HAMMER - A tool for new physics searches in semileptonic decays at Belle II and LHCb

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EPS-HEP Ghent 12.07.19

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DFG Deutsche Forschungsgemeinschaft

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Lawrence Berkeley National Laboratory

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LET THERE BE LIGHT
1868

Helicity Amplitude Module
for Matrix Element Reweighting

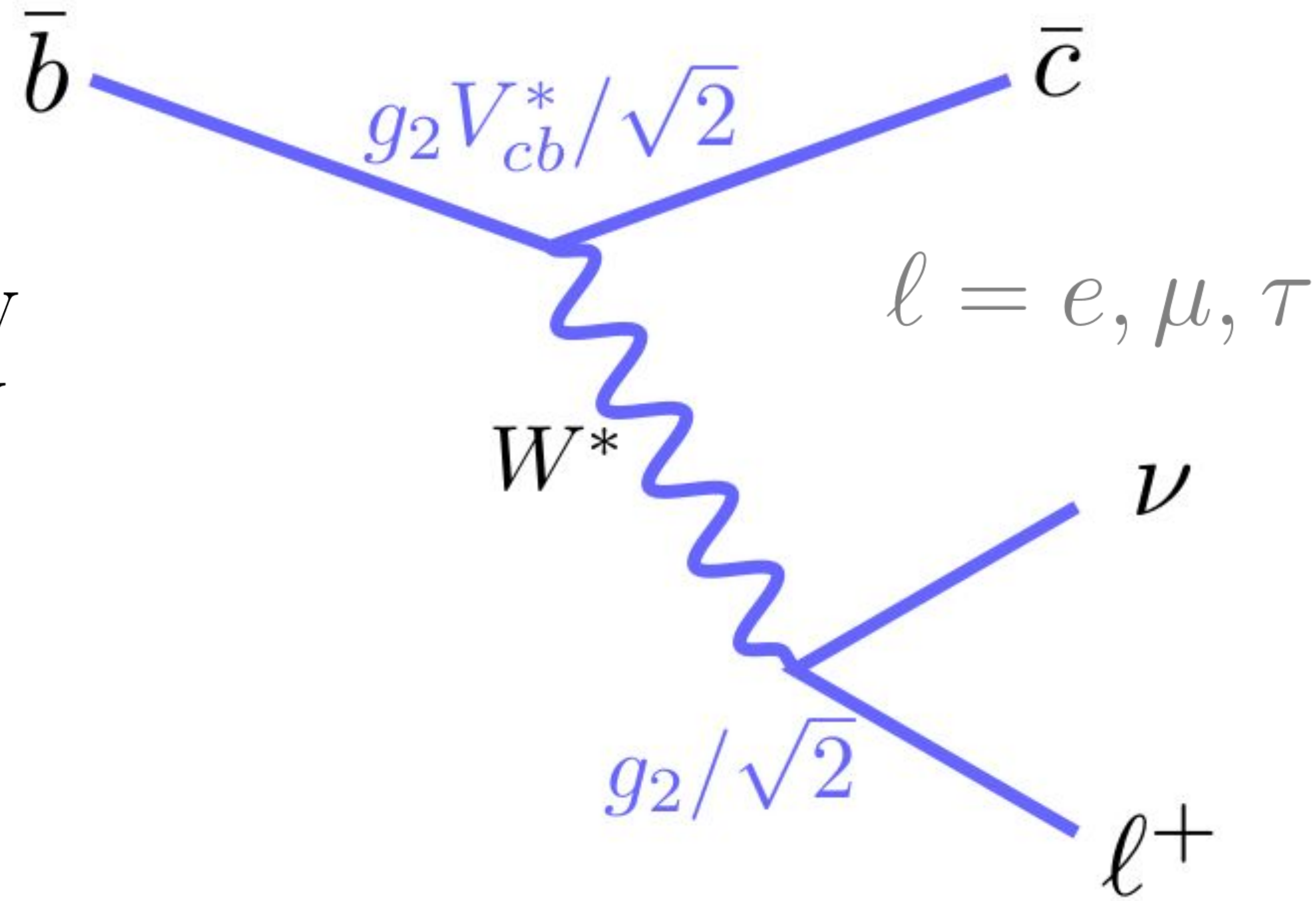
visit us on http://hammer.physics.lbl.gov/

Semileptonic B decays

- Around 25% of all B decays: Huge statistics!
- Tree-level W exchange in the Standard Model (SM)
- Clean probe of Lepton Flavour Universality up to the lepton masses:

$$m_\tau \approx 1.777\ \mathrm{GeV}$$
$$m_\mu \approx 105\ \mathrm{MeV}$$

- CKM matrix element can also be measured (if hadronic matrix elements are known)



