Experimental review of baryons with two heavy quarks (including P_c)

Liming Zhang (Tsinghua University)

Outline

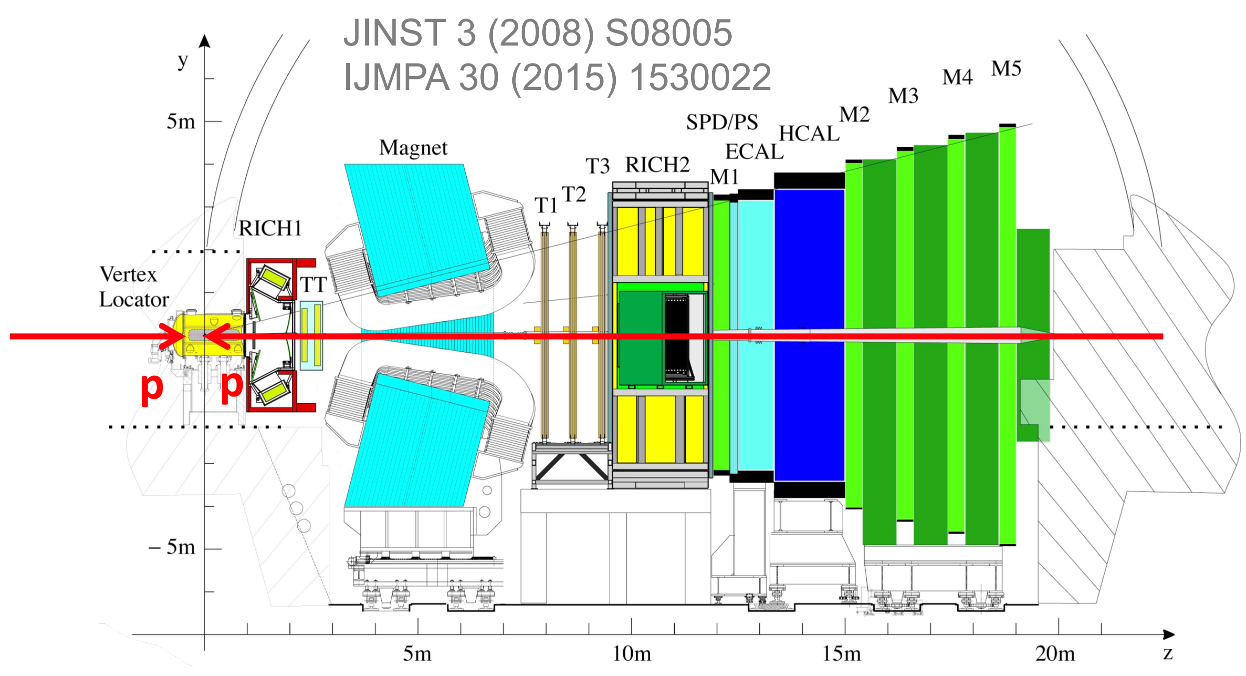
- Doubly-charmed baryon at LHCb
  - Observation of Ξ_{cc}^{++} with $\Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^+ \pi^+$ decays
  - Search for $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$ decays
  - Prospects for other doubly-charmed baryons

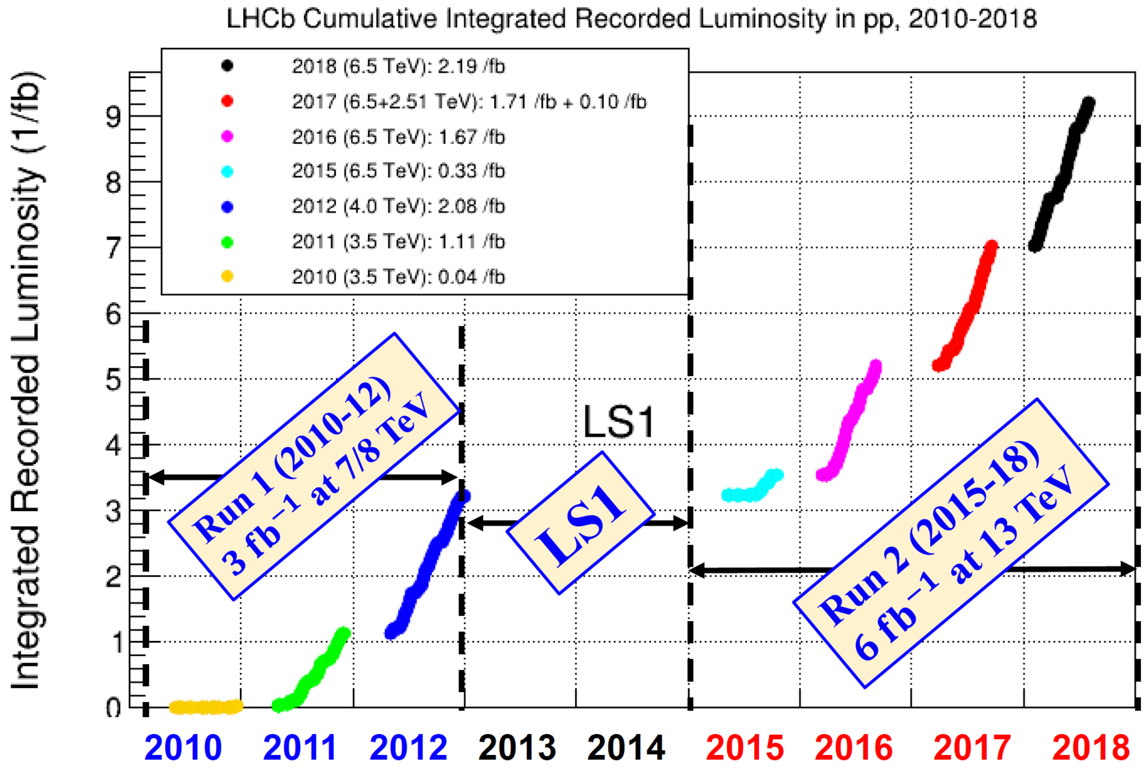
- Hidden-charm pentaquarks
  - Recall of 2015 observation at LHCb
  - Recent pentaquark results at LHCb
  - Pentaquark search at GlueX

The LHCb Experiment

- LHCb is a dedicated flavour physics experiment at the LHC
  - >10^4 $\times$ larger b production rate than the B factories @ $\Upsilon(4S)$
  - Access to all b-hadrons: B^+, B^0, B_s^0, B_c^+, b-baryons
- Can also study hadron spectroscopy and exotic states
- Acceptance optimised for forward $b\bar{b}$ production

> - Ξ_{cc}^{++} results based on 2016 1.7fb^{-1} data
> - Pentaquark results based on full dataset



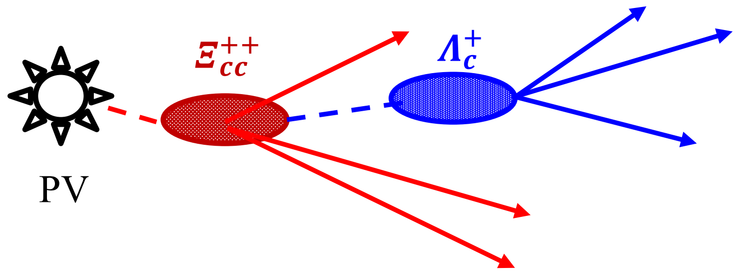


Two methods for spectroscopy at LHCb

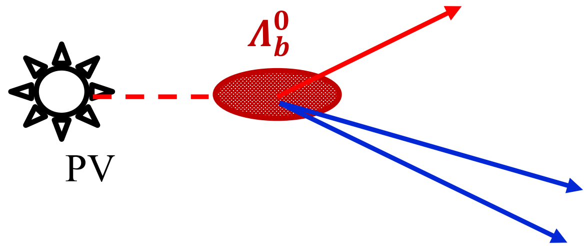
- Direct production in pp collisions
- Combine a heavy flavour (HF) hadron with one or more light particles
- Pros: high statistics
- Cons: large background

- Production by a heavier particle decay, usually with amplitude analysis
- Pros: low background, better determination of J^P
- Cons: less statistics

$\Xi_{cc}^{++} \to K^- \pi^+ \pi^+ \Lambda_c^+ (\to p K^- \pi^+)$

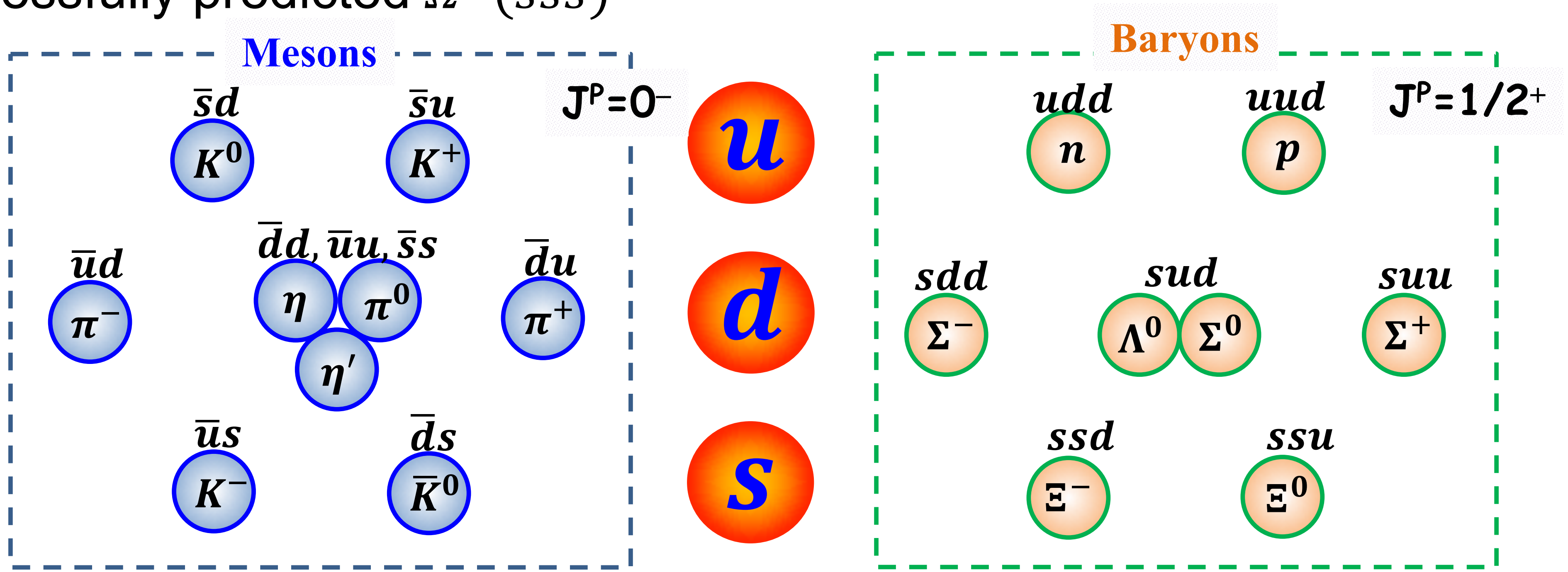


$\Lambda_b^0 \to K^- P_c^+ (\to J/\psi p)$



Quark model (QM)

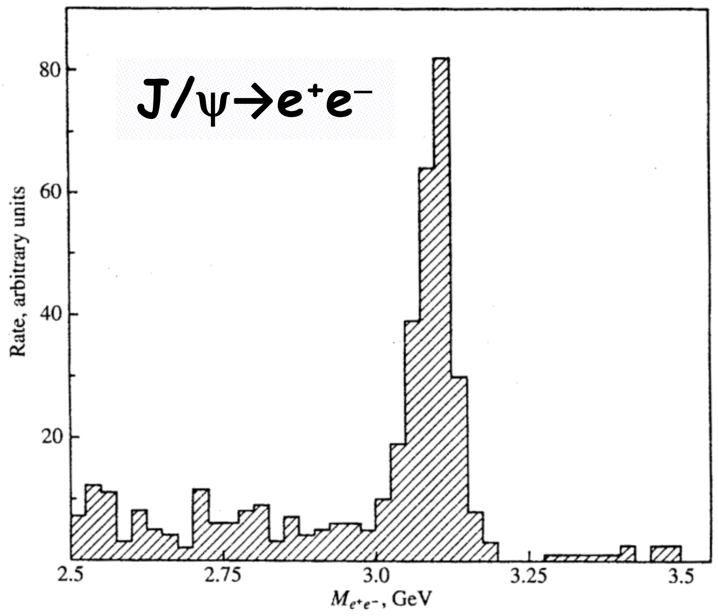
- In 1964, Gell-Mann and Zweig proposed a way to construct the numerous hadrons using three fundamental particles: quarks
- Successfully predicted $\Omega^{-}(sss)$



- Three quarks (*u*, *d*, *s*) can explain all observed particles at that time, called flavor SU(3) multiplets

November Revolution @ 1974

- 1964-1974 was a barren time for particle physics
- The QM had some striking successes, but was in an uncomfortable situation
  - No discovery of free quarks (explained by quark confinement)
- What rescued the QM was completely unexpected: the discovery of J/ψ meson and the fourth quark ***charm***
  - Announced on Nov. 11 1974 independently by S. Ting (BNL) and B. Richter (SLAC)
- The fifth quark ***bottom*** was discovered 3 years later in 1977



Quark model (QM)

Multiquark objects were predicted in the birth of Quark model - now called exotic

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

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.

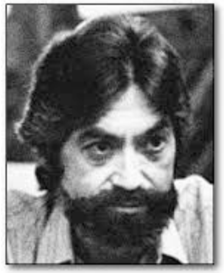
Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example 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

8182/TH.401
17 January 1964



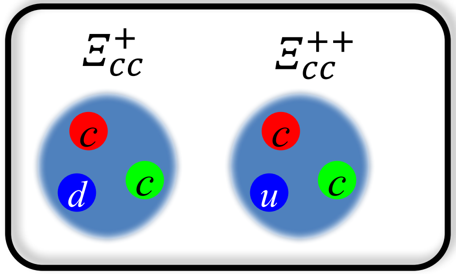
A B S T R A C T

...

In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

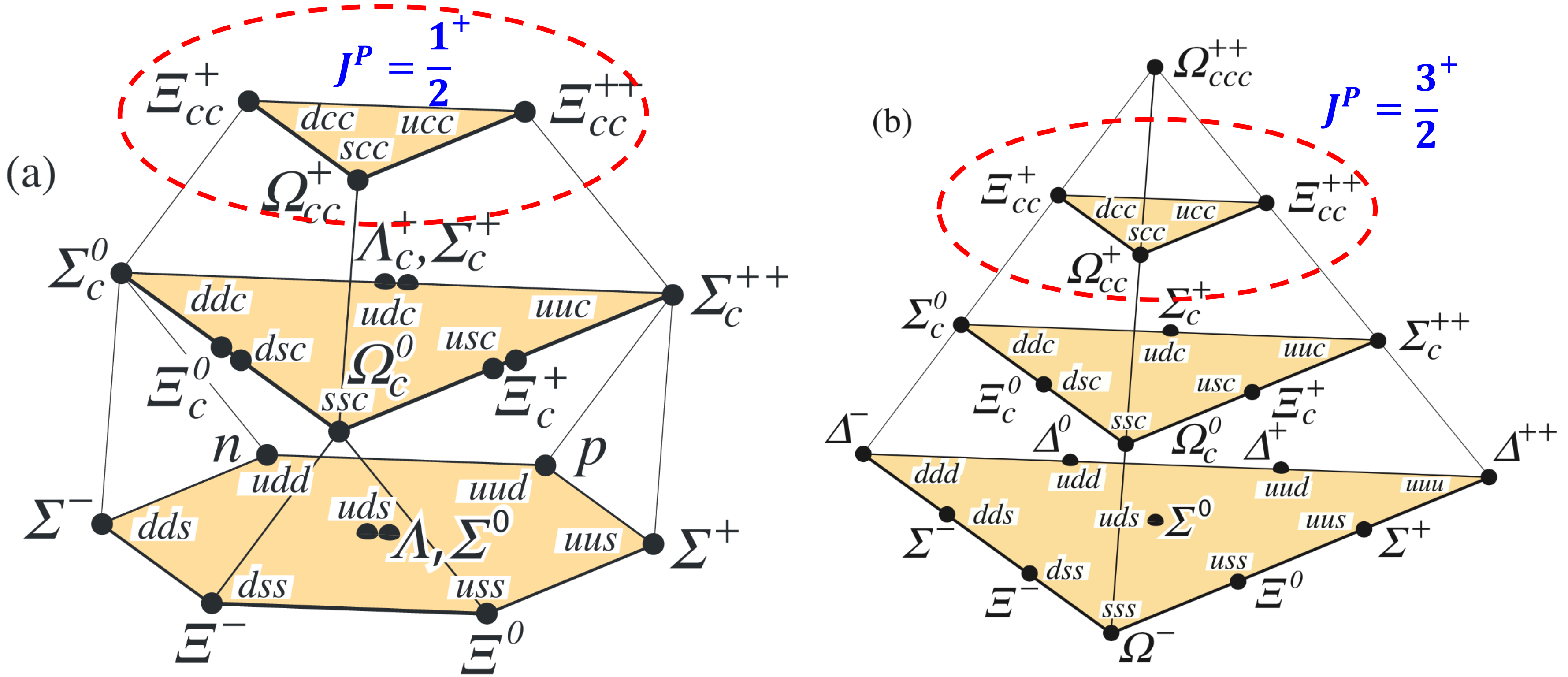
$qqqq\bar{q}$ baryons later called "pentaquarks"

