fastNLO

Fast pQCD Calculations for PDF Fits

Markus Wobisch, Fermilab

in collaboration with T. Kluge, DESY
and K. Rabbertz, Univ. Karlsruhe

XIV Workshop on Deep Inelastic Scattering, DIS 2006
April 20-24, 2006, Tsukuba, Japan

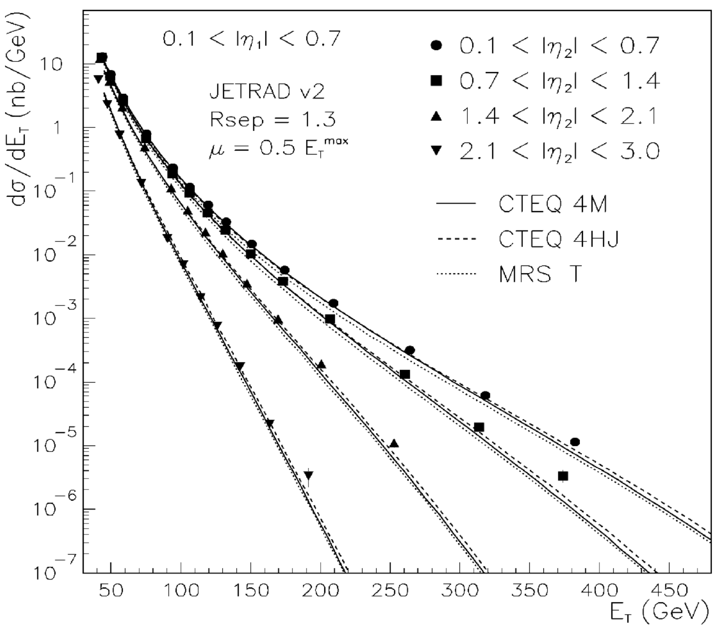
Two QCD Highlights from CDF in Run I

Dijet Cross Section (ET, eta1, eta2)
hep-ex/0012013

Both x-Values Constrained:

$$x_1 = x_T \frac{\exp(\eta_1) + \exp(\eta_2)}{2}$$

$$x_2 = x_T \frac{\exp(-\eta_1) + \exp(-\eta_2)}{2}$$

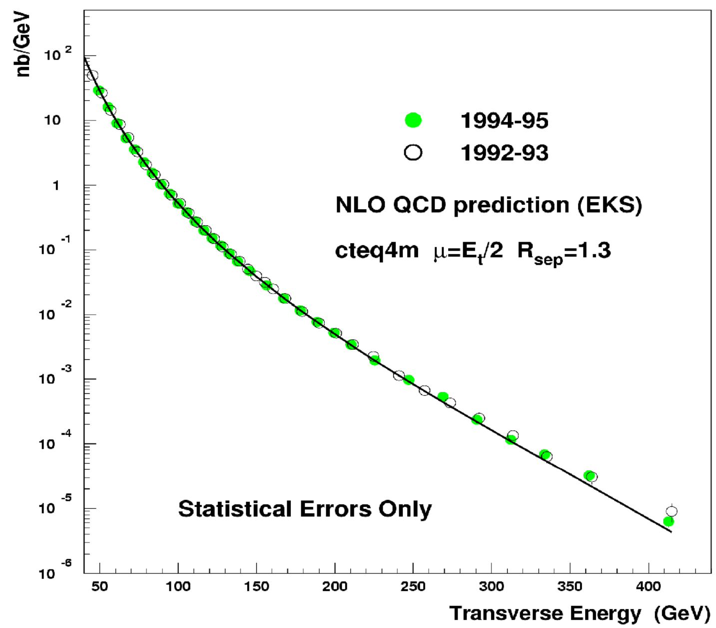


Inclusive Jet Cross Section (ET)
hep-ex/0102074

Only Product of Both x Constrained:

$$\sqrt{x_1 \cdot x_2} \simeq x_T \equiv 2p_T/\sqrt{s}$$

(x_1, x_2, smeared around x_T)



… and their Impact

Dijet Cross Section (ET, eta1, eta2) hep-ex/0012013	Inclusive Jet Cross Section (ET) hep-ex/0102074
Number of Citations until Summer 2002:	
7	23
Number of Citations Summer 2002 - 2004:	
0	31
Number of Citations since 2005:	
0	19
Totally Forgotten	Still Relevant

Why so Different?

Because CTEQ/MRST can't Compute
the Dijet Cross Section
fast enough
in the PDF Fits

also: not a Single High-Precision Jet Cross Section
from HERA has yet been Included in a Global PDF Fit

CTEQ "k-Faktor Approximation"

- For a Given PDF: Compute k-Faktor (once)

  k = sigma-NLO / sigma-LO
- In PDF Fit: Compute Sigma-LO for Arbitrary PDF
- Multiply Sigma-LO with k-Factor → get "NLO" Prediction

k-Factor itself Depends on the PDFs:

- Different for Different Partonic Subprocesses
  - Different x-Coverage in LO and NLO

Limitations & Problems:

- Procedure has Systematic Errors of 2-5%
- Works only for "simple" Cross Sections (Incl. Jets in pp)
- Not for pp-Dijets, DIS Jets, ...
- Even LO Computation is Relatively Slow (Compromise vs. stat. Errors)
- Statistical Errors Distort the Chi2 Contours in Fit

The “fastNLO” Concept

- Produce Exact pQCD Results → Goal: Systematic Precision of 0.1%
- Can be used for any Observable in Hadron-Induced Processes
  (Hadron-Hadron, DIS, Photoproduction, Photon-Photon, Diffraction)
- Can be used in any Order pQCD
- Concept requires existing Flexible Computer Code (e.g. NLOJET++)
- Save no Time during First Computation
  (may take Days, Weeks, Months, ... to achieve High Statistical Precision)

Any further Computation is done in Milliseconds

In the Following: Example for Hadron-Hadron → Jets

The Challenge

Cross Sections in Hadron-Hadron Collisions:

$$\sigma_{\rm hh} = \sum_n \alpha_s^n(\mu_r) \sum_{\text{PDF flavors } a} \sum_{\text{PDF flavors } b} c_{a,b,n}(\mu_r, \mu_f) \otimes f_a(x_1, \mu_f) \otimes f_b(x_2, \mu_f)$$

- Perturbative Coefficients c (include all Information on Observable)
- Alpha-s
- Integral over PDFs f(x)

Standard Method: MC Integration ← Time Consuming

Goal: Separate PDF Information from Integral

The Solution

- Choose Interpolation Eigenfunctions $E^{(i)}$ (EFs)

$$f(x) = \sum_i f(x^{(i)})\, E^{(i)}(x)$$

- Interpolate PDFs f(x) between Fixed Values $f(x^{(i)})$

$$\sigma_{\mathrm{hh}} = \sum_{i,j} f_a(x_1^{(i)}, \mu_f)\, f_b(x_2^{(j)}, \mu_f) \sum_n \alpha_s^n(\mu_r) \sum_{\text{PDFflavors } a} \sum_{\text{PDFflavors } b} c_{a,b,n}(\mu_r, \mu_f) \otimes E_a(x_1^{(i)}, \mu_f) \otimes E_b(x_2^{(j)}, \mu_f)$$

