

Pentaquarks at LHCb: from Run 1–2 studies to Run 3 readiness

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Quark model and exotic multiquark states

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

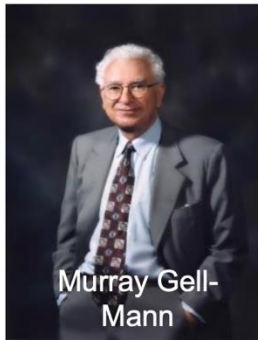
A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN

California Institute of Technology, Pasadena, California

Received 4 January 1964

...
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" 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) , $(qqq\bar{q})$ etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assumed that the lowest baryon configuration (qqq) gives just the representations 1, 8, and 10 that have been observed, while



8419/TH.412

21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

II *)

G. Zweig

CERN---Geneva

*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

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



• Tetraquark: $qq\bar{q}\bar{q}$; pentaquark: $qqqq\bar{q}$

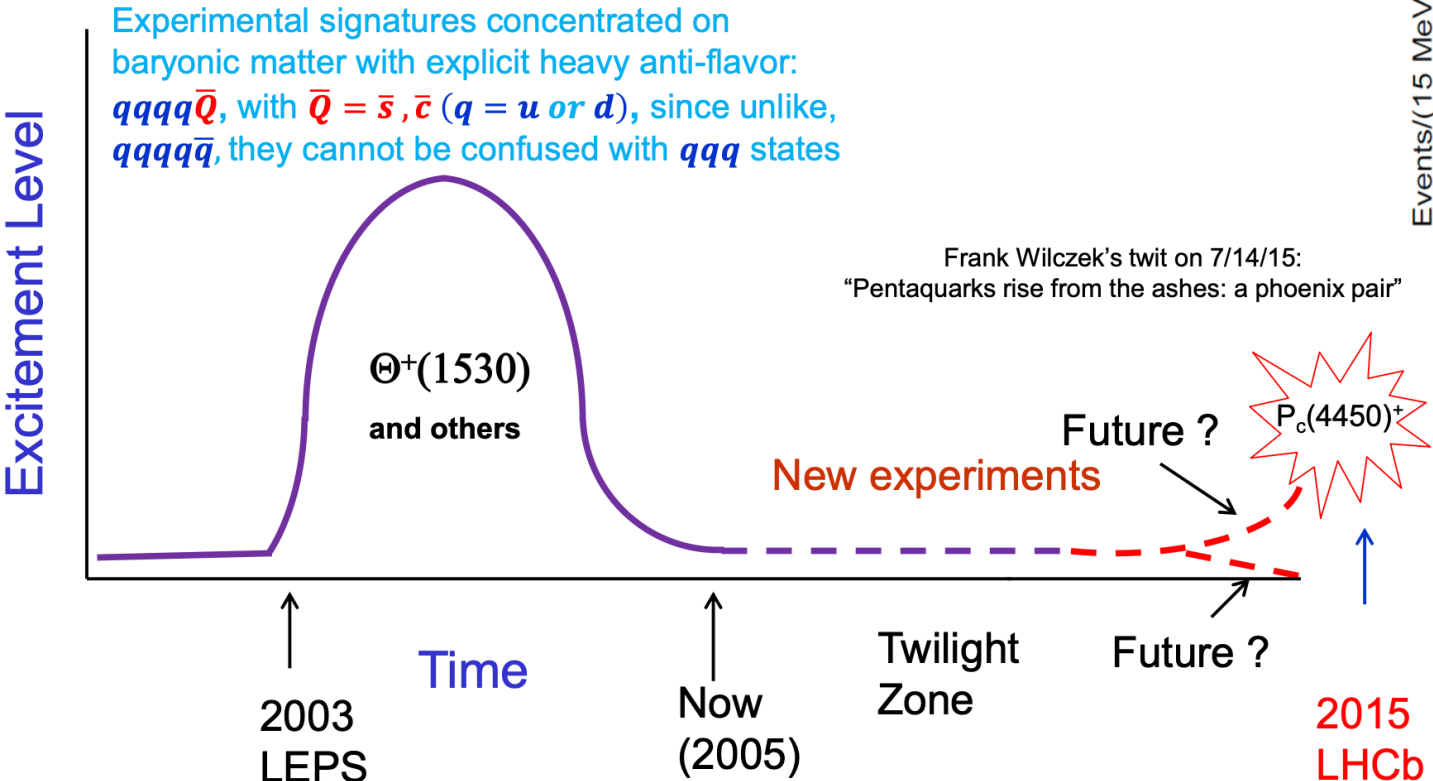
• Complicated inner structures

• More stringent test of our understanding of strong interactions at low energies

Pentaquarks before the LHCb discoveries

Adopted from Wolfgang Lorenzon's slide from his talk "Pentaquarks" on Oct 2005:

Pentaquark Vital Signs



PRL 91 (2003) 012002, 1208 citations

Evidence for $\Theta^+(1530)$ went away with better measurements

In 2003, the field of baryon spectroscopy was almost revolutionized by experimental evidence for the existence of baryon states constructed from five quarks (actually four quarks and an antiquark) rather than the usual three quarks. In a 1997 paper [1], considering only u, d , and s quarks, Diakonov *et al*

.....

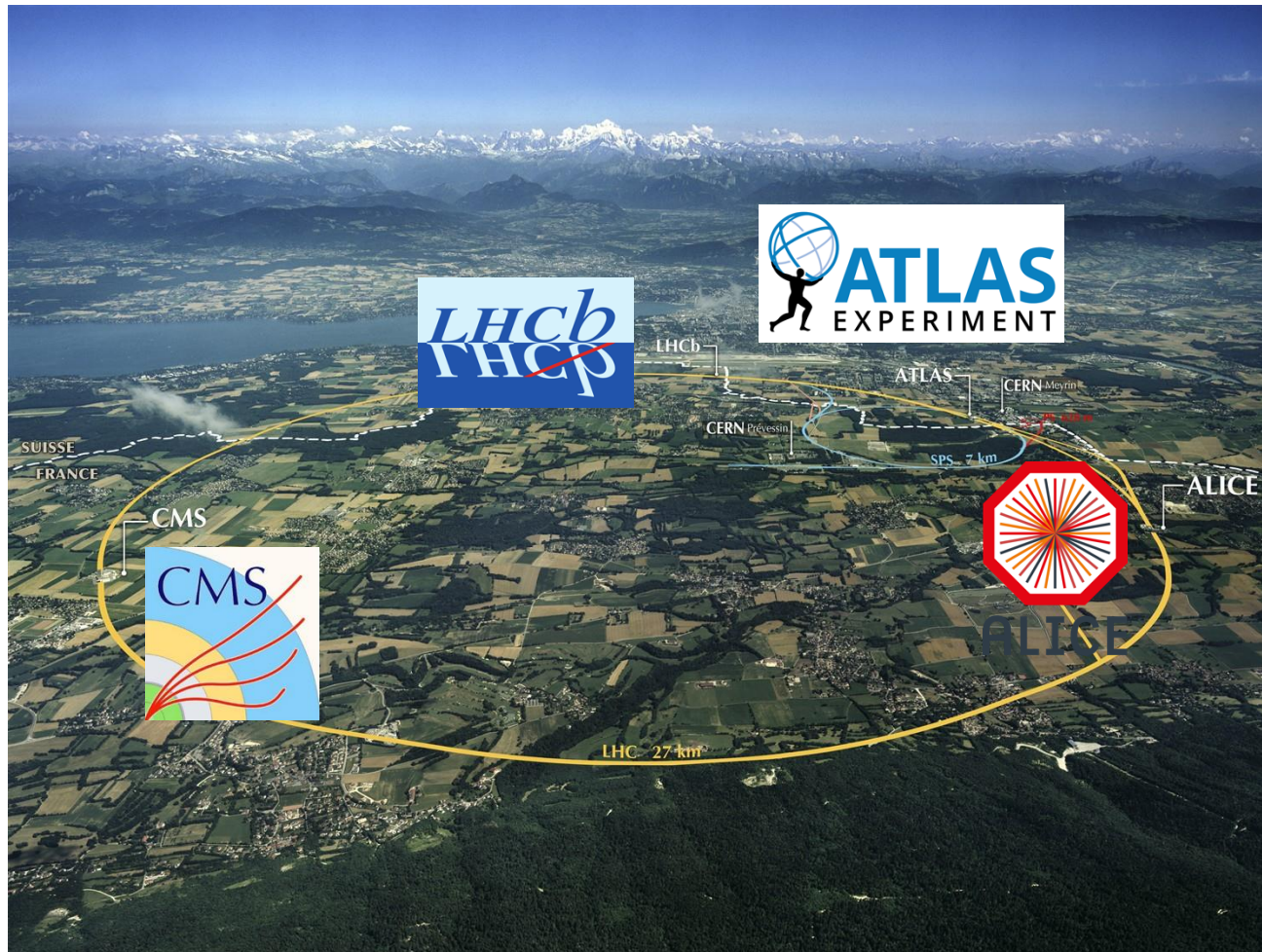
To summarize, with the exception described in the previous paragraph, there has not been a high-statistics confirmation of any of the original experiments that claimed to see the Θ^+ ; there have been two high-statistics repeats from Jefferson Lab that have clearly shown the original positive claims in those two cases to be wrong; there have been a number of other high-statistics experiments, none of which have found any evidence for the Θ^+ ; and all attempts to confirm the two other claimed pentaquark states have led to negative results. The conclusion that pentaquarks in general, and the Θ^+ , in particular, do not exist, appears compelling.

PDG 2006

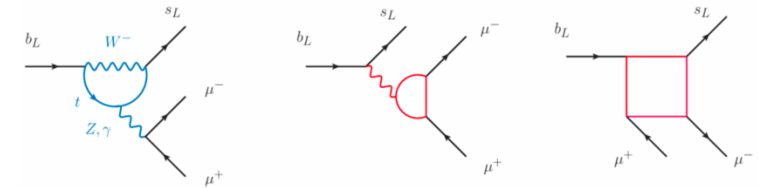
The LHCb experiment @ LHC

Originally designed to search for NP in precision frontier

- Precise measurement of CKM elements
- Decay rate and angular observables of FCNC processes



$$V_{\text{CKM}}(A, \rho, \lambda, \eta) = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$



LHCb physics project has been largely extended in the last 30 years

- Heavy flavor production and spectroscopy
- Precise charm mixing and CPV measurement
- Precise EW measurements at WZ regions
- Indirect search of NP in FCCC processes
- Heavy Ion physics
- Fixed-target (SMOG) program
-

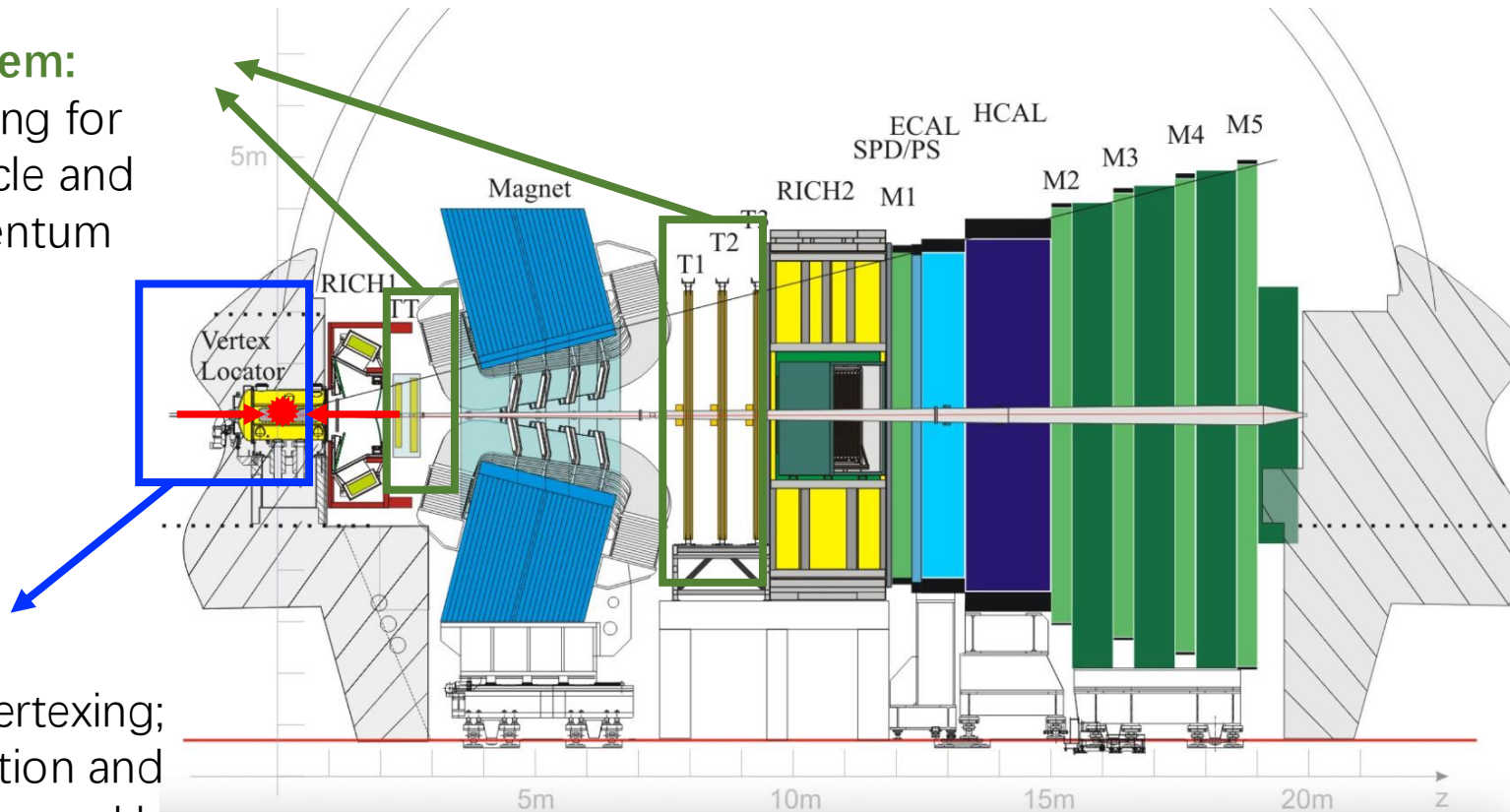
The LHCb detector (Run1-2)

- Single-arm and forward spectrometer, optimized for reconstructing heavy-flavor signals

Tracking system:

Efficient tracking for charged particle and precise momentum measurement

$$\delta p/p \sim 1\%$$



JINST 3 (2008) S08005,
IJMPA 30:07 (2015) 1530022

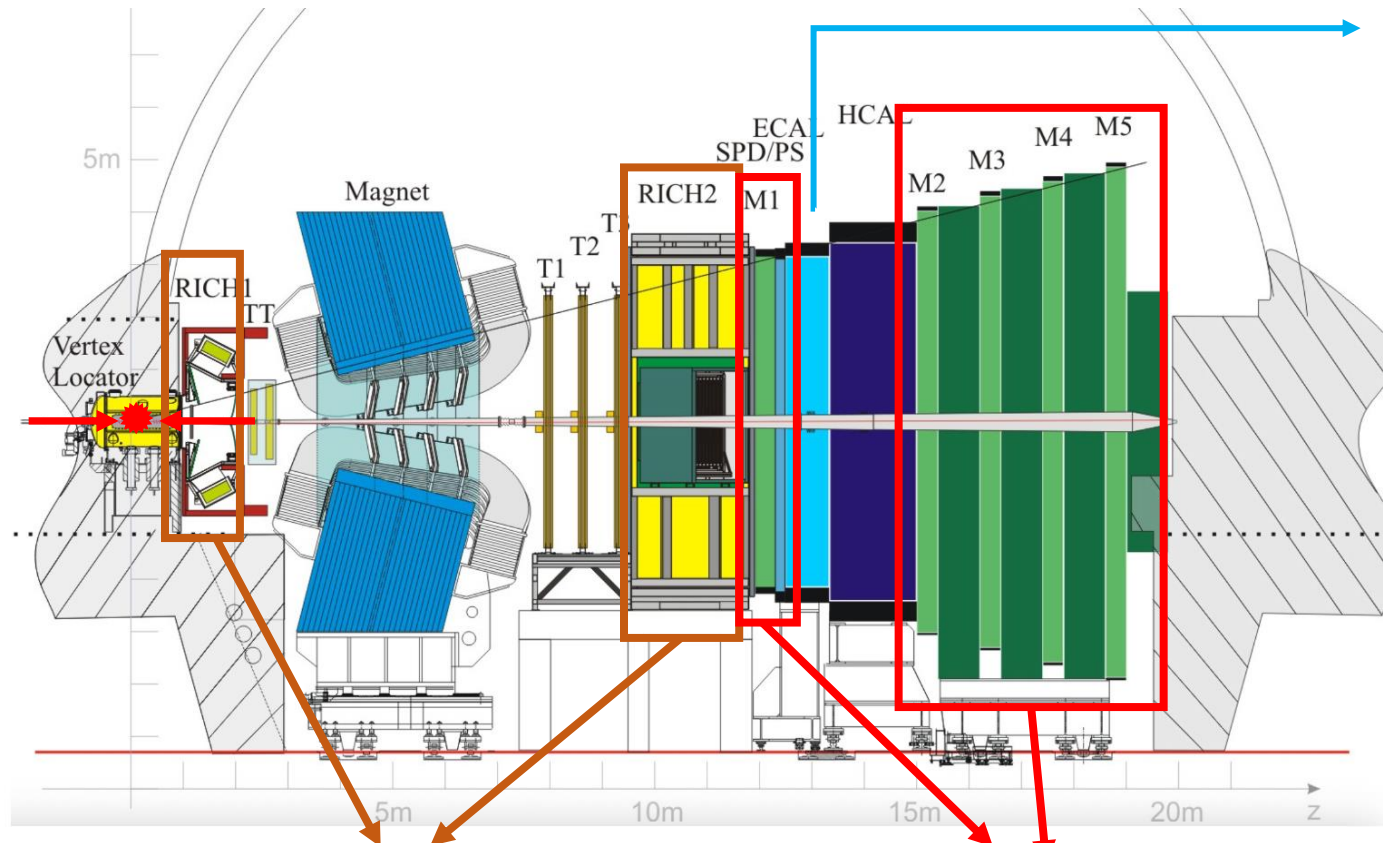
Vertex Locator:

High precision vertexing; separate production and decay vertices for weakly decaying b/c hadrons

$$\sigma_{PV,x/y} \sim 10 \mu\text{m}, \sigma_{PV,z} \sim 60 \mu\text{m}$$

The LHCb detector (Run1-2)

- Single-arm and forward spectrometer, optimized for reconstructing heavy-flavor signals



Calorimeters:
Reconstructing neutral objects and trigger

$$\sigma(E)/E \sim 10\%/\sqrt{E} \oplus 1\%$$

JINST 3 (2008) S08005,
IJMPA 30:07 (2015) 1530022

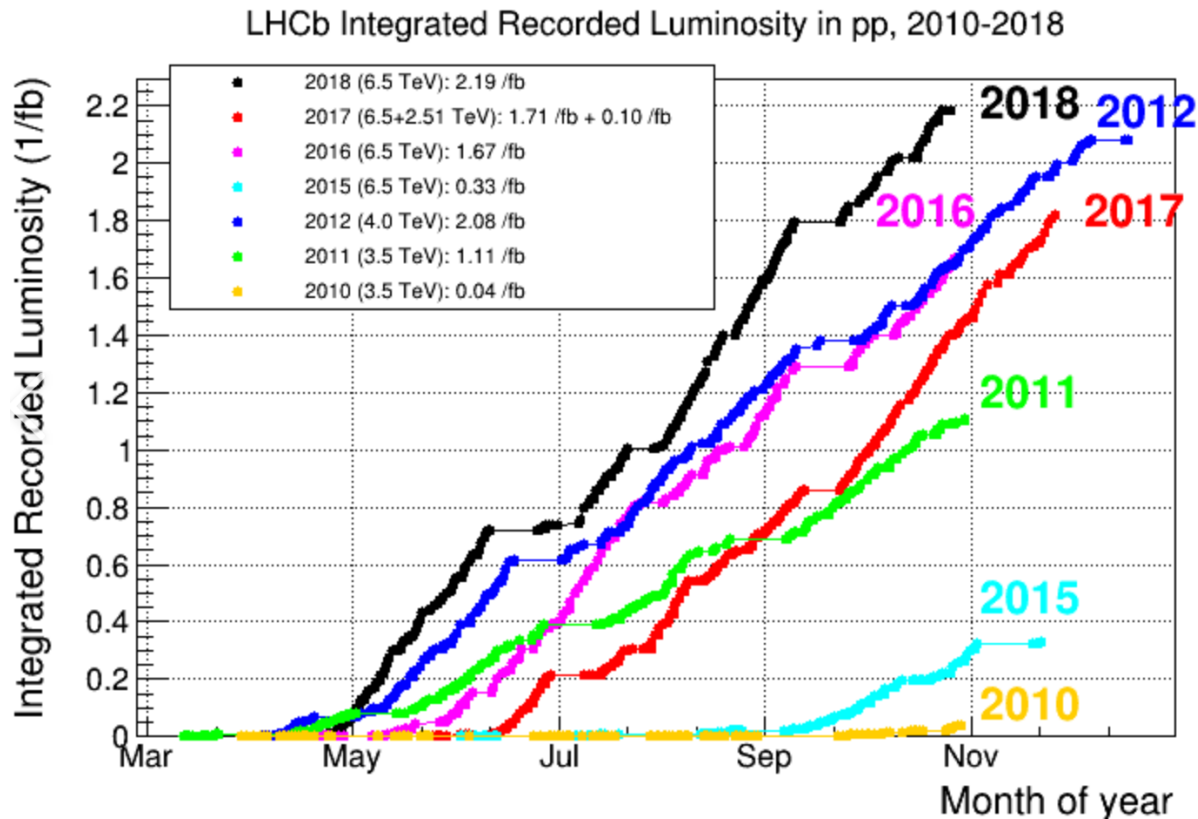
Cherenkov detector:
Efficient charged hadron identification

$$\begin{aligned} \varepsilon(K \rightarrow K) &\sim 95\% \\ @ \text{ misID rate } (\pi \rightarrow K) &\sim 5\% \end{aligned}$$

Muon system (M1-M5):
Efficiency muon identification and trigger

$$\begin{aligned} \varepsilon(\mu \rightarrow \mu) &\sim 97\% \\ @ \text{ misID rate } (\pi \rightarrow \mu) &\sim 1 - 3\% \end{aligned}$$

Pentaquark studies @ LHCb Run 1-2



LHCb Run1:

$\sim 1 \text{ fb}^{-1} @ 7 \text{ TeV} ; \sim 2 \text{ fb}^{-1} @ 8 \text{ TeV}$

LHCb Run2:

$\sim 6 \text{ fb}^{-1} @ 13 \text{ TeV}$

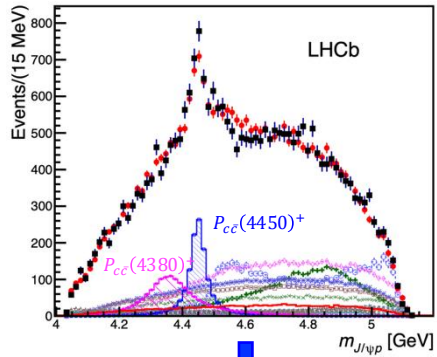
Note: This talk by default use the new pentaquark name convention in PDG.

