Probing effects of new physics in semi-hadronic three-body meson decays by using angular distribution



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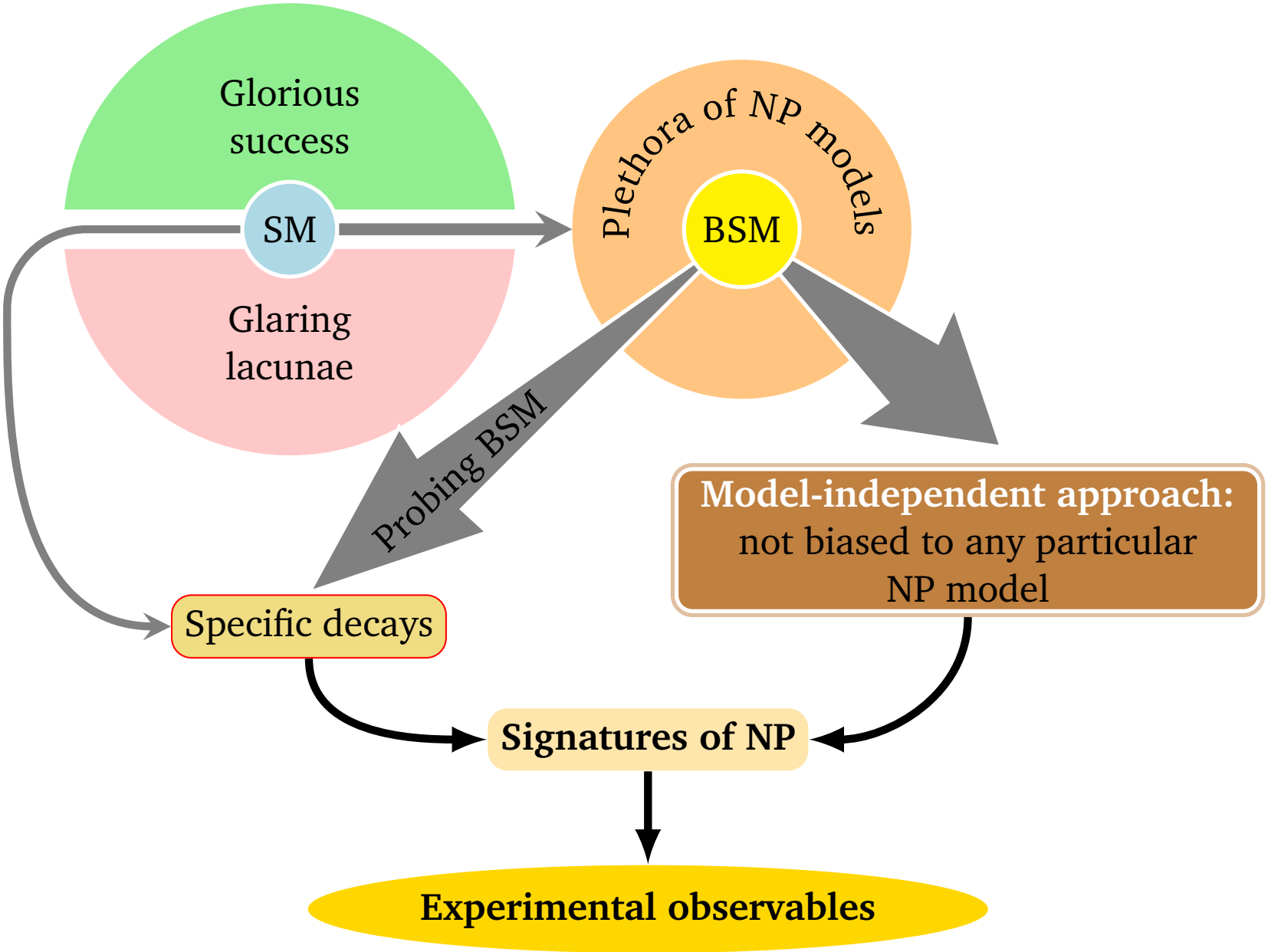
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Plan of the talk



The Standard Model of particle physics is one of the most successful theories of our times.

The various interactions of elementary particles as observed in many particle physics experiments is very well described by the SM.

Some of the most cherished success stories of SM include,

- Prediction and discovery of the Higgs boson, $W^{\pm}$, Z^0, gluons, top, bottom and charm quarks.
- Quark mixing matrix and CP violation in meson sector.
- Prediction of one electroweak mixing angle.
- Precisely accounting for various decays of Z^0.
- Precise prediction of anomalous magnetic dipole moment of electron.

