

Rare Kaon and D-meson decays

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Roma, 8th October 2012

- Minimal Flavour violation
- Short distance dominated $K \rightarrow \pi \bar{\nu} \nu$
- $K_L \rightarrow \pi^0 e^+ e^-$, the related channels $K \rightarrow \pi \gamma \gamma$ and $K_S \rightarrow \pi^0 e^+ e^-$
- CP violation in $K \rightarrow \pi \pi \gamma$, $K \rightarrow \pi \pi e e$
- $D^0 \rightarrow h^+ h^- l^+ l^-$ ($h^+ h^- = \pi \pi, \pi K, K \pi, K K$)
- Conclusions

Cappiello, Cata, G.D., Gao

Cappiello, Cata, G.D.

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Flavour Problem

- the SM Yukawa structure

$$\mathcal{L}_{SM}^Y = \bar{Q} Y_D D H + \bar{Q} Y_U U H_c + \bar{L} Y_E E H + \text{h.c.}$$

FCNC

$$\mathcal{H}_{\Delta F=2}^{SM} \sim \frac{G_F^2 M_W^2}{16\pi^2} \left[\frac{(V_{td}^* m_t^2 V_{tb})^2}{v^4} (\bar{d}_L \gamma^\mu b_L)^2 + \frac{(V_{td}^* m_t^2 V_{ts})^2}{v^4} (\bar{d}_L \gamma^\mu s_L)^2 \right] + \text{charm}$$

- Supersymmetry must be broken

$$-\mathcal{L}_{soft} = \tilde{Q}^\dagger m_Q^2 \tilde{Q} + \tilde{L}^\dagger m_L^2 \tilde{L} + \tilde{U} a_u \tilde{Q} H_u + \dots$$

- $m_Q^2, m_L^2, a_u, \dots$ matrices in flavour space additional (to $Y_{u,d,l}$) non-trivial structures

Theory

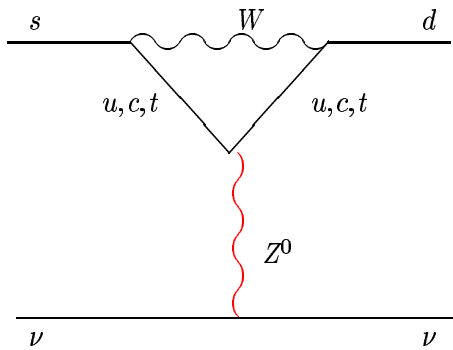
- There is a symmetry that New Physics must obey to satisfy FCNC -constraints

$$G_F = \overbrace{U(3)_Q \otimes U(3)_U \otimes U(3)_D \otimes U(3)_L \otimes U(3)_E}^{\text{global symmetry}} + \overbrace{Y_{U,D,E}}^{\text{spurions}}$$

- Technicolour Chivukula, Georgi
- susy Hall, Randall
- Gauge mediation Dine, Nelson, Shirman; Giudice, Rattazzi

$$K \rightarrow \pi \nu \bar{\nu}$$

$$A(s \rightarrow d \nu \bar{\nu})_{\text{SM}} \sim \bar{s}_L \gamma_\mu d_L \quad \bar{\nu}_L \gamma^\mu \nu_L \times \left[\sum_{q=c,t} V_{qs}^* V_{qd} m_q^2 \right]$$


 $\sim$

$$\left[A^2 \lambda^5 (1 - \rho - i\eta) m_t^2 + \lambda m_c^2 \right]$$

$$\text{SM: } \underbrace{V - A \otimes V - A}_{\Downarrow}$$

Littenberg

$$\Gamma(K_L \rightarrow \pi^0 \nu \bar{\nu}) \quad \left\{ \begin{array}{l} \text{CP violating} \\ \Rightarrow J = A^2 \lambda^6 \eta \\ \text{Only top} \end{array} \right.$$

$$K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

Brod,CKM2010, Straub, Gorbhan

$$B(K^+) \sim \kappa_+ \left[\left(\frac{\text{Im}\lambda_t}{\lambda^5} X_t \right)^2 + \left(\frac{\text{Re}\lambda_c}{\lambda} (P_c + \delta P_{c,u}) + \frac{\text{Re}\lambda_t}{\lambda^5} X_t \right)^2 \right]$$

- κ_+ from K_{l3}
- P_c : SD charm quark contribution (30%±2.5% to BR)
LD $\delta P_{c,u} \sim 4 \pm 2\%$
- $B(K^\pm) = (8.22 \pm 0.27 \pm 0.29) \times 10^{-11}$ first error parametric (V_{cb}),
second non-pert. QCD
- E949 $B(K^\pm) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$

$$K_L$$

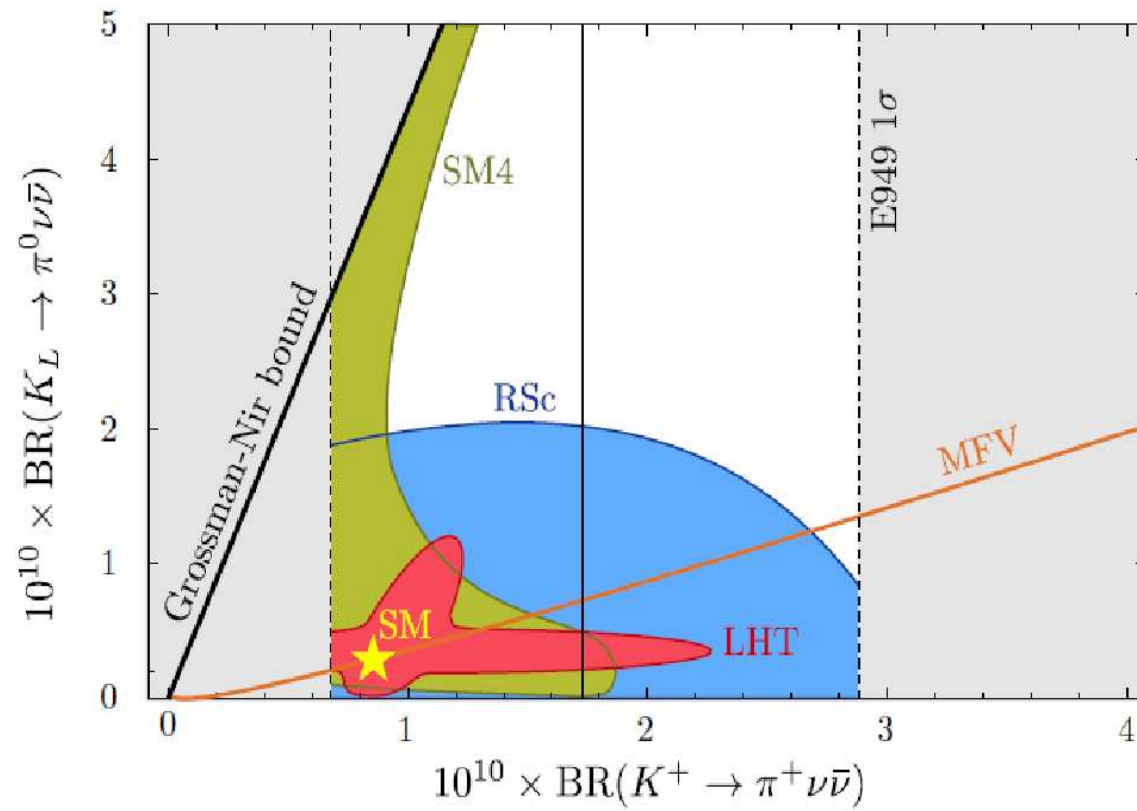
$$B(K_L) = (2.43 \pm 0.25 \pm 0.06) \times 10^{-11} \text{ vs}$$

