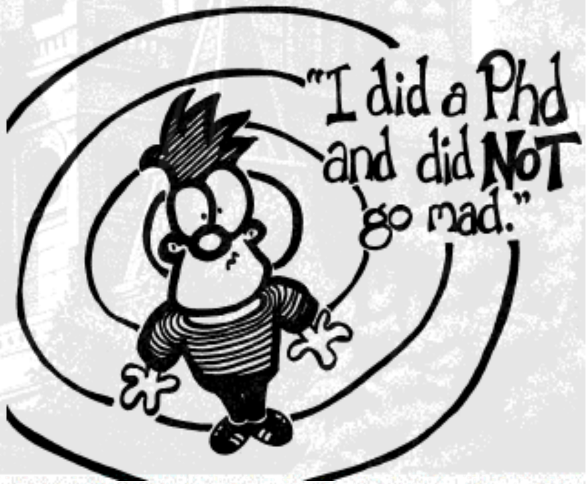
Outline

Charm Physics and New Dynamics (ND).



Rome wasn’t built in a day.

Standard Model: The Big Brother

- It opens up the possibility of FCNCs but the unitary and near-diagonal CKM matrix keeps this to a minimum.

- It opens up the possibility of CP violation but seemingly not enough to drive baryogenesis§.

correlated through the CKM matrix

⬇

§ CP violation is small in strange [$O(10^{-3})$] and expected to be small in charm [$O(10^{-4}$-$10^{-2})$] but is very large in beauty [O(1)].

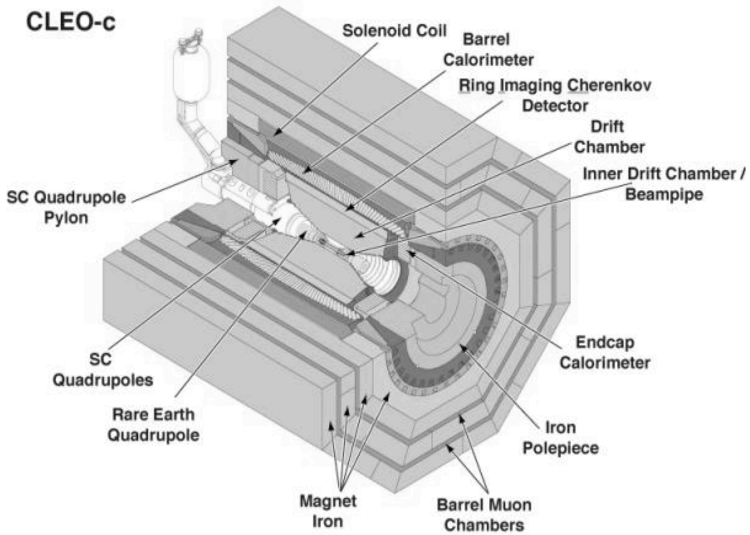
Why Charm?

- Finding ND in beauty is difficult as SM effects are already quite large.
- Charm has very small backgrounds from the SM.
- Only charm in the up sector partakes in oscillations, an important ingredient for CP Violation.

Experiments Past.

Measurements of Charm Dynamics was a Challenge!

Dedicated to Charm.



Pioneering analysis of:

- Lifetime of charm states.
- Neutral charm meson mixing.
- Semileptonic and hadronic decays.
- CP violation
- Rare and forbidden decays.
- etc.

Experiments Present.

Charm

oscillation have been observed:

$$x_D = \frac{\Delta M_D}{\Gamma_D} = (0.63^{+0.19}_{-0.20})\,\% \quad , \quad y_D = \frac{\Delta \Gamma_D}{2\Gamma_D} = (0.75 \pm 0.12)\,\%$$

$$\left|\frac{q}{p}\right| = 0.89^{+0.17}_{-0.15} \quad , \quad \phi_D = \left(-10.1^{+9.4}_{-8.8}\right)^o$$

assuming no DIRECT CP violation:

$$\left|\frac{q}{p}\right| = 1.02 \pm 0.04 \;, \;\; \phi_D = \left(-1.05^{+1.89}_{-1.94}\right)^o$$

There are distinct hints of CP violation but nothing set in stone

and many decay channels remain unmeasured

Note: *Only* quark in the up sector that can participate in oscillations.

~~CP invariance~~ $\rightarrow |q/p| \neq 1 \quad \phi_D \neq 0$

$$
\begin{aligned}
\Delta A_{\mathrm{CP}} &\equiv A_{\mathrm{CP}}(K^+K^-) - A_{\mathrm{CP}}(\pi^+\pi^-) \\
\Delta A_{\mathrm{CP}}|_{\mathrm{LHCb}} &= [-0.82 \pm 0.21(stat.) \pm 0.11(sys.)]\% \\
\Delta A_{\mathrm{CP}}|_{\mathrm{CDF}} &= [-0.62 \pm 0.21(stat.) \pm 0.10(sys.)]\%
\end{aligned}
$$

World average by CDF

$$
\Delta A_{\mathrm{CP}}^{\mathrm{dir}} = (-0.67 \pm 0.16)\%
$$

3.8 σ significance.

FIRST Evidence of CP Violation in charm.

The ONLY evidence of CP Violation in the up type quarks.

Note: Asymmetries have opposite signs for the two modes.
Disclaimer: This is a theory assumption!

Experiments Future.

D Factories

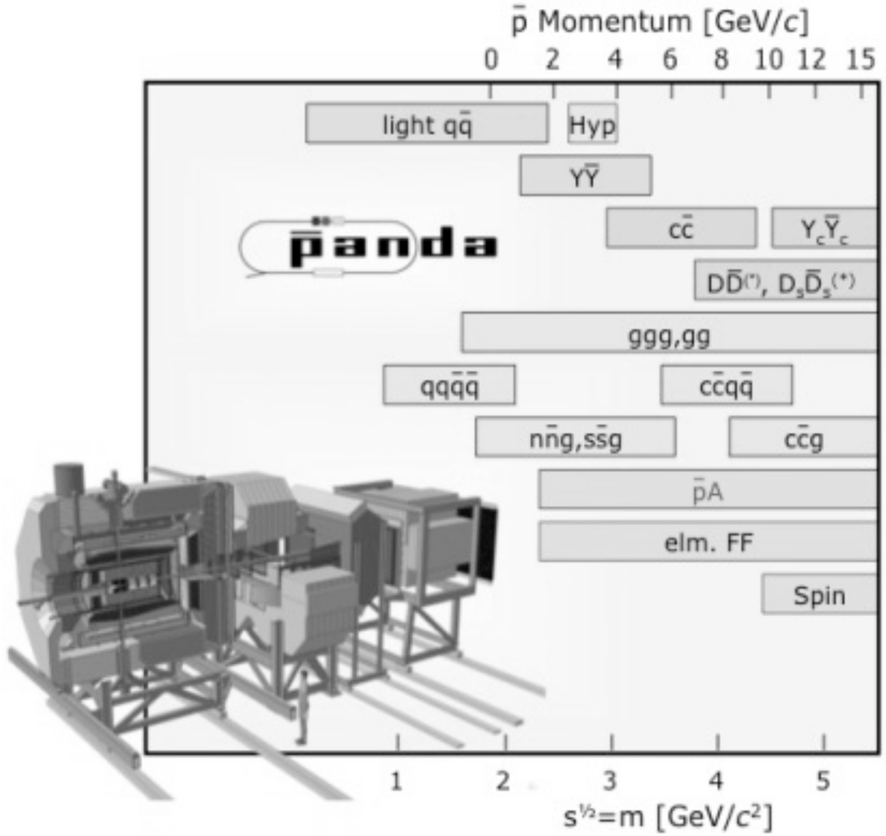
$$e^+e^- \to \psi''(3770) \to D^0\bar{D}^0/D_+D_-/D_1D_2 \to f_af_b$$

- The meson pair is produced in a C odd P wave.
- EPR Correlations comes to the rescue.
- CP violation implied by mere existence of certain final states.
- Both direct and indirect CPV can be probed.

