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)

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

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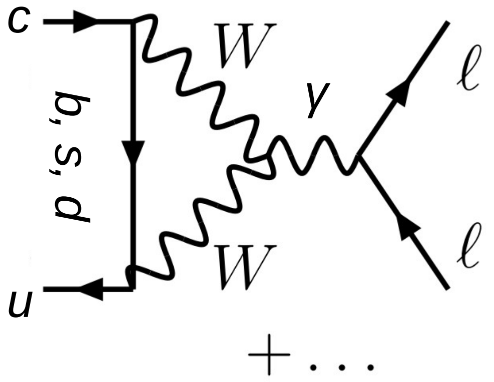
Rare charm decays

- Flavour physics of the **up-type**: <u>complementary</u>, 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

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" ψ_i =


Volume 11, number 3 PHYSICS LETTERS 1 August 1964

ELEMENTARY PARTICLES AND SU(4)

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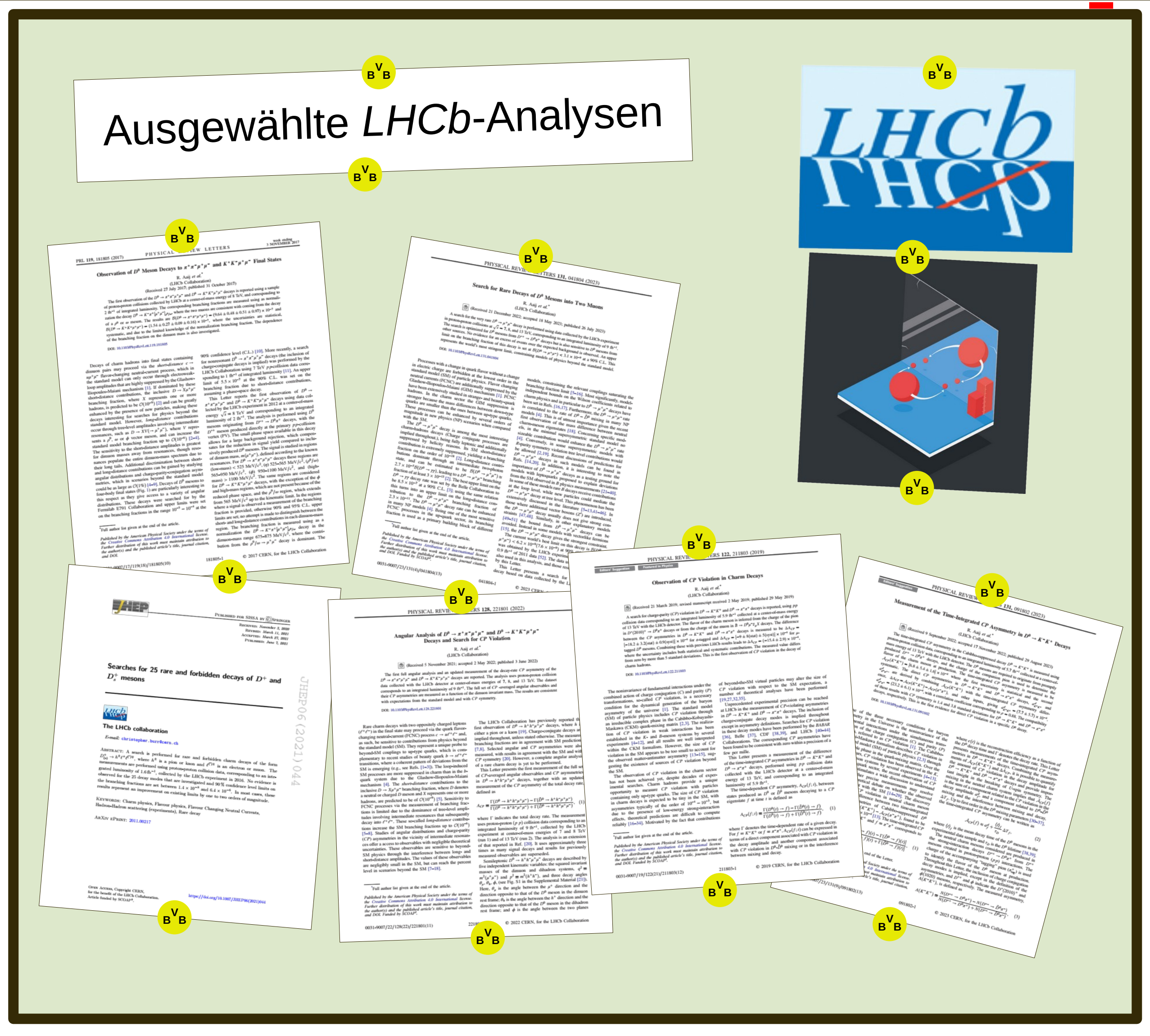
Received 19 June 1964

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



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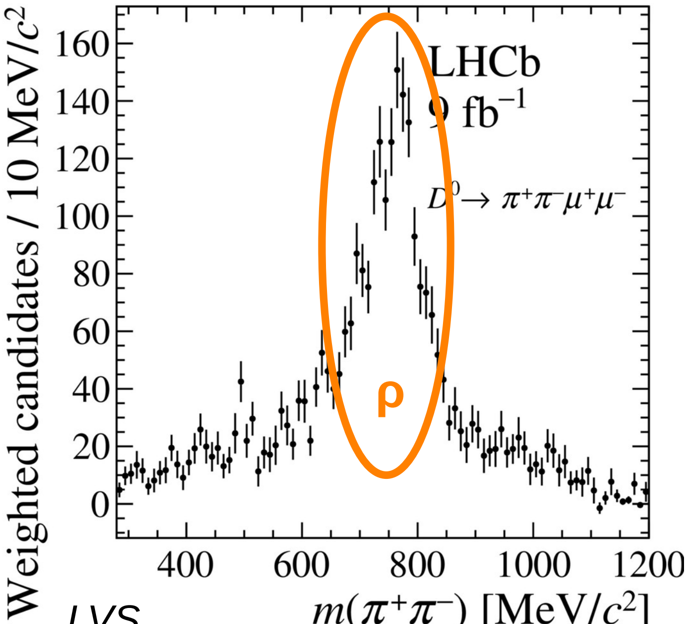
Large available dataset

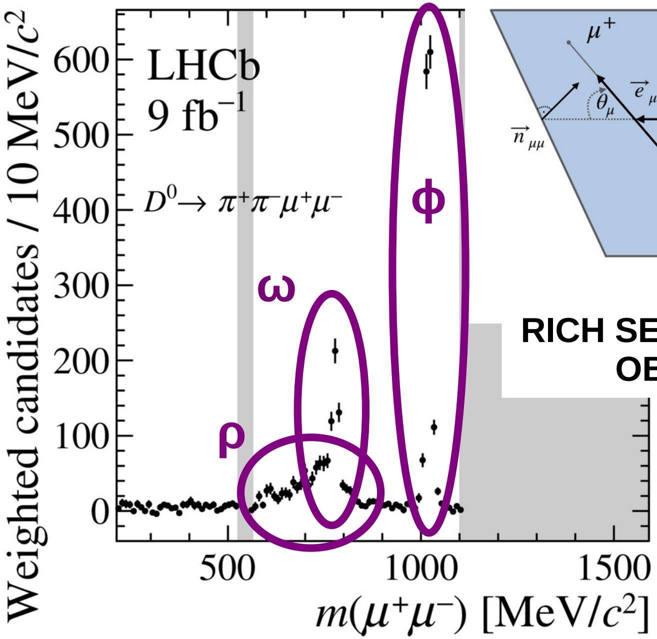
Much more is known about the **muonic** rare decay mode

