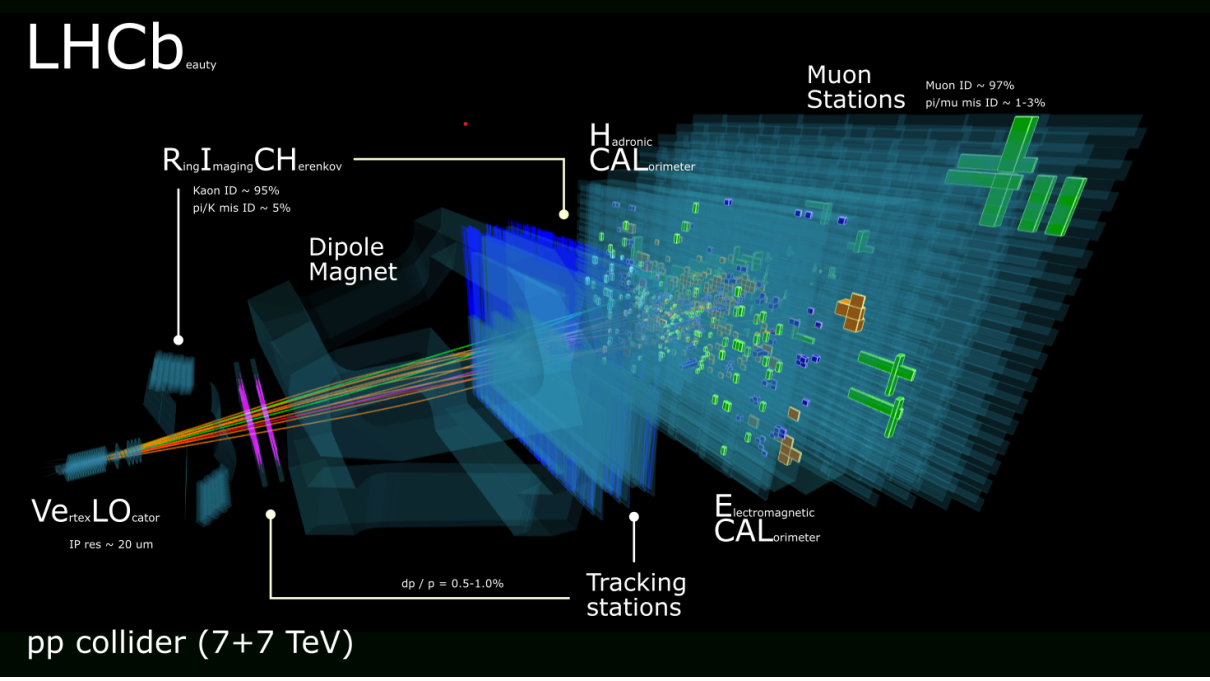
Spectroscopy and Amplitude Analysis at LHCb

Mikhail Mikhasenko

on behalf of LHCb Collaboration

PWA/ATHOS 2019, Rio (Brazio)

September 2nd, 2019

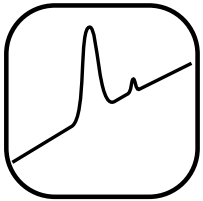

LHCb
eauty
Muon
Stations
Muon ID ~ 97%
pi/mu mis ID ~ 1-3%
Hadronic
CALorimeter
RingImagingCHerenkov
Kaon ID ~ 95%
pi/K mis ID ~ 5%
Dipole
Magnet
VertexLOcator
IP res ~ 20 um
dp / p = 0.5-1.0%
Tracking
stations
Electromagnetic
CALorimeter
pp collider (7+7 TeV)

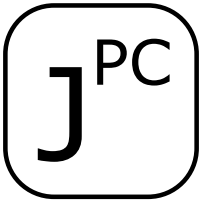
Spectroscopy and amplitude analysis

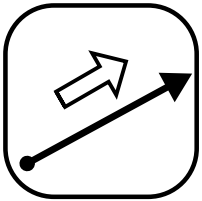
Main motivation

Establishing pattern of QCD
Search of exotic states

Polarization
measurements







Studies of the CP violation in components

Determination of quantum numbers in decays

Tools of LHCb experiment

Techniques at every analysis

- Reaction specific kinematic fit (displaced vertices, invariant masses)
- BDTG by `ROOT-TMVA` trained from MC(signal) + side bands(bgd)

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- Reaction specific kinematic fit (displaced vertices, invariant masses)
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- Spectrum description:
  - Gauss$\oplus$Crystal Ball, ARGUS$\otimes$Gauss, exponent for bgd,
  - Feed-down – MC of missing particles.
  - single pole BW, relativistic BW, dedicated $(\pi\pi/KK)_S$, $(\pi K)_S$, $(\pi D)_S$.

Tools of LHCb experiment

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- **Amplitude analysis**
  - Concept for the multibody decay – sum of truncated PW series:

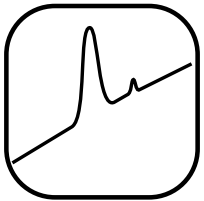
$$0 \to 1\,2\,3: \qquad M = M^{0\to 1(23)} + M^{0\to 2(31)} + M^{0\to 3(12)},$$

  - Formalisms: Helicity by Jacob-Wick, 3-tensors Zemach, covariant.

$$d_{\nu\lambda} \qquad T_{ij\ldots}(\vec{p},\vec{q}) \qquad O_{\mu\nu\ldots}(P,Q)$$

  - Common frameworks: `Laura++`, `GooFit`, `TensorFlowAnalysis`, ...

[arXiv:1711.09854], GooFit-GitHub, TFA-GitLab, ...