Super *B* Factory(ies)

- Super *B* = Super *D*
- *D* produced from *B* offer a cleaner analysis.
- Not only low, but well understood backgrounds.
- The *D* eigenstates are no longer correlated, a disadvantage.

A FAIR PANDA



- ✓ Fixed target antiproton experiment
- ✓ Nearly full solid angle coverage.
- ✓ Very high angular resolution.
- ✓ 1.5 -15 GeV/c antiproton beam.
- ✓ Shiny new detector.
- ✓ Manpower.

Caveat: charm pair production not well understood!

The Challenges of Charm

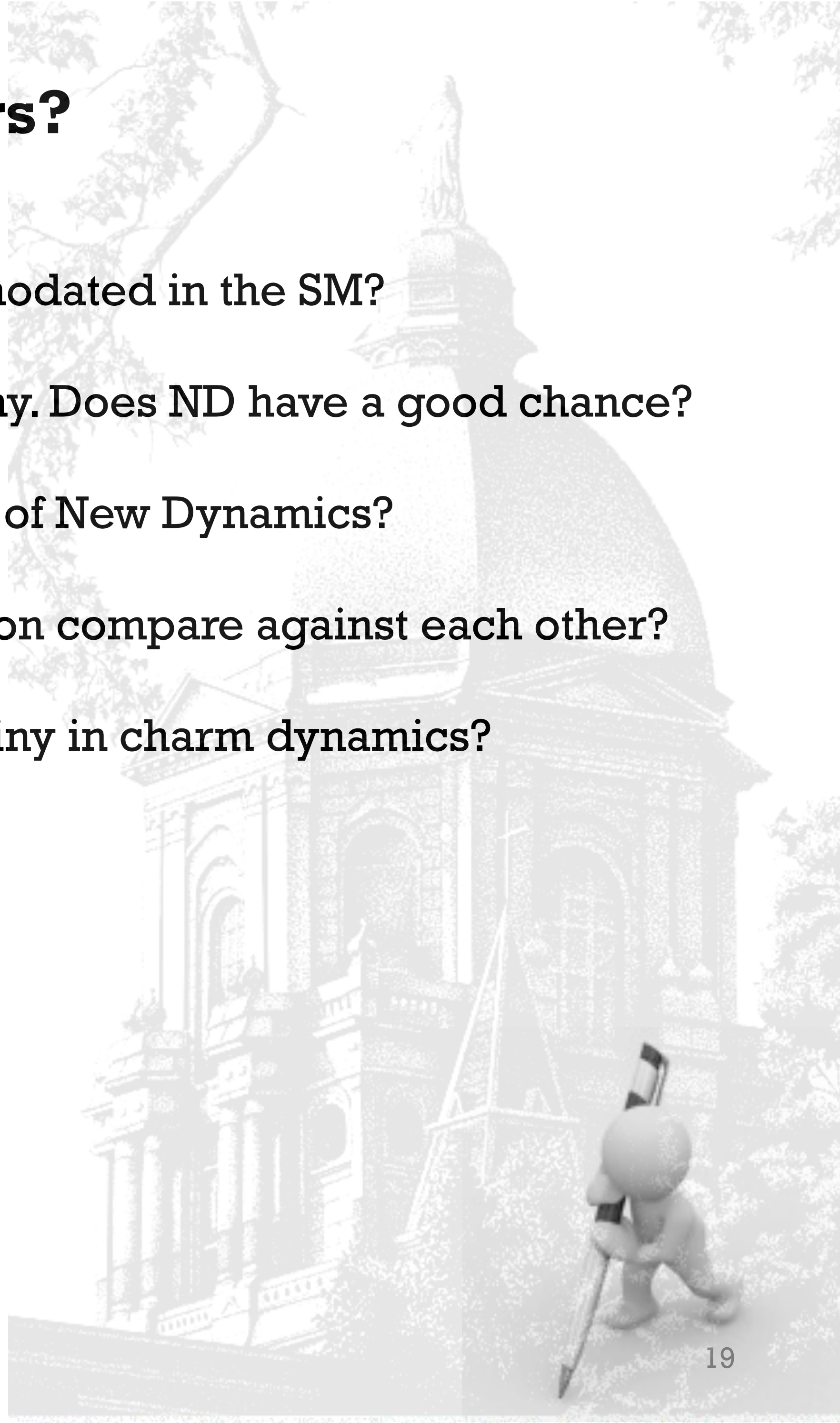
Why not Charm?

- Measurements in charm require very high statistics.
- SM contribution to charm dominated by long distance dynamics.
- Final state interactions (FSI) not under theoretical control.

All roads lead to Rome.

The Theorists' World.

Answers?



± Can oscillations in charm be accommodated in the SM?

± SM contribution to rare decays are tiny. Does ND have a good chance?

± Can charm physics constrain models of New Dynamics?

± How do direct and indirect CP violation compare against each other?

± Why is CP violation predicted to be tiny in charm dynamics?

Charm Changing Neutral Currents

CHANNEL	OBSERVABLE	SM SD	SM LD	EXPERIMENT
$D^0 \to \gamma\gamma$	$\mathrm{BR}(D^0 \to \gamma\gamma)$	$(3.6-8.1)\times 10^{-12\,\dagger}$	$(1-3)\times 10^{-8}$	$< 2.7\times 10^{-5}$
$D^0 \to \mu^+\mu^-$	$\mathrm{BR}(D^0 \to \mu^+\mu^-)$	$6\times 10^{-19\,\dagger}$	$(2.7-8)\times 10^{-13}$	$< 1.3\times 10^{-6}$
$D^\pm \to X_u l^+ l^-$	$\mathrm{BR}(D^\pm \to X_u l^+ l^-)$	$3.7\times 10^{-9\,\dagger}$	$\sim \mathcal{O}(10^{-6})$	$\sim \mathcal{O}(10^{-5})$
	A^c_{FB}	$\sim 2\times 10^{-6\,\dagger}$	-	-
	A^c_{CP}	$\sim 3\times 10^{-4\,\dagger}$	-	-
	$A^{\mathrm{CP}}_{\mathrm{FB}}$	$\sim 3\times 10^{-5\,\dagger}$	-	-
$D^0 \to \pi^+\pi^-$	$BR(D^0 \to \pi^+\pi^-)$	-	$\sim 1.5-2.5\times 10^{-3\,\dagger}$	$(1.397\pm 0.026)\times 10^{-3}$
	$A^{\pi\pi}_{\mathrm{CP}}$	-	$\sim 10^{-4}$	$[+0.22\pm 0.24_{stat.}\pm 0.11_{syst.}]\%$
$D^0 \to \pi^0\pi^0$	$BR(D^0 \to \pi^0\pi^0)$	-	$\sim 4-6\times 10^{-4\,\dagger}$	$(8.0\pm 0.8)\times 10^{-4}$
$D^0 \to K^+K^-$	$BR(D^0 \to K^+K^-)$	-	$\sim 7-8\times 10^{-3\,\dagger}$	$(3.94\pm 0.07)\times 10^{-3}$
	A^{KK}_{CP}	-	$\sim 10^{-4}$	$[-0.24\pm 0.22_{stat.}\pm 0.10_{syst.}]\%$

