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

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based on PRD109 (2024) 3 (2312.07501)

04/06/2024 – PLANCK (IST, Lisbon)

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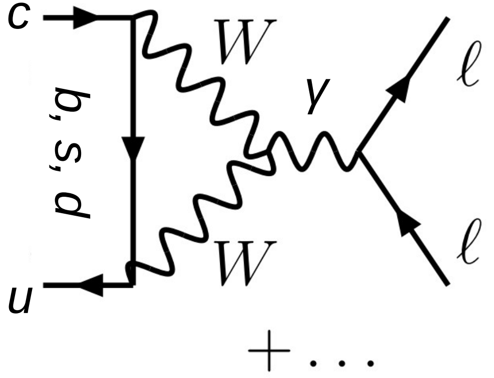
Rare charm decays

- 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; Cappiello, 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

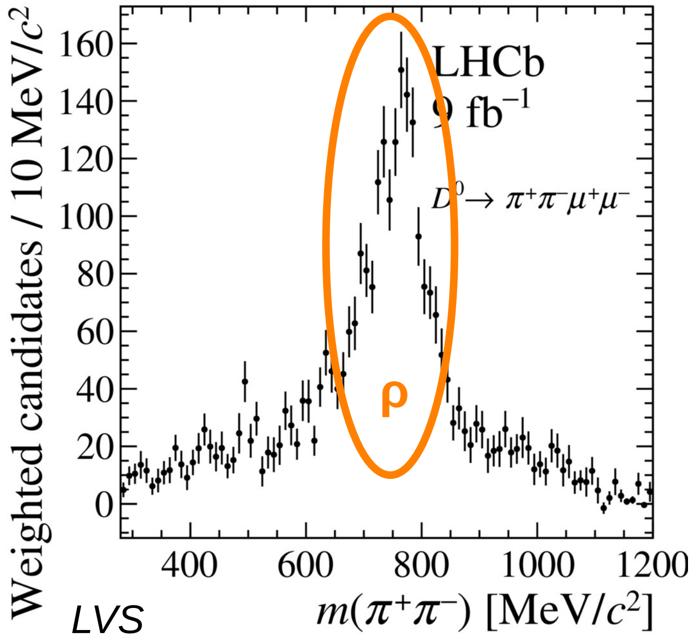
Large available dataset

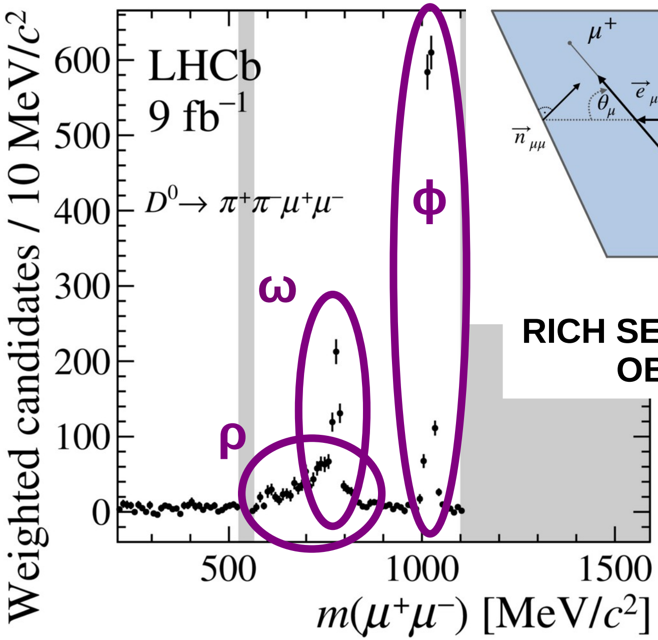
Much more is known about the **muonic** rare decay mode

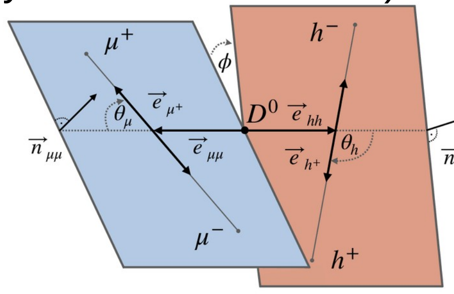
LHCb: $D^0 \to \mu^+\mu^-$ (1305.5059; 2212.11203); **$D^+ \to \pi^+\mu^+\mu^-$** (1304.6365; 2011.00217);

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

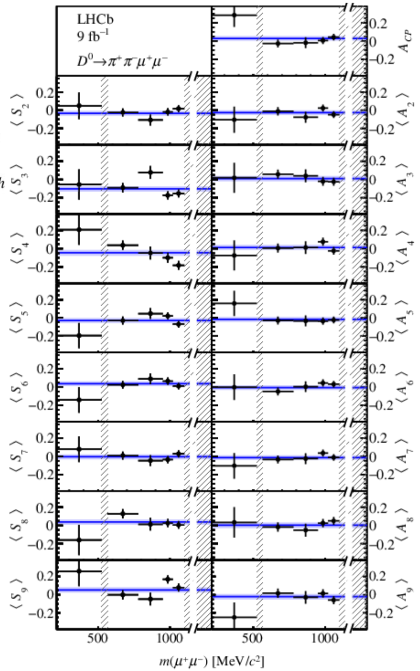
- **Differential BRs**: clear resonant peaks in m(ππ) and m(μμ)
- **Binned angular observables** (CP-sym. "**S**", and CP-asym. "**A**" combinations)







RICH SET OF ANGULAR OBSERVABLES!

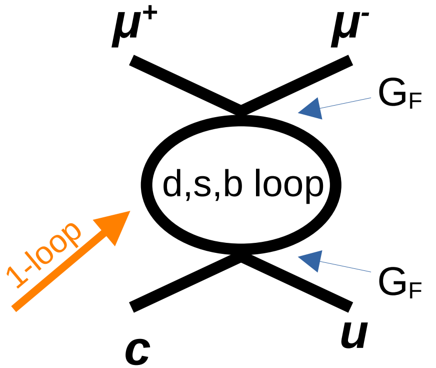


LVS

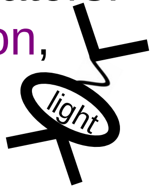
Testing Short-Distance (SD) physics

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

$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} \left[\sum_{i=1}^{2} \underbrace{C_i(\mu) \left(\lambda_d Q_i^d + \lambda_s Q_i^s \right)}_{} - \lambda_b \underbrace{\left(\cancel{C_7}(\mu) Q_7 + \cancel{C_9}(\mu) Q_9 + \cancel{C_{10}}(\mu) Q_{10} \right)}_{} \right] + \text{h.c.}$$



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



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

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

below EW scale
(**c → uνν** is also G_F^2)

