NNLO QCD Corrections to W Boson Production in *NNLOJET*

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in collaboration with: A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, A. Huss

arxiv:hep-ph/1712.07543
PRL **120**,122001 (2018)

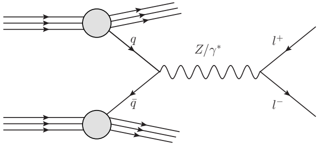
NNLOJET collaboration
IPPP (Durham University)

Motivation - Weak Gauge Boson Production

- Experimentally large cross sections, low systematic error
  - Leptonic decay signature allows high precision
  - Useful standard candle process for hadron colliders in e.g. luminosity determination, detector callibration
- Useful test of precision QCD/EW corrections
  - Determination of EW parameters
  - Important input to PDF fits
  - Highly relevant background for BSM searches

Channel	Fiducial σ [nb]
W^-	$3.50 \pm 0.01 \pm 0.07 \pm 0.07$
W^+	$4.53 \pm 0.01 \pm 0.09 \pm 0.10$
$W^\pm$	$8.03 \pm 0.01 \pm 0.16 \pm 0.17$
Z	$0.779 \pm 0.003 \pm 0.006 \pm 0.0016$

$\sqrt{s} = 13$ TeV ATLAS inclusive V cross sections
[Phys. Lett. **B759** 601 (2016)]



Motivation - p_T^V Distributions

- Fixed order inclusive calculations for $pp \to V + X$ are NNLO QCD starting at $\mathcal{O}(1)$ in α_S, known differentially since early 2000s
- Many different implementations using a variety of methods
  - DYNNLO, FEWZ, VRAP, MCFM-8.0, MATRIX, ***NNLOJET***, ...
- Non-zero p_T^V distribution only begins at $\mathcal{O}(\alpha_S)$
  - Recoiling jet required for momentum conservation
- As a result, inclusive calculations only NLO in p_T^V distributions
  - Room for improvement in theoretical description!

Motivation - p_T^V Distributions

- As p_T^V starts at $\mathcal{O}(\alpha_S)$, QCD corrections for finite p_T $p_T^V > p_{T,\mathrm{cut}}^V$ are well described by V+jet calculation
- Can use NNLO calculations of ZJ, $W^\pm J$ to enhance our predictions for p_T^V in this region
- Leverage existing antenna subtraction ZJ calculation for p_T^Z [hep-ph 1507.02850]
- Use newly implemented $W^\pm J$ in *NNLOJET* for $p_T^{W\pm}$
- Normalise by the NNLO QCD inclusive $W^\pm$, Z calculations for data comparison

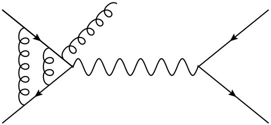
NNLOJET

- Parton level event generator at NN(N)LO QCD using antenna subtraction (projection to Born)
- Processes available: $pp \to H, HJ, Z, ZJ, W^{\pm}, W^{\pm}J, VFH, dijets$
  $ep \to 1, 2J$
  $e^{+}e^{-} \to 3J$
  ...
- Highly flexible machinery for analysis, integration and subtraction with many automated + manual tests
- Actively developed → more processes/functionality to come!
- See also talks from yesterday by Aude Gehrmann-De Ridder, Juan Cruz-Martinez

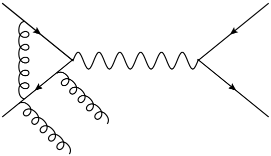
NNLO calculations

- Challenge at NNLO is cancellation of IR singularities between different phase space multiplicities $\Phi_{n}^{VV}, \Phi_{n+1}^{RV}, \Phi_{n+2}^{RR}$
- We have three separate divergent integrals which are finite when summed together [KLN theorem]
- Need to find ways to regulate the divergences so we can make the integrals individually finite
  - Phase space slicing, subtraction based methods
- We use antenna subtraction for this, coming from the universal factorisation of QCD in IR limits

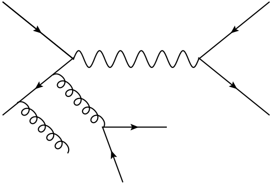
Matrix Elements



- VV
- Poles: $1/\varepsilon^4, 1/\varepsilon^3, 1/\varepsilon^2, 1/\varepsilon$
- No possible unresolved configurations



