Dispersive analyses for Giant CP Violation in B to three light mesons bellow 1 GeV

III CONGRESO DE IPARCOS

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Preliminary results in collaboration with C. Hanhart, L. Heuser, B. Kubis and P. Magalhaes

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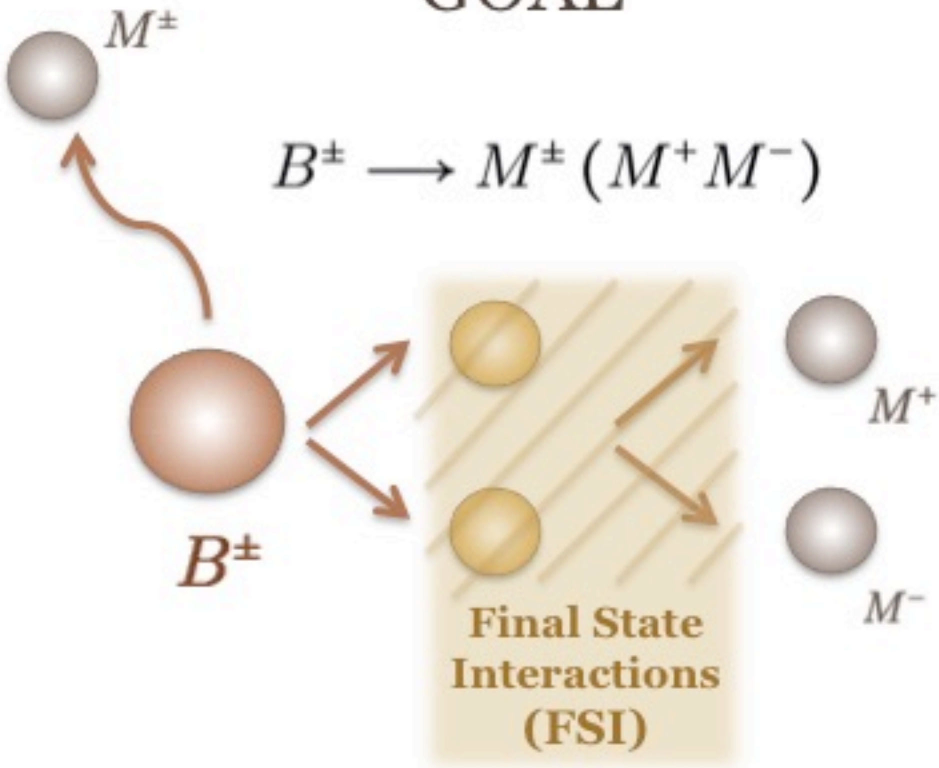
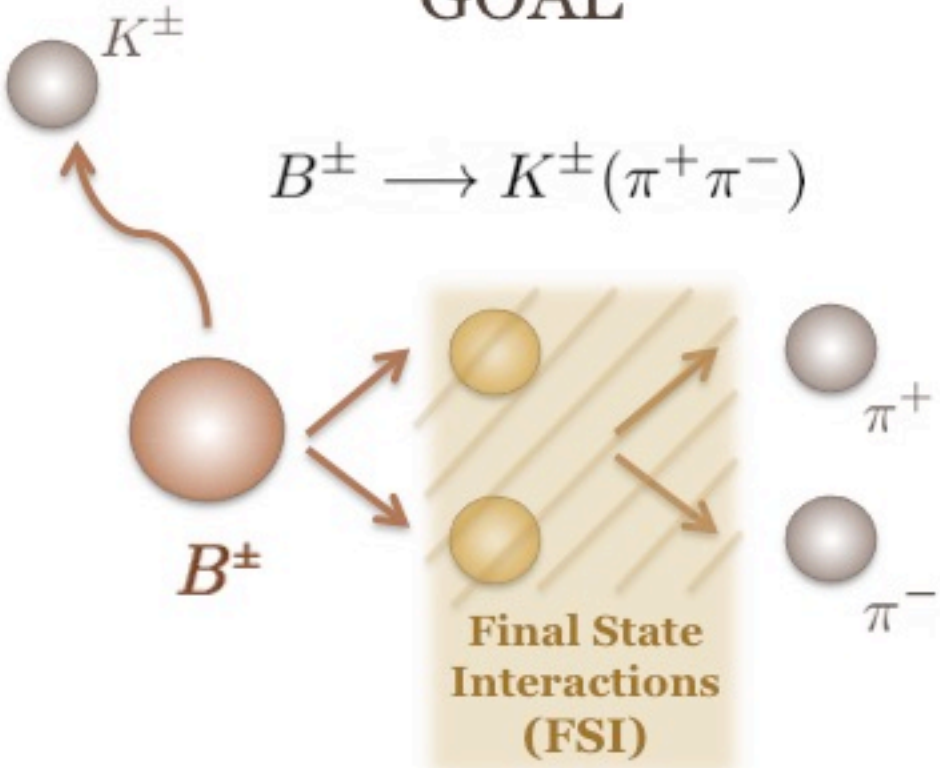
GOAL



Describe B meson decays into three light mesons

GOAL

$$B^{\pm} \longrightarrow K^{\pm}(\pi^{+}\pi^{-})$$



STRUCTURE OF THE PRESENTATION

1. Brief introduction
2. Experimental framework. How can we approach these decays?
3. Formalism for FSI
   - Dispersive analysis via Omnès funtions
   - Problems and solutions
   - Results
4. Conclusions

- CP violation (CPV) relevant for bariogenesis and other open questions within the SM

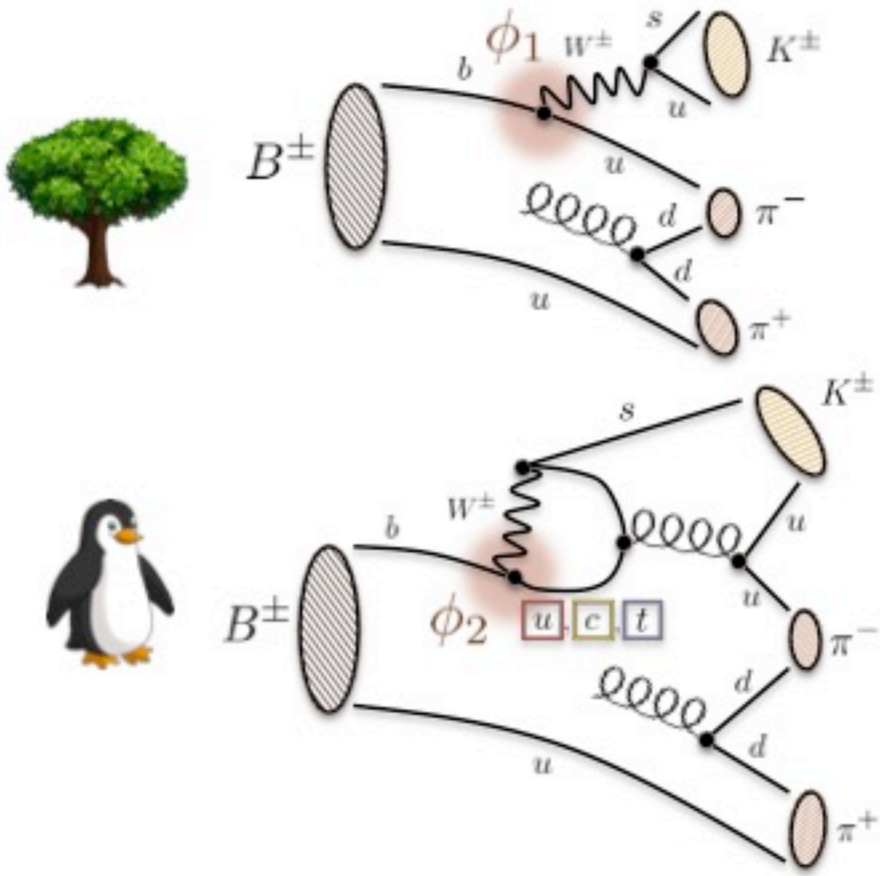
- CPV observed through
  - CP forbidden processes
  - Asymmetries between CP-conjugated decays
    $\mathcal{A}_{CP} \equiv \Delta\Gamma_f = \Gamma(M \to f) - \Gamma(\bar{M} \to \bar{f})$

- In the SM quark/hadron CPV due to "weak" phase in the CKM matrix

To observe such CP phase in an asymmetry we need interference between at least two mechanisms/diagrams with different weak and strong phases

[1] Bander Silverman & Soni PRL 43 (1979) 242

- “Tree+ Penguin”, BSS model



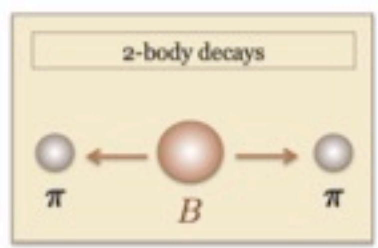
[2] L. Wolfenstein, Phys. Rev. D 43, (1991) 151
[3] M. Suzuki and L. Wolfenstein, Phys. Rev. D 60, (1999) 074019
[4] M. Suzuki, Phys. Rev. D 77, (2008) 054021

- CPV (weak) phase appears in the quark CKM matrix
- Strong imaginary part is due to the loop, which are not physical states

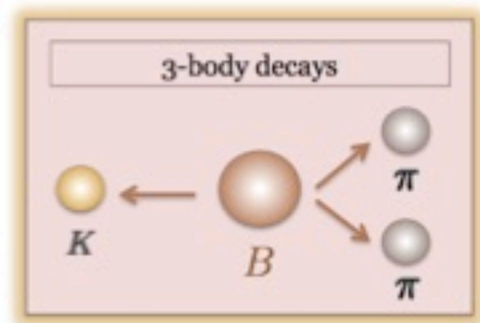
↓

However, strong phases can be generated at the “hadron level” via Hadronic FSI

2-body decays vs 3-body decays



We see a point



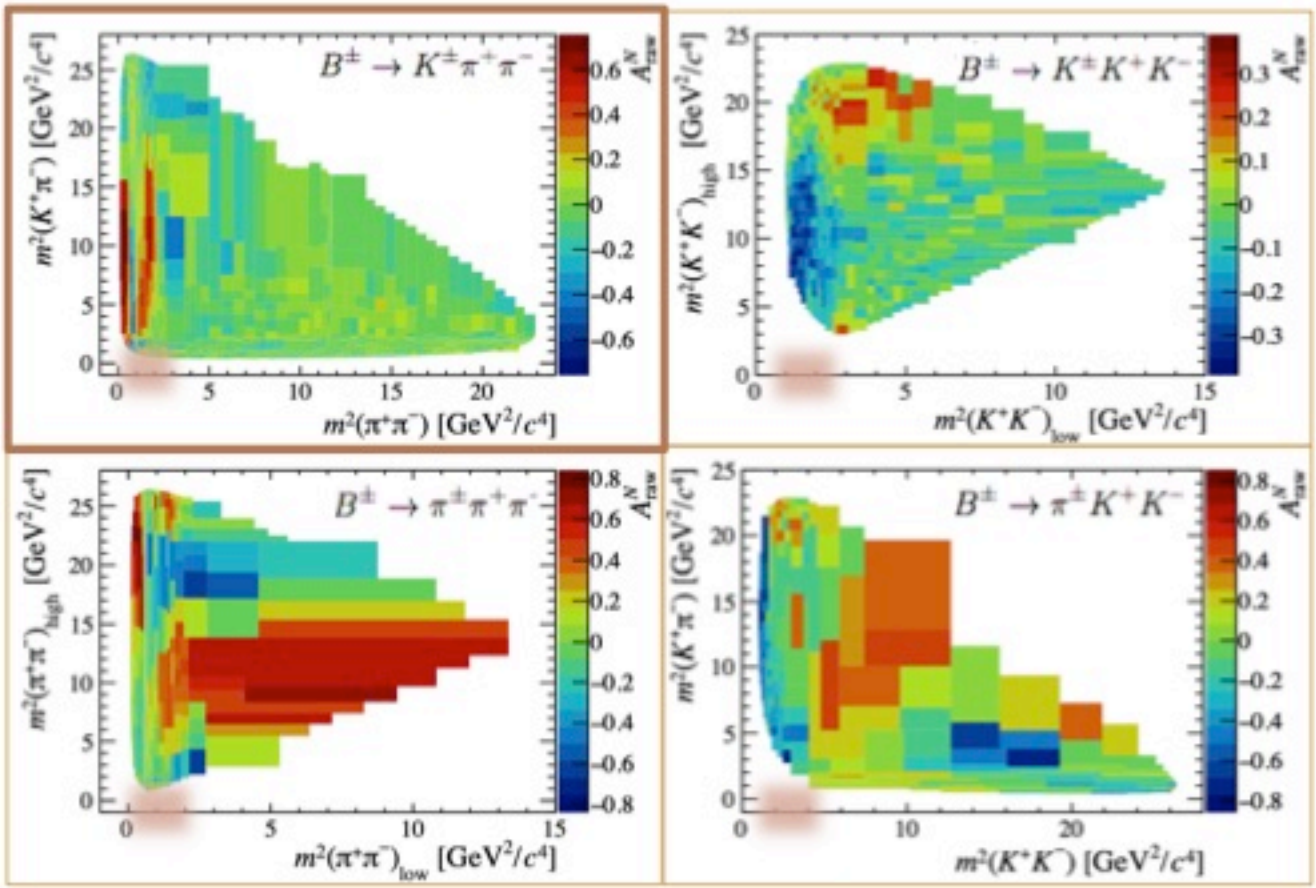
We see a behavior

Giant CPV in charmless B three-body decays at LHCb

- Large **integrated** CPV asymmetries 10 %

$A_{CP}(B^\pm \to K^\pm\pi^+\pi^-) = +0.011 \pm 0.002 \pm 0.003 \pm 0.003,\quad A_{CP}(B^\pm \to \pi^\pm\pi^+\pi^-) = +0.080 \pm 0.004 \pm 0.003 \pm 0.003,$

$A_{CP}(B^\pm \to K^\pm K^+K^-) = -0.037 \pm 0.002 \pm 0.002 \pm 0.003,\quad A_{CP}(B^\pm \to \pi^\pm K^+K^-) = -0.114 \pm 0.007 \pm 0.003 \pm 0.003,$



