Amplitude analysis and its usage in flavor physics

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第四届重味物理与量子色动力学研讨会

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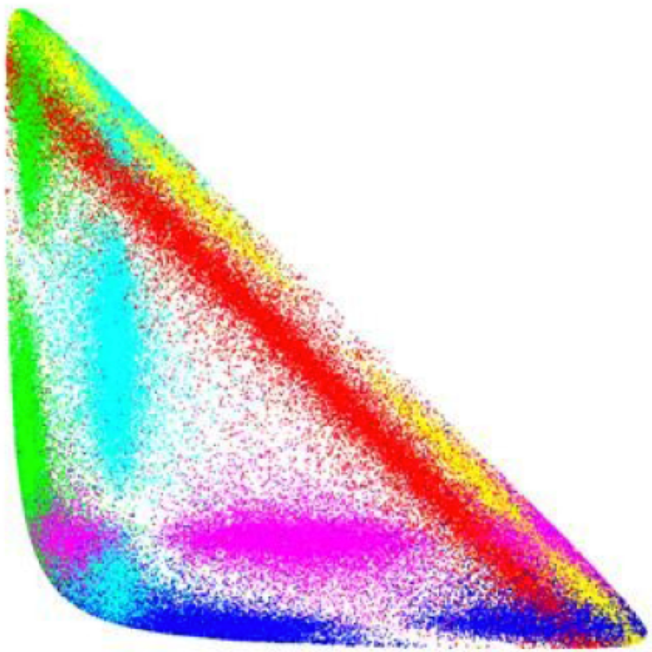
Outline

- **Introduction**
- **A general amplitude analysis tool: TF-PWA**
- **First observation of a double charged tetraquark state and its neutral partner**
- **First observation of a resonant structure near $D_s^+ D_s^-$ threshold**
- **CP violation studies in $B^+ \to \pi^+\pi^+\pi^-$**
- **Conclusion**

Introduction

- **Amplitude analysis widely used in flavor physics**
- **Simplest case: Dalitz plot, a spin 0 particle decays to three spin 0 particles**



$D \to K_S \pi^+ \pi^-$ as an example:

green & blue: $K^*(892)$ vector

cyan & magenta: $K_2^*(1430)$ tensor

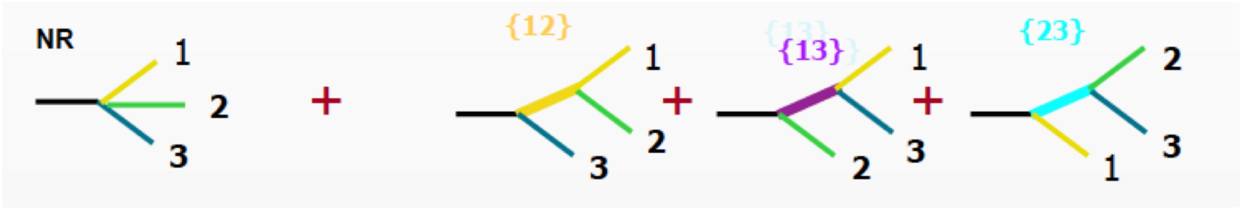
yellow: $\rho(770)$ vector

red: $f_0(980)$ scalar

- **Resonances with different spins behave differently**
- **Separate them and extract information according to interference between them**

Extract resonant information

- Discovery exotic states and measure their properties
- Understanding CP violation effects on the phase space
- Usually Isobar model:



$$A(s_{12}, s_{23}) = \sum_j A_j = \sum_j a_j F_j(s_{12}, s_{23}), \qquad \bar{A}(s_{12}, s_{23}) = \sum_j \overline{A}_j = \sum_j \bar{a}_j \overline{F}_j(s12, s23)$$

- Amplitude analyses very complicated: main limitations to start an analysis
- Enormous data from BESIII, LHCb and other flavor physics experiments: massive CPU time needed to perform analyses
- A general PWA framework using modern acceleration technology (such as GPU, AD,…) eagerly needed
- We have developed a new framework using TensorFlow

TensorFlow

A general and user-friendly partial wave analysis framework

Hao Cai[1], Chen Chen[5], Yi Jiang[2], Pei-Rong Li[3], Yin-Rui Liu[2], Xiao-Rui Lyu[2], Rong-Gang Ping[4], Wenbin Qian[2], Mengzhen Wang[5], Zi-Yi Wang[2], Liming Zhang[5],Yang-Heng Zheng[2]

[1]WHU, [2]UCAS, [3]LZU, [4]IHEP, [5]THU

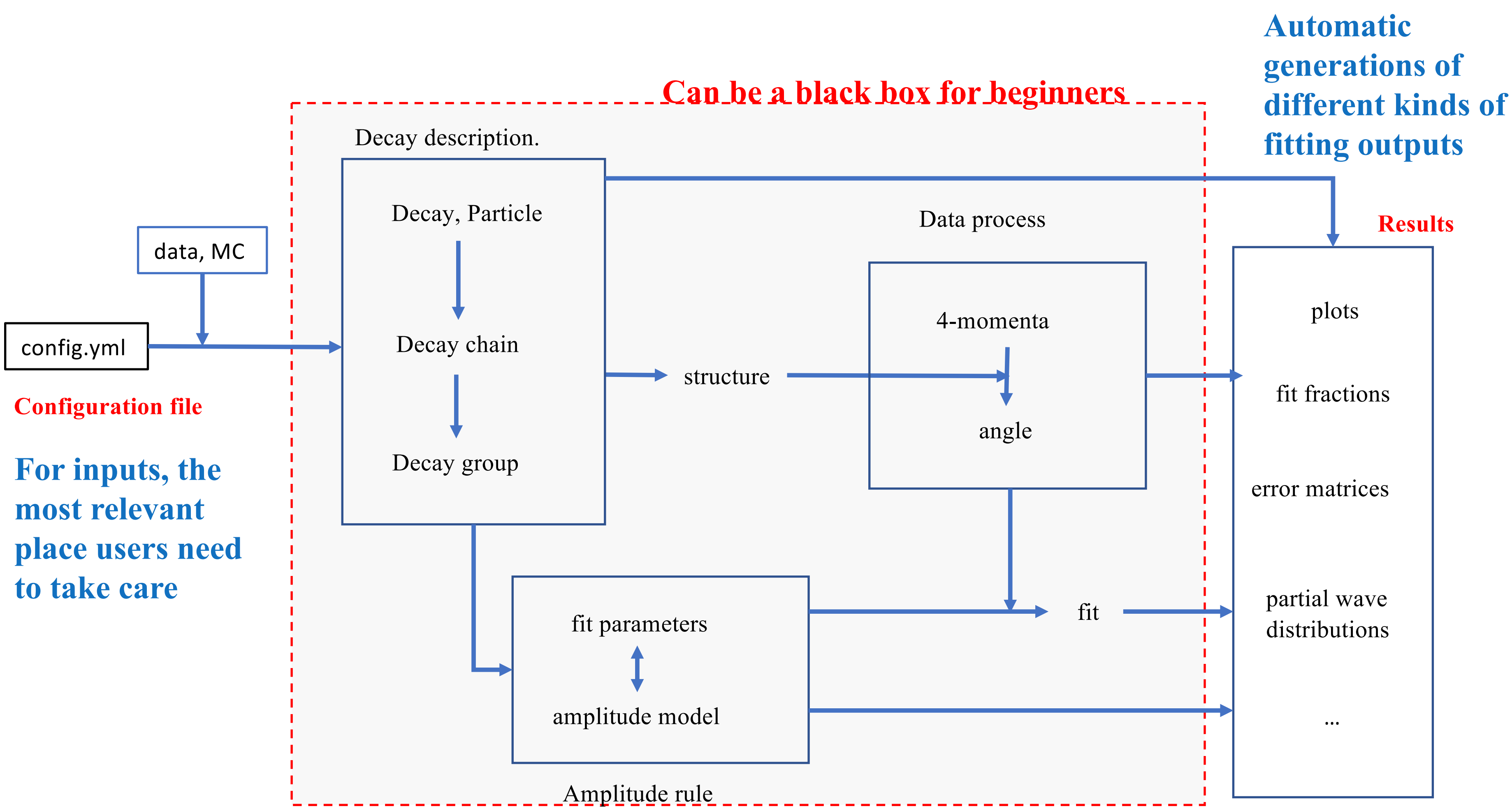
- **Joint efforts + experience on previous analyses + very good students**
- **Cross-checks performed with several independent fitters developed previously for dedicated analyses: e.g. Z(4430)$^+$ and pentaquark search, $B^0 \to \overline{D^0}\pi^+\pi^-$ analysis etc.**

Features

- Based on Tensor-Flow v2
- Fast
  - GPU based
  - Vectorized calculation
  - Automatic differentiation
- General
  - Custom model available
- Easy to use
  - Simple configuration file
  - Automatics process
  - All necessary functions implemented
- Open access and well supported

https://gitlab.com/jiangyi15/tf-pwa

Framework



Can be a black box for beginners
Automatic generations of different kinds of fitting outputs
data, MC
config.yml
Configuration file
For inputs, the most relevant place users need to take care
Decay description.
Decay, Particle
Decay chain
Decay group
structure
Data process
4-momenta
angle
fit parameters
amplitude model
Amplitude rule
fit
Results
plots
fit fractions
error matrices
partial wave distributions
...