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 are the constituents of dark matter, and what is dark energy?
3. How to explain the matter anti-matter asymmetry observed in our universe?
4. How do neutrinos get such tiny masses?
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 electroweak 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, ...),
- Two-Higgs-doublet model,
- Technicolor,
- Preonic models (Rishon model, Quantum Haplodynamics, ...),
- Quantum gravity (loop quantum gravity, SUGRA, ...),
- 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) models around, how do we figure out which model is the correct one.
- Besides, how can we ensure that all conceivable NP possibilities have already been taken care of by existing NP models.
- We need results from more particle physics experiments, concerning various processes that have not been considered so far, to get a better indication of the nature of NP.
- Would it not be better to know how NP, without considering any specific NP model, would affect some processes in a very general manner (except enhancing the probability of their occurance)?
- This is precisely the place where a model-independent analysis of NP plays a very significant role.

Heavy flavor physics is a very popular area where new physics contributions are favourable.

- Heavy flavor physics, mostly involving B decays have been a favourite hunting ground for various new physics searches.

- Recent experimental results from LHCb[†] on $R(K^{(*)})$, $R(D^{(*)})$, $R(J/\psi)$ suggest new physics might just be around the corner.

- Thus analyzing three-body heavy meson decays, in a model independent manner, is very interesting for new physics studies.

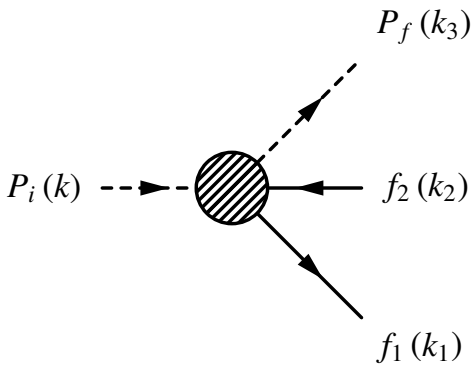
[†] JHEP 1708, 055 (2017);
PRL 115, no. 11, 111803 (2015),
Erratum: [PRL 115, no. 15, 159901 (2015)];
PRL 120, no. 12, 121801 (2018).

We shall consider a fully model independent analysis of decays of the type $P_i \to P_f\, f_1\, f_2$ and look for generic signatures of new physics.

An effective model independent probe of effects of new physics in a large number of heavy meson decays can be analyzed by studying the decay $P_i \to P_f\, f_1\, f_2$, where P_i, P_f are well chosen pseudo-scalar mesons and $f_{1,2}$ denote fermions (which may or may not be leptons) out of which at least one gets detected in experiments.

The masses of particles P_i, P_f, f_1 and f_2 are denoted by m_i, m_f, m_1 and m_2 respectively.

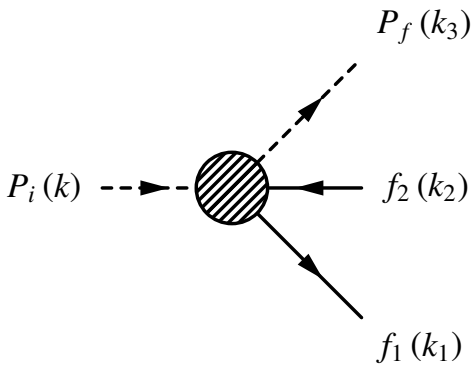
The most general Lagrangian for $P_i \to P_f\, f_1\, f_2$ decays.



$$
\begin{aligned}
\mathscr{L}_{\text{eff}} = & J_S\left(\bar{f}_1 f_2\right) + J_P\left(\bar{f}_1\ \gamma^5\ f_2\right) \\
& + \left(J_V\right)_\alpha\left(\bar{f}_1\ \gamma^\alpha\ f_2\right) \\
& + \left(J_A\right)_\alpha\left(\bar{f}_1\ \gamma^\alpha\gamma^5\ f_2\right) \\
& + \left(J_{T_1}\right)_{\alpha\beta}\left(\bar{f}_1\ \sigma^{\alpha\beta}\ f_2\right) \\
& + \left(J_{T_2}\right)_{\alpha\beta}\left(\bar{f}_1\ \sigma^{\alpha\beta}\gamma^5\ f_2\right) + \text{h.c.},
\end{aligned}
$$

where J_S, J_P, $\left(J_V\right)_\alpha$, $\left(J_A\right)_\alpha$, $\left(J_{T_1}\right)_{\alpha\beta}$, $\left(J_{T_2}\right)_{\alpha\beta}$ are the different hadronic currents which effectively describe the $P_i \to P_f$ quark level transitions.

The most general amplitude for $P_i \to P_f f_1 f_2$ decays.