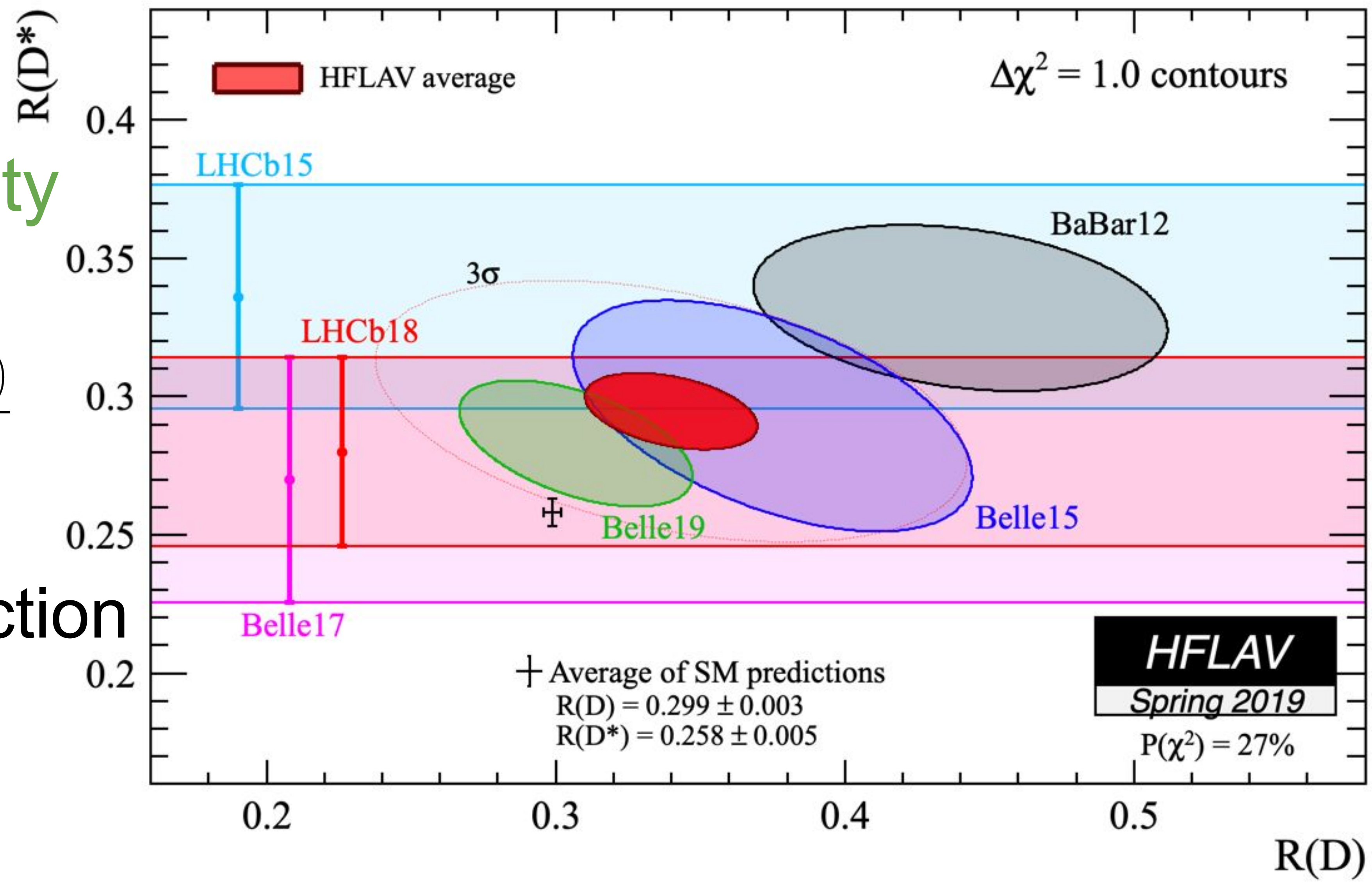
Lepton Flavour Universality Anomalies

- $R(X) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}$ can test Lepton Flavour Universality
  - Universal coupling strength in Standard Model (SM)
    - Different from 1 due to lepton mass effects and hadronic matrix elements

- Hints for Lepton Flavour Universality Violation seen in

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)}$$

- Tension between data and SM prediction at 3σ



Lepton Flavour Universality Anomalies

- Hints to Lepton Flavour Universality Violation also in other channels, i.e.:

$$R(J/\psi) \equiv \frac{\mathcal{B}(B_c \to J/\psi \tau \nu_\tau)}{\mathcal{B}(B_c \to J/\psi \ell \nu_\ell)} = 0.71 \pm 0.17 \pm 0.18$$

1807.02730

$$R(K) \equiv \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

1406.6482

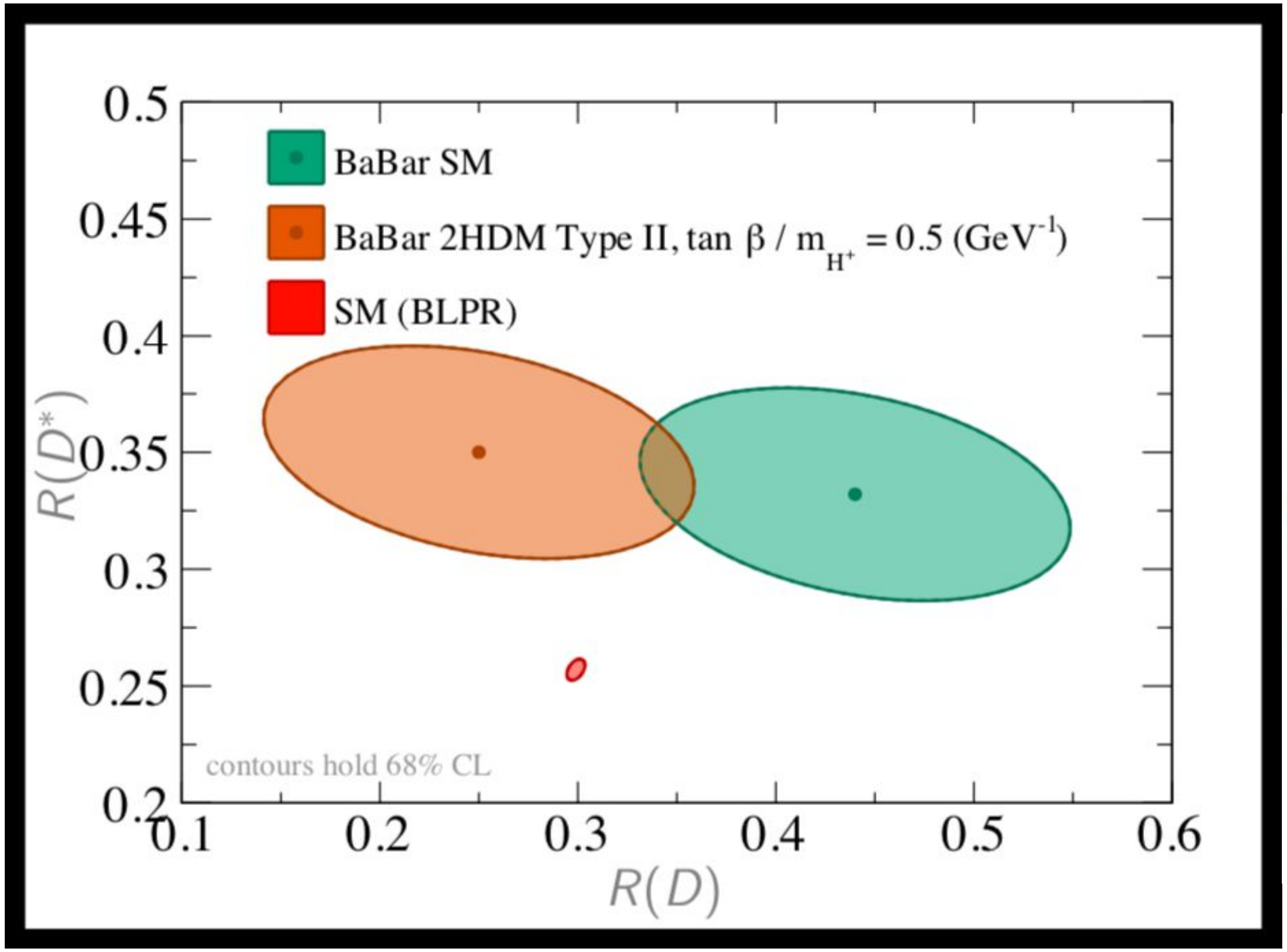
$$R(K^*) \equiv \frac{\mathcal{B}(B^0 \to K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \to K^{*0} e^+ e^-)} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

