Amplitude analyses on charm decays at the LHCb experiment

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on behalf of the LHCb collaboration
@ ICHEP meeting

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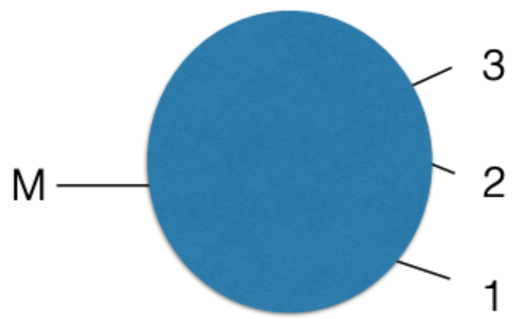
Dalitz plot analysis in 3 body decays

- Dalitz Plot has been a ***fundamental tool*** to study the dynamics of decay processes
- Provides important information of hadronic processes, such as:
  - Revealing and understanding resonances in different final states
  - Study the dynamics of the scalar sector (not well understood)
  - Search and study of CP violation in the beauty and charm sector
  - Study lineshapes and interference patterns



$$\begin{aligned} d\Gamma &= \left|\mathscr{M}_{fi}\right|^2 d\Phi \\ &= \left|\mathscr{M}_{fi}\right|^2 \left|\frac{\partial\Phi}{\partial\left(s_{12}, s_{13}\right)}\right| ds_{12}ds_{13} \\ &= \frac{1}{(2\pi)^2 32M^3}\left|\mathscr{M}_{fi}\right|^2 ds_{12}ds_{13} \end{aligned}$$

$$s_{ij} \equiv \left(p_i + p_j\right)^2 \equiv m_{ij}^2$$

Focus on the latest LHCb charm meson amplitude analyses:

Amplitude analysis of the $D^+ \to \pi^-\pi^+\pi^+$ and $D_s^+ \to \pi^-\pi^+\pi^+$ decays and measurement of the $\pi^-\pi^+$ S-wave amplitude

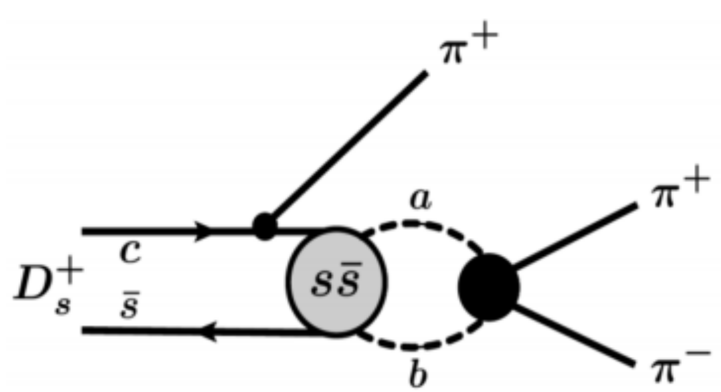
LHCb-PAPER-2022-016 and LHCb-PAPER-2022-030 in preparation

$D^+ \to \pi^-\pi^+\pi^+$ and $D_s^+ \to \pi^-\pi^+\pi^+$ decays

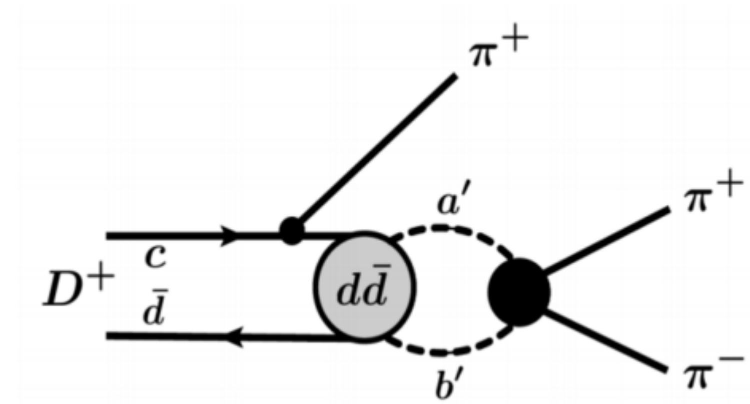
- Previous analyses:
  - **D^+ :** E791 (2001)[1], FOCUS (2004)[2] and CLEO (2007)[3]
    - CLEO's ~2.6k events with 55% purity
  - **D_s^+ :** E791 (2001)[4], BaBar (2009)[5], BESIII (2021)[6]
    - BESIII sample ~13k events with 80% purity

- **S-wave measured to be the major contribution** in the 3π final state
  - **Challenge:** understand the $\pi^-\pi^+$scalar sector with many overlapping resonances;
  - $f_0(980)$ accounts as ~50% of the total decay rate for D_s^+ and $f_0(500)$ with ~50% for D^+
  - Comparison between D_s^+ and D^+ S-wave amplitudes

- LHCb data has larger samples allowing for unprecedented opportunity to study these channels and enlighten our knowledge of their dynamics
- *Quasi-Model Independent approach (QMIPWA)* for S-wave, and Isobar Model for P and D-waves
- Both analysis based on 2012 data sample (Run I)



a,b = K, η



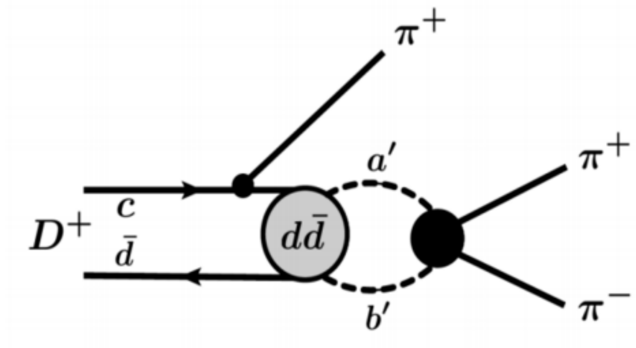
a',b' = π, K, η

[1] PRL 86 (2001) 770
[2] PLB 585 (2004) 200
[3] PRD 76 (2007) 012001
[4] PRL 86 (2001) 765
[5] PRD 79 (2009) 032003
[6] arXiv:2108.10050

$D^+ \to \pi^-\pi^+\pi^+$ decays

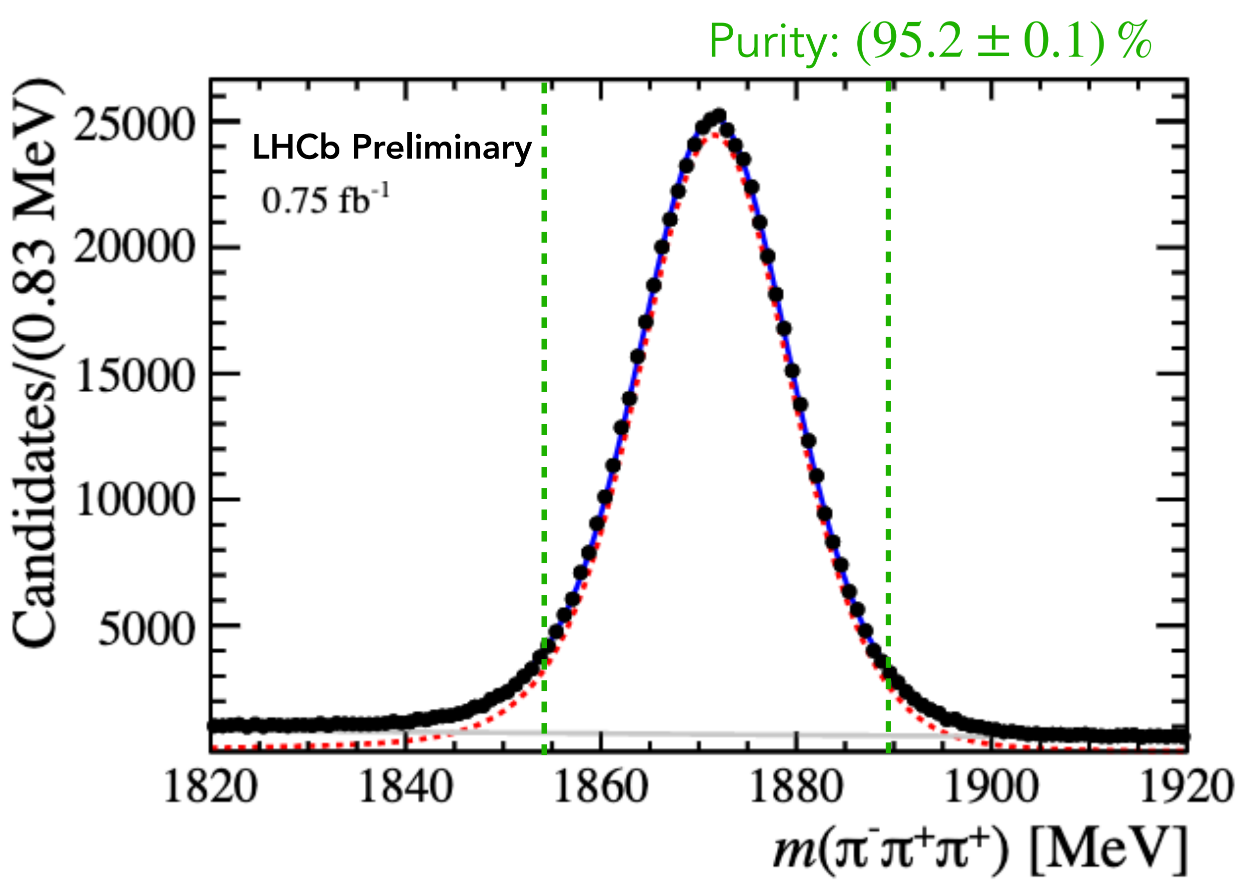
LHCb-PAPER-2022-016 in preparation

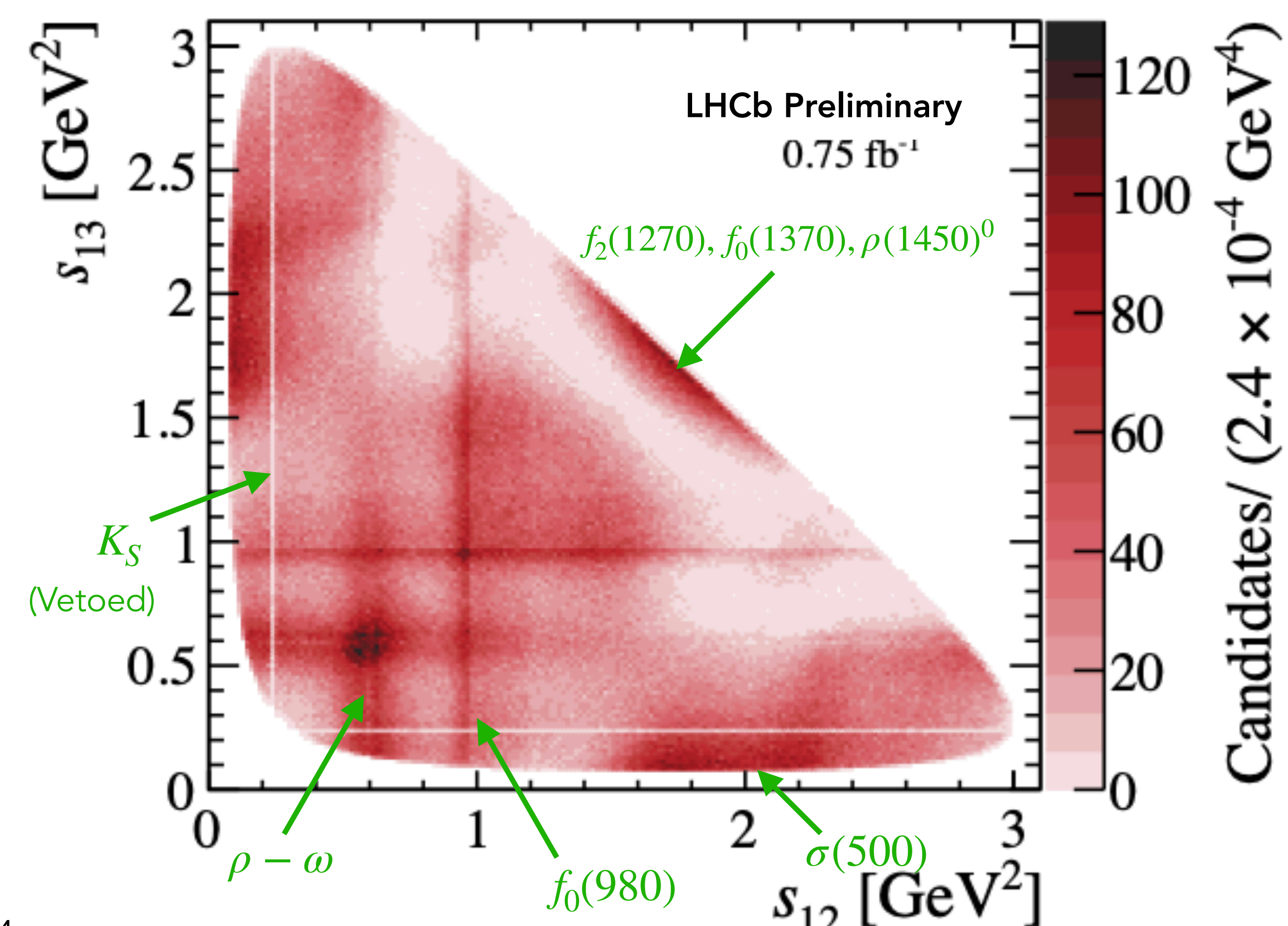
- *No new results since CLEO (15 years ago)!!*
- *First time performing a QMIPWA analysis!!*
- High statistics, thus, sensitive to more details



a',b' = π, K, η

- *Selection:* trigger+ offline pre selection + MVA selection (reduce combinatorial background)
- *Final sample:* ~600k events and ~95% purity (minimise effects of background misparametrisation)
- Use only events within the 2σ window for all Dalitz fits





