the $Z(4430)^-$ mass and width have been fixed to the reported central values.

The data samples were fully compatible.

BaBar chose not to perform amplitude analysis…

Both samples have large statistical errors.

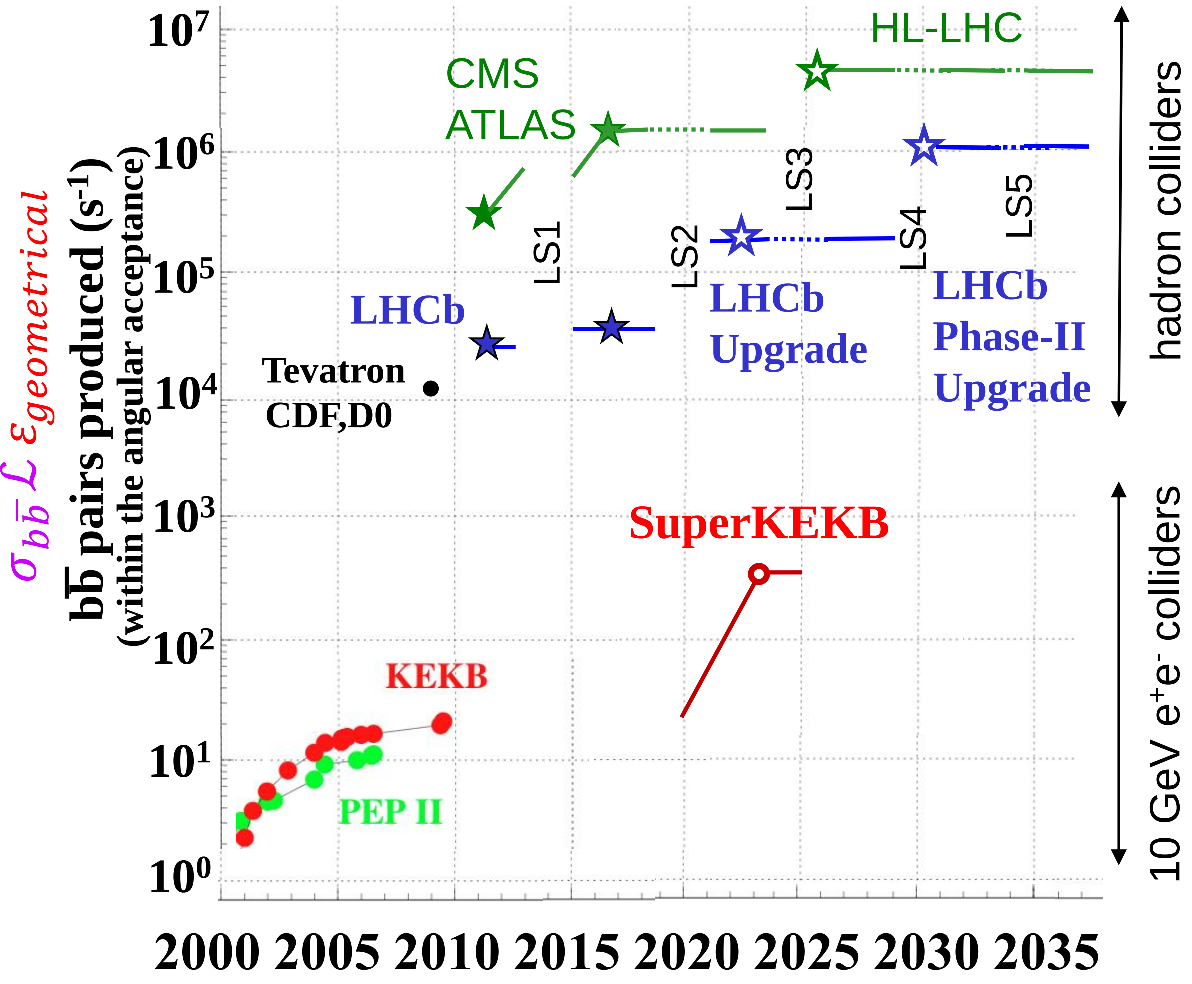
Colliders and $b\bar{b}$ rates



golden age of
10 GeV e^+e^- b-factories
(Belle & BaBar)

under construction
in Japan
(Belle II)

Colliders and $b\bar{b}$ rates



$$\int \mathcal{L}\, dt$$

CDF 10 fb^{-1} , D0 8 fb^{-1}

	Run I	Run II	Run III	Run IV	Run V+VI
LHCb	3 fb^{-1}	5 fb^{-1}		50 fb^{-1}	300 fb^{-1}
ATLAS,CMS	25 fb^{-1}		450 fb^{-1}	3000 fb^{-1}	

- Tremendous rate potential at hadron colliders
  - **physics reach determined by the detector capabilities not by the machine**
- Collect all b-hadron species at the same time:
  - **additional gain by a factor of ~10-100 in integrated B_s rates at hadronic colliders**
  - **time dependent CPV studies of B_s possible**
  - **also get Λ_b, B_c which are out of reach of the 10 GeV e$^+$e$^-$ factories**

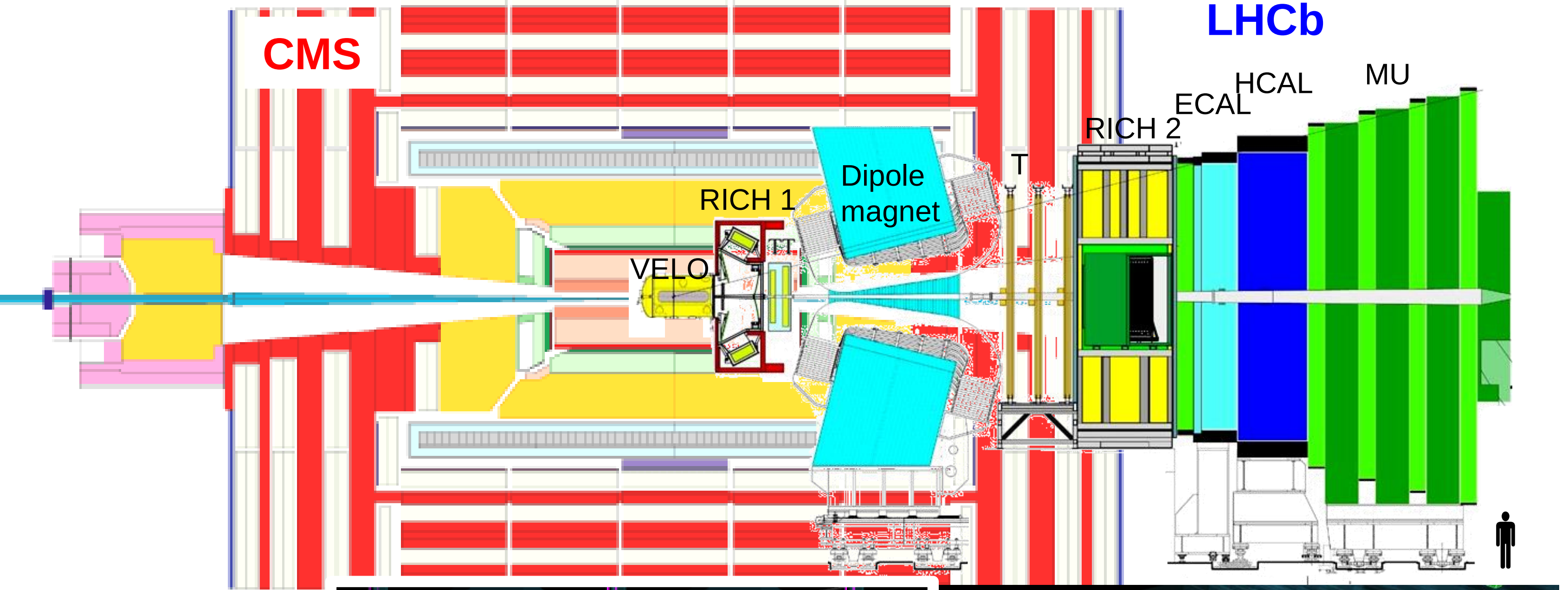
detected events N = produced events $\sigma_{b\bar{b}} \int \mathcal{L}\, dt$ x detector efficiency ε

large

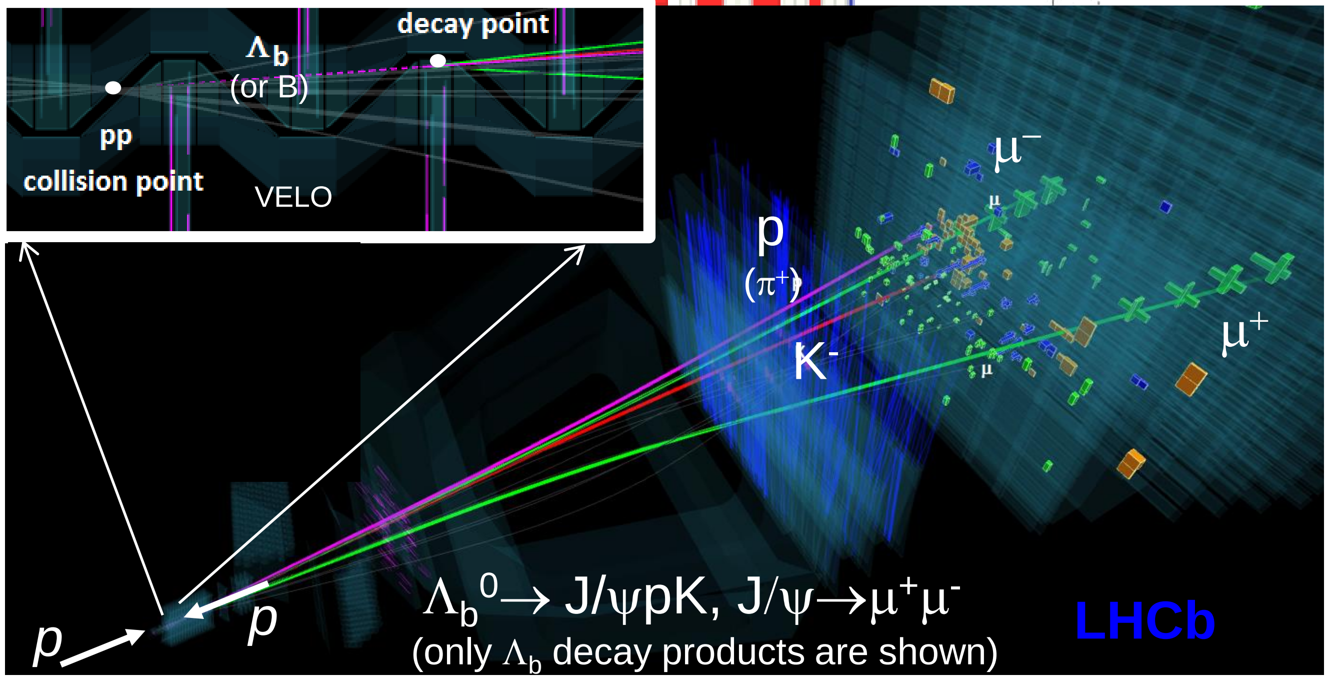
$$\varepsilon = \varepsilon_{geometrical} \cdot \varepsilon_{trigger} \cdot \varepsilon_{rest}$$

major challenge for b,c physics at hadron colliders

LHCb vs central detectors



Trigger on muons or decay points detached from pp collision point



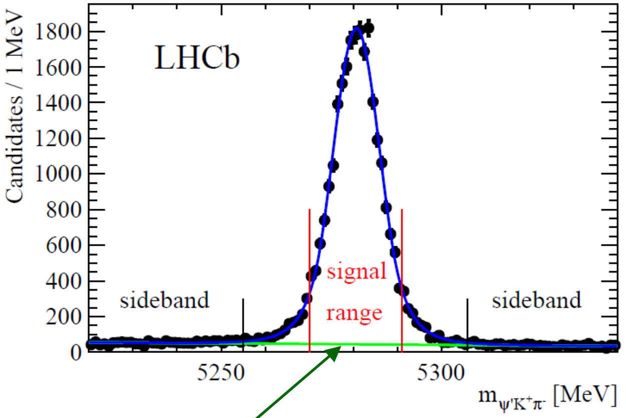
- Advantages of LHCb (forward spectrometer):
  - comparable b cross-section in much smaller solid angle; smaller number of electronic channels; smaller event size; much larger trigger bandwidth to tape (Run I ~5 kHz, Run II ~12 kHz)
  - b and c physics dominate the trigger bandwidth (e.g. CMS b-trigger rate ~25 Hz; almost 3 orders of magnitude less than LHCb)
  - large p for small p_T (in central region p~p_T); can identify muons to lower p_T values
  - large bandwidth important for triggering on purely hadronic final states (central detectors limited to dimuon trigger)
  - large bandwidth important for collecting very large bottom & charm samples
  - space for RICH detectors: p/K/π separation; crucial for background suppression in many channels; increased flavor tagging
- Limitation of present LHCb detector:
  - luminosity limited by the detector readout capabilities (upgrades of the detector will allow increasing the luminosity)
  - compared to Belle: poor γ (i.e. π^0) and K_s detection (will be improved in Phase II upgrade)

$\overline{B^0} \to \psi'\pi^+K^-$ in LHCb

LHCb PRL 112, 222002 (2014)

