New features in version 2 of the fastNLO project

The fastNLO Collaboration

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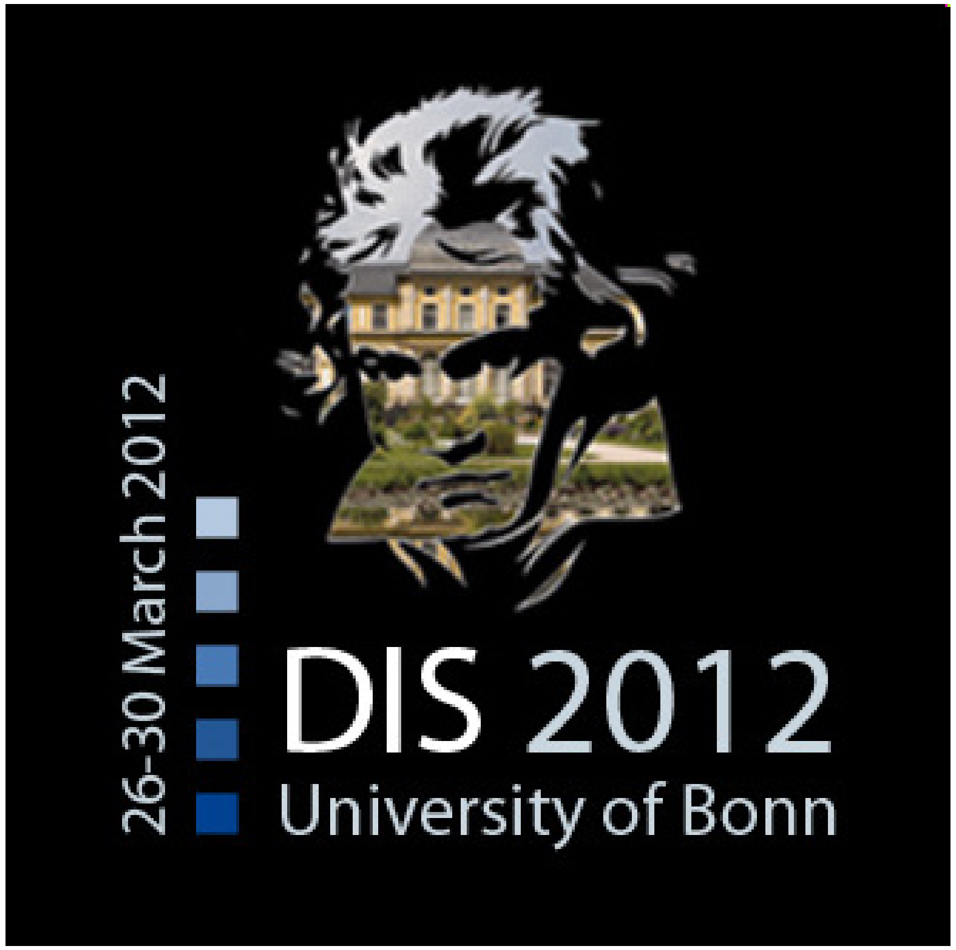
Outline

- **Motivation**
- **FastNLO concept**
- **Applications**
- **New features of FastNLO v2**
- **Generalized Concept in FastNLO v2**
- **FastNLO Precision and Examples**
- **Outlook**



Motivation

Interpretation of experimental data relies on

- Availability of reasonably fast theory calculations
- Often needed: Repeated computation of (almost) same cross sections

Examples for a specific analysis:

- Use of various PDFs (CTEQ, MSTW, NNPDF, …) for data/theory comparison
- Determine PDF uncertainties
- Derivation of scale uncertainties
- 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

- e.g. jet cross sections, Drell-Yan, …

Need procedure for fast repeated computations of NLO cross sections

- Use fastNLO (in use by most PDF fitting groups)

The fastNLO concept

Jetproduction in DIS

Jet cross sections are very slow to calculate

$$\sigma = \sum_{a,n} \int_0^1 dx \alpha_s^n(\mu_r) \cdot c_{a,n}(\frac{x_{Bj}}{x}, \mu_r, \mu_f) \cdot f_a(x, \mu_f)$$

Idea
Remove PDF from convolution integral

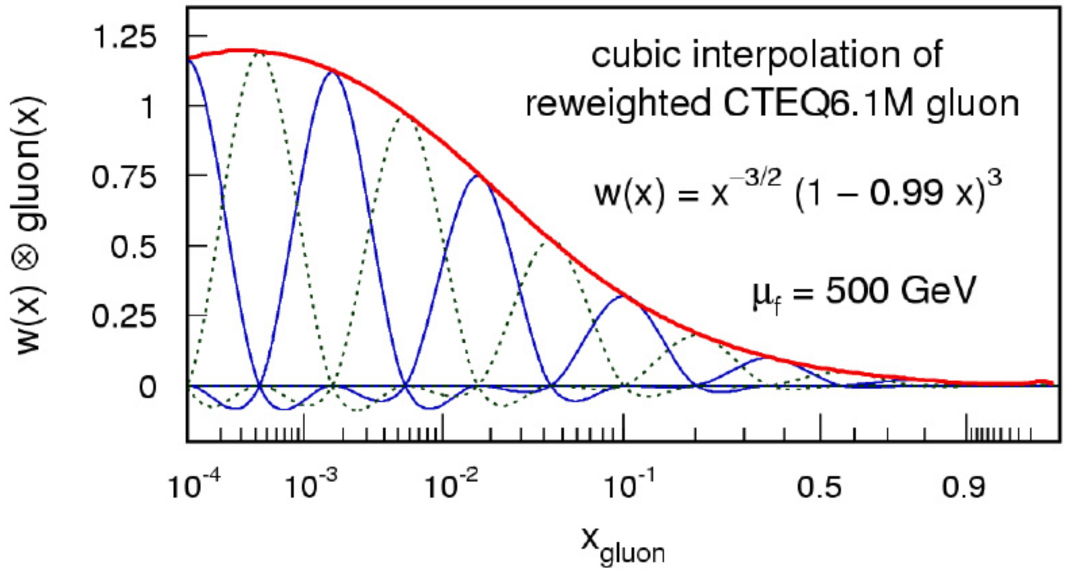
fastNLO Concept

Introduce set of n discrete x-nodes x_i's

- with $x_n < .. < x_i < .. < x_0 = 1$

Around each x_i define Eigenfunction $E_i(x)$

- $E_i(x_i) = 1$, $E_i(x_j) = 0$ $(i \neq j)$, $\Sigma_i E_i(x) = 1$ for all x



Single PDF is replaced by a linear combination of eigenfunctions

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

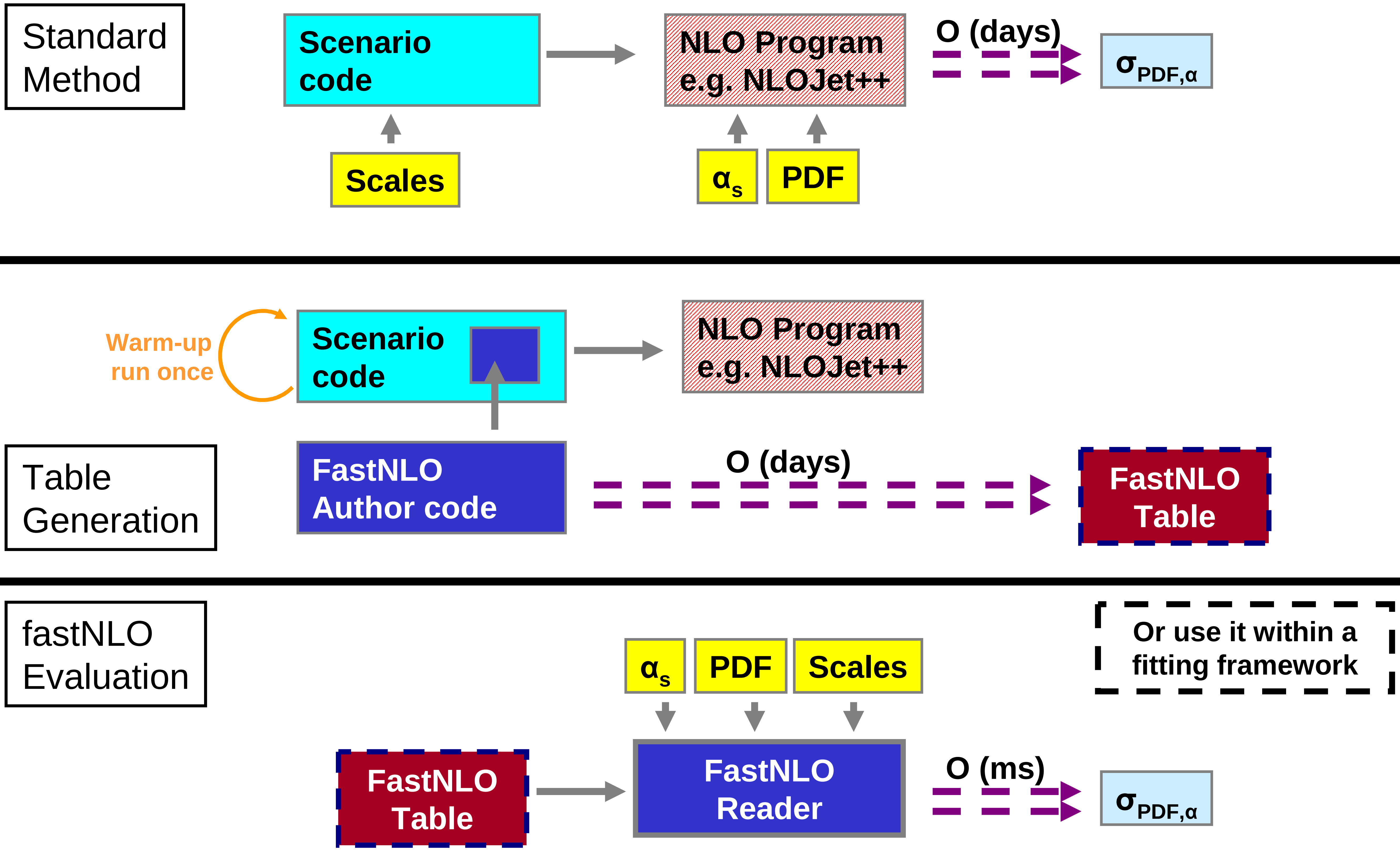
-> More technical details: TeV4LHC Workshop 2005 (Talk: M. Wobisch) and Pascaud, Zomer: LAL 94-42

Convolution of perturbative coefficients with PDFs and α_s is now replaced by a sum

$$\sigma \cong \sum_{a,n,i} \alpha_s^n f_a(x_i) \tilde{\sigma}_{a,n}^{(i)}$$

-> We only have to store a table of the convolution of the pert. coefficients with the interpolation kernel

The fastNLO concept



Applications

Application area

Can be used for any observable in hadron-induced processes

Hadron-hadron, DIS, Photoproduction, Fragmentation functions

Theory prediction

Concept does not include the theoretical calculation itself

Requires flexible computer code, e.g.:

- NLOJET++ (Z. Nagy PRD68 2003, PRL88 2002)
- Threshold corrections (Kidonakis, Owens, PRD 63, 054019 (2001))

