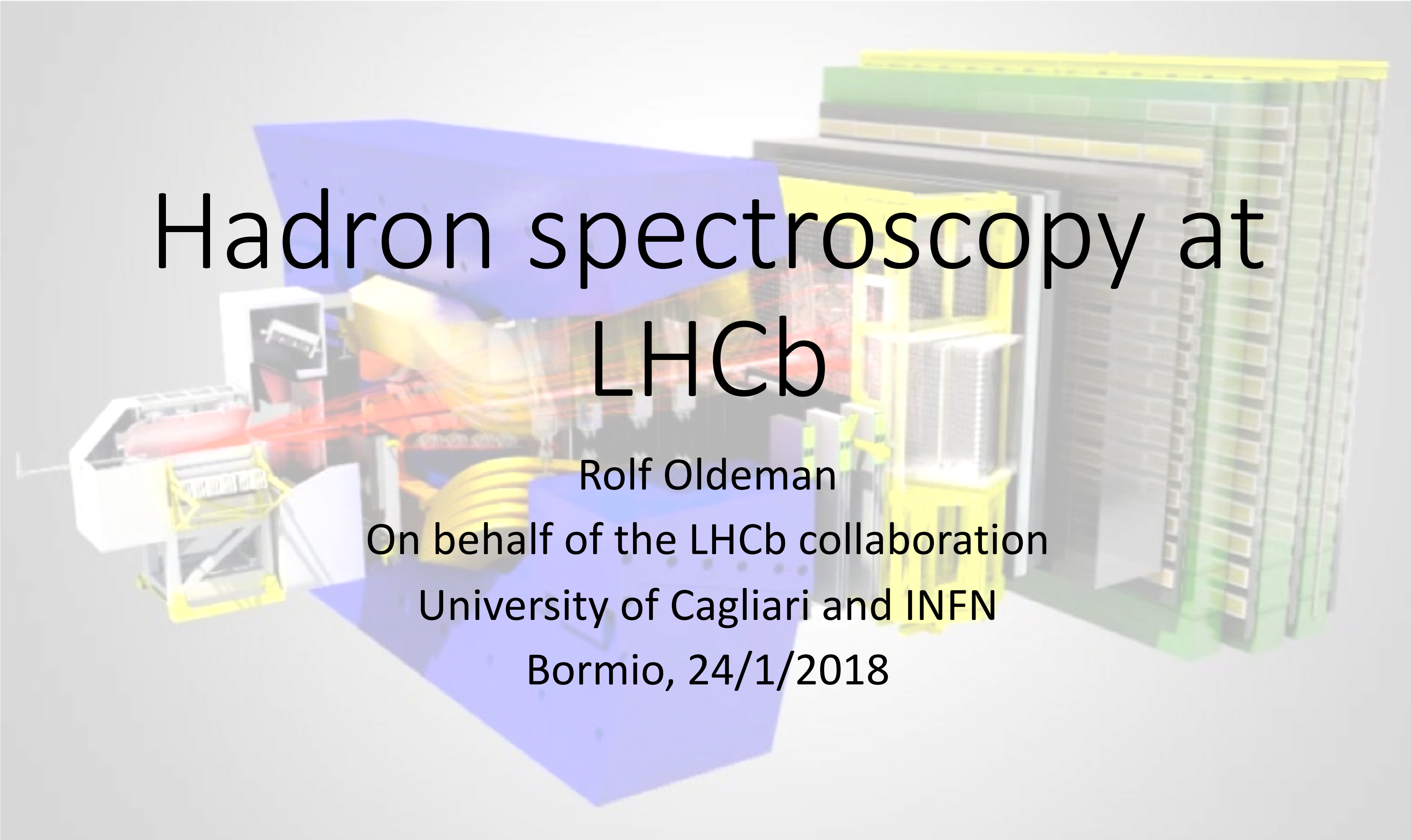


Hadron spectroscopy at LHCb

Rolf Oldeman
On behalf of the LHCb collaboration
University of Cagliari and INFN

Bormio, 24/1/2018

Outline

Hadron spectroscopy

The LHCb experiment

Conventional hadrons:

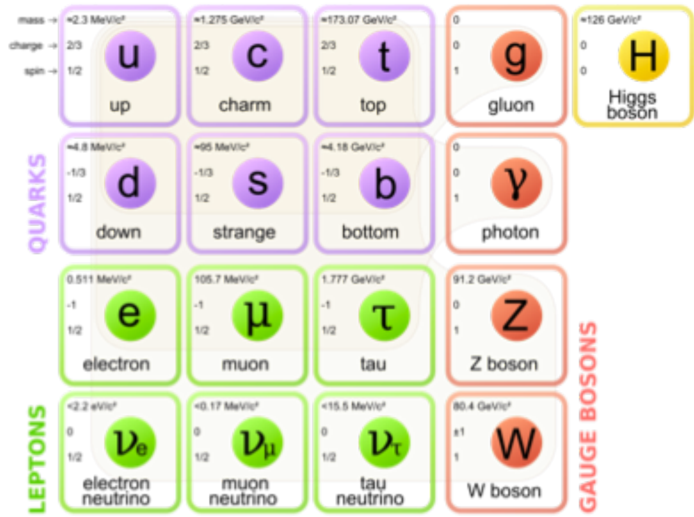
- *Mesons*
- *Baryons*

Exotics hadrons:

- *Tetraquarks*
- *Pentaquarks*

Outlook

Hadron spectroscopy



Hadrons are combinations of quarks

LHCb focuses on Heavy Flavour (HF):

hadrons with ≥ 1 charm (c) or beauty (b) quark

beyond ground-state hadrons:

- *spin excitations*
- *angular momentum excitations*
- *radial excitations*
- *exotic hadrons*

$C = 1$ hadrons:

mesons: $D^+(c\bar{d})$, $D^0(c\bar{u})$, $D_s^+\ (c\bar{s})$

baryons: $\Lambda_c^+(cdu)$, $\Xi_c^+(cus)$, $\Xi_c^0(cds)$, $\Omega_c^0(css)$

$B = 1$ hadrons:

mesons: $B^+(\bar{b}u)$, $B^0(\bar{b}d)$, $B_s^0\ (\bar{b}s)$, $B_c^+\ (\bar{b}c)$

baryons: $\Lambda_b^0(bdu)$, $\Xi_b^0(bus)$, $\Xi_b^-(bds)$, $\Omega_b^-(bss)$

quarkonia:

$J/\psi, \psi'(c\bar{c})$ and $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S), (b\bar{b})$

Experimental program and motivation

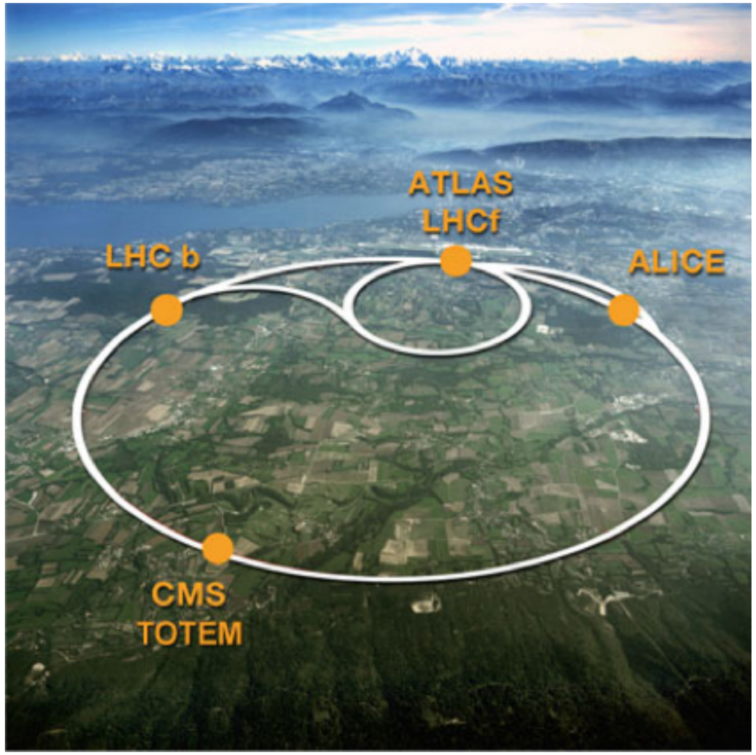
Measure mass, width, decay modes and quantum numbers of known resonances

- *refine or eliminate models of hadron formation*
- *instrumental in reducing hadronic uncertainties in searches for new physics*

Search for new resonances

- *complete the "sky-map" of all hadrons*
- *narrow resonances make ideal flavor-tagging tool*
    - D^0 oscillations observed thanks to $D^{*+} \rightarrow D^0\pi^+$ decay

The LHCb experiment



LHC 27km, at ~-100m

pp collisions every 25ns

2011: E_{cm}=7TeV

2012: E_{cm}=8TeV

2015-2018: E_{cm}=13TeV

~1/100 has $b\bar{b}$, 1/10 has $c\bar{c}$

delivered 120 (7)fb^{-1} to ATLAS,CMS (LHCb)

LHCb: dedicated HF experiment

luminosity levelling: const $\mathcal{L}=4x10^{32}\ cm^{-2}s^{-1}$

forward detector 2<η<5 → low p_T thresholds

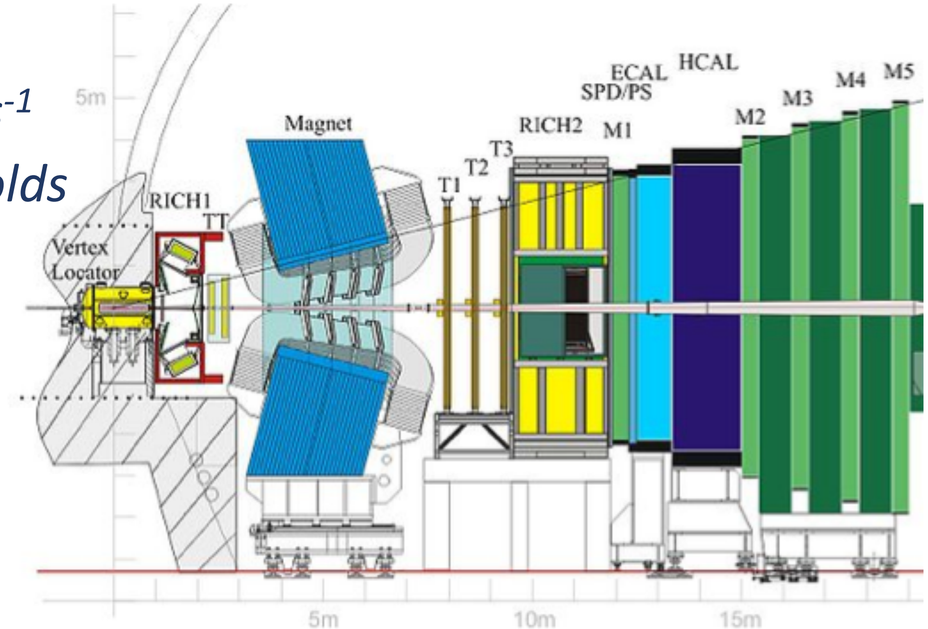
Si strips 8mm from beam, $\sigma_{IP} \approx 20\mu m$

