Pentaquarks at LHCb

(On behalf of the LHCb collaboration)

Liming Zhang (Tsinghua University)

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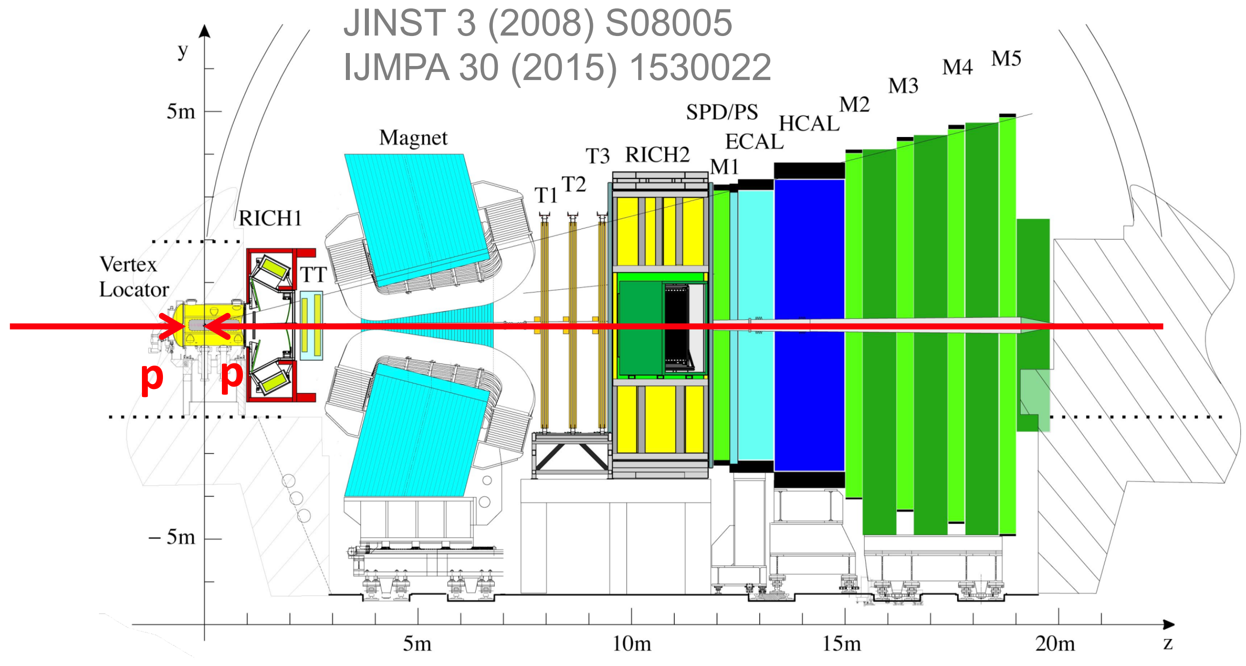
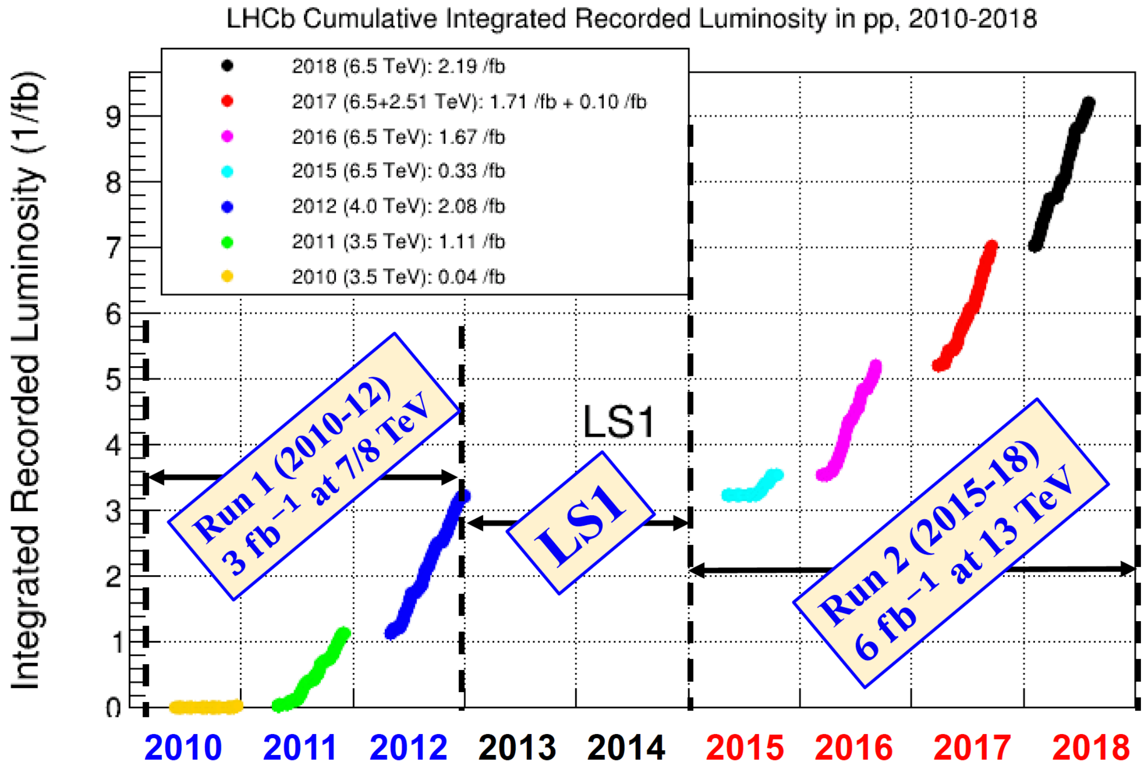
The LHCb Experiment

- LHCb is a dedicated flavour physics experiment at the LHC
  - >10^4 $\times$ larger b production cross-section 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

➢ Pentaquark results based on full dataset

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

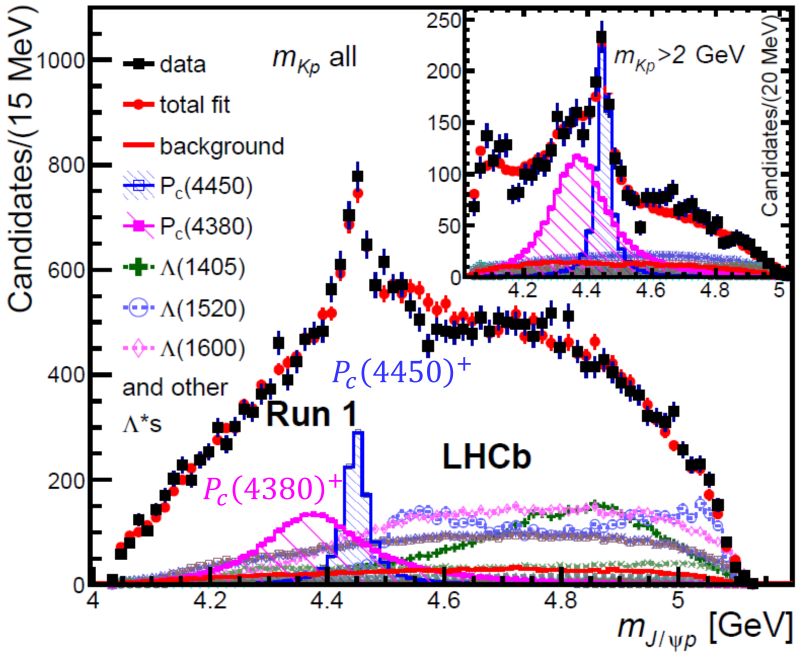


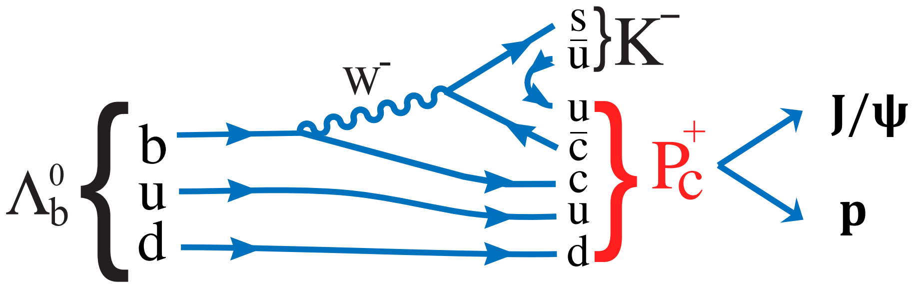


LHCb observation in 2015

- **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





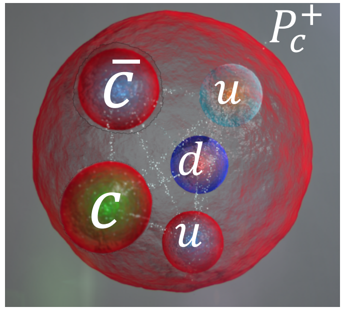
	$P_c(4380)^{\pm}$	$P_c(4450)^{\pm}$
Mass (MeV)	4380 ± 8 ± 29	4449.8 ± 1.7 ± 2.5
Width (MeV)	205 ± 18 ± 86	39 ± 5 ± 19
Fit Fraction (%)	8.4 ± 0.7 ± 4.2	4.1 ± 0.5 ± 1.1

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?

Tightly-bound pentaquark?

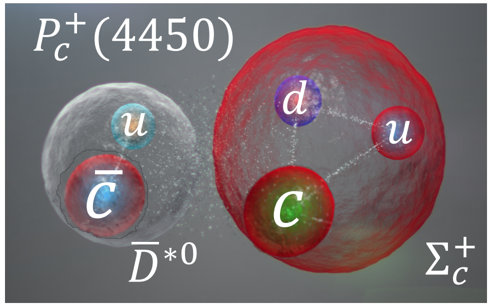
$M_{P_c^+} = M_{J/\psi} + M_p + \sim 400\text{MeV}$



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?

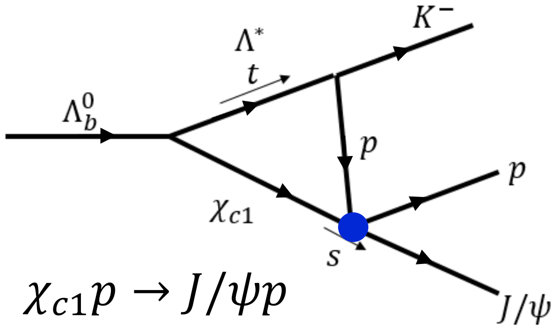
$M_{P_c^+} = M_{\bar{D}^{*0}} + M_{\Sigma_c^+} - \sim\text{few MeV}$



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

Kinematical effect: triangle diagram?

