Hammer Use at LHCb

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- Possible Future Applications in LHCb
  - LHCb ‘Wishlist’ - suggestions for features to be implemented

The HAMMER Tool

The HAMMER Tool

- Hammer Tool (EPJ. C 80, 883 (2020)) by F.U. Bernlochner *et al.*
- Gitlab repository.
- $b \to c\ell\nu$ decays typically need very large simulation samples.
- Very resource intensive to produce.

Helicity Amplitude Module
for Matrix Element Reweighting

- A choice of models has to be made in the production (*e.g.* SM-like properties).
- Trying to ad-hoc use an SM-MC sample allowing new physics (NP) processes can lead to biases.
- Hammer allows the MC to be reweighted to match arbitrary NP cases, whilst avoiding biases.

- Used across Belle II, CMS and also LHCb. Focus on LHCb in this talk.
- In LHCb, RooHammerModel is used to interface with HistFactory and RooFit.
- Typically used on form factors.
- Can also be used to introduce NP with Wilson Coefficients (WCs).
- Proof of concept highlighted by Hammer developers in their paper shown in next few slides.
  - Simulated samples corresponding to two signal and two background channels ($B \to D^{(*)}\tau(\to e\nu\nu)\nu$, $B \to D^{(*)}e\nu$).
  - Generated at Belle II beam energies (7 GeV and 4 GeV) within the acceptance (20° to 150°).

But first, form factors...

Form Factors - I

- Differential decay rate:

$$\frac{d\Gamma(B\to D^*\ell\nu)}{dq^2} = \frac{G_F^2|V_{cb}^2||\eta_{EW}|^2|\vec{p}|^2q^2}{96\pi^3 m_{B^0}^2}\left(1-\frac{m_\ell^2}{q^2}\right)\times\left[\ (|H_+|^2+|H_-|^2+|H_0|^2)\left(1-\frac{m_\ell}{2q^2}\right)+\frac{3}{2}\frac{m_\ell^2}{q^2}|H_t|^2\right]$$

- Helicity amplitudes *H* directly related to form factors.
- Differing forms of parameterisation; Boyd-Grinstein-Lebed (BGL), Caprini-Lellouch-Neubert (CLN), Bernlochner-Ligeti-Papucci-Robinson (BLPR), Bernlochner-Ligeti-Robinson (BLR), *etc.*
- For BGL (PRL 74, 4603 (1995)):

$$H_\pm(\omega) = f(\omega) \mp m_B m_{D^*}\sqrt{\omega^2-1}g(\omega)$$

$$H_0(\omega) = \frac{F_1(\omega)}{\sqrt{q^2}}$$

$$H_t(\omega) = m_B(\frac{r\omega^2-1}{1+r^2-2r\omega}F_2(\omega)).$$

$$f(z) = \frac{1}{P_{1^+}(z)\phi_f(z)}\sum_{n=0}^{N} b_n z^n$$

$$F_1(z) = \frac{1}{P_{1^+}(z)\phi_{F_1}(z)}\sum_{n=0}^{N} c_n z^n$$

$$g(z) = \frac{1}{P_{1^-}(z)\phi_g(z)}\sum_{n=0}^{N} a_n z^n$$

$$F_1(z) = \frac{1}{P_{0^-}(z)\phi_{F_2}(z)}\sum_{n=0}^{N} d_n z^n$$

- where r and ω are related to mass.

- For CLN (Nucl. Phys. B 530 1 (1998)):

$$
\begin{aligned}
h_{A_1}(w) =& h_{A_1}(1)[1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3] \\
R_1(w) =& R_1(1) - 0.12(w-1) + 0.05(w-1)^2, \\
R_2(w) =& R_2(1) + 0.11(w-1) - 0.06(w-1)^2, \\
R_0(w) =& R_0(1) - 0.11(w-1) + 0.01(w-1)^2
\end{aligned}
$$

- Form factors are measured experimentally.