4Tm dipole for Δp/p~0.5-1.0%

2 RICH for π/K/p separation

full detector readout @ 1MHz

IJMPA 30, 1530022 (2015), arXiv:1412.6352

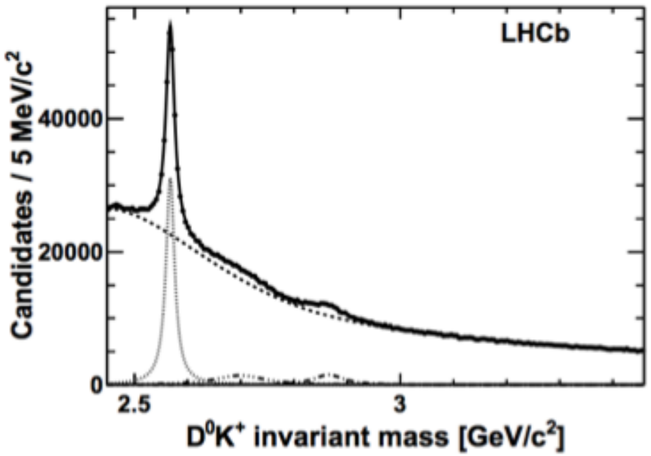


Two methods for spectroscopy

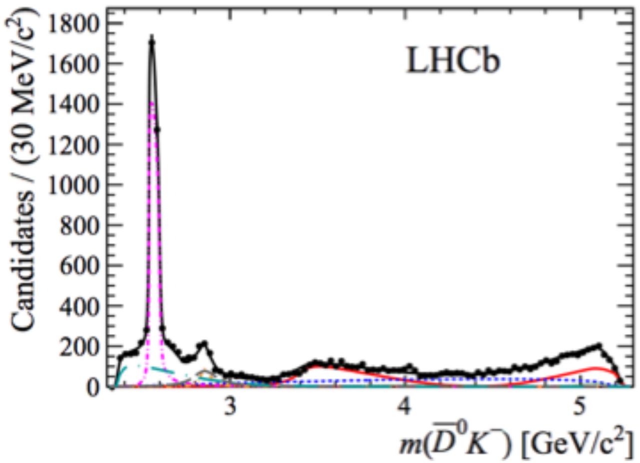
- Direct production in pp collisions
- Combine a HF hadron with one or more light particles
- High statistics
- Works for all hadrons

- Amplitude analysis of heavier state
- Analyze HF+light particle in ≥ 3-body decay of heavier particle
- Low background
- Better determination of quantum numbers J^{PC}

JHEP 1210 (2012) 151, arXiv:1207.6016



PRL113, 162001 (2014), arXiv:1407.7574



Mesons

simplest possible hadron: $q\bar{q}$ states

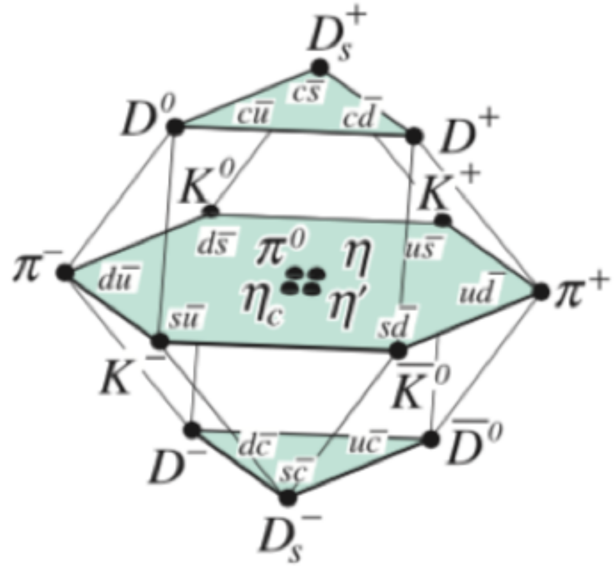
For $\ell = 0$ states:

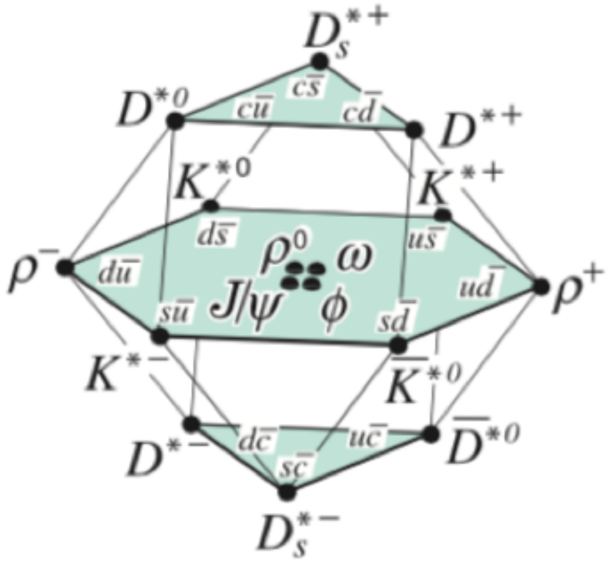
antiparallel quark spin: $J^{PC} = 0^{--}$

parallel quark spin: $J^{PC} = 1^{-+}$

Also $\ell > 0$ states and

radial excitations (e.g. ψ')



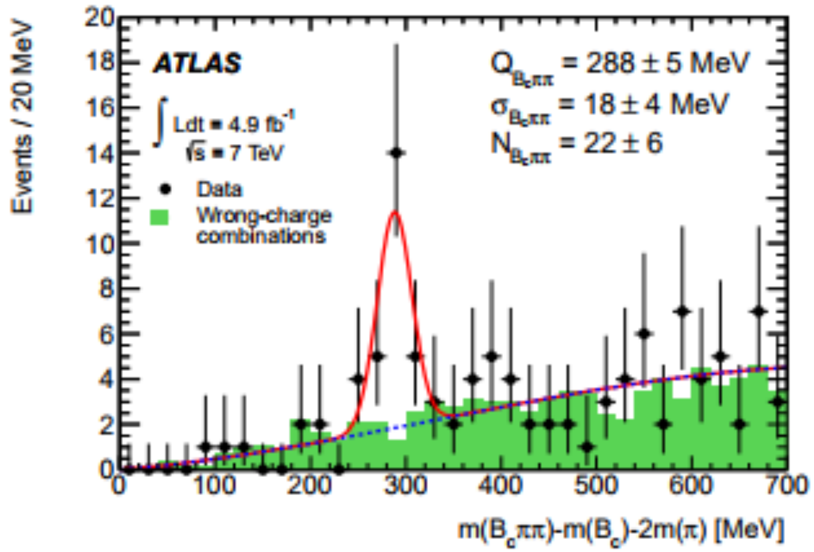


$B_c^{(*)+}(2S) \to B_c^{(*)+}\pi^+\pi^-$ search

Phys. Rev. Lett. 113 (2014) 212004, arXiv:1407.1032.

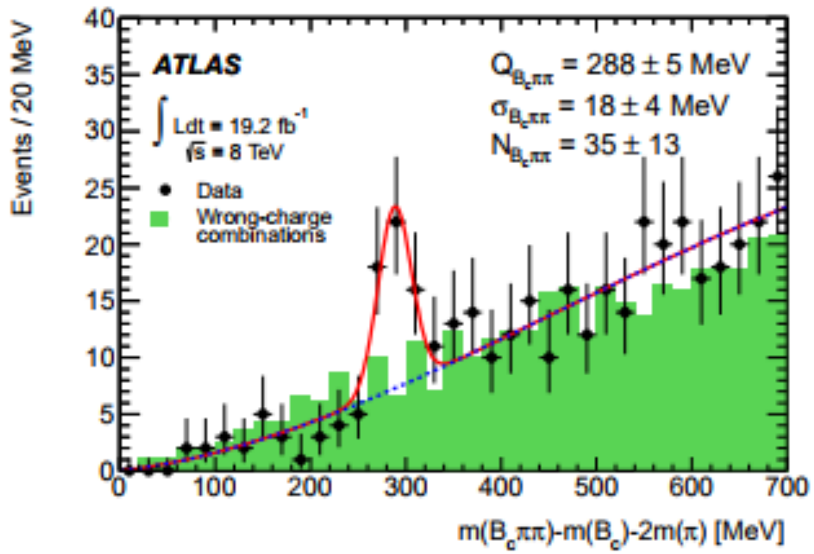
Follow-up on ATLAS observation of peak in $B_c^+\pi^+\pi^-$ spectrum

$m = 6842 \pm 4 \pm 5\ \mathrm{MeV}$



Based on a yield of ~330

$B_c^+ \to J/\psi\pi^+$ decays



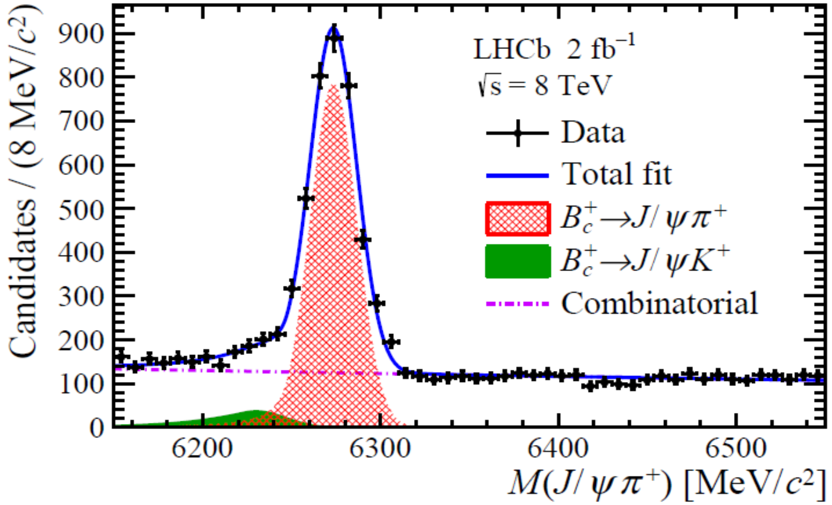
$B_c^{(*)+}(2S) \to B_c^{(*)+}\pi^+\pi^-$ search

arXiv:1712.04094, submitted to JHEP

~3300 $B_c^+ \to J/\psi\pi^+$ decays

Expected mass resolutions:

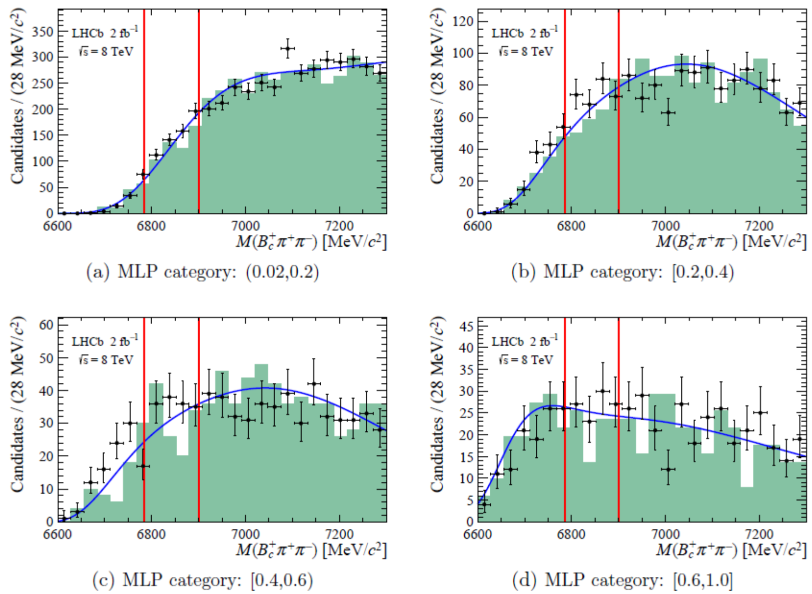
$$\sigma_{\rm w}(B_c(2S)^+) = 2.05 \pm 0.05\,\text{MeV},$$
$$\sigma_{\rm w}(B_c^*(2S)^+) = 3.17 \pm 0.03\,\text{MeV}$$



No $B_c^{(*)+}(2S)$ signal. Measure

$$\mathcal{R} = \frac{\sigma_{B_c^{(*)}(2S)^+}}{\sigma_{B_c^+}} \cdot \mathcal{B}(B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-)$$

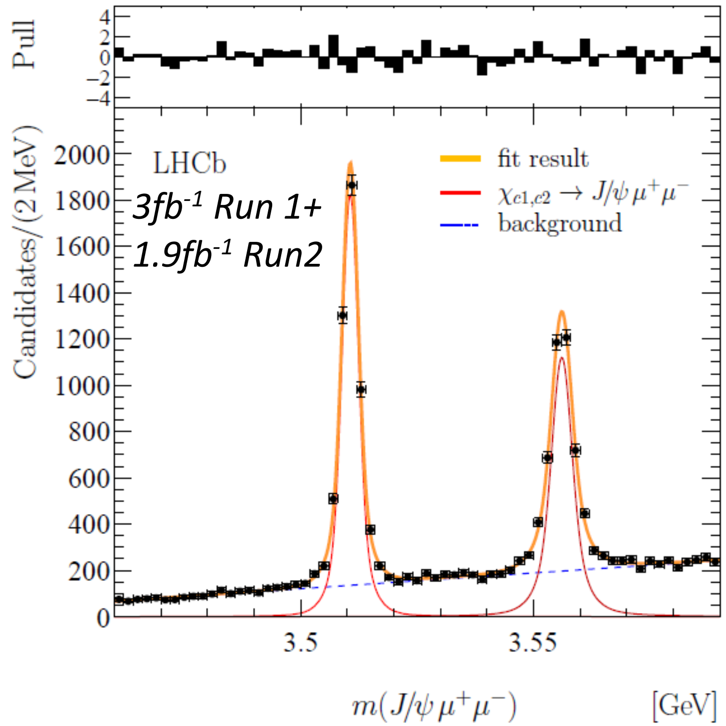
95% CL. Limits on $\mathcal{R}$ in range 0.02-0.14, depending on mass



(a) MLP category: (0.02,0.2)
(b) MLP category: [0.2,0.4)
(c) MLP category: [0.4,0.6)
(d) MLP category: [0.6,1.0]

Muonic decays of χ_{c1} and χ_{c2}

PRL119 (2017) 221801, arXiv:1709.04247



Orbitally excited $c\bar{c}$ states χ_c usually studied in $\chi_c \to J/\psi\gamma$ decays

First observation of $\chi_c \to J/\psi\mu^+\mu^-$ decays!

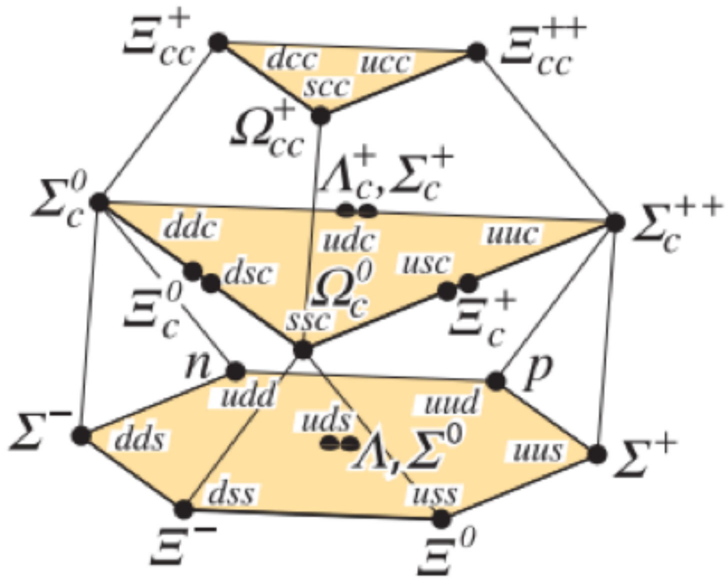
Much better mass resolution allows competitive mass and width measurements.

Quantity [MeV]	LHCb measurement	Best previous measurement	World average
$m(\chi_{c1})$	3510.71 ± 0.10	3510.72 ± 0.05	3510.66 ± 0.07
$m(\chi_{c2})$	3556.10 ± 0.13	3556.16 ± 0.12	3556.20 ± 0.09
$\Gamma(\chi_{c2})$	2.10 ± 0.20	1.92 ± 0.19	1.93 ± 0.11

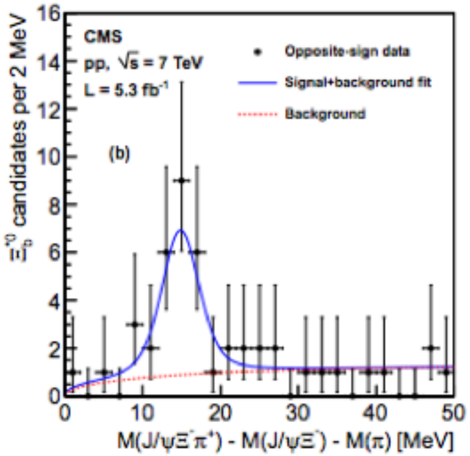
Baryons

qqq states, very rich in weakly decaying ground states

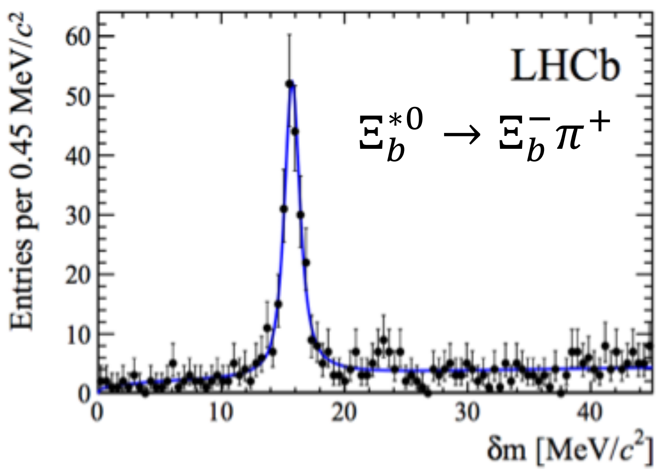
Even richer in excited states!



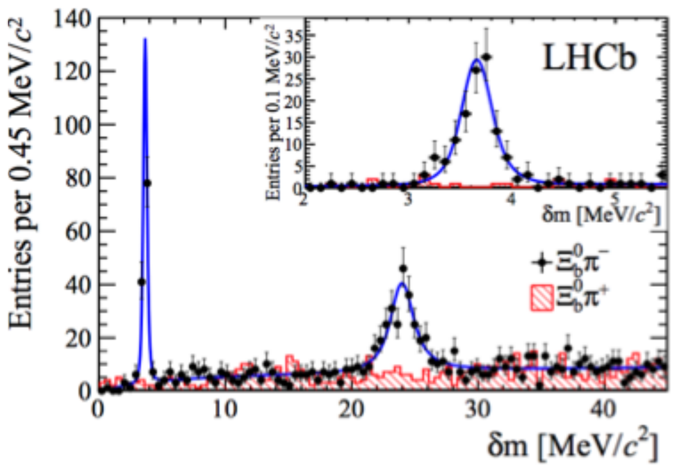
PRL 108, 252002 (2012), arXiv:1204.5955



JHEP 1605 (2016) 161, arXiv:1604.03896



PRL 114, 062004 (2015), arXiv:1411.4849



Doubly charmed baryons

Three weakly decaying C=2 states expected:

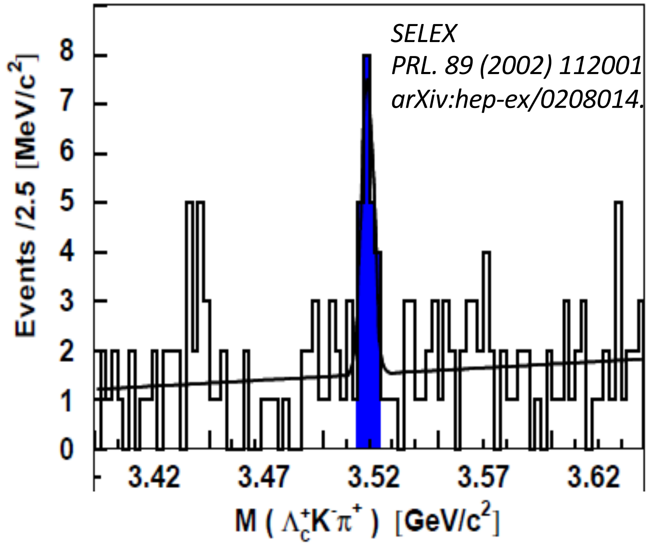
$\Xi_{cc}^{++}\ (ccu)$, $\Xi_{cc}^{+}\ (ccd)$ and $\Omega_{cc}^{+}\ (ccs)$.