For plots from old publications they are still based on old convention.

$$P_c = P_{c\bar{c}} : c\bar{c}uud \text{ state}$$

$$P_{cs} = P_{c\bar{c}s} : c\bar{c}uds \text{ state}$$

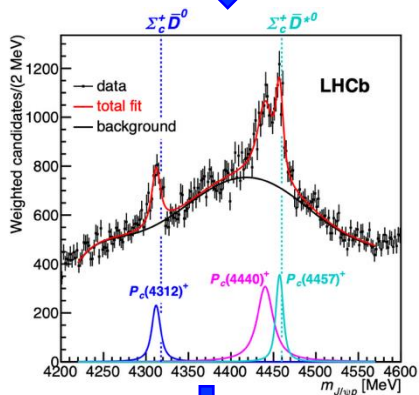
Observation/evidence of pentaquarks at LHCb



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

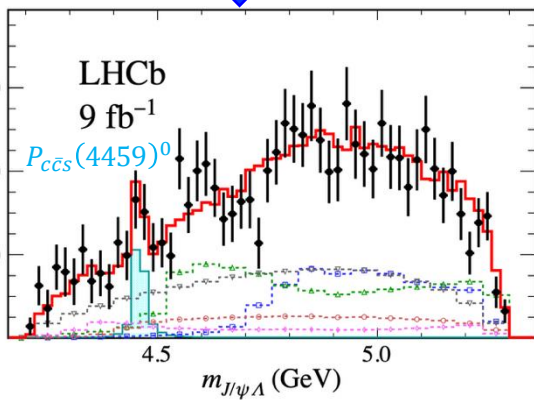
1st observation of $J/\psi p$ resonances consistent with $c\bar{c}uud$ pentaquarks (amplitude analysis)

PRL 115 (2015) 072001



Observation of three narrow $c\bar{c}uud$ pentaquark candidate decaying into $J/\psi p$ (1D mass analysis)

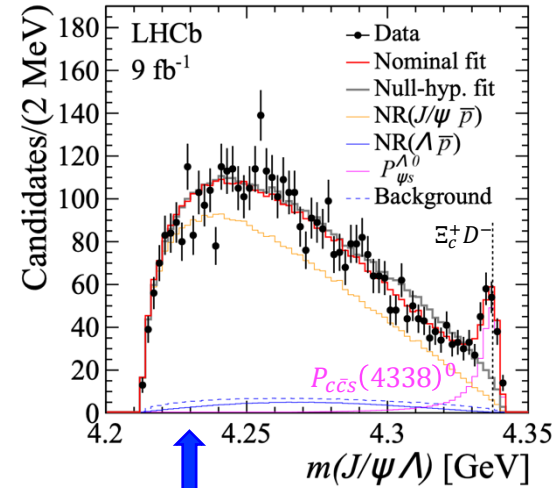
PRL 122 (2019) 222001



Sci.Bull. 66 (2021) 1278-1287

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

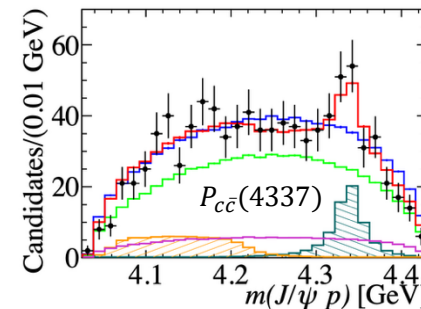
Evidence of $c\bar{c}uds$ states decaying into $J/\psi \Lambda$ (amplitude analysis)



PRL 131 (2023) 031901

$$B^- \rightarrow J/\psi \Lambda \bar{p}$$

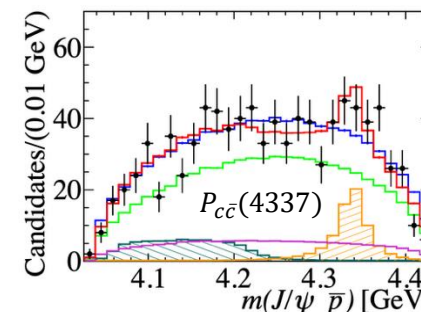
Observation of $c\bar{c}uds$ states decaying into $J/\psi \Lambda$ (amplitude analysis)



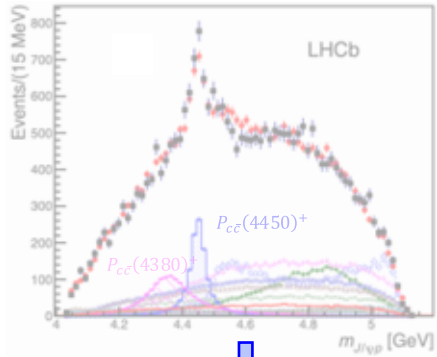
PRL 128 (2022) 062001

$$B_S^0 \rightarrow J/\psi p \bar{p}$$

Evidence of narrow $c\bar{c}uud$ states decaying into $J/\psi p$ (amplitude analysis)



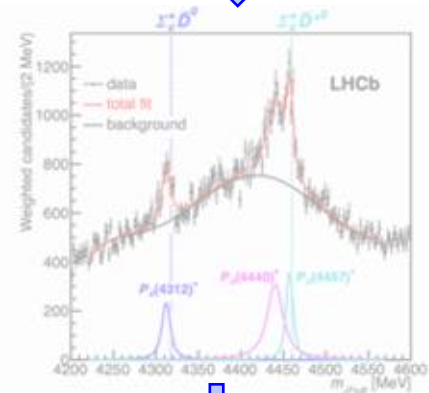
Observation/evidence of pentaquarks at LHCb



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

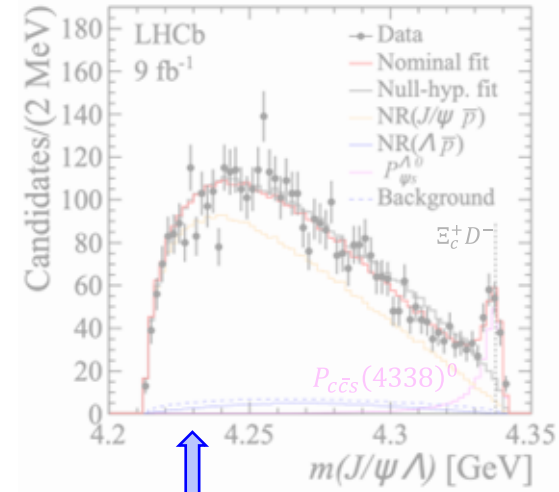
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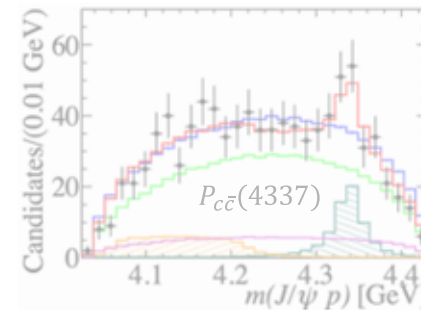
PRL 122 (2019) 222001



PRL 131 (2023) 031901

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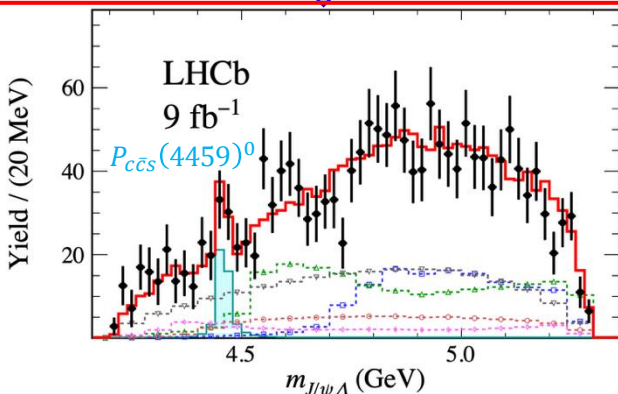
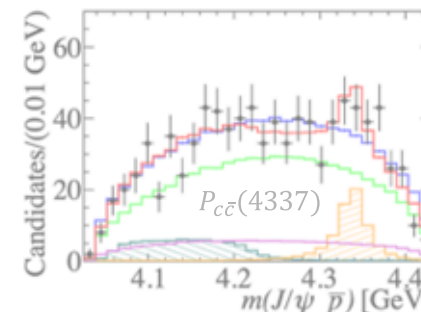
Observation of $c\bar{c}uds$ states decaying into $J/\psi \Lambda$ (amplitude analysis)



PRL 128 (2022) 062001

$$B_S^0 \rightarrow J/\psi p \bar{p}$$

Evidence of narrow $c\bar{c}uud$ states decaying into $J/\psi p$ (amplitude analysis)



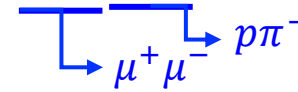
$$\Xi_b^- \rightarrow J/\psi \Lambda K^-$$

Evidence of $c\bar{c}uds$ states decaying into $J/\psi \Lambda$ (amplitude analysis)

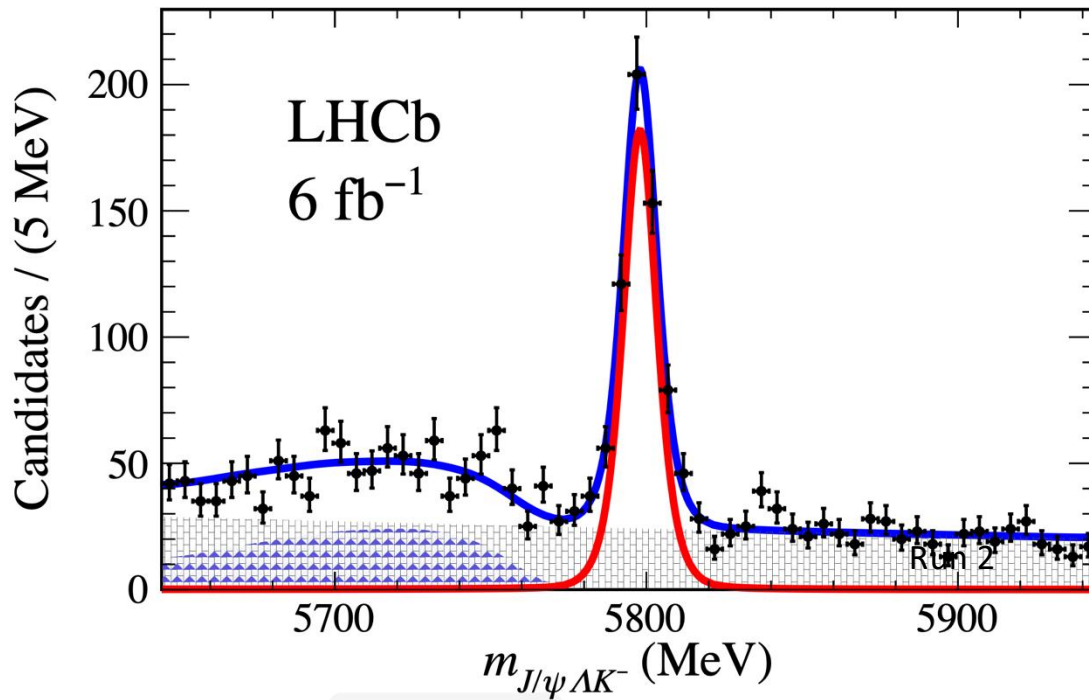
The $\Xi_b^- \rightarrow J/\psi \Lambda K^-$ data sample

- Search for predicted $[udsc\bar{c}]$ pentaquark decaying into $J/\psi \Lambda$
- Run 1 + Run 2 data: ~ 1750 signals, purity $\sim 80\%$

PRC 93 (2016) 065203

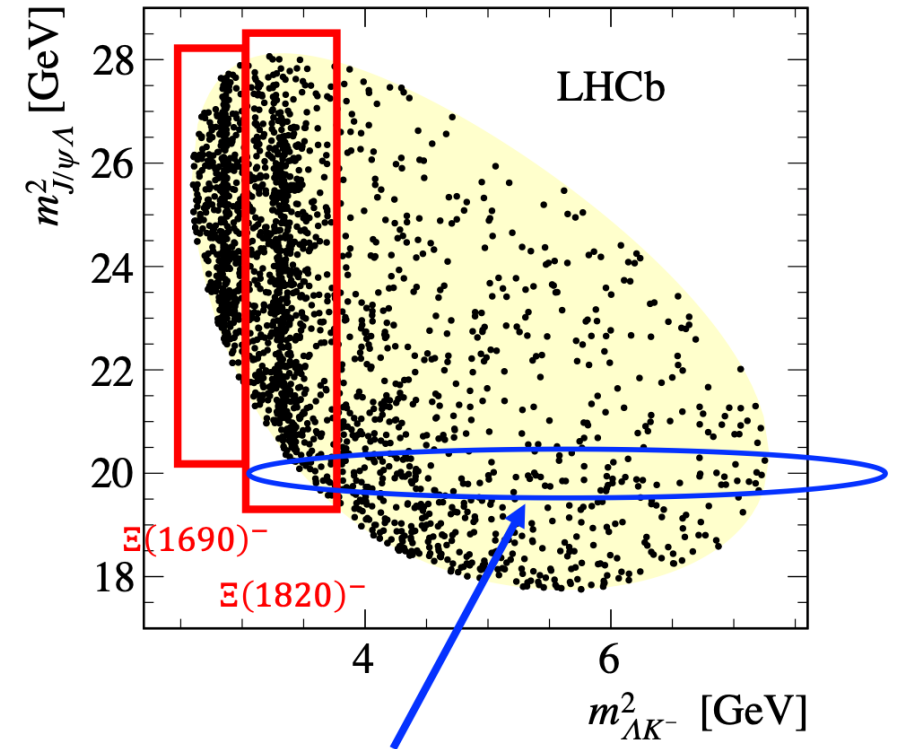


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Sub-dataset as example. Run2, Λ decay outside VELO

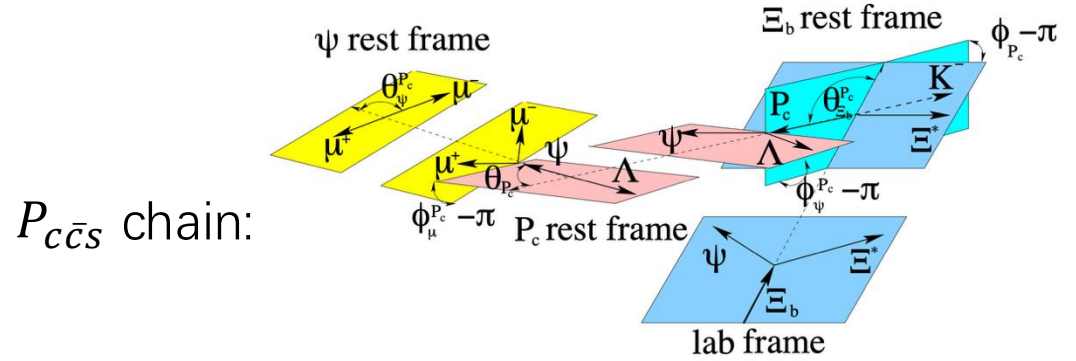
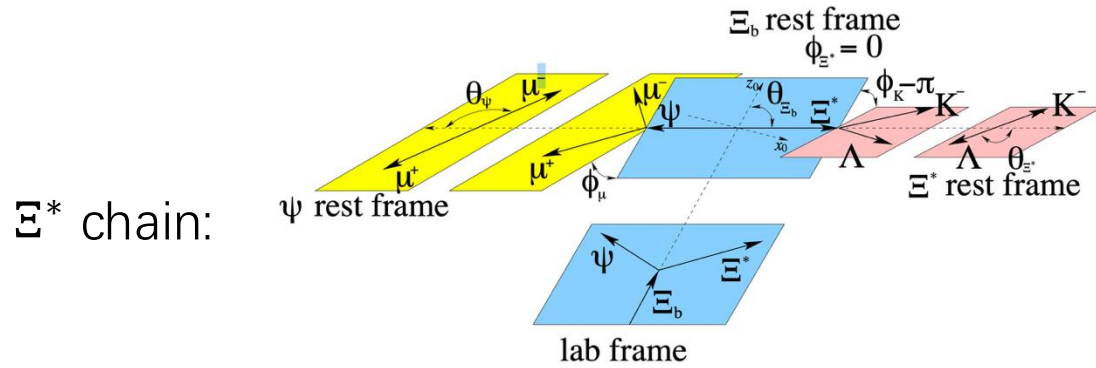
Sci.Bull. 66 (2021) 1278-1287



Potential P_{CS} contribution?
Amplitude analysis required.

$\Xi_b^- \rightarrow J/\psi \Lambda K^-$ amplitude formalism

Helicity formalism. Isobar model.



$$\mathcal{M}_{\lambda_{\Xi_b}, \lambda_{\Lambda}, \Delta\lambda_{\mu}}^{\Xi^*} \equiv \sum_n \sum_{\lambda_{\Xi^*}} \sum_{\lambda_{\psi}} \mathcal{H}_{\lambda_{\Xi^*}, \lambda_{\psi}}^{\Xi_b \rightarrow \Xi_n^* \psi} D_{\lambda_{\Xi_b}, \lambda_{\Xi^*} - \lambda_{\psi}}^{\frac{1}{2}}(0, \theta_{\Xi_b}, 0)^* \mathcal{H}_{\lambda_{\Lambda}, 0}^{\Xi_n^* \rightarrow K \Lambda} D_{\lambda_{\Xi^*}, \lambda_{\Lambda}}^{J_{\Xi_n^*}}(\phi_{\Lambda}, \theta_{\Xi^*}, 0)^* R_{\Xi_n^*}(m_{\Lambda K}) D_{\lambda_{\psi}, \Delta\lambda_{\mu}}^1(\phi_{\mu}, \theta_{\psi}, 0)^*$$

$$\mathcal{M}_{\lambda_{\Xi_b}, \lambda_{\Lambda}^{P_{cs}}, \Delta\lambda_{\mu}^{P_{cs}}}^{P_{cs}} \equiv \sum_j \sum_{\lambda_{P_{cs}}} \sum_{\lambda_{\psi}^{P_{cs}}} \mathcal{H}_{\lambda_{P_{cs}}, 0}^{\Xi_b \rightarrow P_{csj} K} D_{\lambda_{\Xi_b}, \lambda_{P_{cs}}}^{\frac{1}{2}}(\phi_{P_{cs}}, \theta_{\Xi_b}^{P_{cs}}, 0)^* \mathcal{H}_{\lambda_{\psi}^{P_{cs}}, \lambda_{\Lambda}^{P_{cs}}}^{P_{csj} \rightarrow \psi \Lambda} D_{\lambda_{P_{cs}}, \lambda_{\psi}^{P_{cs}} - \lambda_{\Lambda}^{P_{cs}}}^{J_{P_{csj}}}(\phi_{\psi}, \theta_{P_{cs}}, 0)^* R_{P_{csj}}(m_{\psi \Lambda}) D_{\lambda_{\psi}^{P_{cs}}, \Delta\lambda_{\mu}^{P_{cs}}}^1(\phi_{\mu}^{P_{cs}}, \theta_{\psi}^{P_{cs}}, 0)$$

Wigner-D rotations to associate initial and final helicity states of two-body decay nodes

Relativistic Breit-Wigner for resonance lineshapes

Align the final-state definitions of different decay nodes

Total matrix element:

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

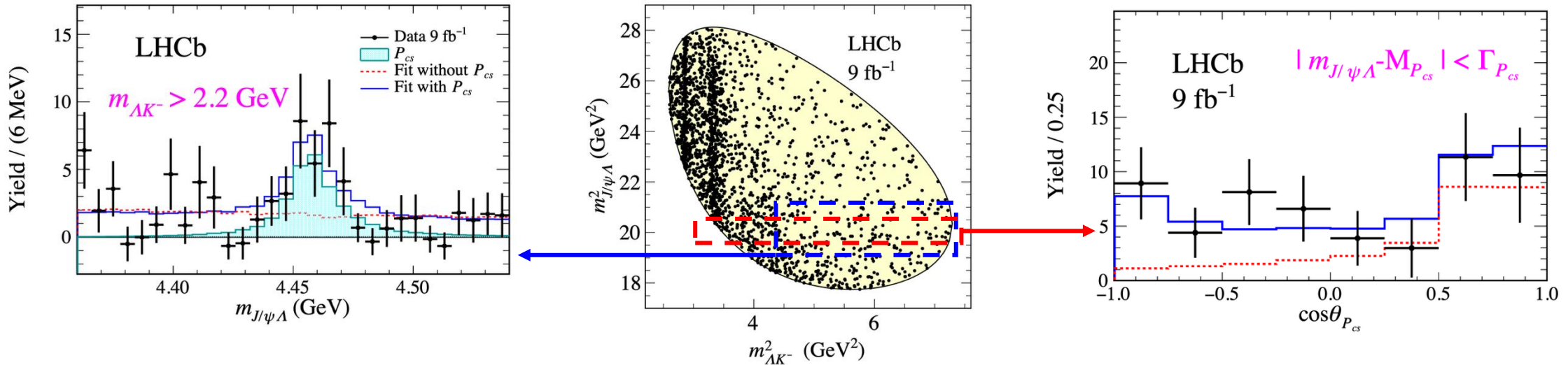
The core of PDF for unbinned maximum likelihood fits that determines properties of resonances (significance, J^P , lineshape.....)

Result of $\Xi_b^- \rightarrow J/\psi \Lambda K^-$ amplitude analysis

Sci.Bull. 66 (2021) 1278-1287

- Adding a $P_{c\bar{c}s}$ state improves $-2\ln L$ by 43 units, $\sim 4.3\sigma$ statistical significance
 - 3.1σ significance when systematic uncertainty considered
 - **First evidence of hidden-charm pentaquark with strangeness**

Adding a $P_{c\bar{c}s}$ improves both mass and angular fit projections



State	M_0 (MeV)	Γ_0 (MeV)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9^{+4.7}_{-1.1}$	$17.3 \pm 6.5^{+8.0}_{-5.7}$
$\Xi(1690)^-$	$1692.0 \pm 1.3^{+1.2}_{-0.4}$	$25.9 \pm 9.5^{+14.0}_{-13.5}$
$\Xi(1820)^-$	$1822.7 \pm 1.5^{+1.0}_{-0.6}$	$36.0 \pm 4.4^{+7.8}_{-8.2}$



Narrow state, peaking at 19MeV below $\Xi_c^0 \bar{D}^{*0}$ threshold

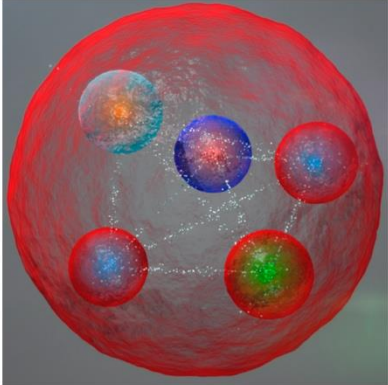


Consistent with PDG with improved precision

Understand internal dynamics of pentaquarks

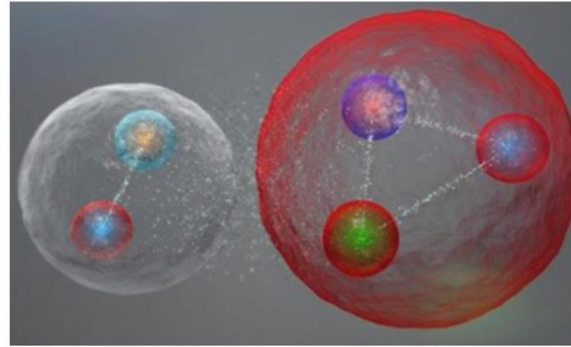
- Although many pentaquarks signals seen in experiment, their nature still under debate

Compact state



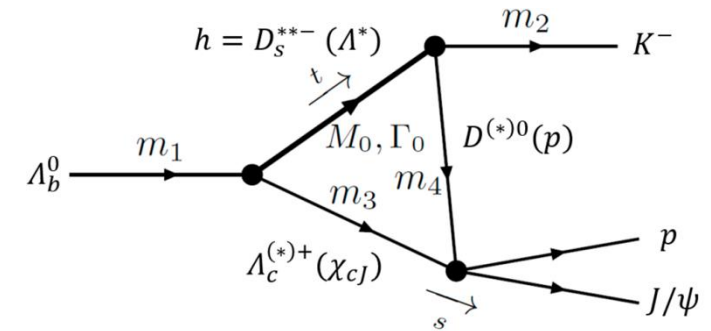
JHEP12(2015)128, PLB749(2015)289–291,
PLB793(2019)365-371, PRD95(2017)5...

Loosely-bound hadronic molecule



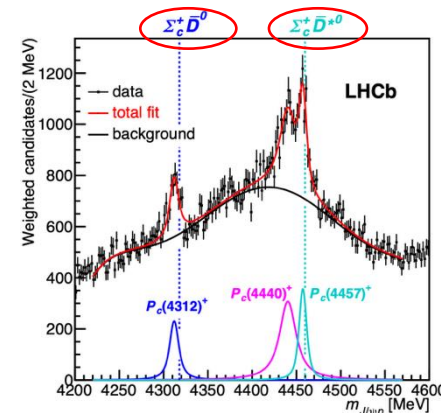
PRL115(2015)122001, PLB753(2016)547–551,
PRC85(2012)044002...

