Modeling of Theoretical Uncertainties

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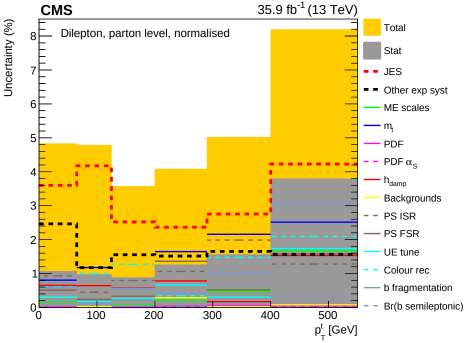
Introduction

- Theoretical uncertainties play an important role in Higgs/Top measurements and their interpretations (and for searches where the corresponding processes are important backgrounds)
- $t\bar{t}(+X)$ is particularly challenging from a QCD standpoint (complex final state, gluon induced, lots of radiation)

Introduction

- A few issues which have already been discussed this week to be expanded on:
  - Two-point vs parameterized modeling uncertainties
  - Correlations of QCD uncertainties between processes and phase space
  - Connection with statistical treatment/interpretation
  - PDF uncertainties
- Summary of some related discussions for precision electroweak measurements and PDF fits

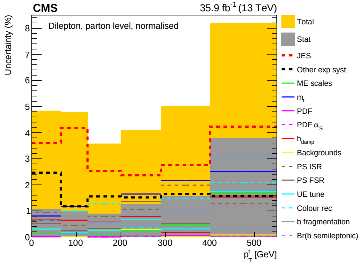
$t\bar{t}$ Modeling Uncertainties



arXiv:1811.06625 (CMS $t\bar{t}$ dilepton)

- Signal modeling treatment in $t\bar{t}$ measurements covers some of the issues present in $t\bar{t}(+X)$ as background in searches/other measurements
- Here is an example from CMS with Powheg+Pythia8 nominal MC sample with a relatively fine-grained breakdown of theory uncertainties

$t\bar{t}$ Modeling Uncertainties



arXiv:1811.06625 (CMS $t\bar{t}$ dilepton)

- **Parametrized Uncertainties:** ME scales, m_t, h_{damp}, PS ISR, PS FSR (PS scales), UE tune (vary tune parameters), PDF+α_S (NNPDF3.0 replicas), b fragmentation (Bowler-Lund model uncertainties)
- **2-point (or N-point) variations**: Colour reconnection (alternate models) B branching fractions (PDG vs pythia values), b fragmentation (Peterson vs Bowler-Lund model)

- Aside: PDF uncertainty including correlations across phase space and processes is straightforward to determine from MC replicas or eigenvectors and straightforward to include in (profile) likelihood fits with eigenvectors

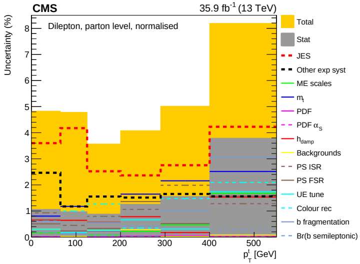
$t\bar{t}$ Modeling Uncertainties

	Uncertainty source	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta G_{e\mu}/G_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	$\Delta\sigma^{\text{fid}}_{t\bar{t}}/\sigma^{\text{fid}}_{t\bar{t}}$ (%)
	Data statistics				0.44	0.44
$t\bar{t}$ mod.	$t\bar{t}$ generator	0.38	0.05	0.05	0.43	0.10
	$t\bar{t}$ hadronisation	0.24	0.42	0.25	0.49	0.67
	Initial/final-state radiation	0.30	0.26	0.16	0.45	0.41
	$t\bar{t}$ heavy-flavour production	0.01	0.01	0.26	0.26	0.26
	Parton distribution functions	0.44	0.05	-	0.45	0.07
	Simulation statistics	0.22	0.15	0.17	0.22	0.18

arXiv:1910.08819 (ATLAS $t\bar{t}$ dilepton)

- ATLAS measurement here also using Powheg+Pythia8 as baseline, with different, but related treatment of theory uncertainties
- **Parametrized Uncertainties:** heavy flavour production (b multiplicity reweighting), Initial/Final state radiation (PS α_s, h_{damp}, ME scales), PDFs (NNPDF3.0 replicas),
- **2-point variations:** generator (Powheg+Pythia8 vs aMC@NLO+Pythia8), hadronisation (Powheg+Pythia8 vs Powheg+Herwig7)

