fastNLO

Tutorial

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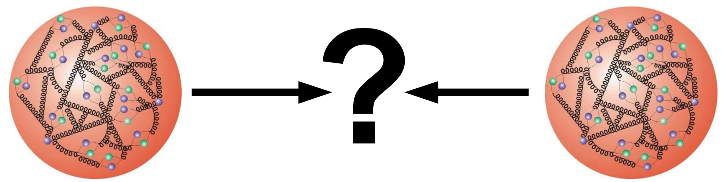
Outline



- Introductory Part
  - Motivation
  - General Concept and Application Overview
  - Application to Jet Analysis at LHC
  - News/Outlook
- Tutorial Part
  - Walk-through of Installation
  - Demonstration of Example Evaluation
  - Code Explanation
- Exercise: Your Turn for at least 45 min !!!

Disclaimer

- This is not meant as a report giving all the latest details on the fastNLO development!
- For this you can go for example to the fastNLO web page at http://fastnlo.hepforge.org and check Daniels presentation at the QCDatLHC 2012 conference
- My aims for the tutorial today are much more modest and concentrate on a simple application example

FastNLO at HepForge

PHYSICS AT THE TERA SCALE
Helmholtz-Alliance

FastNLO - Hepforge - SeaMonkey

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Proton Structure in ... | FastNLO – Hepforge

FastNLO is hosted by Hepforge, IPPP Durham

fastNLO

fast pQCD calculations for hadron-induced processes

Home | Documentation | Interactive | Code | Links

Documentation

Last update: 12. 10. 2012
- recent talks added, more info to come.

fastNLO publications, articles and proceedings

- D. Britzger, K. Rabbertz, F. Stober, M. Wobisch, "New features in version 2 of the fastNLO project", in the proceedings of the XX International Workshop on Deep Inelastic Scattering (DIS12), 26-30th March 2012 hep-ph/1208.3641.
- D. Britzger, T. Kluge, K. Rabbertz, F. Stober, M. Wobisch, "Theory-Data Comparisons for Jet Measurements in Hadron-Induced Processes", arXiv:1109.1310.
- T. Kluge, K. Rabbertz, M. Wobisch, "Fast pQCD calculations for PDF fits", in proceedings "14th International Workshop on Deep Inelastic Scattering (DIS 2006), 20-24 Apr 2006", hep-ph/0609285.

Talks on fastNLO v2

- D. Britzger, H1 Collaboration Meeting, Munich, Germany, September 2012, "fastNLO for Jetproduction in Diffractive DIS", (slides)
- D. Britzger, QCD@LHC Conference, East Lansing, MI, USA, August 2012: (slides)
- D. Britzger, DIS12 Conference, Bonn, Germany, March 2012, "New features in version 2 of the fastNLO project", (slides)
- K. Rabbertz, HERAFitter Users Meeting, Marseille, France, February 2012: (slides)

Motivation

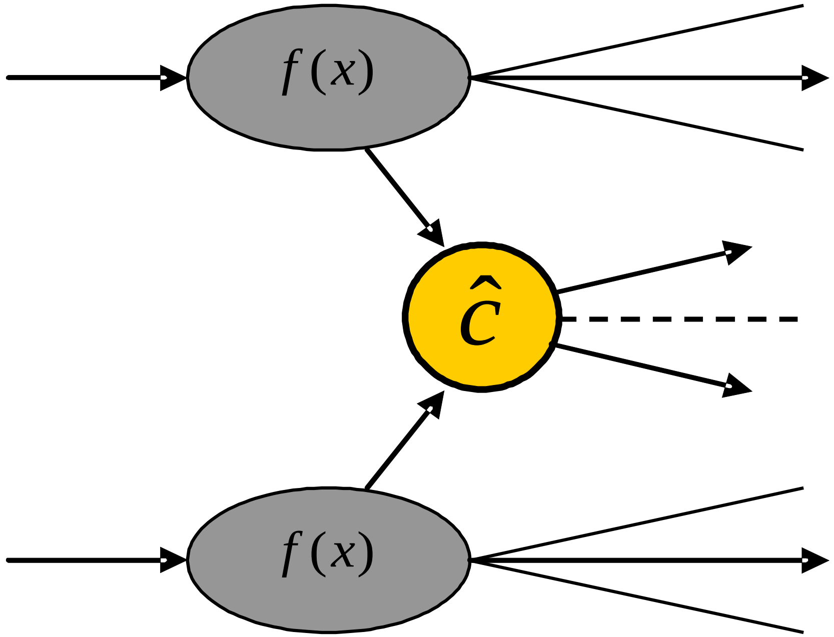
- Interpretation of experiment data relies on:
  - Availability of reasonably fast theory calculations
  - Often needed: Repeated computation of same cross section
- Examples for a specific analysis:
  - Estimate accuracy of perturbative QCD (scale uncertainties)
  - Use of various PDFs (CTEQ, MSTW, NNPDF, HERAPDF, AB(K)M …)
  - Determine PDF uncertainties (PDF error sets)
  - Use data set in fit of PDFs and/or $\alpha_s(M_Z)$
- Sometimes NLO predictions can be computed fast
- But some are very slow, esp. jets, O(1000 CPU h)
- Need procedure for fast repeated computations of NLO cross sections
- Even more so at NNLO when available!