Kinematic effect

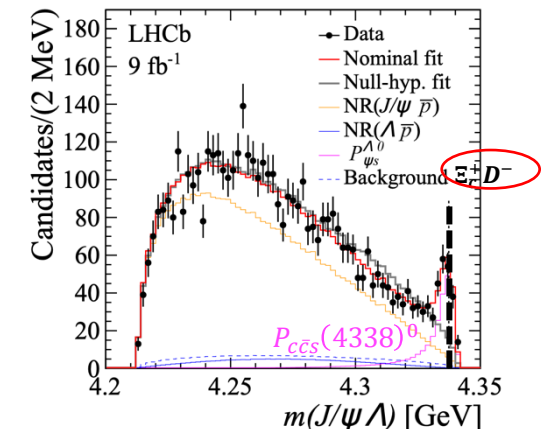


PRD92(2015)071502(R)...

- Although near-threshold peaks & narrow widths prefers molecular picture, further experimental inputs still needed for a solid conclusion



PRL 122 (2019) 222001



PRL 131 (2023) 031901

Experimental probes towards the nature of pentaquarks

- Search for predicted pentaquarks

Broad states that favors the compact picture; missing $\Sigma_c^* D^{(*)}$ molecules ...

- Spin-parity quantum numbers

Molecular picture prefers S-wave J^P of its constituent system ...

- Precise line-shape studies

Special peaking shape of triangle diagram differing from RBW ...

- Measurement of couplings to
different channels

Test if strongly couplings to constituent channels of molecules

-

Experimental probes towards the nature of pentaquarks

- Search for predicted pentaquarks



Amplitude analysis of $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays
using LHCb Run1-2 data

CERN-THESIS-2021-314

- Spin-parity quantum numbers

- Precise line-shape studies

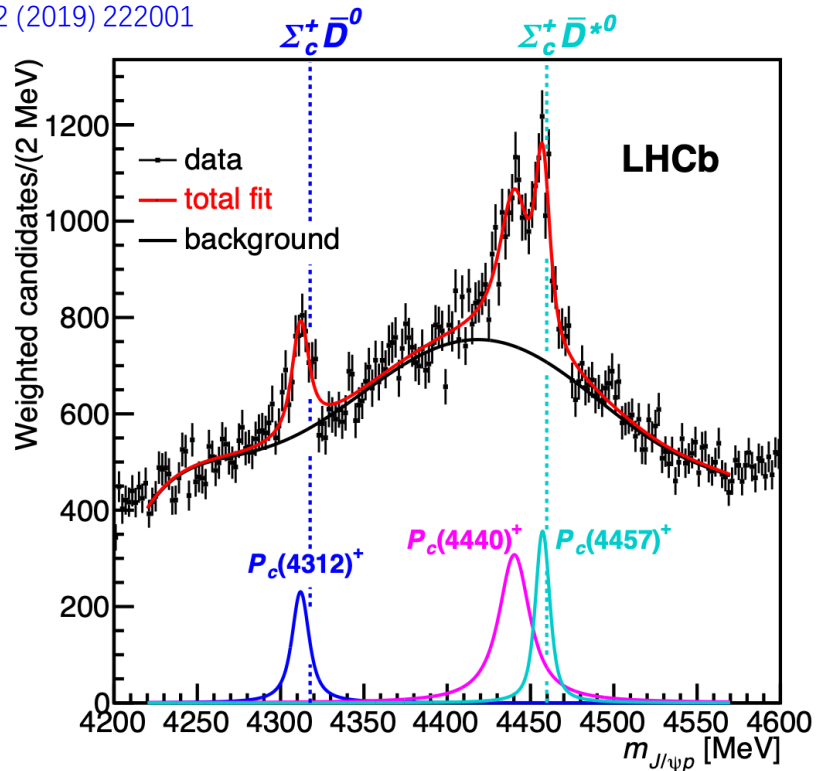
- Measurement of couplings to
different channels

-

Amplitude analysis of $\Lambda_b^0 \rightarrow J/\psi p K^-$ decay (Run1-2)

CERN-THESIS-2021-314

PRL 122 (2019) 222001



Motivation

- Measure **spin-parity quantum numbers** of $P_{c\bar{c}}(4312)^+$ state
- Search for **broad pentaquarks**

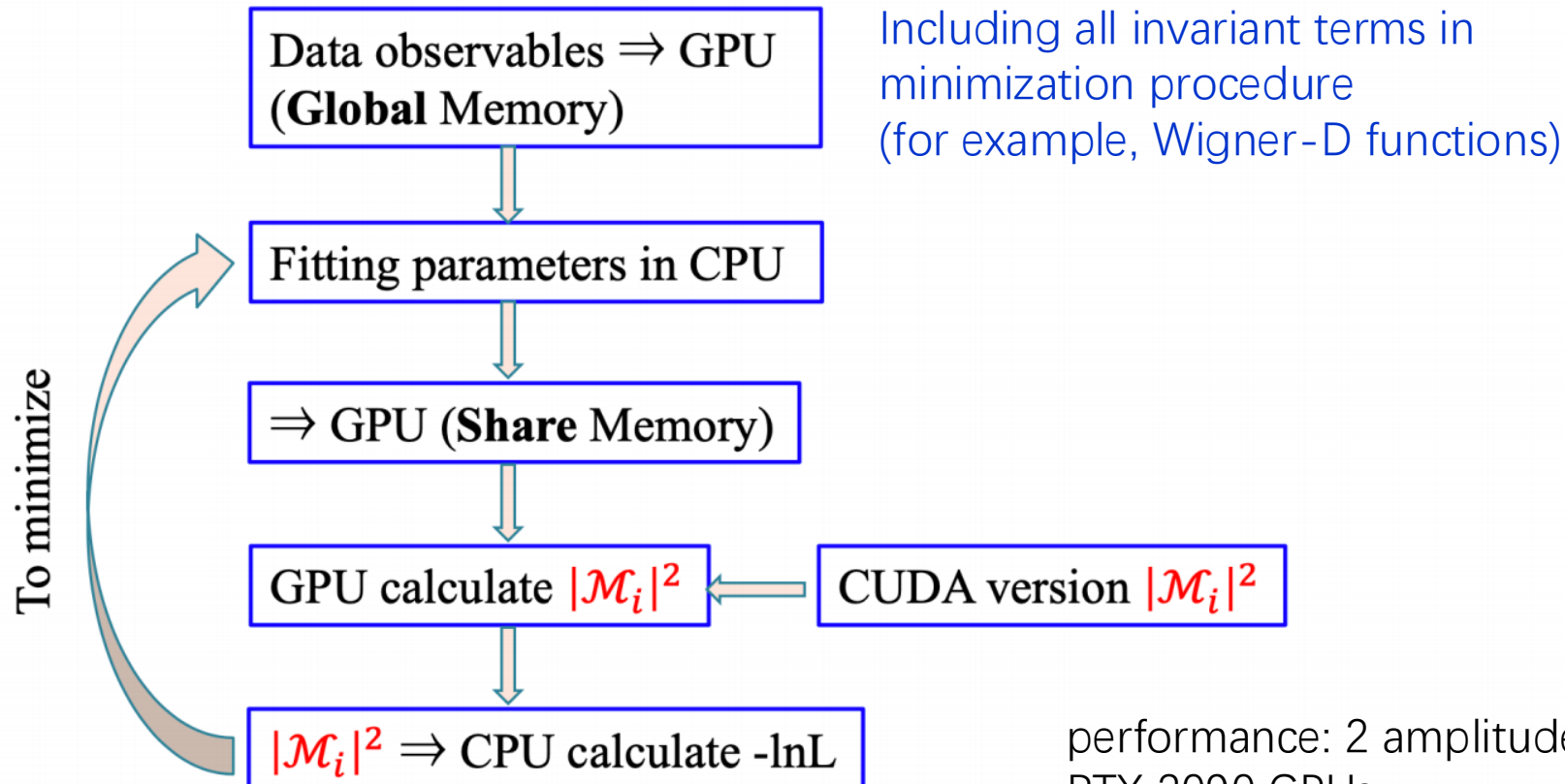
Main challenges

- Huge data sample (0.3 million events) & complicated fit model call for **resource efficient data analysis**
- **Needs precise amplitude model** to fully exploit the high stat. precision
-

- $m(J/\psi p)$ spectrum analysis performed using same dataset. However no sensitivity to spin-parity quantum numbers & existence of broad pentaquarks

Speed up amplitude analysis using GPUs

- **Idea: Let GPU to calculate $|\mathcal{M}_i|^2$**
 - CUDA (GPU based C++) for computation of $|\mathcal{M}_i|^2$
 - CUDA memory transfers between CPU and GPU



performance: 2 amplitude fits/GPU/day using RTX 3090 GPUs

Improve the application of helicity formalism

- The conventional helicity formalism

(SU2)

Decay angles rotating spin states

$$\mathcal{M} = \mathcal{H}_{\lambda_B, \lambda_C}^{A \rightarrow BC} D_{m_A, \lambda_B - \lambda_C}^{J_A}(\phi_B, \theta_A, 0)^*$$

$$\begin{aligned} \phi_B &= \text{atan2}(p_B^y, p_B^x) \\ &= \text{atan2}(\hat{y}_0^{\{A\}} \cdot \vec{p}_B^{\{A\}}, \hat{x}_0^{\{A\}} \cdot \vec{p}_B^{\{A\}}) \\ &= \text{atan2}((\hat{z}_0^{\{A\}} \times \hat{x}_0^{\{A\}}) \cdot \vec{p}_B^{\{A\}}, \hat{x}_0^{\{A\}} \cdot \vec{p}_B^{\{A\}}), \\ \cos \theta_A &= \hat{z}_0^{\{A\}} \cdot \hat{p}_B^{\{A\}}. \end{aligned}$$

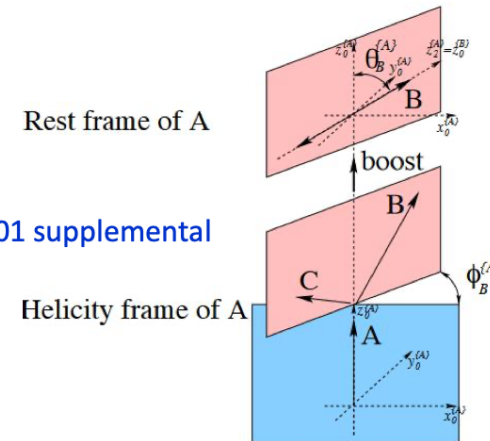
Fully determine



(SO3)

Rotations in momentum space

PRL 115 (2015) 072001 supplemental



Quantum effects missing for **baryons** ?

$$\begin{aligned} d_{\lambda_1, \lambda_2}^J(\theta_A) &= -\mathbf{1} \times d_{\lambda_1, \lambda_2}^J(\theta_A + 2\pi) \\ e^{i\lambda\phi_B} &= -\mathbf{1} \times e^{i\lambda(\phi_B + 2\pi)} \end{aligned}$$

Cannot set a preference between θ_A & $\theta_A + 2\pi$, ϕ_B & $\phi_B + 2\pi$

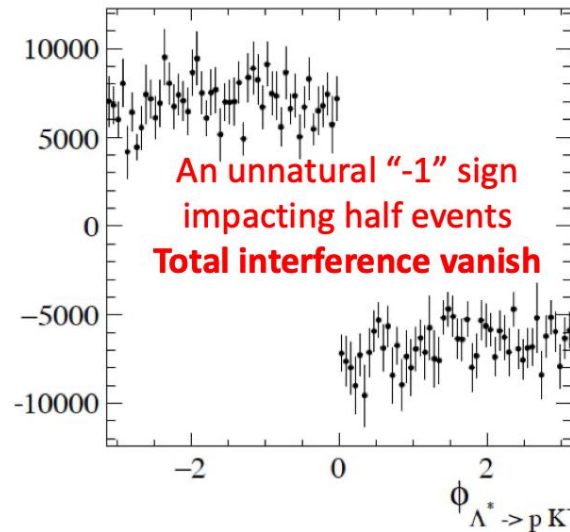
- Arbitrary “-1” terms in any single-chain amplitudes:
 - Generate tricky behavior in interference of different chains

Improve the application of helicity formalism

Chinese Phys. C 45 (2021) 063103

- The Λ^* , P_c interference using the formula for P_c observation

Interference
between P_c and
 Λ^* decay chains



Impact of missing of the quantum effects
consistent with the statement in [PRL 115
\(2015\) 072001](#)

polarization of zero. Interferences between various Λ_n^* and P_{cj}^+ resonances vanish in the integrated rates unless the resonances belong to the same decay chain and have the same quantum numbers.

- Impact on the first P_c analysis:
 - No impact on Λ^* -only fit quality
 - Reduce the flexibility of $\Lambda^* + P_c$ model
 - P_c properties (to be) updated in Run1+2 analysis

[PRL 122\(2019\)222001](#): Two-peak nature of $P_c(4450)$ observed;

Properties of $P_c(4380)$ to be updated in future amplitude analysis

Improve the application of helicity formalism

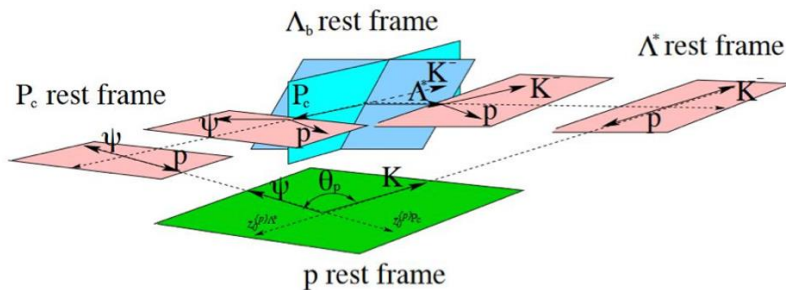
Chinese Phys. C 45 (2021) 063103

- Main idea:
 - Origin of the issue is improper alignment of final-state definitions for each decay chain due to arbitrary “-1” term
 - Seek for new principles for final-state alignment

Conventional method

Rely on graphic picture

Use angles between particle momenta or momentum planes to define alignment operator



New method

Directly write down all rotation/boost operators associating initial/final spin-state frames, using a representation where $\theta \rightarrow \theta + 2\pi$ is visible

Advances in High Energy Physics (2020) 6674595; Chinese Phys. C 45 (2021) 063103

$$R_z(\alpha) = \begin{pmatrix} e^{-i\alpha/2} & 0 \\ 0 & e^{i\alpha/2} \end{pmatrix} R_y(\alpha) = \begin{pmatrix} \cos(\alpha/2) & -\sin(\alpha/2) \\ \sin(\alpha/2) & \cos(\alpha/2) \end{pmatrix}$$

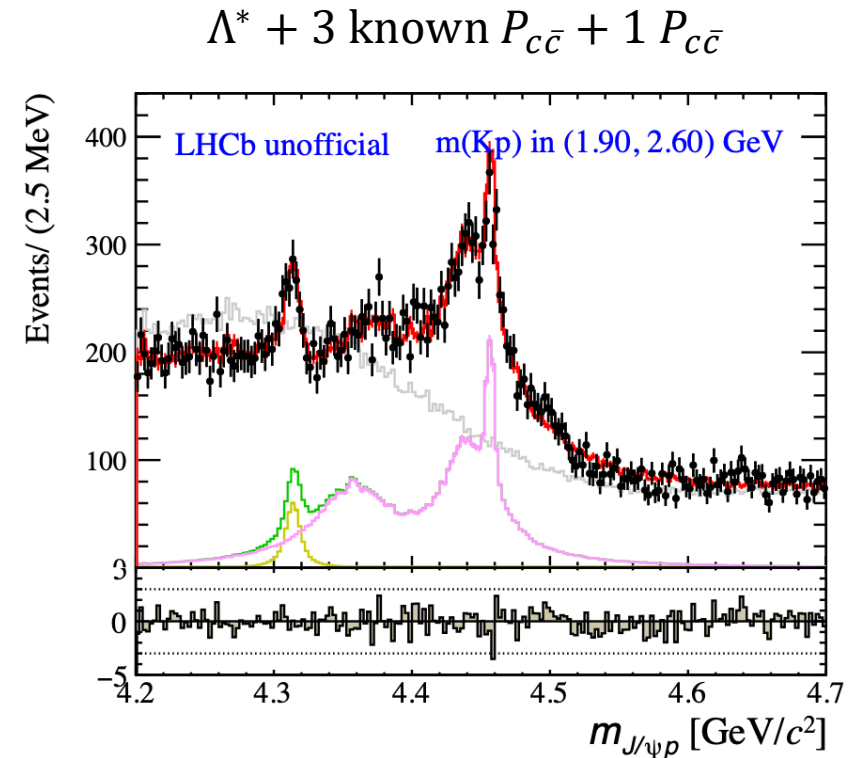
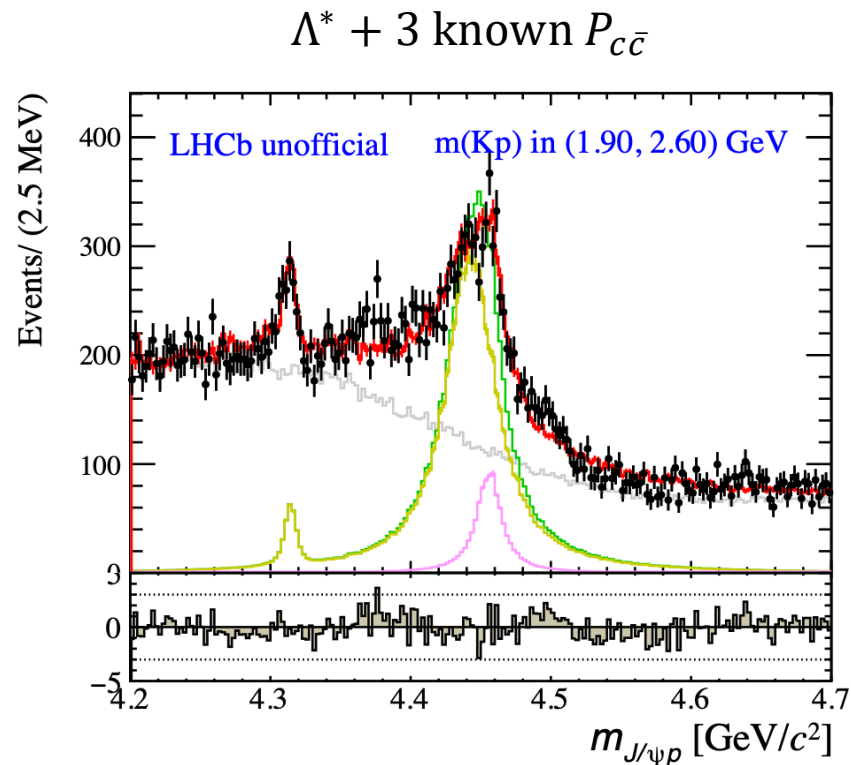
The new method has been used in several LHCb and BESIII amplitude analyses

arXiv.2603.05564; arXiv.2601.07617; JHEP02(2025)212; PRL134(2025)2,021901; JHEP12(2022)033; PRL128(2022)6,062001; Sci.Bull.66(2021)1278-1287

Preliminary results (LHCb unofficial)

CERN-THESIS-2021-314

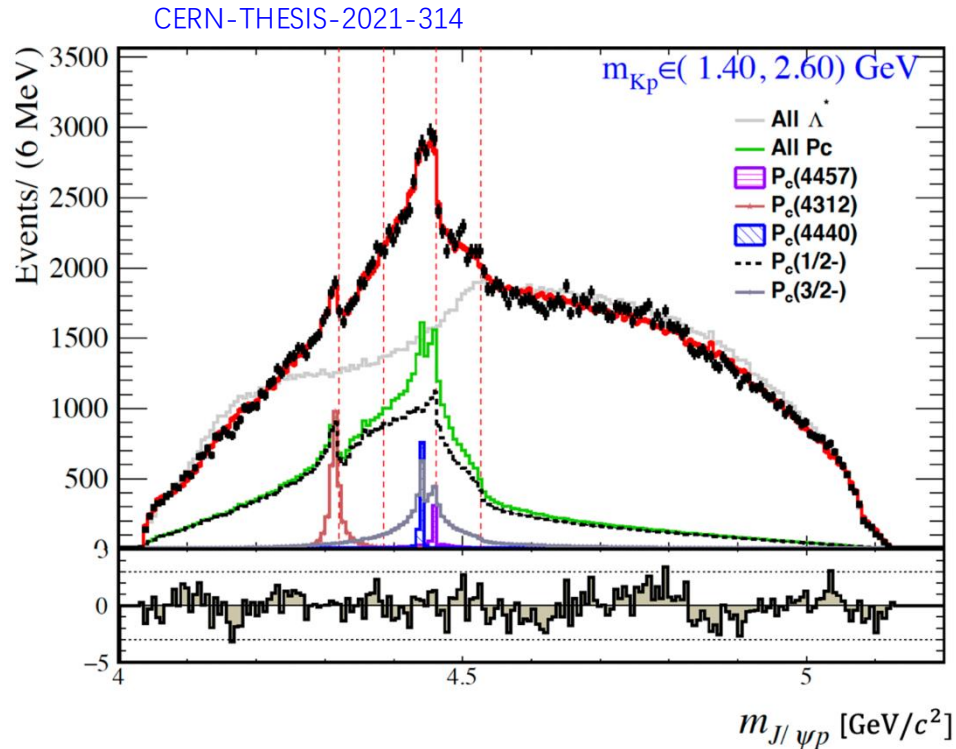
- Adding a new $P_{c\bar{c}}$ significantly improves fit quality;
 - However similar fit quality accessible by introducing $\Sigma_c^{(*)} D^{(*)}$ coupled-channel effect



- Spin-parity preference of $P_{c\bar{c}}(4312)^+$ is model-dependent. Cannot set up a preference with high significance based on the current dataset and analysis strategy

Next step for $\Lambda_b^0 \rightarrow J/\psi p K^-$ Am.An. (Run1-2)

- Precise lineshape study of $P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$ using coupled-channel K-Matrix



- Start from the near-threshold + narrow peak phenomenol, assume pentaquarks strongly couples to $\Sigma_c^{(*)} D^{(*)}$ channels
- **An assumption dependent measurement**

- Further constraint the J^P assumption

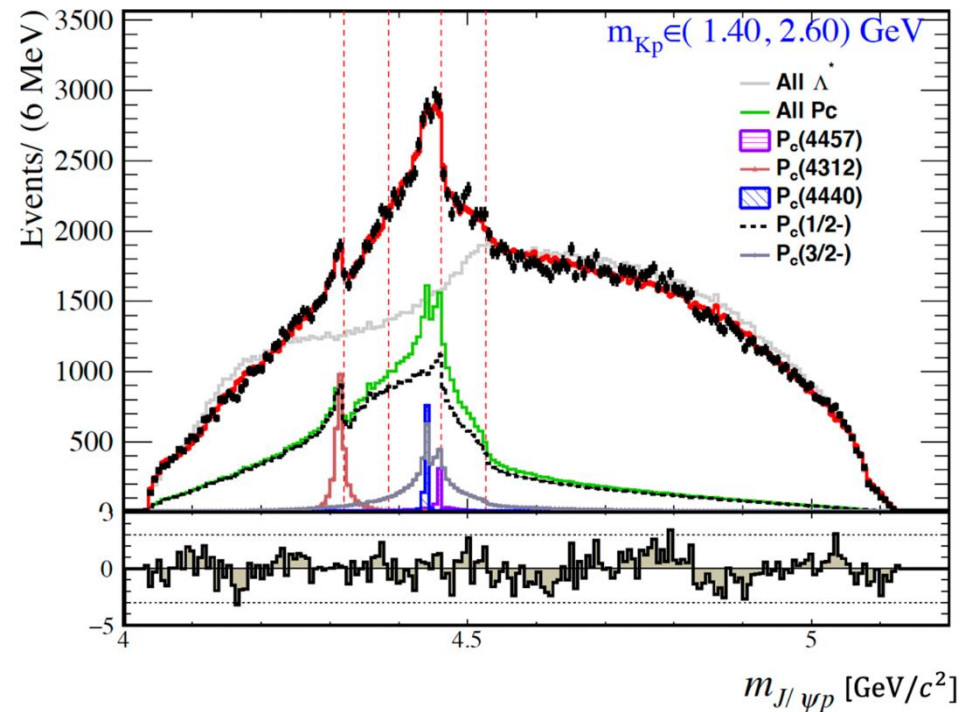
Hierarchy (Hypothesis)	$P_{c\bar{c}}(4312)^+$	$P_{c\bar{c}}(4440)^+$	$P_{c\bar{c}}(4457)^+$
Normal	$\frac{1}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$
Inverted	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{1}{2}^-$

