PROCEEDINGS OF SCIENCE

EOS – A Software for Flavor Physics Phenomenology

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I present EOS, an open-source software dedicated to a variety of tasks in the processing of flavor physics observables. EOS is written in C++ and offers both a C++ and a Python interface. It is developed for three main tasks, the production of theoretical predictions for flavor physics observables; the inference of theoretical parameters from an extensible database of likelihoods; and the production of Monte Carlo samples of flavor processes for sensitivity studies.

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1. Introduction

Recent phenomenological analyses of flavor physics show a consistent pattern of tasks. Large sets of experimental measurements are first analyzed through the prism of improved theoretical models. New measurements are then usually suggested to further test the viability of these models, in accordance to the Standard Model or in new physics scenarios. These tasks mainly require

- the production of publication-quality theory predictions for the experimental observables;
- the inference of theory parameters from an extensible database of likelihoods;
- and possibly the production of Monte Carlo samples for sensitivity studies.

`EOS`[1] [1, 2] has been developed since 2011 [3, 4] to perform these tasks and has already been used in about 30 peer-reviewed and published phenomenological studies [5–33]. Besides these applications in phenomenology, `EOS` also is used by the collaborations of the CDF [34], the CMS [35, 36] and the LHCb [37–42] experiments and is now part of the Belle II analysis framework [43].

`EOS` is not the only openly available flavor software. It competes, amongst others, with `flavio` [44], `SuperIso` [45, 46], `HEPfit` [47] and `FlavBit` [48]. The main distinctions between `EOS` and these programs are:

- the simultaneous inference of hadronic and new physics parameters;
- the modularity of hadronic matrix elements, i.e., the possibility to select from various hadronic models and parametrizations at run time;
- the production of pseudo events for sensitivity studies; and
- the implementation of QCD sum rules for the prediction of hadronic matrix elements.

`EOS` can be installed using `Python` package installer:

```
python3 -m pip install --user eoshep
```

The `EOS` `Python` module can then be accessed, e.g. within a `Jupyter` notebook, using

```
import eos
```

`EOS` documentation [2, 49] includes basic tutorials, detailed examples for advanced use, and automatically updated lists of observables, parameters and constraints.

2. Usage and examples

2.1 Predictions and Uncertainties

Observables are one of the main classes in `EOS`. They are usually defined for several theoretical models, modifiable at run time via a set of options. The numerical evaluation of observables requires a kinematic specification and a set of values for all the parameters.

[1] https://github.com/eos/eos

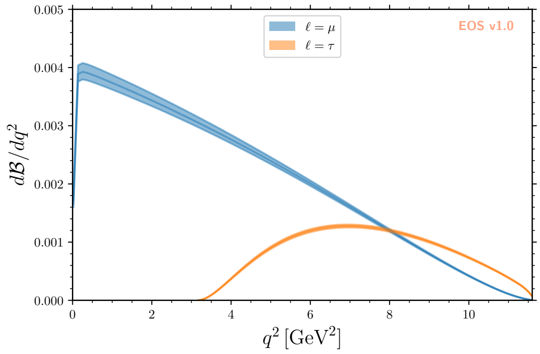

Figure 1: Differential branching ratio of $B \to D\ell\nu_\ell$ for different leptons. The uncertainty bands contain 68% of the samples obtained by varying the parametrization of the hadronic form factors.

```
eos.Observable.make('B->Dlnu::BR', eos.Parameters(),
                    eos.Kinematics({'q2_min': 0.01, 'q2_max': 11.62}),
                    eos.Options({'l': 'mu', 'model': 'SM'})).evaluate()
```

Here, the integrated branching ratio of $B \to D\mu\nu_\mu$ is evaluated between 0.01 and 11.62 GeV^2 in the Standard Model with EOS default parameters. To ensure a fast numerical evaluation of observables, EOS uses multiple threads and reuses objects that are shared between multiple observables. An updated list of built-in observables and parameters can be found in the online documentation [49].
The visualization of observables can also be performed via a versatile `matplotlib`-based [50] plotting framework. Evaluating the differential observable `B->Dlnu::dBR/dq2` for several values of q^2 yields, for example, the middle solid lines of Figure 1.

EOS bases the estimation of theory uncertainties on Monte Carlo techniques and relies on the external `pypmc` library [51]. The sampling of the probability density functions is performed using adaptive Metropolis-Hastings [52–54] and Population Monte Carlo (PMC) [55, 56] sampling. Once the user has provided the set of parameters to be varied and the experimental or theoretical likelihoods to constrain them, samples can be drawn from the joint posterior to predict uncertainties for the observables. Pursuing with the $B \to D\ell\nu$ example, the main source of uncertainty is due to the hadronic form factors that describe the $B \to D$ transition. Using the parametrization of Ref. [57] and independent constraints obtained from lattice QCD simulations by the HPQCD [58] and FNAL/MILC [59], we obtain the uncertainty band presented in Figure 1.
A list of built-in constraints can be found online [49]; new constraints can also be added via the `manual_constraints` method, as also described in the documentation.