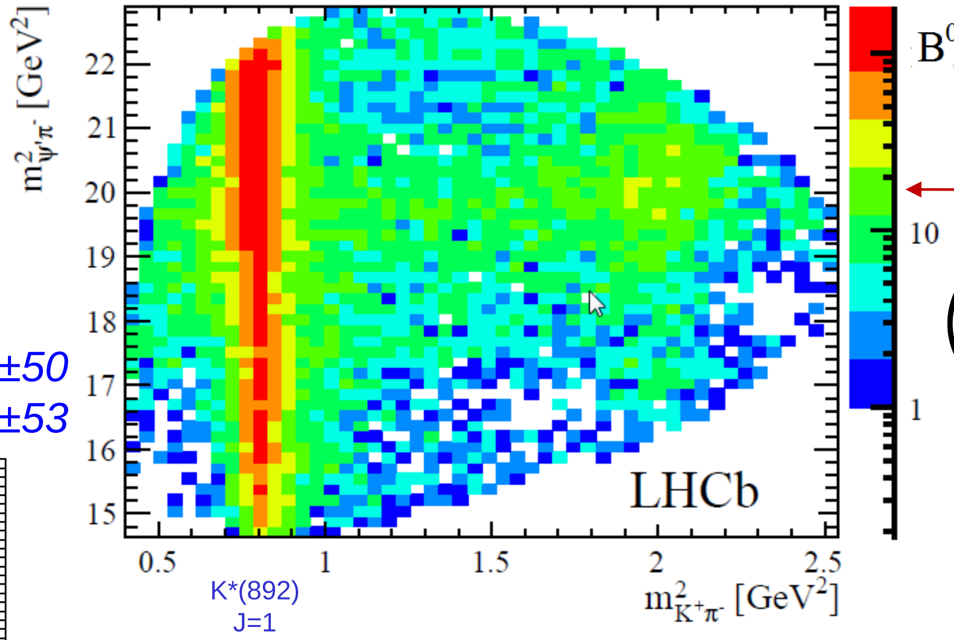
25,176±174
signal events

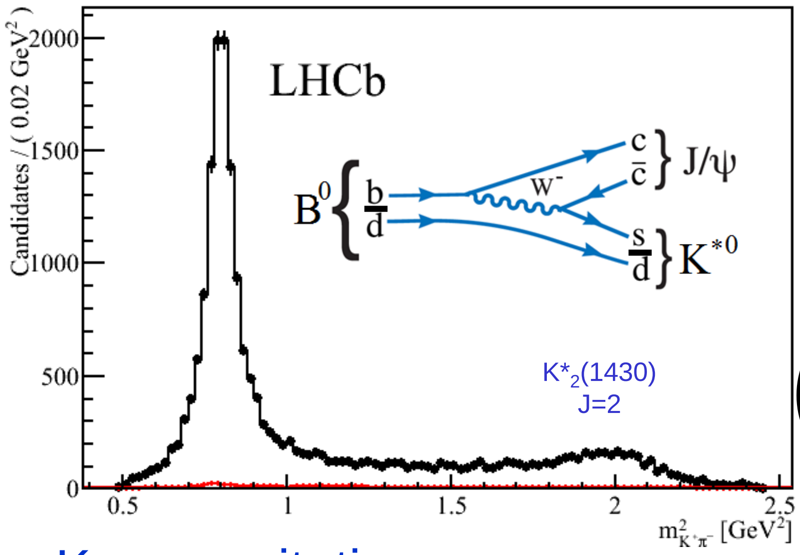
vs
Belle: 2,010±50
BaBar: 2,021±53



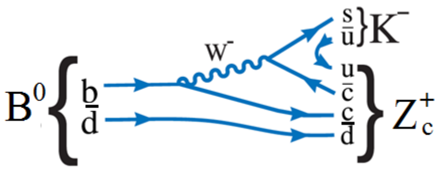
bkg (4.1±0.1)%

vs. bkg in Belle: 7.8%

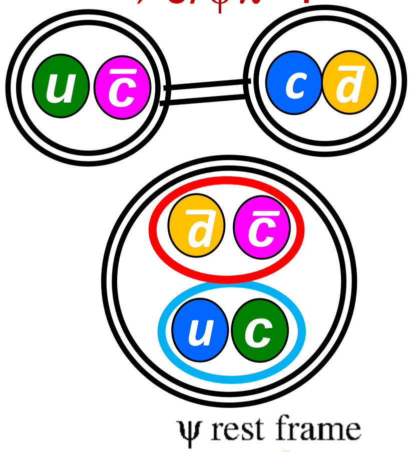


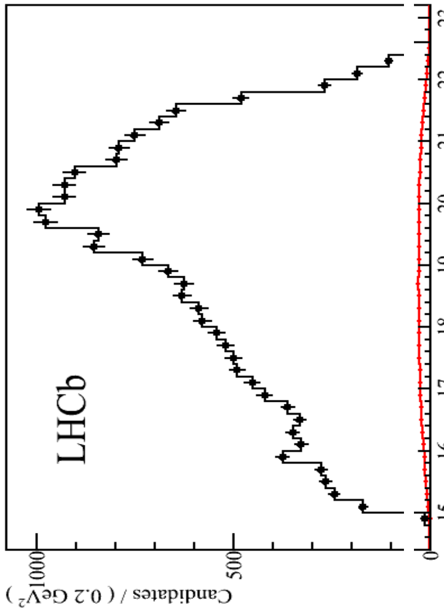


Kaon excitations

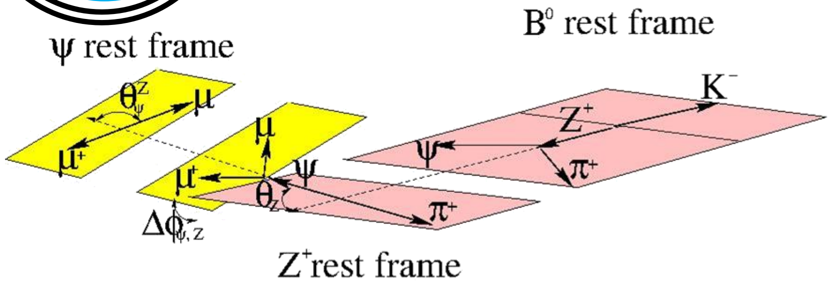


Z_c (4430)$^+$
$\to J/\psi\pi^+$?

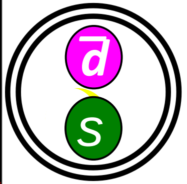


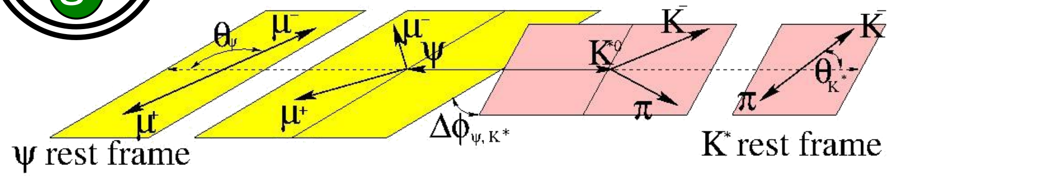


Tetraquark or molecule ?

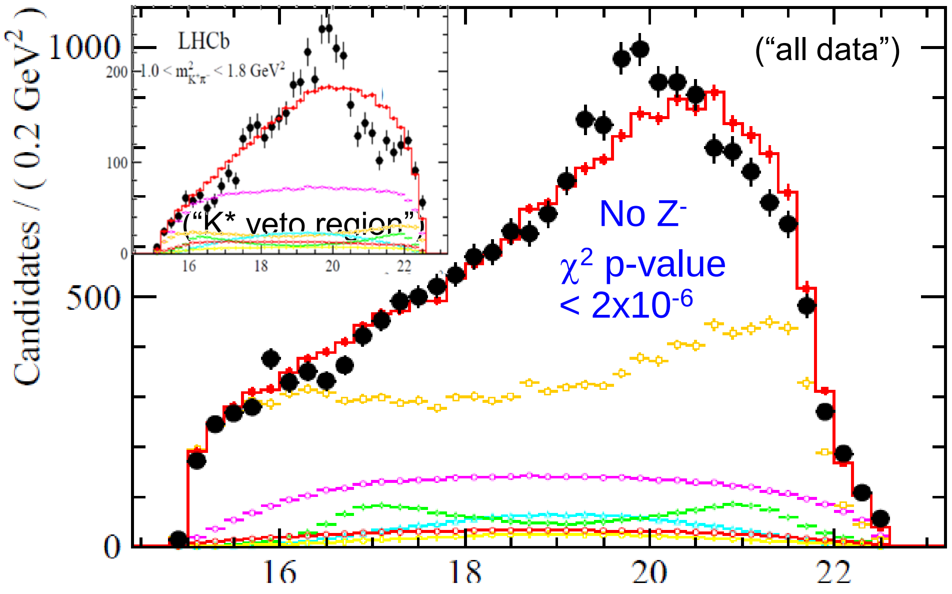


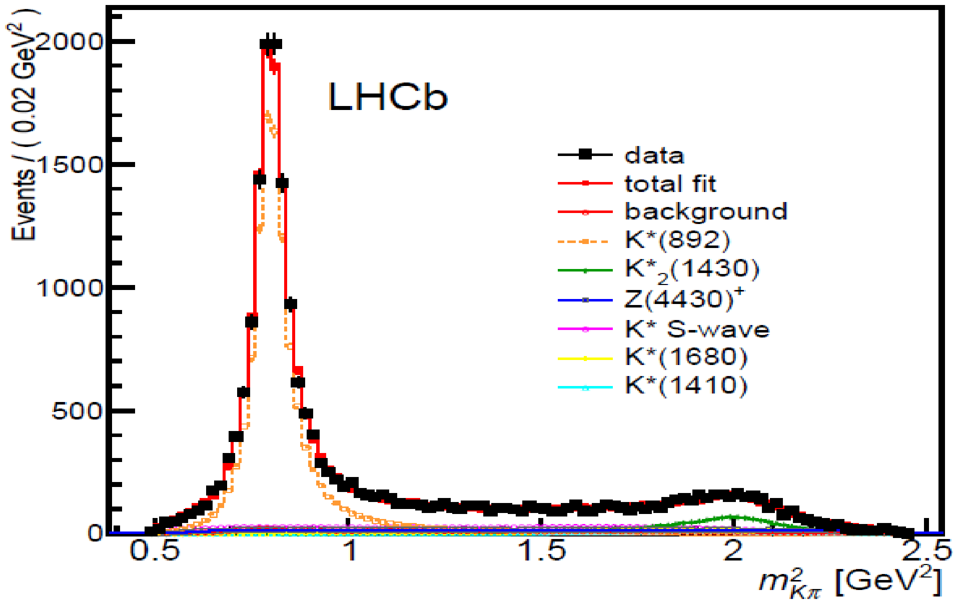
Decay angles contain information on spins of resonances.





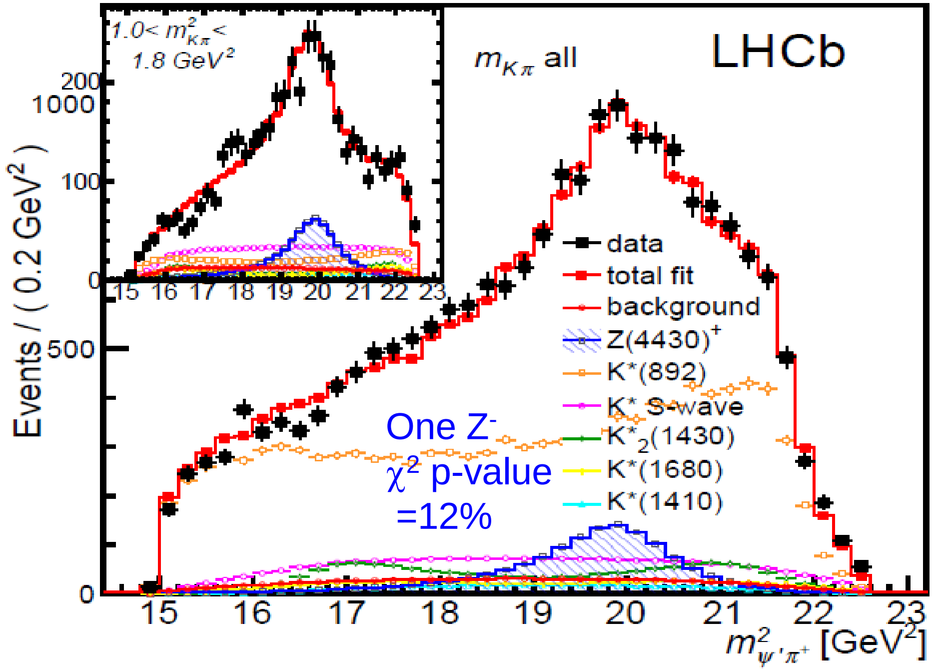
Amplitude fits in LHCb: Z(4430)$^+$ confirmed





Z(4430)$^-$	LHCb	Belle
$M(Z)$ [MeV]	$4475 \pm 7^{+15}_{-25}$	$4485 \pm 22^{+28}_{-11}$
$\Gamma(Z)$ [MeV]	$172 \pm 13^{+37}_{-34}$	200^{+41+26}_{-46-35}
f_Z [%]	$5.9 \pm 0.9^{+1.5}_{-3.3}$	$10.3^{+3.0+4.3}_{-3.5-2.3}$
f_{1-Z} [%]	$16.7 \pm 1.6^{+2.6}_{-5.2}$	
Significance	$> 13.9\sigma$	$> 5.2\sigma$
$J^P=1^+$	9.7σ	3.4σ

Excellent agreement !



2nd Z$^-$ at lower mass?

$J^P=0^-$

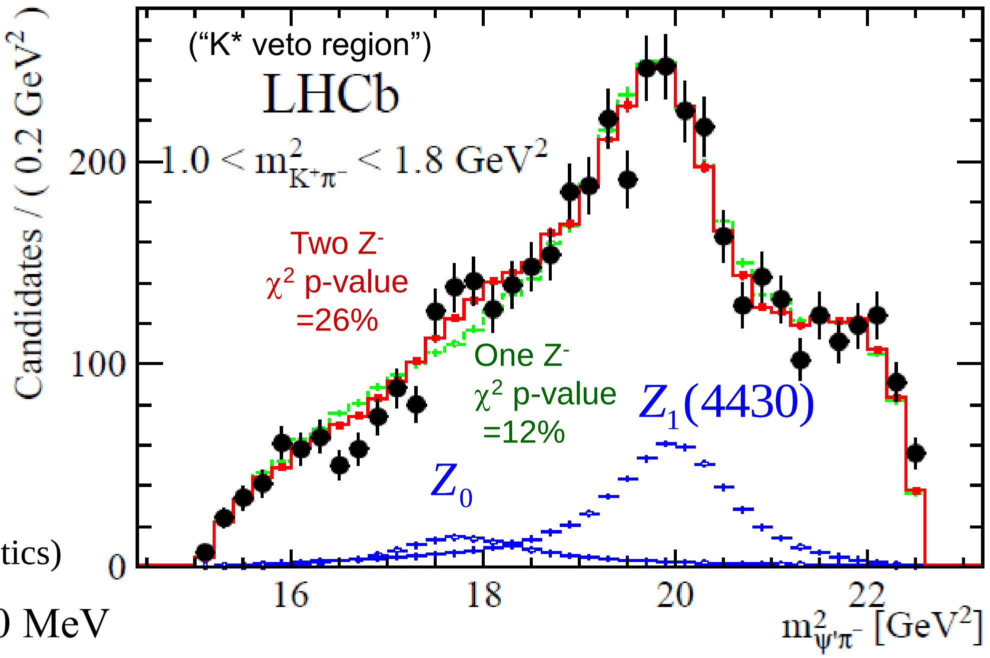
$M(Z_0) = 4239 \pm 18^{+45}_{-10}$ MeV

$\Gamma(Z_0) = 220 \pm 47^{+108}_{-74}$ MeV

$f_{Z_0} = 1.6 \pm 0.5^{+1.9}_{-0.4}$ %

$f^I_{Z_0} = 2.4 \pm 1.1^{+1.7}_{-0.2}$ %

6σ significane (with systematics)



