Recent results from LHCb on Pentaquark search

Liming Zhang (Tsinghua University)

The 11th Workshop on Hadron Physics in China and Opportunities Worldwide

Nankai University

24 August, 2019

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.

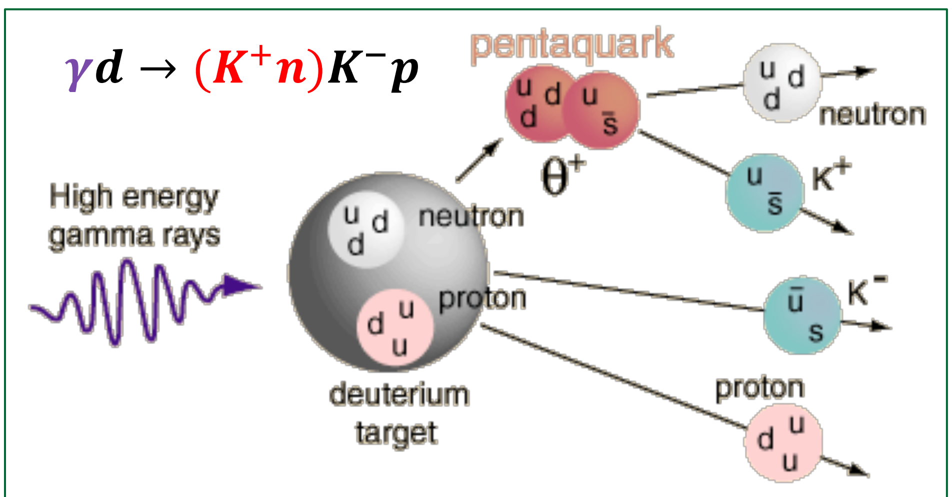
- There is no reason they should not exist
  - Predicted by Gell-Mann (64), Zweig (64), others later in context of specific QCD models: Jaffe (76), Högaasen & Sorba (78), Strottman (79)

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

Past claimed pentaquark

- Search for pentaquark states has been performed by many experiments in the last 50 years

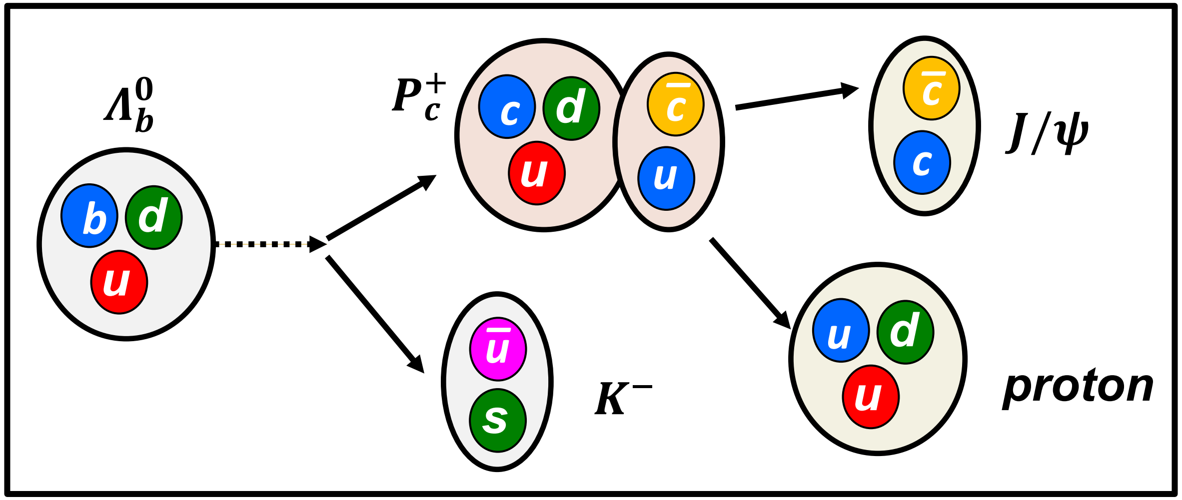
- Early searches are summarized by K. H. Hicks [Eur. Phys. J. H37 (2012) 1]
  - **Example: Θ^+ $[uudd\bar{s}]$ reported by many experiments in early 2000s was concluded to be just a fluctuation**



Past claimed pentaquark

- Search for pentaquark states has been performed by many experiments in the last 50 years
- Only LHCb has given a convincing result in 2015
  - **Two $J/\psi p$ resonances, consistent with pentaquarks, are found in $\Lambda_b^0 \to J/\psi p K^-$ decays**

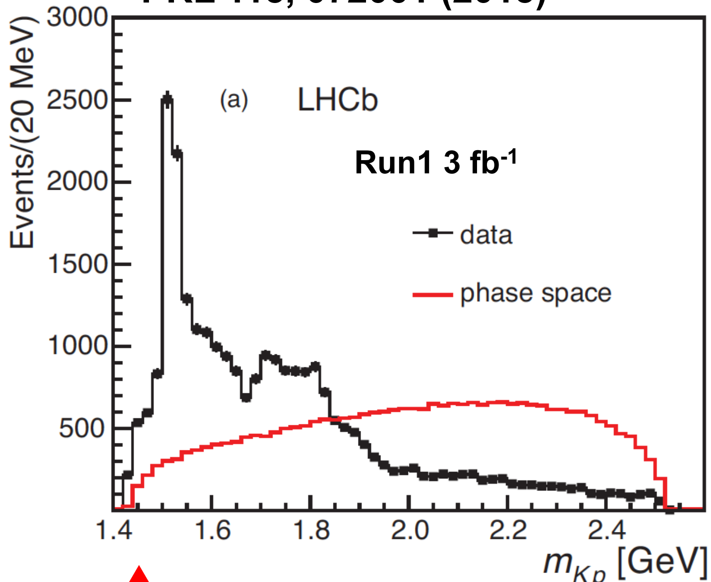
PRL 115, 072001 (2015)

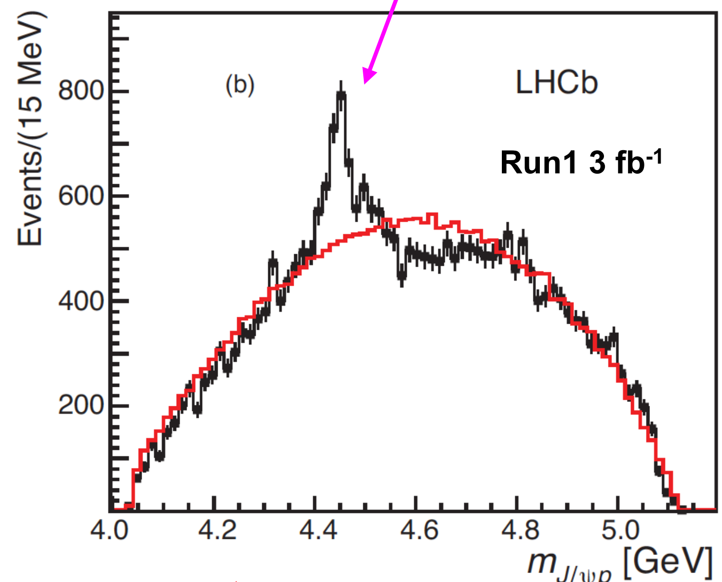


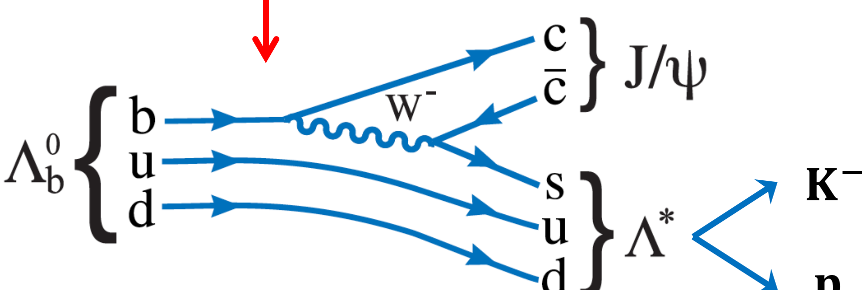
$\Lambda_b^0 \to J/\psi p K^-$ decays

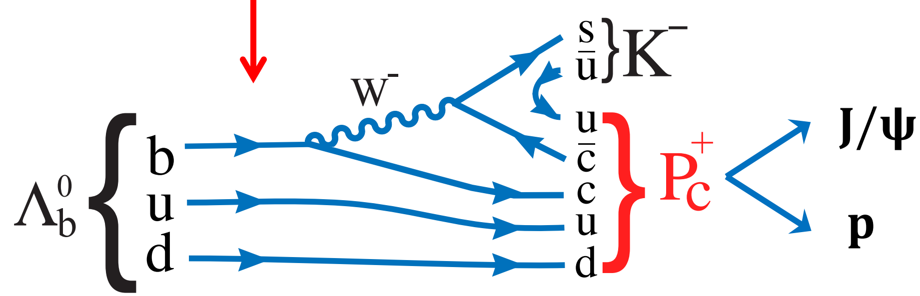
LHCb first observed the Λ_b^0 decay in 2013, and found an **unexpected** structure

PRL 115, 072001 (2015)





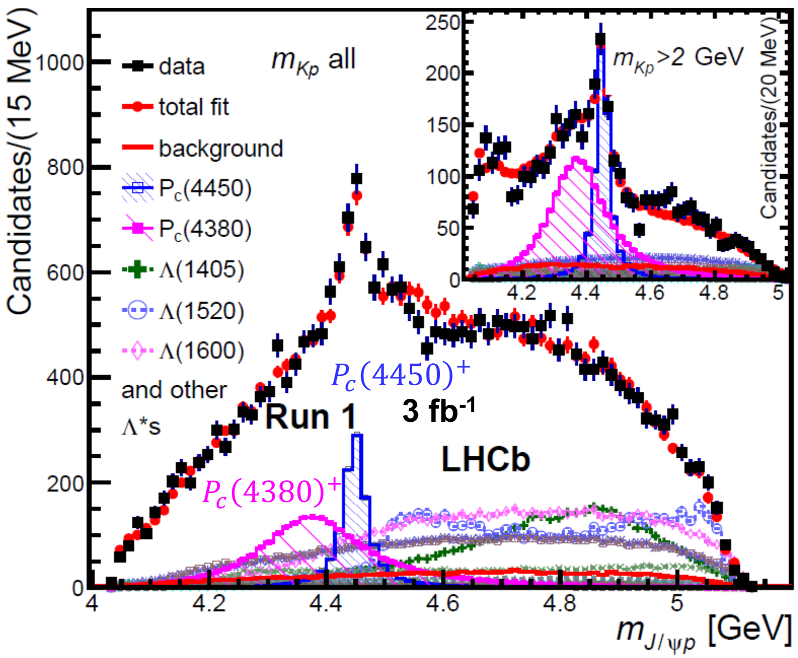




Liming Zhang

LHCb result 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 $uud c\bar{c}$



PRL 115, 072001 (2015)

$P_c(4450)^+$ $M = 4450 \pm 2 \pm 3$ 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
$F.F. = 8.4 \pm 0.7 \pm 4.2$ %