Benchmarks

CPU: i7-9750H@2.6 Hz with 12 cores
GPU: Nvidia 1660 Ti, a cheap GPU

Test based on simple MC (200000) sample of a simple amplitude model of $e^+e^- \to R_1(1^+)\pi, R_1 \to D^*D^*$

Both based on TF-PWA

process	CPU (ms)	GPU (ms)	Ratio
$N = \int \lvert A\rvert^2 d\Phi$	573	53	~11 X 12 = 132
N with $\frac{\partial N}{\partial \vartheta}$	1122	117	~9.5 X 12 = 114

Almost a factor of 100 times faster for GPU than single CPU core.

Automatic differentiation cost the same time as normal evaluation, faster with increase of parameters

Functions implemented

- Toy studies
- Plotting
- Fit fractions, interference fractions
- Simultaneous fit between different datasets
- Parity conversation
- Gaussian constraints on parameters
- 2D chi2 test
- CP violation fit
- Final states with identical particles
- Amplitude factorization
- Resolution
- Simple symbolic formula
- Model independent fit
- Error propagation
- …

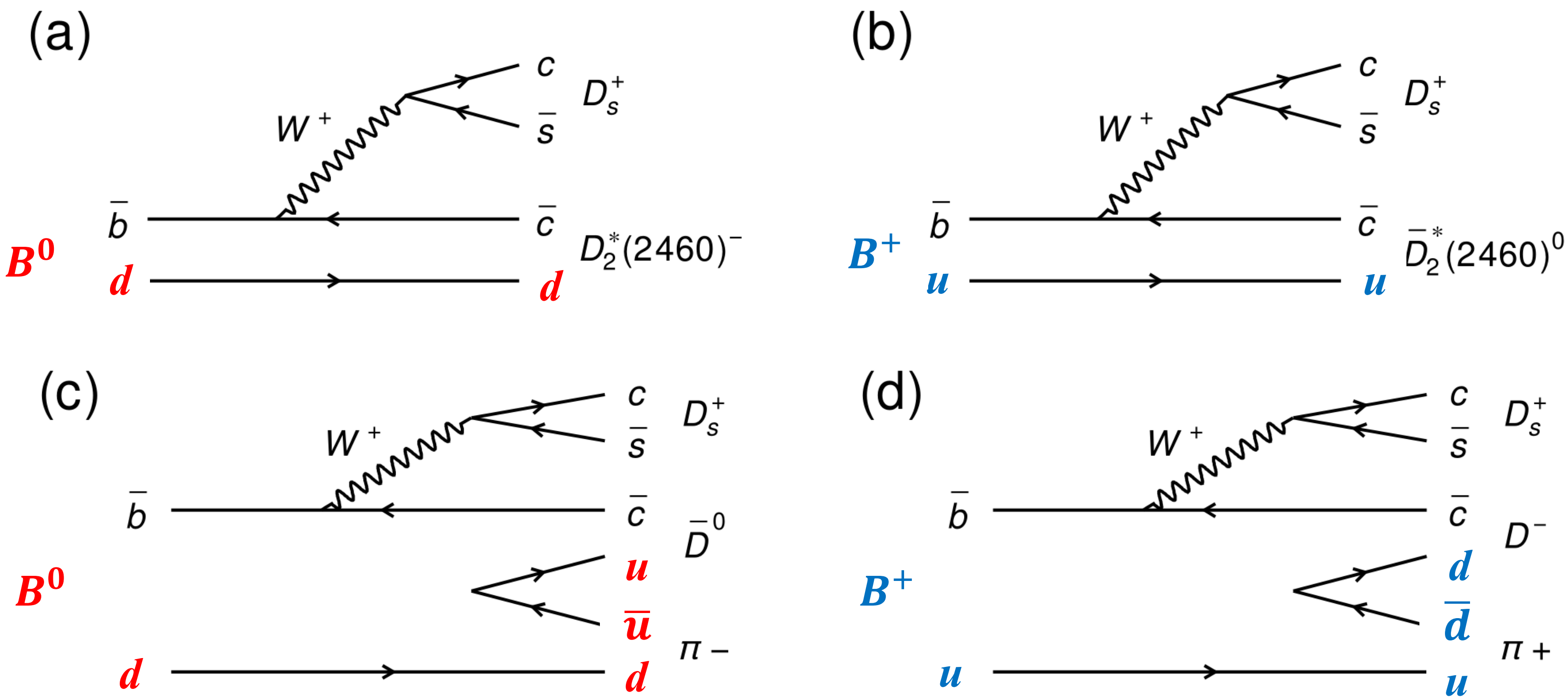
Used in many LHCb/BESIII analyses, including those discussed below

Observation of a double-charged tetra-quark states and its isospin partner

LHCb-PAPER-2022-026
LHCb-PAPER-2022-027

Feynman diagrams

- **Two decays considered:** $B^0 \to \overline{D^0} D_s^+ \pi^-$, $B^+ \to D^- D_s^+ \pi^+$

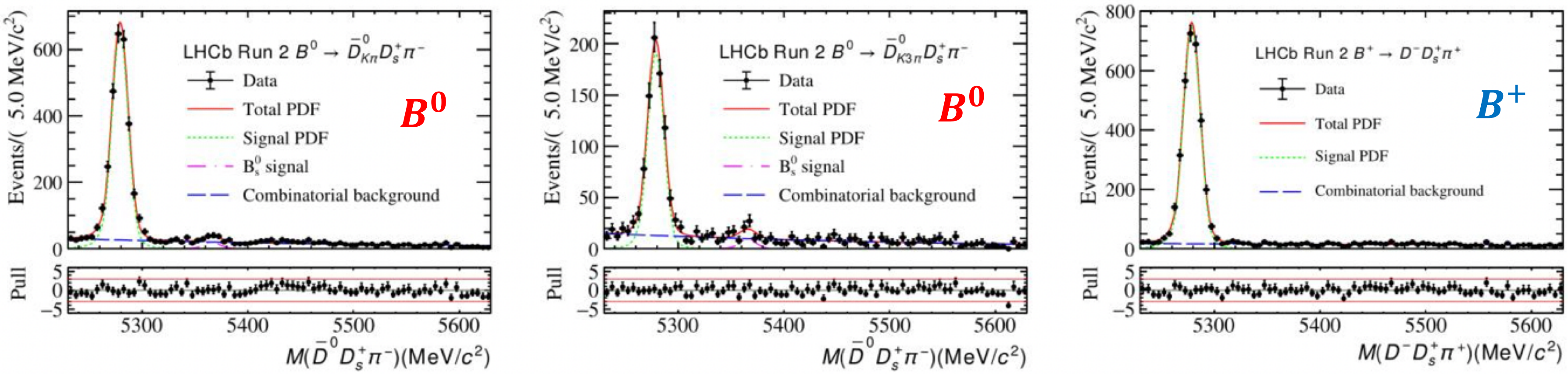


- **Connected by isospin relationship in all aspects**

Signal yields

- Two decays considered: $B^0 \to \overline{D^0} D_s^+ \pi^-$, $B^+ \to D^- D_s^+ \pi^+$

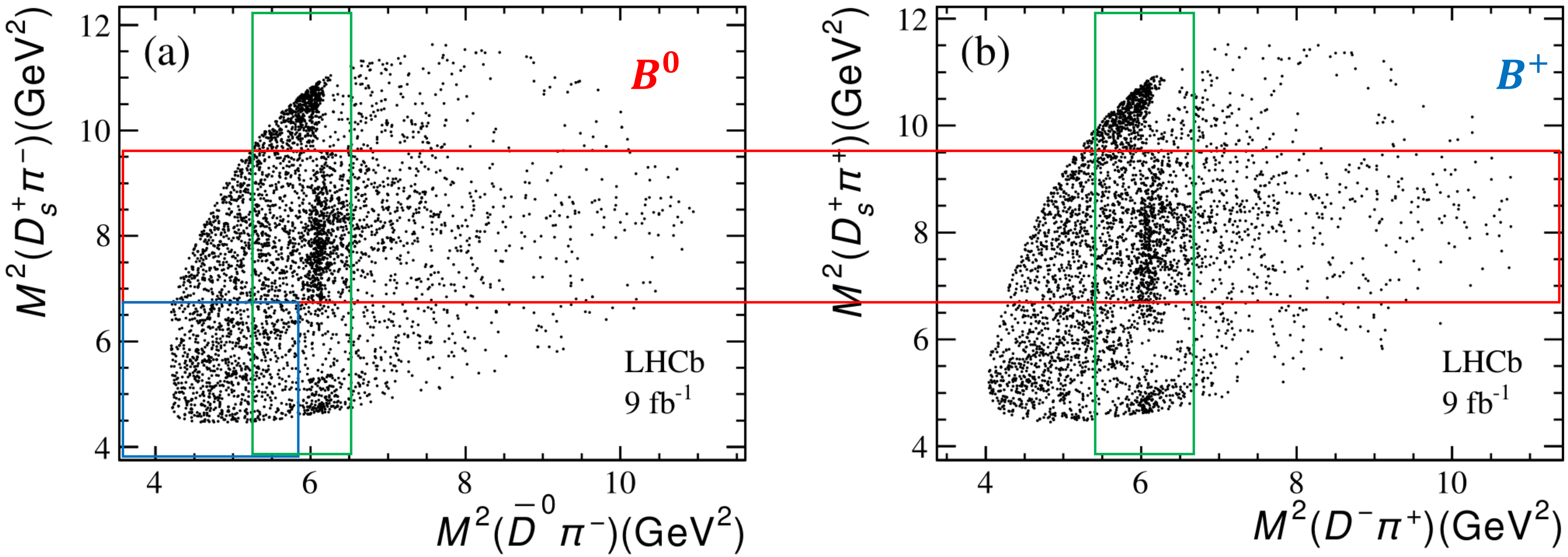
$D^0 \to K^- \pi^+$ $D^0 \to K^- \pi^+ \pi^+ \pi^-$ $D^- \to K^- \pi^+ \pi^+$