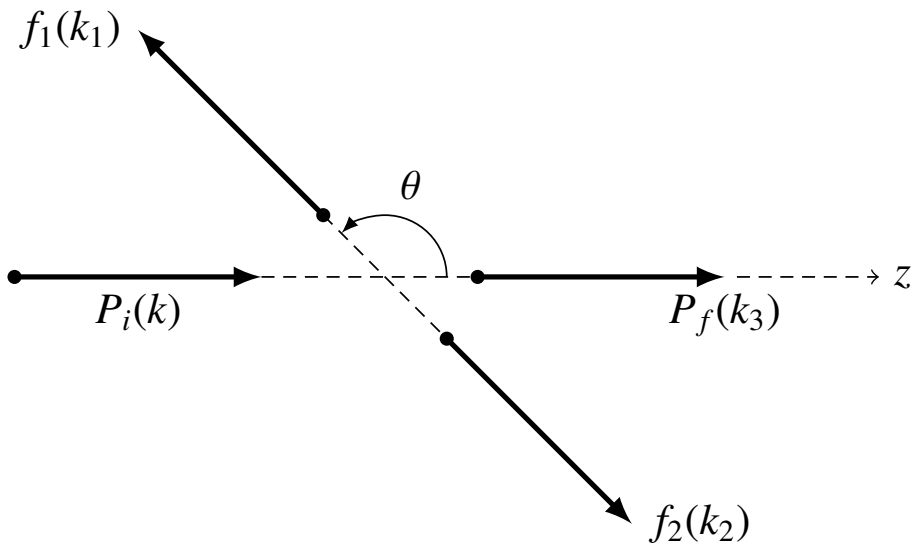
$$\begin{aligned}\mathscr{M}\left(P_i \to P_f f_1 f_2\right) = {} & F_S\left(\bar{f}_1 f_2\right) + F_P\left(\bar{f}_1\,\gamma^5\,f_2\right) \\ & + \left(F_V^+ p_\alpha + F_V^- q_\alpha\right)\left(\bar{f}_1\,\gamma^\alpha\,f_2\right) \\ & + \left(F_A^+ p_\alpha + F_A^- q_\alpha\right)\left(\bar{f}_1\,\gamma^\alpha\,\gamma^5\,f_2\right) \\ & + F_{T_1}\,p_\alpha\,q_\beta\left(\bar{f}_1\,\sigma^{\alpha\beta}\,f_2\right) \\ & + F_{T_2}\,p_\alpha\,q_\beta\left(\bar{f}_1\,\sigma^{\alpha\beta}\,\gamma^5\,f_2\right),\end{aligned}$$

where F_S, F_P, $F_V^\pm$, $F_A^\pm$, F_{T_1} and F_{T_2} are the relevant form factors, with $p \equiv k + k_3$ and $q \equiv k - k_3 = k_1 + k_2$.

In the SM, only vector and axial-vector currents (mediated by photon, $W^\pm$ and Z^0 bosons) and the scalar current (mediated by the Higgs boson) contribute.

All new physics information is contained in the form factors.

We analyse the $P_i \to P_f\, f_1\, f_2$ decays in the Gottfried-Jackson frame.



Notation á la Mandelstam:

$$s = (k_1 + k_2)^2 = (k - k_3)^2,$$
$$t = (k_1 + k_3)^2 = a_t - b\cos\theta,$$
$$u = (k_2 + k_3)^2 = a_u + b\cos\theta.$$

where

$$a_t = m_1^2 + m_f^2 + \frac{1}{2s}\left(s + m_1^2 - m_2^2\right)\left(m_i^2 - m_f^2 - s\right),$$
$$a_u = m_2^2 + m_f^2 + \frac{1}{2s}\left(s - m_1^2 + m_2^2\right)\left(m_i^2 - m_f^2 - s\right),$$
$$b = \frac{1}{2s}\sqrt{\lambda\left(s, m_1^2, m_2^2\right)\ \lambda\left(s, m_i^2, m_f^2\right)},$$

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

The angular distribution for $P_i \to P_f\, f_1\, f_2$ decays has three distinct parts.

$$\frac{d^2\Gamma}{ds\, d\cos\theta} = \frac{b\sqrt{s}\left(C_0 + C_1\cos\theta + C_2\cos^2\theta\right)}{128\,\pi^3\, m_i^2\left(m_i^2 - m_f^2 + s\right)}.$$

Here the coefficients C_0, C_1 and C_2 contain all the NP information that we can extract from the angular distribution.

Owing to the generalness of the amplitude, these coefficients have got complicated expressions.

