fastNLO for Jetproduction in Diffractive DIS

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fastNLO

Motivation

- Calculation of jet cross sections in higher orders are time consuming
- Often: Calculations have to be repeated for same measurement but different PDFs or α_s (e.g. PDF uncertainties, scale variations, etc…)
- Inclusion of jet-data in a fit (e.g. PDF or α_s) requires very fast recomputation of almost the same cross sections

Need procedure for fast repeated computations of NLO cross sections

use: fastNLO

fastNLO

fastNLO concept

- Jet-production cross section in DIS

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

- Introduce interpolation kernels for 'x' using Eigenfunctions $E_i(x)$

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

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

- We can calculate once a table with perturbative coeff. using e.g. nlojet++

- Cross section is then just a sum over all interpolation nodes

$$\sigma_{DIS}^{Bin} = \sum_{i,a,n,m} \alpha_s^n(\mu^{(m)}) \cdot f_a(x_1^{(i)}, \mu^{(m)}) \cdot \tilde{\sigma}_{a,n}^{(i)(m)}$$

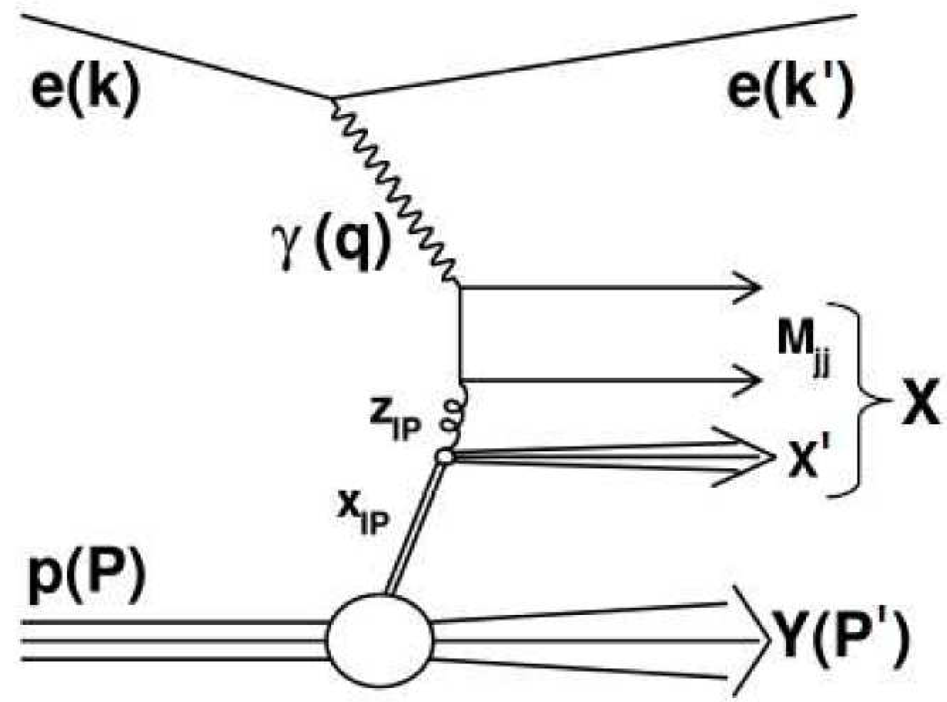
More features of fastNLO

e.g.Scale interpolation, PDF reweighting, scale independent contr., etc..

Jet production in diffractive DIS

Jetproduction in diffractive DIS (t=0)

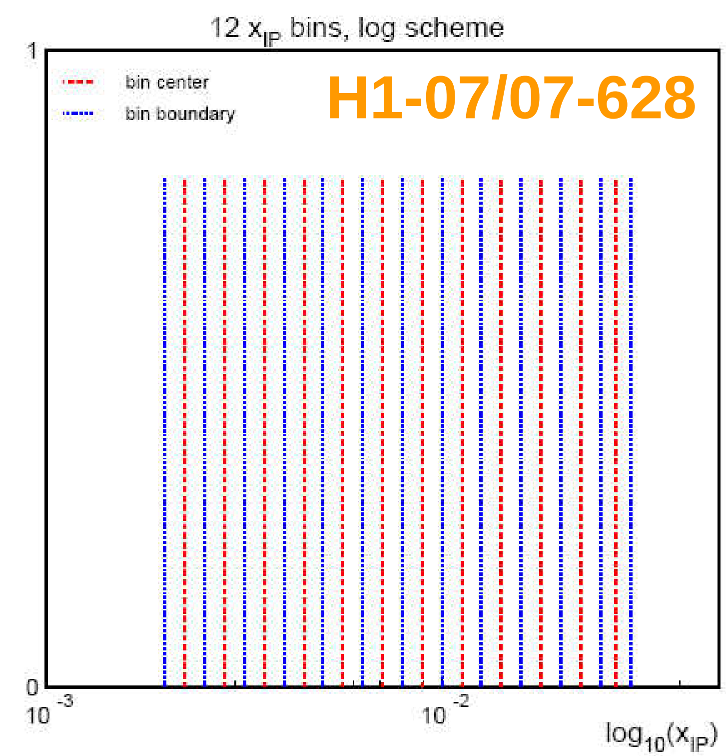
$$\sigma = \sum_{a,n} \int_0^1 dx_{IP} \int_0^1 dz_{IP} \alpha_s^n \cdot c_{a,n} \cdot f_a(x_{IP}, z_{IP}, \mu_f)$$



Standard method of calculating NLO cross sections: 'Slicing method'

- Riemann-Integration of dx_{IP}
  - Discretize the x_{IP} range into k bins (k~10)
- Repeated cross section calculation with reduced hadron energy for each slice of x_{IP}
  - fixed value of $x_{IP,i}$
  - At reduced center of mass energy of sqrt(s) = $x_{IP} \cdot 4E_P E_e$
  - slice-width Δx_{IP}

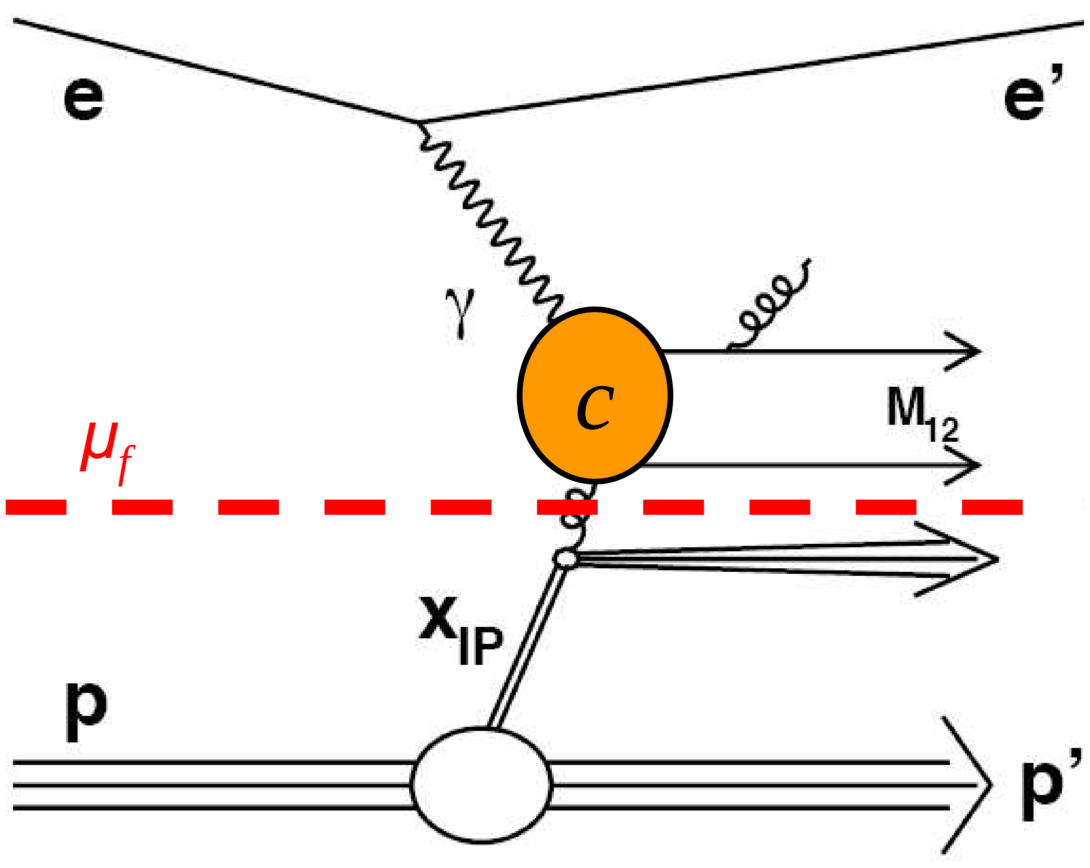
$$\int_0^1 dx_{IP} f_{IP/a}(x_{IP,i}) \sigma_{IP}(x_{IP}) \cong \sum_k \Delta x_{IP,i} f_{IP/a}(x_{IP,i}) \sigma_{IP}(x_{IP})$$