Although labeled "fastNLO" method can be used at any order

Application procedure

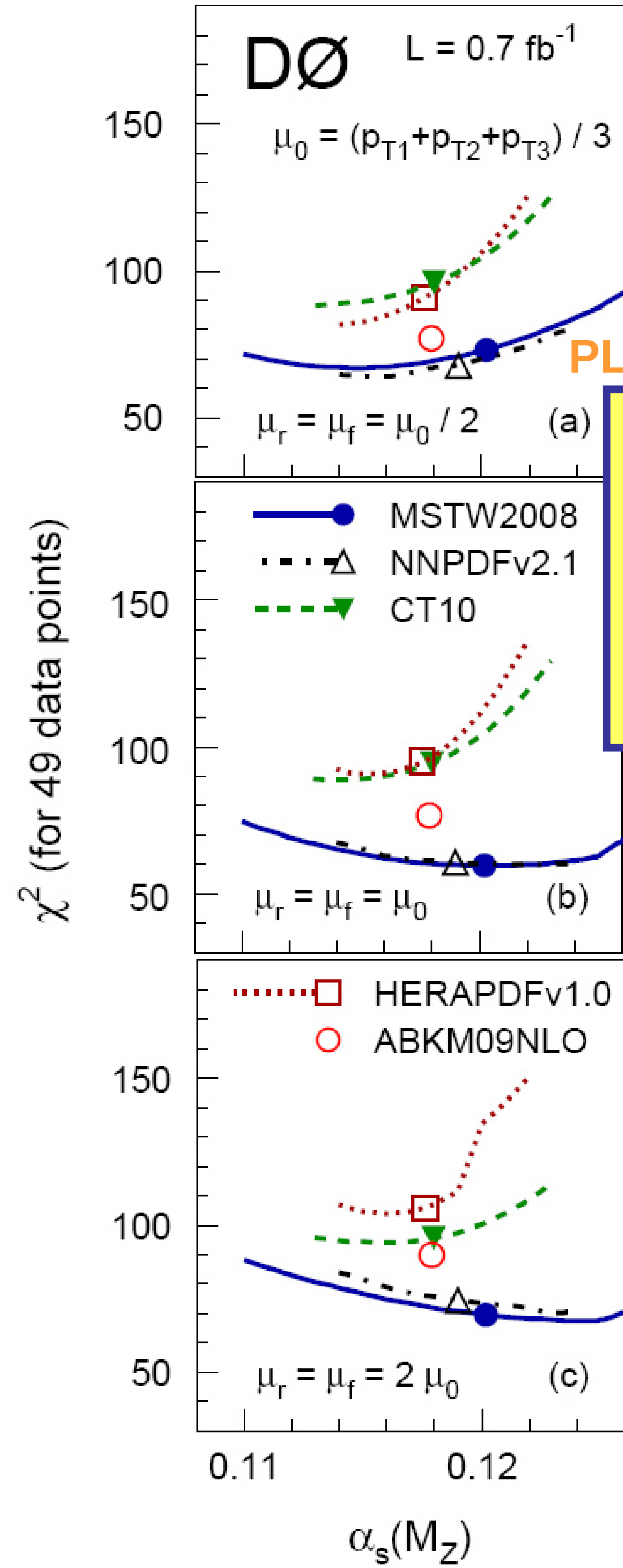
During the first computation no time is saved

Any further recalculation takes only O(ms)

Typical Applications

PDF or α_s fits

PDF uncertainties: e.g. PDF4LHC recommendation needs 239 calculations



PLB 704 (2011) 434-441

3138 repeated NLO calculations

New Features in FastNLO v2.0

fastNLO

Technical Features of pre-computed fastNLO tables

Automatic scan of smallest x-value

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

Comprehensive α_s evolution provided

- 2-,3-,4-loop iterative solution, flavor matching ON/OFF, etc…
- Interface to external α_s evolutions
  e.g. LHAPDF, QCDNUM, etc…

Interface to PDF from LHAPDF and QCDNUM

Easy to install (autotools)

C++ and Fortran version !

- agreement at double precision $O(10^{-10})$

FastNLO Reader

Reader_f

Reader_cc

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

Additional contributions in FastNLO v2.0

Much more flexible Table format

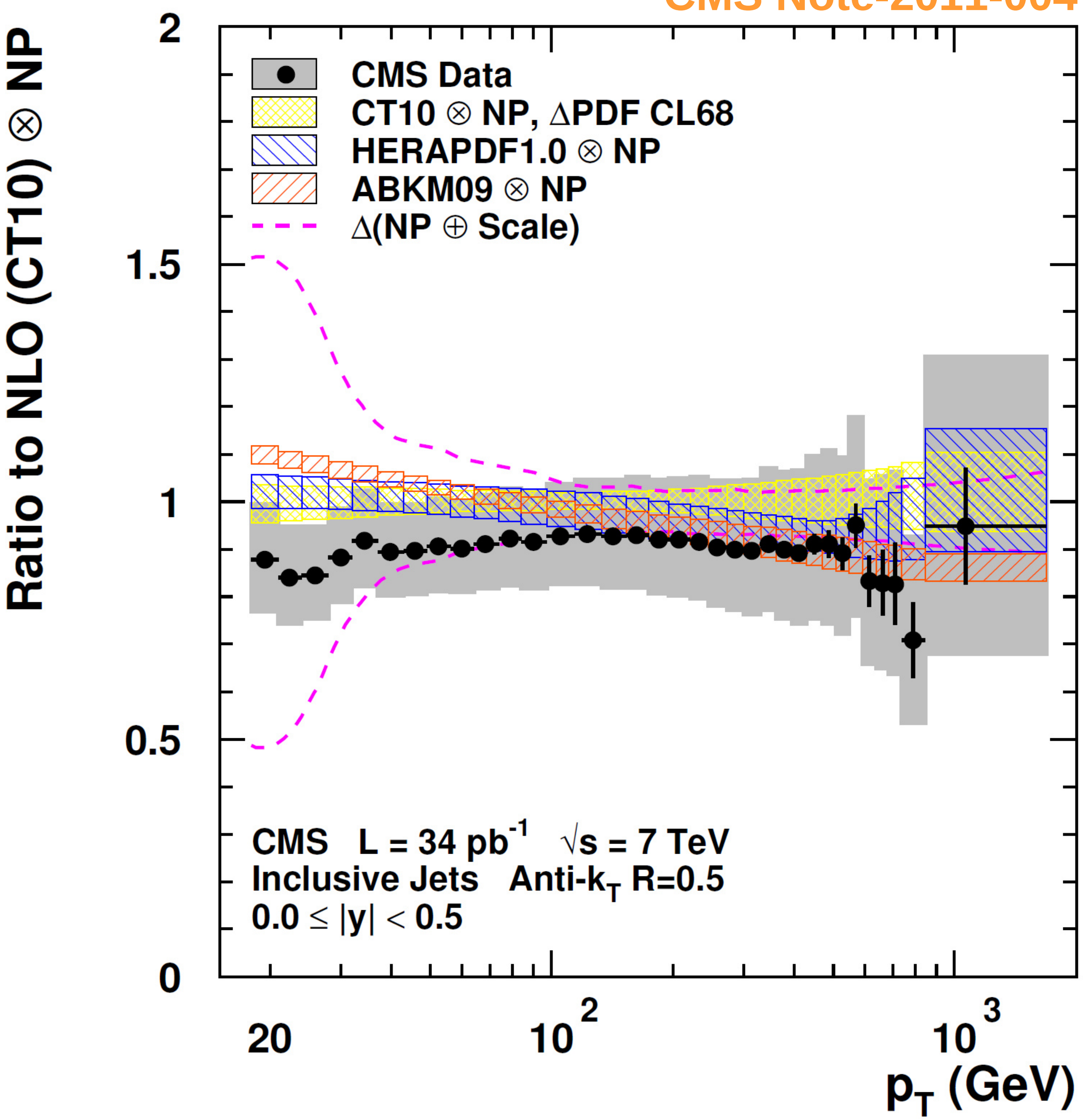
Release on February 14

Format foresees

- Threshold corrections (2-loop)
  - Tables are available
- New physics contributions
- Correction factors
  - Non-perturbative corrections
  - With uncertainties
- Data
  - Including arb. number of correlated and uncorrelated uncertainties
  - Correlation matrix
- Electroweak corrections

Conversion tool for v1.4 tables

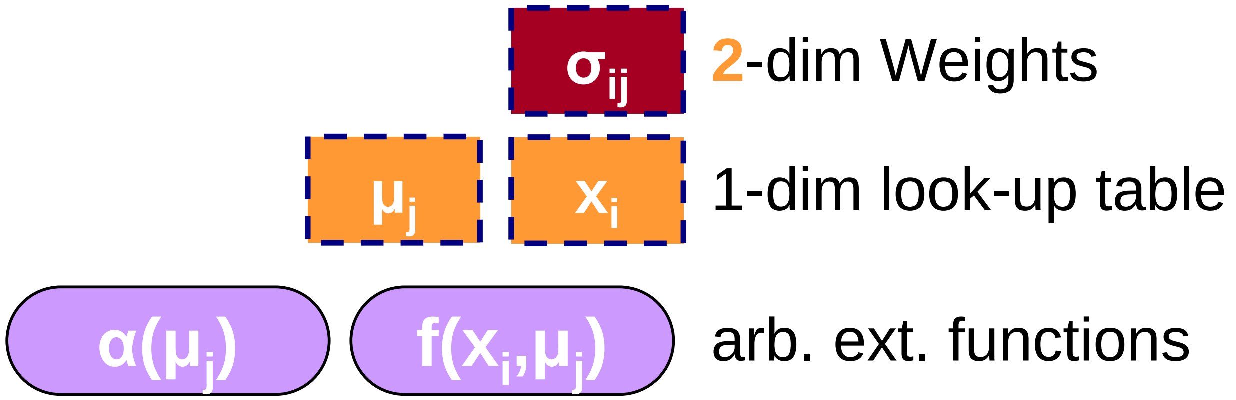
CMS Note-2011-004



Generalized fastNLO concept in v2.0

We know

$$\sigma \xrightarrow{fastNLO} \sum_j^{\mu} \sum_i^{x} \tilde{\sigma}_{ij}(\mu_j)\, f(x_i, \mu_j)\, \alpha_s(\mu_j)$$



We can use variables from look-up tables for 'any' further calculation (like $\alpha_s(\mu)$)

Generalized fastNLO concept in v2.0

fastNLO

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We can use variables from look-up tables for 'any' further calculation (like $\alpha_s(\mu)$)

σ_{ij} — 2-dim Weights

μ_j, x_i — 1-dim look-up table

$\alpha(\mu_j)$, $f(x_i,\mu_j)$ — arb. ext. functions

Scale independent weights

$$\omega(\mu_R,\mu_F) = \omega_0 + \log(\frac{\mu_R}{Q})\omega_R + \log(\frac{\mu_F}{Q})\omega_F$$

- 'log(μ/Q)' can be done at evaluation time

μ's are 'freely' choosable functions

- **μ -> $\mu(Q,p_T)$**

Generalized fastNLO concept in v2.0

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$$\sigma \xrightarrow{fastNLO} \sum_j^{\mu} \sum_i^{x} \tilde{\sigma}_{ij} (\mu_j) f(x_i, \mu_j) \alpha_s(\mu_j)$$

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- **μ ->** $\mu(Q,p_T)$

new in v2.0

σ^0_{ijk} σ^R_{ijk} σ^F_{ijk} — 3-dim Weights

p_T Q^2 x_i — 1-dim look-up table

$\alpha(\mu_R)$ $f(x_i,\mu_F)$ — arb. ext. functions

$\mu_F(Q,p_T)$ $\mu_R(Q,p_T)$ — arb. ext. functions

We store scale independent contribution

Three tables holding the weights

Further scale-variables -> $\sigma_{ijk...}$ need more dimensions

1) We can choose μ_R independently from μ_F

2) We can choose the functional form of $\mu_{R/F}$ as functions of look-up-variables

New Features for Scales

When evaluating fastNLO cross section

- **Choose scale composition** from previously stored scales
  - e.g. $\mu_r^2 = (Q^2 + p_T^2) / 2$
  - $\mu_r^2 = Q^2$
  - $\mu_r^2 = p_T^2$
  - …

