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)

2022 September 22nd

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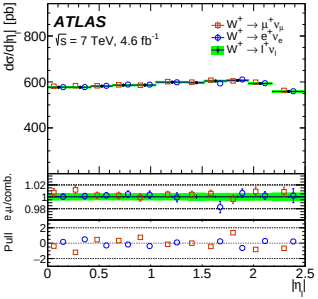
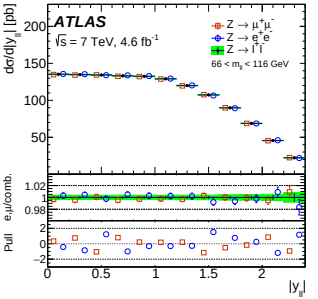
Introduction

LHC is performing really well:

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

$\Rightarrow$ Colorless measurements are systematics dominated

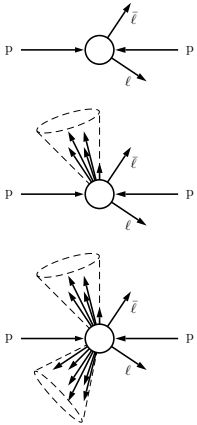




Introduction

To make best of the measurements high accuracy predictions are needed

- In p p collisions (typically) 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



LO

NLO

NNLO

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Introduction

Subtractions or slicing, does it make any difference? (See also Kirill's talk from Tuesday)
The original integral:

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

- Subtraction: zero is added in a clever(ish) way:

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

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

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Introduction

- Slicing: we alter the singular piece of the calculation

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

$$= F(0) \log \delta + \int_{\delta}^{1} \frac{dx}{x} F(x)$$

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 by slicing methods

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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

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Introduction

How to compete with experimental accuracy?

- 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 parameter 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

$\Rightarrow$ Better to check consistency

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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)

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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)

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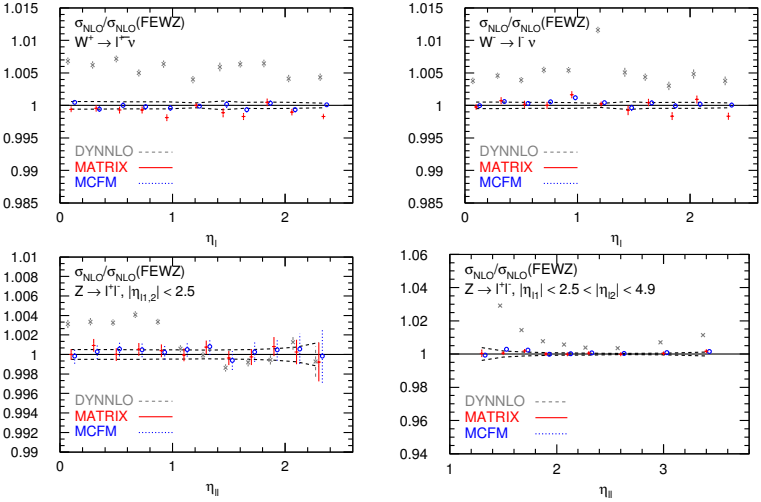
NLO comparisons

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

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



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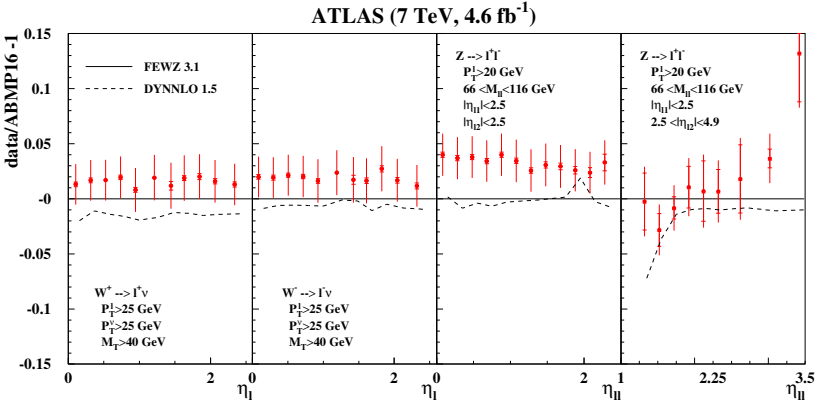
DYNNLO NNLO comparisons