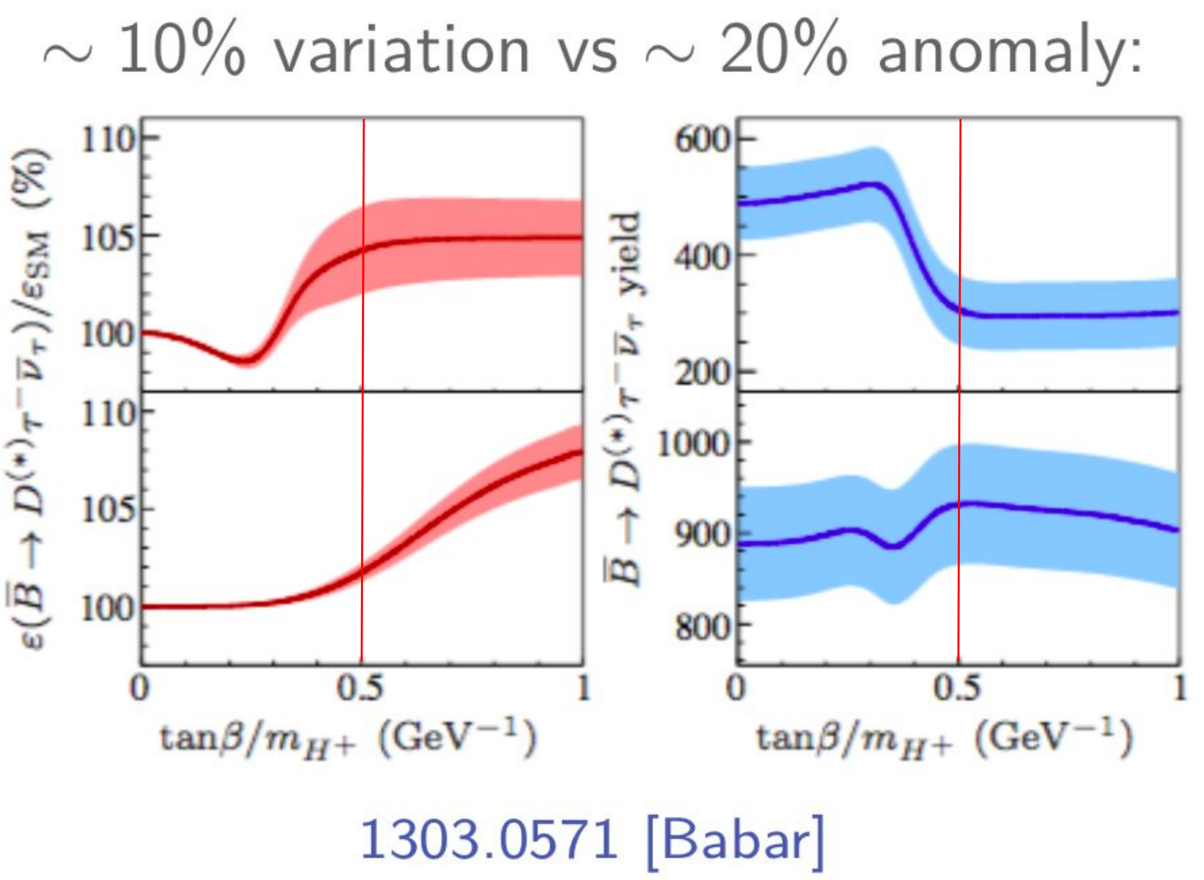
1704.06240

New Physics as cause for the anomalies?

Caveats - BaBar SM to 2HDM

- Example showing the effect NP has on an analysis, based on a real $B \to D^{(*)}\tau\nu_\tau$ analysis made by BaBar (1303.0571)





- New Physics has to be included in analyses a priori!

Probing for New Physics - Caveats

1. Only experimentalists can perform self-consistent NP searches (in $B \to D^{(*)}\tau\nu_\tau$)
   - New Physics (NP) analyses have been done only for specific models/coupling ranges
   - Should do model-independent searches!
2. Arbitrary NP typically not present in MC generators used in the experiments (EvtGen)
3. Big contribution to systematic errors from MC statistics
   - Experimentalists would need a lot more MC statistics for a single New Physics study

Hammer was developed to address these Problems!

Software

- Hammer is:
  - compiled C++ library with Python interface
  - allows fast and efficient computations
  - onboard histogramming service (compatible with ROOT histograms) which is fast enough for fitting
- Multi-Stage effort:
  - Develop state-of-the-art treatments for NP matrix elements
  - Compact expressions for NP decays with high multiplicity final states, i.e. $B \to (D^{(*)} \to DY)(\tau \to \nu X)\nu$

