Fast re-evaluation of the W/Z differential cross-section at the NNLO using APPLGRID interface to DYNNLO framework

Pavel Starovoitov

KIP

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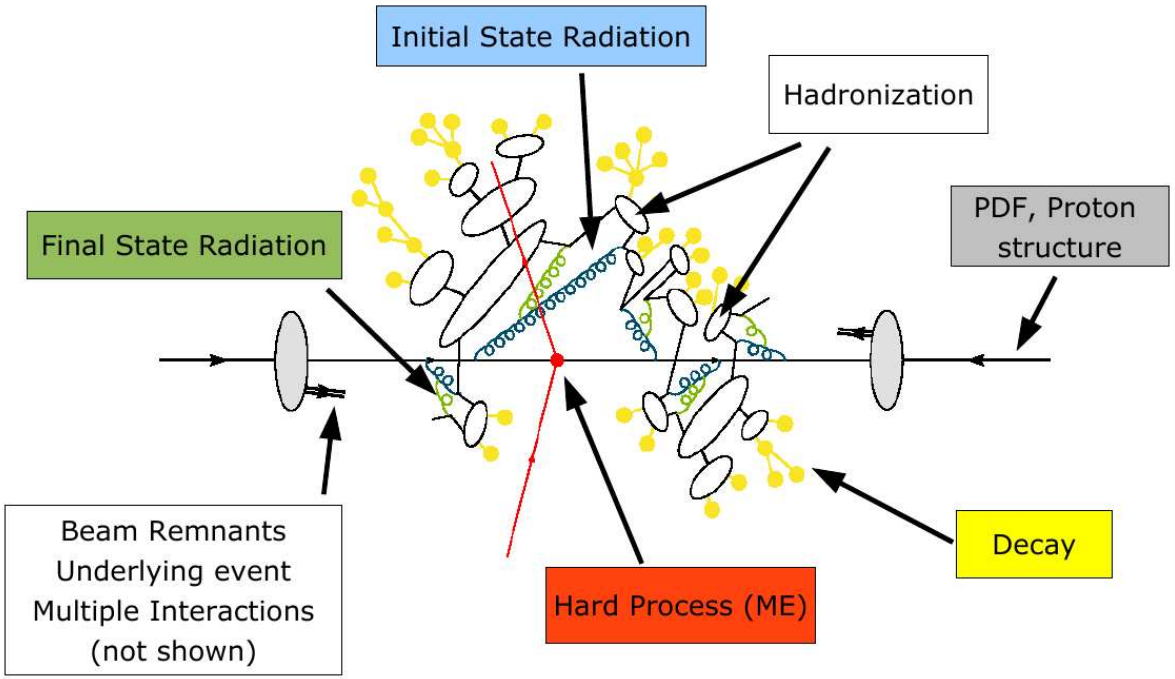
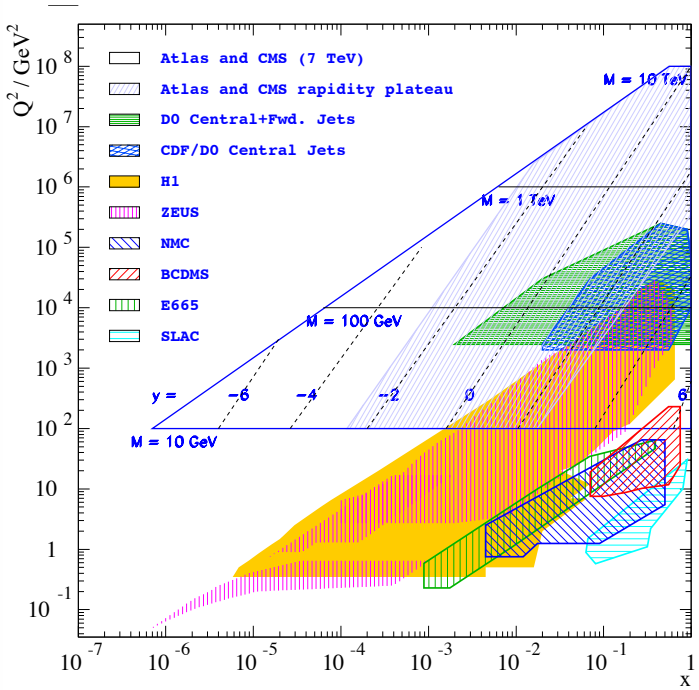
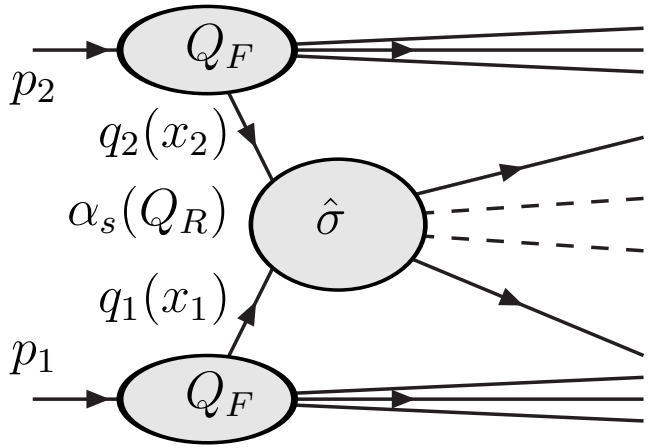
Proton-proton collision





- 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, . . .).