Jet Cross-Sections

- **Jet production in hadron-hadron collisions depends on**

$$\sigma = \sum_{a,b,n} \int_0^1 dx_1 \int_0^1 dx_2 \alpha_s^n(\mu_r) \cdot c_{a,b,n}(x_1, x_2, \mu_r, \mu_f) \cdot f_{1,a}(x_1, \mu_f) f_{2,b}(x_2, \mu_f)$$

- **strong coupling α_s to order n**
- **PDFs of two hadrons f_1, f_2**
- **Parton flavors a, b**
- **perturbative coefficients $c_{a,b,n}$**
- **renormalization and factorization scales**
- **Parton momentum fractions x**



PDF and α_s are external input

Perturbative coefficients are independent from PDF and α_s

Idea: Avoid folding integrals and factorize the PDFs and α_s

The fastNLO concept

Use interpolation kernel

- Introduce set of n discrete x-nodes, x_i's being equidistant in a function f(x)
- Take set of Eigenfunctions $E_i(x)$ around nodes x_i

→ Interpolation kernels

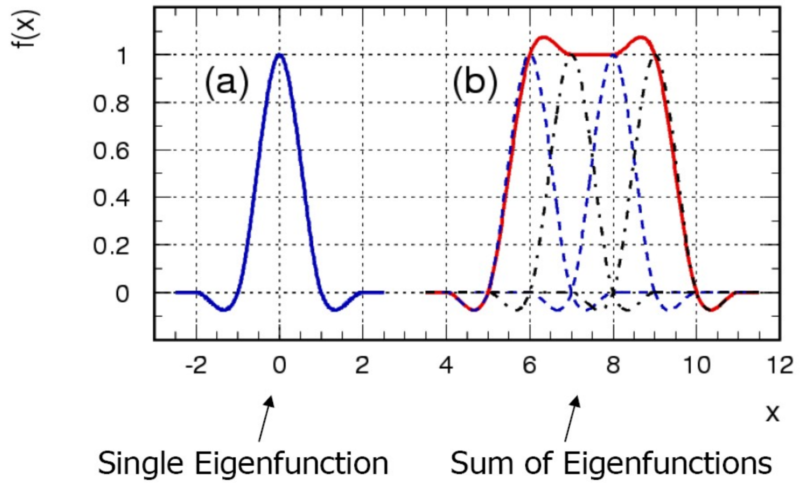
- Actually a rather old idea, see e.g.
  C. Pascaud, F. Zomer (Orsay, LAL), LAL-94-42

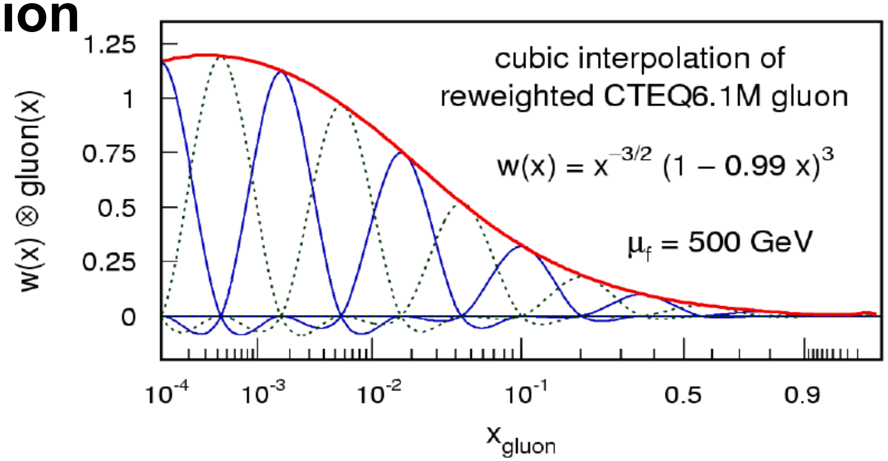
→ Single PDF is replaced by a linear combination of interpolation kernels

$$f_a(x) \cong \sum_i f_a(x_i) \cdot E^{(i)}(x)$$

→ Then the integrals are done only once

→ Afterwards only summation required to change PDF





Store a table with the convolution of the pert. coefficients with the interpolation kernel

Remarks

- In detail a bit more complicated. For each observable bin:
  - Cubic interpolation in x (also used in digital imaging)
  - 2-dimensional binning in (log) x for hh collisions
  - Use reasonable number of x nodes and lower x limit
  - Interpolate reweighted PDFs for improved approximation
  - Scale bins also need interpolation
  - Exploit symmetries between different QCD subprocesses
  - Many optimizations done to keep table small and programs fast
- Strategy applicable in general, NOT restricted to NLO or jets or ...
- Here: Concentrate on jets with NLOJet++ and fastNLO
- Assume that the APPLGRID tutorial covers e.g. other processes

