APPLgrid news

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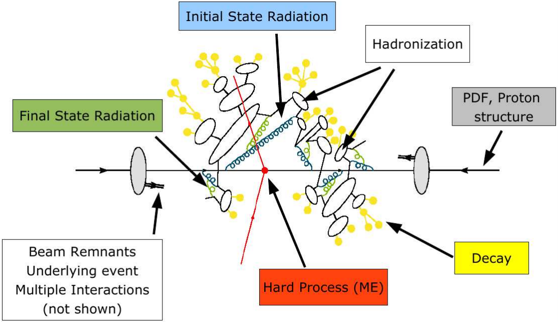
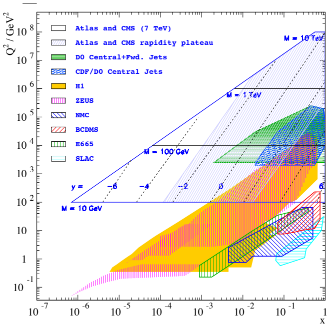
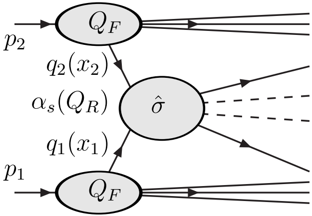
Proton-proton collision





- hard scattering can be calculated to NLO(NNLO) precision
- description of showers and non-perturbative effects comes from MC
- PDFs and strong coupling are determined from precision data (LEP, HERA, TEVATRON, . . .).

$\mathrm{N}^x\mathrm{LO}$ QCD cross section



$$\frac{d\sigma}{dX} \sim \sum_{(i,j,p)} \int d\Gamma \alpha_s^p(Q_R^2)\, q_i(x_1, Q_F^2) q_j(x_2, Q_F^2)\, \frac{d\hat{\sigma}^{ij}_{(p)}}{dX}(x_1, x_2, Q_F^2, Q_R^2;\ S)$$

- Coupling and parton density functions are non-perturbative inputs to calculation (extracted from data)
- Perturbative coefficients are essentially independent from PDF functions due to factorization theorem

Calculating NLO cross-sections
takes a long time ($\sim$ *days*/*weeks*/*months*)

$\Longrightarrow$ we can split calculation into two parts

APPLGRID method

Eur.Phys.J.C66:503-524,2010.

- Step 1 (long run): Collect perturbative weights to grids .
  - binning
  - interpolation
  - initial flavours decomposition : $13 \times 13 \rightarrow \mathcal{L}$ ($\mathcal{L} \sim 10$)

$$\frac{d\hat{\sigma}^{ij}_{(p)}}{dX}(x_1, x_2, Q_F^2, Q_R^2;\ S) \xrightarrow{3D-grid} w^{(p)(l)}(x_1^m, x_2^n, Q^{2^k})\ (Q_R^2 \equiv Q_F^2)$$

- Step 2 ($\sim$ 10–100 ms): Convolute grid with PDF's .
  - integral $\rightarrow$ sum
  - any coupling, PDF

Details of the method (I)

Interpolation

- user defined interpolation orders $n_y, \quad n_\tau$

$$f(x,Q^2) = \sum_{i=0}^{n_y} \sum_{\iota=0}^{n_\tau} f_{k+i,\kappa+\iota}\ I_i^{(n)}\left(\frac{y(x)}{\delta y} - k\right)\ I_\iota^{(n')}\left(\frac{\tau(Q^2)}{\delta\tau} - \kappa\right)$$