The angular distribution for $P_i \to P_f f_1 f_2$ decays has three distinct parts.

$$\frac{d^2\Gamma}{ds\, d\cos\theta} = \frac{b\sqrt{s}\left(C_0 + C_1\cos\theta + C_2\cos^2\theta\right)}{128\,\pi^3\, m_i^2\left(m_i^2 - m_f^2 + s\right)}.$$

$$\begin{aligned}
C_0 =& 2\Big(-\left|F_{T_1}\right|^2\Big(-\Sigma m_{12}^2 s^2 + 2\Sigma m_{12}^2\left(\Sigma m^2\right)_{if} s + \left(\Delta m^2\right)_{12}^2 s - \Delta a_{tu}^2 s - 2\left(\Delta m^2\right)_{12}^2\left(\Sigma m^2\right)_{if} - \left(\Delta m^2\right)_{if}^2\Sigma m_{12}^2 + 2\Delta a_{tu}\left(\Delta m^2\right)_{12}\left(\Delta m^2\right)_{if}\Big) \\
&- 2\mathrm{Im}\left(F_V^+ F_{T_1}^*\right)\Big(-\Sigma m_{12} s^2 + 2\Sigma m_{12}\left(\Sigma m^2\right)_{if} s + \Delta m_{12}\left(\Delta m^2\right)_{12} s - 2\Delta m_{12}\left(\Delta m^2\right)_{12}\left(\Sigma m^2\right)_{if} - \left(\Delta m^2\right)_{if}^2\Sigma m_{12} + \Delta a_{tu}\Delta m_{12}\left(\Delta m^2\right)_{if}\Big) \\
&+ \left|F_{T_2}\right|^2\Big(\Delta m_{12}^2 s^2 - 2\Delta m_{12}^2\left(\Sigma m^2\right)_{if} s - \left(\Delta m^2\right)_{12}^2 s + \Delta a_{tu}^2 s + 2\left(\Delta m^2\right)_{12}^2\left(\Sigma m^2\right)_{if} + \Delta m_{12}^2\left(\Delta m^2\right)_{if}^2 - 2\Delta a_{tu}\left(\Delta m^2\right)_{12}\left(\Delta m^2\right)_{if}\Big) \\
&- 2\mathrm{Im}\left(F_A^+ F_{T_2}^*\right)\Big(\Delta m_{12} s^2 - 2\Delta m_{12}\left(\Sigma m^2\right)_{if} s - \left(\Delta m^2\right)_{12}\Sigma m_{12} s + 2\left(\Delta m^2\right)_{12}\Sigma m_{12}\left(\Sigma m^2\right)_{if} - \Delta a_{tu}\left(\Delta m^2\right)_{if}\Sigma m_{12} + \Delta m_{12}\left(\Delta m^2\right)_{if}^2\Big) \\
&+ \left|F_A^+\right|^2\Big(s^2 - 2\left(\Sigma m^2\right)_{if} s - \Sigma m_{12}^2 s + 2\Sigma m_{12}^2\left(\Sigma m^2\right)_{if} + \left(\Delta m^2\right)_{if}^2 - \Delta a_{tu}^2\Big) \\
&+ \left|F_V^+\right|^2\Big(s^2 - 2\left(\Sigma m^2\right)_{if} s - \Delta m_{12}^2 s + 2\Delta m_{12}^2\left(\Sigma m^2\right)_{if} + \left(\Delta m^2\right)_{if}^2 - \Delta a_{tu}^2\Big) + \left|F_A^-\right|^2\left(\Sigma m_{12}^2 s - \left(\Delta m^2\right)_{12}^2\right) \\
&- 2\mathrm{Re}\left(F_P F_A^{-*}\right)\left(\Sigma m_{12} s - \Delta m_{12}\left(\Delta m^2\right)_{12}\right) - \left|F_V^-\right|^2\left(\left(\Delta m^2\right)_{12}^2 - \Delta m_{12}^2 s\right) - 2\mathrm{Re}\left(F_S F_V^{-*}\right)\left(\left(\Delta m^2\right)_{12}\Sigma m_{12} - \Delta m_{12} s\right) \\
&- \left|F_S\right|^2\left(\Sigma m_{12}^2 - s\right) - \left|F_P\right|^2\left(\Delta m_{12}^2 - s\right) + 2\mathrm{Re}\left(F_A^+ F_A^{-*}\right)\left(\left(\Delta m^2\right)_{if}\Sigma m_{12}^2 - \Delta a_{tu}\left(\Delta m^2\right)_{12}\right) \\
&- 2\mathrm{Re}\left(F_P F_A^{+*}\right)\left(\left(\Delta m^2\right)_{if}\Sigma m_{12} - \Delta a_{tu}\Delta m_{12}\right) - 2\mathrm{Re}\left(F_S F_V^{+*}\right)\left(\Delta a_{tu}\Sigma m_{12} - \Delta m_{12}\left(\Delta m^2\right)_{if}\right) + 2\mathrm{Re}\left(F_V^+ F_V^{-*}\right)\left(\Delta m_{12}^2\left(\Delta m^2\right)_{if} - \Delta a_{tu}\left(\Delta m^2\right)_{12}\right)\Big),
\end{aligned}$$

