Towards an NLO EW PDF fit with NNPDF and `PineAPPL`

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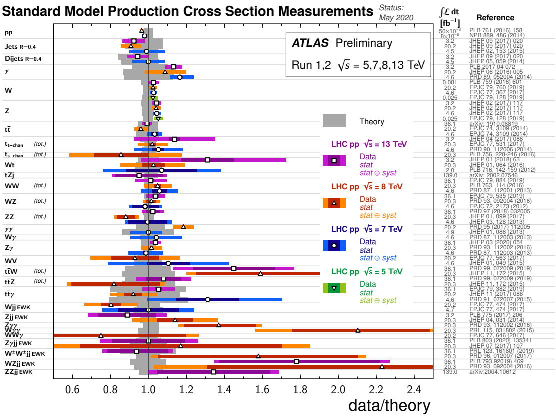
The race for precision at the LHC: Experiment, Theory, PDFs

- No spectacular deviations from SM predictions at the LHC

- LHC Run-1: $\sqrt{s} = 7\,\text{TeV}$ and $\sqrt{s} = 8\,\text{TeV}$
- LHC Run-2: $\sqrt{s} = 13\,\text{TeV}$, $L \approx 140\,\text{fb}^{-1}$
- N^2LO QCD for all $2 \to 2$ and a few $2 \to 3$ processes
- automated NLO EW calculations
- resummations for specific observables up to N^3LL

- small(er) theoretical/experimental uncertainties, stringent tests of the SM
- PDF determinations profit from this and own developments, e.g. better fitting methodologies

$\rightarrow$ better understanding of the structure of the proton (e.g. *reliably* smaller PDF uncertainties)



Plot from [ATLAS Collaboration]

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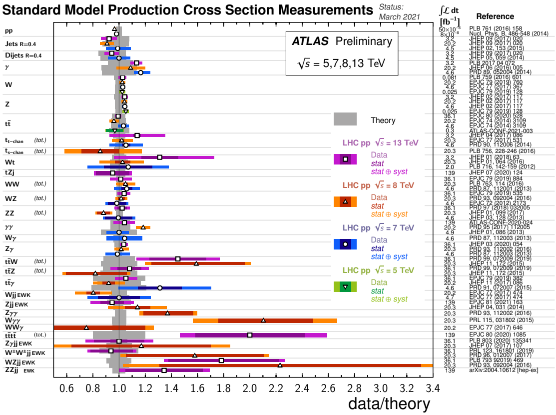
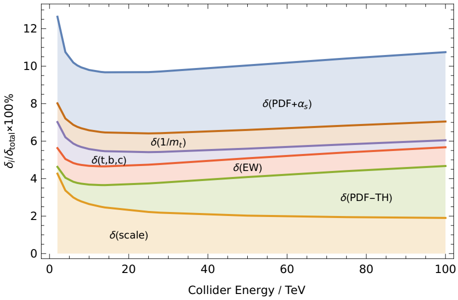


Plot from [ATLAS Collaboration]

Why better understand proton PDFs?

- PDFs interesting on their own, but ...
- contributes to theory uncertainty of observables
- e.g. N^3LO Higgs (right side) with [PDF4LHC15]
- $\delta(\mathrm{PDF} + \alpha_s)$: relative PDF and α_s uncertainty
- $\delta(\mathrm{PDF{-}TH})$: perturbative uncertainty from using N^2LO PDFs and N^3LO calculation

$$\delta(\mathrm{PDF{-}TH}) = \frac{1}{2} \left| \frac{\sigma(\mathrm{NNLO}) - \sigma(\mathrm{NLO})}{\sigma(\mathrm{NNLO})} \right|$$



plot from [F. Dulat, A. Lazopoulos, B. Mistlberger]

- or ATLAS 7 TeV M_W measurement, δm_W [MeV] with [CT10NNLO]
- or any other LHC observable...

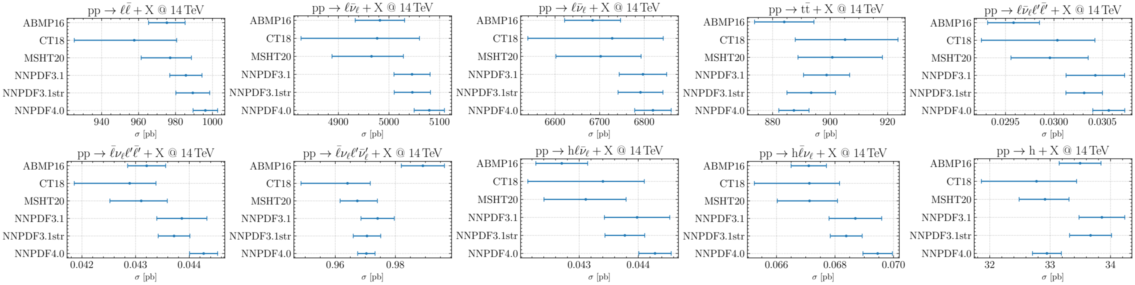
W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

table from [ATLAS Collaboration]