NNLO 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 factorisation theorem

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

$\Longrightarrow$ 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 (x_1, x_2, Q^2)
  - interpolation
  - initial flavours decomposition : $13 \times 13 \to \mathcal{L}$ $(\mathcal{L} \sim 10)$

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

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

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

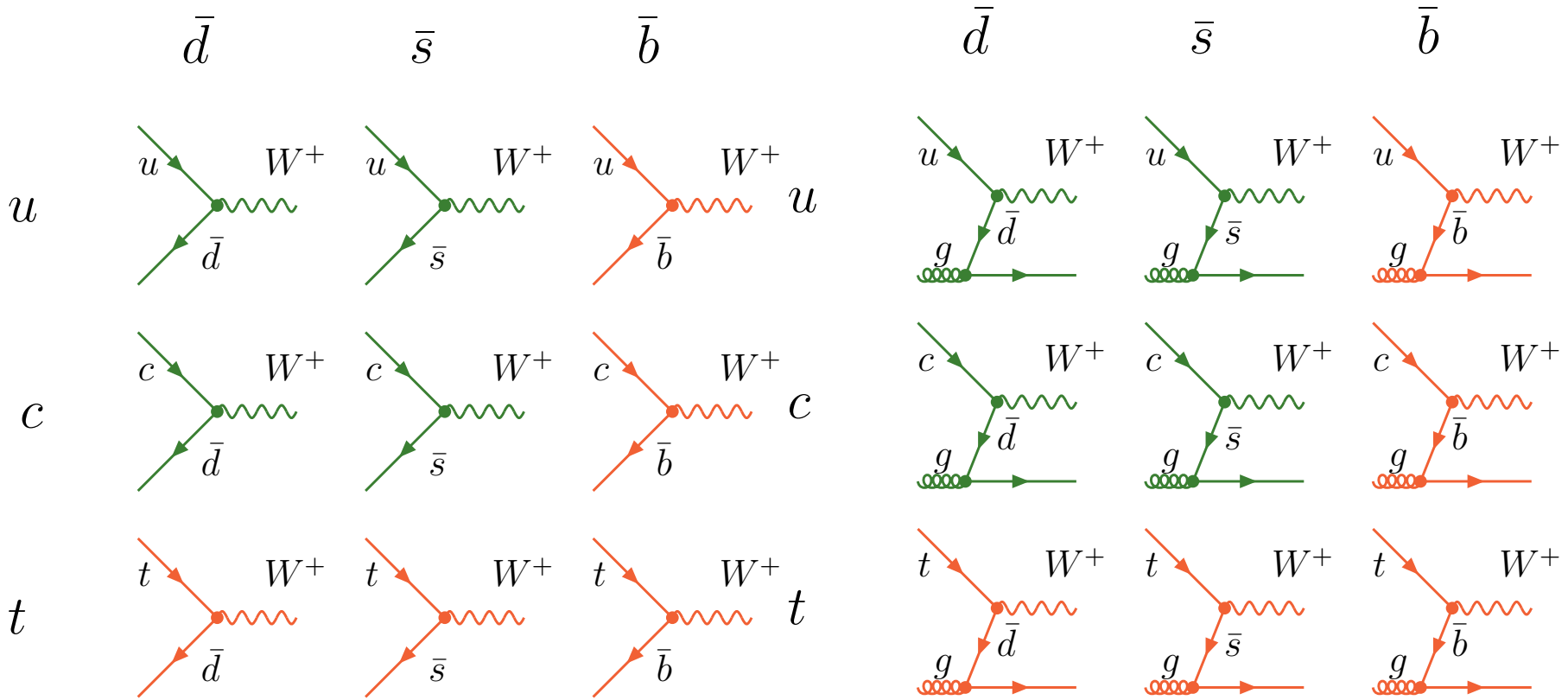
Interface to cross section calculators

- NLOJET++ : Jet production in $pp(\bar{p})-$ and $ep-$ collisions.
  - $2 \to 2$ and $2 \to 3$ at NLO; $2 \to 4$ at LO
    www.desy.de/∼znagy/Site/NLOJet++.htm.
- MCFM : parton-level NLO QCD cross sections calculator for various femtobarn-level processes at hadron-hadron colliders.
  - $V, V + nJet, V + b\bar{b}, VV, Q\bar{Q}, \ldots (\sim \mathcal{O}(300))$ 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

Observable definition

- $W^{\pm}$-boson : $\frac{d\sigma}{dy_{\ell}}$
  - $M_T > 40$ GeV
  - $p_T^{\ell} > 25$ GeV
  - $E_T^{miss} > 25$GeV
- $\frac{d\sigma}{dy_{Z^0}}$
  - $66 < M_{\ell\ell} < 116$ GeV
  - $|\eta_{\ell}| < 2.5$

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



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:

