Using Ratios as More Precise Measurables at Hadron Colliders

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1 Introduction

Many of the physical quantities such as cross-sections that are the subject of measurements and predictions in hadron collider experiments are difficult to measure or predict precisely. Precision measurements would allow the extraction of fundamental parameters as well as comparison to Standard Model (SM) predictions in order to make sensitive searches for non-SM physics. For example, the production cross section for the signature W-boson + N jets has been used to test QCD and also is the background for the top quark discovery, and mass and cross section measurements, as well as being the baseline for searches for 'excesses' in the W+1 jet and W+ 2jet channels (any excess in 3 or 4 jets was subsumed as top). However the measurement of any cross section involving jets has inherent large uncertainties, as also do the predictions. It seems sensible for the experimentalists to look for a set of new quantities that 'span the space' of the same physics parameters, but are more robust against the uncertainties. In many cases such quantities can be found; for example, in the W+ N jets case the ratios $R_N \equiv \sigma(W + NJets)/\sigma(Z + Njets)$ benefit from the (partial) cancellation of the jet energy scale, contributions from the underlying event, initial state radiation, multiple interactions, and effects of jet algorithm, among others. These precision quantities have already proved useful in precision comparisons of W and Z +jets production in Alpgen, Comphep,MadGraph, and MCFM.

2 Some Examples of 'Experimentalist's Variables'

- Soft Physics- Underlying Event.

Old Var.	New Var.	Comment
$dN/d\eta_W$ $dN/d\eta_Z$ $dN/d\eta_{MB}$	$(dN/d\eta_W)/(dN/d\eta_Z)$ $(dN/d\eta_W)/(dN/d\eta_{MB})$	diff. diquark, quarks

- ISR- Jet Et and Eta distributions

Old Var.	New Var.	Comment
$dN/d\eta_W^{jet}$ $dN/d\eta_Z^{jet}$ $dN/d\eta_{MB}^{jet}$	$(dN/d\eta_W^{jet})/(dN/d\eta_Z^{jet})$ $(dN/d\eta_W^{jet})/(dN/d\eta_{MB}^{jet})$	diff. diquark, quarks

- Hard Physics- Precision Top Cross Section

  Define $R_{Top} \equiv \sigma_{Top}/\sigma_W$.
  $R_{WW} \equiv \sigma_{WW}/\sigma_W$.
  etc. (forget luminosity and σ_{tot} for precision work)

Have been studying, with Erin (Collins) Abouzaid:

Hard Physics- Precision W+Njets, Z+Njets

Define $R_N \equiv \sigma_{W+Njets}/\sigma_{Z+Njets}$.

Discuss this one in more detail (MadGraph, MCFM, Alpgen):

1. Published CDF W+Njet Cross Section uncertainties grow rapidly with N and become very large- dominated by systematics.

   Inclusive Cross Sections:

N(Jets)	$\sigma\times$BR (pb)	Sys Unc (pb)	Sys Unc (%)
$\geq$0	2490 pb	120 pb	4.8%
$\geq$1	471 pb	52 pb	11%
$\geq$2	101 pb	18 pb	18%
$\geq$3	18.4 pb	5.1 pb	28%
$\geq$4	3.1 pb	2.3 pb	42%
$\geq$5	0.2 pb	0.3 pb	117%

Table 1: The measured *inclusive* jet cross sections with their absolute and percentage uncertainties. The numbers for N$\geq$1 are from the Duke analysis; the 0-jet bin is from S. Kopp's analysis.

2. Look at sources of systematic uncertainties vs N jets

N(Jets)	Et_J Scale	Und Ev	QCD Bkgd	Mult Int	η_J	Acc	Oblit	Top
≥ 1	6.8%	5.8%	5.2%	3.2%	1.9%	0.8%	0.2%	0.05%
≥ 2	11%	9.8%	5.4%	7.2%	3.7%	1.0%	0.3%	0.3%
≥ 3	17%	16%	9.1%	9.8%	4.8%	1.8%	0.6%	1.3%
≥ 4	23%	21%	15.8%	14%	5.5%	3.5%	1.3%	0.5%

Table 2: Percentage Systematic uncertainties for *Inclusive* W+N jet bins for N=1 to N=4. These are taken from Table 10 of the Duke analysis; the upper error bar is used in all cases. Many of these uncertainties will (partially) cancel in the W/Z ratio.