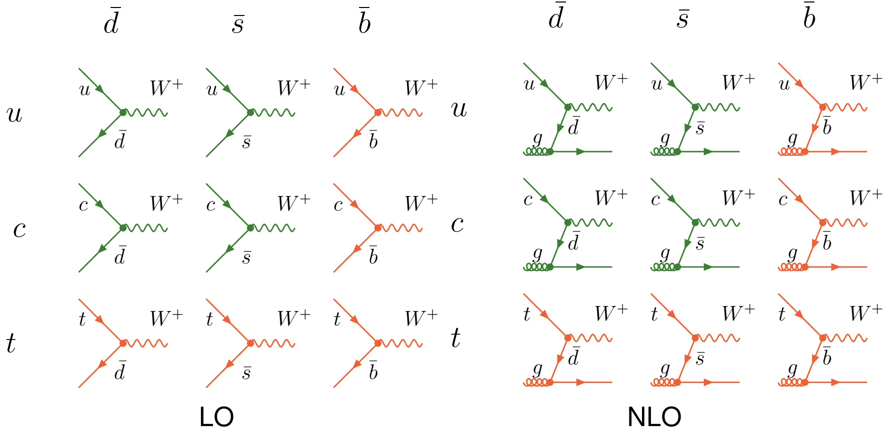
Subprocess decomposition

$13 \times 13 \to \mathcal{L}$ due to the symmetries of the ME weights

$$\sum_{m,n} \nu_{mn}^{(l)}\, f_{m/H_1}\left(x_1, Q^2\right) f_{n/H_2}\left(x_2, Q^2\right) \equiv F^{(l)}\left(x_1, x_2, Q^2\right),$$

“generalised“ PDFs depend on the process and the perturbative order

APPLGRID subprocesses for $W^\pm$ production (I)



APPLGRID subprocesses for $W^{\pm}$ production (II)

The weights for W^{+}-production can be organized in six possible initial state combinations (calculated using MCFM)

$$\bar{D}U: \quad F^{(0)}\left(x_1, x_2, Q^2\right) = \sum_{j=1,3,5} f_{-j/H_1}\left(x_1\right) \sum_{i=2,4,6} f_{i/H_2}\left(x_2\right) V_{ij}^2$$

$$U\bar{D}: \quad F^{(1)}\left(x_1, x_2, Q^2\right) = \sum_{i=2,4,6} f_{i/H_1}\left(x_1\right) \sum_{j=1,3,5} f_{-j/H_2}\left(x_2\right) V_{ij}^2$$

$$\bar{D}g: \quad F^{(2)}\left(x_1, x_2, Q^2\right) = \sum_{i=1,3,5} f_{-i/H_1}\left(x_1\right) \left(V_{iu}^2 + V_{ic}^2 + V_{it}^2\right) f_{0/H_2}\left(x_2\right)$$

$$Ug: \quad F^{(3)}\left(x_1, x_2, Q^2\right) = \sum_{i=2,4,6} f_{i/H_1}\left(x_1\right) \left(V_{id}^2 + V_{is}^2 + V_{ib}^2\right) f_{0/H_2}\left(x_2\right)$$

$$g\bar{D}: \quad F^{(4)}\left(x_1, x_2, Q^2\right) = \sum_{i=1,3,5} f_{0/H_1}\left(x_1\right) \left(V_{iu}^2 + V_{ic}^2 + V_{it}^2\right) f_{-i/H_2}\left(x_2\right)$$

$$gU: \quad F^{(5)}\left(x_1, x_2, Q^2\right) = \sum_{i=2,4,6} f_{0/H_1}\left(x_1\right) \left(V_{id}^2 + V_{is}^2 + V_{ib}^2\right) f_{i/H_2}\left(x_2\right)$$

We separate $u\bar{d}$ from $\bar{d}u$ in order to get the right rapidity distribution for the electron, because of the chiral nature of the $W^{\pm}$ couplings

APPLGRID subprocesses for Z^0 production

We can introduce 12 sub-processes in Z production (calculated using MCFM)

$$\begin{aligned}
U\bar{U}: &\quad F^{(0)}\left(x_1, x_2, Q^2\right) = U_{12}(x_1, x_2) \\
D\bar{D}: &\quad F^{(1)}\left(x_1, x_2, Q^2\right) = D_{12}(x_1, x_2) \\
\bar{U}U: &\quad F^{(2)}\left(x_1, x_2, Q^2\right) = U_{21}(x_1, x_2) \\
\bar{D}D: &\quad F^{(3)}\left(x_1, x_2, Q^2\right) = D_{21}(x_1, x_2) \\
gU: &\quad F^{(4)}\left(x_1, x_2, Q^2\right) = G_1(x_1)U_2(x_2) \\
g\bar{U}: &\quad F^{(5)}\left(x_1, x_2, Q^2\right) = G_1(x_1)\overline{U}_2(x_2) \\
gD: &\quad F^{(6)}\left(x_1, x_2, Q^2\right) = G_1(x_1)D_2(x_2) \\
g\bar{D}: &\quad F^{(7)}\left(x_1, x_2, Q^2\right) = G_1(x_1)\overline{D}_2(x_2) \\
Ug: &\quad F^{(8)}\left(x_1, x_2, Q^2\right) = U_1(x_1)G_2(x_2) \\
\bar{U}g: &\quad F^{(9)}\left(x_1, x_2, Q^2\right) = \overline{U}_1(x_1)G_2(x_2) \\
Dg: &\quad F^{(10)}\left(x_1, x_2, Q^2\right) = D_1(x_1)G_2(x_2) \\
\bar{D}g: &\quad F^{(11)}\left(x_1, x_2, Q^2\right) = \overline{D}_1(x_1)G_2(x_2)
\end{aligned}$$

