EvtGen model for New Physics in $B \to D^*\ell\nu$

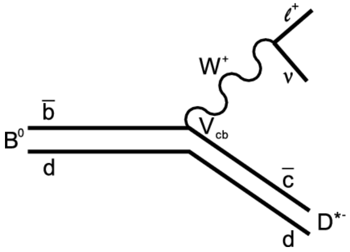
Lopamudra Mukherjee

Nankai University

2023 Belle II Physics Week, KEK

Nov 2, 2023

- Useful in the extraction of $|V_{cb}|$.
- Testing CKM unitarity.
- Sensitive probes of New Physics.
- Test Lepton Flavour Universality of the SM.



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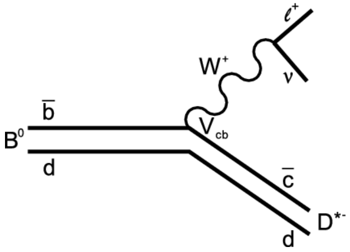

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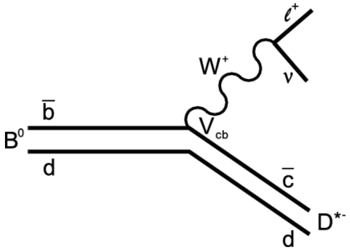

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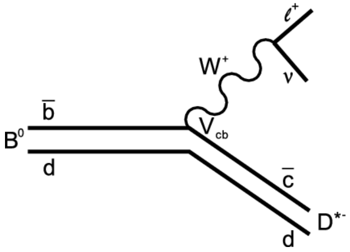

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This talk : **EvtGen model for new physics in** $B \to D^* \ell \nu_\ell$

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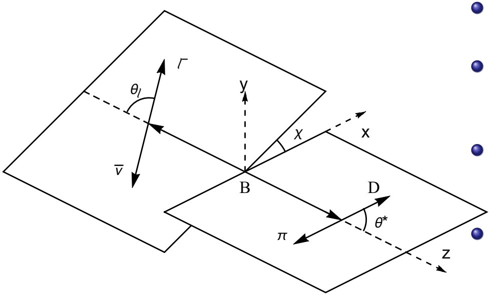

- q^2 : the lepton-neutrino invariant mass squared.
- θ_ℓ : the angle between the direction of the lepton & the direction opposite the D^* meson in the virtual W rest frame.
- θ_{D*} : the angle between the direction of the D^0 meson & the direction of the D^* meson in the D^* rest frame.
- χ : azimuthal angle between the two decay planes.

See talk by Markus Prim

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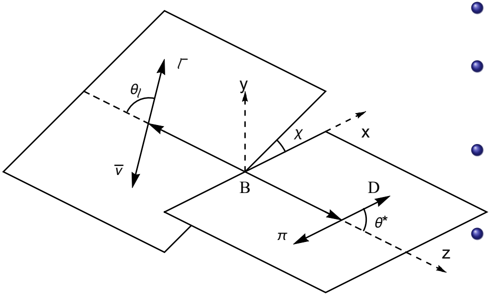

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First tests of LUV in angular distributions, Belle II, 2308.02023

Angular coefficients in $B \to D^* \ell \nu$, Belle, 2310.20286

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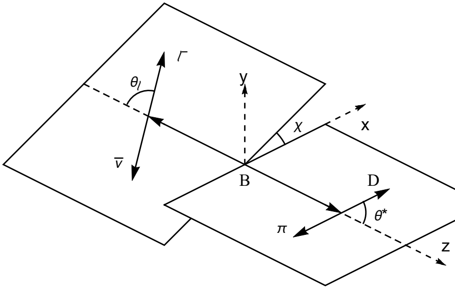

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Angular coefficients in $B \to D^* \ell \nu$, Belle, 2310.20286

Belle II is capable of precisely measuring NP sensitivities in angular observables ⇒ A NP MC in important to correctly estimate detector response

We introduce a new tool to study NP in angular observables of $B \to D^* \ell \nu_\ell$.

$$\mathcal{H}_{eff} = \frac{G_F V_{cb}}{\sqrt{2}} \Big\{ (1 + g_L) \left[\bar{c}\gamma_\mu(1-\gamma_5)b\right] \left[\bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell\right]$$

$$+ g_R \left[\bar{c}\gamma_\mu(1+\gamma_5)b\right] \left[\bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell\right]$$

$$+ g_S \left[\bar{c}b\right] \left[\bar{\ell}(1-\gamma_5)\nu_\ell\right]$$

$$+ g_P \left[\bar{c}\gamma_5 b\right] \left[\bar{\ell}(1-\gamma_5)\nu_\ell\right]$$

$$+ g_T \left[\bar{c}\sigma^{\mu\nu}(1-\gamma_5)b\right] \left[\bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell\right] \Big\} + h.c.$$

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$$+ g_T \; [\bar{c}\sigma^{\mu\nu}(1-\gamma_5)b] \left[\bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell\right] \Big\} + h.c.$$

