

S-wave contribution to rare $D \rightarrow \pi\pi\ell\ell$ decays in the SM and sensitivity to NP

Luiz VALE SILVA

*In collaboration with Svjetlana Fajfer (IJS) and Eleftheria Solomonidi (IFIC, UV – CSIC)
based on PRD109 (2024) 3 (2312.07501)*

24/04/2024 – 2nd CharmInDor (Dortmund)



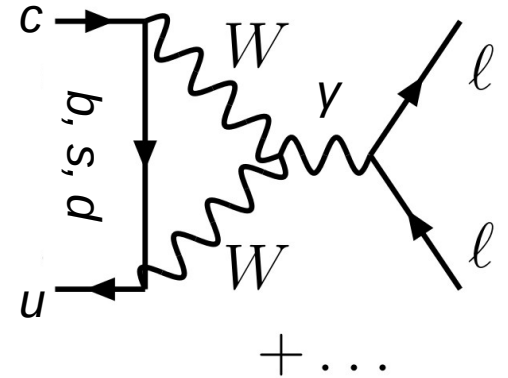
Rare charm decays



- Flavour physics of the **up-type**: complementary, but less well known than **down-type** **strange** (χPT_3) and **bottom** (HQET) sectors

- More effective GIM mechanism, CKM almost diagonal texture: **non-perturbative effects play a very important role**; QCD @ intermediate regime

[Fajfer, Prelovsek '06; Capiello, Cata, D'Ambrosio '13; Feldmann, Muller, Seidel '17; De Boer, Hiller '18; Bharucha, Boito, Meaux '20...]



- **Large data set available**, allowing for a closer look into the SM
[various charm-meson decays: LHCb, BESIII, CLEO, BaBar, etc.]
- Having control over the SM, move to observables measuring **SM–NP interference**: analysis of a **rich set of angular observables**

Bjorken, Glashow '64:

the nonleptonic $\Delta I = \frac{1}{2}$ rule, and a significant "baryon"-lepton symmetry. A new quantum number "charm" is violated only by the weak interactions, and the model predicts the existence of many "charmed" particles whose discovery is the crucial test of the idea.

We call the four fundamental "baryons" $\psi_i =$

Volume 11, number 3 PHYSICS LETTERS 1 August 1964

ELEMENTARY PARTICLES AND SU(4)*

B. J. BJORKEN** and S. L. GLASHOW***
Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark
 Received 19 June 1964

Recently, models of strong interaction symmetry have been proposed [1-3] involving four fundamental Fermions ψ_i and approximate symmetry under SU(4). Mesons are identified with meson states $\psi_i \bar{\psi}_j$ and baryons with baryon states $\psi_i \psi_j \psi_k$. In this note we examine a model of this type whose principal ingredients are: (a) a mass formula relating the masses of the six vector mesons and predicting a ninth pseudoscalar meson of 950 MeV, a description of weak interactions including all selection rules except the octopoleic $\Delta I = 1$ rule, and a significant "baryon"-lepton symmetry. A new quantum number "charm" is violated only by the weak interactions, and the model predicts the existence of many "charmed" particles whose discovery is the crucial test of the idea.

We call the four fundamental "baryons" $\psi_i = (\psi_1^+, \psi_2^+, \psi_3^+, \psi_4^+)$ and assume the strong interactions are approximately invariant under a unitary transformation U in the ψ_i space. For convenience, we let this representation of SU(4) be the 4. We furthermore assume that the strong interactions are also invariant under independent phase transformations of each of the four ψ_i and invariant under the isotopic group. (ψ_1^+ and ψ_2^+ are singlets and (ψ_3^+, ψ_4^+) an isodoublet). The four conserved quantum numbers we define to be baryon number B , charm C , charge Q and hypercharge Y , and their assignments are shown in table 1.

The eightfold way - possibly a more exact symmetry than SU(3) - is a subgroup of SU(4) corresponding to the strong interactions when charm is neglected. The charmed particles comprise an isosinglet ψ_4^+ with $C = Y = 1$ and an isodoublet (ψ_3^+, ψ_2^+) with $C = Y = 0$, and their antiparticles with $C = -1$.

A mass formula with Gell-Mann and Okubo ψ_i can be obtained if we assume that symmetry-breaking effects transform like a number of octets in the adjoint representation of SU(4). This mass splitting and transformation like $\psi_i \bar{\psi}_j$. For pseudoscalar mesons the mass formula contains only three terms, and all masses are determined by

Quantum numbers of the hadronical fields.	B	C	Q	Y	I_3
ψ_1^+	1	1	1	0	0
ψ_2^+	1	0	0	0	1
ψ_3^+	1	0	0	0	0
ψ_4^+	1	0	0	0	0

$M^2 = m_0^2 + a_1 \psi_i \bar{\psi}_i + a_2 \psi_i \bar{\psi}_j + a_3 \psi_i \bar{\psi}_k$
 These 15 mesons form four SU(3) multiplets: a $C = 0$ singlet, a $C = 0$ octet, a Y with $C = 1$, and a Y with $C = -1$. They are conveniently displayed as a 4×4 matrix

$$M = \begin{pmatrix} \psi_1^+ \bar{\psi}_1 & \psi_1^+ \bar{\psi}_2 & \psi_1^+ \bar{\psi}_3 & \psi_1^+ \bar{\psi}_4 \\ \psi_2^+ \bar{\psi}_1 & \psi_2^+ \bar{\psi}_2 & \psi_2^+ \bar{\psi}_3 & \psi_2^+ \bar{\psi}_4 \\ \psi_3^+ \bar{\psi}_1 & \psi_3^+ \bar{\psi}_2 & \psi_3^+ \bar{\psi}_3 & \psi_3^+ \bar{\psi}_4 \\ \psi_4^+ \bar{\psi}_1 & \psi_4^+ \bar{\psi}_2 & \psi_4^+ \bar{\psi}_3 & \psi_4^+ \bar{\psi}_4 \end{pmatrix}$$

The ninth pseudoscalar meson, without charm is called ψ_9 . The charmed particles comprise an isosinglet ψ_4^+ with $C = Y = 1$ and an isodoublet (ψ_3^+, ψ_2^+) with $C = Y = 0$, and their antiparticles with $C = -1$.

A mass formula with Gell-Mann and Okubo ψ_i can be obtained if we assume that symmetry-breaking effects transform like a number of octets in the adjoint representation of SU(4). This mass splitting and transformation like $\psi_i \bar{\psi}_j$. For pseudoscalar mesons the mass formula contains only three terms, and all masses are determined by

Work supported in part by U.S. Office of Naval Research through their grants.

** Alfred P. Sloan Foundation Fellow, on leave from Stanford Linear Accelerator Center, Stanford, California.

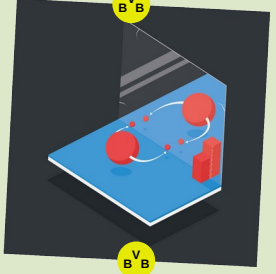
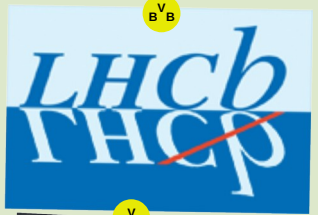
*** Alfred P. Sloan Foundation Fellow, on leave from University of California at Berkeley, Berkeley, California.

It is this model $\psi_i \bar{\psi}_j = \psi_i \bar{\psi}_j + \psi_i \bar{\psi}_k$. This is strong violation of "charm" violation $\Delta C = 1$. This is strong violation of "charm" violation $\Delta C = 1$. This is strong violation of "charm" violation $\Delta C = 1$.

Tarjanne, Teplitz '63, Maki '64, Hara '64; see Olsen [2309.06042] for a historical review

LVS

Ausgewählte LHCb-Analysen



PHYSICAL REVIEW LETTERS

Observation of CP-Meson Decays to $K^+ \pi^+ \pi^0$ and $K^+ K^+ \pi^0$ Final States

14 OCTOBER 2011

The observation of CP-meson decays to $K^+ \pi^+ \pi^0$ and $K^+ K^+ \pi^0$ final states is reported. The decays are observed in the D^0 meson system. The results are consistent with the Standard Model prediction.

PHYSICAL REVIEW LETTERS

Search for Rare Decays of CP-Mesons into Two Mesons

14 OCTOBER 2011

A search for rare decays of CP-mesons into two mesons is presented. The decays are observed in the D^0 meson system. The results are consistent with the Standard Model prediction.

PHYSICAL REVIEW LETTERS

Searches for 25 Rare and Forbidden Decays of D^0 and D^+ Mesons

14 OCTOBER 2011

Searches for 25 rare and forbidden decays of D^0 and D^+ mesons are presented. The decays are observed in the D^0 meson system. The results are consistent with the Standard Model prediction.

PHYSICAL REVIEW LETTERS

Angular Analysis of $B^0 \rightarrow \pi^+ \pi^- \pi^0$ and $B^0 \rightarrow K^+ K^- \pi^0$ Decays and Search for CP Violation

14 OCTOBER 2011

Angular analysis of $B^0 \rightarrow \pi^+ \pi^- \pi^0$ and $B^0 \rightarrow K^+ K^- \pi^0$ decays is presented. The decays are observed in the B^0 meson system. The results are consistent with the Standard Model prediction.

PHYSICAL REVIEW LETTERS

Observation of CP Violation in Charm Decays

14 OCTOBER 2011

Observation of CP violation in charm decays is presented. The decays are observed in the D^0 meson system. The results are consistent with the Standard Model prediction.

PHYSICAL REVIEW LETTERS

Measurement of the Time-Dependent CP Asymmetry in $B^0 \rightarrow K^+ K^- \pi^0$ Decays

14 OCTOBER 2011

Measurement of the time-dependent CP asymmetry in $B^0 \rightarrow K^+ K^- \pi^0$ decays is presented. The decays are observed in the B^0 meson system. The results are consistent with the Standard Model prediction.

