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LHCb

Exotic hadron searches at LHCb

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On behalf of the LHCb collaboration

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LHCb detector

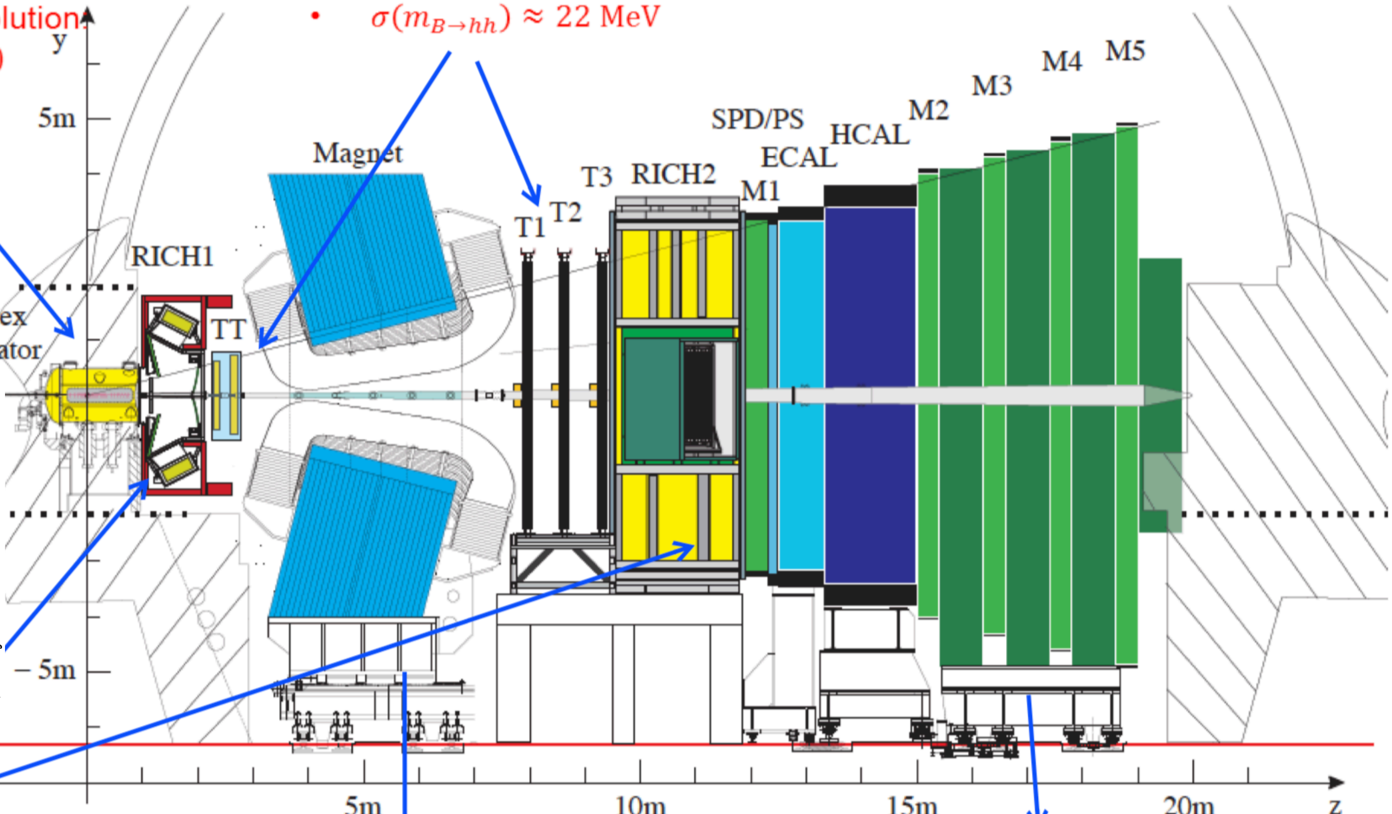
- ➢ **Forward spectrometer @ collider, acceptance: 1.9<η<4.9**

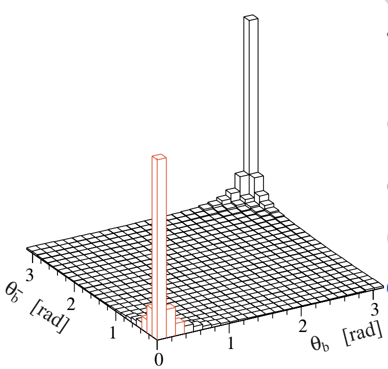
$$\eta = \frac{1}{2}\ln\frac{p+p_z}{p-p_z}$$

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

Vertex Locator(vertex reconstruction)
- Impact parameter resolution: 20 μm
- Decay time resolution 45 fs (τ_B~1.5 ps)

Tracking system(particle reconstruction)
- ϵ(Tracking) ~96%
- $\delta p/p$ ~0.5%-1%(5-200 GeV)
- $\sigma(m_{B\to hh}) \approx 22$ MeV





RICH: particle ID
- $\varepsilon(K\to K)$ ~95%
- Mis-ID: $\varepsilon(\pi\to K)$ ~5%

Magnet
- Bending power: 4 Tm

Muon system
- μ ID: $\varepsilon(\mu\to\mu)$ ~97%
- Mis-ID: $\varepsilon(\pi\to\mu)$ ~1-3%

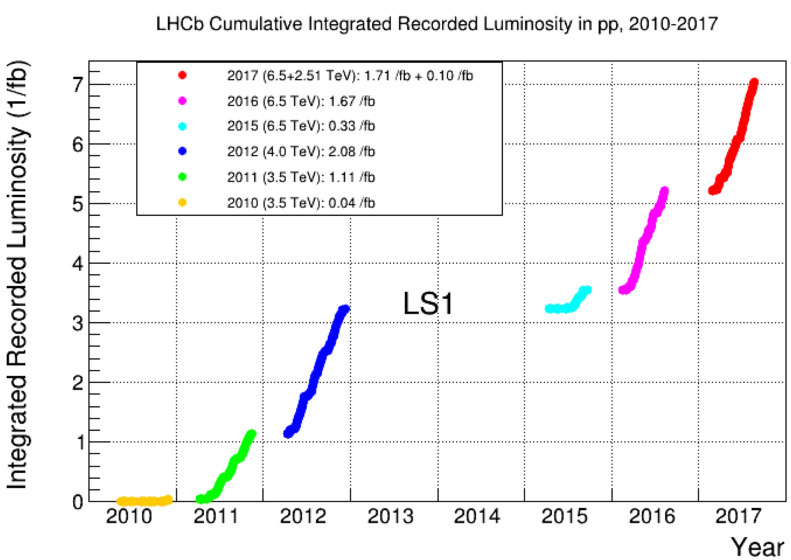
LHCb operation status

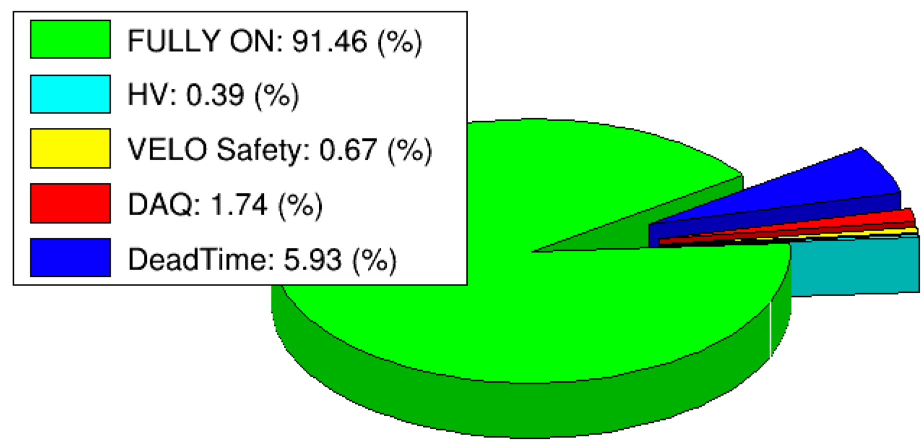
- ➢ **Wonderful performance with the LHCb detector**

- ➢ **In total, we have already collected 7 fb^{-1} data (1 fb^{-1} with 7 TeV, 2 fb^{-1} with 8 TeV and 4 fb^{-1} with 13 TeV)**

- ➢ **Expect 2 fb^{-1} more data in 2018**

- ➢ **More than 90% overall efficiency**





Fundamental questions about QCD

➢ **Theory of the strong interaction between quarks and gluons**

$$\mathcal{L}_{\rm QCD} = \bar{\psi}_i \left(i(\gamma^\mu D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

Three colors
Color confinement
Asymptotic freedom

➢ **Particles formed by quarks and gluons: a more complicated system than that of leptons (i.e. electron + positron) ➜ quark model**

➢ **Quark model: a simple but successful model, lots of questions still unanswered**

How quarks forms particles?

