Z+jet at next-to-next-to-leading order

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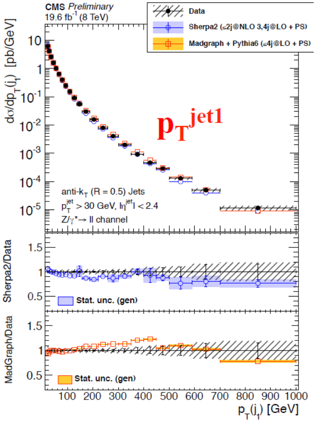
Motivation - Why Z+jet?

- 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 distributions).



from Matthias Weber's talk on Monday

Overview of current calculations

- Calculation of Z+jet including Next-to-Leading Order (NLO) known for a long time - Giele, Glover, Kosower [1993] & Campbell, Ellis [2002]
- Electroweak radiative corrections calculated - Denner, Dittmaier, Tasprzik, Mück [2010]
- NLO calculation matched to parton shower - Alioli, Nason, Oleri, Re [2010]

Theoretical Challenges

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%

- We present preliminary results for channels in blue calculated to NNLO accuracy.
- Work is on going for all the subdominant channels.

Multi-channel NNLO calculations

For the calculation to be used in phenomenology we need to calculate many channels at the same time, preferably full channel.
This poses several problems,

- code must be numerically efficient
- book-keeping numerous channels.

Several options are now on the market for calculations involving jet observables at proton colliders.

- Antenna subtraction
- Sector improved decomposition
- N-jettiness subtraction

We present a calculation of Z+jet at NNLO using antenna subtraction.

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.

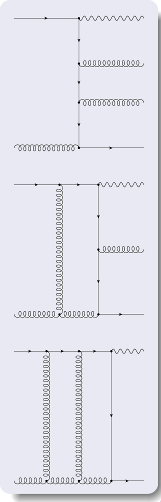
Antenna subtraction in a nutshell

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.

Types of Antenna at NNLO

single unresolved tree level emission

$$X_3^0(1,2,3)$$

Real-Real double unresolved emission

$$X_4^0(1,2,3,4)$$

Real-Virtual single unresolved emission at one loop

$$X_3^1(1,2,3)$$

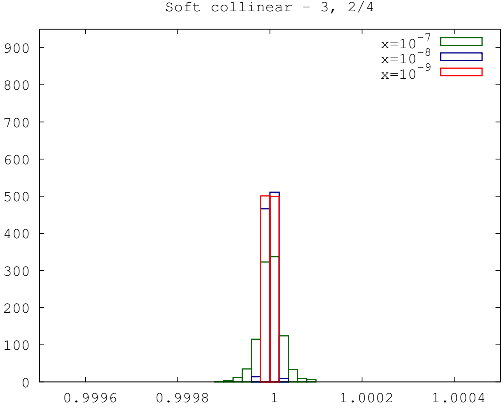
- Each antenna contain many limits
- The antenna used are dependent on the flavour of the partons within the process and the initial state configuration.
- All antenna are integrated analytically.

Testing our subtraction

- 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 $R \to 1$
- Feed in all possible unresolved limits into the matrix element and subtraction term.



Cuts and physical setup

- Included qg, $q\bar{q}$ and $\bar{q}g$ processes including most subleading 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 $2M_Z$

Calculation time

	No. jobs	CPU time per job
Real-Real	1000	12 hours
Real-Virtual	300	15 hours
Virtual-Virtual	1	24 hours

- Warmup is now performed using a multi-threaded setup using openMP, significantly reducing the calculation time.
- All calculations done using double precision.
- Multiple scale choices calculated simultaneously.

