Precision Physics at the LHC: yesterday, today and tomorrow

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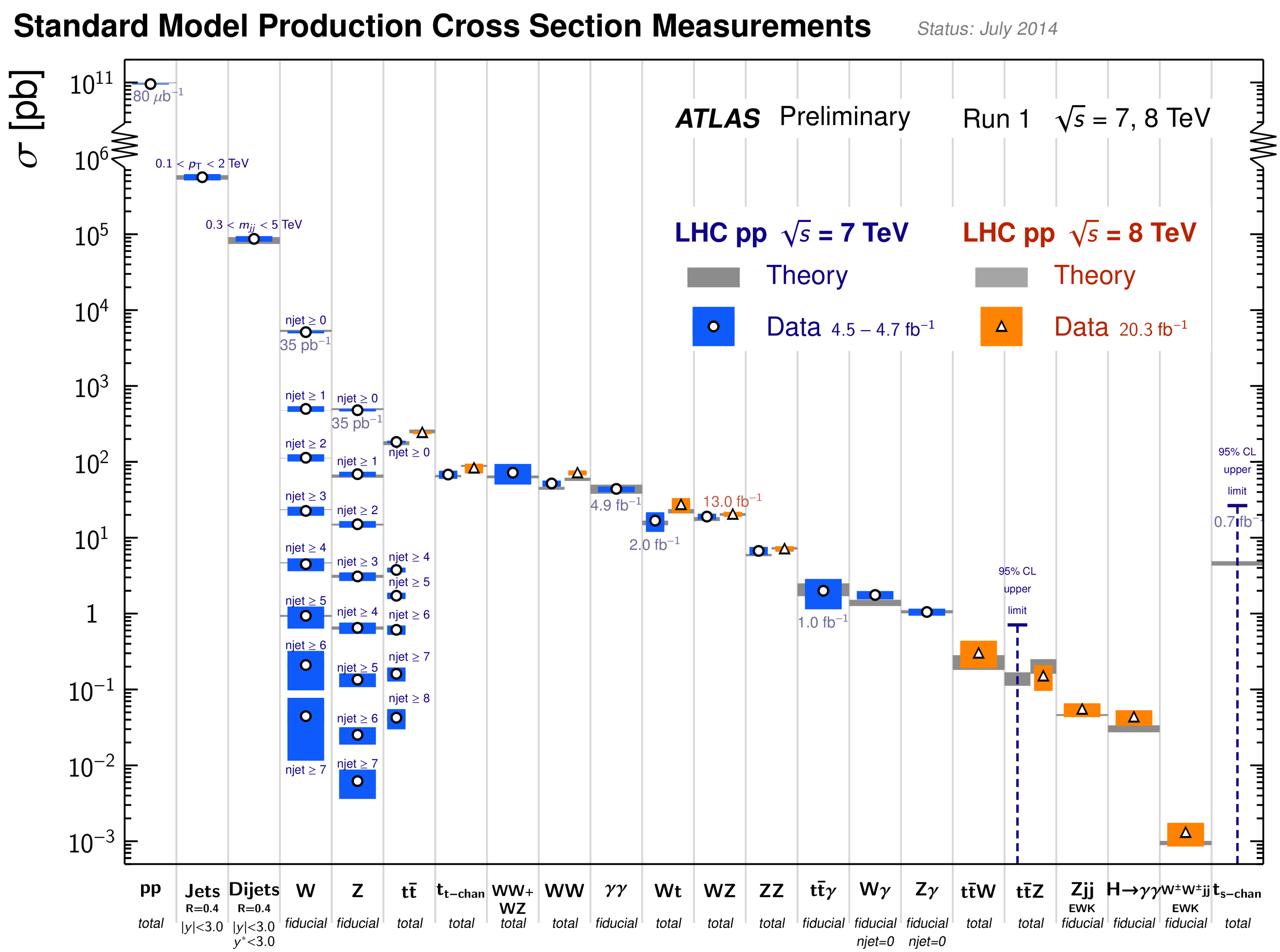
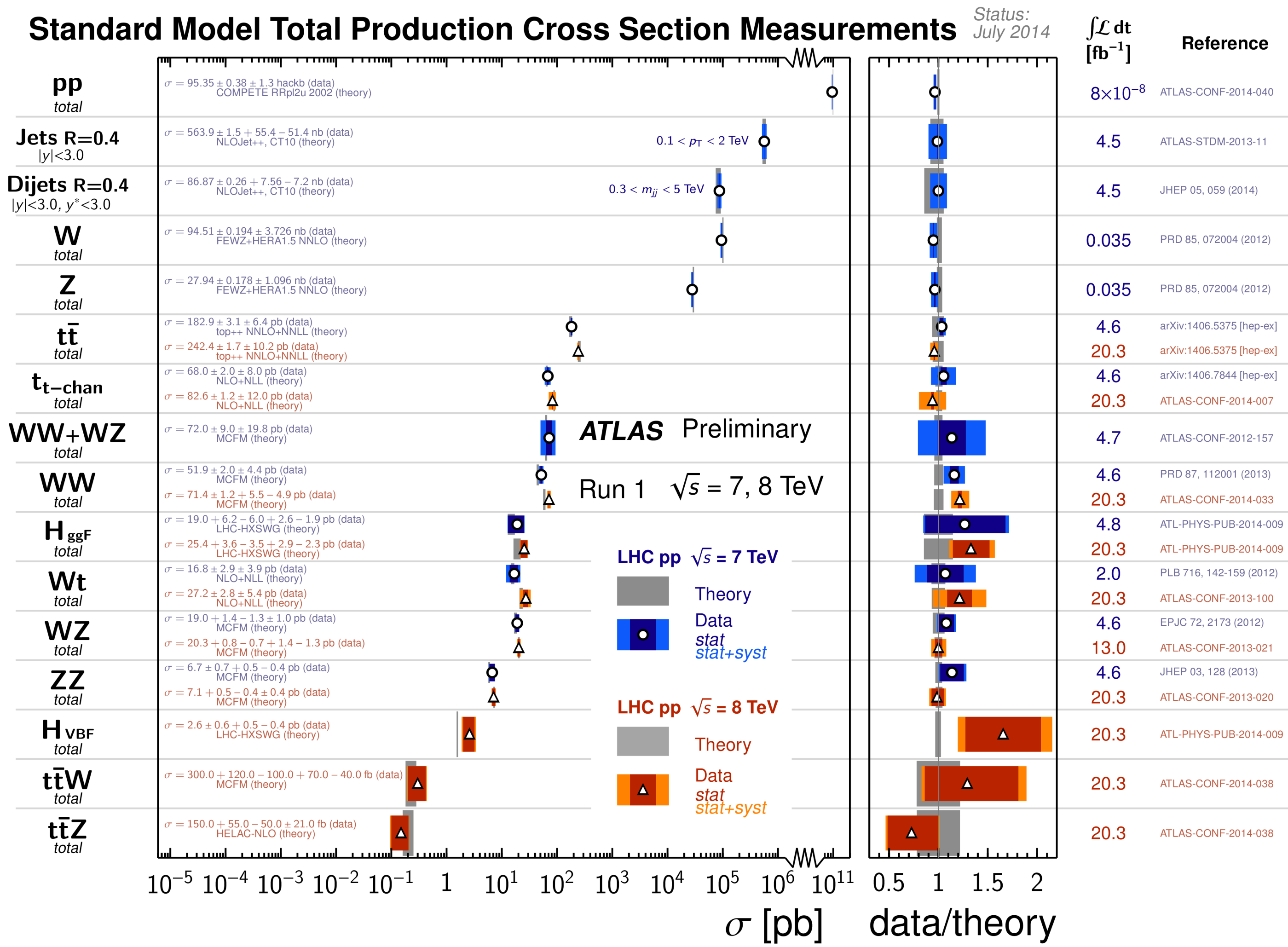
HP^2 Florence 2014

(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.



Physics from Run 1 and Run 2 PDFs

- PDF4LHC: Lay out a coherent coordinated plan for QCD(+EW) measurements, among ATLAS, CMS and LHCb, that can reduce PDF systematics using LHC data
  - systematic errors will be very important
- Wiki is now up, discussed at PDF4LHC meeting in May

https://twiki.cern.ch/twiki/bin/view/PDF4LHC/WebHome

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 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

Realistic wishlist

- 4 top final state

arXiv:1206.3064v1 [hep-ph] 14 Jun 2012

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

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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 evidentiate 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 $pp \to t\bar{t}t\bar{t} + X$. 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

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
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$W+b\bar{b}\leq 3j$	$W+b\bar{b}+\leq 3j$	$WWW+b\bar{b}+\leq 3j$	$t\bar{t}+\gamma+\leq 2j$
$W+c\bar{c}\leq 3j$	$W+c\bar{c}+\leq 3j$	$WWW+\gamma\gamma+\leq 3j$	$t\bar{t}+W+\leq 2j$
$Z+\leq 5j$	$ZZ+\leq 5j$	$Z\gamma\gamma+\leq 3j$	$t\bar{t}+Z+\leq 2j$
$Z+b\bar{b}+\leq 3j$	$Z+b\bar{b}+\leq 3j$	$ZZZ+\leq 3j$	$t\bar{t}+H+\leq 2j$
$Z+c\bar{c}+\leq 3j$	$ZZ+c\bar{c}+\leq 3j$	$WZZ+\leq 3j$	$t\bar{b}\leq 2j$
$\gamma+\leq 5j$	$\gamma\gamma+\leq 5j$	$ZZZ+\leq 3j$	$b\bar{b}+\leq 3j$
$\gamma+b\bar{b}\leq 3j$	$\gamma\gamma+b\bar{b}\leq 3j$		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 the fun going

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.

NNLO QCD+NLO EW wishlist

Higgs

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	$\sigma_{\rm tot}$(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)

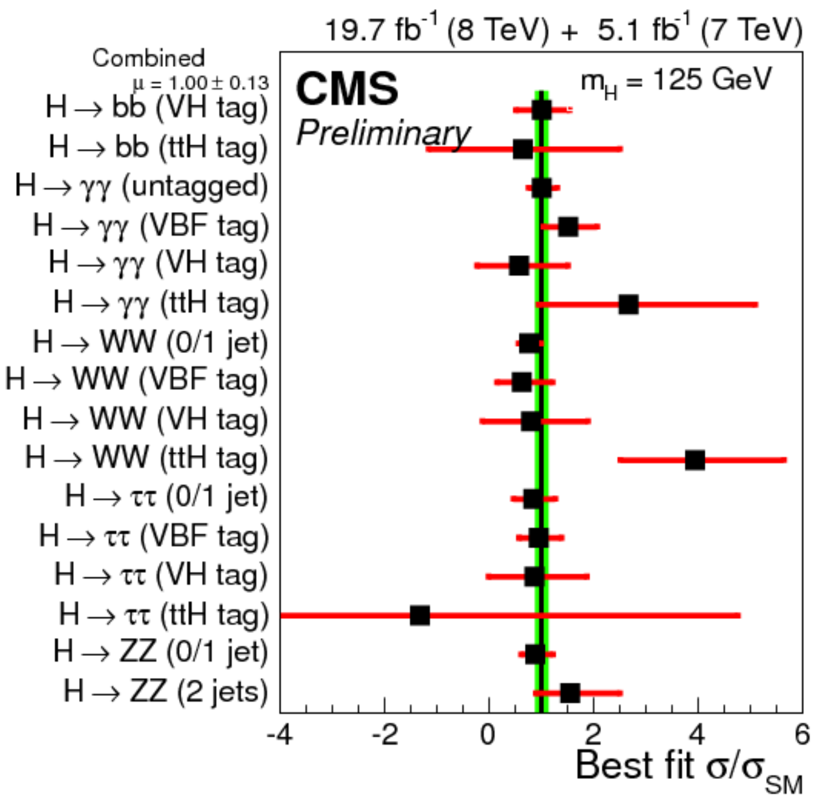
→ justify the requested precision based on current/extrapolated experimental errors

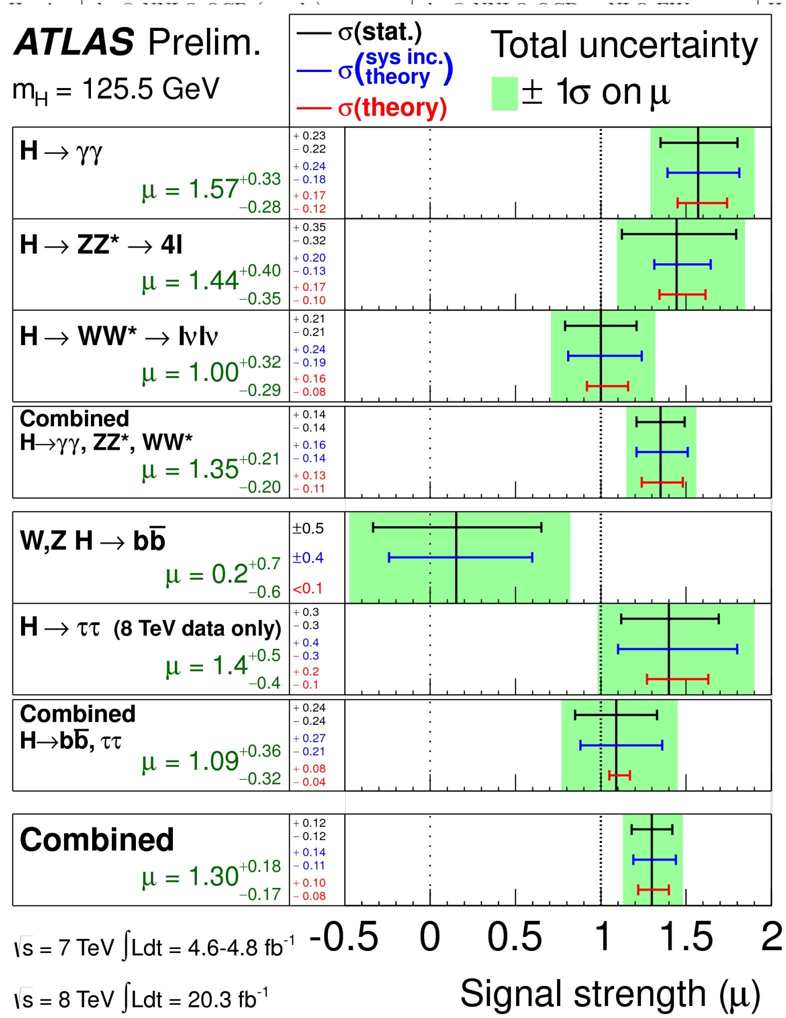
S. Dittmaier, N. Glover, J. Huston

Higgs sector

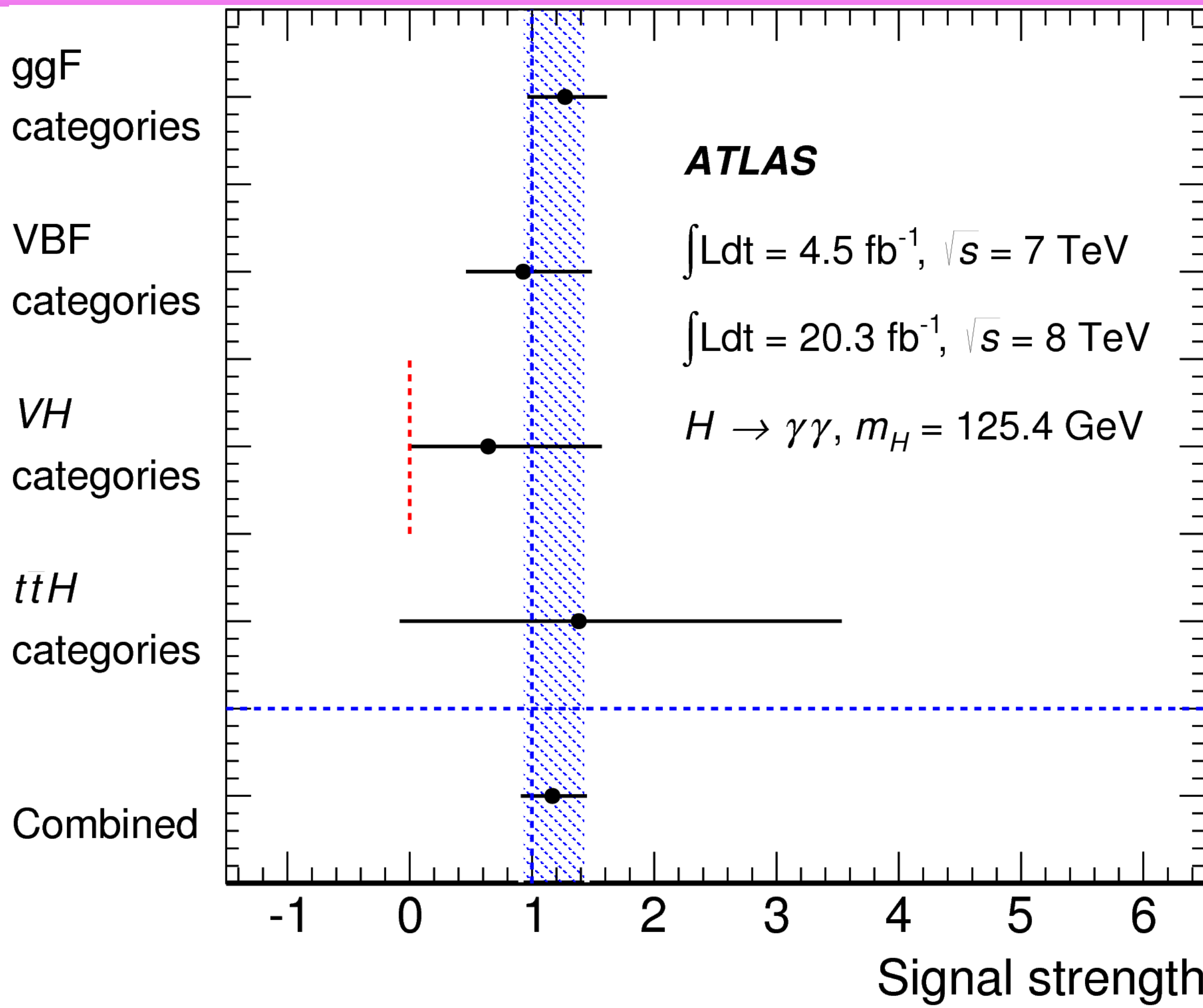
- We currently know the production cross section for gg fusion to NNLO QCD in the infinite m_t limit, including finite quark mass effects at NLO QCD and NLO EW.
- Current experimental uncertainties are of the order of 20-40%

