Long distance charm rescattering and connections to $B \to D\bar{D}h$

Daniel Johnson (CERN),

Méril Reboud (TUM),

Patricia Magalhães (UOB/ITA)

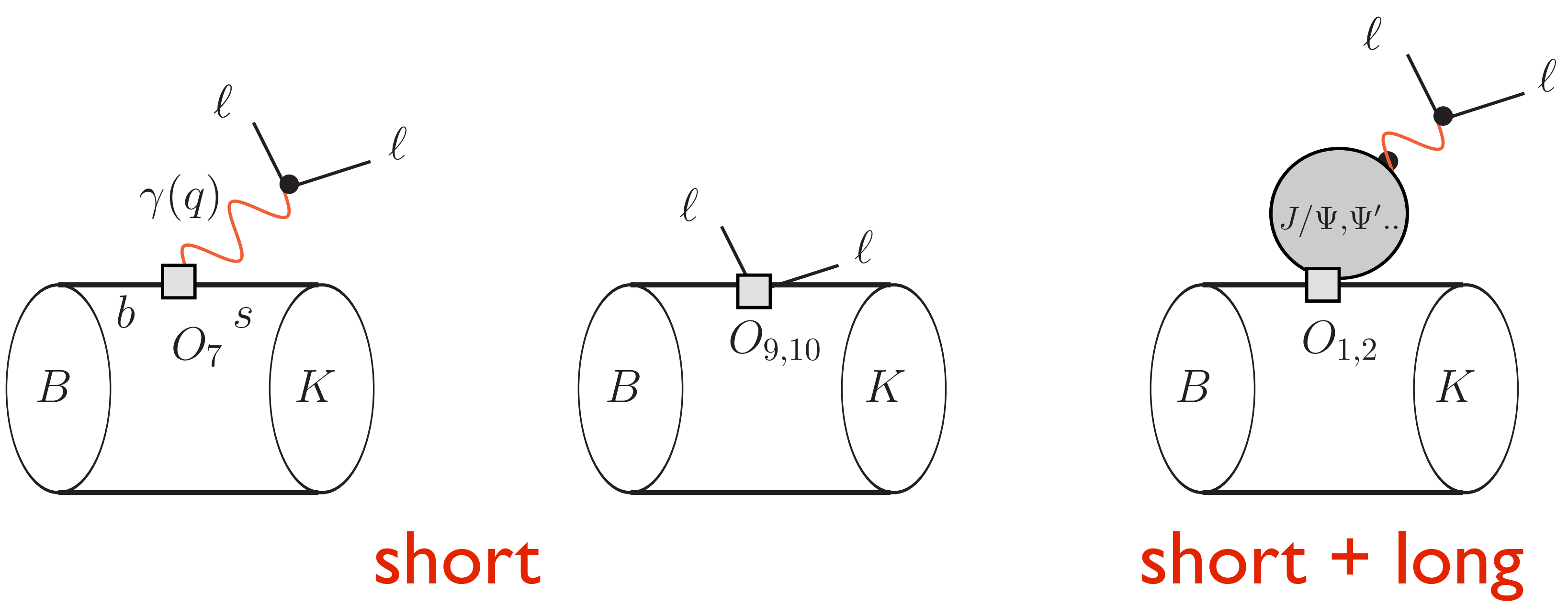
Beyond Flavour Anomalies II
April 2021

daniel.johnson@cern.ch - meril.reboud@tum.de - p.magalhaes@cern.ch

puzzles in flavour physics

- Anomalies in $b \to s\ell\bar{\ell}$
  - tensions with SM predictions

    $B \to K^{(*)}\ell^+\ell^-$
  - QCD picture



→ charm loop and the nonperturbative contribution is trick to account

theoretical challenge !

→ understanding the impact of intermediate $c\bar{c}$ contributions, both resonant and non resonant, is of paramount importance in order to be able to provide reliable and precise SM predictions.

non local charm contribution to $B \to K\mu\mu$

- QCD parametrization

$$\mathcal{A}_\lambda^{L,R}(B \to M_\lambda \ell\ell) = \mathcal{N}_\lambda \left\{ (C_9 \mp C_{10}) \mathcal{F}_\lambda(q^2) + \frac{2 m_b M_B}{q^2} \left[C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

$\hookrightarrow f_+^{B\to K}(q^2)$

  - non-local form-factors:

$$\mathcal{H}_\lambda(q^2) = i\mathcal{P}_\mu^\lambda \int d^4x\, e^{iq\cdot x} \langle \bar{M}_\lambda(k) | T\{\mathcal{J}^\mu_{\text{em}}(x), \mathcal{C}_i \mathcal{O}_i(0)\} | \bar{B}(q+k)\rangle$$

  - size of non-factorisable corrections in $b \to sc\bar{c}$ can be significante

    $\hookrightarrow$ not colour suppressed

non local charm contribution to $B \to K\mu\mu$

- naive factorization

  - charm loops are described by $c\bar{c}$ resonances given by charm vacuum polarization $h_c(q^2)$

$\longrightarrow$ $\langle K|C_1\mathcal{O}_1^c + C_2\mathcal{O}_2^c|B\rangle|_{\mathrm{FA}} \propto (C_1 + C_2/3) f_+^{B\to K}(q^2) h_c(q^2)$

- [Lyon- Zwicky]

$D\bar{D}, D^*\bar{D}, D^*\bar{D}^* \ldots$

used BESII data $\longrightarrow$ $R = \dfrac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu\mu)} \propto \mathrm{Im}\, h_c(q^2)$