Current Hammer (v1.4.1)

Process	FF parametrizations
$B \to D^{(*)}\ell\nu$	ISGW2* [16, 17], BGL*‡ [13–15], CLN*‡ [18], BLPR‡ [19], BLPRXP‡ [20]
$B \to (D^* \to D\pi)\ell\nu$	ISGW2*, BGL*‡, CLN*‡, BLPR‡, BLPRXP‡
$B \to (D^* \to D\gamma)\ell\nu$	ISGW2*, BGL*‡, CLN*‡, BLPR‡, BLPRXP‡
$B \to D_0^*\ell\nu$	ISGW2*, LLSW* [21, 22], BLR‡ [23, 24]
$B \to D_1^*\ell\nu$	ISGW2*, LLSW*, BLR‡
$B \to D_1\ell\nu$	ISGW2*, LLSW*, BLR‡
$B \to D_2^*\ell\nu$	ISGW2*, LLSW*, BLR‡
$B \to (\rho \to \pi\pi)\ell\nu$	ISGW2*, BSZ‡ [25]
$B \to (\omega \to \pi\pi\pi)\ell\nu$	ISGW2*, BSZ‡
$\Lambda_b \to \Lambda_c\ell\nu$	PCR* [26], BLRS‡ [27, 28], BLRSXP [29]‡
$\Lambda_b \to \Lambda_c^*\ell\nu$	PCR*, LSPR‡[30, 31]
$B_c \to (J/\psi \to \ell\ell)\ell\nu$	Kiselev* [32], EFG* [33], BGL*‡ [34], ...
$B \to \pi\ell\nu$	ISGW2*, BCL*‡ [35], GKvD [36]
$B_s \to K\ell\nu$	ISGW2*, BCL*‡[37]
$\tau \to \pi\nu$	—
$\tau \to \ell\nu\nu$	—
$\tau \to 3\pi\nu$	RCT* [38–40]
$D_1 \to (D^* \to D\pi/\gamma)\pi$	PW
$D_2^* \to (D^* \to D\pi/\gamma)\pi$	PW
$D_2^* \to D\pi$	PW
Planned for future release	
$B_{(c)} \to \ell\nu$	MSbar
$\tau \to 4\pi\nu$	RCT*
$\tau \to (\rho \to \pi\pi)\nu$	—

TABLE III. Implemented amplitudes in Hammer and corresponding form factor parametrizations.

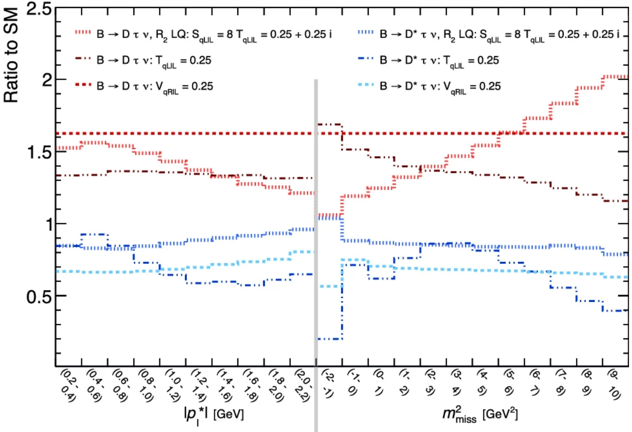
- Reweighting uses ratio of differential rates:

$$r_I = \frac{d\Gamma_I^{\text{new}}/d\mathcal{PS}}{d\Gamma_I^{\text{old}}/d\mathcal{PS}}$$

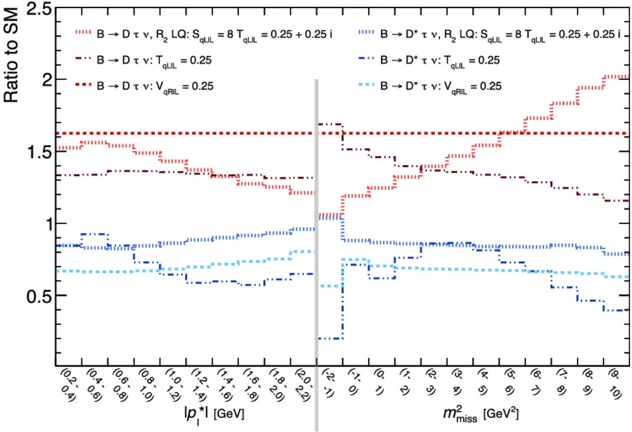
Proof of Concept

Three models used as test:

