PineAPPL: towards NLO EW corrections in NNPDF

arXiv:2008.12789

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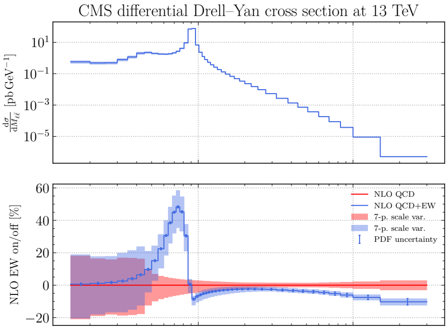
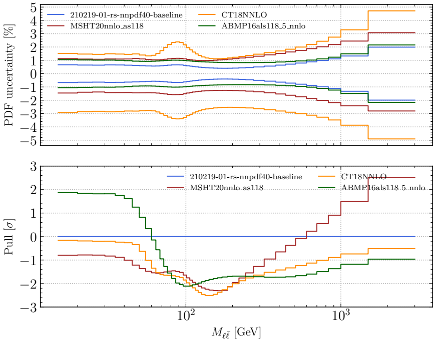
NLO EW PDF fit with NNPDF: motivation

- NNPDF4.0 – see Maria's and Michael/Shayan/Tommaso's talk – aims for $\lesssim 1\,\%$ accuracy/precision
- Further improvement need previously neglected contributions: theory uncertainties, NLO EW, ...
- NLO EW: never been done in a global (all processes) and consistent way (correct data)



- Can include extreme phase-space regions with large EW corrections: large $M_{\ell\ell}$ in Drell–Yan, large p_T of Z/W bosons, ... → constrain high x
- These regions are going to be measured more precisely in the future, e.g. predictions for CMS DY $L = 2.8\,\mathrm{fb}^{-1}$ @ 13 TeV [CMS Collaboration]



NLO EW in a PDF fit: What has to be done?

✓ Theory: Need corrections in the form of interpolation grids: PineAPPL

- interfaced with MG5_aMC@NLO, see [S. Carrazza, E.R. Nocera, C.S., M. Zaro]; now released in v3.1.0: `https://launchpad.net/mg5amcnlo`
- WIP: `SHERPA`/`MCgrid` [E. Bothmann et al.]
- API available in `C`, `C++`, `Fortran`, `Python`, `Rust`

✓ Data: Needs careful selection

- no subtraction of FSR
- no photon-initiated subtraction
- proper observable definition

→ subset of NNPDF4.0's LHC data + ...

✓ Write/test runcards for all PDF processes and ...

✗ Run them (WIP)

✗ Implement changed data (WIP)

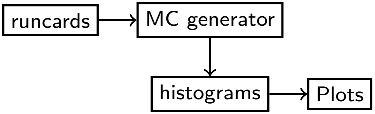
→ Run fit

What is PineAPPL?

PineAPPL

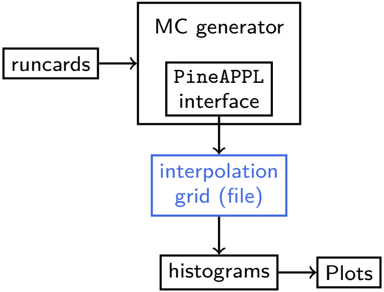
A tool/library for storing PDF-independent theoretical predictions in interpolation grids [S. Carazza, E.R. Nocera, C.S., M. Zaro]

Typical setup:



1. write runcards for your process/distributions
2. MC generates histograms with PDFs baked-in
3. changing PDFs is slow—need to rerun everything

With `PineAPPL`:



- grids can be convolved with arbitrary PDF sets in a matter of seconds

Interpolation techniques and applications

Not a new idea:

- APPLgrid [T. Carli et al.] or
- fastNLO [T. Kluge, K. Rabbertz, M. Wobisch]