The angular distribution for $P_i \to P_f f_1 f_2$ decays has three distinct parts.

$$\frac{d^2\Gamma}{ds\, d\cos\theta} = \frac{b\sqrt{s}\left(C_0 + C_1\cos\theta + C_2\cos^2\theta\right)}{128\,\pi^3\, m_i^2\left(m_i^2 - m_f^2 + s\right)}.$$

$$\begin{aligned}
C_1 =& 8b\Big(\Delta m_{12}\left(\mathrm{Im}\left(F_V^- F_{T_1}^*\right)s - \mathrm{Re}\left(F_P F_A^{+*}\right)\right) + \Sigma m_{12}\left(-\mathrm{Im}\left(F_A^- F_{T_2}^*\right)s + \mathrm{Re}\left(F_S F_V^{+*}\right) - \left(\Delta m^2\right)_{if}\mathrm{Im}\left(F_A^+ F_{T_2}^*\right)\right) \\
&+ \Delta a_{tu}\left(\left(-\left|F_{T_2}\right|^2 - \left|F_{T_1}\right|^2\right)s + \left|F_V^+\right|^2 + \left|F_A^+\right|^2\right) + \left(\mathrm{Im}\left(F_S F_{T_1}^*\right) + \mathrm{Im}\left(F_P F_{T_2}^*\right)\right)s \\
&+ \left(\Delta m^2\right)_{12}\left(\mathrm{Re}\left(F_V^+ F_V^{-*}\right) + \mathrm{Re}\left(F_A^+ F_A^{-*}\right)\right) + \left(\Delta m^2\right)_{if}\left(\Delta m_{12}\mathrm{Im}\left(F_V^+ F_{T_1}^*\right) + \left(\Delta m^2\right)_{12}\left(\left|F_{T_2}\right|^2 + \left|F_{T_1}\right|^2\right)\right)\Big), \\
C_2 =& 8b^2\left(\left(\left|F_{T_2}\right|^2 + \left|F_{T_1}\right|^2\right)s - \left|F_V^+\right|^2 - \left|F_A^+\right|^2\right),
\end{aligned}$$

The angular distribution for $P_i \to P_f f_1 f_2$ decays has three distinct parts.

$$\frac{d^2\Gamma}{ds\, d\cos\theta} = \frac{b\sqrt{s}\left(C_0 + C_1 \cos\theta + C_2 \cos^2\theta\right)}{128\,\pi^3\, m_i^2 \left(m_i^2 - m_f^2 + s\right)}.$$

The expressions for the coefficients C_0, C_1 and C_2 become simpler if we consider the SM contribution alone, as $F_P = F_{T_1} = F_{T_2} = 0$ in the SM.

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

$$A_0 \equiv A_0(s) = \frac{-\frac{1}{6}\left(\int_{-1}^{-1/2} - 7\int_{-1/2}^{+1/2} + \int_{+1/2}^{+1}\right)\frac{d^2\Gamma}{ds\,d\cos\theta}\,d\cos\theta}{d\Gamma/ds} = \frac{3C_0}{6C_0 + 2C_2},$$

$$A_1 \equiv A_1(s) = \frac{-\left(\int_{-1}^{0} - \int_{0}^{+1}\right)\frac{d^2\Gamma}{ds\,d\cos\theta}\,d\cos\theta}{d\Gamma/ds} = \frac{3C_1}{6C_0 + 2C_2},$$

$$A_2 \equiv A_2(s) = \frac{2\left(\int_{-1}^{-1/2} - \int_{-1/2}^{+1/2} + \int_{+1/2}^{+1}\right)\frac{d^2\Gamma}{ds\,d\cos\theta}\,d\cos\theta}{d\Gamma/ds} = \frac{3C_2}{6C_0 + 2C_2}.$$

The feature of three distinct angular components is also the most general feature after integration over s.

We can do the integration over s and define the following normalized angular distribution,

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = T_0 + T_1\cos\theta + T_2\cos^2\theta,$$

where

$$T_j = \frac{3c_j}{6c_0 + 2c_2},$$

for $j = 0, 1, 2$ and with

$$c_j = \int_{(m_1+m_2)^2}^{(m_i-m_f)^2} \frac{b\sqrt{s}\,C_j}{128\pi^3 m_i^2\left(m_i^2 - m_f^2 + s\right)} ds.$$

The three angular components can be easily measured from the Dalitz plot distribution for $P_i \to P_f f_1 f_2$ decays.