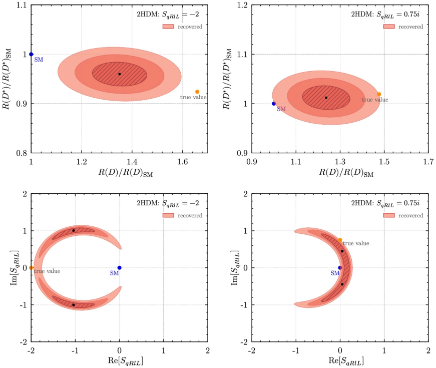
- R_2 leptoquark model, setting $S_{qLlL} \simeq 8\,T_{qLlL}$
- Pure tensor model, using T_{qLlL}
- Right-handed vector model, using V_{qRlL}



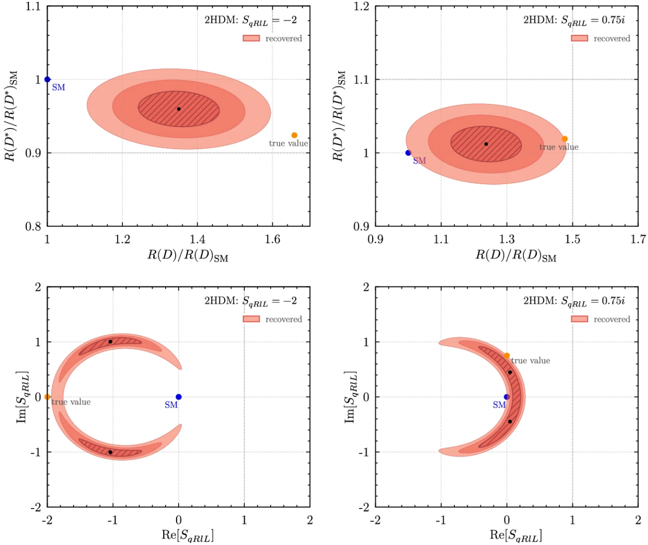
- N.B. V_{qRIL} model gives only normalisation change due to hadronic matrix element for $B \to D$ vanishing from parity/angular momentum conservation.
- Not the case for $B \to D^{*}$.



- Standard practice would be to fit NP models to world-average values of $R(D^{(*)})$.
- But current $R(D^{(*)})$ measurements use SM templates - introduces bias.
- To illustrate this - fit SM MC templates to NP datasets generated with Hammer:



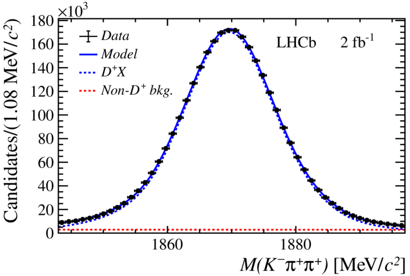
- Using two Higgs doublet model with two different values for S_{qRlL}



Hammer Use in LHCb

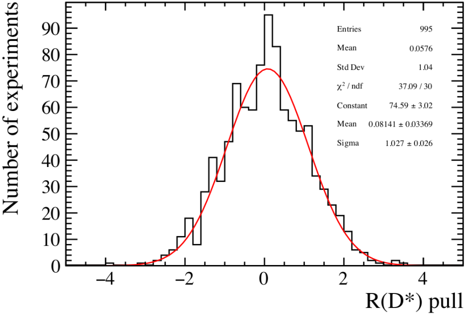
- Hammer has been used in three LHCb papers to date:
  - Measurement of the branching fraction ratios $R(D^{+})$ and $R(D^{*+})$ using muonic τ decays. arXiv:2406.03387 (Submitted to PRL)
  - Measurement of the D^{*} longitudinal polarization in $B^{0} \to D^{*-}\tau^{+}\nu_{\tau}$ decays. arXiv:2311.05224 (Submitted to PRD)
  - Measurement of the $B^{-} \to D^{**0}\tau^{-}\overline{\nu}_{\tau}$ decay rate - see recent talk (LHCb-PAPER-2024-037 in preparation)
- $R(D^{(*)+})$ and $R(D^{**})$ discussed in Biljana's talk.
- Focus explicitly on the Hammer use and advantages in these works.