Interpolate PDFs $f_a(x)$ with kernels $L_i(x), x \mapsto (0,1)$:

$$f_a(x) = \sum_{i=1}^{\infty} f_a^i L_i(x)$$

Convolution turns into a sum:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}} = \sum_a \int \mathrm{d}x\, f_a(x) \frac{\mathrm{d}\sigma_a}{\mathrm{d}\mathcal{O}}(x) = \sum_{a,i} f_a^i G_i$$

Interpolation grid $\{G_i\}_{i=1}^{\infty}$ indep. of PDFs:

$$G_i = \int \mathrm{d}x\, L_i(x) \sigma_a(x)$$

Applications of interpolation grids

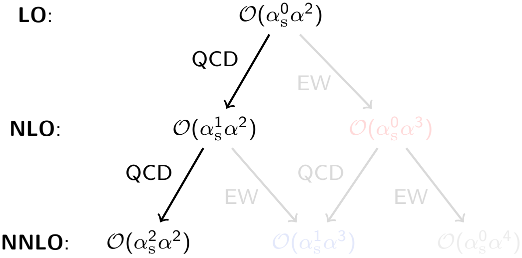
- input for PDF fits or
- study impact of PDFs uncertainties of observables

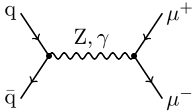
Why PineAPPL?

→ need support EW corrections (any powers of α and/or α_s)

- performance becomes very important: more bins, initial-states, scale variations ...
- powerful tooling (see later slides)

Which EW corrections will be included for $\mathrm{pp} \to \ell\bar{\ell}$?





- NNLO QCD corrections included in PDF fits

→ include also higher-order α contributions in NNPDF 4.x
  - for all processes
  - check impact of the corrections,
  - be more inclusive, etc.

→ `PineAPPL` supports all higher-orders

- $\mathcal{O}(\alpha_s \alpha^3)$ might become available at some point . . .
- lots of progress → talks by A. Behring, A. Sankar, N. Rana, L. Buonocore, A. von Manteuffel

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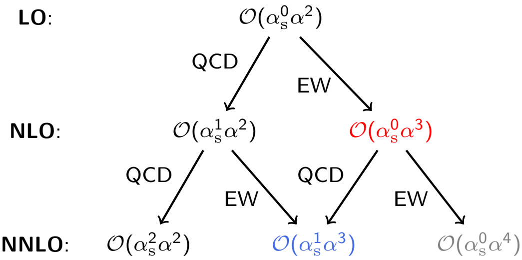

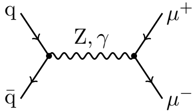

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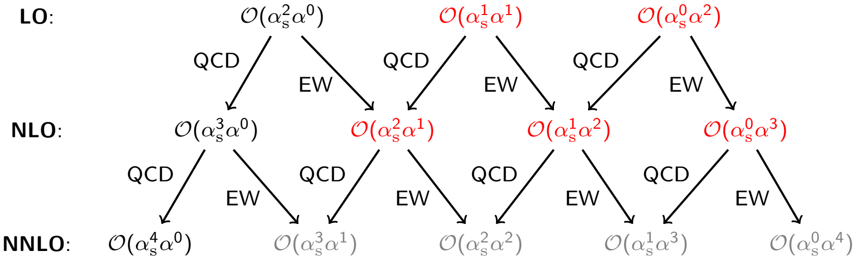

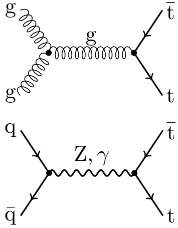

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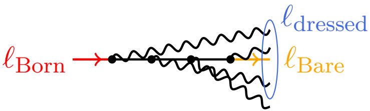
Which datasets do we fit? Final-state radiation (FSR) subtraction



- pre-FSR data/Born leptons: leptons "before they radiate", calculated using shower inversion (PHOTOS), from

→ post-FSR data/dressed leptons: leptons with photons recombined around $\Delta R_{f\gamma}$, typically $\Delta R_{f\gamma} = 0.1$