Gluon balls or tetra-quark or pentaquark states or hybrids?

How quarks are grouped inside particles?

What are contributions of Parton properties to particle properties (i.e. spin etc)

……

➢ **Search for exotic states may shed light on these questions**

X,Y,Z States explanation

Pentaquark

magenta-cyan-yellow
color-singlet 5-q state

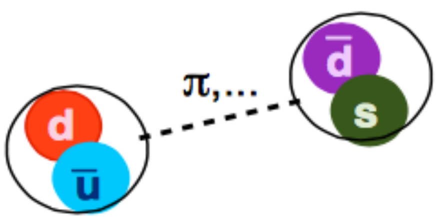
H-dibaryon

magenta-cyan-yellow
color-singlet 6-q state

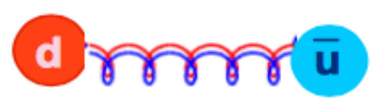
Tetraquark

magenta-green
color-singlet 4-q state

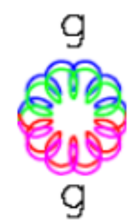
Molecule

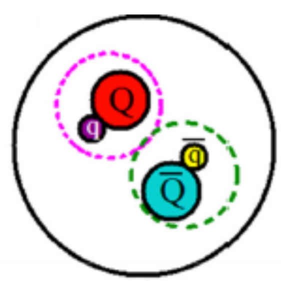


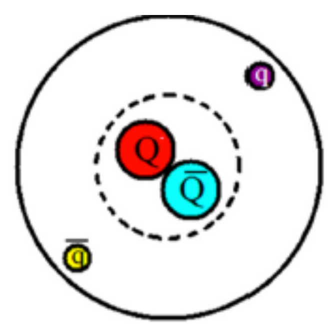
Hybrid



Glueball





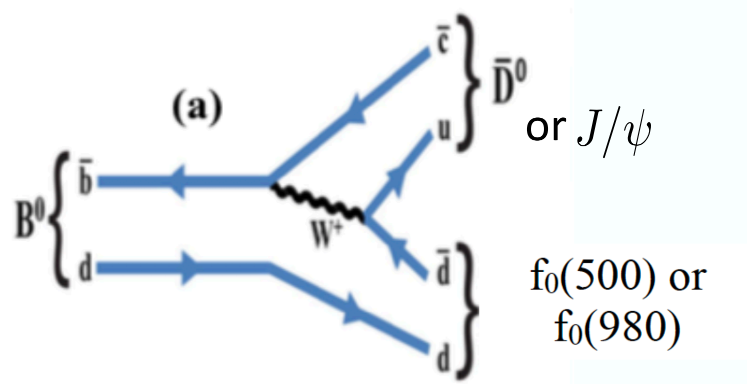


Light exotic searches: $f_0(500)$ and $f_0(980)$

PRL 111(2013) 062001
PRD 90 (2014) 012003
PRD 92 (2015) 032002

- **No light exotic states confirmed yet**
- **The mesons $f_0(500)$ and $f_0(980)$ could be a $q\bar{q}$ or compact $qq\overline{qq}$ state**
- **LHCb studies properties of $f_0(500)$ and $f_0(980)$ using B decays: $B_{(s)} \to J/\psi\pi\pi$ and $B \to \bar{D}^0\pi\pi$**

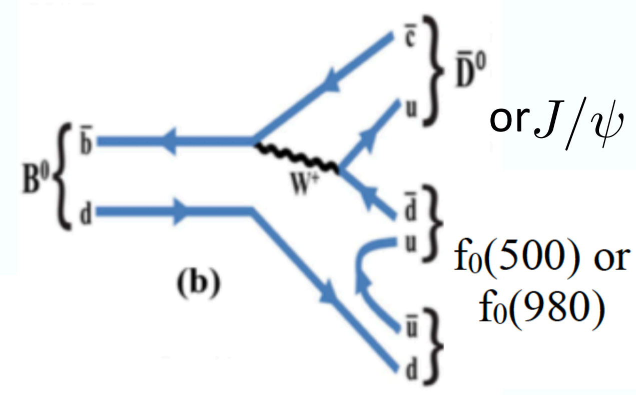
2-q model



$$|f_0(500)>=\frac{1}{\sqrt{2}}(|\bar{u}u>+|\bar{d}d>)\equiv|\bar{n}n>$$

$$|f_0(980)>=|\bar{s}s>$$

4-q model



$$|f_0(500)>=|\bar{u}u\bar{d}d>$$

$$|f_0(980)>=|\bar{n}n\bar{s}s>$$

$$|f_0(980)\rangle = |\bar{s}s\rangle\cos\theta + |\bar{n}n\rangle\sin\theta,$$
$$|f_0(500)\rangle = -|\bar{s}s\rangle\sin\theta + |\bar{n}n\rangle\cos\theta.$$

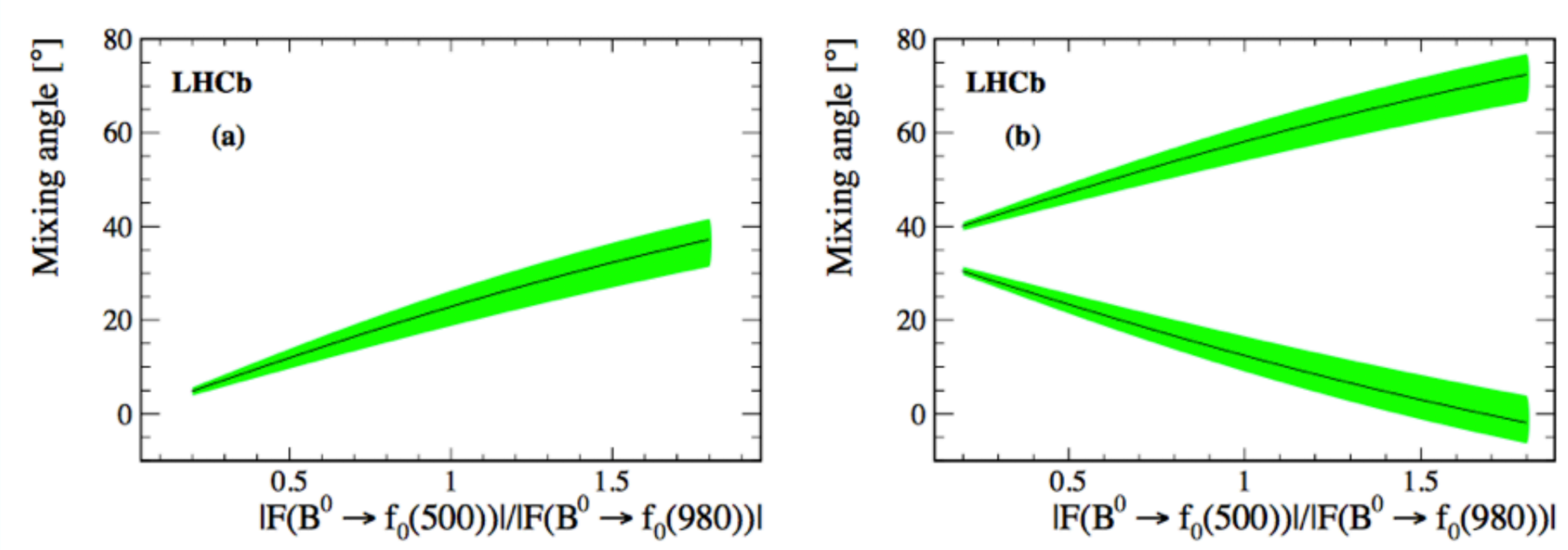
$$|f_0(980)\rangle = |\bar{n}n\bar{s}s\rangle\cos\phi + |\bar{u}u\bar{d}d\rangle\sin\phi,$$
$$|f_0(500)\rangle = -|\bar{n}n\bar{s}s\rangle\sin\phi + |\bar{u}u\bar{d}d\rangle\cos\phi,$$

