Comparison of public codes for Drell-Yan processes at NNLO accuracy

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in collaboration with

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Based on arXiv:2104.02400 (EPJC)

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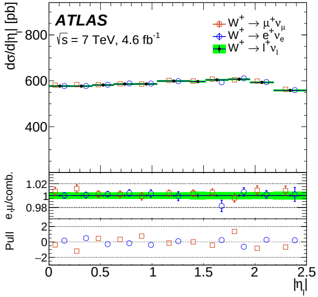
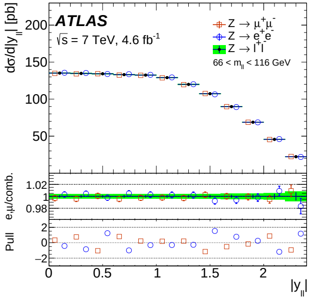
Introduction

LHC is performing really well:

- $\mathcal{O}(1-2\%)$ uncertainty for colorless final states ($\mathrm{W}^{\pm}$ and Z)
- ATLAS Drell-Yan (fiducial) measurements at $7\,\mathrm{TeV}$:
  - $\mathrm{W}^{+} \to \ell^{+}\,\nu$: 0.6% (stat. unc.)
  - $\mathrm{W}^{-} \to \ell^{-}\,\bar{\nu}$: 0.5% (stat. unc.)
  - $\mathrm{Z}/\gamma^{*} \to \ell^{+}\,\ell^{-}$: 0.32% (stat. unc.)
  - Normalization uncertainty: 1.8% (luminosity)

⇒ Colorless measurements are systematics dominated

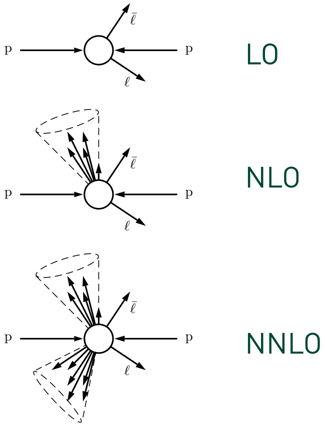




Introduction

To make best of the measurements high accuracy predictions are needed

- In p p collisions massless final states are available at NNLO accuracy in QCD
- NLO accuracy in EW corrections
- These predictions can be obtained by various tools using local subtractions or global slicing methods



Introduction

Subtractions or slicing, does it make any difference?

$$\mathsf{I} = \lim_{\epsilon\to 0}\left[\int_0^1 \frac{\mathrm{d}\mathsf{x}}{\mathsf{x}}\mathsf{x}^\epsilon \mathsf{F}(\mathsf{x}) - \frac{1}{\epsilon}\mathsf{F}(0)\right]$$

When subtracting: zero is added in a clever(ish) way:

$$\mathsf{I} = \lim_{\epsilon\to 0}\left[\int_0^1 \frac{\mathrm{d}\mathsf{x}}{\mathsf{x}}\mathsf{x}^\epsilon \left(\mathsf{F}(\mathsf{x}) - \mathsf{F}(0)\right) + \int_0^1 \frac{\mathrm{d}\mathsf{x}}{\mathsf{x}}\mathsf{x}^\epsilon \mathsf{F}(0) - \frac{1}{\epsilon}\mathsf{F}(0)\right] =$$

$$= \int_0^1 \frac{\mathrm{d}\mathsf{x}}{\mathsf{x}}\left(\mathsf{F}(\mathsf{x}) - \mathsf{F}(0)\right)$$

Introduction

When slicing: we alter the singular piece of the calculation

$$\mathrm{I} \sim \lim_{\epsilon\to 0}\left[F(0)\int_0^{\delta}\frac{dx}{x}x^{\epsilon}+\int_{\delta}^{1}\frac{dx}{x}x^{\epsilon}F(x)-\frac{1}{\epsilon}F(0)\right]=$$
$$=F(0)\log\delta+\int_{\delta}^{1}\frac{dx}{x}F(x)$$

To not to change the value too much δ should be chosen small!