- RV
- Poles: $1/\varepsilon^2, 1/\varepsilon$
- Single unresolved configurations



- RR
- No explicit poles
- Doubly unresolved configurations

Antenna Subtraction - A Primer

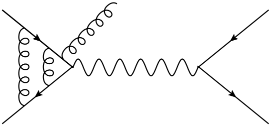
- In unresolved (soft, collinear) limits, we have behaviour in a known, factorisable manner [Universal factorisation of QCD]
  - Dependent on the number and flavour of partons involved
  - Also requires knowlege of initial, final configuration
- For a gluon between a quark pair going soft/collinear:

$$M_3^0(1_q, i_g, 2_{\bar{q}}) \to A_3^0(1_q, i_g, 2_{\bar{q}}) M_2^0((\widetilde{1i})_q, (\widetilde{i2})_{\bar{q}})$$

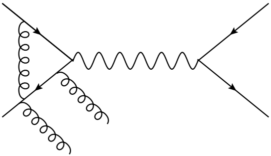
  - Relates matrix elements in different phase space multiplicities $\to$ phase space mapping
- Use ratios of simple processes to construct the antenna functions for general reuse.

Antenna Subtraction - A Primer

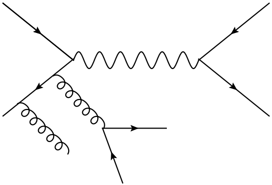
- Can reconstruct our unresolved limits using the unintegrated antenna functions to make our integrands finite in unresolved limits.
- Antenna functions are simple enough that analytic integration over unresolved phase space has been performed for all required classes of divergences.
- Introduce the analytically integrated antenna functions at lower multiplicities to cancel against poles in loop MEs/mass factorisation terms.
- In practice, the antenna functions contain multiple limits which leads to e.g. oversubtraction of certain limits which has to be compensated



- $$\int_{\Phi_n} \left(\mathrm{d}\sigma^{VV,NNLO} - \mathrm{d}\sigma^{U,NNLO}\right)$$

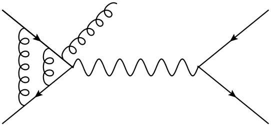


- $$\int_{\Phi_{n+1}} \left(\mathrm{d}\sigma^{RV,NNLO} - \mathrm{d}\sigma^{T,NNLO}\right)$$

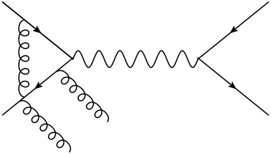


- $$\int_{\Phi_{n+2}} \left(\mathrm{d}\sigma^{RR,NNLO} - \mathrm{d}\sigma^{S,NNLO}\right)$$

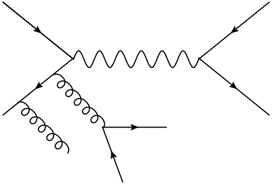
Each integral is IR finite



- $\int_{\Phi_n} (\mathrm{d}\sigma^{VV,NNLO} - \mathrm{d}\sigma^{U,NNLO})$

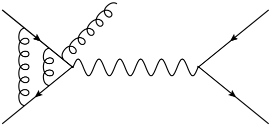


- $\int_{\Phi_{n+1}} (\mathrm{d}\sigma^{RV,NNLO} - \mathrm{d}\sigma^{T,NNLO})$



- $\int_{\Phi_{n+2}} (\mathrm{d}\sigma^{RR,NNLO} - \mathrm{d}\sigma^{S,NNLO})$

$$\int_{\Phi_n} \mathrm{d}\sigma^U + \int_{\Phi_{n+1}} \mathrm{d}\sigma^T + \int_{\Phi_{n+2}} \mathrm{d}\sigma^S = 0$$



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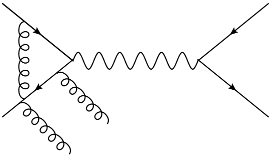

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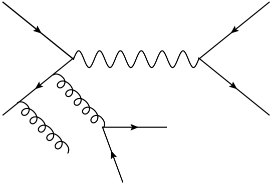


- $\int_{\Phi_{n+2}} (\mathrm{d}\sigma^{RR,NNLO} - \mathrm{d}\sigma^{S,NNLO})$

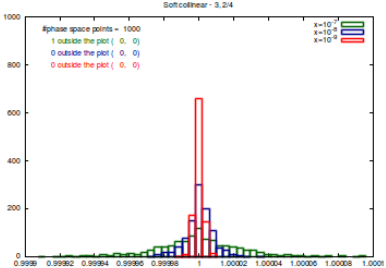
Original integral unchanged!