Preliminary

- Very pure samples, ideal for amplitude analysis
- ~4000 B^0 signals with a purity of ~90%;
- ~3750 B^+ signals with a purity of ~95%

First impression on Dalitz plot



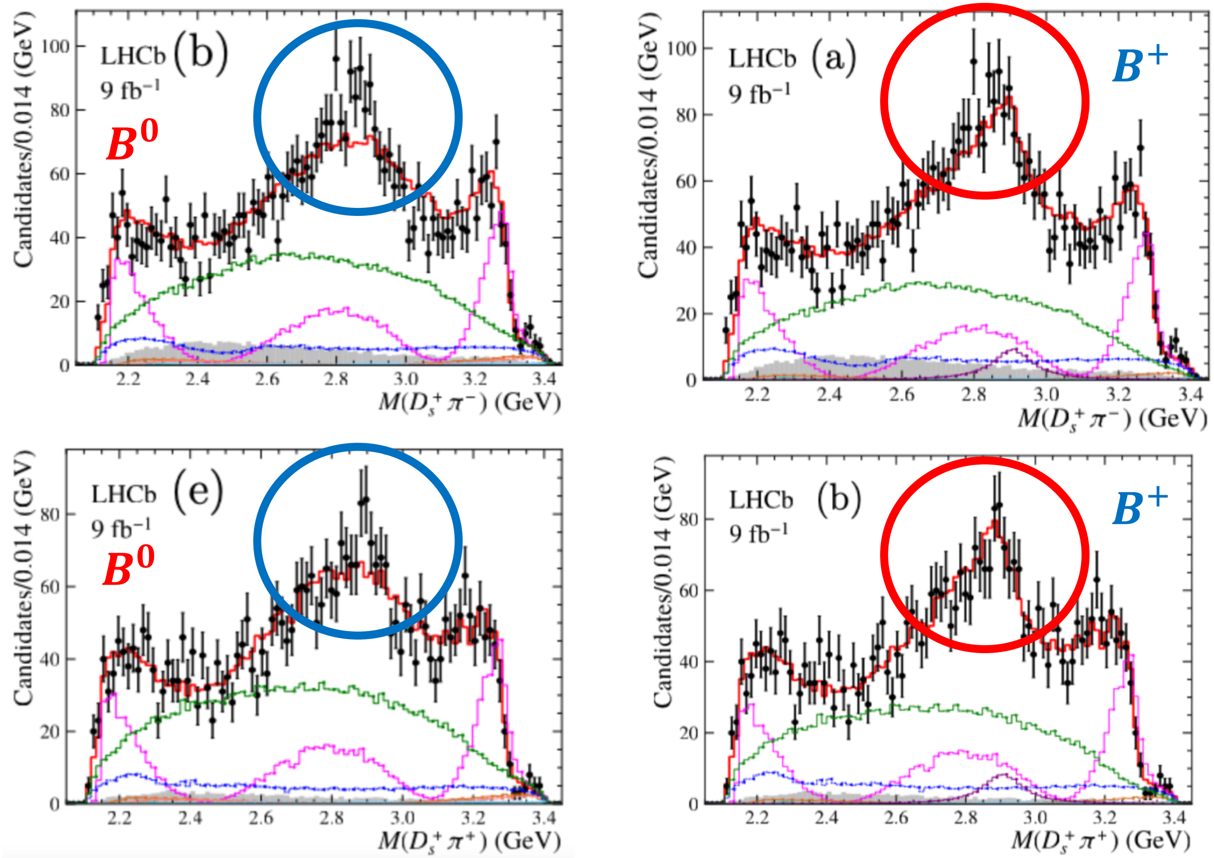
Preliminary

- **Very similar distributions over Dalitz plot**
- **Clear accumulation of events on both channels around 2.9 GeV of $m(D_s^+\pi^-)$ and $m(D_s^+\pi^+)$**
- **$D^{*-}(2010)$ cut-off in B^0 channel; small isospin breaking effects at threshold**
- **Very clear contributions from $D_2(2460)$**

Exotics

Preliminary

Without new states



With new states

- **Not very good description on $m(D_s\pi)$ around 2.9 GeV**
- **Further $m(D\pi)$ or $m(DD_s)$ contributions not help**
- **Add new states on $m(D_s\pi)$, $T^a_{c\bar{s}}(2900)^0$ and $T^a_{c\bar{s}}(2900)^{++}$ help a lot**

More on exotics

- **Isospin relationship imposed on $m(D\pi)$, apart from $D^*(2010)$ and $D^*(2007)$, confirmed by separate fits**
- **Two scenarios considered for $T^a_{c\bar{s}}(2900)^0$ and $T^a_{c\bar{s}}(2900)^{++}$: with and without isospin relationship**

Scenarios	Exotics	Mass (GeV)	Width (GeV)	Significance
No isospin relationship	$\mathrm{T^a_{c\bar{s}}}(2900)^0$	$2892 \pm 14 \pm 15$	$119 \pm 26 \pm 12$	8.0σ
	$\mathrm{T^a_{c\bar{s}}}(2900)^{++}$	$2921 \pm 17 \pm 19$	$137 \pm 32 \pm 14$	6.5σ
With isospin relationship	Both	$2908 \pm 11 \pm 20$	$136 \pm 23 \pm 11$	9.0σ

- **Significance estimated considering look-else-where effects**
- **Two states consist with each other: isospin triplet**
- **$J^P = 0^+$ preferred for both cases**

Discussion

- In $B^+ \to D^+ D^- K^+$ decays, two states observed with quark content $cs\bar{u}\bar{d}$
- $T^a_{cs}(2900)$ have quark content $c\bar{s}\bar{u}d$ and $c\bar{s}u\bar{d}$
- Very similar mass, $T^a_{cs}(2900)$ has larger width
- Only 0^+ $T^a_{cs}(2900)$ states found