Doubly-charmed baryon



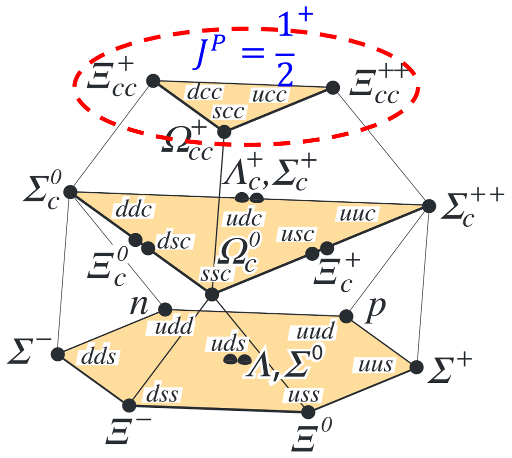
The doubly-charmed baryons

- Two SU(4) baryon 20-plets with $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^+$, each contains a SU(3) triplet with two charm quarks: $\Xi_{cc}^{+}(dcc),\ \Xi_{cc}^{++}(ucc),\ \Omega_{cc}^{+}(scc)$
- $J^P = \frac{3}{2}^+$ expected to decay to $\frac{1}{2}^+$ states via strong/electromagnetic processes
- $J^P = \frac{1}{2}^+$ states decay weakly with a c quark transformed to lighter quarks

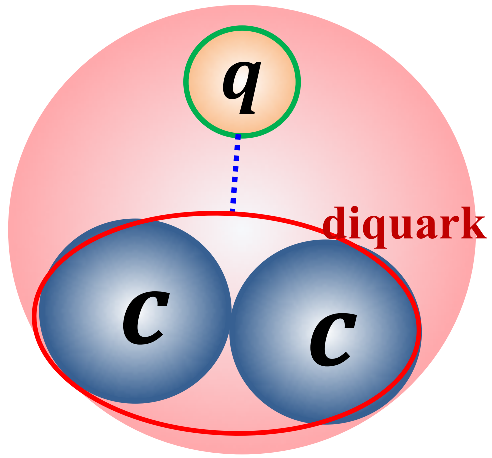


Doubly charmed baryons: motivation

- Doubly charmed baryons are not all established



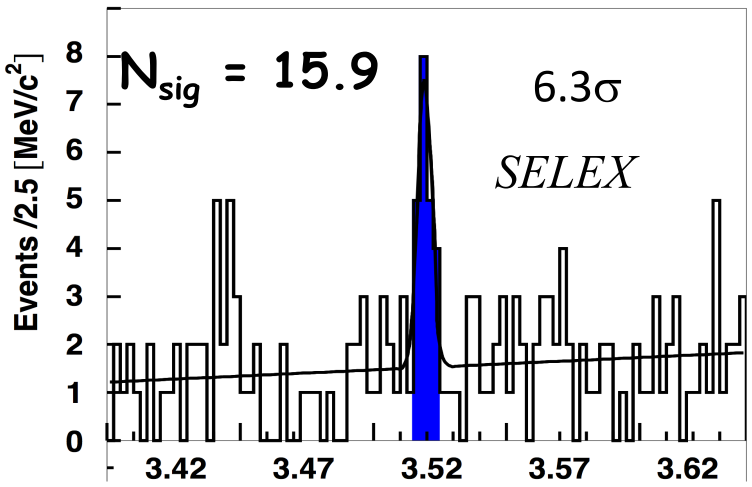
- Baryons with two heavy quarks provide a unique system to test QCD [hep-ph/9811212]
  - **The heavy quarks are nearly static and act as a center of gravity for the hadron**
  - **HQET: two charm quarks considered as a heavy diquark, doubly heavy baryon similar to a heavy meson $\bar{Q}q$**
  - **Such diquark can naturally extend to $\bar{Q}\bar{q}\bar{q} = cc\bar{q}\bar{q}$ exotic system**
  - **Doubly heavy baryons' mass and decay width to test QCD motivated models**



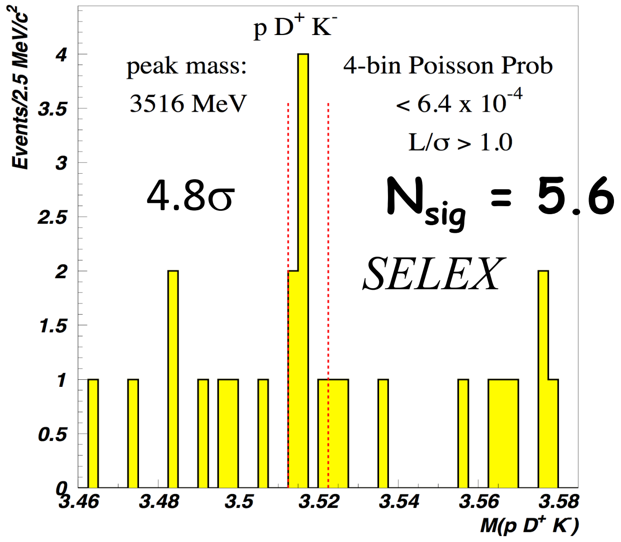
SELEX results on Ξ_{cc}^{+}

- SELEX (Fermilab E781) collides high energy hyperon beams (Σ^{-}) with nuclear targets (p)
- Observation of $\Xi_{cc}^{+}(dcc)$ reported by SELEX
  - Mass: 3518.7 ± 1.7 MeV
  - Short lifetime: $\boldsymbol{\tau(\Xi_{cc}^{+}) < 33}$ **fs** @90% CL, but not zero
  - Large production: $\boldsymbol{R = \frac{\sigma(\Xi_{cc}^{+})\times BF(\Xi_{cc}^{+}\to\Lambda_c^{+}K^{-}\pi^{+})}{\sigma(\Lambda_c^{+})} \sim 20\%}$

$\Xi_{cc}^{+} \to \Lambda_c^{+}K^{-}\pi^{+}$ **PRL 89 (2002) 112001**



$\Xi_{cc}^{+} \to pD^{+}\pi^{-}$ **PLB 628 (2005) 18**

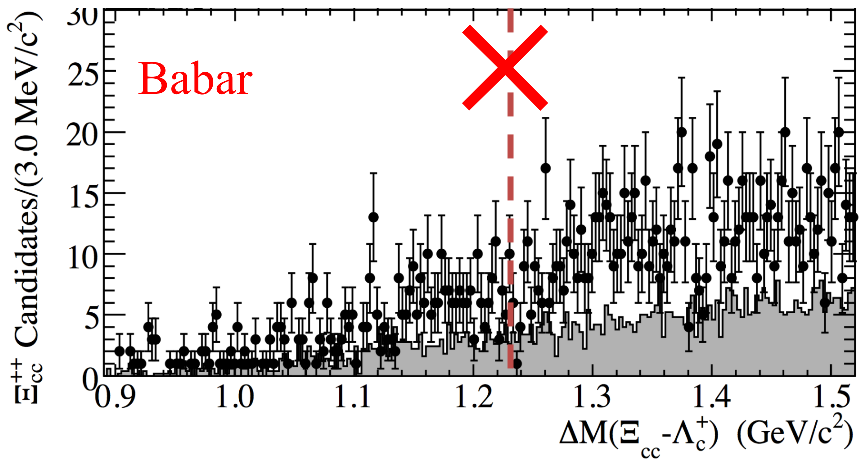


SELEX results not confirmed

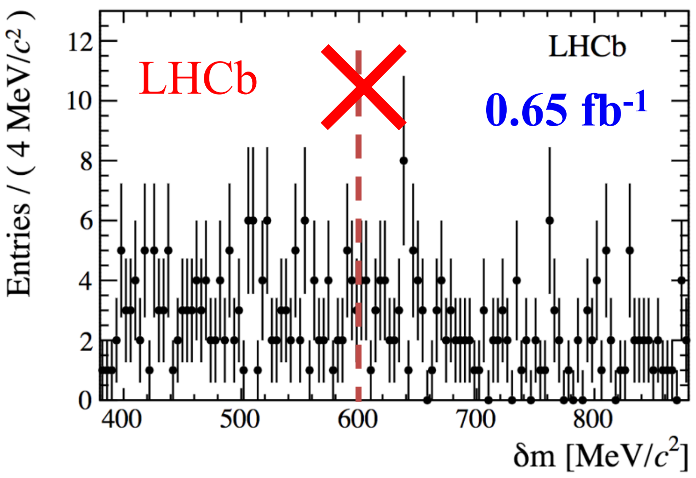
- Not confirmed by FOCUS [Phys. Proc. Supple. 115 (2003) 33], Babar [PRD 74 (2006) 011103], Belle [PRL 97(2006) 162001] , nor LHCb [JHEP 12 (2013) 090]

- However, these experiments have different production environments than that of SELEX

PRD 74 (2006) 011103



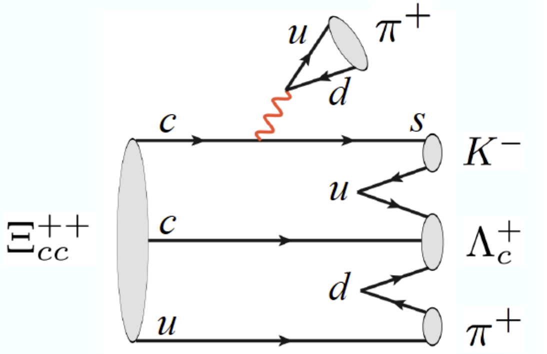
JHEP 12 (2013) 090



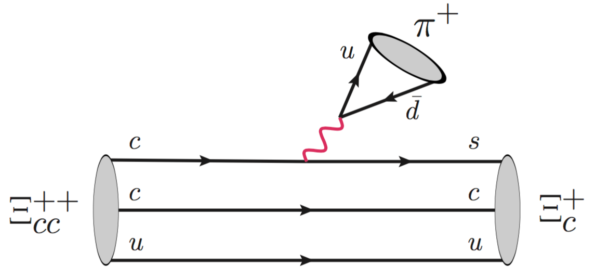
Observation of Ξ_{cc}^{++} from two decay modes

- Expect $\Xi_{cc}^{++}(ucc)$ has higher sensitivity at LHCb due to longer lifetime **[larger $\mathcal{B}$ and higher efficiency]**
  [Yu *et al.*, arXiv:1703.09086, CPC 42 (2018) 051001]

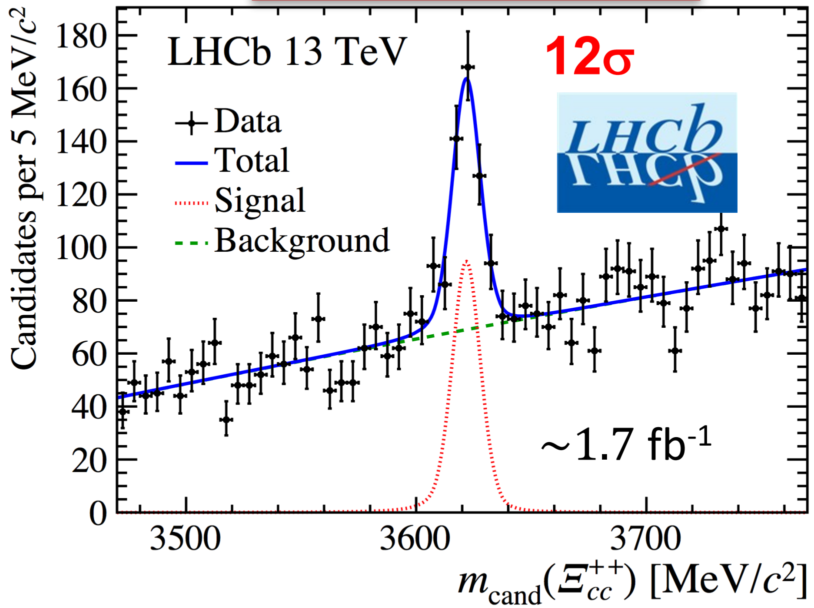
- Observed two suggested decay modes
  - Reconstruct Λ_c^+ and Ξ_c^+ (singly Cabibbo-suppressed) by decay $pK^-\pi^+$
  - $\varepsilon(\Lambda_c^+K^-\pi^+\pi^+)/\varepsilon(\Xi_c^+\pi^+) = 0.110$ due to two more tracks in former decay



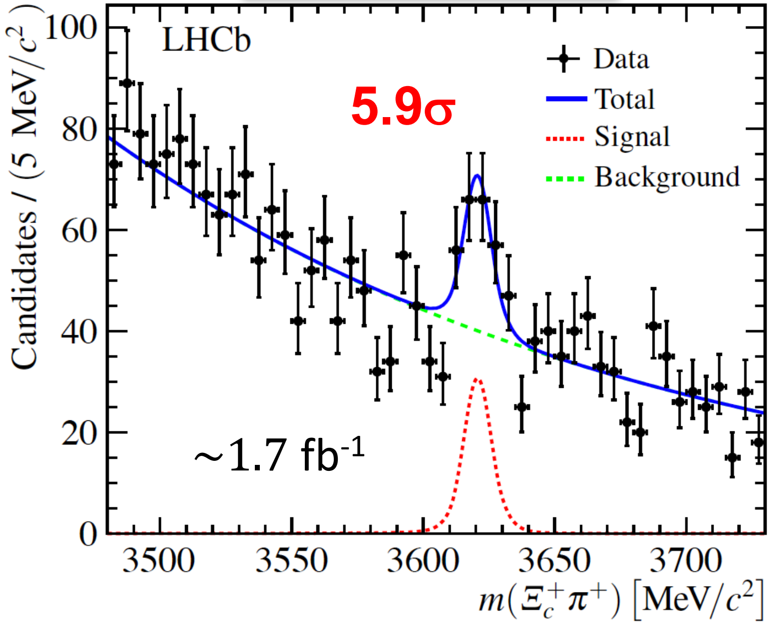
$\Xi_{cc}^{++} \to \Lambda_c^+K^-\pi^+\pi^+$
$N_{\text{sig}} = 313 \pm 33$



$\Xi_{cc}^{++} \to \Xi_c^+\pi^+$
$N_{\text{sig}} = 91 \pm 20$



PRL 119 (2017) 112001



PRL 121 (2018) 162002

Observation of new decay mode $\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+}$

- Ratio of branching fractions

PRL 121 (2018) 162002

$$\mathcal{R} = \frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+}; \Xi_c^{+} \to pK^{-}\pi^{+})}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^{+}K^{-}\pi^{+}\pi^{+}; \Lambda_c^{+} \to pK^{-}\pi^{+})} = (3.5 \pm 0.9 \pm 0.3)\times 10^{-2}$$

- $\mathcal{B}(\Lambda_c^{+} \to pK^{-}\pi^{+}) = (6.28 \pm 0.32)\%$ [PDG] and $\mathcal{B}(\Xi_c^{+} \to pK^{-}\pi^{+}) = (0.45 \pm 0.21 \pm 0.07)\%$

[1st absolute measurement, Belle, arXiv:1904.12093]

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+})}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^{+}K^{-}\pi^{+}\pi^{+})} = 0.49 \pm 0.13(\mathcal{R}) \pm 0.24(\mathcal{B}_{\Xi_c^{+}})$$ [my computation]

- $\Xi_c^{0}\pi^{+}$ would be a good mode to search for Ξ_{cc}^{+}, but the most efficient decay $\Xi_c^{0} \to pK^{-}K^{-}\pi^{+}$ suffers low $\mathcal{B}(\Xi_c^{0} \to pK^{-}K^{-}\pi^{+}) = (0.58 \pm 0.23 \pm 0.05)\%$ [Belle, PRL 122 (2019) 082001]

Observation of new decay mode $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$

