Model independent signatures of New Physics in $B \to D\ell^+\ell^-$ decays

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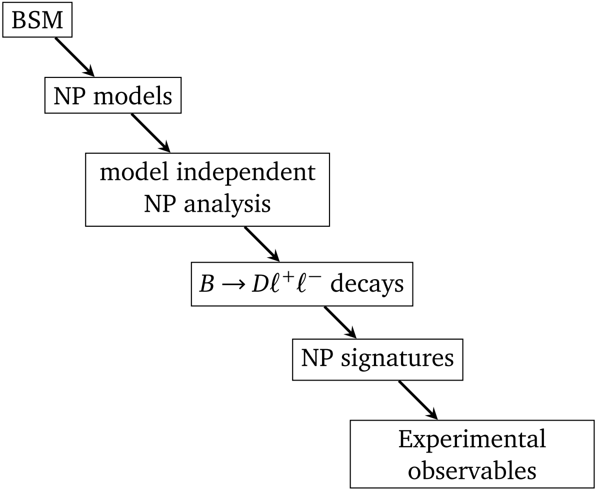
Layout of the talk



SM accomplishes an incomplete description of our observable universe at its most fundamental level.

The Standard Model of particle physics (SM) fails to answer,

1. What is the quantum description of gravity?
2. What is dark matter made up of, and what is dark energy?
3. How is the matter anti-matter asymmetry observed in our universe be explained?
4. How do neutrinos get mass?
5. How to describe the observed muon anomalous magnetic dipole moment $(g-2)$?
6. Why is there no CP violation in strong interaction?
7. Is there any physical understanding of the plethora of SM parameters?
8. Why do quarks and leptons appear in three families?
9. How to unify the strong and electro-weak interactions?

… and so on.

Despite its glaring lacunae, SM is our best description of the experimentally observed zoo of elementary particles except the neutrinos.

With insufficient experimental guidance we are lost in the rain-forest of Beyond SM scenarios (New Physics).

We have many beyond standard model scenarios (New Physics possibilities):

- Grand Unified Theories ($SU(5)$, $SU(8)$, $SO(10)$, ...),
- Supersymmetry (MSSM, NMSSM, ...),
- Extra dimensions (Large ED, warped ED, universal ED, ...),
- Neutrino mass models (see-saw, inverse see-saw, ...),
- Dark matter models (WIMP, SIMP, Axions, ...),
- Technicolor,
- Preonic models (Rishon model, Quantum Haplodynamics, ...),
- Quantum gravity (e.g. loop quantum gravity),
- String theory, ... etc.

Experiment is the touchstone of all new physics possibilities.

Our best strategy to search for new physics is to look for its model-independent signatures.

With so many new physics (NP) possibilities, we must first figure out how, in general, some NP would affect a certain experimental observation.

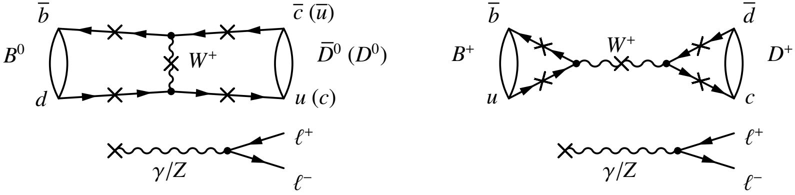
The most popular flavor physics probe for NP has been the $b \to s\ell^+\ell^-$ transition, e.g. in $B \to K^*\ell^+\ell^-$ decays.

However, in analysis of $B \to K^{(*)}\ell^+\ell^-$ decays, the weak annihilation and weak exchange diagrams are neglected in comparison with tree and penguin diagrams as they are suppressed by $\mathcal{O}\left(\Lambda_{QCD}/m_B\right)$.

Nevertheless, processes such as $B^0 \to \bar{D}^0\ell^+\ell^-$ which predominantly take place via weak exchange diagrams, can have large branching ratio $\mathcal{O}\left(10^{-5}\right)$ due to large Wilson coefficients[†].

