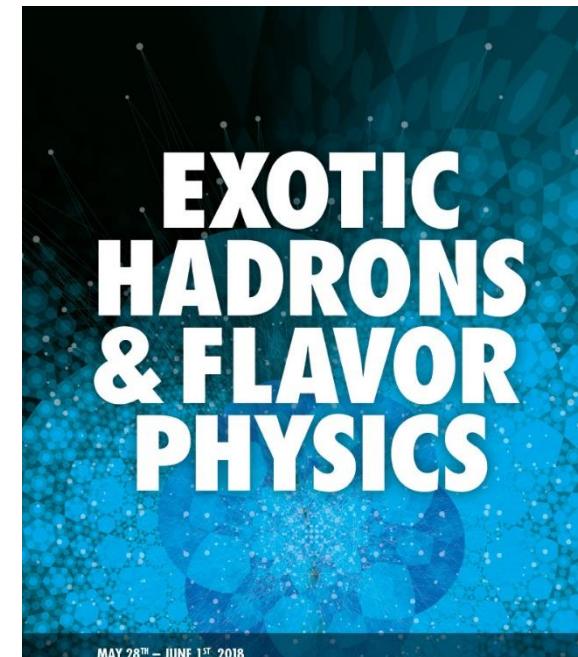


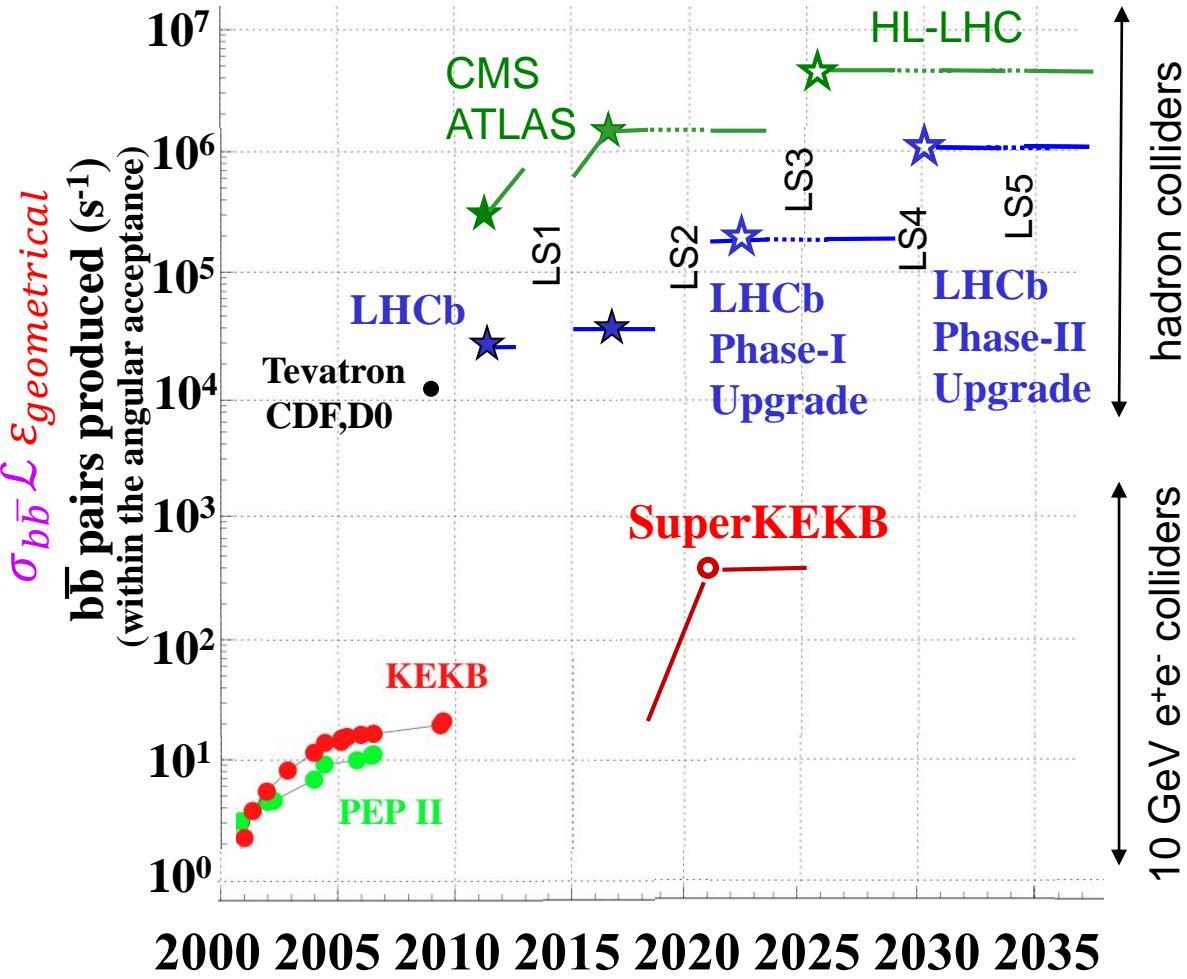
Exotic hadrons at LHCb

Tomasz Skwarnicki

Syracuse University



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}
 $\sqrt{s_{pp}}$ 7-8 TeV 13 TeV 14 TeV 14 TeV (27 TeV HE-LHC?)

- 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 $\sim 10\text{-}100$ in integrated B_s rates at hadronic colliders vs e^+e^- machines
 - 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
 - Clean source of c -hadrons via $b \rightarrow c W^{*+}$
- Prompt charm rates factor of 10 higher than beauty rates:
 - **nuisance and great physics opportunity at the same time**

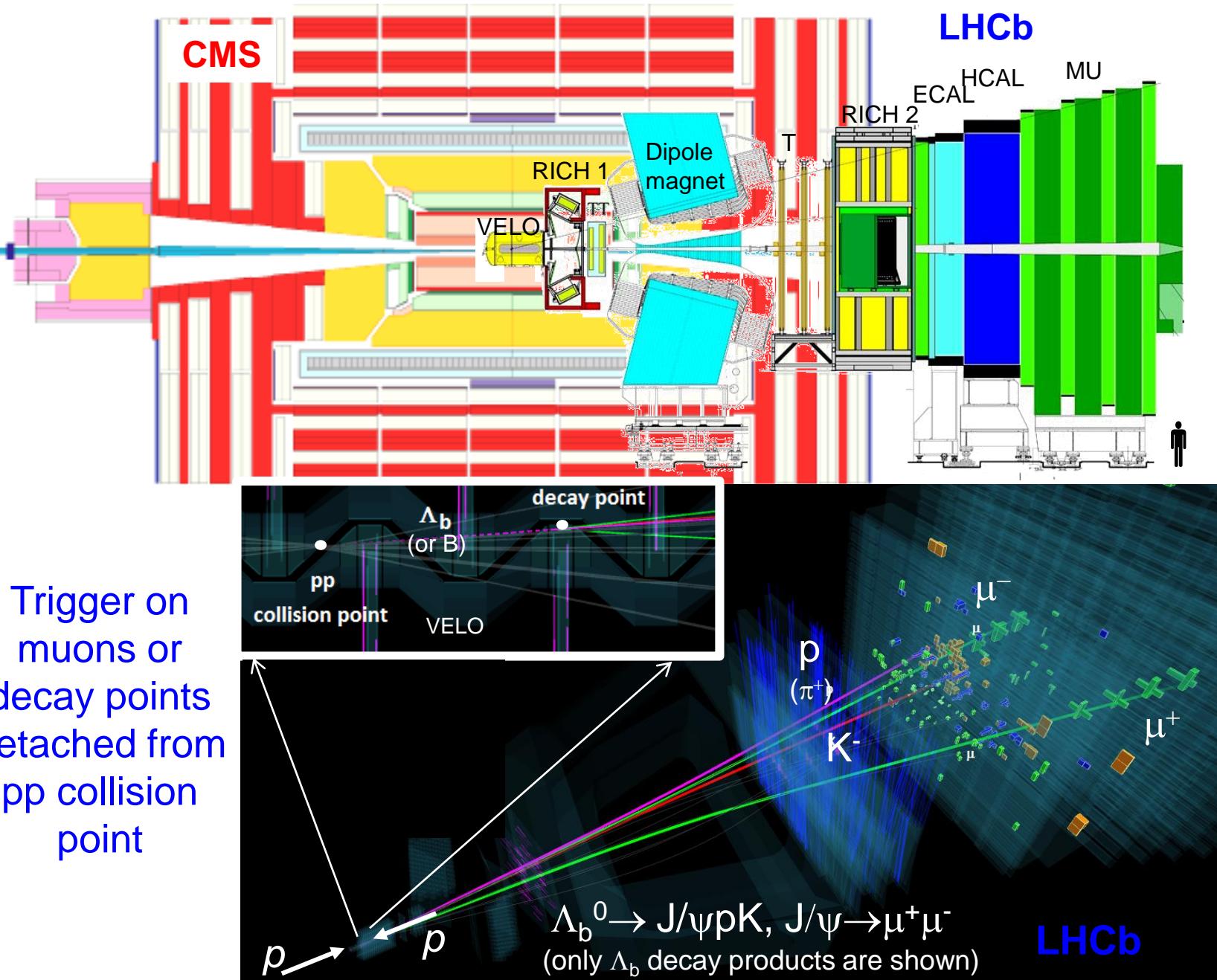
$$\begin{aligned}
 \text{detected events} &= \frac{\text{produced events}}{\sigma_{b\bar{b}} \int \mathcal{L} dt} \times \text{detector efficiency} \\
 N &= \frac{\sigma_{b\bar{b}} \int \mathcal{L} dt}{\epsilon} \cdot \epsilon_{\text{trigger}} \cdot \epsilon_{\text{rest}}
 \end{aligned}$$

$\epsilon = \epsilon_{\text{geometrical}} \cdot \epsilon_{\text{trigger}} \cdot \epsilon_{\text{rest}}$

large

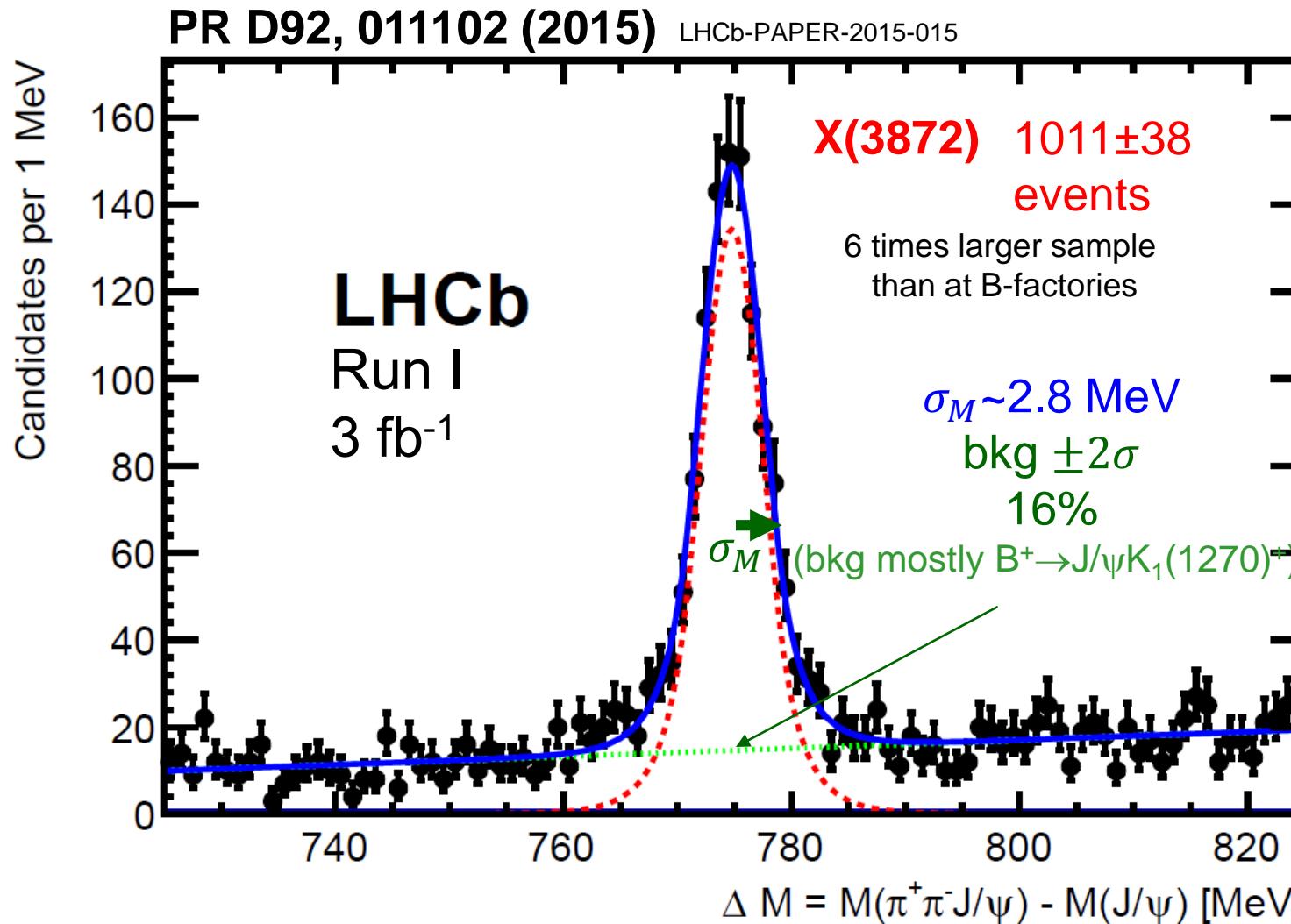
major challenge for b,c physics at hadron colliders

LHCb vs central detectors



- 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 $p \sim p_T$); 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 charm samples**
 - space for RICH detectors: **$p/K/\pi$ 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**)

Reconstruction of X(3872) in exclusive B decays



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

vs. Belle

$\sigma_M \sim 2.3 \text{ MeV}$ PRD84 (2011) 052004
bkg $\pm 2\sigma$
18%

Belle set $\Gamma < 1.2 \text{ MeV}$
at 90% C.L.

LHCb already has a better sensitivity to the natural width than in the Belle analysis.

	LHCb U. Phase I II				Belle II	
Decay mode	3 fb ⁻¹	8 fb ⁻¹	50 fb ⁻¹	300 fb ⁻¹	0.7 ab ⁻¹	50 ab ⁻¹
$B^+ \rightarrow K^+ X(3872)$ ($\rightarrow J/\psi \pi^+ \pi^-$)	1k	5k	33k	200k	0.17k	11k

Many other production channels possible:

$B^0 \rightarrow X(3872)\pi^+K^-$, $B^+ \rightarrow X(3872)\pi^+$, $B_s^0 \rightarrow X(3872)K^+K^-$,
 $B_c^+ \rightarrow X(3872)\pi^+$, $\Lambda_b^0 \rightarrow X(3872)pK^-$, ...