NNPDF4.0: A much more precise/accurate PDF set

- See talks at:
  - PDF4LHC: `https://indi.to/sc8mQ`
  - DIS: `https://www.stonybrook.edu/cfns/dis2021/`
  - LoopFest/Radcor: `https://indi.to/5Q6G8`
- hyperoptimised fitting methodology, more LHC data, nuclear uncertainties, ...
  see Emanuele R. Nocera's talk at DIS 20201: `https://indi.to/F8cFg`
- stronger tests: closure test, future test [J. Cruz-Martinez, S. Forte, E.R. Nocera]

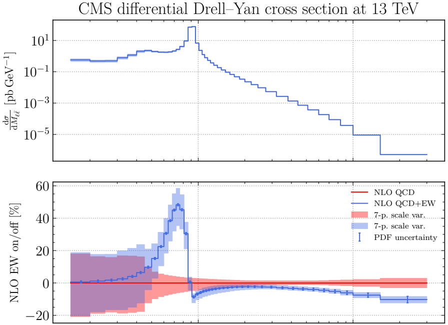
→ goal: $\lesssim 1\,\%$ uncertainties in luminosities, integrated/differential cross sections:



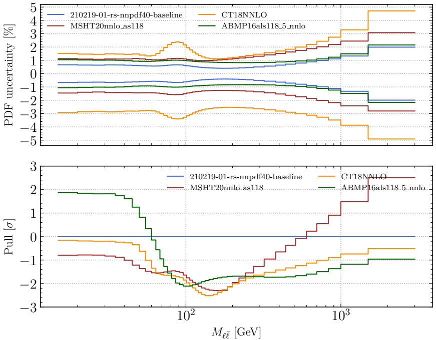
[ABMP16], [CT18], [MSHT20], [NNPDF3.1], [NNPDF3.1str]

Beyond NNPDF4.0: EW corrections

- NNPDF4.0 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 $L = 2.8\,\text{fb}^{-1}$ @ 13 TeV [CMS Collaboration]



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

✓ Photon-PDF: use NNPDF–LUXQED technology [NNPDF Collaboration], [A. Manohar et al.], [A. Manohar et al.]

✓ QED corrections in DGLAP with APFEL [V. Bertone, S. Carrazza, J. Rojo]

✓ 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`

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

✗ Run them (WIP)

✓ Data: Needs careful selection

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

→ subset of NNPDF4.0's LHC data + . . .

→ DIS data?

✗ Implement changed data (WIP)

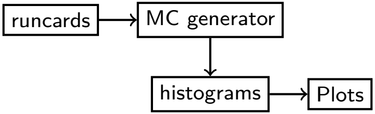
→ Run fit

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:

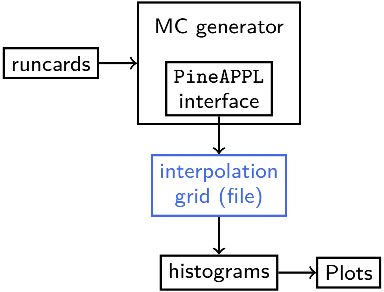


1. write runcards for your process/distributions
2. MC generates histograms with PDFs baked-in
3. changing PDFs is slow—need to rerun everything

Alternatively:

- on-the-fly evaluation of PDFs (typically one PDF set)
- reweighting

With `PineAPPL`:



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

Interpolation techniques and applications

Well-known idea:

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

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

$$f_a(x, Q^2) = \sum_{i=1}^{\infty} f_{ij}^a L_i(x) L_j(Q^2), \quad f_{ij}^a \in \mathbb{R}$$

Convolution turns into a sum:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}} = \sum_a \int \mathrm{d}x \int \mathrm{d}Q^2 \, f_a(x, Q^2) \frac{\mathrm{d}\sigma_a}{\mathrm{d}\mathcal{O}}(x, Q^2) = \sum_{aij} f_{ij}^a G_{ij}^a$$

Interpolation grid $\{G_{ij}^a\}_{aij}$ independent of PDFs:

$$G_{ij}^a = \int \mathrm{d}x \int \mathrm{d}Q^2 \, L_i(x) L_j(Q^2) \sigma_a(x, Q^2)$$

The price we have to pay:

- Interpolation error: typically sub-per mille
- Grids can become quite large (100 MB to 1000 MB)

Why `PineAPPL`?

