LHCb上五夸克态的研究

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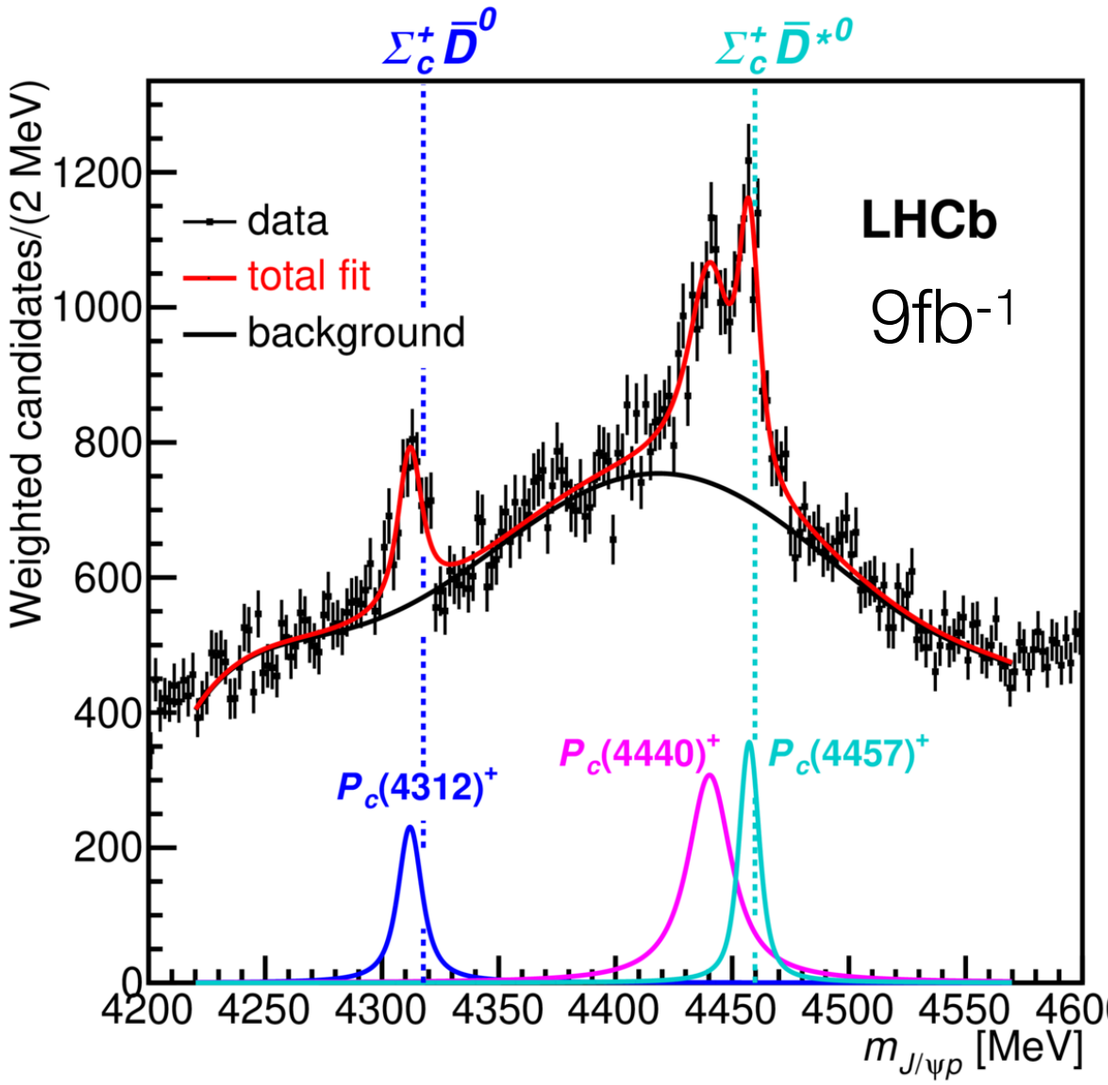
Introduction

- Observed pentaquarks at LHCb indicate interesting physics related to thresholds of charmed mesons and baryons



PRL122(2019)222001

- Narrow widths need excellent resolution

State	M [MeV]	Γ [MeV]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$

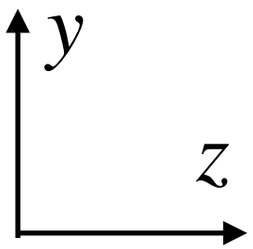
LHCb detector

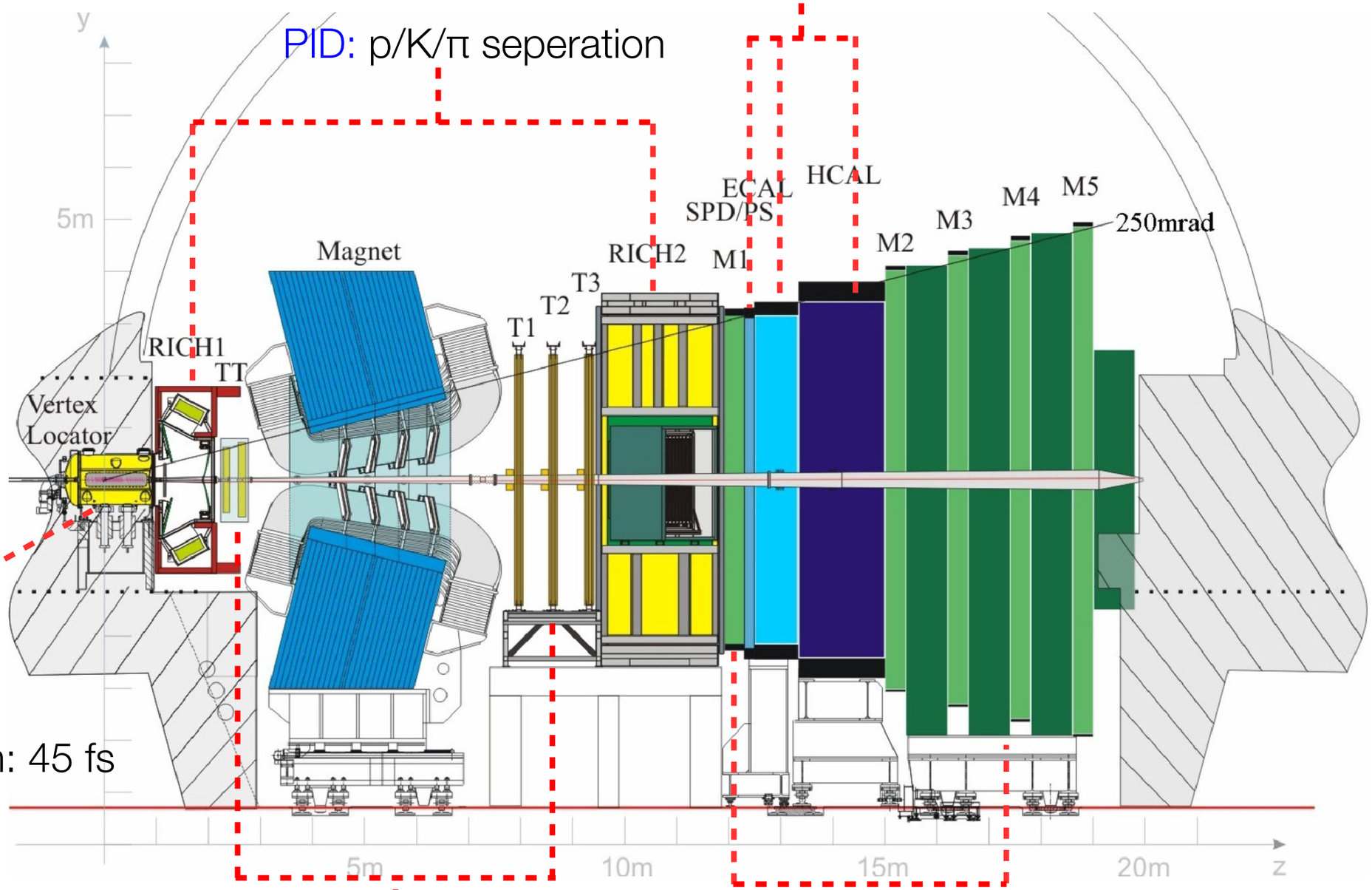
Int. J. Mod. Phys. A 30 (2015) 1530022

Forward single arm detector

Calorimeter system:
trigger + γ/e energy and ID

PID: p/K/π seperation





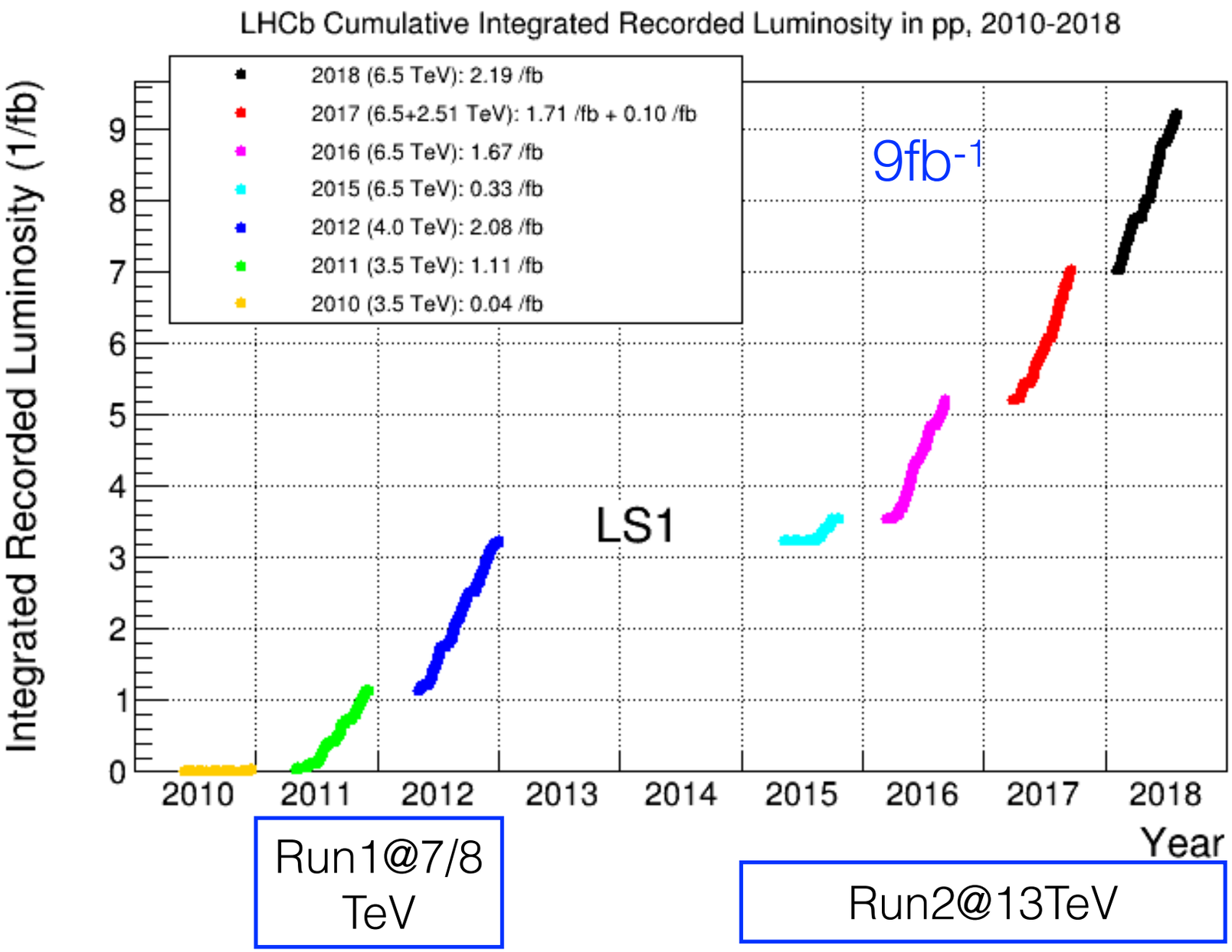
Vertex detector:
precise vertexing,
decay time resolution: 45 fs
IP resolution: 20μm