Determination of X(3872) J^{PC}

Analysis of 5D angular correlations in the decay:

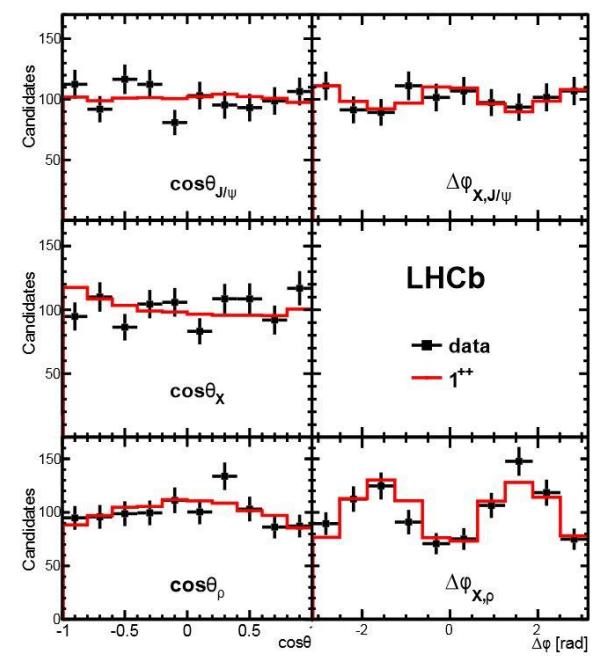
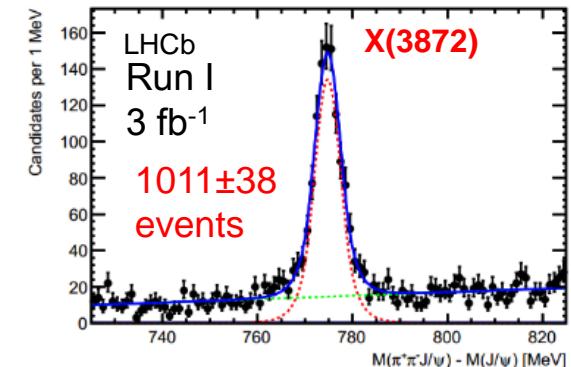
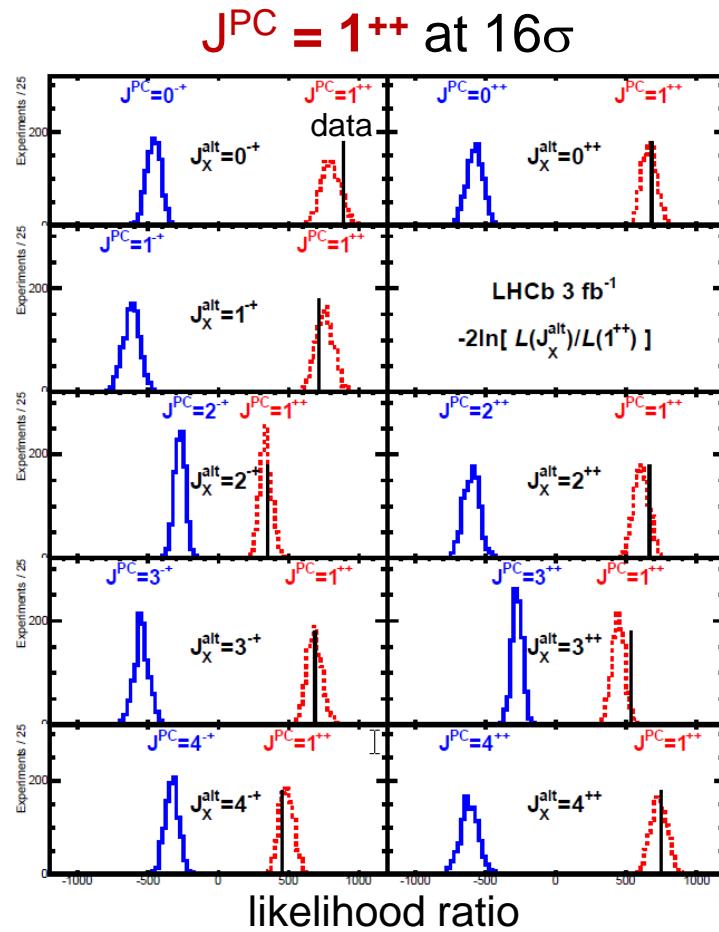
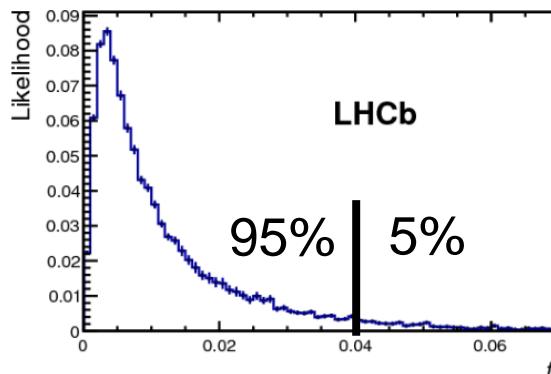
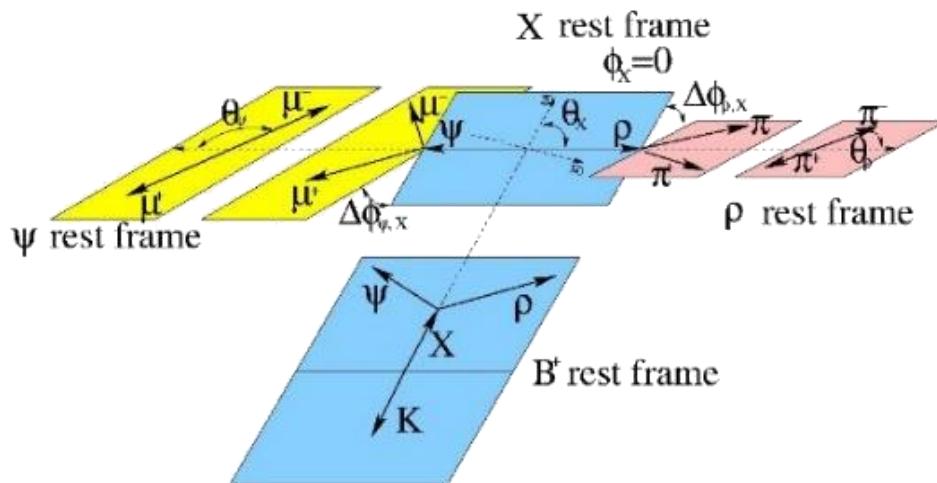
$B^+ \rightarrow X(3872) K^+$, $X(3872) \rightarrow J/\psi \rho$, $J/\psi \rightarrow \mu^+ \mu^-$, $\rho \rightarrow \pi^+ \pi^-$

PRL 110, 222001 (2013),

PR D92, 011102 (2015) LHCb-PAPER-2015-015

Bin Gui Ph.D. Syracuse 2014

<https://surface.syr.edu/etd/189/>



This measurement ruled out $\eta_c(1^1D_2)$.

Remaining options:

$\chi_{c1}(2^3P_1)$ or exotic hadron

Probing $X(3872) \rightarrow J/\psi \omega$

Isospin violating decay

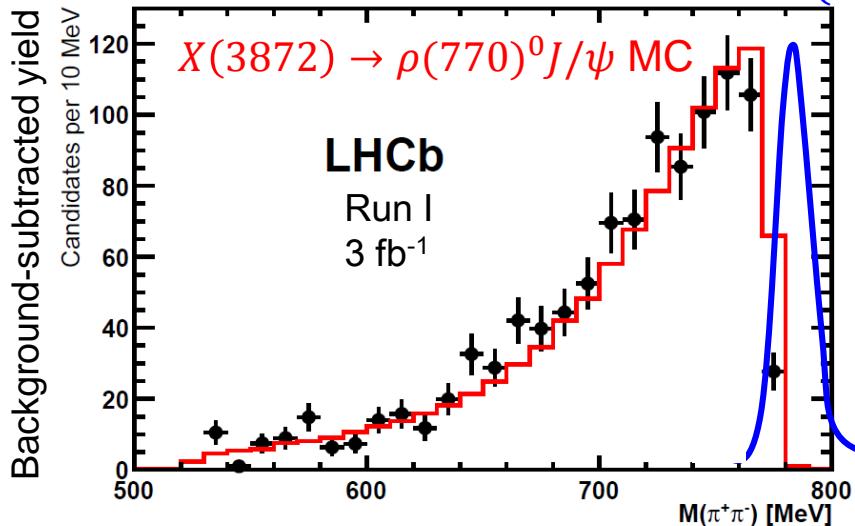
$B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow J/\psi \pi^+\pi^-$, $J/\psi \rightarrow \mu^+\mu^-$

The amplitude analysis for J^{PC} determination averaged over $M(\pi^+\pi^-)$

<http://cds.cern.ch/record/2012165/files/LHCb-PAPER-2015-015-supplemental.zip> $\omega(782)$

The most precise determination of $M(\pi^+\pi^-)$.

LHCb has recorded more data since then!

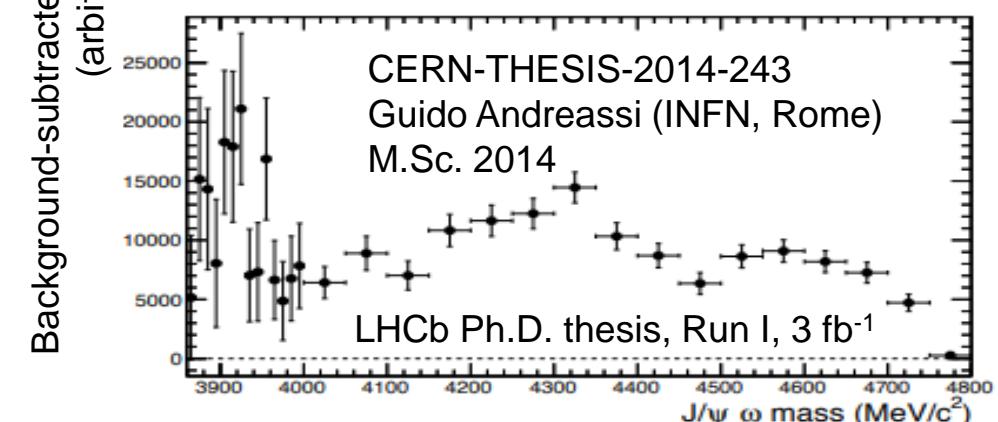
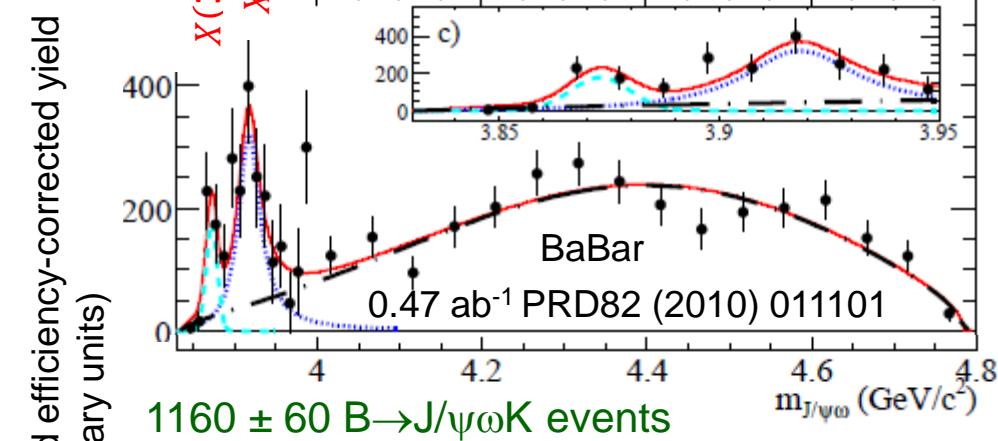


On-going projects: include $M(\pi^+\pi^-)$ in the amplitude fit and determine $\omega(782)$ contribution interfering with $\rho(770)^0$.

	LHCb		U. Phase I		Belle	
Decay mode	3 fb ⁻¹	8 fb ⁻¹	50 fb ⁻¹	300 fb ⁻¹	0.7 ab ⁻¹	50 ab ⁻¹
$B^+ \rightarrow K^+ X(3872)(\rightarrow J/\psi \pi^+\pi^-)$	1k	5k	33k	200k	0.17k	11k
$B^+ \rightarrow K^+ J/\psi \omega(782)(\rightarrow \pi^+\pi^-\pi^0)$	1.7k	7k	43k	340k		40-120k

Isospin conserving decay

$B^+ \rightarrow K^+ J/\psi \omega(782)$, $J/\psi \rightarrow \mu^+\mu^-$
 $\omega(782) \rightarrow \pi^+\pi^-\pi^0$



Radiative decays of X(3872)

phase-space:

LHCb NP B886 (2014) 665
LHCb-PAPER-2014-008

$$\frac{\text{BR}(X(3872) \rightarrow \psi(2S)\gamma)}{\text{BR}(X(3872) \rightarrow J/\psi(1S)\gamma)} = 2.48 \pm 0.64 \pm 0.29 \quad (>0 \text{ at } 4.4\sigma)$$

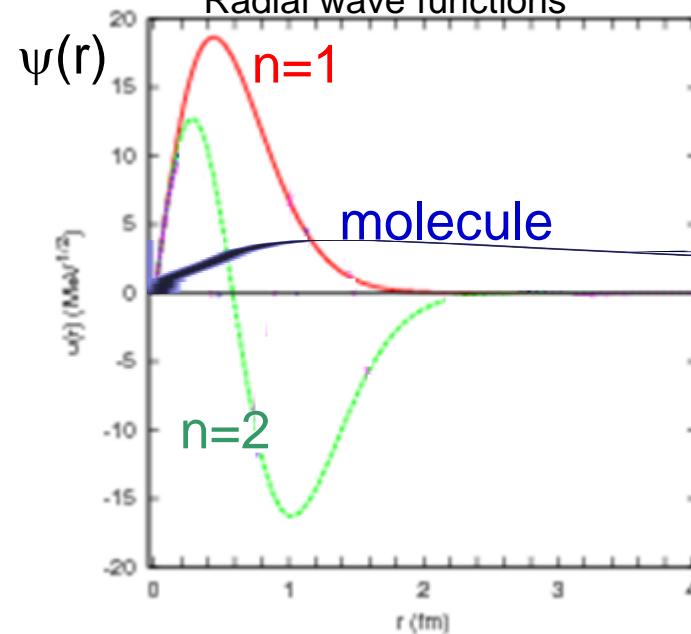
suppressed

favored

by a factor of $\sim 100!$

$$\text{BR} \sim | \langle \psi_f | r | \psi_i \rangle |^2 E_\gamma^3$$

Radial wave functions



$$| \langle 2S | r | 2P \rangle |^2 \gg | \langle 1S | r | 2P \rangle |^2$$

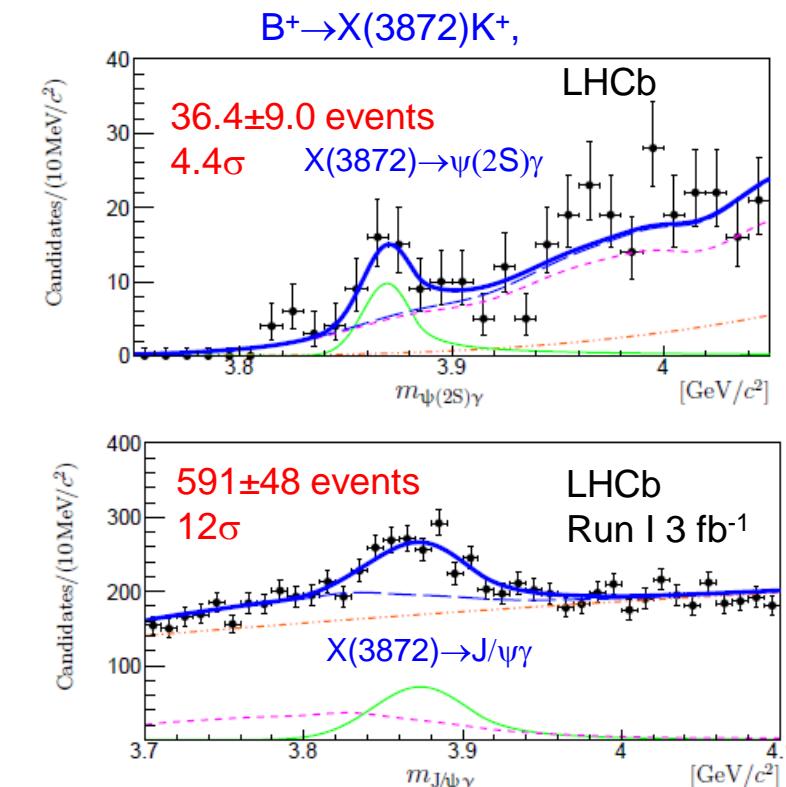
$$\chi_{c1}(2^3P_{1++})$$

$$| \langle 2S | r | \text{mole.} \rangle |^2 \ll | \langle 1S | r | \text{mole.} \rangle |^2$$

molecule

Hard to find mechanism to favor $\psi(2S)\gamma$ over $J/\psi(1S)\gamma$ other than $2P \rightarrow 2S$

- Does not rule out $D\bar{D}^*$ component at large distances
(F.-K. Guo et al., PL B742, 394 (2015); arXiv:1410.6712)

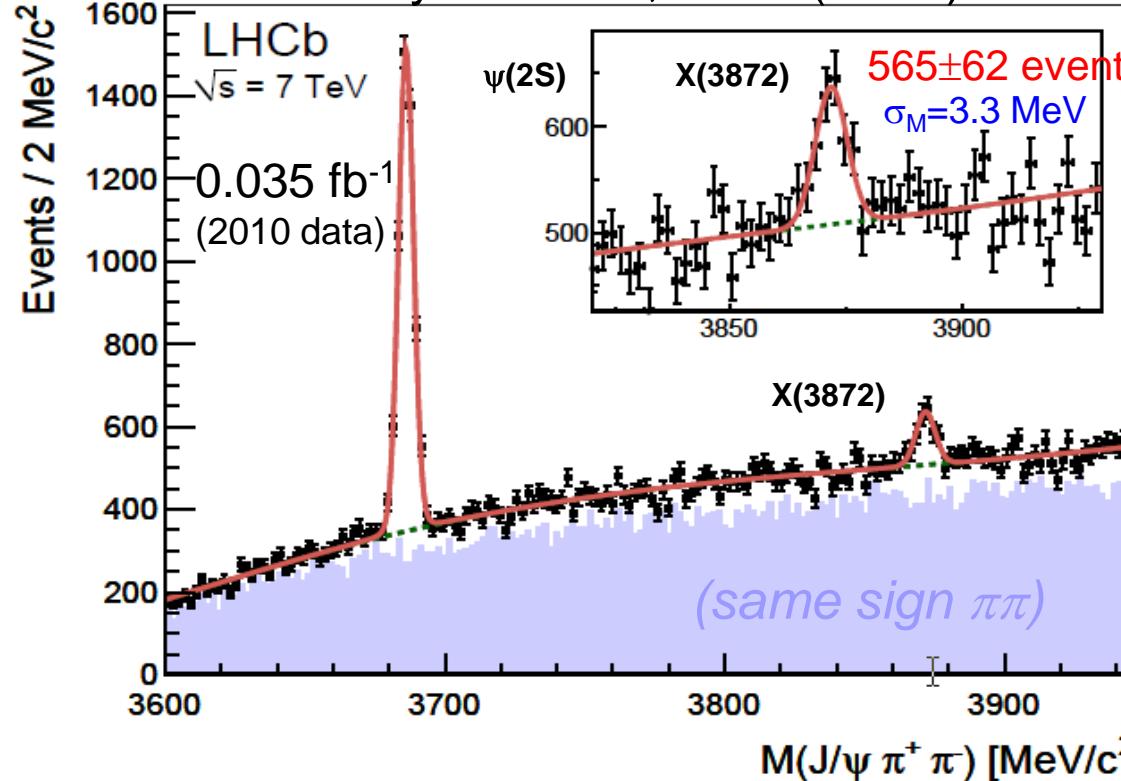


	LHCb		U. Phase I II		Belle II	
Decay mode	3 fb⁻¹	8 fb⁻¹	50 fb⁻¹	300 fb⁻¹	0.7 ab⁻¹	50 ab⁻¹
$B^+ \rightarrow K^+ X(3872) \quad (\rightarrow \psi(2S)\gamma)$	36	0.2k	1k	7k		4k
$B^+ \rightarrow K^+ X(3872) \quad (\rightarrow J/\psi(1S)\gamma)$	0.6k	2.4k	15k	90k	36	2k

