Uncertainties in Monte-Carlo Event Generation

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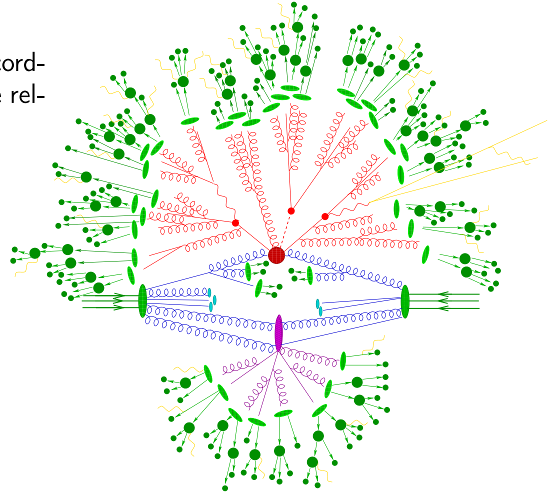
THE ROYAL SOCIETY

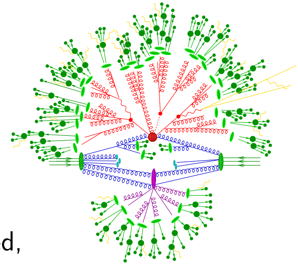
Overview

Factorise into event stages according to characteristic scales, use relevant approximation in each regime

- Hard scattering
- Parton evolution
- Multiple interactions
- Hadronisation
- Hadron decays
- QED corrections



Uncertainties in theoretical predictions



Parametric uncertainties

- reflect dependence on input parameters
  $\rightarrow$ PDFs, couplings, masses, etc.

Perturbative uncertainties

- reflects the fact that perturbation theory is used, both in the fixed-order calculation or the resummation, large-N_c in the parton shower, etc.
  $\rightarrow$ neglected higher-order terms

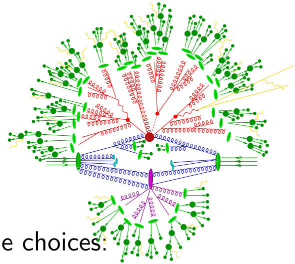
Algorithmic uncertainties

- reflects that choices are made in the implementation of the resummation/parton shower
  $\rightarrow$ evolution variable, non-singular terms, recoil strategy, matching & merging scheme, ...

Modelling uncertainties

- related to incomplete models of non-perturbative physics processes

… and how to estimate them



Parametric uncertainties

- assess through variation of input parameters within limits given by existing data

Perturbative uncertainties

- use that full result must be independent of scale choices:
  renormalisation & factorisation scales
  resummation scales / profile scales / …
  → can always only capture scale-dependent terms, never scale-independent ones

Algorithmic uncertainties

- implement different algorithms
  → always a discrete variation
  → tricky as algorithm development takes up the majority of the time

Modelling uncertainties

- if we knew how physics works in this regime …

Perturbative uncertainties

Matrix element

- scattering amplitudes in fixed-order expansion, LO, NLO, NNLO
- effects from missing higher-orders assessed through μ_R variation

PDFs

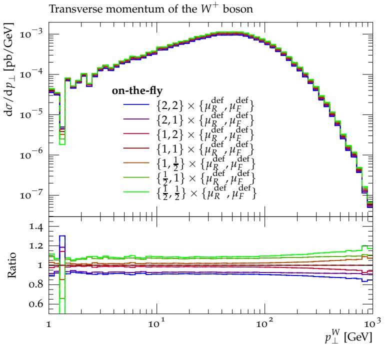
- evolution kernels in a fixed-order expansion, LO, NLO, NNLO
- effects from missing higher-orders assessed through μ_F variation

Parton shower

- evolution kernels in a fixed-order expansion, LO, (NLO)
- effects from missing higher-orders assessed through $(\mu_R^{\text{PS}}, \mu_F^{\text{PS}})$ var
- effects from res. boundary assessed through starting scale variation
- many algorithmic choices that affect the result

Matrix-elements (incl. PDF)

- typically comb. (μ_R, μ_F) var
- conventional variation by factor 2 (excl. extremes) $\rightarrow$ 7-point var
- no statistical interpretation $\rightarrow$ typically choose envelope
- central value distinguished only by authors' bias

