Dalitz Plot Analyses with $B \to Dhh$ decays at LHCb

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Outline

- ➢ **General view of Dalitz plot analyses with B→Dhh**
- ➢ **Results of excited D mesons**
- ➢ **Light meson structure studies**
- ➢ **Conclusion**

Analyses with B→Dhh

Decay Channels	Branching fractions (x10^{-4})	
$B^0 \to \overline{D}^0 \pi^+ \pi^-$	8.46±0.14±0.29±0.40	arXiv: 1505.01710; 3 fb^{-1}
$B_s^0 \to \overline{D}^0 f_0(980)$	0.017±0.010±0.005±0.001	arXiv: 1505.01654; 3 fb^{-1}
$B^0 \to \overline{D}^0 K^+ \pi^-$	0.92±0.06±0.07±0.06	arXiv: 1505.01505; 3 fb^{-1}
$B_s^0 \to \overline{D}^0 K^- \pi^+$	10.0±0.4±1.0±1.0	PRD 90, 072003 (2014); 3 fb^{-1}
$B^0 \to \overline{D}^0 K^- K^+$	0.47±0.09±0.06±0.05	PRL 109, 131801 (2012); 0.62 fb^{-1}
$B_s^0 \to \overline{D}^0 K^- K^+$	0.42±0.19	
$B^- \to D^+ K^- \pi^-$	0.731±0.019±0.022±0.039	PRD 91, 092002 (2015); 3 fb^{-1}
……	……	

Rich physics programs with B→Dhh decays at LHCb:

- ➢ **Understand excited D meson spectroscopy**
- ➢ **Understand ππ, Kπ, KK spectrum**
- ➢ **can be used for further studies to extract CKM angle γ, $\beta_{(s)}$**

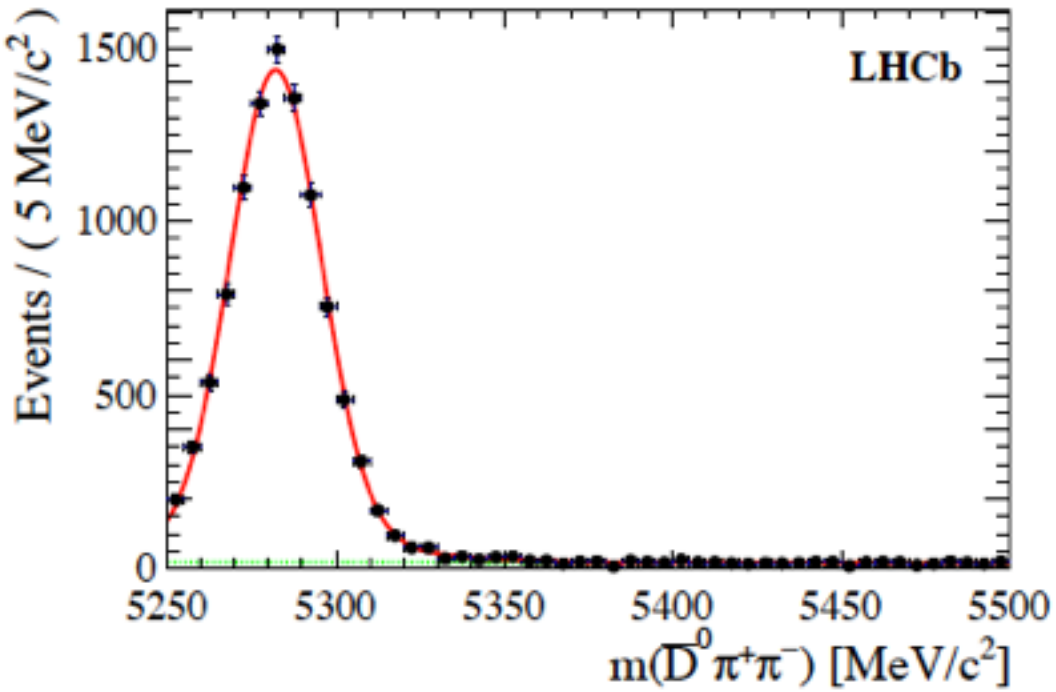
Dalitz plot analyses strategy (1)

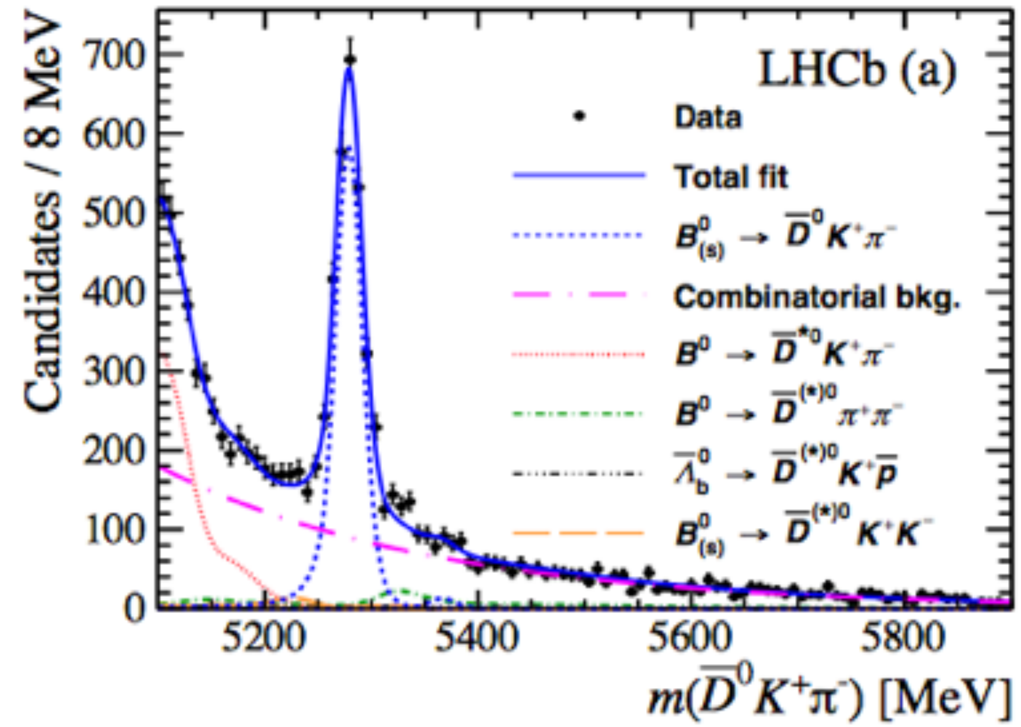
Similar Dalitz plot analysis strategy applied:

