https://hammer.physics.lbl.gov

Helicity Amplitude Module
for Matrix Element Reweighting

HAMMER

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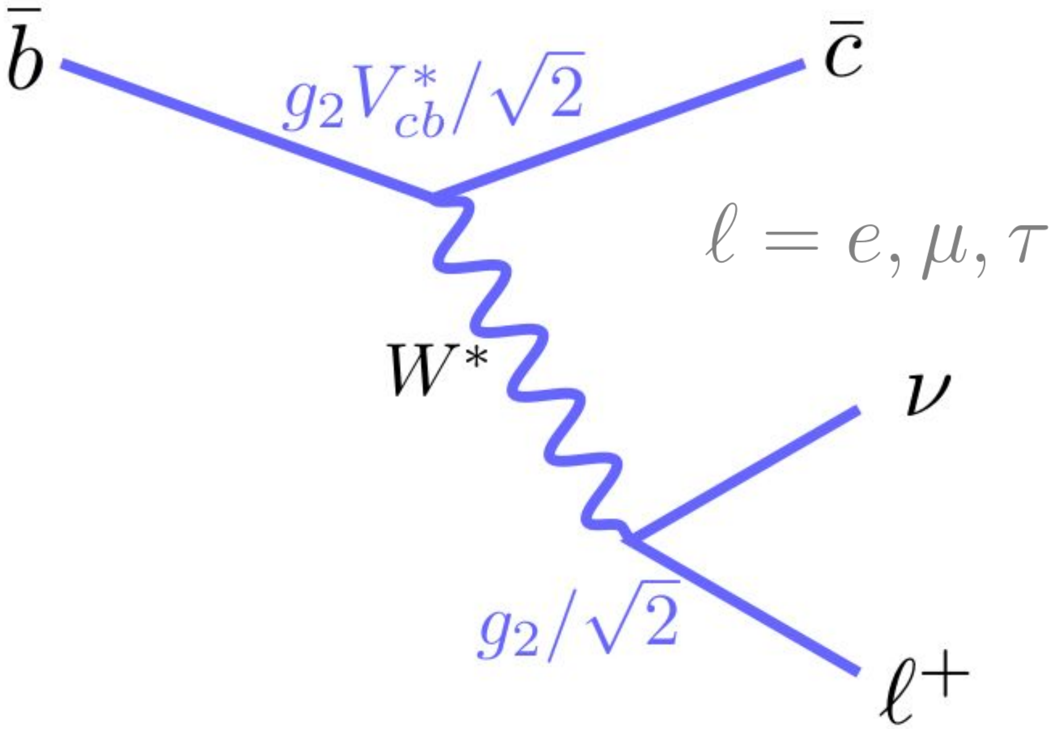
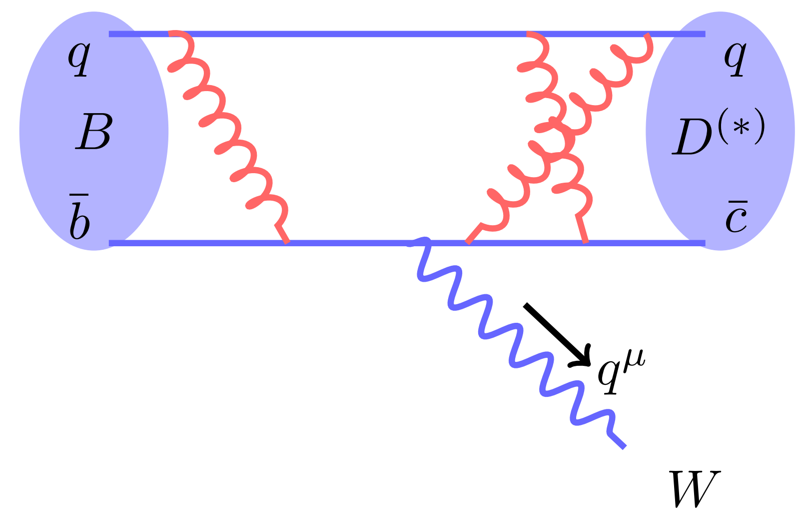
LBNL & Caltech

181x.zzzzz Bernlochner, Duell, Ligeti, MP, Robinson
181x.yyyyy Bernlochner, Duell, Ligeti, MP, Robinson
1812.07593 Bernlochner, Ligeti, Robinson, Sutcliffe
1808.09464 Bernlochner, Ligeti, Robinson, Sutcliffe
1711.03110 Bernlochner, Ligeti, Robinson
1708.07134 Bernlochner, Ligeti, MP, Robinson
1703.05330 Bernlochner, Ligeti, MP, Robinson
1610.02045 Ligeti, MP, Robinson

Sept 10th, 2019

SEMILEPTONIC B → C DECAYS



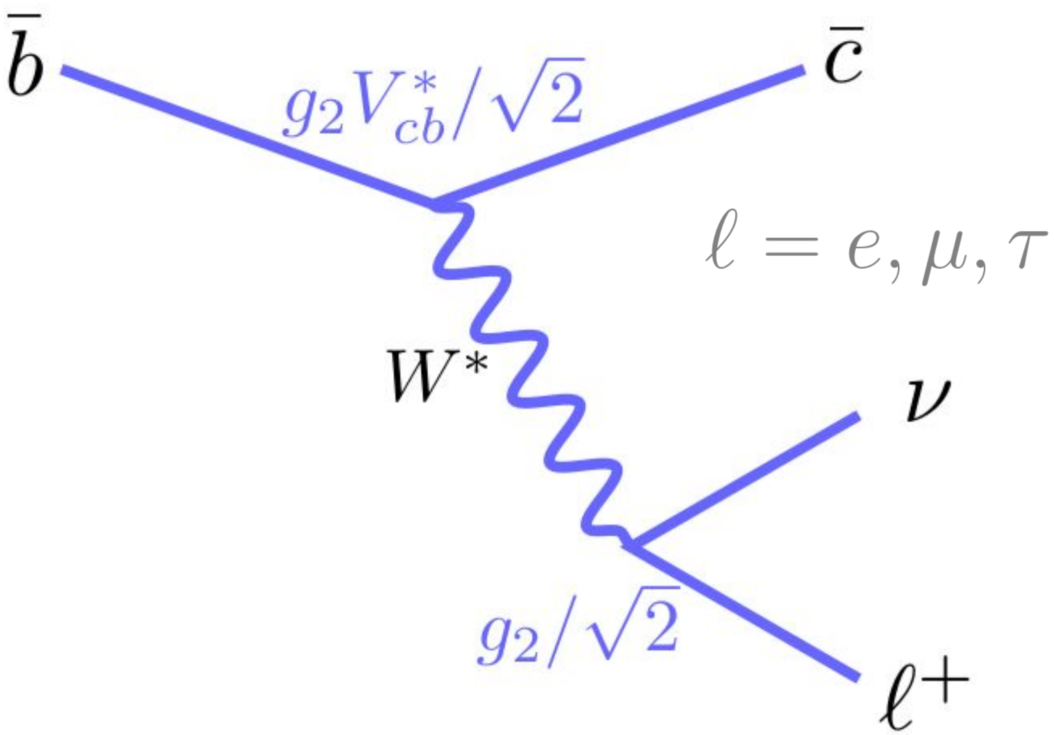


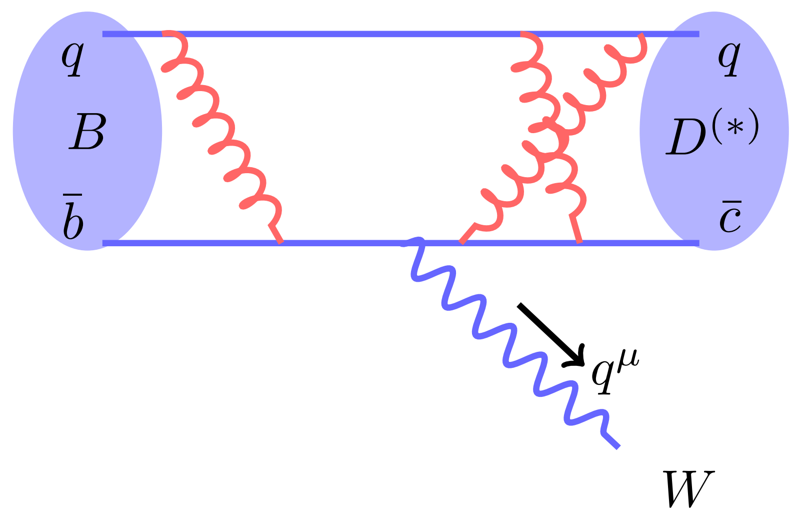
- Huge statistics: ~25% of all B decays
- Clean probe of lepton flavor universality τ vs μ,e (up to mass effects)