Tracking system:
Δp/p 0.4%—0.6%

Muon system: trigger
+ μ ID

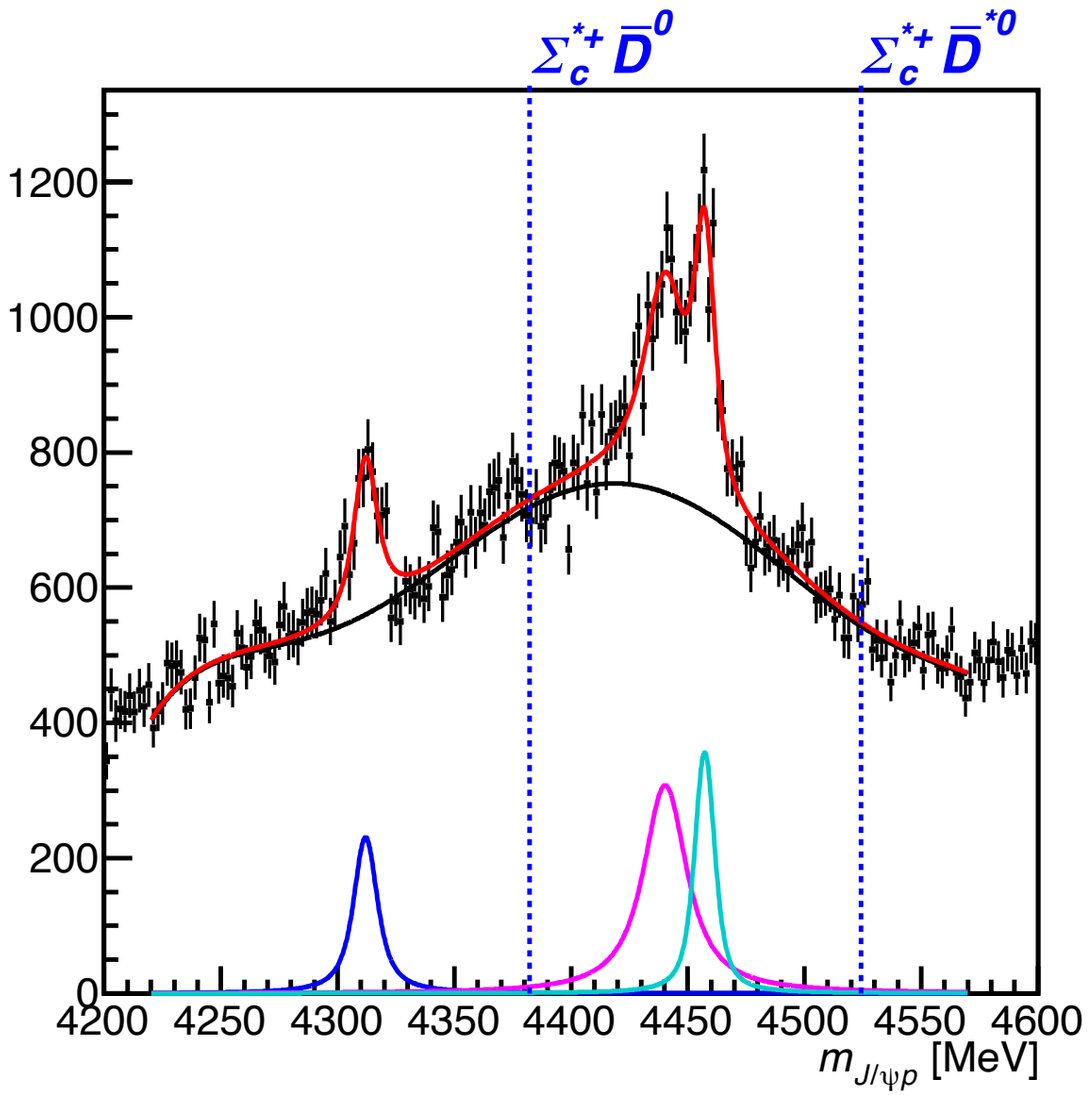
LHCb collected data

- Run1 3fb^{-1}, Run2 6fb^{-1}
- Access to all b hadrons: B^+, B^0, B_s^0, B_c^+, b baryons



More pentaquarks?

- Many structures predicted:
  i.e. Progr.Phys.41(2021)65-93, exist around threshold of any pair of heavy-baryon and antiheavy-meson with attractive interaction



- Studies at LHCb:

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

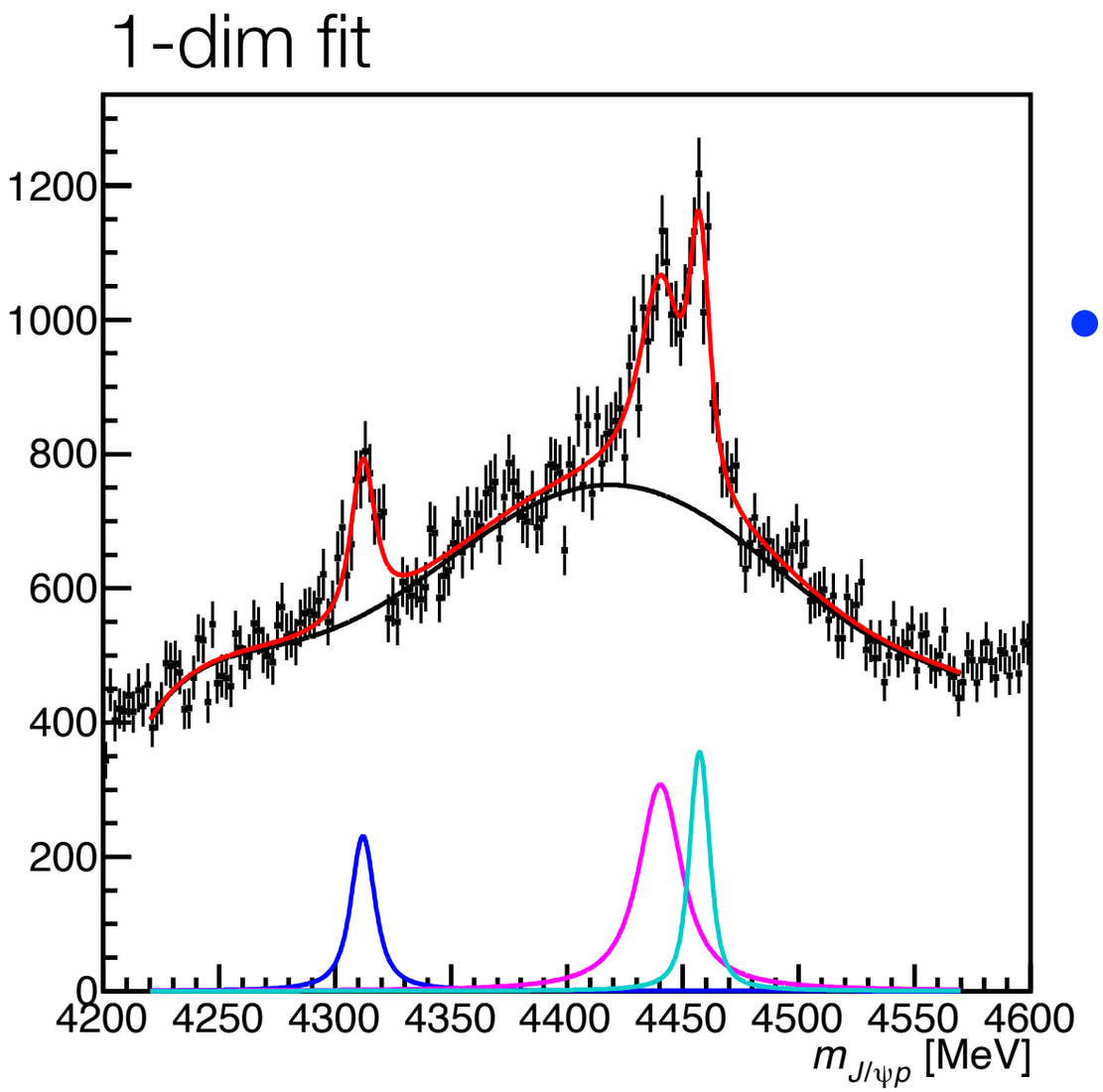
$$\Lambda_b^0 \to \eta_c(1S) p K^-$$

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

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

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

- Proper description of broad structures in $J/\psi p$ distribution required in the amplitude model



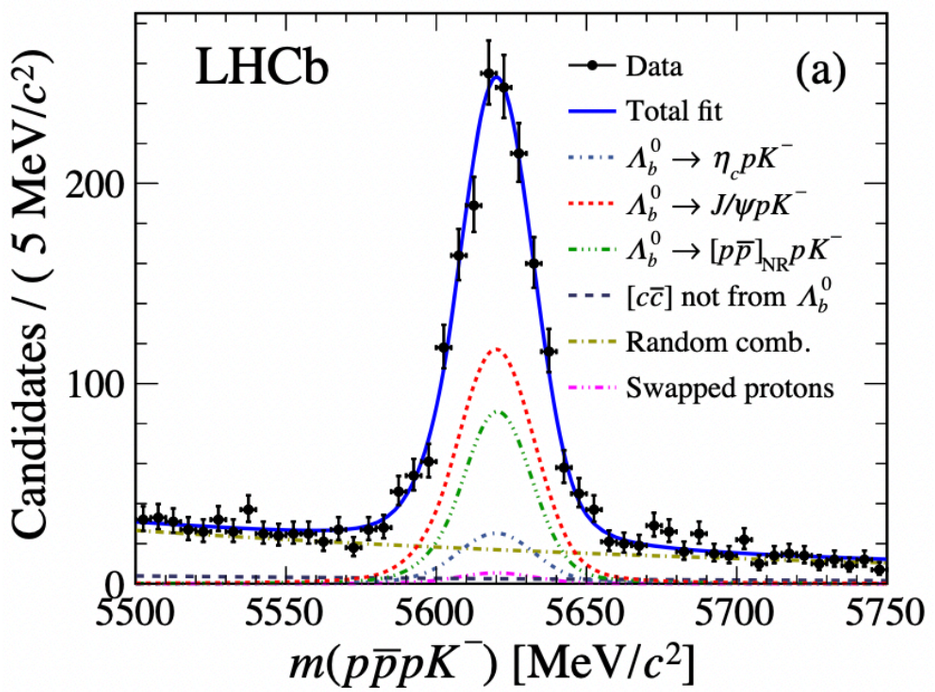
- Breakthrough using P-vector K-matrix for non-resonance $J/\psi p$ contribution

