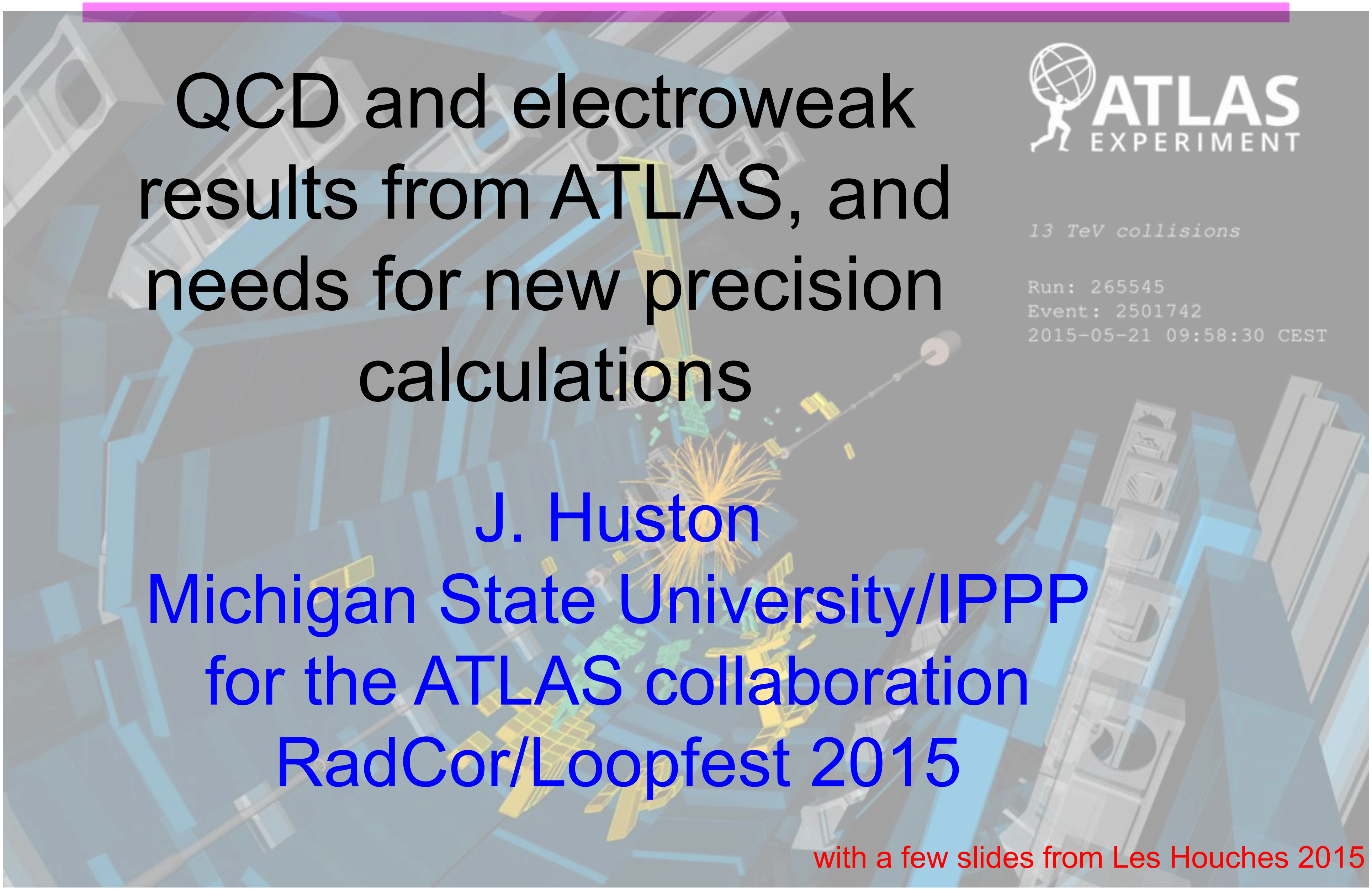
QCD and electroweak results from ATLAS, and needs for new precision calculations

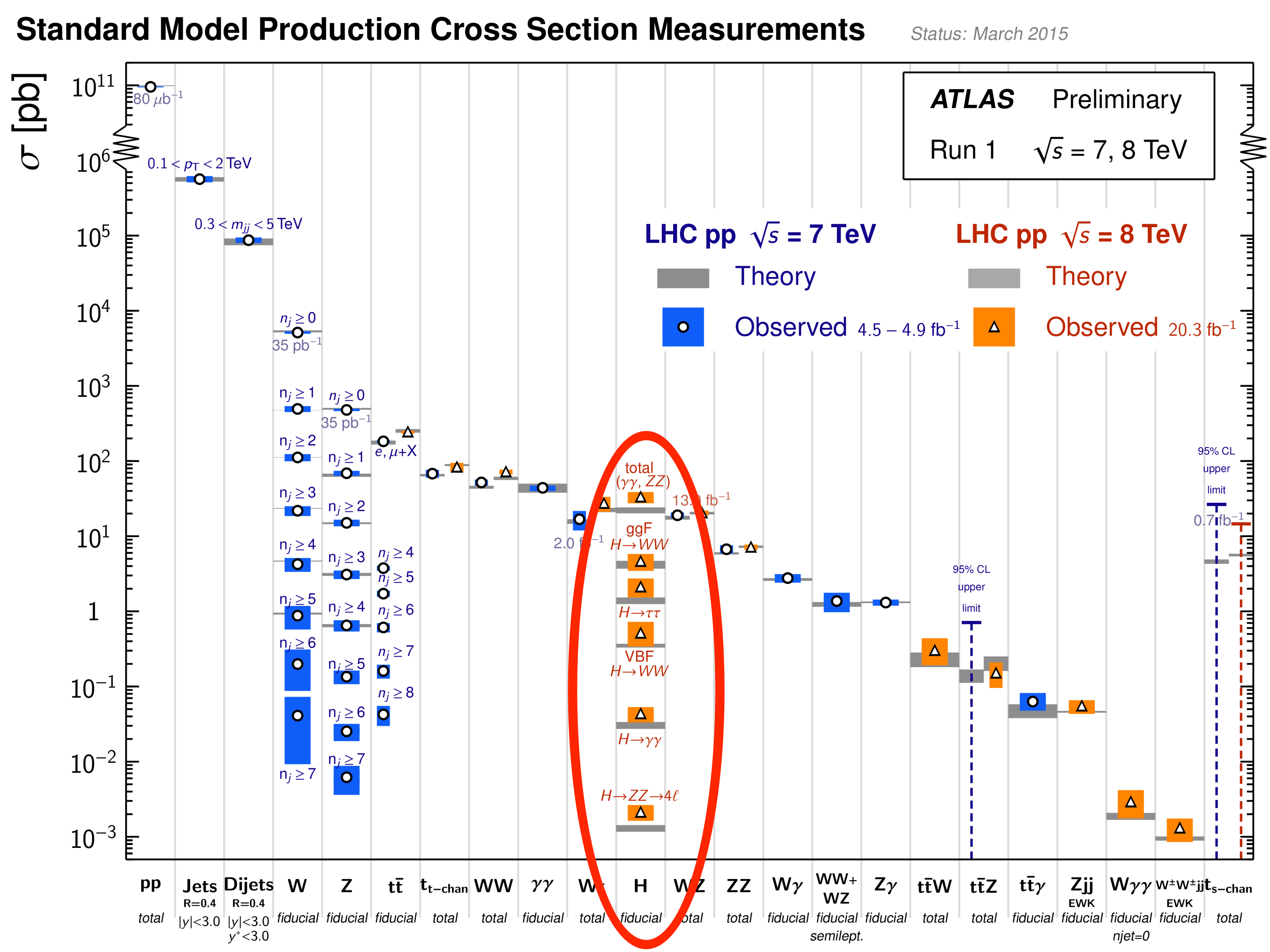


J. Huston
Michigan State University/IPPP
for the ATLAS collaboration

RadCor/Loopfest 2015

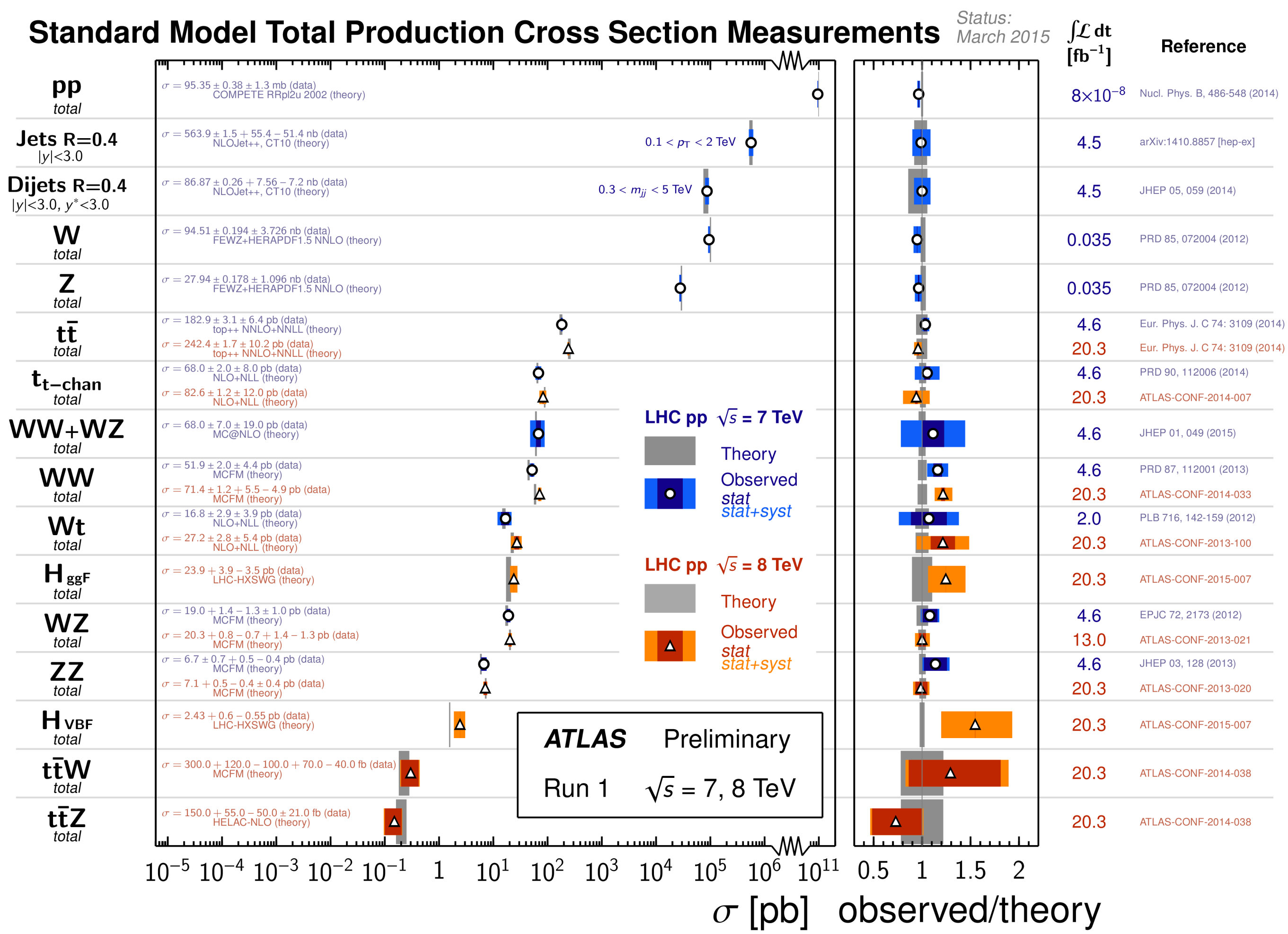
with a few slides from Les Houches 2015

(SM) Physics from Run 1



Physics from Run 1

…in most cases, good agreement with SM predictions (at NLO and higher).
The SM will be tested more stringently (with hopefully BSM physics discovered) in Run 2. We need to have the predictions available to test data vs theory.



A similar need lead to the first wishlist (for the Tevatron)

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 tttt, 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 tttt, 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. $pp \to VV$jet	WWjet completed by Dittmaier/Kallweit/Uwer [4, 5]; Campbell/Ellis/Zanderighi [6]. ZZjet completed by Binoth/Gleisberg/Karg/Kauer/Sanguinetti [7]
2. $pp \to$ Higgs+2jets 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. $pp \to VVV$	ZZZ completed by Lazopoulos/Melnikov/Petriello [11] and WWZ by Hankele/Zeppenfeld [12] (see also Binoth/Ossola/Papadopoulos/Pittau [13])
4. $pp \to t\bar{t}\, b\bar{b}$	relevant for $t\bar{t}H$ computed by Bredenstein/Denner/Dittmaier/Pozzorini [14, 15] and Bevilacqua/Czakon/Papadopoulos/Pittau/Worek [16]
5. $pp \to V$+3jets	calculated by the Blackhat/Sherpa [17] and Rocket [18] collaborations
Calculations remaining from Les Houches 2005	
6. $pp \to t\bar{t}$+2jets	relevant for $t\bar{t}H$ computed by Bevilacqua/Czakon/Papadopoulos/Worek [19]
7. $pp \to VV\, b\bar{b}$,	relevant for VBF $\to H \to VV$, $t\bar{t}H$
8. $pp \to VV$+2jets	relevant for VBF $\to H \to VV$ VBF contributions calculated by (Bozzi/)Jäger/Oleari/Zeppenfeld [20–22]
NLO calculations added to list in 2007	
9. $pp \to b\bar{b}b\bar{b}$	$q\bar{q}$ channel calculated by Golem collaboration [23]
NLO calculations added to list in 2009	
10. $pp \to V$+4 jets	top pair production, various new physics signatures
11. $pp \to Wb\bar{b}j$	top, new physics signatures
12. $pp \to t\bar{t}t\bar{t}$	various new physics signatures
Calculations beyond NLO added in 2007	
13. $gg \to W^*W^*\ \mathcal{O}(\alpha^2\alpha_s^3)$	backgrounds to Higgs
14. NNLO $pp \to t\bar{t}$	normalization of a benchmark process
15. NNLO to VBF and Z/γ+jet	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

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
$\gamma+c\bar{c}\leq 3j$	$\gamma\gamma+c\bar{c}\leq 3j$		
	$WZ+\leq 5j$		
	$WZ+b\bar{b}\leq 3j$		
	$WZ+c\bar{c}\leq 3j$		
	$W\gamma+\leq 3j$		
	$Z\gamma+\leq 3j$		

Going beyond the original wish list: a lot more complexity (loops and legs) required to keep it interesting

A new Les Houches high precision wishlist

- From the 2013 proceedings
  - arxiv: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

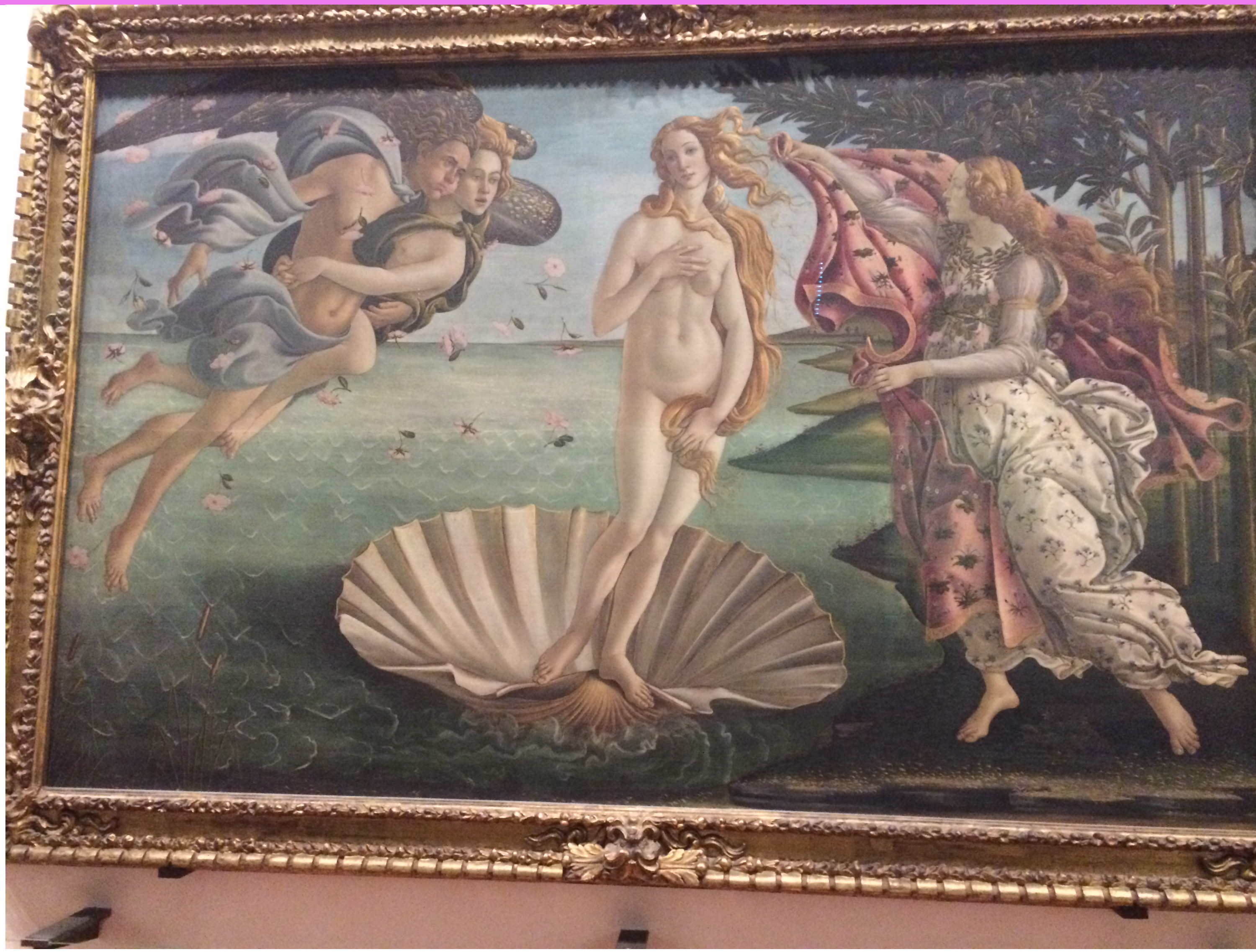
– $\mathrm{LO} \equiv \mathcal{O}(1)$,
– $\mathrm{NLO\ QCD} \equiv \mathcal{O}(\alpha_s)$,
– $\mathrm{NNLO\ QCD} \equiv \mathcal{O}(\alpha_s^2)$,
– $\mathrm{NLO\ EW} \equiv \mathcal{O}(\alpha)$,
– $\mathrm{NNNLO\ QCD} \equiv \mathcal{O}(\alpha_s^3)$,
– $\mathrm{NNLO\ QCD{+}EW} \equiv \mathcal{O}(\alpha_s \alpha)$.

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

Costas: "δεν υπάρχει πρόβλημα"

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.

Many of these calculations require the use of on-shell techniques



…which have been around longer than we realized

Wishlist: Higgs sector

status 2014 — means calculation now available*

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 $H \to b\bar{b}$ @ 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)

***my apologies if your calculation is not yet noted; let me know and I'll add it**

→ justify the requested precision based on current/extrapolated experimental errors

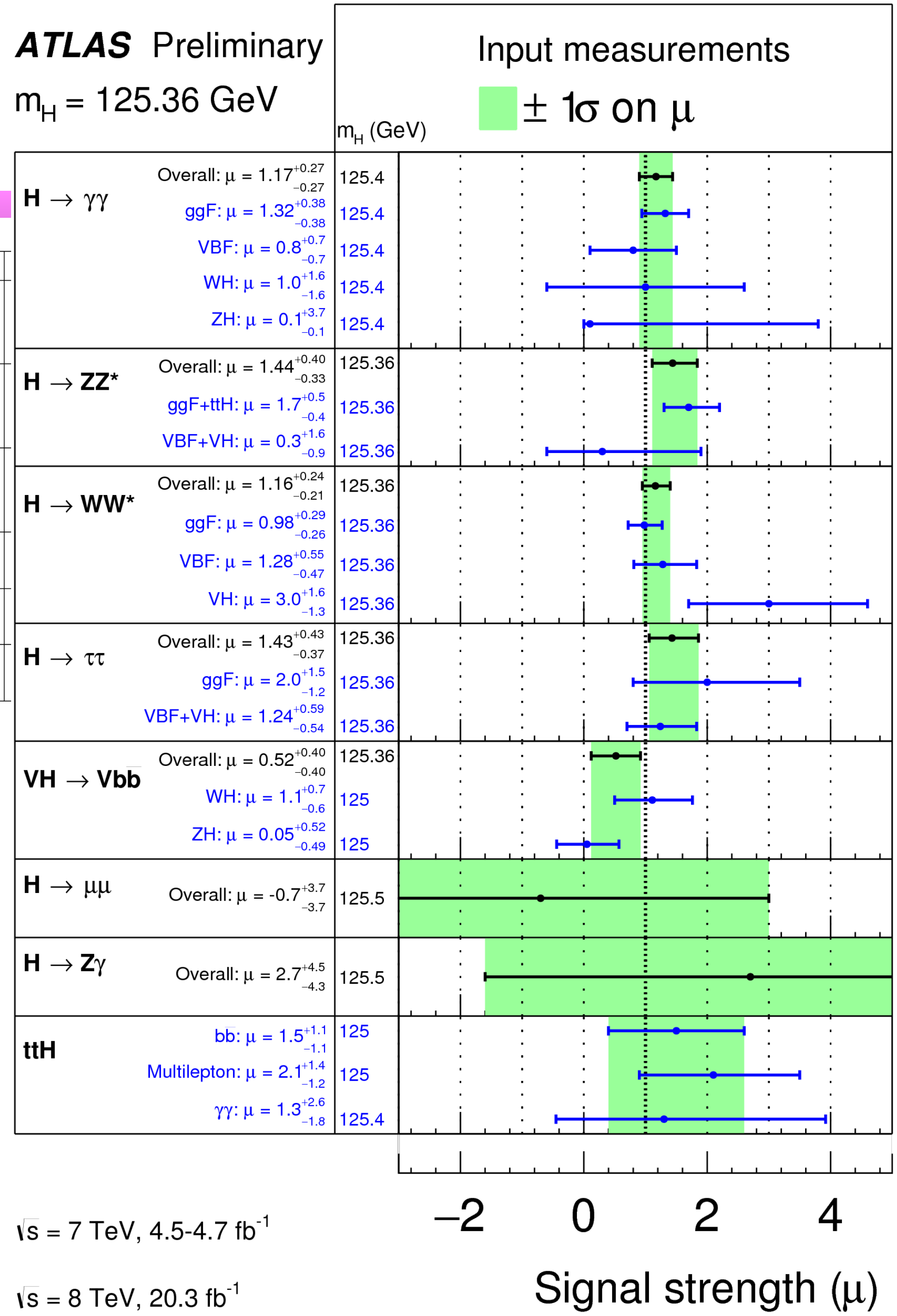
Higgs sector

- We currently know the production cross section for gg fusion to NNNLO QCD in the infinite m_t limit, including finite quark mass effects at NLO QCD and NLO EW.
- Current ATLAS experimental uncertainties are of the order of 20-40%->consistency with SM at that level
- NB: signal strength parameters make use of state-of-art calculations of Higgs cross sections and kinematics
- Global μ:

$$\mu = 1.18^{+0.15}_{-0.14} = 1.18 \pm 0.10(stat) \pm 0.07(expt)^{+0.08}_{-0.07}(theory)$$