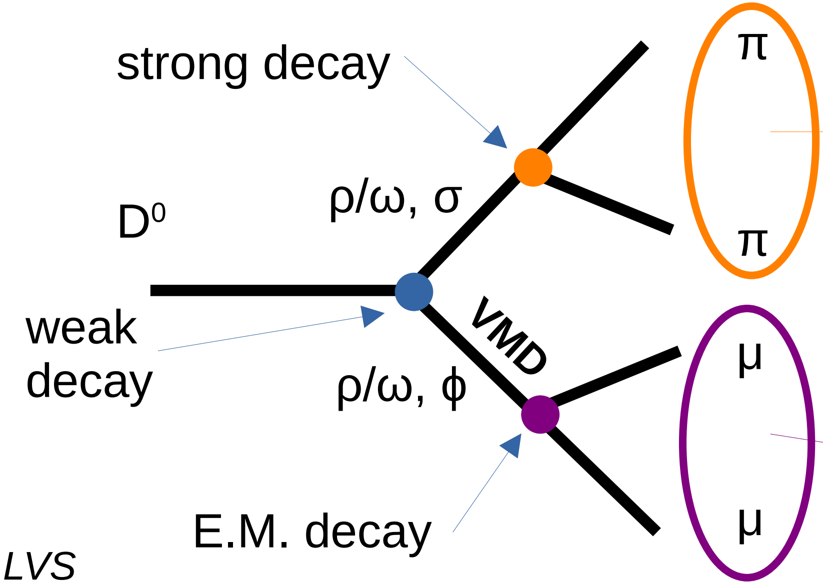
- **SM null tests**, e.g., NP in C_{10}: interference with SM Long-Distance (LD) enhances sensitivity to NP, i.e., $(C_9^{eff})^* \times C_{10}^{NP}$

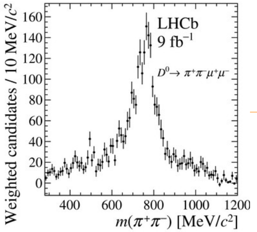
[De Boer, Hiller ‘18]

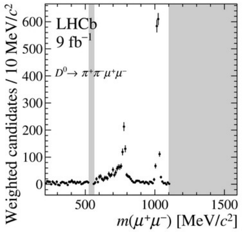
- Tests of SD require good enough description of the LD part

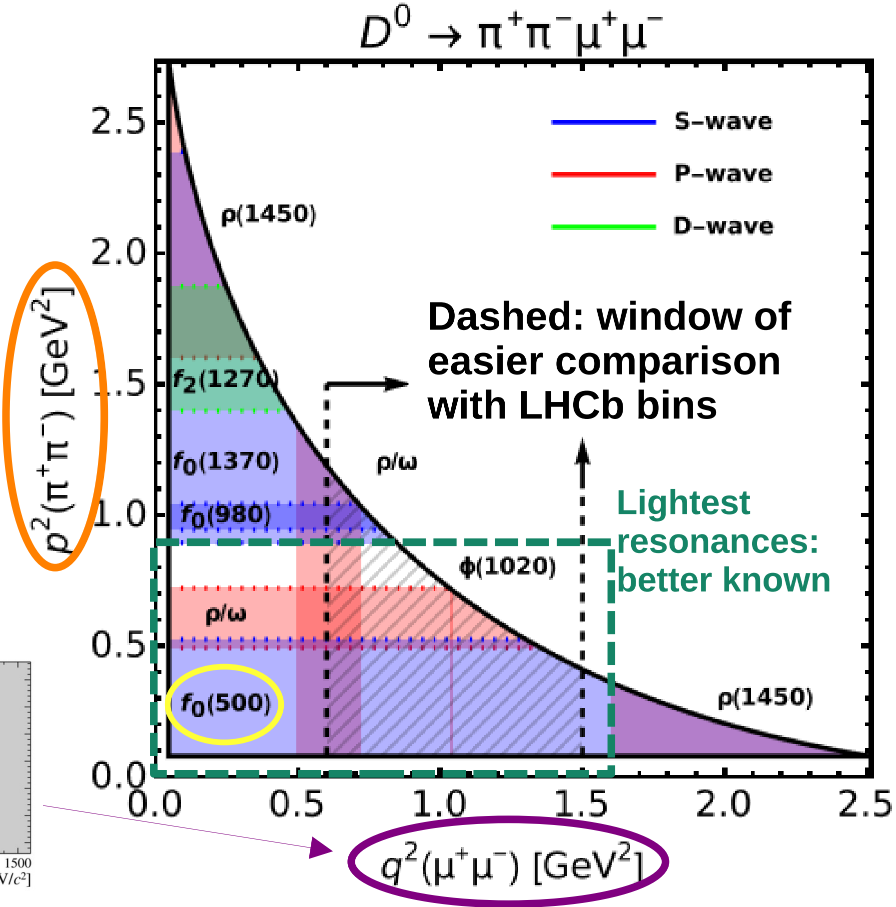
Available phase space

- 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



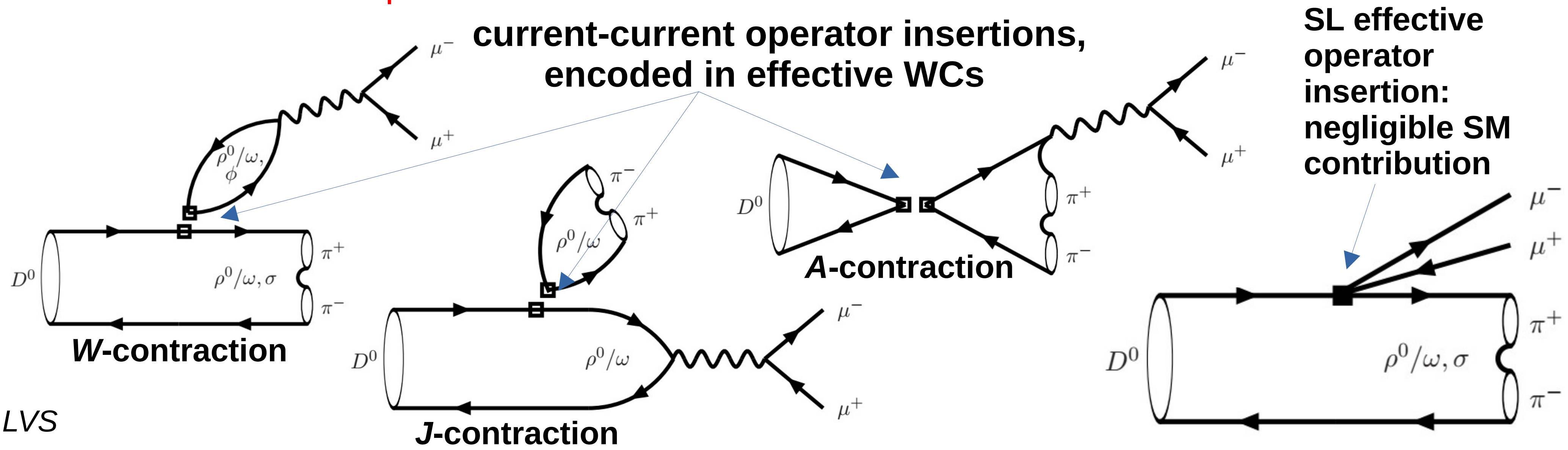






Factorization model

- Required non-perturbative inputs: **decay constants** (from ρ^0, ω, $\phi \to e^+e^-$), **form factors** (BESIII SL $D^+ \to \pi^+\pi^- e^+\nu_e$), **line-shapes** ($\rho^0/\omega \to \pi^+\pi^-$: Gounaris-Sakurai; ϕ, $\omega \to \mu^+\mu^-$: 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

