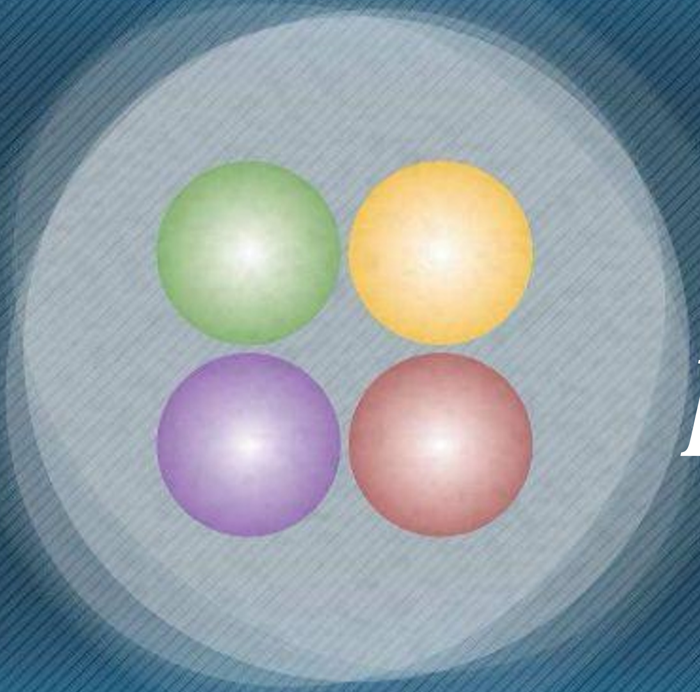


LHCb实验上 $B_{s0}^{*}(5700)^{0}$介子的首次观测

安刘攀

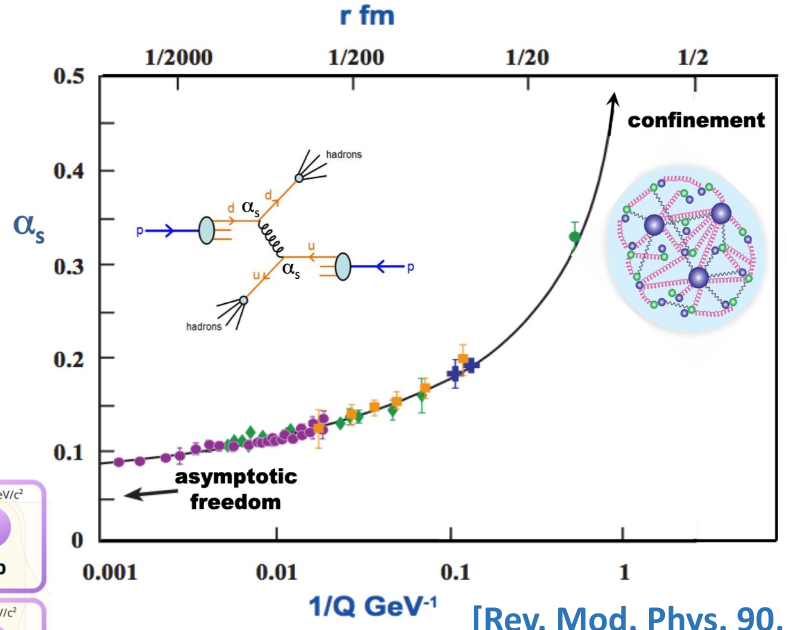
On behalf of the LHCb Collaboration

北京大学

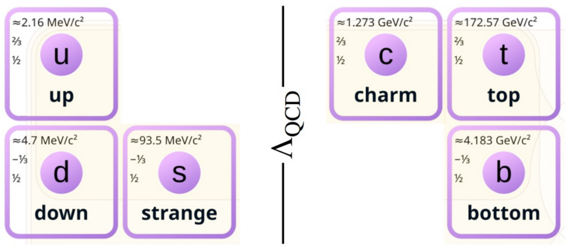
强子物理在线论坛，2026.08.21

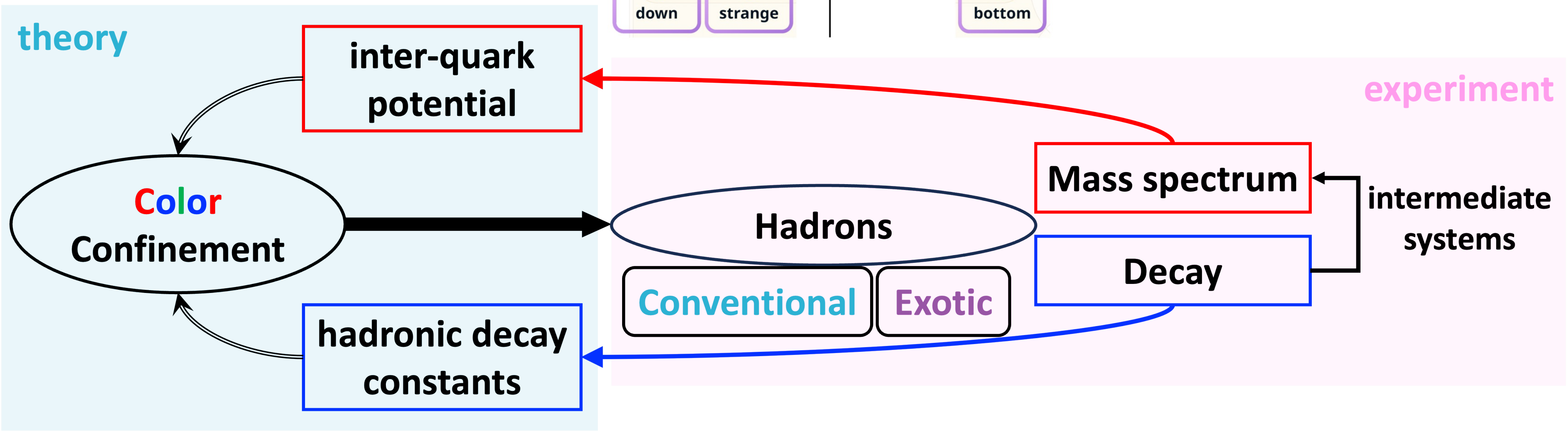
QCD and hadron spectroscopy

- ➢ ***QCD dilemma***: understanding the non-perturbative property of QCD at low-energy scale
  - ✓There are no rigorous, first-principle treatments except ***Lattice QCD***, whose application is yet limited
- ➢ ***Color confinement***: no analytic proof exists



[Rev. Mod. Phys. 90, 15003 (2018)]





Exotic hadrons

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

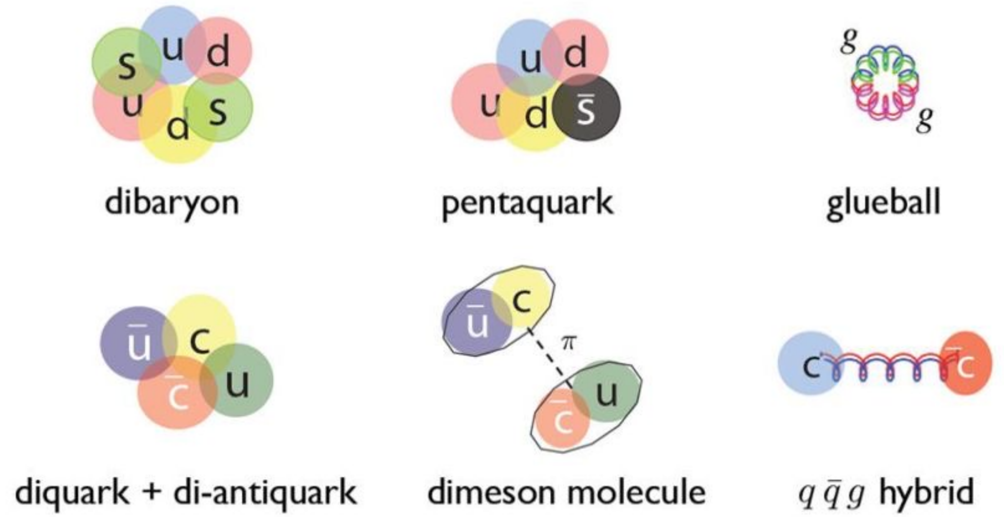
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)
CERN - Geneva

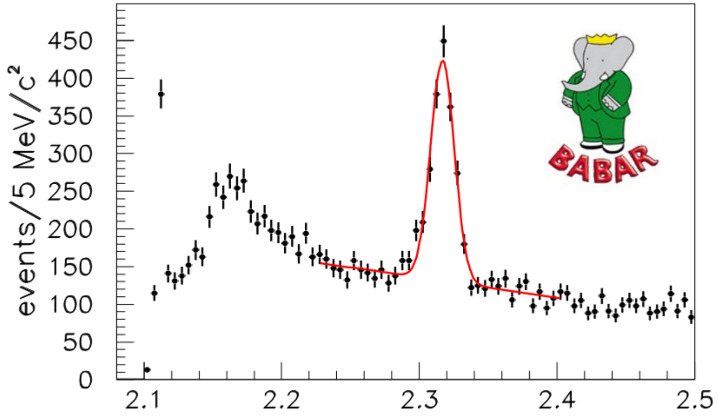
In ... the

product of three aces, AAA, but also from AAAAA, AAAAAAA, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $A\bar{A}$, $AA\bar{A}\bar{A}$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $A\bar{A}$ and AAA, that is, "deuces and treys".



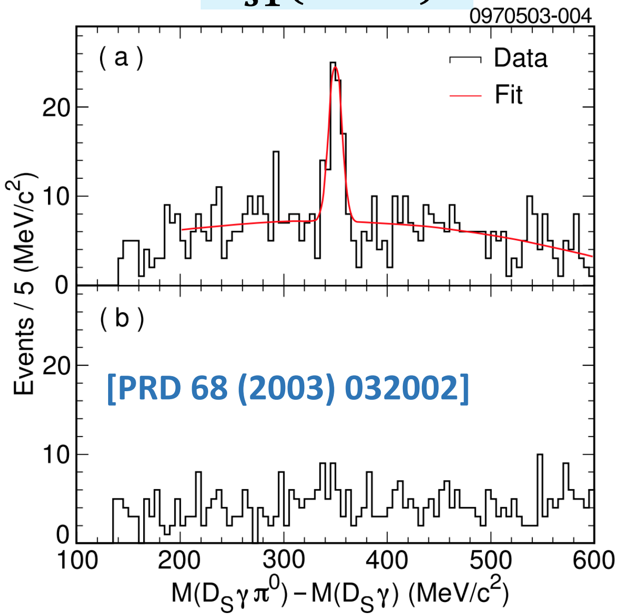
Renaissance of hadron spectroscopy

$D_{s0}^{*}(2317)^{+}$



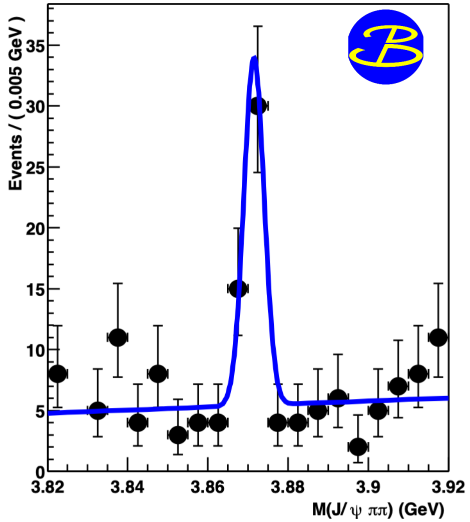
[PRL 90 (2003) 242001]

$D_{s1}(2460)^{+}$

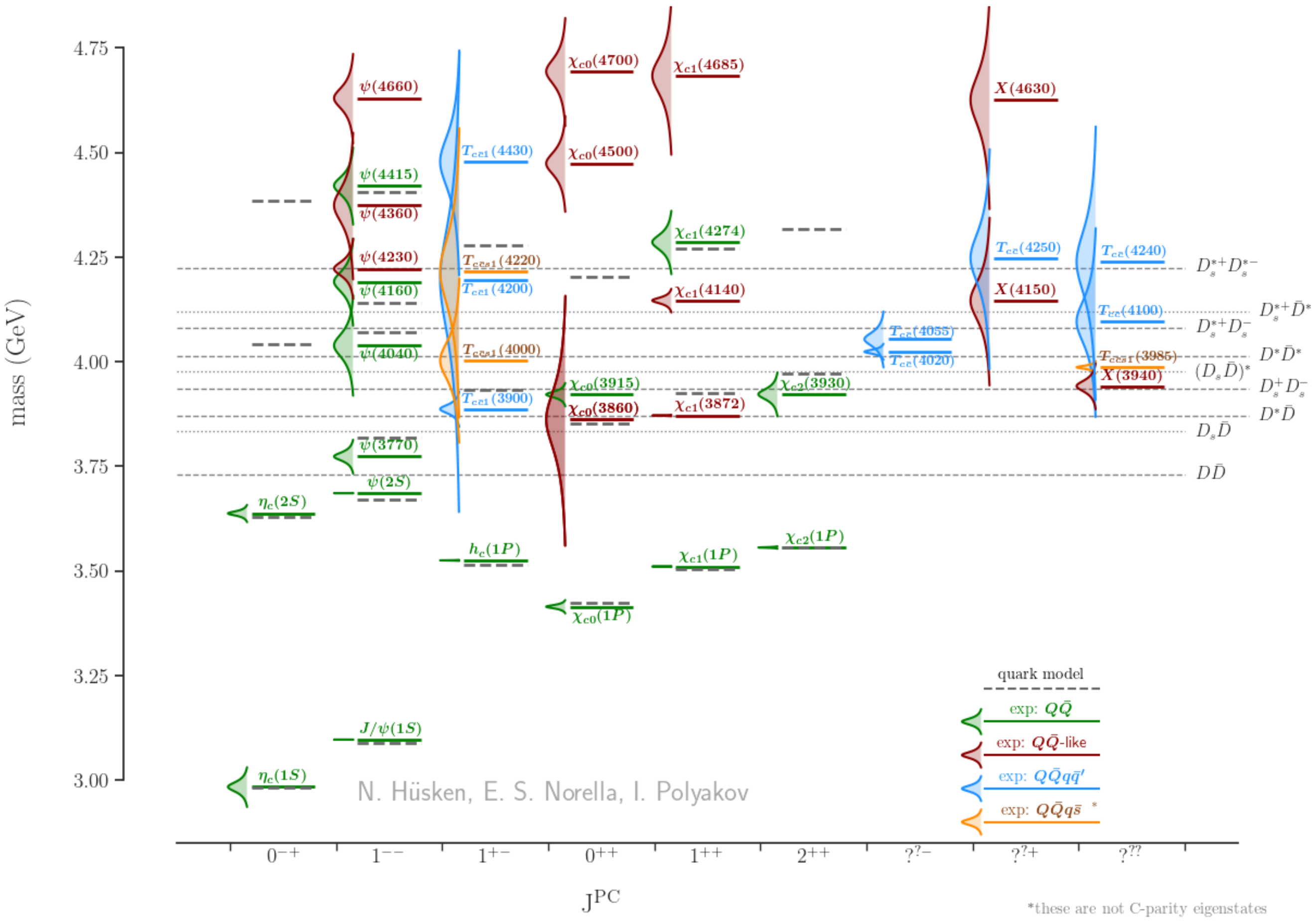


[PRD 68 (2003) 032002]