$$\text{E391a } B(K_L) < 2.6 \times 10^{-8} \text{ at 90\% C.L.}$$

K_L Model-independent bound, based on $SU(2)$ properties dim-6 operators for $\bar{s}d\bar{\nu}\nu$ Grossman-Nir

$$B(K_L) \leq \frac{\tau_L}{\tau_+} \times B(K^\pm)_{\text{E949}} \leq 1.4 \times 10^{-9} \text{ at 90\% C.L.}$$

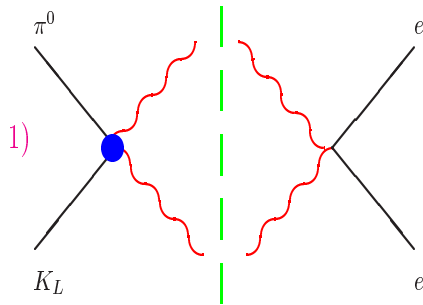
NA62 , KOTO, ORKA



Straub, CKM 2010 workshop (arXiv:1012.3893v2)

$K_L \rightarrow \pi^0 e^+ e^-$: summary

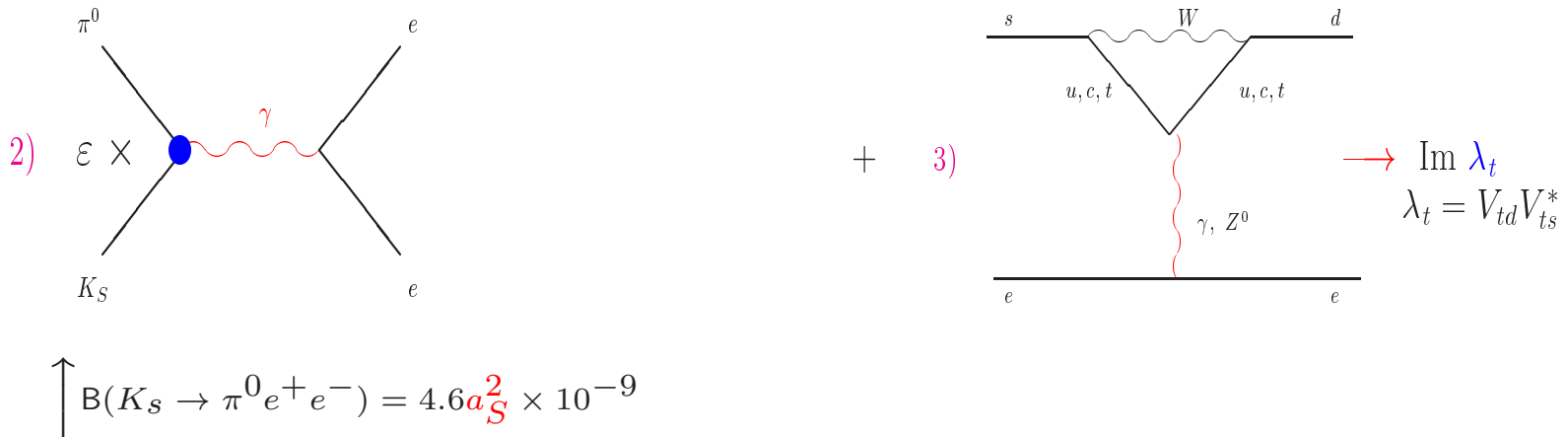
$$\text{Br}(K_L \rightarrow \pi^0 e^+ e^-) \leq 2.8 \cdot 10^{-10} \text{ at 90\% CL} \quad \text{KTeV}$$



CP conserving NA48

$$\text{Br}(K_L \rightarrow \pi^0 e^+ e^-) < 3 \cdot 10^{-12}$$

$$V-A \otimes V-A \Rightarrow \langle \pi^0 e^+ e^- | (\bar{s}d)_{V-A} (\bar{e}e)_{V-A} | K_L \rangle \text{ violates CP}$$

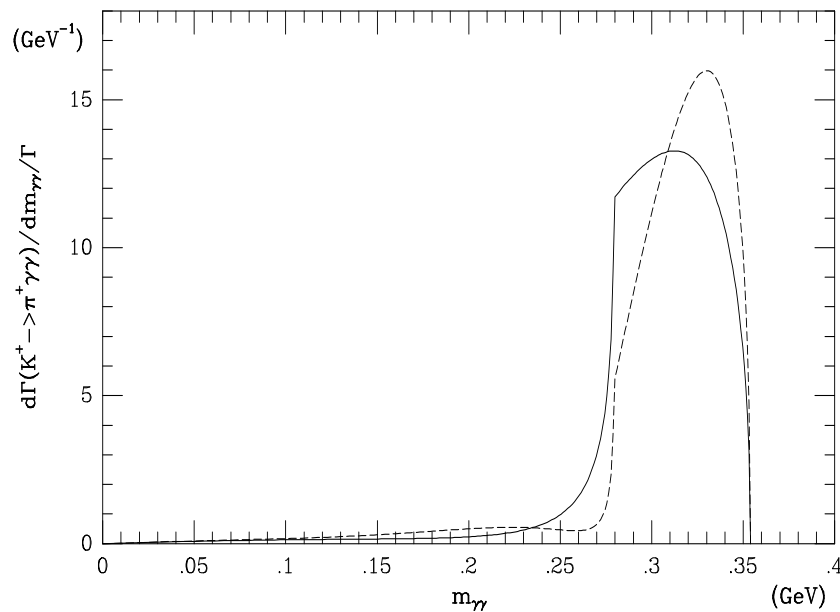


Possible large interference: $a_S < -0.5$ or $a_S > 1$; short distance probe even for a_S large

$$|2) + 3)|^2 = \left[15.3 a_S^2 - 6.8 \frac{\text{Im} \lambda_t}{10^{-4}} a_S + 2.8 \left(\frac{\text{Im} \lambda_t}{10^{-4}} \right)^2 \right] \cdot 10^{-12}$$

$$[17.7 \pm 9.5 + 4.7] \cdot 10^{-12}$$

$$K^+ \rightarrow \pi^+ \gamma \gamma$$



$$\begin{array}{c} \text{---} \hat{c} \\ \text{---} 0 \\ \text{---} -2.3 \end{array}$$