RUN2 5.9 fb^{-1}

[5] R. Aaij, *et al* Phys. Rev. D 108.1 (2023) 012008

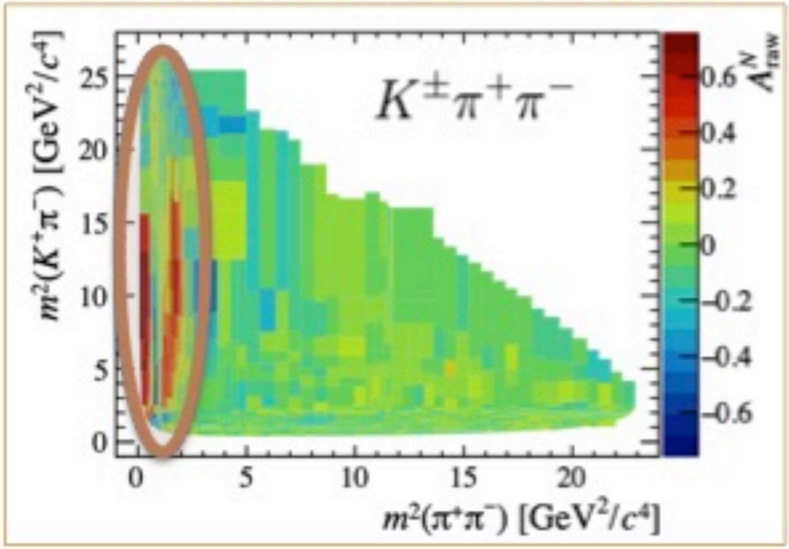
- **GIANT local** CPV asymmetries

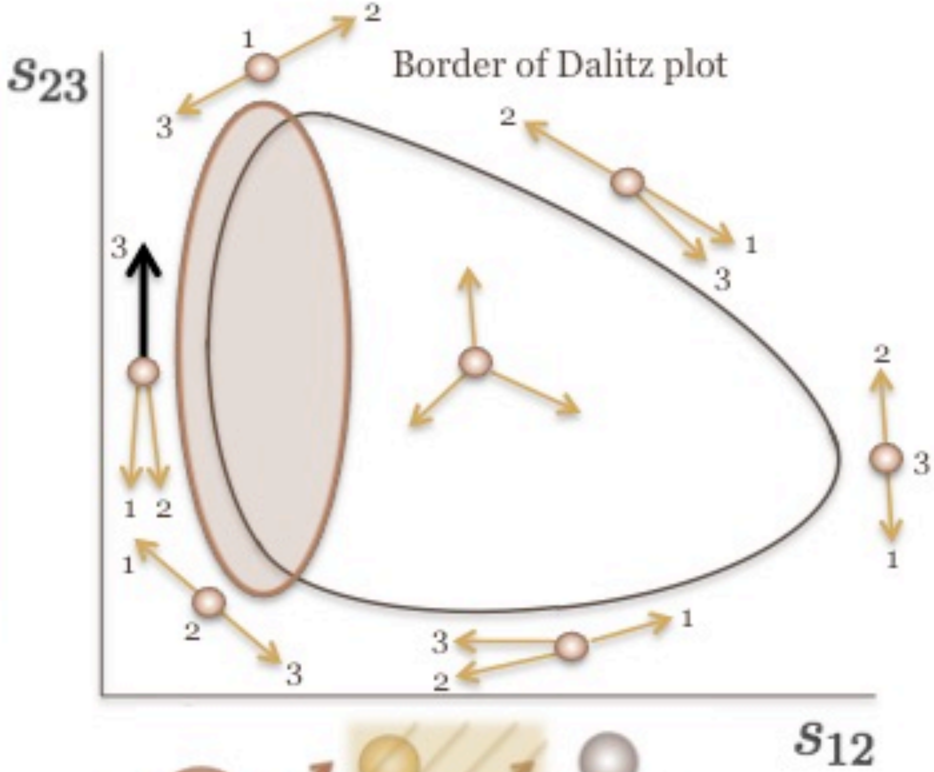
60 % – 80 %

Simplest approach with spectator approximation

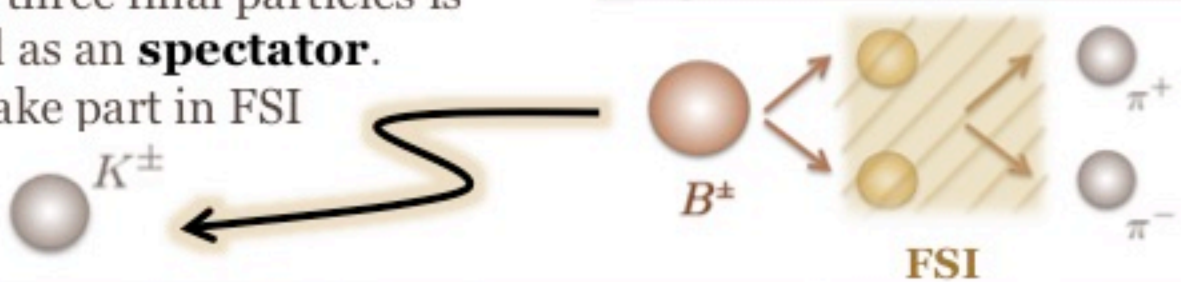
- However, reproducing the full 3-body Dalitz plot needs many contributions and it is a difficult task

LHCb follows this analysis [6]...

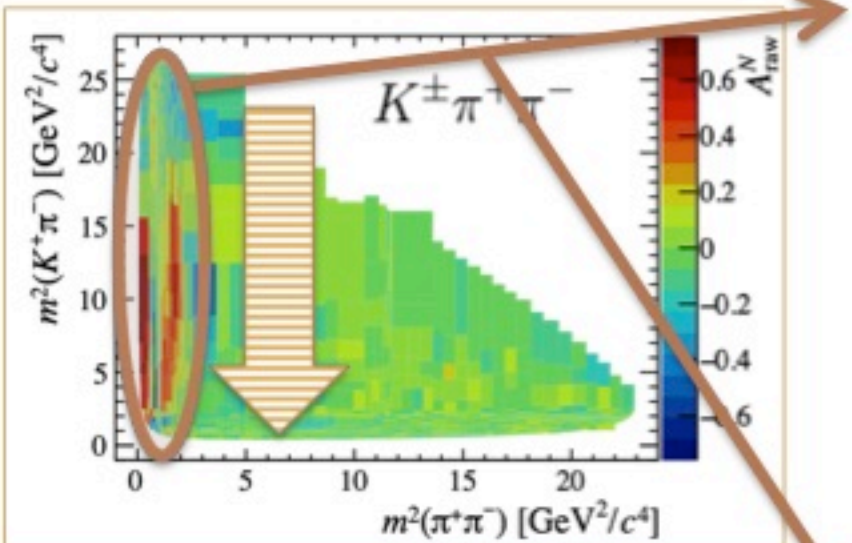




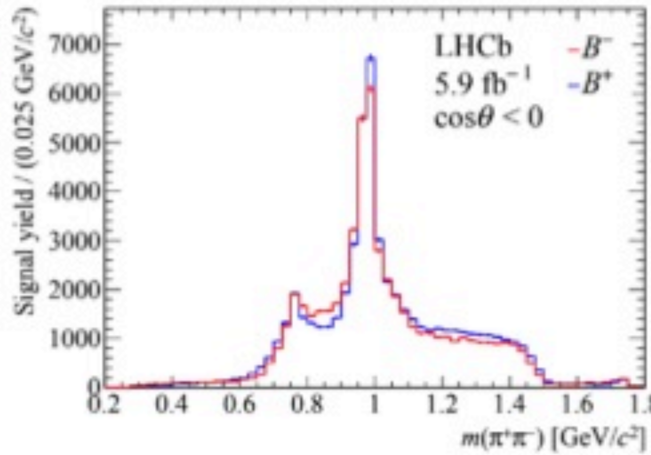
One of the three final particles is considered as an **spectator**. Does not take part in FSI



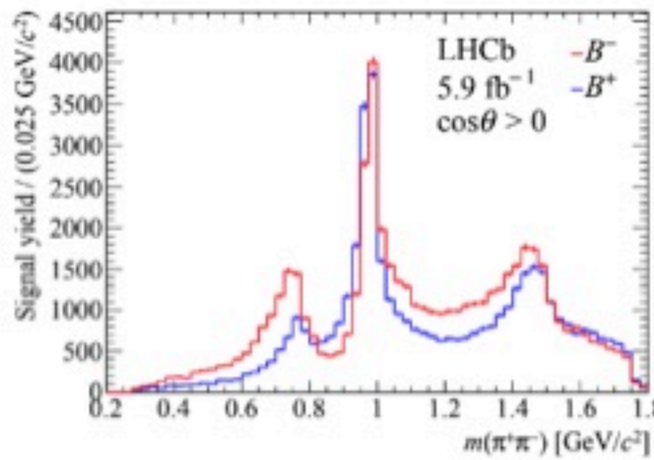
- Large asymmetries found in LHCb data when projected in the elastic region under $1\ \text{GeV}$ where only the $\pi\pi$ state is relevant



[5] R. Aaij, *et al* Phys. Rev. D 108.1 (2023) 012008



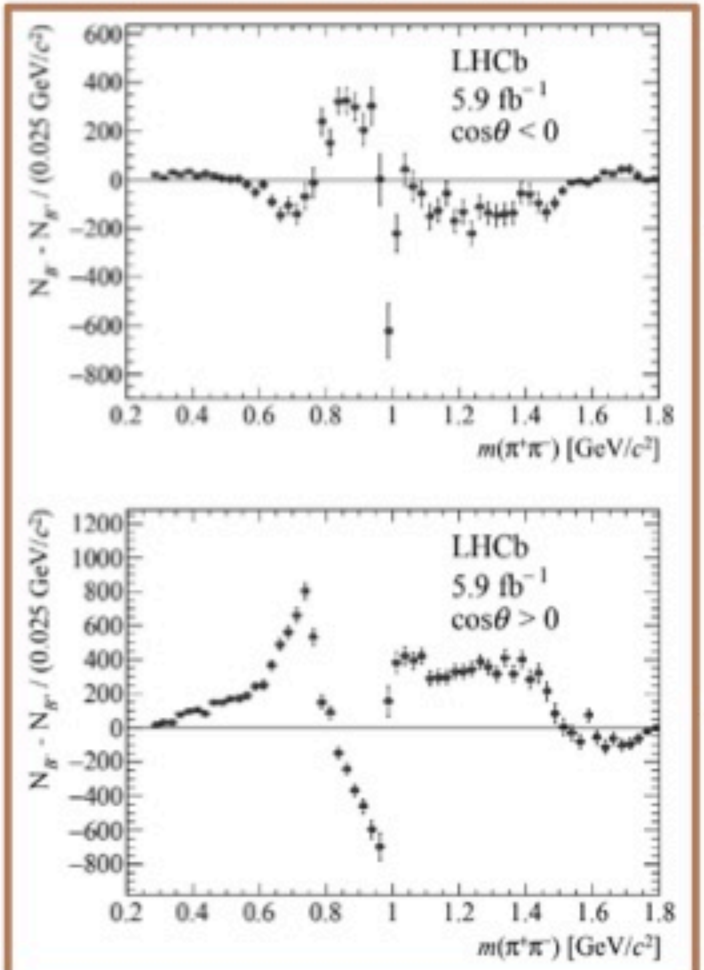
Backward

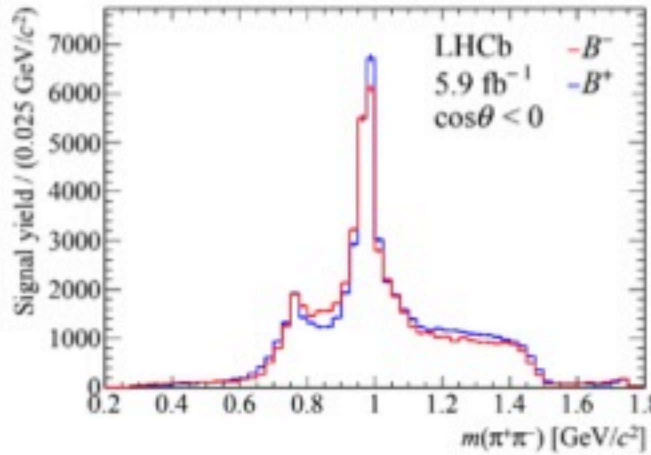


Forward

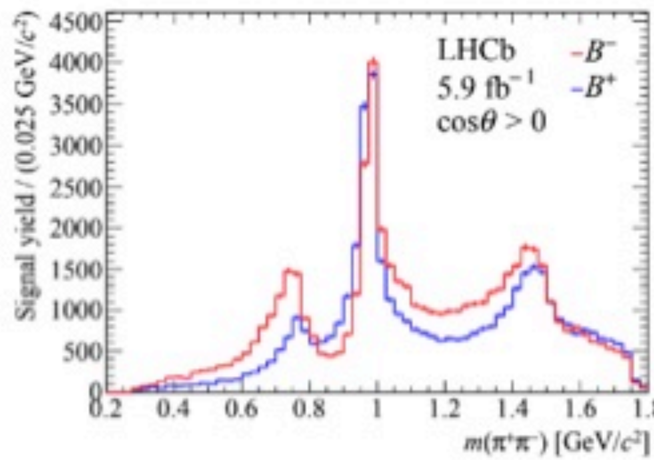
- The $\cos\theta$ is integrated from -1 to 0 to get the **Backward** projection and from 0 to 1 for the **Forward**

- Large asymmetries found in LHCb data when projected in the elastic region under 1 GeV where only the $\pi\pi$ state is relevant





Backward



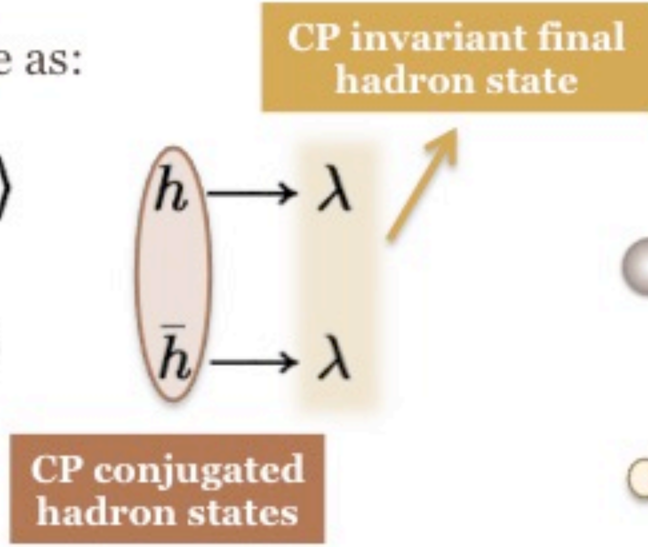
Forward

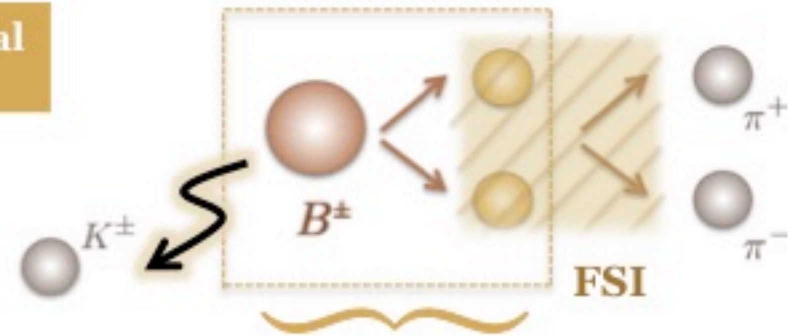
Parameterization assuming the spectator approximation

- Decay amplitude as:

$$\mathcal{A}^{-} = \langle \lambda | \mathcal{H}_{\mathrm{w}} | h \rangle$$

$$\mathcal{A}^{+} = \langle \lambda | \mathcal{H}_{\mathrm{w}} | \bar{h} \rangle$$





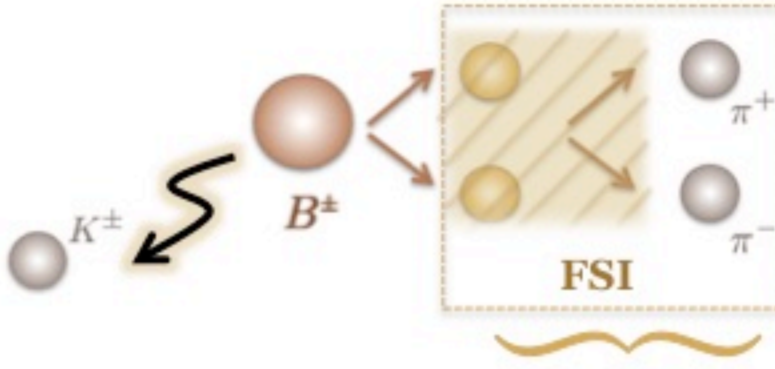
- The spectator does not interact with the other two products