$\chi_{c1}(3872)$

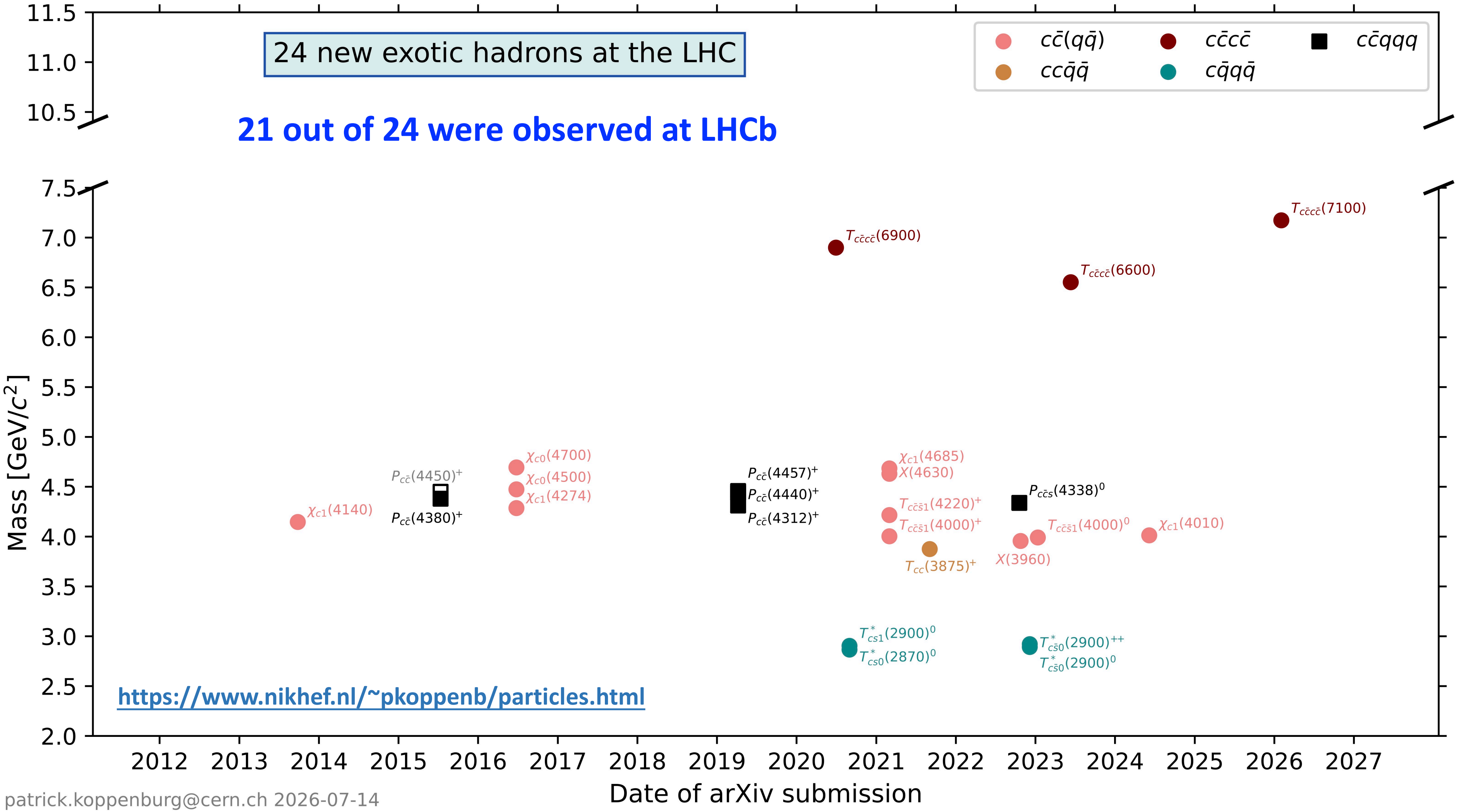


[PRL 91 (2003) 262001]



[Mod. Phys. Lett. A 40 (2025) 17n18, 2530002]

New exotic hadrons at the LHC



LHCb experiment @ LHC

➢The LHCb experiment is one of the four large experiments at the ***LHC***, dedicated to ***heavy flavor physics***

- ***Largest production cross-sections*** of b- and c-hadrons
  - ✓ $\sigma(b\bar{b}) \approx 500\ \mu b$ @ 13 TeV & $\sigma(c\bar{c}) \approx 20\times\sigma(b\bar{b})$

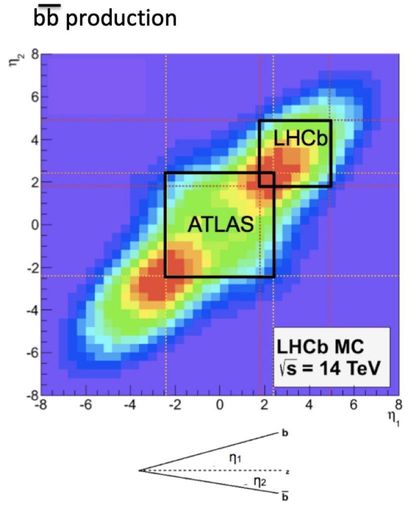
⬇

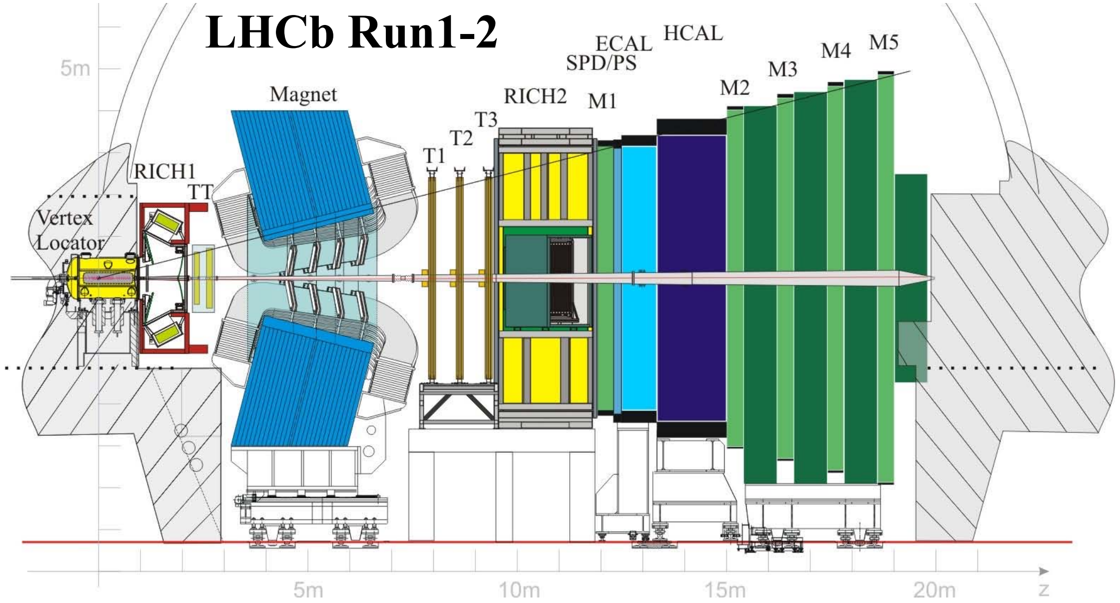
◆A ***single-arm forward spectrometer*** in $2 < \eta < 5$ to effectively cover the dominant kinematic region of heavy quark production

- ***Huge background*** contamination

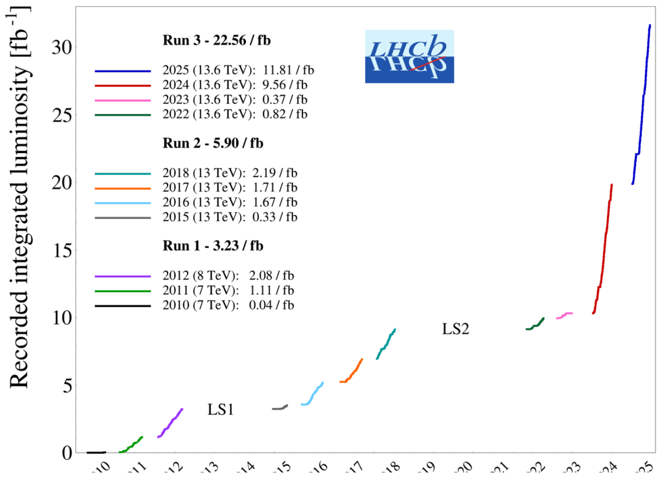
⬇

◆Excellent ***vertexing***, ***tracking*** and ***particle identification (PID)*** performance allowing for effective detection and background suppression





$\mathcal{L}_{\text{int}} = 9\ \text{fb}^{-1}$ @ Run1-2

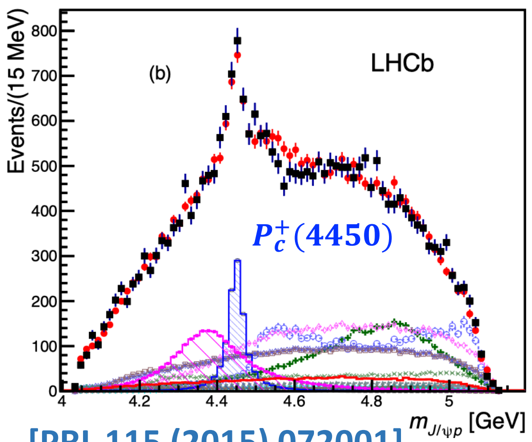


[JINST 3 (2008) S08005]
[IJMPA 30:07 (2015) 1530022]

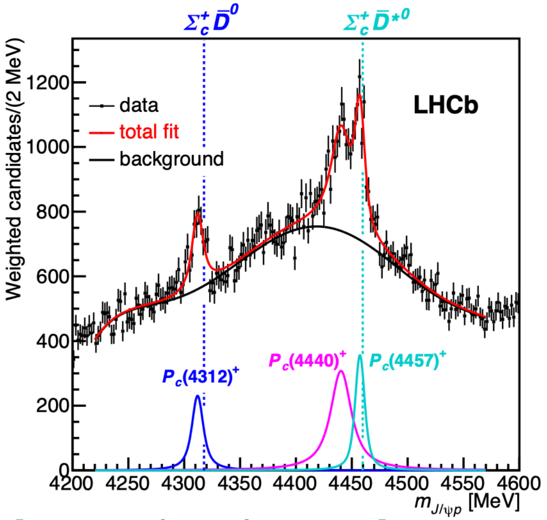
Exotic hadrons at LHCb

At prod.	Charm		Beauty		Charm + Beauty	
$Q\bar{Q}$	$cq\bar{q}\bar{q}$	$c\bar{q}qqq/\bar{c}qqqq$	$bq\bar{q}\bar{q}$	$b\bar{q}qqq/\bar{b}qqqq$		
	$c\bar{c}q\bar{q}$	$c\bar{c}qqq$	$b\bar{b}q\bar{q}$	$b\bar{b}qqq$		
$Q\bar{Q}+Q\bar{Q}$	$cc\bar{q}\bar{q}$	$c\bar{q}cqq$	$bb\bar{q}\bar{q}$	$b\bar{q}bqq$	$bc\bar{q}\bar{q}$	$b\bar{c}qqq/\bar{b}cqqq$
	$cc\bar{c}\bar{q}$	$c\bar{c}cqq$	$bb\bar{b}\bar{q}$	$b\bar{b}bqq$	$bq\bar{c}\bar{q}$	$b\bar{q}cqq$
	$cc\bar{c}\bar{c}$		$bb\bar{b}\bar{b}$		……	

$\Lambda_b^0 \to [J/\psi\, p]K^-$

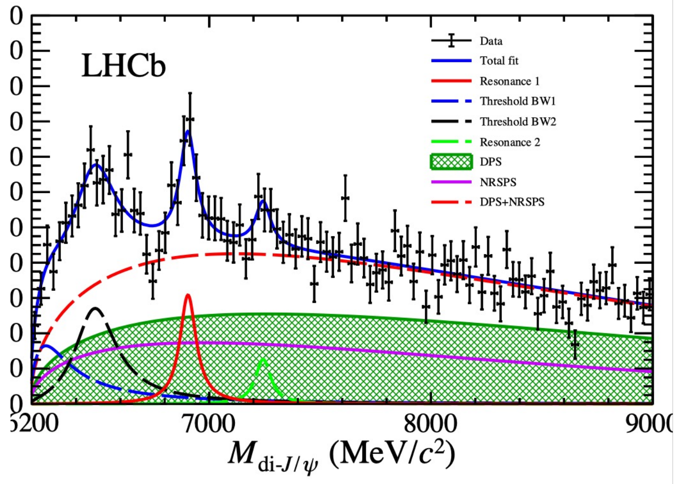


[PRL 115 (2015) 072001]



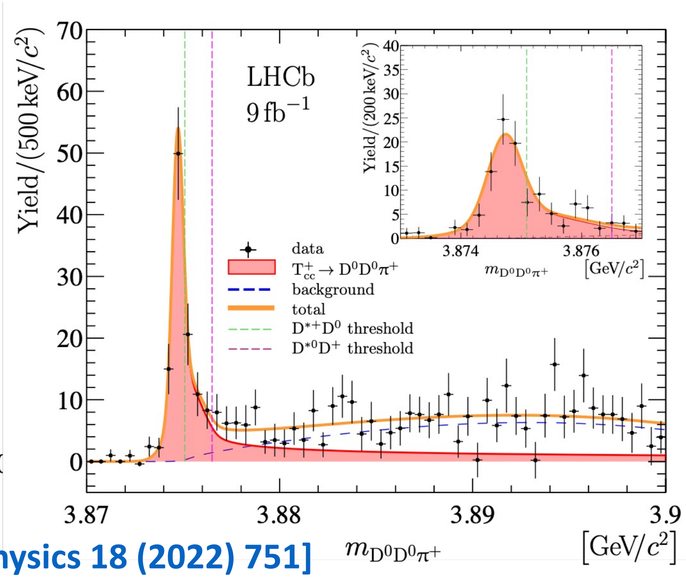
[PRL 122 (2019) 222001]

$J/\psi + J/\psi$



[Science Bulletin 65 (2020) 1983]

$D^0D^0\pi^+$



[Nature Physics 18 (2022) 751]
[Nature Comm. 13 (2022) 3351]

Looking beyond

At prod.	Charm		Beauty		Charm + Beauty	
$Q\bar{Q}$	$cq\bar{q}\bar{q}$	$c\bar{q}qqq/\bar{c}qqqq$	$bq\bar{q}\bar{q}$	$b\bar{q}qqq/\bar{b}qqqq$		
	$c\bar{c}q\bar{q}$	$c\bar{c}qqq$	$b\bar{b}q\bar{q}$	$b\bar{b}qqq$		
$Q\bar{Q}+Q\bar{Q}$	$cc\bar{q}\bar{q}$	$c\bar{q}cqq$	$bb\bar{q}\bar{q}$	$b\bar{q}bqq$	$bc\bar{q}\bar{q}$	$b\bar{c}qqq/\bar{b}cqqq$
	$cc\bar{c}\bar{q}$	$c\bar{c}cqq$	$bb\bar{b}\bar{q}$	$b\bar{b}bqq$	$bq\bar{c}\bar{q}$	$b\bar{q}cqq$
	$cc\bar{c}\bar{c}$		$bb\bar{b}\bar{b}$		……	

- $\boldsymbol{cc\bar{c}\bar{q}}$**?**
- **Single-b multiquark states**: within reach?
- $\bar{b}c$**-like exotic states**: decay modes for some of them are experimentally more friendly than higher excited states, e.g. $B_c^+ + p/K^\pm/\pi^\pm$
- **Pentaquarks other than $c\bar{c}qqq$**: single-c/b may be accessible if exist
- **Hexaquark states?**
- **Weakly decaying exotic hadrons:** T_{bb} widely recognized, but far from reach; T_{bc}?

Looking beyond

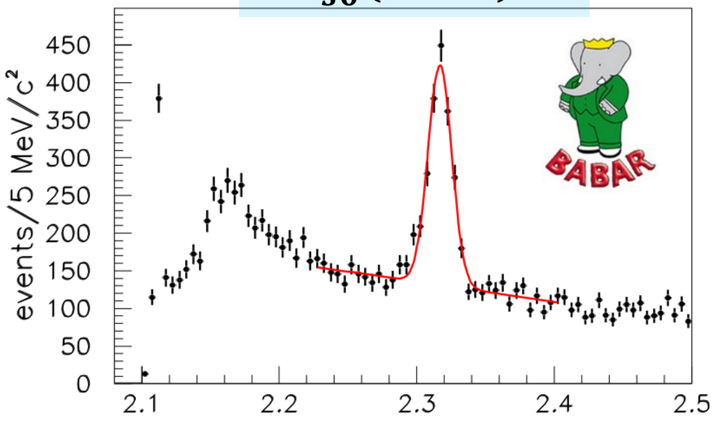
At prod.	Charm		Beauty		Charm + Beauty	
$Q\bar{Q}$	$cq\bar{q}\bar{q}$	$c\bar{q}qqq/\bar{c}qqqq$	$bq\bar{q}\bar{q}$	$b\bar{q}qqq/\bar{b}qqqq$		
	$c\bar{c}q\bar{q}$	$c\bar{c}qqq$	$b\bar{b}q\bar{q}$	$b\bar{b}qqq$		
$Q\bar{Q}+Q\bar{Q}$	$cc\bar{q}\bar{q}$	$c\bar{q}cqq$	$bb\bar{q}\bar{q}$	$b\bar{q}bqq$	$bc\bar{q}\bar{q}$	$b\bar{c}qqq/\bar{b}cqqq$
	$cc\bar{c}\bar{q}$	$c\bar{c}cqq$	$bb\bar{b}\bar{q}$	$b\bar{b}bqq$	$bq\bar{c}\bar{q}$	$b\bar{q}cqq$
	$cc\bar{c}\bar{c}$		$bb\bar{b}\bar{b}$		……	

- $\boldsymbol{cc\bar{c}\bar{q}}$**?**
- **Single-b multiquark states**: b-counterpart of $D_{s0}^{*}(2317)^{+}$ & $D_{s1}(2460)^{+}$
- $\boldsymbol{\bar{b}c}$**-like exotic states**: decay modes for some of them are experimentally more friendly than higher excited states, e.g. $B_c^{+}+p/K^{\pm}/\pi^{\pm}$
- **Pentaquarks other than $\boldsymbol{c\bar{c}qqq}$**: single-c/b may be accessible if exist
- **Hexaquark states?**
- **Weakly decaying exotic hadrons:** T_{bb} widely recognized, but far from reach; T_{bc}?