Theoretical Approach

- General 4-Fermi Basis at dimension 6

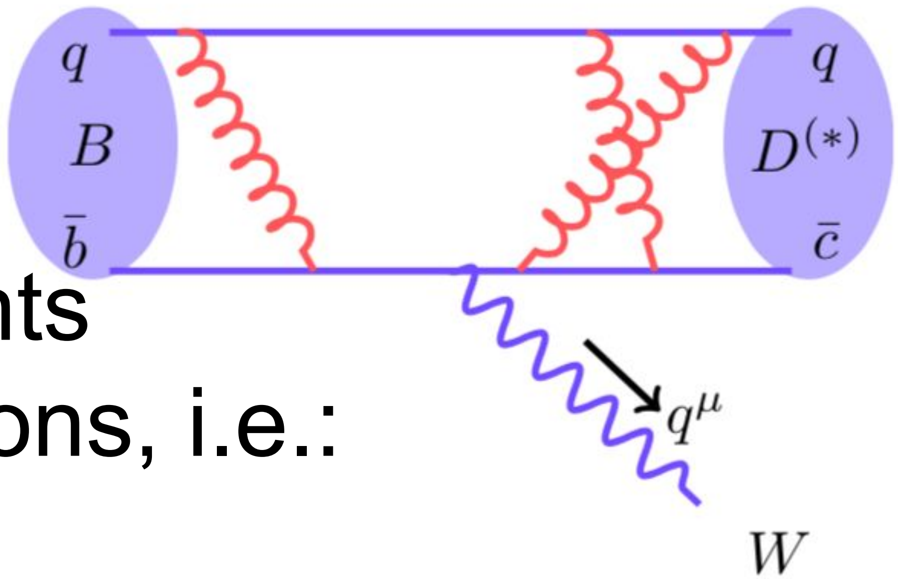
$$\mathcal{O}_6 \sim \frac{C}{\Lambda^2}(\bar{c}\Gamma b)(\bar{\tau}\Gamma'\nu)$$

- New Physics (i.e. additional mediators) included in Wilson Coefficients e.g. for $B \to D^{(*)}\tau\nu_\tau$

LH ν	RH ν
Vector: $C^V_{\mathrm{LL}}, C^V_{\mathrm{RL}}$	(and $C^V_{\mathrm{LR}}, C^V_{\mathrm{RR}}$)
Scalar: $C^S_{\mathrm{LL}}, C^S_{\mathrm{RL}}$	(and $C^S_{\mathrm{LR}}, C^S_{\mathrm{RR}}$)
Tensor: C^T_{LL}	(and C^T_{LR})

Theoretical Approach

- For exclusive processes: Main uncertainty from theory is from mapping partons → hadrons



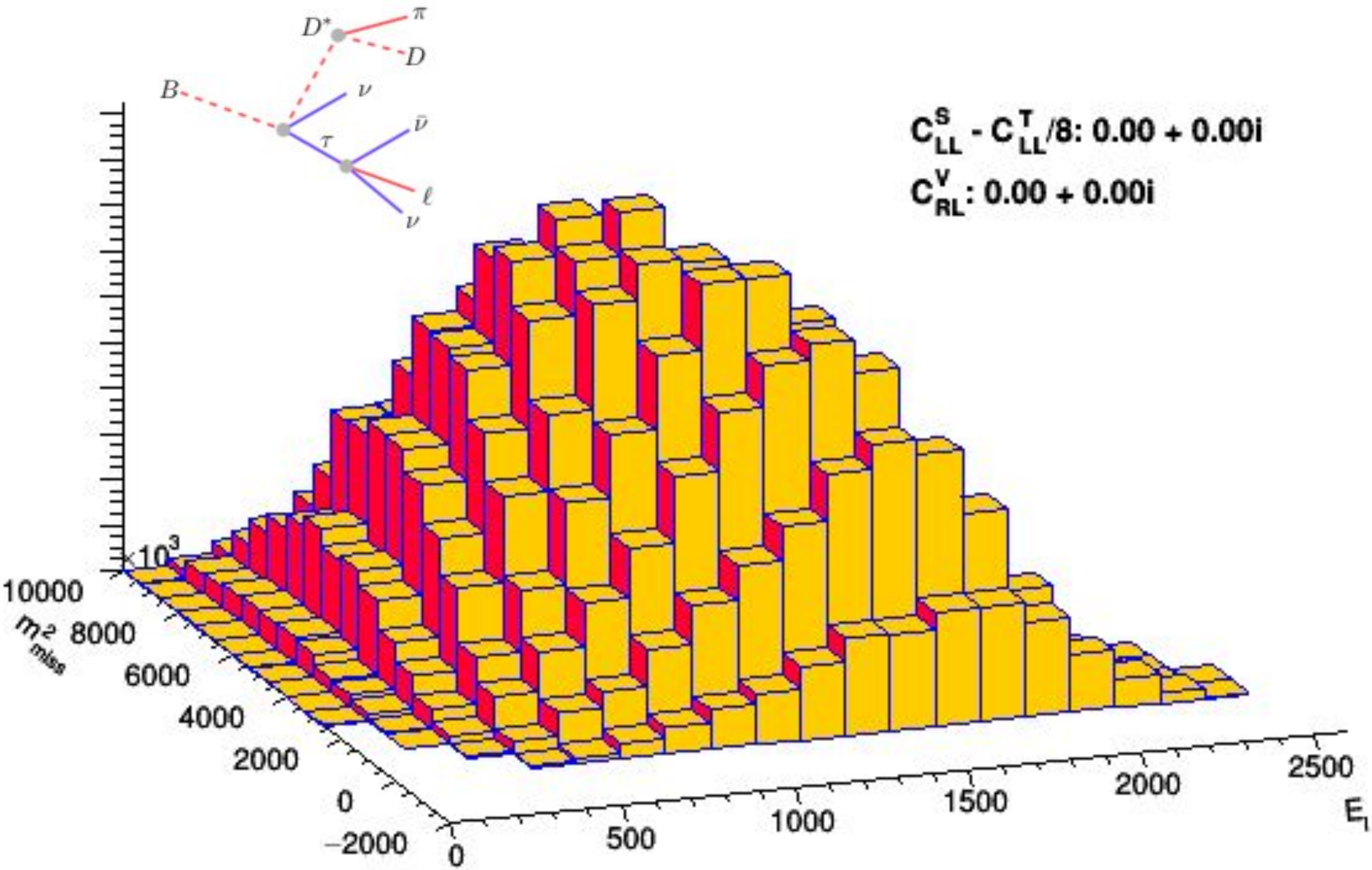
- Form factors encode matrix elements in terms of momenta and polarizations, i.e.:

$$\langle D | \bar{c} \Gamma b | \bar{B} \rangle \sim f_\epsilon(q^2)\epsilon^\mu + f_B(q^2) p_B^\mu + f_D(q^2) p_D^\mu$$