- Theory error is competitive with other errors**->theory improvements needed**

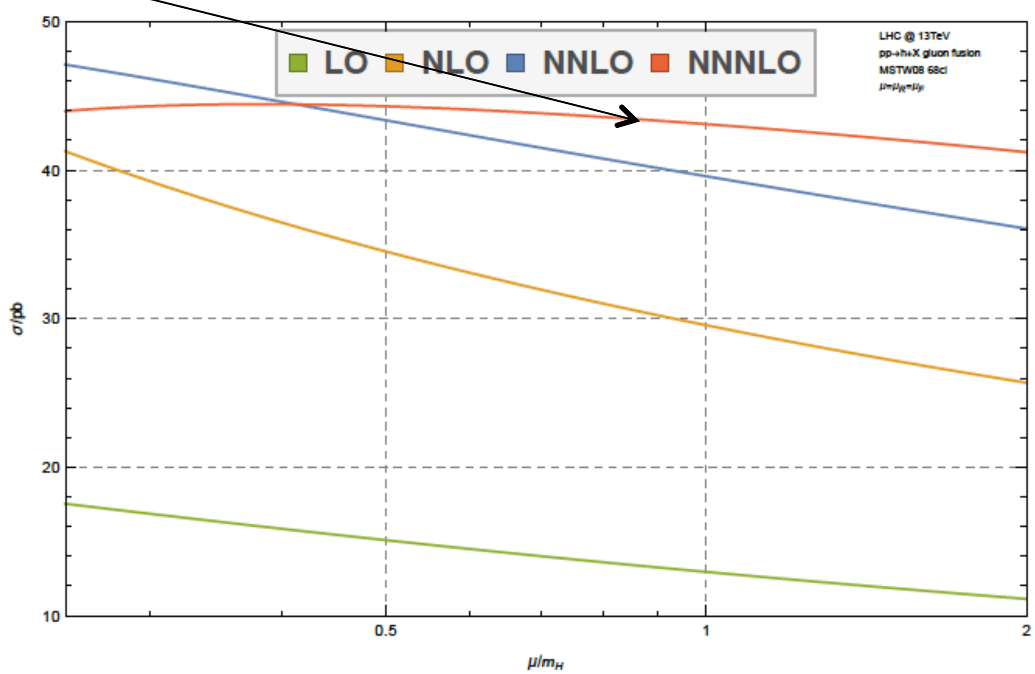
Process
H
H + j
H + 2j
H + V
$t\bar{t}$H
HH



Higgs sector

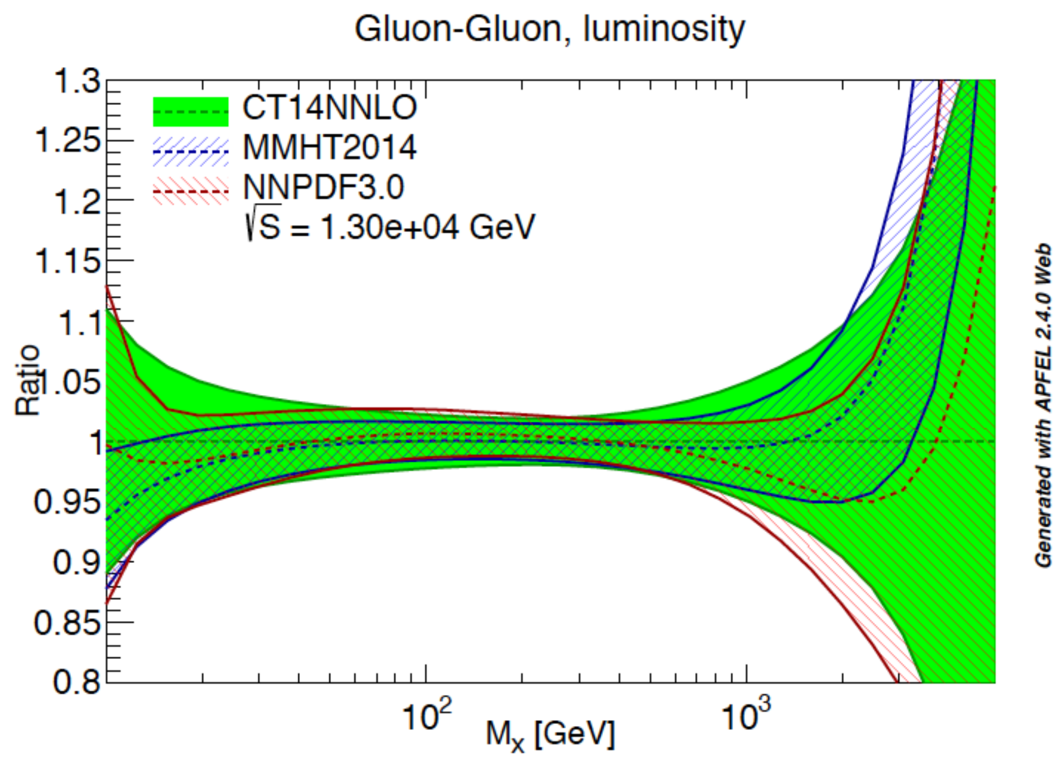
- Previously, uncertainty was of order of 15% with PDF+α_s and higher order uncertainties, both being on the order of 7-8%
    - scale uncertainty now reduced to 2-3%
    - PDF+α_s uncertainty now dominant
    - see next few slides, however
- Expect total experimental error to decrease to <10% in Run 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	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 $H \to b\bar{b}$ @ same accuracy	H couplings



2 NNLO+PS simulations for ggF have already been developed; expect improvements/refinements.

PDFs: the next generation



- NNPDF3.0 (arXiv:1410.8849)
- MMHT14 (arXiv:1412.3989)
- CT14 (on LHAPDF, archive soon
- HERAPDF2.0 (soon)
- The gg PDF luminosities for the first three PDFs are in good agreement with each other in the Higgs mass range
- PDF uncertainty using the CT14, MMHT14, CT14 PDFs would be 2-2.5%, comparable to new scale dependence at NNNLO, and comparable to the as uncertainty

NNPDF down by 2-2.5%, CT14 up by ~1%, MMHT14 down by ~0.5%

partially data, partially corrections in fitting code, partially changes in fitting procedures

new PDF4LHC recommendation in progress; see extra slides

A comparison of ggF at NNLO

scale = m_H	CT14	MMHT2014	NNPDF3.0
8 TeV	18.66 pb -2.2% +2.0%	18.65 pb -1.9% +1.4%	18.77 pb -1.8% +1.8%
13 TeV	42.68 pb -2.4% +2.0%	42.70 pb -1.8% +1.3%	42.97 pb -1.9% +1.9%

The PDF uncertainty using this new generation of PDFs will be similar in size to the NNNLO scale uncertainty and to the $\alpha_s(m_Z)$ uncertainty.

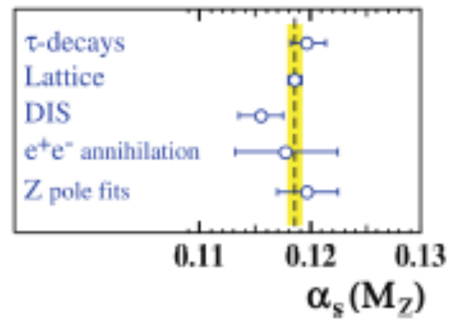
THE VALUE OF α_s

PDG VALUE (AUGUST 2014): $\alpha_s(M_Z) = 0.1185 \pm 0.0006$

to account for perturbative truncation errors

COMMENTS (S.F.)

- LATTICE UNCERTAINTY CURRENTLY ESTIMATED BY FLAG (arXiv:1310.8555) TO BE TWICE THE PDG VALUE (± 0.0012)
- IT IS AN AN AVERAGE OF AVERAGES
- SOME SUB-AVERAGES (E.G. DIS) INCLUDE MUTUALLY INCONSISTENT/INCOMPATIBLE DATA/EXTRACTIONS



- SOME SUB-AVERAGES (E.G. τ OR JETS) INCLUDE DETERMINATIONS WHICH DIFFER FROM EACH OTHER BY EVEN FOUR-FIVE σ
- AVERAGING THE TWO MOST RELIABLE VALUES (GLOBAL EW FIT & τ, BOTH N^{3}LO, NO DEP. ON HADRON STRUCTURE) GIVES

$$\alpha_s = 0.1196 \pm 0.0010$$

NEW PDF4LHC AGREEMENT

- PDG UNCERTAINTY CONSERVATIVELY MULTIPLIED BY 2
- CENTRAL VALUE & UNCERTAINTY ROUNDED: PDF SETS USUALLY GIVEN IN STEPS OF $\Delta\alpha_s(M_z) = 0.001$

$$\alpha_s(M_Z) = 0.118 \pm 0.001$$

-PDFs all evaluated at same value of α_s (0.118).
−α_s uncertainty added in quadrature with PDF uncertainty
-α_s uncertainty is one of the dominant errors now

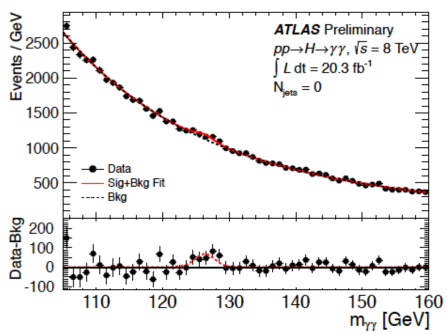
How aggressive should we be on $\alpha_s(m_Z)$ uncertainties?

S. Forte Higgs XSWG meeting
June 8, 2015

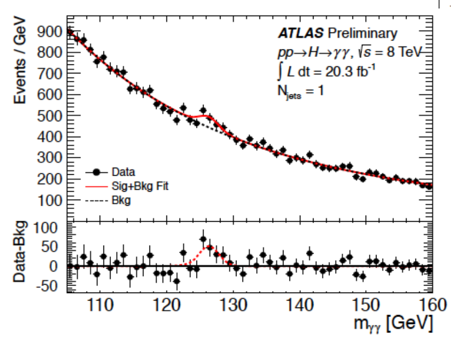
Higgs sector

- First attempts to measure differential Higgs+jets measurements made in diphoton (ZZ*) channel at ATLAS
  - JHEP 1409(2014)112; (Phys. Lett. B738(2014)234)
- Combination with ZZ*
  - arXiv:1504.05833

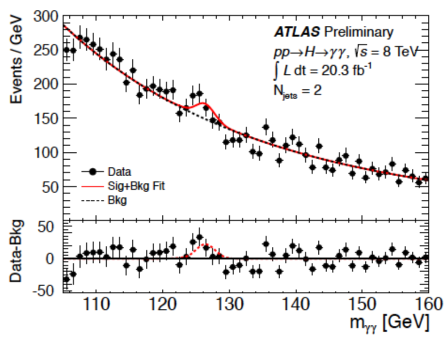
Process	known	desired	details
H	dσ @ NNLO QCD dσ @ NLO EW finite quark mass effects @ NLO	dσ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	dσ @ NNLO QCD (g only) dσ @ NLO EW finite quark mass effects @ LO	dσ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T



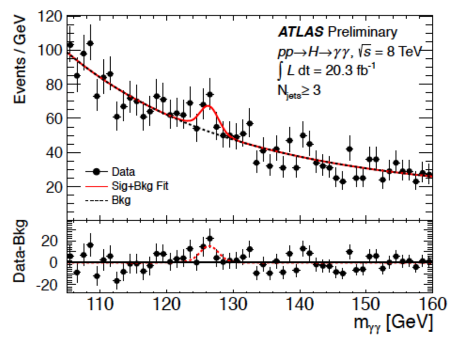
(a) $N_{\rm jets} = 0$



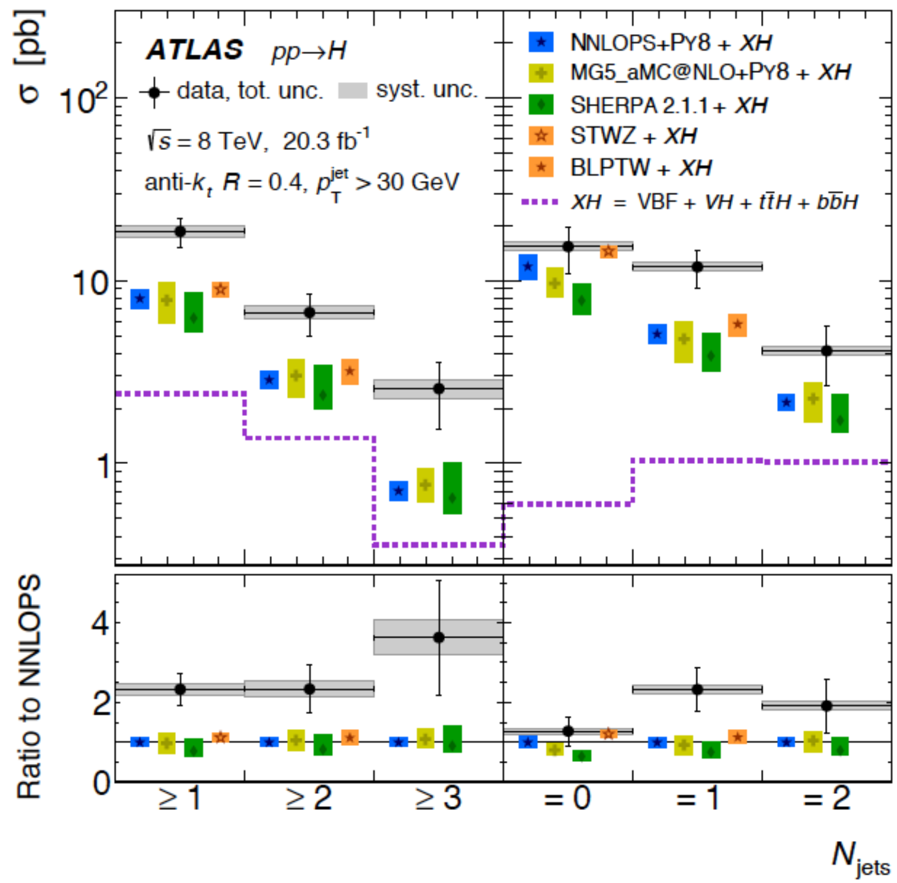
(b) $N_{\rm jets} = 1$



(c) $N_{\rm jets} = 2$

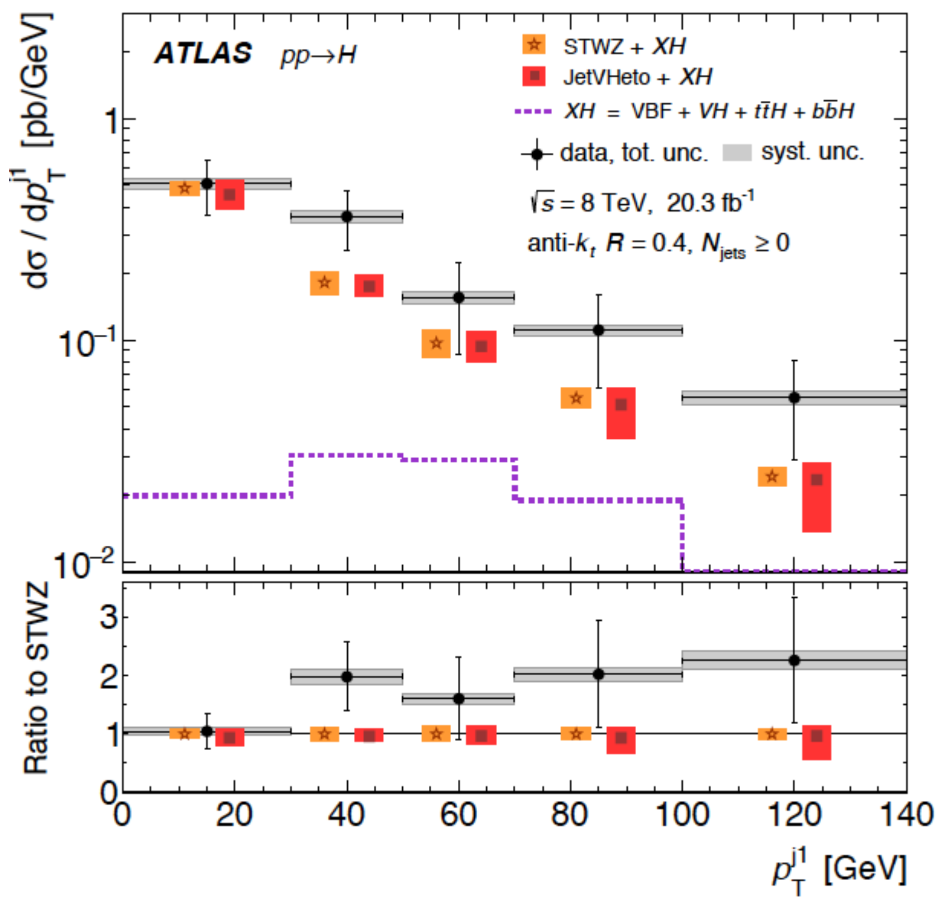


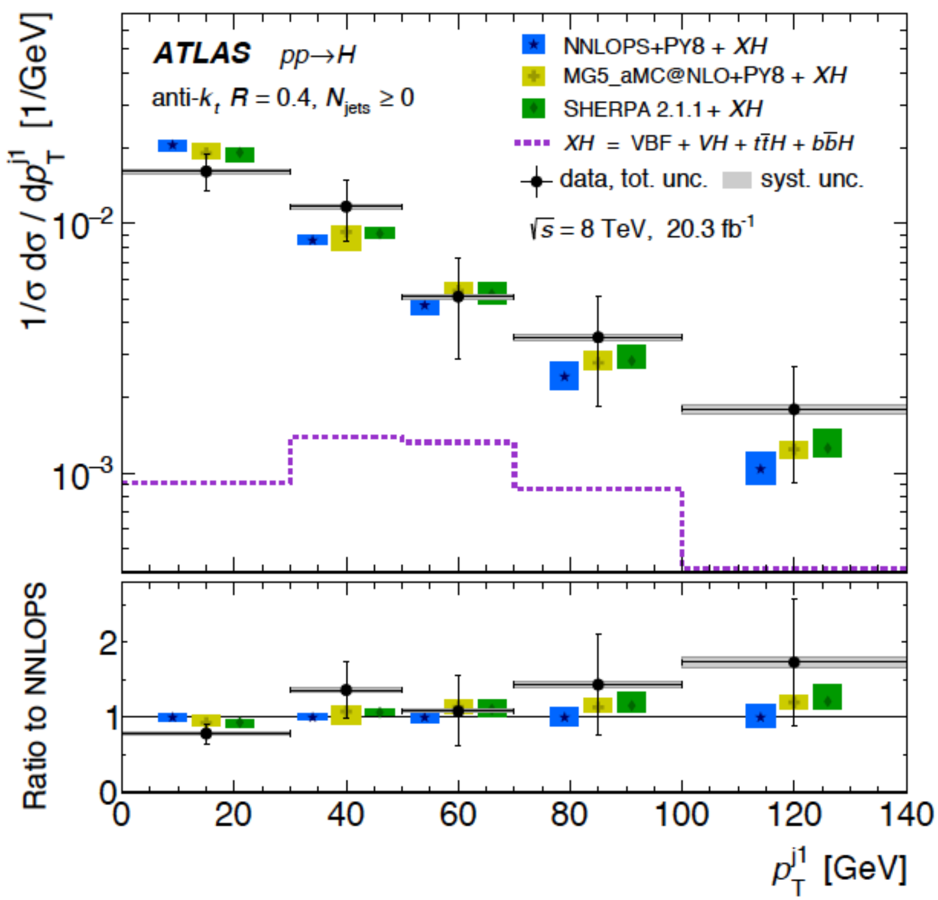
(d) $N_{\rm jets} \geq 3$



ATLAS Higgs+>=1 jet

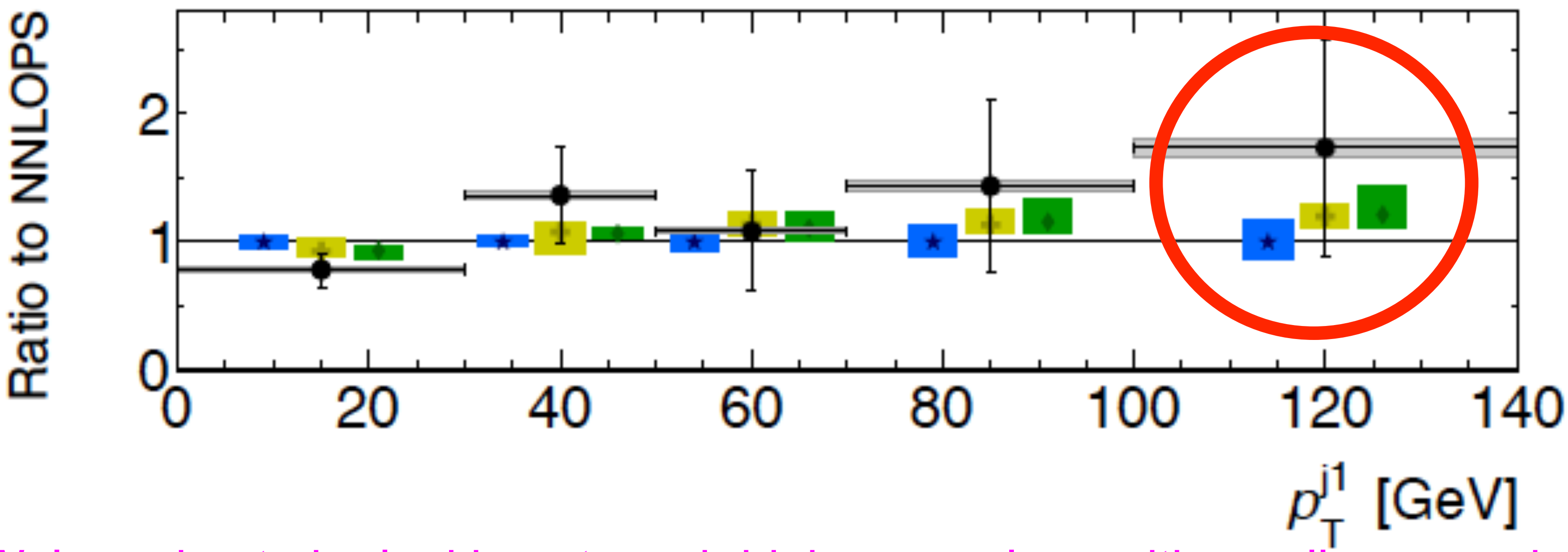
- Comparisons to a wide number of resummation/ME+PS predictions…**but not to fixed order!** (with appropriate non-perturbative corrections)





ATLAS Higgs+>=1 jet

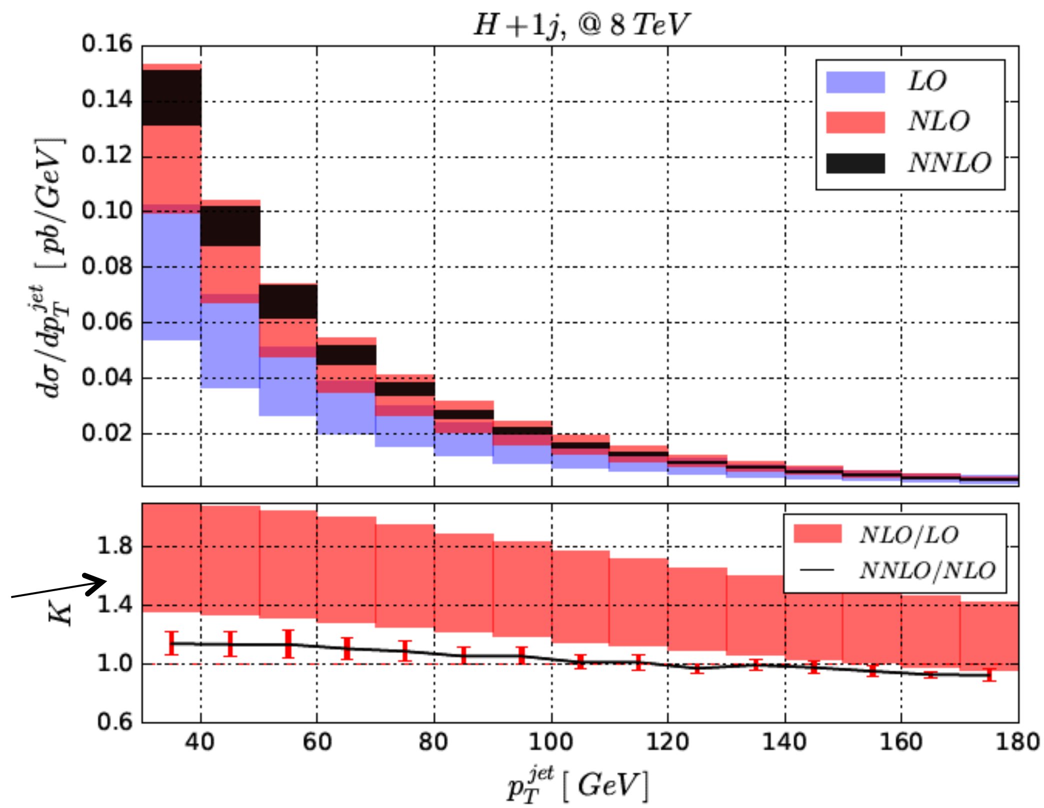
- Comparisons to a wide number of resummation/ME+PS predictions…**but not to fixed order**!
- **Les Houches:compare each prediction to each other, to fixed NLO/NNLO in detailed framework**
    - **wide variety of observables relating to Higgs+jets; Rivet routine available; ntuplereader modification available to talk to Rivet**
- **How well do the resummation calculations anticipate/reproduce the NNLO results**?