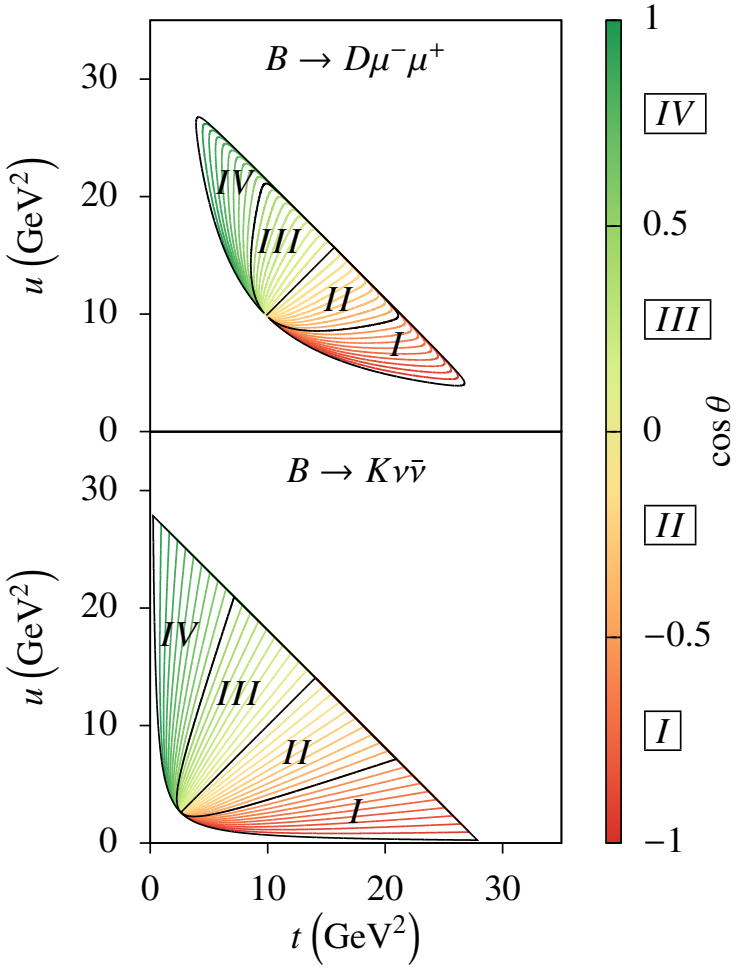
$$T_0 = -\frac{1}{6}\left(\frac{N_I - 7(N_{II}+N_{III})+N_{IV}}{N_I+N_{II}+N_{III}+N_{IV}}\right),$$

$$T_1 = \frac{(N_I+N_{II})-(N_{III}+N_{IV})}{N_I+N_{II}+N_{III}+N_{IV}},$$

$$T_2 = 2\left(\frac{N_I-(N_{II}+N_{III})+N_{IV}}{N_I+N_{II}+N_{III}+N_{IV}}\right),$$

where N_i denotes the number of events in the ith segment of the Dalitz plot.

This is an easier method when the Dalitz plot can be constructed.



An example showing the effect of new physics on angular distribution.

The example process

- We choose a process for which the construction of Dalitz plot is not possible. This is especially true if in $P_i \to P_f\, f_1\, f_2$ the two fermions are missing, such as the case when they are neutrino, anti-neutrino (active or sterile) or some long-lived particles or fermionic dark matter particles.
- We assume that in future with advanced detectors we could at least measure some sort of displaced vertex corresponding to the interaction of either of the fermions with the detector material so that one could deduce the angle θ in the Gottfried-Jackson frame.
- As a specific case let us consider $B \to K \nu \bar{\nu}$. Also, we shall consider two specific NP contributions: scalar type and vector type NP contributions, just to illustrate our methodology.

An example showing the effect of new physics on angular distribution.

SM contribution

- Only vector and axial vector currents contribute and $F_A^{\pm} = -F_V^{\pm}$.
- Angular distribution:

$$\frac{d^2\Gamma^{\rm SM}}{ds\, d\cos\theta} = \frac{b^3\sqrt{s}}{8\,\pi^3\, m_B^2\left(m_B^2 - m_K^2 + s\right)} \left|\left(F_V^+\right)_{\rm SM}\right|^2 \sin^2\theta.$$

Or

$$\frac{1}{\Gamma^{\rm SM}}\frac{d\Gamma^{\rm SM}}{d\cos\theta} = \frac{3}{4}\sin^2\theta,$$

which implies that $T_0 = 3/4 = -T_2$, $T_1 = 0$.

An example showing the effect of new physics on angular distribution.

