Helicity Amplitude Module for Matrix Element Reweighting: Hammer

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Based on:

1610.02045 (Z Ligeti, M Papucci, & DR)
1703.05330 (F Bernlochner, Z Ligeti, M Papucci & DR)
1711.03110 (F Bernlochner, Z Ligeti, & DR)
180x.xxxxx (F Bernlochner, S Duell, M Papucci, Z Ligeti, & DR)

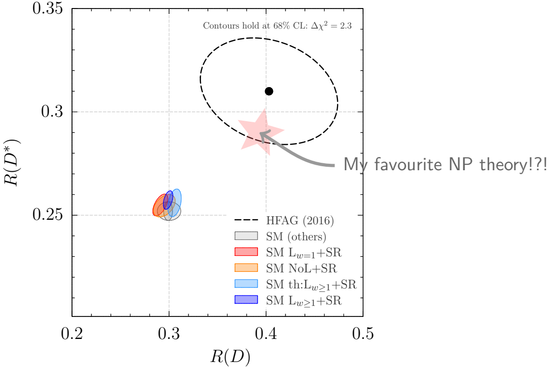
$B \to D^{(*)}$ anomalies

- Non-trivial τ and D^* interference effects
- Non-trivial phase space cuts
- τ frame not* reconstructible
- D^{**} BGs very sensitive to NP! (see 1711.03110)
- Simultaneous BG+signal float: model dependent template!

(Simplistic) e.g: Fix BG shape and detector weights; allow BG and signal normalizations to float wrt data

Cautions

Should be done with caution and caveats:



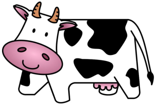
Black ellipse tells us confidence to reject SM, not confidence to accept NP.

Example: $R(D) = 0.375 \pm 0.064 \pm 0.026$ (SM)

vs $R(D) = 0.329 \pm 0.060 \pm 0.022$ (2HDM) [Belle 1507.03233]

Moral (roughly speaking)

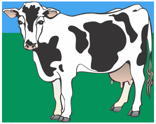
What most NP theory analyses/fits use:



What expts actually see:

Given the right tools, expt collaborations are better equipped to perform NP model fits!

What we aim to supply:



Strategy

- Detector simulation weights commute with model weights.
- Efficiently reweighting truth level information, efficiently reweights fully simulated sample!
- Makes it feasible to explore and run fits over NP model space.

Use compact amplitude expressions for all NP (!) for

$$B \to D^{(*,**)}(\to DY)\tau(\to X\overline{\nu}_\tau)\nu_\tau$$

- $\mathcal{O}(\sum_n m_n)$ terms for n NP currents with m_n internal states, vs $\mathcal{O}((\sum_n m_n)^2)$ for square matrix element.
- Much faster to compute in NP-FF space (more later) for each event (and less space needed to store it)!
- Interference effects trivially included, and scaling of terms easy to see

MC Strategy

- Philosophy: Everything is a tensor
- At amplitude level can linearize in both NP and FF: create an NP-FF-independent amplitude tensor!
- $$\mathcal{M} = \mathcal{M}_{\alpha,i} \mathrm{FF}_{\alpha} v_i$$
  $$\vec{v} = \Big(1\,,\; C^S_{RL}\,,\; C^S_{LL}\,,\; C^S_{LR}\,,\; C^S_{RR}\,,\; C^V_{RL}\,,\; C^V_{LL}\,,\; C^V_{LR}\,,\; C^V_{RR}\,,\; C^T_{RL}\,,\; C^T_{LR}\Big)\,.$$
  FF_{α} is specific FF basis, but any FF param, incl errors.

