`POPxf`: An Exchange Format for Polynomial Observable Predictions

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Science and Technology Facilities Council

University of Southampton

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$1 + n(n+3)/2$ monomials for n Wilson coefficients

Or functions of polynomials, *e.g.*, $BR_{i\to f} \equiv \Gamma_{i\to f}/\Gamma_{\text{tot.}}$

Current status

SMEFT parameterizations can be quite challenging to obtain

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Lots of exp/th interactions: technical expertise required

- Support for existing tools, *e.g.*, **`SMEFTsim`**, **`SMEFTatNLO`**,…
- A lot of re-inventing/re-learning the wheel involved
- Some crucial inputs use analytical results, *e.g.*, $h \to \gamma\gamma$

`POPxf`: what it does

1) Stores the monomial coefficients of a generic polynomial

2) Includes uncertainties & correlation information

- **MC, PDF, scale,…**

3) Sufficient metadata to ensure reproducibility

- **Assumptions, settings, code versions, links to documentation**

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Can help to address the aforementioned challenges

- Re-usable, community-validated parameterisations
- State of the art theory: analytic results, higher orders, latest tools
- State of the art experiment: acceptance effects, tools e.g. **`EFT2Obs`**

➡ Best predictions once-and-for-all: improved interpretations of HEP data

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Applies to a generic polynomial, not limited to SMEFT

- Additional parametric dependences can be encoded, *e.g.*, nuisance parameters

Formalism

A **`POPxf`** file encodes a set of M observable predictions, O_m

- The O_m depend on a basis of S parameters, C_s
- …via K polynomials, P_k, each characterized by polynomial coefficients, $\vec{p}_k$
- Predictions are given by observable expressions, $E_m \Rightarrow O_m = E_m(P_1, P_2, \ldots, P_K)$

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Each polynomial can be expressed as a scalar product between $\vec{p}_k$ and a vector of parameter monomials, $\vec{V}$

$$P_k = \vec{p}_K \cdot \vec{V}$$
$$= a_k + \vec{b}_k \cdot \vec{C} + \vec{c}_k \cdot \mathrm{vech}(\vec{C} \otimes \vec{C})$$

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e.g. for a quadratic polynomial $\vec{V} = \begin{pmatrix} 1 \\ \vec{C} \\ \mathrm{vech}(\vec{C} \otimes \vec{C}) \end{pmatrix}$

- Numerical values of $\vec{p}_k$ uniquely define each polynomial as functions of C_s
- C_s could be real & imaginary components of SMEFT Wilson coefficients

Use modes

In many cases O_m is itself a polynomial ($E_m = P_m$)

- *e.g.*, if O_m are cross sections
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Defined two use modes for the **`POPxf`** format

- Single polynomial (SP) and function-of-polynomials (FOP) modes
- SP dedicated to the case of observables as exact polynomials
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- Single polynomial (SP) and function-of-polynomials (FOP) modes
- SP dedicated to the case of observables as exact polynomials
- In SP the polynomial coefficients are denoted as observable coefficients, $\vec{o}_m$
- FOP predictions can be reduced to SP by Taylor expansion assuming $C_s \ll 1$
- $\vec{o}_m$ of expanded FOP predictions are intended only for evaluating uncertainties
- Allows for identical treatment of uncertainties in both modes (see backup)

`POPxf` format

Use JSON format to serialize polynomial data

- Machine & human readable
- Defined a JSON schema to simplify validation (json.schemastore.org/popxf-1.0.json)
- Correlations must be specified in separate files

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Github page www.github.com/pop-xf with several repos

- **json-schemas** : schema files containing documentation from Section 4 of note
- **parser** : python classes that read-in files & command line validator *work in progress*
- **examples** : complete examples of various use modes