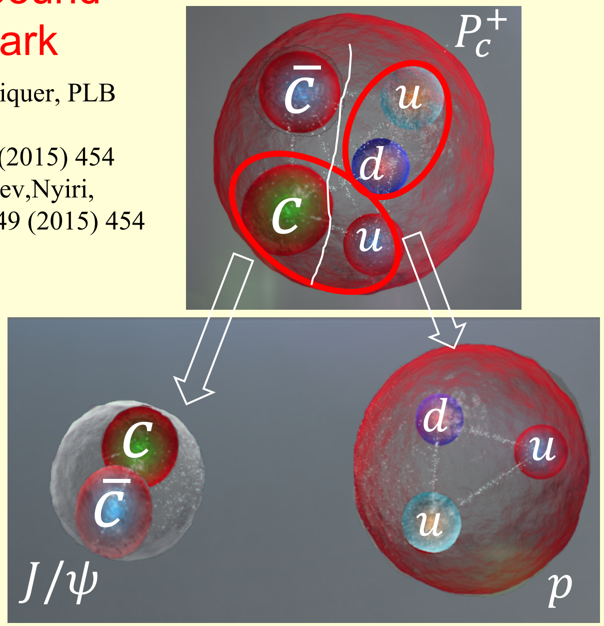
Liming Zhang

Interpretations

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

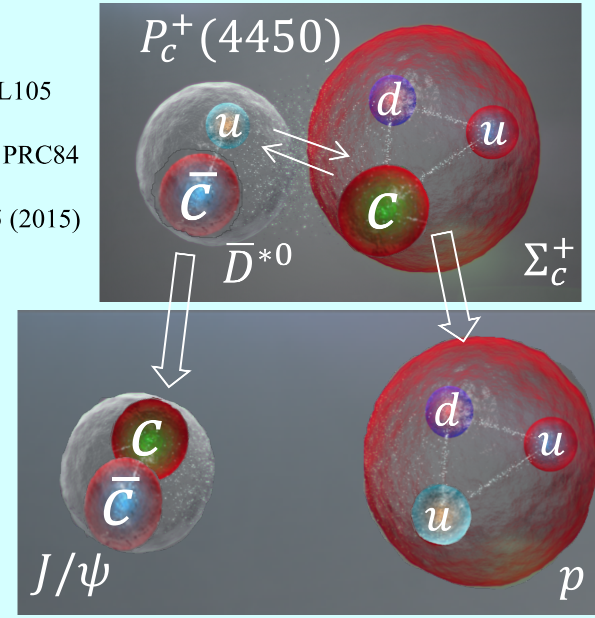
Tightly-bound pentaquark

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

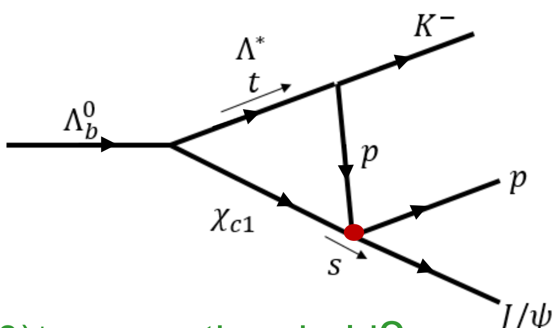


Loosely-bound pentaquark

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



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



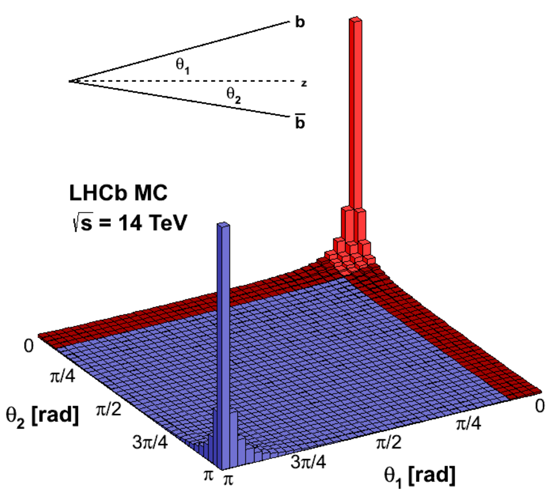
$P_c(4450)^+ = \chi_{c1}p$ threshold?

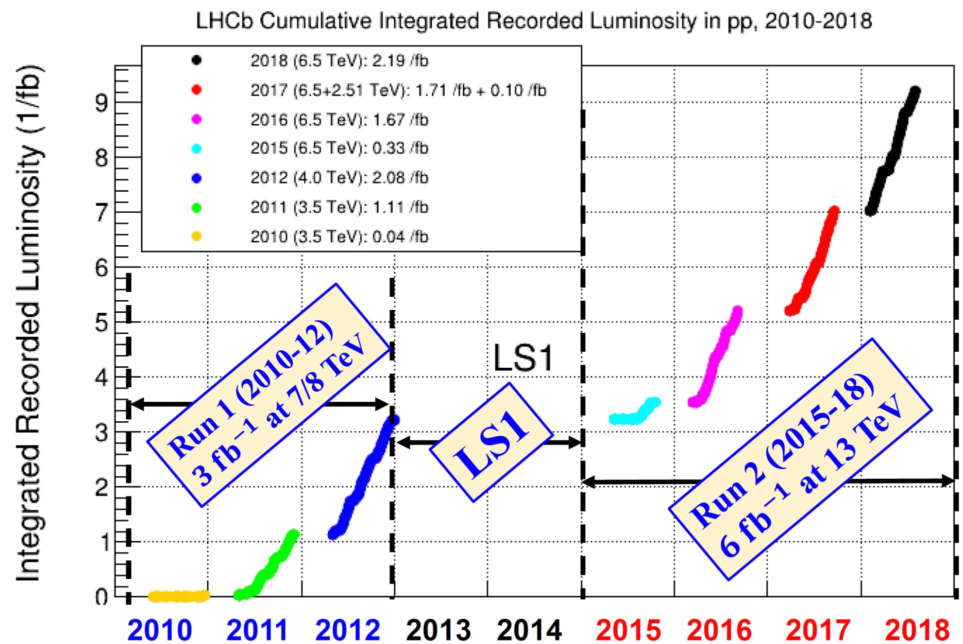
Triangle diagram

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

The LHCb Experiment

- LHCb is a dedicated flavour physics experiment at the LHC
  - $>10^4 \times$ larger b production rate than the B factories @ Υ(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

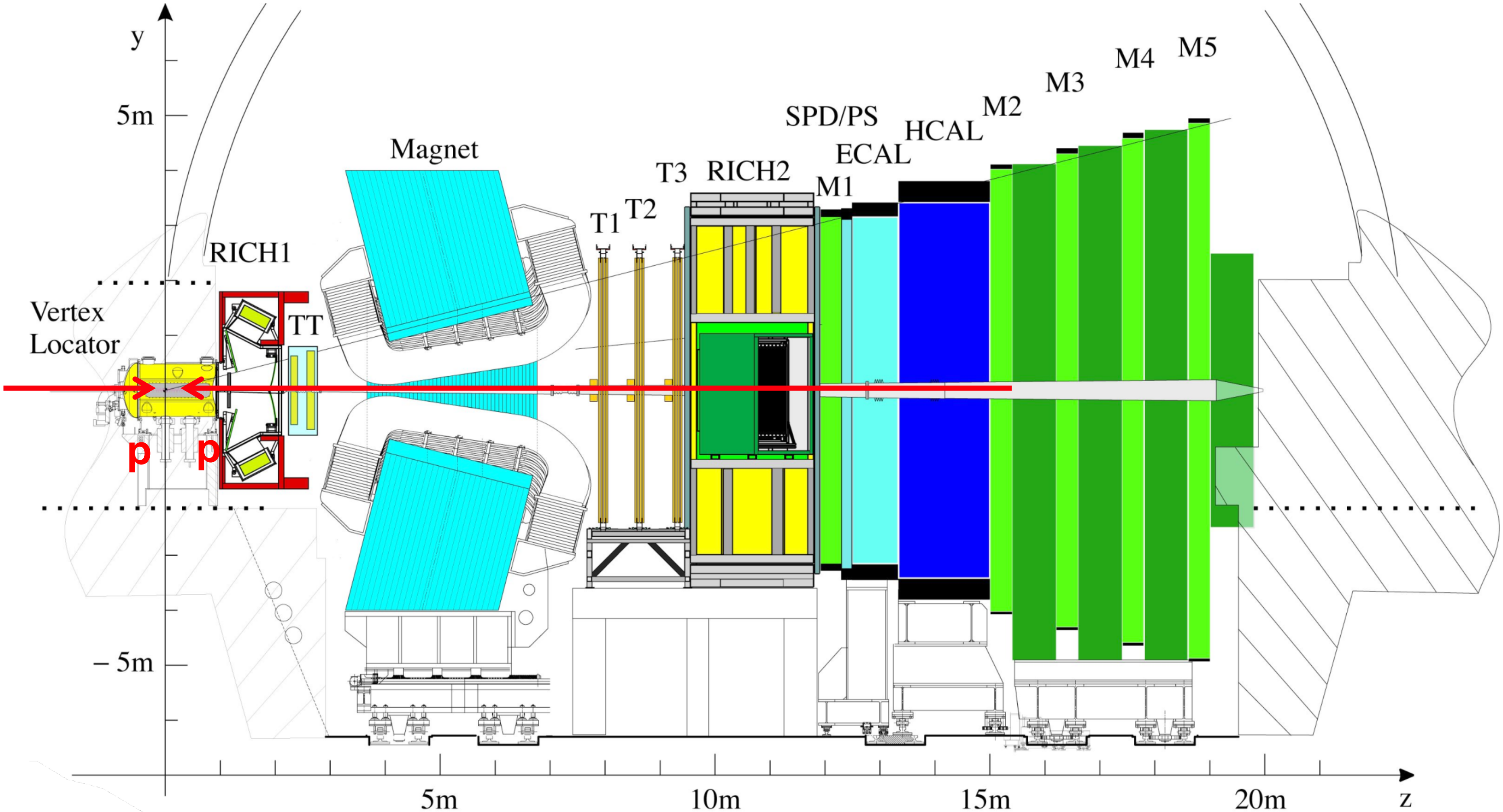




LHCb Detector

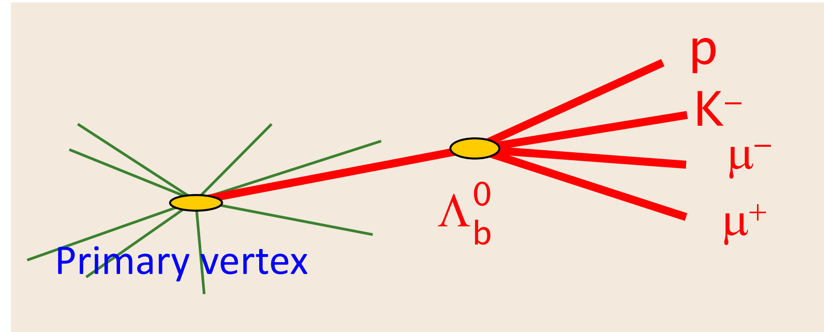
Forward single arm spectrometer 2<η<5

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



Improved selection

- Selection uses the feature of B-hadron decays
  - High p_{T}
  - Detached from primary vertex
  - Hadron ID information

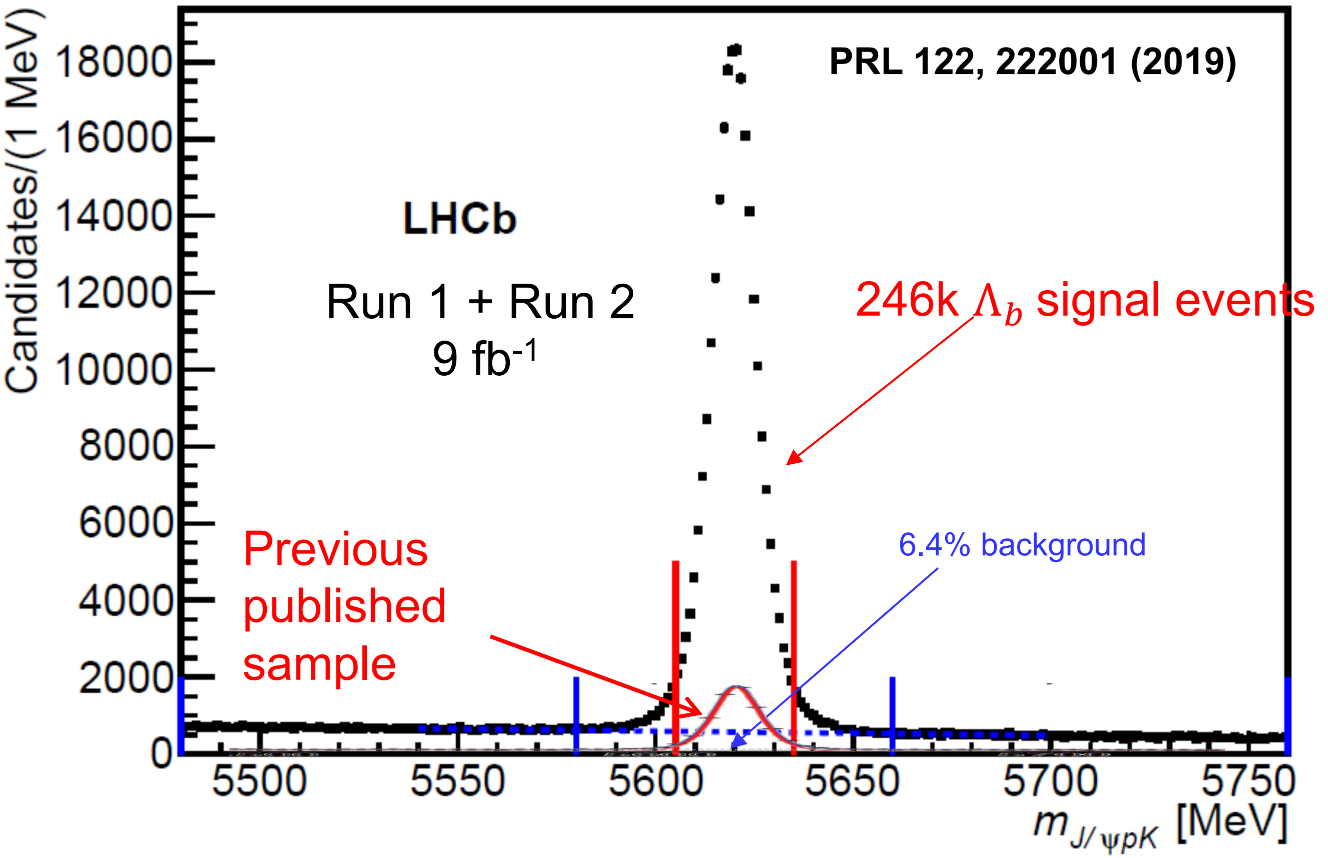


- Selection improved with better uses of hadron ID
  - Hadron ID requirements are put into a multivariate (MVA) based selection. A much powerful MVA is achieved.
  - Use hadron ID to help vetoing $B^0 \to J/\psi K^- \pi^+$, $B_s^0 \to J/\psi K^+ K^-$ and other mis-ID backgrounds.