Prompt production of X(3872) at LHCb

LHCb-PAPER-2011-034

LHCb Eur. Phys. J. C72, 1972 (2012)



$$M[X(3872)] = 3871.95 \pm 0.48 \pm 0.12 \text{ MeV}$$

vs CDF $3871.61 \pm 0.16 \pm 0.19 \text{ MeV}$

Belle $3871.84 \pm 0.27 \pm 0.19 \text{ MeV}$

PDG $3871.69 \pm 0.17 \text{ MeV}$

$$M(D^0) + M(D^{0*}) = 3871.68 \pm 0.10 \text{ MeV}$$

$$M[\psi(2S)] = 3686.12 \pm 0.06 \pm 0.10 \text{ MeV}$$

vs PDG $3686.10 \pm 0.03 \text{ MeV}$

(inclusive X(3872); dominated by prompt production)

	LHCb $p_T > 5 \text{ GeV}$ 7 TeV	CMS $p_T > 10 \text{ GeV}$ 7 TeV	ATLAS $p_T > 10 \text{ GeV}$ 8 TeV
Resolution (σ)	$\sim 3.3 \text{ MeV}$	$\sim 6 \text{ MeV}$	$\sim 6 \text{ MeV}$
signal yield	$\sim 16.1 \text{k/fb}^{-1}$	$\sim 2.5 \text{k/fb}^{-1}$	$\sim 2.6 \text{k/fb}^{-1}$
bkg/signal in $\pm 2\sigma$	5.8	8.6	11.1

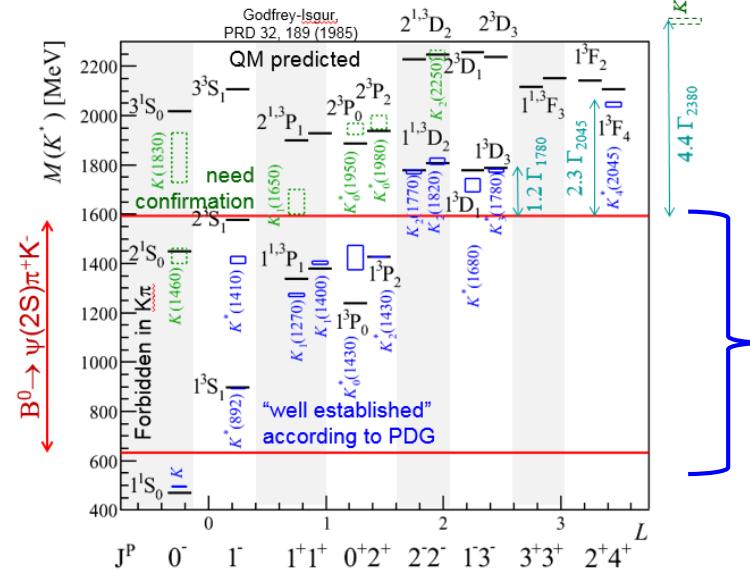
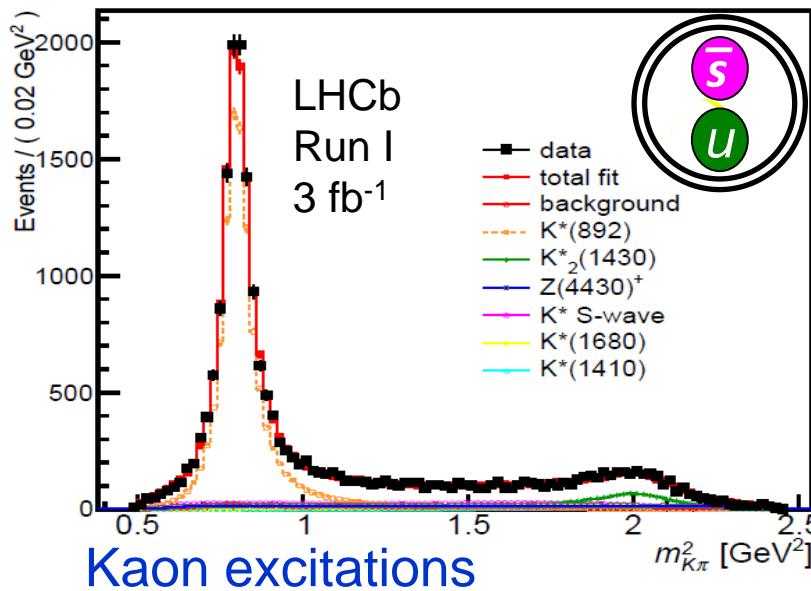
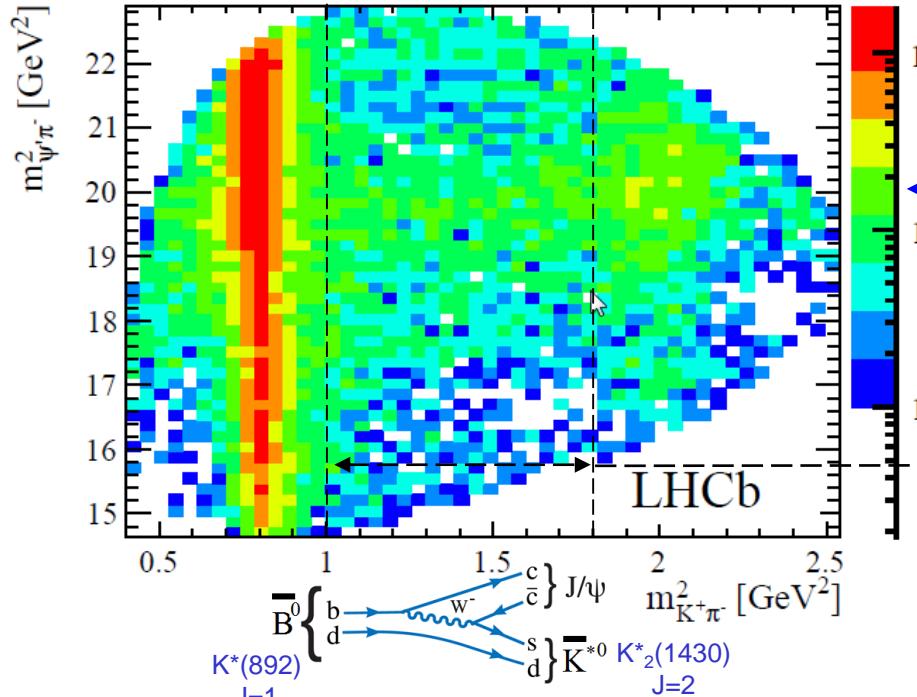
Lower trigger thresholds lead to higher production cross-sections at LHCb, which offset lower luminosities.

Better mass resolution provides for smaller backgrounds.

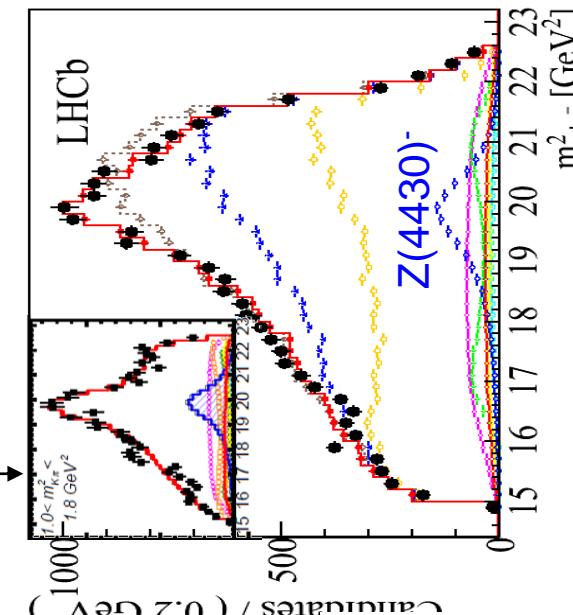
	LHCb U. Phase			
	I	II		
Decay mode	0.03 fb ⁻¹	8 fb ⁻¹	50 fb ⁻¹	300 fb ⁻¹
$pp \rightarrow X(3872) + \dots$ ($\rightarrow J/\psi \pi^+ \pi^-$)	0.6k	130k	0.8M	4.8M

LHCb is also in position to improve X(3872) mass measurement. Since systematics will dominate, exclusive modes may be more suitable for mass and width determination. (work in progress)

Prompt production cross-section in forward region will also be re-measured.

$B^0 \rightarrow \psi(2S)\pi^+K^-$ 

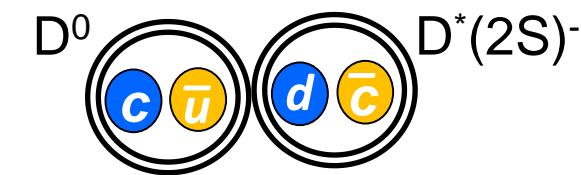
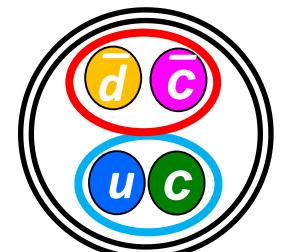
PRL 112, 222002 (2014)



The results improved on the earlier characterization of $Z(4430)^-$ by Belle.

4 expected and well experimentally established kaon resonances in the amplitude fit

include tail of $K^*_3(1780)$ in model variations

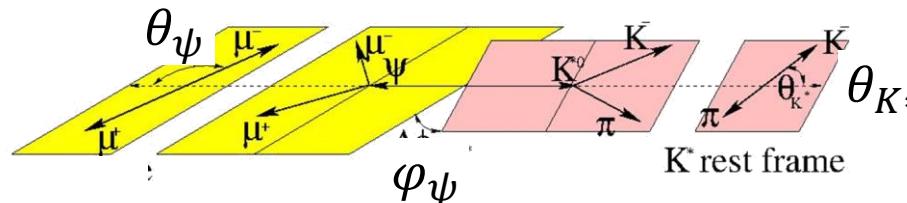


Amplitude analysis of $B^0 \rightarrow \psi(2S)\pi^+K^-$

4D maximum likelihood fit

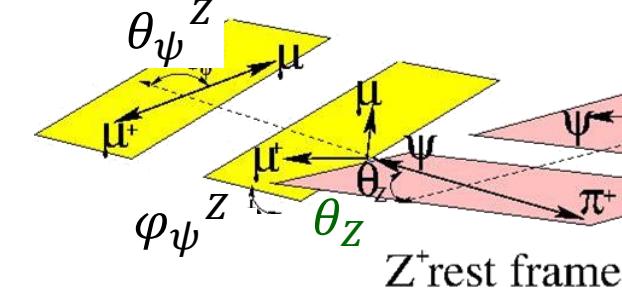
$$(m_{K\pi}^2, m_{\psi\pi}^2, \theta_\psi, \varphi_\psi)$$

ψ rest frame via boost
from B (or K^*) rest frame

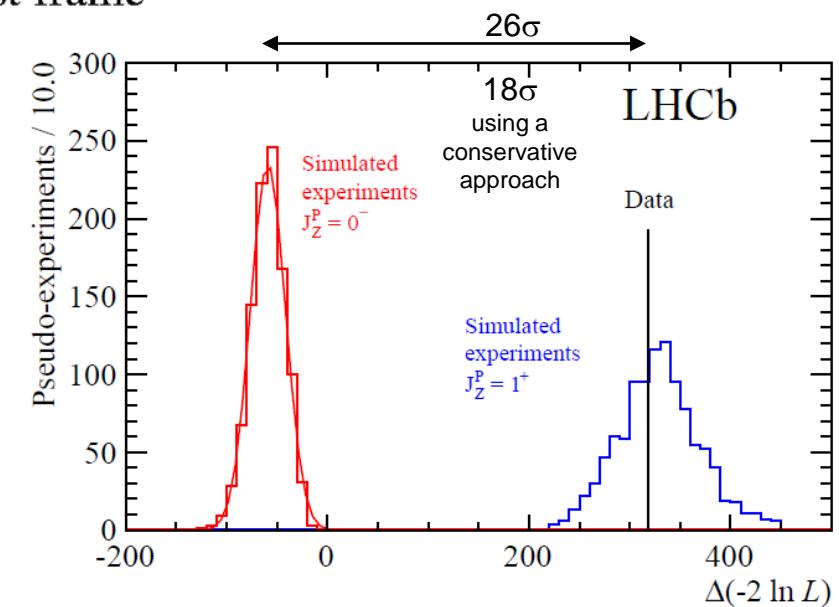
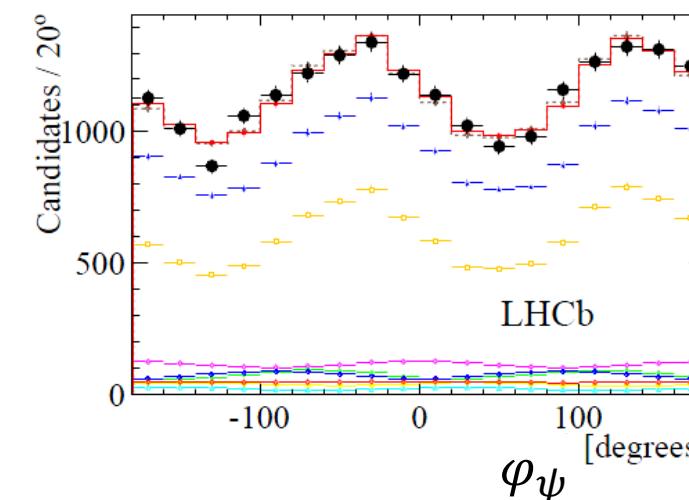
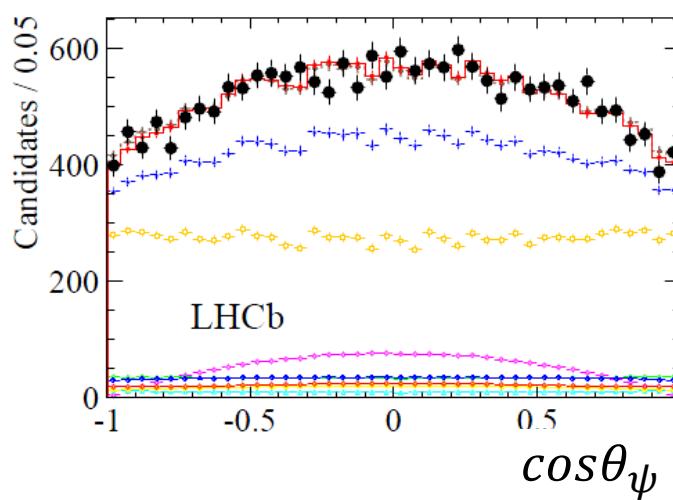