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

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

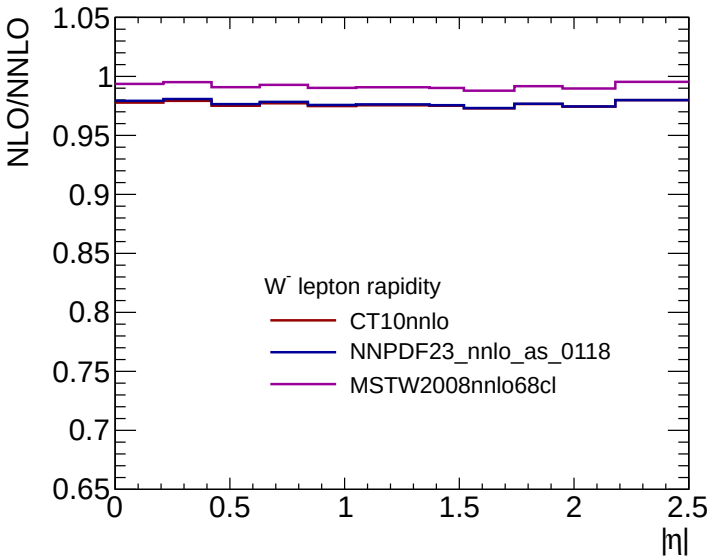
$$U_{12}(x_1, x_2) = \sum_{i=2,4,6} f_{i/H_1}\left(x_1, Q^2\right) f_{-i/H_2}\left(x_2, Q^2\right),$$

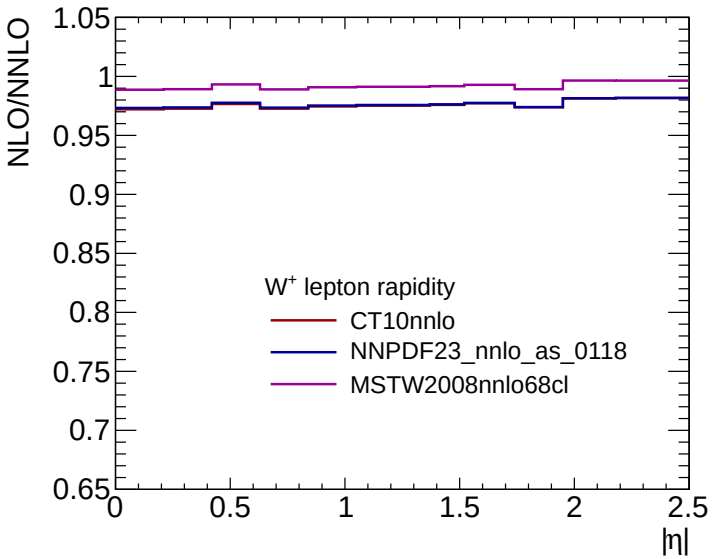
$$D_{12}(x_1, x_2) = \sum_{i=1,3,5} f_{i/H_1}\left(x_1, Q^2\right) f_{-i/H_2}\left(x_2, Q^2\right),$$

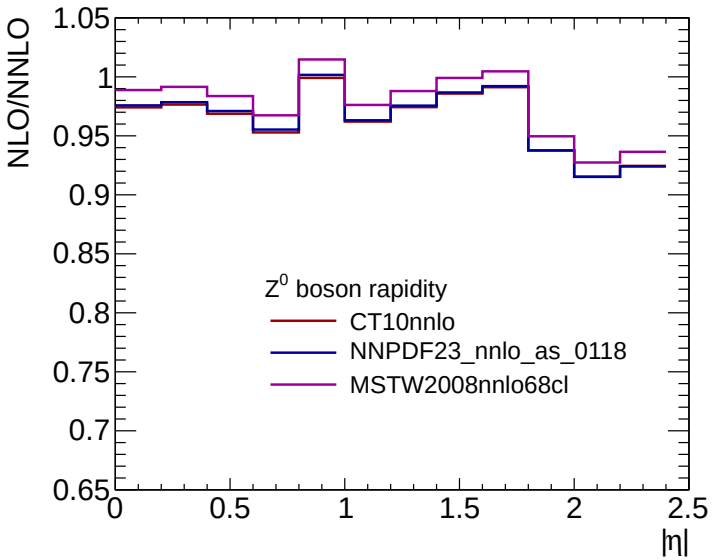
$$U_{21}(x_1, x_2) = \sum_{i=2,4,6} f_{-i/H_1}\left(x_1, Q^2\right) f_{i/H_2}\left(x_2, Q^2\right),$$

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

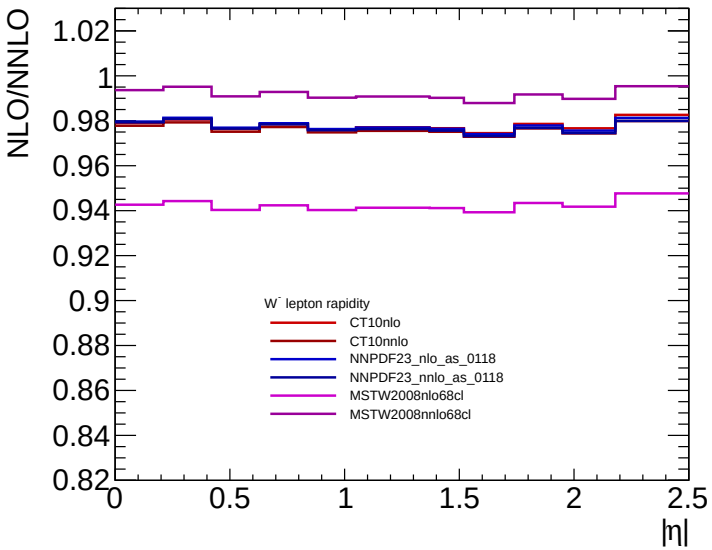
k-factors (NNLO PDFs)