We're going to be looking at much higher p_T values with smaller errors in Run 2. We need to have a better quantitative handle on this.

Higgs + jet

- 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 inside the top quark loop
- H+j cross section now known to NNLO
  - using *conventional* techniques: arXiv:1504.07922
  - using n-jettiness: arXiv: 1505.03893
  - see also Matthieu Jaquiers' talk
  - this cross section will be used to improve comparisons with Run 2 data
- 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



Can n-jettiness be successfully used for other processes, for example Higgs+>=2 jets at NNLO (once appropriate virtual terms are known)?

F. Caola: HXSWG meeting May 7, 2015

LHC13 efficiencies: 0- and 1-jet bin

[Many thanks to P. F. Monni and F. Dulat] preliminary; paper in progress

0-jet bin

ord	$\sigma^{\rm f.o.}_{0-\rm jet}$ (JVE)	$\sigma^{\rm f.o.+NNLL}_{0-\rm jet}$ (JVE)	$\sigma^{\rm f.o.+NNLL}_{0-\rm jet}$ (scales)
NNLO	$26.2^{+4.0}_{-4.0}$ pb	$25.8^{+3.8}_{-3.8}$	$25.8^{+1.6}_{-1.6}$
$\rm N^3LO$	$27.2^{+2.7}_{-2.7}$ pb	$27.2^{+1.4}_{-1.4}$	$27.2^{+0.9}_{-0.9}$

≥1-jet bin

ord	$\sigma^{\rm f.o.}_{\geq 1-\rm jet}$ (scales)	$\sigma^{\rm f.o.}_{\geq 1-\rm jet}$ (JVE)	$\sigma^{\rm f.o.+NNLL}_{\geq 1-\rm jet}$ (JVE)
NLO	$14.7^{+2.8}_{-2.8}$ pb	$14.7^{+3.4}_{-3.4}$	$15.1^{+2.7}_{-2.7}$
NNLO	$17.5^{+1.3}_{-1.3}$ pb	$17.5^{+2.6}_{-2.6}$	$17.5^{+1.1}_{-1.1}$

- Logs completely under control
  (logR: see [Dasgupta, Dreyer, Salam, Soyez (2015)])
- No breakdown of f.o. perturbation theory for $p_T \sim 30$ GeV
- Reliable error estimate from lower orders
- Logs help in reducing uncertainties
- Significant decrease of pert. uncertainty

What is the effect of jet binning on a reasonably inclusive cross section, i.e. H+>=1 jet?

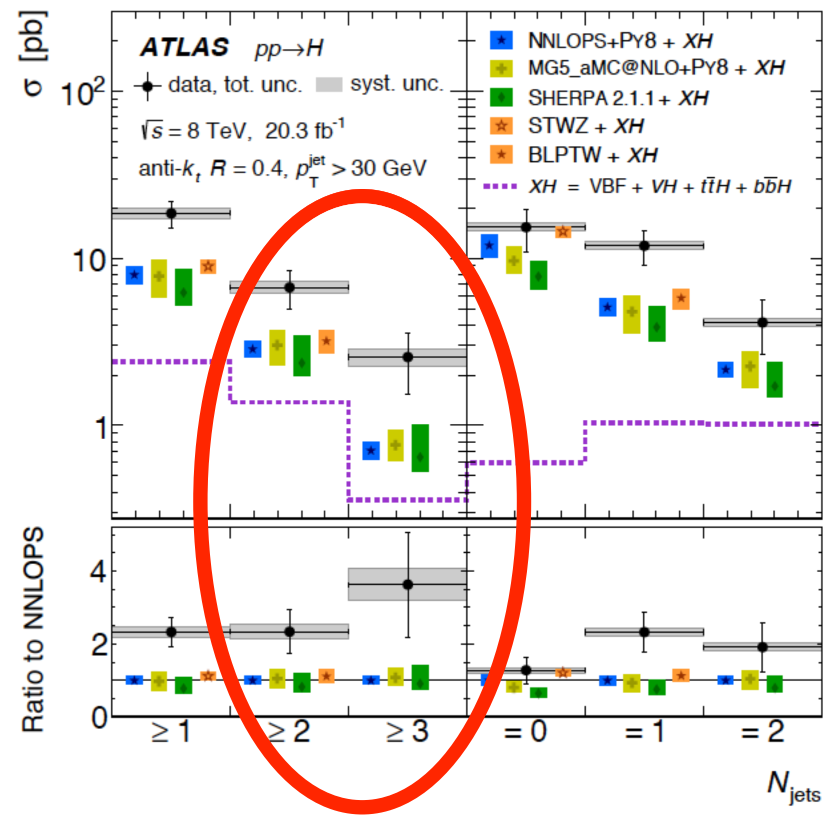
According to this result, the effects are small.

Can we (I) get a better understanding of this? How exclusive can you go?

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	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(gg) @ NLO QCD $d\sigma$(VBF) @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V			
$t\bar{t}$H			
HH			



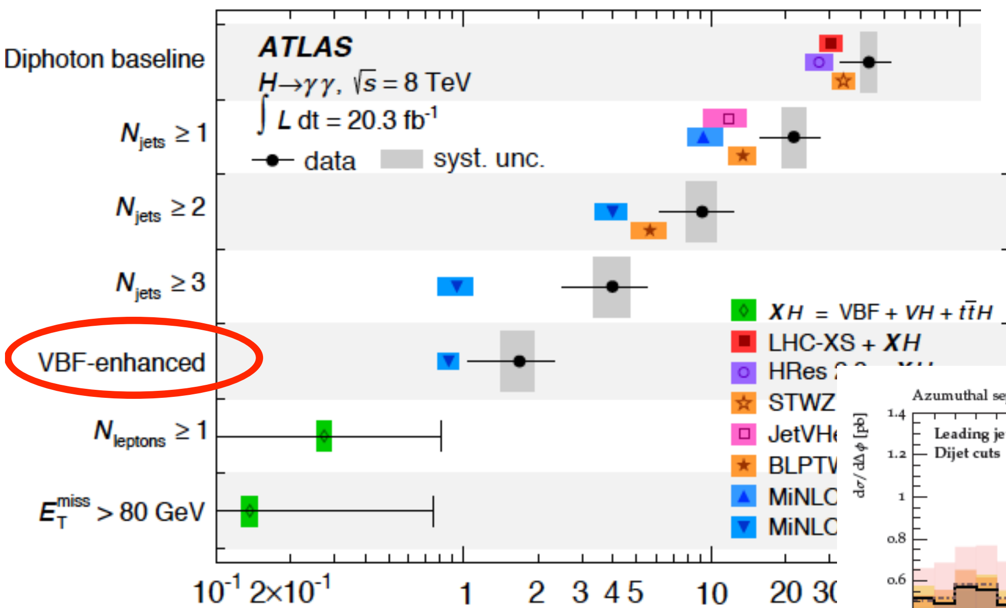
interesting that the (statistically limited) results seem to show a jettier final state than predicted

Higgs sector

- Higgs +>= 2 jets crucial to understand Higgs coupling, in particular through VBF

H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(gg) @ NLO QCD $d\sigma$(VBF) @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings
$t\bar{t}$H	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(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)



study from Les Houches 2013; will be extended in 2015

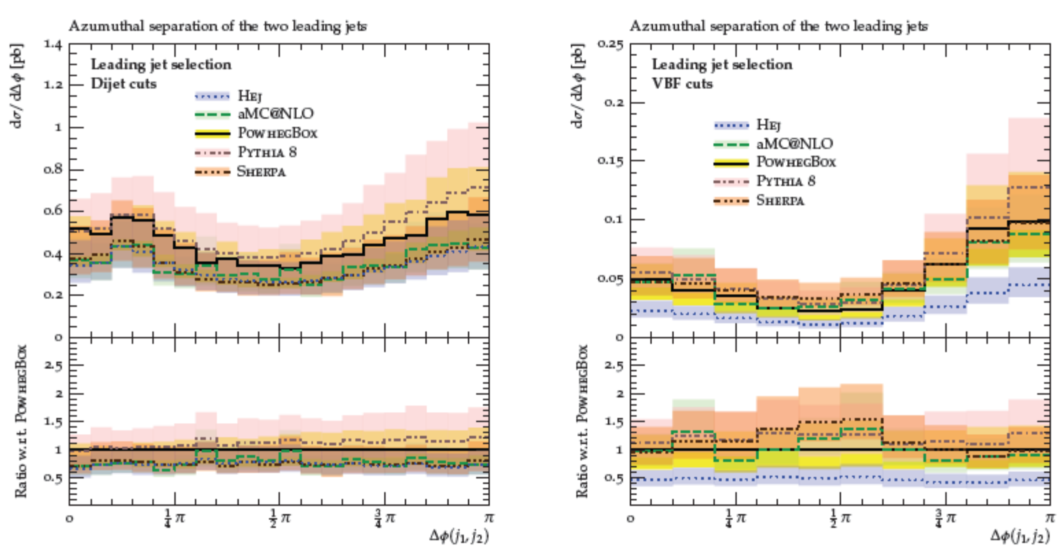
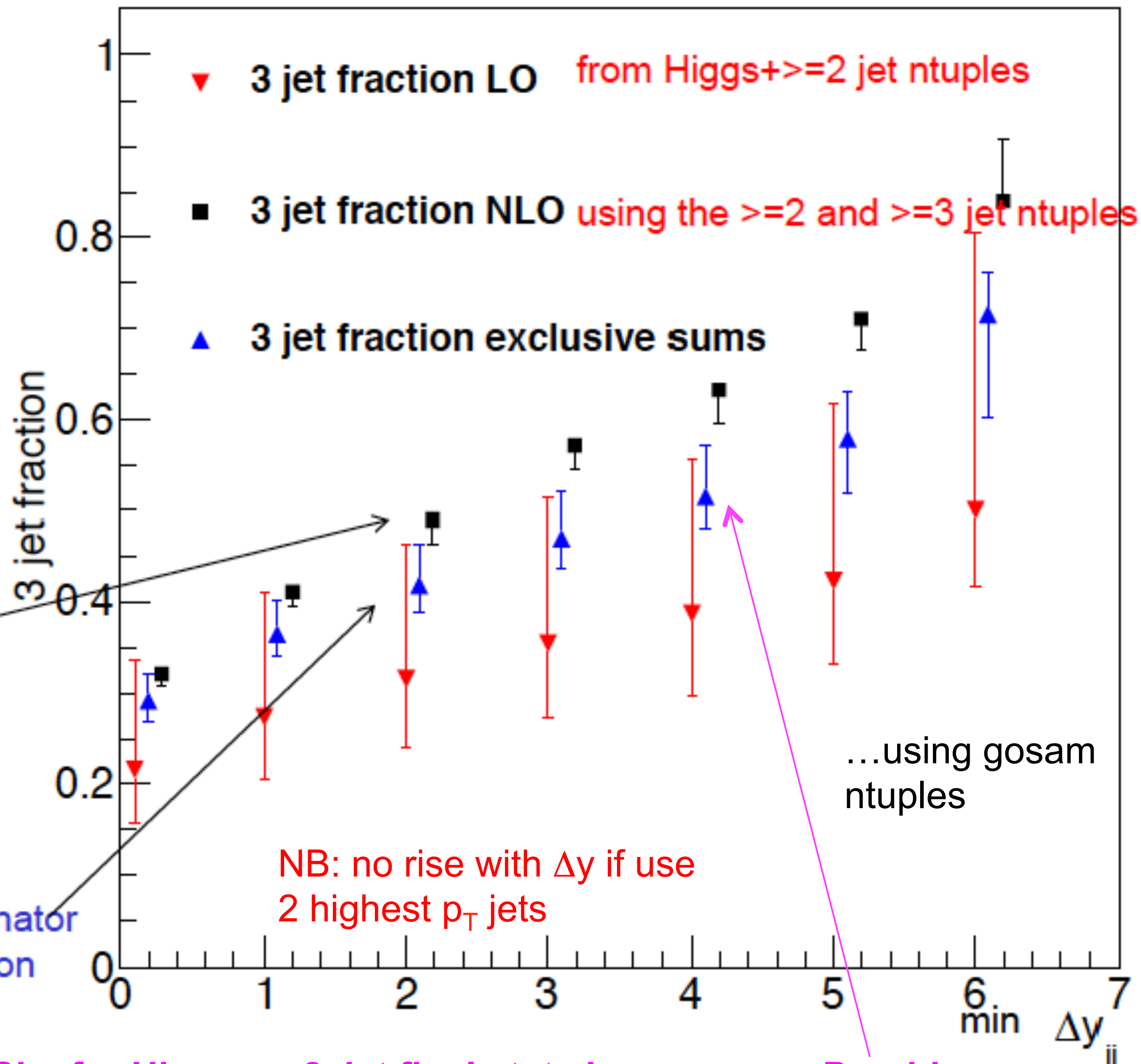


Fig. III.29: Azimuthal separation of the tagging jets before (left) and after (right) the application of the VBF selection cuts in the leading jet selection as predicted by the different generators. The individual sources of uncertainties used to generate the respective bands are described in Sec. 6.2.

can we gain a better quantitative understanding/reduction of ggF contamination in VBF region? It's not enough to say they agree within uncertainties. Many of those uncertainties are in common.

even with VBF cuts, ggF still forms significant background to VBF

fraction of Higgs+>=2 jet events with a 3rd jet as a function of the minimum rapidity separation between the two most forward-backward jets.

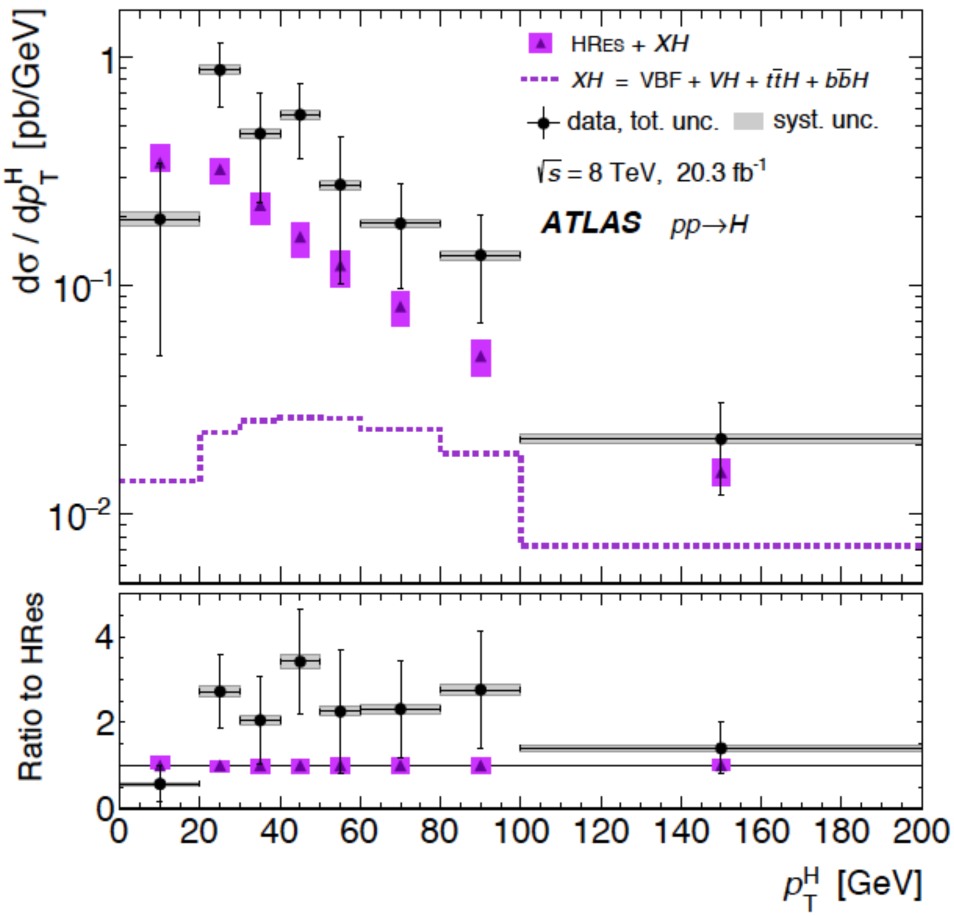


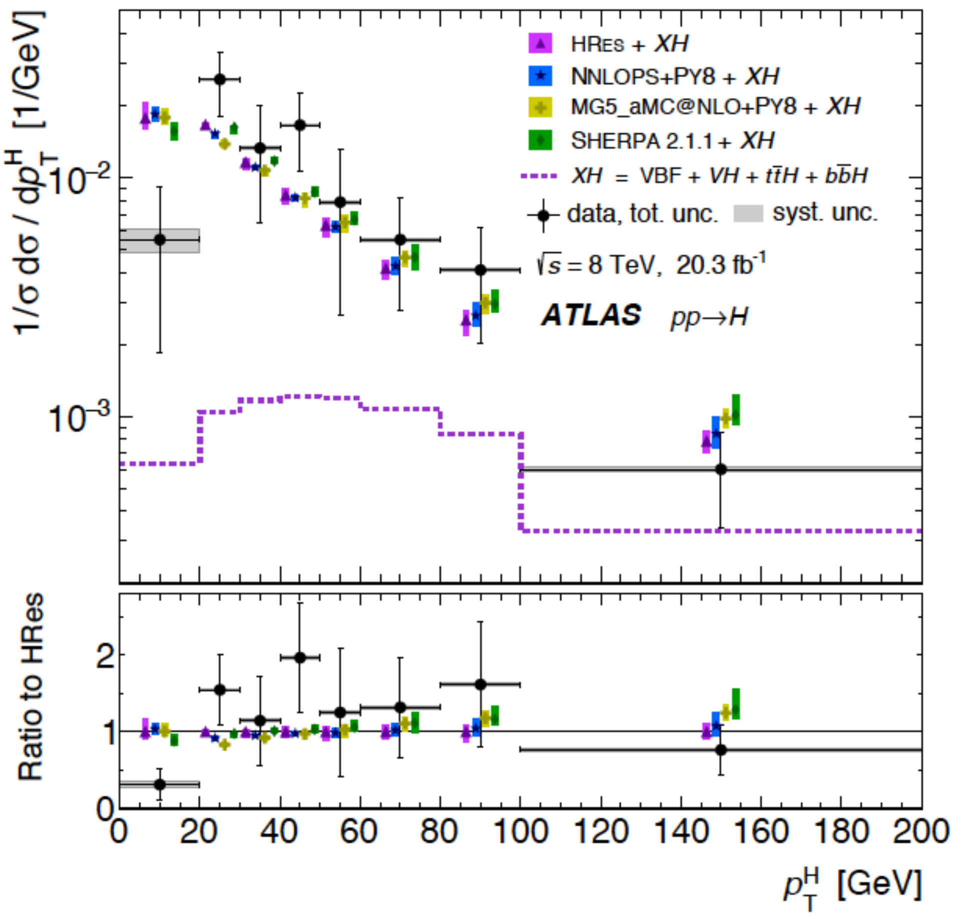
note the small scale dependence for the 3 jet fraction NLO; fractions are larger since >=3 jet cross section is at NLO

exclusive sums fractions are somewhat smaller since >=2 jets in denominator gets increased contribution

Calculation with LoopSim for Higgs+>=2 jet final state in progress. Provide nNLO for Higgs_>=2 jets. Compare to/replace exclusive sums.

Higgs p_T distribution somewhat shifted to higher transverse momentum but of course statistically limited.