Jet production in diffractive DIS

Perturbative coefficients have only dependence on momentum fraction

- No direct dependence of the two momentum fractions x_{IP} and z_{IP}
- Each slice calculates basically same coefficients c
- Factorization is independent of incoming parton



Perform x_{IP}-Integration a-posteriori

Calculate one fastNLO table with hadron energy = proton energy

Calculation of only one single fastNLO table is needed

- Very high statistical precision
- No limitations in x_{IP} integration

Proof of concept

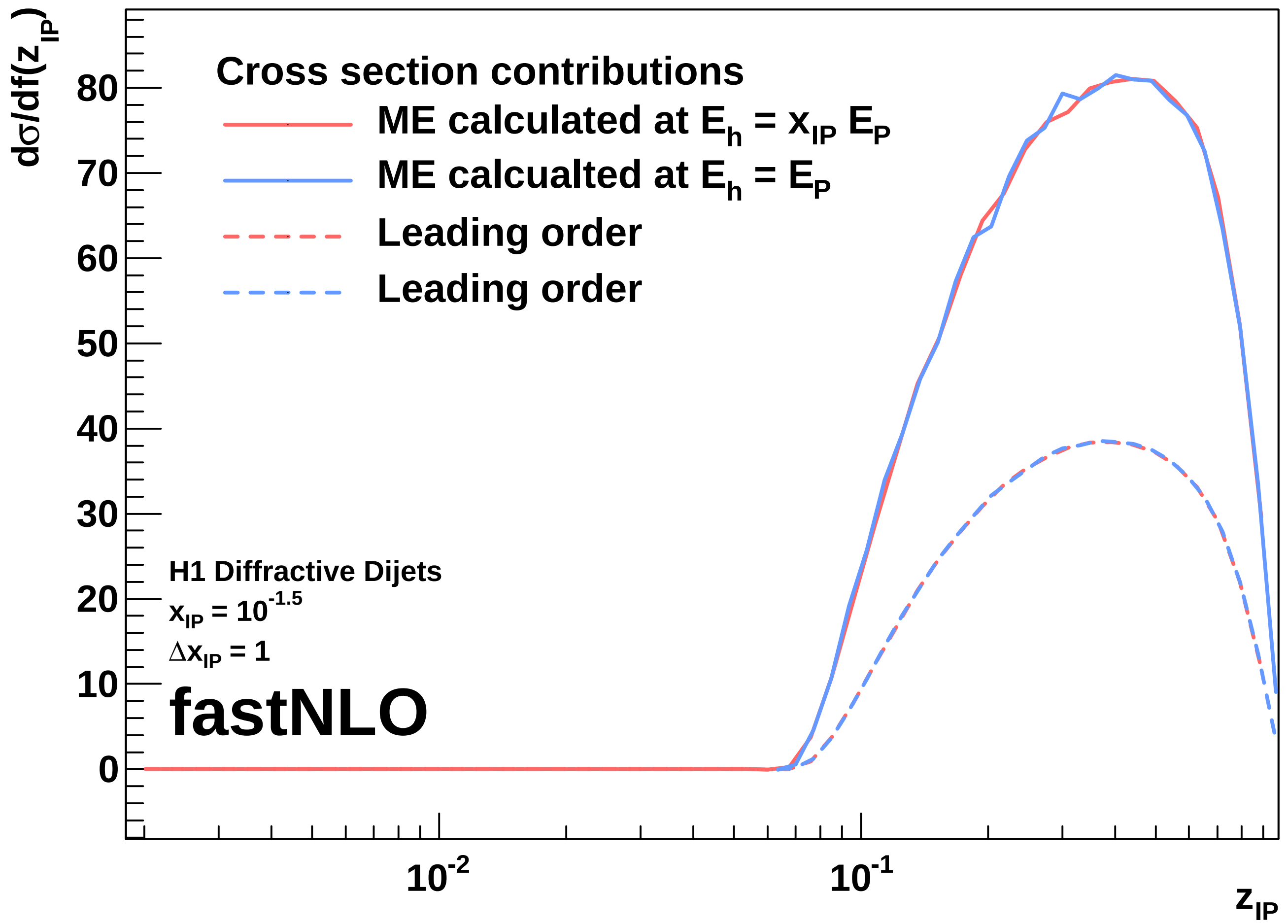
Compare two cross section calculations for one single fixed x_{IP} slice at
$x_{IP} = 10^{-1.5}$

Cross section contribution with reduced CME (standard slicing method)
Hadron = Pomeron
$E_h = x_{IP} \cdot E_P$

Calculate matrix elements using proton energy (new method)
Hadron = Proton
$E_h = E_P$

Compare z_{IP} dependent cross section contribution
$z_{IP} = x_{hadron}$
$z_{IP} = x_{hadron}/x_{IP} < 1$

x_{hadron} being the momentum fraction of the parton wrt. to the incoming hadron (Pomeron) momentum



Perfect agreement

- Perturbative coefficients are identical for each x_{IP} slice

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 x wrt. E_p
- Formulae calculated properly by Federico !!!

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

Integral becomes a standard fastNLO evaluation

Upper integration interval needs to be respected properly

- x-integration runs over discrete x-nodes
- Uppermost x-node is weighted according to its range inside/outside of the integration interval

FastNLO procedure improves previously used approach

Code example for pre-calculated fastNLO table

```
// FastNLO example code in C++ for reading
//   H1 diffractive dijets dP*_T,1
//   Eur.Phys.J. C70 (2010) 15

FastNLODiffH12006FitB fnlodiff( "fnhd1012.tab" );
fnlodiff.SetXPomLinSlicing( 30, 0.0, 0.1 );
vector<double>  xs = fnlodiff.GetDiffCrossSection();

// optional printout
fnlodiff.PrintCrossSections();
```

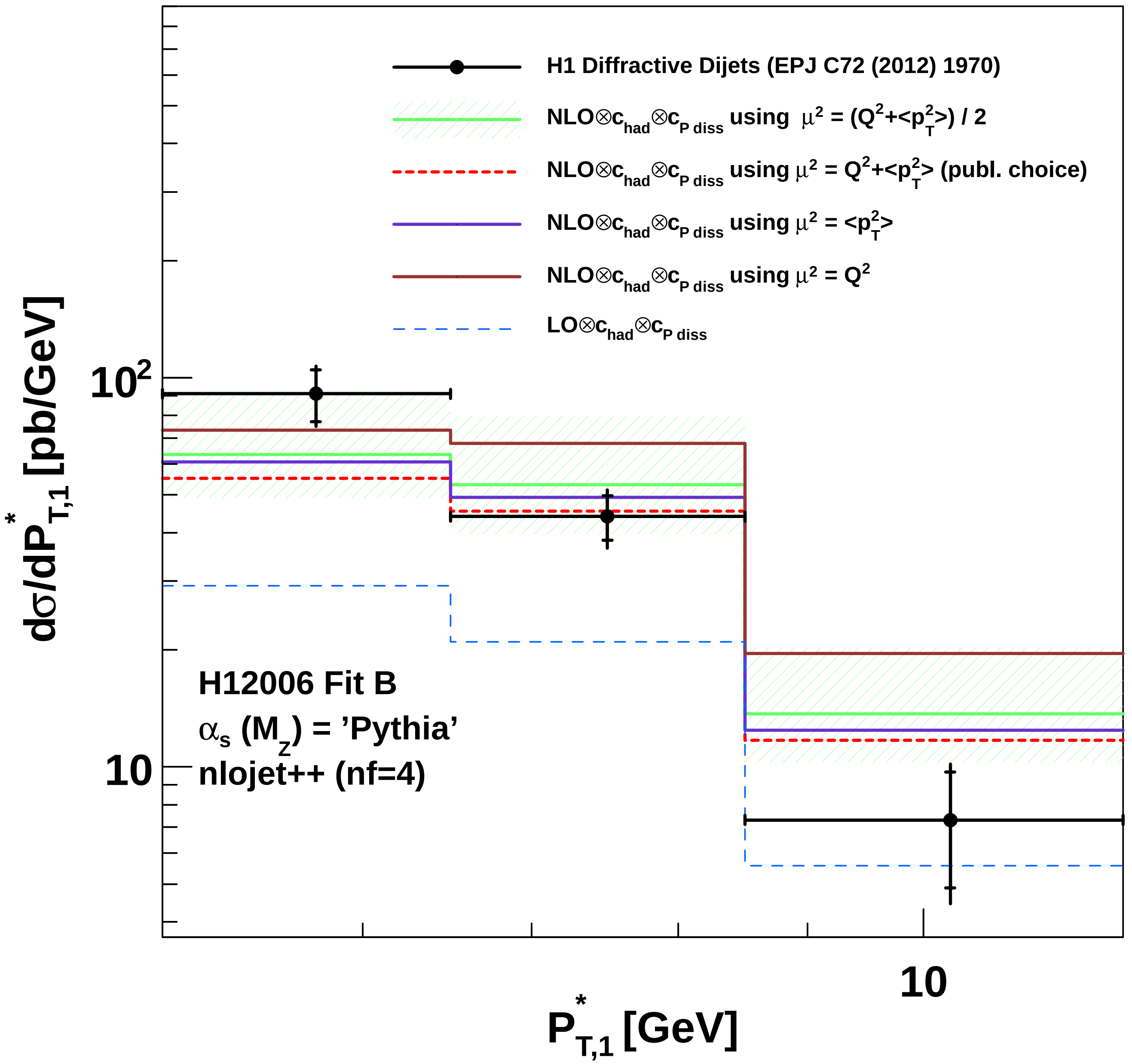
```
// output
 *  This is a single-differential table in p*_T,1.
 *
 * ---  p*_T,1  ---        - Bin -       -- XS-FNLO --
 *      4.000 -     6.500     0          9.4173e+01
 *      6.500 -     8.500     1          6.6364e+01
 *      8.500 -    12.000     2          1.6610e+01
```