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

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

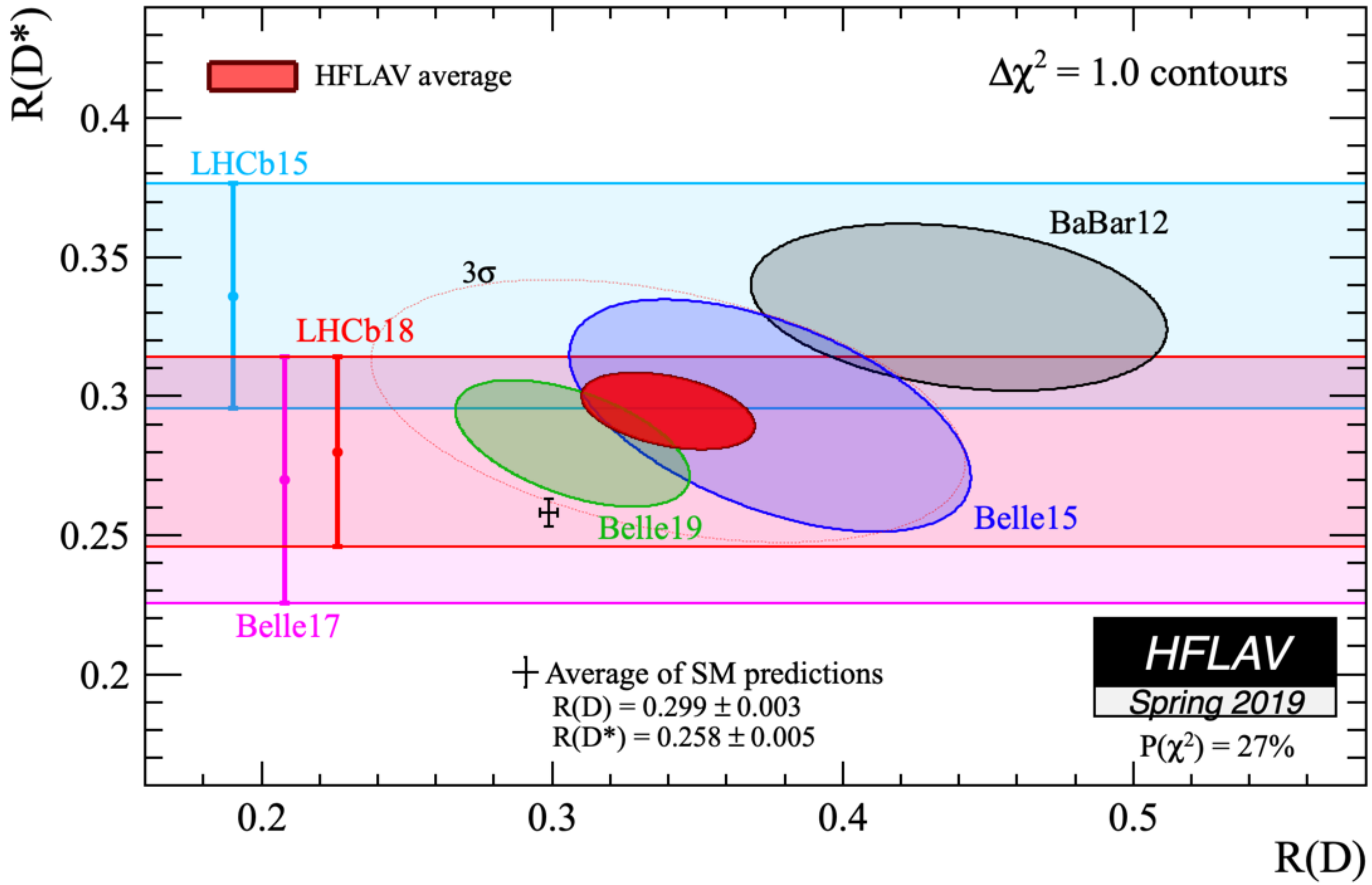
SEMILEPTONIC B → C DECAYS





- Current experimental status:
  - μ,e: tension (~3σ) in $|V_{cb}|$ measurement between exclusive and inclusive modes
  - LFU τ vs μ,e: many measurements, all displaying tensions with Standard Model predictions
- Form factors? Backgrounds? New physics?

LFU TESTS



- >3σ tension with SM prediction in R(D) R(D*) system

LFU TESTS

- Other measurements point in the same direction

$$R(J/\psi) = \frac{\Gamma(B_c \to J/\psi \tau \nu)}{\Gamma(B_c \to J/\psi \mu \nu)} = 0.71 \pm 0.17 \pm 0.18$$

1711.05623 [LHCb]