NLOJet++, Z.Nagy, PRD68 2003, PRL88 2002

Partonic Subprocesses

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- Don't want to deal with 13 X 13 PDFs
- For hh → jets **seven** relevant partonic subprocesses

$$
\begin{array}{llcll}
1) & gg & \Rightarrow & \text{jets} & \propto H_1(x_1,x_2) \\
2) & qg,\bar{q}g & \Rightarrow & \text{jets} & \propto H_2(x_1,x_2) \\
3) & gq,g\bar{q} & \Rightarrow & \text{jets} & \propto H_3(x_1,x_2) \\
4) & q_iq_j,\bar{q}_i\bar{q}_j & \Rightarrow & \text{jets} & \propto H_4(x_1,x_2) \\
5) & q_iq_i,\bar{q}_i\bar{q}_i & \Rightarrow & \text{jets} & \propto H_5(x_1,x_2) \\
6) & q_i\bar{q}_i,\bar{q}_iq_i & \Rightarrow & \text{jets} & \propto H_6(x_1,x_2) \\
7) & q_i\bar{q}_j,\bar{q}_iq_j & \Rightarrow & \text{jets} & \propto H_7(x_1,x_2)
\end{array}
$$

- Need only seven linear combinations H_i of PDFs

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Symmetries

- In addition, symmetries can be exploited:

$$\begin{aligned} H_n(x_1, x_2) &= H_n(x_2, x_1) \quad \text{for} \quad n = 1, 4, 5, 6, 7 \\ H_2(x_1, x_2) &= H_3(x_2, x_1) \end{aligned}$$

- For hadron anti-hadron collisions, replace:

$$\begin{aligned} H_4(x_1, x_2) &\leftrightarrow H_7(x_1, x_2) \\ H_5(x_1, x_2) &\leftrightarrow H_6(x_1, x_2) \end{aligned}$$

- Minimize required table size and computing time!
- Otherwise number of bins in observable times x_1-, x_2-, μ-nodes, … can quickly get huge

hh Jet Cross-Section with fastNLO

Hadron-hadron collisions
- 2D interpolation kernels

$$E^{(i,j)}(x_1,x_2)=E^{(i)}(x_1)E^{(j)}(x_2)$$

$$\sum_{a,b}^{13\times 13} f_{1,a}(x_1,\mu_f)\, f_{2,b}(x_2,\mu_f) \rightarrow \sum_{k}^{7} H_k(x_1,x_2,\mu_f)$$

Final fastNLO cross sections
- Compute σ-table in each bin and store it in fastNLO table

$$\tilde{\sigma}_{k,n}^{(i,j)(m)} = \sigma_{k,n}(\mu)\otimes E^{(i,j)}(x_1,x_2)\otimes E^{(m)}(\mu)$$

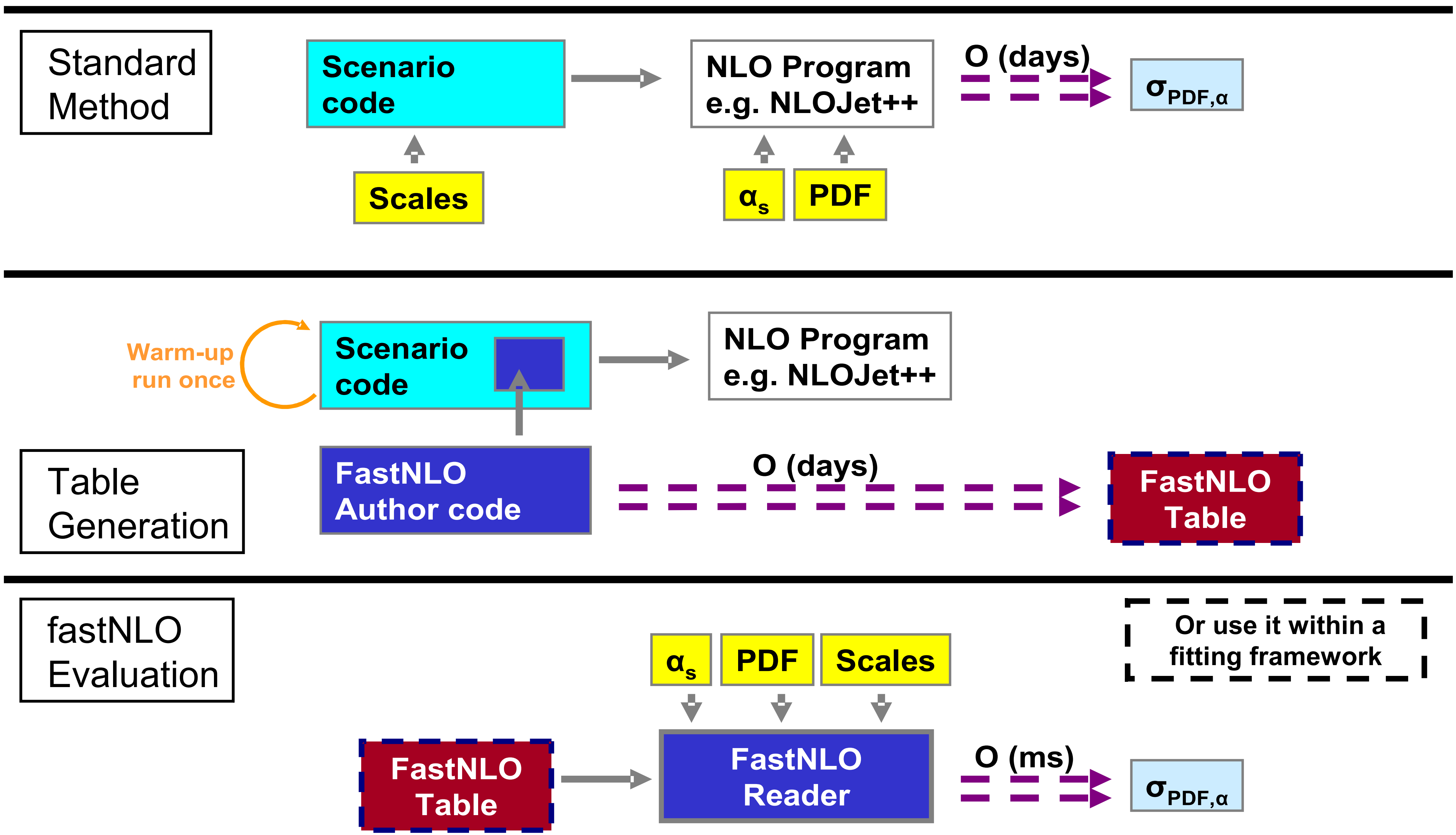
- Contains all information on the observable

