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

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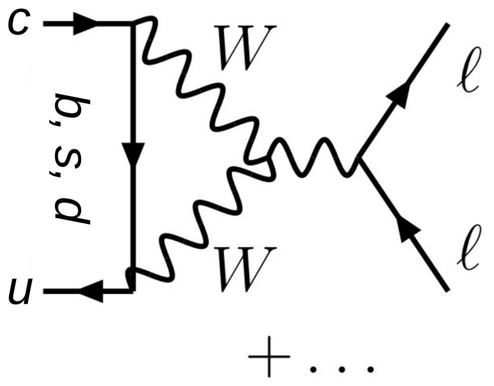
Rare charm meson decays



- More effective GIM mechanism, CKM diagonal texture: non-perturbative effects play a very important role

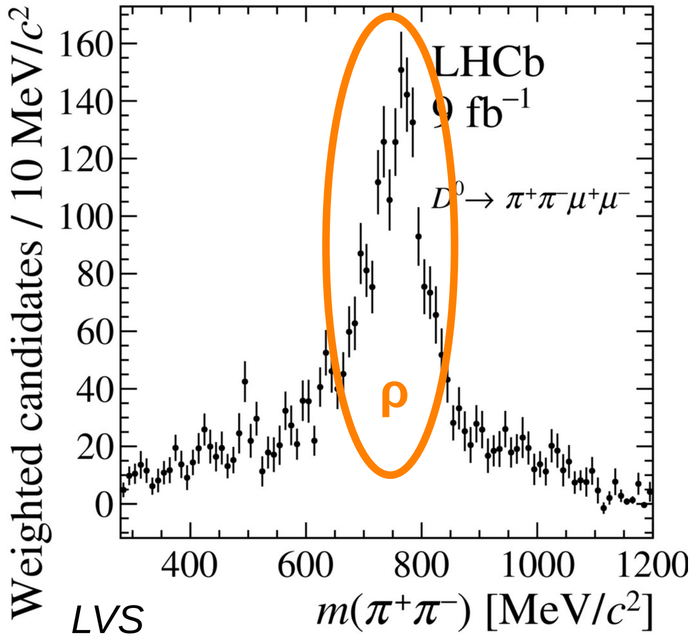
  [Fajfer, Prelovsek ‘06; Cappiello, Cata, D’Ambrosio ‘13; De Boer, Hiller ‘18; ...]

- LHCb, D^0 to ($\pi^+\pi^-$, K^+K^-) $\mu^+\mu^-$: **large data set available**, allowing for a closer look into the SM background

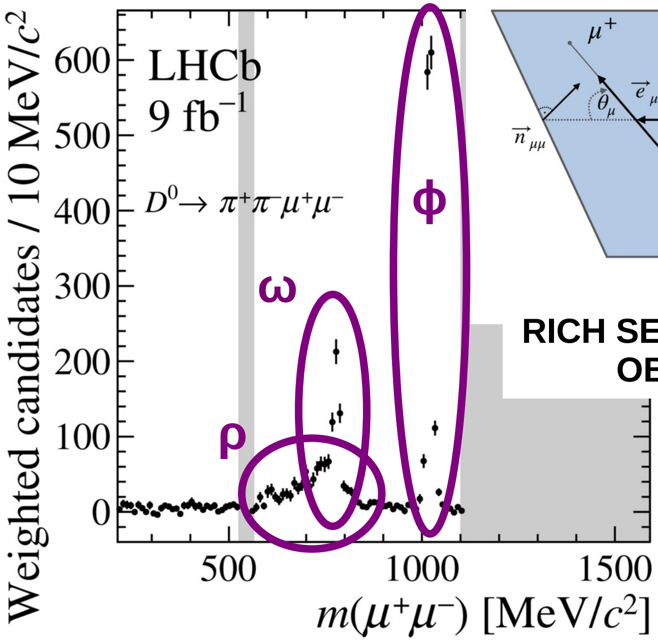
- Having control over the SM, move to observables measuring SM–NP interference: analysis of a rich set of angular observables