Total cross section breakdown

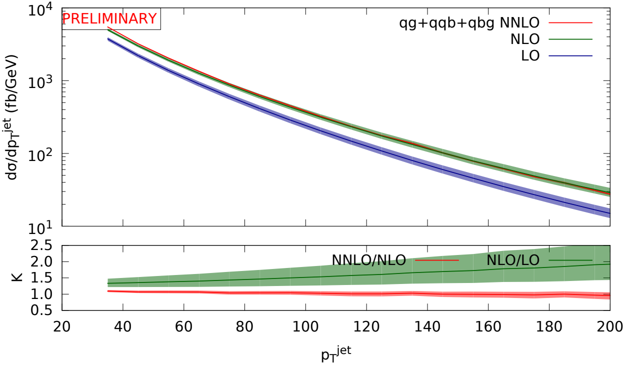
PRELIMINARY

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

$$\sigma_{\mathrm{NLO}} = 147.6^{+9.5}_{-7.6}\,\mathrm{pb}$$

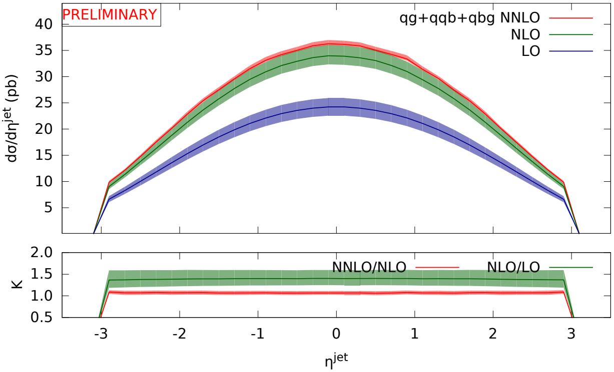
$$\sigma_{\mathrm{NNLO}}(qg + \bar{q}g + q\bar{q}) = 157.6^{+3.4}_{-1.7}\,\mathrm{pb}$$

Distributions - P_T^{jet}



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

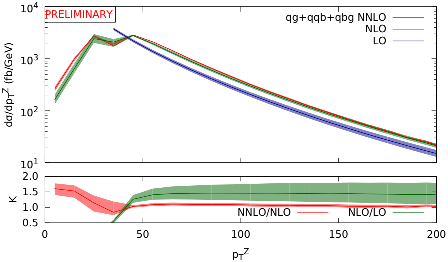
Distributions - η^{jet}



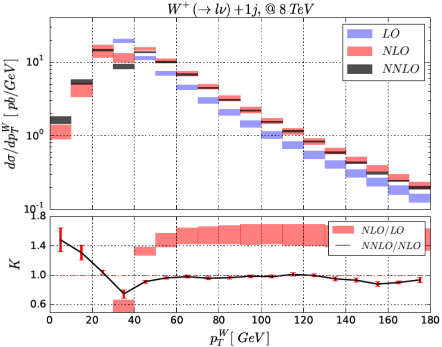
- NNLO corrections uniform in rapidity, approximately 7%.
- Significant reduction in scale uncertainty.

Distributions - P_T^Z

A qualitative comparison of the P_T^Z distribution against the P_T^W distribution from the W+jet calculation at NNLO.

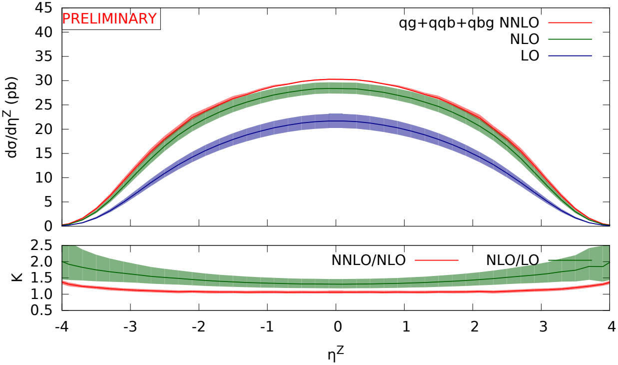


from arXiv:1504.0213



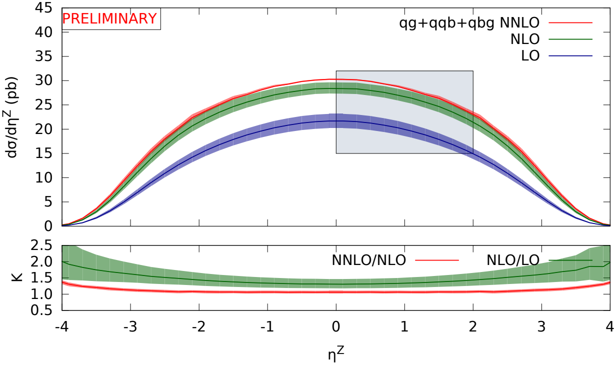
Observe a similar shape to the corrections.

