ATLAS EXPERIMENT

Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

DESY

General treatment of theory uncertainties in kinematic bins

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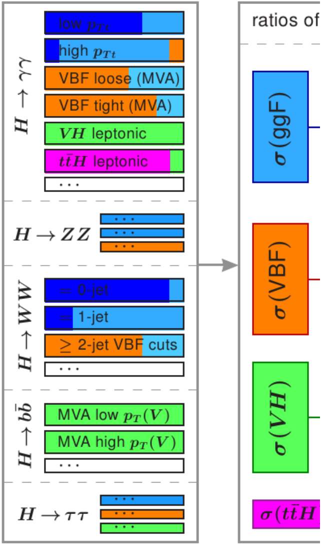
WG1 ggF subgroup meeting: uncertainties in kinematic regions

November 15, 2016

Treatment of theoretical uncertainties in Run1 coupling measurements.

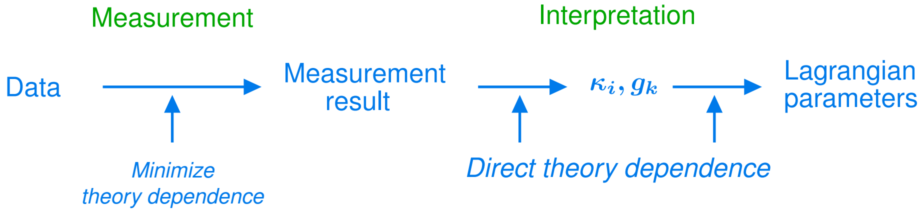
Schematically



- Higgs coupling measurements extract signal strengths (μ) or cross sections per production mode (`Run1 combination paper`)
- Main sources of theoretical uncertainty from missing higher order QCD corrections, PDFs, underlying event and parton shower modeling, Higgs BRs
- In practice estimated from variations of predicted signal yield for the different experimental event categories or global scaling of $(\sigma \cdot \mathcal{B})^{\mathrm{SM}}$
- Uncertainties implemented as nuisance parameters that can be
  - ⋆ 100% correlated (“yield”)
  - ⋆ 100% anticorrelated (“migration”)
  - ⋆ uncorrelated

  between different event categories (across decay channels)

Separating uncertainties in measurement and interpretation.



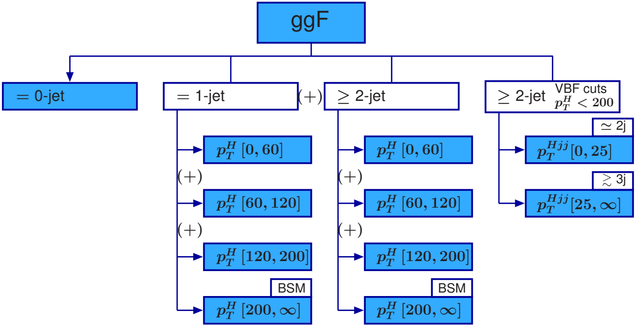
- Run1 coupling measurements: theory uncertainties folded into the measurement
  - ⋆ Cross section measurements not affected by uncertainties that are a global scaling of $(\boldsymbol{\sigma} \cdot \boldsymbol{\mathcal{B}})^{\mathrm{SM}}$
  - ⋆ Uncertainties related to event categorization (e.g. jet bins) completely entangled into measurement

$\rightarrow$ Define "intermediate layer" between data and interpretation with reduced theory dependence

  - ⋆ Improvements in theoretical predictions and uncertainties can be more easily taken advantage of

Simplified template cross sections (STXS).

- Measurement of cross sections per production mode in kinematic “bins”
- Most relevant for ggF: jet bin uncertainties, Higgs p_T shape, ggF with VBF topology (background in VBF selection)
- Reducing these uncertainties in the measurement is what guided the definitions of the bins
- Residual theoretical uncertainties related to “unfolding” experimental event categories to STXS “bins”



Treatment of theoretical uncertainties kinematic bins.