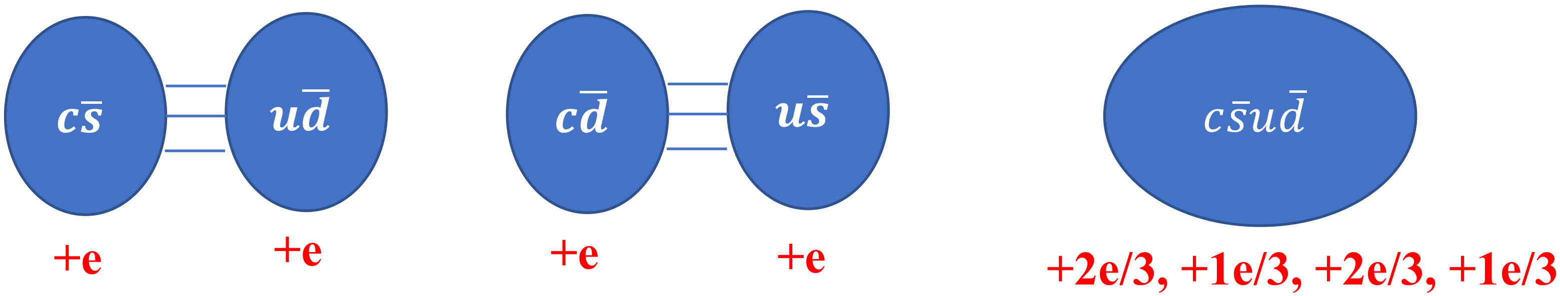
Preliminary

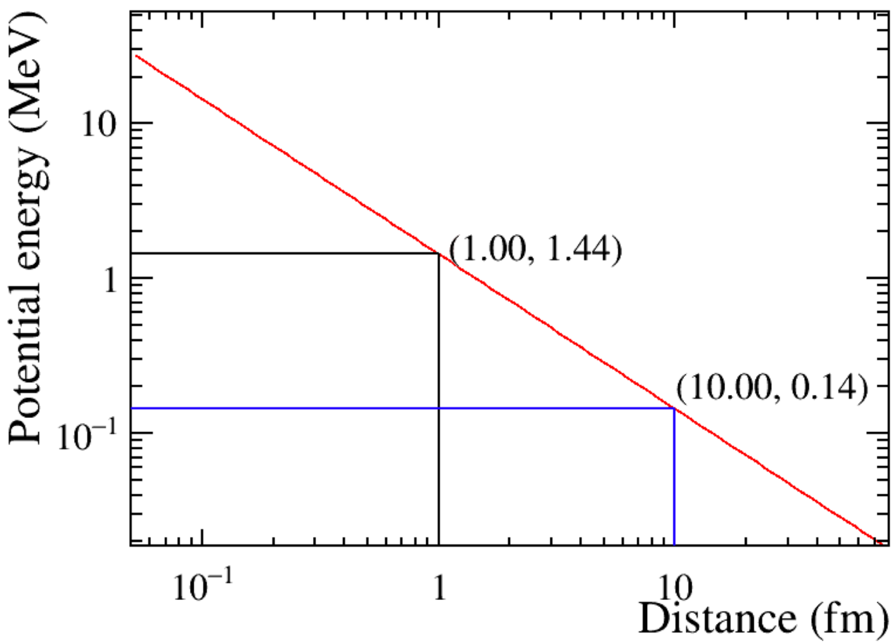
Exotic	Mass (MeV)	Width (MeV)	Spin-parity
$X_0(2900)$	$2866 \pm 7 \pm 2$	$57 \pm 12 \pm 4$	0^+
$X_1(2900)$	$2904 \pm 5 \pm 1$	$110 \pm 11 \pm 4$	1^-
$\mathrm{T}^{\mathrm{a}}_{\mathrm{c\bar{s}}}(2900)^0$	$2892 \pm 14 \pm 15$	$119 \pm 26 \pm 12$	0^+
$\mathrm{T}^{\mathrm{a}}_{\mathrm{c\bar{s}}}(2900)^{++}$	$2921 \pm 17 \pm 19$	$137 \pm 32 \pm 14$	0^+

- $X(5568)$ claimed by D0 collaboration in $B^0_s\pi^\pm$ final states, with quark flavor $b\bar{s}\bar{u}d$, however, negative results from other experiments
- Some suggestions for $T^a_{cs}(2900)$ (1705.10088, 2204.02649, 2008.07145, 2008.07340 et al.)

Charge

- **For double charged tetraquark candidates, if molecular, replusion potential around 1.44 MeV @ 1 fm!**

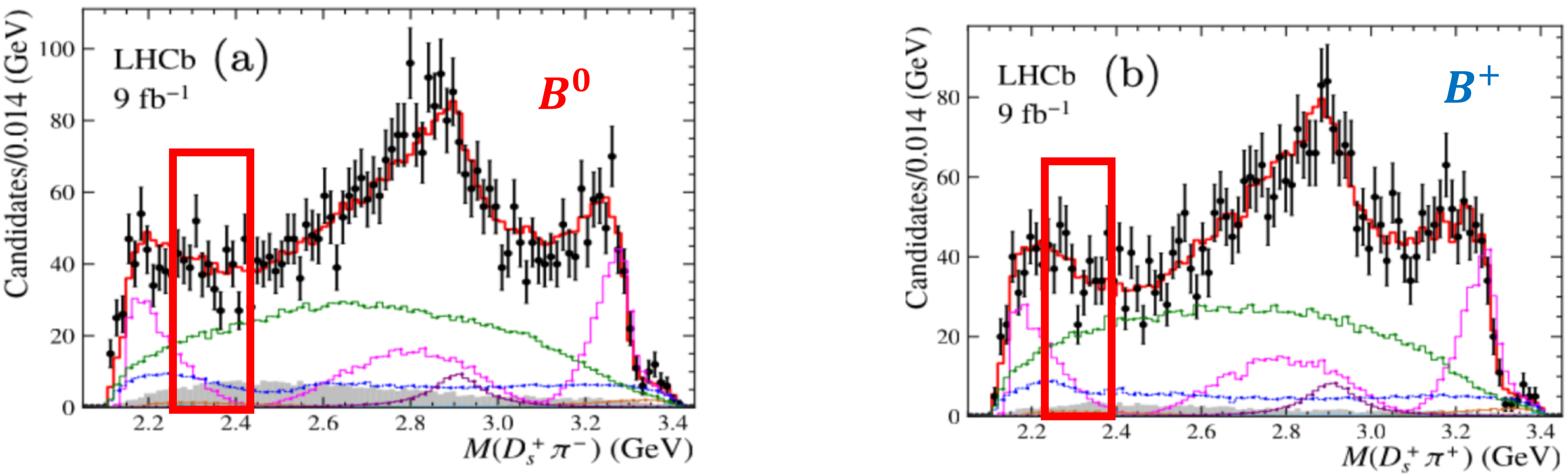




- **If compact states, all four quarks have positive charge**
- **Or may be just cusp**

Isospin

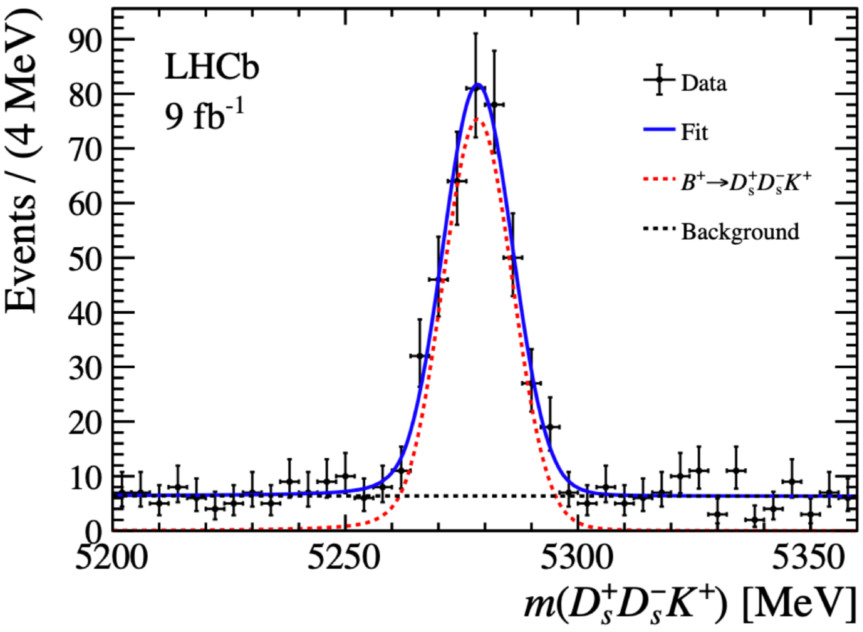
- $T^a_{c\bar{s}}(2900)^0$ and $T^a_{c\bar{s}}(2900)^{++}$ are two of the isospin triplet;
- Missing one ($D_s^+\pi^0$), hard for LHCb, though not entirely impossible;
- Some suggests $D_s^+(2317)$ (decaying into $D_s^+\pi^0$) to be a tetraquark state; though no clue from current charged pion modes (contamination from $D_2(2460)$)
- I = 0 considered to have strong attraction while I = 1 to have weak attraction or even repulsion;