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
			p_T
			couplings
			couplings
			p Yukawa coupling
			ggs self coupling





Revised diphoton results



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%
  - 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	$d\sigma$ @ 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

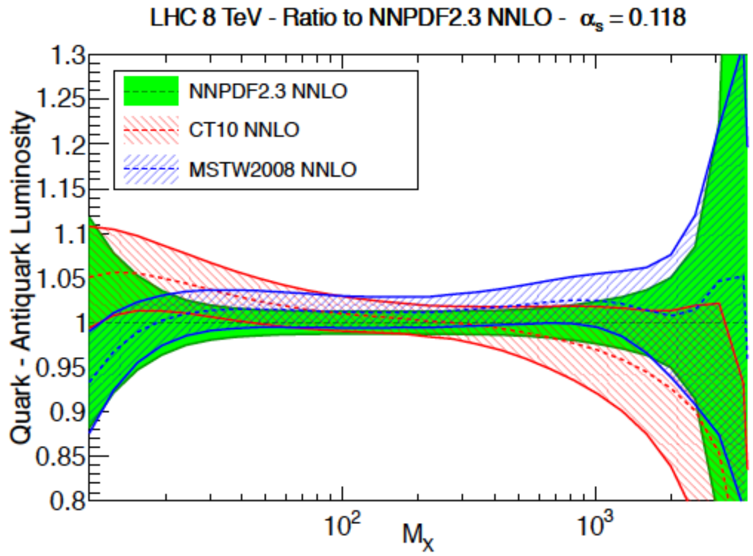
Table 1: Wishlist part 1 – Higgs (V = W, Z)

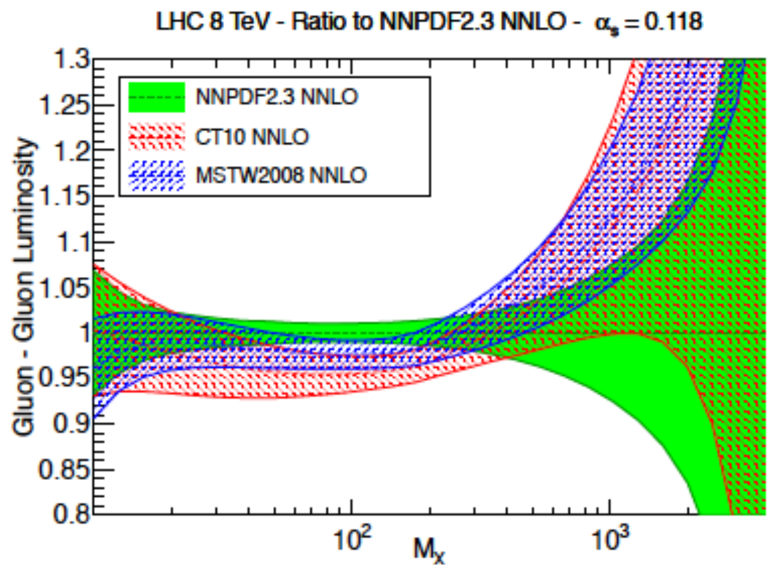
efforts underway for calculation of ggF to NNNLO in QCD.

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

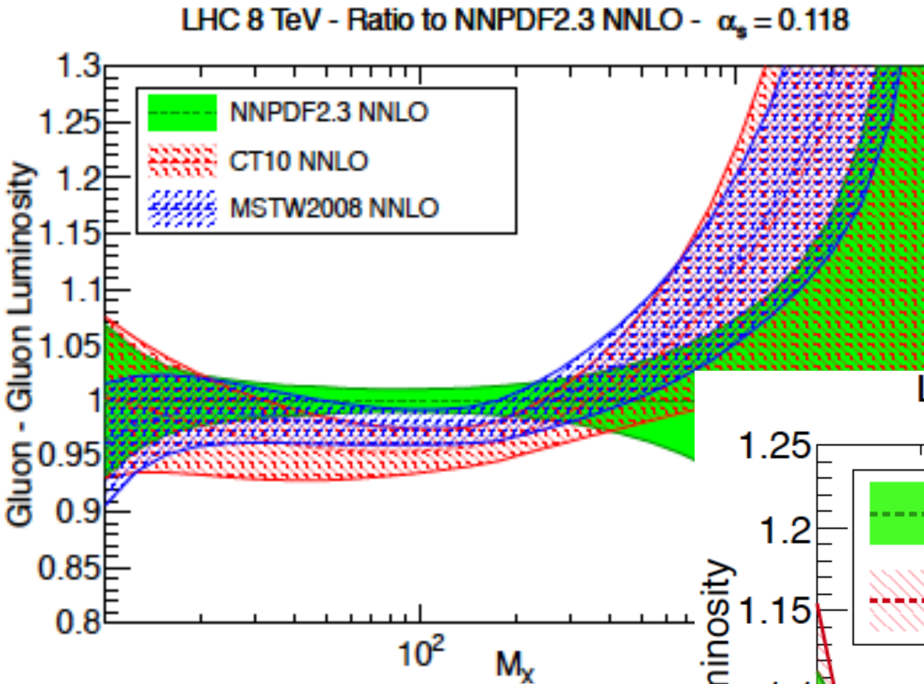
NNLO PDF uncertainties

- Nice convergence for qQ PDF luminosities in range of W/Z masses (at 8 TeV)
  - but not so for lower masses
- Also not so for gg PDF luminosities around 125 GeV at 8 TeV
  - better overlap, but with larger uncertainties, at low mass
  - PDF+α_s error dominant theory error
- Project started at Les Houches
  - understand differences in central luminosity value from CT10, MSTW08, NNPDF2.3 and HERAPDF1.5
  - progress report in Les Houches
  - meetings continuing

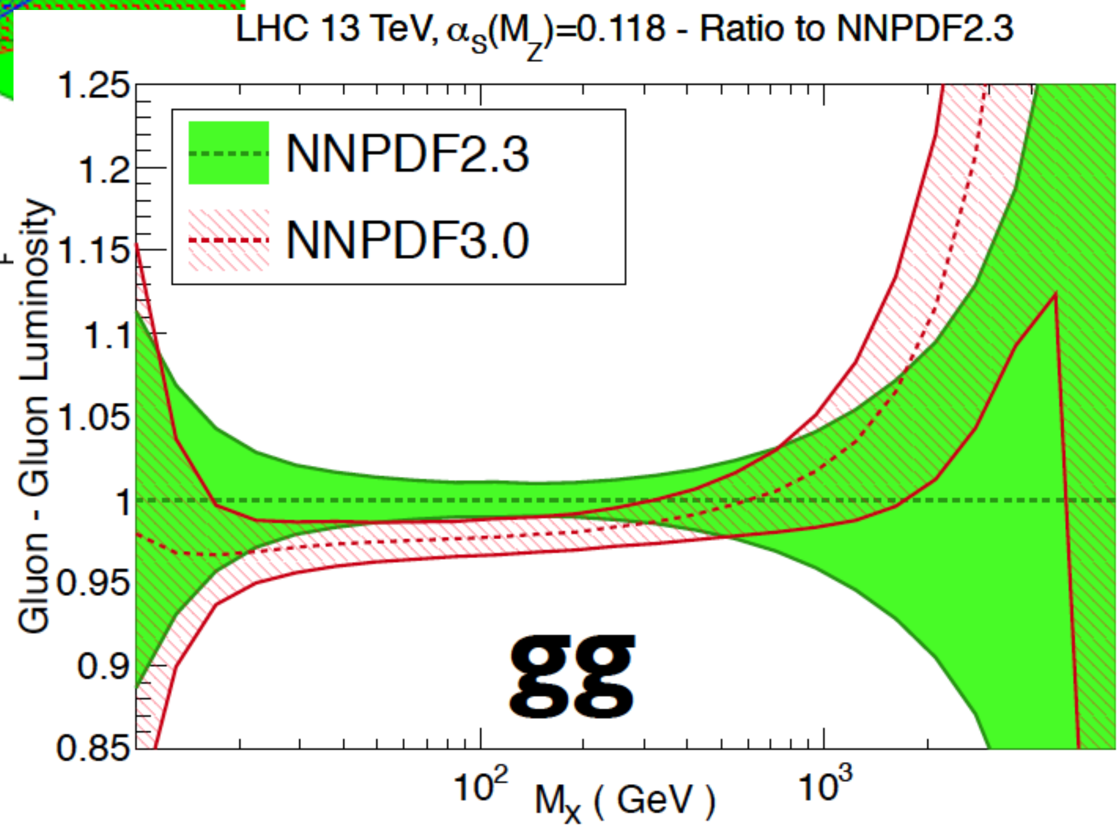




NNLO PDF uncertainties

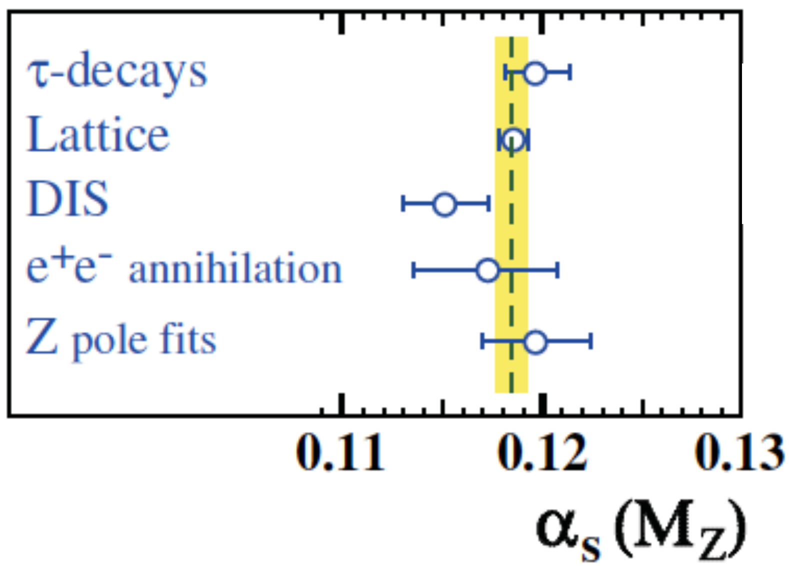


gg PDF luminosity for NNPDF3.0 drops compared to 2.3, so agreement for gg should become similar to that for qQ in new comparisons



$\alpha_s(m_Z)$

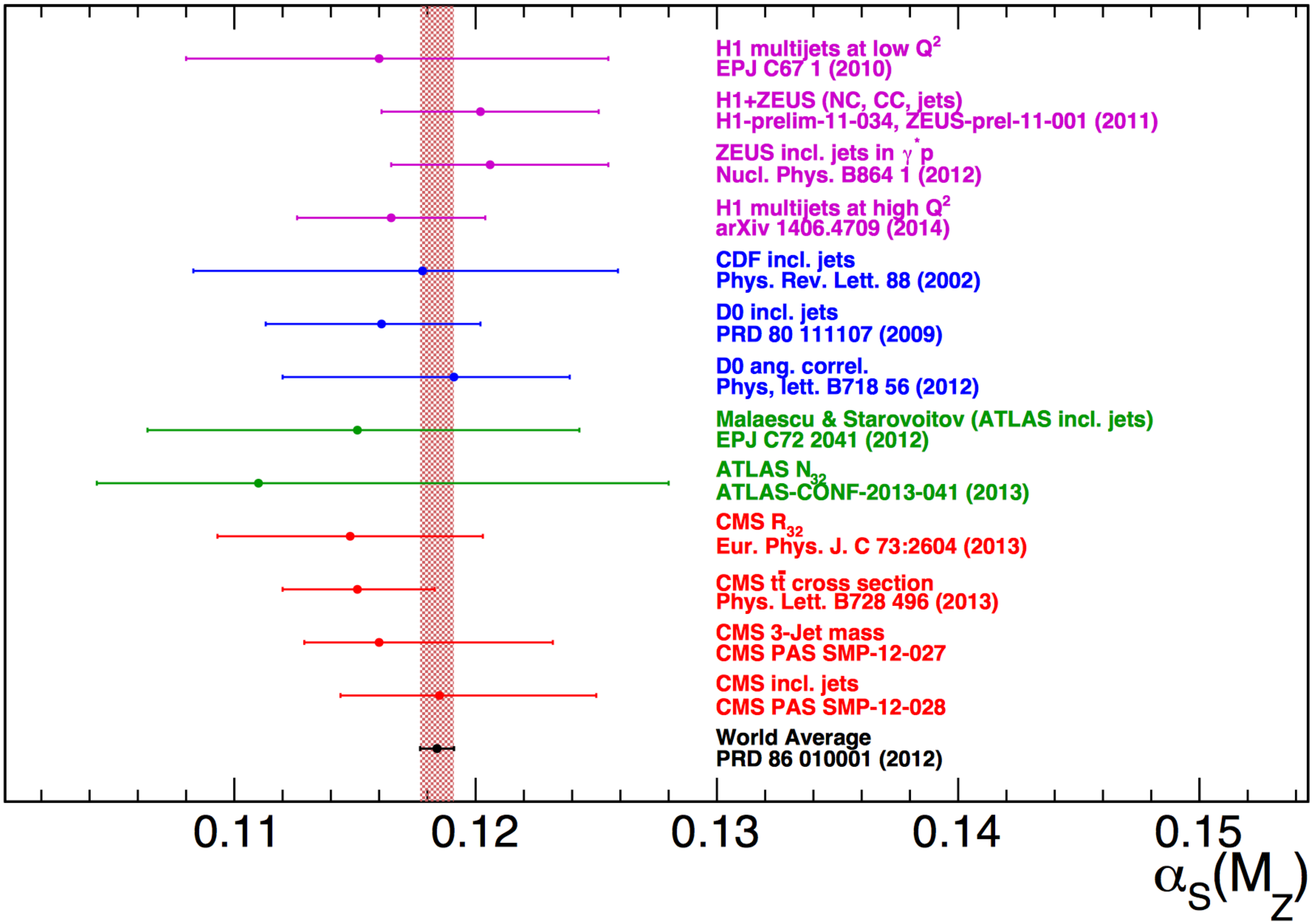
- Right now the Higgs Cross Section Working Group is using a mean value for $\alpha_s(m_Z)$ of 0.118 with 90% CL error of 0.002 (68%CL error of 0.0012), or an inflation of the world average uncertainties; the α_s error is added in quadrature with the PDF error
- The world average is dominated by lattice results
- Are the lattice results are robust enough, so that an uncertainty of 0.0012 (at 68% CL) may be an overestimate?



variety of different calculations/groups results in very compatible results

Figure 1-1. *Summary of values of* $\alpha_s(M_Z^2)$ *obtained for various sub-classes of measurements. The world average value of* $\alpha_s(M_Z^2) = 0.1184 \pm 0.0007$ *is indicated by the dashed line and the shaded band. Figure taken from [1].*