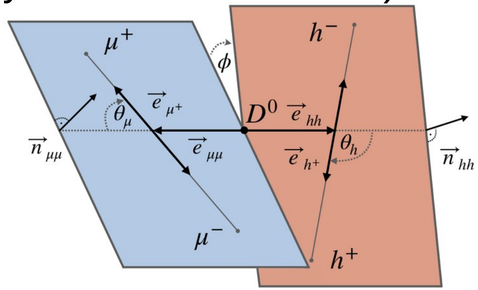
LHCb: $D^0 \to \mu^+\mu^-$ (1305.5059; 2212.11203); **$D^+ \to \pi^+\mu^+\mu^-$** (1304.6365; 2011.00217);

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

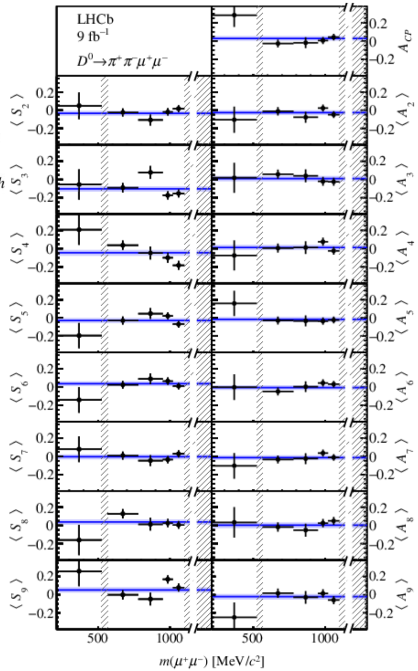
- **Differential BRs**: clear resonant peaks in m(ππ) and m(μμ)
- **Binned angular observables** (CP-sym. "**S**", and CP-asym. "**A**" combinations)







RICH SET OF ANGULAR OBSERVABLES!



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Testing Short-Distance (SD) physics

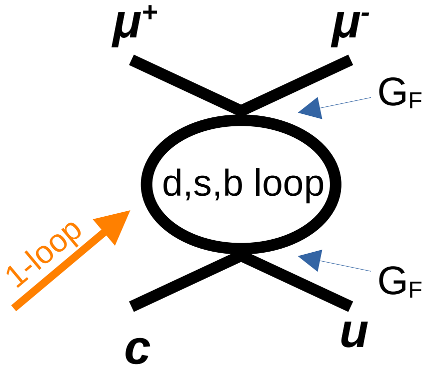
- The SM effective weak interactions for $c \to u\ell^+\ell^-$ @ $\mu \sim m_c$ are:

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

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

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

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

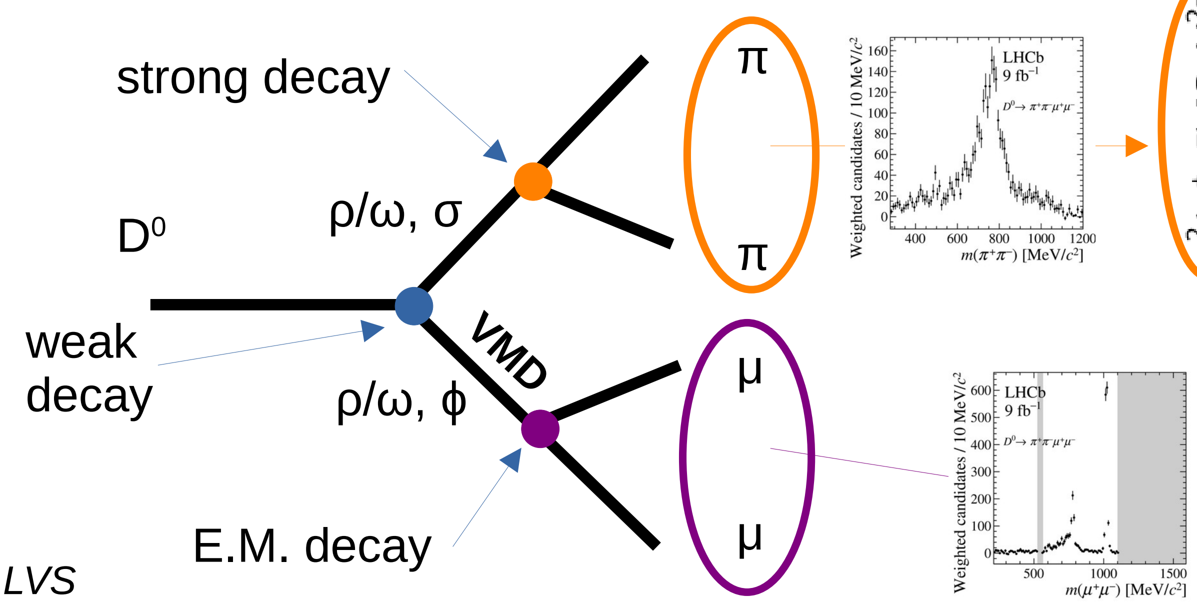


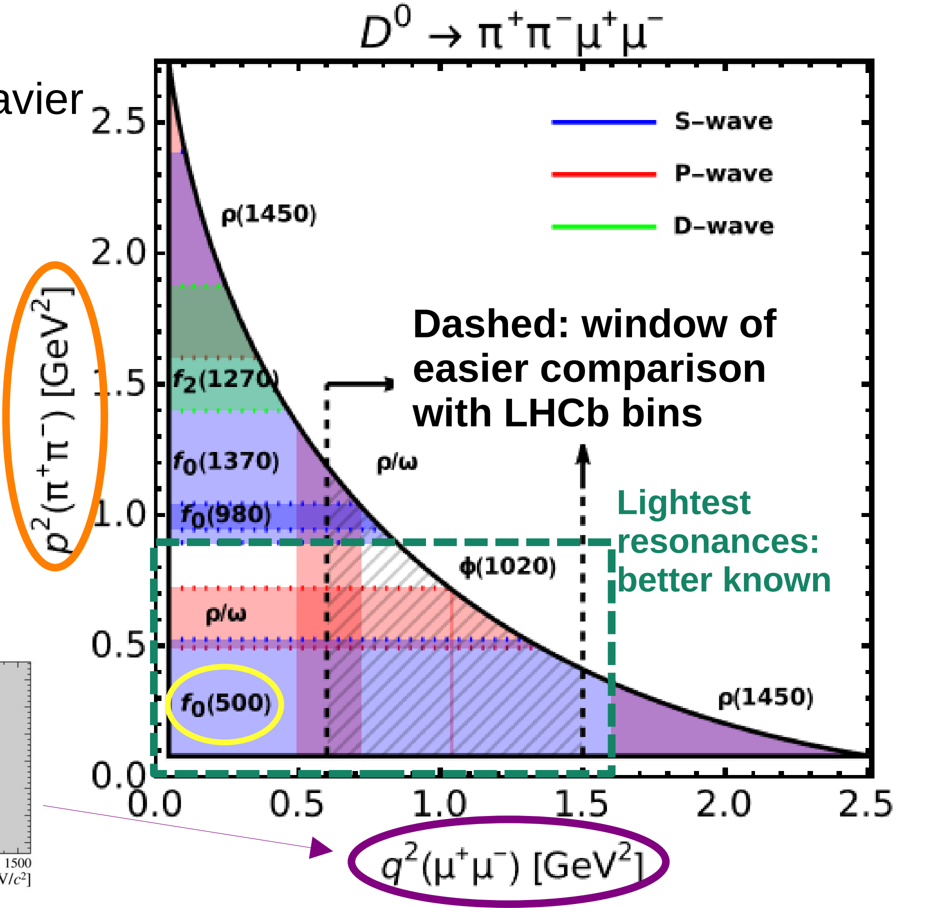
below EW scale
($\mathbf{c \to u\nu\nu}$ is also G_F^2)