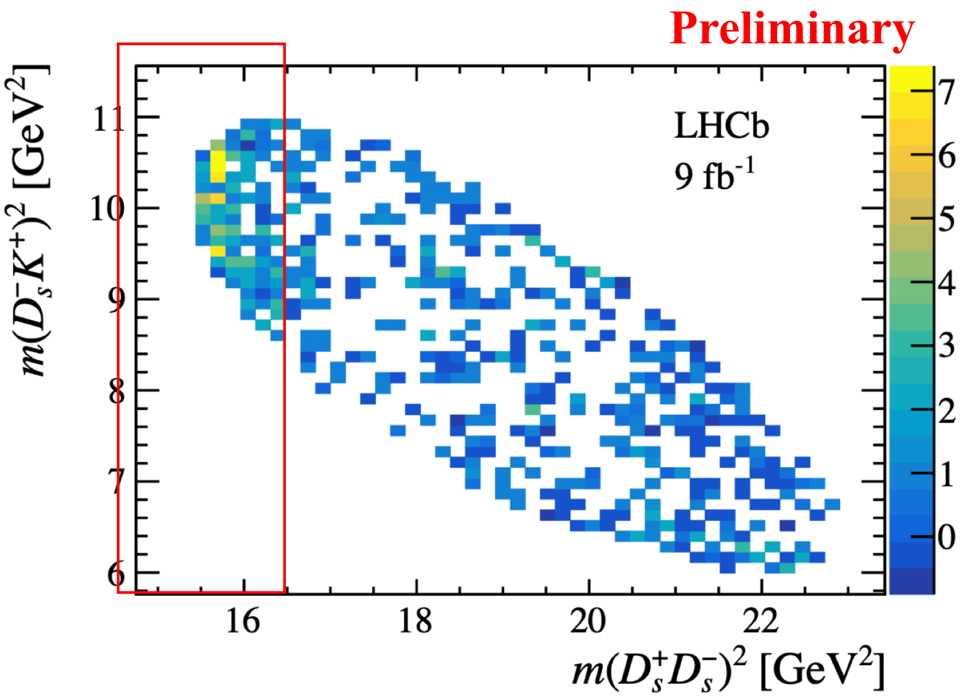


Observation of a resonant structure near the $D_s^+ D_s^-$ threshold

LHCb-PAPER-2022-018
LHCb-PAPER-2022-019

Yields and Dalitz plot distribution

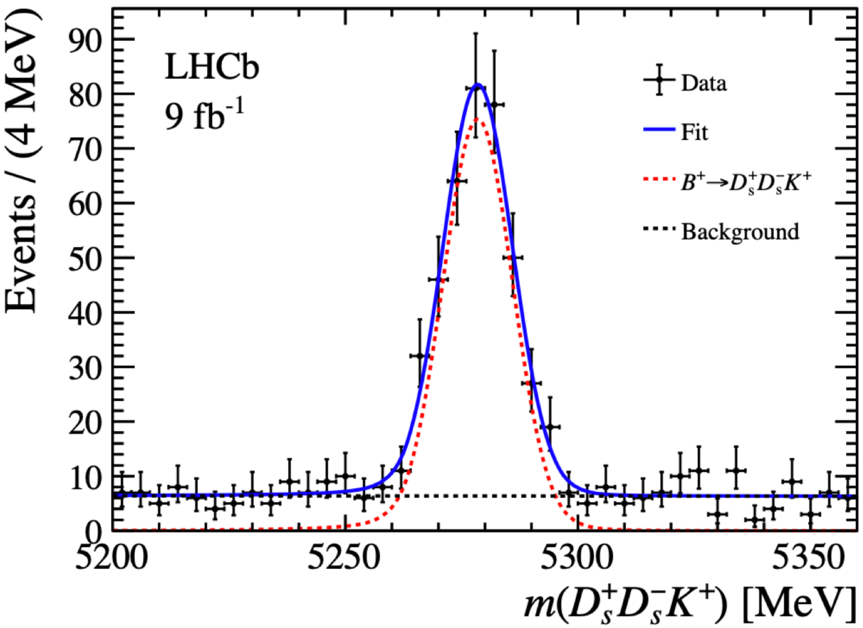


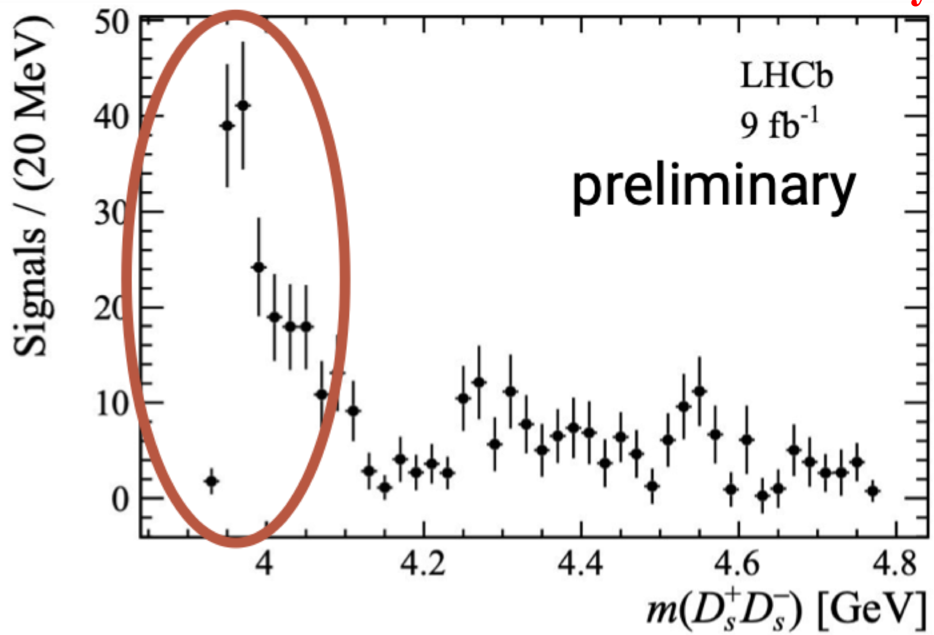


- $B^+ \to D_s^+ D_s^- K^+$: ~360 signal candidates with a purity of ~85%
- No clear structures over Dalitz plot except accumulations at the $m(D_s^+ D_s^-)$ threshold around 3.9 GeV

Yields and Dalitz plot distribution

Preliminary





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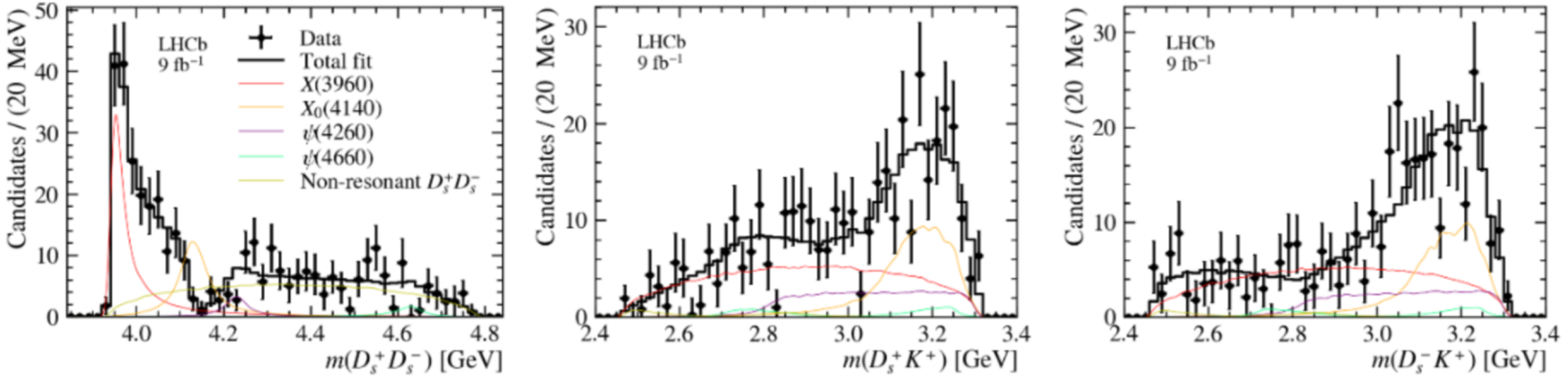
- No clear structures over Dalitz plot except accumulations at the $m(D_s^+ D_s^-)$ threshold around 3.9 GeV

Amplitude fit results

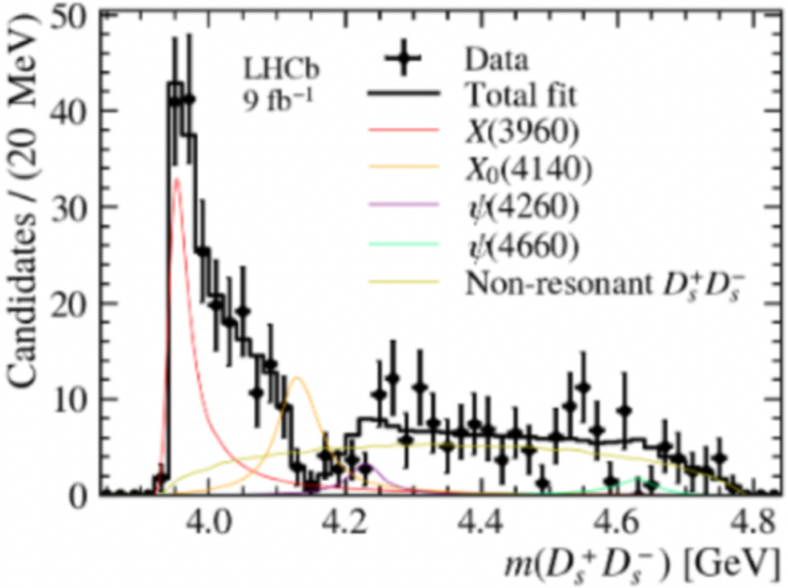
Preliminary



- **Only resonances on $m(D_s^+ D_s^-)$ contribute**
- **Dominant contribution from NR (~46.6%) and a near threshold state $X(3960)$ (~24.2%, more than 12.6 σ)**
- **Evidence of contributions from $\psi(4260), \psi(4660)$ and $X(4140)$**
- **Other states ($\chi_{c0}(4500), \chi_{c0}(4700), \psi(4040), \psi(4160), \psi(4415)$ and $\chi_{c2}(3930)$) also tested, though not significant**

