Z+jet at NNLO using Antenna Subtraction

based on arXiv:1507.02850

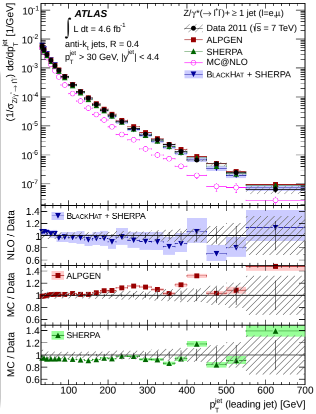
Thomas Morgan

IPPP, Durham University

In collaboration with A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover and A. Huss

Motivation - Why Z+jet?

- An important background for beyond the standard model searches.
- Very precise measurements can be obtained.
  - Provides a fantastic testing ground for precision QCD and electroweak corrections
  - Useful for detector calibration, jet energy scale can be determined from the recoil of the jet against the Z boson.
- Useful process for PDF determination (particularly gluon PDFs).



arXiv:1304.7098

Antenna subtraction in a nutshell

Exploit the universal factorisation of QCD in Infrared (IR) limits.
We pick simple processes and recycle their pole structures for use in more complicated processes.

$$M_3^0(1_q, i_g, 2_{\bar{q}}) \overset{i_g}{\underset{\text{unresolved}}{\longrightarrow}} \overbrace{A_3^0(1_q, i_g, 2_{\bar{q}})}^{\text{Antenna function}} \; \underbrace{M_2^0(\widetilde{(1i)}_q, \widetilde{(i2)}_{\bar{q}})}_{\text{reduced matrix element}} .$$

- We need to define a phase space mapping from the $n+1 \to n$ phase space.
- The processes need to be suitably simple so that they can be integrated analytically.

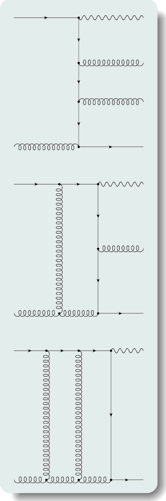
Antenna subtraction in a nutshell

Three separate integrals,

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

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

$$+ \int_{\mathrm{d}\sigma_{n}} \left(\mathrm{d}\hat{\sigma}^{VV,NNLO} - \mathrm{d}\hat{\sigma}^{U,NNLO}\right)$$



Each bracket is IR-finite and

$$\int_{\mathrm{d}\sigma_{n+2}} \mathrm{d}\hat{\sigma}^{S,NNLO} + \int_{\mathrm{d}\sigma_{n+1}} \mathrm{d}\hat{\sigma}^{T,NNLO} + \int_{\mathrm{d}\sigma_{n}} \mathrm{d}\hat{\sigma}^{U,NNLO} = 0$$

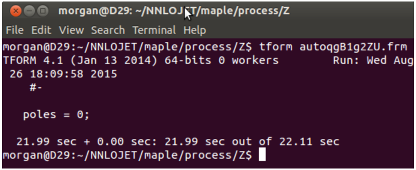
Testing our subtraction

Two main methods

Analytical pole cancellation using FORM.

$$\text{Poles}\left(\mathrm{d}\hat{\sigma}^{RV,NNLO} - \mathrm{d}\hat{\sigma}^{T,NNLO}\right) = 0$$

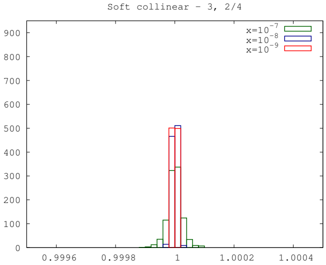
$$\text{Poles}\left(\mathrm{d}\hat{\sigma}^{VV,NNLO} - \mathrm{d}\hat{\sigma}^{U,NNLO}\right) = 0$$



For unresolved singularities, define a ratio of the matrix element against the subtraction term

$$R = \frac{\mathrm{d}\sigma^{M}}{\mathrm{d}\sigma^{S}}$$

In all unresolved limits $R \to 1$



Cuts and physical setup

- Included qg, $q\bar{q}$, $\bar{q}g$ and gg processes leading colour contributions.
- Comparisons to LO and NLO data are all full channel at all colour levels.