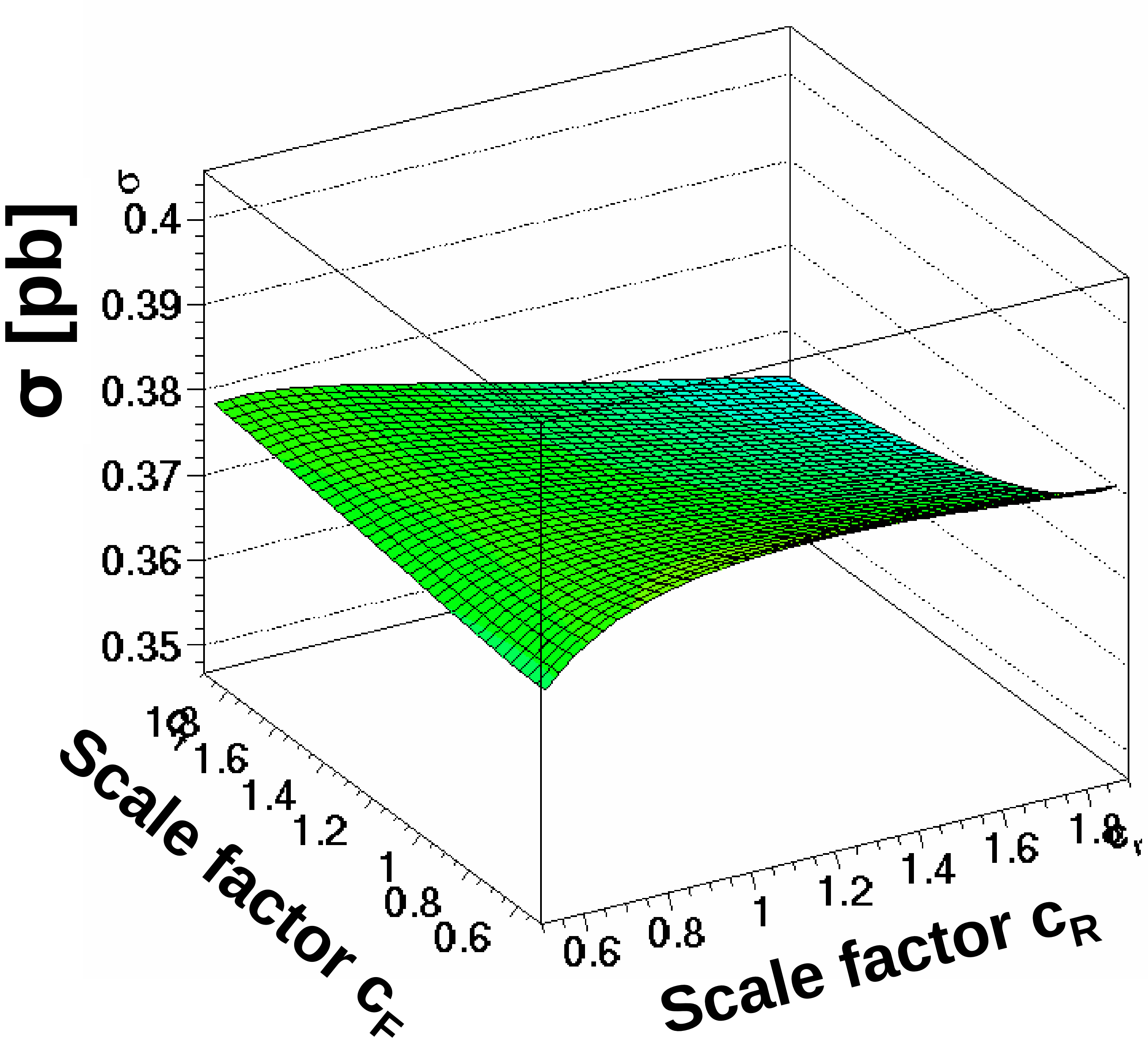
Also scale variation for μ_r and μ_f are thus independently possible **through**

- $\mu_R^2 = c^2_R \times (Q^2 + p_T^2) / 2$
- $\mu_F^2 = c^2_F \times Q^2$

New options for scans of scale dependence

Concept also implemented for pp and ppbar

Zeus Dijets @ High Q²



fastNLO Precision

Free Parameters

- # x-nodes
- # scale nodes
- -> Affect the interpolation precision

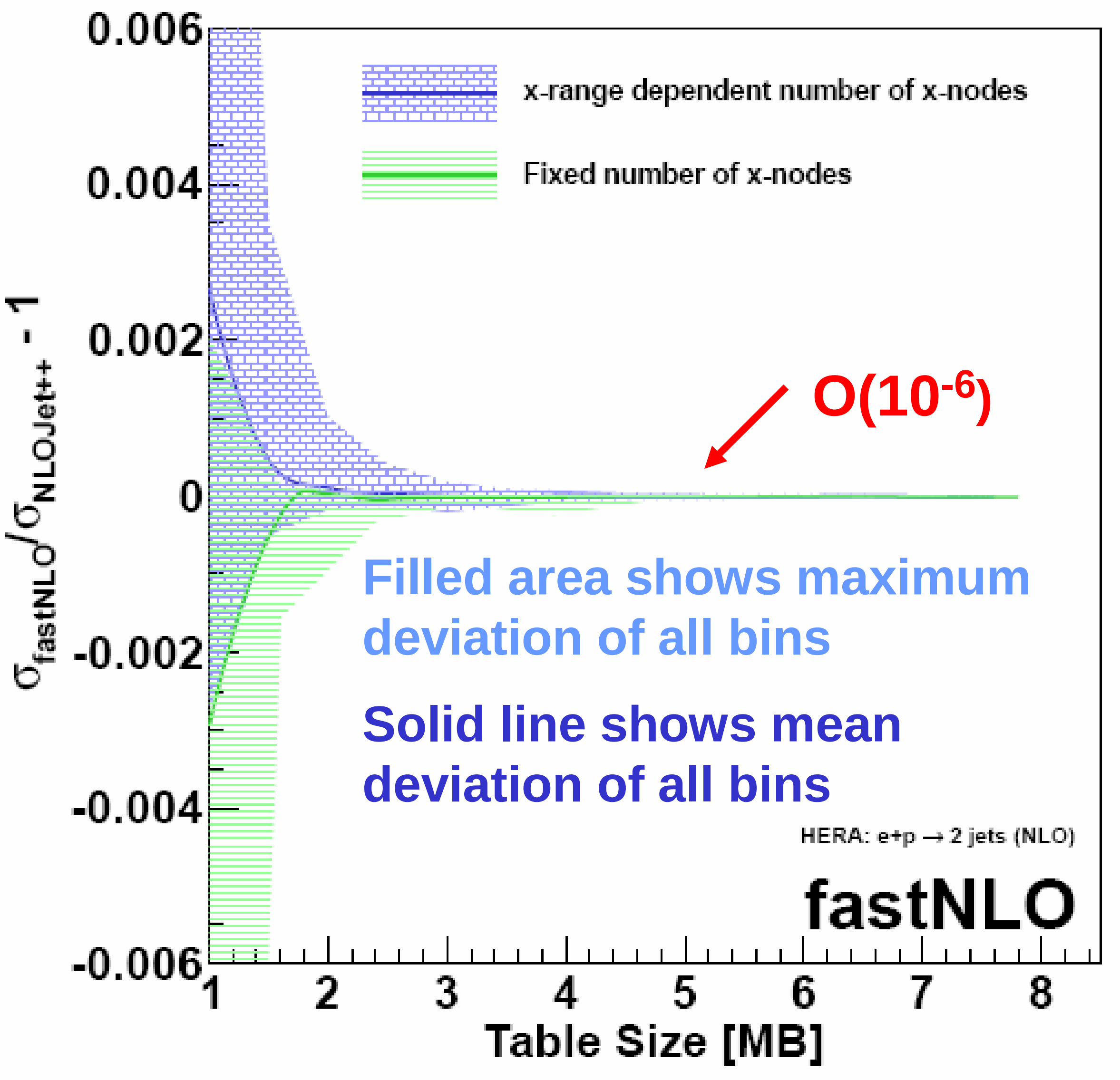
New feature in v2.0

- Flexible # x-nodes
- Number of x-nodes chosen depending on x-range

Comparison vs. 'plain' NLOJet++

- Arbitrary precision possible
- For O(MB) tables, reach better than 1 per mille

H1 Incl. Jets @ High Q^2 (24 bins)



Example: Scale studies with ATLAS Dijet M_{12}

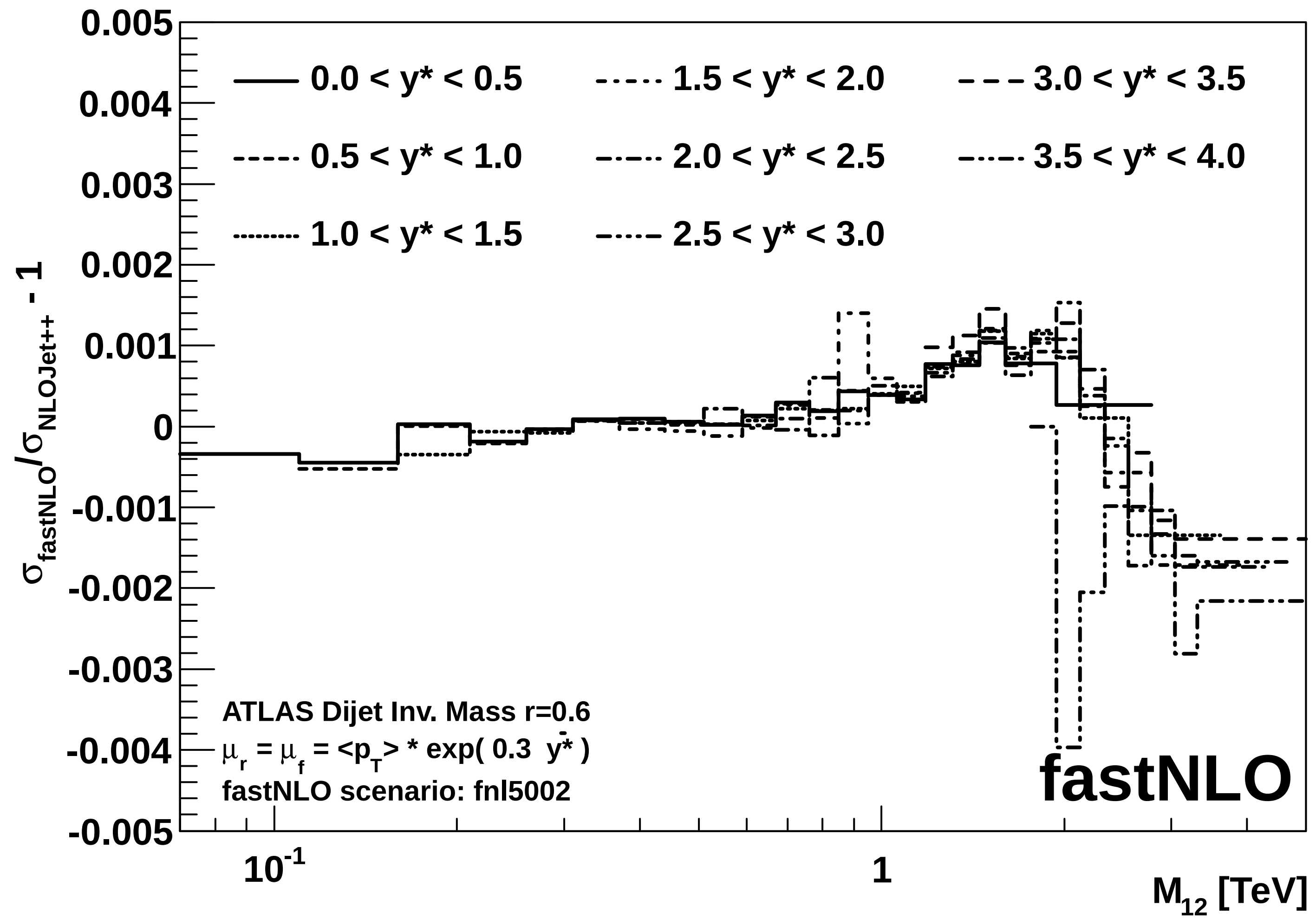
pp and ppbar Scenarios
'flexible scale concept' works as well

ATLAS Dijet Invariant Mass, r=0.6
p_T and y* are stored in table
Ren./fact. scale can be any function of (p_T,y*)