- Implementation of uncertainties (in measurement or interpretation) requires to have uncertainties per bin, and their correlations
  - ⋆ Particularly important when binning introduces source of uncertainties that affects each bin but cancels in their sum
  - ⋆ Implementation of $\pm 100\%$ correlated or uncorrelated nuisance parameters

$\longrightarrow$ Identify and distinguish different sources of uncertainties and evaluate also their corrections between kinematic bins

- Discussion follows YR4 Section 1.4.2a
  - ⋆ Use jet bins as example
  - ⋆ Single bin boundary
    - ▶ Familiar from Run1
  - ⋆ Extension to multiple bin boundaries

Single bin boundary.

- Jet bin example: split total cross section into exclusive 0-jet ($\sigma_0(p_T^{\mathrm{cut}})$) and inclusive 1-jet ($\sigma_{\geq 1}(p_T^{\mathrm{cut}})$) by $p_T^{\mathrm{jet}} \geq p_T^{\mathrm{cut}}$:

$$\sigma_{\geq 0} = \sigma_0(p_T^{\mathrm{cut}}) + \sigma_{\geq 1}(p_T^{\mathrm{cut}})$$

- Uncertainties can be described in terms of fully correlated and fully anticorrelated components:

$$C(\{\sigma_0, \sigma_{\geq 1}\}) = \begin{pmatrix} (\Delta_0^{\mathrm{y}})^2 & \Delta_0^{\mathrm{y}}\,\Delta_{\geq 1}^{\mathrm{y}} \\ \Delta_0^{\mathrm{y}}\,\Delta_{\geq 1}^{\mathrm{y}} & (\Delta_{\geq 1}^{\mathrm{y}})^2 \end{pmatrix} + \begin{pmatrix} \Delta_{\mathrm{cut}}^2 & -\Delta_{\mathrm{cut}}^2 \\ -\Delta_{\mathrm{cut}}^2 & \Delta_{\mathrm{cut}}^2 \end{pmatrix}$$

- General parametrization of a 2×2 symmetric matrix, not specific to any particular calculation or framework

- Straightforward implementation in terms of nuisance parameters κ for $\{\sigma_{\geq 0}, \sigma_0, \sigma_{\geq 1}\}$:

$$\kappa^{\mathrm{y}}: \quad \{\Delta_{\geq 0}^{\mathrm{y}},\, \Delta_0^{\mathrm{y}},\, \Delta_{\geq 1}^{\mathrm{y}}\} \qquad\qquad \kappa_{\mathrm{cut}}: \quad \{0,\, \Delta_{\mathrm{cut}}, -\Delta_{\mathrm{cut}}\}\,,$$

- Physical interpretation: (correlated) yield and (anticorrelated) migration uncertainties

Single bin boundary: application to jet bins at FO.

- No unambiguous way to identify different sources for $\boldsymbol{\Delta}^{y}$ and $\boldsymbol{\Delta}_{\mathbf{cut}}$ for fixed-order predictions
- Different frameworks make different assumptions

FO-ST

$$\boldsymbol{\Delta}_{0}^{\mathbf{y}} = \boldsymbol{\Delta}_{\geq 0}^{\mathbf{y}} = \boldsymbol{\Delta}_{\geq 0}^{\mathbf{FO}}\,, \quad \boldsymbol{\Delta}_{\geq 1}^{\mathbf{y}} = 0\,, \qquad \boldsymbol{\Delta}_{\mathbf{cut}} = \boldsymbol{\Delta}_{\geq 1}^{\mathbf{FO}}$$

- Migration uncertainty is approximated by perturbative uncertainty of $\boldsymbol{\sigma}_{\geq 1}(\boldsymbol{p}_{T}^{\mathbf{cut}})$, motivated by structure of perturbative series
- Perturbative uncertainties in $\boldsymbol{\sigma}_{\geq 0}$ and $\boldsymbol{\sigma}_{\geq 1}$ treated as independent sources