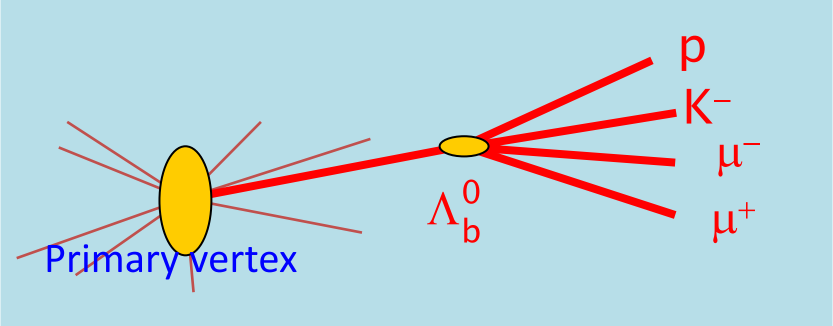
$P_c(4450)^+ = \chi_{c1}p$ threshold?



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

Improved selection

- Selection uses the feature of Λ_b^0 decays
  - High p_{T}
  - Detached from primary vertex
  - Hadron ID information

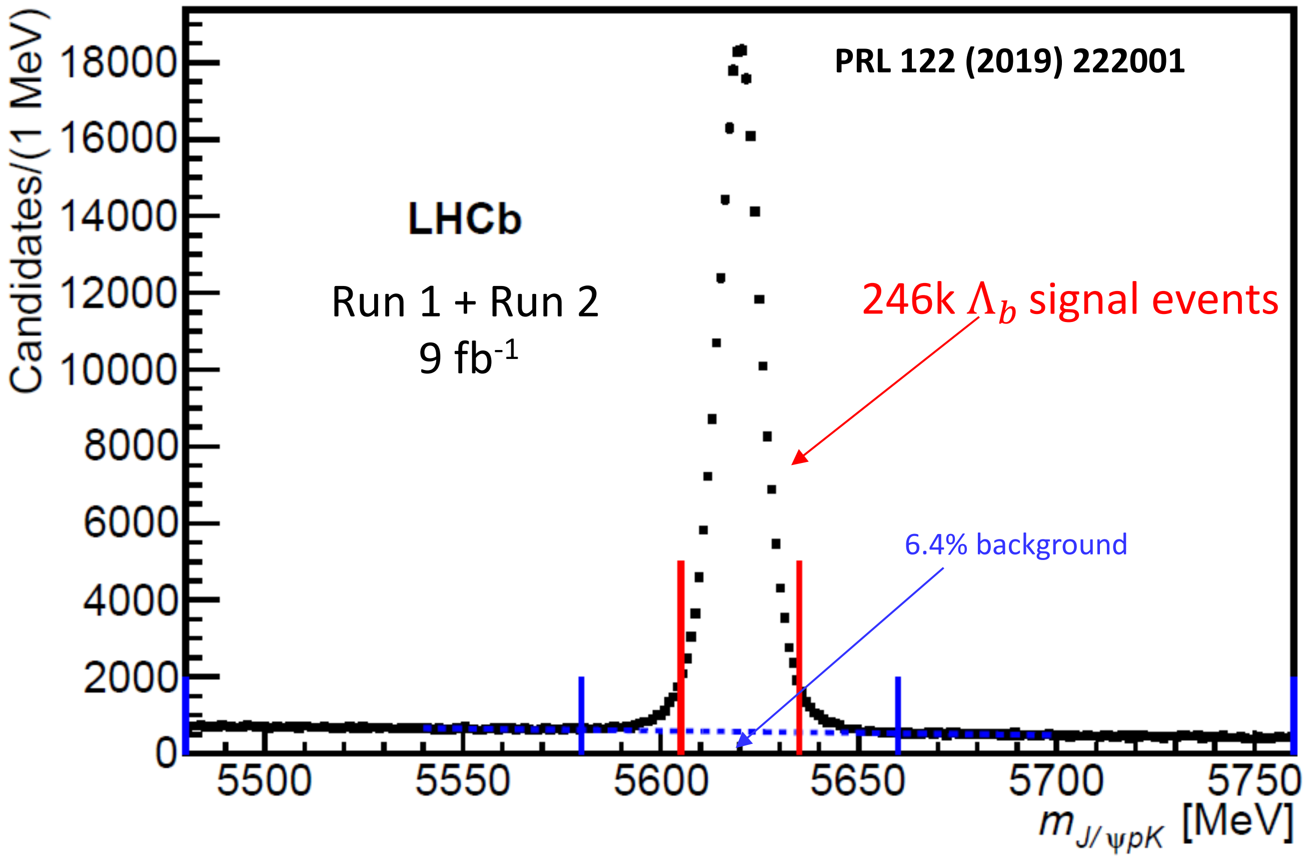


- Selection improved with better uses of hadron ID
  - Hadron ID requirements are put into a multivariate (MVA) based selection. A much powerful MVA is achieved.
  - Use hadron ID to help vetoing $B^0 \to J/\psi K^-\pi^+$, $B_s^0 \to J/\psi K^+K^-$ and other mis-ID backgrounds.

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

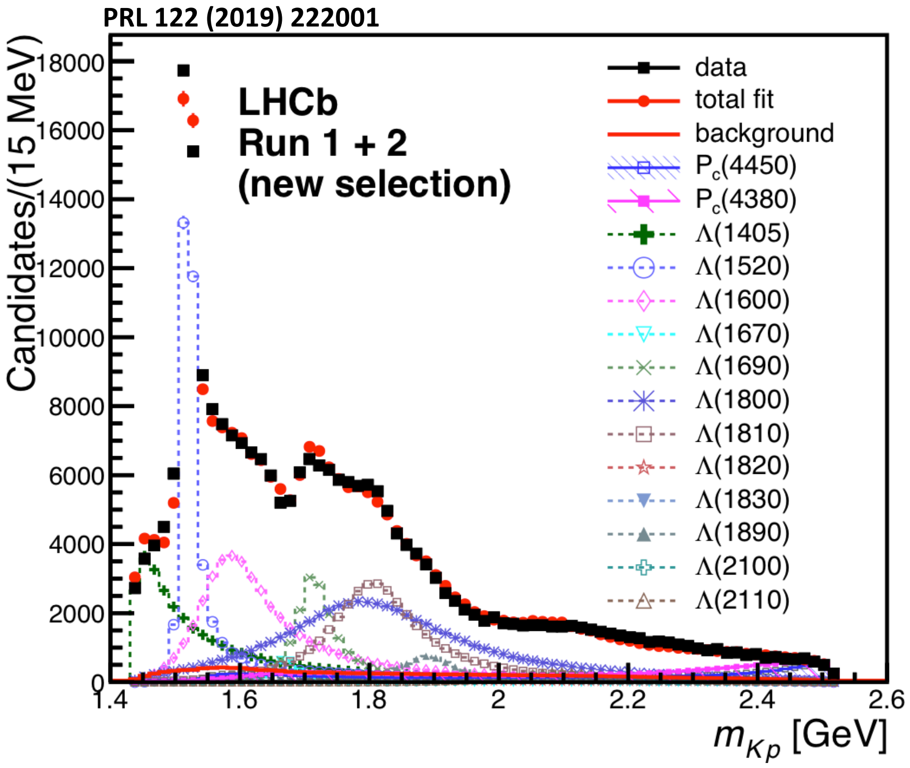
Signal yield

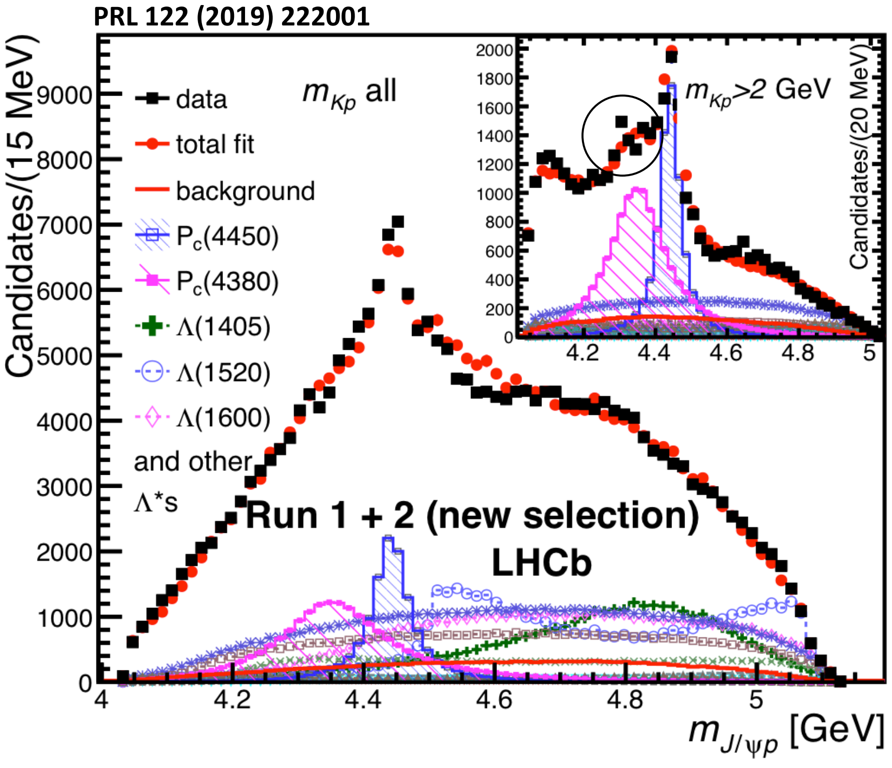
- An order of magnitude increases in signal yield
  - Inclusion of Run 2 data (x 5)
  - Improved data selection (x 2)