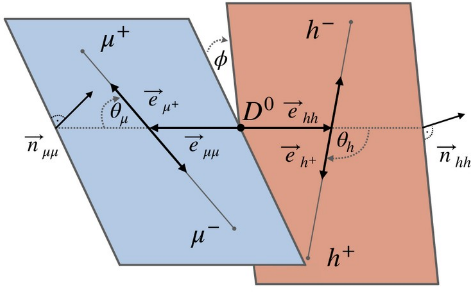
Large available dataset

- LHCb: 1310.2535; 1707.08377; 1806.10793; 2111.03327 (9/fb @ 7, 8, 13 TeV)
- Differential BRs: clear resonant peaks in $m(\pi^+\pi^-)$ and $m(\mu^+\mu^-)$
- Binned angular observables (CP-sym. “**S**”, and CP-asym. “**A**” combinations)

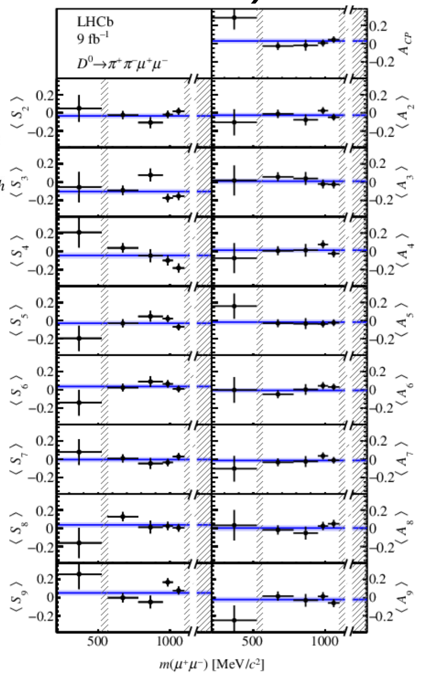


LVS





RICH SET OF ANGULAR OBSERVABLES!



Testing short-distance physics

③

- The effective weak interactions are encoded in:

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

current-current (4-quark) operators:
long-distance contribution

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

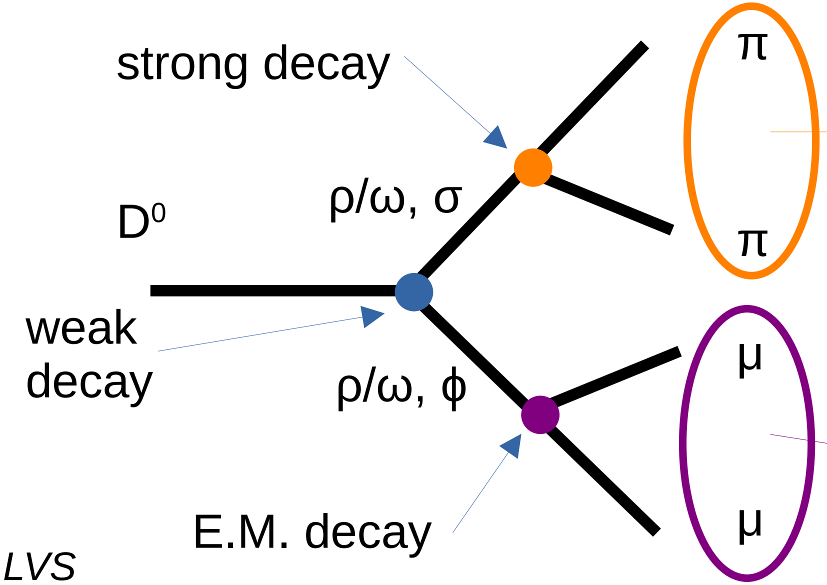
$$Q_{10} = \frac{\alpha_{em}}{2\pi}(\bar{u}\gamma_\mu(\mathbf{1}-\gamma_5)c)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

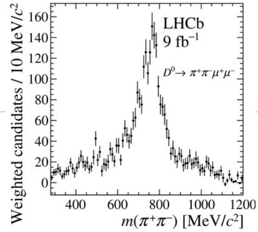
- Tests of SD require good enough description of the LD part
- HERE: address LD/hadronic physics;