Can study variations of ATLAS dijet scale choice $p_T \cdot \exp(0.3 \cdot y^*)$

-> We can vary parameter '0.3'
-> We can use different functions (e.g. cosh)
-> We can e.g. find optimal scale (FAC,PMS)

fastNLO vs. plain NLOJet++ calculation with free choice of ren./fac. scale
Precision ~ 10^{-3}

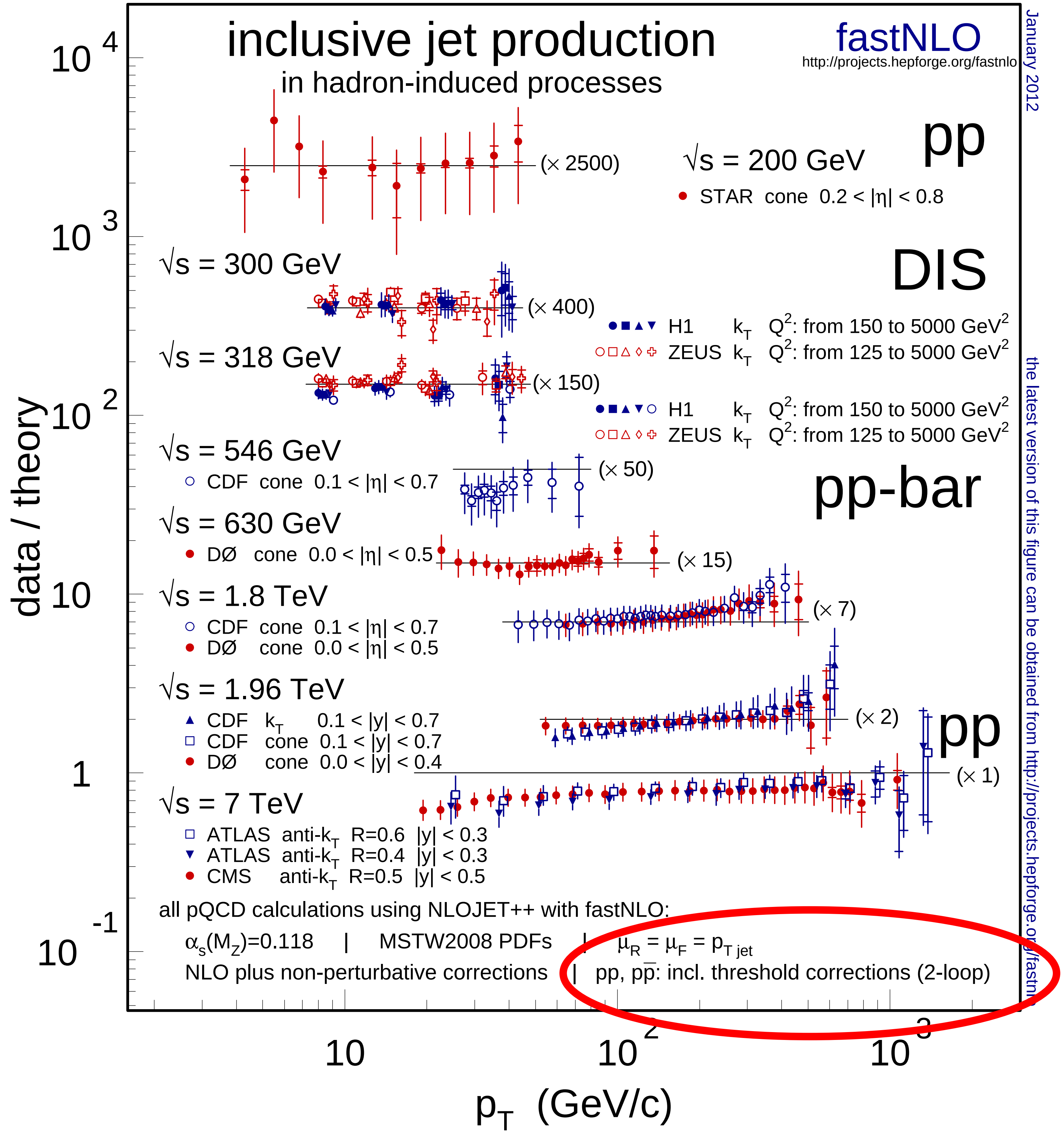


Data/Theory Comparision of Jet Cross Sections

Comparision of inclusive jet data
- STAR @ RHIC
- H1 and ZEUS @ HERA
- CDF and D0 @ TeVatron
- CMS and ATLAS @ LHC

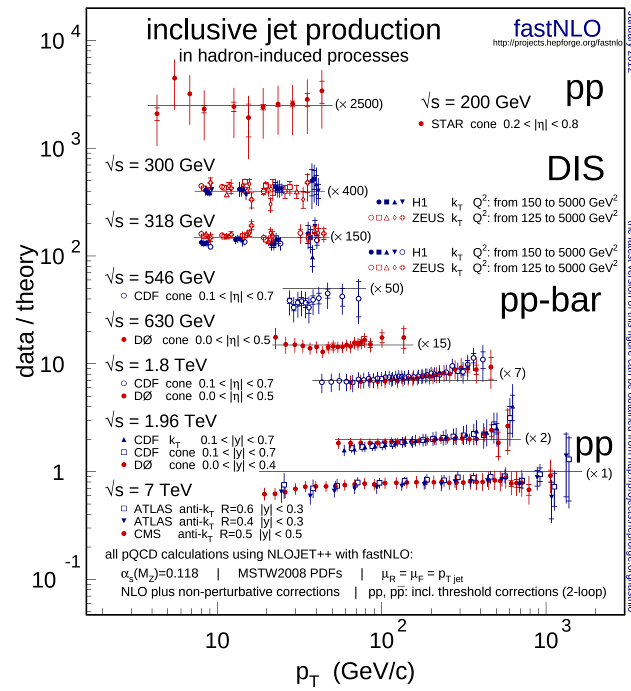
Data/theory comparision
Compatible with NLO pQCD

hadron-hadron including 'threshold corrections' O(2-loop)



fastNLO, arXiv:1109:1310v1, 2011
here: updated plot!
See data references there.

Summary



Release

User code released

C++ and Fortran code (No further dependencies)

Lots of calculations available for all experiments ATLAS, CMS, D0, CDF, ZEUS, H1, STAR

New features

Multiplicative and additive contributions

- threshold corrections, non-perturbative corrections, data, EW contribtions, new physics, etc…

Technicalities

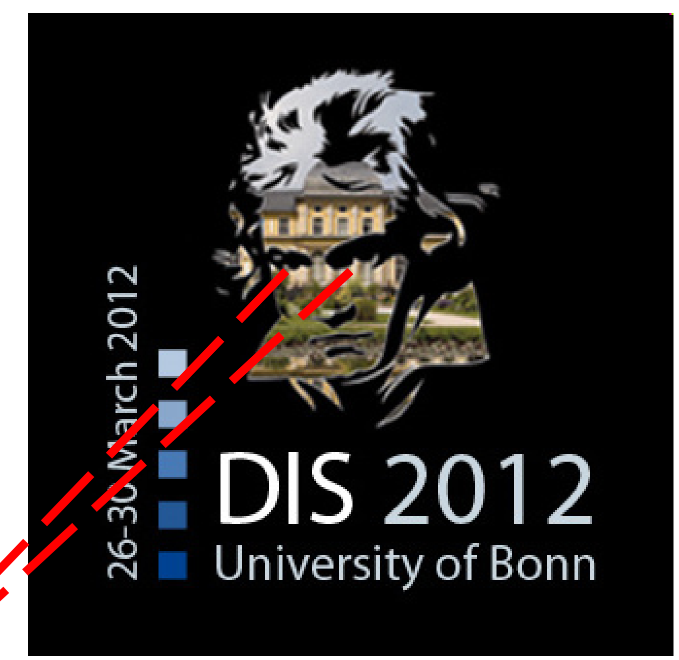
- Automated x-scan, flexible number of x-nodes, Scale gets own dimension, improved interpolation, etc…

'Flexible scale' tables

Choose composition of μ_R and μ_F

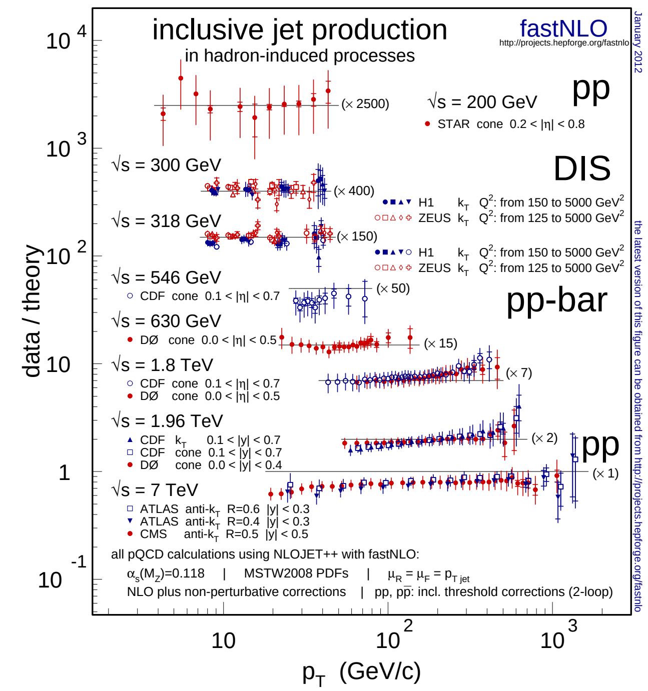
Vary ren./fact. scales independently

Scale varyations also for higher orders without any recalculations or integrations (which might be slow again!)



-> Visit our website: http://fastnlo.hepforge.org

Summary



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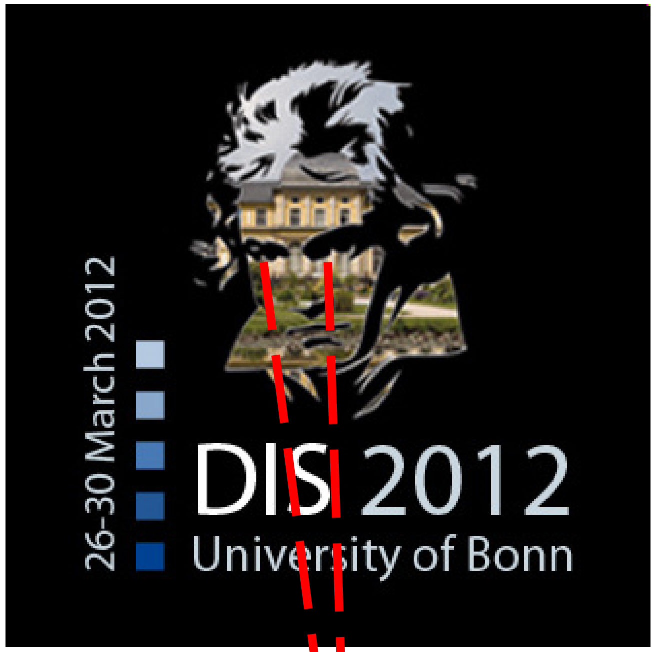