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



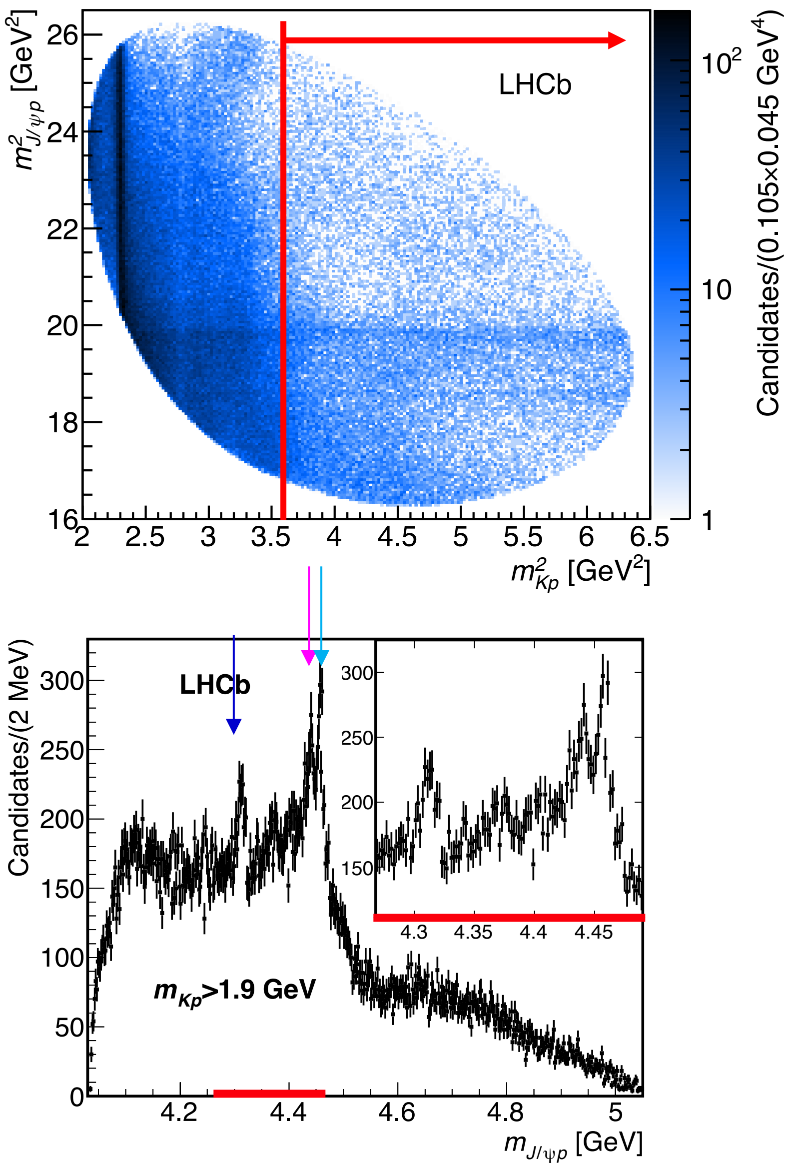


Display in smaller bin size

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 ⊗ 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

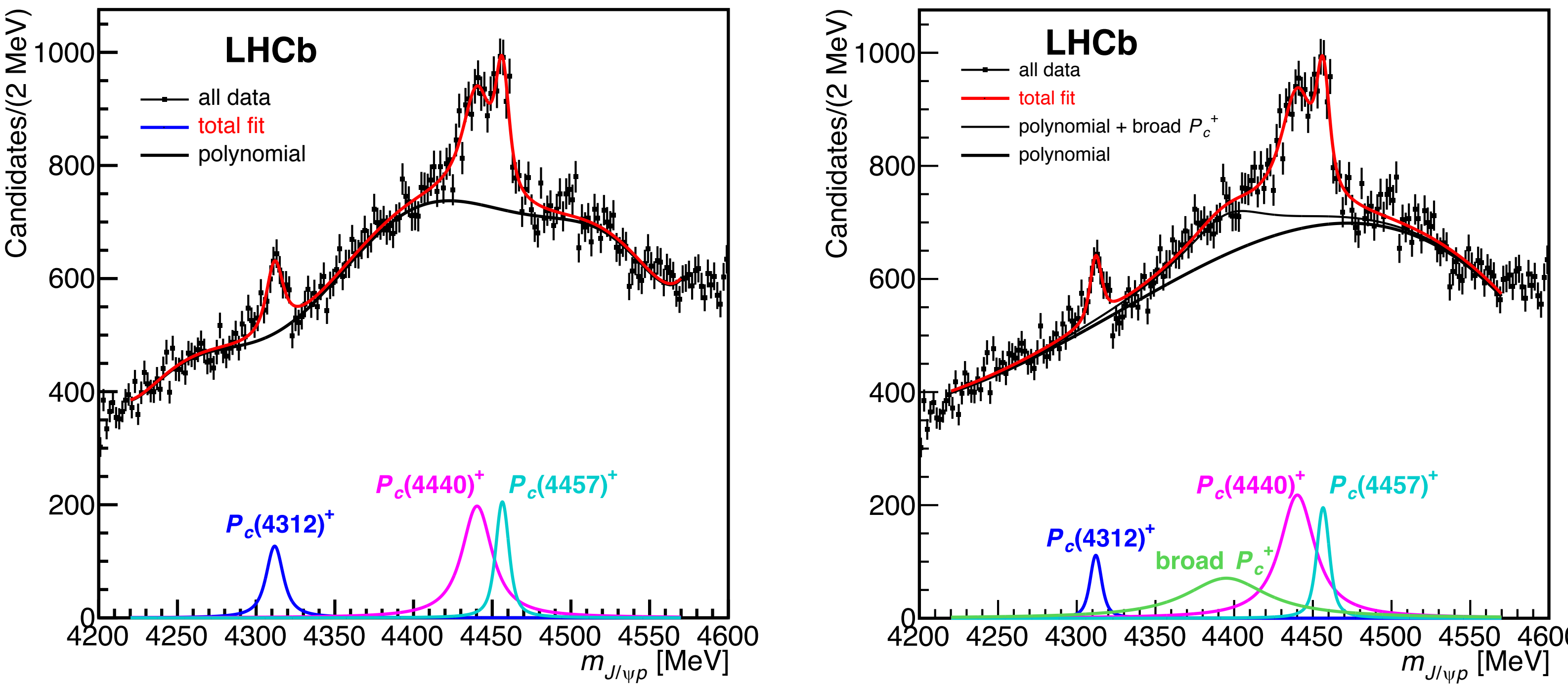
Fit-1: all candidates

PRL 122 (2019) 222001

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

high-order polynomial

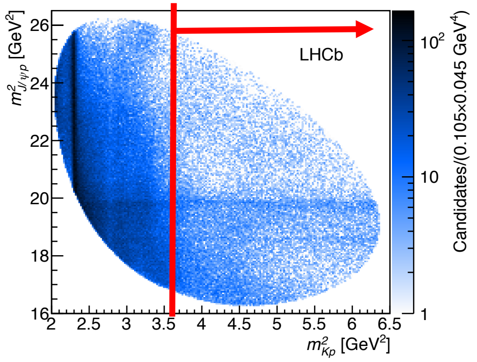
low-order polynomial + broad P_c^+ as bkg.