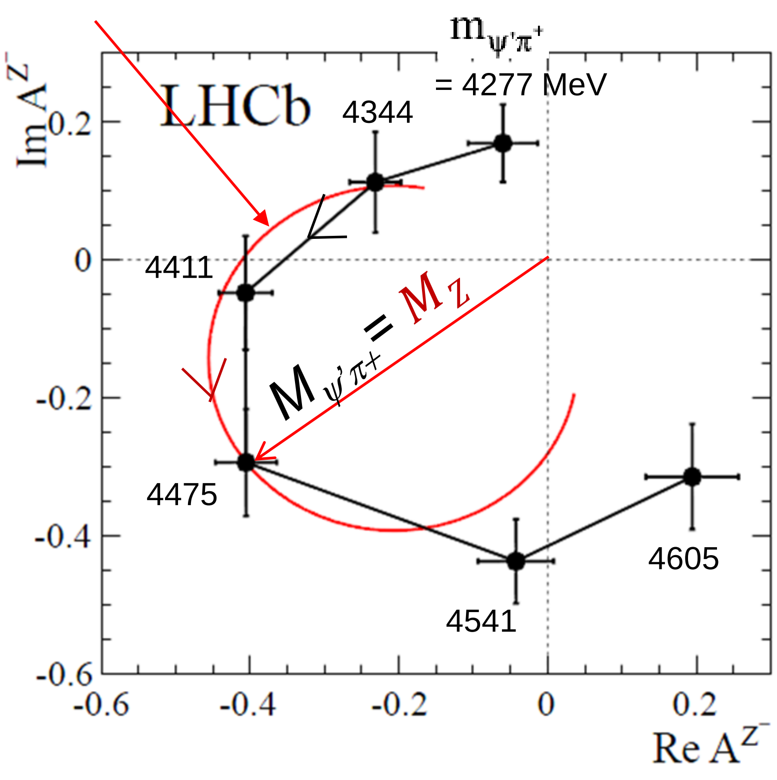
$J^P=1^+$ also possible Γ=660±150 MeV

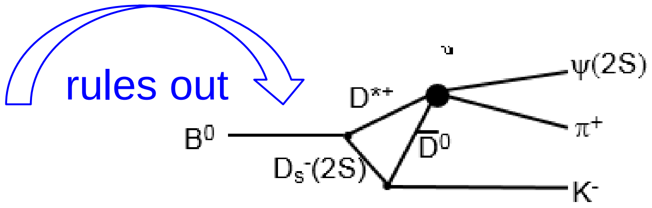
Argand diagram of Z(4430)$^+$

- Thanks to the large data statistics LHCb has been able to extract Argand diagram of Z(4430)$^+$ amplitude from its interference with the K* amplitudes:

$$\frac{1}{M_Z^2 - m_{\psi'\pi^+}^2 - i M_Z \Gamma_Z}$$

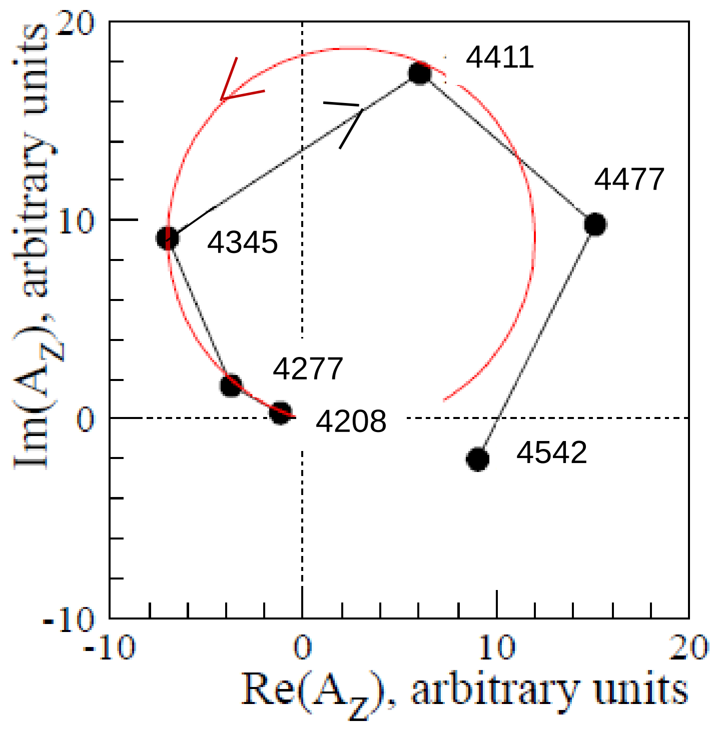
Breit-Wigner amplitude





rescattering model

P. Pakhlov, T. Uglov
PL B748, 183 (2015)



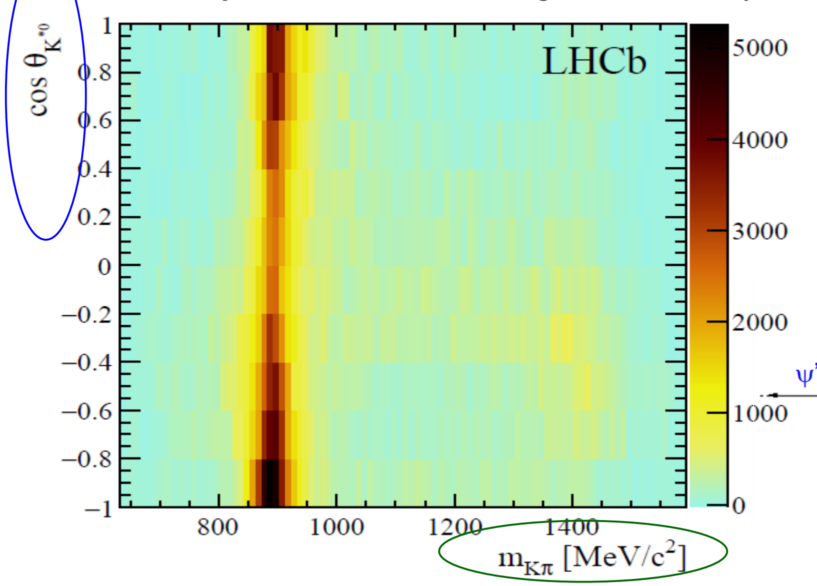
However, the predictions of Pakhlov-Uglov model do not reflect generic behavior of triangle anomalies, which can generate counterclockwise phase changes – just not as circular as the one from a resonance.

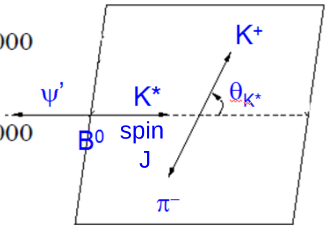
Improving experimental precision of Argand diagram determination is highly desired.

Model independent analysis a la BaBar

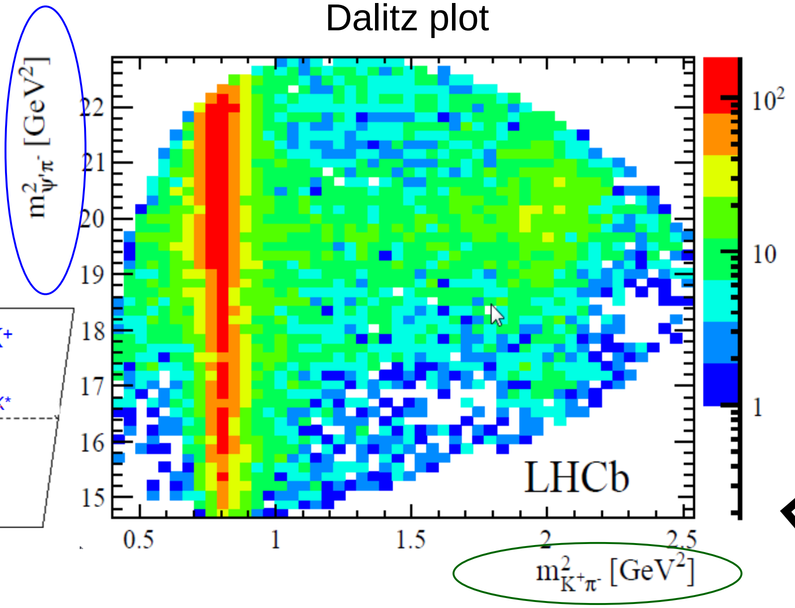
$\overline{B^0} \rightarrow \psi' \pi^+ K^-$

Efficiency-corrected "rectangular" Dalitz plot

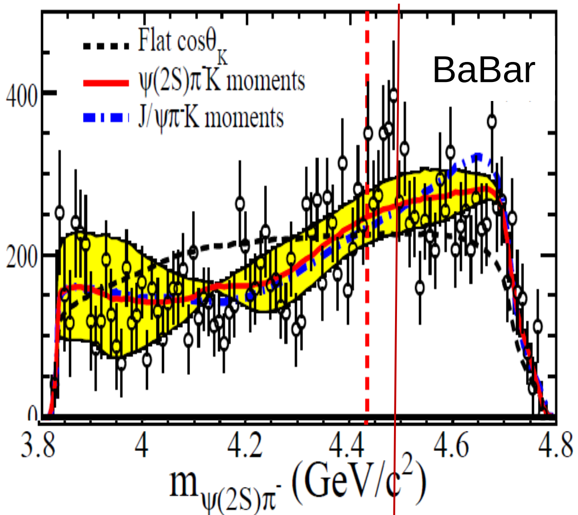




Dalitz plot



BaBar PRD 79, 112001 (2009)



Decompose into Legendre moments

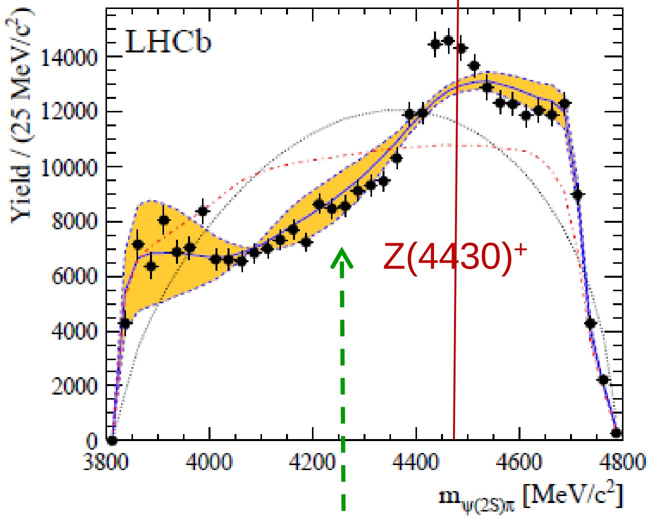
$$< P_l^U >= \sum_{i=1}^{N_{data}} \frac{1}{\varepsilon_i} P_l(\cos\theta_{K^* i})$$

vs. $m_{K+\pi-}$

Pass only moments with l not more than $l_{max}=J_{max}/2$

J_{max} limited from QM and scattering experiments

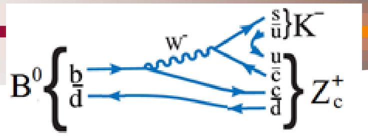
LHCb PRD 92, 112009 (2015)



The lack of "access" at 4239 MeV implies nothing. This method is not sensitive to small and broad structures (see PRL,117,082002 (2016)).

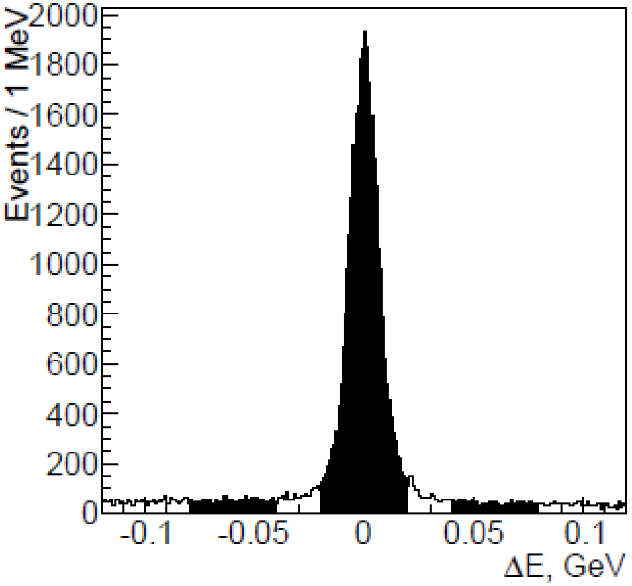
- LHCb data inconsistent with K* contributions alone (>8σ)
- BaBar did not have enough statistics to "see" Z(4430) this way.

$\overline{B^0} \to J/\psi\, \pi^+ K^-$ in Belle



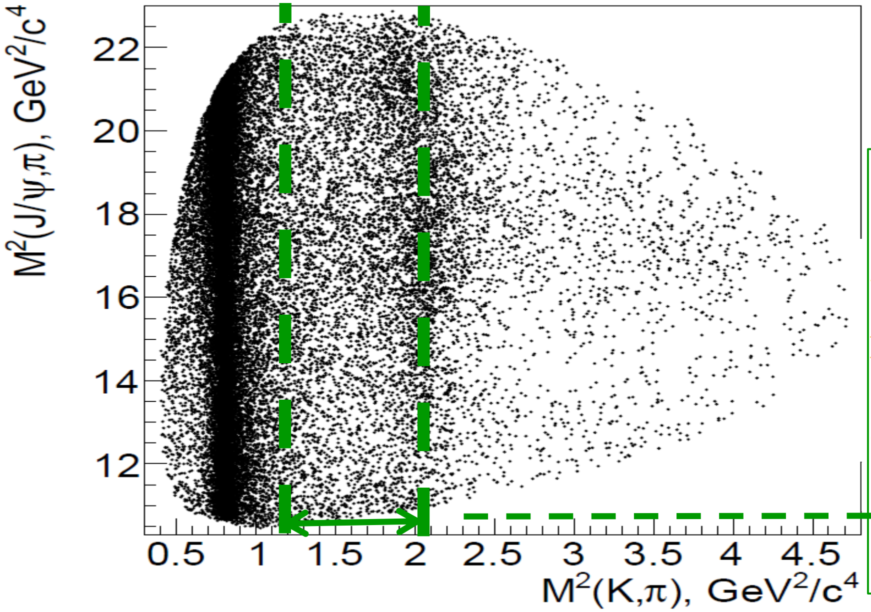
Belle PR D90, 112009 (2014)

29,990±190
signal events



bkg 5.6%

Larger BR → as good a sample as $\overline{B^0} \to \psi' \pi^+ K^-$ in LHCb



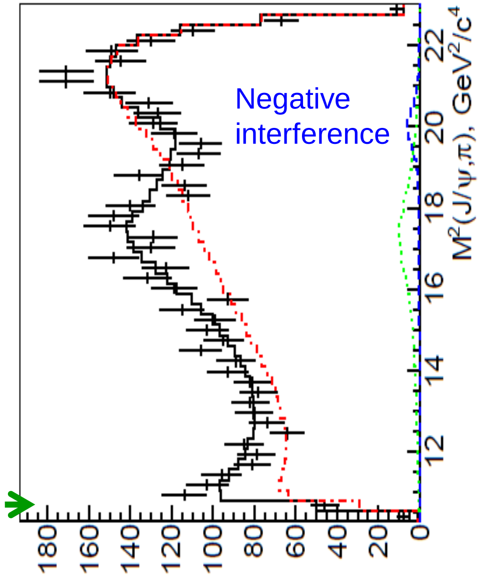
Significance	5.1σ
f_Z [%]	$(0.5^{+0.4}_{-0.1})$%

$Z_c(4430)^+ \to J/\psi\pi^+$

$Z_c(4200)^+ \to J/\psi\pi^+$

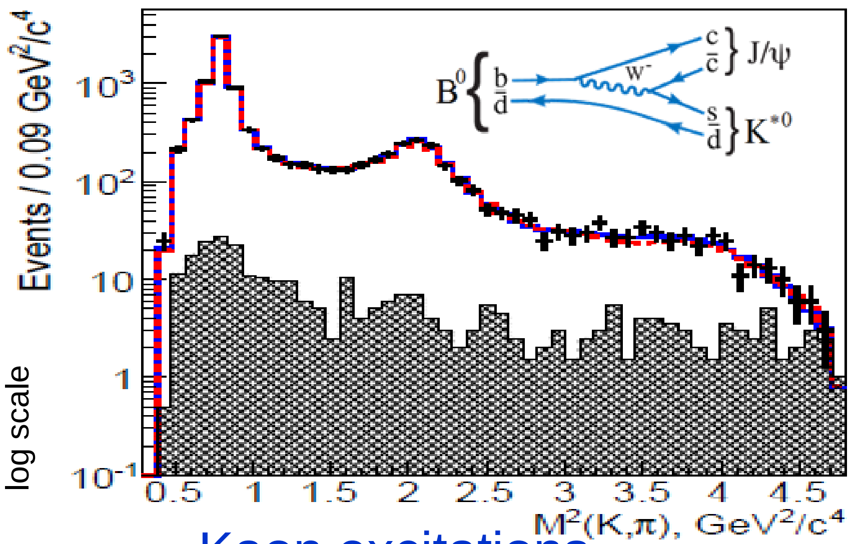
$M(Z)$ [MeV]	4196^{+31+17}_{-29-13}
$\Gamma(Z)$ [MeV]	$370^{+70+70}_{-70-132}$
f_Z [%]	$(1.9^{+0.7}_{-0.5})$%
Significance	6.2σ
$J^P=1^+$	4.4σ

Small fit fractions!