Do the systematics cancel in the ratios?

- **Jet Energy Scale.** As W and Z are color-singlets, no FSR, and hence substantial cancellation. Small differences due to $\hat{s}$, different x distributions of u and d, and different couplings of Z and W.
- **Underlying Event.**
- Should cancel to 1st order.
- **QCD Background.**
- Partially cancels; but backgrounds feeding the 'second leg' of either $\not{E}_t$ (the neutrino) or a high $\mathrm{E_T}$ electron are inherently different.
- **Jets from Multiple Interactions.**
- This should cancel entirely to first order.

- **Eta Cut for Jets.** This uncertainty is due to the cut at $|\eta| = 2.4$ on jets. Because the Z and W are made with different distributions in longitudinal momentum there will be a second-order effect in the jet η distribution, calculable by Monte Carlo.
- **Kinematic and Geometric Acceptances.** Use common 'first leg'- make E_T and $\not{E}_t$ cuts on 2nd leg the same so acceptances are close. Using the bins for n<N to measure the PDF's should make this contribution small compared to the statistical uncertainty in bin N.
- **Obliteration.** This refers to the case where an electron is 'obliterated' by a jet. It presumably can be measured well from the data, and checked by Monte Carlo. Small already.
- **Top Quark.** Signal to measure precisely! Use b-tagging+kinematic fitting.

Bottom Line- To What Precision Could We Measure?

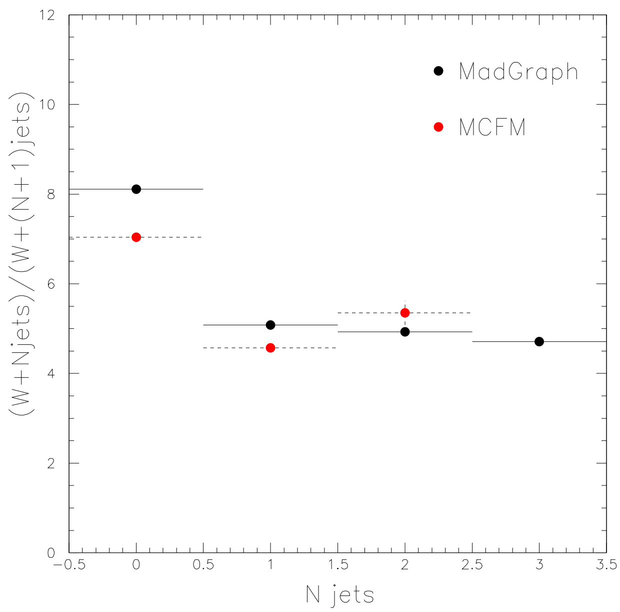
Make a guess based on Kopp's thesis and TDR: systematics for N=0,1,2; Z statistics for N$\geq$3. Gives the following:

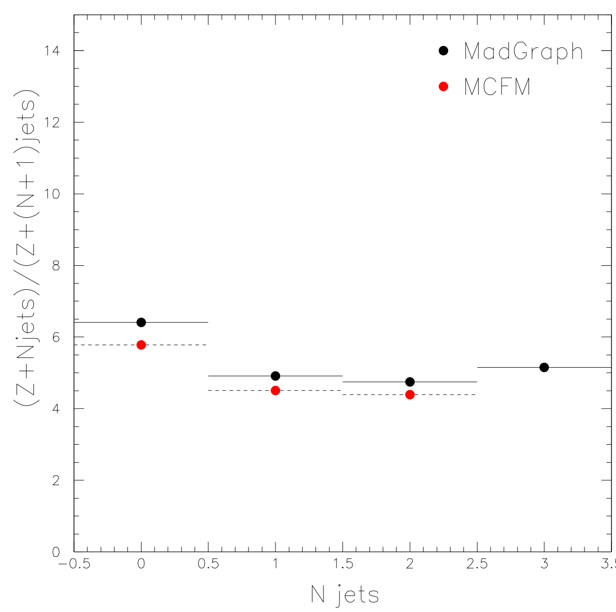
N(Jets)	N_{ev} 2 fb^{-1}	$\Delta(W/Z)$	N_{ev} 15 fb^{-1}	$\Delta(W/Z)$
0	95,000	0.3%	710,000	0.12%
1	19,000	0.7%	145,000	0.26%
2	4200	1.5%	32,000	0.56%
3	870	3.4%	6500	1.2%
4	180	7.4%	1400	2.7%
5	38	16%	283	5.9%
6	7.8	36%	59	13%
7	1.6	78%	12	29%
8	0.3	–%	2.6	63%