$D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ (I)

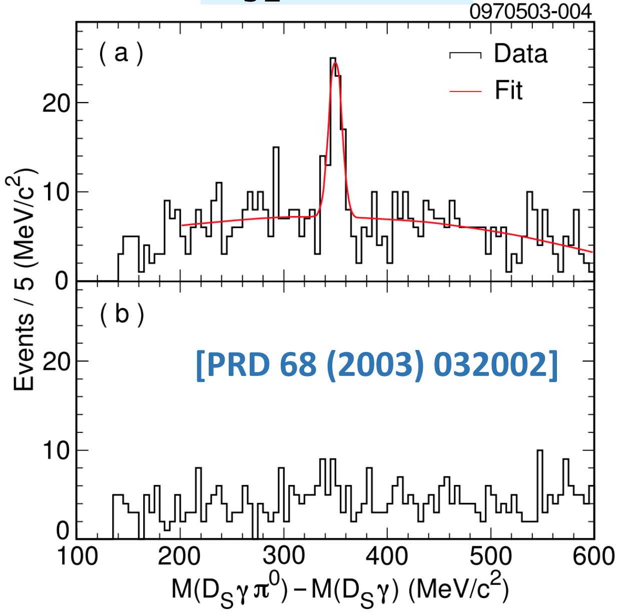
- According to Heavy Quark Effective Theory, $Q\bar{q}$ systems can be classified with $\vec{J}^P = \vec{j}_q + \vec{s}_Q$ with $\vec{j}_q = \vec{s}_q + \vec{L}$
- $D_{s0}^*(2317)^\pm$ is a **paradigm breaker** with a 160 MeV mass deficit wrt quark potential model
- Its spin partner $D_{s1}(2460)^+$ exhibits a coherent mass gap

$D_{s0}^*(2317)^+$

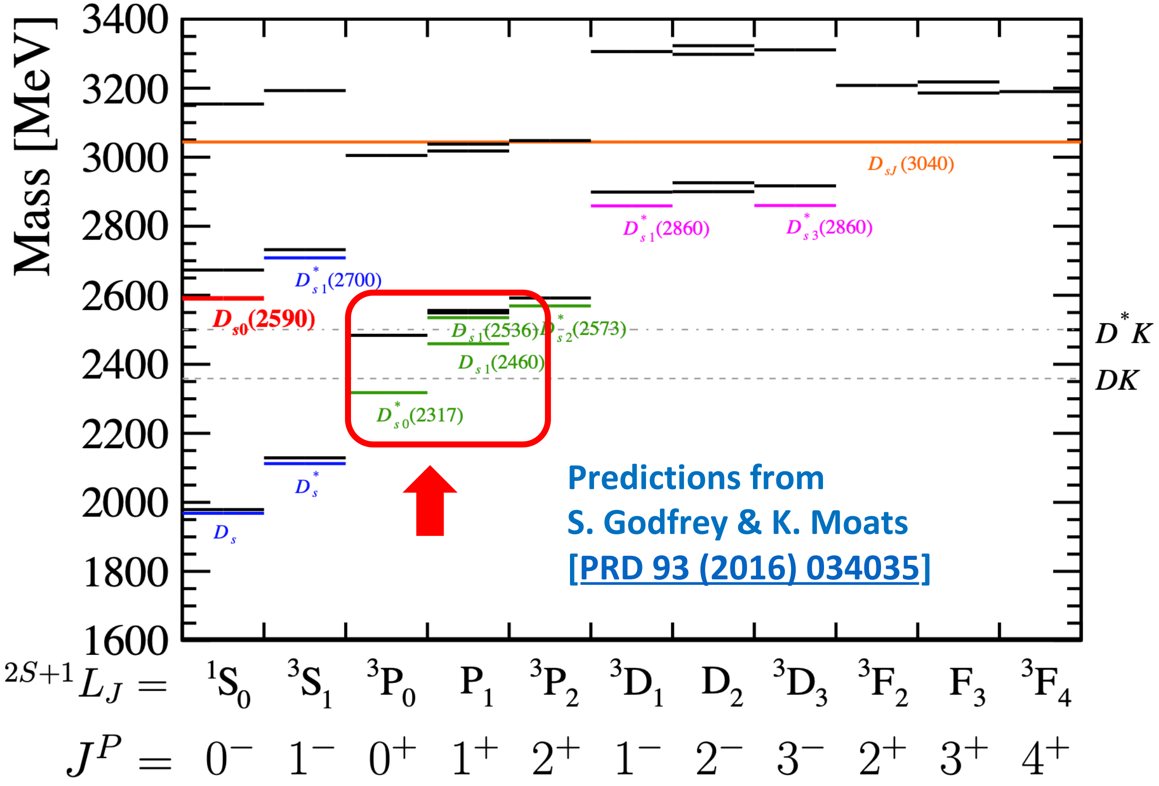


[PRL 90 (2003) 242001]

$D_{s1}(2460)^+$



[PRD 68 (2003) 032002]



Predictions from
S. Godfrey & K. Moats
[PRD 93 (2016) 034035]

$D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ (II)

M.-L. Du et al. [PRD 98 (2018) 094018]

- Anomaly of the $(D_{s0}^*(2317)^+, D_{s1}(2460)^+)$ doublet
  - significant mass deficit compared to quark potential model predictions
  - $m(D_{s0}^*(2317)^\pm) < m\big(D_0^*(2300)\big)$ i.e. $c\bar{u}/c\bar{d}$ heavier than $c\bar{s}$
  - $m(D_{s1}(2460)^\pm) - m(D_{s0}^*(2317)^\pm) \simeq m(D^*) - m(D)$
  - $D_{s0}^*(2317)^\pm$ decay ~100% through the isospin breaking mode $D_s^+\pi^0$

			$D^\pm$	$D_s^\pm$
L	j_q	J^P	M [MeV]	
0	1/2	0^-	1869.66 ± 0.05	1968.35 ± 0.07
		1^-	2010.26 ± 0.05	2112.2 ± 0.4
1	1/2	0^+	2343 ± 10	2317.8 ± 0.5
		1^+	2412 ± 9	2459.5 ± 0.6
	3/2	1^+	2422.1 ± 0.6	2535.11 ± 0.06
		2^+	$2461.1^{+0.7}_{-0.8}$	2569.1 ± 0.8

- ☐ (DK, D^*K) molecules?
  - ✓ can naturally explain the mass anomaly
  - ✓ supported by Lattice QCD calculation
- ☐ driven by chiral symmetry? e.g. chiral doubling theory
  - ✓ $D_{s0}^*(2317)^\pm$ and $D_s^\pm$ form a **chiral doublet**
  - ✓ Mass splitting governed by **chiral condensate** rather than orbital excitation → **universal**
- ☐ mixture?

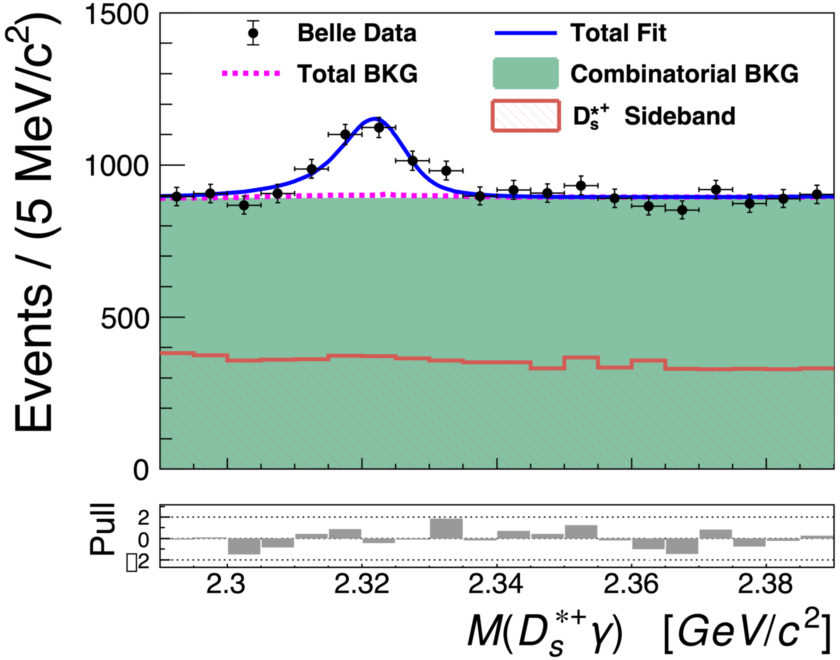
Observation of $D_{s0}^*(2317)^+ \to D_s^{*+}\gamma$

[PRL 136 (2026) 241901]

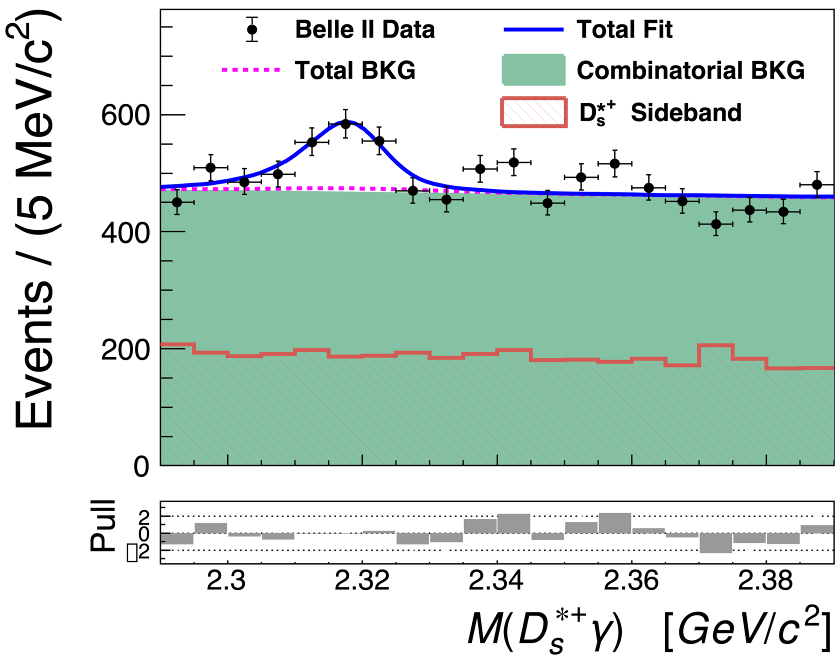
- Observation of the $D_{s0}^*(2317)^+ \to D_s^{*+}\gamma$ decay using 980.4 fb^{-1} Belle data + 427.9 fb^{-1} Belle II data

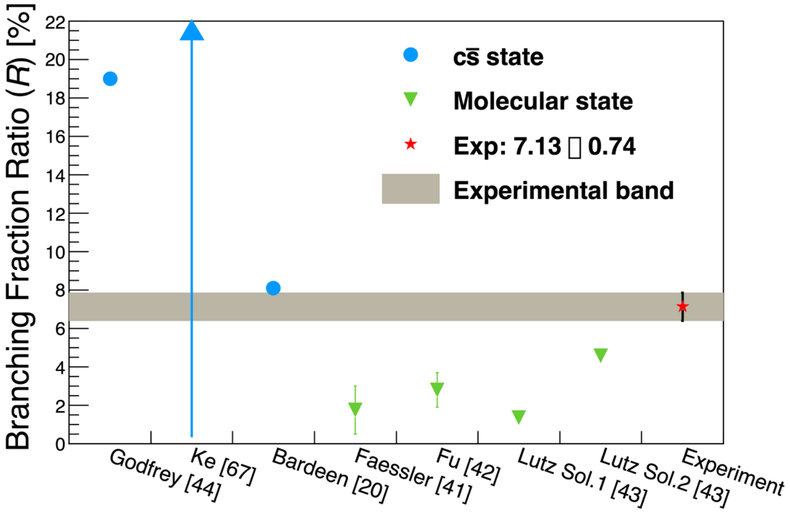
Total signal significance = $\mathbf{10.1\ \sigma}$

Belle: $N = 712 \pm 69$



Belle II: $N = 387 \pm 38$





$$\frac{\mathcal{B}(D_{s0}^*(2317)^+ \to D_s^{*+}\gamma)}{\mathcal{B}(D_{s0}^*(2317)^+ \to D_s^{+}\pi^0)} = [7.14 \pm 0.70(\text{stat}) \pm 0.23(\text{syst})]\%$$

✓ Above molecular prediction;
Below quark-model expectation;
⇒ a mixed configuration?

Prospects on B_{s0}^{*0} and B_{s1}^{0}

H.-L. Fu et al. [EPJ A58 (2022) 4, 70]

Heavy quark flavour symmetry (HQFS) allows one to estimate the masses of the bottom partners of the D_{s0}^* and D_{s1}, independent of the model assumptions for their internal structure. One finds

$$M_{B_{s0}^*} = \bar{M}_c + \Delta_{b-c} + \left(M_{D_{s0}^*} - \bar{M}_c\right)\frac{m_c}{m_b} \simeq 5.71\ \text{GeV},$$

$$M_{B_{s1}} = \bar{M}_c + \Delta_{b-c} + \left(M_{D_{s1}} - \bar{M}_c\right)\frac{m_c}{m_b} \simeq 5.76\ \text{GeV},$$

vs. $M(BK)$~5.77 GeV

Decay channel	Loops	π^0-η mixing	Full result
$B_{s0}^* \to B_s\pi^0$	15 ± 2	22 ± 3	75 ± 6
$B_{s1} \to B_s^*\pi^0$	16 ± 2	23 ± 3	76 ± 7

Decay channel	EC	MM	CT	Full result
$B_{s0}^* \to B_s^*\gamma$	58 ± 8	2.1 ± 0.3	0.02	59 ± 8
$B_{s1} \to B_s\gamma$	70 ± 10	41 ± 6	0.02	220 ± 31
$B_{s1} \to B_s^*\gamma$	110 ± 15	0.20 ± 0.02	0.03	100 ± 15
$B_{s1} \to B_{s0}^*\gamma$	–	0.03 ± 0.01	?	?

