https://hammer.physics.lbl.gov

Helicity Amplitude Module
for Matrix Element Reweighting

HAMMER

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(Caltech)

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2002.00020, PoS ICHEP2016 (2017) 1074, 1610.02045, …

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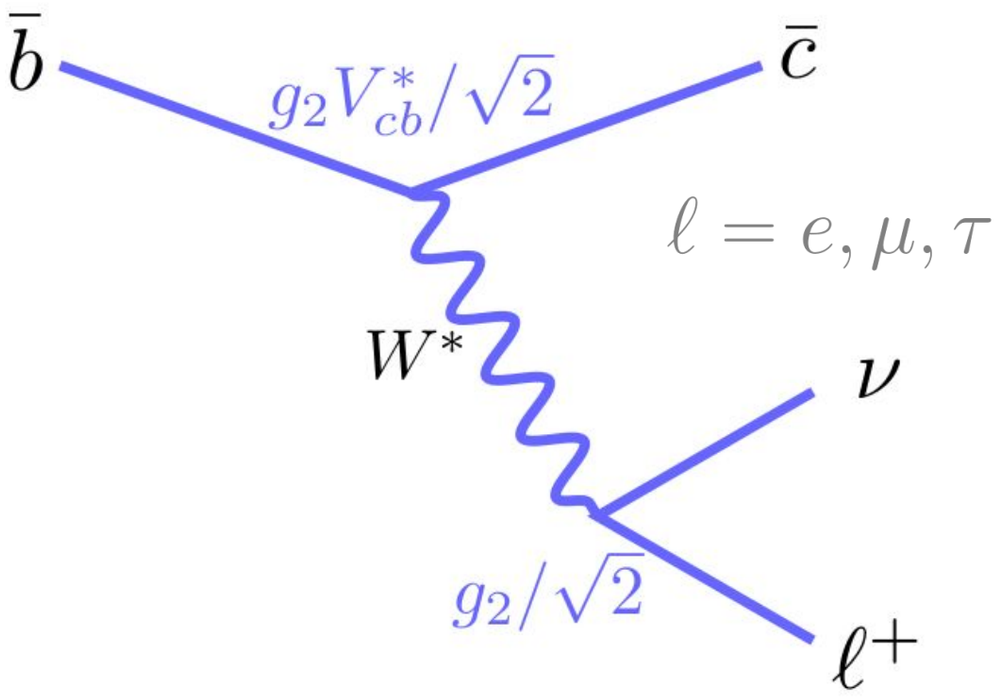
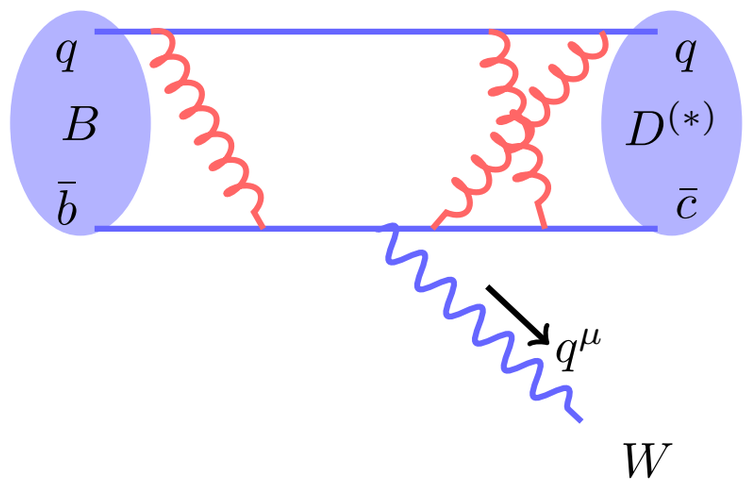
WHAT IS HAMMER?

- HAMMER is a fast & efficient software package to reweigh already generated MonteCarlo events of semileptonic decays to different assumptions of Form Factors parameterizations (FFs) and New Physics Wilson Coefficients (NP WCs)
  - Consistent over the fully differential phase space (unstable particles, interference effects, …)
  - Fast & efficient: enough to be used in fits even for large MC datasets
  - Currently used in LHCb, Belle II, CMS analyses

WHY HAMMER? SEMILEPTONIC B → C DECAYS





- Huge statistics: ~25% of all B decays
- Clean probe of lepton flavor universality τ vs μ,e (up to mass effects)

$$R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\mu\nu)}$$

- Probe of $|V_{cb}|$ (if hadronic form factors are known/measured)

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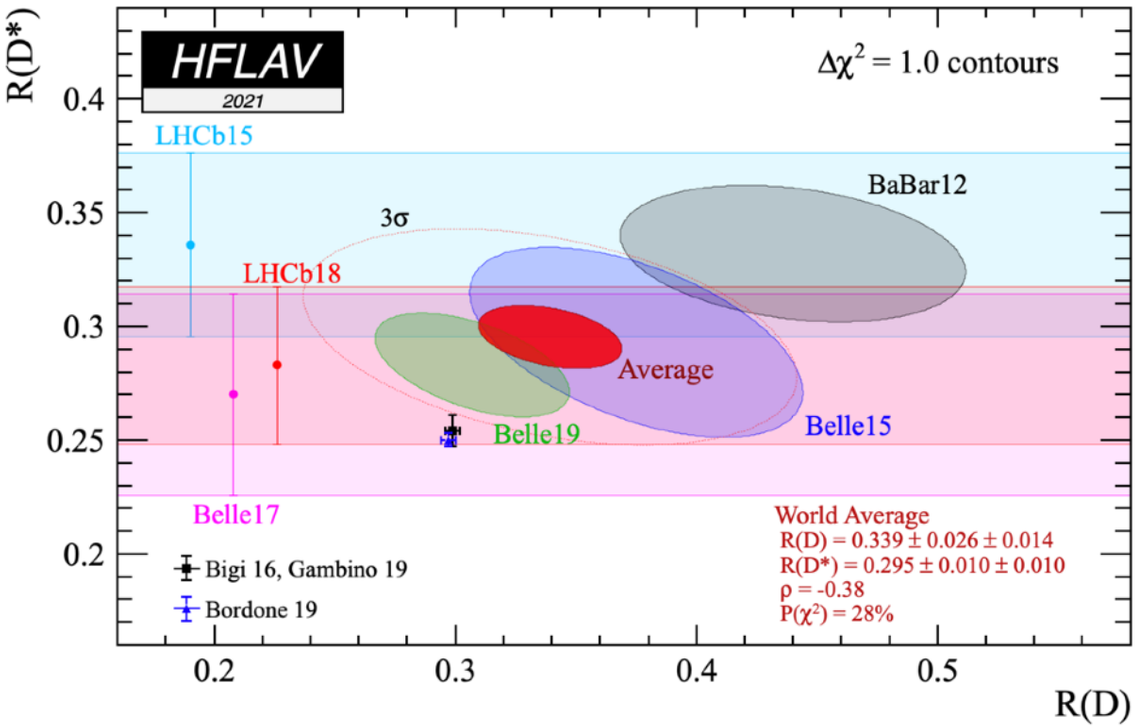