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

Signal yield

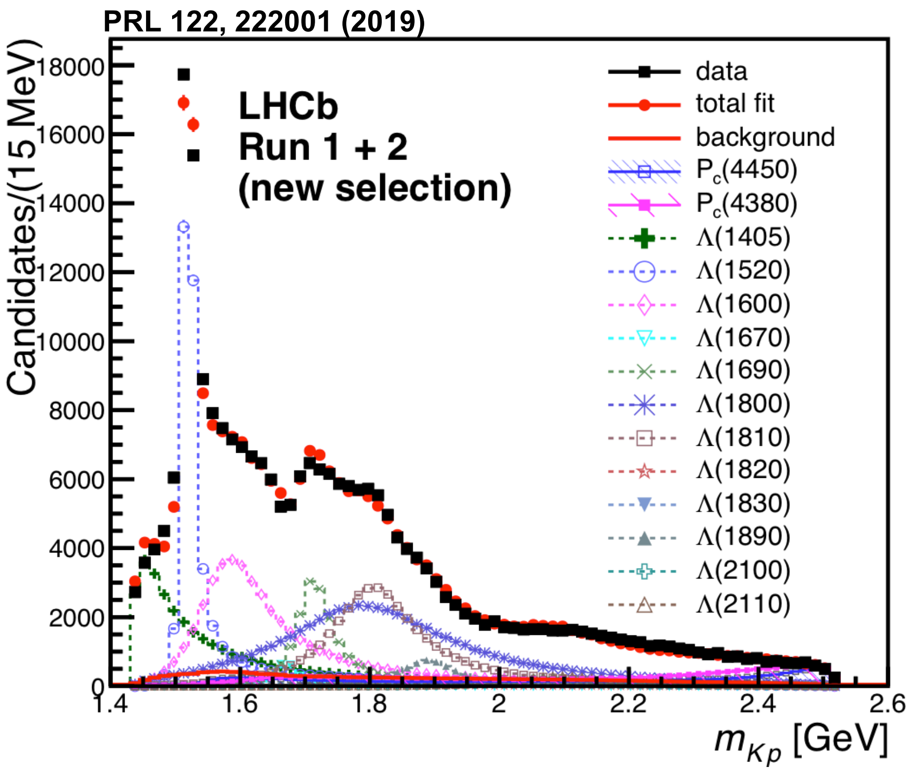
9.5 x more than used in the Run 1 papers

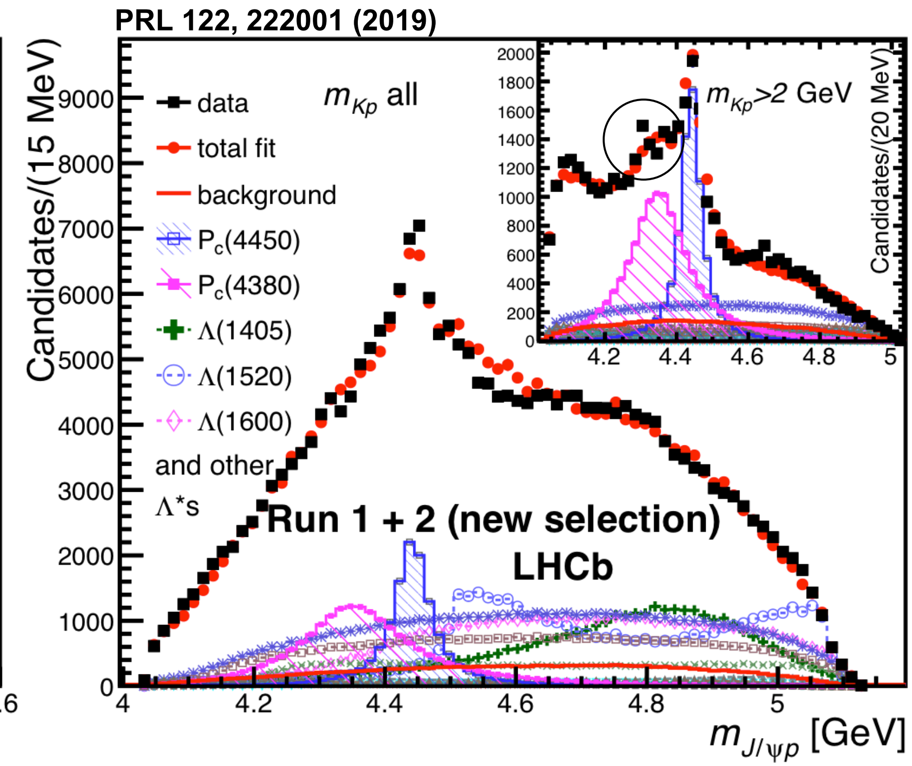


Improvements in the data selection (x 2), integrated luminosity (x 3) and cross-section ($\sqrt{s}$ =13 TeV vs 7-8 TeV)

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

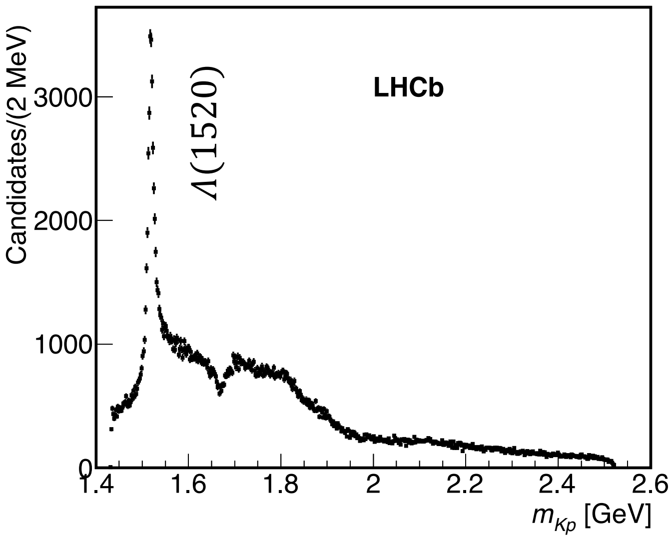


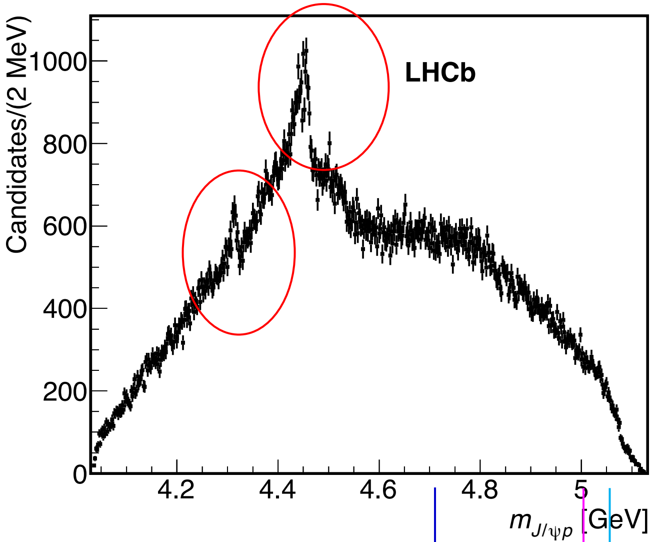


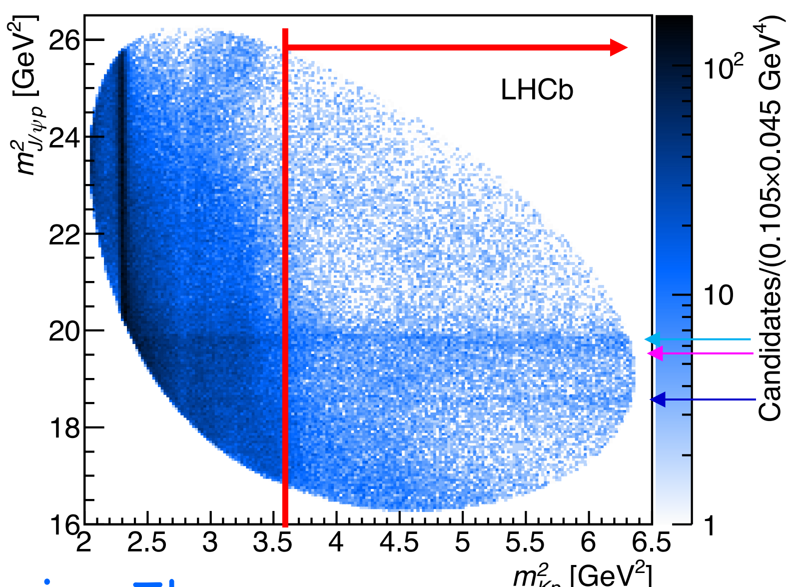
Liming Zhang

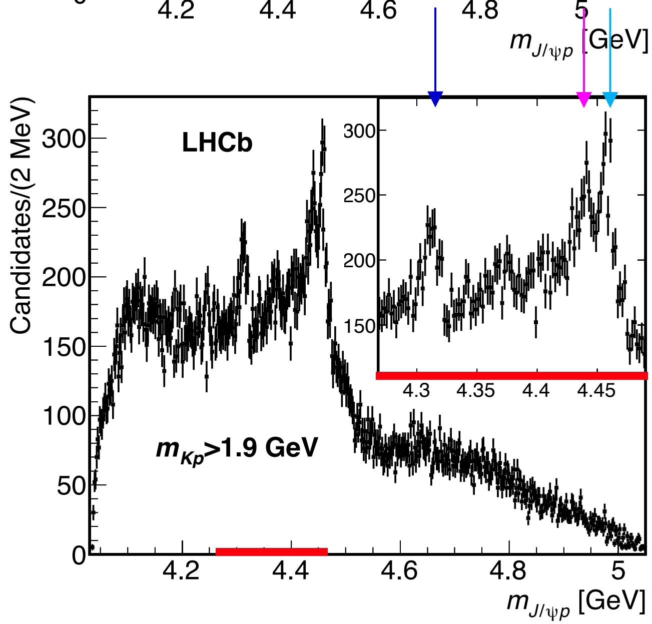
Display in smaller bin size

PRL 122, 222001 (2019)









Liming Zhang

The new data

- 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
- Amplitude analysis faces challenge and takes time:
  - Must consider $m_{J/\psi p}$ resolution effect
  - Large statistics require to improve formulating an amplitude model in order to reduce the systematic uncertainty
  - Work in progress

How to fit the data

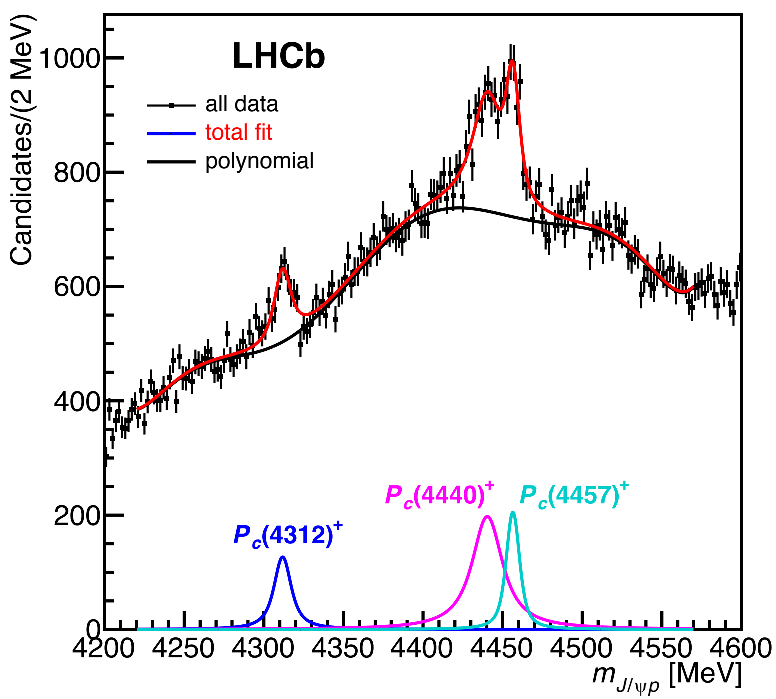
- **Simplified approach** fits to 1D $m_{J/\psi p}$ distribution
  - Narrow signals:
    - three Breit-Wigner (BW) functions ⊗ resolution (2-3 MeV)
  - Background of Λ^* + non-Λ_b^0 + possible broad P_c^+: two models compared
    - higher-order polynomial or
    - low-order polynomial + broad BW
- It 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