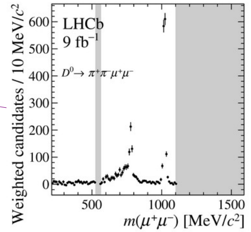
  novelty: S-wave contribution

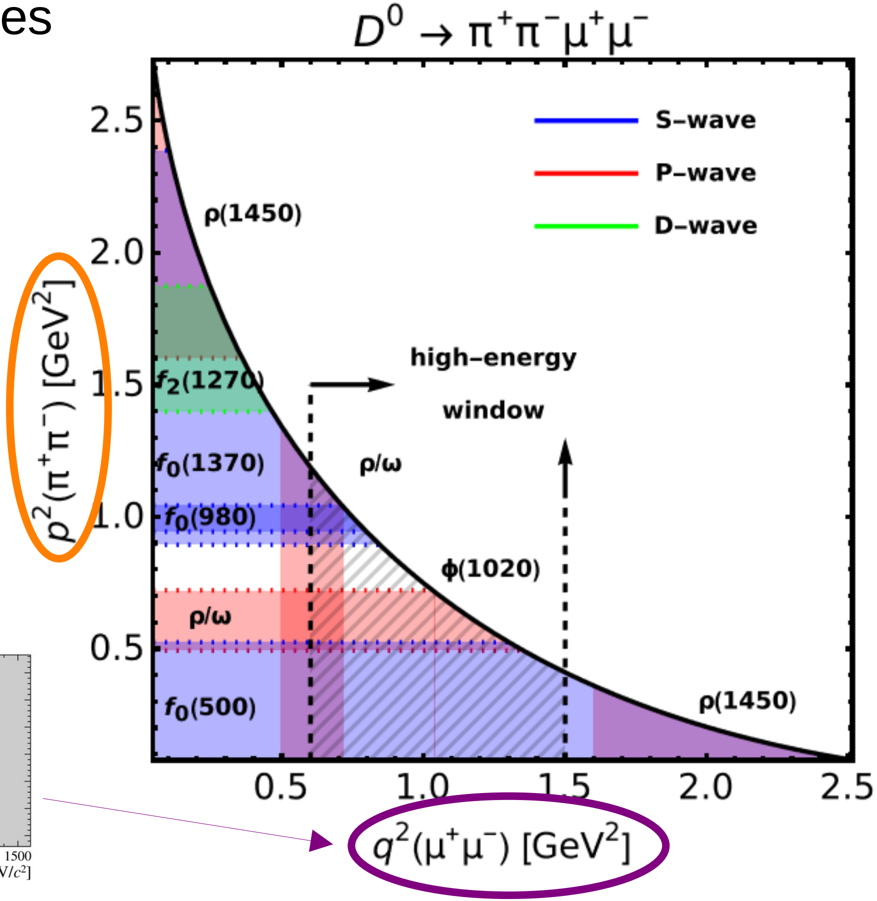
Available phase space

- Phase space heavily populated with resonances
- Quasi-two body (Q2B) decays
- Focus: “high-energy window”, thus avoiding tower of heavier S-, P-, D-resonances