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Top level fields

- **$schema** : "https://json.schemastore.org/popxf-1.0.json"
- **metadata** : contextual & structural information to interpret and reproduce predictions
- **data** : numerical values for polynomial coefficients & uncertainties

metadata

- O_m – **`observable_names`** (***required***): array of observable names;
- C_s – **`parameters`** (***required***): array of model parameters (e.g. names of Wilson coefficients);
- – **`basis`** (***required***): definition of the parameter basis, e.g. the operator basis in an EFT;
- $C_s(\mu)$ – **`scale`** (***required***): renormalisation scale at which the parameters are defined;
- – **`polynomial_names`** (***required* in FOP mode**): array of polynomial names;
- – **`observable_expressions`** (***required* in FOP mode**): Python-like expressions defining how each observable is computed from the named polynomials;
- – **`polynomial_degree`** (***optional***): the order of truncation in the parameter expansion (default: 2);
- – **`reproducibility`** (***optional***): information needed to reproduce the predictions. Array in which each element may include the following fields:
  - – **`inputs`** (***optional***): numerical values of input parameters that have been used to compute the polynomial coefficients, with optional uncertainties and correlations;
  - – **`tool`** (***optional***): information about the tools/methods used to generate the predictions;
  - – **`description`** (***optional***): text field with a summary of how the predictions were obtained.
- – **`misc`** (***optional***): free-form documentation or provenance metadata.

data

$\vec{p}_k$ – **`polynomial_central`** (***required* in FOP mode**): central values of polynomial coefficients $\vec{p}_k$ for each named polynomial P_k.

$\vec{o}_m$ – **`observable_central`** (***required* in SP mode; *optional* in FOP mode**): central values of *observable coefficients* $\vec{o}_m$, the polynomial coefficients for each observable O_m.

$\vec{\sigma}_m$ – **`observable_uncertainties`** (***optional***): uncertainties $\vec{\sigma}_m$ on the observable coefficients.

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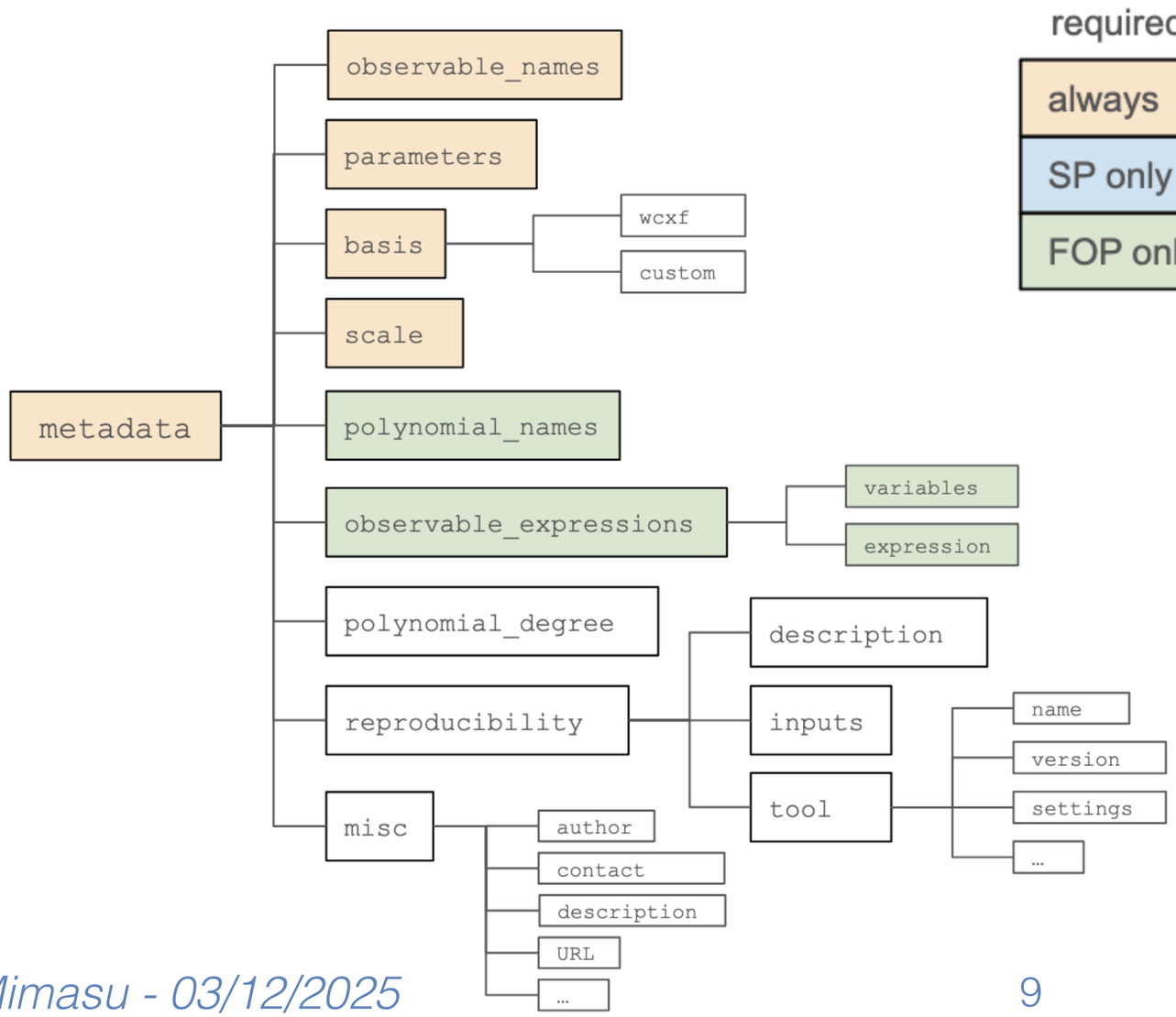