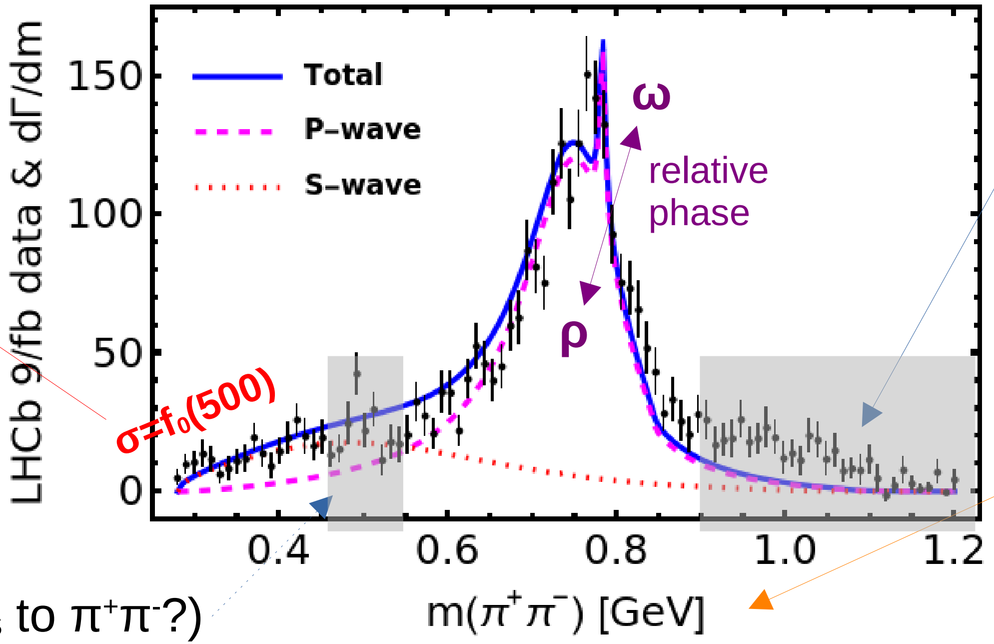


Fits to differential BRs

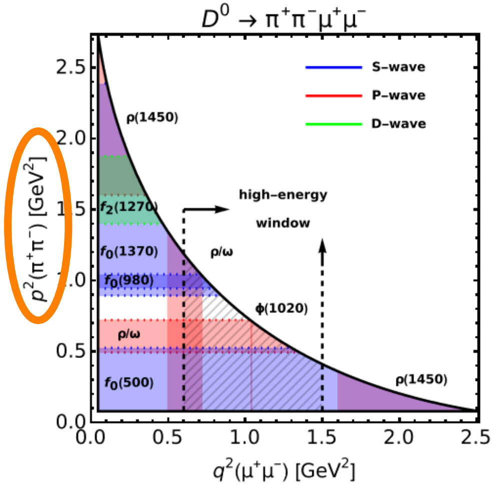
- S-wave: $f_0(500)$ is clearly seen in present data, despite not interfering with the dominant P-wave in the BR
- Consistent with BESIII SL decay: D^+ to $\pi^+\pi^- \ell^+\nu_\ell$

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

At the level of ~20% of total Γ



(Ks to π+π-?)



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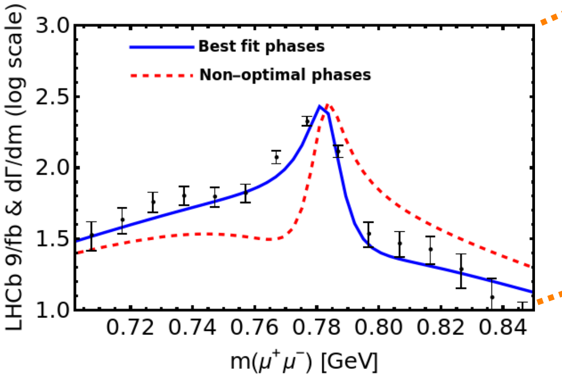
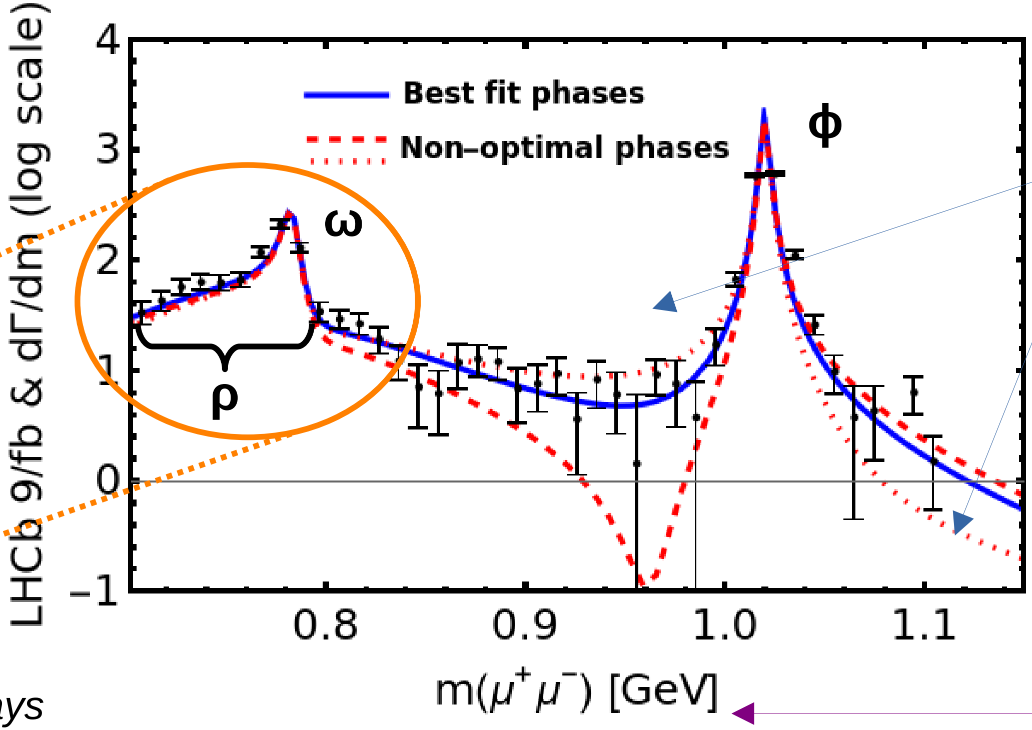
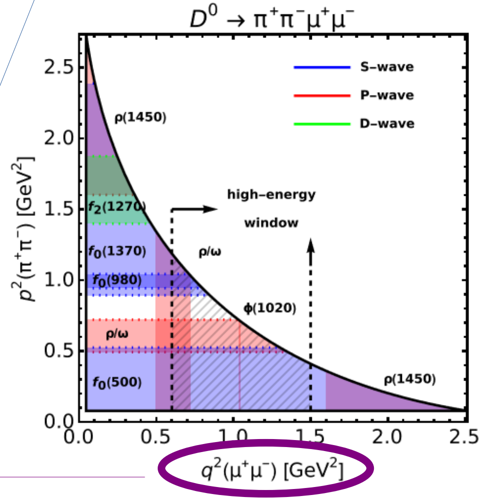
Fits to differential BRs

- Relative strong-phases among resonances: important impact on differential BR
- Such phase differences can be probed by present data





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



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Angular observables

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

- LHCb measured $|S|^2+|P|^2$ (i.e., o) & P-wave only (i.e., x); **straightforward to extend their analysis to include S- and P-waves interference** (i.e., √)
- SM predictions, use previous strong-phase differences ("**S**" stands for CP-symmetric, $I^\dagger_i \equiv \mathbf{S}_i$, i=1, …, 9):
  - $\mathbf{S}_2$, $\mathbf{S}_3$, $\mathbf{S}_4$ ~ -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**)
  - $\mathbf{S}_7$, $\mathbf{S}_8$, $\mathbf{S}_9$ ~ 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