Real coming from QCD interaction and therefore symmetric under CP

$$\mathcal{A}^{0\pm} = a + b\, e^{\pm i\gamma}$$

γ : weak phase changes sign under CP conjugation

- In this kinematic range we are dealing with $\mathcal{LI} = S0, S2, P1$ waves, according to partial wave decomposition



$$\mathcal{A}_{\mathcal{I}}\left(s,\theta\right) = 32\pi \sum_{\mathcal{L}=0}^{\infty} \left(\left(2\mathcal{L}+1\right) P_{\mathcal{L}}(\cos\theta) t_{\mathcal{I}}^{\mathcal{L}}(s)\right)$$

Omnès function

$$\mathcal{A}_{\mathcal{I}}(s,t) = P(s,t)\Omega_{\mathcal{I}}(s)$$

$$\Omega_{\mathcal{I}}(s) = \exp\left\{\frac{s}{\pi}\int_{s_{thr}}^{\infty} \mathrm{d}s' \frac{\delta_{\mathcal{I}}(s')}{s'\left(s'-s-i\epsilon\right)}\right\}$$

[8] J. R. Peláez, A. Rodas, Eur. Phys. J. C 78 (2018) 11, 897 & Phys. Rept. 960 (2022) 1-126

$P(s,t)$ is a general function free of poles and right-hand cuts (usually a polynomial)

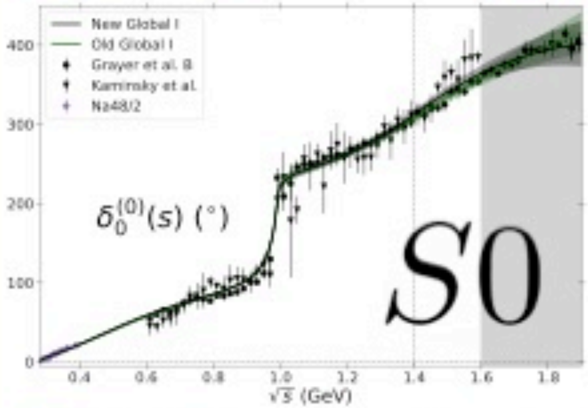
VERY WELL KNOWN

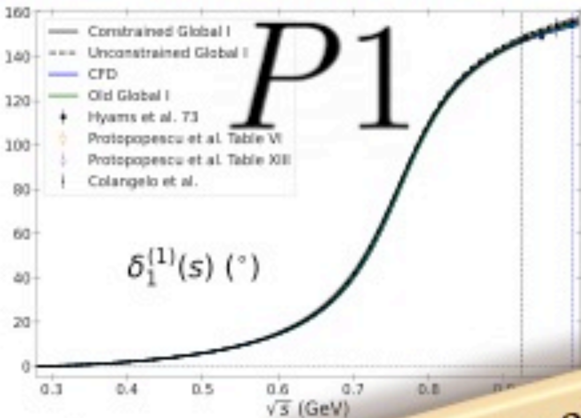
[7] Omnès, Nuovo Cim. 8 (1958) 316-326

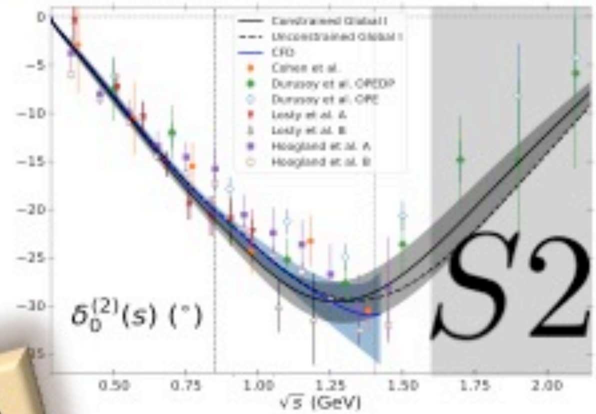
Dispersive approach via Omnès functions

- Phase shifts:

[9] J. R. Peláez, P. Rabán, J. Ruiz de Elvira in preparation

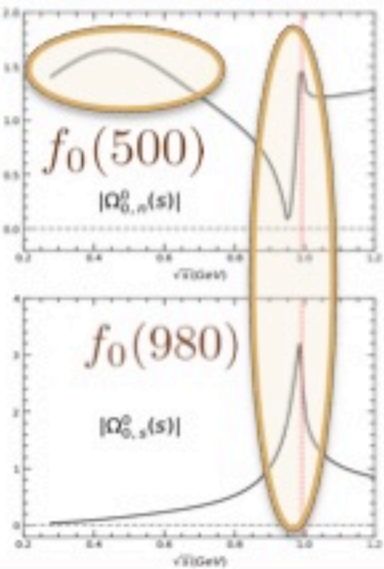


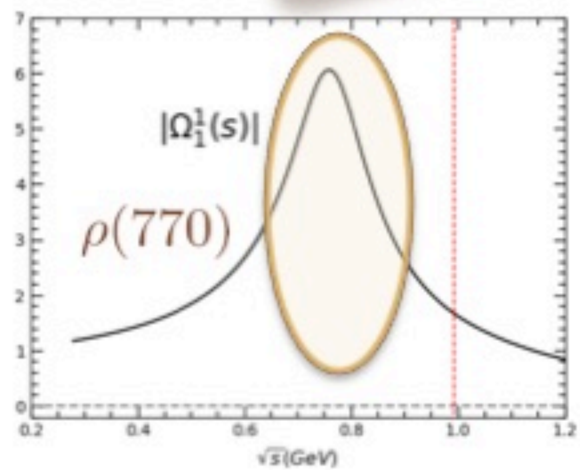


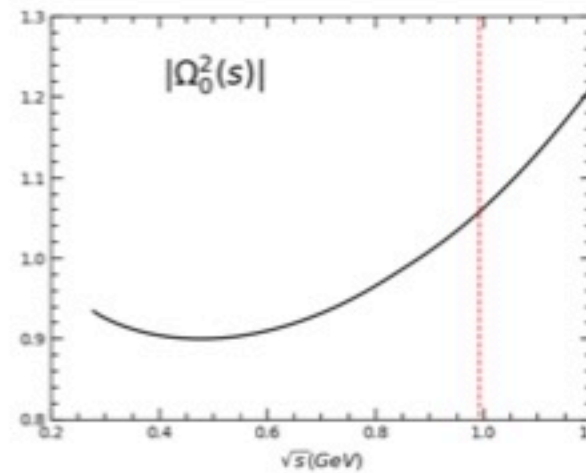


Resonances

- Modulus of the Omnès functions:

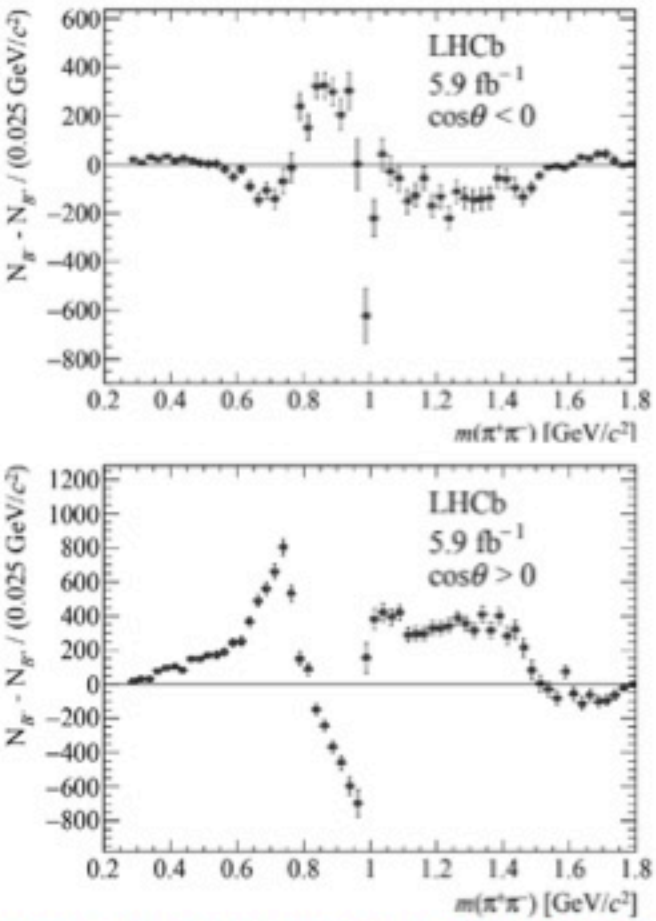






[8] J. R. Peláez, A. Rodas, Eur. Phys. J. C 78 (2018) 11, 897 & Phys. Rept. 960 (2022) 1-126

$$\Delta\Gamma(s, a_i, b_i, |\Omega_i|, \delta_i)$$



Backward

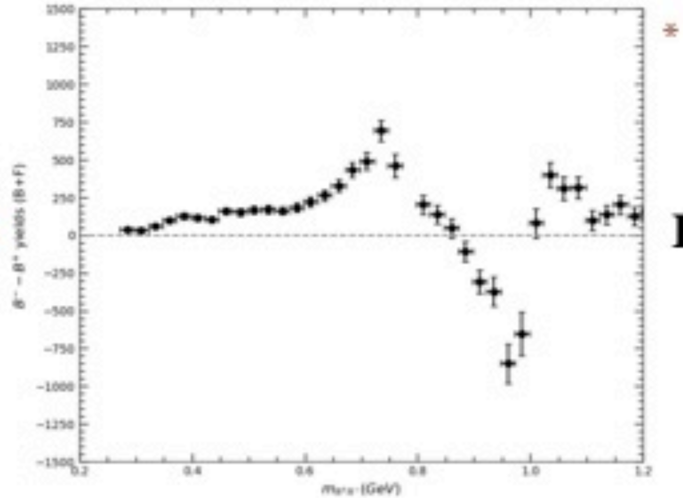
Forward

- Only the $P1$ wave had a $\cos\theta$ dependence

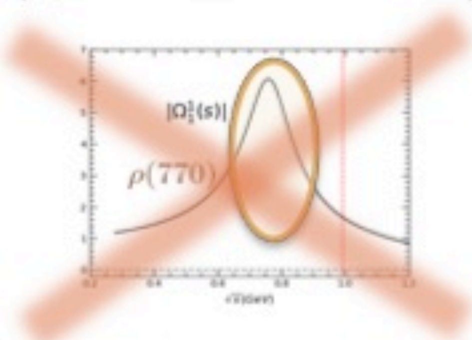
→ **Let' s build combinations of the projections in order to get rid of some interference terms**

- Each of the contributions only appears in one of the combinations

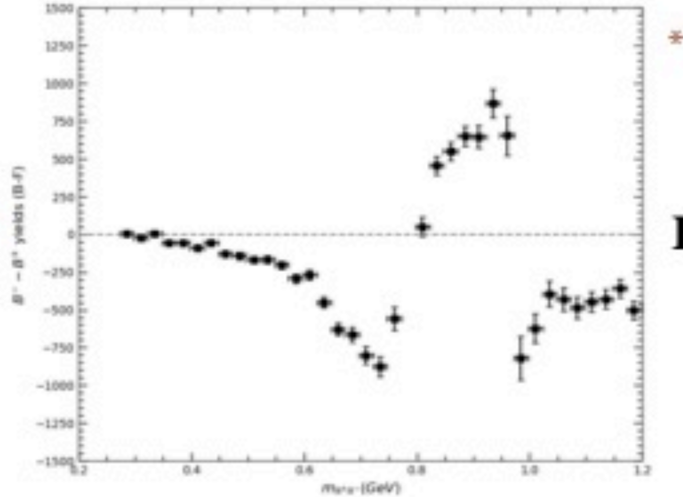
$\Delta\Gamma(s, S-S \text{ interference})$ →



Backward+Forward



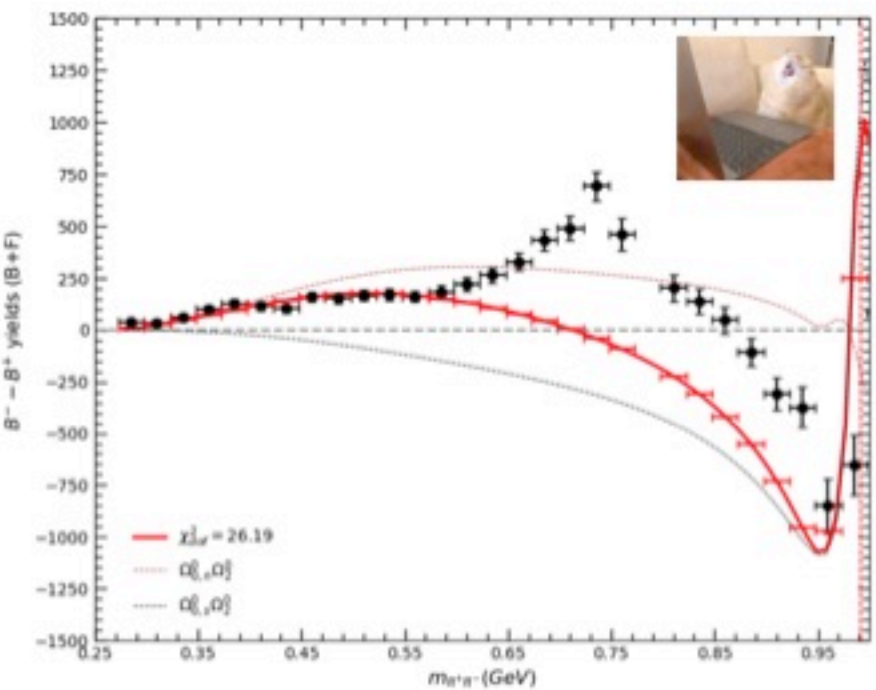
$\Delta\Gamma(s, S-P \text{ interference})$ →