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

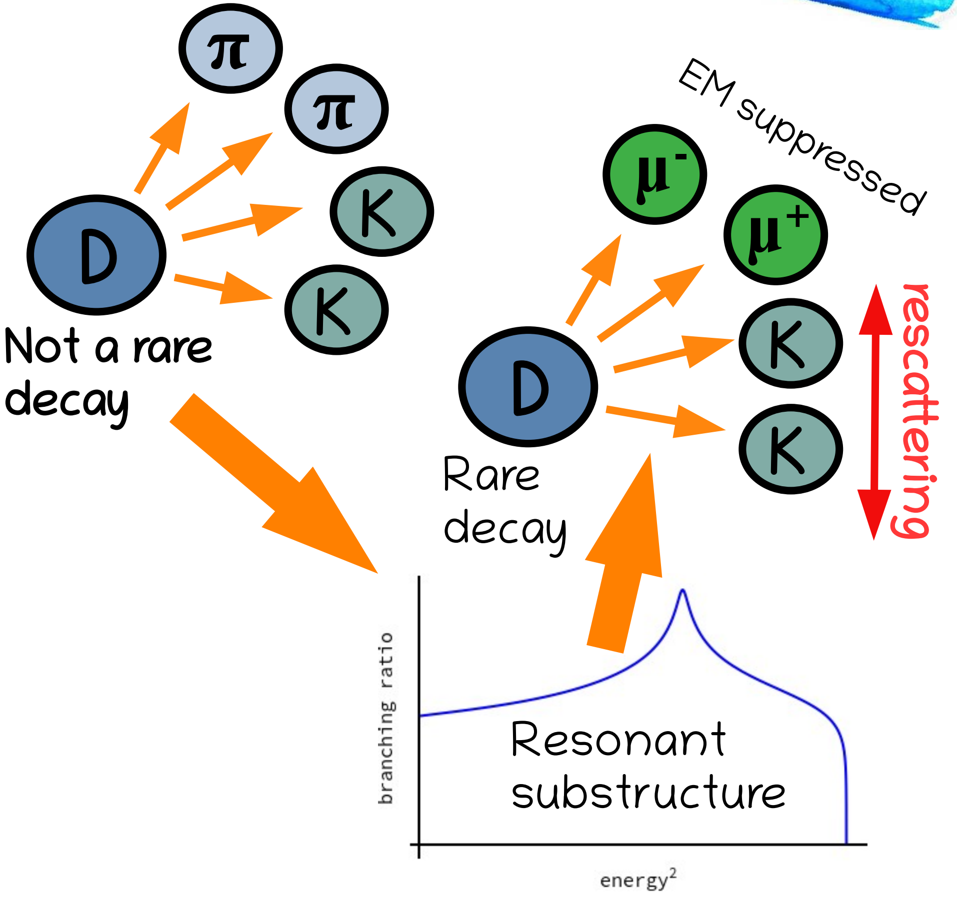
- Phase space heavily populated with resonances (cf. B sector)
- Quasi-two body (Q2B) decays
- Focus: “high-energy window”, thus avoiding tower of heavier S-, P-, D-resonances
- Vector resonances contribute to $\mathbf{D^0 \to V\gamma}$ and $\mathbf{D^0 \to \gamma\gamma}$





Amplitude Analyses (AAs)

- $D^0 \to \pi^+\pi^-\pi^+\pi^-$ (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 $\rho(770)^0$ 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?



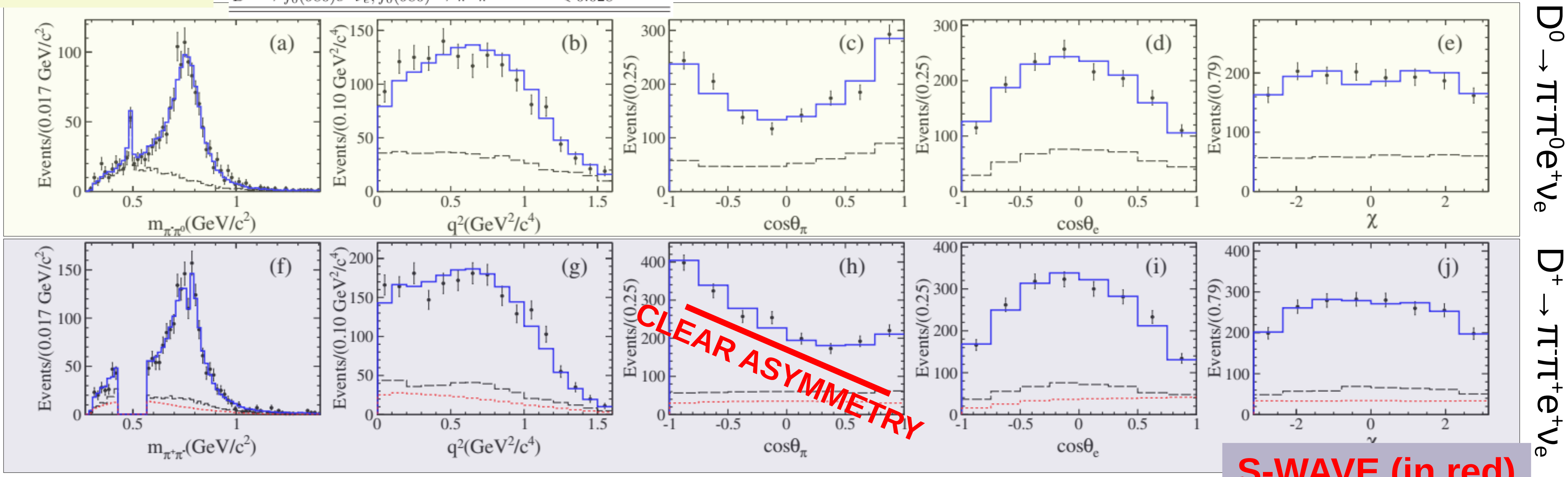
BESIII SL decays: D to $\pi^-\pi\ e^+\nu_e$ [1809.06496]