$\int \langle I_i \rangle^r_- / \Gamma^r$	
i	S-wave
1	✓
2	✓
$4^\dagger$	×
$5^\dagger$	×
$7^\dagger$	×
$8^\dagger$	×

$\int \langle I_i \rangle^r_+ / \Gamma^r$	
i	S-wave
$1^\dagger$	○
$2^\dagger$	○
$3^\dagger$	×
4	✓
5	✓
$6^\dagger$	×
7	✓
8	✓
$9^\dagger$	×

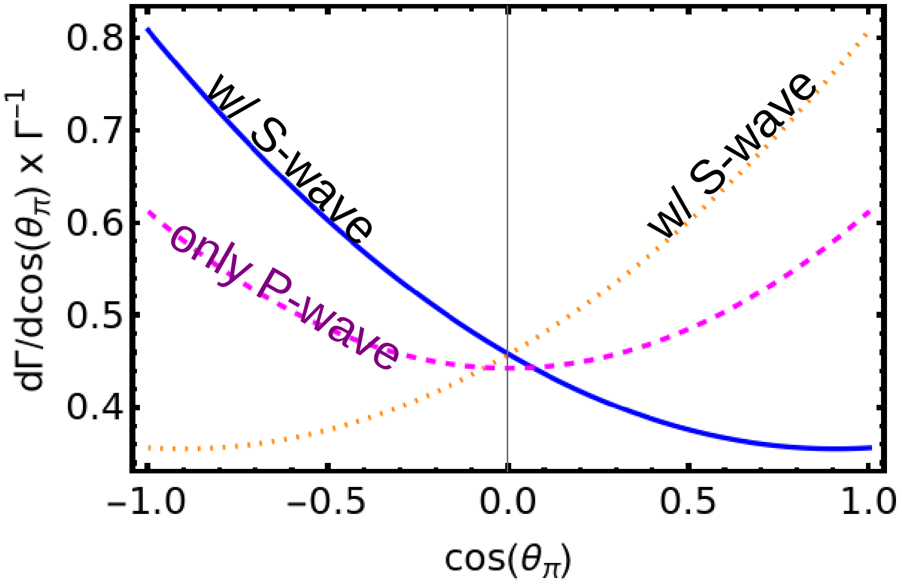
"+" or "-": ways of integrating over $\cos\theta_\pi$

o: $|S|^2+|P|^2$
√: S*P interference
x: only P-wave
†: LHCb 2111.03327

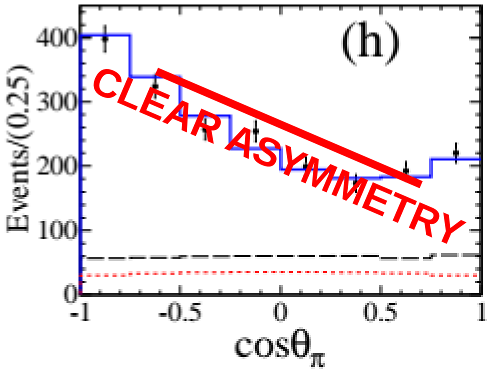
Angular observables

- 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: $D^+ \to \pi^+\pi^- e^+\nu_e$



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

Null tests: SM-NP interference

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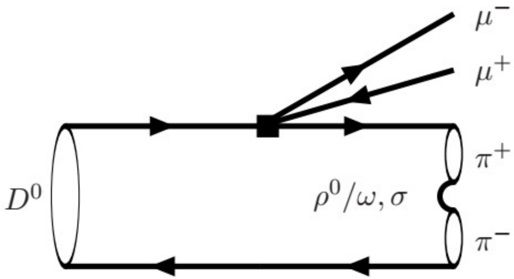
- NP can introduce contributions to semi-leptonic contact interactions, e.g.: $|V_{ub} V_{cb}^* C_{10}^{NP}|<0.43$ @ 95% CL (from $\mathbf{D^0 \to \mu^+\mu^-}$ LHCb, 2212.11203)
  [similar bound from $pp \to \mu^+\mu^-$, Fuentes-M., Greljo, Camalich, Ruiz-A. '20]



- P-wave only: $\mathbf{S_5}$, $\mathbf{S_6}$ 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

Conclusions

- Long-distance is dominant in rare SM modes: must consider resonances for a meaningful phenomenological description
- $D^0 \to \pi^+\pi^-\mu^+\mu^-$: 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**

Thanks!

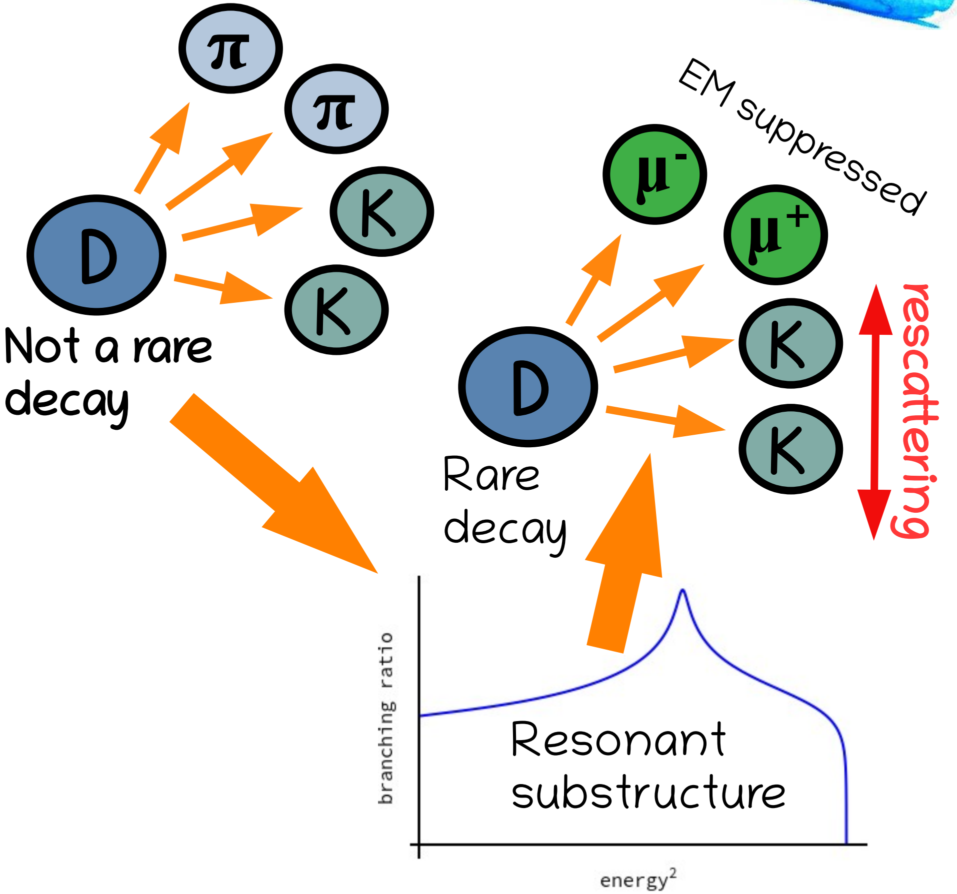
BACK UP

Cover painting: **Joaquín Sorolla**, *María en la playa de Zarautz*

Amplitude Analyses (AAs)