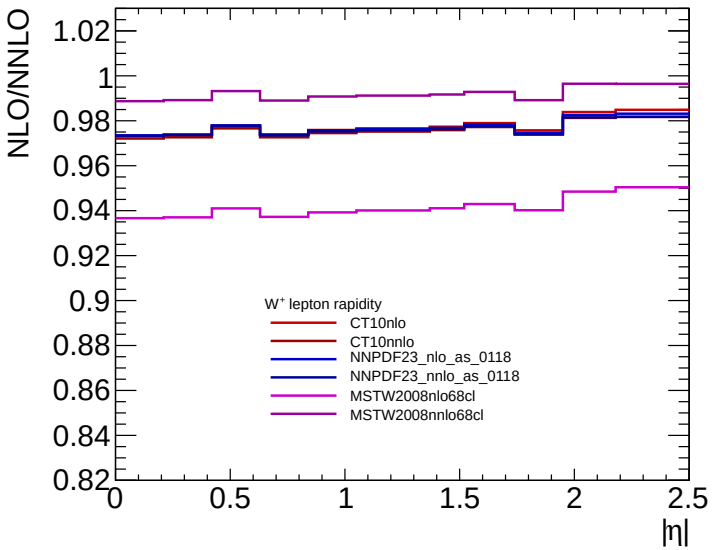


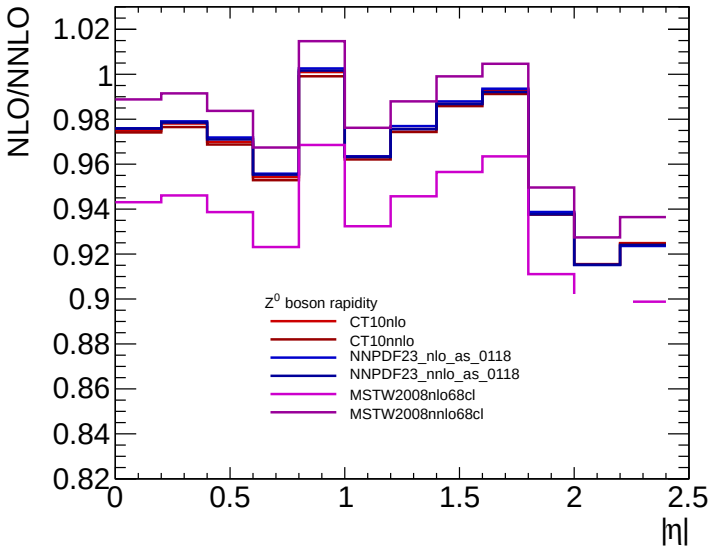




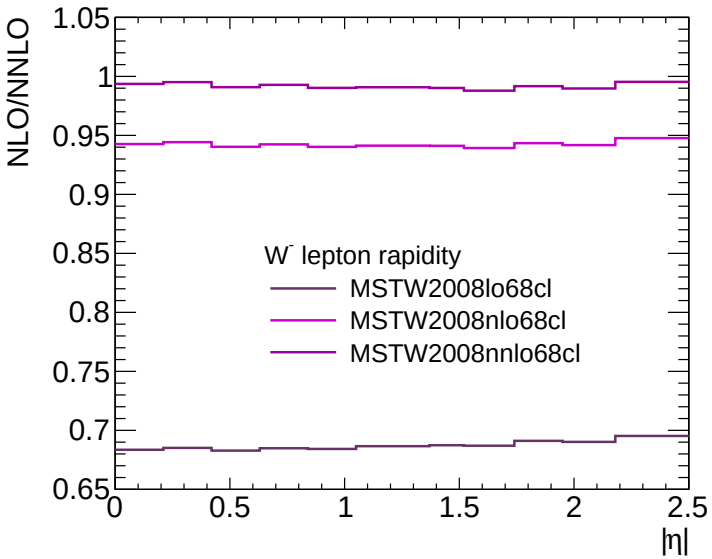
k-factors (NLO/NNLO PDFs)