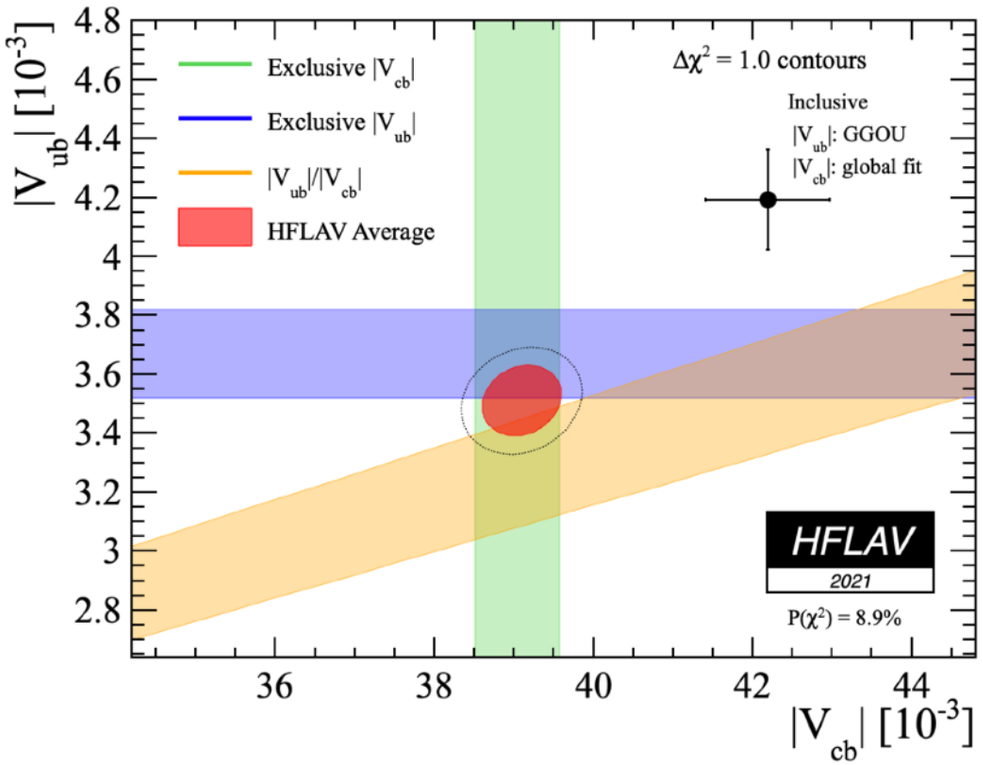

- Current experimental status:
  - μ,e: tension in $|V_{cb}|$ measurement between exclusive and inclusive modes
  - LFU: τ vs μ,e: many measurements for $D^{(*)}$, tensions with Standard Model predictions (also $R(J/\psi)$, $R(X_c)$, …)
- Form factors? Backgrounds? New physics?

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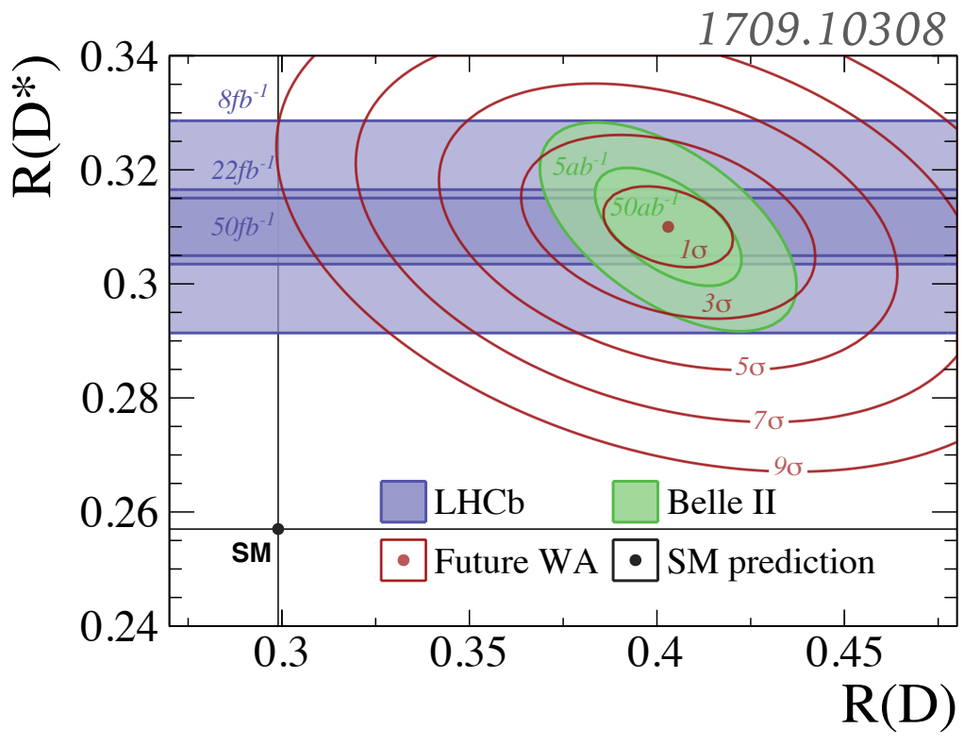

- Huge upcoming statistics: potential to test/resolve these anomalies at many σs
- Many more modes can be studied: $\Lambda_c^{(*)}$, D_s, D^{**}, …
- Lots of upcoming data → 10's * lots of upcoming MC events to simulate to avoid MC statistics to be a systematic uncertainties
- Also true in b → u sector

WHY HAMMER? THE NEED FOR EXPERIMENTAL NP FITS

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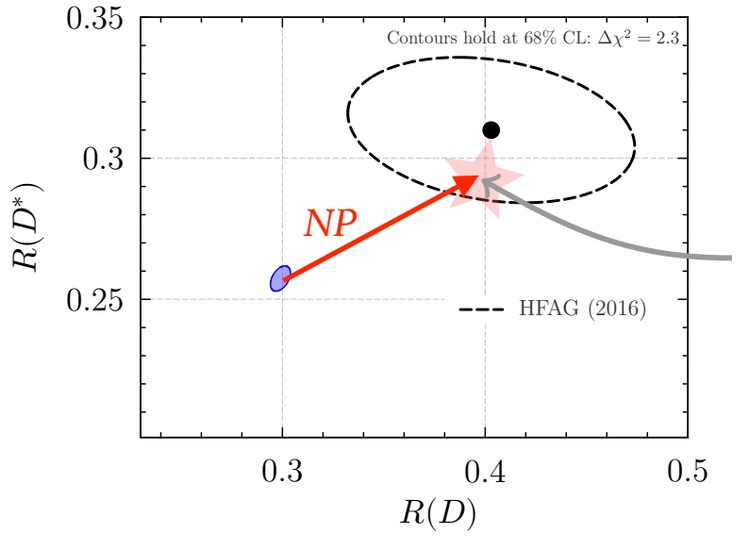

Your favorite model

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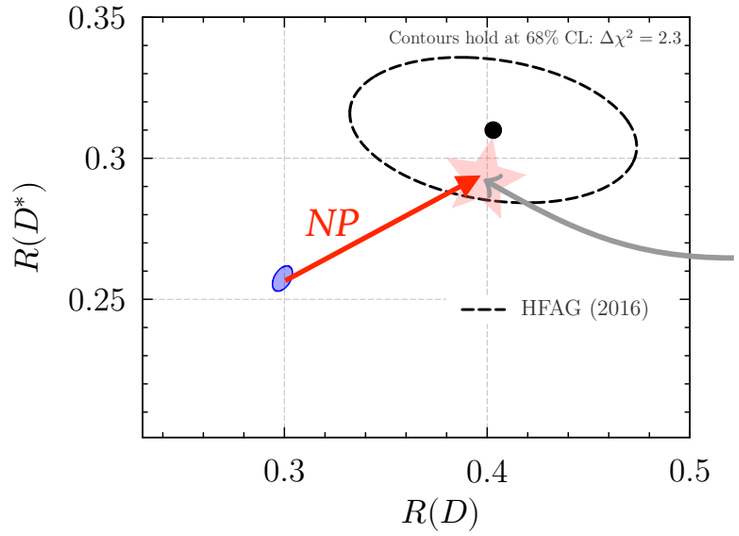