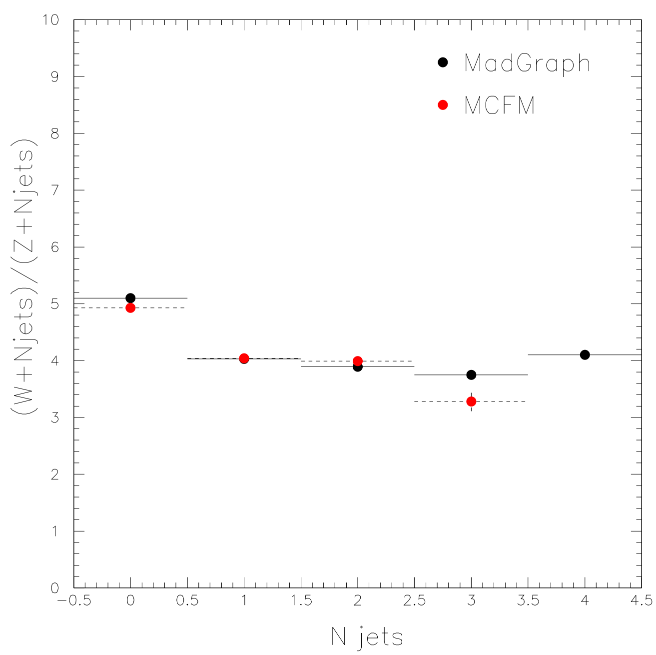
Table 3: The number of expected $Z^0 \to e^+e^-$+N jet events and the percentage statistical uncertainty in the W/Z ratio in 2 fb^{-1}, and in 15 fb^{-1}. The bins up through N=4 use the cross sections of the Duke analysis measured at 1.8 TeV; the N=5 and higher bins have been extrapolated using an exponential fit. Note that the number of $Z^0 \to e^+e^-$ events in each bin will be approximately a factor of 10 smaller than the corresponding number of W events. Using the $Z^0 \to \mu^+\mu^-$ channel one can gain approximately root-2 on these uncertainties. The higher energy also will improve these numbers.

If we can measure this well, would like MC predictions to be better than this level. At LHC, will want much better. (note Johnson's Theorem below).