We separate $u\bar{u}$ from $\bar{u}u$ contributions to include γ/Z interference

APPLGRID subprocesses for Z^0 production II

Use is made of the generalised PDFs defined as:

$$U_H(x) = \sum_{i=2,4,6} f_{i/H}\left(x, Q^2\right), \qquad \overline{U}_H(x) = \sum_{i=2,4,6} f_{-i/H}\left(x, Q^2\right),$$

$$D_H(x) = \sum_{i=1,3,5} f_{i/H}\left(x, Q^2\right), \qquad \overline{D}_H(x) = \sum_{i=1,3,5} f_{-i/H}\left(x, Q^2\right),$$

$$U_{12}(x_1, x_2) = \sum_{i=2,4,6} f_{i/H_1}\left(x_1, Q^2\right) f_{-i/H_2}\left(x_2, Q^2\right),$$

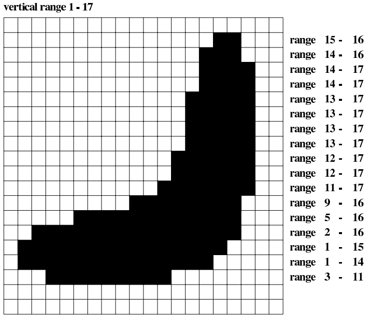
$$D_{12}(x_1, x_2) = \sum_{i=1,3,5} f_{i/H_1}\left(x_1, Q^2\right) f_{-i/H_2}\left(x_2, Q^2\right),$$

$$U_{21}(x_1, x_2) = \sum_{i=2,4,6} f_{-i/H_1}\left(x_1, Q^2\right) f_{i/H_2}\left(x_2, Q^2\right),$$

$$D_{21}(x_1, x_2) = \sum_{i=1,3,5} f_{-i/H_1}\left(x_1, Q^2\right) f_{i/H_2}\left(x_2, Q^2\right),$$

Details of the method (II)

Phasespace optimisation



User just defines max/min possible values of x, Q^2. The optimisation procedure finds appropriate limits for each subprocess/order/observable bin.

$\longleftarrow$ $x_1 x_2$ – phasespace

Final result

$$\frac{d\sigma}{dX} = \sum_p \sum_{l=0}^{L} \sum_{m,n,k} w_{m,n,k}^{(p)(l)} \left(\frac{\alpha_s(Q_k^2)}{2\pi} \right)^{p_l} F^{(l)}\left(x_{1\,m}, x_{2\,n}, Q_k^2\right)$$

Scale dependence

Having the weights $w^{(p)(l)}_{m,n,k}$ determined separately order by order in α_s, it is straightforward to vary the renormalisation μ_R and factorisation μ_F scales a posteriori.
We assume scales to be equal

$$\mu_R = \mu_F = Q$$

in the original calculation.
Introducing ξ_R and ξ_F corresponding to the factors by which one varies μ_R and μ_F respectively,

$$\mu_R = \xi_R \times Q$$
$$\mu_F = \xi_F \times Q$$

Master formula and Scale dependence at NLO

Then for arbitrary ξ_R and ξ_F we may write:

$$
\begin{aligned}
\frac{d\sigma}{dX}(\xi_R, \xi_F) = \sum_{l=0}^{L} \sum_{m} \sum_{n} \sum_{k} \Bigg\{ \left(\frac{\alpha_s\left(\xi_R^2 {Q^2}_k\right)}{2\pi} \right)^{p_{\mathrm{LO}}} \\
\times W_{m,n,k}^{(\mathrm{LO})(l)} F^{(l)}\left(x_{1\,m}, x_{1\,n}, \xi_F^2 {Q^2}_k\right) + \left(\frac{\alpha_s\left(\xi_R^2 {Q^2}_k\right)}{2\pi} \right)^{p_{\mathrm{NLO}}} \\
\times \Bigg[\left(W_{m,n,k}^{(\mathrm{NLO})(l)} + 2\pi\beta_0 p_{\mathrm{LO}} \ln \xi_R^2 \, W_{m,n,k}^{(\mathrm{LO})(l)} \right) F^{(l)}\left(x_{1\,m}, x_{2\,n}, \xi_F^2 {Q^2}_k\right) \\
- \ln \xi_F^2 \, W_{m,n,k}^{(\mathrm{LO})(l)} \\
\times \left(F^{(l)}_{q_1 \to P_0 \otimes q_1}\left(x_{1\,m}, x_{2\,n}, \xi_F^2 {Q^2}_k\right) + F^{(l)}_{q_2 \to P_0 \otimes q_2}\left(x_{1\,m}, x_{2\,n}, \xi_F^2 {Q^2}_k\right) \right) \Bigg] \Bigg\},
\end{aligned}
$$

where $F^{(l)}_{q_1 \to P_0 \otimes q_1}$ is calculated as $F^{(l)}$, but with q_1 replaced with $P_0 \otimes q_1$ (LO splitting function convoluted with PDF), and analogously for $F^{(l)}_{q_2 \to P_0 \otimes q_2}$.

Master formula and Scale dependence at NNLO

$$\frac{d\sigma}{dX}(\xi_R,\xi_F) = \sum_{l=0}^{L}\sum_{m}\sum_{n}\sum_{k} F^{(l)}\left(x_{1\,m}, x_{2\,n}, \xi_F^2 {Q^2}_k\right) \times$$

$$\left\{ \left(\frac{\alpha_s\left(\xi_R^2 {Q^2}_k\right)}{2\pi}\right)^{p_{\mathrm{LO}}} W_{m,n,k}^{(\mathrm{LO})(l)} \right.$$

$$+ \left. \left(\frac{\alpha_s\left(\xi_R^2 {Q^2}_k\right)}{2\pi}\right)^{p_{\mathrm{NLO}}} W_{m,n,k}^{(\mathrm{NLO})(l)} + \left(\frac{\alpha_s\left(\xi_R^2 {Q^2}_k\right)}{2\pi}\right)^{p_{\mathrm{NNLO}}} W_{m,n,k}^{(\mathrm{NNLO})(l)} \right\}$$

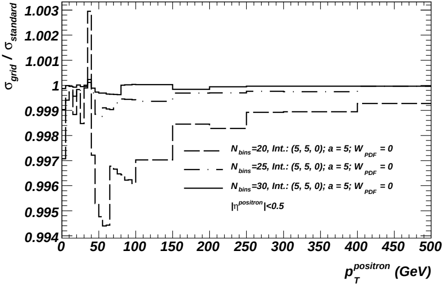
$$+ \sum_{l=0}^{L}\sum_{m}\sum_{n}\sum_{k} \left(\frac{\alpha_s\left(\xi_R^2 {Q^2}_k\right)}{2\pi}\right)^{p_{\mathrm{NNLO}}} \times \left\{ \text{Scale variations termS} \right\}$$

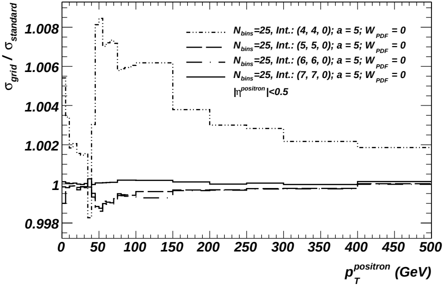
Scale dependence at NNLO

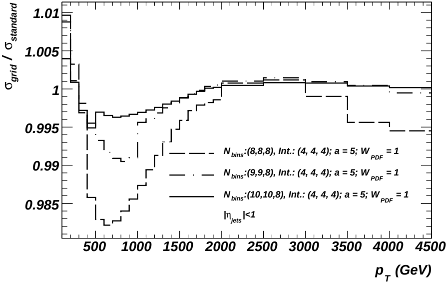
$L_R = \log \xi_R^2, \; L_F = \log \xi_F^2$