BNL 787 (96) got 31 events $\text{Br} \sim (6 \pm 1.6) \cdot 10^{-7}$ $\hat{c} = 1.8 \pm 0.6$

NA48/2 - NA62 preliminary $B = (1.01 \pm 0.07) \cdot 10^{-6}$ and $\hat{c} = 2.00 \pm 0.3$

$$K(p_K) \rightarrow \pi(p_1)\pi(p_2)\gamma(q)$$

- Lorentz + gauge invariance $\Rightarrow$ Electric (E) and Magnetic (M) amplitude

$$A(K \rightarrow \pi\pi\gamma) = F^{\mu\nu} [E \partial_\mu K \partial_\nu \pi + M \varepsilon_{\mu\nu\rho\sigma} \partial^\rho K \partial^\sigma \pi]$$

- Unpolarized photons

$$\frac{d^2\Gamma}{dz_1 dz_2} \sim |E|^2 + |M|^2$$

$$|E^2| = |E_{IB}|^2 + 2\text{Re}(E_{IB}^* E_D) + |E_D|^2$$

$\downarrow$

$$\text{Low Theorem} \Rightarrow E_{IB} \sim \frac{1}{E_\gamma^*} + \text{c} \quad E_D, M \text{ chiral}$$

tests

We need **FIGHT** $DE/IB \sim 10^{-3}$

	IB	DE_{exp}	
$K_S \rightarrow \pi^+ \pi^- \gamma$	10^{-3}	$< 9 \cdot 10^{-5}$	$E1$
$K^+ \rightarrow \pi^+ \pi^0 \gamma$	10^{-4} $(\Delta I = \frac{3}{2})$	$(0.44 \pm 0.07) 10^{-5}$ PDG	$M1, E1$
$K_L \rightarrow \pi^+ \pi^- \gamma$	10^{-5} (CPV)	$(2.92 \pm 0.07) 10^{-5}$ KTeVnew	$M1,$ VMD

CPV is **only** from IB K_L (also measured in $K_L \rightarrow \pi^+ \pi^- e^+ e^-$)

BUT IB suppressed in K^+ and K_L .

$$K^+ \rightarrow \pi^+ \pi^0 \gamma$$

$$A(K \rightarrow \pi \pi \gamma) = F^{\mu\nu} [E \partial_\mu K \partial_\nu \pi + M \varepsilon_{\mu\nu\rho\sigma} \partial^\rho K \partial^\sigma \pi]$$

$E1$ and $M1$ are measured with Dalitz plot

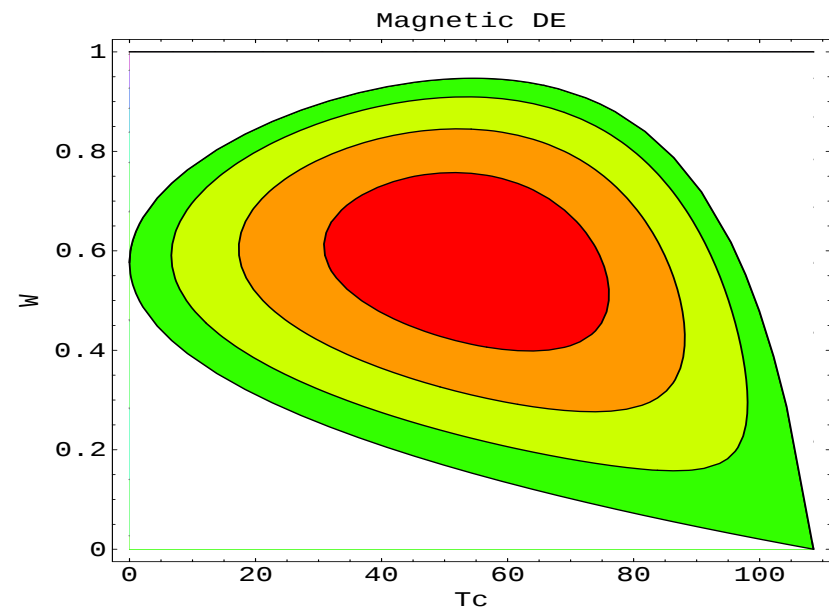
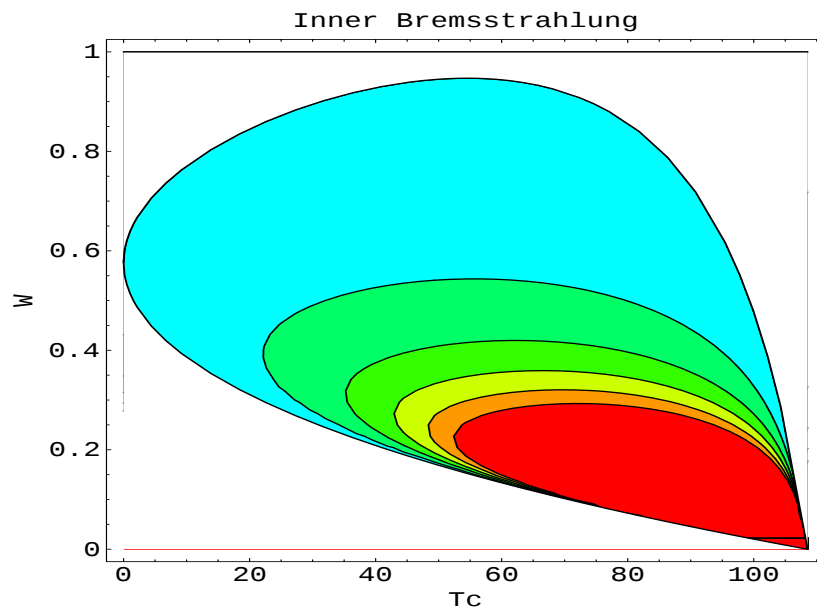
$$\begin{aligned} \frac{\partial^2 \Gamma}{\partial T_c^* \partial W^2} &= \frac{\partial^2 \Gamma_{IB}}{\partial T_c^* \partial W^2} \left[1 + \frac{m_{\pi^+}^2}{m_K^2} 2 \operatorname{Re} \left(\frac{E1}{eA} \right) W^2 \right. \\ &\quad \left. + \frac{m_{\pi^+}^4}{m_K^2} \left(\left| \frac{E1}{eA} \right|^2 + \left| \frac{M1}{eA} \right|^2 \right) W^4 \right] \end{aligned}$$