2.2 Parameter Inference

Parameters inference is theoretically equivalent to uncertainty estimation, and both are treated in the same way in EOS. The parameters of interest are added to the list of varied parameters (which become nuisance parameters) and the experimental measurements from which parameters are to be

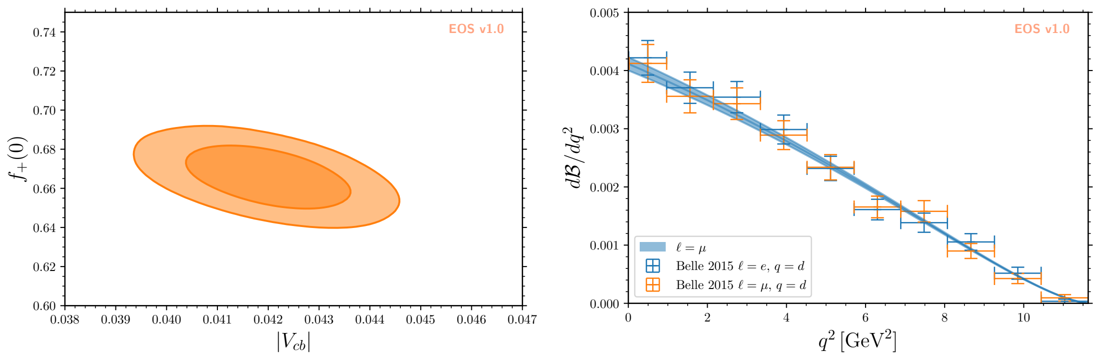

Figure 2: Inference of $|V_{cb}|$ from experimental measurements of $B \to D\ell\nu$: (left) 2D-marginal joint posterior of $|V_{cb}|$ and $f_+^{\bar{B}\to D}(0)$ (68% and 95% probability contours) and (right) juxtaposition of the bin-averaged measurements of $B \to D\ell\nu$ and the 68% uncertainty band estimated by sampling the posterior distribution.

inferred are added to the list of likelihoods. The posterior distribution of the parameters can again be explored using Monte Carlo techniques.

In the case of multimodal distributions, a single Markov chain is usually insufficient to explore the entire posterior distribution. EOS therefore implements PMC sampling, where an initial proposal distribution (obtained for example by running multiple Markov chains) is adjusted stepwise to match the posterior distribution. This allows the user to produce high quality, statistically uncorrelated samples from the posterior distribution.

For example, Belle measurements of $B \to D\ell\nu$ differential branching ratios can be used to extract the Cabibbo-Kobayashi-Maskawa matrix element $|V_{cb}|$ [60]. The posterior samples are genuine Python array and can be analyzed using EOS plotting framework as presented in Figure 1, left panel. The uncertainties obtained on $|V_{cb}|$ and on the observables include both the experimental uncertainties due to branching ratio measurements and the theoretical uncertainties due to the hadronic form factors.

2.3 Simulation of Pseudo-events

Once a model is defined, it is often useful to investigate the experimental sensitivity to new observables that show, for example, a reduced theoretical uncertainty. EOS therefore contains built-in probability density functions (PDF) from which pseudo-events can be simulated. To conclude the $B \to D\ell\nu$ example, we generate samples from the one-dimensional PDF that describes the q^2-differential decay distribution for $\ell = \mu$ and $\ell = \tau$. The samples are shown in Figure 3 overlaid with the implemented PDF for which excellent agreement is found.

3. Conclusion

EOS is a multipurpose flavor physics software. Its large and constantly growing number of built-in observables, parameters and constraints[2] allows a very wide spectrum of studies. These studies

[2]The updated lists can be found on EOS website [49]

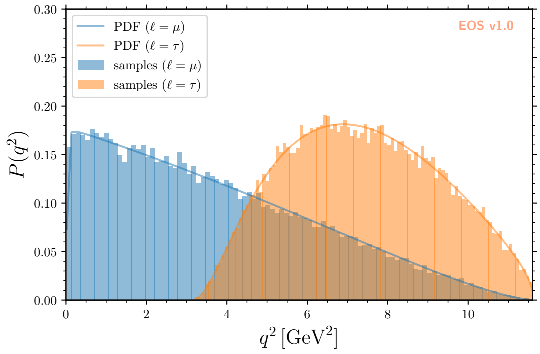

Figure 3: Distribution of $B \to D\ell\nu_\ell$ events for $\ell = \mu, \tau$, as implemented in EOS (solid lines) and as obtained from Markov Chain Monte Carlo importance sampling (histograms).

range from the inference of theory parameters from experimental measurements to sensitivity studies of new observables in new physics scenarios.
EOS developers welcome new contributors, feedback, questions and wishes on https://github.com/eos/eos.

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