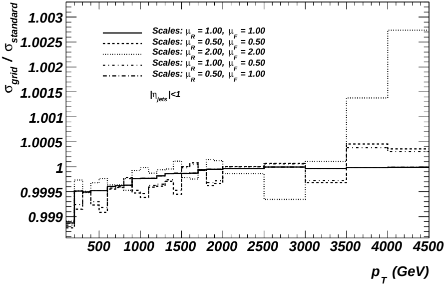
$$
\begin{aligned}
= \quad & L_R \left(p_{\mathrm{NLO}} \beta_0 W_{m,n,k}^{(\mathrm{NLO})(l)} + p_{\mathrm{LO}} \beta_1 W_{m,n,k}^{(\mathrm{LO})(l)} \right) F^{(l)} \\
+ \quad & L_R^2 p_{\mathrm{NLO}} \beta_0^2 W_{m,n,k}^{(\mathrm{LO})(l)} F^{(l)} \\
- \quad & L_F \left(W_{m,n,k}^{(\mathrm{NLO})(l)} \left[F_{q_1 \to P_0 \otimes q_1}^{(l)} + F_{q_2 \to P_0 \otimes q_2}^{(l)} \right] \right. \\
& \qquad \left. + W_{m,n,k}^{(\mathrm{LO})(l)} \left[F_{q_1 \to P_1 \otimes q_1}^{(l)} + F_{q_2 \to P_1 \otimes q_2}^{(l)} \right] \right) \\
+ \quad & L_F^2 W_{m,n,k}^{(\mathrm{LO})(l)} \left(F_{q_1 \to P_0 \otimes q_1 ; q_2 \to P_0 \otimes q_2}^{(l)} + \frac{1}{2} F_{q_1 \to P_0 \otimes P_0 \otimes q_1}^{(l)} + \frac{1}{2} F_{q_2 \to P_0 \otimes P_0 \otimes q_2}^{(l)} \right. \\
& \left. + \frac{1}{2} \beta_0 F_{q_1 \to P_0 \otimes q_1}^{(l)} + \frac{1}{2} \beta_0 F_{q_2 \to P_0 \otimes q_2}^{(l)} \right) \\
- \quad & L_R L_F p_{\mathrm{NLO}} \beta_0 W_{m,n,k}^{(\mathrm{LO})(l)} \left(F_{q_1 \to P_0 \otimes q_1}^{(l)} + F_{q_2 \to P_0 \otimes q_2}^{(l)} \right)
\end{aligned}
$$

APPLGRID accuracy.