$$\text{vs } R(J/\psi)_{SM} = 0.2 - 0.4 \ (95\,\%\,\text{CL})$$ *1807.02730*

- "Inclusive" b→c

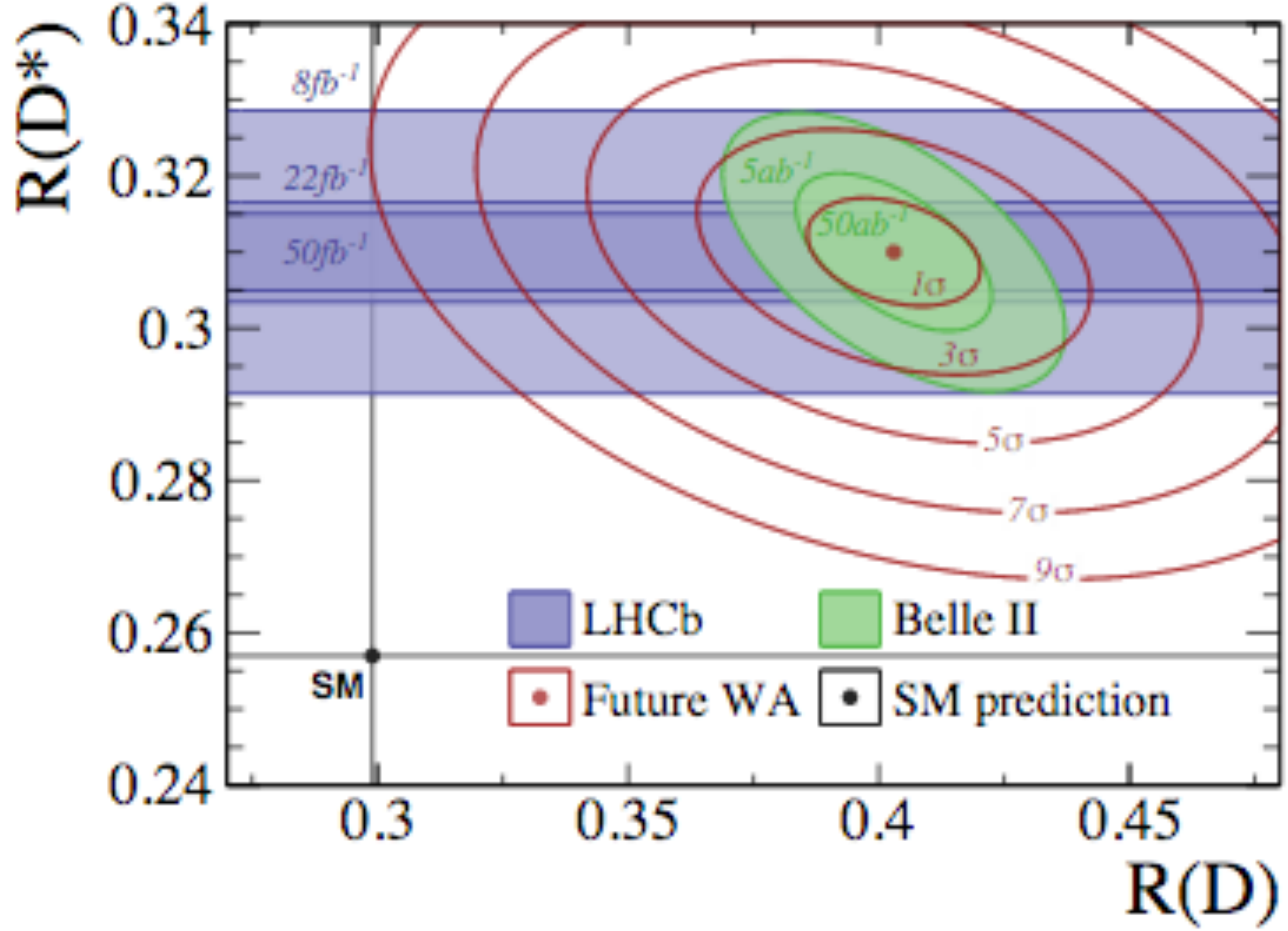
$$R(X_c) = 0.298 \pm 0.012 \pm 0.018$$

[Belle] (thesis only: https://hss.ulb.uni-bonn.de/2018/5101/5101.pdf)

$$\text{vs } R(X_c)_{SM} = 0.223 \pm 0.004$$ *1506.08896*

- (+ LFU anomalies in R(K*): e vs μ — could be related in BSM explanations)

LFU TESTS



- ➤ Huge upcoming statistics: potential to test this anomaly at many σs

IS IT NEW PHYSICS?

- Many theory papers try to explain LFU anomaly with BSM physics
- NP contributions: modify the (bc) (τν) SM 4-fermion operator with other new physics contributions:

$$\text{Vector:} \quad i2\sqrt{2}V_{cb}G_F\left(\frac{m_W}{\Lambda_V}\right)^2 \left[\bar{b}(\alpha_L^V\gamma^\mu P_L + \alpha_R^V\gamma^\mu P_R)c\right]\left[\bar{\nu}_\tau(\beta_L^V\gamma_\mu P_L + \beta_R^V\gamma_\mu P_R)\tau\right],$$

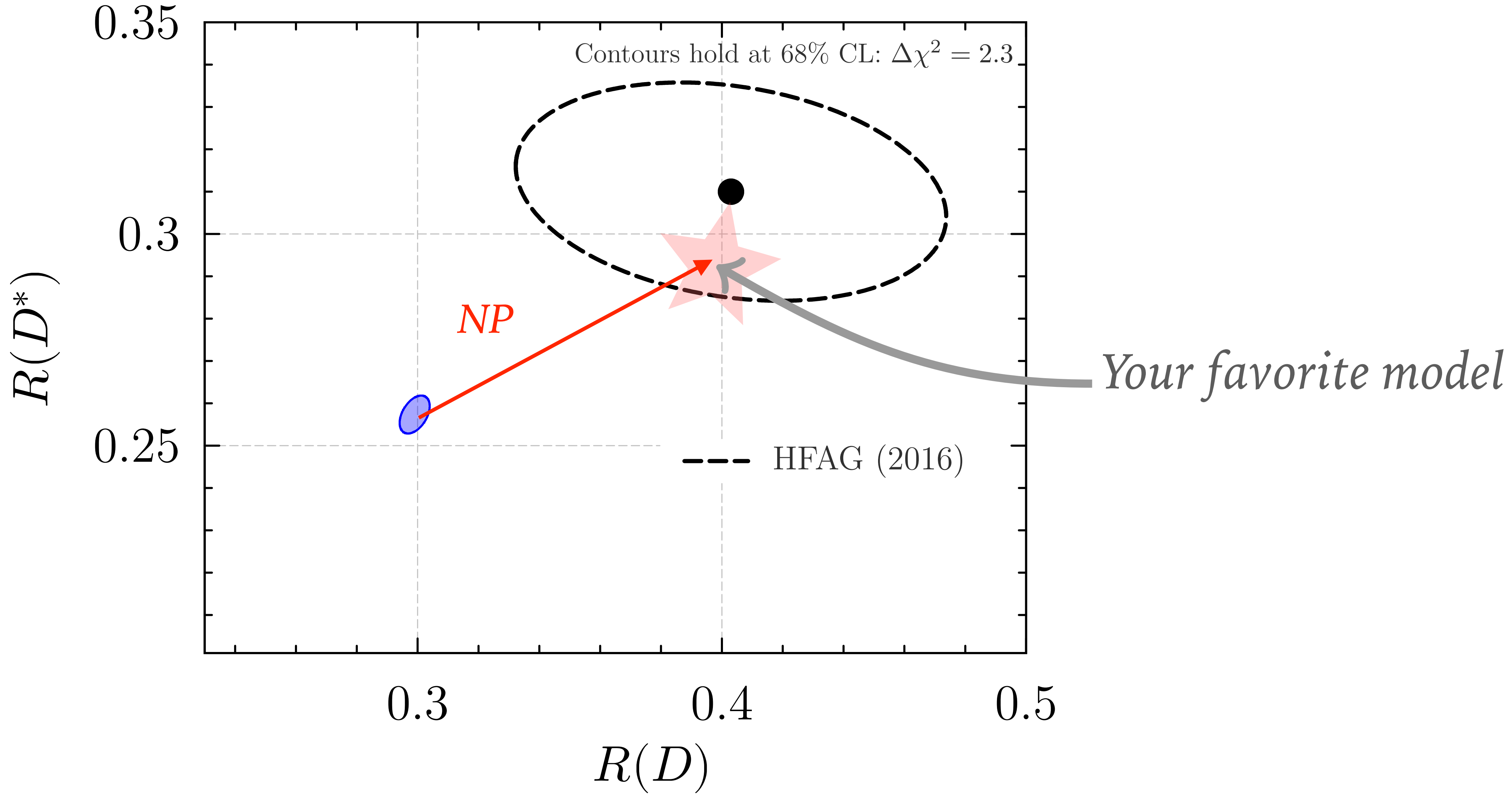
$$\text{Scalar:} \; -i2\sqrt{2}V_{cb}G_F\left(\frac{m_W}{\Lambda_S}\right)^2 \left[\bar{b}(\alpha_L^S P_L + \alpha_R^S P_R)c\right]\left[\bar{\nu}_\tau(\beta_L^S P_R + \beta_R^S P_L)\tau\right],$$

$$\text{Tensor:} \; -i2\sqrt{2}V_{cb}G_F\left(\frac{m_W}{\Lambda_T}\right)^2 \left\{\left[\bar{b}(\alpha_R^T\sigma^{\mu\nu}P_R)c\right]\left[\bar{\nu}_\tau(\beta_L^T\sigma_{\mu\nu}P_R)\tau\right] + \left[\bar{b}(\alpha_L^T\sigma^{\mu\nu}P_L)c\right]\left[\bar{\nu}_\tau(\beta_R^T\sigma_{\mu\nu}P_L)\tau\right]\right\}.$$

  - Tauonic decays: most of NP fits done to R(D) and R(D*), assuming τ and D* stable

IS IT NEW PHYSICS?

