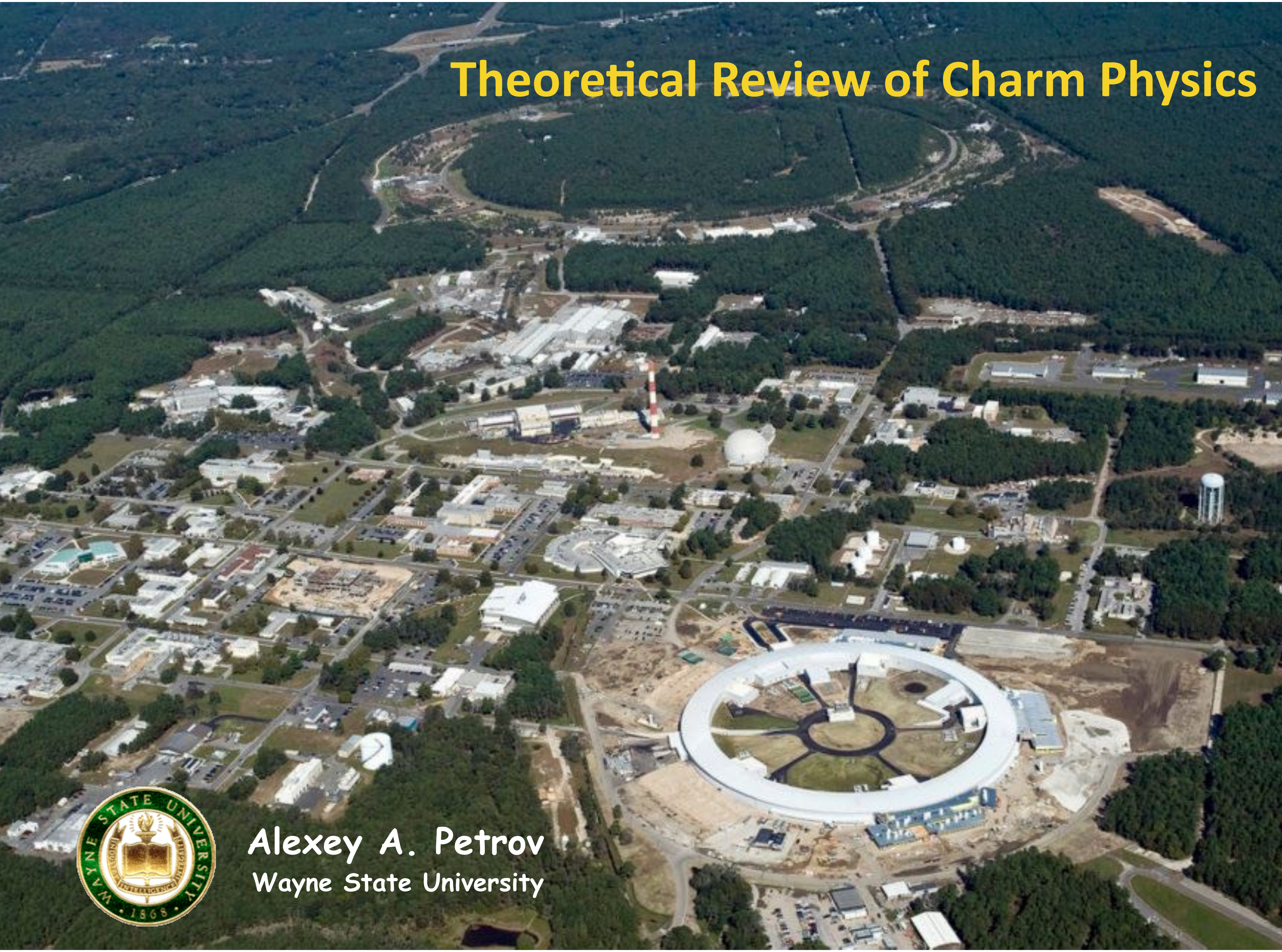
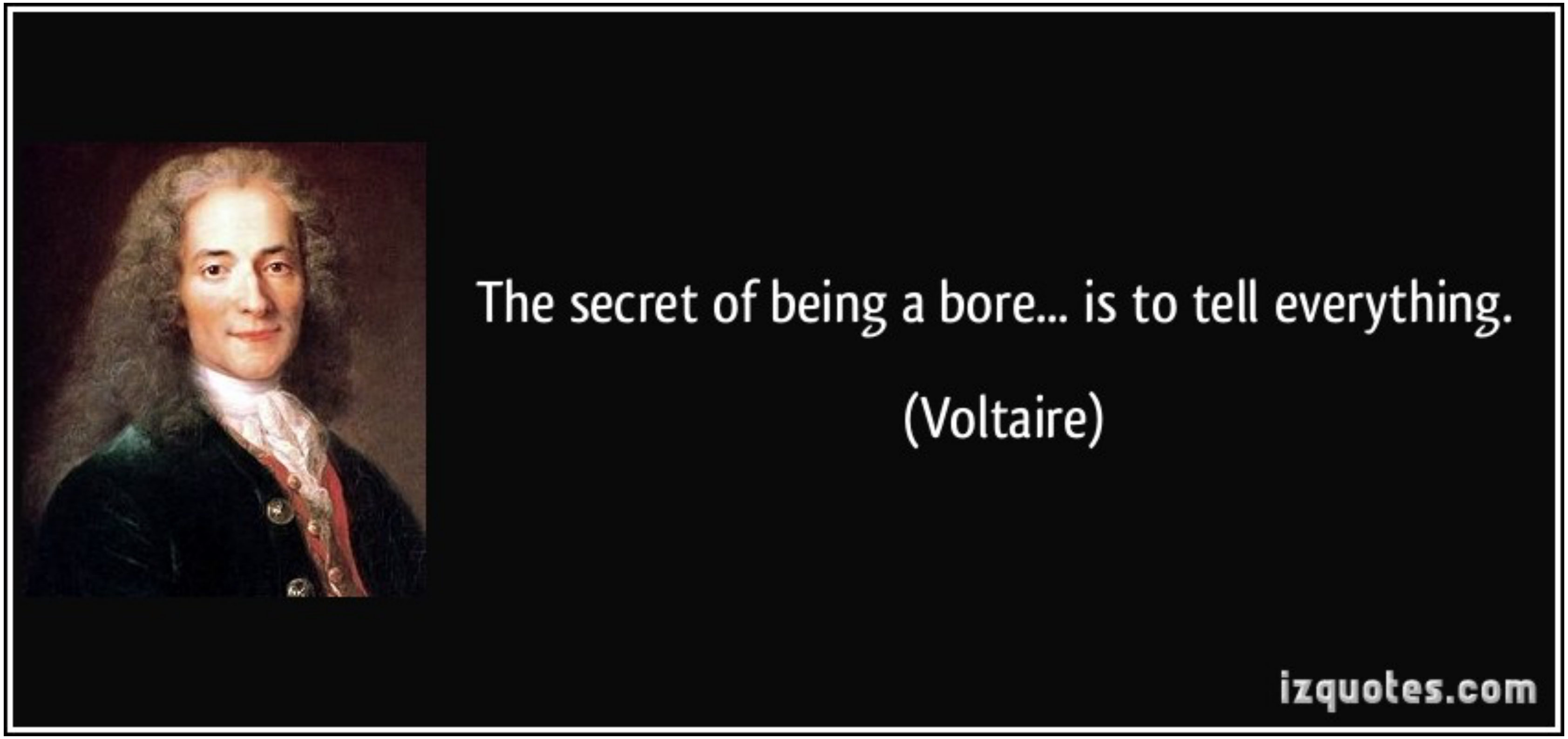
Theoretical Review of Charm Physics



Alexey A. Petrov
Wayne State University



Le secret d'ennuyer est celui de tout dire

★ I will NOT discuss (apologies)

- heavy meson/baryon spectroscopy with charmed states
- QCD exotic states (aka "XYZ-states")
- more theoretical issues (such as "quark-hadron duality" etc.)
- leptonic, rare radiative/semileptonic decays (but see extra slides!)

★ I WILL discuss: indirect searches New Physics with flavor [charm] (apologies)

- … and often use Comic Sans fonts in doing so (again, apologies)

Nature

Theorist's model

★ How can one use flavor data to test New Physics models?

1. Processes allowed in the Standard Model at tree level
   - relations, valid in the SM, but not necessarily in general
   - processes where SM rates and uncertainties are known
   - example: CKM triangle relations

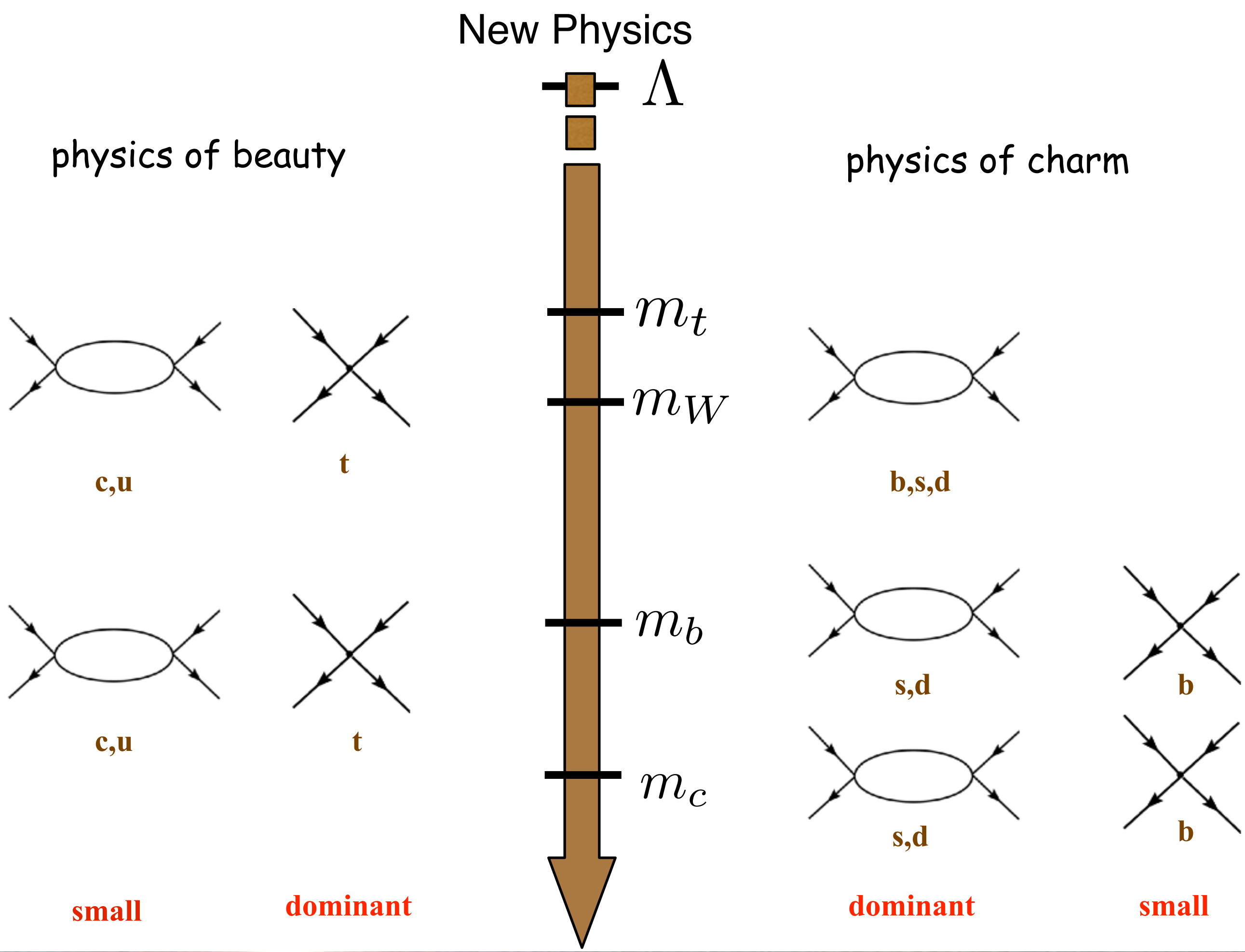
2. Processes forbidden in the Standard Model at tree level
   - can be used for testing both heavy and light NP
   - example: penguin-mediated decays, D-mixing, etc.

3. Processes forbidden in the Standard Model to all orders
   - example: $D^0 \to p^+ \pi^- \nu$

★ Even if LHC discovers NP particles, flavor constraints will help identification

★ Main goal of the exercise: understand physics at the most fundamental scale

★ It is important to understand relevant energy scales for the problem at hand

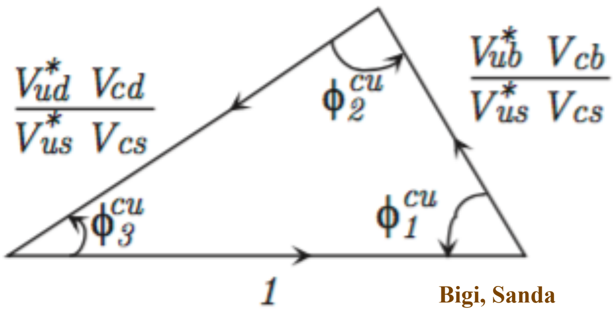


NP with processes allowed in SM

★ Example: CKM matrix $\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$ with $V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$

$$\begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

– charmed CKM triangle is "squashed"



$$1 + \frac{V_{ub}^* V_{cb}}{V_{us}^* V_{cs}} + \frac{V_{ud}^* V_{cd}}{V_{us}^* V_{cs}} = 0$$

$$\left| \frac{V_{ub}^* V_{cb}}{V_{us}^* V_{cs}} \right| \sim \mathcal{O}(\lambda^4) \qquad \left| \frac{V_{ud}^* V_{cd}}{V_{us}^* V_{cs}} \right| = 1 + \mathcal{O}(\lambda^4)$$

– ... with very small angles (but the same area as the "B-triangle")

$$\chi' = \arg\left(\frac{V_{ud}^* V_{cd}}{V_{us}^* V_{cs}}\right) \simeq A^2\lambda^4\eta \simeq 1.6 \cdot 10^{-3}\eta$$ **(essentially due to weak phase γ)**

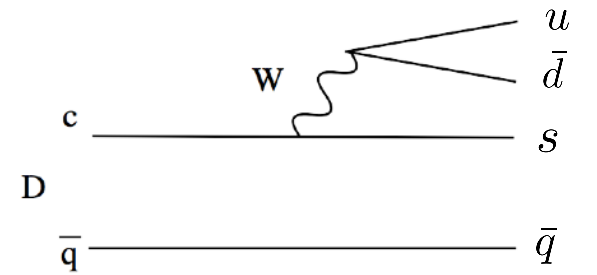
– difference b/w areas of b and c triangles indicates New Physics

NP with processes forbidden in SM at tree level

★ Will spend most of the talk on those processes
  - flavor-changing neutral current (FCNC) processes: mixing and penguin decays
  - (lepton) flavor symmetry violations

★ Charm decays can be classified by SM CKM suppression of tree amplitude ($V_{us} \sim \lambda \sim 0.2$): need it for all exp studies

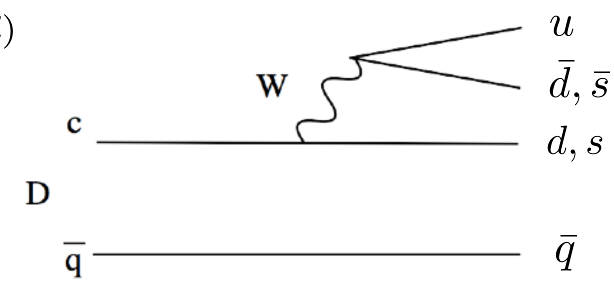
$$V_{cs}V_{ud}^*$$



★ Cabibbo-favored (CF: λ^0) decay

- originates from $c \to s\, u\bar{d}$
- examples: $D^0 \to K^-\pi^+$

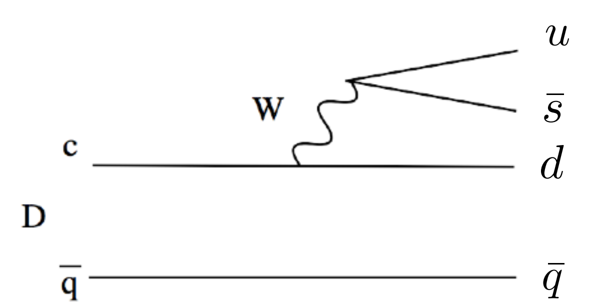
$$V_{cs(d)}V_{us(d)}^*$$



★ Singly Cabibbo-suppressed (SCS: λ^1) decay

- originates from $c \to q\, u\bar{q}$
- examples: $D^0 \to \pi\pi$ and $D^0 \to KK$

$$V_{cd}V_{us}^*$$



★ Doubly Cabibbo-suppressed (DCS: λ^2) decay

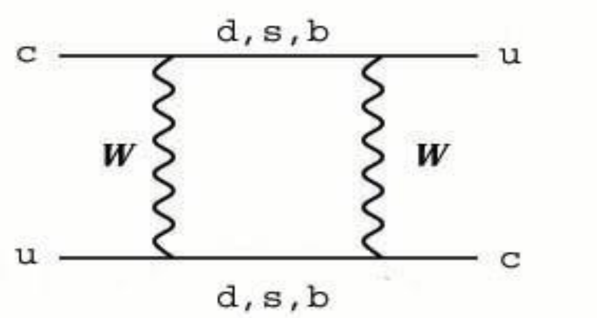
- originates from $c \to d\, u\bar{s}$
- examples: $D^0 \to K^+\pi^-$

Illustration by Patrick Griffin, animated by Mitchell Crites-Krumm

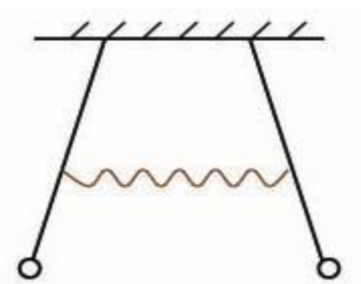
Charm-anticharm mixing

Charm-anticharm mixing

Introduction: $D\bar{D}$ mixing



D-D mixing



Coupled oscillators

$\Delta C=2$: only at one loop in the Standard Model:

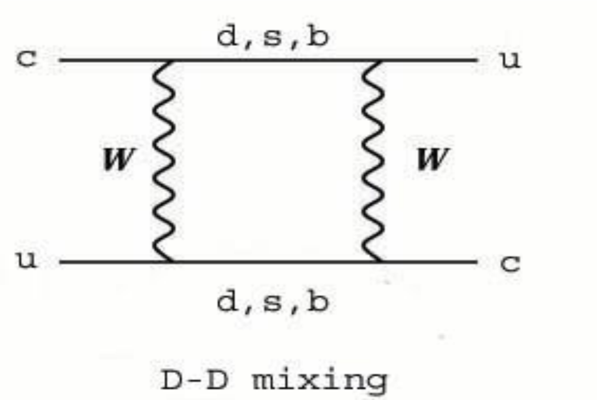
possible new physics particles in the loop

$\Delta C=2$ interaction couples dynamics of D^0 and D^0

$$\left|D(t)\right\rangle = \begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = a(t)\left|D^0\right\rangle + b(t)\left|\overline{D^0}\right\rangle$$