Z.-Y. Zhou & Z. Xiao [EPJ C81 (2021) 6, 551]

$c\bar{s}(1^3P_0)$	DK	2.48	2.48	$\sqrt{s_{r1}} = 2.68 - 0.26i$ $\sqrt{s_b} = 2.32,$	$D_{s0}^*(2317)$	$2.317^{\pm0.0005} - 0.0038^{\pm0.0038}i$
$b\bar{u}(1^3P_0)$	$\bar{B}\pi$	5.76	5.76	$\sqrt{s_{r1}} = 5.85 - 0.26i$ $\sqrt{s_{r2}} = 5.62 - 0.13i$		
$b\bar{s}(1^3P_0)$	$\bar{B}K$	5.83	5.83	$\sqrt{s_{r1}} = 6.11 - 0.22i$ $\boxed{\sqrt{s_b} = 5.72}$		
$c\bar{c}(2^3P_1)$	$D\bar{D}^*$	3.95	3.95	$\sqrt{s_r} = 3.99 - 0.05i$ $\sqrt{s_b} = 3.84$	$\chi_{c1}(4010)$ $X(3872)$	$4.012 \pm 0.031\ GeV$ $3.87169^{\pm0.00017}$

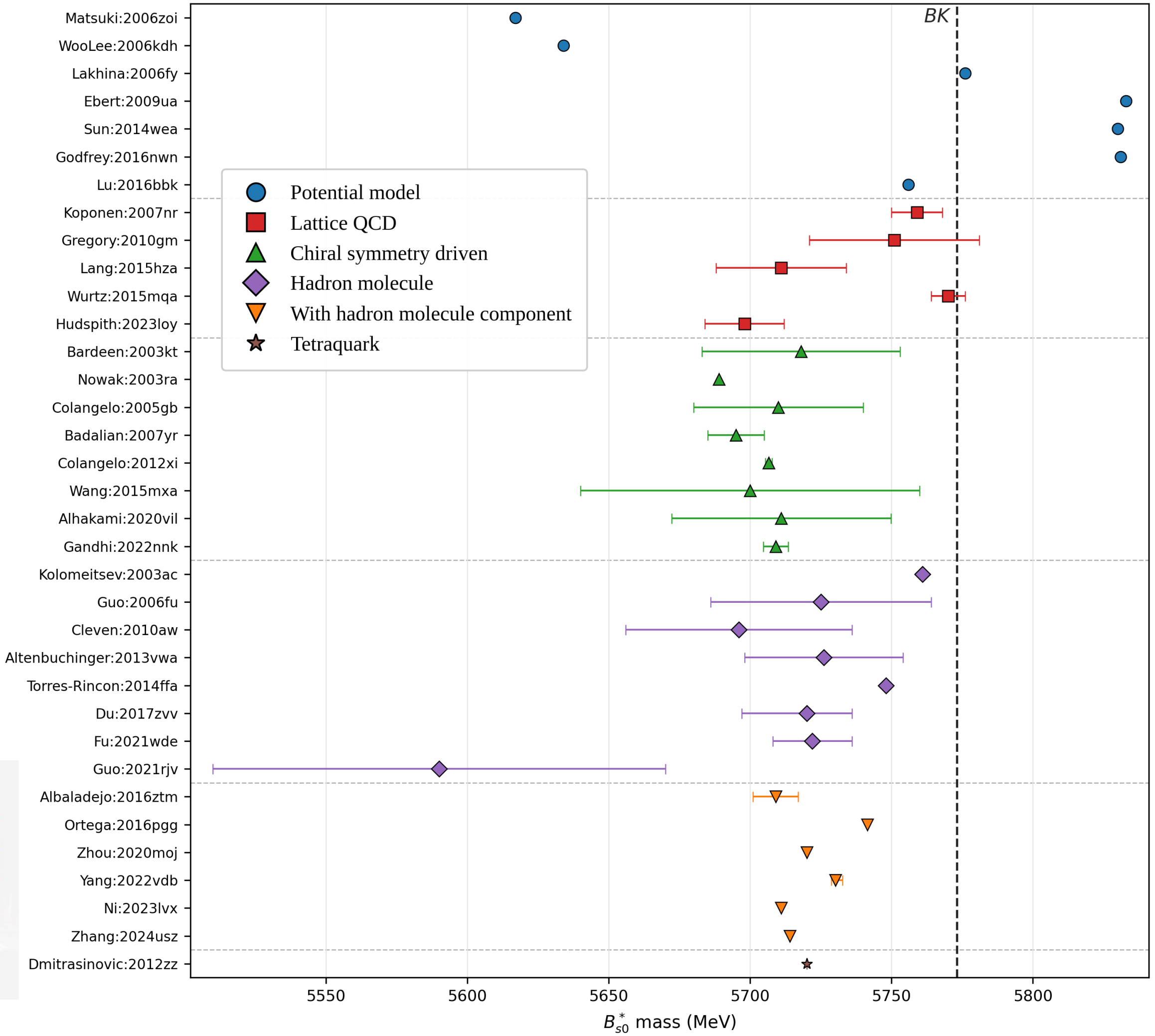
强烈建议LHCb进行寻找，特别是最后一个，类似于$D_{s0}^*(2317)$，窄共振

18

$D_{b0}^*(5720)$

Talk by 周智勇 [link]

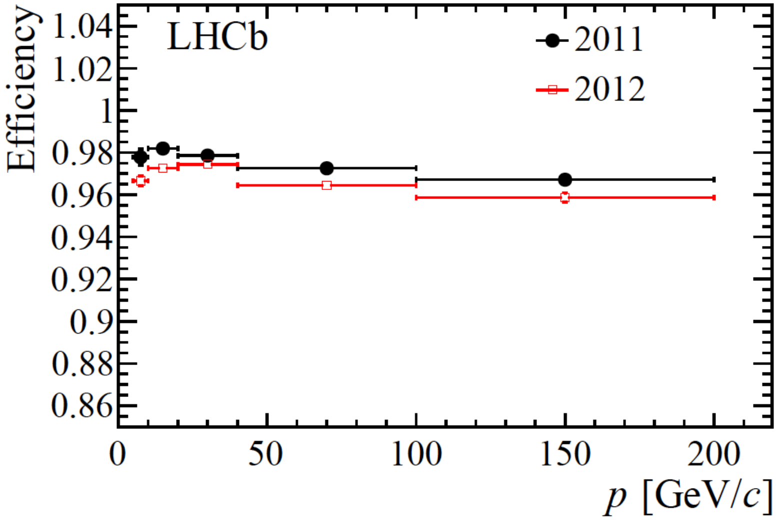
✓ Measurement of B_{s0}^{*0} and B_{s1}^{0} is highly important to constrain the theoretical models



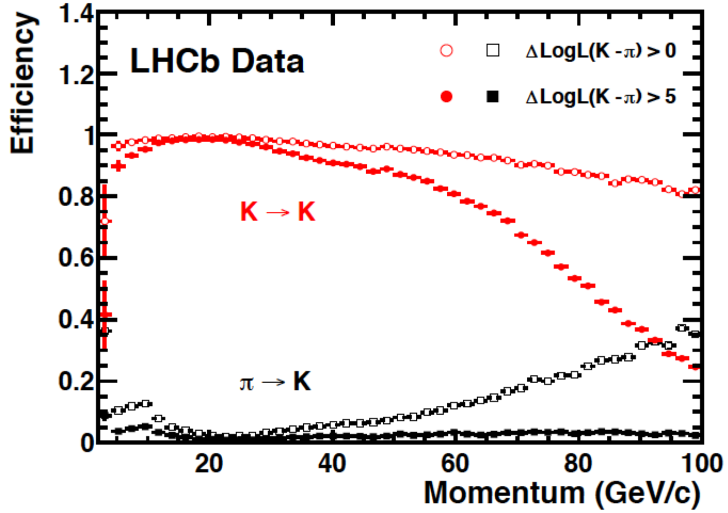
Charged tracks vs Photon (I)

- Reconstruction and selection

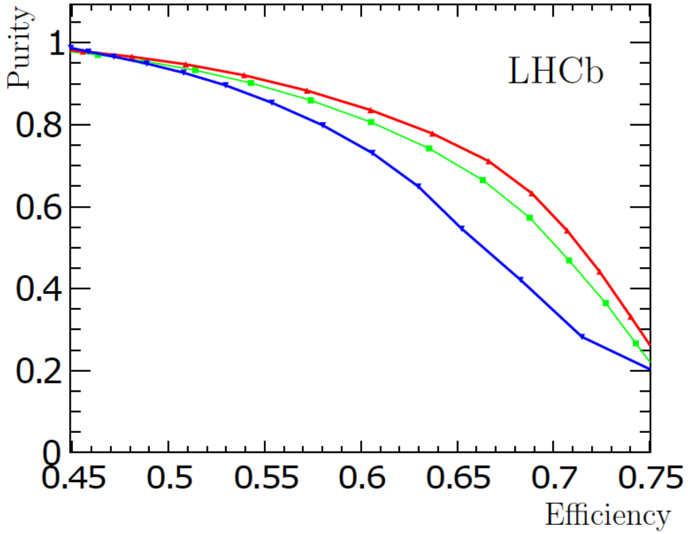
Charged tracks



$\varepsilon(K \to K)$~95% @ misID rate $(\pi \to K)$~5%



Photons



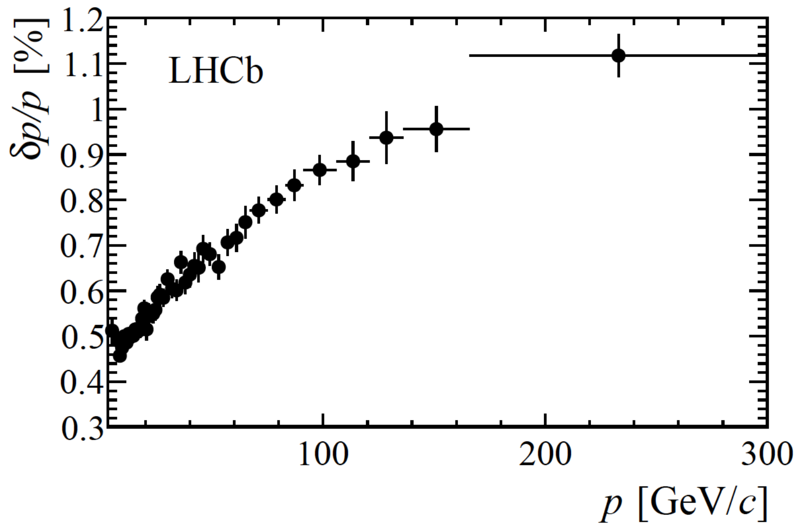
[IJMPA 30:07 (2015) 1530022]

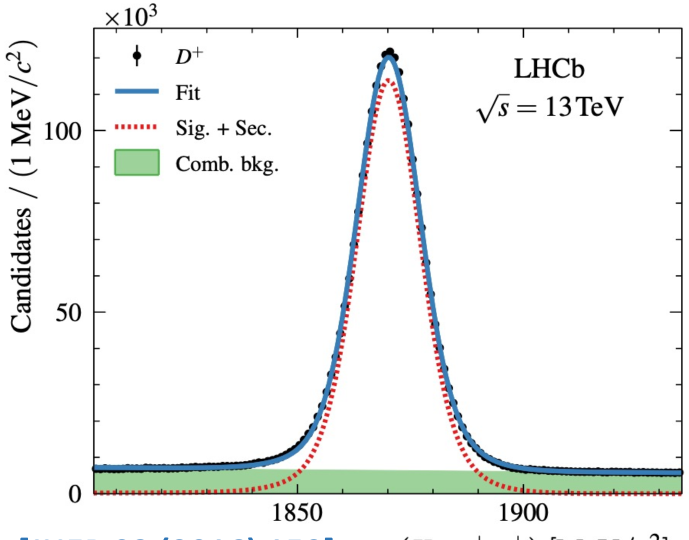
Charged tracks vs Photon (II)

[IJMPA 30:07 (2015) 1530022]

- Resolution

Charged tracks



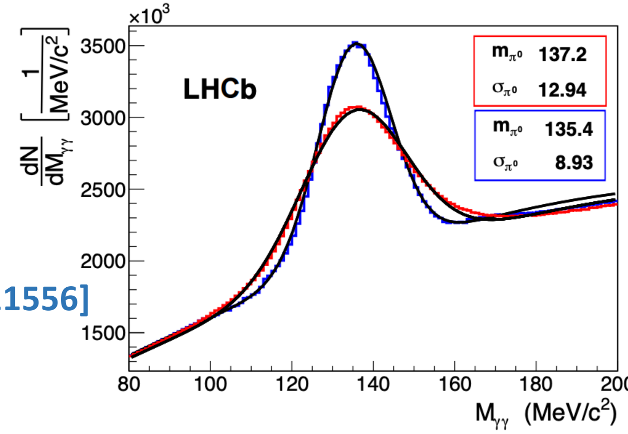


[JHEP 03 (2016) 159]

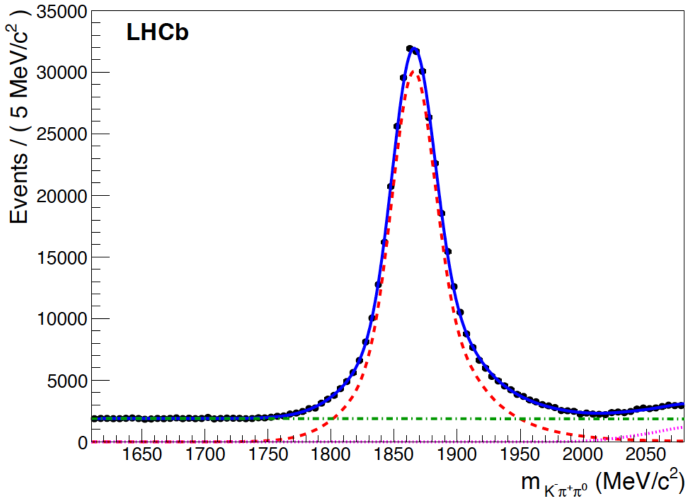
σ~8 MeV

Photons

$\sigma(E)/E \approx 10\%/\sqrt{E} \oplus 1\%$



[arXiv: 2008.11556]