$t\bar{t}$ Modeling Uncertainties



	Uncertainty source
	Data statistics
$t\bar{t}$ mod.	$t\bar{t}$ generator
	$t\bar{t}$ hadronisation
	Initial/final-state radiation
	$t\bar{t}$ heavy-flavour production
	Parton distribution functions
	Simulation statistics

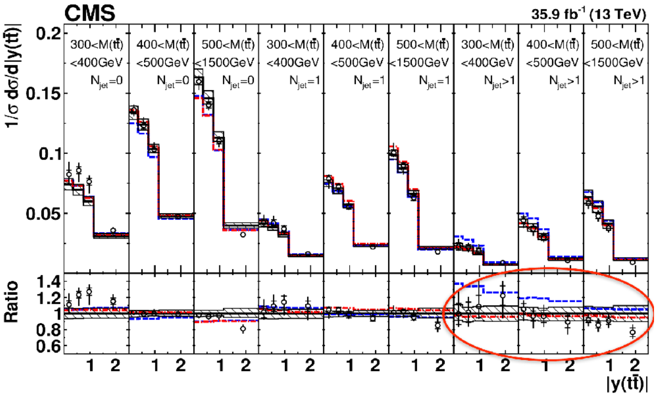
- ME generator 2-point comparison may partly cover uncertainties related to ME renormalization/factorization scale variations and h_{damp} variation (differences and Powheg vs mc@NLO matching schemes should be beyond NLO accuracy)
- Hadronisation 2-point comparison (Pythia vs Herwig) also implies different shower and UE models/tunes
- Variation of heavy flavour production via b multiplicity reweighting at least partly related to variations of final state shower renormalization/factorization scales, which change rate of gluon splitting

2-point vs Parameterized uncertainties

- Parametrized uncertainties allow a finer-grained breakdown, may give a more sensible correlation model depending on how well motivated the parameterization is
- Uncertainties can be underestimated if the model does not have enough degrees of freedom or variations are too small
- Correlations may be problematic and constraints in profile likelihood fits difficult to interpret in case of unphysical parameterizations (e.g. QCD scales...)

2-point vs Parameterized uncertainties

- 2-point uncertainties may account for multiple effects and/or may double count other uncertainties
- Size of difference can be partly "random" especially when comparing models with many degrees of freedom which may have been tuned differently
- Correlation model across phase space/bins can be unphysical, constraints in profile likelihood fits difficult to interpret
- Coarse grained systematics more likely to be spuriously overconstrained in profile likelihood fits
- 2-point uncertainties can account for intrinsic differences between models which may not be accessible by parameter variations
- May also cover additional not-explicitly-accounted-for effects



⇨ 'POW+PYT' provides best description

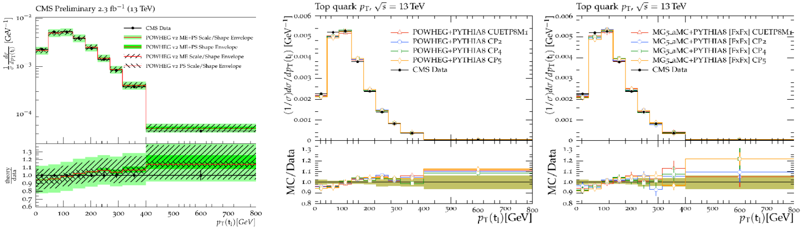
⇨ 'POW+HER' predicts too many events with N_{jet}>1

- Difference between Pythia and Herwig in the $N_{jet} > 1$ region in this case ∼ entirely depends on shower tuning

2-point vs Parameterized uncertainties

- **Ideal world:**
  - Each model/prediction is accompanied by a comprehensive and robust parameterization of its uncertainties
  - Different models/predictions are consistent with each other within those uncertainties $\rightarrow$ 2-point comparisons become a (successful) cross-check and do not imply any additional systematic uncertainty
  - **More systematic comparisons along these lines are needed!**

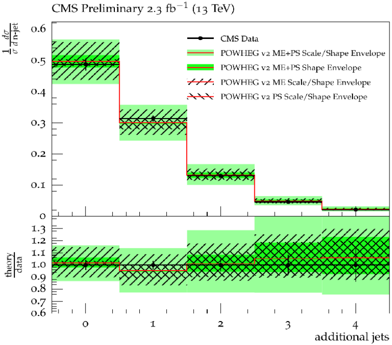
Example: ME Generator Comparison vs Scale variations



CMS-TOP-16-021, arXiv:1903.12179 (CMS Gen Tuning Paper)

- One might conclude from these plots that ME+PS scale variations are sufficient to cover difference between Powheg and aMC@NLO (in this case the uncertainty is mostly from the ME scale variations)
- Aside: This is another case where "canceling" the ME scale variations for normalized distributions (ie treating uncertainty as fully correlated in exclusive vs inclusive phase space) would lead to a large reduction in the uncertainty