α_s from colliders

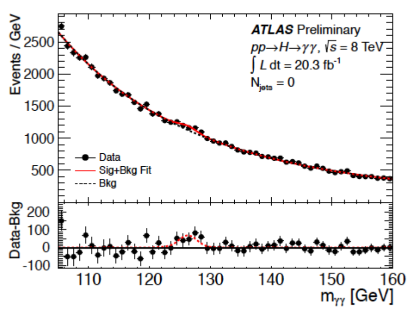


Higgs sector

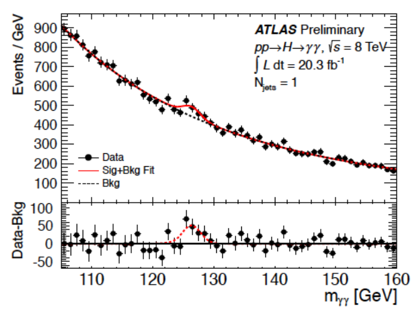
- First attempts to measure differential Higgs+jets measurements made in diphoton channel at ATLAS
  - arxiv.org:1407.4222

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

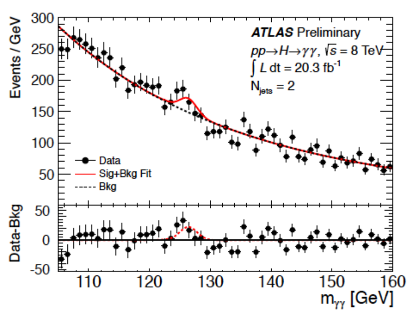
Table 1: Wishlist part 1 – Higgs (V = W, Z)



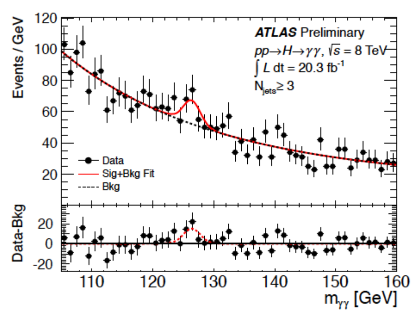
(a) $N_{jets} = 0$



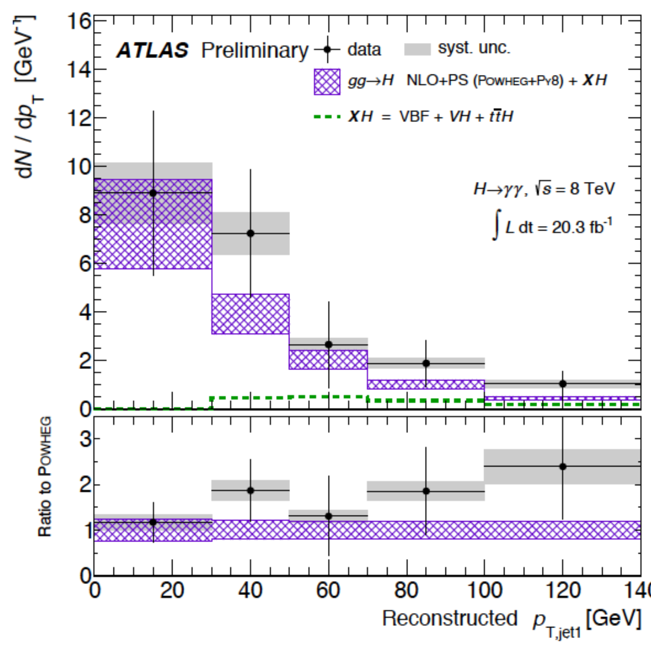
(b) $N_{jets} = 1$



(c) $N_{jets} = 2$

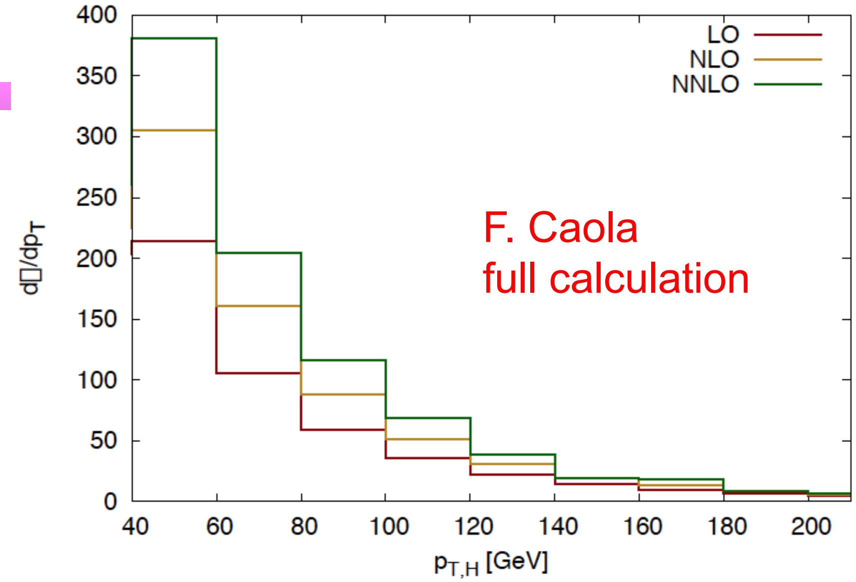


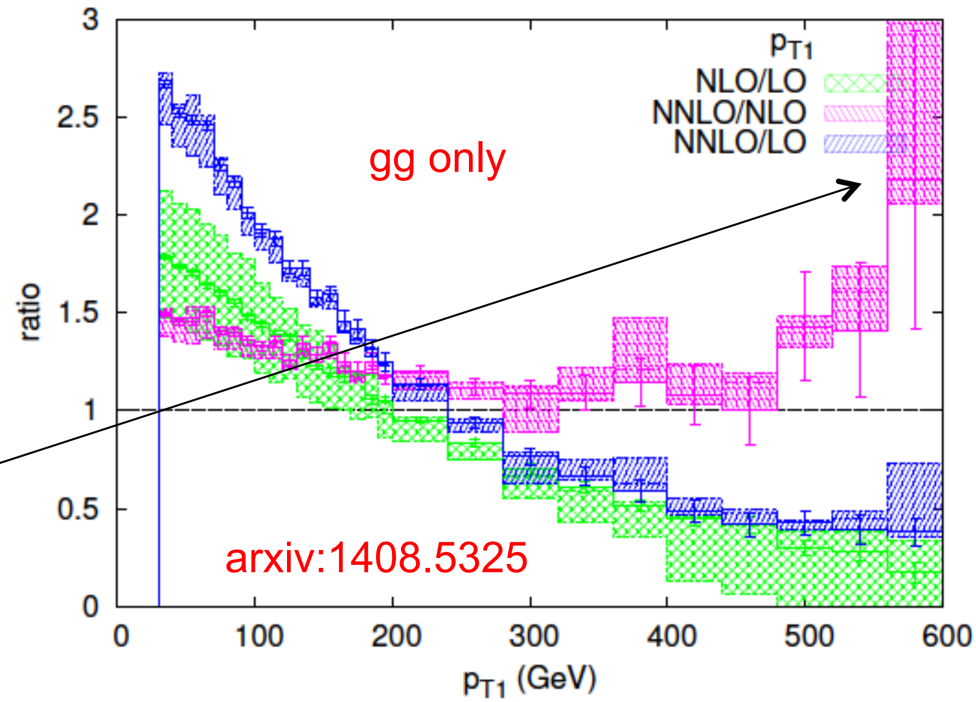
(d) $N_{jets} \geq 3$



Higgs + jet

- First attempts to measure differential Higgs+jets measurements made in diphoton channel at ATLAS
  - paper on archive
- 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 (F. Caola et al)
  - although paper not out yet
- 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





interesting that NNLO >>NLO at very high p_T

Harlander and Neumann: arXiv.org: 1308.2225

- Higher dimensional operators can change the shape of the Higgs/jet transverse momentum distribution above the top quark mass scale
  - resolve non-trivial structure of Higgs-gluon vertex

The effective Lagrangian involving operators through mass dimension 7 which couple a scalar Higgs boson H to gluons can be written as [13, 14] (see also Ref. [15])

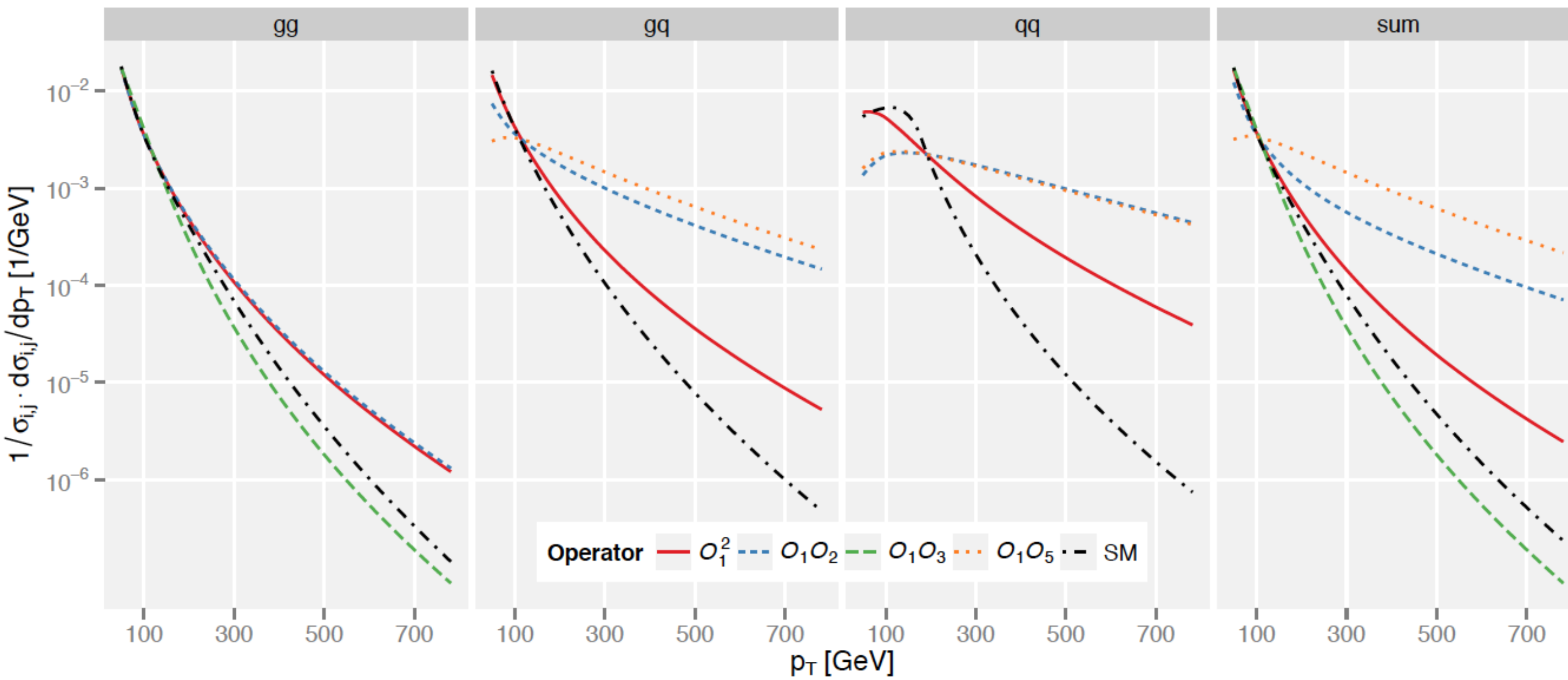
$$\mathcal{L} = \frac{C_1}{\Lambda}\mathcal{O}_1 + \sum_{n=2}^{5}\frac{C_n}{\Lambda^3}\mathcal{O}_n \tag{1}$$

$\Lambda = m_t$, or new physics?

$$\mathcal{O}_1 = HF^a_{\mu\nu}F^{a\,\mu\nu}\,,\quad \mathcal{O}_2 = HD_\alpha F^a_{\mu\nu}D^\alpha F^{a\,\mu\nu}\,,\quad \mathcal{O}_3 = HF^{a\,\mu}_{\nu}F^{b\,\nu}_{\sigma}F^{c\,\sigma}_{\mu}f^{abc}\,,$$
$$\mathcal{O}_4 = HD^\alpha F^a_{\alpha\nu}D_\beta F^{a\,\beta\nu}\,,\quad \mathcal{O}_5 = HF^a_{\alpha\nu}D^\nu D^\beta F^{a\,\alpha}_{\beta}\,, \tag{2}$$

where

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_s f^{abc}A^b_\mu A^c_\nu\,,\qquad D_\mu A^a_\nu = \partial_\mu A^a_\nu - g_s f^{abc}A^b_\mu A^c_\nu\,, \tag{3}$$



if just m_t, then deviations just due to finite top quark mass effects

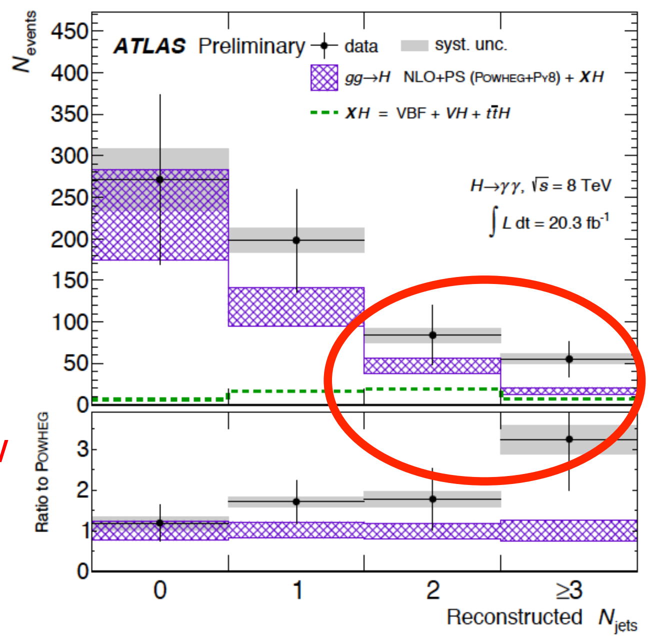
FIG. 1: Normalized Higgs transverse momentum distributions for scalar coupling operators. The normalization factors σ_{ij} are given in table I.

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	$d\sigma$ @ 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

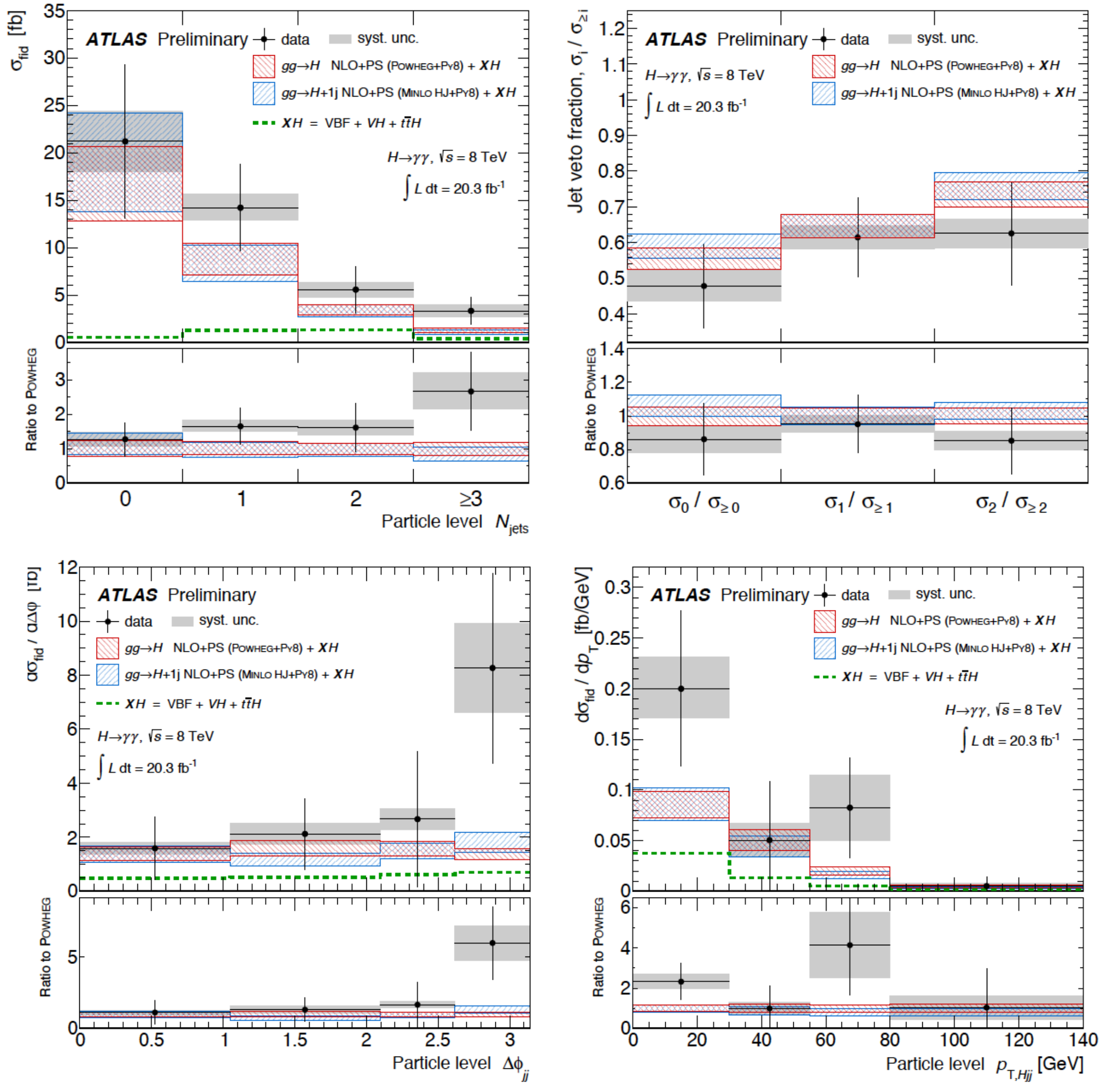
interesting that the (statistically limited) results seem to show a jettier final state than predicted