Pretty easy to use (if fastNLO table is already calculated)

Application: Scale study

Dijet production in diffractive DIS (H1) EPJ C72 (2012) 1970

- Calculations available for
  - $d\sigma/dQ^2$
  - $d\sigma/dp^*_{T,1}$
- Possibility to derive by restricting x_{IP} integration interval
  - $d\sigma/dx_{IP}$



Full fastNLO features accessible

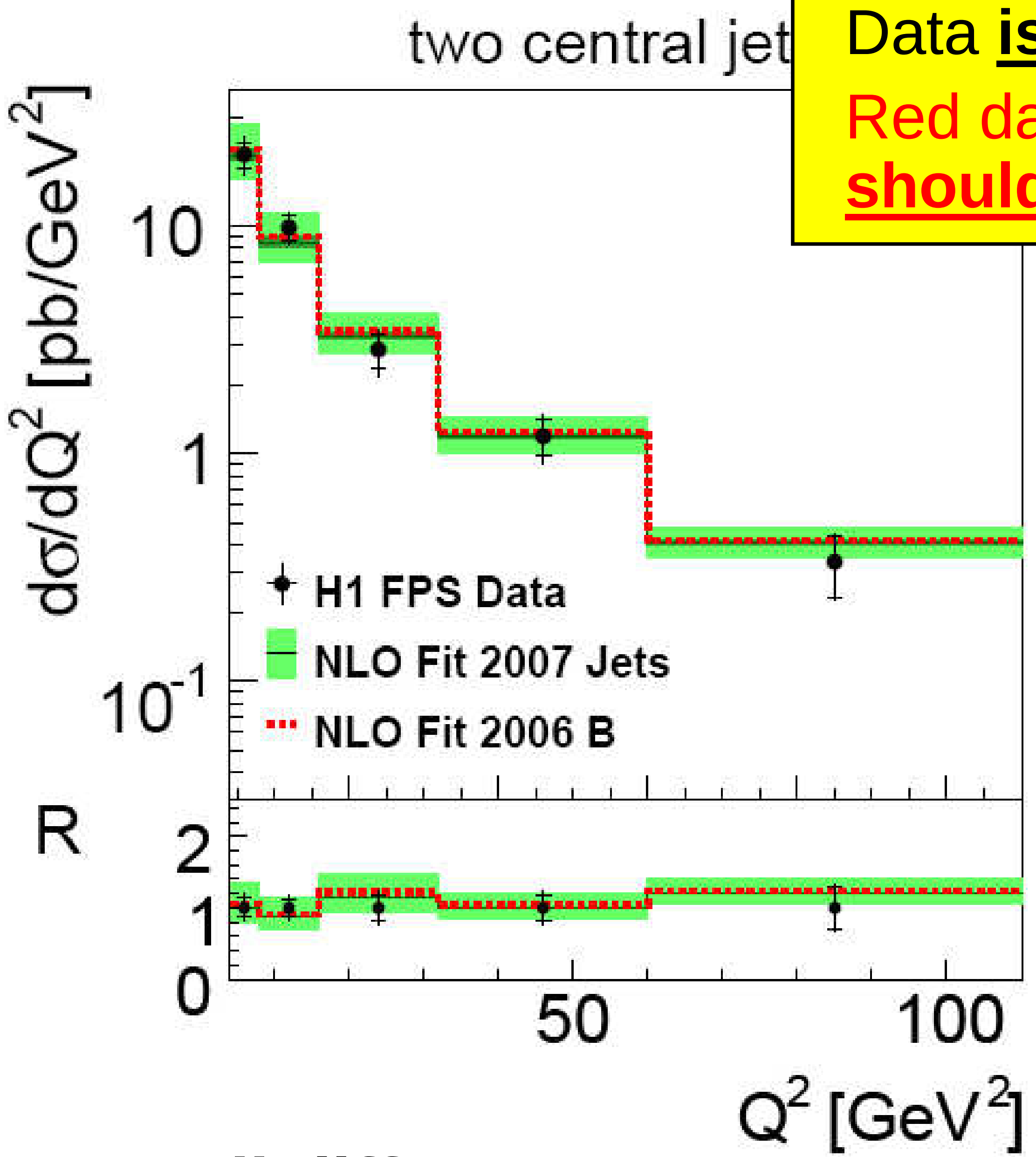
- Scale studies are easily possible
- Compare various scale choices
- Interface various DPDFs
- Direct access to k-factors

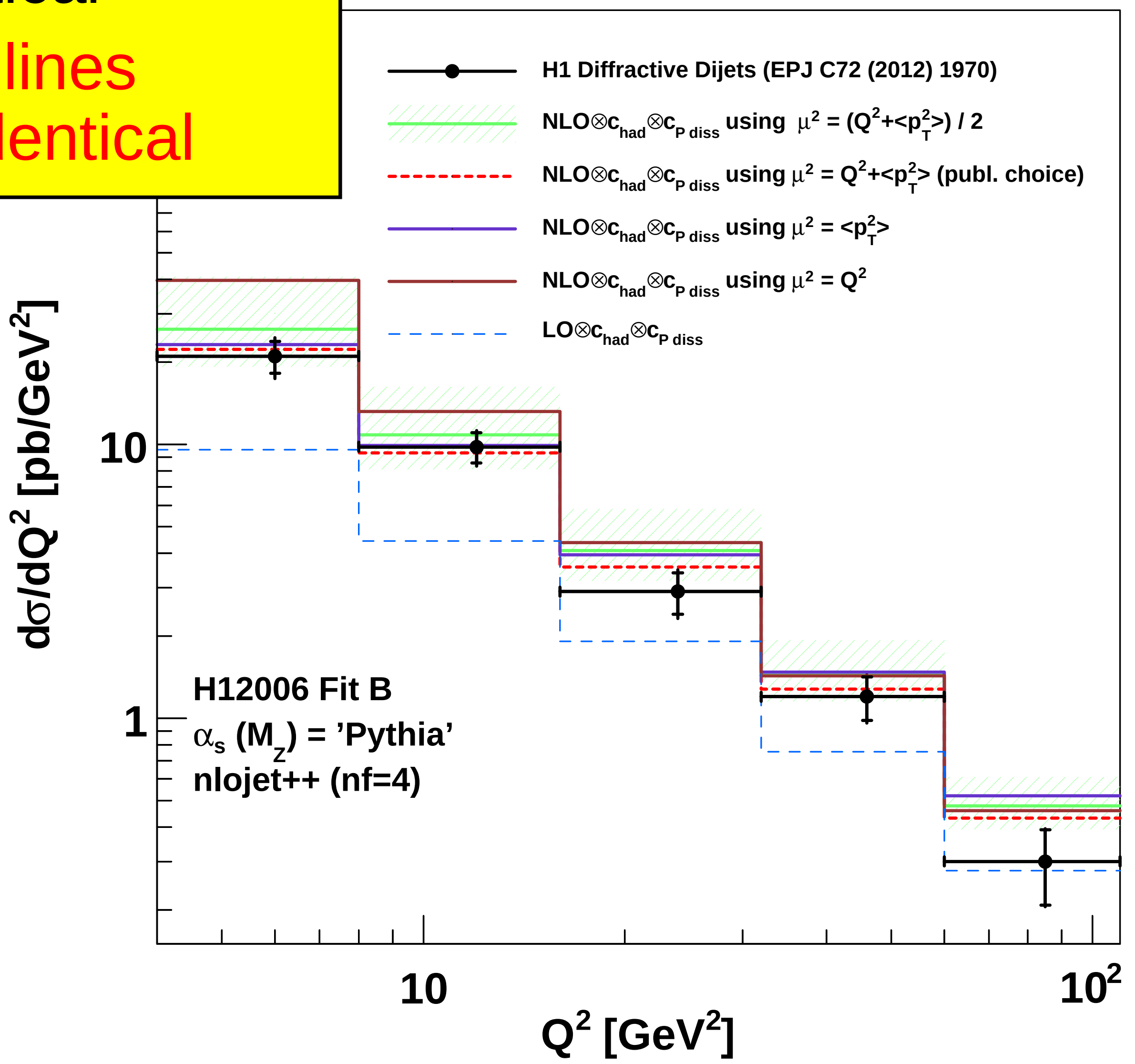
NEW: Facilitate inclusion of diffractive jets in DPDF fits
-> Will help to constrain the gluon in diffractive PDFs

