MCgrid: projecting NLO calculations on grids

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Based on: Hartland, Del Debbio, S. arXiv:1312.4460

Motivation

Enormous progress in NLO QCD calculations

- calculations largely automated
- incorporate virtual MEs in MC frameworks

⇝ OLP: BlackHat, OpenLoops, GoSam, ...

⇝ MC: MadGraph, Helac, Sherpa

based on subtraction approaches (Catani–Seymour, Frixione–Kunszt–Signer)

⇝ large number of new calculations possible/available

NLO the new standard for LHC analyses/phenomenology

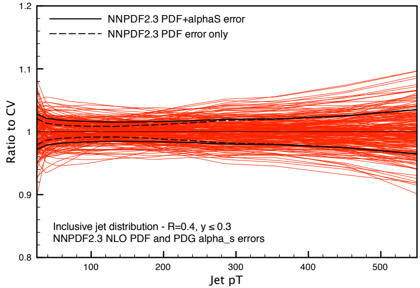
⇝ need to estimate theoretical uncertainties

⇝ inclusion in PDF fits

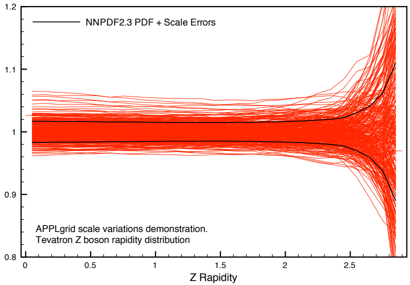
Motivation: Estimating theoretical uncertainties

- estimates for PDF fit dependence, account for error sets/replicas
- dependence on $\alpha_S(M_Z)$
- variations of scales μ_R and μ_F

inclusive jets @ LHC



Drell-Yan @ Tevatron



$\rightsquigarrow$ need for hundreds of repeated calculations

Parameter variations in MC calculations

Changing QCD parameters becomes a space–time trade-off

- direct calculation by re-running simulation (time)
- store full event record and reweight events (space)

$\rightsquigarrow$ re-running prohibitive for high statistics/complicated processes

$\rightsquigarrow$ reweighting is the way to go in practise

$$\sigma^{\mathrm{MC}} = \sum_{e=1}^{N_{\mathrm{evt}}} w_e(Q_e^2, \alpha_S(Q_e^2)) f_e^{(1)}(x_e^{(1)}, Q_e^2) f_e^{(2)}(x_e^{(2)}, Q_e^2)$$

$\rightsquigarrow$ need to express PDF & parameter dependence explicitly

Parameter variations in MC calcs: event files

Need for detailed event information

- trivial at the leading-order
- more complicated PDF dependence in NLO calcs
- express dependence on scale logarithms

$\rightsquigarrow$ SHERPA provides ROOT `Ntuple` format [Bern et al. arXiv:1310.7439]

- allows for very general variations, including functional form of scales
- provides additional weight information, i.e. `urs_wgts`
- widely used by BLACKHAT, NJET, ...

Process	`Ntuples`
$W^{\pm}(\to e^{\pm}\overset{(-)}{\nu}) + 0, 1, 2$ jets	B001, I001, R001, V001
$W^{\pm}(\to e^{\pm}\overset{(-)}{\nu}) + 3$ jets	B001, I001, R001, V001–V002
$W^{-}(\to e^{-}\bar{\nu}) + 4$ jets	B001, I001, R001, V001
$W^{+}(\to e^{+}\nu) + 4$ jets	B001, I001, R001–R005, V001
$Z(\to e^{+}e^{-}) + 0, 1, 2$ jets	B001, I001, R001, V001
$Z(\to e^{+}e^{-}) + 3$ jets	B001, I001, R001, V001–V002
$Z(\to e^{+}e^{-}) + 4$ jets	B001, I001–I003, R001–R006, V001–V006
n jets $(n = 1, 2, 3, 4)$	B001, I001, R001, V001