Quasi Model-Independent Partial Wave Analysis - QMIPWA

- The $m(\pi^-\pi^+)$ mass spectrum is divided into sub-intervals (knots)
- In each knot edge, the amplitude is determined by two real constants, a_k and ϕ_k

$$A^k_{S-wave} = a^k e^{i\phi^k}$$

$k, l \rightarrow$ knots in $m\left(\pi^-\pi^+\right)$

$$A^{k,l}_{S-wave}\left(s_{12}, s_{13}\right) = A^k_{S-wave}\left(m_{12}\right) + A^l_{S-wave}\left(m_{13}\right)$$

A linear spline interpolation is used to get the S-wave amplitude at any point in $m^2(\pi^-\pi^+)$

- P- and D-waves assumed to be well parametrised and included via Isobar Model.
- GooFit: framework for maximum likelihood fits using GPU

Total amplitude

$$\mathscr{A}(s_{12}, s_{13}) = \left[\mathscr{A}_{S-Wave} + \sum_{spin1,spin2} a_i e^{i\delta_i}\mathscr{A}_i\right] \qquad (s_{12} \leftrightarrow s_{13})$$

→ Bose-symmetrisation (2 identical π^+)

$s_{12} = m^2(\pi_1^-\pi_2^+)$ and $s_{13} = m^2(\pi_1^-\pi_3^+)$

Free parameters:

- Spin 1 and 2 contributions: magnitude a_i and phase δ_i
- S-Wave: a^k and ϕ^k

Other information:

- Fit quality via χ^2 test
- Comparison between models: FCN $= -2\log\mathscr{L}$

Fit result: $D^+ \to \pi^-\pi^+\pi^+$

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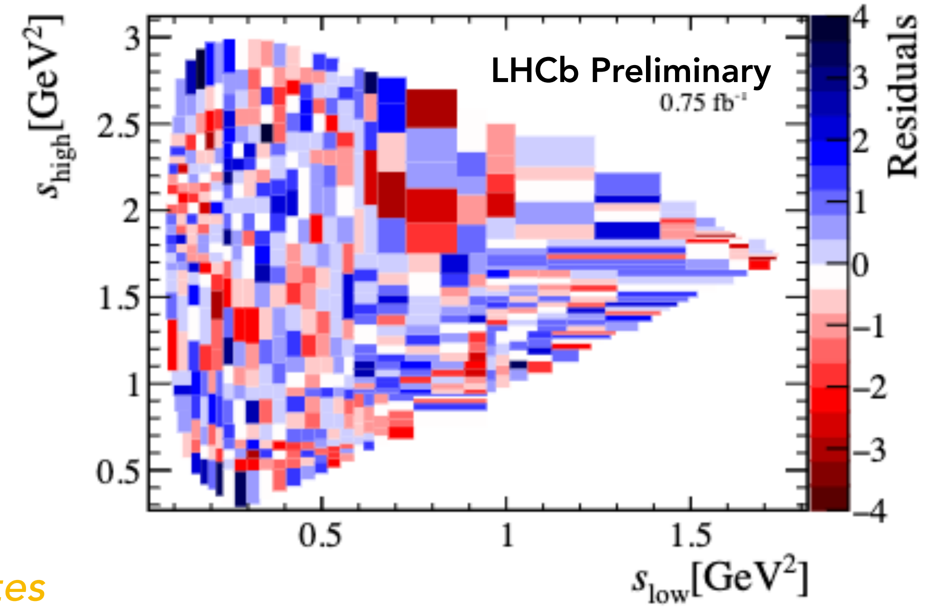
Component	Magnitude	Phase [°]	Fit fraction [%]
$\rho(770)^0\pi^+$	1 [fixed]	0 [fixed]	$26.0 \pm 0.3 \pm 1.6 \pm 0.3$
$\omega(782)\pi^+$	$(1.68 \pm 0.06 \pm 0.15 \pm 0.02) \times 10^{-2}$	$-103.3 \pm 2.1 \pm 2.6 \pm 0.4$	$0.103 \pm 0.008 \pm 0.014 \pm 0.002$
$\rho(1450)^0\pi^+$	$2.66 \pm 0.07 \pm 0.24 \pm 0.22$	$47.0 \pm 1.5 \pm 5.5 \pm 4.1$	$5.4 \pm 0.4 \pm 1.3 \pm 0.8$
$\rho(1700)^0\pi^+$	$7.41 \pm 0.18 \pm 0.47 \pm 0.71$	$-65.7 \pm 1.5 \pm 3.8 \pm 4.6$	$5.7 \pm 0.5 \pm 1.0 \pm 1.0$
$f_2(1270)\pi^+$	$2.16 \pm 0.02 \pm 0.10 \pm 0.02$	$-100.9 \pm 0.7 \pm 2.0 \pm 0.4$	$13.8 \pm 0.2 \pm 0.4 \pm 0.2$
S-wave			$61.8 \pm 0.5 \pm 0.6 \pm 0.5$
$\sum_i \mathrm{FF}_i$			112.8
χ^2/ndof (range)	[1.47 - 1.78]		$-2\log\mathcal{L} = 805622$

S-wave is dominant!

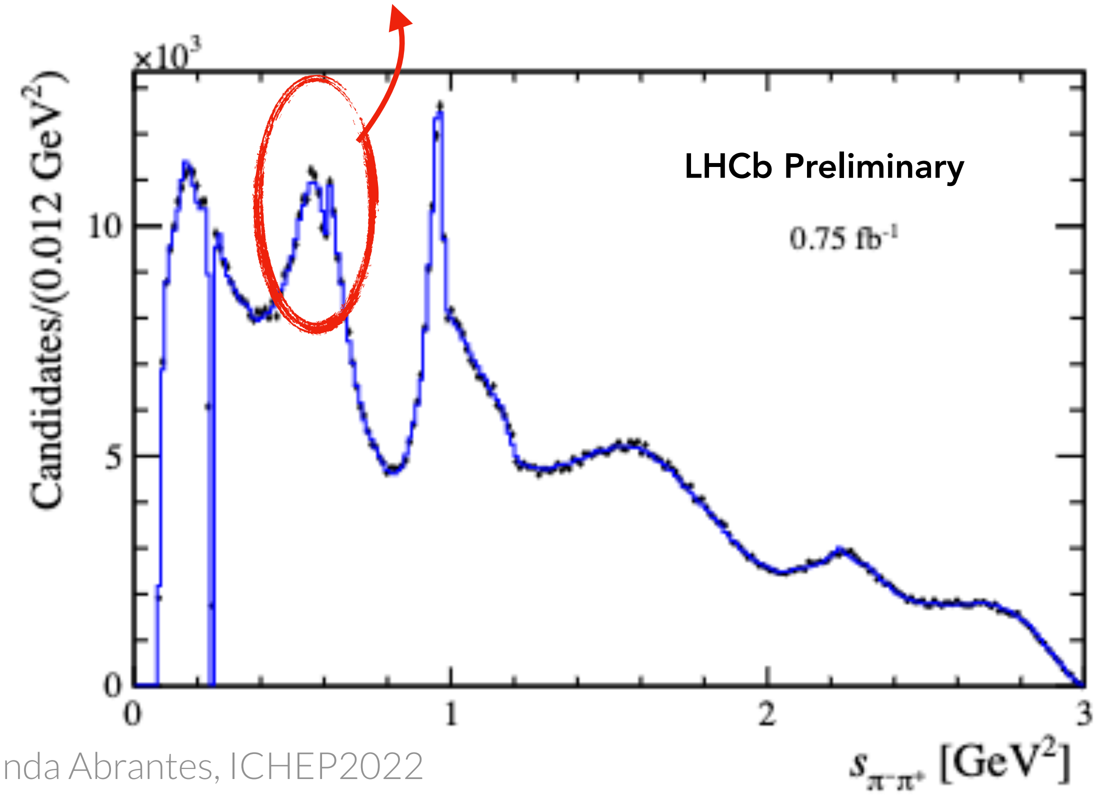


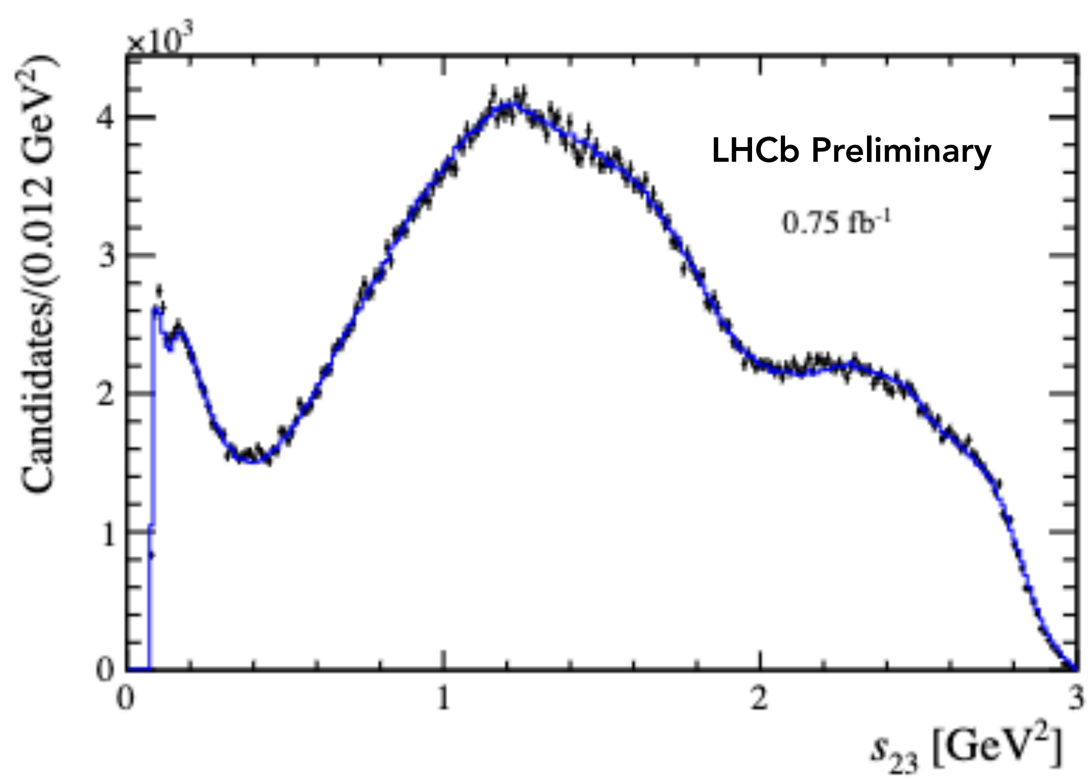
Interference fit fractions

	$\omega(782)\pi^+$	$\rho(1450)^0\pi^+$	$\rho(1700)^0\pi^+$	$f_2(1270)\pi^+$	S-wave
$\rho(770)^0\pi^+$	-0.24 ± 0.06	5.1 ± 0.3	-5.8 ± 0.4	-0.3 ± 0.1	1.8 ± 0.4
$\omega(782)\pi^+$		0.05 ± 0.01	0.05 ± 0.01	0.046 ± 0.004	-0.04 ± 0.01
$\rho(1450)^0\pi^+$			-4.0 ± 0.5	1.1 ± 0.1	1.7 ± 0.2
$\rho(1700)^0\pi^+$				-0.8 ± 0.1	-3.4 ± 0.5
$f_2(1270)\pi^+$					-1.6 ± 0.1

Large interference between ρ states

$\rho - \omega$ interference: first time being observed in this channel!!