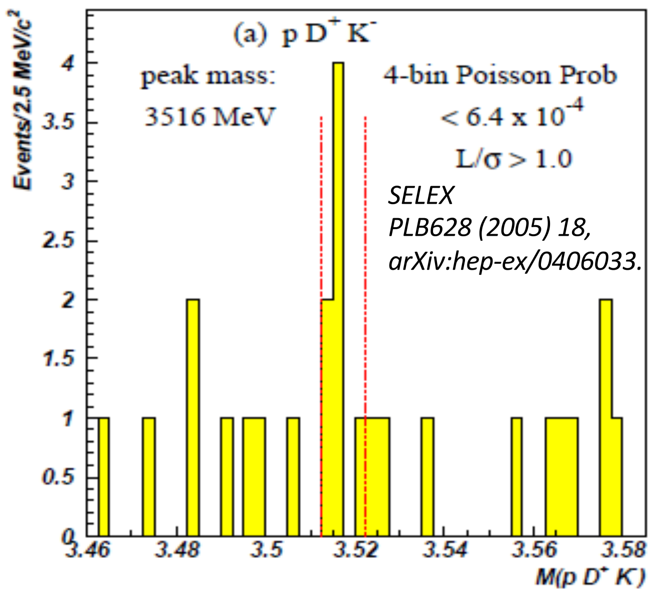
Expect $m(\Xi_{cc}^{++}) \approx m(\Xi_{cc}^{+})$,
but $\tau(\Xi_{cc}^{++}) > \tau(\Xi_{cc}^{+})$.

Observation and confirmation of Ξ_{cc}^{+} reported by SELEX experiment.

Unexpectedly short lifetime and large production.

Not confirmed by BaBar *[PRD74(2006)011103]*, Belle *[PRL97(2006)162001]* nor LHCb *[JHEP 12 (2013) 090]*





The doubly charmed baryon Ξ_{cc}^{++}

Select $\Lambda_c^+ \to pK^-\pi^+$ candidates, combine with K^-, π^+, π^+ tracks

Reject background with neural net (trained on MC for signal, wrong-sign combinations for background)

Peak of 313±33 events (local significance of 12σ), mass

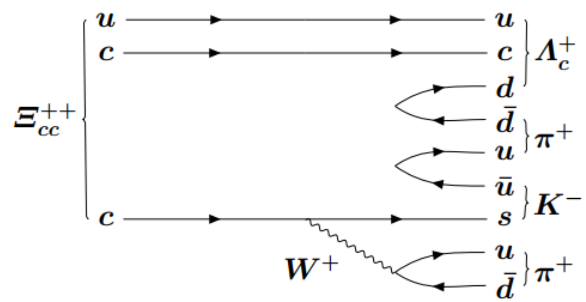
$3621.40 \pm 0.72\,(\mathrm{stat}) \pm 0.27\,(\mathrm{syst}) \pm 0.14\,(\Lambda_c^+)\ \mathrm{MeV}/c^2.$

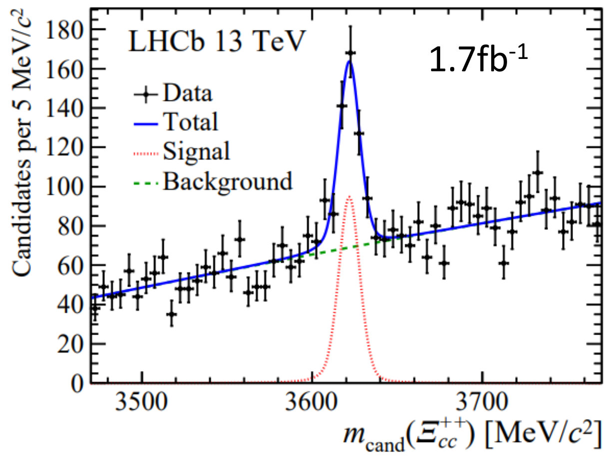
7σ peak also in 8TeV Run1 data

Significant signal also after $t > 5\sigma_t$ cut.

~100MeV more than SELEX Ξ_{cc}^+ peaks

PRL119, 112001 (2017), arXiv:1707.01621





Excited Ω_c^0 states

PRL118, 182001 (2017), arXiv:1703.04639
3.0fb^{-1}Run1 + 0.3fb^{-1} Run2

Previously, the only css baryons known were the ground state Ω_c^0 and the $\Omega_c(2770)^0$

Search for more excited css states in $\Xi_c^+ K^-$ spectrum.

Reconstruct $\Xi_c^+ \rightarrow pK^-\pi^+$

Cabibbo-suppressed but efficient

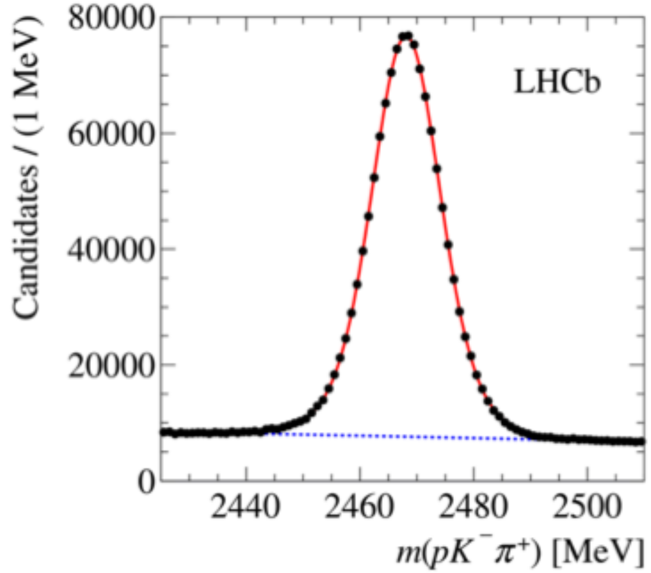
S/B likelihood ratio used to select 1,05M Ξ_c^+ with 83% purity

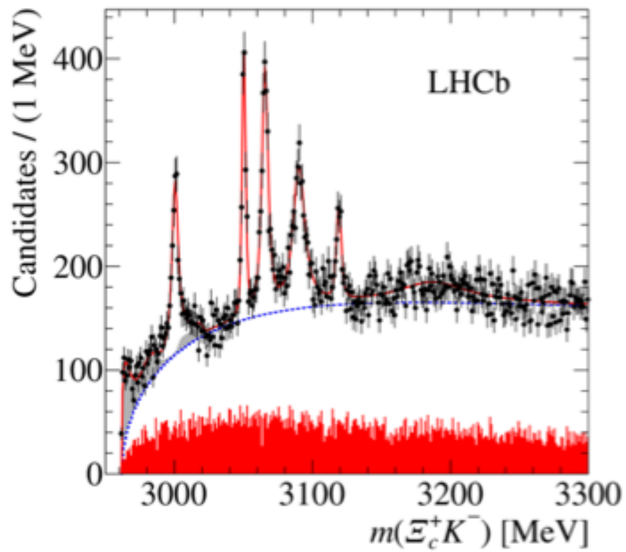
Combine with tight K^- and require $p_{\mathrm{T}} > 4.5\mathrm{GeV}$

5 new narrow resonances

plus $\Omega_c(X)^0 \rightarrow \Xi'^+_c K^-, \Xi'^+_c \rightarrow \Xi_c^+ \gamma$ *feeddown*

No structures in Ξ_c^+ sidebands or $\Xi_c^+ K^+$ spectrum





Excited Ω_c^0 states

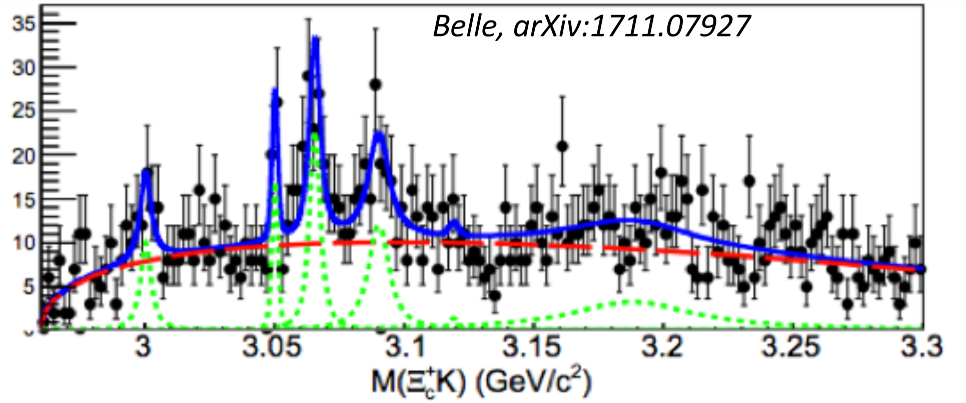
PRL118, 182001 (2017), arXiv:1703.04639
3.0fb^{-1}Run1 + 0.3fb^{-1} Run2

Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		$< 1.2\,\mathrm{MeV}, 95\%$ CL		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		$< 2.6\,\mathrm{MeV}, 95\%$ CL		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{\mathrm{fd}}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{\mathrm{fd}}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{\mathrm{fd}}$			$190 \pm 70 \pm 20$	

Fit improves by including broad high-mass BW shape
Could be single state, multiple states, feeddowns, etc.

