
The new Les Houches high precision wishlist

J. Huston

Michigan State University

Higher order cross sections: The first wishlist

An experimenter's wishlist

Run II Monte Carlo Workshop

Single Boson	Diboson	Triboson	Heavy Flavour
$W^+ \leq 5j$	$WW^+ \leq 5j$	$WWW^+ \leq 3j$	$t\bar{t}^+ \leq 3j$
$W + b\bar{b} \leq 3j$	$W + b\bar{b}^+ \leq 3j$	$WWW + b\bar{b}^+ \leq 3j$	$t\bar{t} + \gamma^+ \leq 2j$
$W + c\bar{c} \leq 3j$	$W + c\bar{c}^+ \leq 3j$	$WWW + \gamma\gamma^+ \leq 3j$	$t\bar{t} + W^+ \leq 2j$
$Z^+ \leq 5j$	$ZZ^+ \leq 5j$	$Z\gamma\gamma^+ \leq 3j$	$t\bar{t} + Z^+ \leq 2j$
$Z + b\bar{b}^+ \leq 3j$	$Z + b\bar{b}^+ \leq 3j$	$ZZZ^+ \leq 3j$	$t\bar{t} + H^+ \leq 2j$
$Z + c\bar{c}^+ \leq 3j$	$ZZ + c\bar{c}^+ \leq 3j$	$WZZ^+ \leq 3j$	$t\bar{b} \leq 2j$
$\gamma^+ \leq 5j$	$\gamma\gamma^+ \leq 5j$	$ZZZ^+ \leq 3j$	$b\bar{b}^+ \leq 3j$
$\gamma + b\bar{b} \leq 3j$	$\gamma\gamma + b\bar{b} \leq 3j$		single top
$\gamma + c\bar{c} \leq 3j$	$\gamma\gamma + c\bar{c} \leq 3j$		
	$WZ^+ \leq 5j$		
	$WZ + b\bar{b} \leq 3j$		
	$WZ + c\bar{c} \leq 3j$		
	$W\gamma^+ \leq 3j$		
	$Z\gamma^+ \leq 3j$		

Realistic wishlist

- Was developed at Les Houches in 2005, and expanded in 2007 and 2009
- Calculations that are important for the LHC AND do-able in finite time
- In 2009, we added $t\bar{t}\bar{t}\bar{t}$, $Wbbj$, $W/Z+4j$ plus an extra column for each process indicating the level of precision required by the experiments
 - ◆ to see for example if EW corrections may need to be calculated
- In order to be most useful, decays for final state particles (t, W, H) need to be provided in the codes as well
- With the calculation of $t\bar{t}\bar{t}\bar{t}$, all processes on the wishlist have been calculated
- The wishlist has been retired since new techniques allow for the semi-automatic generation of new (reasonable) NLO cross sections

Process ($V \in \{Z, W, \gamma\}$)	Comments
Calculations completed since Les Houches 2005	
1. $pp \rightarrow VV\text{jet}$	$WW\text{jet}$ completed by Dittmaier/Kallweit/Uwer [4, 5]; Campbell/Ellis/Zanderighi [6]. $ZZ\text{jet}$ completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [7]
2. $pp \rightarrow \text{Higgs}+2\text{jets}$ note we didn't even think Higgs+3 jets possible	NLO QCD to the gg channel completed by Campbell/Ellis/Zanderighi [8]; NLO QCD+EW to the VBF channel completed by Ciccolini/Denner/Dittmaier [9, 10]
3. $pp \rightarrow V V V$	ZZZ completed by Lazopoulos/Melnikov/Petriello [11] and WWZ by Hankele/Zeppenfeld [12] (see also Binoth/Ossola/Papadopoulos/Pittau [13])
4. $pp \rightarrow t\bar{t}b\bar{b}$	relevant for $t\bar{t}H$ computed by Bredenstein/Denner/Dittmaier/Pozzorini [14, 15] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [16]
5. $pp \rightarrow V+3\text{jets}$	calculated by the Blackhat/Sherpa [17] and Rocket [18] collaborations
Calculations remaining from Les Houches 2005	
6. $pp \rightarrow t\bar{t}+2\text{jets}$	relevant for $t\bar{t}H$ computed by Bevilacqua/Czakon/Papadopoulos/Worek [19]
7. $pp \rightarrow VVb\bar{b}$, 8. $pp \rightarrow VV+2\text{jets}$	relevant for VBF $\rightarrow H \rightarrow VV, t\bar{t}H$ VBF contributions calculated by (Bozzi/Jäger/Oleari/Zeppenfeld [20–22])
NLO calculations added to list in 2007	
9. $pp \rightarrow b\bar{b}b\bar{b}$	$q\bar{q}$ channel calculated by Golem collaboration [23]
NLO calculations added to list in 2009	
10. $pp \rightarrow V+4\text{ jets}$ 11. $pp \rightarrow Wb\bar{b}j$ 12. $pp \rightarrow t\bar{t}\bar{t}\bar{t}$	top pair production, various new physics signatures top, new physics signatures various new physics signatures
Calculations beyond NLO added in 2007	
13. $gg \rightarrow W^*W^* \mathcal{O}(\alpha^2\alpha_s^3)$ 14. NNLO $pp \rightarrow t\bar{t}$ 15. NNLO to VBF and $Z/\gamma+\text{jet}$	backgrounds to Higgs normalization of a benchmark process Higgs couplings and SM benchmark
Calculations including electroweak effects	
16. NNLO QCD+NLO EW for W/Z	precision calculation of a SM benchmark

Table 1: The updated experimenter's wishlist for LHC processes

Realistic wishlist

- 4 top final state

Constraining BSM Physics at the LHC: Four top final states with NLO accuracy in perturbative QCD

G. Bevilacqua^a and M. Worek^b

^a*Institut für Theoretische Teilchenphysik und Kosmologie, RWTH Aachen University, Otto-Blumenthal Str., D-52056 Aachen, Germany*

^b*Theoretische Physik, Fachbereich C, Bergische Universität Wuppertal, Gauss Str. 20, D-42097 Wuppertal, Germany*

E-mail: bevilacqua@physik.rwth-aachen.de,
worek@physik.uni-wuppertal.de

ABSTRACT: Many theories, from Supersymmetry to models of Strong Electroweak Symmetry Breaking, look at the production of four top quarks as an interesting channel to evidence signals of new physics beyond the Standard Model. The production of four-top final states requires large partonic energies, above the $4m_t$ threshold, that are available at the CERN Large Hadron Collider and will become more and more accessible with increasing energy and luminosity of the proton beams. A good theoretical control on the Standard Model background is a fundamental prerequisite for a correct interpretation of the possible signals of new physics that may arise in this channel. In this paper we report on the calculation of the next-to-leading order QCD corrections to the Standard Model process $pp \rightarrow t\bar{t}t\bar{t} + X$. As it is customary for such studies, we present results for both integrated and differential cross sections. A judicious choice of a dynamical scale allows us to obtain nearly constant \mathcal{K} -factors in most distributions.

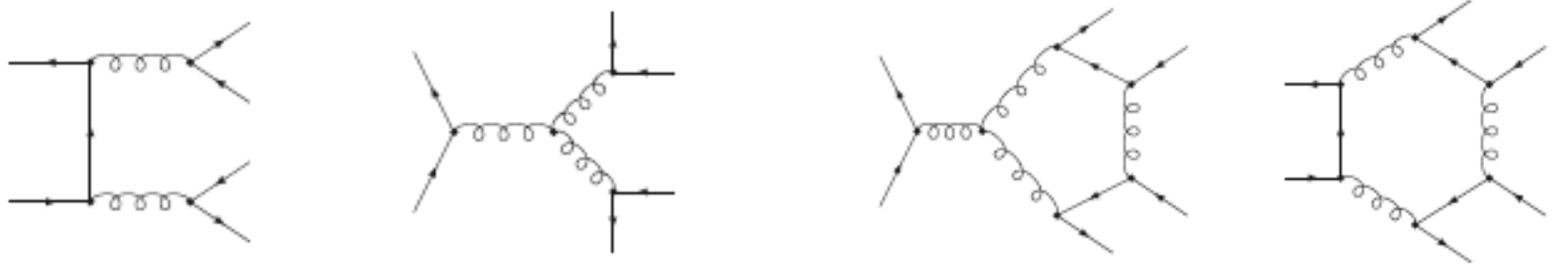
KEYWORDS: NLO Computations, Heavy Quark Physics, Standard Model, Beyond Standard Model

WUB/12-12, TTK-12-22

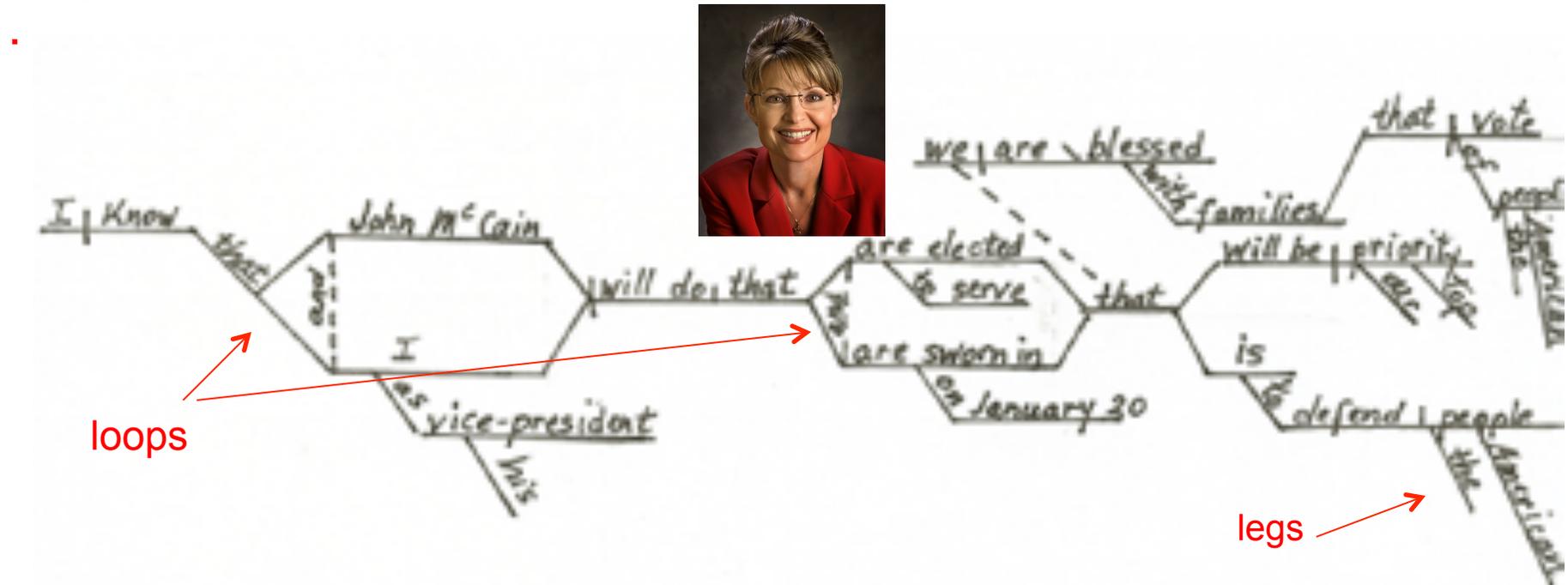


Loops and legs

2->4 is very impressive



but just compare to Sarah Palin's grammar (please run again Sarah)



Note that we have ticked off one cross section from the first list

An experimenter's wishlist

Run II Monte Carlo Workshop

Single Boson	Diboson	Triboson	Heavy Flavour
$W+ \leq 5j$	$WW+ \leq 5j$	$WWW+ \leq 3j$	$t\bar{t}+ \leq 3j$
$W + b\bar{b} \leq 3j$	$W + b\bar{b}+ \leq 3j$	$WWW + b\bar{b}+ \leq 3j$	$t\bar{t} + \gamma+ \leq 2j$
$W + c\bar{c} \leq 3j$	$W + c\bar{c}+ \leq 3j$	$WWW + \gamma\gamma+ \leq 3j$	$t\bar{t} + W+ \leq 2j$
$Z+ \leq 5j$	$ZZ+ \leq 5j$	$Z\gamma\gamma+ \leq 3j$	$t\bar{t} + Z+ \leq 2j$
$Z + b\bar{b}+ \leq 3j$	$Z + b\bar{b}+ \leq 3j$	$ZZZ+ \leq 3j$	$t\bar{t} + H+ \leq 2j$
$Z + c\bar{c}+ \leq 3j$	$ZZ + c\bar{c}+ \leq 3j$	$WZZ+ \leq 3j$	$t\bar{b} \leq 2j$
$\gamma+ \leq 5j$	$\gamma\gamma+ \leq 5j$	$ZZZ+ \leq 3j$	$b\bar{b}+ \leq 3j$
$\gamma + b\bar{b} \leq 3j$	$\gamma\gamma + b\bar{b} \leq 3j$		single top
$\gamma + c\bar{c} \leq 3j$	$\gamma\gamma + c\bar{c} \leq 3j$		
	$WZ+ \leq 5j$		
	$WZ + b\bar{b} \leq 3j$		
	$WZ + c\bar{c} \leq 3j$		
	$W\gamma+ \leq 3j$		
	$Z\gamma+ \leq 3j$		

A new Les Houches high precision wishlist

- From the 2013 proceedings
 - ◆ [arxiv:1405.1067](https://arxiv.org/abs/1405.1067)
 - NB: The counting of orders is done relative to LO QCD independent of the absolute power of α_s in cross section
 - $\alpha \sim \alpha_s^2$ so that NNLO QCD and NLO EW effects are naively of the same size
 - $d\sigma$ represents full differential cross sections
 - The list is very ambitious, but possible to do over the remainder of the LHC running
- LO $\equiv \mathcal{O}(1)$,
 - NLO QCD $\equiv \mathcal{O}(\alpha_s)$,
 - NNLO QCD $\equiv \mathcal{O}(\alpha_s^2)$,
 - NLO EW $\equiv \mathcal{O}(\alpha)$,
 - NNNLO QCD $\equiv \mathcal{O}(\alpha_s^3)$,
 - NNLO QCD+EW $\equiv \mathcal{O}(\alpha_s\alpha)$.

...and of course, as much as possible, we would like matching to a parton shower for fully exclusive final states

In this notation, $d\sigma@NNLO$ QCD+NLO EW indicates a single code computing the fully differential cross section including both order α_s^2 and order α effects. Where possible, full resonance production, including interference with background should be taken into account.

NNLO QCD+NLO EW wishlist

Higgs

Process	known	desired	details
H	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ NLO	$d\sigma$ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW finite quark mass effects @ LO	$d\sigma$ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	$\sigma_{\text{tot}}(\text{VBF})$ @ NNLO(DIS) QCD $d\sigma(\text{gg})$ @ NLO QCD $d\sigma(\text{VBF})$ @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW	with $H \rightarrow b\bar{b}$ @ same accuracy	H couplings
t \bar{t} H	$d\sigma(\text{stable tops})$ @ NLO QCD	$d\sigma(\text{top decays})$ @ NLO QCD + NLO EW	top Yukawa coupling
HH	$d\sigma$ @ LO QCD (full m_t dependence) $d\sigma$ @ NLO QCD (infinite m_t limit)	$d\sigma$ @ NLO QCD (full m_t dependence) $d\sigma$ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

If these seem crazy,
blame these guys

S. Dittmaier, N. Glover, J. Huston

Table 1: Wishlist part 1 – Higgs (V = W, Z)



justify the requested
precision based on
current/extrapolated
experimental errors

Higgs sector

- We currently know the production cross section for gg fusion to NNLO QCD in the infinite m_t limit, including finite quark mass effects at NLO QCD and NLO EW.
- Current experimental uncertainties are of the order of 20-40%
- Theoretically, uncertainty is of order of 15% with PDF+ α_s and higher order uncertainties, both being on the order of 7-8%
- Expect total experimental error to decrease to 10% in Run 2
- So ultimately may want to know NNNLO QCD and mixed NNLO QCD +EW contributions maintaining finite top quark mass effects

Process	known	desired	details
H	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ NLO	$d\sigma$ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW finite quark mass effects @ LO	$d\sigma$ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	$\sigma_{\text{tot}}(\text{VBF})$ @ NNLO(DIS) QCD $d\sigma(\text{gg})$ @ NLO QCD $d\sigma(\text{VBF})$ @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW	with $H \rightarrow b\bar{b}$ @ same accuracy	H couplings
t \bar{t} H	$d\sigma(\text{stable tops})$ @ NLO QCD	$d\sigma(\text{top decays})$ @ NLO QCD + NLO EW	top Yukawa coupling
HH	$d\sigma$ @ LO QCD (full m_t dependence) $d\sigma$ @ NLO QCD (infinite m_t limit)	$d\sigma$ @ NLO QCD (full m_t dependence) $d\sigma$ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

Table 1: Wishlist part 1 – Higgs (V = W, Z)

efforts underway for calculation of ggF to NNNLO in QCD.

a NNLO+PS simulation for ggF has already been developed; expect improvements/refinements.