B^0 rest frame

ψ rest frame via boost
from Z rest frame



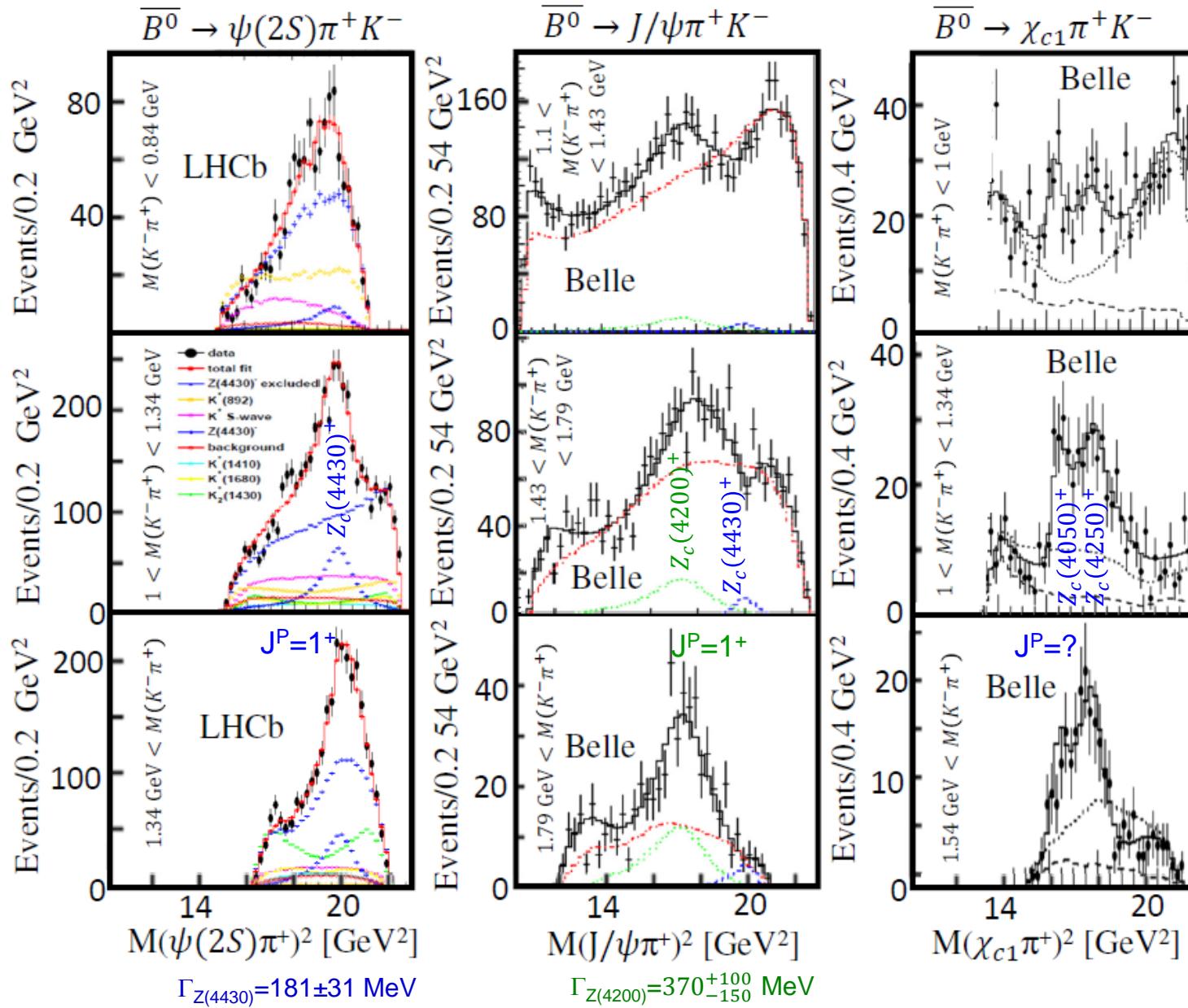
B^0 rest frame



- Use of all decay angles in the fit, in addition to the Dalitz plane, improves sensitivity of the analysis, especially to J^P of various contributions

Charged charmonium-like states in B decays

Amplitude analyses used to distinguish $\bar{K}^*0 \rightarrow \pi^+ K^-$ and $(c\bar{c})\pi^+$ contributions



$Z_c(4200)^+$, $Z_c(4050)^+$, $Z_c(4250)^+$
await confirmation (LHCb has
enough data to do it already)

$Z_c(3900)^+$ and $Z_c(4020)^+$
observed in $e^+e^- \rightarrow \pi^- Z_c^+$, not
observed in $B \rightarrow K Z_c^+$, (and
vice versa).

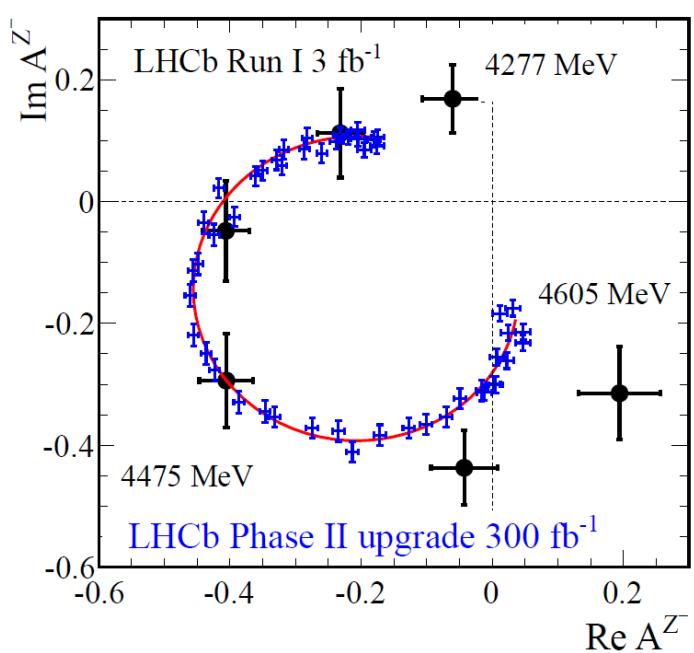
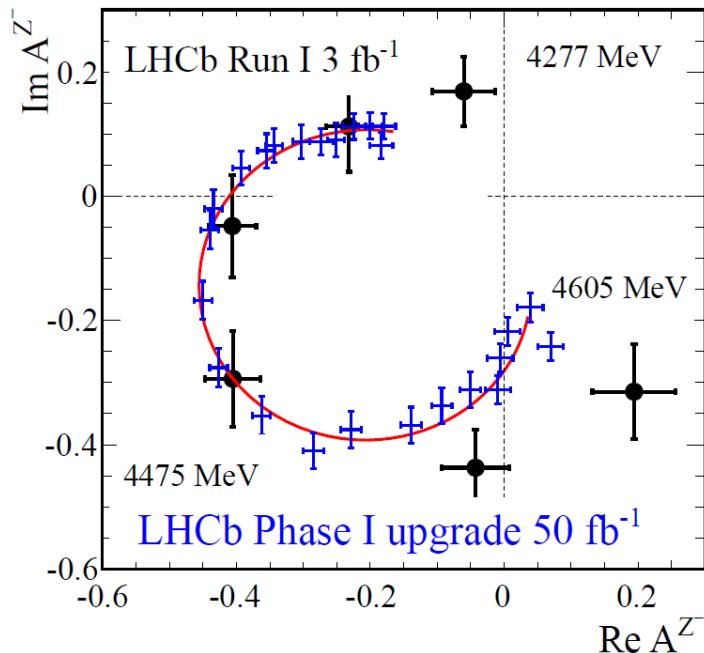
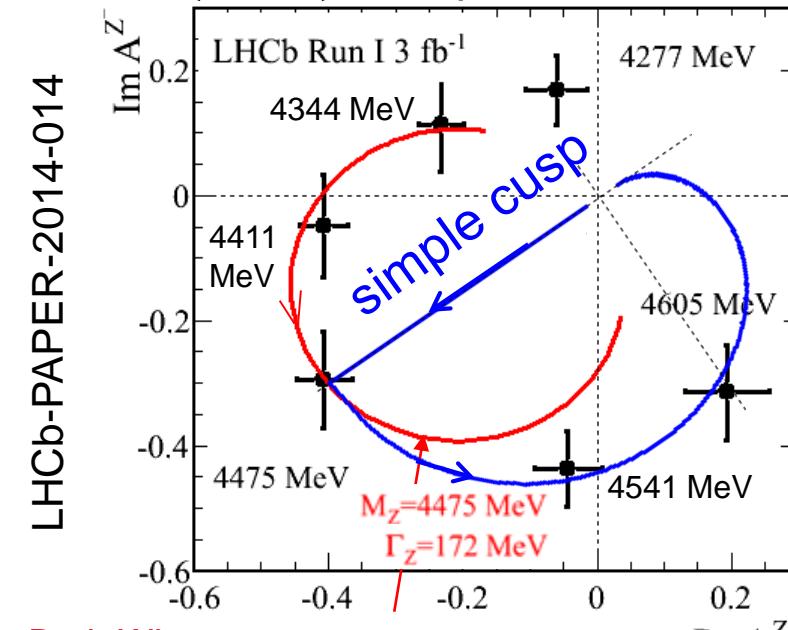
Sensitivity to production
mechanism, points to hadron-
level interactions.

No clear explanations.

- Too broad to be molecular bound states?
- No tetraquark model can accommodate all of them.
- Rescattering effects?
- Artifacts of complicated amplitude analyses?

Resonant structure of Z(4430)⁻ ?

- Detailed studies of “exotic” amplitudes desired to shed light onto their nature: example Argand diagram of $Z(4430)^- \rightarrow \psi(2S)\pi^-$.



$D^0\bar{D}^*(2S)^-$ cusp would be smeared by $\Gamma_{D^*(2600)} = 139 \text{ MeV}$,
and more round if produced via a triangle diagram

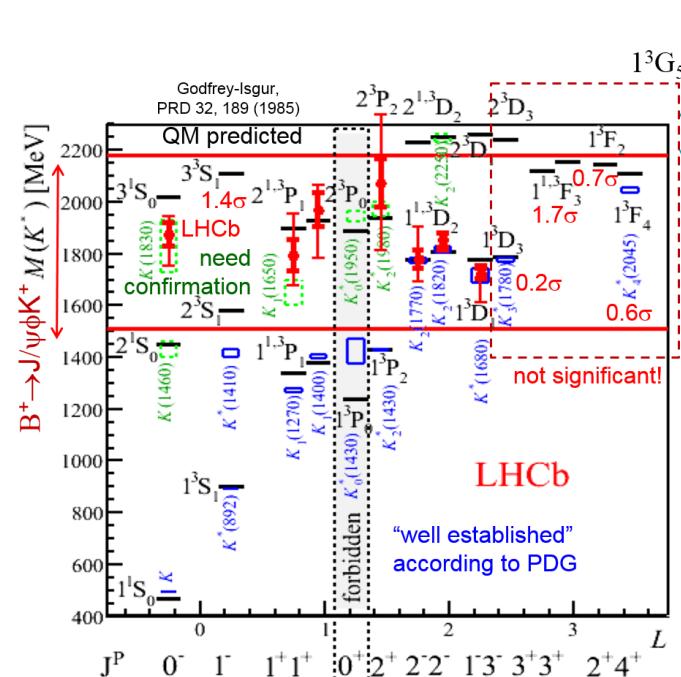
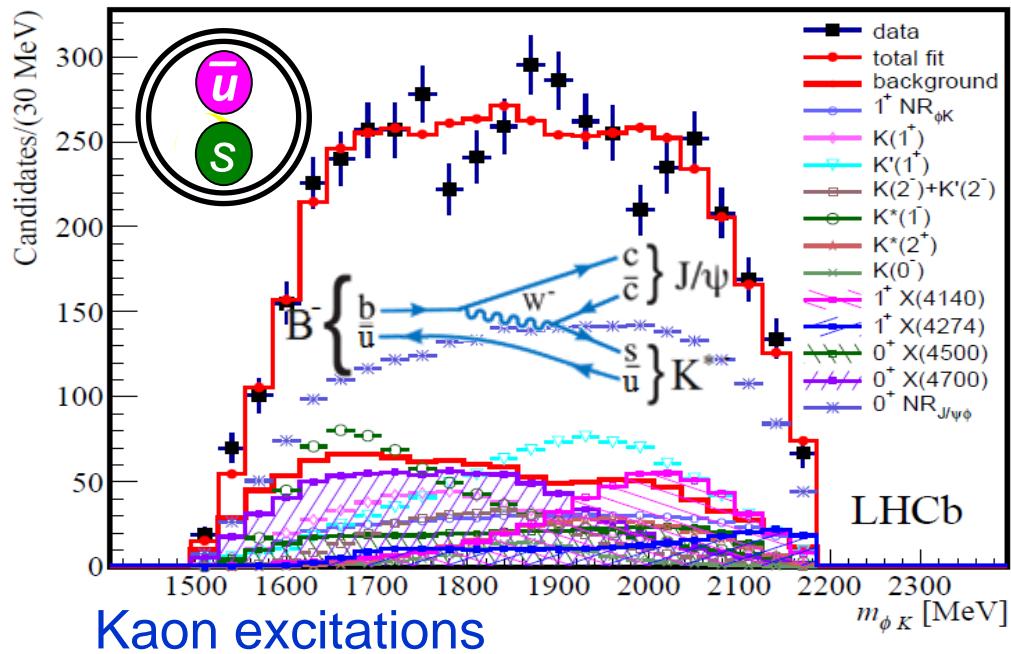
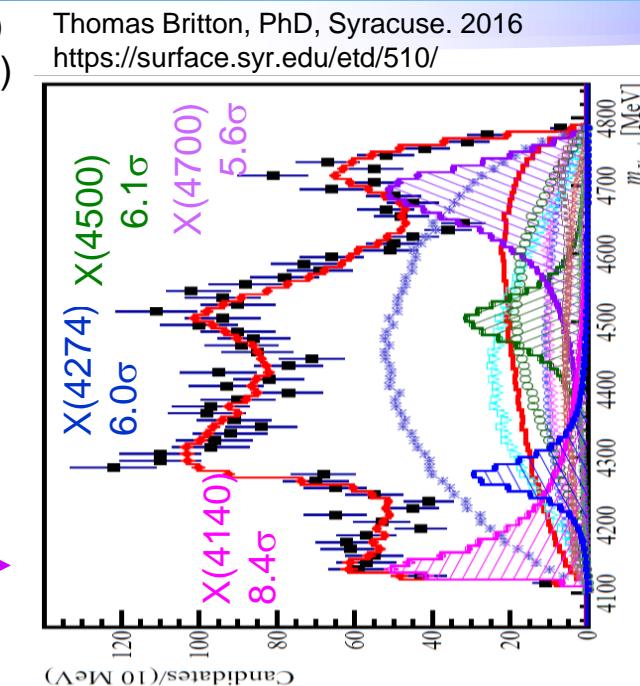
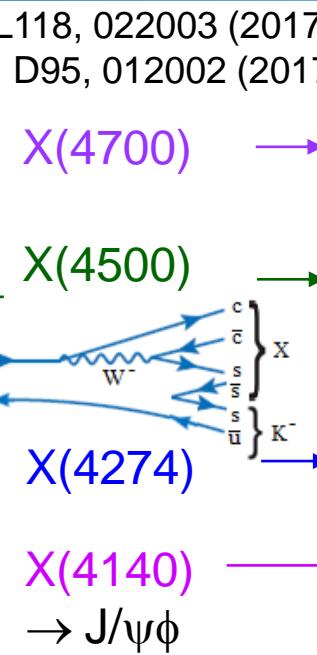
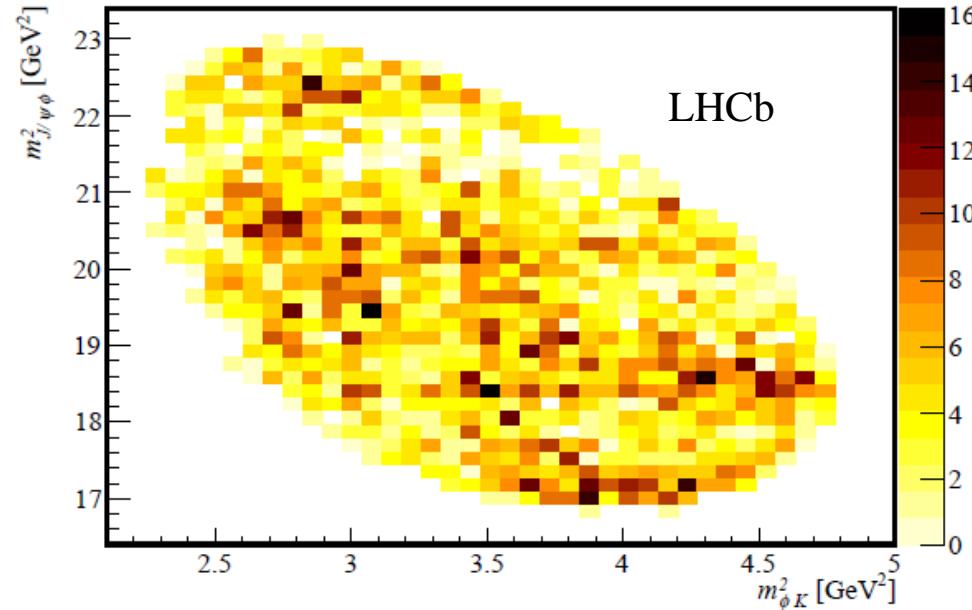
Statistical accuracy will be sufficient to distinguish between resonant poles and cusps/triangles.
Systematic errors hard to predict.

Need to scrutinize dependence on:

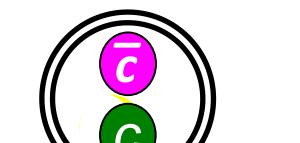
- formalism (work with JPAC; see Mikhasenko et al EPJ, C78, 229 (2018), arXiv:1712.02815)
- K^* model

Huge statistics already for detailed studies of $J/\psi(1S)\pi^-$ exotics. Phase-space in $K\pi$ reaches to $K_4^*(2045)$ pole.