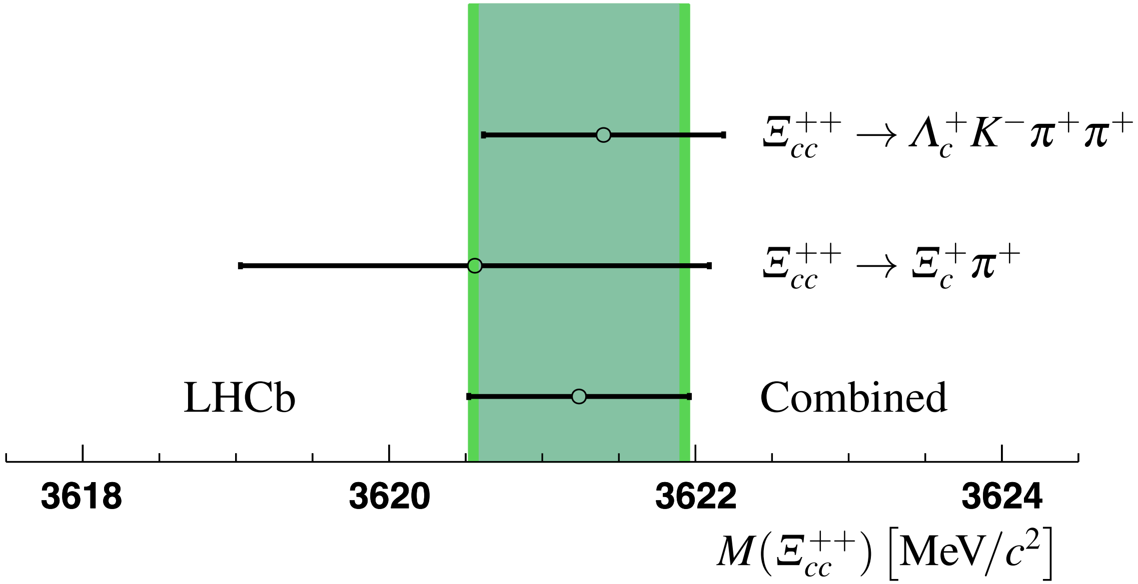
- Consistent mass measurements

PRL 121 (2018) 162002

$$3621.40 \pm 0.72 \pm 0.27 \pm 0.14(\Lambda_c^+)\ \text{MeV}$$

$$3620.56 \pm 1.5 \pm 0.4 \pm 0.3(\Xi_c^+)\ \text{MeV}$$

$$3621.24 \pm 0.65 \pm 0.31\ \text{MeV}$$



Mass difference: $m(\Xi_{cc}^{++})_{\text{LHCb}} - m(\Xi_{cc}^{+})_{\text{SELEX}} = 103 \pm 2$ MeV

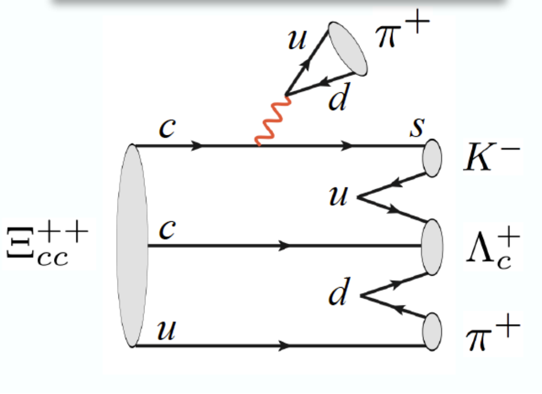
➢ Inconsistent with being isospin partners

Search for $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$

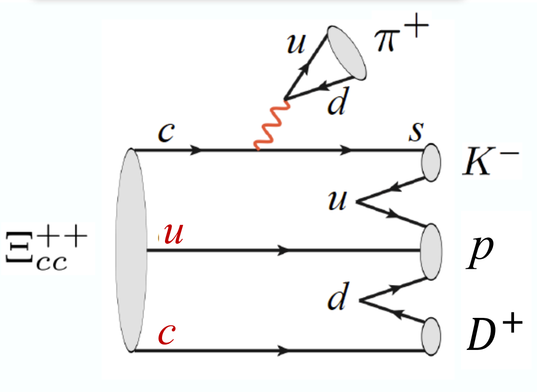
new

- Decay diagram is similar to that of $\Lambda_c^+ K^- \pi^+ \pi^+$, but smaller phase space
  - Just swap u and c quarks
- Efficiency is similar
- No evident signal
- Very stringent upper limit is obtained

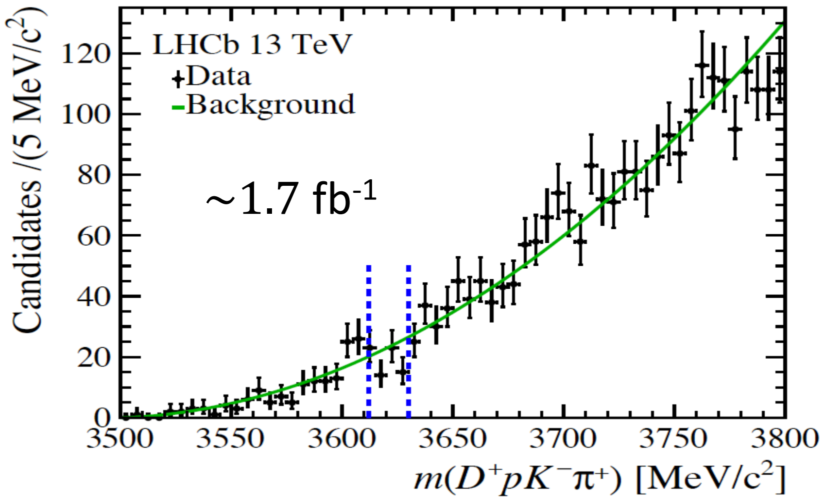
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$



$\Xi_{cc}^{++} \to D^+ p K^- \pi^+$



$$\mathcal{R} = \frac{\mathcal{B}(\Xi_{cc}^{++} \to D^+ p K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)} < 0.021@95\%\ \mathrm{C.L.}$$



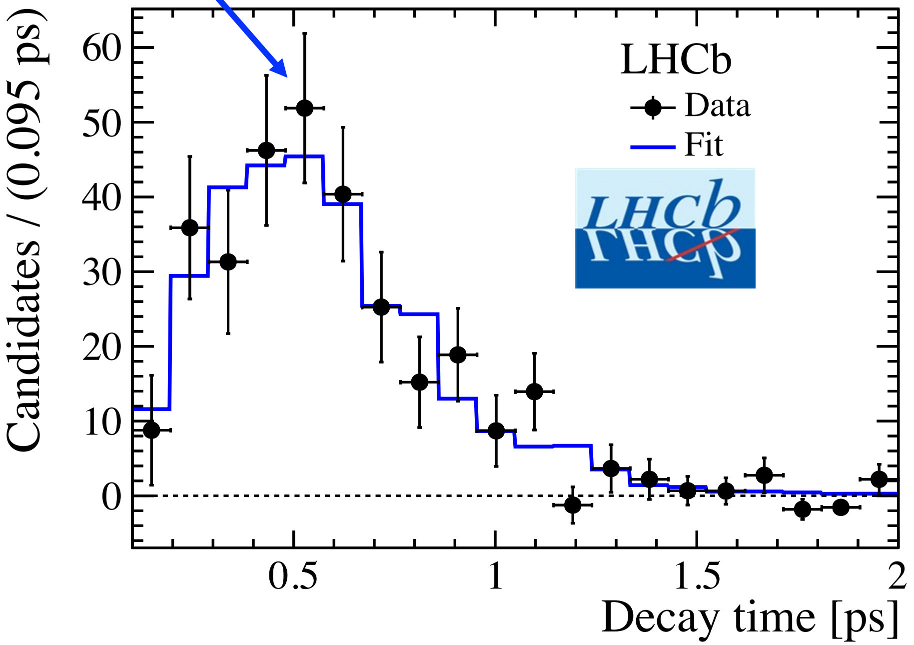
arXiv:1905.02421

More details see "Baryon spectroscopy at LHCb" *on 20/8 (Tues.) at S2 by Ao Xu*

First measurement of Ξ_{cc}^{++} lifetime

- Using $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ decays

$$f_{\Xi_{cc}^{++}}(t) = f_{\Lambda_b^0}(t) \times \frac{\epsilon_{\Xi_{cc}^{++}}}{\epsilon_{\Lambda_b^0}} \times e^{-\left(\frac{t}{\tau_{\Xi_{cc}^{++}}} - \frac{t}{\tau_{\Lambda_b^0}}\right)}$$



PRL 121 (2018) 052002

$$\tau_{\Xi_{cc}^{++}} = 256^{+24}_{-22} \pm 14 \text{ fs}$$

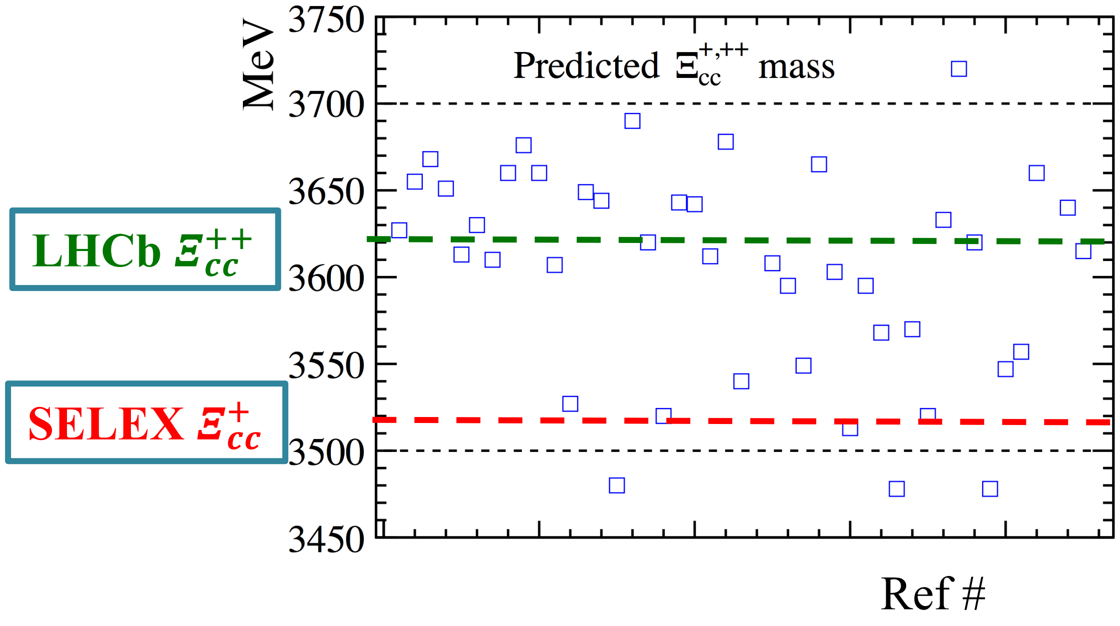
Precision 10.5%

Source	Uncertainty (ps)
Signal and background mass models	0.005
Correlation of mass and decay-time	0.004
Binning	0.001
Data-simulation differences	0.004
Resonant structure of decays	0.011
Hardware trigger threshold	0.002
Simulated Ξ_{cc}^{++} lifetime	0.002
Λ_b^0 lifetime uncertainty	0.001
Sum in quadrature	0.014

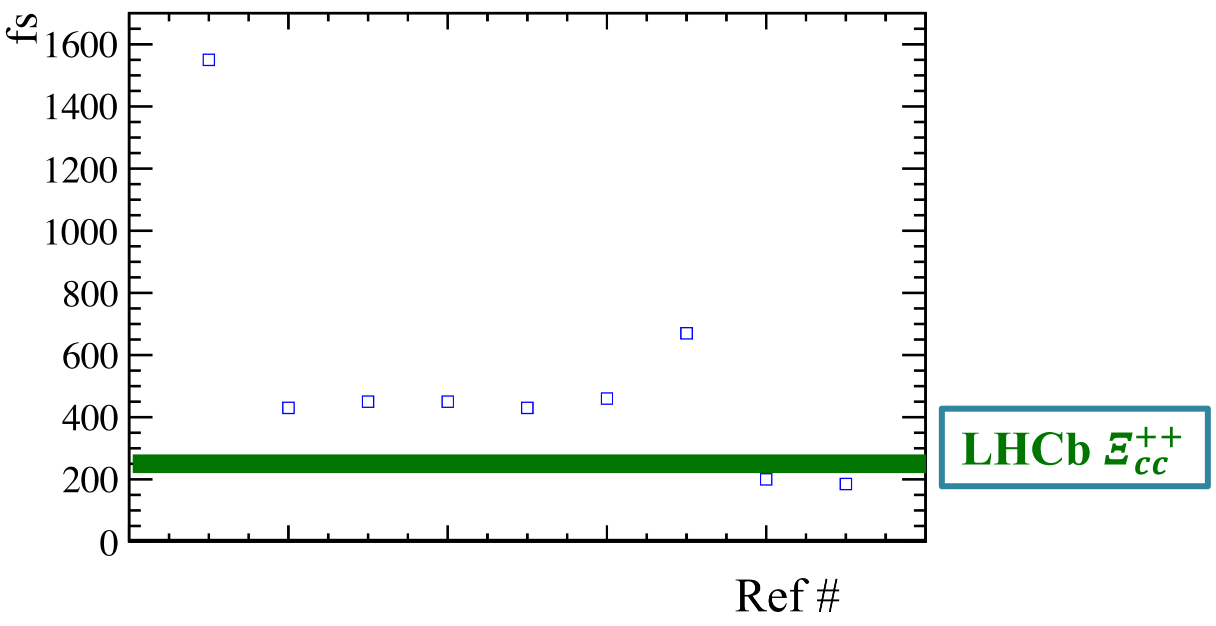
Confirmed it is weakly decaying J = ½ ground state

Mass and lifetime predictions vs measurements

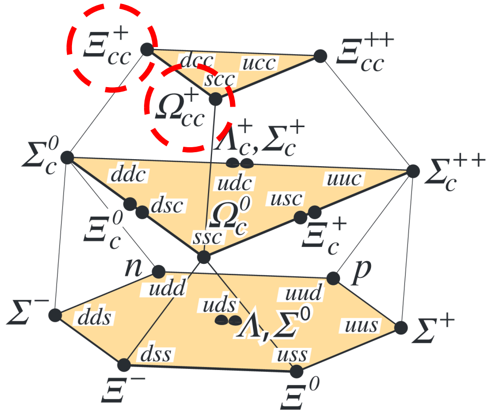
- Predicted $\Xi_{cc}^{+,++}$ masses in range $3.5 - 3.7$ GeV
- Mass splitting between Ξ_{cc}^{+} and Ξ_{cc}^{++} only a few MeV due to u, d symmetry
- Expectation: $\tau(\Xi_{cc}^{++}) \simeq 3\times\tau(\Xi_{cc}^{+})$
- Calculations give $\tau(\Xi_{cc}^{++}) \in [\,200 - 1550]$ fs



Measured lifetime at low side of predictions



Prospects on Ξ_{cc}^{+} and Ω_{cc}^{+} searches at LHCb



- Mass
  $m(\Xi_{cc}^{+}) \approx m(\Xi_{cc}^{++}) = 3621.24 \pm 0.72\ \text{MeV}$
  $m(\Omega_{cc}^{+}) \approx m(\Xi_{cc}^{++}) + 100\ \text{MeV}$
- Lifetime
  $3\tau(\Xi_{cc}^{+}) \approx 3\tau(\Omega_{cc}^{+}) \approx \tau(\Xi_{cc}^{++}) = 0.256 \pm 0.027\ \text{ps}$
- Production
  $\sigma(\Xi_{cc}^{++}):\sigma(\Xi_{cc}^{+}):\sigma(\Omega_{cc}^{+}) \approx 1:1:0.3$
- Shorter lifetime in Ξ_{cc}^{+} and Ω_{cc}^{+} makes numbers of drawbacks
  - Smaller $\mathcal{B}$, lower efficiency and larger background
- Ξ_{cc}^{+}: uncertain with current full LHCb data
  - Expect ~200 reconstructed $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ with full LHCb data, **but how about the background level? exponentially increases?** assuming $\mathcal{R}_\tau = \frac{\tau(\Xi_{cc}^{+})}{\tau(\Xi_{cc}^{++})} = \frac{1}{3}$
- Ω_{cc}^{+}: More challenge

Estimation of golden mode $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$

$$\frac{\mathcal{B}(\Xi_{cc}^{+}\to\Lambda_c^{+}K^{-}\pi^{+})}{\mathcal{B}(\Xi_{cc}^{++}\to\Lambda_c^{+}K^{-}\pi^{+}\pi^{+})} = \left(\frac{\mathcal{R}_\tau}{0.3}\right)\times 0.22$$ [Fu *et. al.*]

Compared to $\Xi_{cc}^{++} \to \Lambda_c^{+} K^{-} \pi^{+} \pi^{+}$

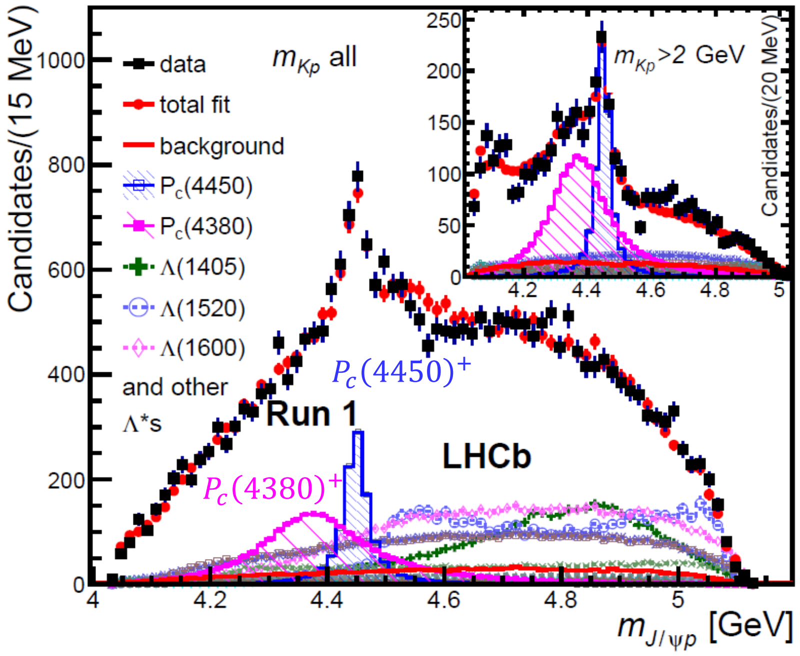
- BR a factor of 1/5
- Similar efficiency: a factor of 1/3 due to τ & a factor of 2 larger due to one less track
- Production cross-section is the same
- Full luminosity is a factor of 4 as 2016 data