$$W^2 = (q \cdot p_K)(q \cdot p_+) / (m_\pi^2 m_K^2)$$

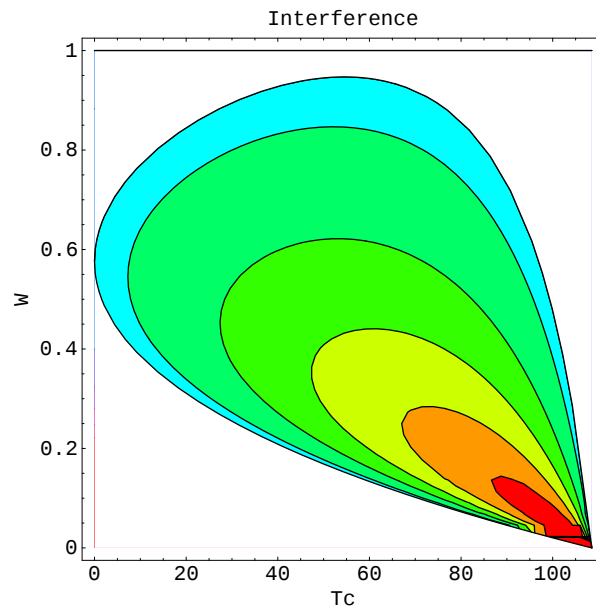
$$A = A(K^+ \rightarrow \pi^+ \pi^0)$$

$K^+ \rightarrow \pi^+ \pi^0 \gamma$ $W - T_c$ Dalitz plot

Integrating over T_c deviations from IB measured



CP asymmetry $K^+ \rightarrow \pi^+ \pi^0 \gamma$



Dalitz plot analysis crucial

$$\text{SM} \leq \mathcal{O}(10^{-5})$$

Paver et al.

$$\text{NP} \leq \mathcal{O}(10^{-4})$$

Colangelo et al.

$$\text{NA48/2} \quad < 1.5 \cdot 10^{-3} \quad \text{at} \quad 90\% \quad \text{CL}$$

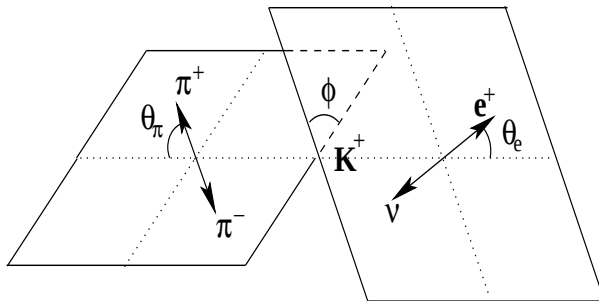
BUT NOT in the interesting interf. kin. region (statistics)

K_{l4} and $\pi\pi$ strong phases $\delta_I^l(s)$

Cabibbo Maksymowicz

$$\frac{G_F}{\sqrt{2}} V_{us} \bar{e} \gamma^\mu (1 - \gamma^5) \nu H_\mu(p_1, p_2, q)$$

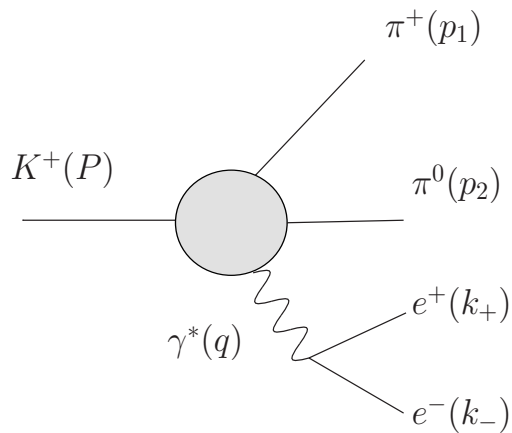
$$H^\mu = F_1 p_1^\mu + F_2 p_2^\mu + F_3 \varepsilon^{\mu\nu\alpha\beta} p_{1\nu} p_{2\alpha} q_\beta. \quad F_i(s) = f_i(s) e^{i\delta_0^0(s)} + ..$$



- crucial to measure $\sin \delta \implies$ interf F_3
- Look angular plane asymmetry

$$K_L \rightarrow \pi^+ \pi^- \gamma^* \rightarrow \pi^+ \pi^- e^+ e^-$$

Sehgal et al; Savage, Wise et al



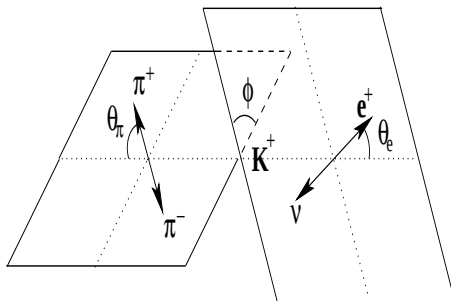
- $\mathcal{M}_{LD} = \frac{e}{q^2} \bar{e} \gamma^\mu (1 - \gamma^5) e H_\mu$
- $H^\mu = F_1 p_1^\mu + F_2 p_2^\mu + \mathbf{F}_3 \varepsilon^{\mu\nu\alpha\beta} p_{1\nu} p_{2\alpha} q_\beta$
- $F_{1,2} \sim \mathbf{E} \quad F_3 \sim \mathbf{M}$

- Interference $\mathbf{E} \quad \mathbf{M}$ novel compared to $K_L \rightarrow \pi^+ \pi^- \gamma$
- $\mathbf{E} \quad \mathbf{M}$ known from $K_L \rightarrow \pi^+ \pi^- \gamma$ (IB and DE)

$$K_L \rightarrow \pi^+ \pi^- \gamma^* \rightarrow \pi^+ \pi^- e^+ e^-$$

$$\begin{aligned} \frac{d^5\Gamma}{dE_\gamma^* dT_c^* dq^2 d\cos\theta_\ell d\phi} = & \mathcal{A}_1 + \mathcal{A}_2 \sin^2 \theta_\ell + \mathcal{A}_3 \sin^2 \theta_\ell \cos^2 \phi \\ & + \mathcal{A}_4 \sin 2\theta_\ell \cos \phi + \mathcal{A}_5 \sin \theta_\ell \cos \phi + \mathcal{A}_6 \cos \theta_\ell \\ & + \mathcal{A}_7 \sin \theta_\ell \sin \phi + \mathcal{A}_8 \sin 2\theta_\ell \sin \phi + \mathcal{A}_9 \sin^2 \theta_\ell \sin 2\phi \end{aligned}$$