$D^+ \to \pi^-\pi^+\pi^+$: Extracted $\pi^-\pi^+$ S-Wave amplitude

Statistical uncertainties

Stat + exp. syst + model syst uncertainties

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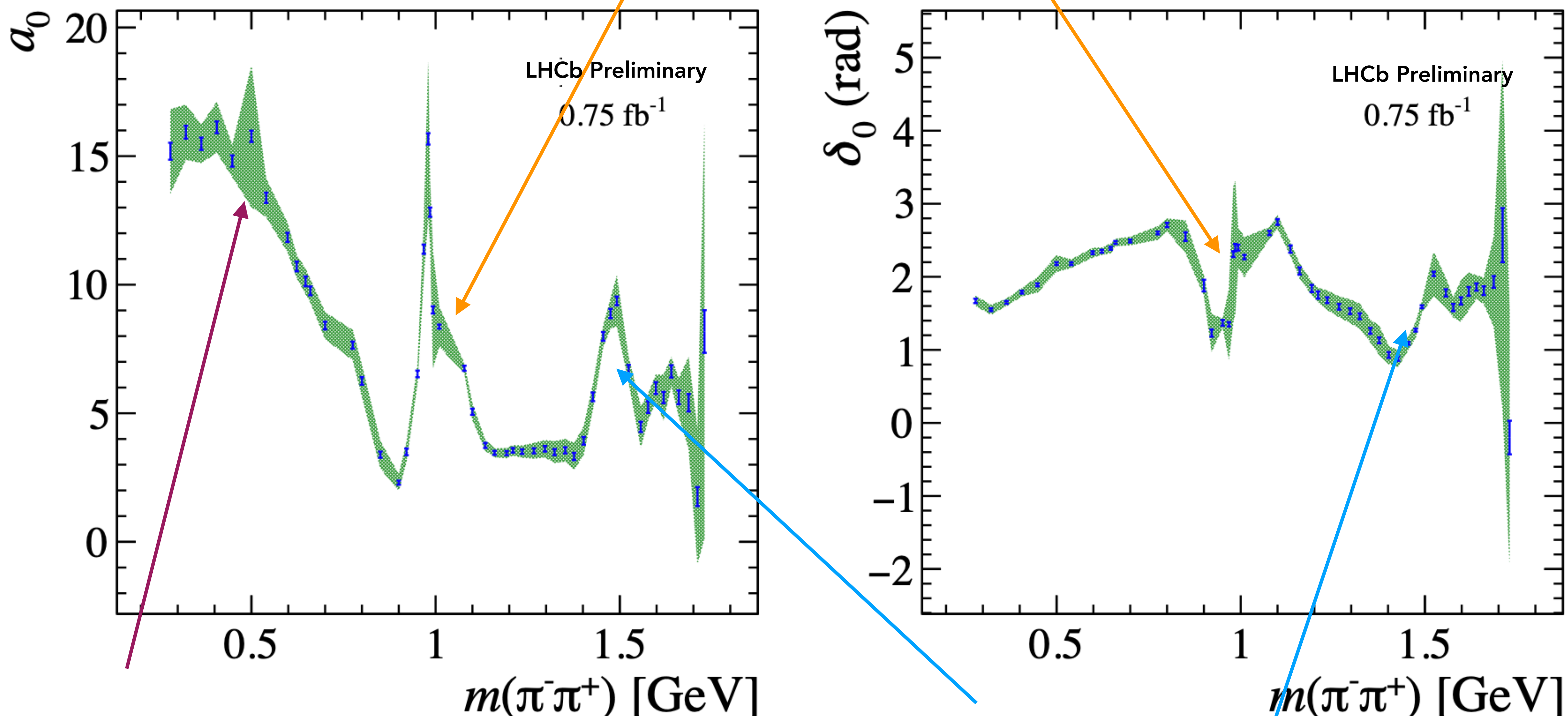
Signature of $f_0(980)$: Peak in the magnitude and large phase variation near 1.0 GeV



Magnitude of the S-wave is larger close to the threshold indicating a dominant contribution from the $f_0(500)$

Rapid growth of phase and amplitude towards the end of the spectrum indicates the presence of at least one more scalar resonance, for instance $f_0(1500)$ (also enhanced by the opening of $\eta\eta'$ channel)

Summary $D^+ \to \pi^-\pi^+\pi^+$

LHCb-PAPER-2022-016 in preparation

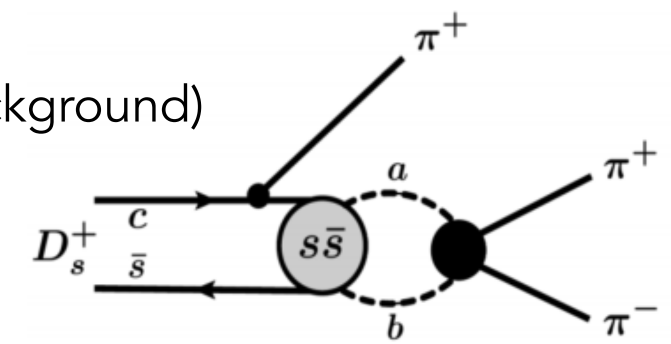
Principal contributions:

- *First QMIPWA analysis for this decay channel!!*
- *Detailed measurement of the $\pi^-\pi^+$ S-wave amplitude*
- $\rho - \omega$: *first time observed* in $D^+ \to \pi^-\pi^+\pi^+$
    - $\omega(782) \to \pi^-\pi^+$: $(0.103 \pm 0.008 \pm 0.014 \pm 0.002)\,\%$
    - $\omega(782) \to \pi^-\pi^+$ *isospin-violating decay*
- $\rho - \omega$ mixing lineshape also tested but no significant difference
    - $|B| = 0.522 \pm 0.019 \pm 0.047 \pm 0.006$ and $\phi_B = (158.8 \pm 2.1 \pm 2.6 \pm 0.4)^o$
- S-wave found to be dominant ~62% (in agreement with previous observations)
- Best fit result includes the $\rho(1700)^0$ state
    - very significant change in the FCN! (-488 units compared to that of the model without it)
    - Only $\rho^0(1450)$ is not enough to describe P wave in the high mass end

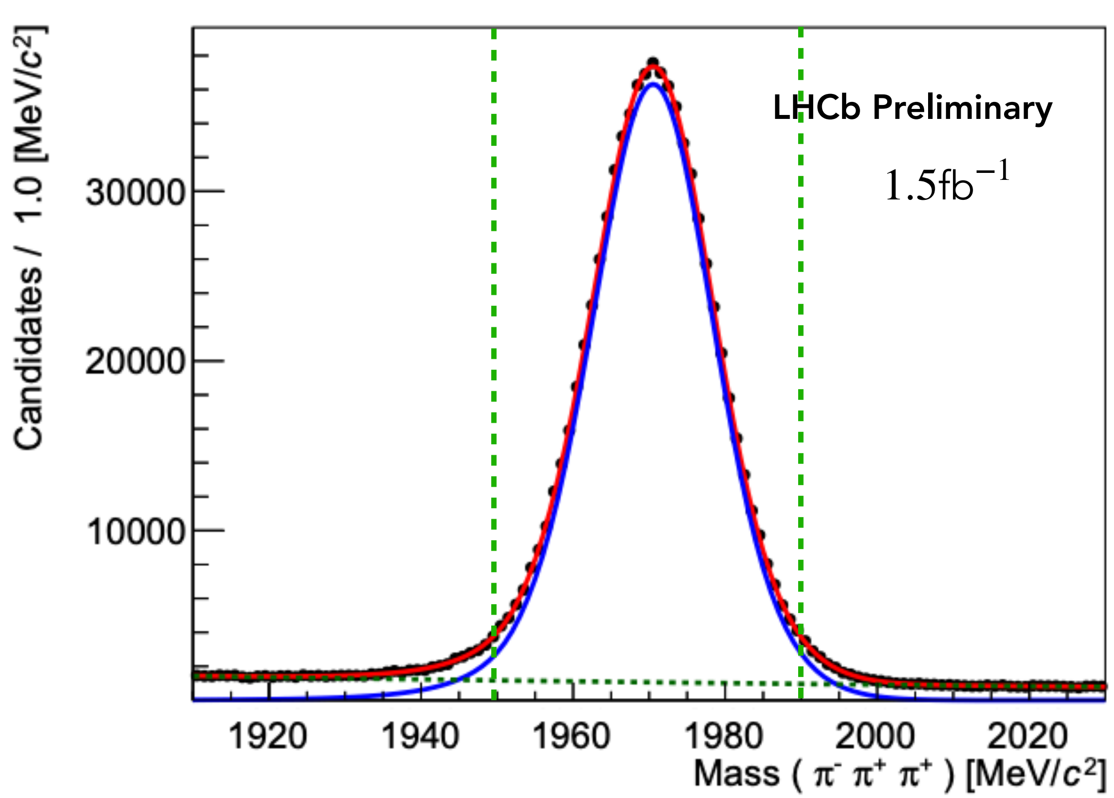
$D_s^+ \to \pi^-\pi^+\pi^+$ decays

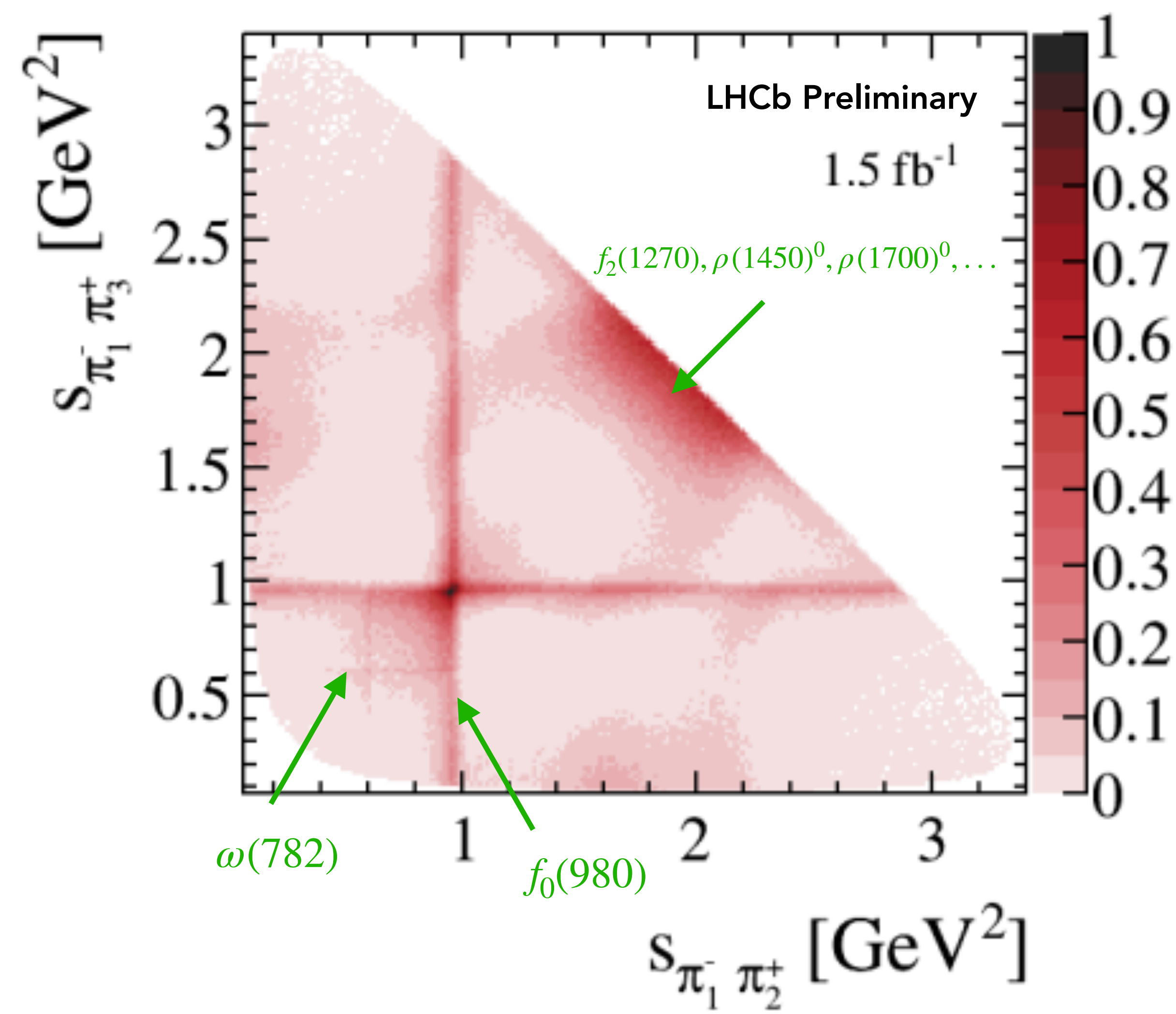
LHCb-PAPER-2022-030 in preparation

- *Latest results from BESIII with a QMIPWA analysis (~1.3k events)*
- Follows the same methodology as the $D^+ \to \pi^-\pi^+\pi^+$ analysis
- **Selection:** trigger + offline pre selection + MVA selection (reduce combinatorial background)
- Final sample with over 700k events and ~95% purity
  - (minimise effects of background misparametrisation)