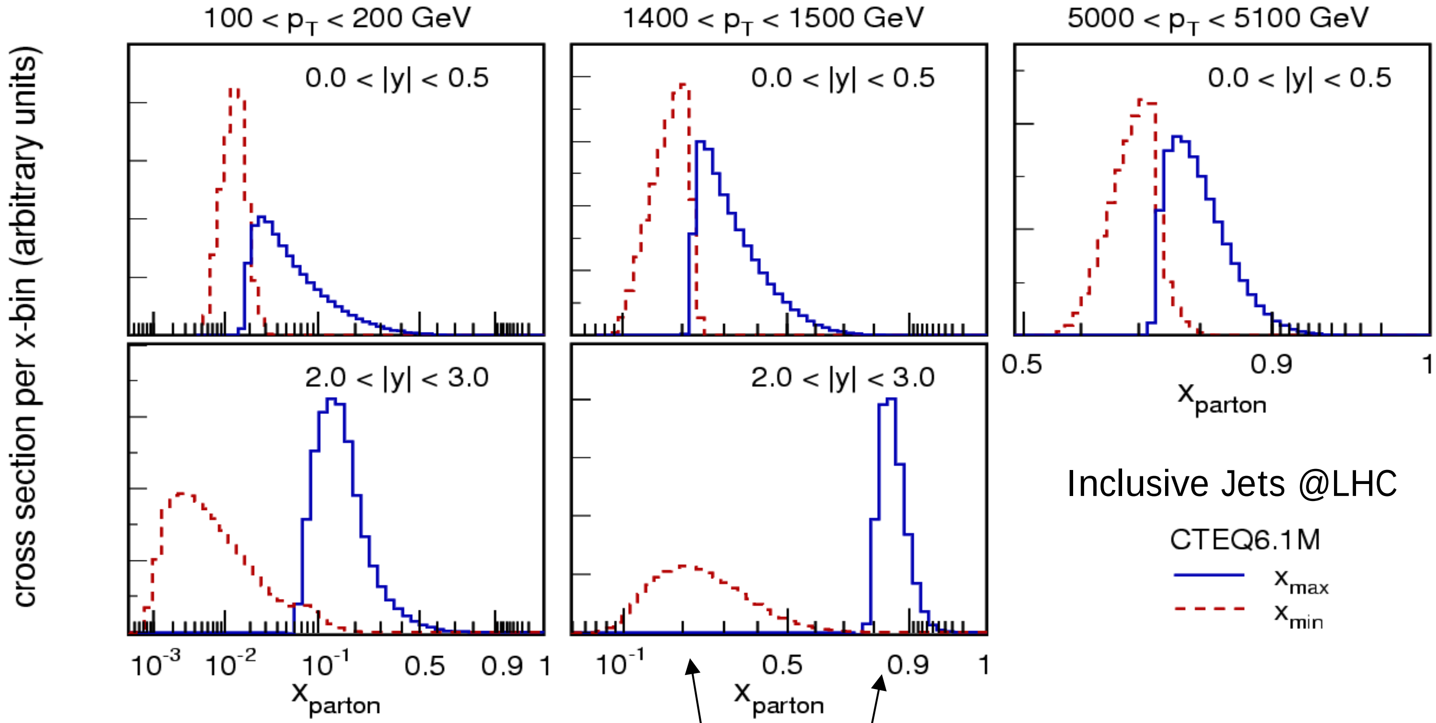
Multiply PDFs / alpha-s later

time-consuming

Compute once!
& Store in Table

(Ignore Renormalization / Factorization Scale Dependence for now)

Step 1: Efficient x-Coverage



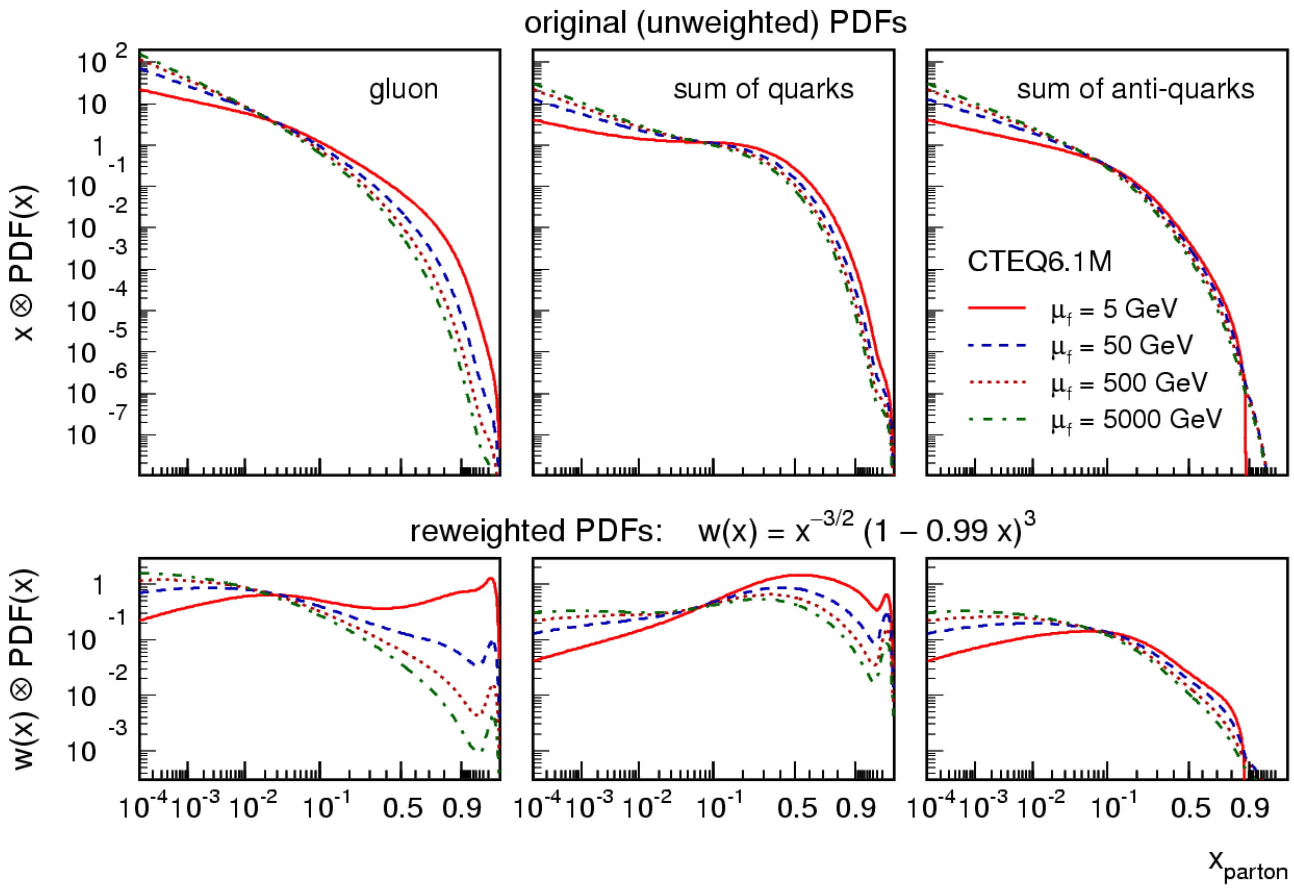
Problem: Forward High pT Jets
One small & one very large x-Value

Major Issue!
Not Addressed in
Talk by D.Clements

- Important: Efficient Distribution of EFs over Accessible x-Range:

→ x-Axis Binning in $\mathrm{sqrt}(\log_{10}(1/x))$

Step 2: Reduce PDF Curvature



First Step was:
- x-Binning in $\sqrt{\log_{10}(1/x)}$

→ "Stretch" High-x Region

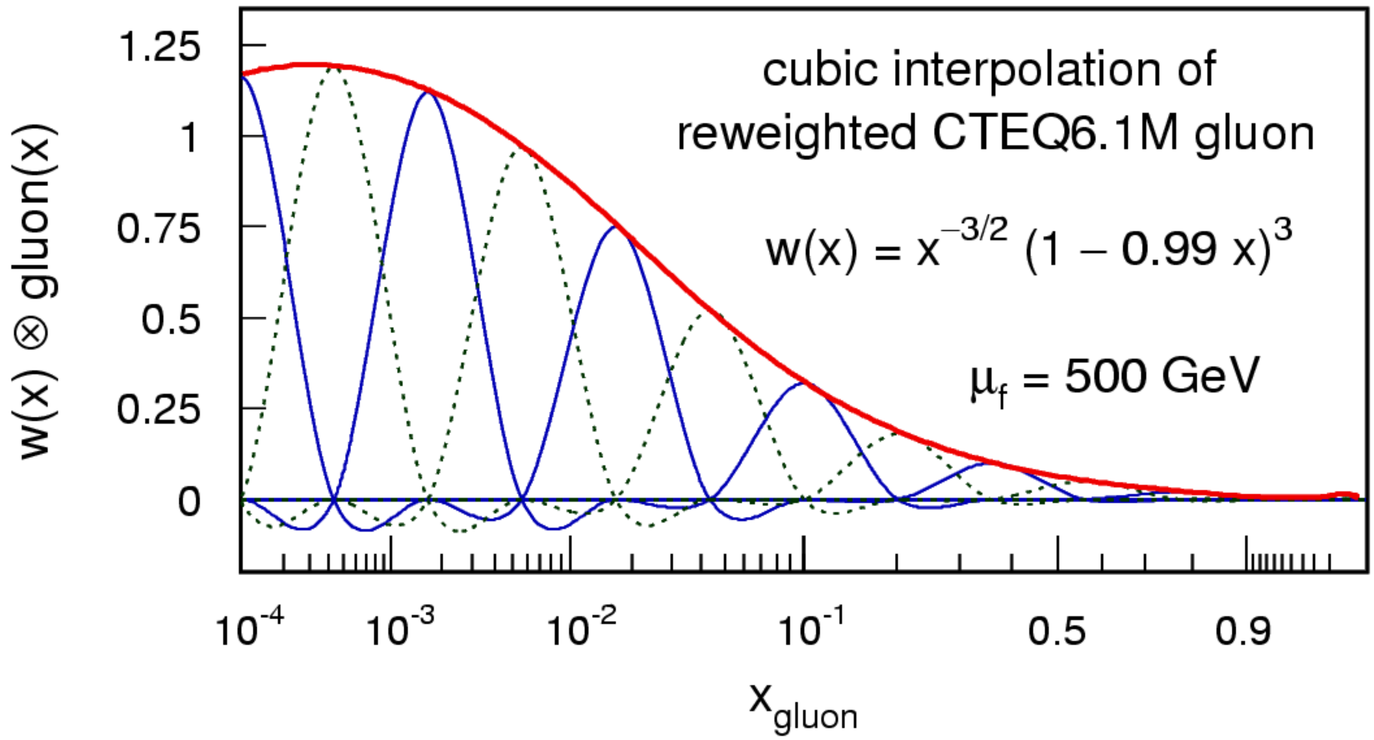
Still: Strongest Curvature at high x

Second Step:
- Reduce PDF Curvature by Reweighting

→ Strong Reduction of Curvature at all Scales
→ Easier for Interpolation

Step 3: Precise Interpolation

→ Use Cubic Interpolation of PDFs



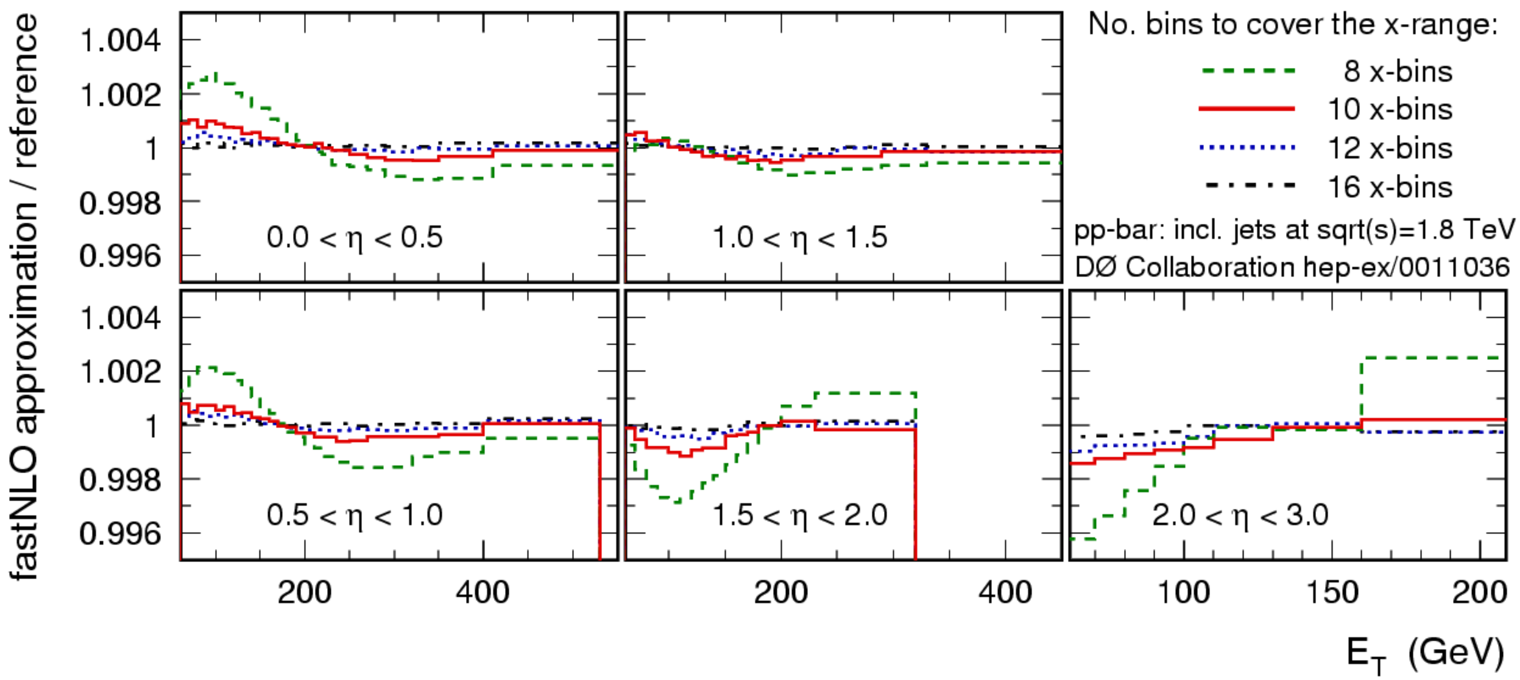
Reweighted CTEQ6.1M Gluon Density

Interpolated by 12 Cubic Eigenfunctions E(x) in: $10^{-4} < x < 1$

Result: High Precision

Study “Real World” Example: DØ Run I Inclusive Jets in 5 Eta Regions

- Including Critical High pT Forward Region -



Optimized x-Range in each Analysis Bin → Study Precision vs. No. EFs

- With 8 x-Bins: Already 0.5% Precision
- Only 10 x-Bins: Achieve Goal of 0.1% Precision

Bonus

NNLO-NLL Threshold Corrections for Inclusive Jet x-Section in Hadron-Hadron

- High pT Jets in Hadron Collisions are Produced mostly at Threshold

→ Incomplete Cancellation of Virtual and Real Contributions at Fixed Order

→ Potentially Large Logarithmic Terms in all Orders(alpha-s)

(see Talk by N. Kidonakis)

N. Kidonakis, J. Owens, Phys. Rev. D63, 054019 (2001):

- Resummed Logarithms from Threshold Corrections
- Calculation of: <u>LO</u> + <u>NLO-NLL</u> + <u>NNLO-NLL</u> Contributions

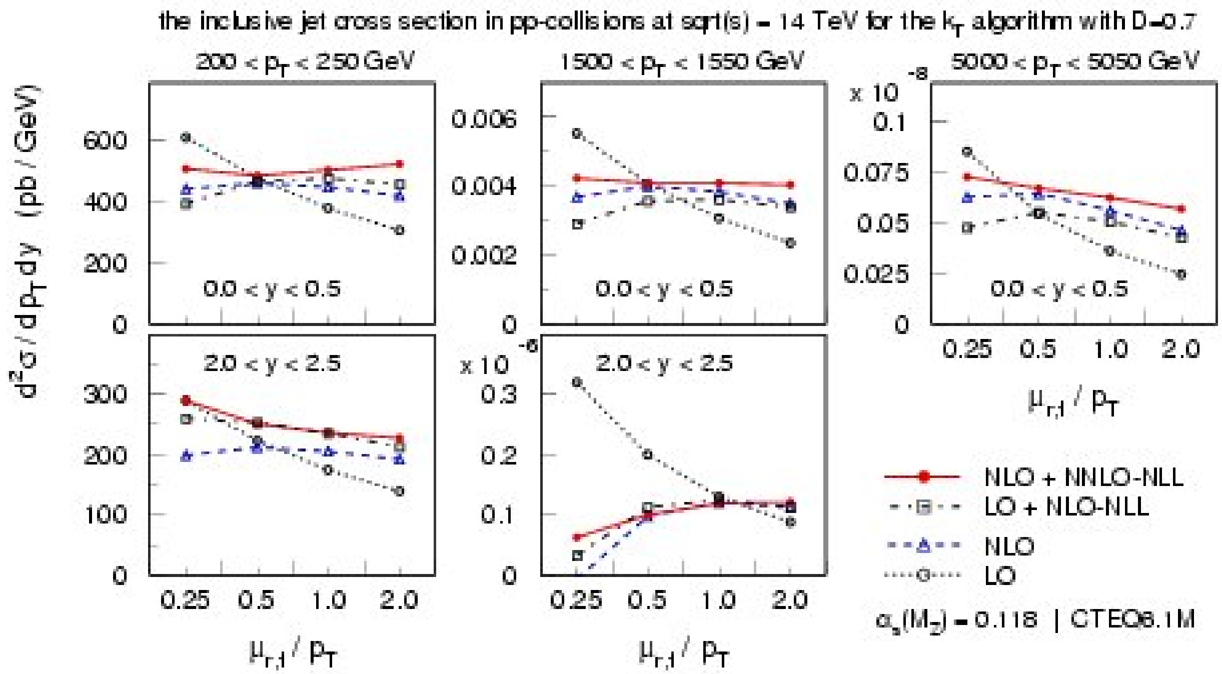
→ Add NNLO-NLL Contribution to NLO Calculation for Inclusive Jets

→ Now Available in fastNLO!