- Many theory papers try to explain LFU anomaly with BSM physics
- Name of the game:



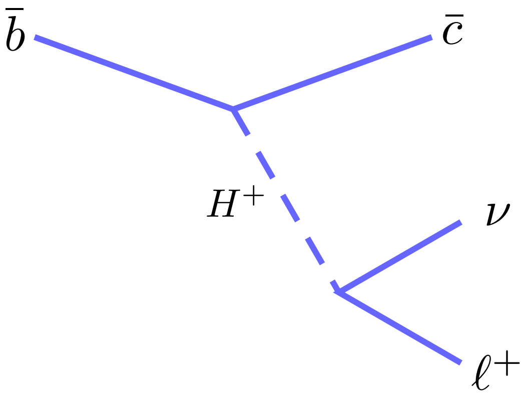
OK as order of magnitude estimate, highly problematic for quantitative conclusions

FITTING NEW PHYSICS IN THE R(D)–R(D*) PLANE

- Many problems:
  - τ and D* unstable: $O(m_\tau/m_b)$ changes in rates due to interference effects (b/c of acceptance cuts, effects are different between SM and BSM)
    - True also for q^2 distributions!!!
  - Some subtracted backgrounds are affected by the same BSM contributions
  - Form factor uncertainties need to be taken into account
  - Cannot angular decompose to a set of $f_i(q^2)$ and unfold (like in $B \to K^*\mu\mu$) because decays not fully reconstructible

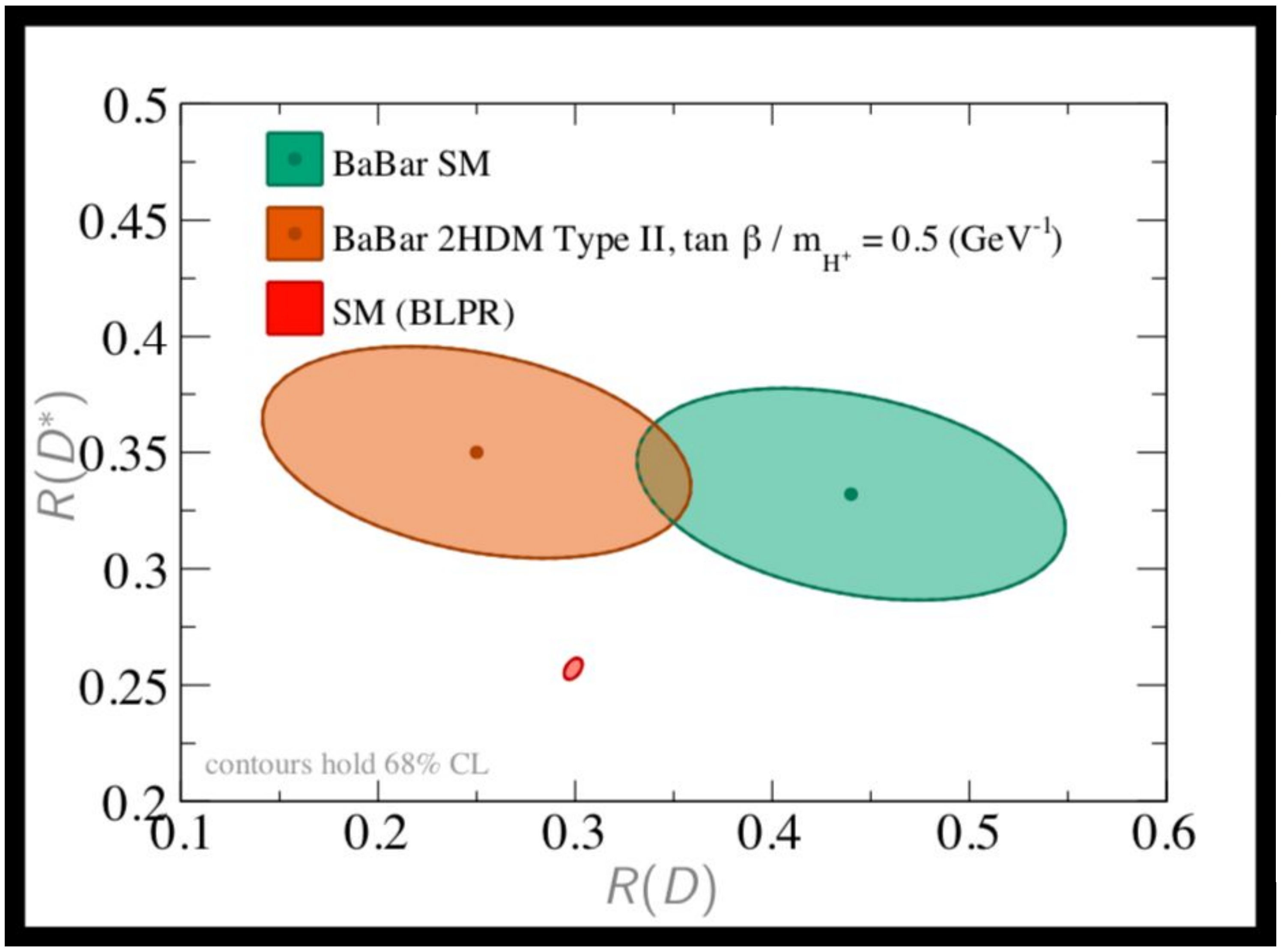
Experiments should provide the constraints on BSM Wilson coefficients directly

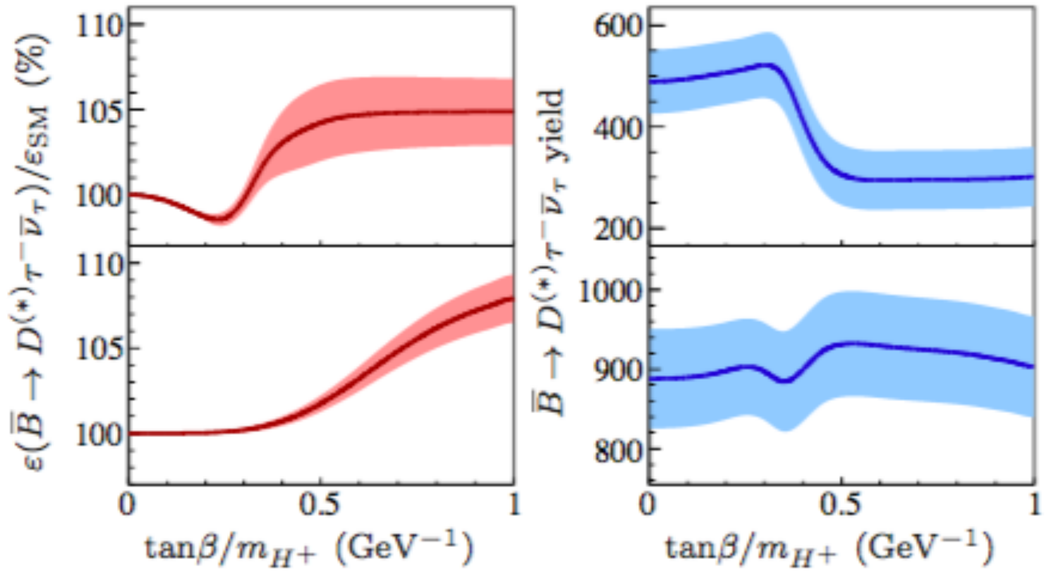
Need proper tools!