Caveats :

1. Neutrinos are always left-handed.
2. Alternate convention :
   $C_{V_L} = 1 + g_L$, $C_{V_R} = g_R$, $C_{S_L} = g_S - g_P$, $C_{S_R} = g_S + g_P$, $C_T = g_T$

EvtGen : A Monte Carlo tool

- **EvtGen** : is a MC event generator that simulates the decays of heavy flavour particles, primarily the B and D mesons.
  - Originally written by Anders Ryd and David Lange. *https://evtgen.hepforge.org/*
  - It has detailed models for semileptonic decays, CP-violating decays and produces correct results for the angular distributions in sequential decays, including all correlations.
  - Decay amplitudes, instead of probabilities, are used for the simulation of decays.
  - For details of the algorithm, see the Tutorial

https://indico.cern.ch/event/411269/contributions/1867718/attachments/835829/1159322/tut-all.pdf

New Physics Implementation in EvtGen

https://github.com/qdcampagna/BTODSTARLNUNP_EVTGEN_Model

*B.Bhattacharya, T.Browder, Q. Campagna, A. Datta, S. Dubey, **LM**, A.Sibidanov,[2203.07189]*

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Basic Idea : Write down the decay amplitude for each spin degree of freedom.

$$B \to D^* \ell \nu, D^* \to D\pi$$

The decay amplitude can be written as

$$\mathcal{A} = \sum_{\lambda_{D^*}, \lambda_\ell} \mathcal{A}^{B \to D^* \ell \nu}_{\lambda_{D^*}, \lambda_\ell} \times \mathcal{A}^{D^* \to D\pi}_{\lambda_{D^*}}$$

A total of six amplitudes in terms of new physics Wilson coefficients are written in a C++ model file : *EvtSemiLeptonicVectorAmpNP.cpp*.

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Usage :

- The NP generator, **BTODSTARLNUNP**, can run either in a standalone mode or be integrated into a software framework of a B-physics experiment.
- If a user wants to simulate B-$\bar{B}$ pairs in the Belle II environment from the $\Upsilon(4S)$ resonance, then use the Makefile to make the *run_dstarlnu2* script.
- The information about the new coefficients are encoded in the user decay file, *BB_dstarlnu_np.dec*.

User Decay File

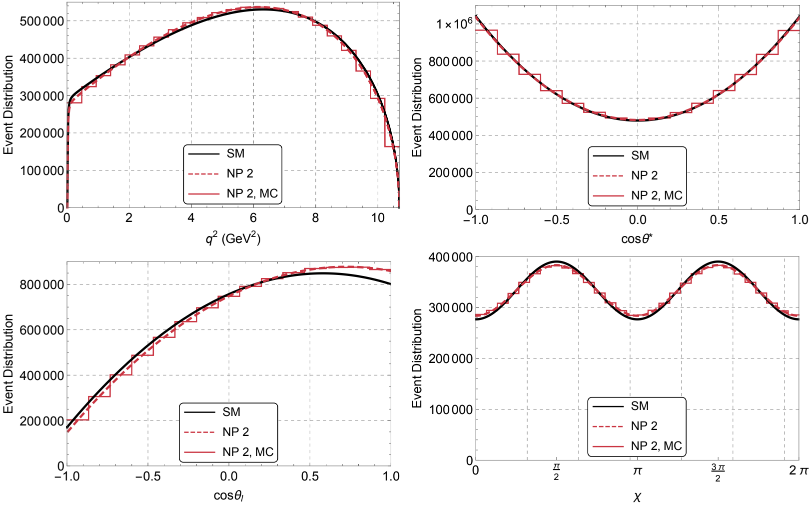
A snippet from the user decay file : BB_dstarlnu_np.dec

```
##need to turn off mixing to prevent B0 from becoming an anti-B0
Define dm_incohMix_B0 0.0

##Decay Upsilon(4S)
1 B0  anti-B0   VSS;
Enddecay

## Enter arguments for new physics parameters
## first argument is cartesian(0) or polar(1) representation of NP coefficients
## which are three consecutive numbers {id, Re(C), Im(C)} or {coeff id,|C|, Arg(C)}
## id==0 \delta C_VL -- left-handed vector coefficient change from SM
## id==1 C_VR -- right-handed vector coefficient
## id==2 C_SL -- left-handed scalar coefficient
## id==3 C_SR -- right-handed scalar coefficient
## id==4 C_T  -- tensor coefficient

Decay B0
## B0 -> D*- e+ nu_e is generated with the Standard Model only
1   D*-  e+  nu_e  BTODSTARLNUNP;
Enddecay

Decay anti-B0
## anti-B0 -> D*+ mu- anti-nu_mu is generated with the addition of New Physics
1   D*+   mu-   anti-nu_mu   BTODSTARLNUNP  0 0 0.06 0 1 0.075 0 2 0 -0.2 3 0 0.2;
Enddecay

End
```

To generate NP distributions, the user inputs several arguments in the user decay file.