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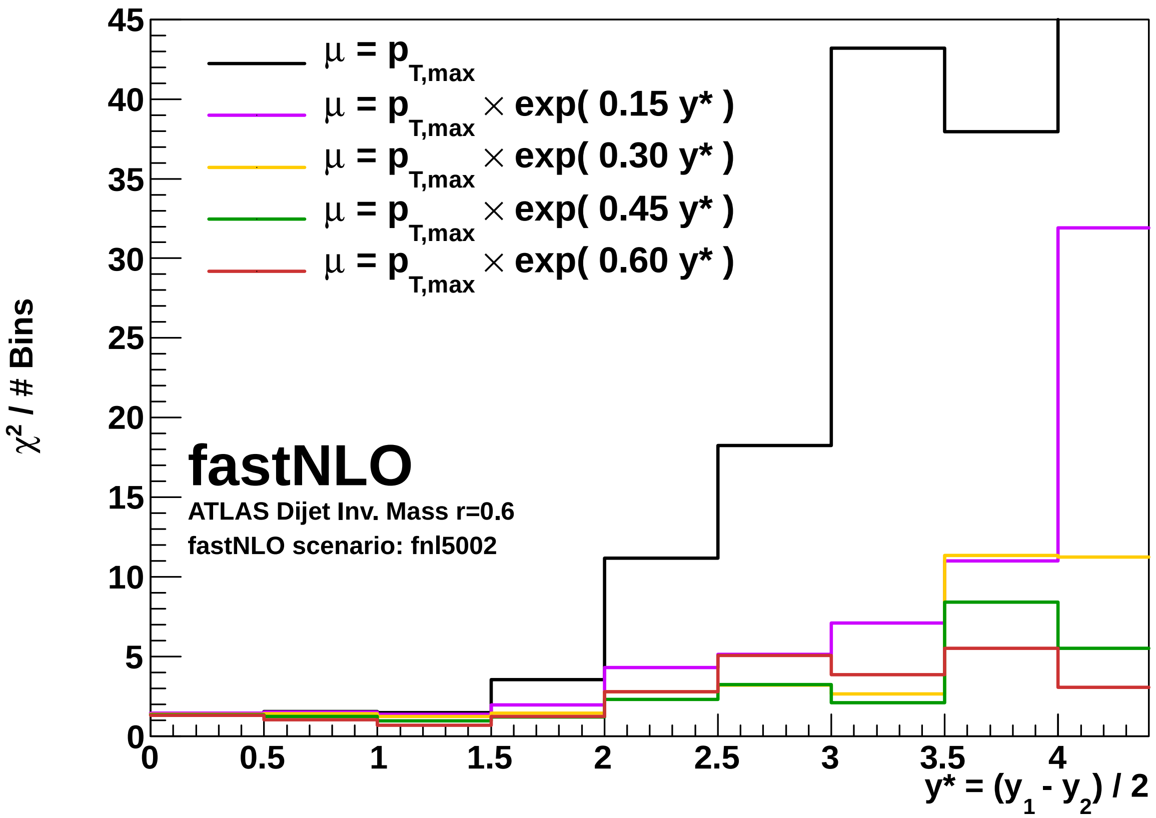
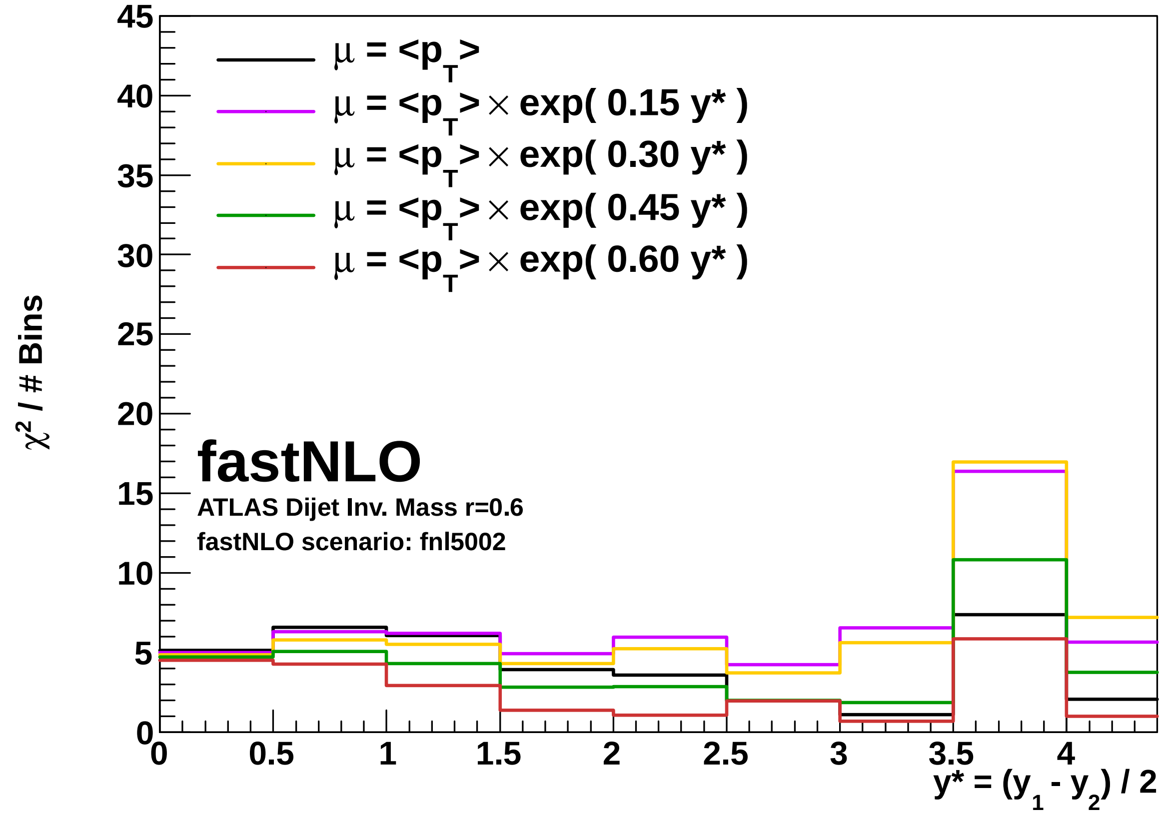
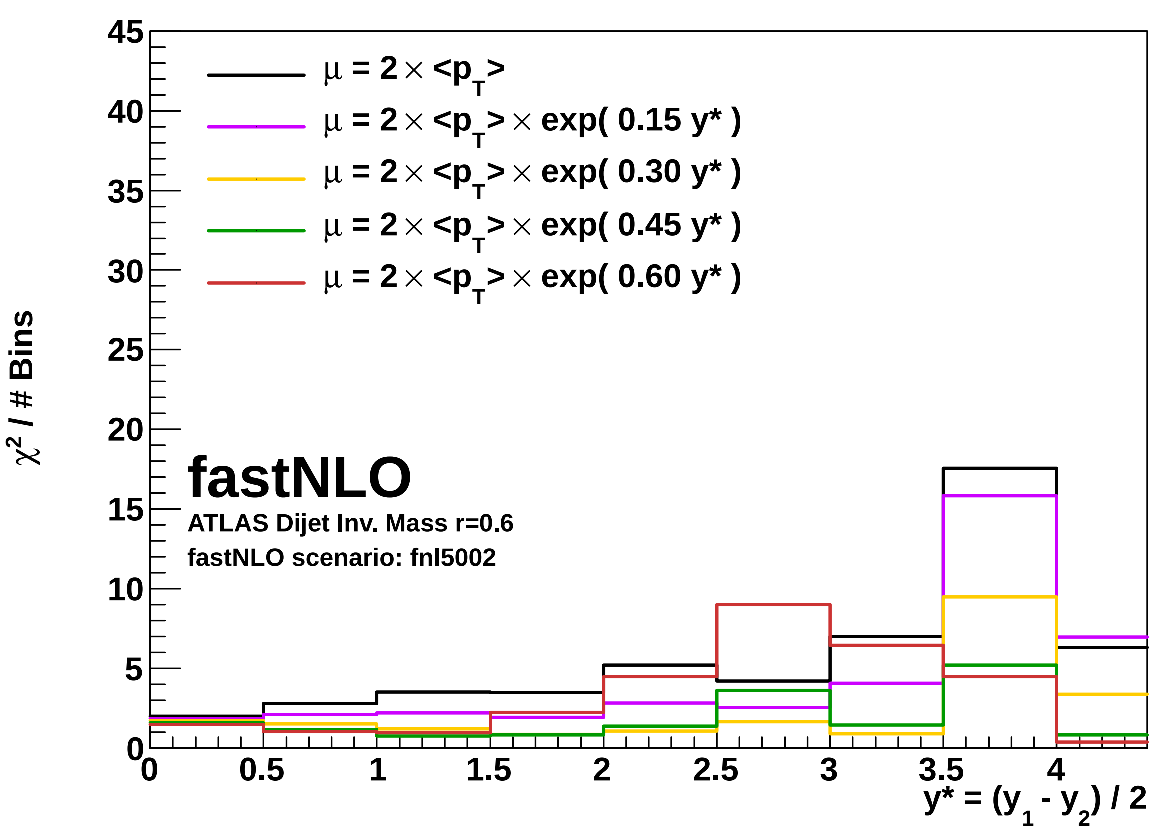
… after the hepforge transition

