Pentaquarks at LHCb

(On behalf of the LHCb collaboration)

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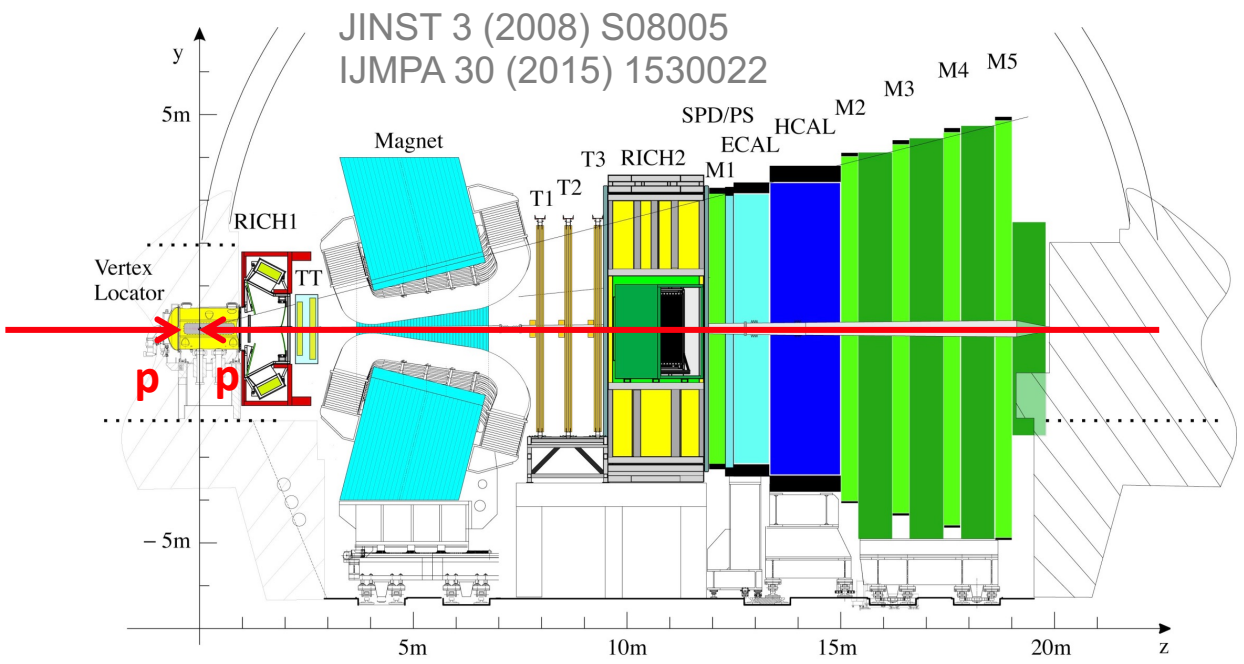
Hadron Spectroscopy:
The Next Big Steps