Constrains on mixing angles

PRD 92 (2015) 032002
JHEP 08 (2015) 005

	$\mathcal{B}(B^0 \to \overline{D}^0 f_0)$	$\mathcal{B}(B_s^0 \to \overline{D}^0 f_0)$
$f_0(500)$	$(11.2 \pm 0.8 \pm 0.5 \pm 2.1 \pm 0.5) \times 10^{-5}$	—
$f_0(980)$	$(1.34 \pm 0.25 \pm 0.10 \pm 0.46 \pm 0.06) \times 10^{-5}$	$(1.7 \pm 1.0 \pm 0.5 \pm 0.1) \times 10^{-6}$

2-q model **4-q model**

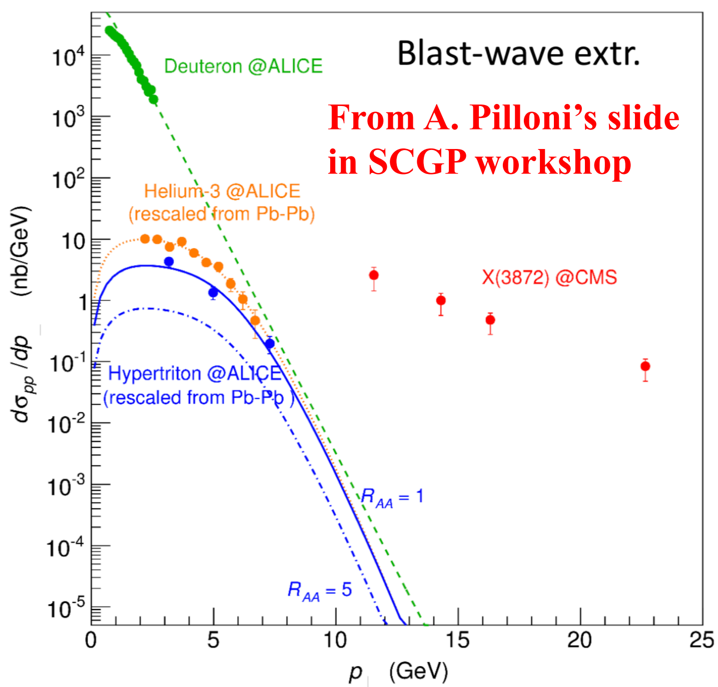


- **Mixing angles of 2-q and 4-q model given as a function of form factor ratios**
- **Results from $B_s^0 \to \overline{D}^0 f_0(980)$, $B^0 \to \overline{D}^0 f_0(980)$ and $B^0 \to \overline{D}^0 f_0(500)$ indicate complicated nature of the system**
- **More complicated when including J/ψ system into analysis**

Understanding X(3872): production

EPJC 72 (2012) 1972

- ➢ Best studied exotic meson candidates: an example on how we understand exotics
- ➢ Current understanding: containing mixture from $\chi_{c1}(2P)$
- ➢ The first exotic found to be produced promptly



May have compact components

PDG

$c\bar{c}$ MESONS
(including possibly non-$q\bar{q}$ states)

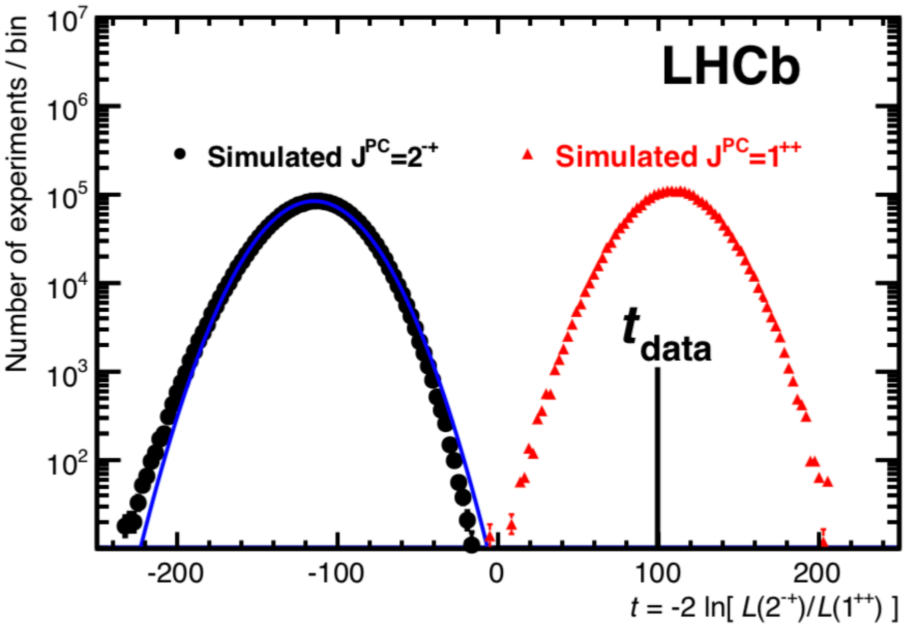
$\chi_{c1}(3872)$ $\quad I^G(J^{PC}) = 0^+(1^{++})$
also known as $X(3872)$

- ➢ LHCb has measured its production at 7 TeV, not distinguishing prompt and secondary
- ➢ Further analyses are ongoing with much more data using pp collisions
- ➢ Studies with p-Pb, Pb-Pb collisions in the future are also quite interesting

Understanding X(3872) : J^{PC}, mass and width

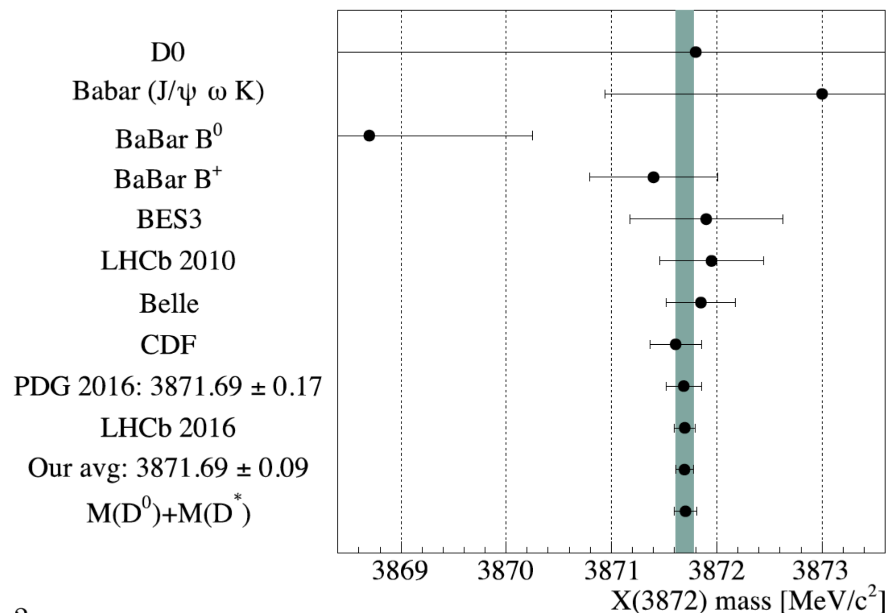
➢ Spin-parity has been set to 1^{++} combining efforts from LHCb and Belle

