Theory implications from rare charm decays

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Rare charm decays

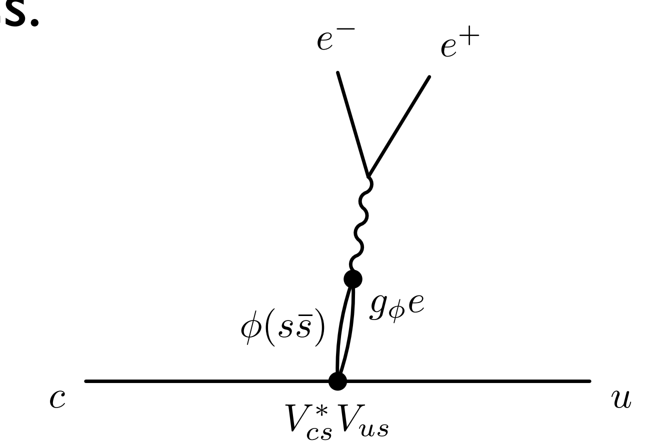
- Small and almost CP conserving short distance FCNCs due to effective GIM cancellation

$$m_d\,, m_s\,, m_b << M_W \qquad \text{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

- Sensitive to NP in up-quarks FCNC
- FCNCs in the up sector are few: D<u>D</u> mixing, rare charm decays, rare t decays

However ...

- GIM broken by nonperturbative effects. Resonances distinguish s and d quarks. Large long distance contributions obscure FCNCs.



Plan

- $c \to u\, \mu^+\mu^-$ probing SUSY-RPV, leptoquarks ... in
  - $D^+ \to \pi^+\mu^+\mu^-$
  - $D^0 \to \mu^+\mu^-$
- Direct CP Vs. Rare decay (in Im[C_7]).
  - $\Delta A_{\rm CP} \equiv A_{\rm CP}(D^0 \to K^+K^-) - A_{\rm CP}(D^0 \to \pi^+\pi^-)$
  - direct CP of on the Φ peak in $D^+ \to \pi^+\mu^+\mu^-$
  - large q^2 region of $D^+ \to \pi^+\mu^+\mu^-$
- Many other interesting decays, LFV, LNV, *not* covered here

$D^0 \to \mu^+e^-, \tau^+e^-$ $\quad D \to PP'\ell^+\ell^-$

$D \to P\mu^+e^-$ $\quad D_{(s)} \to V\ell^+\ell^-$

$D^+_{(s)} \to P^-\mu^+\mu^+$

Effective Hamiltonian for $D \to P\ell^+\ell^-$

$$\mathcal{H}_{\text{eff}} = \lambda_d \mathcal{H}^d + \lambda_s \mathcal{H}^s + \lambda_b \mathcal{H}^{\text{peng}}$$

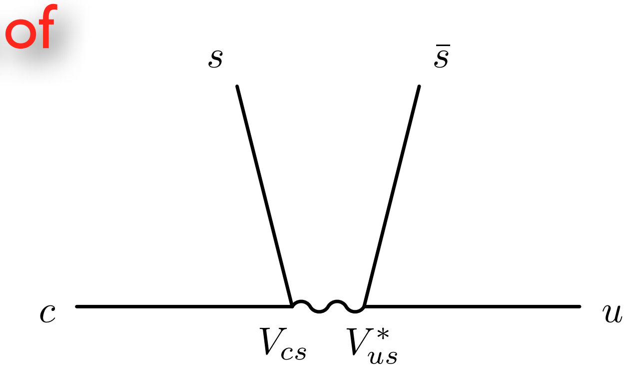
$$\mathcal{H}^{q=d,s} = -\frac{4G_F}{\sqrt{2}}(C_1\mathcal{O}_1^q + C_2\mathcal{O}_2^q)$$

nonlocal contributions of d and s quarks

$$\lambda_i = V_{ci}^* V_{ui}$$

$$\lambda_d \approx -\lambda_s \approx \lambda$$

Singly Cabibbo suppressed, real up to O(λ^5)



$$\mathcal{O}_1^q = (\bar{q}_L^\alpha \gamma^\mu c_L^\alpha)\,(\bar{u}_L^\beta \gamma_\mu q_L^\beta)$$

$$\mathcal{O}_2^q = (\bar{q}_L^\alpha \gamma^\mu c_L^\beta)\,(\bar{u}_L^\beta \gamma_\mu q_L^\alpha)$$

$$C_1^{\text{SM,tree}} = 1, C_2^{\text{SM,tree}} = 0$$

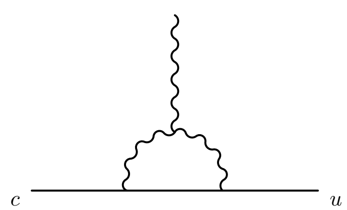
Effective Hamiltonian for $D \to P\ell^+\ell^-$

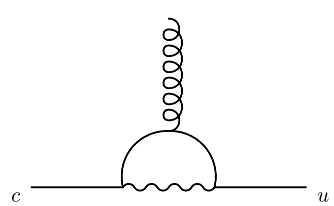
$$\mathcal{H}_{\rm eff} = \lambda_d \mathcal{H}^d + \lambda_s \mathcal{H}^s + \lambda_b \mathcal{H}^{\rm peng}$$

$$\mathcal{H}^{\rm peng} = -\frac{4G_F}{\sqrt{2}} \sum_{i=3,\ldots,10} C_i \mathcal{O}_i \,,$$

QCD penguins $\mathcal{O}_{3\ldots6}$

Magnetic penguins $\mathcal{O}_7, \mathcal{O}_8$

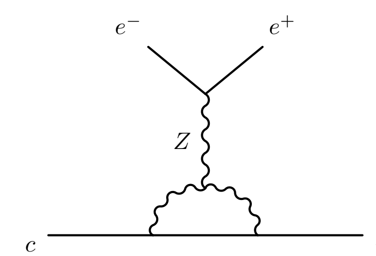




$\lambda_b \sim \lambda^5$ suppressed

$$\mathcal{O}_7 = \frac{em_c}{(4\pi)^2}\, \bar{u}\sigma_{\mu\nu}P_R c\, F^{\mu\nu}$$

EW penguins $\mathcal{O}_{9,10}$



$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}(\bar{u}\gamma^\mu P_L c)(\bar{\ell}\gamma_\mu \ell)\,,$$

$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}(\bar{u}\gamma^\mu P_L c)(\bar{\ell}\gamma_\mu \gamma_5 \ell)$$

Effective Hamiltonian for $D \to P\ell^+\ell^-$

- MSSM with R-parity

Burdman et al, 2002

$$C_{10}^{\tilde{g}} = -\frac{1}{9}\frac{\alpha_s}{\alpha}(\delta_{22}^u)_{LR}(\delta_{12}^u)_{LR}P_{032}(u) \quad = -\frac{C_9^{\tilde{g}}}{1-4\sin^2\theta_W}$$

$$C_7^{\tilde{g}} = -\frac{8}{9}\frac{\sqrt{2}}{G_F M_{\tilde{q}}^2}\pi\alpha_s\left\{(\delta_{12}^u)_{LL}\frac{P_{132}(u)}{4} + (\delta_{12}^u)_{LR}P_{122}(u)\frac{M_{\tilde{g}}}{m_c}\right\},$$

+chirally flipped operators

- MSSM without R-parity / leptoquarks, e.g. (3,2,7/6)

$$\delta C_9 = -\delta C_{10} = \frac{\sin^2\theta_W}{2\alpha^2}\left(\frac{M_W}{m_{\tilde{d}_R^k}}\right)^2 \tilde{\lambda}'_{i2k}\tilde{\lambda}'_{i1k}.$$

$$C'_S = -C'_P \sim \frac{y_{22}y_{12}^*}{m_S^2}$$

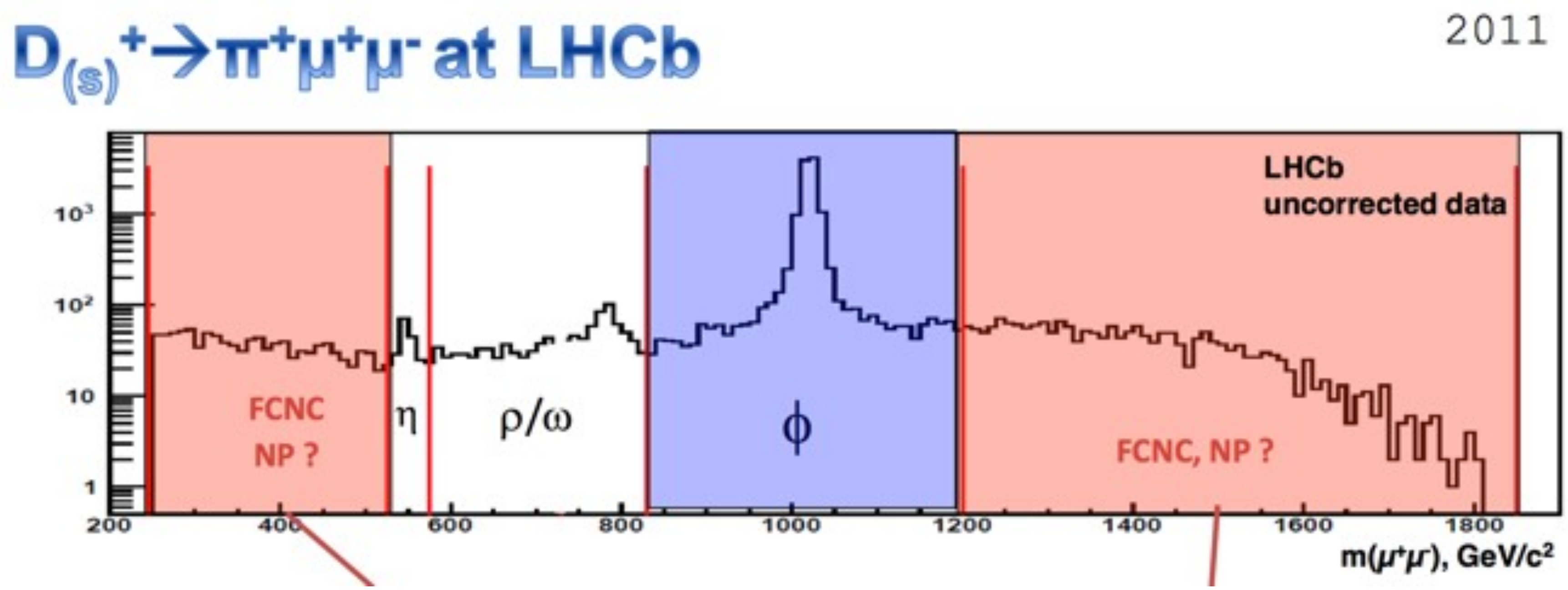
$D \to P\ell^+\ell^-$

$$\mathcal{A}_{\rm SD} = -i\frac{4\pi\alpha G_F}{\sqrt{2}}V_{cb}^*V_{ub}\left[\left(\frac{C_7}{2\pi^2}\frac{m_c}{m_D}+\frac{C_9}{16\pi^2}\right)\bar{u}(p_-)\not{p}v(p_+)+\frac{C_{10}}{16\pi^2}\bar{u}(p_-)\not{p}\gamma_5 v(p_+)\right]f_+(q^2)$$