Drell-Yan processes are calculated at NNLO in QCD both by subtraction and slicing methods

Introduction

Public codes implementing the DY process:

- DYNNLO http://theory.fi.infn.it/grazzini/dy.html
  - q_T subtraction: global slicing method
- FEWZ https://www.hep.anl.gov/fpetriello/FEWZ.html
  - Sector decomposition: local subtraction method
- MATRIX https://matrix.hepforge.org/
  - q_T subtraction: global slicing method
- MCFM https://mcfm.fnal.gov/
  - N-jettiness subtraction: global slicing method
- DYTurbo https://dyturbo.hepforge.org/
  - Reimplementation of DYNNLO with resummation, at fixed order same results as DYNNLO

Introduction

- Theory predictions are numbers stemming from many uncertainties:
  - PDF uncertainty: better PDF fits
  - Dependence on non-physical scales (μ_R, μ_F): going to higher orders
  - Statistical uncertainties:
    - — More PS points in integration
    - — Better integrator
    - — Optimize over special aspects of calculation (dynamics, subtractions, &c.)
  - Method-dependent parameters:
    - — Non-physical
    - — Result cannot depend on them
    - — No dependence or dependence smaller than statistical uncertainty
    - $\Rightarrow$ High precision runs might need refinement

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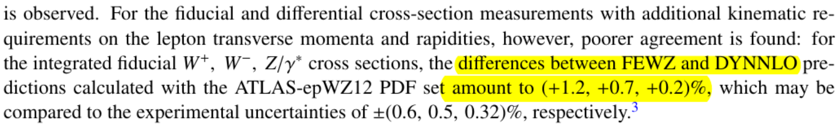
Introduction

- Experimental data reached very high accuracy
- Computational power also increased
- Became possible to deliver (numerically) very precise NNLO computations
- ATLAS reported (arXiv:1612.03016):



is observed. For the fiducial and differential cross-section measurements with additional kinematic requirements on the lepton transverse momenta and rapidities, however, poorer agreement is found: for the integrated fiducial W^+, W^-, Z/γ^* cross sections, the differences between FEWZ and DYNNLO predictions calculated with the ATLAS-epWZ12 PDF set amount to (+1.2, +0.7, +0.2)%, which may be compared to the experimental uncertainties of ±(0.6, 0.5, 0.32)%, respectively.[3]

- Computational tools are black boxes for experiments

⇒ Better to check consistency

Introduction

Idea:

- Take publicly available codes for DY
- Fix parameters
- Validate analysis and parameters through LO and NLO
  - At LO checking parameters through dynamics
  - At NLO most of the tools use Catani-Seymour subtraction
  - $\Rightarrow$ At NLO checking numerical integration
- Target cross section precision is aimed at $\mathcal{O}(0.1‰)$ for each bin
  - Aim is not to compare accuracy for the NNLO contribution
  - Physical cross section should have high accuracy (this is measured)

Calculational setup

Would like to test programs in realistic environment:

- ATLAS data for W$^{\pm}$ and Z/γ^* at $7\,\mathrm{TeV}$ [arXiv:1612.03016].
  - Pseudo-rapidities for decay leptons (e$^{\pm}$ and $\mu^{\pm}$) (W$^{\pm}$) and for decay lepton-pairs (Z/γ^*)
  - Cuts on lepton $p_{\perp}$ and pseudo-rapidities
  - For Z/γ^* central and forward region are considered
- D0 data for W$^{\pm}$ at $1.96\,\mathrm{TeV}$ [arXiv:1412.2862]
  - Electron charge asymmetry (A^e) measured in electron pseudo-rapidity
  - Also in forward region
  - Symmetric $p_{\perp}$ cuts: $p_{\perp}^{\nu} > 25\,\mathrm{GeV}$, $p_{\perp}^{\ell} > 25\,\mathrm{GeV}$
  - Staggered $p_{\perp}$ cuts: $p_{\perp}^{\nu} > 25\,\mathrm{GeV}$, $p_{\perp}^{\ell} > 35\,\mathrm{GeV}$
- EW parameters were chosen to minimize NLO EW corrections (irrelevant for comparisons)