- bare leptons: non-collinear safe
- dressing factors

$$C_{\text{dress}} = \frac{\mathrm{d}\sigma_{\text{post-FSR}}/\mathrm{d}\mathcal{O}}{\mathrm{d}\sigma_{\text{pre-FSR}}/\mathrm{d}\mathcal{O}}$$

  can be very large, up to 50 % in invariant mass distributions

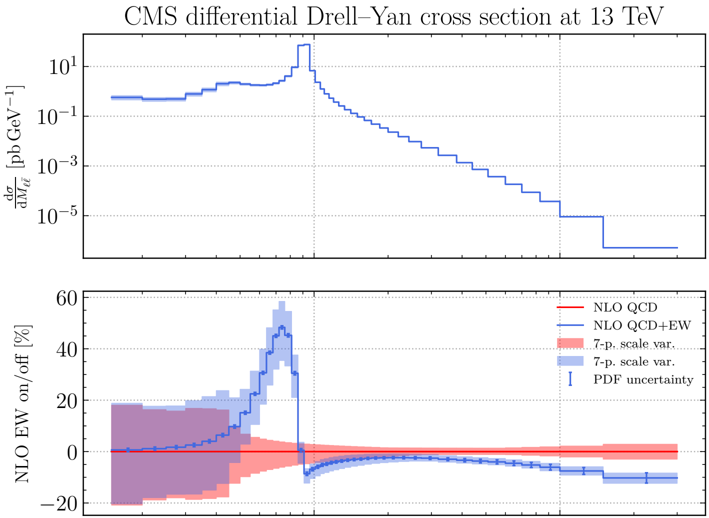
- pre-FSR data for comparisons with QCD-only theory predictions

→ post-FSR data for comparisons with EW corrections (up to one photon at NLO)

- For some analyses post-FSR data (preferred choice) not published: double counting issue with pre-FSR data!
- Often C_{dress} (+uncertainty) and pre-FSR dataset given ⇒ need to change systematic uncertainties!

→ NLO EW PDF dataset largely determinedy by whether dressed-lepton observables/post-FSR dataset is available

Effects of FSR in Drell–Yan



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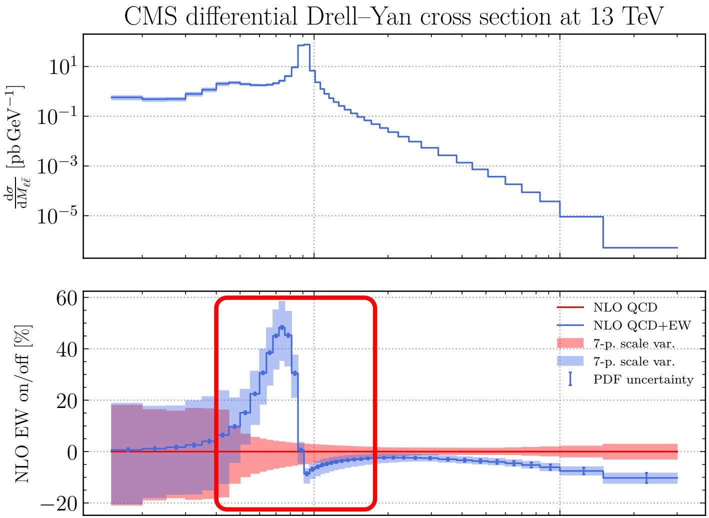

- large distortions of the NLO EW around the Z peak: QED FSR
- very large if bins are small
- subtracted in data in pre-FSR datasets
- scale-variation band much larger: interplay with theory uncertainties in PDF