- Open $\Sigma_c^{(*)} D^{(*)}$ channels in the K-Matrix amplitude

Next step for $\Lambda_b^0 \rightarrow J/\psi p K^-$ Am.An. (Run1-2)

- Precise lineshape study of $P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$ using coupled-channel K-Matrix

CERN-THESIS-2021-314



- Precise measurement of pole positions
 - Physical/unphysical sheet => quasi-bound/quasi-virtual state
- Effective range expansion

$$T(s) = \frac{N}{R(s) - ik(s)}, \quad R(s) = \frac{1}{a} + r \frac{k^2(s)}{2} + O(r^2 k^4).$$

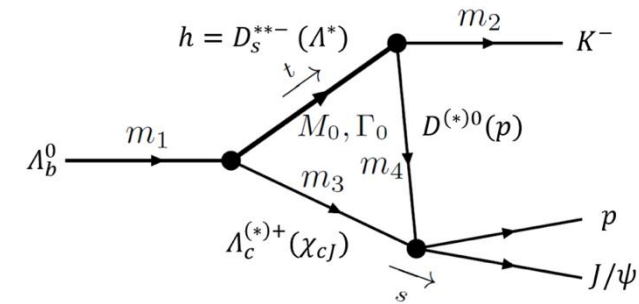
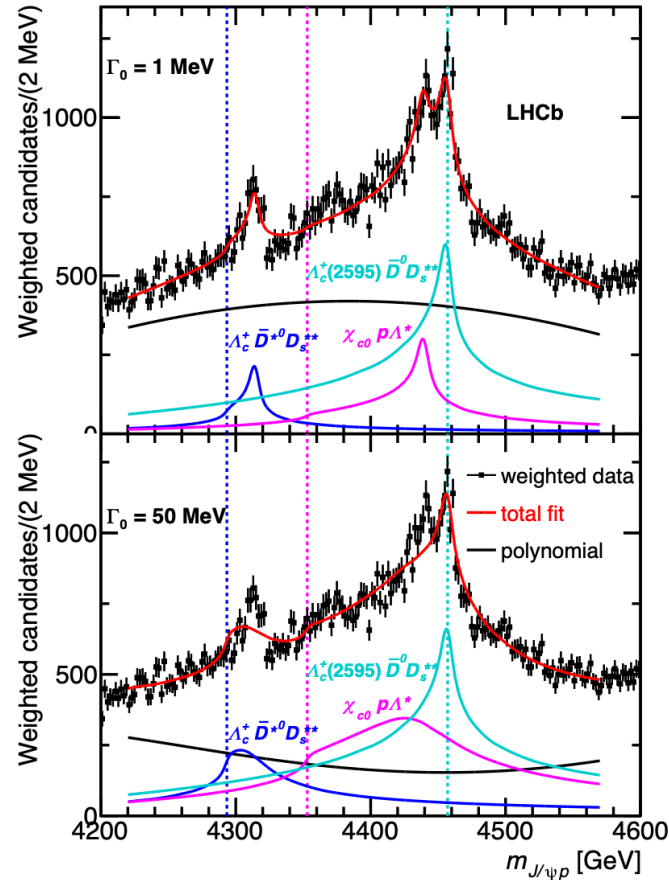
$$Z = 1 - 1/\sqrt{1 + 2r/a}. \quad X = 1 - Z = 1/\sqrt{1 + 2r/a}.$$



Quantify how strongly pentaquarks are built from $\Sigma_c - D^{(*)}$ configuration

Experimental probes towards the nature of pentaquarks

- Search for predicted pentaquarks
- Spin-parity quantum numbers
- **Precise line-shape studies** →
- Measurement of couplings to different channels
-



The $J/\psi p$ mass spectrum of narrow pentaquarks $P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$ cannot be modelled purely by using the triangle mechanism

[PRL 122 \(2019\) 222001](#)

Experimental probes towards the nature of pentaquarks

- Search for predicted pentaquarks

- Spin-parity quantum numbers

- Precise line-shape studies

- Measurement of couplings to different channels



Pentaquark search in $\Lambda_b^0 \rightarrow \eta_c(1S)pK^-$ decays

PRD 102 (2020) 112012

-

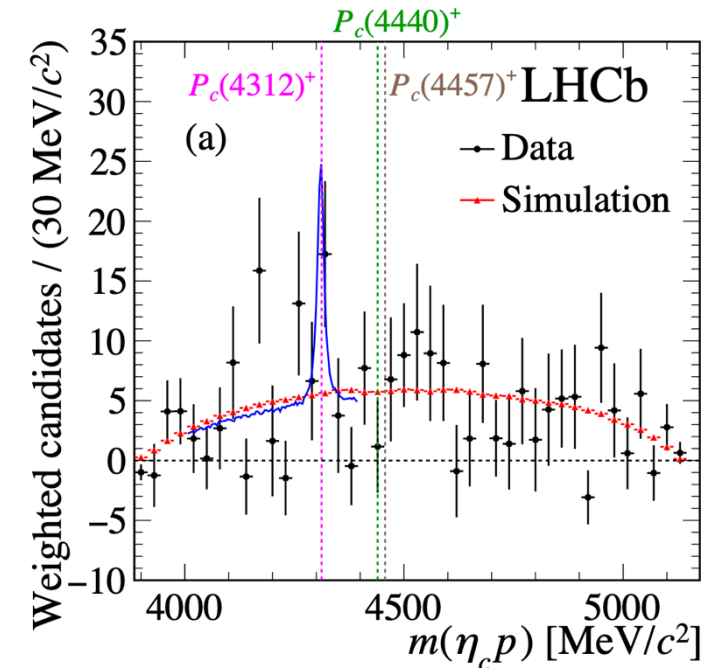
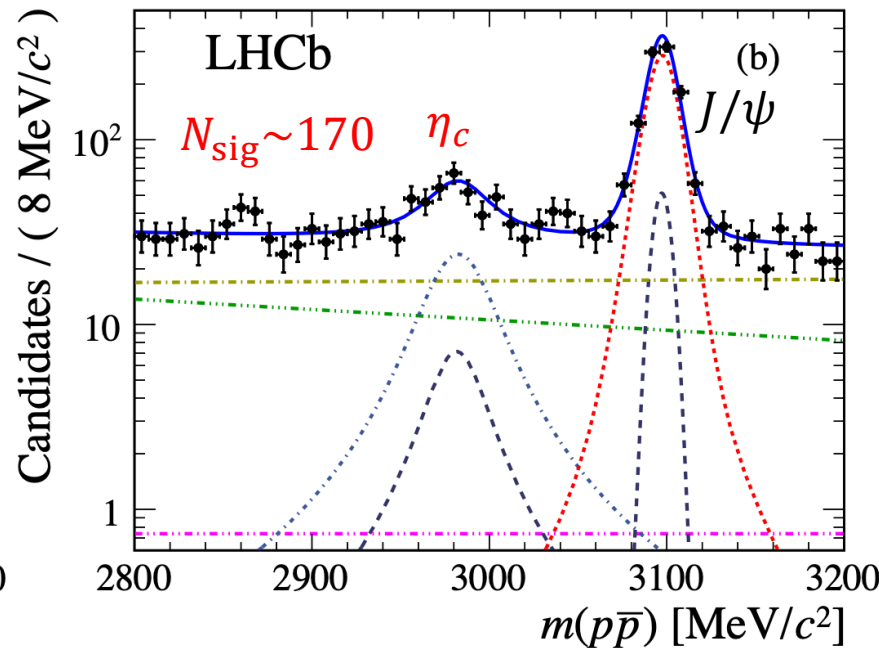
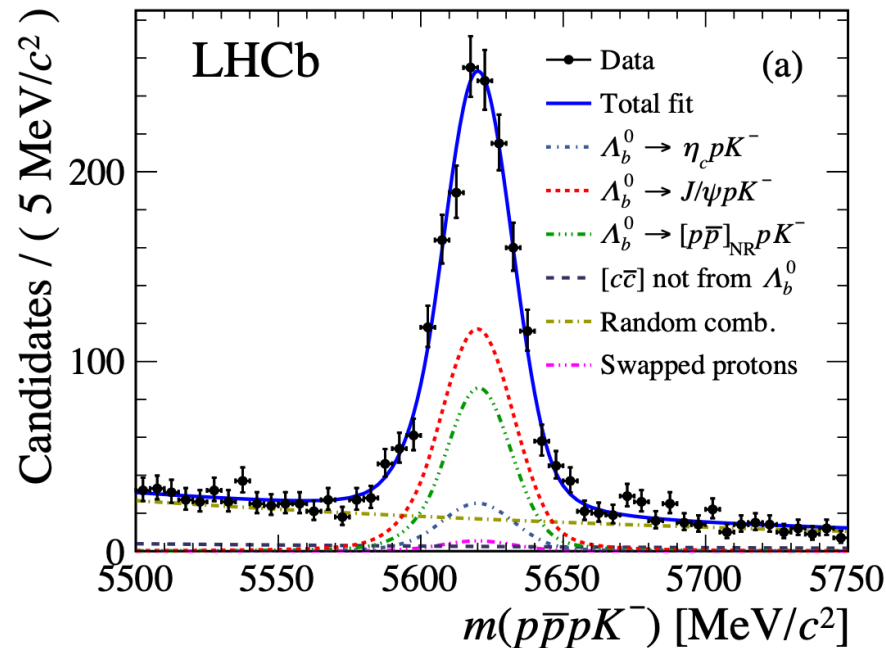
Pentaquark search in $\Lambda_b^0 \rightarrow \eta_c(1S)pK^-$ decay

PRD100(2019)034020; PRD100(2019)074007; PRD102(2020)036012

• Prediction with HQSS: $\frac{\Gamma(P_c \rightarrow \eta_c p)}{\Gamma(P_c \rightarrow J/\psi p)} \sim 3$ if $P_c(4312)^+$ is $\Sigma_c \bar{D}$ molecule

• Analysis with 2016~2018 data, $\mathcal{L} \sim 5.4 \text{ fb}^{-1}$, $\eta_c \rightarrow p\bar{p}$

PRD 102 (2020) 112012



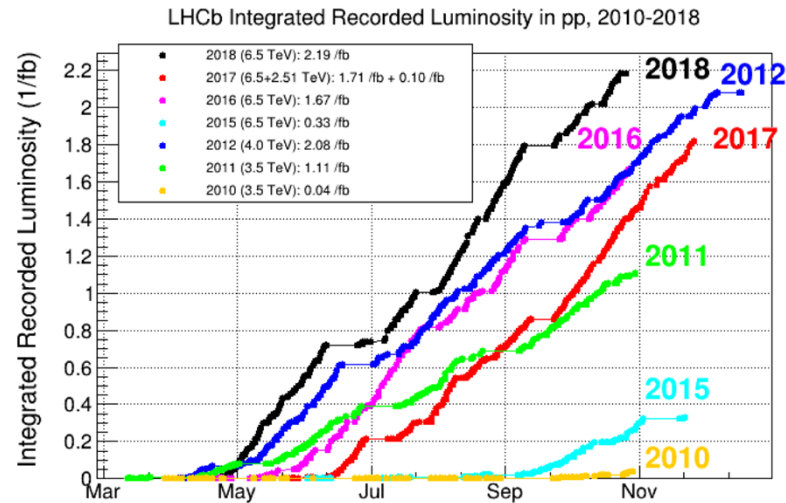
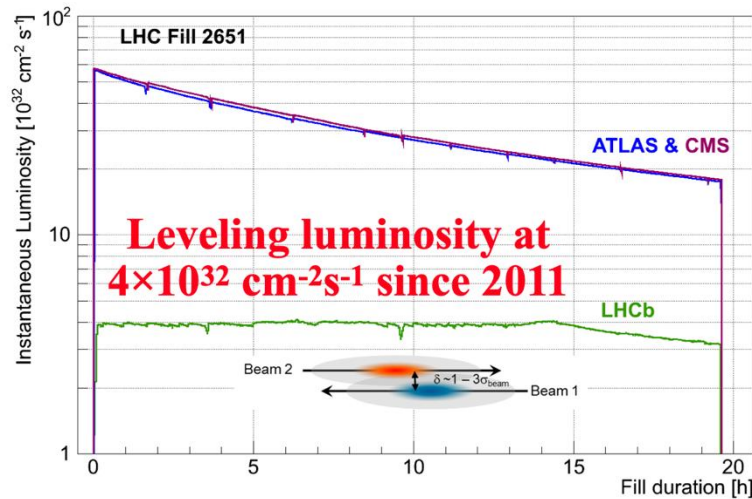
$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \rightarrow P_c(4312)^+ K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \eta_c p K^-)} \mathcal{B}(P_c(4312)^+ \rightarrow \eta_c p) < \underline{0.24} \quad @ 95\% \text{ C.L.}$$

8 times larger than molecule-based prediction. Need more data to better constrain theory. **Run3 needed!**

Towards pentaquarks @ LHCb Run 3

Limitations of LHCb data collection until 2018

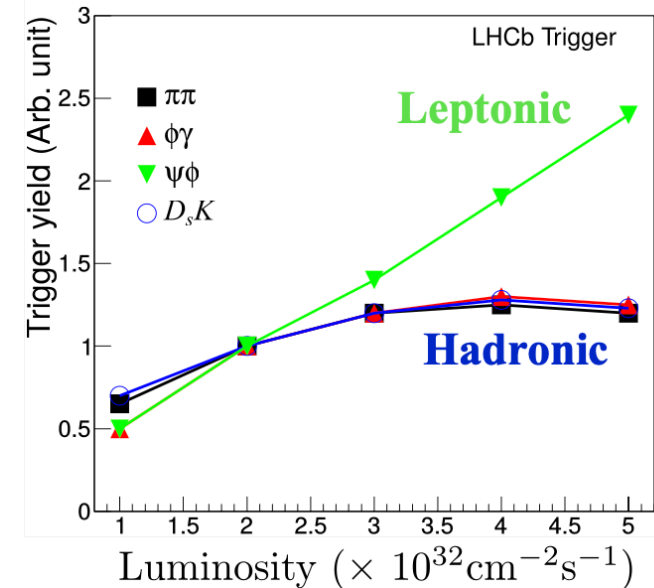
- Data sample limited to $\sim 2\text{fb}^{-1}$ per year



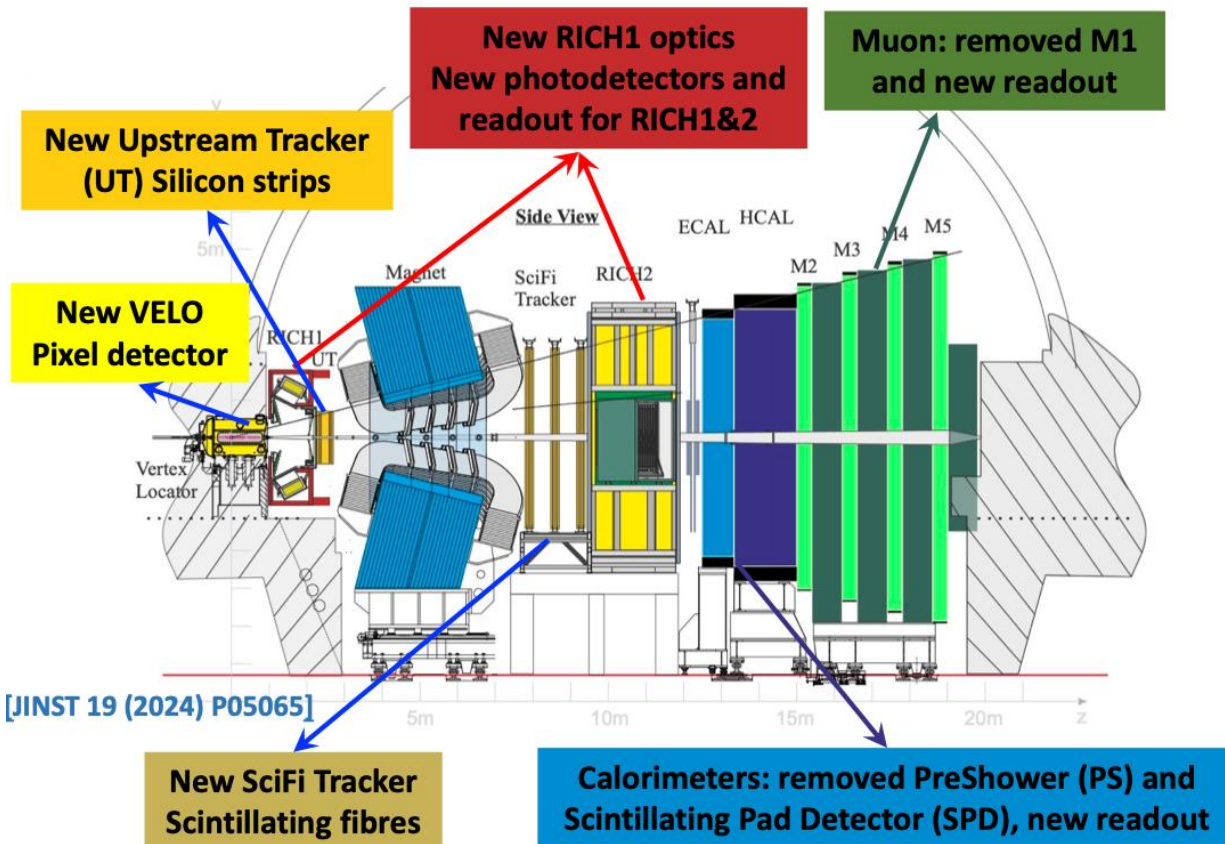
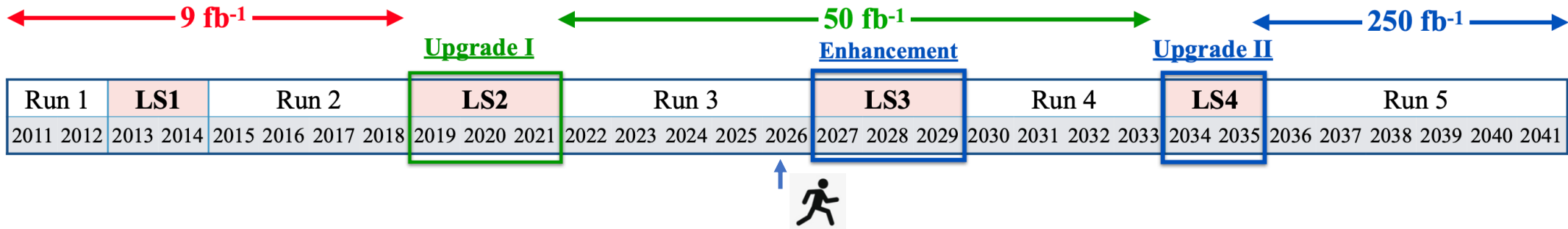
- Limited L0 efficiency for decays with hadronic final state



Hadronic hardware trigger saturates fast
 Would be a show stopper for high-lumi operation



The LHCb Upgrade I



New detectors for tracking system
Pixel VELO, UT, SciFi

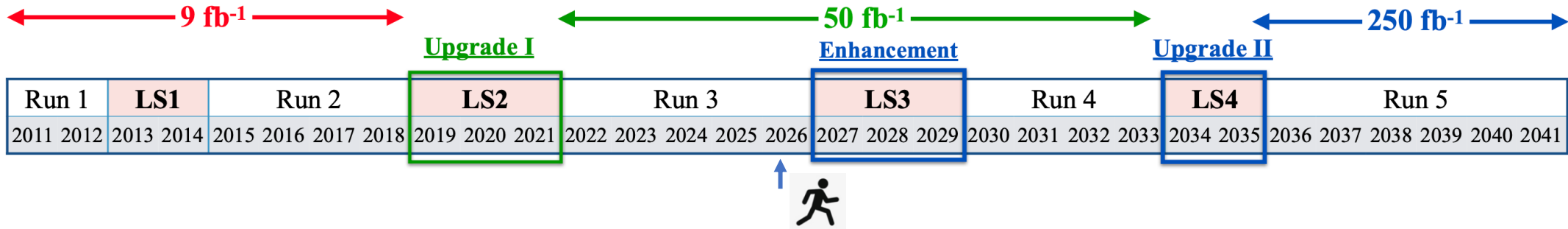
New readout systems for all subdetectors

Installation during 2019-2021;
Commissioning during 2022-2023;
Achieved designed performance in 2024

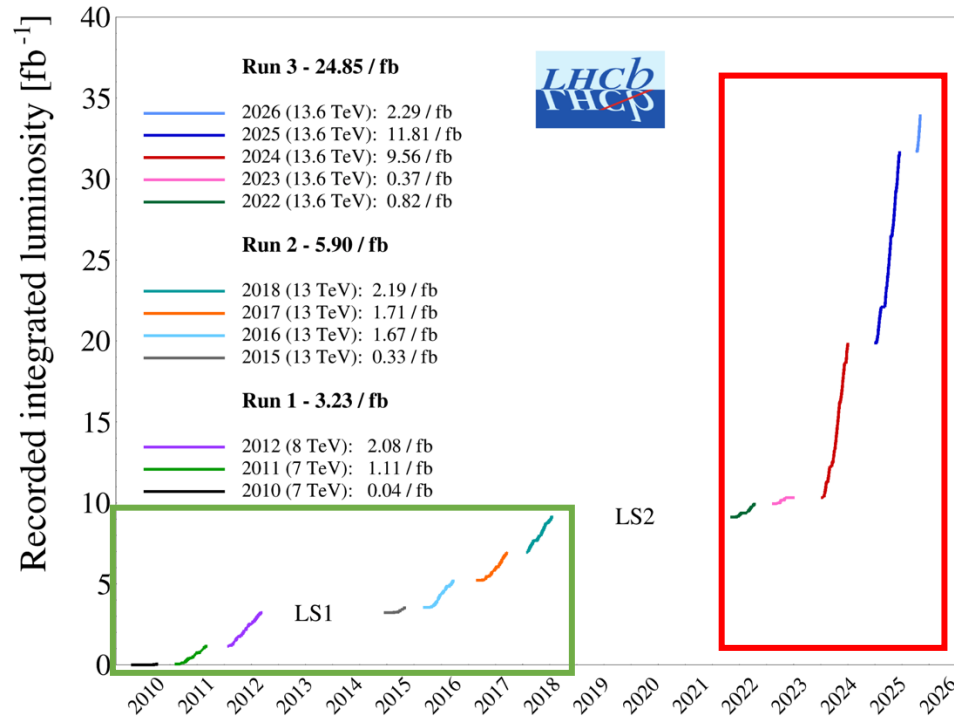
$\mathcal{L} \sim 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, roughly 5x than Run2

Hardware trigger removed
Hadronic channel efficiency X2

The LHCb Upgrade I



Total recorded luminosity – pp – 34.0 fb^{-1}



Run 1-2: $\sim 9 \text{ fb}^{-1}$

Run 3: $\sim 25 \text{ fb}^{-1}$ collected !