- $R_{\text{fit}}(s) = R_{\text{res}}(s) + R_{\text{con}}(s)$

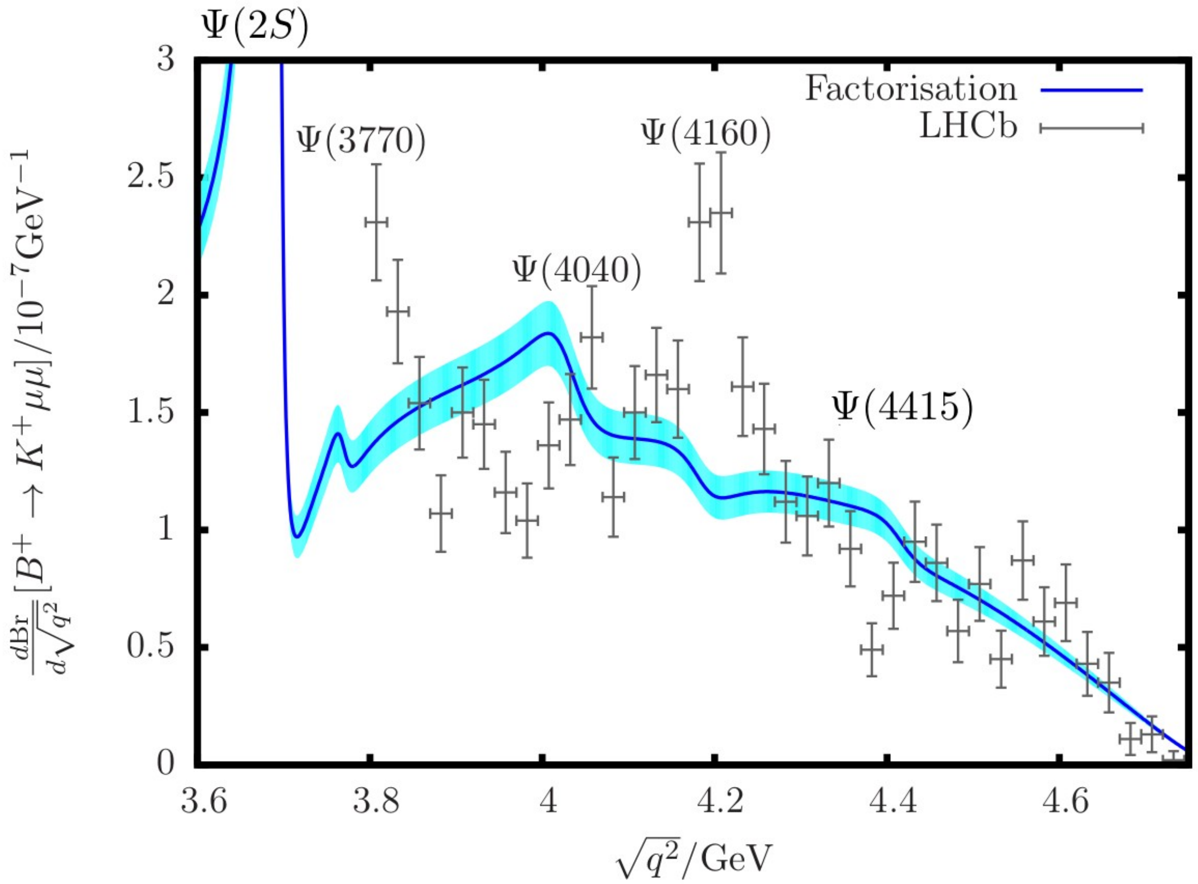
as Breit-Wigner

$\longrightarrow$ non-factorizable effects are important (high-q^2 OPE)!

$\longrightarrow$ not enough to cover the anomaly!

[Lyon-Zwicky] (see also [Brass, Hiller & Nisandzic]): *a posteriori* check of the factorization approach

- Requires additional factors to match measurements



- R ratio **cannot** correctly reproduce the resonances:

e.g. Ψ(3770) is a D-wave resonance so its decay-constant vanishes in the non-relativistic limit!

- More general approach (in collaboration with D. van Dyk and S. Kürten):

$$\mathcal{H}_\lambda^{\text{res}}(q^2) = \sum_\psi \frac{\mathcal{A}(\psi \to \ell\ell)\,\mathcal{A}(BK^{(*)} \to \psi)}{m_\psi^2 - q^2 + i\Gamma_\psi m_\psi}$$

(for illustration only!)

- Fix parameters using:

$$\mathcal{A}(e^+e^- \to D\bar{D}) \propto \sum_\psi \frac{\mathcal{A}(\psi \to D\bar{D})\,\mathcal{A}(\psi \to e^+e^-)}{m_\psi^2 - q^2 + i\Gamma_\psi m_\psi}$$

(BES, BaBar, Belle)

$$\mathcal{A}(B \to K^{(*)}D\bar{D}) \propto \sum_\psi \frac{\mathcal{A}(\psi \to D\bar{D})\,\mathcal{A}(BK^{(*)} \to \psi)}{m_\psi^2 - q^2 + i\Gamma_\psi m_\psi}$$

(LHCb, BaBar, Belle)

Long distance model

- Number of parameters:
  - *Naive approach* (Breit-Wigners): widths and masses are channel dependent → **hundreds** of parameters
  - *K matrix approach*: impose unitarity of the S matrix

$$S = 1 + 2i\,T = 1 + 2i\,\rho^{1/2}\,\hat{T}\,\rho^{1/2}$$

$$\hat{T} = \hat{K}\,(1 - i\rho\,\hat{K})^{-1}$$

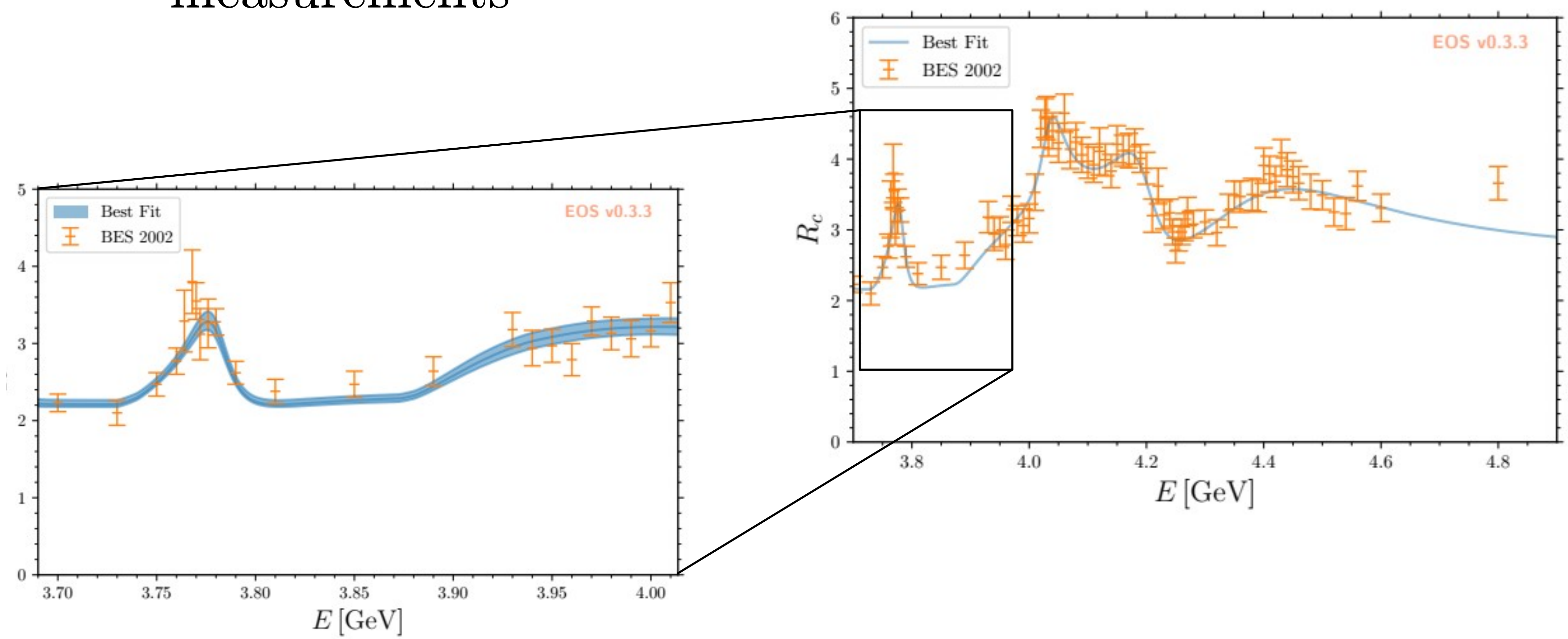
[Chung, Brose, et al. 1995]
[Uglov, Kalashnikova, et al. 2019]

$$\hat{K}_{ij} = \sum_{\psi_r} \frac{g^0_{ri}\,g^0_{rj}}{m^2_{\psi_r} - q^2} + \hat{c}_{ij} \qquad i,j \in \{ee, \mathrm{eff}, D^{(*)}\bar{D}^{(*)}, BK^{(*)}\}$$

g^0_{ri}	real-valued couplings
$\hat{c}_{ij}$	non-resonant contributions
eff	effective channel to light hadrons (needed for the $\psi(2S)$)