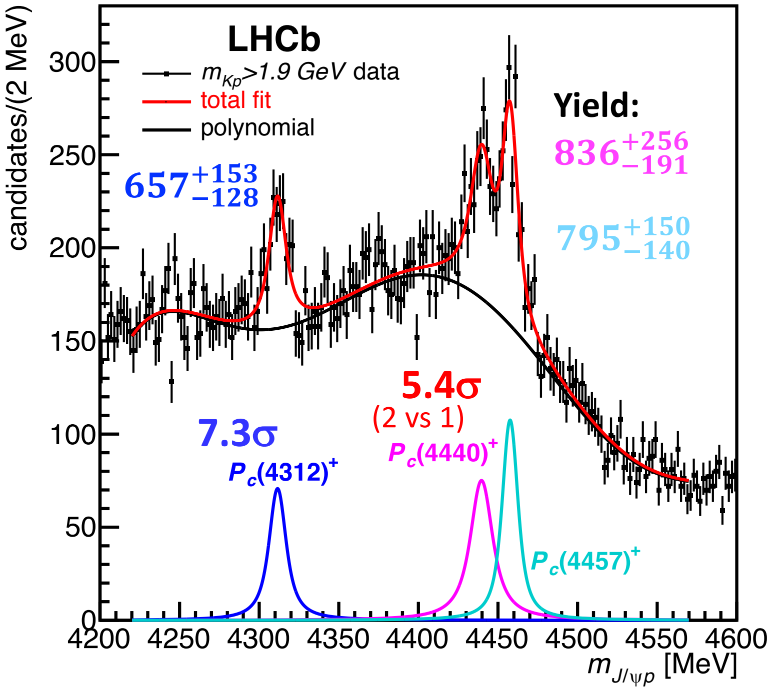


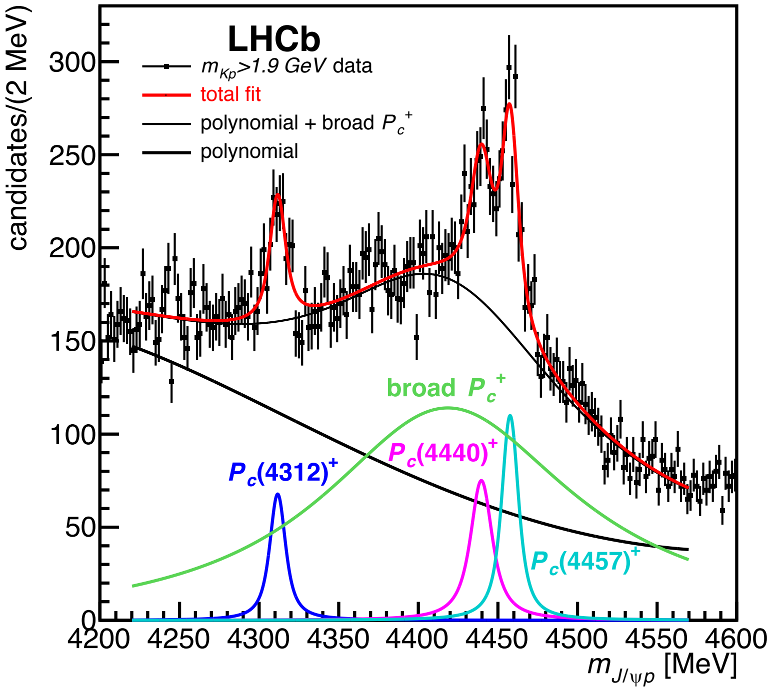
Fit-2: P_c^+ dominated region

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



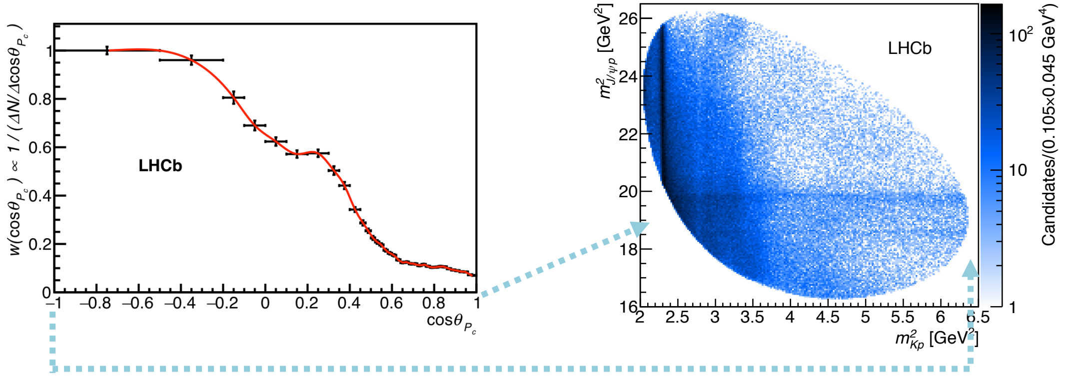




Fit-3: Novel method

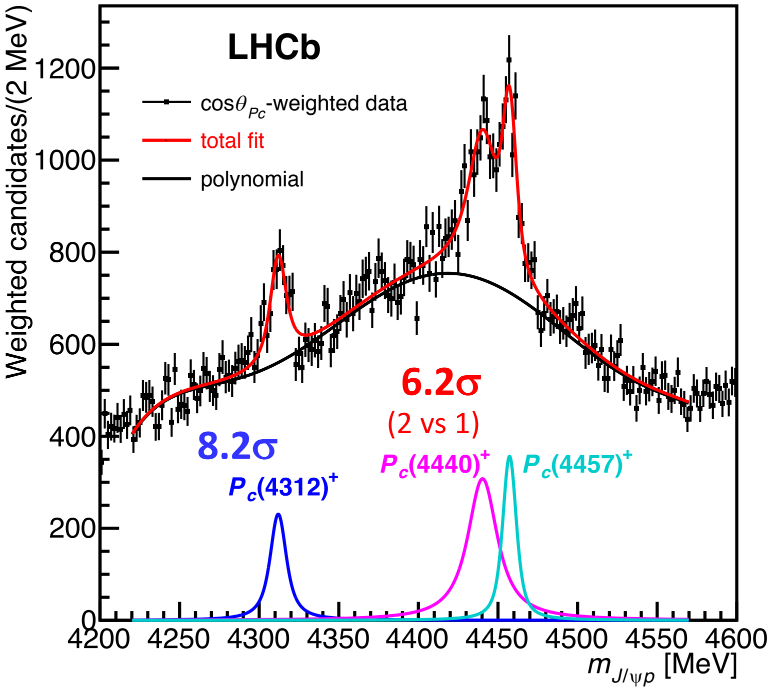
PRL 122 (2019) 222001

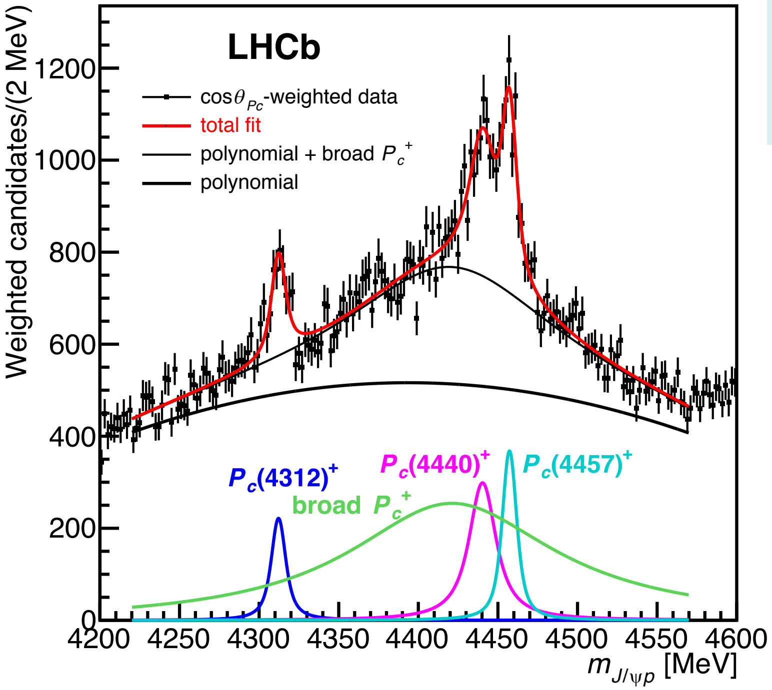
- Candidates weighted by $w(\cos\theta_{P_c}) = \frac{1}{\sigma^2_{\text{stat.}}} \approx \frac{1}{S+B}$
  - w is inverse of $\cos\theta_{P_c}$ distribution of Λ_b^0 candidates with $m_{J/\psi p} \in [4.2, 4.6]$ GeV
- Most statistically sensitive method



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

Nominal fit for M&Γ measurements





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

Systematic uncertainties

PRL 122 (2019) 222001

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**

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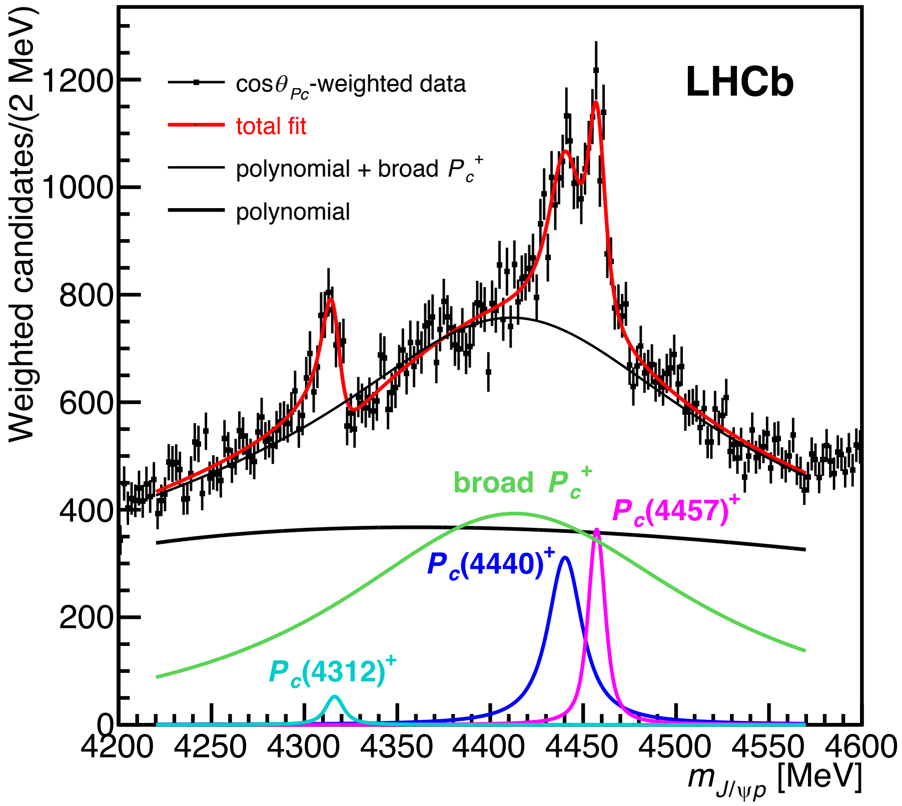
Fits with interferences

PRL 122 (2019) 222001

- 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 interference
  - 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^+