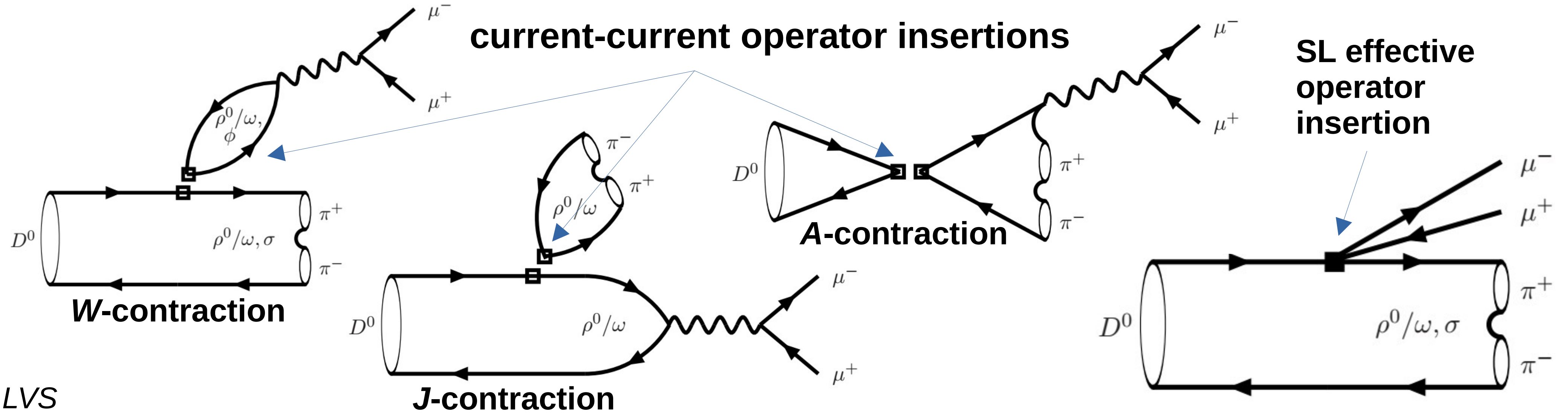




LVS

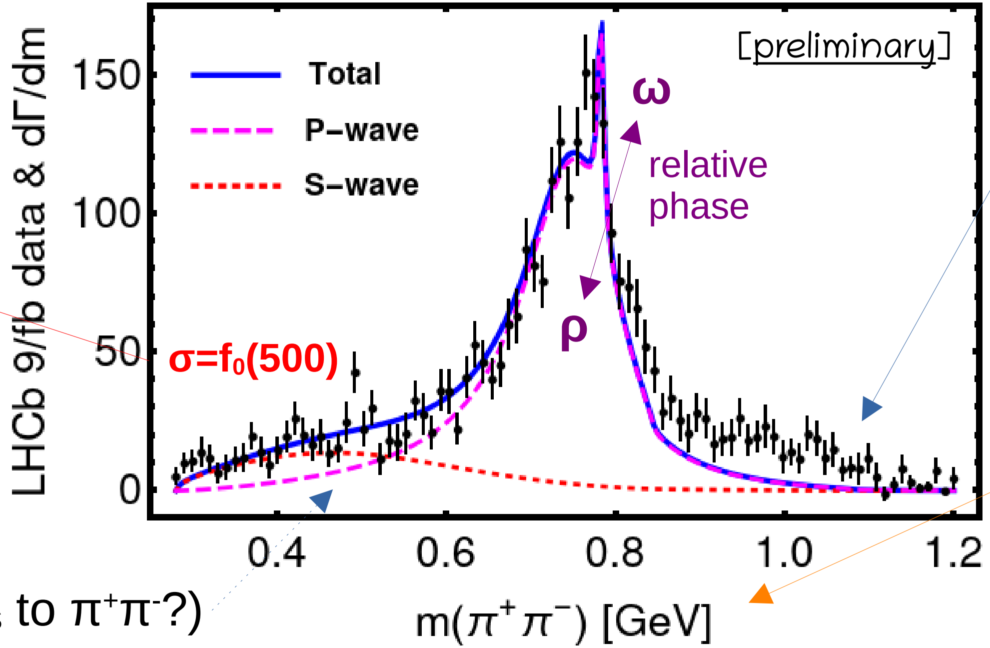
Factorization model

- Distinct topologies are present: *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 $K(*)^+\ell^+\ell^-$: CKM suppressed $V_{ub}{}^*V_{us}/(V_{cb}{}^*V_{cs})$
  - Cappiello, Cata, D'Ambrosio '13: Bremsstrahlung, @ low-m($\mu^+\mu^-$)
- 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; σ: Bugg; ϕ, $\omega\to\mu^+\mu^-$: Breit-Wigner)
- Beyond naive factorization: free O(1) normalization coefs, constant complex phases among intermediate resonances



Fits to differential BRs

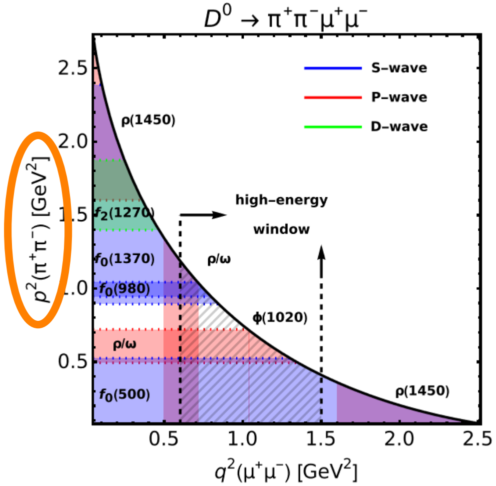
- S-wave: $f_0(500)$ is clearly seen in present data
- Consistent with BESIII SL decay: D^+ to $\pi^+\pi^- e^+\nu_e$



At the level of ~15% of total Γ

(Ks to $\pi^+\pi^-$?)