- Strategy:

  1) Fit the R ratio and $ee \to D^{(*)}\bar{D}^{(*)}$ cross-section measurements



  2) Use it with $B \to K^{(*)} D\bar{D}$ Dalitz plot analysis to predict $B \to K^{(*)}\ell\ell$ spectrum

$B \to D\bar{D}h$ status in LHCb

- First $B \to D\bar{D}h$ results from LHCb in 2020:

JHEP12 139

Measurement of branching fraction ratios for $B^+ \to D^{*+}D^-K^+$, $B^+ \to D^{*-}D^+K^+$, and $B^0 \to D^{*-}D^0K^+$ decays

The LHCb collaboration

4 world-best BFs

PRD102 051102

First observation of the decay $B^0 \to D^0\bar{D}^0K^+\pi^-$

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

(Received 9 July 2020; accepted 27 August 2020; published 22 September 2020)

1 first observation

- First study of amplitude structure, also in 2020, using $B^+ \to D^+D^-K^+$

Model-Independent Study of Structure in $B^+ \to D^+D^-K^+$ Decays

PRL125 242001

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

(Received 2 September 2020; accepted 7 October 2020; published 7 December 2020)

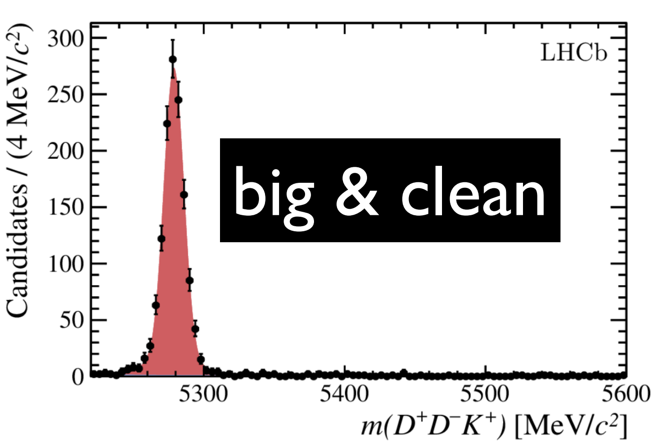
Amplitude analysis of the $B^+ \to D^+D^-K^+$ decay

PRD102 112003

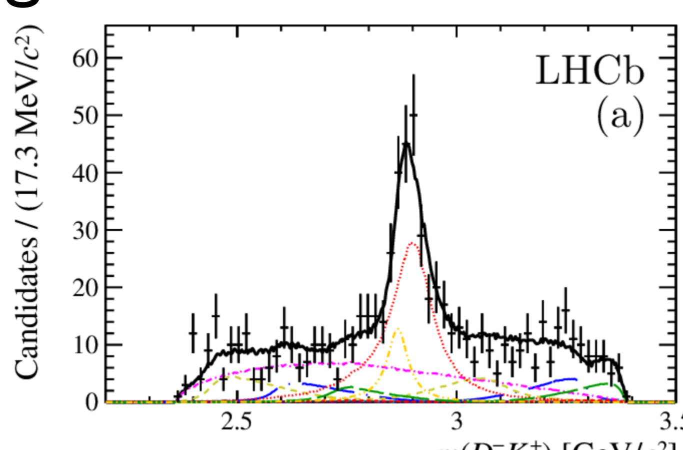
R. Aaij *et al.**
(LHCb Collaboration)

(Received 2 September 2020; accepted 8 October 2020; published 7 December 2020)