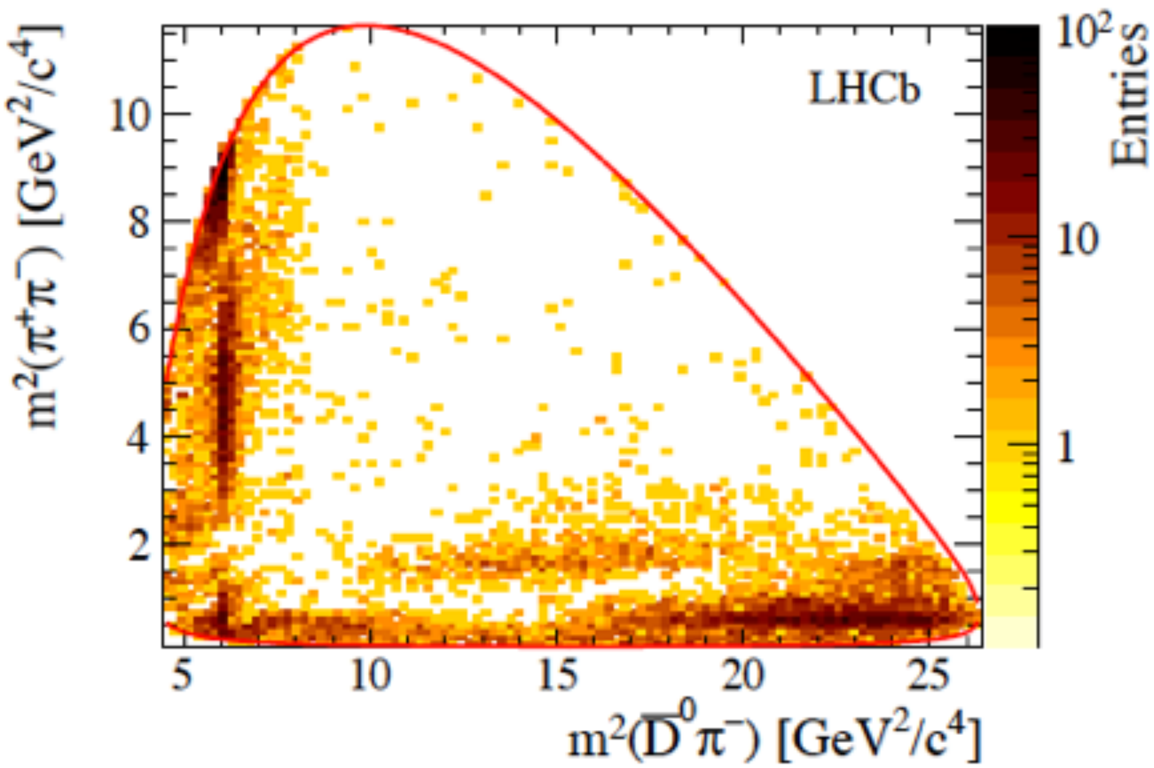
➢ **Optimized selection to achieve clean environment for Dalitz plot analyses**

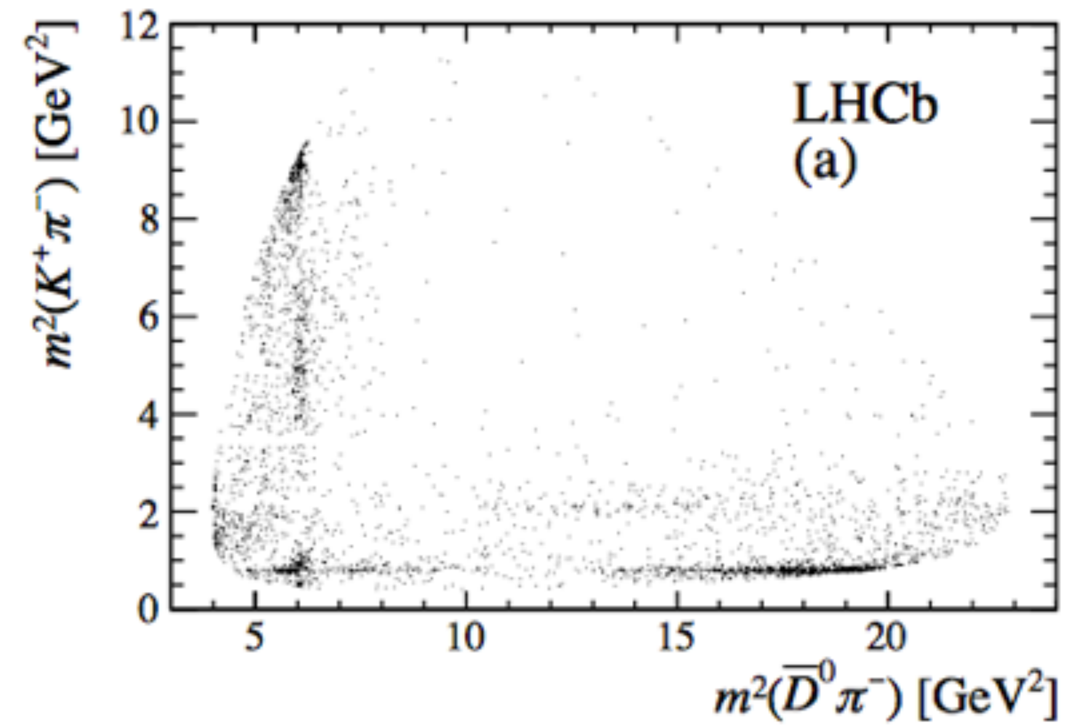
arXiv: 1505.01710; 3 fb^{-1} | $B^0 \to \overline{D}^0 \pi^+ \pi^-$

arXiv: 1505.01505; 3 fb^{-1} | $B^0 \to \overline{D}^0 K^+ \pi^-$







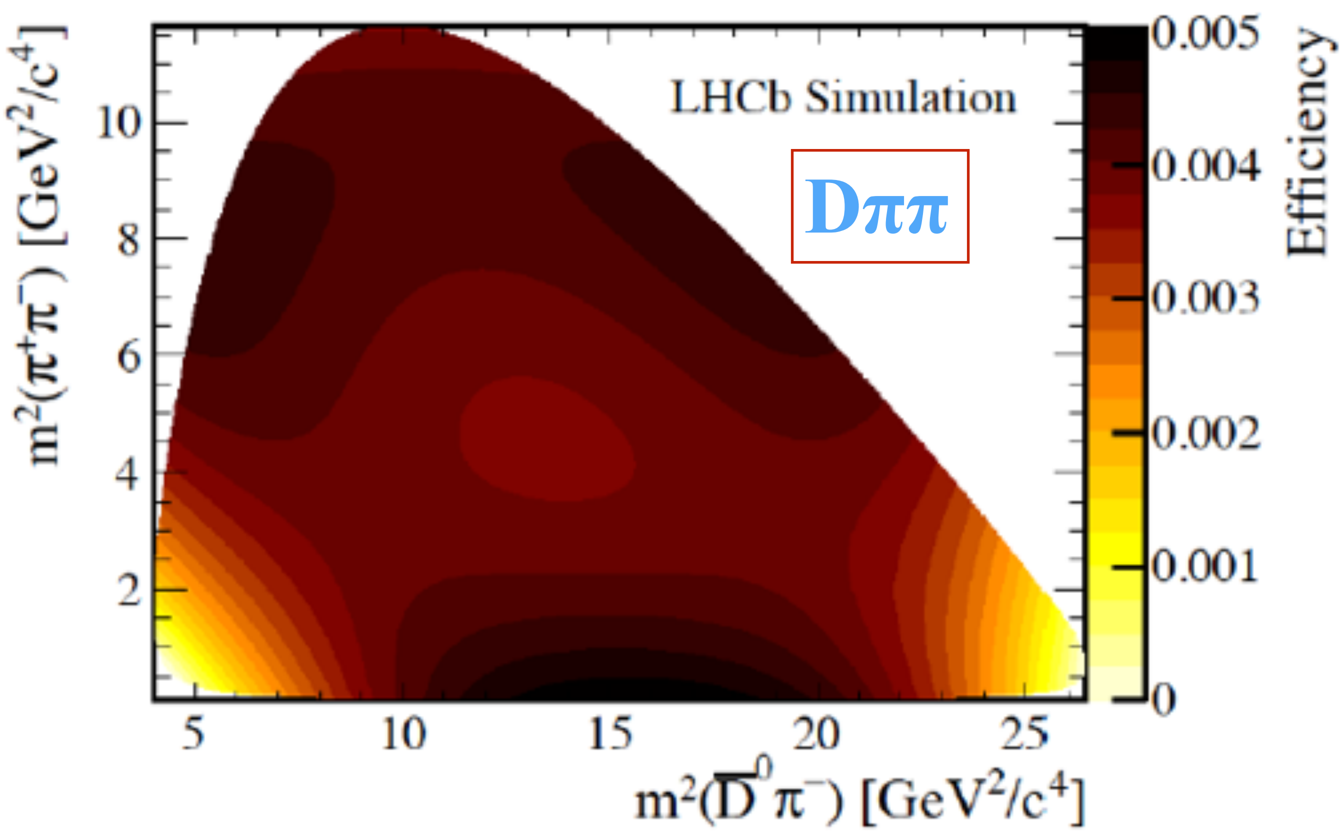


Dalitz plot analyses strategy (2)