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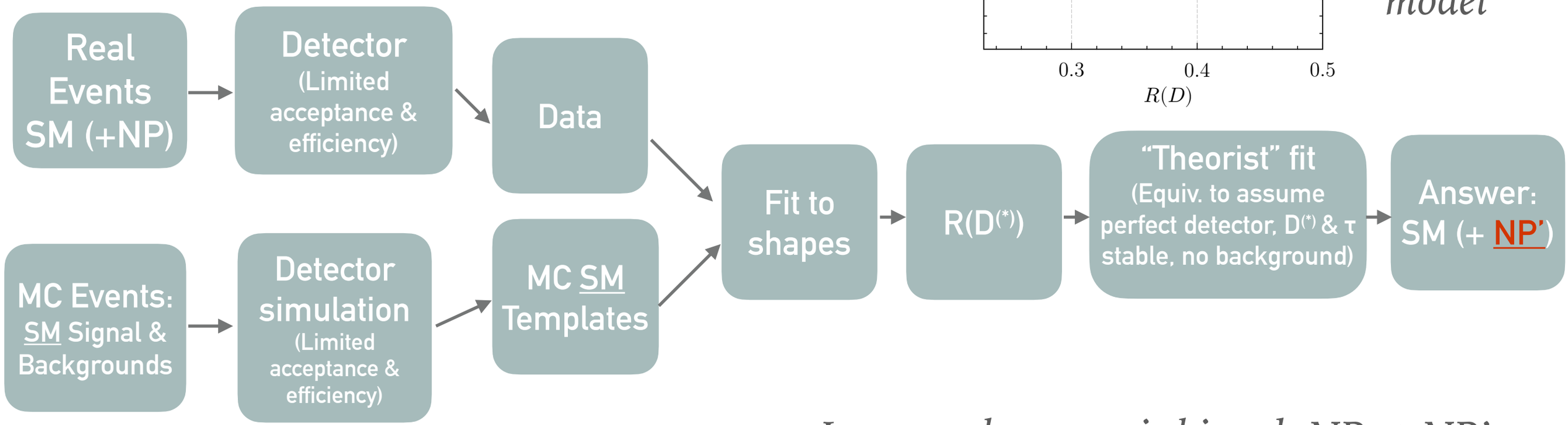

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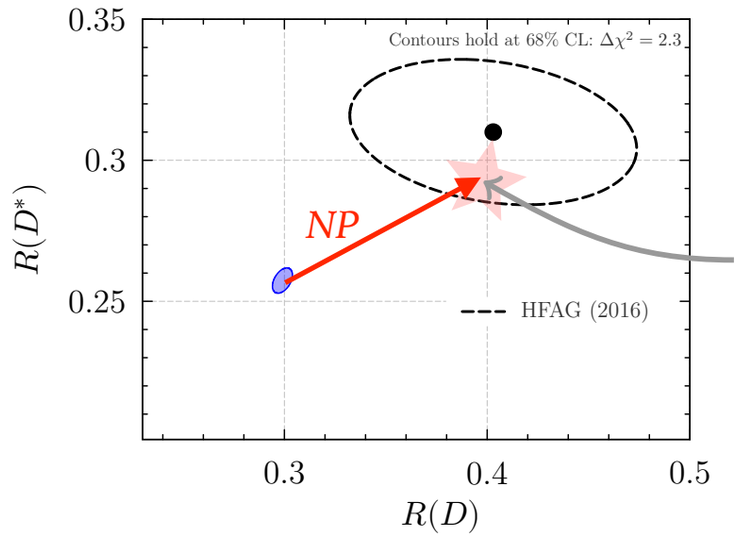

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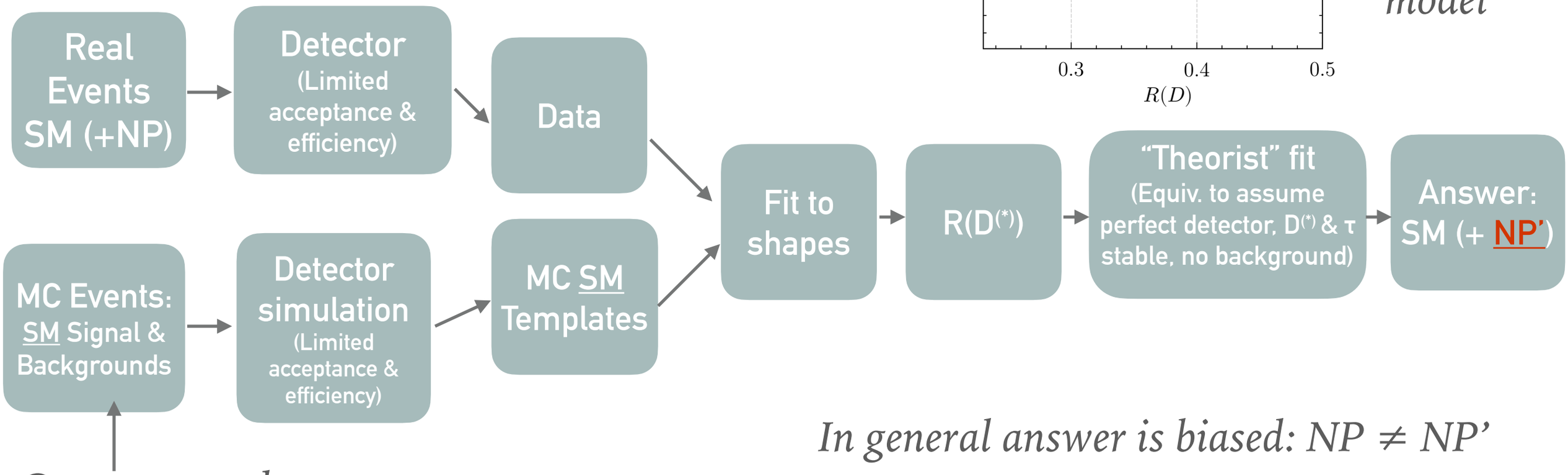

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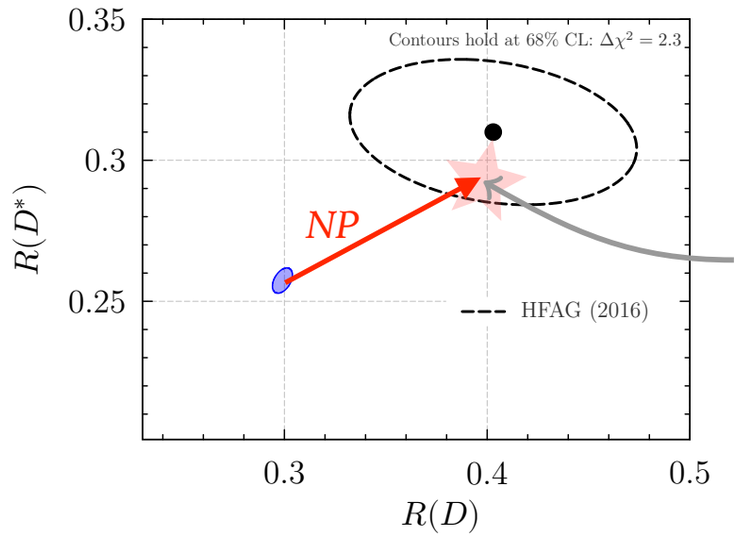

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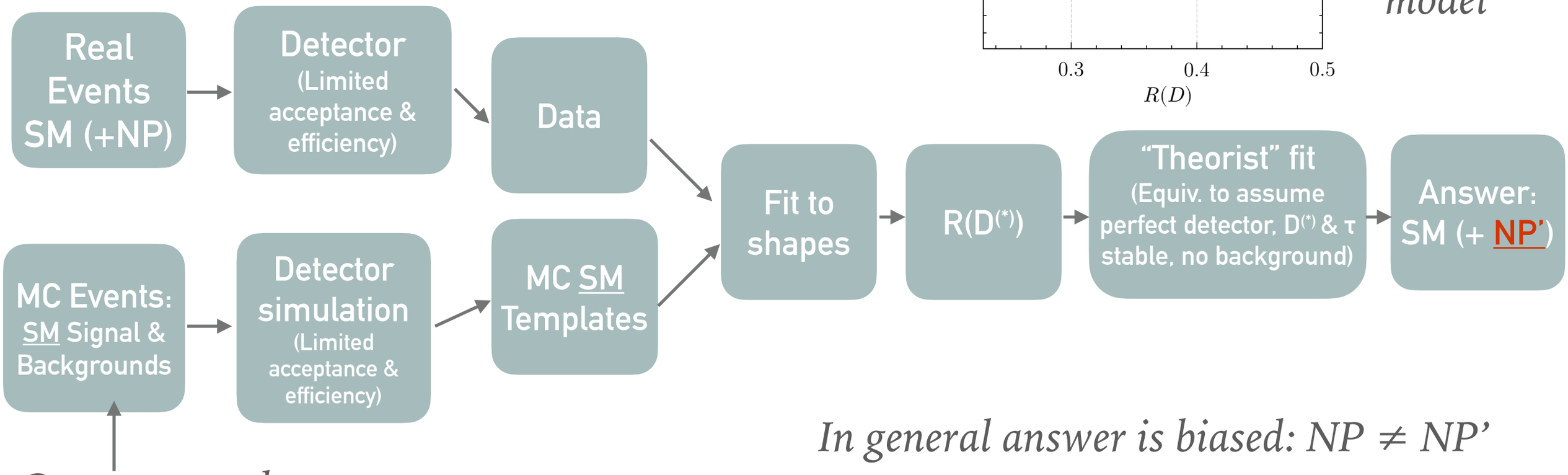