Conceived as a clean insight into charmonium spectrum



big & clean

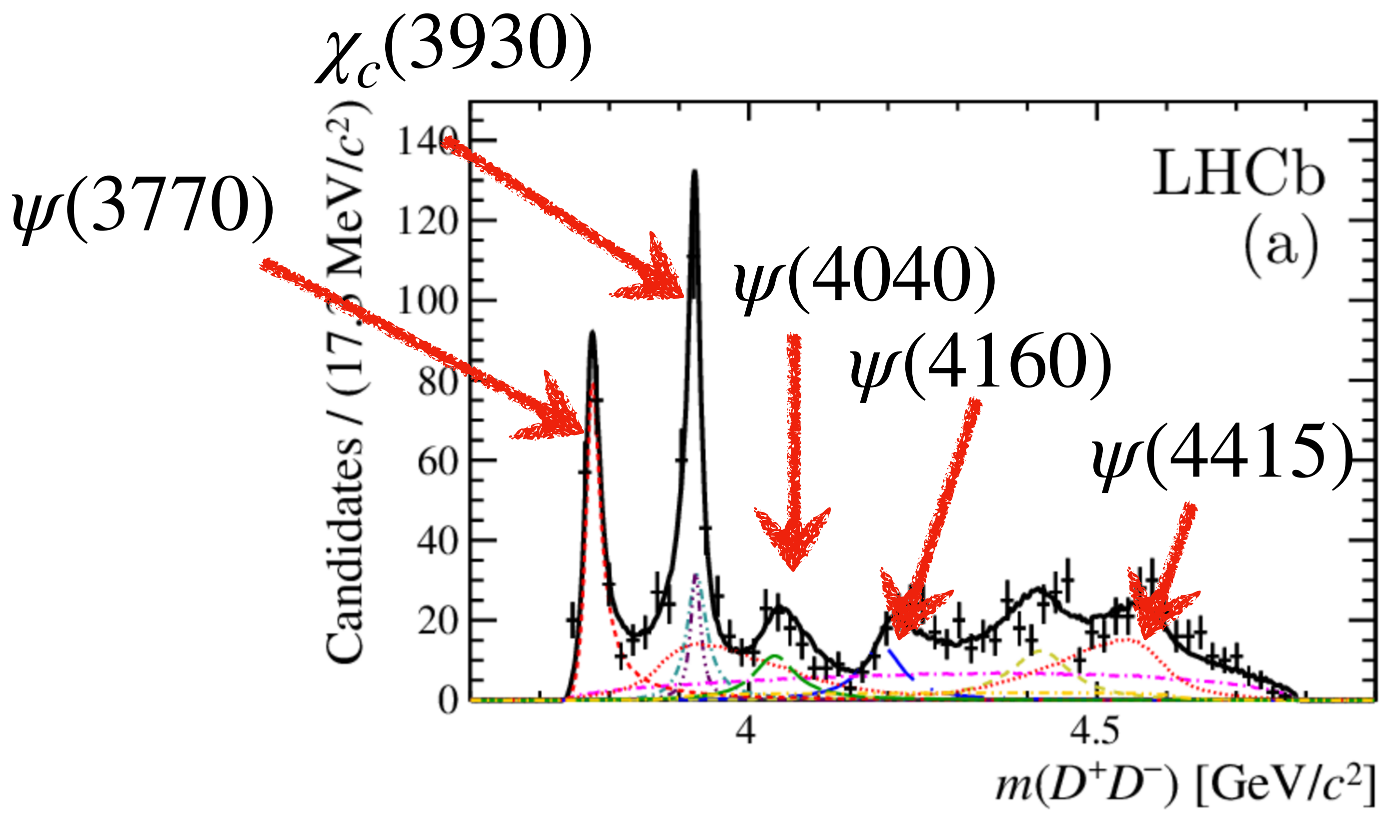


Big surprise in the D^-K^+ spectrum

Model independent and dependent discovery of exotic $cs\bar{u}\bar{d}$ structure

$B \to D\bar{D}h$ status in LHCb

- Despite the exotic reflection, clean access to the charmonium spectrum



Discovery of scalar state

Needed both the expected $\chi_{c2}(3930)$ *and* a new $\chi_{c0}(3930)$

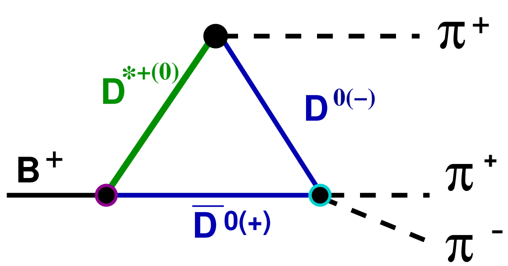
- Exploration of the new D^-K^+ structures is a high priority: incorporating a wide array of $B \to D^{(*)}\overline{D}^{(*)}h^{(*)}$ decays to confirm and probe it
- Will gain further handles on the charmonium states, beyond $D^0\overline{D^0}$ and D^+D^-, through tricky >3-body analyses to access $D^{*+}D^-$ and $D^{*+}D^{*-}$

Key questions:

- Theoretical models for D^-K^+ states: tetra quark? molecule? threshold enhancement?
- Modelling of D^0K^+: several broad, overlapping states

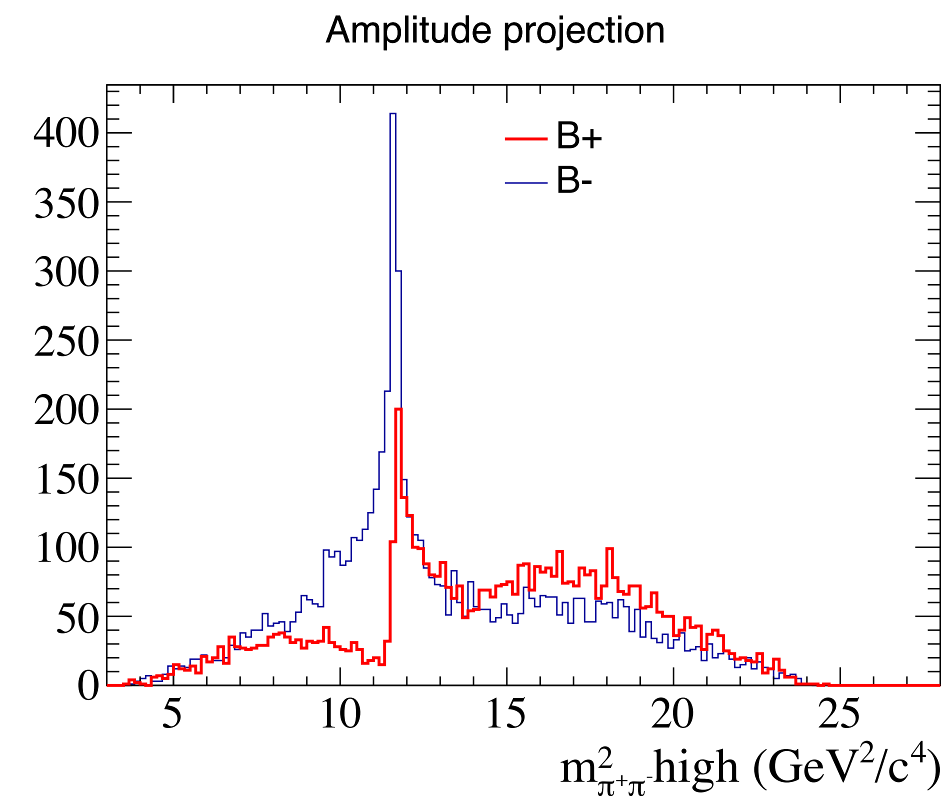
work in progress
Kostas and Roman

- Why we think charm rescattering can play a role?
  - FSI are sources of strong phase variation that can interfere with other sources
- observed this effect in $B \to \pi\pi\pi$



$+ \; a_0 \, e^{\pm i\gamma}$

Bediaga, Frederico, Magalhaes - PLB 806 (2020) 135490



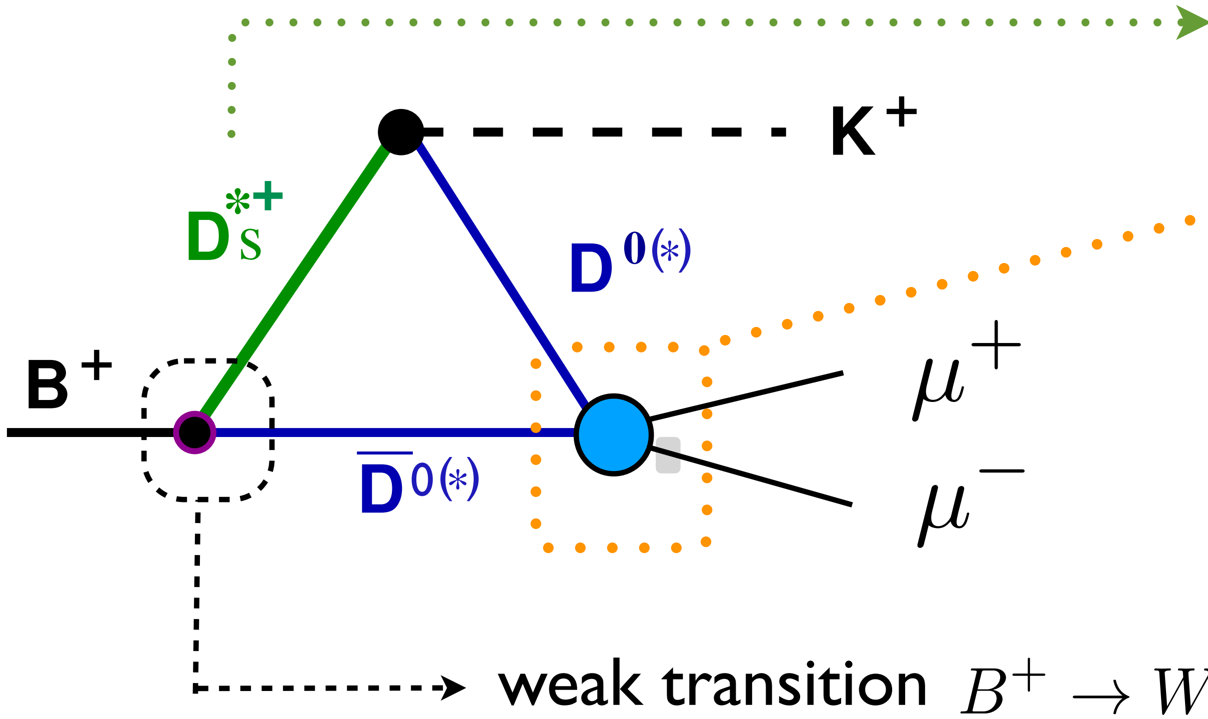
→ explain the observed CP violation (LHCb data) in the middle of the phase space!