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

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MATRIX NNLO comparisons

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

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

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

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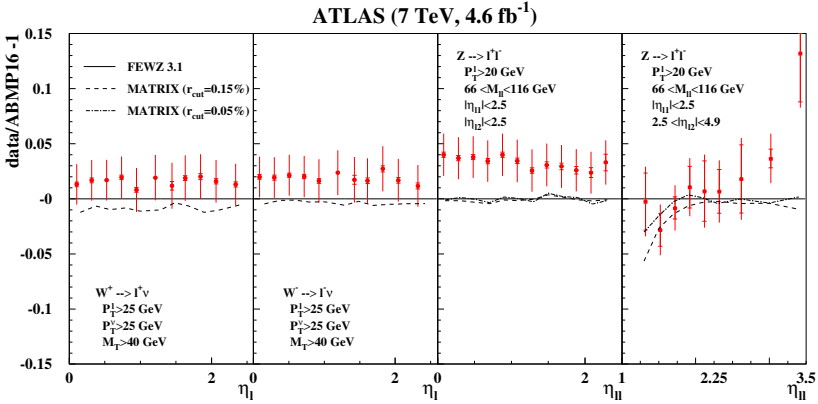
MATRIX NNLO comparisons



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

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MCFM NNLO comparisons

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

$\Rightarrow$ Slicing parameter should be selected carefully:

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

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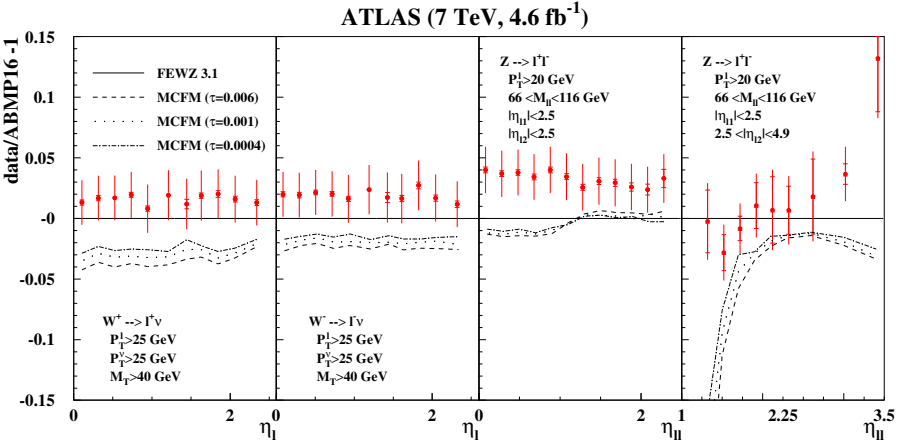
MCFM NNLO comparisons



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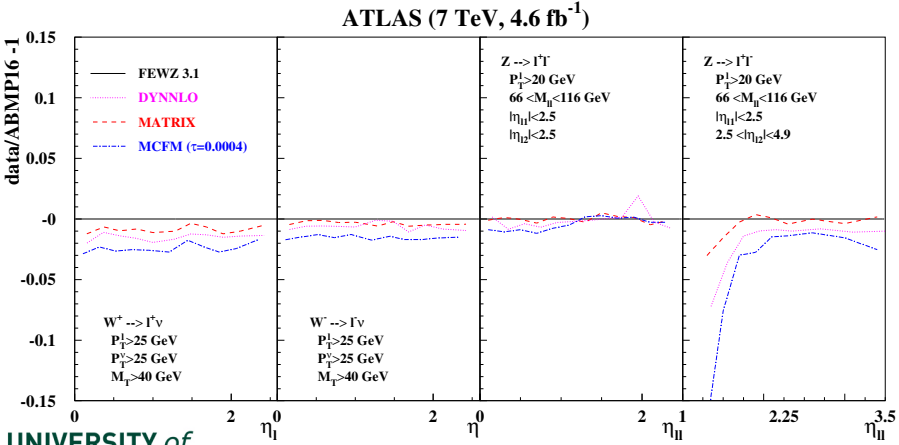
NNLO comparisons