PHYSICAL REVIEW LETTERS

Measurement of the Time-Dependent CP Asymmetry in $B^0 \rightarrow \pi^+ \pi^- \pi^0$ Decays

14 OCTOBER 2011

Measurement of the time-dependent CP asymmetry in $B^0 \rightarrow \pi^+ \pi^- \pi^0$ decays is presented. The decays are observed in the B^0 meson system. The results are consistent with the Standard Model prediction.

PHYSICAL REVIEW LETTERS

Measurement of the Time-Dependent CP Asymmetry in $B^0 \rightarrow K^+ K^- \pi^0$ Decays

14 OCTOBER 2011

Measurement of the time-dependent CP asymmetry in $B^0 \rightarrow K^+ K^- \pi^0$ decays is presented. The decays are observed in the B^0 meson system. The results are consistent with the Standard Model prediction.

Large available dataset

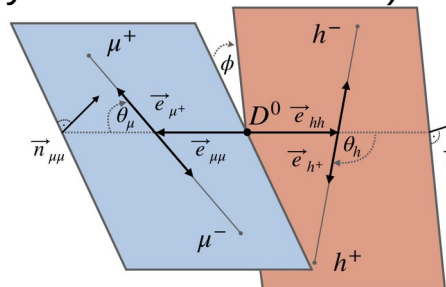
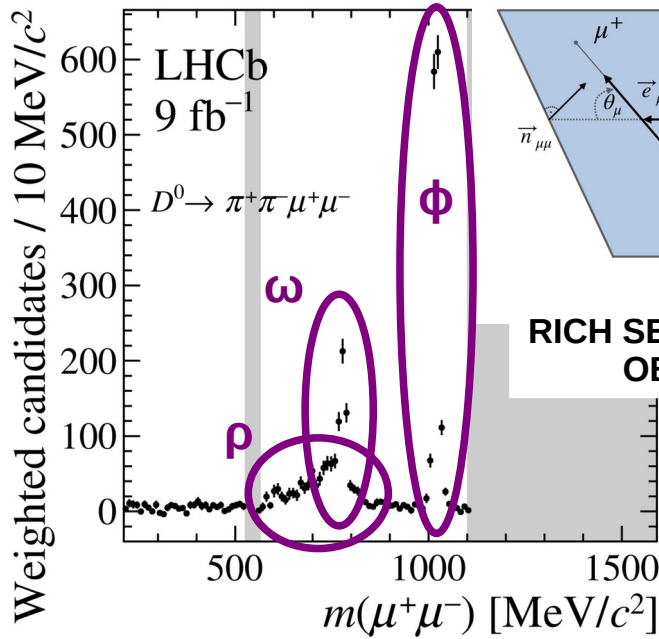
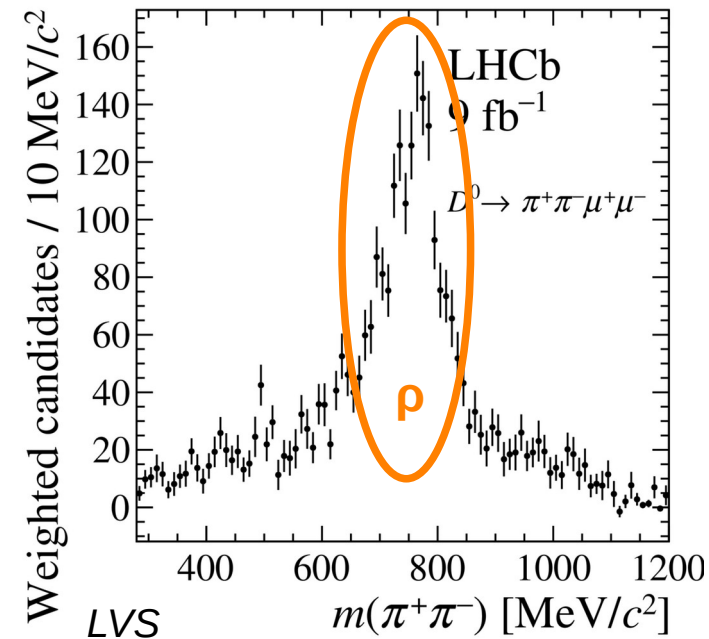


Much more is known about the **muonic** rare decay mode

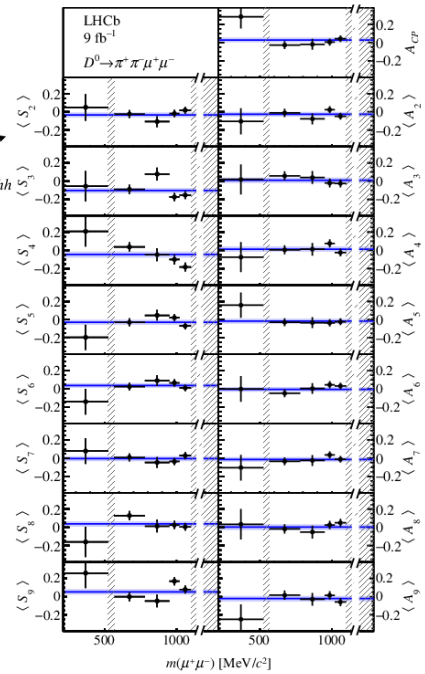
LHCb: $D^0 \rightarrow \mu^+\mu^-$ (1305.5059; 2212.11203); **$D^+ \rightarrow \pi^+\mu^+\mu^-$** (1304.6365; 2011.00217);

$D^0 \rightarrow h^+h^-\mu^+\mu^-$ (1310.2535; 1707.08377; 1806.10793; **2111.03327 - 9/fb @ 7, 8, 13 TeV**); **etc.**

- **Differential BRs**: clear resonant peaks in $m(\pi\pi)$ and $m(\mu\mu)$
- **Binned angular observables** (CP-sym. “S”, and CP-asym. “A” combinations)



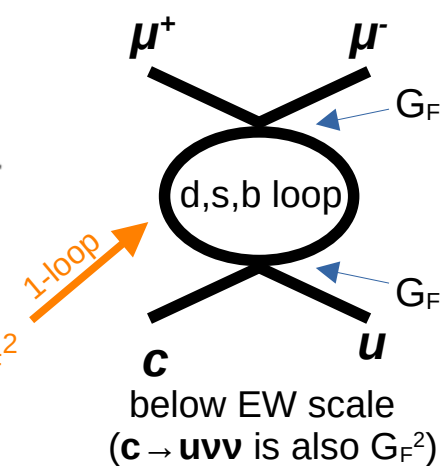
RICH SET OF ANGULAR OBSERVABLES!



Testing Short-Distance (SD) physics 3

- The SM effective weak interactions for $c \rightarrow u\ell^+\ell^-$ @ $\mu \sim m_c$ are:

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \left[\underbrace{\sum_{i=1}^2 C_i(\mu) (\lambda_d Q_i^d + \lambda_s Q_i^s)}_{\text{current-current (4-quark) operators: long-distance contribution, encoded in } C_7^{\text{eff}}, C_9^{\text{eff}}} - \underbrace{\lambda_b (C_7(\mu) Q_7 + C_9(\mu) Q_9 + C_{10}(\mu) Q_{10})}_{\text{GIM \& CKM: small contributions; } C_{10}: \text{higher order in EW interactions } G_F^2}} \right] + \text{h.c.}$$



current-current (4-quark) operators:
long-distance contribution,
 encoded in $C_7^{\text{eff}}, C_9^{\text{eff}}$

GIM & CKM: **small contributions;**
 C_{10} : higher order in EW interactions G_F^2