PRL 110 (2013) 222001



➢ Mass very close to $D^0\bar{D}^{*0}$ threshold, motivates further precise measurement

$$E_b = 11 \pm 146\,\mathrm{keV}/c^2$$



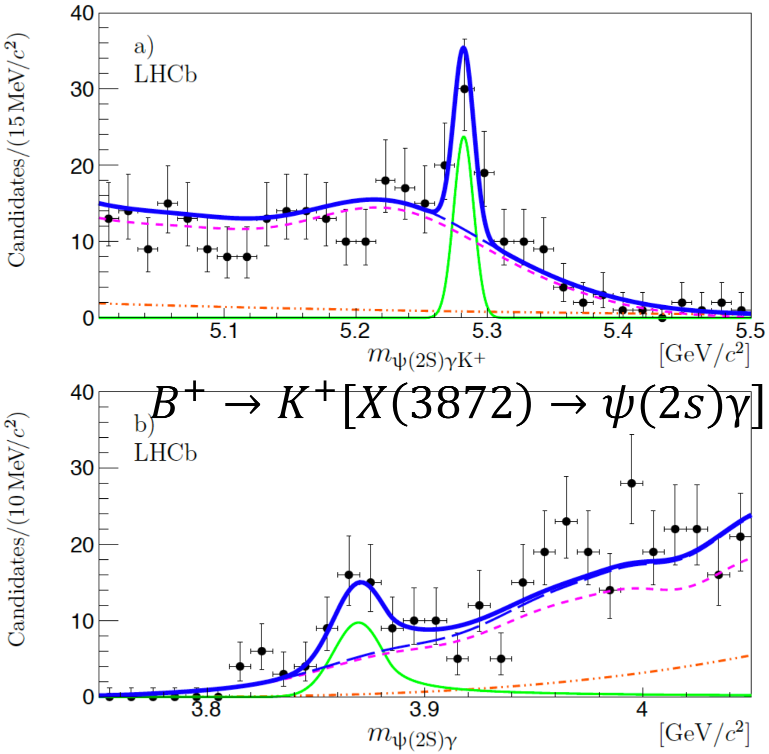
➢ Current width consistent with zero, but data now have sensitivity to that, would be good to think about how to model the lineshape

Understanding X(3872): decays

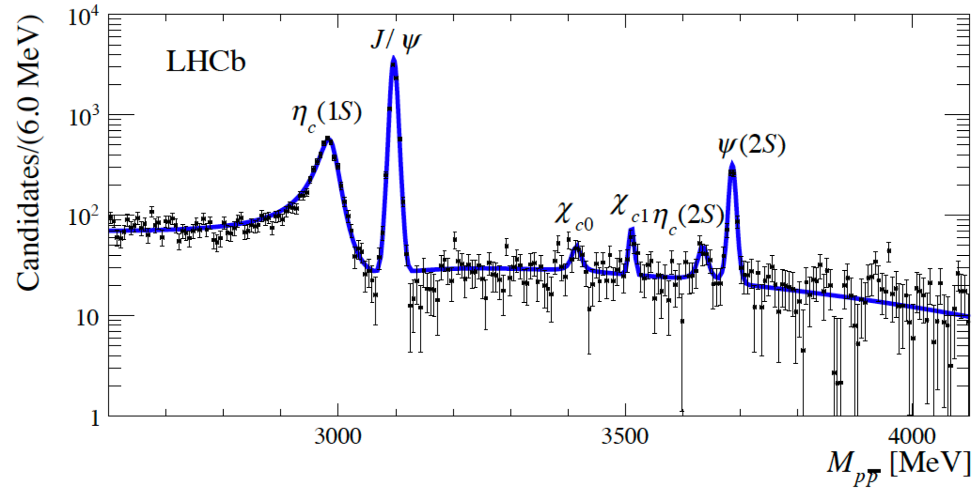
- X(3872) mainly decays to $J/\psi\rho(770)$, $J/\psi\omega(782)$ and $D^0\bar{D}^{*0}$, like loosely bounded molecular

- Other decays are also searched by LHCb

PLB 03 (2017) 046
NPB 886 (2014) 665



$B^+ \to K^+[X(3872) \to \psi(2s)\gamma]$



A null result in $X(3872) \to p\bar{p}$

Evidence seen in Babar not in Belle

LHCb confirms it with 4.4σ, and demonstrates it has contributions of $\chi_{c1}(2P)$

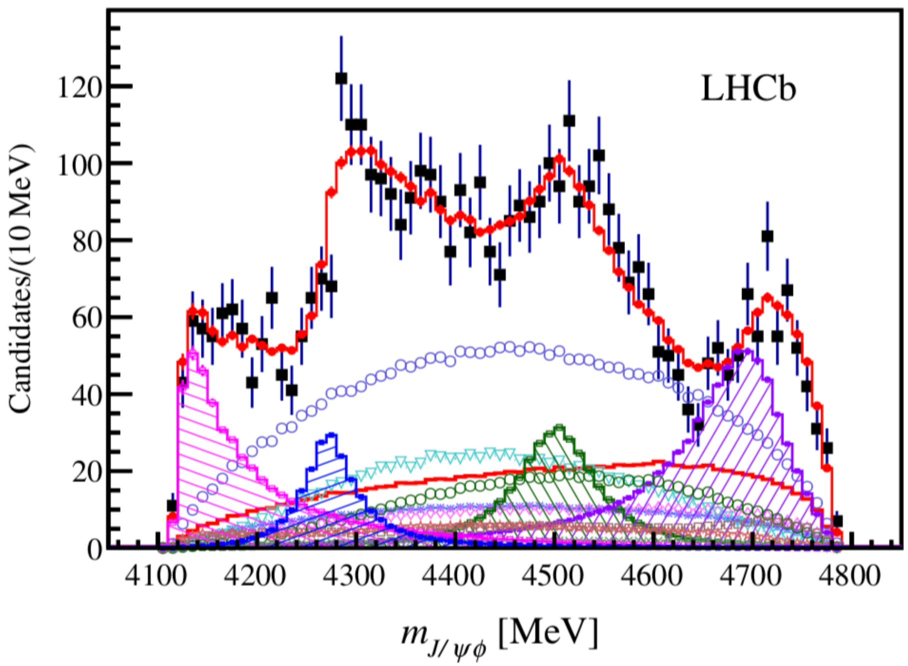
$$R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\,\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

Four exotics in one channel

PRD 95 (2017) 012002
PRL 118 (2017) 022003

➢ **Disagreement on the existence of X(4140) observed from $B^+ \to (J/\psi\phi)\, K^+$ decay using naïve 1D fit from different experiments**

➢ **Careful 6D amplitude analysis firmly confirms its existence with precise measurements on its mass and width; it gives three more exotic states**



J^{PC}	$X(4140)$	$X(4274)$	$X(4500)$	$X(4700)$
0^{++}	10.3σ	7.8σ	preferred	preferred
0^{-+}	12.5σ	7.0σ	8.1σ	8.2σ
1^{++}	preferred	preferred	$\mathbf{5.2}\sigma$	$\mathbf{4.9}\sigma$
1^{-+}	10.4σ	$\mathbf{6.4}\sigma$	6.5σ	8.3σ
2^{++}	$\mathbf{7.6}\sigma$	7.2σ	5.6σ	6.8σ
2^{-+}	9.6σ	$\mathbf{6.4}\sigma$	6.5σ	6.3σ