Other scalar contributions [ππ → KK → ππ (in)elastic rescattering effect], and P- and D-waves; also, isospin-2



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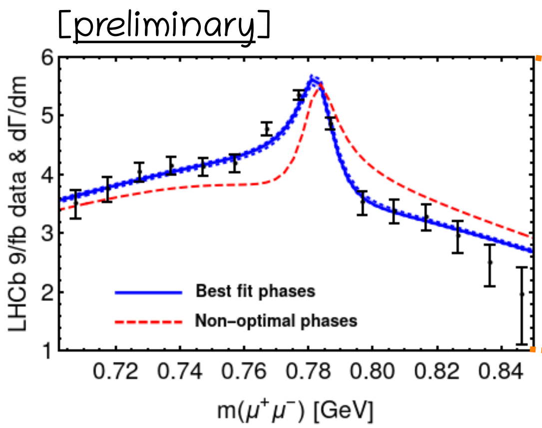
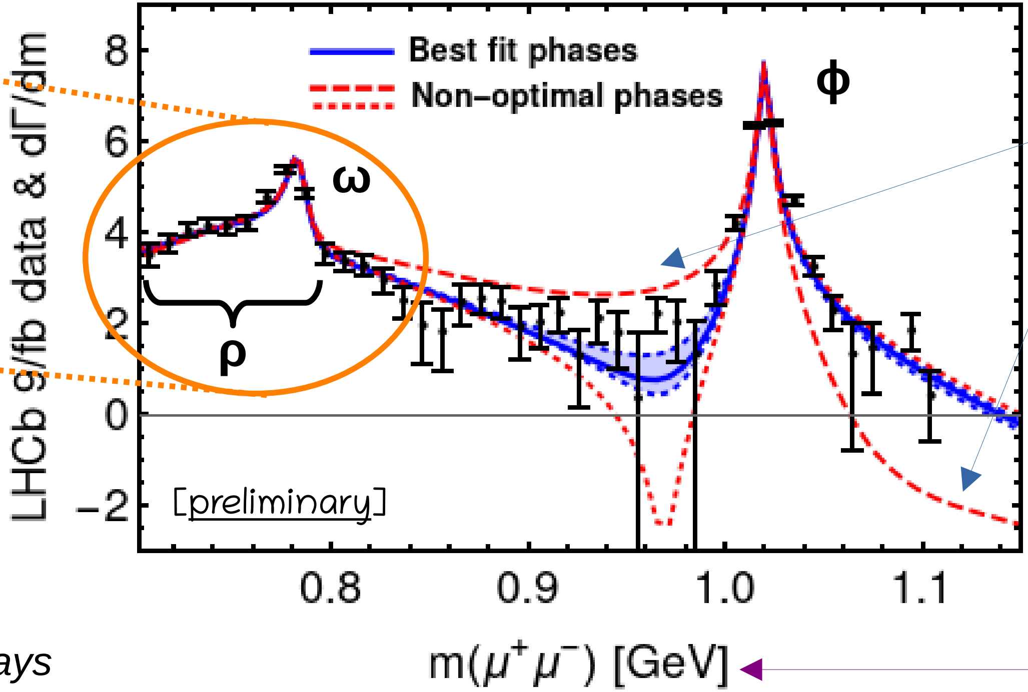
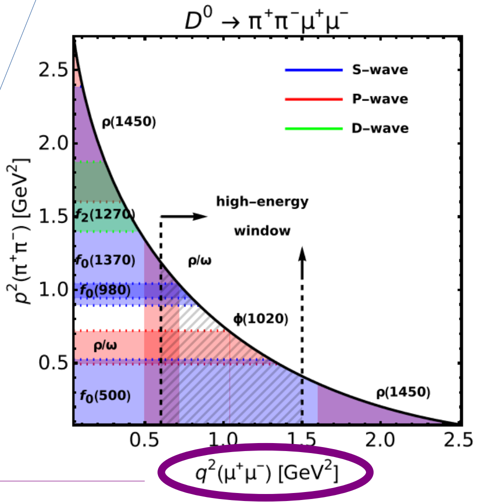
Fits to differential BRs

- Relative strong-phases (4) among resonances: important impact
- Such phase differences can be probed by present data





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



Angular observables

- 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 line-shapes)
  - $\mathbf{A}_1$, …, $\mathbf{A}_9$ ~ 0 (small CP violation)
- 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†	×
5†	×
7†	×
8†	×