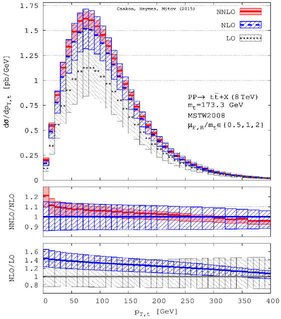
ME vs Parton Shower Scale variations

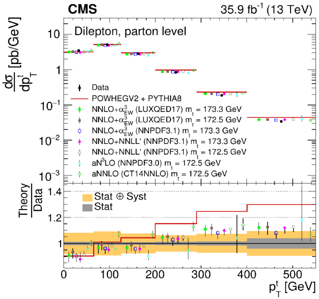


arXiv:1903.12179

- Related to discussion yesterday, here is an example where adding parton shower scale variations on top of POWHEG ME scale variations results in increasing uncertainty with additional jet multiplicity

Correlation of QCD Uncertainties Across Phase Space: p_T^t

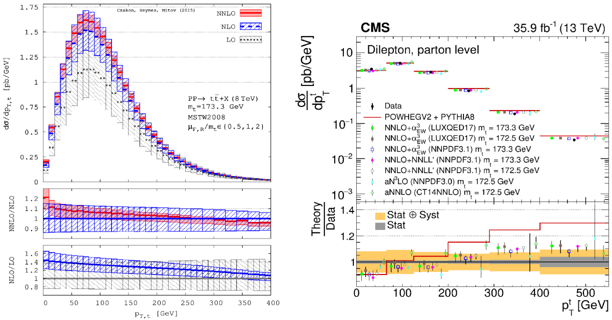




arXiv:1511.00549, arXiv:1811.06625 (CMS $t\bar{t}$ dilepton)

- Uncertainty bands typically make no statement about the correlation of the uncertainties between different regions of phase space/bins in the distribution
- Reading the left plot agnostically, no problem, LO→NLO→NNLO fully consistent
- Naively cancelling uncertainties for normalized distribution could strongly underestimate the uncertainty?

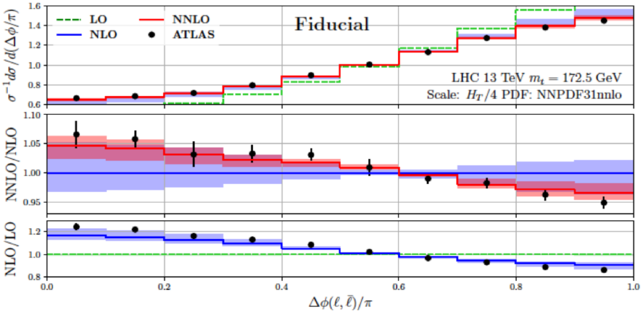
Correlation of QCD Uncertainties Across Phase Space: p_T^t



arXiv:1511.00549, arXiv:1811.06625 (CMS $t\bar{t}$ dilepton)

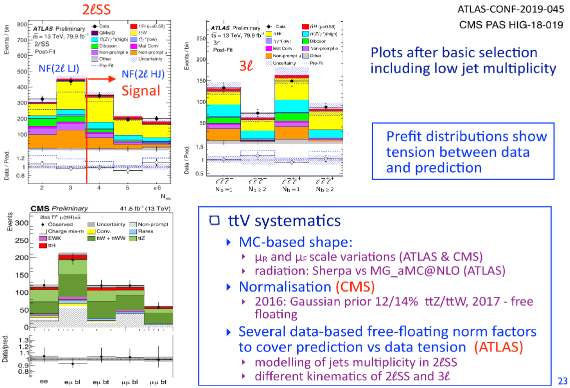
- Reading the left plot agnostically, no problem, LO→NLO→NNLO fully consistent, but no well defined prescription to generate the change in slope
- Could resort to ad-hoc treatments like uncorrelated bin-by-bin missing higher order uncertainties or polynomial expansion within the envelope (but hard to extend beyond a single distribution)

Correlation of QCD Uncertainties Across Phase Space: $\Delta\phi(\ell\ell)$



- An agnostic interpretation of the correlations on these bands could also conclude that NLO is perfectly fine within the uncertainties

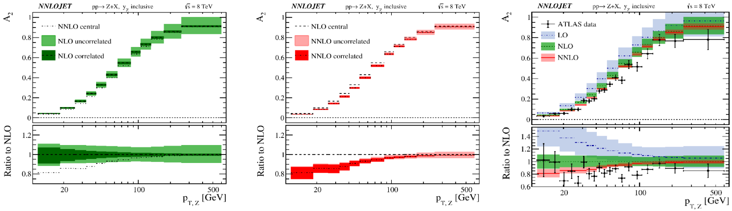
Ad-hoc uncertainties to deal with phase space correlations