Higgs sector

- First attempts to measure differential Higgs+jets measurements made in diphoton channel at ATLAS
 - ◆ paper out for ICHEP
- At 14 TeV, with 300 fb^{-1} , there will be a rich variety of differential jet measurements with on the order of 3000 events with jet p_T above the top quark mass scale, thus probing the top quark loop
- Currently know the H+j cross section for the gg initial state to NNLO; hope for complete cross section later this year
- LO (one-loop) QCD and EW corrections with top mass dependence known, but finite mass contributions at NLO QCD+NLO EW may also be needed

Process	known	desired	details
H	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ NLO	$d\sigma$ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW finite quark mass effects @ LO	$d\sigma$ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	$\sigma_{\text{tot}}(\text{VBF})$ @ NNLO(DIS) QCD $d\sigma(\text{gg})$ @ NLO QCD $d\sigma(\text{VBF})$ @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW	with $H \rightarrow b\bar{b}$ @ same accuracy	H couplings
t \bar{t} H	$d\sigma(\text{stable tops})$ @ NLO QCD	$d\sigma(\text{top decays})$ @ NLO QCD + NLO EW	top Yukawa coupling
HH	$d\sigma$ @ LO QCD (full m_t dependence) $d\sigma$ @ NLO QCD (infinite m_t limit)	$d\sigma$ @ NLO QCD (full m_t dependence) $d\sigma$ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

Table 1: Wishlist part 1 – Higgs (V = W, Z)

Higgs sector

- Higgs + 2 jets crucial to understand Higgs coupling, in particular through VBF
- VBF production known to NNLO QCD in double-DIS approximation together with QCD and EW effects at NLO, while ggF known in infinite top mass limit and to LO QCD retaining top mass effects
- With 300 fb^{-1} , there is the possibility of measuring HWW coupling strength to order of 5%
- This would require both VBF and ggF Higgs + 2 jets cross sections to NNLO QCD and finite mass effects to NLO QCD and NLO EW

Process	known	desired	details
H	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ NLO	$d\sigma$ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW finite quark mass effects @ LO	$d\sigma$ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	$\sigma_{\text{tot}}(\text{VBF})$ @ NNLO(DIS) QCD $d\sigma(\text{gg})$ @ NLO QCD $d\sigma(\text{VBF})$ @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW	with $H \rightarrow b\bar{b}$ @ same accuracy	H couplings
t \bar{t} H	$d\sigma(\text{stable tops})$ @ NLO QCD	$d\sigma(\text{top decays})$ @ NLO QCD + NLO EW	top Yukawa coupling
HH	$d\sigma$ @ LO QCD (full m_t dependence) $d\sigma$ @ NLO QCD (infinite m_t limit)	$d\sigma$ @ NLO QCD (full m_t dependence) $d\sigma$ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

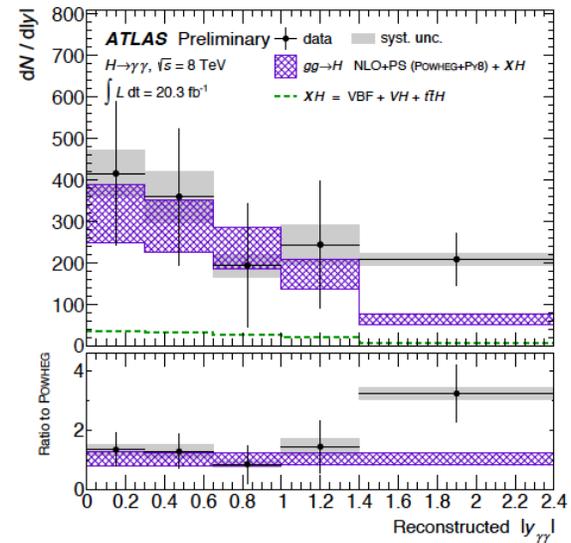
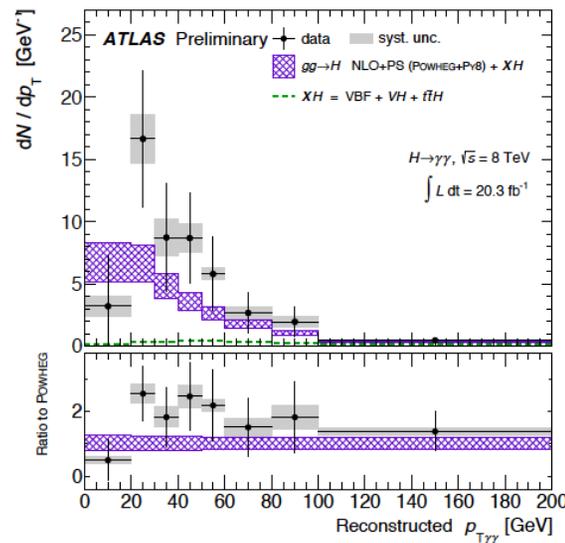
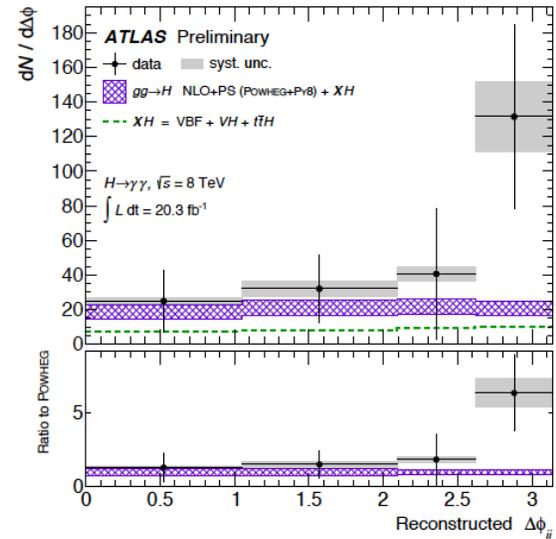
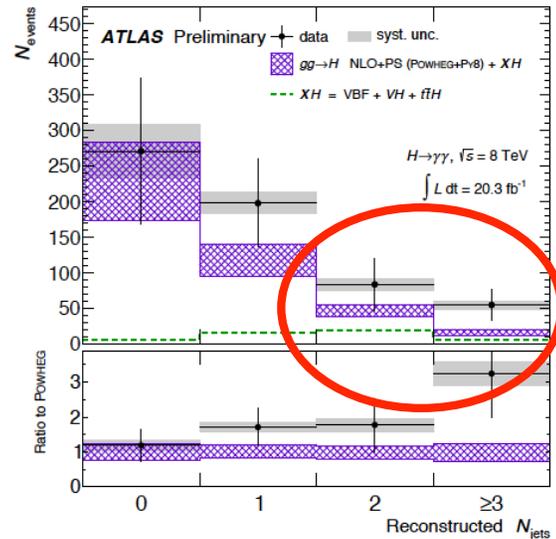
Table 1: Wishlist part 1 – Higgs (V = W, Z)

ATLAS-CONF-2013-072

Interesting that the (statistically limited) results seem to show a jettier final state than predicted

These distributions are from a conf note distributed last summer

paper is currently going through ATLAS approval



Higgs sector

- Coupling of Higgs to top and bottom quarks poorly known
 - ◆ 50% for bottom
 - ◆ 100% for top
- H→bB primarily measured through associated production, known current at NNLO QCD and at NLO EW
- bB decay currently in NLO QCD production in narrow-width approximation; desirable to combine Higgs production and decay processes to same order, NNLO in QCD and NLO in EW for Higgs-strahlung process
- With 300 fb⁻¹ at 14 TeV, signal strength for H→bB should be measured to 10-15% level, shrinking to 5% for 3000 fb⁻¹

Process	known	desired	details
H	dσ @ NNLO QCD dσ @ NLO EW finite quark mass effects @ NLO	dσ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	dσ @ NNLO QCD (g only) dσ @ NLO EW finite quark mass effects @ LO	dσ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p _T
H + 2j	σ _{tot} (VBF) @ NNLO(DIS) QCD dσ(gg) @ NLO QCD dσ(VBF) @ NLO EW	dσ @ NNLO QCD + NLO EW	H couplings
H + V	dσ @ NNLO QCD dσ @ NLO EW	with H → b \bar{b} @ same accuracy	H couplings
t \bar{t} H	dσ(stable tops) @ NLO QCD	dσ(top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	dσ @ LO QCD (full m _t dependence) dσ @ NLO QCD (infinite m _t limit)	dσ @ NLO QCD (full m _t dependence) dσ @ NNLO QCD (infinite m _t limit)	Higgs self coupling

Table 1: Wishlist part 1 – Higgs (V = W, Z)

- Higgs-top couplings may have both scalar and pseudo-scalar components (in presence of CP violation)
- Can be probed in measurements of Higgs production in association with tT or t
- tH (tTH) known to LO (NLO) QCD with stable tops
- Needed to know the cross section (with top decays) at NLO QCD, possibly including NLO EW effects

Higgs sector

- Self-coupling of the Higgs one of the holy grails of extended running at the LHC
 - ◆ directly probes EW potential
- HH production through ggF currently known at LO with full top mass dependence, at NLO with leading finite mass terms, and at NNLO in the infinite top-mass limit
- It may be necessary to compute full top mass dependence at NLO QCD
- With 3000 fb^{-1} at 14 TeV, hope for a 50% precision on self-coupling parameter

Process	known	desired	details
H	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ NLO	$d\sigma$ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW finite quark mass effects @ LO	$d\sigma$ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	$\sigma_{\text{tot}}(\text{VBF})$ @ NNLO(DIS) QCD $d\sigma(\text{gg})$ @ NLO QCD $d\sigma(\text{VBF})$ @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW	with $H \rightarrow b\bar{b}$ @ same accuracy	H couplings
t \bar{t} H	$d\sigma(\text{stable tops})$ @ NLO QCD	$d\sigma(\text{top decays})$ @ NLO QCD + NLO EW	top Yukawa coupling
HH	$d\sigma$ @ LO QCD (full m_t dependence) $d\sigma$ @ NLO QCD (infinite m_t limit)	$d\sigma$ @ NLO QCD (full m_t dependence) $d\sigma$ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

Table 1: Wishlist part 1 – Higgs (V = W, Z)

NNLO QCD + NLO EWK wishlist

heavy quarks, photons, jets

Process	known	desired	details
$t\bar{t}$	σ_{tot} @ NNLO QCD $d\sigma(\text{top decays})$ @ NLO QCD $d\sigma(\text{stable tops})$ @ NLO EW	$d\sigma(\text{top decays})$ @ NNLO QCD + NLO EW	precision top/QCD, gluon PDF, effect of extra radiation at high rapidity, top asymmetries
$t\bar{t} + j$	$d\sigma(\text{NWA top decays})$ @ NLO QCD	$d\sigma(\text{NWA top decays})$ @ NNLO QCD + NLO EW	precision top/QCD top asymmetries
single-top	$d\sigma(\text{NWA top decays})$ @ NLO QCD	$d\sigma(\text{NWA top decays})$ @ NNLO QCD (t channel)	precision top/QCD, V_{tb}
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO weak	$d\sigma$ @ NNLO QCD + NLO EW	Obs.: incl. jets, dijet mass → PDF fits (gluon at high x) → α_s CMS http://arxiv.org/abs/1212.6660
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW	Obs.: $R3/2$ or similar → α_s at high scales dom. uncertainty: scales CMS http://arxiv.org/abs/1304.7498
$\gamma + j$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD +NLO EW	gluon PDF $\gamma + b$ for bottom PDF

Table 2: Wishlist part 2 – jets and heavy quarks

NNLO QCD + NLO EWK wishlist

- Top production is important both as a possible venue for new physics as well as for more mundane purposes such as the determination of the gluon PDF at high x
- Currently, the dilepton final state is known to an experimental uncertainty of 5% and the uncertainty for the leptons+jets final state should be of the same order in Run 2
 - ◆ a sizeable portion of that error is due to the luminosity uncertainty
- Currently know total top cross section to NNLO QCD and NLO EW
 - ◆ 4% uncertainties
- Need differential top cross section to NNLO QCD (with decays) including NLO EW effects

Process	State of the Art	Desired
$t\bar{t}$	$\sigma_{\text{tot}}(\text{stable tops}) @ \text{NNLO QCD}$ $d\sigma(\text{top decays}) @ \text{NLO QCD}$ $d\sigma(\text{stable tops}) @ \text{NLO EW}$	$d\sigma(\text{top decays}) @ \text{NNLO QCD} + \text{NLO EW}$
$t\bar{t} + j(j)$	$d\sigma(\text{NWA top decays}) @ \text{NLO QCD}$	$d\sigma(\text{NWA top decays}) @ \text{NNLO QCD} + \text{NLO EW}$
$t\bar{t} + Z$	$d\sigma(\text{stable tops}) @ \text{NLO QCD}$	$d\sigma(\text{top decays}) @ \text{NLO QCD} + \text{NLO EW}$
single-top	$d\sigma(\text{NWA top decays}) @ \text{NLO QCD}$	$d\sigma(\text{NWA top decays}) @ \text{NNLO QCD} + \text{NLO EW}$
dijet	$d\sigma @ \text{NNLO QCD (g only)}$ $d\sigma @ \text{NLO EW (weak)}$	$d\sigma @ \text{NNLO QCD} + \text{NLO EW}$
3j	$d\sigma @ \text{NLO QCD}$	$d\sigma @ \text{NNLO QCD} + \text{NLO EW}$
$\gamma + j$	$d\sigma @ \text{NLO QCD}$ $d\sigma @ \text{NLO EW}$	$d\sigma @ \text{NNLO QCD} + \text{NLO EW}$

→ so even more useful for PDF determination

NNLO QCD + NLO EWK wishlist

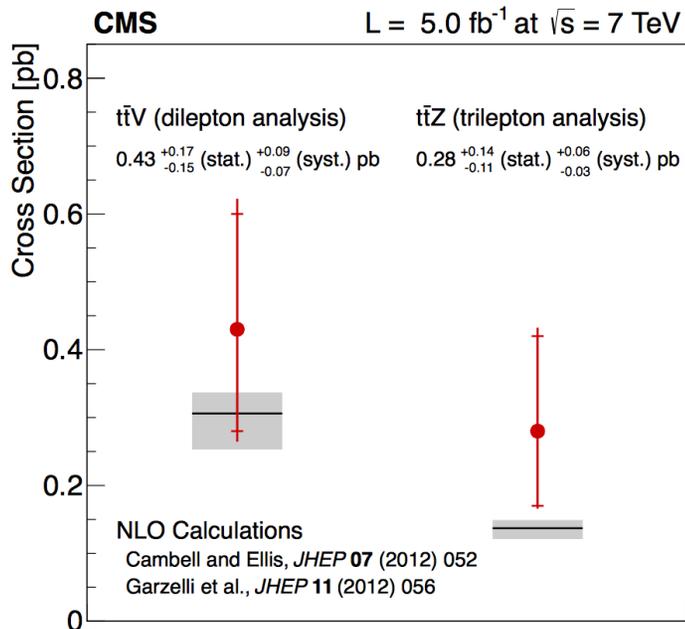
- Due to dominance of gg initial state, basically every tT event is a tTj event
- Currently known at NLO QCD
- Desired to know (with decays) at NNLO QCD with NLO EW effects

Process	State of the Art	Desired
t \bar{t}	σ_{tot} (stable tops) @ NNLO QCD $d\sigma$ (top decays) @ NLO QCD $d\sigma$ (stable tops) @ NLO EW	$d\sigma$ (top decays) @ NNLO QCD + NLO EW
t \bar{t} + j(j)	$d\sigma$ (NWA top decays) @ NLO QCD	$d\sigma$ (NWA top decays) @ NNLO QCD + NLO EW
t \bar{t} + Z	$d\sigma$ (stable tops) @ NLO QCD	$d\sigma$ (top decays) @ NLO QCD + NLO EW
single-top	$d\sigma$ (NWA top decays) @ NLO QCD	$d\sigma$ (NWA top decays) @ NNLO QCD + NLO EW
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW (weak)	$d\sigma$ @ NNLO QCD + NLO EW
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW
γ + j	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW

NNLO QCD + NLO EWK wishlist

- Important process to compare to $t\bar{t}$ Higgs production, but also for measuring coupling of top quark with Z (or W)
- Currently known to NLO with on-shell top decays
- Need to be able to study hard radiation effects in top decays