Tetraquark or meson-meson molecule

16 GeV²/c⁴ < M²(J/ψ,π) < 19 GeV²/c⁴



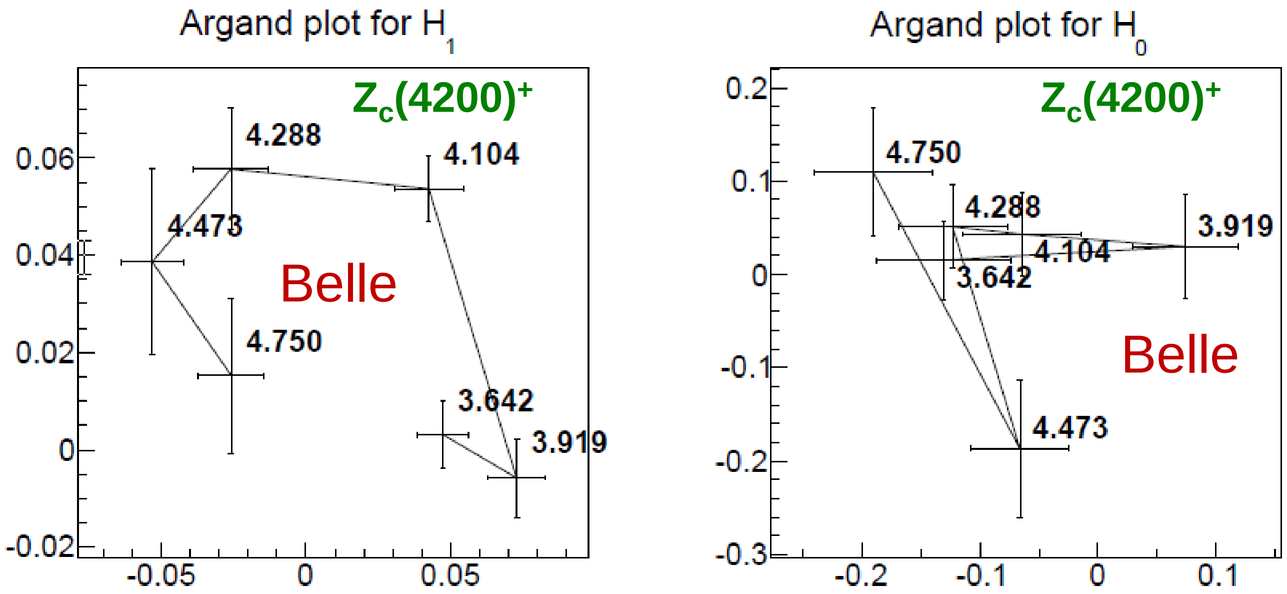
Kaon excitations

- The $Z_c(4430)^+$ observed in the 2nd decay mode!
  - However, with the mass and width fixed in the fit; not quite an independent confirmation of the resonance
- A broad but significant 2nd 1^+ resonances at the lower mass, $Z_c(4200)^+$
  - Possibly the same structure as observed by the LHCb in $\overline{B^0} \to \psi' \pi^+ K^-$ (1^+ was not ruled out by LHCb)

$\overline{B}^0 \to J/\psi\, \pi^+ K^-$ in Belle

- Is the $Z_c(4200)^+$ a resonance, given its large width?

Encouraging results; higher data statistics are needed (and available in LHCb!)



(LHCb neglected D-wave in $Z(4430)^+$ decays: $H_1=H_0$)

$Z(4430)^+$,$Z(4200)^+$ production and decay rates

Belle PR D88, 074026 (2013)

$$\mathcal{B}(B^0 \to Z(4430)^- K^+) \times \mathcal{B}(Z(4430)^- \to \psi' \pi^-) = (6.0^{+1.7+2.5}_{-2.0-1.4}) \times 10^{-5},$$

Averaging fit fractions as determined by Belle & LHCb [PRL 112, 222002 (2014)], $(6.6 \pm 1.6)\%$, and using PDG for $\mathcal{B}(B^0 \to Z(4430)^- K^+)$

$$\mathcal{B}(B^0 \to Z(4430)^- K^+) \times \mathcal{B}(Z(4430)^- \to \psi' \pi^-) = (3.8 \pm 1.0) \times 10^{-5}$$

BaBar PR D79, 112001 (2009)

$$\mathcal{B}(\bar{B}^0 \to Z_c(4430)^+ K^-) \times \mathcal{B}(Z_c(4430)^+ \to J/\psi \pi^+) < 4 \times 10^{-6} \text{ (95\% CL)}$$

However this limit was obtained without amplitude analysis, thus neglected interference effects, which are crucial according to the Belle results:

Belle PR D90, 112009 (2014)

$$\mathcal{B}(\bar{B}^0 \to Z_c(4430)^+ K^-) \times \mathcal{B}(Z_c(4430)^+ \to J/\psi \pi^+) = (5.4^{+4.0+1.1}_{-1.0-0.9}) \times 10^{-6},$$

$$\mathcal{B}(Z(4430)^- \to \psi' \pi^-)/\mathcal{B}(Z(4430)^- \to J/\psi \pi^-) = 7.0^{+2.6}_{-4.4}$$

Motivates models which can explain the preference for ψ' in spite of the smaller phase-space (a factor of 0.6)

LHCb 0^- $Z(4239)^-$

$$\mathcal{B}(B^0 \to Z(4239)^- K^+) \times \mathcal{B}(Z(4239)^- \to \psi' \pi^-) = (0.9^{+1.2}_{-0.4}) \times 10^{-5}$$

Belle 1^+ $Z(4200)^-$

$$\mathcal{B}(\bar{B}^0 \to Z_c(4200)^+ K^-) \times \mathcal{B}(Z_c(4200)^+ \to J/\psi \pi^+) = (2.2^{+0.7+1.1}_{-0.5-0.6}) \times 10^{-5},$$

The Z_c^+ states observed in $e^+e^- \to \pi^- Z_c^+$ not observed in $\bar{B}^0 \to Z_c^+ K^-$ and vice versa

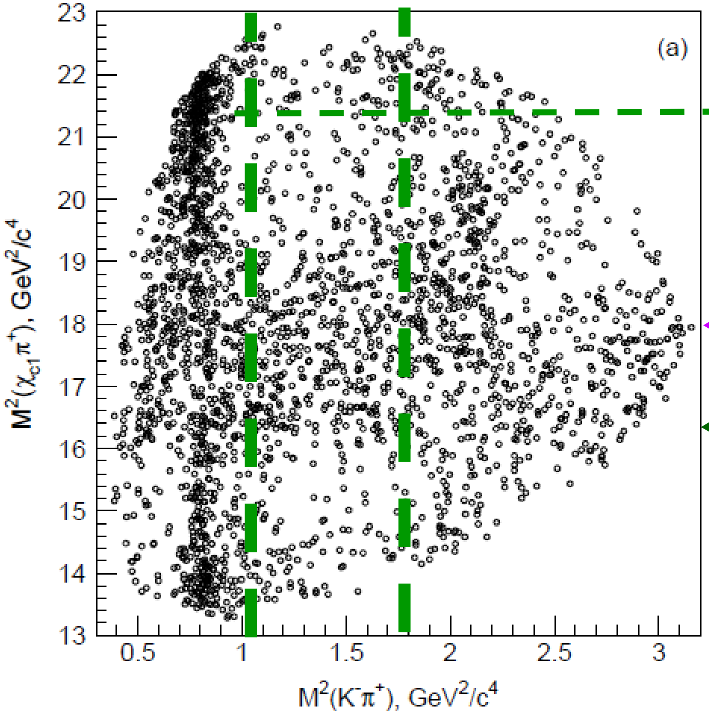
$$\mathcal{B}(\bar{B}^0 \to Z_c(3900)^+ K^-) \times \mathcal{B}(Z_c(3900)^+ \to J/\psi \pi^+) < 9 \times 10^{-7} \text{ (90\% CL).}$$

$\overline{B^0} \to \chi_{c1}\pi^+K^-$, $\chi_{c1} \to \gamma J/\psi$ Belle

Belle PR, D78, 072004 (2008)
2D amplitude analysis
2,126±70 signal events

(non-B bkg.~20%)

BaBar PRD,85,052003 (2012)
Model independent approach
~1,968 signal events



No J^P sensitivity

$M(Z_2) = 4248^{+44}_{-29}{}^{+180}_{-35}$ MeV

$\Gamma(Z_2) = 177^{+54}_{-39}{}^{+316}_{-61}$ MeV

$f_Z = 10.4^{+6.1}_{-2.3}$ %

significance 5σ

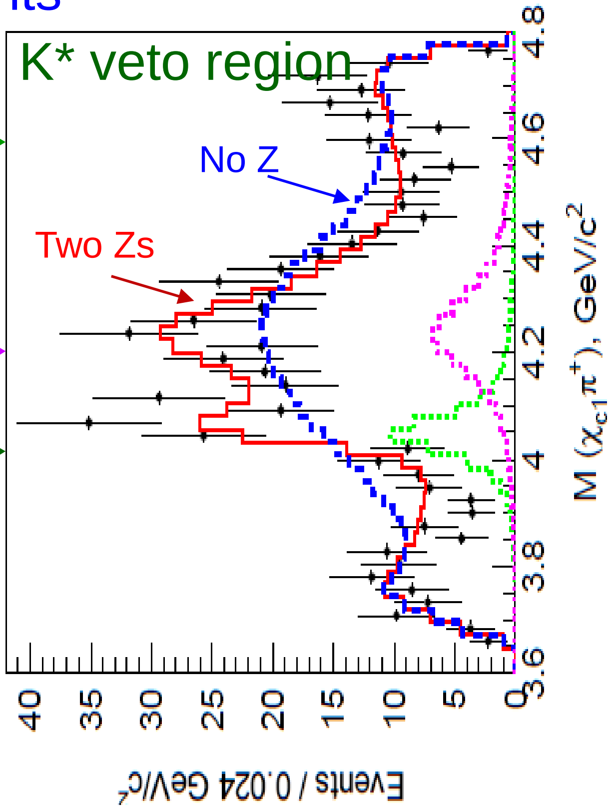
$M(Z_1) = 4051^{+14}_{-14}{}^{+20}_{-41}$ MeV

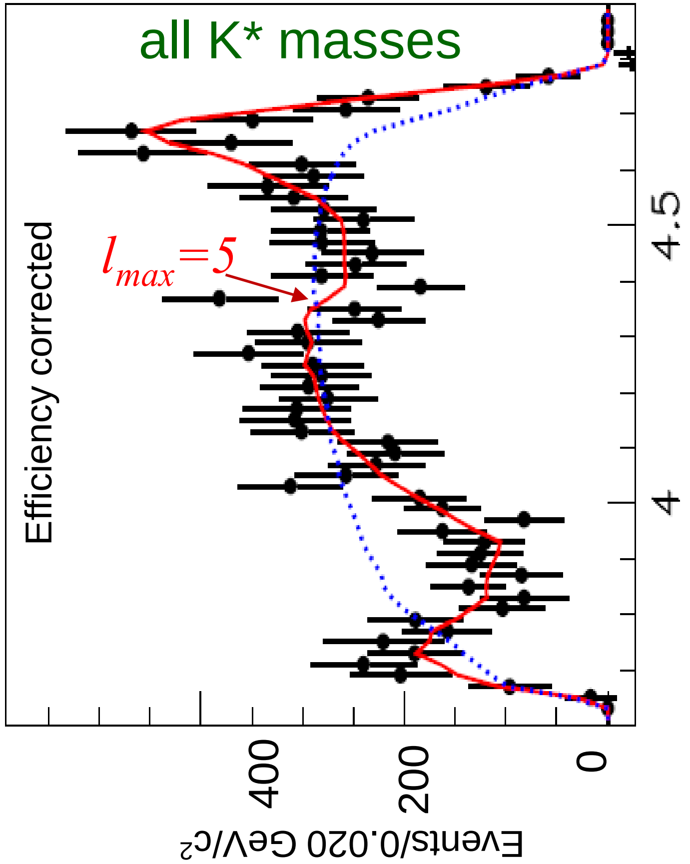
$\Gamma(Z_1) = 82^{+21}_{-17}{}^{+47}_{-22}$ MeV

$f_Z = 8.0^{+3.8}_{-2.2}$ %

significance 5σ

Sizable fit fractions!





One or two states claimed by Belle.