New detectors for tracking system
Pixel VELO, UT, SciFi

New readout systems for all subdetectors

Installation during 2019-2021;
Commissioning during 2022-2023;
Achieved designed performance in 2024

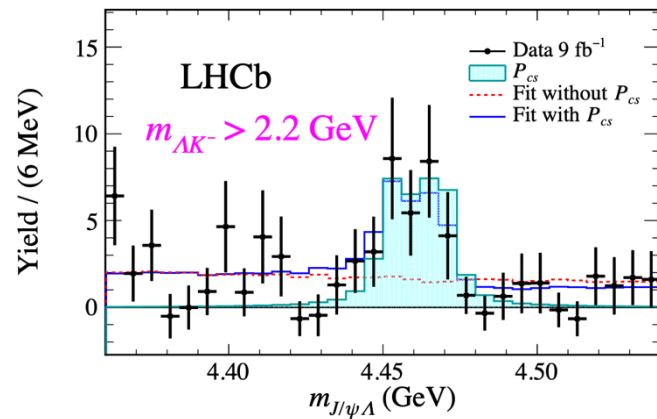
$\mathcal{L} \sim 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, roughly 5x than Run2

Hardware trigger removed
Hadronic channel efficiency X2

Open topics of pentaquark studies for Run3 LHCb

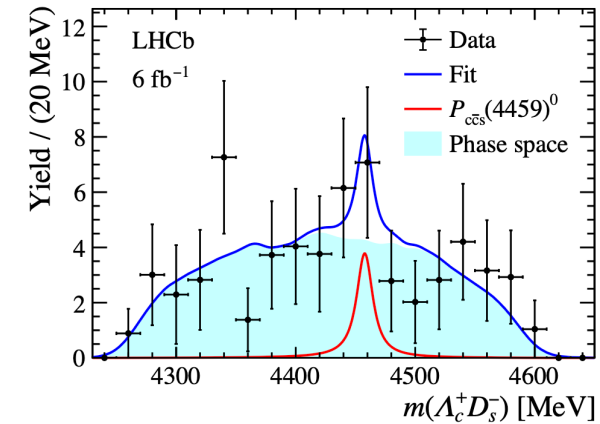
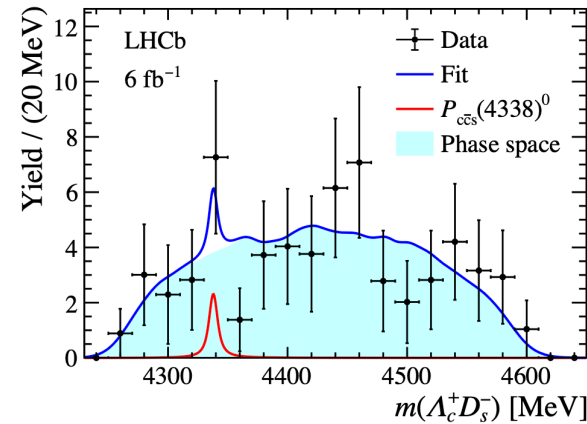
- Natural extension of Run1-2 studies: confirm evidences; search for unobserved pentaquarks & new decay modes with significantly improved precision

Test the two-peak hypothesis of $P_{c\bar{c}s}(4459)^0$



Sci.Bull. 66 (2021) 1278-1287

Pentaquark search in $\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^- K^+ K^-$

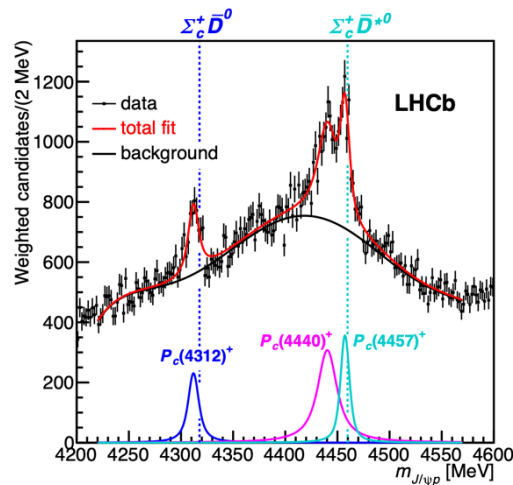


PRD 112 (2025) 5, 052013

- Enable coupled-channel analyses thanks to huge improvement of decays to hadronic final state
- Femtoscopy studies to understand two-body interactions in meson-baryon systems
-

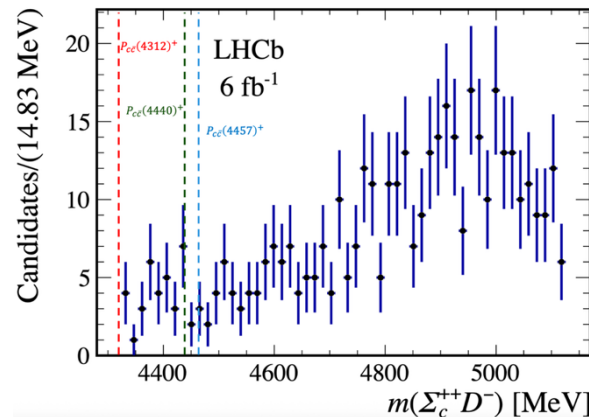
Open topics of pentaquark studies for Run3 LHCb

- Natural extension of Run1-2 studies: confirm evidences; search for unobserved pentaquarks & new decay modes with significantly improved precision
- Enable coupled-channel analyses thanks to large improvement of stat. of hadronic modes



PRL 122 (2019) 222001

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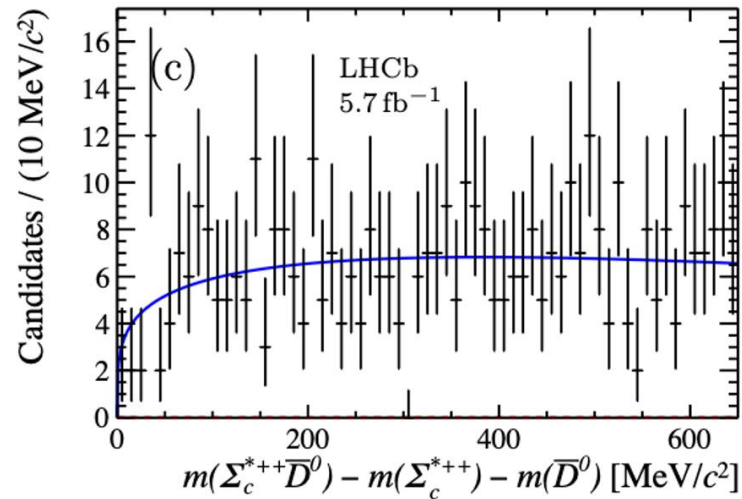
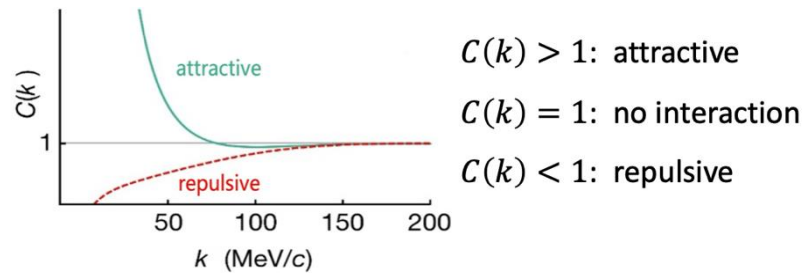
PRD 110 (2024) 3, L031104

= ?

- Femtoscopy studies to understand two-body interactions in meson-baryon systems
-

Open topics of pentaquark studies for Run3 LHCb

- Natural extension of Run1-2 studies: confirm evidences; search for unobserved pentaquarks & new decay modes with significantly improved precision
- Enable coupled-channel analyses thanks to huge improvement of decays to hadronic final state
- Femtoscopy studies to understand two-body interactions in meson-baryon systems



PRD 110 (2024) 3, 032001

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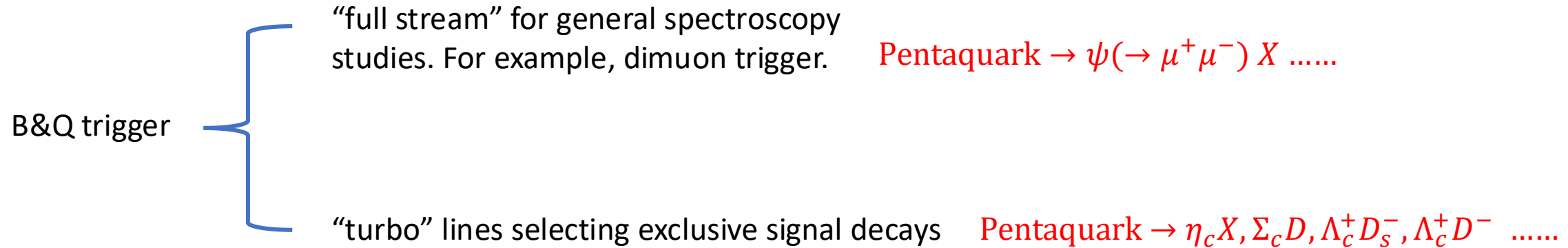
Preparation towards pentaquark @ Run3

- For a successful Run 3 pentaquark program, we needed
- Well covered by the **trigger** system
- Good and stable **data quality**
- Precise knowledge of **tracking** and **particle-identification** performance
- Precise **simulation** for unfolding detector effects
- Benchmark **early measurements** as global test of Run3 operation

Will present a few examples where I led or (co-)supervised the work

Run3 B-hadron and Quarkonium (B&Q) triggers

- Run3 pentaquark program is supported by B&Q trigger system



- Main challenge: Physics output V.S. bandwidth limitation

- Solutions:

- Optimized bandwidth division using **signal-driven priorities**
- **Adaptive trigger strategy** based on computing resource and operation condition
- **Selective event persistency strategy**

Physics-driven Data Quality validation using $J/\psi \rightarrow \mu^+ \mu^-$

- A good and stable data quality is essential for all physics analyses, including pentaquarks
- Use $J/\psi \rightarrow \mu^+ \mu^-$ as a clean & high-stat. benchmark channel to validate the Data Quality
- Run-by-run scan of key observables to visualize the global data-taking condition
- Direct input to offline Data Quality decision, help determine which data can be used for physics

200k signals per pb^{-1} data
with high purity

J/ψ mass resolution stability & improvement
→ monitor of alignment condition

Support DQ flagging

Data-driven determination of track momentum resolution

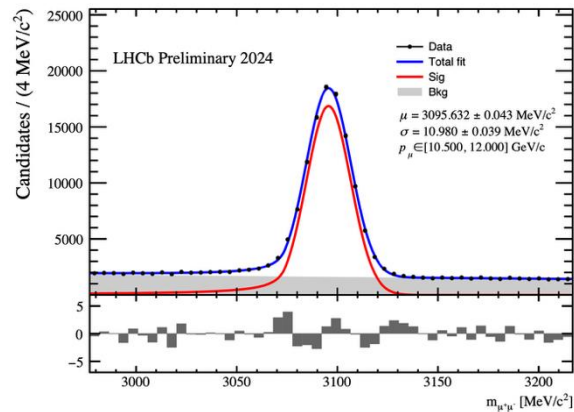
- Track resolution → mass/angular resolutions → input for pentaquark mass and angular analyses
- $J/\psi \rightarrow \mu^+ \mu^-$ as calibration sample. Decompose mass resolution into momentum and angular terms

LHCb-PUB-2024-009

Master formula:

$$\frac{\sigma_p^2}{p^2} = 2 \left(\frac{\sigma_m}{m} \right)^2 - 2 \left(\frac{\sin \theta \sigma_\theta}{2 - 2 \cos \theta} \right)^2$$

From J/ψ mass fit

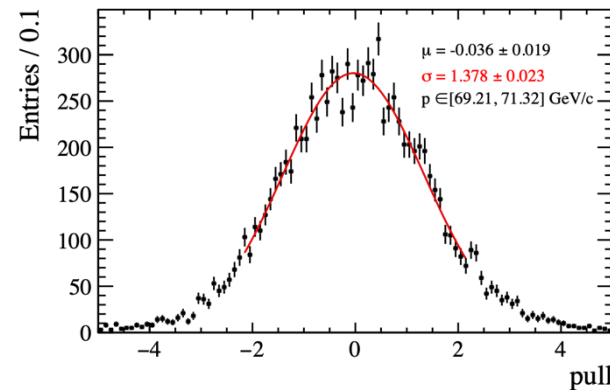


Angular contribution estimated with data-driven correction

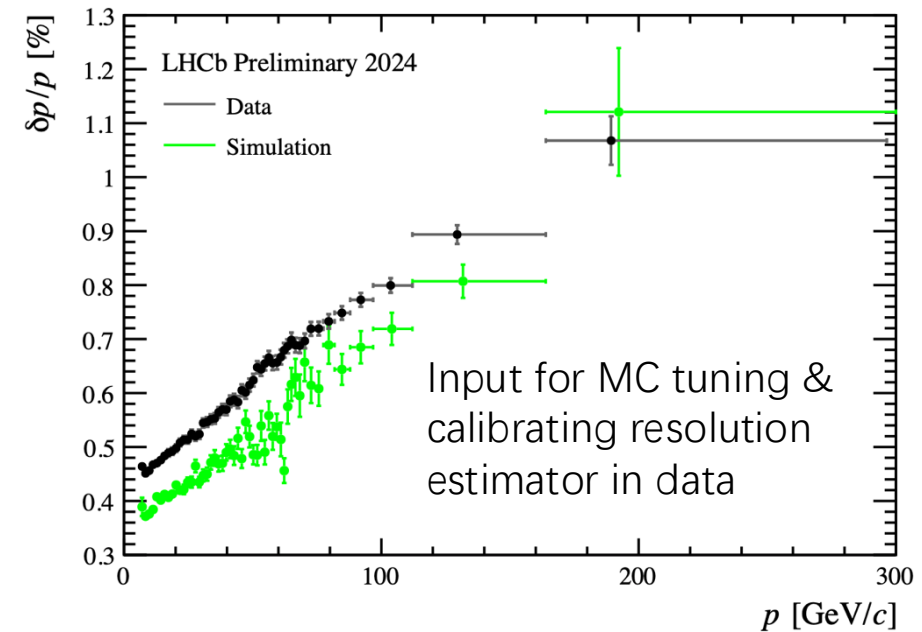
$$\sigma_\theta^2 = \begin{pmatrix} \frac{\partial \theta}{\partial t_{x1}} \\ \frac{\partial \theta}{\partial t_{y1}} \\ \frac{\partial \theta}{\partial t_{x2}} \\ \frac{\partial \theta}{\partial t_{y2}} \end{pmatrix}^T \cdot \begin{pmatrix} \sigma_{t_{x1}}^2 & \text{cov}(t_{x1}, t_{y1}) & 0 & 0 \\ \text{cov}(t_{x1}, t_{y1}) & \sigma_{t_{y1}}^2 & 0 & 0 \\ 0 & 0 & \sigma_{t_{x2}}^2 & \text{cov}(t_{x2}, t_{y2}) \\ 0 & 0 & \text{cov}(t_{x2}, t_{y2}) & \sigma_{t_{y2}}^2 \end{pmatrix} \cdot \begin{pmatrix} \frac{\partial \theta}{\partial t_{x1}} \\ \frac{\partial \theta}{\partial t_{y1}} \\ \frac{\partial \theta}{\partial t_{x2}} \\ \frac{\partial \theta}{\partial t_{y2}} \end{pmatrix}$$

$$= \left(\frac{\partial \theta}{\partial t_{x1}} \right)^2 \sigma_{t_{x1}}^2 + 2 \left(\frac{\partial \theta}{\partial t_{x1}} \right) \left(\frac{\partial \theta}{\partial t_{y1}} \right) \text{cov}(t_{x1}, t_{y1}) + \left(\frac{\partial \theta}{\partial t_{y1}} \right)^2 \sigma_{t_{y1}}^2$$

$$+ \left(\frac{\partial \theta}{\partial t_{x2}} \right)^2 \sigma_{t_{x2}}^2 + 2 \left(\frac{\partial \theta}{\partial t_{x2}} \right) \left(\frac{\partial \theta}{\partial t_{y2}} \right) \text{cov}(t_{x2}, t_{y2}) + \left(\frac{\partial \theta}{\partial t_{y2}} \right)^2 \sigma_{t_{y2}}^2$$



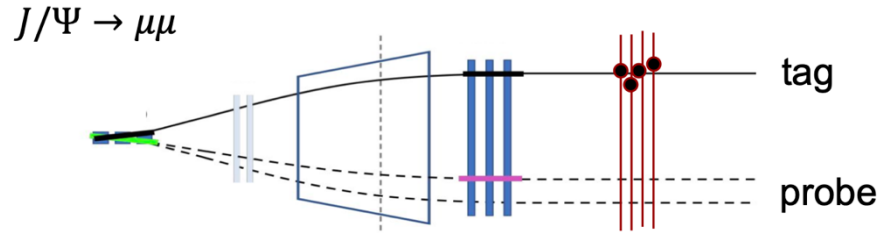
Data-driven determination of σ_p/p as a function of p



Validation of LHCb standard muonID efficiency estimator

- Wide-range of pentaquark analyses use muons. Good calibration of MuonID efficiency critical

- Standard LHCb tag-and-probe method:



Tight selections on one muon.
(including muonID cuts)

Check the efficiency of the other muon

- **Our concern:** Potential bias due to correlated in-efficiencies

Potential global issues on muon stations, shared muon-station hits of tag and probe muons...

- Strategy to quantify the effect:

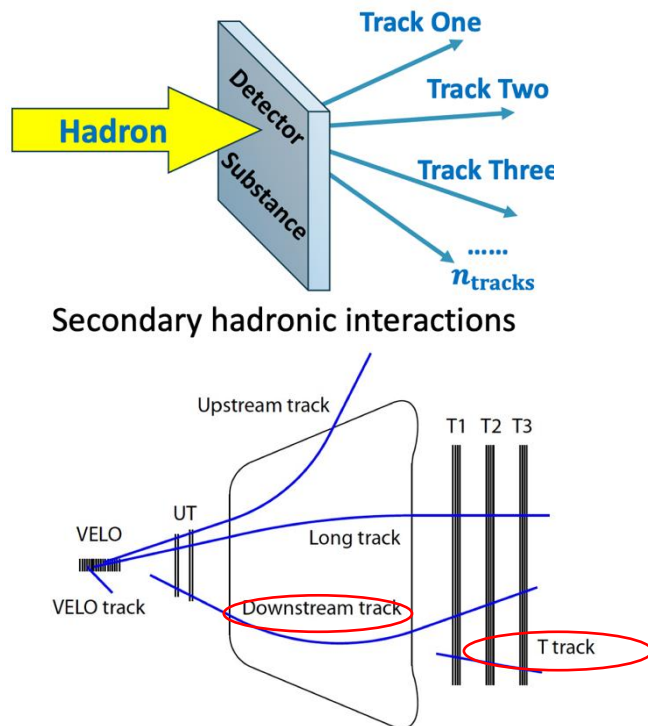
- Use tracker + RICH information to build exclusive $B \rightarrow J/\psi(\rightarrow \mu^+ \mu^-)X$ signals. **MuonID unbiased** sample.
- Existing calibration triggers do not support the study. **Dedicated trigger lines** are developed
- Clean signals obtained for $B^+ \rightarrow J/\psi(\rightarrow \mu^+ \mu^-)K^+$, $B^0 \rightarrow J/\psi(\rightarrow \mu^+ \mu^-)K^+ \pi^-$, $B_s^0 \rightarrow J/\psi(\rightarrow \mu^+ \mu^-)K^+ K^-$ decays

Validation of LHCb standard muonID efficiency estimator

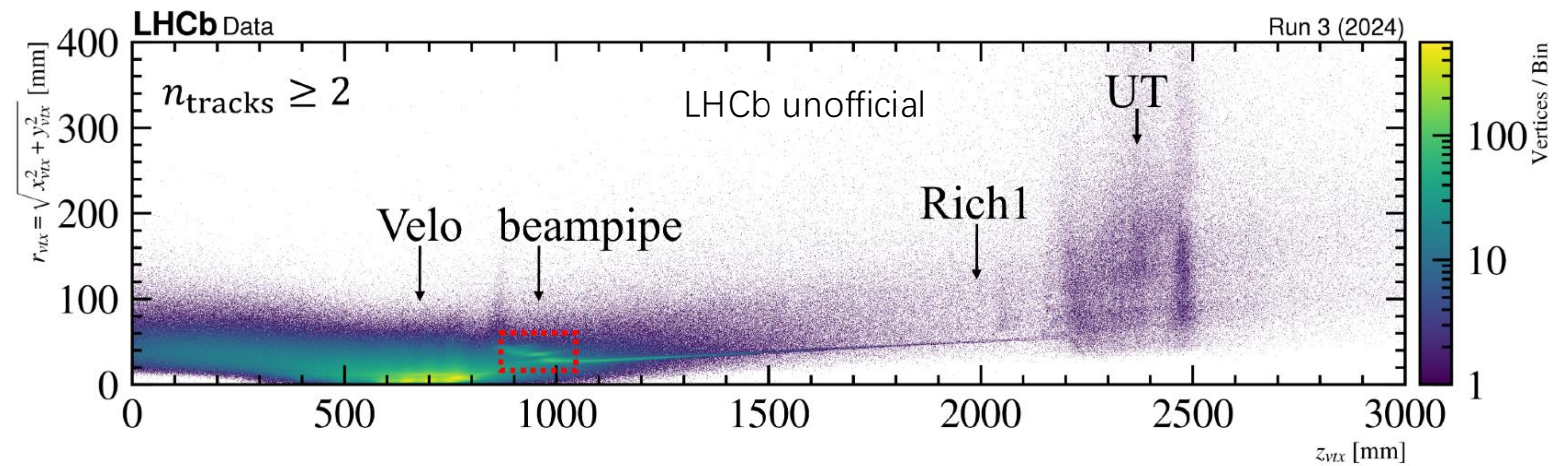
- Strategy to quantify the effect:
 - Compare ratios between probe muon efficiencies **with & without muonID cuts on tag muons**
 - A ratio differing from 1 will indicate the existence of a bias
 - No significant bias observed @ 1% precision level. **Confirm LHCb standard estimator is reliable.**

Search for missing material in LHCb simulation

- Material mismodeling directly affect efficiency estimation
- Tomography: use material interaction vertices to map the **detector and simulated detector**
 - Previously limited to VELO
 - Extend it to downstream and T-tracks, allowing probe the material in UT and further detectors



Detector structures clearly resolved in data
(downstream track)

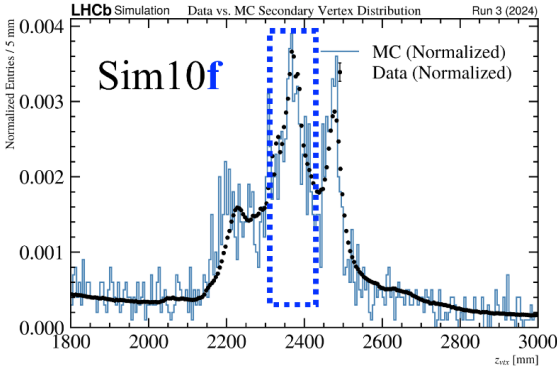
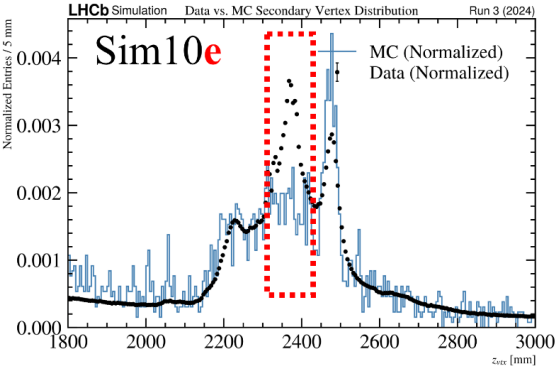


Search for missing material in LHCb simulation

- Downstream track tomography:

Observed missing material in UT region of sim10e

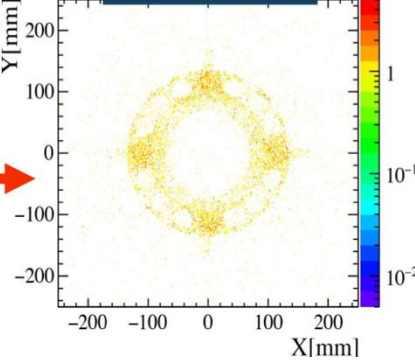
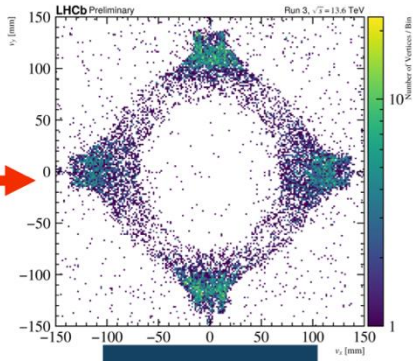
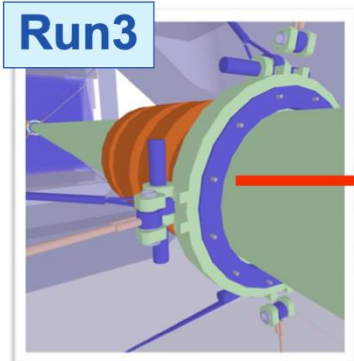
Clearly monitor the fix of the problem in sim10f



- T-track tomography

Beam pipe geometry change from Run1 to Run3 simulation clearly resolved

Feasibility proved. Being further developed to merge into LHCb standard MC tuning procedures.