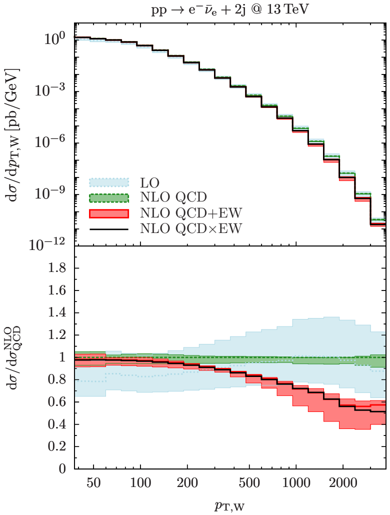


can only capture scale-dependent terms, never scale-independent ones

$\rightarrow$ scale-independent shifts of the central value are possible

The electroweak sector

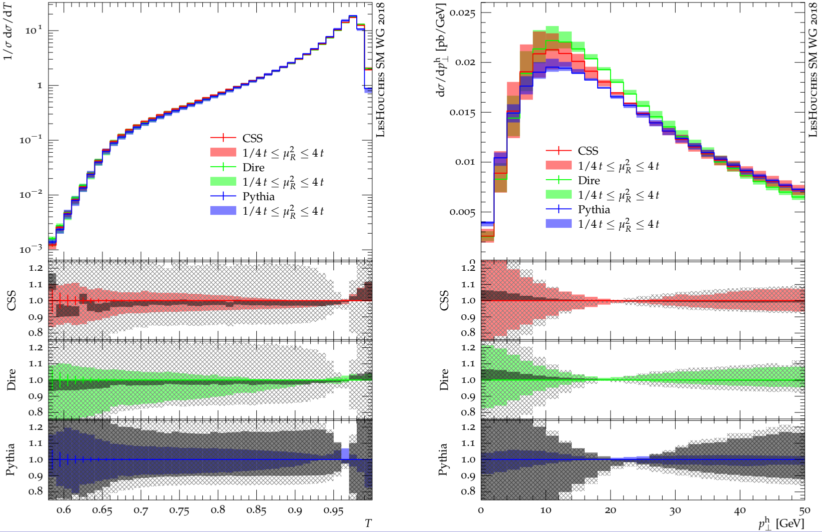
- EW sector typ. renormalised on-shell or at fixed scale
  → EW correction typically has no μ_R dependence (except when it includes QCD corrs. to lower order Born)
- $\mathcal{O}(\alpha_s\alpha)$ unc. through NLO QCD+EW vs. NLO QCD×EW
- $\mathcal{O}(\alpha^2)$ unc. through scheme dependence or comparison with exp. Sudakov limit in TeV regime



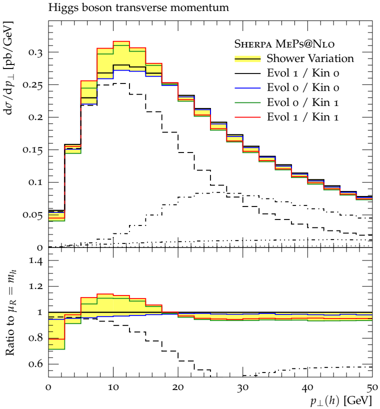
Parton showers

- ongoing effort to increase the perturbative accuracy of the PS
- higher-order splitting function does not automatically mean higher-logarithmic-order resummation, but is one ingredient
- all major parton shower in HERWIG, PYTHIA, and SHERPA offer on-the-fly reweighting of $(\mu_R^{\mathrm{PS}}, \mu_F^{\mathrm{PS}})$, PDF and $\alpha_s(m_Z)$
- shower starting scale variations accessible only through rerunning as phase space is altered
- many algorithmic choices: evolution variable, recoil scheme, inclusion of subleading effects

Parton showers



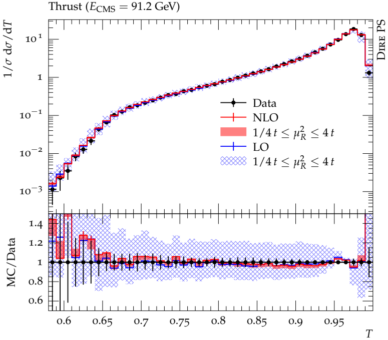
Parton showers



Algorithmic uncertainties

- two different choices of evolution variable
- two different choices of recoil scheme
- non-continuous variation, no statistical interpretation

Parton showers



- LO PS vs. LO+NLO$_{\text{coll}}$
- usual uncertainty reduction
- very similar central values due to decades of experiences with algorithmic choices in PS w/ LO kernels, but LO nature betrayed by uncs