[†]C. S. Kim, R. H. Li and Y. Li, JHEP **1110**, 152 (2011).

The interaction Hamiltonian for $B \to D\ell^+\ell^-$ involves six-fermion interaction.



There are three currents involved in these decays:

- two charged currents involving the valence quarks,
- one neutral current involving the charged leptons.

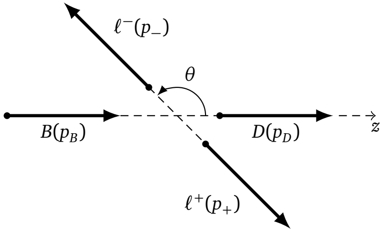
The six-fermion interaction Hamiltonian dictates the most general amplitude for $B \to D\ell^+\ell^-$ decays.

$$
\begin{aligned}
\mathscr{M}\left(B \to D\ell^+\ell^-\right) = \frac{G_F^2}{m_B}\Big\{ & \mathscr{F}_S\left(\bar{\ell}\,\mathbf{1}\,\ell\right) && \textit{Scalar}\\
&+ \mathscr{F}_P\left(\bar{\ell}\,\gamma^5\,\ell\right) && \textit{Pseudoscalar}\\
&+ \left(\mathscr{F}_V^+ p_\alpha + \mathscr{F}_V^- q_\alpha\right)\left(\bar{\ell}\,\gamma^\alpha\,\ell\right) && \textit{Vector}\\
&+ \left(\mathscr{F}_A^+ p_\alpha + \mathscr{F}_A^- q_\alpha\right)\left(\bar{\ell}\,\gamma^\alpha\,\gamma^5\,\ell\right) && \textit{Axialvector}\\
&+ \mathscr{F}_{T_1}\,p_\alpha\,q_\beta\left(\bar{\ell}\,\sigma^{\alpha\beta}\,\ell\right) && \textit{MDM}\\
&+ \mathscr{F}_{T_2}\,p_\alpha\,q_\beta\left(\bar{\ell}\,\sigma^{\alpha\beta}\,\gamma^5\,\ell\right)\Big\}. && \textit{EDM}
\end{aligned}
$$

Here $\mathscr{F}$ denotes form factors, $p \equiv p_B + p_D$ and $q \equiv p_B - p_D = p_+ + p_-$.
All NP information is contained in the form factors.

We analyse the $B \to D\ell^+\ell^-$ decays in the Gottfried-Jackson frame.

Gottfried-Jackson frame



Notation á la Mandelstam:

$$s = (p_+ + p_-)^2 = (p_B - p_D)^2,$$
$$t = (p_D + p_-)^2 \equiv a - b\cos\theta,$$
$$u = (p_D + p_+)^2 \equiv a + b\cos\theta.$$

where

$$a = \frac{1}{2}\left(m_B^2 + m_D^2 + 2m_\ell^2 - s\right),$$
$$b = \frac{1}{2}\left(\sqrt{\lambda\left(m_B^2, m_D^2, s\right)\left(1 - 4m_\ell^2/s\right)}\right),$$

with the Källén function $\lambda(x, y, z)$ defined as

$$\lambda\,(x, y, z) = x^2 + y^2 + z^2 - 2\,(xy + yz + zx)\,.$$

The angular distribution for $B \to D\ell^+\ell^-$ decays has three distinct parts.

$$\frac{d^2\Gamma}{ds\, d\cos\theta} = \frac{b\sqrt{s}}{128\ \pi^3\ m_B^2\left(m_B^2 - m_D^2 + s\right)}\left(\mathcal{T}_0 + \mathcal{T}_1\ \cos\theta + \mathcal{T}_2\ \cos^2\theta\right).$$