Comparison of best predictions:



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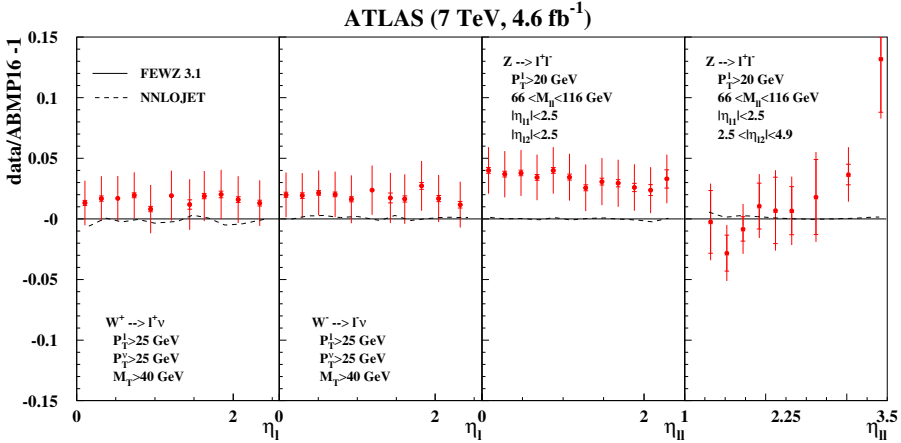
FEWS vs. NNLOJET

Preliminary!



NNLOJET numbers by Alex Huss

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

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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

$\Rightarrow$ Can be decided which is best for each scenario

$\Rightarrow$ Can fine-tune methods to cope with fiducial cut challenges

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The Galileo Galilei Institute For Theoretical Physics

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Arcetri, Firenze

Workshop

Theory Challenges in the Precision Era of the Large Hadron Collider

Aug 28, 2023 - Oct 13, 2023

Apply (deadline: May 01, 2023)

Related events

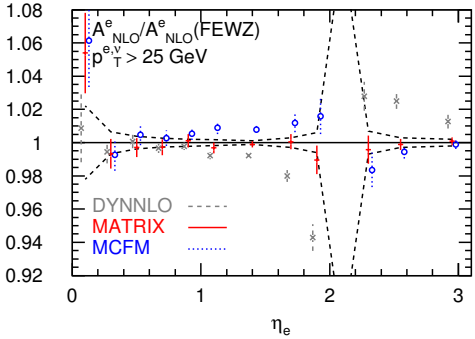
Theory Challenges in the Precision Era of the Large Hadron Collider (Conference) - Aug 28, 2023

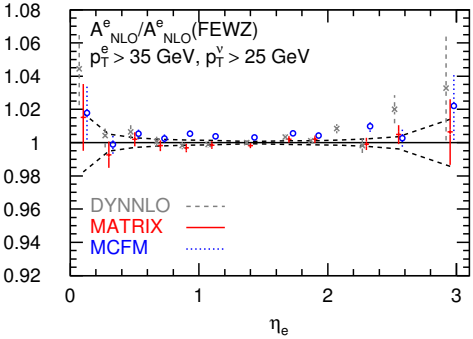
Theory Challenges in the Precision Era of the Large Hadron Collider (Training Week) - Sep 25, 2023

Thank you for your attention!