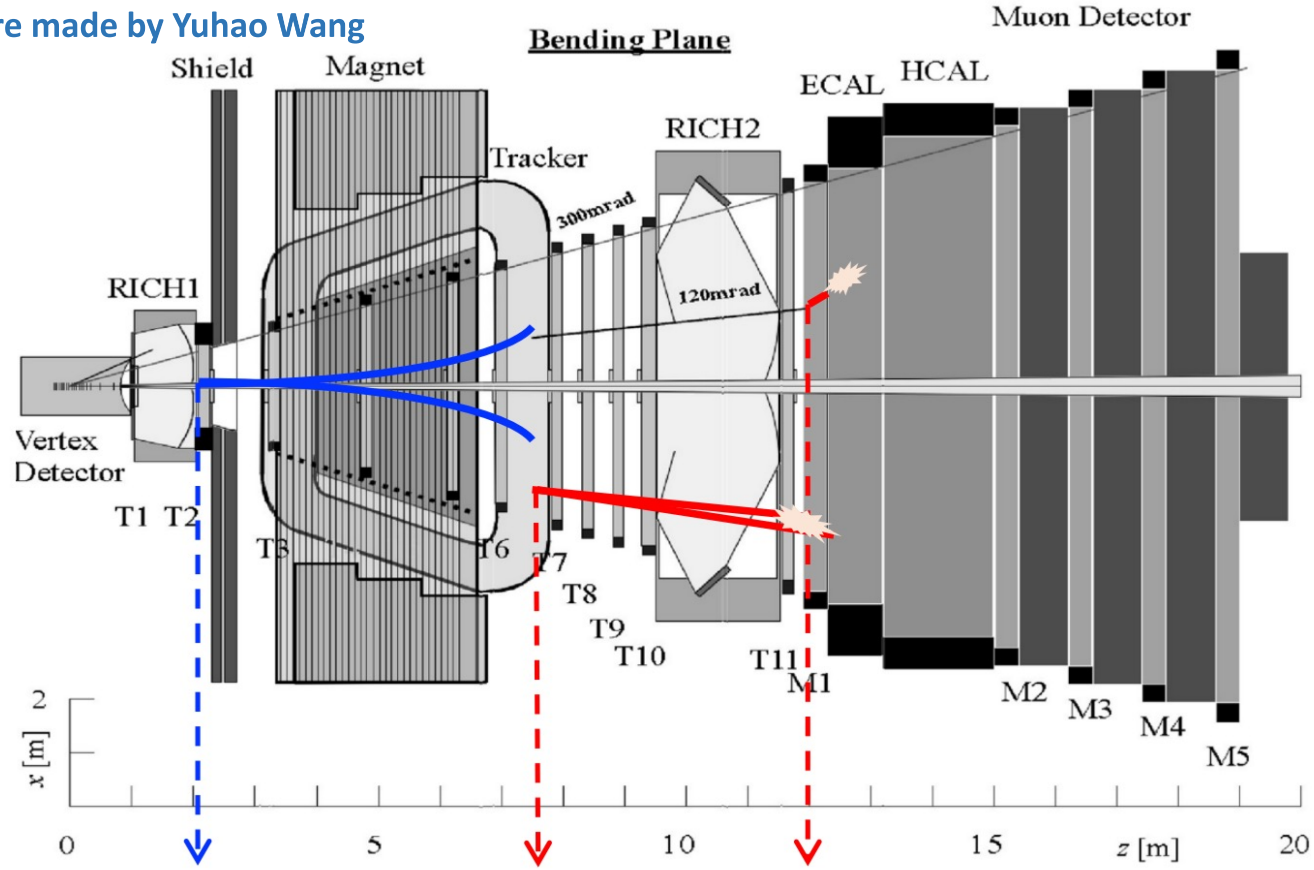
σ~20 MeV

Although challenging, photon and π^0 modes are accessible at LHCb

Photon reconstruction at LHCb

$\chi_c \to J/\psi\,\gamma$

Figure made by Yuhao Wang



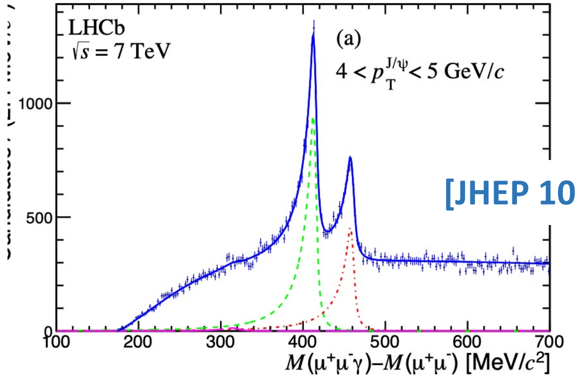
photons convert before magnet

reconstructed from e^+e^-

photons convert after magnet

non-converted photons

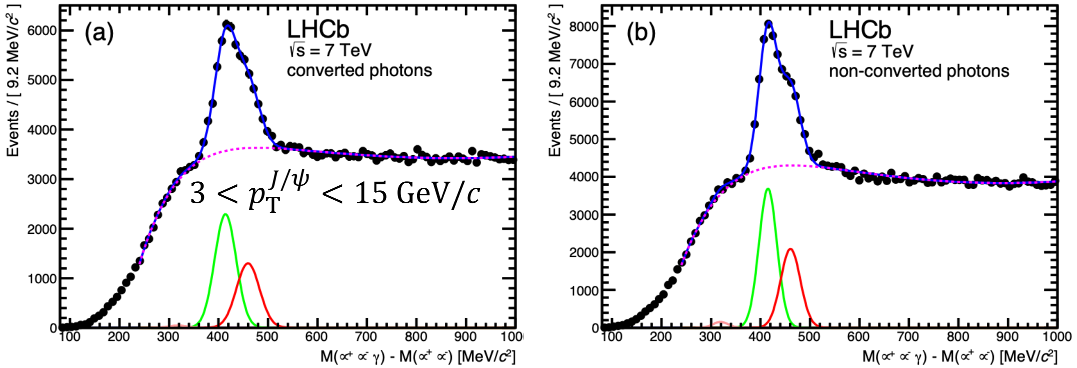
reconstructed as calorimeter clusters



[JHEP 10 (2013) 115]

@1 fb^{-1}

- ✗ Around one order of magnitude smaller statistics, especially at low p_{T}
- ✓ Better mass resolution



[PLB 718 (2012) 431]

- ✓ Much larger statistics
- ✗ Worse mass resolution

@36 pb^{-1}

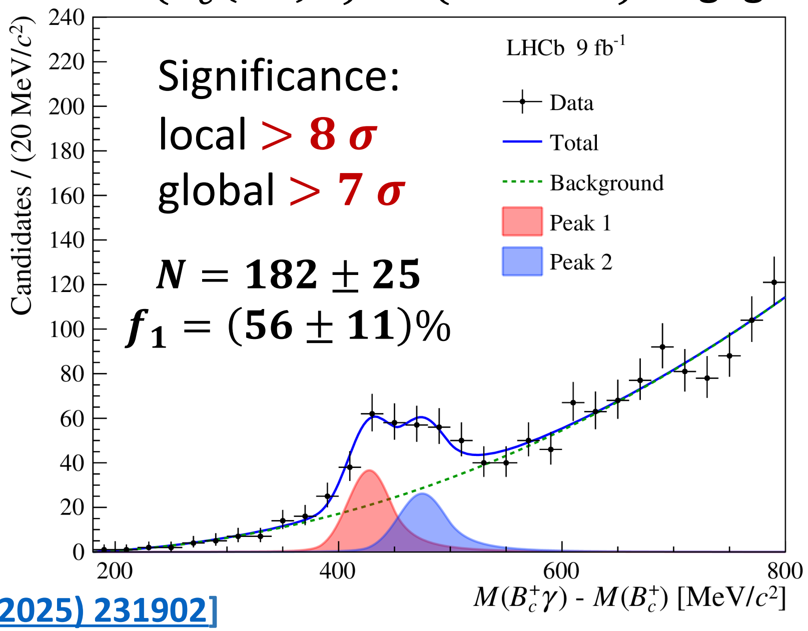
Observation of $B_c(1P)^+$ via $B_c^+\gamma$

◆ Theory-independent fit

- ✓ The visible width is $\sim 37\ \mathrm{MeV}/c^2$
- ✓ Width of a single peak is $\sim 20\ \mathrm{MeV}/c^2$

$\Rightarrow$ a **minimal effective two-peak model**

*$\Gamma(B_c(1P)^+) \sim \mathcal{O}(100\ \mathrm{keV})$ negligible



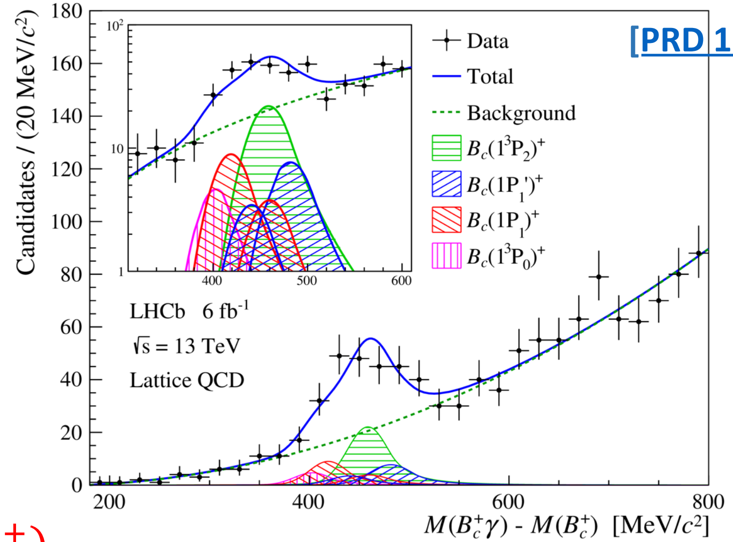
[PRL 135 (2025) 231902]

$M_1 = 6704.8 \pm 5.5(\mathrm{stat.}) \pm 2.8(\mathrm{syst.}) \pm 0.3(B_c^+)\ \mathrm{MeV}/c^2$
$M_2 = 6752.4 \pm 9.5(\mathrm{stat.}) \pm 3.1(\mathrm{syst.}) \pm 0.3(B_c^+)\ \mathrm{MeV}/c^2$

◆ Theory-constrained fit

- ✓ masses and relative yields of six peaks fixed according to predictions

$\Rightarrow$ verification of various QCD models



[PRD 112 (2025) 112003]

$$\frac{\sigma(B_c(1P)^+)}{\sigma(B_c^+)} = 0.20 \pm 0.03(\mathrm{stat.}) \pm 0.02(\mathrm{syst.}) \pm 0.03(\mathrm{theo.})$$

for $p_{\mathrm{T}}(B_c^+) < 20\ \mathrm{GeV}/c, 2.0 < y(B_c^+) < 4.5$ at $\sqrt{s} = 13$ TeV

[Comput. Phys. Commun. 197 (2015) 335]

✓ consistent with BcVegPy calculations

Search for B_{s0}^{*0} in $B_s^0\pi^0$ spectrum

[LHCb-PAPER-2026-021]
in preparation
(not repeated hereafter)

- **Dataset**
  - ✓Run1 & 2 data at LHCb corresponding to $9\ \mathrm{fb}^{-1}$
- **Signal decay modes**
  - ✓$B_s^0 \to D_s^-\pi^+, D_s^- \to K^+K^-\pi^-$
  - ✓$B_s^0 \to J/\psi\phi, J/\psi \to \mu^+\mu^-$
  - ✓$B_s^0 \to D_s^-\pi^+\pi^+\pi^-, D_s^- \to K^+K^-\pi^-$

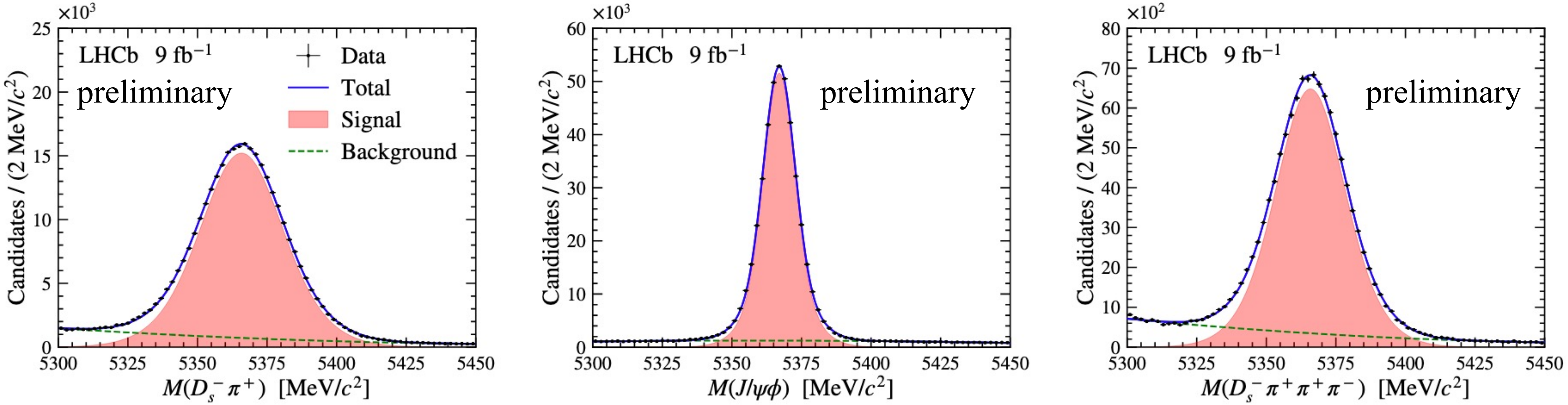
  combined with $\pi^0 \to \gamma\gamma$ using calorimeter photons
- **Trigger**
  - ✓Hardware stage: at least one hadron with large E_T or muon with high p_T
  - ✓Software stage
    $B_s^0 \to D_s^-\pi^+$ &$D_s^-\pi^+\pi^+\pi^-$: multi-track displaced vertex consistent with b-hadron decay
    $B_s^0 \to J/\psi\phi$: dimuon forming a good vertex with invariant mass consistent with J/ψ
- **Simulation**
  - ✓$B_{s0}^{*0} \to B_s^0\pi^0$ for all three decay chains with $M(B_{s0}^{*0}) = 5707\ \mathrm{MeV}/c^2$

Candidate selection (I) - B_s^0

1. **Cut-based preselection**
   - ✓ kinematic requirement; good vertex & track quality; displaced vertex of D_s^- or J/ψ and ϕ
   - ✓ particle identification (PID) responses compatible with the kaon, pion or muon hypotheses
     → peaking backgrounds from D^-, D^0 and Λ_c^+ rejected dedicatedly

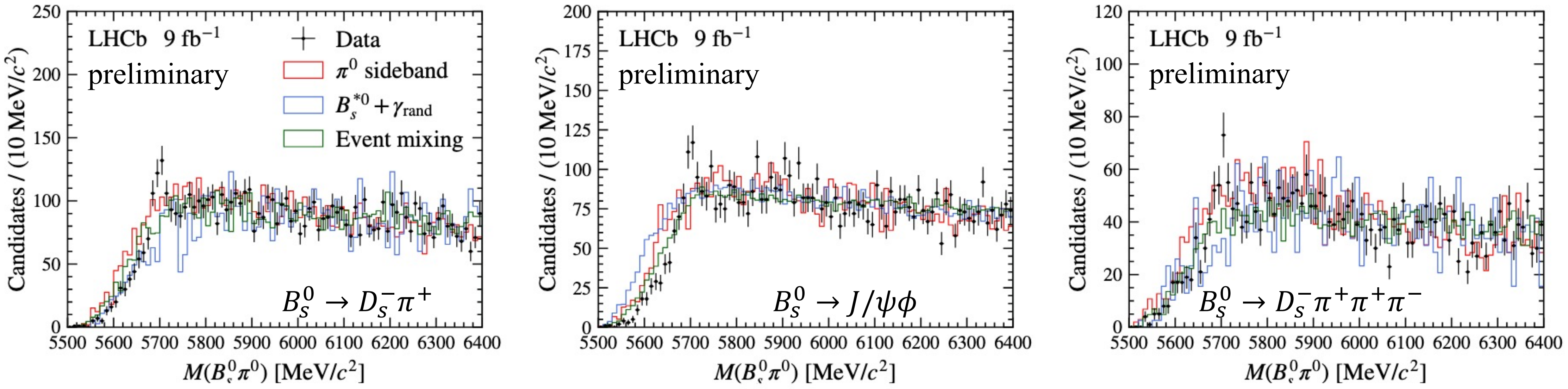
2. **BDT classifier employed separately for each mode**
   - ✓ Signal: simulated sample & Background: high-mass sidebands of B_s^0 mass distribution
   - ✓ Input variables: quality and displacement of B_s^0 vertex, pointing of B_s^0 momentum to primary vertex, kinematic, impact-parameter and PID of intermediate states and final-state tracks
   - ✓ Threshold: to maximize $S/\sqrt{S+B}$ in B_s^0 signal mass window

$N = (2.96 \pm 0.02)\times 10^5$ $N = (4.16 \pm 0.01)\times 10^5$ $N = (1.06 \pm 0.01)\times 10^5$



Candidate selection (II) - $B_s^0\pi^0$

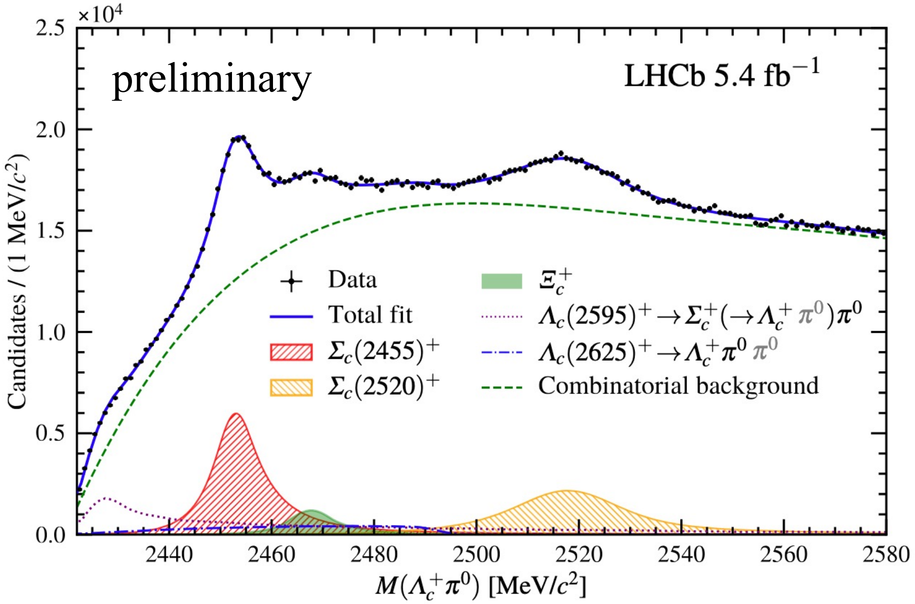
1. **Cut-based preselection**
   - ✓ photons: loose shower-shape and cluster-quality criteria
   - ✓ π^0: sufficient p_{T} and invariant mass compatible with π^0
2. **BDT classifier employed separately for each mode**
   - ✓ Signal: simulated sample & Background: π^0-mass sidebands
   - ✓ Input variables: kinematics of $B_s^0\pi^0$ and π^0; properties of photon
   - ✓ Threshold: to maximize Punzi figure-of-merit $S/\left(5/2+\sqrt{B}\right)$ in predicted signal mass region