Final cross section formula $$\sigma_{hh}^{Bin} = \sum_{i,j,k,n,m} \alpha_s^n(\mu^{(m)})\cdot H_k(x_1^{(i)},x_2^{(j)},\mu^{(m)})\cdot\tilde{\sigma}_{k,n}^{(i,j)(m)}$$

Table Production

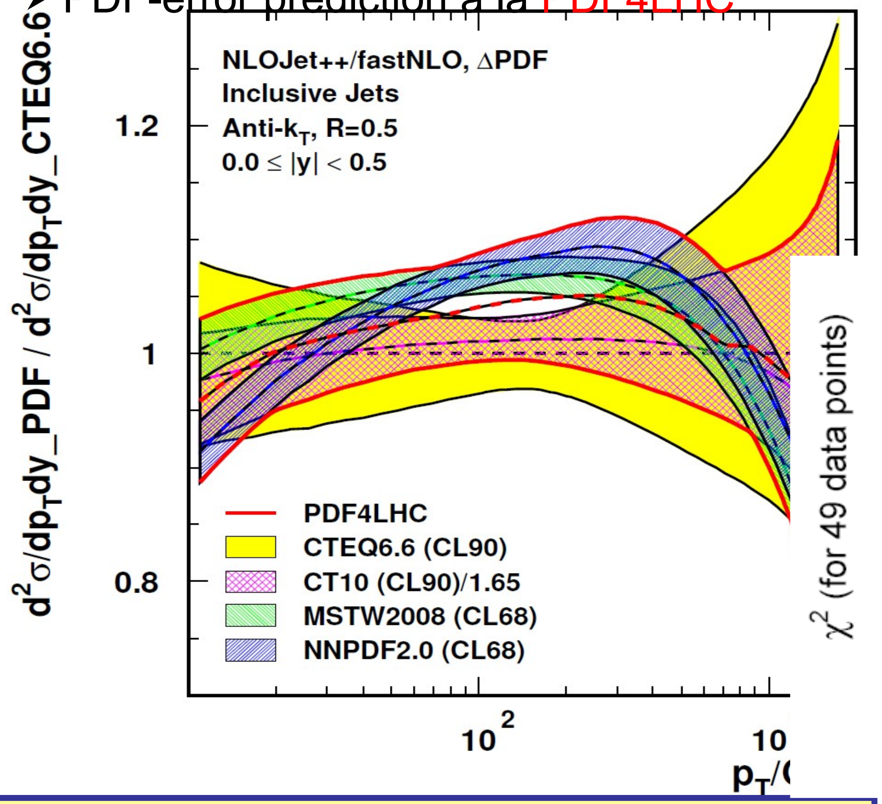
- Not the topic of today's tutorial, somewhat too involved for that
- If somebody wants to try talk to Daniel or me for code and instructions; needs fastNLO, fastjet, slightly mod. NLOJet++.
- Here the general scheme:
  - Program the C++ code for your process, selection and observable (easy when it can be almost copied from existing scenarios)
  - Run a number of NLO jobs to determine lower x and scale limits for each observable bin → to be used in future jobs
  - Do some comparison jobs between original NLOJet++ and rederived fastNLO x sections to make sure the approximation is fine (deviations below permille level or even less); if not start again optimizing settings :-(
  - Start large scale production, i.e. submit O(some 100) jobs on the grid or a batch system in parallel → order of n 1000 CPU hours to harvest
  - Possible to get all tables within a day, fastNLO is set up to combine all the statistically independent calculations into one table
  - As a bonus one gets an estimate of the statistical precision

Conceptual Overview



Example Applications

- **CMS inclusive jets**
  - Study of PDF dependence
  - Determination of PDF envelopes
  - PDF-error prediction à la PDF4LHC



239 repeated NLO calculations

D0 three-jet invariant mass
- Study of PDF dependence
- Study of scale dependence
  $\mu_r = \mu_f = (p_{T1} + p_{T1} + p_{T1})/3$
  $\mu = 2.0 \times \mu_0$
  $\mu = 0.5 \times \mu_0$
- Study of α_s dependence using α_s dependent PDF sets

PLB 704 (2011) 434-441

3138 repeated NLO calculations

Each rederivation takes fractions of a second!