- Similar interaction can happen in $B \to K\mu\mu$
  - amplitude interferes with short-distance component → $C_9^{\text{eff}}(q^2) = C_9 + Y(q^2)$

→ Propose an alternative data-driven approach to calculate this exclude charm-rescattering contribution!

charm rescattering effects in $B \to K\mu\mu$

- Use the same FSI approach as used in $B \to \pi\pi\pi$ for $B \to K\mu\mu$



form factor for $W^+ \to D_s^{*+} \to \bar{D}^0 K^+$

$D^{\bar{0}(*)} D^{0(*)} \to R_{c\bar{c}} \to \mu^+\mu^-$

- Br from $e^+e^- \to D\bar{D}$ BES data with a Dispersion Relation (Roman's work)

weak transition $B^+ \to W^+ \bar{D}^0$

- The charm rescattering amplitude helicity average:

$$A(q^2) = C_W \int \frac{d^4\ell}{(2\pi)^4} \frac{\alpha + \Delta\bar{D}_0 - \Delta_a}{\Delta_{D^0}\,\Delta_{\bar{D}^0}\,\Delta_{D*}\,\Delta_a} T_{D\bar{D}\to\mu^+\mu^-}(q^2,\ell)$$

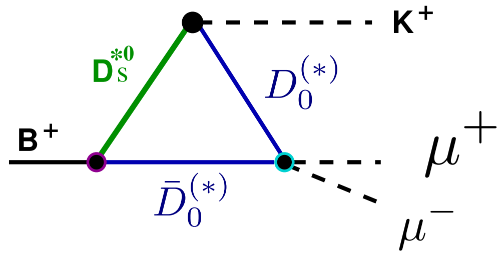
$$C_W = \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* \, m_a^2 \, m_{Ds*}^2 F^{BD}(0) F^{Ds*}(0) \quad \sim 10^{-5}$$