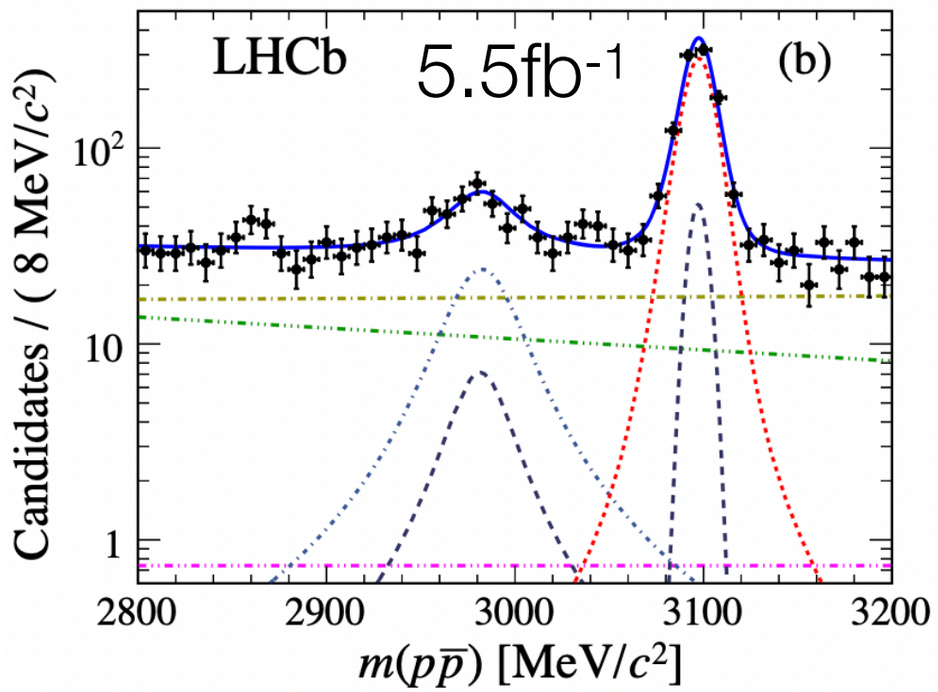
amplitude analysis ongoing

$\Lambda_b^0 \to \eta_c(1S)pK^-$ decay

PRD102(2020)112012

- First observation at LHCb, via $\eta_c(1S) \to p\bar{p}$





- Unique approach to study pentaquark

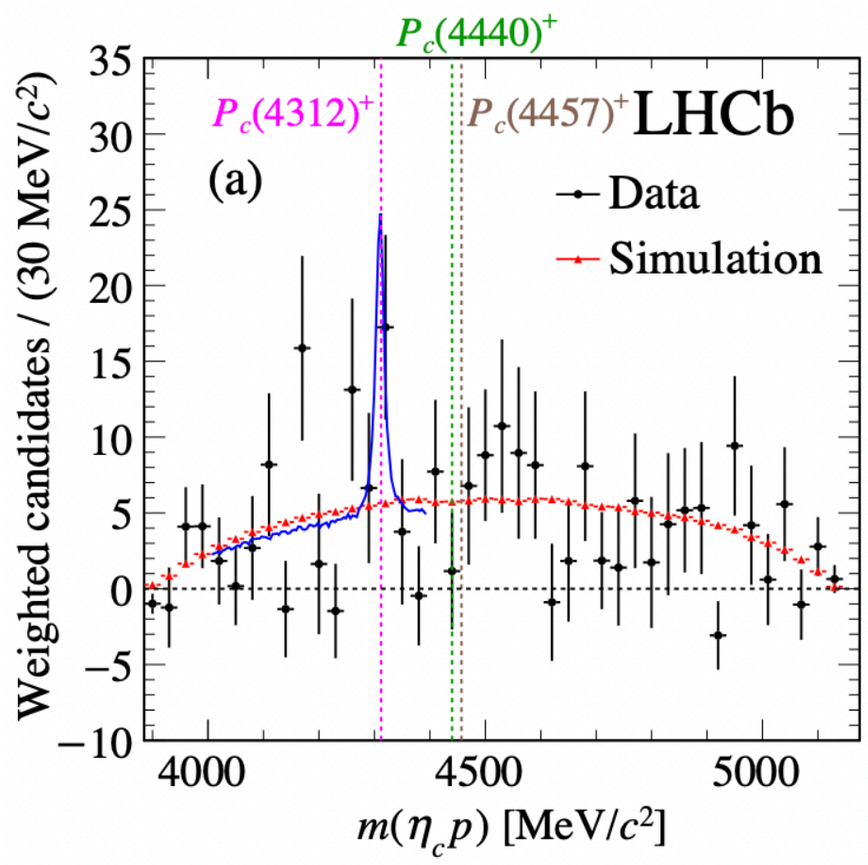
  A $\bar{D}\Sigma_c$ molecular state, ~4265MeV, predicted J.-J. Xie et al.PLB777(2018)447

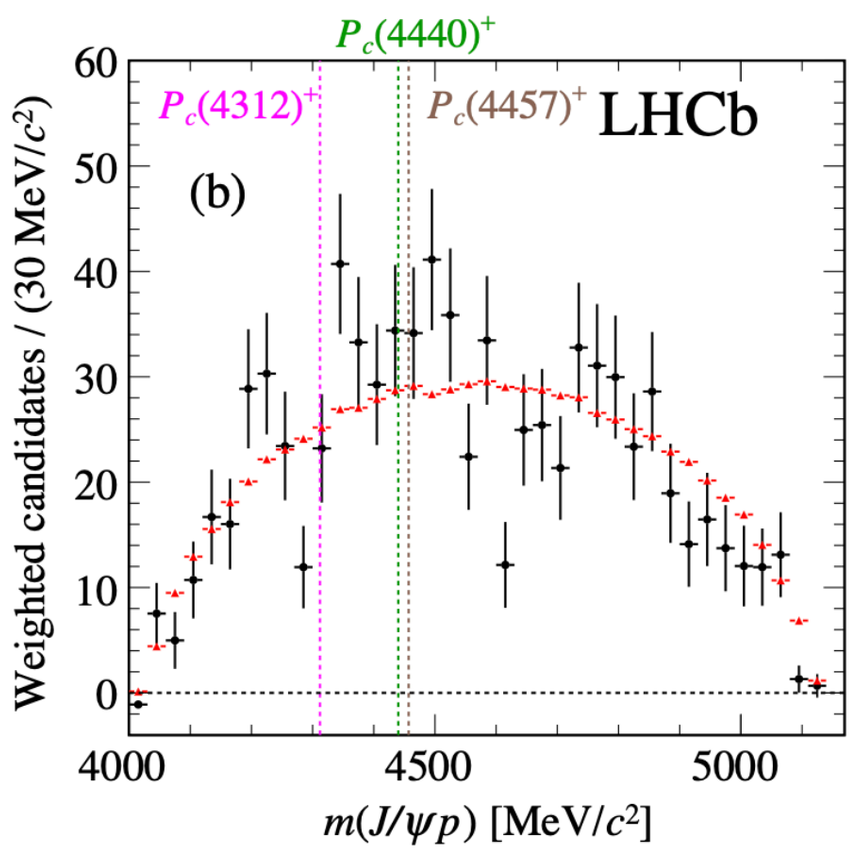
$$\frac{Br(P_c^+(4312) \to \eta_c p)}{Br(P_c^+(4312) \to J/\psi p)} \sim 3$$

GJ Wang et al. PRD102(2020)036012

Results in $\Lambda_b^0 \to \eta_c(1S)pK^-$ decay

PRD102(2020)112012





- No evidence for $P_c^+(4312)$, ~2.2σ

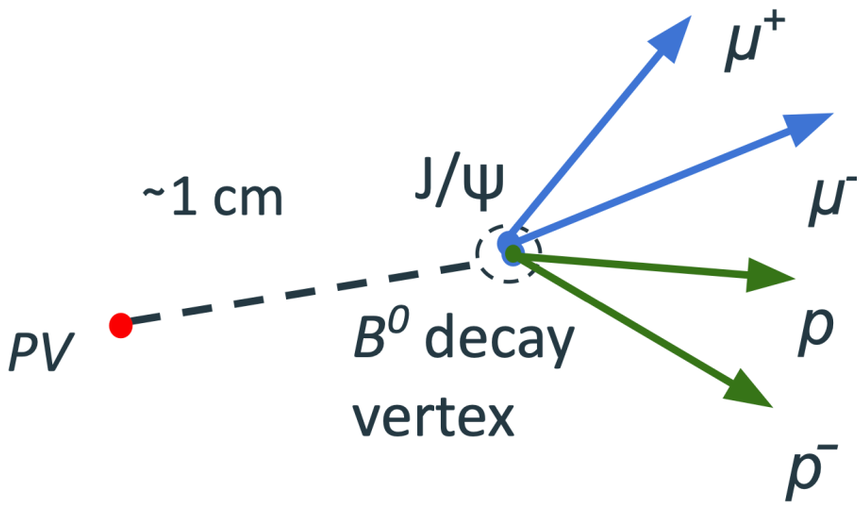
$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to P_c(4312)^+ K^-)}{\mathcal{B}(\Lambda_b^0 \to \eta_c p K^-)} \mathcal{B}(P_c(4312)^+ \to \eta_c p) \quad < 0.24 \text{ @95\% C.L.}$$

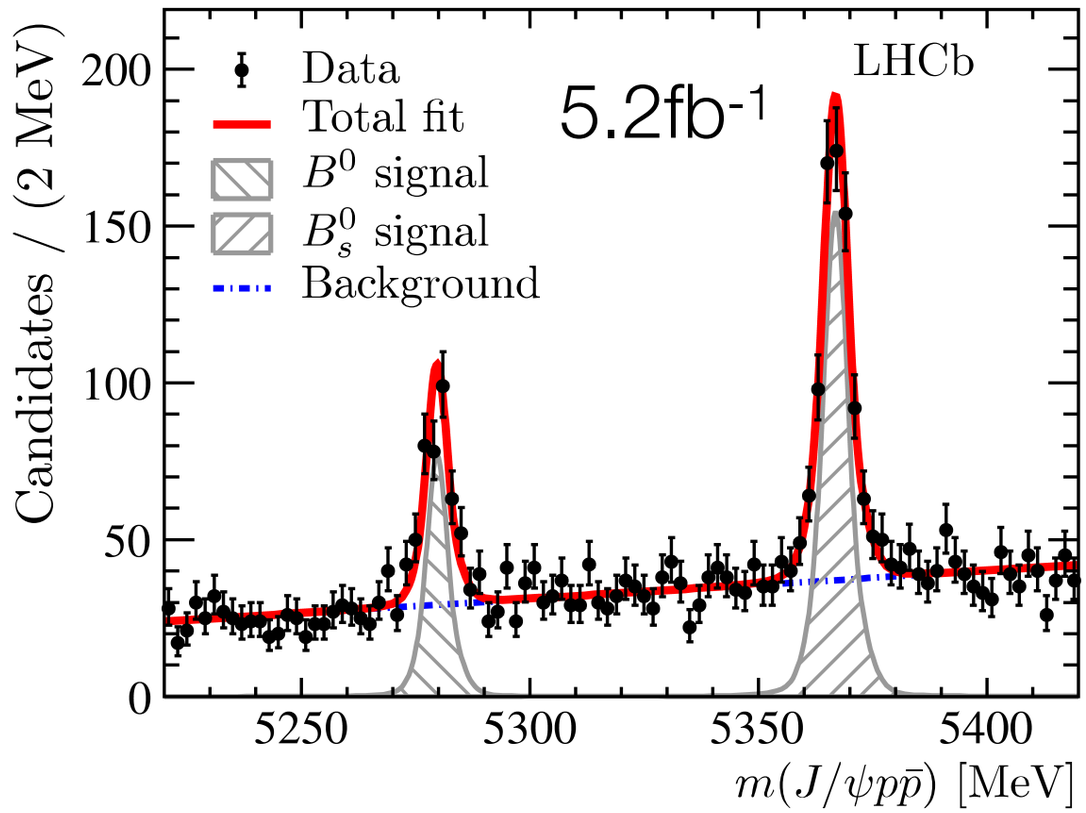
doesn't exclude molecular interpretation $R \sim 0.03$

- No P_c^+ contributions seen in $J/\psi p$ due to limited yield

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

- First observed by LHCb PRL122(2019)191804





- Best $B^0_{(s)}$ mass measurement

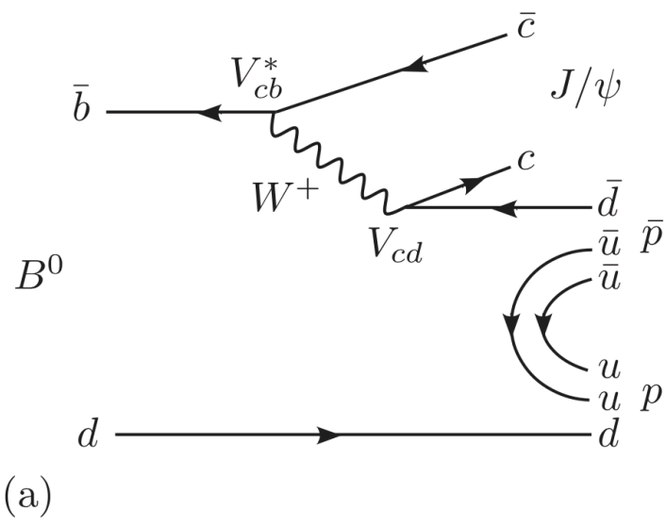
$$m_{B^0} = 5279.74 \pm 0.30(\text{stat}) \pm 0.10(\text{syst})\ \text{MeV}$$

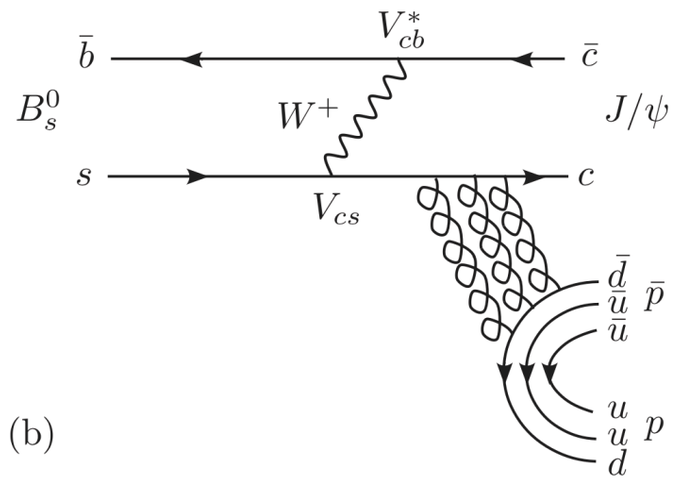
$$m_{B_s^0} = 5366.85 \pm 0.19(\text{stat}) \pm 0.13(\text{syst})\ \text{MeV}$$