Backward-Forward

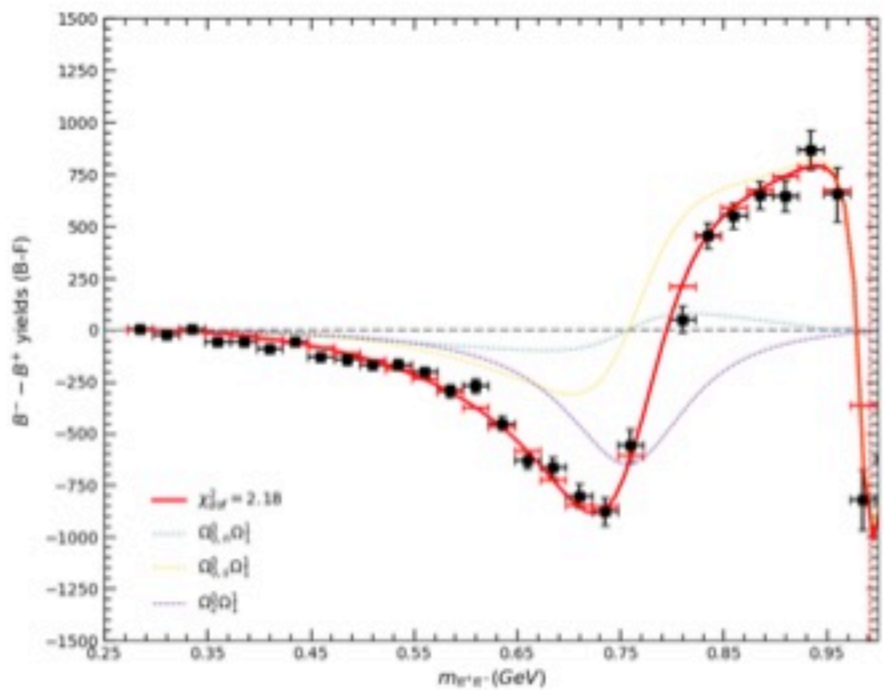
Backward+Forward

$\Delta\Gamma(s, S-S \text{ interference})$

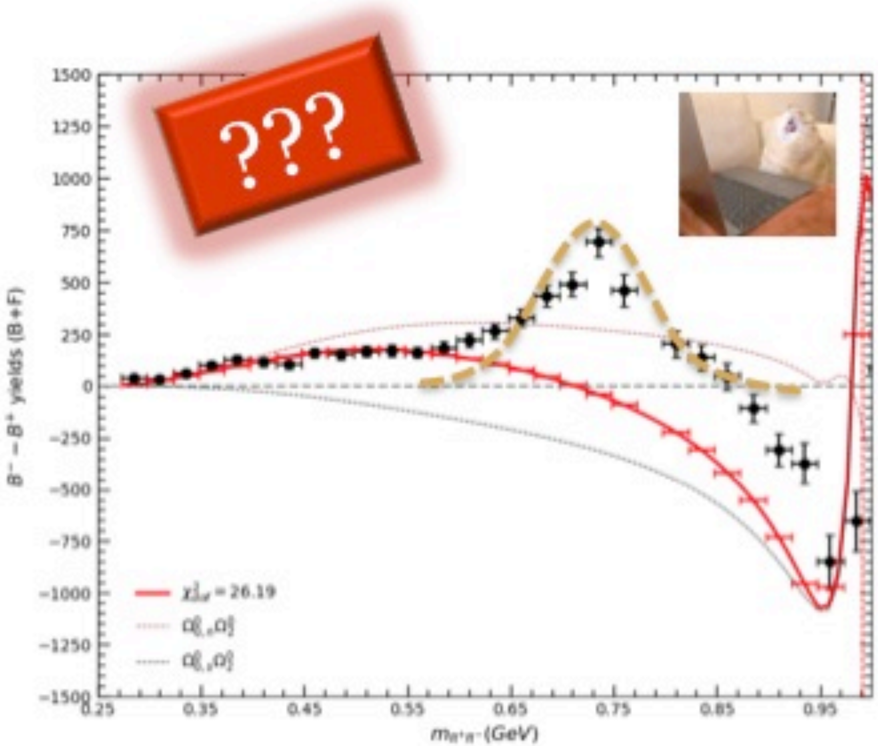


Backward-Forward

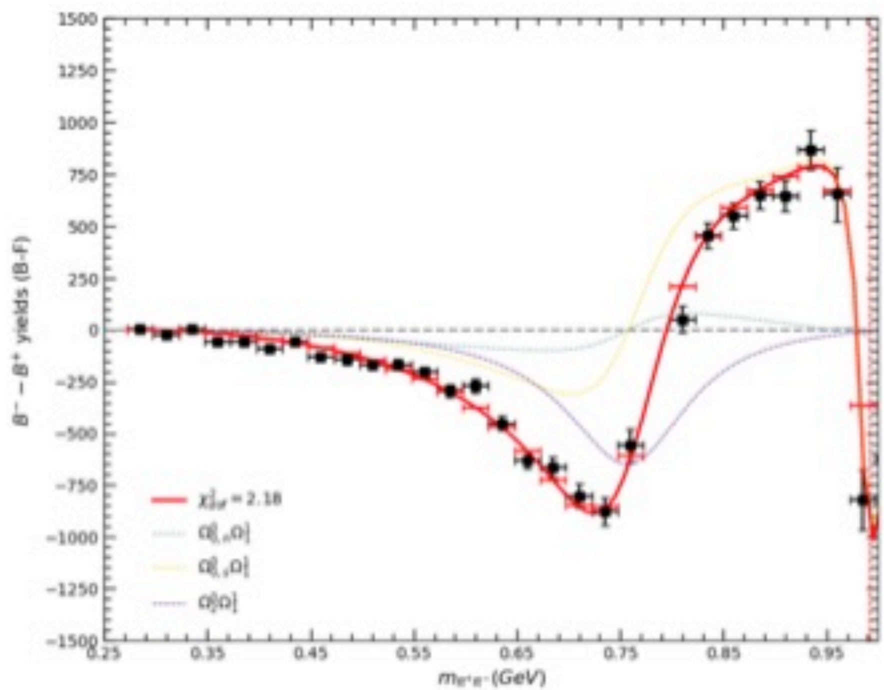
$\Delta\Gamma(s, S-P \text{ interference})$



Backward+Forward
$\Delta\Gamma(s, S - S \text{ interference})$



Backward-Forward
$\Delta\Gamma(s, S - P \text{ interference})$

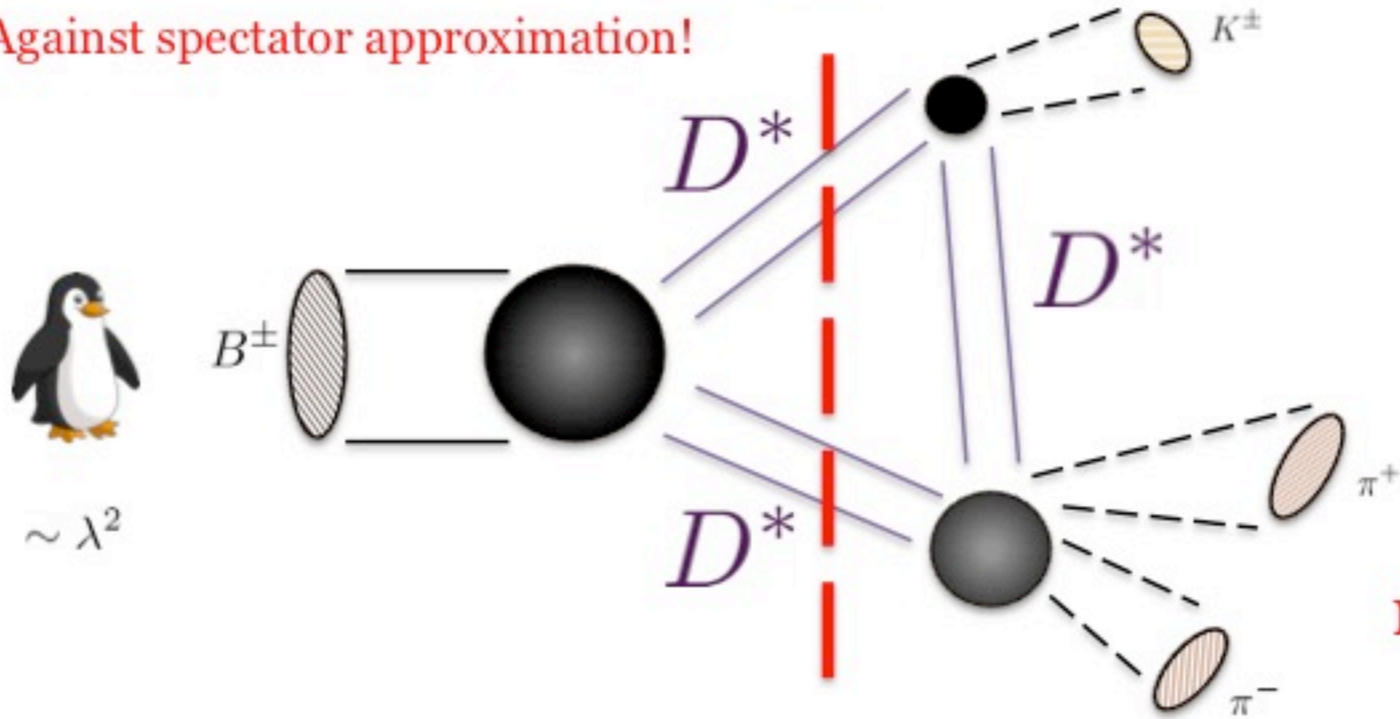


→ **It seems that we are missing a $\rho(770)$ resonance contribution where it is not supposed to appear**

D meson loop on-shell

- Do you remember the Penguin diagram?

Against spectator approximation!



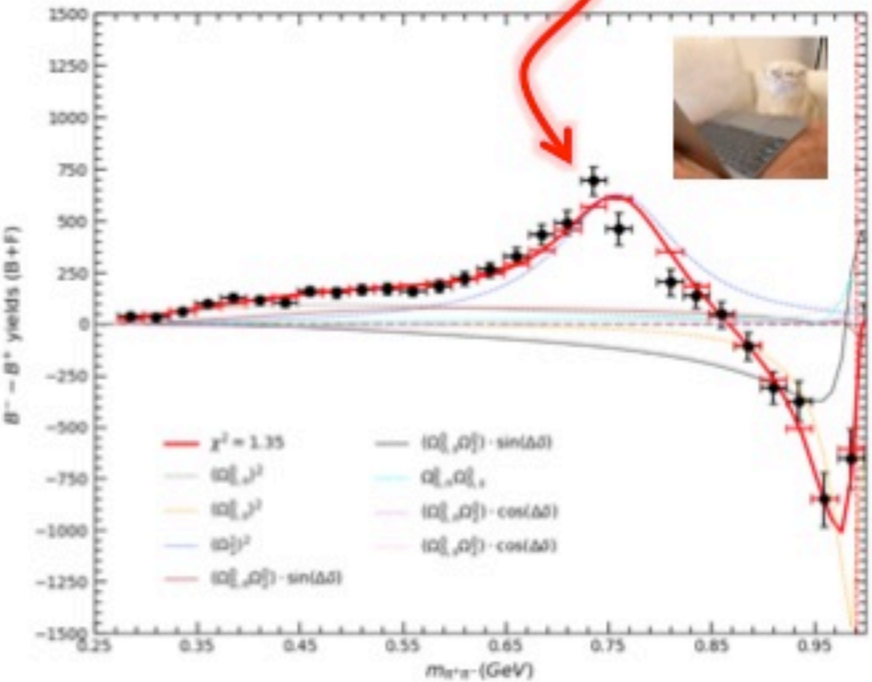
On-shell → Imaginary parts → New parameters in the model → New contributions in the fitting

$$\mathcal{A}^{0\pm} = a + b\ e^{\pm i\gamma} \longrightarrow \mathcal{A}^{0\pm} = a_R + i a_I + b\ e^{i\pm\gamma}$$

→ **Now the $P1$ wave can also appear in the Backward+Forward**

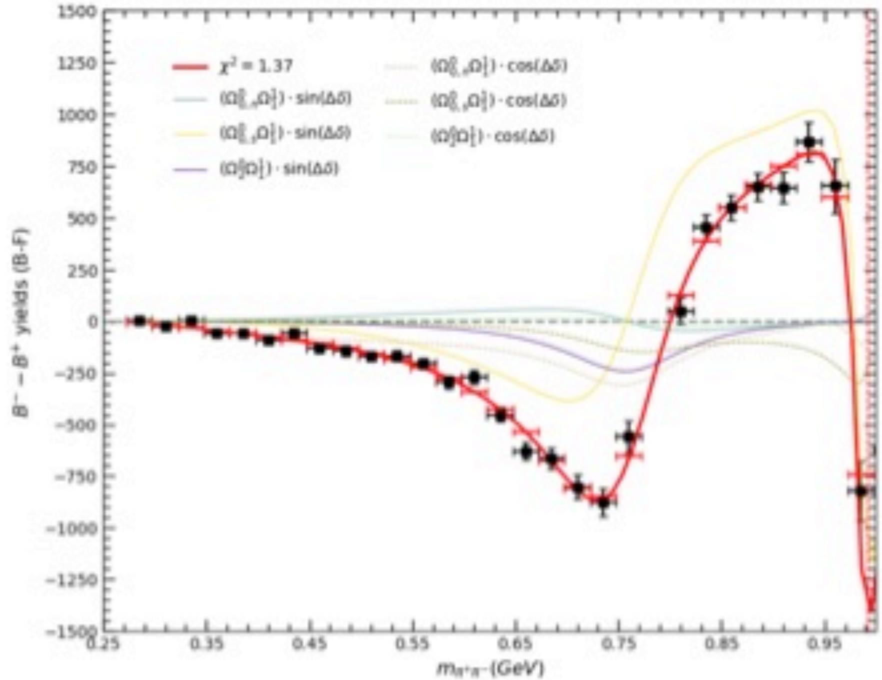
Backward+Forward

$\Delta\Gamma(s, S-S \text{ and } P-P \text{ interference})$



Backward-Forward

$\Delta\Gamma(s, S-P \text{ interference})$



$\chi^2_{dof} \approx 1$

- We have developed a formalism able to reproduce the Giant CP Violation in the asymmetries found by the LHCb collaboration

- The strong phases are found to come from hadronic interactions (FSI). The relevant role of hadronic physics is clear since the $\pi\pi$ resonances are the ones that happen to explain the energy dependence in this CP asymmetries

- This formalism has the potential to describe other data sets and other processes with reasonable accuracy

- The spectator approximation can not reproduce this CP asymmetries

- We have shown the relevant role of the D loop. It provides a necessary contribution for obtaining a $\rho(770)$ resonance in a place where it can not be generated if assuming the spectator approximation


SPARE
SLIDES

- Matter-antimatter asymmetry in the universe → The three necessary Sakharov conditions:

  - Baryon number violation
  - **CP violation**
  - Out of thermal equilibrium interactions (phase transition)

Primitive Universe

$$\eta \equiv \frac{n_B}{n_\gamma} = \frac{n_{\bar{B}}}{n_\gamma} \approx 10^{-19}$$

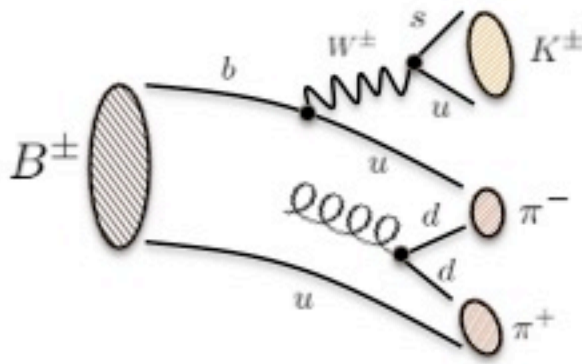
Today Universe

$$\eta \approx 10^{-9} >> \frac{n_{\bar{B}}}{n_\gamma}$$

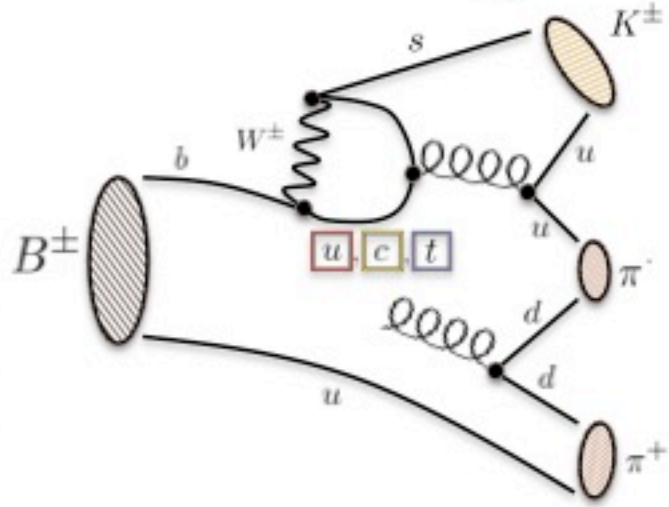
→ **The CP violation magnitude found to date is not enough to explain the cosmological matter-antimatter asymmetry**