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

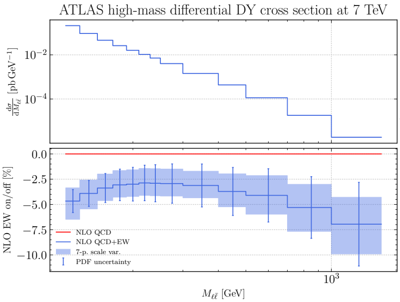
- performance becomes very important: more bins, initial-states, scale variations . . .
- better tooling (see later slides)

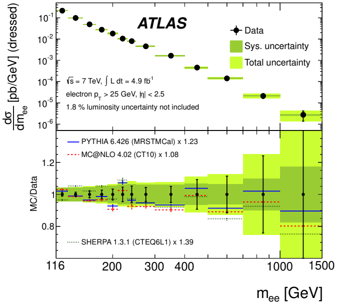
Applications of interpolation grids

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

Interpolation grids as input for PDF fits

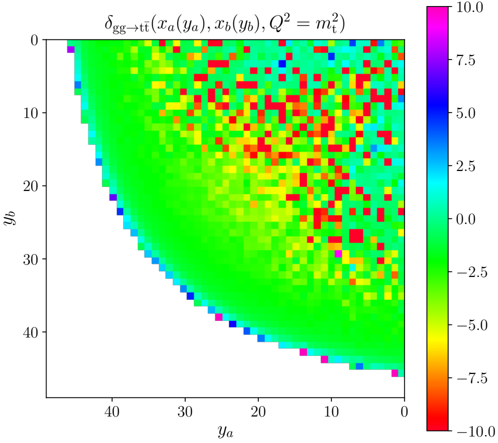
$$T_n = \frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}} = \sum_{abijk} f_{ik}^a f_{jk}^b \boxed{G_{ijk}^{ab}} \qquad \chi^2 = \sum_{nm} (D_n - T_n) C_{nm}^{-1} (D_m - T_m)$$

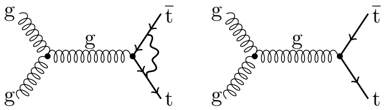




1. calculate **interpolation grids G_{ijk}^{ab}** for many process (shown is ATLAS DY high-mass 7 TeV [ATLAS Collaboration])
2. parametrise PDFs f_{ij}^a (neural networks)
3. get the corresponding measurements D_n and experimental covariancee matrix C_{nm}
4. calculate theory predictions T_n for all observables of all experiments
5. calculate χ^2
6. update PDF parameters
7. repeat 4 to optimize χ^2/N_{dof}

How does an interpolation grid look like: $\mathcal{O}(\alpha_s^2\alpha)/\mathcal{O}(\alpha_s^2)$ for $gg \to t\bar{t}$ @ 8 TeV





- integrated correction of $\mathcal{O}(\alpha_s^2\alpha)/\mathcal{O}(\alpha_s^2)$ roughly $-0.5\,\%$
- corrections differential in x_1 and x_2
- y: bin indices; $y = 0 \mapsto x = 1$, $y = 50 \mapsto x_{\text{min}} = 10^{-7}$
- $y_a \leftrightarrow y_b$ symmetry: initial-state symmetry of $gg \to t\bar{t}$
- lower left corner $\to$ production threshold at $8\,\text{TeV} \cdot \sqrt{x_1 x_2} > 2m_t$
- at threshold: Coulomb singularity
- negative correction for larger x_a, x_b

- no interpolation in y_a, y_b, or Q^2
- $y_{a/b}(x) \propto -\ln x_{a/b} + 5(1 - x_{a/b})$

Alternative: K factors + NLO QCD interpolation grids

Sometimes it's not possible to generate higher-order interpolation grids; use K factors:

$$K_{\text{NNLO}} = \frac{\mathrm{d}\sigma_{\text{NNLO}}/\mathrm{d}\mathcal{O}}{\mathrm{d}\sigma_{\text{NLO}}/\mathrm{d}\mathcal{O}} \qquad K_{\text{EW}} = \frac{\mathrm{d}\sigma_{\text{EW}}/\mathrm{d}\mathcal{O}}{\mathrm{d}\sigma_{\text{QCD}}/\mathrm{d}\mathcal{O}} \qquad \frac{\mathrm{d}\sigma^{\text{NNLO}}}{\mathrm{d}\mathcal{O}} \approx \sum_{aij} K_{\text{NNLO}} f_{ij}^{a} G_{ij}^{a,\text{NLO}}$$

- NNPDF (and ABMP, CT, MSHT) use NNLO QCD K_{NNLO} factors instead of interpolation grids
- MSHT20 uses K_{EW} factors for some NLO EW corrections

Features of K factors:

- very easy to handle, especially if MCs aren't public
- if $K \approx 1$, they won't impact the PDF fit
- however: K factors are blind to initial-state parton flavours, x_1, x_2 and Q^2

$\rightarrow$ new partonic channels opening up NNLO or NLO EW are zero!