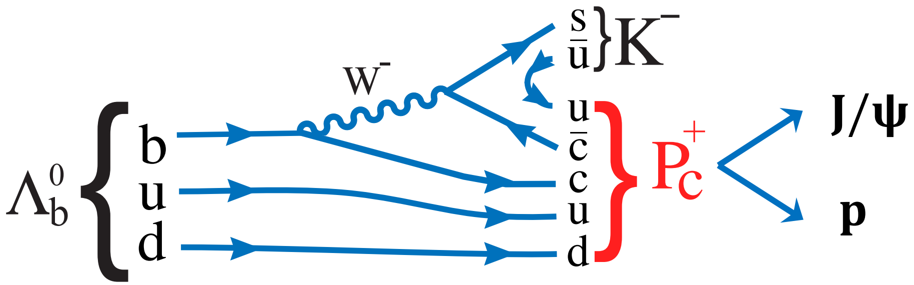
Hidden-charm pentaquarks

LHCb observation in 2015

- **Two $J/\psi p$ resonant structures** are revealed by a full 6D amplitude analysis
  - $P_c(4450)^+$ ← the prominent peak
  - $P_c(4380)^+$ ← required to obtain a good fit to the data
  - Consistent with **pentaquarks** with minimal quark content of $uudc\bar{c}$

PRL 115 (2015) 072001





$P_c(4450)^+$ $M = 4450 \pm 2 \pm 3$ MeV
$\Gamma = 39 \pm 5 \pm 19$ MeV
$F.F. = 4.1 \pm 0.5 \pm 1.1$ %

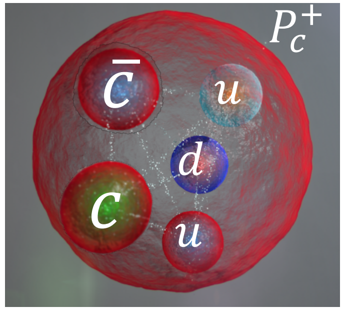
$P_c(4380)^+$ $M = 4380 \pm 8 \pm 29$ MeV
$\Gamma = 205 \pm 18 \pm 86$ MeV
$F.F. = 8.4 \pm 0.7 \pm 4.2$ %

Limited knowledge of P_c

- Observation of LHCb opens a gate to study pentaquarks
- To interpret the nature of P_c, more studies are needed
  - J^P, spectroscopy, decay modes and production mechanism?

$M_{P_c^+} = M_{J/\psi} + M_p + \sim 400\text{MeV}$

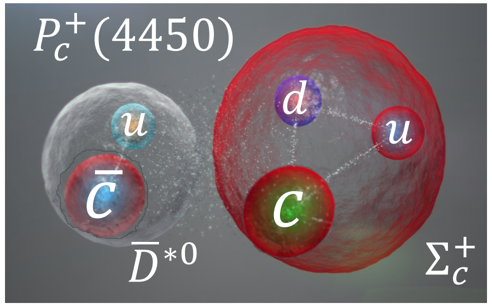
Tightly-bound pentaquark?



Maiani,Polosa, Riquer, PLB 749 (2015) 289
Lebed, PLB 749 (2015) 454
Anisovich,Matveev,Nyiri, Sarantsev PLB 749 (2015) 454
and others

$M_{P_c^+} = M_{\bar{D}^{*0}} + M_{\Sigma_c^+} - \sim\text{few MeV}$

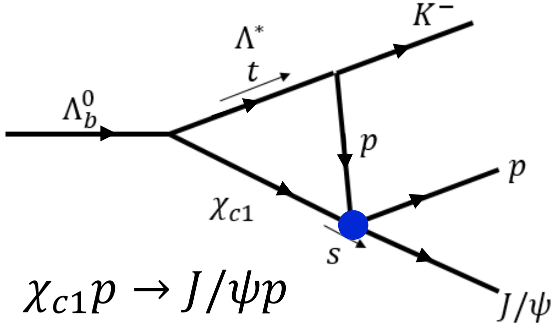
Loosely-bound pentaquark?



Wu,Molina,Oset,Zou, PRL105 (2010) 232001
Wang,Huang,Zhang,Zou, PRC84 (2011) 015203
Karliner,Rosner, PRL 115 (2015) 122001
and others

$P_c(4450)^+ = \chi_{c1}p$ threshold?

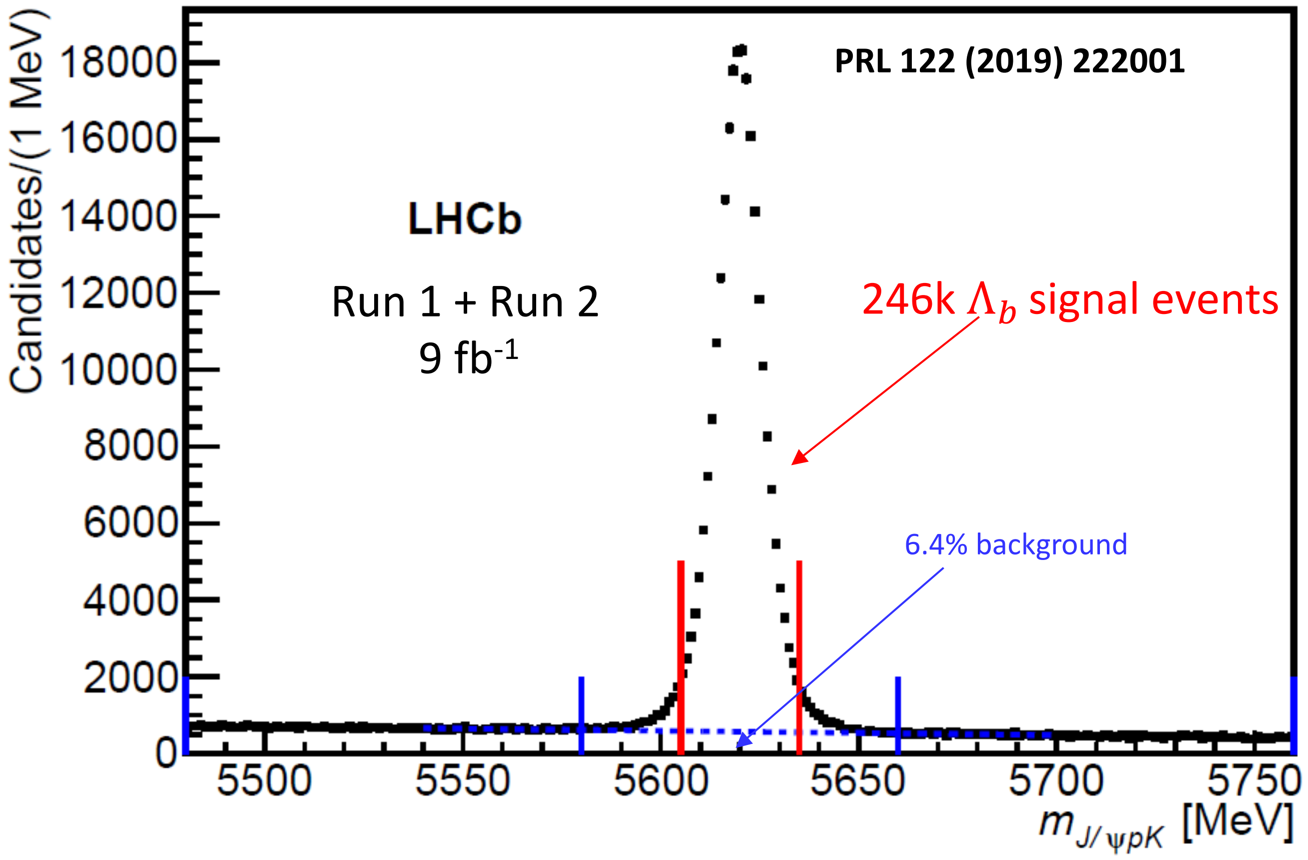
Kinematical effect: triangle diagram?



Guo,Meissner,Wang,Yang, PRD 92 (2015) 071502
Liu, Wang, Zhao, PLB 757 (2016) 231
Mikhasenko, arXiv:1507.06552
Szczepaniak, PLB 757 (2016) 61
and others

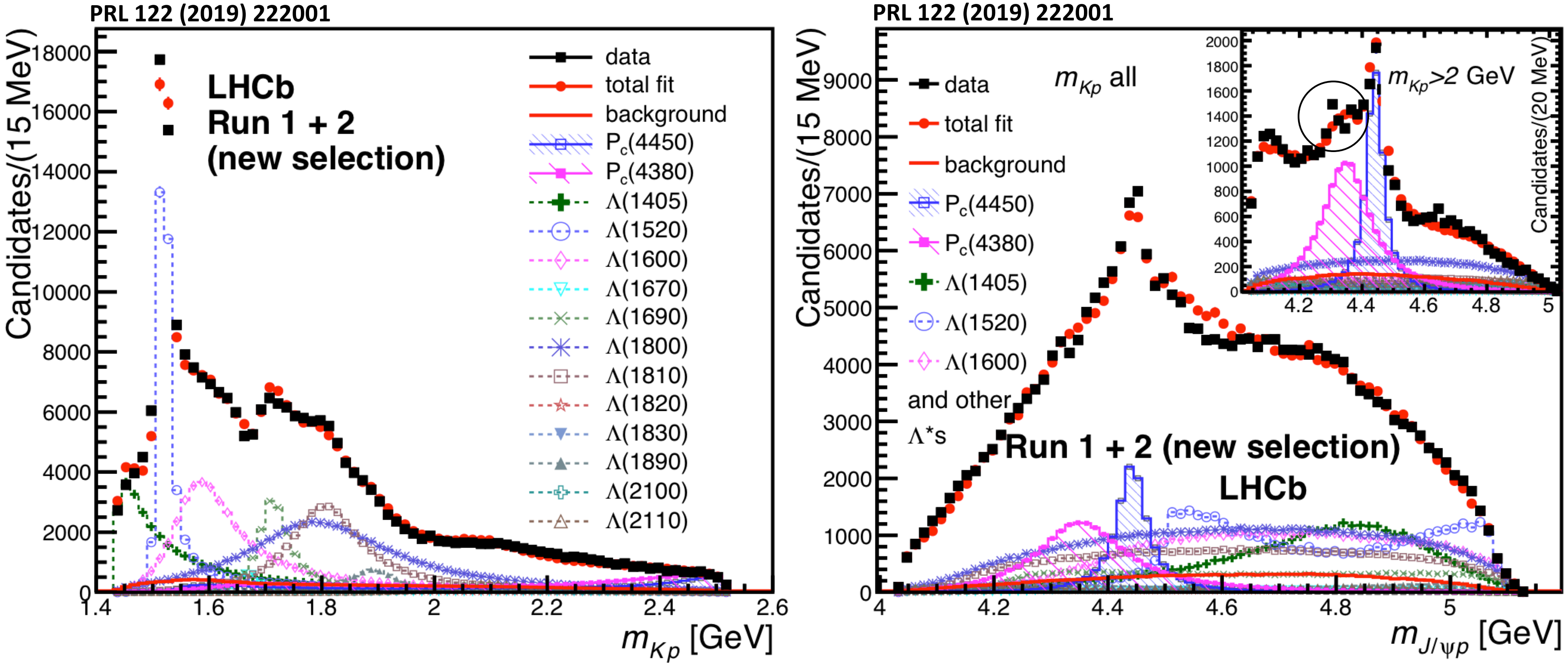
Signal yield

- An order of magnitude increases in signal yield
  - Inclusion of Run 2 data (x 5)
  - Improved data selection (x 2)



Consistency check

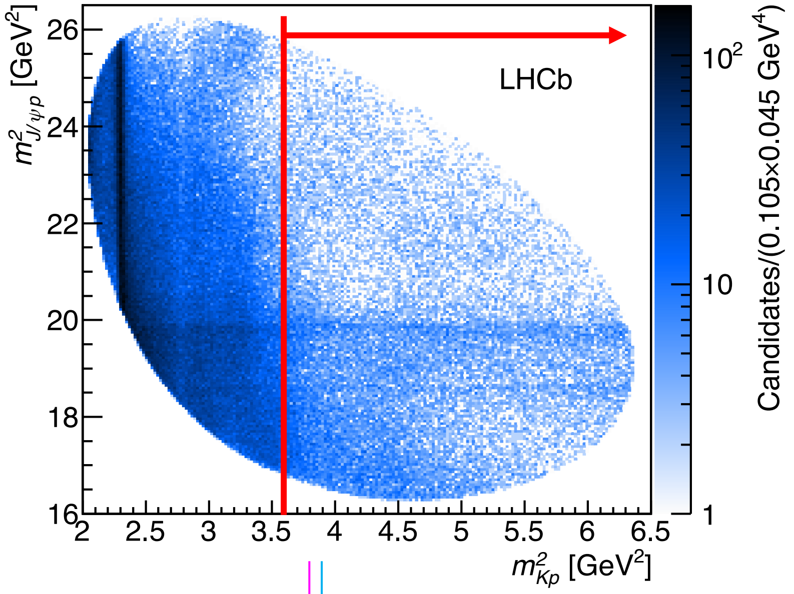
- We can reproduce the results in the previous publication, when fitting the new data with 2015 amplitude model
- But the fit is only considered as a cross-check

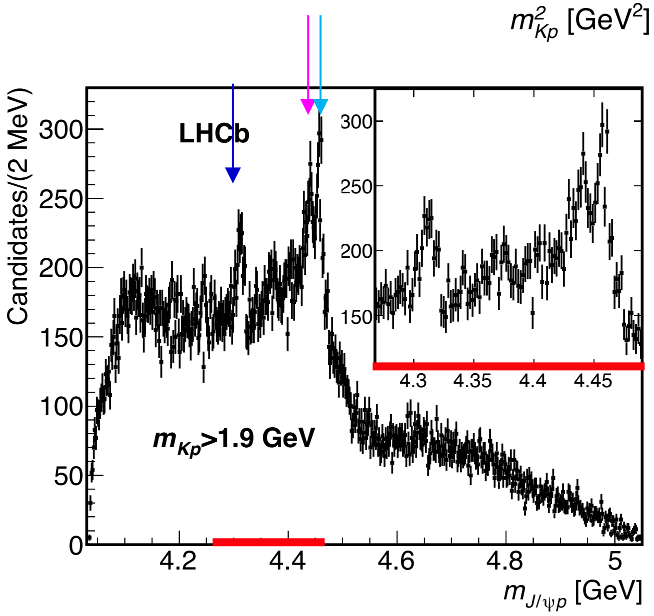


Display in smaller bin size

PRL 122 (2019) 222001

- Confirms the peaking structure at ~4450 MeV, which is resolved into two narrower pentaquark states with nearly identical masses
  - Unable to resolve in earlier smaller data set because mass split is small, and comparable to natural widths of the two states
- A new narrow peak at lower mass is also uncovered
  - Size too small to have been detected in earlier smaller data set





How to fit the data

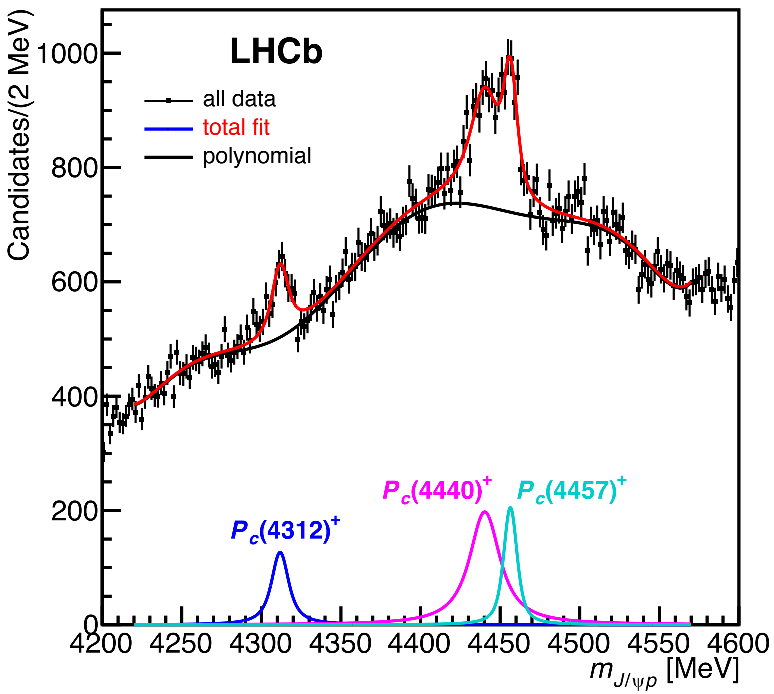
- **Simplified approach** fits to 1D $m_{J/\psi p}$ distribution
  - Narrow signals:
    - three Breit-Wigner (BW) functions $\otimes$ resolution (2-3 MeV)
  - Background of Λ^* + non-Λ_b^0 + possible broad P_c^+: two models compared
    - higher-order polynomial or
    - low-order polynomial + broad BW
- It can robustly determine M and Γ of **narrow** structures
  - Shown by studies of toy simulations
  - But not sensitive to J^P
  - Not sensitive to broad peaks, like $P_c(4380)^+$
- Several $m_{J/\psi p}$ distributions with different selection or weighting for systematic evaluation