Scalar type NP contribution

- We consider $F_S \neq 0$, $F_P = F_V^{\pm} = F_A^{\pm} = F_{T_1} = F_{T_2} = 0$.
- Angular distribution (NP only):

$$\frac{d^2\Gamma^{\rm NP}}{ds\, d\cos\theta} = \frac{b\sqrt{s}}{64\,\pi^3\, m_B^2\left(m_B^2 - m_K^2 + s\right)}\left(s - 4m^2\right)|F_S|^2 .$$

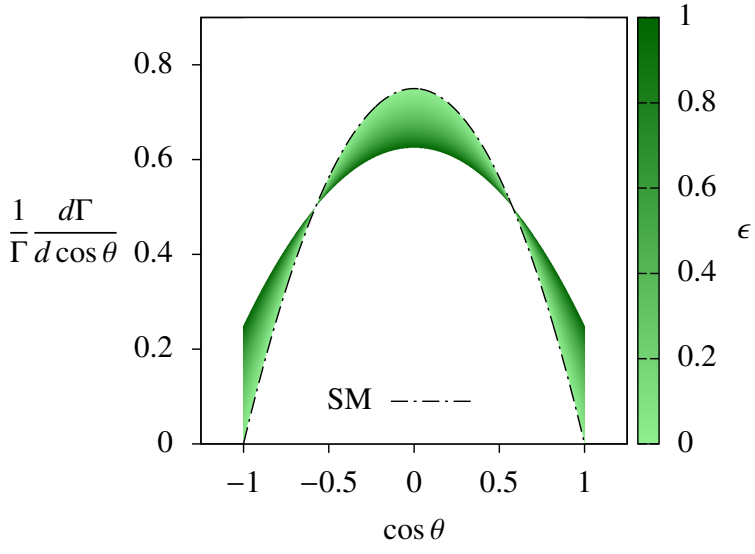
Or

$$\frac{1}{\Gamma^{\rm NP}}\frac{d\Gamma^{\rm NP}}{d\cos\theta} = \frac{1}{2}.$$

- Angular distribution (SM + NP):

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{3\sin^2\theta + 2\epsilon}{4(1+\epsilon)},$$

where the effect of NP is parametrized by $\epsilon = \Gamma^{\rm NP}/\Gamma^{\rm SM}$.



An example showing the effect of new physics on angular distribution.

Vector type NP contribution

- We consider $F_V^+ = F_V^{\rm NP} \neq 0$ and other form factors are zero.
- Angular distribution (NP only):

$$\frac{d^2\Gamma^{\rm NP}}{ds\, d\cos\theta} = \frac{b\left|F_V^{\rm NP}\right|^2 \lambda\left(s, m_B^2, m_K^2\right)\left(s\sin^2\theta + 4m^2\cos^2\theta\right)}{64\,\pi^3\, m_B^2\left(m_B^2 - m_K^2 + s\right)\sqrt{s}}.$$

Or

$$\frac{1}{\Gamma^{\rm NP}}\frac{d\Gamma^{\rm NP}}{d\cos\theta} = \frac{3\left(\mathscr{S}\sin^2\theta + \mathscr{C}\cos^2\theta\right)}{2(2\mathscr{S} + \mathscr{C})},$$

where

$$\mathscr{S} = \int_{4m^2}^{(m_B - m_K)^2} \frac{d\Gamma^{\rm NP}}{ds}\left(\frac{s}{s + 2m^2}\right) ds,$$

$$\mathscr{C} = \int_{4m^2}^{(m_B - m_K)^2} \frac{d\Gamma^{\rm NP}}{ds}\left(\frac{4m^2}{s + 2m^2}\right) ds.$$

An example showing the effect of new physics on angular distribution.

Vector type NP contribution

- Angular distribution (SM + NP):

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{3(1+\epsilon_s)\sin^2\theta + 3\epsilon_c\cos^2\theta}{4(1+\epsilon_s)+2\epsilon_c}.$$

  where

$$\epsilon_s = \mathscr{S}/\Gamma^{\mathrm{SM}}, \qquad \epsilon_c = \mathscr{C}/\Gamma^{\mathrm{SM}},$$