$\rightarrow$ $K = 1$ and massive reshuffling between flavours/scales?

Goals:

- For NLO EW we chose interpolation grids to be on the safe side
- We want to switch from NNLO QCD K factors to grids at some point

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

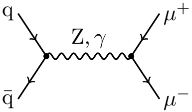
LO: $\mathcal{O}(\alpha_s^0 \alpha^2)$

QCD ↙ EW ↘

NLO: $\mathcal{O}(\alpha_s^1 \alpha^2)$ $\mathcal{O}(\alpha_s^0 \alpha^3)$

QCD ↙ EW ↘ QCD ↙ EW ↘

NNLO: $\mathcal{O}(\alpha_s^2 \alpha^2)$ $\mathcal{O}(\alpha_s^1 \alpha^3)$ $\mathcal{O}(\alpha_s^0 \alpha^4)$



- NNLO QCD corrections included in PDF fits

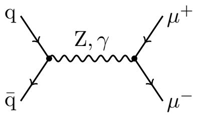
→ include also higher-order α contributions in NNPDF 4.x
  - for all processes
  - check impact of the corrections,
  - be more inclusive, etc.

→ PineAPPL supports all higher-orders

- $\mathcal{O}(\alpha_s \alpha^3)$ might become available at some point . . .

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

$$\begin{tikzcd}[column sep=small]
\textbf{LO:} & & & \mathcal{O}(\alpha_s^0\alpha^2) \arrow[dl, "\text{QCD}"'] \arrow[dr, "\text{EW}"] & & \\
\textbf{NLO:} & & \mathcal{O}(\alpha_s^1\alpha^2) \arrow[dl, "\text{QCD}"'] \arrow[dr, "\text{EW}"] & & \color{red}{\mathcal{O}(\alpha_s^0\alpha^3)} \arrow[dl, "\text{QCD}"'] \arrow[dr, "\text{EW}"] & \\
\textbf{NNLO:} & \mathcal{O}(\alpha_s^2\alpha^2) & & \color{blue}{\mathcal{O}(\alpha_s^1\alpha^3)} & & \color{gray}{\mathcal{O}(\alpha_s^0\alpha^4)}
\end{tikzcd}$$



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

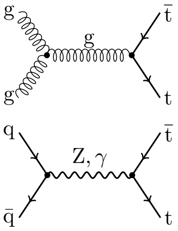
LO: $\mathcal{O}(\alpha_s^2\alpha^0)$ $\mathcal{O}(\alpha_s^1\alpha^1)$ $\mathcal{O}(\alpha_s^0\alpha^2)$

QCD EW QCD EW QCD EW

NLO: $\mathcal{O}(\alpha_s^3\alpha^0)$ $\mathcal{O}(\alpha_s^2\alpha^1)$ $\mathcal{O}(\alpha_s^1\alpha^2)$ $\mathcal{O}(\alpha_s^0\alpha^3)$

QCD EW QCD EW QCD EW QCD EW

NNLO: $\mathcal{O}(\alpha_s^4\alpha^0)$ $\mathcal{O}(\alpha_s^3\alpha^1)$ $\mathcal{O}(\alpha_s^2\alpha^2)$ $\mathcal{O}(\alpha_s^1\alpha^3)$ $\mathcal{O}(\alpha_s^0\alpha^4)$



- NNLO QCD corrections included in PDF fits

$\to$ include also higher-order α contributions in NNPDF 4.x

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Lepton observables: what do we call a lepton?

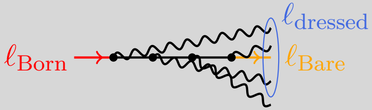
Basic lepton facts:

- very important for PDF processes: DY, W boson prod., Z-boson p_{T}, ...
- they radiate: lots of collinear and/or soft photons!
- in NNLO QCD: no additional photon radiation
- in NLO EW: up to one extra photon

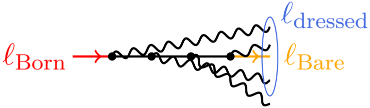
$\rightarrow$ we must be able to calculate what is being measured; understand lepton definition!

Three possible definitions for 'lepton'

1. Only charged object is the lepton: bare lepton
2. Add photons around some ΔR of the lepton: dressed lepton
3. Lepton before it radiates: Born lepton



Which lepton observable definition do we adopt?