Process	State of the Art	Desired
$t\bar{t}$	$\sigma_{\text{tot}}(\text{stable tops})$ @ NNLO QCD $d\sigma(\text{top decays})$ @ NLO QCD $d\sigma(\text{stable tops})$ @ NLO EW	$d\sigma(\text{top decays})$ @ NNLO QCD + NLO EW
$t\bar{t} + j(j)$	$d\sigma(\text{NWA top decays})$ @ NLO QCD	$d\sigma(\text{NWA top decays})$ @ NNLO QCD + NLO EW
$t\bar{t} + Z$	$d\sigma(\text{stable tops})$ @ NLO QCD	$d\sigma(\text{top decays})$ @ NLO QCD + NLO EW
single-top	$d\sigma(\text{NWA top decays})$ @ NLO QCD	$d\sigma(\text{NWA top decays})$ @ NNLO QCD + NLO EW
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW (weak)	$d\sigma$ @ NNLO QCD + NLO EW
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW
$\gamma + j$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW



NNLO QCD + NLO EWK wishlist

- Important for precision top physics and in particular the measurement of V_{tb}
- Current experimental precision is on the order of 10% and a precision of the order of 5% likely in Run 2
- Both ATLAS and CMS have evidence for tW , with approximately 40% uncertainties (dominated by statistics)
- Currently single top cross section known to NLO in QCD
 - ◆ soft gluon and threshold effects at NNLO
- tW known theoretically to within 10% and tZ to within 5%
- Would like single top cross section to NNLO QCD including NLO EW effects

Process	State of the Art	Desired
$t\bar{t}$	$\sigma_{\text{tot}}(\text{stable tops}) @ \text{NNLO QCD}$ $d\sigma(\text{top decays}) @ \text{NLO QCD}$ $d\sigma(\text{stable tops}) @ \text{NLO EW}$	$d\sigma(\text{top decays}) @ \text{NNLO QCD} + \text{NLO EW}$
$t\bar{t} + j(j)$	$d\sigma(\text{NWA top decays}) @ \text{NLO QCD}$	$d\sigma(\text{NWA top decays}) @ \text{NNLO QCD} + \text{NLO EW}$
$t\bar{t} + Z$	$d\sigma(\text{stable tops}) @ \text{NLO QCD}$	$d\sigma(\text{top decays}) @ \text{NLO QCD} + \text{NLO EW}$
single-top	$d\sigma(\text{NWA top decays}) @ \text{NLO QCD}$	$d\sigma(\text{NWA top decays}) @ \text{NNLO QCD} + \text{NLO EW}$
dijet	$d\sigma @ \text{NNLO QCD (g only)}$ $d\sigma @ \text{NLO EW (weak)}$	$d\sigma @ \text{NNLO QCD} + \text{NLO EW}$
$3j$	$d\sigma @ \text{NLO QCD}$	$d\sigma @ \text{NNLO QCD} + \text{NLO EW}$
$\gamma + j$	$d\sigma @ \text{NLO QCD}$ $d\sigma @ \text{NLO EW}$	$d\sigma @ \text{NNLO QCD} + \text{NLO EW}$

NNLO QCD + NLO EWK wishlist

- One of key processes for perturbative QCD
 - ◆ covers largest kinematic range with jets produced in the multi-TeV range
 - ◆ EW effects very important in this range
- Only process currently included in global fits not known at NNLO
 - ◆ gg channel has been calculated
- Current experimental precision on the order of 5-10% for jets from 200 GeV/c to 1 TeV/c
- Would like better precision for theory
 - ◆ so need NNLO QCD and NLO EW
- We also need a better understanding of the impact of parton showers on the fixed order cross section

Process	State of the Art	Desired
$t\bar{t}$	$\sigma_{\text{tot}}(\text{stable tops})$ @ NNLO QCD $d\sigma(\text{top decays})$ @ NLO QCD $d\sigma(\text{stable tops})$ @ NLO EW	$d\sigma(\text{top decays})$ @ NNLO QCD + NLO EW
$t\bar{t} + j(j)$	$d\sigma(\text{NWA top decays})$ @ NLO QCD	$d\sigma(\text{NWA top decays})$ @ NNLO QCD + NLO EW
$t\bar{t} + Z$	$d\sigma(\text{stable tops})$ @ NLO QCD	$d\sigma(\text{top decays})$ @ NLO QCD + NLO EW
single-top	$d\sigma(\text{NWA top decays})$ @ NLO QCD	$d\sigma(\text{NWA top decays})$ @ NNLO QCD + NLO EW
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW (weak)	$d\sigma$ @ NNLO QCD + NLO EW
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW
$\gamma + j$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW

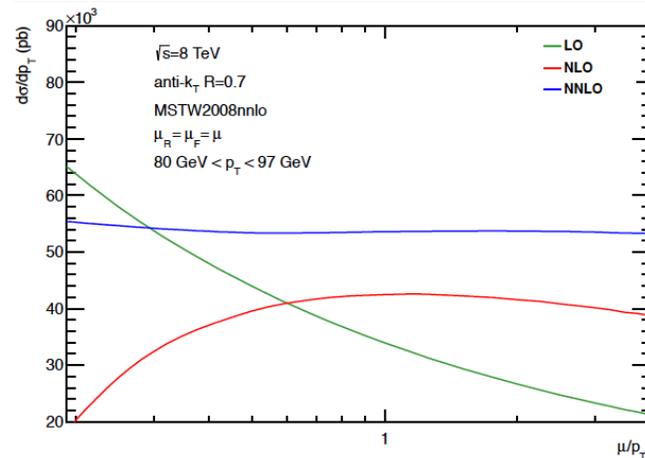


FIG. 2: Scale dependence of the inclusive jet cross section for pp collisions at $\sqrt{s} = 8$ TeV for the anti- k_T algorithm with $R = 0.7$ and with $|y| < 4.4$ and $80 \text{ GeV} < p_T < 97 \text{ GeV}$ at NNLO (blue), NLO (red) and LO (green).

...but, arXiv:1407.7031

- NNLO/NLO corrections smaller (on the order of 5%) and flat as a function of jet p_T if scale of inclusive jet p_T is used rather than p_T of the lead jet
- ...which is what should be used in any case
- expect corrections for other subprocesses to be of similar order

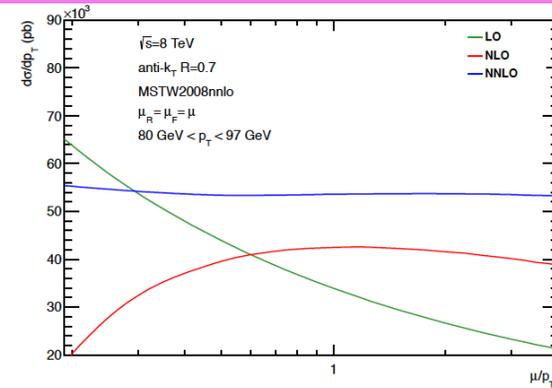


FIG. 2: Scale dependence of the inclusive jet cross section for pp collisions at $\sqrt{s} = 8$ TeV for the anti- k_T algorithm with $R = 0.7$ and with $|y| < 4.4$ and $80 \text{ GeV} < p_T < 97 \text{ GeV}$ at NNLO (blue), NLO (red) and LO (green).

Casimir for biggest color representation final state can be in

Simplistic rule

$$C_{i1} + C_{i2} - C_{f,\max}$$

L. Dixon

Casimir color factors for initial state

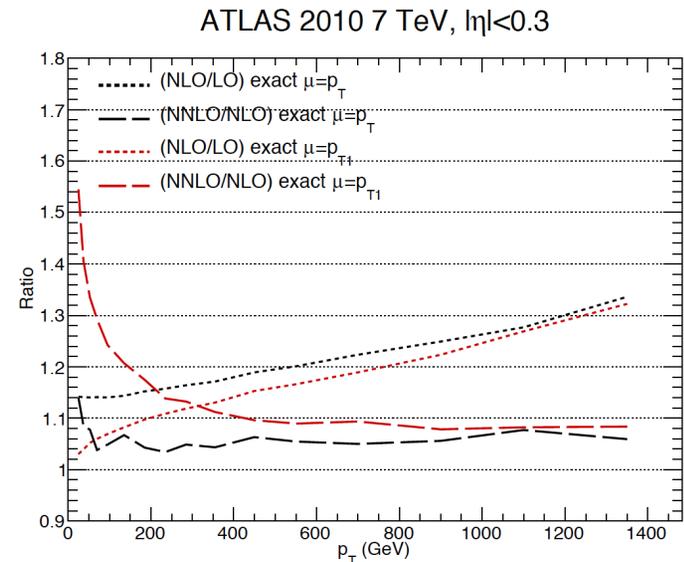


Figure 8: NLO/LO and NNLO/NLO exact k -factors for the gg -channel evaluated with the renormalisation and factorisation scales $\mu_R = \mu_F = p_T$ and $\mu_R = \mu_F = p_{T1}$.

NNLO QCD + NLO EWK wishlist

- Useful for determination of the running of the strong coupling constant over a wide dynamic range
- Many experimental uncertainties cancel in the ratio of $3j/2j$
 - ◆ for example jet energy scale uncertainty for ratio can be reduced to $<1\%$
- Largest theoretical uncertainty is residual scale dependence at NLO
 - ◆ 5% at high p_T
- So like the dijet case, would like to know $3j$ production at NNLO QCD +NLO EW

Process	State of the Art	Desired
$t\bar{t}$	$\sigma_{\text{tot}}(\text{stable tops}) @ \text{NNLO QCD}$ $d\sigma(\text{top decays}) @ \text{NLO QCD}$ $d\sigma(\text{stable tops}) @ \text{NLO EW}$	$d\sigma(\text{top decays}) @ \text{NNLO QCD} + \text{NLO EW}$
$t\bar{t} + j(j)$	$d\sigma(\text{NWA top decays}) @ \text{NLO QCD}$	$d\sigma(\text{NWA top decays}) @ \text{NNLO QCD} + \text{NLO EW}$
$t\bar{t} + Z$	$d\sigma(\text{stable tops}) @ \text{NLO QCD}$	$d\sigma(\text{top decays}) @ \text{NLO QCD} + \text{NLO EW}$
single-top	$d\sigma(\text{NWA top decays}) @ \text{NLO QCD}$	$d\sigma(\text{NWA top decays}) @ \text{NNLO QCD} + \text{NLO EW}$
dijet	$d\sigma @ \text{NNLO QCD (g only)}$ $d\sigma @ \text{NLO EW (weak)}$	$d\sigma @ \text{NNLO QCD} + \text{NLO EW}$
$3j$	$d\sigma @ \text{NLO QCD}$	$d\sigma @ \text{NNLO QCD} + \text{NLO EW}$
$4j + j$	$d\sigma @ \text{NLO QCD}$ $d\sigma @ \text{NLO EW}$	$d\sigma @ \text{NNLO QCD} + \text{NLO EW}$

NNLO QCD + NLO EWK wishlist

- Useful for determination of the gluon distribution, especially at high x
- Final state cleaner than dijet production (at high p_T)
- So like the dijet case, would like to know $\gamma+j$ production at NNLO QCD +NLO EW

Process	State of the Art	Desired
$t\bar{t}$	$\sigma_{\text{tot}}(\text{stable tops}) @ \text{NNLO QCD}$ $d\sigma(\text{top decays}) @ \text{NLO QCD}$ $d\sigma(\text{stable tops}) @ \text{NLO EW}$	$d\sigma(\text{top decays}) @ \text{NNLO QCD} + \text{NLO EW}$
$t\bar{t} + j(j)$	$d\sigma(\text{NWA top decays}) @ \text{NLO QCD}$	$d\sigma(\text{NWA top decays}) @ \text{NNLO QCD} + \text{NLO EW}$
$t\bar{t} + Z$	$d\sigma(\text{stable tops}) @ \text{NLO QCD}$	$d\sigma(\text{top decays}) @ \text{NLO QCD} + \text{NLO EW}$
single-top	$d\sigma(\text{NWA top decays}) @ \text{NLO QCD}$	$d\sigma(\text{NWA top decays}) @ \text{NNLO QCD} + \text{NLO EW}$
dijet	$d\sigma @ \text{NNLO QCD (g only)}$ $d\sigma @ \text{NLO EW (weak)}$	$d\sigma @ \text{NNLO QCD} + \text{NLO EW}$
$3j$	$d\sigma @ \text{NLO QCD}$	$d\sigma @ \text{NNLO QCD} + \text{NLO EW}$
$\gamma + j$	$d\sigma @ \text{NLO QCD}$ $d\sigma @ \text{NLO EW}$	$d\sigma @ \text{NNLO QCD} + \text{NLO EW}$

NNLO QCD + NLO EWK wishlist

Vector bosons

Process	known	desired	details
V	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD}$ $d\sigma(\text{lept. V decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. V decay}) @ \text{NNNLO QCD} + \text{NLO EW}$ MC@NNLO	precision EW, PDFs
V + j	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$ $d\sigma(\text{lept. V decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	Z + j for gluon PDF W + c for strange PDF
V + jj	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	study of systematics of H + jj final state
VV'	$d\sigma(\text{V decays}) @ \text{NLO QCD}$ $d\sigma(\text{stable V}) @ \text{NLO EW}$	$d\sigma(\text{V decays}) @ \text{NNLO QCD} + \text{NLO EW}$	off-shell leptonic decays TGCs
gg → VV	$d\sigma(\text{V decays}) @ \text{LO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	bkg. to $H \rightarrow VV$ TGCs
V γ	$d\sigma(\text{V decay}) @ \text{NLO QCD}$ $d\sigma(\text{PA, V decay}) @ \text{NLO EW}$	$d\sigma(\text{V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	TGCs
Vb \bar{b}	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$ massive b	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD}$ massless b	bkg. for $VH \rightarrow b\bar{b}$
VV' γ	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs
VV'V''	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs, EWSB
VV' + j	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	bkg. to H, BSM searches
VV' + jj	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs, EWSB
$\gamma\gamma$	$d\sigma @ \text{NNLO QCD}$		bkg to $H \rightarrow \gamma\gamma$

Table 3: Wishlist part 3 – EW gauge bosons ($V = W, Z$)

NNLO QCD + NLO EWK wishlist

- Perhaps key collider benchmark process
- Known experimentally to 1-2% (excluding luminosity uncertainties)
- To take full advantage, would like to know process to NNNLO QCD and NNLO QCD+EW

Process	known	desired	details
V	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD}$ $d\sigma(\text{lept. V decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. V decay})$ @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
V + j	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$ $d\sigma(\text{lept. V decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. V decay})$ @ NNLO QCD + NLO EW	Z + j for gluon PDF W + c for strange PDF
V + jj	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$	$d\sigma(\text{lept. V decay})$ @ NNLO QCD + NLO EW	study of systematics of H + jj final state
VV'	$d\sigma(\text{V decays}) @ \text{NLO QCD}$ $d\sigma(\text{stable V}) @ \text{NLO EW}$	$d\sigma(\text{V decays})$ @ NNLO QCD + NLO EW	off-shell leptonic decays TGCs
gg → VV	$d\sigma(\text{V decays}) @ \text{LO QCD}$	$d\sigma(\text{V decays})$ @ NLO QCD	bkg. to $H \rightarrow VV$ TGCs
V γ	$d\sigma(\text{V decay}) @ \text{NLO QCD}$ $d\sigma(\text{PA, V decay}) @ \text{NLO EW}$	$d\sigma(\text{V decay})$ @ NNLO QCD + NLO EW	TGCs
Vb \bar{b}	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$ massive b	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD}$ massless b	bkg. for $VH \rightarrow b\bar{b}$
VV' γ	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays})$ @ NLO QCD + NLO EW	QGCs
VV'V''	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays})$ @ NLO QCD + NLO EW	QGCs, EWSB
VV' + j	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays})$ @ NLO QCD + NLO EW	bkg. to H, BSM searches
VV' + jj	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays})$ @ NLO QCD + NLO EW	QGCs, EWSB
$\gamma\gamma$	$d\sigma @ \text{NNLO QCD}$		bkg to $H \rightarrow \gamma\gamma$

Table 3: Wishlist part 3 – EW gauge bosons (V = W, Z)

NNLO QCD + NLO EWK wishlist

- Useful for PDF determination
 - ◆ Z+jet for gluon determination
 - ◆ W+c for strange quark determination
- Useful to study systematics of multiple jet production in a system with a large mass (->Higgs), with a wide accessible kinematic range
- Currently know V+1,2 jets to NLO QCD; NLO EW corrections known for V+1 jet, including V decays and off-shell effects
- For Z+2 jets, NLO EW corrections known for on-shell, and are in progress for off-shell
- Differential theoretical uncertainties can reach 10-20% for high jet momenta, exceeding experimental uncertainties