- $\mathcal{A}_{8,9}$, odd in θ_ℓ *B-M interf.*



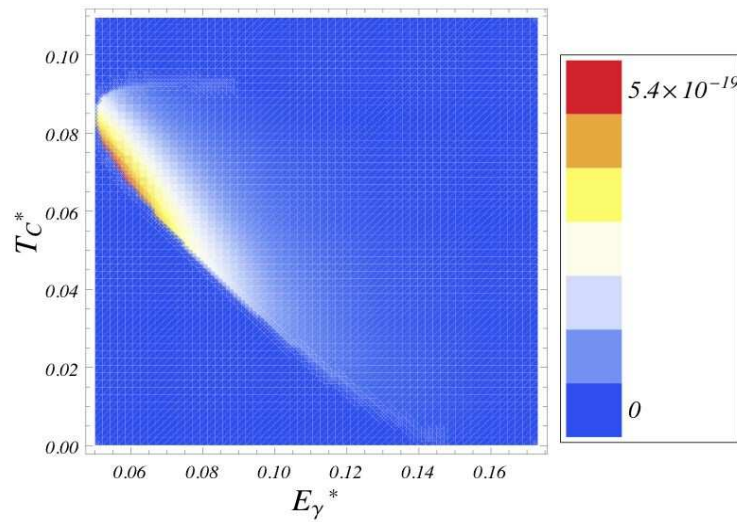
- $\frac{\Re(E_B M^*)}{|E_B|^2 + |M|^2}$ is maximal,
- $\mathcal{A}_{5,6,7}$ interf. axial leptonic current

$$K^+ \rightarrow \pi^+ \pi^0 \gamma^* \rightarrow \pi^+ \pi^0 e^+ e^-$$

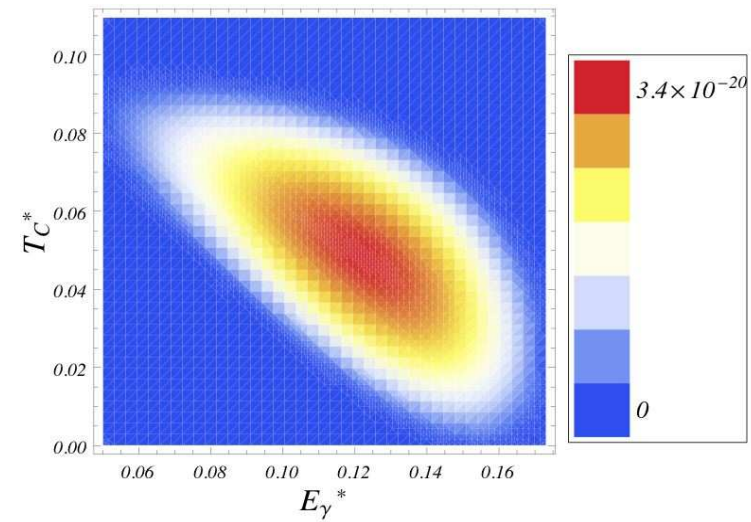
Cappiello, Cata, G.D. and Gao,

- the asymm. , $\frac{\Re(E_B M^*)}{|E_B|^2 + |M|^2}$, not as lucky $E_B \gg M$:
- $B(K^+)_{IB} \sim 3.3 \times 10^{-6} \sim 50 B(K^+)_{DE}$
- Short distance info without having simultaneously K^+ and K^- , asymm. in phase space, (P-violation) interesting! No ϵ -contamination
- interesting Dalitz plots (at fixed q^2) to disentangle M from E_B
- at $q^2 = 50\text{MeV}$ IB only 10 times larger than DE

q_c (MeV)	B [10^{-8}]	B/M	B/E	B/BE	B/BM
$2m_l$	418.27	71	4405	128	208
55	5.62	12	118	38	44
100	0.67	8	30	71	36
180	0.003	12	5	-19	44



IB



DE

How to extract SD from $K^+ \rightarrow \pi^+ \pi^0 e^+ e^-$

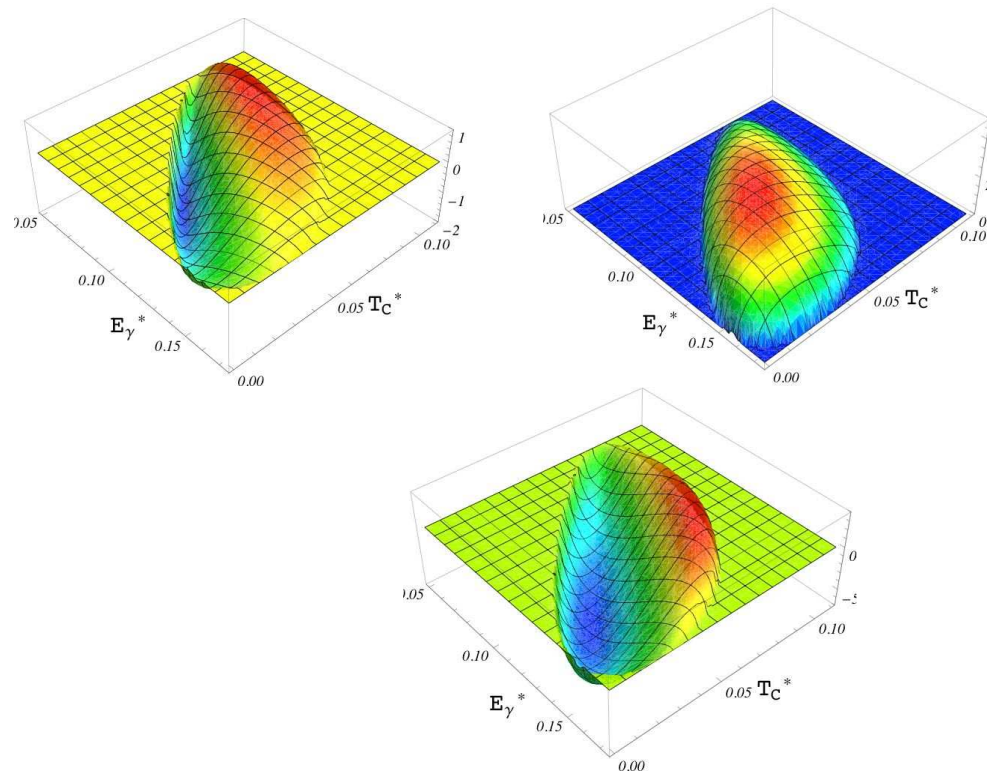
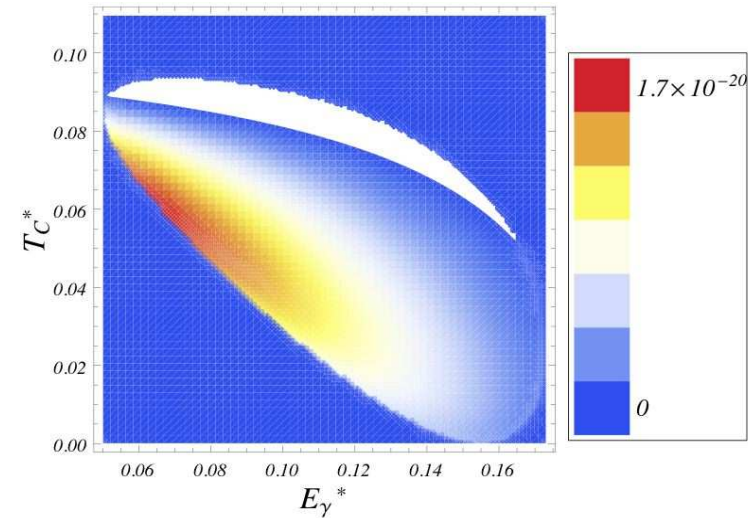
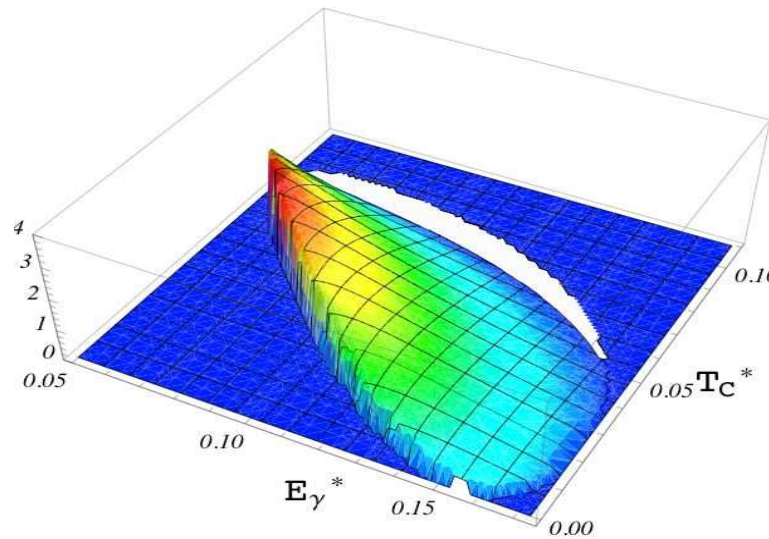