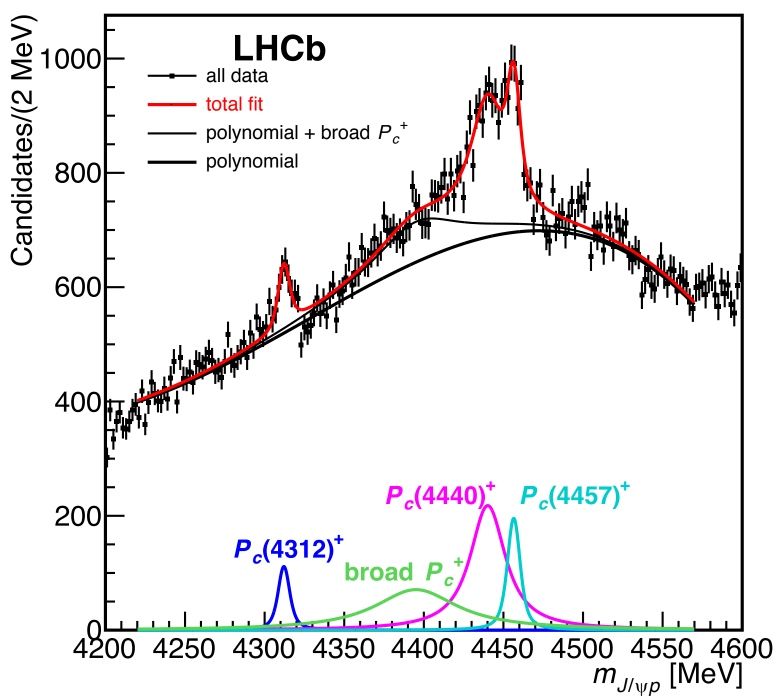
PRL 122, 222001 (2019)

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

high-order polynomial



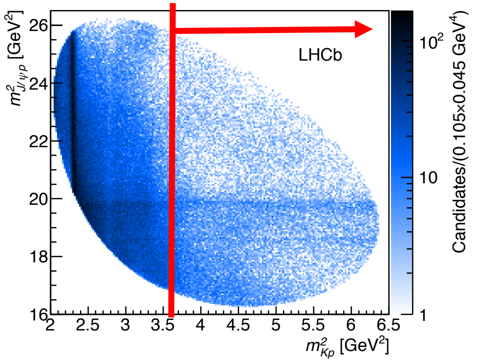
low-order polynomial + broad P_c^+ as bkg.

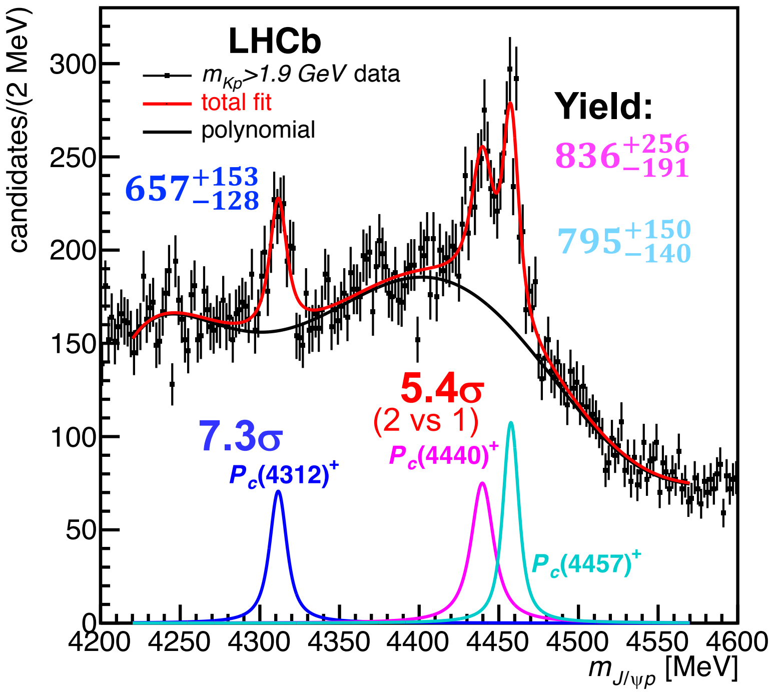


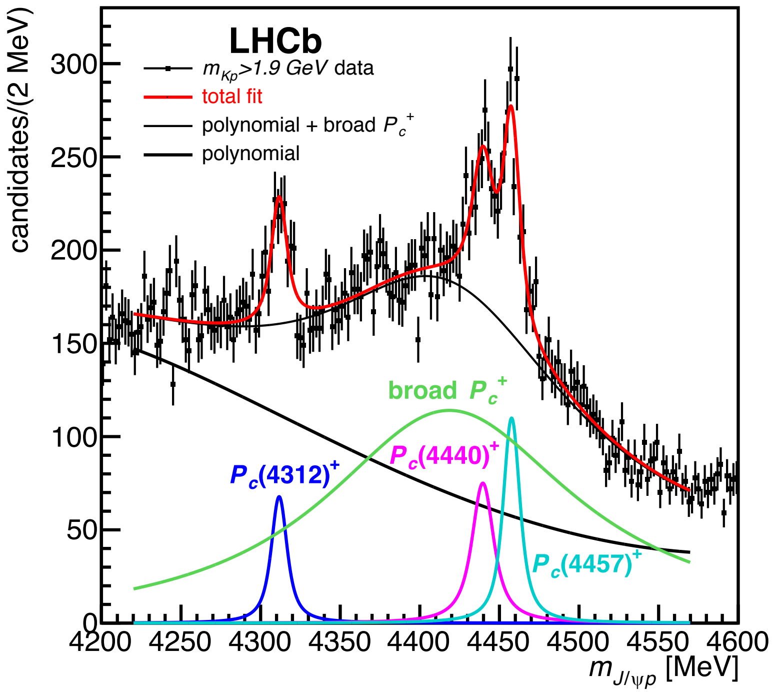
Fit-2: P_c^+ dominated region

PRL 122, 222001 (2019)

- 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

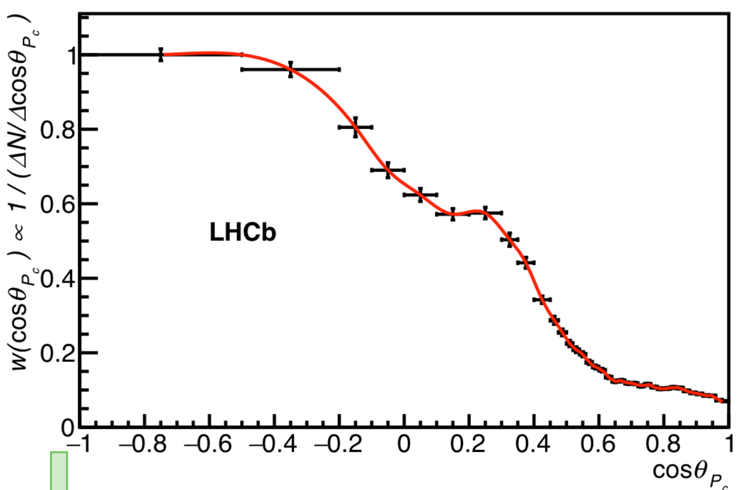


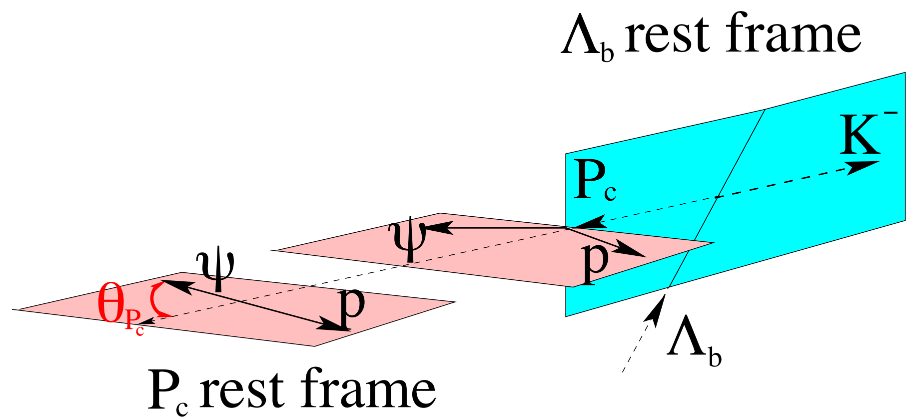




Fit-3: Novel method

- 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
- θ_{P_c} is P_c helicity angle
  - Angle between $\vec{p}_{J/\psi}$ and $-\vec{p}_K$ in $J/\psi p$ rest frame





high m_{pK}
less Λ^*
high w

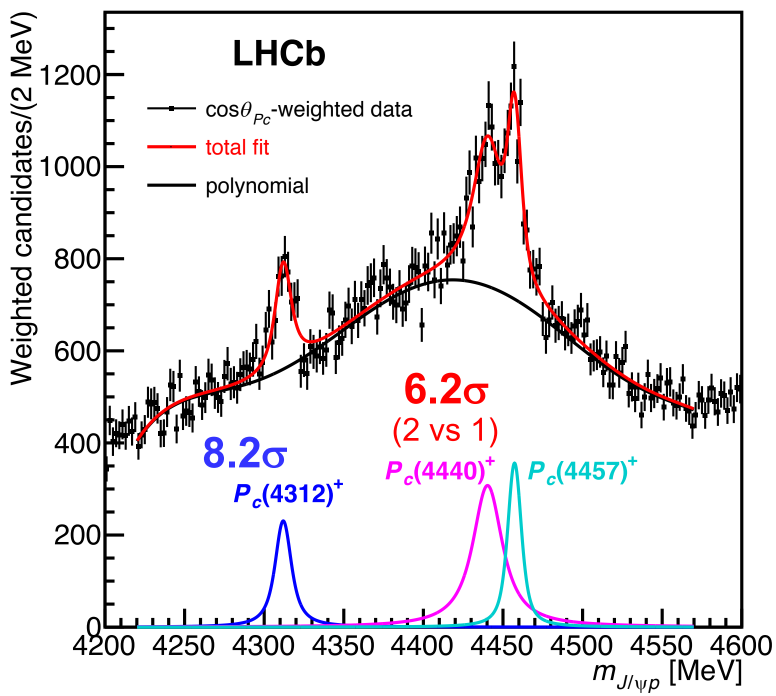
low m_{pK}
more Λ^*
low w

PRL 122, 222001 (2019)

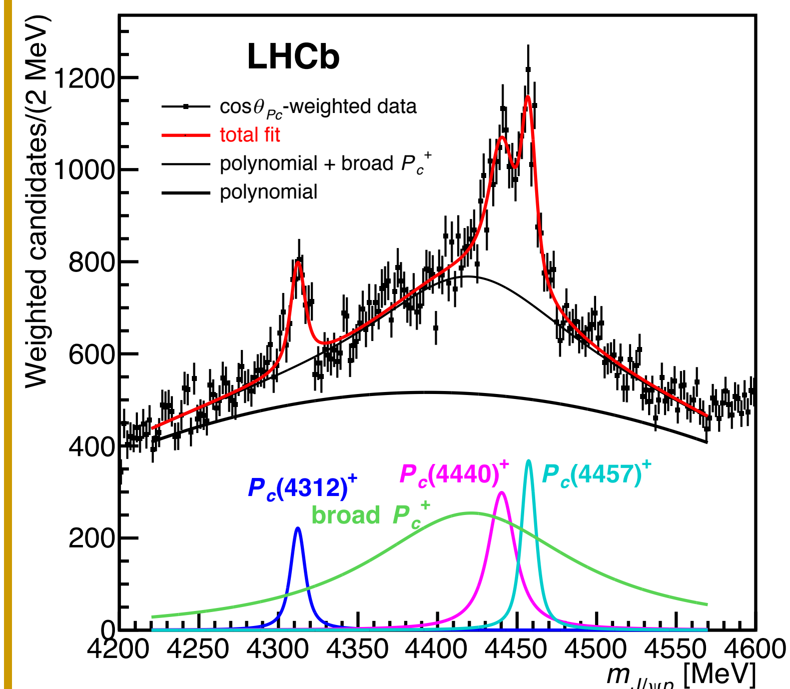
Fit-3: Novel method

PRL 122, 222001 (2019)

- 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



the nominal M&Γ measurements



Results

PRL 122, 222001 (2019)

- 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)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

Systematic uncertainties

Systematic uncertainties are taken to be the largest deviations observed among all fits, including

- Six fits described above
- Change the order of polynomial for the background shape
- Use P-wave factors instead of S-wave in the BW amplitudes
  - **Negligible effect on the results**
- $P_c(4312)^+$ fit in narrow 4.22-4.44 GeV mass range
- Fits to sample from an alternative selection without MVA
- Fits with interference considered
  - **Source of the largest uncertainty**

