Techniques for hadron spectroscopy studies at LHCb

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2023/06/07

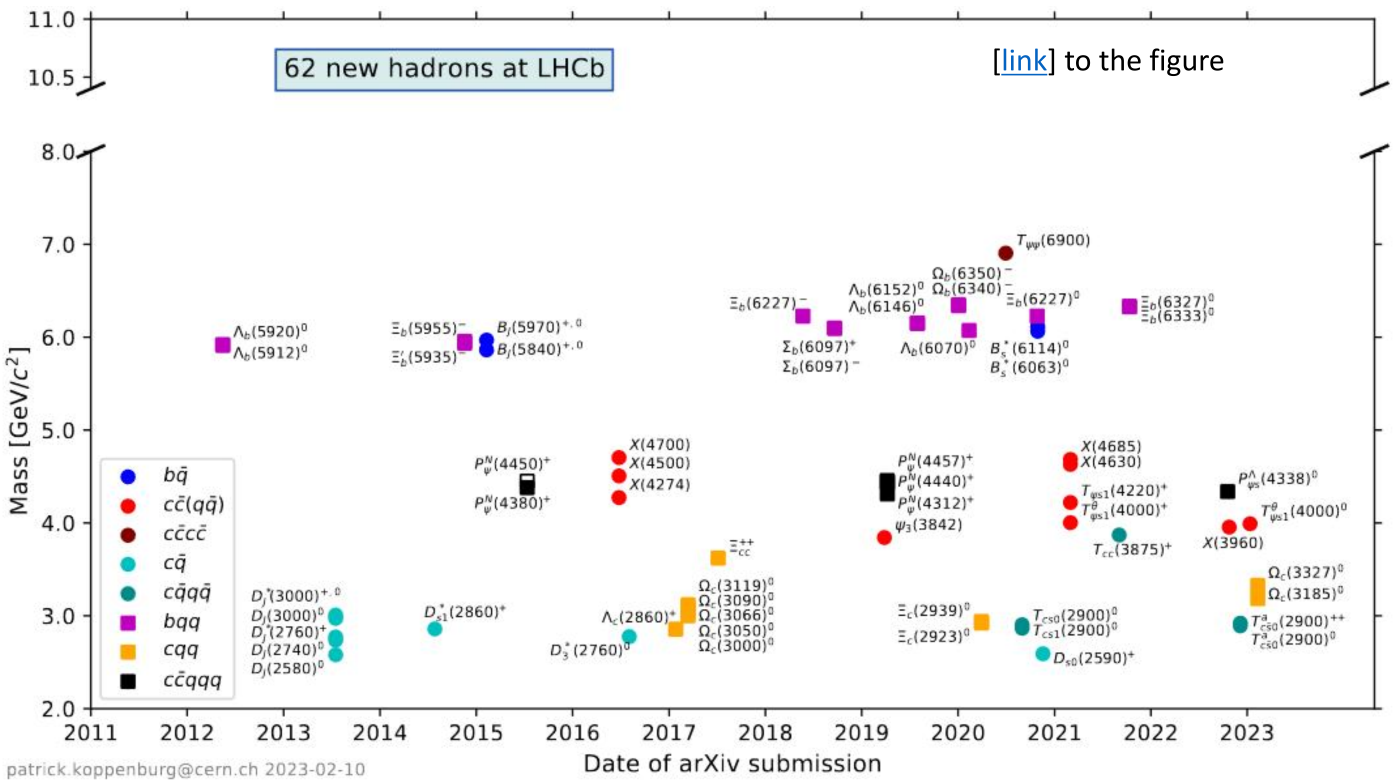
On behalf of the LHCb collaboration

Hadrons 2023

05-09 June 2023, Genova, Italy

b, c spectroscopy at LHCb

- LHCb: one of the major players of hadron spectroscopy study
  - Search for **new hadrons**
  - Measure **hadron properties** (lineshape, lifetime, decay modes…)



b, c spectroscopy at LHCb

- Benefit from...

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

Large b, c hadron **production cross-section** @ LHC

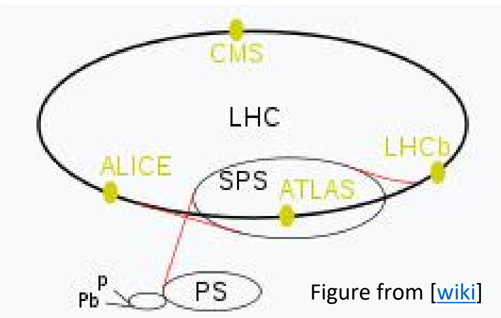
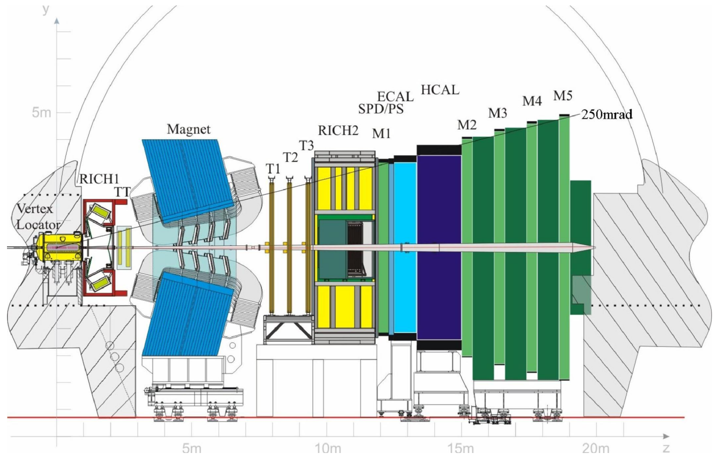


Figure from [wiki]

+

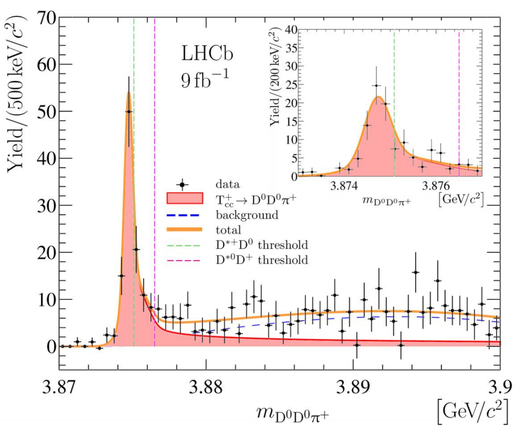
LHCb **detector optimized** for the collection, reconstruction and identification of b, c signals



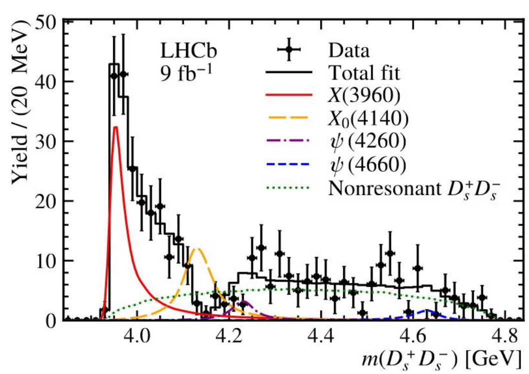
= **High-stat. and good-quality heavy flavor dataset**

Data analysis

Improved knowledge about hadron spectroscopy



Nature Communicatitions, 13, 3351 (2022)
Observation of doubly-charm tetraquark candidate



arXiv:2210.15153, Tetraquark candidate in $D_s^+D_s^-$ final state

Menu of today:

Development of data-analysis techniques benefiting recent LHCb results
(Focus on amplitude analysis)

Selected topics

- **Development of helicity amplitude formalism**

PRL 115 (2015) 072001
$P_c(4380)$, $P_c(4450)$ observation ← Conventional helicity formalism
Annals Phys. 7 (1959) 404

arXiv:2208.03262
Study of $\Lambda_c^+ \to pK\pi^-$ decay amplitude

Science Bulletin 66 (2021) 1278
Pentaquark evidence in $\Xi_b^- \to \boldsymbol{J/\psi\Lambda}K^-$