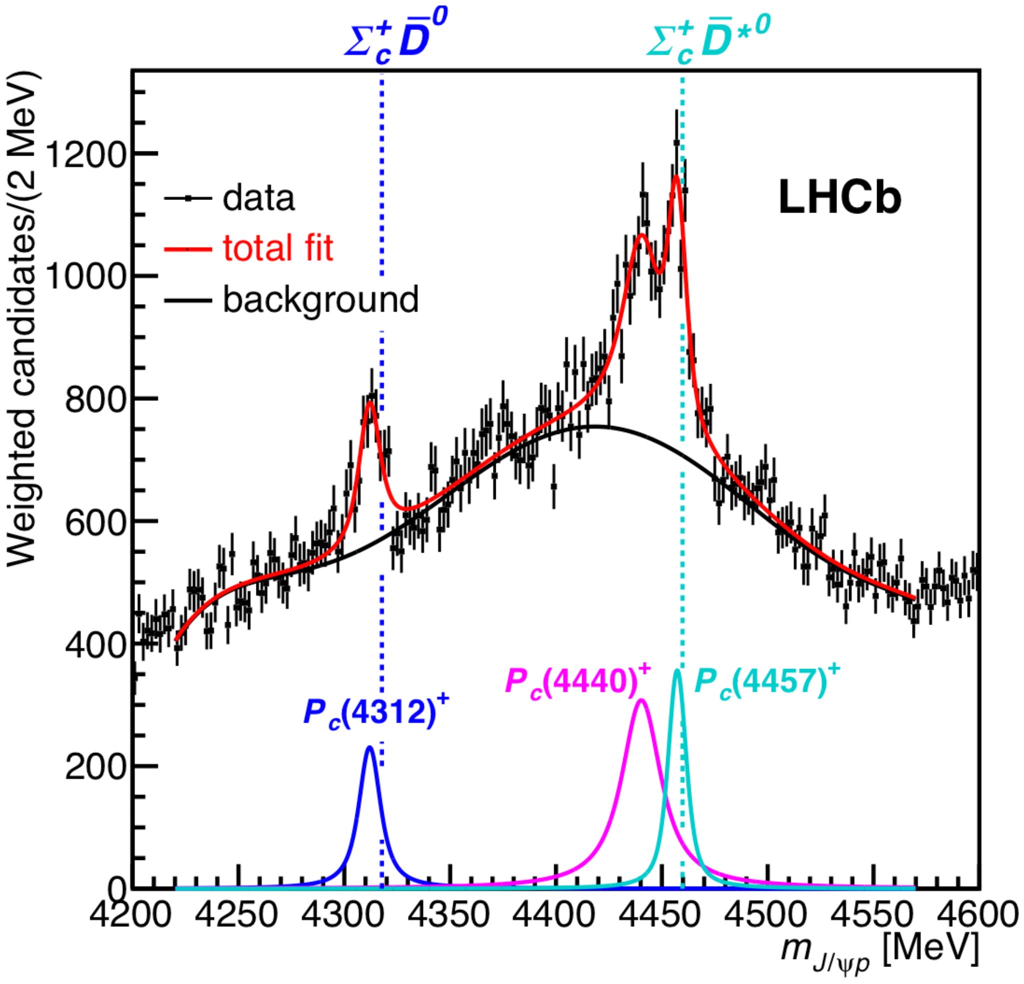
Plausible interpretation

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**

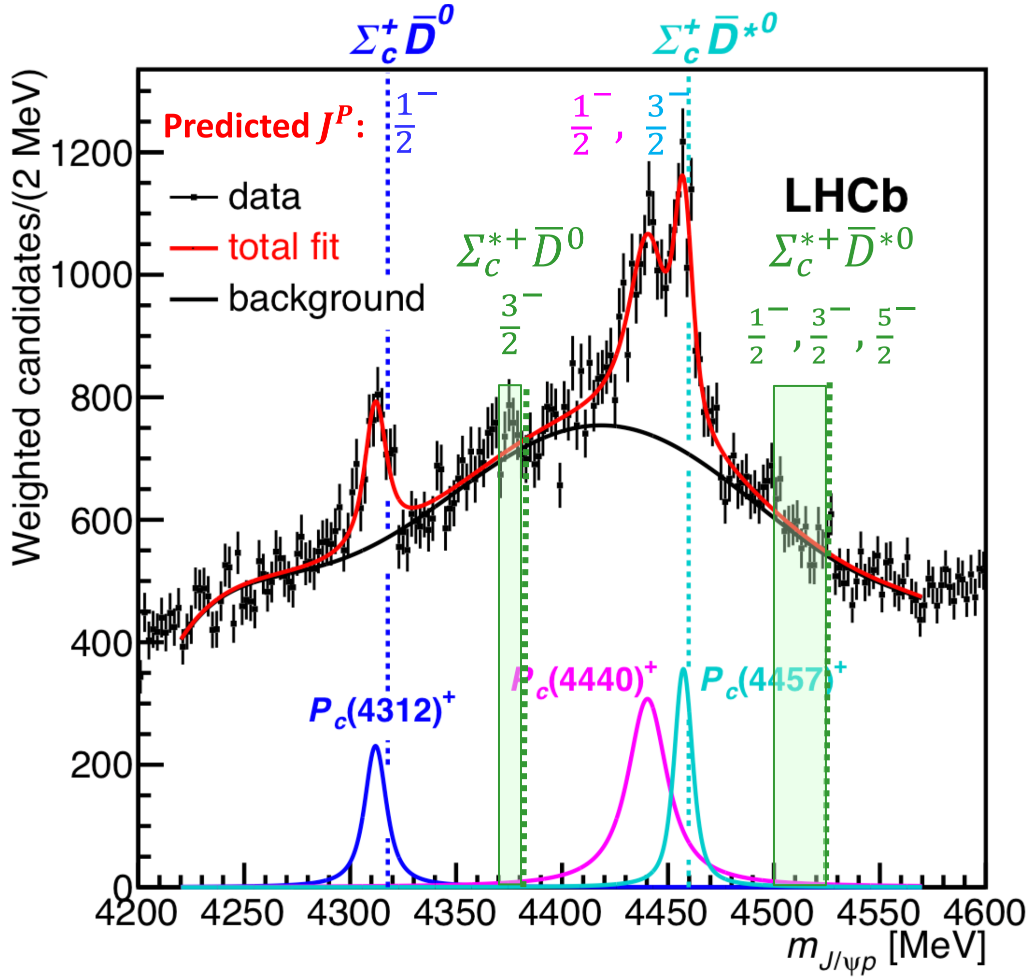


Predictions with molecular picture

- 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	$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	$3.2-3.5$	$4523.3-4523.6$



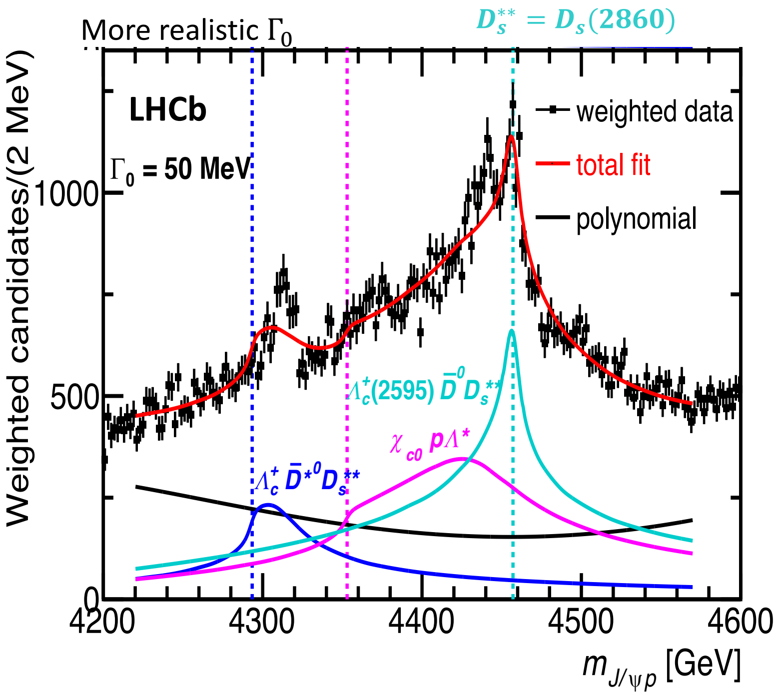
Triangle diagrams?

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

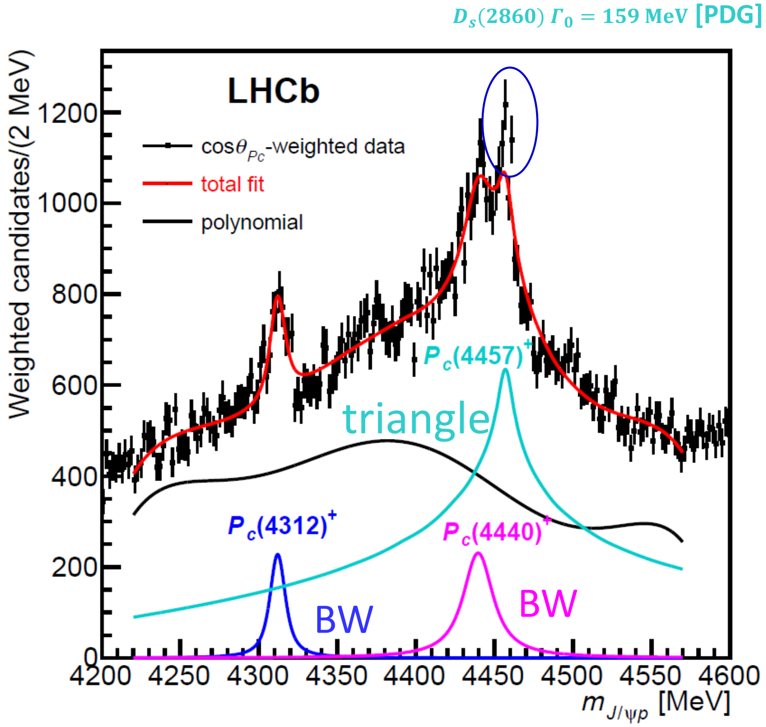
$P_c(4312)^+$, $P_c(4440)^+$ are too far from any rescattering thresholds

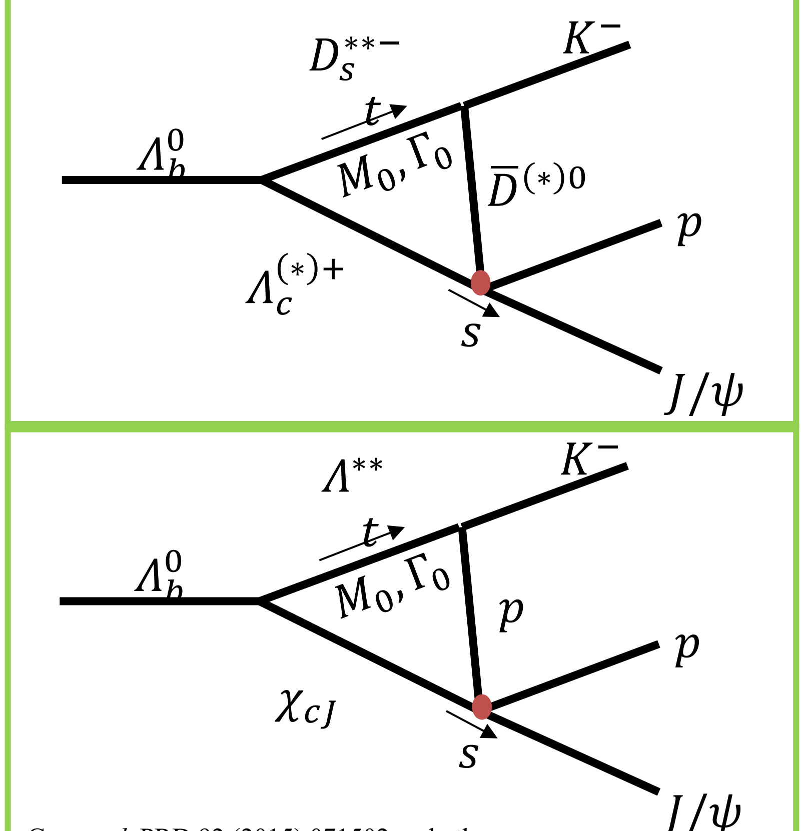
3 triangle-diagram amplitudes + polynomial



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

2BW + 1 triangle-diagram amplitudes + polynomial





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

Prospects

Analyses to update

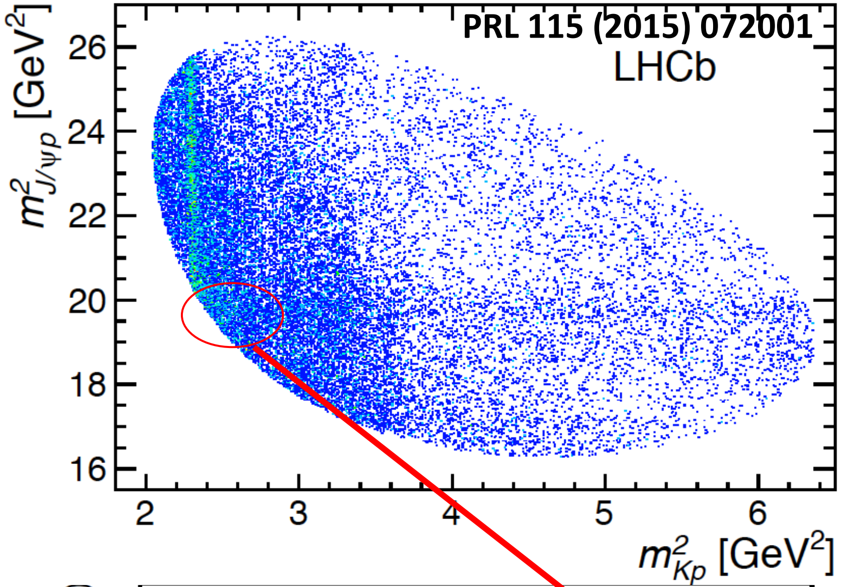
- $\Lambda_b^0 \to J/\psi p K^-$ amplitude analysis
  - J^P and $P_c(4380)^+$?
- $\Lambda_b^0 \to J/\psi p \pi^-$ amplitude analysis
  - To study the production of observed P_c^+
  - Find evidence of exotic hadron contribution in Run-1 data [PRL 117 (2016) 082003]