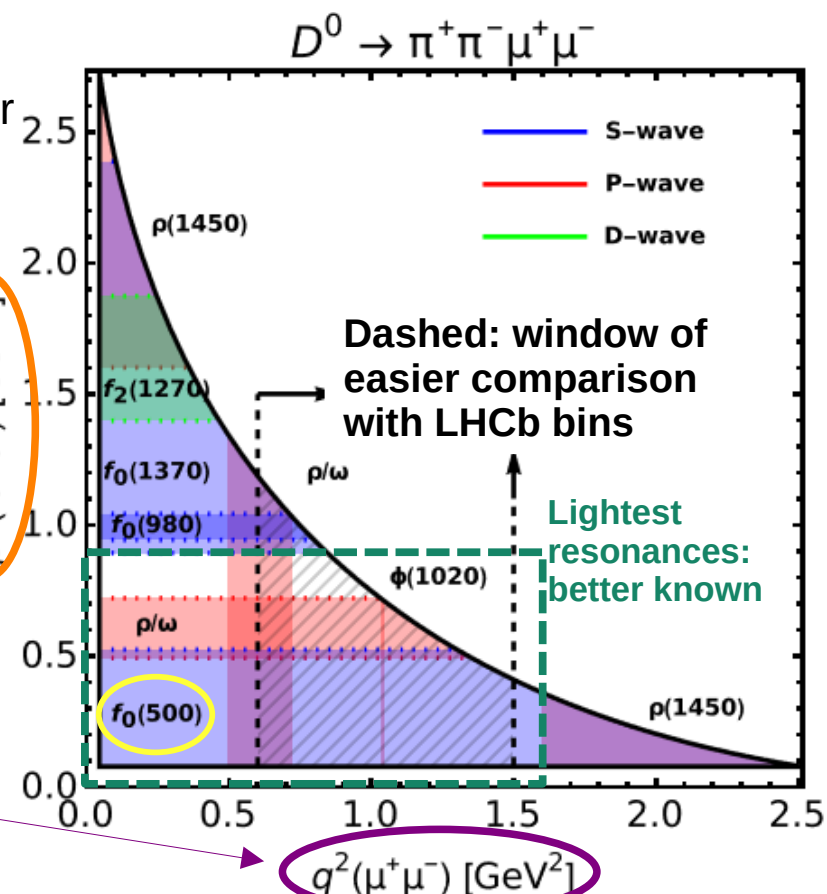
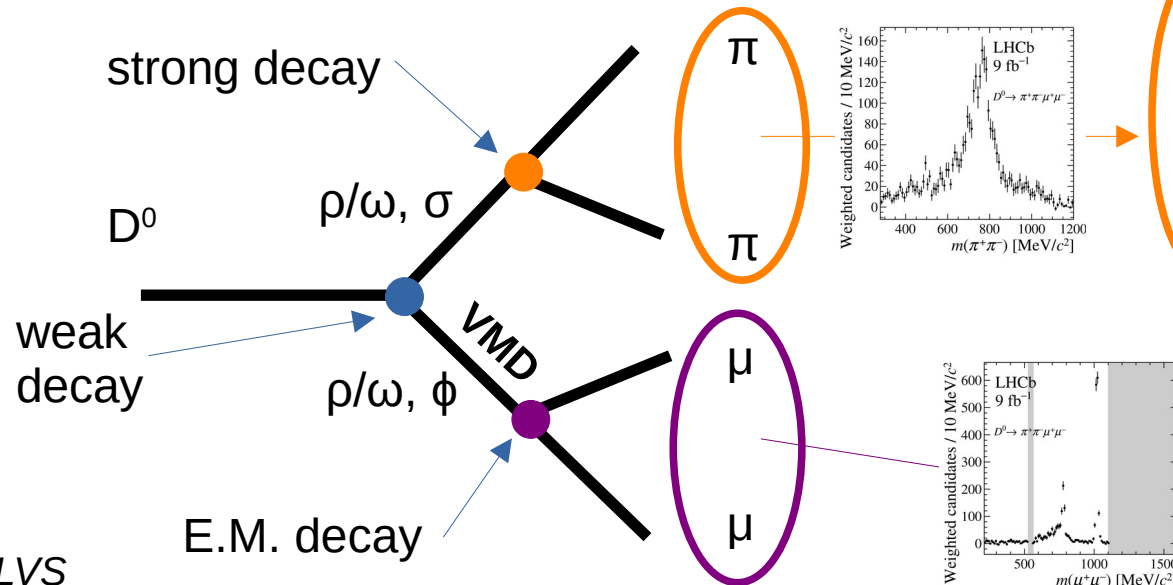
$$Q_{10} = \frac{\alpha_{em}}{2\pi} (\bar{u}\gamma_\mu(1 - \gamma_5)c)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

- SM null tests**, e.g., NP in C_{10} : interference with SM Long-Distance (LD) enhances sensitivity to NP, i.e., $(C_9^{\text{eff}})^* \times C_{10}$ [De Boer, Hiller '18]
- Tests of SD require good enough description of the LD part**
- Forbidden decays (e.g., **LFV, LNV, BNV**): no SM contribution

Available phase space

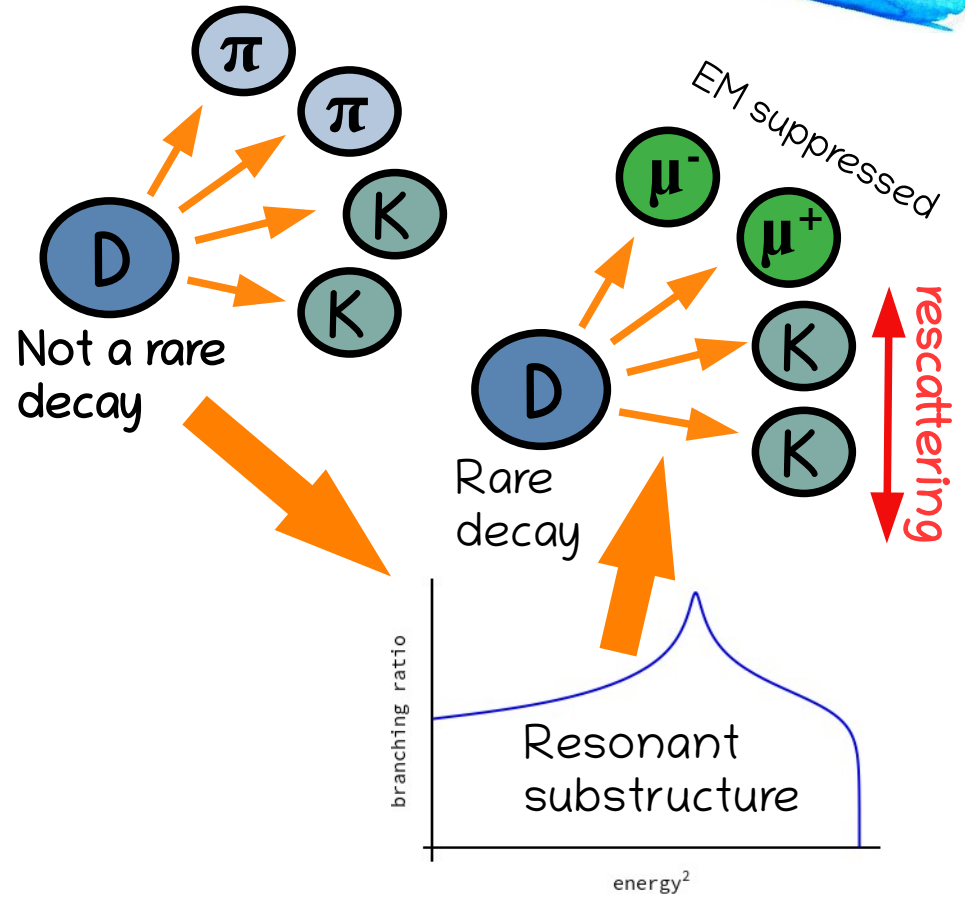


- Phase space heavily populated with resonances (cf. B sector)
- Quasi-two body (Q2B) decays
- Focus: “high-energy window”, thus avoiding tower of heavier S-, P-, D-resonances
- Vector resonances contribute to $D^0 \rightarrow V\gamma$ and $D^0 \rightarrow \gamma\gamma$



Amplitude Analyses (AAs)

- $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ (CLEO 1703.08505; BESIII 2312.02524), $D^0 \rightarrow K^+K^-\pi^+\pi^-$ (LHCb 1811.08304)
- $D^0 \rightarrow f_0(500)\rho(770)^0$ distinguished
- $D^0 \rightarrow f_0(500)\phi(1020)$ suppressed
- Cascade topologies $D^0 \rightarrow \pi^-a_1(1260)^+$, $D^0 \rightarrow K^-K_1(1270)^+$ ($\mu^+\mu^-$ -peak at $\rho(770)^0$ or $\phi(1020)$) may give relevant contributions
- At the moment, only a qualitative use is made of AAs in the present analysis
- D to hhll 5-dimensional AA: extraction of possible NP contamination?



BESIII SL decays: D to $\pi^-\pi^+e^+\nu_e$ [1809.06496]

6

Signal mode	this analysis ($\times 10^{-3}$)
$D^0 \rightarrow \pi^-\pi^0e^+\nu_e$	$1.445 \pm 0.058 \pm 0.039$
$D^0 \rightarrow \rho^-e^+\nu_e$	$1.445 \pm 0.058 \pm 0.039$
$D^+ \rightarrow \pi^-\pi^+e^+\nu_e$	$2.449 \pm 0.074 \pm 0.073$
$D^+ \rightarrow \rho^0e^+\nu_e$	$1.860 \pm 0.070 \pm 0.061$
$D^+ \rightarrow \omega e^+\nu_e$	$2.05 \pm 0.66 \pm 0.30$
$D^+ \rightarrow f_0(500)e^+\nu_e, f_0(500) \rightarrow \pi^+\pi^-$	$0.630 \pm 0.043 \pm 0.032$
$D^+ \rightarrow f_0(980)e^+\nu_e, f_0(980) \rightarrow \pi^+\pi^-$	< 0.028

S-wave at the level of 25%!

Also, BESIII SL decays: $D^+ \rightarrow \pi^+\pi^-\mu^+\nu_\mu$ [2401.13225]