$\rightsquigarrow$ potentially lots of storage space, can be too slow for certain applications

Parameter variations in MC calcs: cross section grids I

Alternative approach: interpolating cross section grids

- replace convolution with PDFs by sum over interpolated version
- interpolate PDFs on finite size x_i, Q^2 grids

$$f(x, Q^2) = \sum_{\alpha=0}^{N_x} \sum_{\tau=0}^{N_Q} f(x_\alpha, Q^2_\tau) \mathcal{I}^{(\alpha)}(x) \mathcal{I}^{(\tau)}(Q^2)$$

$\rightsquigarrow$ cross section represented by simple sum

$$\sigma^{\mathrm{MC}} = \sum_{e=1}^{N_{\mathrm{evt}}} \sum_{\alpha,\beta=0}^{N_x} \sum_{\tau=0}^{N_Q} f^{(1)}(x_\alpha, Q^2_\tau) f^{(2)}(x_\beta, Q^2_\tau) \mathcal{I}^{(\alpha)}(x_e^{(1)}) \mathcal{I}^{(\beta)}(x_e^{(2)}) \mathcal{I}^{(\tau)}(Q^2_e) w_e$$

$\rightsquigarrow$ can store the table of perturbative coefficients at LO, NLO in α_S

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$\rightsquigarrow$ APPLGRID [Carli et al. arXiv:0911.2985] and FASTNLO [Kluge et al. hep-ph/0609285] tools

- very quick re-evaluation of specific cross sections, crucial for PDF fits
- small grid files $\mathcal{O}(10\mathrm{MB})$, Root format for APPLGRID
- allows for fully general PDF and α_S variations
- multiplicative scale variations, CM energy changes
- limited by availability of grids, need for interfaces to (new) MC generators

Parameter variations in MC calcs: cross section grids II

Interpolating cross section grids: anatomy

- keep track of perturbative order
- individual grids for distinct initial state flavor combinations

⇝ most general flavor basis: $11 \times 11 = 121$ grids

⇝ option to identify equivalent processes, e.g. for LHC jet production

$$
\begin{aligned}
\mathrm{gg}:\quad F^{(0)}(x_1, x_2; Q^2) &= G_1(x_1)G_2(x_2)\\
\mathrm{qg}:\quad F^{(1)}(x_1, x_2; Q^2) &= \left(Q_1(x_1) + \overline{Q}_1(x_1)\right) G_2(x_2)\\
\mathrm{gq}:\quad F^{(2)}(x_1, x_2; Q^2) &= G_1(x_1) \left(Q_2(x_2) + \overline{Q}_2(x_2)\right)\\
\mathrm{qr}:\quad F^{(3)}(x_1, x_2; Q^2) &= Q_1(x_1)Q_2(x_2) + \overline{Q}_1(x_1)\overline{Q}_2(x_2) - D(x_1, x_2)\\
\mathrm{qq}:\quad F^{(4)}(x_1, x_2; Q^2) &= D(x_1, x_2)\\
\mathrm{q\bar{q}}:\quad F^{(5)}(x_1, x_2; Q^2) &= \overline{D}(x_1, x_2)\\
\mathrm{q\bar{r}}:\quad F^{(6)}(x_1, x_2; Q^2) &= Q_1(x_1)\overline{Q}_2(x_2) + \overline{Q}_1(x_1)Q_2(x_2) - \overline{D}(x_1, x_2)
\end{aligned}
$$

- lacking a method to automatically identify minimal flavor basis
- fully exclusive MC generators produce event in the full flavor basis

The MCgrid ansatz

projecting event weights on APPLGRID tables

- supplemented HEPMC event record with additional weights in `HepMC::WeightContainer` object

$\rightsquigarrow$ keep track of event's full PDF dependence

- hand over event to RIVET to analyse and select event final states
- project kinematics on cross section/observable bin
- consistent fill of corresponding APPLGRID objects
- automatic generation of minimal subprocess basis, uses SHERPA's process mapping files