Back-up slides

NLO comparisons at D0





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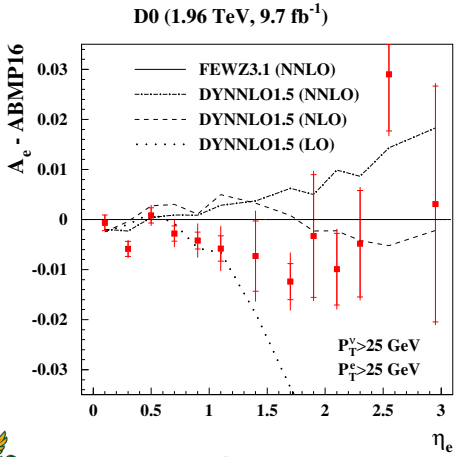
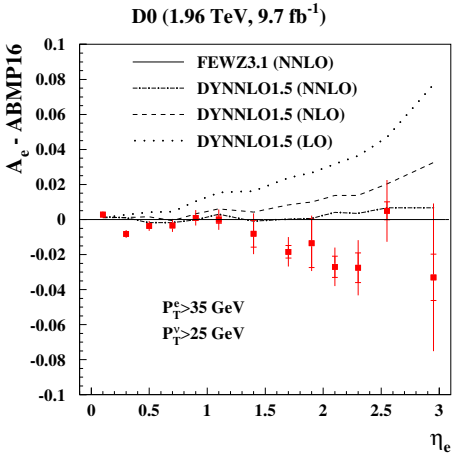
NNLO comparisons at D0 for DYNNLO





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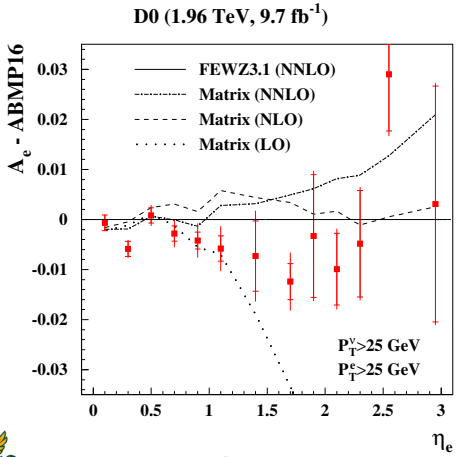
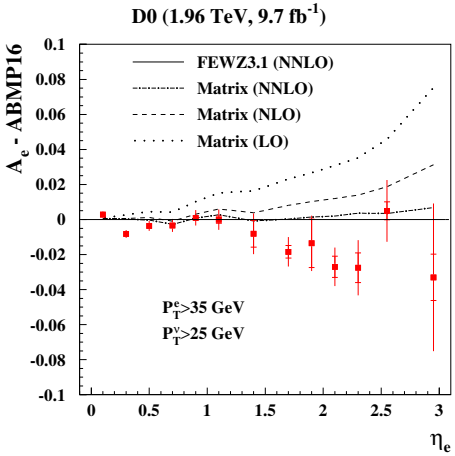
NNLO comparisons at D0 for MATRIX





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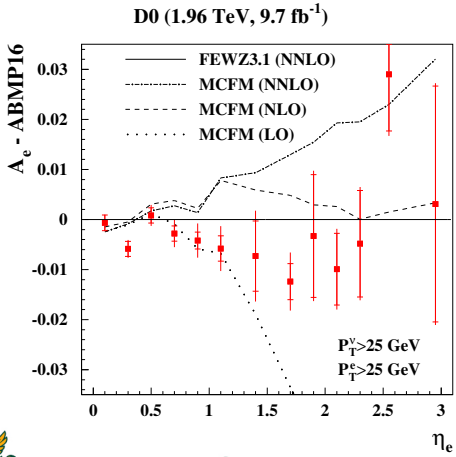
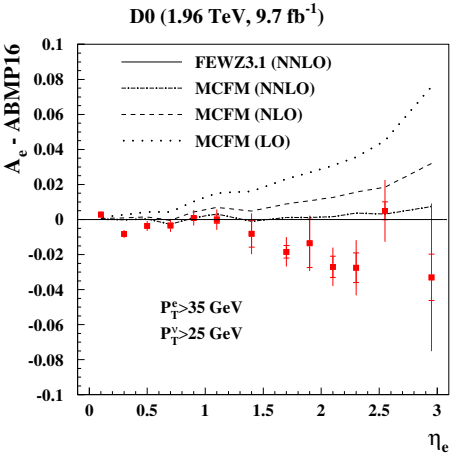
NNLO comparisons at D0 for MCFM