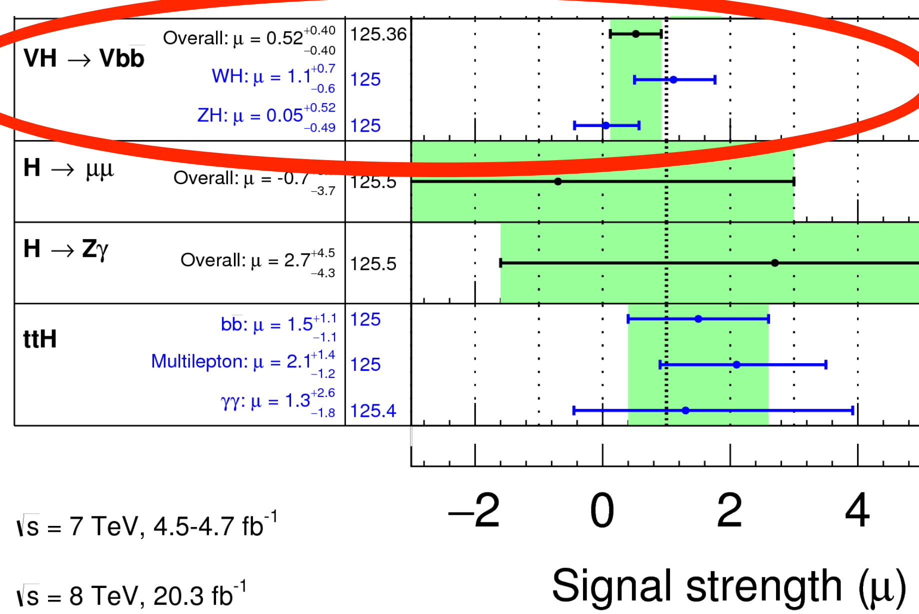


Higgs sector

- Coupling of Higgs to top and bottom quarks poorly known
  - 50% for bottom
  - 100% for top
- H->bB primarily measured through asociated production, known currently 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}
- NB: gg->ZH at NLO critical component

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	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(gg) @ NLO QCD $d\sigma$(VBF) @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings
$t\bar{t}$H	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(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)

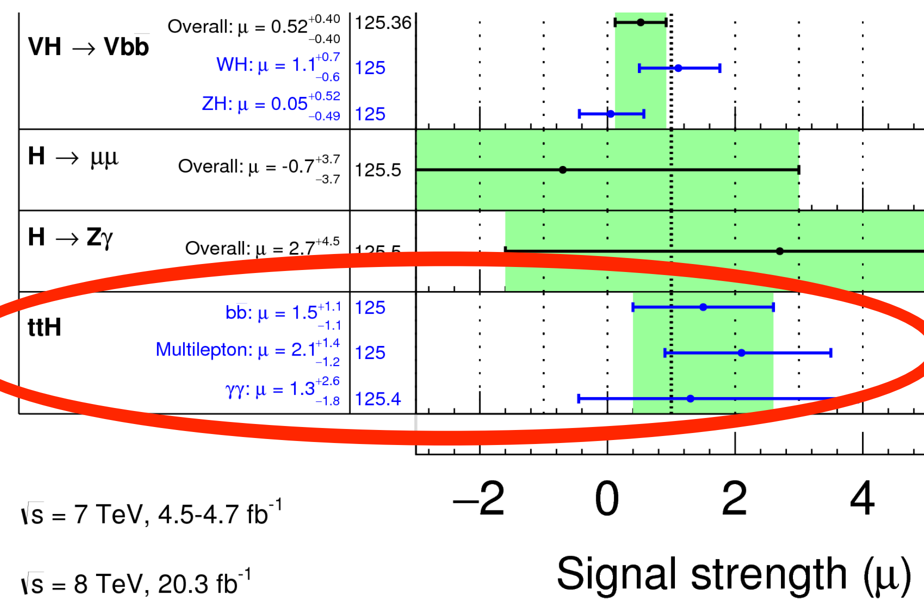


Higgs sector

- Coupling of Higgs to top and bottom quarks poorly known
  - 50% for bottom
  - 100% for top
- 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 wth stable tops
- Need to know the cross section (with top decays) at NLO QCD, possibly including NLO EW 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	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(gg) @ NLO QCD $d\sigma$(VBF) @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings
$t\bar{t}$H	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(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

- 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	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 $H \to b\bar{b}$ @ 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)

The various decays of the Standard Model Higgs boson offer a variety of final states which can be studied, and the most interesting of these are given in Table 1, along with their branching ratios and the approximate event yield in the anticipated High-Luminosity LHC (HL-LHC) dataset corresponding to 3000 fb^{-1}.

Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b} + b\bar{b}$	33%	40,000
$b\bar{b} + W^+W^-$	25%	31,000
$b\bar{b} + \tau^+\tau^-$	7.3%	8,900
$ZZ + b\bar{b}$	3.1%	3,800
$W^+W^- + \tau^+\tau^-$	2.7%	3,300
$ZZ + W^+W^-$	1.1%	1,300
$\gamma\gamma + b\bar{b}$	0.26%	320
$\gamma\gamma + \gamma\gamma$	0.0010%	1.2

Table 1: Branching ratios for different HH final states, and their corresponding approximate expected yields in 3000 fb^{-1} of data before any event selection is applied, assuming a total production cross section of 40.8 fb and m_H = 125 GeV.

despite small BR, one of the most promising channels; best significance using boosted regime

ATL-PHYS-PUB-2014-019

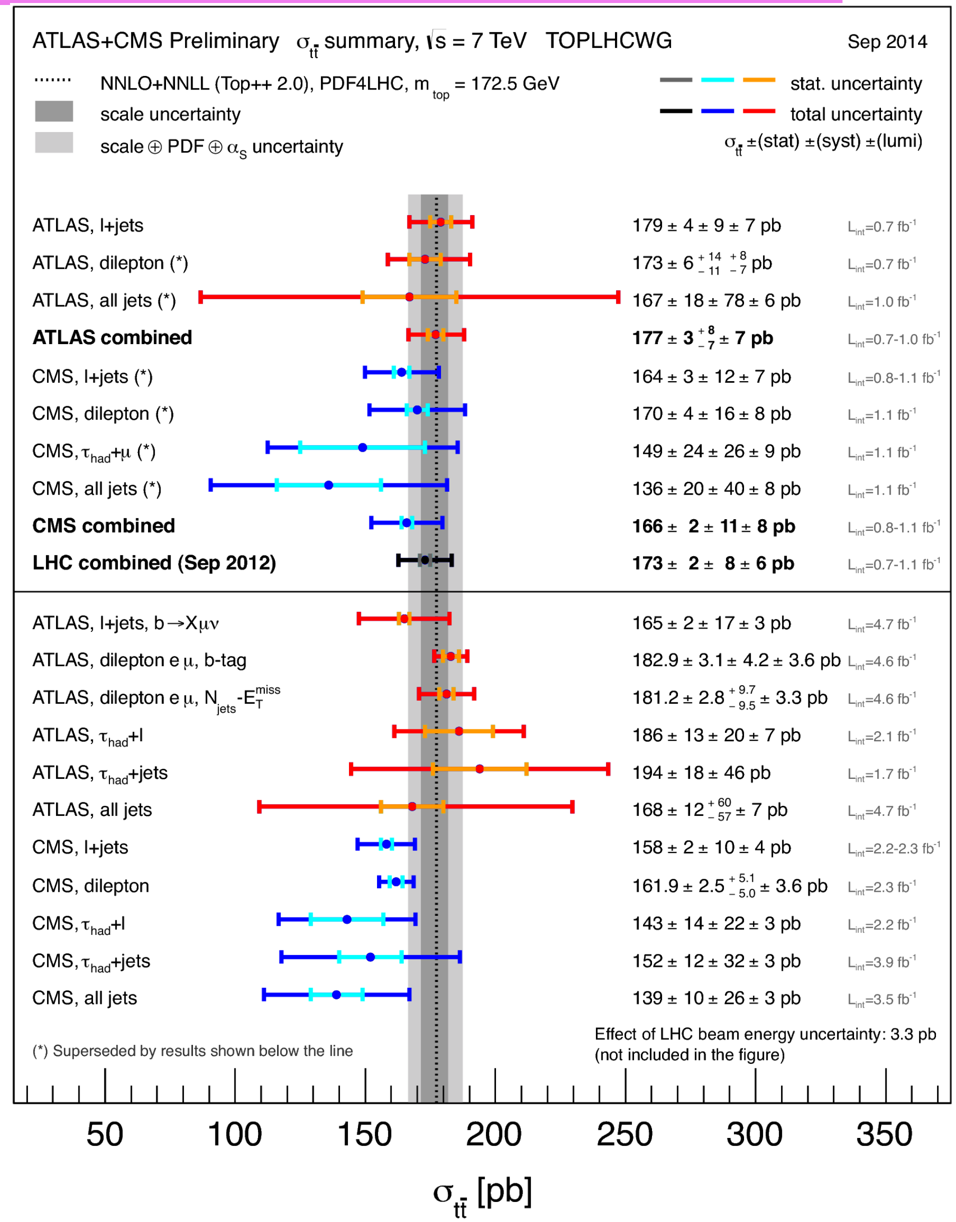
heavy quarks, photons, jets

Process	known	desired	details
$t\bar{t}$	σ_{tot} @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW	precision top/QCD, gluon PDF, effect of extra radiation at high rapidity, top asymmetries
$t\bar{t} + j$	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW	precision top/QCD top asymmetries
single-top	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(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 $\rightarrow$ PDF fits (gluon at high x) $\rightarrow \alpha_s$ CMS http://arxiv.org/abs/1212.6660
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW	Obs.: $R3/2$ or similar $\rightarrow \alpha_s$ 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 heay quarks

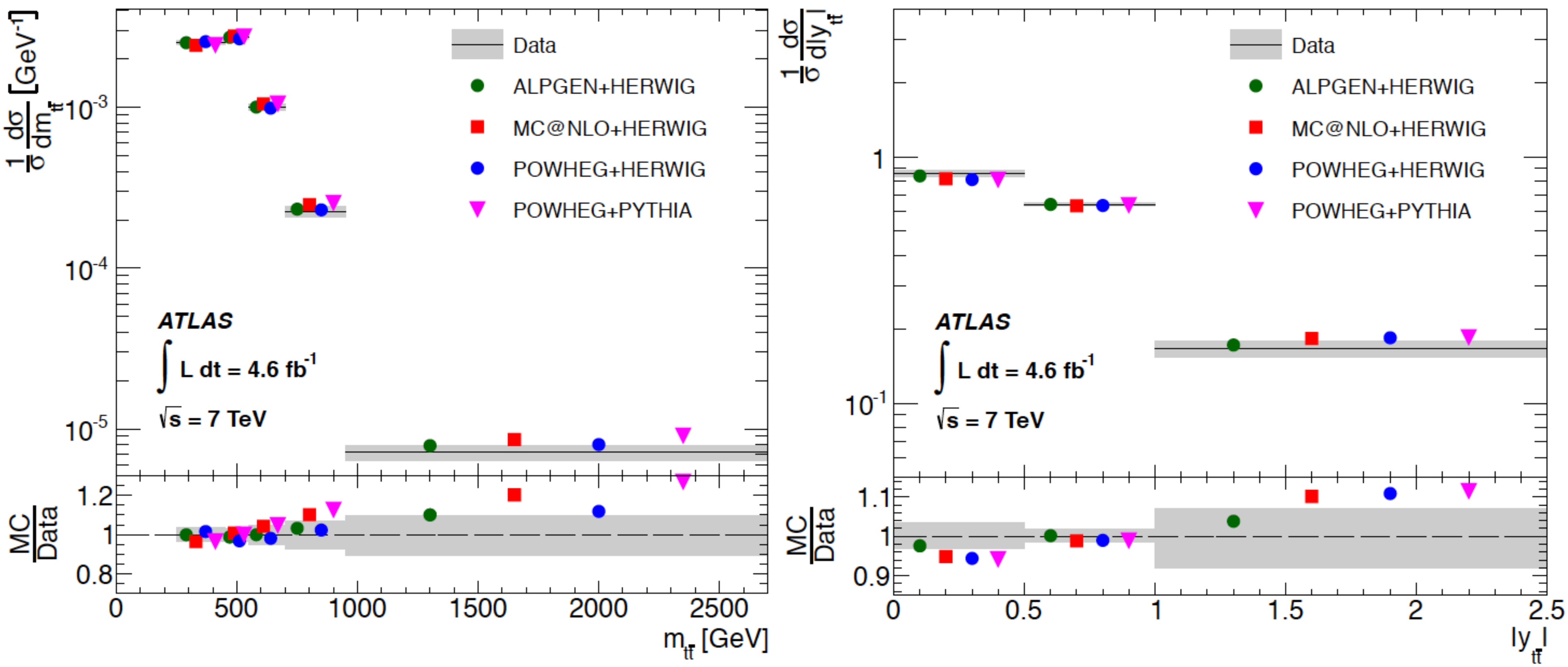
Top pair production

- 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 4% 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



Mass and rapidity distributions

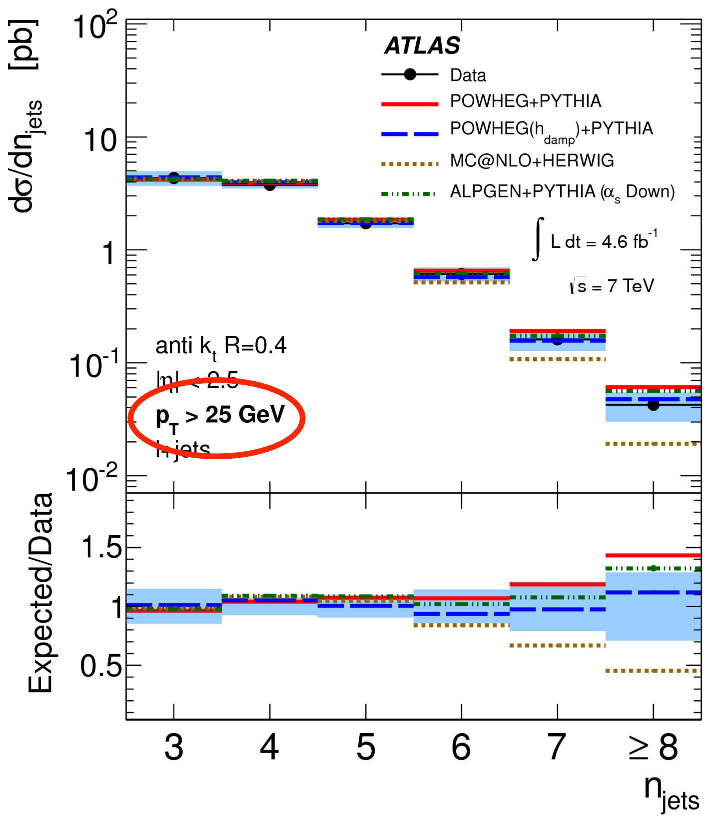
- gg channel is dominant; differential predictions at NNLO will help constrain high x gluon distribution
  - weaker gluon at high x than needed for jet production?
- …but, NLO EW corrections also important

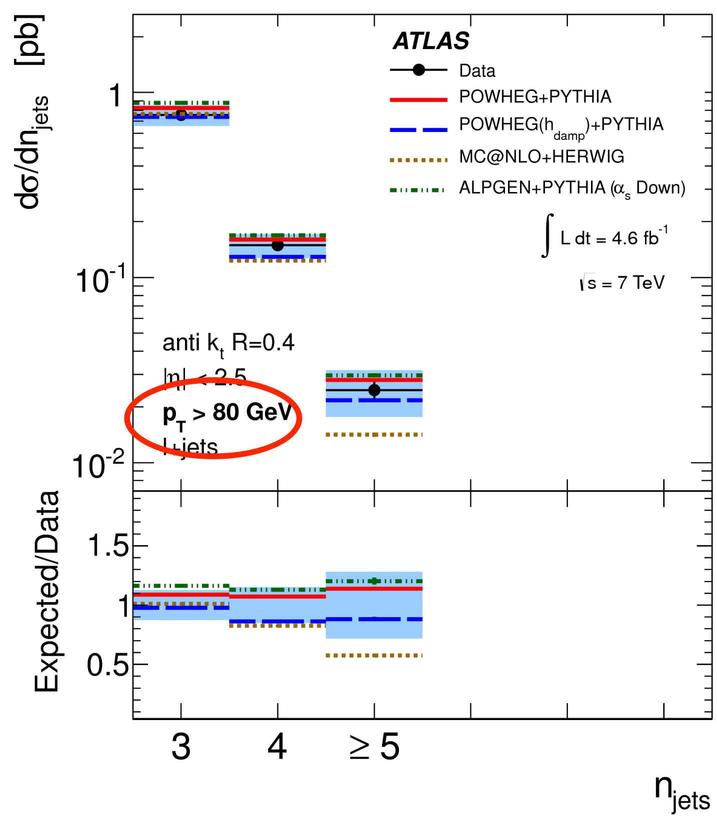


tT+jets

- 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
		NLO QCD + NLO EW
		NLO QCD + NLO EW
		NLO QCD + NLO EW

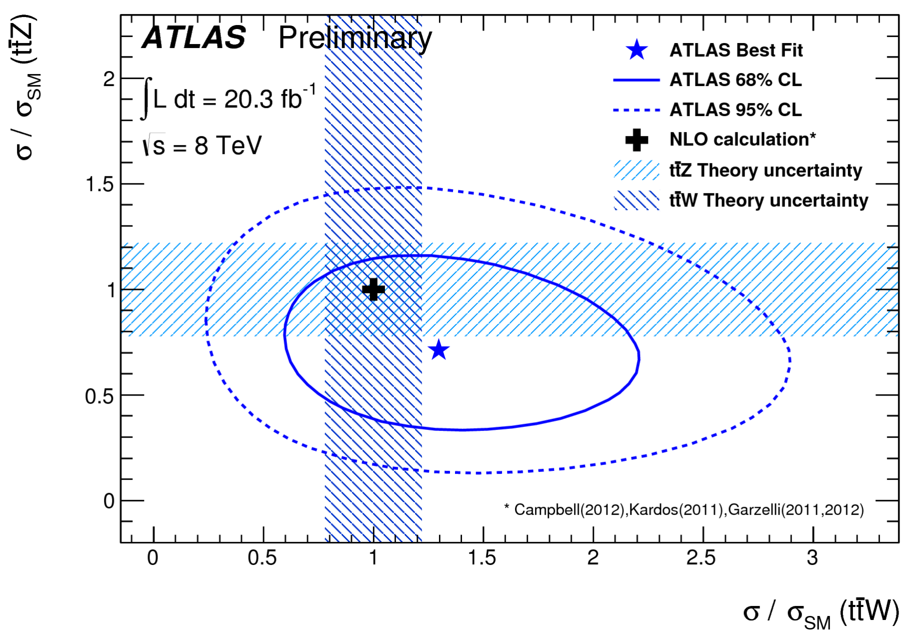




tTZ

- Important process to compare to tTH 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
$t\bar{t}$	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
$t\bar{t}+\mathrm{j(j)}$	$d\sigma$(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
$\gamma+\mathrm{j}$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW

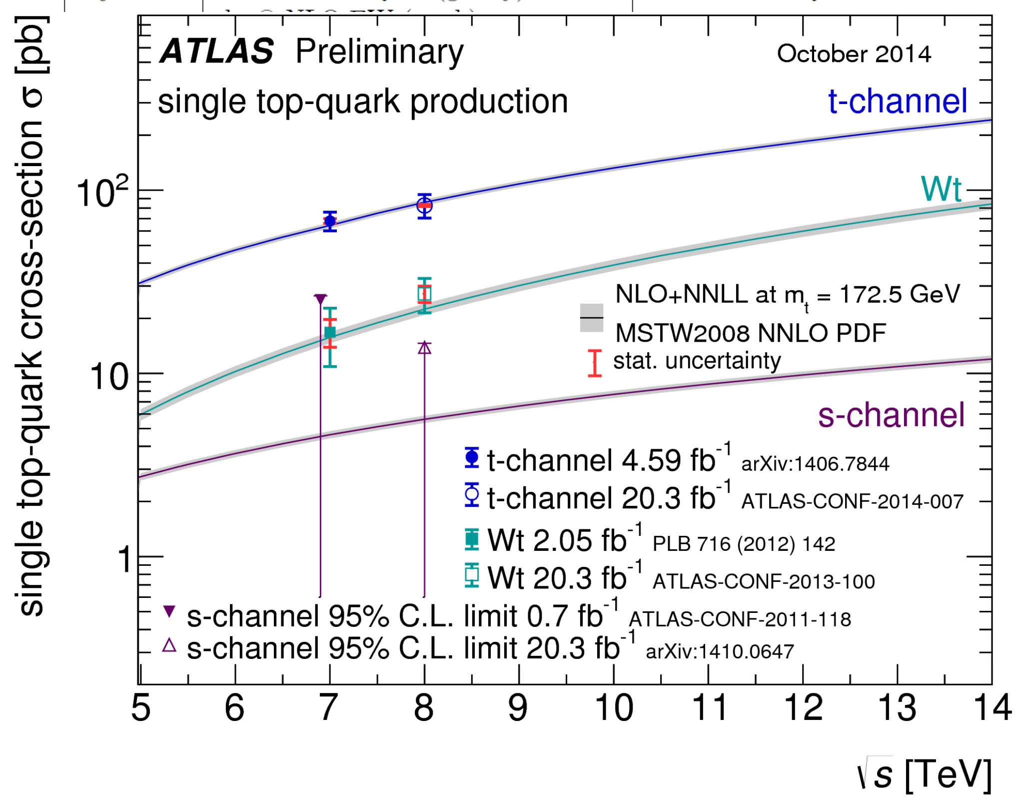


agreement (within large uncertainty) with the standard model prediction

Single top

- Important for precision top physics and in particular the measurement of Vtb
- Current experimental precision is on the order of 10% and a precision of the order of 5% desireable/possible in Run 2
- Both ATLAS and CMS have observed tW, with approximately 20% uncertainties (dominated by statistics)
  - <10% for Run 2
- Currently single top cross section known to NNLO in QCD
  - arXiv:1404.7116
- 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
$t\bar{t}$	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)	$d\sigma$ @ NNLO QCD + NLO EW



Dijets

- 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
- <u>We also need a better understanding of the impact of parton showers on the fixed order cross section</u>

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

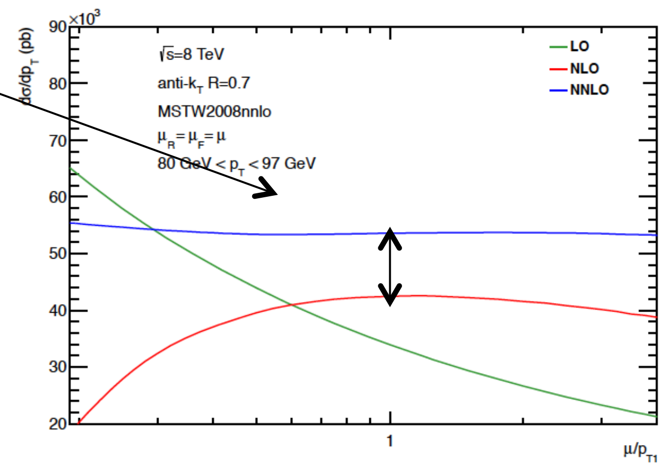


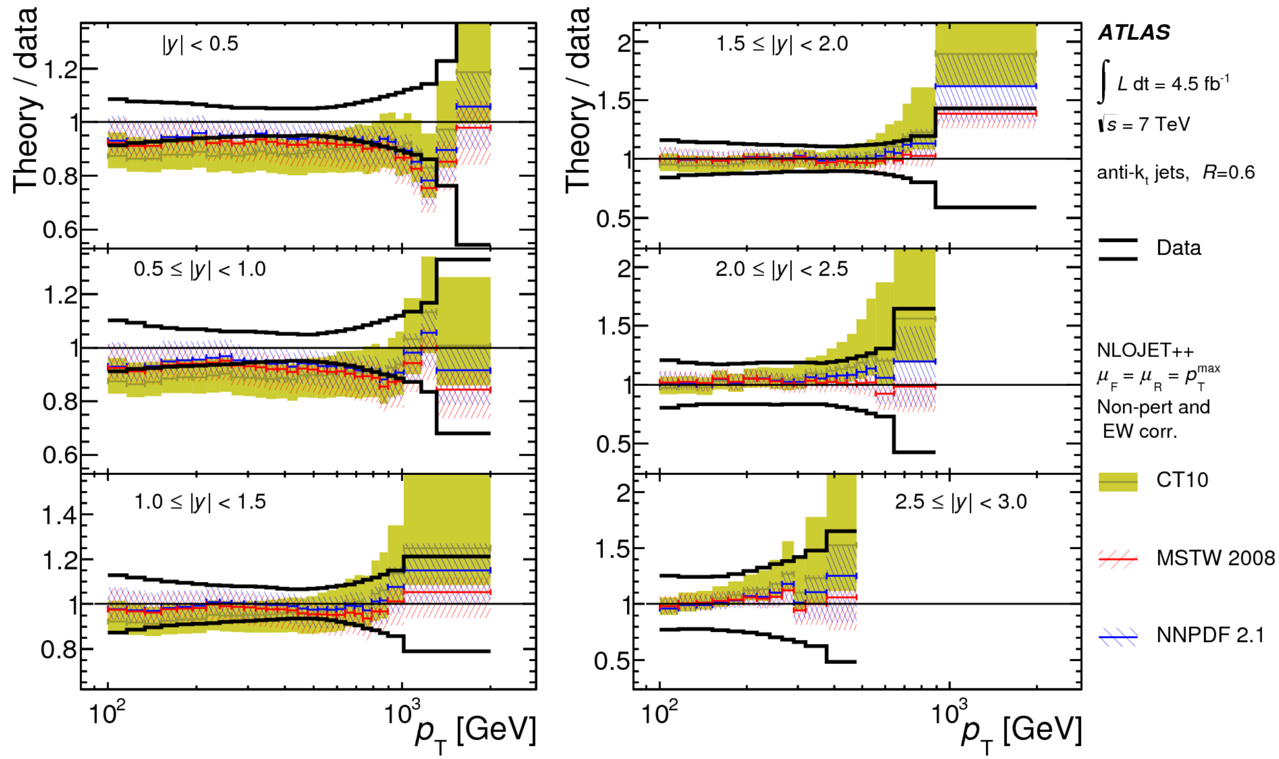
FIG. 2: Scale dependence of the inclusive jet cross section for pp collisions at $\sqrt{s} = 8$ TeV for the anti-k_T algorithm with $R = 0.7$ and with $|y| < 4.4$ and 80 GeV $< p_T <$ 97 GeV at NNLO (blue), NLO (red) and LO (green).