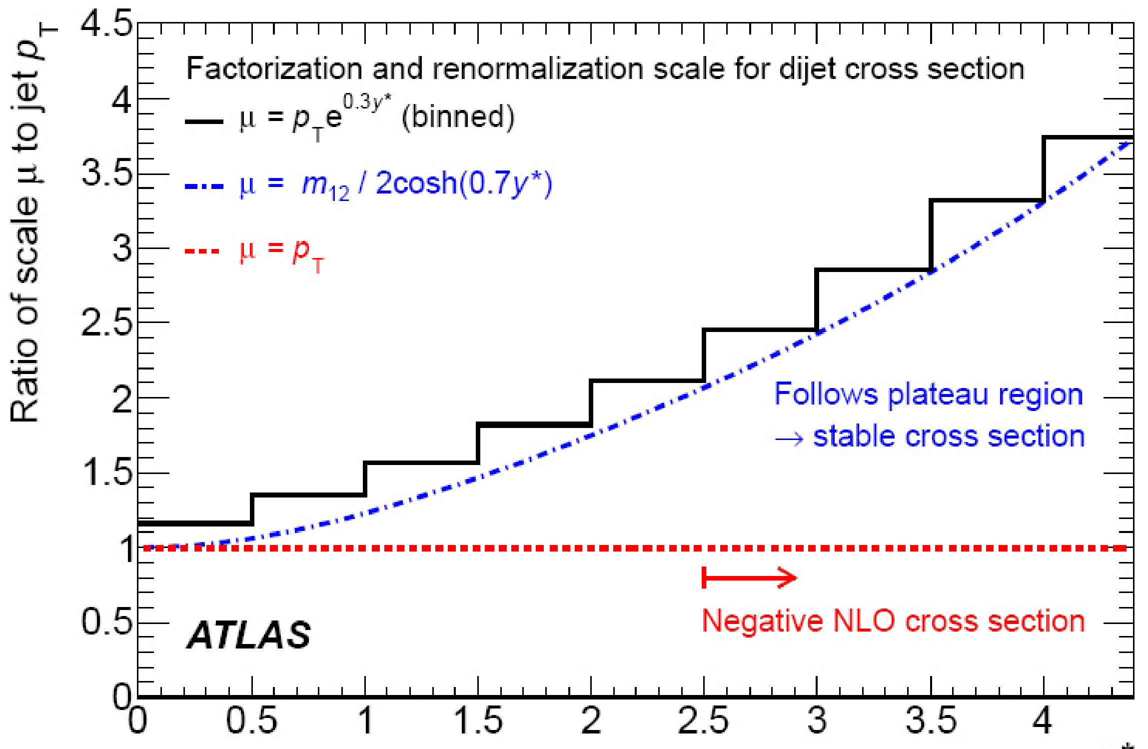
Backup

Stuying the scale choice of ATLAS



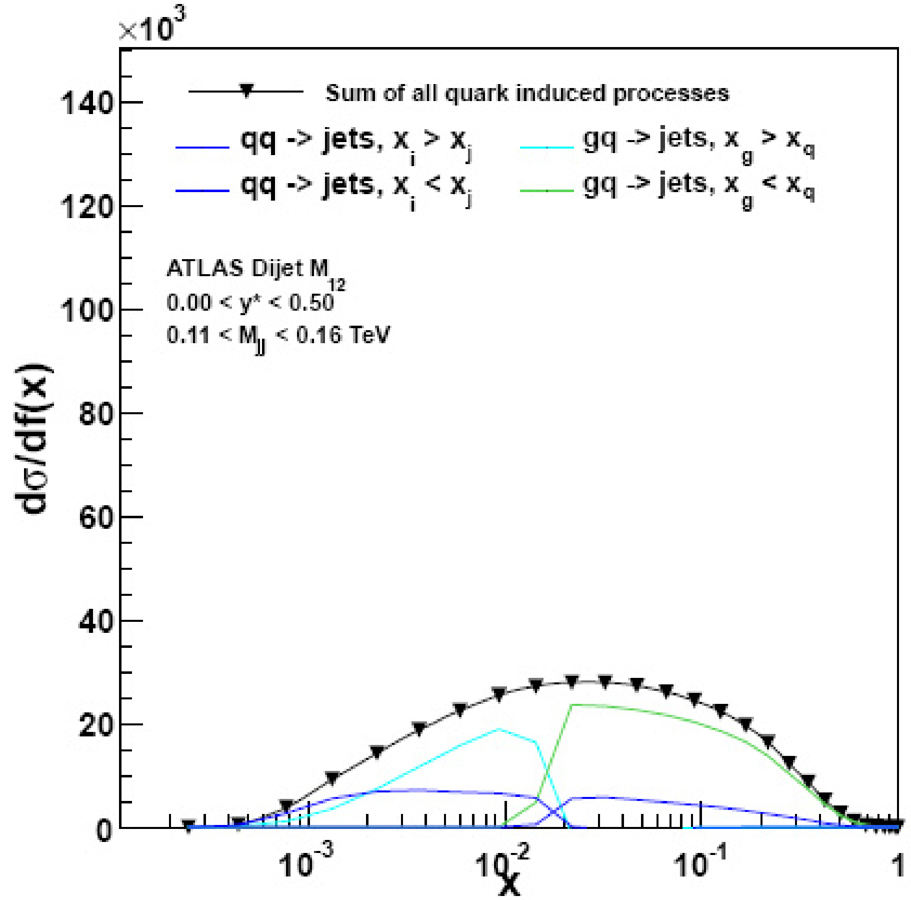




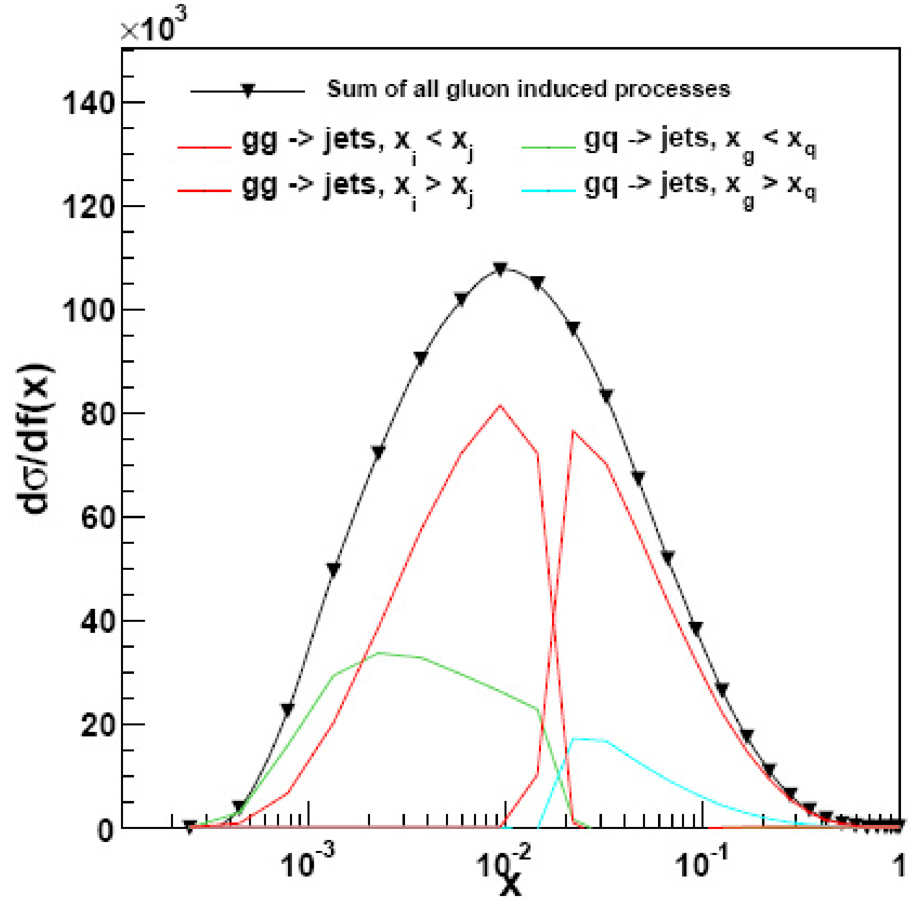


arXiv:1112.6297 [hep-ex]

Quark contributions



Gluon contributions



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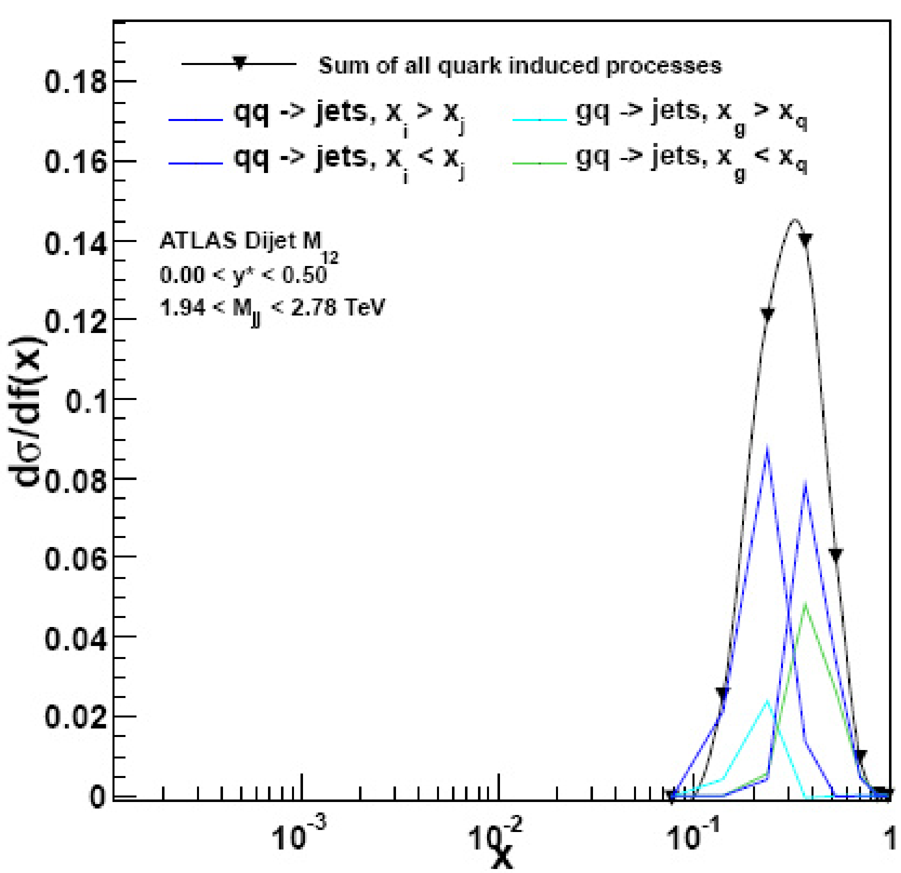
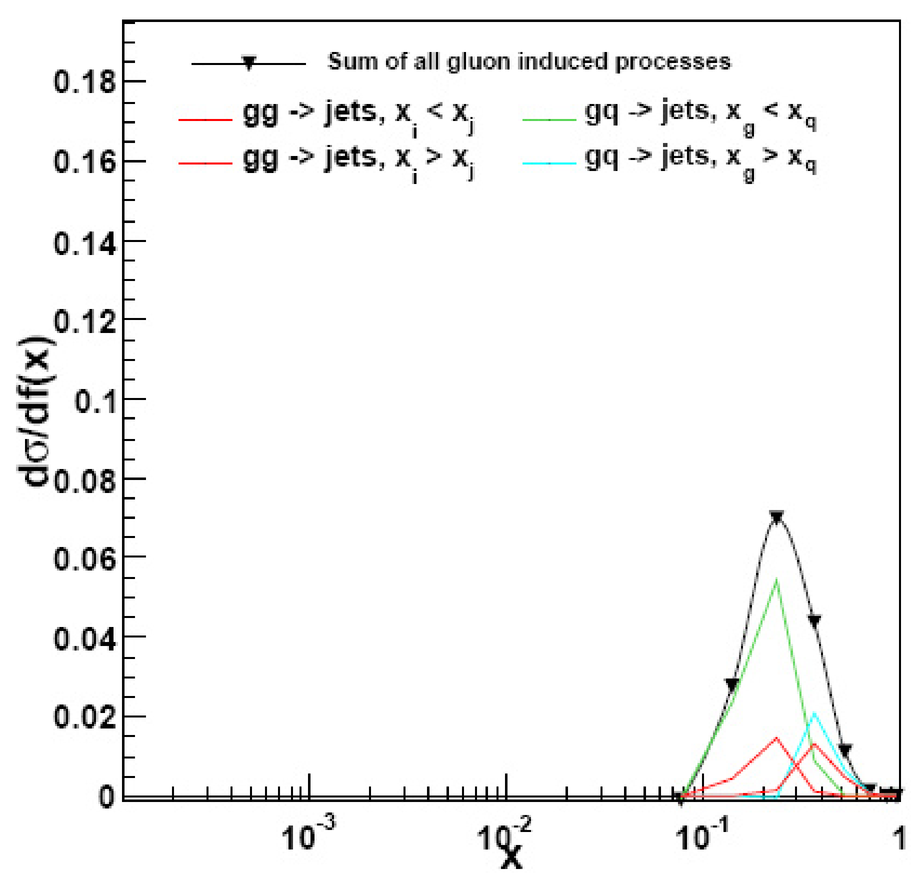


Gluon contributions



Applications

Application area

Can be used for any observable in hadron-induced processes

- Hadron-hadron
- DIS
- Photoproduction
- Fragmentation functions

Theory prediction

Although labeled "fastNLO" method can be used at any order

Concept does not include the theoretical calculation itself

Requires flexible computer code, e.g.:

- NLOJET++ (Z. Nagy PRD68 2003, PRL88 2002)
- Threshold corrections (Kidonakis, Owens, PRD 63, 054019 (2001))