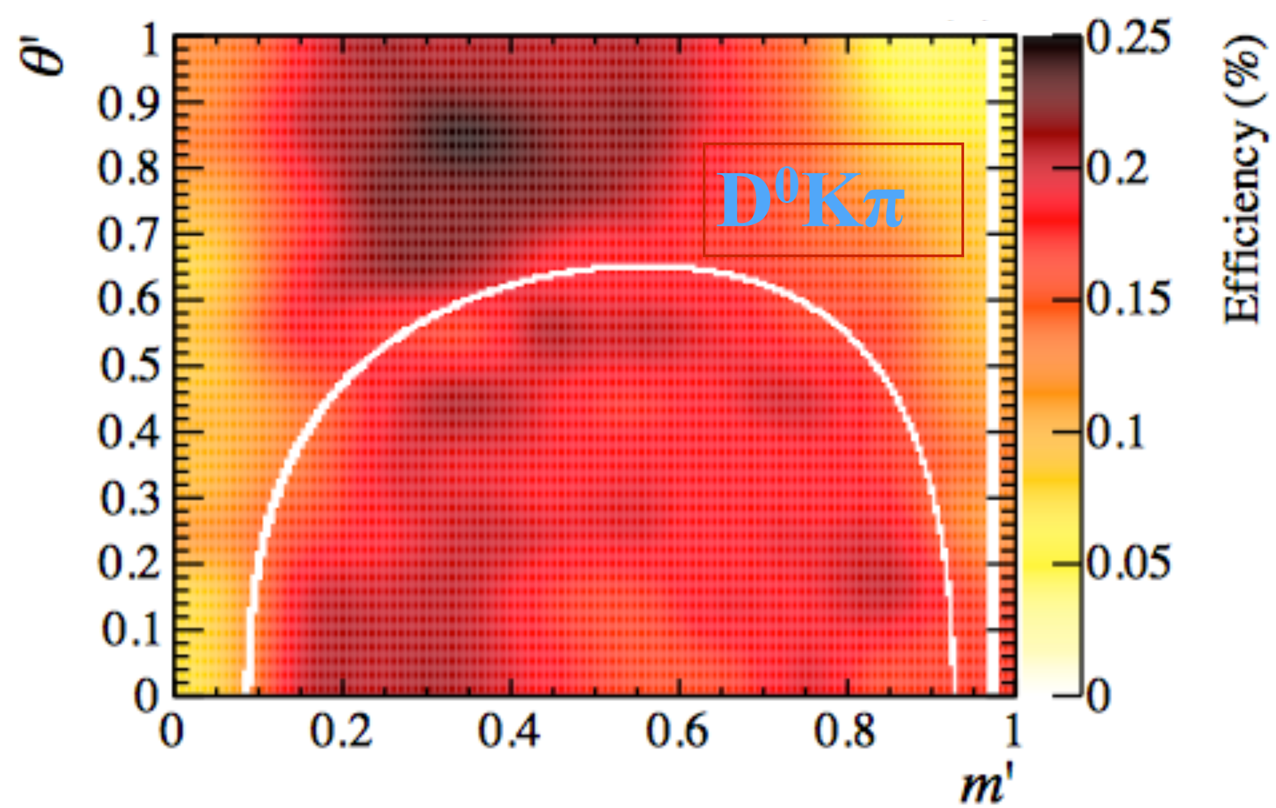
Similar Dalitz plot analysis strategy applied:

➢ **Efficiency obtained from Monte Carlo with data-driven method to correct for data and Monte Carlo difference**

arXiv: 1505.01710; 3 fb^{-1} $B^0 \to \overline{D}^0 \pi^+ \pi^-$



arXiv: 1505.01505; 3 fb^{-1} $B^0 \to \overline{D}^0 K^+ \pi^-$

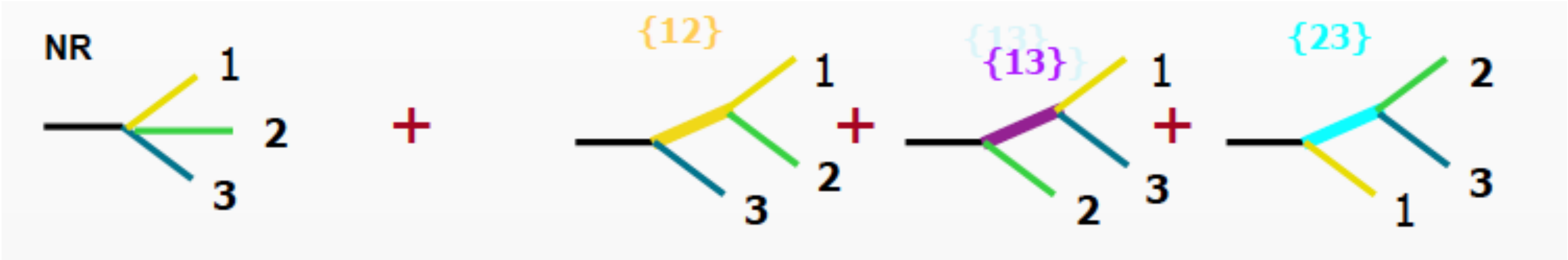


➢ **Combinatorial background modeled from sidebands**

➢ **Peaking background either suppressed to negligible level or modeled using Dalitz model obtained from other analyses**

Dalitz formalism with B→Dhh

Modeled by Isobar formalism: total amplitude as coherent sum of quasi-two-body contributions (ππ S-wave also uses K-matrix formalism)



$$A(s_{12}, s_{23}) = \sum_j A_j = \sum_j a_j F_j(s_{12}, s_{23})$$

CP violation effect negligible in current analyses

- **s_{12}, s_{23} are the invariant mass squared of two of the three decay particles**
- **sum over all resonant contributions**
- **a_j: complex fit parameters to describe relative contributions between resonances**
- **$F_j(s_{12}, s_{23})$: strong dynamics including resonant line shapes, angular distributions etc.**

Output of Dalitz plot analyses

- **Resonant contributions, relative amplitudes and phases of resonances, fit fractions, resonant properties etc.**