NB: relatively large corrections

Dijets

- 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

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
$t\bar{t}+\mathrm{j(j)}$	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
$t\bar{t}+\mathrm{Z}$	$d\sigma$(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



…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

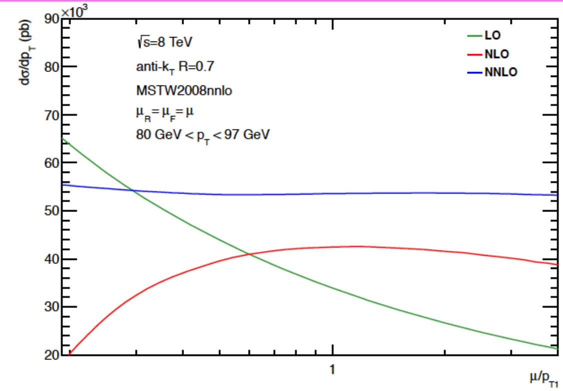


FIG. 2: Scale dependence of the inclusive jet cross section for pp collisions at $\sqrt{s} = 8$ TeV for the anti-k_T algorithm with $R = 0.7$ and with $|y| < 4.4$ and 80 GeV $< p_T <$ 97 GeV at NNLO (blue), NLO (red) and LO (green).

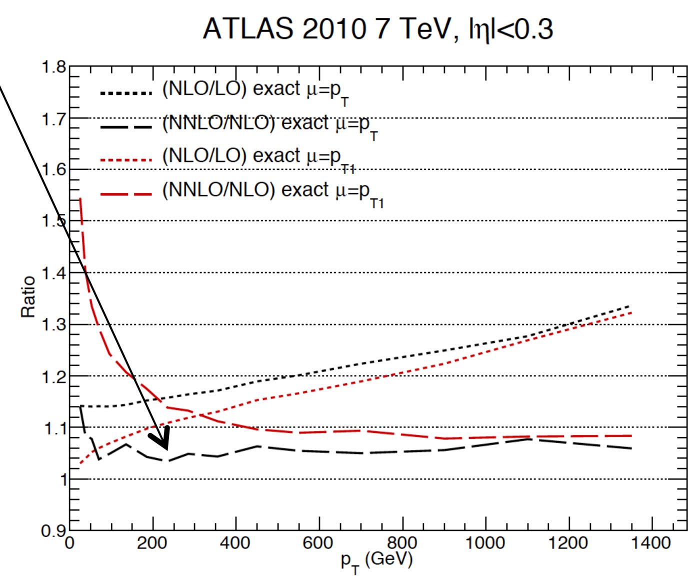
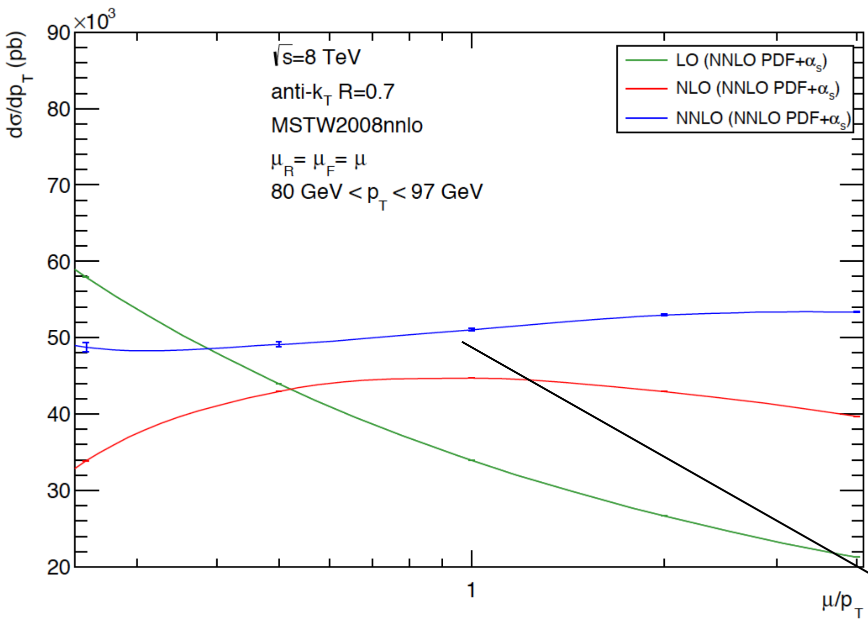


Figure 8: NLO/LO and NNLO/NLO exact k-factors for the gg-channel evaluated with the renormalisation and factorisation scales $\mu_R = \mu_F = p_T$ and $\mu_R = \mu_F = p_{T1}$.

…but, revision of the paper

- The referee made the same request I did, to show the plot to the right using a scale of p_T, rather than p_{T1}



- Note that NLO goes up (as expected) but NNLO also comes down…and a bit more scale dependence

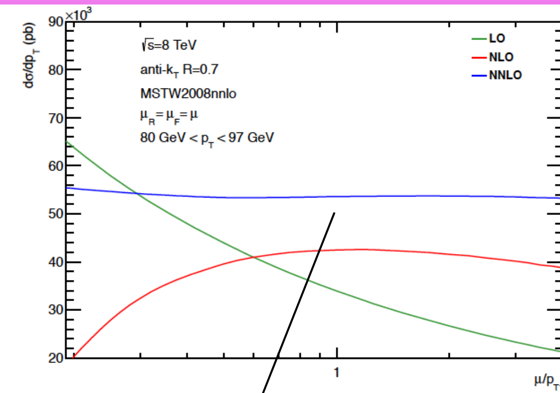


FIG. 2: Scale dependence of the inclusive jet cross section for pp collisions at $\sqrt{s} = 8$ TeV for the anti-k_T algorithm with $R = 0.7$ and with $|y| < 4.4$ and 80 GeV $< p_T <$ 97 GeV at NNLO (blue), NLO (red) and LO (green).

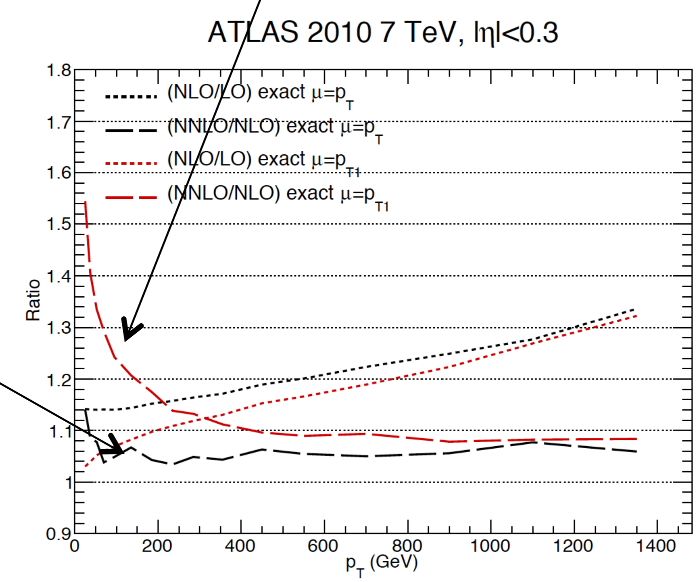


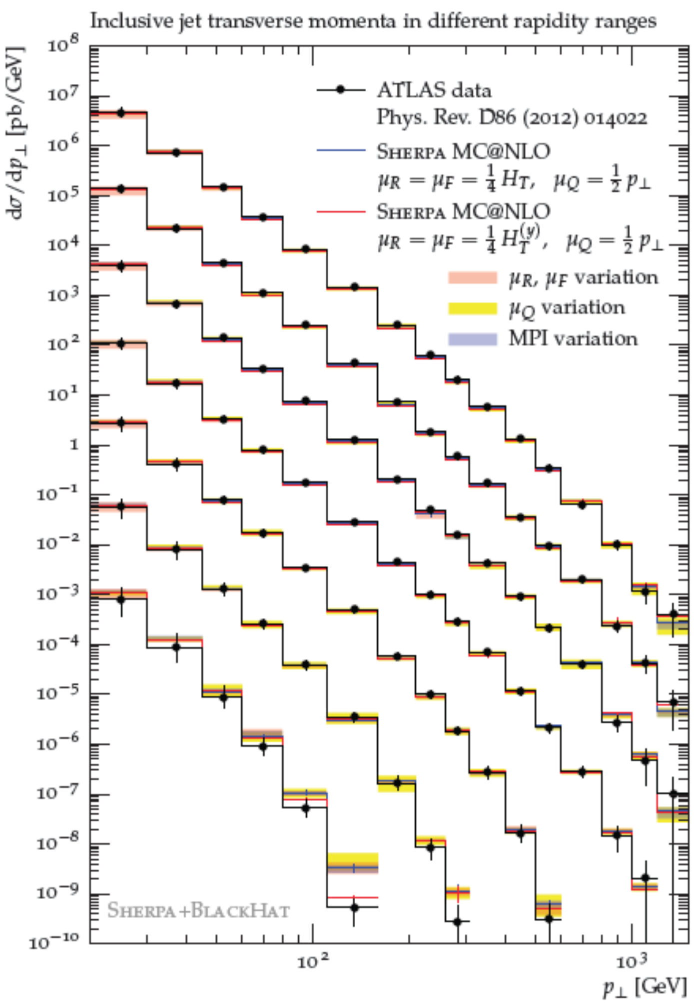
Figure 8: NLO/LO and NNLO/NLO exact k-factors for the gg-channel evaluated with the renormalisation and factorisation scales $\mu_R = \mu_F = p_T$ and $\mu_R = \mu_F = p_{T1}$.

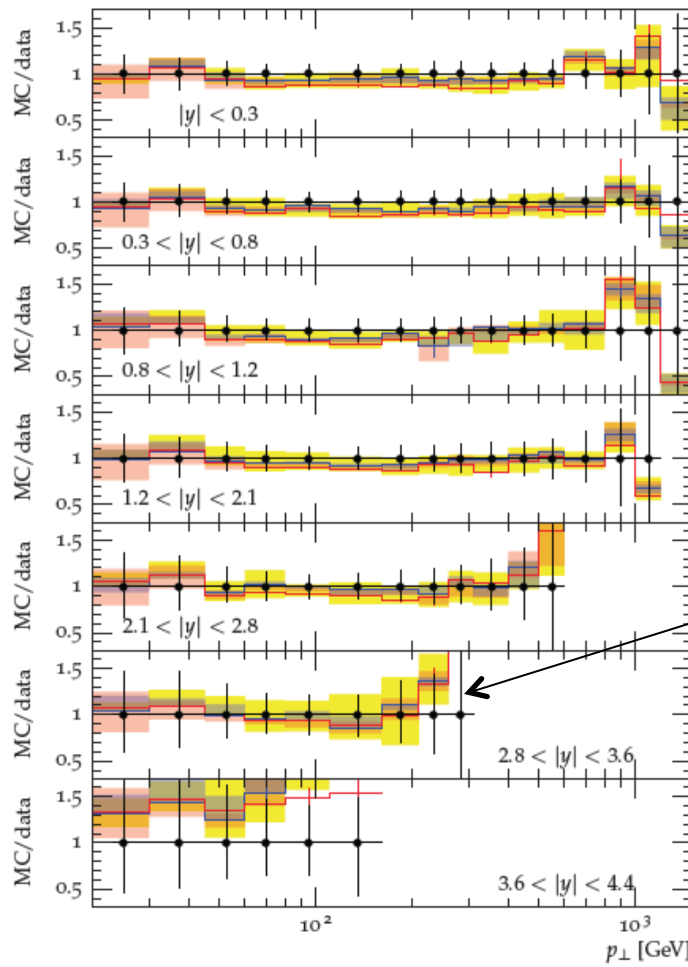
Inclusive jet production

- **We also need a better understanding of the impact of parton showers on the fixed order cross section**

Sherpa MC@NLO seems to do a good job in describing ATLAS data (but PDF dependent statement)

Compare to fixed order with same PDF





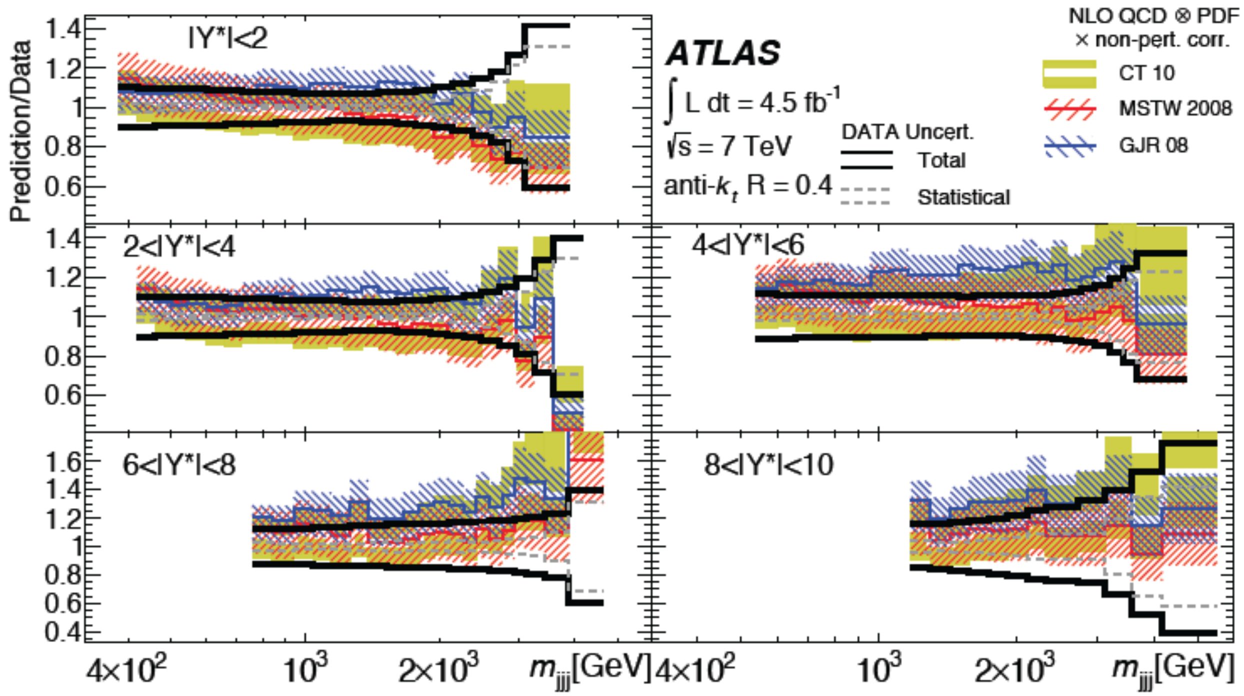
S. Hoeche, Marek Schoenherr for Sherpa; would be useful for other MC's as well

resummation scale uncertainties seem small except at extremes of phase space (as expected)

3 jets

- 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

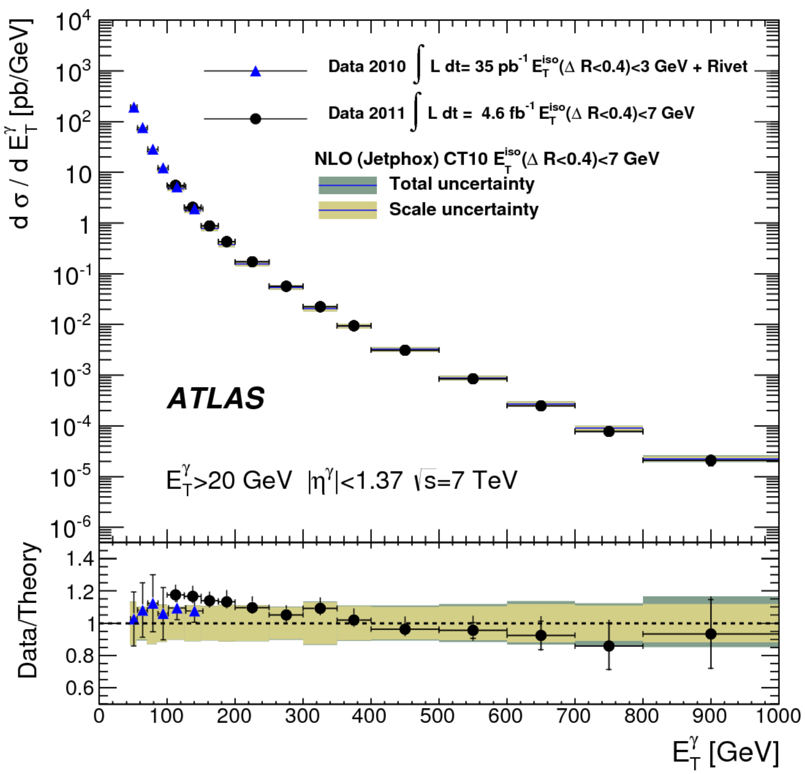
Process	State of the Art	Desired
$t\bar{t}$	σ_{tot}(stable tops) @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW
$t\bar{t}+j(j)$	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
$t\bar{t}+Z$	$d\sigma$(stable 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

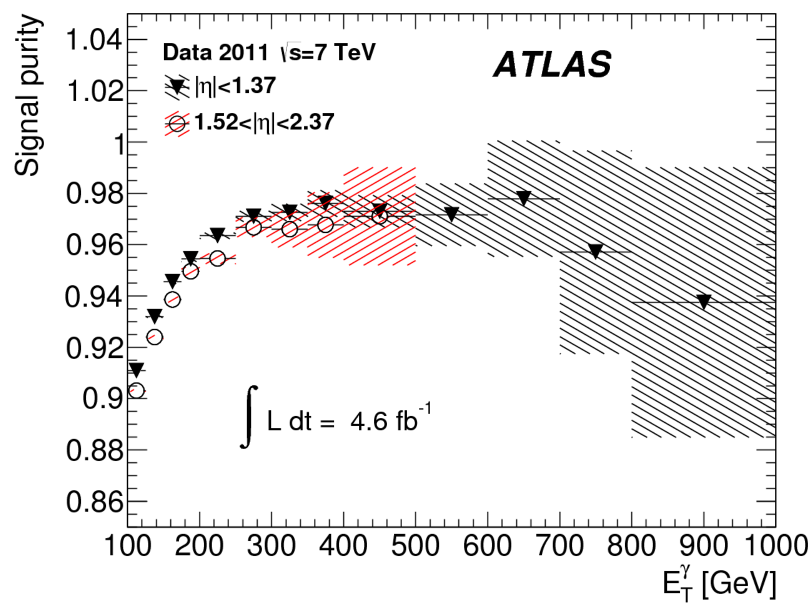


Inclusive photons

- 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 γ+j production at NNLO QCD +NLO EW

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
$\gamma+j$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW





Note any isolated high p_T EM object is a photon …if not in your analysis, then why not

L. Cieri: Paris photon workshop

Les Houches accord 2013

[Les Houches 2013: Physics at TeV Colliders: Standard Model Working Group Report]

"LH tight photon isolation accord"

Can we explore this with more processes?
->Les Houches project

- EXP: use (tight) Cone isolation — solid and well understood
- TH: use smooth cone with same R and E_{Tmax} — accurate, better than using cone with LO fragmentation

Estimate TH isolation uncertainties using different profiles in smooth cone

should work to 1% if fragmentation contribution less than 20%

While the definition of "tight enough" might slightly depend on the particular observable (that can always be checked by a lowest order calculation), our analysis shows that at the LHC isolation parameters as $E_T^{max} \leq 5$ GeV (or $\epsilon < 0.1$), $R \sim 0.4$ and $R_{\gamma\gamma} \sim 0.4$ are safe enough to proceeed.

This procedure would allow to extend available NLO calculations to one order higher (NNLO) for a number of observables, since the direct component is always much simpler to evaluate than the fragmentation part, which identically vanishes under the smooth cone isolation.