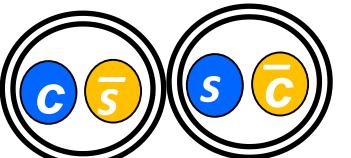
	LHCb	U.Phase I	II	Belle	II	
Decay mode	3 fb^{-1}	8 fb^{-1}	50 fb^{-1}	300 fb^{-1}	0.7 ab^{-1}	50 ab^{-1}
$B^0 \rightarrow \psi(2S)\pi^- K^+$	25k	0.13M	0.8M	5M	2k	0.14M
$B^0 \rightarrow J/\psi(1S)\pi^- K^+$	0.4M	1.3M	10M	62M	30k	2M
$B^0 \rightarrow \chi_{c1}\pi^- K^+$	19k	0.1M	0.5M	3M	2.7k	0.19M



Tetraquarks ?



Charmonium ?



Molecules or cusps?

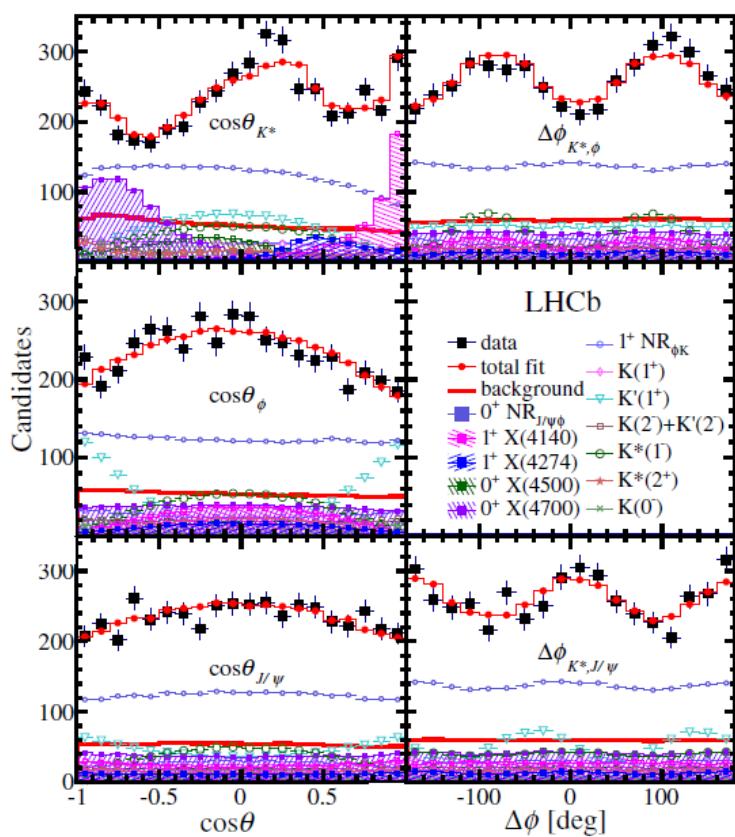
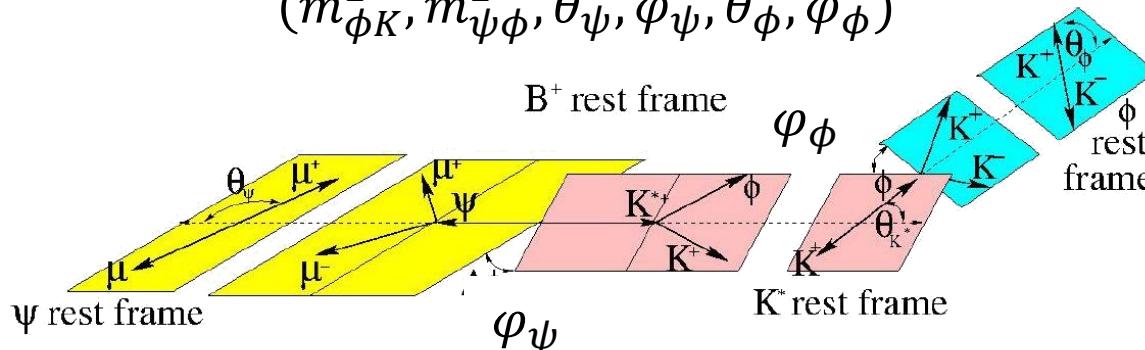
Since mostly **not established** states, we determined $K^* \rightarrow \phi K^+$ content entirely from our data (red points): 6 K^* resonances (of 4 different J^P) + 1 NR ϕK

Previously $X(4140)$, $X(4274)$ were observed by CDF,CMS and D0

Amplitude analysis of $B^+ \rightarrow J/\psi \phi K^+$, $\phi \rightarrow K^+ K^-$

6D maximum likelihood fit

$$(m_{\phi K}^2, m_{\psi \phi}^2, \theta_\psi, \varphi_\psi, \theta_\phi, \varphi_\phi)$$

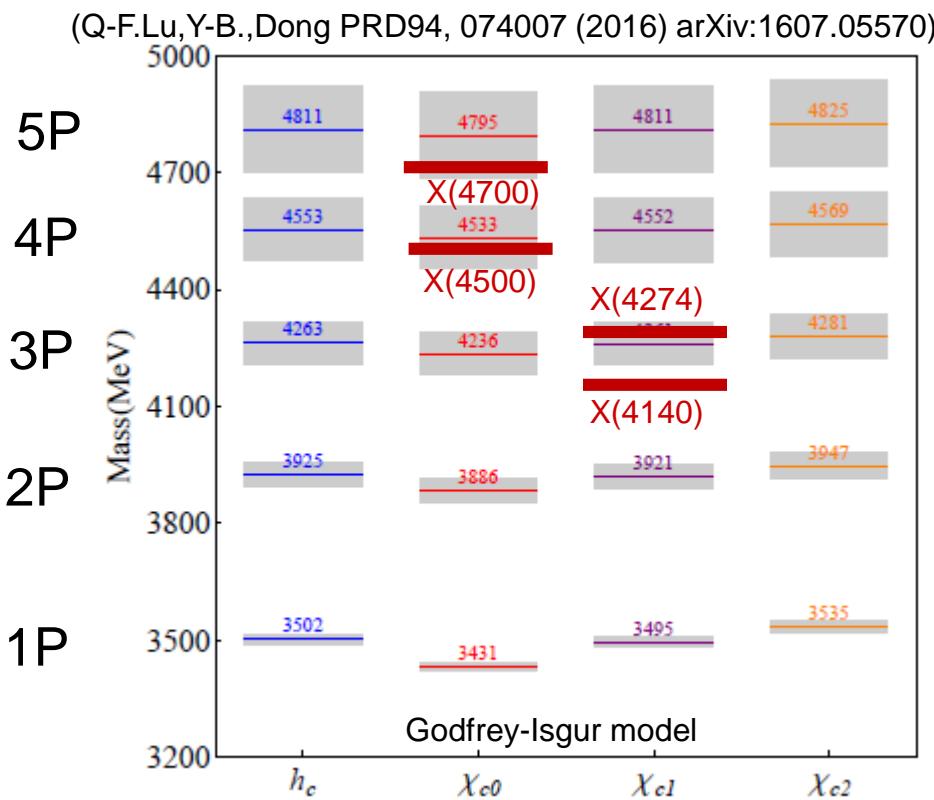


The inclusion of all decay angles in the amplitude fit, allowed resolution of various $K\phi$ partial waves, and led to a firm determination of J^{PC} of $J/\psi\phi$ resonances:

- $X(4140)$: 1^{++} determined at 5.7σ
- $X(4274)$: 1^{++} determined at 5.8σ
- $X(4500)$: 0^{++} determined at 4.0σ ,
- $X(4700)$: 0^{++} determined at 4.5σ

Interpretation of $J/\psi\phi$ structures?

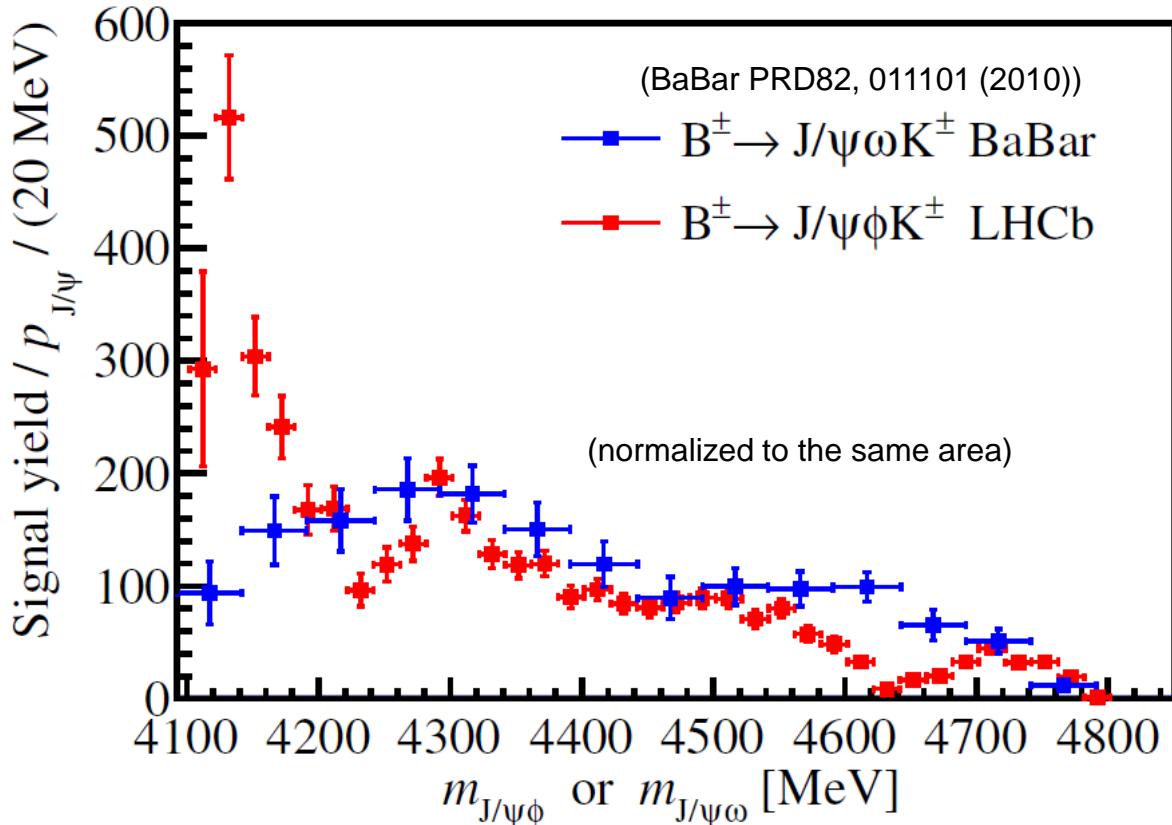
- P-wave charmonia?



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



from Olsen,Skwarnicki,Zieminska
Rev.Mod.Phys. 90, 015003 (2018); arXiv:1708.04012

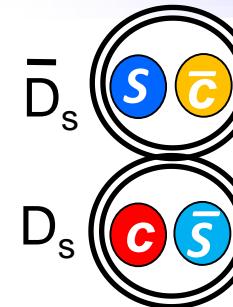
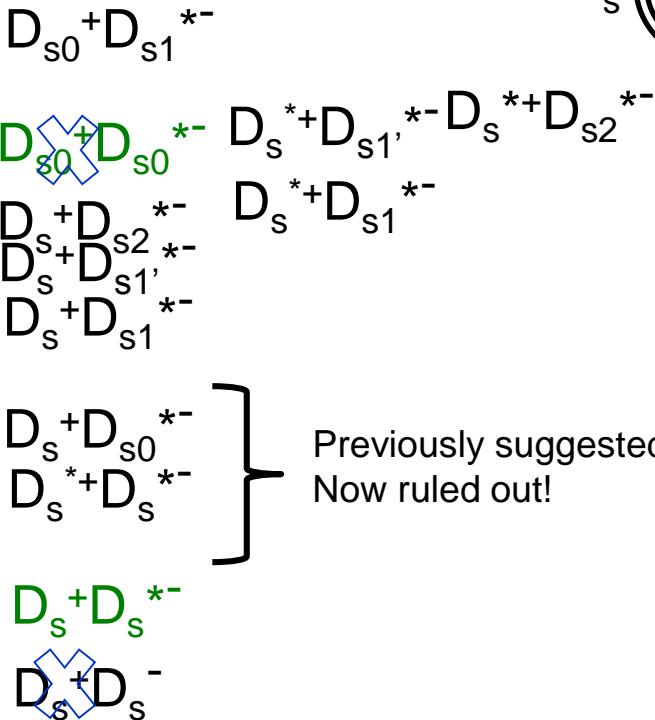
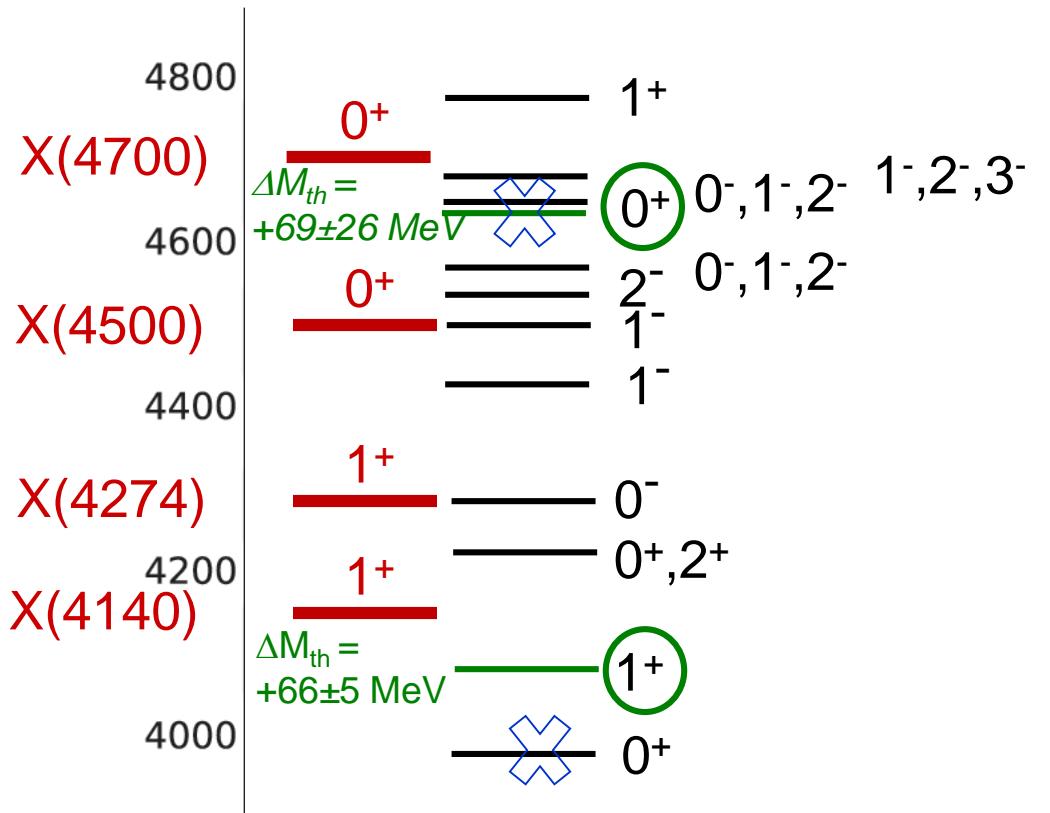


$\chi_{cJ}(nP)$ states would couple to $J/\psi\phi$ and $J/\psi\omega$ the same way. The $J/\psi\phi$ structures do not show up in $J/\psi\omega$ spectrum.

- It appears unlikely that the $J/\psi\phi$ states are pure $c\bar{c}$ states.
- Interplay of $\chi_{cJ}(nP)$ states with $(c\bar{s})(\bar{c}s)$ or $((cs)(\bar{c}\bar{s}))$?

Interpretation of J/ψ structures?

- A molecule/threshold effect?



No π -exchange forces ($I=0$)!

η -exchange possible, unless crossed-over (M.Karliner,J.L.Rosner *Nucl.Phys. A954 (2016) 365*, arXiv:1601.00565)

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

Interpretation of $J/\psi\phi$ structures?

- Tetraquarks?

X(4500)

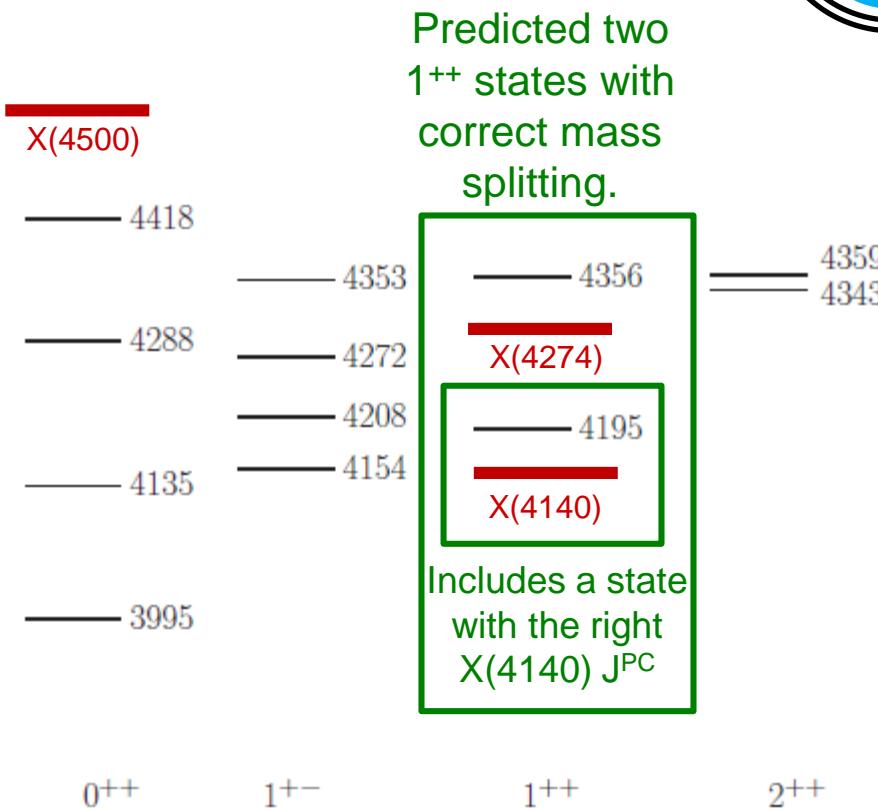


PREDICTION

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 MORE RECENT PAPERS

e.g. L. Maiani, A.D. Polosa, V. Riquer
PRD94, 054026 (2016) 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 ($n=1$).