- Computation for 8TeV LHC using NNPDF2.3 set, $\alpha_s(M_z) = 0.118$
- Anti-k_T jet clustering algorithm with R=0.5, $p_T^{\mathrm{jet}} > 30$ GeV and $|\eta^{\mathrm{jet}}| < 3$
- 80 GeV $< m_{\mathrm{ll}} <$ 100 GeV and $|\eta^{\mathrm{l}}| < 5$
- Central scale $\mu_R = \mu_F = M_z$ with scale variation between $0.5M_z$ and $2M_Z$

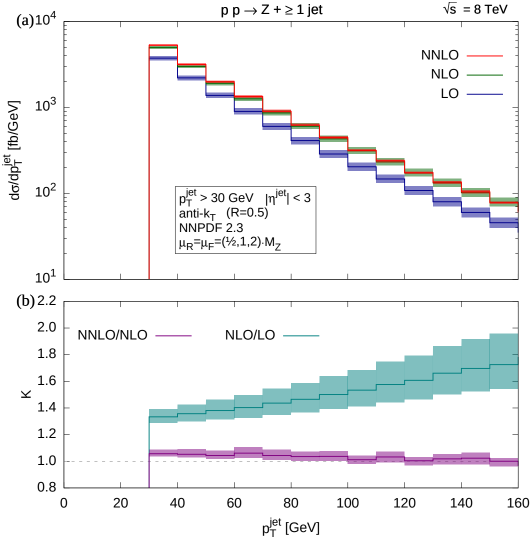
Total cross section breakdown

$$\sigma_{\mathrm{LO}} = 103.6^{+7.7}_{-7.5}\,\mathrm{pb}$$

$$\sigma_{\mathrm{NLO}} = 144.3^{+9.0}_{-7.2}\,\mathrm{pb}$$

$$\sigma_{\mathrm{NNLO}}(qg + \bar{q}g + q\bar{q} + gg) = 151.0^{+4.9}_{-3.6}\,\mathrm{pb}$$

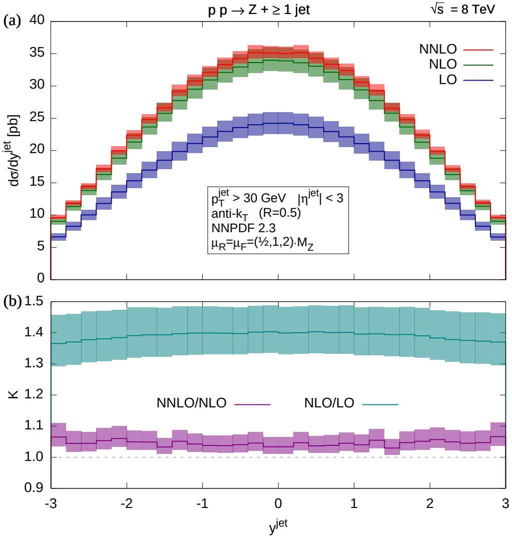
Distributions - P_T^{jet}



- Excellent convergence of NNLO in the high p_T tail of the distribution.
- Significant reduction in the scale uncertainty.

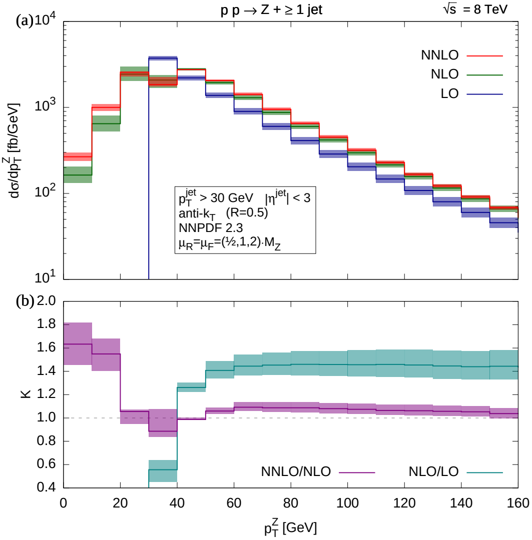
$$K = \frac{d\sigma^{(N)NLO}(\mu)}{d\sigma^{(N)LO}(\mu = M_z)}$$

Distributions - y^{jet}



- NNLO corrections uniform in rapidity, approximately 4%.
- Significant reduction in scale uncertainty.