a,b = K, η





Fit result: $D_s^+ \to \pi^-\pi^+\pi^+$

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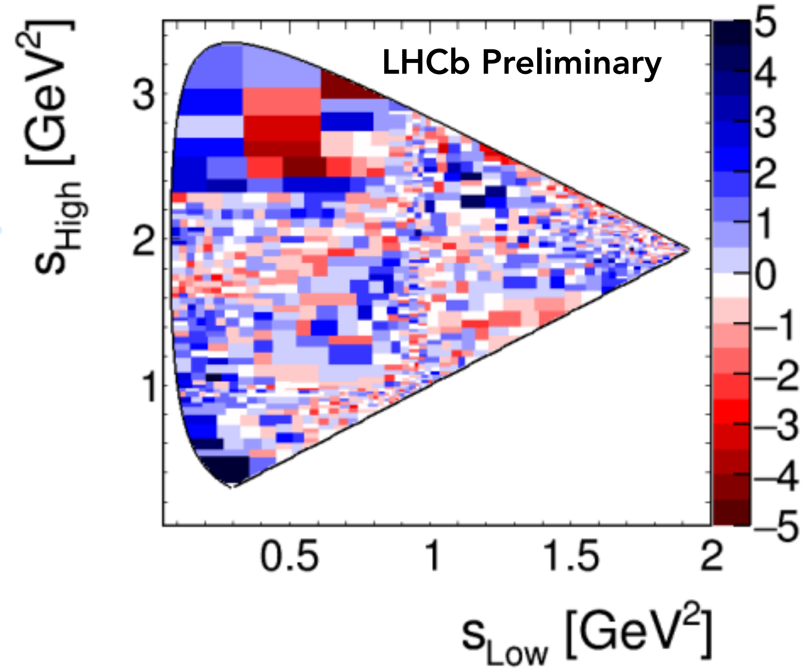
Resonance	Magnitude	Phase [^{o}]	Fit Fraction (%)
$\rho(770)^0$	$0.1201 \pm 0.0030 \pm 0.0050 \pm 0.0062$	$79.4 \pm 1.8 \pm 7.8 \pm 4.4$	$1.038 \pm 0.054 \pm 0.097 \pm 0.11$
$\omega(782)$	$0.04001 \pm 0.00090 \pm 0.0018 \pm 0.00086$	$-109.9 \pm 1.7 \pm 0.94 \pm 1.4$	$0.360 \pm 0.016 \pm 0.034 \pm 0.016$
$\rho(1450)^0$	$1.277 \pm 0.026 \pm 0.023 \pm 0.48$	$-115.2 \pm 2.6 \pm 2.8 \pm 10$	$3.86 \pm 0.15 \pm 0.14 \pm 2.0$
$\rho(1700)^0$	$0.873 \pm 0.061 \pm 0.054 \pm 0.62$	$-60.9 \pm 6.1 \pm 6.7 \pm 12$	$0.365 \pm 0.050 \pm 0.045 \pm 0.34$
$f_2(1270)$	1 (fixed)	0 (fixed)	$13.69 \pm 0.14 \pm 0.22 \pm 0.49$
$f_2'(1525)$	$0.1098 \pm 0.0069 \pm 0.019 \pm 0.015$	$178.1 \pm 4.2 \pm 12 \pm 7$	$0.0528 \pm 0.0070 \pm 0.015 \pm 0.0087$
S-wave			$84.97 \pm 0.14 \pm 0.30 \pm 0.63$

S-wave is dominant!

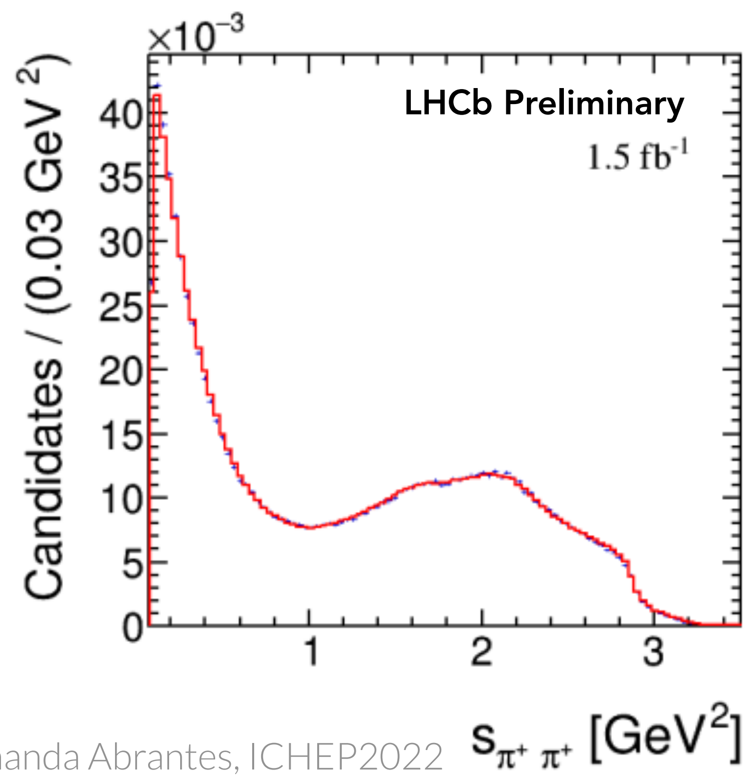


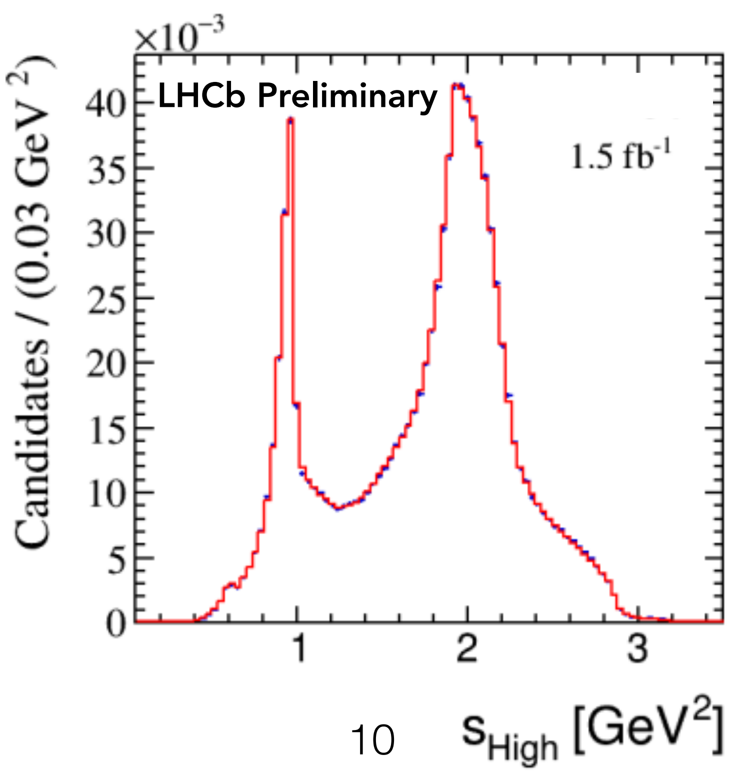
Interference fit fractions

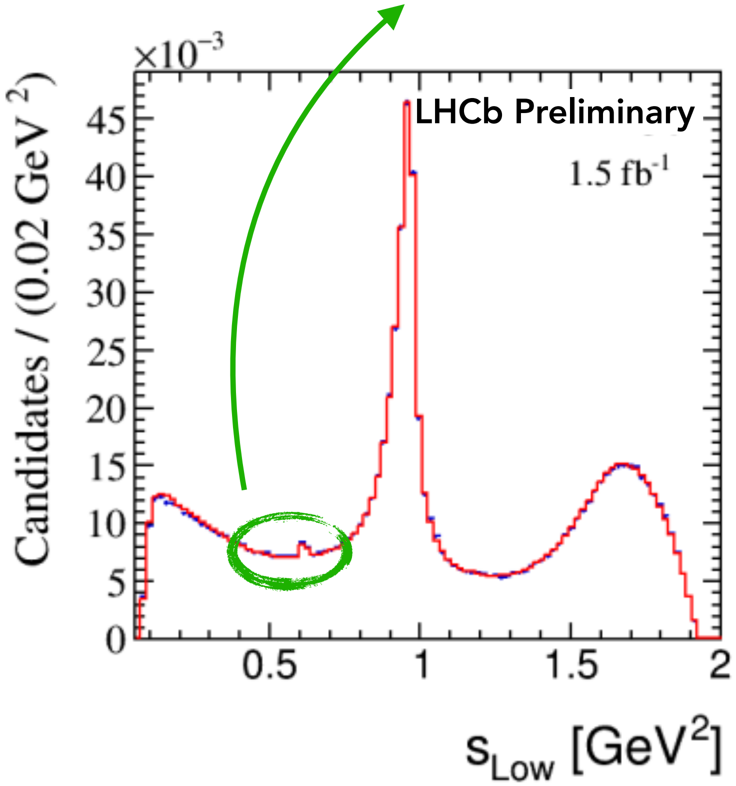
	$\omega(782)$	$\rho(770)^0$	$\rho(1450)^0$	$\rho(1700)^0$
$\omega(782)$	0.360 ± 0.016			
$\rho(770)^0$	0.128 ± 0.013	1.038 ± 0.054		
$\rho(1450)^0$	0.36 ± 0.14	0.148 ± 0.14	3.86 ± 0.15	
$\rho(1700)^0$	0.089 ± 0.010	$-0.307 \pm 0.0.55$	1.92 ± 0.20	0.365 ± 0.050
$f_2(1270)$	-0.1540 ± 0.0040	0.280 ± 0.029	-1.10 ± 0.047	-0.376 ± 0.047
$f_2'(1525)$	0.00827 ± 0.00063	0.00283 ± 0.0038	0.066 ± 0.0021	0.0200 ± 0.0021
S-wave	-0.053 ± 0.0099	0.804 ± 0.076	-1.520 ± 0.086	-0.934 ± 0.086

	$f_2(1270)$	$f_2'(1525)$	S-wave
$f_2(1270)$	13.69 ± 0.14		
$f_2'(1525)$	-0.429 ± 0.072	0.0455 ± 0.0070	
S-wave	-3.460 ± 0.092	0.20 ± 0.013	84.97 ± 0.14

$\omega(782)$: first time being observed in this channel!!



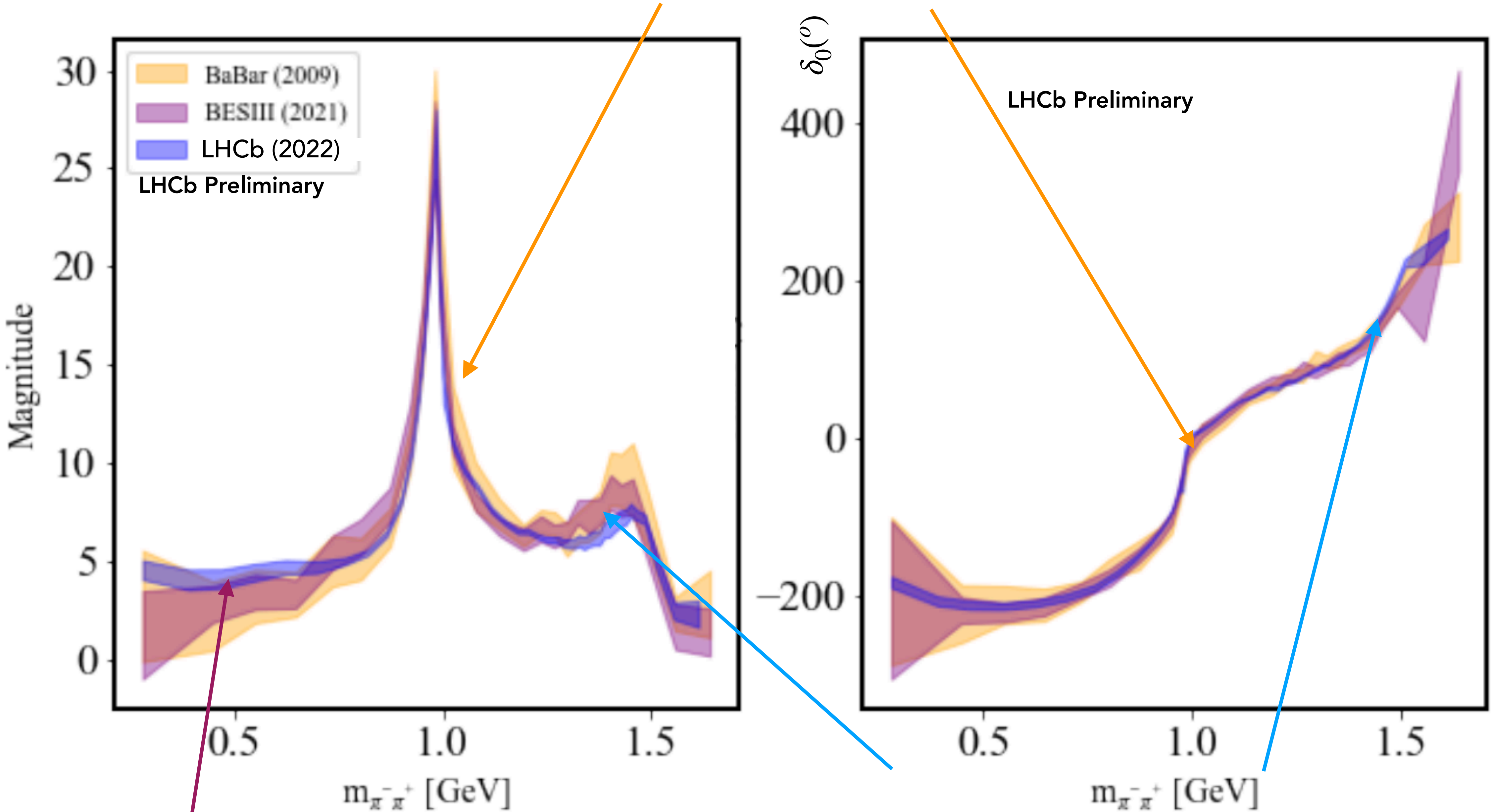




$D_s^+ \to \pi^-\pi^+\pi^+$: Extracted $\pi^-\pi^+$ S-Wave amplitude

LHCb-PAPER-2022-030 in preparation

Signature of $f_0(980)$: Peak in the magnitude and large phase variation near 1.0 GeV