New in fastNLO Version 2.0

- **Features of pre-computed fastNLO tables**
  - Automatic adjustment of phase space boundaries
  - Flexible # x-nodes for analysis bins
  - Improved interpolation in ren./fact. scales
  - Arbitrary number of dimensions for binning of observable

FastNLO Table

- **Features of fastNLO reading tools**
  - α_s evolutions provided via
    - 2-,3-,4-loop iterative solution
    - Interface to external α_s evolutions, e.g. LHAPDF, QCDNUM, …
    - Interface to CrunDec (B. Schmitt, M. Steinhauser, KIT)
  - Interface to PDFs/evolution from LHAPDF and QCDNUM
  - Easy implementation of new interfaces
  - Easy to install (autotools)
  - Easy to implement in fitting codes and to interface PDFs
  - Independent C++ and Fortran versions
    - agreement at double precision $O(10^{-10})$

FastNLO Reader

Reader_f

Reader_cc

- **Pre-release version fastnlo_reader_2.1.0_1273 for this tutorial today!**

No further dependencies (No ROOT, No CERNLIB, etc…)

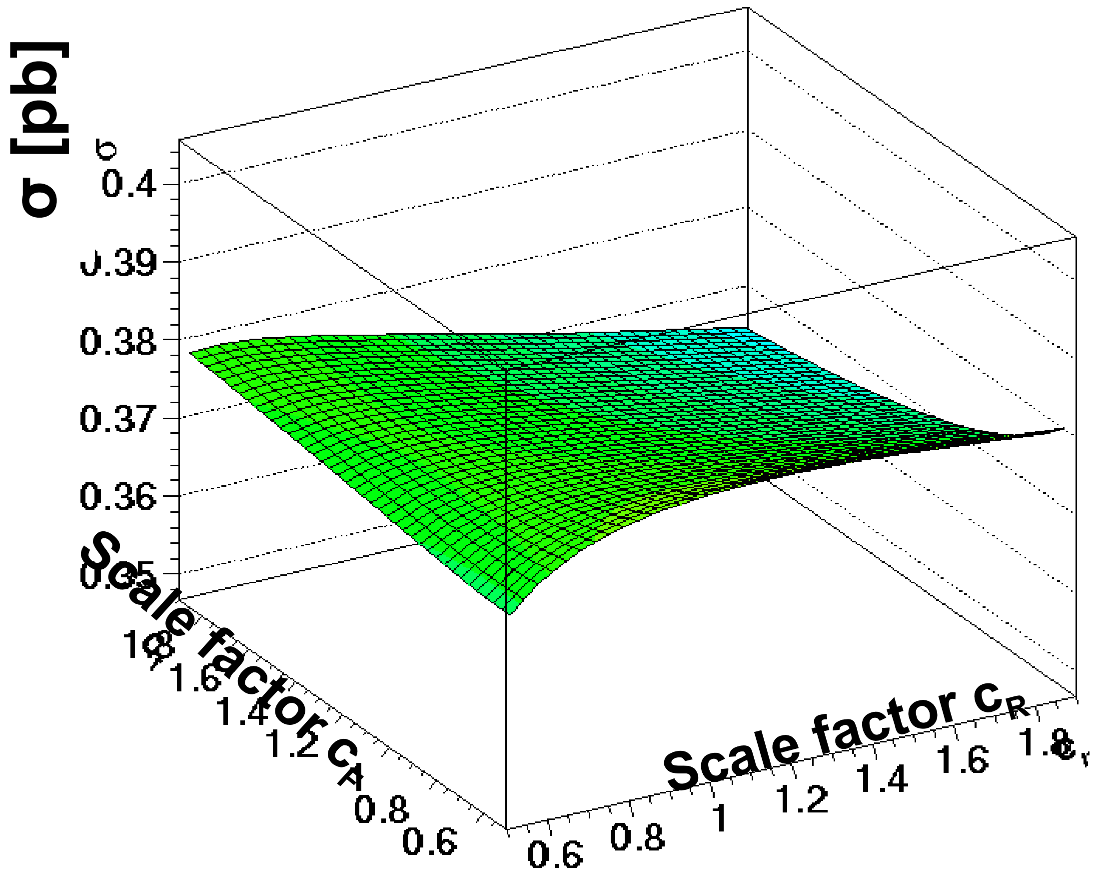
New in v2: Scales

- Scales can be functions of multiple observables
  - e.g. for DIS jets
    Scale observables are p_T and Q^2
  - Scales can be
    $\mu_r^2 = (Q^2 + p_T^2) / 2$
    $\mu_r^2 = Q^2$
    $\mu_r^2 = p_T^2$
    $\mu_r^2 = 0.8\, Q^2 + 0.3\, p_T^2 + Q \cdot p_T$