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Theory tools

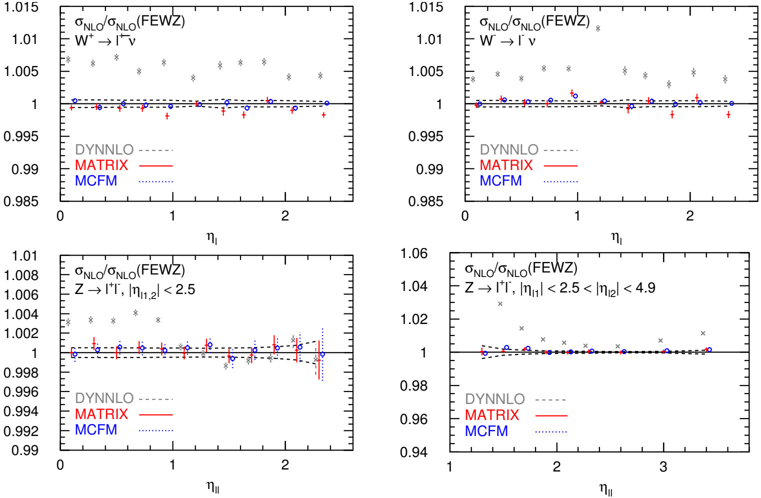
Used publicly available tools for the comparisons:

- DYNNLO (version 1.5)
    - Legacy code
    - Used by experiments
    - Superseded by MATRIX
- FEWZ (version 3.1)
    - Used as baseline due to being local subtraction
- MATRIX (version 1.0.4)
- MCFM (version 9.0)

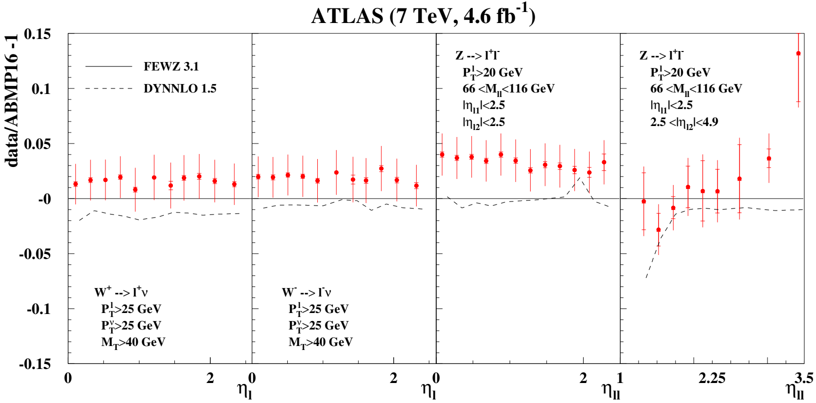
NLO comparisons

NLO check at $7\,\mathrm{TeV}$

- $W^{\pm}$ in central
- Z/γ^{*} in central
- Z/γ^{*} in forward region



DYNNLO NNLO comparisons



Default $r_{\text{cut}}^{\text{min}} = q_\perp^{\text{min}}/M_V = 0.8\%$ slicing parameter was used

MATRIX NNLO comparisons

- MATRIX employes the $q_\perp$ subtraction: a global slicing method

⇒ Slicing parameter should be selected carefully:
  - Default slicing parameter for $W^\pm$: $r_{\mathrm{cut}}^{\mathrm{min}} = 0.15\%$
  - Default slicing parameter for Z/γ^*: $r_{\mathrm{cut}}^{\mathrm{min}} = 0.05\%$

- MATRIX offers to extrapolate $r_{\mathrm{cut}}^{\mathrm{min}}$ to 0

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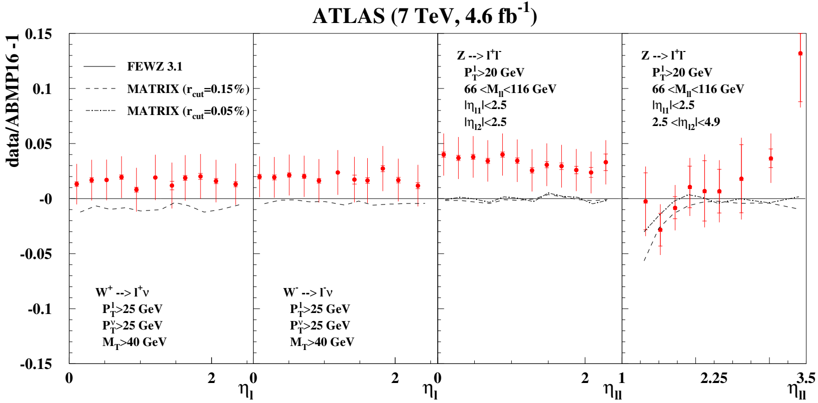
MATRIX NNLO comparisons