Spectroscopy of charmed mesons

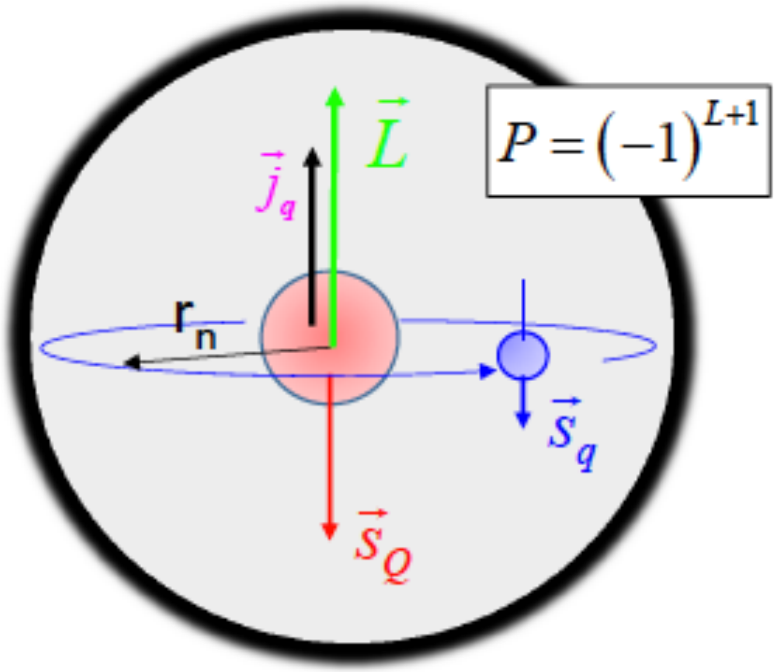
➢ **Tests of HQET, potential models, Lattice QCD, …**

➢ **Inputs for other studies, exotic states, R(D$^{(*)}$), …**

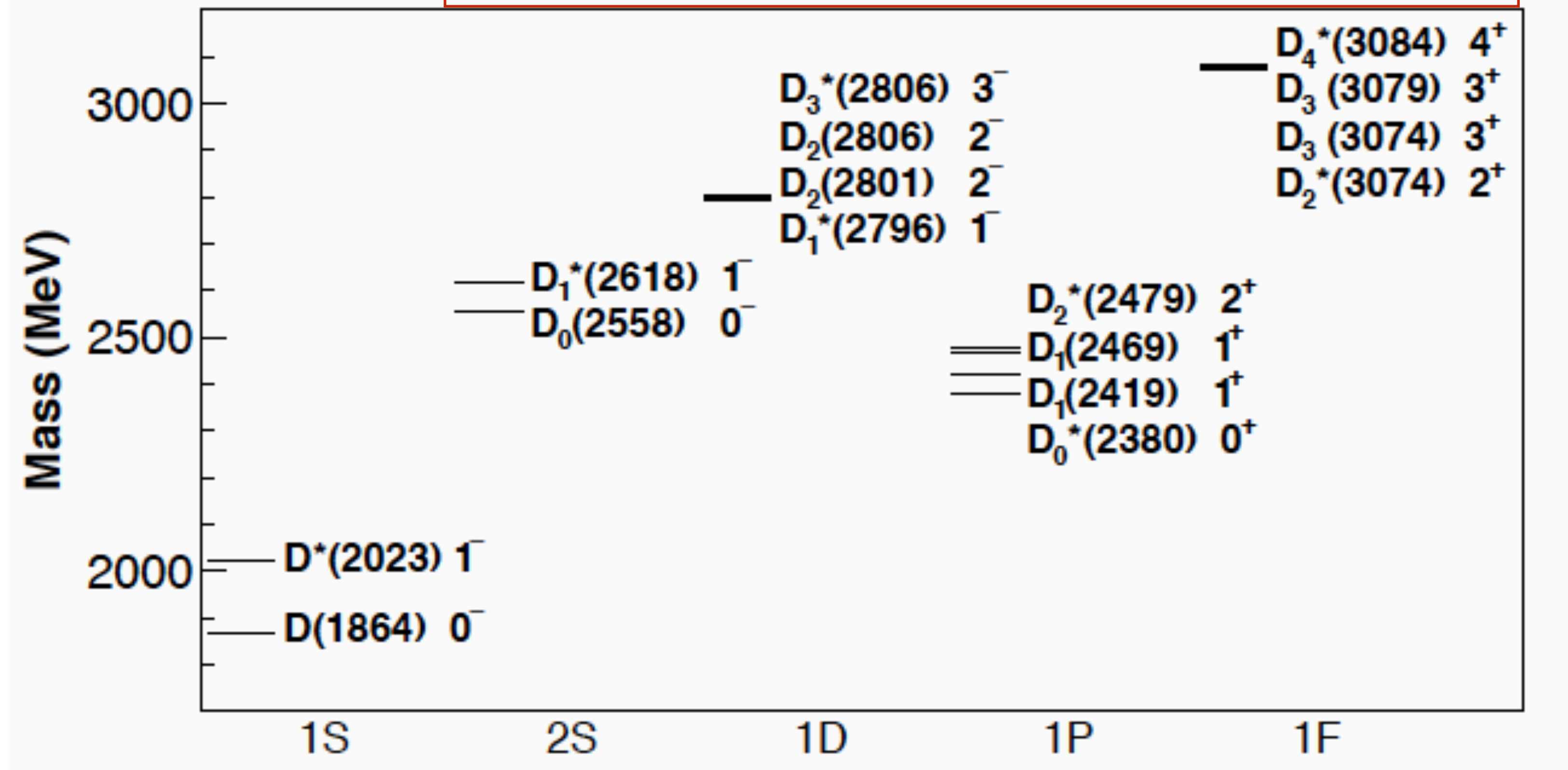
$J^P \; Q\bar{q}$ meson

$\vec{J} = \vec{j}_q + \vec{s}_Q$

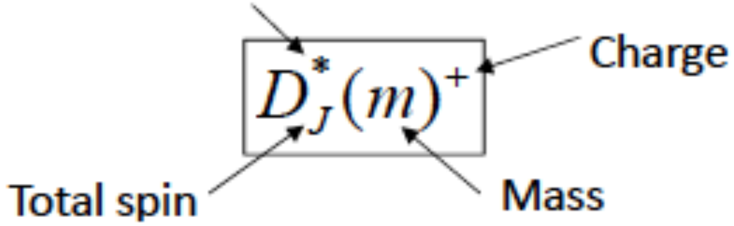
$\vec{j}_q = \vec{L} + \vec{s}_q$



S. Godfrey, N. Isgur, Phys. Rev. D32, 189 (1985)



* Indicates "natural" parity (0⁺, 1⁻, 2⁺ ...)