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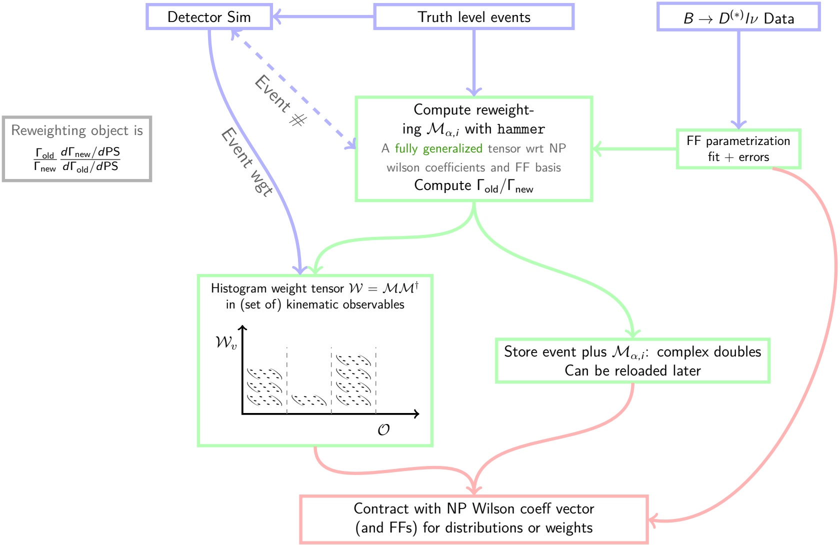
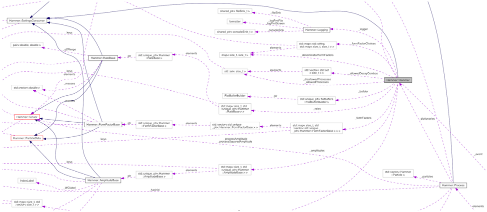
  FF_α is specific FF basis, but any FF param, incl errors.
- From $\mathcal{M}_{\alpha,i}$ construct a weight tensor
  $$\mathcal{W} \equiv [\mathcal{M}_{\beta,j}]^\dagger\mathcal{M}_{\alpha,i}\,.$$
  The event weight for any given NP theory is then just $\vec{FF}^\dagger\vec{v}^\dagger\,\mathcal{W}\,\vec{v}\vec{FF}$.
- Can histogram $\mathcal{W}$ rather than the weights. Very rapidly produce differential kinematic distributions for different NP and FFs by contraction

Rough hammer workflow



Progress!

`hammer_v0.9`α is on the way to completion:



Included processes so far:

$b \to c$

- $B \to D l \nu$
- $B \to (D^* \to D\pi) l \nu$
- $B \to (D^* \to D\gamma) l \nu$

τ modes

- $\tau \to \ell \nu \nu$
- $\tau \to \pi \nu$
- $\tau \to 3\pi \nu$

FFs

- CLN
- BLPR (HQET $1/m$)
- BGL
- ISGW2

Planned progress

Coming soon(ish):

$b \to c$

- $B \to (D^{**} \to ...)l\nu$
- $B_c \to (J/\psi \to ee)l\nu$

τ modes

- floating tunes for $\tau \to 3\pi\nu$
- $\tau \to \rho\nu$
- $\tau \to 4\pi\nu$

FFs

- ISGW2 for NP
- NP Blaschke factors and outer functions

- We will supply a python wrapper
- Demo C++ and python code, including histogramming examples

Question: Are there other features that should be classified as (more) urgent?

- Is a PS reweighting option needed?

Run Cards

Capabilities of `hammer` best understood from run cards (yaml format)

For (technical reasons and) convenience `hammer` uses 2 run cards (or more):

- Process and FF specification
- FF parameters & Wilson coefficient lists

All process, FF and WC choices can also be made programatically

Implementations aim for flexibility: Lets user be as crazy as they like

Process Card

This card specifies which processes will be reweighed, and which FF parametrizations are attached to input and output for each.