- bare leptons: non-collinear safe, useful for muons, see e.g. [S. Dittmaier, A. Kabelschacht, T. Kasprzik]
- Born leptons: leptons "before they radiate", calculated using shower inversion (PHOTOS), from
→ dressed leptons: leptons with photons recombined around $\Delta R_{f\gamma}$, typically $\Delta R_{f\gamma} = 0.1$
- dressing factors

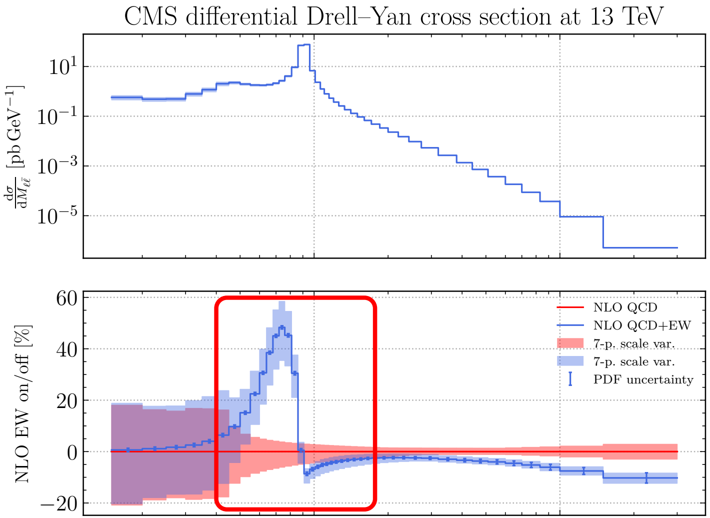
$$C_{\mathrm{dress}} = \frac{\mathrm{d}\sigma_{\mathrm{dressed}}/\mathrm{d}\mathcal{O}}{\mathrm{d}\sigma_{\mathrm{Born}}/\mathrm{d}\mathcal{O}}$$

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

- Born leptons for comparisons with QCD-only theory predictions
→ dressed leptons for comparisons with EW (+QCD) corrections

- For some analyses dressed-lepton data not published: double counting issue with Born-lepton data!
→ NLO EW PDF dataset largely determinedy by whether dressed-lepton dataset is available; sometimes we can't tell

Effects of FSR in Drell–Yan: CMS 13 TeV $L = 2.8\,\mathrm{fb}^{-1}$ [CMS Collaboration]



- large corrections of the NLO EW around the Z peak: QED FSR
- very large if bins are small (LHC run II feature)
- probably calls for resummation
- subtracted in data in pre-FSR datasets
- scale-variation band much larger: interplay with theory uncertainties in PDF?
- not described by FSR: weak corrections for large $M_{\ell\ell}$ → need full EW corrections
- dressed-lepton data sometimes not available

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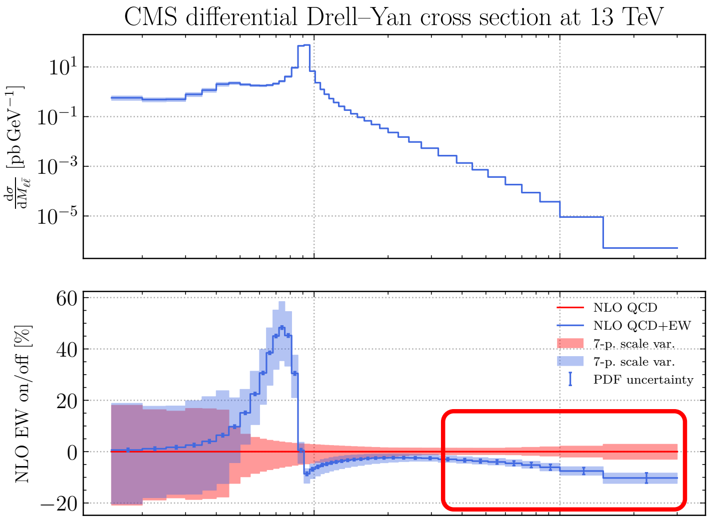

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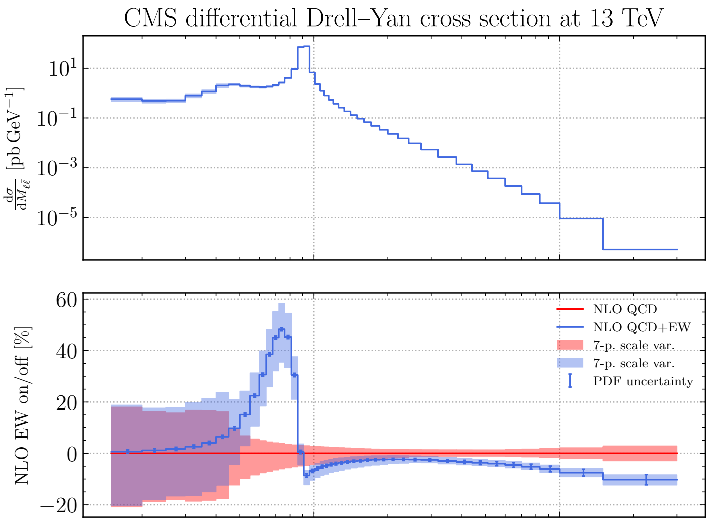