	LHCb		U. Phase	
	I	II		
Decay mode	3 fb^{-1}	8 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+ \rightarrow J/\psi\phi K^+$	4.3k	15k	0.1M	0.6M

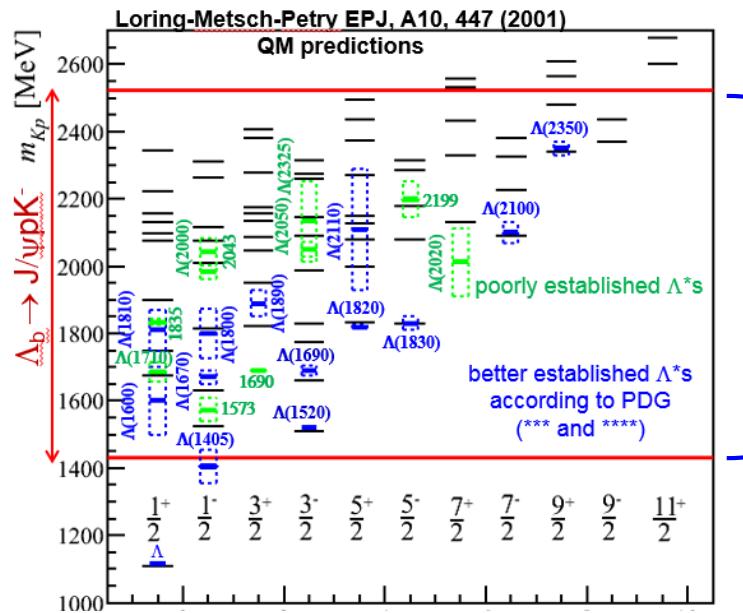
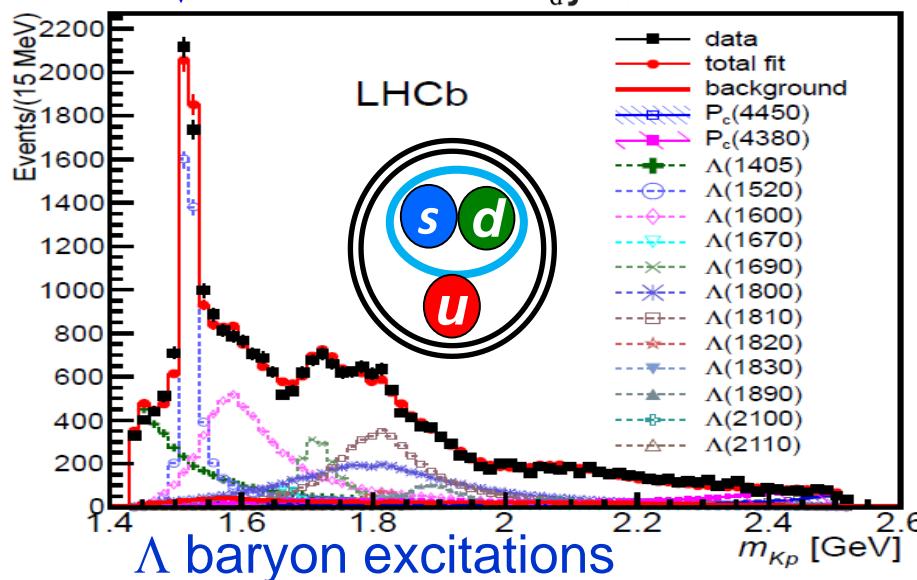
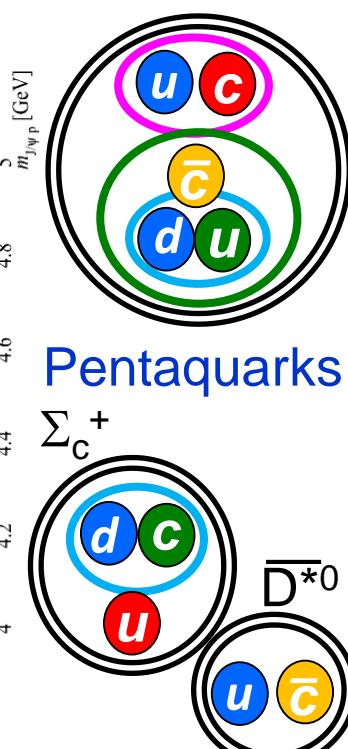
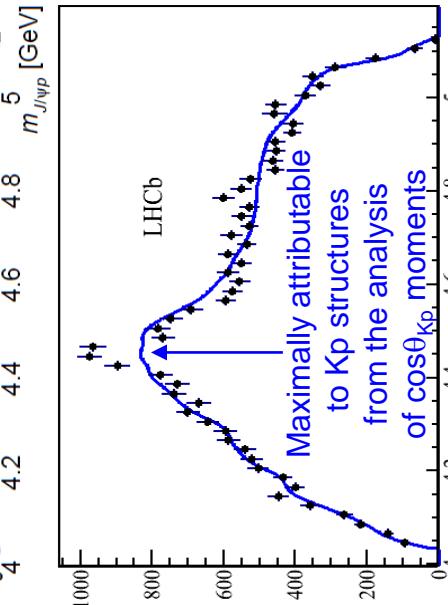
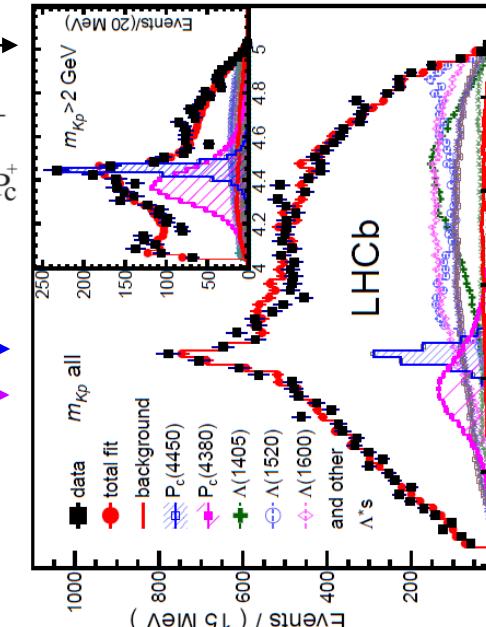
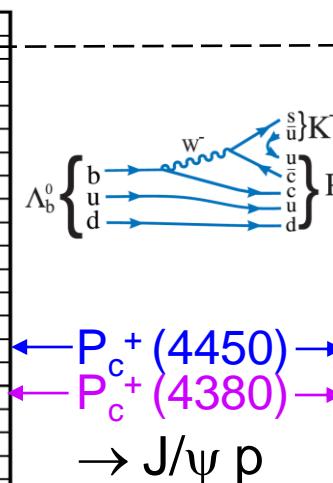
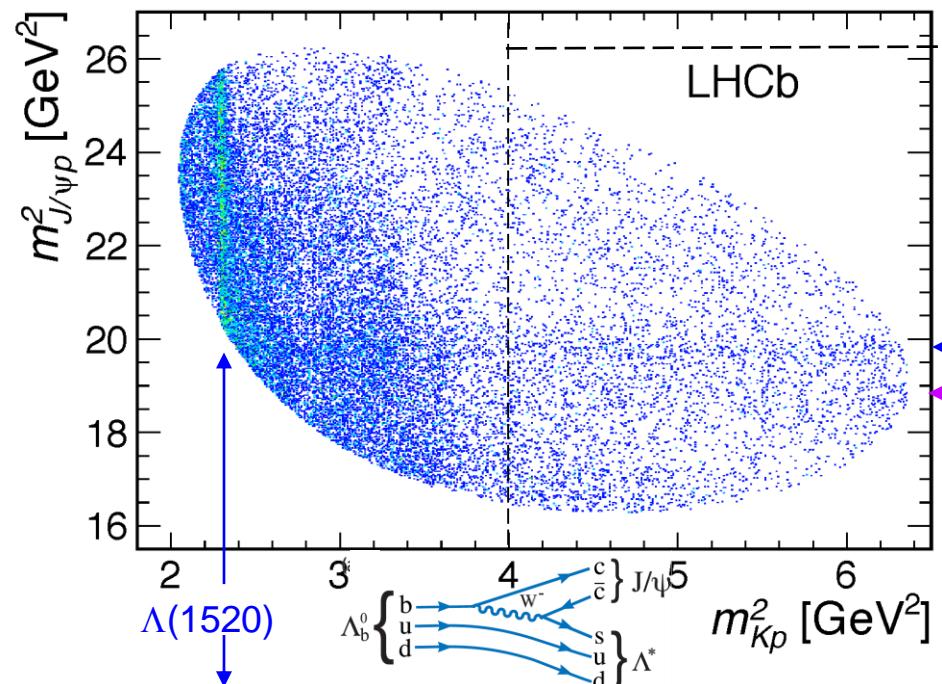
$\Lambda_b^0 \rightarrow J/\psi p K^-$: unexpected $J/\psi p$ structures

Nathan Jurik, Ph.D., Syracuse 2016

<https://surface.syr.edu/etd/640/>

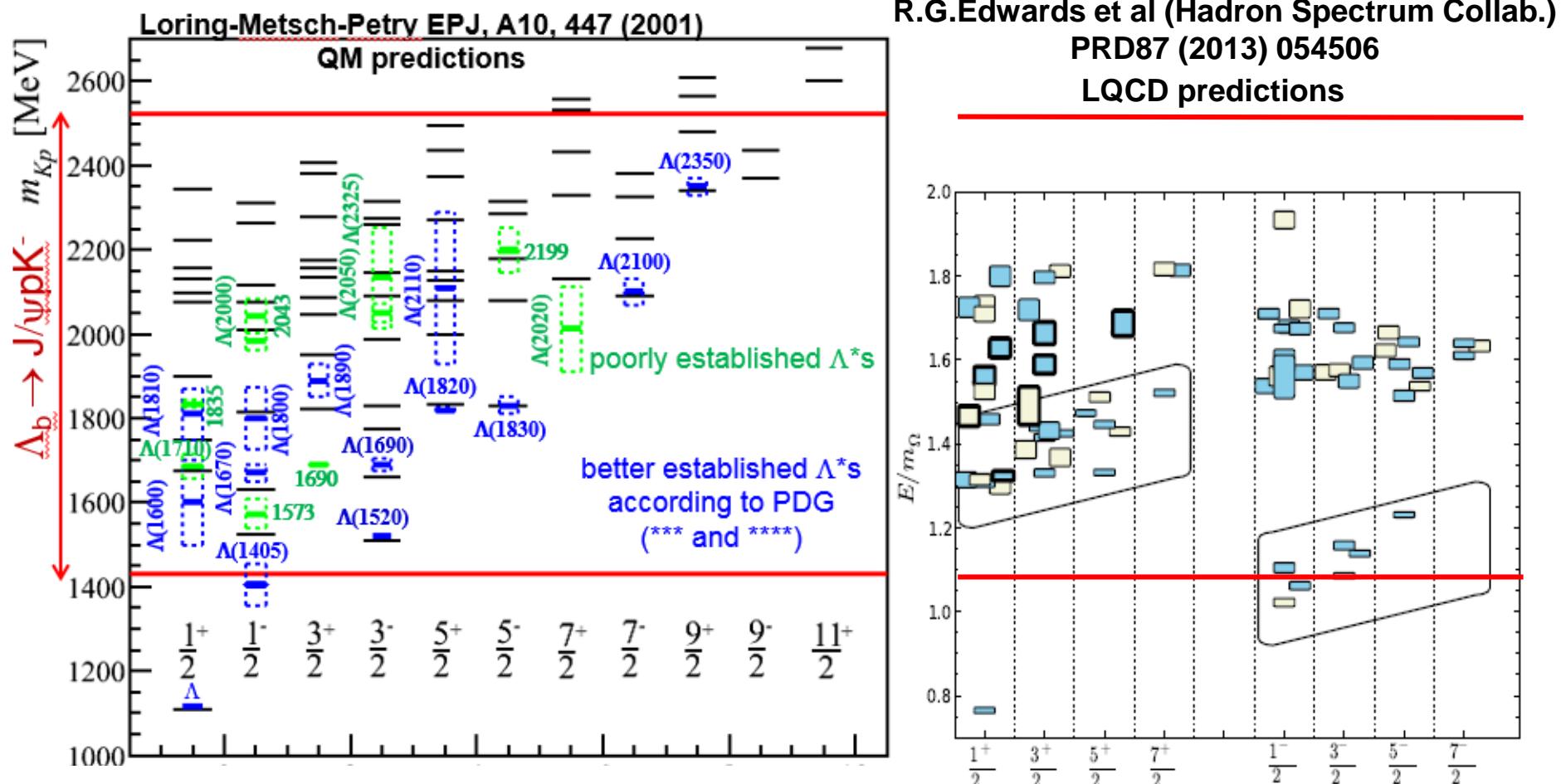
PRL 115, 072001 (2015)

PRL 117, 082002 (2016)



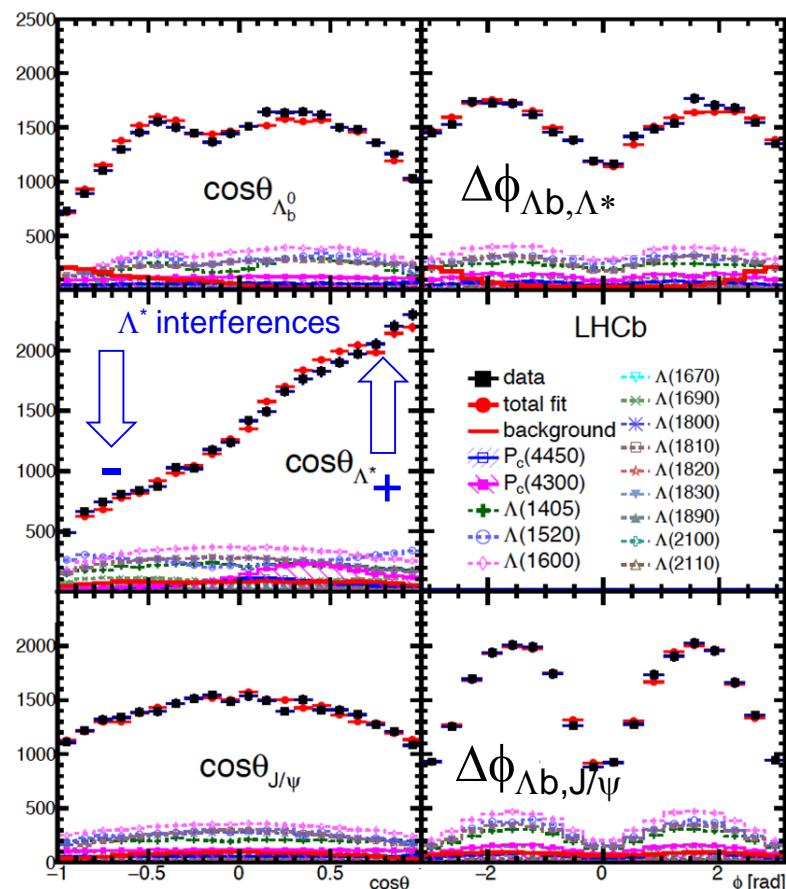
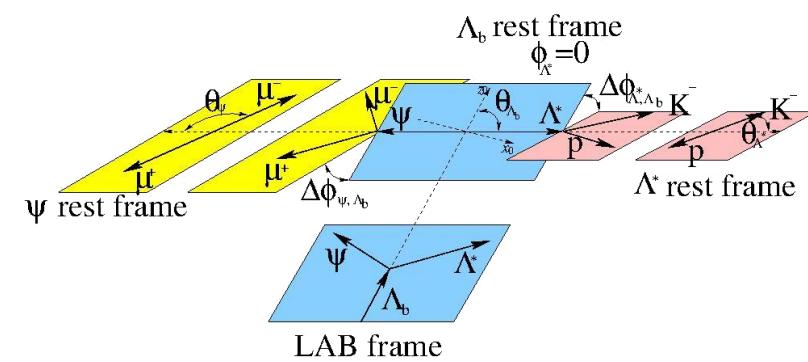
13 better established Λ^* states (** and ****).
in the amplitude fit.
Over 60 expected from the quark model.