Independent scale variations of μ_r and μ_f are possible

$\mu_R^2 = c_R^2 \times (Q^2 + p_T^2) / 2$

$\mu_F^2 = c_F^2 \times Q^2$



More flexibility for studies of scale dependencies

Outlook

- Prerelease of fastNLO_reader_2.1.0_1273 for this tutorial
- Changes to previous release of fastNLO_reader_2.1.0_1062
  - Check and reactivate asymmetric scale variations in Fortran part
  - Some small inconsistencies between Fortran and C++ fixed
  - Numerous changes in interface to improve flexibility and user-friendliness (this is sometimes in contradiction :-)).
  - Improved documentation
- Short-term plan
  - Provide this as a linkable library
- Further developments
  - Provide more and new-type precalculated tables for DIS and LHC
  - Improve user-friendliness and docu for the production code and release
  - Integrate new processes and corrections, e.g. electroweak, and much more ...

Your feedback is very welcome here!

Tutorial Part

Installation

- Install packages produced with standard autotools, just run
  - ./configure - -prefix=your/local/dir
  - make; make install
- In case of different location of LHAPDF use
  - ./configure –prefix=your/local/dir --with-lhapdf=path/to/lhapdf
  - Error message with hints if still not found
- For more options check
  - ./configure -help
- And also look into the README file
- Executables: fnlo-fread and fnlo-cppread, type
  - fnlo-fread -h (or fnlo-cppread -h)
- for command line arguments (table file, PDF file)

Initial Output

```
##############################################################################
#
# fastNLO_reader_2.1.0_1062
#
# Fortran program to read fastNLO v2 tables and
# derive QCD cross sections using PDFs from LHAPDF
#
#-----------------------------------------------------------------------------
#
# Copyright (C) 2011 fastNLO Collaboration
# D. Britzger, T. Kluge, K. Rabbertz, F. Stober, M. Wobisch
#
# This program is free software: you can redistribute it and/or modify
# it under the terms of the GNU General Public License as published by
# the Free Software Foundation, either version 3 of the License, or
# (at your option) any later version.
#
# This program is distributed in the hope that it will be useful,
# but WITHOUT ANY WARRANTY; without even the implied warranty of
# MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the
# GNU General Public License for more details.
#
# You should have received a copy of the GNU General Public License
# along with this program. If not, see <http://www.gnu.org/licenses/>.
#
#-----------------------------------------------------------------------------
#
# The projects web page can be found at:
#   http://projects.hepforge.org/fastnlo
#
# If you use this code, please cite:
#   T. Kluge, K. Rabbertz, M. Wobisch, hep-ph/0609285
#   D. Britzger, T. Kluge, K. Rabbertz, F. Stober, M. Wobisch, arXiv:1109.1310
#
##############################################################################
```

Version and svn revision number

People

GPLv3 License

Web Page

References
(will be updated)

Program Start

```
################################################################################
# fnlo-read: Program Steering
#-------------------------------------------------------------------------------
# fnlo-read: Evaluating table: fnl1014_v2_all.tab
# fnlo-read: Using PDF set   : cteq66.LHgrid
################################################################################

################################################################################
# alphas-grv: First call:
################################################################################
# ALPHAS-GRV: PI               =  3.141592653589793
# ALPHAS-GRV: M_Z/GeV          = 91.187600
# ALPHAS-GRV: a_s(M_Z)         =  0.118500
# APLHAS-GRV: a_s loop         =  2
# APLHAS-GRV: flavor-matching =    F
# APLHAS-GRV: nf (M_Z)         =  5
################################################################################
```

Start parameters of default internal alpha_s code for comparison

Basic evaluation code ...
Other evolution code can be used/interfaced e.g. from LHAPDF
→ edit, recompile
Default output: List of LO and NLO x sections for selected PDF
Loop over scale variations, PDF members, alpha_s variations …
→ edit, recompile

Scenario Information 1

```
##################################################################################
# Information on fastNLO scenario: fnl1014
#---------------------------------------------------------------------------------
# Description:
#   d2sigma-jet_dpTd|y|_[pb_GeV]
#   CMS_Collaboration
#   Inclusive_Jet_pT
#   anti-kT_R=0.5
#   arXiv:1106.0208, Phys. Rev. Lett. 107, 132001 (2011).
#
# Centre-of-mass energy Ecms:  7000.     GeV
#
# Tot. no. of observable bins: 176 in 2 dimensions:
#
# No. of contributions: 5
# Contribution 1:
#   LO
#   No. of events:      30000000000
#   provided by:
#   NLOJet++_4.1.3
#   Z. Nagy, Phys. Rev. Lett. 88, 122003 (2002),
#   Z. Nagy, Phys. Rev. D68, 094002 (2003).
#   Scale dimensions: 1
#     Scale description for dimension 1:          pT_jet_[GeV]
#     Number of scale variations for dimension 1: 1
#     Available scale settings for dimension 1:
#       Scale factor number 1:                       1.0000
#     Number of scale nodes for dimension 1:      6
```

Exceptional!
Normally 2 or 3.