← New principles for final-state alignment in helicity-based amplitude
Advances in High Energy Physics (2020) 6674595
Chinese Phys. C 45 (2021) 063103
Phys.Rev.D 95 (2017) 7, 076010

arXiv:2210.10346
Observation of $P_{\psi s}^{\Lambda}(4338)$ ← Dalitz-plot decomposition formula
Phys. Rev. D 101 (2020) 034033

- **Speed up amplitude fits using GPUs**

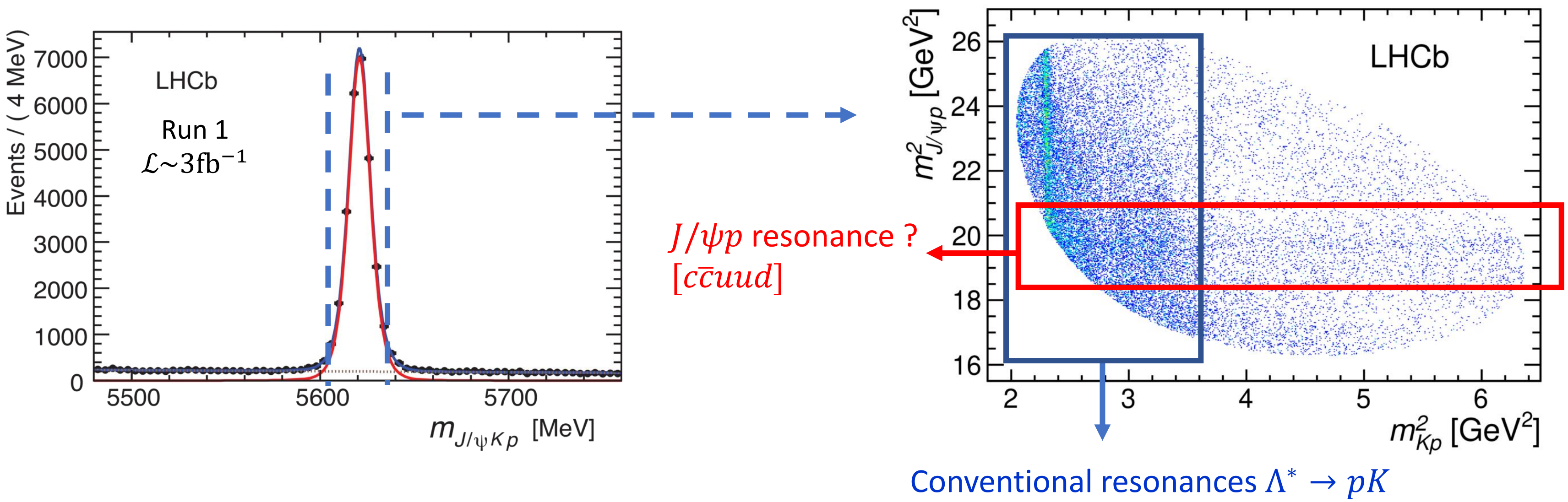
arXiv:2301.04899
Evidence of tetraquark candidate $T_{\psi s1}^{\theta}(4000)^0$ ← A CUDA + RooFit based fit framework

Focus on techniques. For relevant physics results, see the talks by Elisabetta [link] and Bo [link]

Development of helicity-based amplitude formalisms

PRL 115 (2015) 072001

Helicity formalism & P_c observation



- $\sim 20k\ \Lambda_b^0 \to J/\psi p K^-$ signals collected in Run1
- Clear $J/\psi p$ structure seen in Dalitz plot
- Multi-dimension amplitude analysis to extract properties of $J/\psi p$ intermediate states

PRL 115 (2015) 072001, PRL 115 (2015) 072001 supplemental

Helicity formalism & P_c observation

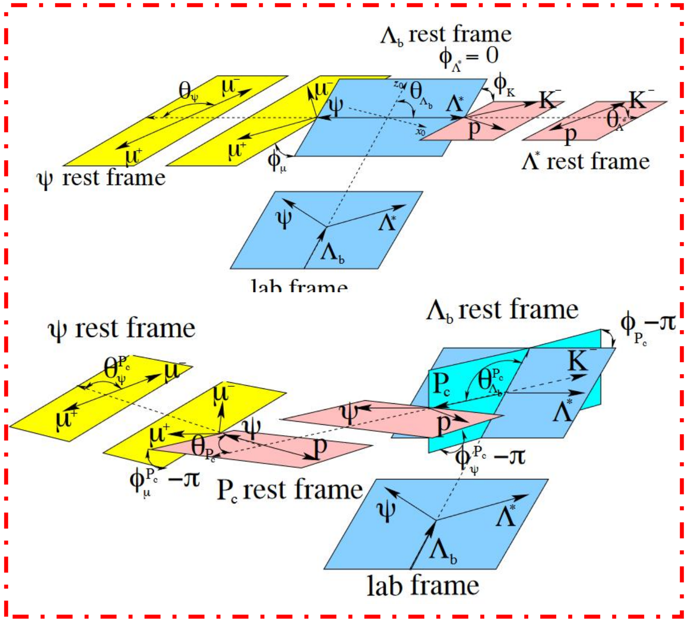
- **Two decay chains: Λ^* or P_c as intermediate state**

Λ^* chain:

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

P_c chain: RBW-based lineshape

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

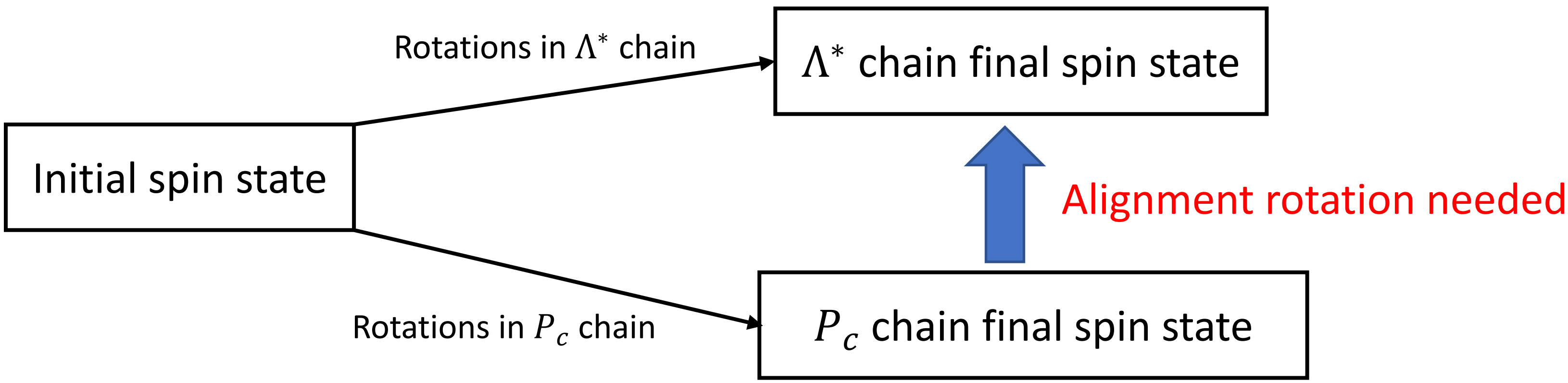


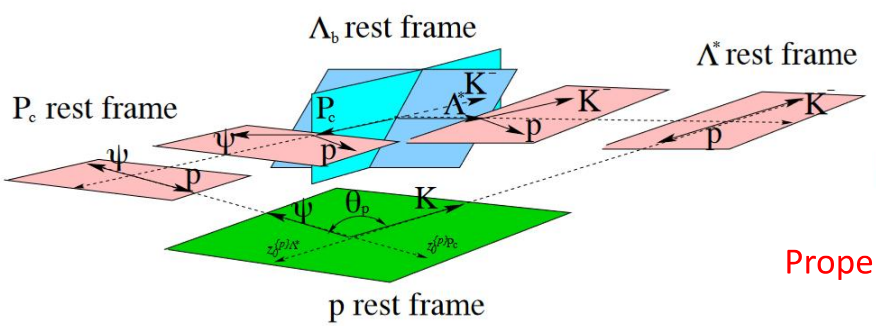
Wigner-D function to associate initial & final spin states of each two-body decay node