Any process with $D^* \to D\pi$ **and** $\tau \to \pi\nu$ final states

Any process with charged $B \to D\tau\nu$

```
# Hammer v0.9 process card

Allow:  [ [ D*Dpi, TauPiNu ] , B+DTau+Nu ]
Deny:  [ [ B+DTau+Nu, TauEllNuNu ] ]
FormFactors:
 NumeratorChoices:
   MixedChoice: { BD: BLPR, BD*:  CLN }
   AllHQET: { BD: BLPR, BD*:  BLPR }
 Denominator: { BD: ISGW2, BD*:  ISGW2 }
```

Except charged $B \to D\tau\nu$ with semileptonic τ

FF output choices: multiple allowed!

`hammer` philosophy: Let the user be crazy

Tell `hammer` FFs of the input

FF & NP parameter card I

This card specifies FF parameters for different available parametrizations

Can toggle tracking of weight^2 errors

FF error handling or linearized FF parametrizations also available

```
# Hammer v0.9 FF & NP parameter card

Run1:
    Histos:  KeepErrors:  True
    BtoDstarCLN:
        a:        1.0
        RhoSq:    1.207
        F1:       0.908
        R1:       1.401
        R2:       0.854
        R0:       1.14

    BtoDBLPR:
        RhoSq:    1.24
        a:        1.067
        as:       0.26
        mb:       4.710
        mc:       1.310
        la:       0.57115
        ebR/eb:   0.861
        chi21:    -0.06
        chi2p:    -0.00
        chi3p:    0.05
        eta1:     0.30
        etap:     -0.05
        dV20:     0.
.
.
.
```

FF parameters may also be specified programatically

Up to user to supply self-consistent FF data

Default values are loaded if no card exists or other inputs

FF & NP parameter card II

It also specifies Wilson coefficients for different leptonic final states. (One may separate these cards if they wish)

Turns on a tensor current
Notation $[a, b] = a + bi$

```
# Hammer v0.9 FF & NP parameter card
.
.
.
Run423:
    BtoCTauNu:
        SM:         1.0
        T_aLbR:     [0.3, 0.5]
        V_aRbL:     [0.1, 0.1]
    BtoCMuNu:
        SM:         1.0
    BtoCENu:
        SM:         1.0

Run424:
    BtoCTauNu:
        SM:         1.0
        T_aLbR:     [0.4, 0.5]
        S_aRbL:     [0.2, 0.1]
    BtoCMuNu:
        SM:         1.0
    BtoCENu:
        SM:         1.0
.
.
.
```

Turns on a right-handed vector current

WCs may also be specified programatically

Can interate over long lists: the whole point!!

Basis of WC coefficients defined in manual/readme

Sample code

```
int main() {
    auto io = unique_ptr<HepMC::IO_GenEvent>(new HepMC::IO_GenEvent("", std::ios::in));
    if (io->rdstate() != 0) {
        return -1;
    }
    Hammer::Hammer ham{};
    ham.allowDecay("B+D0barTau+Nut");
    ham.addFFChoice("Run1", {{"B+D0bar", "HQET"}});
    ham.setFFBase({{"B+D0bar", "ISGW2"}});
    ham.addHistogram("H1",{10});
    ham.initRun();
    HepMC::GenEvent ge;
    for(size_t i =0; i < 1000; i++) {
        if (io->rdstate() != 0 || !io->fill_next_event(&ge)) {
            ham.initEvent();
            auto processes = parseGenEvent(ge, {521, -521, 511, -511});
            for(auto& elem : processes) {
                ham.addProcess(elem);
            }
            ham.setEventHistogramBin("H1", {4});
            ham.processEvent();
        }
    }
    ham.setWilsonCoefficients("BtoCTauNu", {{"SM",1.0},{"T_aRbL", 0.25}});

}
```

Proto-Output

Study theories nearby a tensor-like best fit theory for $R(D^{(*)})$ anomaly (Freytsis, Ruderman, Ligeti 1506.08896)
Apply PS cuts