Measurement

Total no. of bins
No. of table contributions

Info for 1st contribution:
LO from NLOJet++
Referenz for used code is included in table where it belongs!

Scenario Information 2

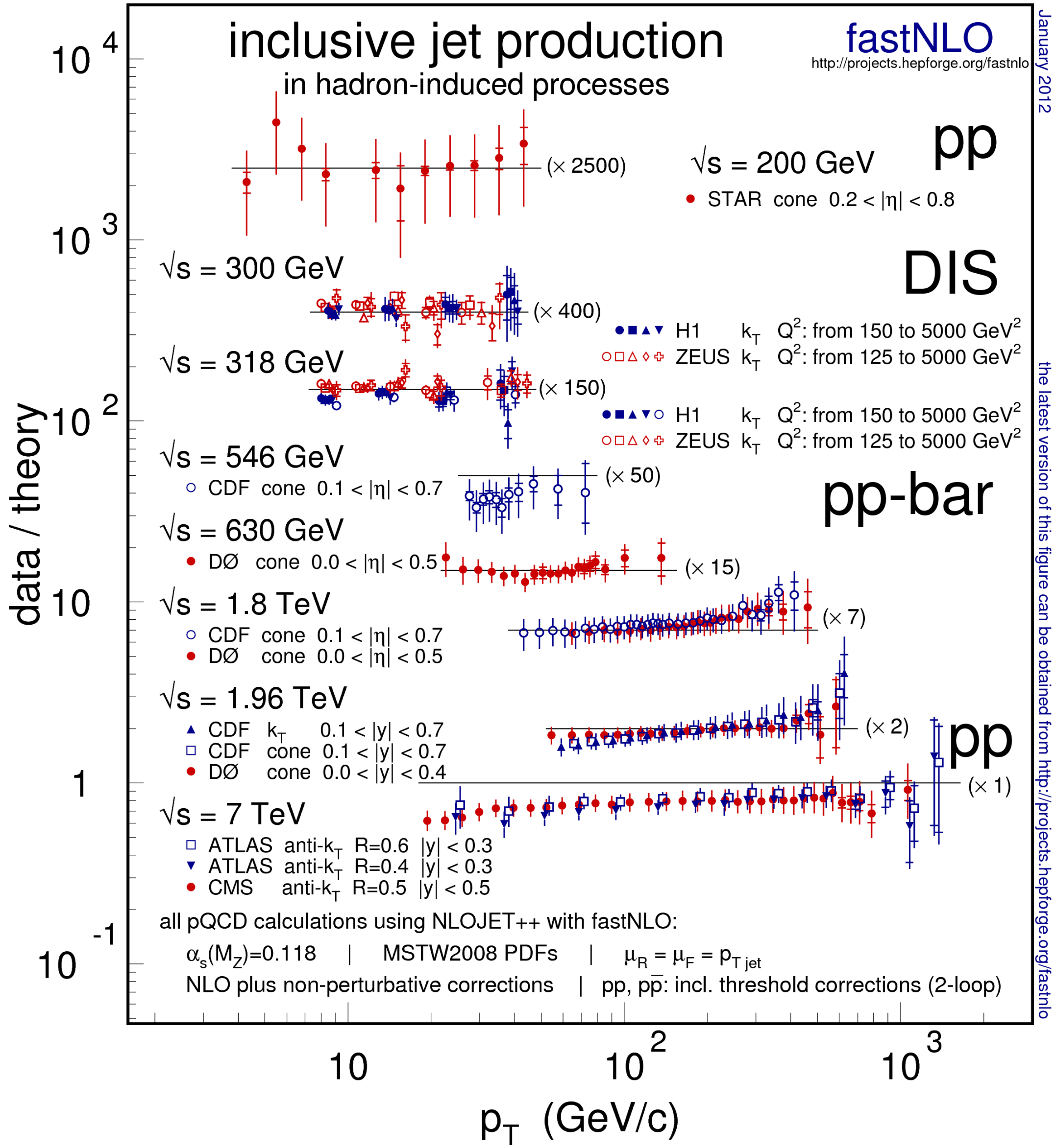
```
# Contribution 3:
#   THC_2-loop
#   No. of events:        270336000
#   provided by:
#   Owens/Wobisch
#   2-loop threshold corrections for the inclusive jet
#   cross section in pp and ppbar according to:
#   N. Kidonakis, J.F. Owens, Phys. Rev. D63, 054019 (2001).
#   Scale dimensions: 1
#     Scale description for dimension 1:          pT_jet_[GeV]
#     Number of scale variations for dimension 1: 1
#     Available scale settings for dimension 1:
#       Scale factor number 1:                       1.0000
#     Number of scale nodes for dimension 1:      6
# Contribution 4:
#   NP Correction
#   No. of events:                0
#   provided by:
#   Pythia6 D6T & Herwig++ 2.3
#   T. Sjöstrand, S. Mrenna, P. Skands, JHEP 05, 026 (2006),
#   R. Field, Acta Phys. Polon. B39, 2611 (2008),
#   M. Bähr et al., Eur. Phys. J. C58, 639 (2008),
#   CMS Collaboration, arXiv:1106.0208, Phys. Rev. Lett. 107, 132001 (2011).
#   Scale dimensions: 0
```