Test scenario: Diffractive Dijets dQ^2

Data **is** identical

Red dashed lines **should** be identical

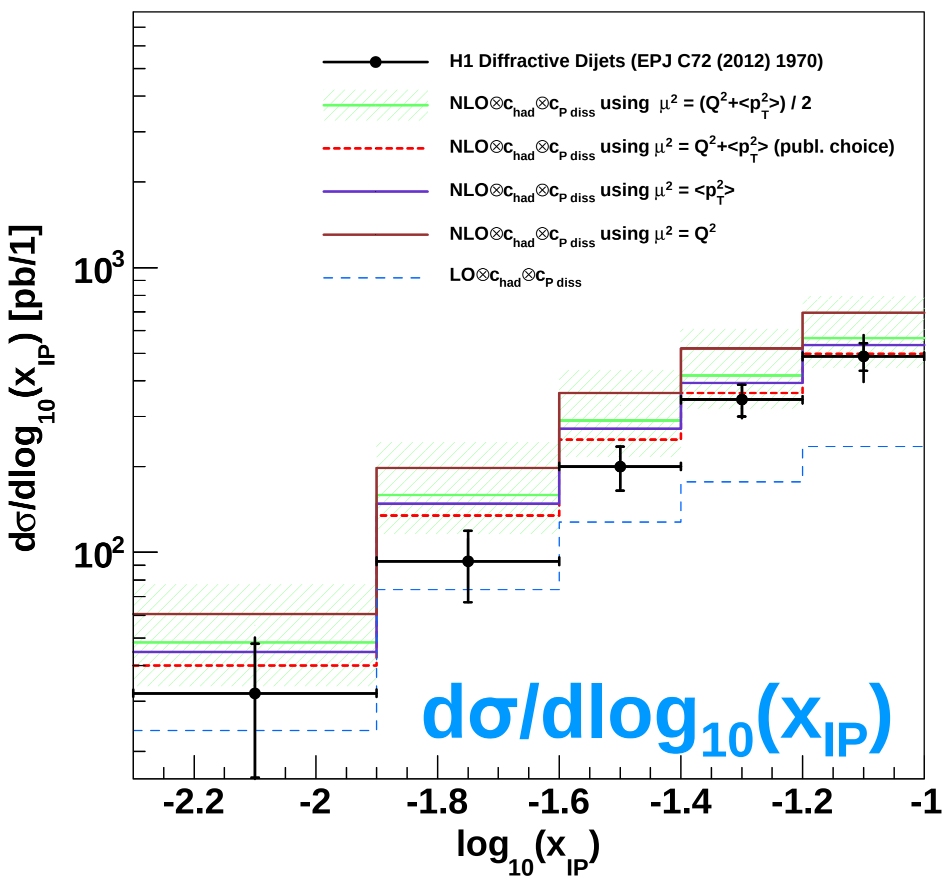


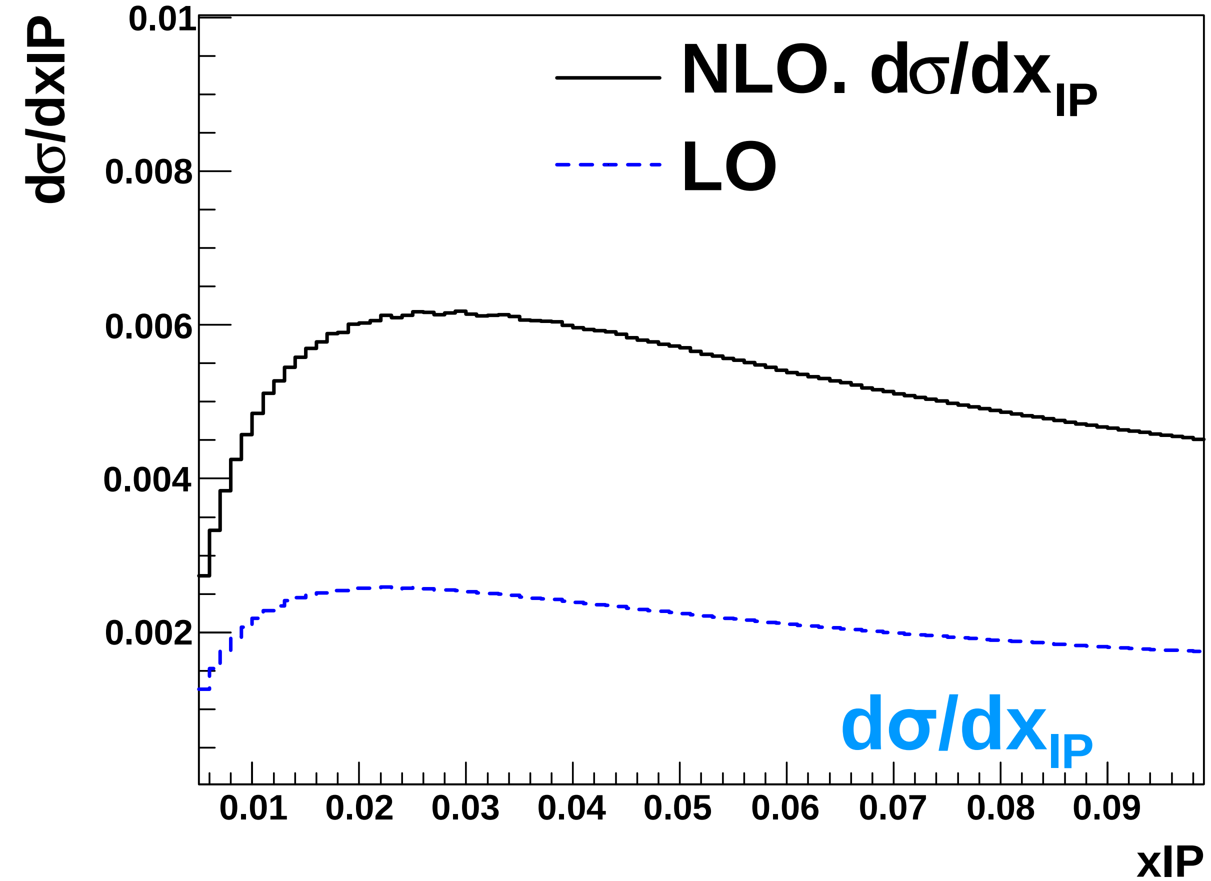


Small differences

- Automatic (but wrong) nlojet++ interpolation of NLO subtraction terms
- Jet-finder recombination scheme (~1%)
- Different (but very fine) xIP (and dxIP) slicing (~0-2%)
- Limited statistic (26×6·106) vs. very high statistic (2·1010) (<1%)

Which slicing is preferred?