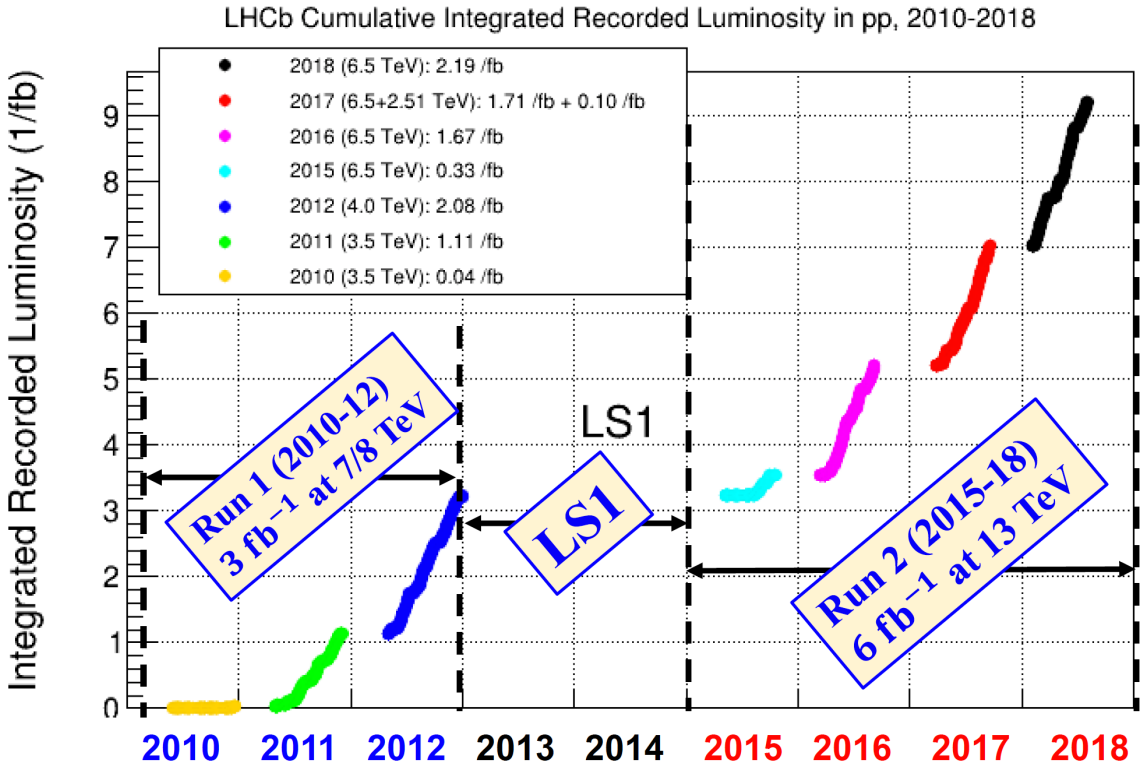
14-25, March, 2022

MITP, virtual workshop

The LHCb Experiment

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

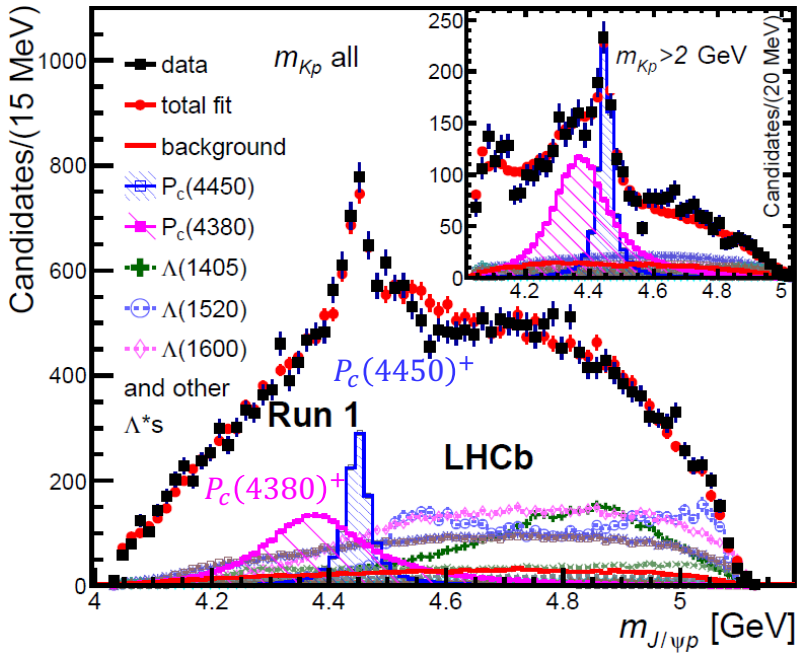


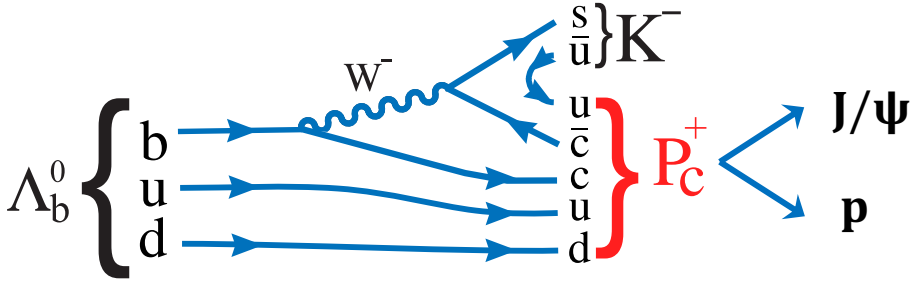


LHCb observation in 2015

- **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 $uudc\bar{c}$

26k Λ_b signals **PRL 115 (2015) 072001 (most cited paper at LHCb so far)**





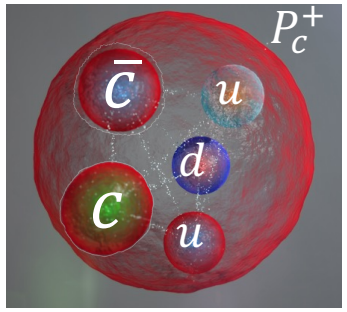
	$P_c(4380)^\pm$	$P_c(4450)^\pm$
Mass (MeV)	4380 ± 8 ± 29	4449.8 ± 1.7 ± 2.5
Width (MeV)	205 ± 18 ± 86	39 ± 5 ± 19
Fit Fraction (%)	8.4 ± 0.7 ± 4.2	4.1 ± 0.5 ± 1.1

Lots of open questions

- Observation of LHCb opens a gate to study pentaquarks
- To interpret the nature of P_c, more studies are needed
  - J^P, mode decay modes, production mechanism …?
  - SU(3) partners, hidden-bottom pentaquarks?
  - Inner structures?

Tightly-bound pentaquark?

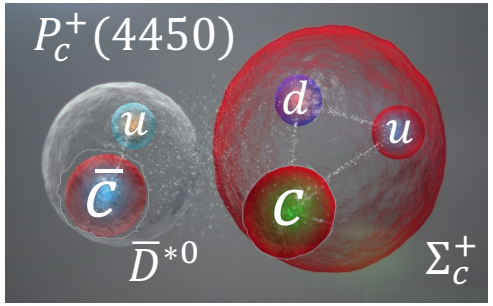
$M_{P_c^+} = M_{J/\psi} + M_p + \sim 400\text{MeV}$



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?

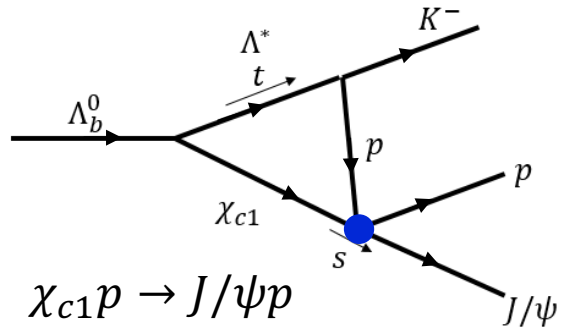
$M_{P_c^+} = M_{\bar{D}^{*0}} + M_{\Sigma_c^+} - \sim$few MeV



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?



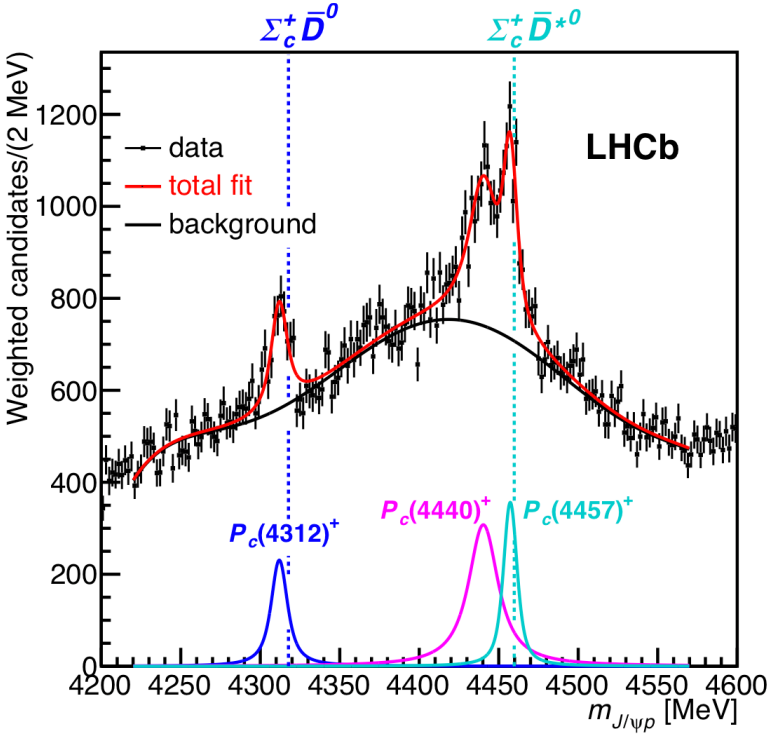
Guo,Meissner,Wang,Yang, PRD 92 (2015) 071502
Liu, Wang, Zhao, PLB 757 (2016) 231
Mikhasenko, arXiv:1507.06552
Szczepaniak, PLB 757 (2016) 61
and others

Fine structures from update

- Run1+Run2, x10 $\Lambda_b^0 \to J/\psi p K^-$ yield
  - Inclusion of Run 2 data (x 5)
  - Improved data selection (x 2)
- $P_c(4312)^+$ is observed
- $P_c(4450)^+$ peak structure is an overlap of two narrower states, $P_c(4440)^+$ and $P_c(4457)^+$
- Their near-threshold masses **favour** "molecular" pentaquarks with meson-baryon substructure, but **other hypotheses are not ruled out**

246k Λ_b signals

PRL 122 (2019) 222001



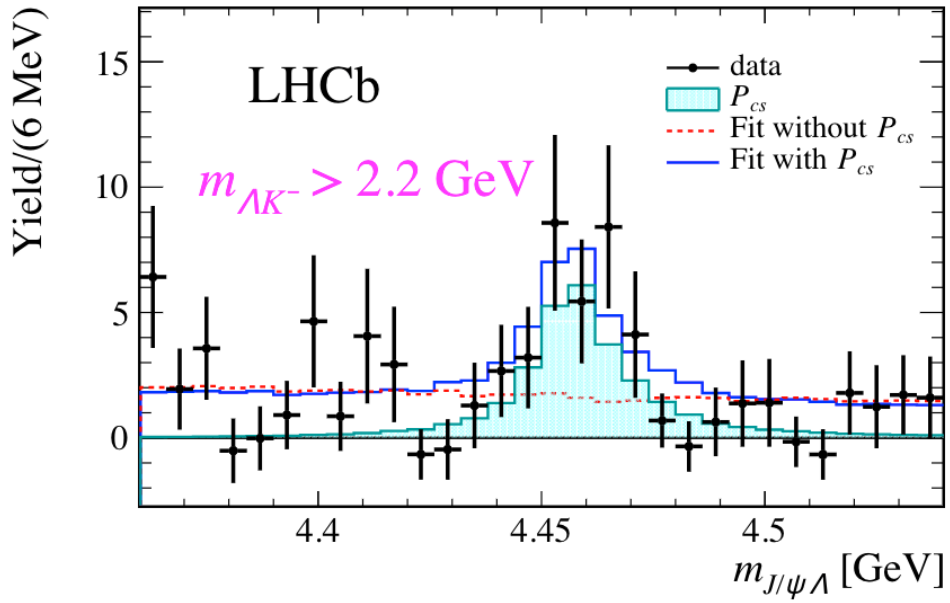
State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3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