NO S-WAVE

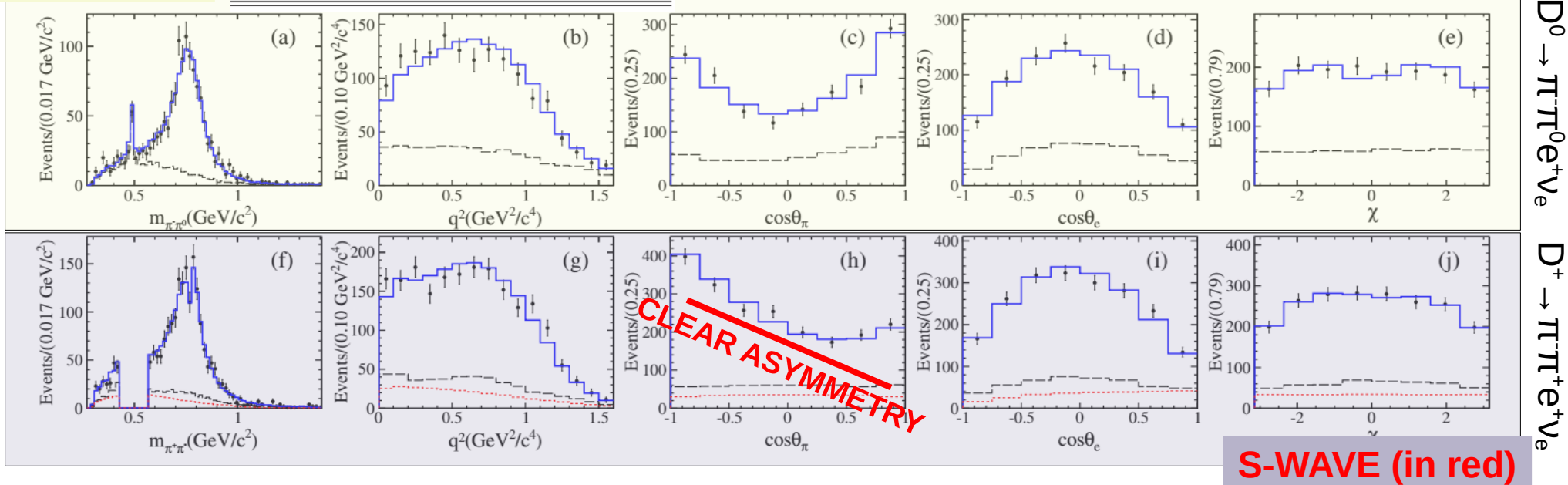
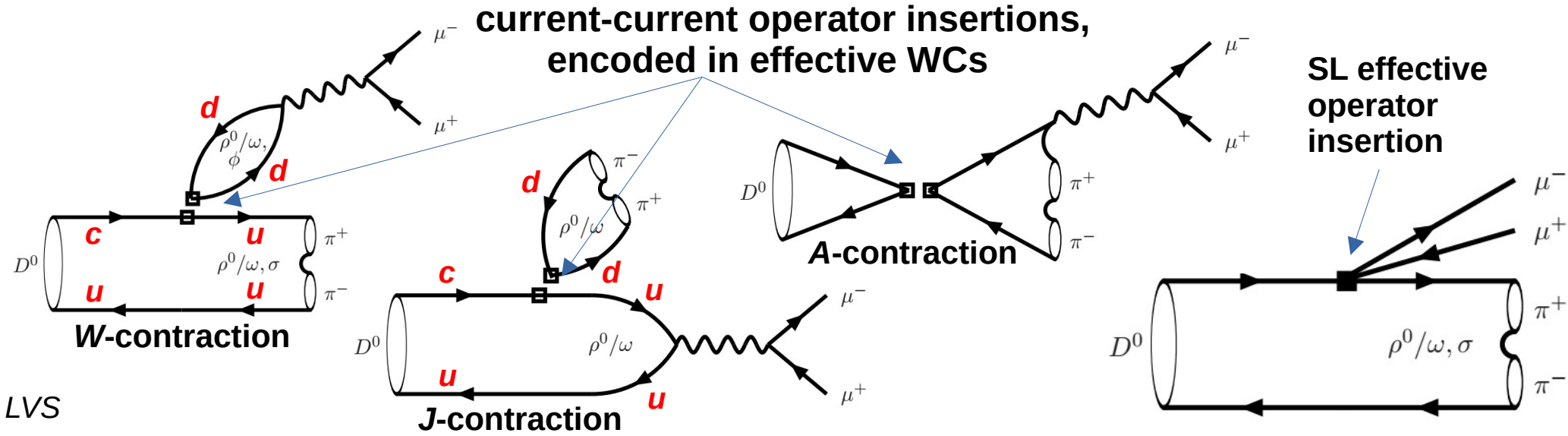


FIG. 2. Projections of the data and simultaneous PWA fit onto the five kinematic variables for $D^0 \rightarrow \pi^-\pi^0e^+\nu_e$ (top) and $D^+ \rightarrow \pi^-\pi^+e^+\nu_e$ (bottom) channels. The dots with error bars are data, the solid lines are the fits, the dashed lines show the MC simulated backgrounds, and the short-dashed lines in (f)–(j) show the component of $D^+ \rightarrow f_0(500)e^+\nu_e$.

Factorization model



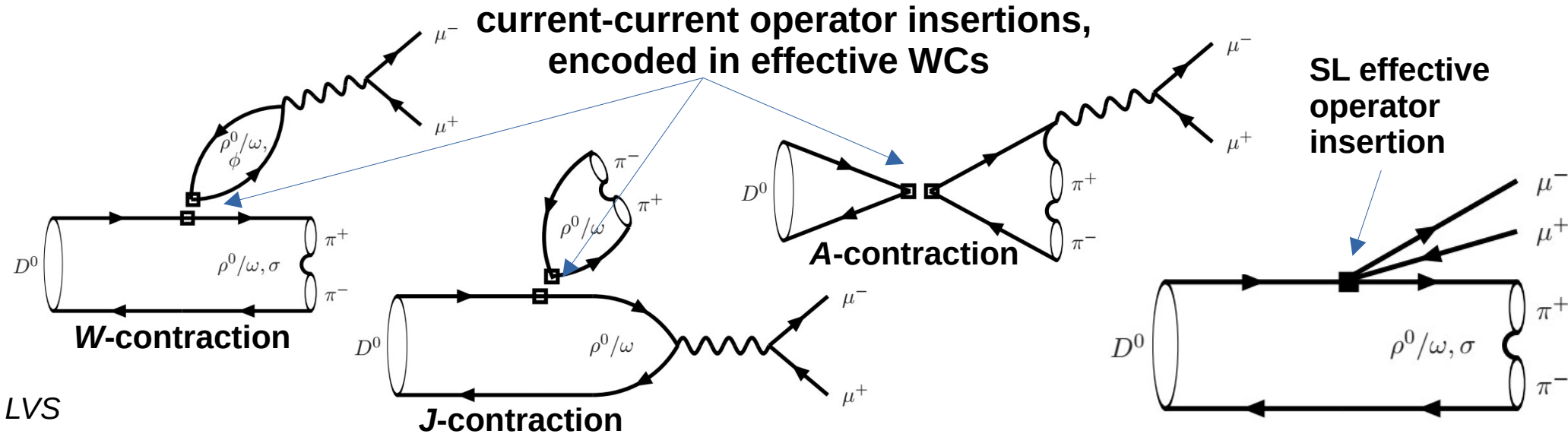
- More crude than QCD factorization ($1/m_c$, α_s), but allows a good phenomenological description of the binned data
- **Distinct contributions**: W -, J - and A -contractions; SM short-distance negligible
 - A -contraction: suppressed in naive factorization by light quark masses [Bauer, Stech, Wirbel '87]
 - J -contraction in B^+ to $K^{(*)+}\ell^+\ell^-$: light flavours are CKM suppressed $V_{ub}^*V_{us}/(V_{cb}^*V_{cs})$
 - Cappiello, Cata, D'Ambrosio '13: Bremsstrahlung, @ low- $m(\mu^+\mu^-)$



Factorization model

8

- Required **non-perturbative inputs**: **decay constants** (from $\rho^0, \omega, \phi \rightarrow e^+e^-$), **form factors** (BESIII SL $D^+ \rightarrow \pi^+\pi^-e^+\nu_e$), **line-shapes** ($\rho^0/\omega \rightarrow \pi^+\pi^-$: Gounaris-Sakurai; $\phi, \omega \rightarrow \mu^+\mu^-$: Breit-Wigner; σ : Bugg)
- Beyond naive factorization: free $O(1)$ normalization coefs, constant complex phases among intermediate resonances (no clear need for dynamics in these parameters)
- We **fit these free parameters from LHCb data**



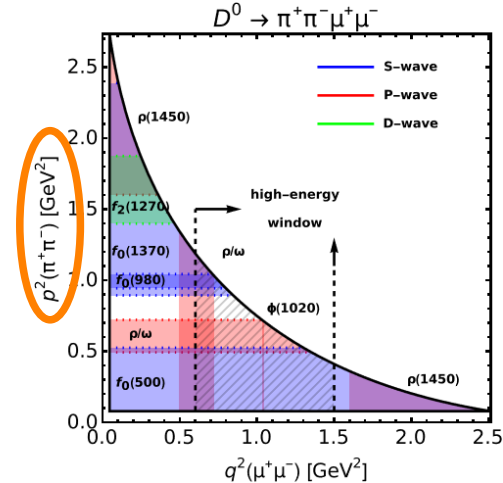
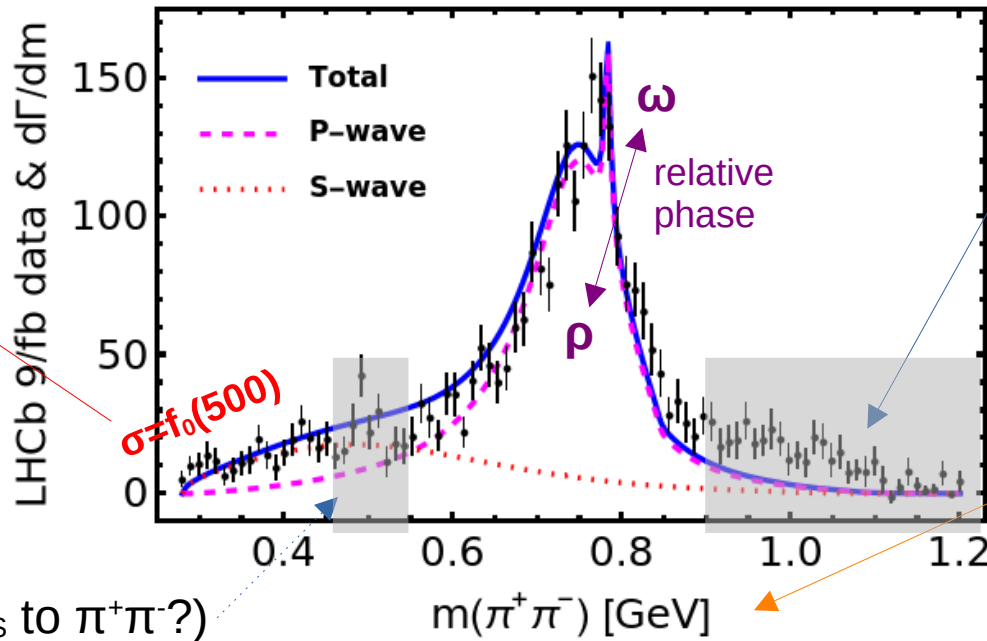
Fits to differential BRs