NEW PHYSICS AND SHAPES

- Fitting SM+NP can change the R(D) and R(D*) values
- Need NP acceptances to estimate NP contributions



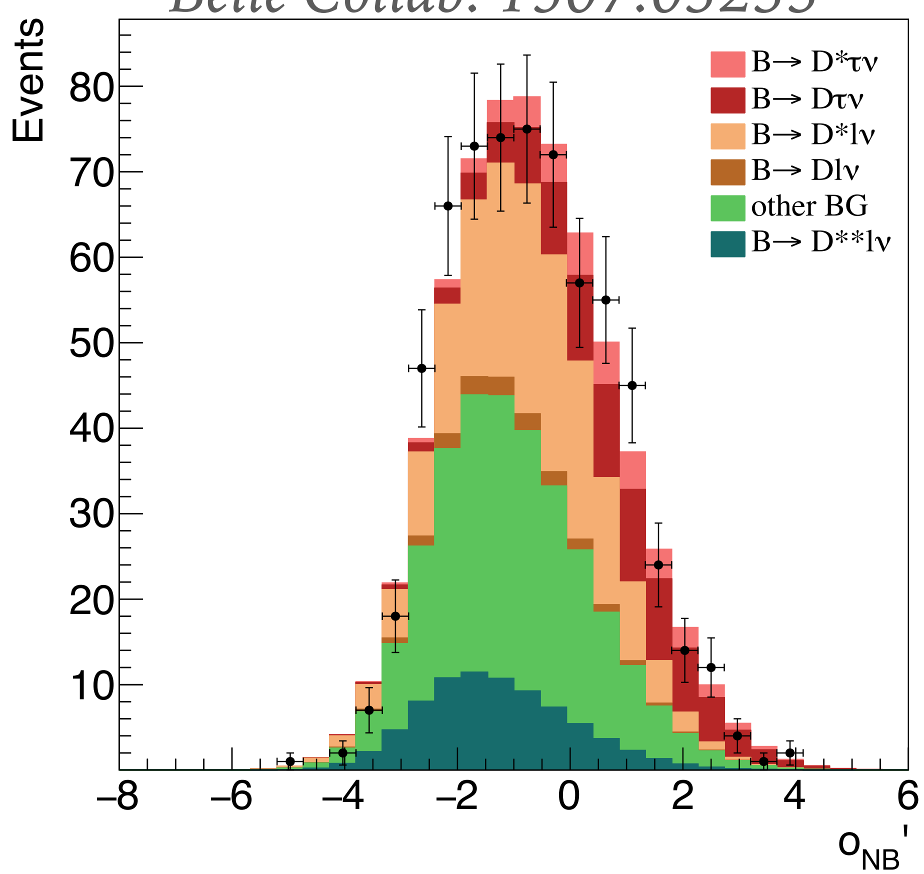


1303.0571 [Babar]

BACKGROUNDS & NEW PHYSICS

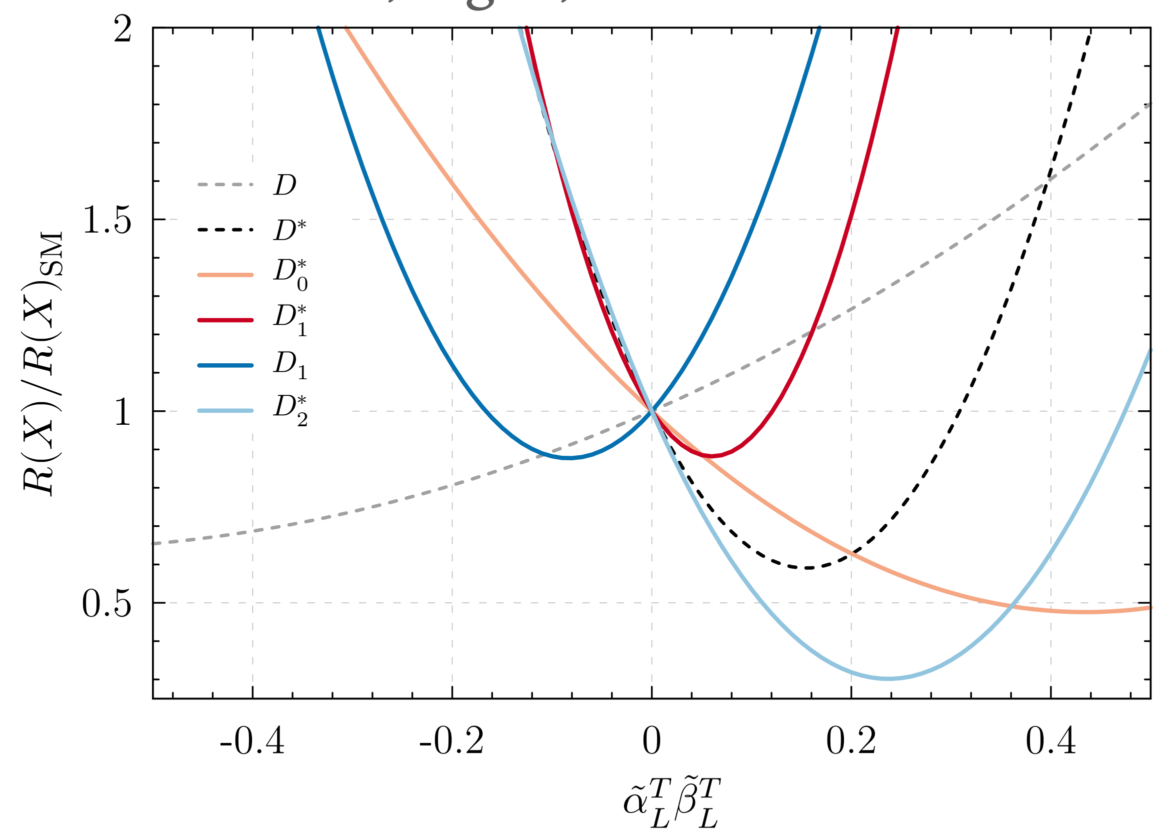
- Semileptonic decays to D** (higher orbital states) are important backgrounds:

Belle Collab. 1507.03233



- B→D**τν more sensitive to new physics than D and D*!