- Variety of theoretical input for how to treat form factors, available in Hammer at the moment:
  - ISGW2 $(B \to D^{(*)})$
  - BGL $(B \to D^{(*)})$
  - CLN $(B \to D^{(*)})$
  - BLPR $(B \to D^{(*)})$
  - PCR $(\Lambda_b \to \Lambda_c)$
  - BLRS $(\Lambda_b \to \Lambda_c)$

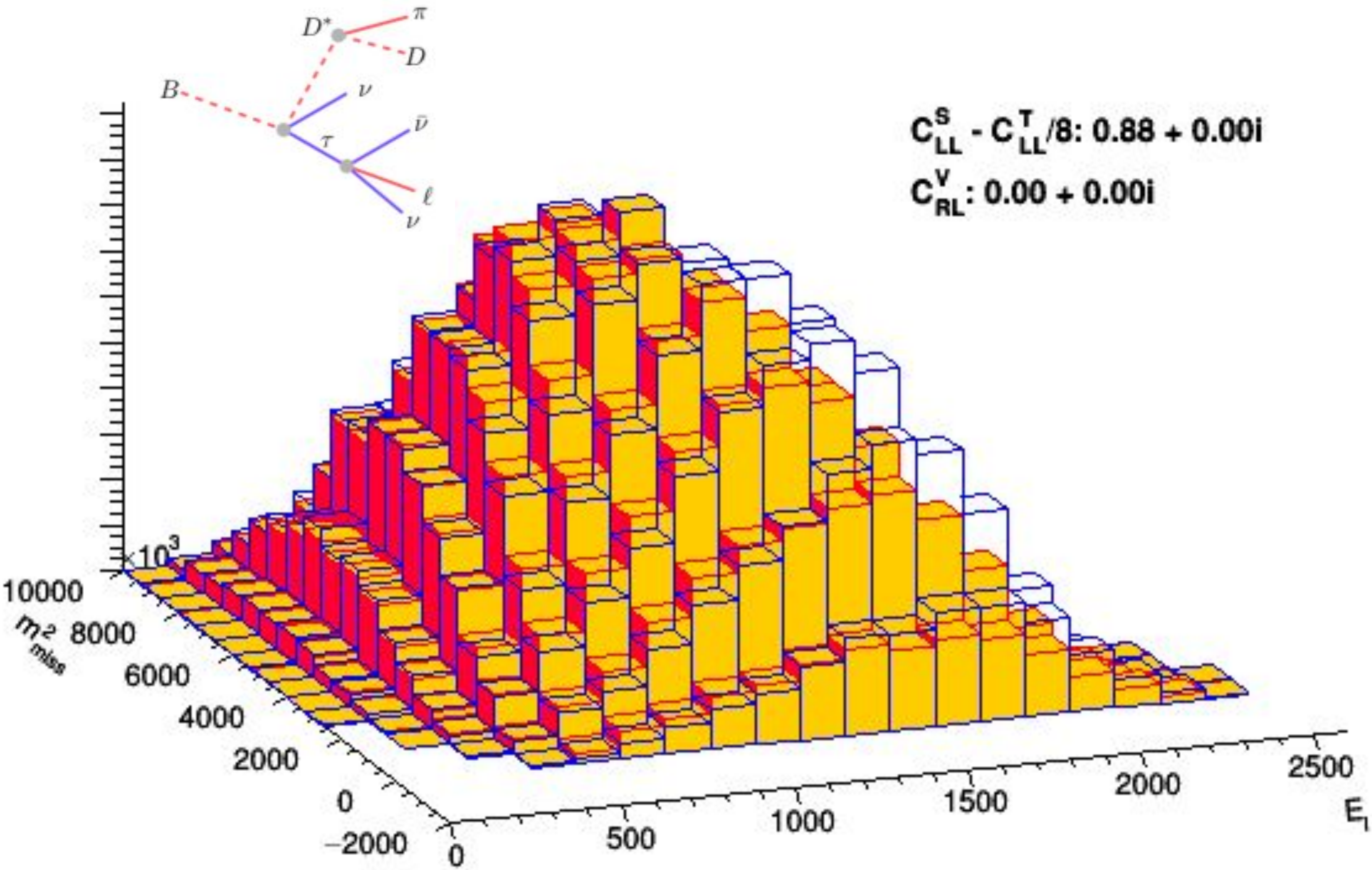
- <u>Planned</u>:
  - LLSW $(B \to D^{**})$
  - BLR $(B \to D^{**})$
  - and more, i.e. $B \to J/\psi, \pi, \rho, \omega, \ldots$

Examples



D^*
π
D
B
ν
$\bar{\nu}$
τ
ℓ
ν
C^S_{LL} - C^T_{LL}/8: 0.00 + 0.00i
C^V_{RL}: 0.00 + 0.00i
$\times 10^3$
10000
8000
6000
4000
2000
0
−2000
m^2_{miss}
0
500
1000
1500
2000
2500
E_l