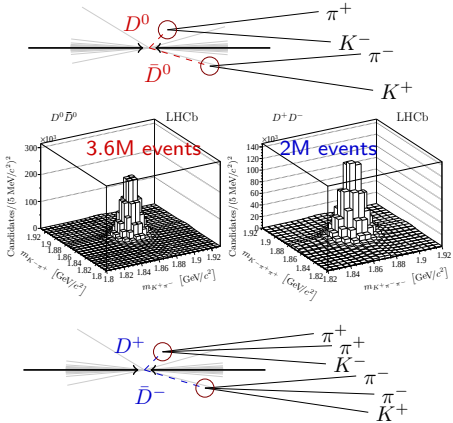
New narrow charmonium state $X(3842)$

[JHEP 07 (2019) 035]

- kinematic fit, BDT, spectrum fit, feed-down

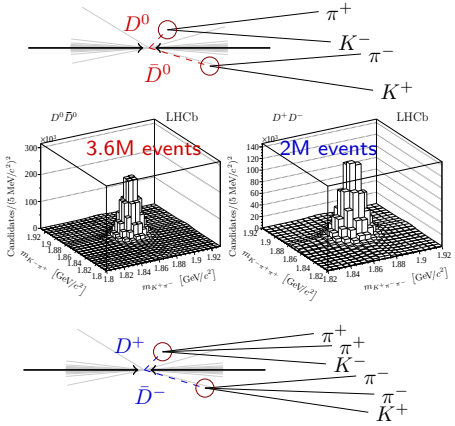
Near threshold $D\bar{D}$ spectroscopy

[JHEP 07 (2019) 035]



- displaced vertices
- $80 - 90\,\%$ purity

Near threshold $D\bar{D}$ spectroscopy



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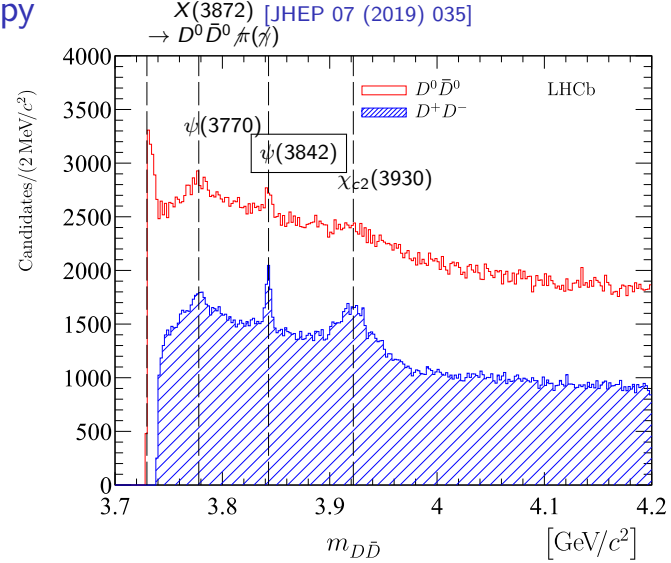

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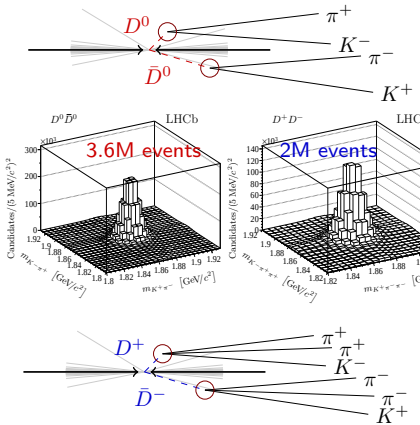

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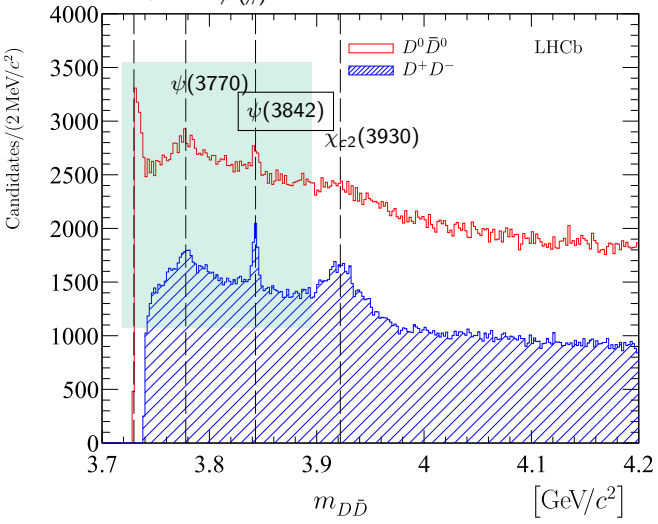
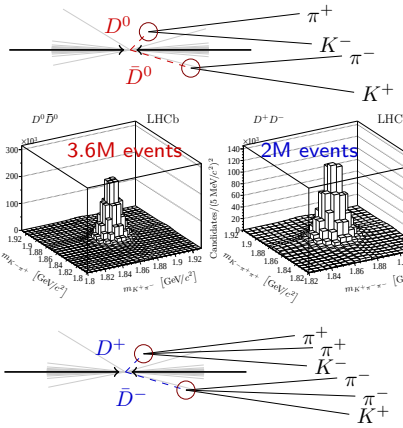
$X(3872)$ [JHEP 07 (2019) 035]
$\to D^0\bar{D}^0\pi(\gamma)$



New state is consistent with 1^3D_3 ($\psi_3(1D)$), $J^{PC}=3^{--}$.