Need confirmation and J^P determination

$$\mathcal{B}(\bar{B}^0 \to K^- Z_1^+) \times \mathcal{B}(Z_1^+ \to \pi^+\chi_{c1}) = (3.0^{+1.5+3.7}_{-0.8-1.6}) \times 10^{-5},$$

$$\mathcal{B}(\bar{B}^0 \to K^- Z_2^+) \times \mathcal{B}(Z_2^+ \to \pi^+\chi_{c1}) = (4.0^{+2.3+19.7}_{-0.9-\ 0.5}) \times 10^{-5}.$$

$$\mathcal{B}(\overline{B}^0 \to Z_1(4050)^+K^-) \times \mathcal{B}(Z_1(4050)^+ \to \chi_{c1}\pi^+) < 1.8 \times 10^{-5},$$

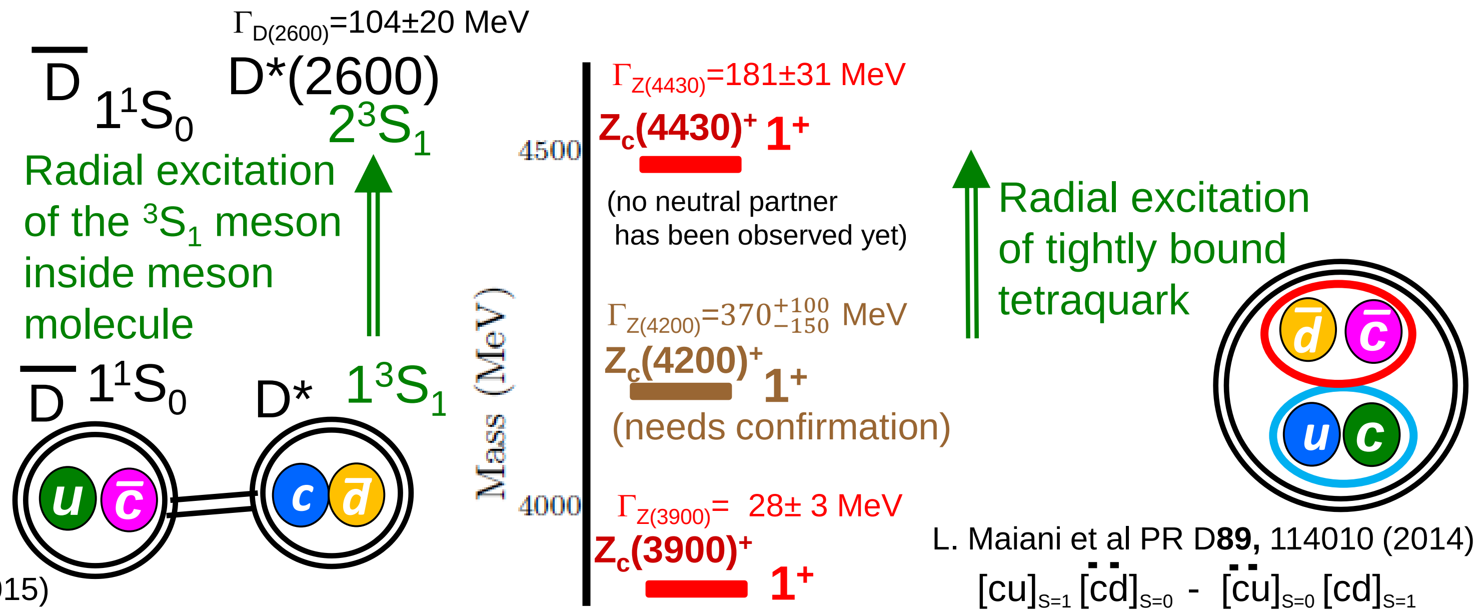
(90% CL)

$$\mathcal{B}(\overline{B}^0 \to Z_2(4250)^+K^-) \times \mathcal{B}(Z_2(4250)^+ \to \chi_{c1}\pi^+) < 4.0 \times 10^{-5},$$

Obtained by neglecting any interference effects and statistical correlations between direct and moments-filtered mass spectra

BaBar did confirm these states, but did not contradict them either

Interpretations of Z_c^+ states observed in B decays



L. Ma et al PRD 90, 037502 (2014)
T. Barnes et al, PRD 91, 014004 (2015)

Absence of $Z_c(3900)^+$ in B decays makes it questionable to pair it up with $Z_c(4430)^+$

No molecular thresholds can explain $Z_c(4200)^+$

While it has been suggested $Z_c(4200)^+$ is a tetraquark, no tetraquark model can accommodate it together with $Z_c(4430)^+$
C.Deng et al PR D92, 034027 (2015)

Vivid and confusing history of X(4140)

All 1D fits to m(J/ψϕ) with naïve bkg shapes

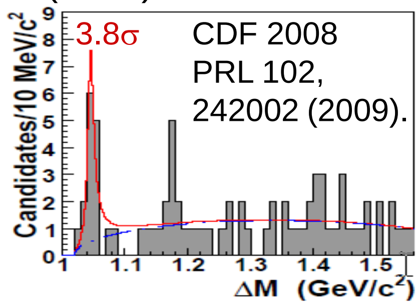
Year	Experiment luminosity	$B \to J/\psi\phi K$ yield	Mass (MeV)	X(4140) peak Width (MeV)	Significance	Fraction (%)
2008	CDF 2.7 fb^{-1} [1]	58 ± 10	$4143.0 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{-5.0} \pm 3.7$	3.8σ	
2009	*Belle* [22]	325 ± 21	*4143.0 fixed*	*11.7 fixed*	1.9σ	
2011	*CDF 6.0 fb^{-1}* [29]	115 ± 12	$4143.4^{+2.9}_{-3.0} \pm 0.6$	$15.3^{+10.4}_{-6.1} \pm 2.5$	5.0σ	$14.9 \pm 3.9 \pm 2.4$
2011	LHCb 0.37 fb^{-1} [21]	346 ± 20	4143.4 fixed	15.3 fixed	1.4σ	<7 @ 90% CL
2013	CMS 5.2 fb^{-1} [25]	2480 ± 160	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$	5.0σ	10 ± 3 (stat.)
2013	D0 10.4 fb^{-1} [26]	215 ± 37	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+1.0}_{-8.0}$	3.0σ	$21 \pm 8 \pm 4$
2014	*BABAR* [24]	189 ± 14	4143.4 fixed	15.3 fixed	1.6σ	<13.3 @ 90% CL
2015	D0 10.4 fb^{-1} [27]	$p\bar{p} \to J/\psi\phi....$	$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$	4.7σ (5.7σ)	
Average			4147.1 ± 2.4	15.7 ± 6.3		

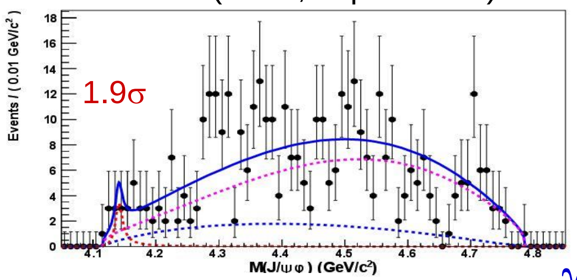
Γ ↗ ΔΓ ↗

Year	Experiment luminosity	$B \to J/\psi\phi K$ yield	Mass (MeV)	X(4274–4351) peaks(s) Width (MeV)	Significance
2011	*CDF 6.0 fb^{-1}* [29]	115 ± 12	$4274.4^{+8.4}_{-6.7} \pm 1.9$	$32.3^{+21.9}_{-15.3} \pm 7.6$	3.1σ
2011	LHCb 0.37 fb^{-1} [21]	346 ± 20	4274.4 fixed	32.3 fixed	
2013	CMS 5.2 fb^{-1} [25]	2480 ± 160	$4313.8 \pm 5.3 \pm 7.3$	$38^{+30}_{-15} \pm 16$	
2013	D0 10.4 fb^{-1} [26]	215 ± 37	4328.5 ± 12.0	30 fixed	
2014	*BABAR* [24]	189 ± 14	4274.4 fixed	32.3 fixed	1.2σ
2010	Belle [32]	$\gamma\gamma \to J/\psi\phi$	$4350.6^{+4.6}_{-5.1} \pm 0.7$	$13^{+18}_{-9} \pm 4$	3.2σ

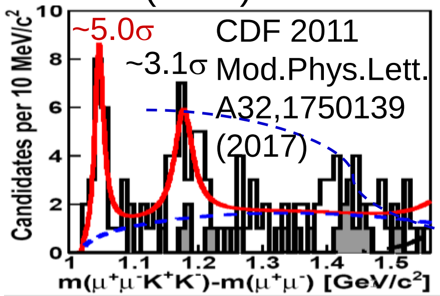
X(4140) ?

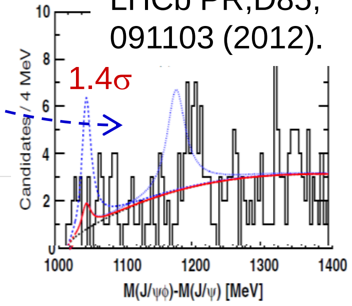
B→J/ψϕK



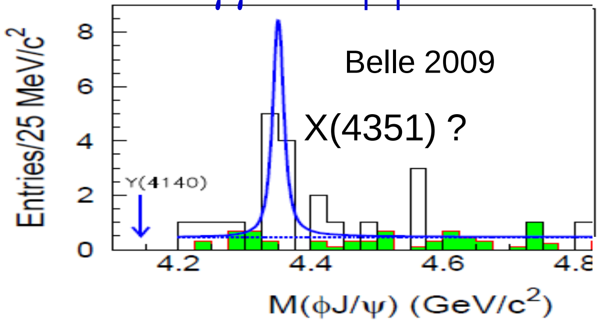


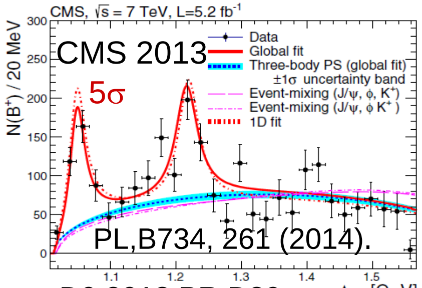
X(4274) ?

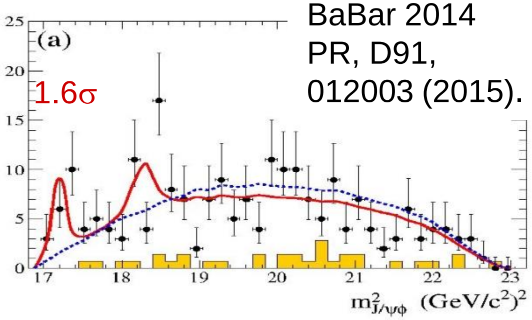


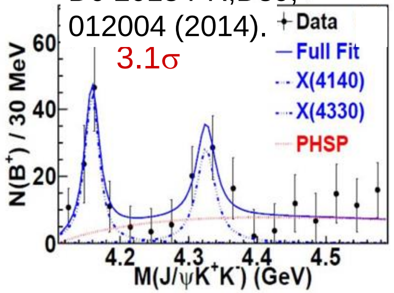


γγ→J/ψϕ



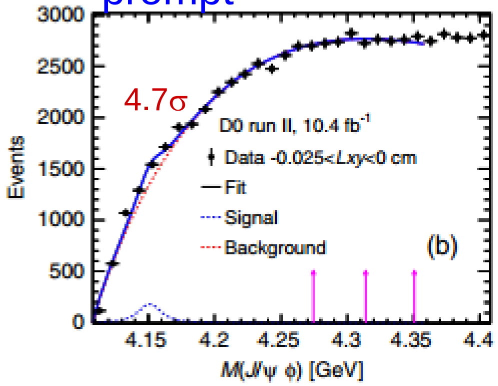


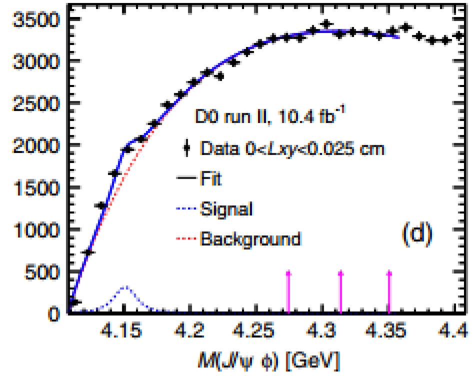




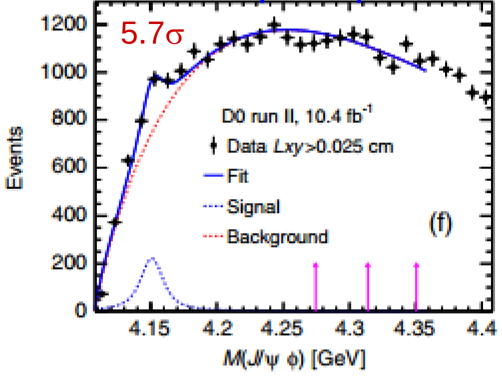
pp̄→J/ψϕ… (systemtics of ad hoc bkg shape not investigated)
D0 PRL 115, 232001 (2015).

prompt





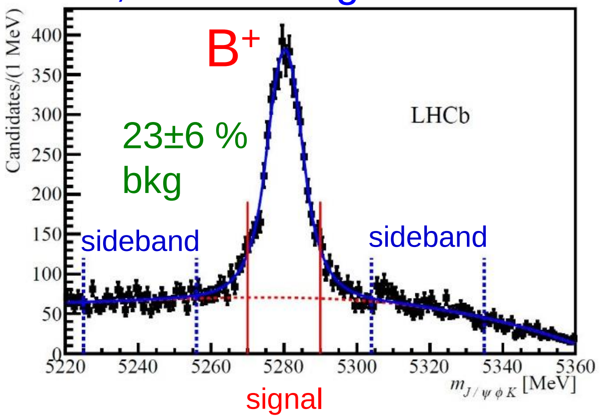
not-prompt



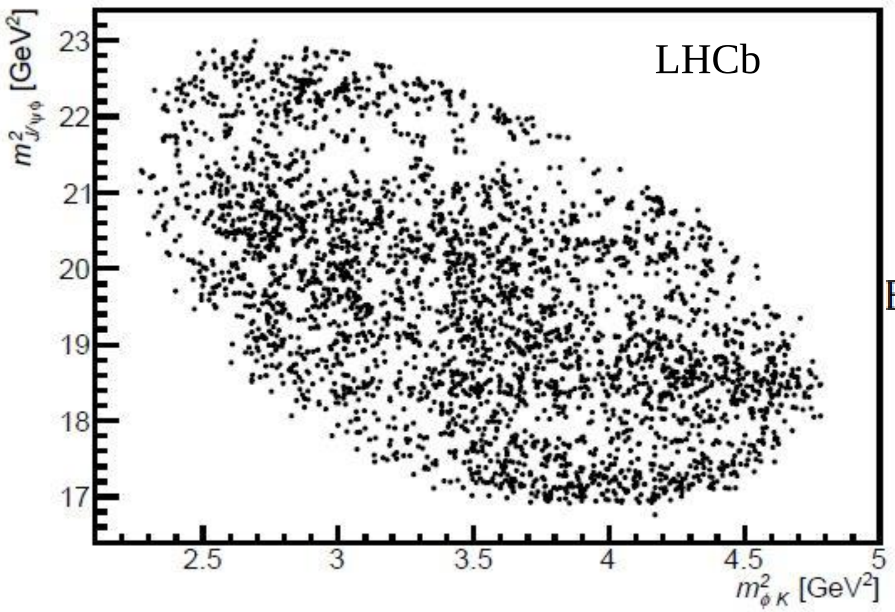
(events dominated by non-ϕ bkg.)

$B^+ \to J/\psi\ \phi\ K^+$

4,289±151 signal events



signal range

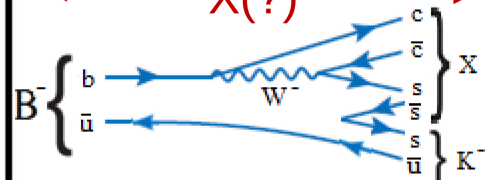


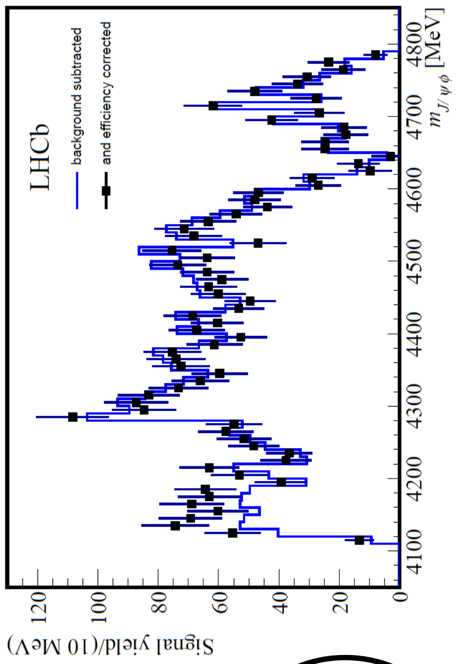
X(?)