★ Time-dependence: coupled Schrödinger equations

$$i\frac{\partial}{\partial t}\left|D(t)\right\rangle = \left(M - \frac{i}{2}\Gamma\right)\left|D(t)\right\rangle = \begin{bmatrix} A & p^2 \\ q^2 & A \end{bmatrix}\left|D(t)\right\rangle$$



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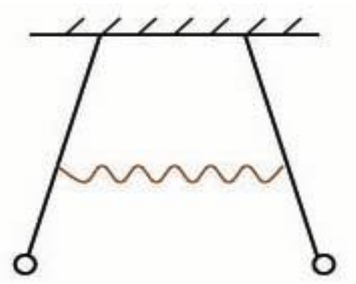
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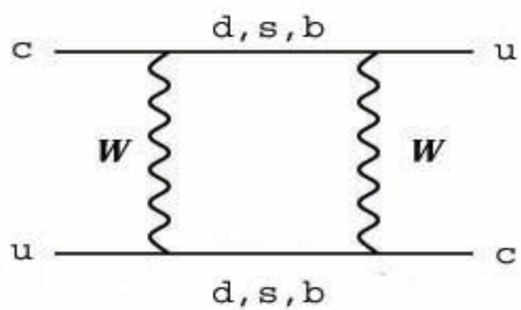
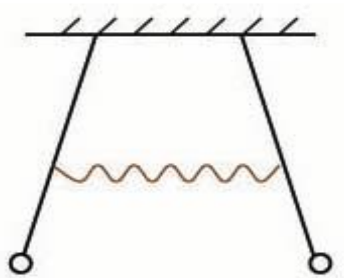
Introduction: D$\bar{\text{D}}$ mixing



D-D mixing



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★ Time-dependence: coupled Schrödinger equations

$$i\frac{\partial}{\partial t}|D(t)\rangle = \left(M - \frac{i}{2}\Gamma\right)|D(t)\rangle = \begin{bmatrix} A & p^2 \\ q^2 & A \end{bmatrix}|D(t)\rangle$$

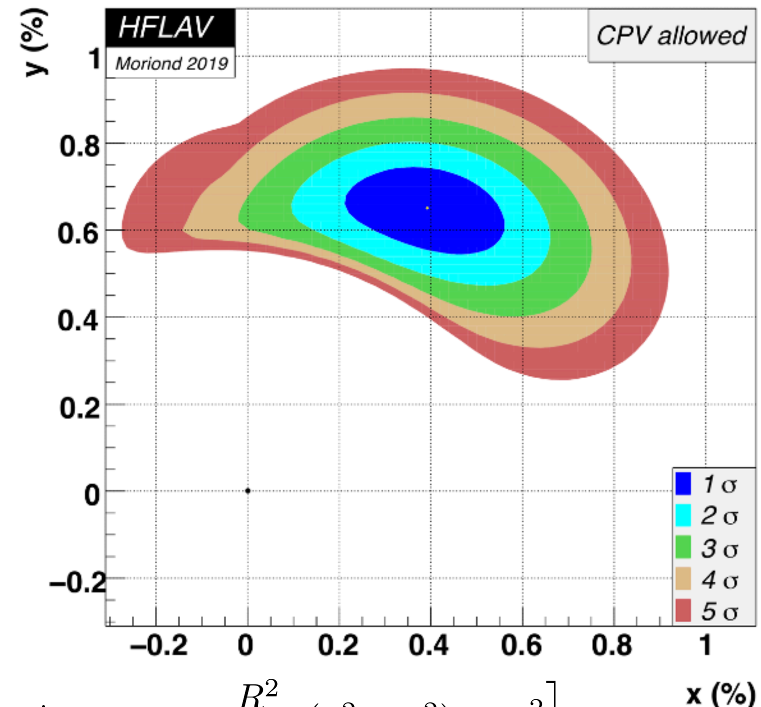
Q: this Hamiltonian is clearly non-Hermitian!
How does it square against what you learned in Quantum Mechanics?

★ Idea: look for a wrong-sign final state

1. Time-dependent or time-integrated semileptonic analysis

$$rate \propto x^2 + y^2$$

Quadratic in x,y: not so sensitive



2. Time-dependent $D^0 \to K^+K^-$ analysis (lifetime difference)

$$y_{CP} = \frac{\tau(D \to \pi^+ K^-)}{\tau(D \to K^+ K^-)} - 1 = y \cos\phi - x \sin\phi \frac{1 - R_m}{2}$$

3. Time-dependent $D^0(t) \to K^+\pi^-$ analysis

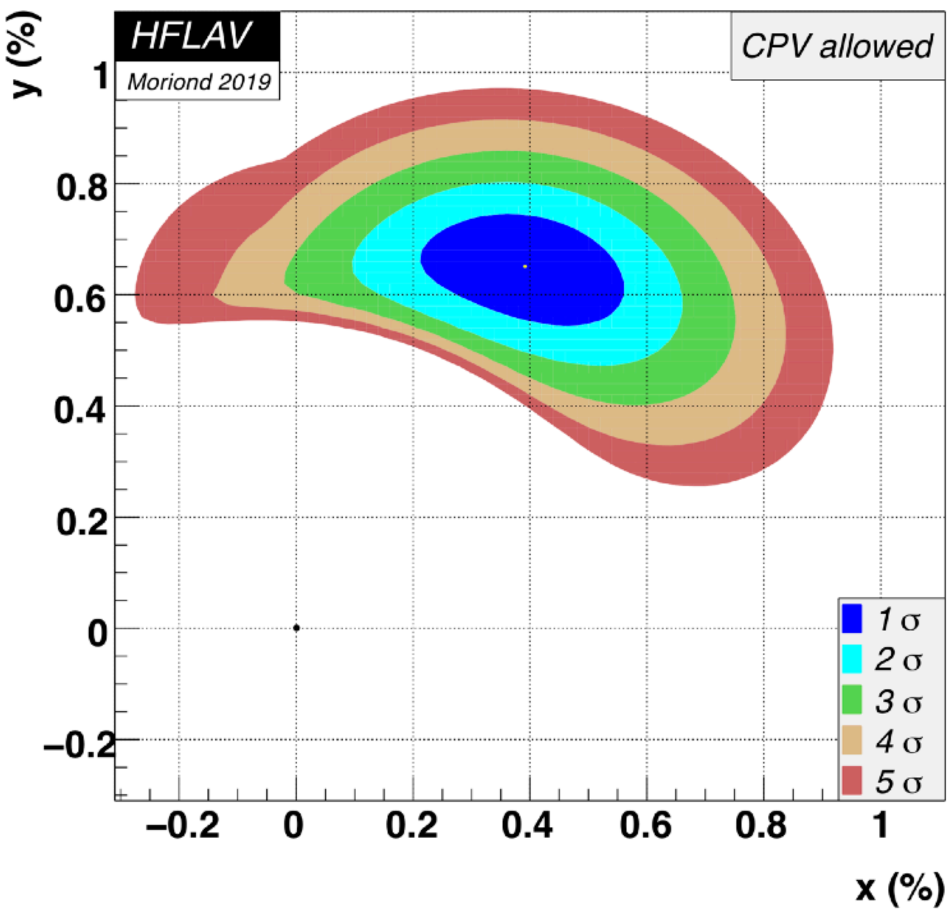
$$\Gamma[D^0(t) \to K^+\pi^-] = e^{-\Gamma t} \left|A_{K^+\pi^-}\right|^2 \left[R + \sqrt{R} R_m \left(y' \cos\phi - x' \sin\phi\right) \Gamma t + \frac{R_m^2}{4} \left(x^2 + y^2\right) (\Gamma t)^2\right]$$

4. Dalitz analyses $D^0(t) \to K\pi\pi, KKK$
5. Quantum correlations analyses

$$R_m^2 = \left|\frac{q}{p}\right|^2, \quad x' = x\cos\delta + y\sin\delta, \; y' = y\cos\delta - x\sin\delta$$

Sensitive to DCS/CF strong phase δ

★ Experimental fact: charm mixing parameters are non-zero



$$x_D = \frac{M_2 - M_1}{\Gamma_D}, \quad y_D = \frac{\Gamma_2 - \Gamma_1}{2\Gamma_D}$$

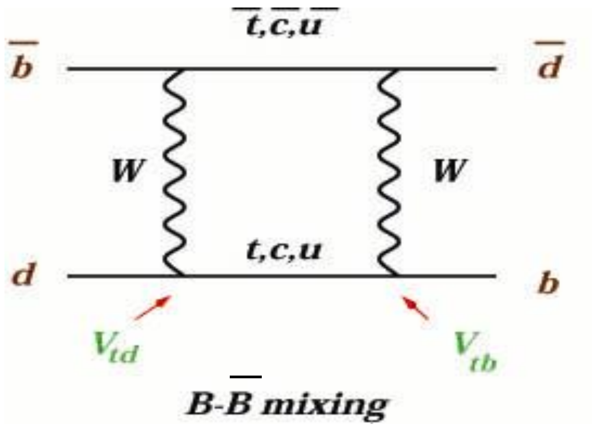
★ ... and rather large

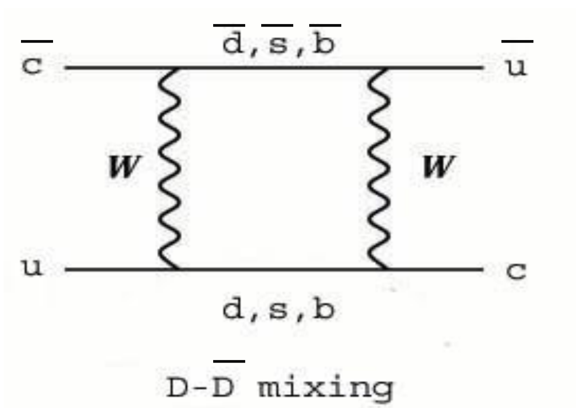
- if CP-violation is neglected...

$$x = (0.50^{+0.13}_{-0.14})\%$$
$$y = (0.62 \pm 0.07)\%$$

- if CP-violation is allowed

$$x = (0.39^{+0.11}_{-0.12})\%$$
$$y = (0.651^{+0.063}_{-0.069})\%$$





$\overline{D^0} - D^0$ mixing	$\overline{B^0} - B^0$ mixing
• intermediate down-type quarks • SM: b-quark contribution is negligible due to $V_{cd}V_{ub}^*$ • $rate \propto f(m_s) - f(m_d)$ (zero in the SU(3) limit) Falk, Grossman, Ligeti, and A.A.P. Phys.Rev. D65, 054034, 2002 2nd order effect!!!	• intermediate up-type quarks • SM: t-quark contribution is dominant • $rate \propto m_t^2$ (expected to be large)
1. Sensitive to long distance QCD 2. Small in the SM: New Physics! (must know SM x and y)	1. Computable in QCD (*) 2. Large in the SM: CKM!

(*) up to matrix elements of 4-quark operators

Mixing: SM predictions

★ How can one tell that a process is dominated by long-distance or short-distance?

★ To start thing off, mass and lifetime differences of mass eigenstates...

$$x_D = \frac{M_2 - M_1}{\Gamma_D}, \quad y_D = \frac{\Gamma_2 - \Gamma_1}{2\Gamma_D}$$

★ ...can be calculated as real and imaginary parts of a correlation function

$$y_{\rm D} = \frac{1}{2M_{\rm D}\Gamma_{\rm D}} {\rm Im}\, \langle \overline{D^0} | \, i \int {\rm d}^4x \, T \Big\{ \mathcal{H}_w^{|\Delta C|=1}(x) \, \mathcal{H}_w^{|\Delta C|=1}(0) \Big\} | D^0 \rangle$$

bi-local time-ordered product

$$x_{\rm D} = \frac{1}{2M_{\rm D}\Gamma_{\rm D}} {\rm Re} \left[2\langle \overline{D^0} | H^{|\Delta C|=2} | D^0 \rangle + \langle \overline{D^0} | \, i \int {\rm d}^4x \, T \Big\{ \mathcal{H}_w^{|\Delta C|=1}(x) \, \mathcal{H}_w^{|\Delta C|=1}(0) \Big\} | D^0 \rangle \right]$$

local operator
(b-quark, NP): small?

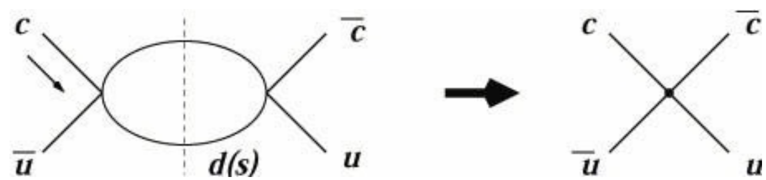
bi-local time-ordered product

★ ... or can be written in terms of hadronic degrees of freedom...

$$y = \frac{1}{2\Gamma} \sum_n \rho_n \left[\langle D^0 | H_W^{\Delta C=1} | n \rangle \langle n | H_W^{\Delta C=1} | \overline{D}^0 \rangle + \langle \overline{D}^0 | H_W^{\Delta C=1} | n \rangle \langle n | H_W^{\Delta C=1} | D^0 \rangle \right]$$

Let's insist on $1/m_c$ expansion, hope for quark-hadron duality

★ SD calculation: expand the operator product in $1/m_c$, e.g.



E. Golowich and A.A.P.
Phys. Lett. B625 (2005) 53

★ Note that $1/m_c$ is not small, while factors of m_s make the result small

- keep $V_{ub} \neq 0$, so the leading SU(3)-breaking contribution is suppressed by $\lambda_b^2 \sim \lambda^{10}$
- ... but it is tiny, so look for SU(3)-breaking effects that come from mass insertions and quark condensates

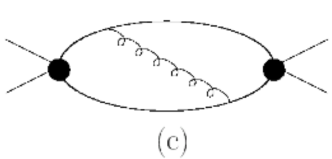
H. Georgi, …
I. Bigi, N. Uraltsev

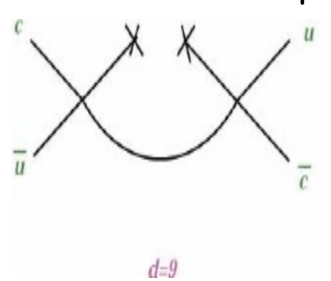
M. Bobrowski et al
JHEP 1003 (2010) 009

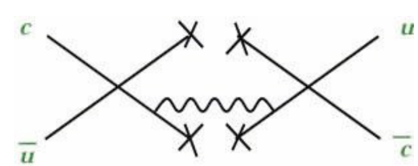
$$\Gamma_{12} = -\lambda_s^2 \left(\Gamma_{12}^{ss} - 2\Gamma_{12}^{sd} + \Gamma_{12}^{dd}\right) + 2\lambda_s\lambda_b \left(\Gamma_{12}^{sd} - \Gamma_{12}^{dd}\right) - \lambda_b^2\, \Gamma_{12}^{dd}$$

LO:	$O(m_s^4)$	$O(m_s^2)$	$O(1)$
NLO:	$O(m_s^3)$	$O(m_s^1)$	$O(1)$

- ... main contribution comes from dim-12 operators!!!







Guestimate: $x \sim y \sim 10^{-3}$?

Inclusive approach to mixing: quark-hadron duality

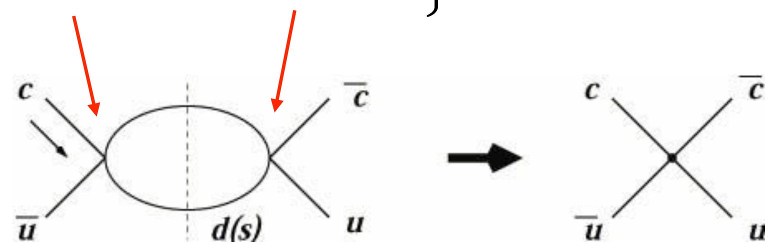
★ How can one tell that a process is dominated by long-distance or short-distance?

$$y = \frac{1}{2\Gamma} \sum_n \rho_n \left[\langle D^0 | H_W^{\Delta C=1} | n \rangle \langle n | H_W^{\Delta C=1} | \overline{D}^0 \rangle + \langle \overline{D}^0 | H_W^{\Delta C=1} | n \rangle \langle n | H_W^{\Delta C=1} | D^0 \rangle \right]$$

★ It is important to remember that the expansion parameter is $1/E_{released}$

$$y_D = \frac{1}{2 M_D \Gamma_D} \mathrm{Im} \langle \overline{D^0} | \, i \int d^4x \, T \left\{ \mathcal{H}_w^{|\Delta C|=1}(x) \, \mathcal{H}_w^{|\Delta C|=1}(0) \right\} | D^0 \rangle$$

OPE-leading contribution:



★ In the heavy-quark limit $m_c \rightarrow \infty$ we have $m_c \gg \sum m_{intermediate\ quarks}$, so $E_{released} \sim m_c$

- the situation is similar to B-physics, where it is "short-distance" dominated
- one can consistently compute pQCD and 1/m corrections

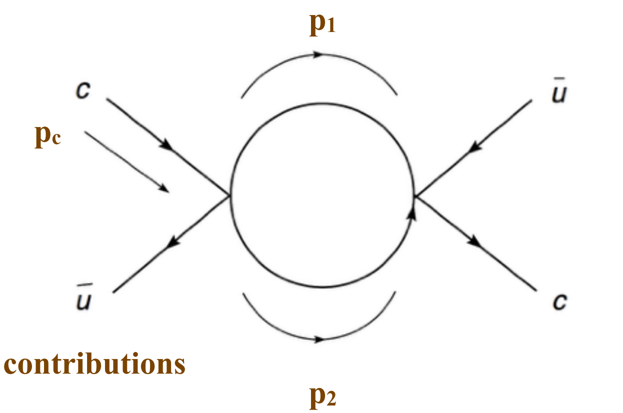
★ But wait, m_c is NOT infinitely large! What happens for finite m_c???

- how is large momentum routed in the diagrams?
- are there important hadronization (threshold) effects?

Inclusive approach to mixing: quark-hadron duality

★ How can one tell that a process is dominated by long-distance or short-distance?

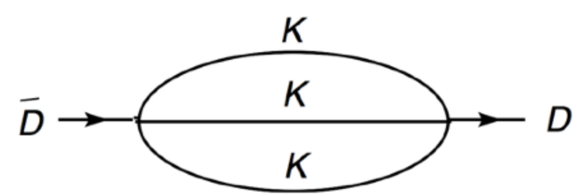
★ Let's look at how the momentum is routed in a leading-order diagram
  - injected momentum is $p_c \sim m_c$
  - thus, $p_1 \sim p_2 \sim m_c/2 \sim O(\Lambda_{QCD})$?



Still OK with OPE, signals large nonperturbative contributions

★ For a particular example of the lifetime difference, have hadronic intermediate states

-let's use an example of KKK intermediate state
- in this example, $E_{released} \sim m_D - 3\, m_K \sim O(\Lambda_{QCD})$



★ Similar threshold effects exist in B-mixing calculations
  - but $m_b \gg \sum m_{intermediate\ quarks}$, so $E_{released} \sim m_b$ (almost) always
  - quark-hadron duality takes care of the rest!

Let's saturate correlators by hadronic states

Exclusive approach to mixing: use data?