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

PRL122(2019)191804

- Suppressed by limited phsp, Cabibbo or OZI suppression





- Intermediate structures indicated by Branching fraction

$$\mathcal{B}(B^0 \to J/\psi p\bar{p}) = [4.51 \pm 0.40(\text{stat}) \pm 0.44(\text{syst})] \times 10^{-7}$$

$$\mathcal{B}(B_s^0 \to J/\psi p\bar{p}) = [3.58 \pm 0.19(\text{stat}) \pm 0.39(\text{syst})] \times 10^{-6}$$

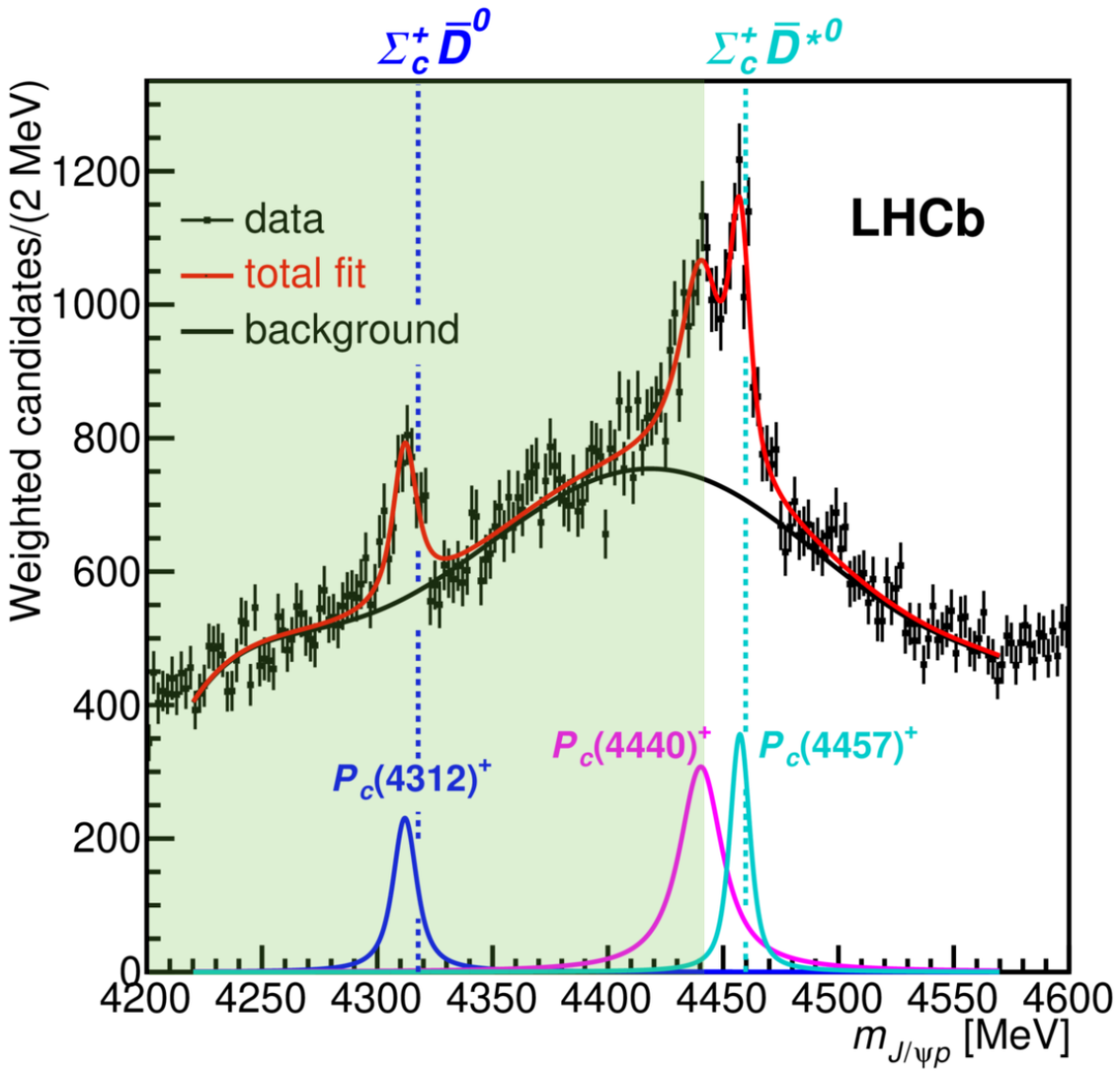
naive B_s^0 Br expectation

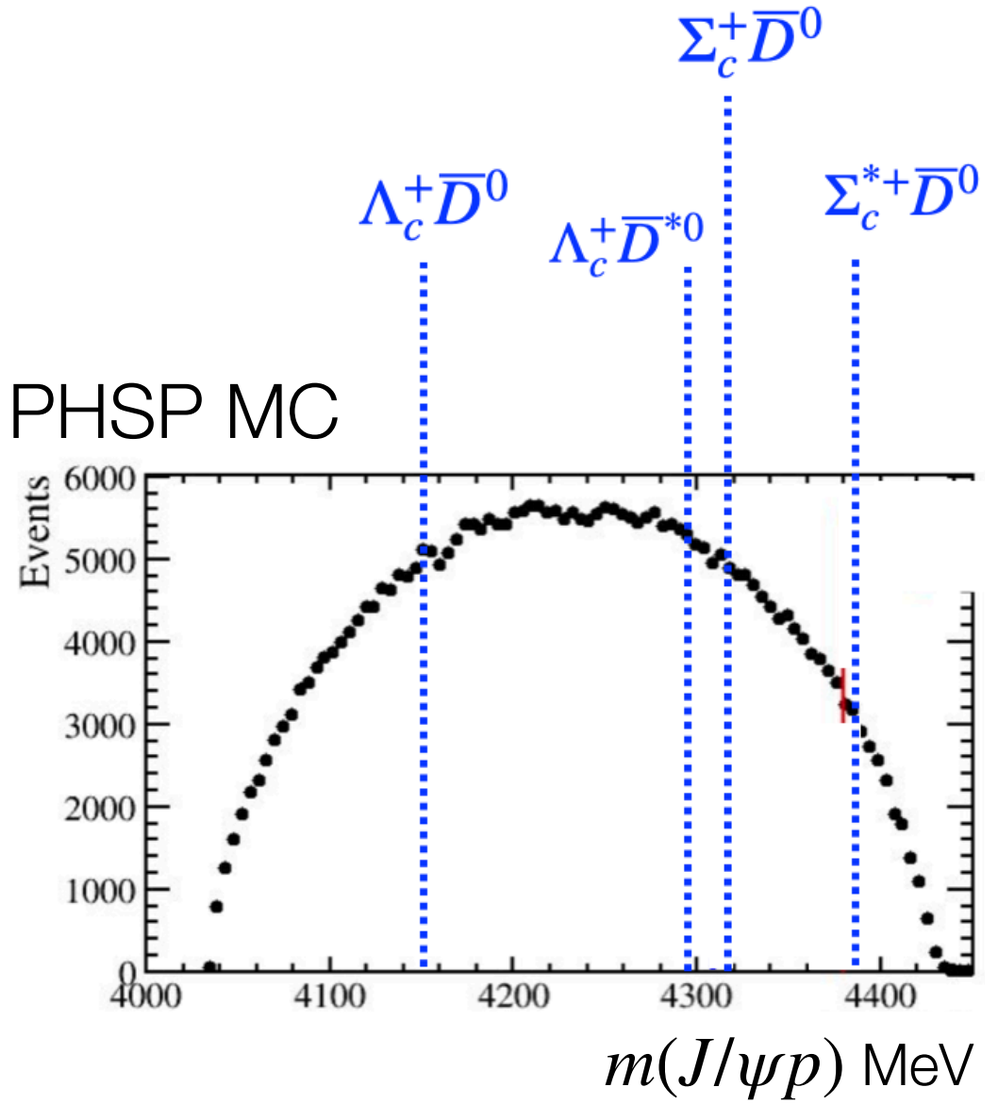
10^{-9}

Y.K.Hsiao et al, EPJC75(2015)101

Invariant mass coverage

- Many thresholds covered in the $m(J/\psi p)$ distribution
- Check $P_c^+(4312)$, $P_c^+(4440)$

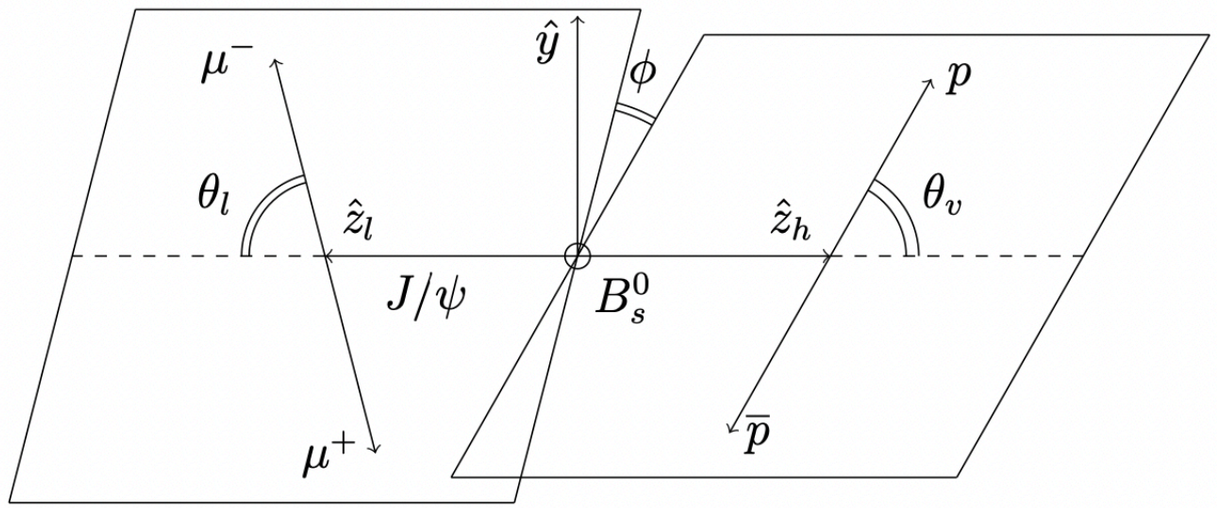




Helicity amplitude

- Build 4-dim amplitude using helicity formalism

$$m(p\bar{p}),\ \cos\theta_\mu,\ \cos\theta_p,\ \phi$$



- Untagged B decay

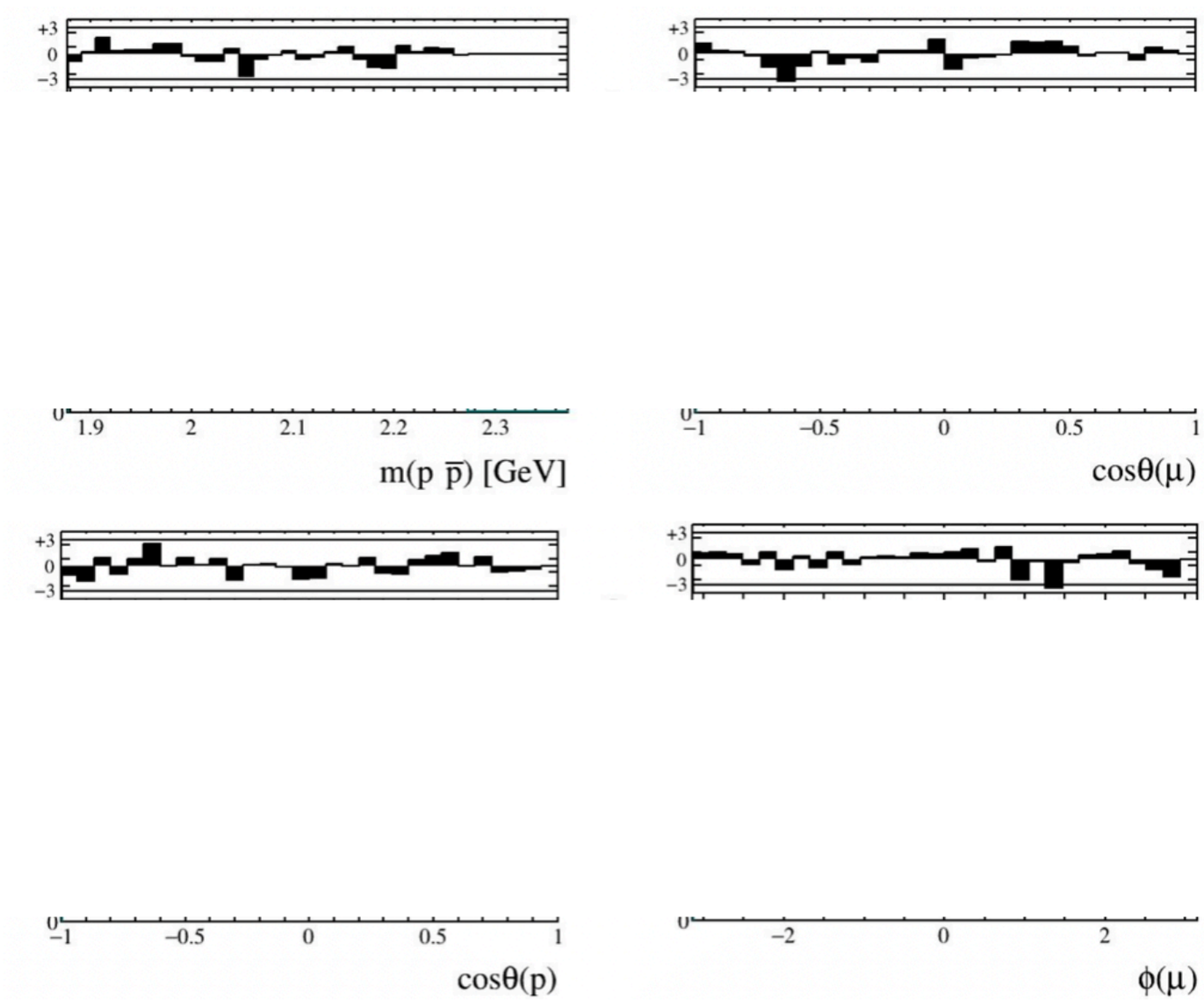
CP conservation: $\mathcal{M}(\bar{B}^0) = \mathcal{M}(B^0)$