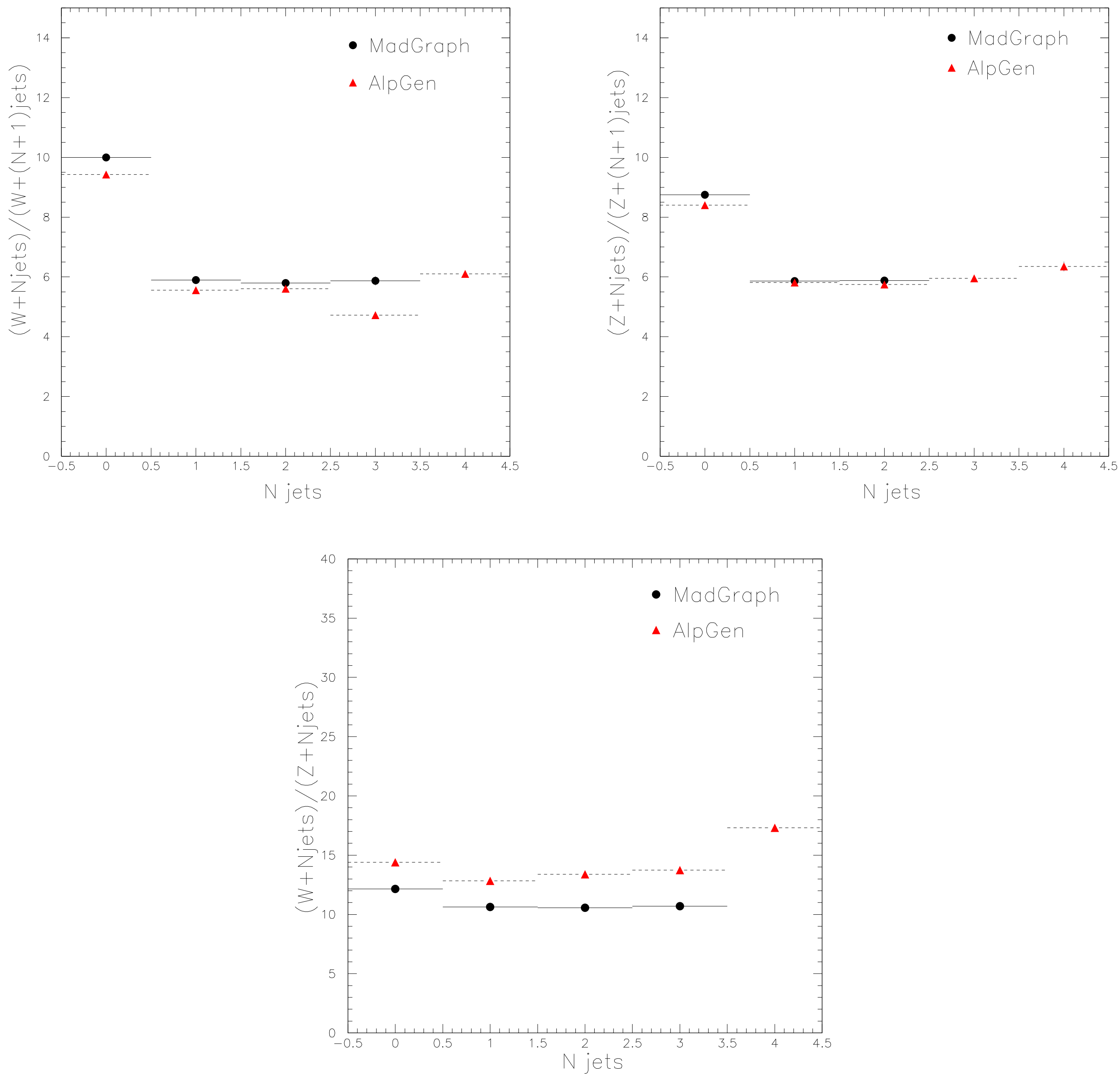
Some comparisons between MadGraph, MCFM, Alpgen, and Comphep. (Apologies- First attempts with not all parameters set equal). Many thanks to Tim Stelzer, John Campbell, Keith Ellis, Michelangelo Mangano, Andrea Messina, and Steve Mrenna.