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(non V-A) NP interpretations of the $R(D^{(*)})$ anomaly should be taken cum granum salis

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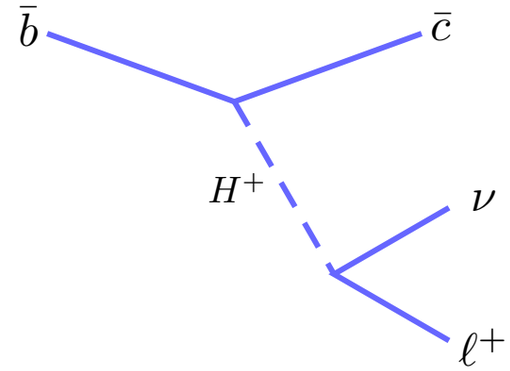
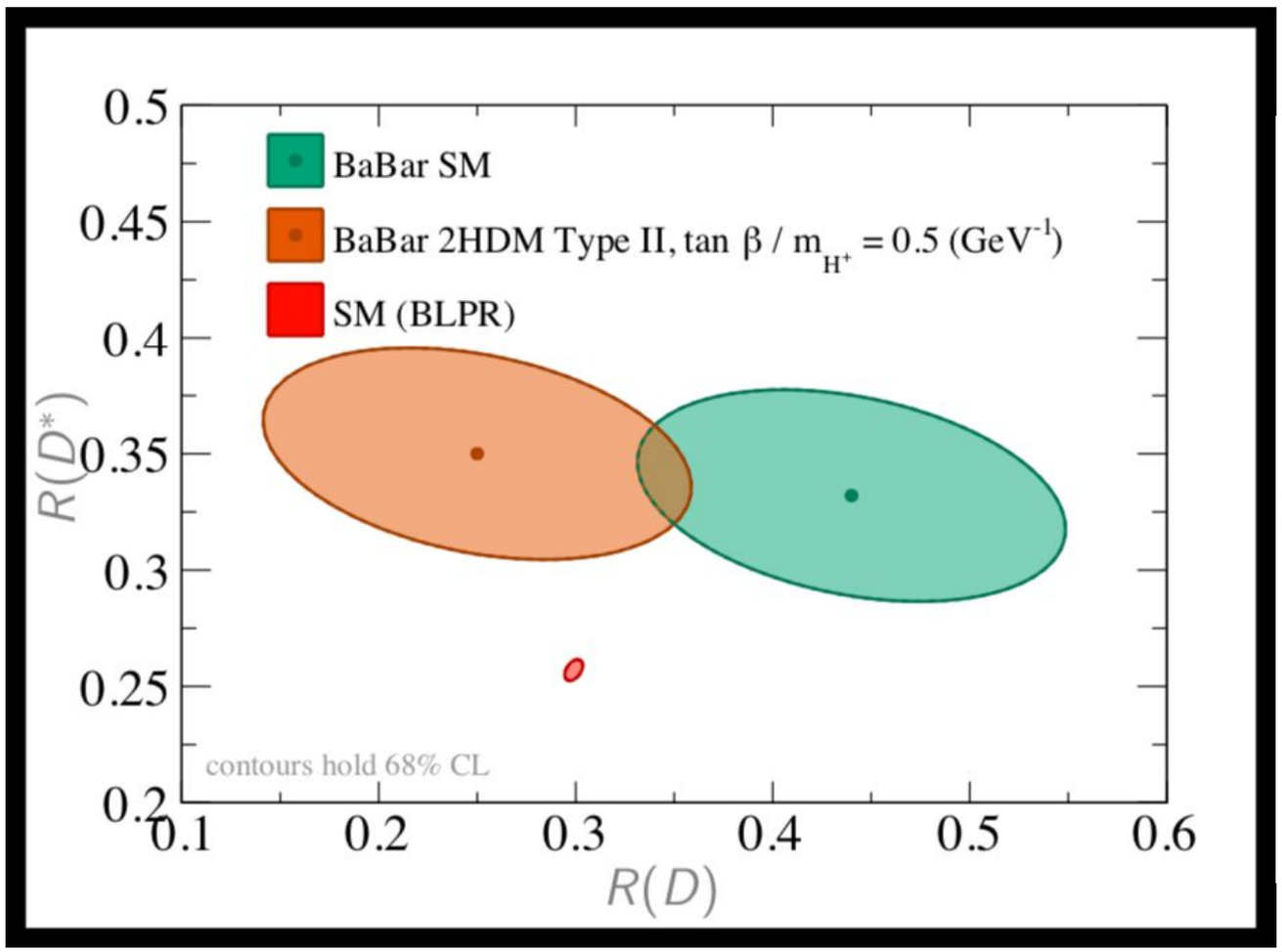
Experiments should provide the constraints on BSM Wilson coefficients directly

Need proper tools!

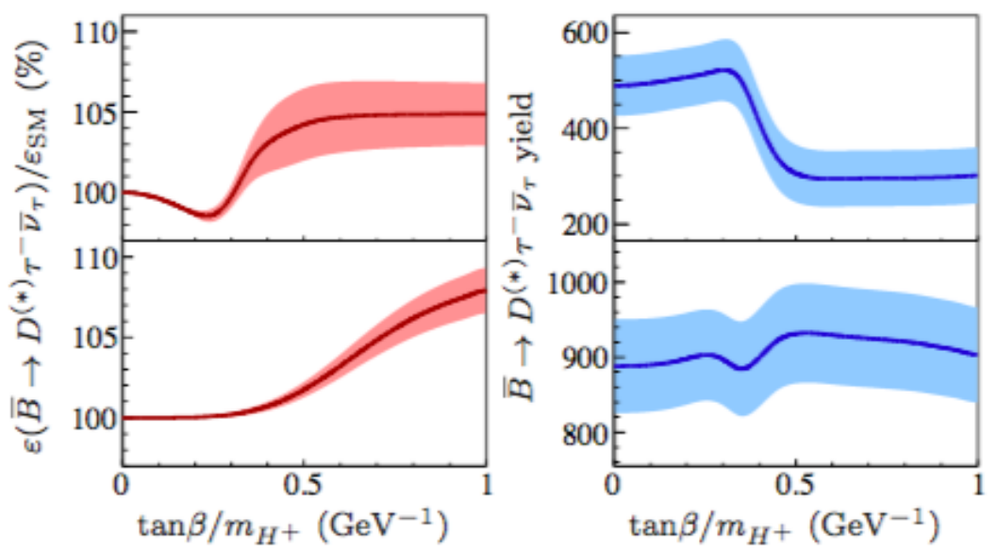
NEW PHYSICS AND SHAPES



- Existence of bias in extracting NP is nothing new
- Fitting SM+NP can change the R(D) and R(D*) values
- Need NP acceptances to estimate NP contributions



Plot by F.Bernlochner



1303.0571 [Babar]