LD amplitudes include t-channel vector resonances (Φ, ω, ρ)

q^2 spectrum

1 fb^{-1}
2011 data



O. Kochebina, EPS '13

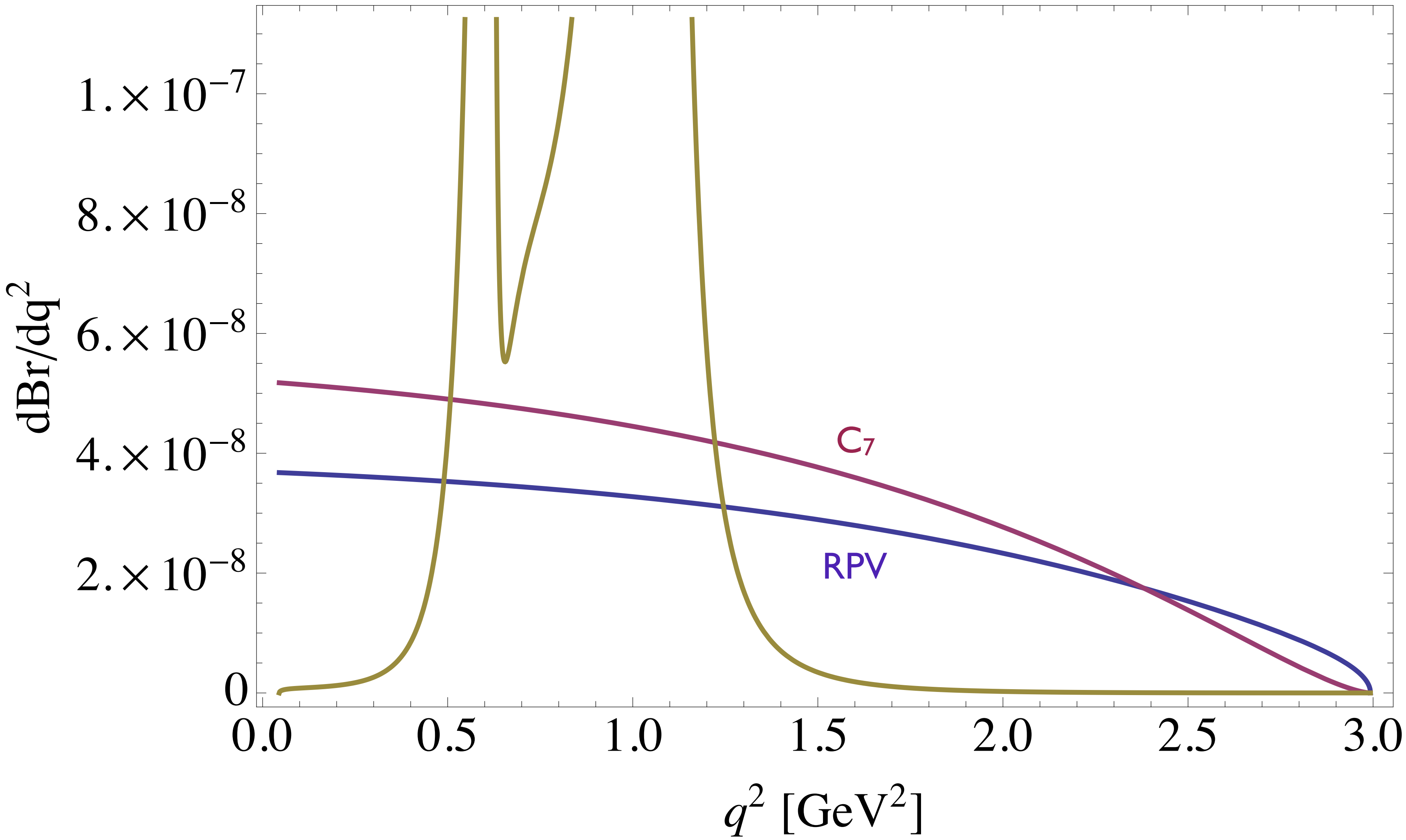
1) For the rate measurements, focus on low or high $m^2_{\mu\mu}$ (= q^2)

2) No reliable predictions for rate in the resonant region. Short distance effects are overwhelmed.

$D \to P\ell^+\ell^-$

Decay	Bin	90% [$\times 10^{-8}$]
$D^+ \to \pi^+\mu^+\mu^-$	low-$m(\mu^+\mu^-)$	2.0
	high-$m(\mu^+\mu^-)$	2.6
	Total	7.3

LHCb, Physics Letters B 724 (2013) 203



Constraints from the high-q^2 region:

$$|\lambda_b \delta C_{9,10}^{\mathrm{RPV}}| < 2.5$$

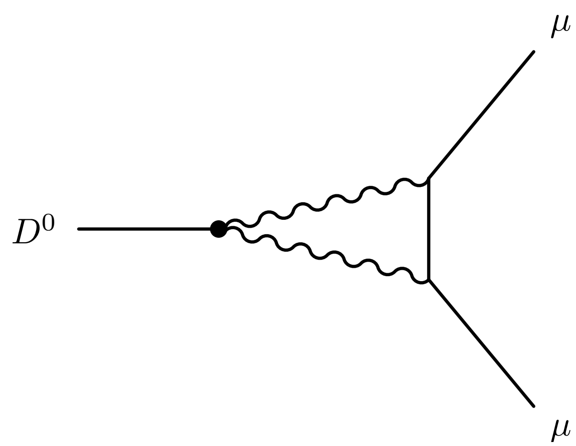
One order improvement in few years.

$$|\lambda_b \delta C_7| < 0.8$$

Close to what is required for direct CP in 2 body decays

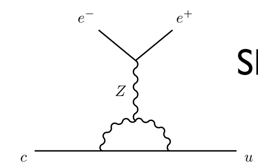
$D^0 \to \ell^+\ell^-$

Long distance effects in $D^0 \to \gamma\gamma$ dominate



$$\mathrm{Br}(D^0 \to \mu^+\mu^-) \simeq 2.7 \cdot 10^{-5} \times \mathrm{Br}(D^0 \to \gamma\gamma)$$

Burdman et al, 2002



SM short-distance contribution is negligible, GIM!

Combined with experimentally bounded γγ branching fraction, < 2.2 x 10^{-6} at 90% CL :

BaBar, 2012

$$\mathrm{Br}(D^0 \to \mu^+\mu^-)^{\mathrm{SM}} \lesssim 10^{-10}$$

Almost null test of the SM

$$\mathrm{Br}(D^0 \to \mu^+\mu^-)^{\mathrm{LHCb}} < 6.2 \times 10^{-9}$$

LHCb, Physics Letters B 725 (2013) 15

$D^0 \to \ell^+\ell^-$

Neglect SM contribution, insert a New physics (NP) candidate:

$$\mathrm{Br}_{\mathrm{th}}^{\mathrm{NP}}\left(D^0 \to \mu^+\mu^-\right) = \tau_D f_D^2 m_D^3 \frac{G_F^2\alpha^2}{64\pi^3}|V_{ub}V_{cb}^*|^2 \beta_\ell(m_D^2)\left[\frac{m_D^2}{m_c^2}\left|C_S - C_S'\right|^2\left(1-\frac{4m_\ell^2}{m_D^2}\right) + \left|\frac{m_D}{m_c}\left(C_P - C_P'\right) + 2\frac{m_\ell}{m_D}\left(C_{10}-C_{10}'\right)\right|^2\right]$$

$$\mathrm{Br}_{\mathrm{th}}^{\mathrm{NP}}(c_i, m_i, \ldots) < \mathrm{Br}^{\mathrm{exp}}$$

Three combinations enter

$$C_{10} - C_{10}', \quad C_S - C_S', \quad C_P - C_P'$$

Helicity suppression of axial lepton current operator, nevertheless better bound than from semileptonic decay