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

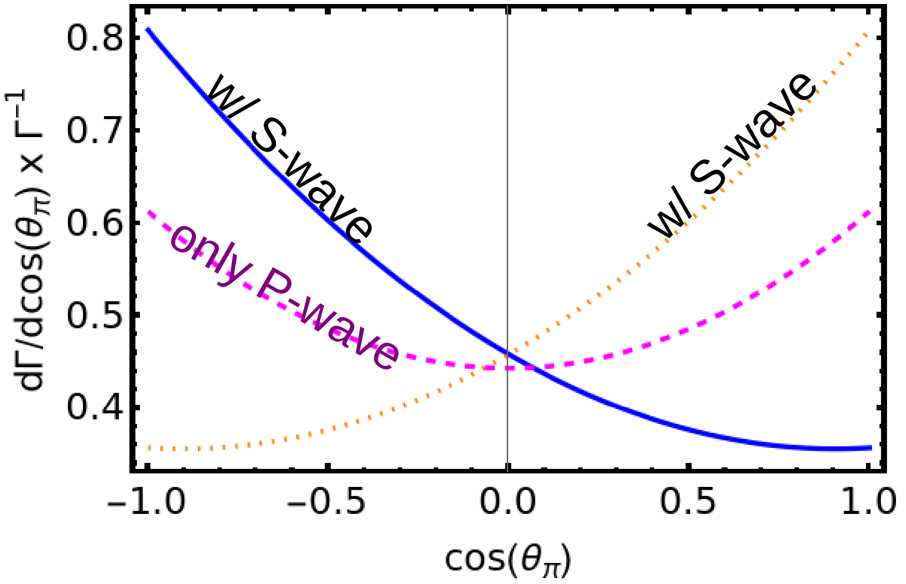
"+" or "-": ways of integrating over $\cos\theta_\pi$

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

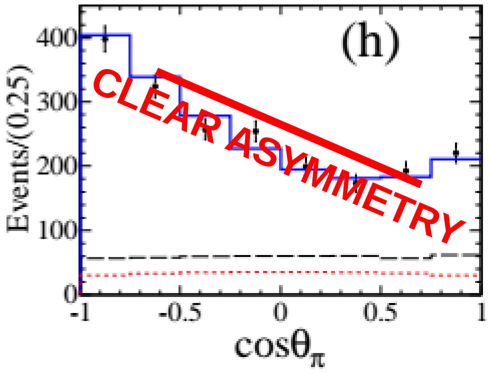
Angular observables

- Probe S- and P-waves interference also with distinct binned 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, which can reach **O(10)%**

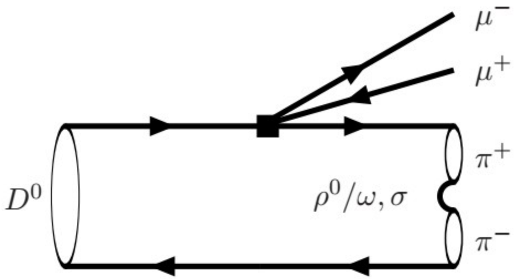


BESIII (1809.06496)
SL: $D^+ \to \pi^+\pi^- e^+\nu_e$



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

Null tests: SM-NP interference



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

- Impact of present data on the charm sector
- Phase-space dominated by resonances
- **First** quantitative assessment of the S-wave
- Extra, straightforward LHCb measurements will further probe the S-wave
- **S-wave provides novel null tests of the SM**

Thanks!

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

App 1

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%!