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

Helicity formalism & P_c observation

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





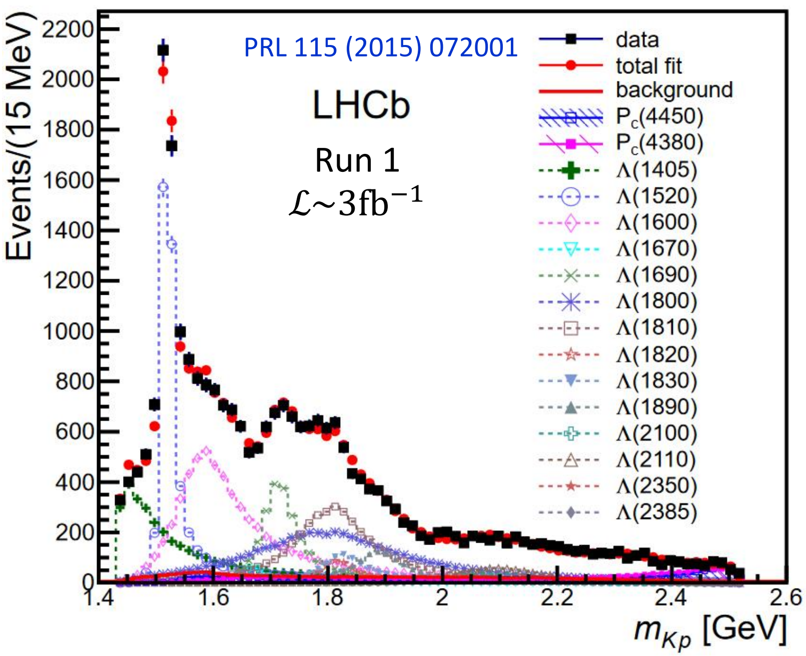
$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b^0}=\pm\frac{1}{2}} \sum_{\lambda_p=\pm\frac{1}{2}} \sum_{\Delta\lambda_\mu=\pm 1} \left| \mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} + e^{i\,\Delta\lambda_\mu\alpha_\mu} \sum_{\lambda_p^{P_c}} d^{\frac{1}{2}}_{\lambda_p^{P_c},\lambda_p}(\theta_p)\,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

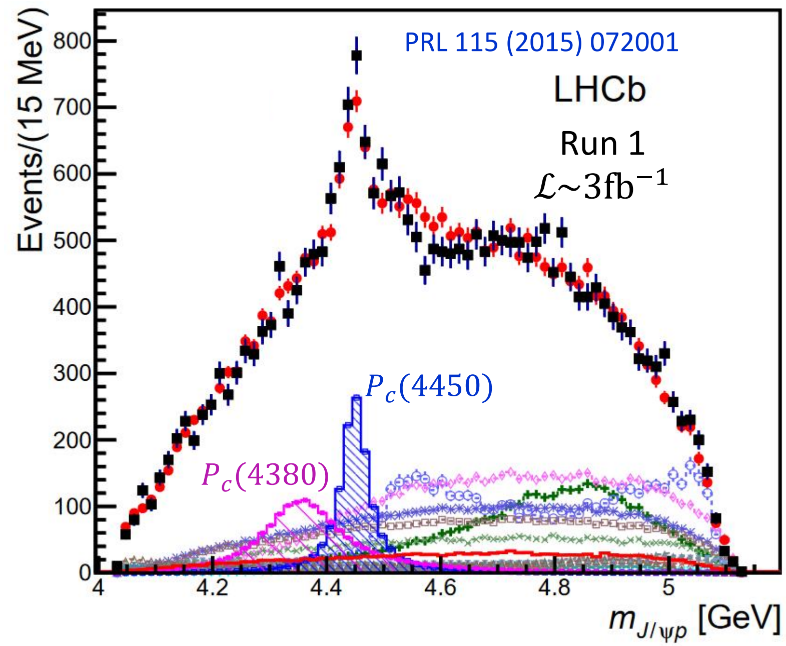
Properly align the definition of final-state spin states in different chains

PRL 115 (2015) 072001

Helicity formalism & P_c observation

- Two $J/\psi p$ resonances with significance $> 5\sigma$
  - minimal quark content $[c\bar{c}uud]$, good candidate for pentaquarks





- Follow-up analyses:
  - Confirmed in Model-independent analysis PRL 117(2016)082002
  - Similar structure seen in Cabibbo suppressed $\Lambda_b^0 \to J/\psi p\pi^-$ PRL 117(2016)082003
  - $P_c(4312)$, $P_c(4440)$, $P_c(4457)$ observed in Run1+2 data PRL 122(2019)222001

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

The missing quantum effect ?

- The conventional helicity formalism

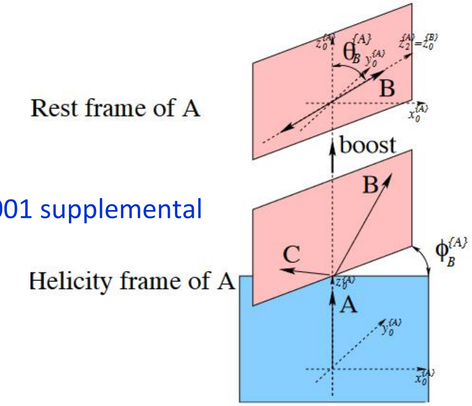
(SU2)
Decay angles rotating spin states

Fully determine ←

(SO3)
Rotations in momentum space

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

$$\phi_B = \text{atan2}\left(p_B^{\{A\}}{}_y, p_B^{\{A\}}{}_x\right)$$
$$= \text{atan2}\left(\hat{y}_0^{\{A\}}\cdot\vec{p}_B^{\{A\}}, \hat{x}_0^{\{A\}}\cdot\vec{p}_B^{\{A\}}\right)$$
$$= \text{atan2}\left((\hat{z}_0^{\{A\}}\times\hat{x}_0^{\{A\}})\cdot\vec{p}_B^{\{A\}}, \hat{x}_0^{\{A\}}\cdot\vec{p}_B^{\{A\}}\right),$$
$$\cos\theta_A = \hat{z}_0^{\{A\}}\cdot\hat{p}_B^{\{A\}}.$$



PRL 115 (2015) 072001 supplemental

Quantum effects missing for **baryons** ?

$$d^J_{\lambda_1,\lambda_2}(\theta_A) = -\mathbf{1}\times d^J_{\lambda_1,\lambda_2}(\theta_A+\mathbf{2\pi})$$
$$e^{i\lambda\phi_B} = -\mathbf{1}\times e^{i\lambda(\phi_B+\mathbf{2\pi})}$$

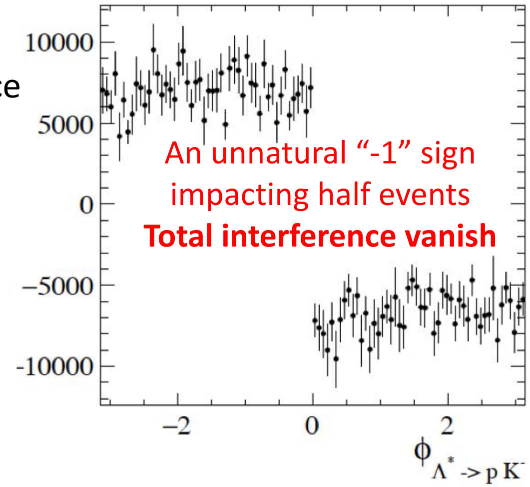
Cannot set a preference between
θ_A & $\theta_A+\mathbf{2\pi}$, ϕ_B & $\phi_B+\mathbf{2\pi}$