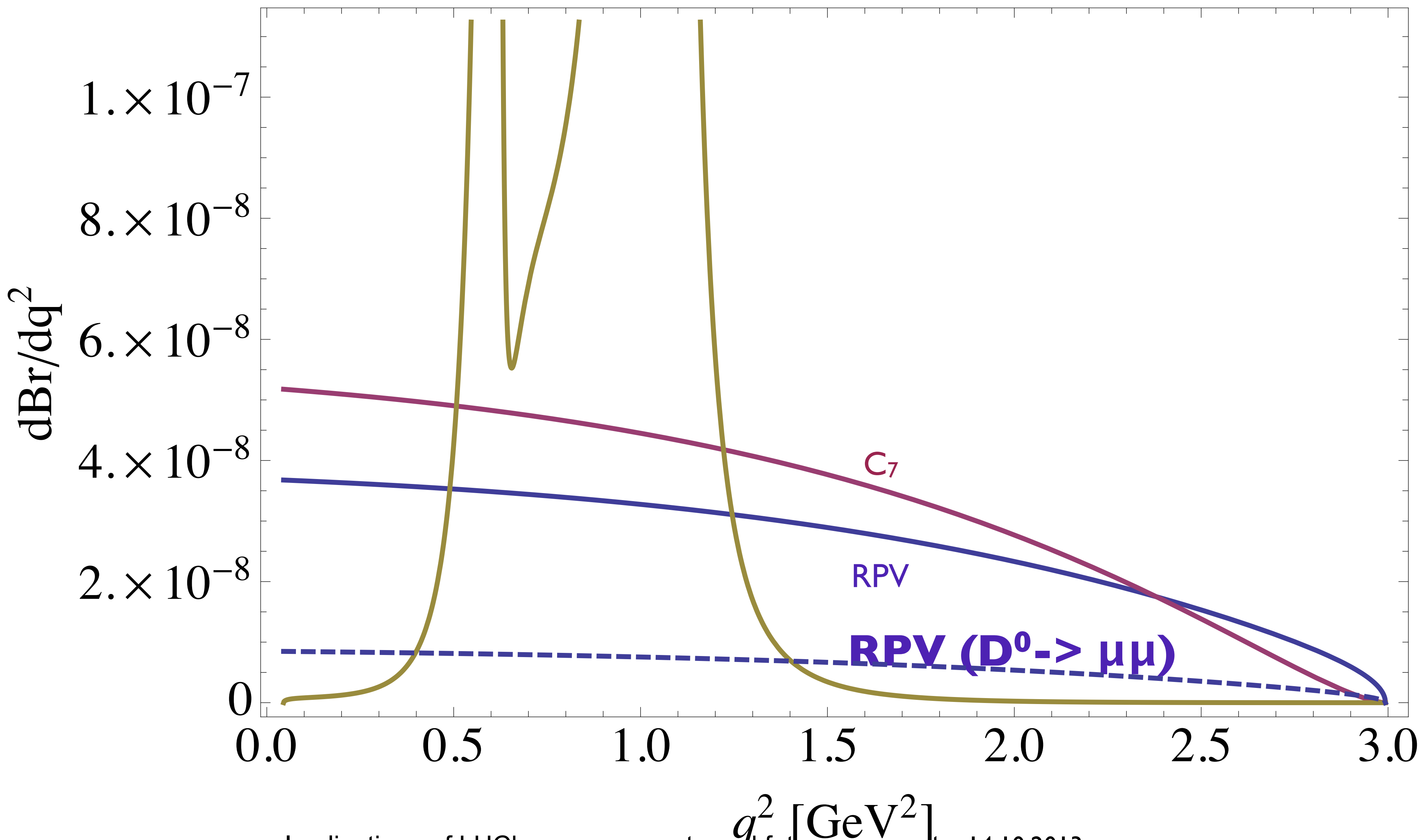
$$|\lambda_b \delta C_9^{\mathrm{RPV}}|, |\lambda_b \delta C_{10}^{\mathrm{RPV}}| < 1.2$$

$D^0 \to \ell^+\ell^-$

$|\lambda_b \delta C_9^{\mathrm{RPV}}|, |\lambda_b \delta C_{10}^{\mathrm{RPV}}| < 1.2$

Stronger than from semileptonic decay!

Repercussions for $D \to P\ell^+\ell^-$



$D^0 \to \ell^+ \ell^-$

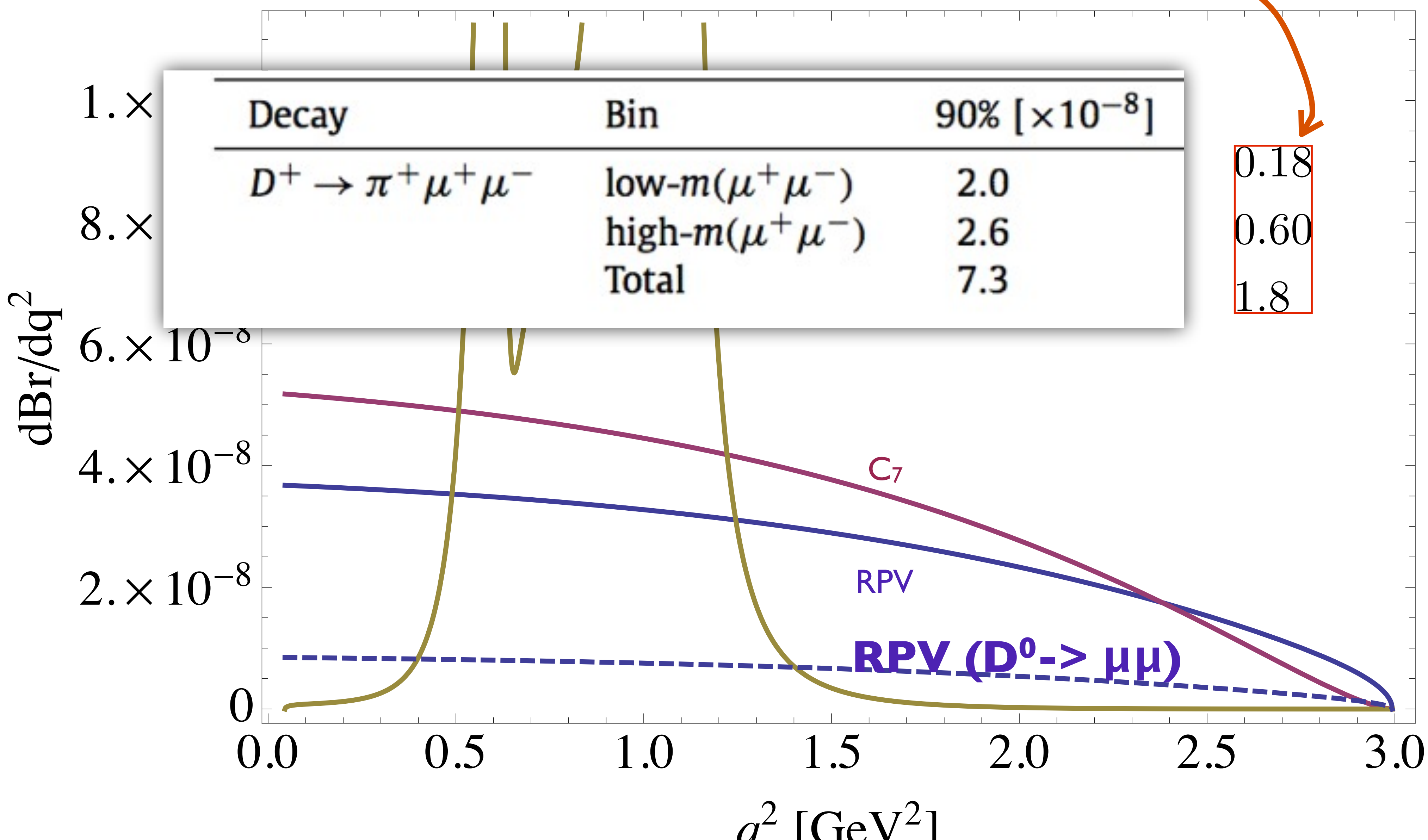
$|\lambda_b \delta C_9^{\rm RPV}|, |\lambda_b \delta C_{10}^{\rm RPV}| < 1.2$

Stronger than from semileptonic decay!

Repercussions for $D \to P \ell^+ \ell^-$

Decay	Bin	90% [$\times 10^{-8}$]
$D^+ \to \pi^+ \mu^+ \mu^-$	low-$m(\mu^+\mu^-)$	2.0
	high-$m(\mu^+\mu^-)$	2.6
	Total	7.3