Fit-1: all candidates

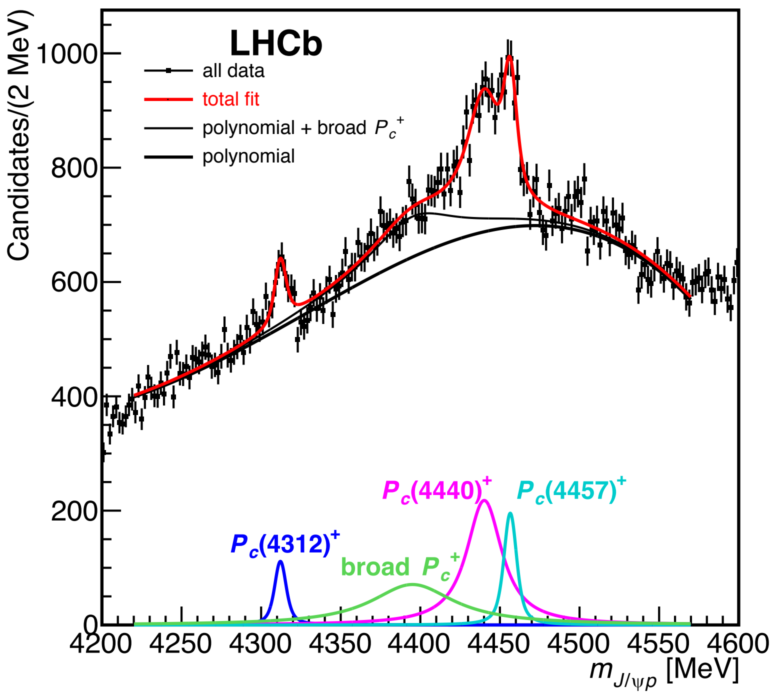
PRL 122 (2019) 222001

- Fit inclusive $m_{J/\psi p}$ distribution
- Clear narrow structures, but background is high

high-order polynomial



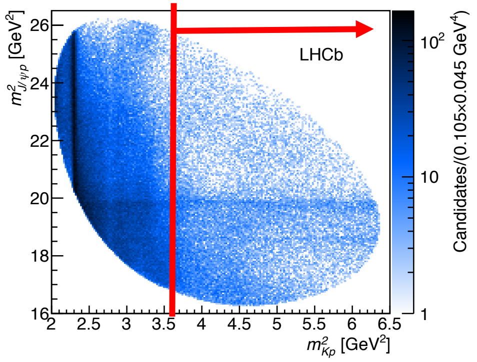
low-order polynomial + broad P_c^+ as bkg.

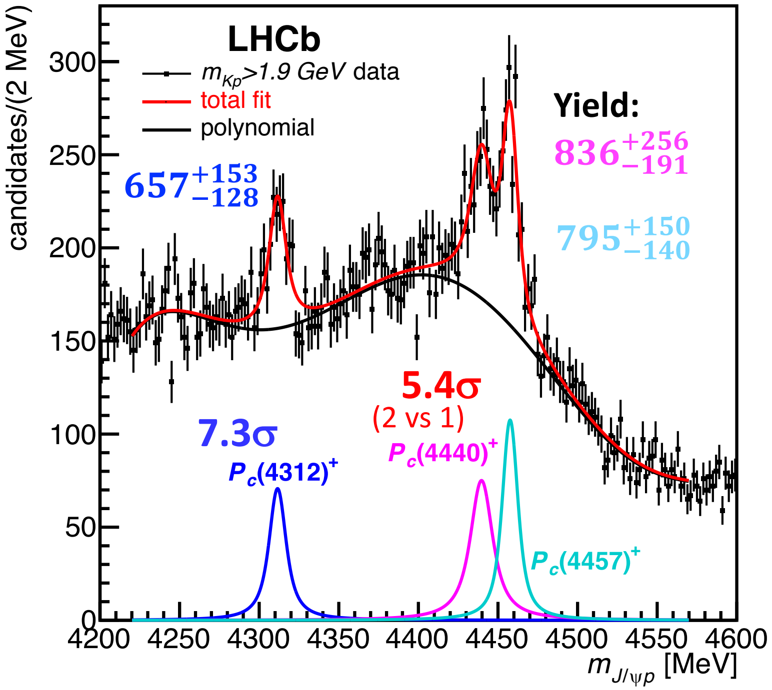


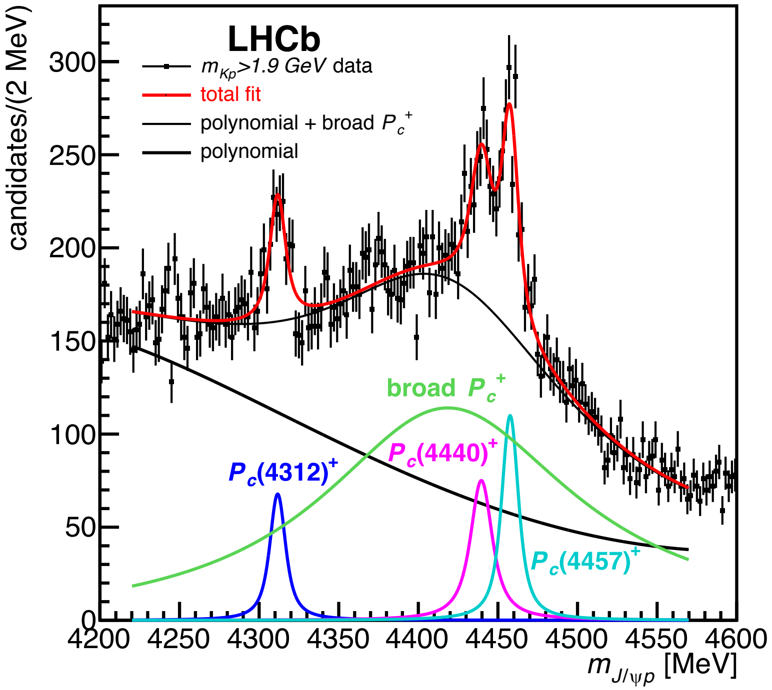
Fit-2: P_c^+ dominated region

PRL 122 (2019) 222001

- Fit $m_{Kp} > 1.9$ GeV events, ~80% Λ^* bkg removed
- Significances: $P_c(4312)^+$, **7.3σ**;
  2 peaks over 1 around 4450 MeV, **5.4σ**
  - Evaluated with toy simulations from 6D amplitude model
  - Have taken account of look elsewhere effect



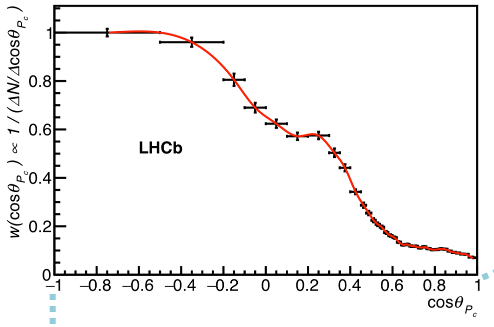


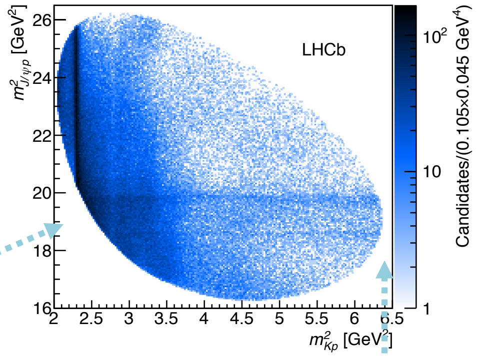


Fit-3: Novel method

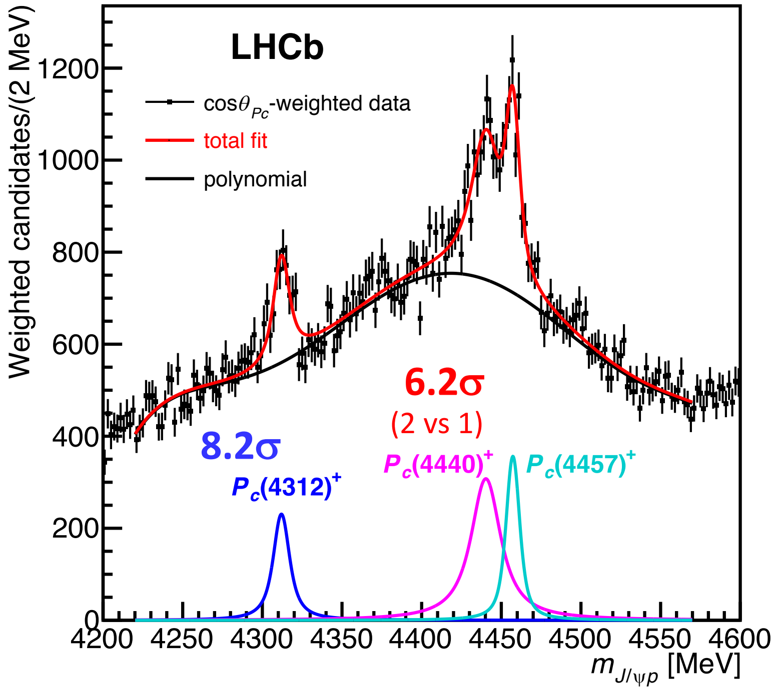
PRL 122 (2019) 222001

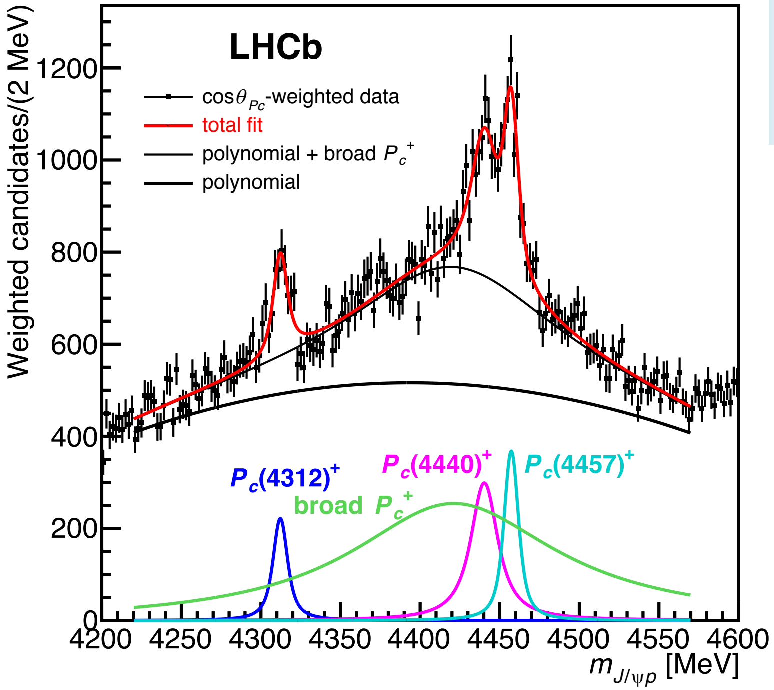
- Candidates weighted by $w(\cos\theta_{P_c}) = \frac{1}{\sigma^2_{\text{stat.}}} \approx \frac{1}{S+B}$
  - w is inverse of $\cos\theta_{P_c}$ distribution of Λ_b^0 candidates with $m_{J/\psi p} \in [4.2, 4.6]$ GeV
- Most statistically sensitive method





Nominal fit for M&Γ measurements





θ_{P_c} is P_c helicity angle, correlated with m_{Kp}

Results

PRL 122 (2019) 222001

- Masses and widths are shown
- Relative P_c^+ production rates are determined

$$\mathcal{R} = \frac{\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}$$

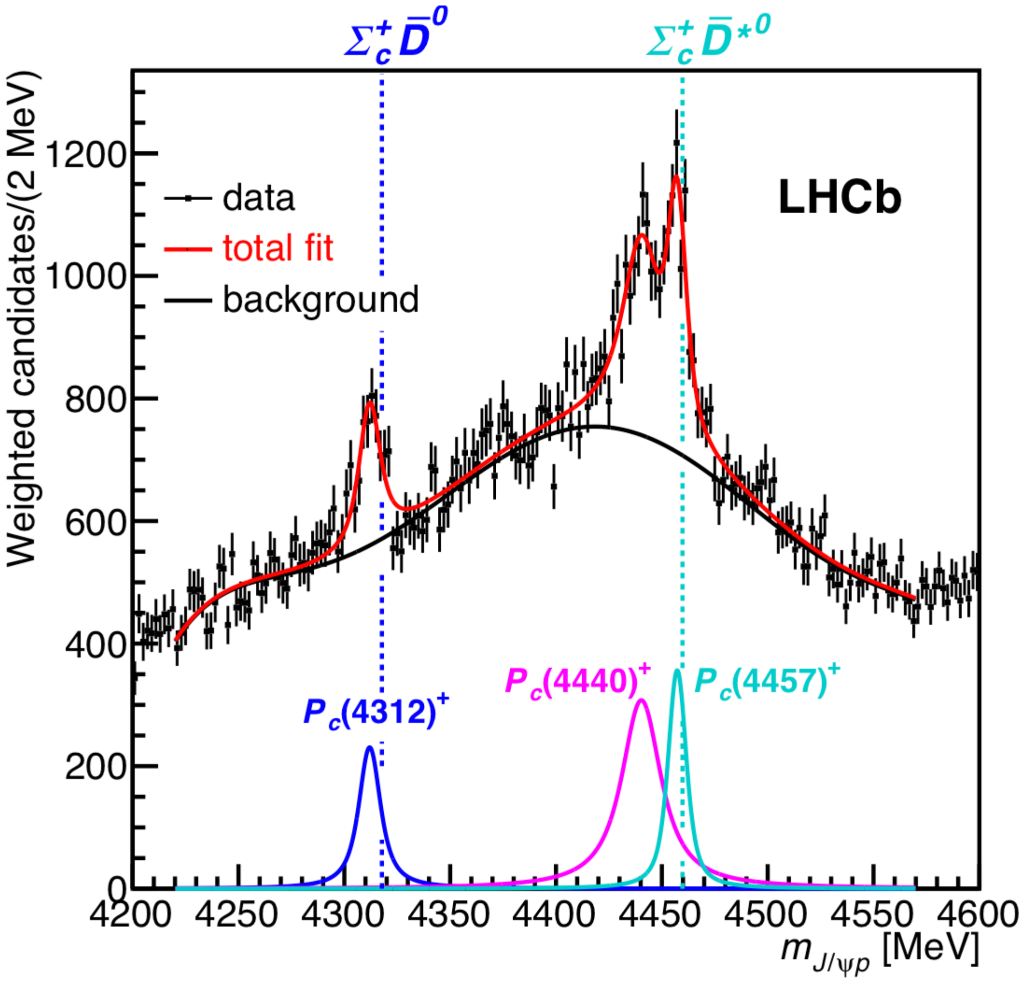
  - Fit inclusive $m_{J/\psi p}$ with efficiency correction
- The fit is not sensitive to broad peaks, like $P_c(4380)^+$

State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

Plausible interpretation

PRL 122 (2019) 222001

- The near-threshold masses of $P_c(4312)^+$, $P(4440)^+$, $P_c(4457)^+$ **favour** "molecular" pentaquarks with meson-baryon substructure, but **other hypotheses are not ruled out**
- The 1D fit provides limited information. More work needed
  - J^P measures and information of $P_c(4380)^+$ require amplitude analysis
  - To find isospin partners, and other decay modes
- **Regardless of the binding mechanism, the new pentaquarks suggest the existence of a whole new family of such particles**

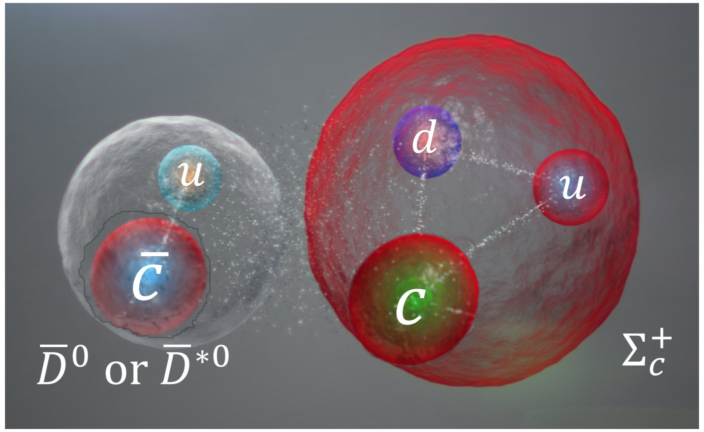


Predictions with molecular picture

- Several theoretical predictions for $\Sigma_c^+\bar{D}^{(*)0}$ bound states before 2015
- **Some are in good agreement with the LHCb data**
  - Wu,Molina,Oset,Zou, PRL105 (2010) 232001
  - **Wang,Huang,Zhang,Zou, PR C84 (2011) 015203**
  - **Yang,Sun,He,Liu,Zhu, Chin. Phys. C36 (2012) 6**
  - **Wu,Lee,Zou, PR C85 (2012) 044002**
  - Karliner,Rosner, PRL 115 (2015) 122001
- J^P and more states at $\Sigma_c^*\bar{D}^{(*)}$ thresholds are predicted