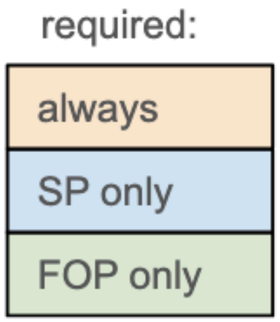

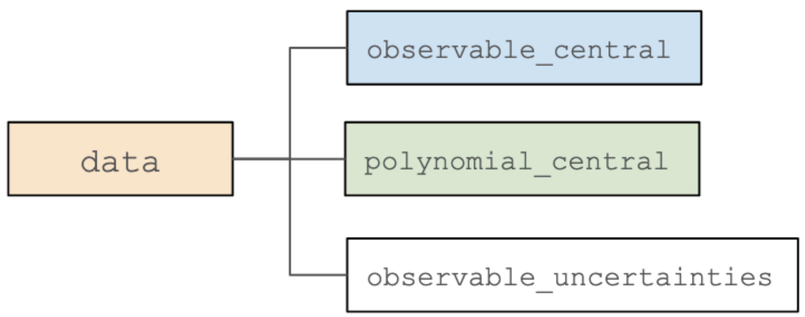

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Array with JSON objects describing ‘steps’ to get the result

- **`description`** - human readable information
- **`inputs`** - parameters with errors & correlations, Gaussian or arbitrary PDFs
- **`tool`** - details of the numerical/analytic methods employed
  - **`version`**, documentation, links,…
  - **`settings`**
    - PDFs, scale choice, phase space cuts,…
    - Conventions: schemes, approximations,…
- **`misc`** - free form additional information

Polynomial data

- `polynomial_central` $(\vec{p}_k)$
- `observable_central` $(\vec{o}_m)$
- `observable_uncertainties` $(\vec{\sigma}_m)$

Each component of the polynomial data labeled by a monomial key

- "Stringified" tuple of model parameters with length equal to **`polynomial_degree`**
- Optional real/imaginary tag to indicate which part (defaults to real)

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parameter-independent (SM)	linear	quadratic
`"('','')"`	`"('','C1')"`	`"('C1','C2')"`
`"('','','RR')"`	`"('','C1','RR')"`	`"('C1','C2','RI')"`
	`"('','C1','RI')"`	`"('C1','C2','II')"`

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Values are arrays of numbers

```
"observable_central": {
  "('', '')": [1.0, 1.1, 2.3],
  "('', 'C1')": [1.2, 1.3, 0.3],
  "('C1', 'C2')": [1.4, 1.5, 0.7],
  "('C1', 'C3')": [1.6, 1.7, 0.5]
}
```

$\Leftrightarrow$

$$O_1 = 1.0 + 1.2\,C_1 + 1.4\,C_1C_2 + 1.6\,C_1C_3\,,$$
$$O_2 = 1.1 + 1.3\,C_1 + 1.5\,C_1C_2 + 1.7\,C_1C_3\,,$$
$$O_3 = 2.3 + 0.3\,C_1 + 0.7\,C_1C_2 + 0.5\,C_1C_3\,.$$

FOP example: $R_{ij} \equiv \Gamma(W \to \ell_i \nu_i)/\Gamma(W \to \ell_j \nu_j)$