X(4140) slightly better with cusp
X(4274) significantly worse with cusp

➢ **Clearly harder to explain 4 exotics at one go ➔ a model killer**

➢ **A first try to not only use "normal" RBW but also use models like cusp in the analysis ➔ close collaboration with theorists well motivated**

Confirmation of Z(4430)

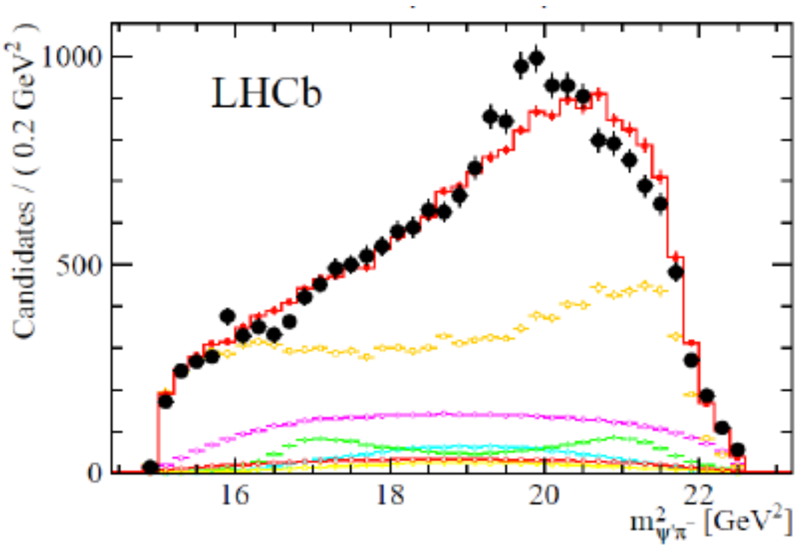
PRL 112 (2014) 222002

➢ While it is not easy to distinguish neutral tetraquark candidates from $c\bar{c}$ or $b\bar{b}$ states, charged candidates are smoking gun for being tetraquarks

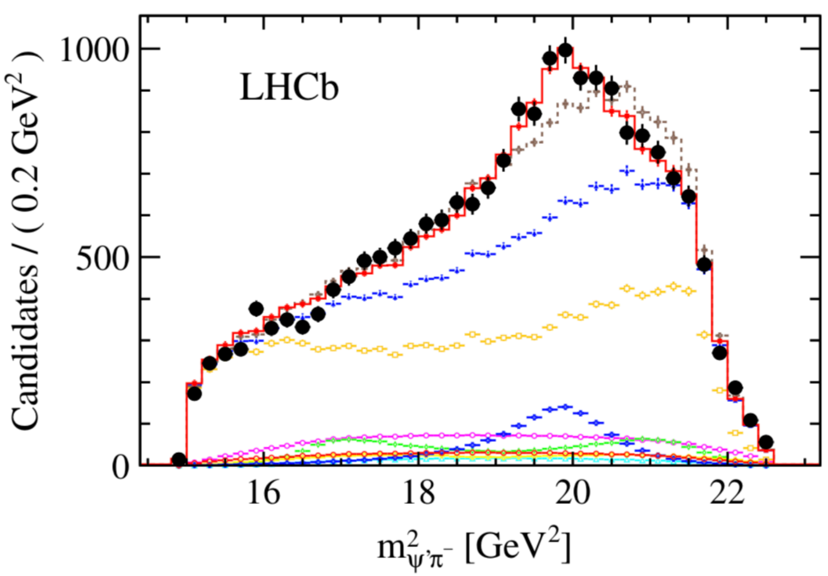
➢ First charged candidates Z(4430) by Belle, and then followed by many others from BESIII

➢ A long saga on the existence of Z(4430): first seen by Belle in 1D mass Fit of m(ψ'π) from $B^0 \to \psi' K\pi$; but not confirmed by Babar; 1D or 2D analysis not enough

➢ LHCb confirms its existence without doubt using its unprecedent data sample with 4D amplitude analysis



without Z(4430)

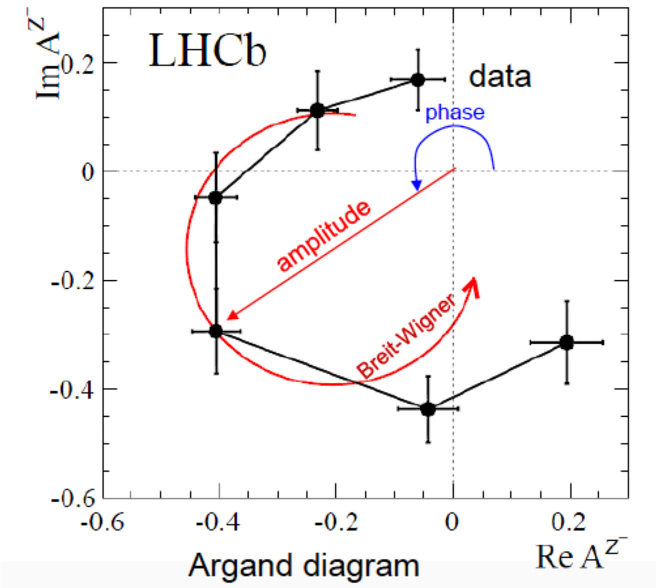


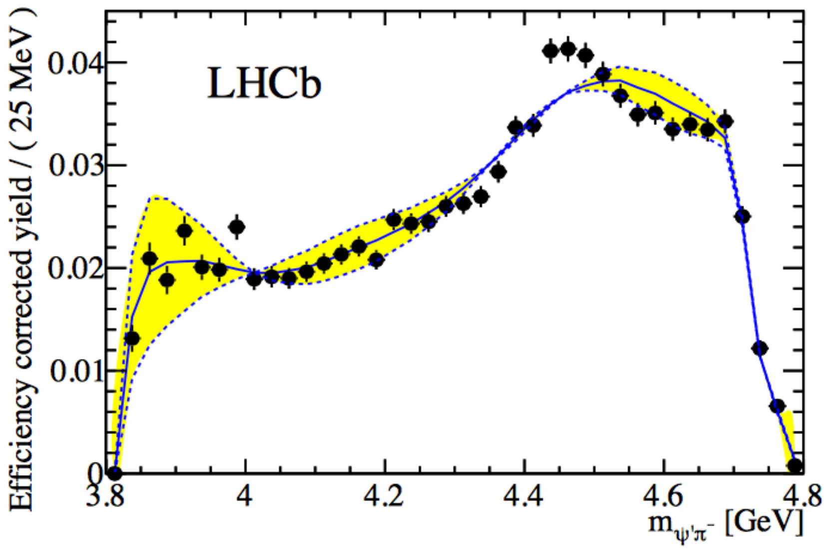
with Z(4430)

Properties of Z(4430)

PRL 112 (2014) 222002

➢ **First time the resonant behavior of tetra-quark candidates shown on Argand plot without any assumption on its lineshape**





➢ **A model-independent method also developed to confirm the existence of Z(4430)**

➢ **The spin-parity of Z(4430) also determined to be 1^+**

Including systematic variations:

	Rejection level relative to 1^+	
Disfavored J^P	LHCb	Belle
0-	9.7σ	3.4σ
1-	15.8σ	3.7σ
2+	16.1σ	5.1σ
2-	14.6σ	4.7σ