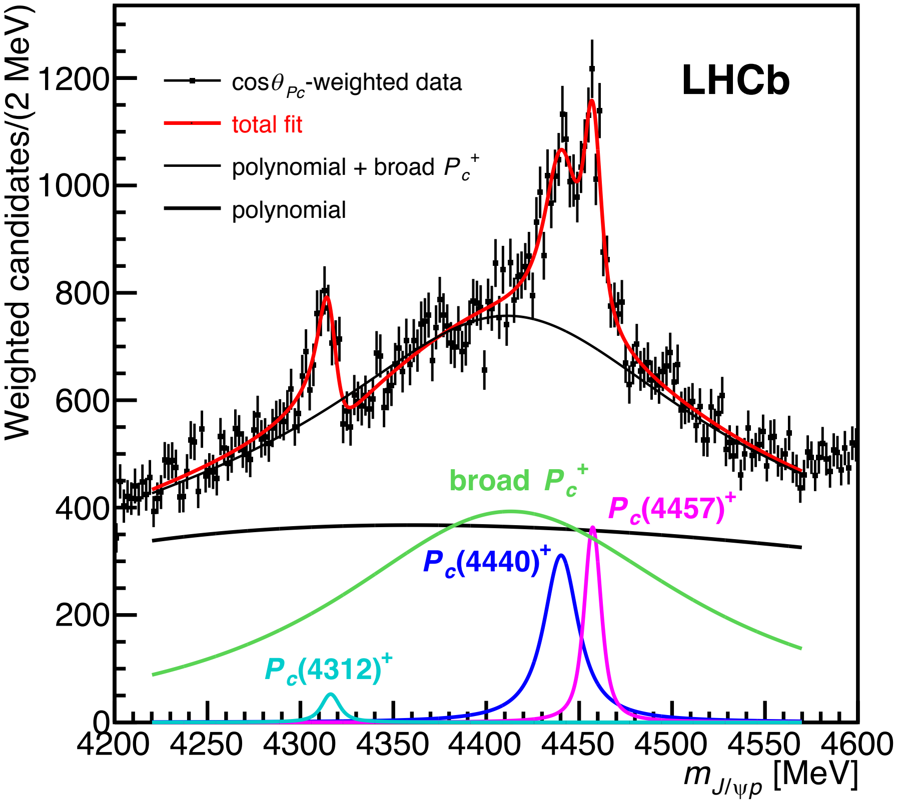
State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3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

Fits with interferences

PRL 122, 222001 (2019)

- Interference effect is important only if two overlying P_c^+ have same J^P
- Nominal fits use incoherent sum of BW amplitudes
- Systematic uncertainty considers fits with coherent sum, including broad P_c^+ state
  - No evidence for interferences
  - But this source gives the largest uncertainty on mass and width measurements, e.g. +6.8 MeV for $P_c(4312)^+$ mass

Example of a fit with interference:
$P_c(4312)^+$ interfering with the broad P_c^+



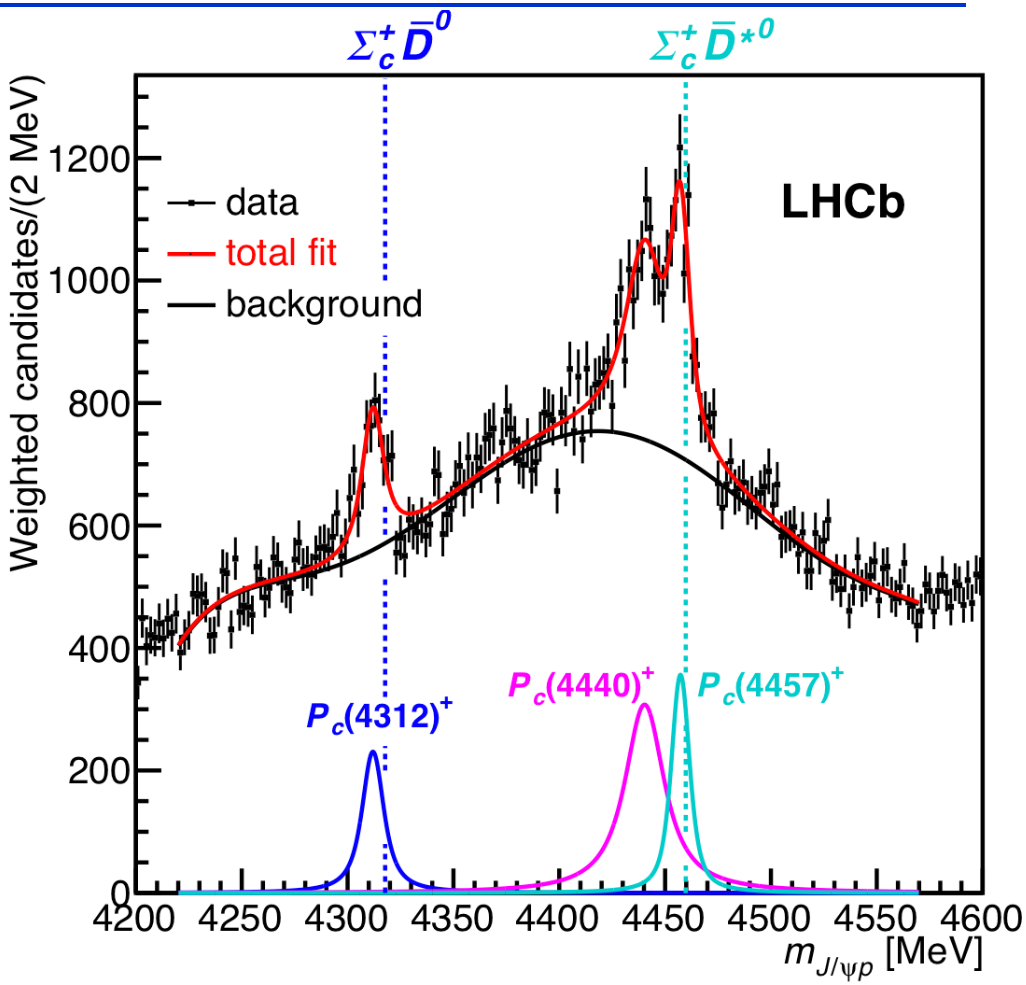
Liming Zhang

Plausible interpretation

PRL 122, 222001 (2019)

- 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**

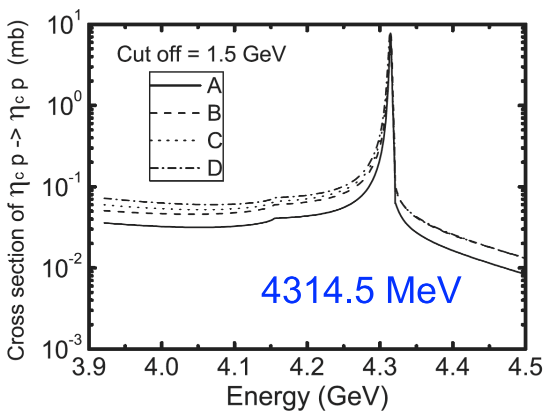
- The 1D fit provides limited information. More work needed
  - **J^P measures and confirmation of $P_c(4380)^+$ require amplitude analysis**
  - **To find isospin partners, and other decay modes**



Earlier predictions with molecular picture

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

PR C85 044002 (2012)



$M_{\text{LHCb}} = 4311.9 \pm 0.7^{+6.8}_{-0.6}$ MeV

Example: Predicted three I=1/2 doublets

PR C85 044002 (2012)

		PB System		VB System	
$J^P = \frac{1}{2}^-$	Λ	$M - i\Gamma/2$	ΔE	$M - i\Gamma/2$	ΔE
	650	-	-	-	-
	800	-	-	$4462.178 - 0.002i$	0.002
	1200	$4318.964 - 0.362i$	1.826	$4459.513 - 0.417i$	2.667
	1500	$4314.531 - 1.448i$	6.259	$4454.088 - 1.662i$	8.092
	2000	$4301.115 - 5.835i$	19.68	$4438.277 - 7.115i$	23.90
$J^P = \frac{3}{2}^-$					
	650	-	-	-	-
	800	-	-	$4462.178 - 0.002i$	0.002
	1200	-	-	$4459.507 - 0.420i$	2.673
	1500	-	-	$4454.057 - 1.681i$	8.123
	2000	-	-	$4438.039 - 7.268i$	23.14

Λ : cut off on exchanged meson mass

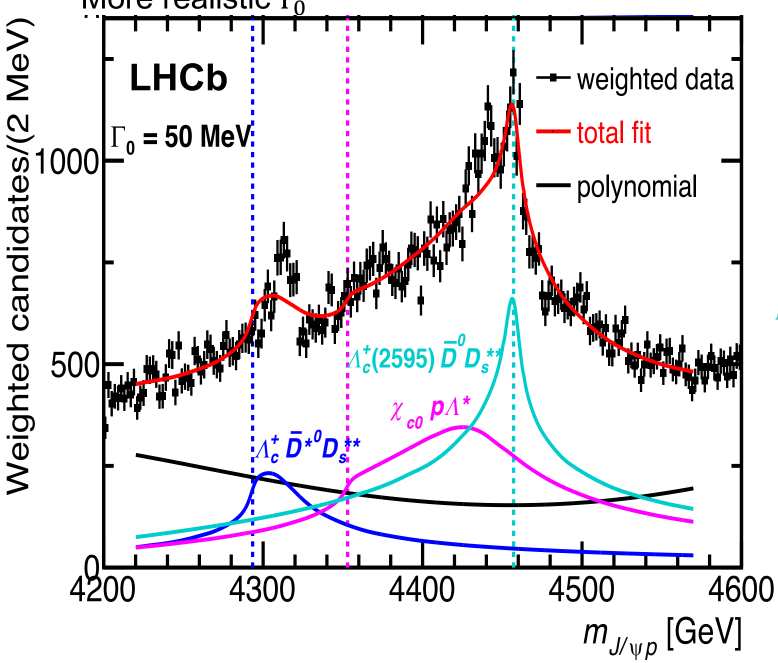
$\Delta E = E_{\text{thr}} - M$: "binding energy"

Triangle diagrams?

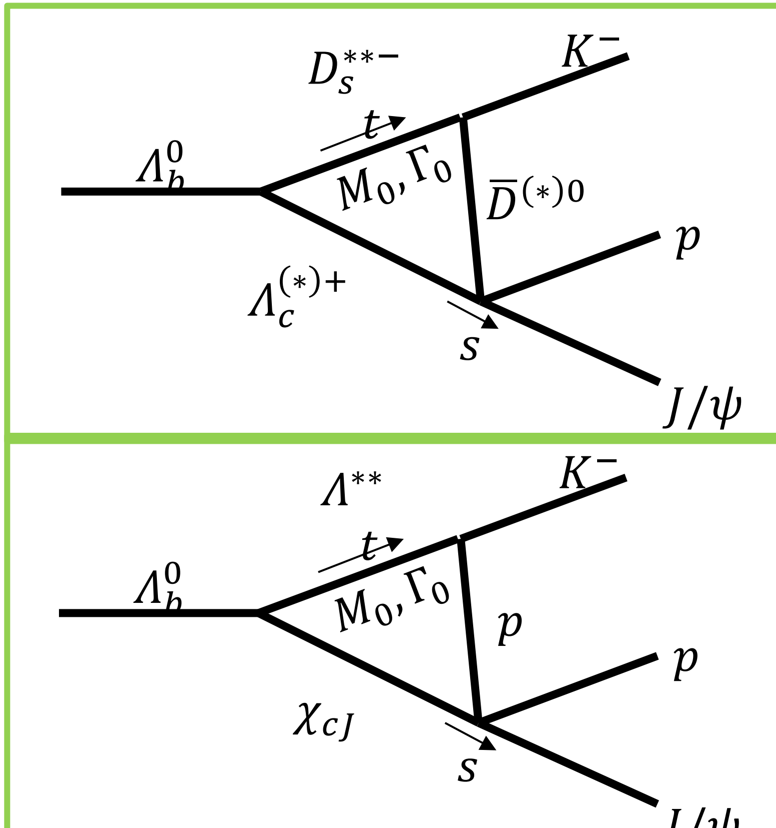
- Can produce peaking structure at or above mass threshold, but not below