Near threshold $D\bar{D}$ spectroscopy

[JHEP 07 (2019) 035]



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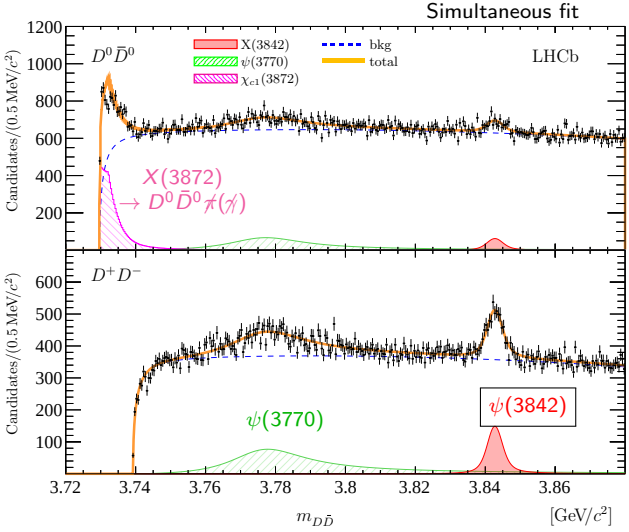
Simultaneous fit



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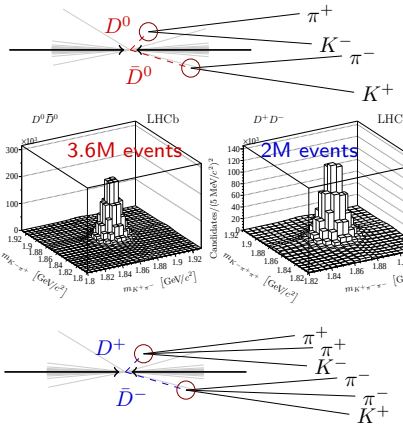

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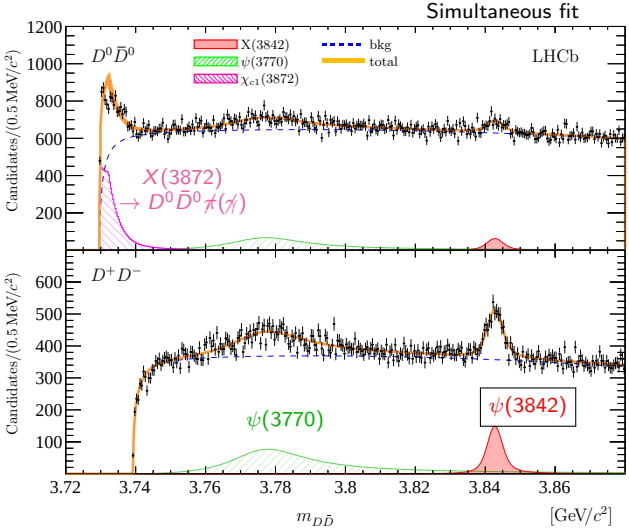

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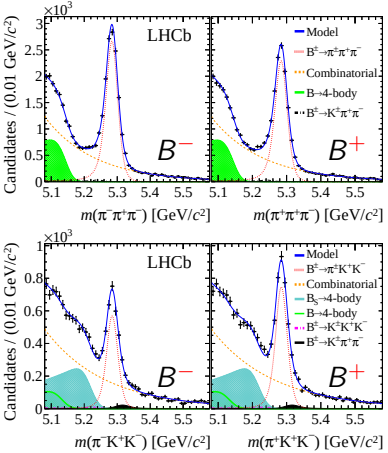
Origin of CP violation in $B^{\pm} \to h^{\pm}h^{+}h^{-}$

- kinematic constants, BDT, spectrum fit

Direct CP violation in B decays

[PRD 90, 112004 (2014)]



(see a talk of Patricia Magalhães on Thursday for detains on $B \to 3\pi$, $D \to 3\pi$).

Appearance of CPV effects:

$$B \to f: \quad A = \sum_i |A_i| e^{i(\delta_i+\phi_i)}$$

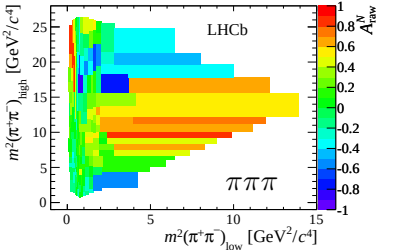
$$\overline{B} \to \overline{f}: \quad \overline{A} = \sum_i |A_i| e^{i(\delta_i-\phi_i)},$$

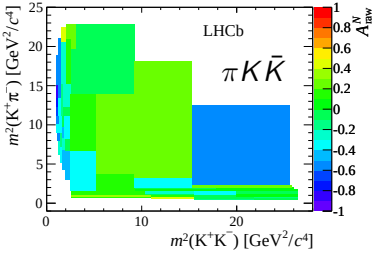
- Strong phase (δ) does not change under CP,
- Weak phase (ϕ) flip the sign.

$$\mathcal{A}_{CP} = \frac{|A|^2 - |\overline{A}|^2}{|A|^2 + |\overline{A}|^2}$$

$$\to \sum_i |A_i||A_j| \sin(\delta_i-\delta_j) \sin(\phi_i-\phi_j$$

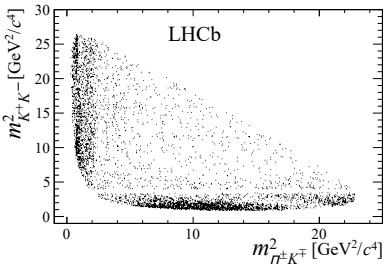
!! hadronization !! $\longrightarrow$





Amplitude Analysis of $B^{\pm} \to \pi^{\pm} K^{+} K^{-}$

[arXiv:1905.09244 (sent to PRL)]