Threshold Corrections

- Add NNLO-NLL Contribution to NLO Calculation for Inclusive Jets

  → Significant Reduction of Scale Dependence



Example for Inclusive Jets at the LHC

First Step towards NNLO Calculation

→ Important for Including Inclusive Jet Data in NNLO PDF Fits

(see also Talk by R. Thorne) (used by DØ - see Talks by M. Voutilainen, C. Royon)

Existing fastNLO Calculations

Internal Name	hep-ex No.	Brief Description	
fnt1001	hep-ph/0102074	Run I, CDF incl. jets @1800 GeV	Tevatron Run I
fnt1002	hep-ex/0011036	Run I, D0 incl jets @1800 GeV	
fnt1003	hep-ex/0012013	Run I, CDF dijets pT @1800 GeV	
fnt1004	hep-ex/0012046	Run I, D0 incl jets @ 630 GeV	
fnt1005	hep-ex/0012046	Run I, D0 incl jets, scaled ratio 630/1800 GeV	
fnt1007	hep-ex/9912022	Run I, CDF dijet-mass @1800 GeV	
fnt1008	hep-ex/0012046	Run I, D0 dijet-mass @1800 GeV	
fnt2002	hep-ex/0512020	Run II, CDF incl. jets, cone @1960GeV	Tevatron Run II
fnt2003	hep-ex/0512062	Run II, CDF incl. jets kT @ 1960GeV	
... Preliminiary D0 inclusive jets			
... Preliminiary CDF inclusive jets w/ kT algo			
fnh1001	hep-ex/0010054	HERA, H1 incl. jets (ET, Q2)	HERA
fnh1002	hep-ex/0208037	HERA, ZEUS incl. jets (ET, Q2)	
fnh1003	hep-ex/0206029	HERA, H1 incl. forward jets (low Q2)	
fnh1004	hep-ex/0010054	HERA, H1 dijets (ET, Q2)	
... Preliminary H1 incl. jets			
fnr0001		RHIC, incl. jets kT algo	RHIC / LHC
fnl0001		LHC, incl. jets kT algo	

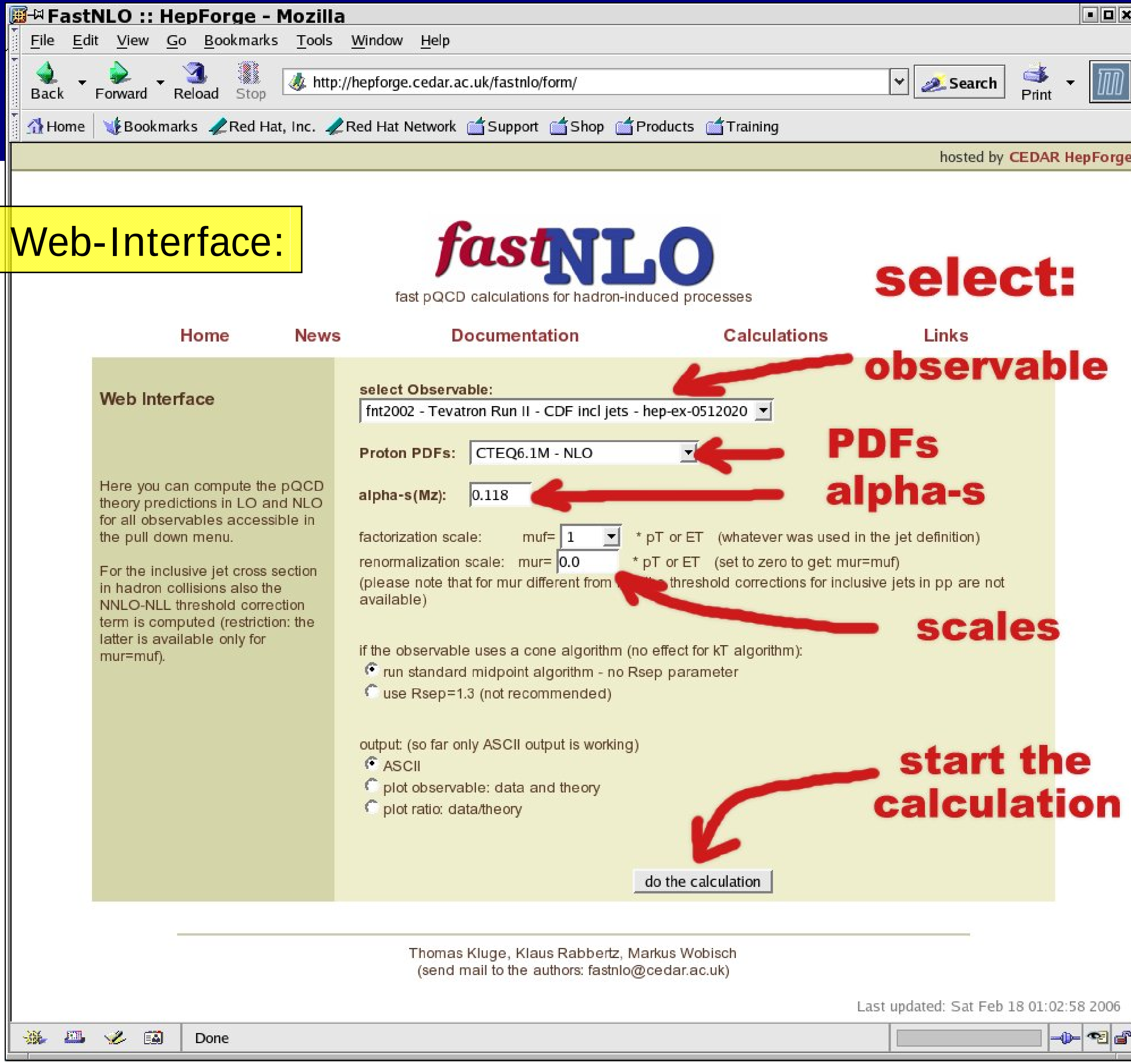
All with high statistics

Up to 6 CPU Months!!

www.cedar.ac.uk/fastnlo

- Soon: Download Documentation & Tables & Usercode for all Measurements
- Now: Webinterface for Interactive Calculations

Interactive Web-Interface:



FastNLO :: HepForge - Mozilla

File Edit View Go Bookmarks Tools Window Help

Back Forward Reload Stop http://hepforge.cedar.ac.uk/fastnlo/form/cgi-bin/test.cgi?Scenario=fnt2002&ProtonPDF= Search Print

Home Bookmarks Red Hat, Inc. Red Hat Network Support Shop Products Training

1 second later …

```
#         available renormalization scale settings:
#            1  (mur/mu0)=  0.25
#            2  (mur/mu0)=  0.5
#            3  (mur/mu0)=  1.
#            4  (mur/mu0)=  2.
#         (in LO and NLO, the renormalization scale
#          can be varied arbitrarily afterwards.
#          This is, however, not possible for the
#          NNLO-NLL threshold corrections.)
#
#    --> in the first call the scales are chosen to be:
#     (mur/mu0) =   1.0000    (muf/mu0) =   1.0000
#
###############################################################

--  fastNLO - results for  d2sigma-jet_dpT_dy_(nb_GeV)
--    cross sections:              LO          NLOcorr      NNLOcorr      total
--------  muf/mu0=  1.     mur/mu0=  1.
       from   0.1 -    0.7  in:  y
pT_in_GeV      61.00-   67.00:  0.5689E+01  0.1969E+01  0.1140E+01  0.8798E+01
pT_in_GeV      67.00-   74.00:  0.3286E+01  0.1142E+01  0.6354E+00  0.5063E+01
pT_in_GeV      74.00-   81.00:  0.1898E+01  0.6597E+00  0.3541E+00  0.2912E+01
pT_in_GeV      81.00-   89.00:  0.1107E+01  0.3880E+00  0.1996E+00  0.1695E+01
pT_in_GeV      89.00-   97.00:  0.6478E+00  0.2248E+00  0.1129E+00  0.9855E+00
pT_in_GeV      97.00-  106.00:  0.3829E+00  0.1355E+00  0.6461E-01  0.5830E+00
pT_in_GeV     106.00-  115.00:  0.2274E+00  0.8015E-01  0.3714E-01  0.3447E+00
pT_in_GeV     115.00-  125.00:  0.1363E+00  0.4856E-01  0.2160E-01  0.2065E+00
pT_in_GeV     125.00-  136.00:  0.8034E-01  0.2842E-01  0.1233E-01  0.1211E+00
pT_in_GeV     136.00-  158.00:  0.3833E-01  0.1376E-01  0.5699E-02  0.5779E-01
pT_in_GeV     158.00-  184.00:  0.1403E-01  0.5105E-02  0.1972E-02  0.2110E-01
pT_in_GeV     184.00-  212.00:  0.5027E-02  0.1835E-02  0.6680E-03  0.7530E-02
pT_in_GeV     212.00-  244.00:  0.1786E-02  0.6595E-03  0.2261E-03  0.2672E-02
pT_in_GeV     244.00-  280.00:  0.6027E-03  0.2250E-03  0.7308E-04  0.9007E-03
pT_in_GeV     280.00-  318.00:  0.1970E-03  0.7374E-04  0.2307E-04  0.2938E-03
pT_in_GeV     318.00-  360.00:  0.6208E-04  0.2358E-04  0.7136E-05  0.9280E-04
pT_in_GeV     360.00-  404.00:  0.1833E-04  0.7078E-05  0.2099E-05  0.2751E-04
pT_in_GeV     404.00-  464.00:  0.4392E-05  0.1734E-05  0.5171E-06  0.6643E-05
pT_in_GeV     464.00-  530.00:  0.7168E-06  0.2949E-06  0.8907E-07  0.1101E-05
pT_in_GeV     530.00-  620.00:  0.7254E-07  0.3175E-07  0.1014E-07  0.1144E-06


  in the matrixelements you use  alpha_s(Mz)=  0.118

Tue Feb 21 06:04:53 GMT 2006
```

… cross sections, based on 6 months of CPU time!