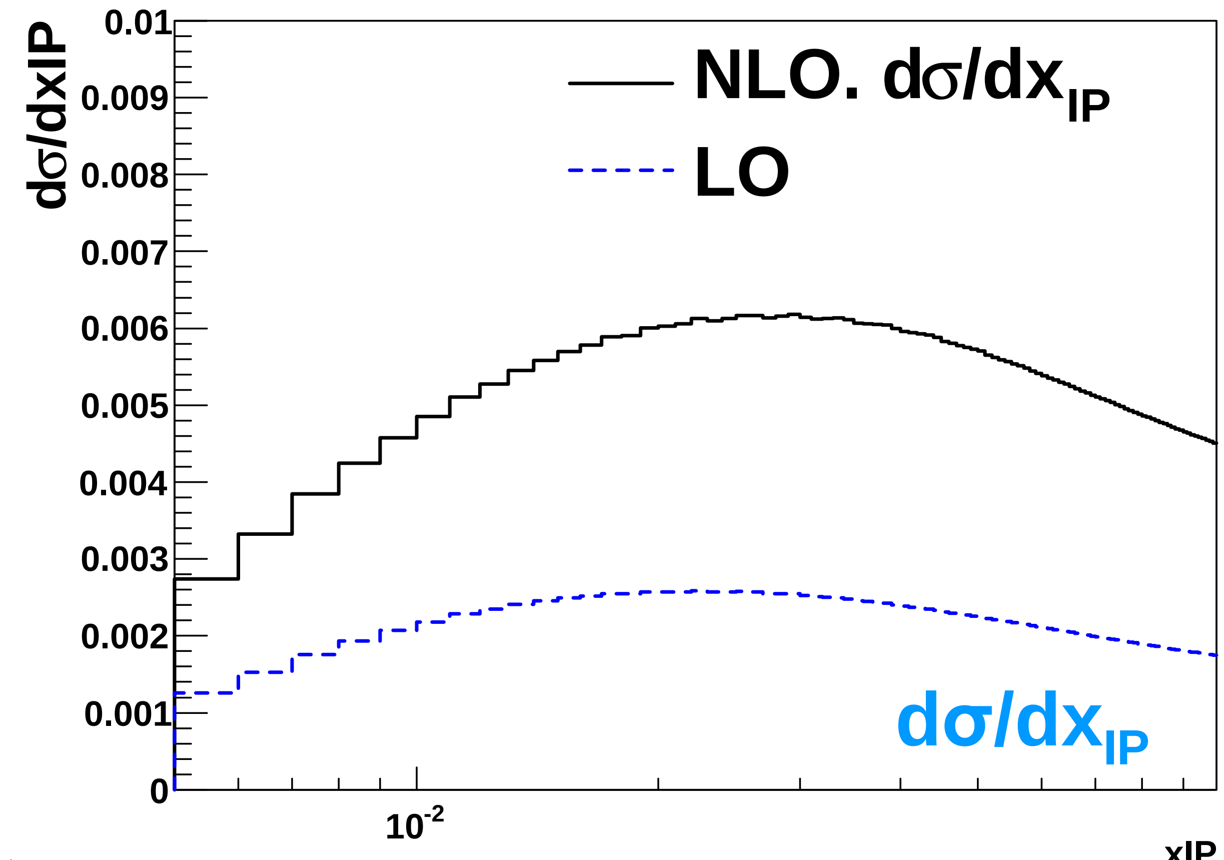
Linear or logarithmic slicing of xIP ?

Both are available

```
fnlodiff.SetXPomLinSlicing( 30, 0.0, 0.1 );
fnlodiff.SetXPomLogSlicing( 30, 0.0, 0.1 );
```

Or any other

```
double xp[] = {…};
double dxp[] = {…};
fnlodiff.SetXPomSlicing( 30, xp, dxp );
```



Convergence of slicing method

Study cross section dependence on number of x_{IP} slices

Compare:
linear and logarithmic slicing

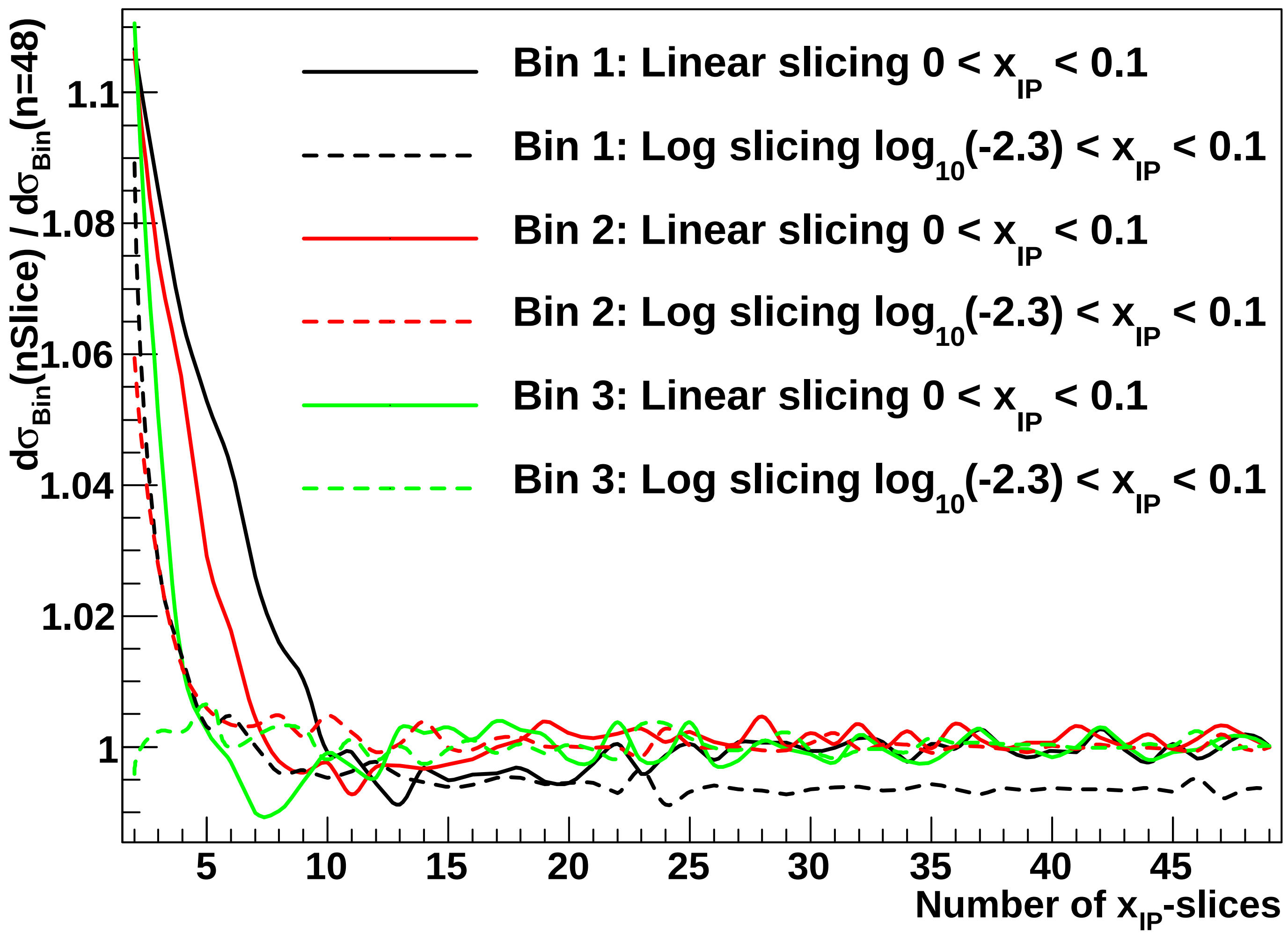
Convergence after 10 slices

Logarithmic slicing seems to converge faster

But one must know lowest x_{IP}
-> Otherwise bias!

Fluctuations

- arise from discrete x_{hadron} interpolation within fastNLO
- despite (simple) 'smoothing' at upper integration interval at
  $x_{hadron} \sim x_{IP,k}$



- **Very fast convergence of cross section**
- **FastNLO accuracy (for this table) could be estimated to < 0.25 %**
  - Accuracy smaller than cut on $\log(x_{IP,min})$ for log slicing

What about dσ/dz_{IP} ??

Warning!