Fit-model components:

- $K^*(892)$, $K^*(1430)$, $f_2(1270)$, $\rho(1450)$,
- phenom. $(K\overline{K})_S$ and $(K\pi)_S$
  - $(K\pi)_S$: a left-hand pole $(1\,\text{GeV}^2 + m^2_{K\pi})^{-1}$
  - $(K\overline{K})_S$: LH pole $\times$ $f^{\text{(Pelaez et al.)}}_{\pi\pi\to K\bar{K}}$

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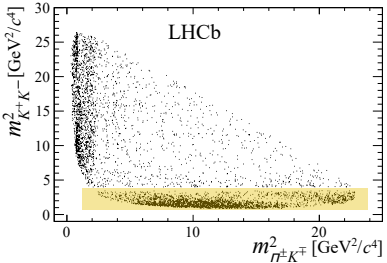

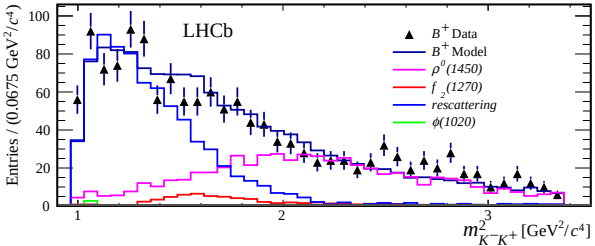

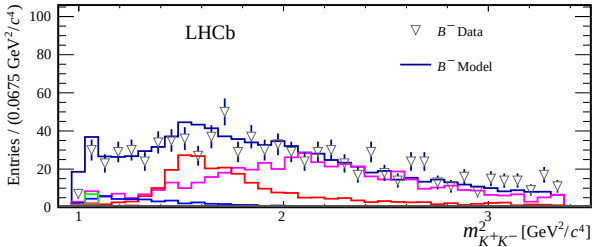

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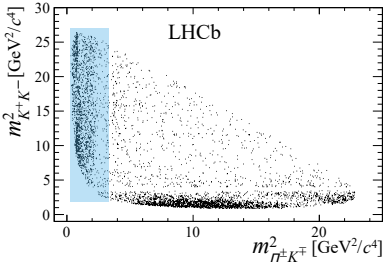

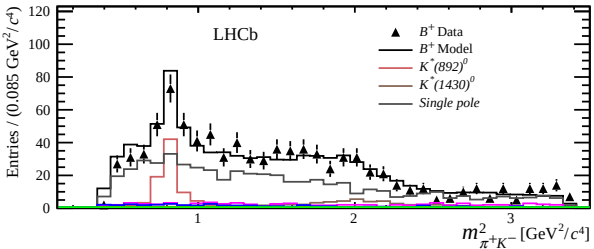

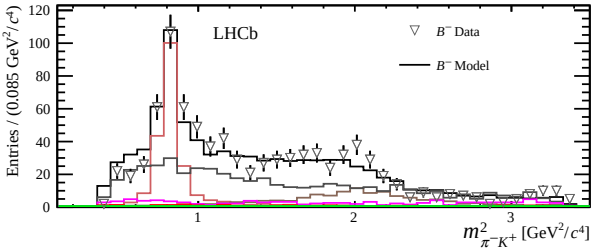

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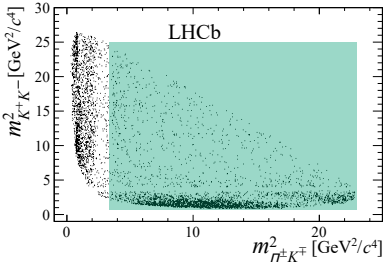

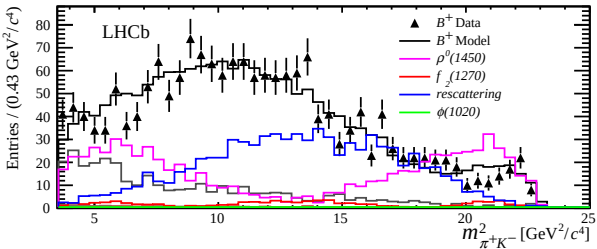

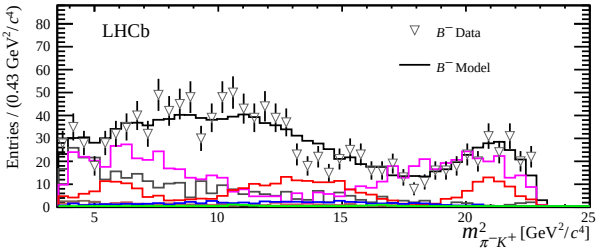

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Amplitude analysis of $B \to 3\pi$

[PAPER-2019-017 (LHCb), PAPER-2019-018 (LHCb)]

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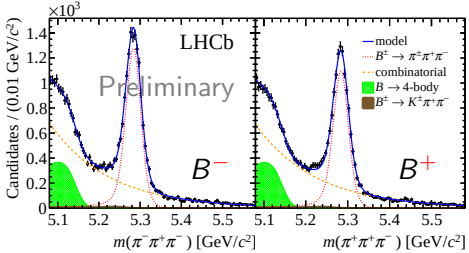