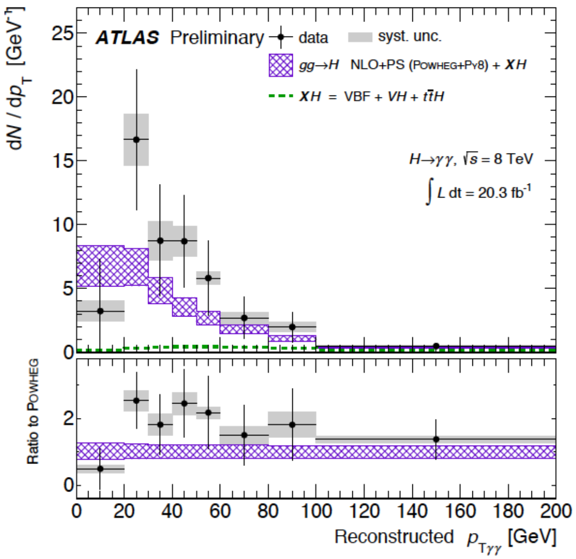
(a) N_{jets}

Higgs sector

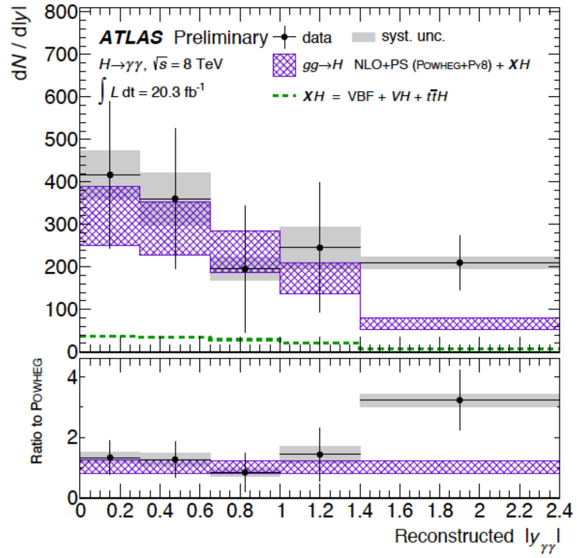
- Similar results from other predictions



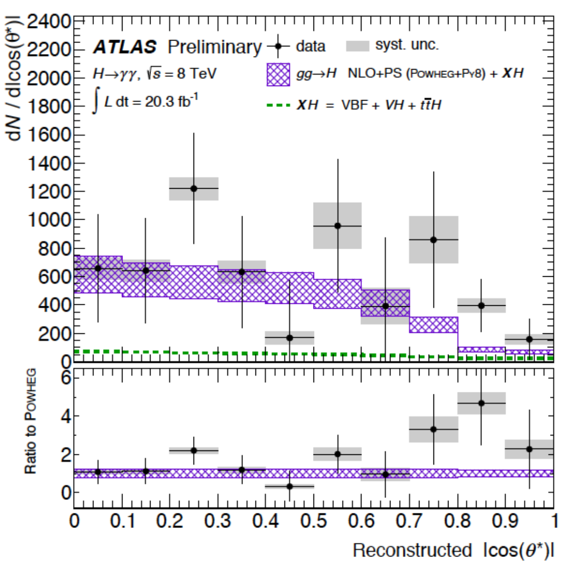
arxiv.org:1407.4222

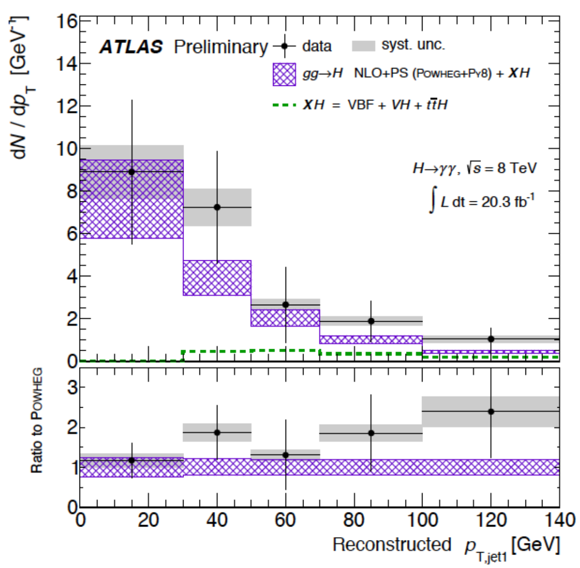


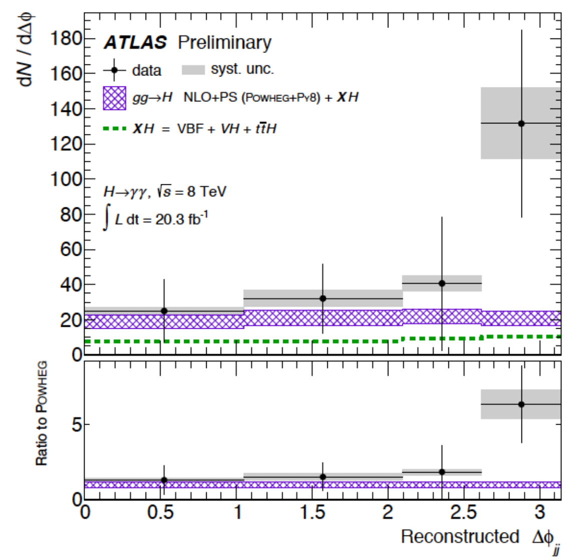
(a) $p_{\mathrm{T}}^{\gamma\gamma}$



(b) $|y^{\gamma\gamma}|$



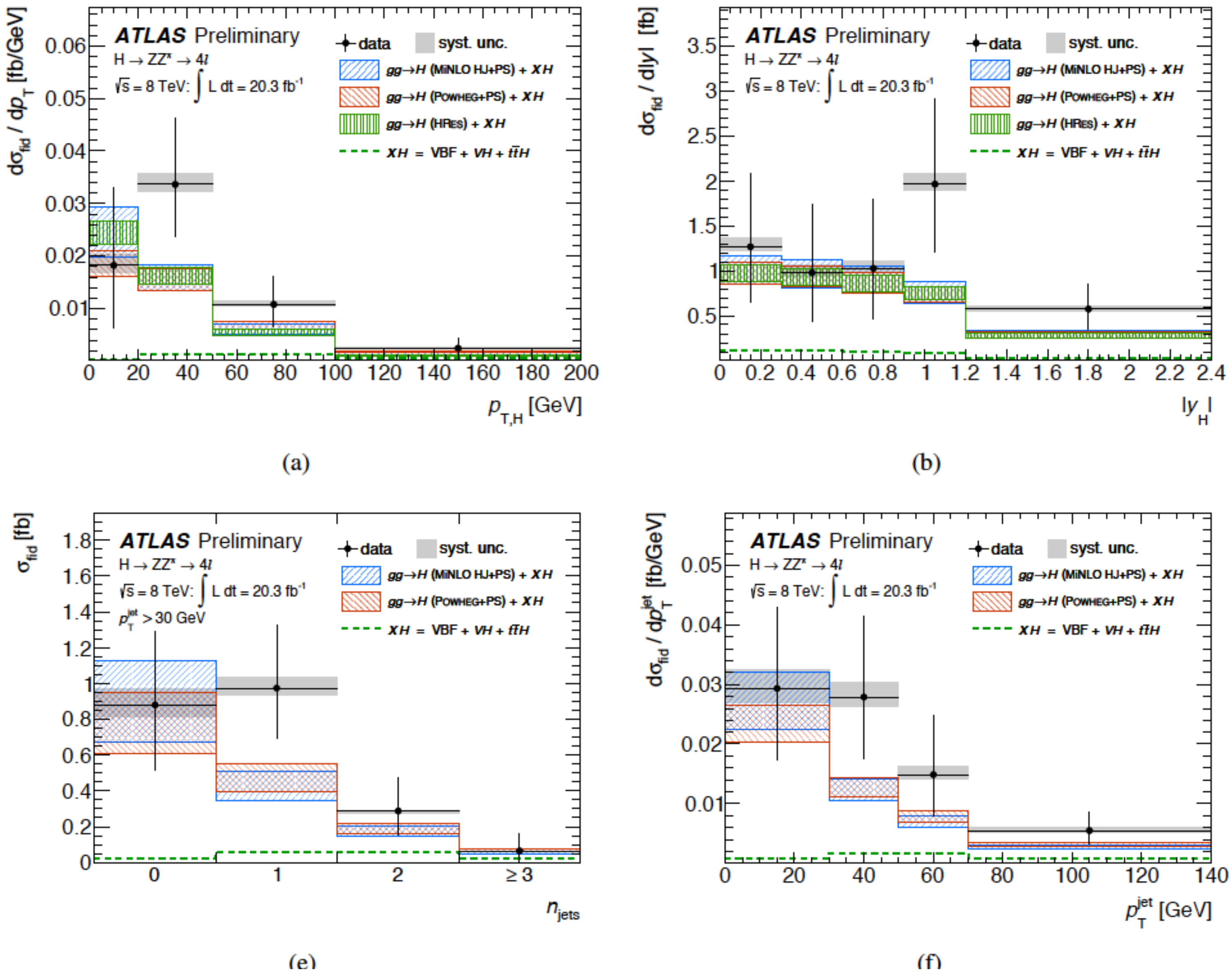




(b) $\Delta\phi_{jj}$

ATLAS-CONF-2014-044

similar results, but even more statistically limited for H->ZZ*



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 current at NNLO QCD and at NLO EW
- bB decay currently in NLO QCD production in narrow-width approximation; desireable to combir 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	$d\sigma$ @ 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-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
- 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	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)

S. Dittmaier, N. Glover, J. Huston

NNLO QCD + NLO EWK wishlist

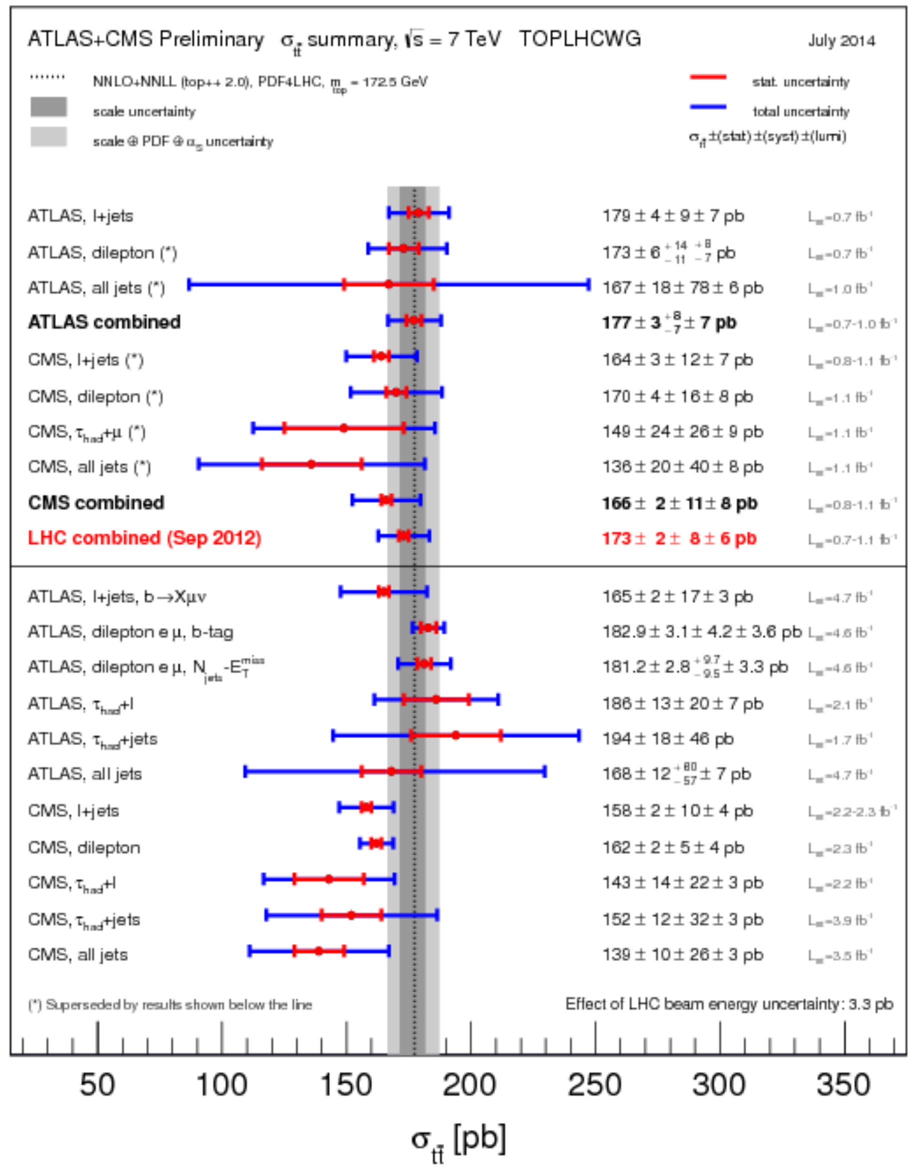
heavy quarks, photons, jets

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
$t\bar{t} + \text{j}$	$d\sigma$(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
$\gamma + \text{j}$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD +NLO EW	gluon PDF $\gamma + \text{b}$ for bottom PDF

Table 2: Wishlist part 2 – jets and heay quarks

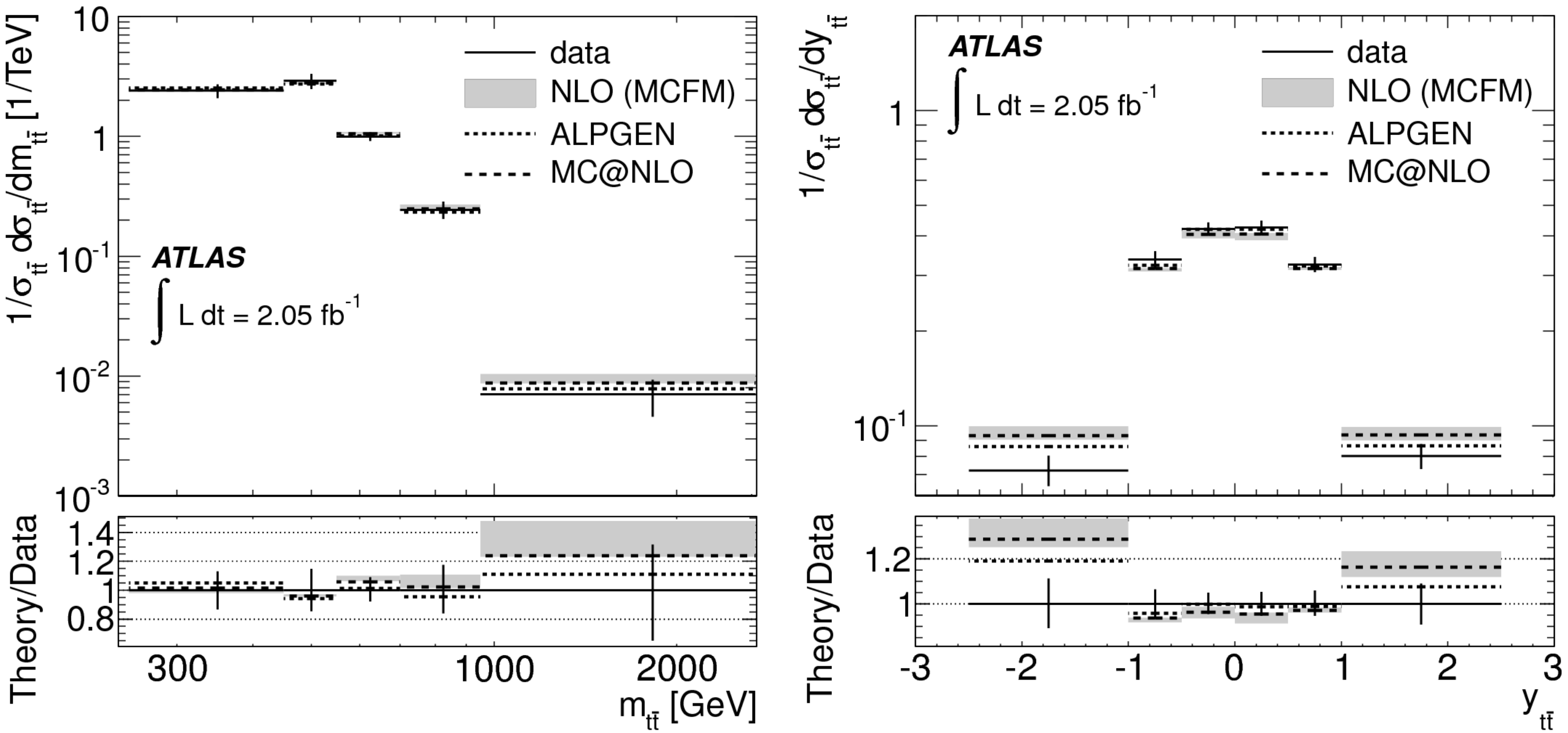
Top pair production

- 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 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