[1] Bander Silverman & Soni PRL 43 (1979) 242

- "Tree+ Penguin", BSS model



$\sim \lambda^4$



$\sim \lambda^4$

$\sim \lambda^2$

$\sim \lambda^2$

- CPV (weak) phase appears in the quark CKM matrix

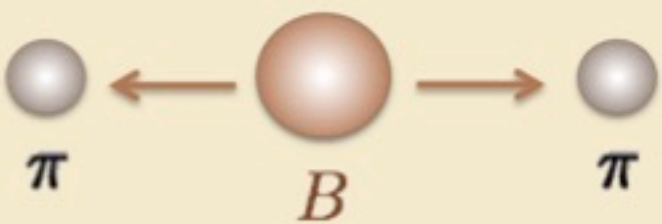
$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$+\mathcal{O}(\lambda^4)$$

[2] L. Wolfenstein, Phys. Rev. D 43, (1991) 151
[3] M. Suzuki and L. Wolfenstein, Phys. Rev. D 60, (1999) 074019
[4] M. Suzuki, Phys. Rev. D 77, (2008) 054021

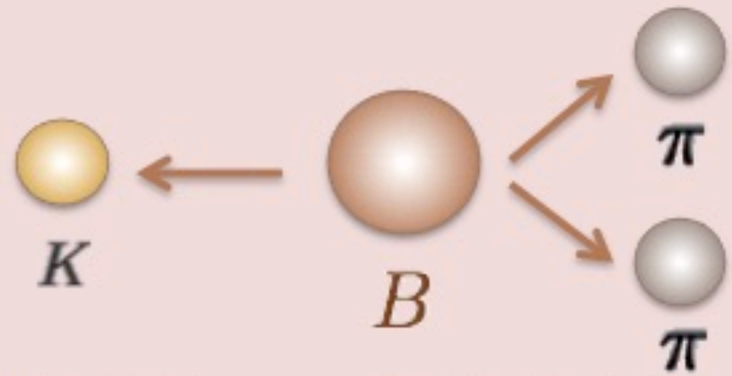
2-body decays



- Decaying particle mass fixes products' momenta
- Hadronization/FSI is just a number after angular integration
- Simpler to estimate

We see a point

3-body decays



- Available energy is distributed between the three final particles
- Strong FSI phase is a **FUNCTION** of two energy variables. NOT FIXED
- No so simple to reproduce…

We see a behavior

Quark content

Particle: Name	Particle: Symbol	Mass* (MeV/c^2)	J	B	Q (e)	I_3	C	S	T	B'	Antiparticle: Name	Antiparticle: Symbol
First generation												
up	u	2.3 ±0.7 ± 0.5	$\frac{1}{2}$	$+\frac{1}{3}$	$+\frac{2}{3}$	$+\frac{1}{2}$	0	0	0	0	antiup	$\bar{u}$
down	d	4.8 ±0.5 ± 0.3	$\frac{1}{2}$	$+\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	0	0	0	0	antidown	$\bar{d}$
Second generation												
charm	c	1275 ±25	$\frac{1}{2}$	$+\frac{1}{3}$	$+\frac{2}{3}$	0	+1	0	0	0	anticharm	$\bar{c}$
strange	s	95 ±5	$\frac{1}{2}$	$+\frac{1}{3}$	$-\frac{1}{3}$	0	0	−1	0	0	antistrange	$\bar{s}$
Third generation												
top	t	173 210 ±510 ± 710 *	$\frac{1}{2}$	$+\frac{1}{3}$	$+\frac{2}{3}$	0	0	0	+1	0	antitop	$\bar{t}$
bottom	b	4180 ±30	$\frac{1}{2}$	$+\frac{1}{3}$	$-\frac{1}{3}$	0	0	0	0	−1	antibottom	$\bar{b}$

Familia	Símbolo	Antipartícula	Quarks	Spin	Masa (MeV/c²)	S	C	B	Vida media (s)
Phi	ϕ	el mismo	$s\bar{s}$	1	1 020	0	0	0	20×10^{-23}
D	D^+	D^-	$c\bar{d}$	0	1 869,4	0	+1	0	$10,6\times10^{-13}$
	D^-	D^+	$\bar{c}d$	0	1 869,4	0	-1	0	$10,6\times10^{-13}$
	D^0	$\overline{D}^0$	$c\bar{u}$	0	1 864,6	0	+1	0	$4,2\times10^{-13}$
	$\overline{D}^0$	D^0	$\bar{c}u$	0	1 864,6	0	-1	0	$4,2\times10^{-13}$
	D_S^+	D_S^-	$c\bar{s}$	0	1 969	+1	+1	0	$4,7\times10^{-13}$
	D_S^-	D_S^+	$\bar{c}s$	0	1 969	-1	-1	0	$4,7\times10^{-13}$
J/ψ	J/ψ	el mismo	$c\bar{c}$	1	3 096,9	0	0	0	$0,8\times10^{-20}$
B	B^+	B^-	$u\bar{b}$	0	5 279	0	0	+1	$1,5\times10^{-12}$
	B^-	B^+	$\bar{u}b$	0	5 279	0	0	-1	$1,5\times10^{-12}$
	B^0	B^0	$d\bar{b}$	0	5 279	0	0	+1	$1,5\times10^{-12}$
Upsilon	Υ	el mismo	$b\bar{b}$	1	9 460,4	0	0	0	$1,3\times10^{-20}$

Familia	Símbolo	Antipartícula	Quarks	Spin	Masa (MeV/c²)	S	C	B	Vida media (s)
Pion	π^+	π^-	$u\bar{d}$	0	139,6	0	0	0	$2,60\times10^{-8}$
	π^-	π^+	$\bar{u}d$	0	139,6	0	0	0	$2,60\times10^{-8}$
	π^0	el mismo	$(u\bar{u} + d\bar{d})/\sqrt{2}$[1]	0	135,0	0	0	0	$0,83\times10^{-16}$
Kaón	K^+	K^-	$u\bar{s}$	0	493,7	+1	0	0	$1,24\times10^{-8}$
	K^-	K^+	$\bar{u}s$	0	493,7	-1	0	0	$1,24\times10^{-8}$
	K^0	$\bar{K}^0$	$d\bar{s}$	0	497,7	+1	0	0	—[2]
	K_S^0	K_S^0	$(d\bar{s} - s\bar{d})/\sqrt{2}$[1]	0	497,7	—[3]	0	0	$0,89\times10^{-10}$
	K_L^0	K_L^0	$(d\bar{s} + s\bar{d})/\sqrt{2}$[1]	0	497,7	—[3]	0	0	$5,2\times10^{-8}$
Êta	η^0	el mismo	$(u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6}$[1]	0	548,8	0	0	0	$< 10^{-18}$
Rho	ρ^+	ρ^-	$u\bar{d}$	1	770	0	0	0	$0,4\times10^{-23}$
	ρ^-	ρ^+	$\bar{u}d$	1	770	0	0	0	$0,4\times10^{-23}$
	ρ^0	el mismo	$(\bar{u}u - d\bar{d})/\sqrt{2}$[1]	1	770	0	0	0	$0,4\times10^{-23}$

LHCb intense research program involving large CPV asymmetries in $B \longrightarrow 3M$ …

PRL **111,** 101801 (2013) PHYSICAL REVIEW LETTERS

Measurement of CP Violation in the Phase Space of $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to K^{\pm}K^{+}K^{-}$ Decays

R. Aaij *et al.**
(LHCb Collaboration)
(Received 5 June 2013; published 3 September 2013)

The charmless decays $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to K^{\pm}K^{+}K^{-}$ are reconstructed using data, corresponding to an integrated luminosity of 1.0 fb^{-1}, collected by LHCb in 2011. The inclusive charge asymmetries of these modes are measured as $A_{CP}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}) = 0.032 \pm 0.008(\mathrm{stat}) \pm 0.004(\mathrm{syst}) \pm 0.007(J/\psi K^{\pm})$ and $A_{CP}(B^{\pm} \to K^{\pm}K^{+}K^{-}) = -0.043 \pm 0.009(\mathrm{stat}) \pm 0.003(\mathrm{syst}) \pm 0.007(J/\psi K^{\pm})$, where the third uncertainty is due to the CP asymmetry of the $B^{\pm} \to J/\psi K^{\pm}$ reference mode. The significance of $A_{CP}(B^{\pm} \to K^{\pm}K^{+}K^{-})$ exceeds three standard deviations and is the first evidence of an inclusive CP asymmetry in charmless three-body B decays. In addition to the inclusive CP asymmetries, larger asymmetries are observed in localized regions of phase space.

LHCb intense research program involving large CPV asymmetries in $B \longrightarrow 3M$ …

PRL **111,** 101801 (2013) PHYSICAL REVIEW LETTERS

M

PRL **112,** 011801 (2014) PHYSICAL REVIEW LETTERS

Measurement of *CP* Violation in the Phase Space of $B^{\pm} \to K^{+}K^{-}\pi^{\pm}$ and $B^{\pm} \to \pi^{+}\pi^{-}\pi^{\pm}$ Decays

(Received 18 October 2013; published 7 January 2014)

The charmless decays $B^{\pm} \to K^{+}K^{-}\pi^{\pm}$ and $B^{\pm} \to \pi^{+}\pi^{-}\pi^{\pm}$ are reconstructed in a data set of pp collisions with an integrated luminosity of 1.0 fb^{-1} and center-of-mass energy of 7 TeV, collected by LHCb in 2011. The inclusive charge asymmetries of these modes are measured to be $A_{CP}(B^{\pm} \to K^{+}K^{-}\pi^{\pm}) = -0.141 \pm 0.040\,(\mathrm{stat}) \pm 0.018\,(\mathrm{syst}) \pm 0.007(J/\psi K^{\pm})$ and $A_{CP}(B^{\pm} \to \pi^{+}\pi^{-}\pi^{\pm}) = 0.117 \pm 0.021\,(\mathrm{stat}) \pm 0.009\,(\mathrm{syst}) \pm 0.007(J/\psi K^{\pm})$, where the third uncertainty is due to the *CP* asymmetry of the $B^{\pm} \to J/\psi K^{\pm}$ reference mode. In addition to the inclusive *CP* asymmetries, larger asymmetries are observed in localized regions of phase space.

Giant CPV in charmless B three-body decays at LHCb

PHYSICAL REVIEW D **90**, 112004 (2014)

Measurements of *CP* violation in the three-body phase space of charmless $B^{\pm}$ decays

R. Aaij *et al.**
(LHCb Collaboration)
(Received 25 August 2014; published 11 December 2014)

The charmless three-body decay modes $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$, $B^{\pm} \to K^{\pm}K^{+}K^{-}$, $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ and $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ are reconstructed using data, corresponding to an integrated luminosity of 3.0 fb^{-1}, collected by the LHCb detector. The inclusive *CP* asymmetries of these modes are measured to be

$$A_{CP}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}) = +0.025 \pm 0.004 \pm 0.004 \pm 0.007,$$
$$A_{CP}(B^{\pm} \to K^{\pm}K^{+}K^{-}) = -0.036 \pm 0.004 \pm 0.002 \pm 0.007,$$
$$A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = +0.058 \pm 0.008 \pm 0.009 \pm 0.007,$$
$$A_{CP}(B^{\pm} \to \pi^{\pm}K^{+}K^{-}) = -0.123 \pm 0.017 \pm 0.012 \pm 0.007,$$

where the first uncertainty is statistical, the second systematic, and the third is due to the *CP* asymmetry of the $B^{\pm} \to J/\psi K^{\pm}$ reference mode. The distributions of these asymmetries are also studied as functions of position in the Dalitz plot and suggest contributions from rescattering and resonance interference processes.

FSI experimental signs

Giant CPV in charmless B three-body decays at LHCb

THE LARGEST CP ASYMMETRY REPORTED TO DATE

PHYS... ...ERS **123,** 231802 (2019)

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

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 12 June 2019; revised manuscript received 15 October 2019; published 6 December 2019)

The first amplitude analysis of the $B^{\pm} \to \pi^{\pm} K^{+} K^{-}$ decay is reported based on a data sample corresponding to an integrated luminosity of 3.0 fb^{-1} of pp collisions recorded in 2011 and 2012 with the LHCb detector. The data are found to be best described by a coherent sum of five resonant structures plus a nonresonant component and a contribution from $\pi\pi \leftrightarrow KK$ S-wave rescattering. The dominant contributions in the $\pi^{\pm} K^{\mp}$ and $K^{+} K^{-}$ systems are the nonresonant and the $B^{\pm} \to \rho(1450)^{0}\pi^{\pm}$ amplitudes, respectively, with fit fractions around 30%. For the rescattering contribution, a sizable fit fraction is observed. This component has the largest *CP* asymmetry reported to date for a single amplitude of $(-66 \pm 4 \pm 2)\%$, where the first uncertainty is statistical and the second systematic. No significant *CP* violation is observed in the other contributions.

of pp
LHCb
$\pi^{\pm}) =$
(stat)$\pm$
$B^{\pm} \to$
rved in

of the $B^{\pm} \to J/\psi K^{\pm}$ reference mode. The distributions of these asymmetries are also studied as functions of position in the Dalitz plot and suggest contributions from rescattering and resonance interference processes.