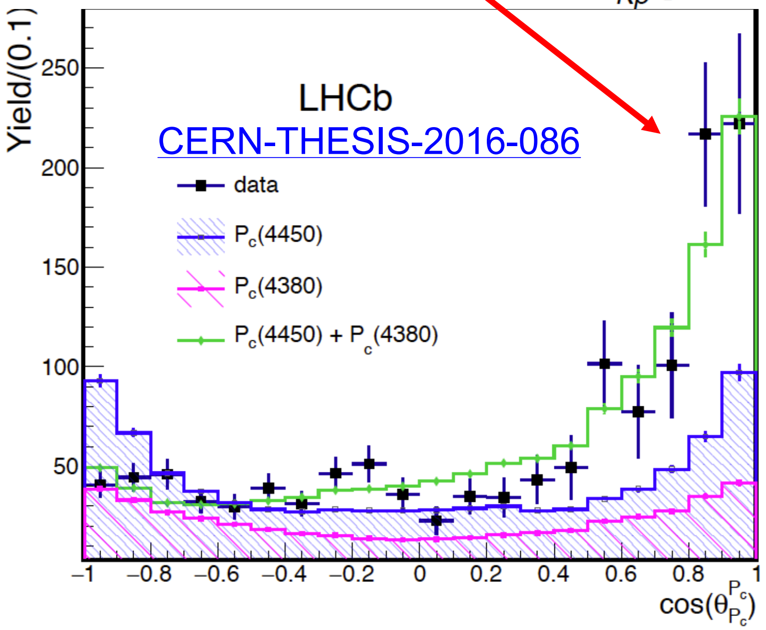
More interesting ideas

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

Amplitude analysis of $\Lambda_b^0 \to J/\psi p K^-$

- Works needed
  - Include $m(J/\psi p)$ resolution
  - Improve resonance modelling
- To cross-check our helicity-formalism with covariant approach [A. Pilloni *et. al.* arXiv: 1805.02113]
  - Previous publication, 2nd P_c^+ with opposite parity was motivated, because asymmetric P_c^+ angular distribution was found
  - Helicity-formalism shows interference with Λ^* cannot generate asymmetric P_c^+
- We would also like to check triangle diagram in the amplitude fit
  - Need 2D distribution model of triangle diagram

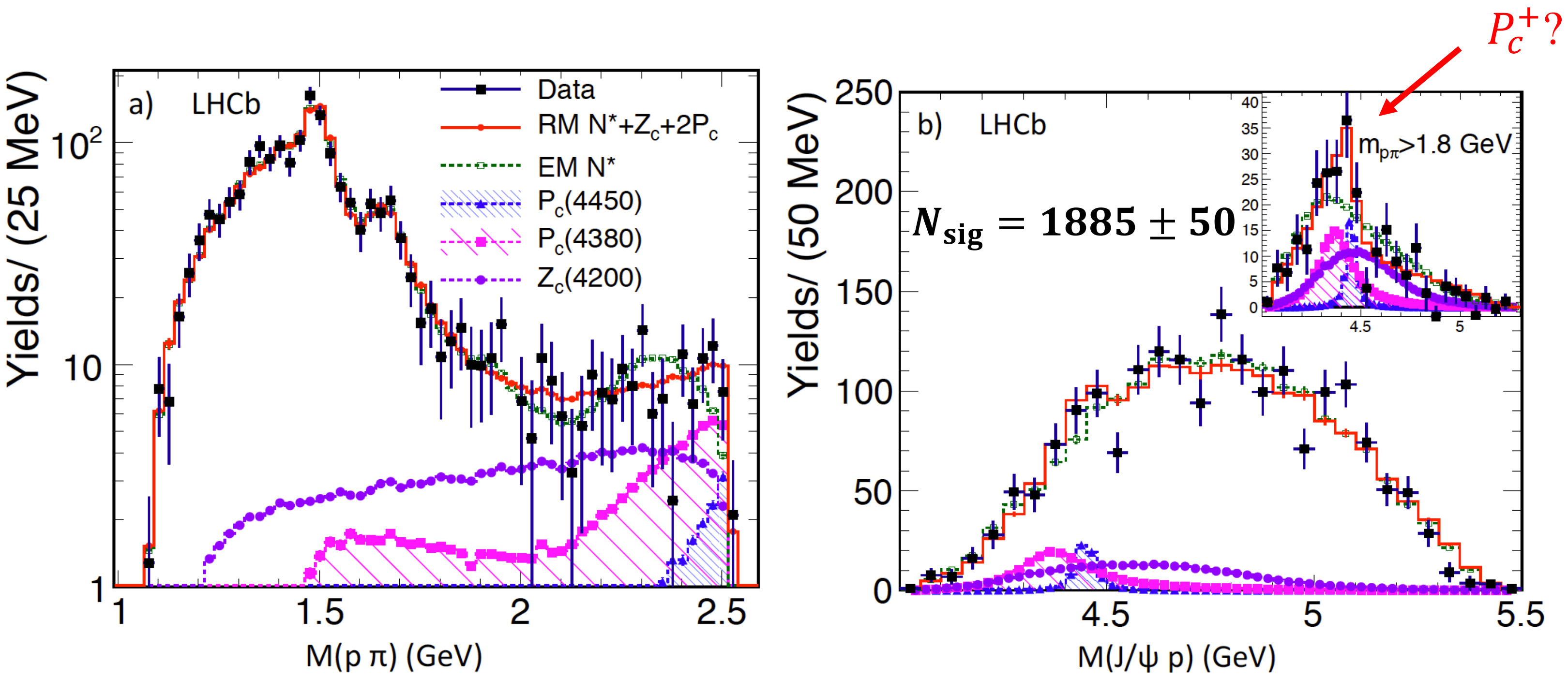




Amplitude analysis of $\Lambda_b^0 \to J/\psi p \pi^-$

- Finding the same P_c^+ in Cabbibo suppressed decays may suggest P_c^+ is not a triangle singularity
- Run-1 data shows evidence of exotic hadron contributions in this channel
  - Possible contribution from P_c^+'s and $Z_c(4200)^-$
- **~10,000 signal events are expected in full LHCb dataset**

PRL 117 (2016) 082003



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

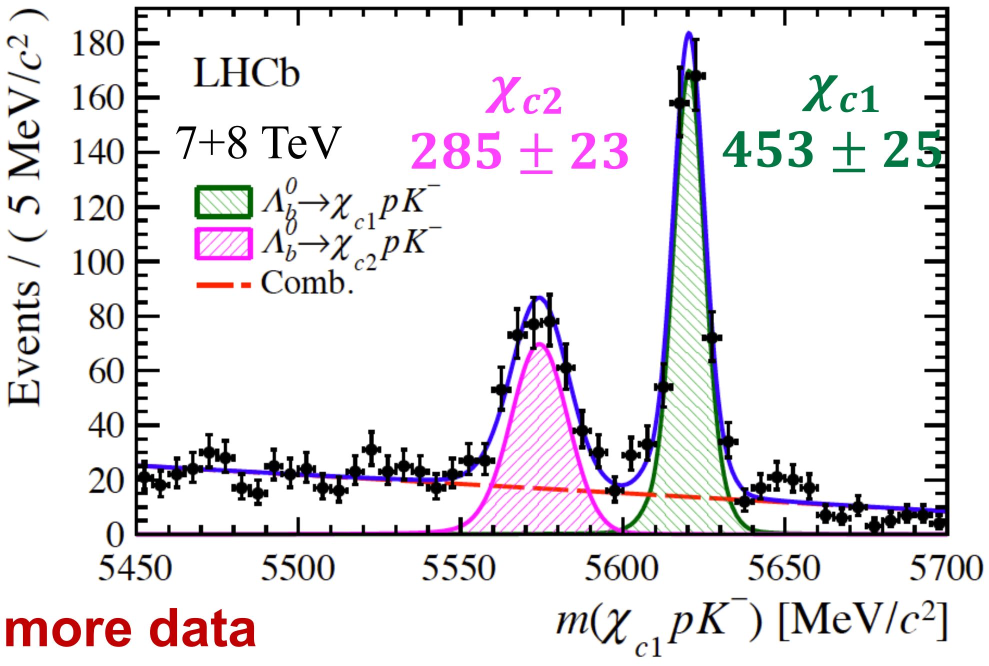
- First step: observe the decays, measure $\mathcal{B}$
- Use $\chi_{c(1,2)} \to J/\psi\gamma$, constrain $J/\psi\gamma$ mass to known χ_{c1} mass

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

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

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

PRL 119 (2017) 062001

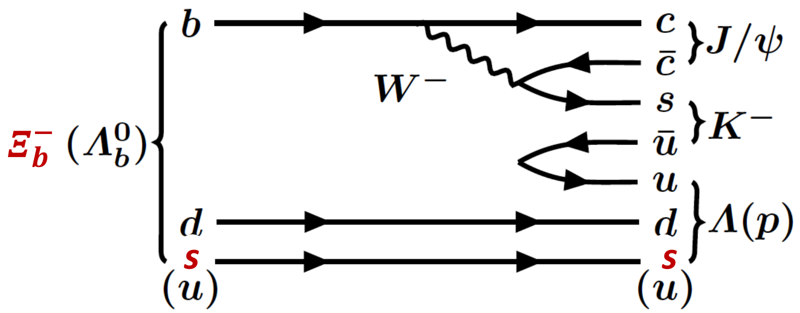


Next step: full amplitude analysis with more data

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

PLB 772 (2017) 265-273

- Strange pentaquark $P_{cs}^0(uds c\bar{c})$ predicted in
  [PRL 105 (2010) 232001]
- Can be searched for in the Ξ_b^- decay
  [PRC 93 (2016) 065203]

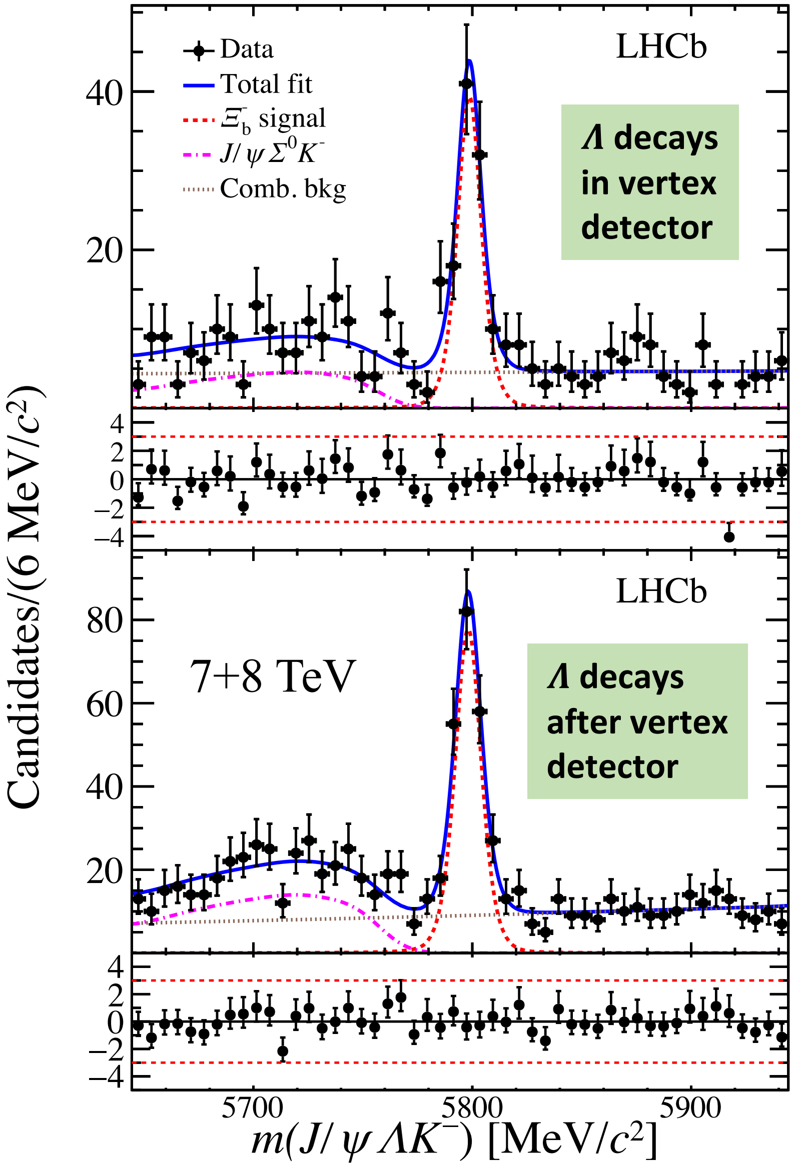


$N_{\rm sig} = 308 \pm 21$ (21σ)

Expect ~1500 signals with full dataset

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

Other possible channel to study P_{cs}^0, such as $\Lambda_b^0 \to J/\psi \Lambda \phi, J/\psi \Lambda \pi^+\pi^-$



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 information of the broad P_c^+ seen before will need detailed amplitude analysis.
- To further decipher their nature, the J^P measurement will be essential.