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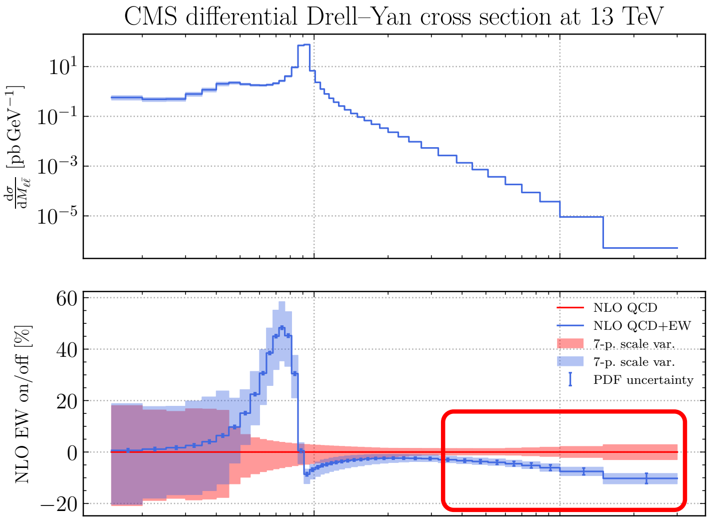

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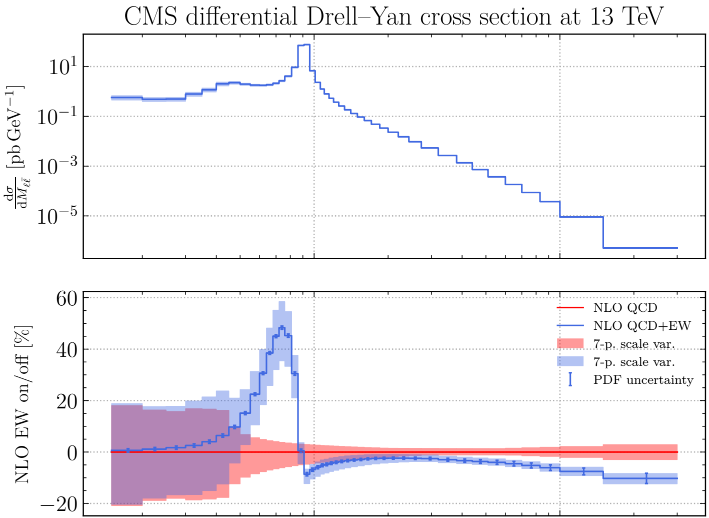

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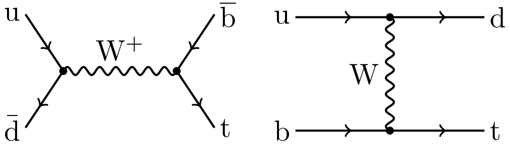
- Experiments: please publish (also) dressed-lepton observables/post-FSR datasets – we can't use it otherwise

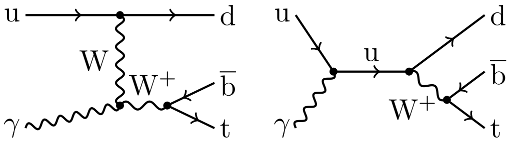
t-channel single-top production

Not properly/easily definable at NLO EW (see also [R. Frederix, D. Pagani, I. Tsinikos]):

- Analyses, e.g. [ATLAS collaboration], treat s-channels as irreducible background
- will be included in NNPDF4.0
- single-production at LO:



- but at NLO EW not (gauge-invariantly) separable:



$\rightarrow$ ignore these datasets

- probably not too important, but see [E.R. Nocera, M. Ubiali, C. Voisey]

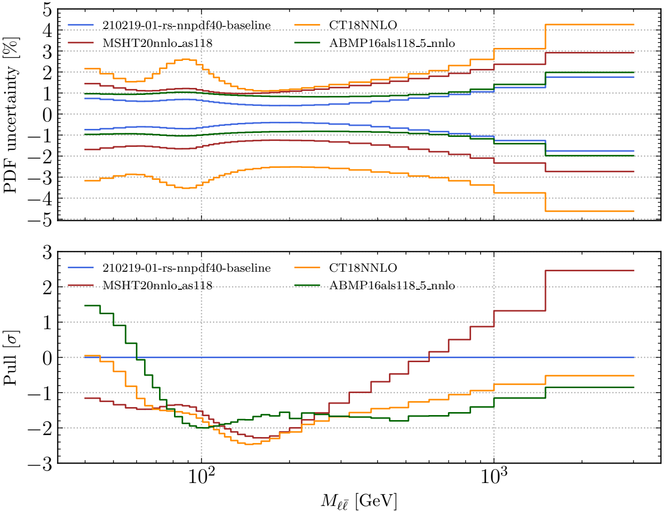
How can I use Madgraph5_aMC@NLO+PineAPPL?