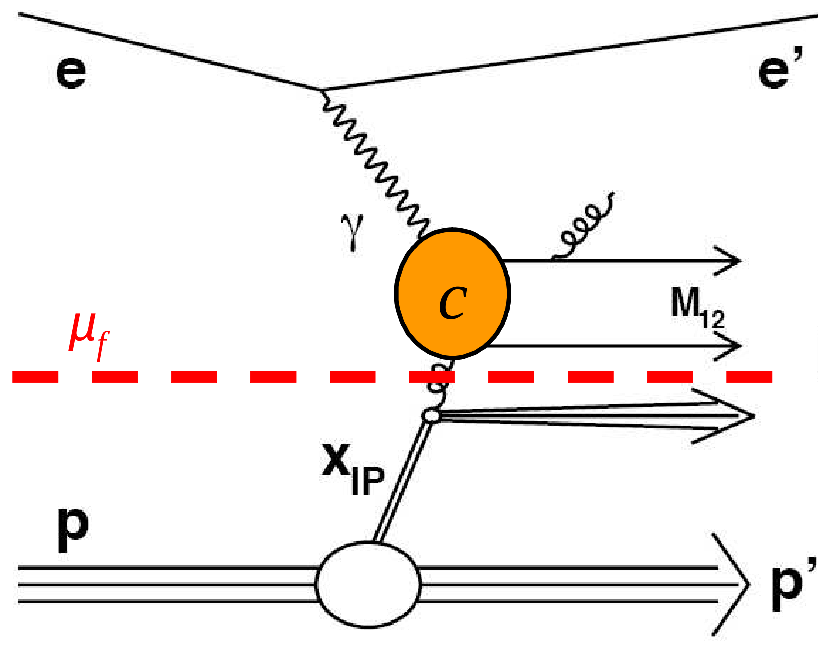
No **d$\boldsymbol{\sigma}$/d$\boldsymbol{z_{IP}}$** available through restricting z_{IP} integration interval

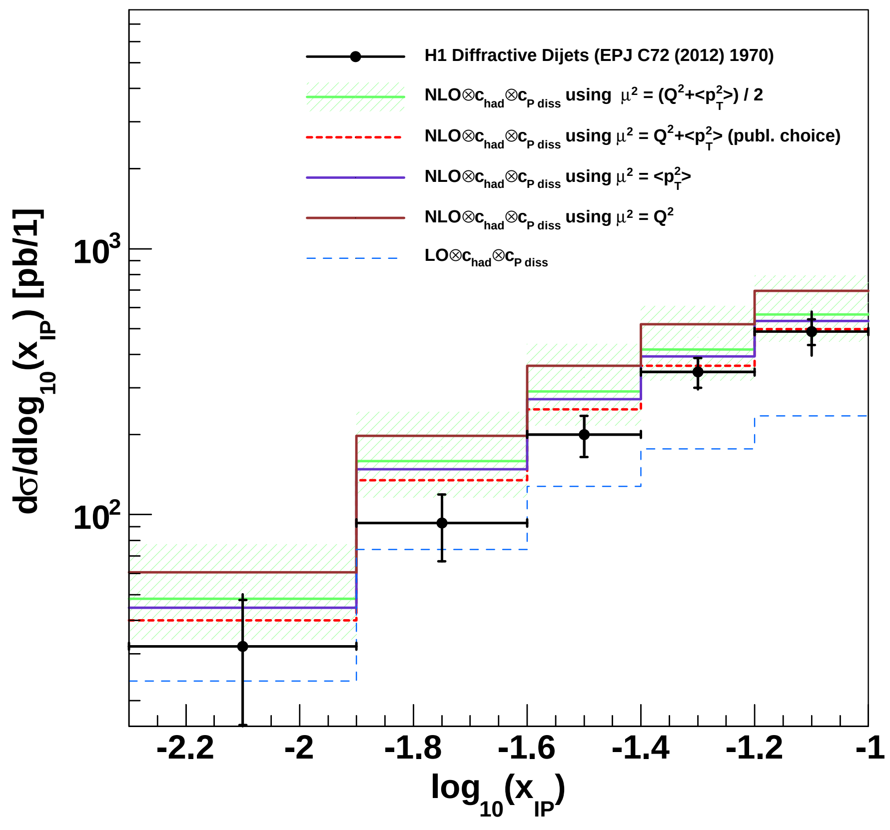
$z_{IP} \neq \xi_{IP}$ in higher orders

z_{IP} = Parton momentum fraction compared to Hadron (Pomeron)
$\xi_{IP} = \beta_{Bj} \cdot (1+M_{jj}/Q^2)$

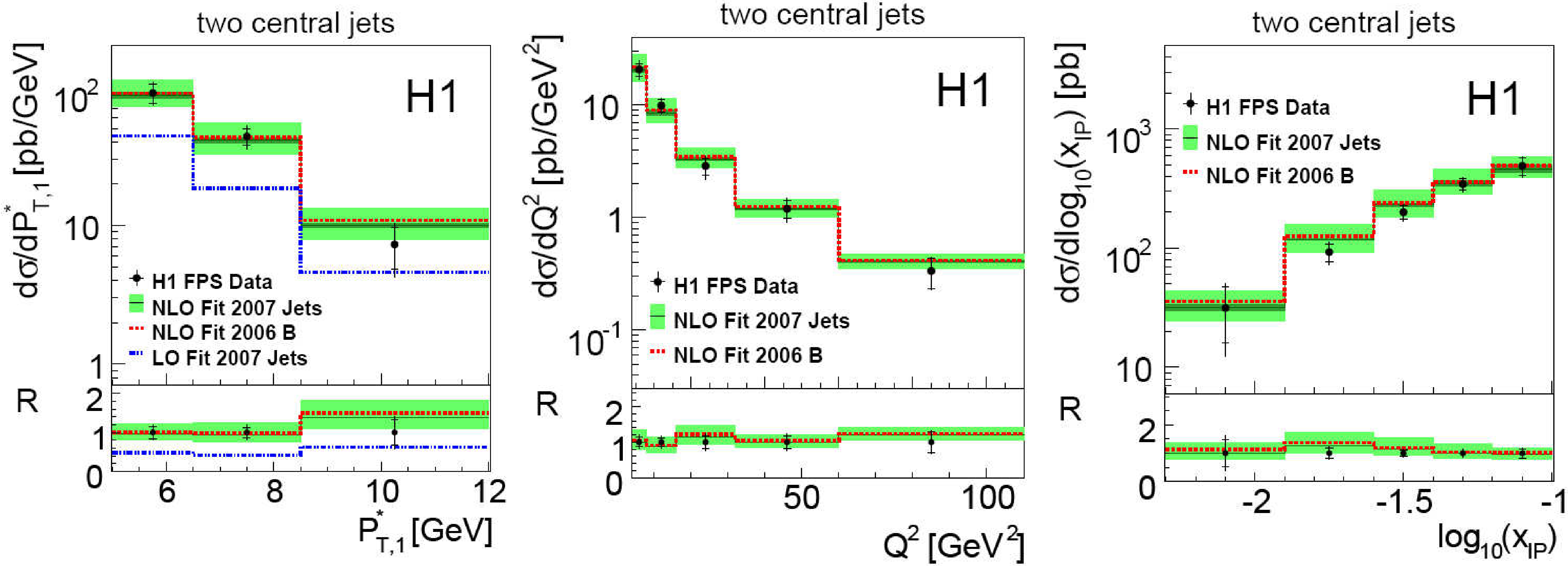
Summary

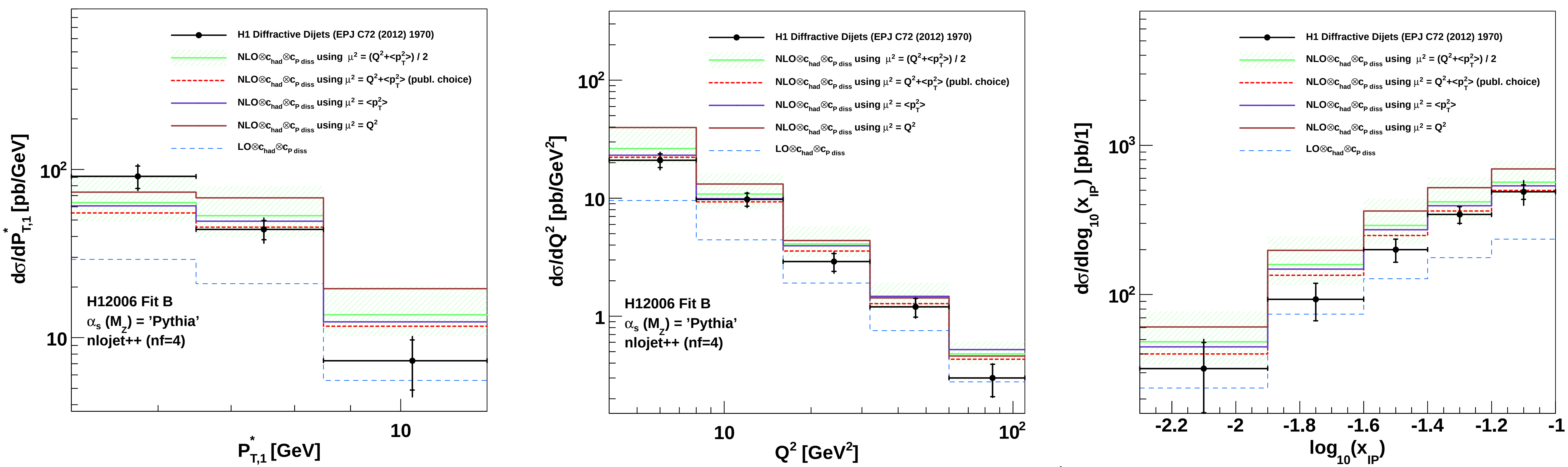
- **New method of calculating diffractive jet-cross sections was developed**
- **FastNLO code was developed and intensively tested**
- **FastNLO for jet production in diffractive DIS is ready to use**
- **Use it for your analysis or for fits of diffractive PDFs**