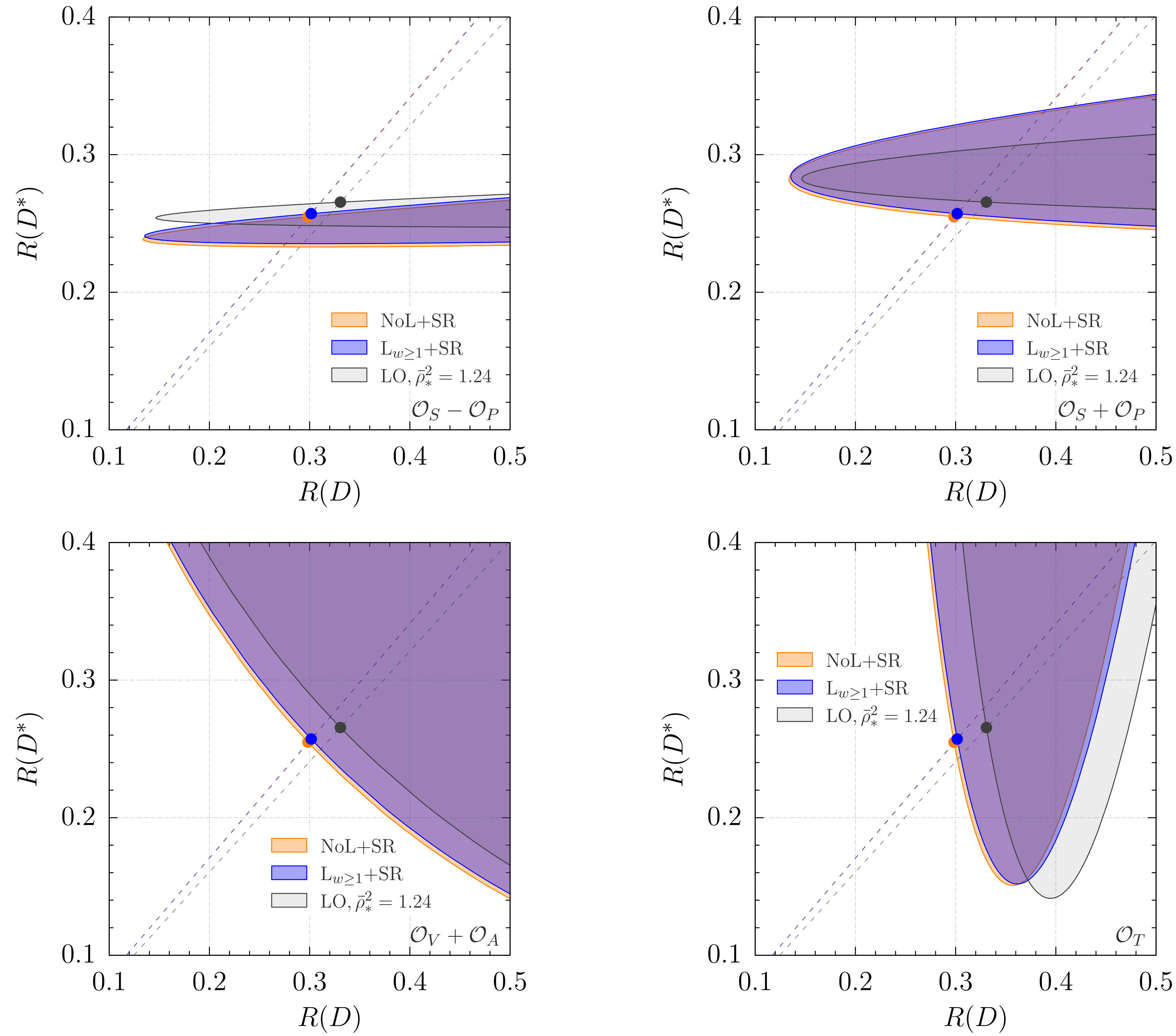
Bernlocher, Ligeti, Robinson 1711.03110



→ *Need to float signal and background simultaneosly in NP fit*

FORM FACTORS & NEW PHYSICS

- New physics $\leftrightarrow$ observables relations (obviously) depend on form factors
- sizable shifts in allowed new physics range if changing FFs
- need to take into account form factor uncertainties



HQET LO: Tanaka 1212.1878
HQET NLO: Bernlocher, Ligeti, MP, Robinson 1703.05330

HAMMER'S GOALS

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

Hammer designed to overcome these issues

HAMMER'S IDEA

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

Depends on NP *Independent of NP*

$$[\mathcal{M}]^{s_{\nu_\tau}}_{s_{\bar{\nu}_\tau} s_\ell s_{\nu_\ell}} = \vec{v} \cdot [\vec{\mathcal{M}}_v]^{s_{\nu_\tau}}_{s_{\bar{\nu}_\tau} s_\ell s_{\nu_\ell}} ,$$

$$\vec{v} = \left(1\,,\; C^S_{RL}\,,\; C^S_{LL}\,,\; C^S_{LR}\,,\; C^S_{RR}\,,\; C^V_{RL}\,,\; C^V_{LL}\,,\; C^V_{LR}\,,\; C^V_{RR}\,,\; C^T_{RL}\,,\; C^T_{LR}\right)$$

Strip NP coefficients and compute <u>once</u> the NP-independent amplitude (complex) tensor for each event

HAMMER'S IDEA

- Squared matrix element w/o NP physics coefficients:
  - complex weight matrix:

$$\mathcal{W}_{\alpha,\beta} = (FF \cdot \mathcal{M}_\alpha)^\dagger \, (FF \cdot \mathcal{M})_\beta$$

- Perform all operations in terms of weight matrices (tensors) (histogramming, …)
- Real weights can be obtained by simple dot products at the end (e.g. inside a fit minimization)

$$W = v^\dagger \cdot \mathcal{W} \cdot v$$

HAMMER'S IDEA

- Similar treatment can be used for form factors: from weight matrix to rank-4 tensor:

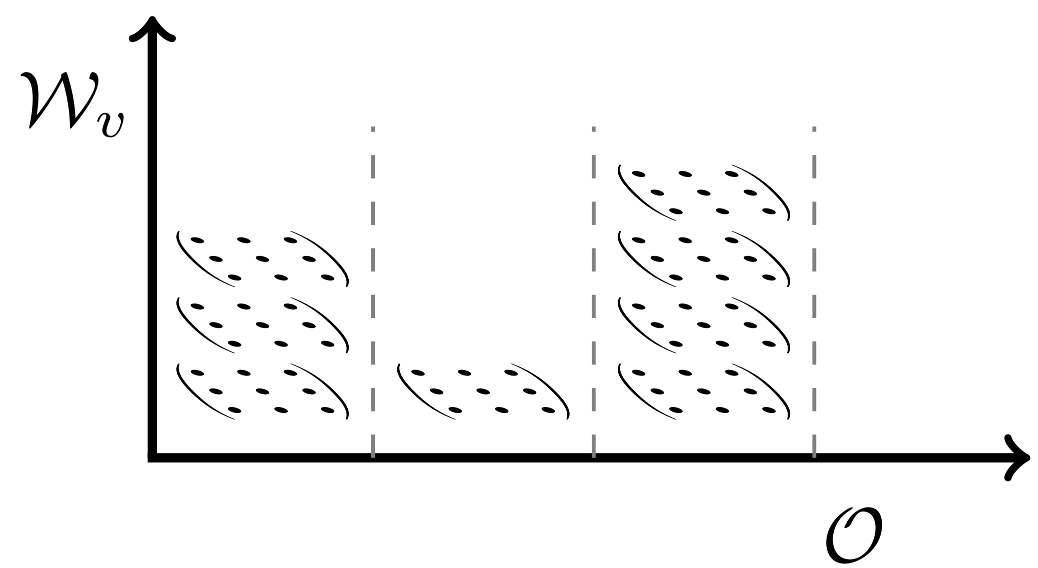
$$\mathcal{W}^{ij}_{\alpha,\beta} = \left(\mathcal{M}^{i}_{\alpha}\right)^{\dagger} \mathcal{M}^{j}_{\beta}$$

$$W = \left|v^{\alpha} F F_i \, \mathcal{M}^{i}_{\alpha}\right|^2$$

- Facilitates switching form factors parameterizations and/or including FF uncertainties ($FF_i \rightarrow FF_i^{\beta}$)

HAMMER'S IDEA

- Event reweighing brings you only so far:
  - $N_{weights} \sim N_{events} * (N_{variations})^D$
- Large number of computations for large statistics samples
- Tensor histograms!
  - Bin tensors directly and collapse to conventional histogram when contracting with external vectors



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

HAMMER'S CODE

- C++ library (w/ Python bindings)
- Input MC: truth level particle 4-momenta & decay chains (multiple decay chains per event supported, e.g. $e^+e^- \to B^+B^-$)
- Handles multiple different, simultaneous FF parameterization choices
- Tensorial histogramming (can be eval to ROOT histograms for D<=3)
- Storage of per-event information or histograms. Data storage agnostic format can be saved in ROOT TTree