★ LD calculation: saturate the correlator by hadronic states, e.g.

$$y = \frac{1}{2\Gamma} \sum_n \rho_n \left[\langle D^0 | H_W^{\Delta C=1} | n \rangle \langle n | H_W^{\Delta C=1} | \overline{D}^0 \rangle + \langle \overline{D}^0 | H_W^{\Delta C=1} | n \rangle \langle n | H_W^{\Delta C=1} | D^0 \rangle \right]$$

… with n being all states to which D^0 and $\overline{D}^0$ can decay. Consider ππ, πK, KK intermediate states as an example…

J. Donoghue et. al.
L. Wolfenstein
P. Colangelo et. al.

H.Y. Cheng and C. Chiang

$$\begin{aligned} y_2 &= Br(D^0 \to K^+K^-) + Br(D^0 \to \pi^+\pi^-) \\ &- 2\cos\delta \sqrt{Br(D^0 \to K^+\pi^-) Br(D^0 \to \pi^+K^-)} \end{aligned}$$

If every Br is known up to O(1%) ⇒ the result is expected to be O(1%)!

The result here is a series of large numbers with alternating signs, SU(3) forces 0

If experimental data on Br is used, are we only sensitive to exit. uncertainties?

★ Need to "repackage" the analysis: look at complete multiplet contribution

$$y = \sum_{F_R} y_{F,R}\, Br(D^0 \to F_R) = \sum_{F_R} y_{F,R} \frac{1}{\Gamma} \sum_{n \in F_R} \Gamma(D^0 \to n)$$

Falk, Grossman, Ligeti, Nir. A.A.P.
Phys.Rev. D69, 114021, 2004
Falk, Grossman, Ligeti, and A.A.P.
Phys.Rev. D65, 054034, 2002

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cancellation expected

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Exclusive approach to mixing: use data!

★ What if we insist on using experimental data anyway?

★ Ex., one can employ Factorizaton-Assisted Topological Amplitudes

in units of 10^{-3}

Modes	$\mathcal{B}$(exp)	$\mathcal{B}$(FAT)	Modes	$\mathcal{B}$(exp)	$\mathcal{B}$(FAT)	Modes	$\mathcal{B}$(exp)	$\mathcal{B}$(FAT)
$\pi^0\overline{K}^0$	24.0 ± 0.8	24.2 ± 0.8	$\pi^0\overline{K}^{*0}$	37.5 ± 2.9	35.9 ± 2.2	$\overline{K}^0\rho^0$	$12.8^{+1.4}_{-1.6}$	13.5 ± 1.4
π^+K^-	39.3 ± 0.4	39.2 ± 0.4	π^+K^{*-}	54.3 ± 4.4	62.5 ± 2.7	$K^-\rho^+$	111.0 ± 9.0	105.0 ± 5.2
$\eta\overline{K}^0$	9.70 ± 0.6	9.6 ± 0.6	$\eta\overline{K}^{*0}$	9.6 ± 3.0	6.1 ± 1.0	$\overline{K}^0\omega$	22.2 ± 1.2	22.3 ± 1.1
$\eta'\overline{K}^0$	19.0 ± 1.0	19.5 ± 1.0	$\eta'\overline{K}^{*0}$	< 1.10	0.19 ± 0.01	$\overline{K}^0\phi$	$8.47^{+0.66}_{-0.34}$	8.2 ± 0.6
$\pi^+\pi^-$	1.421 ± 0.025	1.44 ± 0.02	$\pi^+\rho^-$	5.09 ± 0.34	4.5 ± 0.2	$\pi^-\rho^+$	10.0 ± 0.6	9.2 ± 0.3
K^+K^-	4.01 ± 0.07	4.05 ± 0.07	K^+K^{*-}	1.62 ± 0.15	1.8 ± 0.1	K^-K^{*+}	4.50 ± 0.30	4.3 ± 0.2
$K^0\overline{K}^0$	0.36 ± 0.08	0.29 ± 0.07	$K^0\overline{K}^{*0}$	0.18 ± 0.04	0.19 ± 0.03	$\overline{K}^0K^{*0}$	0.21 ± 0.04	0.19 ± 0.03
$\pi^0\eta$	0.69 ± 0.07	0.74 ± 0.03	$\eta\rho^0$		1.4 ± 0.2	$\pi^0\omega$	0.117 ± 0.035	0.10 ± 0.03
$\pi^0\eta'$	0.91 ± 0.14	1.08 ± 0.05	$\eta'\rho^0$		0.25 ± 0.01	$\pi^0\phi$	1.35 ± 0.10	1.4 ± 0.1
$\eta\eta$	1.70 ± 0.20	1.86 ± 0.06	$\eta\omega$	2.21 ± 0.23	2.0 ± 0.1	$\eta\phi$	0.14 ± 0.05	0.18 ± 0.04
$\eta\eta'$	1.07 ± 0.26	1.05 ± 0.08	$\eta'\omega$		0.044 ± 0.004			
$\pi^0\pi^0$	0.826 ± 0.035	0.78 ± 0.03	$\pi^0\rho^0$	3.82 ± 0.29	4.1 ± 0.2			
π^0K^0		0.069 ± 0.002	π^0K^{*0}		0.103 ± 0.006	$K^0\rho^0$		0.039 ± 0.004
π^-K^+	0.133 ± 0.009	0.133 ± 0.001	π^-K^{*+}	$0.345^{+0.180}_{-0.102}$	0.40 ± 0.02	$K^+\rho^-$		0.144 ± 0.009
ηK^0		0.027 ± 0.002	ηK^{*0}		0.017 ± 0.003	$K^0\omega$		0.064 ± 0.003
$\eta'K^0$		0.056 ± 0.003	$\eta'K^{*0}$		0.00055 ± 0.00004	$K^0\phi$		0.024 ± 0.002

Jiang, Yu, Qin, Li, and Lu, 2017

★ … but it appears to yield a smaller result, $y_{PP+PV} = (0.21 \pm 0.07)\%$,

Exclusive approach to mixing: use data!

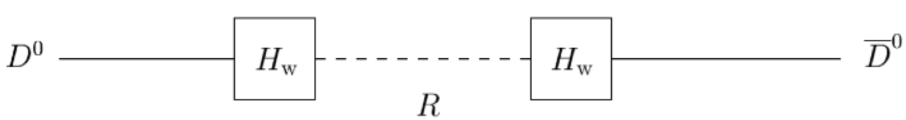
★ What if we insist on using experimental data anyway?

★ Possible additional contributions?

- each intermediate state has a finite width, i.e. is not a proper asymptotic state
- within each multiplet widths experience (incomplete) SU(3) cancelations
- this effect already happens for the simplest intermediate states!

★ Consider, for illustration, a set of single-particle intermediate states:

$$-\Sigma_{p_D}(p_D)\Big|_{\rm tot}^{\rm res} = \frac{1}{2m_D}\sum_R Re\,\frac{\langle D_L|\mathcal{H}_W|R\rangle\langle R|\mathcal{H}_W^\dagger|D_L\rangle}{m_D^2 - m_R^2 + i\Gamma_R m_D} \quad - \quad (D_L \to D_S)$$



$$\Delta m_D\Big|_{\rm R}^{\rm res} \propto \frac{m_D^2 - m_R^2}{(m_D^2 - m_R^2)^2 + \Gamma_R^2 m_D^2}$$

$$\Delta\Gamma_D\Big|_{\rm R}^{\rm res} \propto -\frac{\Gamma_R m_D}{(m_D^2 - m_R^2)^2 + \Gamma_R^2 m_D^2}$$

★ Each resonance contributes to $\Delta\Gamma$ only because of its finite width!

Finite width effects: one-body contributions

★ Multiplet effects for (single-particle) intermediate states

- in this simple example: heavy pion, kaon and eta/eta'
- each single-particle intermediate state has a rather large width

$$\Delta\Gamma_D|^{\text{res}}_{\text{octet}} = \Delta\Gamma_D^{(K_H)} - \frac{1}{4}\Delta\Gamma_D^{(\pi_H)} - \frac{3\cos^2\theta_{\text{H}}}{4}\Delta\Gamma_D^{(\eta_H)} - \frac{1\sin^2\theta_{\text{H}}}{4}\Delta\Gamma_D^{(\eta'_H)}$$

- where for each state $\Delta\Gamma_D^{\text{res}} = -Cf_R^2 \frac{\mu_R\gamma_R}{(1-\mu_R)^2+\gamma_R^2}$ with $\mu_R = m_R^2/m_D^2$, $\gamma_R = \Gamma_R/m_D$
- … and a model calculation gives $C \equiv 2m_D(G_F a_2 f_D \xi_d/\sqrt{2})^2$
- SU(3) forces cancellations: a new SU(3) breaking effect due to widths!

Table: Magnitudes of Pseudoscalar Resonance Contributions.

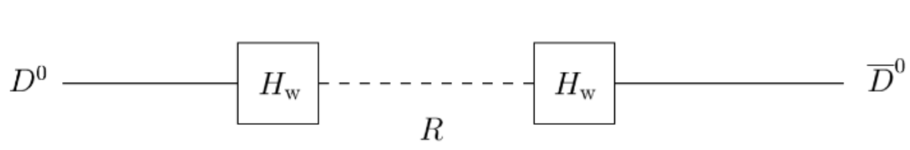
Resonance	$\lvert\Delta m_D\rvert \times 10^{-16}$ (GeV)	$\lvert\Delta\Gamma_D\rvert \times 10^{-16}$ (GeV)
$K(1460)$	$\sim 1.24\ (f_{K(1460)}/0.025)^2$	$\sim 0.88\ (f_{K(1460)}/0.025)^2$
$\eta(1760)$	$(0.77 \pm 0.27)\ (f_{\eta(1760)}/0.01)^2$	$(0.43 \pm 0.53)\ (f_{\eta(1760)}/0.01)^2$
$\pi(1800)$	$(0.13 \pm 0.06)\ (f_{\pi(1800)}/0.01)^2$	$(0.41 \pm 0.11)\ (f_{\pi(1800)}/0.01)^2$
$K(1830)$	$\sim 0.29\ (f_{K(1830)}/0.01)^2$	$\sim 1.86\ (f_{K(1830)}/0.01)^2$

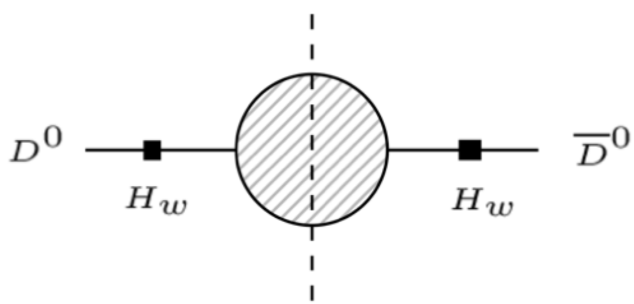
E. Golowich and A.A.P.
PLB427 (1998) 172-178

Finite width effects: one-body contributions

★ Let us take another look at those one-body contributions

- the width of each excited light quark state $\Gamma_R = \Gamma(R \to P_1 P_2) + \Gamma(R \to P_1 P_2 P_3) + \ldots$
- … which is equivalent to accounting for resonant FSI in 2-body intermediate state!



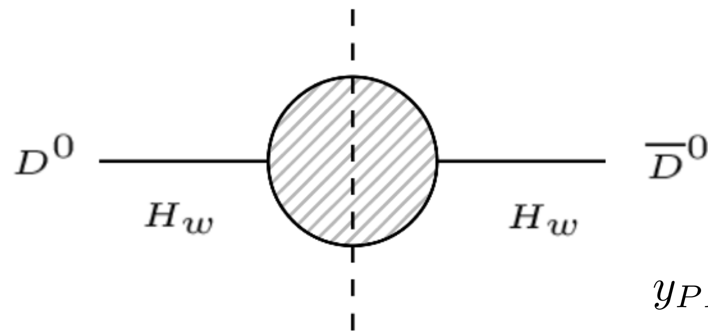


Since we shall be using experimental data to compute 2-body contributions, this effect will be taken into account automatically!

It's consistent to omit 1-body IntSt if experimental data is used

Finite width effects: two-body contributions

★ Let us apply similar logic to two-body contributions
  - consider contributions from the stable (wrt strong interactions) octet of pions, kaons, etas

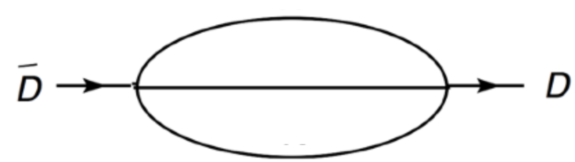


$$y_{PP} = (0.1 - 20) \times 10^{-4}$$

Falls short of the experimentally observed value of y

★ What about other two body contributions (PV, SP, SS, etc.)?
  - can use similar techniques to evaluate contribution to mixing as above 2BIS…
  - … but V, P', S states are not good asymptotic states!
  - we get new SU(3)-breaking contribution from the widths of those states!

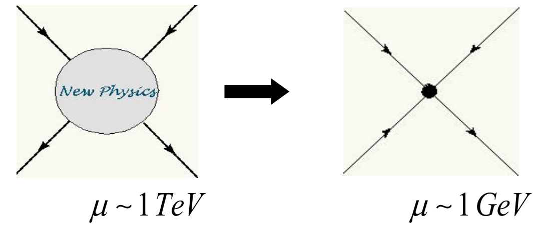
Since we are to use experimental data,
use Dalitz plot analyses to get at these contributions



A.A.P.. arXiv:1908.xxxx

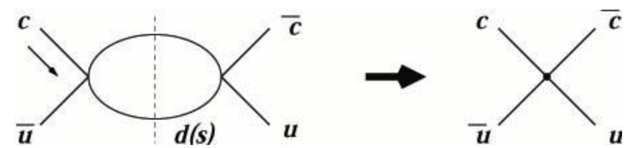
Mixing: new physics in x and y?

- Local ΔC=2 piece of the mass matrix affects x:



$$\left(M - \frac{i}{2}\Gamma\right)_{ij} = m_D^{(0)}\delta_{ij} + \frac{1}{2m_D}\left\langle D_i^0 \left| H_W^{\Delta C=2} \right| D_j^0 \right\rangle + \frac{1}{2m_D}\sum_I \frac{\left\langle D_i^0 \left| H_W^{\Delta C=1} \right| I \right\rangle \left\langle I \left| H_W^{\Delta C=1} \right| D_j^0 \right\rangle}{m_D^2 - m_I^2 + i\varepsilon}$$

- Double insertion of ΔC=1 affects x and y:



Amplitude $\quad A_n = \left\langle D^0 \left| \left(H_{SM}^{\Delta C=1} + H_{NP}^{\Delta C=1} \right) \right| n \right\rangle \equiv A_n^{SM} + A_n^{NP}$

Suppose $\quad \left|A_n^{NP}\right| / \left|A_n^{SM}\right| \sim O(\text{exp. uncertainty}) \le 10\%$

Example: $\quad y = \frac{1}{2\Gamma}\sum_n \rho_n \left(\overline{A}_n^{SM} + \overline{A}_n^{NP}\right)\left(A_n^{SM} + A_n^{NP}\right) \approx \frac{1}{2\Gamma}\sum_n \rho_n \overline{A}_n^{SM} A_n^{SM} + \frac{1}{2\Gamma}\sum_n \rho_n \left(\overline{A}_n^{SM} A_n^{NP} + \overline{A}_n^{NP} A_n^{SM}\right)$

phase space

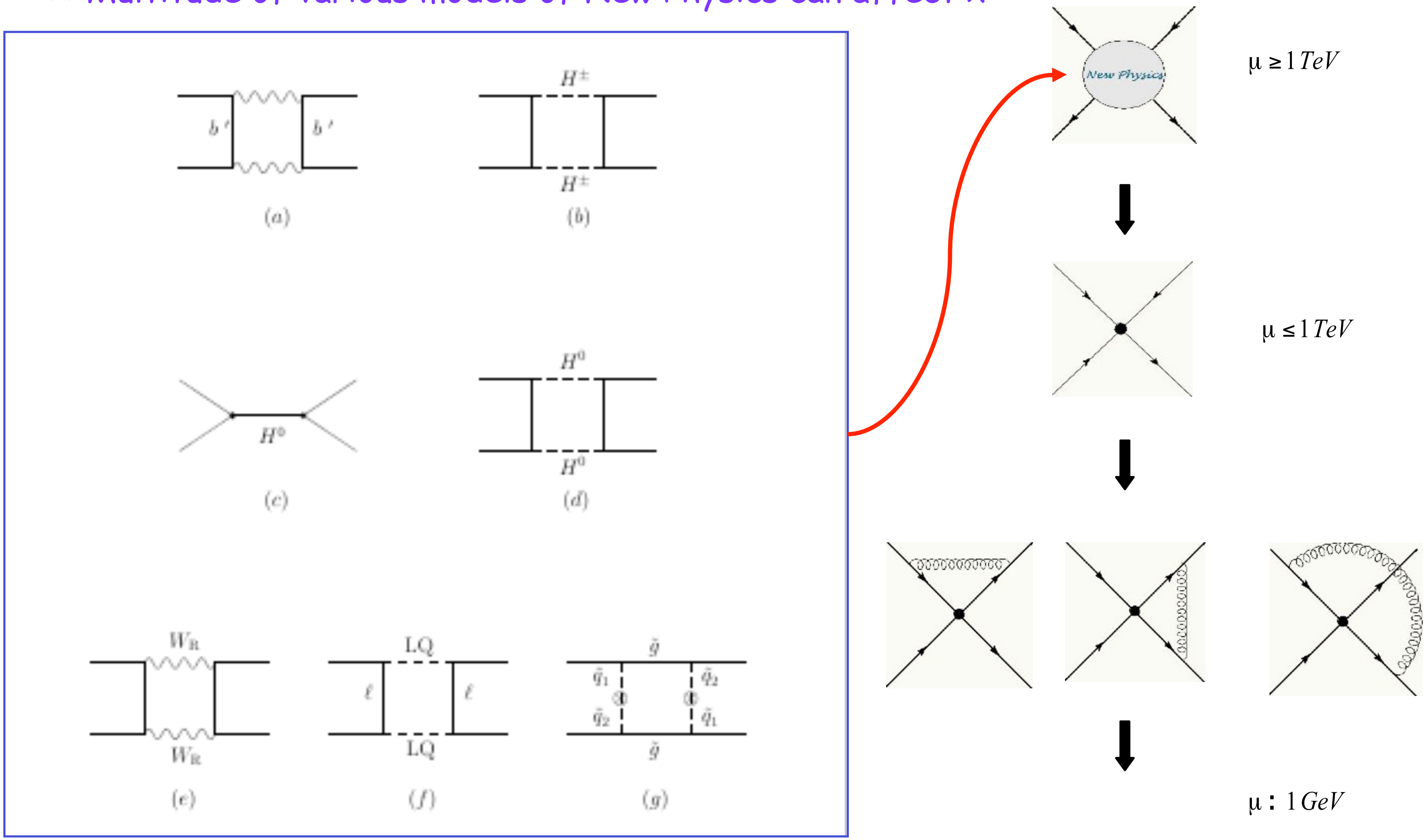
Zero in the SU(3) limit

Can be significant!!!

Falk, Grossman, Ligeti, and A.A.P. Phys.Rev. D65, 054034, 2002

2nd order effect!!!