Diffractive dijets





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 $\alpha_s(\mu)$)

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 ->** $\mu(Q,p_T)$

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

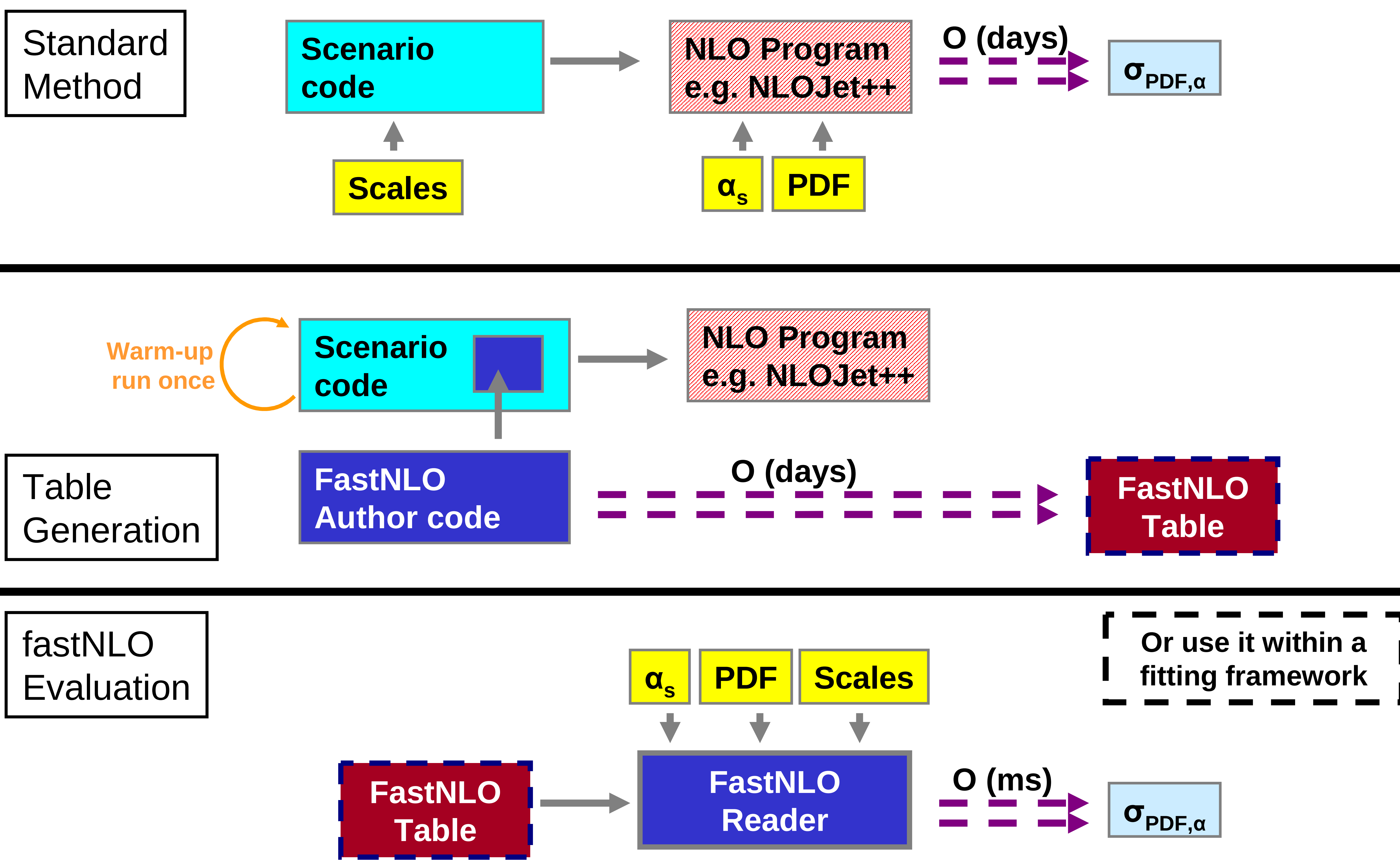
We store scale independent contribution

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

The fastNLO concept

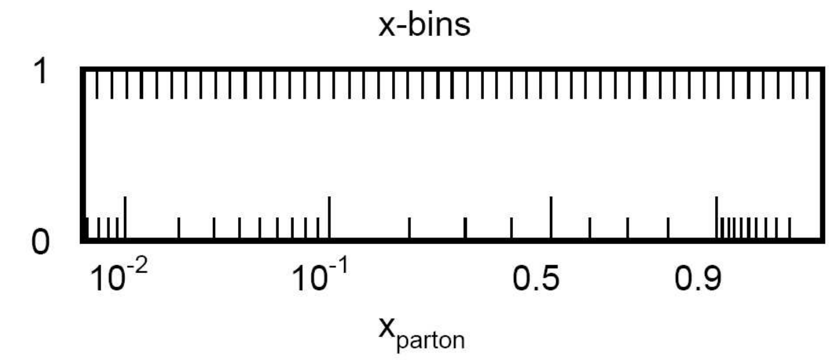


The fastNLO concept

Introduce n discrete x-nodes x_i's

- with $x_n < .. < x_i < .. < x_0 = 1$
- x_n is lowest x-value in each bin
- needs reasonable choice of discretization e.g.

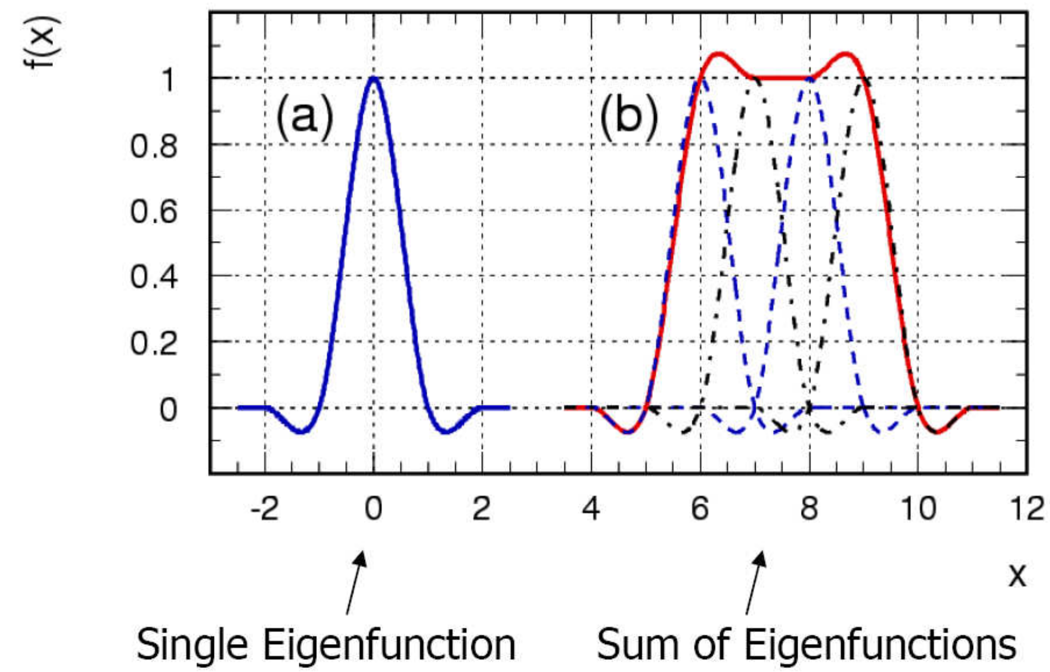
$$f(x) = -\sqrt{\log_{10}(1/x)}$$



Around each x_i define n (cubic) Eigenfunction $E_i(x)$

$$E_i(x_j) = \begin{cases} 1 & (i = j) \\ 0 & (i \neq j) \end{cases}$$

$$\sum_i E_i(x) = 1 \quad \text{for all } x$$



Hadron-hadron collision need two dimensions

2D-Eigenfunctions

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

13×13 partonic subprocesses reduce to 7

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

$gg \rightarrow$ jets			$\propto$	$H_1(x_1, x_2)$
$qg \rightarrow$ jets	plus	$\bar{q}g \rightarrow$ jets	$\propto$	$H_2(x_1, x_2)$
$gq \rightarrow$ jets	plus	$g\bar{q} \rightarrow$ jets	$\propto$	$H_3(x_1, x_2)$
$q_i q_j \rightarrow$ jets	plus	$\bar{q}_i \bar{q}_j \rightarrow$ jets	$\propto$	$H_4(x_1, x_2)$
$q_i q_i \rightarrow$ jets	plus	$\bar{q}_i \bar{q}_i \rightarrow$ jets	$\propto$	$H_5(x_1, x_2)$
$q_i \bar{q}_i \rightarrow$ jets	plus	$\bar{q}_i q_i \rightarrow$ jets	$\propto$	$H_6(x_1, x_2)$
$q_i \bar{q}_j \rightarrow$ jets	plus	$\bar{q}_i q_j \rightarrow$ jets	$\propto$	$H_7(x_1, x_2)$