Subtraction Testing

Unresolved Limits

Test that in divergent regions:

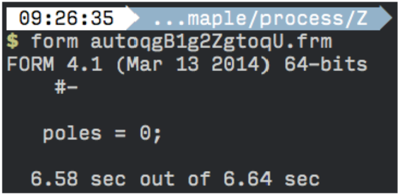
$$d\sigma^{RR}/d\sigma^{S} \to 1$$
$$d\sigma^{RV}/d\sigma^{T} \to 1$$



$$q(1)\bar{q}(2) \to Z\, g(3)g(4)g(5)$$

Analytic Pole Cancellation

$$\text{Poles}(d\sigma^{RV} - d\sigma^{T}) = 0$$
$$\text{Poles}(d\sigma^{VV} - d\sigma^{U}) = 0$$



Subtraction Testing

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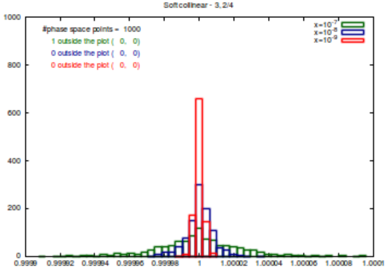

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Analytic Pole Cancellation

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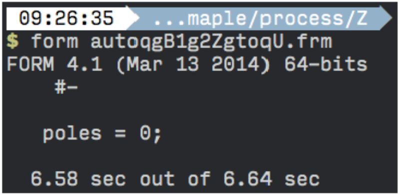


Now for numerical integration...

Practicalities

- In practice, numerical integration takes a long time, particularly for the RR contributions to *VJ*:
  - High multiplicity final state phase space to integrate over
  - Complex matrix elements/subtraction terms to repeatedly evaluate
- As a representative benchmark, the RR integration for each of the VJ calculations require $\mathcal{O}(100,000)$ CPU hours
  - Distributed computing essential for results in reasonable timeframe
  - The bulk of the following results were produced in $\sim 2-3$ weeks

p_T^V Distributions: Setup

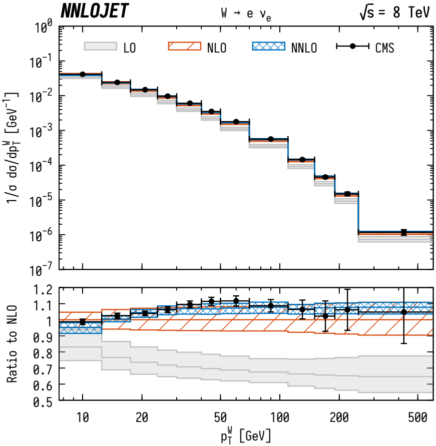
Data from CMS low luminosity run for W,Z p_T distributions and ratios, normalised to inclusive cross section [hep-ex 1606.05864].

- NNPDF31 NNLO
- $\alpha_S = 0.118$
- $\sqrt{s} = 8$ TeV
- $p_V^T > 7.5$ GeV
  $(60 < M_{ll}^Z < 120)$

- Leptonic cuts
  - $p_e^T > 25$ GeV, $|y_e| < 2.5$
  - $p_\mu^T > 20$ GeV, $|y_\mu| < 2.1$
- $\mu_{R,F} = \sqrt{{M_{l\nu}}^2 + {p_W^T}^2}, \sqrt{{M_{ll}}^2 + {p_Z^T}^2}$
- $W = W^+ + W^-$

Impose $\frac{1}{2} \leq \mu/\mu' \leq 2$ between the scales of the numerator and denominator in $1/\sigma \; \mathrm{d}\sigma/\mathrm{d}p_T^V \rightarrow$ 31pt scale variation

$W\ p_T$ Distributions



- Distribution mostly stable compared to NLO $\rightarrow$ good perturbative convergence