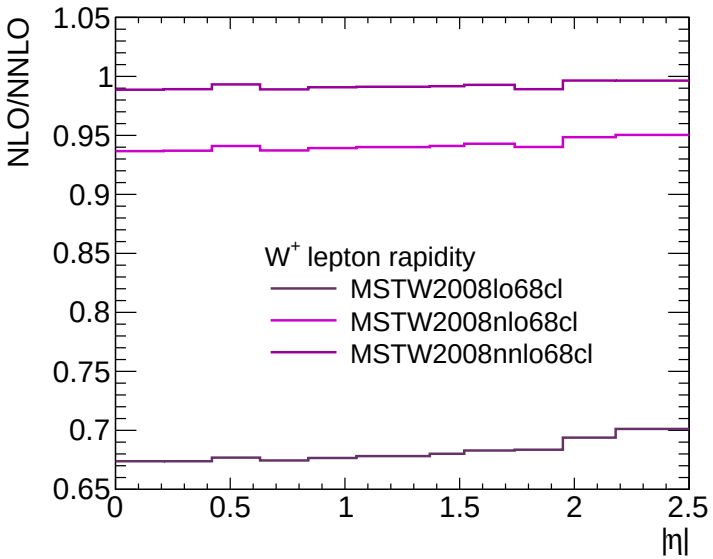


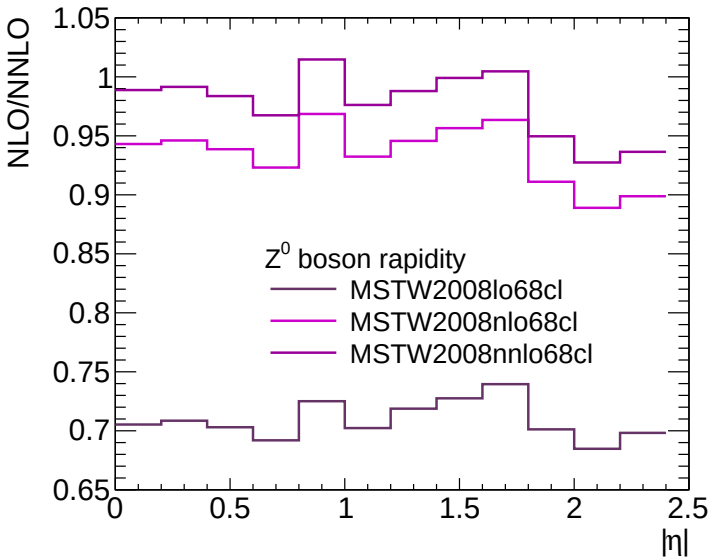




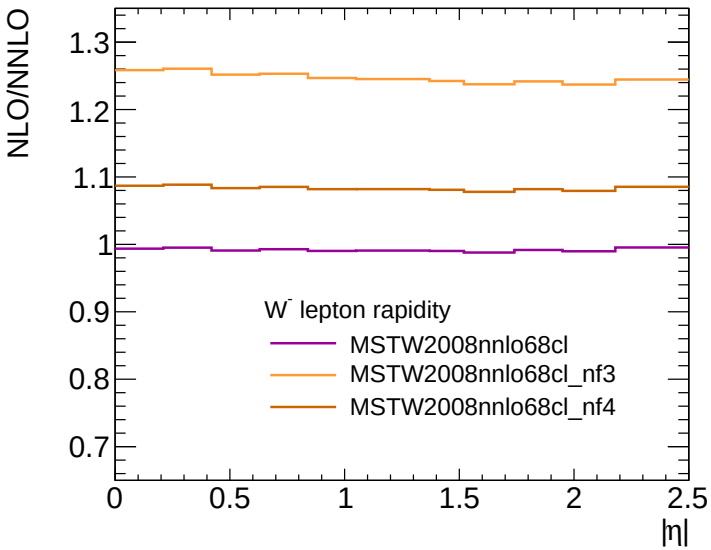
k-factors (LO/NLO/NNLO PDFs)