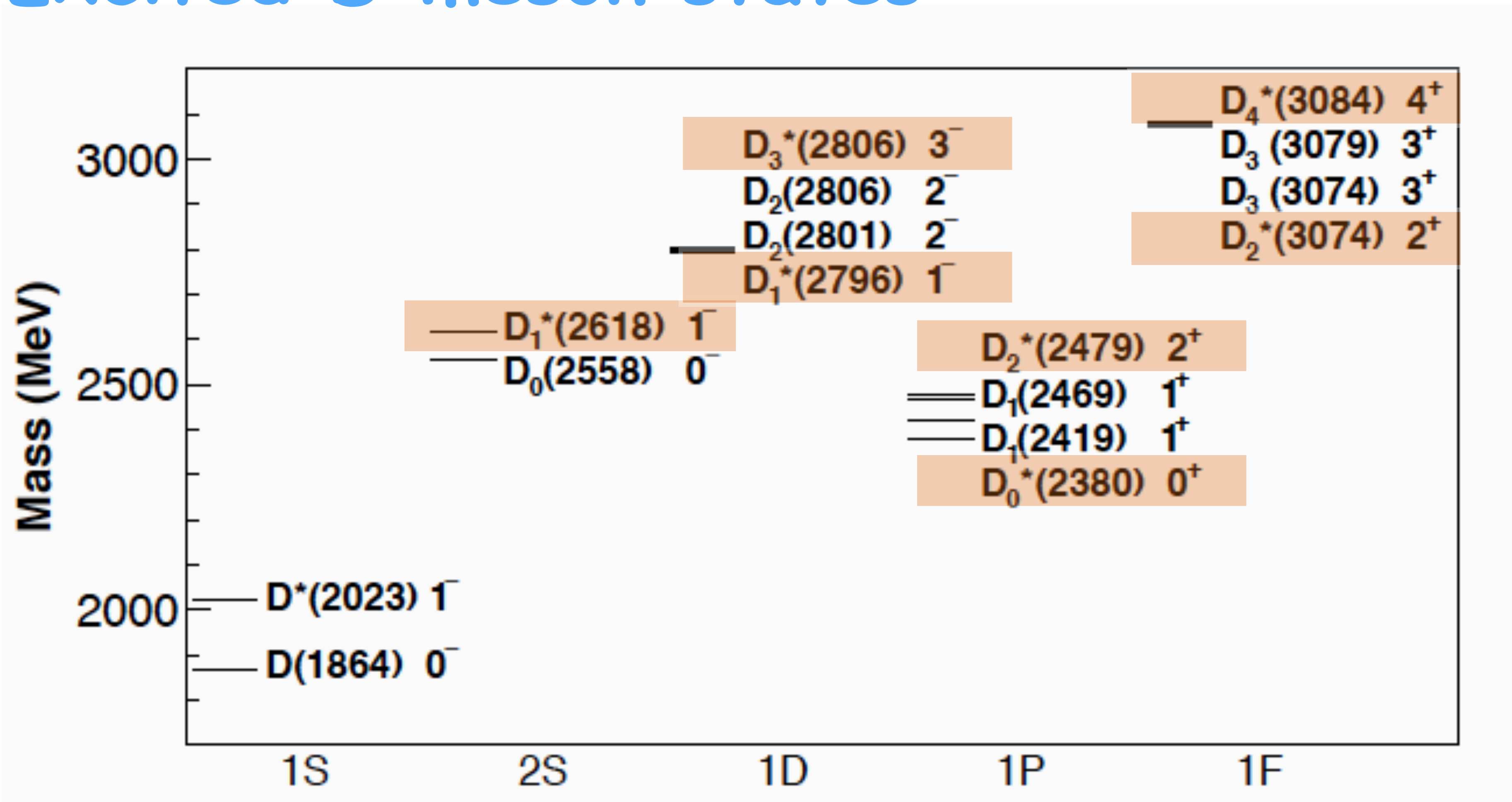


States appear in doublet with similar widths: one with "natural" parity (0^+, 1^-, 2^+,…) and one with "unnatural" parity (0^-, 1^+, 2^-,…)

Similar for D^{*0}, D^{*+}, Ds^{*+}

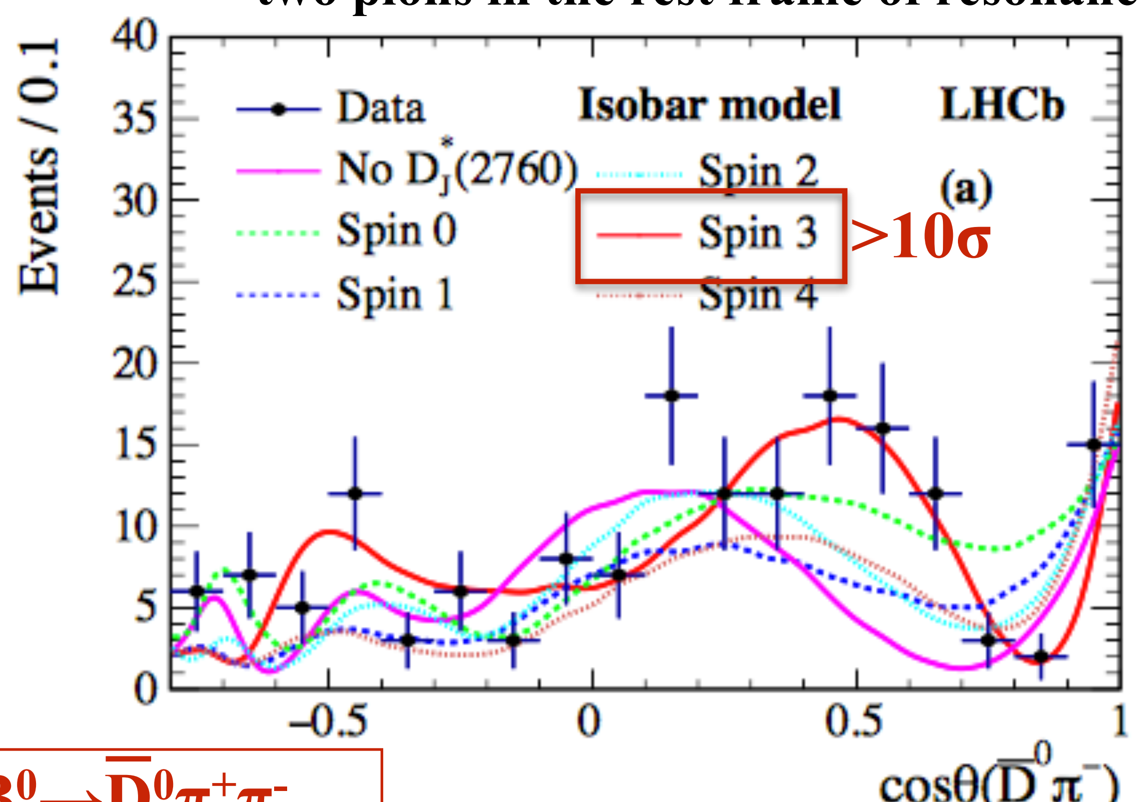
Excited D meson states

arXiv: 1505.01710; 3 fb^{-1}
PRD 91, 092002 (2015); 3 fb^{-1}
JHEP 09, 145 (2013); 3 fb^{-1}



States in $B^0 \to \overline{D}^0 \pi^+ \pi^-$, $B^0 \to \overline{D}^0 K^+ \pi^-$, $B^- \to D^+ K^- \pi^-$, Dalitz plot analysis

$\theta(D\pi)$ is helicity angle defined between directions of two pions in the rest frame of resonance



$B^0 \to \overline{D}^0 \pi^+ \pi^-$

- **$D_0(2400)$, $D_2(2460)$ dominant in all analyses**
- **Many new D^* states observed in inclusive D spectroscopy: $D^*(2650)$, $D^*(2760)$, $D^*(3000)$**
- **A D^* with spin 3 and mass around 2800 MeV observed in $B^0 \to \overline{D}^0 \pi^+ \pi^-$ analysis**
- **A D^* with spin 1 and mass around 2791 MeV observed in $B^- \to D^+ K^- \pi^-$ analysis**