Mass and rapidity distributions

- gg channel is dominant; differential predictions at NNLO will help constrain high x gluon distribution

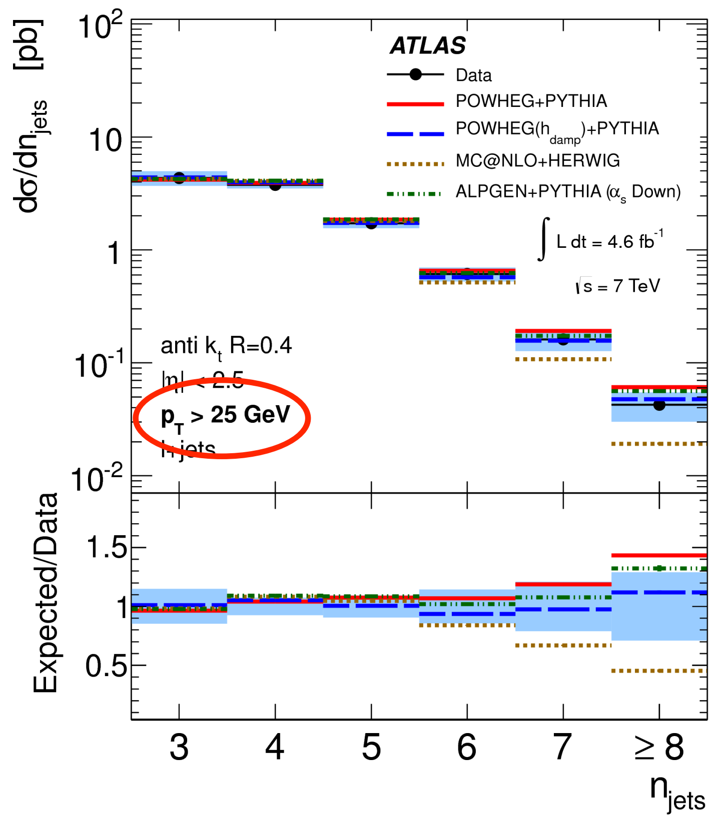


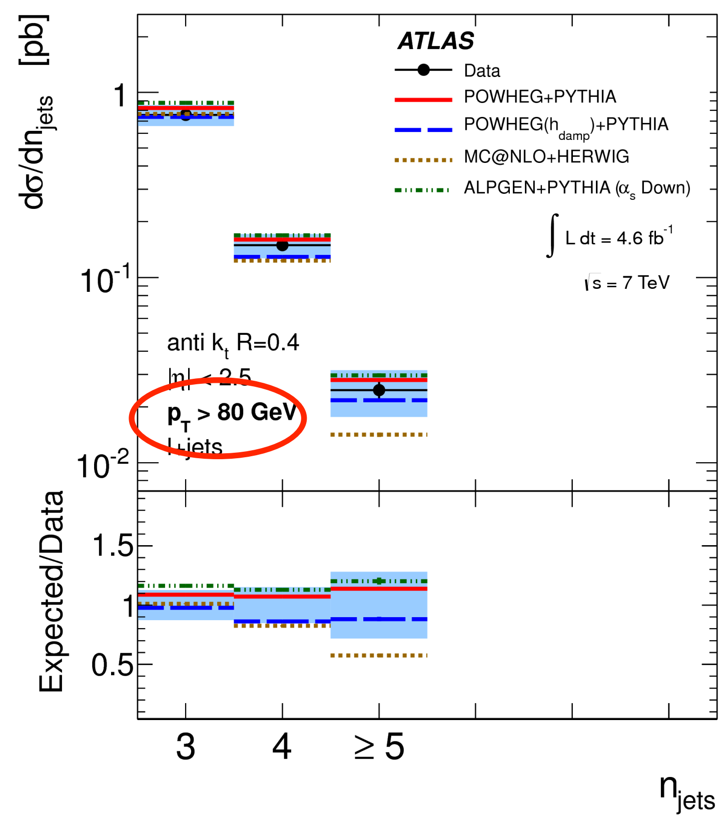
$t\bar{T}$+jets

- 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

NNLO QCD + NLO EW
NNLO QCD + NLO EW
NNLO QCD + NLO EW

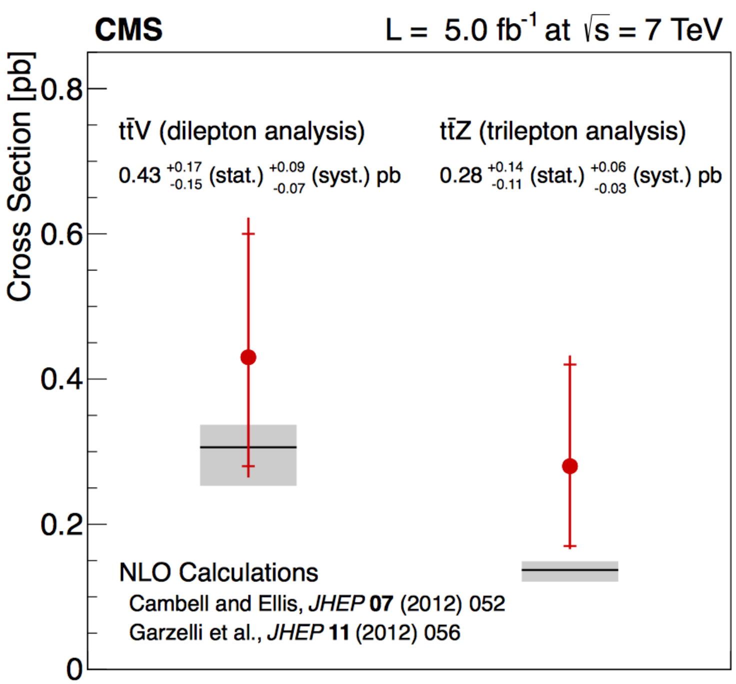


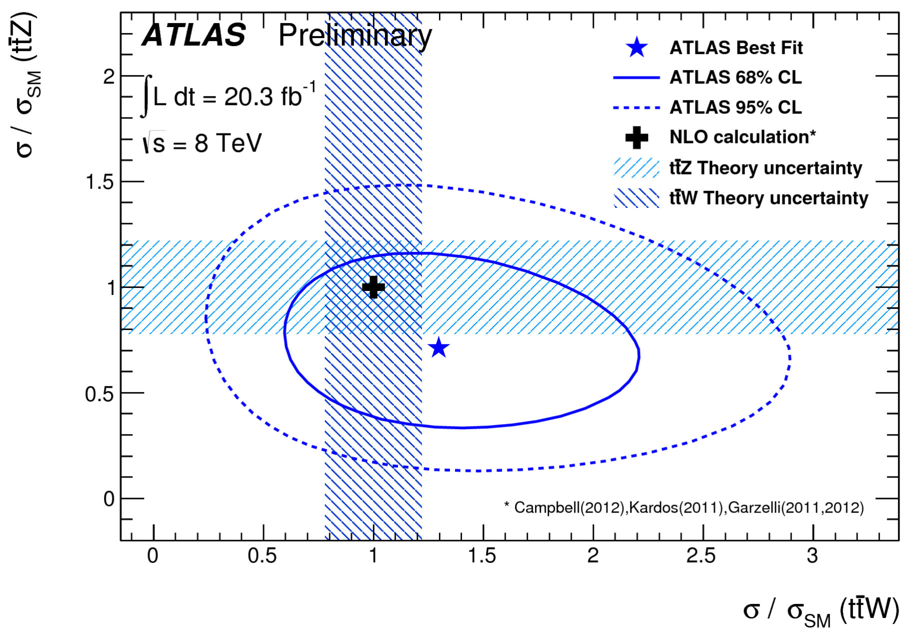


tTZ

- 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
$t\bar{t}+j(j)$	$d\sigma$(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

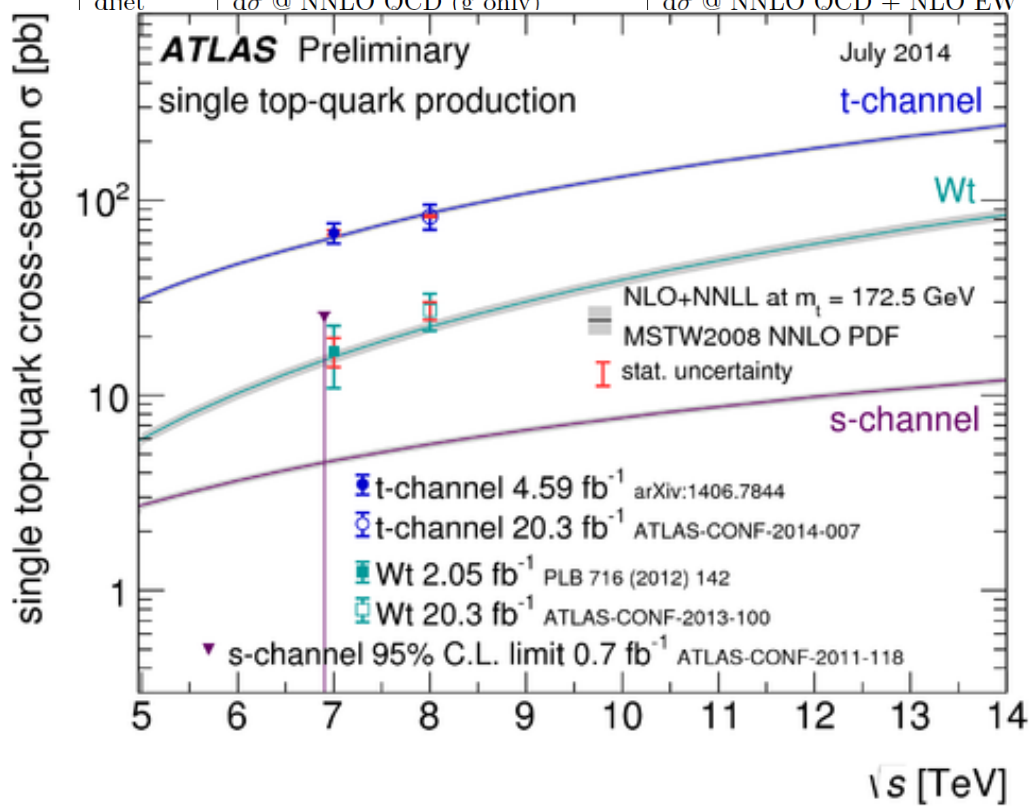




Single top

- 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% 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
$t\bar{t}$	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



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
$t\bar{t}$	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

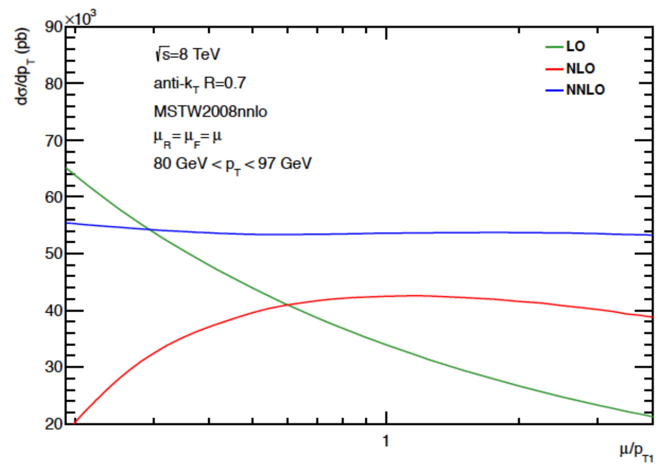


FIG. 2: Scale dependence of the inclusive jet cross section for pp collisions at $\sqrt{s}=8$ TeV for the anti-k_T algorithm with $R=0.7$ and with $|y|<4.4$ and 80 GeV $< p_T <$ 97 GeV at NNLO (blue), NLO (red) and LO (green).

…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

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

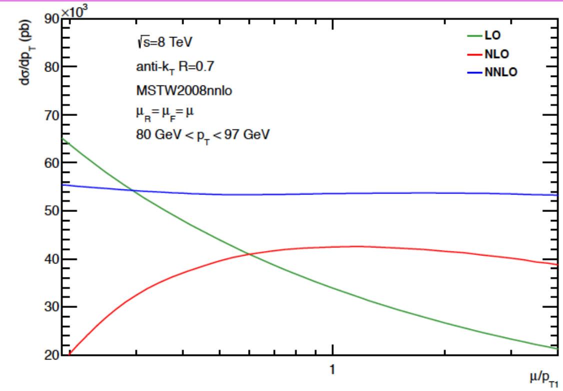


FIG. 2: Scale dependence of the inclusive jet cross section for pp collisions at $\sqrt{s} = 8$ TeV for the anti-k_T algorithm with $R = 0.7$ and with $|y| < 4.4$ and 80 GeV $< p_T <$ 97 GeV at NNLO (blue), NLO (red) and LO (green).