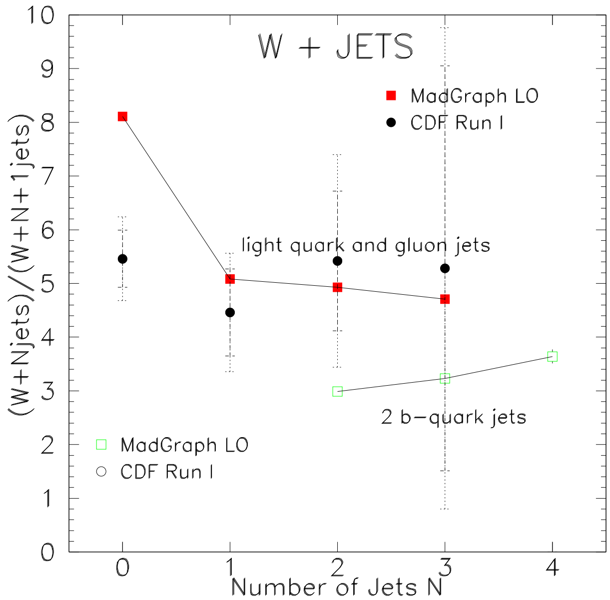


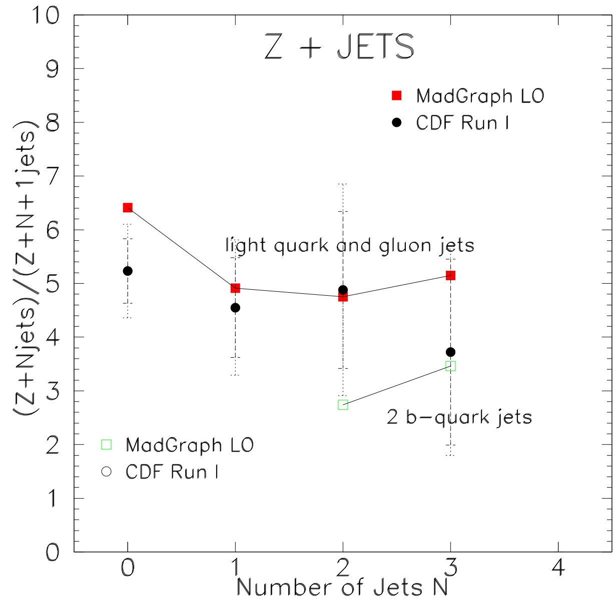


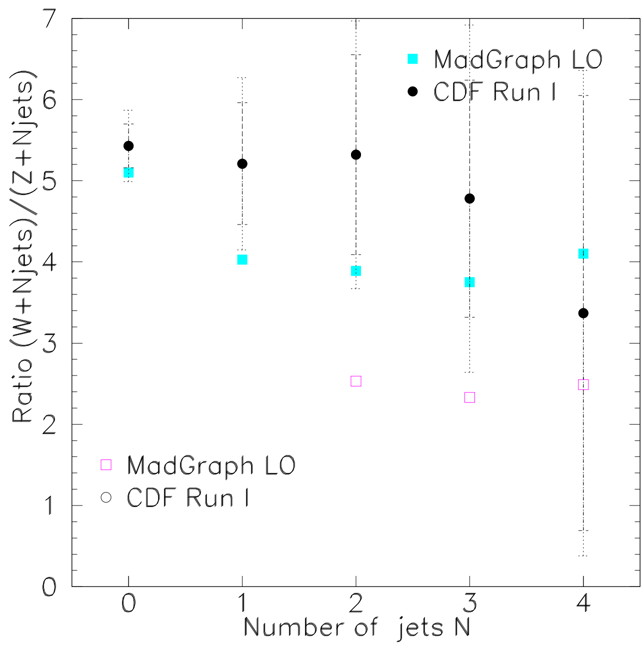
Alpgen/MadGraph Comparison- saw discrepancy in W/Z ratio comparing their published numbers with Madgraph- problem in Alpgen (new program!) now fixed. Don't have new numbers/version yet.