Figure 1: Dalitz plot for the contributions to $A_P^{(S)}$ (in arbitrary units) at $q^2 = (50 \text{ MeV})^2$.

Novel CP violation contributions (compared to $A_{CP}(K^+ \rightarrow \pi^+\pi^0\gamma)$)

$$A_{CP} = \frac{\Gamma(K^+ \rightarrow \pi^+\pi^0 e^+ e^-) - \Gamma(K^- \rightarrow \pi^-\pi^0 e^+ e^-)}{\Gamma(K^+ \rightarrow \pi^+\pi^0 e^+ e^-) + \Gamma(K^- \rightarrow \pi^-\pi^0 e^+ e^-)}$$



Rare B-decays: NP searches

$$\mathcal{H}_{\text{eff}} = -\frac{4 G_F}{\sqrt{2}} V_{tb} V_{tq}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C'_i O''_i) + \text{h.c.} ,$$

$$O_7^{(\prime)} = \frac{m_b}{e} (\bar{q} \sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}, \quad O_8^{(\prime)} = \frac{g m_b}{e^2} (\bar{q} \sigma_{\mu\nu} T^a P_{R(L)} b) G^{\mu\nu a},$$

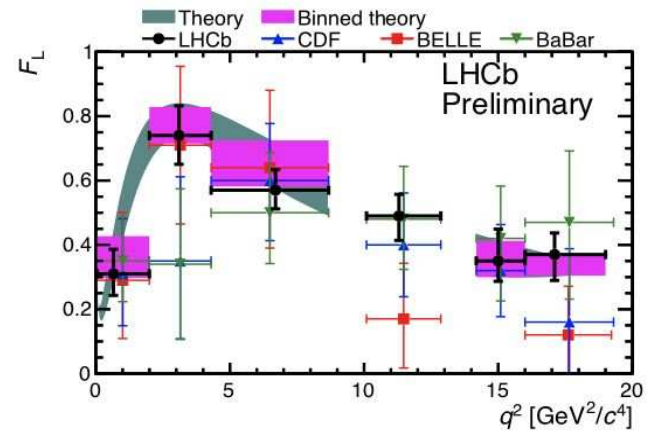
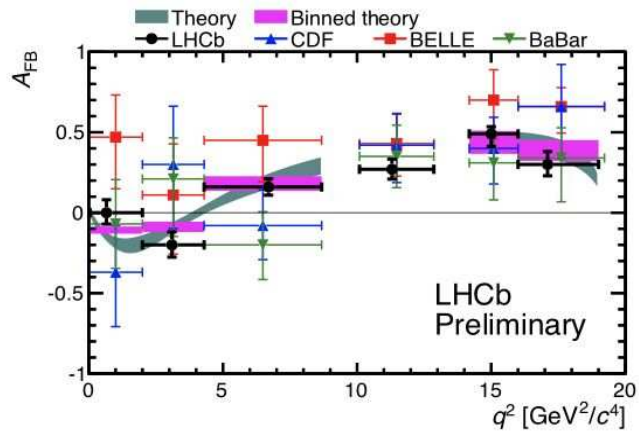
$$O_9^{(\prime)} = (\bar{q} \gamma_\mu P_{L(R)} b) (\bar{\ell} \gamma^\mu \ell), \quad O_{10}^{(\prime)} = (\bar{q} \gamma_\mu P_{L(R)} b) (\bar{\ell} \gamma^\mu \gamma_5 \ell),$$

$$O_S^{(\prime)} = \frac{m_b}{m_{B_q}} (\bar{q} P_{R(L)} b) (\bar{\ell} \ell), \quad O_P^{(\prime)} = \frac{m_b}{m_{B_q}} (\bar{q} P_{R(L)} b) (\bar{\ell} \gamma_5 \ell),$$

$B \rightarrow K^* \mu \mu$: K^* long. polar. and A_{FB}

$$\frac{d\Gamma'}{d\theta_K} = \frac{3\Gamma'}{4} \sin \theta_K \left[2F_L \cos^2 \theta_K + (1 - F_L) \sin^2 \theta_K \right]$$

$$\frac{d\Gamma'}{d\theta_\ell} = \Gamma' \left(\frac{3}{4} F_L \sin^2 \theta_\ell + \frac{3}{8} (1 - F_L) (1 + \cos^2 \theta_\ell) + A_{FB} \cos \theta_\ell \right) \sin \theta_\ell$$



CP violation in D-decays

$$a_{CP} \equiv \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow f)}$$

$$\Delta a_{CP} \equiv a_{CP}^{KK} - a_{CP}^{\pi\pi}$$

$$\Delta a_{CP} = (-0.68 \pm 0.15)\%$$

4.3 σ 's from 0 (SM)