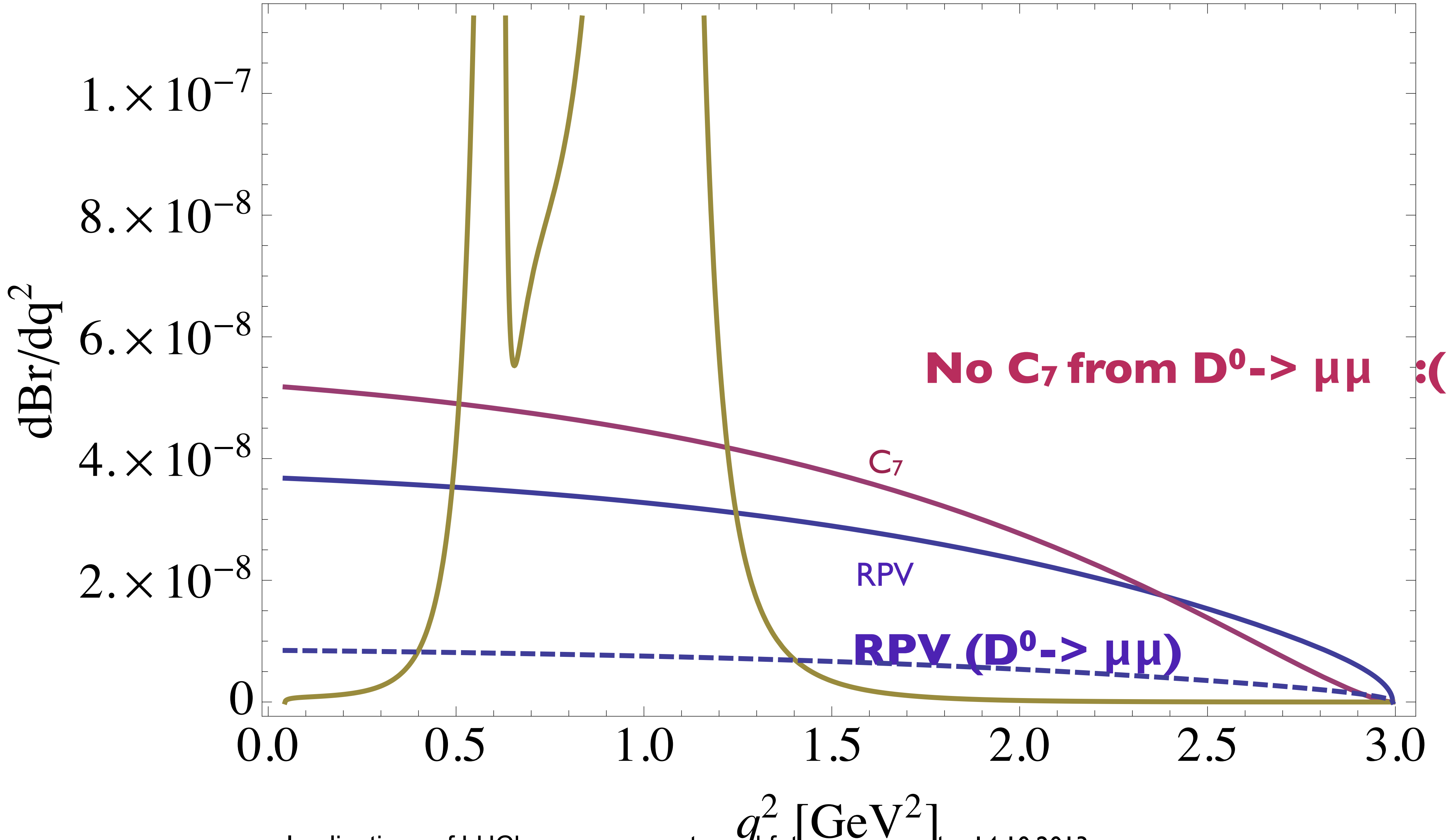
0.18
0.60
1.8



$D^0 \to \ell^+\ell^-$

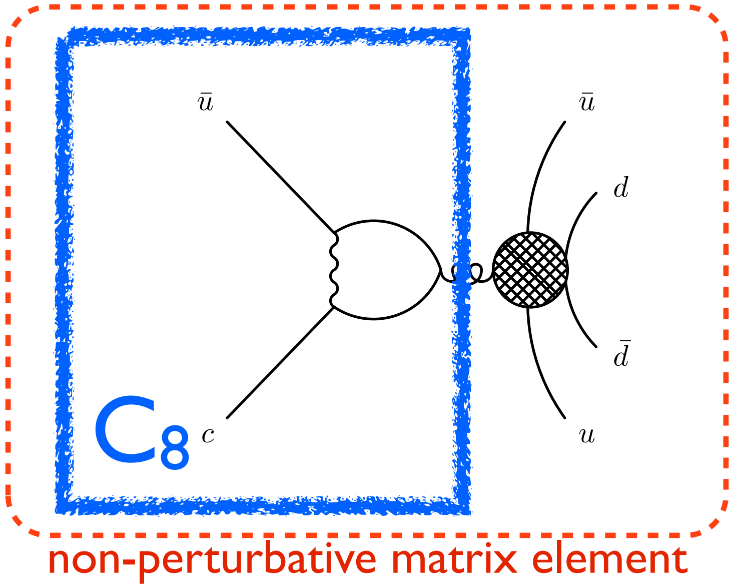
$|\lambda_b \delta C_9^{\mathrm{RPV}}|, |\lambda_b \delta C_{10}^{\mathrm{RPV}}| < 1.2$ Stronger than from semileptonic decay!

Going back to $D \to P\ell^+\ell^-$



Motivation for NP phase in C_7

- Natural explanation of CPV observed in $D \to \pi\pi$ and $D \to KK$ via non-standard phase in C_8



$$\Delta A_{\rm CP} \equiv A_{\rm CP}(D^0 \to K^+K^-) - A_{\rm CP}(D^0 \to \pi^+\pi^-)$$
$$= \begin{cases} (-0.34 \pm 0.15 \pm 0.10)\,\% & ; \quad \text{LHCb '13} \\ (-0.62 \pm 0.21 \pm 0.10)\,\% & ; \quad \text{CDF '12} \end{cases}$$

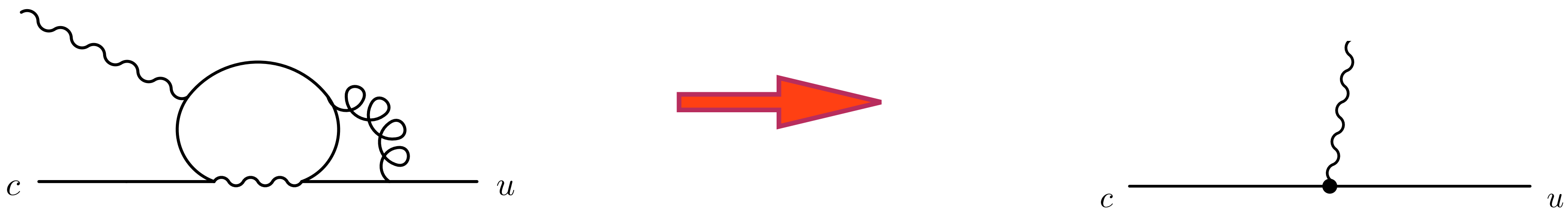
- Gluonic penguin (C_8) usually present together with photonic penguin (C_7) in concrete NP models (e.g. gluino loop in SUSY)

Isidori et al, '11
Giudice et al, '12

- Even if $C_7 = 0$ at high scale, QCD renormalization mixes C_8 into C_7

Motivation for NP phase in C_7

QCD renormalization



$$C_7(m_c) = \tilde{\eta}\,[\eta C_7(M) + 8(\eta - 1)C_8(M)]$$

Isidori, Kamenik '12

$$\eta = \left[\frac{\alpha_s(M)}{\alpha_s(m_t)}\right]^{2/21} \left[\frac{\alpha_s(m_t)}{\alpha_s(m_b)}\right]^{2/23} \left[\frac{\alpha_s(m_b)}{\alpha_s(m_c)}\right]^{2/25}$$

$$\tilde{\eta} = \left[\frac{\alpha_s(M)}{\alpha_s(m_t)}\right]^{14/21} \left[\frac{\alpha_s(m_t)}{\alpha_s(m_b)}\right]^{14/23} \left[\frac{\alpha_s(m_b)}{\alpha_s(m_c)}\right]^{14/25}$$

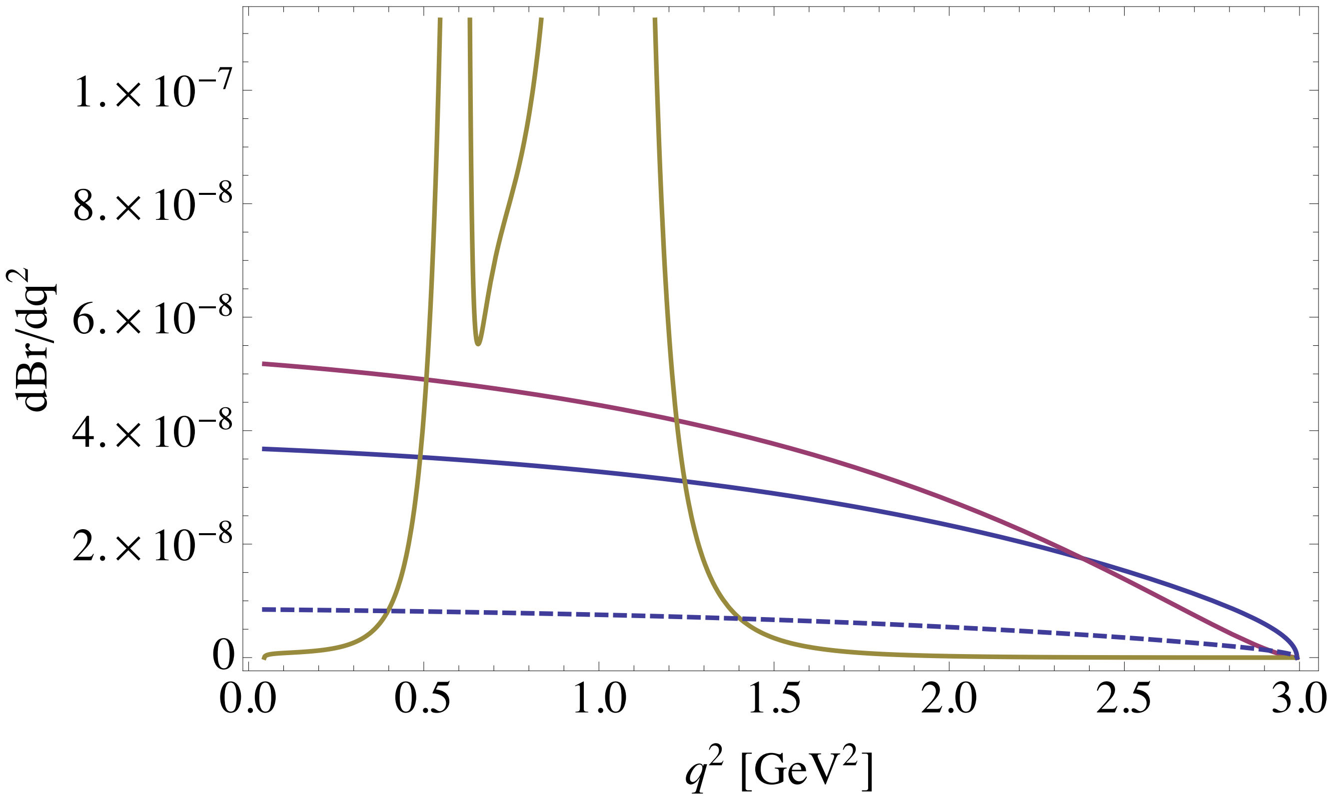
If C_7(1 TeV) $\ll$ C_8(1 TeV)

$$\mathrm{Im}[\lambda_b C_7(m_c)] \approx \mathrm{Im}[\lambda_b C_8(m_c)] \approx (0.2 - 0.8) \times 10^{-2}$$

ΔA_{CP}

Independently test CP phase in C_7 sensitive processes!