$X(3960)$

Preliminary



- J^{PC} of 0^{++} is significantly preferred
- Mass and width determined to be

	M_0 (MeV)	Γ_0(MeV)
One channel	$3956 \pm 5 \pm 11$	$43 \pm 13 \pm 8$

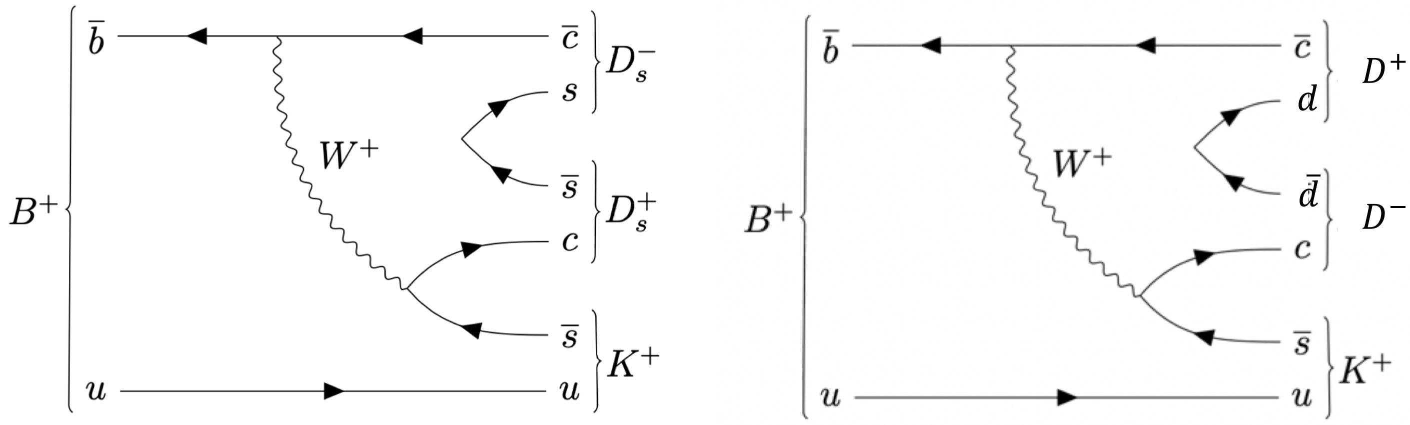
- $D_s^+ D_s^-$ threshold: ~3938 MeV

$$R(m \mid M_0, g_j) = \frac{1}{M_0^2 - m^2 - iM_0 \sum_j \boxed{g_j} \boxed{\rho_j(m)}},$$

Coupling constant Phase space factor

- Default: only with one channel = RBW
- Two channels considered: $D_s^+ D_s^-$ ($D^+ D^-$) with couplings: 0.33 ± 1.18 (0.15 ± 0.33) GeV, simultaneous fits with $B^+ \to D^+ D^- K^+$ decays needed

$X(3960)$



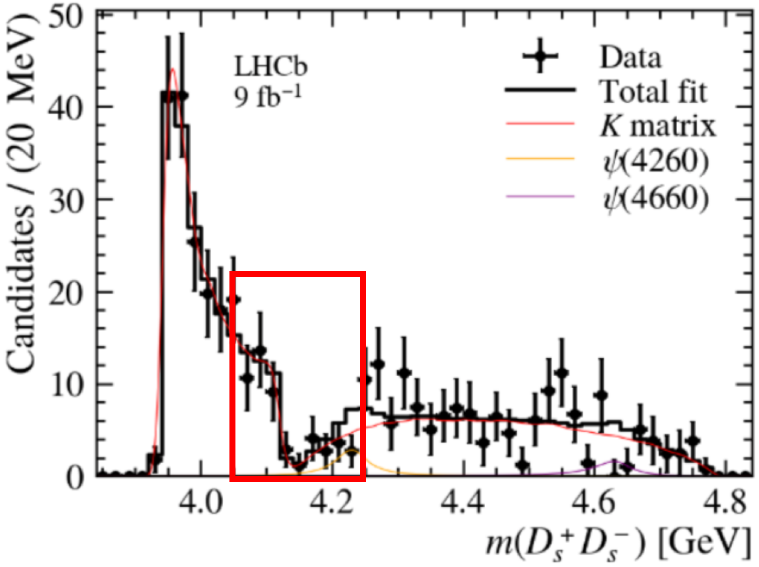
$$\frac{\mathcal{B}(B^+ \to D_s^+ D_s^- K^+)}{\mathcal{B}(B^+ \to D^+ D^- K^+)} = \frac{N_{\mathrm{sig}}^{\mathrm{corr}}}{N_{\mathrm{con}}^{\mathrm{corr}}} \left[\frac{\mathcal{B}(D^+ \to K^- \pi^+ \pi^+)}{\mathcal{B}(D_s^+ \to K^- K^+ \pi^+)}\right]^2 = 0.525 \pm 0.033,$$

Preliminary

$$\frac{\Gamma(X \to D^+ D^-)}{\Gamma(X \to D_s^+ D_s^-)} = \frac{\mathcal{B}^{(1)} \mathcal{F}_X^{(1)}}{\mathcal{B}^{(2)} \mathcal{F}_X^{(2)}} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08,$$

- **Phase space of $D_s^+ D_s^-$ smaller than $D^+ D^-$**
- **Suspiciously smaller branching fraction into $D^+ D^-$ final states: different resonances or a tetraquark with $c\bar{c}s\bar{s}$**

$X(4140)$



- **Dip around 4140 MeV can be seen clearly**
- **Significance around 3.9σ; mass and width determined to be**

	M_0 (MeV)	Γ_0(MeV)
RBW	$4133 \pm 6 \pm 11$	$67 \pm 17 \pm 7$

- **$J/\psi\phi$ threshold: ~4116.4 MeV**

- **A KMatrix with single resonance with two decay channels**

$$\begin{pmatrix} \mathcal{M}_{D_s^+ D_s^- \to D_s^+ D_s^-} & \mathcal{M}_{D_s^+ D_s^- \to J/\psi\phi} \\ \mathcal{M}_{J/\psi\phi \to D_s^+ D_s^-} & \mathcal{M}_{J/\psi\phi \to J/\psi\phi} \end{pmatrix} \equiv \begin{pmatrix} \mathcal{K}_{11} & \mathcal{K}_{12} \\ \mathcal{K}_{21} & \mathcal{K}_{22} \end{pmatrix}, \quad \mathcal{K}_{ab}(m) = \sum_R \frac{g_b^R g_a^R}{M_R^2 - m^2} + f_{ab},$$

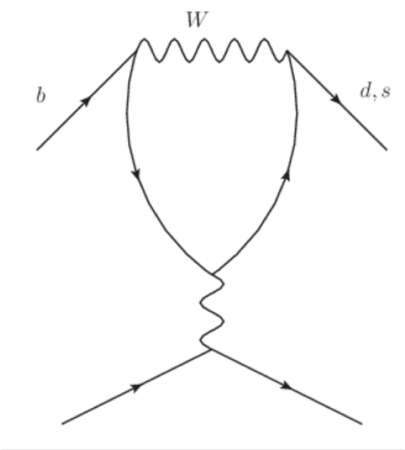
- **Can't conclude whether the dip is due to resonances or due to opening of new decay channel**

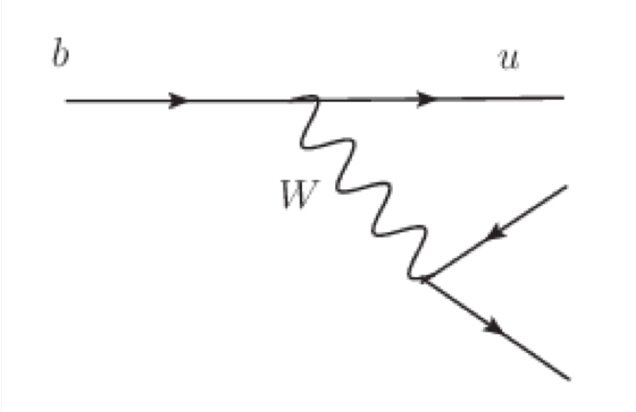
CP violation of $B^+ \to \pi^+\pi^+\pi^-$

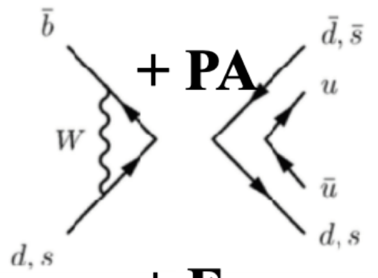
LHCb-PAPER-2019-017
LHCb-PAPER-2019-018

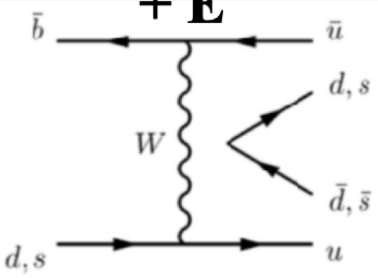
Looking for new physics in penguins

- **New sources of CP violation easy to enter in penguins: smoking gun for NP search**
- **Competitive contributions from tree and penguin diagrams: large CPV**