1D $m_{J/\psi p}$ is fitted, full amplitude study is very advanced

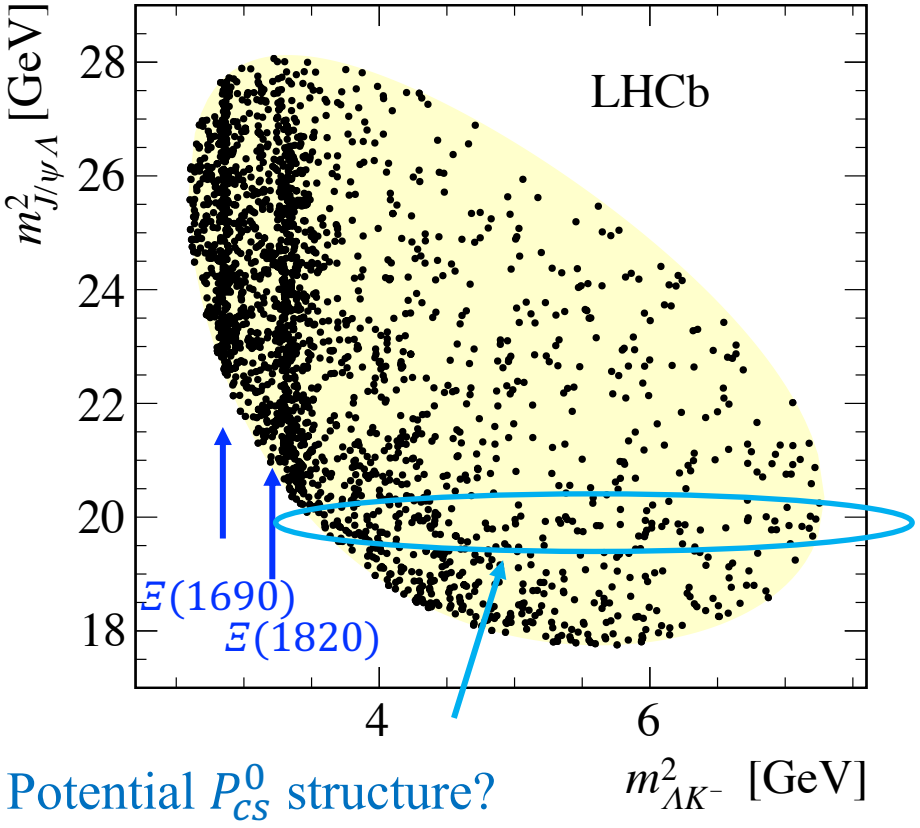
Evidence of $J/\psi\Lambda$ structure

[Science Bulletin 66 (2021) 1278]

- Hidden-charm pentaquark with strangeness P_{cs} is predicted, and suggested to search for in $\Xi_b^- \to J/\psi\Lambda K^-$
  [JJ Wu PRL 105 (2010) 232001; HX Chen PRC 93(2016) 064203]
- Amplitude analysis with improved helicity formalism
  - $P_{cs}(4459)^0$ found, significance >3.1σ



~1750 $\Xi_b^- \to J/\psi\Lambda K^-$ signals (purity ~80%)



Potential P_{cs}^0 structure?

Evidence of $J/\psi\Lambda$ structure

- **$P_{cs}(4459)^0$ mass is about 19 MeV below $\Xi_c^0\bar{D}^{*0}$ threshold**

State	M_0 [MeV]	Γ[MeV]	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$	$2.7\,^{+1.9\,+0.7}_{-0.6\,-1.3}$

- The peak position is consistent with $\Xi_c^0\bar{D}^{*0}$ molecule model prediction
- **More P_{cs} states are expected**; Molecular model predicted 10 states

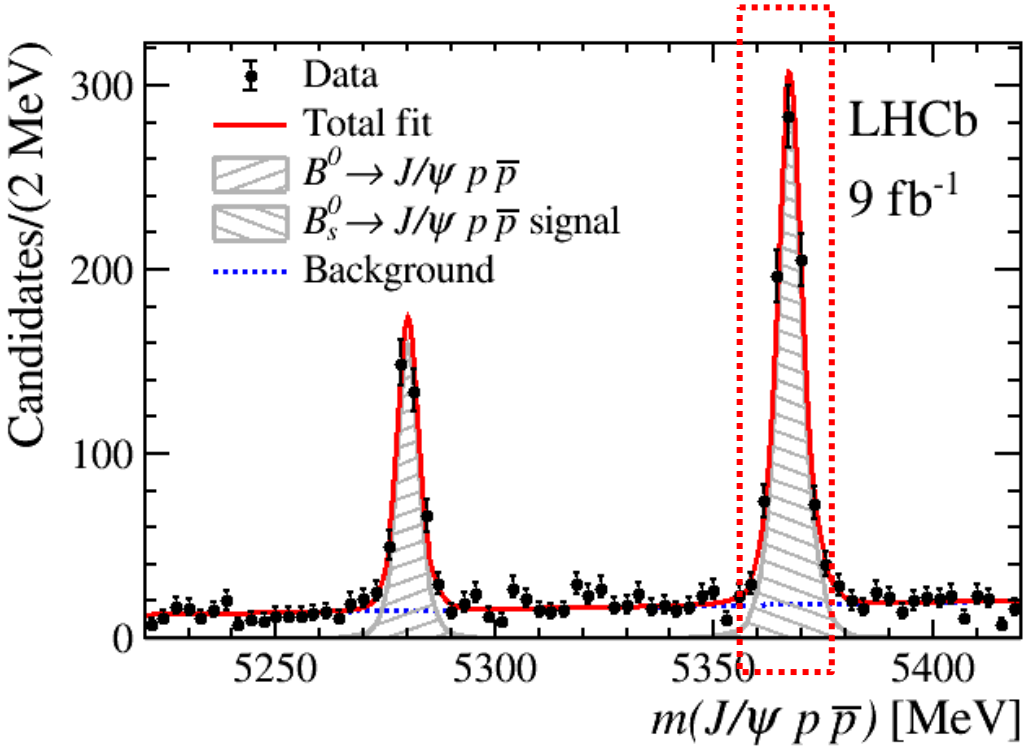
System	$[\Xi_c'\bar{D}]_{\frac{1}{2}}$	$[\Xi_c'\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c'\bar{D}^*]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{5}{2}}$	$[\Xi_c\bar{D}]_{\frac{1}{2}}$	$[\Xi_c\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c\bar{D}^*]_{\frac{3}{2}}$
ΔE	$-18.5^{+6.4}_{-6.8}$	$-15.6^{+6.4}_{-7.2}$	$-2.0^{+1.8}_{-3.3}$	$-7.5^{+4.2}_{-5.3}$	$-17.0^{+6.7}_{-7.5}$	$-8.0^{+4.5}_{-5.6}$	$-0.7^{+0.7}_{-2.2}$	$-13.3^{+2.8}_{-3.0}$	$-17.8^{+3.2}_{-3.3}$	$-11.8^{+2.8}_{-3.0}$
M	$4423.7^{+6.4}_{-6.8}$	$4568.7^{+6.4}_{-7.2}$	$4582.3^{+1.8}_{-3.3}$	$4502.9^{+4.2}_{-5.3}$	$4635.4^{+6.7}_{-7.5}$	$4644.4^{+4.5}_{-5.6}$	$4651.7^{+0.7}_{-2.2}$	$4319.4^{+2.8}_{-3.0}$	$4456.9^{+3.2}_{-3.3}$	$4463.0^{+2.8}_{-3.0}$