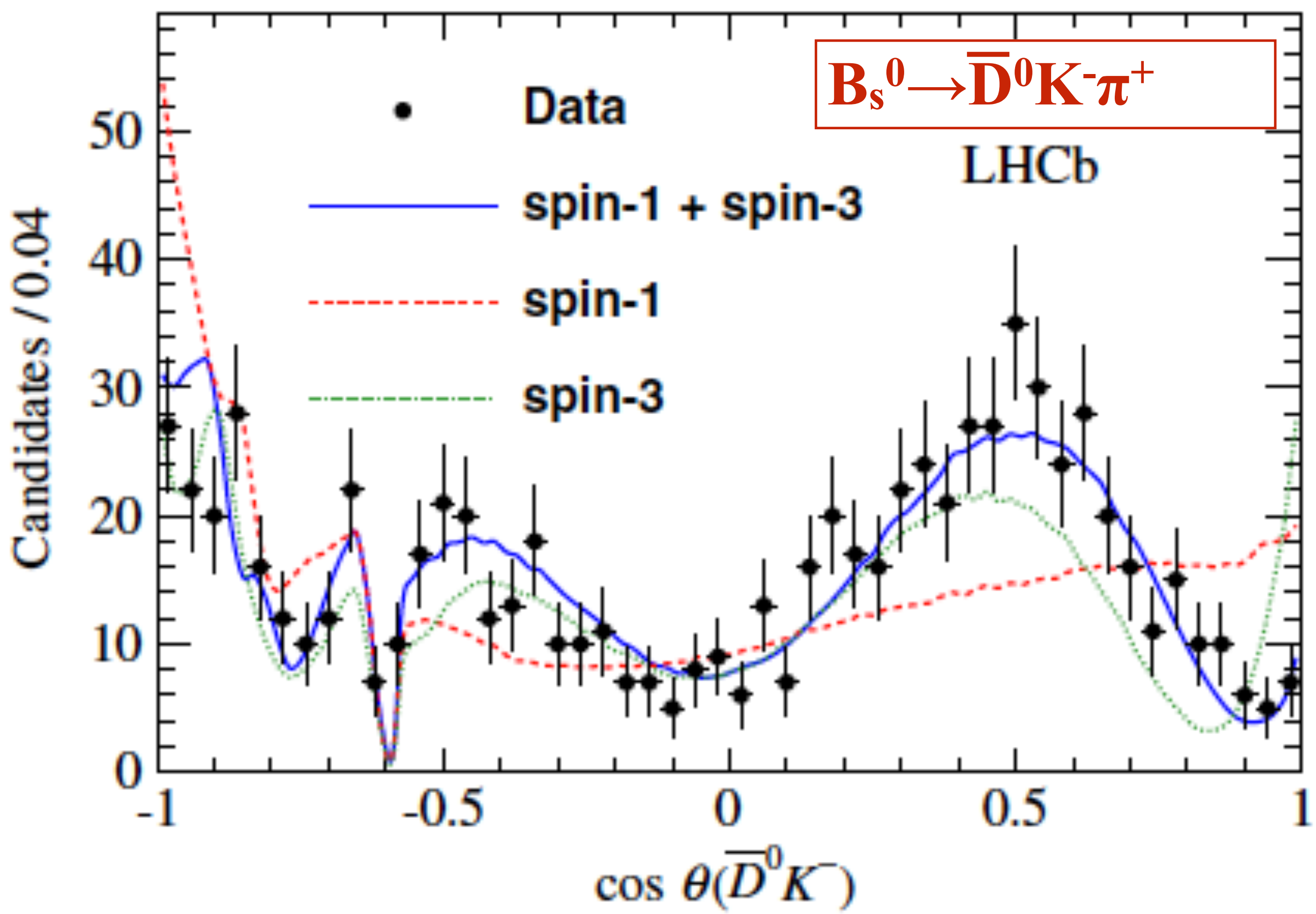
Excited D_s meson states

LHCb, PRD 90, 072003 (2014); 3 fb^{-1}
LHCb, JHEP 10, 151 (2012); 1 fb^{-1}
Babar, PRD 80, 092003 (2009)

State	Mass	Width	Comment
	BABAR		
$D^*_{s1}(2700)^-$	$2710 \pm 2^{+12}_{-7}$	$149 \pm 7^{+39}_{-52}$	Seen in DK and D^*K
$D^*_{sJ}(2860)^-$	$2862 \pm 2^{+5}_{-2}$	$48 \pm 3 \pm 6$	Seen in DK and D^*K
$D_{sJ}(3040)^-$	$3044 \pm 8^{+30}_{-5}$	$239 \pm 35^{+46}_{-42}$	Seen in D^*K only
	LHCb		
$D^*_{s1}(2700)^-$	$2709.2 \pm 1.9 \pm 4.5$	$115.8 \pm 7.3 \pm 12.1$	Only DK studied
$D^*_{sJ}(2860)^-$	$2866.1 \pm 1.0 \pm 6.3$	$69.9 \pm 3.2 \pm 6.6$	

- **Many new D_s^* states also observed in inclusive D_s spectroscopy: $D_s^*(2700)$, $D_s^*(2860)$, $D_s^*(3040)$**

- **A structure around 2860 MeV with both spin 1 and spin 3 resonant contributions is found**



Excited D meson masses and widths

arXiv: 1505.01710; 3 fb^{-1}
PRD 91, 092002 (2015); 3 fb^{-1}
PRD 90, 072003 (2014); 3 fb^{-1}

➢ **Spin 3 D^* meson around 2800 MeV from $B^0 \to \overline{D}^0 \pi^+ \pi^-$**

		Isobar	K-matrix
$D_3^*(2760)$	m	$2798 \pm 7 \pm 1 \pm 7$	$2802 \pm 11 \pm 10 \pm 3$
	Γ	$105 \pm 18 \pm 6 \pm 23$	$154 \pm 27 \pm 13 \pm 9$

➢ **Spin 1 D^* meson around 2791 MeV from $B^- \to D^+ K^- \pi^-$**

$D_1^*(2760)$	m	$2791 \pm 18 \pm 11 \pm 6$
	Γ	$177 \pm 32 \pm 20 \pm 7$

➢ **Spin 1 and spin 3 mixture of D_s^* meson around 2860 MeV from $B_s^0 \to \overline{D}^0 K^- \pi^+$**

$D_{s1}^*(2860)$	m	$2859 \pm 12 \pm 6 \pm 23$
	Γ	$159 \pm 23 \pm 27 \pm 72$
$D_{s3}^*(2860)$	m	$2860.5 \pm 2.6 \pm 2.5 \pm 6.0$
	Γ	$53 \pm 7 \pm 4 \pm 6$

➢ **More precise and accurate also for other D^* states like $D_0^*(2400)$, $D_2^*(2460)$ etc compared to previous measurements**