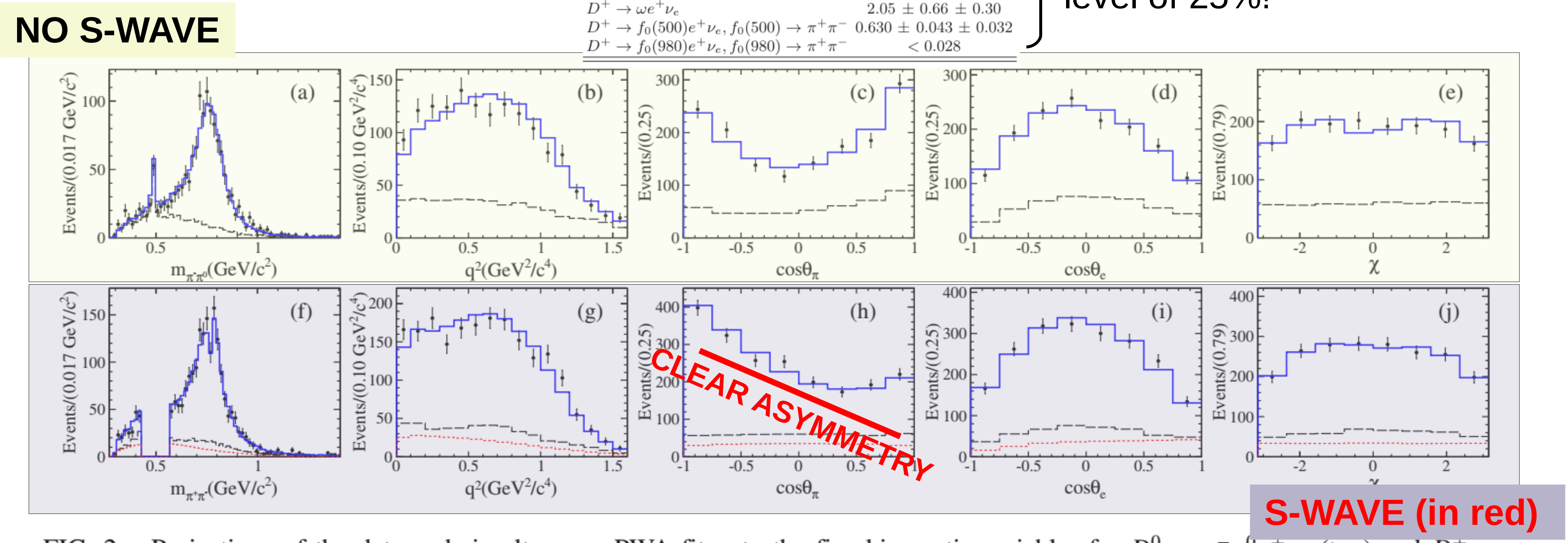


FIG. 2. Projections of the data and simultaneous PWA fit onto the five kinematic variables for $D^0 \to \pi^-\pi^0 e^+\nu_e$ (top) and $D^+ \to \pi^-\pi^+ e^+\nu_e$ (bottom) channels. The dots with error bars are data, the solid lines are the fits, the dashed lines show the MC simulated backgrounds,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

Angular observables

App 2

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]

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

with the angular basis, c_i, defined as

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

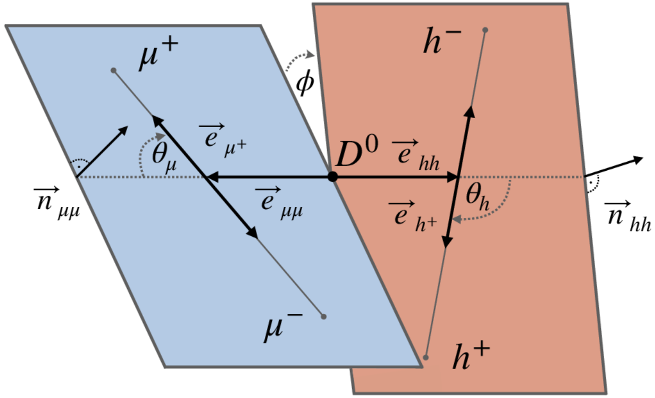
The normalised and integrated observables $\langle I_i \rangle$ are defined as

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

The observables reported in the Letter are the CP averages, $\langle S_{\rm i} \rangle$, and asymmetries, $\langle A_{\rm i} \rangle$, defined as

$$\begin{aligned} \langle S_{\rm i} \rangle &= \frac{1}{2}\left[\langle I_{\rm i} \rangle + (-)\langle \overline{I}_{\rm i} \rangle\right],\\ \langle A_{\rm i} \rangle &= \frac{1}{2}\left[\langle I_{\rm i} \rangle - (+)\langle \overline{I}_{\rm i} \rangle\right], \end{aligned} \tag{11}$$

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



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

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

Rare semi-leptonic decays

App 3

- Main problem: strong dynamics
- **Data-driven approaches**
  - (i) data on purely hadronic decay modes
    - *D to ππππ, D to ππKK, etc.: not rare decays*
  - (ii) data on rescattering of final states
    - *ππ to KK*

Amplitude analyses:
CLEO: 1703.08505 &
LHCb: 1811.08304
indicate that cascade topologies may give sizeable contributions