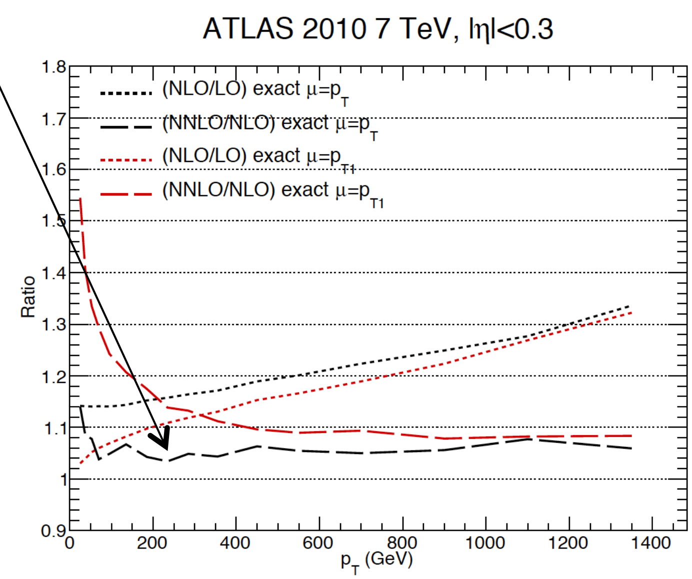
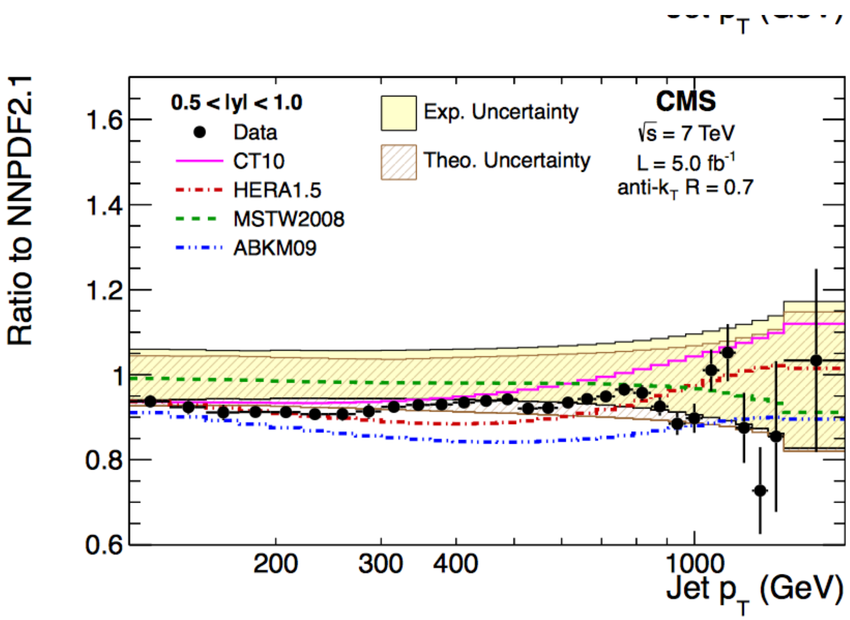
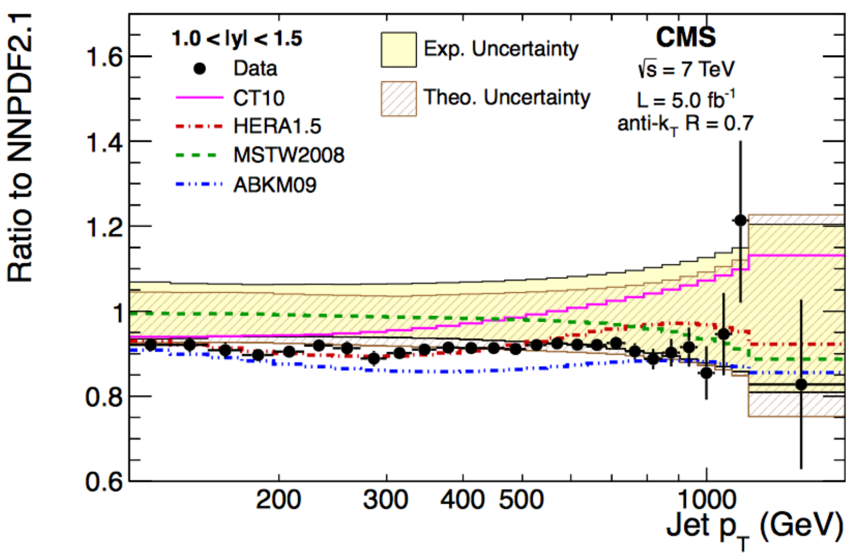
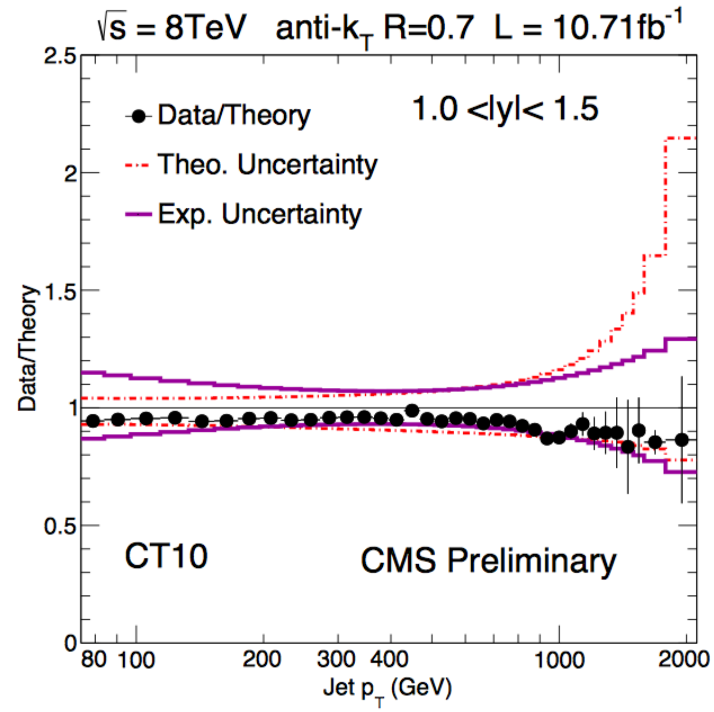


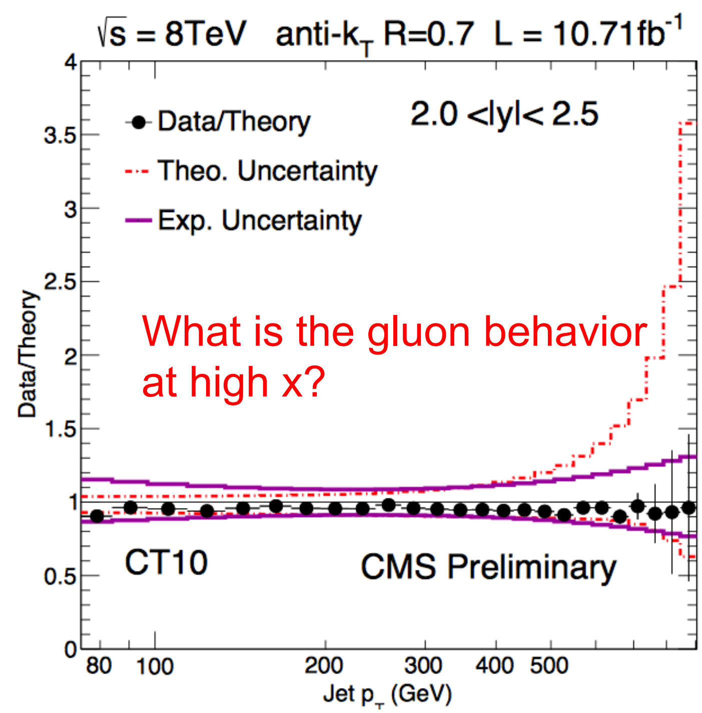
Figure 8: NLO/LO and NNLO/NLO exact k-factors for the gg-channel evaluated with the renormalisation and factorisation scales $\mu_R = \mu_F = p_T$ and $\mu_R = \mu_F = p_{T1}$.

Compare CMS 7 to 8 TeV data





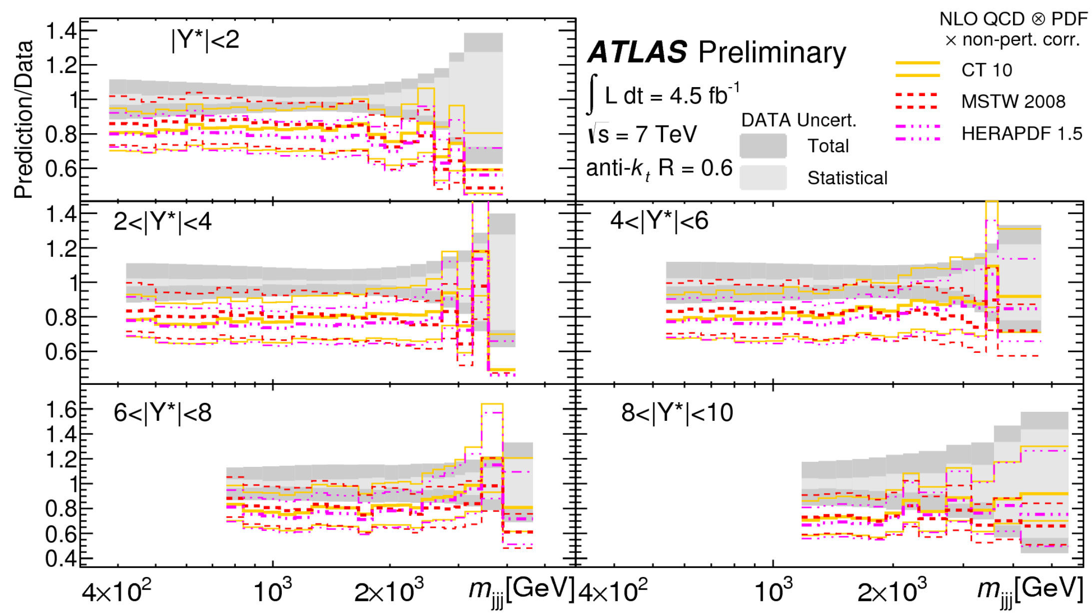




NNLO QCD + NLO EWK wishlist

- 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

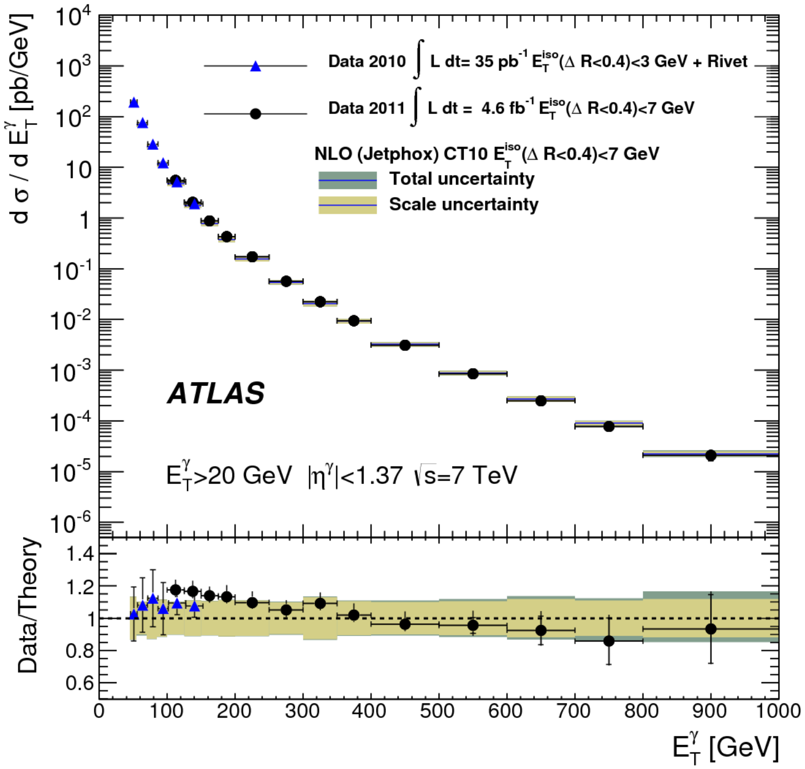
Process	State of the Art	Desired
$t\bar{t}$	σ_{tot}(stable tops) @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW
$t\bar{t}$ + j(j)	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
$t\bar{t}$ + Z	$d\sigma$(stable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

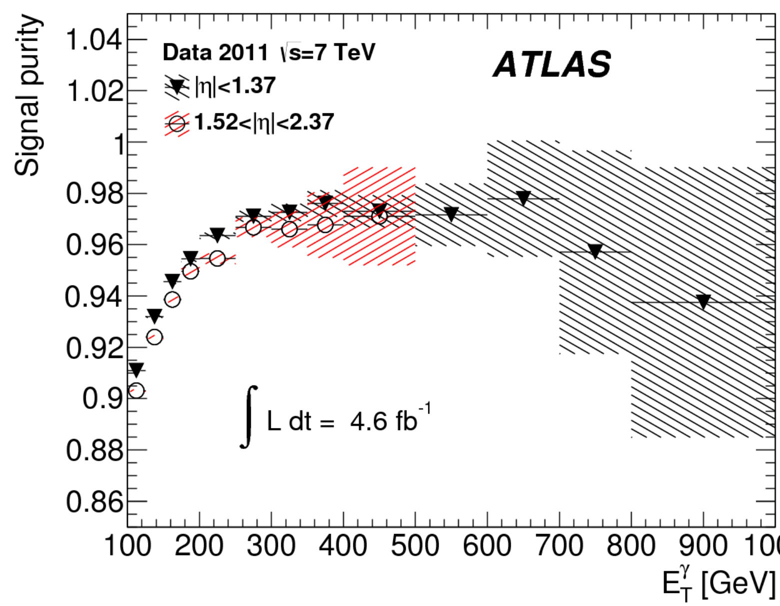


NNLO QCD + NLO EWK wishlist

- 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

NNLO QCD + NLO EWK wishlist

Vector bosons

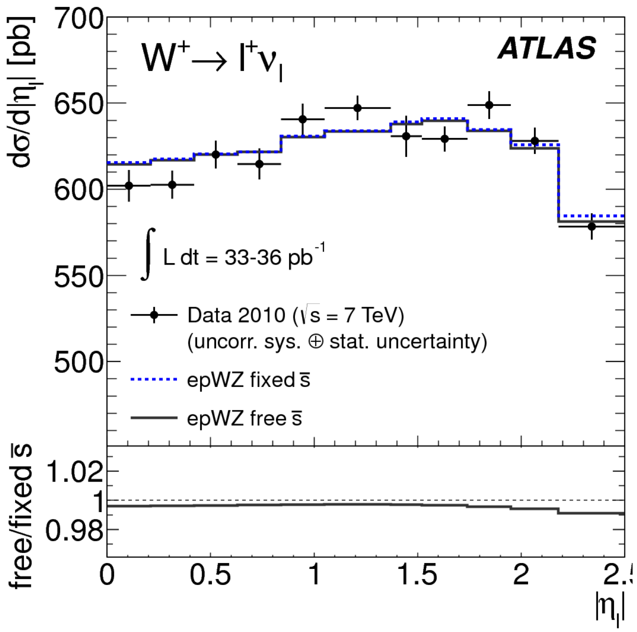
Process	known	desired	details
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
$V+j$	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	$Z+j$ 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 $H \to \gamma\gamma$

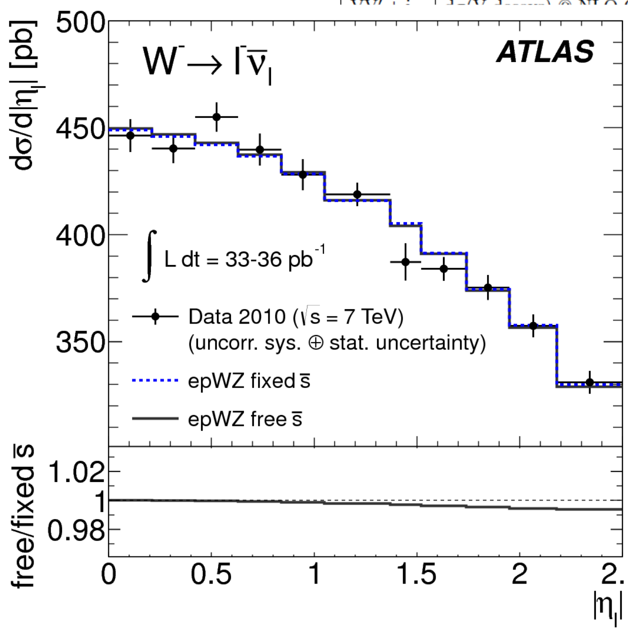
Table 3: Wishlist part 3 – EW gauge bosons ($V = W, Z$)

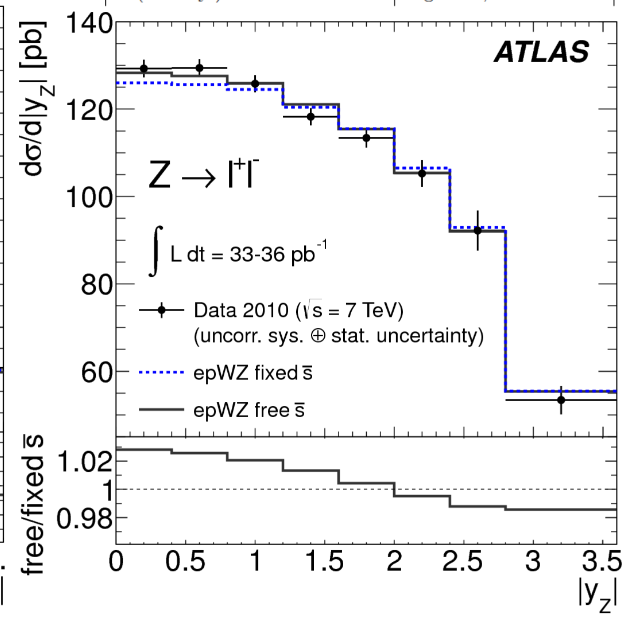
Vector boson production

- 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	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 → 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
$Vb\bar{b}$	dσ(lept. V decay) @ NLO QCD massive b	dσ(lept. V decay) @ NNLO QCD massless b	bkg. for VH → $b\bar{b}$
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
[illegible]	dσ(V decays) @ NLO QCD	dσ(V decays)	bkg. to H, BSM searches