Expected complexity of Λ excitation spectrum within the mass range relevant to $\Lambda_b^0 \rightarrow J/\psi p K^-$ amplitude analysis



- Many overlapping states at high mass. Widths and couplings to pK not well predicted.

Amplitude analysis of $\Lambda_b^0 \rightarrow J/\psi p K^-$



6D maximum likelihood fit
 $(m_{pK}^2, m_{\psi p}^2, \theta_\psi, \varphi_\psi, \theta_\Lambda, \varphi_\Lambda)$

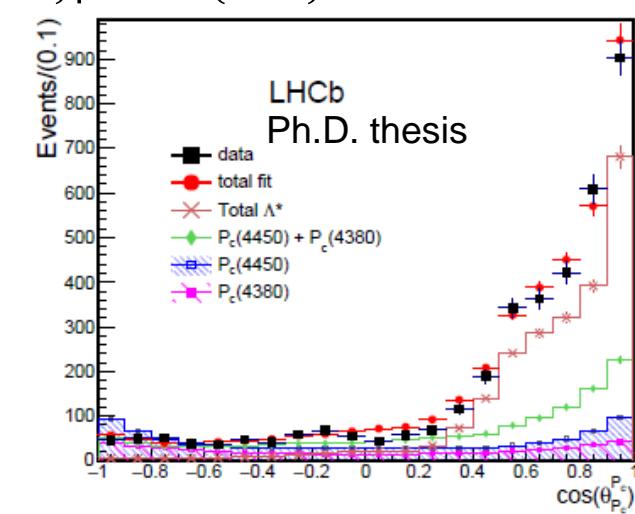
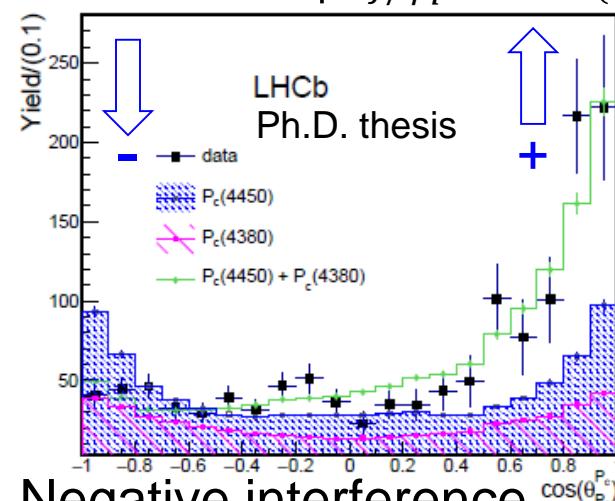
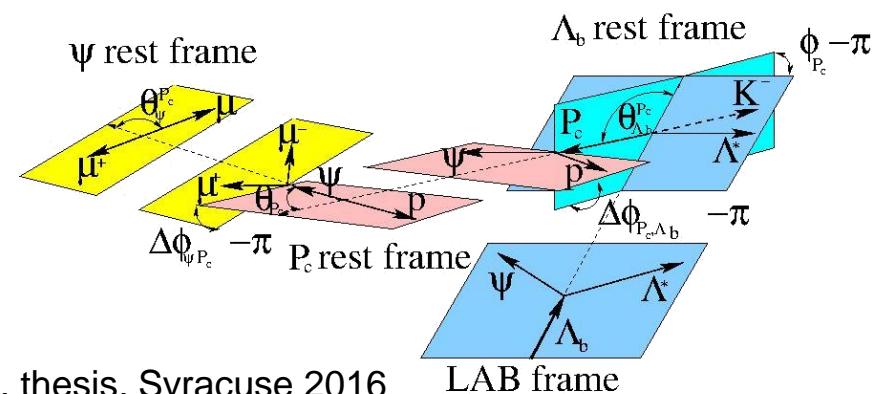
All fit displays with

$$J^P = \frac{3}{2}^- \text{ for } P_c(4380)^+$$

$$J^P = \frac{5}{2}^+ \text{ for } P_c(4450)^+$$

Nathan Jurik, Ph.D. thesis, Syracuse 2016

$$|m_{J/\psi p} - m_{P_c(4450)}| < \Gamma_{P_c(4450)}$$



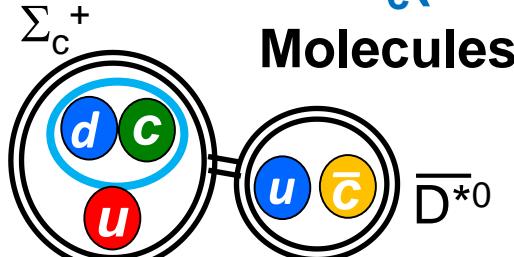
Negative interference
between the P_c states

Requires two P_c
states of
opposite parity

Subtraction of Λ^* contributions
peaking at large $\cos\theta_{P_c}$

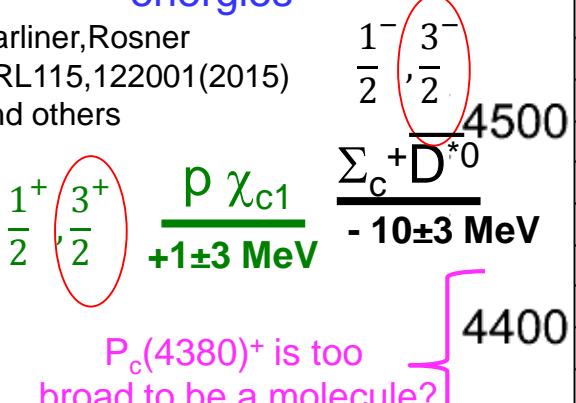
Source of ambiguities in J^P
determination of P_c s.

Interpretations of $P_c(4450)^+$, $P_c(4380)^+$?

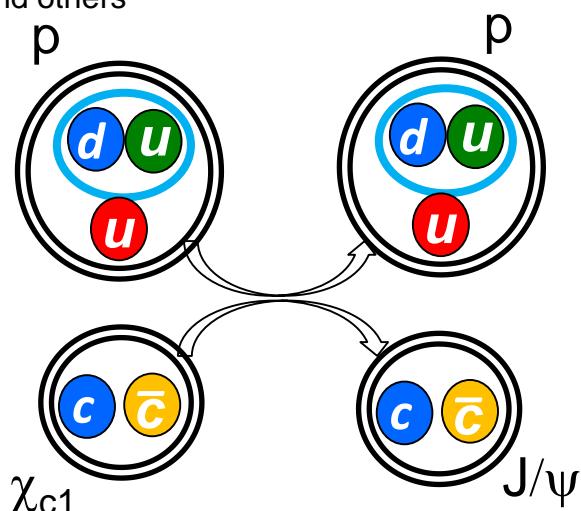


No $\frac{5}{2}^\pm$ molecules in this mass range with reasonable values of binding energies

Karliner,Rosner
PRL115,122001(2015)
and others

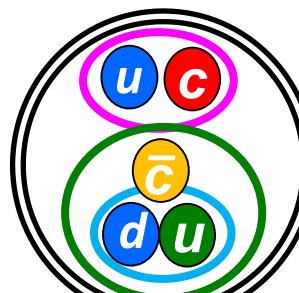


Szczepaniak PL,B747, 410 (2015)
Guo,Meissner et al PRD92, 071502 (2015)
Mikhasenko arXiv:1507.06552
and others



Realistic rescattering mechanisms (cusps, triangle anomalies) have the same J^P selection rules as realistic molecular models (must happen in S-wave)

Tightly-bound pentquark



Can accommodate $\frac{5}{2}^\pm$ when at least one diquark in $S=1$ state

Maiani et al PLB749, 289 (2015);
Ali et al PRD94, 054001 (2016);
and others

Such mass difference and the opposite parity can be explained by $\Delta L=1$ and $\Delta S=1$

It is crucial to determine J^P s!

Need more robust verifications of resonant hypothesis.

Both require better understanding of $\Lambda \rightarrow pK$ contributions (work in progress)

	LHCb	U. Phase	
	I	II	
Decay mode	3 fb ⁻¹	8 fb ⁻¹	50 fb ⁻¹
$\Lambda_b \rightarrow J/\psi p K^-$	25k	0.13M	0.8M
			5M

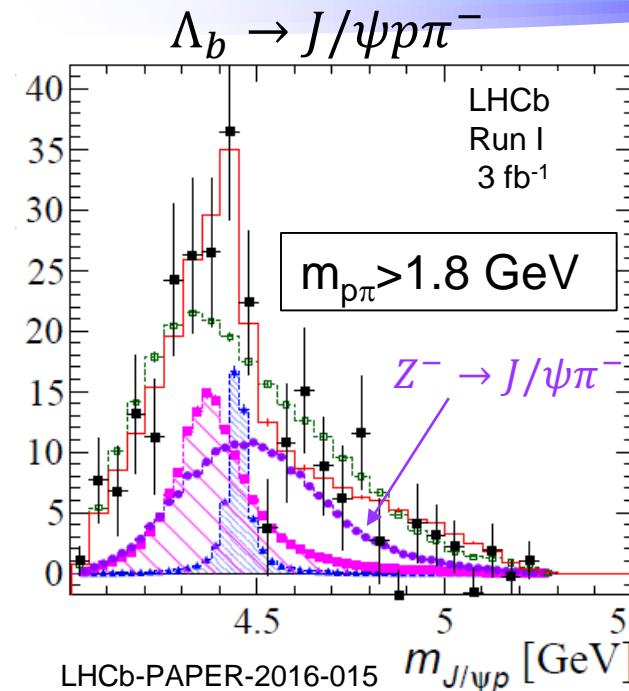
Other channels related to $P_c(4450)^+$, $P_c(4380)^+$

	LHCb		U. Phase	
	I	II		
Decay mode	3 fb^{-1}	8 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$\Lambda_b \rightarrow J/\psi p K^-$	26k	0.13M	0.8M	5M
$\Lambda_b \rightarrow J/\psi p \pi^-$	1.9k	10k	63k	0.4M
$\Lambda_b \rightarrow \chi_{c1} p K^-$	0.45k	2.2k	15k	0.1M

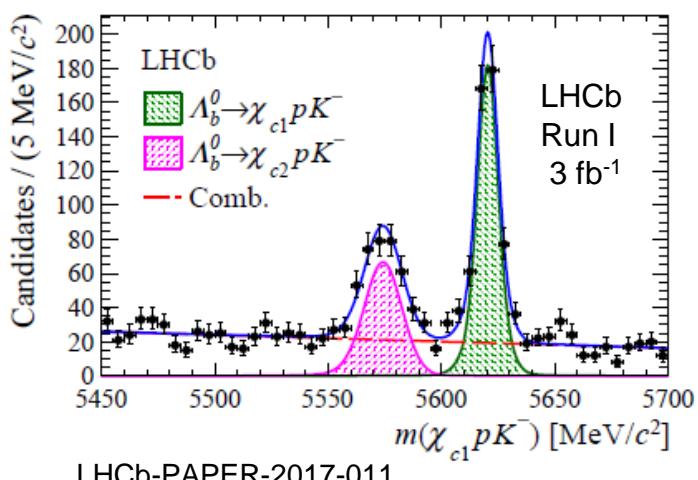
 $\Lambda_b \rightarrow J/\psi p K_s^0 \pi^-$ $\Lambda_b \rightarrow J/\psi p \bar{p}$

...

Upgrade statistics will allow for amplitude analyses of sensitivity comparable (much better) than in the discovery paper

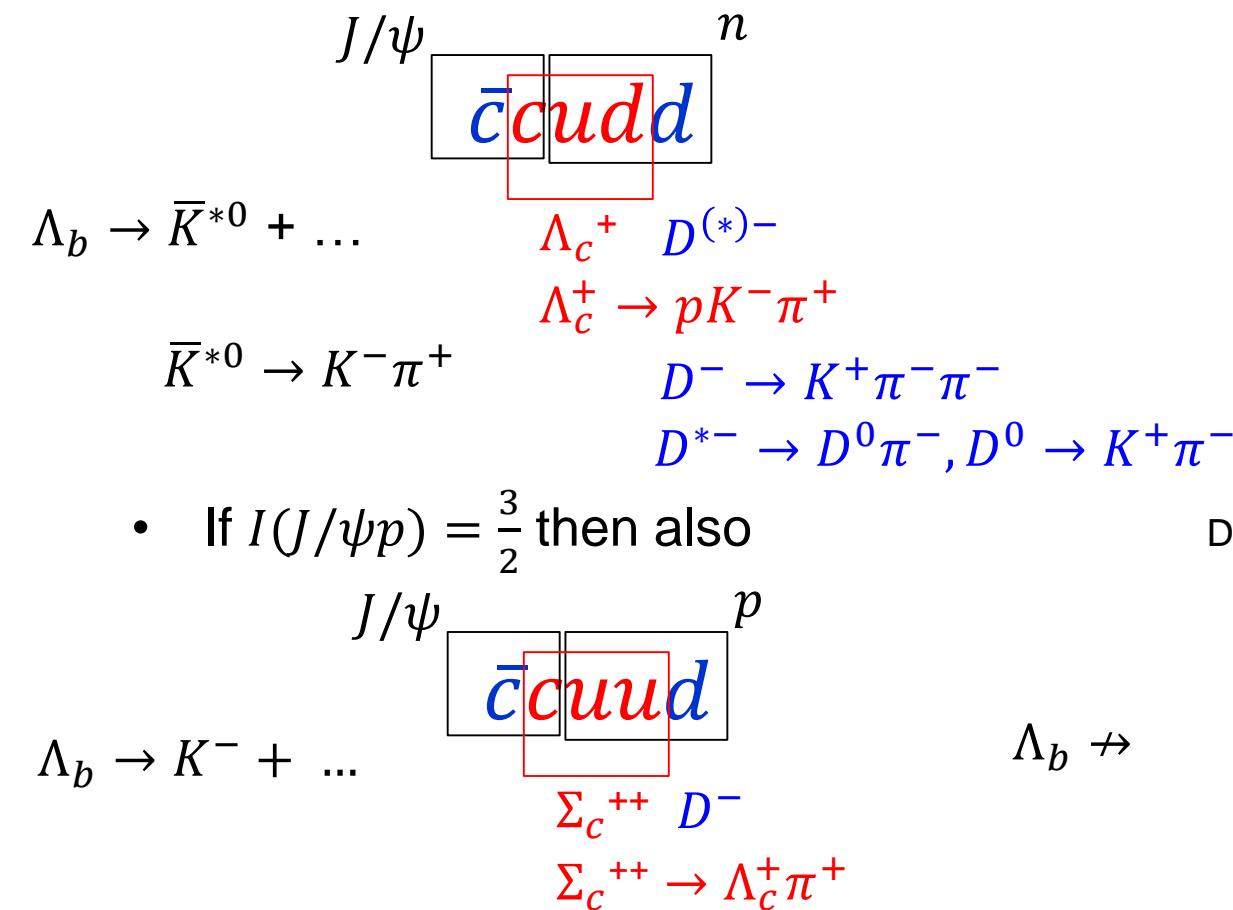


Hints of $J/\psi p$ structure; complicated by ambiguities with $Z^- \rightarrow J/\psi \pi^-$
A coupled-channel to $J/\psi p$. The $\chi_{c1} p$ mass threshold near $P_c(4450)^+$.



Isospin partners of $P_c(4450)^+$, $P_c(4380)^+$?

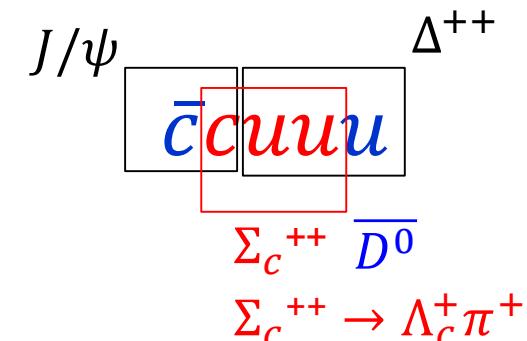
- $I_3(J/\psi p) = +\frac{1}{2}$
- Whatever the nature of these states is, $I_3(J/\psi n) = -\frac{1}{2}$ partners should exist. Unfortunately neutrons are not detectable in LHCb.
- However such states can decay to open charm final states



- If $I(J/\psi p) = \frac{3}{2}$ then also

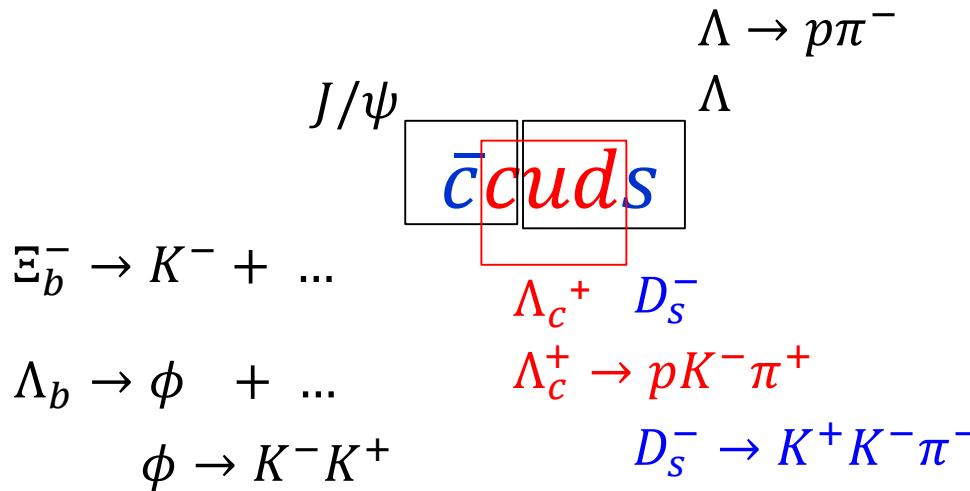
- Relative to $J/\psi(\rightarrow \mu^+ \mu^-)p$ extra 4 tracks to reconstruct and no dimuon to trigger on (efficiency loss by a factor of ~50).
- Upgrade luminosities are essential to reach sensitivity in these channels

Doubly-charged partner (prompt production?)