Measurement of the branching fraction ratios $R(D^+)$ and $R(D^{*+})$ using muonic τ decays



- First LHCb analysis to use Hammer.
- First LHCb measurement using D^+ ground state - using $2\,\text{fb}^{-1}$ (2015 + 16).
- Using $D^{*+} \to D^+\pi^0/\gamma$ allows access to $R(D^{*+})$ with same final state.
- Form factors not reported here, but measurement ongoing to publish values.
- Template fits made based on simulation in order to model shape of form factors. Using Hammer:
  - $B \to D^+$, $B \to D^{*+}$ samples are reweighted from CLN model to BGL model.
  - $B \to D^{**}$ samples reweighted from Isgur-Scora-Grinstein-Wise (ISGW2) model (PRD 39, 799 (1989)) to BLR model (PRD 97, 075011 (2018)).

- This analysis necessitated the creation of an interface between the new Hammer tool and the existing packages (HistFactory, RooFit *etc.*) - RooHammerModel (JINST 17 T04006 (2022))
- Constructor is fully independent of decay channel and decay-amplitude parameterisation.
- Parallelisation of pre-processing of files is possible.
- Toy studies show that fitting using RooHammerModel package does not introduce bias.



- Groundwork for interfacing Hammer with other frameworks?

Measurement of the D^* longitudinal polarization in $B^0 \to D^{*-}\tau^+\nu_\tau$ decays

- Uses Run 1 and 2015+16 ($5\,\mathrm{fb}^{-1}$) datasets.
- Information on longitudinal D^* polarization can be complementary to $R(D^*)$.
- Even with $R(D^*)$ being compatible with SM, a contribution from NP could still be seen.

$$F_L^{D^*} = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}$$

- a_{θ_D} is polarised, c_{θ_D} is unpolarised contributions.
- Belle measurement (arXiv:1903.03102): $F_L^{D^*} = 0.60 \pm 0.08 \pm 0.04$
- SM: $F_L^{D^*} = 0.45$
- NP models predict $F_L^{D^*}$ below SM prediction.

- Hammer allows the form-factors to be reweighted from ISGW2 model to the CLN parameterisation.
- Form-factors can also be floated in the fit.
- Also uses RooHammerModel.
- Hammer can also be used to vary configuration of WCs and repeat fit, in order to quantify systematic errors.

$$q^2 < 7\,\text{GeV}^2/c^4 \ : \quad 0.52 \pm 0.07\,(\text{stat}) \pm 0.04\,(\text{syst}),$$
$$q^2 > 7\,\text{GeV}^2/c^4 \ : \quad 0.34 \pm 0.08\,(\text{stat}) \pm 0.02\,(\text{syst}),$$
$$q^2 \text{ whole range} : \quad 0.41 \pm 0.06\,(\text{stat}) \pm 0.03\,(\text{syst}).$$

- Consistent with SM and Belle II result.

Analysis Systematics

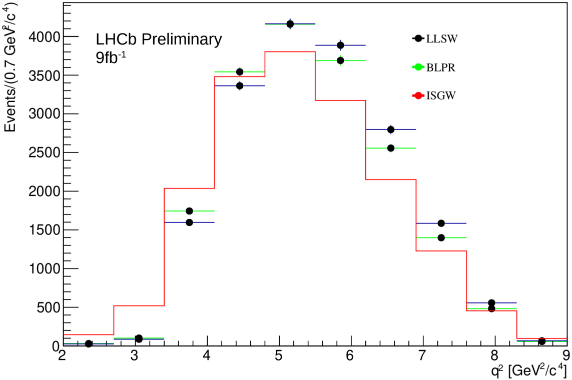
Source	low-q^2	high-q^2	whole q^2 range
Fit validation	0.003	0.002	0.003
FF model	0.007	0.003	0.005
FF parameters	0.013	0.006	0.011
Limited template statistics	0.027	0.017	0.019
Fraction of signal $\tau \to \pi^+\pi^-\pi^+\pi^0\nu_\tau$ decays	0.001	0.001	0.001
Fraction of D^{**} feed-down	0.001	0.004	0.003
Signal selection	0.005	0.004	0.005
Bin migration	0.008	0.006	0.007
$F_L^{D^*}$ in simulation	0.007	0.003	0.007
D_s^+ decay model	0.008	0.009	0.009
Shape of $\cos_{\theta_D}$ template in $D^{*-}D_s^+$ decays	0.002	0.001	0.002
Shape of $\cos_{\theta_D}$ template in $D^{*-}D_s^{*+}$ decays	0.007	0.002	0.004
Shape of $\cos_{\theta_D}$ template in $D^{*-}D_s^+X$ decays	0.007	0.006	0.007
Shape of $\cos_{\theta_D}$ template in $D^{*-}D^+X$ decays	0.002	0.002	0.003
Shape of $\cos_{\theta_D}$ template in $D^{*-}D^0X$ decays	0.002	0.002	0.003
$F_L^{D^*}$ integration method	-	-	0.002
Total	0.036	0.023	0.029

- Hammer is essential in quantifying systematic uncertainties.