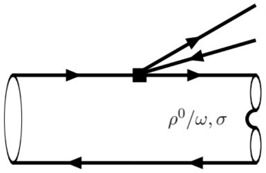
App

- $D^0 \to \pi^+\pi^-\pi^+\pi^-$ (CLEO 1703.08505; BESIII 2312.02524), $D^0 \to K^+K^-\pi^+\pi^-$ (LHCb 1811.08304)
- $D^0 \to f_0(500)\rho(770)^0$ distinguished
- $D^0 \to f_0(500)\phi(1020)$ suppressed
- Cascade topologies $D^0 \to \pi^- a_1(1260)^+$, $D^0 \to K^- K_1(1270)^+$ ($\mu^+\mu^-$-peak at $\phi(1020)$ or $\rho(770)^0$) 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: D to $\pi^-\pi\ e^+\nu_e$ [1809.06496]

App

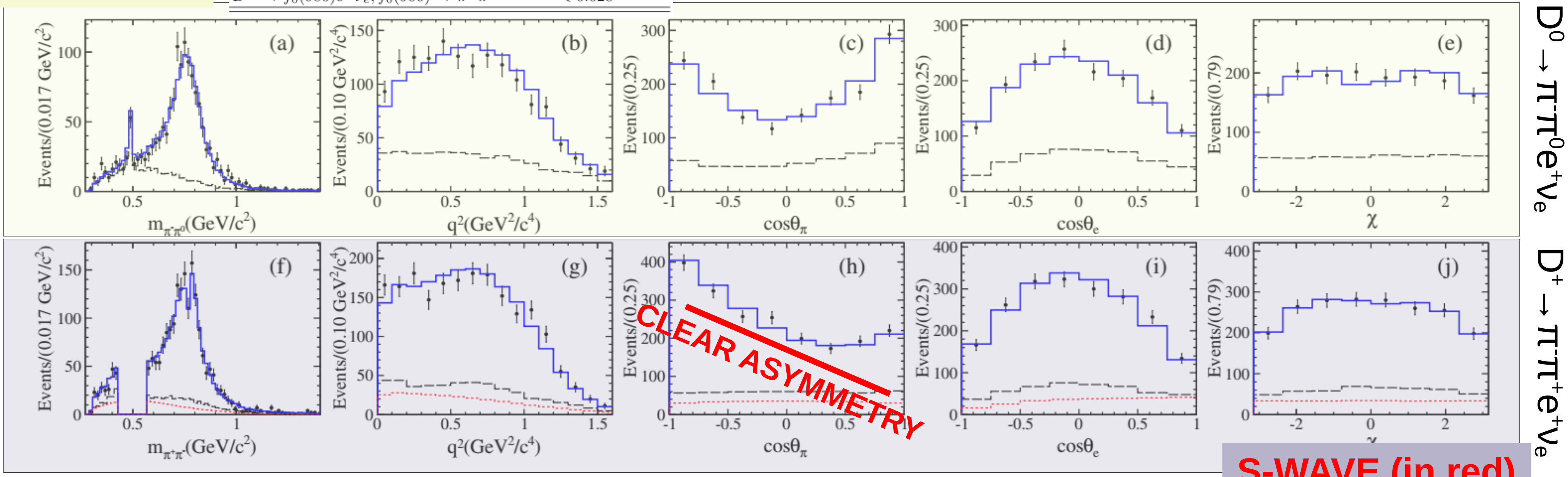


NO S-WAVE

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

S-wave at the level of 25%!

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



S-WAVE (in red)

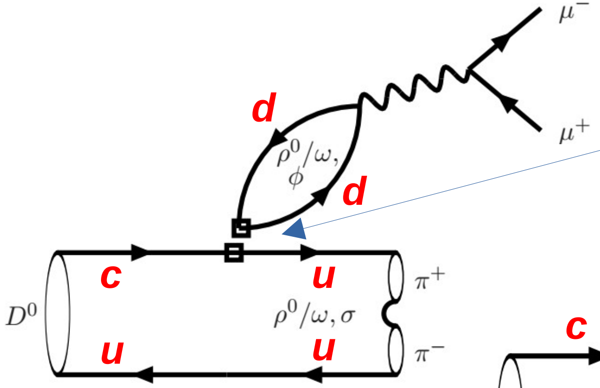
FIG. 2. Projections of the data and simultaneous PWA fit onto the five kinematic variables for $D^0 \to \pi^-\pi^0 e^+\nu_e$ (top) and $D^+ \to \pi^-\pi^+ e^+\nu_e$ (bottom) channels. The dots with error bars are data, the solid lines are the fits, the dashed lines show the MC simulated backgrounds,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

Factorization model

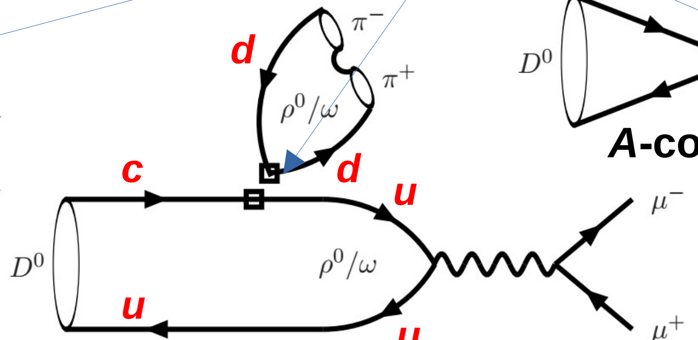
- More crude than QCD factorization ($1/m_c$, α_s), but allows a good phenomenological description of the binned data
- Distinct contributions: *W*-, *J*- and *A*-contractions; SM short-distance negligible
  - *A*-contraction: suppressed in naive factorization by light quark masses [Bauer, Stech, Wirbel '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-$m(\mu^+\mu^-)$

current-current operator insertions, encoded in effective WCs

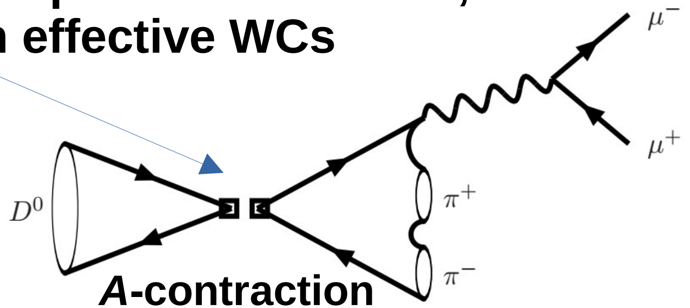
SL effective operator insertion: negligible SM contribution



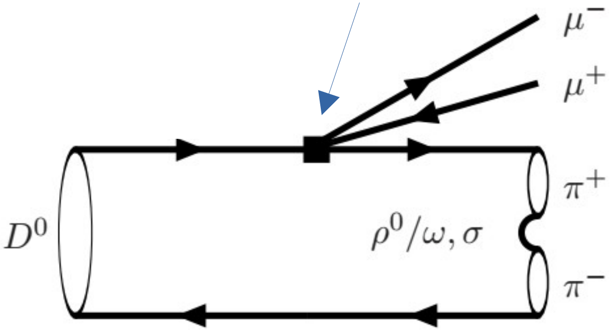
***W*-contraction**



***J*-contraction**



***A*-contraction**



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

App

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

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

$$\begin{aligned}\langle I_1\rangle_+ &= \frac{1}{8}\Big[2|\mathcal{F}_S|^2\rho^-_{1,S} + \frac{2}{3}|\mathcal{F}_P|^2\rho^-_{1,P} + 2|\mathcal{F}_\parallel|^2\rho^-_{1,P} + 2|\mathcal{F}_\perp|^2\rho^+_{1,P}\Big] \\ &\xrightarrow{\mathrm{SM}} +\frac{1}{8}\Big\{2|\mathcal{F}_S|^2|C_9^{\mathrm{eff}:S}|^2 + \Big[\frac{2}{3}|\mathcal{F}_P|^2 + 2(|\mathcal{F}_\parallel|^2 + |\mathcal{F}_\perp|^2)\Big]|C_9^{\mathrm{eff}:P}|^2\Big\}, \quad (64)\end{aligned}$$