U-spin partners of $P_c(4450)^+$, $P_c(4380)^+$?

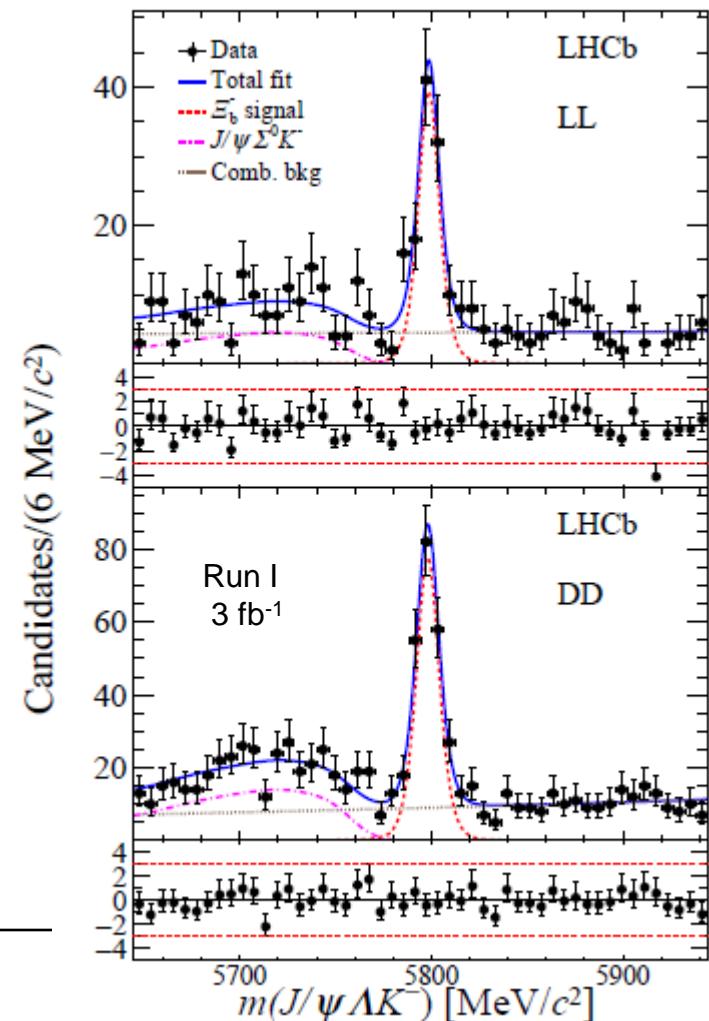
- Strange partners:



	LHCb		U. Phase I II	
Decay mode	3 fb^{-1}	8 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$\Lambda_b \rightarrow J/\psi \Lambda \phi$	80	0.4k	3k	16k
$\Xi_b^- \rightarrow J/\psi \Lambda K^-$	300	1.6k	10k	60k

This will allow amplitude analyses

[PLB 772 (2017) 265]



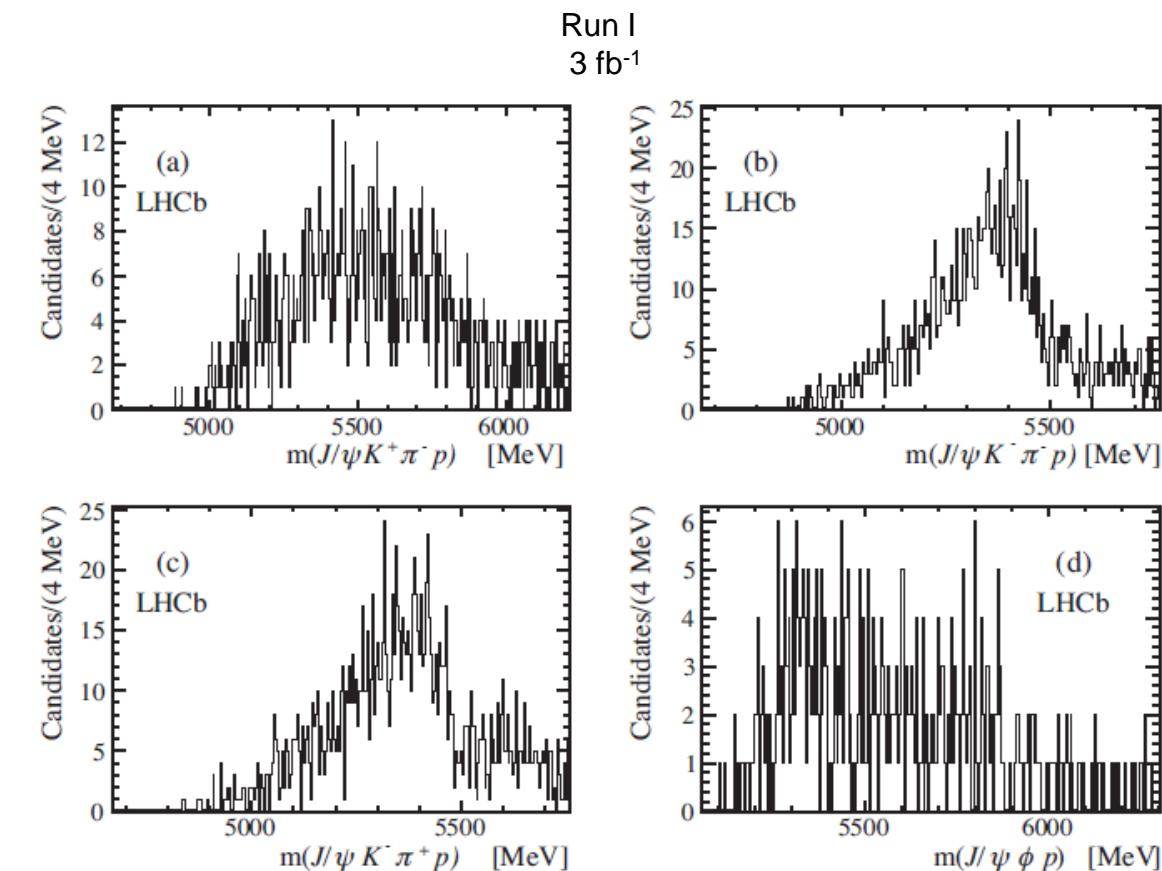
LHCb-PAPER-2016-053

Beautiful analogs of $P_c(4450)^+$, $P_c(4380)^+$?

- Binding of hadrons with beauty quark(s) is “deeper” than with charm quark(s)
- If molecular structures, then masses must be very near relevant baryon-meson thresholds ($\Sigma_b B^*$, $\Sigma_b^* B$, $\Sigma_b^* B^*$, $\Lambda_b B^*$, $\Lambda_b^* B$)
- Beautiful analogs of the P_c^+ states ($\bar{b}buud$) would decay to easily detectable final state: $\Upsilon(\rightarrow \mu^+ \mu^-) p$ (if $\bar{b}busd$ exists in $\Upsilon(\rightarrow \mu^+ \mu^-) \Lambda$)
- Unfortunately, can only be searched for in prompt production:
 - Large backgrounds from protons produced in primary pp collision (no secondary vertex formed)
 - If compact pentaquarks then prompt production can be sizeable, but prompt production of the P_c^+ states have not been observed so far

Beautiful $\bar{b}qqqq$ pentaquarks with lifetime

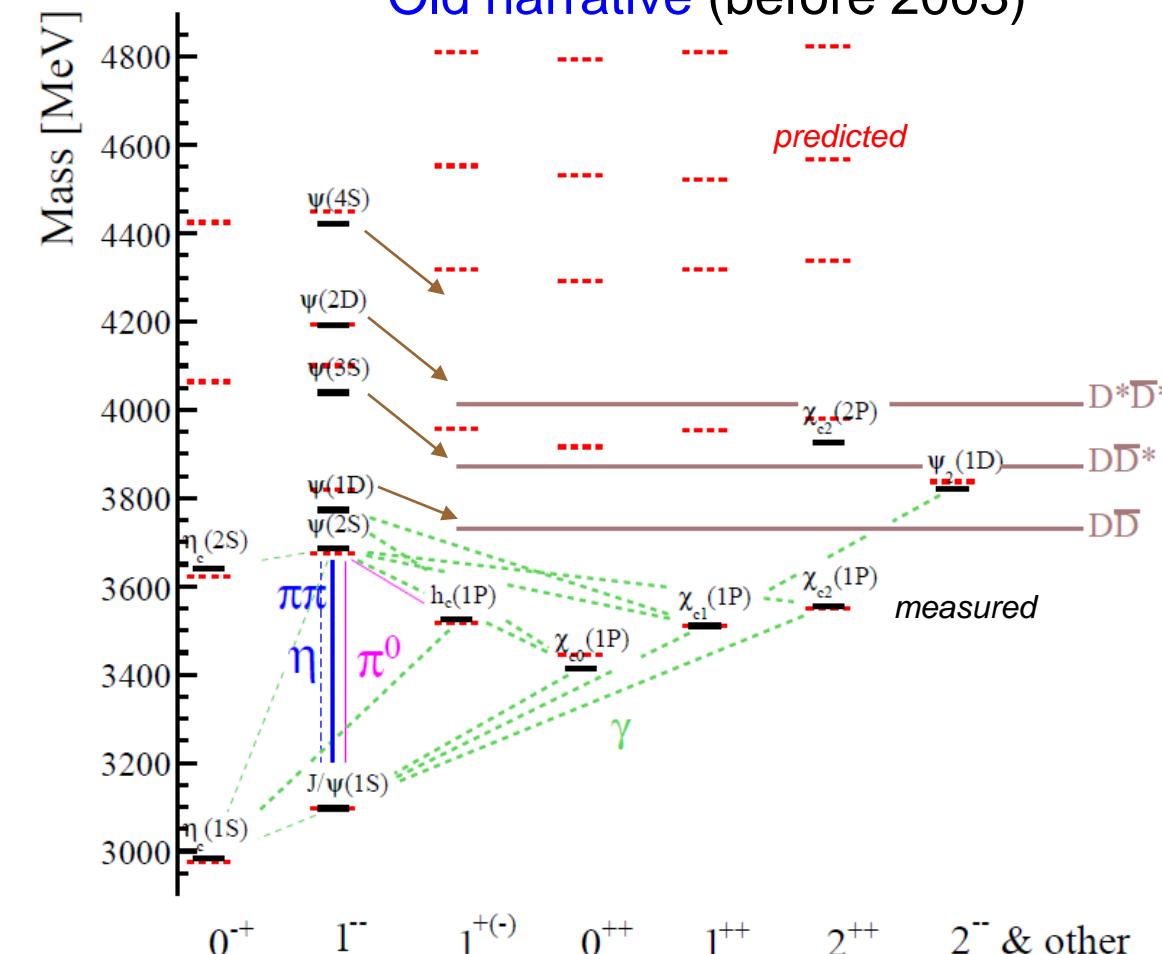
- If binding was large enough, the lightest ones might have masses below the relevant baryon-meson threshold and decay weakly
- A secondary vertex eliminates combinatorial background from the particles produced at the primary vertex
- LHCb has searched for stable $\bar{b}duud$, $\bar{b}suud$, $b\bar{u}udd$, $b\bar{d}uud$ in $J/\psi ph^+h^-$ ($h = K$ or π) in Run I; found no evidence, and set upper limits on their production rate
- Such searches will have a better sensitivity with larger integrated luminosity



PRD97, 032010 (2018)
LHCb-PAPER-2017-043

New particle zoo: charmonium above flavor threshold

Old narrative (before 2003)



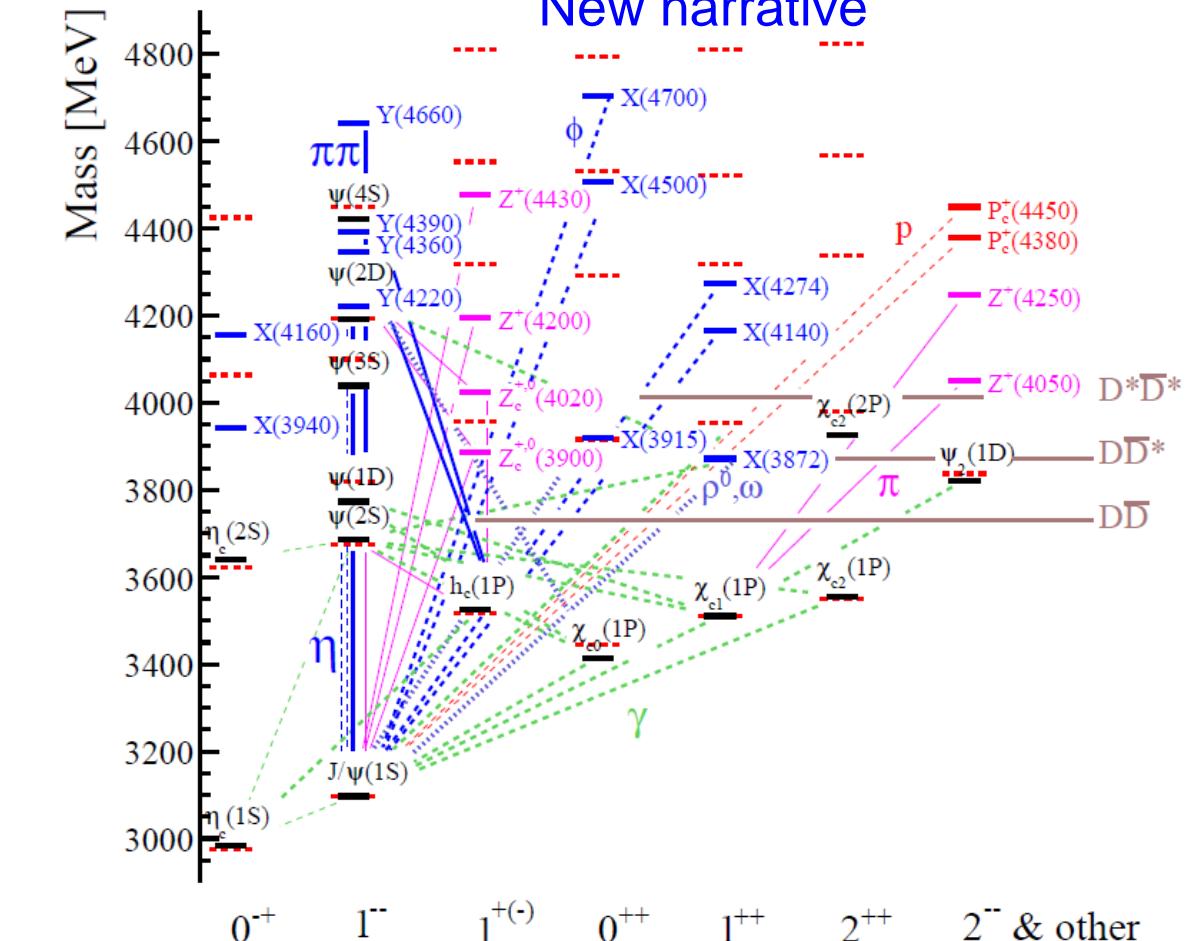
Figures from Olsen,Skwarnicki,Zieminska
Rev.Mod.Phys. 90, 015003 (2018); arXiv:1708.04012

Mesons are ($q\bar{q}$) bound states.

All excited light hadrons are above “the open flavor threshold”!

Above the flavor threshold: More exotic states than $c\bar{c}$ states!

New narrative



Mesons are predominantly ($q\bar{q}$) bound states below the open flavor threshold. They are more complex structures above it, and we have not yet understood them.

Summary

- LHC offers enormous rates of heavy quarks via hadronic production cross-sections and large instantaneous luminosity
- Good place to study hadron spectroscopy with heavy quarks, including multi-quark exotics:
- Unique gateway to states produced in decays of b-baryons, B_c
- LHCb is well suited for such studies, thanks to hadron ID and large trigger bandwidth devoted to heavy flavors
- Near and farther future upgrades of the LHCb detector to take better advantage of the opportunity offered by the LHC:
 - Precision studies on already observed exotic hadron candidates
 - Hopes for detection of stable or narrow doubly-flavored tetraquarks (see Marco Pappagallo's talk)
 - Judging from the recent history we should also expect unexpected!