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

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

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

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

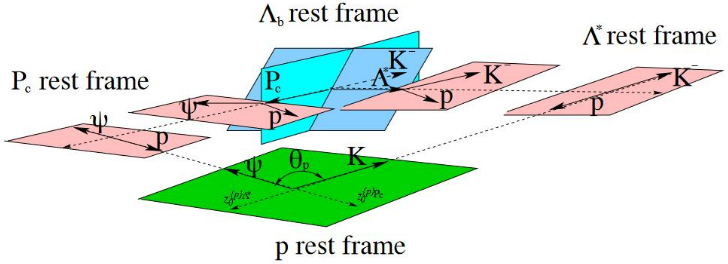
Recover the missing quantum effect

- 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



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

Recover the missing quantum effect

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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

$$\hat{R}\left(\alpha_1^{W,R}, \beta_1^{W,R}, \gamma_1^{W,R}\right)\hat{R}(\phi_R, \theta_R, 0)\hat{R}\left(\phi_1^R, \theta_1^R, 0\right)|\mathbf{p}_1^R, s_1, \lambda_1^R\rangle = \sum_{\mu_1^R} D^{s_1}_{\mu_1^R,\lambda_1^R}\left(\phi_1^R, \theta_1^R, 0\right) \times \sum_{\nu_1^R} D^{s_1}_{\nu_1^R,\mu_1^R}(\phi_R, \theta_R 0) \sum_{m_1} D^{s_1}_{m_1,\nu_1^R} \times \left(\alpha_1^{W,R}, \beta_1^{W,R}, \gamma_1^{W,R}\right)|\mathbf{p}_1^A, s_1, m_1\rangle.$$

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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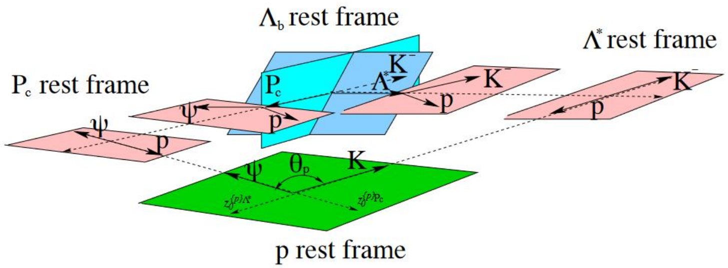

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Advances in High Energy Physics (2020) 6674595

$$\hat{R}\left(\alpha_1^{W,R},\beta_1^{W,R},\gamma_1^{W,R}\right)\hat{R}(\phi_R,\theta_R,0)\hat{R}\left(\phi_1^R,\theta_1^R,0\right)|\mathbf{p}_1^R,s_1,\lambda_1^R\rangle$$
$$=\sum_{\mu_1^R} D^{s_1}_{\mu_1^R,\lambda_1^R}\left(\phi_1^R,\theta_1^R,0\right)\times\sum_{\nu_1^R} D^{s_1}_{\nu_1^R,\mu_1^R}(\phi_R,\theta_R,0)\sum_{m_1} D^{s_1}_{m_1,\nu_1^R}$$
$$\times\left(\alpha_1^{W,R},\beta_1^{W,R},\gamma_1^{W,R}\right)|\mathbf{p}_1^A,s_1,m_1\rangle.$$

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

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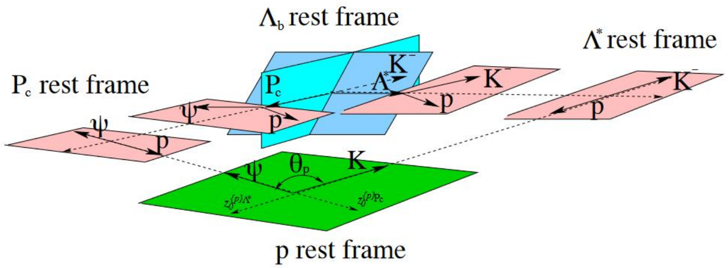


New method implemented in

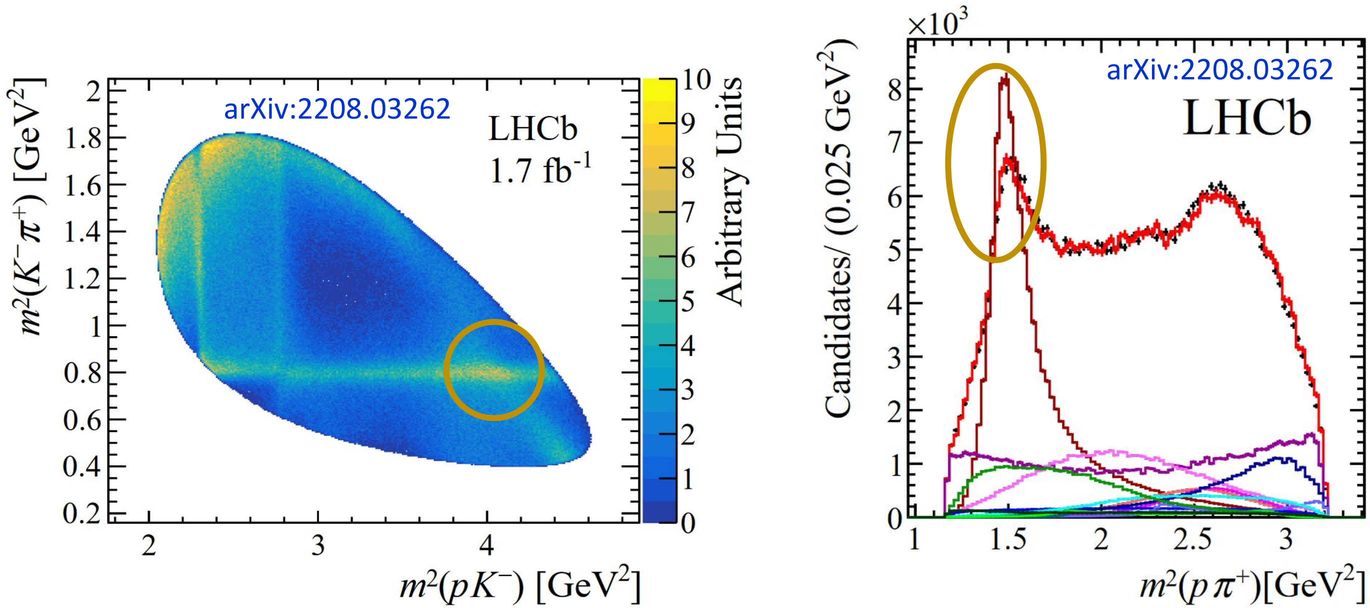
$\Lambda_c^+ \to pK\pi^-$ amplitude analysis arXiv:2208.03262

$\Xi_b^- \to J/\psi\Lambda K^-$ amplitude analysis for pentaquark search Science Bulletin 66 (2021) 1278

arXiv:2208.03262

$\Lambda_c^+ \to pK^-\pi^+$ amplitude analysis

- 2016 data, $\mathcal{L} = 0.5\text{fb}^{-1}$; $\sim 400\text{k}$ signals;
- Helicity-based Am.An.; Measure polarization, resonance fractions and decay parameters
- Large interference seen between different chains



Large **interference** between $\Delta(1232)^{++}$ and $K^*(892)$

See the talks by Elisabetta [link] and Bo [link]