Process	known	desired	details
V	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD}$ $d\sigma(\text{lept. V decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$ MC@NNLO	precision EW, PDFs
V + j	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$ $d\sigma(\text{lept. V decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	Z + j for gluon PDF W + c for strange PDF
V + jj	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	study of systematics of H + jj final state
VV'	$d\sigma(\text{V decays}) @ \text{NLO QCD}$ $d\sigma(\text{stable V}) @ \text{NLO EW}$	$d\sigma(\text{V decays}) @ \text{NNLO QCD} + \text{NLO EW}$	off-shell leptonic decays TGCs
gg → VV	$d\sigma(\text{V decays}) @ \text{LO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	bkg. to $H \rightarrow VV$ TGCs
V γ	$d\sigma(\text{V decay}) @ \text{NLO QCD}$ $d\sigma(\text{PA, V decay}) @ \text{NLO EW}$	$d\sigma(\text{V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	TGCs
Vb \bar{b}	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$ massive b	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD}$ massless b	bkg. for $VH \rightarrow b\bar{b}$
VV' γ	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs
VV'V''	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs, EWSB
VV' + j	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	bkg. to H, BSM searches
VV' + jj	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs, EWSB
$\gamma\gamma$	$d\sigma @ \text{NNLO QCD}$		bkg to $H \rightarrow \gamma\gamma$

Table 3: Wishlist part 3 – EW gauge bosons (V = W, Z)

Would like to know both cross sections at NNLO QCD+NLO EW

NNLO QCD + NLO EWK wishlist

- Provides a handle on the determination of triple gauge couplings, and possible new physics
- Cross sections are known to NLO QCD (with V decays) and to NLO EW (with on-shell V's)
- WZ cross sections currently have a (non-luminosity) uncertainty of the order of 10%
- Theoretical uncertainty is 6%
- Thorough knowledge of VV cross section is needed because of triple gauge couplings and backgrounds to Higgs measurements
- Non-luminosity errors for VV are of the order of 10% or less
- Experimental uncertainties will improve, so would like cross sections to NNLO QCD+NLO EW (with V decays)

Process	known	desired	details
V	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD}$ $d\sigma(\text{lept. V decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$ MC@NNLO	precision EW, PDFs
V + j	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$ $d\sigma(\text{lept. V decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	Z + j for gluon PDF W + c for strange PDF
V + jj	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	study of systematics of H + jj final state
VV'	$d\sigma(V \text{ decays}) @ \text{NLO QCD}$ $d\sigma(\text{stable V}) @ \text{NLO EW}$	$d\sigma(V \text{ decays}) @ \text{NNLO QCD} + \text{NLO EW}$	off-shell leptonic decays TGCs
gg → VV	$d\sigma(V \text{ decays}) @ \text{LO QCD}$	$d\sigma(V \text{ decays}) @ \text{NLO QCD}$	bkg. to $H \rightarrow VV$ TGCs
Vγ	$d\sigma(V \text{ decay}) @ \text{NLO QCD}$ $d\sigma(\text{PA, V decay}) @ \text{NLO EW}$	$d\sigma(V \text{ decay}) @ \text{NNLO QCD} + \text{NLO EW}$	TGCs
Vb \bar{b}	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$ massive b	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD}$ massless b	bkg. for $VH \rightarrow b\bar{b}$
VV'γ	$d\sigma(V \text{ decays}) @ \text{NLO QCD}$	$d\sigma(V \text{ decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs
VV'V''	$d\sigma(V \text{ decays}) @ \text{NLO QCD}$	$d\sigma(V \text{ decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs, EWSB
VV' + j	$d\sigma(V \text{ decays}) @ \text{NLO QCD}$	$d\sigma(V \text{ decays}) @ \text{NLO QCD} + \text{NLO EW}$	bkg. to H, BSM searches
VV' + jj	$d\sigma(V \text{ decays}) @ \text{NLO QCD}$	$d\sigma(V \text{ decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs, EWSB
γγ	$d\sigma @ \text{NNLO QCD}$		bkg to $H \rightarrow \gamma\gamma$

Table 3: Wishlist part 3 – EW gauge bosons (V = W, Z)

NNLO QCD + NLO EWK wishlist

- Formally, this is suppressed by a factor of α_s^2 with respect to dominant q-qbar subprocess, but still contributes 5-10% to cross section due to large gluon flux
- For some Higgs background regions, it can be over 10%
- Needed for determination of off-shell Higgs boson signal strength in high-mass ZZ final state
- Currently subprocess is known (with lepton decays) at LO QCD
- Need to know to NLO QCD
 - ◆ calculation is feasible, but tensor basis somewhat messy
 - ◆ Thomas Gehrmann says 'a few months'

Process	known	desired	details
V	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD}$ $d\sigma(\text{lept. V decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$ MC@NNLO	precision EW, PDFs
V + j	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$ $d\sigma(\text{lept. V decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	Z + j for gluon PDF W + c for strange PDF
V + jj	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	study of systematics of H + jj final state
VV'	$d\sigma(\text{V decays}) @ \text{NLO QCD}$ $d\sigma(\text{stable V}) @ \text{NLO EW}$	$d\sigma(\text{V decays}) @ \text{NNLO QCD} + \text{NLO EW}$	off-shell leptonic decays TGCs
gg → VV	$d\sigma(\text{V decays}) @ \text{LO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	bkg. to $H \rightarrow VV$ TGCs
V _{PA}	$d\sigma(\text{V decay}) @ \text{NLO QCD}$ $d\sigma(\text{PA, V decay}) @ \text{NLO EW}$	$d\sigma(\text{V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	TGCs
Vb \bar{b}	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$ massive b	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD}$ massless b	bkg. for $VH \rightarrow b\bar{b}$
VV' γ	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs
VV'V''	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs, EWSB
VV' + j	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	bkg. to H, BSM searches
VV' + jj	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs, EWSB
$\gamma\gamma$	$d\sigma @ \text{NNLO QCD}$		bkg to $H \rightarrow \gamma\gamma$

Table 3: Wishlist part 3 – EW gauge bosons (V = W, Z)

NNLO QCD + NLO EWK wishlist

- Serve as precision tests for EW sector and also a probe for possible new physics in triple gauge boson couplings, or in production of new vector meson resonances in $V\gamma$
- Experimental uncertainties are on the order of 10% and theoretical errors on the order of 5-10%
- Currently, $W\gamma$ production is known (with decays) at NLO QCD, $Z\gamma$ production at NNLO QCD
- NLO corrections known in the pole approximation (resonant V bosons with decays)
- Need to know cross sections to NNLO QCD + NLO EW

Process	known	desired	details
V	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD}$ $d\sigma(\text{lept. V decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$ MC@NNLO	precision EW, PDFs
V + j	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$ $d\sigma(\text{lept. V decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	Z + j for gluon PDF W + c for strange PDF
V + jj	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	study of systematics of H + jj final state
VV'	$d\sigma(\text{V decays}) @ \text{NLO QCD}$ $d\sigma(\text{stable V}) @ \text{NLO EW}$	$d\sigma(\text{V decays}) @ \text{NNLO QCD} + \text{NLO EW}$	off-shell leptonic decays TGCs
gg → VV	$d\sigma(\text{V decays}) @ \text{LO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	bkg. to $H \rightarrow VV$ TGCs
$V\gamma$	$d\sigma(\text{V decay}) @ \text{NLO QCD}$ $d\sigma(\text{PA, V decay}) @ \text{NLO EW}$	$d\sigma(\text{V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	TGCs
$Vb\bar{b}$	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$ massive b	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD}$ massless b	bkg. for $VH \rightarrow b\bar{b}$
VV'\gamma	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs
VV'V''	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs, EWSB
VV' + j	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	bkg. to H, BSM searches
VV' + jj	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs, EWSB
$\gamma\gamma$	$d\sigma @ \text{NNLO QCD}$		bkg to $H \rightarrow \gamma\gamma$

Table 3: Wishlist part 3 – EW gauge bosons (V = W, Z)

NNLO QCD + NLO EWK wishlist

- Associated Higgs production, with Higgs decaying into $b\bar{b}$ is key to understanding Higgs couplings to b-quarks
- $Vb\bar{b}$ is significant background
- Current state of the art is NLO QCD (including b-quark mass effects)
- Experimental and theoretical uncertainties are of the order of 20%
- As experimental uncertainties will improve with more data, crucial to extend the theoretical accuracy by extending the calculation to NNLO QCD (massless b quarks)
- Includes an understanding of uncertainties in 4-flavor vs 5-flavor approaches

Process	known	desired	details
V	$d\sigma(\text{lept. } V \text{ decay}) @ \text{NNLO QCD}$ $d\sigma(\text{lept. } V \text{ decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. } V \text{ decay}) @ \text{NNLO QCD} + \text{NLO EW}$ MC@NNLO	precision EW, PDFs
V + j	$d\sigma(\text{lept. } V \text{ decay}) @ \text{NLO QCD}$ $d\sigma(\text{lept. } V \text{ decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. } V \text{ decay}) @ \text{NNLO QCD} + \text{NLO EW}$	Z + j for gluon PDF W + c for strange PDF
V + jj	$d\sigma(\text{lept. } V \text{ decay}) @ \text{NLO QCD}$	$d\sigma(\text{lept. } V \text{ decay}) @ \text{NNLO QCD} + \text{NLO EW}$	study of systematics of H + jj final state
VV'	$d\sigma(V \text{ decays}) @ \text{NLO QCD}$ $d\sigma(\text{stable } V) @ \text{NLO EW}$	$d\sigma(V \text{ decays}) @ \text{NNLO QCD} + \text{NLO EW}$	off-shell leptonic decays TGCs
gg → VV	$d\sigma(V \text{ decays}) @ \text{LO QCD}$	$d\sigma(V \text{ decays}) @ \text{NLO QCD}$	bkg. to $H \rightarrow VV$ TGCs
V γ	$d\sigma(V \text{ decay}) @ \text{NLO QCD}$ $d\sigma(\text{PA, } V \text{ decay}) @ \text{NLO EW}$	$d\sigma(V \text{ decay}) @ \text{NNLO QCD} + \text{NLO EW}$	TGCs
Vb \bar{b}	$d\sigma(\text{lept. } V \text{ decay}) @ \text{NLO QCD}$ massive b	$d\sigma(\text{lept. } V \text{ decay}) @ \text{NNLO QCD}$ massless b	bkg. for $VH \rightarrow b\bar{b}$
VV' γ	$d\sigma(V \text{ decays}) @ \text{NLO QCD}$	$d\sigma(V \text{ decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs
VV'V''	$d\sigma(V \text{ decays}) @ \text{NLO QCD}$	$d\sigma(V \text{ decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs, EWSB
VV' + j	$d\sigma(V \text{ decays}) @ \text{NLO QCD}$	$d\sigma(V \text{ decays}) @ \text{NLO QCD} + \text{NLO EW}$	bkg. to H, BSM searches
VV' + jj	$d\sigma(V \text{ decays}) @ \text{NLO QCD}$	$d\sigma(V \text{ decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs, EWSB
$\gamma\gamma$	$d\sigma @ \text{NNLO QCD}$		bkg to $H \rightarrow \gamma\gamma$

Table 3: Wishlist part 3 – EW gauge bosons (V = W, Z)

NNLO QCD + NLO EWK wishlist

- Cross sections currently known to NLO QCD, but NLO EW corrections only known for WWZ (in approximation of stable W and Z bosons)
- Triple gauge boson production processes serve as channels for determination of quartic gauge boson couplings and will allow for better understanding of EW symmetry breaking
- Analyses are currently statistically limited (no published results so far), but precision measurements will be possible in Run 2
- Desire calculation of final states to NLO QCD + NLO EW

Process	known	desired	details
V	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD}$ $d\sigma(\text{lept. V decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$ MC@NNLO	precision EW, PDFs
V + j	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$ $d\sigma(\text{lept. V decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	Z + j for gluon PDF W + c for strange PDF
V + jj	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	study of systematics of H + jj final state
VV'	$d\sigma(\text{V decays}) @ \text{NLO QCD}$ $d\sigma(\text{stable V}) @ \text{NLO EW}$	$d\sigma(\text{V decays}) @ \text{NNLO QCD} + \text{NLO EW}$	off-shell leptonic decays TGCs
gg → VV	$d\sigma(\text{V decays}) @ \text{LO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	bkg. to $H \rightarrow VV$ TGCs
V γ	$d\sigma(\text{V decay}) @ \text{NLO QCD}$ $d\sigma(\text{PA, V decay}) @ \text{NLO EW}$	$d\sigma(\text{V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	TGCs
Vb \bar{b}	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$ massive b	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD}$ massless b	bkg. for $VH \rightarrow b\bar{b}$
VV' γ	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs
VV'V''	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs, EWSB
VV' + j	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	bkg. to H, BSM searches
VV' + jj	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs, EWSB
$\gamma\gamma$	$d\sigma @ \text{NNLO QCD}$		bkg to $H \rightarrow \gamma\gamma$

Table 3: Wishlist part 3 – EW gauge bosons (V = W, Z)

NNLO QCD + NLO EWK wishlist

- $VV'+j(j)$ currently known to NLO QCD
- $VV'+j$ useful as a background to Higgs boson production and for BSM searches
- $VV'+jj$ production contains EW vector boson scattering subprocess that is particularly sensitive to EW quartic gauge couplings and to details of EW symmetry breaking
- EW corrections to these processes are unknown, although as important as QCD corrections in vector boson scattering channels

Process	known	desired	details
V	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD}$ $d\sigma(\text{lept. V decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$ MC@NNLO	precision EW, PDFs
V + j	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$ $d\sigma(\text{lept. V decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	Z + j for gluon PDF W + c for strange PDF
V + jj	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	study of systematics of H + jj final state
VV'	$d\sigma(\text{V decays}) @ \text{NLO QCD}$ $d\sigma(\text{stable V}) @ \text{NLO EW}$	$d\sigma(\text{V decays}) @ \text{NNLO QCD} + \text{NLO EW}$	off-shell leptonic decays TGCs
gg → VV	$d\sigma(\text{V decays}) @ \text{LO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	bkg. to $H \rightarrow VV$ TGCs
$V\gamma$	$d\sigma(\text{V decay}) @ \text{NLO QCD}$ $d\sigma(\text{PA, V decay}) @ \text{NLO EW}$	$d\sigma(\text{V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	TGCs
Vbb̄	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$ massive b	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD}$ massless b	bkg. for $VH \rightarrow b\bar{b}$
VV'γ	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs
VV'V''	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs, EWSB
VV' + j	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	bkg. to H, BSM searches
VV' + jj	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs, EWSB
γγ	$d\sigma @ \text{NNLO QCD}$		bkg to $H \rightarrow \gamma\gamma$

Table 3: Wishlist part 3 – EW gauge bosons (V = W, Z)

NNLO QCD + NLO EWK wishlist

- Diphoton cross section known to NNLO QCD and to NLO EW
- Need q_T resummation at NNLL matched to the NNLO calculation
- If DY and Higgs production are known in fully differential form at NNNLO, then it should be possible to extend those calculations to $\gamma\gamma$
- ...of course, the most complex calculations are being carried out by someone not present here

Process	known	desired	details
V	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD}$ $d\sigma(\text{lept. V decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. V decay}) @ \text{NNNLO QCD} + \text{NLO EW}$ MC@NNLO	precision EW, PDFs
V + j	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$ $d\sigma(\text{lept. V decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	Z + j for gluon PDF W + c for strange PDF
V + jj	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	study of systematics of H + jj final state
VV'	$d\sigma(\text{V decays}) @ \text{NLO QCD}$ $d\sigma(\text{stable V}) @ \text{NLO EW}$	$d\sigma(\text{V decays}) @ \text{NNLO QCD} + \text{NLO EW}$	off-shell leptonic decays TGCs
gg → VV	$d\sigma(\text{V decays}) @ \text{LO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	bkg. to $H \rightarrow VV$ TGCs
V γ	$d\sigma(\text{V decay}) @ \text{NLO QCD}$ $d\sigma(\text{PA, V decay}) @ \text{NLO EW}$	$d\sigma(\text{V decay}) @ \text{NNLO QCD} + \text{NLO EW}$	TGCs
Vb \bar{b}	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$ massive b	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD}$ massless b	bkg. for $VH \rightarrow b\bar{b}$
VV' γ	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs
VV'V''	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs, EWSB
VV' + j	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	bkg. to H, BSM searches
VV' + jj	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD} + \text{NLO EW}$	QGCs, EWSB
$\gamma\gamma$	$d\sigma @ \text{NNLO QCD}$		bkg to $H \rightarrow \gamma\gamma$

Table 3: Wishlist part 3 – EW gauge bosons (V = W, Z)

The frontier

$\lambda_{k_1} \tilde{\lambda}_{k_1} + \lambda_{k_2} \tilde{\lambda}_{k_2} - \lambda_{k_1} \tilde{\lambda}_{k_2} - \lambda_{k_2} \tilde{\lambda}_{k_1}$

$\lambda_{k_2} = \frac{1}{2} \lambda_k - \lambda_{k_2}$

$\lambda_{k_6} = \lambda_{k_1} + \lambda_{k_2} \frac{\begin{bmatrix} 2 & 3 \\ 3 & 3 \end{bmatrix}}{\begin{bmatrix} 3 & 3 \end{bmatrix}}$

$|\langle m \rangle|^2 = \left| \text{Diagram 1} - \text{Diagram 2} - \text{Diagram 3} \right|^2$

$\lambda_{k_1} \tilde{\lambda}_{k_1} = \lambda_{k_1} \tilde{\lambda}_{k_1} - \lambda_{k_1} \tilde{\lambda}_{k_1}$

$\lambda_{k_2} \tilde{\lambda}_{k_2} = \lambda_{k_1} \tilde{\lambda}_{k_1} - \lambda_{k_2} \tilde{\lambda}_{k_2}$

$\lambda \propto \lambda_{k_1} \propto \lambda_{k_2}$

$\tilde{\lambda}_{k_1} \propto \tilde{\lambda}_{k_2} \propto \tilde{\lambda}_{k_1}$

$\tilde{\lambda}_{k_2} \propto \tilde{\lambda}_{k_1} \propto \tilde{\lambda}_{k_2}$

what we left at Les Houches for the BSM session



If a tree falls...