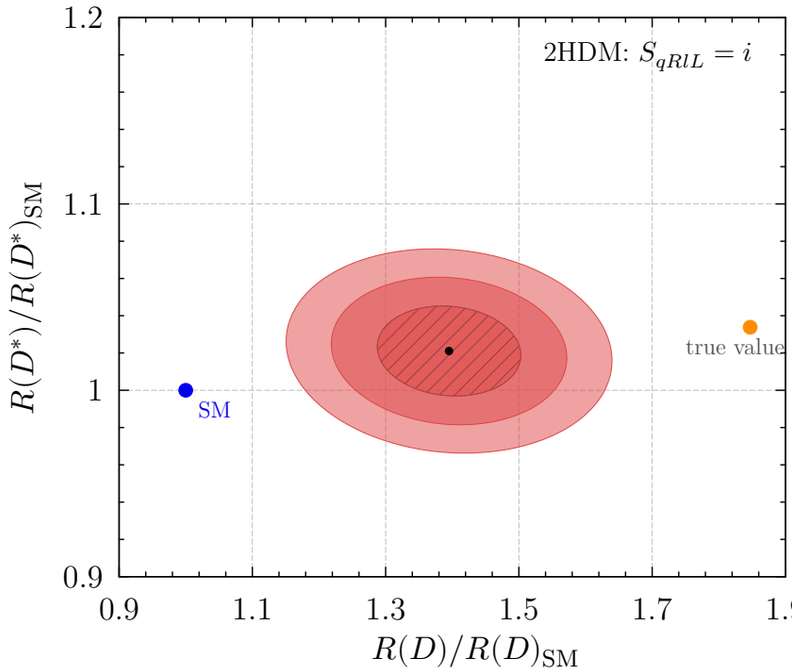
NEW PHYSICS AND SHAPES

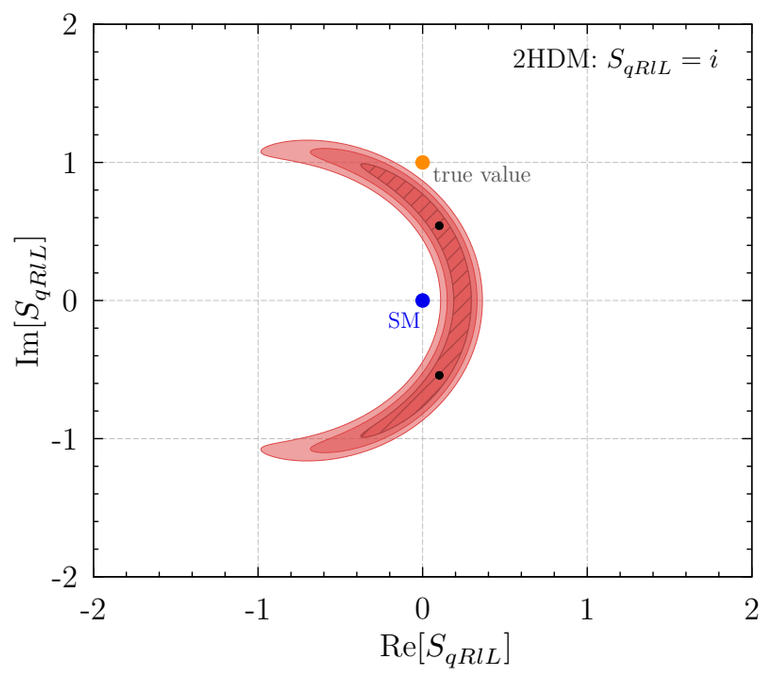
2002.00020

- Mock analysis to study biases:
  - Belle-like detector response (acceptance, efficiency thresholds, smearing …)
  - Fit binned m^2_{miss}, $|p_\ell|$ distributions
  - Include background downfeeds from $D^* \to D$, $\tau \to \ell$
- Data scaled to 5/ab
- Two MC event samples with different SM+NP assumptions: one is "data", the other "fitting templates"
- Two studies:
  - "Measure" R(D), R(D*) assuming SM template, then fit NP' to $R(D^{(*)})$
  - Fit directly SM+NP' template to SM+NP data

NEW PHYSICS AND SHAPES

- Truth: 2HDM
- Measure R(D$^{(*)}$) using SM only
- Fit <u>same</u> 2HDM to R(D$^{(*)}$)





- Truth: R2 leptoquark
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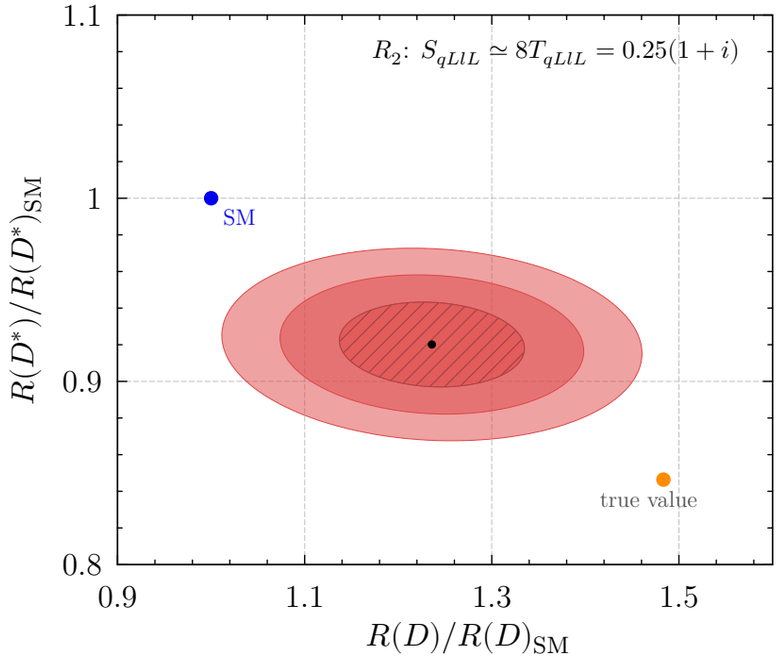
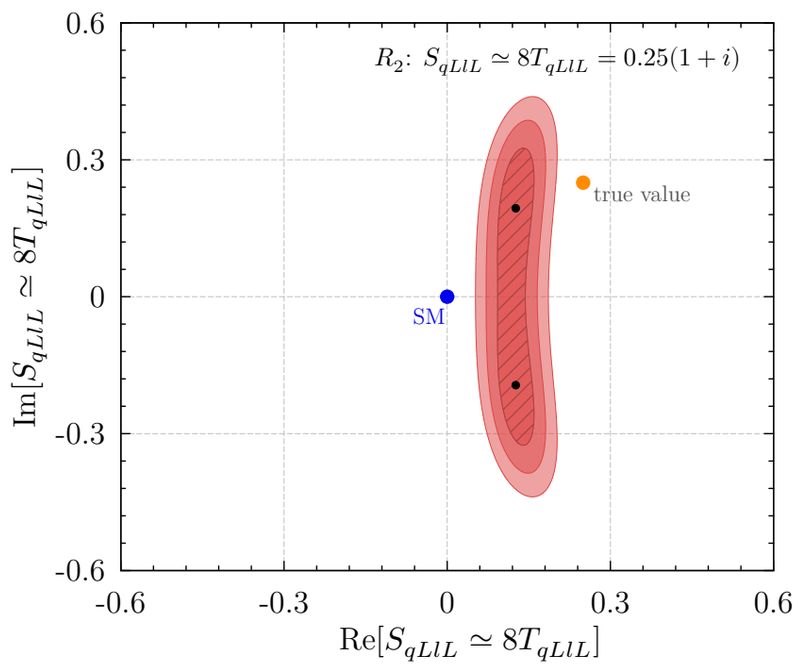
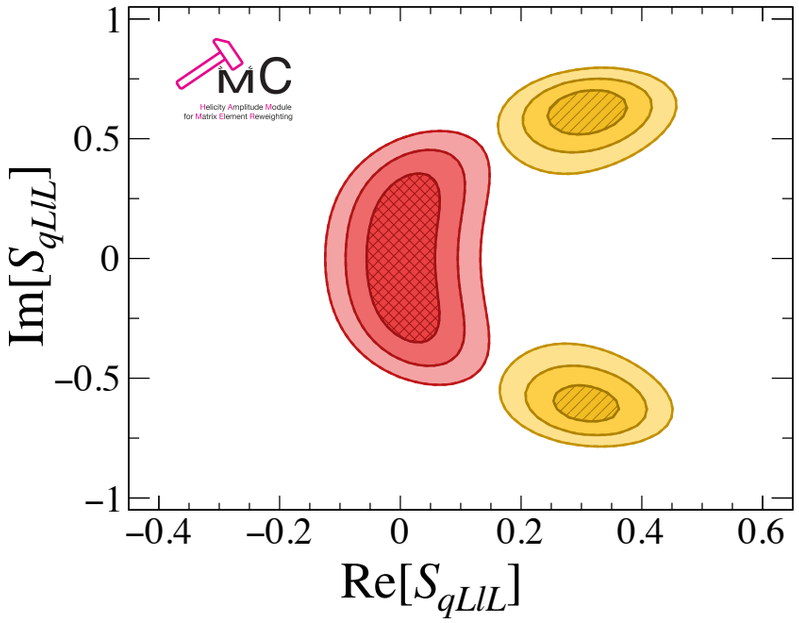
- Fit <u>same</u> R2 model to R(D$^{(*)}$)