Measurement of the $B^- \to D^{**0}\tau^-\overline{\nu}_\tau$ decay rate

- For full details see Biljana's talk.
- ISGW2 model used for MC generation.
- Investigate effect of reweighting to BLPR or LLSW models.

- Significant change when reweighting from default model.
- 4% change in yield of $D^{**}\tau\nu_\tau$ yield.



Source	Relative systematic uncertainty in %
Form factors	3.7
$D_2^{*0}(2460)$ fraction	4.4
Finite size of the simulated sample	4.1
Variables and binning choices	5
Other potential background	3.6
Efficiency determination	4.3
Selection and analysis	2
Vertex resolution effects	4.0
WS background description	2
Total	11.4

- Form factor systematic is estimated using Hammer.

$$\mathcal{R}(D_1(2420)^0 + D_2^*(2460)^0) = 0.13 \pm 0.03\,(\text{stat}) \pm 0.01\,(\text{syst}) \pm 0.02(\text{ext}).$$

- SM prediction RMP 94, 015003 (2022) is 0.09 ± 0.02.
- Compatible with SM within 1σ.

- Previous LHCb result PRD 108, 012018 (2023) gives fraction of $D^{**}\tau^-\overline{\nu}_\tau$ in $R(D^*)$ as 3.5%.
- Fraction of $D^{**}\tau^-\overline{\nu}_\tau$ in $R(D^*)$ calculated to be $8.9 \pm 2.1\%$.
- Compatible with previous result.

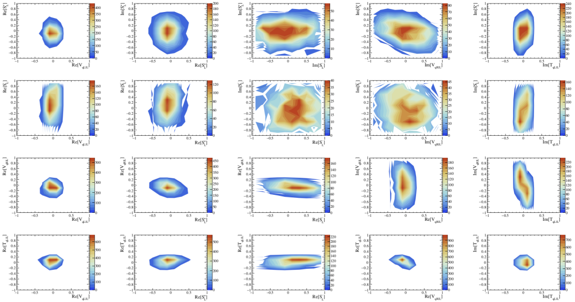
Ongoing & Future Hammer Applications in LHCb

- Possibility of extending $R(D^{(*)+})$ analysis to also fit WCs - Needs Hammer!

$$\mathcal{H}_{eff} = \frac{G_F}{2} V_{cb} \sum_i \mathcal{C}_i \mathcal{O}_i,$$

$$\mathcal{C}_i = \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP}$$

  - Variation of both WCs and FFs can be investigated.



S. Meloni Thesis

Angular Analysis

- Decay rate is described by 12 angular coefficients, I_i.
- I_i depend on form factors, q^2, WCs.

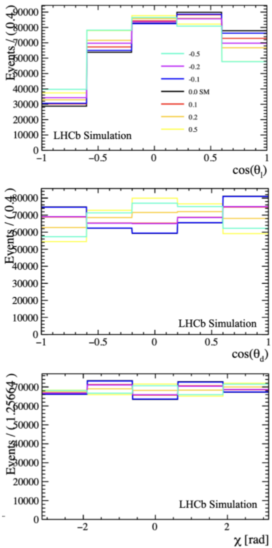
$$\frac{d^4\Gamma}{dq^2\, d(\cos\theta_D)\, d(\cos\theta_L)\, d\chi} \propto I_{1c}\cos^2\theta_D + I_{1s}\sin^2\theta_D + [I_{2c}\cos^2\theta_D + I_{2s}\sin^2\theta_D]\cos 2\theta_L + [I_{6c}\cos^2\theta_D + I_{6s}\sin^2\theta_D]\cos\theta_L + [I_3\cos 2\chi + I_9\sin 2\chi]\sin^2\theta_L\sin^2\theta_D + [I_4\cos\chi + I_8\sin\chi]\sin 2\theta_L\sin 2\theta_D + [I_5\cos\chi + I_7\sin\chi]\sin\theta_L\sin 2\theta_D\,,$$

CP Violation

$$\frac{d^4\Gamma}{dq^2 d\theta_l d_{\theta d} d\chi} = P_{tot} = P_{even} + P_{odd}$$

- P_{odd} can be extracted and used to constrain the NP couplings.