P-wave unsuppressed

$$\begin{aligned}\langle I_2\rangle_+ &= -\frac{1}{8}\Big[2|\mathcal{F}_S|^2\rho^-_{1,S} + \frac{2}{3}\{|\mathcal{F}_P|^2\rho^-_{1,P} - |\mathcal{F}_\parallel|^2\rho^-_{1,P} - |\mathcal{F}_\perp|^2\rho^+_{1,P}\}\Big] \\ &\xrightarrow{\mathrm{SM}} -\frac{1}{8}\Big\{2|\mathcal{F}_S|^2|C_9^{\mathrm{eff}:S}|^2 + \frac{2}{3}(|\mathcal{F}_P|^2 - |\mathcal{F}_\parallel|^2 - |\mathcal{F}_\perp|^2)|C_9^{\mathrm{eff}:P}|^2\Big\}, \quad (65)\end{aligned}$$

$$\begin{aligned}\langle I_3\rangle_+ &= \frac{1}{6}[|\mathcal{F}_\perp|^2\rho^+_{1,P} - |\mathcal{F}_\parallel|^2\rho^-_{1,P}] \\ &\xrightarrow{\mathrm{SM}} \frac{1}{6}(|\mathcal{F}_\perp|^2 - |\mathcal{F}_\parallel|^2)|C_9^{\mathrm{eff}:P}|^2, \quad (66)\end{aligned}$$

P-wave suppression!

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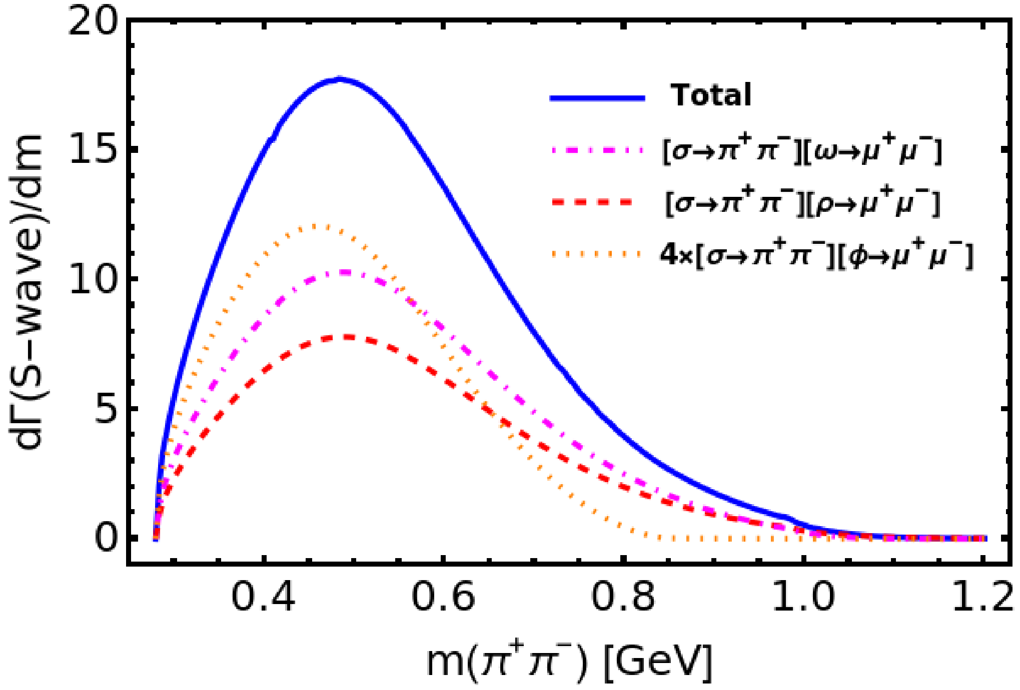
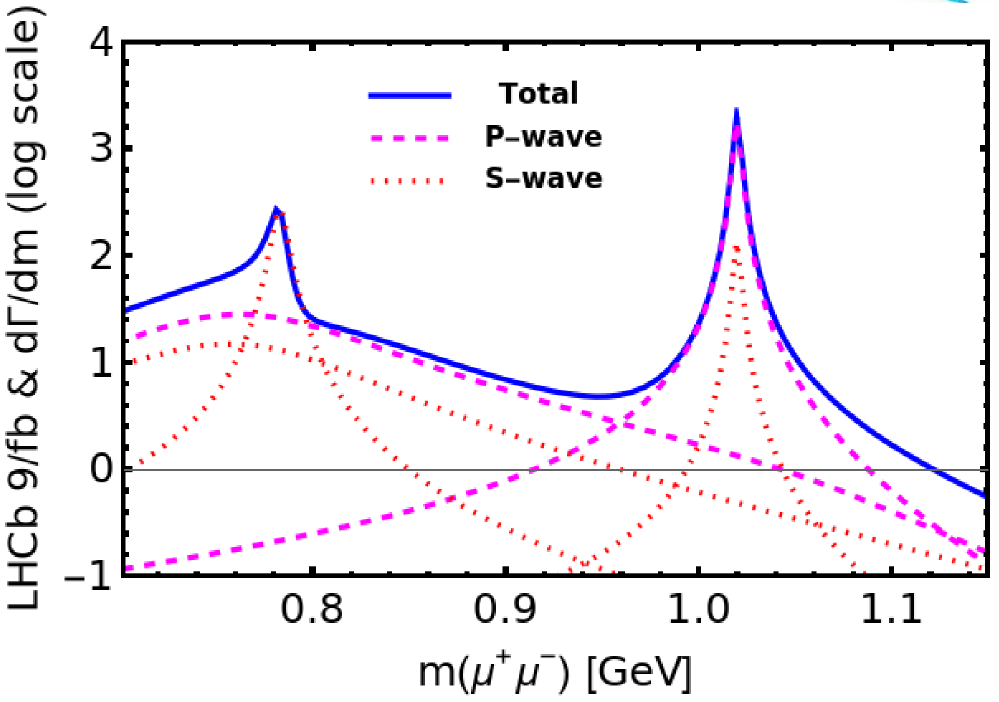
Resonant components





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))

Parameters extracted from the fit

App

(A$_1$(0): FF normalization)

- **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 $D^0 \to K^+K^-\pi^+\pi^-$
- In the ballpark of BESIII SL
- Large impact in q^2 distribution

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

$$0.8 \lesssim B_\phi/B_{\rho^0} \lesssim 0.9\,,$$
$$0.9 \lesssim B_\omega^{(S)}/B_{\rho^0}^{(S)} \lesssim 1.1\,,$$

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

$$0.001 \lesssim a_\omega \lesssim 0.005\,,$$
$$1.1\,\pi \lesssim \phi_\omega \lesssim 1.7\,\pi\,,$$
$$39\ \text{GeV} \lesssim \frac{a_S(0)}{A_1(0)} \lesssim 62\ \text{GeV}$$

$$0.5\,\pi \lesssim \Delta_1 \lesssim 0.9\,\pi$$
$$0.2\,\pi \lesssim \Delta_4 \lesssim 0.5\,\pi$$