Studies of these states in B decays will allow determination of quantum numbers

Confirmed by Belle:
Suppression of the 5th state in e^+e^- expected if it is a pentaquark



Tetraquarks

$q\bar{q}q\bar{q}$ states that cannot be described as $q\bar{q}$

2008: Evidence from Belle of a $\psi'\pi^-$ peak in $B^+ \to \psi' K^+ \pi^-$ decays (1D analysis)

Difficult to distinguish unambiguously from reflections of $K^+\pi^-$ resonances

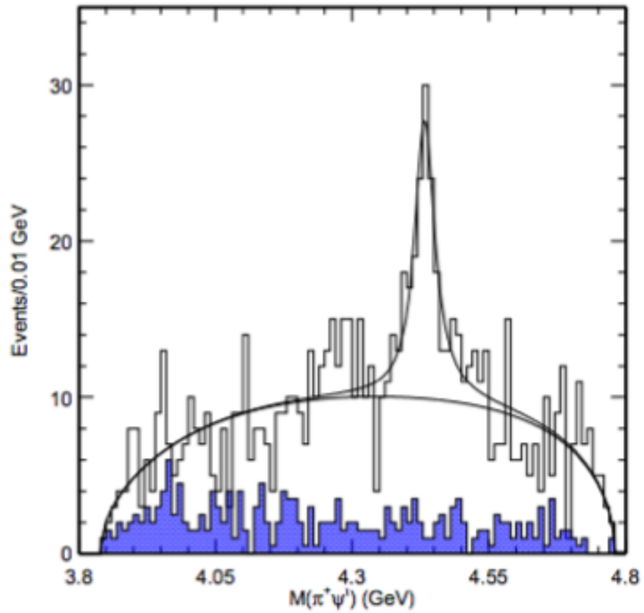
2009 BaBar analysis in 4D managed to describe with $K^+\pi^-$ resonances alone

2014 high-stat LHCb analysis: incompatible with $K^+\pi^-$ resonances alone

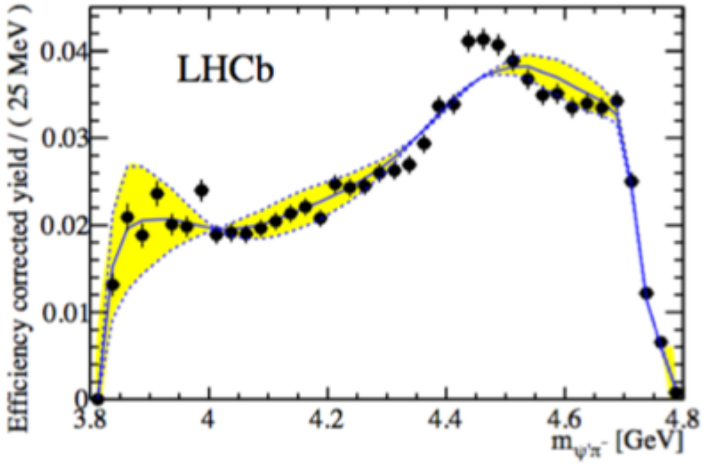
amplitude fit Z(4430): > 13σ

phase motion consistent with BW

PRL100 (2008) 142001, arXiv:0708.1790



PRL112, 222002 (2014), arXiv:1404.1903
PRD92, 112009 (2015), arXiv:1510.01951



Exotic $J/\psi\phi$ states in $B^+ \to J/\psi\phi K^+$ decays

First evidence for $J/\psi\phi$ structure from CDF:

3.8σ excess at 4140MeV based on 75 $B^+ \to J/\psi\phi K^+$ decays

Also excess at higher mass

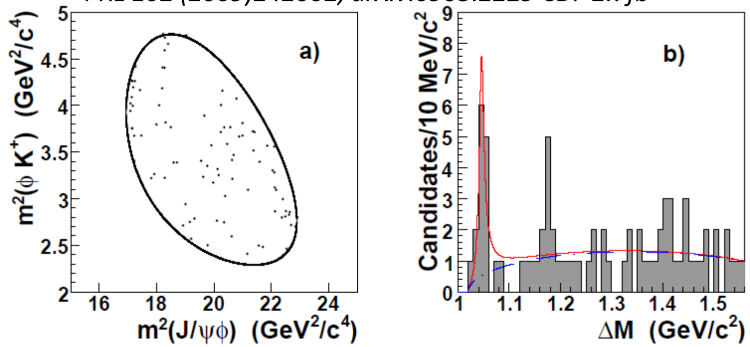
Not confirmed in 0.37fb^{-1} LHCb search, using 382 decays

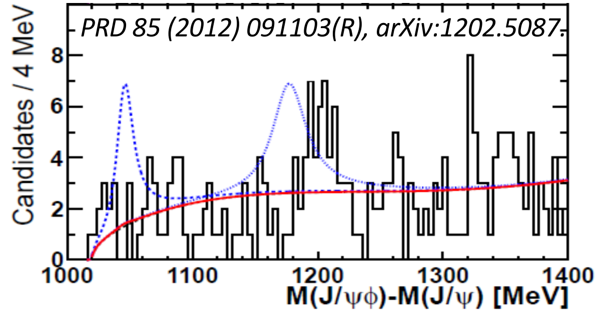
But confirmed by CMS

and D0

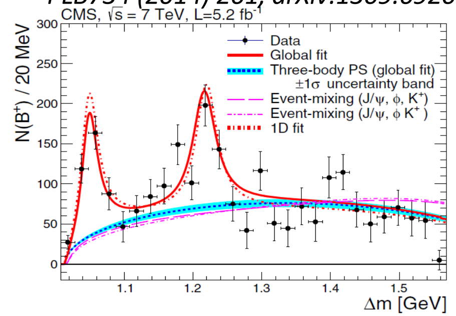
both in $B^+ \to J/\psi\phi K^+$ decays and in prompt production

PRL 102 (2009)242002, arXiv:0903.2229 CDF 2.7fb^{-1}

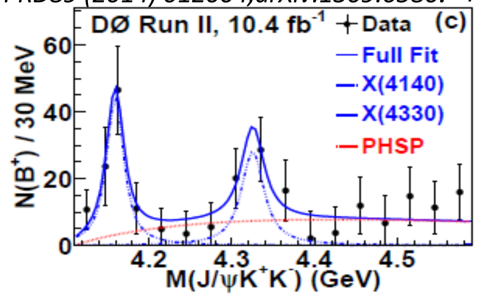




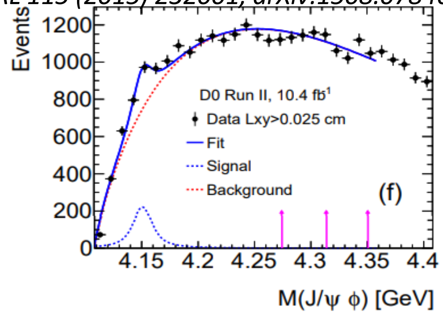
PLB734 (2014) 261, arXiv:1309.6920.



PRD89 (2014) 012004,arXiv:1309.6580.



PRL 115 (2015) 232001, arXiv:1508.07846.



Exotic $J/\psi\phi$ states in $B^+ \to J/\psi\phi K^+$ decays

PRL118, 022003 (2017), arXiv:1606.07895
PRD 95, 012002 (2017), arXiv:1606.07898

LHCb performed full 6D amplitude analysis

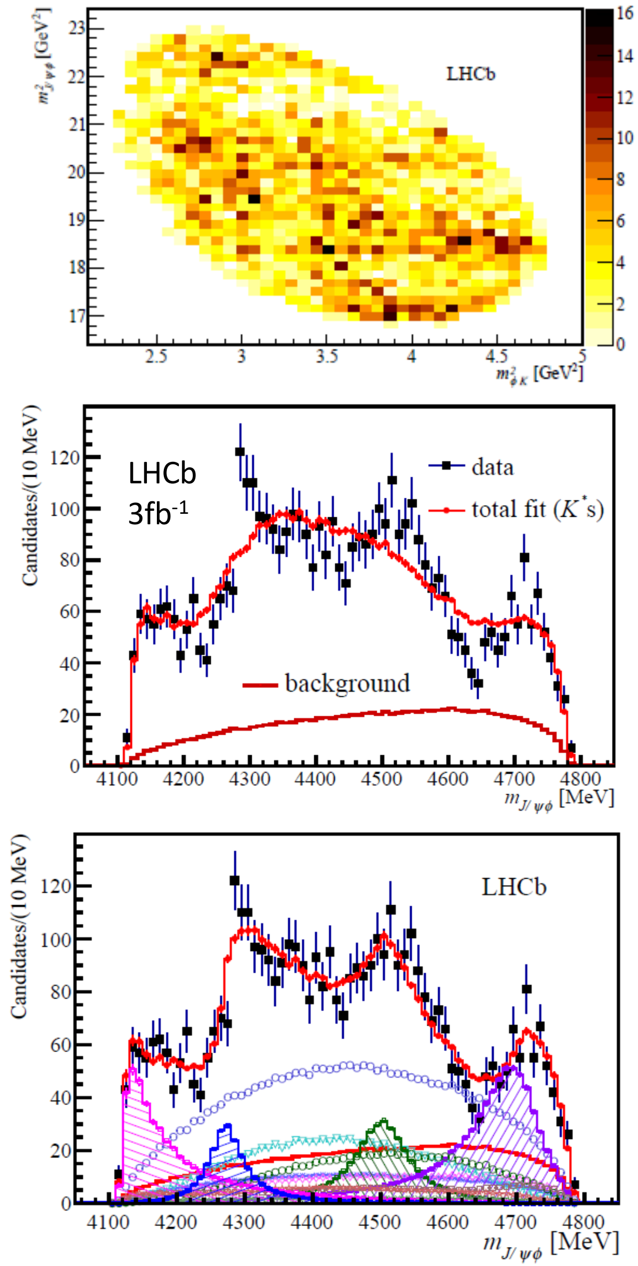
Data cannot be described with ϕK^+ resonances alone.

Four new $J/\psi\phi$ resonances are observed with >5 σ each

A wide X(4140), $\Gamma = 80 \pm 30\text{MeV}$, $J^{PC} = 1^{++}$

X(4274) $\Gamma \sim 60$ MeV, $J^{PC} = 1^{++}$

X(4500) and X(4600) $\Gamma \sim 100$ MeV $J^{PC} = 1^{++}$



Structures in the $B_s^0\pi^\pm$ spectrum

D0 reported 3.9-5.1 σ evidence for a resonance in the $B_s^0(\to J/\psi\phi)\pi^\pm$ spectrum, dubbed $X(5568)$,
$\Gamma = 22 \pm 7\text{MeV}$,
$\sigma(X)/\sigma(B_s^0) = 0.086 \pm 0.022$

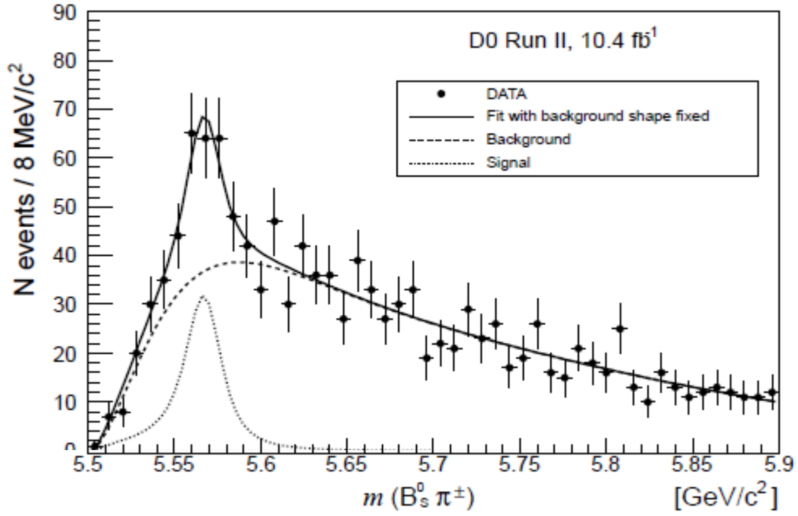
Uniquely interesting:

- *4-flavour quark content: $b\bar{s}u\bar{d}$*
- *Mass dominated by single heavy quark*

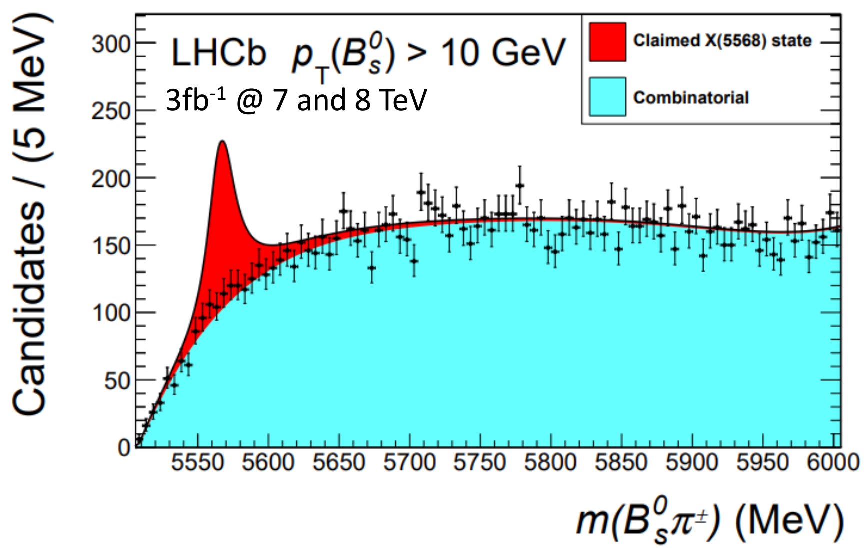
LHCb checked with 20x larger $B_s^0 \to J/\psi\phi, D_s^-\pi^+$ sample

$X(5568)$ **not confirmed**, find $\sigma(X)/\sigma(B_s^0) < 0.02$

PRL117 (2016) 022003, arXiv:1602.07588



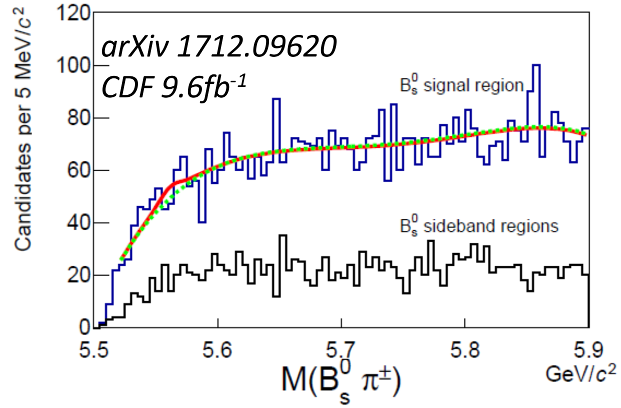
PRL117 (2016) 152003, arXiv:1608.00435



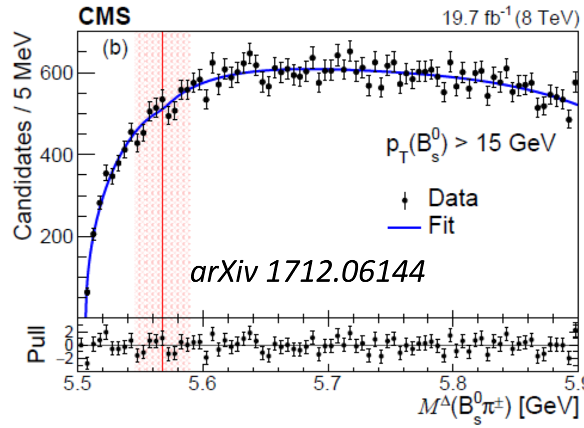
Structures in the $B_s^0\pi^\pm$ spectrum

Lastest news on the X(5568):

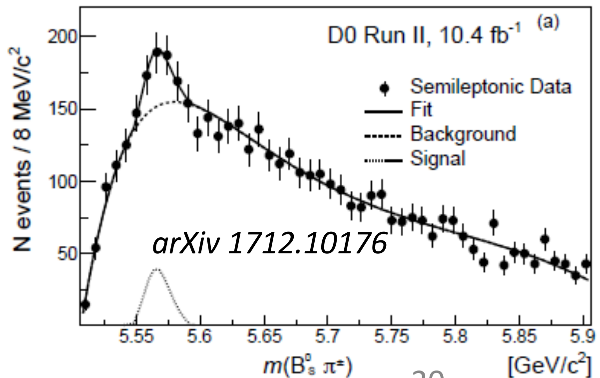
CDF finds no evidence and sets limit on $\sigma(X)/\sigma(B_s^0) < 0.067$



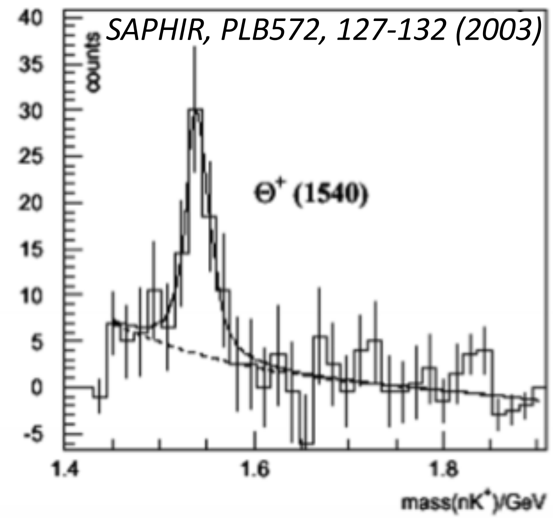
CMS finds no evidence and sets limits on $\sigma(X)/\sigma(B_s^0) < 0.010$



D0 confirms the observation with semileptonic B_s^0 decays



Pentaquarks



5-quark $qqqq\bar{q}$ states

A bit of a rocky history with many unconfirmed claims:

2002-2003: >10 claims of $\Theta^{+}(1540) \rightarrow nK^{+}, pK^{0}$

also peaks in $\Xi^{-}\pi^{-}$ and $D^{*-}p$

None of the claims confirmed with overwhelming $(> 10\sigma)$ significance

Soon many null-results came in

later also by high-stat runs of experiments that claimed original observations

EPJH37 (2012) 1.

$J/\psi p$ resonances in $\Lambda_b^0 \to J/\psi p K^-$

PRL 115, 072001 (2015), arxiv:1507.03414 ***3fb^{-1}***

Large (26K) clean ($S/B \sim 20$) sample of $\Lambda_b^0 \to J/\psi p K^-$ decays with intriguing Dalitz plot

Fit to 6D amplitude model
helicity formalism + BW

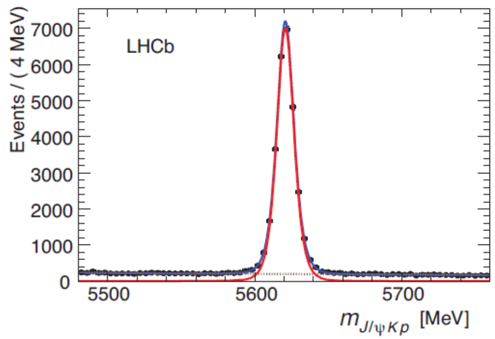
Model with only $\Lambda^* \to pK^-$ resonances gives very poor description.

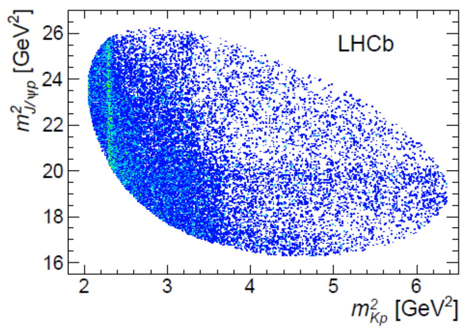
Fit much improved when adding two $J/\psi p$ resonances

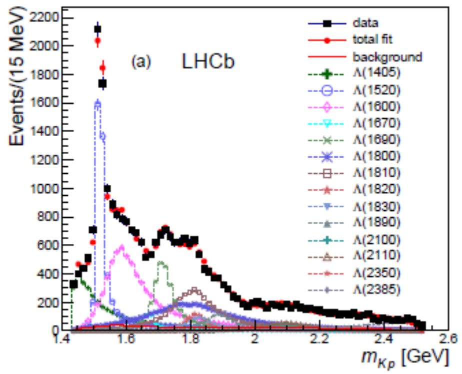
$P_c(4380)$: $\Gamma \approx 200\text{MeV}$, 9σ

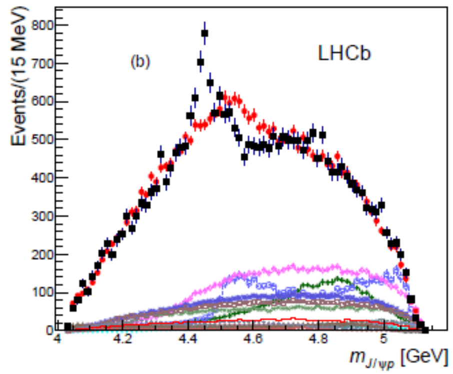
$P_c(4450)$: $\Gamma \approx 40\text{MeV}$, 12σ

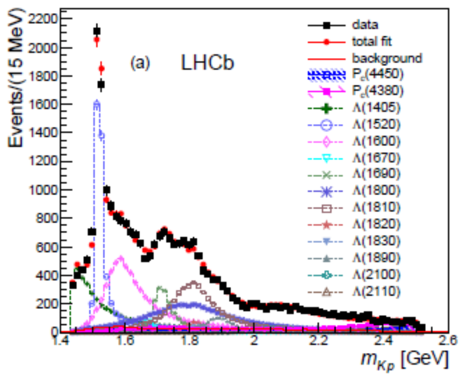
phase motion consistent with BW

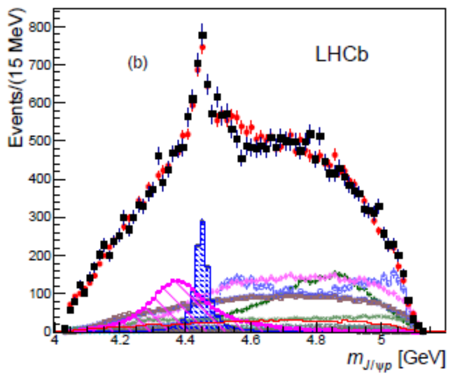












Model-independent confirmation

PRL117, 082002 (2016), arXiv:1604.05708

2D analysis in m_{pK}, $\cos\theta_{\Lambda^*}$
efficiency corrections in 6D

Expand in Legendre polynomials

$$dN/d\cos\theta_{\Lambda^*} = \sum_{l=0}^{l_{\max}} \langle P_l^U \rangle P_l(\cos\theta_{\Lambda^*})$$