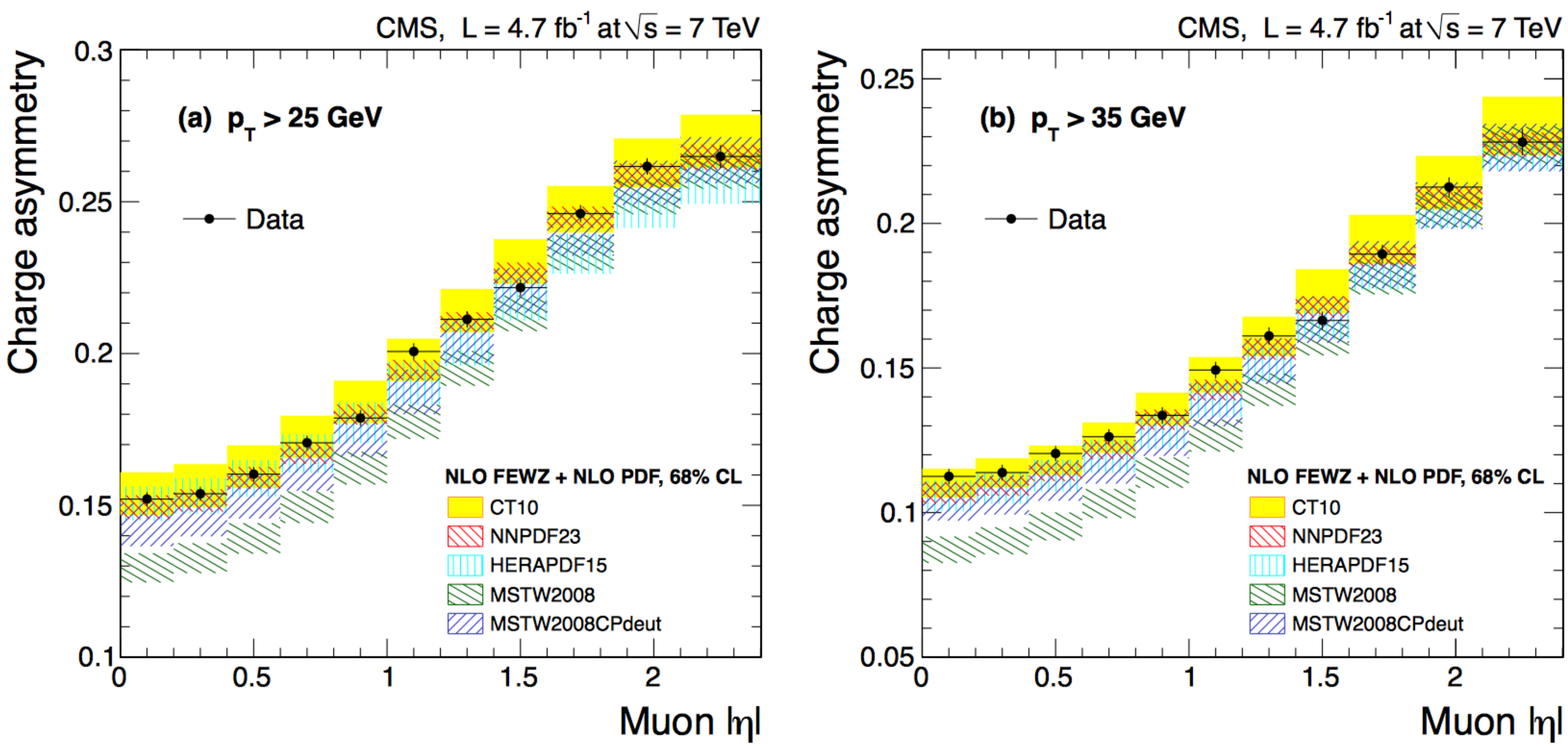






One example of a dataset that will be constraining

…because this is a ratio, where the systematic errors are very small, and because it covers a relatively wide kinematic range



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+1-5 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

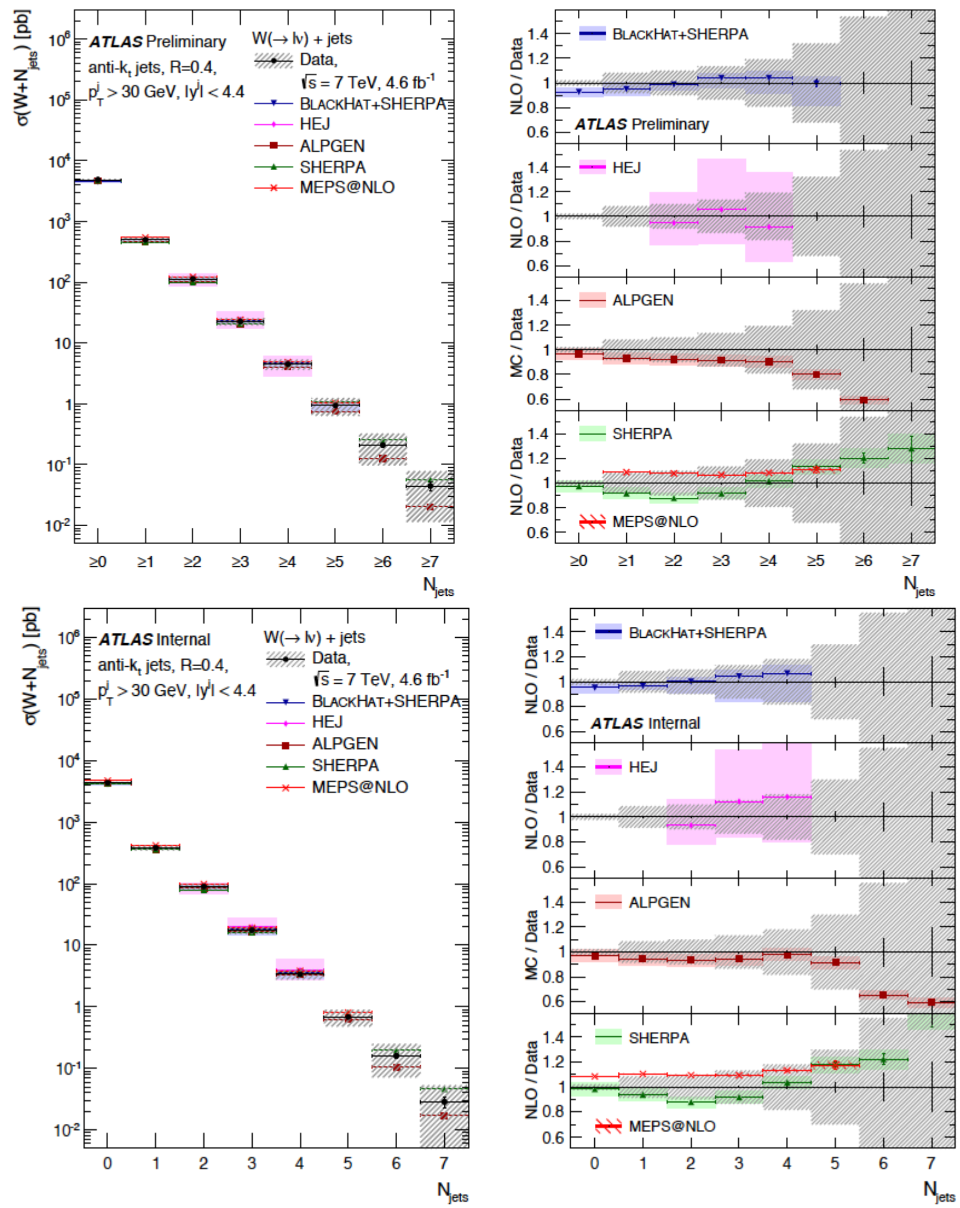
Process	known	desired	details
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
V + j	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	Z + j 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 $d\sigma$(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)

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

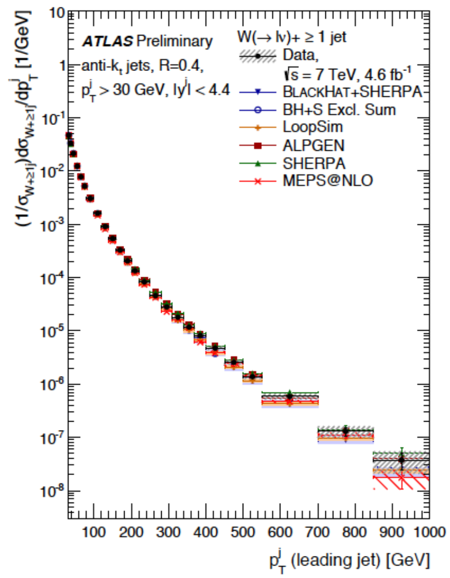
W+jets

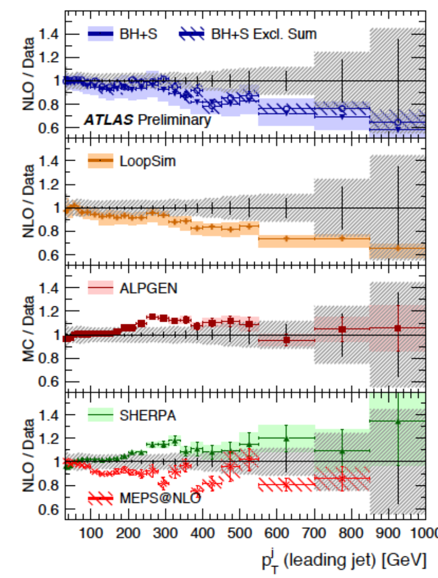
- ATLAS has measured up to 7 jets in the final state
  - both inclusive and exclusive final states
  - good agreement with Blackhat+Sherpa

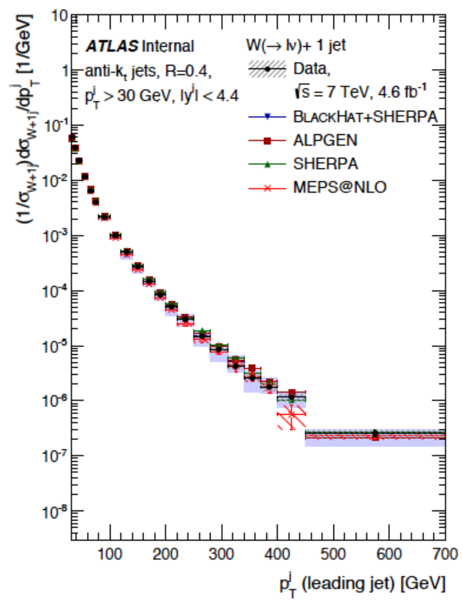


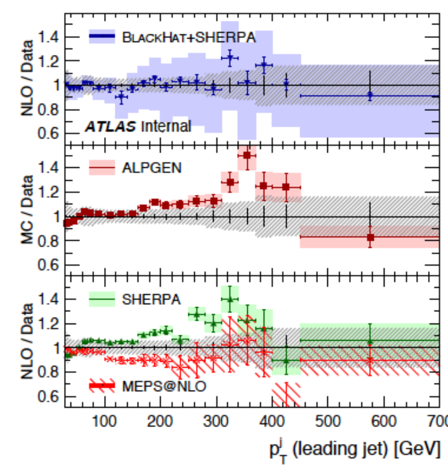
Leading jet p_T

- 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?



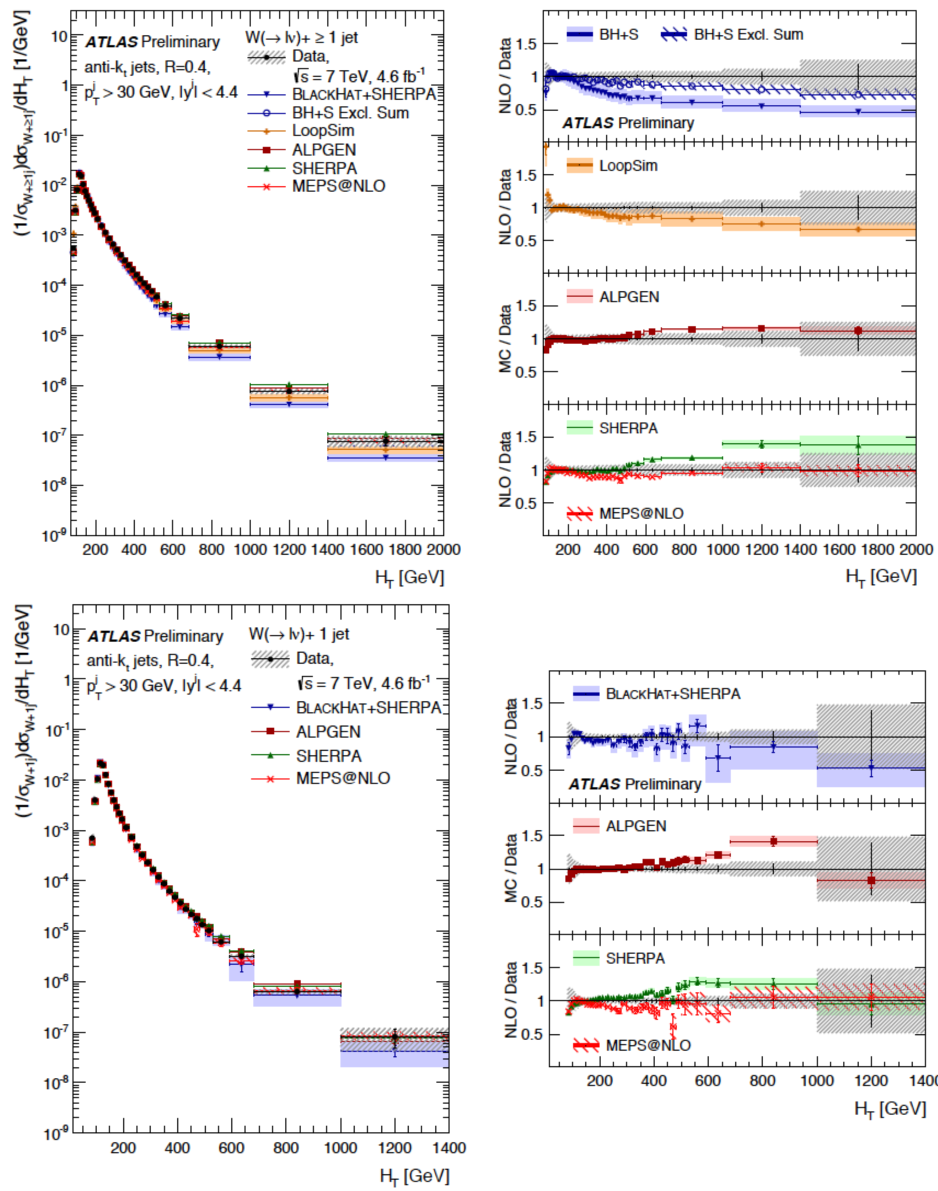






H_T

- 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



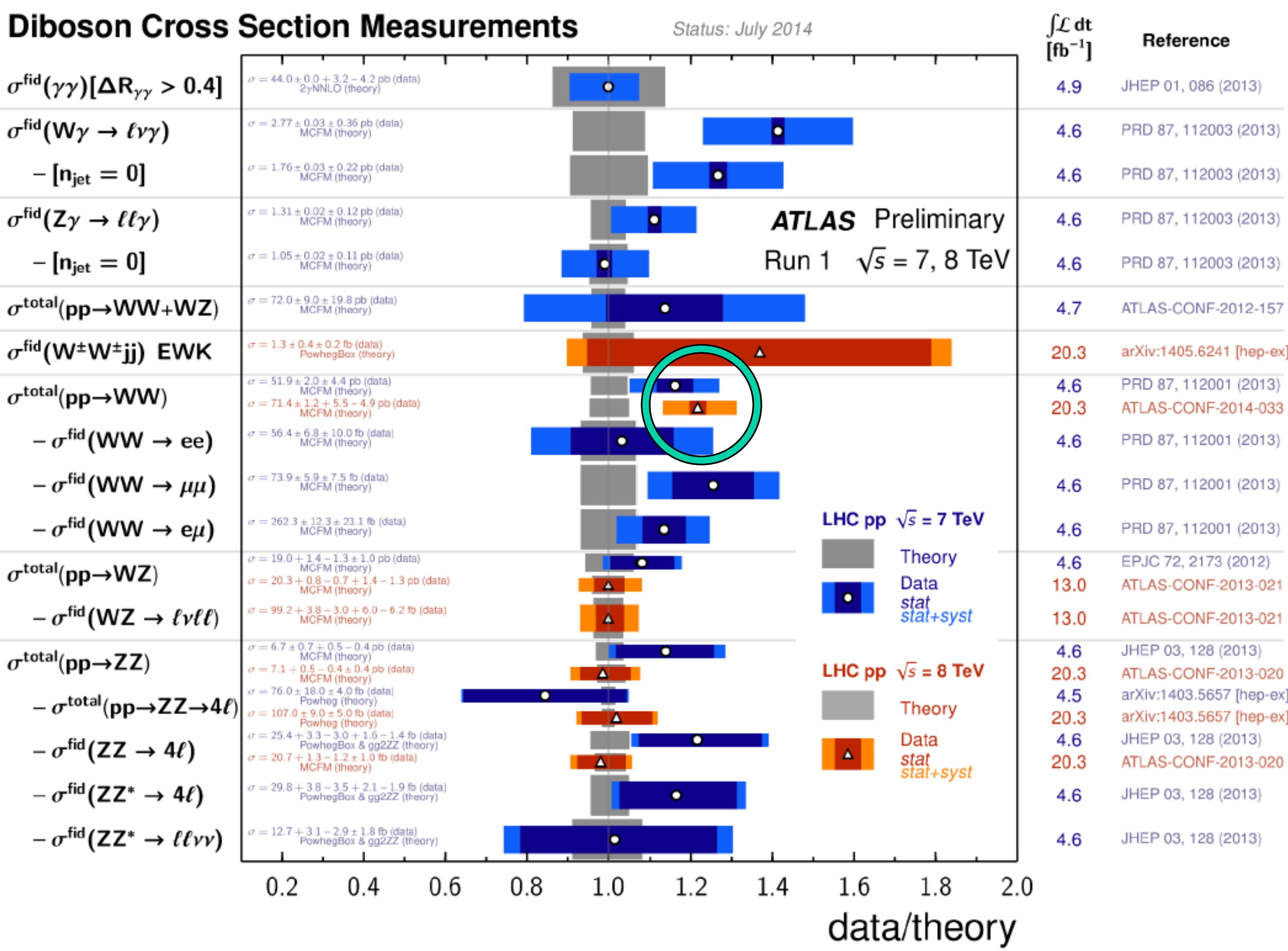
NNLO QCD + NLO EWK wishlist

- 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)