Total amplitude: $|\bar{\mathcal{M}}|^2 = \frac{1}{2}(|\mathcal{M}(B^0)|^2 + |\mathcal{M}(\bar{B}^0)|^2)$

Results in $B_s^0 \to J/\psi p\bar{p}$ decay

LHCb-PAPER-2021-018

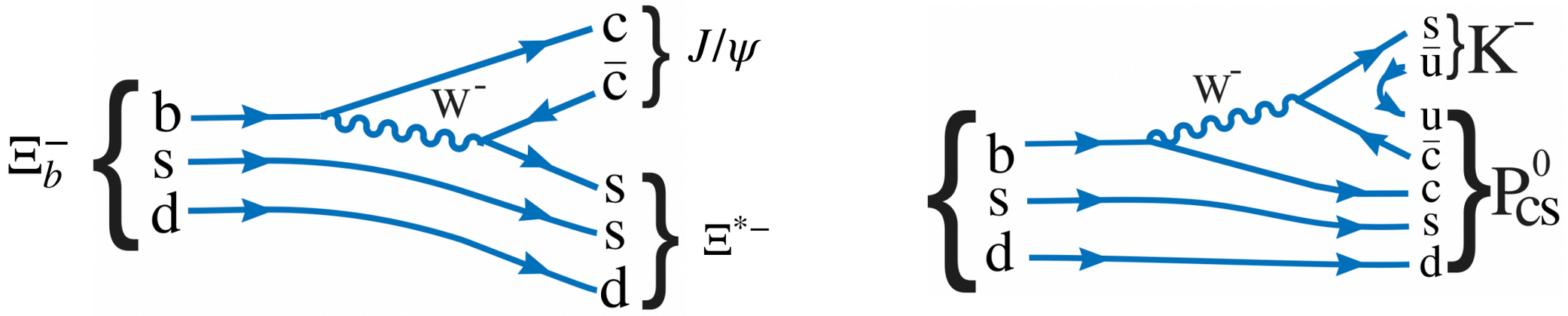
- LHCb unapproved results with 9fb^{-1}, paper to be circulated soon



$\Xi_b^- \to J/\psi \Lambda K^-$ decay

- P_{cs}^0 proposed to search in $\Xi_b^- \to J/\psi \Lambda K^-$ decay

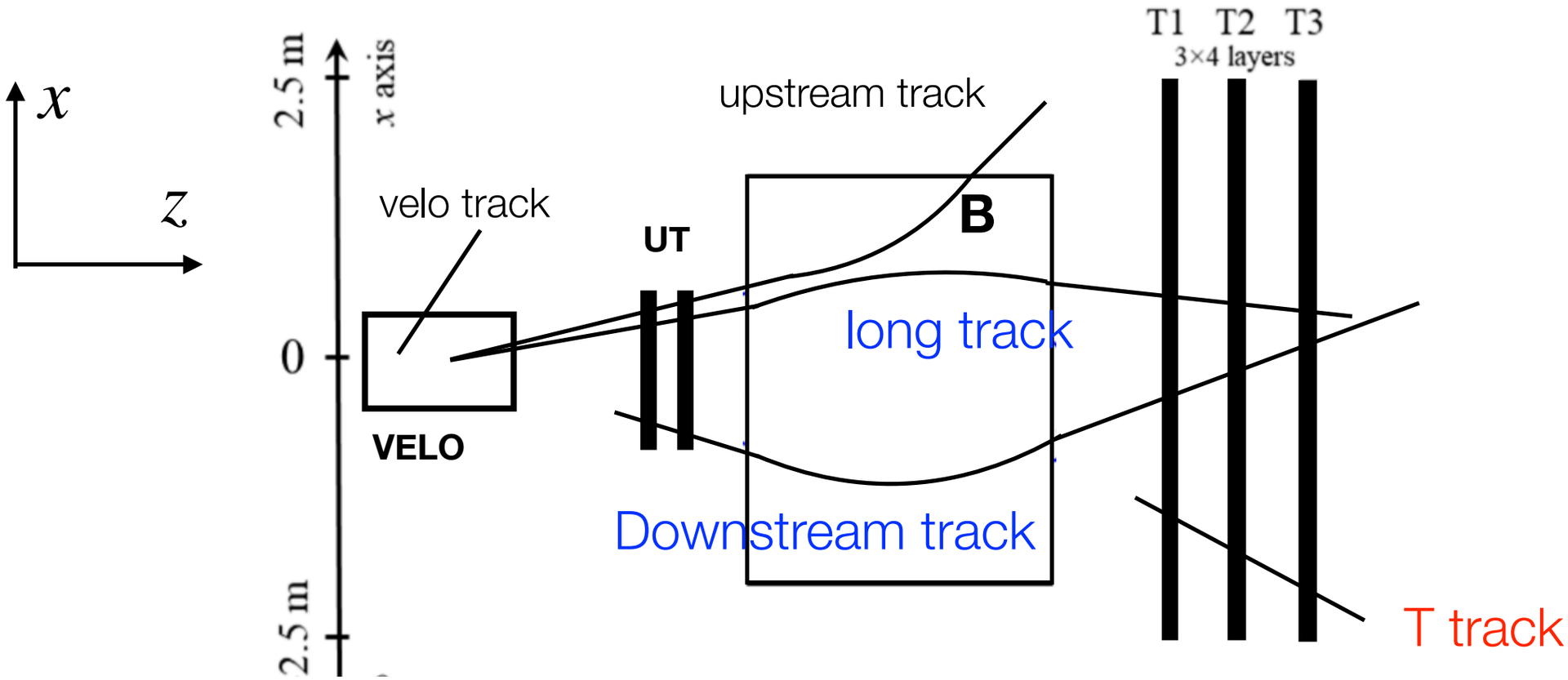
JJ Wu PRL105(2010)232001 HX Chen PRC93(2016)064203



- $\Xi_b^- \to J/\psi \Lambda K^-$ first observed by LHCb using 3fb^{-1}, ~300 signal decays