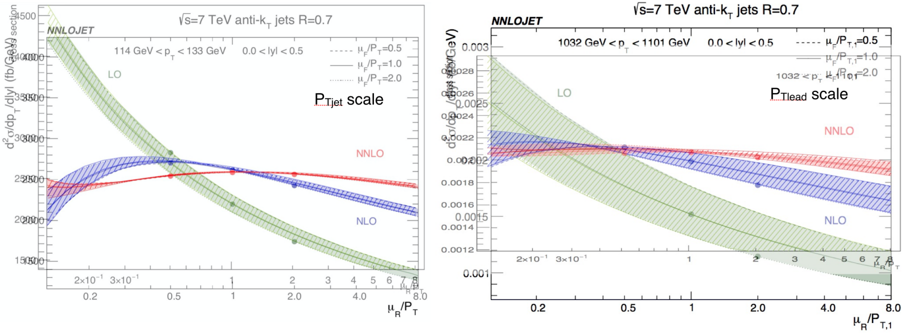






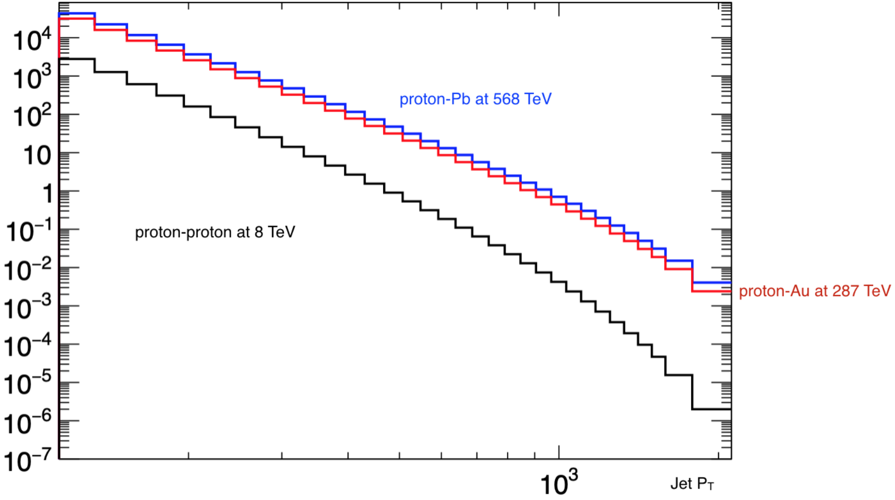


Scale variations validation



- Horizontal axis - renormalisation scale
- Shaded bands - factorisation scale variations from original NNLOJET paper
- Unshaded, hatched bands - APPLgrid scale valuation

Changing PDFs and centre-of-mass-energy



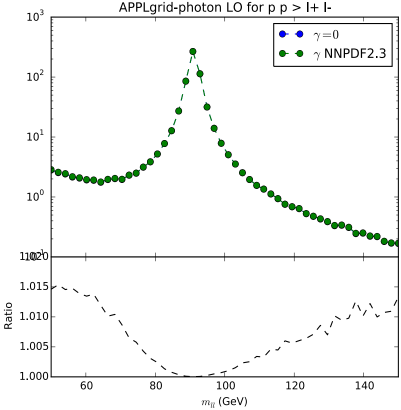
Inclusive jet production

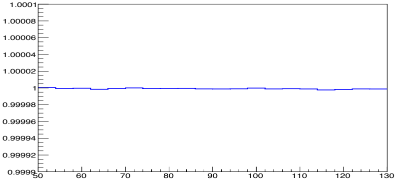
Photon-induced processes

- Currently use a modification of the lhaglue type LHAPDF interface

```
extern "C" void evolvepdf(const double& x, const double& Q, double* x
   xfx += 6;
   for (int i = -6; i < 7; i++) xfx[i] = pdf->xfxQ(i, x, Q);
   xfx[7] = pdf->xfxQ(22, x, Q);
}
```

- Use native LHAPDF 6 calls with call to access photon density, in lhaglue type wrapper
- APPLgrid intrinsic lumi_pdf class allows additional parton - 7 or 22 for the photon