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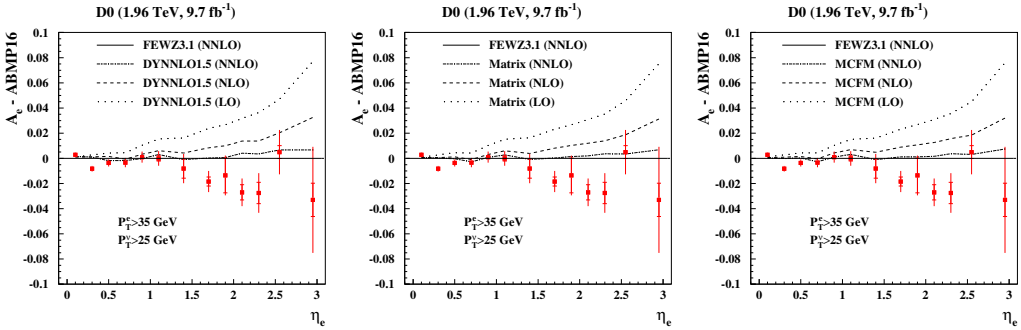
NNLO comparisons at D0 for staggered cuts



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CPU times

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

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]
$W^{\pm}$	180.000
Z/γ^* Central	160.000
Z/γ^* Forward	50.000

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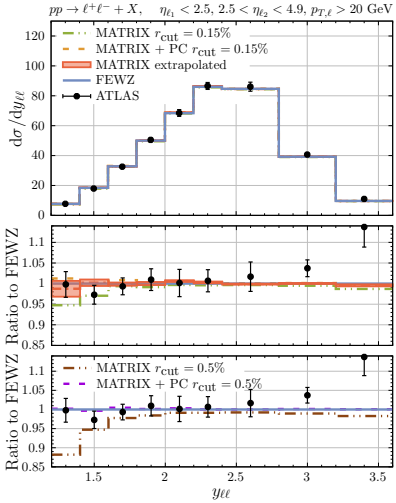
MATRIX improvements

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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Power corrections

- Power corrections can be defined through slicing parameters:

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

- The phase space is partitioned into two disjoint regions:

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

- 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

$\Rightarrow$ 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:

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

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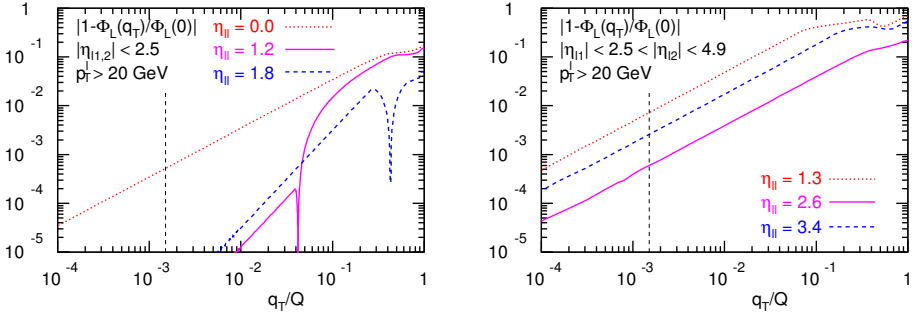
Power corrections



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

η_{ll}: gauge boson pseudo-rapidity

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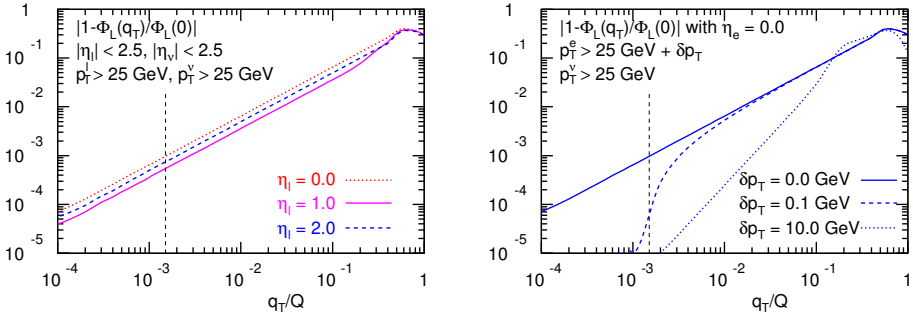
Power corrections



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

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