Note: no extrapolation applied. Extrapolation is not enough to eradicate differences

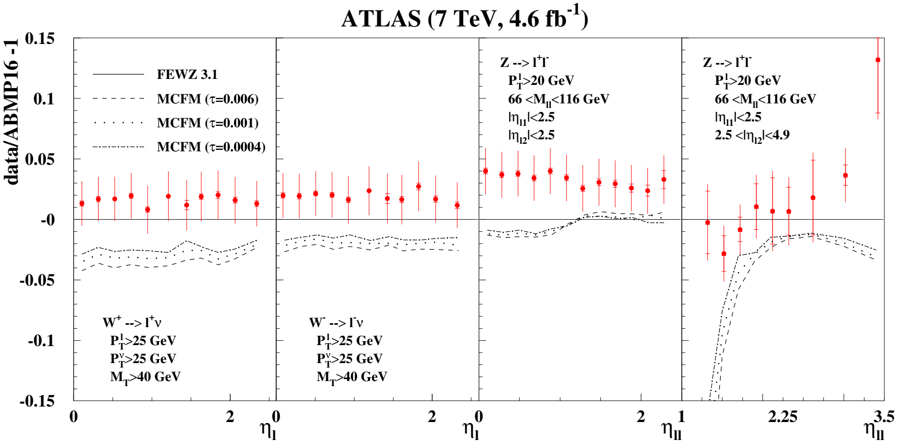
MCFM NNLO comparisons

- MCFM employs the N-jettiness subtraction: a global slicing method

⇒ Slicing parameter should be selected carefully:

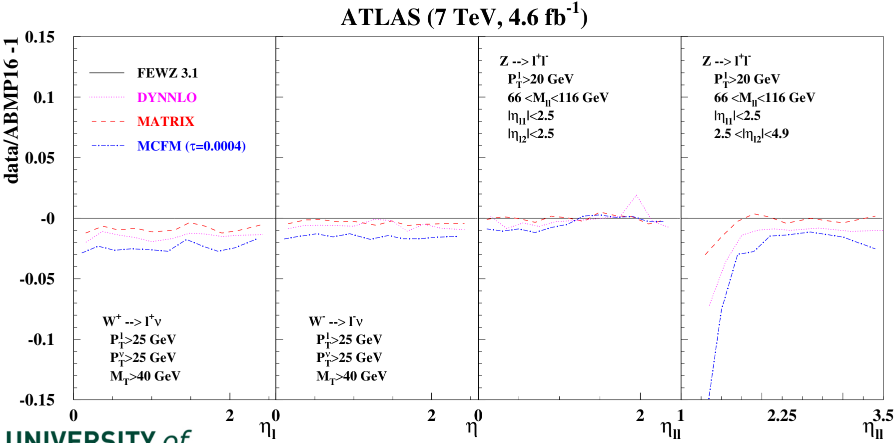
  - Default slicing parameter: $\tau_{\text{cut}} = 6 \cdot 10^{-3}$
  - Decreased as much as possible to be still in reasonable run times
  - Tried $\tau_{\text{cut}} = 10^{-3}$ and $\tau_{\text{cut}} = 4 \cdot 10^{-4}$

MCFM NNLO comparisons



NNLO comparisons

Comparisons of best predictions:



NNLO comparisons

- MC integration was pushed to have negligible (stat.) uncertainty on plots
- Decreasing slicing parameters and extrapolation helped to bring predictions closer
- Specialties of the experimental cuts put pressure on theory calculations
  - Symmetric cuts
  - Forward region
- Staggered cuts in central region gives the best agreement between codes
- Missing power corrections can be a reason for deviations

Power corrections

- Power corrections can be defined through slicing parameters:

$$\tau = \frac{q_\perp^2}{Q^2} = \frac{\left(\sum_i \mathbf{k}_{\perp,i}\right)^2}{Q^2}\ (q_\perp\ \text{slicing})\,, \quad \tau = \frac{\sum_i 2\min\left(p_a\cdot k_i, p_b\cdot k_i\right)}{Q^2}\ (\text{jettiness slicing})$$