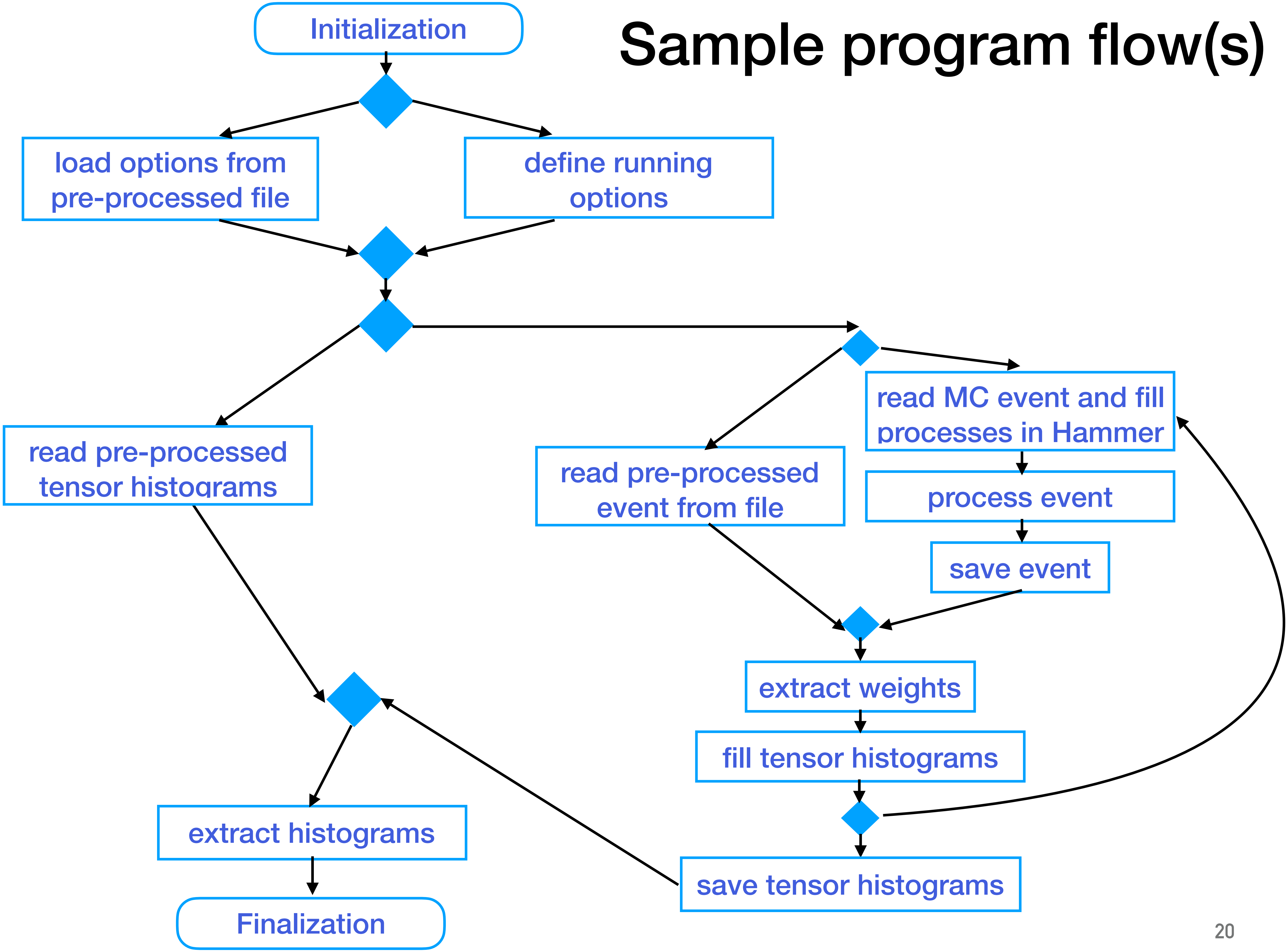
Scope (from manual)

HAMMER'S LIBRARY

- Amplitudes:
  - $B \to D\ell\nu, \quad \ell = e, \mu, \tau$
  - $B \to D^*\ell\nu, \quad \ell = e, \mu, \tau, \quad D^* \to D\pi, D\gamma$
  - $B \to D^{**}\ell\nu, \quad \ell = e, \mu, \tau$
  - $\Lambda_b \to \Lambda_c\ell\nu, \quad \ell = e, \mu, \tau$
  - $\tau \to \ell\nu\nu, \pi\nu, 3\pi\nu$ (w/o BSM)
- Form factor parameterizations:
  - $B \to D, D^*$: ISGW2, CLN, BGL, BLPR
  - $B \to D^{**}$: ISGW2, LLSW, BLR
  - $\Lambda_b \to \Lambda_c$: PCR, BLRS
  - $\tau \to 3\pi$: RCT

\+ *more to come!*
($B_c \to J/\psi\ell\nu$, $B \to \rho\ell\nu$, $\tau \to 4\pi\nu$, ...)

Sample program flow(s)

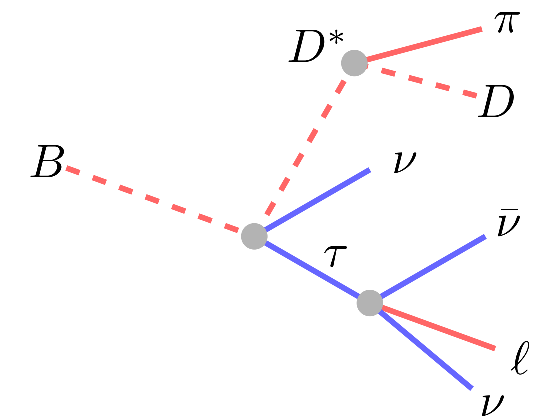


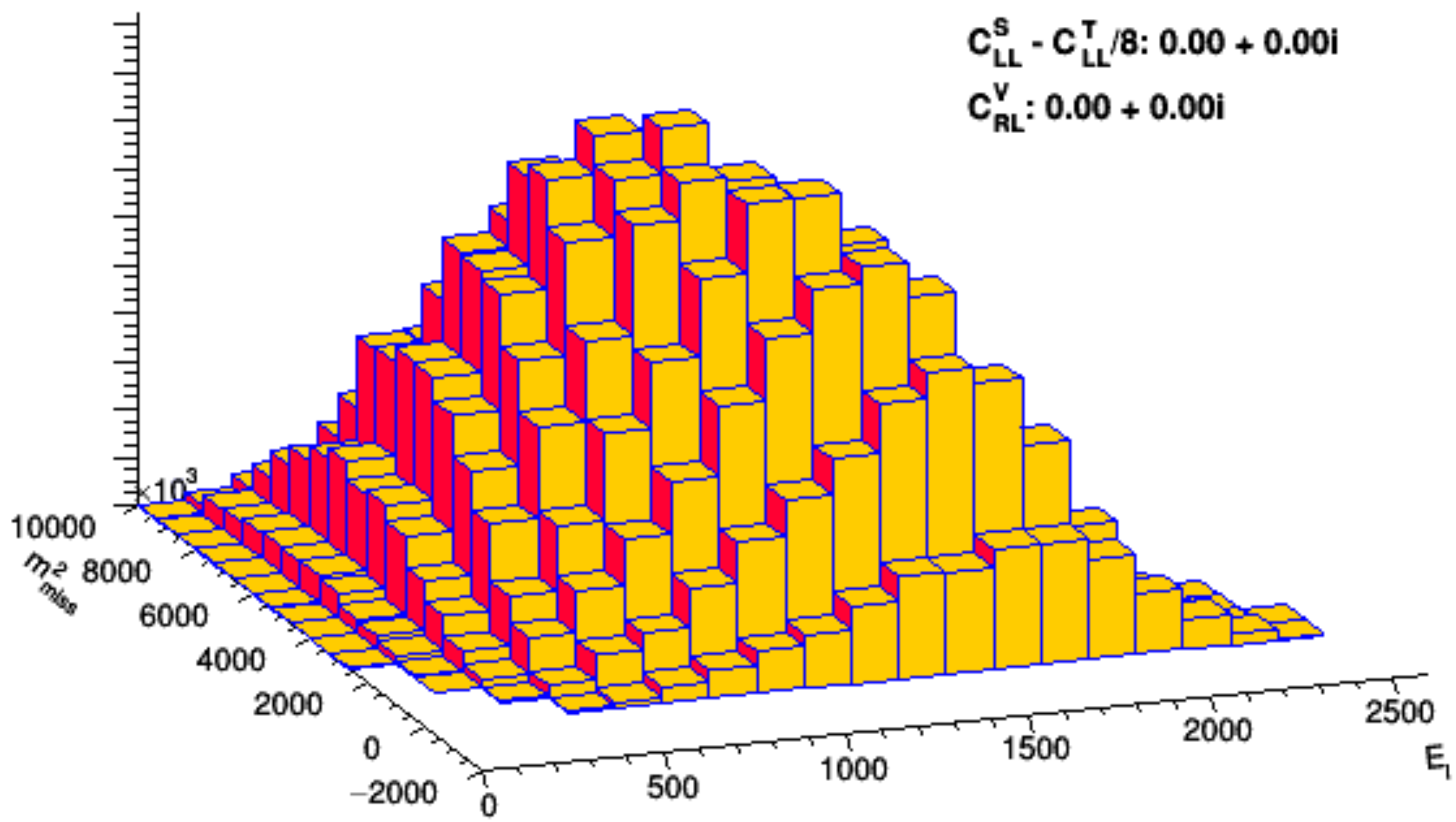
ADOPTION STATUS

- LHCb:
  - Delivered beta version in Oct 2018, integrated in their software framework. Used hammer to reweigh MC tuples and integrated Hammer histograms in Roostat/Histfactory/Minuit fit
  - 1908.04643 used Hammer
- Belle II:
  - first hackaton in March 2019, integration underway
- CMS:
  - Olmo is trying it out
- Official public version + physics paper + manual coming this Fall