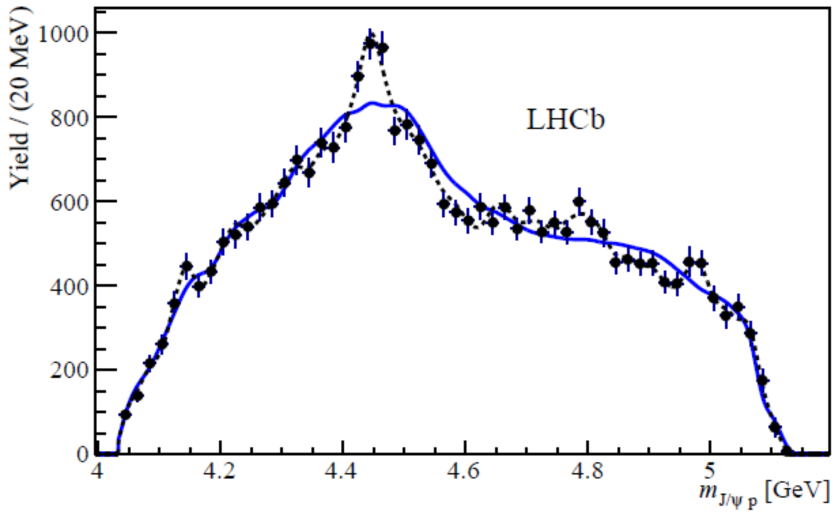
$l_{max} = 3\ (m_{pK} < 1.64)\ -\ 9\ (m_{pK} > 2.05)$

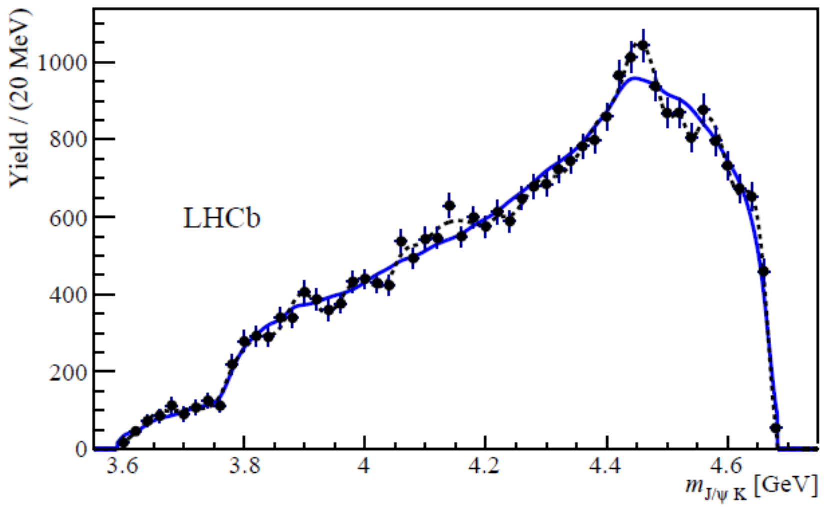
Compare to data, projected on $m_{J/\psi p}$ or $m_{J/\psi K}$

Demonstrated that $\Lambda_b^0 \to J/\psi p K^-$ cannot be described by pK^- contributions alone.

$> 9\sigma$ incompatible in $m_{J/\psi p}$

$> 5\sigma$ incompatible in $m_{J/\psi K}$





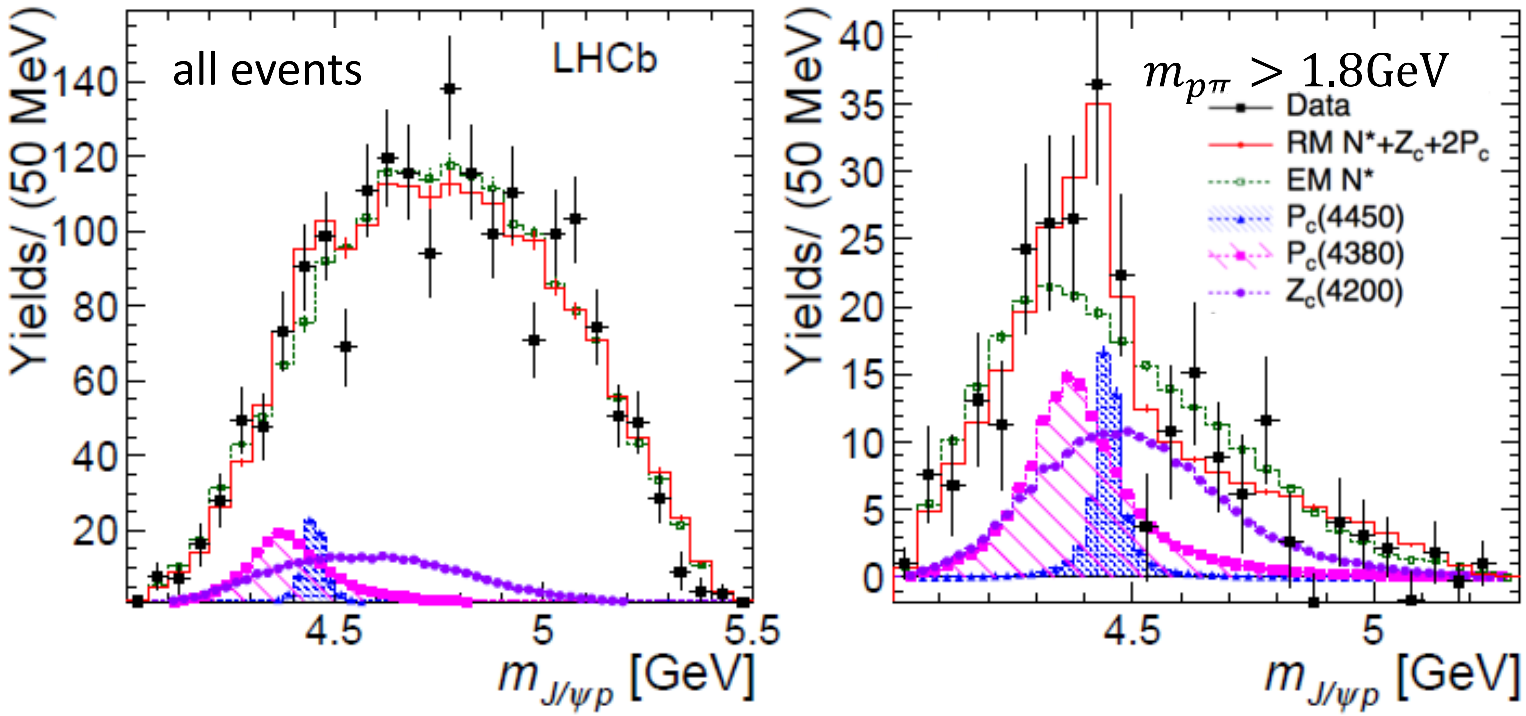
PQ in other channels

$\Lambda_b^0 \to J/\psi p \pi^-$: smaller yield than $\Lambda_b^0 \to J/\psi p K^-$

6D amplitude fit improves when including $P_c(4450)$ and $P_c(4380)$ and/or $Z_c(4200)^-$ tetraquark *Phys. Rev. D90 (2014) 112009, arXiv:1408.6457*.

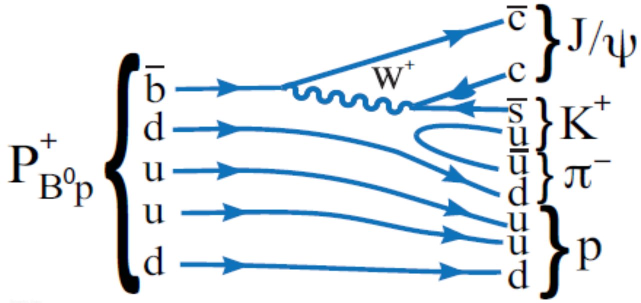
3.3σ evidence for sum of PQ, assuming no $Z_c(4200)^-$