A new resonance consistently presents across three channels and is robust against all checks

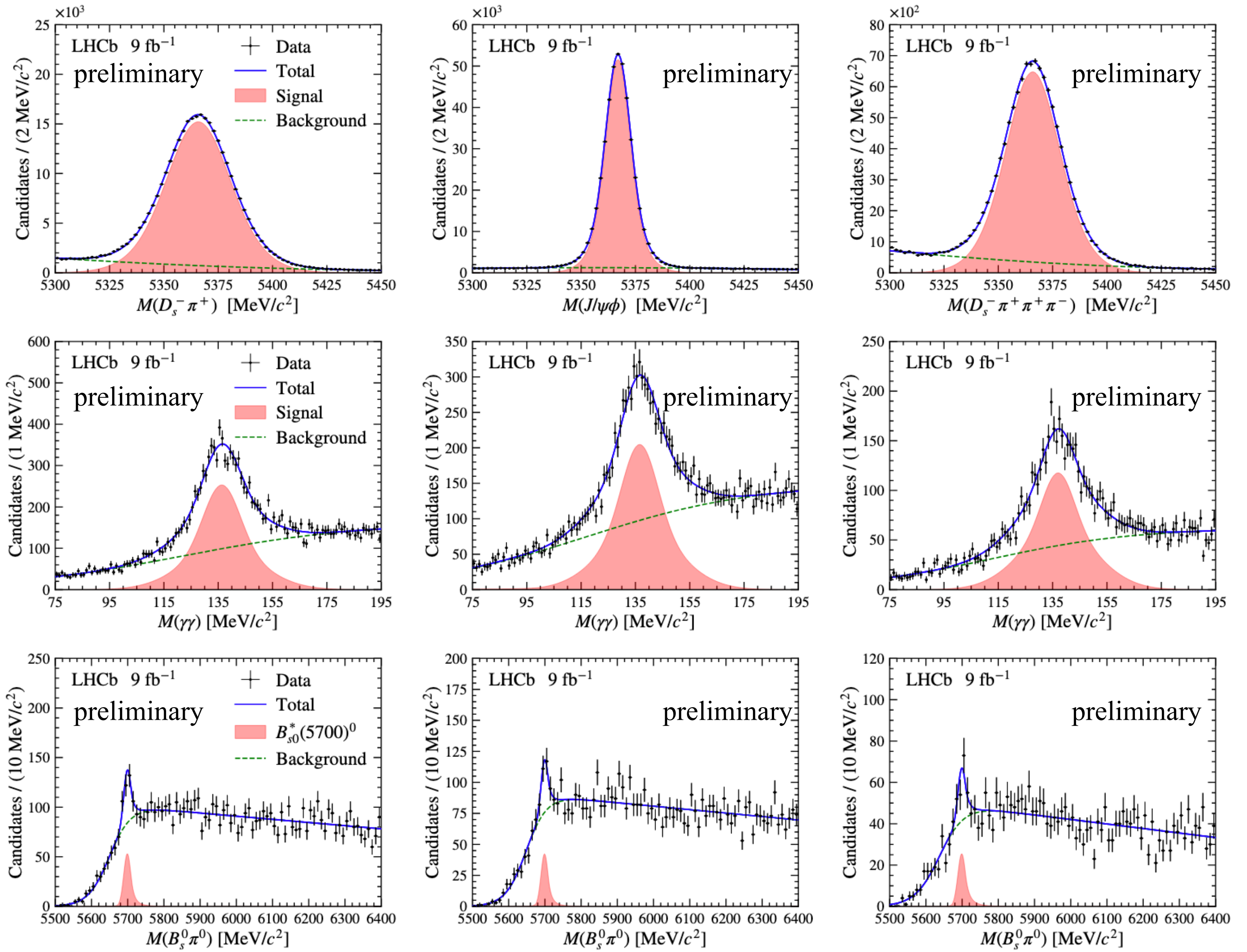
$B_s^0\pi^0$ mass fit

- A simultaneous extended unbinned maximum-likelihood fit is performed to $M(B_s^0\pi^0)$ for all three channels
  - ✓ Signal: relativistic Breit-Wigner ⊗ resolution of Gaussian kernel with tails → validated by $\Lambda_c^+\pi^0$



  - ✓ background: sigmoid modulated by 1st order polynomial

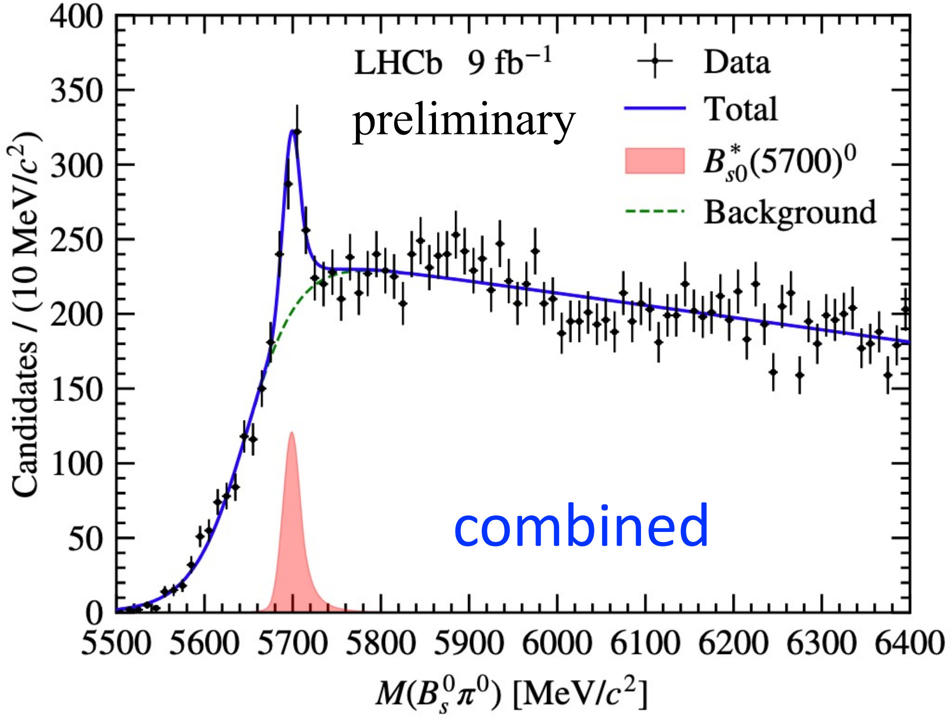
$B_s^0 \to D_s^-\pi^+$ | $B_s^0 \to J/\psi\phi$ | $B_s^0 \to D_s^-\pi^+\pi^+\pi^-$

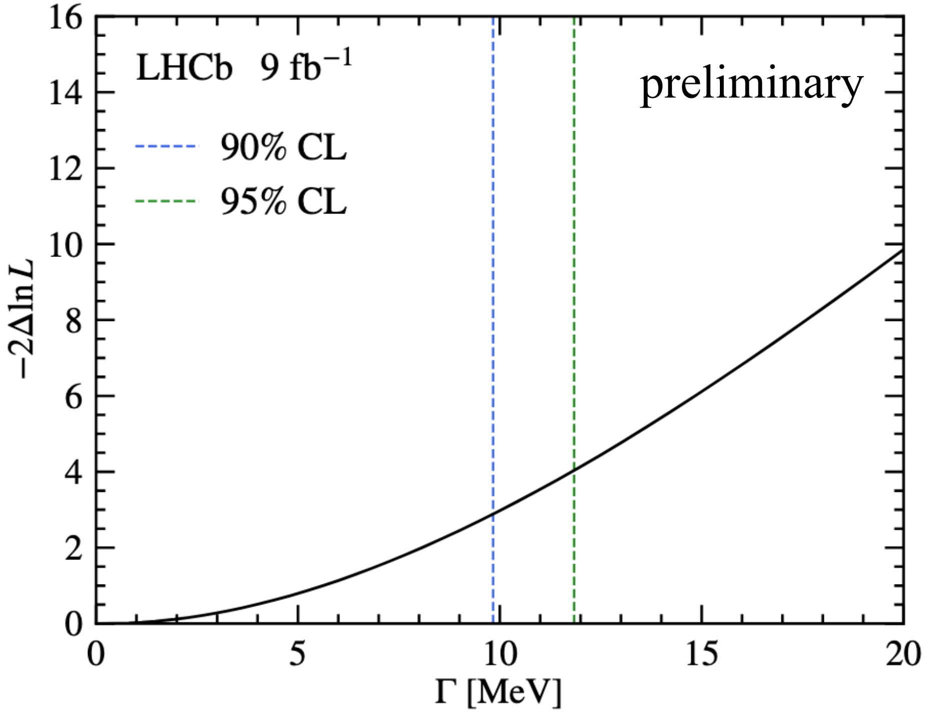


$N = 148^{+29}_{-26}$ | $N = 116^{+26}_{-25}$ | $N = 79^{+21}_{-19}$

Mass and width measurement

➢A new resonance is established in the $B_s^0\pi^0$ spectrum with global significance $> \boldsymbol{7\sigma}$



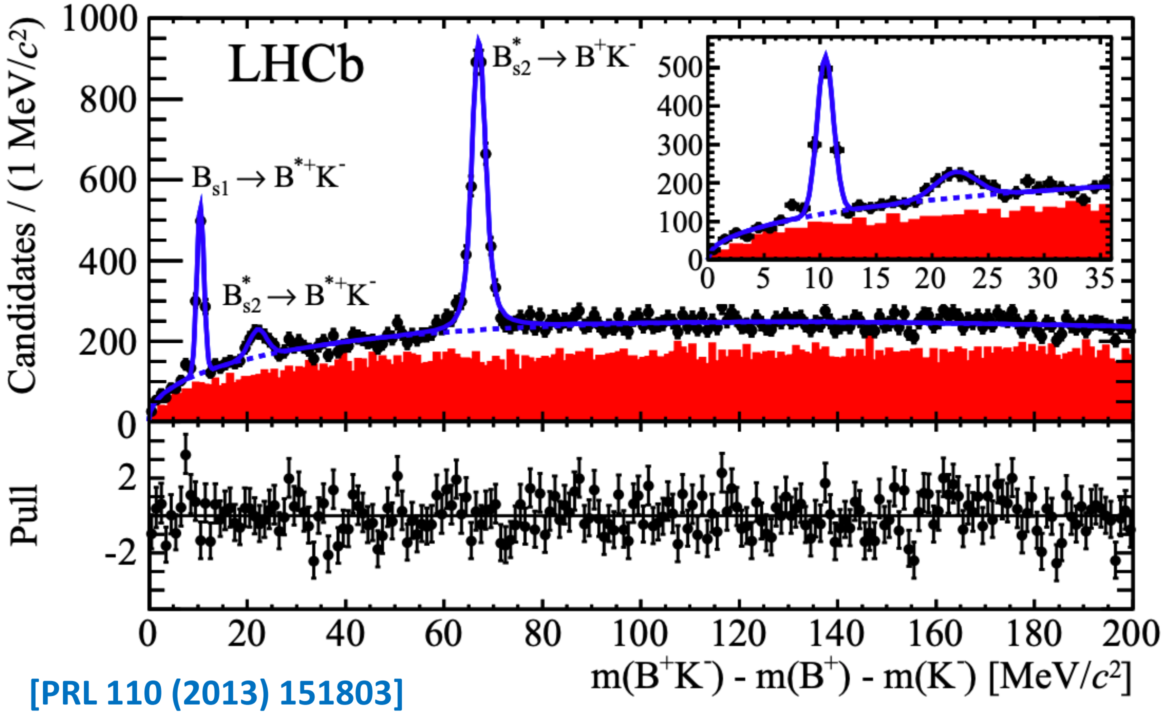


$$M = 5698.9 \pm 1.5(\mathrm{stat}) \pm 0.6(\mathrm{syst}) \pm 0.1(\mathrm{ext})\ \mathrm{MeV}/c^2$$

$\Gamma < 9.8\ (11.8)$ MeV at 90% (95%) confidence level

Interpretation of the new state (I)

- A state decaying to two pseudoscalars must have a natural spin-parity $J^P = 0^+, 1^-, 2^+, \ldots$
- The $J^P = 2^+$ state has already been observed in $B^{(*)}K$



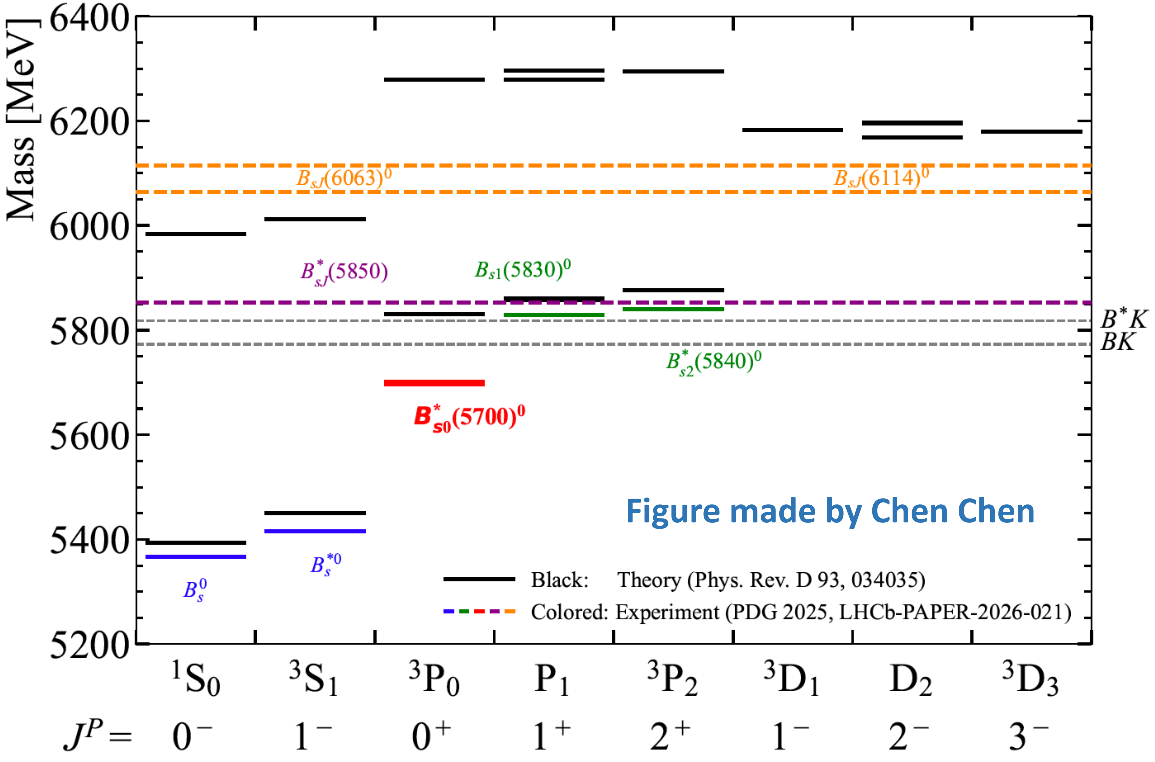
[PRL 110 (2013) 151803]