Examples



D^*
π
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$C^S_{LL} - C^T_{LL}/8$: 0.88 + 0.00i
C^V_{RL}: 0.00 + 0.00i
$\times 10^3$
10000
8000
6000
4000
2000
0
−2000
m^2_{miss}
0
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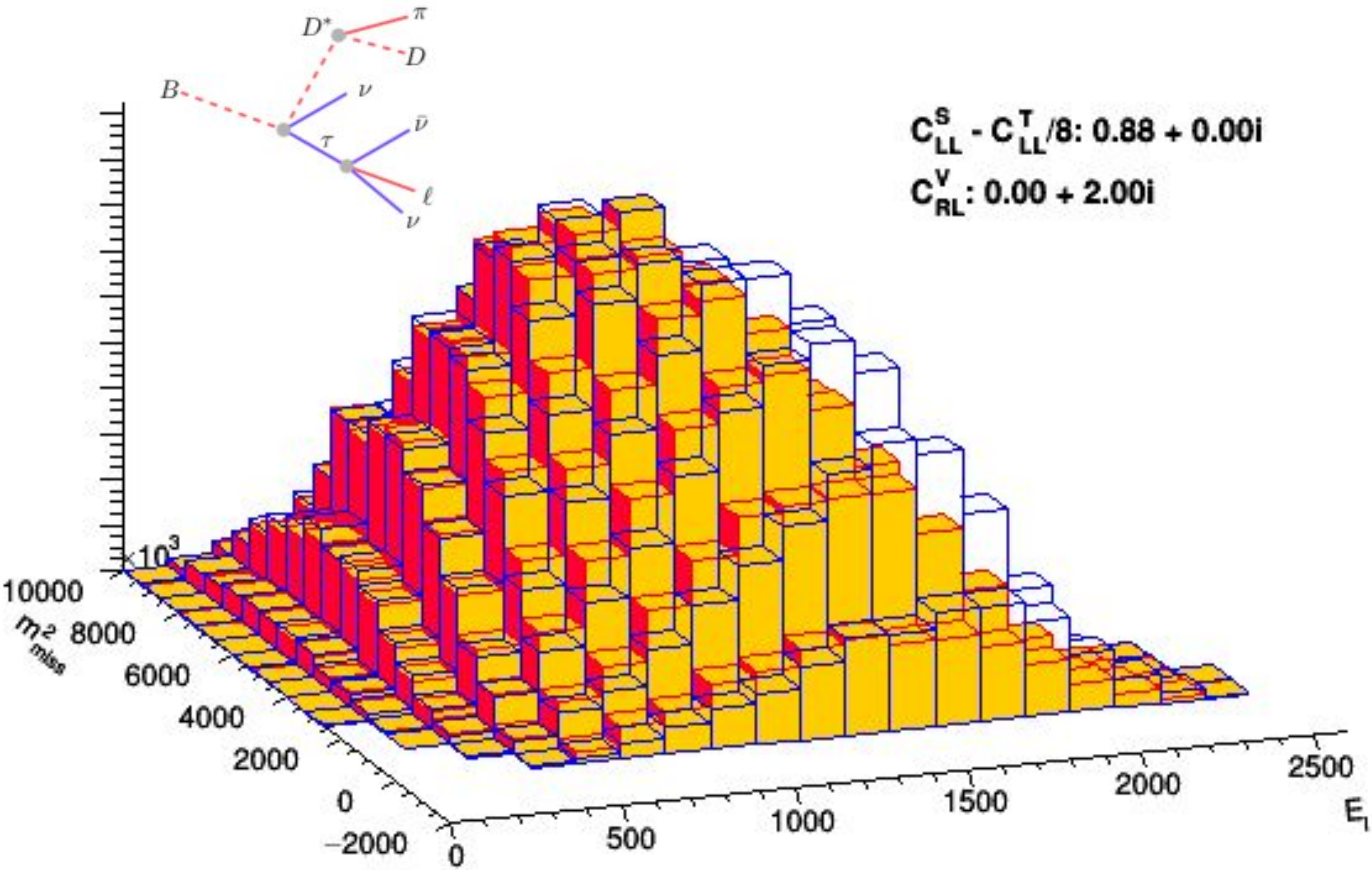
1000
1500
2000
2500
E_l

Examples



D^*
π
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B
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$\bar{\nu}$
ℓ
ν
$C^S_{LL} - C^T_{LL}/8$: 0.88 + 0.00i
C^V_{RL}: 0.00 + 2.00i
$\times 10^3$
10000
8000
6000
4000
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0
−2000
m^2_{miss}
0
500
1000
1500
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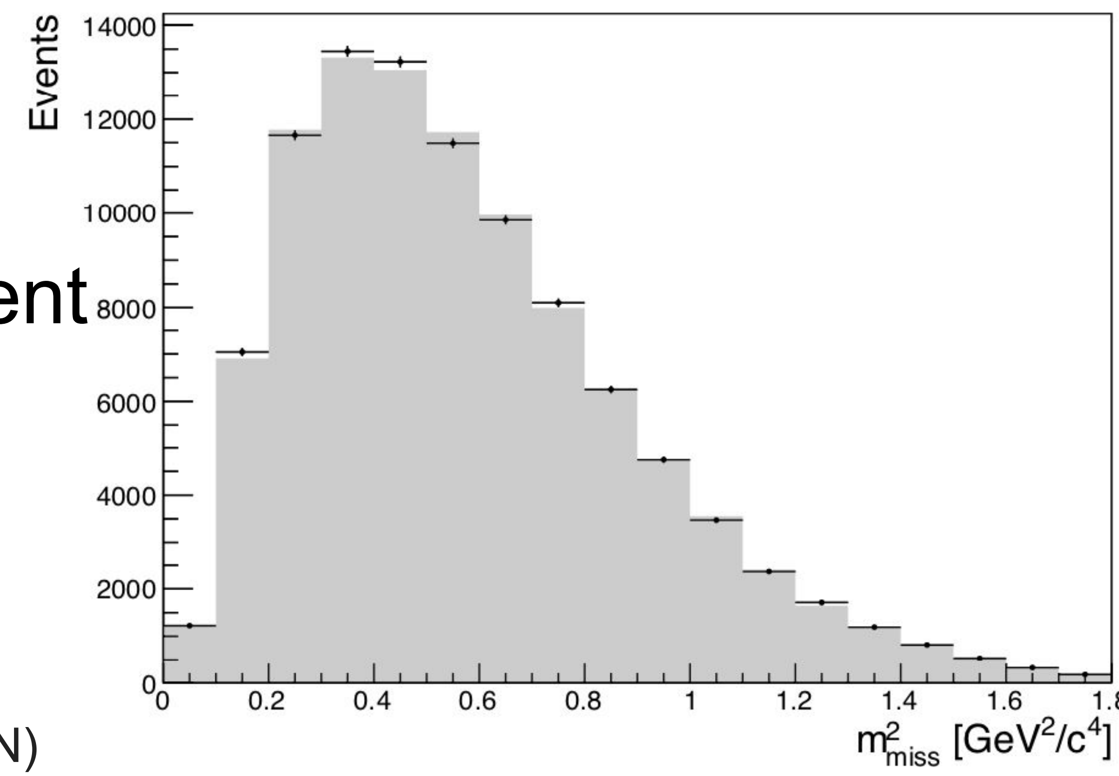
2500
E_l