† Estimates from our recent work on these decay channels.

A. Paul, I. I. Bigi and S. Recksiegel, *$D^0 \to \gamma\gamma$ and $D^0 \to \mu^+\mu^-$ rates on an unlikely impact of the littlest Higgs model with T parity*. Phys. Rev. **D 82** (2010) 094006. [arXiv:1008:3141].

A. Paul, I. I. Bigi and S. Recksiegel, *On $D \to X_u l^+ l^-$ within the Standard Model and Frameworks like the littlelest Higgs model with T Parity*. Phys. Rev. **D 83** (2011) 114006. [arXiv:1101.6053].

I. I. Bigi, A. Paul and S. Recksiegel, *Theoretical Conclusions from CDF Analyses of CP Violation in $D^0 \to \pi^+\pi^-, K^+K^-$ and Future Tasks*. JHEP**06** (2011) 089. [arXiv:1103.5785].

Littlest Higgs Model with T Parity
A solution to the Hierarchy Problem

Particle Content

- The T-even sector:
  - SM gauge bosons
  - SM fermions
  - SM Higgs doublet
  - A heavy partner to the top, T_+

← **SM**

- The T-odd sector:
  - The heavy gauge bosons
  - A set of mirror fermions
  - The scalar triplet: ϕ^{++} ϕ^{+} ϕ^{0} ϕ^{P}
  - A T-parity partner to the heavy partner of the top, T_-

← **ND**

Model Parameters

$$f,\ m_h,\ s_\lambda \equiv \frac{\lambda_2}{\sqrt{\lambda_1^2+\lambda_2^2}} = \frac{m_{T_-}}{m_{T_+}},\ \kappa_i,\ \theta_{12}^H,\ \theta_{13}^H,\ \theta_{23}^H,\ \delta_{12}^H,\ \delta_{13}^H,\ \delta_{23}^H$$

Non-Minimal Flavour Violation: A side effect of LHT.

$$A(decay) = \sum_i B_i \eta^i_{QCD} V^i_{CKM} \left[F^i_{SM} + F^i_{ND}\right] + \sum_k B^{ND}_k \eta^k_{QCD} V^k_{ND} \left[G^k_{ND}\right]$$

minimal **non-minimal**

$$V^\dagger_{Hd} V_{Hu} = V_{CKM}$$

- V_{Hd} and V_{Hu} are not independent, hence, parameterizing one fixes the other.
- A 3x3 unitary matrix can have 3 angles and 6 phases.
- Unlike the CKM matrix, we can rotate away only three phases using the phase freedom of three mirror quarks.
- 3 angles and 3 CP violating phases = new FCNC and new CP Violation.

$$V_{Hd} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c^d_{23} & s^d_{23} e^{-i\delta^d_{23}} \\ 0 & -s^d_{23} e^{i\delta^d_{23}} & c^d_{23} \end{pmatrix} \cdot \begin{pmatrix} c^d_{13} & 0 & s^d_{13} e^{-i\delta^d_{13}} \\ 0 & 1 & 0 \\ -s^d_{13} e^{i\delta^d_{13}} & 0 & c^d_{13} \end{pmatrix} \cdot \begin{pmatrix} c^d_{12} & s^d_{12} e^{-i\delta^d_{12}} & 0 \\ -s^d_{12} e^{i\delta^d_{12}} & c^d_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Charm Changing Neutral Currents

CHANNEL	OBSERVABLE	SM	ND Effects	EXPERIMENT
$D^0 \to \gamma\gamma$	$\mathrm{BR}(D^0 \to \gamma\gamma)$	$(1-3)\times 10^{-8}$	SM LD Dominated	$< 2.7\times 10^{-5}$
$D^0 \to \mu^+\mu^-$	$\mathrm{BR}(D^0 \to \mu^+\mu^-)$	$(2.7-8)\times 10^{-13}$	$\sim \mathcal{O}(10\%) \Uparrow$	$< 1.3\times 10^{-6}$
$D^\pm \to X_u l^+ l^-$	$\mathrm{BR}(D^\pm \to X_u l^+ l^-)$	$\sim \mathcal{O}(10^{-6})$	SM LD Dominated	$\sim \mathcal{O}(10^{-5})$
	A^c_{FB}	$\sim 2\times 10^{-6\,\dagger}$	$\sim \mathcal{O}(1\%)$	-
	A^c_{CP}	$\sim 3\times 10^{-4\,\dagger}$	$\sim \mathcal{O}(10\%) \Uparrow$	-
	$A^{\mathrm{CP}}_{\mathrm{FB}}$	$\sim 3\times 10^{-5\,\dagger}$	$\sim \mathcal{O}(10\%) - \mathcal{O}(100\%)$	-
$D^0 \to \pi^+\pi^-$	$BR(D^0 \to \pi^+\pi^-)$	$\sim 1.5-2.5\times 10^{-3\,\dagger}$	-	$(1.397\pm 0.026)\times 10^{-3}$
	$A^{\pi\pi}_{\mathrm{CP}}$	$\sim 10^{-4}$	$\sim 10^{-3}-10^{-2}$	$[+0.22\pm 0.24_{stat.}\pm 0.11_{syst.}]\%$
$D^0 \to \pi^0\pi^0$	$BR(D^0 \to \pi^0\pi^0)$	$\sim 4-6\times 10^{-4\,\dagger}$	-	$(8.0\pm 0.8)\times 10^{-4}$
$D^0 \to K^+K^-$	$BR(D^0 \to K^+K^-)$	$\sim 7-8\times 10^{-3\,\dagger}$	-	$(3.94\pm 0.07)\times 10^{-3}$
	A^{KK}_{CP}	$\sim 10^{-4}$	$\sim 10^{-3}-10^{-2}$	$[-0.24\pm 0.22_{stat.}\pm 0.10_{syst.}]\%$

†Estimates from our recent work on these decay channels.

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Details of the Fermion Sector

⌘ N families of fermions. For SM N = 3

⌘ Isodoublets of a broken SU(2) X U(1).