Vector bosons

Vector bosons

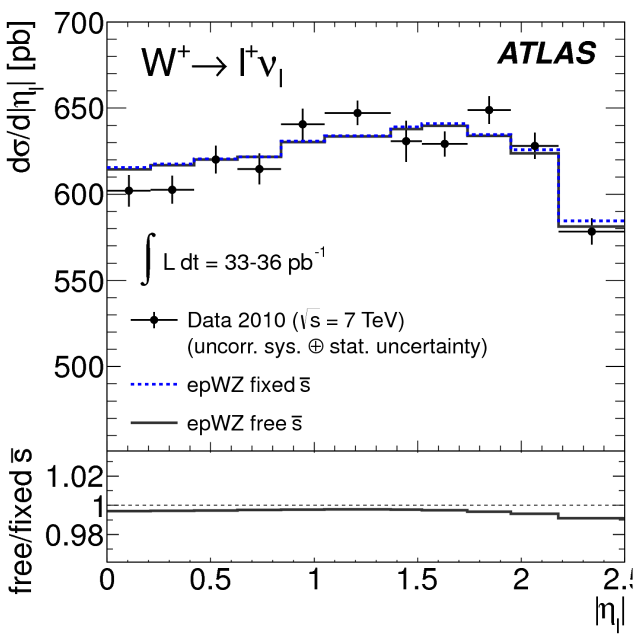
Process	known	desired	details
V	dσ(lept. V decay) @ NNLO QCD dσ(lept. V decay) @ NLO EW	dσ(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
V + j	dσ(lept. V decay) @ NLO QCD dσ(lept. V decay) @ NLO EW	dσ(lept. V decay) @ NNLO QCD + NLO EW	Z + j for gluon PDF W + c for strange PDF
V + jj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

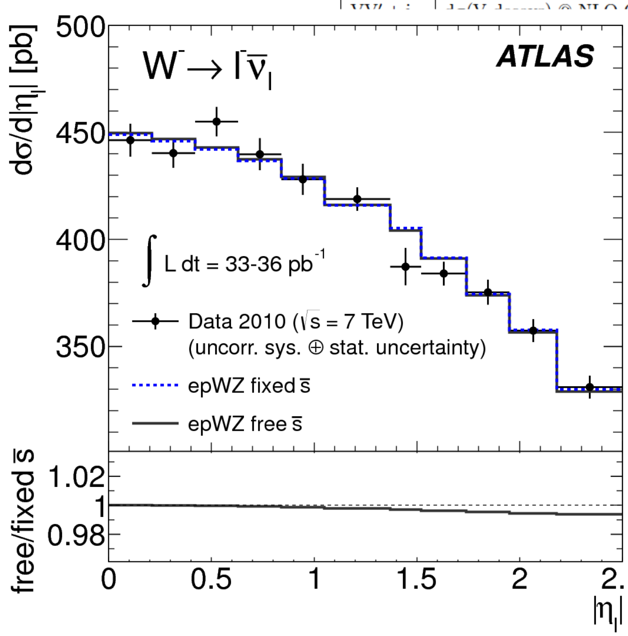
Table 3: Wishlist part 3 – EW gauge bosons (V = W, Z)

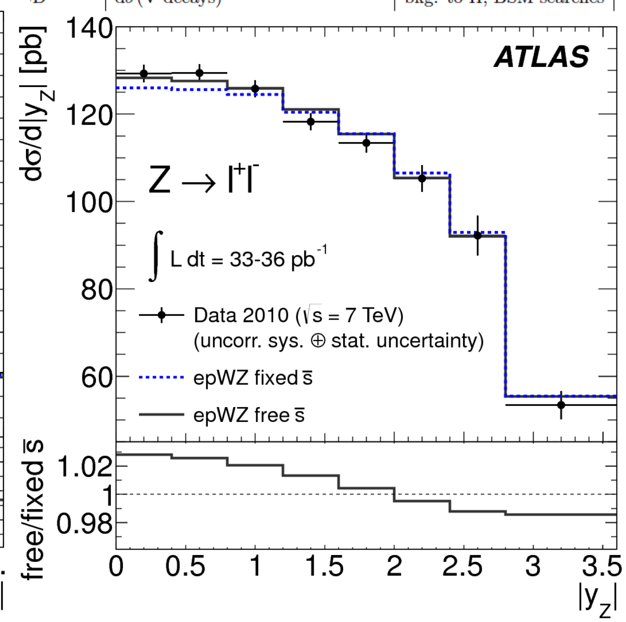
Vector boson production

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



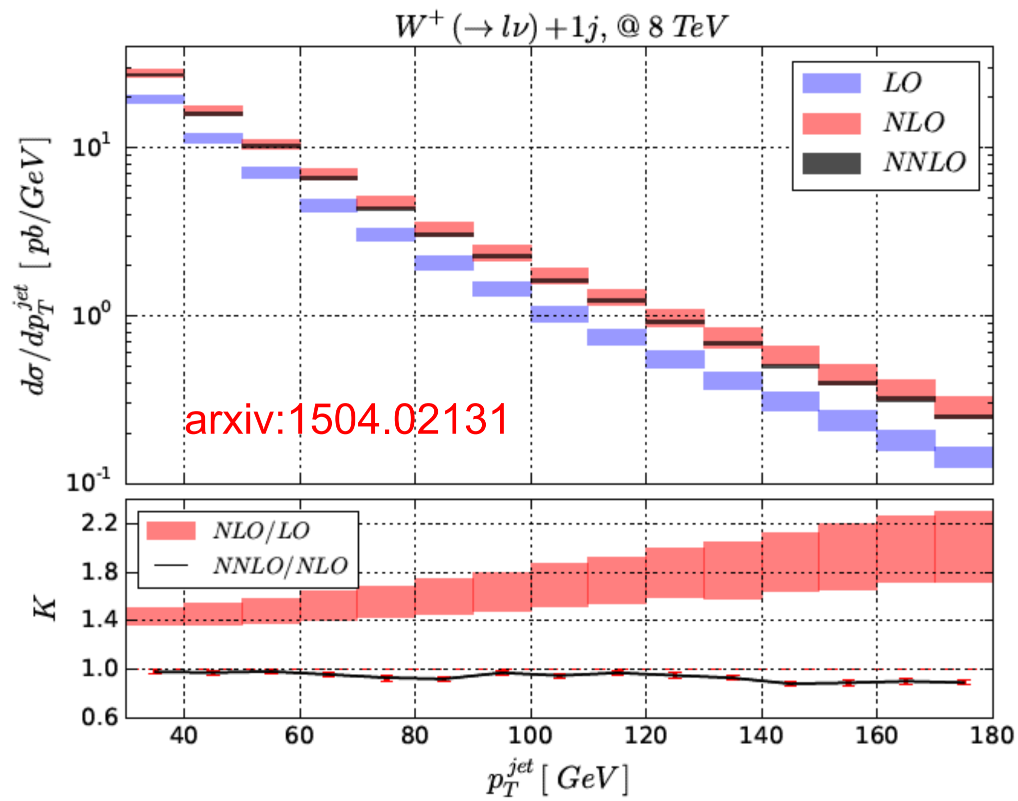




Vector bosons+jets

- 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 W+>=1 jet to NNLO QCD
  - cross section seems very stable
- V+1-5 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

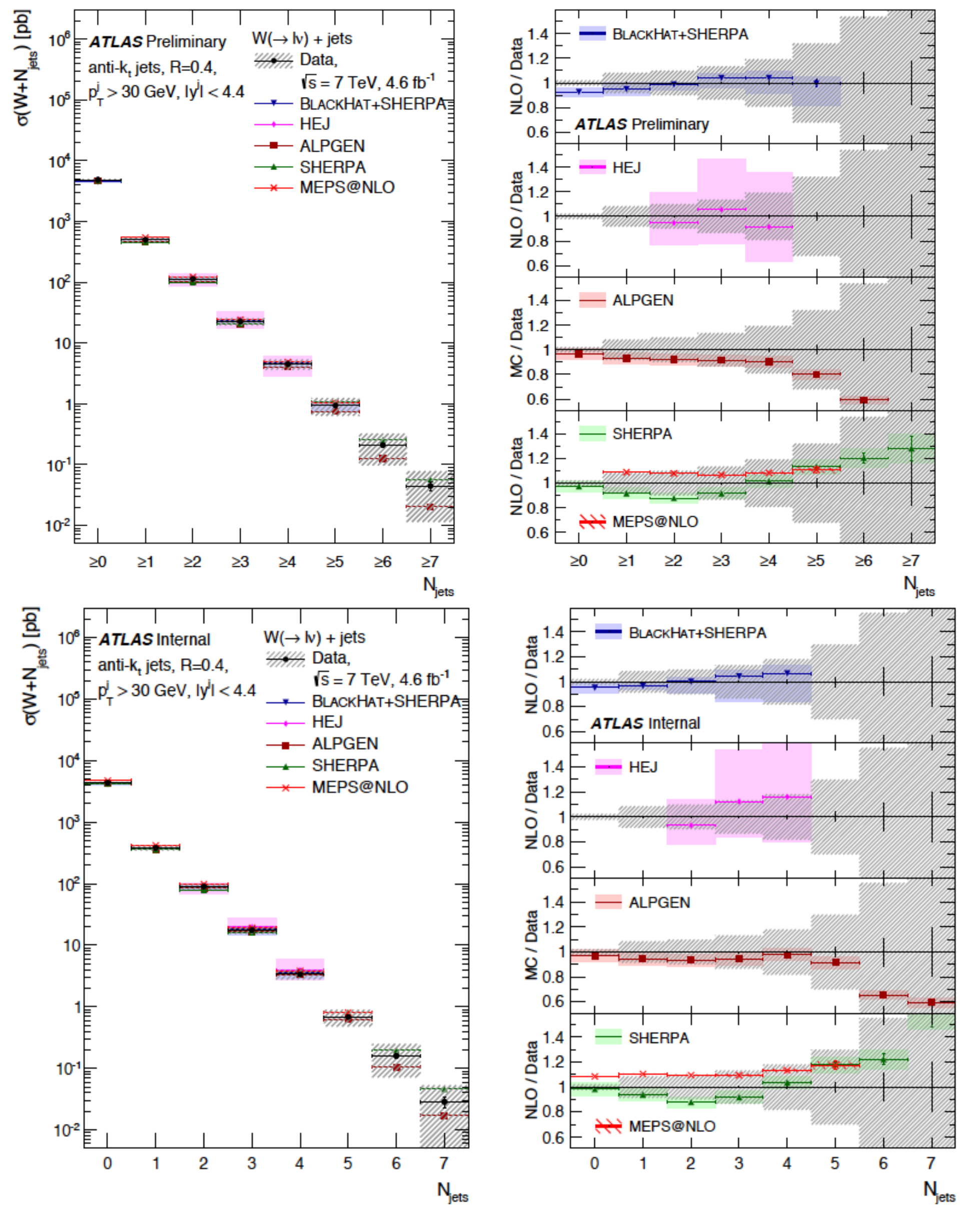
Process	known	desired	details
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
V + j	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	Z + j for gluon PDF W + c for strange PDF
V + jj	$d\sigma$(lept. V decay) @ NLO QCD	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	study of systematics of H + jj final state
VV′	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays)	off shell leptonic decays



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

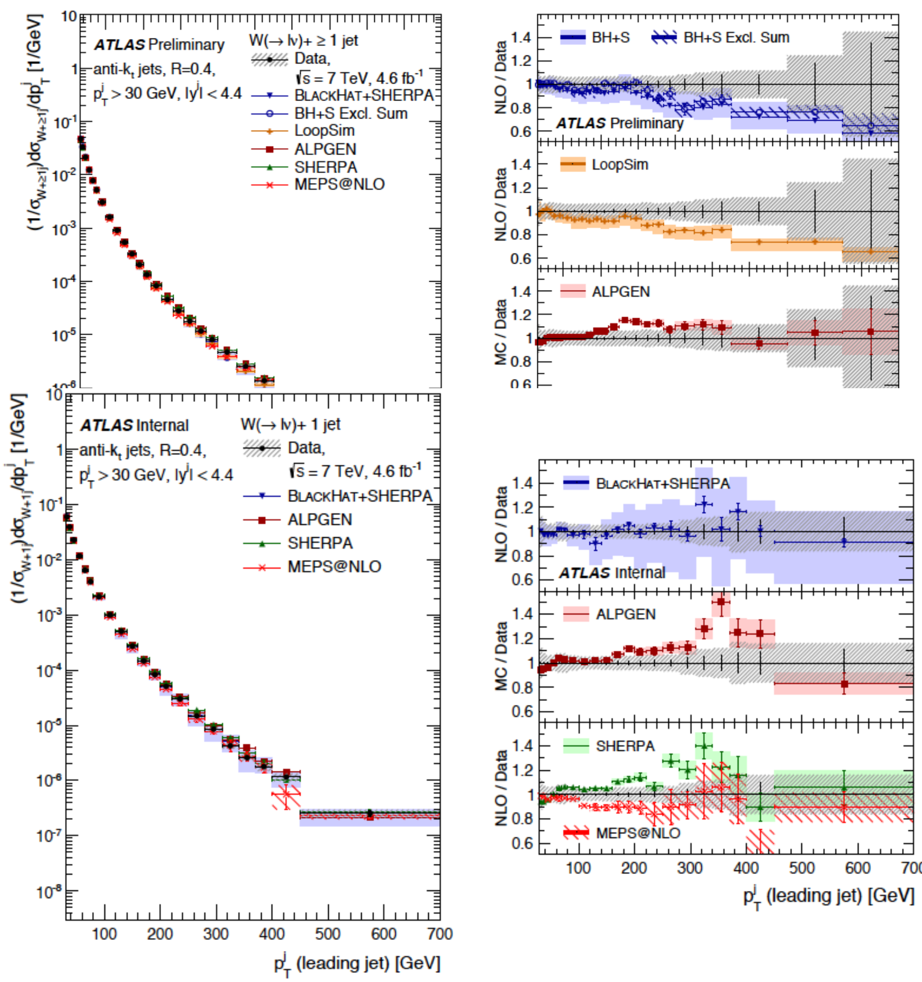
W+jets

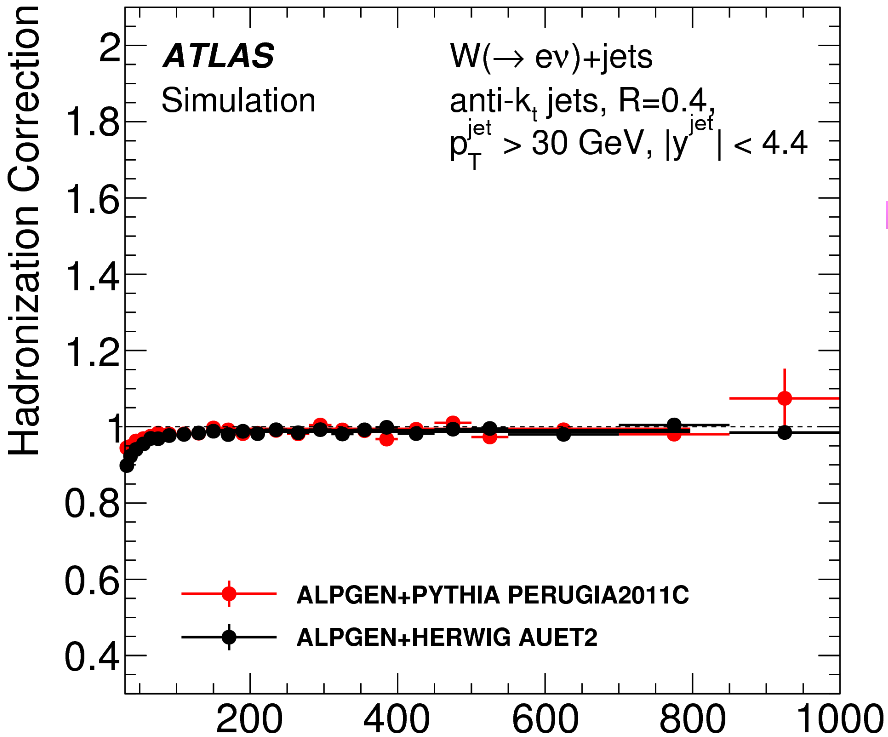
- ATLAS has measured up to 7 jets in the final state
  - both inclusive and exclusive final states
  - good agreement with Blackhat+Sherpa in general
    - with non-perturbative corrections
  - comparisons to a variety of predictions more thoroughly tests physics of process

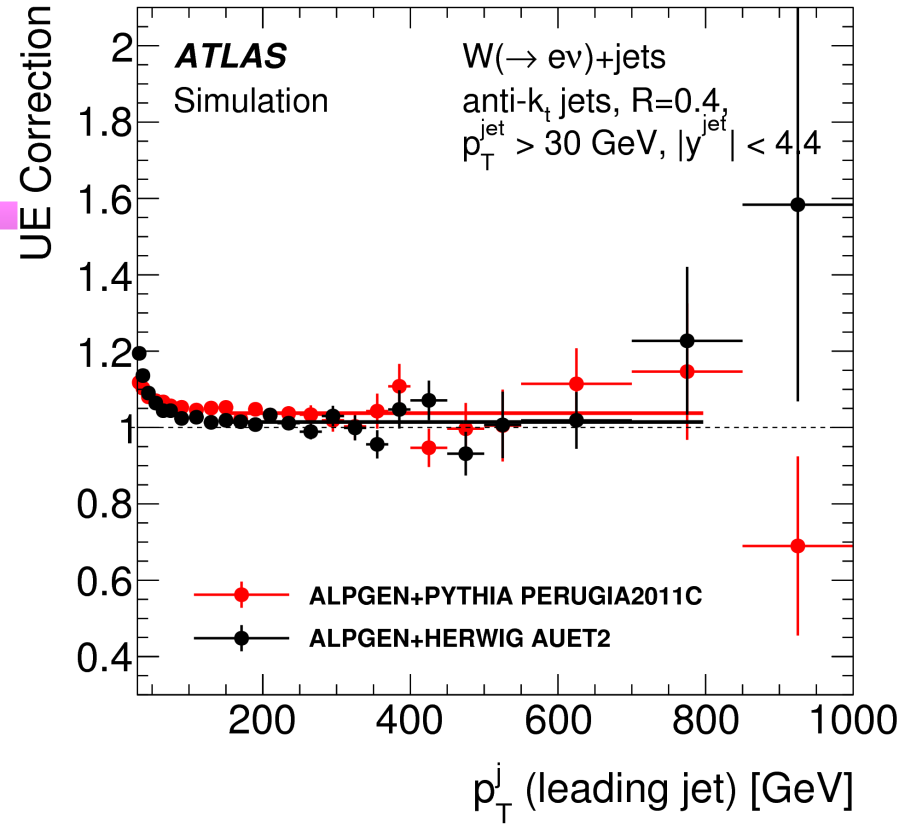


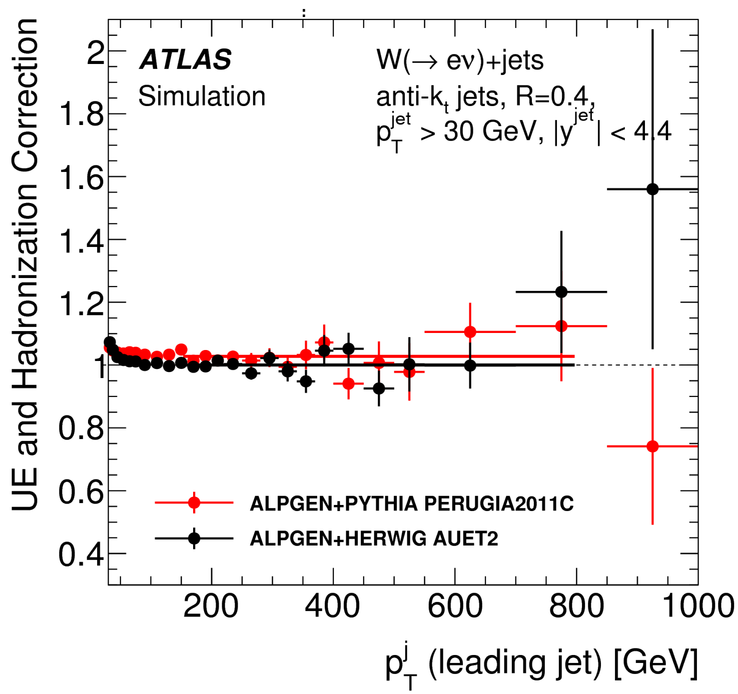
Leading jet p_T

- Inclusive leading jet p_T distribution higher than NLO prediction at high transverse momentum
  - 1 TeV/c!
- Exclusive lead jet p_T agrees very well with NLO prediction up to 700 GeV/c
  - why should fixed order work so well when such an exclusive final state is probed?->jet veto logs
- arXiv:1501.01059
  - R. Boughezal et al
  - due to ATLAS analysis, additional jet allowed if it is collinear to a lepton





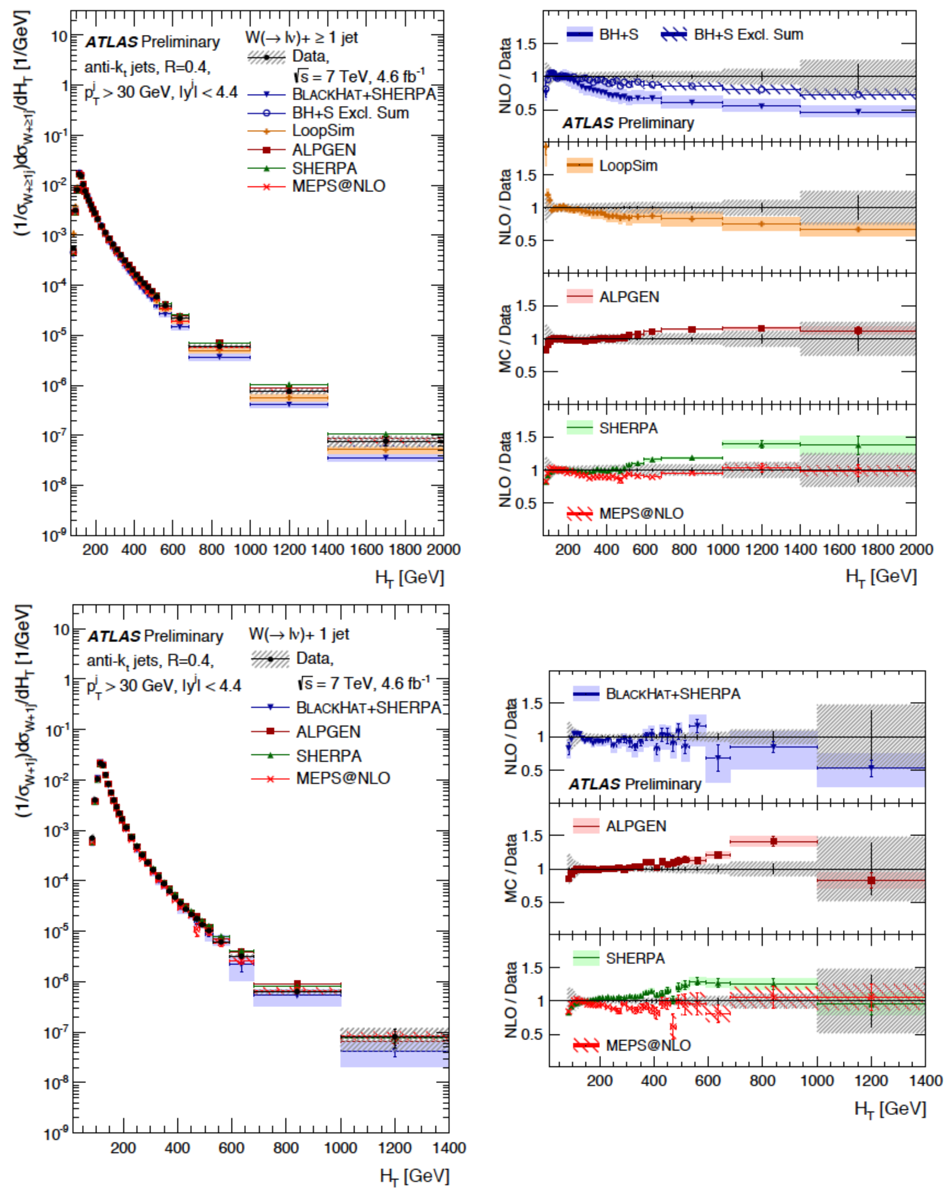




*The net correction is small and dies away quickly with increasing p_T, as expected for power corrections.
*Non-perturbative corrections for higher multiplicity final states are separately (UE and hadronization) but still cancel.