MadGraph/CDF comparison

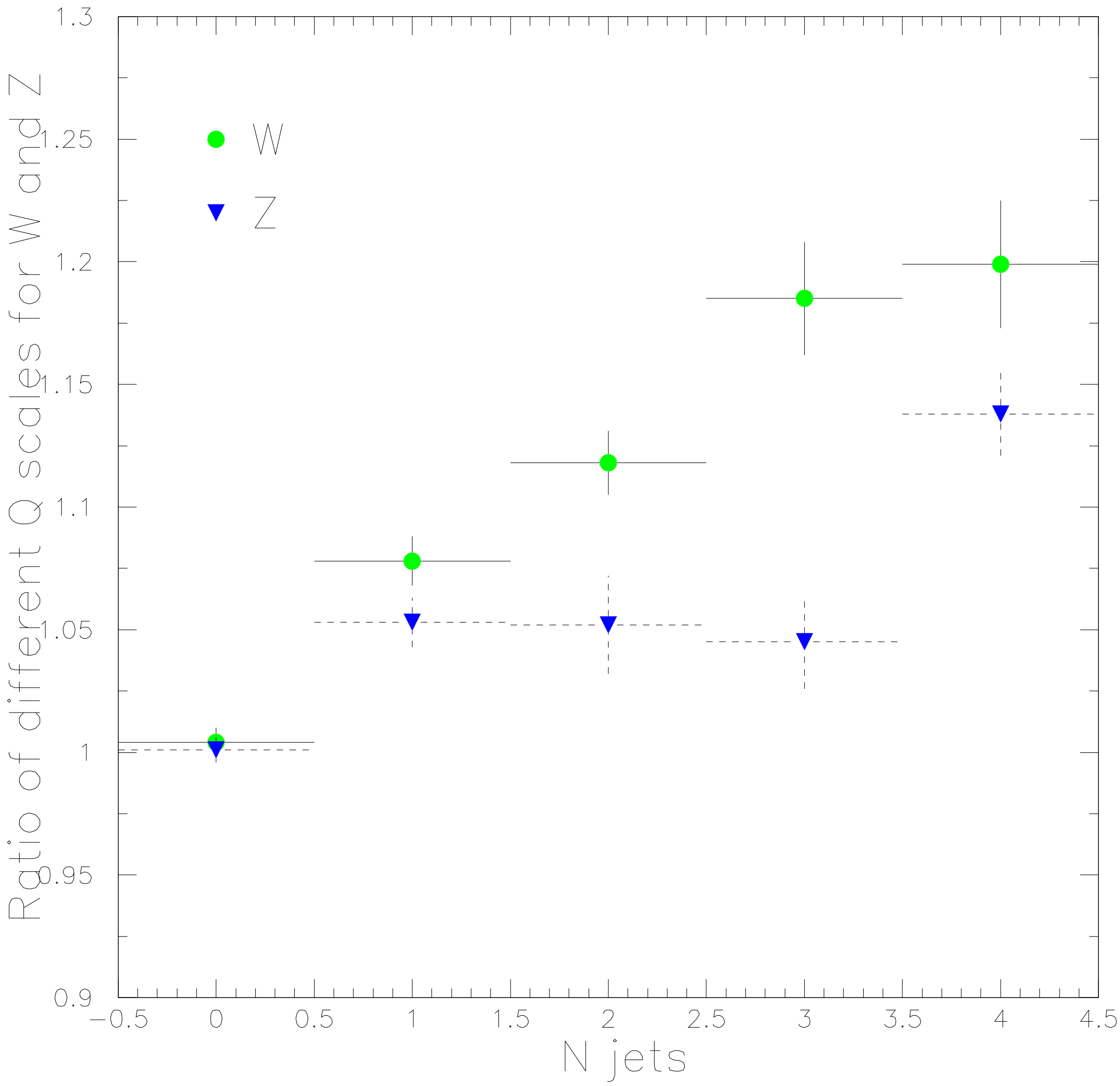




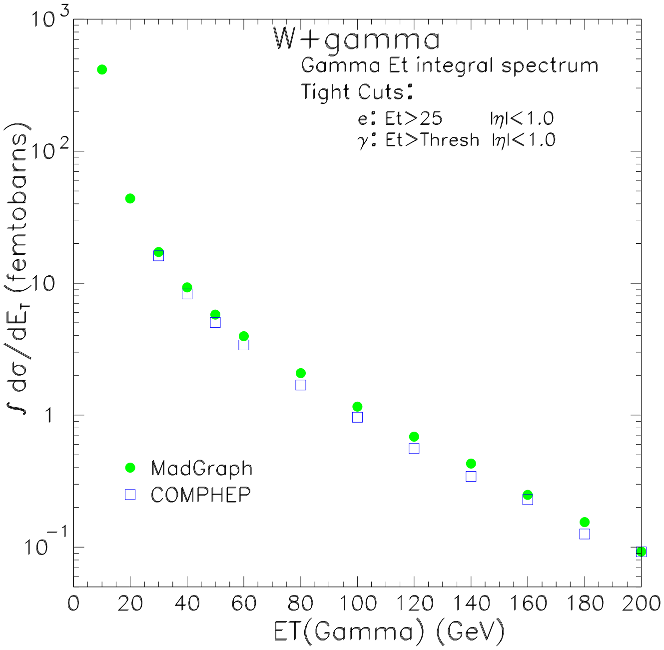


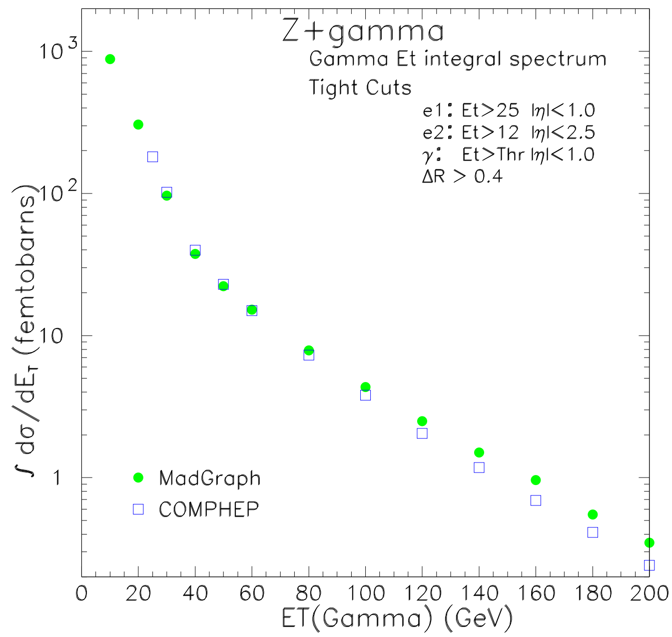
Some mysteries- e.g.- MadGraph predicts that the Q^2 dependence is stronger in W+jets than in Z+jets. Once we have agreement in the N>0 channels with MCFM will see if MCFM agrees.