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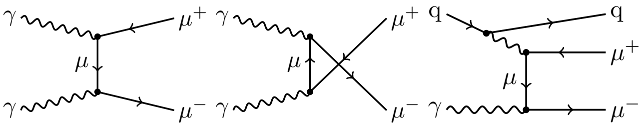
Subtraction of photon–photon contribution

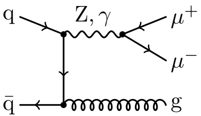


- For ATLAS and CMS it seems to be standard procedure to subtract double-photon induced contributions:

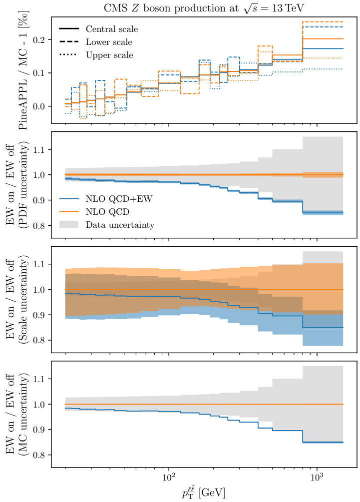
  The photon-induced process, $\gamma\gamma \to \ell\bar{\ell}$, is simulated at LO using Pythia 8 and the MRST2004qed PDF set.

- not considered part of "Drell–Yan lepton pair production"
- Problem for our exercise: proton contains photons, should be counted towards signal!
- Subtracted in data, original data most likely lost
- Size of the LO contribution can become significant in large-invariant-mass bins (3 % to 6 %) depending on the used PDF

Z transverse momentum



$$\mu = \sqrt{M_Z^2 + (p_T^{\ell\bar{\ell}})^2}$$



- FSR issues similar to DY, but typically $60\,\mathrm{GeV} < M_{\ell\bar{\ell}} < 120\,\mathrm{GeV}$ $\rightarrow$ small QED corrections
- plot on the RHS: predictions for CMS 13 TeV $L = 35.8\,\mathrm{fb}^{-1}$ [CMS Collaboration]
- compare size of NLO EW (blue) vs. data uncertainty (gray)
- no photon subtraction (small contribution)

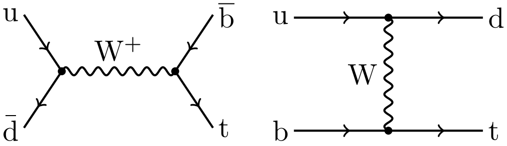
$\rightarrow$ large weak corrections at large transverse momentum, similar to data uncertainty (with $L = 35.8\,\mathrm{fb}^{-1}$)

- use a resummed prediction for $p_T < 30\,\mathrm{GeV}$: very precise data

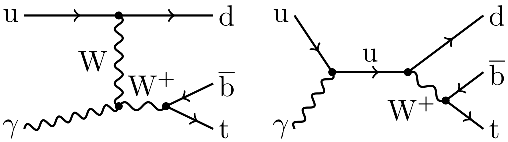
t-channel single-top production

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

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



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



$\rightarrow$ ignore these datasets

- better idea: partonic cross section with zero b jets?
- probably not too important [E.R. Nocera, M. Ubiali, C. Voisey], due to larger data uncertainty

How can I play with PineAPPL?

1. Install Madgraph5_aMC@NLO (at least v3.1.x): 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
```

PineAPPL: --help

```
$ pineappl --help
pineappl 0.5.0-alpha
Read, write, and query PineAPPL grids

USAGE:
    pineappl [FLAGS] <SUBCOMMAND>

FLAGS:
    -h, --help              Prints help information
        --silence-lhapdf    Prevents LHAPDF from printing banners
    -V, --version           Prints version information