Distributions - Z Boson



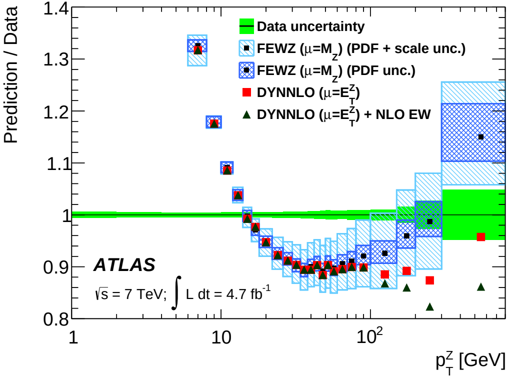
- 'Sudakov shoulder' at $p_T \sim 30$ GeV
- Soft-gluon resummation will smooth out region

Not fully inclusive in QCD radiation

Fully inclusive P_T^Z distribution

- Measure the inclusive Z P_T distribution without any jet cut - very clean experimentally.
- large discrepancy between theory and experiment

NNLO calculations of Drell-Yan are only accurate to NLO in this observable!
Z must recoil against a hard emission - Z+jet(s)



arXiv:1406.3660v2

Can we make the same distribution?

Change of cuts

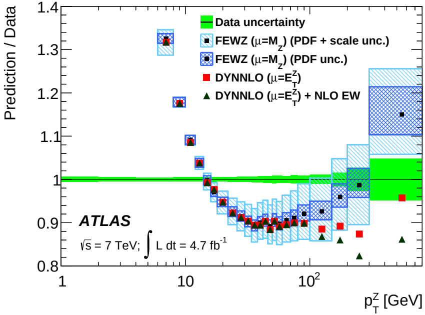
- Included qg, $q\bar{q}$, $\bar{q}g$ and gg processes leading colour contributions.
- Comparisons to LO and NLO data are all full channel at all colour levels.

- Computation for 8TeV LHC using NNPDF2.3 set, $\alpha_s(M_z) = 0.118$
- Anti-k_T jet clustering algorithm with R=0.5, $p_T^{\text{jet}} > 30$ GeV and $|\eta^{\text{jet}}| < 3$
- 80 GeV $< m_{\text{ll}} <$ 100 GeV and $|\eta^{\text{l}}| < 5$
- Central scale $\mu_R = \mu_F = M_z$ with scale variation between $0.5M_z$ and $2M_Z$

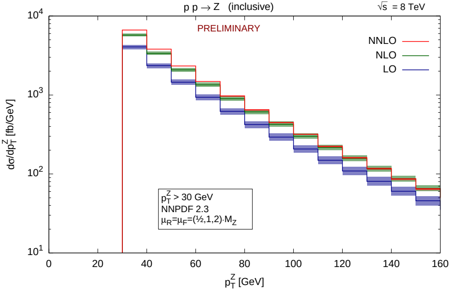
Include also,

$$p_T^{\text{Z}} > 30 \text{ GeV}$$

Inclusive p_T distribution of the Z boson



Preliminary results!



- Significant reduction in scale uncertainty
- Work is on going to push to higher P_T (qq channel missing) with dynamic scale choices.

Conclusions and Outlook

Conclusions

- Antenna subtraction is a powerful subtraction scheme that extracts the infrared singularities analytically and enables the pole cancellation to be verified analytically.
- We have computed the dominant NNLO corrections for Z+jet production.
- We get an excellent scale reduction compared to NLO calculations both in the total cross section and in differential distributions.
- We present preliminary results of the fully inclusive Z P_T distribution accurate to NNLO.

Outlook

- Complete subdominant channels and subleading colour corrections.
- Comparisons to data using dynamic scales will be coming in due course.

Backup Slides

Z+jet has a very rich set of partonic channels that contribute to it. At NLO for a given set of cuts and scale choice,

Initial state	σ (pb)	% contribution
qg	80.2	55.6%
$q\bar{q}$	33.1	22.9%
$\bar{q}g$	33.1	22.9%
gg	-4.0	-2.7%
qq	1.8	1.2%
$\bar{q}\bar{q}$	0.1	0.1%
Total	144.3	100.0%