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]

NO S-WAVE

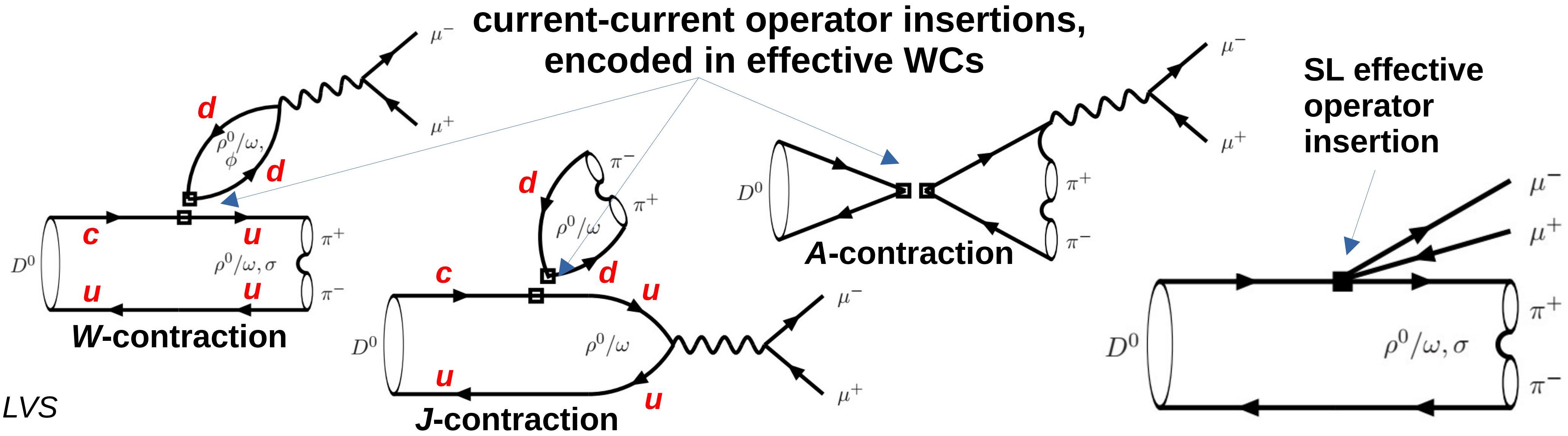


S-WAVE (in red)

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 $D^+ \to f_0(500)e^+\nu_e$.

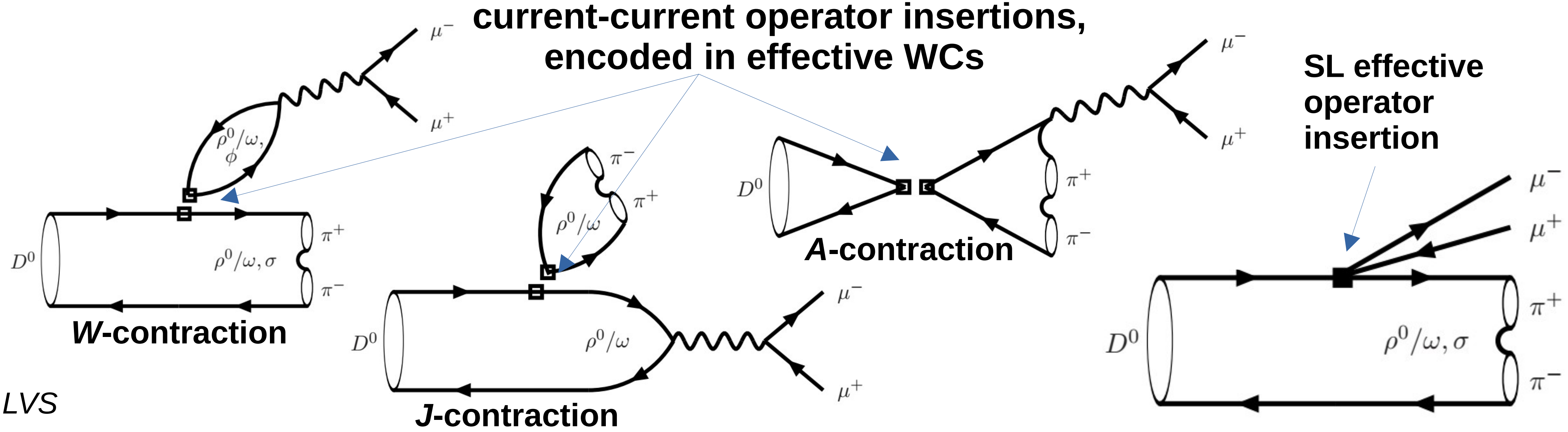
Factorization model

- 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-$m(\mu^+\mu^-)$



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



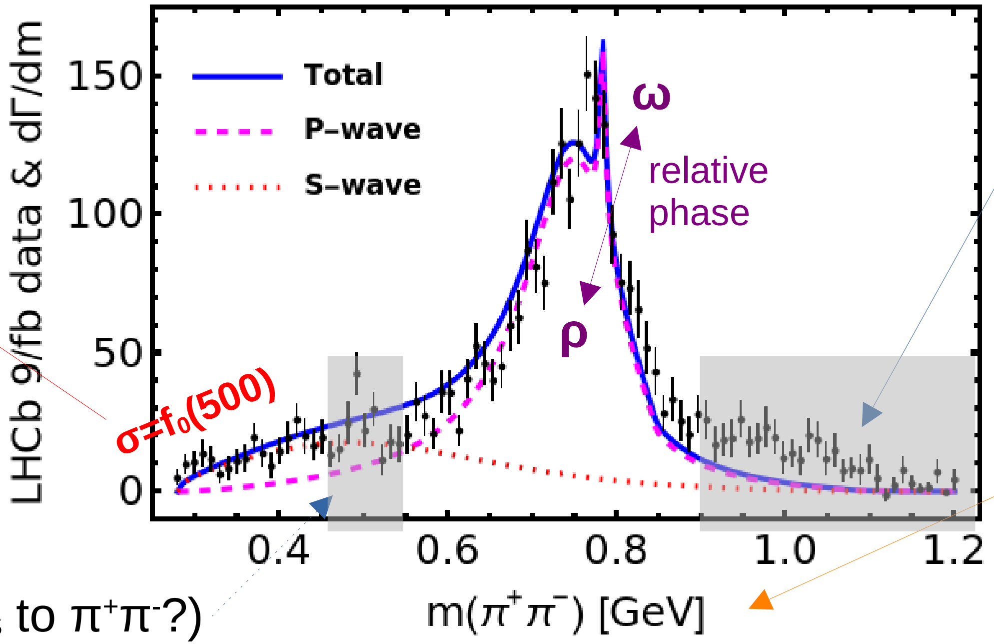
Fits to differential BRs

- S-wave: $f_0(500)$ is clearly seen in present data, despite not interfering with the dominant P-wave in the BR