WCxf basis specification

polynomial expressions

```
"metadata": {
  "observable_names": ["Rmue(W->lnu)", "Rtaue(W->lnu)", "Rtaumu(W->lnu)"],
  "parameters": ["phil3_11", "phil3_22", "phil3_33"],
  "basis": {
    "wcxf": {
      "eft": "SMEFT",
      "basis": "Warsaw",
      "sectors": ["dB=de=dmu=dtau=0"]
    }
  },
  "polynomial_names": ["Gamma(W->enu)", "Gamma(W->munu)", "Gamma(W->taunu)"],
  "observable_expressions": [
    {
      "expression": "num / den",
      "variables": {"num": "Gamma(W->munu)", "den": "Gamma(W->enu)"}
    },
    {
      "expression": "num / den",
      "variables": {"num": "Gamma(W->taunu)", "den": "Gamma(W->enu)"}
    },
    {
      "expression": "num / den",
      "variables": {"num": "Gamma(W->taunu)", "den": "Gamma(W->munu)"}
    }
  ],
  "scale": 80.387,
  "reproducibility": [{"tool": {"name": "flavio", "version": "2.6.2"}}],
  "misc": {
    "description": "Using the (alpha, G_F, m_Z) input scheme.",
    "author": ["A. Smolkovic", "P. Stangl"]
  }
},
```

FOP example: $R_{ij} \equiv \Gamma(W \to \ell_i \nu_i)/\Gamma(W \to \ell_j \nu_j)$ continued...


```
"data": {
  "polynomial_central": {
    "('', '')": [0.227, 0.227, 0.227],
    "('', 'phi3_11')": [7737.419, -19812.903, -19812.903],
    "('', 'phi3_22')": [-19812.903, 7737.419, -19812.903],
    "('', 'phi3_33')": [0, 0, 27550.322],
    "('phi3_11', 'phi3_11')": [929672417.073, 1295705157.301, 1295705157.301],
    "('phi3_11', 'phi3_22')": [1390270692.689, 1390270692.689, 2591410314.602],
    "('phi3_11', 'phi3_33')": [0, 0, -1201139621.914],
    "('phi3_22', 'phi3_22')": [1295705157.301, 929672417.073, 1295705157.301],
    "('phi3_22', 'phi3_33')": [0, 0, -1201139621.914],
    "('phi3_33', 'phi3_33')": [0, 0, 835106881.686]
  }
}
```

SP example: $\Gamma(W \to \ell\nu)$


```
"metadata": {
  "basis": {
    "custom": {
      "eft": "SMEFT",
      "basis": "SMEFTatNLO",
      "definition": "https://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO"
    }
  },
  "scale": 80.387,
  "parameters": [ "c3pl1", "c3pl2", "cll" ],
  "observable_names": ["Gamma(W -> mu nu_m)"],
  "reproducibility": [{
    "description": "Fixed-order Monte Carlo computation.",
    "tool": {
      "name": "MadGraph5_aMC@NLO",
      "version": "3.4.1",
      "settings":{ "UFO":"SMEFTatNLO 1.0.2",  "perturbative_order":"LO" }
    },
    "inputs":{ "m_W": 80.387, "G_F": 1.1663787e-5, "m_Z": 91.1876, "Lambda":1000 }
  }],
  "misc":{
    "description":"W-boson partial width to mu nu_m [GeV], (m_W,G_F,m_Z) scheme",
    "author": ["E. Celada", "L. Mantani", "K. Mimasu"],
    "contact": "ken.mimasu@soton.ac.uk"
  }
},
```

SP example: $\Gamma(W \to \ell\nu)$ continued…


```
"data": {
  "observable_central": {
     "('', '')": [0.22729],
     "('', 'c3pl1')": [-0.0137796],
     "('', 'c3pl2')": [0.0137786],
     "('', 'cll')": [0.0137796],
     "('c3pl1', 'c3pl1')": [0.000208845],
     "('c3pl2', 'c3pl2')": [0.00020885],
     "('cll', 'cll')": [0.00020884],
     "('c3pl1', 'c3pl2')": [-0.00041769],
     "('c3pl1', 'cll')": [-0.00041768],
     "('c3pl2', 'cll')": [0.00041768]
}
```