Examples - A LHCb implementation of Hammer

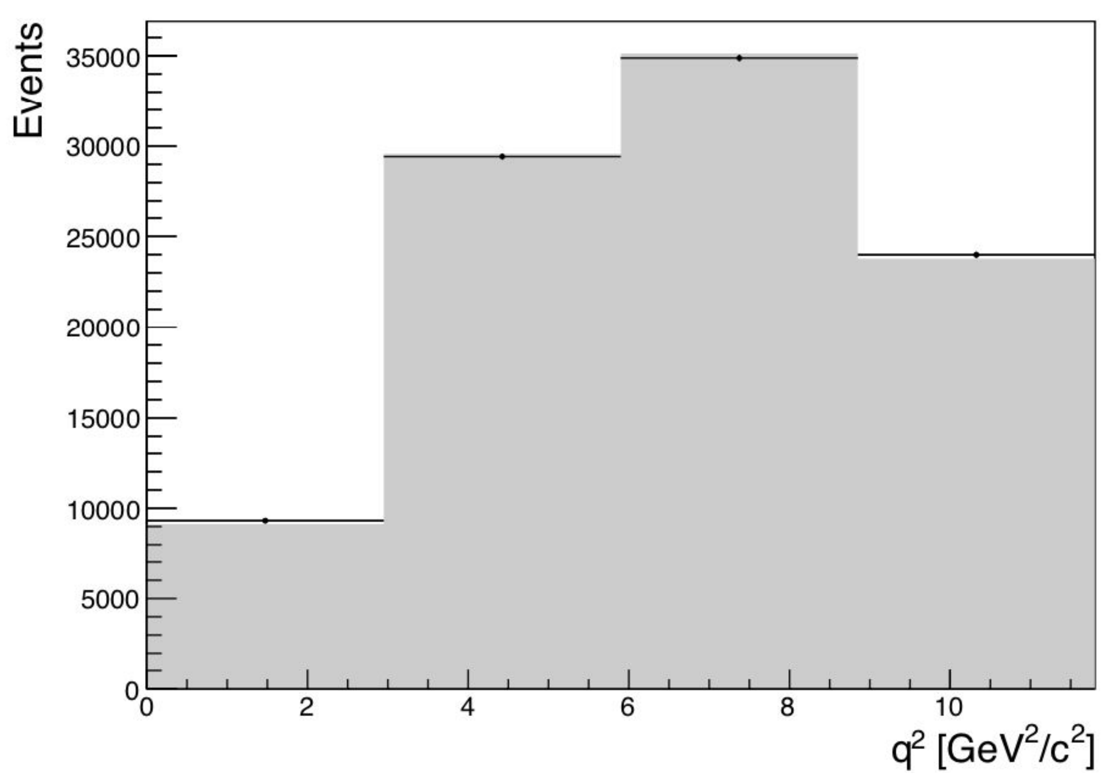
- Example: $B \to D^{*}(\to D\pi^{0})\mu\nu_{\mu}$
- Hammer in a LHCb analysis 'pipeline' (Hammer + HistFactory)
- other implementations in development
- 3D fit of sample reweighted with Hammer to generated CLN sample
- ρ^2, R_1, R_2 correctly recovered from fit

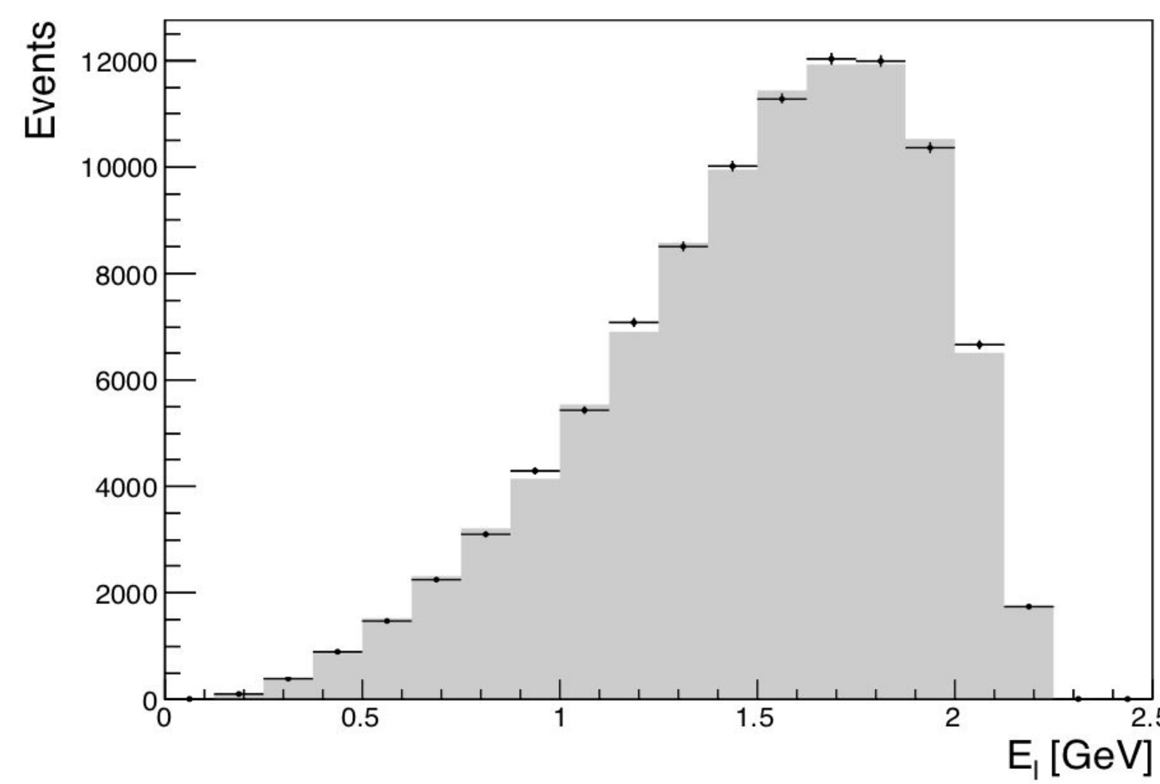
Samples were generated with RapidSim



Pseudo Data (CLN)

Reweighted sample using Hammer





Courtesy of Julian Garcia Pardinas, Simone Meloni and Patrick Owen (LHCb)

Summary

- Hints of lepton flavour universality violation in semileptonic B decays
- Identifying NP requires direct fits from experiments to NP Wilson Coefficients
- Want to provide a general purpose software tool for FF reweighting and New Physics searches - Hammer
- Many options for $B \to D^{(*)}$ (and $\Lambda_b \to \Lambda_c$) already included, more to come i.e. $B \to J/\psi, \pi, \rho, \omega, ...$

Thank you for listening!