3 triangle-diagram amplitudes + polynomial

More realistic Γ_0 **PRL 122, 222001 (2019)**



$D_s^{**} = D_s(2860)$



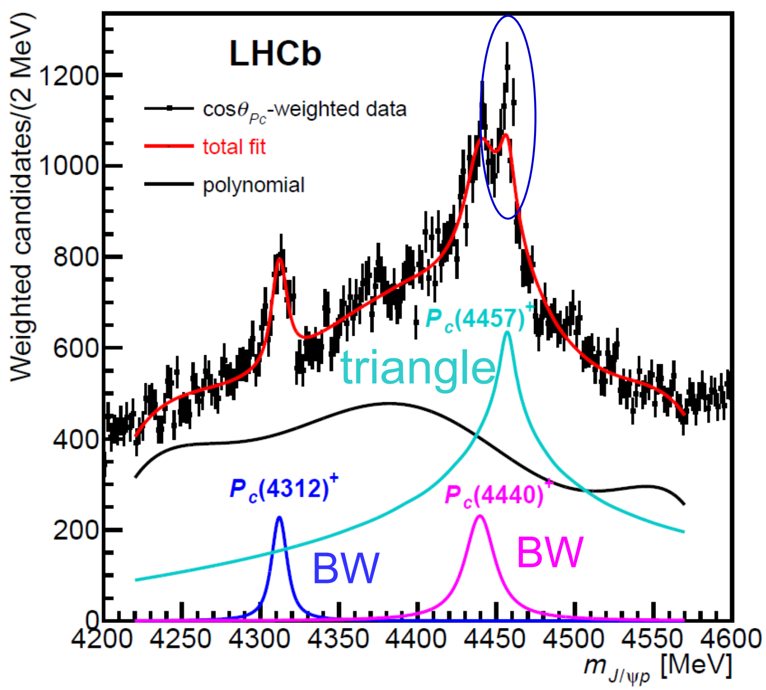
Guo *et al*, PRD 92 (2015) 071502 and others

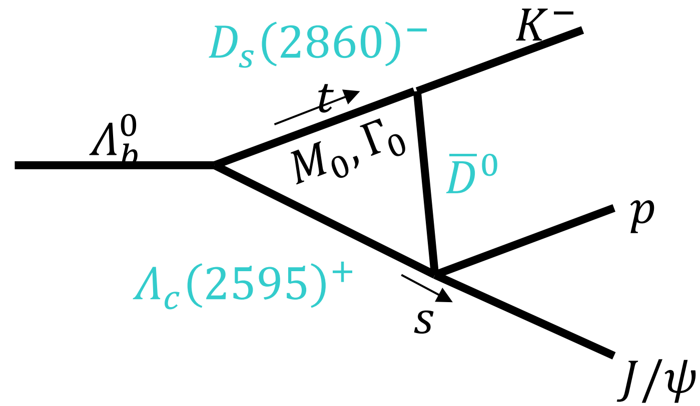
$P_c(4312)^+$, $P_c(4440)^+$ are too far from any rescattering thresholds to be triangle diagram peaks

Triangle diagrams?

- Can produce peaking structure at or above mass threshold, but not below

PRL 122, 222001 (2019) $D_s(2860)\ \Gamma_0 = 159$ MeV





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

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

Two BWs + triangle for $P_c(4457)^+$ fit is acceptable

Summary

- Thanks to excellent LHC performance, and improved selection, we achieved almost an order of magnitude increases in signal yield.
- We confirmed the $P_c(4450)^+$ peak structure, and found it's actually a combination of two narrower states, $P_c(4440)^+$ and $P_c(4457)^+$.
- We also observed a new narrow state $P_c(4312)^+$.
- The experimental information sheds more light onto the nature of these observed narrow pentaquark states. 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.

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]

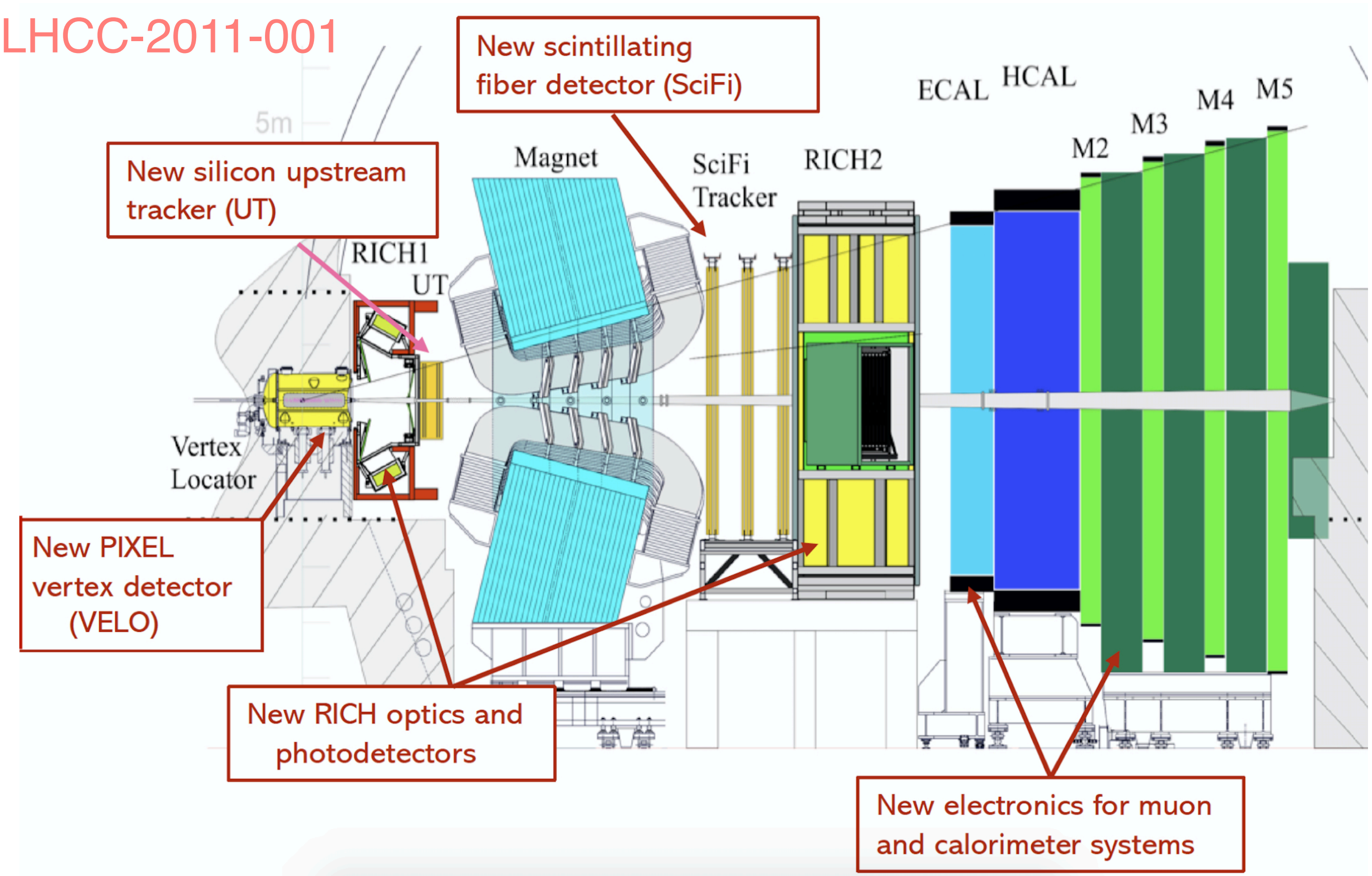
More interesting ideas

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

LHCb Upgrade I

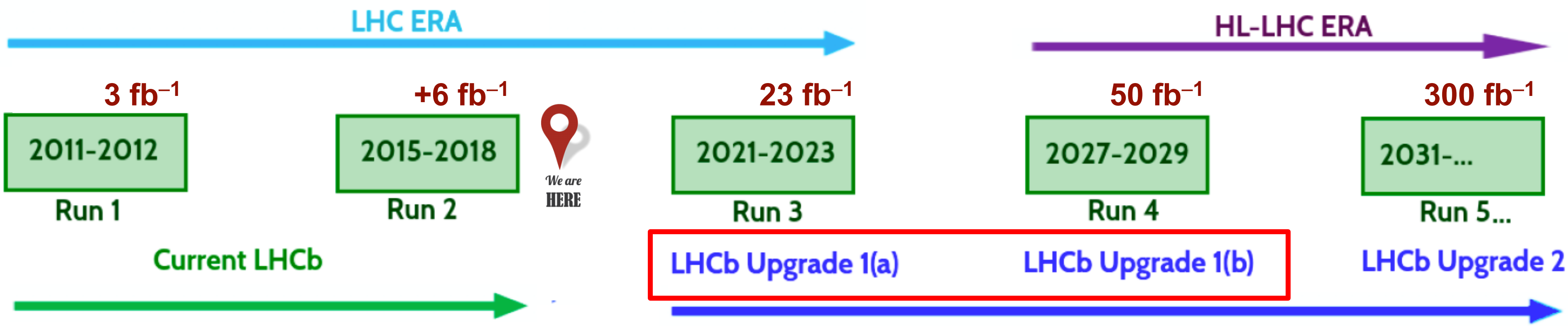
Upgrade I: installation ongoing

CERN-LHCC-2011-001



Almost a new detector for factor 5 luminosity increase

LHCb Upgrade I

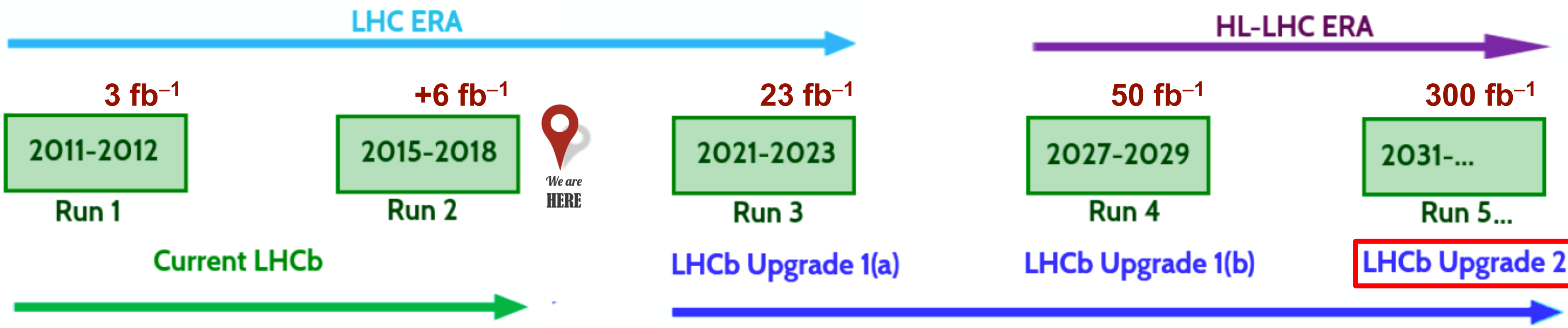


CERN-LHCC-2011-001

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 $\mathcal{L} = 2\times10^{34}$, 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)

Thank you!

Expected yields in future

- We are now boosting our 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

Decay mode	LHCb $23\,\text{fb}^{-1}$	LHCb $50\,\text{fb}^{-1}$	LHCb $300\,\text{fb}^{-1}$
$B^+ \to X(3872)(\to J/\psi\,\pi^+\pi^-)K^+$	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

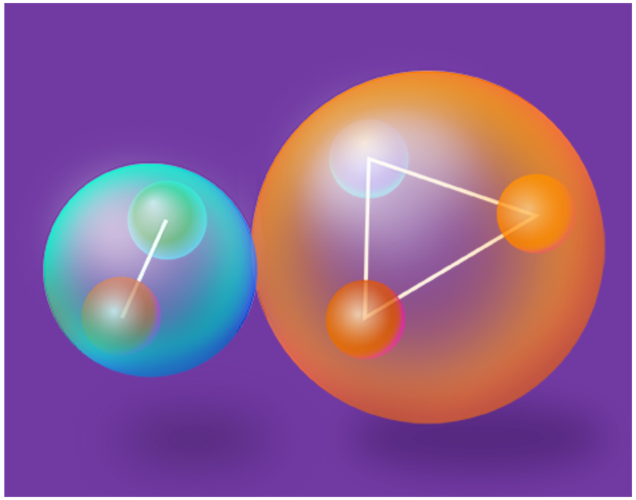
[*] updated according to the latest result