★ Multitude of various models of New Physics can affect x



Mixing: new physics in x

★ Comparing to experimental value of x, obtain constraints on NP models
- assume x is dominated by the New Physics model
- assume no accidental strong cancellations b/w SM and NP

$$\mathcal{H}_{NP}^{\Delta C=2} = \frac{1}{\Lambda_{NP}^2} \sum_{i=1}^{8} z_i(\mu) Q'_i$$

$$\begin{aligned} Q_1^{cu} &= \bar{u}_L^\alpha \gamma_\mu c_L^\alpha \bar{u}_L^\beta \gamma^\mu c_L^\beta, \\ Q_2^{cu} &= \bar{u}_R^\alpha c_L^\alpha \bar{u}_R^\beta c_L^\beta, \\ Q_3^{cu} &= \bar{u}_R^\alpha c_L^\beta \bar{u}_R^\beta c_L^\alpha, \end{aligned} + \left\{ \begin{array}{c} L \\ \updownarrow \\ R \end{array} \right\} + \begin{aligned} Q_4^{cu} &= \bar{u}_R^\alpha c_L^\alpha \bar{u}_L^\beta c_R^\beta, \\ Q_5^{cu} &= \bar{u}_R^\alpha c_L^\beta \bar{u}_L^\beta c_R^\alpha, \end{aligned}$$

★ ... which are

$$|z_1| \lesssim 5.7 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$
$$|z_2| \lesssim 1.6 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$
$$|z_3| \lesssim 5.8 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$
$$|z_4| \lesssim 5.6 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$
$$|z_5| \lesssim 1.6 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2.$$

New Physics is either at a very high scales

tree level: $\Lambda_{NP} \geq (4-10) \times 10^3$ TeV

loop level: $\Lambda_{NP} \geq (1-3) \times 10^2$ TeV

or have highly suppressed couplings to charm!

Gedalia, Grossman, Nir, Perez
Phys.Rev.D80, 055024, 2009

E.Golowich, J. Hewett, S. Pakvasa and A.A.P.
Phys. Rev. D76:095009, 2007

★ Constraints on particular NP models available

Extra fermions

Extra gauge bosons

Extra scalars

Extra dimensions

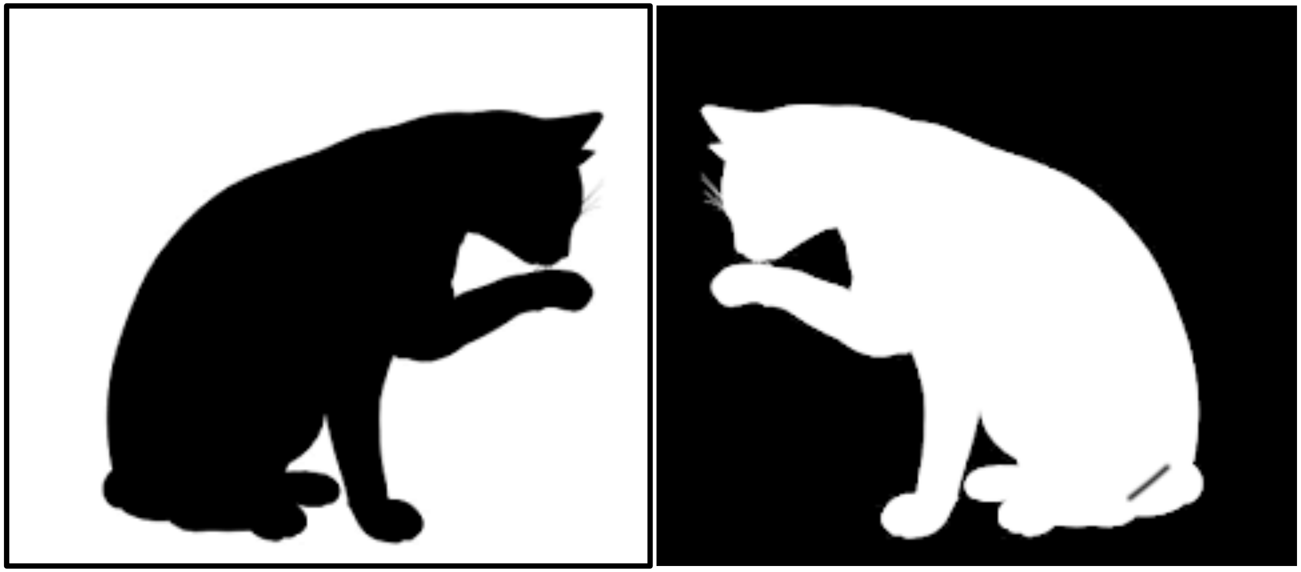
SUSY

Model	Approximate Constraint
Fourth Generation (Fig. 2)	$|V_{ub'}V_{cb'}| \cdot m_{b'} < 0.5$ (GeV)
$Q = -1/3$ Singlet Quark (Fig. 4)	$s_2 \cdot m_S < 0.27$ (GeV)
$Q = +2/3$ Singlet Quark (Fig. 6)	$|\lambda_{uc}| < 2.4 \cdot 10^{-4}$
Little Higgs	Tree: See entry for $Q = -1/3$ Singlet Quark
	Box: Region of parameter space can reach observed x_D
Generic Z' (Fig. 7)	$M_{Z'}/C > 2.2 \cdot 10^3$ TeV
Family Symmetries (Fig. 8)	$m_1/f > 1.2 \cdot 10^3$ TeV (with $m_1/m_2 = 0.5$)
Left-Right Symmetric (Fig. 9)	No constraint
Alternate Left-Right Symmetric (Fig. 10)	$M_R > 1.2$ TeV ($m_{D_1} = 0.5$ TeV)
	$(\Delta m/m_{D_1})/M_R > 0.4$ TeV^{-1}
Vector Leptoquark Bosons (Fig. 11)	$M_{VLQ} > 55(\lambda_{PP}/0.1)$ TeV
Flavor Conserving Two-Higgs-Doublet (Fig. 13)	No constraint
Flavor Changing Neutral Higgs (Fig. 15)	$m_H/C > 2.4 \cdot 10^3$ TeV
FC Neutral Higgs (Cheng-Sher ansatz) (Fig. 16)	$m_H/|\Delta_{uc}| > 600$ GeV
Scalar Leptoquark Bosons	See entry for RPV SUSY
Higgsless (Fig. 17)	$M > 100$ TeV
Universal Extra Dimensions	No constraint
Split Fermion (Fig. 19)	$M/|\Delta y| > (6 \cdot 10^2$ GeV$)$
Warped Geometries (Fig. 21)	$M_1 > 3.5$ TeV
Minimal Supersymmetric Standard (Fig. 23)	$|(\delta^u_{12})_{LR,RL}| < 3.5 \cdot 10^{-2}$ for $\tilde{m} \sim 1$ TeV
	$|(\delta^u_{12})_{LL,RR}| < .25$ for $\tilde{m} \sim 1$ TeV
Supersymmetric Alignment	$\tilde{m} > 2$ TeV
Supersymmetry with RPV (Fig. 27)	$\lambda'_{12k}\lambda'_{11k}/m_{\tilde{d}_{R,k}} < 1.8 \cdot 10^{-3}/100$ GeV
Split Supersymmetry	No constraint

E.Golowich, J. Hewett, S. Pakvasa and A.A.P.
Phys. Rev. D76:095009, 2007

Gedalia, Grossman, Nir, Perez
arXiv:0906.1879 [hep-ph]

Bigi, Blanke, Buras, Recksiegel,
JHEP 0907:097, 2009



CP-violation in charm

- How can CP-violation be observed in charm system?
  - can be observed by comparing CP-conjugated decay rates in various ways, both with and w/out time dependence

$$a_{\rm CP}(f) = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})},$$

  - can manifest itself in charm ΔC=1 transitions (direct CP-violation)

$$\Gamma(D \to f) \neq \Gamma(CP[D] \to CP[f]) \qquad \textbf{dCPV}$$

  - or in ΔC=2 transitions (indirect CP-violation): mixing $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D^0}\rangle$

$$R_m^2 = |q/p|^2 = \left|\frac{2M_{12}^* - i\Gamma_{12}^*}{\Delta m - (i/2)\Delta\Gamma}\right|^2 = 1 + A_m \neq 1 \qquad \textbf{CPVmix}$$

  - or in the interference b/w decays (ΔC=1) and mixing (ΔC=2)

$$\lambda_f = \frac{q}{p}\frac{\overline{A_f}}{A_f} = R_m e^{i(\phi+\delta)}\left|\frac{\overline{A_f}}{A_f}\right| \qquad \textbf{CPVint}$$

Direct CP-violation in charm: realities of life

★ IDEA: consider the DIFFERENCE of decay rate asymmetries: $D \to \pi\pi$ vs $D \to KK$!
For each final state the asymmetry

D^0: no neutrals in the final state!

$$a_f = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})} \Rightarrow a_f = a_f^d + a_f^m + a_f^i$$

direct — mixing — interference

★ A reason: $a^m_{KK} = a^m_{\pi\pi}$ and $a^i_{KK} = a^i_{\pi\pi}$ (for CP-eigenstate final states), so, ideally, mixing asymmetries cancel ($r_f = P_f/A_f$)!

$$a_f^d = 2 r_f \sin\phi_f \sin\delta_f$$

★ ... and the resulting DCPV asymmetry is $\Delta a_{CP} = a^d_{KK} - a^d_{\pi\pi} \approx 2 a^d_{KK}$ (double!)

$$A_{KK} = \frac{G_F}{\sqrt{2}} \lambda \left[(T + E + P_{sd}) + a\lambda^4 e^{-i\gamma} P_{bd} \right]$$

$$A_{\pi\pi} = \frac{G_F}{\sqrt{2}} \lambda \left[(-(T + E) + P_{sd}) + a\lambda^4 e^{-i\gamma} P_{bd} \right]$$

★ ... so it is doubled in the limit of $SU(3)_F$ symmetry

SU(3) is badly broken in D-decays

Experimental analysis from LHCb

★ Since we are comparing rates for D^0 and anti-D^0: need to tag the flavor at production

$$D^{*+} \to D^0 \pi_s^+$$

"D*-trick" -- tag the charge of the slow pion (or muon for D's produced in B-decays)

★ The difference Δa_{CP} is also preferable experimentally, as

$$a_f^{\rm raw} = a_f^{CP} + a_f^{\rm detect,\ D} + a_D^{\rm detect,\ \pi_s} + a_{D*}^{\rm prod}$$

- a_f^{CP}: physics
- $a_f^{\rm detect,\ D}$: detection asymmetry of D^0
- $a_D^{\rm detect,\ \pi_s}$: detection asymmetry of soft pion
- $a_{D*}^{\rm prod}$: production asymmetry of D^{*+}

★ D* production asymmetry and soft pion asymmetries are the same for KK and ππ final states-- they cancel in Δa_{CP}!

★ Integrate over time,

$$a_{CP,\ f} = \int_0^\infty a_{CP}(f;t) D(t) dt = a_f^d + \frac{\langle t \rangle}{\tau} a_f^{ind}$$

$D(t)$: distribution of proper decay time

★ Viola! Report observation!

Aftermath

- Experimental results
  - note that while the new result does constitute an observation of CP-violation in the difference…

$$\Delta a_{CP}^{dir} = a_{CP}(K^-K^+) - a_{CP}(\pi^-\pi^+) = (-0.156 \pm 0.029)\%$$

LHCb 2019

  - … it is not yet so for the individual decay asymmetries

$$a_{CP}(K^-K^+) = (0.04 \pm 0.12\ (\mathrm{stat}) \pm 0.10\ (\mathrm{syst}))\%\,,$$
$$a_{CP}(\pi^-\pi^+) = (0.07 \pm 0.14\ (\mathrm{stat}) \pm 0.11\ (\mathrm{syst}))\%\,.$$

LHCb 2017

- Need confirmation from other experiments (Belle II)
- What does this result mean? New Physics? Standard Model?

Theoretical troubles

IPPP/19/25
March 26, 2019

ΔA_{CP} within the Standard Model and beyond

Mikael Chala, Alexander Lenz, Aleksey V. Rusov and Jakub Scholtz

Institute for Particle Physics Phenomenology, Durham University,
DH1 3LE Durham, United Kingdom

Implications on the first observation of charm CPV at LHCb

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[1]*Institute of Physics, Academia Sinica,*

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The Emergence of the $\Delta U = 0$ Rule in Charm Physics

Yuval Grossman[*] and Stefan Schacht[†]

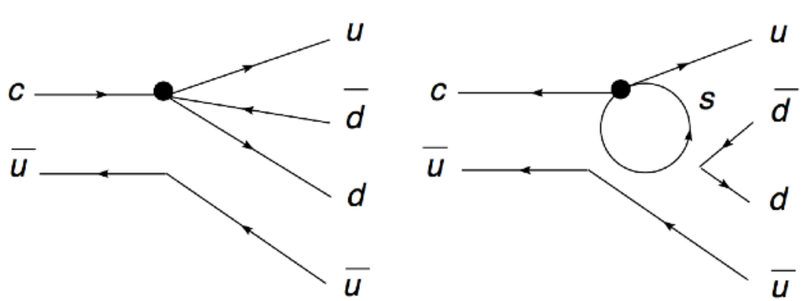
Department of Physics, LEPP, Cornell University, Ithaca, NY 14853, USA

Theoretical troubles

★ These asymmetries are notoriously difficult to compute

★ In the Standard Model

- need to estimate size of penguin/penguin contractions vs. tree



- unknown penguin contribution (similar to $\Delta I = 1/2$)
  - SU(3) analysis: some ME are enhanced?

    Golden & Grinstein PLB 222 (1989) 501; Pirtshalava & Uttayarat 1112.5451
  - could expect large $1/m_c$ corrections

    Isidori et al PLB 711 (2012) 46; Brod et al 1111.5000
  - no assumptions, flavor-flow diagrams

    Broad et al 1203.6659; Bhattacharya et al PRD 85 (2012) 054014; Cheng & Chiang 1205.0580

★ Theoretical progress?

- QCD sum rule calculations of Δa_{CP} Khodjamirian, AAP
- SU(3) breaking analyses of $D \to PV, VV$
- constant (but slow) lattice QCD progress in $D \to \pi\pi, \pi\pi\pi$

  Hansen, Sharpe

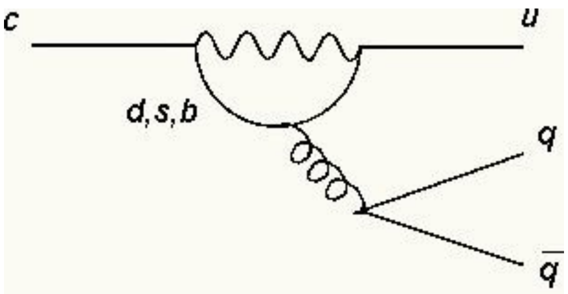
★ Other points: CP-fractions in Dalitz plot analyses

★ e.g., why is $D \to \pi^+\pi^-\pi^0$ ~97% CP-even? Bhattacharya, et al; Gronau, Rosner

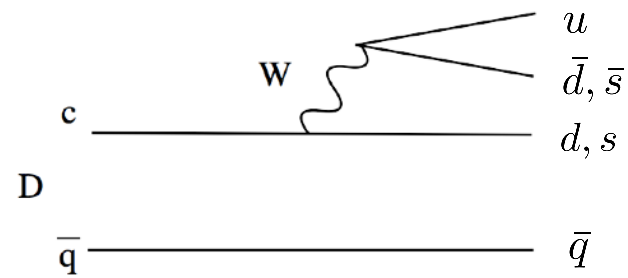
Generic expectations for sizes of CPV effects

★ Generic expectation is that CP-violating observables in the SM are small

Δc = 1 amplitudes allow to reach third -generation quarks!



"Penguin" amplitude



"Tree" amplitude

★ The Unitarity Triangle relation for charm:

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$$

$$\sim\lambda \qquad \sim\lambda \qquad \sim\lambda^5$$

With b-quark contribution neglected: only **2** generations contribute $\Rightarrow$ **real 2x2 Cabibbo matrix**

Any CP-violating signal in the SM will be small, at most $O(V_{ub}V_{cb}^*/V_{us}V_{cs}^*) \sim 10^{-3}$

Thus, O(1%) CP-violating signal can provide a "smoking gun" signature of New Physics

- Effective Hamiltonian for singly Cabibbo-suppressed (SCS) decays
  - drop all "penguin" operators (Q_i for i ≥ 3) as C_i are small, $\lambda_q = V_{uq} V_{cq}^*$,

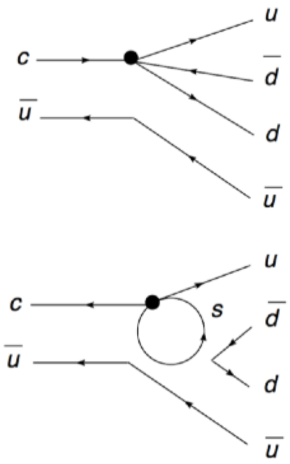
$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} \left[\sum_{q=d,s} \lambda_q \left(C_1 \mathcal{Q}_1^q + C_2 \mathcal{Q}_2^q \right) - \lambda_b \sum_{i=3,\dots,6,8g} C_i \mathcal{Q}_i \right]$$

$$\mathcal{Q}_1^q = (\bar{u}\Gamma_\mu q)(\bar{q}\Gamma^\mu c)\,, \qquad \mathcal{Q}_2^q = (\bar{q}\Gamma_\mu q)(\bar{u}\Gamma^\mu c)$$

  - recall that $\sum_{q=d,s,b} \lambda_q = 0 \;\; \text{or} \;\; \lambda_d = -(\lambda_s + \lambda_b)$ and $\mathcal{O}^q \equiv \frac{G_F}{\sqrt{2}} \sum_{i=1,2} C_i \mathcal{Q}_i^q\,, \quad \text{with} \;\; q = d, s.$

without QCD

with QCD



Amplitude decomposition

- Recipe for calculation of CPV asymmetry
  - prepare decay amplitudes

$$A(D^0 \to \pi^-\pi^+) = \lambda_d \langle \pi^-\pi^+|\mathcal{O}^d|D^0\rangle + \lambda_s \langle \pi^-\pi^+|\mathcal{O}^s|D^0\rangle$$
$$A(D^0 \to K^-K^+) = \lambda_s \langle K^-K^+|\mathcal{O}^s|D^0\rangle + \lambda_d \langle K^-K^+|\mathcal{O}^d|D^0\rangle$$

  - add and subtract $\lambda_b \langle \pi^-\pi^+|\mathcal{O}^s|D^0\rangle$, put in a new form

$$A(D^0 \to \pi^-\pi^+) = -\lambda_s \mathcal{A}_{\pi\pi} \left[1 + \frac{\lambda_b}{\lambda_s}\left(1 + r_\pi \exp(i\delta_\pi)\right)\right]$$
$$A(D^0 \to K^-K^+) = \lambda_s \mathcal{A}_{KK} \left[1 - \frac{\lambda_b}{\lambda_s} r_K \exp(i\delta_K)\right]$$

  - define things we cannot compute (extract from branching ratios)

$$\mathcal{A}_{\pi\pi} = \langle \pi^-\pi^+|\mathcal{O}^d|D^0\rangle - \langle \pi^-\pi^+|\mathcal{O}^s|D^0\rangle$$
$$\mathcal{A}_{KK} = \langle K^-K^+|\mathcal{O}^s|D^0\rangle - \langle K^-K^+|\mathcal{O}^d|D^0\rangle$$