H_T

- NLO substantially below data at high H_T (50% discrepancy)
- Large contributions from qq->qq'W not fully taken into account in W+>=1 jet prediction
- Formalisms in which such contributions are added (LoopSim/exclusive sums) have better agreement with data



Vector boson pairs

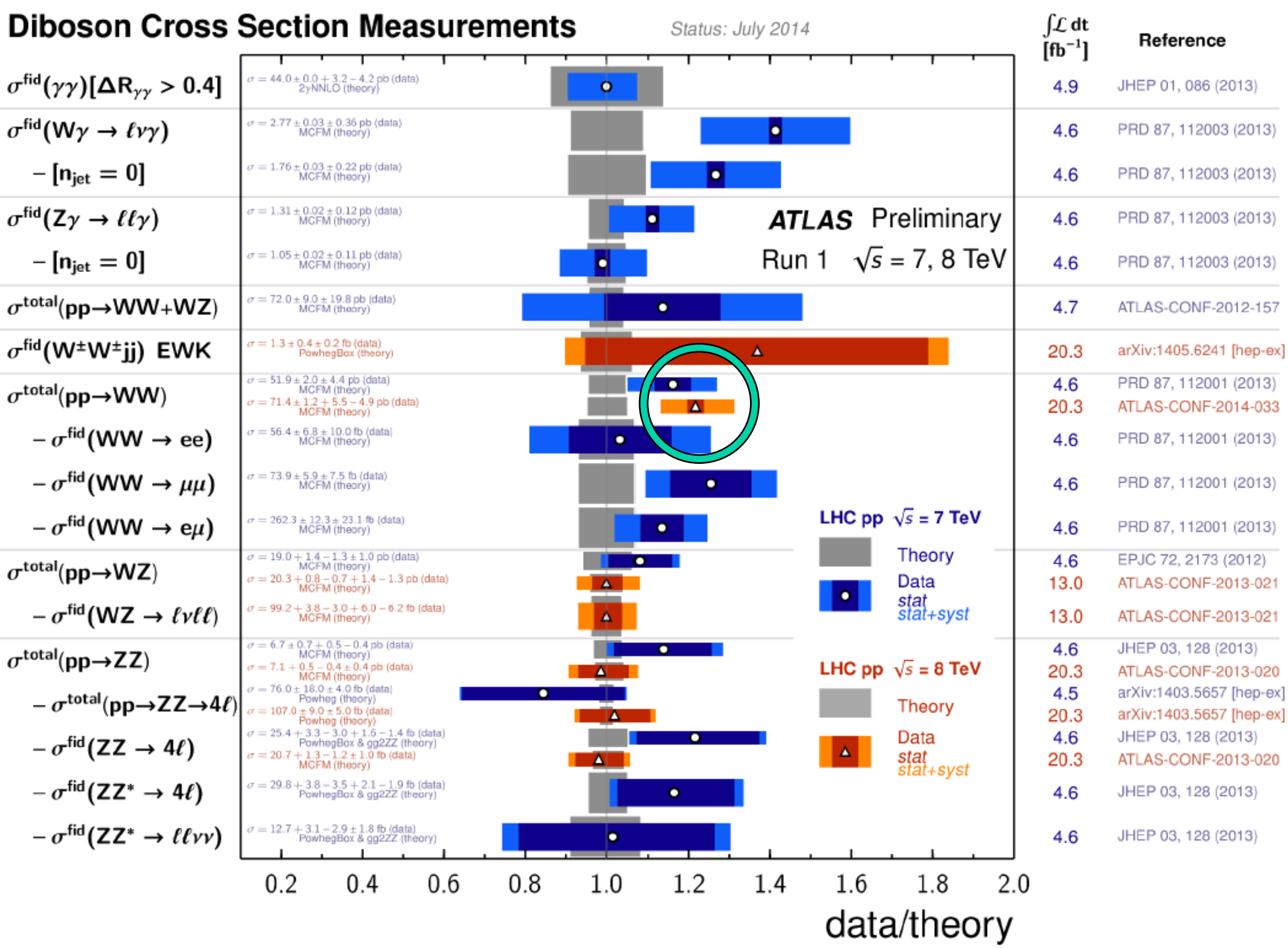
- Provides a handle on the determination of triple gauge couplings, and possible new physics
- Cross sections are known to NLO/ NNLO QCD (with V decays) and to NLO EW (with on-shell V's)
- WZ cross sections currently have a (non-luminosity) uncertainty of the order of 10%
  - will decrease in Run 2 of course
- 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	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
$V + j$	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	$Z + j$ for gluon PDF $W + c$ for strange PDF
$V + jj$	$d\sigma$(lept. V decay) @ NLO QCD	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	study of systematics of $H + jj$ final state
VV'	$d\sigma$(V decays) @ NLO QCD $d\sigma$(stable V) @ NLO EW	$d\sigma$(V decays) @ NNLO QCD + NLO EW	off-shell leptonic decays TGCs
$gg \to VV$	$d\sigma$(V decays) @ LO QCD	$d\sigma$(V decays) @ NLO QCD	bkg. to $H \to VV$ TGCs
$V\gamma$	$d\sigma$(V decay) @ NLO QCD $d\sigma$(PA, V decay) @ NLO EW	$d\sigma$(V decay) @ NNLO QCD + NLO EW	TGCs
$Vb\bar{b}$	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD massless b	bkg. for $VH \to b\bar{b}$
$VV'\gamma$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs
$VV'V''$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
$VV' + j$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	bkg. to H, BSM searches
$VV' + jj$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
$\gamma\gamma$	$d\sigma$ @ NNLO QCD		bkg to $H \to \gamma\gamma$

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

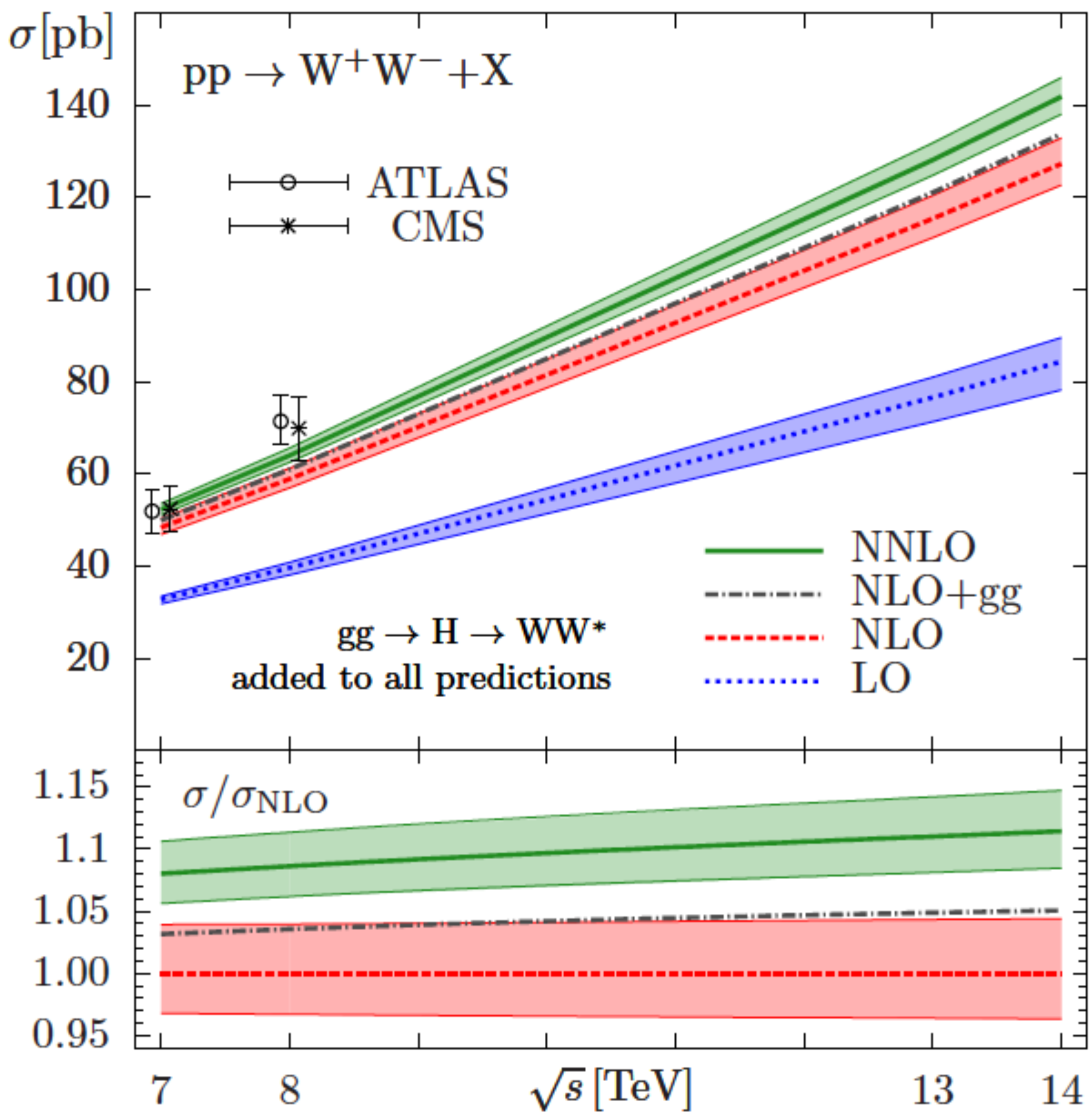
We also rely on theoretical predictions of VV* for Higgs measurements in that decay channel.

ATLAS diboson cross sections



…but arxiv:1408.5243

- NNLO calculation of WW production recently completed
- Modest increase in size of cross section
- Decrease in size of excess
- QCD issues with extrapolation of jet vetoed cross section to full cross section mean that uncertainty is larger than assumed in experimental papers



arXiv:1410.4745

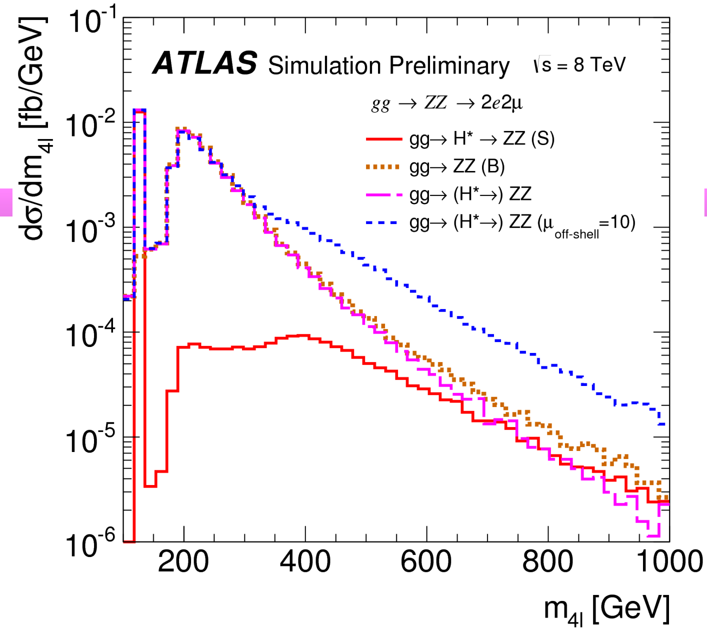
Fiducial cross sections in agreement with NNLO+NNLL. Powheg provides too large of an extrapolation from fiducial to full inclusive.

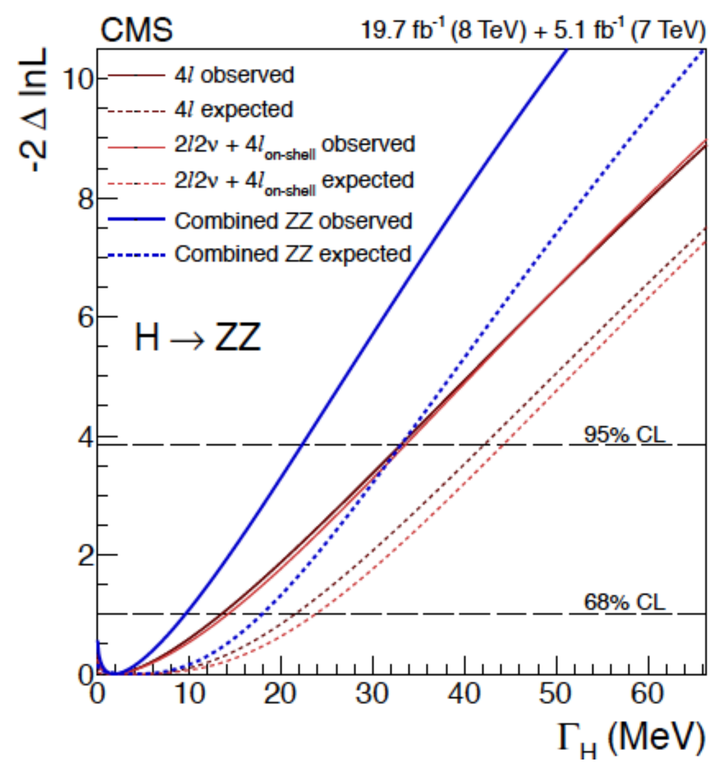
decay mode	$\sigma^{\text{exp.}}_{\text{fid.}}$ [fb]	$\sigma^{\text{th.}}_{\text{fid.}}$ [fb]
$e^+\mu^- + e^-\mu^+$	$377.8^{+6.9}_{-6.8}(\text{stat.})^{+25.1}_{-22.2}(\text{syst.})^{+11.4}_{-10.7}(\text{lumi.})$	$357.9^{+14.4}_{-14.4}$
e^+e^-	$68.5^{+4.2}_{-4.1}(\text{stat.})^{+7.7}_{-6.6}(\text{syst.})^{+2.1}_{-2.0}(\text{lumi.})$	$69.0^{+2.7}_{-2.7}$
$\mu^+\mu^-$	$74.4^{+3.3}_{-3.2}(\text{stat.})^{+7.0}_{-6.0}(\text{syst.})^{+2.3}_{-2.1}(\text{lumi.})$	$75.1^{+3.0}_{-3.0}$

Table 4 Comparison between the measured fiducial cross section and the theory prediction with estimated NNLL+NNLO effects. Theory uncertainties have been symmetrized and combined in quadrature.

gg->VV

- 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%
- ZZ needed for determination of off-shell Higgs boson signal strength in high-mass ZZ final state
  - interferes with gg->H->ZZ$^{(*)}$
- Currently subprocess is known (with lepton decays) at LO QCD
- Need to know to NLO QCD
  - arXiv:1503.0127 for two loop gg->ZZ with heavy top mass
  - arXiv:1503.08759, arXiv: 1503.08835 for two-loop massless case
  - **what about putting it all together?**





Vector boson + photon

- 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 Vγ
- Experimental uncertainties are on the order of 10% and theoretical errors on the order of 5-10%
- Currently, Wγ production is known (with decays) at NNLO QCD, Zγ 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

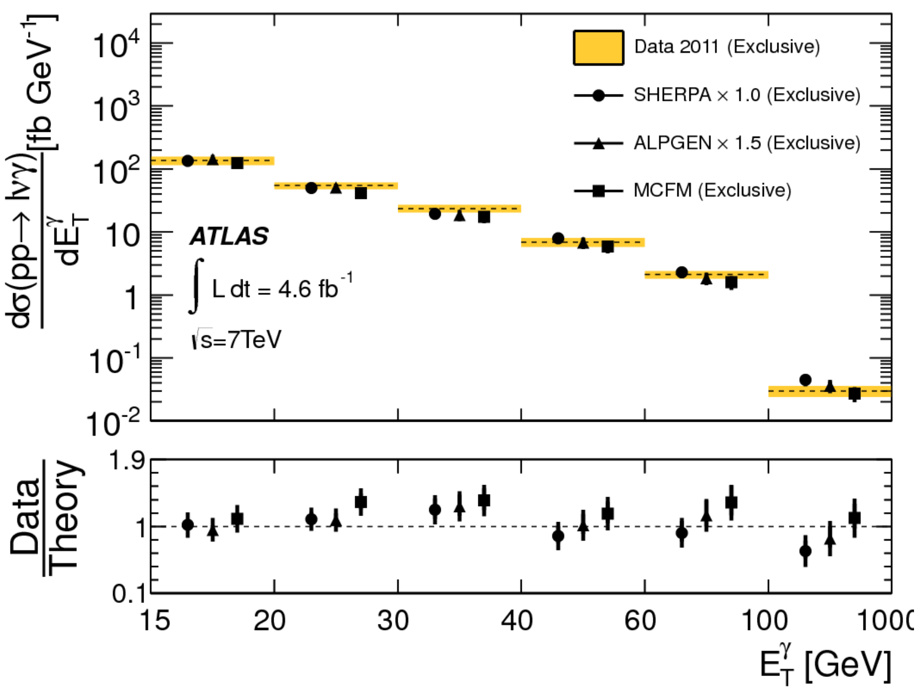
Process	known	desired	details
V	dσ(lept. V decay) @ NNLO QCD dσ(lept. V decay) @ NLO EW	dσ(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
V + j	dσ(lept. V decay) @ NLO QCD dσ(lept. V decay) @ NLO EW	dσ(lept. V decay) @ NNLO QCD + NLO EW	Z + j for gluon PDF W + c for strange PDF
V + jj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

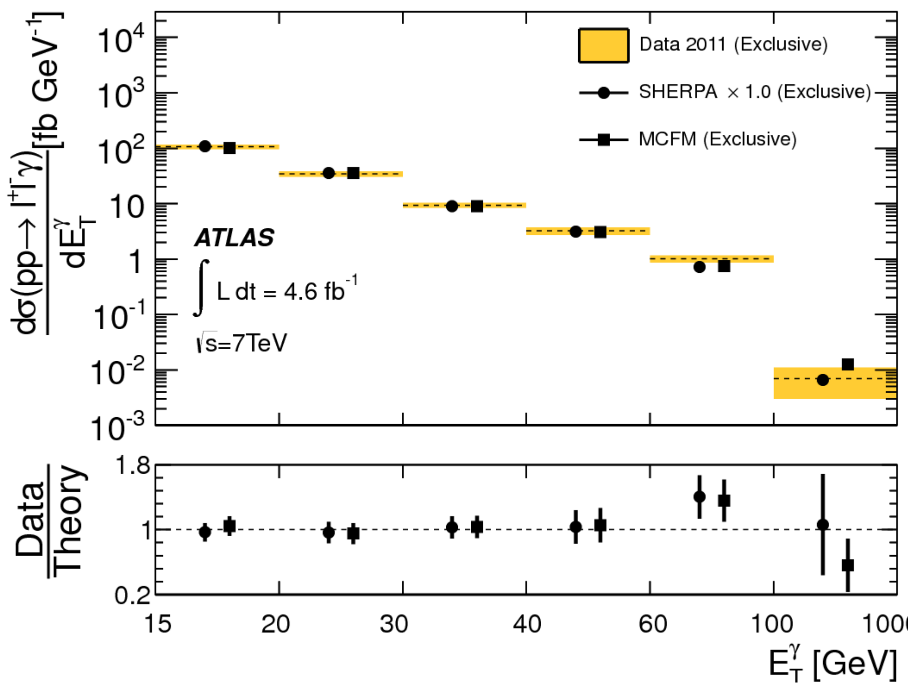
Table 3: Wishlist part 3 – EW gauge bosons (V = W, Z)

Vector boson + photon

- 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 Vγ

VV'	$d\sigma$(V decays) @ NLO QCD $d\sigma$(stable V) @ NLO EW	$d\sigma$(V decays) @ NNLO QCD + NLO EW	off-shell leptonic decays TGCs
$gg \to VV$	$d\sigma$(V decays) @ LO QCD	$d\sigma$(V decays) @ NLO QCD	bkg. to $H \to VV$ TGCs
$V\gamma$	$d\sigma$(V decay) @ NLO QCD $d\sigma$(PA, V decay) @ NLO EW	$d\sigma$(V decay) @ NNLO QCD + NLO EW	TGCs
Vbb	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD massless b	bkg. for $VH \to b\bar{b}$

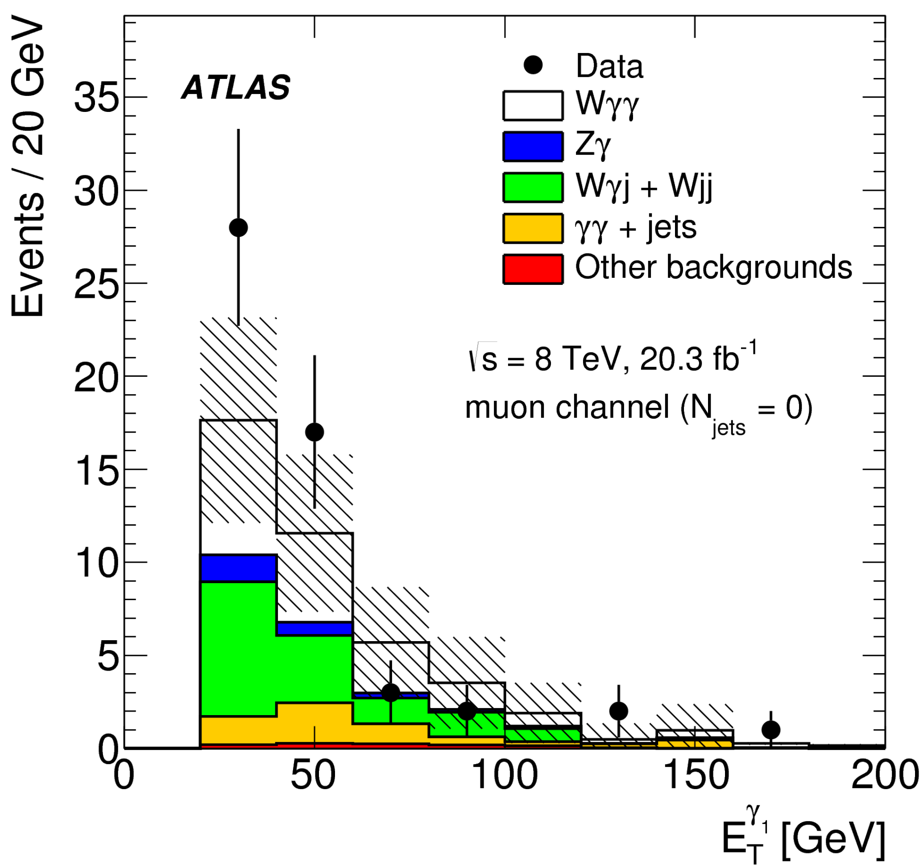


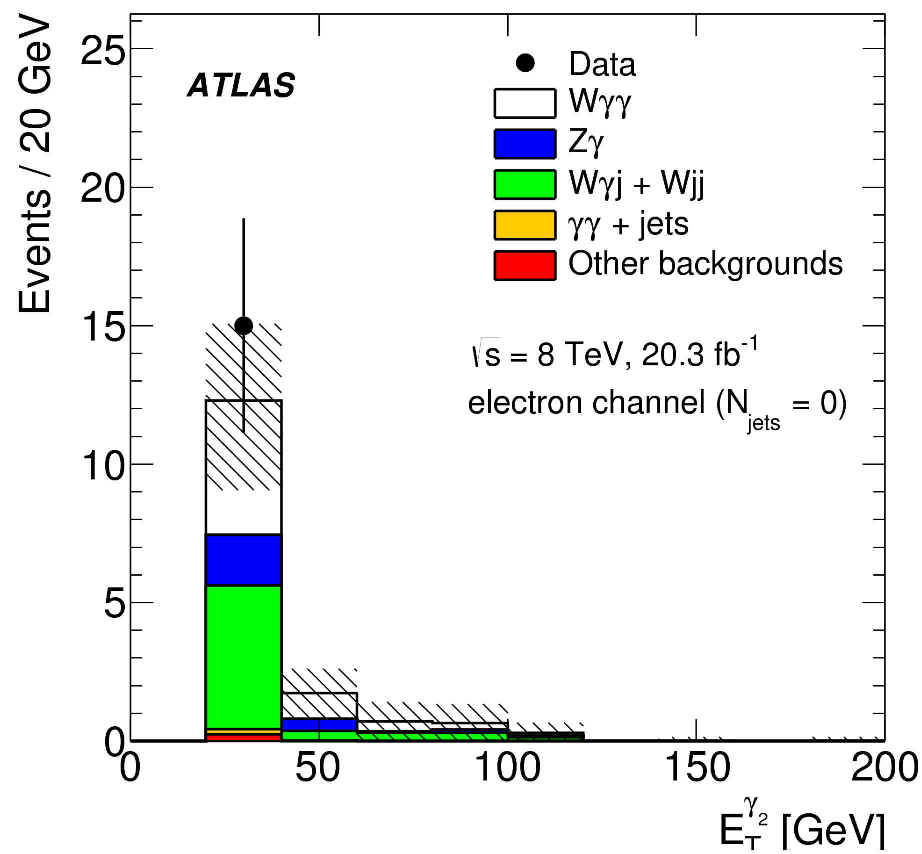


Vector boson + photons

- Evidence for $W\gamma\gamma$ production

VV'	$d\sigma$(V decays) @ NLO QCD $d\sigma$(stable V) @ NLO EW	$d\sigma$(V decays) @ NNLO QCD + NLO EW	off-shell leptonic decays TGCs
$gg \to VV$	$d\sigma$(V decays) @ LO QCD	$d\sigma$(V decays) @ NLO QCD	bkg. to $H \to VV$ TGCs
$V\gamma$	$d\sigma$(V decay) @ NLO QCD $d\sigma$(PA, V decay) @ NLO EW	$d\sigma$(V decay) @ NNLO QCD + NLO EW	TGCs
Vbb	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD massless b	bkg. for $VH \to b\bar{b}$