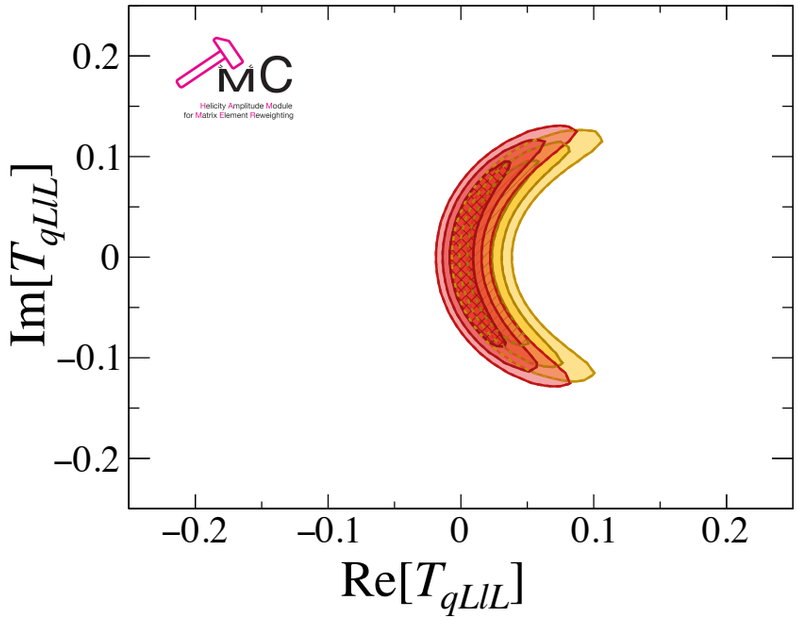


NEW PHYSICS AND SHAPES

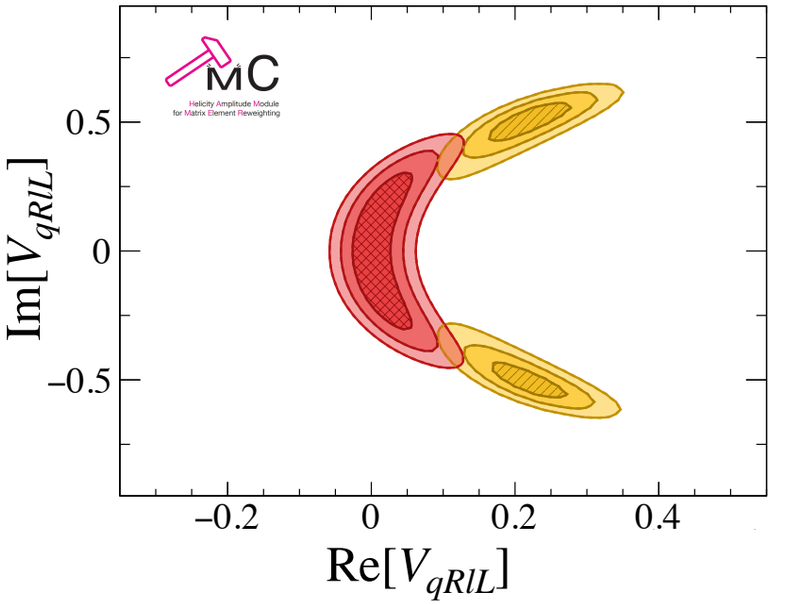
- Truth: SM or 2HDM with $S_{qLlR}=-2$
- Fit shapes directly to 3 different NP assumptions



R2 leptoquark $S_{qLlL}=8$ T_{qLlL}



Pure tensor



Right-handed vector

Important to use the whole NP parameter space in fit

Bias is analysis dependent (due to cuts, etc.) → different analyses will be affected differently

HAMMER TO THE RESCUE

- New physics not present in EvtGen and cannot be easily added a posteriori under τ and D* stable particle assumptions
- Many parameters for general SM + NP fit (10 Wilson coeffs, FF uncert', …) → need fast matrix element evaluation
- Changing FF parameterization / scanning on FF parameters requires either rerunning EvtGen or non-streamlined reweighing code
- Experiments need huge event samples to reduce MC systematics (billions of events)

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HAMMER designed to overcome these issues

HAMMER'S IDEA

- Compute helicity amplitudes instead of squared matrix elements for general SM+NP (speed: O(n) vs O(n^2) terms)
- Keep full spin correlation & interference effects in decays
- Tensorialize amplitudes:

$$\mathscr{M} = \mathscr{M}_{\alpha,i} FF_\alpha C_i$$

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q^2 & FF param. dependent, NP independent can be further expanded in (linearized) uncertainties/parameters: $FF_\alpha(q^2, \vec{a}) = FF_{\alpha,\lambda}(q^2, \vec{a}_0)\delta a_\lambda$, with δa_λ event independent

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C_i are NP Wilson Coefficients, $C_i = (1, V_{LL}, V_{RL}, V_{RL}, V_{RR}, S_{LL}, S_{RL}, S_{LR}, S_{RR}, T_{LL}, T_{RR})$

$FF_{\alpha,\lambda}$ are central value and gradient w.r.t. to parameters, $\delta a_\lambda = (1, \vec{\delta a})$

(e.g. coefficients of Taylor expansions of IW functions, BGL parameters, …)

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- Squared matrix element is

$$|M|^2 = \left(C_i C_{i'}^\dagger\right)\ \left(\delta a_\lambda \delta a_{\lambda'}\right) \left(FF_{\alpha,\lambda} FF_{\alpha',\lambda'}^\dagger\right)\ \left(\mathscr{M}_{\alpha,i} \mathscr{M}_{\alpha',i'}^\dagger\right)$$

- Scalar event weight is $W = |M_{new}|^2 / |M_{old}|^2$
- Define NP-independent, FF-independent tensor event weight

$$\mathscr{W}_{\alpha\alpha',ii'} = \left(\mathscr{M}_{\alpha,i} \mathscr{M}_{\alpha',i'}^\dagger\right) / |M_{old}|^2$$

- Pre-compute once & store $\mathscr{W}_{\alpha\alpha',ii'}$, $FF_{\alpha,\lambda}$ (and/or $\mathscr{W}_{\lambda\lambda',ii'}$)
- Scalar weight W for a given choice of $C_i, \delta a_\lambda$ can then be retrieved from simple (and fast) dot products
- Same philosophy for tensor decay rates: $\Gamma_{\lambda\lambda',ii'}/\Gamma_{old}$ (necessary for e.g. reweighing branching ratios)

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FF parameterizations → $FF_{\alpha,\lambda} FF_{\alpha',\lambda'}^\dagger$