JVE

- Perturbative uncertainties of $\boldsymbol{\epsilon}_{0} = \boldsymbol{\sigma}_{0}(\boldsymbol{p}_{T}^{\mathbf{cut}})/\boldsymbol{\sigma}_{\geq 0}$ and $\boldsymbol{\sigma}_{\geq 0}$ treated as independent sources

$$\boldsymbol{\Delta}_{\geq 0}^{\mathbf{y}} = \boldsymbol{\Delta}_{\geq 0}^{\mathbf{FO}}\,, \quad \boldsymbol{\Delta}_{0}^{\mathbf{y}} = \boldsymbol{\epsilon}_{0}\,\boldsymbol{\Delta}_{\geq 0}^{\mathbf{FO}}$$

$$\boldsymbol{\Delta}_{\geq 1}^{\mathbf{y}} = (1 - \boldsymbol{\epsilon}_{0})\,\boldsymbol{\Delta}_{\geq 0}^{\mathbf{FO}}\,, \qquad \boldsymbol{\Delta}_{\mathbf{cut}} = \boldsymbol{\sigma}_{\geq 0}\,\boldsymbol{\Delta}(\boldsymbol{\epsilon}_{0})$$

Multiple bin boundaries.

- Each bin can have multiple boundaries, and each boundary can be shared by different bins
- 2×2 covariance matrix decomposition applied to any single bin boundary when all additional subdivisions are removed
- Consider binning cut “a/b” with $\sigma_{ab} = \sigma_a + \sigma_b$ and associated $\Delta^{a/b}_{\text{cut}}$ (anticorrelated between σ_a and σ_b)
- Allow for additional subbins such that $\sigma_a = \sum_i \sigma_a^i$ and $\sigma_b = \sum_j \sigma_b^j$
- Consider binning uncertainty as fully correlated among subbins and implement with a single nuisance parameter

$$\kappa^{a/b}_{\text{cut}}: \quad \Delta^{a/b}_{\text{cut}} \times \left\{\{x_a^i\}, -\{x_b^j\}\right\} \qquad \text{with} \qquad \sum_i x_a^i = \sum_j x_b^j = 1$$

  where x_a^i and x_b^j specify how $\Delta^{a/b}_{\text{cut}}$ gets distributed among the subbins
- Consider each binning cut/bin boundary as source for migration cut
- In addition, one or more correlated yield uncertainties

Multiple bin boundaries: example.

- 3 mutually exclusive jet bins: $\{\sigma_0, \sigma_1, \sigma_{\geq 2}\}$
- Identify 2 boundaries: $\sigma_{\geq 0} = \sigma_0 + \sigma_{\geq 1}$ and $\sigma_{\geq 1} = \sigma_1 + \sigma_{\geq 2}$
- Nuisance parameters for five observables $\{\sigma_{\geq 0}, \sigma_0, \sigma_{\geq 1}, \sigma_1, \sigma_{\geq 2}\}$

$$\kappa^{\mathrm{y}}: \quad \{\Delta^{\mathrm{y}}_{\geq 0}, \Delta^{\mathrm{y}}_{0}, \Delta^{\mathrm{y}}_{\geq 1}, \Delta^{\mathrm{y}}_{1}, \Delta^{\mathrm{y}}_{\geq 2}\} \quad \text{with}$$

$$\Delta^{\mathrm{y}}_{\geq 0} = \Delta^{\mathrm{y}}_{0} + \Delta^{\mathrm{y}}_{\geq 1}\,, \qquad \Delta^{\mathrm{y}}_{\geq 1} = \Delta^{\mathrm{y}}_{1} + \Delta^{\mathrm{y}}_{\geq 2}$$

$$\kappa^{0/1}_{\mathrm{cut}}: \quad \Delta^{0/1}_{\mathrm{cut}} \times \{0, 1, -1, -(1-x_1), -x_1\}$$

$$\kappa^{1/2}_{\mathrm{cut}}: \quad \Delta^{1/2}_{\mathrm{cut}} \times \{0, x_2, -x_2, 1-x_2, -1\}$$

  - ⋆ x_1 determines how $\Delta^{0/1}_{\mathrm{cut}}$ is split between σ_1 and $\sigma_{\geq 2}$
  - ⋆ x_2 determines how $\Delta^{1/2}_{\mathrm{cut}}$ is split between σ_0 and σ_1

- Independent of particular theory framework, and maintains interpretation in terms of underlying physical sources
  - ⋆ Allows to judge correlations between different observables
  - ⋆ Associate each source with one nuisance parameter