M. Z. Liu *et al.*, PRL 122 (2019) 242001

Scenario	Molecule	J^P	B (MeV)	M (MeV)
B	$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	7.8 – 9.0	4311.8 – 4313.0
B	$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	8.3 – 9.2	4376.1 – 4377.0
B	$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	Input	4440.3
B	$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	Input	4457.3
B	$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$	25.7 – 26.5	4500.2 – 4501.0
B	$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}^-$	15.9 – 16.1	4510.6 – 4510.8
B	$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	3.2 – 3.5	4523.3 – 4523.6



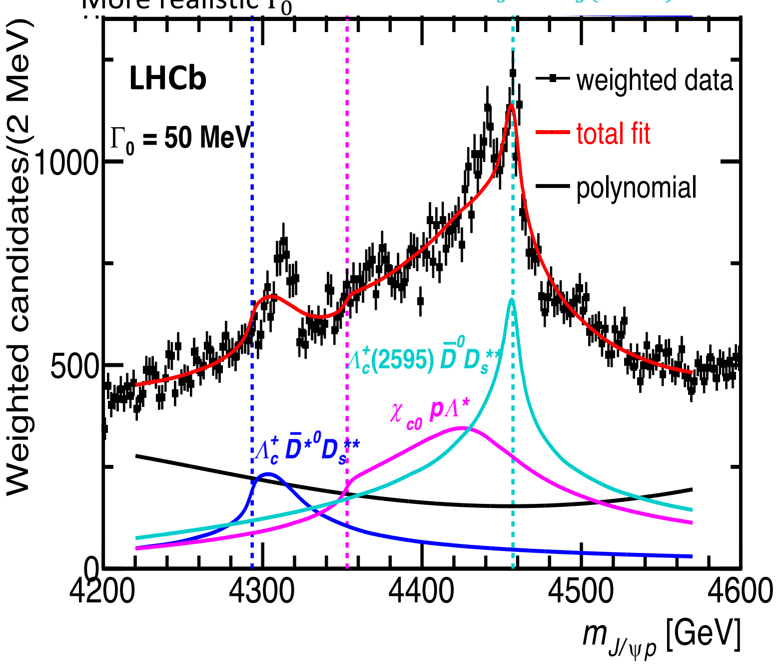
Triangle diagrams?

PRL 122 (2019) 222001

- Can produce peaking structure at or above mass threshold, but not below
- Cannot rule out $P_c(4457)^+$ as a triangle effect

$P_c(4312)^+$, $P_c(4440)^+$ are too far from any rescattering thresholds

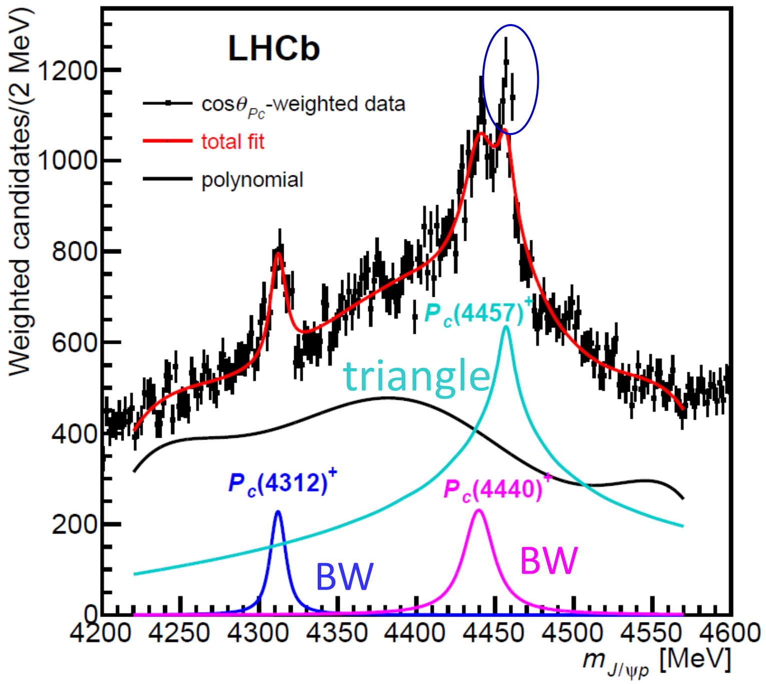
3 triangle-diagram amplitudes + polynomial

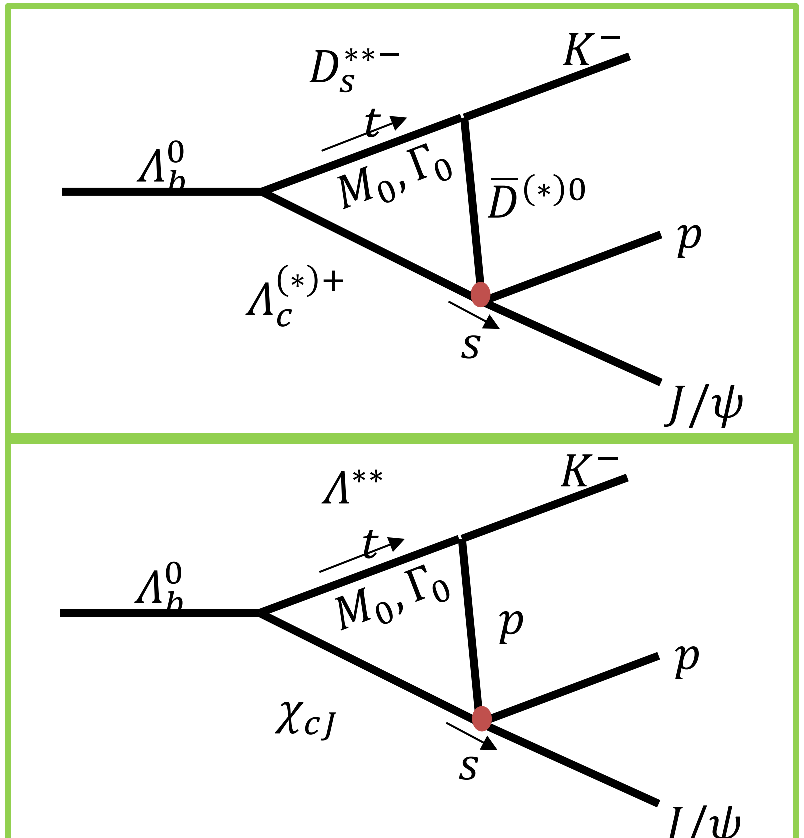


$P_c(4457)^+$ is right at the $\Lambda_c(2595)^+\bar{D}^0$ threshold

2BW + 1 triangle-diagram amplitudes + polynomial

$\Gamma_0 = 159$ MeV [PDG]

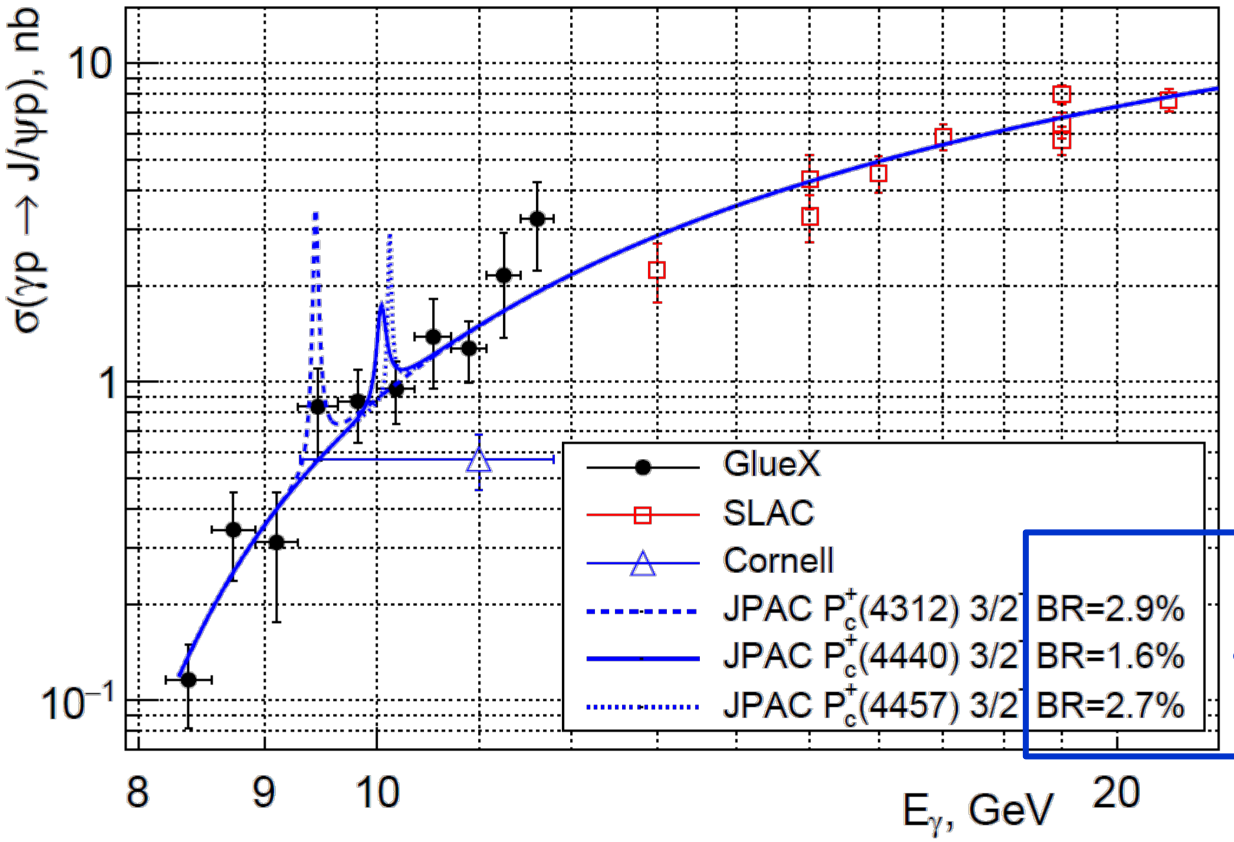




Guo *et al*, PRD 92 (2015) 071502 and others

Very recent GlueX results

"First measurement of near-threshold J/ψ exclusive photoproduction off the proton"
GlueX Collaboration, **May 26, 2019**, arXiv:1905.10811 [nucl-ex]



"GlueX Physics" on 18/8 (Sun.) at S1 by M. SHEPHERD

Model-dependent upper limits at 90% C.L. from JPAC model [PRD 94 (2016) 034002]

A less model-dependent limit at 90% C.L.:

$\sigma_{\max}(\gamma p \to P_c^+)\times\mathcal{B}(P_c^+ \to J/\psi p) < 4.6, 1.8, 3.9$ nb for $P_c(4312)^+, P_c(4440)^+, P_c(4457)^+$, respectively.

→ at the resonance maximum

Summary

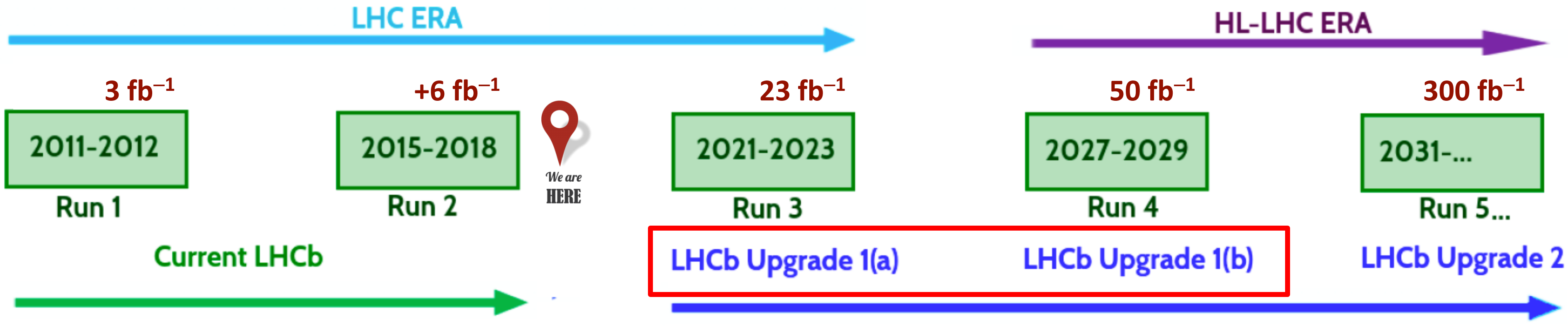
$$m(\Xi_{cc}^{++}) = 3621.24 \pm 0.65 \pm 0.31\ \text{MeV}$$

$$\tau_{\Xi_{cc}^{++}} = 256_{-22}^{+24} \pm 14\ \text{fs}$$

- Ξ_{cc}^{++} has been firmly established by LHCb
  - Observed by two decay modes
  - Properties are first measured
- Searches for the other doubly-heavy baryons are underway at LHCb

- Recent pentaquark result at LHCb is presented
  - An order of magnitude increases in signal yield is achieved with respect to 2015 result
  - $P_c(4450)^+$ peak structure is an overlap of two narrower states, $P_c(4440)^+$ and $P_c(4457)^+$.
  - A new narrow state $P_c(4312)^+$ is also observed
  - The mass thresholds play an important role in the dynamics of these states
  - The analysis is not sensitive to broad P_c^+, so confirmation of the broad P_c^+ seen before will need detailed amplitude analysis
  - To further decipher their nature, the J^P measurement will be essential

LHCb Upgrade I

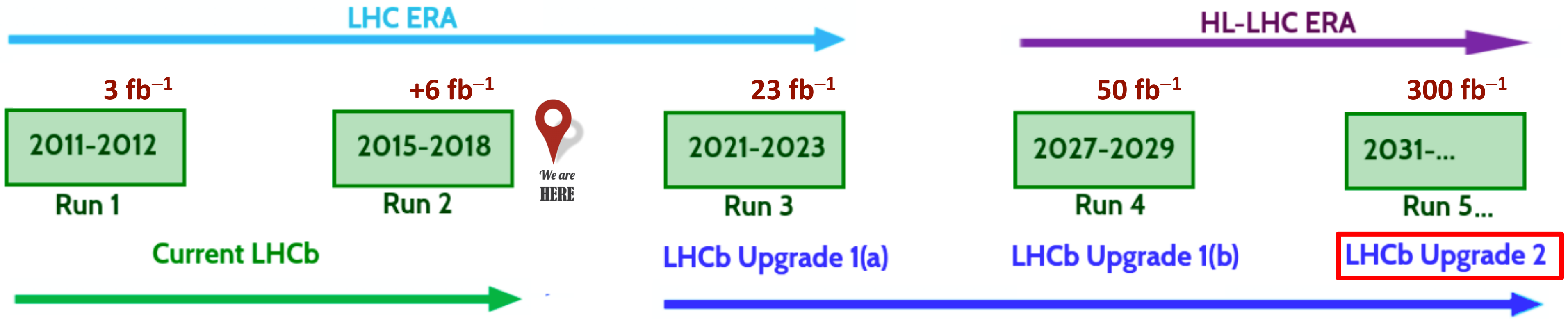


CERN-LHCC-2011-001

Upgrade I: installation ongoing

- Almost a new detector for factor 5 luminosity increase
- Remove the hardware trigger → all detector read out at 40 MHz
- Expect to have data of **23 fb^{-1}** by 2023 and of **50 fb^{-1}** by 2029

LHCb Upgrade II



Upgrade II: started to investigate

- Aim to collect > **300 fb^{-1}**
- Instantaneous $\mathcal{L} = 2 \times 10^{34}$, x10 with respect to Upgrade I
- Expression of Interest issued in 2017 [CERN-LHCC-2017-003]
- Physics case document released [CERN-LHCC-2018-027]
- Green light from LHCC to proceed to TDRs (expected ~late 2020)

Expected yields in future

- LHCb is now boosting the data to a new level
  - Expect to **7x** more data (**14x** more hadronic events) by 2029 than current data
  - Could have another factor of **6** increase from Upgrade II

CERN-LHCC-2018-027
arXiv:1808.08865

Decay mode	LHCb $23\,\mathrm{fb}^{-1}$	LHCb $50\,\mathrm{fb}^{-1}$	LHCb $300\,\mathrm{fb}^{-1}$
$B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$	14k	30k	180k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100
$\Lambda_b^0 \to J/\psi\, pK^-$ [*]	680k	1.4M	8M
$\Xi_b^- \to J/\psi\, \Lambda K^-$	4k	10k	55k
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$	7k	15k	90k
$\Xi_{bc}^+ \to J/\psi\, \Xi_c^+$	50	100	600