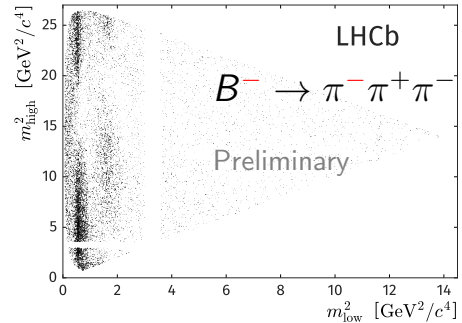

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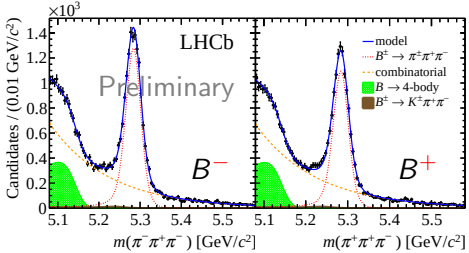

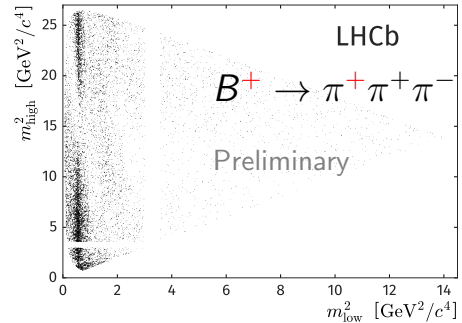

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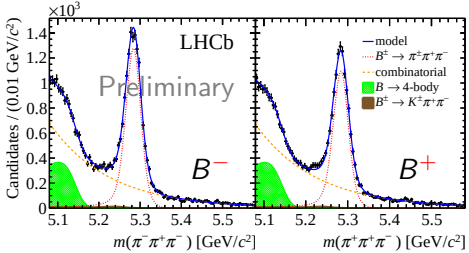

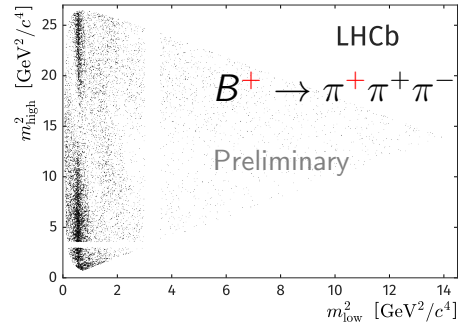

Amplitude analysis to investigate the origin:

- $\rho(770)$ with ω interference
- $f_2(1260)$ and $\rho_3(1690)$ by the RBW
- $(\pi\pi)_S$ coupled to $K\overline{K}$
  1. BW for σ + LH pole $\times$ $f^{\text{(Pelaez et al.)}}_{\pi\pi\to K\bar{K}}$
  2. P-vector with K-matrix by Anisovich-Sarantsev.
  3. binned freed lineshape (QMI)

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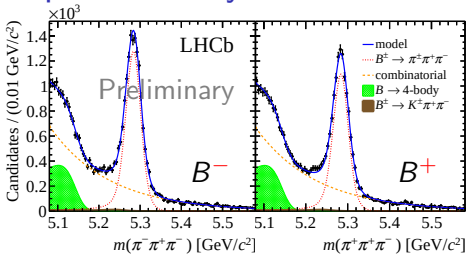

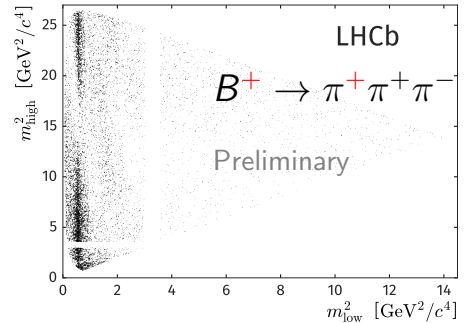

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Several sources of the CP violation are observed:

- $(\pi\pi)_S$-wave (in 2 slides)
- $\rho(770)/(\pi\pi)_S$ interference
- $f_2(1260)$

K–matrix parametrization

Anisovich-Sarantsev model fit to scattering data [EPJ A16 (2003]

- Scattering — five-channel K–matrix ($\pi\pi$, $K\bar{K}$, 4π, $\eta\eta$, $\eta\eta'$)
- P–vector for the production amplitude $F = P(1 - i\rho K)^{-1}$

$$K_{ij}(s) = \left(\sum_R \frac{g_j^{(R)} g_j^{(R)}}{m_R^2 - s} + \frac{b_{ij}^{\text{scatt}}}{s + s_0} \right) f_{A0}(s) \qquad P_i(s) = \sum_R \frac{\beta^{(R)} g_i^{(R)}}{m_R^2 - s} + \frac{b_i^{\text{prod}}}{s + s_0}$$

- g_i^R, b_{ij}^{scatt} are constants fixed in the original work,
- b_i^{prod}, $\beta^{(R)}$ are reaction-specific fit parameters;
- $f_{A0}(s)$ — Adler-zero term (rational).

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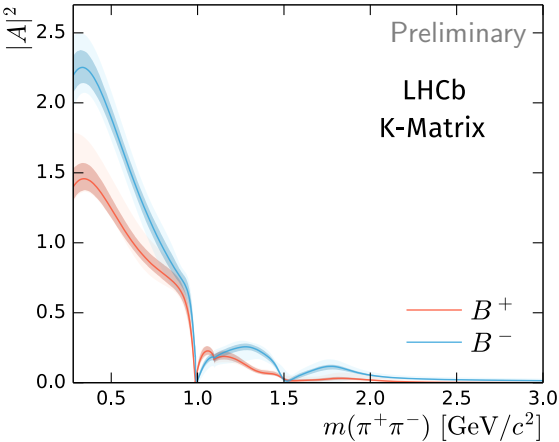
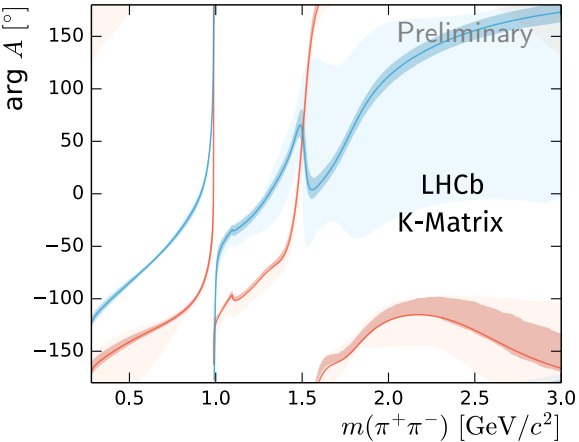
Side comment — alternative parametrizations:

- Garcia-Martin et al. [PRD 83 (2011)]: $\pi\pi/K\bar{K}$ up to 1.4 GeV with the analyticity constant.
- Ropertz et al. [EPJ C78 (2018)]: K–matrix extension of (above) up to 2.5 GeV (with three channels $\pi\pi/K\bar{K}/4\pi$) fit to LHCb data on $B_s \to J/\psi\pi\pi$ decay.

Extracted $(\pi\pi)_S$ production amplitude

[PAPER-2019-017 (LHCb)]





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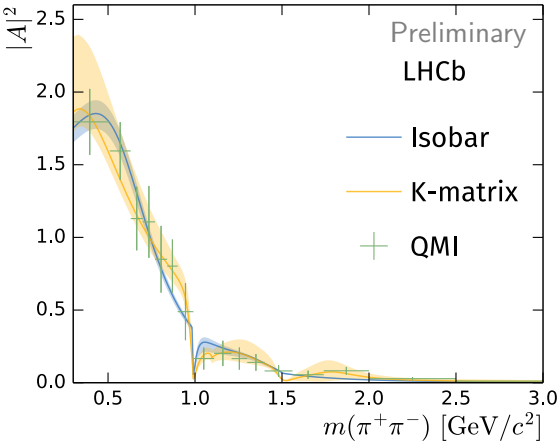
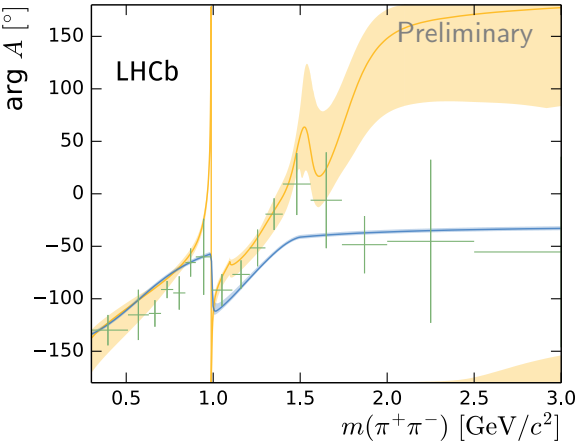
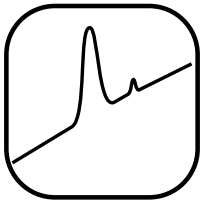




- Clear difference in $(\pi\pi)_S$ amplitude in B^+ and in B^-
- Different parametrizations are broadly consistent to each other



Observation of new Λ_b states

[arXiv:1907.13598]

- kinematic fits, BDT, spectrum fit, amplitude analysis

Λ_b combined with $\pi^+\pi^-$

Excitation at the primary vertex vertex

- 900k Λ_b candidates in $\Lambda_c(\to pK\pi)\,\pi$
- Alternative decay channel $\Lambda_b \to J/\psi Kp$

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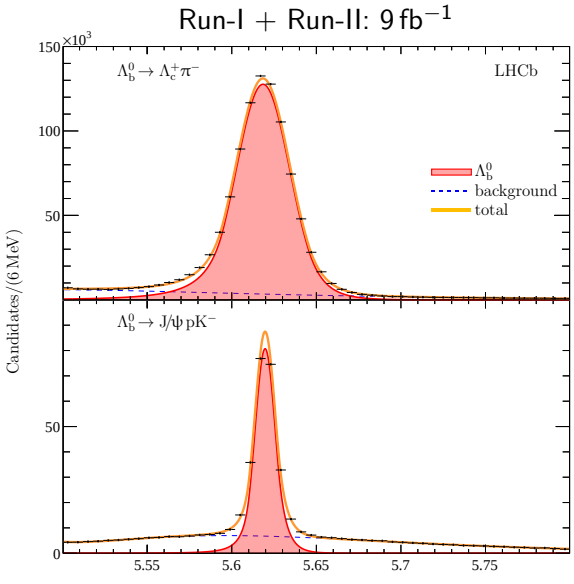

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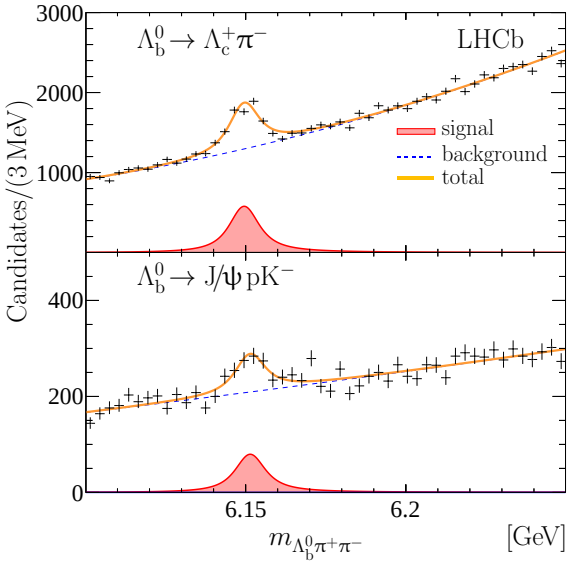