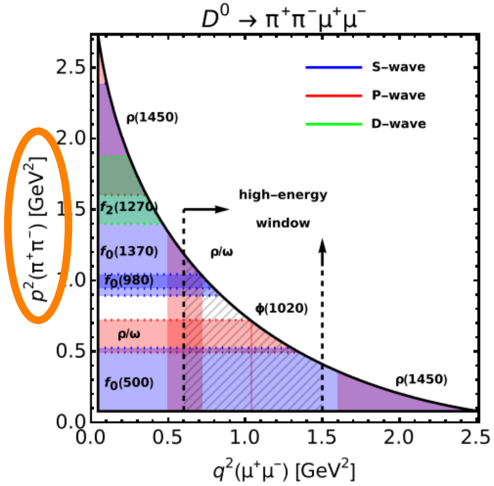
- Consistent with BESIII SL decay: D^+ to $\pi^+\pi^- e^+\nu_e$

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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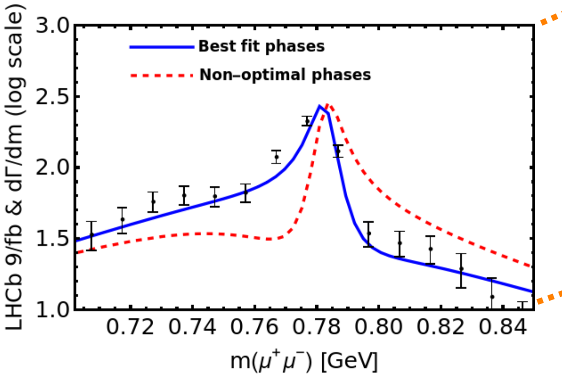
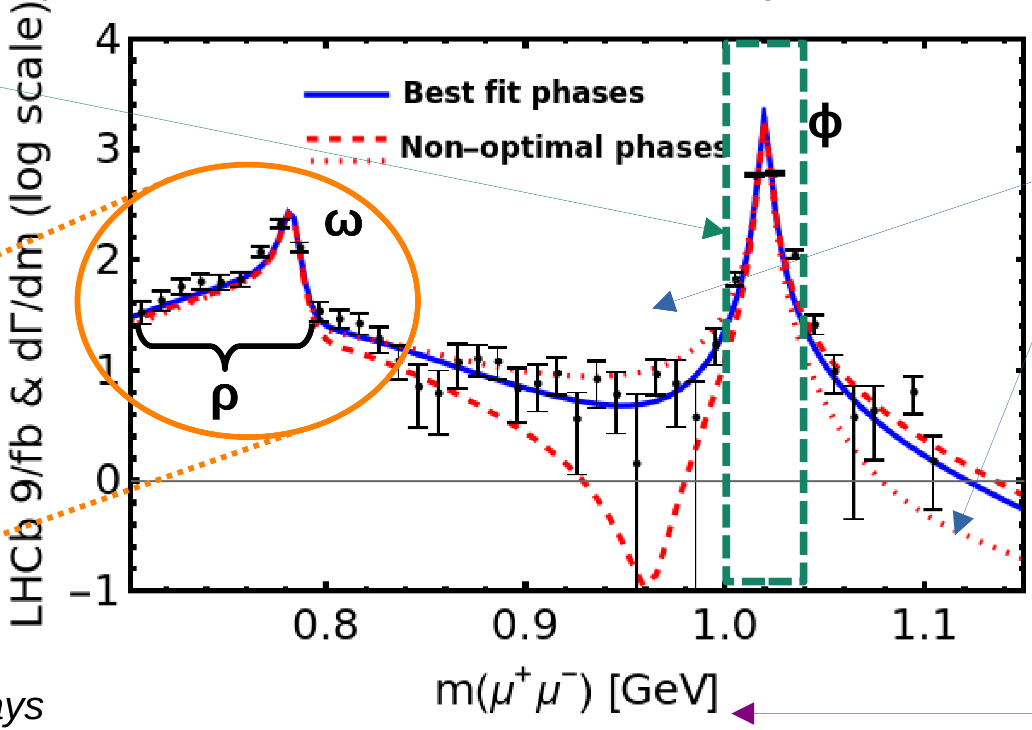
Fits to differential BRs

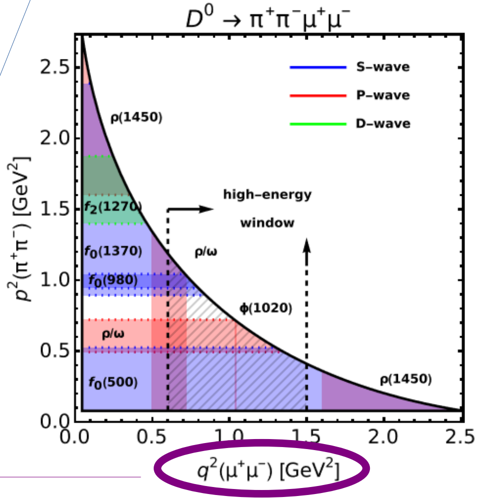
- Relative strong-phases among resonances: important impact on differential BR
- Such phase differences can be probed by present data
- About 60% broader ϕ resonance in the data than expected: LHCb resolution

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

($A_1(0)$: FF normalization)

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

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

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

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

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

Angular observables

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

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

with the angular basis, c_i, defined as

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

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

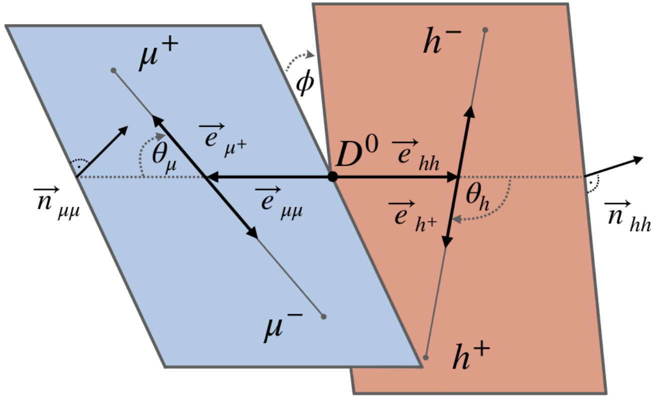
$$\langle I_{2,3,6,9} \rangle = \frac{1}{\Gamma}\int_{q^2_{\min}}^{q^2_{\max}} dq^2 \int_{p^2_{\min}}^{p^2_{\max}} dp^2 \int_{-1}^{+1} d\cos\theta_h\, I_{2,3,6,9}\,,$$
$$\langle I_{4,5,7,8} \rangle = \frac{1}{\Gamma}\int_{q^2_{\min}}^{q^2_{\max}} dq^2 \int_{p^2_{\min}}^{p^2_{\max}} dp^2 \left[\int_{0}^{+1}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

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

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

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

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

- 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
$1^\dagger$	o
$2^\dagger$	o
$3^\dagger$	×
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