Test: direct CP on Φ resonance



$$|\mathcal{A}_{LD} + \mathcal{A}_{SD}|^2 \approx |\mathcal{A}_{LD}|^2 + 2\Re[\mathcal{A}_{LD}\mathcal{A}_{SD}^*]$$

$$a_{\mathrm{CP}} \sim \mathrm{Im}[\mathcal{A}_{SD}]/|\mathcal{A}_{LD}|$$

- Linear effect (interference)
- If the LD amplitude is CP even, measuring CPV is a null-test

Direct CP

$$\mathcal{A}(D^+ \to \pi^+\ell^+\ell^-) = \mathcal{A}^{\phi}_{\rm LD} + \mathcal{A}^{\rm CPV}_{\rm SD}\,,$$
$$\overline{\mathcal{A}}(D^- \to \pi^-\ell^+\ell^-) = \mathcal{A}^{\phi}_{\rm LD} + \overline{\mathcal{A}}^{\rm CPV}_{\rm SD}$$

$$a_{CP}(q^2) \equiv \frac{|\mathcal{A}|^2 - |\overline{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\overline{\mathcal{A}}|^2}$$
$$= \frac{-3}{2\pi^2}\frac{m_c}{m_D + m_\pi}\,\mathrm{Im}\left[\frac{\lambda_b}{\lambda_s}C_7\right]\frac{f_T(q^2)}{a_\phi}\left[\cos\delta_\phi - \frac{q^2 - m_\phi^2}{m_\phi\Gamma_\phi}\sin\delta_\phi\right]$$

Fajfer, NK, '12

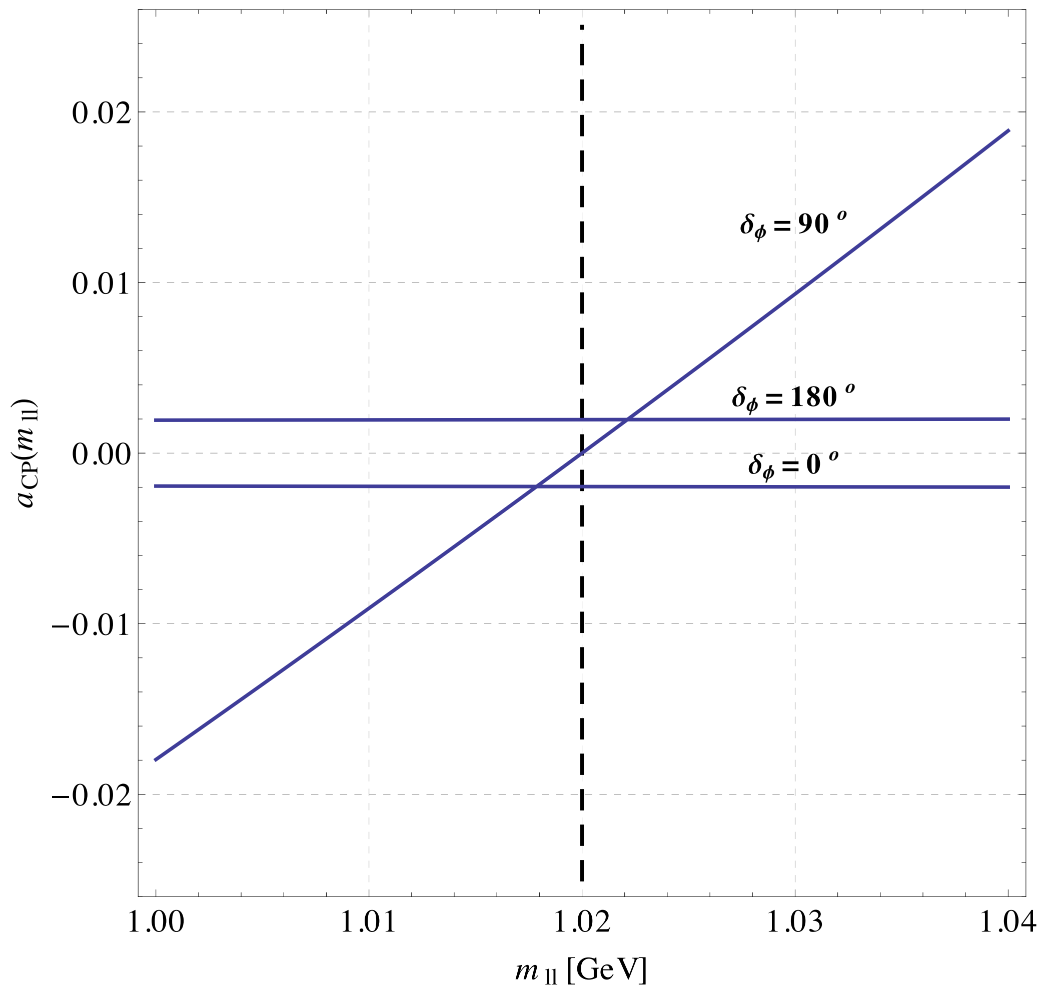
resonance and form factor dependence

$$\mathrm{Im}\left[\frac{\lambda_b}{\lambda_s}C_7\right] \approx \frac{\mathrm{Im}[\lambda_b C_7]}{\mathrm{Re}[\lambda_s]}$$

- Behaviour around the peak crucially depends on the value of δ_Φ

Direct CP

$$a_{CP}(q^2) = \frac{-3}{2\pi^2}\frac{m_c}{m_D + m_\pi}\mathrm{Im}\left[\frac{\lambda_b}{\lambda_s}C_7\right]\frac{f_T(q^2)}{a_\phi}\left[\cos\delta_\phi - \frac{q^2 - m_\phi^2}{m_\phi \Gamma_\phi}\sin\delta_\phi\right]$$



few %

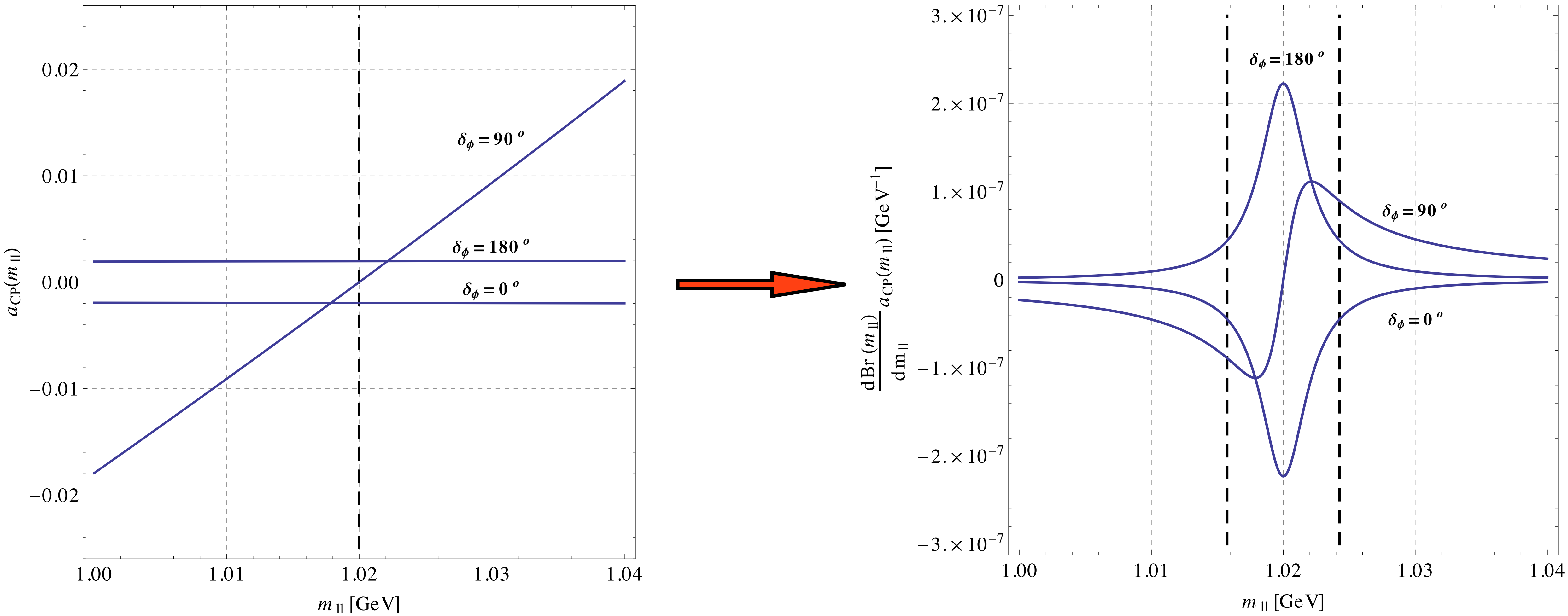
for $\mathrm{Im}[\lambda_b C_7] = 0.8 \times 10^{-2}$

(needed for ΔA_{CP})

- $a_{CP}(q^2)$ antisymmetric around Φ for $\delta_\Phi = \pm\pi/2$
- ‘‘ symmetric around Φ for $\delta_\Phi = 0,\pi$

Direct CP, sensitivity

- However, event decay rate is tiny



- Not very promising, constraint from decay rate at low/high q^2 will be more revealing

$$\mathrm{Im}[\lambda_b C_7] = 0.8 \times 10^{-2}$$

(needed for ΔA_{CP})

Vs

$$|\lambda_b \delta C_7| < 0.8$$

From semileptonic

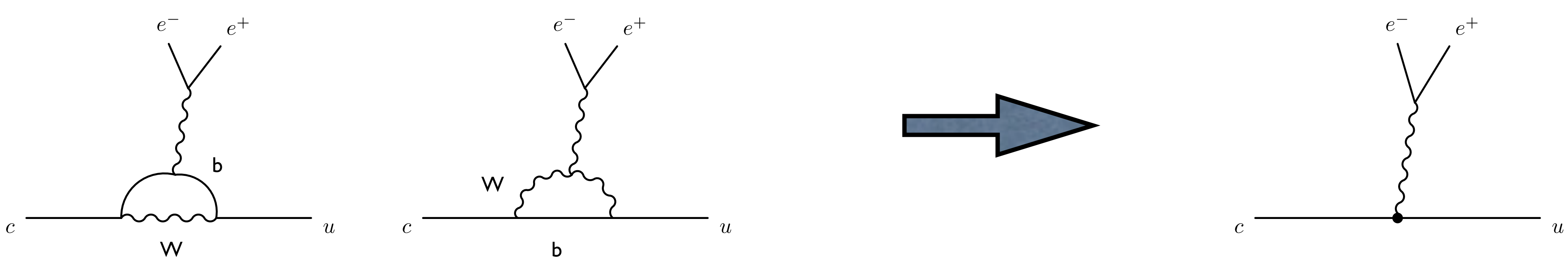
Summary and conclusion

- Semileptonic $D \to P\ell^+\ell^-$ offers windows into short-distance physics
- Leptonic decay $D^0 \to \ell^+\ell^-$ is Standard Model free (not for long)
  - Future: important interplay with $D^0 \to \gamma\gamma$
- Example I, we have constrainted RPV trilinear terms
  - Huge improvement in last few years, thanks to new experimental bounds
  - Leptonic decay slightly more powerful probe
- Example II, C_7 with CPV phase, required by ΔA_{CP}
  - Independent test: direct CP on the Φ resonance. Tiny.
  - Affects semileptonic decay, not leptonic. Constraint is 2 orders of magnitude short of testing ΔA_{CP}