- S-wave: $f_0(500)$ is clearly seen in present data, **despite** not interfering with the dominant P-wave in the BR
- Consistent with BESIII SL decay: $D^+ \rightarrow \pi^+\pi^- e^+\nu_e$

Other scalar contributions [$\pi\pi \rightarrow KK \rightarrow \pi\pi$ (inelastic rescattering effect)], and P- and D-waves; also, isospin-2, and Bremsstrahlung

At the level of ~20% of total Γ



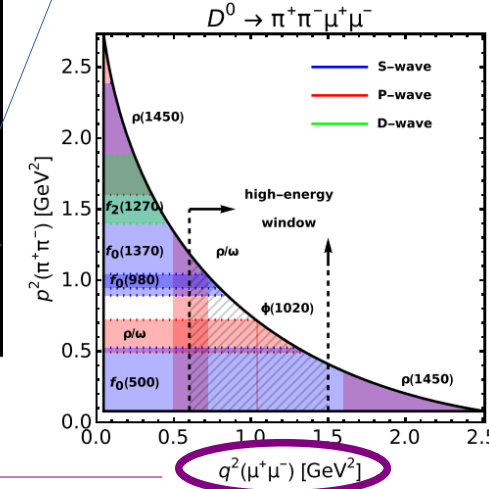
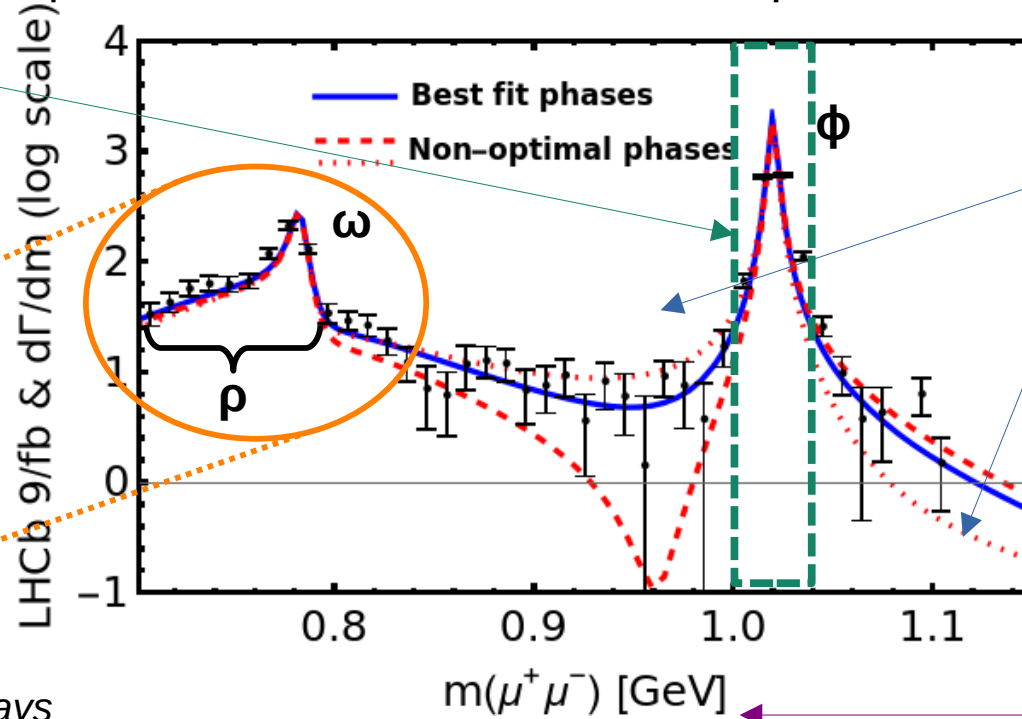
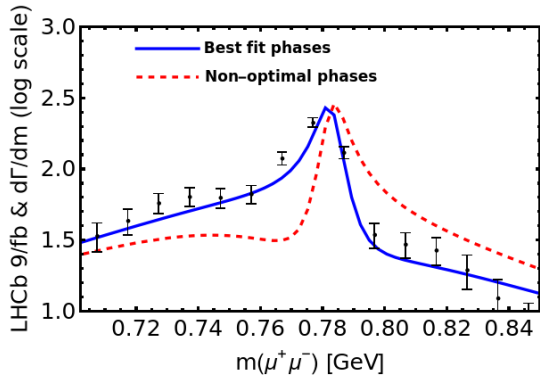
Fits to differential BRs



- Relative strong-phases among resonances: important impact on differential BR
- Such phase differences can be probed by present data
- About 60% broader ϕ resonance in the data than expected: **LHCb resolution**

Not currently employing LHCb resolution template; collect four ϕ bins

(Anti)Correlation of the prediction in the inter-resonant region with the region above the ϕ



Parameters extracted from the fit

- 6 norm. parameters (B's, a_ω , $a_S(0)$),
3 strong phase differences (ϕ_ω , $\Delta_{1,4}$)
- Overall normalization from **LHCb BR** [1707.08377]
- Expected from **factorization**
- **Suppression** also seen in the hadronic decay mode $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$
- In the ballpark of **BESIII SL**
- Large impact in **q^2 distribution**

($A_1(0)$: FF normalization)

$$0.8 \lesssim A_1(0) B_{\rho^0} \lesssim 1.2$$

$$0.8 \lesssim B_\phi / B_{\rho^0} \lesssim 0.9,$$

$$0.9 \lesssim B_\omega^{(S)} / B_{\rho^0}^{(S)} \lesssim 1.1,$$

$$0.05 \lesssim B_\phi^{(S)} / B_{\rho^0}^{(S)} \lesssim 0.27.$$

$$0.001 \lesssim a_\omega \lesssim 0.005,$$

$$1.1 \pi \lesssim \phi_\omega \lesssim 1.7 \pi,$$

$$39 \text{ GeV} \lesssim \frac{a_S(0)}{A_1(0)} \lesssim 62 \text{ GeV}$$

$$0.5 \pi \lesssim \Delta_1 \lesssim 0.9 \pi$$

$$0.2 \pi \lesssim \Delta_4 \lesssim 0.5 \pi$$

Angular observables

12

The angular distribution of $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$ ($h = \pi, K$) decays can be written as 8

$$\frac{d^5\Gamma}{dq^2 dp^2 d\vec{\Omega}} = \frac{1}{2\pi} \left[\sum_{i=1}^9 c_i(\theta_\mu, \phi) \underbrace{I_i(q^2, p^2, \cos\theta_h)} \right], \quad (5)$$

with the angular basis, c_i , defined as

WCs, hadronic inputs

$$\begin{aligned} c_1 &= 1, \quad c_2 = \cos 2\theta_\mu, \quad c_3 = \sin^2 \theta_\mu \cos 2\phi, \quad c_4 = \sin 2\theta_\mu \cos \phi, \quad c_5 = \sin \theta_\mu \cos \phi, \\ c_6 &= \cos \theta_\mu, \quad c_7 = \sin \theta_\mu \sin \phi, \quad c_8 = \sin 2\theta_\mu \sin \phi, \quad c_9 = \sin^2 \theta_\mu \sin 2\phi. \end{aligned} \quad (6)$$

The normalised and integrated observables $\langle I_i \rangle$ are defined as

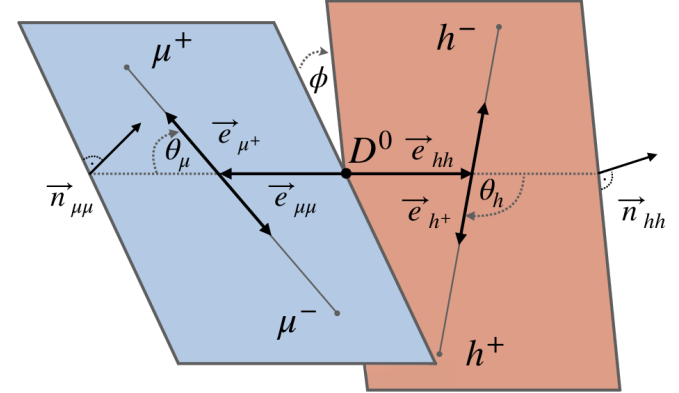
$$\begin{aligned} \langle I_{2,3,6,9} \rangle &= \frac{1}{\Gamma} \int_{q_{\min}^2}^{q_{\max}^2} dq^2 \int_{p_{\min}^2}^{p_{\max}^2} dp^2 \int_{-1}^{+1} d\cos\theta_h I_{2,3,6,9}, \\ \langle I_{4,5,7,8} \rangle &= \frac{1}{\Gamma} \int_{q_{\min}^2}^{q_{\max}^2} dq^2 \int_{p_{\min}^2}^{p_{\max}^2} dp^2 \left[\int_0^{+1} d\cos\theta_h - \int_{-1}^0 d\cos\theta_h \right] I_{4,5,7,8}. \end{aligned} \quad (10)$$

The observables reported in the Letter are the CP averages, $\langle S_i \rangle$, and asymmetries, $\langle A_i \rangle$, defined as

$$\begin{aligned} \langle S_i \rangle &= \frac{1}{2} [\langle I_i \rangle + (-)\langle \bar{I}_i \rangle], \\ \langle A_i \rangle &= \frac{1}{2} [\langle I_i \rangle - (+)\langle \bar{I}_i \rangle], \end{aligned} \quad (11)$$

for the CP -even (CP -odd) coefficients $\langle I_{2,3,4,7} \rangle$ ($\langle I_{5,6,8,9} \rangle$).