Example: uncertainties & correlations

total, parameter dependent

```
"observable_uncertainties": {
  "total": {
    "('', '')": [0.05, 0.06, 0.01],
    "('', 'C1')": [0.1, 0.12, 0.01],
    "('C1', 'C2')": [0.02, 0.03, 0.02],
    "('C1', 'C3')": [0.05, 0.06, 0.01]
  }
}
```

breakdown

```
"observable_uncertainties": {
  "MC_stats": {
    "('', '')": [0.002, 0.0012, 0.001],
    "('', 'C1')": [0.001, 0.0015, 0.0001]
  },
  "scale": {
    "('', '')": [0.04, 0.05, 0.06],
    "('', 'C1')": [0.1, 0.12, 0.01]
  },
  "PDF": {
    "('', '')": [0.03, 0.04, 0.05],
    "('', 'C1')": [0.02, 0.08, 0.01]
  }
}
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  }
}
```

Sample correlation file

```
{
  "$schema": "https://json.schemastore.org/popxf-corr-1.0.json",
  "593771630098eb5325684131f80b4224": {
    "row_names": ["BR(Bs->mumu)", "BR(B0->mumu)"],
    "col_names": ["BR(Bs->mumu)", "BR(B0->mumu)"],
    "correlations": {
      "total":[
        [1.0, 0.407],
        [0.407, 1.0]
      ]
    }
  }
}
```

parameter-independent (SM) correlations

- Also has a JSON schema
- Many observables x many parameters
- Potential for very large files
- Alternative hdf5 format serialization for correlations

User-friendliness

```
(syspy3.11) LQPJQJXFNX:parser ken$ bin/validate-popxf -h
usage: validate-popxf [-h] [-v] [-q] [--show-data] [--show-uncertainties] input_file

Validate and parse POPxf JSON files.

positional arguments:
  input_file            Path to the POPxf JSON file to parse

options:
  -h, --help            show this help message and exit
  -v, --verbose         Print detailed information about the parsed data
  -q, --quiet           Suppress output (only show errors)
  --show-data           Display polynomial data (can be large)
  --show-uncertainties  Display uncertainty information

Examples:
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  validate-popxf input.json --verbose
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Command line validation tool

```
(syspy3.11) LQPJQJXFNX:parser ken$ bin/validate-popxf examples/Wlnu.json

======================================================================
Reading JSON file: examples/Wlnu.json
======================================================================
✓ examples/Wlnu.json is valid
======================================================================
POPxfParser Object Properties
======================================================================