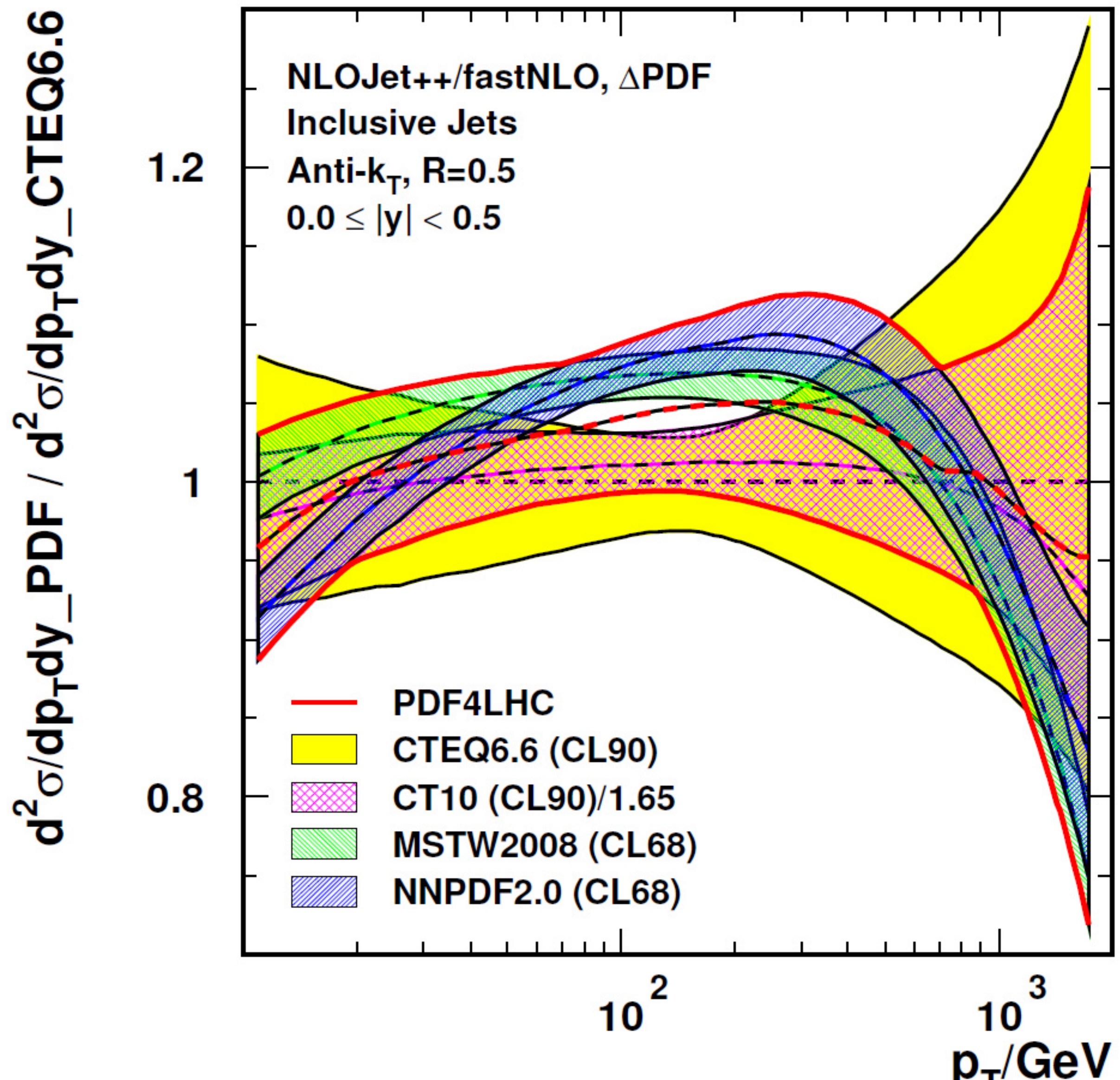
Application procedure

During the first computation no time is saved

Any further recalculation takes only O(ms)

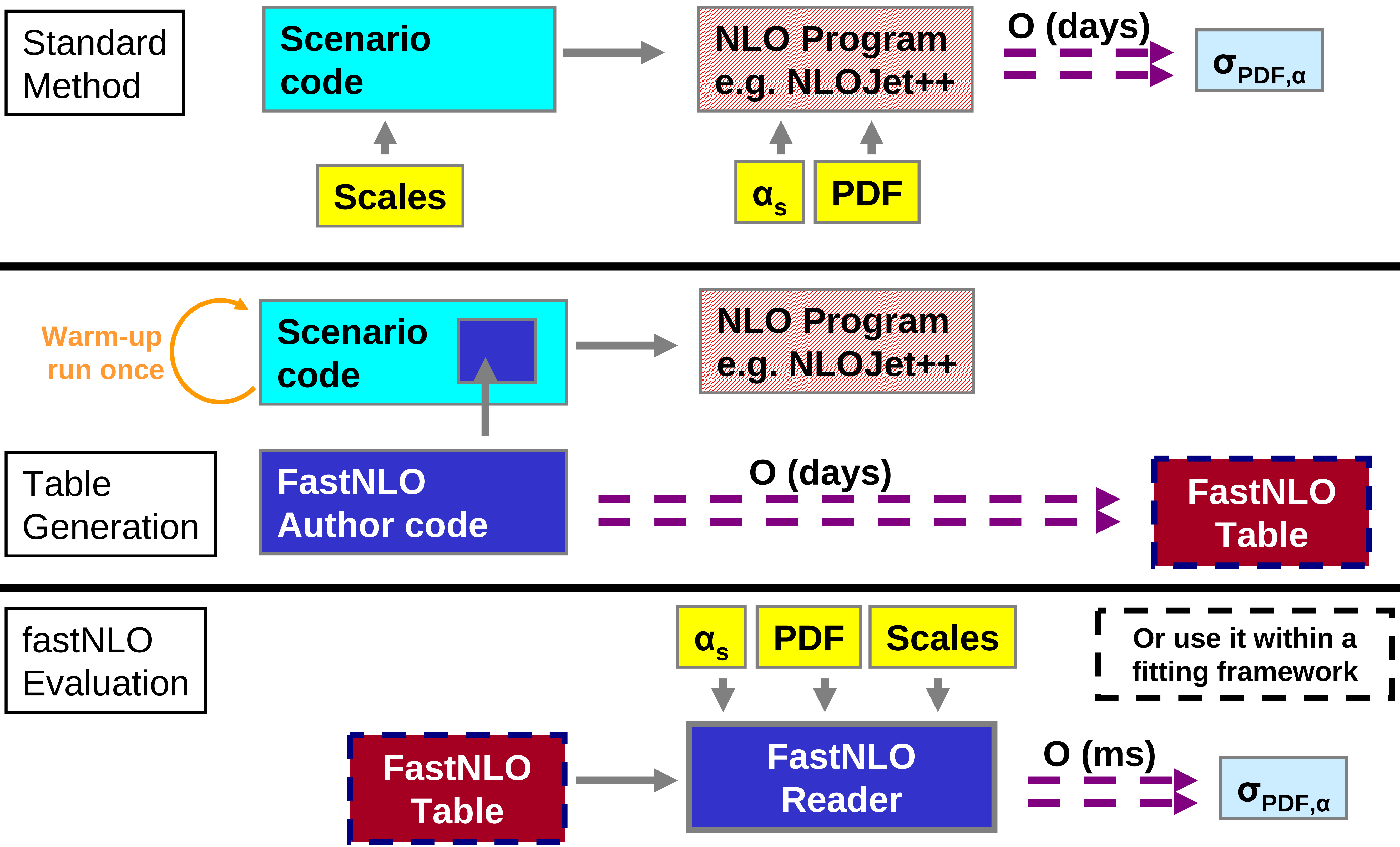
Example: PDF-Error predictions à la PDF4LHC recommendation

Envelope of predictions of CT10, MSTW and NNPDF at CL68. Compared to CTEQ6.6 (CL90)



239 NLO repeated calculations

The fastNLO concept



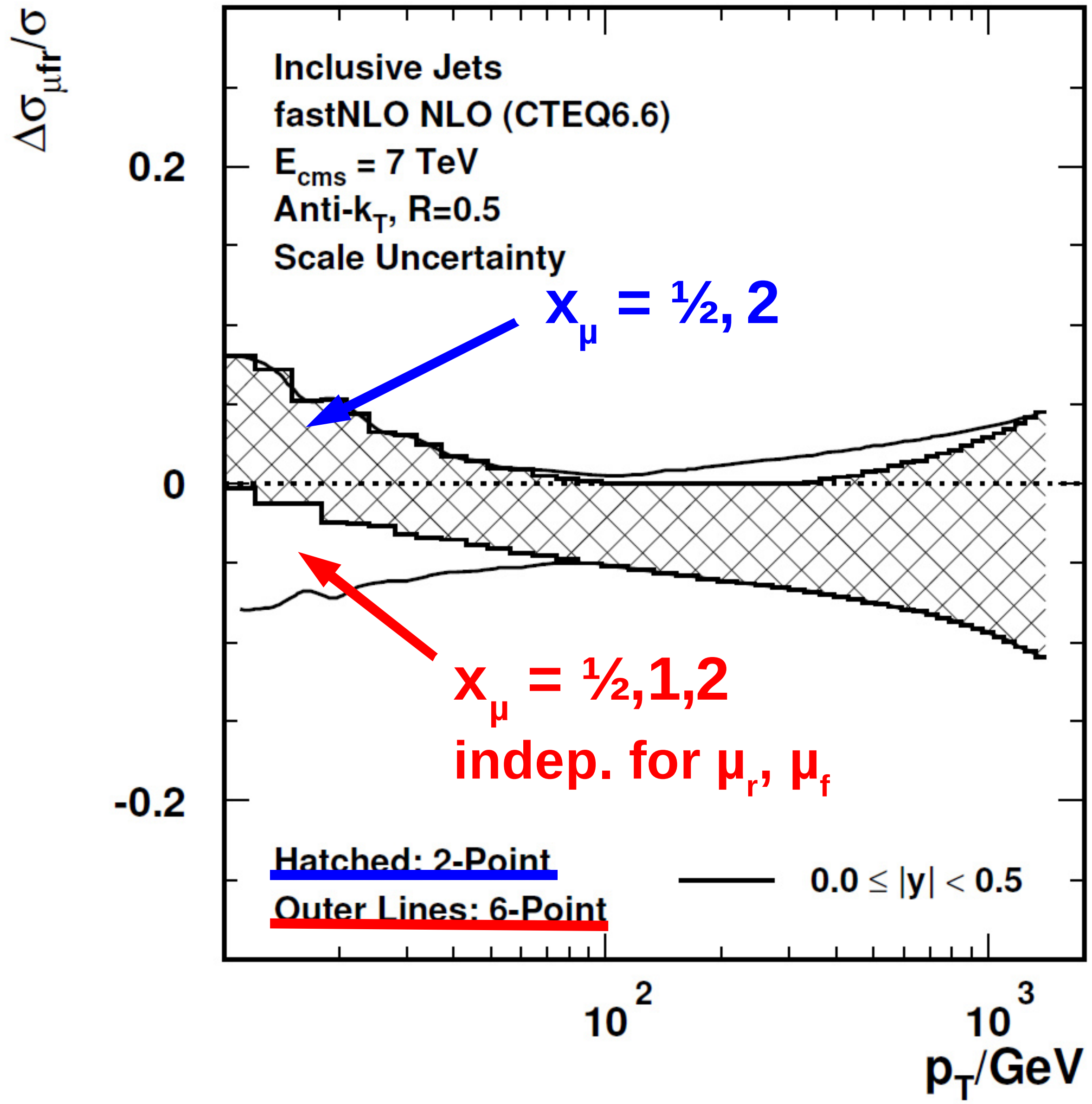
Scales in FastNLO

FastNLO tables come with 3 (4) simultaneous scale variations tables

- e.g. 0.5, 1.0, 2.0 times the nominal scale

A posteriori scale variation **of the renormalizatoin scale allows study of** asymetric scale **variations**

- e.g. 6-points: (1/2,1/2), (1/2,1), (1,1/2), (1,2), (2,1), (2,2)
- avoiding of rel. 'factor' 4.