The pentaquarks

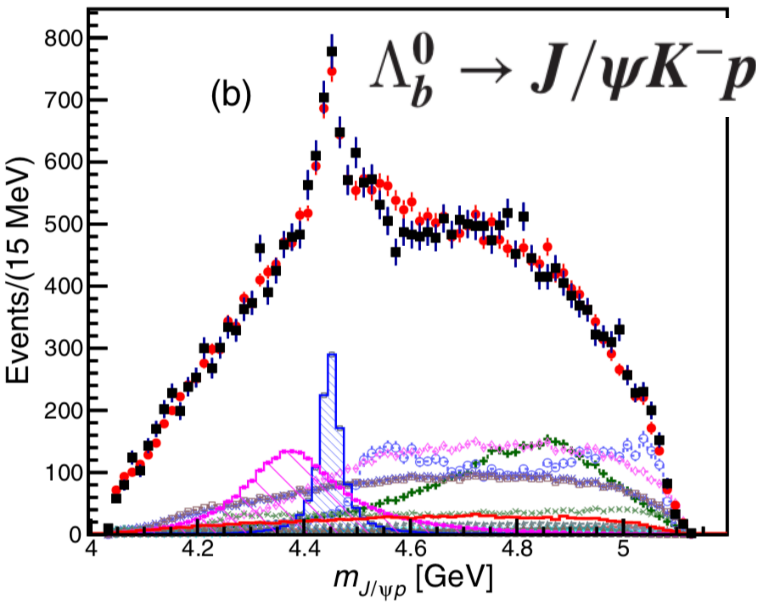
PRL 115 (2015) 072001

- A nature extension of the search is to see if we have pentaquark states

- A "complicated" 6D amplitude analysis is essential

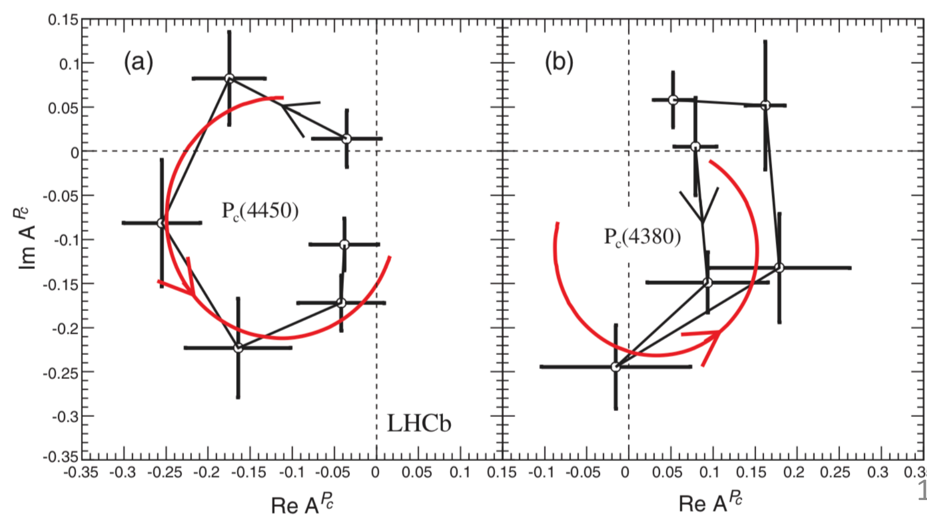
$P_c(4380)^+$: $4380 \pm 8 \pm 29$ MeV
$205 \pm 18 \pm 86$ MeV — **8.4%**

$P_c(4450)^+$: $4449.8 \pm 1.7 \pm 2.5$ MeV
$39 \pm 5 \pm 19$ MeV — **4.1%**



Massive production

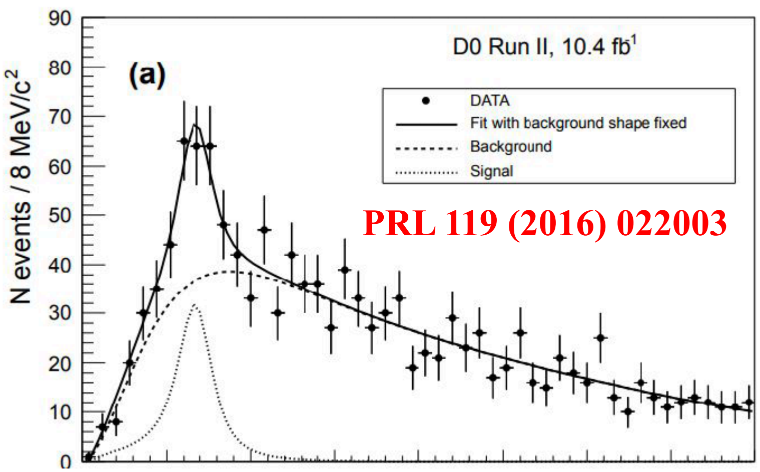
$J^P = (3/2^-, 5/2^+)$
aso possible $(3/2^+, 5/2^-)$, $(5/2^+, 3/2^-)$

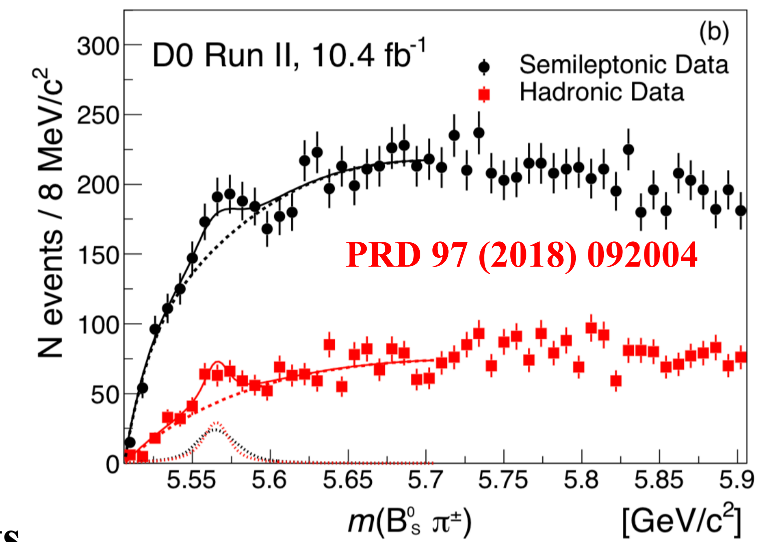


- Understanding further their properties is clearly key elements for the following studies

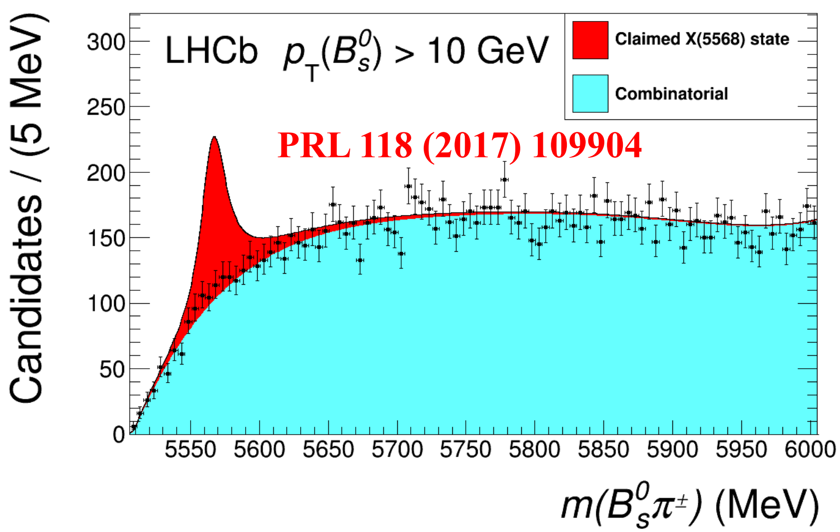
Exotics with four different flavors

➢ **Exotic states with four different quark flavors clearly different from those observed before, possible candidates: $D_{s1}(2317)$ and $X(5568)$**





➢ **Seen in D0 but not in all other experiments**



$$m = 5567.8 \pm 2.9\,(\text{stat})^{+0.9}_{-1.9}\,(\text{syst})\ \text{MeV}/c^2$$

$$\Gamma = 21.9 \pm 6.4\,(\text{stat})^{+5.0}_{-2.5}\,(\text{syst})\ \text{MeV}/c^2$$