Magnitude of the S-wave is small indicating no contribution from the $f_0(500)$

Rapid growth of phase towards the end of the spectrum indicates the presence of at least one more scalar resonance, for instance $f_0(1500)$ (also enhanced by the opening of $\eta\eta'$ channel)

Summary $D_s^+ \to \pi^-\pi^+\pi^+$

LHCb-PAPER-2022-030 in preparation

Principal contributions:

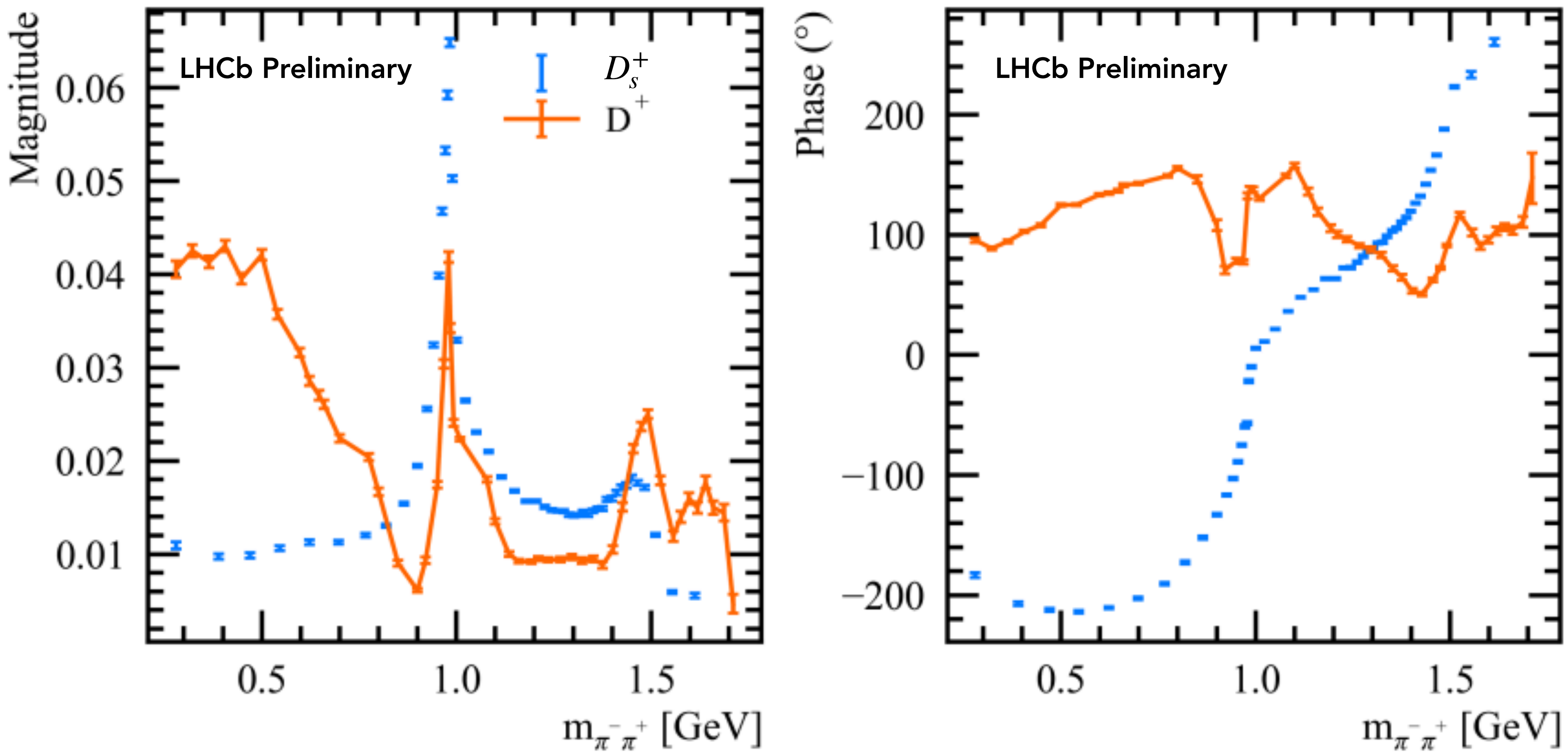
- *Detailed measurement of the $\pi^-\pi^+$ S-wave amplitude*
  - Precision improved from previous analyses
- $D_s^+ \to (\omega(782) \to \pi^-\pi^+)\pi^+$: *first time observed* in $D_s^+ \to \pi^-\pi^+\pi^+$
  - $\omega(782) \to \pi^-\pi^+$: $(0.360 \pm 0.016 \pm 0.034 \pm 0.016)$ %
- $D_s^+ \to \rho(1700)^0\pi^+$ *and* $D_s^+ \to f_2'(1525)\pi^+$ also *observed for the first time* in $D_s^+ \to \pi^-\pi^+\pi^+$
- S-wave also found to be dominant (in agreement with previous observations) ~85%
- Small contribution from $\rho(770)^0\pi^+$ (in agreement with previous analyses)
- Best fit result includes the $\rho(1700)^0$ state
  - Combined fit fraction of the $\rho(1450)^0$ and $\rho(1700)^0$ amplitudes is stable

Let's now compare the two channels…

D_s^+ vs D^+: S-wave

LHCb-PAPER-2022-030 in preparation

(Statistical uncertainties only)



- S-wave as the major contribution (~85% for D_s^+ and ~61% for D^+)
- $f_0(980)$ is the most prominent contribution in D_s^+ and $f_0(500)$ in D^+
- No indication of a scalar resonance at low $\pi^-\pi^+$ mass for D_s^+
- Indication of at least one scalar resonances near 1.5 MeV for both modes
  - Enhanced by the opening of the $\eta\eta'$ channel
- *Different composition for D_s^+ and D^+: S-wave produced from different sources…*

D_s^+ vs D^+: P- and D-waves

P-wave

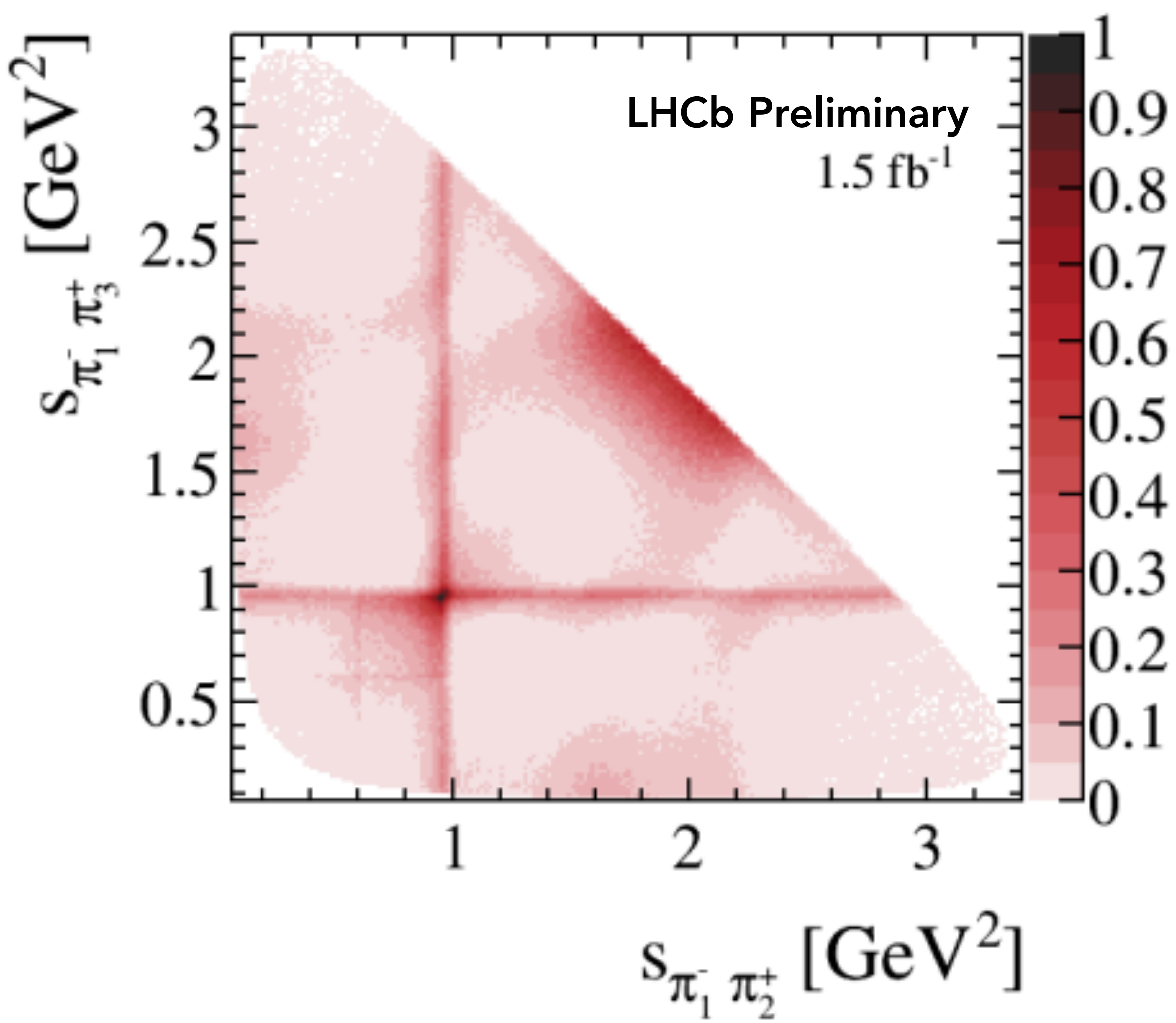
- $D_{(s)}^+ \to (\omega(782) \to \pi^-\pi^+)\pi^+$: first time observed in both channels
    - $\omega(782)$ is produced by different mechanisms in both decays
    - $\rho(770)^0$ contributes with ~26% for D^+ and ~1% for D_s^+
- $D_{(s)}^+$: Both $\rho(1450)^0$ and $\rho(1700)^0$ are necessary for a good fit
    - Combined contributions are very similar, $(6.14 \pm 0.27)\,\%$ in D_s^+, and $(7.1 \pm 0.8)\,\%$ in D^+

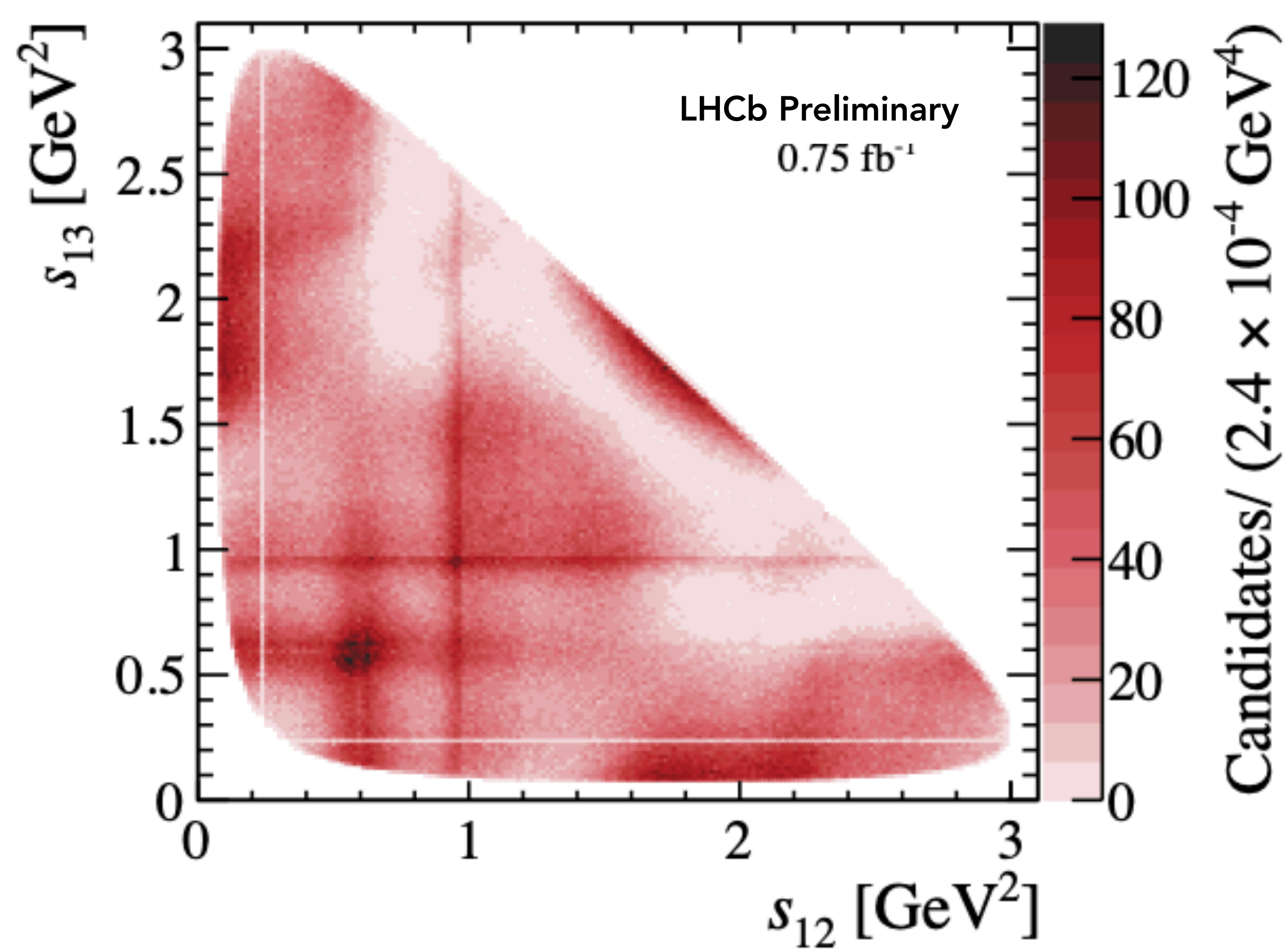
Same resonances in both D_s^+ and D^+ modes but very different contributions!!