  - … and things we can $\mathcal{P}^s_{\pi\pi} = \langle \pi^-\pi^+|\mathcal{O}^s|D^0\rangle\,, \quad \mathcal{P}^d_{KK} = \langle K^-K^+|\mathcal{O}^d|D^0\rangle$

$$r_\pi = \left|\frac{\mathcal{P}^s_{\pi\pi}}{\mathcal{A}_{\pi\pi}}\right|, \quad r_K = \left|\frac{\mathcal{P}^d_{KK}}{\mathcal{A}_{KK}}\right|$$

Direct CP-violating asymmetries

- QCD-based calculation of direct CPV asymmetry
  - each amplitude has two parts with own weak and strong phases

$$A(D^0 \to \pi^-\pi^+) = -\lambda_s \mathcal{A}_{\pi\pi}\left[1 + \frac{\lambda_b}{\lambda_s}\left(1 + r_\pi \exp(i\delta_\pi)\right)\right]$$
$$A(D^0 \to K^-K^+) = \lambda_s \mathcal{A}_{KK}\left[1 - \frac{\lambda_b}{\lambda_s} r_K \exp(i\delta_K)\right]$$

  - this implies for the direct CP-violating asymmetries ($r_b e^{-i\gamma} = \frac{\lambda_b}{\lambda_s}$)

$$a_{CP}^{dir}(K^-K^+) = -2 r_b r_K \sin\delta_K \sin\gamma$$
$$a_{CP}^{dir}(\pi^-\pi^+) = 2 r_b r_\pi \sin\delta_\pi \sin\gamma$$

  - … and for their difference

$$\Delta a_{CP}^{dir} = -2 r_b \sin\gamma (r_K \sin\delta_K + r_\pi \sin\delta_\pi)$$

- We need to compute $r_{\pi(K)}$ and $\delta_{\pi(K)}$

dCPV: amplitude decomposition

- Some things to keep in mind
  - "penguin-type amplitudes" $\mathcal{P}^s_{\pi\pi}$ and $\mathcal{P}^d_{KK}$ denote matrix elements of operators that contain quark-antiquark pair that does not match the valence content of the final state mesons; otherwise no relation to penguin topological amplitudes

$$\mathcal{P}^s_{\pi\pi} = \langle \pi^-\pi^+ | \mathcal{O}^s | D^0 \rangle \,, \quad \mathcal{P}^d_{KK} = \langle K^- K^+ | \mathcal{O}^d | D^0 \rangle \;\; \& \;\; r_\pi = \left| \frac{\mathcal{P}^s_{\pi\pi}}{\mathcal{A}_{\pi\pi}} \right| \,, \quad r_K = \left| \frac{\mathcal{P}^d_{KK}}{\mathcal{A}_{KK}} \right|$$

  - calculate $\mathcal{P}^s_{\pi\pi}$ and $\mathcal{P}^d_{KK}$ using a modified light-cone QCD sum rules

$$\delta_{\pi(K)} = \arg\left[\mathcal{P}^{s(d)}_{\pi\pi(KK)}\right] - \arg\left[\mathcal{A}_{\pi\pi(KK)}\right]$$

  - extract $\mathcal{A}_{\pi\pi}$ and $\mathcal{A}_{KK}$ amplitudes from measured branch. fractions

$$|\mathcal{A}_{\pi\pi}| \simeq \lambda_s^{-1} \left| A(D \to \pi^-\pi^+) \right| = (2.10 \pm 0.02) \times 10^{-6} \text{ GeV} \,,$$
$$|\mathcal{A}_{KK}| \simeq \lambda_s^{-1} \left| A(D \to K^-K^+) \right| = (3.80 \pm 0.03) \times 10^{-6} \text{ GeV} \,.$$

dCPV: calculating matrix elements

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- Use modified light-cone QCD Sum Rule (LCSR) method
  - start with the correlation function ($j_5^{(D)} = im_c \bar{c}\gamma_5 u$ and $j_{\alpha 5}^{(\pi)} = \bar{d}\gamma_\alpha\gamma_5 u$)

$$F_\alpha(p,q,k) = i^2 \int d^4x e^{-i(p-q)x} \int d^4y e^{i(p-k)y} \langle 0|\ T\left\{ j_{\alpha 5}^{(\pi)}(y) \mathcal{Q}_1^s(0) j_5^{(D)}(x) \right\} |\pi^+(q)\rangle$$
$$= (p-k)_\alpha F((p-k)^2, (p-q)^2, P^2) + \ldots,$$

  - use dispersion relation in (p-k) and (p-q), perform Borel transform, extract matrix element:

$$\langle \pi^-(-q)\pi^+(p)|\mathcal{Q}_1^s|D^0(p-q)\rangle = \frac{-i}{\pi^2 f_\pi f_D m_D^2} \int_0^{s_0^\pi} ds e^{-s/M_1^2} \int_{m_c^2}^{s_0^D} ds' e^{(m_D^2-s')/M_2^2} \mathrm{Im}_{s'} \mathrm{Im}_s F(s,s',m_D^2)$$

  - perform LC expansion of F(s, s' m_D^2) to get $\mathcal{P}_{\pi\pi}^s$
  - note that $C_1 \mathcal{Q}_1^s + C_2 \mathcal{Q}_2^s = 2C_1 \widetilde{\mathcal{Q}}_2^s + \left(\frac{C_1}{3} + C_2\right) \mathcal{Q}_2^s$ with $\widetilde{\mathcal{Q}}_2^s = \left(\bar{s}\Gamma_\mu \frac{\lambda^a}{2} s\right)\left(\bar{u}\Gamma^\mu \frac{\lambda^a}{2} c\right)$

thus $\mathcal{P}_{\pi\pi}^s = \frac{2G_F}{\sqrt{2}} C_1 \langle \pi^+\pi^-|\widetilde{\mathcal{Q}}_2^s|D^0\rangle$

dCPV: calculating matrix elements

- Evaluate (leading) diagrams contributing to the correlation function
  - calculate OPE in terms of known LC DAs

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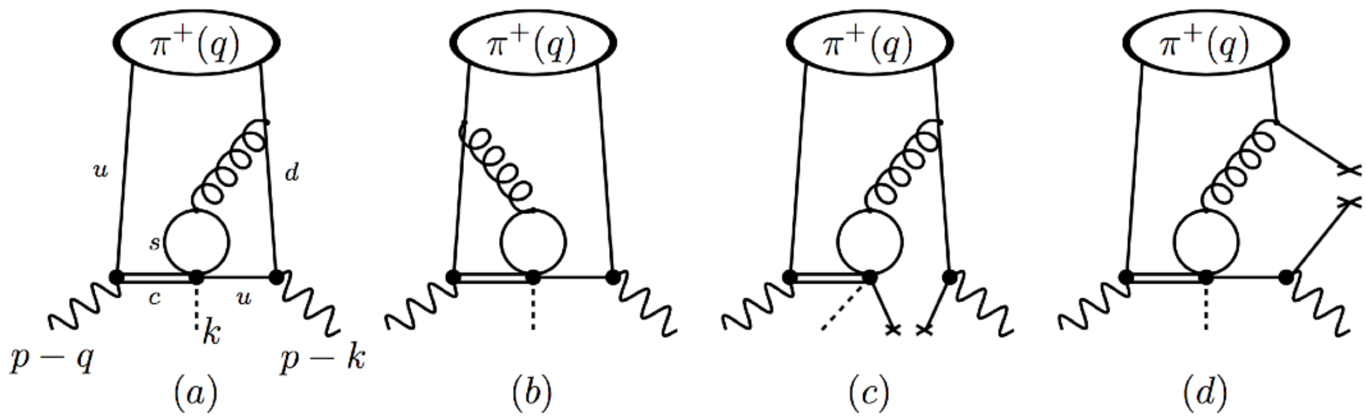

  - analytically continue from the space-like region of $P^2=(p-k-q)^2$ (with auxiliary 4-momentum $k\neq0$) to $P^2 = m_D^2$, relying on the local quark-hadron duality
  - extract absolute value and the phase of matrix element $\mathcal{P}^s_{\pi\pi}$
  - vary parameters of the calculation to estimate uncertainties

dCPV predictions

- As a result… $\langle \pi^+\pi^-|\widetilde{\mathcal{Q}}_2^s|D^0\rangle = (9.50 \pm 1.13) \times 10^{-3} \exp[i(-97.5^o \pm 11.6)]\,\mathrm{GeV}^3$

$$\langle K^+K^-|\widetilde{\mathcal{Q}}_2^d|D^0\rangle = (13.9 \pm 2.70) \times 10^{-3} \exp[i(-71.6^o \pm 29.5)]\,\mathrm{GeV}^3$$

- Thus, $r_\pi = \frac{|\mathcal{P}^s_{\pi\pi}|}{|\mathcal{A}_{\pi\pi}|} = 0.093 \pm 0.011\,, \qquad r_K = \frac{|\mathcal{P}^d_{KK}|}{|\mathcal{A}_{KK}|} = 0.075 \pm 0.015$

and with $\Delta a_{CP}^{dir} = -2 r_b \sin\gamma (r_K \sin\delta_K + r_\pi \sin\delta_\pi)$

- Phases of $r_{\pi\pi(KK)}$ are given by the phases of $\mathcal{P}^{s(d)}_{\pi\pi(KK)}$?

No:

$$\left|a_{CP}^{dir}(\pi^-\pi^+)\right| < 0.012 \pm 0.001\%,$$
$$\left|a_{CP}^{dir}(K^-K^+)\right| < 0.009 \pm 0.002\%,$$
$$\left|\Delta a_{CP}^{dir}\right| < 0.020 \pm 0.003\%\,.$$

Yes:

$$a_{CP}^{dir}(\pi^-\pi^+) = -0.011 \pm 0.001\%,$$
$$a_{CP}^{dir}(K^-K^+) = \quad 0.009 \pm 0.002\%.$$
$$\Delta a_{CP}^{dir} = \quad 0.020 \pm 0.003\%\,.$$

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- Again, experiment: $\Delta a_{CP}^{dir} = (-0.156 \pm 0.029)\%$

Error budget: parameter uncertainties

Parameter values and references	Parameter rescaled to $\mu = 1.5$ GeV
$\alpha_s(m_Z) = 0.1181 \pm 0.0011$ [6]	0.351
$\bar{m}_c(\bar{m}_c) = 1.27 \pm 0.03$ GeV [6]	1.19 GeV
$\bar{m}_s(2\,\text{GeV}) = 96^{+8}_{-4}\,\text{MeV}$ [6]	105 MeV
$\langle \bar{q}q \rangle(2\,\text{GeV}) = (-276^{+12}_{-10}\,\text{MeV})^3$ [6]	$(-268\,\text{MeV})^3$
$\langle \bar{s}s \rangle = (0.8 \pm 0.3)\langle \bar{q}q \rangle$ [21]	$(-249\ \text{MeV})^3$
$a_2^\pi(1\,\text{GeV}) = 0.17 \pm 0.08$ [22]	0.14
$a_4^\pi(1\,\text{GeV}) = 0.06 \pm 0.10$ [22]	0.045
$\mu_\pi(2\,\text{GeV}) = 2.48 \pm 0.30\,\text{GeV}$ [6]	2.26 GeV
$f_{3\pi}(1\,\text{GeV}) = 0.0045 \pm 0.015\ \text{GeV}^2$ [19]	$0.0036\,\text{GeV}^2$
$\omega_{3\pi}(1\,\text{GeV}) = -1.5 \pm 0.7$ [19]	-1.1
$a_1^K(1\,\text{GeV}) = 0.10 \pm 0.04$ [23]	0.09
$a_2^K(1\,\text{GeV}) = 0.25 \pm 0.15$ [19]	0.21
$\mu_K(2\,\text{GeV}) = 2.47^{+0.19}_{-0.10}\ \text{GeV}$ [6]	2.25
$f_{3K} = f_{3\pi}$	$0.0036\,\text{GeV}^2$
$\omega_{3K}(1\,\text{GeV}) = -1.2 \pm 0.7$ [19]	-0.99
$\lambda_{3K}(1\,\text{GeV}) = 1.6 \pm 0.4$ [19]	1.5

Things to take home

- The magnitude of hadronic MEs defining CPV are computed

$$r_\pi = \frac{|\mathcal{P}^s_{\pi\pi}|}{|\mathcal{A}_{\pi\pi}|} = 0.093 \pm 0.011\,, \qquad r_K = \frac{|\mathcal{P}^d_{KK}|}{|\mathcal{A}_{KK}|} = 0.075 \pm 0.015$$

- The magnitude of direct CPV asymmetry in $D \to \pi^+\pi^-$ and $D \to K^+K^-$ can be predicted from the calculation of the relevant hadronic matrix elements from LCSRs

$$\Delta a^{dir}_{CP} = 0.020 \pm 0.003\%$$

- No topological amplitude decomposition was used (note that OPE hierarchy sorts out the leading penguin-type diagrams)
- The strong phase difference is not yet reliably accessible: duality violations are not easily identifiable (e.g. broad scalar resonances influencing hadronic matrix elements)

(Lepton) flavor violation in charm

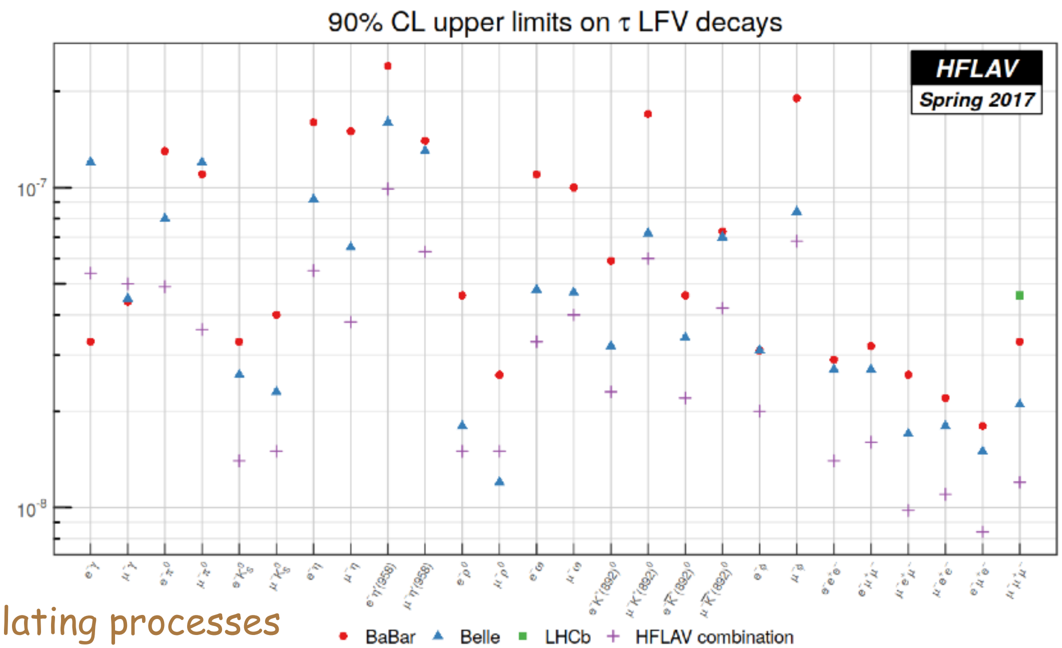
Introduction: leptonic FCNC

★ Why study flavor-changing neutral currents (FCNC)?

★ No trivial FCNC vertices in the Standard Model: sensitive NP tests

★ Possible experimental studies of a lepton sector at Belle II

- lepton-flavor violating processes
  - $\mu \to e\gamma$, $\tau \to e\gamma$, etc.
  - $\mu \to eee$, $\tau \to \mu ee$, etc.
  - $\mu^+ e^- \to e^- \mu^+$
  - $Z^0 \to \mu e$, τe, etc.
  - $H \to \mu e$, τe, etc.
  - K^0 (B^0, D^0, ...) $\to \mu e$, τe, etc.
  - K^+ (B^+, D^+, ...) $\to \pi^+ \mu e$, $\pi^+ \tau e$, etc.
  - $\mu^- + (A, Z) \to e^- + (A, Z)$



- lepton number and lepton-flavor violating processes
  - $(A, Z) \to (A, Z\pm2) + e^{\mp} e^{\mp}$
  - $\mu^- + (A, Z) \to e^+ + (A, Z-2)$

★ Highly suppressed in the Standard Model, e.g. $Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{M^2_W} \right|^2 < 10^{-54}$

Effective Lagrangians

★ Naive power counting: largest contribution from lowest dimensional operators

★ Can write the most general LFV Lagrangian $\mathcal{L}_{LFV} = \mathcal{L}_D + \mathcal{L}_{lq} + \mathcal{L}_G + \ldots$

- dipole operators

$$\mathcal{L}_D = -\frac{m_2}{\Lambda^2}\left[\left(C_{DR}\bar{\ell}_1\sigma^{\mu\nu}P_L\ell_2 + C_{DR}\bar{\ell}_1\sigma^{\mu\nu}P_R\ell_2\right)F_{\mu\nu} + h.c.\right]$$

- four-fermion operators

$$\begin{aligned}\mathcal{L}_{\ell q} = -\frac{1}{\Lambda^2}\sum_q \Big[& \left(C_{VR}^{q\ell_1\ell_2}\ \bar{\ell}_1\gamma^\mu P_R\ell_2 + C_{VL}^{q\ell_1\ell_2}\ \bar{\ell}_1\gamma^\mu P_L\ell_2\right)\ \bar{q}\gamma_\mu q \\ & + \left(C_{AR}^{q\ell_1\ell_2}\ \bar{\ell}_1\gamma^\mu P_R\ell_2 + C_{AL}^{q\ell_1\ell_2}\ \bar{\ell}_1\gamma^\mu P_L\ell_2\right)\ \bar{q}\gamma_\mu\gamma_5 q \\ & + m_2 m_q G_F\left(C_{SR}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_L\ell_2 + C_{SL}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_R\ell_2\right)\ \bar{q}q \\ & + m_2 m_q G_F\left(C_{PR}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_L\ell_2 + C_{PL}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_R\ell_2\right)\ \bar{q}\gamma_5 q \\ & + m_2 m_q G_F\left(C_{TR}^{q\ell_1\ell_2}\ \bar{\ell}_1\sigma^{\mu\nu}P_L\ell_2 + C_{TL}^{q\ell_1\ell_2}\ \bar{\ell}_1\sigma^{\mu\nu}P_R\ell_2\right)\ \bar{q}\sigma_{\mu\nu}q\ +\ h.c.\ \Big].\end{aligned}$$

- gluonic operators

$$\begin{aligned}\mathcal{L}_G = -\frac{m_2 G_F}{\Lambda^2}\frac{\beta_L}{4\alpha_s}\Big[& \left(C_{GR}\bar{\ell}_1 P_R\ell_2 + C_{GL}\bar{\ell}_1 P_L\ell_2\right)G_{\mu\nu}^a G^{a\mu\nu} \\ & + \left(C_{\tilde{G}R}\bar{\ell}_1 P_R\ell_2 + C_{\tilde{G}L}\bar{\ell}_1 P_L\ell_2\right)G_{\mu\nu}^a \widetilde{G}^{a\mu\nu} + h.c.\Big]\end{aligned}$$

Effective Lagrangians: designer states

★ There are many effective operators, so a single operator dominance hypothesis (SODH) is usually applied to get constraints on relevant Wilson coefficients.