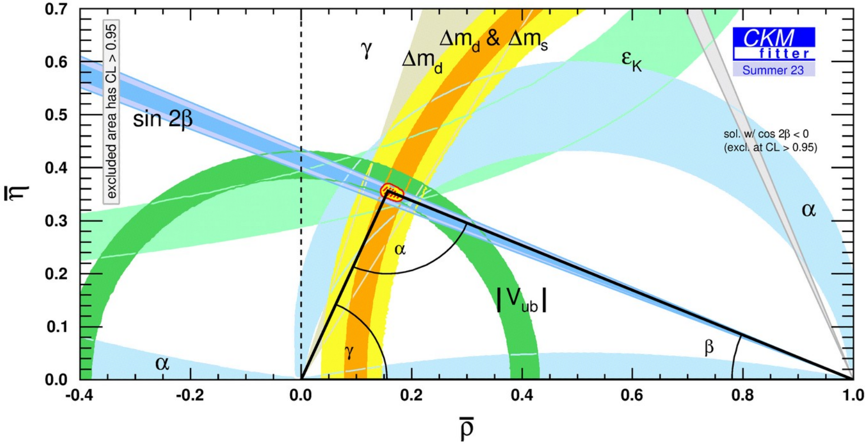
CP violation in the charm sector

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

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)

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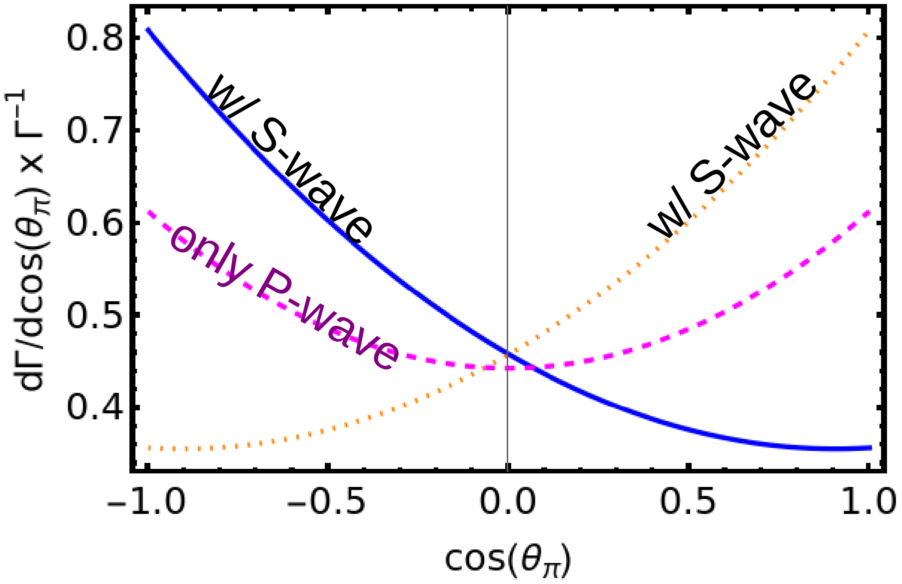
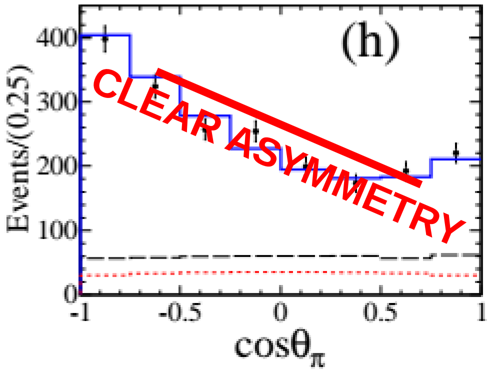
Angular observables

- 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



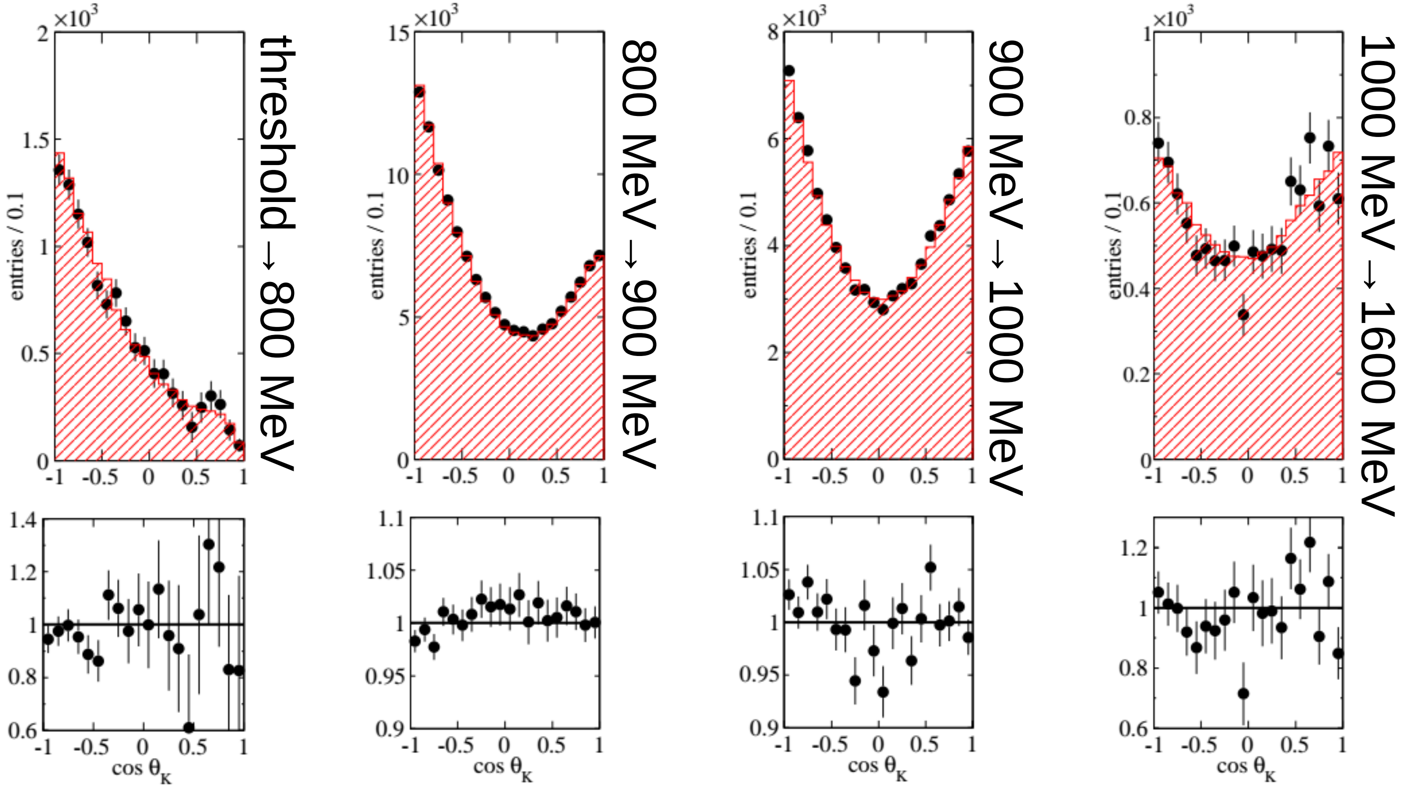
BESIII (1809.06496)
SL: $D^+ \to \pi^+\pi^- e^+\nu_e$