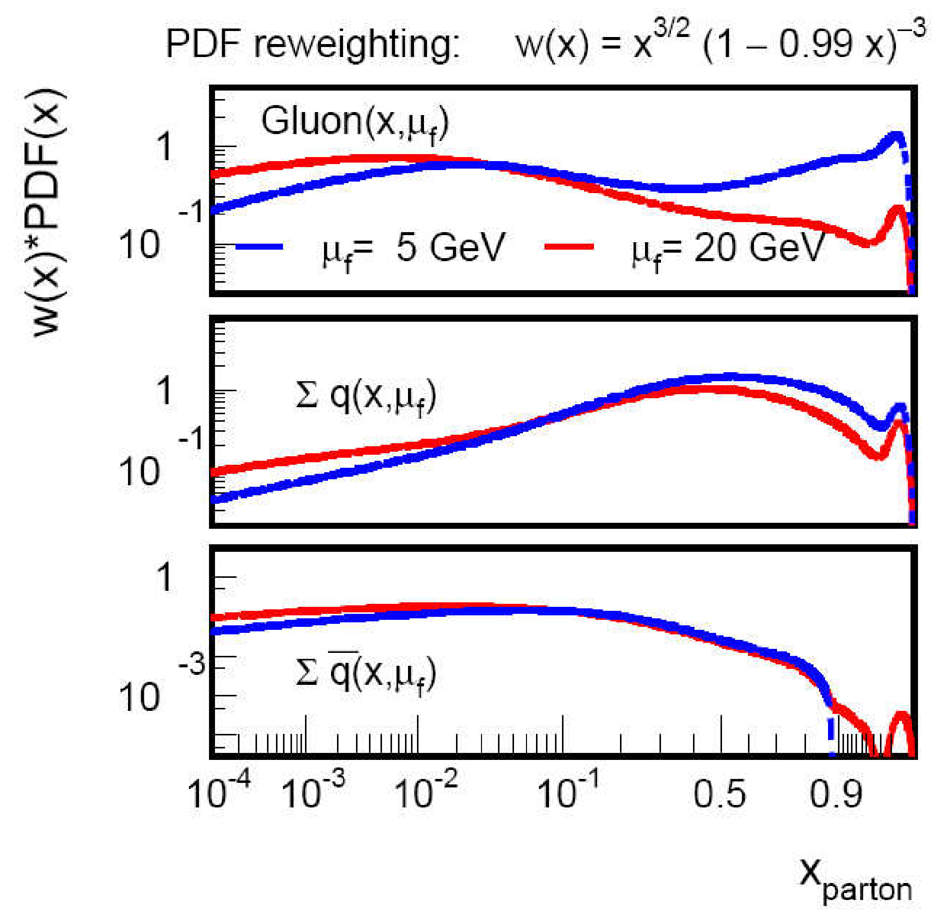
The fastNLO concept

Flatten PDFs by reweighting with simple function $w(x)$

We choose

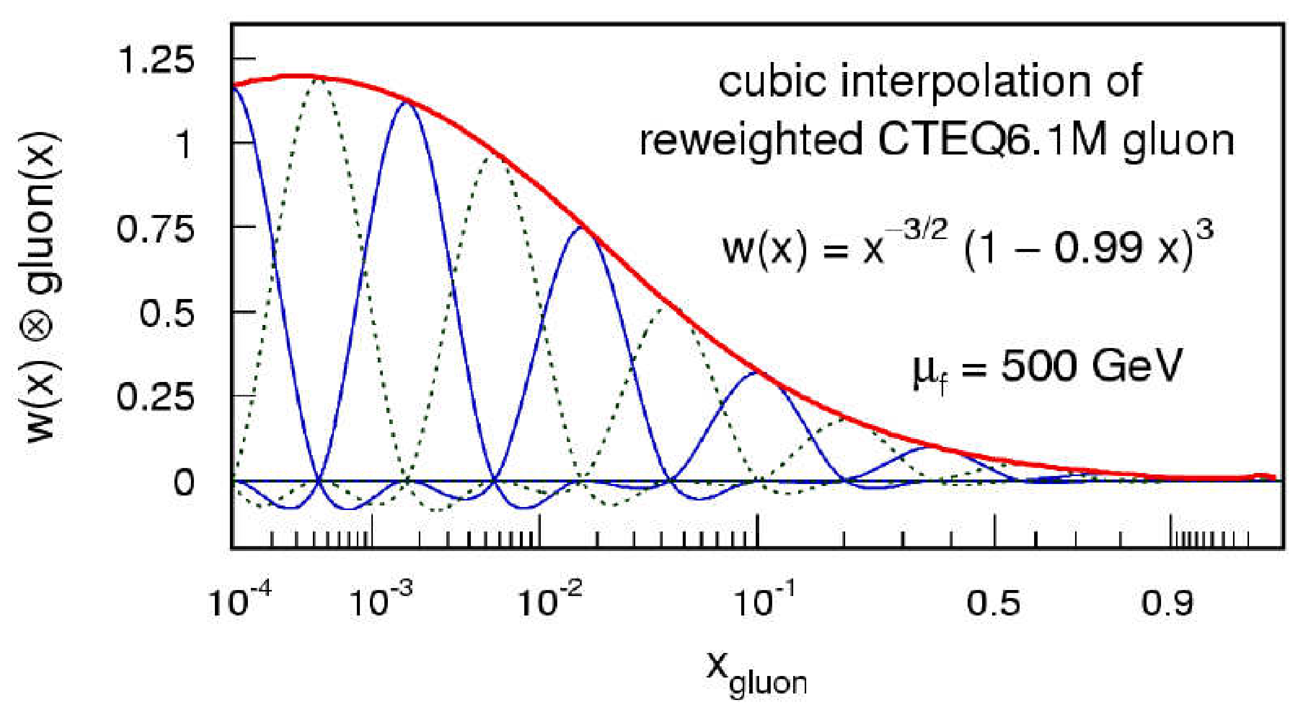
$$w(x) = x^{-3/2}(1-0.99x)^3$$

- Improve high-x gluon
- PDF curvatures are reduced for all scales
- independent of μ_f
- $w(x)^{-1}$ is absorbed in E_i



Single PDF is replaced by a linear combination of eigenfunctions

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



The fastNLO concept

With these definitions the cross section reads

$$\sigma_{hh} = \int dx_1 \int dx_2 \sum_n \alpha_s^n(\mu_r) \sum_{k=1}^{7} c_{k,n}(x_1, x_2, \mu_r, \mu_f) H_k(x_1, x_2, \mu_f)$$

Now express PDF linear combinations H_k by the 2D-eigenfunction

$$\sigma_{hh} = \int dx_1 \int dx_2 \sum_n \alpha_s^n(\mu_r) \sum_{k=1}^{7} c_{k,n}(x_1, x_2, \mu_r, \mu_f) \left(\sum_{i,j} H_k(x^{(1)}, x^{(2)}) \cdot E^{(i,j)}(x_1, x_2) \right)$$

Rewrite the cross section

$$\sigma_{hh} = \sum_n \alpha_s^n(\mu_r) \sum_{k=1}^{7} \sum_{i,j} H_k(x_1^{(i)}, x_2^{(j)}) \cdot \underbrace{\int dx_1 \int dx_2 c_{k,n}(\mu_r, \mu_f) \cdot E^{(i,j)}(x_1, x_2)}_{\text{Independent of PDFs and } \alpha_s}$$

Important: Integral is independent of PDFs!

Last steps

Scale dependence

- Perturbative coefficients are scale dependent
- PDFs and α_s need to be evaluated at certain scale values

Introduce interpolation procedure also for scales

- Assume $\mu_r = \mu_f$
- Introduce m scale nodes with distances

$$f(\mu) = \log(\log(4 \cdot \mu))$$

Coefficient table gets one additional dimension for μ

Final fastNLO cross sections

- Define σ-table and store it as 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 $$\sigma_{hh}^{Bin} = \sum_{i,j,k,n,m} \alpha_s^n(\mu^{(m)}) \cdot H_k(x_1^{(i)}, x_2^{(j)}, \mu^{(m)}) \cdot \tilde{\sigma}_{k,n}^{(i,j)(m)}$$