Giant CPV in charmless B three-body decays at LHCb

PHYSICAL REVIEW LETTERS **123,** 231802 (2…

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

Looking forward to the whole RUN2 data

PHYSICAL REVIEW D **108,** 012008 (2023)

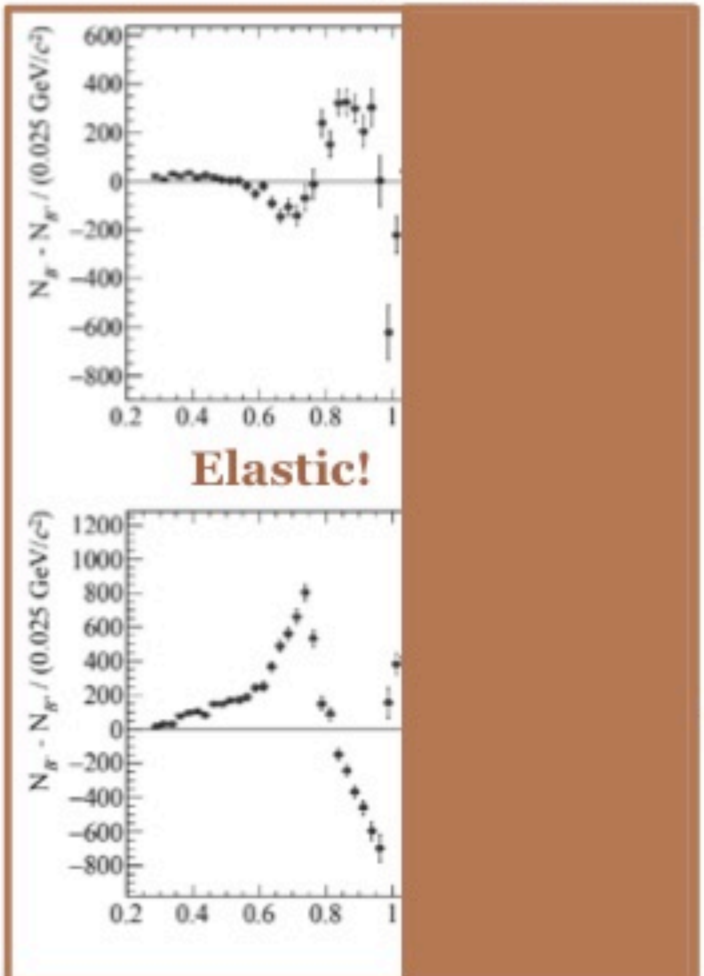
Direct *CP* violation in charmless three-body decays of $B^{\pm}$ mesons

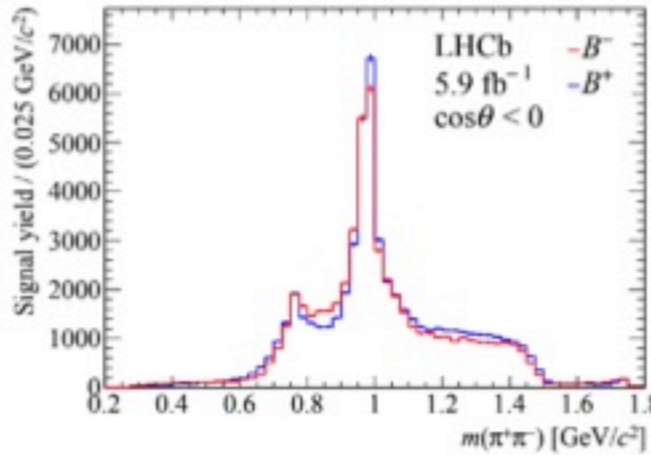
R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 20 June 2022; accepted 19 August 2022; published 13 July 2023)

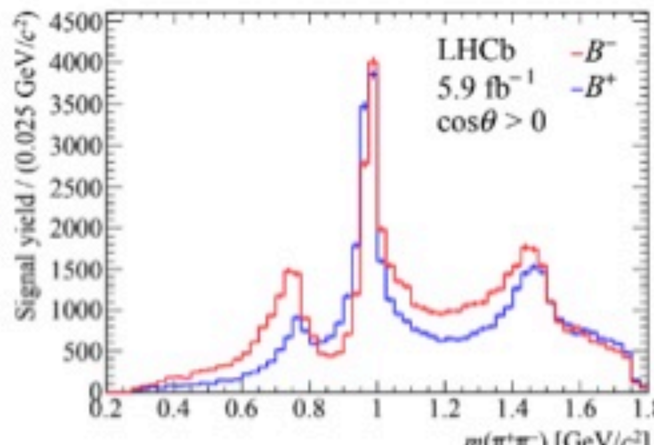
Measurements of *CP* asymmetries in charmless three-body decays of $B^{\pm}$ mesons are reported using proton-proton collision data collected by the LHCb detector, corresponding to an integrated luminosity of 5.9 fb^{-1}. The previously observed *CP* asymmetry in $B^{\pm} \to \pi^{\pm} K^{+} K^{-}$ decays is confirmed, and *CP* asymmetries are observed with a significance of more than five standard deviations in the $B^{\pm} \to \pi^{\pm} \pi^{+} \pi^{-}$ and $B^{\pm} \to K^{\pm} K^{+} K^{-}$ decays, while the *CP* asymmetry of $B^{\pm} \to K^{\pm} \pi^{+} \pi^{-}$ decays is confirmed to be compatible with zero. The distributions of these asymmetries are also studied as a function of the three-body phase space and suggest contributions from rescattering and resonance interference processes. An indication of the presence of the decays $B^{\pm} \to \pi^{\pm} \chi_{c0}(1P)$ in both $B^{\pm} \to \pi^{\pm} \pi^{+} \pi^{-}$ and $B^{\pm} \to \pi^{\pm} K^{+} K^{-}$ decays is observed, as is *CP* violation involving these amplitudes.

- Large asymmetries found in LHCb data when projected in the elastic region under 1 GeV where only the $\pi\pi$ state is relevant





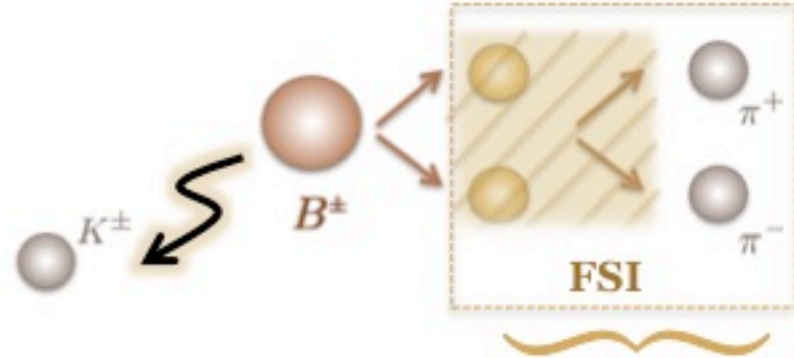
Backward



Forward

Dispersive approach via Omnès functions

- In this kinematic range we are dealing with $\mathcal{LI} = S0, S2, P1$ waves, according to partial wave decomposition



$$\mathcal{A}_{\mathcal{I}}(s,\theta) = 32\pi \sum_{\mathcal{L}=0}^{\infty} \left((2\mathcal{L}+1)\, P_{\mathcal{L}}(\cos\theta) t_{\mathcal{I}}^{\mathcal{L}}(s)\right)$$

- For purely elastic interactions we have $S_{\mathcal{I}} = e^{2i\delta_{\mathcal{I}}}$ and the discontinuity relation for the production of $\pi\pi$ is given by:

$$Disc[\mathcal{A}_{\mathcal{I}}(s,t)] = e^{-i\delta_{\mathcal{I}}(s)} \sin(\delta_{\mathcal{I}}(s)) \mathcal{A}_{\mathcal{I}}(s,t)$$

[8] J. R. Peláez, A. Rodas, Eur. Phys. J. C 78 (2018) 11, 897 & Phys. Rept. 960 (2022) 1-126

→ Solution

$$\mathcal{A}_{\mathcal{I}}(s,t) = P(s,t)\Omega_{\mathcal{I}}(s)$$

$$\Omega_{\mathcal{I}}(s) = \exp\left\{\frac{s}{\pi}\int_{s_{thr}}^{\infty} \mathrm{d}s' \frac{\delta_{\mathcal{I}}(s')}{s'(s'-s-i\epsilon)}\right\}$$

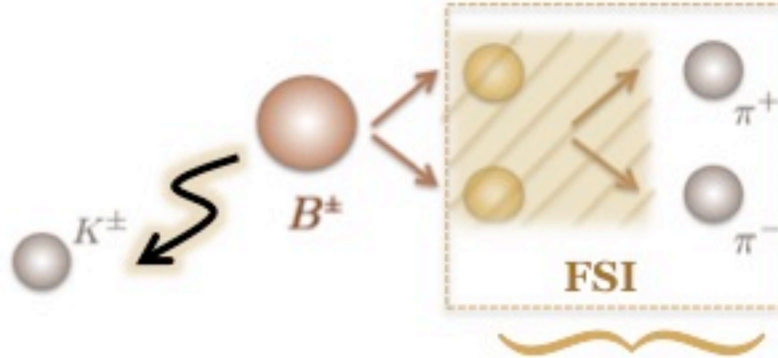
Omnès function

VERY WELL KNOWN

$P(s,t)$ is a general function free of poles and right-hand cuts (usually a polynomial)

[7] Omnès, Nuovo Cim. 8 (1958) 316-326

- In this kinematic range we are dealing with $\mathcal{LI} = S0, S2, P1$ waves, according to partial wave decomposition



$$\mathcal{A}_{\mathcal{I}}(s,\theta) = 32\pi \sum_{\mathcal{L}=0}^{\infty} \left((2\mathcal{L}+1) P_{\mathcal{L}}(\cos\theta) t_{\mathcal{I}}^{\mathcal{L}}(s) \right)$$

$\mathcal{LI}$ — Coupled channels

$S0 \begin{cases} S0_n \rightarrow \Omega_1(s) \\ S0_s \rightarrow \Omega_2(s) \end{cases}$

$S2 \rightarrow \Omega_3(s)$

$P1 \rightarrow \Omega_4(s)$

$$\mathcal{A}^{\pm}(s,\cos\theta) = \sum_{i=1}^{4} k_i(s,\cos\theta) P(s)\Omega_i(s) \mathcal{A}_i^{0\pm}$$

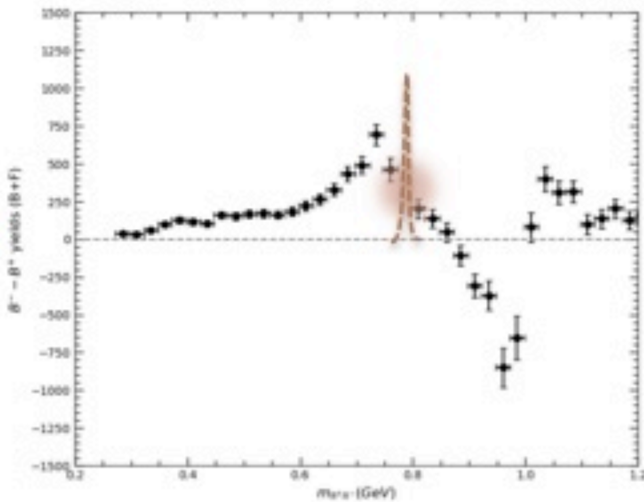
$$\mathcal{A}_{\mathcal{I}}(s,t) = P(s,t)\Omega_{\mathcal{I}}(s)$$

$$\mathcal{A}^{0\pm} = a + b\, e^{\pm i\gamma}$$

- Finally we can get the CP asymmetry as the difference of the decay widths of both CP conjugated processes

- Each of the contributions only appears in one of the combinations

$\Delta\Gamma(s, S-S \text{ interference})$ →



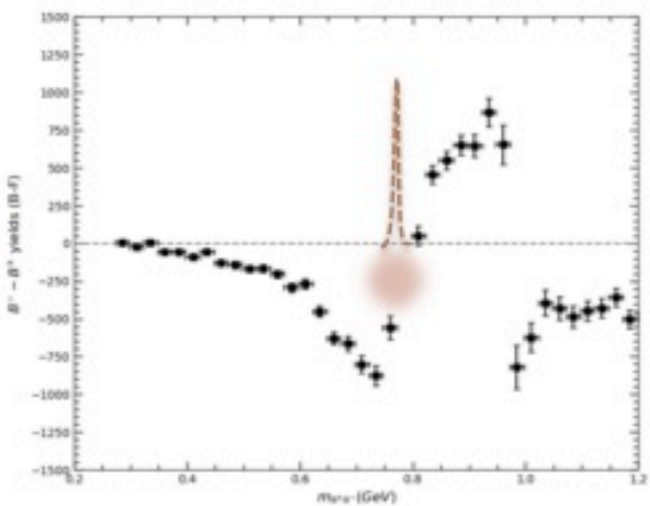
Backward+Forward

***We have deleted the one point that might be affected bay the $\omega(782)$ resonance, which has been excluded from the formalism**

ω(782) WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
8.49±0.08 OUR AVERAGE					
8.68±0.23±0.10	11200	[1] AKHMETSHIN	04	CMD2	$e^+e^- \to \pi^+\pi^-\pi^0$
8.68±0.04±0.15	1.2M	[2] ACHASOV	03D	RVUE	0.44–2.00 $e^+e^- \to \pi^+\pi^-\pi^0$
8.2 ±0.3	19500	WURZINGER	95	SPEC	1.33 $pd \to {}^3He\,\omega$
8.4 ±0.1		[3] AULCHENKO	87	ND	$e^+e^- \to \pi^+\pi^-\pi^0$
8.30±0.40		BARKOV	87	CMD	$e^+e^- \to \pi^+\pi^-\pi^0$
9.8 ±0.9	1488	KURDADZE	83B	OLYA	$e^+e^- \to \pi^+\pi^-\pi^0$
9.0 ±0.8	433	CORDIER	80	DM1	$e^+e^- \to \pi^+\pi^-\pi^0$
9.1 ±0.8	451	BENAKSAS	72B	OSPK	$e^+e^- \to \pi^+\pi^-\pi^0$

$\Delta\Gamma(s, S-P \text{ interference})$ →

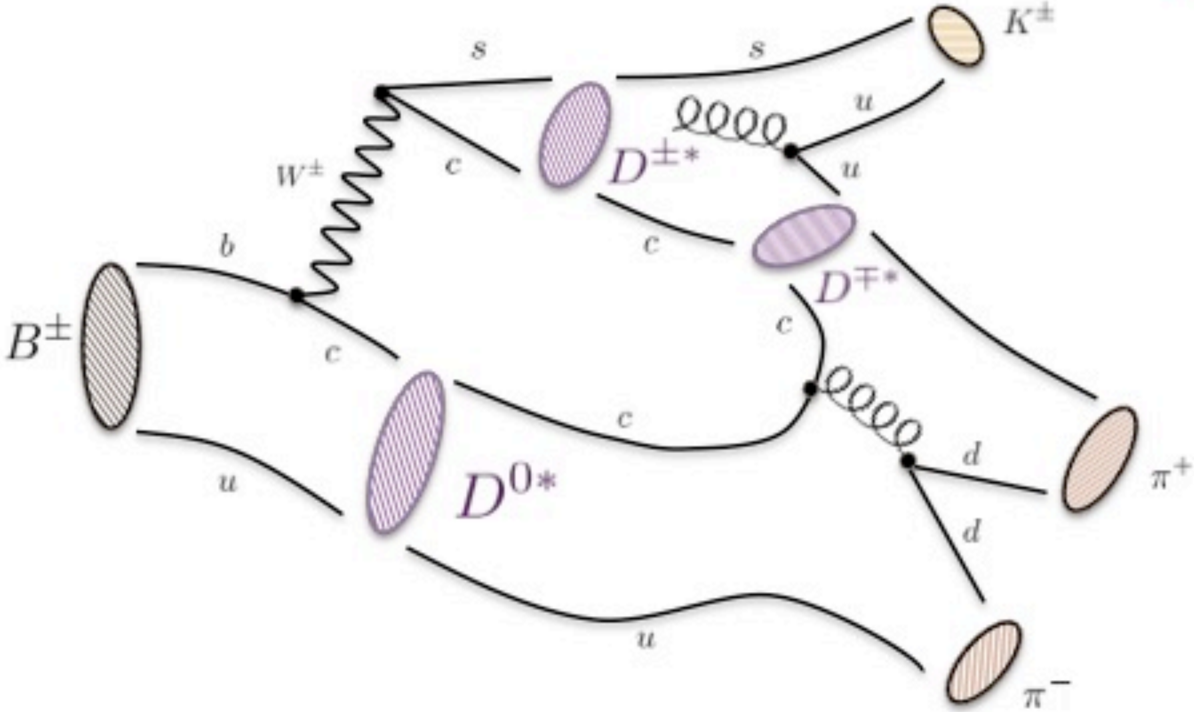


Backward-Forward

- Do you remember the Penguin diagram?

Against spectator approximation!