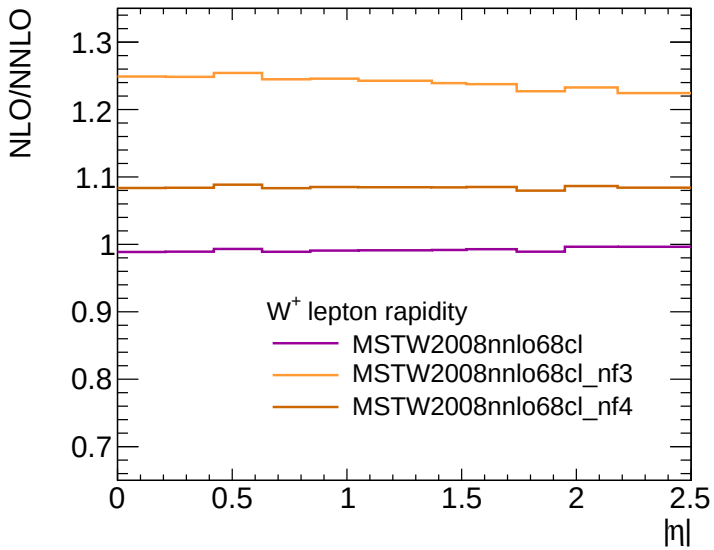


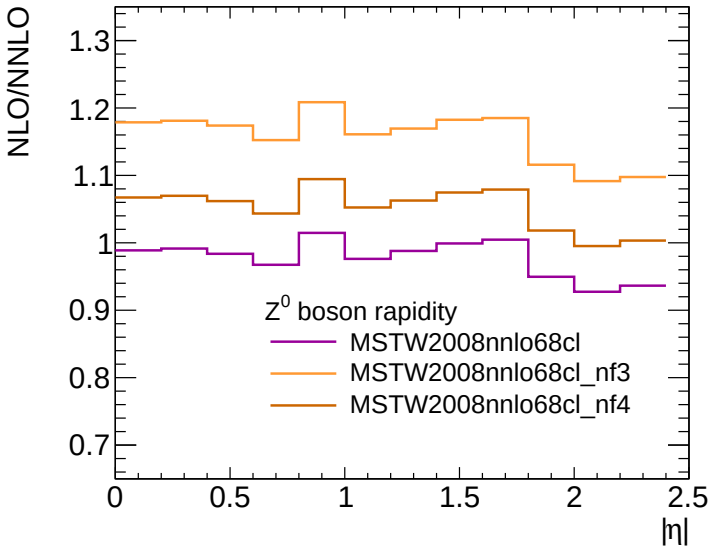




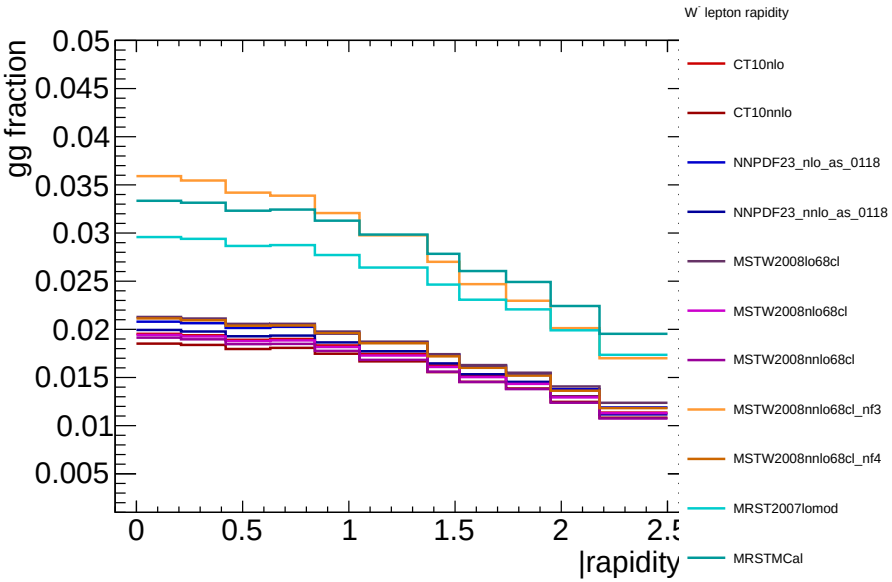
k-factors (FF PDFs)