Backup

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

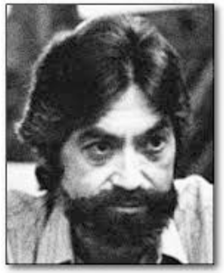
If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting 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"

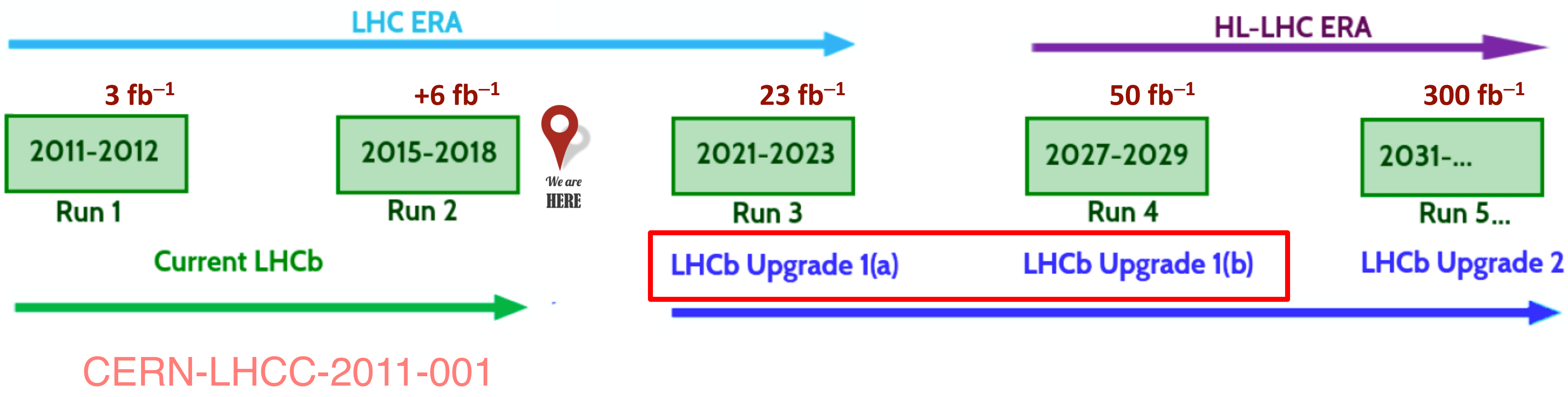
Why pentaquarks?

- Interest in pentaquarks arises from the fact that they would be new type of particles beyond 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

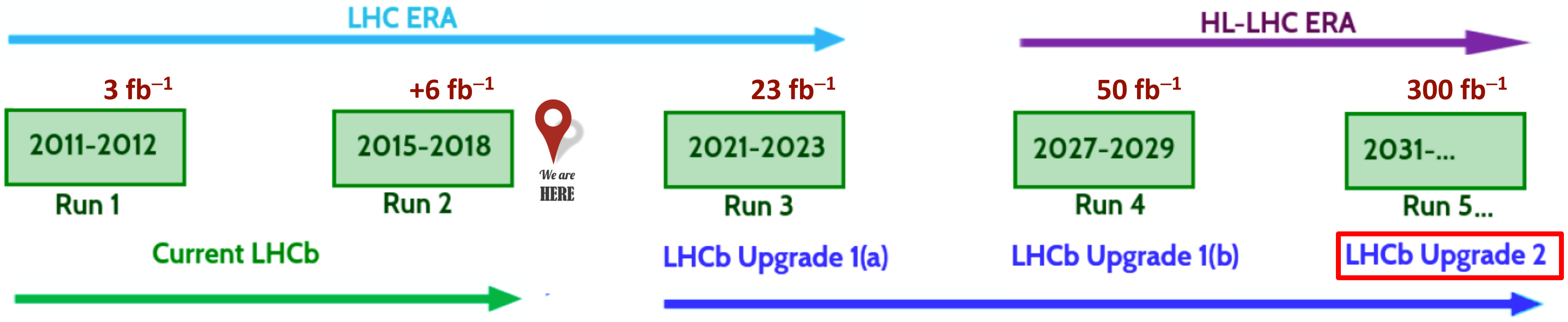
LHCb Upgrade I



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

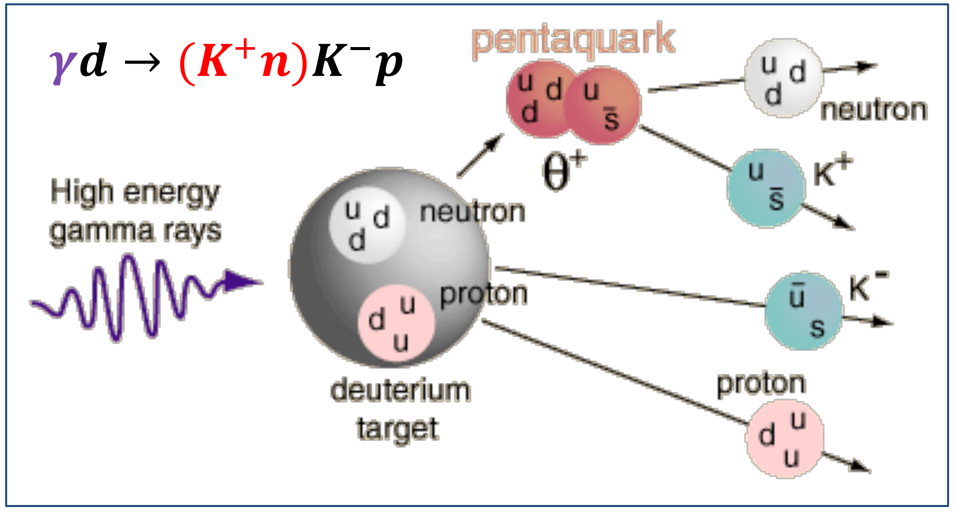
Decay mode	LHCb $23\,\text{fb}^{-1}$	LHCb $50\,\text{fb}^{-1}$	LHCb $300\,\text{fb}^{-1}$
$B^+ \to X(3872)(\to J/\psi\,\pi^+\pi^-)K^+$	14k	30k	180k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100
$\Lambda_b^0 \to J/\psi\, pK^-$ [*]	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

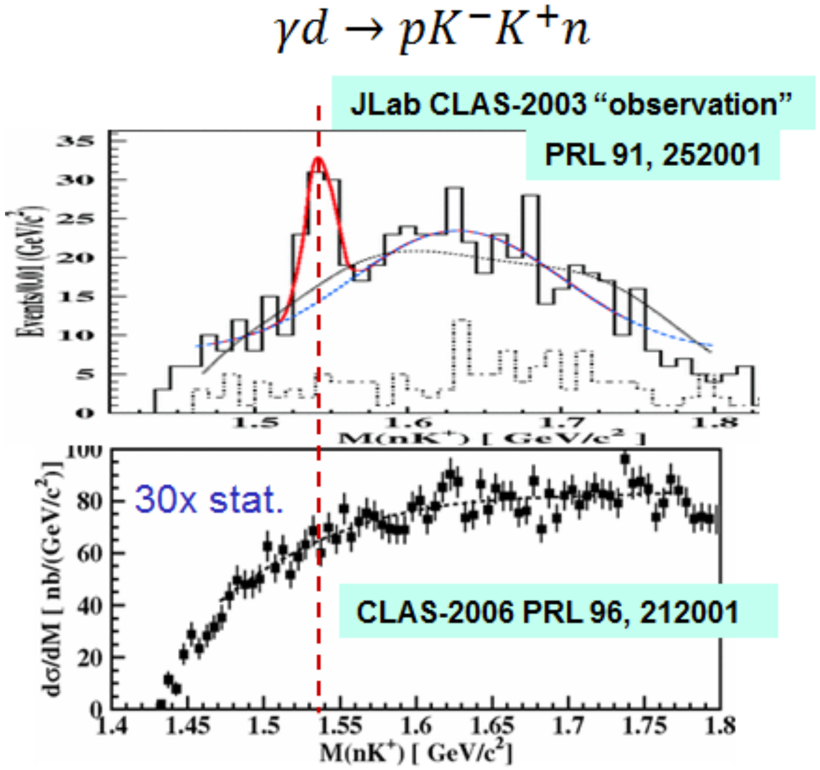
[*] updated according to the latest result