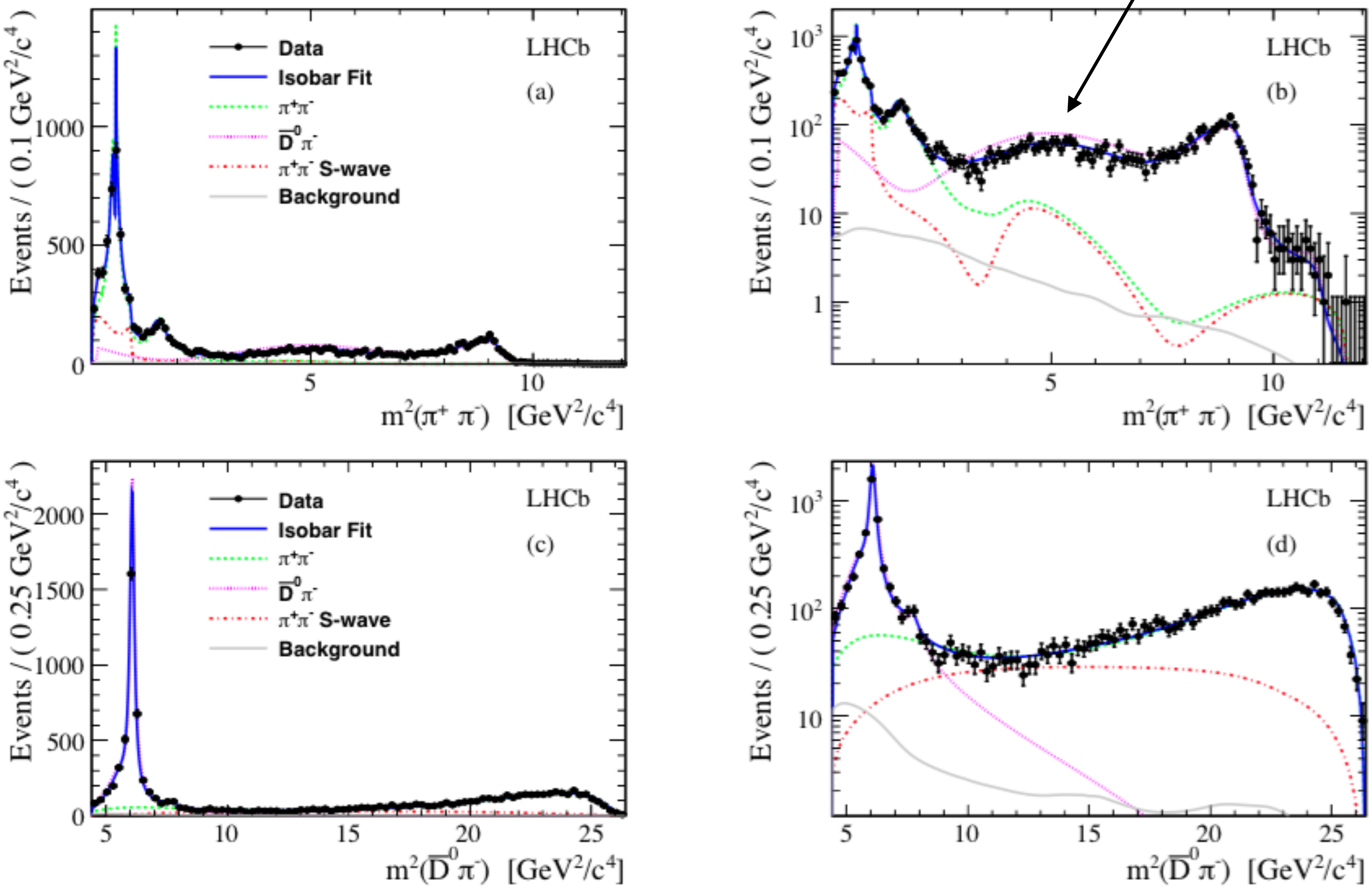
Dalitz fit display: $B^0 \to \overline{D}^0 \pi^+ \pi^-$

arXiv: 1505.01710; 3 fb^{-1}

larger subcomponent due to interference

ππ

Dπ



linear

log

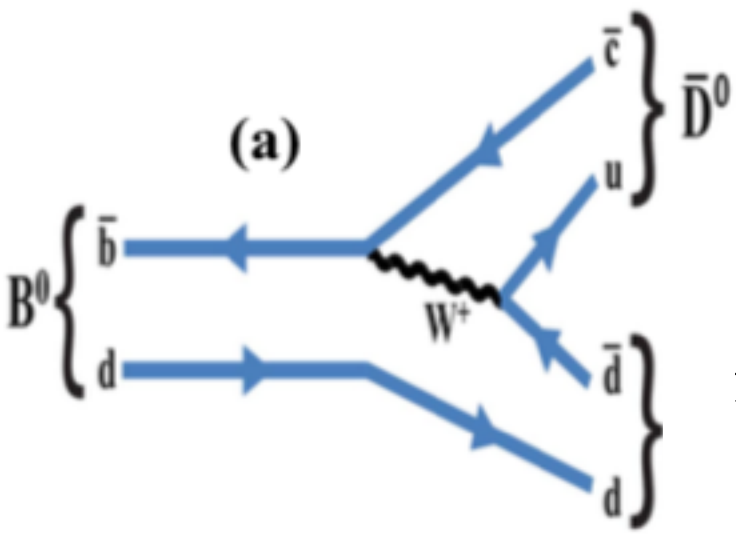
Dalitz fit display: $B^0 \to \overline{D}{}^0 \pi^+ \pi^-$

arXiv: 1505.01710; 3 fb^{-1}

Resonance	Isobar ($\times 10^{-5}$)	K-matrix ($\times 10^{-5}$)
$f_0(500)$	$11.2 \pm 0.8 \pm 0.5 \pm 2.1 \pm 0.5$	n/a
$f_0(980)$	$1.34 \pm 0.25 \pm 0.10 \pm 0.46 \pm 0.06$	n/a
$f_0(2020)$	$1.35 \pm 0.31 \pm 0.14 \pm 0.85 \pm 0.06$	n/a
S-wave	$14.1 \pm 0.5 \pm 0.6 \pm 1.3 \pm 0.7$	$14.2 \pm 0.6 \pm 1.5 \pm 0.9 \pm 0.7$
$\rho(770)$	$32.1 \pm 1.0 \pm 1.2 \pm 0.9 \pm 1.5$	$31.0 \pm 1.0 \pm 2.1 \pm 0.7 \pm 1.5$
$\omega(782)$	$0.42 \pm 0.11 \pm 0.02 \pm 0.03 \pm 0.02$	$0.43 \pm 0.11 \pm 0.02 \pm 0.02 \pm 0.02$
$\rho(1450)$	$1.36 \pm 0.28 \pm 0.08 \pm 0.19 \pm 0.06$	$1.91 \pm 0.37 \pm 0.73 \pm 0.19 \pm 0.09$
$\rho(1700)$	$0.33 \pm 0.11 \pm 0.06 \pm 0.05 \pm 0.02$	$0.73 \pm 0.18 \pm 0.53 \pm 0.10 \pm 0.03$
$f_2(1270)$	$9.5 \pm 0.5 \pm 0.4 \pm 1.0 \pm 0.4$	$9.1 \pm 0.6 \pm 0.8 \pm 0.5 \pm 0.4$
$D_0^*(2400)^-$	$7.7 \pm 0.5 \pm 0.3 \pm 0.3 \pm 0.4$	$8.0 \pm 0.5 \pm 0.8 \pm 0.4 \pm 0.4$
$D_2^*(2460)^-$	$24.4 \pm 0.7 \pm 1.0 \pm 0.4 \pm 1.2$	$23.8 \pm 0.7 \pm 1.2 \pm 0.5 \pm 1.1$
$D_3^*(2760)^-$	$1.03 \pm 0.16 \pm 0.07 \pm 0.08 \pm 0.05$	$1.34 \pm 0.19 \pm 0.16 \pm 0.06 \pm 0.06$

Light meson structure (1)

2-q model



f₀(500) or f₀(980)