Parametric uncertainties

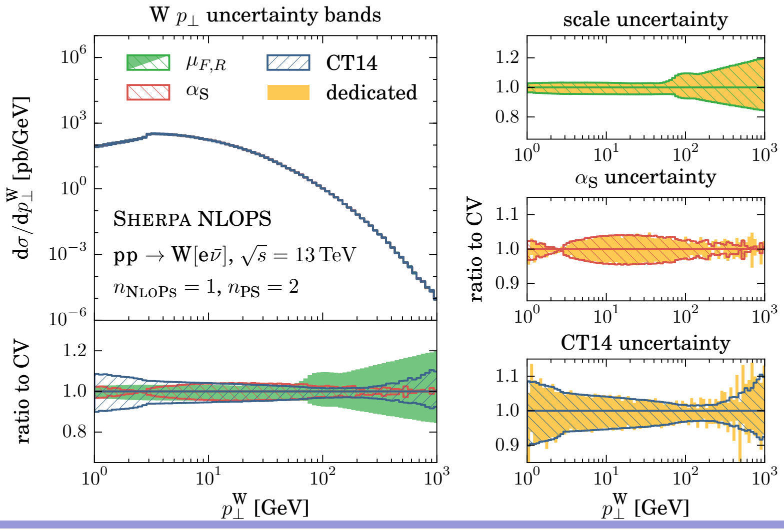
Main sources:

- uncertainties in model parameters
  - $\alpha_s(m_Z)$, $\alpha(m_Z)$, G_F, ..., f_π, hadronic form factors, ...
  - m_W, m_Z, m_h, m_t, m_b, ..., Γ_W, Γ_Z, Γ_h, Γ_t, Γ_b, ..., m_ρ, ..., Γ_ρ, ...
- non-perturbative inputs
  - PDF at reference scale
  - fragmentation function at reference scale

Uncertainty assessment:

- PDFs/FFs and couplings lead to different event weights with identical kinematics
  $\rightarrow$ can be reweighted, use same formalism as for pert. uncs
- masses and widths also lead to different event kinematics
  $\rightarrow$ no reweighting possible, need to be regenerated

Parametric uncertainties



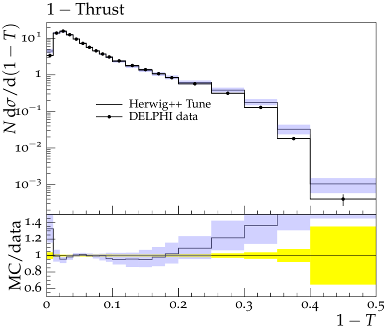
Uncertainties in non-perturbative models

This relates mostly to hadronisation and multiple interaction modelling. Since these are mostly physics inspired parametrisations of measured data with tuned parameters, the uncertainty estimate amounts to estimating the uncertainty of the tuning.

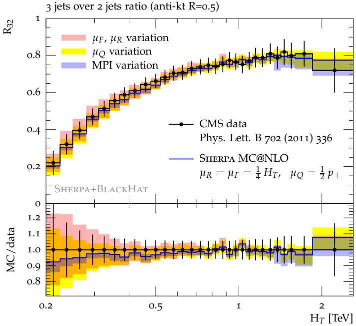
$\rightarrow$ conceptually the same as PDF/FF uncertainty
$\rightarrow$ every tune comes with a set of eigentunes along the independent directions of its χ^2 minimisation
$\rightarrow$ available from PROFESSOR

Some debate on whether to correlate or decorrelate with perturbative uncertainties.

Uncertainties in non-perturbative models



full eigentunes



simplified vars

Contrary to PDF uncs., they cannot be assessed on-the-fly, owing to the fully differential nature of the MC. Thus, the number of eigentunes induced by the large parameter space make a full variation impractical. Dedicated simplified estimates need to be studied in detail where needed.

Improving non-perturbative modelling uncertainties

Example: Softish jet production at high eta.
Typically, underlying event measurements are restricted to central region where there is tracking data, particle ID etc. The models (multiple interactions, beam remnant hadronisation) are (mostly) tuned here. In the forward region they extrapolate with the physics biases of the authors. Can effect many otherwise inconspicuous observables like m_{jj} due the occasional production of just-hard-enough forward activity.

Similar to PDFs at very high/very low x, but worse.

Only way out at the moment, define sufficiently all-encompassing dataset (which should be as free of perturbative physics as possible) to tune models to such that all measurements that depend on non-perturbative modelling need to interpolate, not extrapolate.

Conclusions

- many perturbative uncertainties can be assessed through on-the-fly reweighting (large development efforts in recent years)
- some parametric non-perturbative uncertainties can also be assessed through on-the-fly reweighting
- anything else (most algorithmic, some parametric non-perturbative and all tuning non-perturbative uncertainties) need to be assessed through rerunning
- open questions/debates about how to correlate the different sources of uncertainties
- **most uncertainties do not have a statistical interpretation**
  exception: PDF and tuning uncertainty
  $\rightarrow$ no clear way of combining, prejudice-driven recipes
  (not a statistical problem, but rather one of modelling)

Backup