FF uncert' → $\delta a_\lambda \delta a_{\lambda'}$

NP, FF-indep' → $\mathscr{M}_{\alpha,i} \mathscr{M}_{\alpha',i'}^\dagger$

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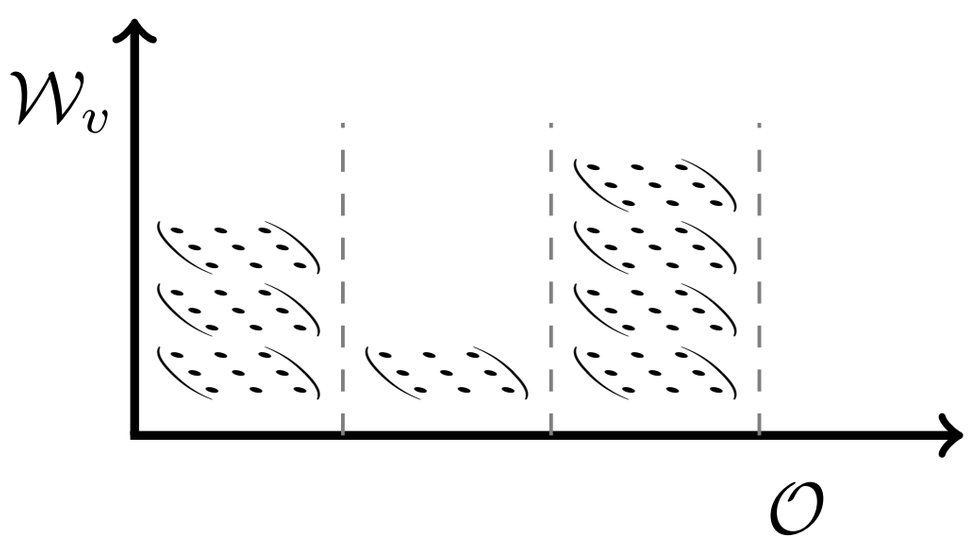
- Event reweighing alone brings you only so far:

$$N_{weights} \sim N_{events} * (N_{variations})^{D}$$

Still very large — *Weight tensorialization helps here*

- Large number of computations for large statistics samples
- For binned analyses further help is possible: Tensor histograms!
  - Bin tensors directly (weights and squared weights) and collapse to conventional histogram at the end when contracting with external vectors



- Trade $N_{events} \rightarrow N_{bins}$, space for speed

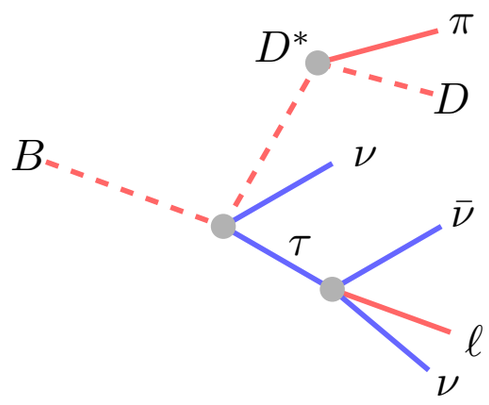
HAMMER RUN FLOWS

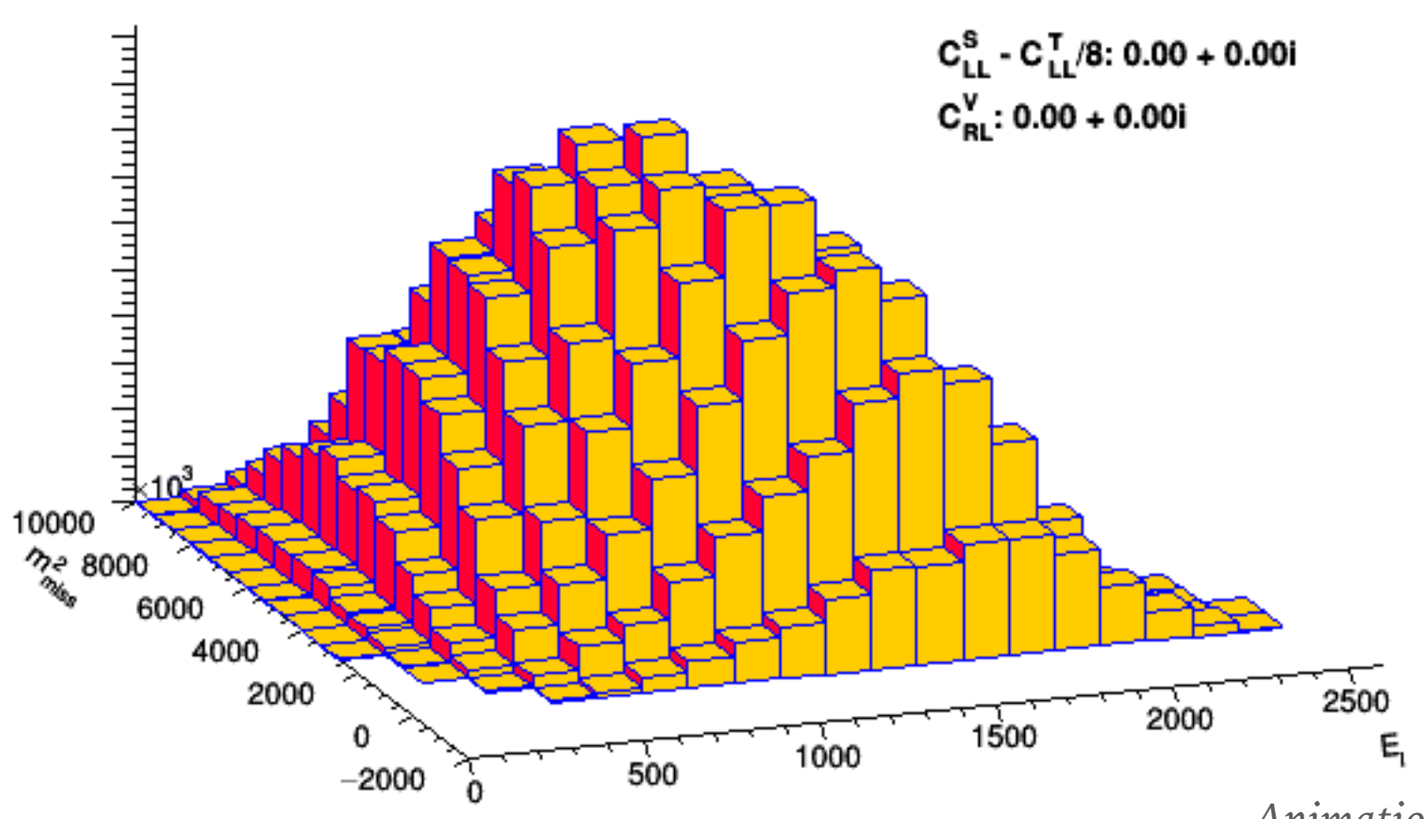
- Preprocessing:
  - Define run options, which process(es) to reweigh and which FF param. to use
  - Loop over events:
    - compute tensor weight
    - fill tensor histograms (optional)
    - save tensor event weight
- (Optional) save histograms
- Wrap up

- Reloading and reweighing:
  - Load preprocessed information from file(s) (possibly merging multiple runs)
  - Retrieve event (tensor) weights or histograms
  - Compute scalar weights or histograms for a given choice of WCs values and/or FF uncert' values
  - For fitting this phase can be wrapped in a function called by the fitter

EXAMPLES

- "Real-time" reweighing of 2D tensor histogram of (reco) E_μ, m^2_{miss} based on 100k $B \to D^* \tau\nu$, $D^* \to D\pi$, $\tau \to \mu\nu\nu$ for a particular direction in Wilson coefficient space