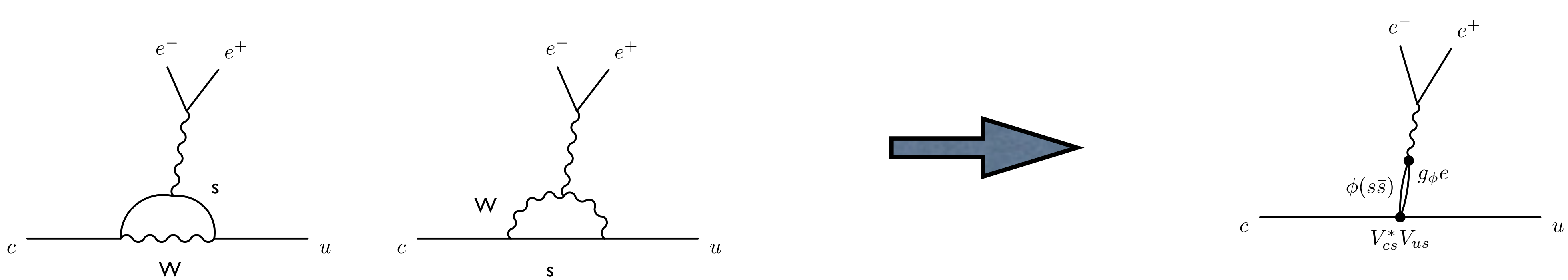
Backup

Definition (of short and long distance amplitudes)

SD amplitude := of local Hamiltonian (and nonlocal propagation of colorless particles)



LD contribution* := not SD



*limited to resonant in this talk

Pole model for Φ resonance

$$\mathcal{H}_{\rm eff} = \lambda_d \mathcal{H}^d + \lambda_s \mathcal{H}^s + \lambda_b \mathcal{H}^{\rm peng}$$

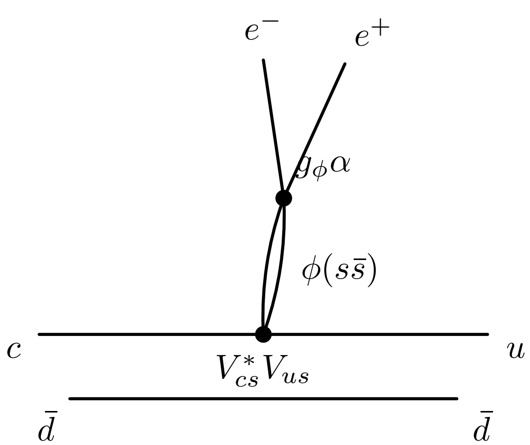
A^{Φ}_{LD} = $\langle \phi \pi^+ | -\frac{4G_F}{\sqrt{2}} \lambda_s (\bar{s}_L \gamma^\mu c_L)(\bar{u}_L \gamma_\mu s_L) | D^+ \rangle$

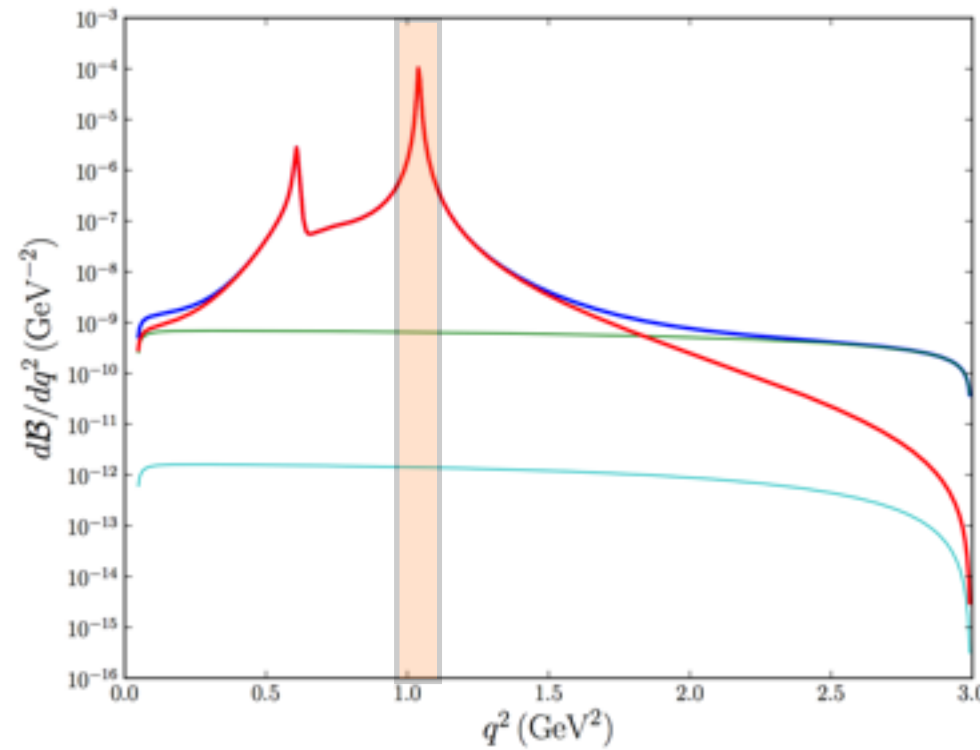
×

Breit-Wigner propagator

×

A(Φ→μμ)





Φ

$$\mathcal{A}^{\phi}_{\rm LD}\left[D \to \pi\phi \to \pi \ell^- \ell^+\right] = \frac{iG_F}{\sqrt{2}} \lambda_s \frac{8\pi\alpha}{3} a_\phi e^{i\delta_\phi} \frac{m_\phi \Gamma_\phi}{q^2 - m_\phi^2 + i m_\phi \Gamma_\phi} \bar{u}(k_-) \not{p}\, v(k_+)$$

Pole model for Φ resonance

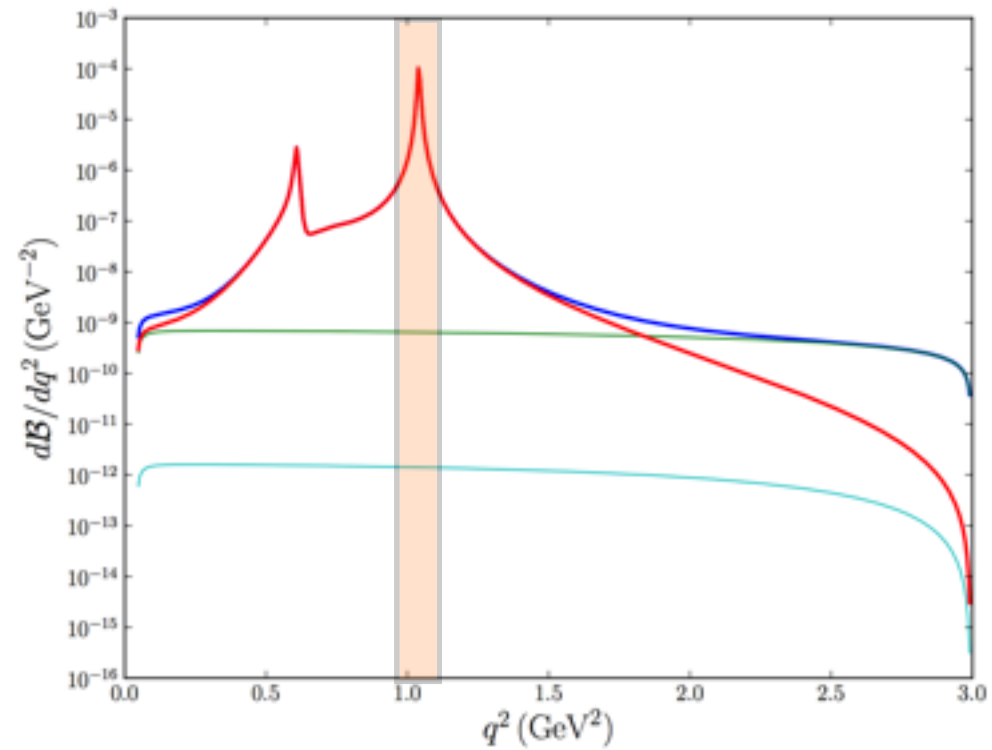
$$\mathcal{A}^{\phi}_{\rm LD}\left[D\to\pi\phi\to\pi\ell^-\ell^+\right] = \frac{iG_F}{\sqrt{2}}\lambda_s\frac{8\pi\alpha}{3}\,a_\phi e^{i\delta_\phi}\,\frac{m_\phi\Gamma_\phi}{q^2-m_\phi^2+im_\phi\Gamma_\phi}\,\bar{u}(k_-)\,\not{p}\,v(k_+)$$

a_ϕ, δ_ϕ real parameters

$$\mathrm{Br}(D^+\to\phi\pi^+) = (2.65\pm0.09)\times10^{-3}\,,$$
$$\mathrm{Br}(\phi\to\mu^+\mu^-) = (0.287\pm0.019)\times10^{-3}$$

$$a_\phi = 1.23\pm0.05$$

δ_ϕ = strong phase, smoothly varying



Φ

Caveat: We neglect CPV C_8 contributions to the LD amplitude. Perturbatively, they are loop suppressed w.r.t. to the C_7 contribution.