1. Install Madgraph5_aMC@NLO: `https://launchpad.net/mg5amcnlo`
2. Install PineAPPL: `https://github.com/N3PDF/pineappl`
3. Example for generating the DY plot (next page) available at `https://github.com/N3PDF/pineappl/tree/master/examples/mg5amcnlo`

- only one line needs to be added in the mg5amc runcard (rhs)
- No two-phase generation of the grids needed
- Replaces the `aMCfast` [V. Bertone et al.] interface in Madgraph5_aMC@NLO v2.x
- `PineAPPL`'s CLI allows to easily produce convolutions and plots

```
launch processname
[..]
set ptl = 25.0
set etal = 2.5
set mll_sf = 116
set req_acc_FO 0.001
set pineappl True
done
quit
```

Example: DY plot




```
$ pineappl --silent-lhapdf plot \
    DY_14.pineappl.lz4 \
    210219-01-rs-nnpdf40-baseline \
    MSHT20nnlo_as118 \
    CT18NNLO \
    ABMP16als118_5_nnlo > plot.py
$ python3 plot.py
```

- PDF uncertainties for
  - NNPDF 4.0 candidate fit
  - MSHT20
  - CT18 (only main set)
  - ABMP16
- pull: weighted difference w.r.t. NNPDF 4.0 in units of σ

Summary

- NLO EW corrections for PDF fits: upgrading the precision of PDF processes
- `PineAPPL`: interpolation tool/library for storing PDF-independent theoretical predictions `https://github.com/N3PDF/pineappl`
- Built-in support in Madgraph5_aMC@NLO v3.1.0
- data issues: FSR subtraction, photon-initiated subtraction, ...

$\rightarrow$ effectively determines the datasets we can use for the fit

Outlook:

- We will publish grids for ATLAS/CMS/LHCb analyses (PDF processes) soon

$\rightarrow$ `PineAPPL` already public and Open Source: `https://n3pdf.github.io/pineappl`

- NLO EW PDF fit not too far away

Interpolation grids

For PDF fitting we need PDF independent predictions. Use Lagrange interpolation,

$$f_a(x_1, Q^2) f_b(x_2, Q^2) \approx \sum_{i,j,k} f_a(x_i, Q_k^2) f_b(x_j, Q_k^2) L_i(x_1) L_j(x_2) L_k(Q^2),$$

with Lagrange polynomials L_i over the 3D grid $\left\{(x_i, x_j, Q_k^2)\right\}_{i,j,k}$. Insert into master formula:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}} = \sum_{a,b} \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2 \int_{Q^2_{\mathrm{min}}}^{Q^2_{\mathrm{max}}} \mathrm{d}Q^2\, f_a(x_1, Q^2) f_b(x_2, Q^2) \frac{\mathrm{d}\sigma_{ab}}{\mathrm{d}\mathcal{O}}(x_1, x_2, Q^2, \mathcal{O})$$

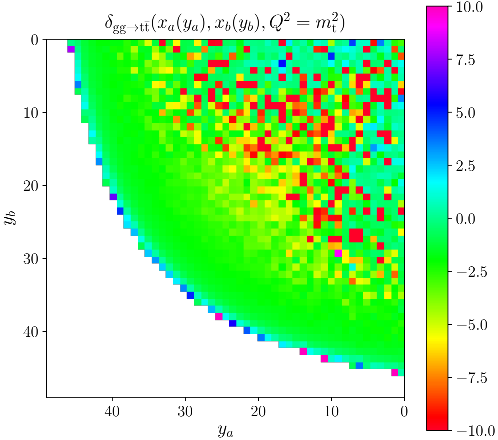
$$= \sum_{a,b} \sum_{i,j,k} \sum_{m,n} f_a(x_i, Q_k^2) f_b(x_j, Q_k^2) \alpha_{\mathrm{s}}^m(Q^2) \alpha^n \frac{\mathrm{d}\Sigma_{abijkmn}}{\mathrm{d}\mathcal{O}}$$