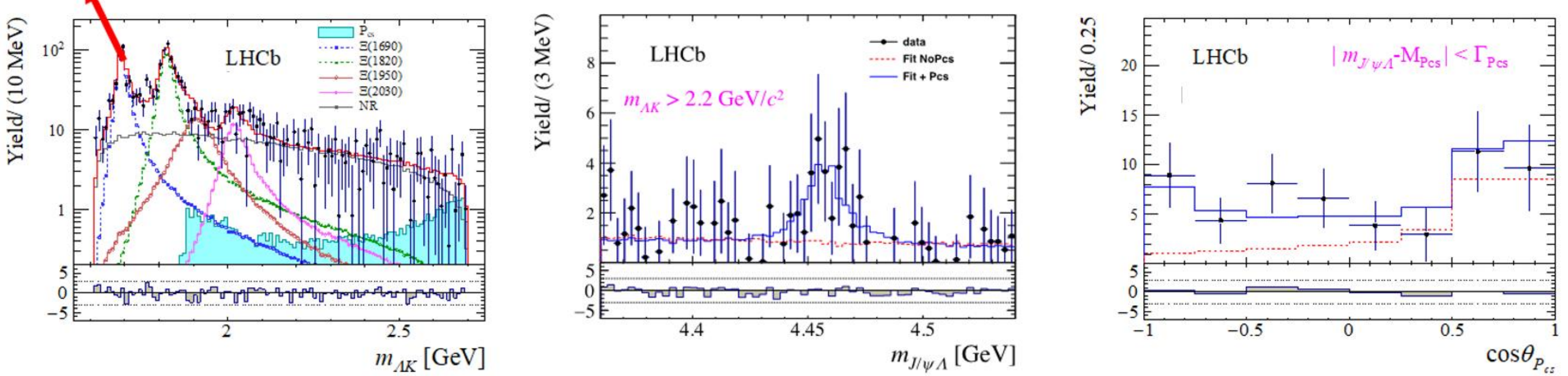
Science Bulletin 66 (2021) 1278

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

- Consider Λ as final-state particle, similar spin structure as $\Lambda_b^0 \to J/\psi p K^-$ decay
- Use same amplitude formalism, with alignment-issue fixed
  - **3.1σ significance** when syst. uncertainty considered

Two Ξ^{*-} states

Zooms in to P_{cs} signal region for better visibility



P_{cs} mass 19MeV below the $\Xi_c^0 \bar{D}^{*0}$ threshold. Statistic not enough for J^P determination.

Science Bulletin 66 (2021) 1278

Phys. Rev. D 101 (2020) 034033

Dalitz-plot decomposition (DPD) formula

- $\mathcal{M} \sim <\text{init.}\,|\,\text{fin.}> \sim <\text{init.}\,|\sum_i R_i> \ldots <\sum_i R_i\,|\text{fin.}>$

Wigner-D functions

Choice of intermediate spin state/frame not unique. Alternative choice: DPD formula

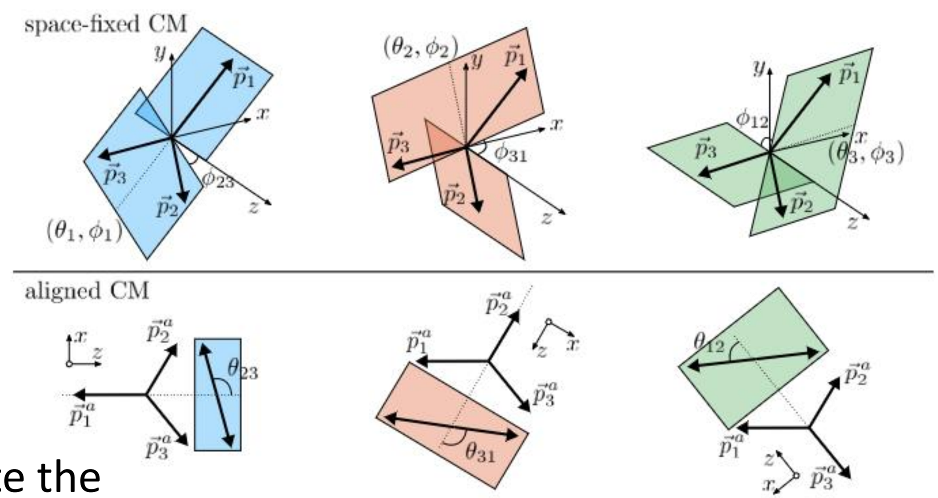
- DPD formula for 3-body decay
  - $0 \rightarrow 123$

An arbitrary initial spin frame

Same Euler rotation for all decay chains
(One Wigner-D function)

All momenta (spin-axis of helicity states) aligned to x-z plane; $\hat{p}_1 = -\hat{z}$

Use conventional helicity formula to write the rest part of amplitude



Phys. Rev. D 101 (2020) 034033

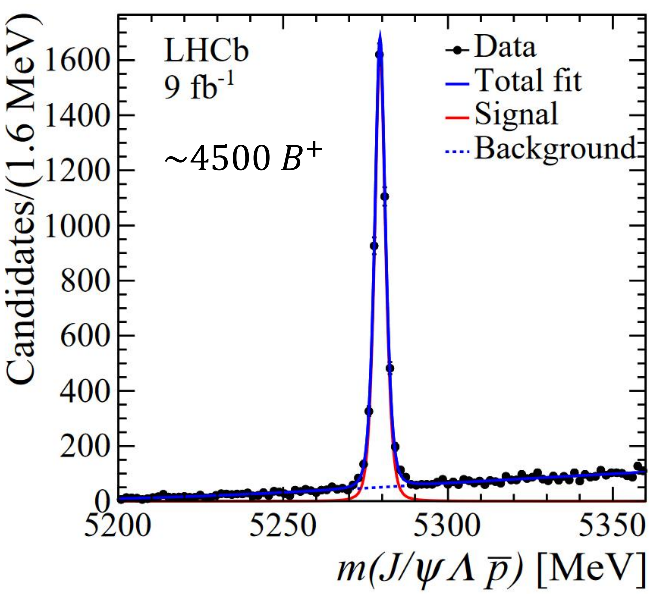
Angular variables can be derived using Dalitz-plot variables

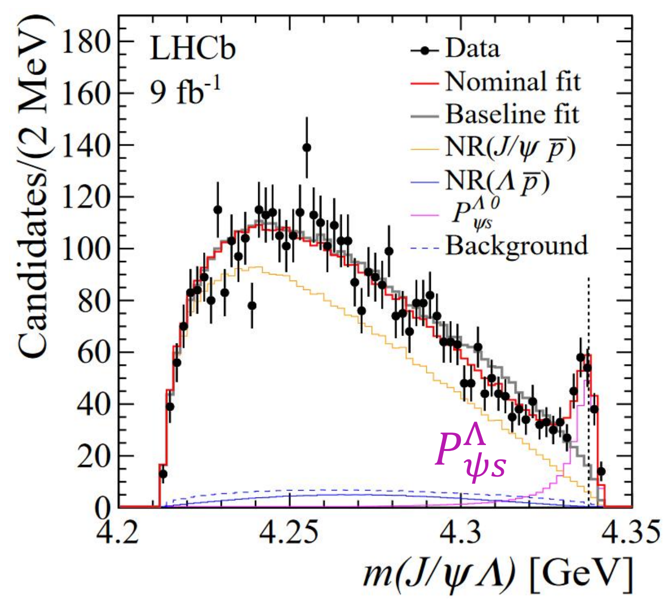
See the talks by Elisabetta [link] and Bo [link]

arXiv:2210.10346

Observation of $P_{\psi s}^{\Lambda}(4338)$

- Search for $J/\psi p$ and $J/\psi\Lambda$ states in $B^+ \to J/\psi p\bar{\Lambda}$
  - B^+ is spin-zero. 1st Euler rotation is a constant term
  - 2D Dalitz amplitude for 3-body B^+ decay (DPD) arXiv:2210.10346; supplemental A
  - 2D amplitude of $J/\psi \to \mu^+\mu^-$ + 2D amplitude of $\Lambda \to p\pi$
- 6D amplitude analysis on $\sim 4500\ B^+ \to J/\psi p\bar{\Lambda}$ decays
  - $P_{\psi s}^{\Lambda}$ significance $> 10\sigma$