- Once we have the calculations, how do we (experimentalists) use them?
- If a theoretical calculation is done, but it can not be used by any experimentalists, does it make a sound?
 - ◆ or create a citation?
- We need public programs and/or public ntuples
- Oftentimes, the program is too complex to be run by non-authors
- In that case, ROOT ntuples may be the best solution
- May be too disk-intensive, though, for most NNLO calculations



Summary

- (Relatively) new NLO (and NNLO) PDFs are available: CT10, NNPDF2.3, HERAPDF1.5, ABM11, in addition to MSTW2008
 - ◆ expect new updates for all in the near future
 - ◆ HERA2.0 data set should have an impact
- Higgs cross section predictions have been updated using the new NLO and NNLO PDFs
- A new prescription based on the same families of PDFs would lead to a central prediction (and uncertainties) similar to what was used in 2010
 - ◆ note that quark-quark luminosity uncertainties have been reduced; gluon-gluon luminosity uncertainties (at least in the 125 GeV range) have not
- Ongoing work on trying to understand the differences among CT10, NNPDF2.3, MSTW08 and HERAPDF1.5 for gg PDF luminosities
- A new prescription (somewhat more sophisticated) is being developed; more powerful tools (such as meta-PDFs) will also be used in the near future
- The new high precision Les Houches wishlist presents some real (and important) challenges for QCD and EW calculators

Wu Ki Tung Award for Early Career Research on QCD

- See information at http://tigger.uic.edu/~varelas/tung_award/
- Contribute at <https://www.givingto.msu.edu/gift/?sid=1480>
- **MSU will match any donations**

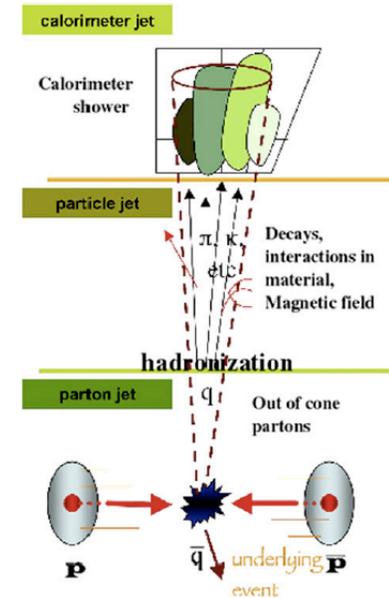




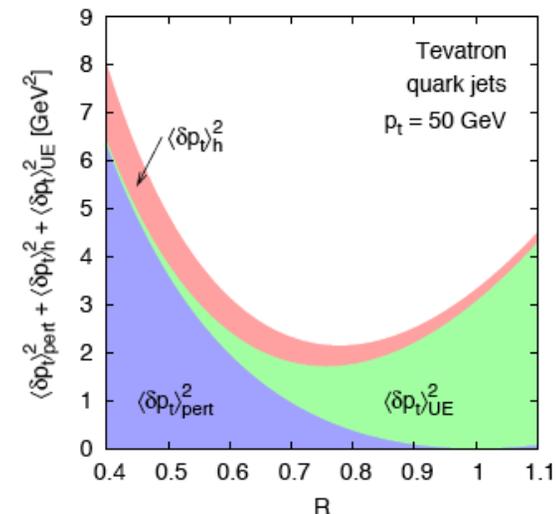
Varying the jet size

Choosing jet size

- Experimentally
 - ◆ in complex final states, such as $W + n$ jets, it is useful to have jet sizes smaller so as to be able to resolve the n jet structure
 - ◆ this can also reduce the impact of pileup/underlying event
- Theoretically
 - ◆ hadronization effects become larger as R decreases
 - ◆ for small R , the $\ln R$ perturbative terms can become noticeable
 - ◆ this restriction in the gluon phase space can affect the scale dependence, i.e. the scale uncertainty for an n -jet final state can depend on the jet size,



Dasgupta, Magnea, Salam arXiv0712.3014

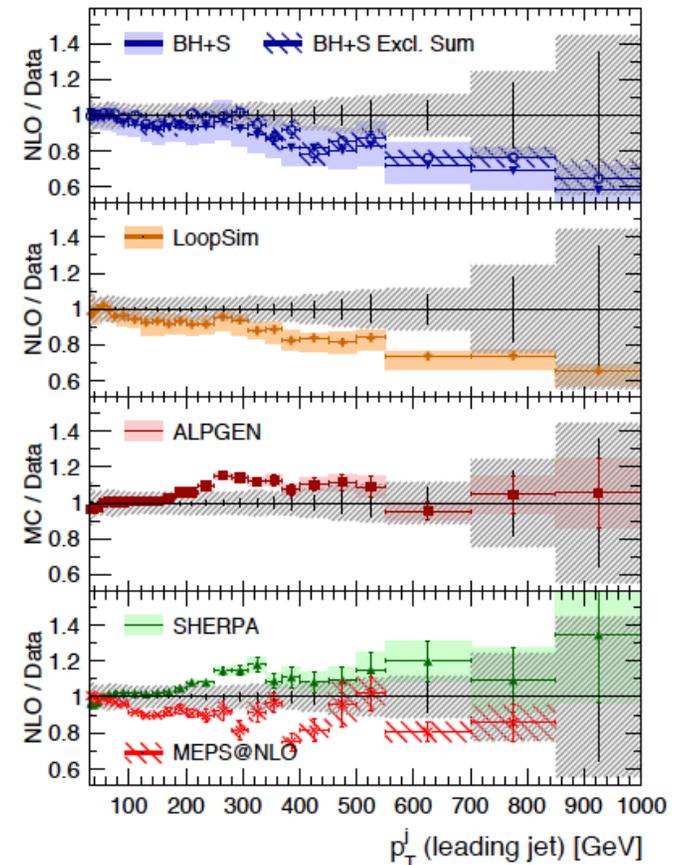
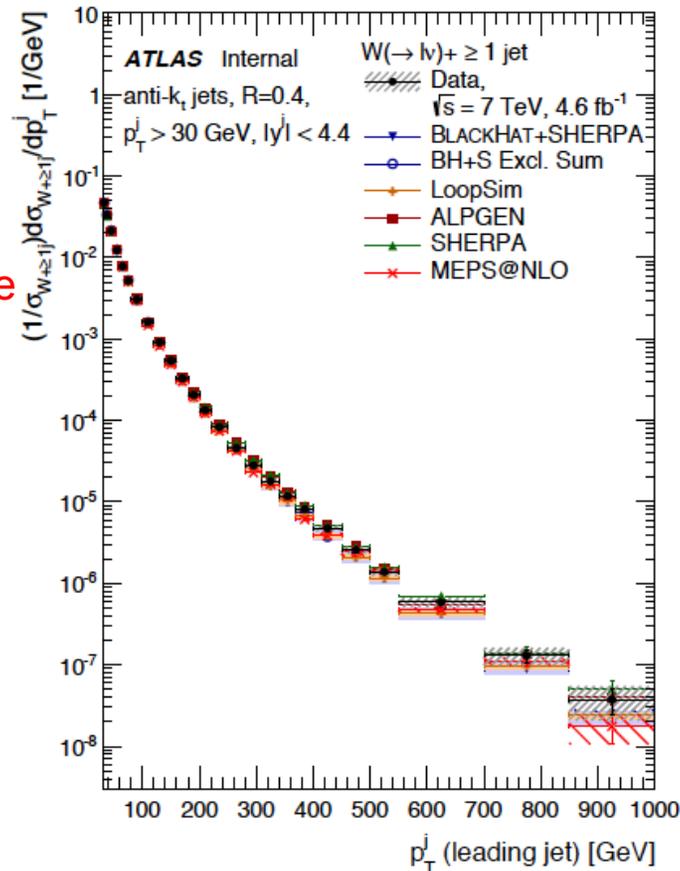


Another motivation for the use of multiple jet algorithms/parameters in LHC analyses.

2011 W+jets

- For the 2011 7 TeV data (just as for the 2010 data), we used (only) antikt4 for jet clustering
- It would have been nice to try out other jet sizes or even algorithms, but there was a need to keep the task to something manageable

This particular distribution does not agree well with the theoretical predictions, at least partially because of higher order QCD corrections, but it would have been useful to look at the jet size dependence.



Aside: scale dependence

- Write cross section indicating explicit scale-dependent terms
- First term (lowest order) in (3) leads to monotonically decreasing behavior as scale increases (the LO piece)
- Second term is negative for $\mu < p_T$, positive for $\mu > p_T$
- Third term is negative for factorization scale $M < p_T$
- Fourth term has same dependence as lowest order term
- Thus, lines one and four give contributions which decrease monotonically with increasing scale while lines two and three start out negative, reach zero when the scales are equal to p_T , and are positive for larger scales
- At NLO, result is a roughly parabolic behavior (if you're lucky)
- Note that each of these terms depends on the kinematics (jet size) of the cross section under investigation, i.e. the parabola can/will change

Consider a large transverse momentum process such as the single jet inclusive cross section involving only massless partons. Furthermore, in order to simplify the notation, suppose that the transverse momentum is sufficiently large that only the quark distributions need be considered. In the following, a sum over quark flavors is implied. Schematically, one can write the lowest order cross section as

$$E \frac{d^3\sigma}{dp^3} \equiv \sigma = a^2(\mu) \hat{\sigma}_B \otimes q(M) \otimes q(M) \quad (1)$$

where $a(\mu) = \alpha_s(\mu)/2\pi$ and the lowest order parton-parton scattering cross section is denoted by $\hat{\sigma}_B$. The renormalization and factorization scales are denoted by μ and M , respectively. In addition, various overall factors have been absorbed into the definition of $\hat{\sigma}_B$. The symbol \otimes denotes a convolution defined as

$$f \otimes g = \int_x^1 \frac{dy}{y} f\left(\frac{x}{y}\right) g(y). \quad (2)$$

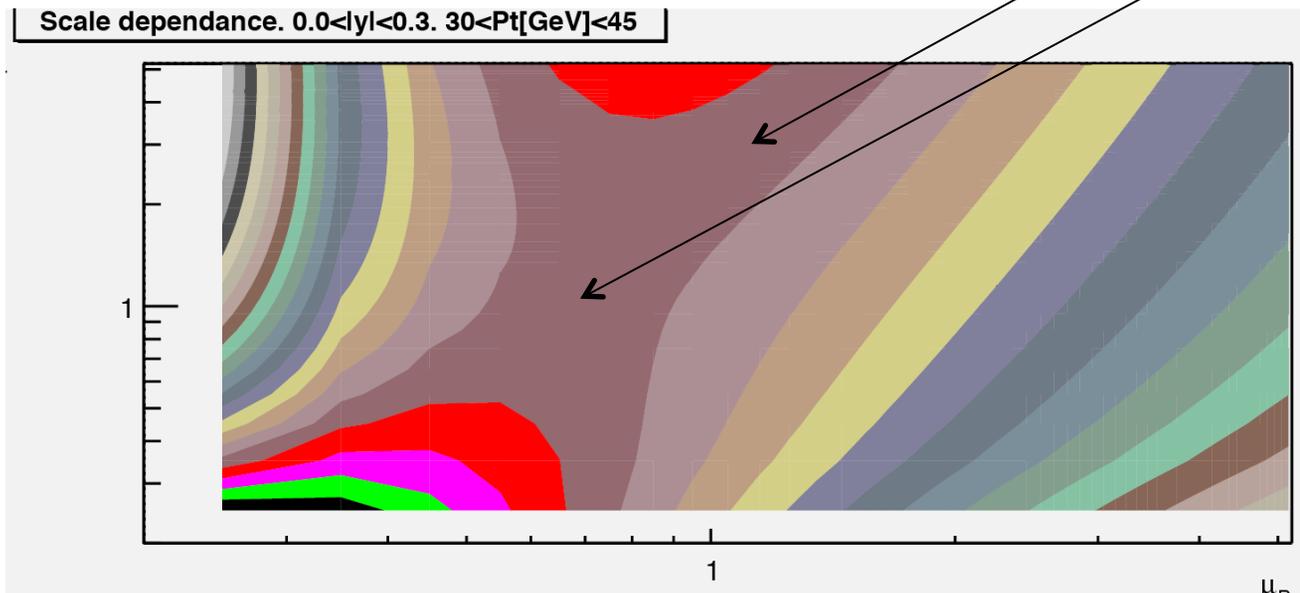
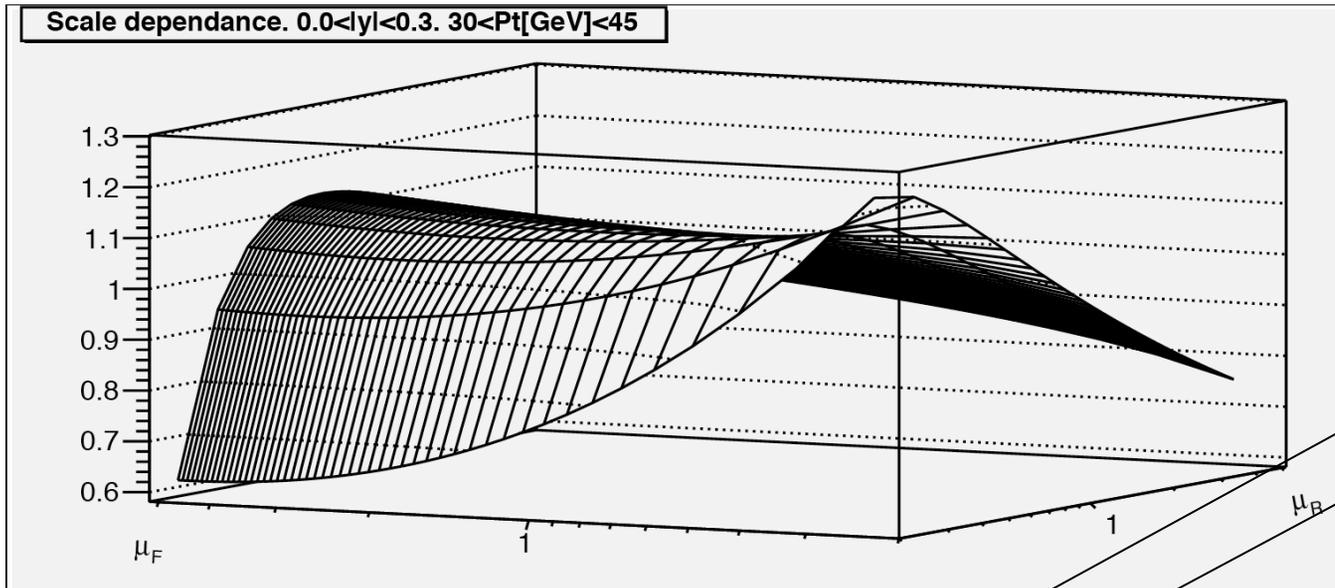
When one calculates the $\mathcal{O}(\alpha_s^3)$ contributions to the inclusive cross section, the result can be written as

$$\begin{aligned} (1) \quad \sigma &= a^2(\mu) \hat{\sigma}_B \otimes q(M) \otimes q(M) \\ (2) \quad &+ 2a^3(\mu) b \ln(\mu/p_T) \hat{\sigma}_B \otimes q(M) \otimes q(M) \\ (3) \quad &+ 2a^3(\mu) \ln(p_T/M) P_{qq} \otimes \hat{\sigma}_B \otimes q(M) \otimes q(M) \\ (4) \quad &+ a^3(\mu) K \otimes q(M) \otimes q(M). \end{aligned} \quad (3)$$

In writing Eq. (3), specific logarithms associated with the running coupling and the scale dependence of the parton distributions have been explicitly displayed; the remaining higher order corrections have been collected in the function K in the last line of Eq. (3). The μ

This is true for all perturbative processes.