- The phase space is partitioned into two disjoint regions:

$$\sigma = \int \mathrm{d}\tau \frac{\mathrm{d}\sigma}{\mathrm{d}\tau} = \int_{\tau_\text{cut}} \mathrm{d}\tau \frac{\mathrm{d}\sigma}{\mathrm{d}\tau} + \int^{\tau_\text{cut}} \mathrm{d}\tau \frac{\mathrm{d}\sigma}{\mathrm{d}\tau} = \sigma(\tau_\text{cut}) + \int^{\tau_\text{cut}} \mathrm{d}\tau \frac{\mathrm{d}\sigma}{\mathrm{d}\tau}$$

- Analytical integration in first term using universal QCD factorization:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\tau} \sim \delta(\tau) + \sum_i \left[\frac{\log^i \tau}{\tau}\right]_+ + \sum_j \tau^{p-1}\log^j\tau + \mathcal{O}(\tau^p)$$

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Power corrections

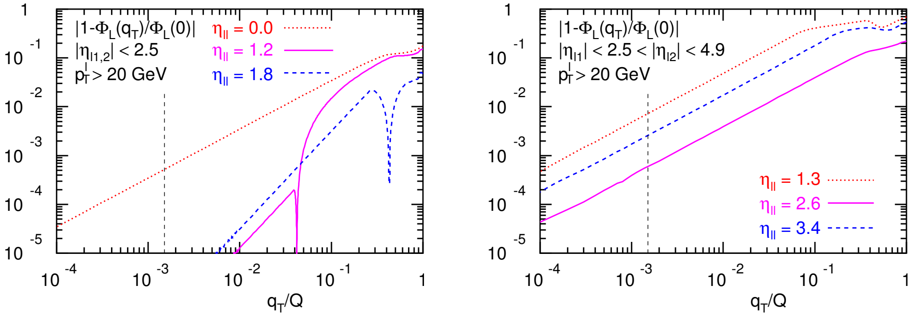
- Fiducial cuts affect decay phase space

⇒ Decay phase space has effect on power corrections due to $q_\perp$ dependent terms

- Can get idea about linear power corrections through decay phase spaces [arXiv:1911.08486, arXiv:2006.11382]
  - $\Phi_L(q_\perp)$ leptonic phase space with $q_\perp$ transverse momentum
  - $\Phi_L(0)$ leptonic phase space with zero transverse momentum
- Linear power corrections are estimated through difference from Born decay phase space:

$$\left|1 - \frac{\Phi_L(q_\perp)}{\Phi_L(0)}\right|$$

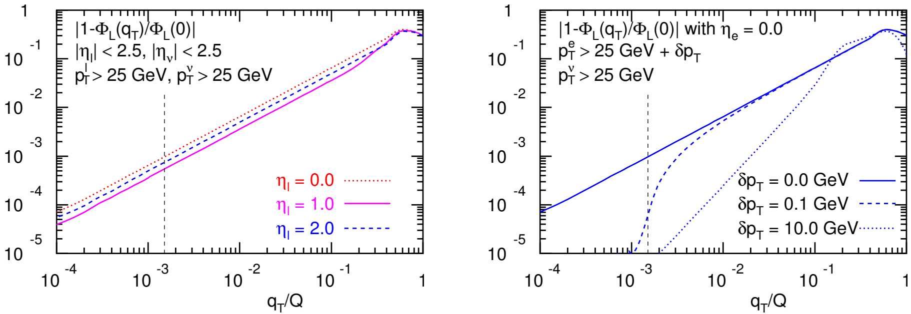
Power corrections



vertical dashed line: $r_{\rm cut}^{\rm min} = 0.15\%$ used in MATRIX

η_{ll}: gauge boson pseudo-rapidity

Power corrections



vertical dashed line: $r_{\text{cut}}^{\text{min}} = 0.15\%$ used in MATRIX

Conclusions

- NNLO calculations are really tough
- People put extraordinary efforts to deliver NNLO predictions to experiments
- NNLO predictions are driving forces behind activity at colliders
- All NNLO methods and calculations mirror the exceptional genius of people behind them
- Experiments reached really high precision
- Experiments can probe regions of phase space challenging to some methods
- Luckily we have several methods

⇒ Can be decided which is best for each scenario

⇒ Can fine-tune methods to cope with fiducial cut challenges

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Thank you for your attention!