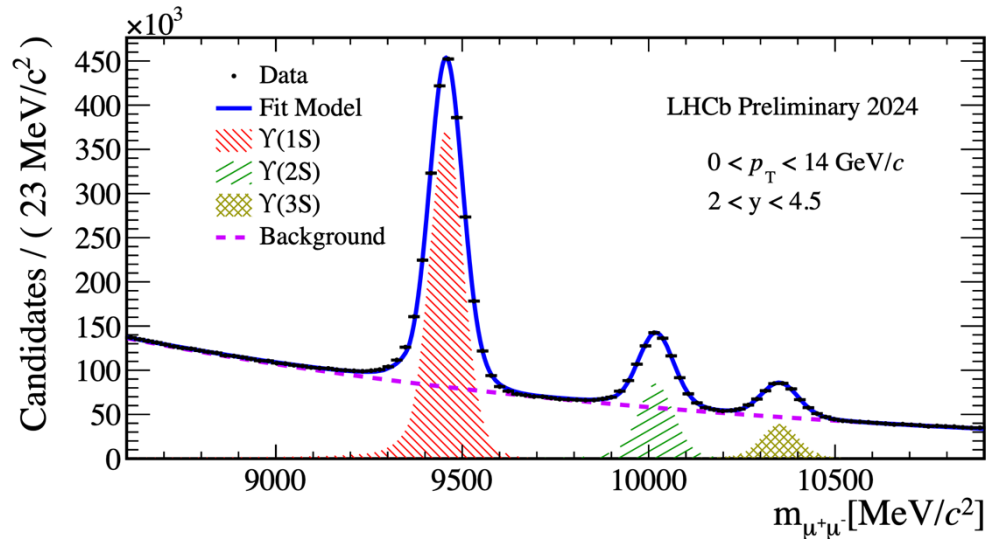


Hu, J., Wang, M., & Xu, M. (2025). <https://doi.org/10.17181/5rx2r-h2m98>
Moritz Karbach summer student prize 2025

Quarkonium production measurements

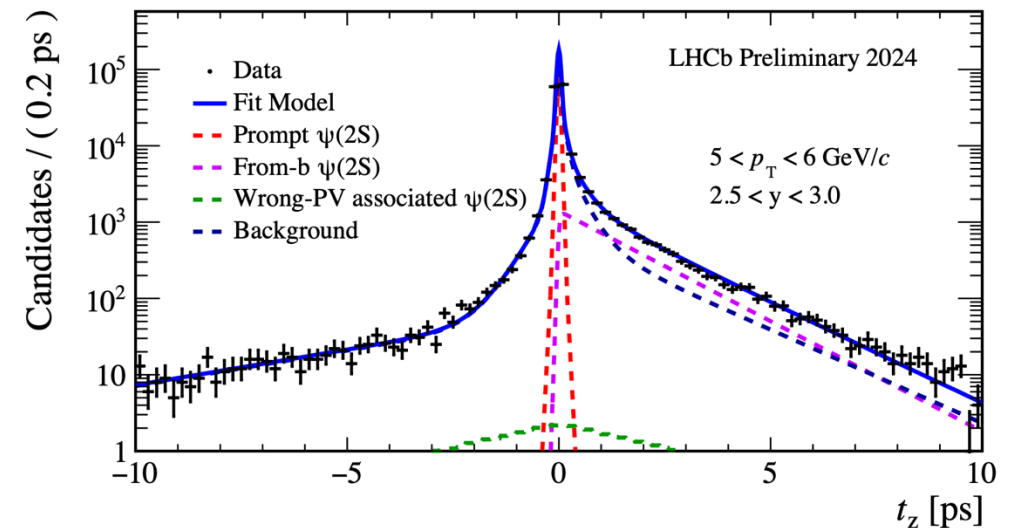
- Quarkonium production measurements (J/ψ , $\psi(2S)$, $\Upsilon(1S, 2S, 3S)$)
 - Sensitive to multiple detector and operation components simultaneously
 - Trigger, tracking, muonID, lumi, simulation, data processing
 - A physics-driven probe of the full detector performance

LHCb-Figure-2024-025



Υ mass peaks: sensitive probe to alignment condition

LHCb-Figure-2024-024



ψ pseudo-lifetime spectrum: probe of time resolution, lifetime bias, PV association accuracy

Quarkonium production measurements

- Physics-driven debugging for operation

$\sigma_{J/\psi, \text{prompt}} / \sigma_{J/\psi, b\text{-decay}}$
significantly differs from Run-2



Find strongly asymmetric
distribution of J/ψ pseudo-lifetime



Find and fix a dimuon trigger bug
that removes all J/ψ with $P_z < 0$.
Save half of the signals for prompt
charmonium physics

Mass fit of $\Upsilon \rightarrow \mu^+ \mu^-$
samples cannot converge



Find a biased momentum
resolution in MC, leading to
biased mass-parameter
constraint in real-data fit

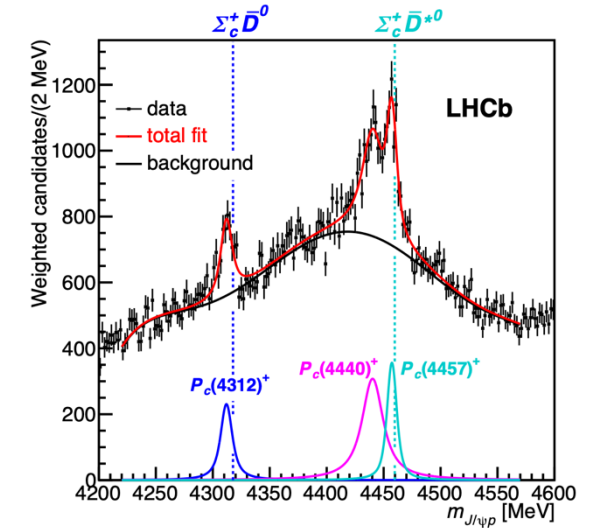


Collaborate with simulation group
to identify the reason. Found issue
fixed after an update of UT tracker
geometry in simulation

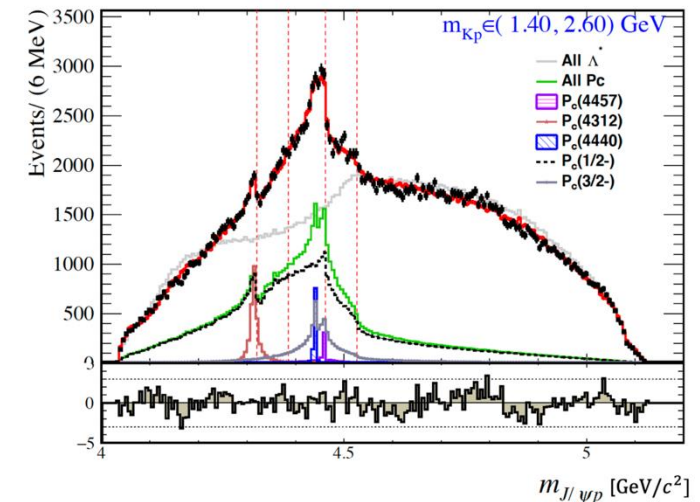
- Quarkonium production measurement has served a system-level diagnostic of Run 3 operation
- Related physics analyses providing input to NRQCD is currently under internal review

Summary

- LHCb has made significant achievement on pentaquark discoveries
 - 4 states observed; 2 evidences found
- LHCb has an ongoing effort to understand the dynamic of these discovered states
 - Lineshape, J^P determination, search for new states, measure couplings to different channels
- Many topics limited by statistic precision. High-precision Run 3 data offers new possibility of resolving the puzzles



From discovery to precise measurements



Summary

- We are well-prepared for Run 3 pentaquark studies
 - **Trigger** of pentaquark signals are being well supported by B&Q trigger system
 - $J/\psi \rightarrow \mu^+ \mu^-$ run-by-run property scan to support the **data quality flagging**
 - **Track momentum resolution** calibrated using real data
 - Independent validation of standard **muonID efficiency** estimator in LHCb
 - Feasibility study of using tomography to improve **material description in LHCb simulation**
 - **Quarkonium cross-section measurement** on going, acting as a system-level diagnostic of Run 3 operation
- Stay tuned !

Efforts have been made from all aspects to support pentaquark program @ Run3, many of which have broader impact on hadron spectroscopy and the experiment as a whole

Thank you for your attention !

Any questions or comments ?

Back up

$\Lambda_b^0 \rightarrow J/\psi p K^-$ amplitude analysis (Run1+2)

Amplitude analysis of $\Lambda_b^0 \rightarrow J/\psi p K^-$ decay (Run1+2)

PRL 122 (2019) 22, 222001

Performing a rigorous amplitude analysis of this new data sample is computationally challenging. The $m_{J/\psi p}$ mass resolution must be taken into account, and the size of the data sample to fit has greatly increased. Formulating an amplitude model whose systematic uncertainties are comparable to the statistical precision provided by this larger data sample is difficult given the large number of Λ^* excitations [22,23], coupled-channel effects [24], and the possible presence of one or more wide P_c^+ contributions, like the previously reported $P_c(4380)^+$ state. Fortunately, the newly observed peaks are so narrow

- $\Lambda_b^0 \rightarrow J/\psi p K^-$ amplitude analysis with full LHCb Run1-2 dataset helps understand several important questions (J^P , missing broad states), but technically challenging
- Efforts have been made to overcome those challenges
 - Updated formula for helicity formalism
 - Using GPU technique to speed up the fits

More about helicity formalism

- Two decay chains: Λ^* or P_c as intermediate state

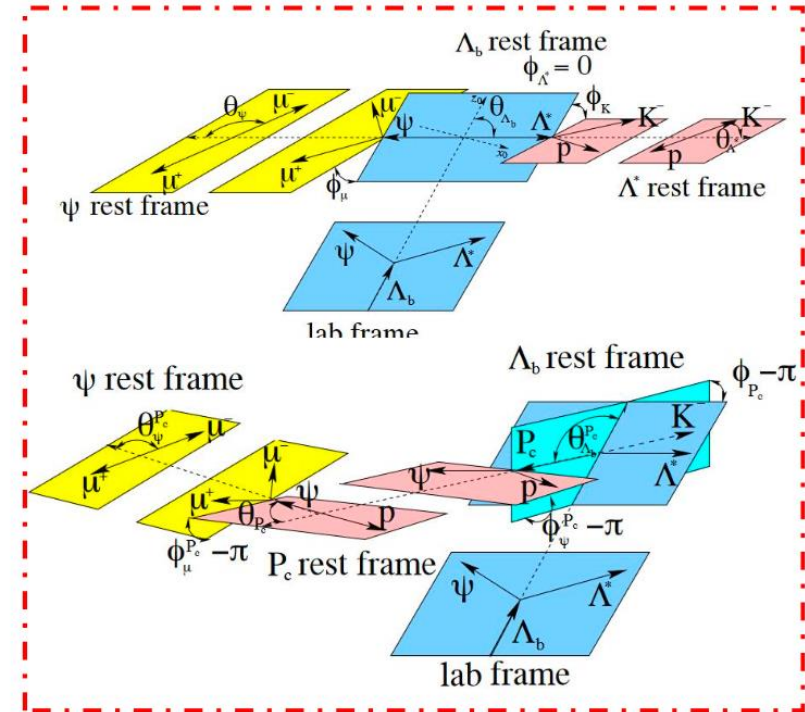
Λ^* chain:

$$\mathcal{M}_{\lambda_{\Lambda_b^0}, \lambda_p, \Delta\lambda_\mu}^{\Lambda^*} = \sum_n R_{\Lambda_n^*}(m_{Kp}) \mathcal{H}_{\lambda_p}^{\Lambda_n^* \rightarrow Kp} \sum_{\lambda_\psi} e^{i\lambda_\psi \phi_\mu} d_{\lambda_\psi, \Delta\lambda_\mu}^1(\theta_\psi) \\ \times \sum_{\lambda_{\Lambda^*}} \mathcal{H}_{\lambda_{\Lambda^*}, \lambda_\psi}^{\Lambda_b^0 \rightarrow \Lambda_n^* \psi} e^{i\lambda_{\Lambda^*} \phi_K} d_{\lambda_{\Lambda_b^0}, \lambda_{\Lambda^*} - \lambda_\psi}^{\frac{1}{2}}(\theta_{\Lambda_b^0}) d_{\lambda_{\Lambda^*}, \lambda_p}^{J_{\Lambda_n^*}}(\theta_{\Lambda^*}).$$

P_c chain:

RBW-based lineshape

$$\mathcal{M}_{\lambda_{\Lambda_b^0}, \lambda_p^{P_c}, \Delta\lambda_\mu^{P_c}}^{P_c} = e^{i\lambda_{\Lambda_b^0} \phi_{P_c}} \sum_j R_{P_{cj}}(M_{\psi p}) \sum_{\lambda_\psi^{P_c}} e^{i\lambda_\psi^{P_c} \phi_\mu^{P_c}} d_{\lambda_\psi^{P_c}, \Delta\lambda_\mu^{P_c}}^1(\theta_\psi^{P_c}) \\ \times \sum_{\lambda_{P_c}} \mathcal{H}_{\lambda_{P_c}}^{\Lambda_b^0 \rightarrow P_{cj} K} e^{i\lambda_{P_c} \phi_\psi^{P_c}} d_{\lambda_{\Lambda_b^0}, \lambda_{P_c}}^{\frac{1}{2}}(\theta_{\Lambda_b^0}^{P_c}) \mathcal{H}_{\lambda_\psi^{P_c}, \lambda_{P_c}}^{P_{cj} \rightarrow \psi p} d_{\lambda_{P_c}, \lambda_\psi^{P_c} - \lambda_p^{P_c}}^{J_{P_{cj}}}(\theta_{P_c}),$$

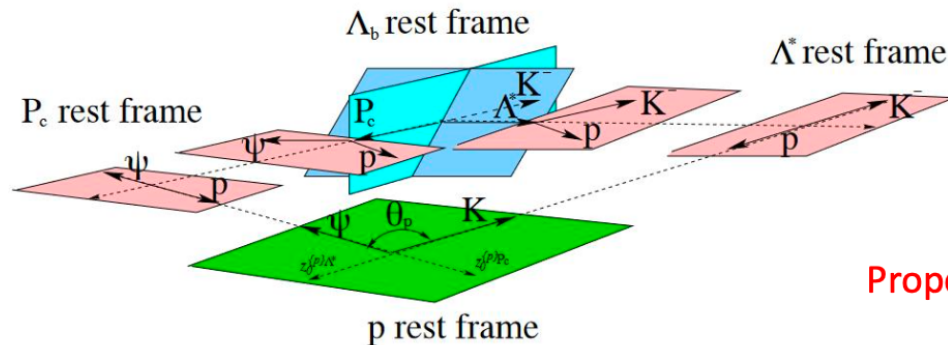
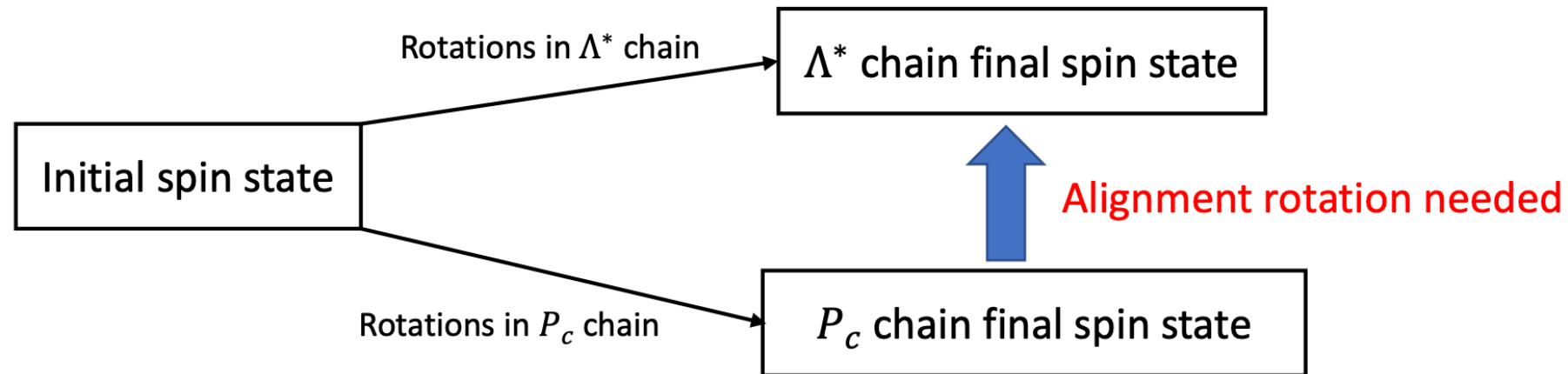


Wigner-D function to associate initial & final spin states of each two-body decay node

Use angles between particle momenta/momentum planes to obtain angular variables

More about helicity formalism

- **Combine two chains to get final matrix element**
 - Need a consistent definition of initial & final spin state



$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b^0} = \pm\frac{1}{2}} \sum_{\lambda_p = \pm\frac{1}{2}} \sum_{\Delta\lambda_\mu = \pm 1} \left| \mathcal{M}_{\lambda_{\Lambda_b^0}, \lambda_p, \Delta\lambda_\mu}^{\Lambda^*} + e^{i\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p^{P_c}} d_{\lambda_p^{P_c}, \lambda_p}^{\frac{1}{2}}(\theta_p) \mathcal{M}_{\lambda_{\Lambda_b^0}, \lambda_p^{P_c}, \Delta\lambda_\mu}^{P_c} \right|^2$$

Properly align the definition of final-state spin states in different chains

Missing quantum effect ?

- The conventional helicity formalism

(SU2)
Decay angles rotating spin states

Fully determine

(SO3)
Rotations in momentum space

$$\mathcal{M} = \mathcal{H}_{\lambda_B, \lambda_C}^{A \rightarrow BC} D_{m_A, \lambda_B - \lambda_C}^{J_A}(\phi_B, \theta_A, 0)^*$$

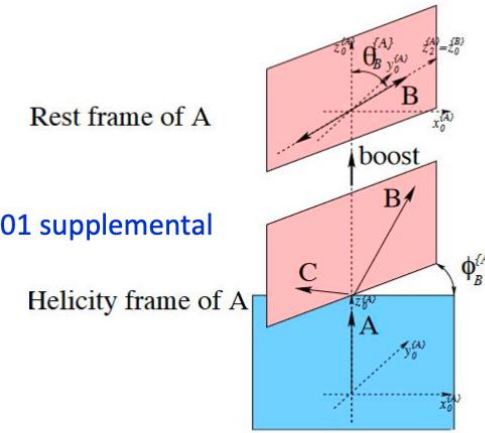
$$\phi_B = \text{atan2}(p_B^{\{A\}y}, p_B^{\{A\}x})$$

$$= \text{atan2}(\hat{y}_0^{\{A\}} \cdot \vec{p}_B^{\{A\}}, \hat{x}_0^{\{A\}} \cdot \vec{p}_B^{\{A\}})$$

$$= \text{atan2}((\hat{z}_0^{\{A\}} \times \hat{x}_0^{\{A\}}) \cdot \vec{p}_B^{\{A\}}, \hat{x}_0^{\{A\}} \cdot \vec{p}_B^{\{A\}}),$$

$$\cos \theta_A = \hat{z}_0^{\{A\}} \cdot \hat{p}_B^{\{A\}}.$$

PRL 115 (2015) 072001 supplemental



Quantum effects missing for **baryons** ?

$$d_{\lambda_1, \lambda_2}^J(\theta_A) = -\mathbf{1} \times d_{\lambda_1, \lambda_2}^J(\theta_A + 2\pi)$$

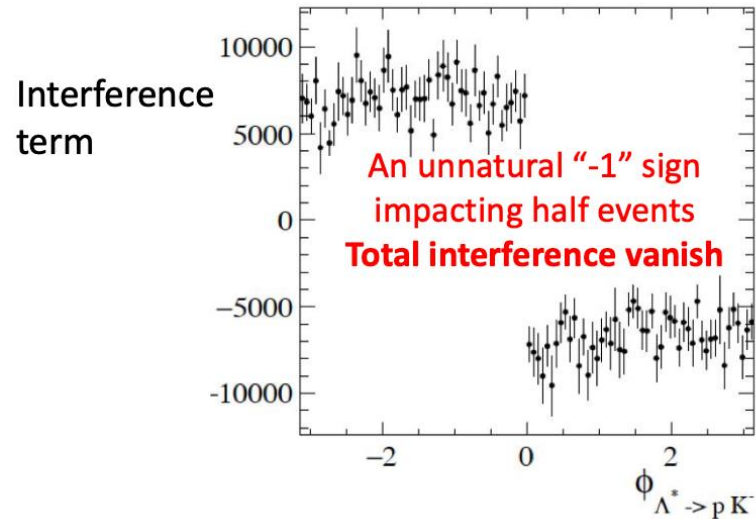
$$e^{i\lambda\phi_B} = -\mathbf{1} \times e^{i\lambda(\phi_B + 2\pi)}$$

Cannot set a preference between
 θ_A & $\theta_A + 2\pi$, ϕ_B & $\phi_B + 2\pi$

- Arbitrary “-1” terms in any single-chain amplitudes:
 - Generate tricky behavior in interference of different chains

Impact on interference

- The Λ^* , P_c interference using the formula for P_c observation



Impact of missing of the quantum effects consistent with the statement in [PRL 115 \(2015\) 072001](#)

polarization of zero. Interferences between various Λ_n^* and P_{cj}^+ resonances vanish in the integrated rates unless the resonances belong to the same decay chain and have the same quantum numbers.