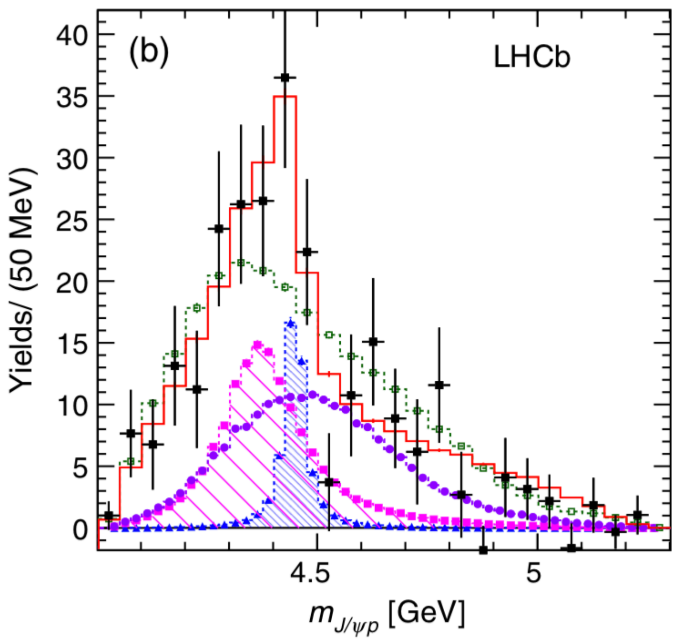
➢ **The existence of X(5568) seems doubtful**

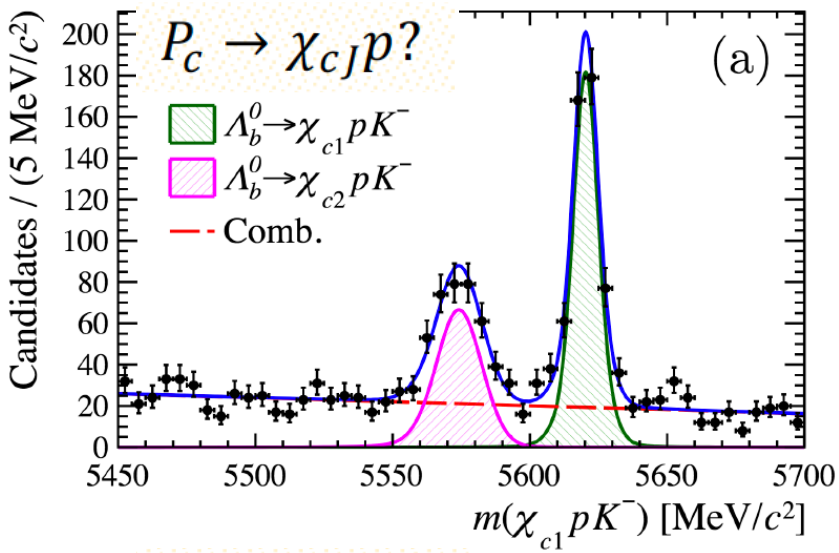
➢ **But the continuing search of these kind of exotics is very interesting**

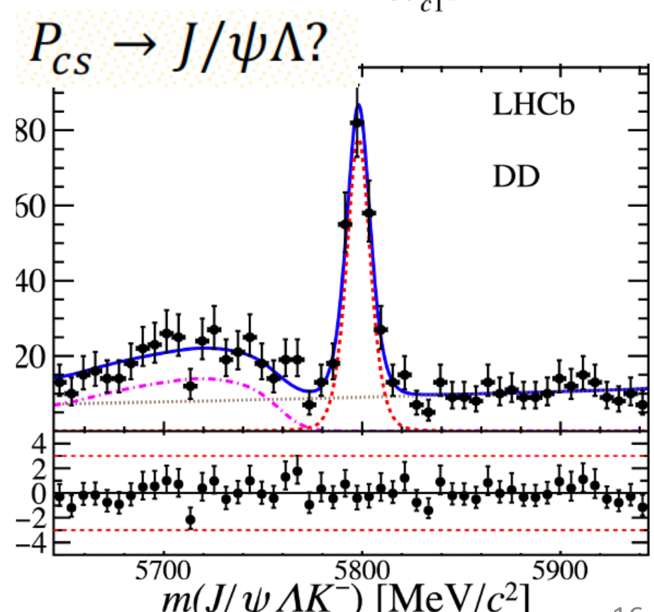
Exotics in the pipeline

PRL 117 (2016) 082003
PRL 119 (2017) 062001
PLB 772 (2017) 265

$\Lambda_b^0 \to J/\psi p \pi^-$







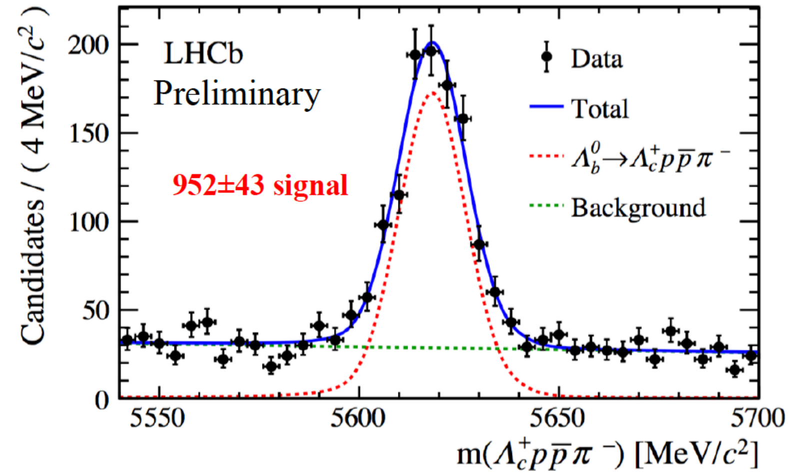
3 fb^{-1} shows a > 3σ exotic contributions
More data to understand which are which