X(?)

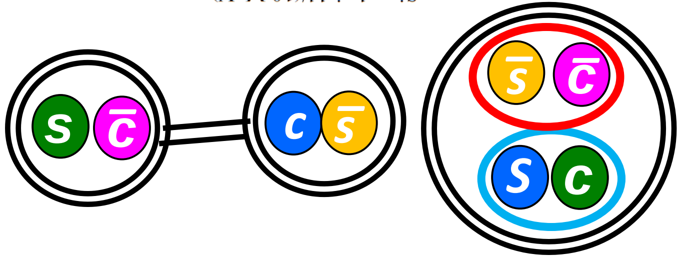
X(4274) ?

X(4140) ?
$\to J/\psi\phi$

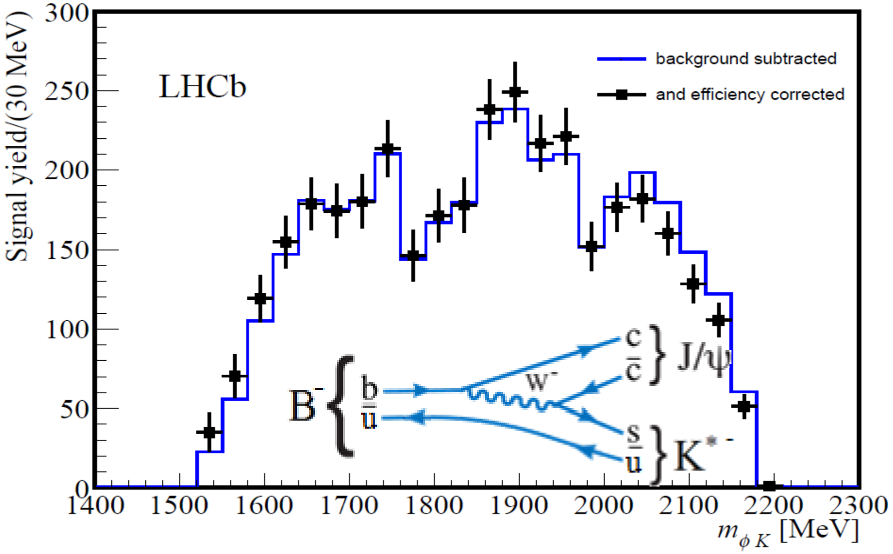




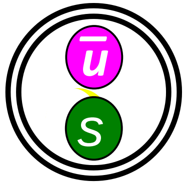
Tetraquarks or $D_s\bar{D}_s$ molecules

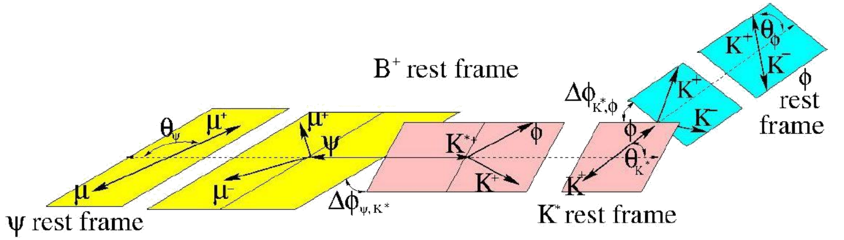


Perform first amplitude analysis (6D) of $B^+ \to J/\psi\ \phi\ K^+$



Kaon excitations



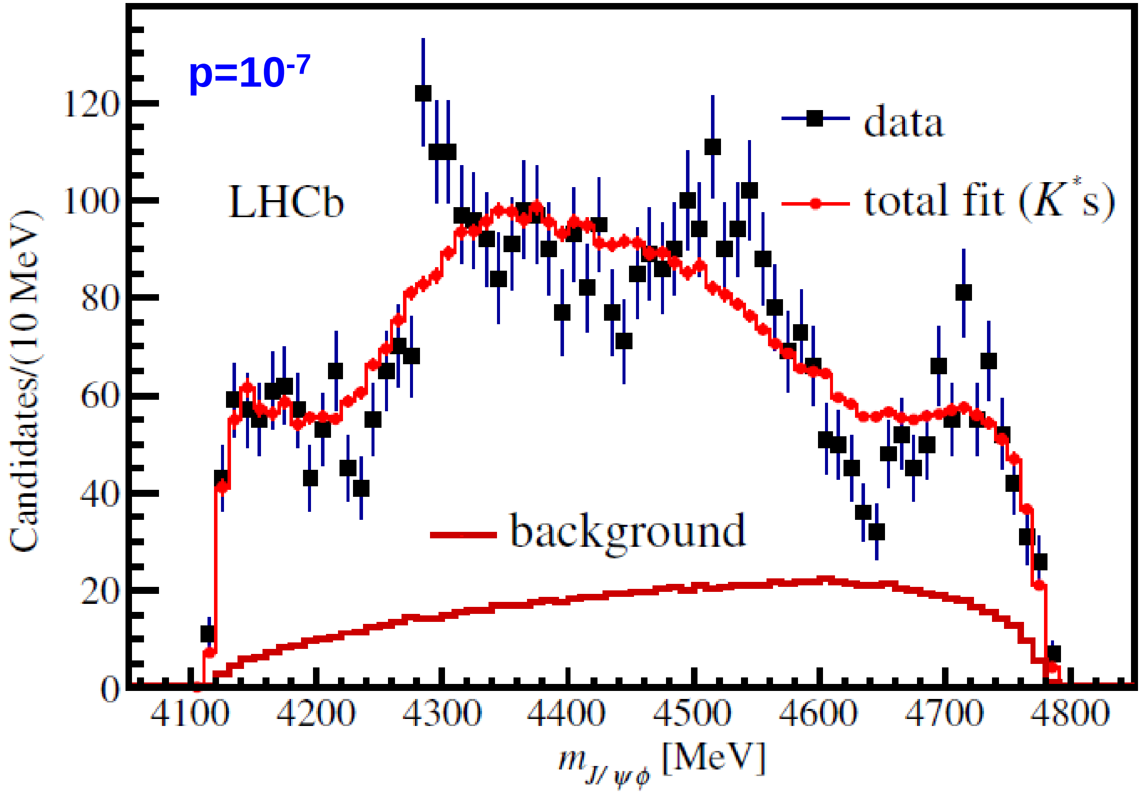


LHCb PRL118, 022003 (2017)
PR, D95, 012002 (2017)

Amplitude fit results

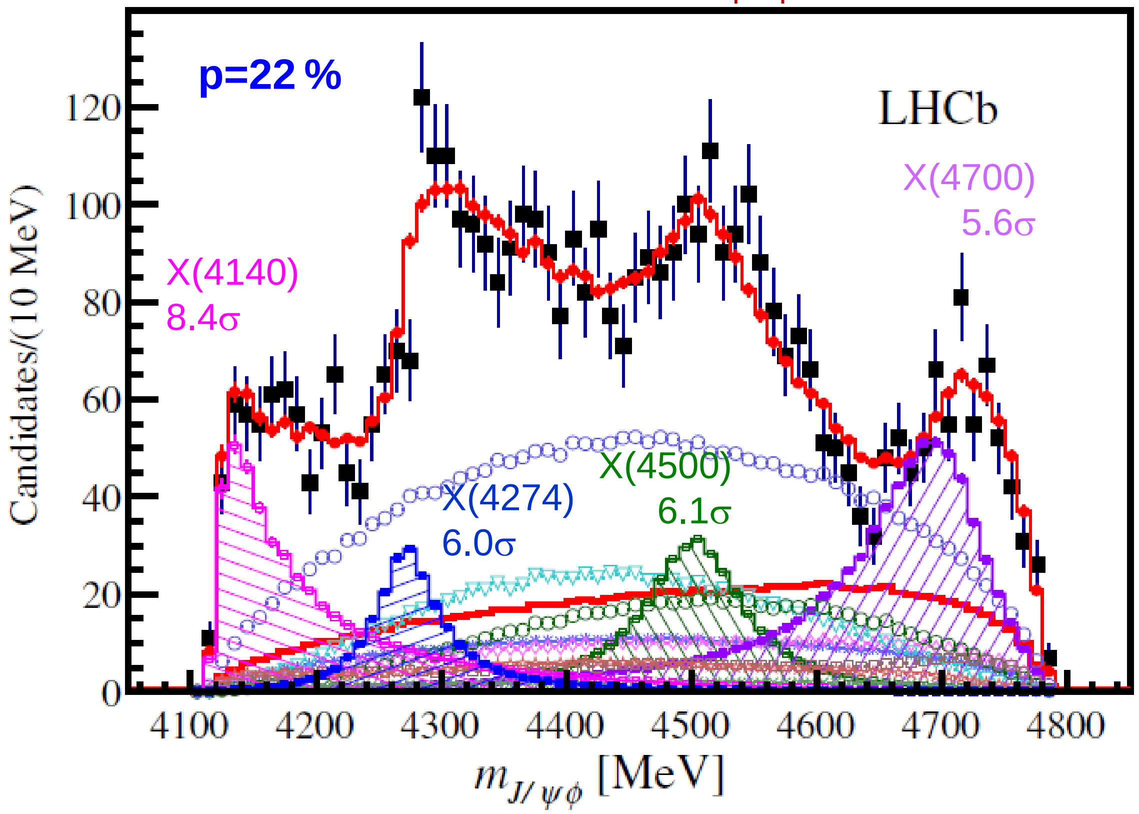
LHCb PRL118, 022003 (2017)
PR, D95, 012002 (2017)

$B^+ \to J/\psi K^{*+}$, $K^{*+} \to \phi K^+$ **only**

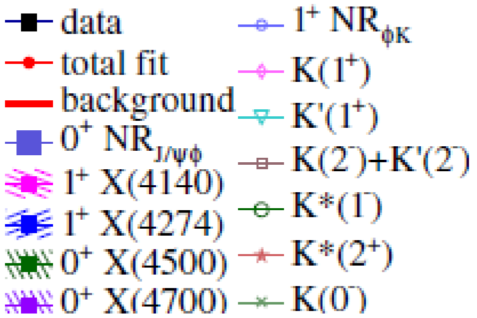


NR ϕK 1^+, two $2P_{1+}$, two $2D_{2-}$, and one of 1^3F_{3+}, 1^3D_{1-}, 3^3S_{1-}, 3^1S_{0-}, 2^3P_{2+}, 1^3F_{2+}, 1^3D_{3-}, 1^3F_{4+}. Fit 104 free parameters.

$+ B^+ \to X K^+$, $X \to J/\psi \phi$



NR ϕK 1+, two $2P_{1+}$, two $2D_{2-}$, and one of 1^3D_{1-}, 3^1S_{0-}, 2^3P_{2+}. Two 1^+ X, Two 0^+ X, NR 0^+ $J/\psi\phi$. Fit 98 free parameters.



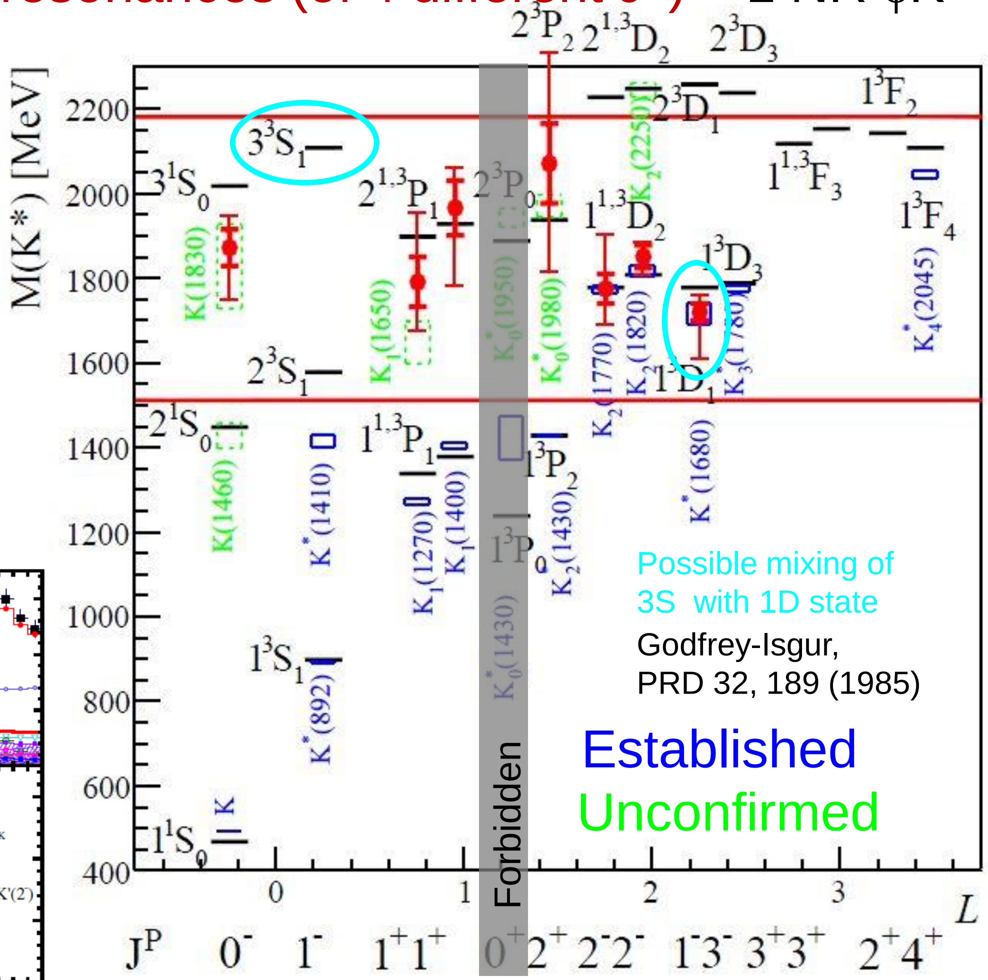
- Unlike in the other amplitude analyses, K^{*+} resonance composition (number,J^P,m,Γ) are not constrained to other experimental results (little is known about high mass kaon excitations)