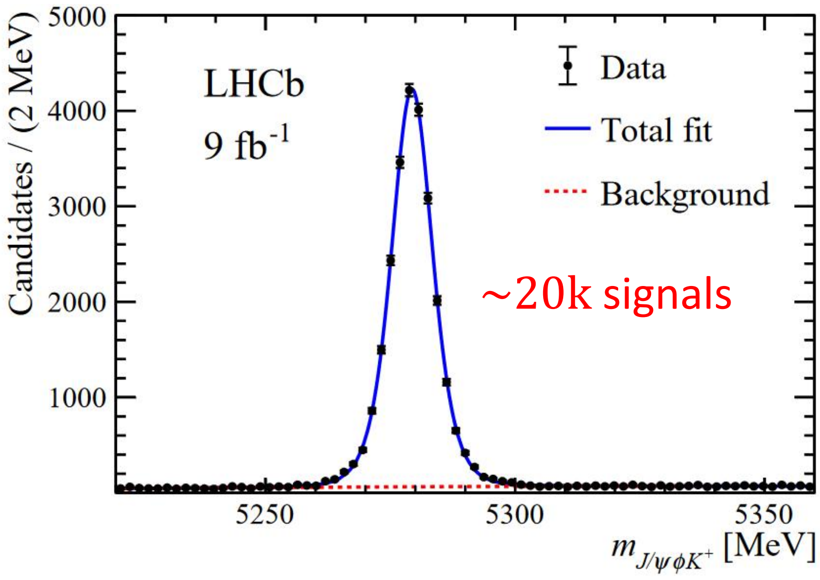




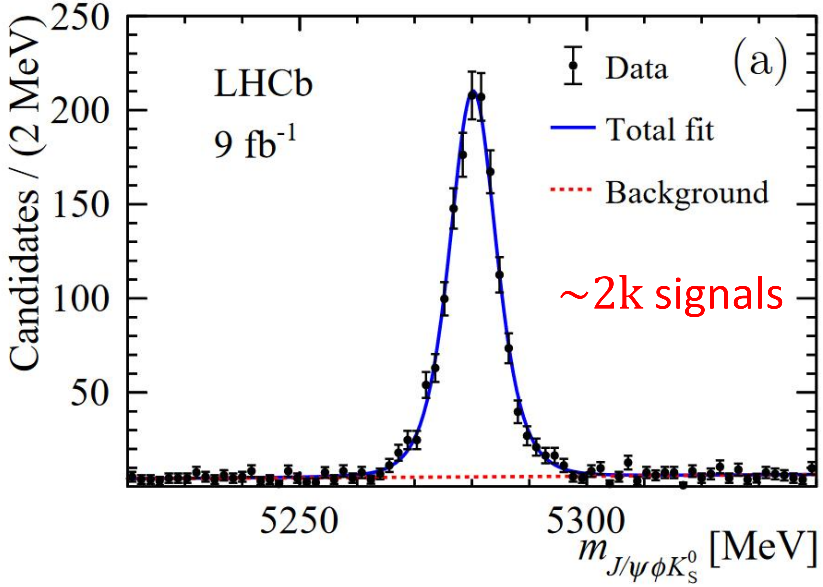
Speed up amplitude fits using GPUs

Study of $B^0 \to J/\psi K_S^0 \phi$ decay

- $T^{\theta}_{\psi s1}(4000)^+$ observed in $B^+ \to \boldsymbol{J/\psi K^+}\phi$ channel
- Search for its isospin partner in $B^0 \to \boldsymbol{J/\psi K_S^0}\phi$ decay
  - Joint amplitude fit using $B^+ \to \boldsymbol{J/\psi K^+}\phi$ and $B^0 \to \boldsymbol{J/\psi K_S^0}\phi$ events collected in LHCb Run1+Run2



PRL 117 (2021) 082001



arXiv:2301.04899

Construction of likelihood function

- To obtain a log-likelihood value:

Loop over all data events in signal region ($\sim 20\mathrm{k}$)

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

Parameterized using sideband data

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

Loop over uniform phase-space MC events passing all event selections ($400\mathrm{k}$)

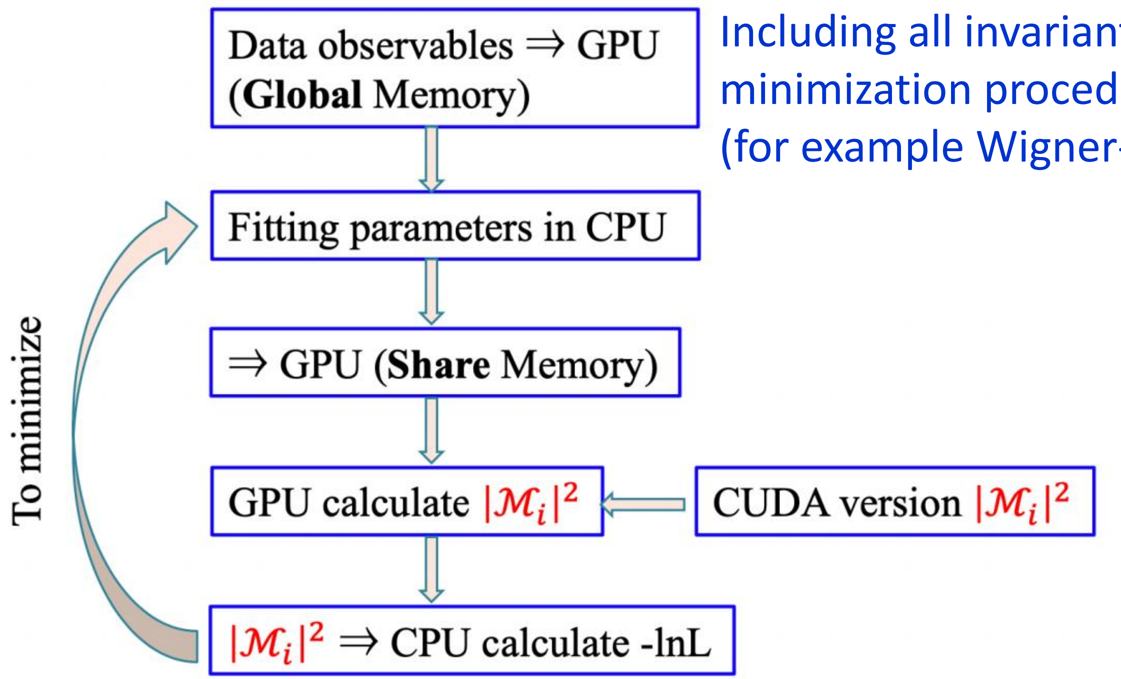
Norm. factor obtained numerically using MC: $I_{\mathrm{norm}} = \sum_j \left|\mathcal{M}_j(\vec{\omega})\right|^2$

- Need to calculate matrix element for $\sim 0.4\mathrm{M}$ times
- Amplitude computations for each data/MC events are independent on each other. Use GPUs to handle the them in parallel

CUDA + RooFit based 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

Version 1



Including all invariant terms in minimization procedure
(for example Wigner-D functions)