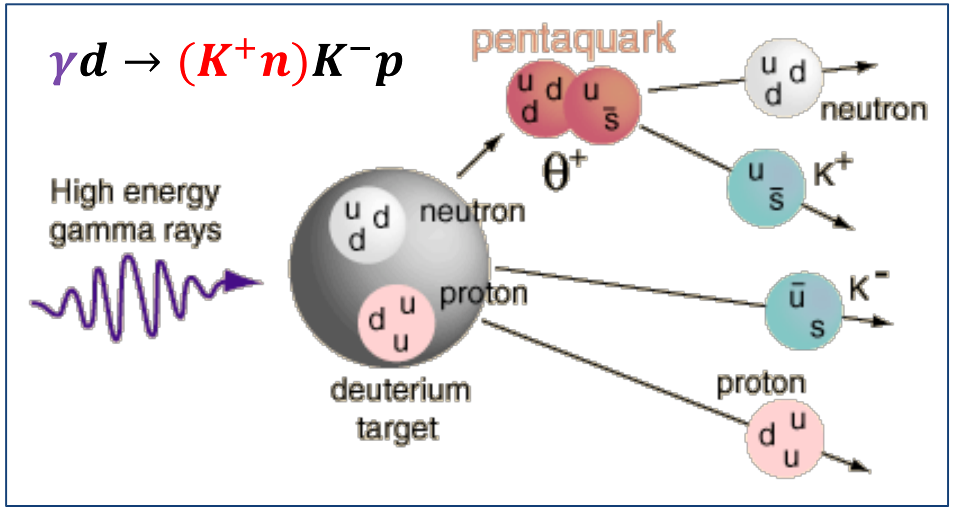
[*] updated according to the latest result

BES3, Belle2, JLab, PANDA, EIC… also contribute important knoweledge to hadron spectroscopy

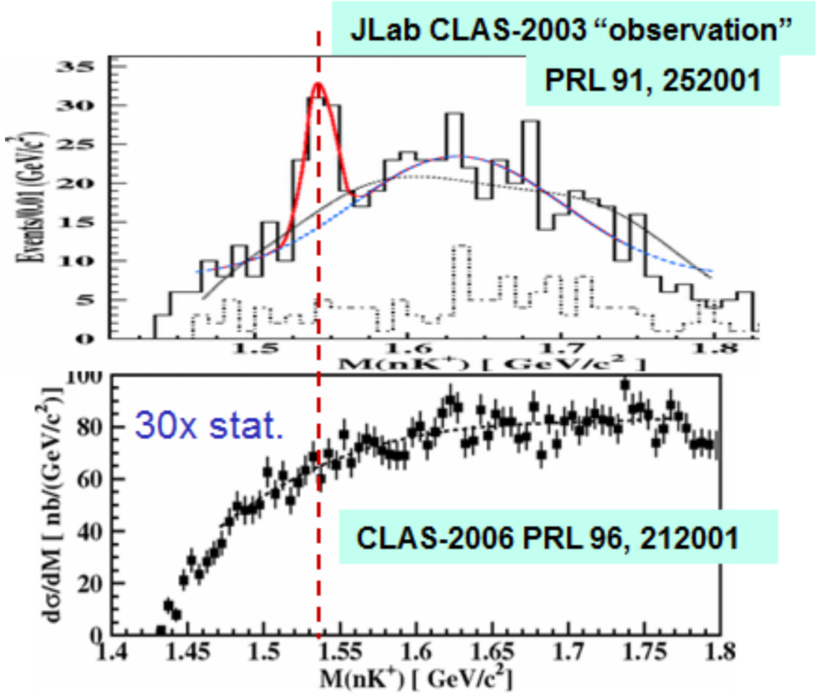
Backup

Past claimed pentaquark

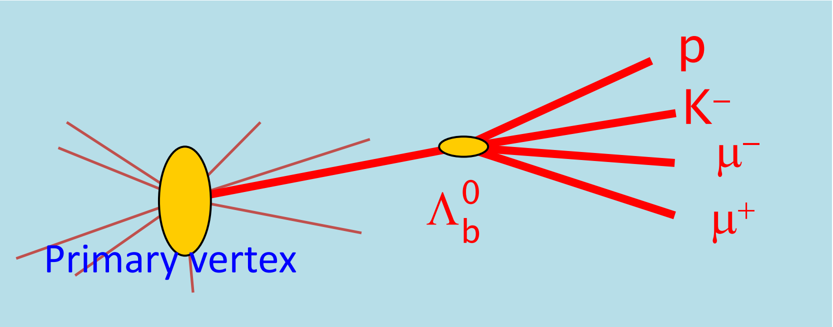
- Search for pentaquark states has been performed by many experiments in the last 50 years
- Early searches are summarized by K. H. Hicks [Eur. Phys. J. H37 (2012) 1]
  - **Example: Θ^+ $[uudd\bar{s}]$ reported by many experiments in early 2000s was concluded to be just a fluctuation**



$\gamma d \to p K^- K^+ n$



Improved selection



- Selection uses the feature of B-hadron decays
  - High p_T
  - Detached from primary vertex
  - Hadron ID information

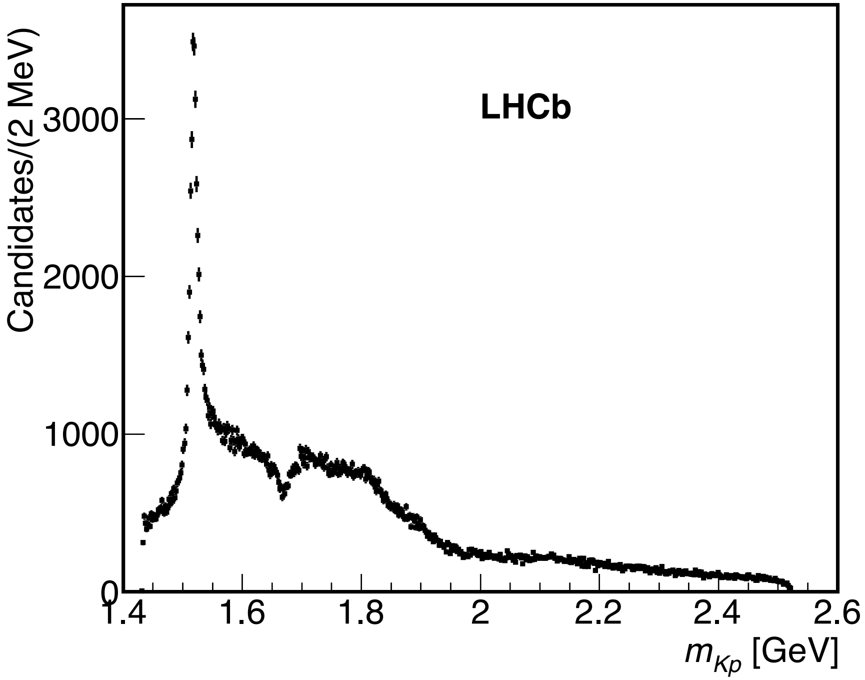
- Selection improved with better uses of hadron ID
  - Hadron ID requirements are put into a multivariate (MVA) based selection. A much powerful MVA is achieved.
  - Use hadron ID to help vetoing $B^0 \to J/\psi K^- \pi^+$, $B_s^0 \to J/\psi K^+ K^-$ and other mis-ID backgrounds.

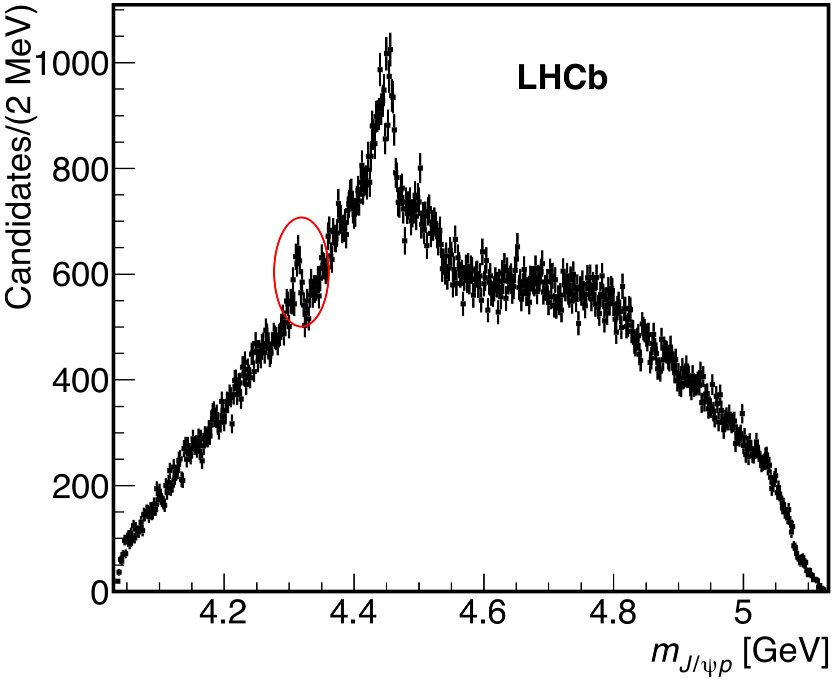
- Efficiency is doubled while maintaining similar background fraction, compared to the previous publication

Display in smaller bin size

- More narrow structures emerge, shown in a 2 MeV (≈ mass resolution) bin size

PRL 122, 222001 (2019)

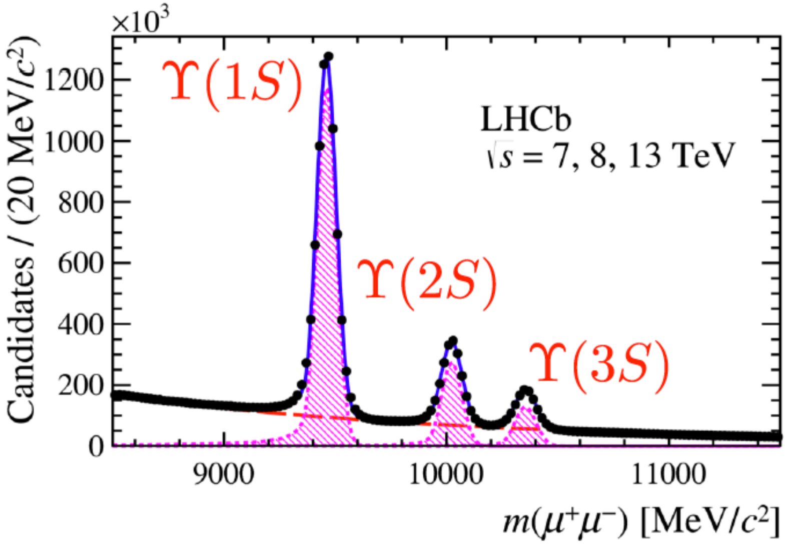


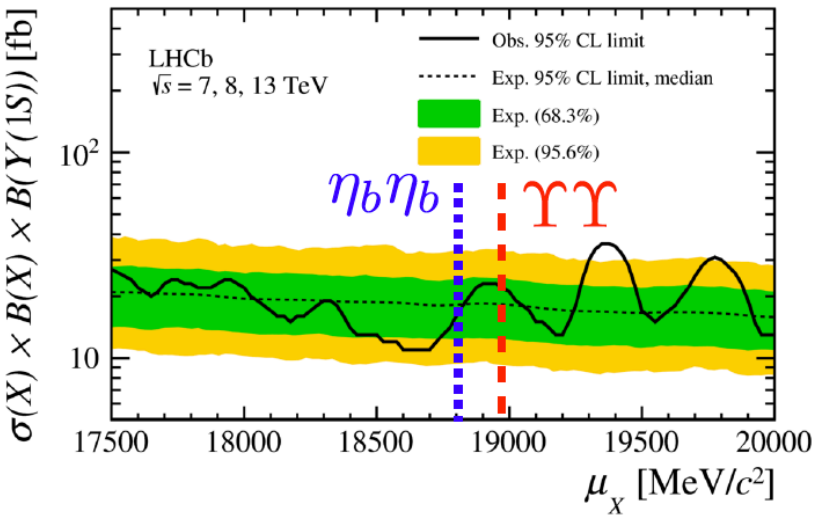


Search for $X_{bb\bar{b}\bar{b}} \to \Upsilon(1S)\mu^+\mu^-$

JHEP 10 (2018) 086

- Binding of double-heavy $b\bar{b}$ pairs quite different to $c\bar{c}$+light meson cloud
- Ground state bound $b\bar{b}b\bar{b}$ tetraquark $\sim 18-19$ GeV in many phenomenological models.
- Typically below $\eta_b\eta_b$ threshold. Can decay to $\Upsilon(1S)\mu^+\mu^-$
- No hint of a structure in LHCb search with 2011-2016 data. Upper limits placed.





Prospects

Analyses to update

- $\Lambda_b^0 \to J/\psi p K^-$ amplitude analysis
  - J^P and $P_c(4380)^+$?
- $\Lambda_b^0 \to J/\psi p \pi^-$ amplitude analysis
  - To study the production of observed P_c^+
  - Find evidence of exotic hadron contribution in Run-1 data [PRL 117 (2016) 082003]

More interesting ideas

- Decay modes to other charmonium states than J/ψ?
- Hidden-charmonium pentaquarks with strangeness?
- Open charm baryon meson final state, eg. $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-$?

Observation of $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$

- Search for $P_c(4450)^+$ in $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$ decays
  $\Rightarrow$Test hypothesis of kinematic rescattering effect

PRD 92 (2015) 071502

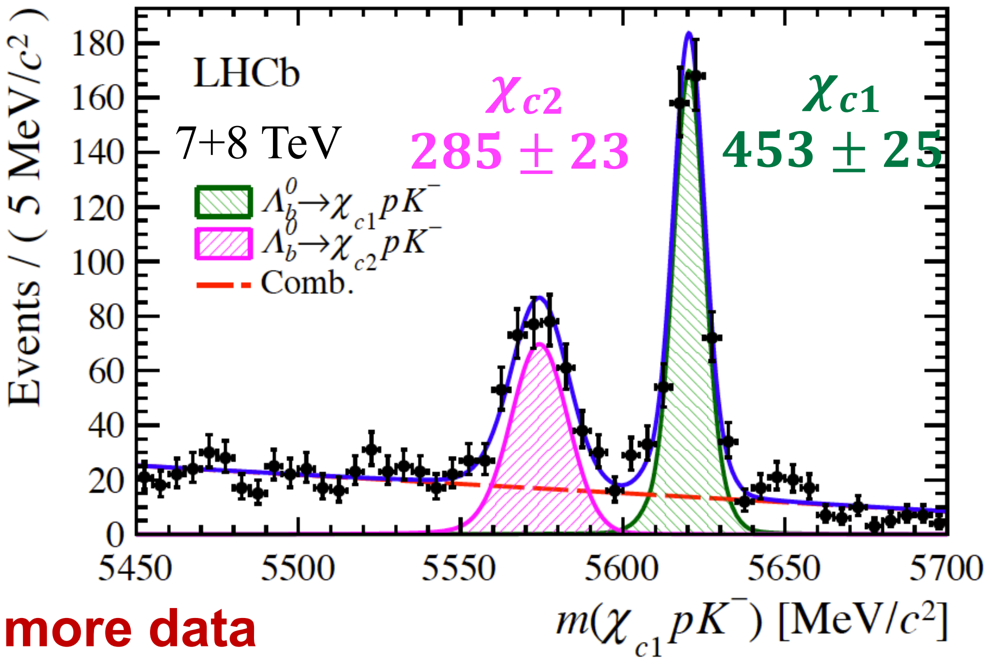
- First step: observe the decays, measure $\mathcal{B}$
- Use $\chi_{c(1,2)} \to J/\psi\gamma$, constrain $J/\psi\gamma$ mass to known χ_{c1} mass

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.248 \pm 0.020 \pm 0.014 \pm 0.009$$