Improvements in v 2.0

- scales get own dimension
- bicubic interpolation of scale-value to scale nodes
- typically 6 scale nodes
- examples already for
  - CMS incl. jets
  - D0 3-jet mass
  - …

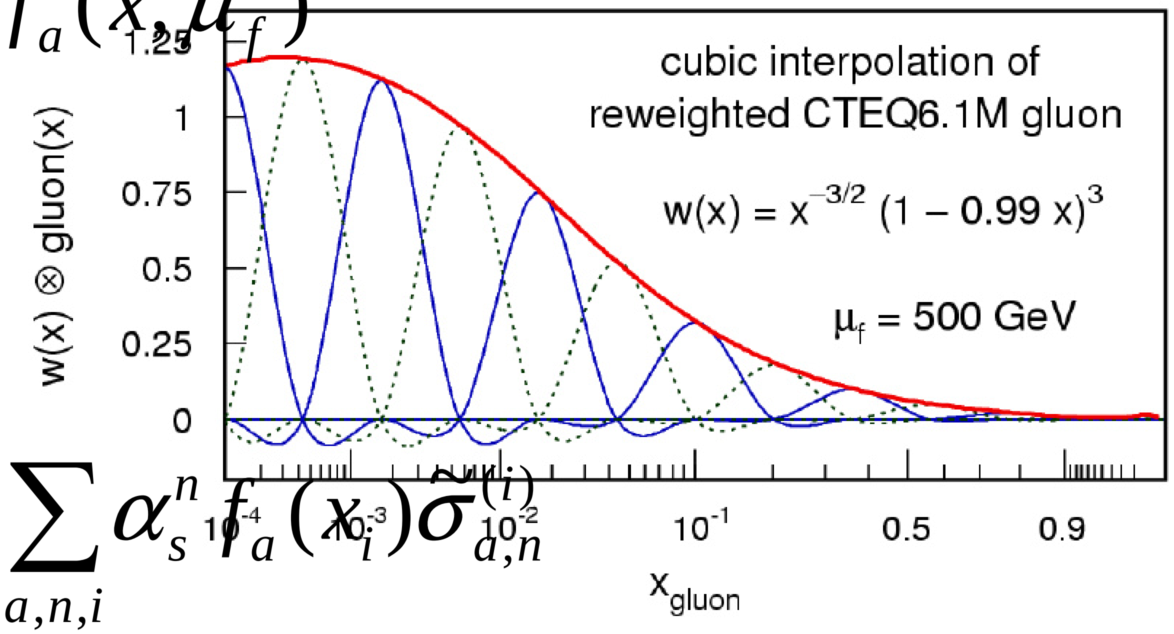
Standard methods for higher-order pQCD calculations of cross sections in hadron-induced collisions are time-consuming. The fastNLO project uses multi-dimensional interpolation techniques to convert the convolutions of perturbative coefficients with parton distribution functions and the strong coupling into simple products. By integrating the perturbative coefficients for a given observable with interpolation kernels, fastNLO can store the results of the time-consuming calculation in tables which can subsequently be used for very fast calculations of the same observable for arbitrary PDFs, alpha_s, and different scales. These tables and corresponding user codes are currently available for a large number of jet measurements at the LHC, the Fermilab Tevatron, and HERA. fastNLO is currently used in publications of experimental results by the ATLAS, CMS, CDF, D0, and H1 collaborations, and in all recent global PDF analyses by MSTW, CTEQ, and NNPDF. This talk will focus on new developments, implemented in the new version 2 of fastNLO, which enhance and broaden the functionality.

The fastNLO concept

Jet cross sections are very slow to calculate
-> Need of method for very fast repeated calculation **of cross sections**

$$\sigma = \sum_{a,n} \int_0^1 dx \alpha_s^n(\mu_r) \cdot c_{a,n}\left(\frac{x_{Bj}}{x}, \mu_r, \mu_f\right) \cdot f_a(x, \mu_f)$$

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



$$\sigma \cong \sum_{a,n,i} \alpha_s^n f_a(x_i) \underbrace{\int dx c_{a,n}\left(\frac{x_{Bj}}{x}\right) E^{(i)}(x)}_{\tilde{\sigma}} = \sum_{a,n,i} \alpha_s^n f_a(x_i) \tilde{\sigma}_{a,n}^{(i)}$$

FastNLO **factorizes the cross section calculation for an** a-posteriori **inclusion of pdf's and alpha_s for e.g. jet-production**

Introduce set of n discrete **$x_{(i)}$'s**
with $x_n < .. < x_i < .. < x_0 = 1$
Around each $x_{(i)}$ define eigen function **$E^{(i)}(x)$ with:**
$E^{(i)}(x_i) = 1$, $E^{(i)}(x_j) = 0$ ($i \neq j$), $\Sigma_i E^{(i)}(x) = 1$ for all x
single pdf is replaced by a linear combination of eigenfunctions
integrals are replaced by sums
Better: Usage of bi-cubic interpolation **and** pdf reweighting

hadron-hadron -> everything just more complicated, but same concept

Which x-region do we test with jet data?

E.g. H1 dijets @ high Q^2

four bins:

- low and high Q^2
- low and high <pt>

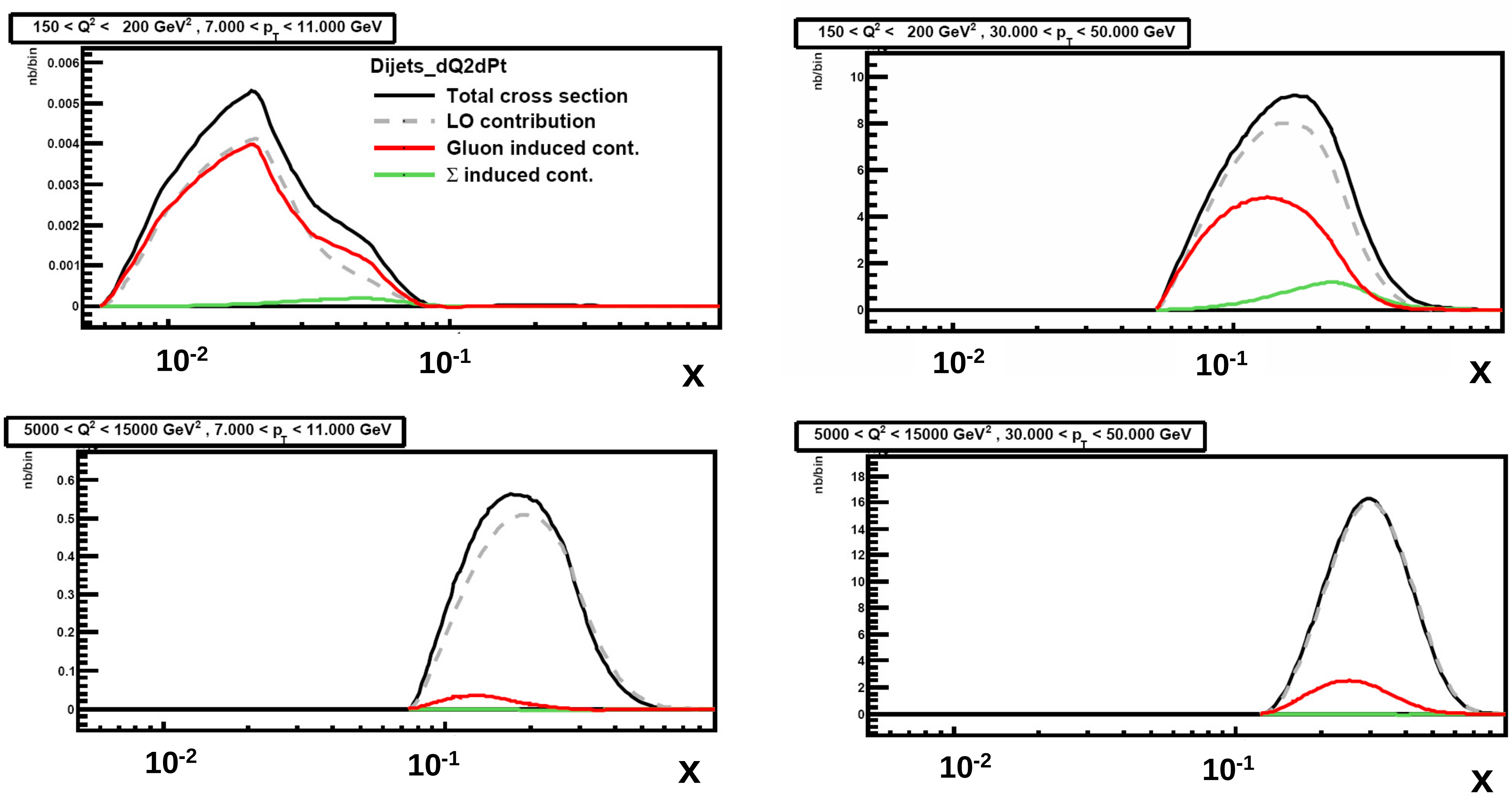
Only three contributions in DIS

Gluon, Delta, Sigma induced processes

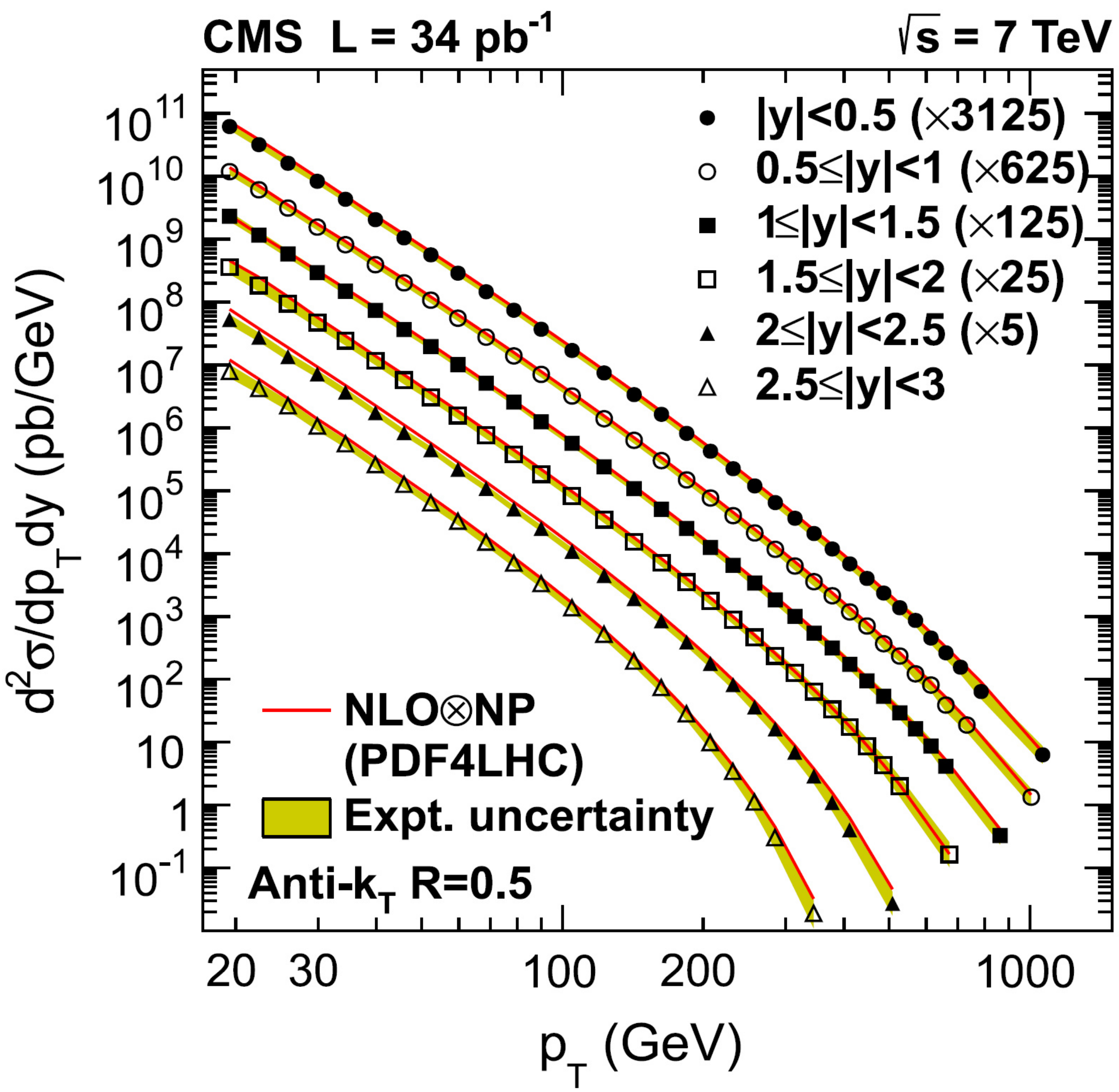
low Q^2 is mostly gluon induced

High Q^2 is mostly Delta induced

'low' x-region only at low <pt> and low Q^2



Can we do the same for CMS incl. jets?



CMS, PRL 107, 132001, 2011

CMS inclusive jets
176 bins
6 rapidity regions

To which 'x'-regions and to which pdfs are we sensitive to???