$$\alpha = M_B^2 + M_K^2 - 2s_{12} + M_{D_0}^2 + M_{\bar{D}_0}^2 - m_a^2;$$

$$\Delta_{D_i} = P_{D_i} - m_{D_i}^2 + i\epsilon$$

tensor integral to deal with angular distribution

All triangles combinations

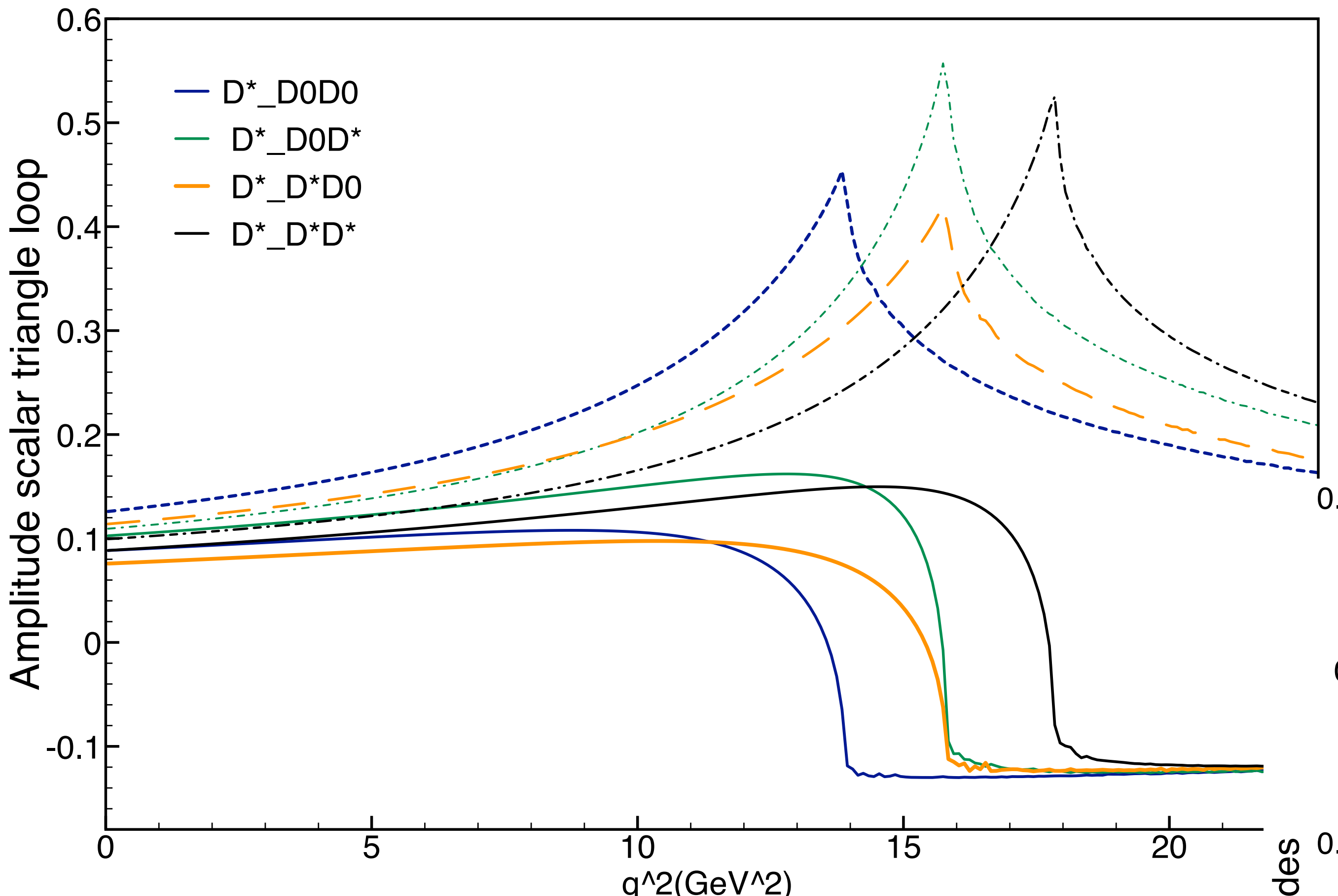
- $\sum$ 

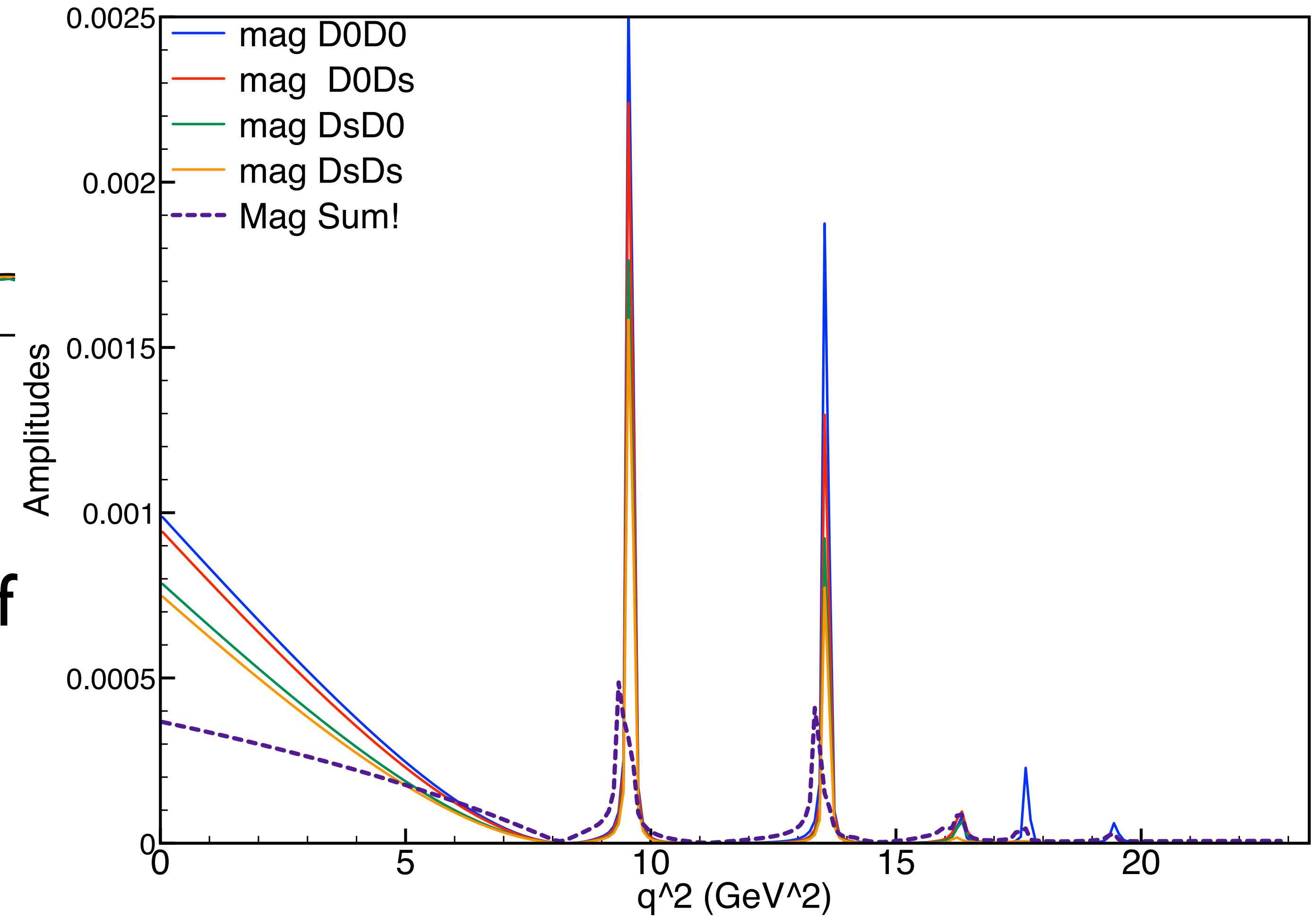
we considered in the HQ spin symmetry 4 different triangle contributions and weight the different contributions of BR

BR[B$\rightarrow$ $D_s^* \bar{D}_0] = 7.6 \times 10^{-3}$

BR[B $\rightarrow D_s^* D_0^* (\bar{2}007)] = 1.7 \times 10^{-2}$

(PDG) - The other variations don't make difference - backup slide

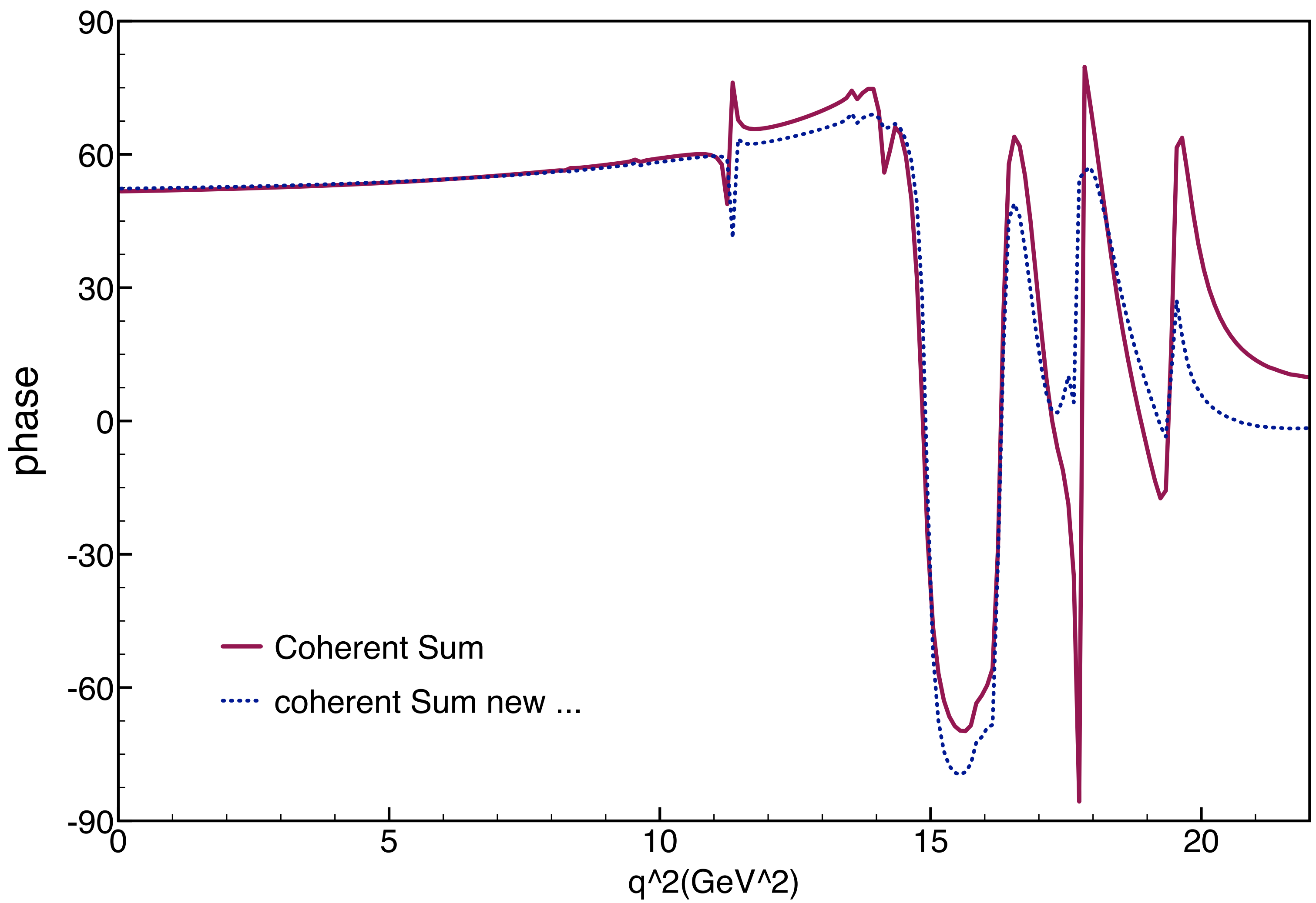




- we could also float the overall size of the amplitude in a fit to the data

Remarks

- Phase highlight the q^2 dependence effect



- significant even at low q^2 !