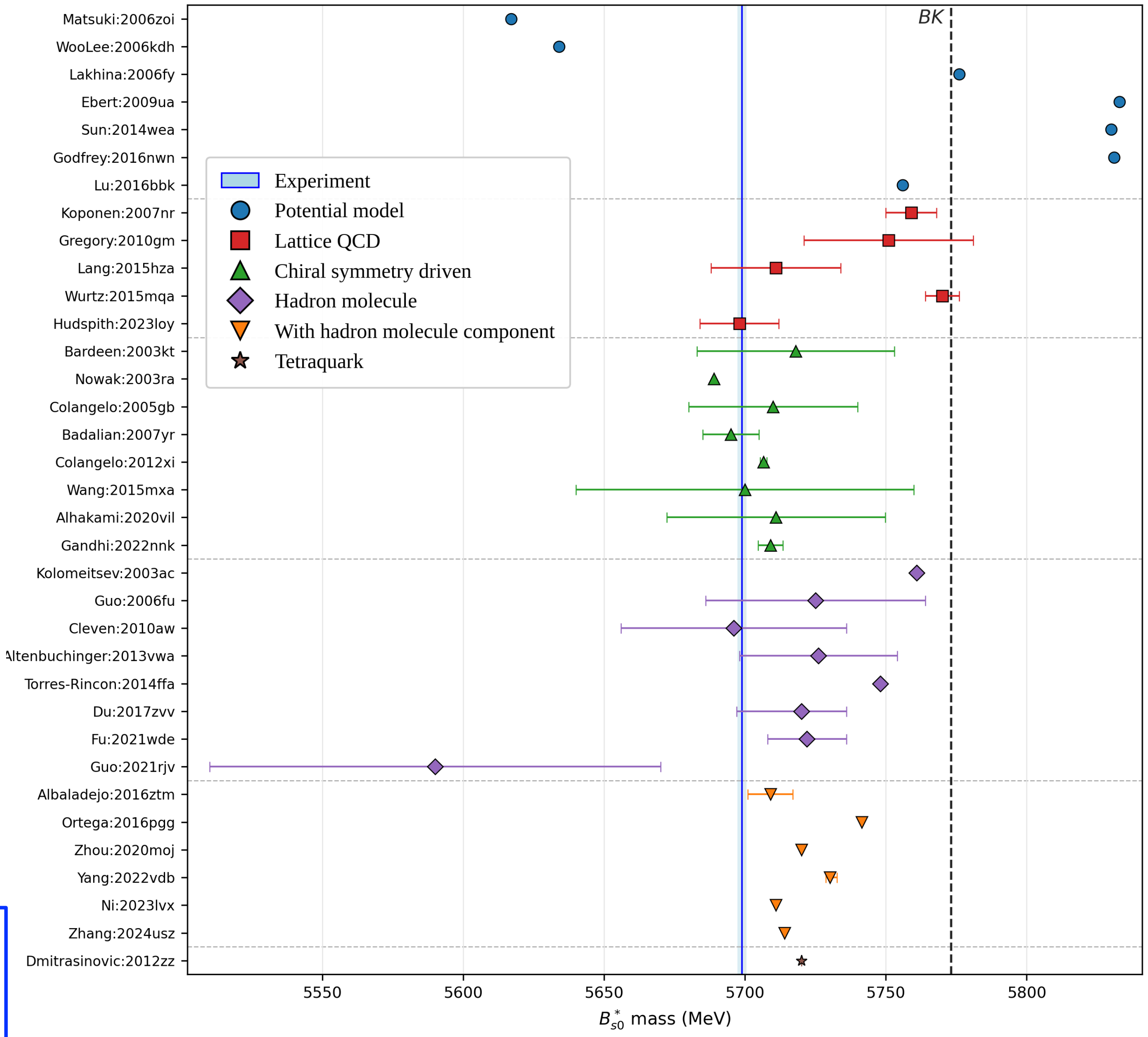
$\Rightarrow$ Natural interpretation is the $J^P = 0^+$ state, named $\boldsymbol{B^*_{s0}(5700)^0}$

L	j_q	J^P	State	Dominant Decays
0	1/2	0^-	B_s	....
		1^-	B^*_s	$B_s\gamma$
1	1/2	$\boldsymbol{0^+}$	$\boldsymbol{B^*_{s0}}$	$B^*_s\gamma$ $\boldsymbol{B_s\pi^0}$
		1^+	B'_{s1}	$B_s\gamma$ $B^*_s\gamma$ $B^*_s\pi^0$
	3/2	1^+	$B_{s1}(5830)$	B^*K
		2^+	$B^*_{s2}(5840)$	BK, B^*K
2	....			

Test of theoretical scenarios

- Analogous to $D_{s0}^*(2317)^+$, the mass of $\boldsymbol{B_{s0}^*(5700)^0}$ is significantly below potential model predictions





$$M(B_s^*(5700)^0) - M(B_s^0) = 332.0 \pm 1.5 \pm 0.6\ \text{MeV}$$
$$M(D_{s0}^*(2317)^\pm) - M(D_s^\pm) = 349.2 \pm 0.7\ \text{MeV}$$

Interpretation of the new state (II)

- The observed structure is also consistent with $B_{s1} \to B_s^{*0}(\to B_s^0\gamma)\pi^0$ where the low-energy photon is not reconstructed → **it will not defeat its importance**
- Under the B_{s1} hypothesis, it will have

$$M = 5748.3 \pm 1.5(\mathrm{stat}) \pm 0.6(\mathrm{syst}) \pm 0.2(\mathrm{ext})\ \mathrm{MeV}/c^2$$

$\Gamma < 9.8\ (11.8)$ MeV at 90% (95%) confidence level

- It could also be overlapping combination of $B_{s0}^{*}\&B_{s1}$
  - ✓ this would imply a fine-tuning of $M(B_{s1}) - M(B_{s0}^{*0})$ to match $M(B_s^{*0}) - M(B_s^0)$ at $\mathcal{O}(1\ \mathrm{MeV})$ level
- The ambiguity can potentially be addressed via study of the $B_s^0\gamma$ spectrum
  - □ $\boldsymbol{B_{s0}^{*0}} \to 5649.5 \pm 1.6\ \mathrm{MeV}/c^2$
  - □ $\boldsymbol{B_{s1}^{0}} \to 5748.3 \pm 1.6\ \&\ 5698.9 \pm 1.6\ \mathrm{MeV}/c^2$

L	j_q	J^P	State	Dominant Decays
0	1/2	0^-	B_s	....
		1^-	B_s^*	$B_s\gamma$
1	1/2	$\boldsymbol{0^+}$	$\boldsymbol{B_{s0}^*}$	$B_s^*\gamma$ $\boldsymbol{B_s\pi^0}$
		$\boldsymbol{1^+}$	$\boldsymbol{B_{s1}}$	$B_s\gamma$ $B_s^*\gamma$ $\boldsymbol{B_s^*\pi^0}$
	3/2	1^+	$B_{s1}(5830)$	B^*K
		2^+	$B_{s2}^*(5840)$	BK, B^*K
2	....			

Prospects I - heavy-light system

- Non-strange B sector
  - ✓the lowest-lying $(0^+, 1^+)$ doublet undiscovered yet
  - ✓Given universal mass splitting according to chiral doubling mechanism, we expect

W. Bardeen et al. [PR D68 (2003) 054024]
M. Novak et al. [PR D48 (1993) 4370]

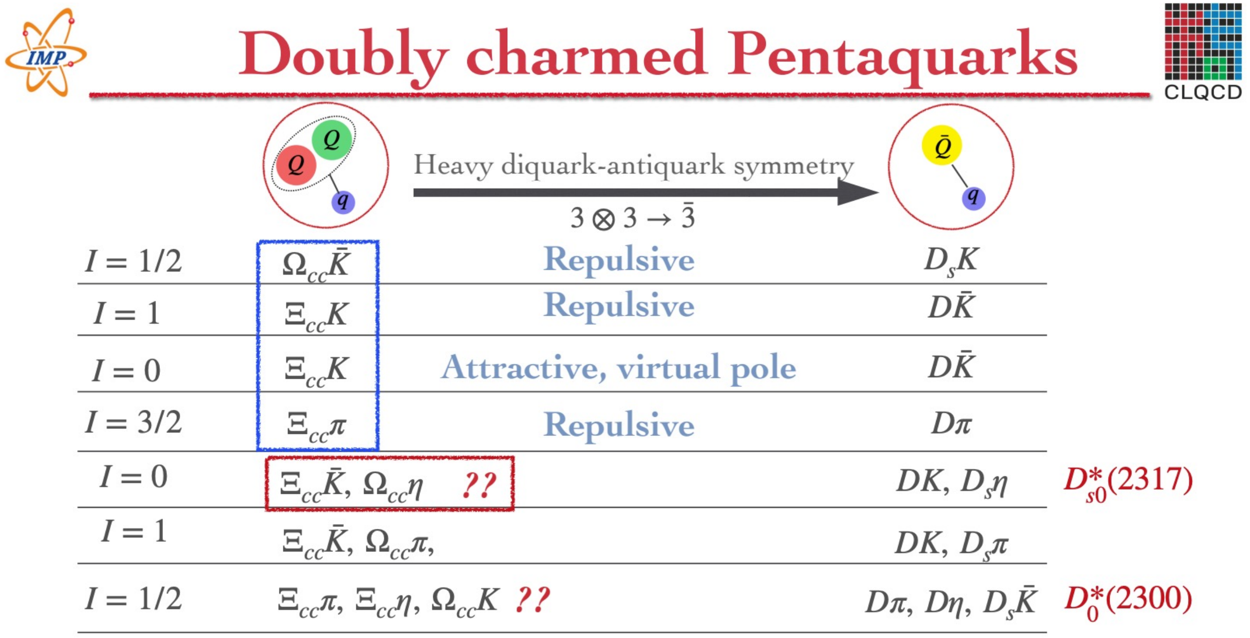
$$\left.\begin{array}{l} \square\ \boldsymbol{B_0^*} \to 5611.5 \pm 1.6\ \mathrm{MeV}/c^2 \\ \square\ \boldsymbol{B_1^0} \to 5656.8 \pm 1.6\ \mathrm{MeV}/c^2 \end{array}\right\}\ \text{broad, decay through } B\pi$$

- Doubly heavy baryons
  - ✓double-heavy diquark in anti-triplet color → heavy antiquark
  - ✓chiral doubling mechanism implies

□ $(1/2)^- \ \Xi_{cc} \to (3952, 3969)\ \mathrm{MeV}/c^2$:
broad, decay via $\Xi_{cc}\pi$

□ $(1/2)^- \ \Omega_{cc}^+ \to (4058, 4075)\ \mathrm{MeV}/c^2$:
narrow, decay via isospin-violating mode $\Omega_{cc}^+\pi^0$

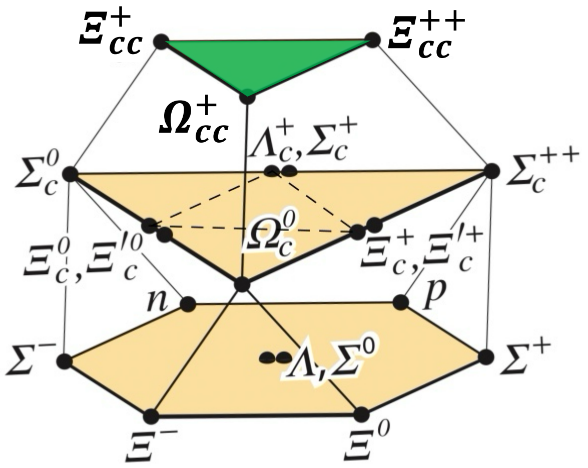
Talk by 刘柳明 [link]



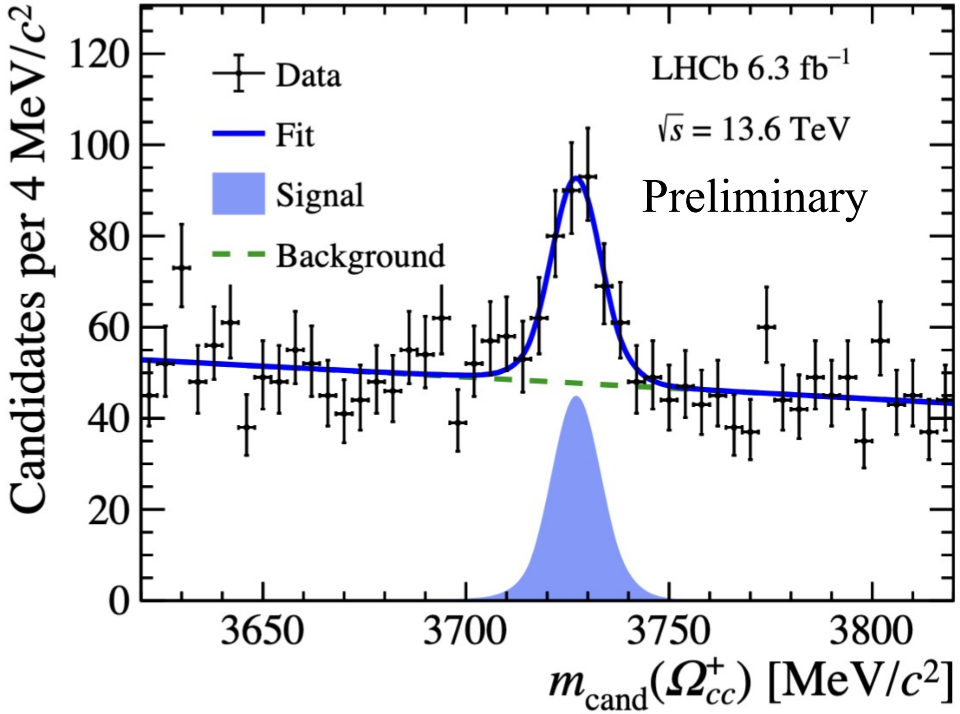
Observation of Ω_{cc}^{+} at LHCb Run3

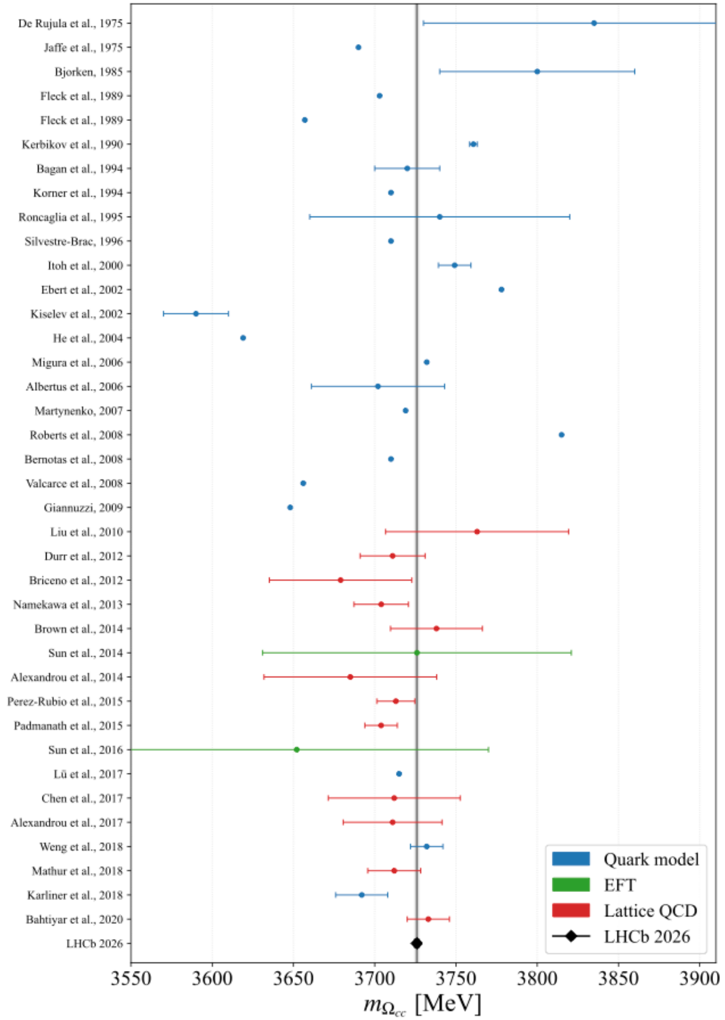
[LHCb-PAPER-2026-022]
in preparation

- **Dataset:** 6.3 fb^{-1} LHCb Run3 data collected in 2024
- **Decay chain:** $\Omega_{cc}^{+} \to \Omega_c^0\pi^+, \Omega_c^0 \to pK^-K^-\pi^+$ to exploit the large $\tau(\Omega_c^0)\sim280$ fs
- $\boldsymbol{\Omega_{cc}^{+}}$ **is observed at** $> 8\,\sigma$
  $\to$ **final piece of the SU$(4)_f$ J $= 1/2$ 20-plet**