$|V_{td}|e^{i\beta}$ or $-|V_{ts}|e^{-i\beta_s}$

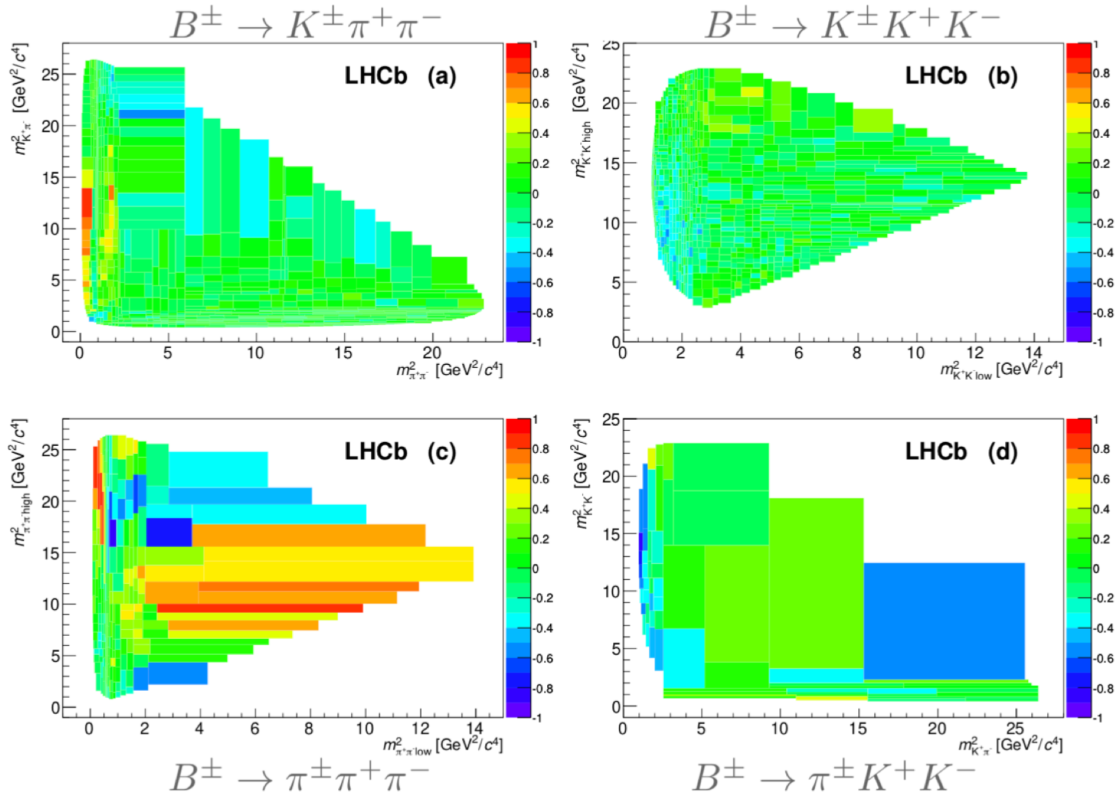
$|V_{ub}|e^{-i\gamma}$

+ New Physics

CPV in three-body charmless B decays

PRL 112 (2014) 011081
PRL 111 (2013) 101801
PRD 90 (2014) 112004

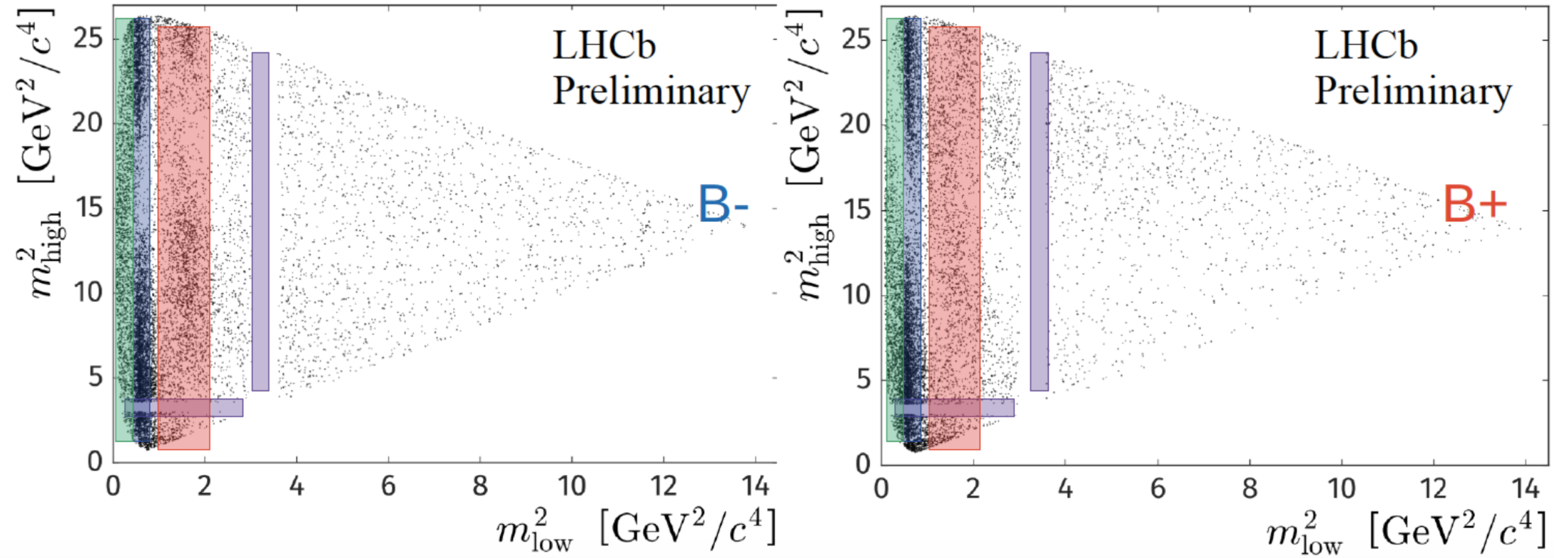
- **Interesting CPV pattern seen on Dalitz plot of $B^+ \to h^+h^-h'^+, h^{(\prime)} = K, \pi$**
- **Dalitz plot analysis needed to shed more light on understanding nature of these CPV**



- **Now, amplitude analyses of $B^+ \to \pi^+\pi^-\pi^+$ and $B^+ \to K^+K^-\pi^+$, with much larger statistics than previous B-factory analyses, has been performed**

Dalitz plot analysis with $B^+ \to \pi^+\pi^-\pi^+$

- **Dalitz plot analysis with 20594 ±1569 events (3 fb^{-1} data)**



- **Resonant contributions:**

  $\rho-\omega, f_0(500), f_0(980)$,region: S-P wave interference

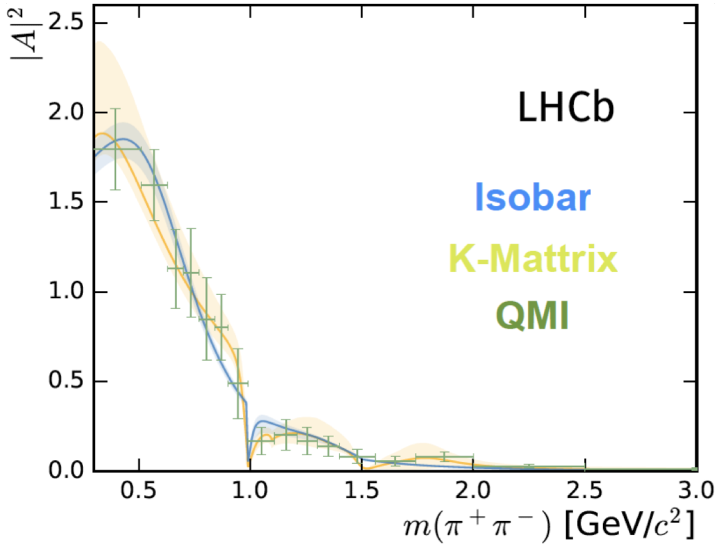
  $f_2(1270)$ region: D-S, P wave interference

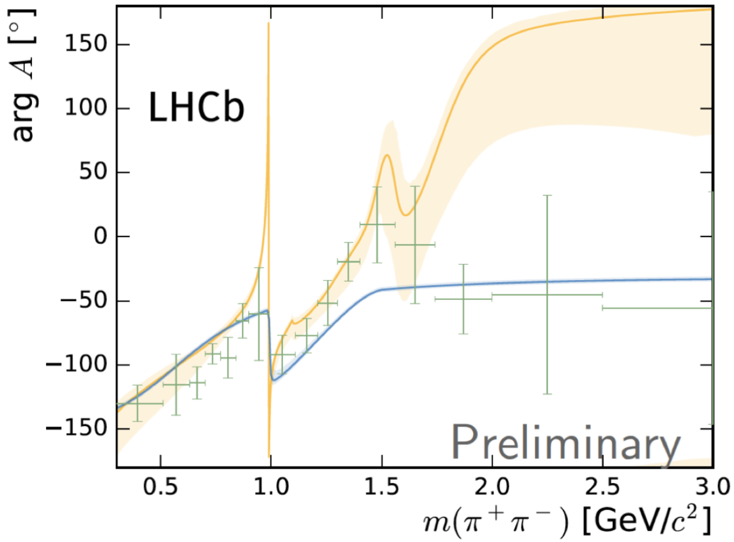
  High mass: $KK-\pi\pi$ rescattering

- **Three different methods to describe S-wave: Isobar model, K-Matrix approach, quasi model independent approach**