Caveats

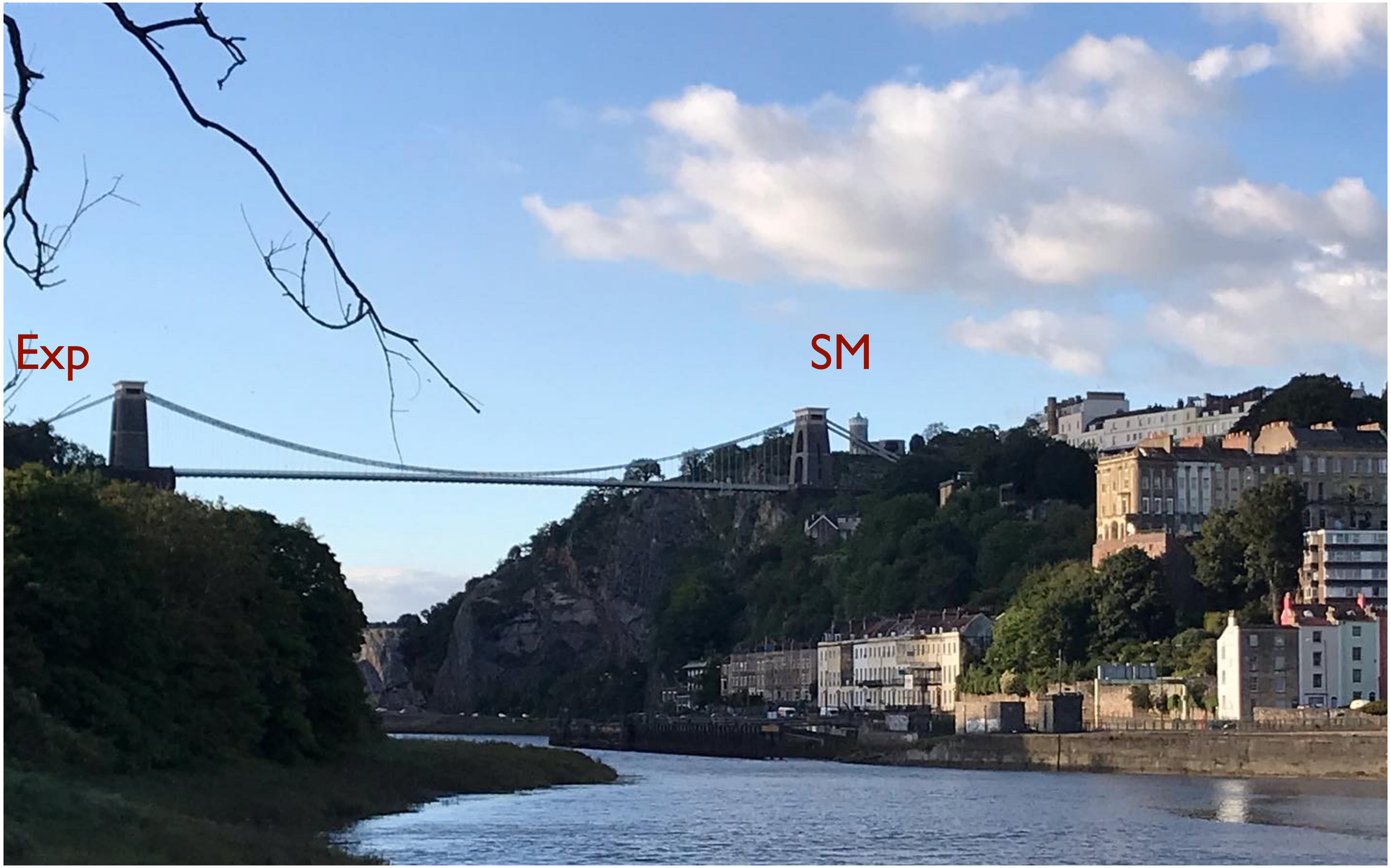
- improve our description of the relative FF and BR (?)
- accuracy on the relative coupling $D^{\bar{0}(*)} D^{0(*)} \to R_{c\bar{c}} \to \mu^+\mu^-$
- care is needed as BES input already sums over muon helicities

- To include this amplitude in the full description of $B \to K\mu\mu$:

→ add it coherently in a isobar description together with resonant and non resonant $c\bar{c}$ components to fit data

$$\frac{d^2\Gamma}{dq^2\, d\cos\theta_\ell} = \sum_{\lambda_1,\lambda_2=-1/2}^{+1/2} \left| \mathcal{M}_{\lambda_1,\lambda_2}^{B\to K\mu\mu} + \mathcal{M}_{\lambda_1,\lambda_2}^{B\to DD^*\to K\mu\mu} \right|^2$$

how we do the bridge ?



Discussion

- How to improve the accuracy on the relative couplings $\begin{cases} D^{\bar{0}(*)} D^{0(*)} \to R_{c\bar{c}} \\ R_{c\bar{c}} \to \mu^+ \mu^- \end{cases}$

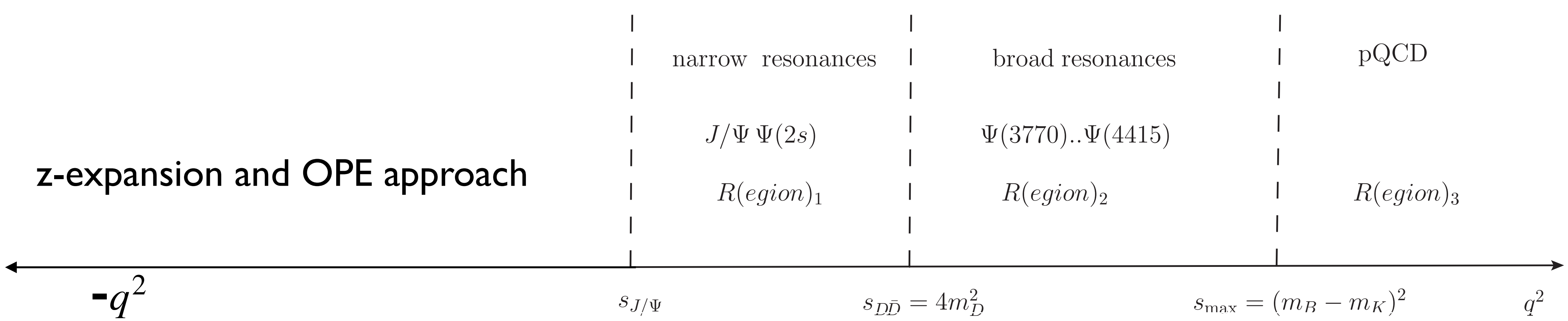
  ↳ LHCb new data

- Not possible to avoid the DK resonances in $B \to D\bar{D}h$

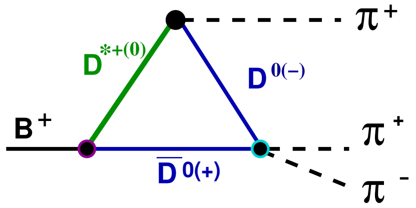
  ↳ not well defined theoretically

- Non-resonant charm contributions:
  - not negligible in hadronic approach!
  - how to model it in QCD approach?