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

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**

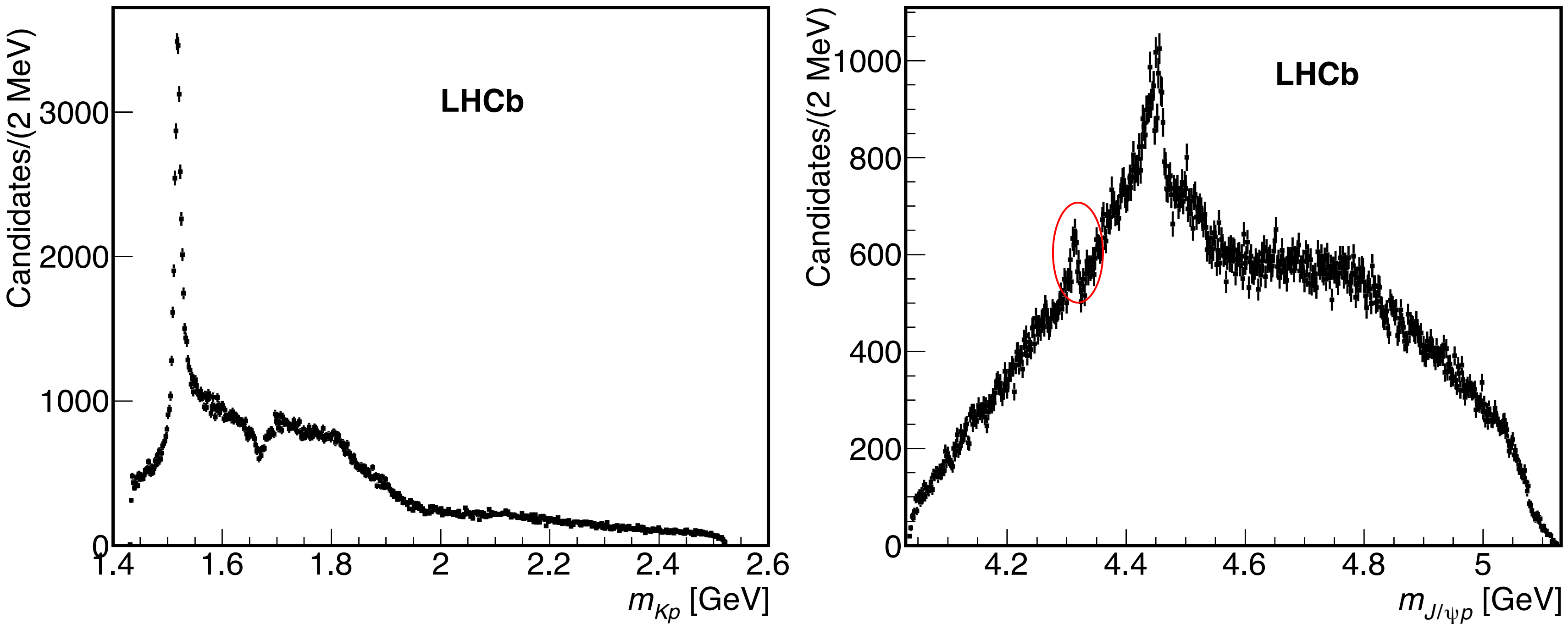




Display in smaller bin size

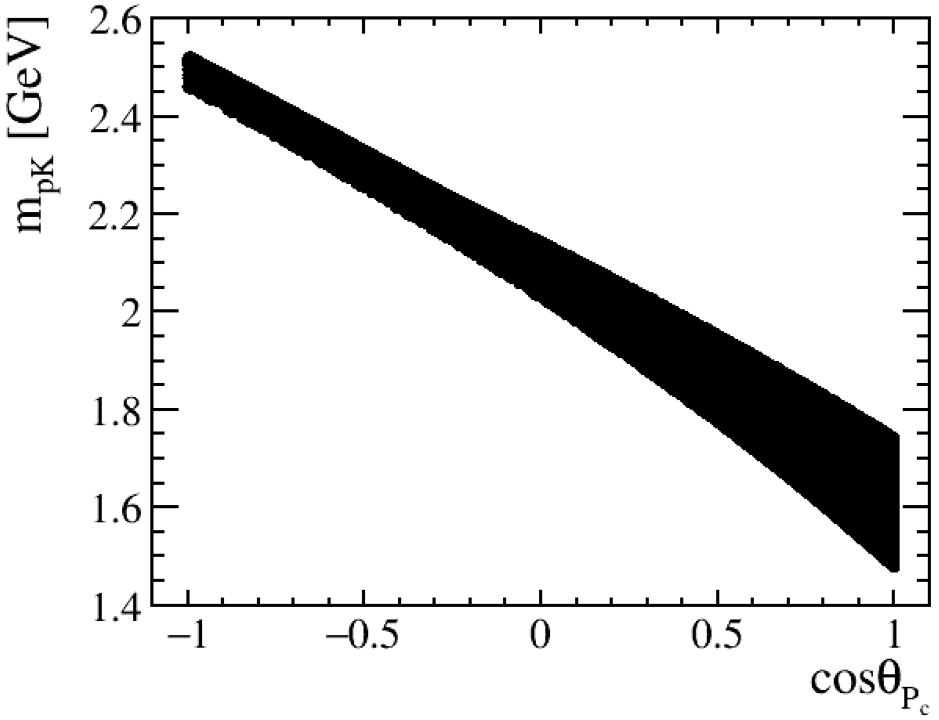
- More narrow structures emerge, shown in a 2 MeV (≈ mass resolution) bin size

PRL 122, 222001 (2019)



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

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



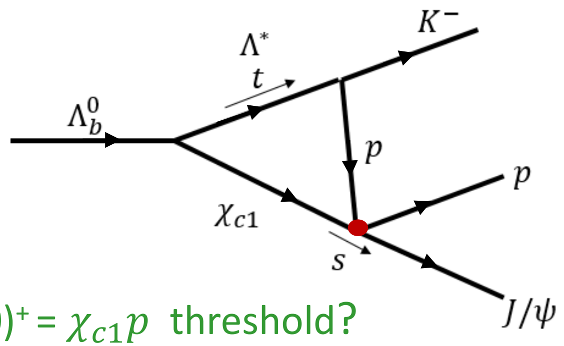
Systematic uncertainty

- The largest ones are due to interference effect

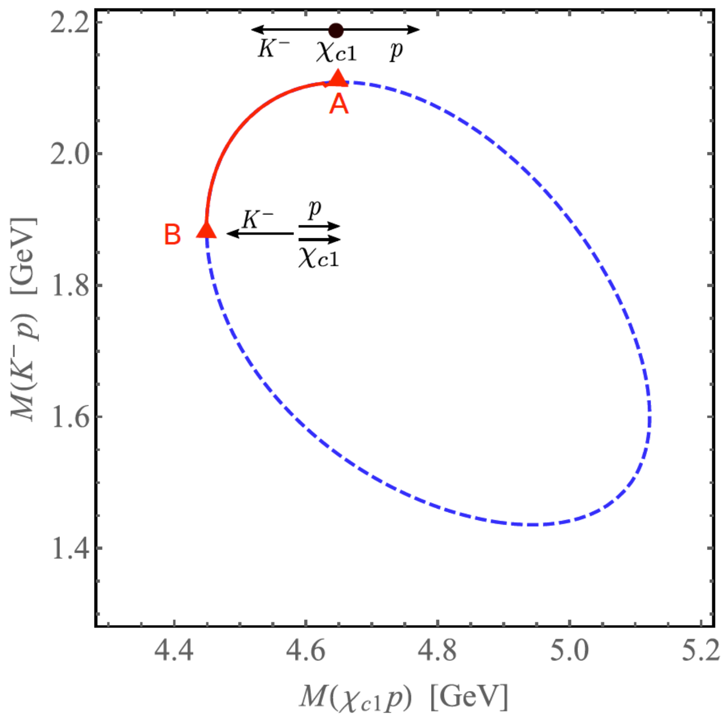
	$P_c(4312)^+$		$P_c(4400)^+$		$P_c(4457)^+$	
	M MeV	Γ MeV	M MeV	Γ MeV	M MeV	Γ MeV
value $\pm$ statistical error	4311.9 ± 0.7	9.8 ± 2.7	4440.3 ± 1.3	20.6 ± 4.9	4457.3 ± 0.6	6.4 ± 2.0
bkg.subtr. & cut variation	${}^{+0.8}_{-0.6}$	${}^{+3.7}_{-4.5}$	${}^{+0.1}_{-1.1}$	${}^{+4.6}_{-8.2}$	${}^{+0.4}_{-1.7}$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

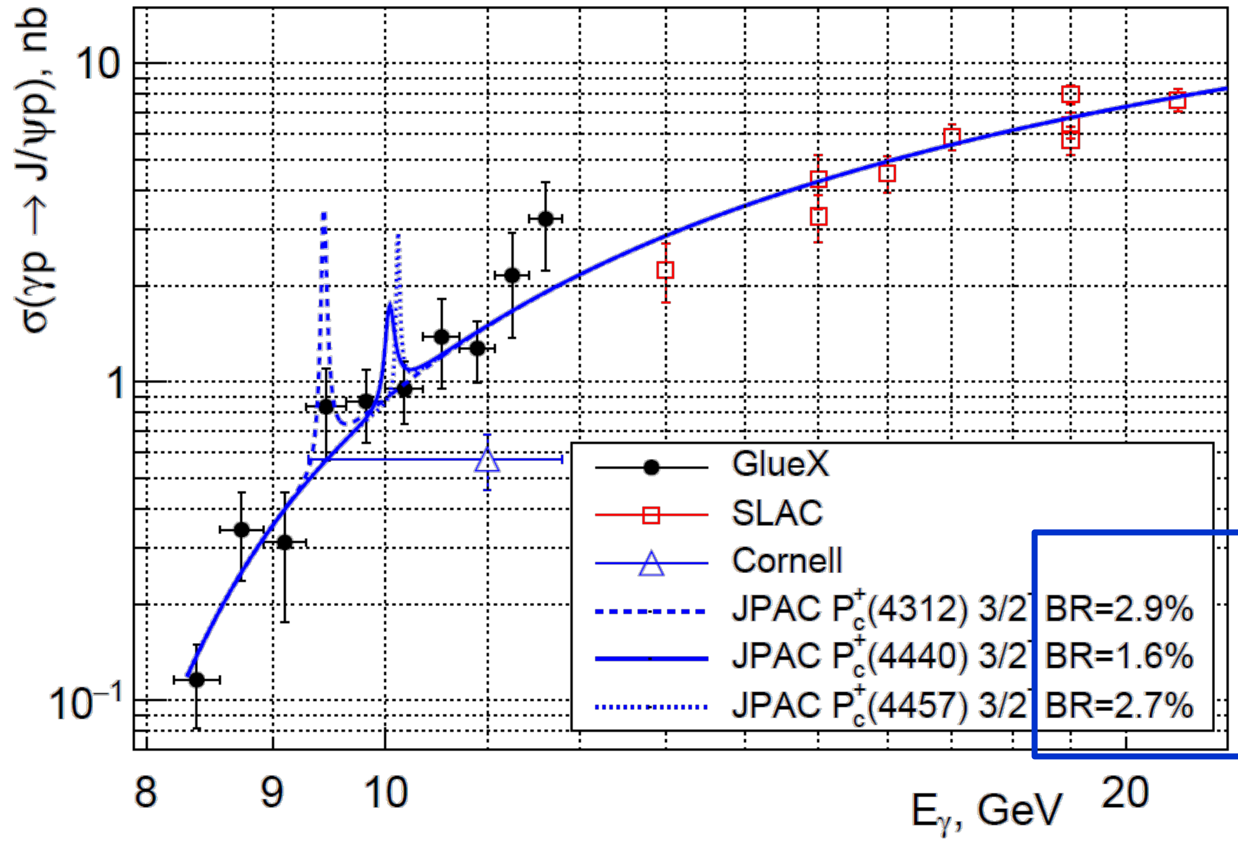


Requirements:

- 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

Very recent GlueX results

"First measurement of near-threshold J/ψ exclusive photoproduction off the proton"
GlueX Collaboration, **May 26, 2019**, PRL 123 (2019) 072001



"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