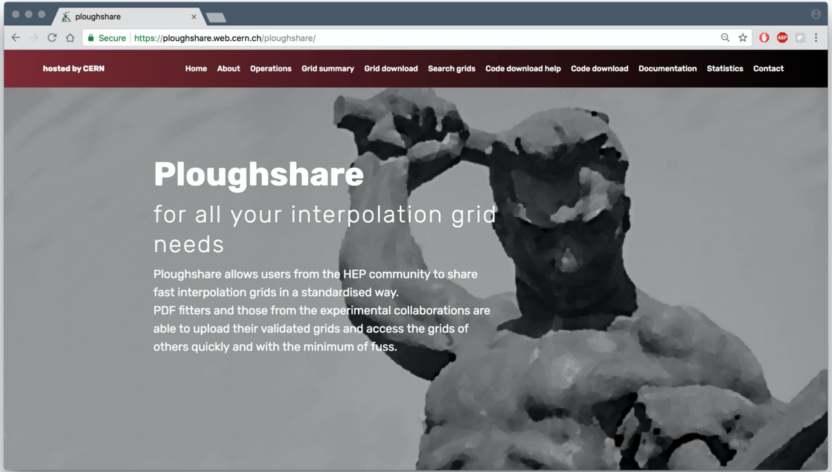


Interface to cross section calculators

- NLOJET++ : Jet production in $pp(\bar{p})-$ and $ep-$ collisions.
  - $2 \rightarrow 2$ and $2 \rightarrow 3$ at NLO; $2 \rightarrow 4$ at LO www.desy.de/~znagy/Site/NLOJet++.htm.
- MCFM : parton-level NLO(NNLO) QCD cross sections calculator for various femtobarn-level processes at hadron-hadron colliders.
  - V, $V + nJet$, $V + b\bar{b}$, VV, $Q\bar{Q}$,. . . ($\sim \mathcal{O}(300)$) mcfm.fnal.gov/
- SHERPA : Simulation of High-Energy Reactions of PArticles in lepton-lepton, lepton-photon, photon-photon, lepton-hadron and hadron-hadron collisions.
  - A huge amount of scattering processes sherpa.hepforge.org.
- aMC@NLO : A framework for the computation of hard events at the NLO or LO, to be subsequently showered (infrared-safe observables at the NLO or LO).
  - Matrix elements calculations from Madgraph 5 amcatnlo.web.cern.ch/amcatnlo/; madgraph.phys.ucl.ac.be/.
- DYNNLO : NNLO calculation of Drell-Yan processes at hadron colliders theory.fi.infn.it/grazzini/dy.html
- NNLOJET : NNLO calculation of vector boson, V+jet, Higgs, inclusive jet/dijet at hadron colliders

Grid distribution: Ploughshare

ploughshare.web.cern.ch



Grid distribution: Ploughshare II

Full analysis records

Measurement of inclusive jet and dijet production in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector

Inclusive jet and dijet cross sections have been measured in proton-proton collisions at a centre-of-mass energy of 7 TeV using the ATLAS detector at the Large Hadron Collider. The cross sections were measured using jets clustered with the anti-kT algorithm with parameters R=0.4 and R=0.6. These measurements are based on the 2010 data sample, consisting of a total integrated luminosity of 37 inverse picobarns. Inclusive jet double-differential cross sections are presented as a function of jet transverse momentum, in bins of jet rapidity. Dijet double-differential cross sections are studied as a function of the dijet invariant mass, in bins of half the rapidity separation of the two leading jets. The measurements are performed in the jet rapidity range |y|<4.4, covering jet transverse momenta from 20 GeV to 1.5 TeV and dijet invariant masses from 70 GeV to 5 TeV. The data are compared to expectations based on next-to-leading order QCD calculations corrected for non-perturbative effects, as well as to next-to-leading order Monte Carlo predictions. In addition to a test of the theory in a new kinematic regime, the data also provide sensitivity to parton distribution functions in a region where they are currently not well-constrained.

journal: Phys.Rev. D86 (2012) 014022 (doi: 10.1103/PhysRevD.86.014022)
arxiv: 1112.6297
inspire: https://inspirehep.net/record/1082936
HepData: https://hepdata.net/record/ins1082936

link to full tarball

links to specific hep data table

Experiment	Physics process	Beam energy	Calculation	direct link	
ATLAS	pp	7 TeV	NLOjet++	atlas-atlas-dijets-arxiv-1112.6297 tarball	
				atlas-atlas-dijets-arxiv-1112.6297-xsec000.root	:: Table 19 : d2sigma/dm_{12}dy* [pb/TeV], Anti-kT R=0.4, 0.0<y*<0.5
				atlas-atlas-dijets-arxiv-1112.6297-xsec001.root	:: Table 20 : d2sigma/dm_{12}dy* [pb/TeV], Anti-kT R=0.4, 0.5<y*<1.0
				atlas-atlas-dijets-arxiv-1112.6297-xsec002.root	:: Table 21 : d2sigma/dm_{12}dy* [pb/TeV], Anti-kT R=0.4, 1.0<y*<1.5
				atlas-atlas-dijets-arxiv-1112.6297-xsec003.root	:: Table 22 : d2sigma/dm_{12}dy* [pb/TeV], Anti-kT R=0.4, 1.5<y*<2.0
				atlas-atlas-dijets-arxiv-1112.6297-xsec004.root	:: Table 23 : d2sigma/dm_{12}dy* [pb/TeV], Anti-kT R=0.4, 2.0<y*<2.5
				atlas-atlas-dijets-arxiv-1112.6297-xsec005.root	:: Table 24 : d2sigma/dm_{12}dy* [pb/TeV], Anti-kT R=0.4, 2.5<y*<3.0
				atlas-atlas-dijets-arxiv-1112.6297-xsec006.root	:: Table 26 : d2sigma/dm_{12}dy* [pb/TeV], Anti-kT R=0.4, 3.5<y*<4.0