⌘ The fermions are at most familywise mass degenerate. $h_i^1 = h_i^2$

⌘ Flavour eigenstates are misaligned from mass eigenstates.

$$\sum_{i=1}^{N} \lambda_i = 0 \ , \quad \text{with} \ \ \lambda_i = V_{ji}^* V_{ik} \ , \ i \neq j, k$$

$$m_i^a = m_1^a h_i^a \quad \forall i = 1(1)N \quad h_1^a = 1 \quad 0 < h_i^a < \infty$$

$$x_i^a = (m_i^a / m_G)^2$$

Note on m_1^a **:**

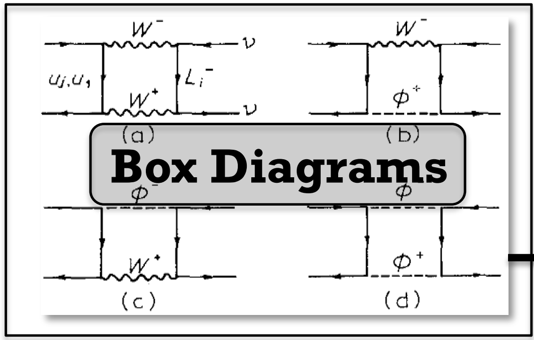
⌘ It does not need to be from the first family or the lightest.

⌘ It does not need to be the mass of any of the fermions.

Boxes and Penguins

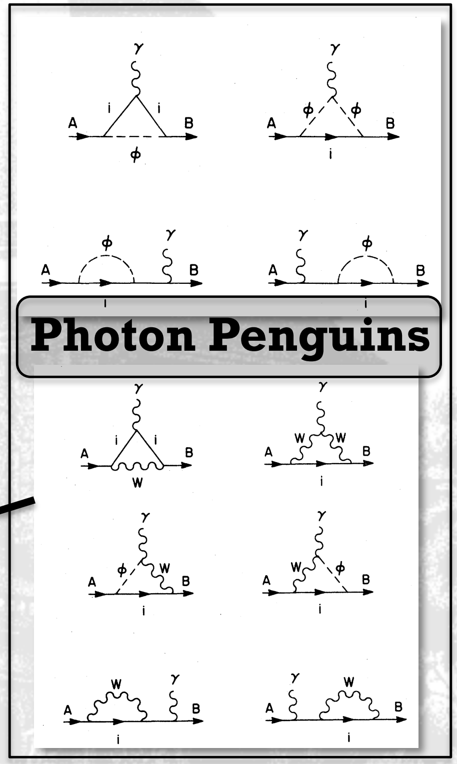
$$F(x) = f_n(x)(\log(x))^m \text{ where, } f_n(x) = x^n, n \in \mathbb{Z}, m = 0, 1$$

$$\mathcal{M} \sim \sum_{i=1}^{N} \lambda_i F(x_i) \longrightarrow \sum_{i=1}^{N} \lambda_i F(x_i) = f_n(x_1) \sum_{i=1}^{N} \lambda_i F(h_i^2) + F(x_1) \sum_{i=1}^{N} \lambda_i f_n(h_i^2)$$



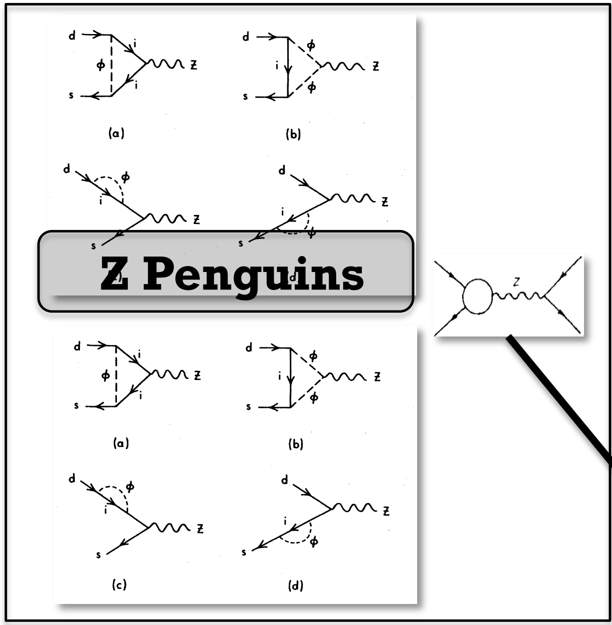
$n = 1$ and $m = 0$ $\sim x$

$$\mathcal{M} \sim x_1 \sum_{i=1}^{N} \lambda_i h_i^2$$



$n = 0$ and $m = 1$ $\sim \log(x)$

$$\mathcal{M} \sim \sum_{i=1}^{N} \lambda_i \log\left(h_i^2\right)$$



$n = 1$ and $m = 1$ $\sim x \log(x)$

$$\mathcal{M} \sim x_1 \sum_{i=1}^{N} \lambda_i h_i^2 \log\left(h_i^2\right) + x_1 \log\left(x_1\right) \sum_{i=1}^{N} \lambda_i h_i^2$$

Model Generalizations

Defining LHT-like (or MGFS?)

LHT: ***L***ittle ***H***iggs Model with ***T*** parity
MGFS: ***M***ultiple ***G***auge ***F***ermion ***S***ectors

★ A second sector of fermions that are an exact copy of the SM ones.

★ New forces that mediate interactions.

★ New mass mixing matrices that are mathematically constrained by the CKM matrix.

★ Possible large angles and phases in the mass mixing matrices.

★ Possible large hierarchies in the masses of the mirror fermions.

★ A symmetry to protect large contributions to FCNC. The symmetry can be discrete or continuous.

A. Paul, I. I. Bigi and S. Recksiegel, *$D^0 \to \gamma\gamma$ and $D^0 \to \mu^+\mu^-$ rates on an unlikely impact of the littlest Higgs model with T parity*. Phys. Rev. **D 82** (2010) 094006. [arXiv:1008:3141].
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Defining MHDMs

- A model of ND with an expanded Higgs sector.
- Can have *n* families of Higgs doublets and *m* families of triplets. (Careful with the triplets though!)
- Possibilities of new CP violating phases.
- Possible existence of CP violations arising from the mixing of scalars and psuedoscalars.
- Possible alignment of the Yukawas to save FCNCs.

Realizing MHDs

- Virtually any model can be given an extended Higgs sector, of course after paying due respect to experimental constraints.