This does <u>not</u> happen in most NP models!

$$
\begin{aligned}
\mathcal{L}_{\ell q} = -\frac{1}{\Lambda^2}\sum_q \Big[& \left(C_{VR}^{q\ell_1\ell_2}\,\overline{\ell}_1\gamma^\mu P_R\ell_2 + C_{VL}^{q\ell_1\ell_2}\,\overline{\ell}_1\gamma^\mu P_L\ell_2\right)\,\overline{q}\gamma_\mu q \\
& + \left(C_{AR}^{q\ell_1\ell_2}\,\overline{\ell}_1\gamma^\mu P_R\ell_2 + C_{AL}^{q\ell_1\ell_2}\,\overline{\ell}_1\gamma^\mu P_L\ell_2\right)\,\overline{q}\gamma_\mu\gamma_5 q \\
& + m_2 m_q G_F\left(C_{SR}^{q\ell_1\ell_2}\,\overline{\ell}_1 P_L\ell_2 + C_{SL}^{q\ell_1\ell_2}\,\overline{\ell}_1 P_R\ell_2\right)\,\overline{q}q \\
& + m_2 m_q G_F\left(C_{PR}^{q\ell_1\ell_2}\,\overline{\ell}_1 P_L\ell_2 + C_{PL}^{q\ell_1\ell_2}\,\overline{\ell}_1 P_R\ell_2\right)\,\overline{q}\gamma_5 q \\
& + m_2 m_q G_F\left(C_{TR}^{q\ell_1\ell_2}\,\overline{\ell}_1\sigma^{\mu\nu} P_L\ell_2 + C_{TL}^{q\ell_1\ell_2}\,\overline{\ell}_1\sigma^{\mu\nu} P_R\ell_2\right)\,\overline{q}\sigma_{\mu\nu} q \;+\; h.c.\Big].
\end{aligned}
$$

- Can (partially) do away with SODH if designer initial/final states are used
- This can be done in case of restricted kinematics (e.g. 2-body decays)

★ Much tighter constraints on dipole operators are obtained from lepton radiative decays: <u>drop</u> them from quarkonium decay analyses in what follows

Effective Lagrangians: designer states

★ By selecting appropriate quantum numbers of a decaying state we can probe all Wilson coefficients of LFV Lagrangian!

$$
\begin{aligned}
\mathcal{L}_{\ell q} = -\frac{1}{\Lambda^2} \sum_q \Big[& \left(C_{VR}^{q\ell_1\ell_2}\ \bar{\ell}_1 \gamma^\mu P_R \ell_2 + C_{VL}^{q\ell_1\ell_2}\ \bar{\ell}_1 \gamma^\mu P_L \ell_2 \right)\ \bar{q}\gamma_\mu q \\
& + \left(C_{AR}^{q\ell_1\ell_2}\ \bar{\ell}_1 \gamma^\mu P_R \ell_2 + C_{AL}^{q\ell_1\ell_2}\ \bar{\ell}_1 \gamma^\mu P_L \ell_2 \right)\ \bar{q}\gamma_\mu \gamma_5 q \\
& + m_2 m_q G_F \left(C_{SR}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_L \ell_2 + C_{SL}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_R \ell_2 \right)\ \bar{q} q \\
& + m_2 m_q G_F \left(C_{PR}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_L \ell_2 + C_{PL}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_R \ell_2 \right)\ \bar{q}\gamma_5 q \\
& + m_2 m_q G_F \left(C_{TR}^{q\ell_1\ell_2}\ \bar{\ell}_1 \sigma^{\mu\nu} P_L \ell_2 + C_{TL}^{q\ell_1\ell_2}\ \bar{\ell}_1 \sigma^{\mu\nu} P_R \ell_2 \right)\ \bar{q}\sigma_{\mu\nu} q + \ h.c. \Big].
\end{aligned}
$$

also dipole operators

Vector meson decays: $\Upsilon(nS) \to \bar{\mu}\tau, \psi(nS) \to \bar{\mu}\tau, \rho \to \bar{\mu}e, \ldots$

D. Hazard and A.A.P., PRD94 (2016), 074023
D. Hazard and A.A.P., PRD98 (2018), 015027

★ By selecting appropriate quantum numbers of a decaying state we can probe all Wilson coefficients of LFV Lagrangian!

$$\mathcal{L}_{\ell q} = -\frac{1}{\Lambda^2}\sum_q \Big[\left(C_{VR}^{q\ell_1\ell_2}\ \bar{\ell}_1\gamma^\mu P_R\ell_2 + C_{VL}^{q\ell_1\ell_2}\ \bar{\ell}_1\gamma^\mu P_L\ell_2 \right)\ \bar{q}\gamma_\mu q$$
$$+ \left(C_{AR}^{q\ell_1\ell_2}\ \bar{\ell}_1\gamma^\mu P_R\ell_2 + C_{AL}^{q\ell_1\ell_2}\ \bar{\ell}_1\gamma^\mu P_L\ell_2 \right)\ \bar{q}\gamma_\mu\gamma_5 q$$
$$+ m_2 m_q G_F \left(C_{SR}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_L\ell_2 + C_{SL}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_R\ell_2 \right)\ \bar{q}q$$
$$+ m_2 m_q G_F \left(C_{PR}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_L\ell_2 + C_{PL}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_R\ell_2 \right)\ \bar{q}\gamma_5 q$$
$$+ m_2 m_q G_F \left(C_{TR}^{q\ell_1\ell_2}\ \bar{\ell}_1\sigma^{\mu\nu} P_L\ell_2 + C_{TL}^{q\ell_1\ell_2}\ \bar{\ell}_1\sigma^{\mu\nu} P_R\ell_2 \right)\ \bar{q}\sigma_{\mu\nu} q\ +\ h.c.\ \Big].$$

also gluonic operators

Pseudoscalar meson decays: $\eta_b \to \overline{\mu}e, \eta_c \to \overline{\mu}\tau, \eta^{(\prime)} \to \overline{\mu}e, \ldots$

D. Hazard and A.A.P., PRD94 (2016), 074023
D. Hazard and A.A.P., PRD98 (2018), 015027

Effective Lagrangians: designer states

★ By selecting appropriate quantum numbers of a decaying state we can probe all Wilson coefficients of LFV Lagrangian!

$$\mathcal{L}_{\ell q} = -\frac{1}{\Lambda^2} \sum_q \Big[\left(C_{VR}^{q\ell_1\ell_2}\ \bar{\ell}_1 \gamma^\mu P_R \ell_2 + C_{VL}^{q\ell_1\ell_2}\ \bar{\ell}_1 \gamma^\mu P_L \ell_2 \right)\ \bar{q}\gamma_\mu q$$
$$+ \left(C_{AR}^{q\ell_1\ell_2}\ \bar{\ell}_1 \gamma^\mu P_R \ell_2 + C_{AL}^{q\ell_1\ell_2}\ \bar{\ell}_1 \gamma^\mu P_L \ell_2 \right)\ \bar{q}\gamma_\mu\gamma_5 q$$
$$+ m_2 m_q G_F \left(C_{SR}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_L \ell_2 + C_{SL}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_R \ell_2 \right)\ \bar{q}q$$
$$+ m_2 m_q G_F \left(C_{PR}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_L \ell_2 + C_{PL}^{q\ell_1\ell_2}\ \bar{\ell}_1 P_R \ell_2 \right)\ \bar{q}\gamma_5 q$$
$$+ m_2 m_q G_F \left(C_{TR}^{q\ell_1\ell_2}\ \bar{\ell}_1 \sigma^{\mu\nu} P_L \ell_2 + C_{TL}^{q\ell_1\ell_2}\ \bar{\ell}_1 \sigma^{\mu\nu} P_R \ell_2 \right)\ \bar{q}\sigma_{\mu\nu} q\ +\ h.c. \Big].$$

also gluonic operators

Scalar meson decays: $\chi_{b0} \to \overline{\mu}\tau,\ \chi_{c0} \to \overline{\mu}\tau,\ \ldots$

D. Hazard and A.A.P., PRD94 (2016), 074023
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LFV vector quarkonia decays

★ Most LFV experimental data available V → μe, τe, etc.

$\ell_1\ell_2$	$\mu\tau$	$e\tau$	$e\mu$
$\mathcal{B}(\Upsilon(1S) \to \ell_1\ell_2)$	6.0×10^{-6}	$\cdots$	$\cdots$
$\mathcal{B}(\Upsilon(2S) \to \ell_1\ell_2)$	3.3×10^{-6}	3.2×10^{-6}	$\cdots$
$\mathcal{B}(\Upsilon(3S) \to \ell_1\ell_2)$	3.1×10^{-6}	4.2×10^{-6}	$\cdots$
$\mathcal{B}(J/\psi \to \ell_1\ell_2)$	2.0×10^{-6}	8.3×10^{-6}	1.6×10^{-7}
$\mathcal{B}(\phi \to \ell_1\ell_2)$	FPS	FPS	4.1×10^{-6}
$\mathcal{B}(\ell_2 \to \ell_1\gamma)$	4.4×10^{-8}	3.3×10^{-8}	5.7×10^{-13}

★ Decay amplitude:

$$\mathcal{A}(V \to \ell_1\bar{\ell}_2) = \bar{u}(p_1, s_1)\left[A_V^{\ell_1\ell_2}\gamma_\mu + B_V^{\ell_1\ell_2}\gamma_\mu\gamma_5 + \frac{C_V^{\ell_1\ell_2}}{m_V}(p_2 - p_1)_\mu + \frac{iD_V^{\ell_1\ell_2}}{m_V}(p_2 - p_1)_\mu\gamma_5\right] v(p_2, s_2)\ \epsilon^\mu(p).$$

★ Decay rate:

$$\frac{\mathcal{B}(V \to \ell_1\bar{\ell}_2)}{\mathcal{B}(V \to e^+e^-)} = \left(\frac{m_V(1-y^2)}{4\pi\alpha f_V Q_q}\right)^2 \Big[(|A_V^{\ell_1\ell_2}|^2 + |B_V^{\ell_1\ell_2}|^2) + \frac{1}{2}(1-2y^2)(|C_V^{\ell_1\ell_2}|^2 + |D_V^{\ell_1\ell_2}|^2) + y\mathrm{Re}(A_V^{\ell_1\ell_2}C_V^{\ell_1\ell_2 *} + iB_V^{\ell_1\ell_2}D_V^{\ell_1\ell_2 *})\Big].$$

Form-factors depend on vector, tensor, and dipole Wilson coefficients

LFV (pseudo)scalar quarkonia decays

★ Most general decay rate for P/S → μe, τe, etc ($P = \eta_b, \eta_c, \eta^{(\prime)}, \dots$):
$S = \chi_{b0}, \chi_{c0}, \dots$

D. Hazard and A.A.P., PRD94 (2016), 074023

$$\mathcal{B}(M \to \ell_1 \bar{\ell}_2) = \frac{m_M}{8\pi\Gamma_M} \left(1 - y^2\right)^2 \left[\left|E_M^{\ell_1\ell_2}\right|^2 + \left|F_M^{\ell_1\ell_2}\right|^2 \right]$$

… for pseudoscalar operators

$$E_P^{\ell_1\ell_2} = y \frac{m_P}{4\Lambda^2} \left[-i f_P \left[2 \left(C_{AL}^{cc\ell_1\ell_2} + C_{AR}^{cc\ell_1\ell_2} \right) - m_P^2 G_F \left(C_{PL}^{cc\ell_1\ell_2} + C_{PR}^{cc\ell_1\ell_2} \right) \right] \right]$$

$$F_P^{\ell_1\ell_2} = -y \frac{m_P}{4\Lambda^2} \left[f_P \left[2 \left(C_{AL}^{cc\ell_1\ell_2} - C_{AR}^{cc\ell_1\ell_2} \right) - m_P^2 G_F \left(C_{PL}^{cc\ell_1\ell_2} - C_{PR}^{cc\ell_1\ell_2} \right) \right] \right]$$

… and for scalar operators

$$E_S^{\ell_1\ell_2} = i y f_S m_c \frac{m_S^2 G_F}{2\Lambda^2} \left(C_{SL}^{ccl_1l_2} + C_{SR}^{ccl_1l_2} \right)$$

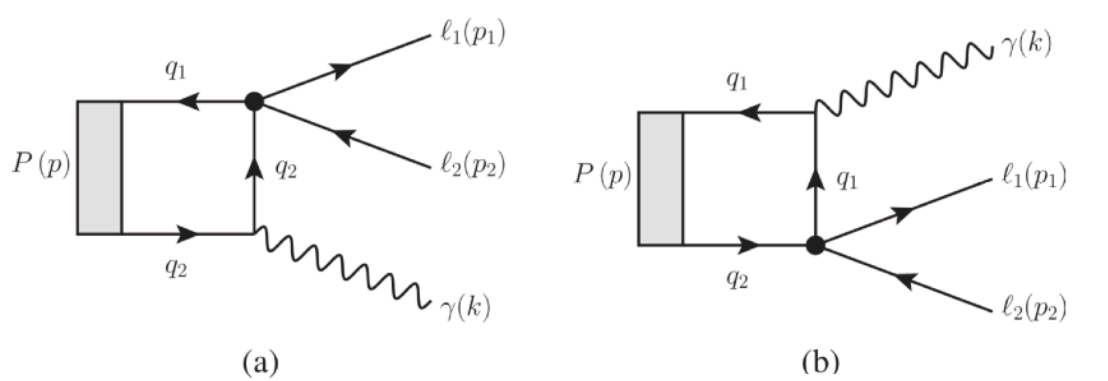
$$F_S^{\ell_1\ell_2} = y f_S m_c \frac{m_S^2 G_F}{2\Lambda^2} \left(C_{SL}^{ccl_1l_2} - C_{SR}^{ccl_1l_2} \right)$$

Gluonic operators?

There is NO experimental data on LFV (pseudo)scalar quarkonia decays!!!

★ More data is needed: use radiative decays: $A(P(p) \to \gamma(k)\ell_1(p_1)\bar{\ell}_2(p_2))$

$$= \bar{u}(p_1, s_1) M^\mu(p,k,q) v(p_2, s_2) \varepsilon^*_\mu(k),$$



★ Most general parameterization: $M^\mu(p,k,q)$

$$= \gamma^\mu (M_1^{P\ell_1\ell_2} + \not{k} M_2^{P\ell_1\ell_2}) + i\gamma_5\gamma^\mu (M_3^{P\ell_1\ell_2} + \not{k} M_4^{P\ell_1\ell_2})$$
$$+ q^\mu (M_5^{P\ell_1\ell_2} + \not{k} M_6^{P\ell_1\ell_2}) + i\gamma_5 q^\mu (M_7^{P\ell_1\ell_2} + \not{k} M_8^{P\ell_1\ell_2})$$
$$+ p^\mu (M_9^{q\ell_1\ell_2} + \not{k} M_{10}^{q\ell_1\ell_2}) + i\gamma_5 p^\mu (M_{11}^{P\ell_1\ell_2} + \not{k} M_{12}^{P\ell_1\ell_2}).$$

★ Not the most minimal set: gauge invariance? Project $P^{\mu\nu} = g^{\mu\nu} - \frac{p^\mu k^\nu}{(p \cdot k)}$

$$P^{\mu\nu} M_\nu = M^\mu \text{ and } k_\mu P^{\mu\nu} = 0,$$

D. Hazard and A.A.P., PRD98 (2018), 015027

★ A minimal set of amplitudes can be obtained

$$A(P(p) \to \gamma(k)\ell_1(p_1)\bar{\ell}_2(p_2)) = \bar{u}(p_1, s_1)M^\mu(p,k,q)v(p_2,s_2)\epsilon^*_\mu(k),$$

$$M^\mu(p,k,q) = \sum_i L_i^\mu(p,q,k)A_i^{P\ell_1\ell_2}(p^2,\ldots)$$

$$L_1^\mu = \gamma^\mu \not{k}, \qquad L_2^\mu = i\gamma_5\gamma^\mu\not{k},$$
$$L_3^\mu = (p\cdot k)q^\mu - (k\cdot q)p^\mu,$$
$$L_4^\mu = i\gamma_5[(p\cdot k)q^\mu - (k\cdot q)p^\mu],$$
$$L_5^\mu = (p\cdot k)\gamma^\mu - p^\mu\not{k},$$
$$L_6^\mu = i\gamma_5[(p\cdot k)\gamma^\mu - p^\mu\not{k}],$$
$$L_7^\mu = q^\mu\not{k} - (k\cdot q)\gamma^\mu,$$
$$L_8^\mu = i\gamma_5[q^\mu\not{k} - (k\cdot q)\gamma^\mu].$$

★ These amplitudes can be related to hadronic form-factors and Wilson coefficients. Complicated expression: single operator dominance again?

★ Simplification: select resonance region

$$\mathcal{B}(V \to \gamma\ell_1\bar{\ell}_2) = \mathcal{B}(V \to \gamma M)\mathcal{B}(M \to \ell_1\bar{\ell}_2)$$

$$\mathcal{B}(\psi(2S) \to \gamma\chi_{c0}(1P)) = 9.99 \pm 0.27\%,$$
$$\mathcal{B}(\psi(3770) \to \gamma\chi_{c0}(1P)) = 0.73 \pm 0.09\%.$$
$$\mathcal{B}(J/\psi \to \gamma\eta_c) = 1.7 \pm 0.4\%,$$
$$\mathcal{B}(\psi(2S) \to \gamma\eta_c) = 0.34 \pm 0.05\%.$$

$$\mathcal{B}(\Upsilon(2S) \to \gamma\chi_{b0}(1P)) = 3.8 \pm 0.4\%,$$
$$\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{b0}(1P)) = 0.27 \pm 0.04\%,$$
$$\mathcal{B}(\Upsilon(3S) \to \gamma\chi_{b0}(2P)) = 5.9 \pm 0.6\%.$$

D. Hazard and A.A.P., PRD94 (2016), 074023
D. Hazard and A.A.P., PRD98 (2018), 015027

Conclusions

- Indirect probes for new physics compete well with direct searches
  - for some observables sensitive to scales way above LHC
- Charm provides great opportunities for New Physics studies
  - unique access to up-type quark sector, not as constrained by experiments
- Calculational techniques for heavy flavors are well-established
  - but don't always work well: "heavy-quark-expansion" techniques for charm often miss threshold effects
  - "hadronic" techniques that sum over large number of intermediate states can be used, BUT one cannot use current experimental data on D-decays
- Calculations of New Physics contributions to mixing are in better shape
- Can correlate mixing and rare decays with New Physics models
  - signals in B/D-mixing vs B/D rare decays help differentiate among models

More conclusions

- Indirect effects of New Physics at flavor factories help to distinguish among models possibly observed at the LHC
  - a combination of bottom/charm sector studies
  - don't forget measurements unique to tau-charm factories
- Rare decays with missing energy provide excellent opportunities to constrain parameters of models with light Dark Matter
  - both scalar and sermonic DM models can be constrained
- Observation of CP-violation in the current round of experiments could have provided a "smoking gun" signals for New Physics
  - But latest LHCb observation seem to broadly consistent with Standard Model

$$\Delta a_{CP}^{dir} = (-0.156 \pm 0.029)\%$$

LHCB-PAPER-2019-006

  - Maybe if we only have a reliable calculation of the SM effects…

$$\left|\Delta a_{CP}^{dir}\right| < 0.020 \pm 0.003\%$$

Khodjamirian, AAP: PLB774 (2017) 235

  - The smoke is quickly dissipating…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WOULD YOU LIKE TO KNOW MORE?