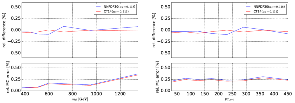
links to individual grids

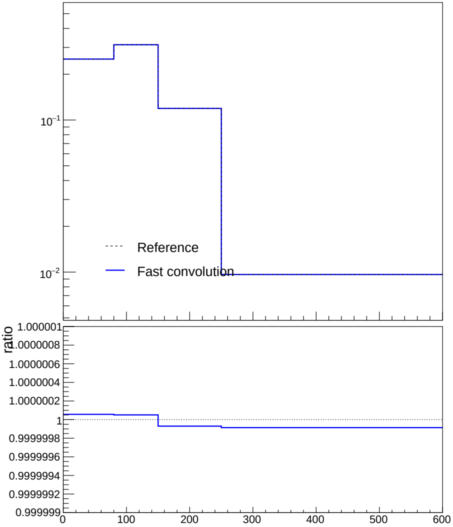
optional grid desciption

- Full title and abstract
- Links to …
  - Journal paper (DOI)
  - Preprint
  - Inspire
  - HepData
  - Table with all available grids

- This information is determined automatically from the required preprint ID when you upload grids
- For grids with no corresponding paper, a dummy arrive number arxiv: 0000.00000 can be used
- Users will be able to provide an additional HTML fragment in the tgz file if they require
- In the case of no available preprint the HTML fragment will be used as the analysis record …

Top production grids





- The fastNLO top grids for the CMS measurement [arXiv:1703.01630] at NNLO released by Czakon et al [arXiv:1704.08551]. Link
  - Code is not available
  - Poor performance : slow convolution and high memory consumption
- Tables converted to full APPLgrid tables. Link
  - Disk: 2.85 MB → 1.41 MB
  - Memory: 6052500 B → 3003750 B
  - Time: 182 ms → 126 ms

Current developments : MCFM v9.0

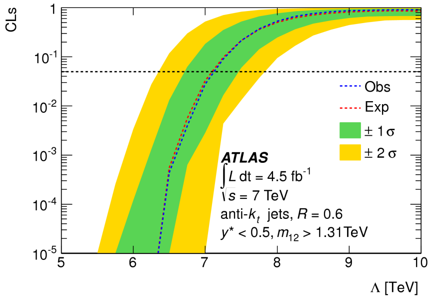
- MCFM group has released new version on 25.09.2019 [arXiv:1909.09117]
- Features: improved integration algorithm, better control of numerical accuracy, new code structure, new processes for off-shell SM and SMEFT single-top-quark production, high-pt treatment of mass effects in H+jet process, several NNLO color-singlet processes
- APPLgrid interface is off. The old one wouldn't work anyway, due to many changes in the MCFM code
- In contact with authors to re-enable the APPLgrid interface for the new versions $^{(*)}$
  - LO, REAL, VIRT contributions already implemented and validated
  - NNLO contribution is in progress
  - The mcmf-bridge user interface is updated
  - based on the text steering file
  - allows to fully configure the observable w/o recompiling the package

(∗) together with Vlad Danilov (CMS-DESY)

Contact interactions in jet production

- NLO calculations done by Jun Gao [arXiv:1204.4773]
- Original code takes some ideas from APPLgrid and generates matrix elements tables in a special (internal) format. The convolution script allows predictions for any PDF/strong coupling/Lambda a-posteriori

- Works nicely for plotting, but quite inconvenient, for fitting purposes...
- Interface C-APPLgrid is in progress



Summary

Precision measurements of QCD improve knowledge of PDFs and strong coupling constant and might facilitate discoveries at the LHC.

- APPLgrid is an open project, complete source code is available as HEPforge package
- A posteriori evaluation of uncertainties from renormalisation and factorisation scale variations, strong coupling measurement and PDFs error sets in a very short time
- Allows rigorous inclusion of collider data in a PDF/strong coupling fit.
- Other functionality, such as $\sqrt{S}$ rescaling, change of initial hadrons
- A list of QCD and electroweak processes can be studied
  - Jet production studied using NLOJET++ , NNLOJET
  - Drell-Yan production via NNLOJET, MCFM, DYNNLO
  - Many other processes via MCFM , SHERPA, aMC@NLO, ContactInteractions
    - W/Z/γ; W/Zγ+jet; $t\bar{t}$, $b\bar{b}$, $c\bar{c}$; W+charm, any process with a basic decomposition

BACK-UP