GPU type: RTA 3090

Optimization of the framework

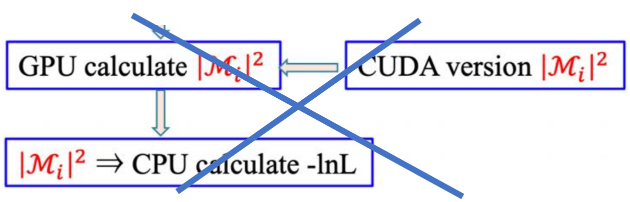
- Optimization of the GPU sector

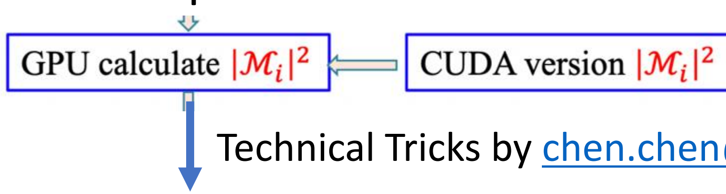
zhihong.shen@cern.ch

  - Tools: Nsight Systems (nsys) and Nsight Compute (ncu) by Nivdia

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





Technical Tricks by chen.chen@cern.ch

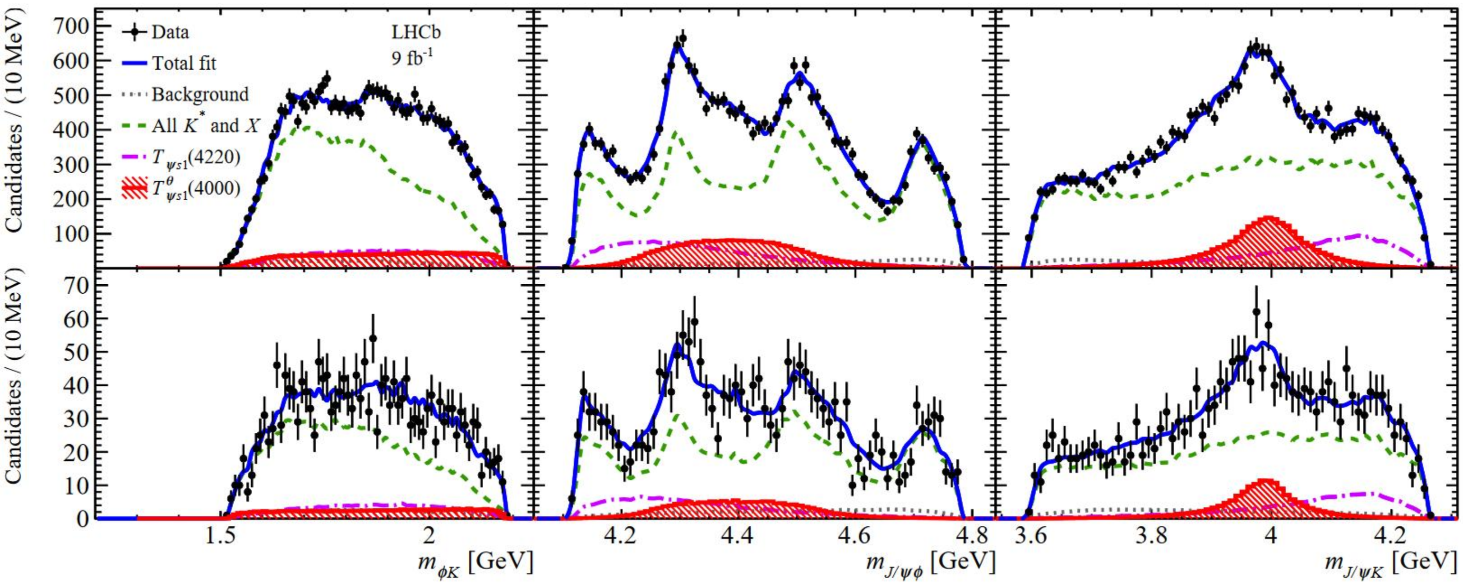
GPU organize $|\mathcal{M}_i|^2$ to form NLL
GPU forward NLL to CPU to do minimization (Minuit)

See the talk by Elisabetta [link]

arXiv:2301.04899

Performance & achievement

- ~ 10mins to run an amplitude fit
  - Even fast enough for toy studies with hundreds of fits needed
- Physics result



$B^+ \to J/\psi \phi K^+$

$B^0 \to J/\psi \phi K^0_s$

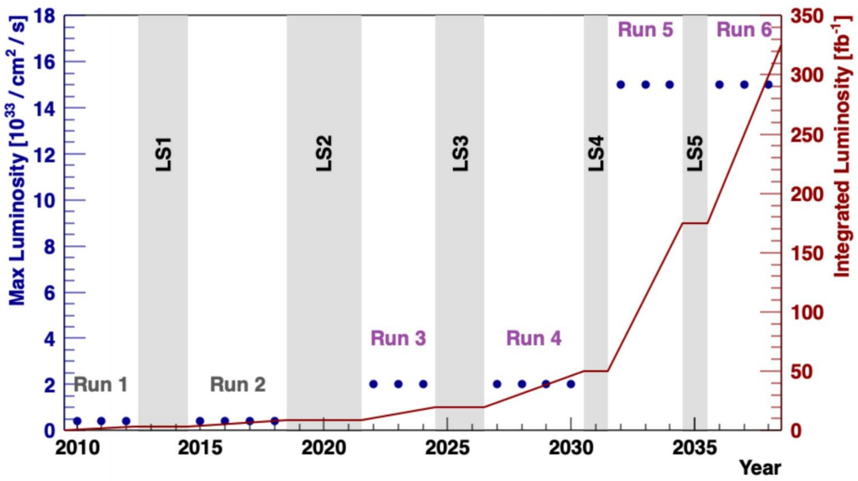
- Evidence of $T^{\theta}_{\psi s1}(4000)^0$ seen in $J/\psi K^0_S$ system ($\sim 4\sigma$)
- Mass, width consistent with $T^{\theta}_{\psi s1}(4000)^+$ isospin partner

Summary

Summary

- LHCb has made a great contribution to hadron spectroscopy studies, and is smoothly boosting the field to a new level

More & more high-quality data is coming.
Improved stat. precision



Stay tuned ☺
Thank you for your attention !

To persist the **ability of handling the ever larger** data flow:
Improved trigger system, Real-Time Analysis
Advanced software tools for Data Processing and Analysis

Example in this talk:
Use GPUs to speed up amplitude analysis

Develop & use **new phenomenological models** in data analysis, minimize relevant systematic uncertainties, to match the ever better stat. precision

Example in this talk:
Development of the general formalism for helicity amplitudes

Back up

Phys. Rev. D 101 (2020) 034033

Dalitz-plot decomposition (DPD) formula

- Split the amplitude into different sectors featuring different aspects of the decays
  - Example: $\Lambda_b^0 \to J/\psi p K^-$ amplitude

$$(M^{\Lambda}_{\lambda,\xi})_{\rm LHCb} = \sum_{\nu,\mu} D^{J*}_{\Lambda,\nu}(\phi_1,\theta_1,\phi_{23})$$

Shared by P_c, Λ^* chains

Dalitz-variable-dependent amplitude $\mathcal{M}_{P_c} + \mathcal{M}_{\Lambda^*}$, dominate the interference behavior

$$\times \Bigg(\sum_{s}^{\Lambda^*\to pK} \sum_{\tau} \sqrt{2} n_s\, d^{1/2}_{\nu,\tau-\mu}(0)\, H^{0\to(23),1}_{\tau,\mu}\, X_s(\sigma_1)\, d^{s}_{\tau,\lambda}(\theta_{23})\, H^{(23)\to 2,3}_{\lambda,0}$$

Λ^* chain

$$+ \sum_{s}^{P_c\to J/\psi p} \sum_{\tau,\mu',\lambda'} \sqrt{2} n_s\, d^{1/2}_{\nu,\tau}(\hat{\theta}_{3(1)})\, H^{0\to(12),3}_{\tau,0}\, X_s(\sigma_3)\, d^{s}_{\tau,\mu'-\lambda'}(\theta_{12})\, H^{(12)\to 1,2}_{\mu',\lambda'}\, d^{1/2}_{\lambda'\lambda}(\zeta^2_{3(1)})\, d^{1}_{\mu'\mu}(\zeta^1_{3(1)}) \Bigg)$$