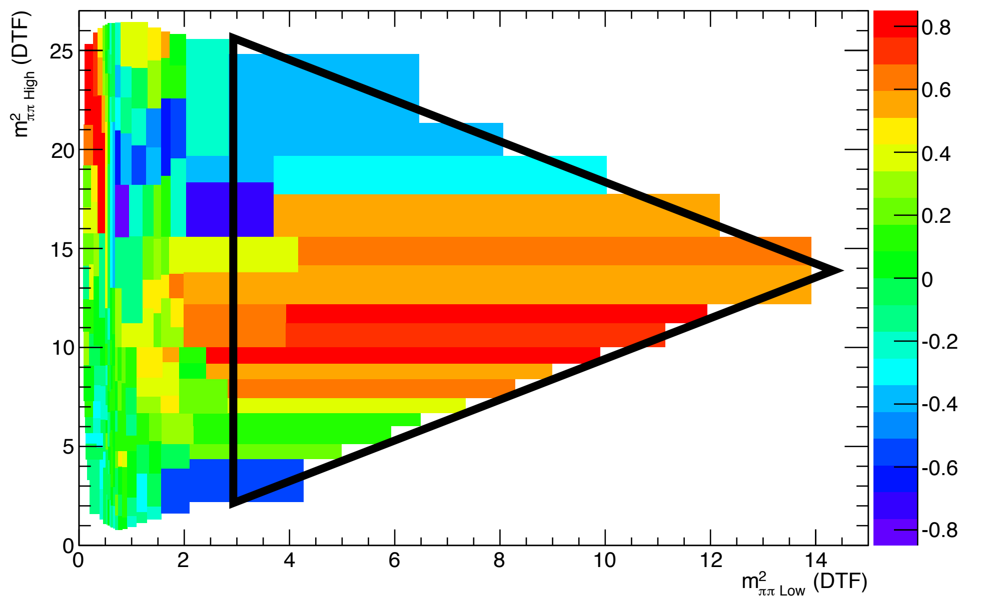
- How to connect our knowledge from diff regions?

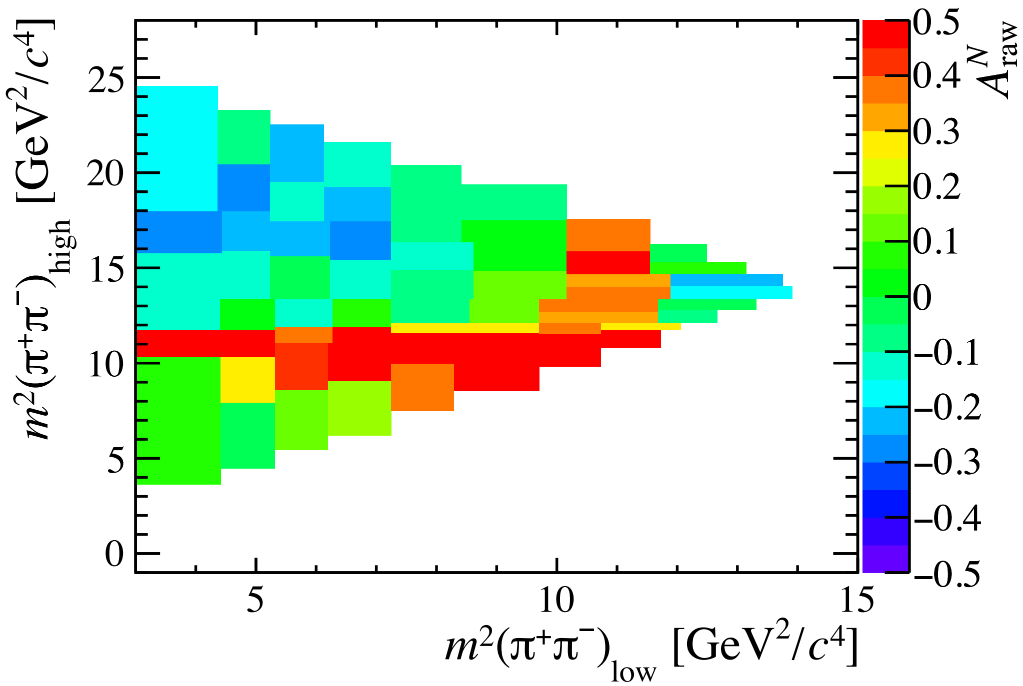


The charm rescattering as a new mechanism to generate CP violation at high mass region of $B \to \pi\pi\pi$ phase-space

- $A_{B^\pm\to\pi^-\pi^+\pi^\pm}(s_{12}, s_{23}) =$  $+ \quad a_0\, e^{\pm i\gamma}$

- LHCb Run I
- our model





- Rescattering model

PDG BR

$$B \to D^{\bar{0}(*)} D_{s1}(2536)^+ \times B(D_{s1}(2536) \to D^*(2007)^0 K^+) \qquad (2.2 \pm 0.7) \times 10^{-4}$$

$$B \to \bar{D}^*(2007)^0 D_{s1}(2536)^+ \times B(D_{s1}(2536) \to D^*(2007)^0 K^+) \qquad (5.5 \pm 1.6) \times 10^{-4}$$

$$B \to \bar{D}^0 D_{sJ}(2700)^+ \times B(D_{sJ}(2700)^+ \to D^0 K^+) \qquad (5.6 \pm 1.8) \times 10^{-4}$$

Long distance model issues

- Open issues (some thought in the following slides)

1) Centrifugal barrier factors (finite size effects)

2) Non-resonant contributions $\hat{c}_{ij}$

3) Experimental inputs (choice of channels, fit model(s))

4) Relation to the OPE description at small q^2

1) Centrifugal barrier factors (finite size effects) [Blatt, Weisskopf, 1952]

$$\hat{K}_{ij} = \sum_{\psi_r} \frac{g^0_{ri}\, g^0_{rj}\, B^L_{ri}(q,q_\alpha) B^L_{rj}(q,q_\alpha)}{m^2_{\psi_r} - q^2} + \hat{c}_{ij}$$

$$F_0(q) = 1$$

$$B^l_{\alpha i}(q,q_\alpha) = \frac{F_l(q)}{F_l(q_\alpha)}$$

$$F_1(q) = \sqrt{\frac{2z}{z+1}}$$

$$F_2(q) = \sqrt{\frac{13z^2}{(z-3)^2+9z}}$$

$z = (q/q_R)^2$ and q_R corresponds to the range of interaction.

Are these factors really needed?

2) Non-resonant contributions

$$\hat{K}_{ij} = \sum_{\psi_r} \frac{g^0_{ri}\, g^0_{rj}}{m^2_{\psi_r} - q^2} + \hat{c}_{ij}$$

$(\mathrm{N}_{\mathrm{channel}})^2$ parameters

- These constants account for $\mathrm{R}_{\mathrm{udsc}}$ - $\mathrm{R}_{\mathrm{uds}}$
- $\hat{c}_{ij}$ with $\mathrm{i} = 0$ are enough to get a good fit of $ee \rightarrow c\bar{c}$
- Can we safely set the other to zero?

3) Experimental inputs (choice of channels, fit model(s))

- The charge assignment in $B \to K^{(*)} D\bar{D}$ allows to avoid $K^{(*)}D$ resonances

- We need access to specific waves contributions:

	DD	DD*	D*D*
S - wave	✦	★	✦
P - wave	★		★
D - wave			✦
F - wave			★

★ Needed contribution

✦ Contribution that need to be under control

4) Relation to the OPE description at small q^2

- The z parametrization describes the spectrum below the $D\bar{D}$ threshold

- The K matrix approach describes the spectrum above the $D\bar{D}$ threshold

- A fit can vary them independently but they are connected to the same OPE!
  - How do we reconcile the two parametrizations?
  - In principle they should be continuous and smooth at the threshold