Thanks to Julian Garcia Pardinas, Simone Meloni and Patrick Owen from LHCb for extensive Beta testing

More info on:

http://hammer.physics.lbl.gov/

Compact Expressions

- Approach: Decompose amplitudes into vector of amplitudes and NP Wilson coefficients

$$\mathcal{M} = \vec{v}[\vec{\mathcal{M}}_v]$$

- $\vec{\mathcal{M}}_v$ is independent of particular NP model!
- Linearization in Form Factors also possible

$$\vec{v}_a \mathrm{FF}_i [\vec{\mathcal{M}}_{a,i}]$$

- Construct a weight tensor $\mathcal{W} = [\mathcal{M}_{\beta,j}]^\dagger [\mathcal{M}_{\alpha,i}]$
- Event weight for arbitrary FF/NP theory is then

$$\vec{\mathrm{FF}}^\dagger \vec{v}^\dagger \mathcal{W} \vec{v} \vec{\mathrm{FF}}$$

Amplitude calculations (BLPR)

$B \to D(\tau \to \ell\nu\nu)\nu$ 1610.02045 [Ligeti, Papucci, & DR]

SM contribution

Amplitude level: SM plus all 10 NP operators:

$$\mathcal{A}_1^- = -i2\sqrt{2}V_{cb}G_F\sqrt{q^2-m_\tau^2}\Big\{\frac{1}{2}f_S(q^2)(\alpha_L^S+\alpha_R^S)\beta_L^S + \frac{f_0(q^2)(-m_B^2+m_D^2)m_\tau(1+(\alpha_L^V+\alpha_R^V)\beta_L^V)}{2q^2} + \frac{f_+(q^2)m_Bm_\tau|\boldsymbol{q}^*|(1+(\alpha_L^V+\alpha_R^V)\beta_L^V)\cos(\theta_\tau)}{q^2} - 4f_T(q^2)m_B|\boldsymbol{q}^*|\alpha_R^T\beta_L^T\cos(\theta_\tau)\Big\},$$

$$\mathcal{A}_2^- = -i2\sqrt{2}V_{cb}G_F\sqrt{q^2-m_\tau^2}\Big\{-\frac{f_+(q^2)m_B|\boldsymbol{q}^*|(1+(\alpha_L^V+\alpha_R^V)\beta_L^V)\sin(\theta_\tau)}{\sqrt{q^2}} + \frac{4f_T(q^2)m_Bm_\tau|\boldsymbol{q}^*|\alpha_R^T\beta_L^T\sin(\theta_\tau)}{\sqrt{q^2}}\Big\},$$

$$\mathcal{A}_1^+ = -i2\sqrt{2}V_{cb}G_F\sqrt{q^2-m_\tau^2}\Big\{-\frac{f_+(q^2)m_B|\boldsymbol{q}^*|(\alpha_L^V+\alpha_R^V)\beta_R^V\sin(\theta_\tau)}{\sqrt{q^2}} + \frac{4f_T(q^2)m_Bm_\tau|\boldsymbol{q}^*|\alpha_L^T\beta_R^T\sin(\theta_\tau)}{\sqrt{q^2}}\Big\},$$

$$\mathcal{A}_2^+ = -i2\sqrt{2}V_{cb}G_F\sqrt{q^2-m_\tau^2}\Big\{-\frac{1}{2}f_S(q^2)(\alpha_L^S+\alpha_R^S)\beta_R^S + \frac{f_0(q^2)(m_B^2-m_D^2)m_\tau(\alpha_L^V+\alpha_R^V)\beta_R^V}{2q^2} - \frac{f_+(q^2)m_Bm_\tau|\boldsymbol{q}^*|(\alpha_L^V+\alpha_R^V)\beta_R^V\cos(\theta_\tau)}{q^2} + 4f_T(q^2)m_B|\boldsymbol{q}^*|\alpha_L^T\beta_R^T\cos(\theta_\tau)\Big\},$$

and the $\tau \to \ell\nu\bar{\nu}_\tau$ amplitudes ($[\mathcal{B}^\ell]_{1,2}^+ = e^{i(\phi_\tau-\phi_W)}[\mathcal{B}^\ell]_{1,2}^-$)

$$[\mathcal{B}^\ell]_1^- = i2\sqrt{2}G_F\sqrt{m_\tau^2-p^2}\Big\{m_\tau\cos\frac{\theta_W}{2}\sin\theta_\ell + 2e^{i(\phi_\ell-\phi_W)}\sqrt{p^2}\cos^2\frac{\theta_\ell}{2}\sin\frac{\theta_W}{2}\Big\},$$

$$[\mathcal{B}^\ell]_2^- = -i2\sqrt{2}e^{-i(\phi_\tau-\phi_W)}G_F\sqrt{m_\tau^2-p^2}\Big\{2e^{i(\phi_\ell-\phi_W)}\sqrt{p^2}\cos^2\frac{\theta_\ell}{2}\cos\frac{\theta_W}{2} - m_\tau\sin\theta_\ell\sin\frac{\theta_W}{2}\Big\},$$

Software

Hammer is a C++ library that includes the amplitude level calculations and more

- Input MC → efficient calculational strategy computes NP-FF-generalized event weights
- Handling for multiple different, simultaneous FF parametrization choices
- Storage and (re-)generation of NP-FF-generalized histograms (ROOT compatible!)
  - very rapidly produce histograms for arbitrary NP or FF parametrizations

Scope (from manual)

III. The **Hammer** Forge
- A. From the process tree to an amplitude tensor
- B. Available vertex and edge amplitudes
- C. Including and excluding processes
- D. Form factor schemes
- E. Form factor duplication
- F. Units
- G. Processing events
- H. Retrieving event weights
- I. Setting Wilson Coefficients and FF Eigenvectors
- J. Adding and retrieving histograms
- K. Pure phase space vertices
- L. PHOTOS
- M. Rates