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implementation issues

- implemented and tested for SHERPA
- allows for multiple Catani–Seymour dipole integrated dipoles per σ_I event

⇝ most general PDF dependence, cf. ROOT Ntuple format

- supposed to work for other (N)LO generators that feature HEPMC output
- build as simple analysis plugins to RIVET

The MCgrid ansatz: implementation I

APPLGRID enhanced RIVET analyses: analysis init phase

- book grids along with corresponding histograms

```
// Book histograms
_h_yZ = bookHisto1D(2, 1, 1);
// Set up grid architecture
MCgrid::gridArch arch(50,1,5,0);
// Subprocess PDF
const string PDFname = "MCgrid_CDF_2009_S8383952.config";
MCgrid::bookPDF(PDFname, histoDir(), MCgrid::BEAM_PROTON,
MCgrid::BEAM_ANTIPROTON);
// Book APPLgrids
_a_yZ = MCgrid::bookGrid(_h_yZ, histoDir(), PDFname, 0, 1E-5,
1, 8315.18, 8315.18, arch);
```

The MCgrid ansatz: implementation II

APPLGRID enhanced RIVET analyses: analysis phase

- fill grids along side with the histograms

```
// Classify APPL event
MCgrid::PDFHandler::HandleEvent(event);
// Event selection & cuts, observable calculation
...
// Fill histograms and grids
_h_yZ->fill(yZ, weight);
_a_yZ->fill(yZ,event);
```

The MCgrid ansatz: implementation II

APPLGRID enhanced RIVET analyses: analysis phase

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```
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MCgrid::PDFHandler::HandleEvent(event);
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```
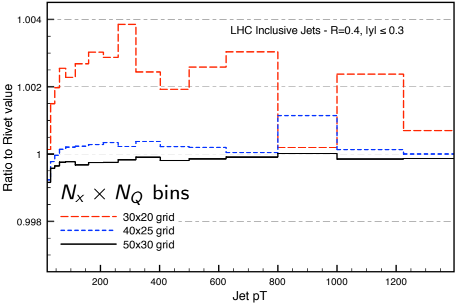

APPLGRID enhanced RIVET analyses: finalize phase

```
// Normalize histograms & grids
scale(_h_yZ, crossSection()/sumOfWeights());
_a_yZ->scale(crossSection()/sumOfWeights());
// Export APPLgrids
_a_yZ->exportgrid();
```

Reproducing the input cross section

inclusive jets @ LHC

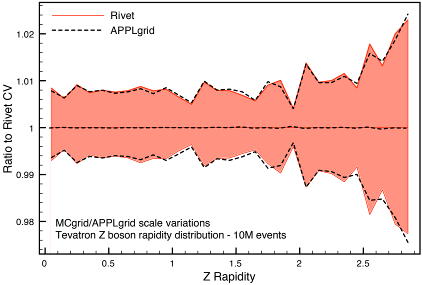


- test coarser and finer grid binning in x & Q^2
- reproduction of input cross section at permille accuracy ✓
- re-calculation within *ms* ✓

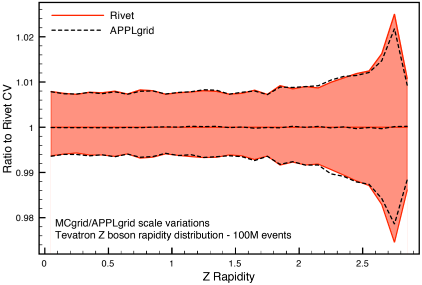
Reproducing scale variations: Drell-Yan @ Tevatron

- scale variations via APPLGRID & compared to direct calc
- assume $\mu_R = \mu_F$, variation by factors 2 & 0.5
- test statistics dependence