CP Violation

Oscillations and CPV

Oscillations 101

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0 \\ \bar{D}^0 \end{pmatrix} = \begin{pmatrix} M_{11}^D - \frac{i}{2}\Gamma_{11}^D & M_{12}^D - \frac{i}{2}\Gamma_{12}^D \\ M_{12}^{D*} - \frac{i}{2}\Gamma_{12}^{D*} & M_{11}^D - \frac{i}{2}\Gamma_{11}^D \end{pmatrix}\begin{pmatrix} D^0 \\ \bar{D}^0 \end{pmatrix}$$

$$\frac{q}{p} = \sqrt{\frac{M_{12}^{D*} - \frac{i}{2}\Gamma_{12}^{D*}}{M_{12}^D - \frac{i}{2}\Gamma_{12}^D}} \qquad \phi_{12}^D = \frac{1}{2}\arg\left(\frac{M_{12}^D}{\Gamma_{12}^D}\right)$$

$$|D_1\rangle = \frac{1}{\sqrt{p^2+q^2}}\left(p|D^0\rangle + q|\bar{D}^0\rangle\right)$$

$$|D_2\rangle = \frac{1}{\sqrt{p^2+q^2}}\left(p|D^0\rangle - q|\bar{D}^0\rangle\right)$$

$$CP|D^0\rangle = +|\bar{D}^0\rangle$$

$$\Delta M_D = M_1 - M_2 = 2\Re\left[\frac{q}{p}\left(M_{12}^D - \frac{i}{2}\Gamma_{12}^D\right)\right] = 2\Re\sqrt{|M_{12}^D|^2 - \frac{1}{4}|\Gamma_{12}^D|^2 - i\Re\left(\Gamma_{12}^D M_{12}^{D*}\right)}$$

$$\Delta\Gamma_D = \Gamma_1 - \Gamma_2 = -4\Im\left[\frac{q}{p}\left(M_{12}^D - \frac{i}{2}\Gamma_{12}^D\right)\right] = -4\Im\sqrt{|M_{12}^D|^2 - \frac{1}{4}|\Gamma_{12}^D|^2 - i\Re\left(\Gamma_{12}^D M_{12}^{D*}\right)}$$

mass ⟵ CP

$$|D_1\rangle = \frac{1}{\sqrt{1+|\bar{\epsilon}|^2}}\left(|D_+\rangle + \bar{\epsilon}|\bar{D}_-\rangle\right)$$

$$|D_2\rangle = \frac{1}{\sqrt{1+|\bar{\epsilon}|^2}}\left(\bar{\epsilon}|D_+\rangle + |\bar{D}_-\rangle\right)$$

$$\bar{\epsilon} = \frac{1-\frac{q}{p}}{1+\frac{q}{p}}$$

mass ⟵ flavour

$$|D_1\rangle = \frac{1}{\sqrt{2(1+|\bar{\epsilon}|^2)}}\left((1+\bar{\epsilon})|D^0\rangle + (1-\bar{\epsilon})|\bar{D}^0\rangle\right)$$

$$|D_2\rangle = \frac{1}{\sqrt{2(1+|\bar{\epsilon}|^2)}}\left((1+\bar{\epsilon})|D^0\rangle - (1-\bar{\epsilon})|\bar{D}^0\rangle\right)$$

$$\langle D_1|D_2\rangle = \frac{|p|^2 - |q|^2}{|p|^2 + |q|^2} = \frac{2\,\Re(\bar{\epsilon})}{1+|\bar{\epsilon}|^2}$$

CP Violation in Charm 101

$$\left|T(D^0(t)\to f)\right|^2 = \frac{1}{2}e^{-\bar{\Gamma}t}\left[\left(|A_f|^2+\left|\frac{q}{p}\right|^2|\bar{A}_f|^2\right)\cosh\left(y_D\frac{t}{\tau_{D^0}}\right)+\left(|A_f|^2-\left|\frac{q}{p}\right|^2|\bar{A}_f|^2\right)\cos\left(x_D\frac{t}{\tau_{D^0}}\right)+\right.$$
$$\left.+2\Re\left(\frac{q}{p}\bar{A}_f\otimes A_f^*\right)\sinh\left(y_D\frac{t}{\tau_{D^0}}\right)-2\Im\left(\frac{q}{p}\bar{A}_f\otimes A_f^*\right)\sin\left(x_D\frac{t}{\tau_{D^0}}\right)\right]$$

$$\left|T(\bar{D}^0(t)\to \bar{f})\right|^2 = \frac{1}{2}e^{-\bar{\Gamma}t}\left[\left(|\bar{A}_{\bar{f}}|^2+\left|\frac{p}{q}\right|^2|A_{\bar{f}}|^2\right)\cosh\left(y_D\frac{t}{\tau_{D^0}}\right)+\left(|\bar{A}_{\bar{f}}|^2-\left|\frac{p}{q}\right|^2|A_{\bar{f}}|^2\right)\cos\left(x_D\frac{t}{\tau_{D^0}}\right)+\right.$$
$$\left.+2\Re\left(\frac{p}{q}A_{\bar{f}}\otimes \bar{A}_{\bar{f}}^*\right)\sinh\left(y_D\frac{t}{\tau_{D^0}}\right)-2\Im\left(\frac{p}{q}A_{\bar{f}}\otimes \bar{A}_{\bar{f}}^*\right)\sin\left(x_D\frac{t}{\tau_{D^0}}\right)\right]$$

$$\frac{\Gamma(D^0\to l^-X)-\Gamma(\bar{D}^0\to l^+X)}{\Gamma(D^0\to l^-X)+\Gamma(\bar{D}^0\to l^+X)} = \frac{|q/p|^2-|p/q|^2}{|q/p|^2+|p/q|^2}$$

$$\frac{|T(D^0(t)\to K_S\phi)|^2-|T(\bar{D}^0(t)\to K_S\phi)|^2}{|T(D^0(t)\to K_S\phi)|^2+|T(\bar{D}^0(t)\to K_S\phi)|^2} \simeq \frac{1}{2}\frac{t}{\tau_D}\left[y_D\left(\left|\frac{q}{p}\right|-\left|\frac{p}{q}\right|\right)\cos\phi_D - x_D\left(\left|\frac{q}{p}\right|+\left|\frac{p}{q}\right|\right)\sin\phi_D\right]$$

~~CP invariance~~ $\rightarrow |q/p| \neq 1 \quad \phi_D \neq 0$

$$\frac{\Gamma(D^0(t)\to f)-\Gamma(\bar{D}^0(t)\to \bar{f})}{\Gamma(D^0(t)\to f)+\Gamma(\bar{D}^0(t)\to \bar{f})} = a_{\mathrm{CP}}^{dir} + a_{\mathrm{CP}}^{ind}\frac{t}{\tau_{D^0}}$$

Two body problems.