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

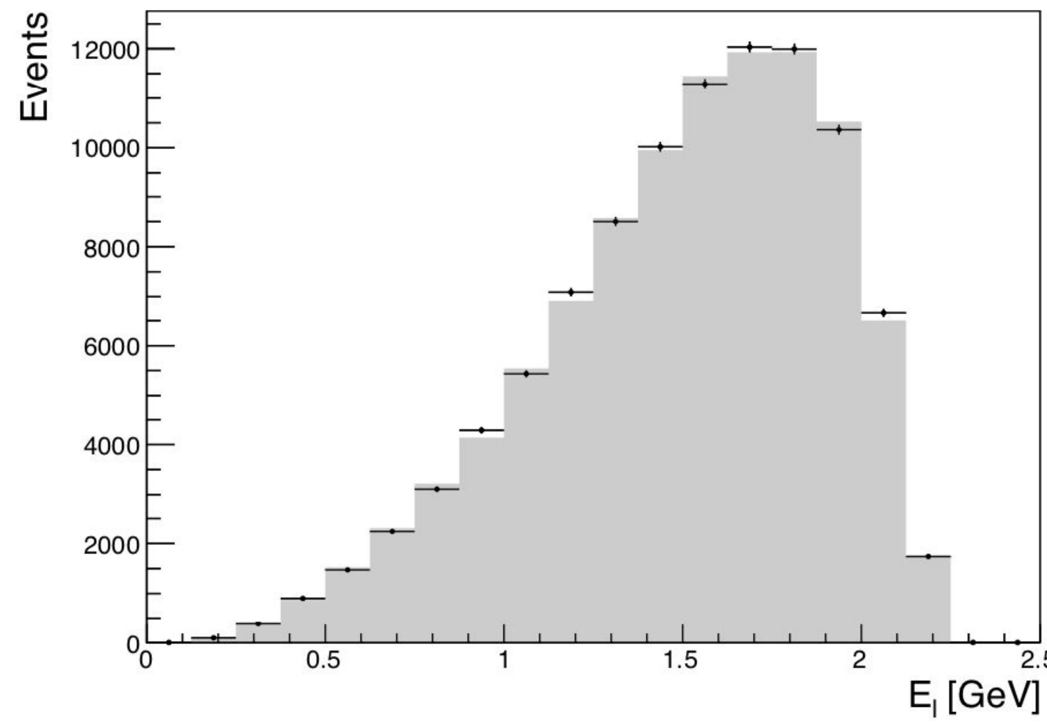


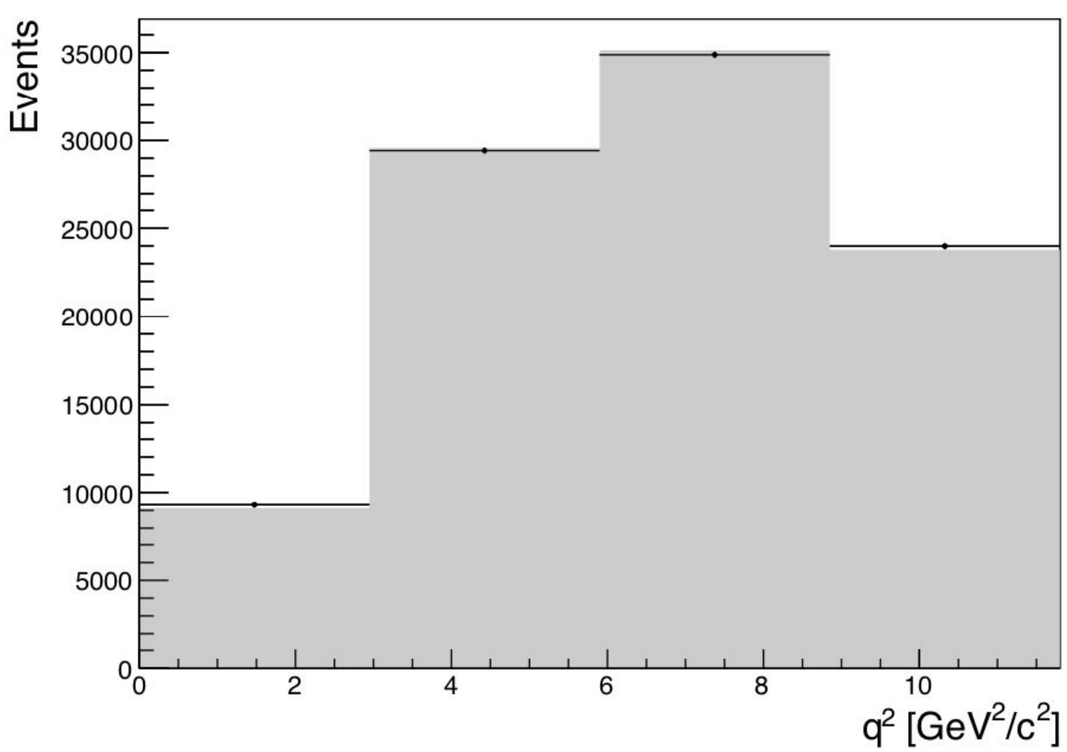


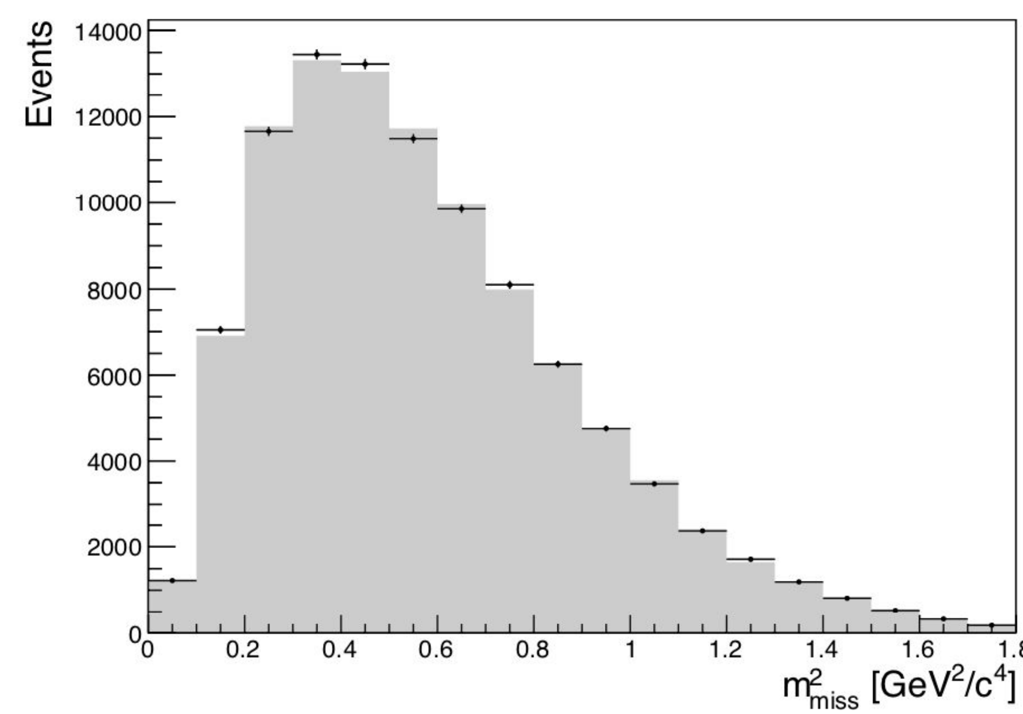
Animation here

EXAMPLES

- LHCb: $B \to D^{(*)}\mu\nu$ reweighed from phase space to CLN and fitted to CLN generated with EvtGen. ρ^2, R_1, R_2 recovered in 3D fit







Courtesy of J.Garcia Pardinas, S.Meloni, P.Owen (LHCb)

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 may have applications beyond semileptonic B decays
- New processes/form factors can be added upon request

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