See LHCb (2111.03327);
De Boer, Hiller '18



$$\cos \theta_\mu = \vec{e}_{\mu\mu} \cdot \vec{e}_{\mu^+},$$

$$\cos \theta_h = \vec{e}_{hh} \cdot \vec{e}_{h^+}.$$

$$\cos \phi = \vec{n}_{\mu\mu} \cdot \vec{n}_{hh},$$

$$\sin \phi = [\vec{n}_{\mu\mu} \times \vec{n}_{hh}] \cdot \vec{e}_{hh},$$

Angular observables

13

$$\langle I_i \rangle_- \equiv \left[\int_0^{+1} d \cos \theta_\pi - \int_{-1}^0 d \cos \theta_\pi \right] I_i, \quad \langle I_i \rangle_+ \equiv \int_{-1}^{+1} d \cos \theta_\pi I_i$$

- LHCb measured $|S|^2+|P|^2$ (i.e., \circ) & P-wave only (i.e., \times); **straightforward to extend their analysis to include S- and P-waves interference** (i.e., \checkmark)
- SM predictions, use previous strong-phase differences (“S” stands for CP-symmetric, $I_i^\dagger \equiv \mathbf{S}_i$, $i=1, \dots, 9$):

- $\mathbf{S}_2, \mathbf{S}_3, \mathbf{S}_4 \sim -10\%$ (\mathbf{S}_1 is related to Γ and \mathbf{S}_2)
- $\mathbf{S}_5, \mathbf{S}_6, \mathbf{S}_7 = 0$ (null tests of the SM)
- $\mathbf{S}_7, \mathbf{S}_8, \mathbf{S}_9 \sim 0$ (imaginary part among P-wave contributions)

- exp vs. theo: **similar pattern seen in LHCb data**, but large exp and theo uncertainties of O(few)% prevent better tests of the SM

$\int \langle I_i \rangle_-^r / \Gamma^r$		$\int \langle I_i \rangle_+^r / \Gamma^r$	
i	S-wave	i	S-wave
1	\checkmark	1^\dagger	\circ
2	\checkmark	2^\dagger	\circ
4^\dagger	\times	3^\dagger	\times
5^\dagger	\times	4	\checkmark
7^\dagger	\times	5	\checkmark
8^\dagger	\times	6^\dagger	\times
		7	\checkmark
		8	\checkmark
		9^\dagger	\times

“+” or “-”: ways of integrating over $\cos\theta_\pi$

\circ : $|S|^2+|P|^2$

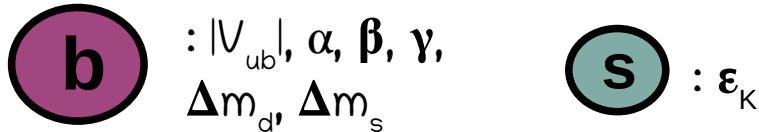
\checkmark : S*P interference

\times : only P-wave

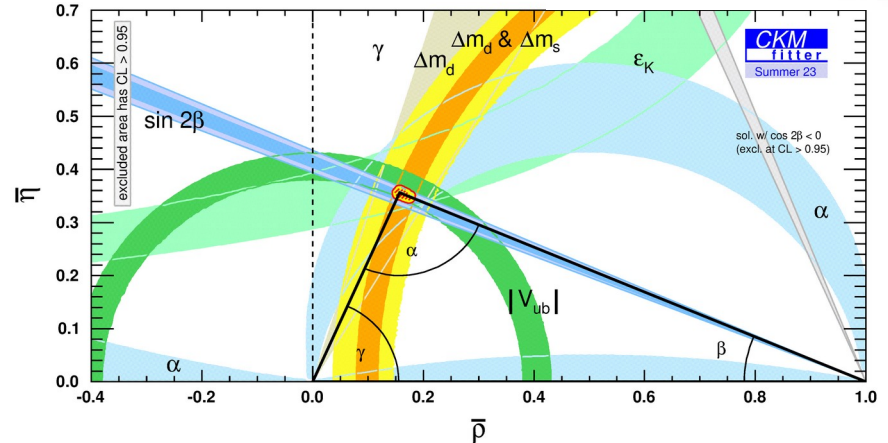
\dagger : LHCb 2111.03327

CP violation in the charm sector

- CKM: a single CP-odd phase must be responsible for **CPV phenomena** in all quark flavour sectors of the SM



[CKMfitter Collaboration: Charles, Deschamps, Descotes-G., Monteil, Orloff, Qian, Tisserand, Trabelsi, Urquijo, LVS]



- Direct CP violation discovered by LHCb (2019) in $D^0 \rightarrow h^+h^-$
- Unclear yet whether this can be explained within the SM

[Khodjamirian, Petrov '17; Li, Lu, Yu '19; Soni '19; Cheng, Chiang '19; Pich, Solomonidi, LVS '23; Lenz, Piscopo, Rusov '23; ...]

- Rare charm-meson decays consistent with no CP violation:

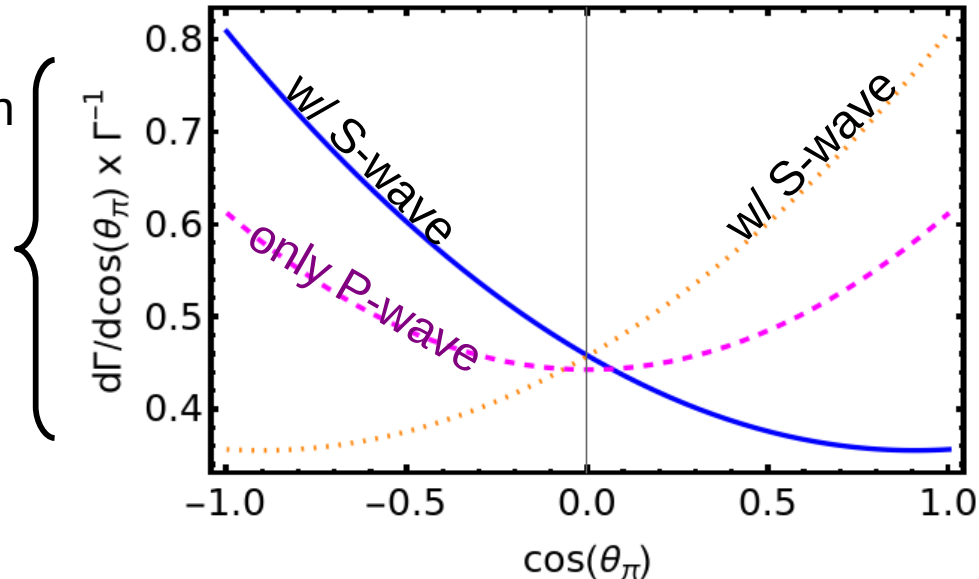
- $A_1, \dots, A_9 \sim 0$ (small CP violation)

Angular observables

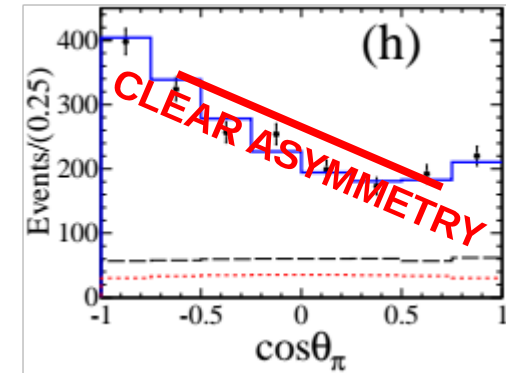


- Probe S- and P-waves interference also with distinct differential quantities

Observable depends on an S- and P-waves relative phase not probed by $d\Gamma/dq^2$, but by the previous S*P observables



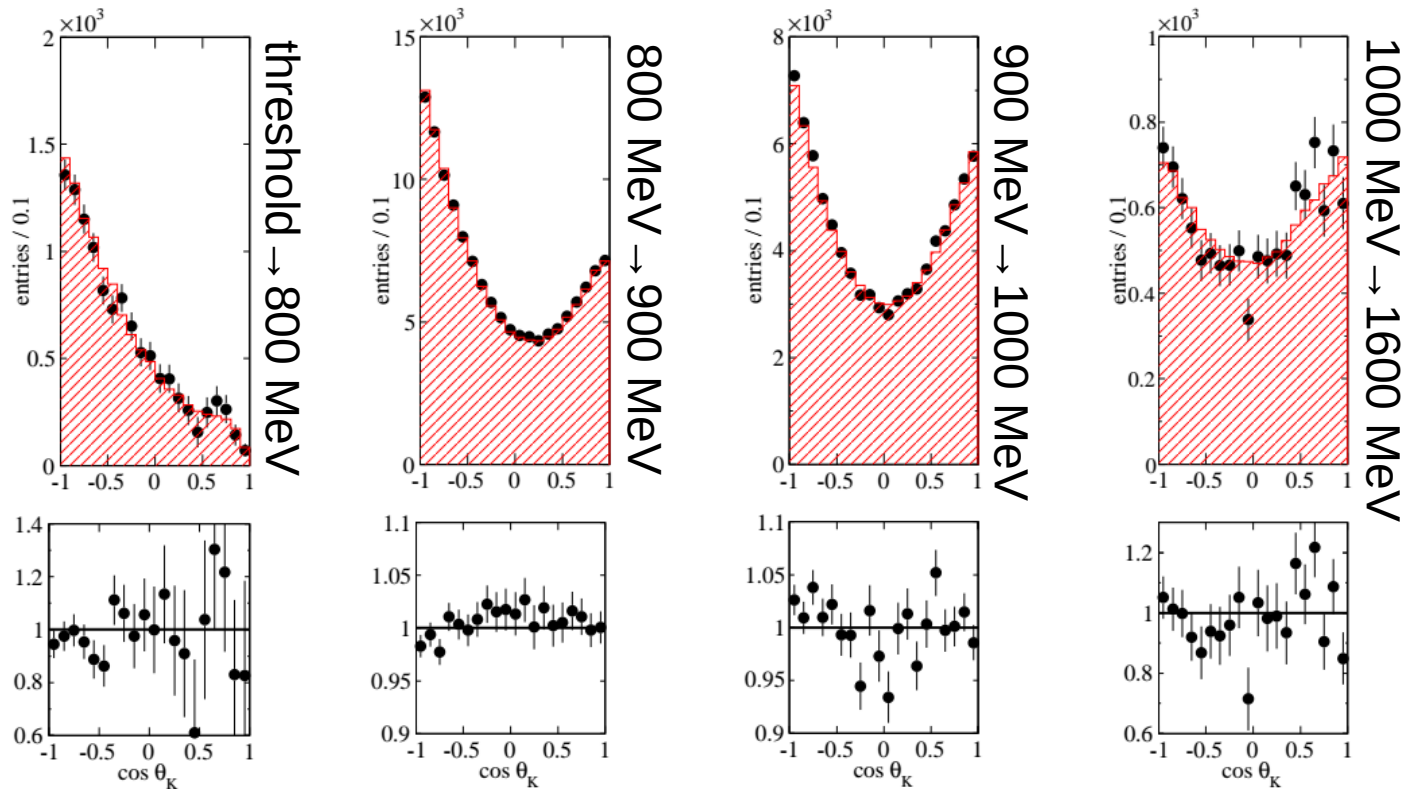
BESIII (1809.06496)
SL: $D^+ \rightarrow \pi^+ \pi^- e^+ \nu_e$