Back-up slides

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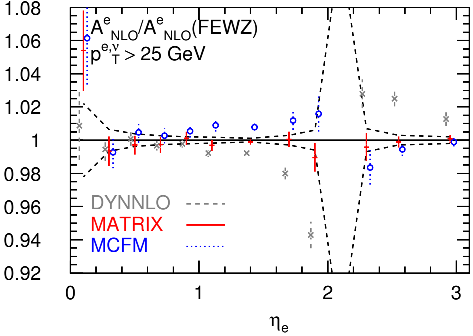
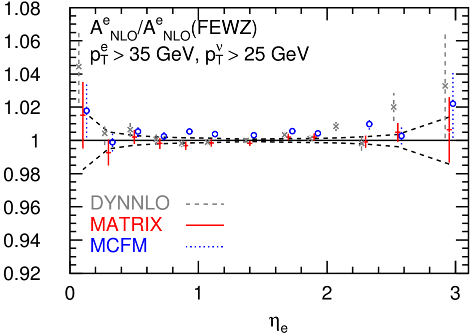
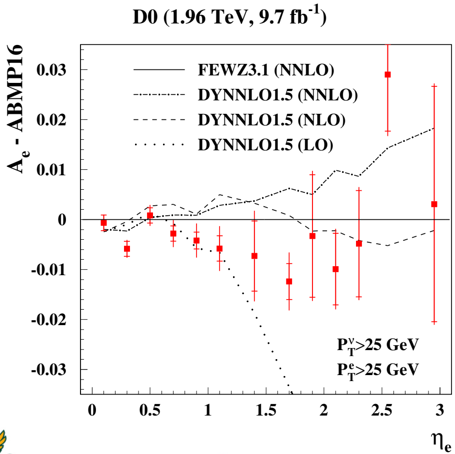
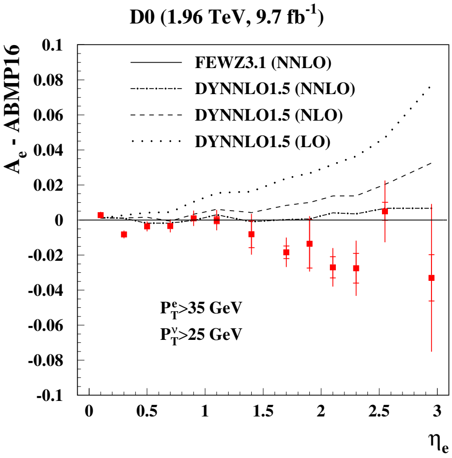
NLO comparisons at D0