Angular observables

App

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

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

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

WCs, hadronic inputs

with the angular basis, c_i, defined as

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

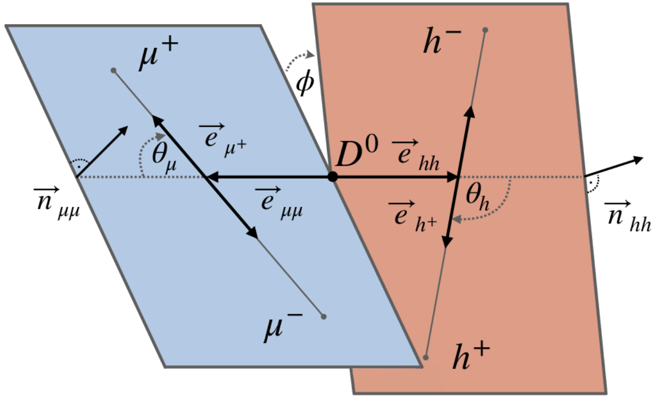
The normalised and integrated observables $\langle I_i \rangle$ are defined as

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

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

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

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



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

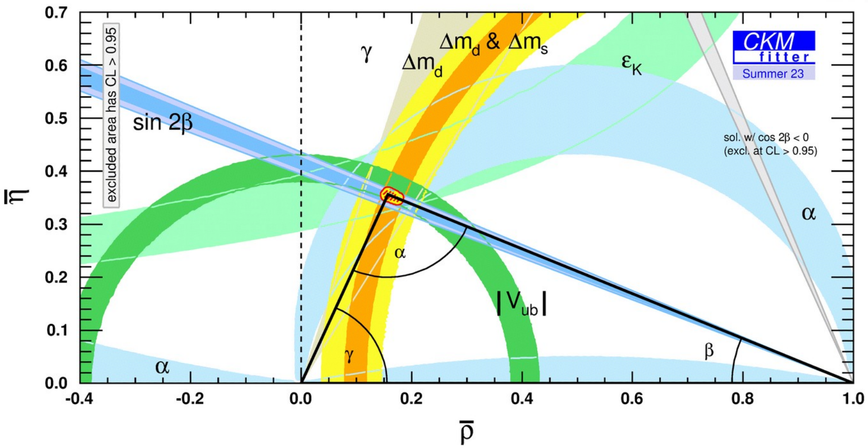
$$\cos\phi = \vec{n}_{\mu\mu}\cdot\vec{n}_{hh},$$
$$\sin\phi = [\vec{n}_{\mu\mu}\times\vec{n}_{hh}]\cdot\vec{e}_{hh},$$

CP violation in the charm sector

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

b : $|V_{ub}|$, α, β, γ, Δm_d, Δm_s **s** : ε_K

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



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

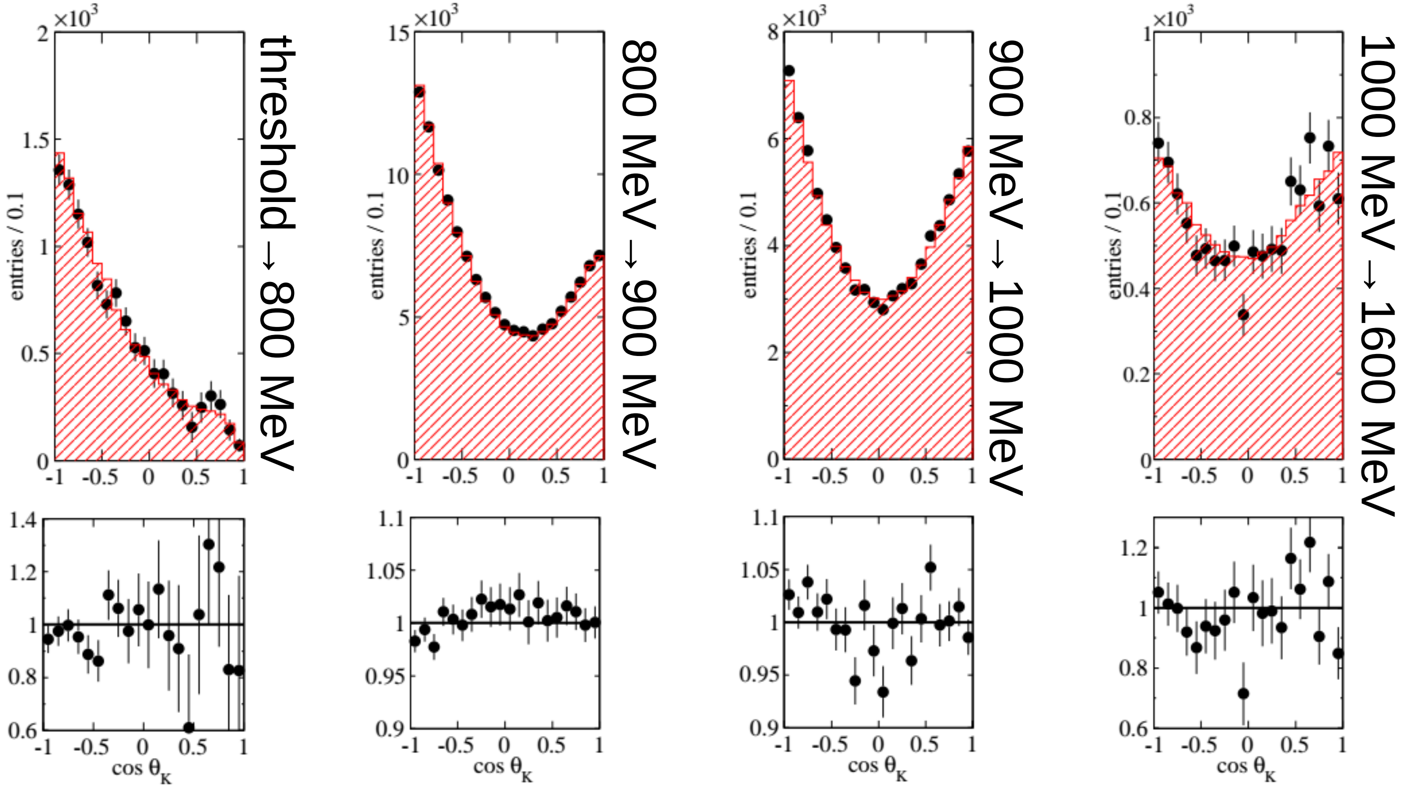
[Khodjamirian, Petrov ‘17; Li, Lu, Yu ‘19; Soni ‘19; Cheng, Chiang ‘19; **Pich, Solomonidi, LVS ‘23**; Lenz, Piscopo, Rusov ‘23; ...]