Animation by D.Robinson

Animation here

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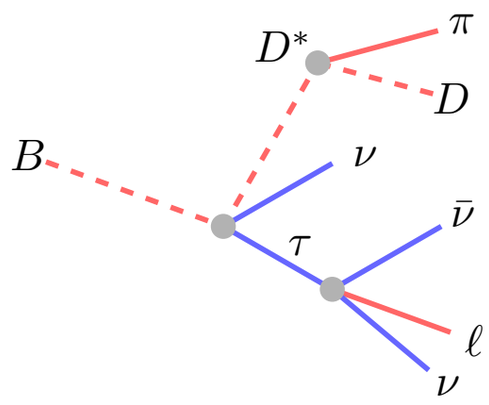

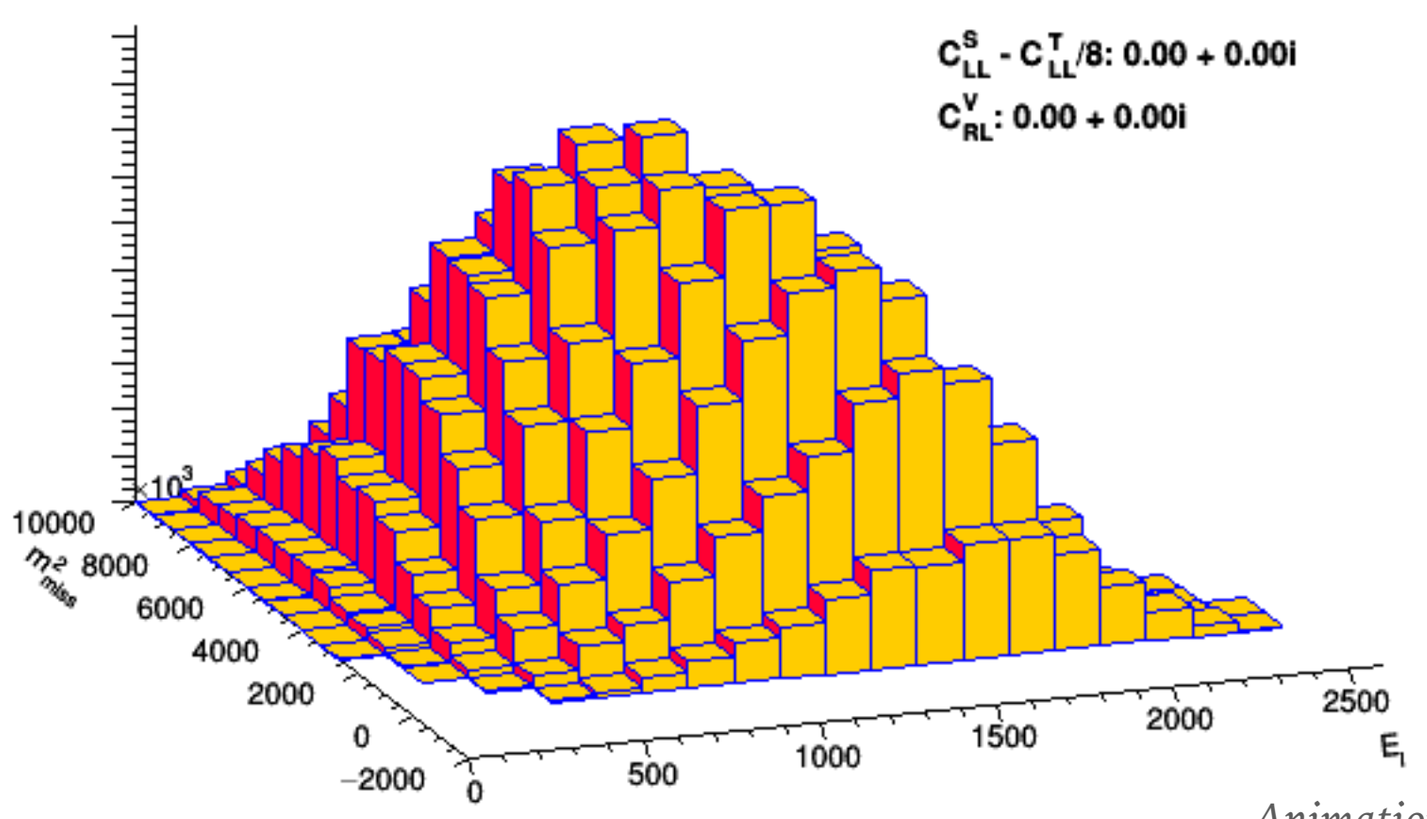

Animation by D.Robinson

Animation here

HAMMER'S CODE DETAILS

- C++ library (w/ Python bindings)
- Input MC: truth level particle 4-momenta & decay chains (MC event file agnostic)
- Handles multiple different, simultaneous FF parameterization choices w
- Tensorial histogramming (can be eval to ROOT histograms for D<=3)
- Storage of per-event information or tensorial histograms. Data storage agnostic format that can be saved in ROOT TTree
- Abstracted tensor storage representation & algorithms: can be tuned for speed and space
- Multithreading-friendly tensor weights/histograms evaluation (for parallel fitting)
- Can reweigh events after PHOTOS radiative corr.
- Many "quality of life" running options & switches
- Active development (v1.2 went public in Oct 2021)

CONTENTS

I. Introduction 3

II. Design Overview 5
A. Reweighting 5
B. New Physics generalization 6
C. Hadronic generalization 7
D. Rates 8
E. Primary code functionalities 8
F. Code flow 9

III. The Hammer Forge 11
A. From the process tree to an amplitude tensor 11
B. Available vertex and edge amplitudes 14
C. Including and excluding processes 14
D. Form factor schemes 17
E. Form factor duplication 19
F. Units 19
G. Processing events 19
H. Retrieving event weights 21
I. Setting Wilson Coefficients 21
J. Setting FF eigenvectors 22
K. Specialization of Wilson Coefficients 23
L. Histograms 23
1. Adding 24
2. Filling 25
3. Compression 25
4. Retrieval 25
5. Specialization 26
6. Uncertainties 26
7. Projection 27
M. Pure phase space vertices 27
N. PHOTOS 28
O. Rates 30
P. Multithreading 31

IV. The Hammer Buffer 31
A. Saving 31
1. Headers, Events and Rates 31
2. Histograms 32
3. ROOT 32
B. (Re)loading 33
C. Parallelization and merging 34

Hammer manual

HAMMER'S LIBRARY (V. 1.2)

➤ Available Amplitudes & Form Factor parameterizations:

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

$$\ell = e, \mu, \tau\,,$$

$$B = B^0, B^+, B_s\,,$$

Etc.

Other processes / FFs can be added upon request

HAMMER RESOURCES

- Various code examples in C++ & Python on how to use HAMMER in different situation cases
  - interface it with HepMC
  - interface it with ROOT for TTree saving loading data and TH*D output of evaluated tensor histograms
- RooHammerModel: interface to HistFactory publicly available 2007.12605 by J.Garcia Pardiñas, S. Meloni, L. Grillo, P. Owen, M.Calvi, N. Serra, (+ kudos for their patience as early adopters/beta testers!)
- HAMMER manual
- Email us

FUTURE DEVELOPMENTS

- Short term:
  - New amplitudes: $\tau \to 4\pi\nu, \tau \to (\rho \to \pi\pi)\nu, B_{(c)} \to \ell\nu$
  - New form factor parameterizations: BLPR-XP for B→D$^{(*)}$ (adds $\alpha_s/M_{b,c}, 1/M_c^2, 1/M_bM_c$, with a new self-consistent truncation of 1/M^2 terms to a manageable number for fitting current data)
    - Additional processes & form factors requested by users
- Further into the future:
  - Speed/space optimizations if/when needed
  - Alternative treatment of radiative photons beyond PHOTOS (caveat: new SD functions that need to be constrained, see e.g. 2110.13154)

CONCLUSIONS

- HAMMER can help analyses in semileptonic B decays
  - Scan over FF parameterizations (and parameters) for measuring hadronic matrix elements
  - Constrain/fit new physics Wilson coefficients efficiently (multi-dim fit)
- Tensorial weights / tensor histograms engine allows working with large MC event samples (and may have applications beyond semileptonic B decays)
- New processes/form factors can be added upon request

https://hammer.physics.lbl.gov