Also, BaBar (1012.1810)
SL: $D^+ \rightarrow K^- \pi^+ e^+ \nu_e$

BaBar SL decays: D^+ to $K^-\pi^+ e^+\nu_e$ [1012.1810]

Different $K\pi$ -energy slices



S- and P-waves interference produces $\cos(\theta_K)$ term; “P-wave only” gives a $\cos^2(\theta_K)$ term

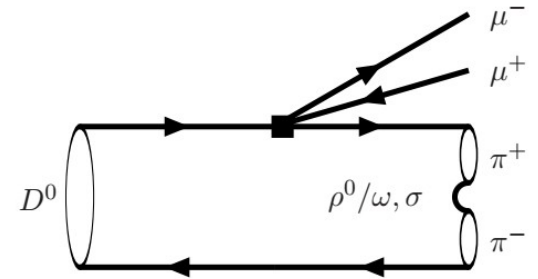
S-wave from $K_0^*(800)=\kappa$ and $K_0^*(1430)$

Null tests: SM-NP interference

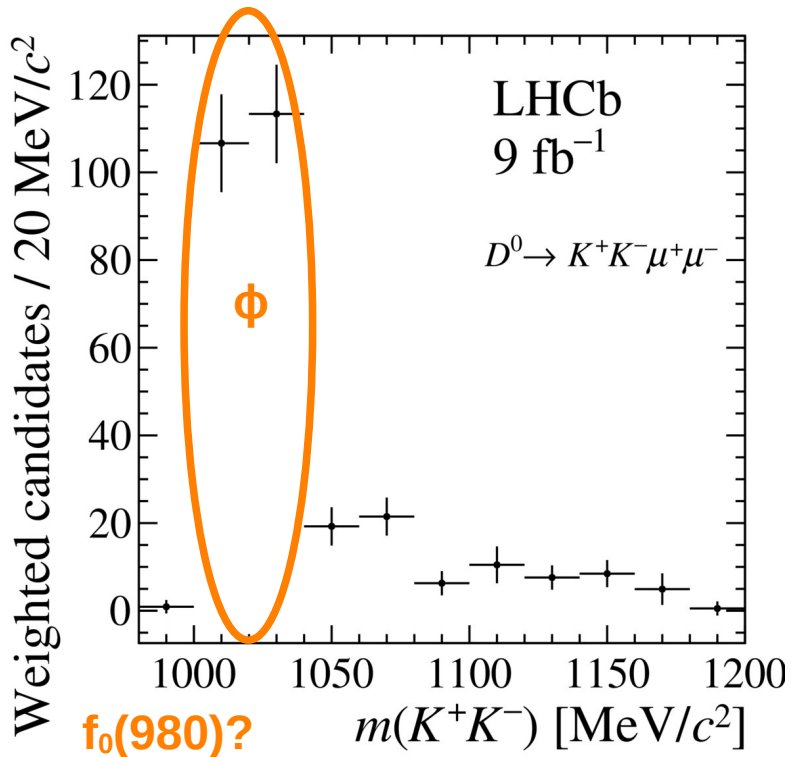
- NP can introduce contributions to **semi-leptonic contact interactions**, e.g.: $|V_{ub} V_{cb}^* C_{10}| < 0.43$ @ 95% CL (from $D^0 \rightarrow \mu^+ \mu^-$ LHCb, 2212.11203)

[similar bound from $pp \rightarrow \mu^+ \mu^-$, Fuentes-M., Greljo, Camalich, Ruiz-A. '20]

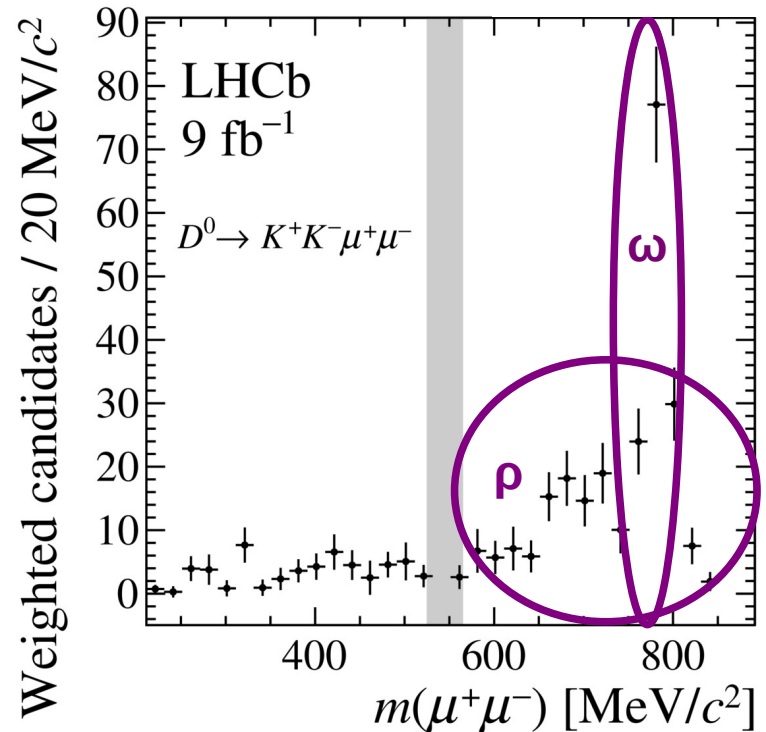
- P-wave only: S_5, S_6 can reach **O(few)%**
- **Claiming NP requires exhaustive tests**; similar **O(few)%** reach in analogous S- and P-waves interference observables
- **Not possible to conclude yet about novel bounds on NP**, given bounds from other decay processes & presence of extra strong-phases in the theo prediction & experimental precision



Related channel: $D^0 \rightarrow K^+K^-\mu^+\mu^-$



Threshold effects complicate the description of $f_0(980)$



Dedicated analysis still needed; having $f_0(980)$ and ϕ close may produce an interesting S- and P-waves interference effect

Conclusions



19

- Long-distance is dominant in rare SM modes: must consider resonances for a meaningful phenomenological description
- $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$: impact of **present data (new LHCb binned analysis)** on the charm sector
- **Improved SM description**: first quantitative assessment of the S-wave
 - Significant ingredient of the non-perturbative dynamics
 - **Straightforward LHCb measurements will further probe the S-wave**
 - **S-wave provides novel null tests of the SM**

Outlook

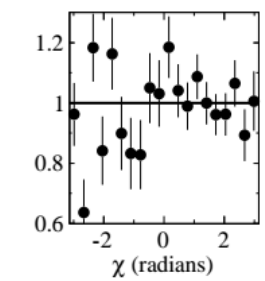
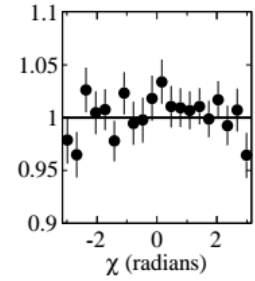
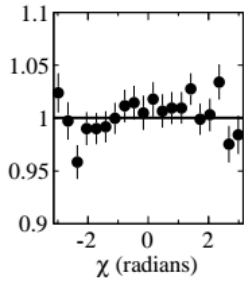
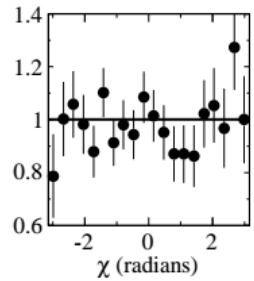
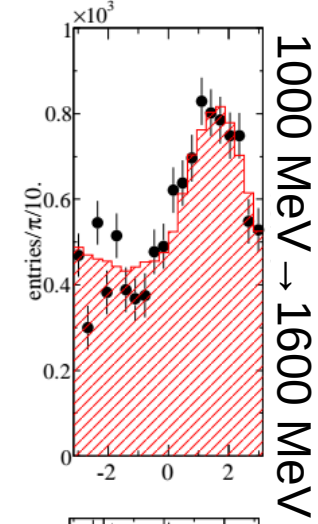
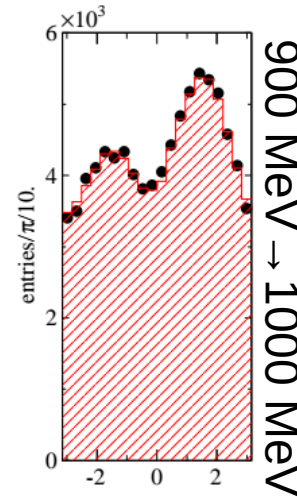
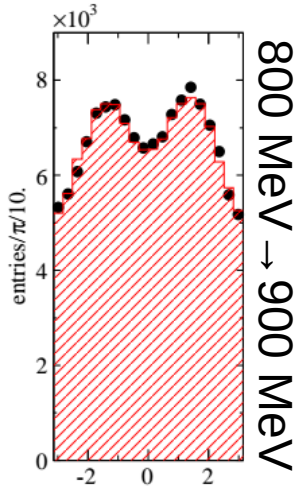
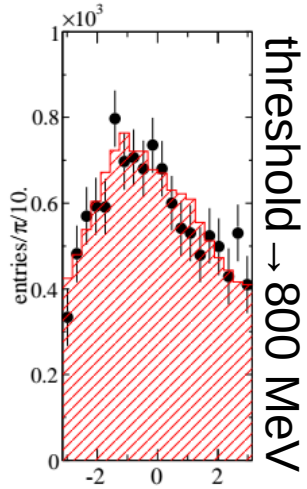
20

- SL (hadronic) modes: quantitative (qualitative) information
- Currently only looking at a fraction of the allowed phase space
- Long-term goal (**dreaming out loud**): **more intensive data-driven approach**
 - (i) data on **semi-leptonic decay modes**
 - D to $\pi\pi\ell\nu_\ell$
 - (ii) data on **alternative rare decay modes**, including **radiative** ones
 - D to $KK\ell\ell$, D to hhy , etc.
 - (iii) data on **purely hadronic decay modes**
 - D to $\pi\pi\pi\pi$, D to $\pi\pi KK$, etc.
 - (iv) data on **rescattering of final states**
 - $\pi\pi$ to KK

Thanks!