In the massless lepton limit (i.e. $m_\ell \to 0$), which is a very good approximation at B mass scale, we have

$$\mathcal{T}_0 = 8\ b^2\left(\left|\mathcal{F}_A^+\right|^2 + \left|\mathcal{F}_V^+\right|^2\right) + 2\ s\left(|\mathcal{F}_P|^2 + |\mathcal{F}_S|^2\right),$$

$$\mathcal{T}_1 = 8\ b\ s\left(\mathrm{Im}\left(\mathcal{F}_{T_2}\mathcal{F}_P^*\right) + \mathrm{Im}\left(\mathcal{F}_{T_1}\mathcal{F}_S^*\right)\right),$$

$$\mathcal{T}_2 = -8b^2\left(\left|\mathcal{F}_A^+\right|^2 + \left|\mathcal{F}_V^+\right|^2 - s\left(\left|\mathcal{F}_{T_1}\right|^2 + \left|\mathcal{F}_{T_2}\right|^2\right)\right).$$

When only, photon γ and Z boson give rise to final $\ell^+\ell^-$, then $\mathcal{F}_S = \mathcal{F}_P = \mathcal{F}_{T_1} = \mathcal{F}_{T_2} = 0$. Thus, in this case,

$$\mathcal{T}_0 = -\mathcal{T}_2 = 8b^2\left(\left|\mathcal{F}_A^+\right|^2 + \left|\mathcal{F}_V^+\right|^2\right), \qquad \text{and} \qquad \mathcal{T}_1 = 0.$$

We define three angular asymmetries that are sensitive to the three distinct parts of the angular distribution.

$$A_0 = \frac{1}{6}\left(\int_{-1}^{-1/2} - 7\int_{-1/2}^{1/2} + \int_{1/2}^{1}\right)\frac{d^2\Gamma}{ds\, d\cos\theta}\, d\cos\theta \qquad = \mathscr{C}\ \mathscr{T}_0,$$

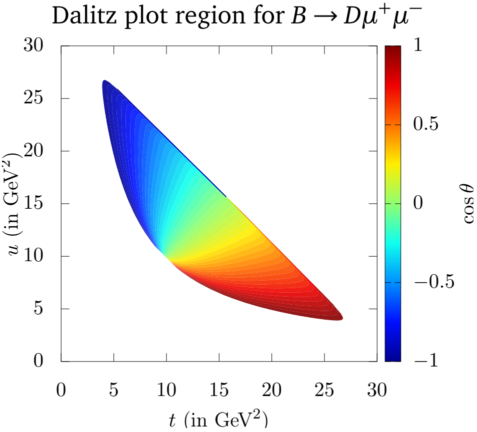
$$A_1 = -\left(\int_{-1}^{0} - \int_{0}^{1}\right)\frac{d^2\Gamma}{ds\, d\cos\theta}\, d\cos\theta \qquad = \mathscr{C}\ \mathscr{T}_1,$$

$$A_2 = 2\left(\int_{-1}^{-1/2} - \int_{-1/2}^{1/2} + \int_{1/2}^{1}\right)\frac{d^2\Gamma}{ds\, d\cos\theta}\, d\cos\theta \qquad = \mathscr{C}\ \mathscr{T}_2,$$

where $\mathscr{C} = \left(b\ \sqrt{s}\right)/\left(128\ \pi^3\ m_B^2\left(m_B^2 - m_D^2 + s\right)\right)$. Forward-backward asymmetry:

$$A_{FB} = -A_1 \propto \mathscr{T}_1.$$

Signatures of New Physics in $B \to D\ell^+\ell^-$ decays



Signatures of NP:

1. $A_1 \neq 0$,
2. $A_0 + A_2 \neq 0$.

The model independent signatures do not depend upon the *B* or *D* meson we consider.

The model independent signatures are the same for $B^0 \to D^0 \ell^+ \ell^-$, $B^0 \to \bar{D}^0 \ell^+ \ell^-$, $B^+ \to D^+ \ell^+ \ell^-$ as well as their CP conjugate modes.

These signatures are not affected by $B^0 - \bar{B}^0$ or $D^0 - \bar{D}^0$ mixings.

Conclusion

Any NP contribution in $B \to D\ell^+\ell^-$ decays, irrespective of the particulars of NP model, will leave some characteristic signatures in the corresponding Dalitz plot which can be quantified by easily observable angular asymmetries A_0, A_1 and A_2.

Thank you