D-wave

- $f_2(1270)$ as the largest contribution for both channels
    - Identical contribution in both channels (~13%)
    - *Intriguing result!* Given its quark content, one would expect the production of the $f_2(1270)$ at a higher rate from a $d\bar{d}$ source (D^+) than an $s\bar{s}$ source as in D_s^+
- $f_2'(1525)$ only seen in the D_s^+ channel: dominant $s\bar{s}$ and small $(d\bar{d} + u\bar{u})$ component

D_s^+ vs D^+: Conclusions





- *Very different resonant structure in spite of the final state being the same*
- *Conclusion: Scalar resonances are produced by different mechanisms in these decays*

LHCb-PAPER-2022-016 and LHCb-PAPER-2022-030 in preparation

Thank you!

Backup Slides

D^+ : previous analyses

E791

Mode	Fit 1 Fraction (%) magnitude phase	Fit 2 Fraction (%) magnitude phase
$\sigma\pi^+$	...	46.3 ± 9.0 ± 2.1
	...	1.17 ± 0.13 ± 0.06
	...	(205.7 ± 8.0 ± 5.2)°
$\rho^0(770)\pi^+$	20.8 ± 2.4	33.6 ± 3.2 ± 2.2
	1 (fixed)	1 (fixed)
	0 (fixed)	0 (fixed)
NR	38.6 ± 9.7	7.8 ± 6.0 ± 2.7
	1.36 ± 0.20	0.48 ± 0.18 ± 0.09
	(150.1 ± 11.5)°	(57.3 ± 19.5 ± 5.7)°
$f_0(980)\pi^+$	7.4 ± 1.4	6.2 ± 1.3 ± 0.4
	0.60 ± 0.07	0.43 ± 0.05 ± 0.02
	(151.8 ± 16.0)°	(165.0 ± 10.9 ± 3.4)°
$f_2(1270)\pi^+$	6.3 ± 1.9	19.4 ± 2.5 ± 0.4
	0.55 ± 0.08	0.76 ± 0.06 ± 0.03
	(102.6 ± 16.0)°	(57.3 ± 7.5 ± 2.9)°
$f_0(1370)\pi^+$	10.7 ± 3.1	2.3 ± 1.5 ± 0.8
	0.72 ± 0.12	0.26 ± 0.09 ± 0.03
	(143.2 ± 9.7)°	(105.4 ± 17.8 ± 0.6)°
$\rho^0(1450)\pi^+$	22.6 ± 3.7	0.7 ± 0.7 ± 0.3
	1.04 ± 0.12	0.14 ± 0.07 ± 0.02
	(45.8 ± 14.9)°	(319.1 ± 39.0 ± 10.9)°

PRL 86 (2001) 770

CLEO

PRD 76 (2007) 012001

Mode	Amplitude (a.u.)	Phase (°)	Fit fraction (%)
$\rho(770)\pi^+$	1 (fixed)	0 (fixed)	20.0 ± 2.3 ± 0.9
$f_0(980)\pi^+$	1.4 ± 0.2 ± 0.2	12 ± 10 ± 5	4.1 ± 0.9 ± 0.3
$f_2(1270)\pi^+$	2.1 ± 0.2 ± 0.1	−123 ± 6 ± 3	18.2 ± 2.6 ± 0.7
$f_0(1370)\pi^+$	1.3 ± 0.4 ± 0.2	−21 ± 15 ± 14	2.6 ± 1.8 ± 0.6
$f_0(1500)\pi^+$	1.1 ± 0.3 ± 0.2	−44 ± 13 ± 16	3.4 ± 1.0 ± 0.8
σ pole	3.7 ± 0.3 ± 0.2	−3 ± 4 ± 2	41.8 ± 1.4 ± 2.5

FOCUS

PLB 585 (2004) 200

P-vector parameters	modulus	phase (deg)
β_1	1 (fixed)	0 (fixed)
β_2	2.471 ± 0.431	82.5 ± 10.3
β_3	1.084 ± 0.386	102.8 ± 23.5
f_{11}^{prod}	2.565 ± 0.737	155.4 ± 18.3
f_{12}^{prod}	6.312 ± 0.967	−160.0 ± 8.7

decay channel	fit fraction (%)	phase (deg)	amplitude coefficient
(S-wave) π^+	56.00 ± 3.24 ± 2.08	0 (fixed)	1 (fixed)
$f_2(1270)\,\pi^+$	11.74 ± 1.90 ± 0.23	−47.5 ± 18.7 ± 11.7	1.147 ± 0.291 ± 0.047
$\rho^0(770)\,\pi^+$	30.82 ± 3.14 ± 2.29	−139.4 ± 16.5 ± 9.9	1.858 ± 0.505 ± 0.033
Fit C.L.	7.7 %		

D_s^+ : previous analyses

PRL 86 (2001) 765 **E791**

	Fit A fraction (%) magnitude phase
$f_0(980)\pi^+$	56.5 ± 4.3 ± 4.7 1 (fixed) 0 (fixed)
Nonresonant	0.5 ± 1.4 ± 1.7 0.09 ± 0.14 ± 0.04 (181 ± 94 ± 51)°
$\rho^0(770)\pi^+$	5.8 ± 2.3 ± 3.7 0.32 ± 0.07 ± 0.19 (109 ± 24 ± 5)°
$f_2(1270)\pi^+$	19.7 ± 3.3 ± 0.6 0.59 ± 0.06 ± 0.02 (133 ± 13 ± 28)°
$f_0(1370)\pi^+$	32.4 ± 7.7 ± 1.9 0.76 ± 0.11 ± 0.03 (198 ± 19 ± 27)°
$\rho^0(1450)\pi^+$	4.4 ± 2.1 ± 0.2 0.28 ± 0.07 ± 0.01 (162 ± 26 ± 17)°
$m_{f_0(980)}$(MeV/c^2)	977 ± 3 ± 2
g_π	0.09 ± 0.01 ± 0.01
g_K	0.02 ± 0.04 ± 0.03
$m_{f_0(1370)}$(MeV/c^2)	1434 ± 18 ± 9
$\Gamma_{f_0(1370)}$(MeV/c^2)	172 ± 32 ± 6
χ^2/ν	71.8/68
C.L.	35%
$-2\ln\mathcal{L}_{max}$	−3204

BaBar PRD 79 (2009) 032003

Decay mode	Decay fraction (%)	Amplitude	Phase (rad)
$f_2(1270)\pi^+$	10.1 ± 1.5 ± 1.1	1.0 (fixed)	0.0 (fixed)
$\rho(770)\pi^+$	1.8 ± 0.5 ± 1.0	0.19 ± 0.02 ± 0.12	1.1 ± 0.1 ± 0.2
$\rho(1450)\pi^+$	2.3 ± 0.8 ± 1.7	1.2 ± 0.3 ± 1.0	4.1 ± 0.2 ± 0.5
S wave	83.0 ± 0.9 ± 1.9	Table II	Table II
Total	97.2 ± 3.7 ± 3.8		
χ^2/NDF	$\frac{437}{422-64} = 1.2$		

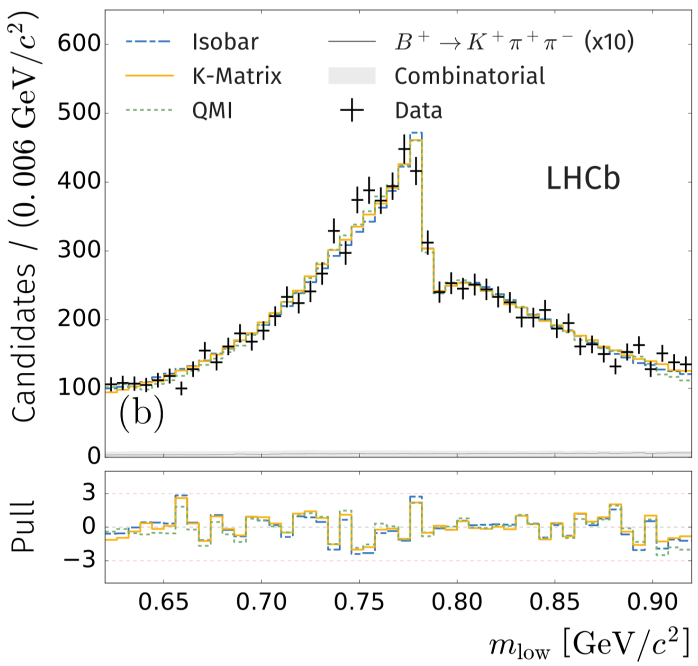
BESIII arXiv:2108.10050

Decay mode	Fit fraction (%)	Magnitude	Phase (radians)
$f_2(1270)\pi^+$	10.5 ± 0.8 ± 1.2	1. (Fixed)	0. (Fixed)
$\rho(770)\pi^+$	0.9 ± 0.4 ± 0.5	0.13 ± 0.03 ± 0.04	5.44 ± 0.25 ± 0.62
$\rho(1450)\pi^+$	1.3 ± 0.4 ± 0.5	0.91 ± 0.16 ± 0.22	1.03 ± 0.32 ± 0.51
S wave	84.2 ± 0.8 ± 1.3	Table III	Table III
Total	96.8 ± 2.4 ± 3.5		

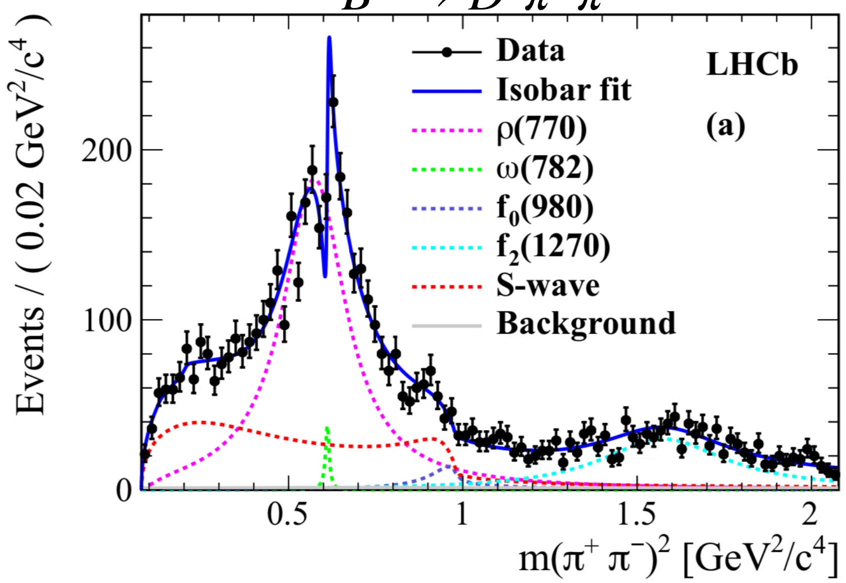
$\rho - \omega$ interference

Different ρ-ω profiles depending on the decay channel!