PLB 772(2017)265

Λ reconstruction at LHCb

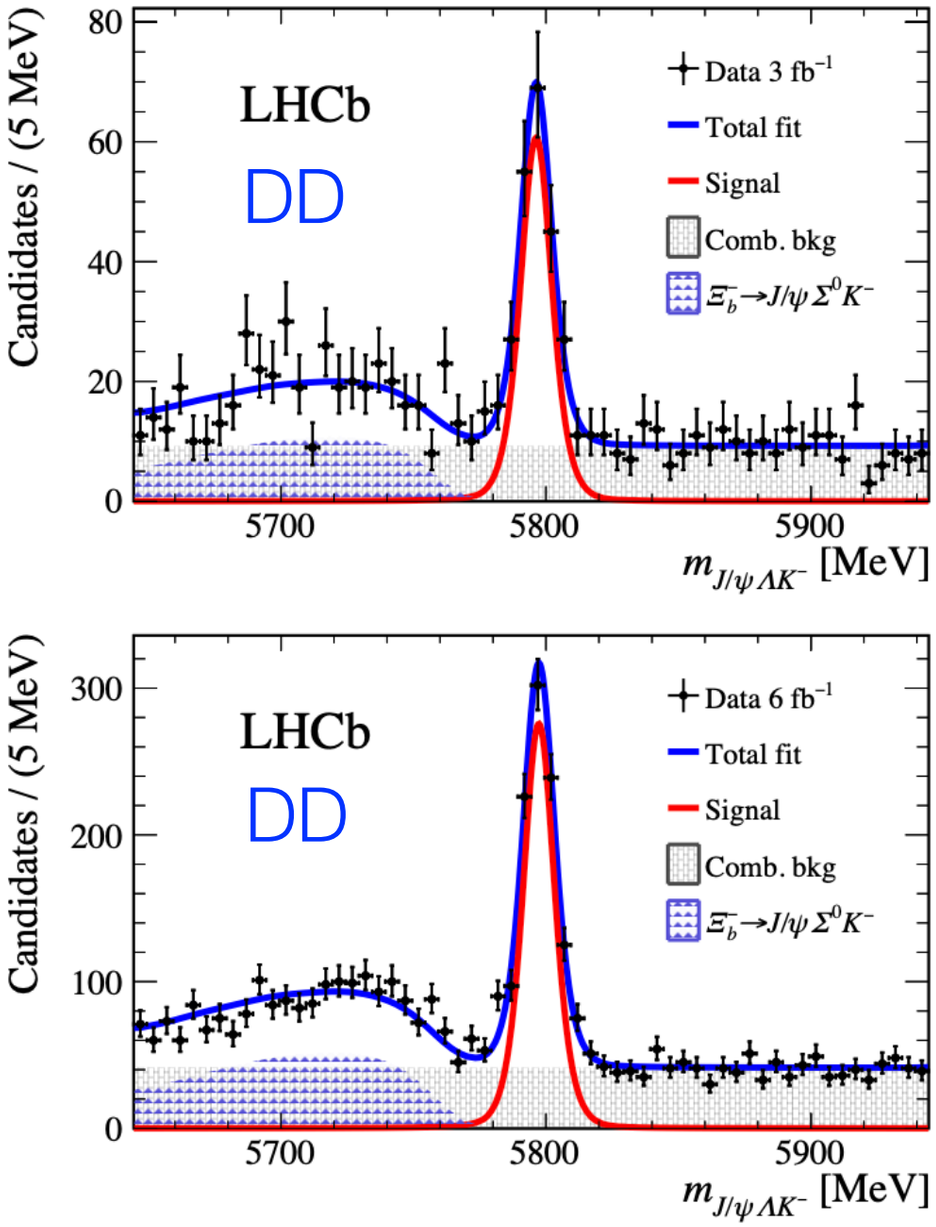


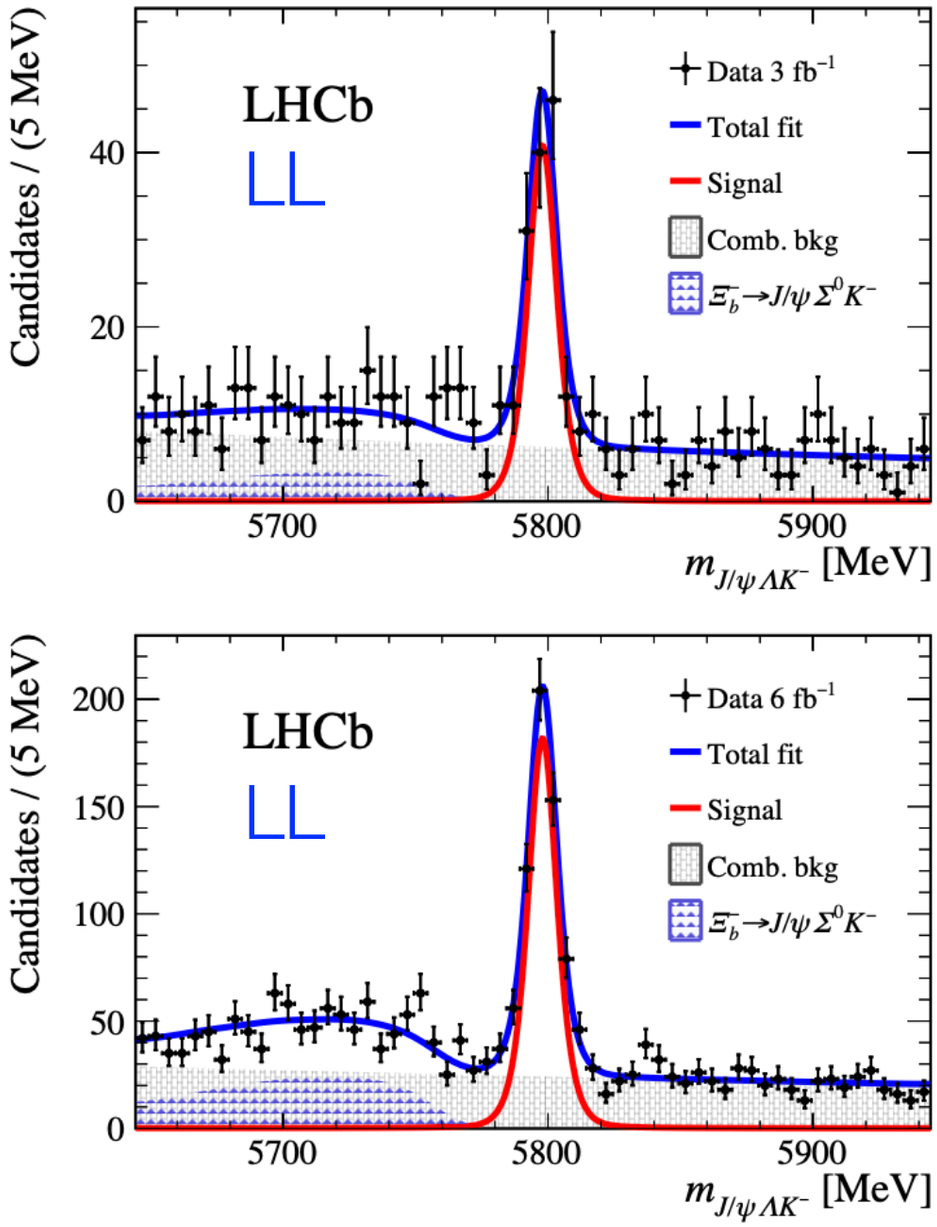
- Λ decays in different sections of detectors
- Long and Downstream tracks well reconstructed
- T tracks poor reconstruction but demonstrated suitable for physics

$\Xi_b^- \to J/\psi \Lambda K^-$ decay

LHCb-PAPER-2020-039

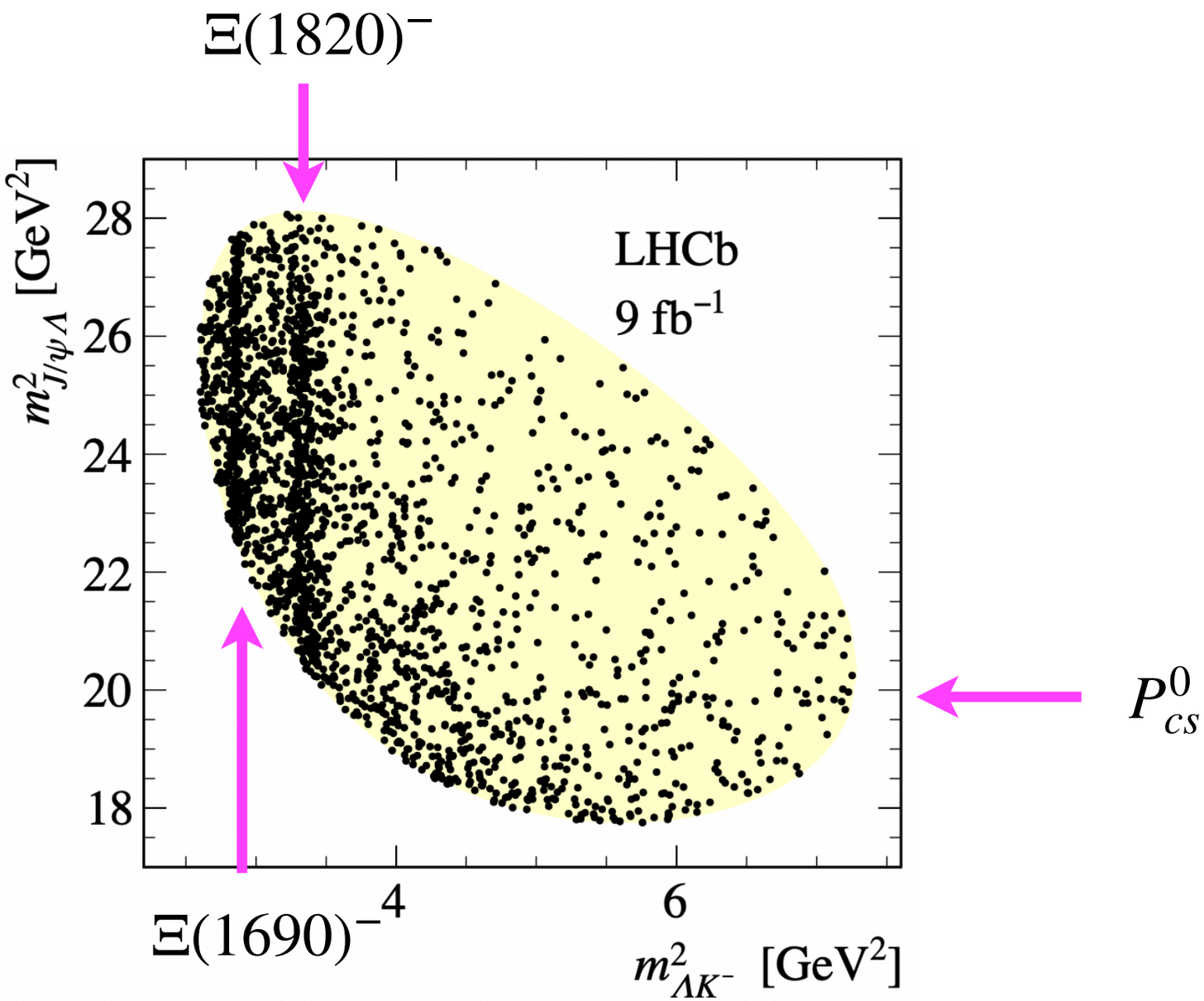
- 1750 signal candidates using 9fb^{-1} data, purity ~80%
- S-weighted signals for amplitude analysis





$\Xi_b^- \to J/\psi \Lambda K^-$ Dalitz plot

- Clear structures of Ξ^{*-}, hint for P_{cs}^0 ? Amplitude analysis needed



Ξ^{*-} resonances in decay

- Ξ^{*-} resonances not well understood

$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	$3/2^-$	***
$\Xi(1950)$		***
$\Xi(2030)$	$\frac{5}{2}^?$	***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*

- Contributions in default fit model

State	M_0 [MeV]	Γ_0 [MeV]	LS couplings	J^P examined
$\Xi(1690)^-$	1690 ± 10	< 30	4 (6)	$(1/2, 3/2)^{\pm}$
$\Xi(1820)^-$	1823 ± 5	24^{+15}_{-10}	3 (6)	$3/2^-$
$\Xi(1950)^-$	1950 ± 15	60 ± 20	3 (6)	$(1/2, 3/2, 5/2)^{\pm}$
$\Xi(2030)^-$	2025 ± 5	20^{+15}_{-5}	3 (6)	$5/2^{\pm}$
NR ΛK^-	-	-	4 (4)	$1/2^-$

$\Xi_b^- \to J/\psi \Lambda K^-$ amplitude analysis

- Construct 6-dim amplitude with helicity formalism

$$m_{J/\psi\Lambda},\ \cos\theta_{\Xi_b},\ \cos\theta_{J/\psi},\ \cos\theta_{\Xi},\ \phi_{\Lambda},\ \phi_{\mu}$$

- Two interfering decay chains

$$\Xi_b^- \to J/\psi \Xi^{*-}(\to \Lambda K^-) \qquad \mathcal{M}^{\Xi^*}_{\lambda_{\Xi_b}, \boxed{\lambda_\Lambda, \Delta\lambda_\mu}}$$

$$\Xi_b^- \to P_{cs}^0(\to J/\psi\Lambda)K^- \qquad \mathcal{M}^{P_{cs}}_{\lambda_{\Xi_b}, \boxed{\lambda_\Lambda^{P_{cs}}, \Delta\lambda_\mu^{P_{cs}}}}$$

- Add coherently

$$|\mathcal{M}|^2 = \sum_{\lambda_{\Xi_b}} \sum_{\lambda_\Lambda} \sum_{\Delta\lambda_\mu} \left| \mathcal{M}^{\Xi^*}_{\lambda_{\Xi_b}, \lambda_\Lambda, \Delta\lambda_\mu} + \boxed{e^{i\,\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_\Lambda^{P_{cs}}} d^{\frac{1}{2}}_{\lambda_\Lambda^{P_{cs}}, \lambda_\Lambda}(\theta_\Lambda)} \mathcal{M}^{P_{cs}}_{\lambda_{\Xi_b}, \lambda_\Lambda^{P_{cs}}, \Delta\lambda_\mu} \right|^2$$

sFit method

- sFit: s-weighted data, total PDF=signal PDF

$$\mathcal{P}_{\rm sig}(m_{\Lambda K},\Omega|\vec{\omega}) = \frac{1}{I(\vec{\omega})}\left|\mathcal{M}(m_{\Lambda K},\Omega|\vec{\omega})\right|^2\Phi(m_{\Lambda K})\epsilon(m_{\Lambda K},\Omega)$$

$\vec{\omega}$ fit parameters: mass, width, couplings

ϵ efficiency

$$I(\vec{\omega}) \propto \sum_j^{N_{\rm MC}} w_j^{\rm MC}\left|\mathcal{M}(m_{\Lambda K\ j},\Omega_j|\vec{\omega})\right|^2$$