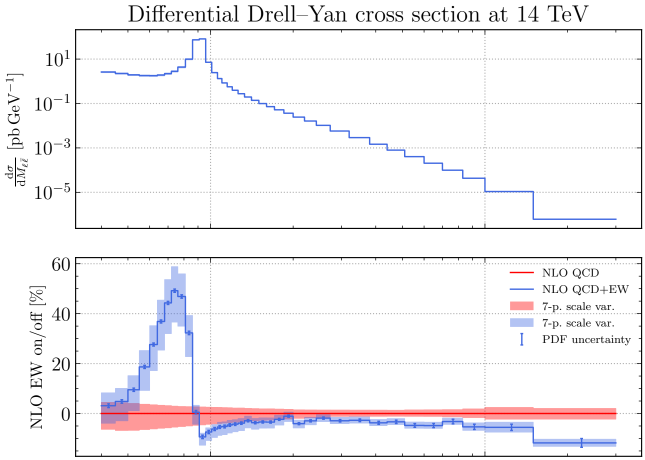
SUBCOMMANDS:
    channels          Shows the contribution for each partonic channel
    convolute         Convolutes a PineAPPL grid with a PDF set
    diff              Compares the contents of two grids with each other
    info              Shows information about the grid
    luminosity        Shows the luminosity function
    merge             Merges one or more PineAPPL grids together
    optimize          Optimizes the internal data structure to minimize memory usage
    orders            Shows the predictions for all bin for each order separately
    pdf_uncertainty   Calculates PDF uncertainties
    plot              Creates a matplotlib script plotting the contents of the grid
    remap             Modifies the bin dimensions, widths and normalizations
    set               Modifies the internal key-value storage
    subgrids          Print information about the internal subgrid types
    sum               Sums two or more bins of a grid together
```

PineAPPL: convolute

```
$ pineappl convolute NNPDF_DY_14TEV_40_PHENO.pineappl.lz4 \
> NNPDF31_nlo_as_0118_luxqed
bin    Mll       dsig/dMll   neg unc pos unc
---+----+----+------------+-------+-------
  0   40   45  2.5430906e0  -6.34%   4.43%
  1   45   50  2.1991339e0  -7.05%   4.57%
  2   50   55  1.9127949e0  -7.45%   4.86%
  3   55   60  1.7689139e0  -7.85%   5.37%
  4   60   64  1.7440995e0  -8.20%   5.87%
  5   64   68  1.8550755e0  -8.49%   6.30%
  6   68   72  2.1362930e0  -8.71%   6.63%
  7   72   76  2.7074748e0  -8.69%   6.69%
  8   76   81  4.1704013e0  -8.40%   6.44%
  9   81   86  9.4844889e0  -7.47%   5.51%
 10   86   91  7.0167791e1  -4.99%   2.88%
 11   91   96  7.7155277e1  -3.79%   1.68%
 12   96  101  6.8573762e0  -3.79%   1.86%
 13  101  106  2.3582461e0  -3.72%   1.94%
 14  106  110  1.2757496e0  -3.67%   2.01%
 15  110  115 8.1275105e-1  -3.51%   1.95%
 16  115  120 5.4706411e-1  -3.43%   1.98%
 17  120  126 3.8159272e-1  -3.20%   1.83%
 18  126  133 2.6919040e-1  -3.15%   1.92%
 19  133  141 1.9164180e-1  -2.97%   1.83%
 20  141  150 1.3594679e-1  -2.75%   1.74%
 21  150  160 9.7852913e-2  -2.55%   1.63%
 22  160  171 7.1471465e-2  -2.48%   1.68%
 23  171  185 5.1601085e-2  -2.35%   1.67%
```

- `bin`: bin index
- `Mll`: lower and upper limit of $M_{\ell\bar{\ell}}$ bin
- `dsig/Mll`: differential cross section for the bin
- `neg unc`/texttttpos unc: 7-point scale variation uncertainty

PineAPPL: plot

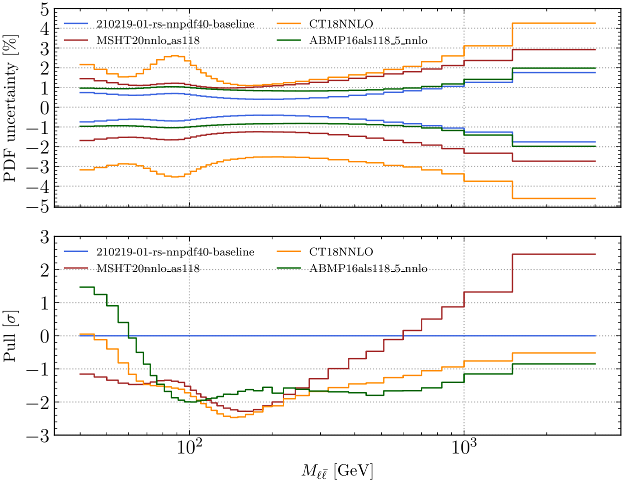