- Rare charm-meson decays consistent with no CP violation:
  - **A_1, …, A_9** ~ 0 (small CP violation)

LVS

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

Different Kπ-energy slices



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

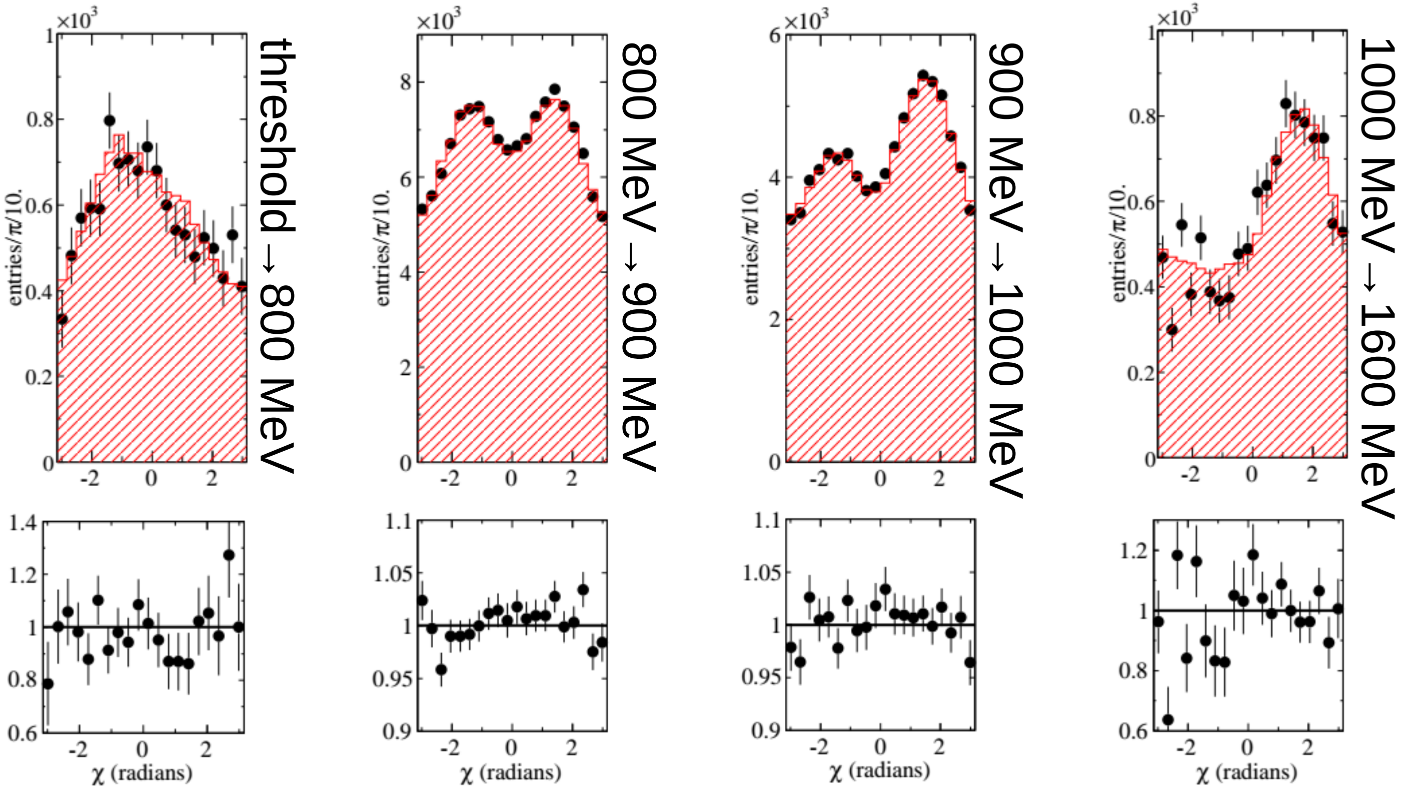
S-wave from $K_0^*(800)=\kappa$ and $K_0^*(1430)$

LVS

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

App

Different Kπ-energy slices

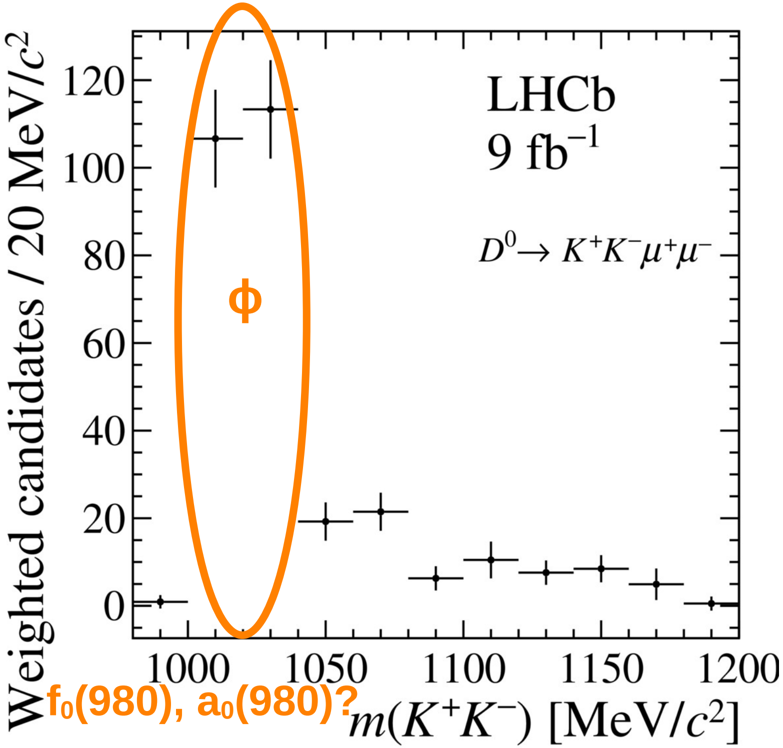


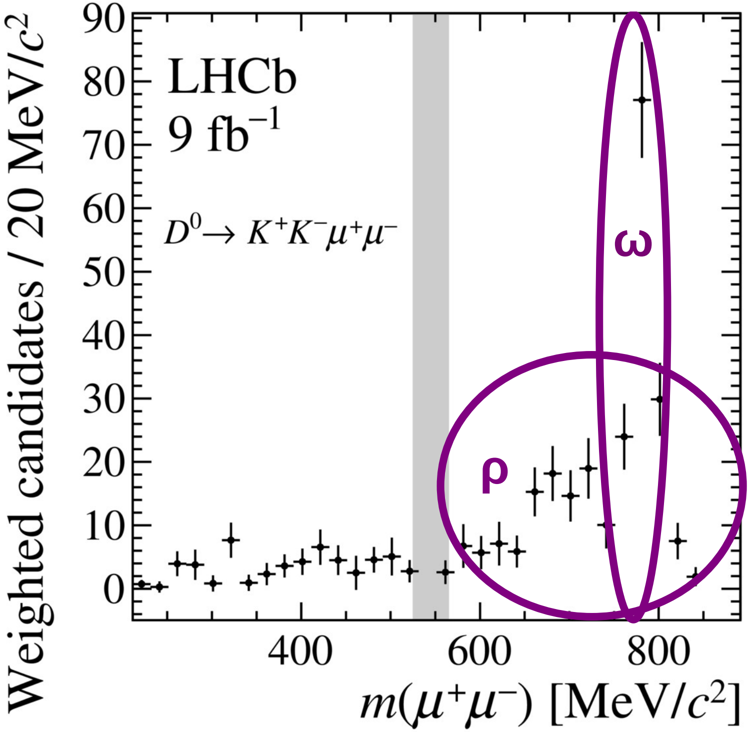
S- and P-waves interference produces sin(χ) term, and also cos(χ) term; "P-wave only" gives a cos(2χ) term

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

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

App





Threshold effects complicate the description of $f_0(980)$, $a_0(980)$

Dedicated analysis still needed; having $f_0(980)$, $a_0(980)$ and ϕ close may produce an interesting S- and P-waves interference effect

Outlook

- 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* $hh\gamma$, *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