$B^+ \to J/\psi\, K^{*+}$, $K^{*+} \to \phi\, K^+$

Default model: 6 K* resonances (of 4 different J^P) + 1 NR ϕK

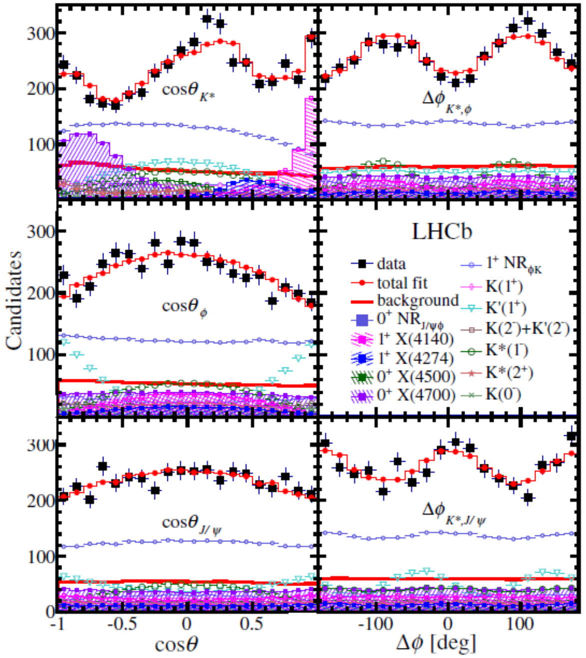
LHCb PRL118, 022003 (2017)
PR, D95, 012002 (2017)

LHCb results are given by the red points with error bars

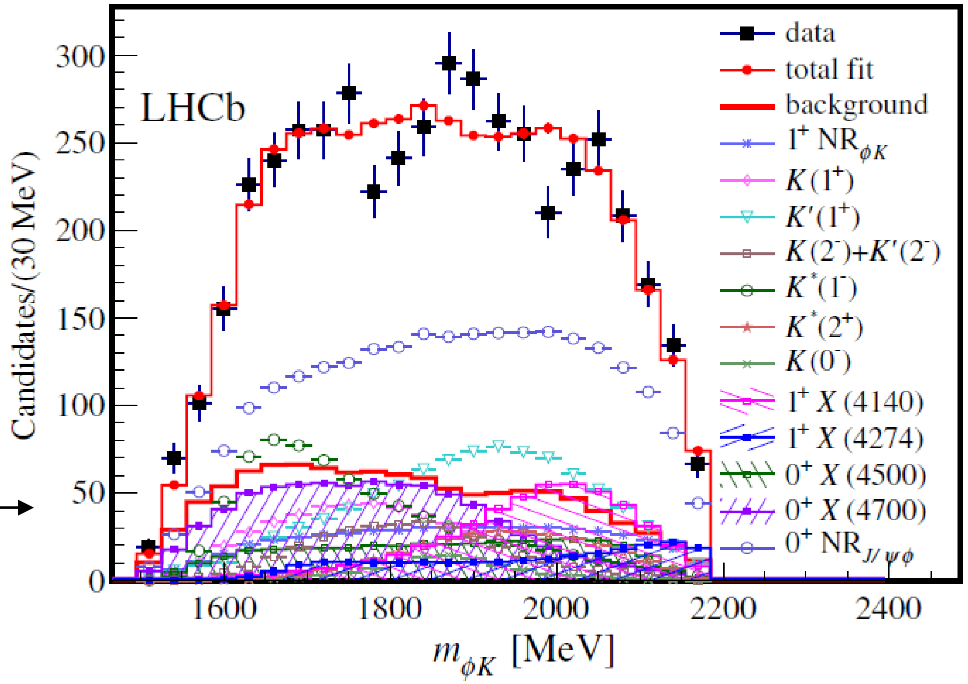


High spin states (3-4) not observed but also expected to be suppressed by orbital angular momentum barrier in B decay

Excellent agreement between the LHCb results and both the QM expectations and the previous experiments



$m_{\phi K}$ is featureless
but angular correlations resolve various K* resonances



Amplitude fit results

LHCb PRL118, 022003 (2017)
PR, D95, 012002 (2017)

Contribution	Significance or Reference	M_0 (MeV)	Γ_0 (MeV)	FF (%)
All $K(1^+)$	8.0σ			$42 \pm 8^{+5}_{-9}$
$NR_{\phi K}$				$16 \pm 13^{+35}_{-6}$
$K(1^+)$	7.6σ	$1793 \pm 59^{+153}_{-101}$	$365 \pm 157^{+138}_{-215}$	$12 \pm 10^{+17}_{-6}$
2^1P_1	[53]	1900		
$K_1(1650)$	[36]	1650 ± 50	150 ± 50	
$K'(1^+)$	1.9σ	$1968 \pm 65^{+70}_{-172}$	$396 \pm 170^{+174}_{-178}$	$23 \pm 20^{+31}_{-29}$
2^3P_1	[53]	1930		
All $K(2^-)$	5.6σ			$11 \pm 3^{+2}_{-5}$
$K(2^-)$	5.0σ	$1777 \pm 35^{+122}_{-77}$	$217 \pm 116^{+221}_{-154}$	
1^1D_2	[53]	1780		
$K_2(1770)$	[36]	1773 ± 8	188 ± 14	
$K'(2^-)$	3.0σ	$1853 \pm 27^{+18}_{-35}$	$167 \pm 58^{+83}_{-72}$	
1^3D_2	[53]	1810		
$K_2(1820)$	[36]	1816 ± 13	276 ± 35	
$K^*(1^-)$	8.5σ	$1722 \pm 20^{+33}_{-109}$	$354 \pm 75^{+140}_{-181}$	$6.7 \pm 1.9^{+3.2}_{-3.9}$
1^3D_1	[53]	1780		
$K^*(1680)$	[36]	1717 ± 27	322 ± 110	
$K^*(2^+)$	5.4σ	$2073 \pm 94^{+245}_{-240}$	$678 \pm 311^{+1153}_{-559}$	$2.9 \pm 0.8^{+1.7}_{-0.7}$
2^3P_2	[53]	1940		
$K_2^*(1980)$	[36]	1973 ± 26	373 ± 69	
$K(0^-)$	3.5σ	$1874 \pm 43^{+59}_{-115}$	$168 \pm 90^{+280}_{-104}$	$2.6 \pm 1.1^{+2.3}_{-1.8}$
3^1S_0	[53]	2020		
$K(1830)$	[36]	~ 1830	~ 250	
All $X(1^+)$				$16 \pm 3^{+6}_{-2}$
$X(4140)$	8.4σ	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	$13.0 \pm 3.2^{+4.8}_{-2.0}$
Averages from	Table I	4147.1 ± 2.4	15.7 ± 6.3	
$X(4274)$	6.0σ	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	$7.1 \pm 2.5^{+3.5}_{-2.4}$
CDF	[29]	$4274.4^{+8.4}_{-6.7} \pm 1.9$	$32^{+22}_{-15} \pm 8$	
CMS	[25]	$4313.8 \pm 5.3 \pm 7.3$	$38^{+30}_{-15} \pm 16$	
All $X(0^+)$				$28 \pm 5 \pm 7$
$NR_{J/\psi\phi}$	6.4σ			$46 \pm 11^{+11}_{-21}$
$X(4500)$	6.1σ	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	$6.6 \pm 2.4^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	$12 \pm 5^{+9}_{-5}$

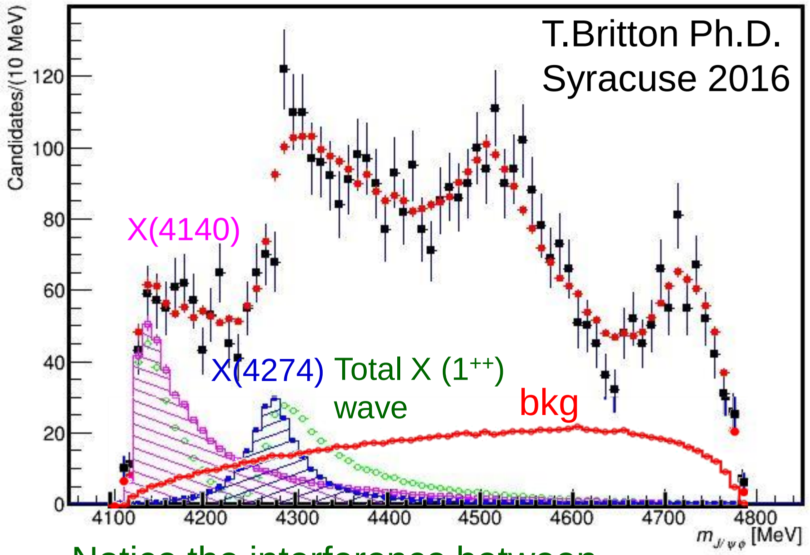
FF ~ 65% $B^+ \to J/\psi\, K^{*+}$, $K^{*+} \to \phi\, K^+$

- The most sizable contribution of "exotic" part of the amplitude among analyzed B decay channels (related to the smallest Q in the B decay?)

FF ~44% $B^+ \to X\, K^+$, $X \to J/\psi\, \phi$

X(1⁺⁺)

http://surface.syr.edu/etd/510/



Notice the interference between the two 1^{++} states!

LHCb PRL118, 022003 (2017)
PR, D95, 012002 (2017)

Contribution	sign. or Ref.	M_0 MeV	Γ_0 MeV	F.F. %
All $X(1^+)$				$16\pm3\ ^{+\ 6}_{-\ 2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\ ^{+4.6}_{-2.8}$	$83\pm21\ ^{+21}_{-14}$	$13.0\pm3.2\ ^{+4.8}_{-2.0}$
ave.		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		$4274.4\ ^{+8.4}_{-6.7}\pm1.9$	$32\ ^{+22}_{-15}\pm8$	
CMS		$4313.8\pm5.3\pm7.3$	$38\ ^{+30}_{-15}\pm16$	

X(4140): Good consistency in mass; 2.6σ tension in width — Γ ↗, ΔΓ ↗

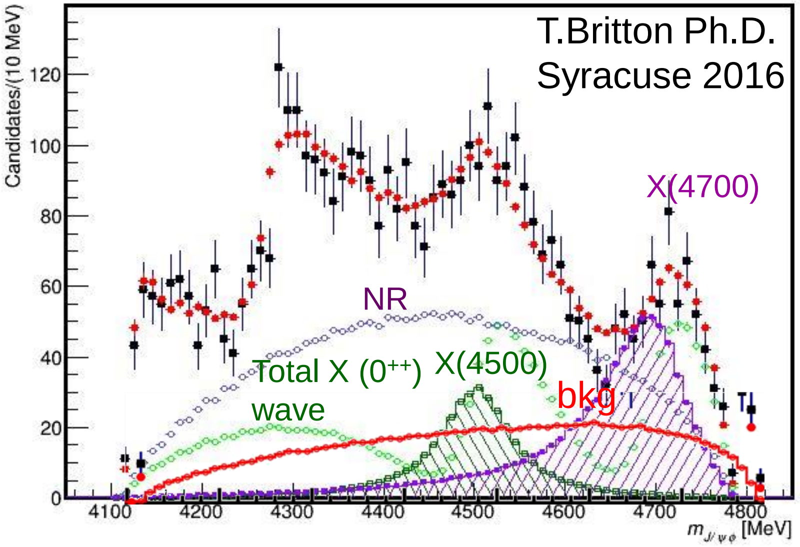
X(4274) / CDF: Good consistency

CDF / CMS: 3.2σ disagreement in mass

- Significant X(4140) 8.4σ,
  - mass consistent with the previous measurements, but the width substantially larger (2.6σ "tension" with the previous 1D fits)
  - $J^{PC}=1^{++}$ determined at 5.7σ including systematic errors
- Significant X(4274) 6.0σ,
  - Consistent with the unpublished CDF results. First significant claim for this structure.
  - $J^{PC}=1^{++}$ determined at 5.8σ including systematic errors

X(0^{++})

http://surface.syr.edu/etd/510/



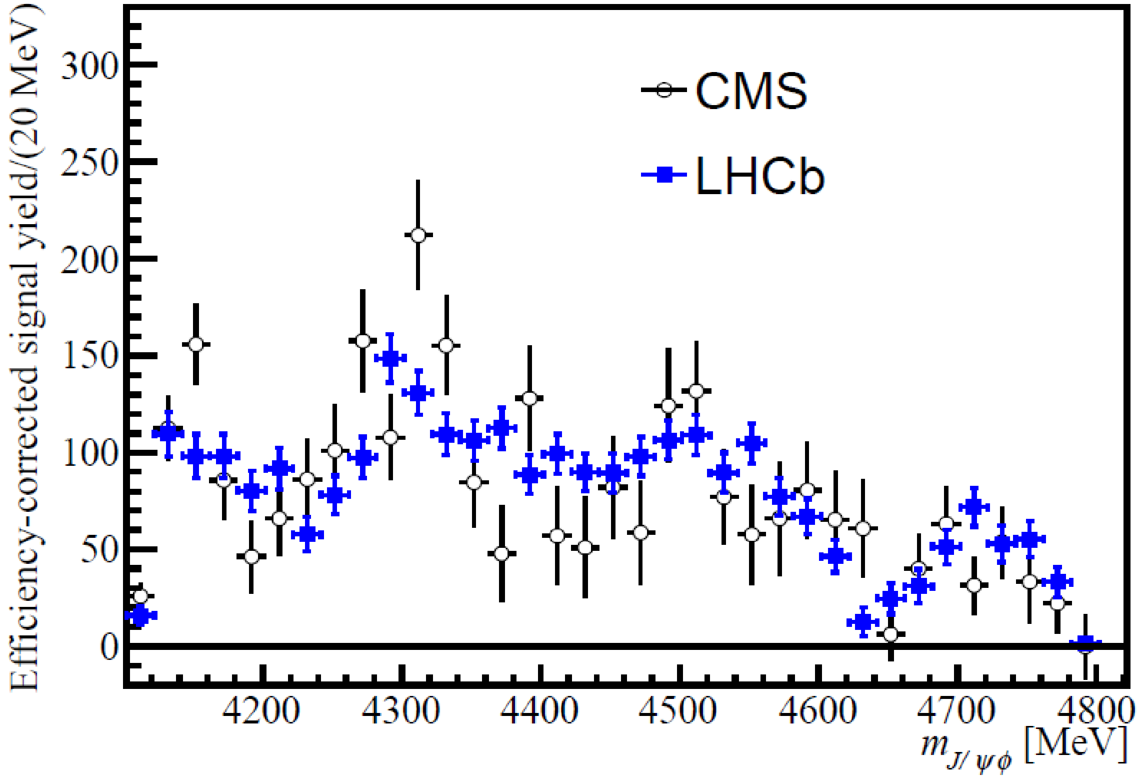
First observations

Contri-bution	sign.	M_0 MeV	Γ_0 MeV	F.F. %
All $X(0^+)$				$28\pm\ 5\ ^{+7}_{-7}$
$NR_{J/\psi\phi}$	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	$4704\pm10\ ^{+14}_{-24}$	$120\pm31\ ^{+42}_{-33}$	$12\pm\ 5\ ^{+\ 9}_{-\ 5}$

- Significant structures at higher masses, best described by two new 0^{++} resonances X(4500),X(4700):
  - Significances of 6.1σ, 5.6σ
  - $J^{PC}=0^{++}$ determined at 4.0σ, 4.5σ, respectively
  - Hints of these structures can be found in Belle & CMS data (see next)

LHCb vs CMS data

- Compare $m_{J/\psi\phi}$ to the CMS data (the previous best sample).
- Non-B background subtracted, corrected for signal efficiency.