- Impact on the first P_c analysis:
 - No impact on Λ^* -only fit quality
 - Reduce the flexibility of $\Lambda^* + P_c$ model
 - P_c properties (to be) updated in Run1+2 analysis

[PRL 122\(2019\)222001](#): Two-peak nature of $P_c(4450)$ observed;

Properties of $P_c(4380)$ to be updated in future amplitude analysis

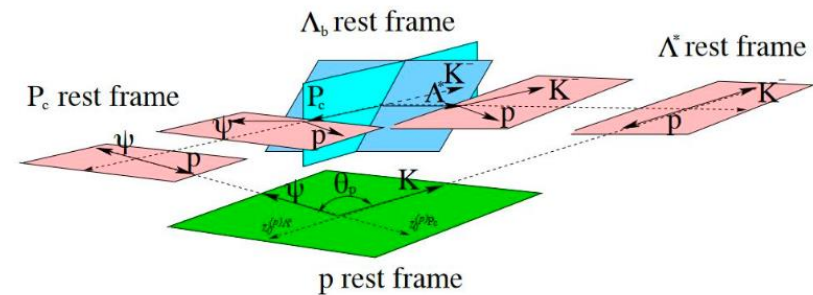
Recover the missing quantum effect

- Main idea:
 - Origin of the issue is improper alignment of final-state definitions for each decay chain due to arbitrary “-1” term
 - Seek for new principles for final-state alignment

Conventional method

Rely on graphic picture

Use angles between particle momenta or momentum planes to define alignment operator



Recover the missing quantum effect

- Main idea:
 - Origin of the issue is improper alignment of final-state definitions for each decay chain due to arbitrary “-1” term
 - Seek for new principles for final-state alignment

New method

Directly write down all rotation/boost operators associating initial/final spin-state frames, using a representation where $\theta \rightarrow \theta + 2\pi$ is visible

Advances in High Energy Physics (2020) 6674595

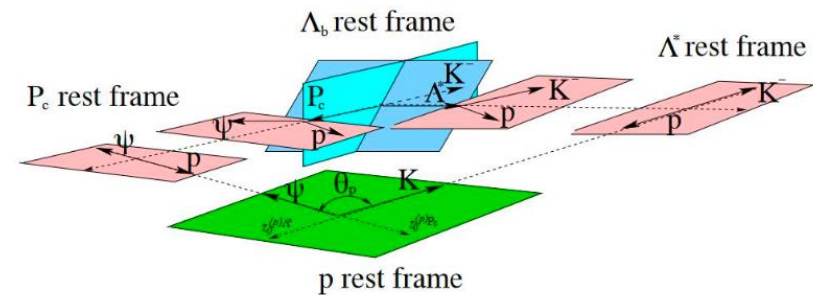
$$\begin{aligned} & \hat{R}(\alpha_1^{W,R}, \beta_1^{W,R}, \gamma_1^{W,R}) \hat{R}(\phi_R, \theta_R, 0) \hat{R}(\phi_1^R, \theta_1^R, 0) |\mathbf{P}_1^R, s_1, \lambda_1^R\rangle \\ &= \sum_{\mu_1^R} D_{\mu_1^R, \lambda_1^R}^{s_1}(\phi_1^R, \theta_1^R, 0) \times \sum_{\nu_1^R} D_{\nu_1^R, \mu_1^R}^{s_1}(\phi_R, \theta_R, 0) \sum_{m_1} D_{m_1, \nu_1^R}^{s_1} \\ & \times (\alpha_1^{W,R}, \beta_1^{W,R}, \gamma_1^{W,R}) |\mathbf{P}_1^A, s_1, m_1\rangle. \end{aligned}$$

Advances in High Energy Physics (2020) 6674595; Chinese Phys. C 45 (2021) 063103

$$R_z(\alpha) = \begin{pmatrix} e^{-i\alpha/2} & 0 \\ 0 & e^{i\alpha/2} \end{pmatrix} \quad R_y(\alpha) = \begin{pmatrix} \cos(\alpha/2) & -\sin(\alpha/2) \\ \sin(\alpha/2) & \cos(\alpha/2) \end{pmatrix}$$

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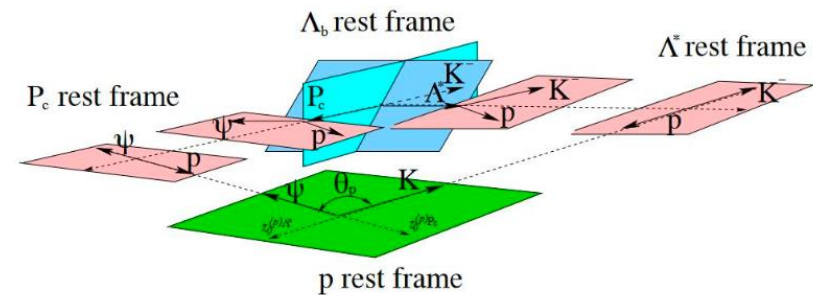
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Advances in High Energy Physics (2020) 6674595; Chinese Phys. C 45 (2021) 063103

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Conventional method

Rely on graphic picture
Use angles between particle momenta or momentum planes to define alignment operator



New method implemented in

$\Lambda_c^+ \rightarrow pK\pi^-$ amplitude analysis
[arXiv:2208.03262](https://arxiv.org/abs/2208.03262)

$\Xi_b^- \rightarrow J/\psi \Lambda K^-$ amplitude analysis for pentaquark search
[Science Bulletin 66 \(2021\) 1278](https://www.sciencebulletin.com/2021/12/78)

The GPU-based fit framework

To obtain a log-likelihood value:

$$\ln \mathcal{L} = \sum_i (\ln(1 - \beta) P_{i,\text{sig}}(\vec{\omega}) + \beta P_{i,\text{bkg}})$$

Loop over all data events in signal region (~20k)
Parameterized using sideband data

$$\text{Signal PDF: } P_{i,\text{sig}} = \frac{|\mathcal{M}_i(\vec{\omega})|^2 \times \Phi_i \times \epsilon_i}{I_{\text{norm}}(\vec{\omega})}$$

Loop over uniform phase-space MC events passing all event selections (400k)

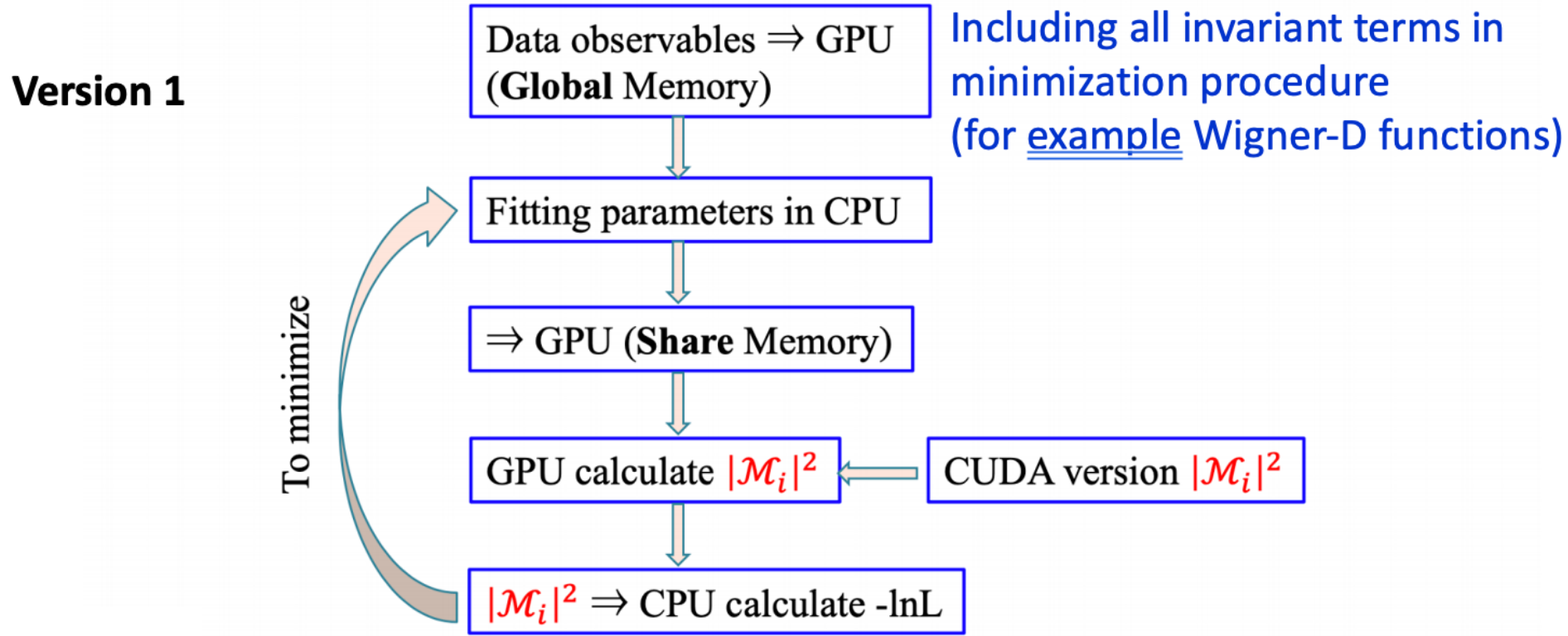
$$\text{Norm. factor obtained numerically using MC: } I_{\text{norm}} = \sum_j |\mathcal{M}_j(\vec{\omega})|^2$$

Need to calculate matrix element for ~0.4M times

Amplitude computations for each data/MC events are independent on each other. Use GPUs to handle the them in parallel

The GPU-based fit framework

- Idea: Let GPU to calculate $|\mathcal{M}_i|^2$ for events of both data and MC
 - CUDA (GPU based C++) for computation of $|\mathcal{M}_i|^2$
 - CUDA memory transfers between CPU and GPU

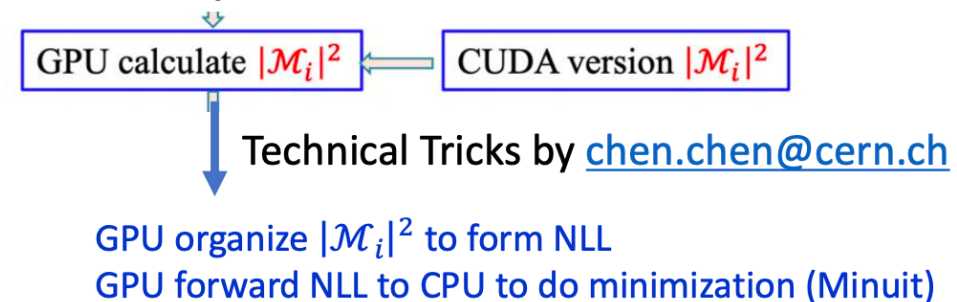
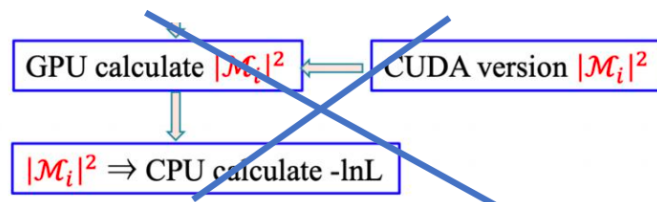


The GPU-based fit framework

- Optimization of the GPU sector zhihong.shen@cern.ch
 - Tools: [Nsight Systems](#) (nsys) and [Nsight Compute](#) (ncu) by Nvidia

Methods	Impact on GPU time calculating one log-likelihood value
Malloc once and reuse the memory	8.8ms -> 7.7ms
Double -> Float	7.7ms -> 3.7ms
Use less registers	3.7ms -> 3.4ms
Reduce branch structure	3.4ms -> 2.6ms

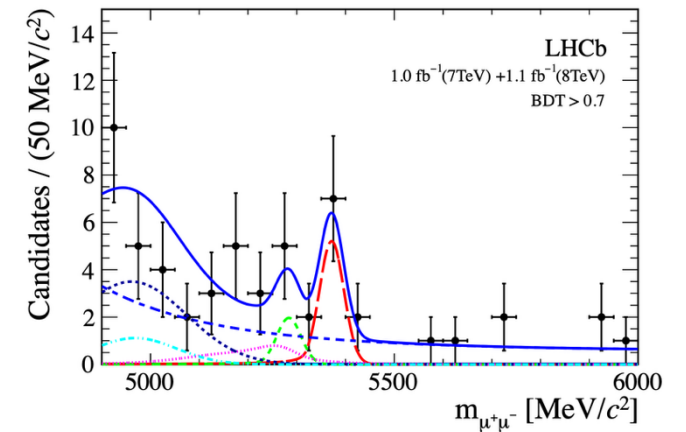
- Re-organize the task of GPU and CPU
 - CPU part start to dominate the time consumption



The LHCb experiment @ LHC



Originally designed as a precision-frontier experiment indirectly searching for NP



Has been developed to a general purpose experiment covering a wide range of topics

- Spectroscopy
- heavy-ion
- Exotica

.....

Nature of the known pentaquarks ?

- Different J^P interpretations

	PLB793(2019)365-371	PRL122(2019)242001	PRD92(2015)071502(R)
	Compact	Molecule	Triangle
$P_c(4312)^+$	3^- $\frac{1}{2}$	1^- $\frac{1}{2}$	1^- $\frac{1}{2}$
$P_c(4440)^+$	3^+ $\frac{1}{2}$	1^- (3^-) $\frac{1}{2}$ ($\frac{1}{2}$)	1^+ $\frac{1}{2}$
$P_c(4457)^+$	5^+ $\frac{1}{2}$	3^- (1^-) $\frac{1}{2}$ ($\frac{1}{2}$)	1^+ $\frac{1}{2}$

- New pentaquarks

Compact model

PLB793(2019)365-371

J^P	Mass(MeV)
$1/2^-$	3830 ± 34
	4150 ± 29
$1/2^+$	4030 ± 39
	4351 ± 35
	4430 ± 35
$3/2^+$	4040 ± 39
	4361 ± 35

Molecule

PRL122(2019)242001

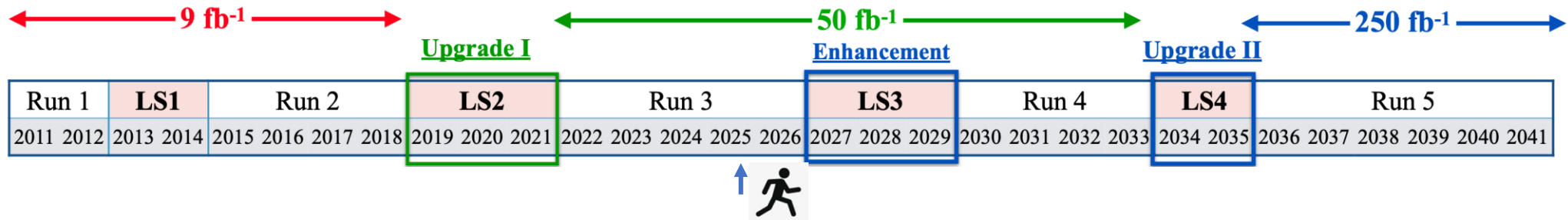
J^P	Width(MeV)	Mass(MeV)
3^- $\frac{1}{2}$	8.3 – 9.2	4376.1 – 4377.0
1^- $\frac{1}{2}$	25.7 – 26.5	4500.2 – 4501.0
3^- $\frac{3}{2}$	15.9 – 16.1	4510.6 – 4510.8
5^- $\frac{1}{2}$	3.2 – 3.5	4523.3 – 4523.6

- New decay patterns

Branching fraction related to inner structure

PRD100(2019)034020; PRD100(2019)074007;
PRD102(2020)036012

The LHCb Upgrade II

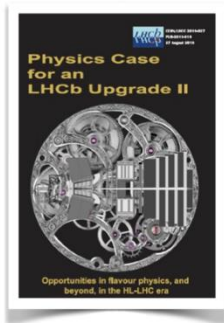


- LHCb Upgrade II: Further upgrade to fully exploit HL-LHC

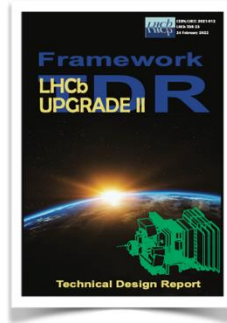
Expression of Interest
[CERN-LHCC-2017-003](#)



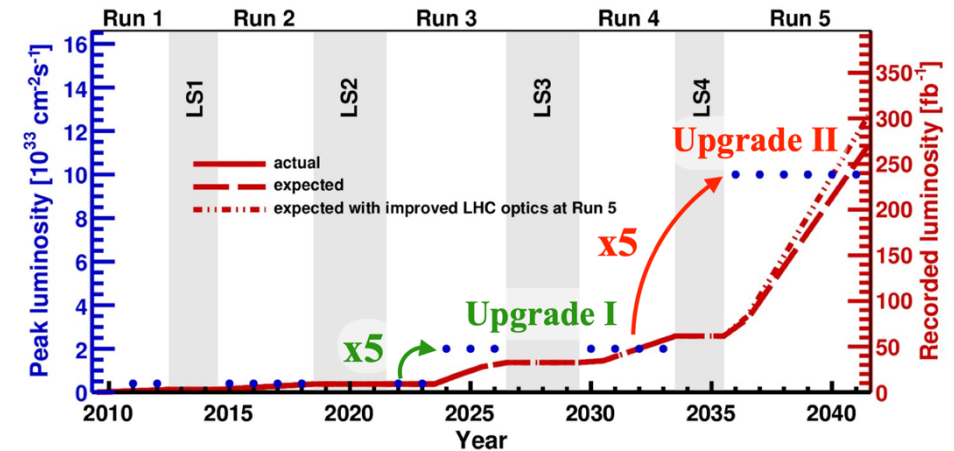
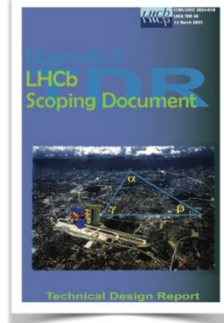
Physics case
[CERN-LHCC-2018-027](#)



Framework TDR
[CERN-LHCC-2021-012](#)



Scoping document
[CERN-LHCC-2024-010](#)



- Peaking luminosity: $(1.0 \sim 1.5) \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

- 5~8 times higher than Run3

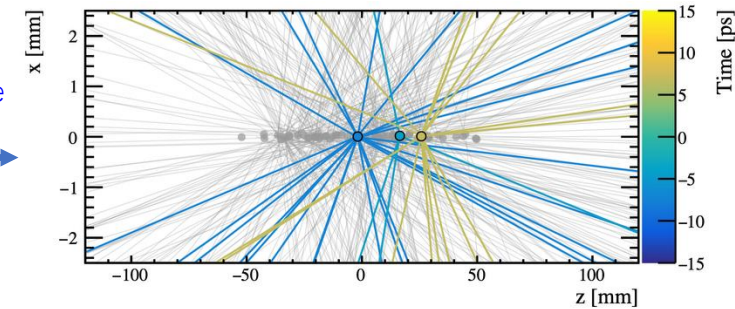
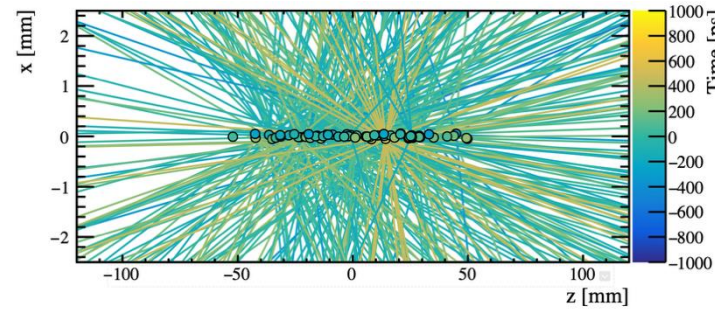
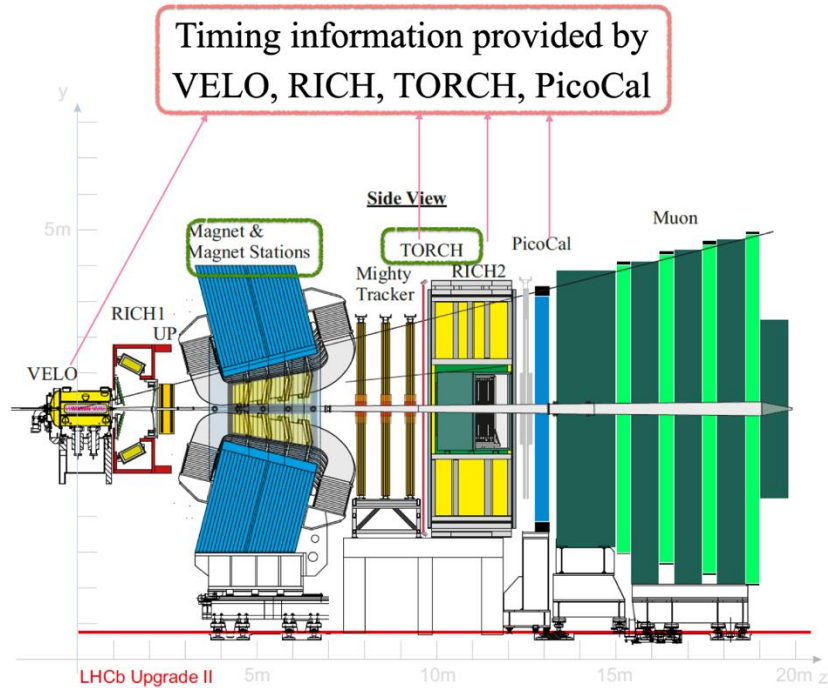
- Aiming for 300 fb^{-1}

- **One order of magnitude higher** than now. New opportunities for quarkonium physics

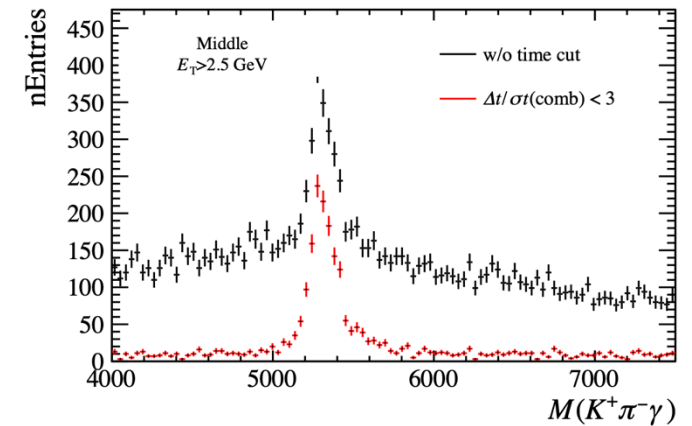
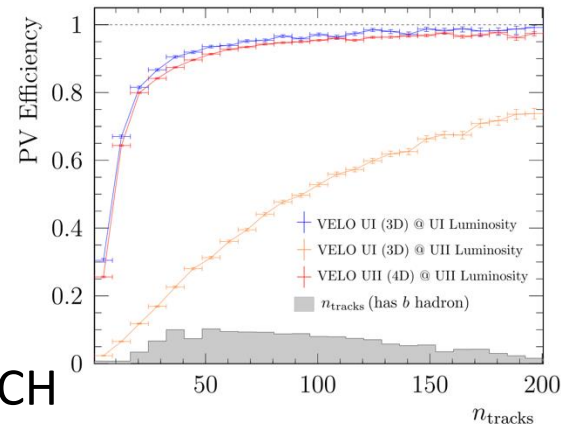
The LHCb Upgrade II

- Major challenge: Extremely high pile-ups, **~ 40 visible collisions per event**
- Time** information necessary. Provided by several new detectors

LHCb-TDR-026 (U2 scoping document)

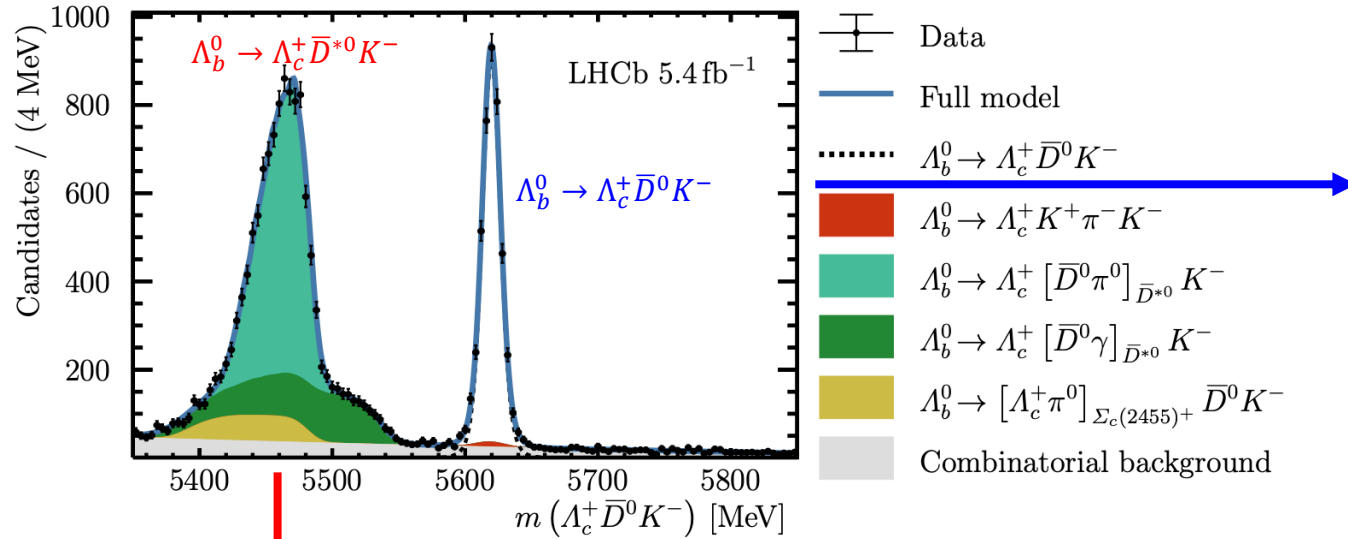


- All subdetectors to be upgraded
- Two new subdetectors: Magnet Station & TORCH
 - For Tracking and PID of low-momentum particles

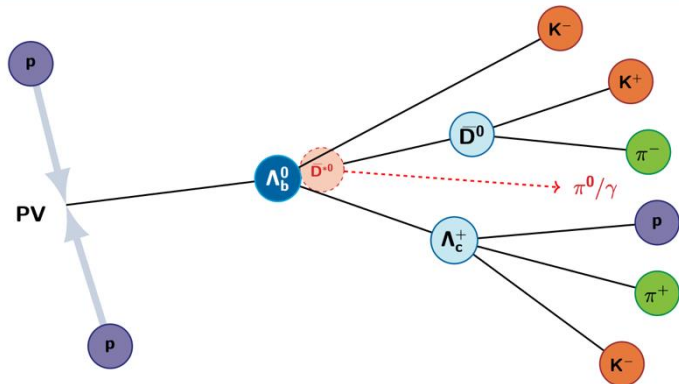


Study of $\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^{(*)0} K^-$ decay