$N = 184 \pm 24$





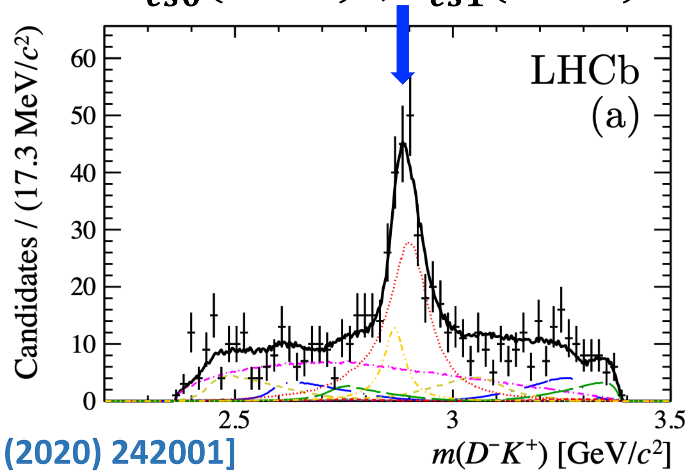
$$M(\Omega_{cc}^{+}) = 3725.9 \pm 1.0(\mathrm{stat}) \pm 0.2(\mathrm{syst}) \pm 0.4(\tau) \pm 0.6(\mathrm{ext})\ \mathrm{MeV}/c^2$$
$$M(\Omega_{cc}^{+}) - M(\Xi_{cc}^{++}) = 104.3 \pm 1.0(\mathrm{stat}) \pm 0.2(\mathrm{syst}) \pm 0.4(\tau) \pm 0.5(\mathrm{ext})\ \mathrm{MeV}/c^2$$

**List to be completed*

Prospects II - single beauty tetraquarks

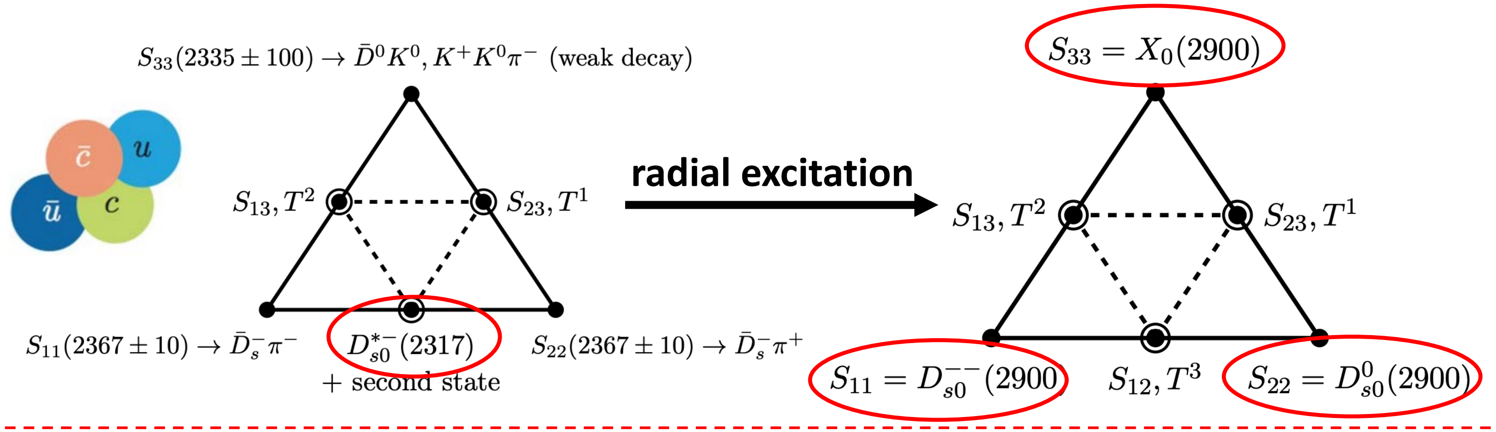
L. Maiani et al. [PRD 110 (2024) 034014]

$T^*_{cs0}(2870)^0, T^*_{cs1}(2900)^0$

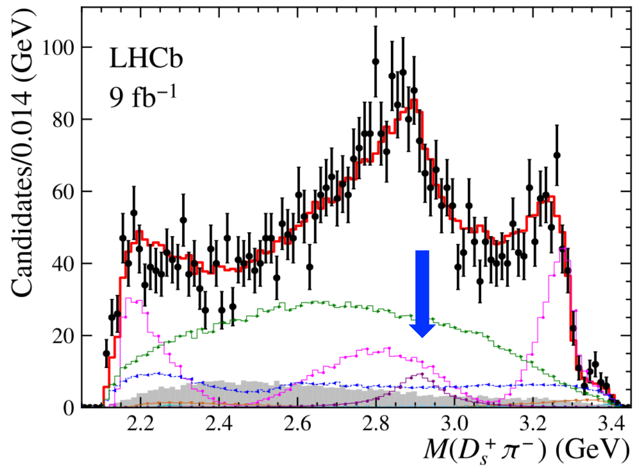


[PRL 125 (2020) 242001]
[PR D102 (2020) 112003]

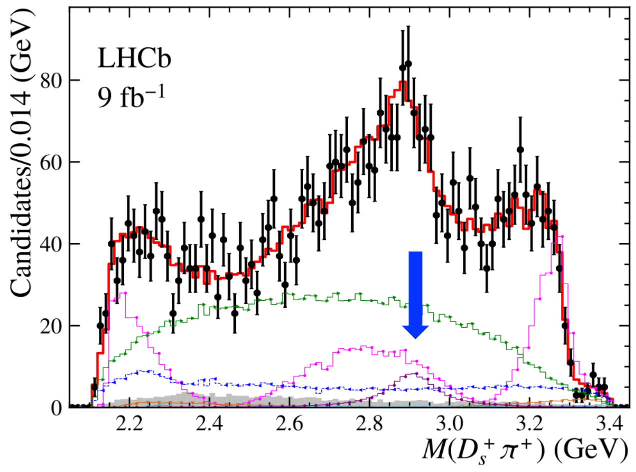
Compact multiquark



$T^*_{c\bar{s}0}(2900)^0$

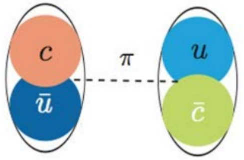


$T^*_{c\bar{s}0}(2900)^{++}$



[PRL 131 (2023) 041902]

Hadron molecule



$D^*_{s0}(2317)^+ \to DK$
$D_{s1}(2460)^+ \to D^*K$
$T^*_{c\bar{s}0}(2900)^{0/++} \to D^*K^*$

✓ b-counterpart also expected according to HQFS?

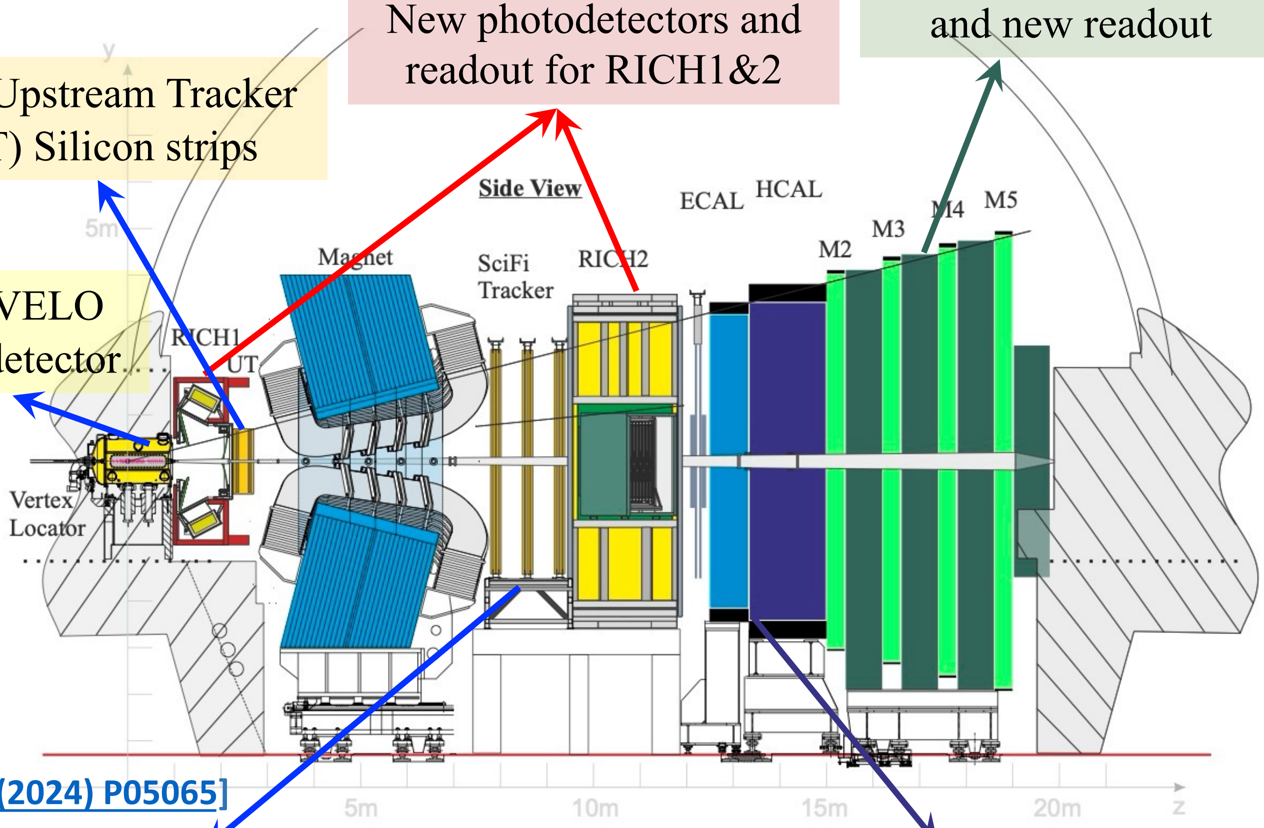
New dataset - Run3 of LHCb

New Upstream Tracker (UT) Silicon strips

New RICH1 optics
New photodetectors and readout for RICH1&2

Muon: removed M1 and new readout

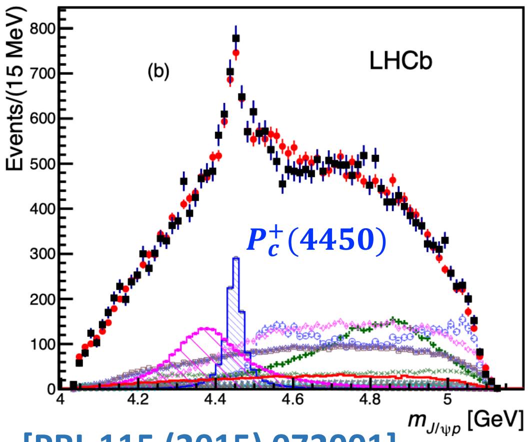
New VELO Pixel detector



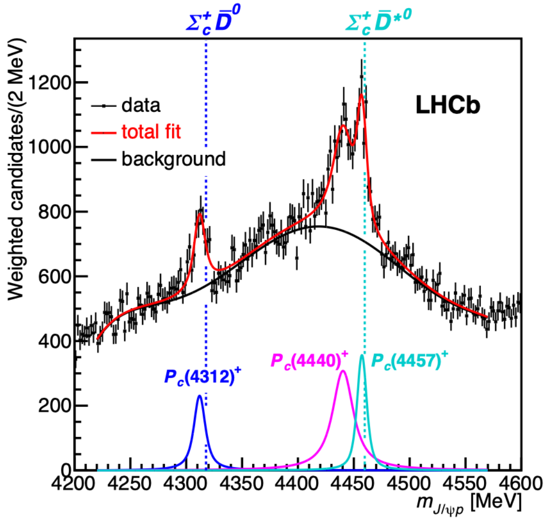
[JINST 19 (2024) P05065]

New SciFi Tracker Scintillating fibres

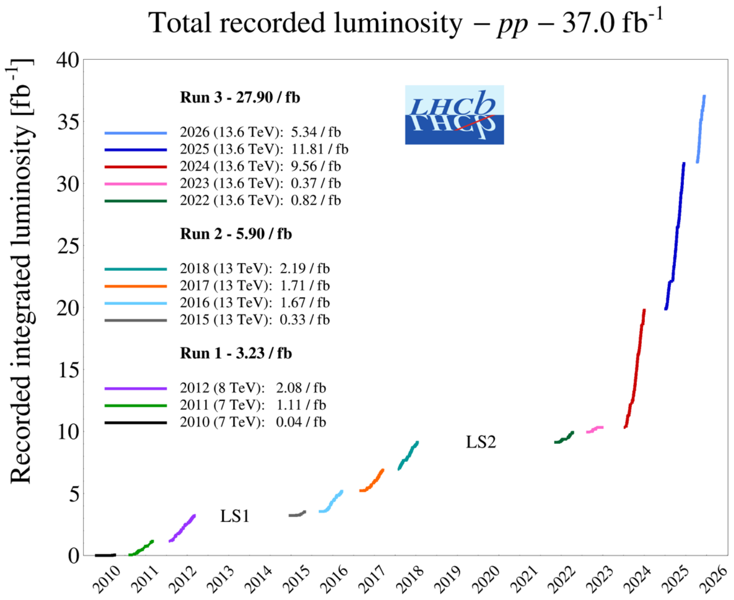
Calorimeters: removed PreShower (PS) and Scintillating Pad Detector (SPD), new readout



[PRL 115 (2015) 072001]



[PRL 122 (2019) 222001]



- ➢ **Luminosity**: 9 fb^{-1} @ Run 1-2 → **37 fb^{-1}** by Run 3
- ➢ **Software-only trigger**: efficiency of hadronic modes **×2 to 4**

Looking beyond

At prod.	Charm		Beauty		Charm + Beauty	
$Q\bar{Q}$	$cq\bar{q}\bar{q}$	$c\bar{q}qqq/\bar{c}qqqq$	$bq\bar{q}\bar{q}$	$b\bar{q}qqq/\bar{b}qqqq$		
	$c\bar{c}q\bar{q}$	$c\bar{c}qqq$	$b\bar{b}q\bar{q}$	$b\bar{b}qqq$		
$Q\bar{Q}+Q\bar{Q}$	$cc\bar{q}\bar{q}$	$c\bar{q}cqq$	$bb\bar{q}\bar{q}$	$b\bar{q}bqq$	$bc\bar{q}\bar{q}$	$b\bar{c}qqq/\bar{b}cqqq$
	$cc\bar{c}\bar{q}$	$cc\bar{c}qq$	$bb\bar{b}\bar{q}$	$bb\bar{b}qq$	$bq\bar{c}\bar{q}$	$b\bar{q}cqq$
	$cc\bar{c}\bar{c}$		$bb\bar{b}\bar{b}$		……	

- $\boldsymbol{cc\bar{c}\bar{q}}$**?**
- **Single-b multiquark states**: b-counterpart of $D_{s0}^{*}(2317)^{+}$ & $D_{s1}(2460)^{+}$ ✅
- $\boldsymbol{\bar{b}c}$**-like exotic states**: decay modes for some of them are experimentally more friendly than higher excited states, e.g. $B_c^{+}+p/K^{\pm}/\pi^{\pm}$
- **Pentaquarks other than** $\boldsymbol{c\bar{c}qqq}$: single-c/b may be accessible if exist
- **Hexaquark states?**
- **Weakly decaying exotic hadrons:** T_{bb} widely recognized, but far from reach; T_{bc}?

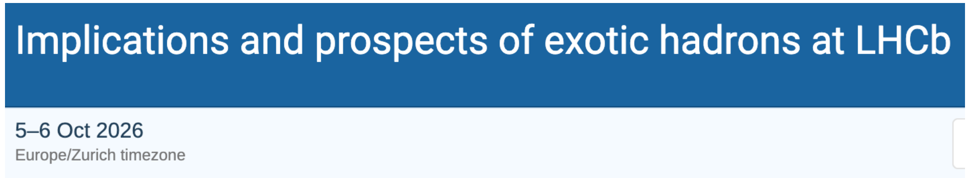
Summary

- The long-sought b-counterpart of $D_{s0}^*(2317)^+$ is observed at LHCb

$$M(B_{s0}^*(5700)^0) = 5698.9 \pm 1.5(\text{stat}) \pm 0.6(\text{syst}) \pm 0.1(\text{ext})\ \text{MeV}/c^2$$

$$\Gamma(B_{s0}^*(5700)^0) < 9.8\ (11.8)\ \text{MeV at 90\% (95\%) confidence level}$$

- The mass measurement provides important input to theoretical models
- The discovery drives various prospects for the future
  - ✓Study of the $B_s^0\gamma$ spectrum
  - ✓More (potentially exotic?) excitations in heavy-light system
  - ✓More single beauty tetraquarks?
  - ✓A broader range of spectroscopy utilizing π^0 modes



The importance of theoretical predictions in directing experimental efforts is highly acknowledged!

Thank you!