- Greatly reduced scale uncertainty

- 5-10% correction to lineshape at NNLO improves agreement with CMS data

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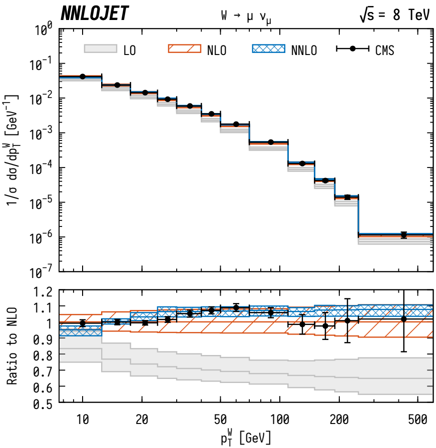

- Distribution mostly stable compared to NLO $\rightarrow$ good perturbative convergence

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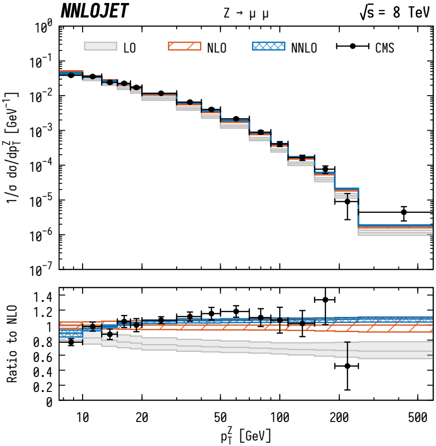
$Z\ p_T$ Distribution



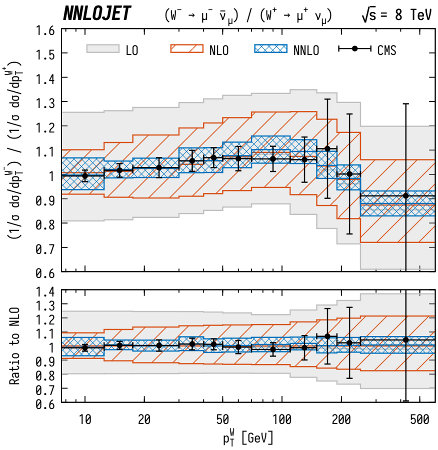
- Similar scale uncertainty and NNLO correction behaviour for the Z case

- CMS data much more statistically limited, particularly for high p_T^Z

Ratios of p_T^V Distributions

- EW Sudakov logarithms present at high p_T^V largely cancel in ratios of distributions
- Unlike at $p\bar{p}$ colliders, W^+ and W^- are produced at different rates in pp collisions due to different u/d valence quark contents in proton PDFs
- Z/W ratio highly relevant in the determination of W mass where p_W^T is found indirectly through p_Z^T
  - Gives a handle on QCD modelling uncertainty between the Z and the W
  - Important due to reconstruction of missing energy required for W but not Z
- Again restrict to $\frac{1}{2} \leq \mu/\mu' \leq 2$ between the all pairs of scales in $(1/\sigma \; \mathrm{d}\sigma/\mathrm{d}p_T^V)/(1/\sigma \; \mathrm{d}\sigma/\mathrm{d}p_T^V) \rightarrow$ 691pt scale variation

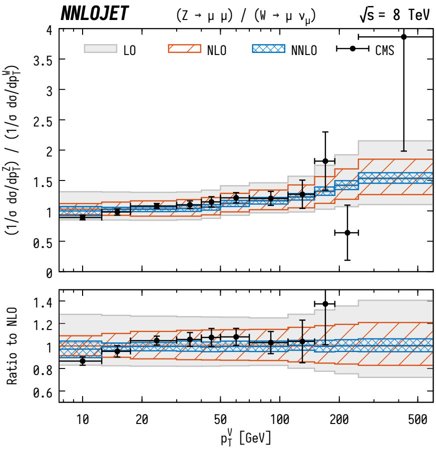
W^- / W^+ Ratio



- Very accurate modelling of lineshape

- W^+, W^- distribution differences come only from the PDFs, which model the data well

Z/W Ratio



- QCD corrections very stable, behaviour very similar between W and Z production

- High correlation between the two demonstrates cross compatibility for e.g. M_W extraction

Summary

- $pp \to W^{\pm} J$ process now fully implemented and running in *NNLOJET*
- Inclusion of the NNLO QCD corrections give $\mathcal{O}(5 - 10\%)$ corrections to the p_T^W spectrum along with substantially decreased scale uncertainty
- We see very good agreement with CMS data in first set of results
- Now looking to provide further relevant theory predictions as needed for further pheno studies

Thanks for listening!