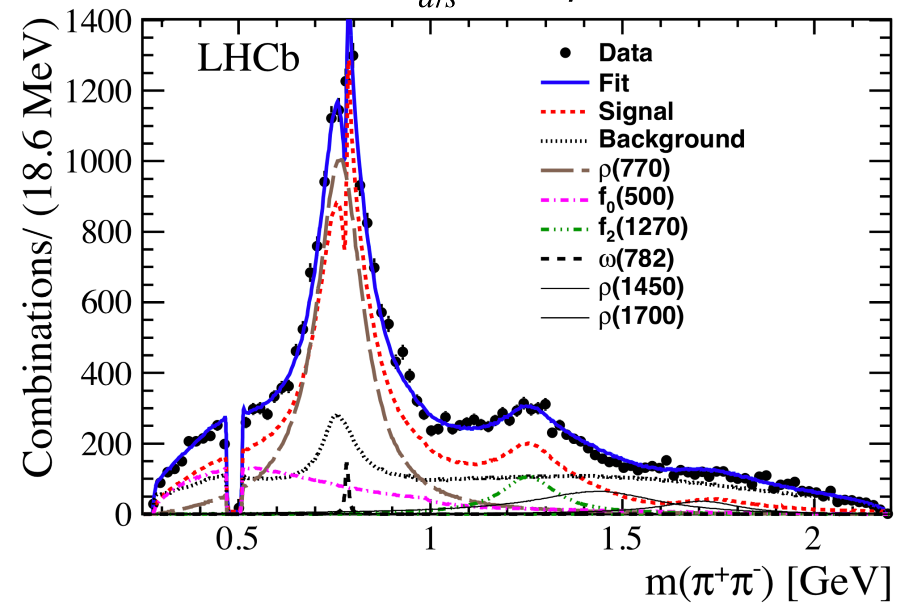
$B^\pm \to \pi^\pm \pi^+ \pi^-$ [1]



$B^0 \to \bar{D}^0 \pi^+ \pi^-$ [2]



$\bar{B}^0_{d/s} \to J/\psi \pi \pi$ [3]



Possible mixing parametrisation

$$A_{\rho-\omega} = A_\rho \left[\frac{1 + A_\omega \Delta |B| \exp\left(i\phi_B\right)}{1 - \Delta^2 A_\rho A_\omega} \right] \qquad \Delta = \delta \left(m_\rho + m_\omega \right)$$

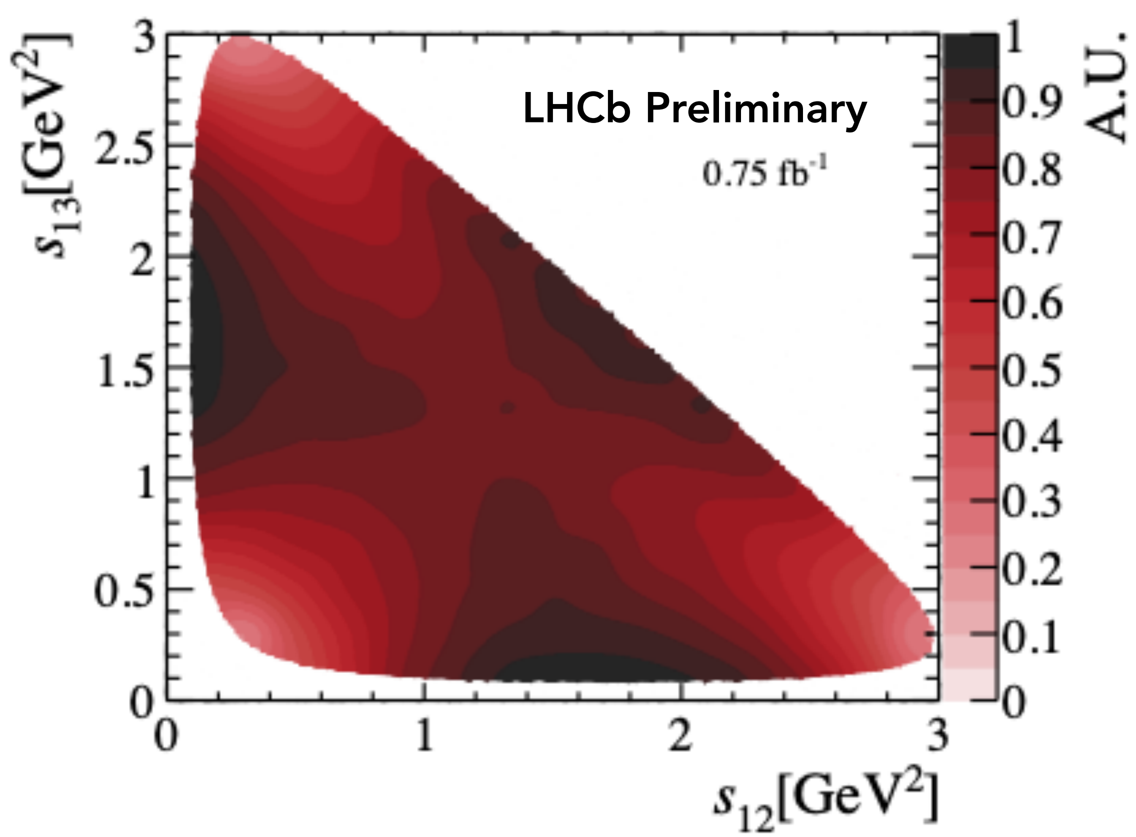
$$\delta \approx 2.15 MeV$$

[1] *Phys. Rev. D* 101 (2020) 012006
[2] arXiv: 1505.01710v2 [hep-ex]
[3] Phys. Lett. B 742 (2015) 38

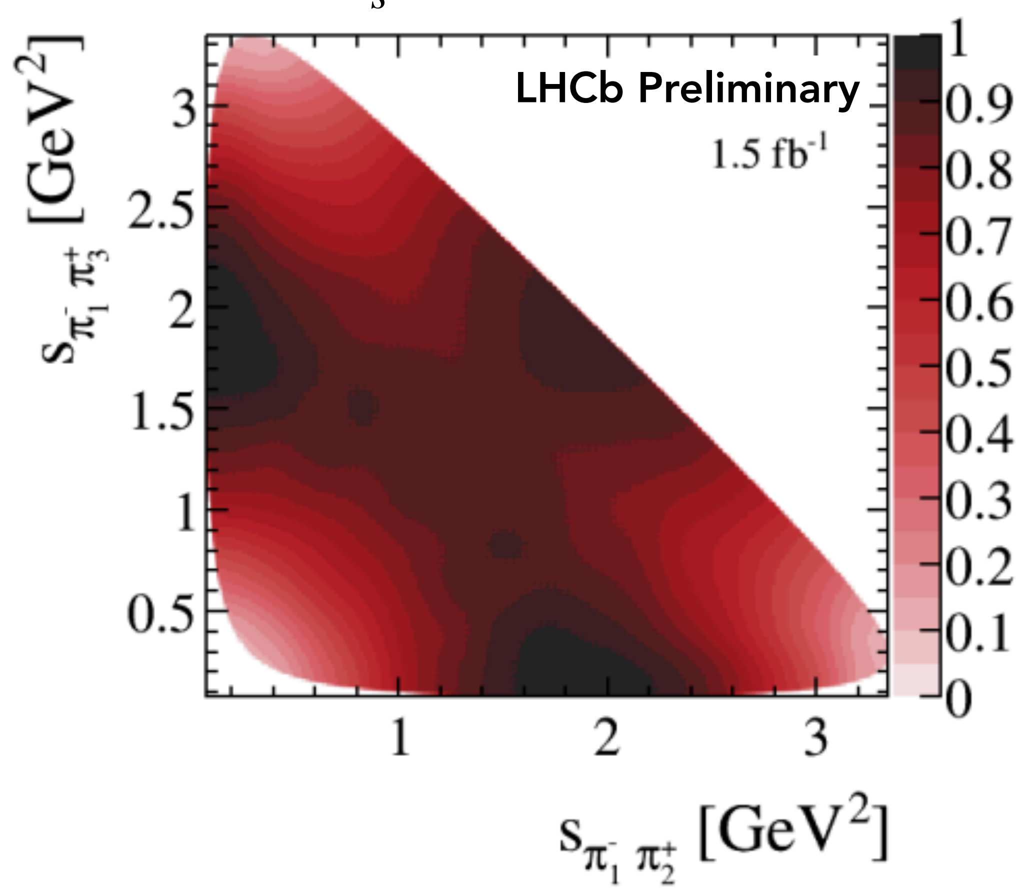
Efficiency maps

- Obtained from total simulated sample, which was generated as an uniform Dalitz Plot distribution
- Incorporates all steps of the selection process with except of PID
- PID incorporated through per-event weights to the simulated decays, from data calibration samples
- 15x15 bins
- 2D cubic spline based on the code LauCubicSpline from Laura++[1] to produce a high resolution smoothed histogram.

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



$D_s^+ \to \pi^-\pi^+\pi^+$

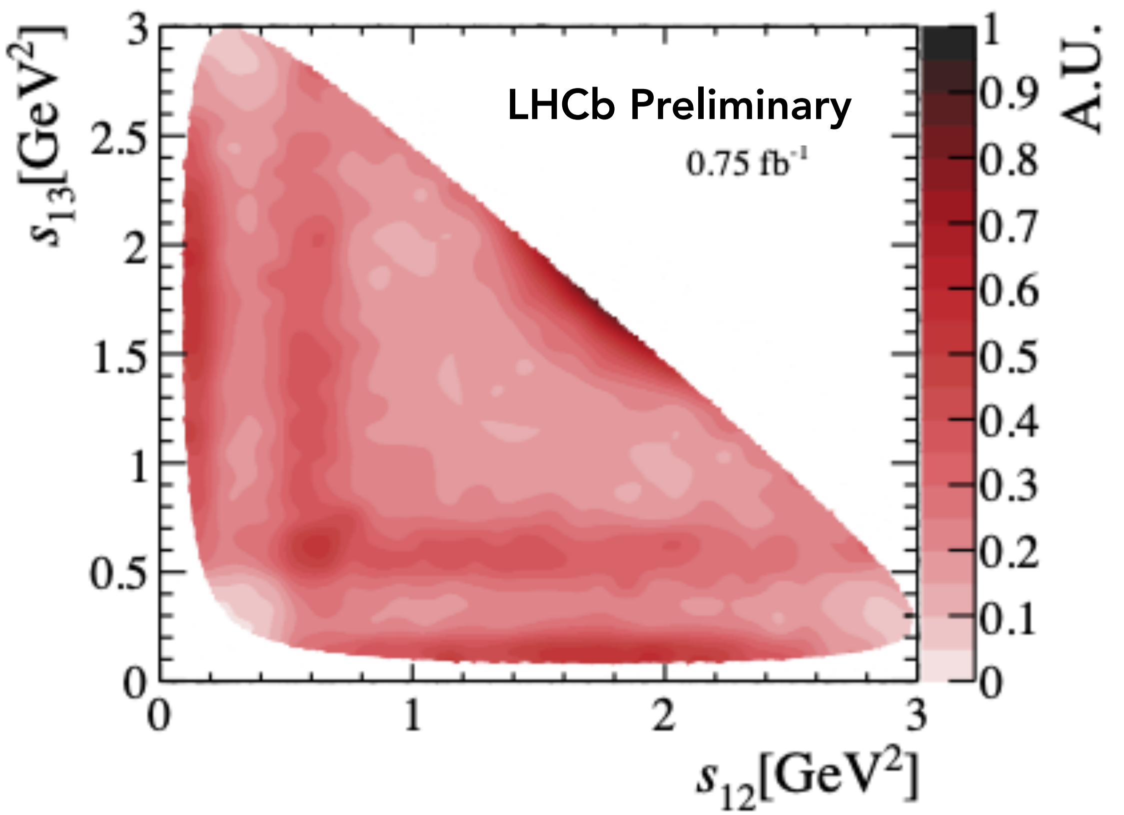


[1] J. Back et al., Laura++: A Dalitz plot fitter, Computer Physics Communications 231 (2018) 198.

D^+: Background

- Composition: 3-track random combinations + $D^+_{(s)} \to \eta(')\pi^+$ + random $\rho\pi$ combination + negligible partially reconstructed charm
- Approximately 5% of our final data sample
- Background within the signal region is assumed to be a composition of both sidebands
- Spline procedure based on Laura++ code

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

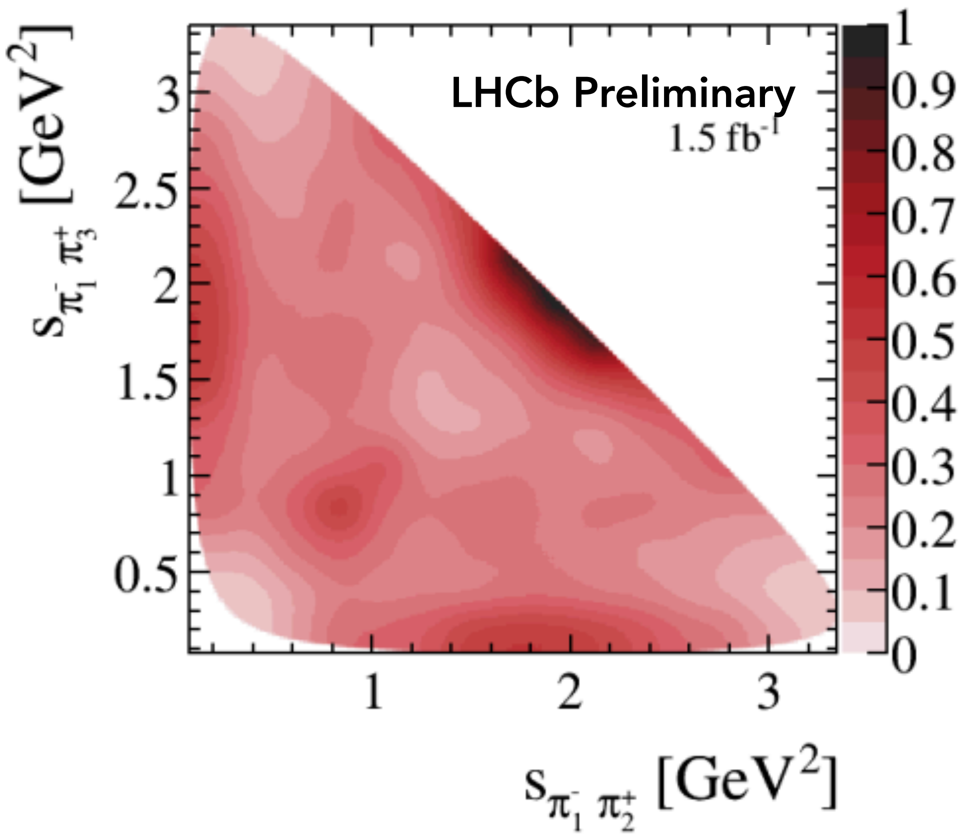


Events populating:

[1810,1830] MeV

[1910,1930] MeV

$D^+_s \to \pi^-\pi^+\pi^+$



Events populating:

[1920,1940] MeV

[2000,2020] MeV

Systematic Uncertainties

- Sources considered:

  Experimental uncertainties: efficiency correction, background parametrisation, selection, finite detector resolution

  Model systematics: uncertainties in lineshape parameters

Efficiency:

- Finite size of simulated sample: vary bin content within its uncertainty
- PID efficiency: size of calibration sample. Vary values of efficiency and correction factors
- Binning scheme: 12x12, 15x15, 20x20

Background:

- Purity: vary $\pm 1\sigma$ according to the uncertainty from the mass fit
- Shape: only left or right wing as background model

QMIPWA:

- Parametrisation of the S-wave: vary the number of knots used

Fit bias and QMIPWA modelling:

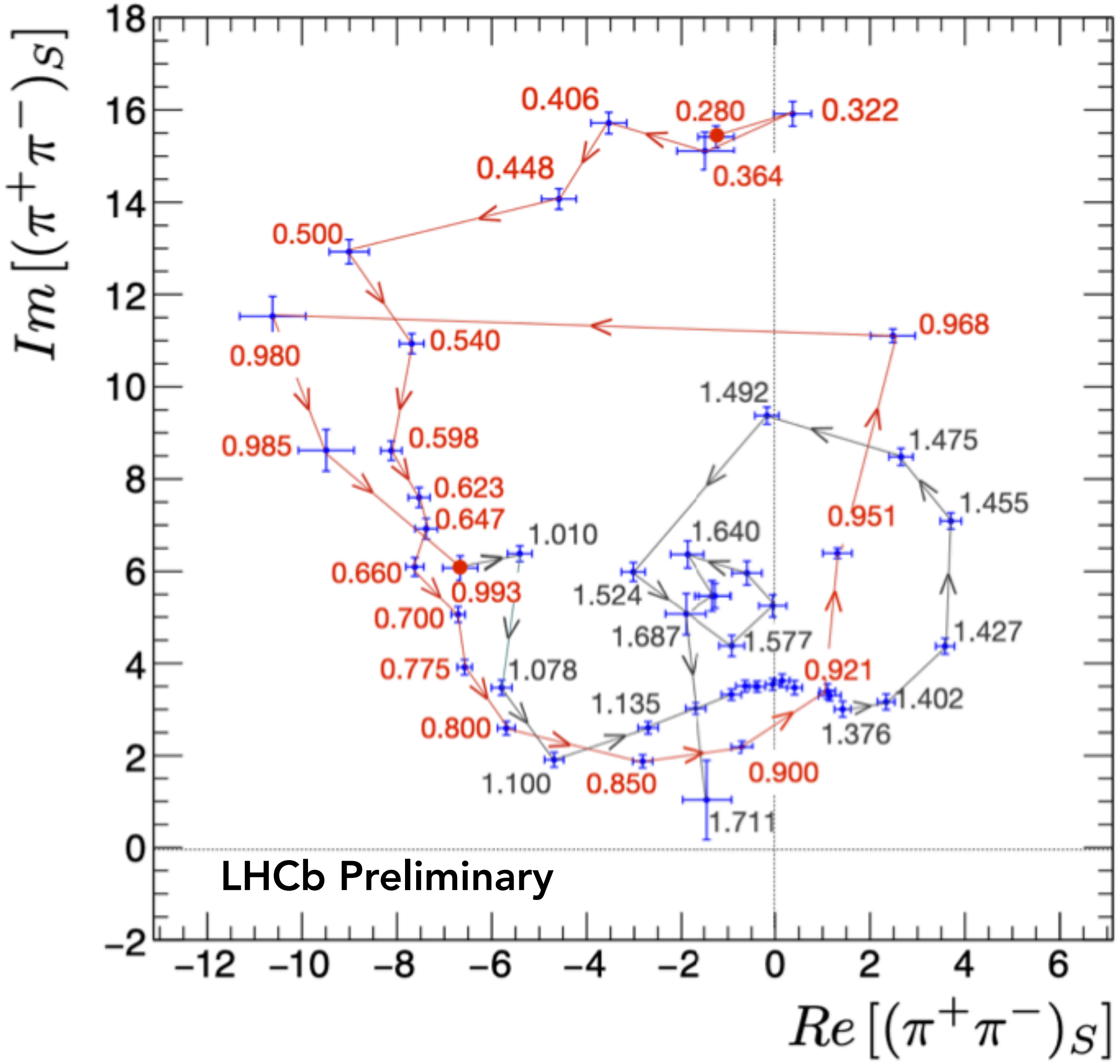
- Generate toys with a given binning scheme and fit each toy using the nominal binning. Observe the resulting distributions for each parameter and compare with the input.

Model systematics:

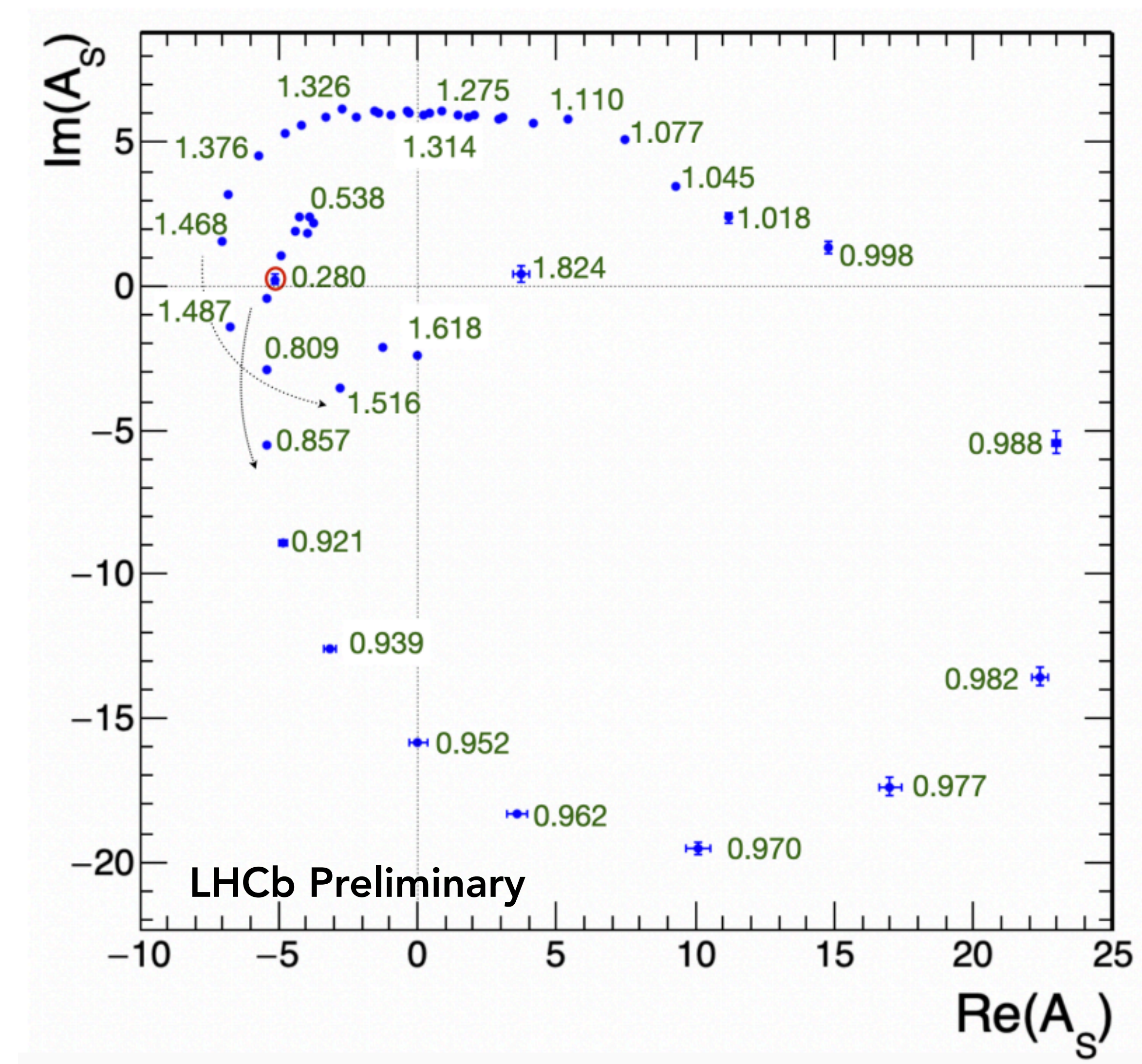
- Amplitude components: vary each lineshape parameter (masses and widths) within $\pm 1\sigma$
- Effective barrier radii of mesons: vary Blatt Weisskopf radius $r_{F_{D,Rp_3}} = 4.0,\ 5.0,\ 6.0$ GeV^{-1} and $r_{F_{R,p_1p_2}} = 1.0,\ 1.5,\ 2.0$ GeV^{-1}

Argand plots

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

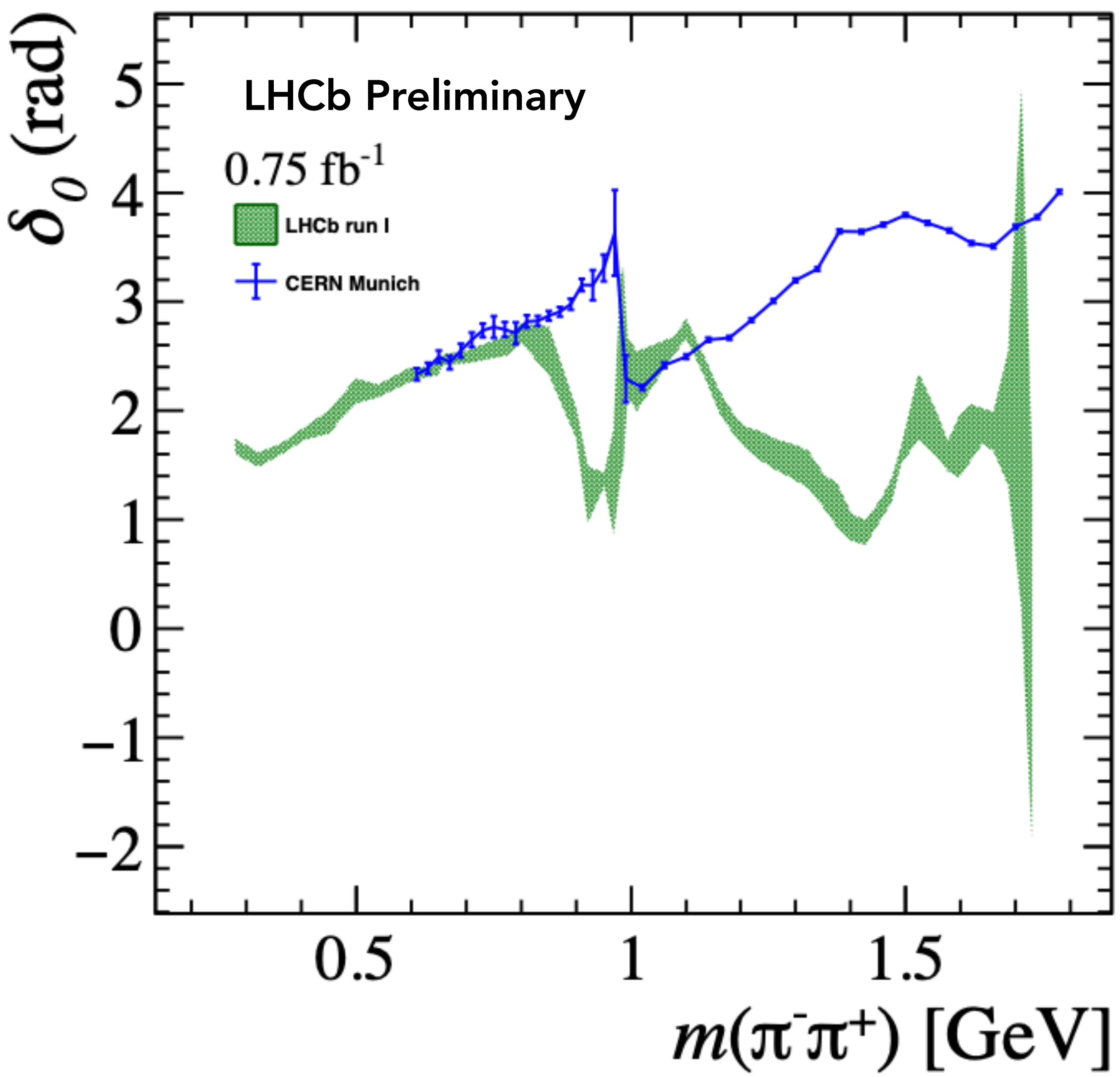


$D_s^+ \to \pi^-\pi^+\pi^+$



Comparison with scattering experiment

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



$D_s^+ \to \pi^-\pi^+\pi^+$