Threshold Corrections

Non-perturbative Corrections

Jets Data / Theory

- Comparison of jet data from
  - STAR at RHIC
  - H1 and ZEUS at HERA
  - CDF and D0 at Tevatron
- Compatible with QCD
- Includes measurements from LHC
- New: Updated with ATLAS inclusive jets



fastNLO, to be uploaded, arXiv:1109:1310v2, 2012

Backup Slides

Scale flexibility in fastNLO v2.0

Perturbative coefficients beyond LO have scale dependence

$$\sigma \propto \alpha_s^n c_{born} + \alpha_s^{n+1} c_{NLO}(\mu_r, \mu_f)$$

Scale dependence can be factorized

$$\sigma \propto \alpha_s^n c_{born} + \alpha_s^{n+1}\left(c_0 + \log(\mu_r^2) c_r + \log(\mu_f^2) c_f\right)$$

Store individual scale **independent** coefficients

Scales can be arbitrary values - or functions of observables

- Scales can be functions of multiple variables e.g. p_T and y*

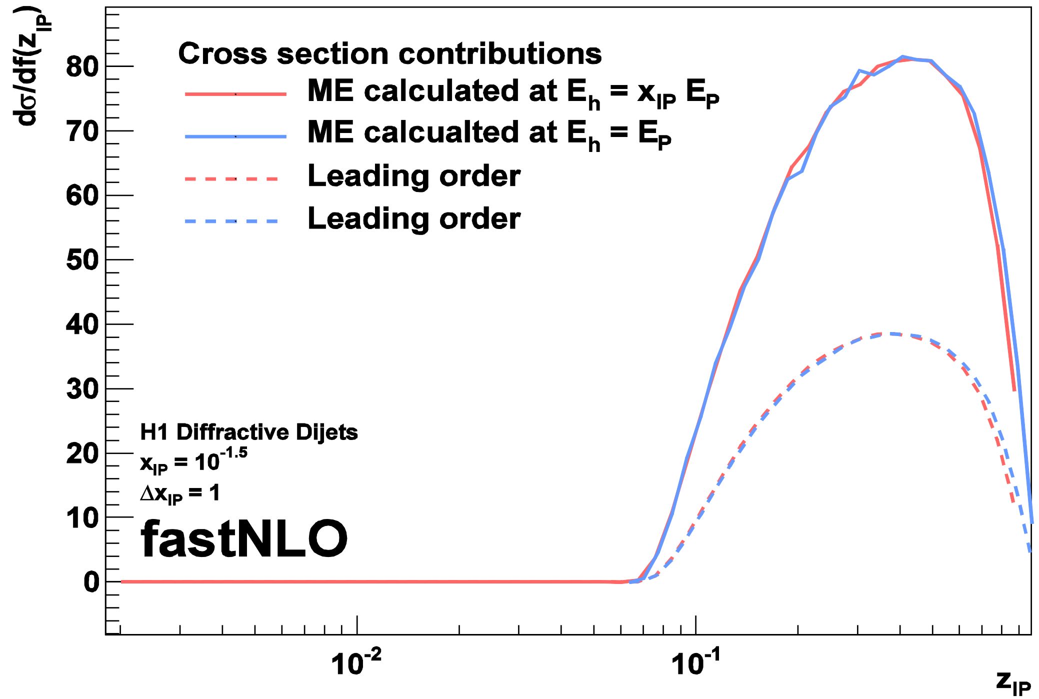
$$\mu_{r/f} \rightarrow \mu_{r/f}(p_T, y^*) \qquad e.g.\ \mu = 0.5 \cdot p_T \quad or \quad \mu = p_T \cdot e^{0.3y}$$

- Final scale can be chosen to be any function of both

Scales can be functions of multiple observables

Jets in diffractive DIS with fastNLO

- 1. Fixed center-of-mass calculation
  - Calculate only one fastNLO table at proton energy E_p
  - Increased number of x-nodes in low-x region
- 2. Adapt the slicing method
  - Define arbitrary x_{IP} slicing
  - Calculate cross section by Rieman-integrating x_{IP}
  - Integrate over x wrt. E_p



$$\sigma_{n,a} = \sum_k \Delta x_{\mathrm{IP},k} \int_0^{x_{\mathrm{IP},k}} \frac{dx}{x_{\mathrm{IP},k}} \alpha_s^n \cdot c_0(x) \cdot f_a\left(x_{\mathrm{IP},k}, z_{\mathrm{IP}} = \frac{x}{x_{\mathrm{IP},k}}, \mu_f\right)$$

Integral becomes a standard fastNLO evaluation

Upper integration interval needs to be respected properly

FastNLO procedure improves previously used approach