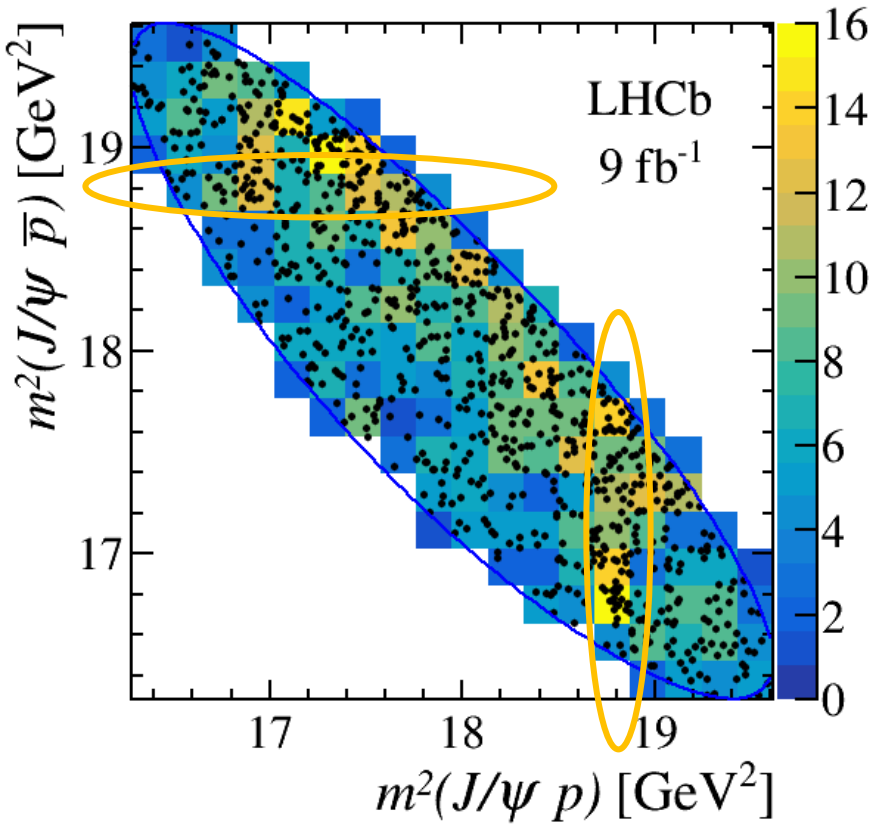
[Bo Wang, Lu Meng, Shi-Lin Zhu，PRD 101 (2020) 034018]

$B_s^0 \to J/\psi p\bar{p}$ decays

[arXiv:2108.04720]

- 9 fb^{-1} Run 1+2 data: ~800 signals, purity ~85%
- Hints for new $J/\psi p$ ($J/\psi \bar{p}$) structure ?

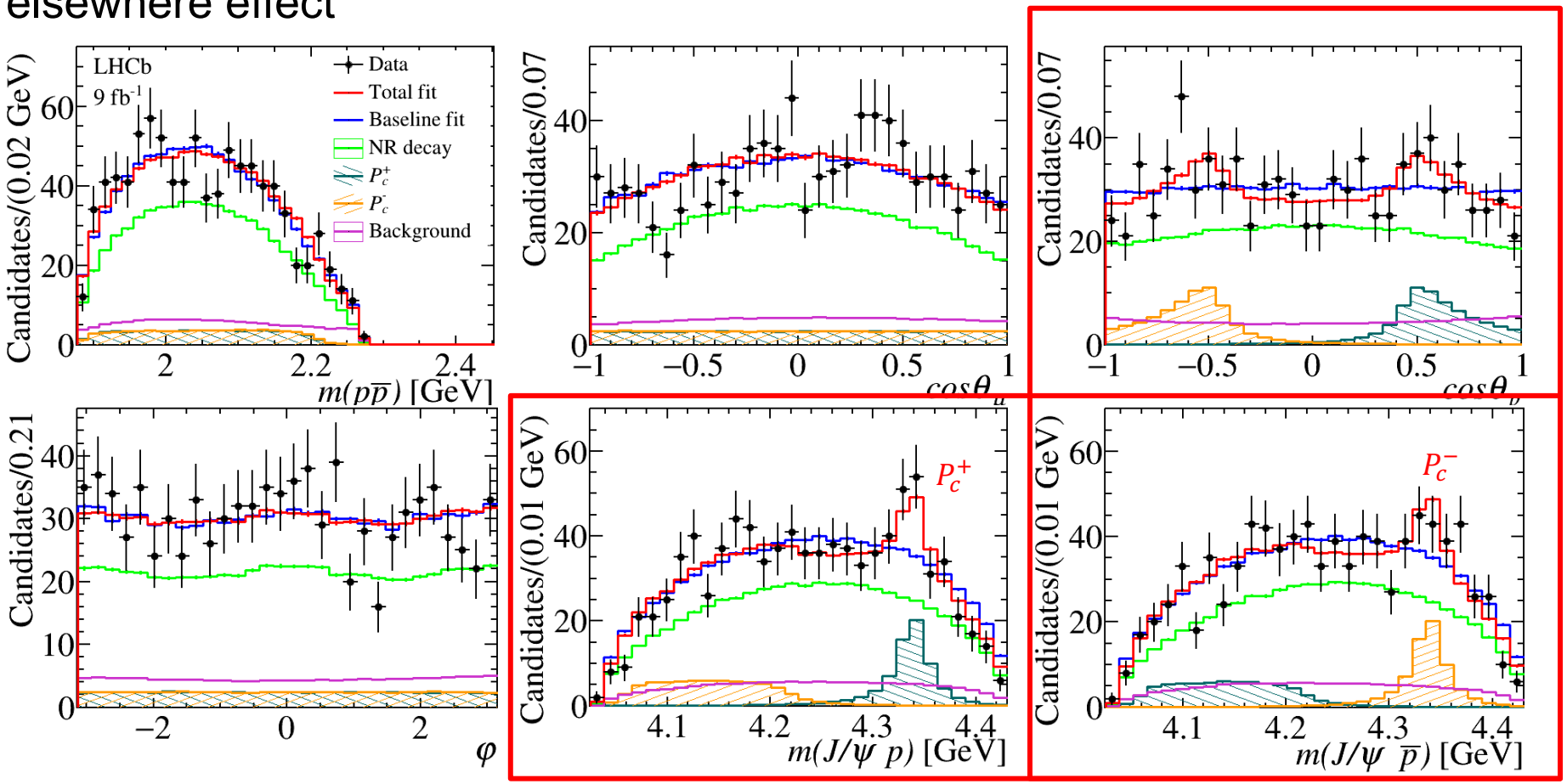




4D amplitude analysis

[arXiv:2108.04720]

- Untagged *B* decay, assuming *CP* conservation, the same mass, width and couplings for $P_c^{\pm}$
- Significance 3.1σ~3.7σ for J^P $(\frac{1}{2}^{\pm}, \frac{3}{2}^{\pm})$, after considering syst. uncertainties and look-elsewhere effect



No $P_c^{\pm}$ fit

W/ $P_c^{\pm}$ fit

Adding $P_c^{\pm}$ → better description of data distributions

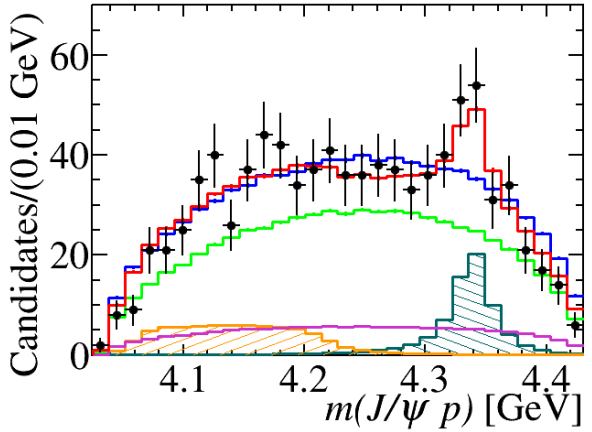
Evidence of $P_c(4337)$

[arXiv:2108.04720]