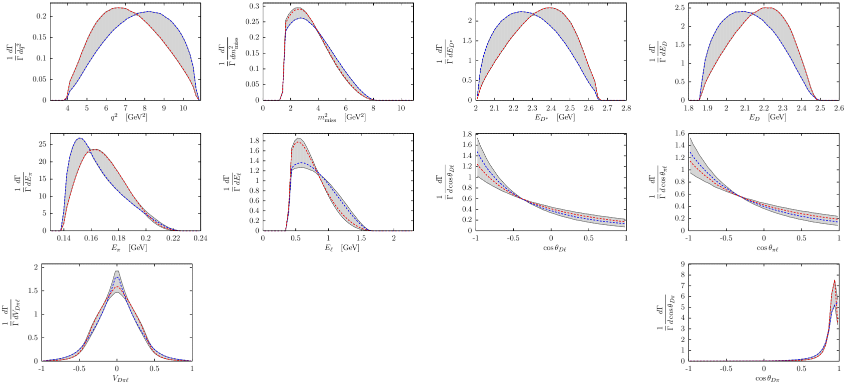
$$E_\ell > 400\text{ MeV}\,, \qquad m^2_{\text{miss}} > 1.5\text{ GeV}^2\,, \qquad q^2 > 4\text{ GeV}^2\,.$$

and examine 10 observables

$$q^2\,, \quad E_{D^*}\,, \quad E_D\,, \quad E_\pi\,, \quad E_\ell\,, \quad \cos\theta_{D\pi}, \quad \cos\theta_{\pi\ell}, \quad \cos\theta_{D\ell}\,,$$

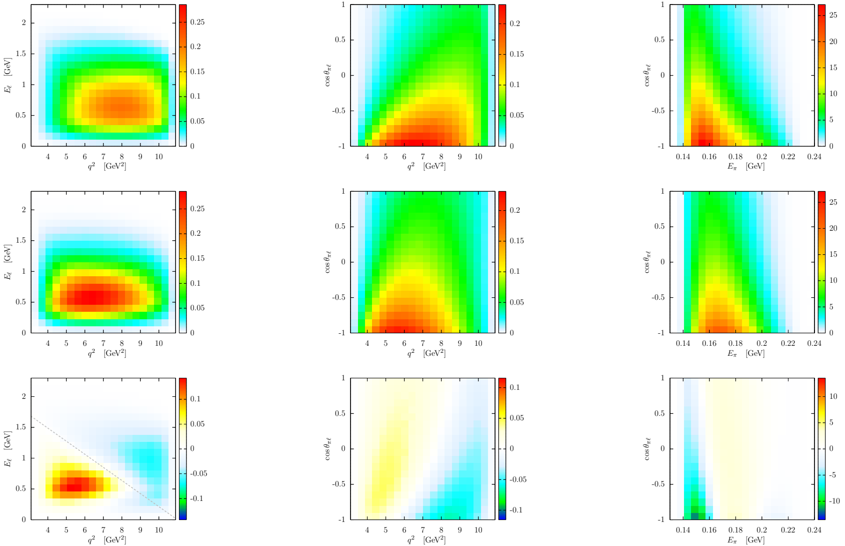
$$V_{D\pi\ell} \equiv \widehat{\boldsymbol{p}}_D \cdot (\widehat{\boldsymbol{p}}_\pi \times \widehat{\boldsymbol{p}}_\ell)\,, \qquad \text{and} \qquad m^2_{\text{miss}} \equiv (k_{\nu_\tau} + k_{\overline{\nu}_\tau} + k_{\nu_\ell})^2\,.$$

1D Distributions



Gray regions formed by couplings ranging over tensor WC coeff $g_T \in [-0.76, 0]$. The blue (red) dashed curves show the SM ($g_T = -0.38$).

2D distributions



SM (top row), $g_T = -0.38$ (middle row) and their difference (bottom row).

Summary (so far)

- v0.9 of `hammer` is on the way!
  - Efficient, model independent and process-flexible handling of generic NP and FF parametrizations (and tunes)
  - Rapid histogramming
- This is a critical time for design decision inputs from LHCb and Belle
  - Specific FF uses we haven't accomodated?
  - Is there a specific format preferred for data?
  - ...