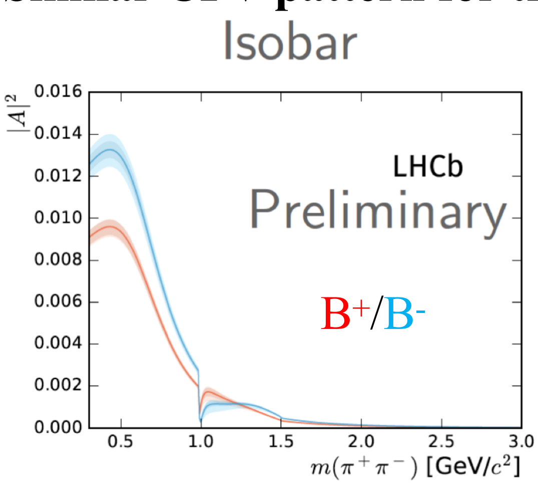
$\pi^+\pi^-$ S-wave

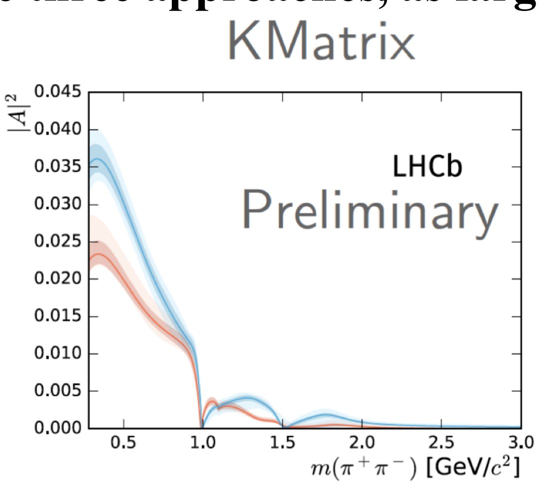
- **Good agreement between the three approaches**

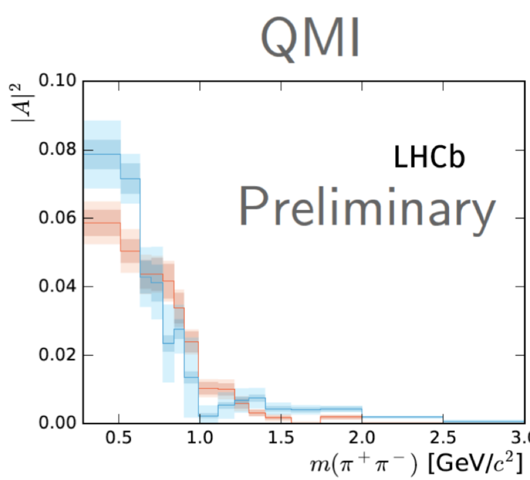




- **Similar CPV pattern for the three approaches, as large as 10σ**







CP violation results

LHCb-PAPER-2019-017
LHCb-PAPER-2019-018

- **Fit fractions:**

Component	Isobar	K-matrix	QMI
$\rho(770)^0$	$55.5 \pm 0.6 \pm 0.7 \pm 2.5$	$56.5 \pm 0.7 \pm 1.5 \pm 3.1$	$54.8 \pm 1.0 \pm 1.9 \pm 1.0$
$\omega(782)$	$0.50 \pm 0.03 \pm 0.03 \pm 0.04$	$0.47 \pm 0.04 \pm 0.01 \pm 0.03$	$0.57 \pm 0.10 \pm 0.12 \pm 0.12$
$f_2(1270)$	$9.0 \pm 0.3 \pm 0.8 \pm 1.4$	$9.3 \pm 0.4 \pm 0.6 \pm 2.4$	$9.6 \pm 0.4 \pm 0.7 \pm 3.9$
$\rho(1450)^0$	$5.2 \pm 0.3 \pm 0.4 \pm 1.9$	$10.5 \pm 0.7 \pm 0.8 \pm 4.5$	$7.4 \pm 0.5 \pm 3.9 \pm 1.1$
$\rho_3(1690)^0$	$0.5 \pm 0.1 \pm 0.1 \pm 0.4$	$1.5 \pm 0.1 \pm 0.1 \pm 0.4$	$1.0 \pm 0.1 \pm 0.5 \pm 0.1$
S-wave	$25.4 \pm 0.5 \pm 0.7 \pm 3.6$	$25.7 \pm 0.6 \pm 2.6 \pm 1.4$	$26.8 \pm 0.7 \pm 2.0 \pm 1.0$

- **Dominant contributions from S-wave and $\rho(770)$**

- **CP asymmetries:**

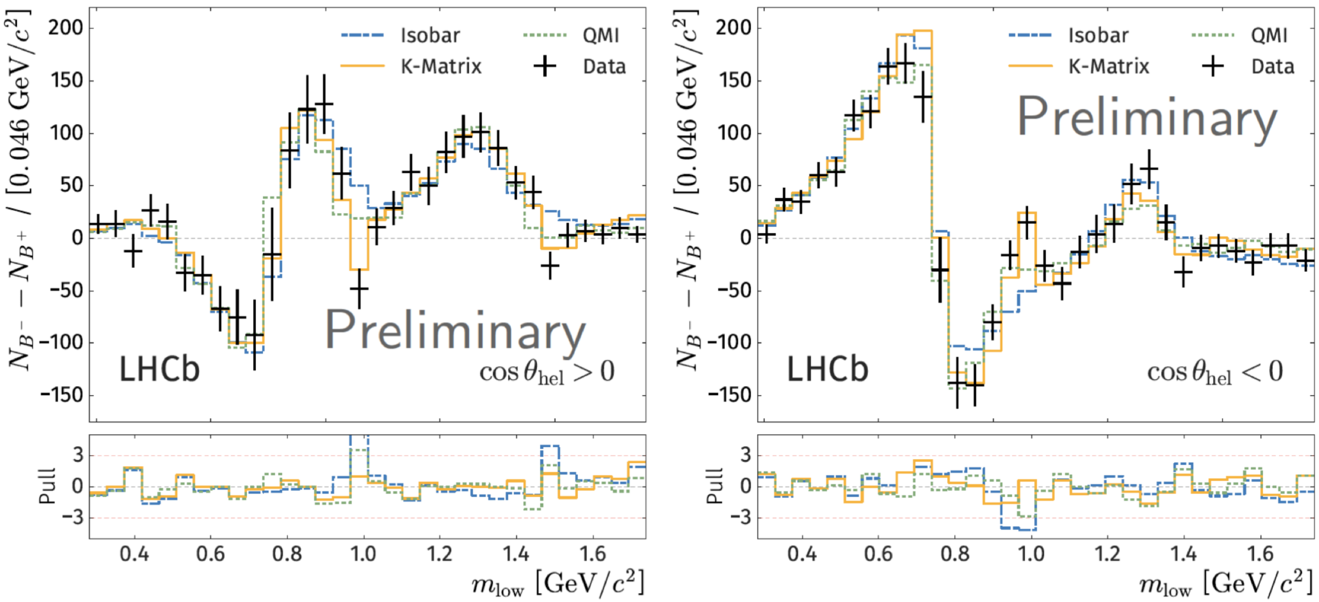
Component	Isobar	K-matrix	QMI
$\rho(770)^0$	$+0.7 \pm 1.1 \pm 1.2 \pm 1.5$	$+4.2 \pm 1.5 \pm 2.6 \pm 5.8$	$+4.4 \pm 1.7 \pm 2.3 \pm 1.6$
$\omega(782)$	$-4.8 \pm 6.5 \pm 6.6 \pm 3.5$	$-6.2 \pm 8.4 \pm 5.6 \pm 8.1$	$-7.9 \pm 16.5 \pm 14.2 \pm 7.0$
$f_2(1270)$	$+46.8 \pm 6.1 \pm 3.6 \pm 4.4$	$+42.8 \pm 4.1 \pm 2.1 \pm 8.9$	$+37.6 \pm 4.4 \pm 6.0 \pm 5.2$
$\rho(1450)^0$	$-12.9 \pm 3.3 \pm 7.0 \pm 35.7$	$+9.0 \pm 6.0 \pm 10.8 \pm 45.7$	$-15.5 \pm 7.3 \pm 14.3 \pm 32.2$
$\rho_3(1690)^0$	$-80.1 \pm 11.4 \pm 13.5 \pm 24.1$	$-35.7 \pm 10.8 \pm 8.5 \pm 35.9$	$-93.2 \pm 6.8 \pm 8.0 \pm 38.1$
S-wave	$+14.4 \pm 1.8 \pm 2.1 \pm 1.9$	$+15.8 \pm 2.6 \pm 2.1 \pm 6.9$	$+15.0 \pm 2.7 \pm 4.2 \pm 7.0$

- **Large CPV from S-wave and $f_2(1270)$ (first observation)**

New CP violation patterns

LHCb-PAPER-2019-017
LHCb-PAPER-2019-018

- CP violation around $\rho(770)$ pole well described by the three S-wave models



- Over 25σ significance for CPV due to S-P interference, first observation
- CP violation sign flips around $\rho(770)$ pole and over helicity angle

Conclusion

- **Amplitude analysis widely used in flavor physics to study exotic states and to understand CP violation over phase space**
- **A general amplitude analysis tool, TF-PWA, has been developed for it**
- **Using TF-PWA, three new tetra-quark states have been observed by the LHCb experiment, one with double charges ($T_{cs}^{a}(2900)^{++}$) together with its neutral isospin partner, $T_{cs}^{a}(2900)^{0}$, and the third $X(3960)$**
- **Amplitude analysis in CP violation also results in interesting results**
- **You are welcomed to use TF-PWA to your favorite physics**

Thank You for Your Attention