- 5D template fits - three angles, q^2 and m^2_{miss}.
- Form factors floating in fit control signal and background shapes.
- Direct fit to WCs allowing NP.
- SM fit uses CLN and BGL models, NP fit uses BLPR model.
- Varying $Re(V_{qRlLl})$ using Hammer.



- Fitting WCs with BLPR.
- Would like to float WCs with BGL model - not yet available in Hammer.
- Several possible configurations:
  - Fitting one NP operator at a time.
  - Right-handed vector/scalar and left-handed tensor.
  - Values for real and imaginary parts of WCs.

	Statistical uncertainty LHCb Run I	
Parameters	One par.	Multi par.
Im $V_{qR\ell L\ell}$	$O(10^{-2})$	$O(10^{-2})$
Re $V_{qR\ell L\ell}$	$O(10^{-3})$	$O(10^{-2})$
Im $S_{qR\ell L\ell}$	$O(10^{-1})$	$O(10^{-1})$
Re $S_{qR\ell L\ell}$	$O(10^{-1}$	$O(10^{-1}$
Im $T_{qL\ell L\ell}$	$O(10^{-3})$	$O(10^{-3})$
Re $T_{qL\ell L\ell}$	$O(10^{-3})$	$O(10^{-2})$

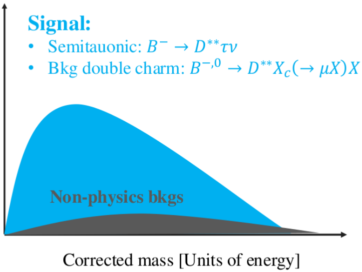
- Floating more than one NP parameter at a time decreases sensitivity.

- Asking a few colleagues, I have put together a list of a few things we would like to see implemented in future releases:
  - Ability to run multi-threaded - with increasing size of dataset, processing will begin to take even longer.
  - Ability to plot parameters before/after reweighting - helpful for sanity checks on models after reweighting. Also good plots for publications.
  - To allow modelling of interference between various D^{**} resonances (as discussed by Abhijit in "Challenges in Semileptonic B Decays" workshop) in Vienna - would allow to investigate CP violation in $B^- \to D^{**}\tau\nu$ decays.
  - Ability to float the NP WCs in the BGL form factor parameterisation.
  - Reweighting for $\tau \to \pi^-\pi^+\pi^-\pi^0$ decay - Prominent background in measurements using hadronic τ decays.

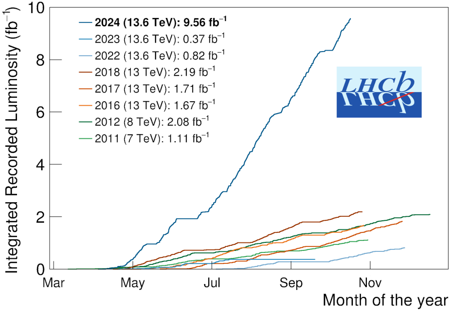
Problem 2

➢Hard to disentangle $B^- \to D^{**}\tau\nu$ from bkgs.

→ Don't, bkg's don't exhibit no CP violation (highly suppressed).



(taken directly from workshop talk)

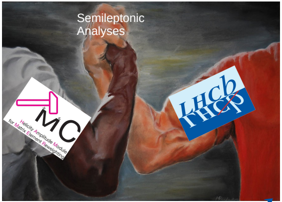


- LHCb Run 3 dataset is already larger than full Run 1 + 2 dataset! (Figure source)
- Fits with Hammer can take long.
- More data will exacerbate this even further.
- Multi-threading in Hammer would combat this (along with other potential speedups).