```
$ pineappl --silent-lhapdf plot \
    DY_14.pineappl.lz4 \
    210219-01-rs-nnpdf40-baseline \
    MSHT20nnlo_as118 \
    CT18NNLO \
    ABMP16als118_5_nnlo > plot.py
$ python3 plot.py
```

- generates self-contained matplotlib script (can be modified easily)

- absolute predictions
- NLO EW on vs. NLO EW off (relative)
- 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

PineAPPL: plot




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

```
$ pineappl luminosity \
> NNPDF_DY_14TEV_40_PHENO.pineappl.lz4
 id     entry            entry             entry
---+------------+------------+------------
#0   1 x ( 2, -2) 1 x ( 4, -4)
#1   1 x (22, -4) 1 x (22, -2)
#2   1 x ( 0, -4) 1 x ( 0, -2)
#3   1 x ( 2, 22) 1 x ( 4, 22)
#4   1 x ( 2,  0) 1 x ( 4,  0)
#5   1 x ( 1, -1) 1 x ( 3, -3)
#6   1 x (22, -3) 1 x (22, -1)
#7   1 x ( 0, -3) 1 x ( 0, -1)
#8   1 x ( 1, 22) 1 x ( 3, 22)
#9   1 x ( 1,  0) 1 x ( 3,  0)
#10  1 x ( 5, -5)
#11  1 x (22, -5)
#12  1 x ( 0, -5)
#13  1 x ( 5, 22)
#14  1 x ( 5,  0)
#15  1 x (22, 22)
#16  1 x (-5, 22) 1 x (-3, 22) 1 x (-1, 22)
#17  1 x ( 1, 22) 1 x ( 3, 22) 1 x ( 5, 22)
```

- 2 = up quark, 0 = gluon, 22 = photon, ...
- (22, 22): # 15, $\gamma\gamma$ initial state

```
$ pineappl channels NNPDF_DY_14TEV_40_PHENO.pineappl.lz4 \
> NNPDF31_nlo_as_0118_luxqed --limit 4
bin    Mll     lumi  size   lumi  size   lumi   size    lumi  size
---+----+----+----+------+----+------+----+-------+----+-------
 14  106  110   #5 58.28%  #0 48.56%  #10   5.06%   #7  -3.12%
 15  110  115   #5 56.55%  #0 50.12%  #10   4.85%   #7  -2.97%
 16  115  120   #5 54.32%  #0 51.64%  #10   4.58%   #7  -2.75%
 17  120  126   #0 53.05%  #5 52.82%  #10   4.42%   #7  -2.67%
 18  126  133   #0 54.51%  #5 50.62%  #10   4.11%   #2  -2.47%
 19  133  141   #0 56.39%  #5 48.56%  #10   3.93%   #2  -2.47%
 20  141  150   #0 57.07%  #5 47.26%  #10   3.78%  #15   2.61%
 21  150  160   #0 59.31%  #5 45.00%  #10   3.46%  #15   2.79%
 22  160  171   #0 60.02%  #5 43.35%  #10   3.36%  #15   3.12%
 23  171  185   #0 60.78%  #5 42.28%  #15   3.48%  #10   3.05%
 24  185  200   #0 62.90%  #5 40.28%  #15   3.57%  #10   2.77%
 25  200  220   #0 62.25%  #5 40.38%  #15   3.87%  #10   2.76%
 26  220  243   #0 64.55%  #5 37.83%  #15   3.87%   #4  -2.50%
 27  243  273   #0 65.04%  #5 36.77%  #15   4.04%   #4  -2.37%
 28  273  320   #0 66.25%  #5 35.56%  #15   4.44%   #4  -2.77%
 29  320  380   #0 67.41%  #5 33.93%  #15   4.65%   #4  -2.72%
 30  380  440   #0 68.82%  #5 32.79%  #15   4.15%   #4  -2.88%
 31  440  510   #0 68.22%  #5 32.32%  #15   4.83%   #4  -2.72%
 32  510  600   #0 70.50%  #5 30.18%  #15   4.65%   #4  -2.86%
 33  600  700   #0 70.40%  #5 29.92%  #15   4.64%   #4  -2.60%
 34  700  830   #0 71.47%  #5 28.59%  #15   4.52%   #4  -2.35%
 35  830 1000   #0 72.87%  #5 27.30%  #15   4.45%   #4  -2.94%
 36 1000 1500   #0 75.13%  #5 25.33%  #15   4.56%   #4  -3.34%
 37 1500 3000   #0 76.19%  #5 21.76%  #15   6.43%   #4  -2.84%
```

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, ...

→ effectively determines the datasets we can use for the fit

Outlook:

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

→ `PineAPPL` already public and Open Source: `https://n3pdf.github.io/pineappl`

- NLO EW PDF fit not too far away