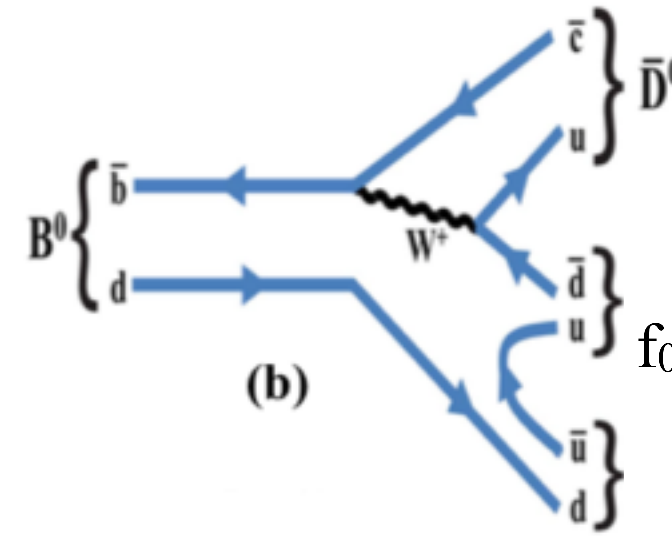
$$|f_0(500)>=\frac{1}{\sqrt{2}}(|\bar{u}u>+|\bar{d}d>)\equiv|\bar{n}n>$$

$$|f_0(980)>=|\bar{s}s>$$

$$|f_0(980)\rangle = |\bar{s}s\rangle\cos\theta+|\bar{n}n\rangle\sin\theta,$$

$$|f_0(500)\rangle = -|\bar{s}s\rangle\sin\theta+|\bar{n}n\rangle\cos\theta.$$

4-q model



$f_0(500)$ or $f_0(980)$

$$|f_0(500)>=|\bar{u}u\bar{d}d>$$

$$|f_0(980)>=|\bar{n}n\bar{s}s>$$

$$|f_0(980)\rangle = |\bar{n}n\bar{s}s\rangle\cos\phi+|\bar{u}u\bar{d}d\rangle\sin\phi,$$

$$|f_0(500)\rangle = -|\bar{n}n\bar{s}s\rangle\sin\phi+|\bar{u}u\bar{d}d\rangle\cos\phi,$$

- **Proposals given to use $B_{(s)}\rightarrow J/\psi\pi\pi$ to understand nature of light mesons $f_0(500)$ and $f_0(980)$ and has been performed by LHCb to set upper limits on mixing angles**

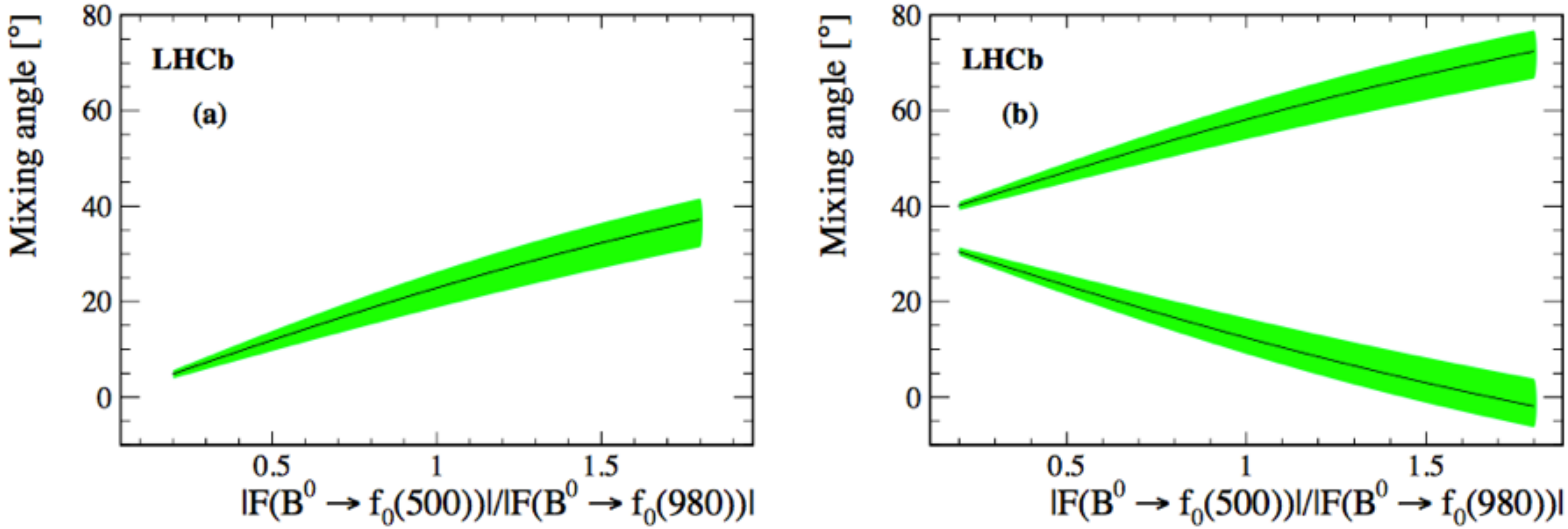
- **Similar studies can also be done for $B_{(s)}\rightarrow\overline{D}^0\pi\pi$ decays**

Light meson structure (2)

arXiv: 1505.01710; 3 fb^{-1}
arXiv: 1505.01654; 3 fb^{-1}

	$\mathcal{B}(B^0 \to \overline{D}^0 f_0)$	$\mathcal{B}(B_s^0 \to \overline{D}^0 f_0)$
$f_0(500)$	$(11.2 \pm 0.8 \pm 0.5 \pm 2.1 \pm 0.5) \times 10^{-5}$	—
$f_0(980)$	$(1.34 \pm 0.25 \pm 0.10 \pm 0.46 \pm 0.06) \times 10^{-5}$	$(1.7 \pm 1.0 \pm 0.5 \pm 0.1) \times 10^{-6}$

2-q model **4-q model**



- ➢ **Mixing angles of 2-q and 4-q model given as a function of form factor ratios**
- ➢ **Results from $B_s^0 \to \overline{D}^0 f_0(980)$, $B^0 \to \overline{D}^0 f_0(980)$ and $B^0 \to \overline{D}^0 f_0(500)$ indicate complicated nature of the system**

Other results

LHCb-PAPER-2014-070; 3 fb^{-1}

Channels	Isobar x 10^{-5}	K-Matrix
$\rho(770)(\pi^+\pi^-)$	$32.1 \pm 1.4 \pm 1.2 \pm 0.9 \pm 1.5$	$31.0 \pm 1.4 \pm 2.1 \pm 0.7 \pm 1.5$

- **Isospin symmetry between three decays: $B^+ \to D^0\rho^+$, $B^0 \to D^-\rho^+$, $B^0 \to \overline{D}^0\rho^0$,**

$$\begin{aligned} A(\overline{D}^0\rho^+) &= \sqrt{3}A_{3/2}, \\ A(D^-\rho^+) &= \sqrt{1/3}A_{3/2} + \sqrt{2/3}A_{1/2}, \\ A(\overline{D}^0\rho^0) &= \sqrt{2/3}A_{3/2} - \sqrt{1/3}A_{1/2}, \end{aligned}$$

In factorization approximation:

$$R_{D\rho} = \frac{|A_{1/2}|}{\sqrt{2}|A_{3/2}|} = 1 + \mathcal{O}(\Lambda_{QCD}/m_b) \qquad \delta_{D\rho} = \arg\left(\frac{A_{1/2}}{A_{3/2}}\right) \sim \mathcal{O}(\Lambda_{QCD}/m_b)$$

Model	$R_{D\rho}$	$\cos\delta_{D\rho}$
Isobar	0.69 ± 0.15	$0.984^{+0.113}_{-0.048}$
K-matrix	0.69 ± 0.15	$0.987^{+0.114}_{-0.048}$

- **Uncertainties mainly from Br of $D^+\rho^+$ and $D^0\rho^-$**

- **The results are not different from the prediction of factorization**

Conclusion

- **Rich physics in $B \to Dhh$ systems using Dalitz plot techniques**

- **Studies have been performed to understand their resonant contributions, excited D^* spectroscopy, light meson structures etc.**

- **Stay tuned for more analyses in the $B \to Dhh$ system**

Thank You