The measured mass and width:

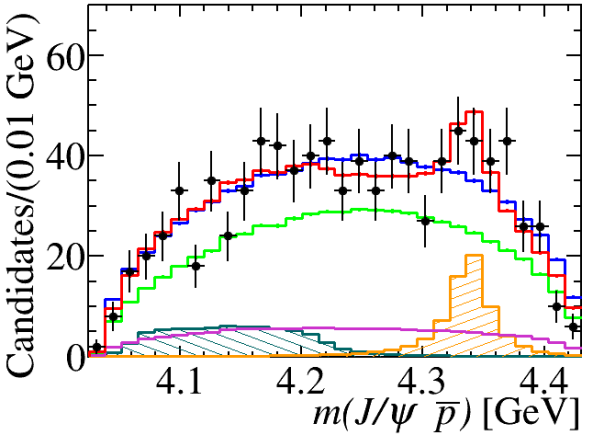
$$M_{P_c} = 4337^{+7}_{-4}(\text{stat})^{+2}_{-2}(\text{syst})\,\text{MeV},$$
$$\Gamma_{P_c} = 29^{+26}_{-12}(\text{stat})^{+14}_{-14}(\text{syst})\,\text{MeV},$$

Can't distinguish J^P due to limited sample size



Other contributions are tested, no evidence is seen:

- $P_c(4312)^+$ seen in $\Lambda_b^0 \to J/\psi p K^-$ [PRL 122 (2019) 222001]
- Predicted glueball state $f_J(2220)(\to p\bar{p})$ [EPJC 75, 101 (2015)]



Prospects

Analyses to update

- $\Lambda_b^0 \to J/\psi p K^-$ amplitude analysis (onging)
  - J^P and $P_c(4380)^+$?
  - A lots of improvements: model, formalism, resolution included, very good fit achieved
- $\Lambda_b^0 \to J/\psi p \pi^-$ amplitude analysis

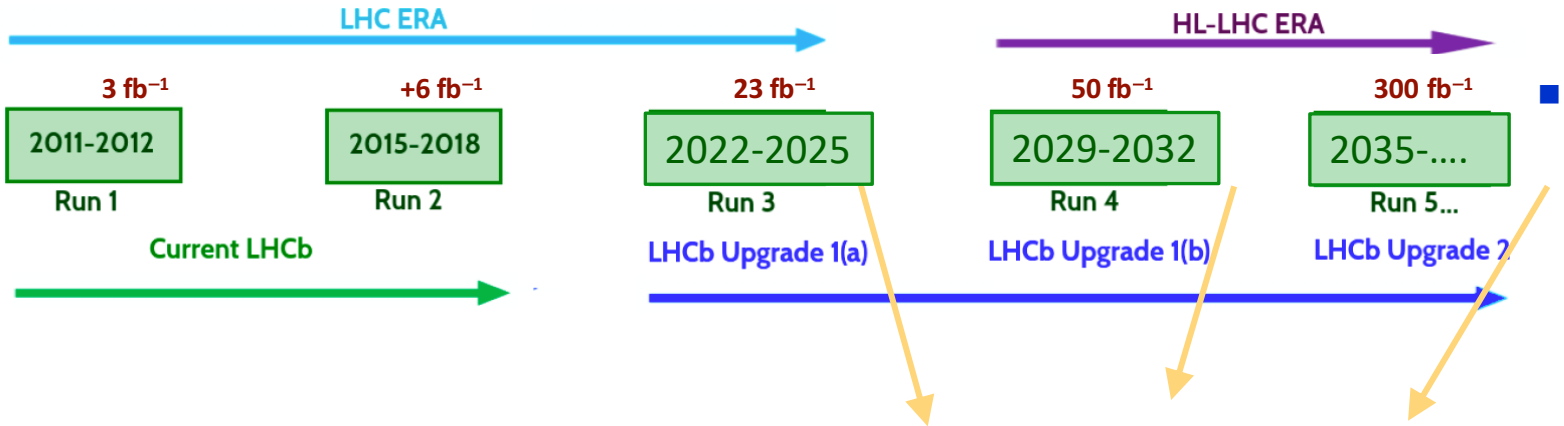
More interesting ideas

- Decay modes to other charmonium states than J/ψ, eg. η_c, χ_{c1}?
- Open charm baryon meson final state, eg. $\Sigma_c^{++} D^-$?
- Prompt production?
- **Open-charm pentaquarks?**

Most need more data

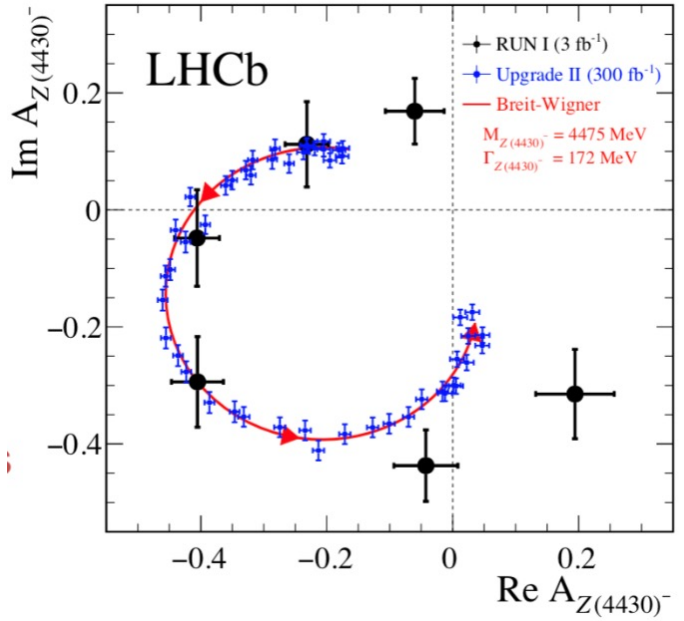
Prospects

[arXiv:1808.08865]



- **LHCb is now boosting the data to a new level**
  - **Expect to 3x data (6x hadronic events) by 2025**

Decay mode	LHCb 23 fb^{-1}	LHCb 50 fb^{-1}	LHCb 300 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
$\Lambda_b^0 \to J/\psi p K^-$ [*]	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