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

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 $K_0^*(1430)$

Null tests: SM-NP interference

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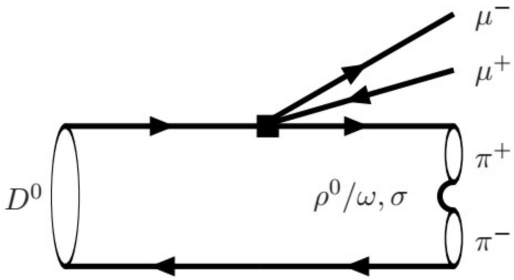
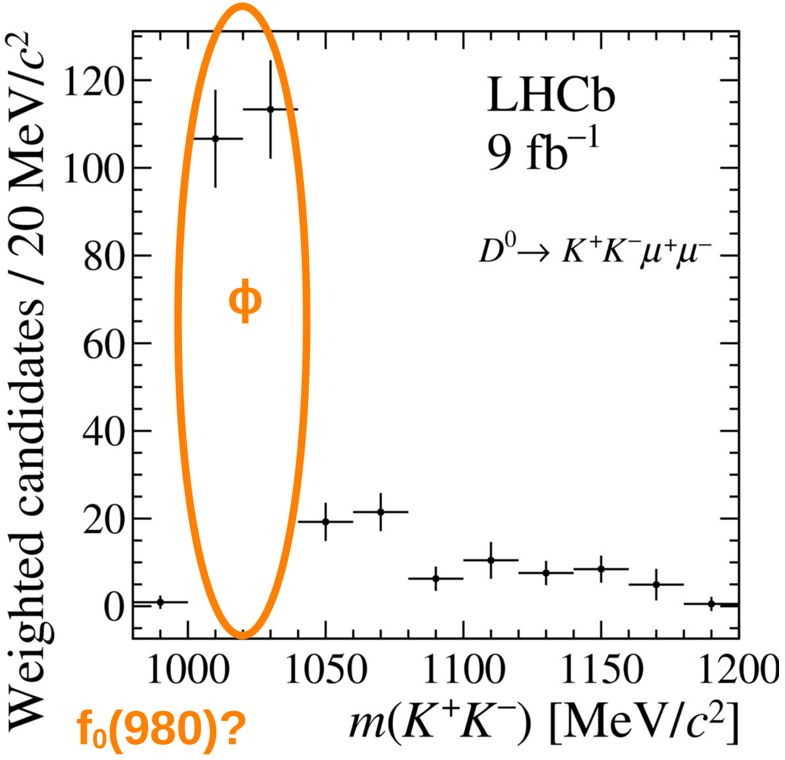
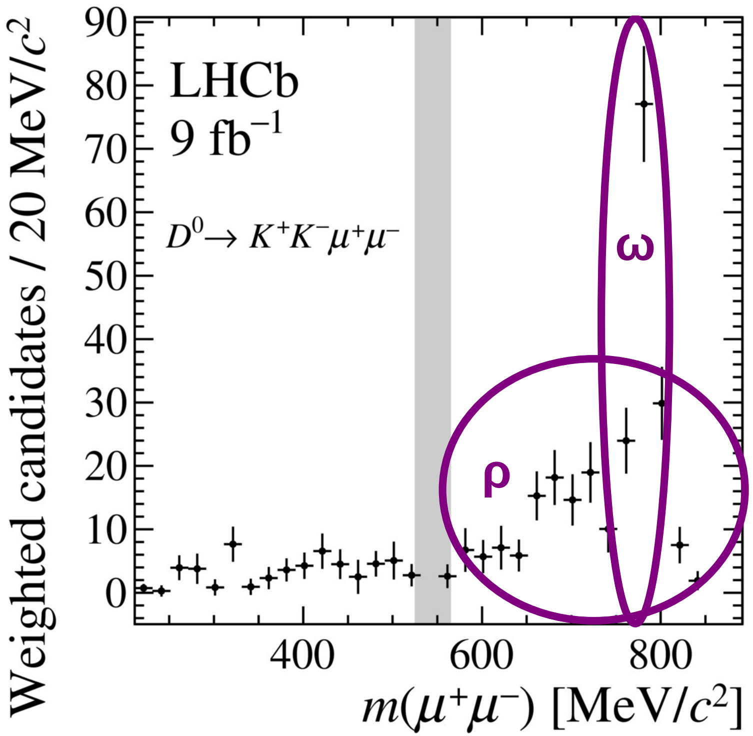
- NP can introduce contributions to semi-leptonic contact interactions, e.g.: $|V_{ub} V_{cb}^* C_{10}|<0.43$ @ 95% CL (from **$D^0 \to \mu^+\mu^-$** LHCb, 2212.11203)
  [similar bound from $pp \to \mu^+\mu^-$, Fuentes-M., Greljo, Camalich, Ruiz-A. '20]



- P-wave only: **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: $D^0 \to K^+K^-\mu^+\mu^-$