SM explanation still possible

NP Operators

Isidori, J.F.K, Ligeti Perez

Franco, Mishima, Silvestrini

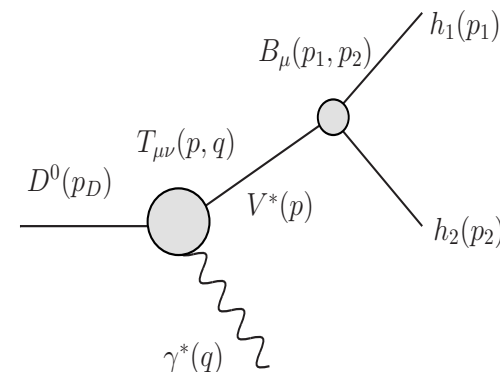
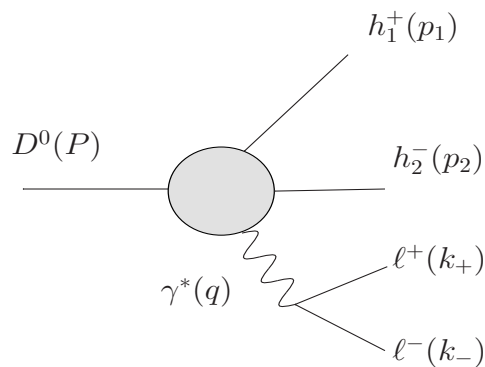
Alternative channels $D \rightarrow X\gamma$, $D \rightarrow Xe^+e^-$, $D \rightarrow V\gamma$

Delaunay et al, Isidori Kamenik

$$D^0 \rightarrow h^+ h^- l^+ l^- \quad (h^+ h^- = \pi\pi, \pi K, K\pi, KK)$$

Cappiello, Cata, G.D.

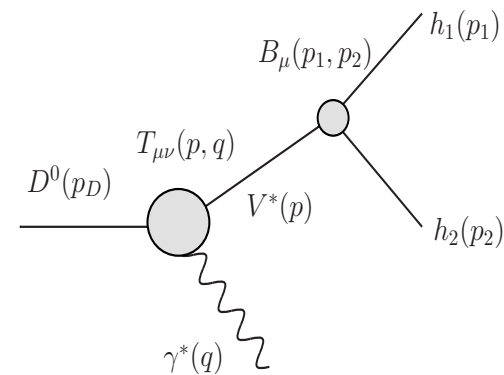
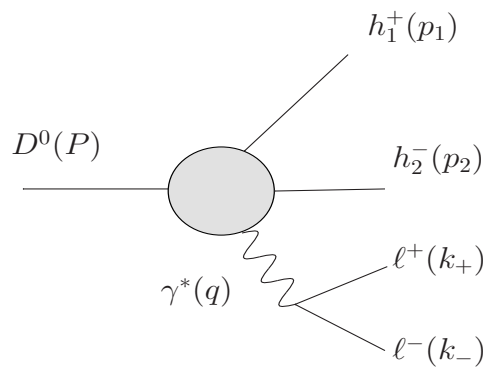
- Previous literature only order of magnitude estimate Biigi, Paul
- Motivated by LHCb workshop; they are asking for a prediction
- We establish the SM prediction (IB, DE). Exploratory work: short distance and NP require more work



$$D^0 \rightarrow h^+ h^- l^+ l^- \quad (h^+ h^- = \pi\pi, \pi K, K\pi, KK)$$

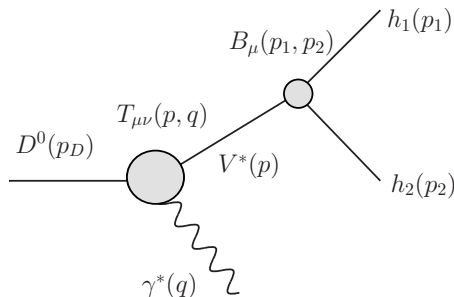
Cappiello, Cata, G.D.

- IB $\Gamma(D^0 \rightarrow h^+ h^-)$ from expts; similar to $K^+ \rightarrow \pi^+ \pi^0 e^+ e^-$
- DE determined from $D^0 \rightarrow VV \rightarrow V\gamma^*$



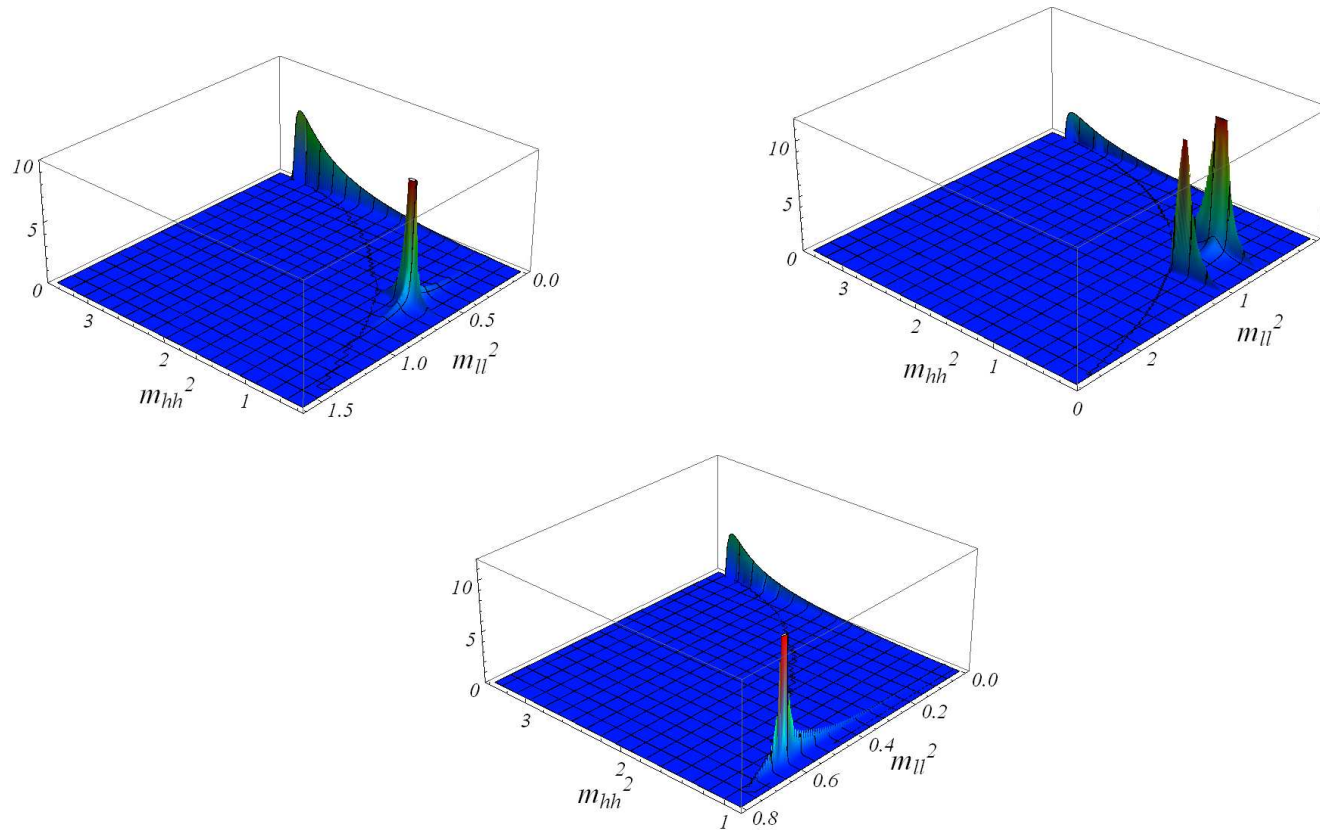
DE: form factor generated from $D \rightarrow VV$