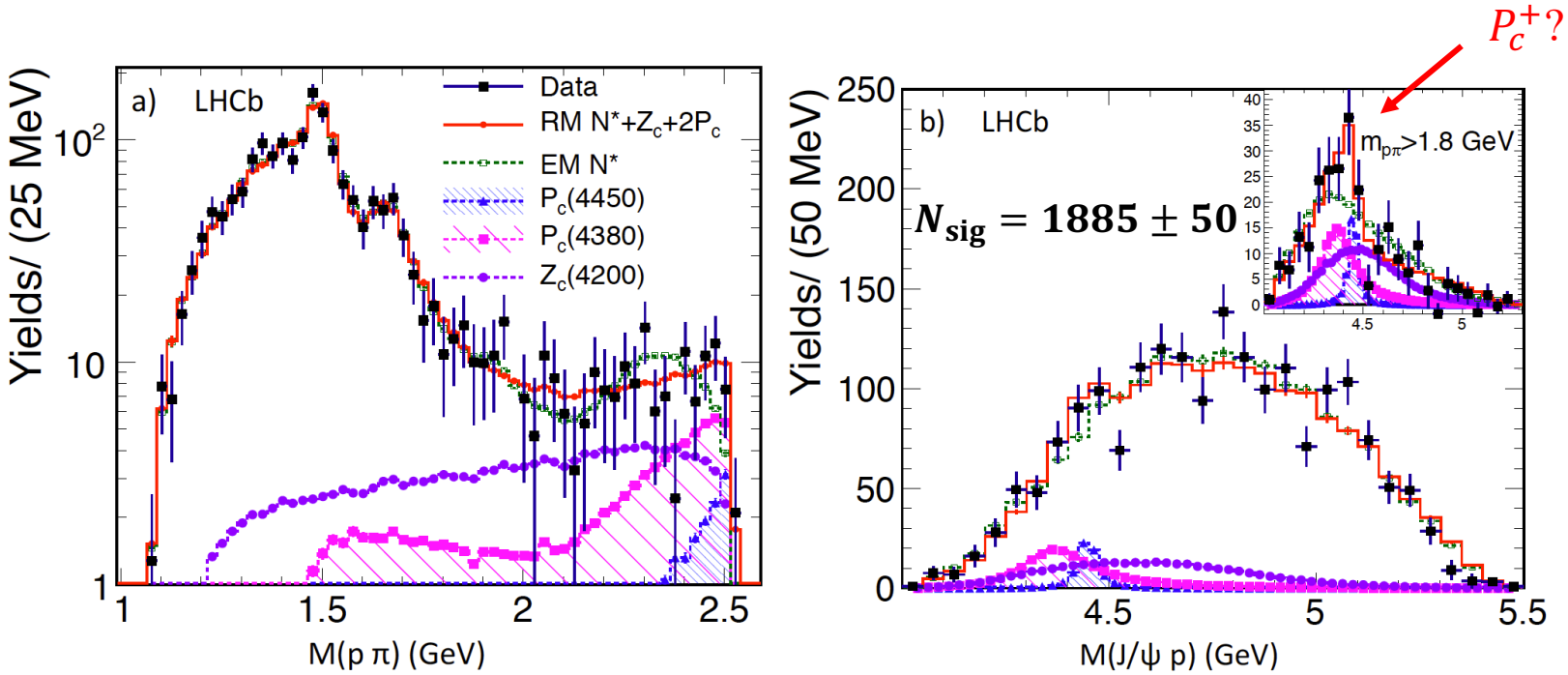


[*] updated according to the latest result

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

- Finding the same P_c^+ in other 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 $Z_c(4200)^-$
- **~10k signal events are expected in Run1+2 data, May need to wait for Run3 data to see the fine structure**

PRL 117 (2016) 082003



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

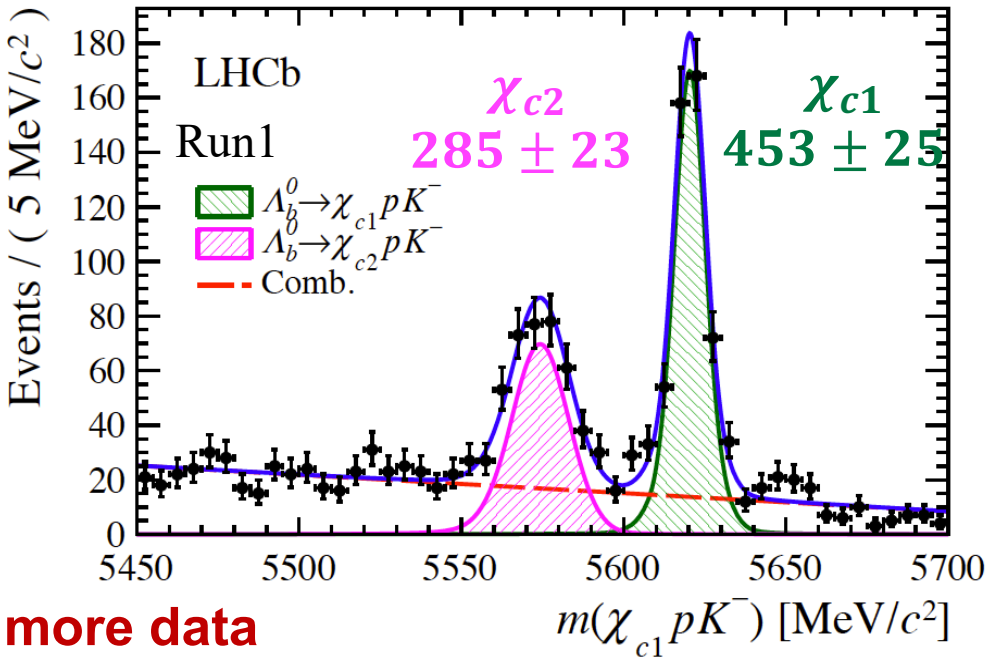
- Search for $P_c(4450)^+$ in $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$ decays PRD 92 (2015) 071502
  ⇒Test hypothesis of kinematic rescattering effect
- Expect ~2000 signal in run1+2 data

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

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

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

PRL 119 (2017) 062001



Next step: full amplitude analysis with more data

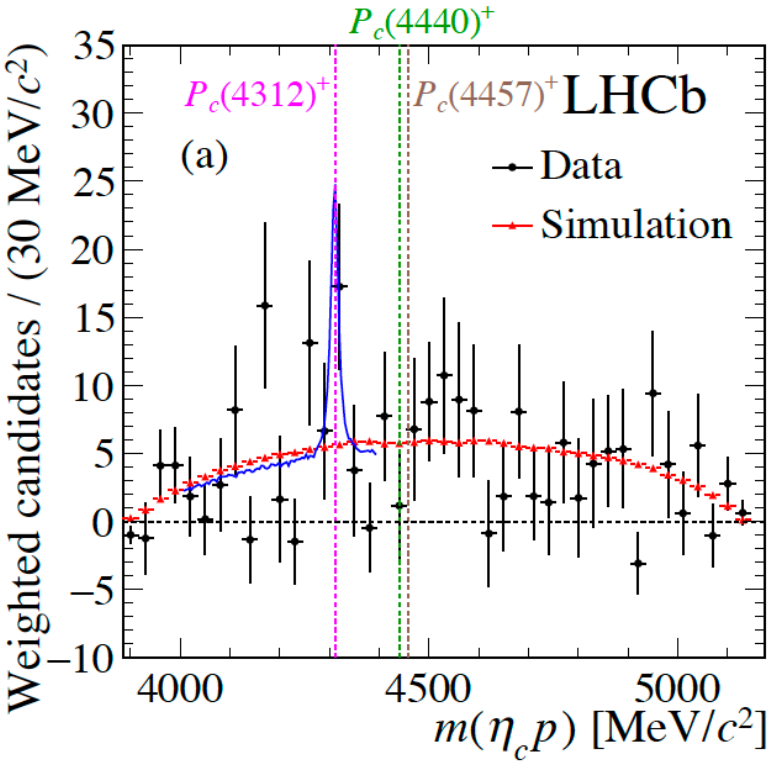
$\Lambda_b^0 \to \eta_c p K^-$

[PRD 102 (2020) 112012]

- **$\eta_c p$ final state is very sensitive to $1/2^-$ P_c, where $\eta_c p$ is in S-wave**
- If $P_c(4312)^+$ is $\Sigma_c \bar{D}$ molecule, predicted $\frac{\mathcal{B}(P_c(4312)^+ \to \eta_c p)}{\mathcal{B}(P_c(4312)^+ \to J/\psi p)} \sim 3$

  [PRD 100 (2019) 034020, 100 (2019) 074007, 102 (2020) 036012]
- 1st observation of the Λ_b^0 decays with run2 data (5.5 fb^{-1})
  - η_c reconstructed using $\eta_c \to p\bar{p}$

~170 $\Lambda_b^0 \to \eta_c p K^-$ signals



No significant $P_c(4312)^+$ contribution (~2σ)

Relative P_c^+ production rates

$R(P_c(4312)^+) < 0.24$ @ 95% C.L.