$\boldsymbol{D^0 \to \pi^+\pi^-,\ K^+K^-}$

$$a^{ind}_{D^0 \to f}(t) \simeq \frac{1}{2}\frac{t}{\tau_D}\left[y_D\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\phi_D - x_D\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\phi_D\right]$$

$$a^{\rm dir}_{D\to f} = \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2} = \frac{-2|A_1||A_2|\sin\Delta\alpha \times \sin\Delta\phi}{|A_1|^2 + |A_2|^2 + 2|A_1||A_2|\cos\Delta\alpha \times \cos\Delta\phi}$$

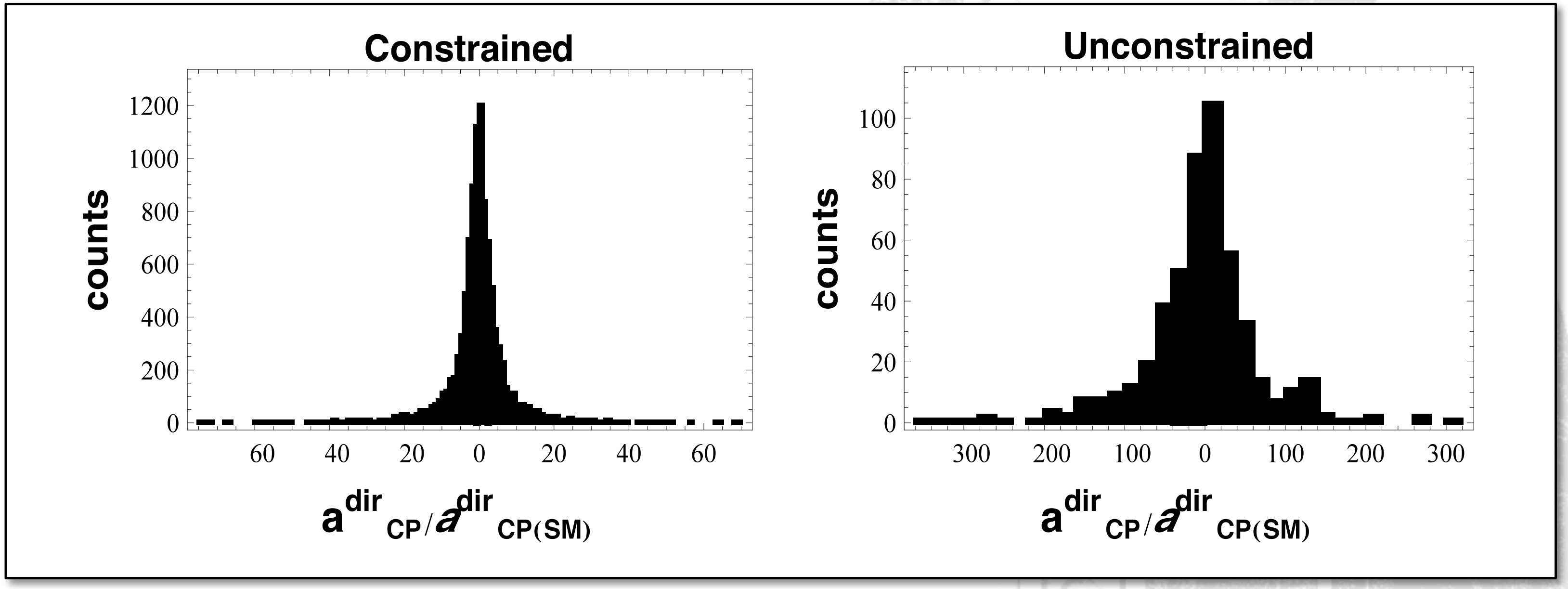
$$\langle A^{\rm CDF}_{\rm CP}(D^0 \to \pi^+\pi^-)\rangle = (+0.22 \pm 0.24_{stat} \pm 0.11_{syst})\%$$
$$\langle A^{\rm CDF}_{\rm CP}(D^0 \to K^+K^-)\rangle = (-0.24 \pm 0.22_{stat} \pm 0.10_{syst})\%\ .$$

Within the SM,

- Indirect CP violation ~ 10^{-5}.
- Direct CP violation ~ 10^{-4}.
- CDF measurement is in excess of SM predictions.
- The differences cited by LHCb and CDF are open to interpretation.

I. I. Bigi, A. Paul and S. Recksiegel, *Theoretical Conclusions from CDF Analyses of CP Violation in* $D^0 \to \pi^+\pi^-, K^+K^-$ *and Future Tasks*. JHEP**06** (2011) 089. [arXiv:1103.5785].

Direct CPV in LHT-like Models



- Enhancement to direct CP asymmetry is O(10%).
- ND *cannot* enhance direct CP asymmetry significantly.
- ND *can* enhance indirect CP asymmetry to account for experimental values.
- If CDF measurements are interpreted as NP effects, it is probably indirect CPV.

I. I. Bigi, A. Paul and S. Recksiegel, *Theoretical Conclusions from CDF Analyses of CP Violation in* $D^0 \to \pi^+\pi^-, K^+K^-$ *and Future Tasks*. JHEP**06** (2011) 089. [arXiv:1103.5785].

The Future of Charm

Three body problems.

$D^{\pm}_{(s)} \rightarrow h_1 h_2 h_3$

- Separation of weak and strong phase possible.
- CP asymmetry does not depend on relative production of CP conjugate states.

$D^0/\bar{D}^0 \rightarrow K_S K^+ K^- \quad D^0/\bar{D}^0 \rightarrow K_S \pi\pi$

- Possible intervention of ND.
- SM cannot generate direct CP violation.

✓ 2D Dalitz Plot analysis needs to be done.
✓ CP asymmetry does not depend on relative production of CP conjugate states.
✓ More data necessary but more information can be gleaned.

I. I. Bigi and A. Paul, *On CP Asymmetries in Two-, Three- and Four-Body D Decays.* JHEP**03** (2012) 021 [arXiv:1110.2862].

Four body problems.

$D_L \to h^+h^-l^+l^-$

$$D_L \xrightarrow{\not{CP}} h^+h^- \xrightarrow{\text{IB}} h^+h^-\gamma \text{ and } D_L \xrightarrow{\text{M1,E1}} h^+h^-\gamma.$$

$$D_L \to h^+h^-\gamma^* \to h^+h^-l^+l^-$$

$\mathrm{BR}(D \to \pi^+\pi^-l^+l^-) \sim 10^{-9}$

$\mathrm{BR}(D \to K^+K^-l^+l^-) \sim 10^{-10} - 10^{-9}$

$$\frac{\mathrm{d}}{\mathrm{d}\Phi}\Gamma(D_L \to h^+h^-l^+l^-) = \Gamma_1 \cos^2\Phi + \Gamma_2 \sin^2\Phi + \Gamma_3 \cos\Phi \sin\Phi.$$

$$A_{\mathrm{T}}^D = \frac{\left[\left(\int_0^{\frac{\pi}{2}} + \int_{\pi}^{\frac{3\pi}{2}}\right) - \left(\int_{\frac{\pi}{2}}^{\pi} + \int_{\frac{3\pi}{2}}^{2\pi}\right)\right] \frac{d\Gamma}{d\Phi} d\Phi}{\int_0^{2\pi} \frac{d\Gamma}{d\Phi} d\Phi} = \frac{2\Gamma_3}{\pi(\Gamma_1 + \Gamma_2)}.$$

$$\eta_{h^+h^-}^{D(h)} \equiv \frac{\langle h^+h^-|H_W|D_L\rangle}{\langle h^+h^-|H_W|D_S\rangle} = \epsilon_D + \epsilon'_D, \quad \arg\left(\eta_{h^+h^-}^{D(h)}\right) \equiv \Phi_{\pm}^{D(h)}$$