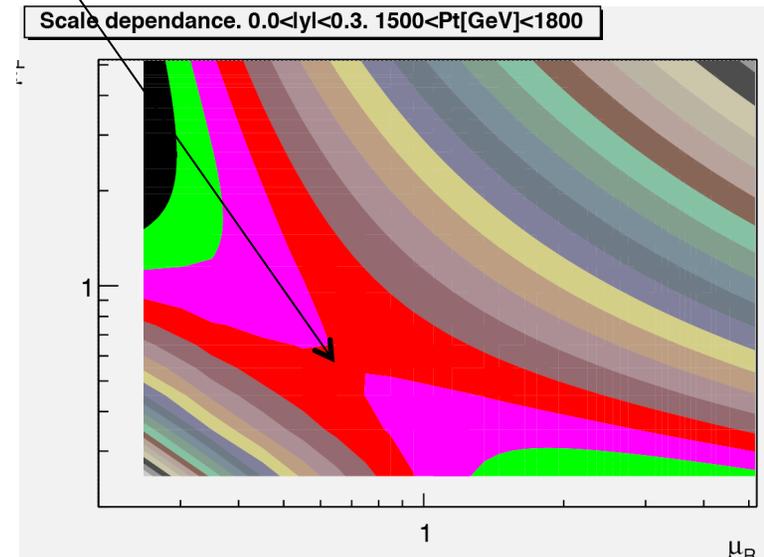
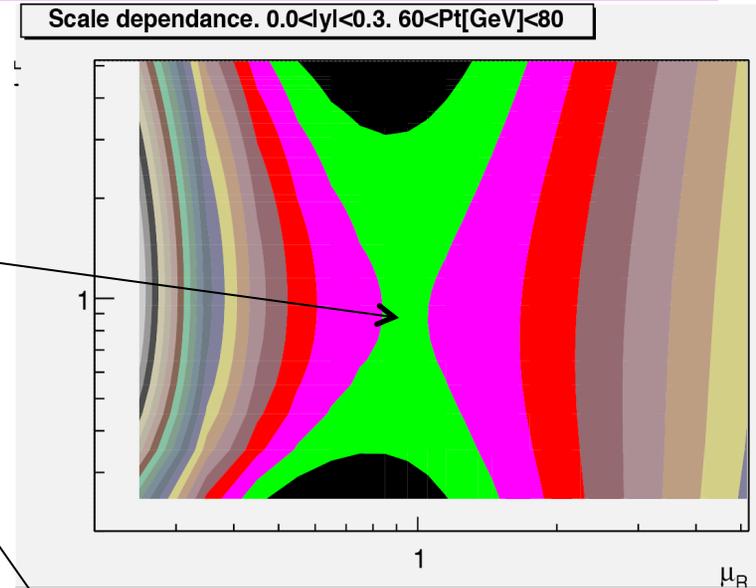
It's useful to use a log-log scale (μ_R vs μ_F) in 2-D



- ...since perturbative QCD is logarithmic
- Note that there's a saddle region, and a saddle point, where locally there is no slope for the cross section with respect to the two scales
- This is kind of the 'golden point' and typically around the expected scale (p_T^{jet} in this case)

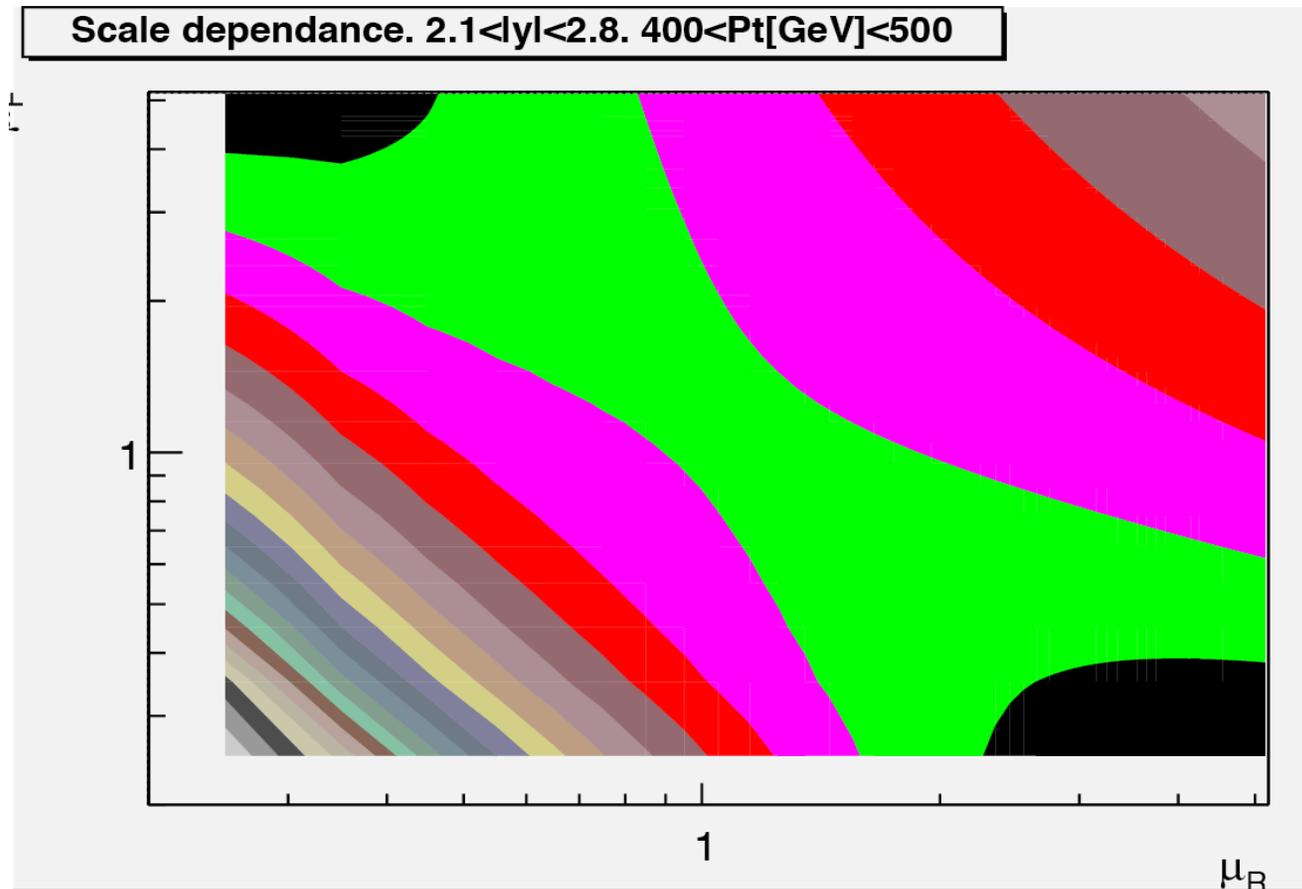
Scale choices

- Take inclusive jet production at the LHC
- Canonical scale choice at the LHC is $\mu_r = \mu_f = 1.0 * p_T$
 - ◆ CDF used $0.5p_T$
 - ◆ CTEQ6.6 used this scale for determination of PDFs
 - ◆ new CT PDFs use p_T
- Close to saddle point for low p_T
- But saddle point moves down for higher p_T (and the saddle region rotates)
- Our typical scale choices don't work for all LHC kinematics; more extreme movements for some of measured cross sections
- Rather than look for some magic formula, we should try to understand what is going on the kinematic/scale point-of-view



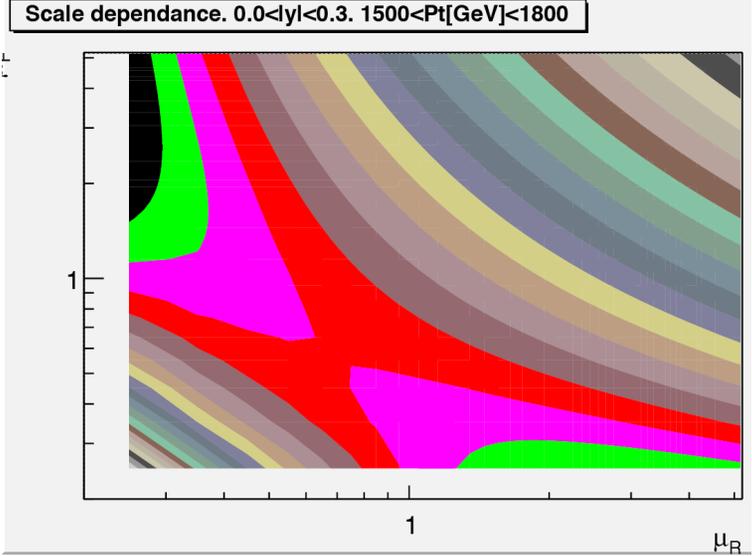
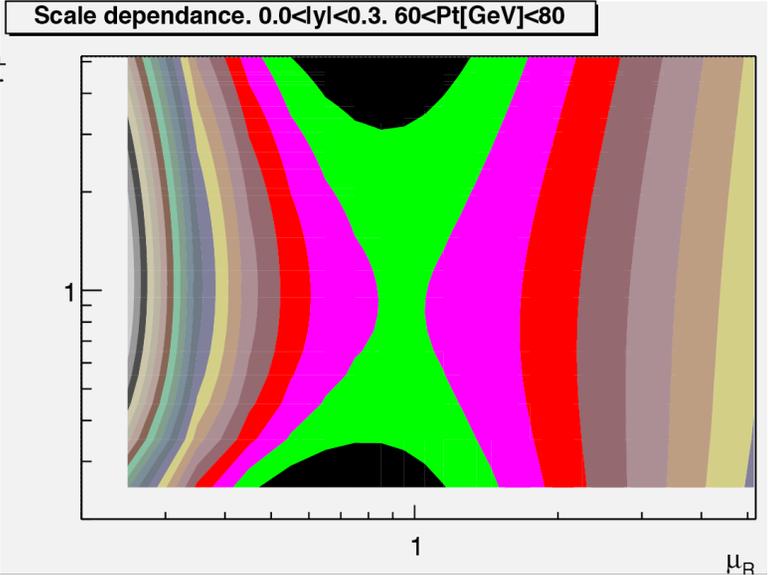
Scale dependence depends on rapidity

- The saddle point tends to move upwards in scale as the rapidity increases
- Is the physics changing; no, just the kinematics

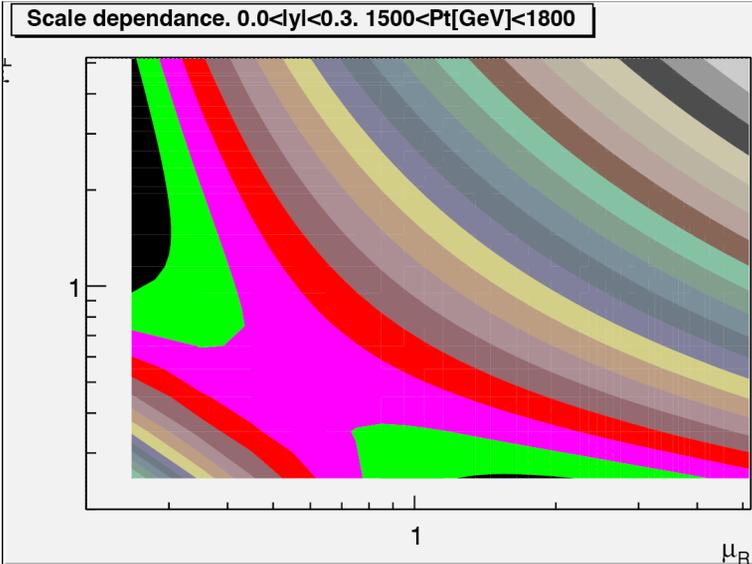
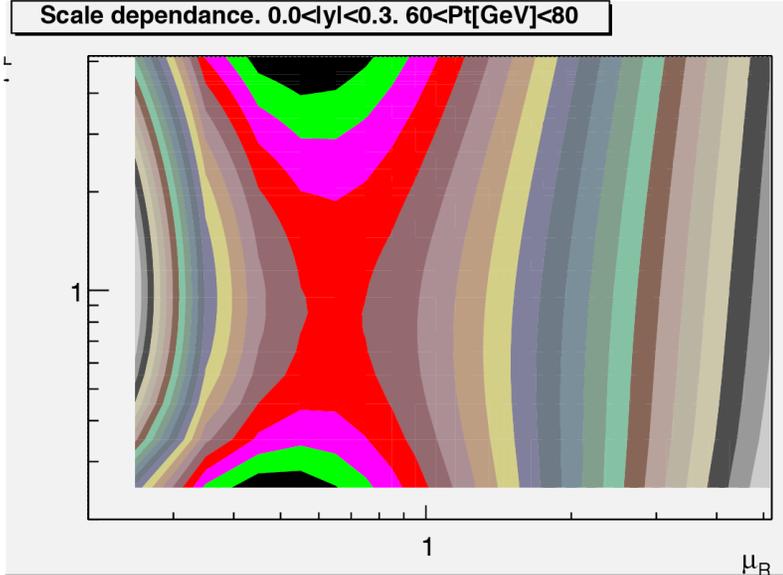


Scale dependence also depends on jet size; again see equation on previous slide

R=0.4
antikT



R=0.6
antikT



Aside: W+jets with B+S

NLO with BlackHat+Sherpa

NLO cross section

$$\sigma_n^{NLO} = \int_n \overset{\text{Born}}{\sigma_n^{tree}} + \int_n \left(\overset{\text{loop: lc and fmlc}}{\sigma_n^{virt}} + \underset{\text{vsub}}{\sum_n^{sub}} \right) + \int_{n+1} \overset{\text{real}}{(\sigma_{n+1}^{real} - \sigma_{n+1}^{sub})}$$



BlackHat

so this is not Sherpa the parton shower, but Sherpa used as a (very efficient) fixed order matrix element generator



Sherpa

How it's put together

NLO with BlackHat+Sherpa

NLO cross section

$$\sigma_n^{NLO} = \int_n \overset{\text{Born}}{\sigma_n^{tree}} + \int_n \overset{\text{loop: lc and fmlc}}{(\sigma_n^{virt} + \underbrace{\sum_n^{sub}}_{\text{vsub}})} + \int_{n+1} \overset{\text{real}}{(\sigma_{n+1}^{real} - \sigma_{n+1}^{sub})}$$

for W+3 jets,
W+3 parton tree-level
matrix elements

the dipole subtraction terms
evaluated in n-body phase space;
to make matters more complex,
vsub can be either + or -,
compensated by other
terms in the total cross
section; note the sum
over all quarks and
antiquarks; makes matters
more complex when coming to scale uncertainties

all of the real emission terms,
(W+4 partons for W + 3 jets),
modified by the dipole
subtraction terms; divergences
are gone

all of the virtual terms, both leading color and full-minus-
leading color; the latter is typically a few % effect, but much
of the complexity of the calculation

How it's put together

NLO with BlackHat+Sherpa

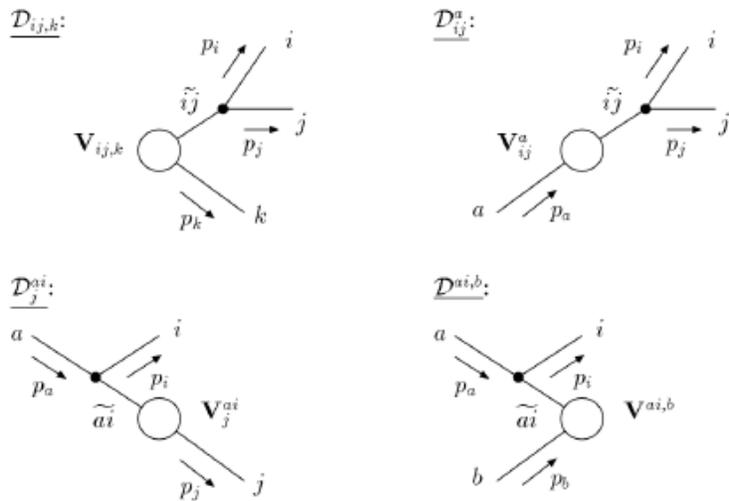
NLO cross section

$$\sigma_n^{NLO} = \int_n \sigma_n^{tree} + \int_n (\sigma_n^{virt} + \sum_n^{sub}) + \int_{n+1} (\sigma_{n+1}^{real} - \sigma_{n+1}^{sub})$$