normalization using phsp MC

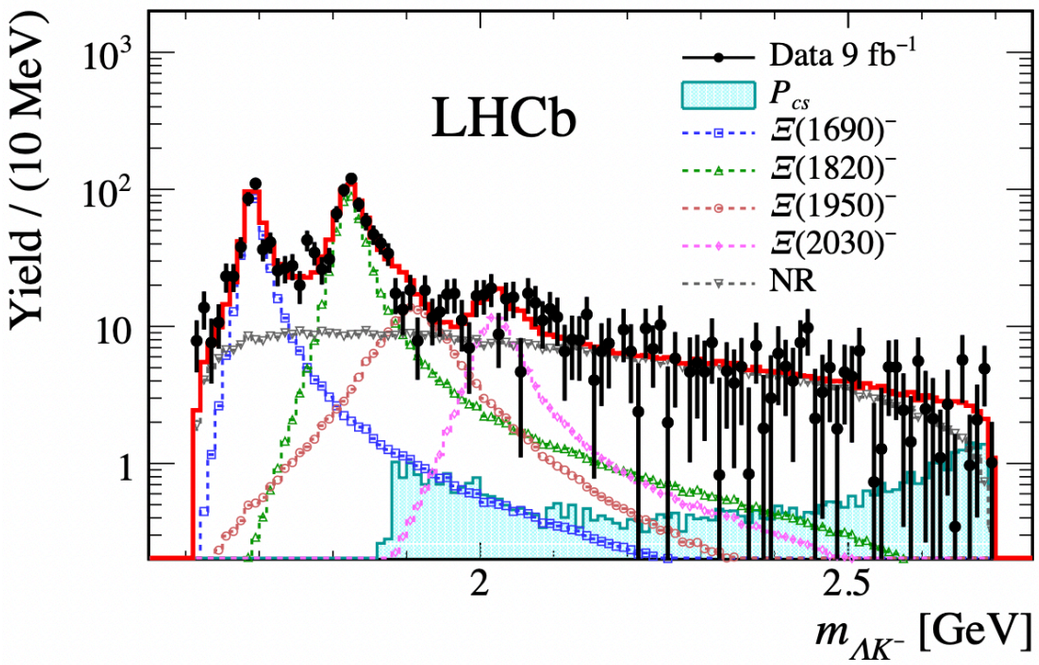
- Fit by minimizing

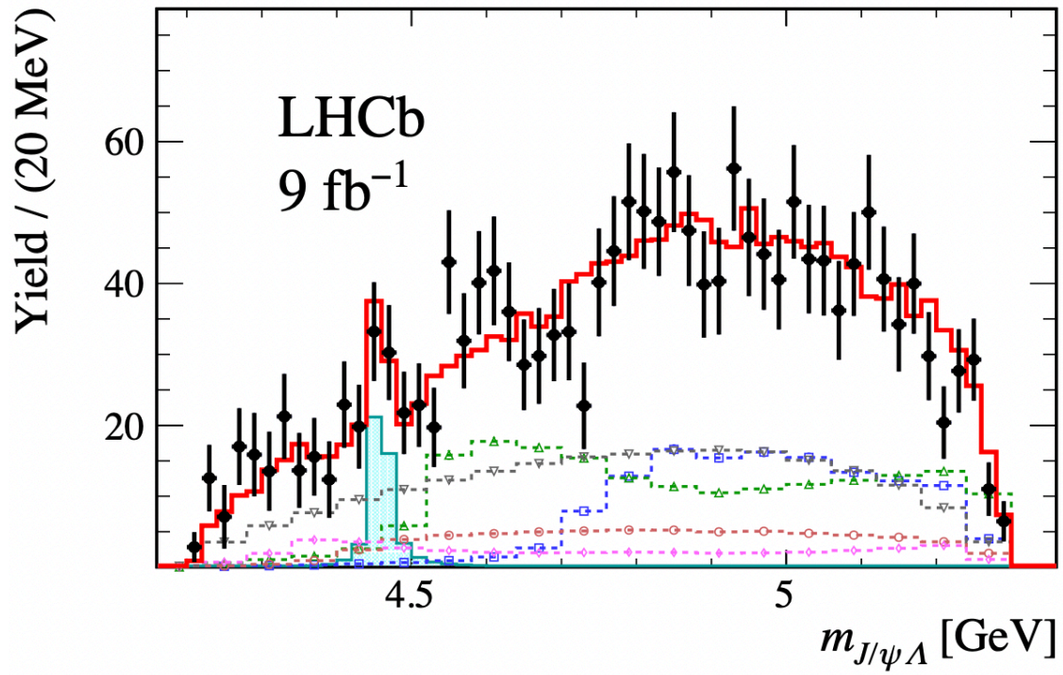
$$\begin{aligned}-2\ln\mathcal{L}(\vec{\omega}) &= -2s_W\sum_i W_i\ln\mathcal{P}_{\rm sig}(m_{\Lambda K\ i},\Omega_i|\vec{\omega})\\ &= -2s_W\sum_i W_i\ln\left|\mathcal{M}(m_{\Lambda K\ i},\Omega_i|\vec{\omega})\right|^2 + 2s_W\ln I(\vec{\omega})\sum_i W_i\\ &\quad \boxed{-2s_W\sum_i W_i\ln[\Phi(m_{\Lambda K\ i})\epsilon(m_{\Lambda K\ i},\Omega_i)].}\end{aligned}$$

Constant, can be dropped

Results in $\Xi_b^- \to J/\psi\Lambda K^-$ decay

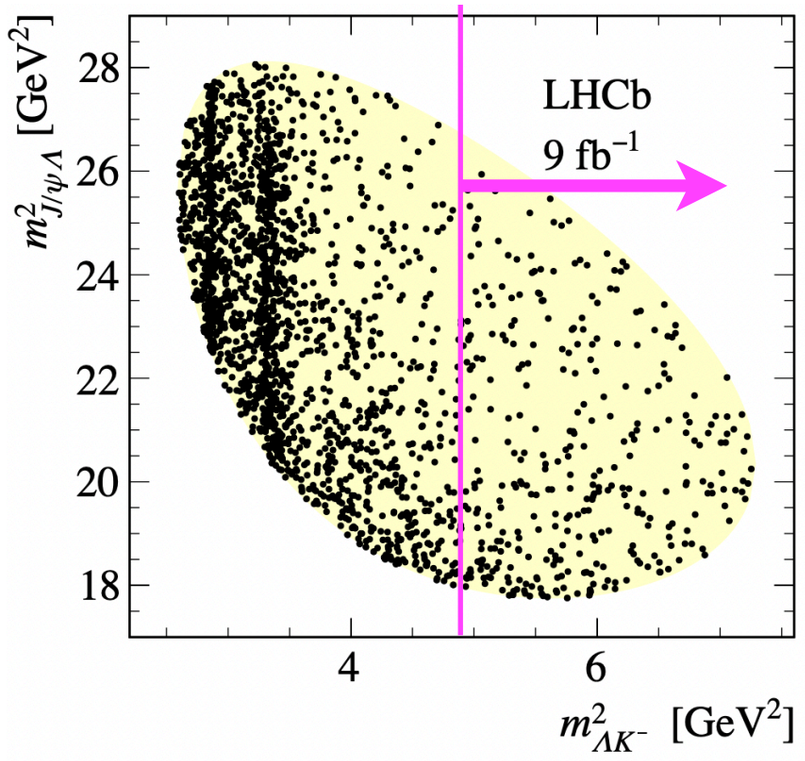
- First evidence for hidden-charm pentaquark with strangeness $P_{cs}(4459)^0$, with significance of 3.1σ



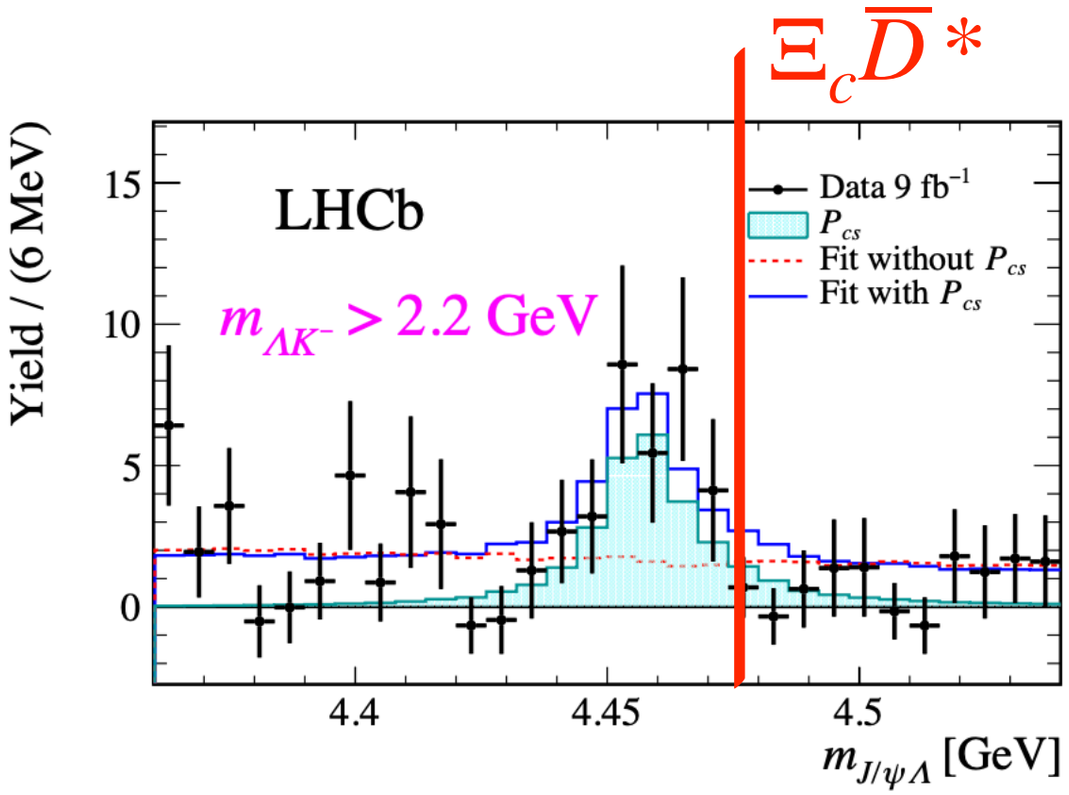


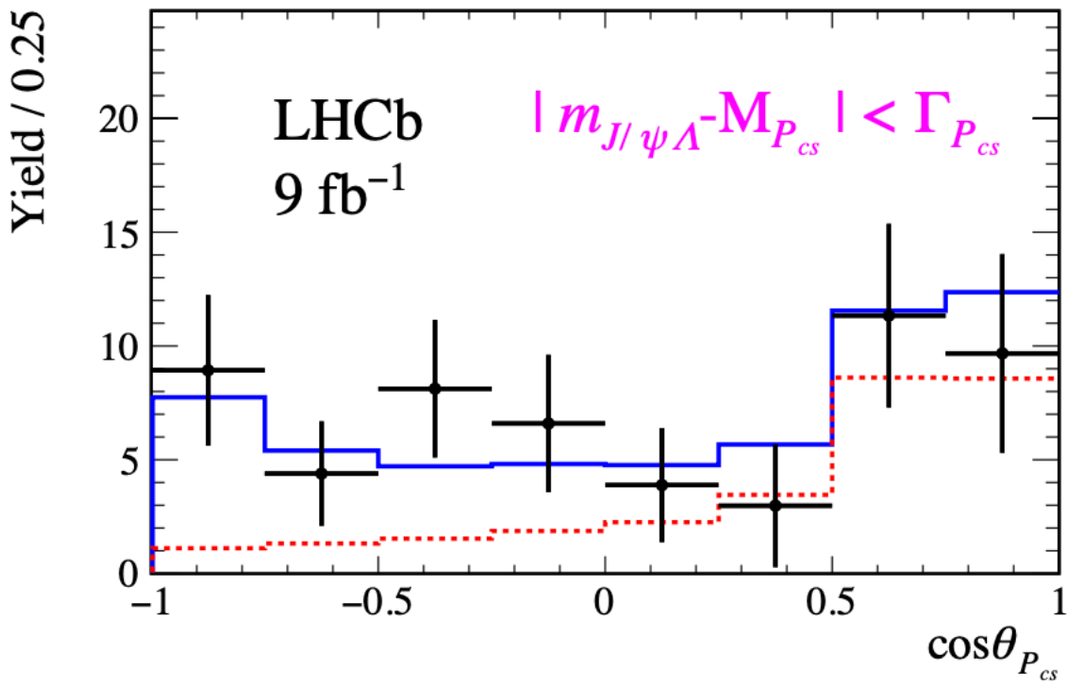
State	M_0 [MeV]	Γ_0 [MeV]	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$	$2.7\,^{+1.9+0.7}_{-0.6-1.3}$
$\Xi(1690)^-$	$1692.0 \pm 1.3\,^{+1.2}_{-0.4}$	$25.9 \pm 9.5\,^{+14.0}_{-13.5}$	$22.1\,^{+6.2+6.7}_{-2.6-8.9}$
$\Xi(1820)^-$	$1822.7 \pm 1.5\,^{+1.0}_{-0.6}$	$36.0 \pm 4.4\,^{+7.8}_{-8.2}$	$32.9\,^{+3.2+6.9}_{-6.2-4.1}$
$\Xi(1950)^-$	1910.6 ± 18.4	105.7 ± 23.2	$11.5\,^{+5.8+49.9}_{-3.5-\ 9.4}$
$\Xi(2030)^-$	2022.8 ± 4.7	68.2 ± 8.5	$7.3\,^{+1.8+3.8}_{-1.8-4.1}$
NR	–	–	$35.8\,^{+4.6+10.3}_{-6.4-11.2}$