$$K_L \to e^+e^-\pi^+\pi^-$$

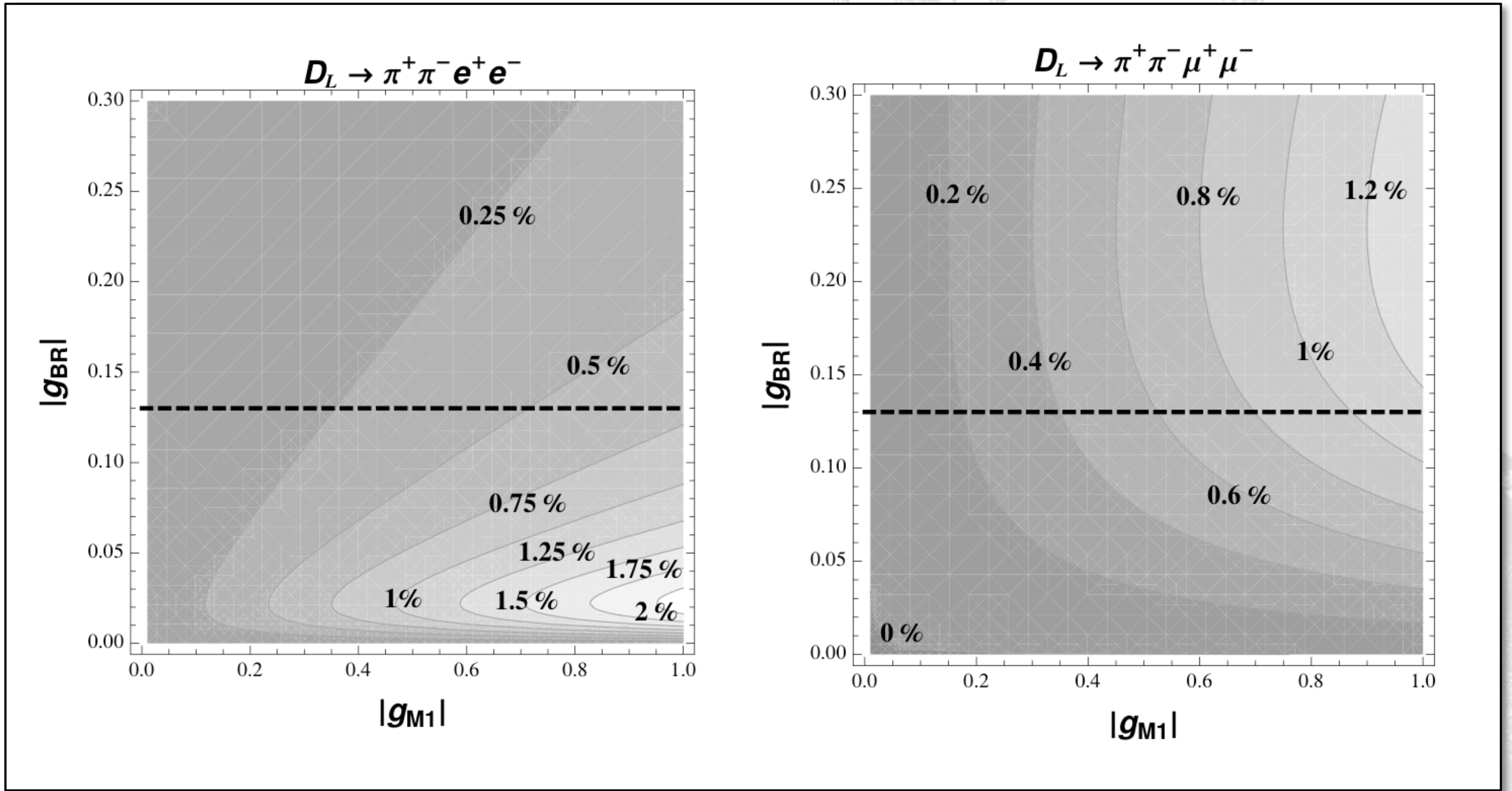
$$A_{\mathrm{T}}|_{\text{theory}} = (14.3 \pm 1.3)\%$$

$$A_{\mathrm{T}}|_{exp} = (13.7 \pm 1.5)\%$$

L. M. Sehgal, M. Wanninger, *CP Violation in the Decay* $K_L \to \pi^+\pi^-e^+e^-$. Phys. Rev. **D 46** (1992) 1035; *Erratum:* Phys. Rev. **D 46** (1992) 5209.

The Outcome.

$D_L \to h^+h^-l^+l^-$



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I. I. Bigi and A. Paul, *On CP Asymmetries in Two-, Three- and Four-Body D Decays.* JHEP**03** (2012) 021 [arXiv:1110.2862].

The Outcome.

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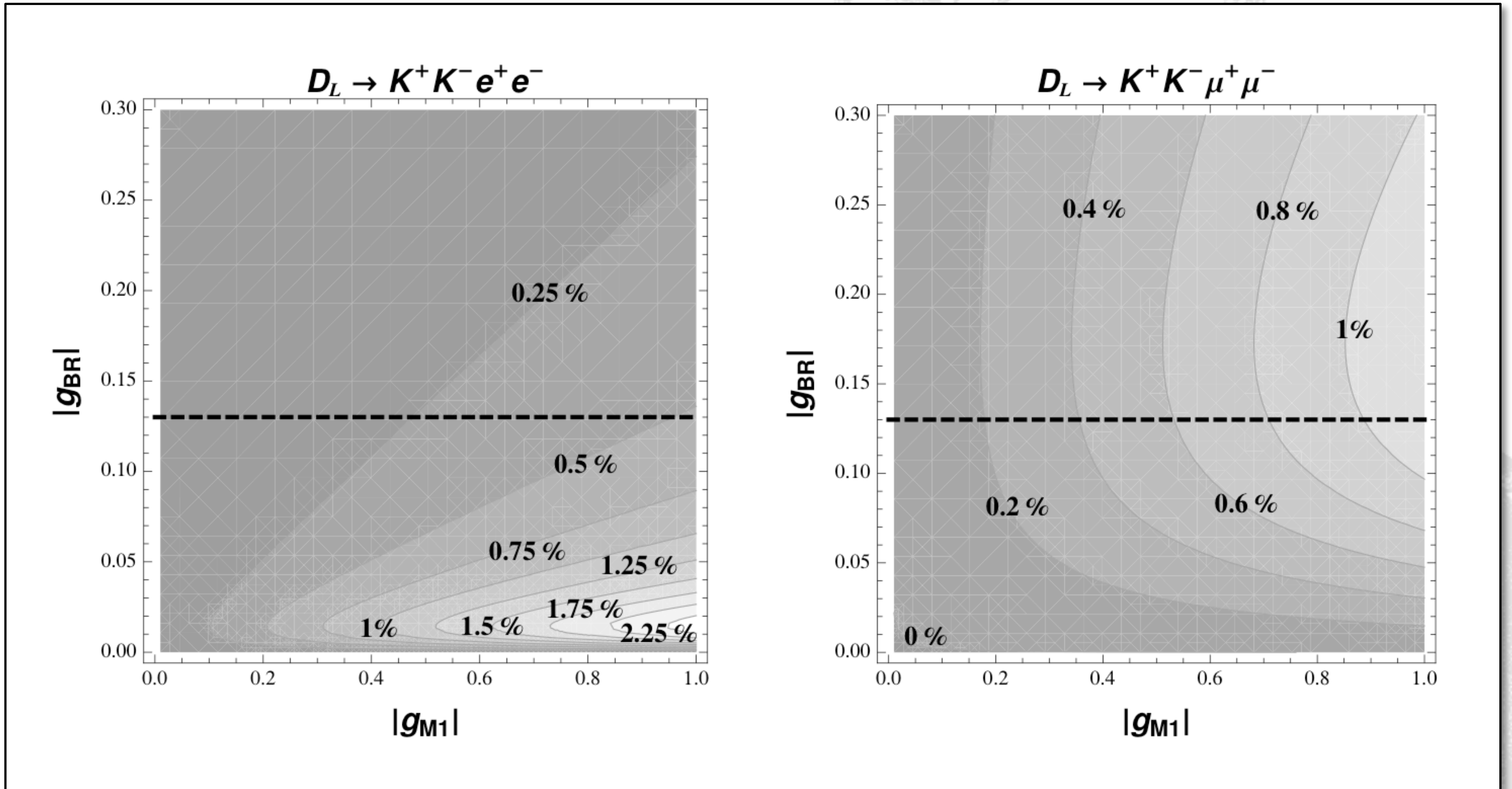