Thomas Kluge, Klaus Rabbertz, Markus Wobisch
(send mail to the authors: fastnlo.ac.uk)

Last updated: Sat Feb 18 01:02:58 2006

Done

World Jet Data in fastNLO

Inclusive Jet Data from different

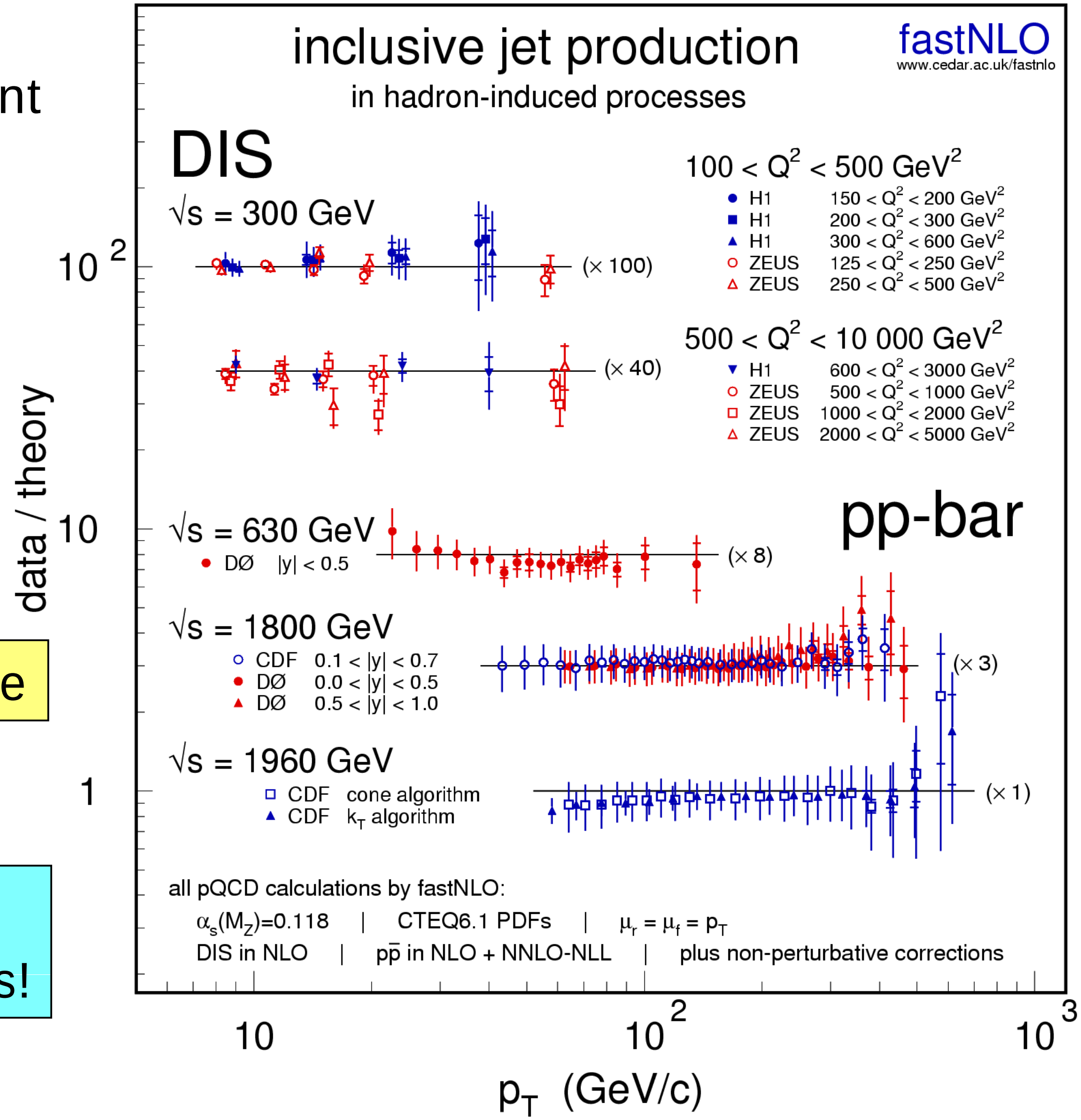
- Experiments
- Processes
- Center-of-Mass Energies

compared to fastNLO

- for CTEQ6.1M PDFs

Good Description Everywhere

All these Jet Data can now easily be included in PDF Fits!



Summary

- After one year of hard work: fastNLO is now finalized
- Computation of Jet Cross Section in Milliseconds → suited for PDF Fits
- Trivial to Interface with any PDF Fit

Soon:

- Collection of Coefficient Tables and Software for many Jet Measurements

  www.cedar.ac.uk/fastnlo (or: first Google Search Result)

Near Future:

- Include Photoproduction @NLO, Drell-Yan @NNLO

- Global PDF Fitters: A Large Number of Jet Data Sets is Waiting
- HERA Experiments: check your PDF Fits against Jet Data (or include them?)
- LHC Experiments: Which Computations do you need (pT, y Bins) for Jet-Studies?

Outlook

Today:

- www.arXiv.org for Publications of Experimental Measurements

with links to:

- Durham Database for Experimental Data Tables

Future Perspective:

- Establish Archive of Theory Predictions for Existing Measurements in fastNLO Framework

Option:

- Recompute Theory Predictions for Older Measurements for Recent PDFs

→ More Future Impact for Old Measurement

Additional Slides …

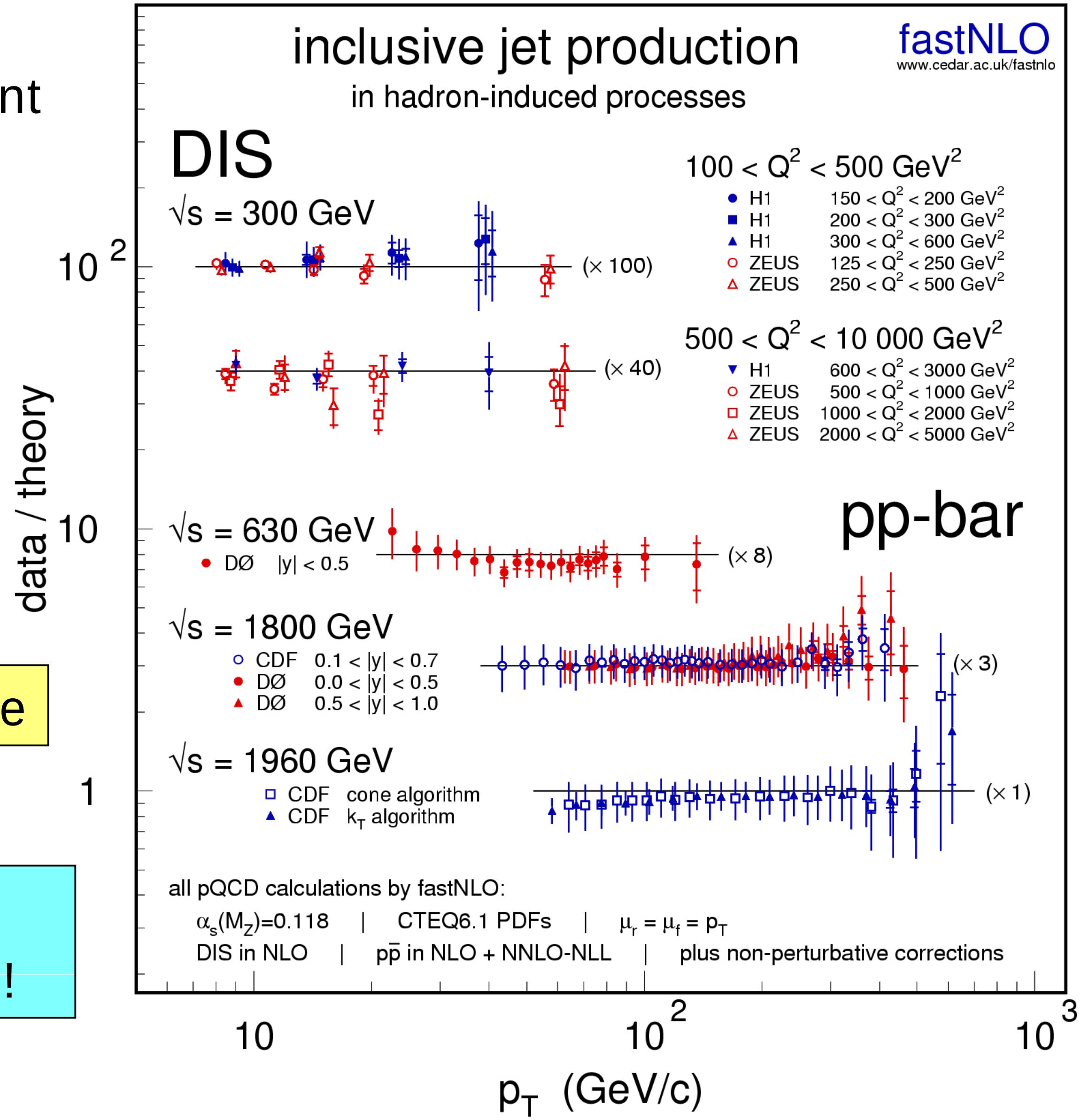
World Jet Data in fastNLO

Inclusive Jet Data from different
- Experiments
- Processes
- Center-of-Mass Energies

compared to fastNLO
- With CTEQ6.1M PDFs

Good Description Everywhere

All these Jet Data can now easily be included in PDF Fits!