E. Shabalina

- ATLAS treatment here of additional free parameters in different signal/control regions for ttW can be thought of as an ad-hoc decorrelation of the theory uncertainties in order to be sufficiently conservative

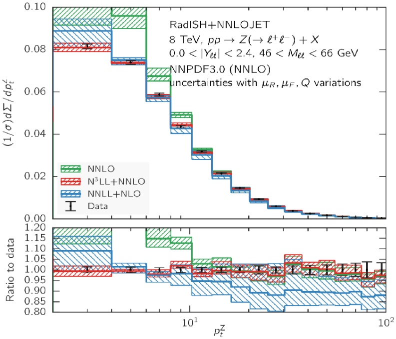
Correlation of scale variations for normalized quantities



arXiv:1708.00008

- Angular coefficients in Drell Yan production are computed as projections of lepton kinematics onto spherical harmonics divided by total cross section
- A similar ambiguity for computing uncertainties arises as for normalized cross sections (whether scale variations should be correlated or uncorrelated between numerator and denominator)
- In this particular case the authors opted for the uncorrelated treatment as the nominal

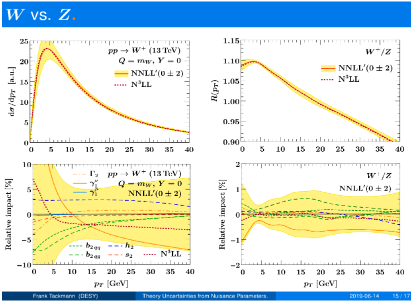
Related Discussion for Precision Electroweak Measurements



arXiv:1805.05916

- Very precise theoretical predictions of p_T^Z, p_T^W and their ratio needed for precise m_W measurements at LHC
- Theoretical predictions becoming increasingly precise, but lack of well-defined correlation model across phase space and between Z and W still problematic

Beyond Scale Variations?



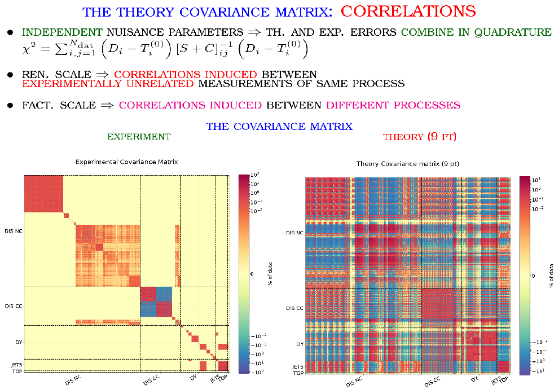
F. Tackmann

- Some interesting work ongoing to have a better-defined correlation model at least for the resummation-related uncertainties in this case

Theory Uncertainties in Global Fits

- Global EFT fits will require a coherent treatment of theoretical uncertainties on the predictions across many processes and phase space regions
- Correlations of uncertainties across processes and phase space likely critical
- Global PDF fits in principle face a similar issue
- Missing higher order uncertainty so far neglected there, assuming that NNLO QCD accuracy is sufficient compared to other uncertainties
- Work towards including missing higher order uncertainties in global PDF fits e.g. arXiv:1906.10698 from the NNPDF collaboration

Theory Uncertainties in PDF Fits

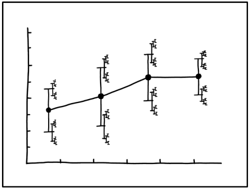


S. Forte

- Somewhat arbitrary choices are required for correlation model (in this case, renormalization scale is correlated across all bins within groups of similar processes (DIS NC, DIS CC, DY, JET, TOP)

Conclusions

- Theoretical uncertainties play a critical role in many measurements/searches/interpretations e.g. in the top sector
- Better parameterized uncertainty models are needed to fully understand and/or replace 2-point uncertainties
- In particular for predictions/interpretations/fits across different phase space regions, accurate modeling of correlations for uncertainties is an important and difficult problem (and this has already contributed to difficulties in interpreting e.g. top p_T discrepancy with MC)
- Issue likely to become even more critical for global EFT(+parameter extraction+PDF) fits
- More accurate predictions and Monte Carlo generators obviously help



I DON'T KNOW HOW TO PROPAGATE ERROR CORRECTLY, SO I JUST PUT ERROR BARS ON ALL MY ERROR BARS.