Distributions - η^Z



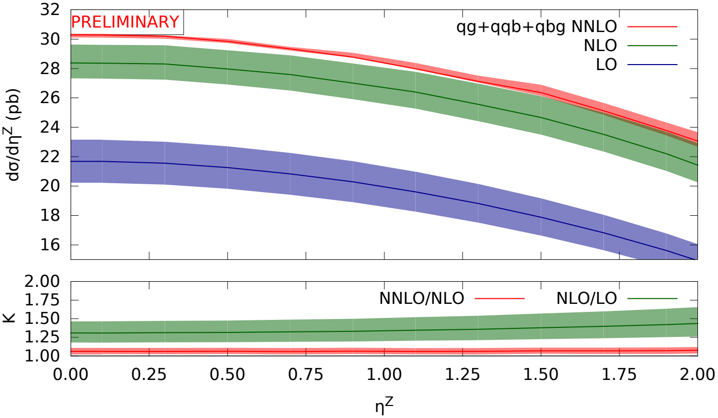
- We see a separation between the NNLO and NLO results in the central η region

Distributions - η^Z



- We see a separation between the NNLO and NLO results in the central η region
- Zoom in on this transition region

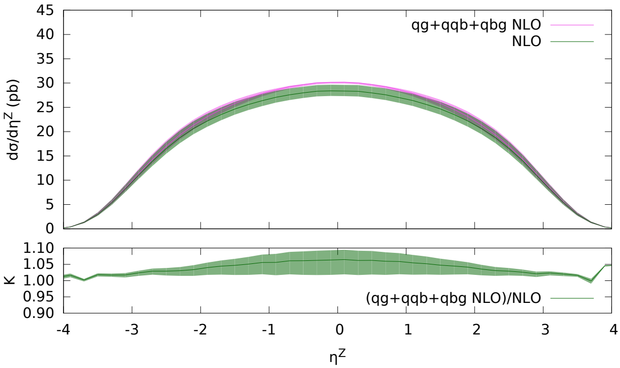
Distributions - η^Z



- Scale uncertainty drops in the central region

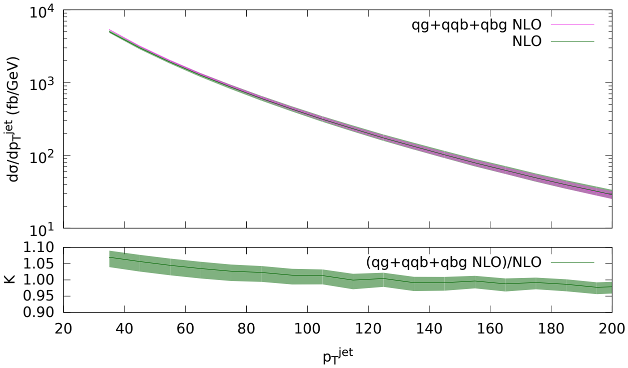
Learning from NLO

Comparing the full NLO result to a partial NLO result where we have removed the gg, qq and $\bar{q}\bar{q}$ channels.



- Distribution is distorted across the whole central region
- gg is a new channel at NLO, scale uncertainty is therefore larger than existing channels

Learning from NLO



- Overshoot at low p_T - missing gg channel
- Small undershoot at very high p_T - missing qq channel

Learning from NLO

Moral of the story

- Even channels that give a small contribution to the total cross section can have a huge impact on the differential distributions.
- Only by doing the full calculation can we determine the importance of channels at a given order.

Conclusions and Outlook

- Antenna subtraction is a powerful subtraction scheme that extracts the infrared singularities analytically and enables the pole cancellation to be verified analytically.
- All of the relevant antenna are available in unintegrated and integrated form, enabling the systematic evaluation of NNLO corrections to a variety of processes relevant to the LHC.
- We present preliminary results for Z+jet production at NNLO including the most dominant channels (qg, $\bar{q}g$ and $q\bar{q}$).
- We get an excellent scale reduction compared to NLO calculations both in the total cross section and in differential distributions.
- Subdominant channels will be calculated in due course.
- We expect the gg channel to have an impact on the η^Z distribution in the central region. Exactly how much of an impact requires a full calculation.

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