EPJC 84 (2024) 575

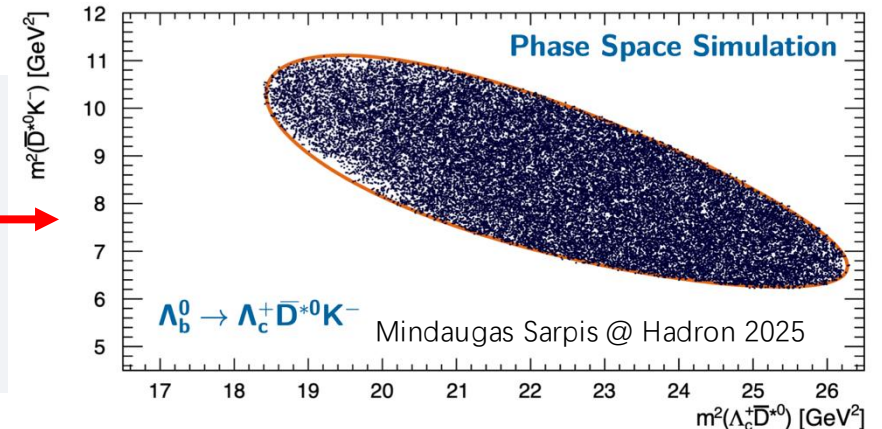
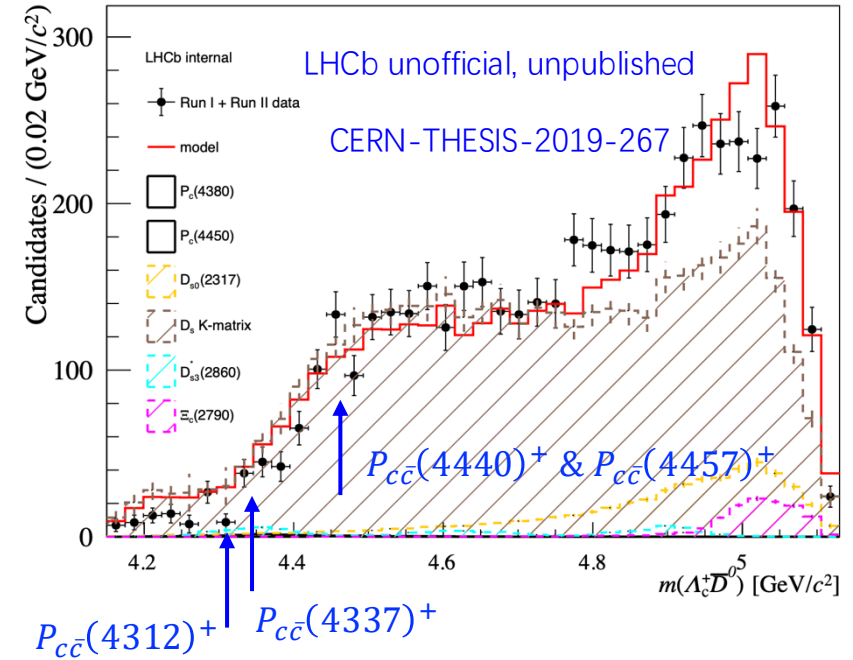


Possible to use Clone Closure method to reconstruct the missing π^0, γ momentum



ECC Constraints

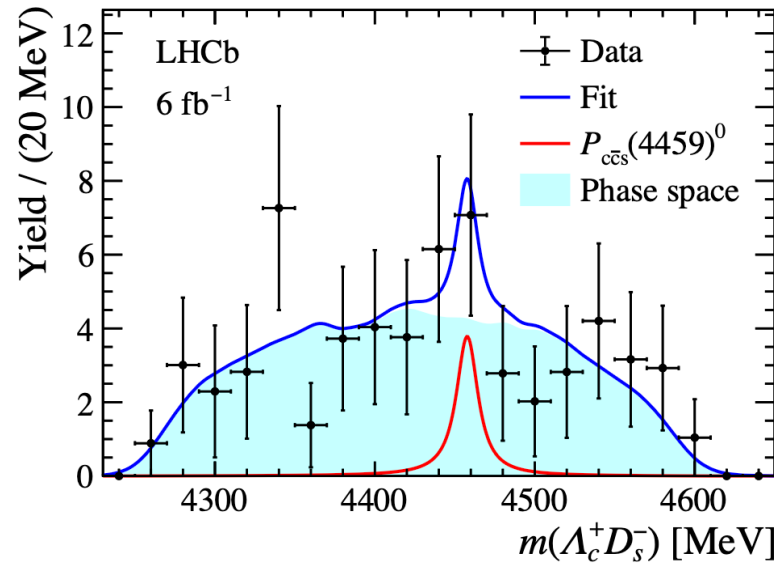
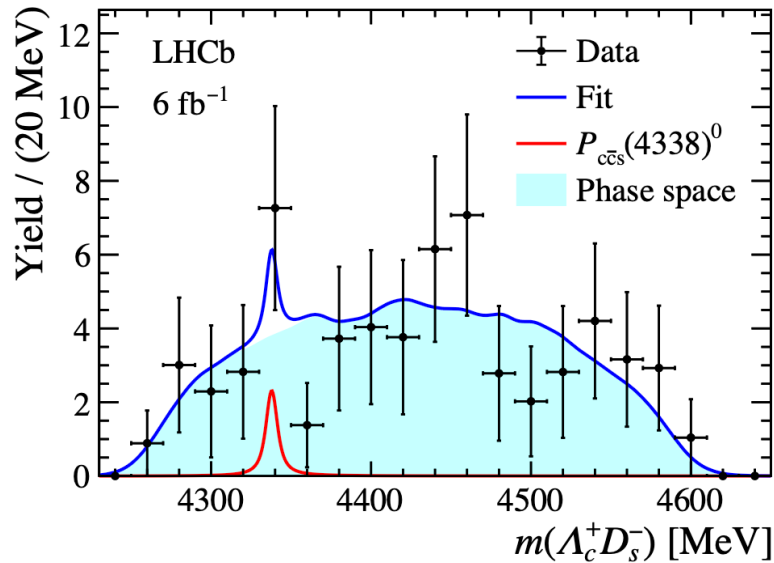
- $m_{\Lambda_b^0} \rightarrow 5619.6$ MeV
- $m_{\bar{D}^{*0}} \rightarrow 2006.8$ MeV
- m_X 0 MeV or 135 MeV (γ or π^0)
- Flight direction of Λ_b^0 points to PV



Search of pentaquarks decaying into $\Lambda_c^+ D_s^-$

- No significant pentaquark contribution in background suppressed $m(\Lambda_c^+ D_s^-)$ spectrum
- Upper limit assigned on relative contribution from $P_{c\bar{c}s}(4338)^0$ and $P_{c\bar{c}s}(4459)^0$ states

PRD 112 (2025) 5, 052013



Comb. BKG suppressed using sPlot

Pentaquarks described using RBW, mass & width fixed to known value

Uniform phase space MC used to model non-Pcs component

$$\mathcal{R}_{P_{c\bar{c}s}^0} \equiv \frac{\mathcal{B}(\Lambda_b^0 \rightarrow P_{c\bar{c}s} K^+ K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^- K^+ K^-)} \cdot \mathcal{B}(P_{c\bar{c}s}^0 \rightarrow \Lambda_c^+ D_s^-),$$

$$\mathcal{R}_{P_{c\bar{c}s}(4338)^0} < 0.12(0.10) @ 95(90) \% \text{ CL}$$

$$\mathcal{R}_{P_{c\bar{c}s}(4459)^0} < 0.20(0.17) @ 95(90) \% \text{ CL}$$

Run3 trigger lines for hidden-charm pentaquark studies

	Pentaquark decaying into $J/\psi, \psi(2S) + \text{baryon}$	Pentaquarks decaying into hadronic final states
Promptly produced pentaquark	Lifetime unbiased $J/\psi, \psi(2S) \rightarrow \mu^+ \mu^-$ trigger. Require ψ candidates with $p_T > 3\text{GeV}$	Dedicated trigger lines to save events where two open-charm hadrons are found
Pentaquark from b-decays	Detached $J/\psi, \psi(2S) \rightarrow \mu^+ \mu^-$ trigger. No p_T requirement on ψ candidates	The general topological-b triggers save events with two or three detached tracks consistent with originating from partially reconstructed b-decays

Example of impact on pentaquark study: $\Lambda_b^0 \rightarrow \eta_c p K^-$

- A promising Run 3 analysis !
 - 1000 signals available for am. an.
- Feasibility:

	$\Xi_b^- \rightarrow J/\psi \Lambda K^-$ am. an. (Run1+2, published)	$\Lambda_b^0 \rightarrow \eta_c p K^-$ am. an. (Run1~3, proposed)
Yield of b -hadron decays	~1750	~1000
Relative contribution from pentaquark states	~2.7% (measured)	~3% (predicted)
(Expected) achievements	$P_{cs}(4459)^0$ with 3σ , fit fraction reported	Measurement (more precise upper limit) of $P_c(4312)^+$ fit fraction
For J^P determination	not determined. Need Run3 data	not expected. Run4 data would be required.

$\Xi_b^- \rightarrow J/\psi \Lambda K^-$ amplitude fit

- Multi-dimensional unbinned-maximum-likelihood fit to extract properties of resonances

Helicity-based decay amplitude \leftarrow

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

\rightarrow Phase-space factor and efficiency

Single-event weight for suppressing combinatorial background \leftarrow

$$-2 \ln \mathcal{L}(\vec{\omega}) = -2s_W \sum_i W_i \ln \mathcal{P}_{\text{sig}}(m_{\Lambda K, i}, \Omega_i | \vec{\omega})$$

$$= -2s_W \sum_i W_i \ln |\mathcal{M}(m_{\Lambda K, i}, \Omega_i | \vec{\omega})|^2 + 2s_W \ln I(\vec{\omega}) \sum_i W_i$$

\rightarrow Normalization factor. Obtained using MC with amplitude weights

$$-2s_W \sum_i W_i \ln [\Phi(m_{\Lambda K, i}) \epsilon(m_{\Lambda K, i}, \Omega_i)].$$

\rightarrow Constant. Neglected during minimization

- Fit with a default model containing

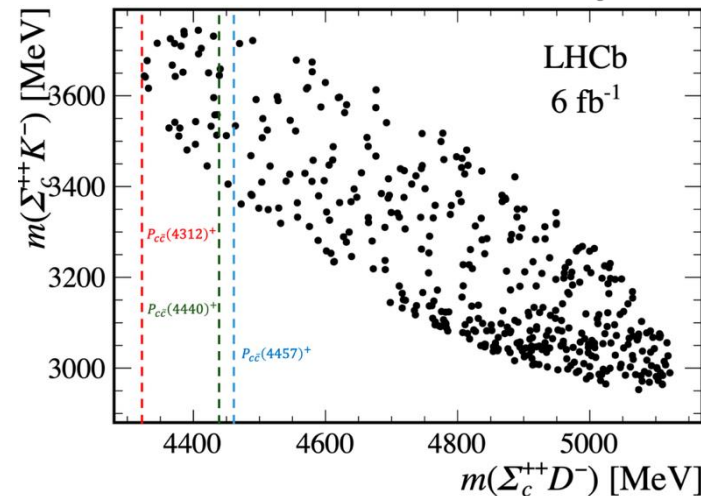
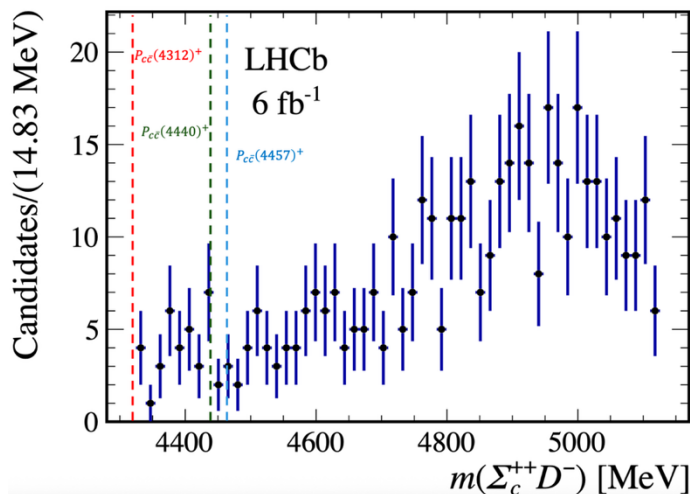
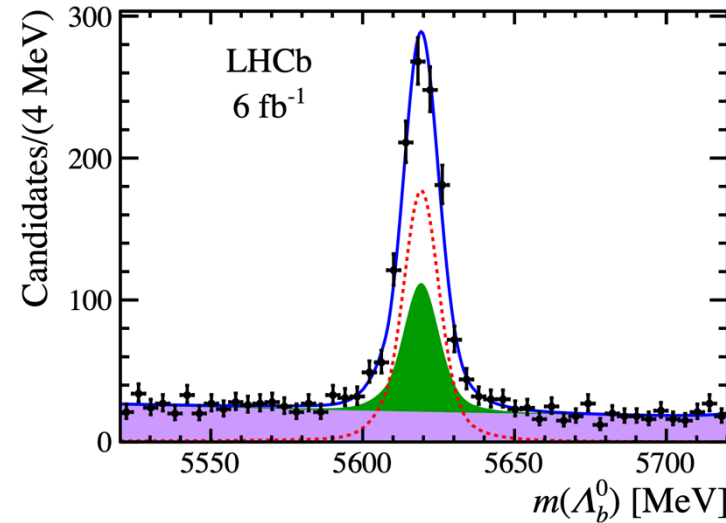
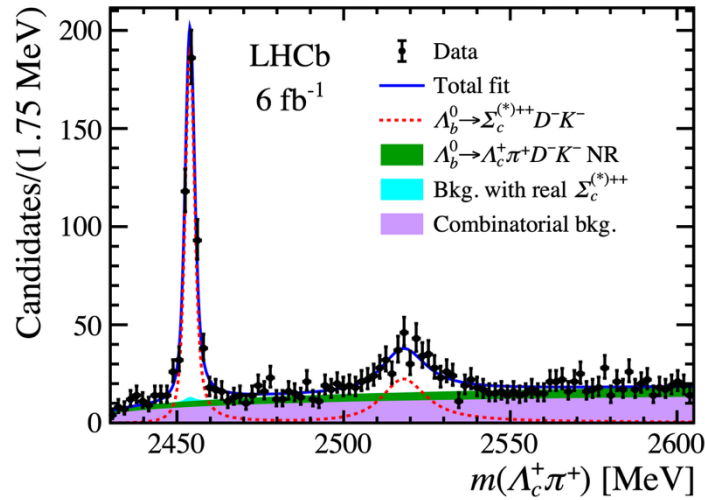
State	J^P	M_0 (MeV)	Γ_0 (MeV)	Couplings used (max)	J^P examined
$\Xi(1690)^-$??	1690 ± 10	< 30	4 (6)	$(1/2, 3/2)^\pm$
$\Xi(1820)^-$	$3/2^-$	1823 ± 5	24_{-10}^{+15}	3 (6)	$3/2^-$
$\Xi(1950)^-$??	1950 ± 15	60 ± 20	3 (6)	$(1/2, 3/2, 5/2)^\pm$
$\Xi(2030)^-$	$5/2^?$	2025 ± 5	20_{-5}^{+15}	3 (6)	$5/2^\pm$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

with/without an additional $P_{c\bar{c}s}$

Study of $\Lambda_b^0 \rightarrow \Sigma_c^{(*)++} D^{(*)-} K^-$ decay

PRD 110 (2024) 3, L031104

- Motivated by searching for pentaquarks in the potential constituent channels



Based on LHCb Run2 dataset

For all channels significance $\gg 5\sigma$.

100~500 signals collected for each decay

No significant $\Sigma_c^{++} D^-$ structures visible in mass spectrum or Dalitz plot

Another example of calling for more data to improve the statistical precision

Run 3 needed !

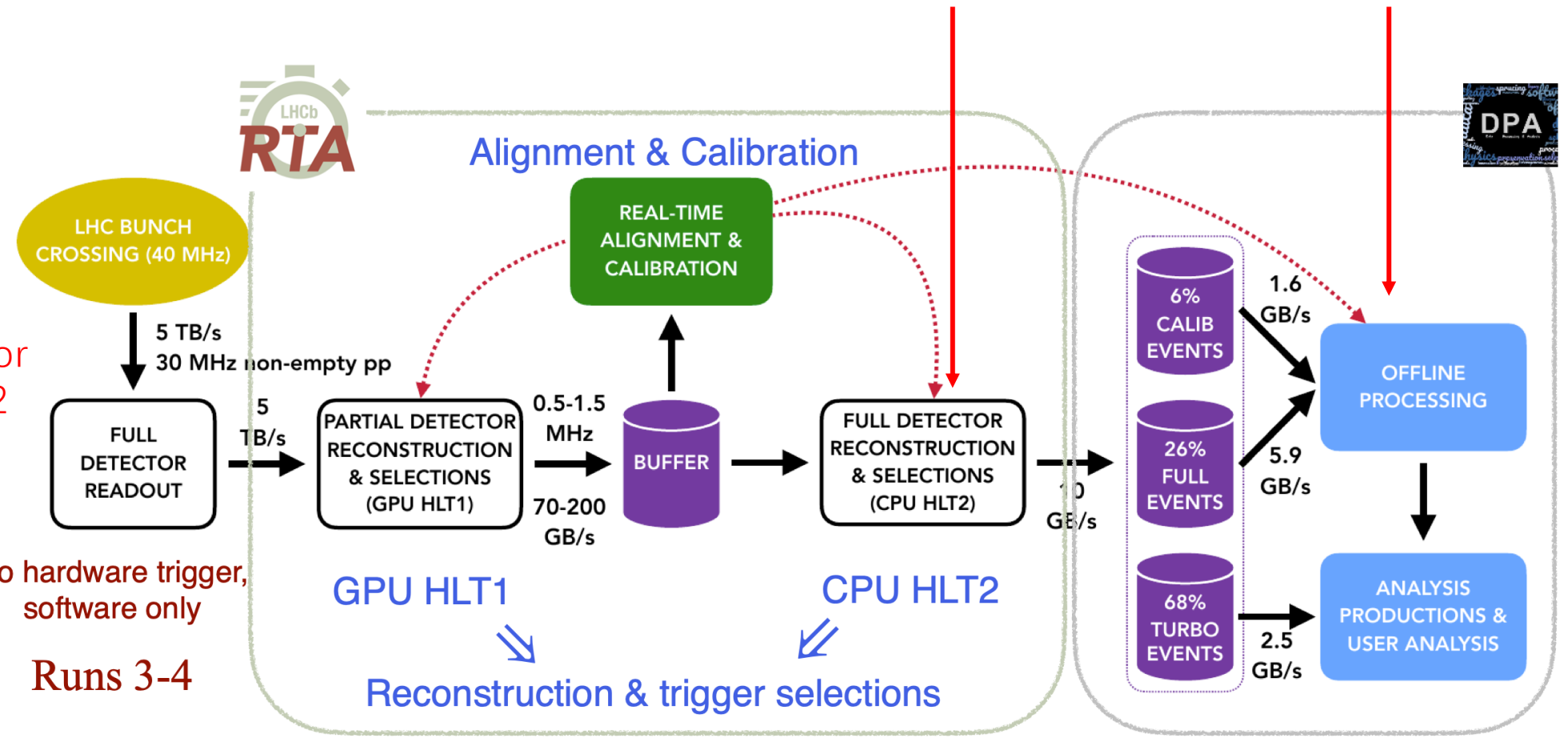
Run3 trigger of B-hadron and Quarkonium (B&Q) physics

- LHCb trigger & offline data processing

Selections designed by each Physics Working Group

Trigger efficiency for hadronic decays X2 compared to Run2

No hardware trigger, software only
Runs 3-4

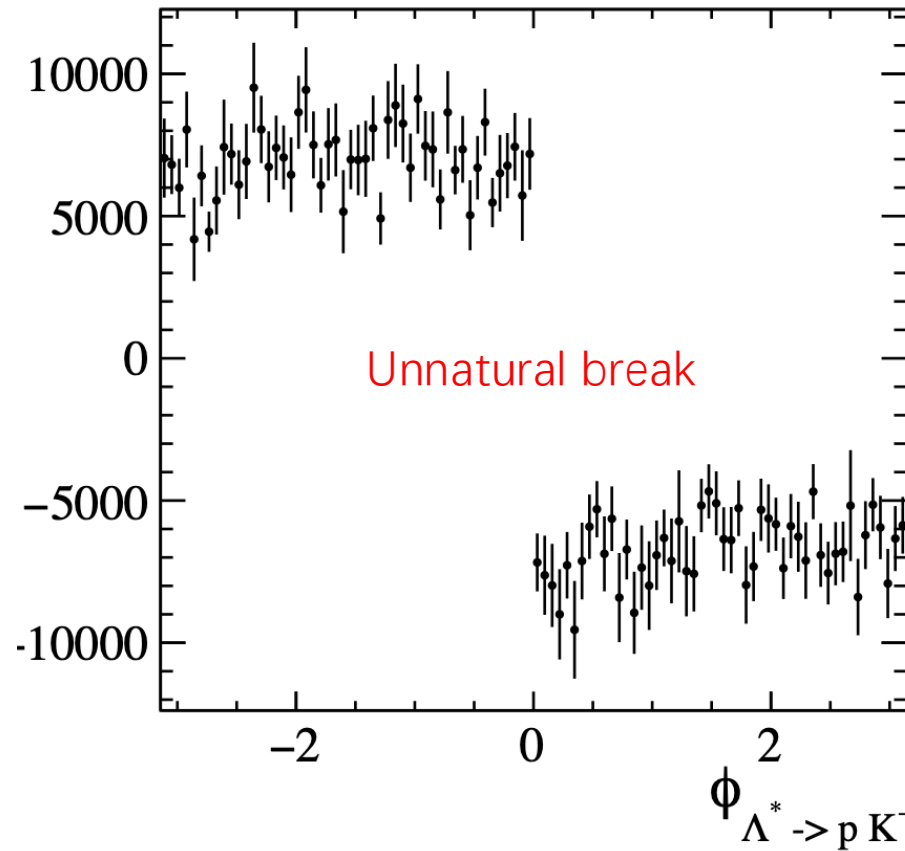


Improve the application of helicity formalism

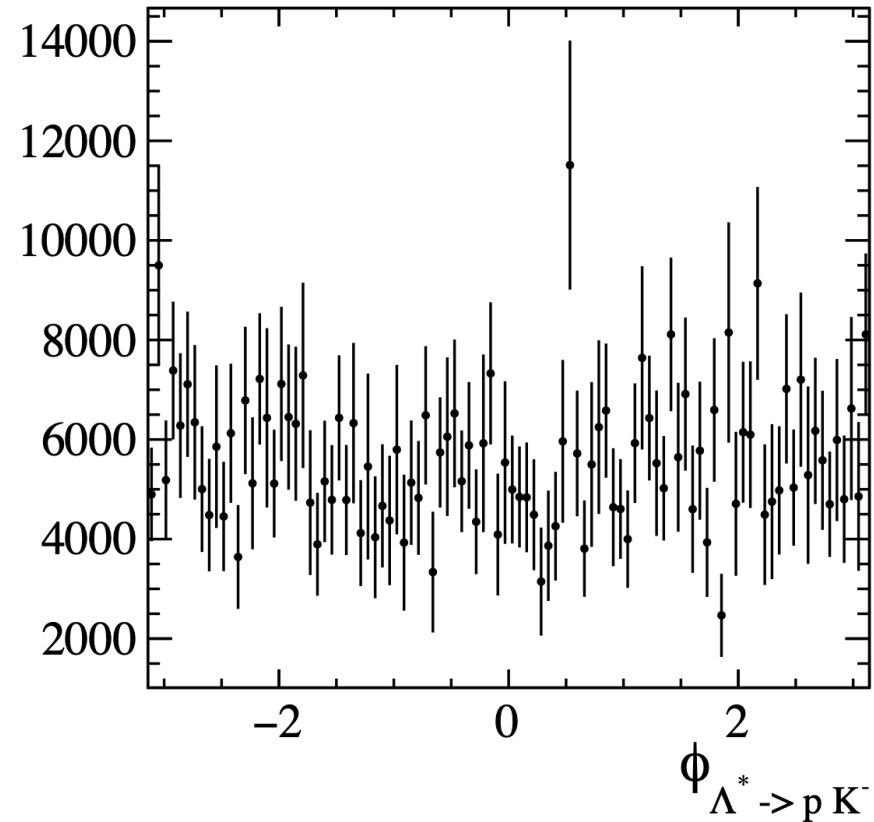
Chinese Phys. C 45 (2021) 063103

- Develop new method to align final-state definitions of different decay chains

Λ^* and P_c interference under **traditional method**



Λ^* and P_c interference using **new method**



- The new method has been used in several LHCb and BESIII amplitude analyses

arXiv.2603.05564; arXiv.2601.07617; JHEP02(2025)212; PRL134(2025)2,021901;
JHEP12(2022)033; PRL128(2022)6,062001; Sci. Bull.66(2021)1278-1287