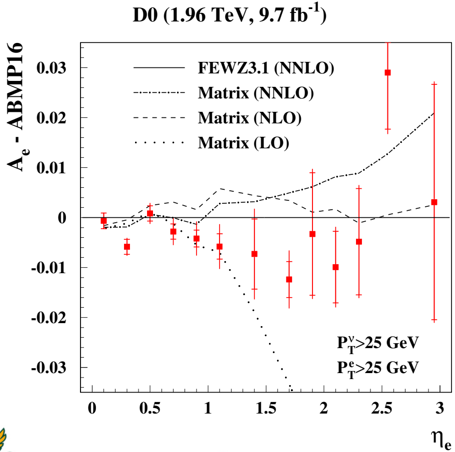


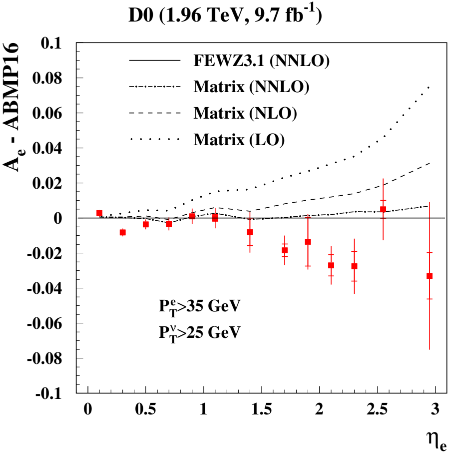
NNLO comparisons at D0 for DYNNLO



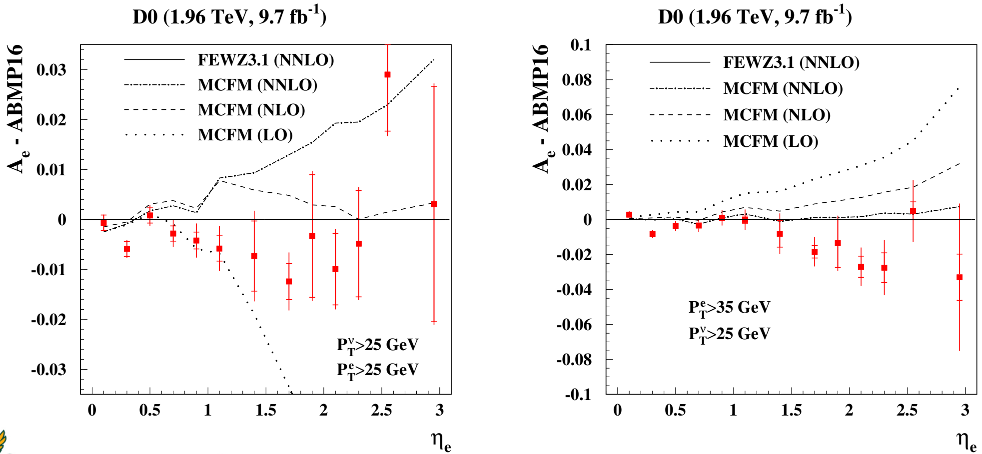


NNLO comparisons at D0 for MATRIX





NNLO comparisons at D0 for MCFM



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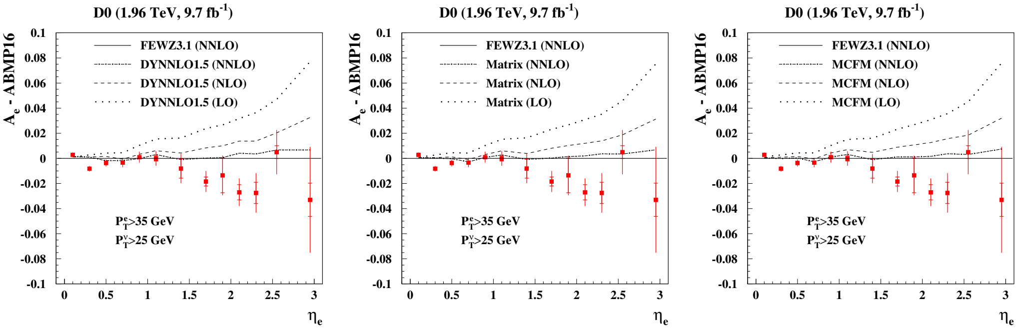
NNLO comparisons at D0 for staggered cuts



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CPU times

MATRIX CPU times for $\mathrm{r}_{\mathrm{cut}}^{\mathrm{min}} = 0.05\%$:

Region	CPU time [h]
Central	200.000
Forward	350.000

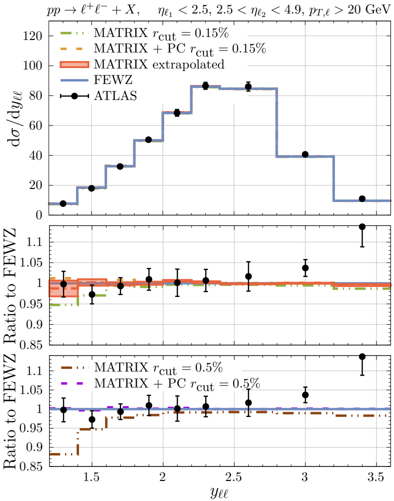
MCFM CPU times for $\tau_{\mathrm{cut}} = 4 \cdot 10^{-4}$

Process	CPU time [h]
$\mathrm{W}^{\pm}$	180.000
Z/γ^{*} Central	160.000
Z/γ^{*} Forward	50.000

MATRIX improvements

In arXiv:2111.13661:

- ”Transverse-momentum cuts on undistinguished particles in two-body final states induce an enhanced sensitivity to low momentum scales”
- Linear power corrections are implemented to ”circumventing the numerical instabilities related to the use of a tiny value of the slicing parameter”
- Inclusion of linPCs resulted in an agreement with FEWZ



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