CERN-LHCC-2018-027
arXiv:1808.08865

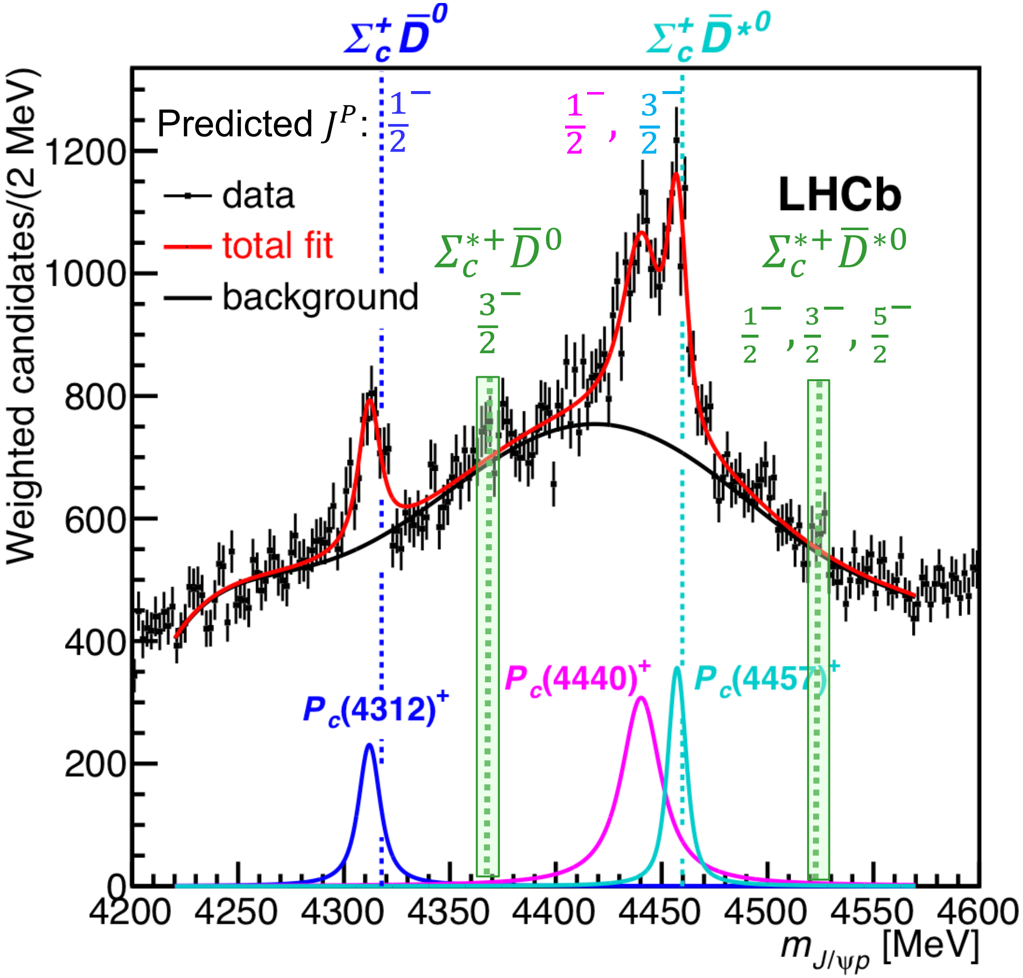
Predictions with molecular picture

- Predict J^P in S-wave
  - All $P = -1$
- Predict 4 additional partners at $\Sigma_c^* \bar{D}^{(*)}$ thresholds

[Liu *et al.* PRL 122 (2019) 242001]



PRL 122, 222001 (2019)

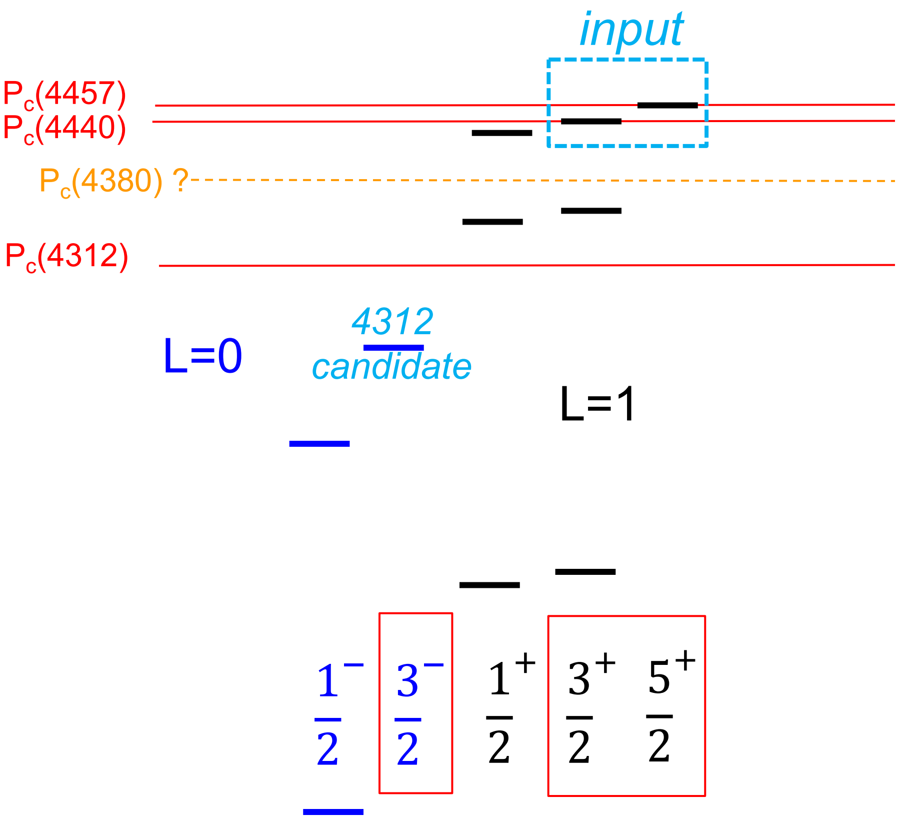


Tightly bound pentaquarks

Diquark model

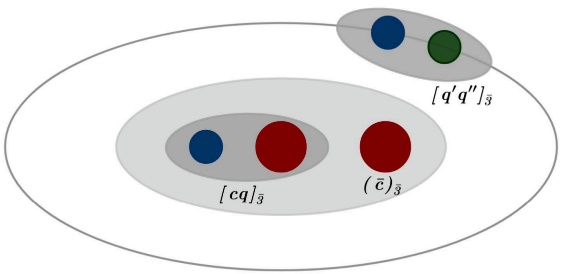
$((uc)_{S=0,1}(ud)_{S=0}\bar{c}_{S=1/2})_{L=0}$

$((uc)_{S=0,1}(ud)_{S=0}\bar{c}_{S=1/2})_{L=1}$



Models of tightly bound pentaquarks predict a very rich spectrum

And predicted different J^P for the observed narrow $P_c's$ than that from the molecular model

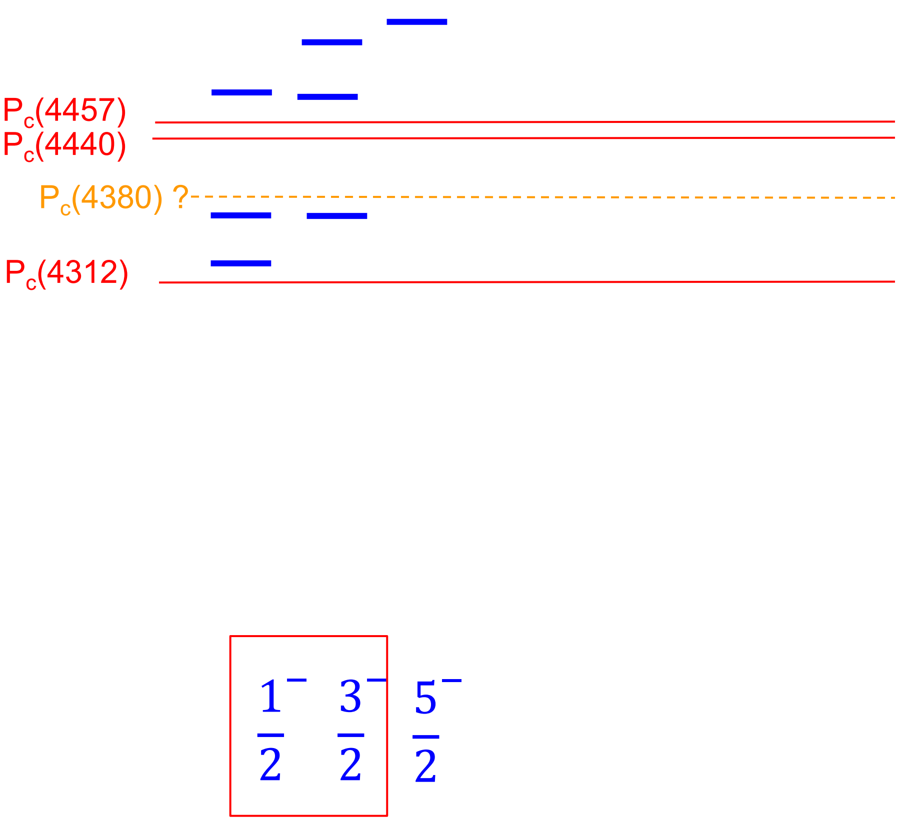


Ali *et al*, PLB 793, 365 (2019);
Ali *et al*, 1907.06507 predicts more states with $(ud)_{S=1}$

Tightly bound pentaquarks

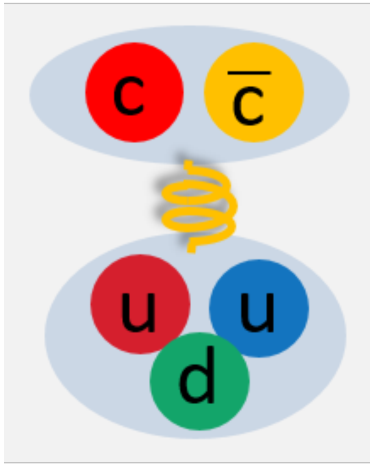
Different color-binding

$$\left((c\bar{c})((ud)u)\right)_{L=0}$$



Models of tightly bound pentaquarks predict a very rich spectrum

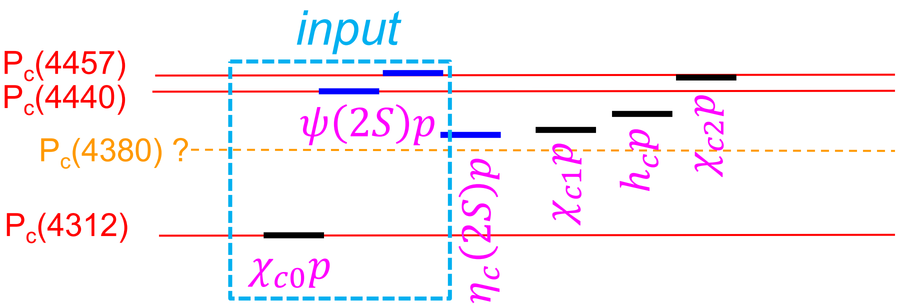
Use the chromomagnetic model to study the mass spectra



Weng *et al*, arxiv:1904.09891

Hadro-charmonium model

$\left((c\bar{c})(uud)\right)_{\text{color-binding}}$



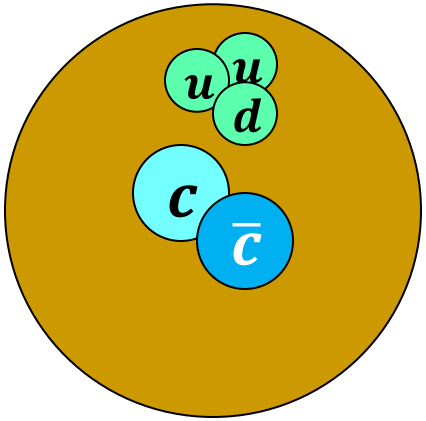
$\frac{1}{2}^+$ $\frac{1}{2}^+$ $\frac{5}{2}^+$

$\frac{1}{2}^+$ $\frac{1}{2}^-$ $\frac{3}{2}^-$ $\frac{1}{2}^-$ $\frac{3}{2}^+$ $\frac{3}{2}^+$ $\frac{3}{2}^+$

Compact ($c\bar{c}$) surrounded by light quarks

P_c^+	Bound state	Binding E (MeV)	J^P
4312	$\chi_{c0}p$	42	$1/2^+$
4440	$\psi(2S)p$	~170	$1/2^-$
4457	$\psi(2S)p$	~170	$3/2^-$