where

$$\frac{\mathrm{d}\Sigma_{abijkmn}}{\mathrm{d}\mathcal{O}} = \int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2 \int_{Q^2_{\mathrm{min}}}^{Q^2_{\mathrm{max}}} \mathrm{d}Q^2\, L_i(x_1) L_j(x_2) L_k(Q^2) \frac{\mathrm{d}\sigma_{ab}^{(i,k)}}{\mathrm{d}\mathcal{O}}(x_1, x_2, Q^2, \mathcal{O})$$

$\rightarrow$ generate $\frac{\mathrm{d}\Sigma_{abijkmn}}{\mathrm{d}\mathcal{O}}$ once, perform PDF convolutions very quickly off-line

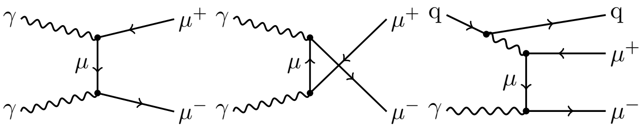
Example: $\Sigma_{\mathrm{gg}ij021}/\Sigma_{\mathrm{gg}ij020}$, $\mathcal{O}(\alpha_\mathrm{s}^2\alpha)/\mathcal{O}(\alpha_\mathrm{s}^2)$ for $\mathrm{gg} \to \mathrm{t\bar{t}}$ @ 8 TeV



- no interpolation in y_a, y_b, or Q^2
- correction for ixs roughly $-0.5\,\%$
- $y_{a/b}(x) = -\ln x_{a/b} + 5(1 - x_{a/b})$, $y(1) = 0$

- lower left corner → production threshold
- at threshold: Coulomb singularity
- $y_a \leftrightarrow y_b$ symmetry: initial-state symmetry of $\mathrm{gg} \to \mathrm{t\bar{t}}$
- negative correction for larger x_a, x_b

Subtraction of photon–photon contribution

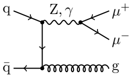


- For ATLAS and CMS it seems to be standard procedure to subtract double-photon induced contributions:

  The photon-induced process, $\gamma\gamma \to \ell\bar{\ell}$, is simulated at LO using Pythia 8 and the MRST2004qed PDF set.

- I am not sure why this is done
- This is a problem: proton contains photons, should be counted towards signal!
- Size of the LO contribution can become significant in large-invariant-mass bins (3 %) depending on the used PDF—up to twice as large for pre-LUXQED photon PDFs

Z transverse momentum



$$\mu = M_{\mathrm{Z}} \text{ vs. } \mu = \sqrt{M_{\mathrm{Z}}^2 + (p_{\mathrm{T}}^{\ell\bar{\ell}})^2}$$

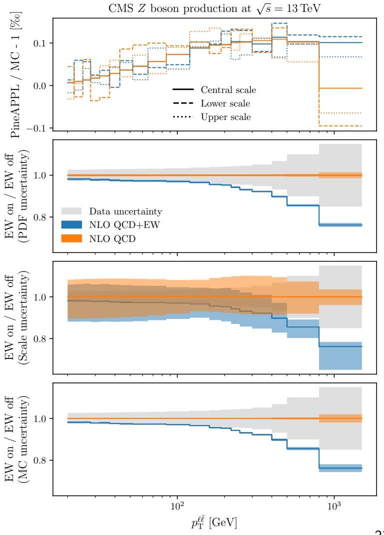
- FSR issues similar to DY
- no photon subtraction

static scale:

- accidental cancellation of NLO QCD correction → uncertainty band shrinks
- NLO EW are artificially enhanced because of normalisation

dynamic scale:

- scale variation is stabilised
- still significant EW corrections, comparable to data uncertainty



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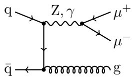

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