(Uncertainty is too large to give any conclusion yet)

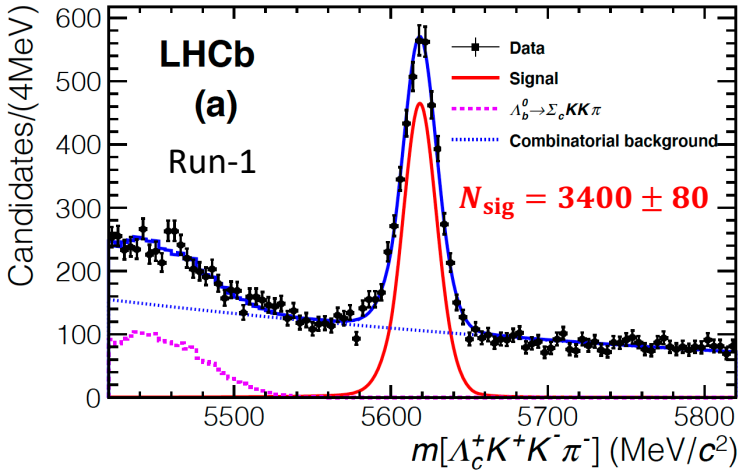
- **With Run-3 data, >1000 signals are expected, amplitude fit can be performed**

Search for open-charm pentaquark

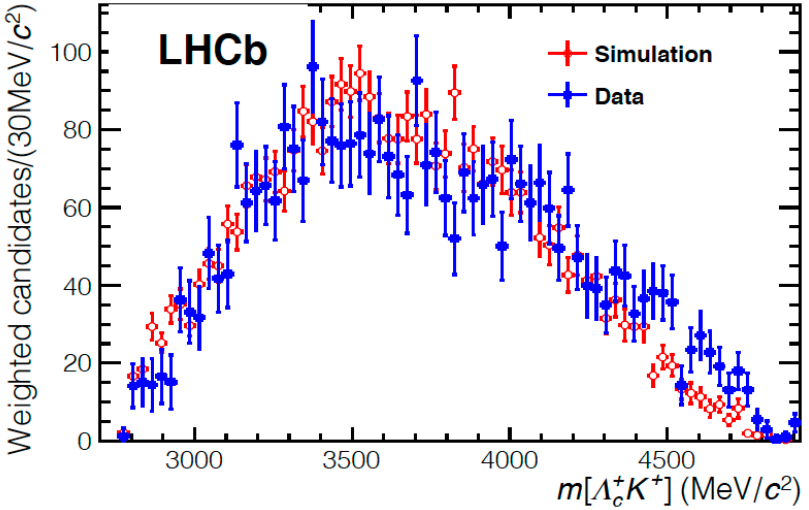
- Potential open-charm pentaquark $[c\bar{s}uud]$ decay to $\Lambda_c^+ K^+$
- **1st observation of $\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-$ (run1)**

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = (9.26 \pm 0.29 \pm 0.46 \pm 0.26) \times 10^{-2},$$

$$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-) = (1.02 \pm 0.03 \pm 0.05 \pm 0.10) \times 10^{-3}$$



- No excess observed in $m(\Lambda_c^+ K^+)$ spectrum
- Will search with more data and can also look for pentaquark $[c\bar{s}udd]$ in $\Lambda_c^+ K^+ \pi^-$ system



[Phys. Lett. B 815 (2021) 136172]

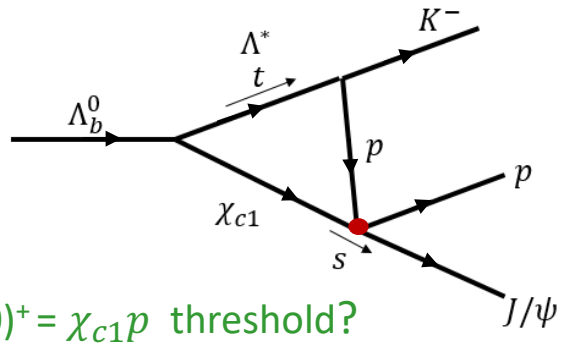
Summary

- Thanks to excellent LHC performance, we have made a lot of progress.
- We have observed a new narrow state $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$. The mass thresholds play an important role in the dynamics of these states.
- We also have evidence for the first $P_{cs}(4459)^0$, and another $P_c(4337)^+$.
- Amplitude analysis of $\Lambda_b^0 \to J/\psi p K^-$ is in advanced stage.
- We have lots of ideas for run3.