$\sim \lambda^2$



The only Penguin giving a significant contribution and where we can put the loop on-shell

Coupled channels assuming the spectator approximation

1. One of the three final particles is considered as an **spectator**

2. Use CPT constrains at hadron level so that h and $\bar{h}$ must have the same TOTAL decay widths. CPV can only occur in PARTIAL decay widths

$$\Gamma_{Total} = \Gamma_1 + \Gamma_2 + \Gamma_3 + \Gamma_4 + \ldots$$
$$\bar{\Gamma}_{Total} = \bar{\Gamma}_1 + \bar{\Gamma}_2 + \bar{\Gamma}_3 + \bar{\Gamma}_4 + \ldots$$

$$\Delta\Gamma_{Total} = \Gamma_{Total} - \bar{\Gamma}_{Total} = 0$$

3. **Golden mode** → Just two coupled channels

$$\Gamma_{Total} = \Gamma_1 + \Gamma_2$$
$$\bar{\Gamma}_{Total} = \bar{\Gamma}_1 + \bar{\Gamma}_2$$

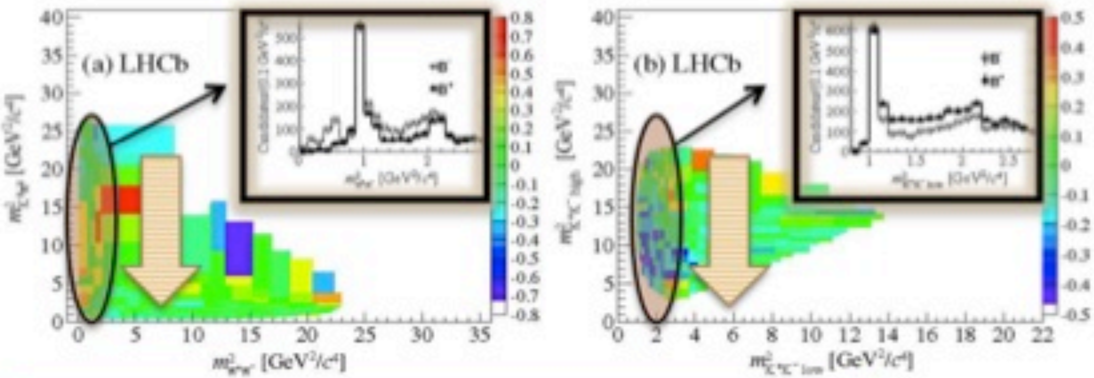
$$\Delta\Gamma_1 + \Delta\Gamma_2 = 0$$
$$\Delta\Gamma_2 \approx -\Delta\Gamma_1$$

Is this found anywhere?

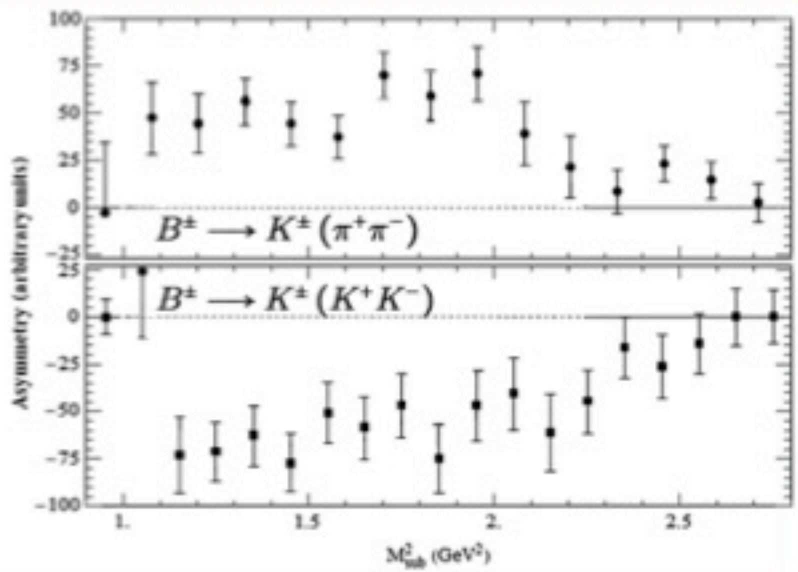
[6] Bediaga, Frederico, Lourenco, Phys. Rev. D 89 (2014) 094013

Coupled cahnnels assuming the spectator approximation

→ $B^\pm \longrightarrow K^\pm(K^+K^-)$ and $B^\pm \longrightarrow K^\pm(\pi^+\pi^-)$ in the $1-1.5$ GeV region



- Large asymmetries found in LHCb data when projected in the **1 – 1.5 GeV** region, where only $\pi\pi$ and KK are relevant



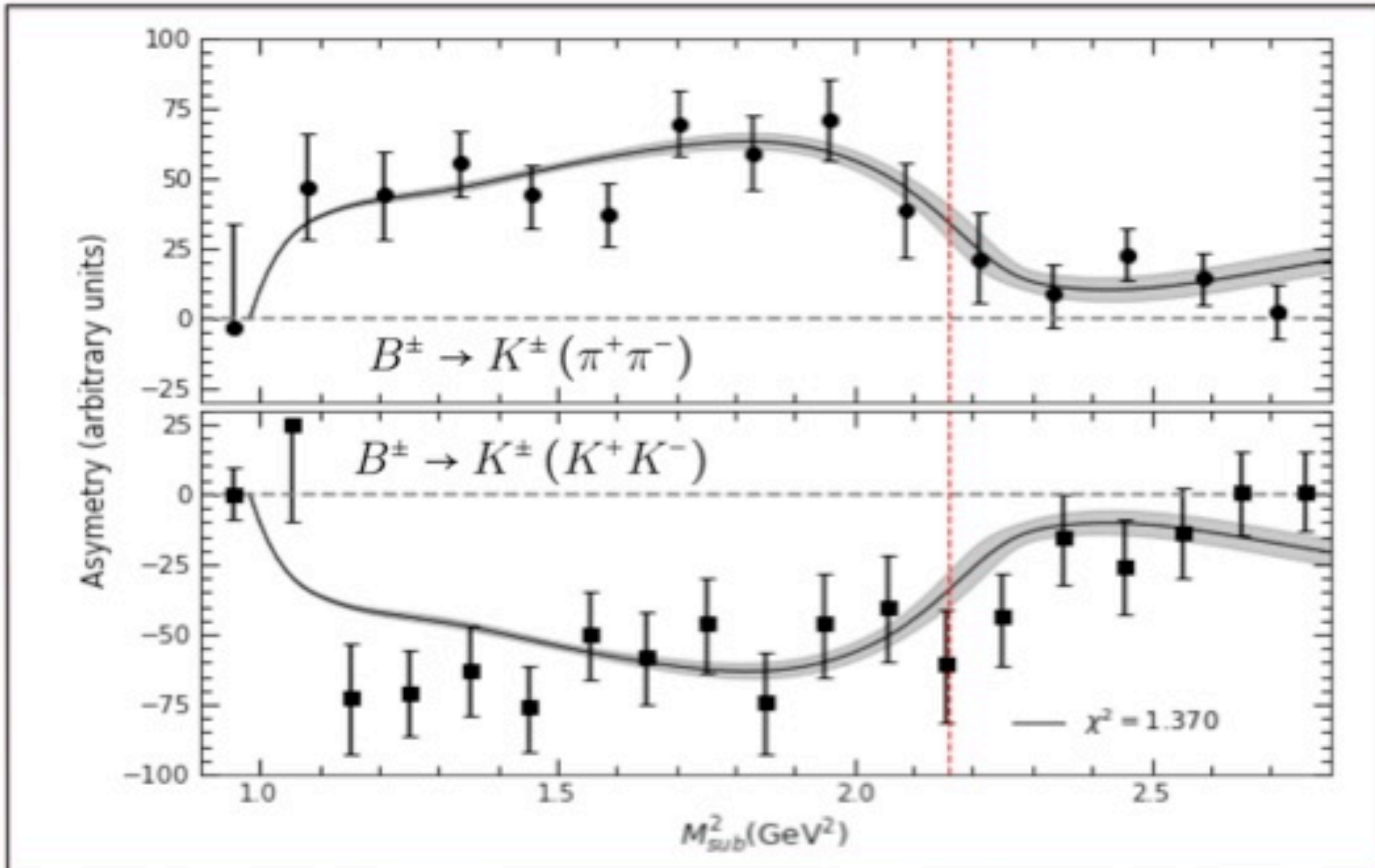
In that projection [5]:

$$\Delta\Gamma_{\pi\pi} + \Delta\Gamma_{KK} = 0$$

$$\Delta\Gamma_{KK} \approx -\Delta\Gamma_{\pi\pi}$$

- **Clear indication of DOMINANT role of FSI between the two hadronic states!**

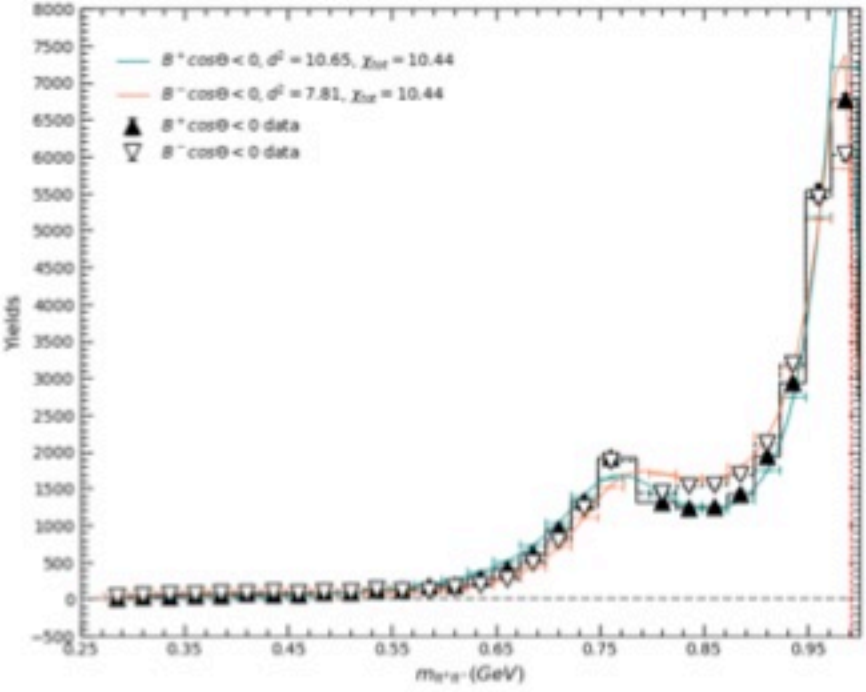
CP asymmetry with $\pi\pi \to KK$ parameterizations beyond LO



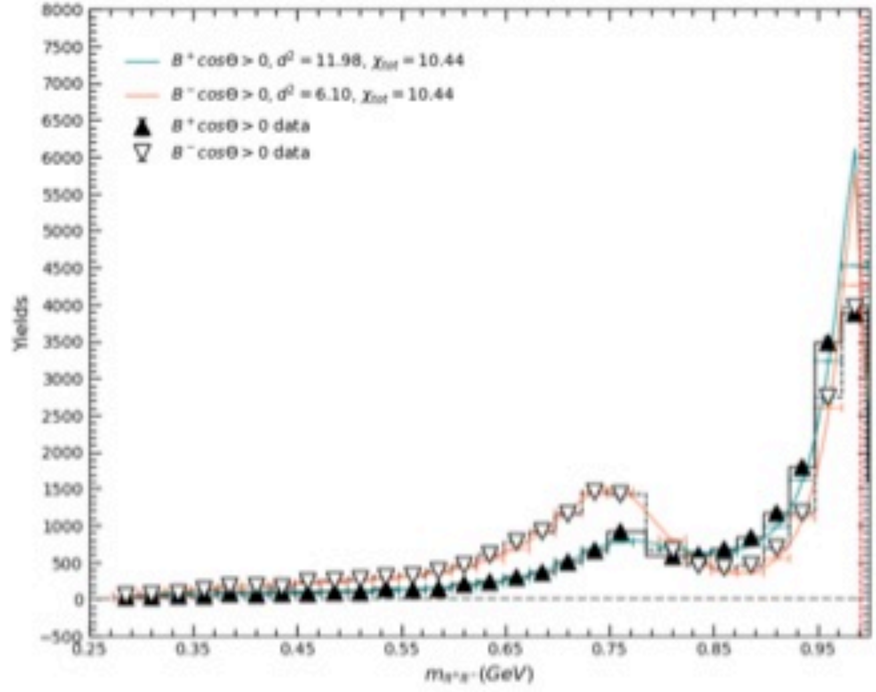
Fitted up to the $K\bar{K}$ threshold and only considering the S0 wave.

- Trying to fit the whole decay widths:

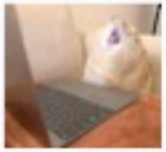
Backward



Forward

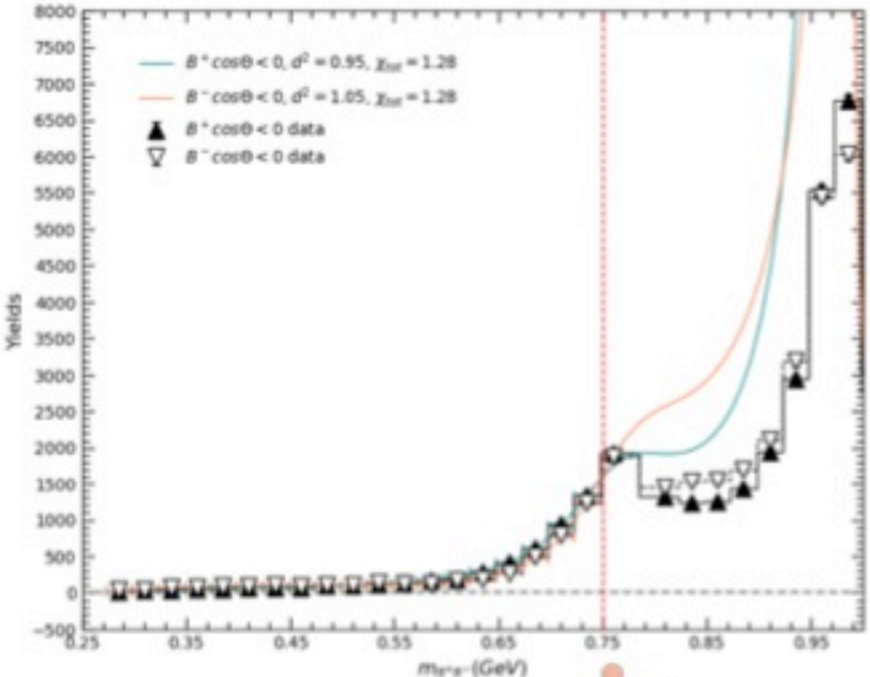


$\chi^2_{dof} \approx 10$ → **The experimental uncertainties are super small. Again, problems**

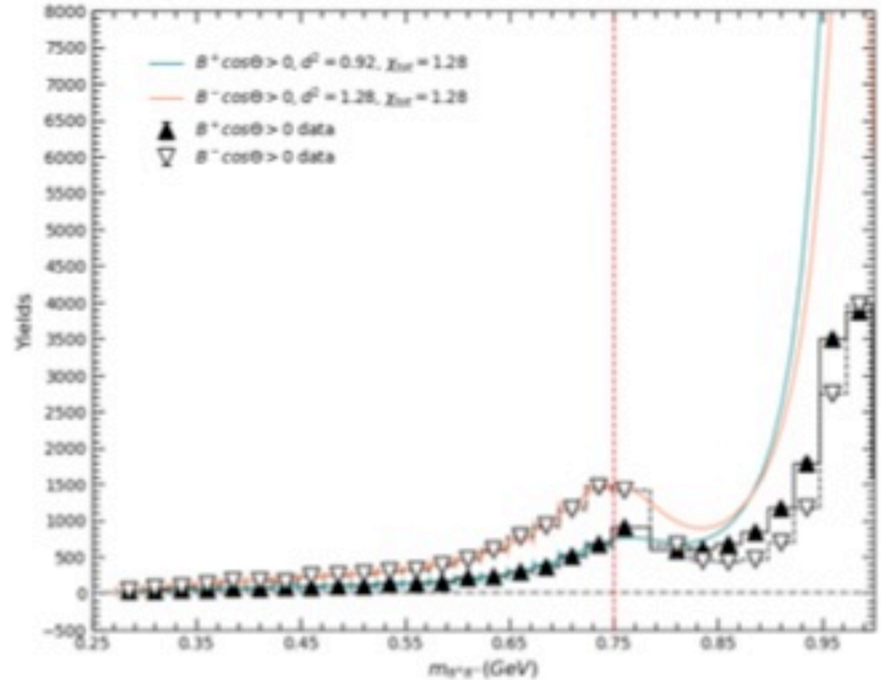


- We have checked if we get at least a good description at lower energies:

Backward



Forward

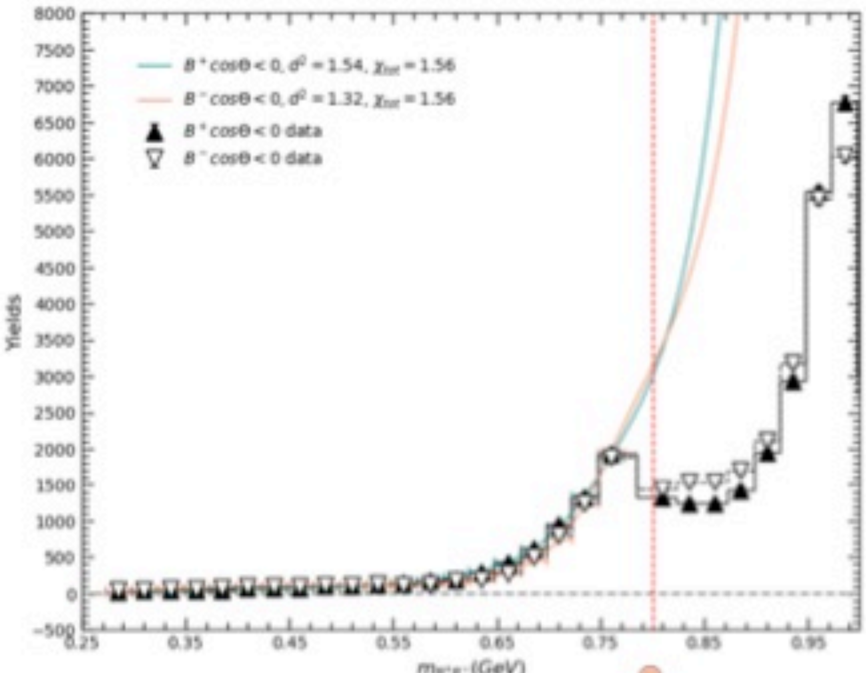


Fitting up to $0,75$ GeV

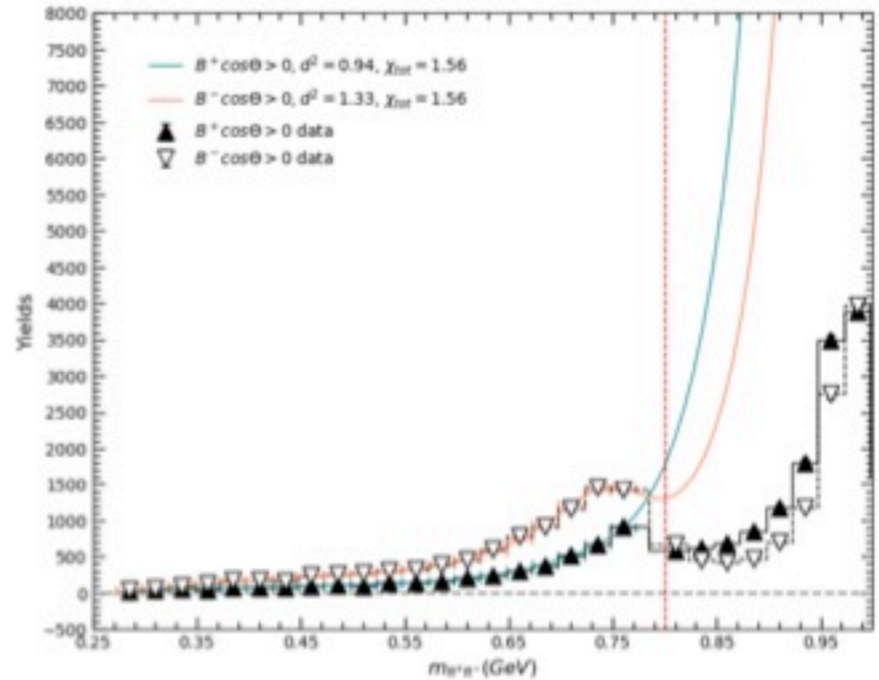
$\chi^2_{dof} \approx 1$

- We have checked if we get at least a good description at lower energies:

Backward



Forward

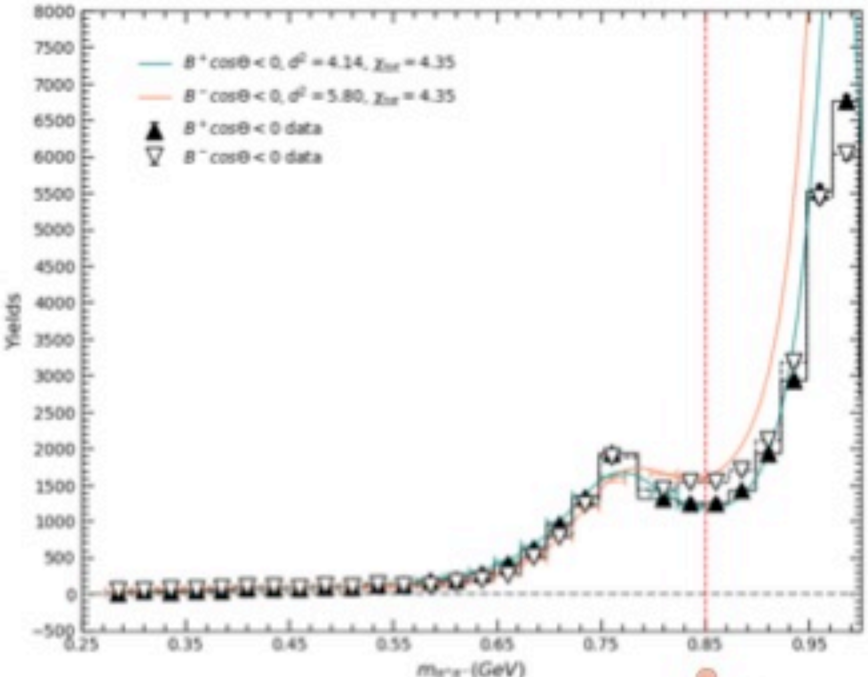


Fitting up to $0,8\ \mathrm{GeV}$

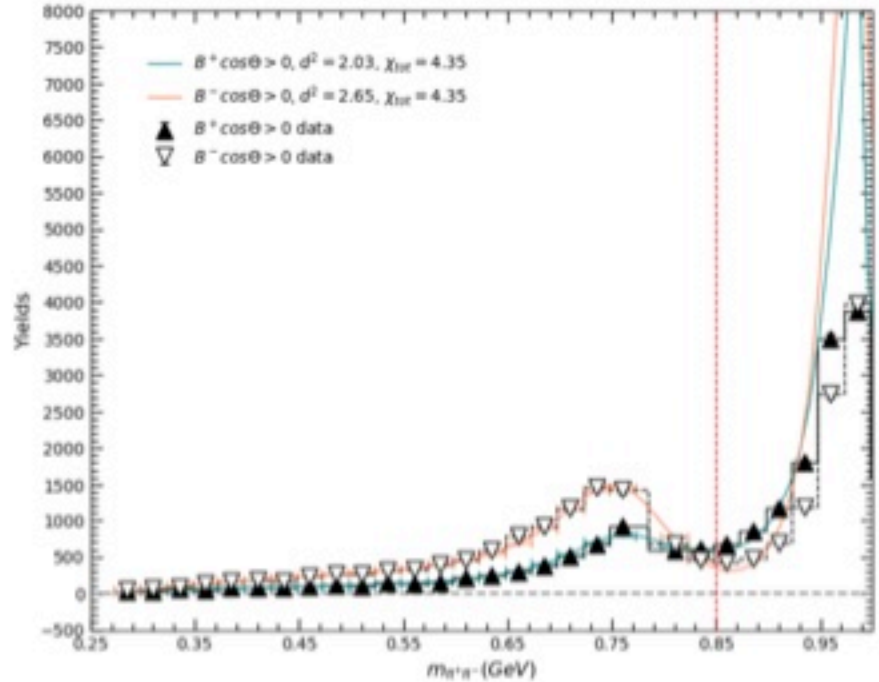
$$\chi^2_{dof} \approx 1$$

- We have checked if we get at least a good description at lower energies:

Backward



Forward

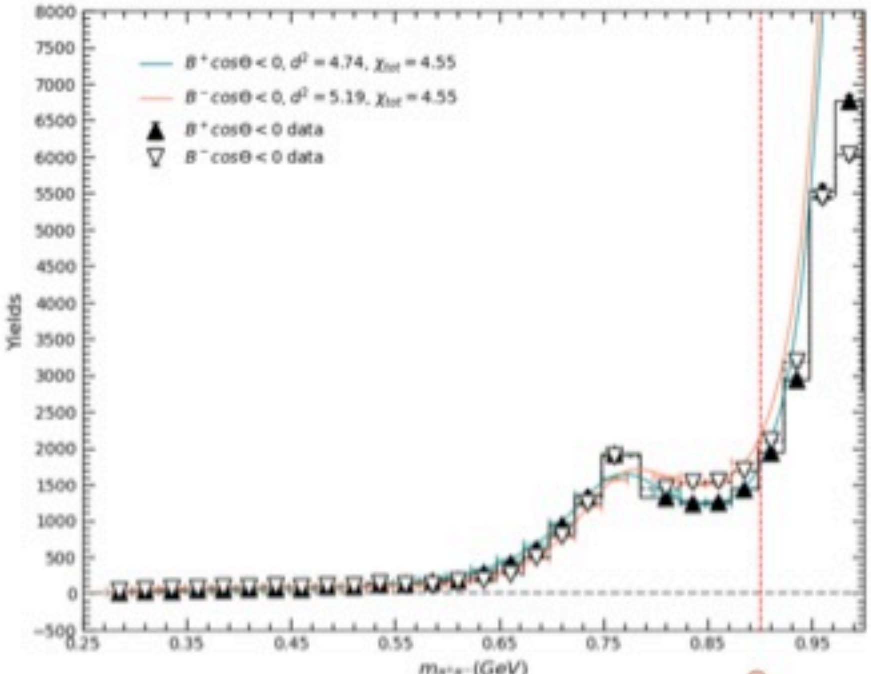


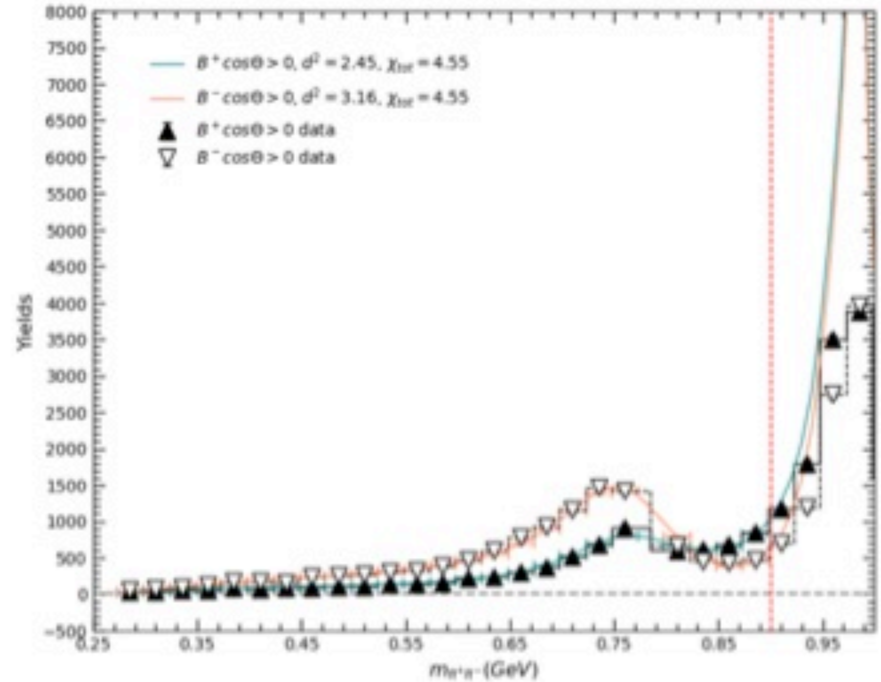
Fitting up to $0,85\ \mathrm{GeV}$

$$\chi^2_{dof} \approx 4$$

- We have checked if we get at least a good description at lower energies:

Backward **Forward**



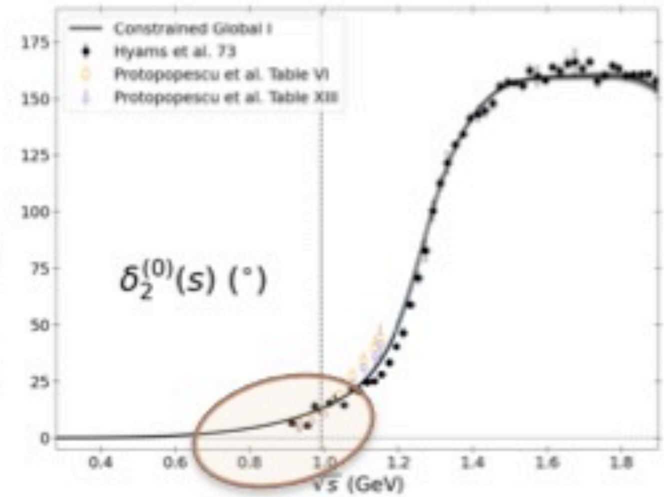


Fitting up to $0,9\ \text{GeV}$ **D wave contribution effects!!**

$$\chi^2_{dof} \approx 5$$

- Reproduce not only the CP asymmetry but also the whole decay widths, these involve extra the contributions which are invariant (or symmetric) under CP. This is specially challenging due to the extremely small experimental uncertainties
- Describe the CP asymmetries and decay widths of the other processes $B^{\pm} \to K^{\pm}(K^{+}K^{-})$, $B^{\pm} \to \pi^{\pm}(\pi^{+}\pi^{-})$ and $B^{\pm} \to \pi^{\pm}(K^{+}K^{-})$
- Go over KK threshold and develop a coupled channels formalism
- Connect our parameters introduced in the production with quark level physics

- Apparently, the accuracy of the data is so high that they are starting to see the $D0$ wave and therefore we will need to take it into account in the formalism



[9] J. R. Peláez, P. Rabán, J. Ruiz de Elvira in preparation

- Describe the CP asymmetries and decay widths of the other processes $B^{\pm} \to K^{\pm}(K^{+}K^{-})$, $B^{\pm} \to \pi^{\pm}(\pi^{+}\pi^{-})$ and $B^{\pm} \to \pi^{\pm}(K^{+}K^{-})$

- Go over KK threshold and develop a coupled channels formalism

- Connect our parameters introduced in the production with quark level physics