Application : NP in $B \to D^* \mu\nu$

✓ Test our module against SM and NP

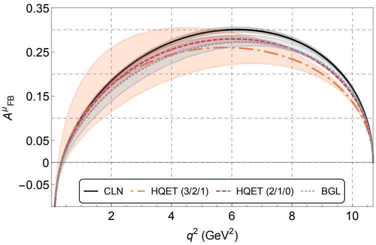


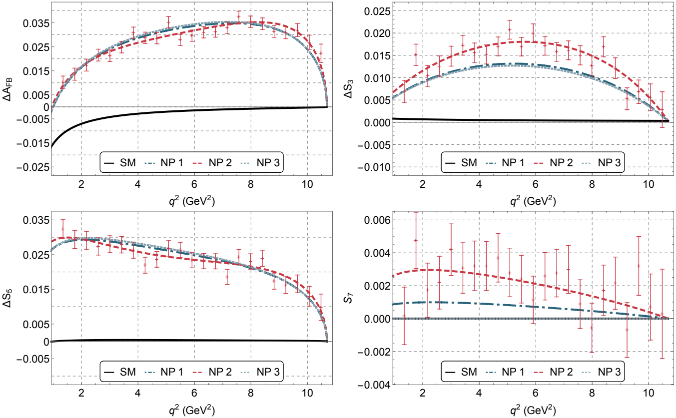
Angular Analyses

✓Simulate new physics distributions

	g_L	g_R	g_P
NP1:	0.06	0.075	$0.2i$
NP2:	0.08	0.090	$0.6i$
NP3:	0.07	0.075	0

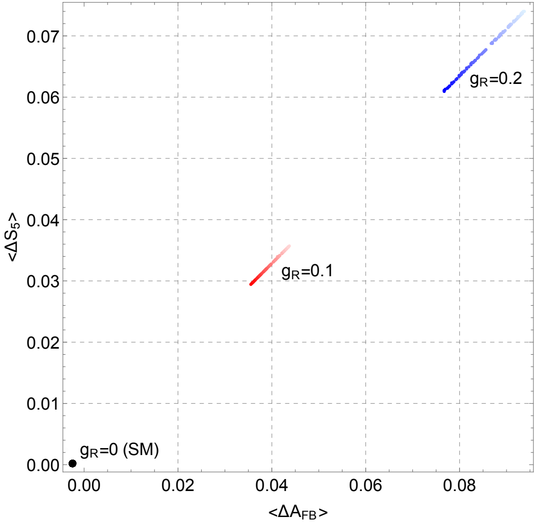
- $\mathcal{R}_{\mu/e} = 1.00 \pm 0.03 \Rightarrow$
  No modification to R_{D^*}
- Reduce effects of FF variations to reliably extract NP
  (See talk by Marco Fedele)
- $\Delta X = X_\mu - X_e$ robust against FF variations.





Plots with 10M events MC dataset at 50 ab^{-1} in q^2 bins of 0.4 GeV^2

- Delta observables robust again FF variations.
- Correlated signals
- Higher statistics required to extract true CP violating observables like S_7.

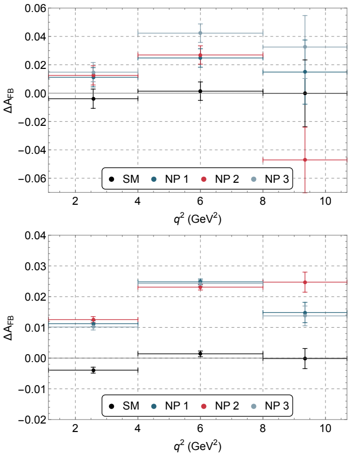


g_L is varied between 0 and 0.2 (light to dark in the color scale)

Correlated signals between ΔA_{FB} and ΔS_5

Belle II sensitivities

- Here we use Belle fiducial cuts :
  - $p_T^{\mu,e} > 0.8$ GeV
  - $p_T^{\pi} > 0.1$ GeV
  - Angular acceptance of all final state particles : $-0.866 < \cos\theta < 0.956$
- Note that we use the same p_T cut for electron and muon since we did not include detector efficiencies for the leptons separately.



Stat unc. from MC with $\mathcal{L}_{\rm int} = 1\ {\rm ab}^{-1}$ (top) and $50\ {\rm ab}^{-1}$ (bottom)

Limitations & the way forward...

Limitations :

- The MC fails for tensor new physics scenarios (... not fully understood why?)
- FFs : BGL (default), IgWa* and CLN FFs are incorporated but not automated nor set as free parameters.
  Iguro, Watanabe, 2004.10208

Work in progress/ Future directions :

- Improve upon the limitations.
- Include new decay modes : $B \to D\tau\nu$, $B \to D^*(\to D\pi)\tau(\to \mu\nu\bar{\nu})\nu$
- Include new physics models : eg., RHNs, SMEFT, etc.
- Suggestions welcome for new ideas for improvement.

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THANK YOU!