Born loop: lc and fmlc real

vsub

possible Catani-Seymour dipoles, for FF, FI, IF and II situations



the dipole subtraction terms evaluated in n-body phase space; to make matters more complex, vsub can be either + or -, compensated by other terms in the total cross section; note the sum over all quarks and antiquarks

all of the real emission terms, (W+4 partons for W + 3 jets), modified by the dipole subtraction terms; divergences are gone

many counterevents due to C-S dipoles that are correlated; have to use special weights/procedures to get correct statistical error

note the need for a 3rd parton, the 'spectator'; in the soft limit, it's the color partner

Branches in B+S ntuples

branch name	type	Notes
id	I	id of the event. Real events and their associated counterterms share the same id. This allows for the correct treatment of statistical errors.
nparticle	I	number of particles in the final state
px	F[nparticle]	array of the x components of the final state particles
py	F[nparticle]	array of the y components of the final state particles
pz	F[nparticle]	array of the z components of the final state particles
E	F[nparticle]	array of the energy components of the final state particles
alphas	D	α_s value used for this event
kf	I	PDG codes of the final state particles
weight	D	weight of the event
weight2	D	weight of the event to be used to treat the statistical errors correctly in the real part
me_wgt	D	matrix element weight, the same as weight but without pdf factors
me_wgt2	D	matrix element weight, the same as weight2 but without pdf factors
x1	D	fraction of the hadron momentum carried by the first incoming parton
x2	D	fraction of the hadron momentum carried by the second incoming parton
x1p	D	second momentum fraction used in the integrated real part
x2p	D	second momentum fraction used in the integrated real part
id1	I	PDG code of the first incoming parton
id2	I	PDG code of the second incoming parton
fac_scale	D	factorization scale used
ren_scale	D	renormalization scale used
nuwgt	I	number of additional weights
usr_wgts	D[nuwgt]	additional weights needed to change the scale

Reweighting

can reweight each event to new

- PDF
- factorization scale
- renormalization scale
- $-\alpha_s$ (tied to the relevant PDFs)

based on weights stored in ntuple (and linking with LHAPDF)

so, for example, the events were generated with CTEQ6, and were re-weighted to CTEQ6.6

2.1 Born and real contributions

The new weight is given by

$$w = \text{me_wgt2} \cdot f(\text{id1}, \mathbf{x1}, \mu_F) F(\text{id2}, \mathbf{x2}, \mu_F) \frac{\alpha_s(\mu_R)^n}{(\text{alphas})^n} \quad (1)$$

with μ_F the new factorization scale, μ_R the new factorization scale, f the new PDF, α_s the corresponding running coupling and n the number of strong coupling (the number of jets n_j for the born contribution and $n_j + 1$ for the real contribution). If the factorization scale is not changed, one can simplify the computation (and save the pdf function call):

$$w = \text{weight2} \frac{\alpha_s(\mu_R)^n}{(\text{alphas})^n} \quad (2)$$

2.2 Virtual contribution

The virtual contribution is treated like the real and born contribution, but the matrix element has a dependence on the renormalization scale parametrized using the additional weights `usr_wgts`.

$$w = m \cdot f(\text{id1}, \mathbf{x1}, \mu_F) F(\text{id2}, \mathbf{x2}, \mu_F) \frac{\alpha_s(\mu_R)^n}{(\text{alphas})^n} \quad (3)$$

$$m = \text{me_wgt2} + l \text{usr_wgts}[0] + \frac{l^2}{2} \text{usr_wgts}[1] \quad (4)$$

$$l = \log\left(\frac{\mu_R^2}{\text{ren_scale}^2}\right) \quad (5)$$

Reweighting, cont.

2.3 Integrated subtraction

The computation of the new weight for the integrated subtraction is the most complicated. The ROOT file has 16 additional weights to make this possible.

$$w = m \frac{\alpha_s(\mu_R)^n}{(\text{alphas})^n} \quad (6)$$

$$m = \text{me_wgt2} \cdot f(\text{id1}, \mathbf{x1}, \mu_F) f(\text{id2}, \mathbf{x2}, \mu_F) \quad (7)$$

$$+ (f_a^1 \omega_1 + f_a^2 \omega_2 + f_a^3 \omega_3 + f_a^4 \omega_4) F_b(x_b) \quad (8)$$

$$+ (F_b^1 \omega_5 + F_b^2 \omega_6 + F_b^3 \omega_7 + F_b^4 \omega_8) f_a(x_a) \quad (9)$$

$$\omega_i = \text{usr_wgts}[i - 1] + \text{usr_wgts}[i + 7] \log \left(\frac{\mu_R^2}{\text{ren_scale}^2} \right) \quad (10)$$

complex:
carry both
single and double
logs

where

$$f_a^1 = \begin{cases} a = \text{quark} & : f_a(x_a, \mu_F) \\ a = \text{gluon} & : \sum_{\text{quarks}} f_q(x_a, \mu_F) \end{cases} \quad (11)$$

$$f_a^2 = \begin{cases} a = \text{quark} & : \frac{f_a(x_a/x'_a, \mu_F)}{x'_a} \\ a = \text{gluon} & : \sum_{\text{quarks}} \frac{f_q(x_a/x'_a, \mu_F)}{x'_a} \end{cases} \quad (12)$$

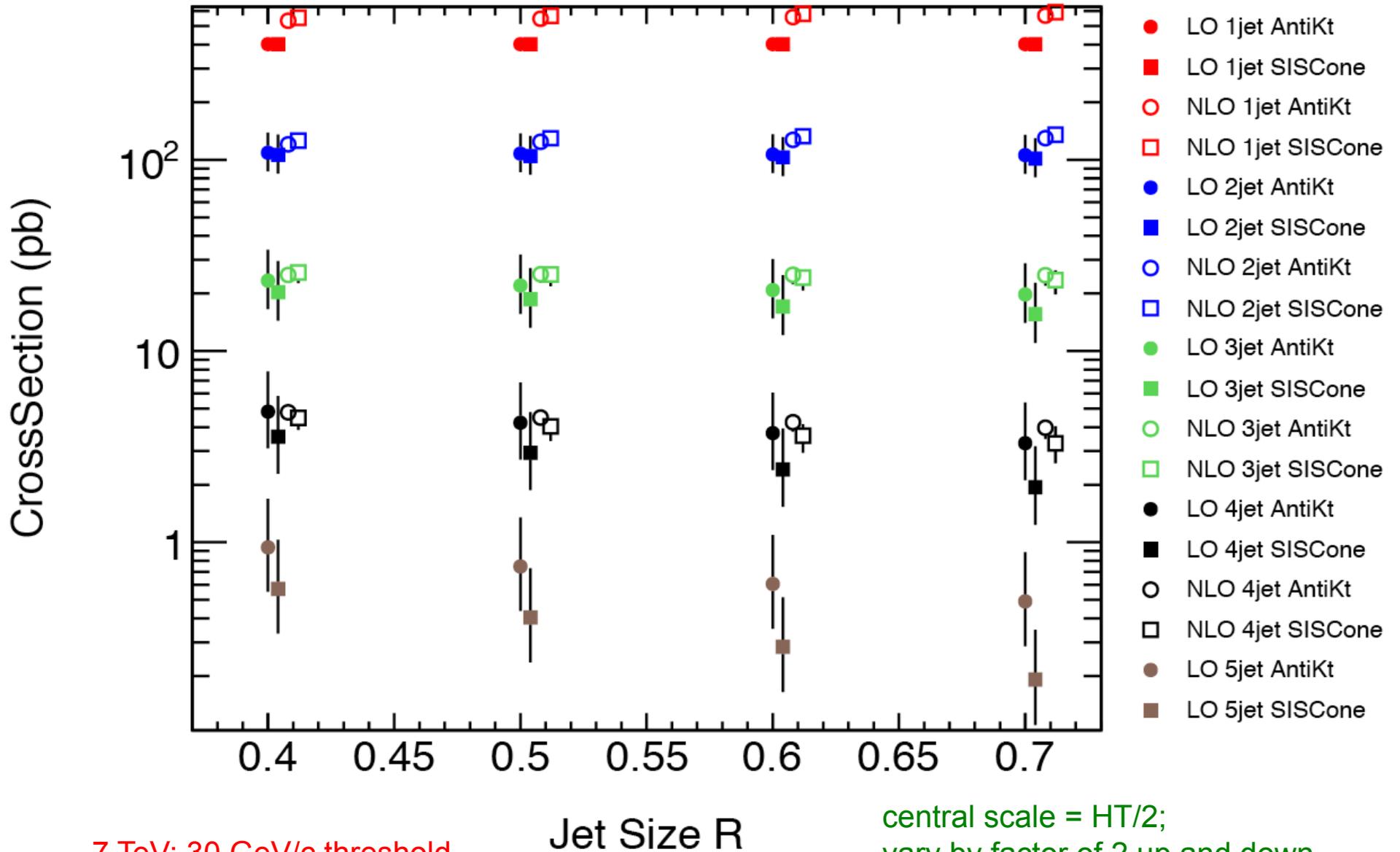
$$f_a^3 = f_g(x_a, \mu_F) \quad (13)$$

$$f_a^4 = \frac{f_g(x_a/x'_a, \mu_F)}{x'_a} \quad (14)$$

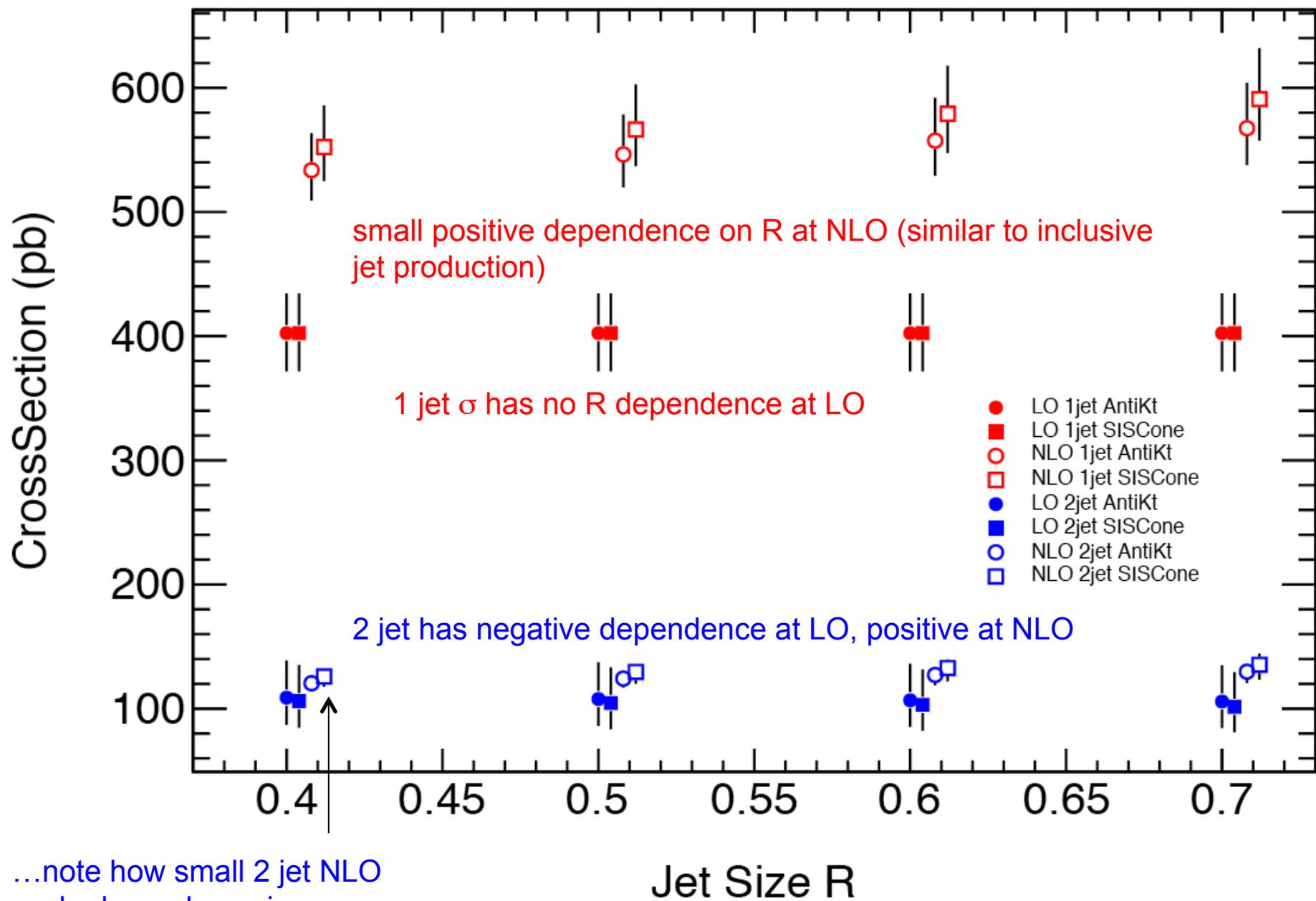
we run into the
sum over quarks
and antiquarks
again

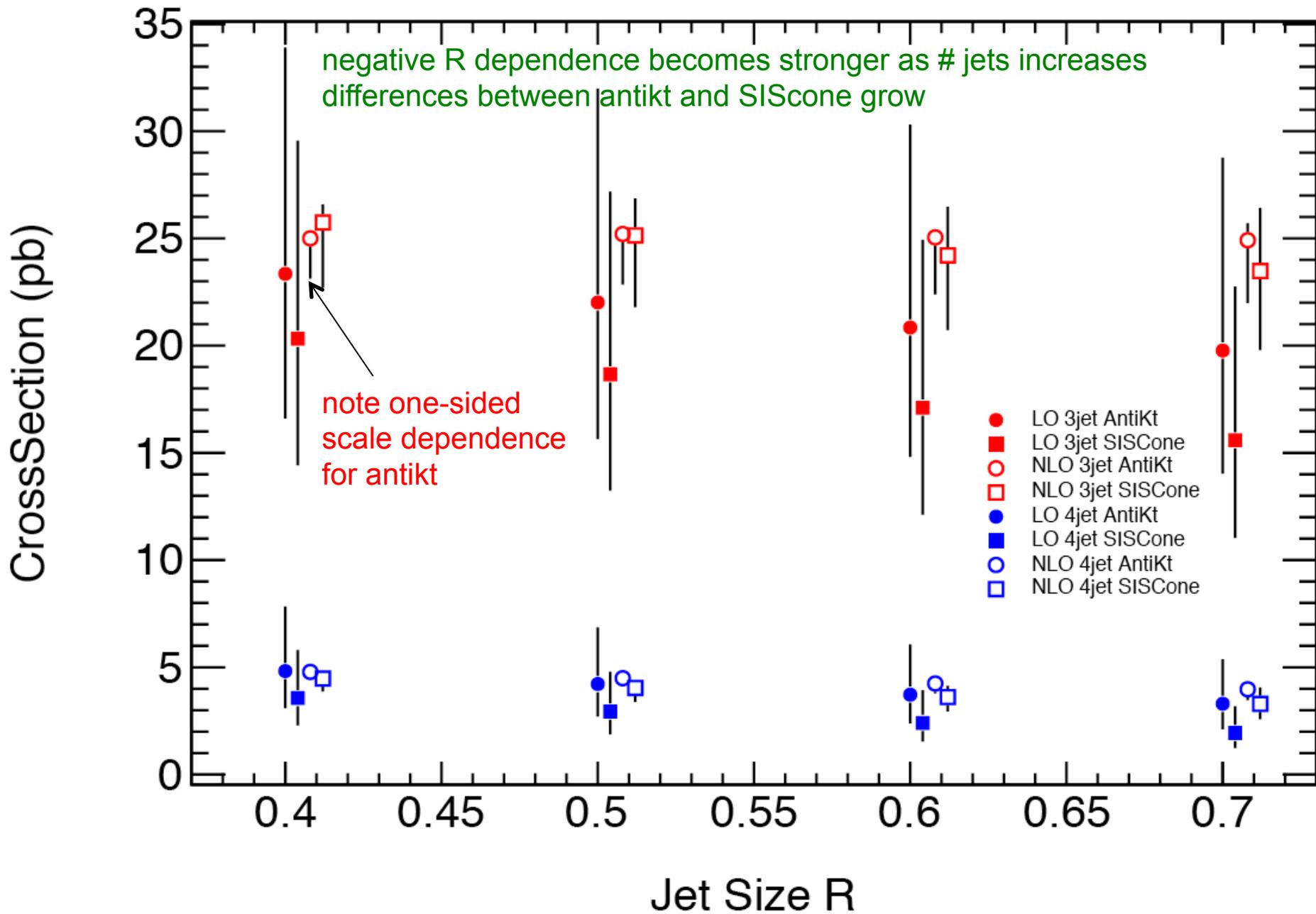
and $n = n_j + 1$.