Short distance amplitude

- C_7, C_9, C_{10} (λ^4 suppressed w.r.t. LD in the SM)
- C_7 carries non-standard CP phase, C_9, C_{10} are SM-like

$$\mathcal{A}_{\rm SD}^{\rm CPV} = -\frac{i\sqrt{2}G_F\alpha}{\pi}\,\lambda_b C_7(m_c)\,\frac{m_c}{m_D+m_\pi}\,f_T(q^2)\,\bar{u}(k_-)\not{p}v(k_+)$$

tensor form factor

$$\tilde{f}_T(q^2) \equiv \frac{m_{D^*}}{m_D+m_\pi}\frac{f_{D^*}^V}{f_{D^*}^T(\mu)}\,f_T(q^2;\mu)$$

$$\langle\pi(p')|\bar{u}\sigma_{\mu\nu}c|D(p)\rangle = -i\left(p_\mu p'_\nu - p_\nu p'_\mu\right)\frac{2f_T(q^2)}{m_D+m_\pi}$$

$$\tilde{f}_T(q^2) = \frac{\tilde{f}_T(0)}{\left(1-\frac{q^2}{m_{D^*}^2}\right)\left(1-a_T\frac{q^2}{m_{D^*}^2}\right)}$$

$$\tilde{f}_T(0) = 0.56(5)\,, \qquad a_T = 0.18(16)$$

Abada et al 2001, Becirevic 2012

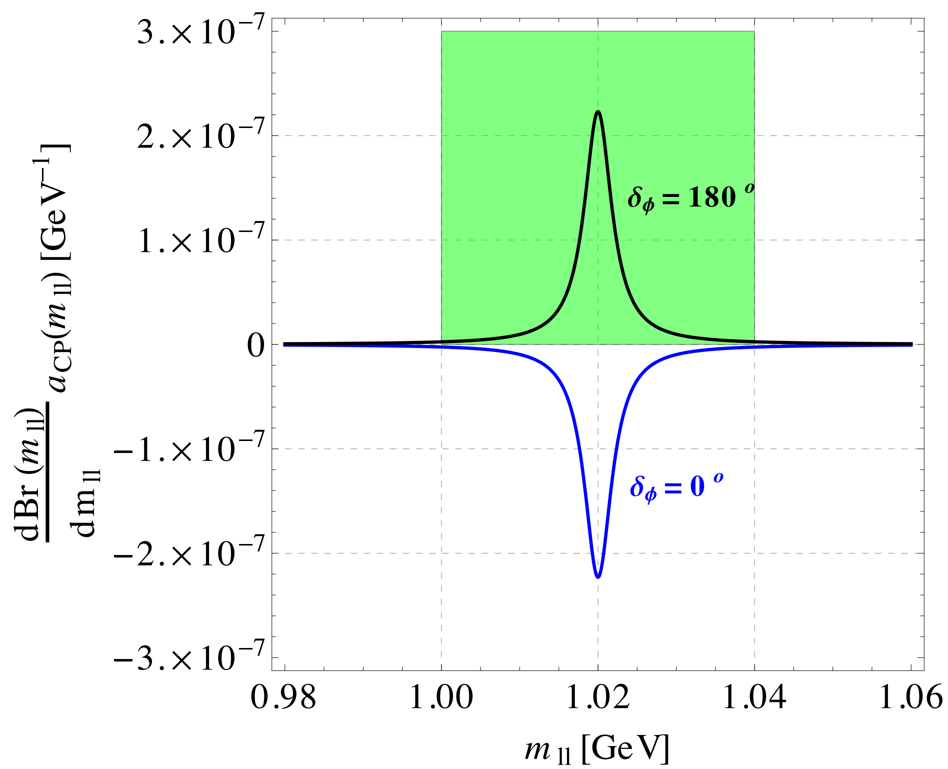
Quenched lattice calculation

Direct CP observables

- Partial width asymmetry

$$A_{\rm CP}(m_1,m_2) = \frac{\Gamma(m_1 < m_{\ell\ell} < m_2) - \bar{\Gamma}(m_1 < m_{\ell\ell} < m_2)}{\Gamma(m_1 < m_{\ell\ell} < m_2) + \bar{\Gamma}(m_1 < m_{\ell\ell} < m_2)}$$
$$= \frac{\int_{m_1^2}^{m_2^2} dq^2 R(q^2)\, a_{\rm CP}(\sqrt{q^2})}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 R(q^2)}$$

- Defined on a symmetric bin around m_ϕ (±20 MeV)

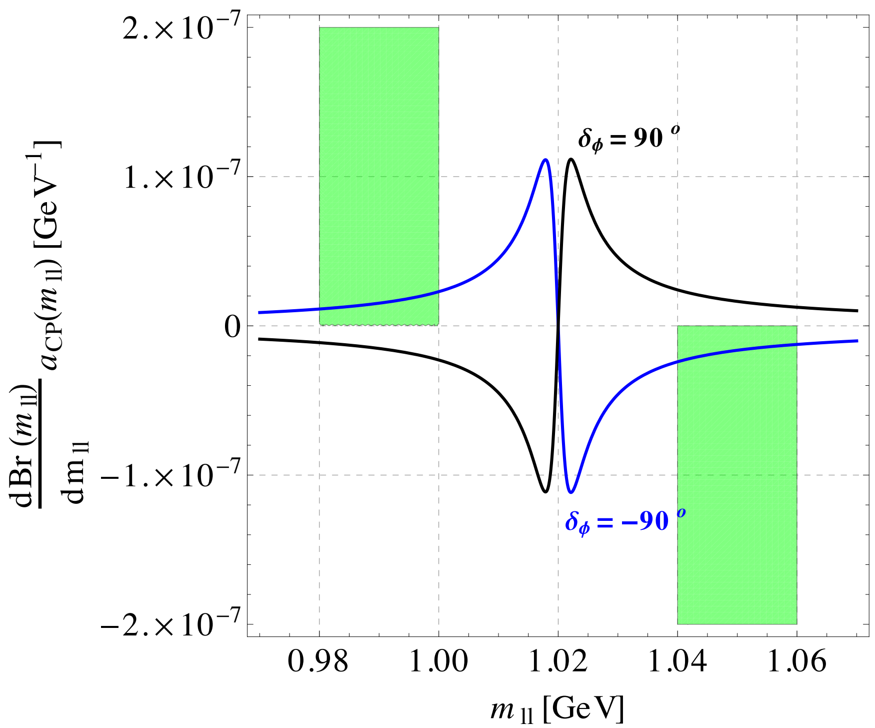


$$C^{\phi}_{\rm CP} \equiv A_{CP}(m_\phi - 20\,{\rm MeV}, m_\phi + 20\,{\rm MeV})$$

Sensitive to scenarios with $\delta_\phi \approx 0,\pi$

Direct CP observables

How to detect cases with $\delta_\phi \approx \pi/2, -\pi/2$?

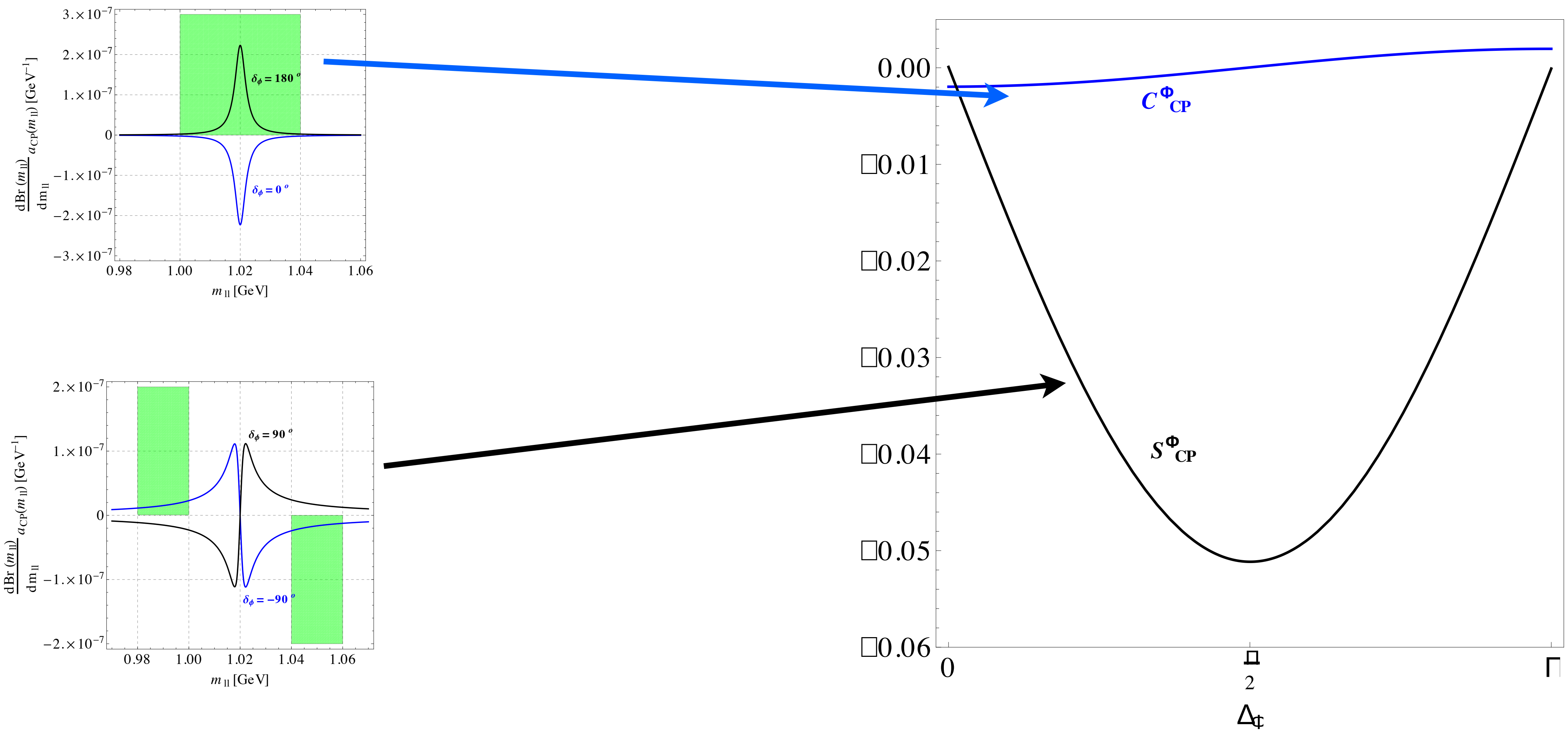


Difference of two asymmetries, above and below the peak

$$S_{CP}^{\phi} \equiv A_{CP}(m_\phi - 40\,\mathrm{MeV}, m_\phi - 20\,\mathrm{MeV}) - A_{CP}(m_\phi + 20\,\mathrm{MeV}, m_\phi + 40\,\mathrm{MeV})$$