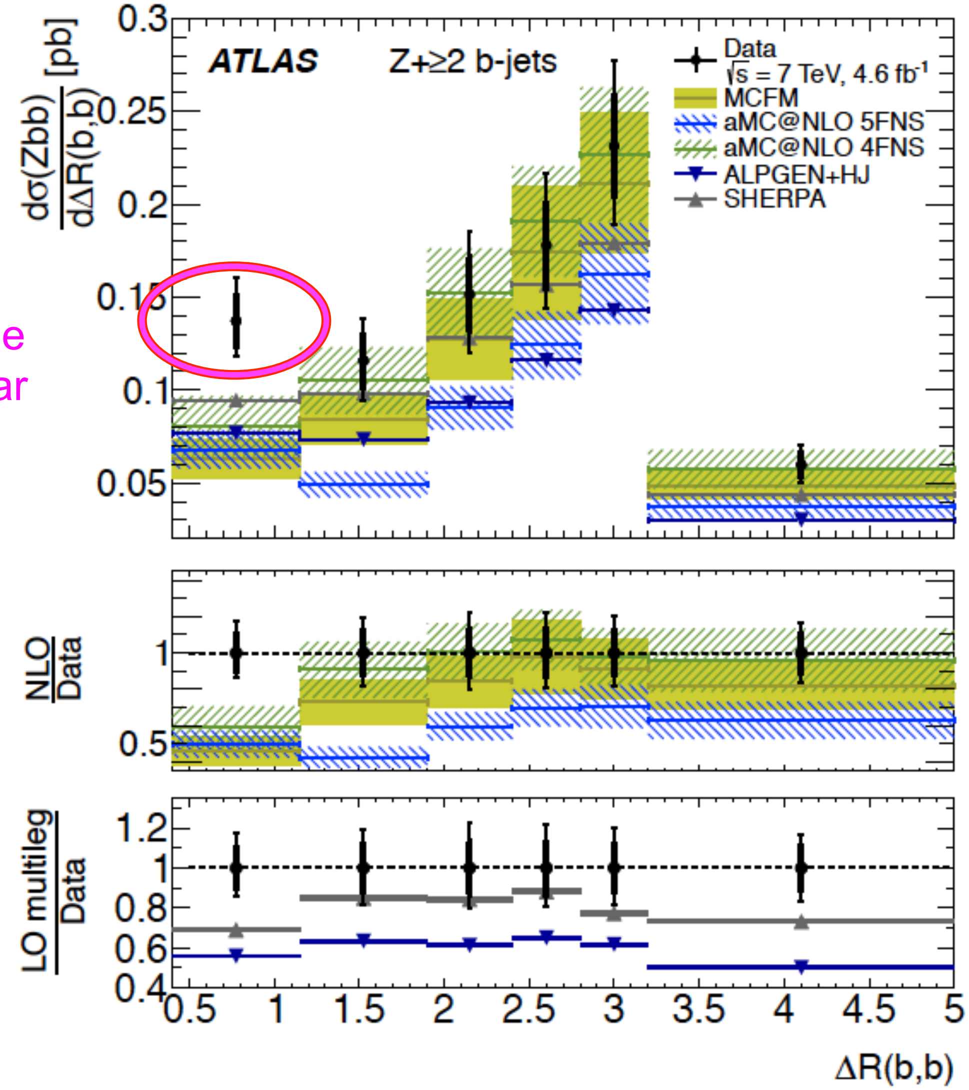


VbB

- Associated Higgs production, with Higgs decaying into bB is key to understanding Higgs couplings to b-quarks
- VbB 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

	$d\sigma$(PA, V decay) @ NLO EW	@ NNLO QCD + NLO EW	
$Vb\bar{b}$	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD massless b	bkg. for $VH \to b\bar{b}$
$VV'\gamma$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays)	QGCs

better knowledge of collinear gluon splitting needed?



VVV

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

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

VVj(j)

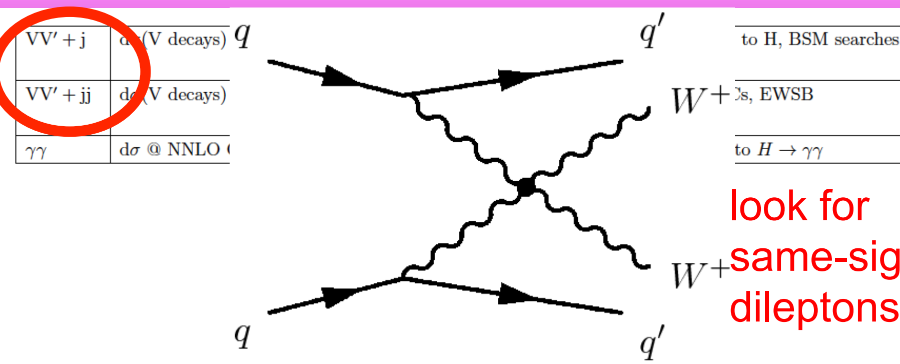
- VV'+j(j) currently known to NLO QCD
- VV'+j useful as a background to Higgs boson production and for BSM searches
- VV'+jj production contains EW vector boson scattering subprocess that is particularly sensitive to EW quartic gauge couplings and to details of EW symmetry breaking
- EW corrections to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

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

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

VV’jj

- 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



look for same-sign dileptons

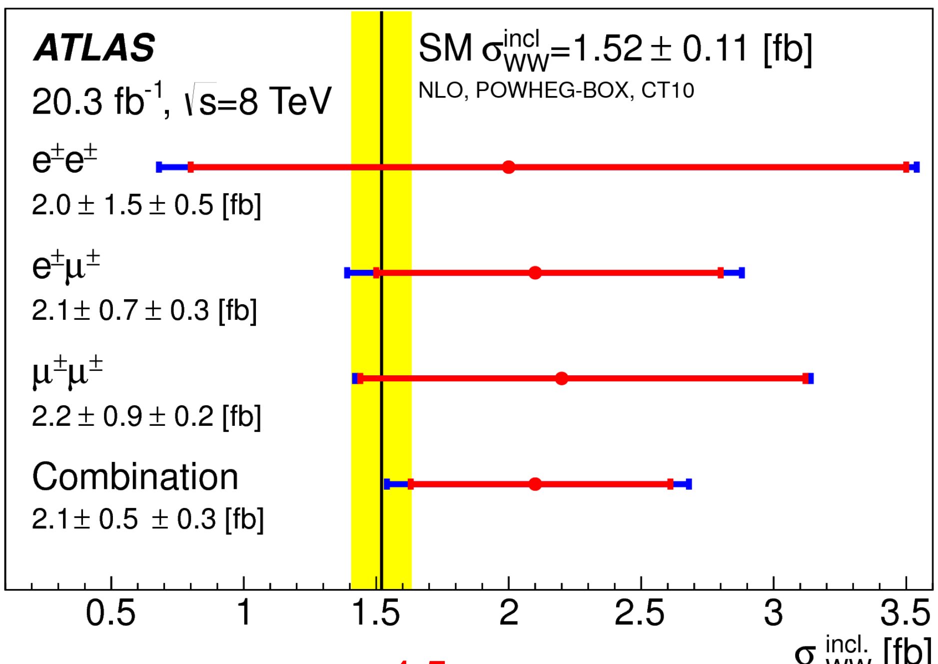
VVj(j)

- 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

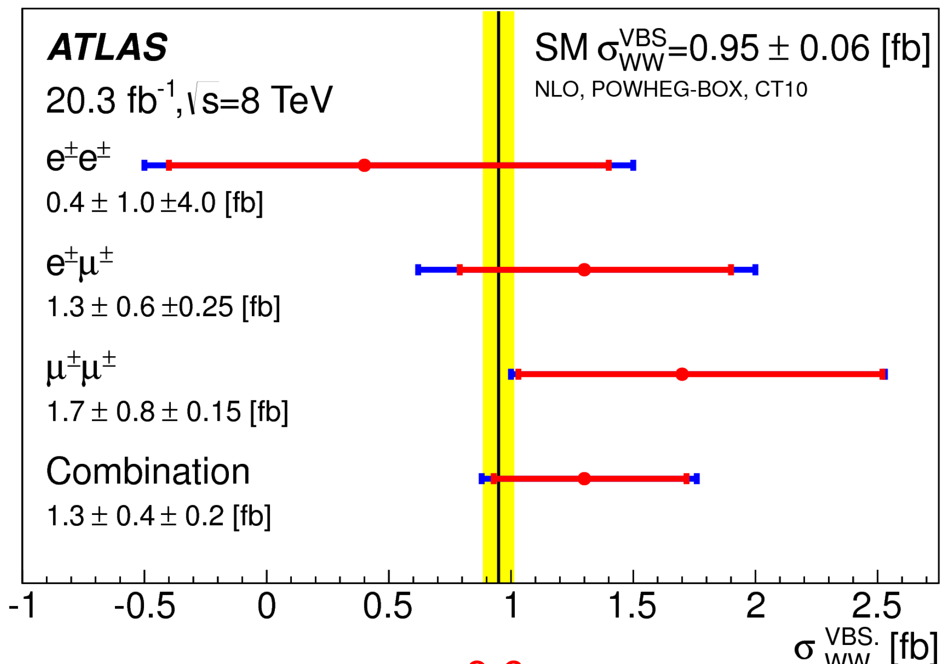
VV' + j	dσ(V decays) @ NLO QCD	dσ(V decays) @ NLO QCD + NLO EW	bkg. to H, BSM searches
VV' + jj	dσ(V decays) @ NLO QCD	dσ(V decays) @ NLO QCD + NLO EW	QGCs, EWSB
γγ	dσ @ NNLO QCD		bkg to $H \to \gamma\gamma$

	Inclusive Region			VBS Region		
	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$
Prompt	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5
Conversions	3.2 ± 0.7	2.4 ± 0.8	–	2.1 ± 0.5	1.9 ± 0.7	–
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19
$W^\pm W^\pm jj$ Strong	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08
$W^\pm W^\pm jj$ Electroweak	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4
Total background	6.8 ± 1.2	10.3 ± 2.0	3.0 ± 0.6	5.0 ± 0.9	8.3 ± 1.6	2.6 ± 0.5
Total predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8
Data	12	26	12	6	18	10

TABLE II: Estimated background yields, observed number of data events, and predicted signal yields for the three channels are shown with their systematic uncertainty. Contributions due to interference are included in the $W^\pm W^\pm jj$ electroweak prediction.



4.5σ

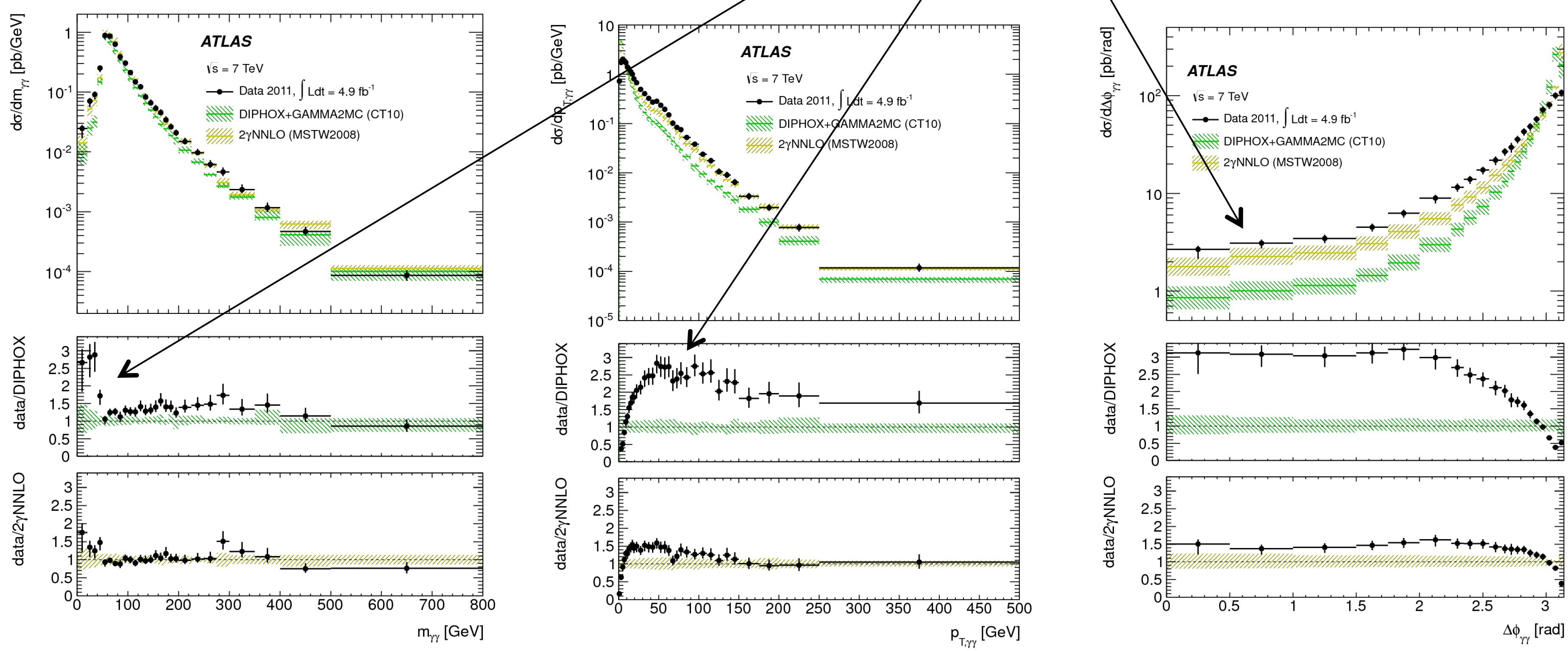


3.6σ

Diphoton production

- 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 $\gamma\gamma$

importance of higher multiplicity contributions clear in some corners of phase space



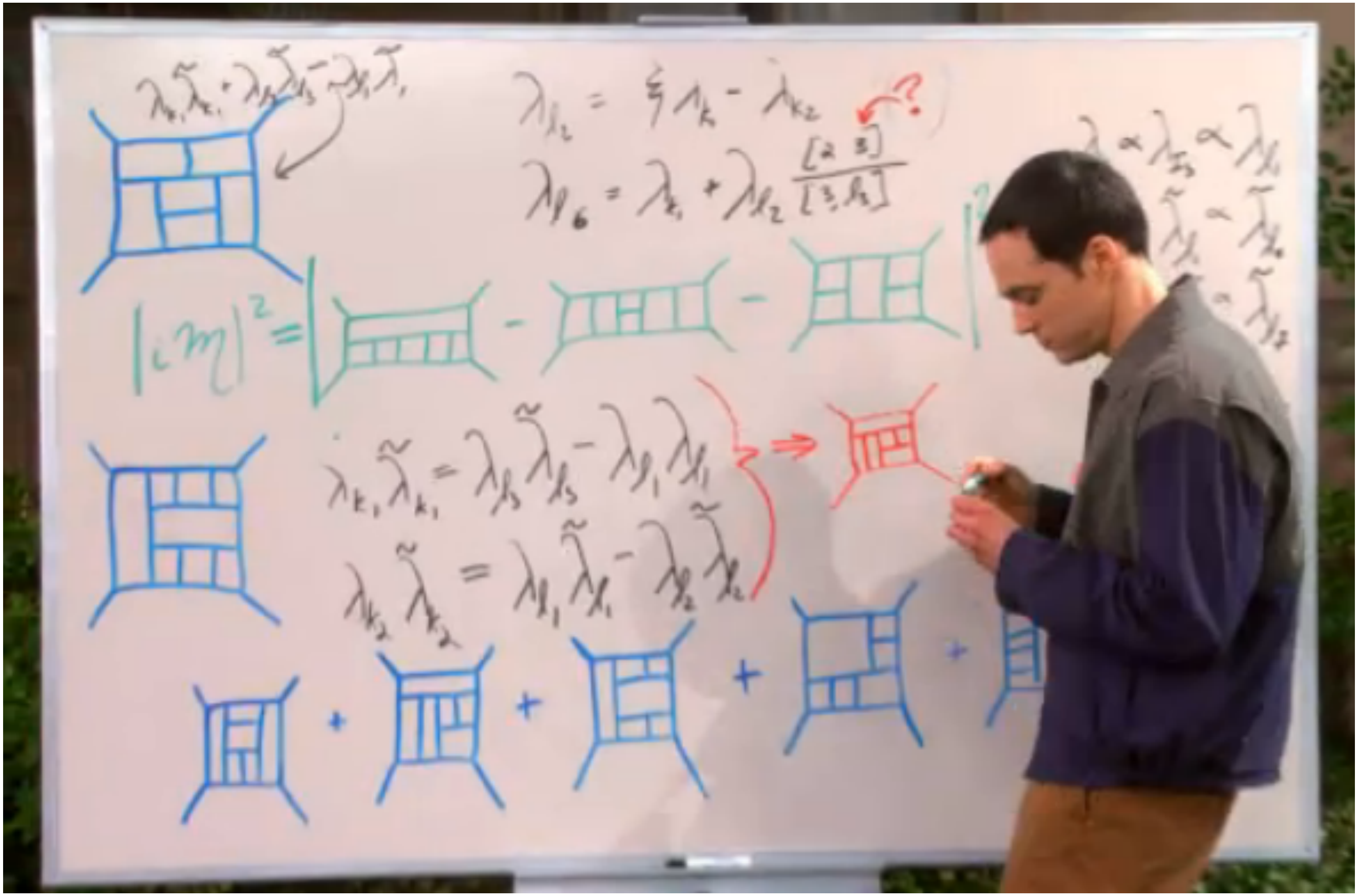
NNLO QCD + NLO EWK wishlist

- 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
- …he was insulted that he was only offered a talk in a parallel session

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

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

The frontier



Summary

- The new high precision Les Houches wishlist presents some real (and important) challenges for QCD and EW calculators
  - **in 2015, we will take another look at the wishlist, setting some priorities, perhaps modifying some requests**
- The data to be taken in Run 2 by ATLAS and CMS requires the effort
- Don't delay
- …and just remember

Summary


Because you know it's all about that
Higgs, 'Bout that Higgs, no SUSY
REGAN

Some more slides from Les Houches

Updating the PDF4LHC prescription

- We are working on an updated prescription, at NNLO and NLO, using information from CT14, MMHT14, NNPDF3.0, that have similar theoretical treatments/data sets
- We are currently examining two techniques for reducing the number of error PDFs needed
  - Hessian
    - META PDFs
    - MC2Hessian
  - Compression
    - CMC PDFs

Note that measurements should be compared to individual PDFs. Error PDFs derived in this way are useful when a more general definition of the PDF uncertainty is required.

Specialized PDFs can also be made available, i.e. to look at directions sensitive to Higgs physics, W mass, etc.

- See for example the presentation and discussion from PDF4LHC meeting in April
  - https://indico.cern.ch/event/355287/
- …and the one here last Thursday
  - https://indico.cern.ch/event/399439/
- Followup meeting later this month at CERN; paper in preparation

Scale determination (and uncertainty)

- We (almost universally) use a scale of $H_T/2$ for complex fixed order calculations, and the scale seems to work well, with variations a factor of 2 up and down to give uncertainties
- However, the optimal scale choice depends on kinematics and factors such as the jet size/algorithm
- **Can we understand this scale choice better for example through an implementation of the MINLO procedure in fixed order ntuples?**
  - **implementation in progress (S. Badger and D. Maitre)**
- **Can we adapt LoopSim to provide ~NNLO predictions for final states for which such calculations are not available?**
  - **implementation available for NLO ntuples (S. Badger)**
  - **how well does it work for states for which NNLO is available?**
    - **comparison with NNLO numbers from F. Petriello in progress**

Ntuple discussion

- As mentioned in the introductory talk, B+S ntuple format now universal among fixed order NLO calculations
- Want to be able to pipe Ntuples into Rivet, keeping track of correlated weight information; allows comparisons, for example Higgs+>=1 jet

New in twiki

Rivet for correlated weights

David Grellscheid and Daniel Maitre tested the feature of the new Rivet version that allows correlated weights to be taken into account correctly in Rivet analyses. This new feature allows to pipe nTuples directly into Rivet. An example implementation and the updated nTupleReader library is attached.

nTuple2Rivet program

nTupleReader library

The program can be called with

```
nTuple2Rivet RIVET_ANALYSIS_NAME nTupleFile1.root nTupleFile2.root ....
```

and will create a RIVET_ANALYSIS_NAME.yoda file with the analysis histograms.

This only works for a new version of Rivet.

Wu Ki Tung Award for Early Career Research on QCD

- See 2015 information at

http://tigger.uic.edu/~varelas/tung_award/

- 2014 winner: Stefan Hoeche
- Contribute at

https://www.givingto.msu.edu/gift/?sid=1480

- **MSU will match any donations**