World Jet Data – H1 2000 PDFs

Inclusive Jet Data from Different

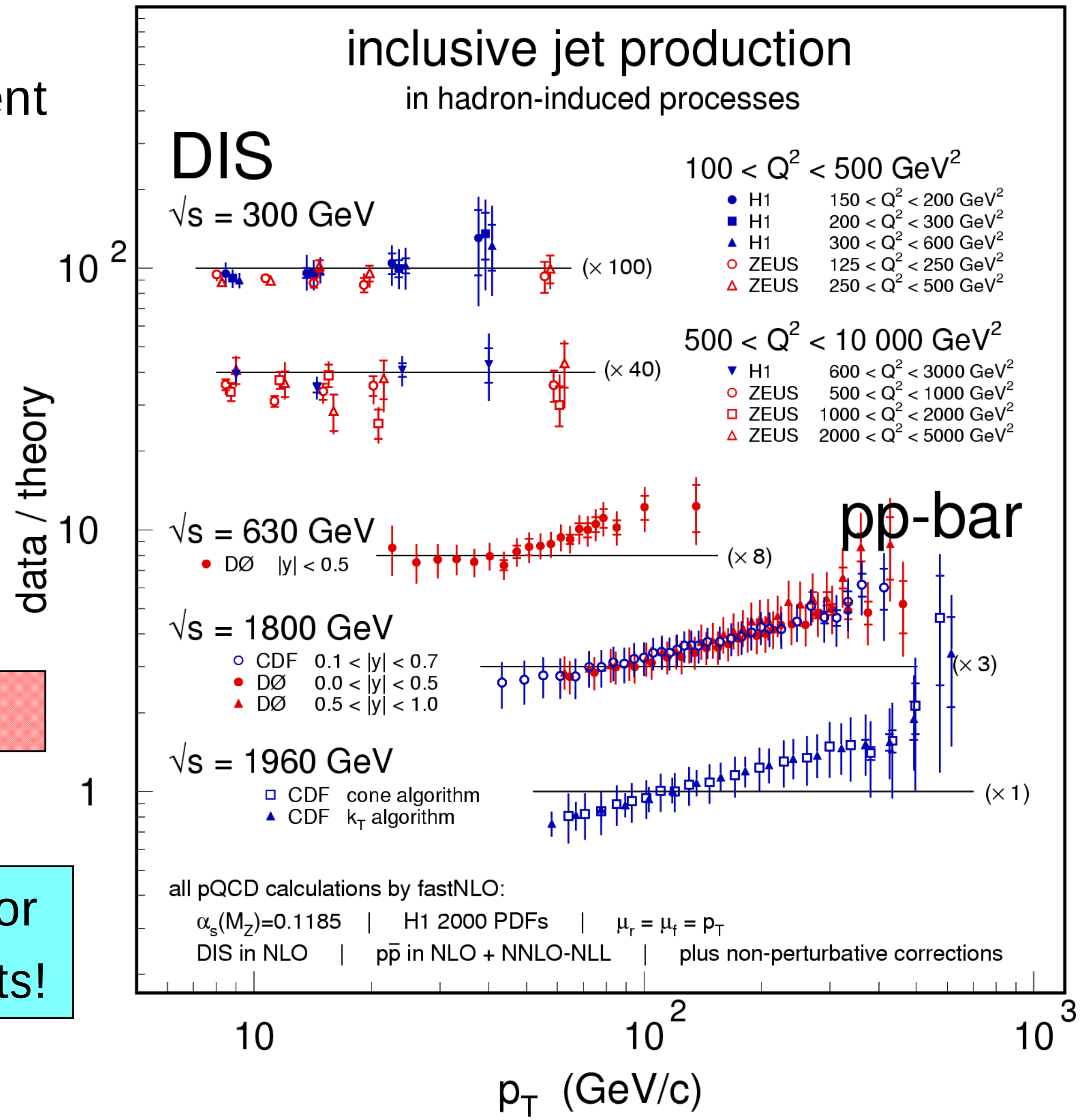
- Experiments
- Processes
- Center-of-Mass Energies

compared to fastNLO

- with “H1 2000” PDFs

Poor Description

→ need to include Jet Data for Meaningful PDF Fits Results!



CTEQ “k-Faktor Approximation”

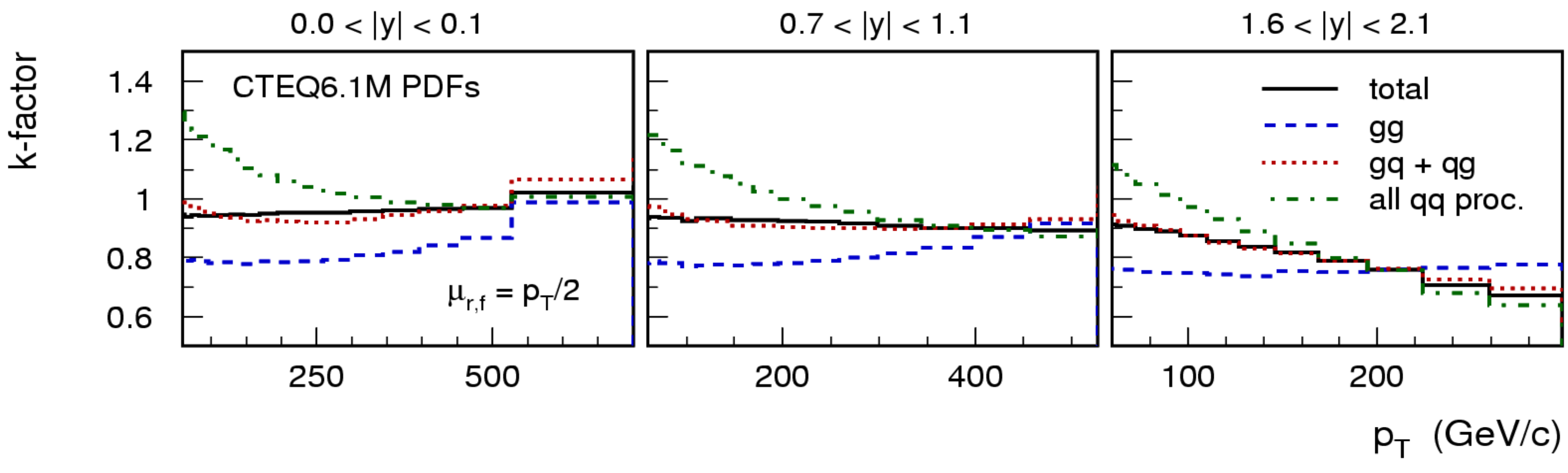
- For a given PDF: Compute k-Faktor (once)

  k = sigma-NLO / sigma-LO
- Compute Sigma-LO for arbitrary PDF (in PDF Fit)
- Multiply Sigma-LO with k-Factor → get “NLO” Prediction

k-Factor itself depends on the PDFs:

- Different for Different Partonic Subprocesses
  - Different x-Coverage in LO and NLO

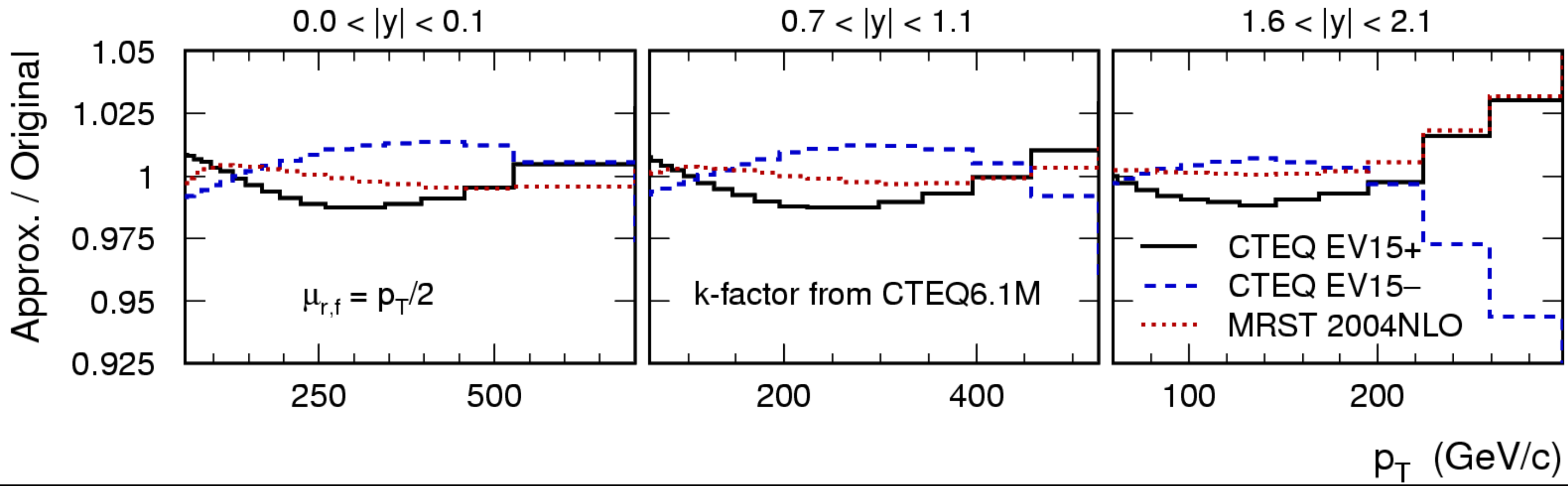
k-Factors for new prelim. CDF kT jet measurement (see talk by O. Norniella):