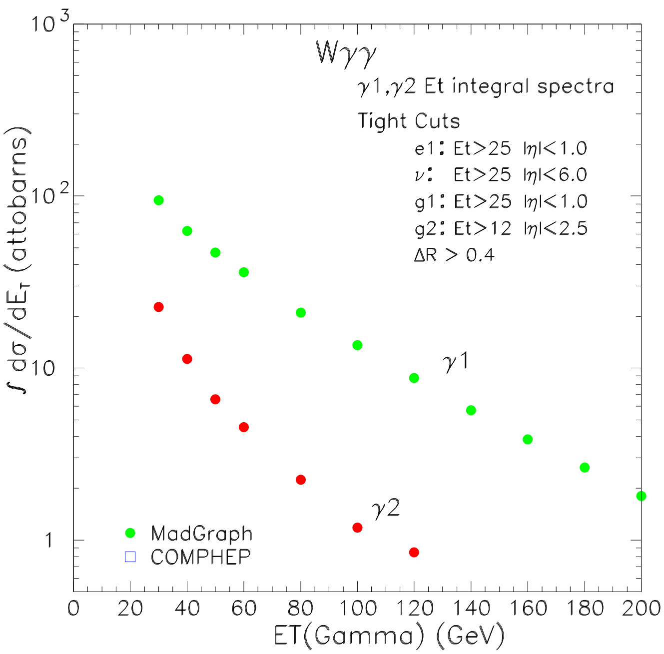
Compare $Q^2 = M^2$ to $Q^2 = M^2 + \mathrm{p}_\mathrm{T}^2$

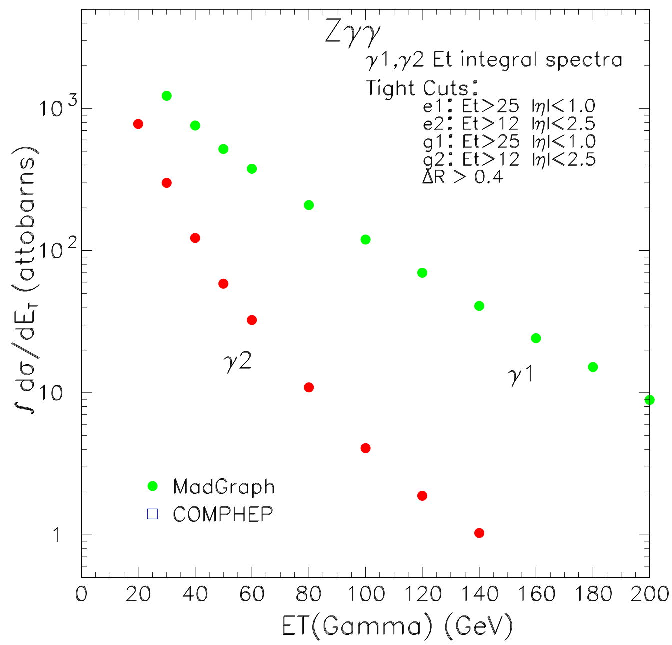


Compare W+gamma, Z+gamma, Wgammagamma, Zgammagamma in MadGraph and MCFM:









Don't yet understand differences...

Issues that have come up in MadGraph/Comphep/MCFM/Alpgen comparisons

Bold (hence arguable) Statement: The dominant experience so far is that no two programs agree so far at the level of precision we may be able to measure eventually in the ratios (e.g. 1%). Issues are:

- Hidden and/or Hard-wired parameters.
- 'Gauge-invariance on/off' (see MadGraph/COMPHEP W+γ comparison).
- 'Mass-dependent Width' (ditto)
- Tabulated CETQ vs Interpolated CTEQ
- 4-flavor pdf vs 5-flavor pdf

Summary: At the LHC measurements of W, Z, WW, top, top+W, all +jets, will be statistics limited; those measurements that can be done with the smallest systematics (e.g., ratios of cross sections rather than cross sections themselves) will be the best tests.

Final Optimistic Thought

Lastly, 'Rol Johnson's Theorem'- any effect large enough to make a difference can be measured. We can turn effects that presently contribute to uncertainties into measurements- e.g. Q^2 scale, underlying event, ISR.

The End