PRL 117, 082003 (2016), arXiv:1606.06999



Weakly decaying b-flavoured pentaquarks

arXiv:1712.08086, submitted to PRD



Skyrme model : heavy quarks give tightly bound PQ

Search for masses below strong decay threshold

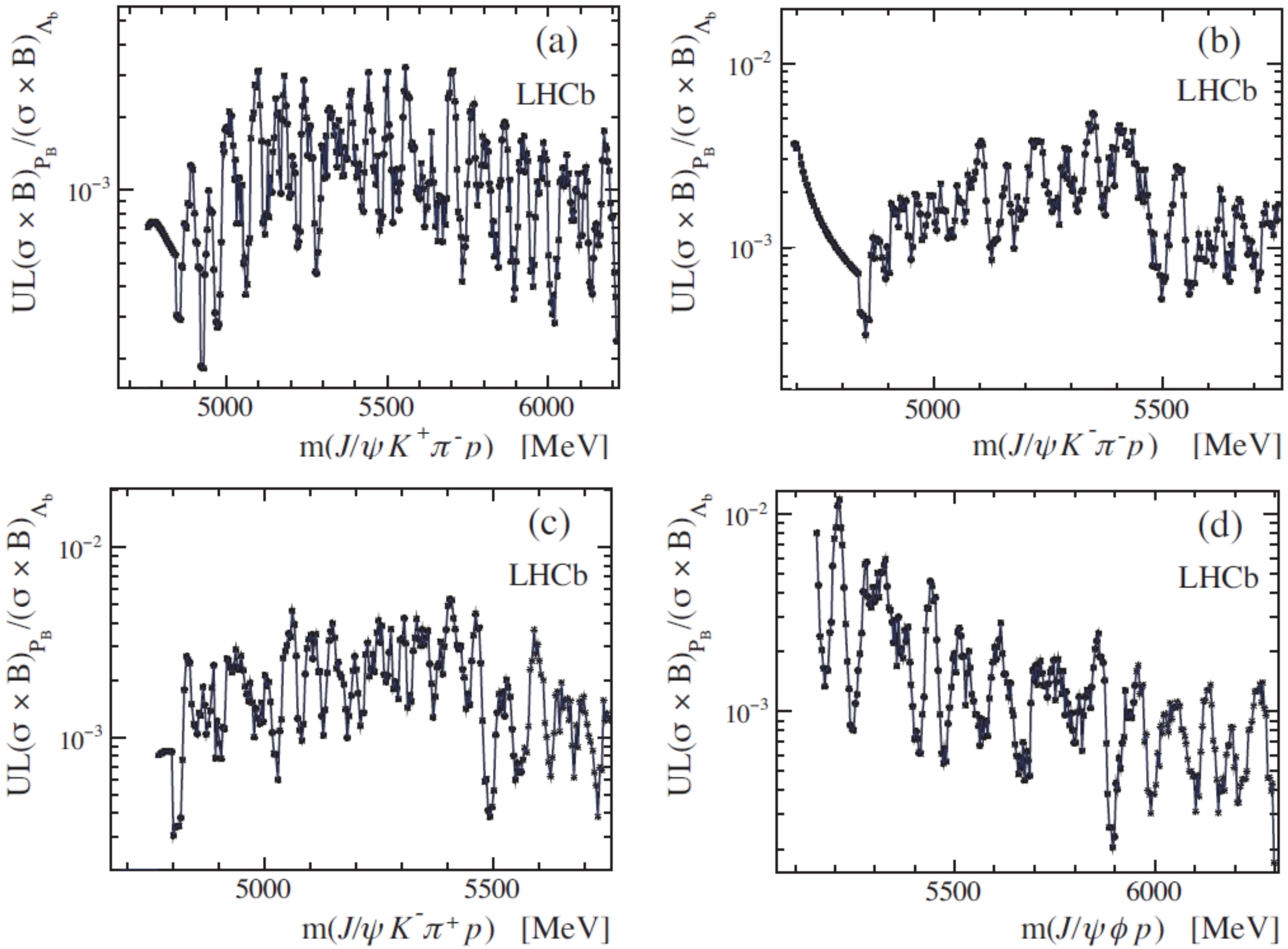
Mode	Quark content	Decay mode	Search window
I	$\bar{b}duud$	$P^+_{B^0p} \to J/\psi\, K^+\pi^-p$	4668–6220 MeV
II	$b\bar{u}udd$	$P^-_{\Lambda^0_b\pi^-} \to J/\psi\, K^-\pi^-p$	4668–5760 MeV
III	$b\bar{d}uud$	$P^+_{\Lambda^0_b\pi^+} \to J/\psi\, K^-\pi^+p$	4668–5760 MeV
IV	$\bar{b}suud$	$P^+_{B^0_sp} \to J/\psi\, \phi p$	5055–6305 MeV

Measure $R = \dfrac{\sigma(pp \to P_B X)\cdot\mathcal{B}(P_B \to J/\psi\, X)}{\sigma(pp \to \Lambda^0_b X)\cdot\mathcal{B}(\Lambda^0_b \to J/\psi\, K^-p)}$

Weakly decaying b-flavoured pentaquarks

arXiv:1712.08086, submitted to PRD
3fb^{-1} @ 7 and 8 TeV

No evidence for signal, limits on R<10^{-2}-10^{-3}



Outlook

New data

Run 2 continues in 2018, already >2xRun 1

New channels

Many combinations still unexplored

New triggers and data formats

Store B or D with few tracks only

New detector

Upgrade with 40MHz readout, 5x$\mathcal{L}$ ready in 2021

Ideas, R&D for phase-2 upgrade another 5x$\mathcal{L}$ aim for Run 5, 2031

New people with new ideas

Conclusions

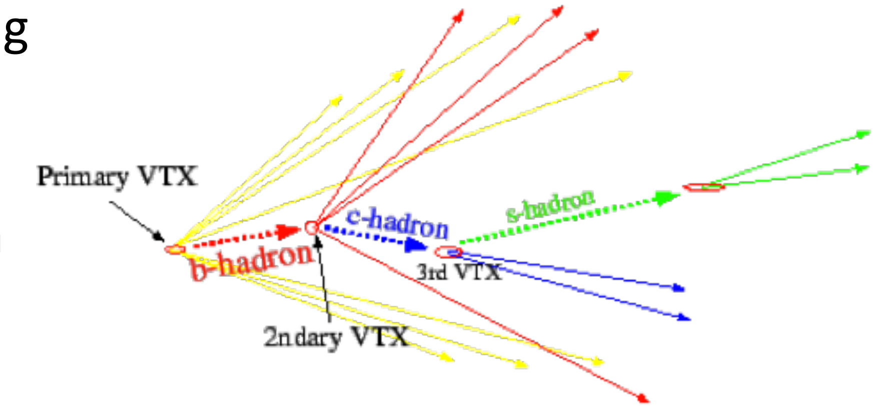
- Large HF data samples from LHCb used for detailed spectroscopy measurements
- Existence of baryons beyond mesons and baryons now well established
- Keep going on with new data, and new ideas

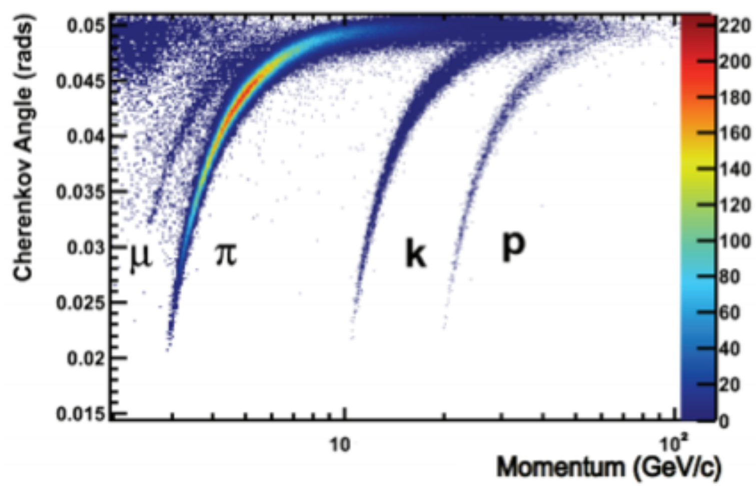
BACKUP

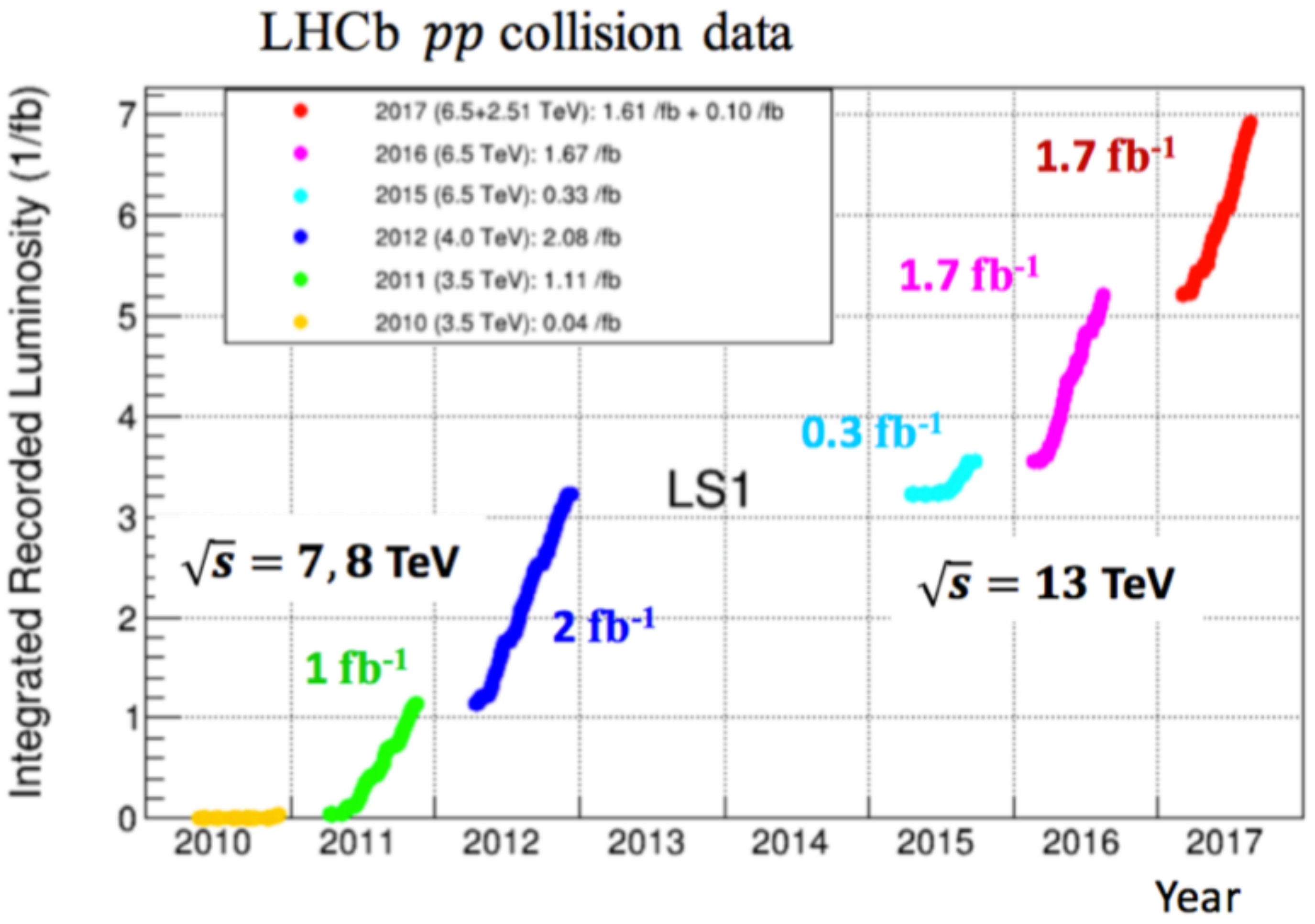
Experimental considerations

- Lifetime key to identifying weakly decaying charm ($c\tau \sim 0.3 - 1.2\text{mm}$) and beauty ($c\tau \sim 1.5\text{mm}$) hadrons
- A HF hadron decay results in tracks with a large impact parameter that fit to a secondary vertex that point back to the primary pp vertex
- The $J/\psi \to \mu^+\mu^-$ decay is particular enough that it can be identified even if produced promptly
- Identifying a track as π, K or p is key to suppressing peaking backgrounds
- Charm data samples too large to store full events

  TURBO/TURBO++: record only reconstructed candidate or candidate + nearby tracks






LHCb pp collision data
2017 (6.5+2.51 TeV): 1.61 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
1.7 fb-1
1.7 fb-1
0.3 fb-1
LS1
√s = 7,8 TeV
2 fb-1
1 fb-1
√s = 13 TeV
Integrated Recorded Luminosity (1/fb)
Year
2010
2011
2012
2013
2014
2015
2016
2017