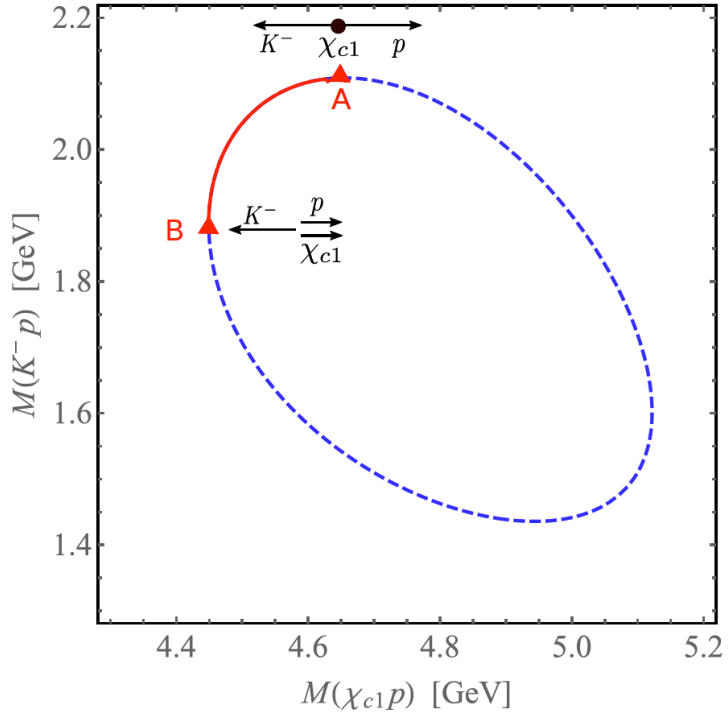
Backup

Triangle diagram

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



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

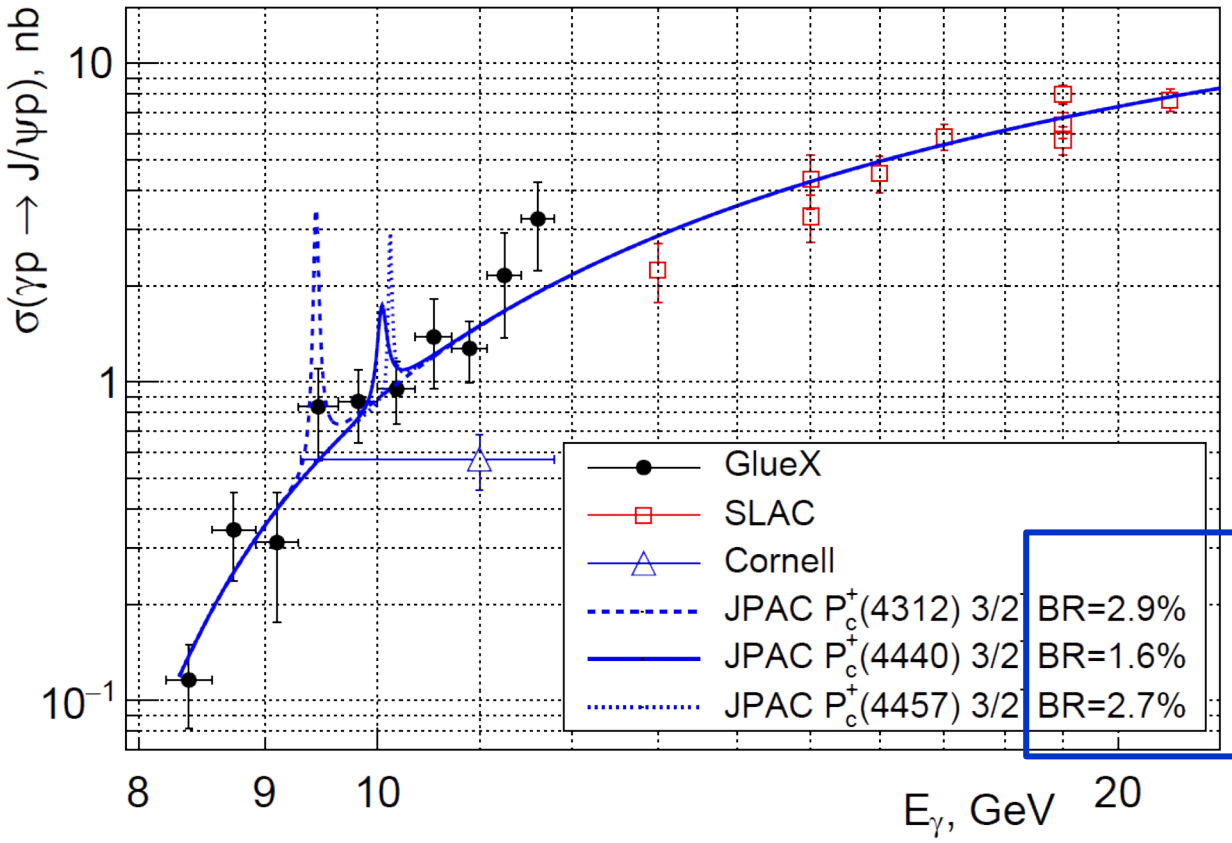


Requirements:

- 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

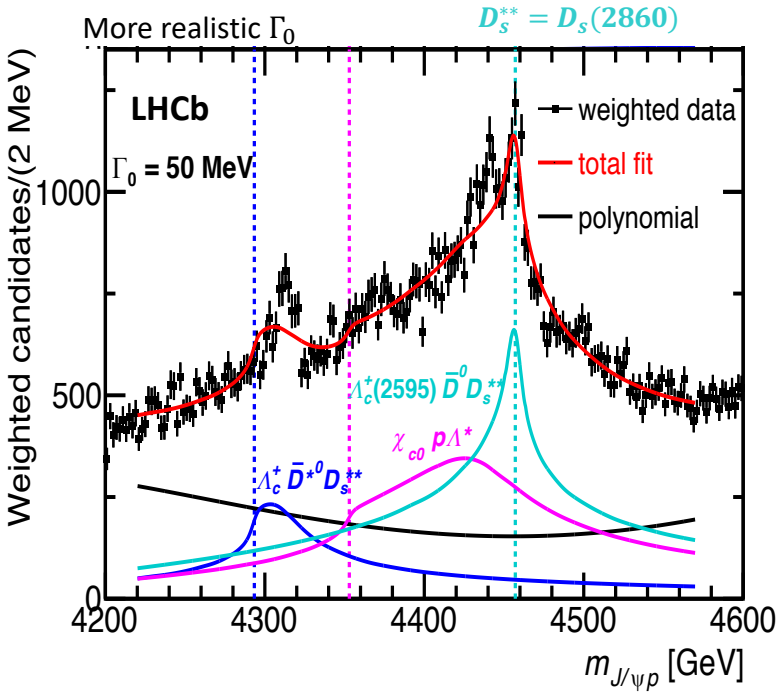
Triangle diagrams?

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

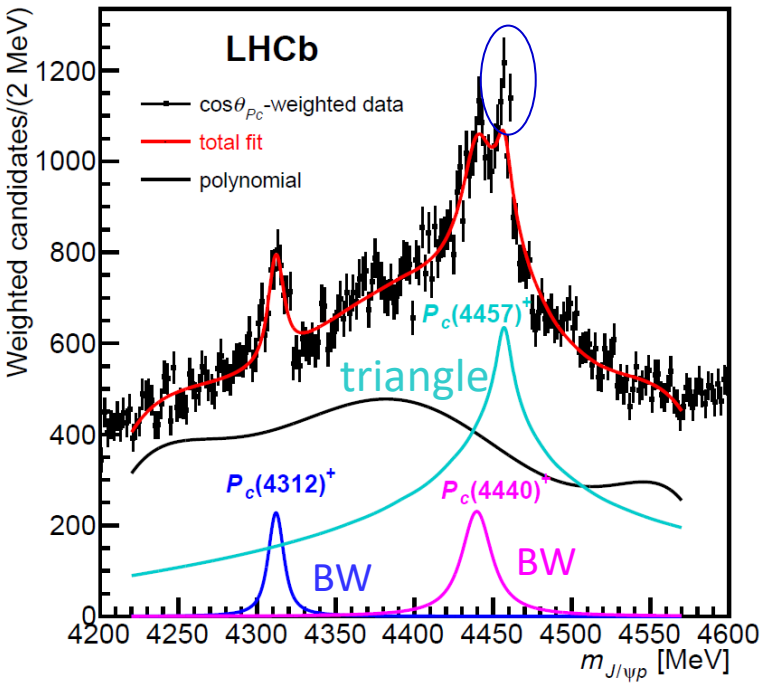
3 triangle-diagram amplitudes + polynomial

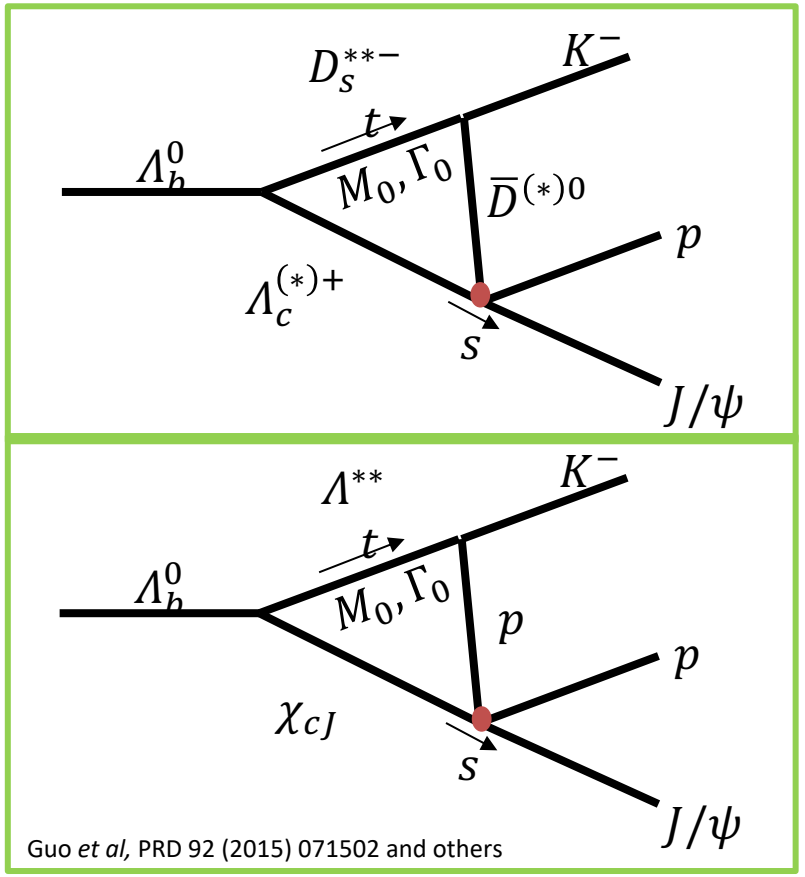


$P_c(4457)^+$ is right at the $\Lambda_c(2595)^+\bar{D}^0$ threshold

2BW + 1 triangle-diagram amplitudes + polynomial

$D_s(2860)$ Γ_0 = 159 MeV [PDG]





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