$P_{cs}^{0}(4459)$ contribution



$P_{cs}^{0}(4459)$ improves the description of mass and angular distribution

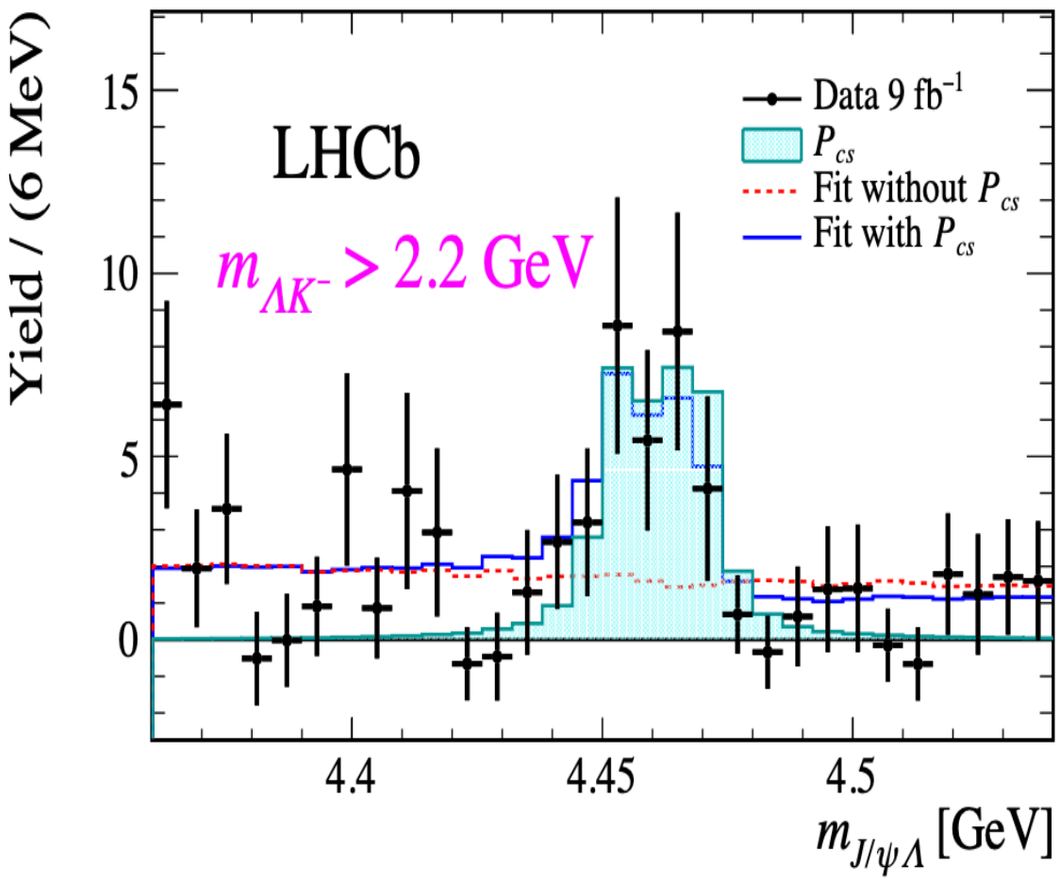




Two pentaquarks ?

- 19MeV bellow $\Xi_c^0 \overline{D}*$ threshold: $1/2^+ \bigotimes 1^- = 1/2^- \bigoplus 3/2^-$

- Fit with fixed JP can not exclude two-peak hypothesis due to limited yield



m=4454.9±2.7 Γ=7.5±9.7 MeV

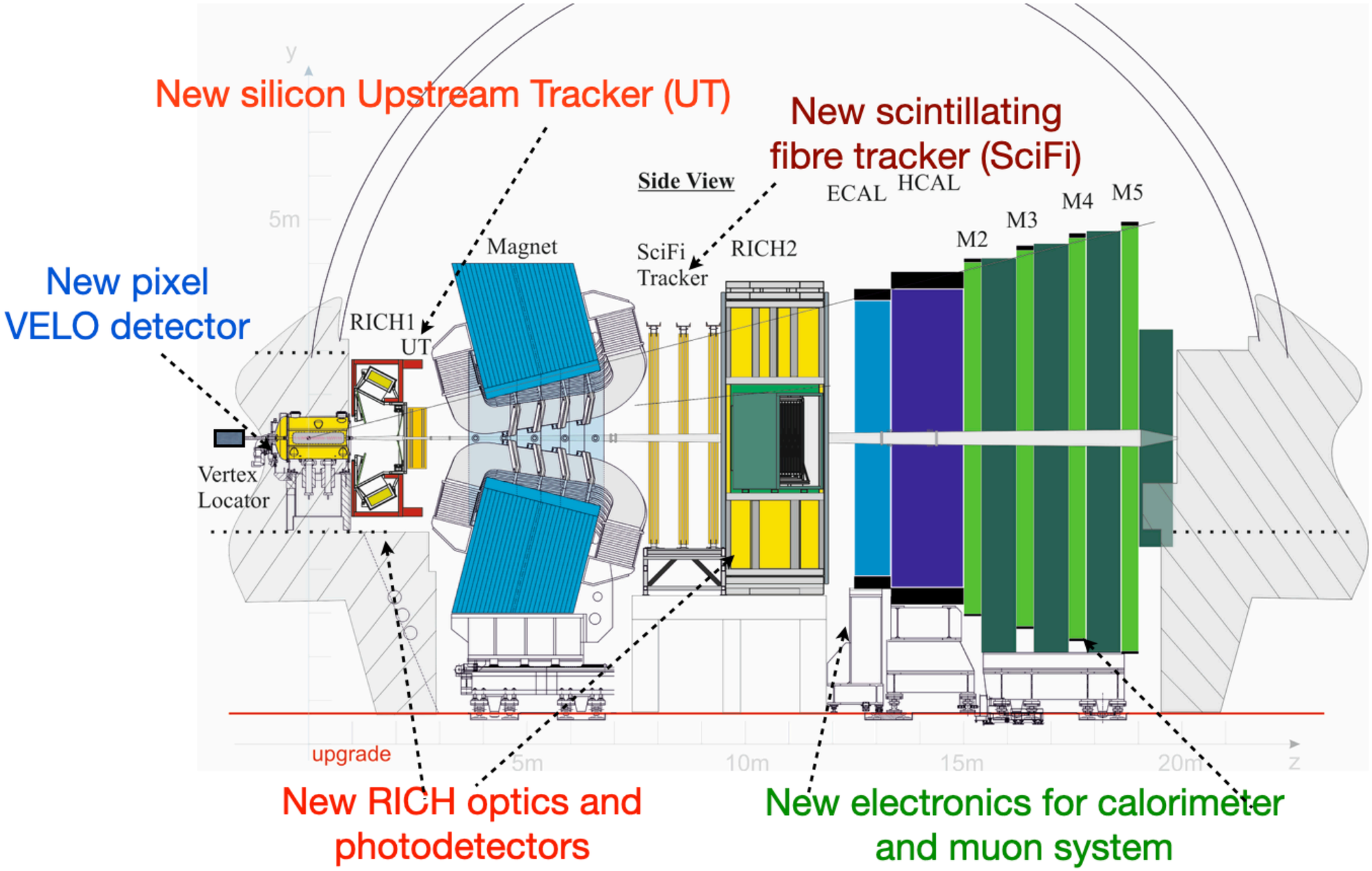
m=4467.8±3.7 Γ=5.2±5.3 MeV

System	$[\Xi_c \bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c \bar{D}^*]_{\frac{3}{2}}$
ΔE	$-17.8^{+3.2}_{-3.3}$	$-11.8^{+2.8}_{-3.0}$
M	$4456.9^{+3.2}_{-3.3}$	$4463.0^{+2.8}_{-3.0}$

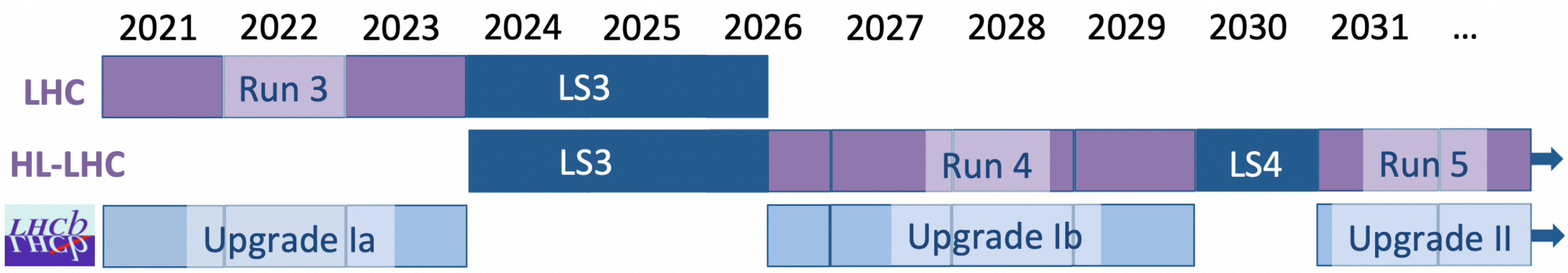
B. Wang et al. PRD101(2020)034018

LHCb detector for Upgrade I

LHCB-TDR-017



LHCb Upgrade



Upgrade I

$2x10^{33}$ $cm^{-2}s^{-1}$

$23fb^{-1}$ run3 by 2023

$50fb^{-1}$ run4 by 2029

Upgrade II

$2x10^{34}$ $cm^{-2}s^{-1}$

$>300fb^{-1}$ run5

Expected yields

- Expected data samples at Upgrade II for key modes
- 7 times (14 times hadronic events) current data by 2029

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

Physics case for an LHCb Upgrade II, CERN-LHCC-2018-027

Summary

- First evidence of hidden-charm pentaquark with strangeness $P_{cs}(4459)^0$ found after observation of three Pc states

- Four pentaquark states imply searches new narrow structures around thresholds

State	M [MeV]	Γ [MeV]	
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	$\Sigma_c^+ \overline{D}^0$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	$\Sigma_c^+ \overline{D}^{*0}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	
$P_{cs}(4459)^0$	$4458.8 \pm 2.9^{+4.7}_{-1.1}$	$17.3 \pm 6.5^{+8.0}_{-5.7}$	$\Xi_c^0 \overline{D}^{*0}$

- Several analysis stay tuned

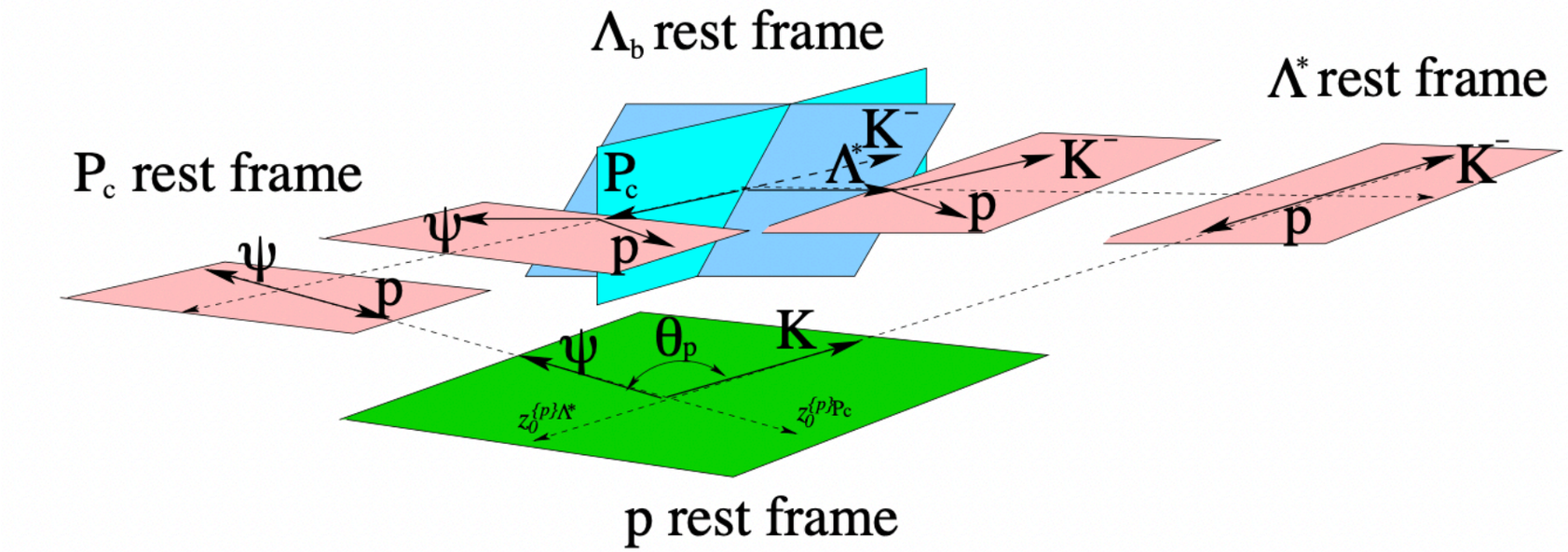
- More structures are expected from LHCb Upgrade

Thank you!

Alignment

Λ -> Ξ

p -> Λ



$$|\lambda_p\rangle = \sum_{\lambda_p^{P_c}} D^{J_p}_{\lambda_p^{P_c},\lambda_p}(\alpha_p, \theta_p, 0)^* \, |\lambda_p^{P_c}\rangle = \sum_{\lambda_p^{P_c}} e^{i\lambda_p^{P_c}\alpha_p} d^{1/2}_{\lambda_p^{P_c},\lambda_p}(\theta_p) \, |\lambda_p^{P_c}\rangle$$