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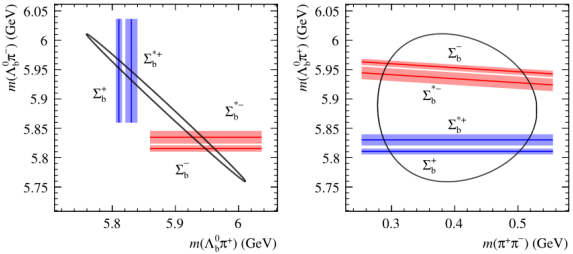
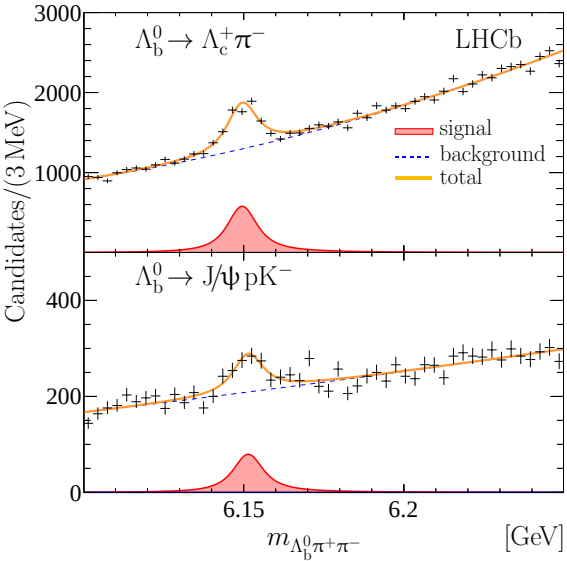
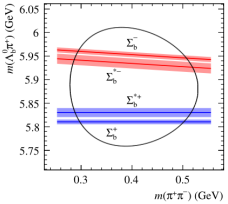
- Σ_b substructures on Dalitz Plot





Separation by the final state

- Three fit regions:
  - Σ_b region
  - Σ_b^* region
  - rest (NR region)



- A simultaneous fit:
  - Two-signal hypothesis with 7σ
  - Almost degenerate narrow states

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\begin{aligned}
m_{\Lambda_b(6146)^0} &= 6146.17 \pm 0.33 \pm 0.22 \pm 0.16\,\text{MeV}\,, \\
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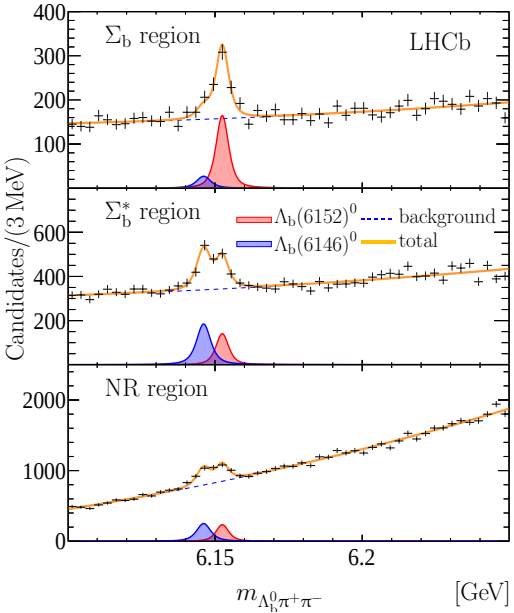

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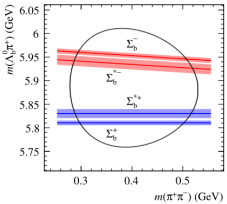

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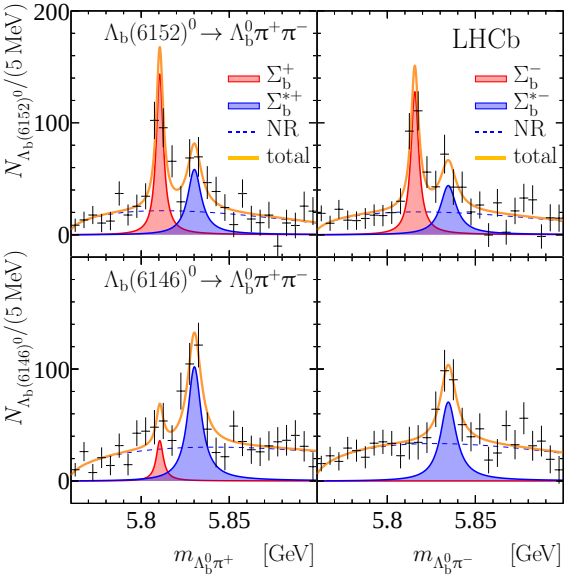

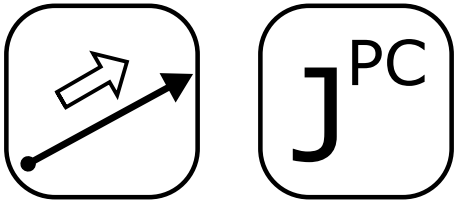

Quantum numbers and polarization

- investigation of the angular analysis formalism (LHCb+JPAC)
  [EPJ C78 (2018) 727 (JPAC), EPJ C78 (2018) 229 (JPAC), MM et al. (JPAC, in preparation)]

Conventional helicity approach

Complicated cases: particles with spin in isobar model [Herndon(1975)], [Hansen (1974)]