10M events



100M events



The MCgrid ansatz: validation II

Reproducing scale variations: Drell-Yan @ Tevatron

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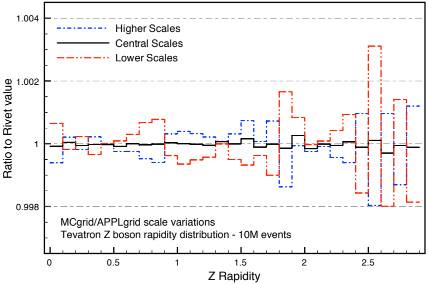
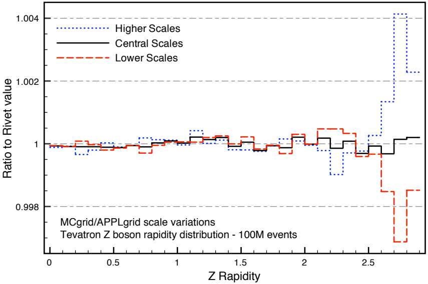


100M events



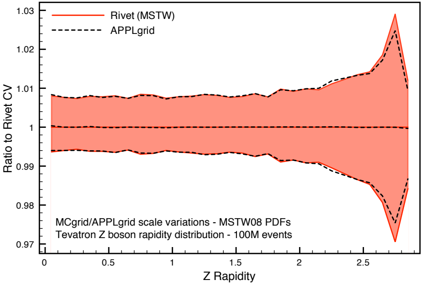
$\leadsto$ scale dependence determination agrees within permille level ✓

The MCgrid ansatz: validation III

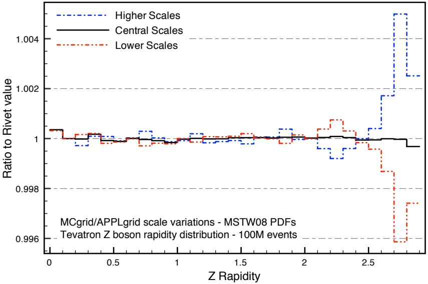
Reproducing PDF changes: Drell-Yan @ Tevatron

- detailed check of PDF variations by changing from CT10 to MSTW08
- grid produced with CT10 PDF
- re-convoluted with MSTW08, compared to straight MSTW08 simulation

scale variations



ratios

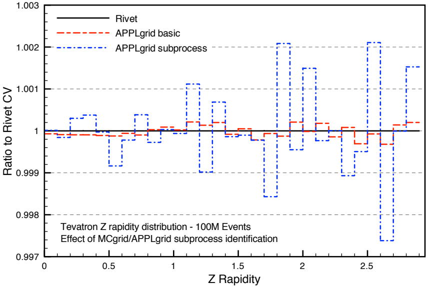


$\rightsquigarrow$ PDF dependence properly accounted ✓

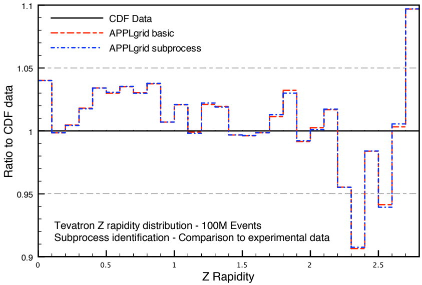
Subprocess identification: Drell-Yan @ Tevatron

- compare full set of partonic processes to subprocess identification

ratio to Rivet



ratio to data



⇝ subprocess identification works, has improved statistics ✓

⇝ smaller grids, faster convolution for subprocesses basis ✓

Summary & Outlook

MCgrid: projecting NLO cross sections on grids

- use of RIVET for projecting event kinematics on observable bin
- fill APPLGRID objects for given analysis observables
- automatic determination of subprocess flavor basis
- relying on standard HEPMC event record, largely generator independent

$\rightsquigarrow$ fast uncertainty evaluation, incorporate NLO in PDF fits

still to come

- repository of pre-produced grid files
- translation script for existing `Root` Ntuples
- attempt to include resummation/parton shower effects

`http://mcgrid.hepforge.org/`