EXTRA!

A. Rare leptonic decays of charm

★ Standard Model contribution to $D \to \mu^+\mu^-$.

★ Short distance analysis

$$Q_{10} = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \gamma_5 \ell,$$

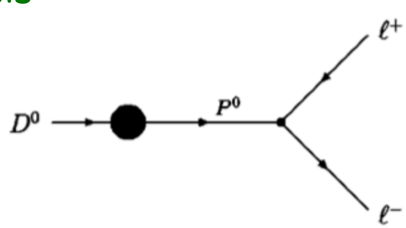
$$B^{(\mathrm{s.d.})}_{D^0 \ell^+ \ell^-} \simeq \frac{G_F^2 M_W^2 f_D m_\ell}{\pi^2} F\,,$$

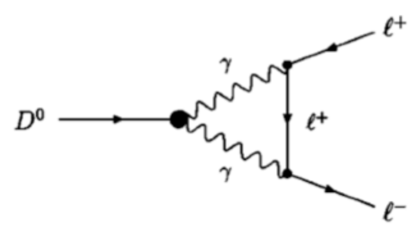
$$F = \sum_{i=d,s,b} V_{ui} V_{ci}^* \left[\frac{x_i}{2} + \frac{\alpha_s}{4\pi} x_i \cdot \left(\ln^2 x_i + \frac{4+\pi^2}{3} \right) \right]$$

- only Q_{10} contribute, SD effects amount to Br ~ 10^{-18}
- single non-perturbative parameter (decay constant)

UKQCD, HPQCD; Jamin, Lange; Penin, Steinhauser; Khodjamirian

★ Long distance analysis





Burdman, Golowich, Hewett, Pakvasa; Fajfer, Prelovsek, Singer

Update soon: Healey, AAP

$$B^{(\mathrm{mix})}_{D^0 \ell^+ \ell^-} = \sum_{P_n} \langle P_n | \mathcal{H}^{(\mathrm{p.c.})}_{wk} | D^0 \rangle \frac{1}{M_D^2 - M_{P_n^2}} B_{P_n \ell^+ \ell^-}$$

$$\mathcal{Im}\, \mathcal{M}_{D^0 \to \ell^+ \ell^-} = \frac{1}{2!} \sum_{\lambda_1, \lambda_2} \int \frac{d^3 q_1}{2\omega_1 (2\pi)^3} \frac{d^3 q_2}{2\omega_2 (2\pi)^3} \times \mathcal{M}_{D \to \gamma\gamma} \mathcal{M}^*_{\gamma\gamma \to \ell^+ \ell^-} (2\pi)^4 \delta^{(4)} (p - q_1 - q_2)$$

- LD effects amount to Br ~ 10^{-13}
- could be used to study NP effects in correlation with D-mixing

Generic NP contribution to D → $\mu^+\mu^-$

★ Most general effective Hamiltonian:

$$\langle f|\mathcal{H}_{NP}|i\rangle = G\sum_{i=1} \widetilde{\mathrm{C}}_i(\mu)\ \langle f|Q_i|i\rangle(\mu)$$

$$\widetilde{Q}_1 = (\overline{\ell}_L\gamma_\mu\ell_L)\ (\overline{u}_L\gamma^\mu c_L)\ , \qquad \widetilde{Q}_4 = (\overline{\ell}_R\ell_L)\ (\overline{u}_R c_L)\ ,$$

$$\widetilde{Q}_2 = (\overline{\ell}_L\gamma_\mu\ell_L)\ (\overline{u}_R\gamma^\mu c_R)\ , \qquad \widetilde{Q}_5 = (\overline{\ell}_R\sigma_{\mu\nu}\ell_L)\ (\overline{u}_R\sigma^{\mu\nu} c_L)\ ,$$

$$\widetilde{Q}_3 = (\overline{\ell}_L\ell_R)\ (\overline{u}_R c_L)\ ,$$

plus L ↔ R

★ ... thus, the amplitude for D → $e^+e^-/\mu^+\mu^-$ decay is

$$\mathcal{B}_{D^0\to\ell^+\ell^-} = \frac{M_D}{8\pi\Gamma_{\rm D}}\sqrt{1-\frac{4m_\ell^2}{M_D^2}}\left[\left(1-\frac{4m_\ell^2}{M_D^2}\right)|A|^2+|B|^2\right]\ ,$$

$$\mathcal{B}_{D^0\to\mu^+e^-} = \frac{M_D}{8\pi\Gamma_{\rm D}}\left(1-\frac{m_\mu^2}{M_D^2}\right)^2\left[|A|^2+|B|^2\right]\ ,$$

$$|A| = G\frac{f_D M_D^2}{4m_c}\left[\widetilde{C}_{3-8}+\widetilde{C}_{4-9}\right]\ ,$$

$$|B| = G\frac{f_D}{4}\left[2m_\ell\left(\widetilde{C}_{1-2}+\widetilde{C}_{6-7}\right)+\frac{M_D^2}{m_c}\left(\widetilde{C}_{4-3}+\widetilde{C}_{9-8}\right)\right], \quad \widetilde{C}_{i-k}\equiv\widetilde{C}_i-\widetilde{C}_k$$

Many NP models give contributions to both D-mixing and D → $e^+e^-/\mu^+\mu^-$ decay: correlate!!!

Mixing vs rare decays: a particular model

★ Recent experimental constraints

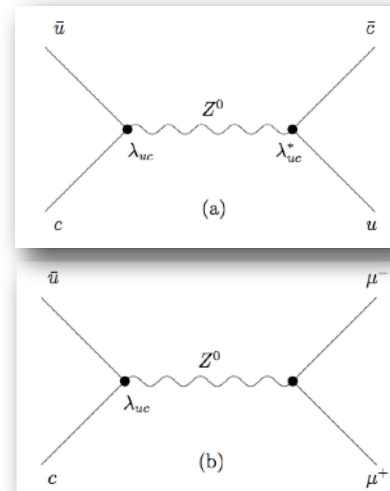
$$\mathcal{B}_{D^0\to\mu^+\mu^-} \le 1.3\times 10^{-6}, \qquad \mathcal{B}_{D^0\to e^+e^-} \le 1.2\times 10^{-6},$$

$$\mathcal{B}_{D^0\to\mu^\pm e^\mp} \le 8.1\times 10^{-7} \ ,$$

E.Golowich, J. Hewett, S. Pakvasa and A.A.P. PRD79, 114030 (2009)

★ Relating mixing and rare decay

- consider an example: heavy vector-like quark (Q=+2/3)
  - appears in little Higgs models, etc.



$$\lambda_{uc} \equiv -\left(V^*_{ud}V_{cd} + V^*_{us}V_{cs} + V^*_{ub}V_{cb}\right)$$

Mixing:

$$\mathcal{H}_{2/3} = \frac{g^2}{8\cos^2\theta_w M_Z^2}\lambda_{uc}^2\, Q_1 \ = \ \frac{G_F\lambda_{uc}^2}{\sqrt{2}}Q_1$$

$$x_{\rm D}^{(+2/3)} = \frac{2G_F\lambda_{uc}^2 f_D^2 M_D B_D r(m_c,M_Z)}{3\sqrt{2}\Gamma_D}$$

Rare decay:

$$A_{D^0\to\ell^+\ell^-} = 0 \qquad B_{D^0\to\ell^+\ell^-} = \lambda_{uc}\frac{G_F f_{\rm D} m_\mu}{2}$$

$$\mathcal{B}_{D^0\to\mu^+\mu^-} = \frac{3\sqrt{2}}{64\pi}\,\frac{G_F m_\mu^2 x_{\rm D}}{B_{\rm D} r(m_c,M_Z)}\left[1-\frac{4m_\mu^2}{M_{\rm D}}\right]^{1/2}$$
$$\simeq\ 4.3\times 10^{-9} x_{\rm D}\ \le\ 4.3\times 10^{-11}\ .$$

Note: a NP parameter-free relation!

B. Rare semileptonic decays of charm

- These decays also proceed at one loop in the SM; GIM is very effective
  - SM rates are expected to be small

★ Rare decays $D \to M\, e^+e^-/\mu^+\mu^-$ just like $D \to e^+e^-/\mu^+\mu^-$ are mediated by $c \to u\, ll$

$$\mathcal{L}^{SD}_{\rm eff} = \frac{G_F}{\sqrt{2}} V^*_{cb} V_{ub} \sum_{i=7,9,10} C_i Q_i,$$

$$Q_9 = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \ell, \quad Q_{10} = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \gamma_5 \ell,$$

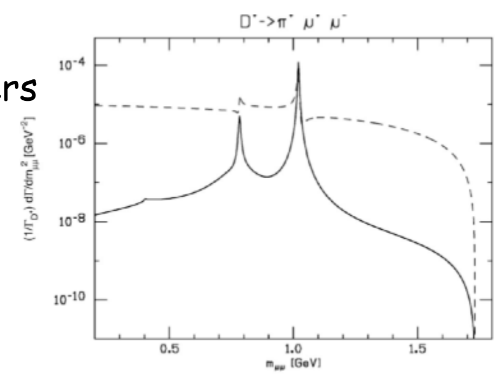
- SM contribution is dominated by LD effects
- could be used to study NP effects

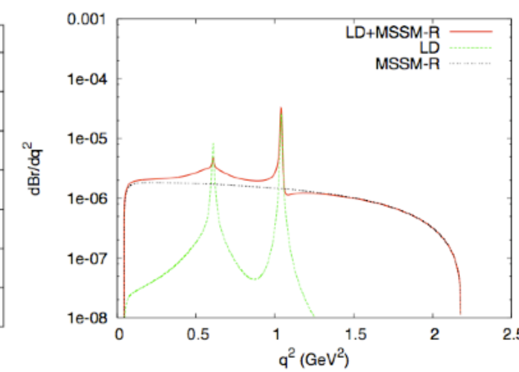
Burdman, Golowich, Hewett, Pakvasa;
Fajfer, Prelovsek, Singer

Mode	LD	Extra heavy q	LD + extra heavy q
$D^+ \to \pi^+ e^+ e^-$	2.0×10^{-6}	1.3×10^{-9}	2.0×10^{-6}
$D^+ \to \pi^+ \mu^+ \mu^-$	2.0×10^{-6}	1.6×10^{-9}	2.0×10^{-6}
Mode	MSSM$\not{R}$	LD + MSSM$\not{R}$	
$D^+ \to \pi^+ e^+ e^-$	2.1×10^{-7}	2.3×10^{-6}	
$D^+ \to \pi^+ \mu^+ \mu^-$	6.5×10^{-6}	8.8×10^{-6}	

★ Example: R-partity-violating SUSY
- operators with the same parameters contribute to D-mixing
- feed results into rare decays

Fajfer, Kosnik, Prelovsek



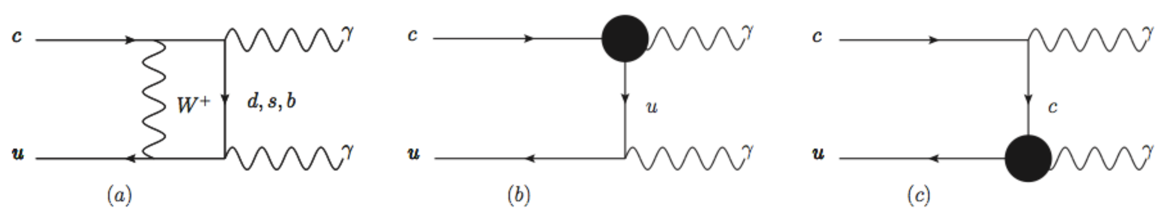


★ Standard Model contribution to D → γγ

$$A(D \to \gamma\gamma) = \epsilon_{1\mu}\epsilon_{2\nu}\left[A_{PC}\epsilon^{\mu\nu\alpha\beta}k_{1\alpha}k_{2\beta} + iA_{PV}\left(g^{\mu\nu} - \frac{k_2^\mu k_1^\nu}{k1 \cdot k_2}\right)\right]$$

$$\Gamma(D \to \gamma\gamma) = \frac{m_D^3}{64\pi}\left[\left|A_{PC}\right|^2 + \frac{4}{m_D^4}\left|A_{PV}\right|^2\right]$$

★ Short distance analysis $\mathcal{L} = -\frac{G_f}{\sqrt{2}}V_{us}V_{cs}^* C_{7\gamma}^{eff}\frac{e}{4\pi^2}F_{\mu\nu}m_c\left(\bar{u}\sigma^{\mu\nu}\frac{1}{2}(1+\gamma_5)c\right)$



Paul, Bigi, Recksiegel (2011)

- only one operator contributes
- including QCD corrections, SD effects amount to Br = (3.6-8.1)x10^{-12}

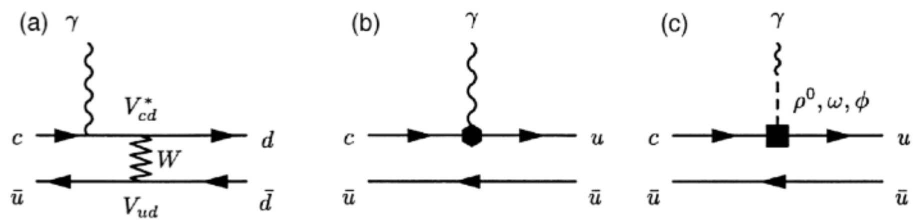
★ Long distance analysis

- long distance effects amount to Br = (1-3)x10^{-8}

Burdman, Golowich, Hewett, Pakvasa (02); Fajfer, Singer, Zupan (01)

★ Try to find combinations of decays where LD contributions cancel

★ Consider exclusive decays D → γϱ, γω: $\omega^{(I=0)} = \frac{1}{\sqrt{2}}(\bar{u}u + \bar{d}d)\,, \qquad \rho^{(I=1)} = \frac{1}{\sqrt{2}}(\bar{u}u - \bar{d}d)$



$V_{cd}^* V_{ud} \sim \lambda$ $\qquad$ $V_{cb}^* V_{ub} \sim \lambda^5$

+ QCD penguins and diagrams with photon emission from spectators

- Extract c → uu γ: LD contribution cancels in $R_{uu\gamma} = \frac{\Gamma(D^0 \to \omega\gamma) - \Gamma(D^0 \to \rho\gamma)}{\Gamma(D^0 \to \omega\gamma)}$

- Consider isospin asymmetries $R_I = \frac{2\Gamma(D^0 \to \rho^0\gamma) - \Gamma(D^+ \to \rho^+\gamma)}{2\Gamma(D^0 \to \rho^0\gamma) + \Gamma(D^+ \to \rho^+\gamma)}$ (same with omega)

- isospin asymmetries are sensitive to 4-fermion operators with photon emissions from "spectators"

★ Indirect CP-violation manifests itself in $D\overline{D}$-oscillations

- see time development of a D-system:

$$i\frac{d}{dt}|D(t)\rangle = \left(M - \frac{i}{2}\Gamma\right)|D(t)\rangle$$

$$\langle D^0|\mathcal{H}|\overline{D^0}\rangle = M_{12} - \frac{i}{2}\Gamma_{12} \qquad \langle \overline{D^0}|\mathcal{H}|D^0\rangle = M_{12}^* - \frac{i}{2}\Gamma_{12}^*$$

★ Define "theoretical" mixing parameters

$$y_{12} \equiv |\Gamma_{12}|/\Gamma, \quad x_{12} \equiv 2|M_{12}|/\Gamma, \quad \phi_{12} \equiv \arg(M_{12}/\Gamma_{12})$$

★ Assume that direct CP-violation is absent ($\mathrm{Im}\,(\Gamma_{12}^*\bar{A}_f/A_f) = 0$, $|\bar{A}_f/A_f| = 1$)

- can relate x, y, φ, |q/p| to x_{12}, y_{12} and φ_{12}

"superweak limit"

$$xy = x_{12}y_{12}\cos\phi_{12}, \qquad x^2 - y^2 = x_{12}^2 - y_{12}^2,$$

$$(x^2 + y^2)|q/p|^2 = x_{12}^2 + y_{12}^2 + 2x_{12}y_{12}\sin\phi_{12},$$

$$x^2\cos^2\phi - y^2\sin^2\phi = x_{12}^2\cos^2\phi_{12}.$$

★ Four "experimental" parameters related to three "theoretical" ones

- a "constraint" equation is possible

E. Rare D(B)-decays with missing energy

- D-decays with missing energy can probe both heavy and light (DM) NP

★ SM process: D → $\nu\nu$ and D → $\nu\nu\gamma$:
- for B-decays $J^{\mu}_{Qq} = \bar{q}_L \gamma^\mu b_L$
- for D-decays $J^{\mu}_{Qq} = \bar{u}_L \gamma^\mu c_L$

★ For B(D) → $\nu\nu$ decays SM branching ratios are tiny
- SM decay is helicity suppressed, e.g.

$$\mathcal{B}(B_s \to \nu\bar{\nu}) = \frac{G_F^2 \alpha^2 f_B^2 M_B^3}{16\pi^3 \sin^4\theta_W \Gamma_{B_s}} |V_{tb} V_{ts}^*|^2 X(x_t)^2 x_\nu^2$$

- NP: other ways of flipping helicity?
- more important: Br(B(D) → 4ν) >> Br(B(D) → $\nu\nu$)

Bhattacharya, Grant, AAP, PRD99 (2019) 093010

Decay	Branching ratio
$B_s \to \nu\bar{\nu}$	3.07×10^{-24}
$B_d \to \nu\bar{\nu}$	1.24×10^{-25}
$D^0 \to \nu\bar{\nu}$	1.1×10^{-30}

What would happen if a photon is added to the final state?

★ For B(D) → $\nu\nu\gamma$ decays SM branching ratios are still tiny
- need form-factors to describe the transition
- helicity suppression is lifted

Decay	Branching ratio
$B_s \to \nu\bar{\nu}\gamma$	3.68×10^{-8}
$B_d \to \nu\bar{\nu}\gamma$	1.96×10^{-9}
$D^0 \to \nu\bar{\nu}\gamma$	3.96×10^{-14}

★ BUT: missing energy does not always mean neutrinos
- nice constraints on light Dark Matter properties!!!