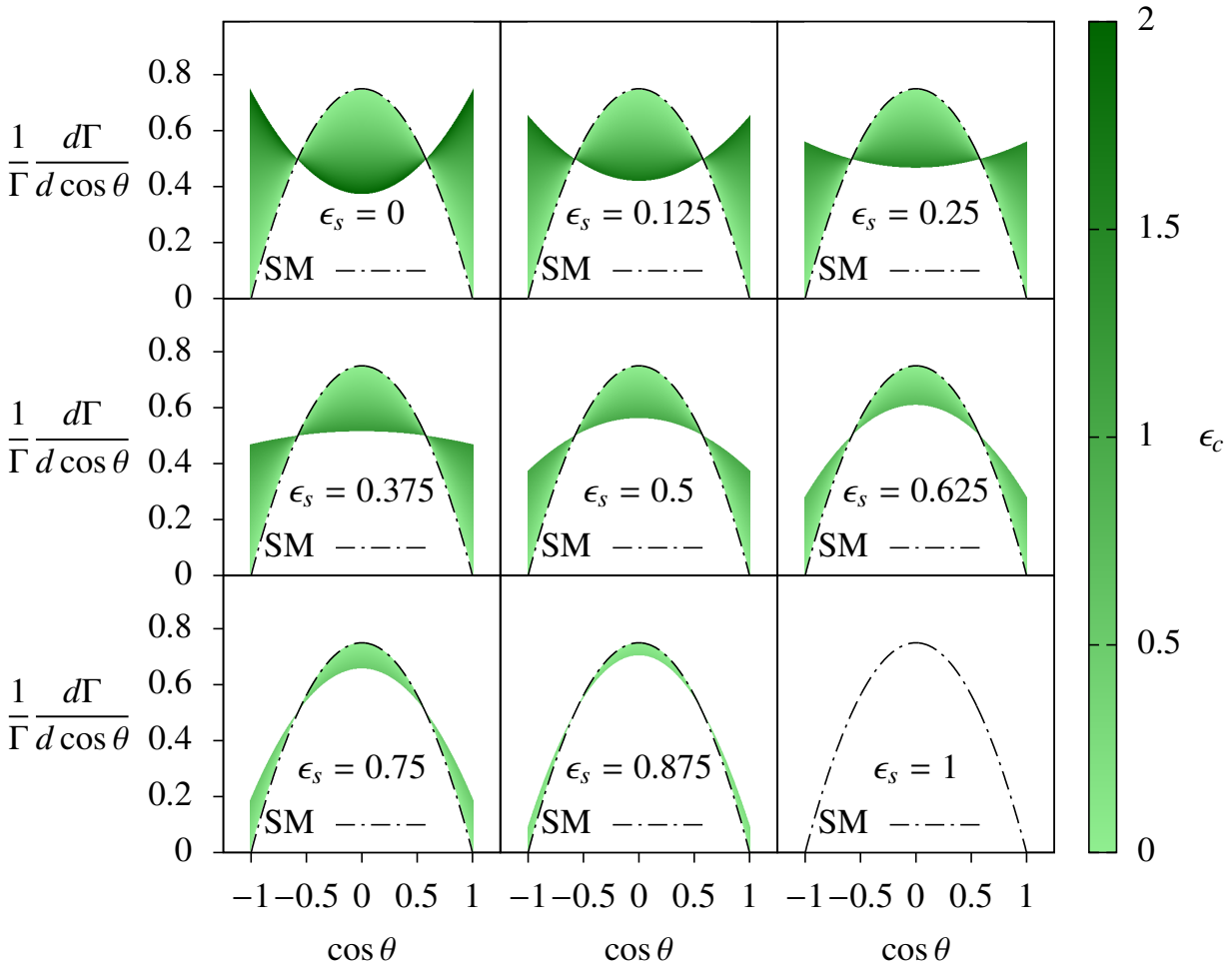
  are the two parameters that describe the effect of vector NP.

- If we consider the mass of the fermion f to be zero, i.e. $m = 0$, then $\mathscr{C} = 0 \implies \epsilon_c = 0$. In such a case we get back the SM result, as this situation is indistinguishable from the SM case.

An example showing the effect of new physics on angular distribution.

Vector type NP contribution

- Assuming $0 \leqslant \Gamma^{NP} \leqslant \Gamma^{SM}$, we get $0 \leqslant \epsilon_s \leqslant 1$ and $0 \leqslant \epsilon_c \leqslant 2(1-\epsilon_s)$.



An example showing the effect of new physics on angular distribution.

Discussion

- Both scalar type and vector type new physics effects vanish at $\cos\theta = \pm 1/\sqrt{3}$. The fundamental reason for this is the absence of any term linear in $\cos\theta$ in the angular distribution.
- Vector type of new physics can accommodate much larger variation in angular distribution than the scalar type scenario.
- However, when $\epsilon = \dfrac{3\epsilon_c}{2(1+\epsilon_s-\epsilon_c)}$, both scalar type and vector type new physics contributions give similar angular distribution.
- In any case, we are able to look into the effects of NP in a way which is not affected by hadronic uncertainties in form factors etc.
- This provides a methodology to parametrize and constraint NP contributions in a model independent manner.

Conclusion

- Any NP contribution in $P_i \to P_f\, f_1\, f_2$ decays, irrespective of the particulars of NP model, would leave behind some generic signatures in the corresponding Dalitz plot or angular distribution, which can be quantified by easily observable angular asymmetries A_0, A_1 and A_2 (or T_0, T_1 and T_2).
- In certain cases, NP can be searched for and constrained in a fully exact manner without any hadronic uncertainties.

Thank you