Many more states predicted in 4380 region

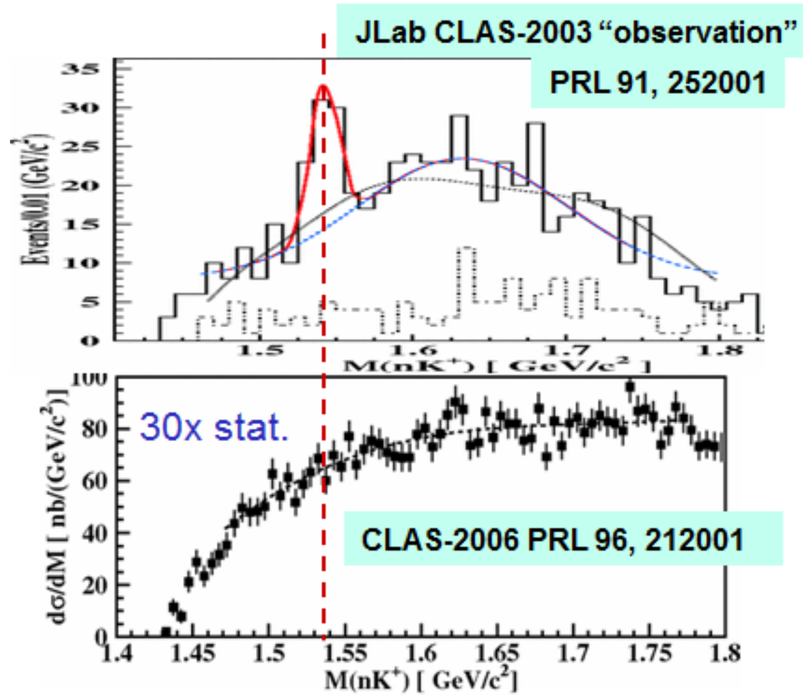


I. Eides *et al*, arXiv:1904.11616 and previous works

Past claimed pentaquark

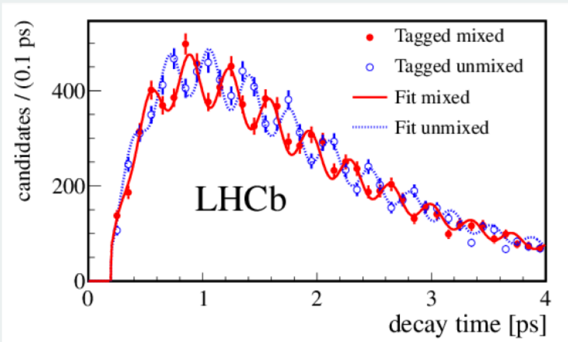
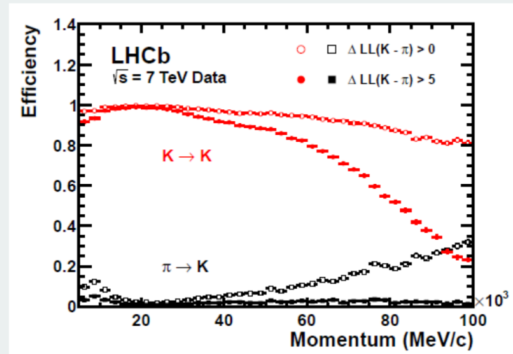
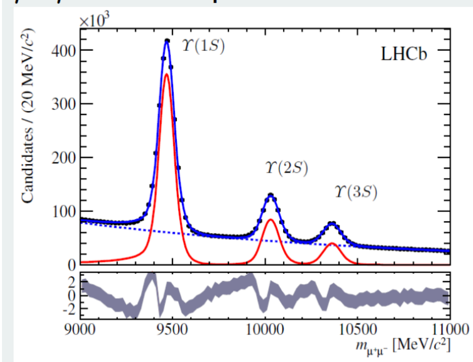
- No convincing states 50 years after Gell-mann paper proposing $qqqq\bar{q}$ states
- Prediction: Θ^+ ($uudd\bar{s}$) could exist with m ≈1530 MeV
- In 2003,10 experiments reported evidences of narrow peaks of $K^0 p$ or $K^+ n$, all >4 σ
- High statistics repeats from JLab showed the original claims were fluctuation

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



See summary by [K. H. Hicks, Eur. Phys. J. H37 (2012) 1]

Detector performance

Vertexing	PID	Tracking
B_s^0 oscillations with $B_s^0 \to D_s\pi$	K/π ID efficiency and misID rate	$\mu^+\mu^-$ mass spectrum
		
[New J. Phys. 15 (2013) 053021]	[EPJ C73 (2013) 2431]	[PRL 111 (2013) 101805]

Impact parameter:	$\sigma_{\text{IP}} = 20\ \mu\text{m}$
Proper time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4\sim0.6\%\ (5 - 100\ \text{GeV}/c)$
Mass:	$\sigma_m = 8\ \text{MeV}/c^2$ for $B \to J/\psi X$ (constrained $m_{J/\psi}$)
RICH $K - \pi$ separation:	$\epsilon(K \to K) \sim 95\%$ mis-ID $\epsilon(\pi \to K) \sim 5\%$
Muon ID:	$\epsilon(\mu \to \mu) \sim 97\%$ mis-ID $\epsilon(\pi \to \mu) \sim 1 - 3\%$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\text{GeV})}$

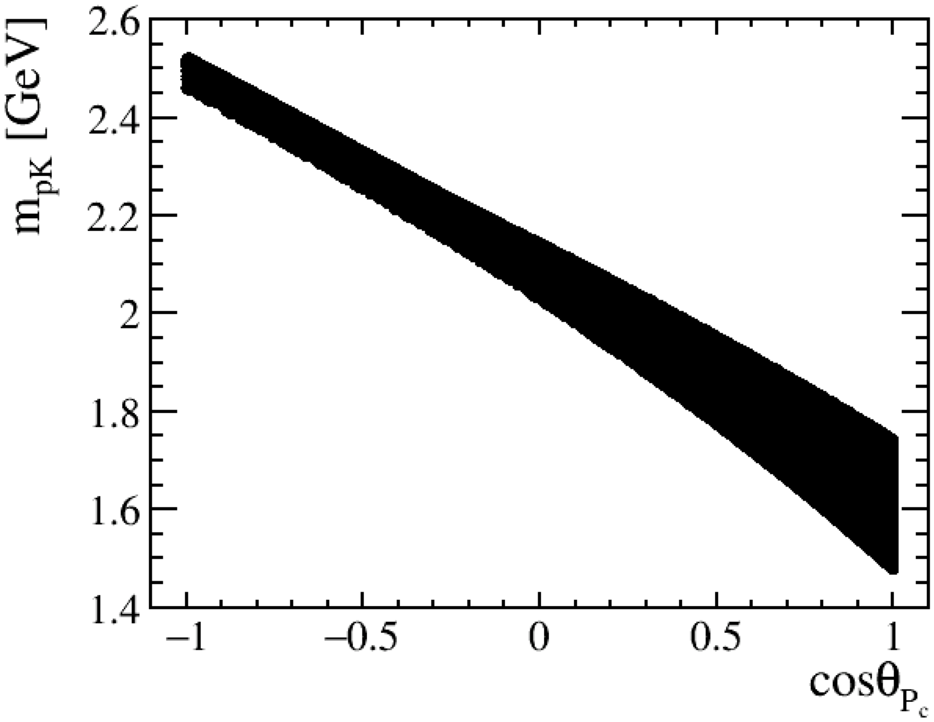
Molecular interpretations

- If molecular hypothesis is true, existence of $P_c(4312)^+$ points to the importance of vector meson (ρ, ω) exchanges in binding the charmed baryon and meson, since a pion cannot be exchanged in the $\Sigma_c\bar{D}$ system

- This may also imply that $D\bar{D}$ or $B\bar{B}$ can form bound states [arXiv:1905.13156], calling for improved experimental searches

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

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



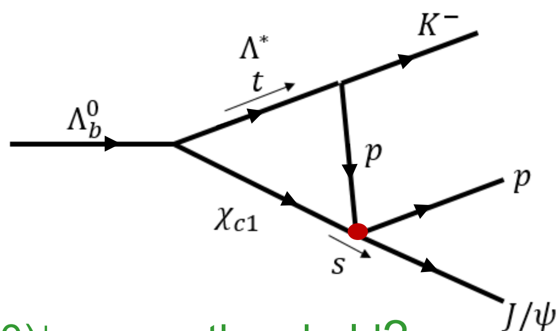
Systematic uncertainty

- The largest ones are due to interference effect

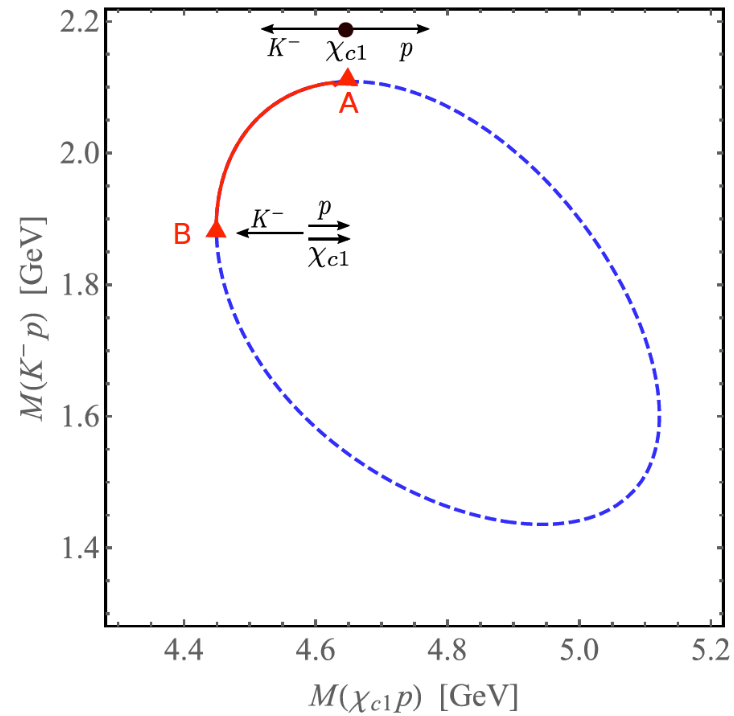
	$P_c(4312)^+$		$P_c(4400)^+$		$P_c(4457)^+$	
	M MeV	Γ MeV	M MeV	Γ MeV	M MeV	Γ MeV
value $\pm$ statistical error	4311.9 ± 0.7	9.8 ± 2.7	4440.3 ± 1.3	20.6 ± 4.9	4457.3 ± 0.6	6.4 ± 2.0
bkg.subtr. & cut variation	$^{+0.8}_{-0.6}$	$^{+3.7}_{-4.5}$	$^{+0.1}_{-1.1}$	$^{+4.6}_{-8.2}$	$^{+0.4}_{-1.7}$	$^{+3.6}_{-0.9}$
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?

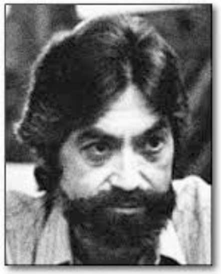


Requirements:

- 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

Quark model

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".

Successfully describes all the hadrons observed in the last century

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**.

Helps to explain how the strong force binds the quarks to form a particle

Liming Zhang

Quark model

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

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".

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.

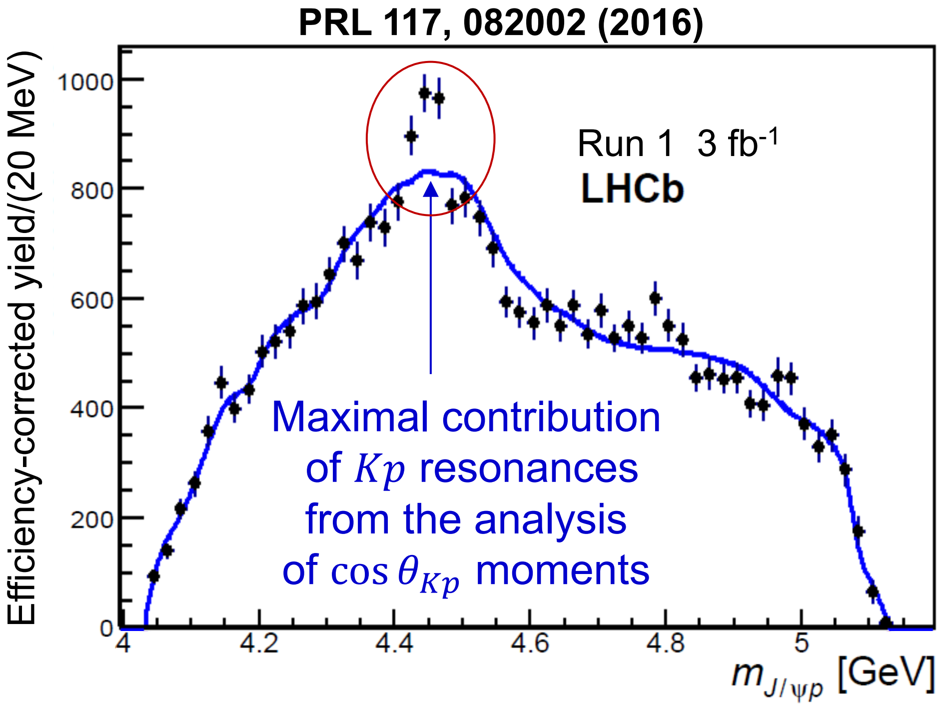
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the 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 (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) 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**.

$qqqq\bar{q}$ baryons later called "pentaquarks"; $qq\bar{q}\bar{q}$ meson called "tetraquarks"

Liming Zhang

LHCb result in 2015

- A model-independent analysis showed that the 4450 MeV peak is too narrow to be explained by reflections of Kp resonances



Contents

- Introduction
- Pentaquarks observed by LHCb in 2015
- LHCb experiment
- Recent pentaquark results
- Summary and prospects