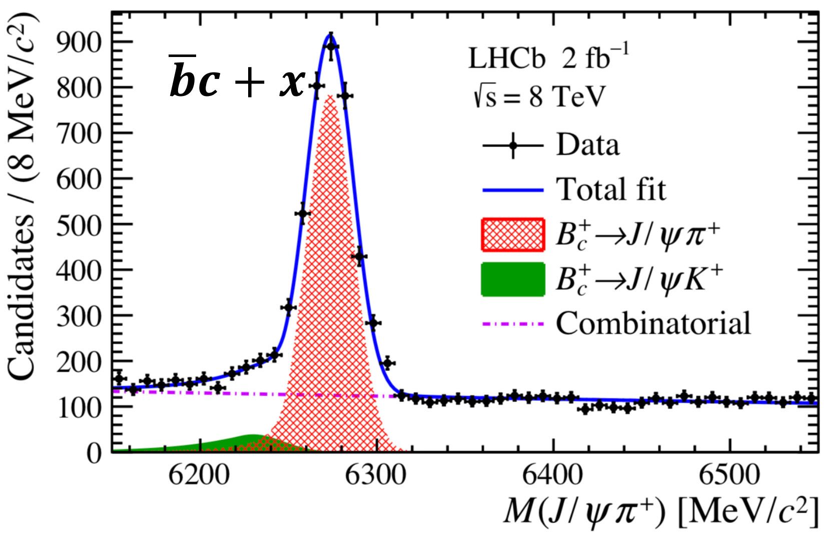
And more under study

Other possible exotic searches

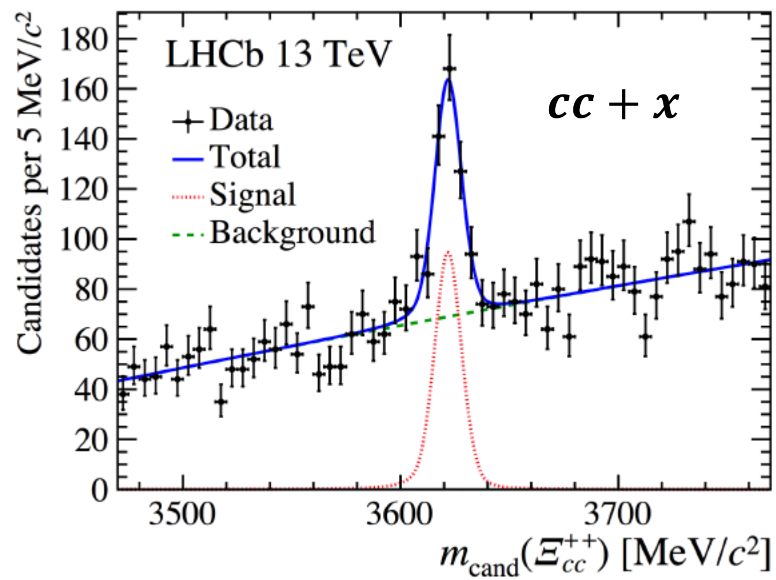
- ➢ **Exotics with more than one charge?**
- ➢ **Exotics with a $\bar{b}c$ quark?**
- ➢ **Exotics with more than 2 heavy quarks or with bb or cc? (PRL 119 (2017) 202001, PRD 96 (2017) 074004)**
- ➢ **Long lived exotics? For example, $uuddss$ in arXiv: 1708.08951**
- ➢ **A sexaquark or di-baryon**

LHCb-PAPER-2018-005



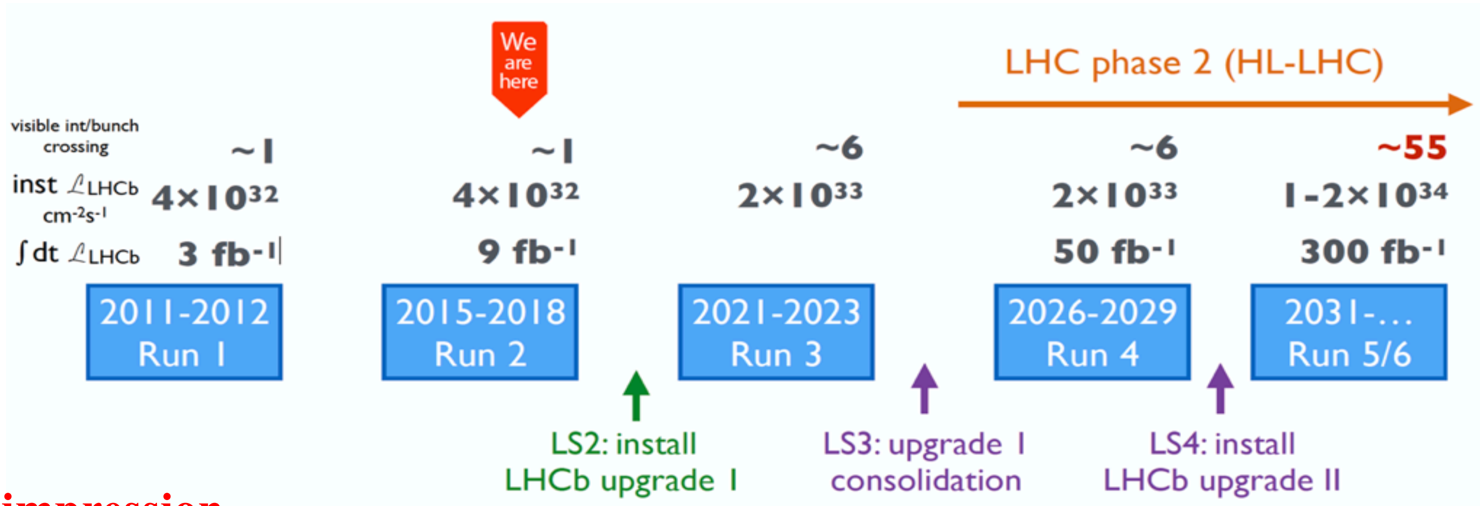


3.3K with 2 fb^{-1}

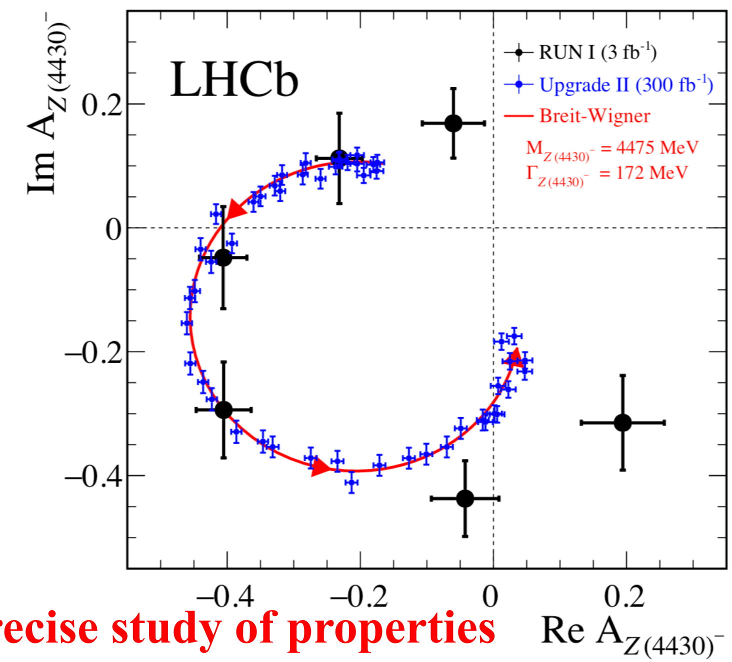


The future

➢ **Clearly hard to predict future, but we will have much more data**

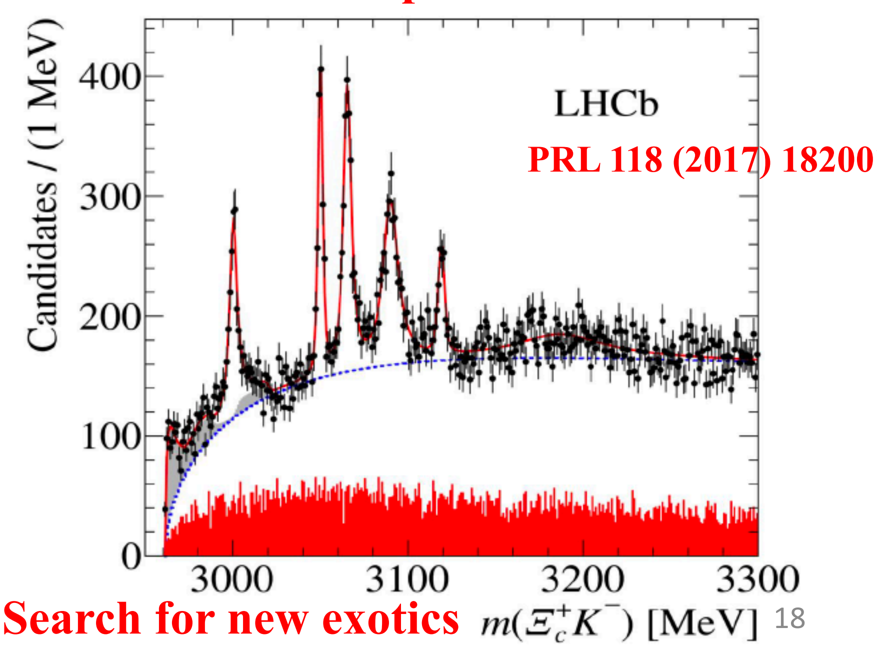


An impression



Precise study of properties

A possible scenario



Search for new exotics