Schema version: popxf-1.0.json

Mode: Function-Of-Polynomials (FOP)
Polynomial Degree: 2
Length (number of observables): 3
Observable Names: ['Rmue(W->lnu)', 'Rtaue(W->lnu)', 'Rtaumu(W->lnu)']
Parameters: ['ll_1221', 'phiD', 'phiWB', 'phil3_11', 'phil3_12', 'phil3_13', 'phil3_22', 'phil3_23', 'phil3_33']
Scale: 80.387 [GeV]
```

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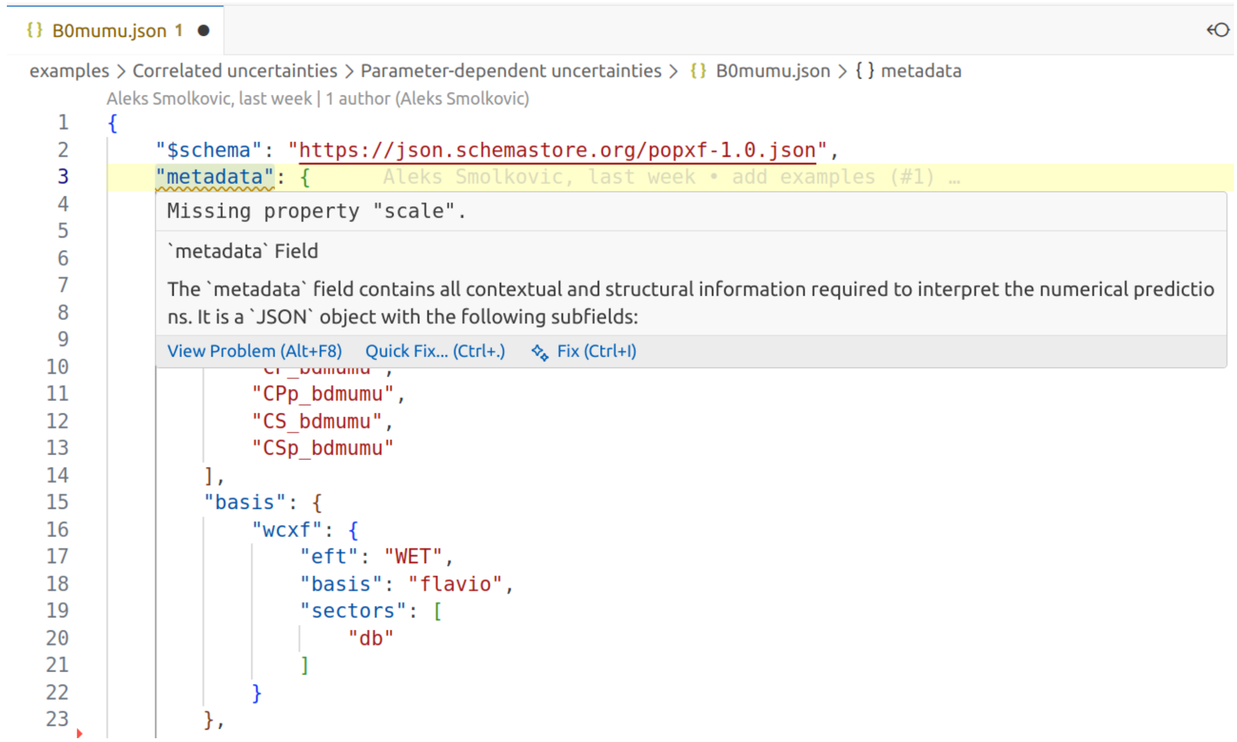
JSON schema ⇒ tooltips for standard IDEs



Outlook

POPxf will hopefully become a standard for EFT parameterisations

- Now its up to all of us to adopt it! experiment & theory (see Aleks' talk yesterday)

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- Higgs STXS (activity in WG2), EWPOs *[Mildner; 2412.07651]*, analytic results

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https://github.com/pop-xf/parser

- Final structure of the validations/parsing tools is not fixed
- More functionality planned
- Evaluating predictions, comparing files, constructing covariance matrices,…
- Conversions to/from other formats can be built from here (fitting groups, **`EFT2Obs`**,…)
- Contributions welcome!

Backup

Scale

$$O_m = a_m + \vec{C}(\mu) \cdot \vec{b}_m(\mu) + \dots$$

Common scale, μ, at which Wilson coefficients are defined

- $\vec{b}_m(\mu)$: observable is scale-independent up to higher orders

Relevant when RG effects are taken into account

- Important to document how this was done in **`reproducibility`**
- If no running is included, set the scale to the scale of the observable, *e.g.*, m_h, m_Z,…

Can be an array for multiple observables

```
"scale": 91.1876
```
common scale

```
"scale": [100.0, 200.0, 300.0, 400.0, 500.0]
```
distribution with no running included

- *restricted usage of arrays in FOP mode

Uncertainties

for details see [POPxf; 2511.17348] & [Altmanshofer & Stangl; 2103.13370]

Consider Gaussian uncertainties in the O_m

- Can be correlated and depend on the parameters
- Uncertainties on $[\vec{o}_m]_\alpha \Rightarrow [\vec{\sigma}_m]_\alpha$ and correlation matrix $[\rho_{mm'}]_{\alpha\alpha'}$

m : *observables* α : *parameter monomials* $(1, C_1, C_2, C_1C_2, \ldots)$

Correlations can be given across different POPxf files (n)

- $[\vec{\sigma}_m^{(n)}]_\alpha$ and correlation matrix $[\rho_{mm'}^{(nn')}]_{\alpha\alpha'} \Rightarrow \left[\tilde{\Sigma}_{mm'}^{(nn')}\right]_{\alpha\alpha'} = \left[\vec{\sigma}_m^{(n)}\right]_\alpha \left[\rho_{mm'}^{(nn')}\right]_{\alpha\alpha'} \left[\vec{\sigma}_{m'}^{(n)'}\right]_{\alpha'}$

parameter-dependent *parameter-independent*

$$\left[\Sigma^{(nn')}\right]_{mm'} = \sum_{\alpha,\alpha'} \left[\vec{V}(n)\right]_\alpha \left[\tilde{\Sigma}_{mm'}^{(nn')}\right]_{\alpha\alpha'} \left[\vec{V}(n')\right]_{\alpha'} \supset \left[\tilde{\Sigma}_{mm'}^{(nn')}\right]_{00}$$

- Can also specify a breakdown into different sources, *e.g.,* PDF, scale, …