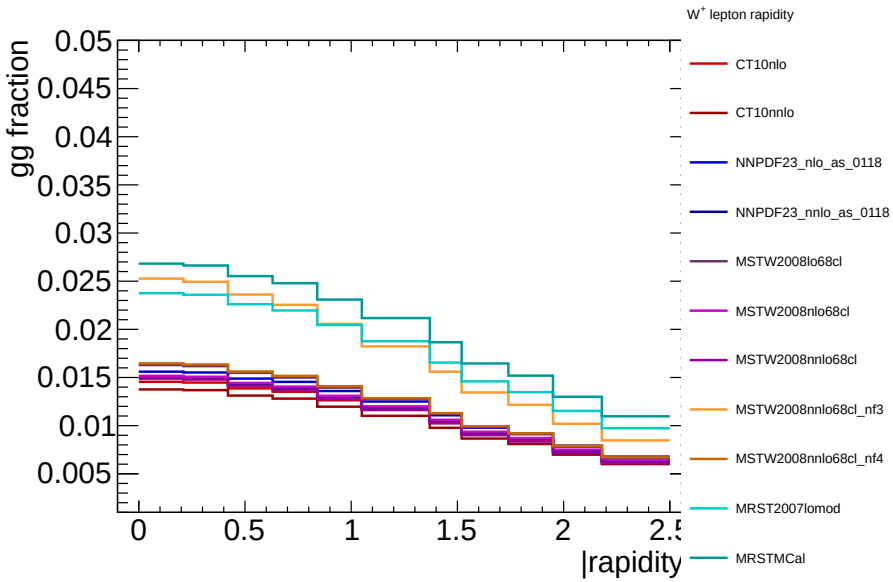


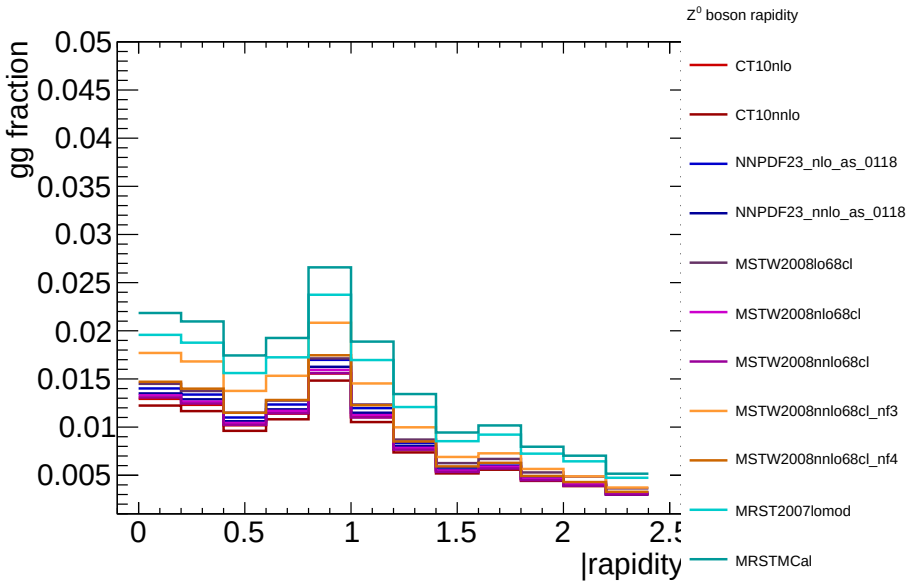




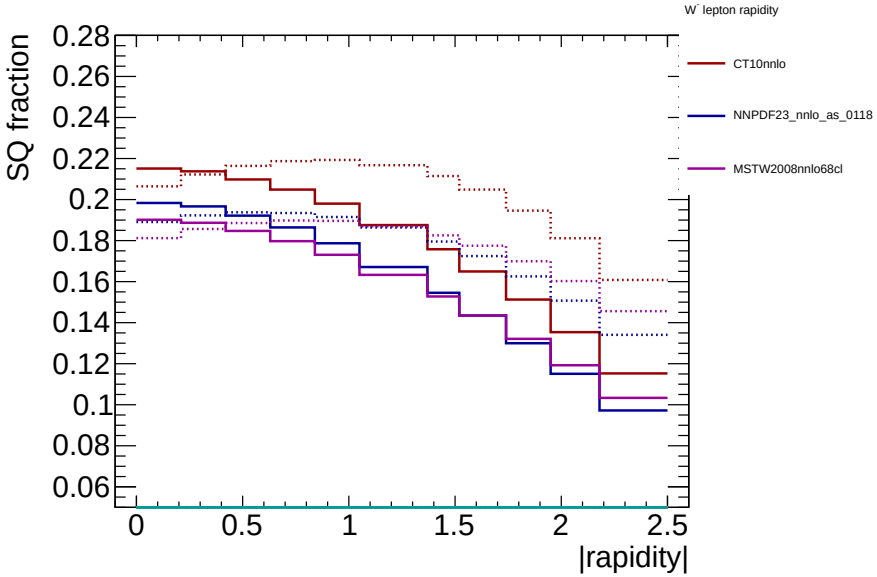
gg contribution

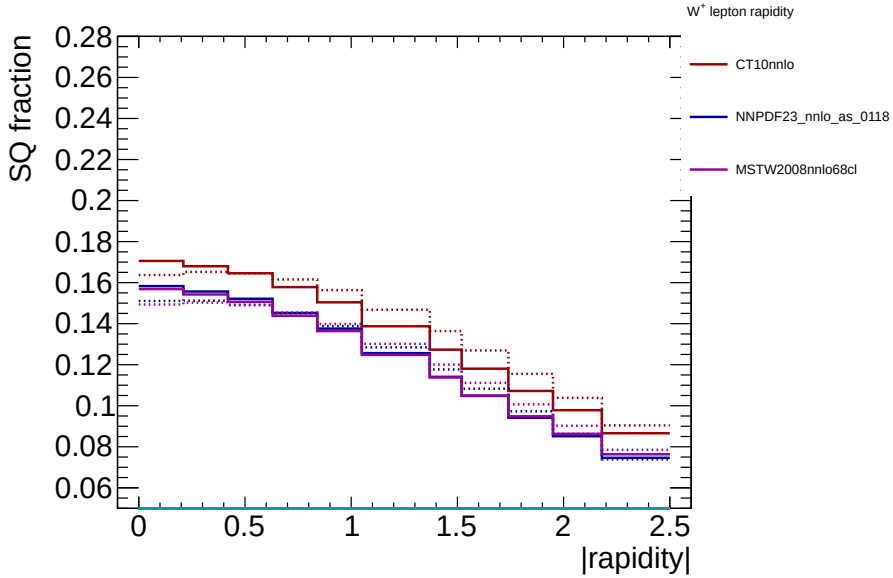


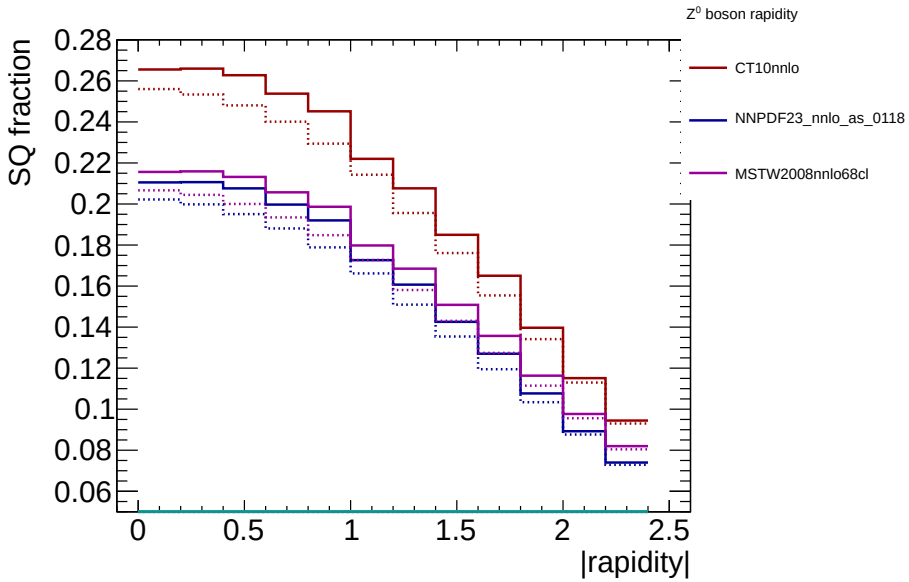




Strange-Quark contribution

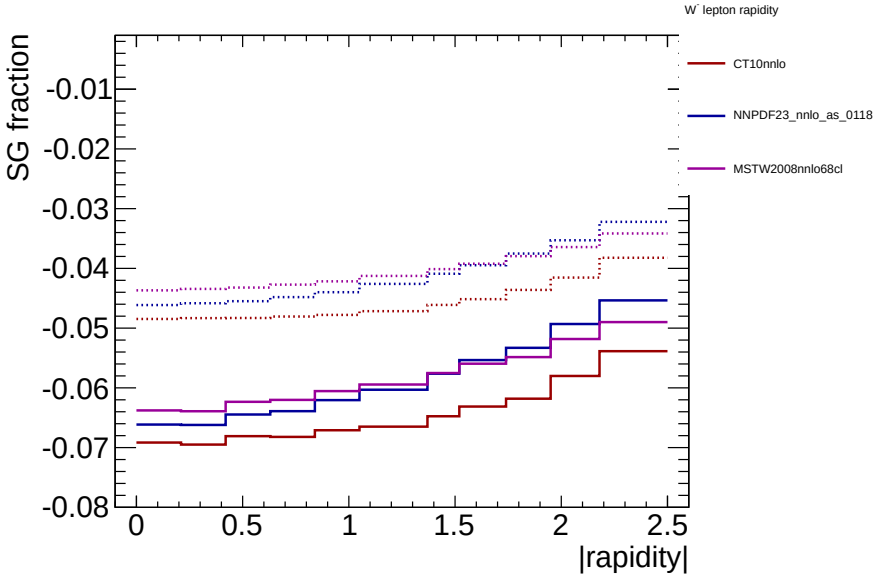


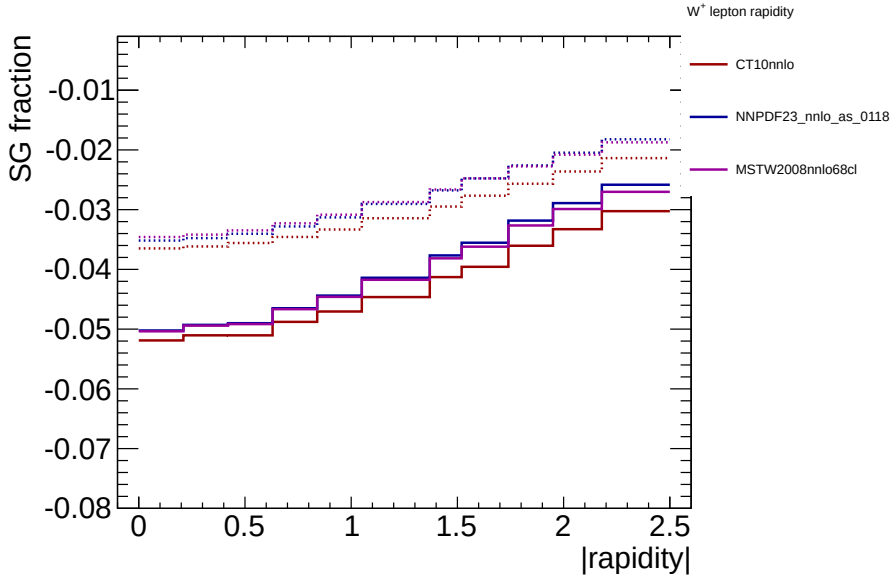


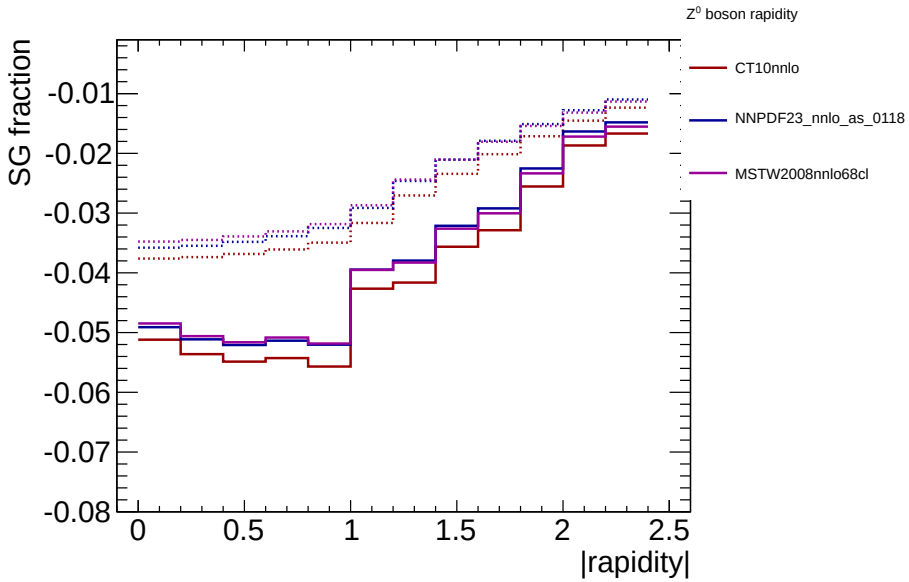


dashed line - NLO

Strange-gluon contribution







dashed line - NLO

Summary & Discussion

- A list of QCD and electroweak processes can be studied
  - Jet production cross sections studied using NLOJET++
  - Electroweak observables, $t\bar{t}$ or generally $Q\bar{Q}$, + many more are included using MCFM
  - A list of other processes via SHERPA, aMC@NLO
  - W/Z production at NNLO via DYNNLO
  - Other processes? Sub-processes?
- A posteriori evaluation of uncertainties from renormalisation and factorisation scale variations, strong coupling measurement and PDFs error sets in a very short time
  - Scales at LO/NLO (+)
  - Scales at NNLO (-) ...yet...

Discussion

- Convolution
  - Time consumption (PDFs calculation time is the limiting factor)
  - Memory issues (Observable binning, grid architecture and initial flavour decomposition are limiting factors)
  - Multi-thread convolution have been implemented in 1.4.72. For lhapdf 5 the gain in time was a factor of 2-5. Need to check with lhapdf 6. (PDF cache is the limiting factor there)
  - Grid architecture (interplay between accuracy and performance)
    - ★ can try to provide reduction constructors (grid(40,40,6)→grid(10,10,3) with PDF-shape re-weighting and reasonable accuracy)
- Grid library : Existing grids are being collected on the appgrid.hepforge.org and spectrum.web.cern.ch
  - How much effort should we put into it (ideology is to provide the code/help to our users)

APPLGRID accuracy.