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$A_T|_{\text{theory}} = (14.3 \pm 1.3)\%$

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Similar analysis for $D^0 \to K^+\pi^-l^+l^-$ vs. $\bar{D}^0 \to K^-\pi^+l^+l^-$

I. I. Bigi and A. Paul, *On CP Asymmetries in Two-, Three- and Four-Body D Decays.* JHEP**03** (2012) 021 [arXiv:1110.2862].

Four body problems.

$D^0 \rightarrow K^+K^-\pi^+\pi^-$

- ✓ Time dependent CP analysis can be done.
- ✓ T odd correlation can be probed.
- × Theoretically more challenging.

$D^\pm \rightarrow K_S K^\pm l^+ l^-$: CP violation from FSI, none from ND.

$D^\pm \rightarrow K_S \pi^\pm l^+ l^-$ $\qquad \dfrac{\Gamma(D^+ \rightarrow K_S\pi^+) - \Gamma(D^- \rightarrow K_S\pi^-)}{\Gamma(D^+ \rightarrow K_S\pi^+) + \Gamma(D^- \rightarrow K_S\pi^-)} \simeq 2\mathrm{Re}(\epsilon_K) \simeq 3.3 \times 10^{-3}$

- ✓ CA mode, CP violation possible within SM through interference with DCSD.
- ✓ ND contribution possible.
- ✓ T odd correlation can be probed.

I. I. Bigi and A. Paul, *On CP Asymmetries in Two-, Three- and Four-Body D Decays.* JHEP**03** (2012) 021 [arXiv:1110.2862].

Old parameterization of the CKM

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta + i\eta\frac{1}{2}\lambda^2) \\ -\lambda & 1-\frac{1}{2}\lambda^2 - i\eta A^2\lambda^4 & A\lambda^2(1+i\lambda^2\eta) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$A = 0.808^{+0.022}_{-0.015}\,, \quad \lambda = 0.2253 \pm 0.0007\,,$$

$$\bar{\rho} = 0.132^{+0.022}_{-0.014}\,, \quad \bar{\eta} = 0.341 \pm 0.013\,,$$

New parameterization of the CKM

$$\begin{pmatrix} 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8}-\frac{\lambda^6}{16} & \lambda & \tilde{h}\lambda^4 e^{-i\delta_{\rm QM}} \\ -\lambda+\frac{\lambda^5}{2}f^2 & 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8}(1+4f^2)-f\tilde{h}\lambda^5 e^{i\delta_{\rm QM}}+\frac{\lambda^6}{16}(4f^2-4\tilde{h}^2-1) & f\lambda^2+\tilde{h}\lambda^3 e^{-i\delta_{\rm QM}}-\frac{\lambda^5}{2}\tilde{h}e^{-i\delta_{\rm QM}} \\ f\lambda^3 & -f\lambda^2-\tilde{h}\lambda^3 e^{i\delta_{\rm QM}}+\frac{\lambda^4}{2}f+\frac{\lambda^6}{8}f & 1-\frac{\lambda^4}{2}f^2-f\tilde{h}\lambda^5 e^{-i\delta_{\rm QM}}-\frac{\lambda^6}{2}\tilde{h}^2 \end{pmatrix}$$

$$f = 0.754^{+0.016}_{-0.011}\,, \qquad \tilde{h} = 1.347^{+0.045}_{-0.030}\,, \quad \delta_{\rm QM} = (90.4^{+0.36}_{-1.15})^\circ\,.$$

Significant Change in the CKM Landscape due to Expansion through $\mathcal{O}(\lambda^6)$

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So…
What do I bring to the table?

But this is what I did to earn a PhD…

- **I Learnt:**
  - Calculations within the Standard Model.
  - Oscillations and CP violation and charm dynamics.
  - Little Higgs Models.
  - To do what Ikaros* tells me to.

- **I Worked:**
  - Calculated rare decays of charmed mesons in LHT-like models.
  - CP violation in two- three- and four-body decay modes of charmed mesons.
  - Did what Ikaros told me to.

- **I Understood:**
  - Charm dynamics is plagued by theoretical uncertainties.
  - It is best to do what Ikaros tells me to.

- **So why should I be given a PhD?**
  - It is the beginning of another era of charm dynamics, both in the theoretical and experimental fronts and from here, all roads lead to Rome.

* Ikaros: a.k.a. my advisor.

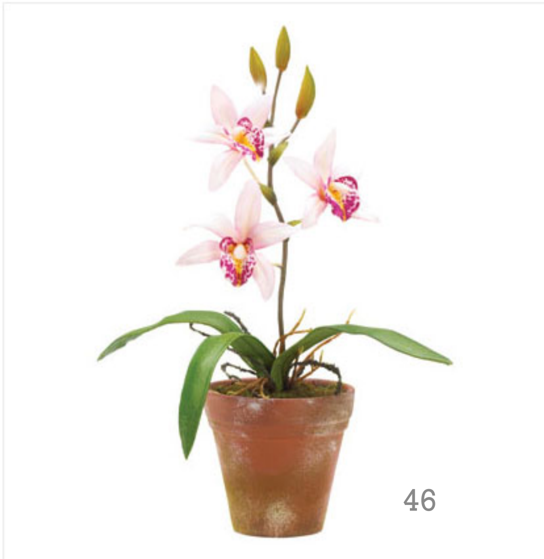
"Ghost of the Future," he exclaimed, "I fear you more than any spectre I have seen. But as I know your purpose is to do me good, and as I hope to live to be another man from what I was, I am prepared to bear you company, and do it with a thankful heart. Will you not speak to me?"

Charles Dickens
A Christmas Carol

In Rome you live like the Romans do.

("… Best of Luck, you will need it!!")*

Thank you…!!



* Ikaros would say…