Direct CP observables

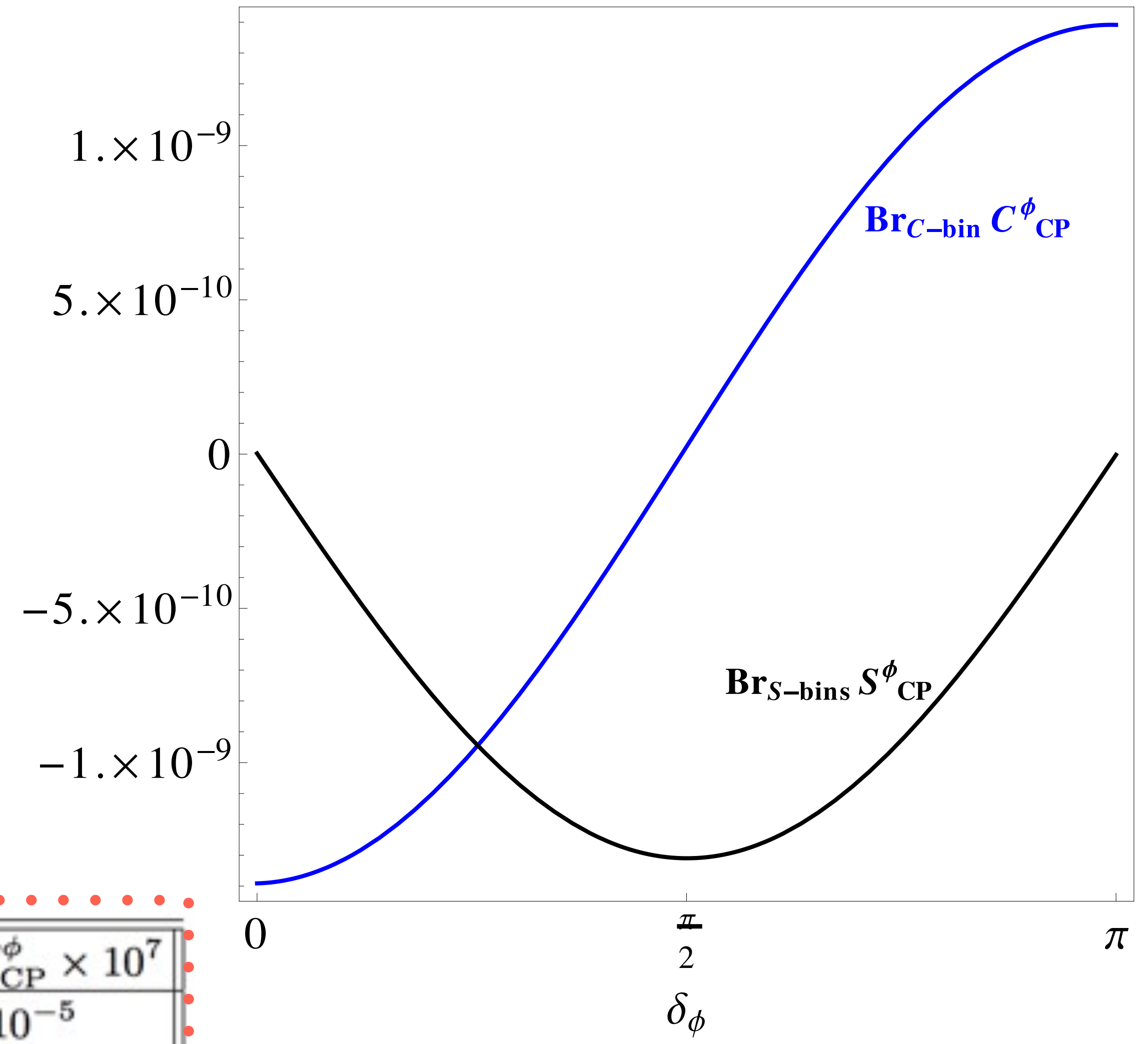
Scan over the strong phase



Sensitivity

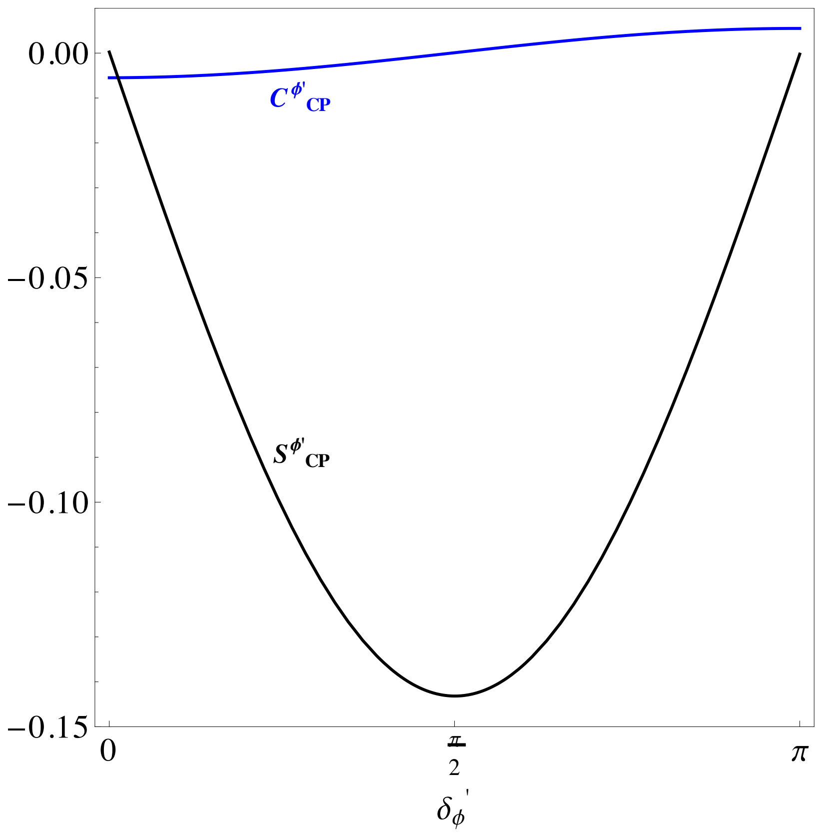
:= Branching ratio × CP asymmetry

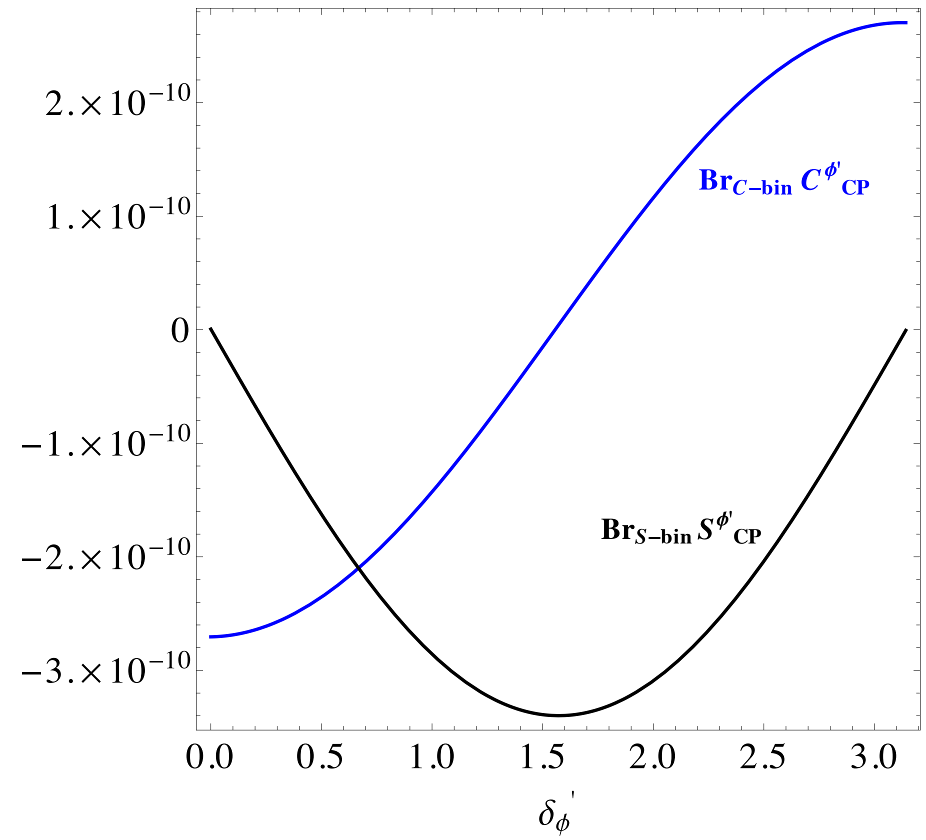
Even coverage over δ_ϕ.



δ_ϕ	$C^{\phi}_{\rm CP}\times10^2$	$S^{\phi}_{\rm CP}\times10^2$	Br(C-bin) $C^{\phi}_{\rm CP}\times10^7$	Br(S-bin) $S^{\phi}_{\rm CP}\times10^7$
$0,\pi$	∓0.20	±0.008	∓0.014	$\pm2\times10^{-5}$
$\pm\pi/2$	±0.003	∓5.1	$\pm2.4\times10^{-4}$	∓0.013

Sensitivity ($D_s \to K^+ \mu^+\mu^-$)





δ'_ϕ	$C^{\phi\prime}_{\rm CP} \times 10^2$	$S^{\phi\prime}_{\rm CP} \times 10^2$	Br(C-bin) $C^{\phi\prime}_{\rm CP} \times 10^7$	Br(S-bin) $S^{\phi\prime}_{\rm CP} \times 10^7$
$0,\pi$	∓ 0.55	± 0.024	∓ 0.0027	$\pm 1 \times 10^{-5}$
$\pm\pi/2$	± 0.008	∓ 14	$\pm 4 \times 10^{-5}$	∓ 0.007