P_c chain

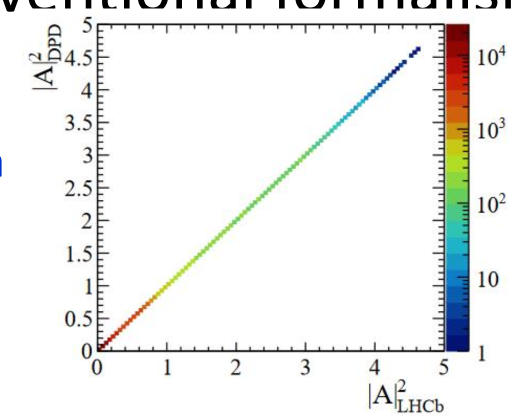
$$\times \sqrt{3}\, e^{i\mu(\phi_{23}+\phi''_{+})}\, d^{1}_{\mu\xi}(\theta_{+})\, H^{1\to\mu^+,\mu^-}_{\lambda_+,\lambda_-}$$

, $J/\psi \to \mu^+\mu^-$ decay amplitude shared by two chains

- A good agreement found with the conventional formalism

Chinese Phys. C 45 (2021) 063103

DPD V.S. conventional helicity formula

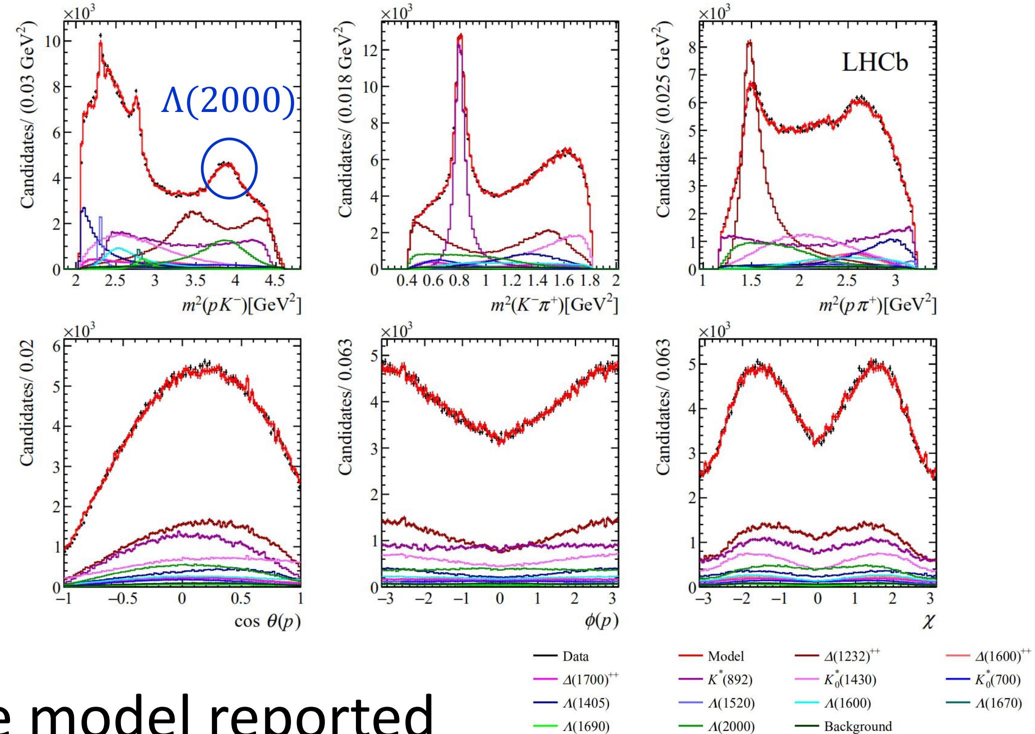


arXiv:2208.03262

$\Lambda_c^+ \to pK^-\pi^+$ amplitude analysis

- 2016 data, $\mathcal{L} = 0.5\text{fb}^{-1}$; $\sim$400k signals; helicity-based Am.An.

Resonance	J^P	Mass (MeV)	Width (MeV)
$\Lambda(1405)$	$1/2^-$	1405.1	50.5
$\Lambda(1520)$	$3/2^-$	1515 − 1523	10 − 20
$\Lambda(1600)$	$1/2^+$	1630	250
$\Lambda(1670)$	$1/2^-$	1670	30
$\Lambda(1690)$	$3/2^-$	1690	70
$\Lambda(2000)$	$1/2^-$	1900 − 2100	20 − 400
$\Delta(1232)^{++}$	$3/2^+$	1232	117
$\Delta(1600)^{++}$	$3/2^+$	1640	300
$\Delta(1700)^{++}$	$3/2^-$	1690	380
$K_0^*(700)$	0^+	824	478
$K^*(892)$	1^-	895.5	47.3
$K_0^*(1430)$	0^+	1375	190



- All parameters of amplitude model reported
- Mass and width of $\Lambda(2000)$ determined

$$m = 1988 \pm 2 \pm 21\,\text{MeV} \qquad \Gamma = 179 \pm 4 \pm 16\,\text{MeV}$$

Λ_c^+ polarization measurement

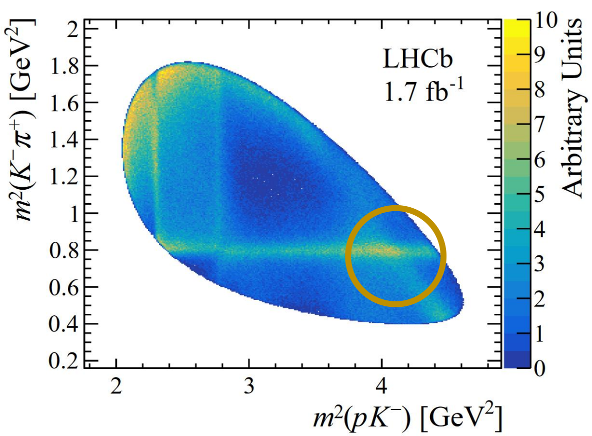
$$p(\Omega, \boldsymbol{P}) = \frac{1}{\mathcal{N}} \sum_{m_p=\pm 1/2} \Big\{ (1 + P_z) |\mathcal{A}_{1/2,m_p}(\Omega)|^2 + (1 - P_z) |\mathcal{A}_{-1/2,m_p}(\Omega)|^2 + 2\mathrm{Re}\left[(P_x - iP_y) \mathcal{A}^*_{1/2,m_p}(\Omega) \mathcal{A}_{-1/2,m_p}(\Omega) \right] \Big\},$$

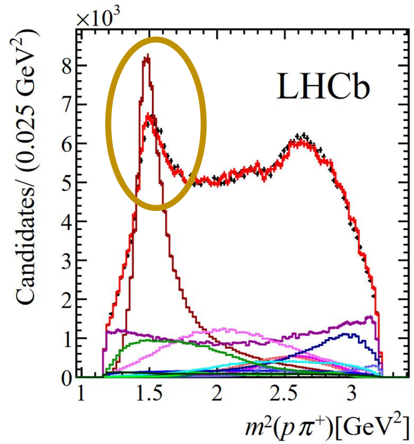
Final-state kinematics

Initial spin structure of Λ_c^+

- Large interference seen between different chains

Advances in High Energy Physics (2020) 7463073





Large **interference** between $\Delta(1232)^{++}$ and $K^*(892)$

Λ_c^+ polarization from semileptonic b-decays measured, with 2 different definitions of initial spin axis

Component	Value (%)
P_x (*lab*)	$60.32 \pm 0.68 \pm 0.98 \pm 0.21$
P_y (*lab*)	$-0.41 \pm 0.61 \pm 0.16 \pm 0.07$
P_z (*lab*)	$-24.7 \pm 0.6 \pm 0.3 \pm 1.1$
P_x ($\tilde{B}$)	$21.65 \pm 0.68 \pm 0.36 \pm 0.15$
P_y ($\tilde{B}$)	$1.08 \pm 0.61 \pm 0.09 \pm 0.08$
P_z ($\tilde{B}$)	$-66.5 \pm 0.6 \pm 1.1 \pm 0.1$

Model dependency contributes to the **largest syst.** uncertainty (second term)