Look at jet size, algorithm dependences; scale uncertainty



7 TeV; 30 GeV/c threshold



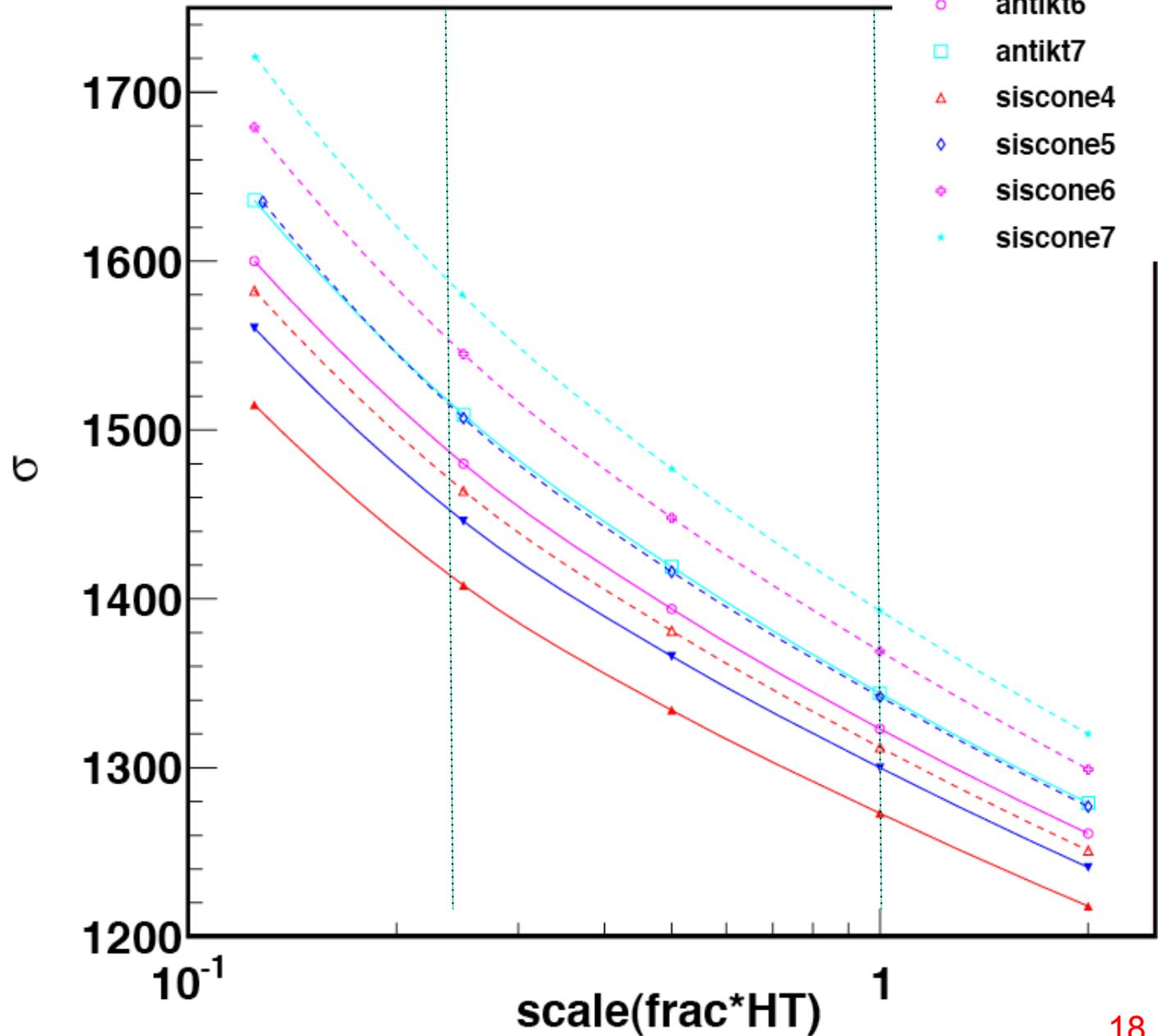


W+1 jets scale dependence

note monotonic scale dependence at NLO, similar to what is seen in a typical LO calculation

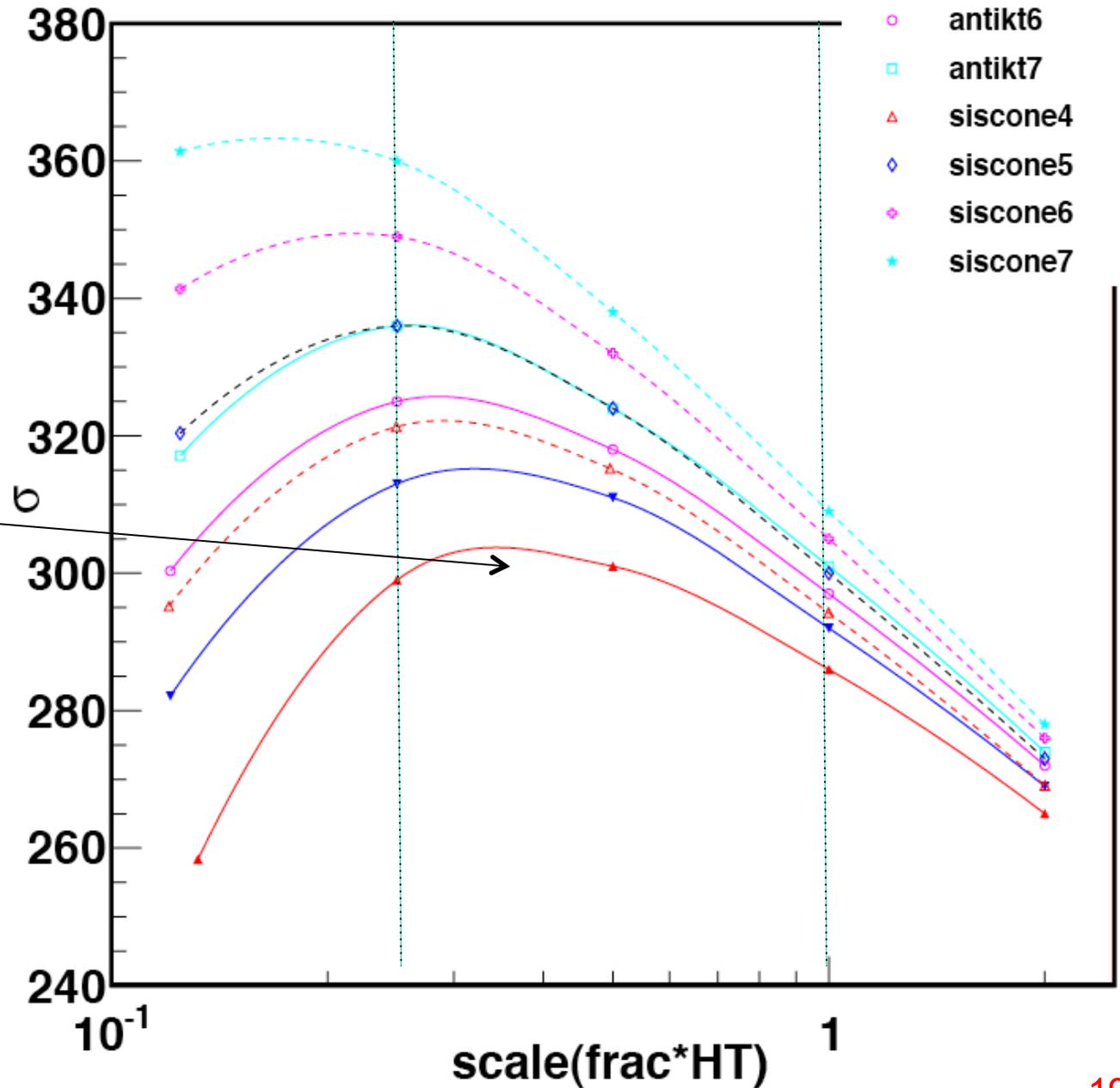
...indicates the need for higher order corrections

solid=antikt
dashed=siscone



W+2 jets scale dependence

- ▲ antikt4
- ▼ antikt5
- antikt6
- antikt7
- △ siscone4
- ◇ siscone5
- ◇ siscone6
- ★ siscone7



See parabolic shape for W+2 jets

Note that for antikt4, the scale $H_T/2$ is at the same point as $H_T/4$; scale dependence will appear smaller

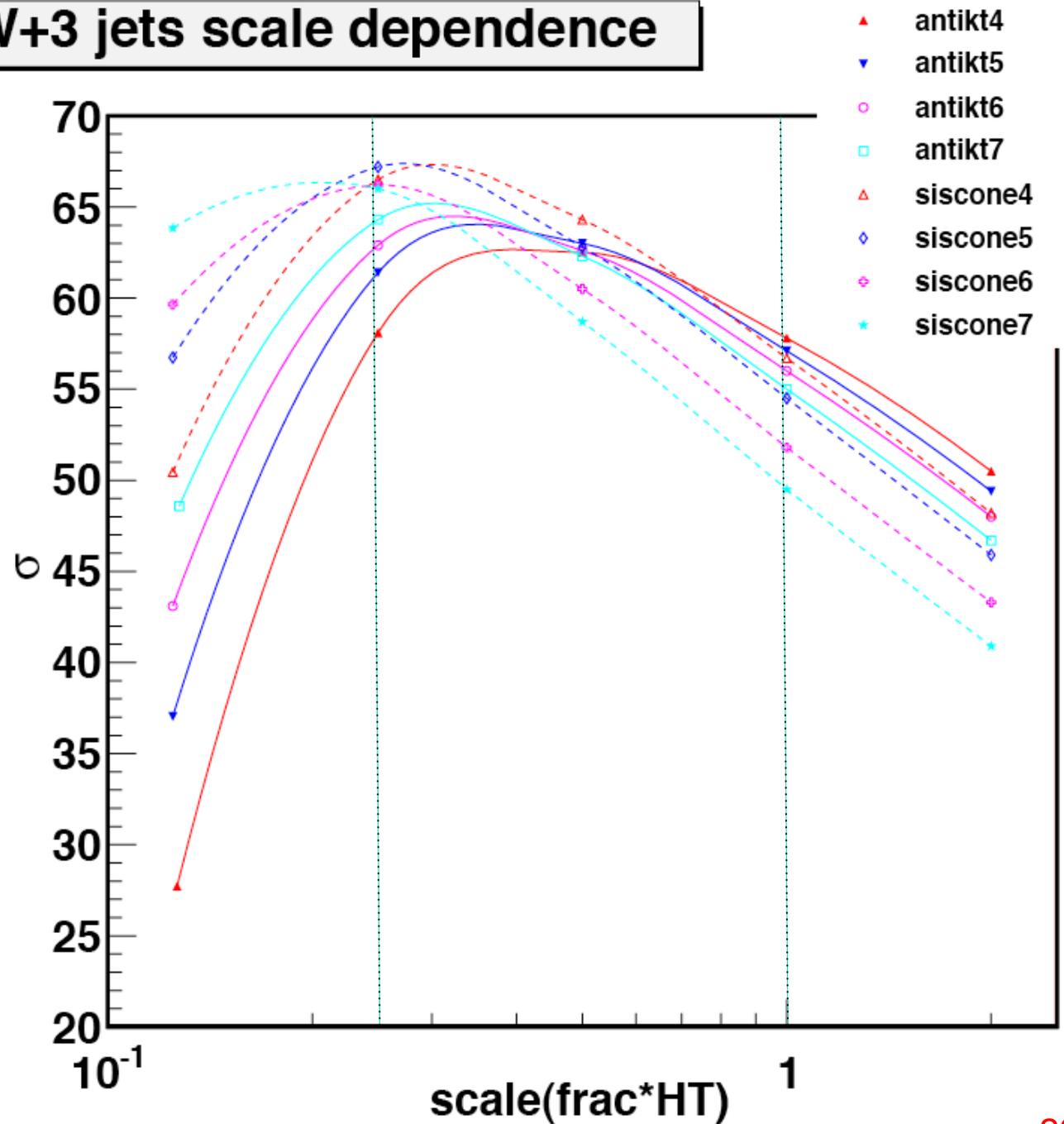
may be better to look for max/min over scale range (in 2D)

solid=antikt
dashed=siscone

W+3 jets scale dependence

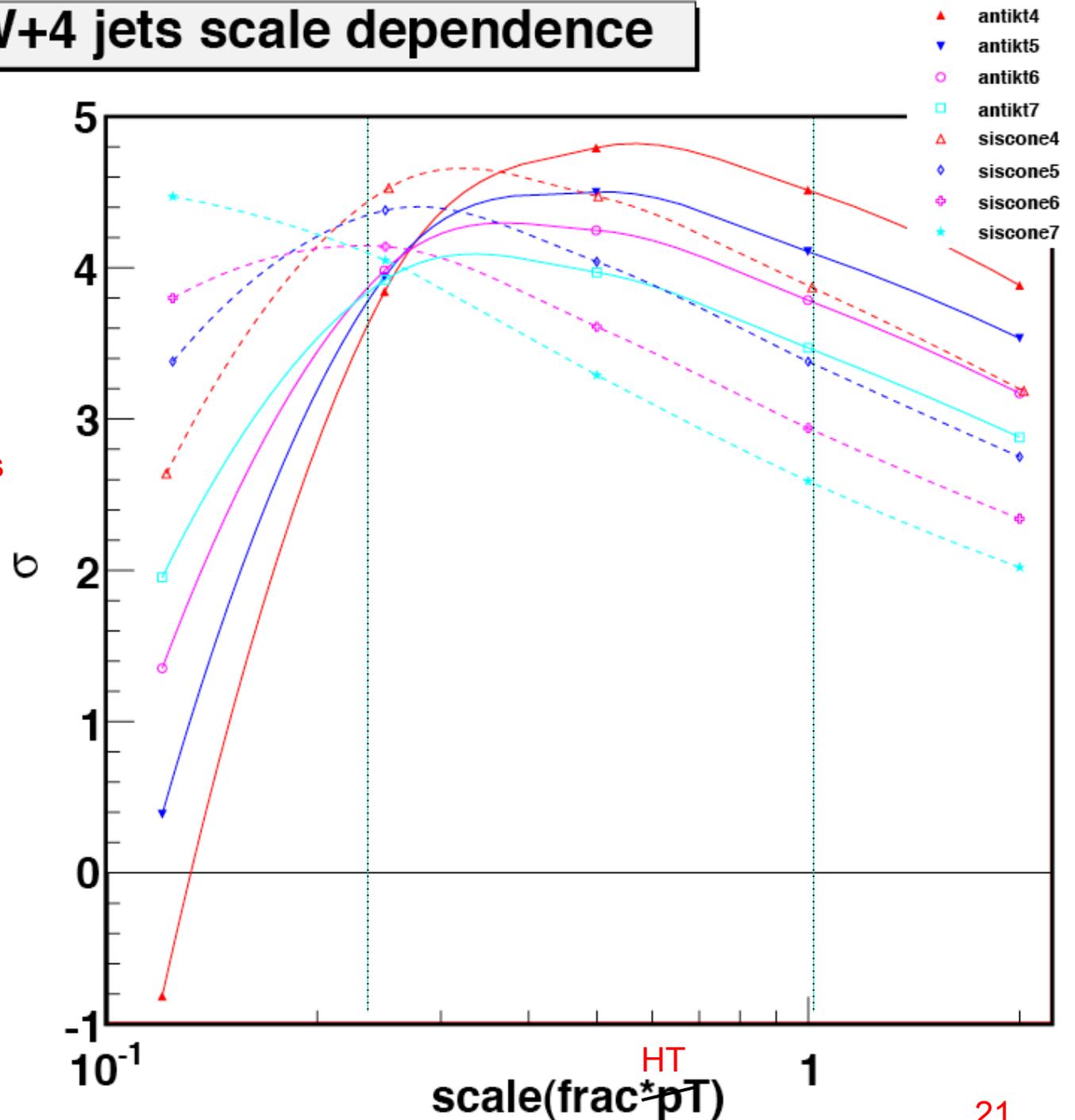
Note that at scale of HT/2, all antiK_T cross sections are equal

solid=antiK_T
dashed=siscone



W+4 jets scale dependence

- A scale of HT/2 is ~ the peak for antikt4; so all deviations are negative
- Siscone peaks around HT/3
- Moves to smaller scales for larger R
- @HT/4, all antikt R give same result; that scale seems to be around HT/5 for siscone
- it is difficult to make conclusions about the uncertainty of any particular W + n jet cross section without understanding the scale dependence as the jet size/algorithm is varied



Summary

- We have the tools in ATLAS to vary the jet size/algorithm, but rarely use them (one exception is the inclusive jet cross section where we have used both antikt4 and antikt6, which interestingly enough have pointed to the need for a NNLO inclusive jet cross section calculation)
- It would be interesting and useful to extend this to other analyses, which will help us to learn more about the perturbative and non-perturbative structures of the physics processes we are studying
-especially as Higgs+1 jet is now done at NNLO; W/Z +jet will follow soon, maybe more processes

Look at 2D scale dependence