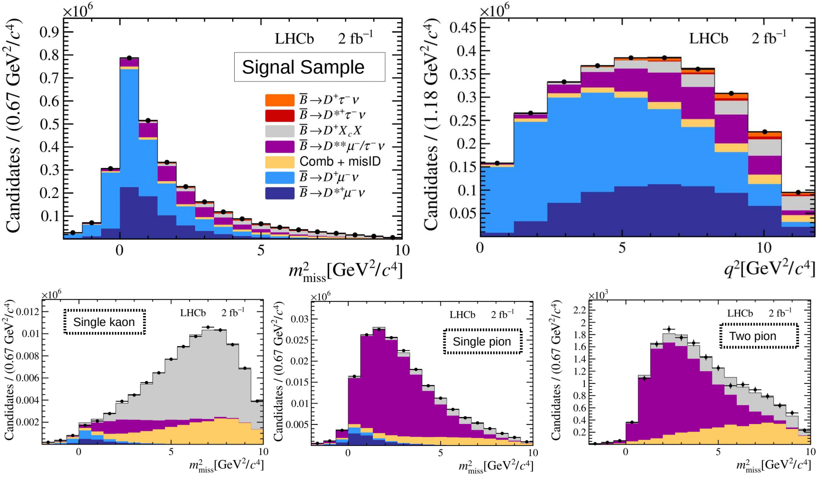
Conclusions

Conclusions

- Hammer is an exceptionally useful tool:
  - MC samples can be much more versatile
  - Saves computational power and time
  - Allows analyses to be done that would otherwise be difficult
- Uptake of Hammer in LHCb is increasing:
  - Three published (or close to) examples shown today where Hammer is integral to the result
  - Many ongoing and future applications, *e.g.* WC analyses, angular analyses *etc.*
  - More on the way...
- Some changes suggested by LHCb analysts:
  - Allowing other analyses to be done
  - Making some analyses easier
  - Future-proofing for larger data
  - Some work ongoing within LHCb to provide interface between Hammer and HistFactory



Backup


LHCb 2 fb^{-1}
Signal Sample
$\overline{B}\to D^{+}\tau^{-}\nu$
$\overline{B}\to D^{*+}\tau^{-}\nu$
$\overline{B}\to D^{+}X_{c}X$
$\overline{B}\to D^{**}\mu^{-}/\tau^{-}\nu$
Comb + misID
$\overline{B}\to D^{+}\mu^{-}\nu$
$\overline{B}\to D^{*+}\mu^{-}\nu$
Candidates / (0.67 GeV^2/c^4)
Candidates / (1.18 GeV^2/c^4)
$m^2_{\rm miss}$[GeV^2/c^4]
q^2[GeV^2/c^4]
Single kaon
Single pion
Two pion

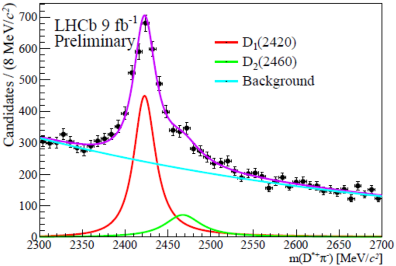
Source	$R(D^+)$	$R(D^{*+})$
Form factors	0.023	0.035
$\bar{B} \to D^{**}[D^+X]\mu/\tau\nu$ fractions	0.024	0.025
$\bar{B} \to D^+X_cX$ fraction	0.020	0.034
Misidentification	0.019	0.012
Simulation size	0.009	0.030
Combinatorial background	0.005	0.020
Data/simulation agreement	0.016	0.011
Muon identification	0.008	0.027
Multiple candidates	0.007	0.017
Total systematic uncertainty	0.047	0.085
Statistical uncertainty	0.043	0.081

- Systematic errors dominated by parameterisation of form factors as well as modelling of backgrounds.

- Compatible with SM at 0.78σ.
- Compatible with world average at 1.09σ.

$$R(D^+) = 0.249 \pm 0.043 \pm 0.047,$$
$$R(D^{*+}) = 0.402 \pm 0.081 \pm 0.085,$$

- Using full Run 1 + Run 2 dataset ($9\,\text{fb}^{-1}$).
- Goal:
  - Measure branching fraction of D^{**0} states.
  - Predict amount of feed-down of D^{**} states expected in $R(D^{(*)+})$ analyses.



- States easily seen after veto-ing other excited DD states.
- $B^- \to D^{**} D_s^+$ chosen as normalisation - same final state.

- Fit of good quality.
- $\chi^2/\text{ndf} = 0.89$