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

- 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**

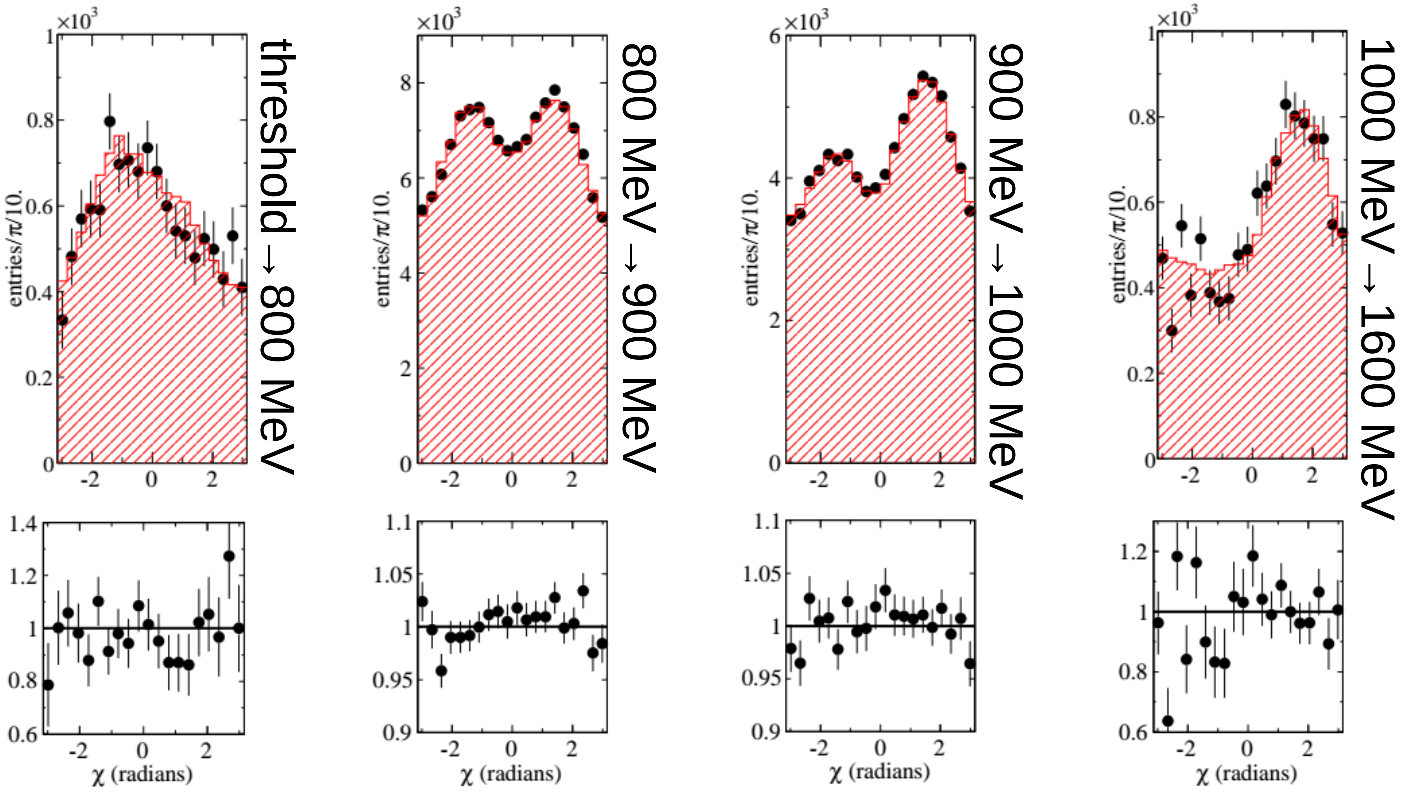
Outlook

- 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*

Thanks!

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

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 $K_0^*(800)$=κ and $K_0^*(1430)$

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

App 2

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]

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

P-wave unsuppressed

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

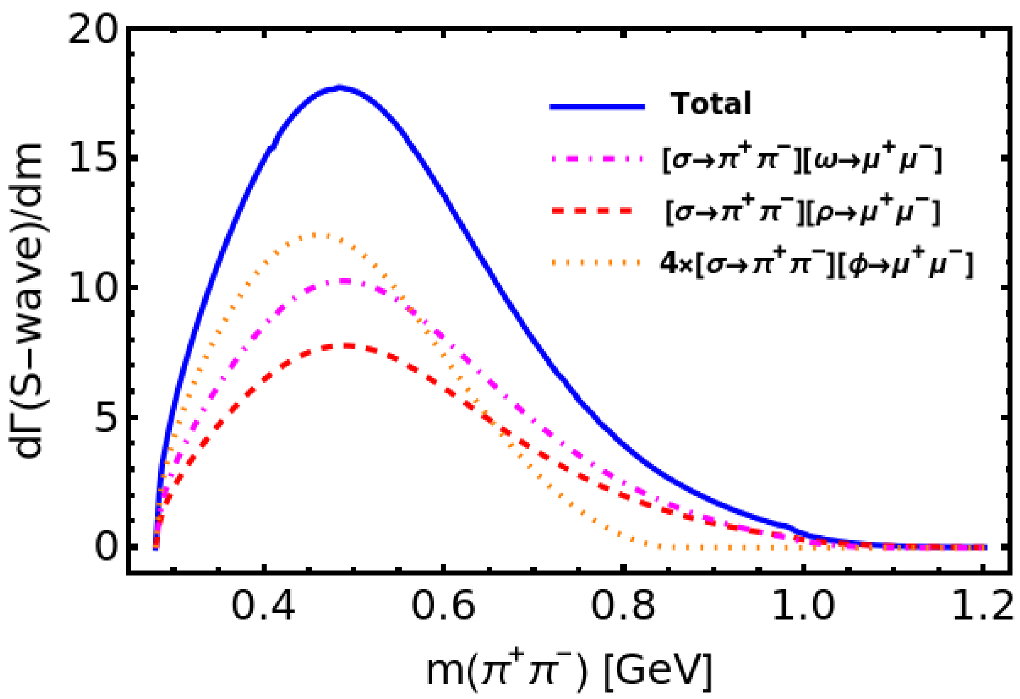
$$\langle I_2\rangle_+ = -\frac{1}{8}\Big[2|\mathcal{F}_S|^2\rho^-_{1,S} + \frac{2}{3}\{|\mathcal{F}_P|^2\rho^-_{1,P} - |\mathcal{F}_\parallel|^2\rho^-_{1,P} - |\mathcal{F}_\perp|^2\rho^+_{1,P}\}\Big] \xrightarrow{\mathrm{SM}} -\frac{1}{8}\Big\{2|\mathcal{F}_S|^2|C_9^{\mathrm{eff}:S}|^2 + \frac{2}{3}(|\mathcal{F}_P|^2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

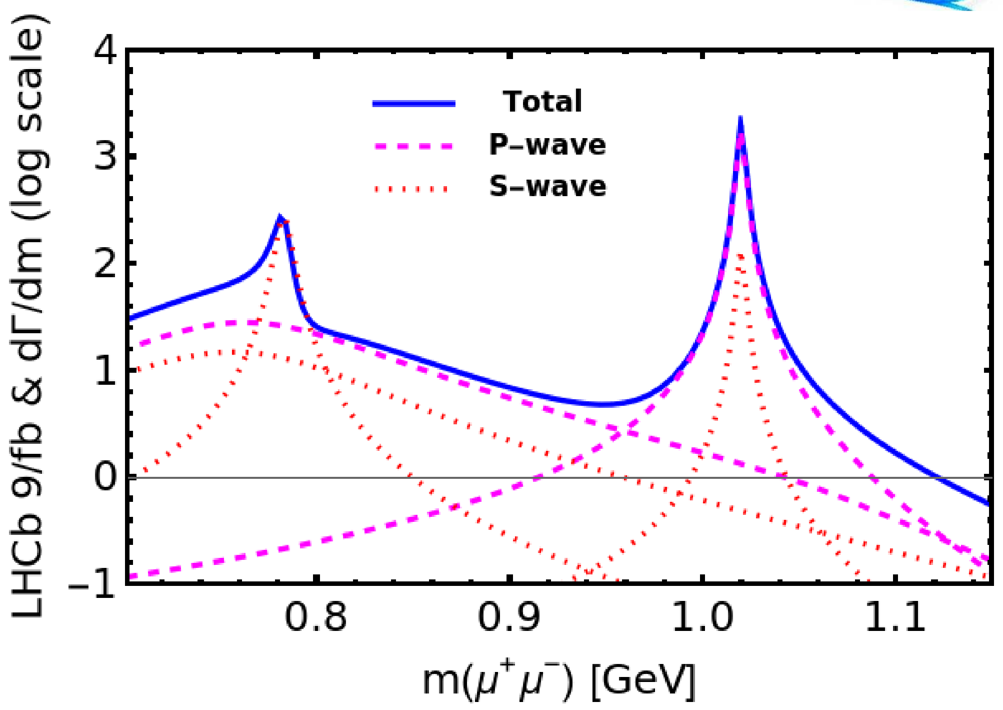
$$\langle I_3\rangle_+ = \frac{1}{6}[|\mathcal{F}_\perp|^2\rho^+_{1,P} - |\mathcal{F}_\parallel|^2\rho^-_{1,P}] \xrightarrow{\mathrm{SM}} \frac{1}{6}(|\mathcal{F}_\perp|^2 - |\mathcal{F}_\parallel|^2)|C_9^{\mathrm{eff}:P}|^2, \quad (66)$$

P-wave suppression!

LVS

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))