BaBar SL decays: D^+ to $K^-\pi^+ e^+\nu_e$ [1012.1810]

Different $K\pi$ -energy slices



S- and P-waves interference produces $\sin(\chi)$ term, and also $\cos(\chi)$ term; “P-wave only” gives a $\cos(2\chi)$ term

S-wave from $K_0^*(800)=\kappa$ and $K_0^*(1430)$

P-wave suppressions in $S_{2,3}$

q^2 -bin r	Γ^r (SM)	$\frac{\Gamma^r}{\Gamma^r} [\%]$	$\int \langle I_2 \rangle_+^r \times 100$	$\frac{\int \langle I_2 \rangle_+^r}{\int \langle I_2 \rangle_+^r} [\%]$	$\int \langle I_3 \rangle_+^r \times 100$	$\int \langle I_4 \rangle_-^r \times 100$
$r(\rho: \text{sup})$	[0.64, 0.87]	[23, 43]	[-16, -8.5]	[59, 78]	[-7.2, -4.7]	[8.3, 13]
$r(\phi: \text{inf})$	[1.6, 1.9]	[0.3, 8]	[-11, -6.2]	[3, 45]	[-30, -26]	[36, 41]
$r(\phi: \text{sup})$	[1.2, 1.3]	[0.8, 10]	[-8.7, -4.3]	[8, 53]	[-22, -19]	[26, 29]

$$\langle I_1 \rangle_+ = \frac{1}{8} \left[2|\mathcal{F}_S|^2 \rho_{1,S}^- + \frac{2}{3} |\mathcal{F}_P|^2 \rho_{1,P}^- + 2|\mathcal{F}_\parallel|^2 \rho_{1,P}^- + 2|\mathcal{F}_\perp|^2 \rho_{1,P}^+ \right]$$

$$\xrightarrow{\text{SM}} + \frac{1}{8} \left\{ 2|\mathcal{F}_S|^2 |C_9^{\text{eff}:S}|^2 + \frac{2}{3} (|\mathcal{F}_P|^2 + 2(|\mathcal{F}_\parallel|^2 + |\mathcal{F}_\perp|^2)) |C_9^{\text{eff}:P}|^2 \right\}, \quad (64)$$

P-wave unsuppressed

$$d^2\Gamma/dq^2 dp^2 = 2\langle I_1 \rangle_+ - \frac{2}{3}\langle I_2 \rangle_+$$

$$\langle I_2 \rangle_+ = -\frac{1}{8} \left[2|\mathcal{F}_S|^2 \rho_{1,S}^- + \frac{2}{3} \{ |\mathcal{F}_P|^2 \rho_{1,P}^- - |\mathcal{F}_\parallel|^2 \rho_{1,P}^- - |\mathcal{F}_\perp|^2 \rho_{1,P}^+ \} \right]$$

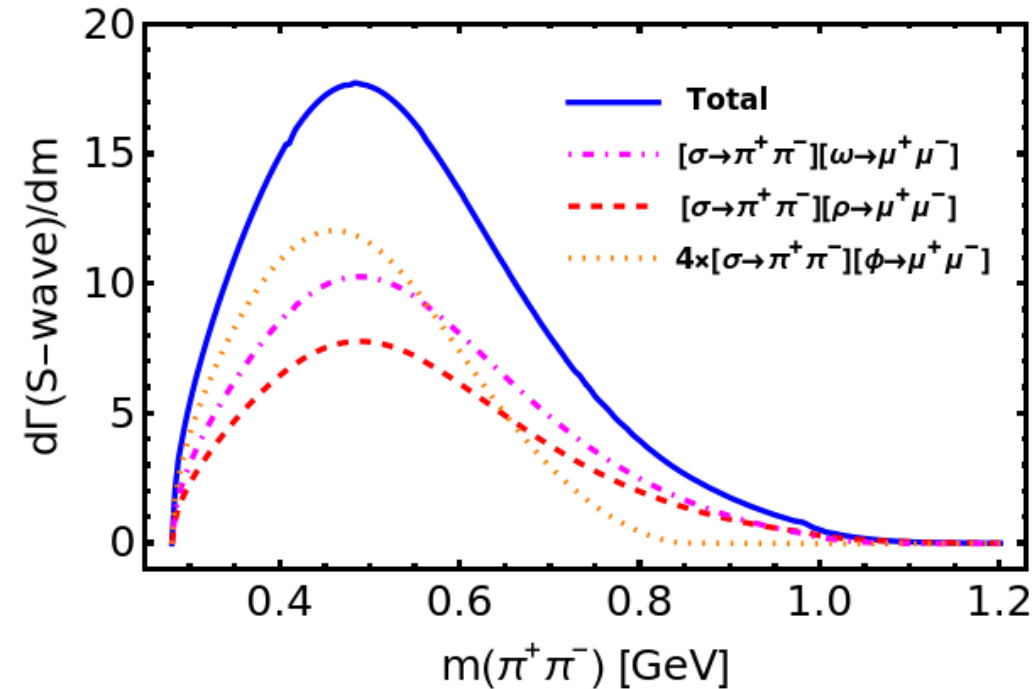
$$\xrightarrow{\text{SM}} -\frac{1}{8} \left\{ 2|\mathcal{F}_S|^2 |C_9^{\text{eff}:S}|^2 + \frac{2}{3} (|\mathcal{F}_P|^2 - |\mathcal{F}_\parallel|^2 - |\mathcal{F}_\perp|^2) |C_9^{\text{eff}:P}|^2 \right\}, \quad (65)$$

$$\langle I_3 \rangle_+ = \frac{1}{6} [|\mathcal{F}_\perp|^2 \rho_{1,P}^+ - |\mathcal{F}_\parallel|^2 \rho_{1,P}^-]$$

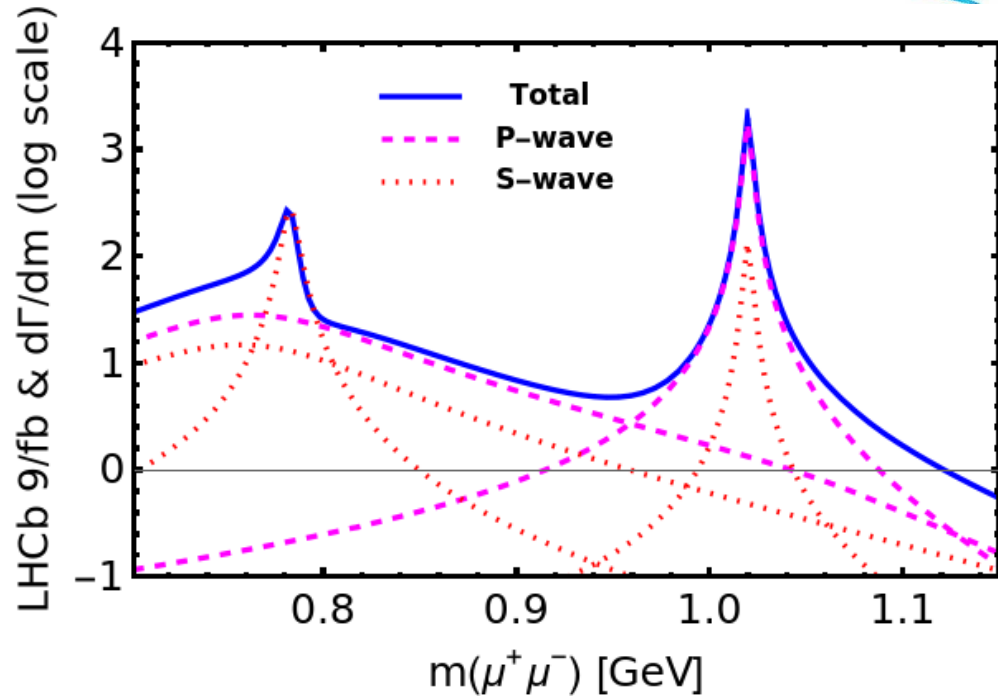
$$\xrightarrow{\text{SM}} \frac{1}{6} (|\mathcal{F}_\perp|^2 - |\mathcal{F}_\parallel|^2) |C_9^{\text{eff}:P}|^2, \quad (66)$$

P-wave suppression!

Resonant components



ϕ from S-wave: distinct $m(\pi^+\pi^-)$ dependence (see 2D plot displaying resonances); it helps in constraining its size



Naive factorization: ω from P-wave suppressed (simpler (BW) description of ρ (from P-wave) and ω (from S-wave))