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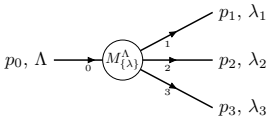
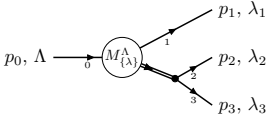
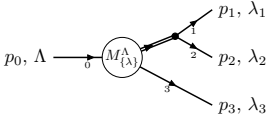
$$\underbrace{M^{\Lambda}_{\{\lambda\}}}$$

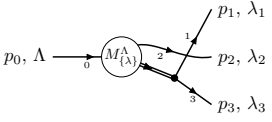


$$= \underbrace{H_1 D(\phi_1, \theta_1, 0)\, D(\phi_1', \theta_1', 0) W_1(\dots)} + \underbrace{H_3 D(\phi_3, \theta_3, 0)\, D(\phi_3', \theta_3', 0) W_3(\dots}$$





$$+ \underbrace{H_2 D(\phi_2, \theta_2, 0)\, D(\phi_2', \theta_2', 0) W_2(\dots)}$$



- A special set of angles for every decay chain

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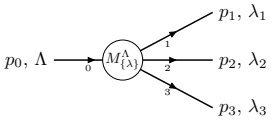

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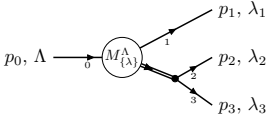

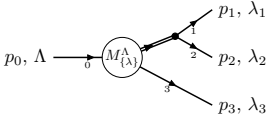

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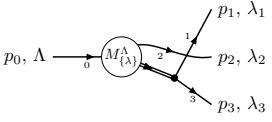
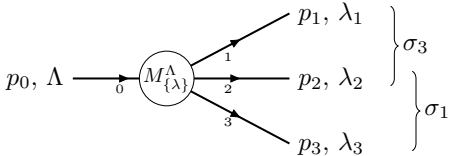


- A special set of angles for every decay chain
- Consistently of quantization direction – **Wigner rotations** $W_i(\dots) = D^{j_1}(\tilde{\phi}_1^i, \tilde{\theta}_1^i, 0)\, D^{j_2}(\tilde{\phi}_2^i, \tilde{\theta}_2^i, 0)\, D^{j_3}(\tilde{\phi}_3^i, \tilde{\theta}_3^i, 0)$

The Dalitz-Plot decomposition

[MM (JPAC) in preparation]

Reformulation of the helicity approach



$$= \sum_{\nu} \underbrace{D^{J*}_{\Lambda\nu}(\phi_1, \theta_1, \phi_1')}_{\text{Decay-plane orientation}} \times \underbrace{O^{\nu}_{\{\lambda\}}(\sigma_3^2, \sigma_1^2)}_{\text{Dalitz-plot function}}$$

Model-independent factorization of the overall rotation:

- Exploits properties of the Lorentz group (orientation – just three Euler angles)
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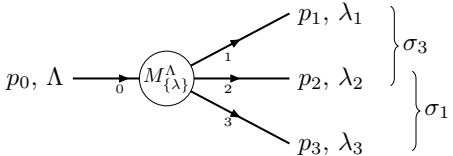

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Gives significant benefits to

- Pentaquark analysis, Λ_b/Λ_c polarionation measurements, Baryonic decay chains,...

$\Lambda_c \to pK\pi$ polarization studies

[JPAC+LHCb in preparation]

- proposal for the electromagnetic dipole moments of charged baryons
  [EPJC 77 (2017) 181, arXiv:1708.08483]
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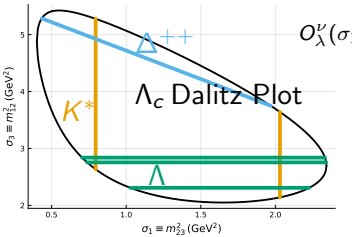

$$O^{\nu}_{\lambda}(\sigma_1,\sigma_3) = \sum_{s}^{K^*\to K\pi} \sum_{\tau} H^{0\to(23),1}_{\tau,\lambda}\, d^{1/2}_{\nu,\tau-\lambda}(0)\, X_s(\sigma_1)\, H^{(23)\to 2,3}_{0,0}\, d^{s}_{\tau,0}(\theta_{23})$$
$$+ \sum_{s}^{\Delta\to\pi p} \sum_{\tau,\lambda'} H^{0\to(31),2}_{\tau,0}\, d^{1/2}_{\nu,\tau}(\hat{\theta}_{2(1)})\, X_s(\sigma_2)\, H^{(31)\to 3,1}_{0,\lambda'}\, d^{s}_{\tau,-\lambda'}(\theta_{31})\, d^{1/2}_{\lambda',\lambda}(\tilde{\theta}^{1}_{2(1)})$$
$$+ \sum_{s}^{\Lambda\to pK} \sum_{\tau,\lambda'} H^{0\to(12),3}_{\tau,0}\, d^{1/2}_{\nu,\tau}(\hat{\theta}_{3(1)})\, X_s(\sigma_3)\, H^{(12)\to 1,2}_{\lambda',0}\, d^{s}_{\tau,\lambda'}(\theta_{12})\, d^{1/2}_{\lambda',\lambda}(\tilde{\theta}^{1}_{3(1)}).$$

Couplings (H) and lineshapes (X) are only model-dependent inputs

Summary

- LHCb collected $9\,\text{fb}^{-1}$ (Run-I + Run-II)
- It has already impacted spectroscopy and a lot to be discovered (Run-II)

Well-established tool chain:

- PID, momentum scaling, kinematic fitters are built in standardized programs,
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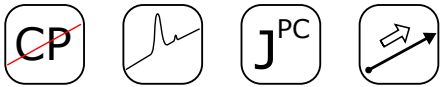
$\Rightarrow$ Great results with intense rate 

Thank you for the attention