$\mathcal{B}(\chi_{cJ})$

PRL 119 (2017) 062001

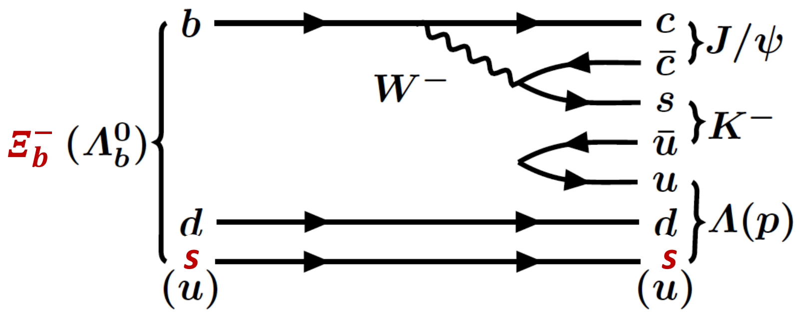


Next step: full amplitude analysis with more data

Observation of $\Xi_b^- \to J/\psi \Lambda K^-$

PLB 772 (2017) 265-273

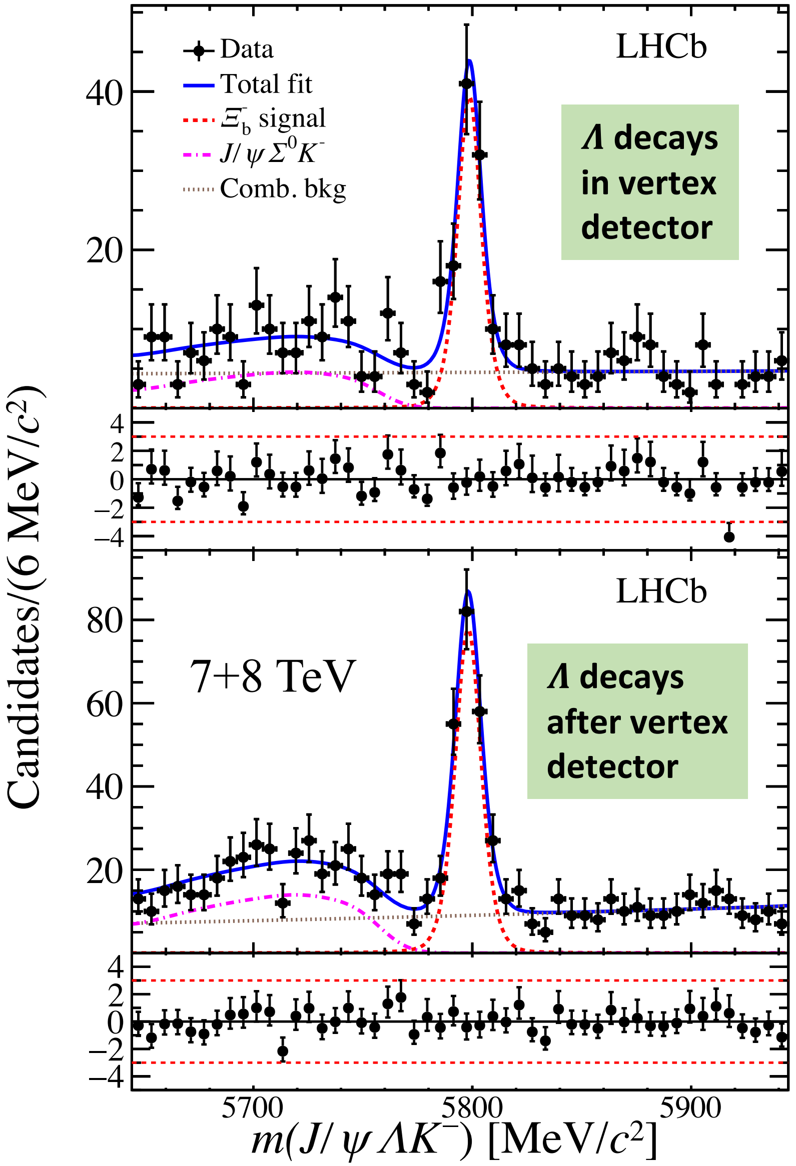
- Strange pentaquark ($udsc\bar{c}$) predicted in [PRL 105 (2010) 232001]
- Can be searched for in the Ξ_b^- decay [PRC 93 (2016) 065203]



$N_{sig} = 308 \pm 21$ (21σ)

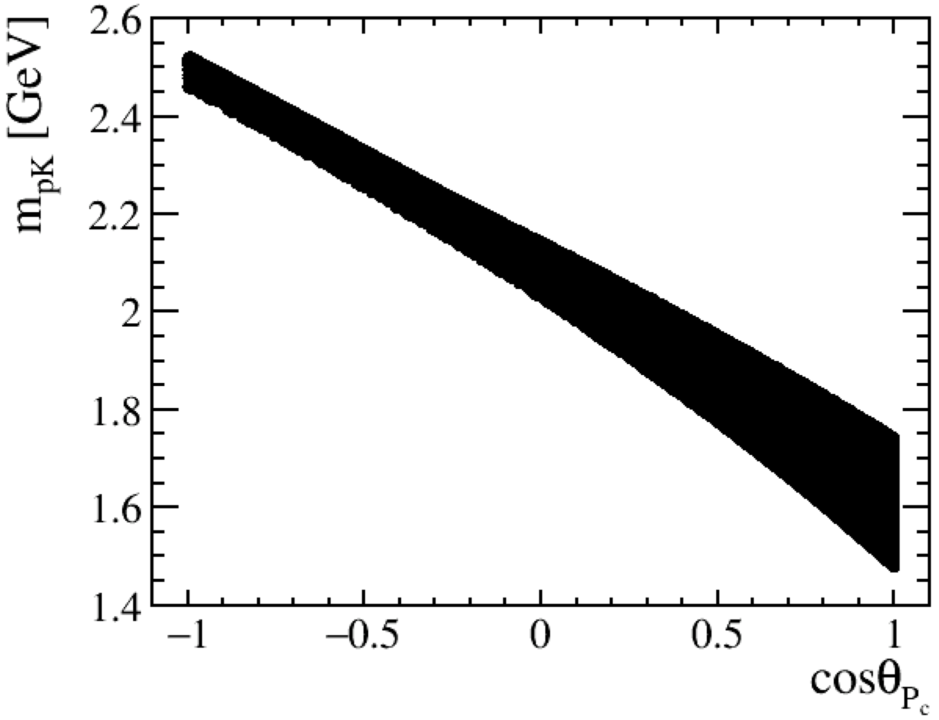
$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{\mathcal{B}(\Xi_b^- \to J/\psi \Lambda K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi \Lambda)} = (4.19 \pm 0.29 \pm 0.15) \times 10^{-2}$$

Expect ~1500 signals after 2018 for amplitude analysis



Correlation of $cos\theta_{P_c}$ and m_{pK}

- For events with $m_{J/\psi p} \in [4.2, 4.6]$ GeV



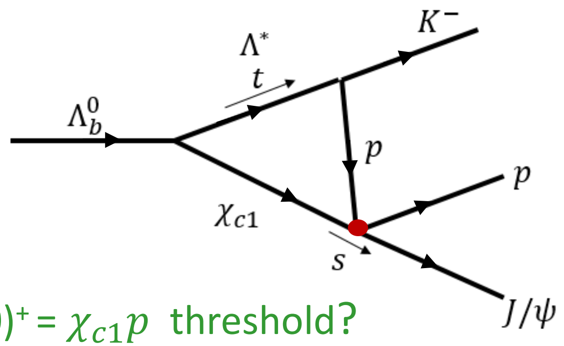
Systematic uncertainty

- The largest ones are due to interference effect

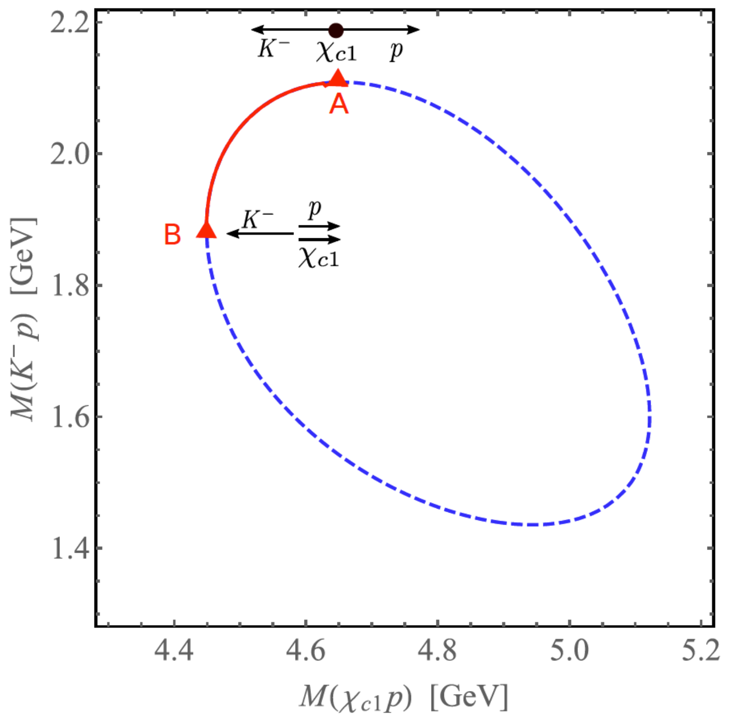
	$P_c(4312)^+$		$P_c(4400)^+$		$P_c(4457)^+$	
	M MeV	Γ MeV	M MeV	Γ MeV	M MeV	Γ MeV
value ± statistical error	4311.9 ± 0.7	9.8 ± 2.7	4440.3 ± 1.3	20.6 ± 4.9	4457.3 ± 0.6	6.4 ± 2.0
bkg.subtr. & cut variation	$^{+0.8}_{-0.6}$	$^{+3.7}_{-4.5}$	$^{+0.1}_{-1.1}$	$^{+4.6}_{-8.2}$	$^{+0.4}_{-1.7}$	$^{+3.6}_{-0.9}$
including interferences	$^{+6.8}_{-0.6}$	$^{+3.7}_{-4.5}$	$^{+4.1}_{-4.7}$	$^{+\ 8.7}_{-10.1}$	$^{+4.1}_{-1.7}$	$^{+5.7}_{-1.9}$
mass resolution	< 0.1	$^{+0.3}_{-0.5}$	$^{+0.1}_{-0.0}$	± 0.2	$^{+0.0}_{-0.1}$	$^{+0.7}_{-0.8}$
mass scale	< 0.2	—	< 0.2	—	< 0.2	—
Blatt-Weisskopf factors	< 0.1	$^{+0.0}_{-0.1}$	< 0.1	< 0.1	< 0.1	< 0.1
efficiency in fit function	< 0.1	$^{+0.0}_{-0.1}$	< 0.1	$^{+0.0}_{-0.2}$	< 0.1	< 0.1

Triangle diagram

Guo *et al*, PRD 92 (2015) 071502



$P_c(4450)^+ = \chi_{c1}p$ threshold?



Requirements:

- All the intermediate states are on shell
- The proton emitted from the decay of the Λ^* moves along the same direction as the χ_{c1} and can catch up with it to rescatter
- Can only happen on the red line of the Dalitz-plot boundary

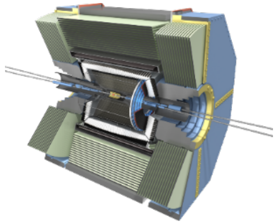
Future

2018 2020 2025 2030 2035

$50\ ab^{-1}$

Belle II

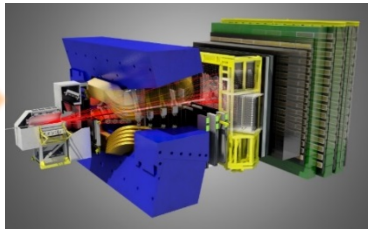
$\approx 55\times10^{9}\ B\bar{B}$ pairs



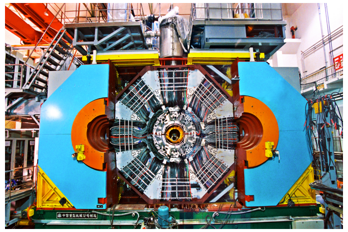
$9\ fb^{-1}$ $\sim23\ fb^{-1}$ $\sim50\ fb^{-1}$ $300\ fb^{-1}$

LHCb → **LHCb Upgrade 1** → Phase I → **Phase 1b Upgrade** → Phase 1b → **Phase 2 Upgrade** → Phase 2 (proposed)

$\approx 3\times10^{12}\ b\bar{b}$ pairs



BES III

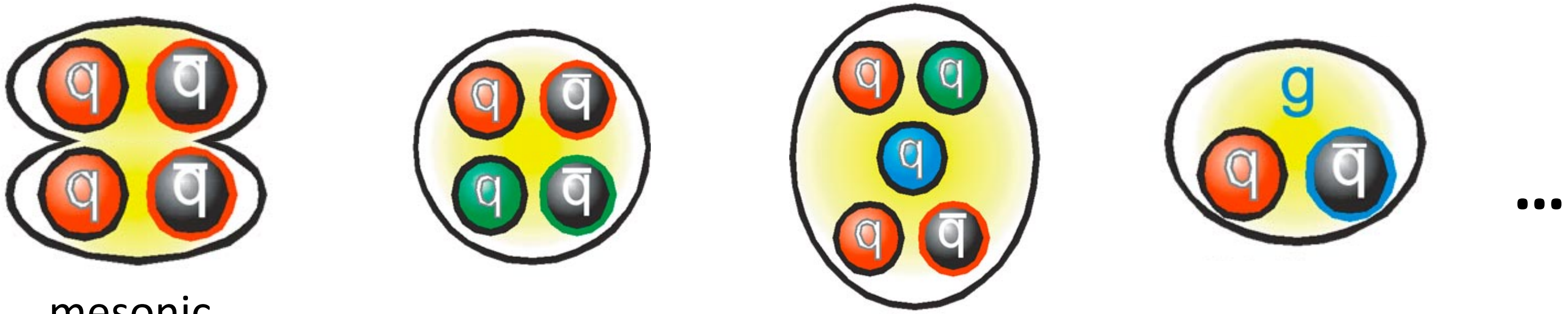


Continue to run for 8-10 years

Increase E_{cm} => 4.9 GeV

Introduction

- QCD describing strong interaction between quarks and gluons is not well understood due to its non-perturbative nature at low energy scale
- Hadron spectroscopy provides opportunities to test QCD and its effective models
  - e.g. lattice QCD, diquark model, potential model …
- Exotic hadrons provide unique probe to QCD
  - Predicted in quark model
  - Recent results show strong evidence for their existence



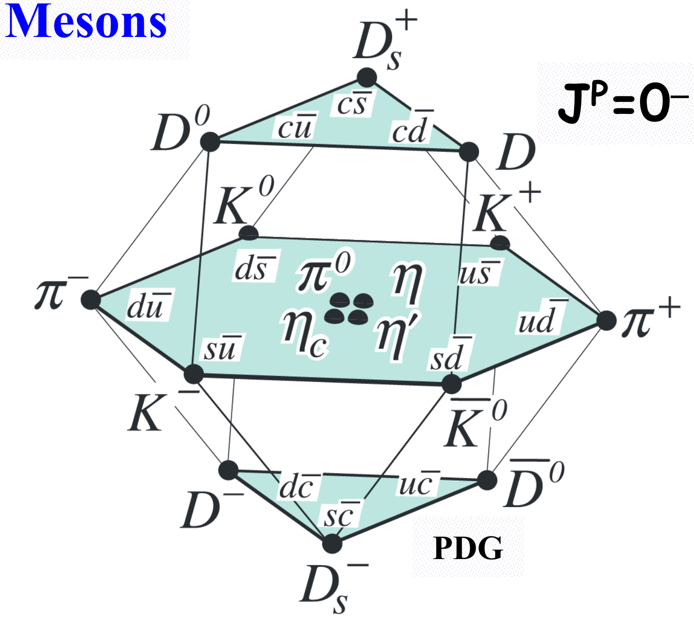
mesonic molecule ?　tetraquark ?　pentaquark ?　hybrid ?

Quark model (QM)

- Extended to SU(4) and SU(5) to include new quarks : charm (c), bottom (b)

Mesons

$J^P=0^-$

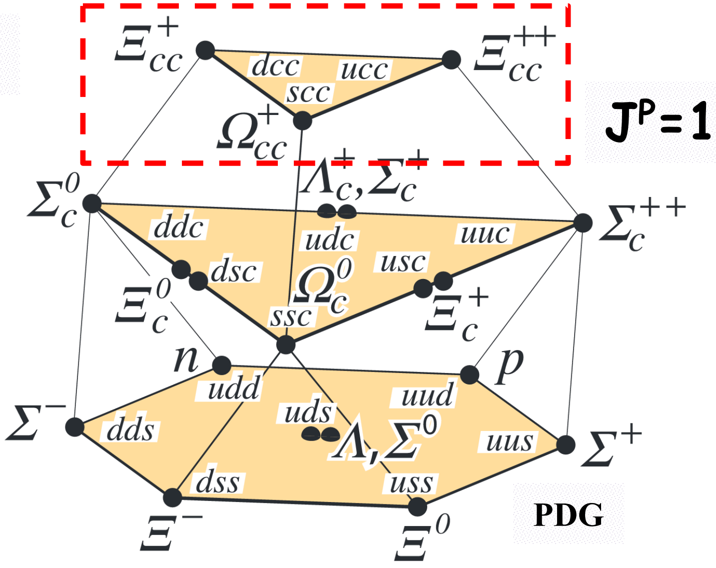


SU(4) for $u\ d\ s\ c$

Remain to discover/confirm

Baryons

$J^P=1/2^+$



SU(4) for $u\ d\ s\ c$

- ☐ **16 mesons of SU(4) were all discovered**
- ☐ **Double-charmed baryons remain to discover/confirm**

Why pentaquarks?

- Interest in pentaquarks arises from the fact that they would be new type of particles beyond the the simplest quark combination. Could teach us a lot about strong force and QCD.

- There is no reason they should not exist
  - Predicted by Gell-Mann (64), Zweig (64), others later in context of specific QCD models: Jaffe (76), Högaasen & Sorba (78), Strottman (79)

- Name of “pentaquark” is coined by Lipkin (87), who proposed existence of a $D_s^- p$ bound state