$$\frac{e}{q^2} \bar{l} \gamma^\mu l H_\mu(p_1, p_2, q) \quad H^\mu = F_1 p_1^\mu + F_2 p_2^\mu + F_3 \varepsilon^{\mu\nu\alpha\beta} p_{1\nu} p_{2\alpha} q_\beta.$$



- general ff then VMD + Factorization
Bauer, Stech, Wirbel
- We use D_{l4} data from Focus;
CKM workshop: treatment OK!
Babar much more precise

(m_{ll}^2, m_{hh}^2) plane $K^\mp \pi^\pm$ (K^*), $\pi^+ \pi^-$ (ρ) and $K^+ K^-$ (ϕ), $e^+ e^-$



m_{ll} and m_{hh} are given in GeV. Dimuon brems strongly suppressed

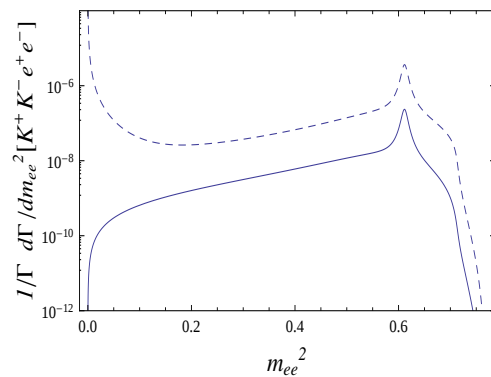
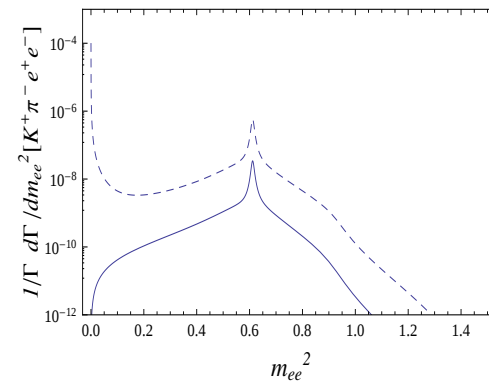
Branchings

Decay mode	Bremss	(E)	(M)
$D^0 \rightarrow K^- \pi^+ e^+ e^-$	$9.9 \cdot 10^{-6}$	$6.2 \cdot 10^{-6}$	$4.8 \cdot 10^{-7}$
$D^0 \rightarrow \pi^+ \pi^- e^+ e^-$	$5.3 \cdot 10^{-7}$	$1.3 \cdot 10^{-6}$	$1.3 \cdot 10^{-7}$
$D^0 \rightarrow K^+ K^- e^+ e^-$	$5.4 \cdot 10^{-7}$	$1.1 \cdot 10^{-7}$	$5.0 \cdot 10^{-9}$
$D^0 \rightarrow K^+ \pi^- e^+ e^-$	$3.7 \cdot 10^{-8}$	$1.7 \cdot 10^{-8}$	$1.3 \cdot 10^{-9}$
$D^0 \rightarrow K^- \pi^+ \mu^+ \mu^-$	$8.6 \cdot 10^{-8}$	$6.2 \cdot 10^{-6}$	$4.8 \cdot 10^{-7}$
$D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$	$5.6 \cdot 10^{-9}$	$1.3 \cdot 10^{-6}$	$1.3 \cdot 10^{-7}$
$D^0 \rightarrow K^+ K^- \mu^+ \mu^-$	$3.3 \cdot 10^{-9}$	$1.1 \cdot 10^{-7}$	$5.0 \cdot 10^{-9}$
$D^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$	$3.3 \cdot 10^{-10}$	$1.7 \cdot 10^{-8}$	$1.3 \cdot 10^{-9}$

Table 1: *Long-distance contributions to the branching ratio for the different decay modes.*

E-M interference; $A_\phi = \langle \text{sgn}(s_\phi c_\phi) \rangle$

$$Br(E - M \text{ interf}) \sim 10^{-7} \quad A_\phi \sim 2\%$$

 $K^+ K^- ee$

 $K^+ \pi^- ee$


A_ϕ -normalized distr. (solid) vs LD bkg (dashed)

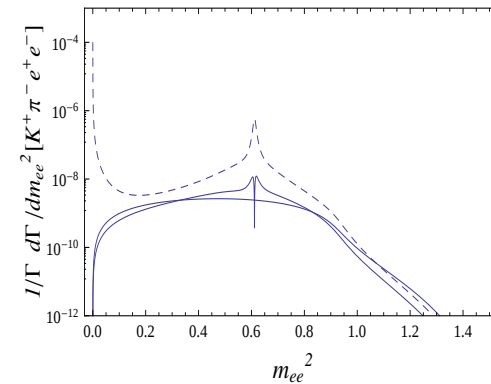
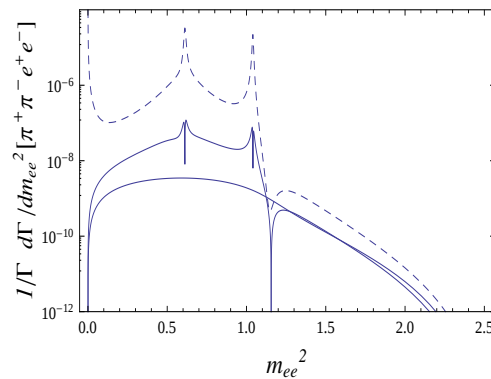
Q_{10} and Forward-Backward asymmetry

$$C_{10} \sim 4$$

$$Br(sd - LD \text{ interf}) \sim 10^{-8} \quad A_{FB} \sim 2\%$$

$$\pi^+ \pi^- ee$$

$$K^+ \pi^- ee$$



Normalized distr. (solid): spikes due LD interf. vs LD bkg (dashed)

Conclusions

- Precision physics required in all directions
- Alternative channels