CTEQ "k-Faktor Approximation"

k-Factor Approximation has Systematic Errors of 2-5%:

Compare CTEQ Approximation with Exact NLO Calculation (for new prel. CDF kT measurement):

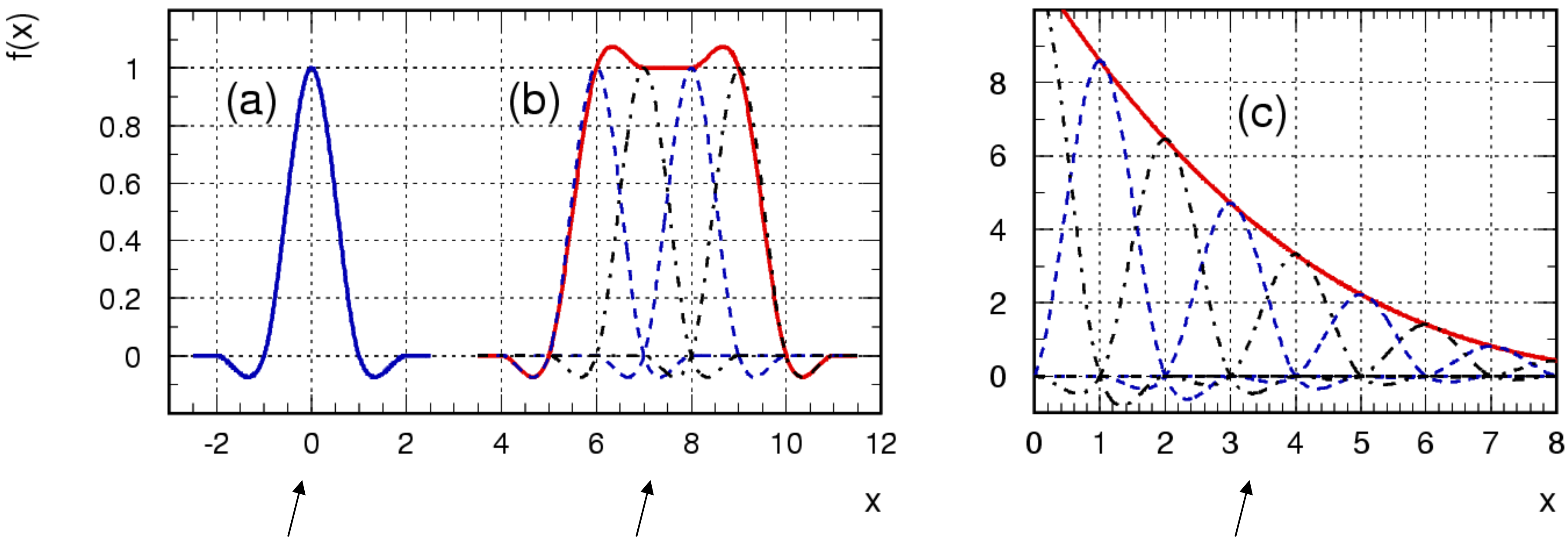


Further Limitations & Problems:

- Works only for "simple" Cross Sections (Incl. Jets in pp)
- Not for pp-Dijets, DIS Jets, ...
- Even LO Computation is Relatively Slow (Compromise vs. Stat. Errors)
- Statistical Errors Distort the Chi2 Contours in Fit

Interpolation → Eigenfunctions

- Cubic Interpolation → Continuous Function and 1st Derivative
- Very Good Precision → Small Number of Eigenfunctions
  → Small Table Size & Fast Processing



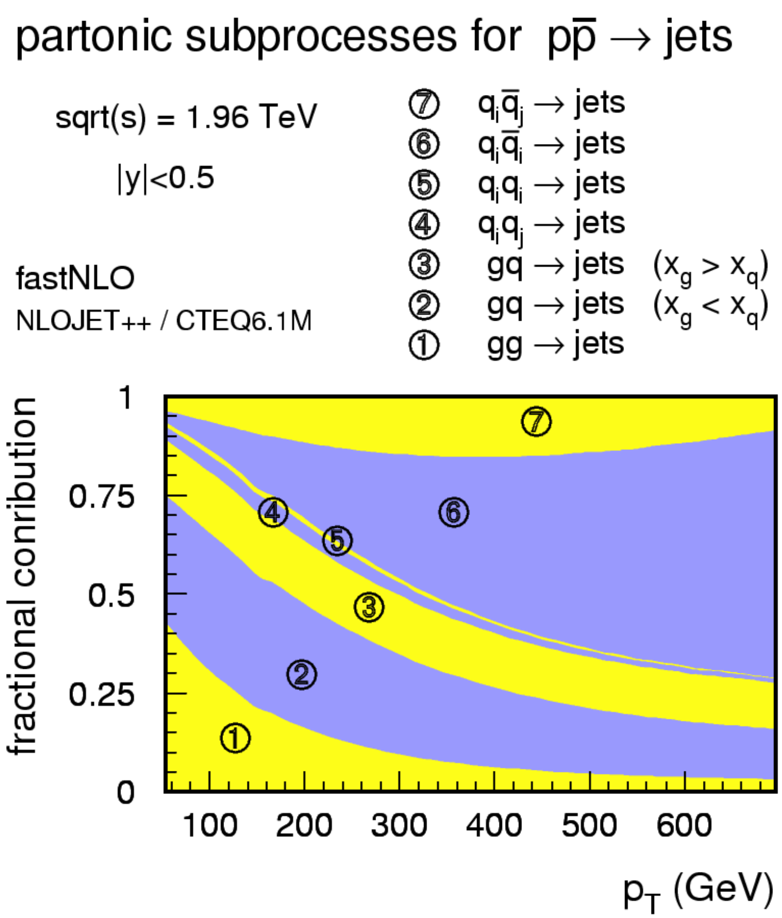
Single Eigenfunction Sum of Eigenfunctions Weighted Sum of EF

Partonic Subprocesses

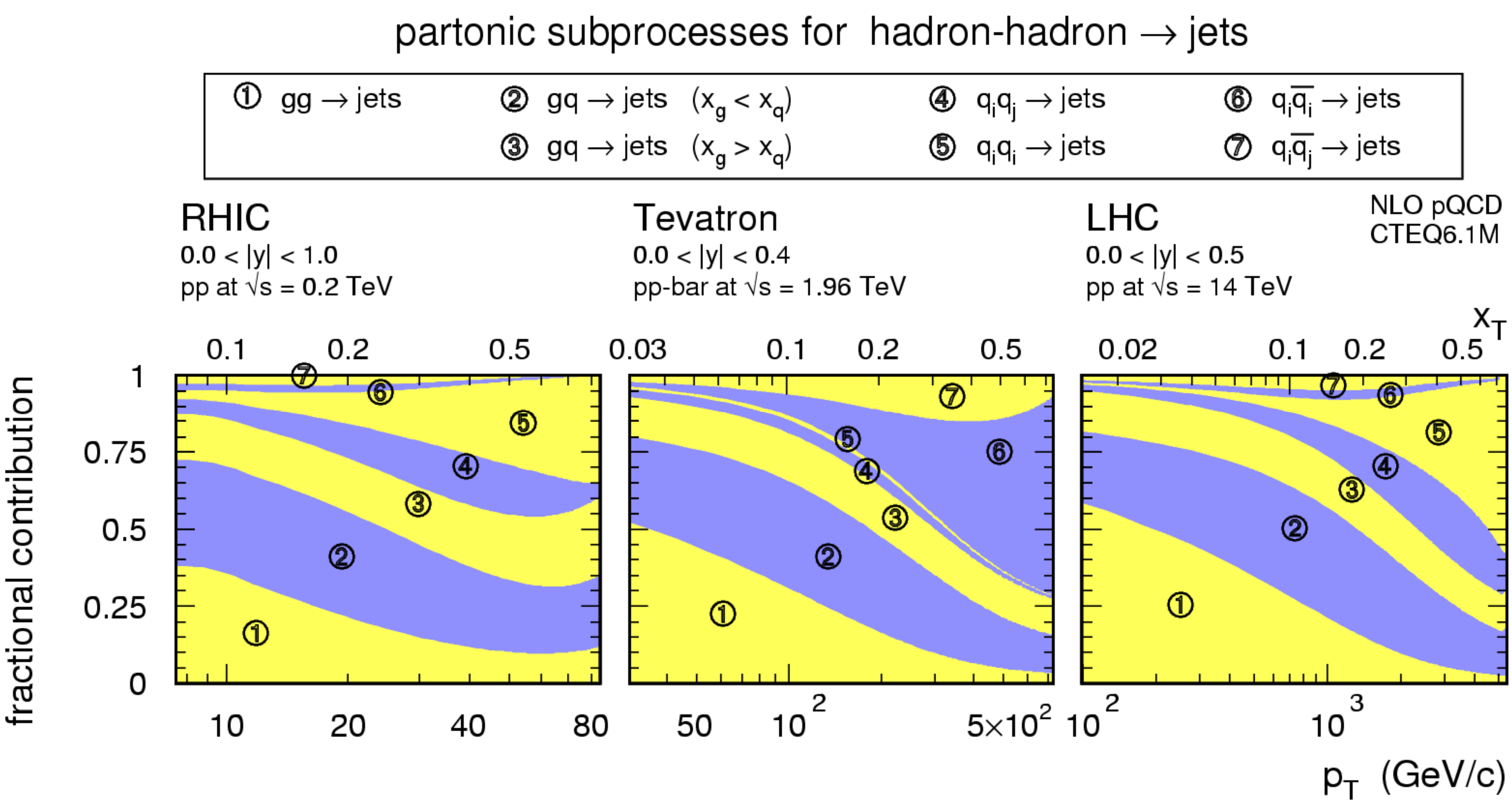
Seven Relevant Partonic Subprocesses:

$$gg \longrightarrow \text{jets} \qquad\qquad\qquad \propto H_1(x_1,x_2)$$
$$qg \longrightarrow \text{jets} \quad \text{plus} \quad \bar{q}g \longrightarrow \text{jets} \quad \propto H_2(x_1,x_2)$$
$$gq \longrightarrow \text{jets} \quad \text{plus} \quad g\bar{q} \longrightarrow \text{jets} \quad \propto H_3(x_1,x_2)$$
$$q_iq_j \longrightarrow \text{jets} \quad \text{plus} \quad \bar{q}_i\bar{q}_j \longrightarrow \text{jets} \quad \propto H_4(x_1,x_2)$$
$$q_iq_i \longrightarrow \text{jets} \quad \text{plus} \quad \bar{q}_i\bar{q}_i \longrightarrow \text{jets} \quad \propto H_5(x_1,x_2)$$
$$q_i\bar{q}_i \longrightarrow \text{jets} \quad \text{plus} \quad \bar{q}_iq_i \longrightarrow \text{jets} \quad \propto H_6(x_1,x_2)$$
$$q_i\bar{q}_j \longrightarrow \text{jets} \quad \text{plus} \quad \bar{q}_iq_j \longrightarrow \text{jets} \quad \propto H_7(x_1,x_2)$$

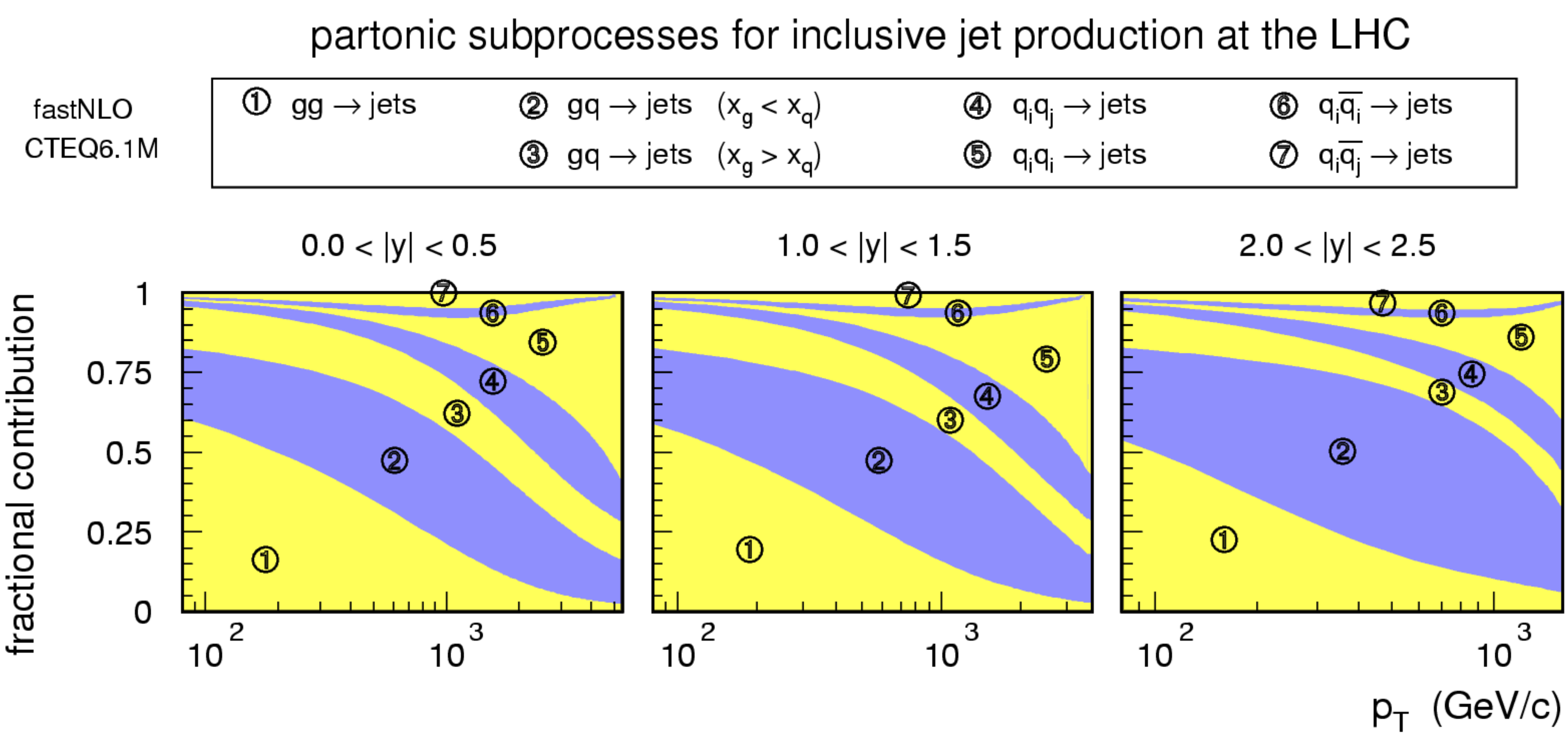
The H are Linear Combinations of PDFs



Partonic Subprocesses vs. ECM



Partonic Subprocesses vs. |y|



The Scales ...

Treatment of Renormalization and Factorization Scales:

(assume: scales proportional to jet pT)

Observable with small pT Bins (Inclusive jets as function of pT):

- Choose fixed scale at bin-center (one Scale-Bin)

Observables with larger pT Range (Dijet Mass Bins):

- Linear Interpolation between pT-min, pT-max (two Scale-Bins)

Observables with hughe pT Range (not yet happened):

- Cubic Interpolation over whole pT Range (multiple Scale-Bins)

Motivation

- Interpretation of Experimental Data $\leftrightarrow$ Availability of Theory Calculations
- also: Ability to perform the Calculation fast

PDF Fits:

need repeated Calculation of the same Cross Section
for different PDFs and/or alpha-s Values

Some Calculations are very fast
- DIS Structure Functions

Some Calculations are extremely slow
- Jet Cross Sections & Drell Yan

... but these data are important in PDF fits!

Implementation Steps

- to implement a new observable in fastNLO:
- find theorist to provide flexible computer code
- identify elementary subprocesses & relevant PDF linear combinations
- define analysis bins (e.g. pT , |y|)
- define Eigenfunctions E(x); E(x1; x2) (e.g. cubic) & the set of x-i
- to optimize x-range: find lower x-limit (xlimit < x < 1) (for each analysis bin)
- example: DØ Run I measurement of Incl. Jet Cross Section, Phys. Rev. Lett.86, 1707 (2001)
- 90 analysis bins in (ET, eta)
- 3 orders of alpha-s(pT) (LO & NLO & NNLO-NLL)
- 7 partonic subprocesses
- No. of x-intervals for each bin: 10
- $(n^2 + n)/2 = 55$ Eigenfunctions E(i,j)(x1, x2)
- 4 Settings for Renormalization and Factorization Scales
- stored in huge table!!! (few MB)
- compute VERY long to achieve very high precision

  → (after all: needs to be done only once!)