Used publically available CMS background-free distribution and CMS efficiency dependence on $m_{J/\psi\phi}$

LHCb efficiency corrections via 6D parameterization of efficiency in all dimensions of the decay phase-space.

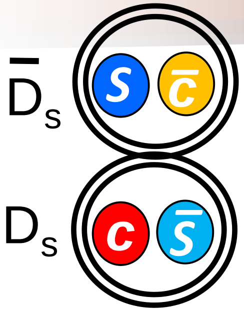
Normalized to the same area.

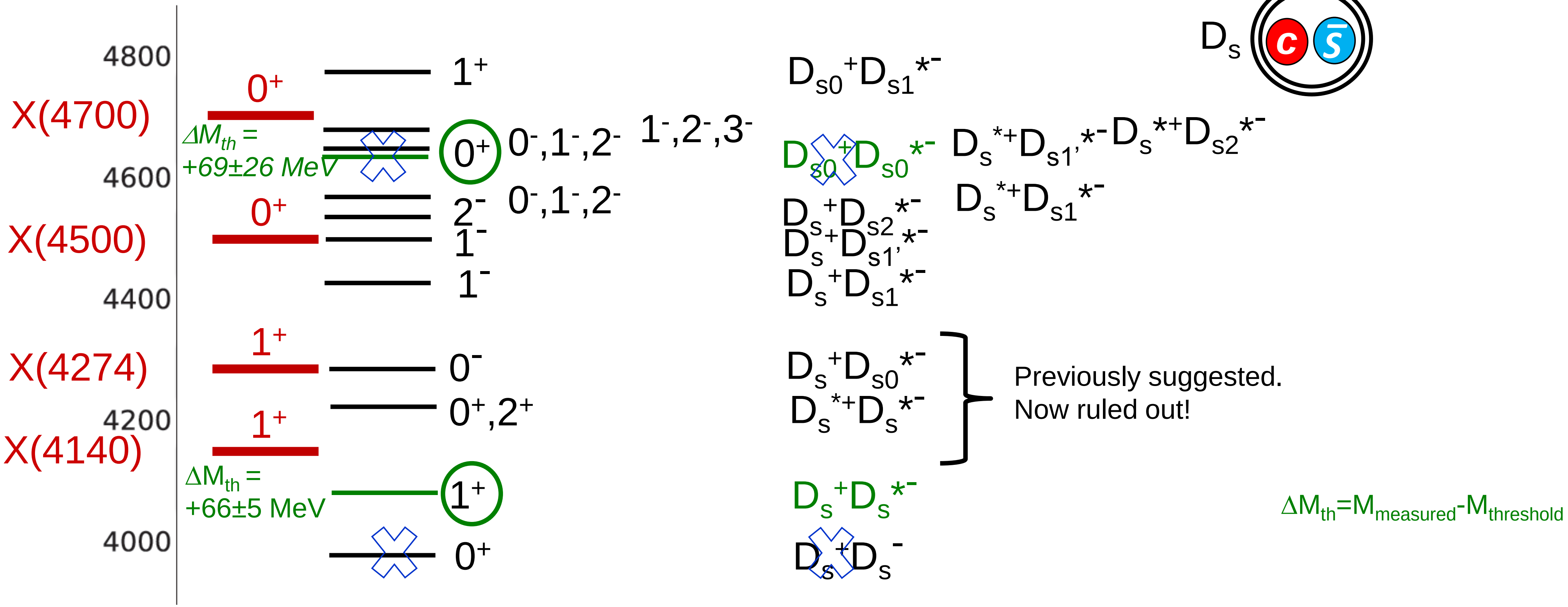
The vertical scale is arbitrary.

- LHCb data more precise.
- Qualitative agreement over the full mass range.
- Can’t rely on naïve 1D mass fits to determine resonant composition.

Interpretation of J/ψφ structures?

- A molecule/threshold effect?





No π-exchange forces (*I*=0)!

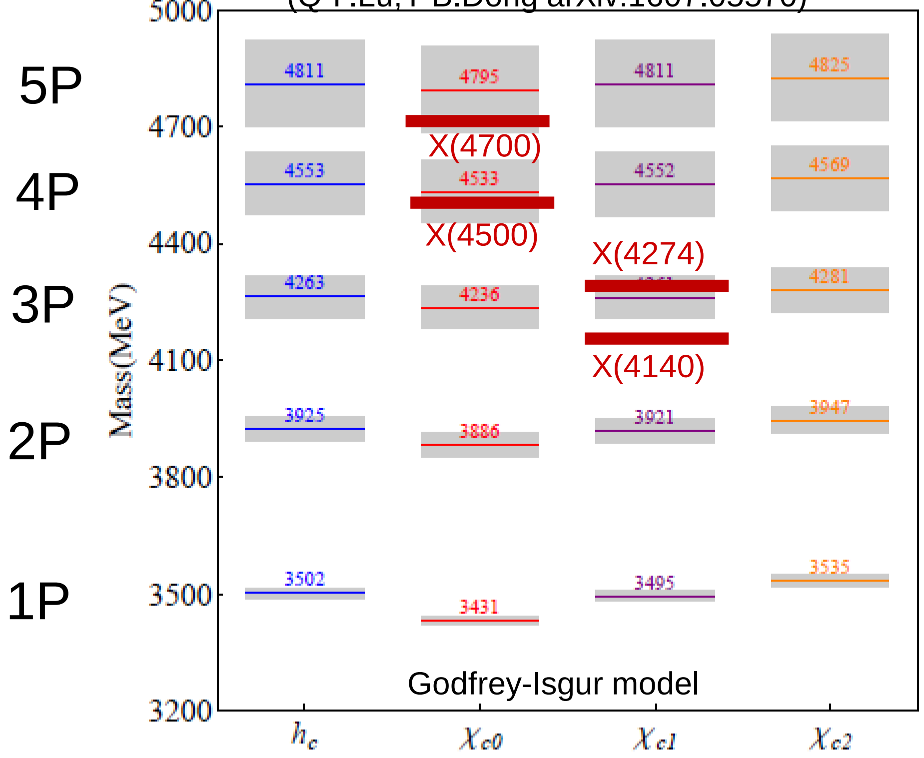
η-exchange possible (unless crossed-over above) (M.Karliner,J.L.Rosner arXiv:1601.00565)

- Except for X(4140) being possibly affected by a $D_s^+D_s^{*-}$ threshold, the observed J/ψφ structures don't fit the D_{sJ}(*)-pair mass thresholds or their quantum numbers.

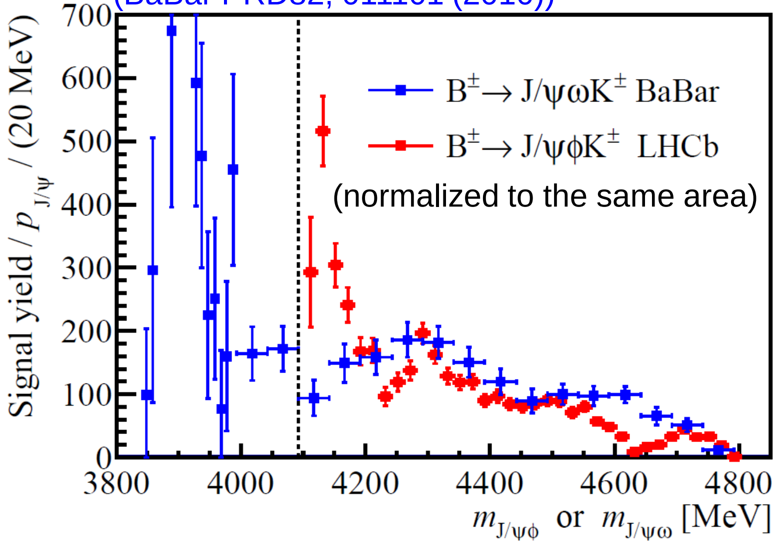
Interpretation of J/ψϕ structures?

- P-wave charmonia?

(Q-F.Lu,Y-B.Dong arXiv:1607.05570)



(BaBar PRD82, 011101 (2010))



It is possible to find matching χ_{cJ}(nP) states but the J^P-mass patterns are different

χ_{cJ}(nP) states would couple to J/ψϕ and J/ψω the same way.
The J/ψϕ structures do not show up in J/ψω spectrum.

- Not a plausible explanation.

Interpretation of J/ψϕ structures?

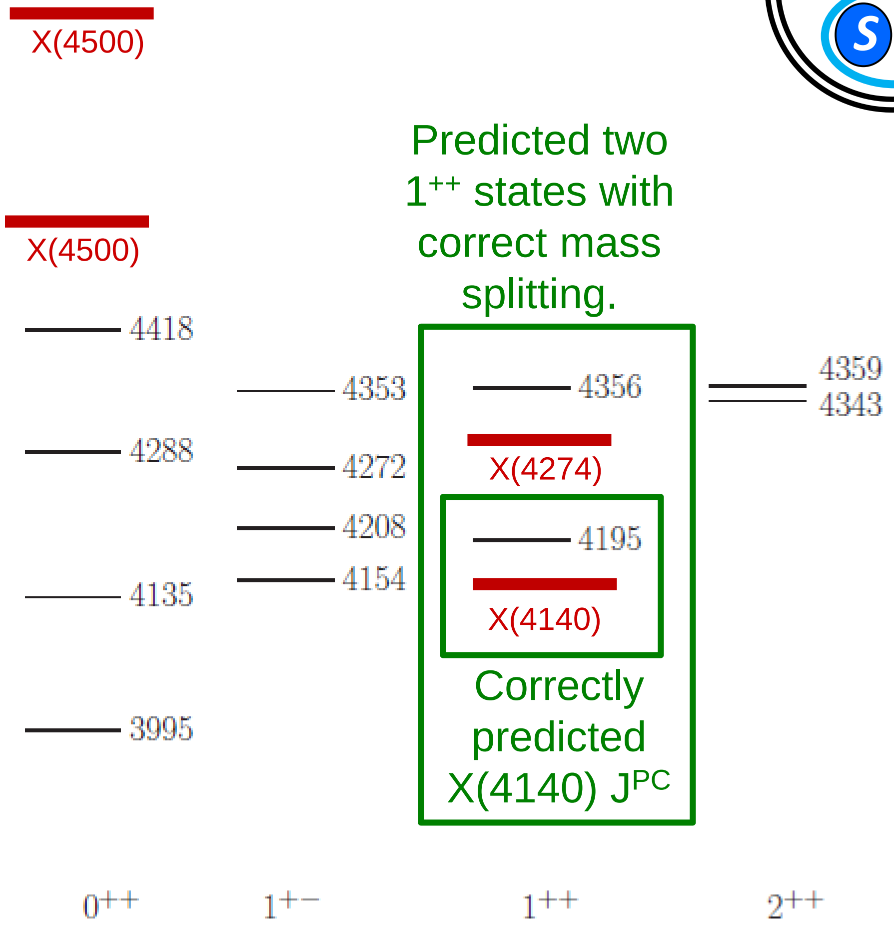
- Tetraquarks?

PREDICTION

F. Stancu,
J. Phys. G37 (2010) 075017, arXiv:0906.2485

Allow S=0 and S=1 diquarks.
Allow diquarks in color triplet and sextet configurations.

Calculated n=0,L=0 states.



MANY POSTDICTIONS

e.g. L. Maiani, A.D. Polosa, V. Riquer **arXiv:1607.02405**

Allow diquarks only in color triplet configuration; cuts # of states in half. Only one 1^{++} state.
Describe X(4500),X(4700) 0^{++} states as the radial excitations (n=1).

Conclusions - I

- There are a number of very significant $[c\bar{c}\bar{u}d]$ structures observed in $B \to [(c\bar{c})\pi^+]K$ decays. Interpretations of them is far from clear.
  - Only one, $Z_c(4430)^+ \to \psi(2S)\pi^+$, was observed by two experiments, but there is no reason to doubt the others, $Z_c(4200)^+ \to J/\psi\pi^+$ (confirmation needed), at least one $Z_c^+ \to \chi_{c1}\pi^+$ (confirmation and J^P determination are needed).
  - $Z_c(4430)^+$ was observed in 2^{nd} decay mode ($\to J/\psi\pi^+$), but a confirmation of this, especially with mass and width free in the fit, will be important. $Z_c(4200)^+$ is also likely present in $\psi(2S)\pi^+$, which requires a clarification. Non-observation in the other decay modes (e.g. in Cabibbo suppressed $B \to [(c\bar{c})\pi^+]\pi$ decays) needs to be quantified.
  - They are both 1^+ (S wave decay possible) and require $l = 1$ in the parity-violating production in the B decay ($0^- \to 1^+0^-$), just like πK S wave in $B \to (J/\psi, \psi(2S))[\pi^+ K]$ ($0^- \to 1^-0^+$). Dominance of the lowest angular momenta not surprising for any dynamics, but why aren't we seeing other J^P values in $[\psi\pi^+]$ like we do in $[\pi^+ K]$ system? Need 6D amplitude fits to $B \to \chi_{c1}\pi^+K$ to verify the claimed $\chi_{c1}\pi^+$ states and determine their quantum numbers .
  - Argand diagrams for $Z_c(4430)^+$ and $Z_c(4200)^+$ are consistent with resonances, but improvements in experimental uncertainties are highly desired.
  - They are not the same as the structures observed in $e^+e^- \to [J/\psi\pi^+]\pi^-$, $e^+e^- \to [\psi(2S)\pi^+]\pi^-$,… Exotic hadron model builders need to take this into account (the current trend is to ignore it).
  - Why aren't we seeing $[c\bar{c}\bar{q}s]$ (q=u or d) exotics?

Conclusions - II

- Low fit fraction signals, e.g. $B \to [(J/\psi)\pi^+]K$, may be susceptible to the approximations made in matrix element formulation (e.g. sum over Breit-Wigners); ought to explore better approximations.
- Isospin partners in $B \to [(c\bar{c})\pi^0]K$? Quantitative results from coupled-channels $B \to [c\bar{u}][\bar{c}d]K$?

- There are four significant $[c\bar{c}\bar{s}s]$ structures observed in $B \to [J/\psi\phi]K$. Interpretations of them is also unclear.
  - X(4140) is well established. Evolution of its width determination has follow the $Z_c(4430)^+$ path ($\Gamma \nearrow$, $\Delta\Gamma \nearrow$). Results for any resonance with observable decay width should not be trusted without amplitude analysis.
  - X(4274) is also rather well established.
  - Their quantum numbers were determined to be 1^{++} in complex amplitude analysis. They require independent confirmation.
  - Observation of X(4140) in prompt production in high energy $p\bar{p}$ collisions has been claimed. If confirmed this would be the only 2nd exotic hadron candidate observed in B decays and in prompt productions (after X(3872)). Why would X(4140) be produced promptly, but not X(4274)?
  - X(4500),X(4700) 0^+ states, and a significant non-resonant 0^+ $J/\psi\phi$ component were also needed to describe the data well. All require independent confirmation.
  - Studies of coupled-channels $B \to [c\bar{s}][\bar{c}s]K$ are highly desired.
- Further progress in understanding of exotic meson candidates observed in amplitude analyses of B decays will only by made by more experimental studies:
  - Good prospects for substantially larger data samples in upgraded LHCb, Belle II, …