Badin, AAP (2010)

Rare D(B)-decays: scalar DM

- Let us discuss B and D-decays simultaneously: physics is similar

Badin, AAP (2010)

★ Generic interaction Lagrangian: $\mathcal{H}_{eff} = \sum_i \frac{2C_i^{(s)}}{\Lambda^2} O_i$

- respective neutral currents for B-and D-decays

$$O_1 = m_Q \left(J_{Qq}\right)_{RL} \ \left(\chi_0^* \chi_0\right)$$
$$O_2 = m_Q \left(J_{Qq}\right)_{LR} \ \left(\chi_0^* \chi_0\right)$$
$$O_3 = \left(J_{Qq}^\mu\right)_{LL} \ \left(\chi_0^* \overleftrightarrow{\partial}_\mu \chi_0\right)$$
$$O_4 = \left(J_{Qq}^\mu\right)_{RR} \ \left(\chi_0^* \overleftrightarrow{\partial}_\mu \chi_0\right)$$

★ Scalar DM does not exhibit helicity suppression

- $B(D) \to E_{mis}$ is more powerful than $B(D) \to E_{mis}\,\gamma$

$$\mathcal{B}(B_q \to \chi_0 \chi_0) = \frac{(C_1^{(s)} - C_2^{(s)})^2}{4\pi M_{B_q} \Gamma_{B_q}} \left(\frac{f_{B_q} M_{B_q}^2 m_b}{\Lambda^2 (m_b + m_q)} \right)^2 \times \sqrt{1 - 4x_\chi^2},$$

$$\mathcal{B}(B_q \to \chi_0^* \chi_0 \gamma) = \frac{f_{B_q}^2 \alpha C_3^{(s)} C_4^{(s)} M_{B_q}^5}{6\Lambda^4 \Gamma_{B_q}} \left(\frac{F_{B_q}}{4\pi} \right)^2 \times \left(\frac{1}{6} \sqrt{1 - 4x_\chi^2} (1 - 16x_\chi^2 - 12x_\chi^4) - 12x_\chi^4 \log \frac{2x_\chi}{1 + \sqrt{1 - 4x_\chi^2}} \right).$$

$$\left(\frac{C_1^{(s)} - C_2^{(s)}}{\Lambda^2} \right)^2 \le 2.07 \times 10^{-16}\ \text{GeV}^{-4} \quad \text{for } m_\chi = 0.1 \times M_{B_d},$$

$$\frac{C_3^{(s)}}{\Lambda^2} \frac{C_4^{(s)}}{\Lambda^2} \le 1.55 \times 10^{-12}\ \text{GeV}^{-4} \quad \text{for } m = 0,$$

$$\frac{C_3^{(s)}}{\Lambda^2} \frac{C_4^{(s)}}{\Lambda^2} \le 7.44 \times 10^{-11}\ \text{GeV}^{-4} \quad \text{for } m = 0.4 \times M_{B_d}$$

These general bounds translate into constraints onto constraints for particular models

Example of a particular model of scalar DM

★ Several different models of light scalar DM
- simplest: singlet scalar DM
- more sophisticated - less restrictive

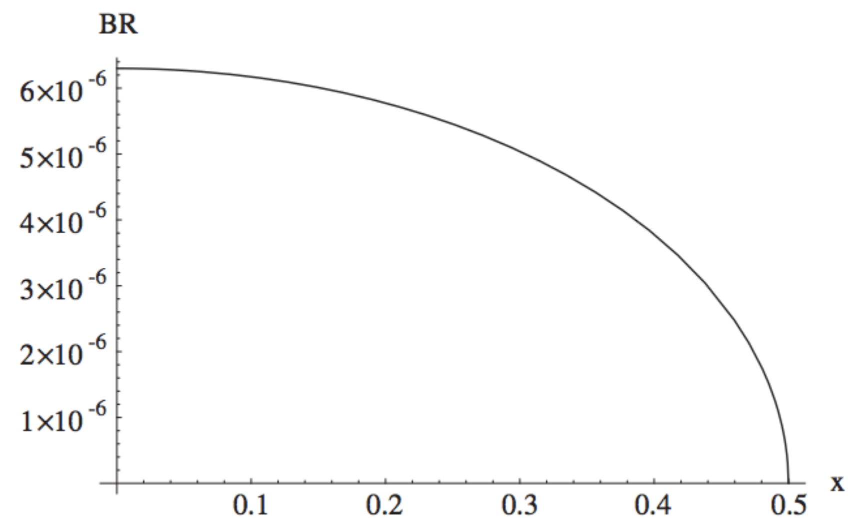
$$-\mathcal{L}_S = \frac{\lambda_S}{4}S^4 + \frac{m_0^2}{2}S^2 + \lambda S^2 H^\dagger H$$
$$= \frac{\lambda_S}{4}S^4 + \frac{1}{2}(m_0^2 + \lambda v_{\rm EW}^2)S^2 + \lambda v_{\rm EW} S^2 h$$
$$+ \frac{\lambda}{2}S^2 h^2,$$

★ B(D) decays rate in this model

$$\mathcal{B}(B_q \to SS) = \left[\frac{3g_w^2 V_{tb}V_{tq}^* x_t m_b}{128\pi^2}\right]^2 \frac{\sqrt{1-4x_S^2}}{16\pi M_B \Gamma_{B_q}} \left(\frac{\lambda^2}{M_H^4}\right) \times \left(\frac{f_{B_q} M_{B_q}^2}{m_b + m_q}\right)^2,$$

- fix λ from relic density

$$\sigma_{\rm ann} v_{\rm rel} = \frac{8 v_{\rm EW}^2 \lambda^2}{M_H^2} \times \lim_{m_{h^*} \to 2m_S} \frac{\Gamma_{h^* X}}{m_h^*}$$



These results are complimentary to constraints from quarkonium decays with missing energy

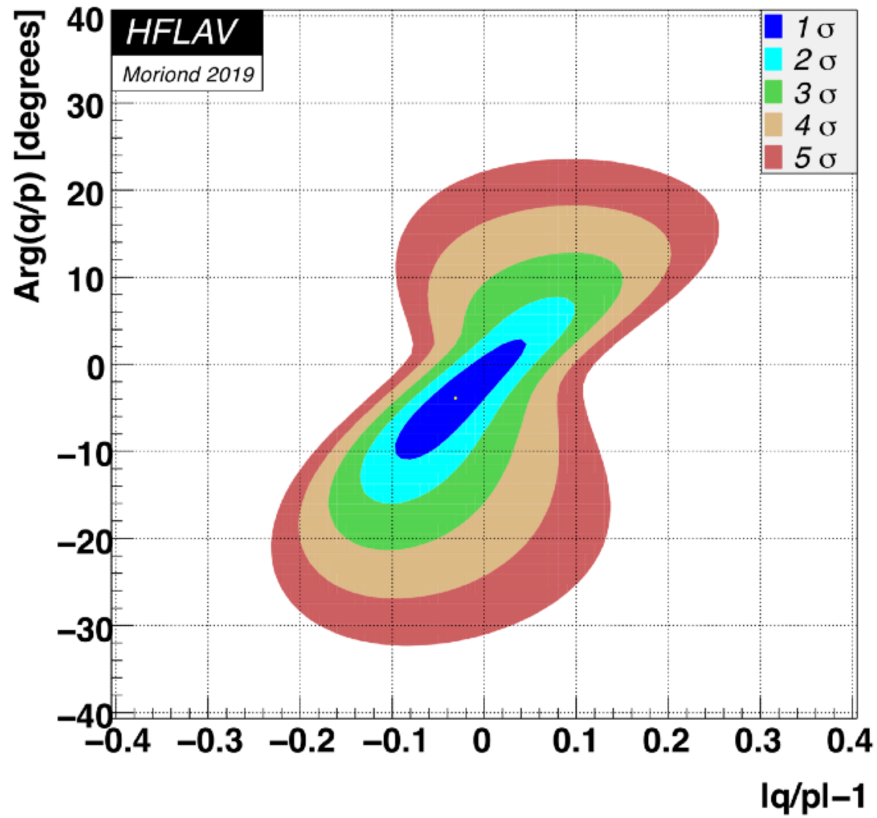
★ Relation; data from HFAG's compilation

$$\frac{x}{y} = \frac{1-|q/p|}{\tan\phi} = -\frac{1}{2}\frac{A_m}{\tan\phi}$$

- it might be experimentally $x_D < y_D$
- this has implications for NP searches in charm CP-violating asymmetries!

- that is, if $|M_{12}| < |\Gamma_{12}|$:

$$\begin{aligned} x/y &= 2\,|M_{12}/\Gamma_{12}|\cos\phi_{12}, \\ A_m &= 4\,|M_{12}/\Gamma_{12}|\sin\phi_{12}, \\ \phi &= -2\,|M_{12}/\Gamma_{12}|^2\sin 2\phi_{12}. \end{aligned}$$



Note: CPV is suppressed even if M_{12} is all NP!!!

Bergmann, Grossman, Ligeti, Nir, AAP
PL B486 (2000) 418

★ With available experimental constraints on x, y, and q/p, one can bound WCs of a generic NP Lagrangian -- bound any high-scale model of NP

CP-violation: indirect

★ Assume that direct CP-violation is absent $(\mathrm{Im}\,(\Gamma_{12}^* \bar{A}_f/A_f) = 0, \;\; |\bar{A}_f/A_f| = 1)$

- experimental constraints on x, y, φ, |q/p| exist
- can obtain generic constraints on Im parts of Wilson coefficients

$$\mathcal{H}_{NP}^{\Delta C=2} = \frac{1}{\Lambda_{NP}^2} \sum_{i=1}^{8} z_i(\mu) Q_i'$$

★ In particular, from $x_{12}^{\rm NP} \sin\phi_{12}^{\rm NP} \lesssim 0.0022$

$$\mathcal{I}m(z_1) \lesssim 1.1 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\;TeV}\right)^2,$$
$$\mathcal{I}m(z_2) \lesssim 2.9 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\;TeV}\right)^2,$$
$$\mathcal{I}m(z_3) \lesssim 1.1 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\;TeV}\right)^2,$$
$$\mathcal{I}m(z_4) \lesssim 1.1 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\;TeV}\right)^2,$$
$$\mathcal{I}m(z_5) \lesssim 3.0 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\;TeV}\right)^2.$$

New Physics is either at a very high scales

tree level: $\Lambda_{NP} \geq (4-10) \times 10^3\;\;\mathrm{TeV}$

loop level: $\Lambda_{NP} \geq (1-3) \times 10^2\;\;\mathrm{TeV}$

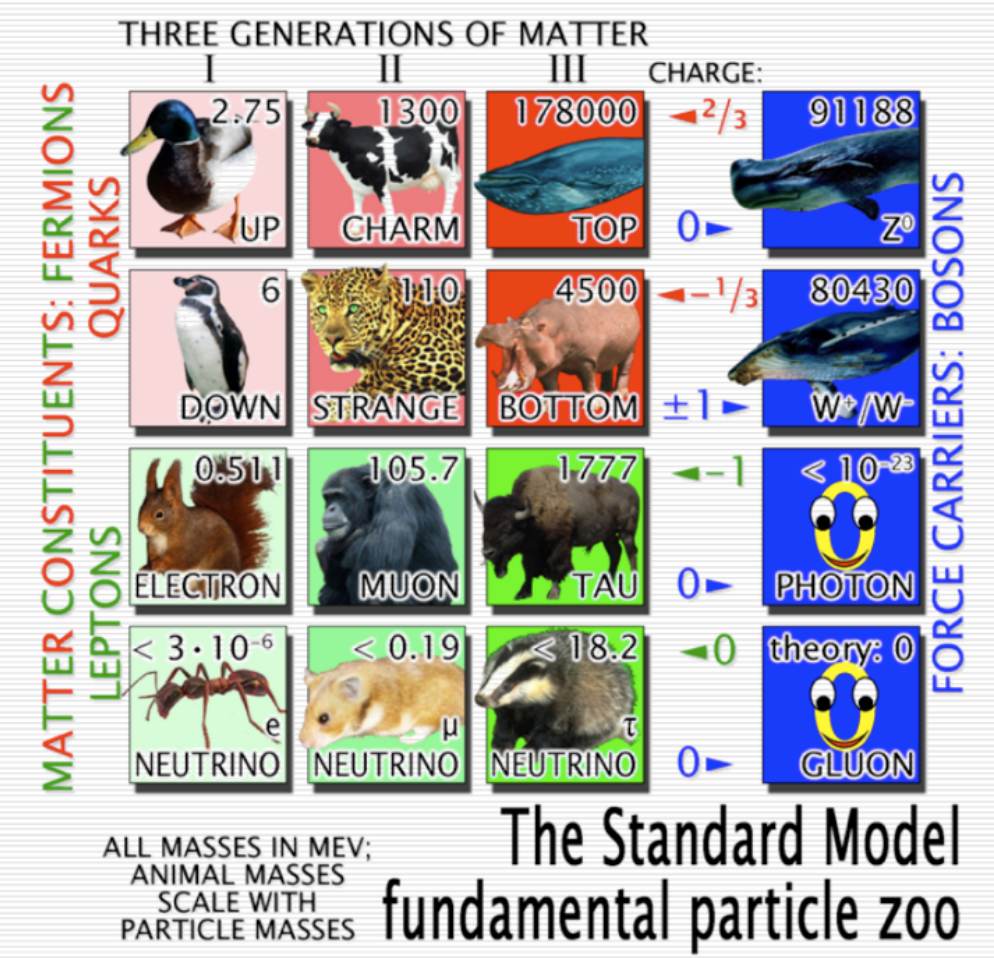
or have highly suppressed couplings to charm!

Gedalia, Grossman, Nir, Perez
Phys.Rev.D80, 055024, 2009

Bigi, Blanke, Buras, Recksiegel,
JHEP 0907:097, 2009

★ Constraints on particular NP models possible as well

G. Flavor problem: hierarchy of scales



E. Lunghi

★ Ratios of masses of quarks and leptons

- quarks

$$\frac{m_d}{m_u} \simeq 2\ , \quad \frac{m_s}{m_d} \simeq 21\ ,$$
$$\frac{m_t}{m_c} \simeq 267\ , \quad \frac{m_c}{m_u} \simeq 431\ , \quad \frac{m_t}{m_u} \simeq 1.2 \times 10^5\ .$$

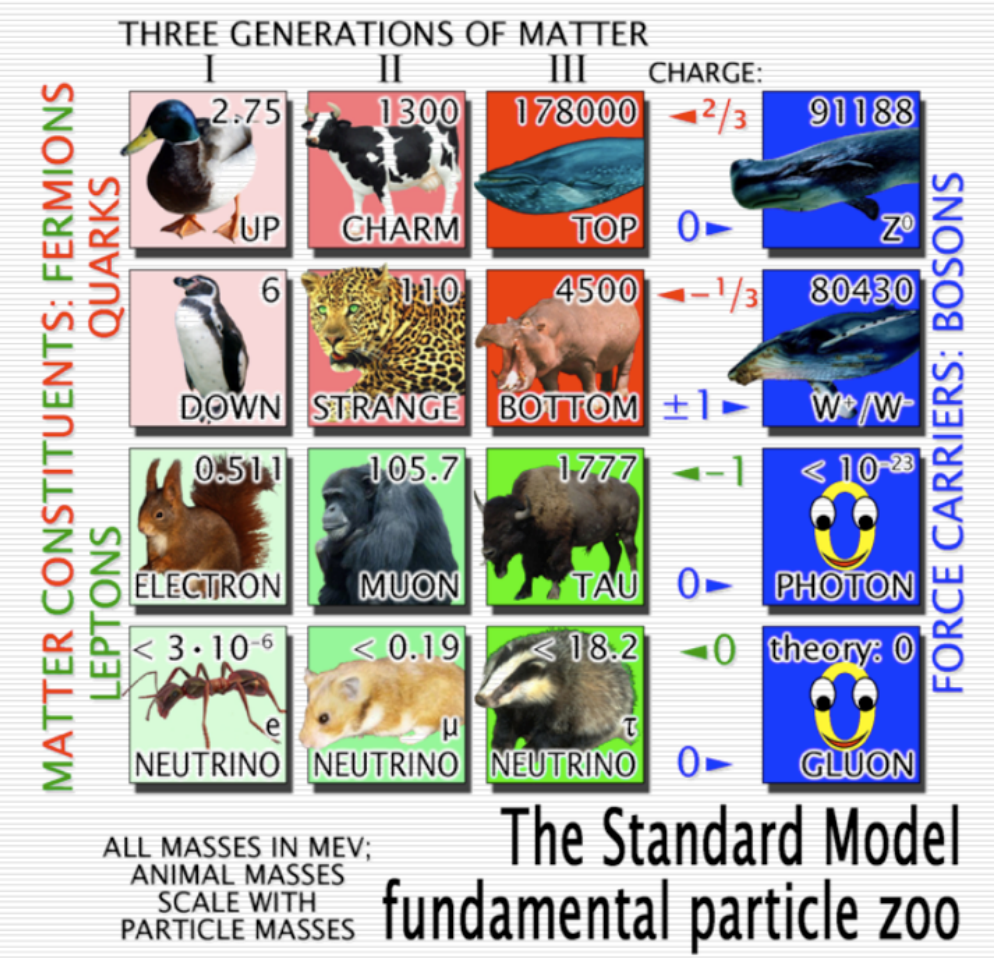
- leptons

$$\frac{m_\tau}{m_\mu} \simeq 17\ , \quad \frac{m_\mu}{m_e} \simeq 207\ .$$

★ Quark mixing (Cabibbo-Kobayashi-Maskawa) matrix parameters

$$V_{ud} \sim 1, V_{us} \sim 0.2,\ V_{cb} \sim 0.04,\ V_{ub} \sim 0.004$$

G. Flavor problem: hierarchy of scales



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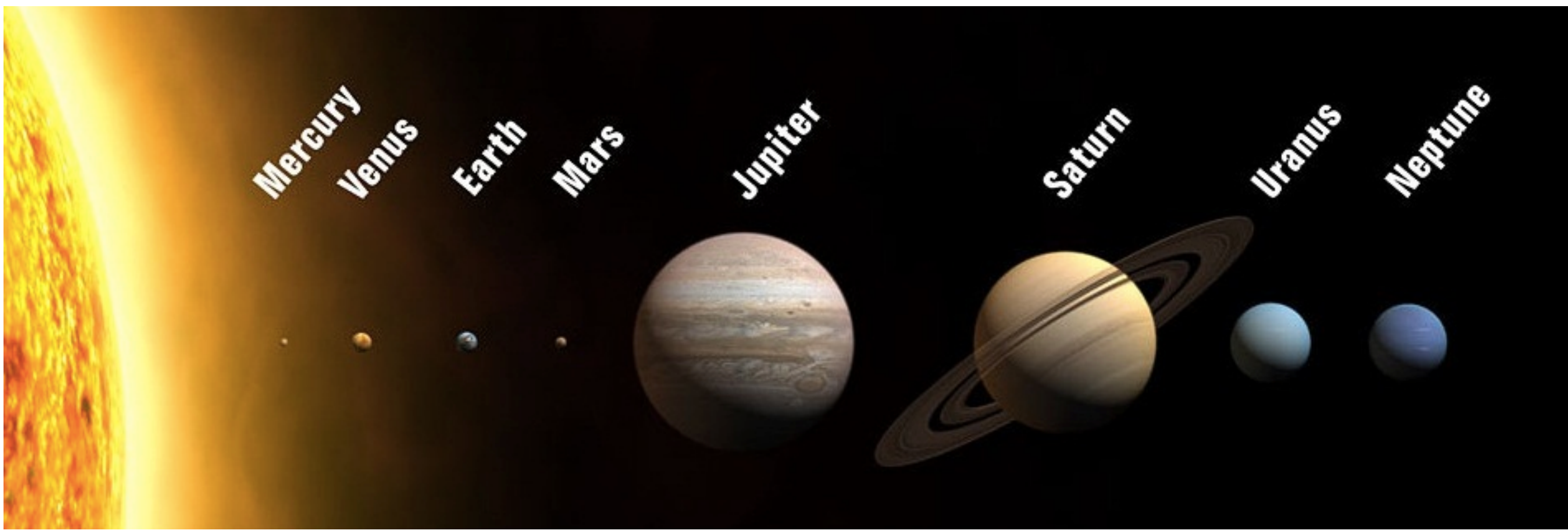
Problem: why such hierarchy?

Flavor problem: hierarchy of scales (counterargument)

It might well be similar to this:



Why is $M_{Jupiter} >> M_{Mercury}$?