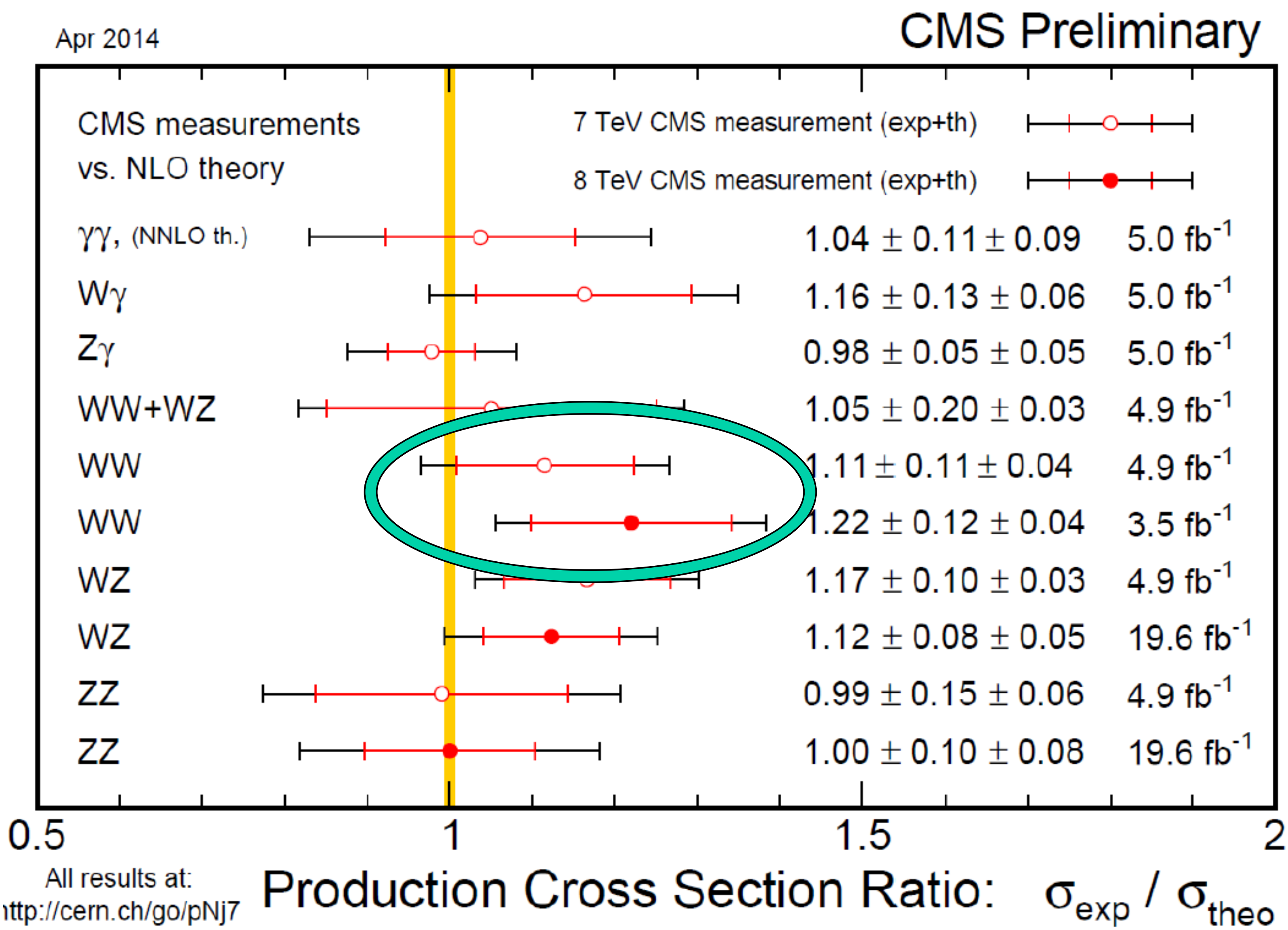
Process	known	desired	details
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
V + j	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	Z + j 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)

ATLAS diboson cross sections

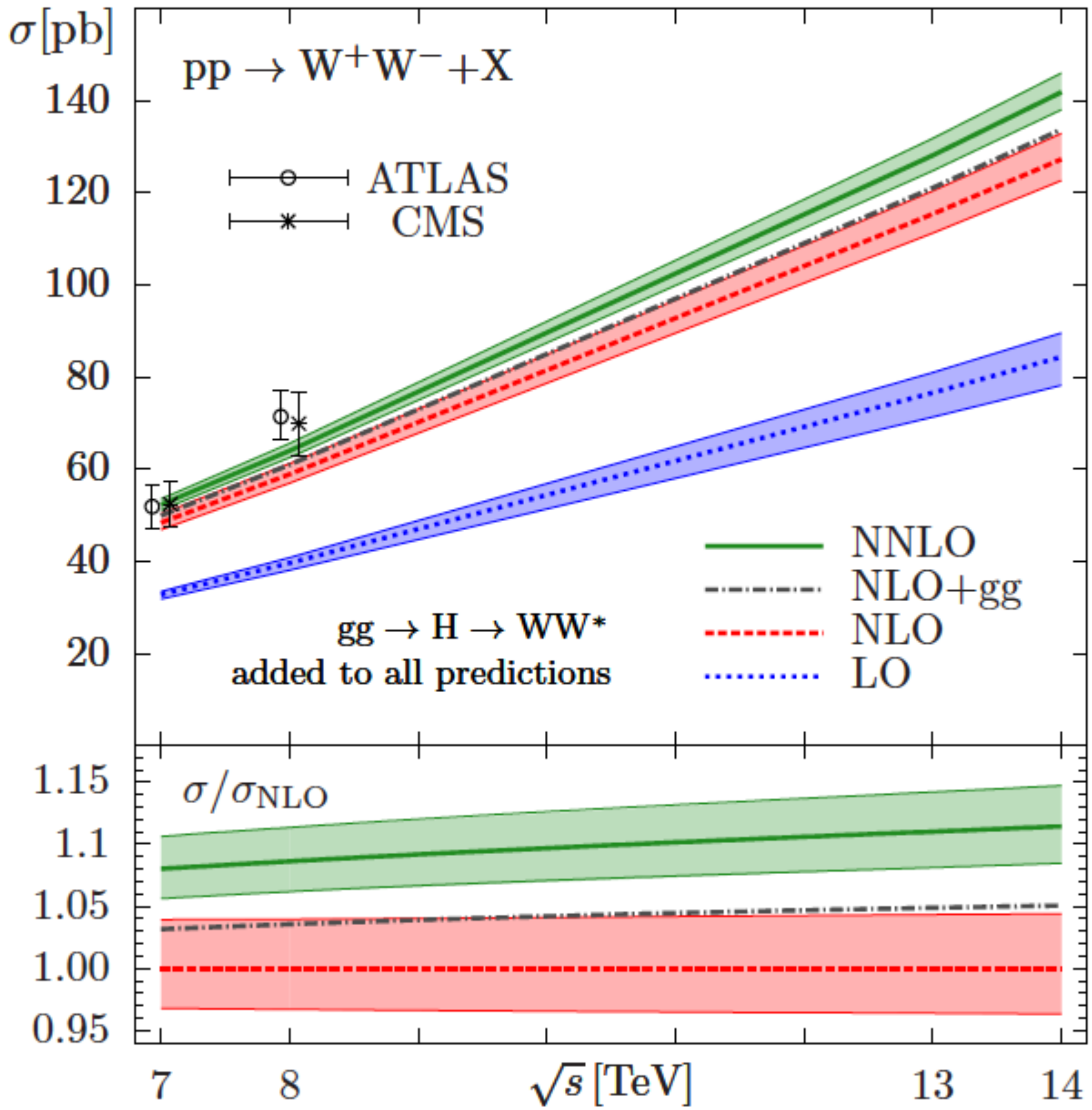


CMS diboson cross sections



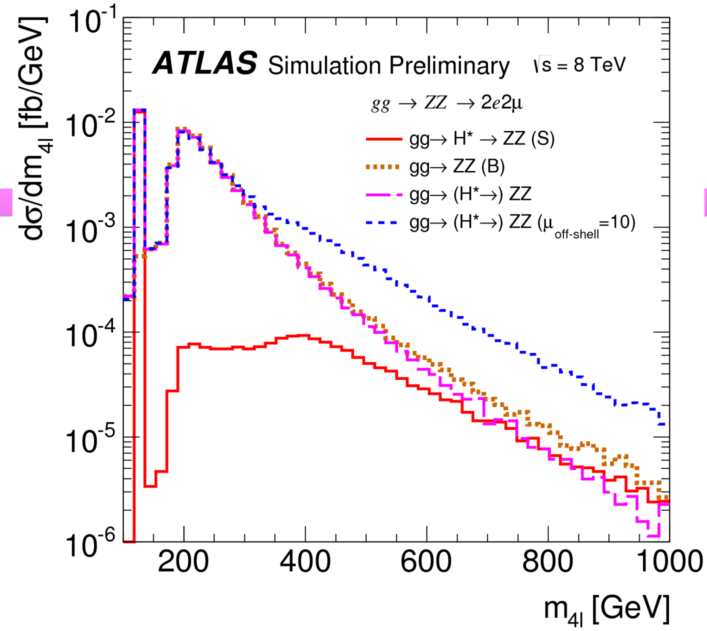
…but arxiv:1408.5243

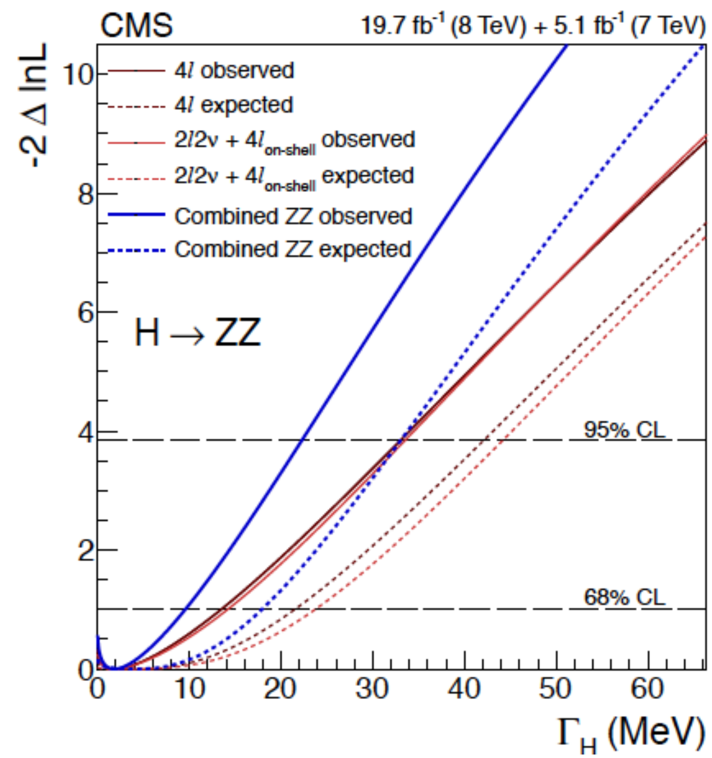
- NNLO calculation of WW production recently completed
- Modest increase in size of cross section
- Decrease in size of excess
- QCD issues with extrapolation of jet vetoed cross section to full cross section mean that uncertainty is larger than assumed in experimental papers



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
  - ZZ calculation is feasible, but tensor basis somewhat messy
  - Thomas Gehrmann says 'a few months'
  - what about WW?





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 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 NLO 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 → 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$\bar{b}$	dσ(lept. V decay) @ NLO QCD massive b	dσ(lept. V decay) @ NNLO QCD massless b	bkg. for VH → 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
γγ	dσ @ NNLO QCD		bkg to $H \to \gamma\gamma$

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

NNLO QCD + NLO EWK wishlist

- Associated Higgs production, with Higgs decaying into 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

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)

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	$d\sigma$(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
Vb$\bar{b}$	$d\sigma$(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)

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

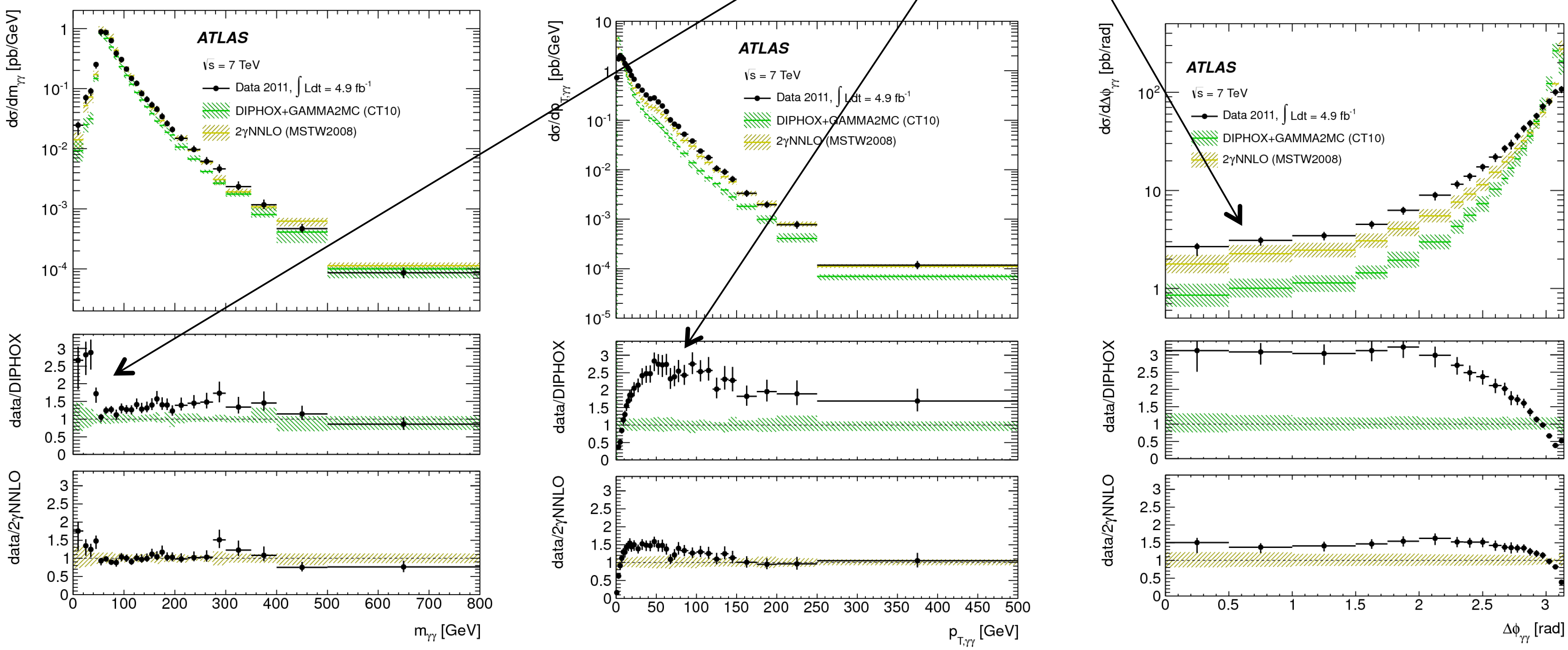
Process	known	desired	details
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
V + j	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	Z + j 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)

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



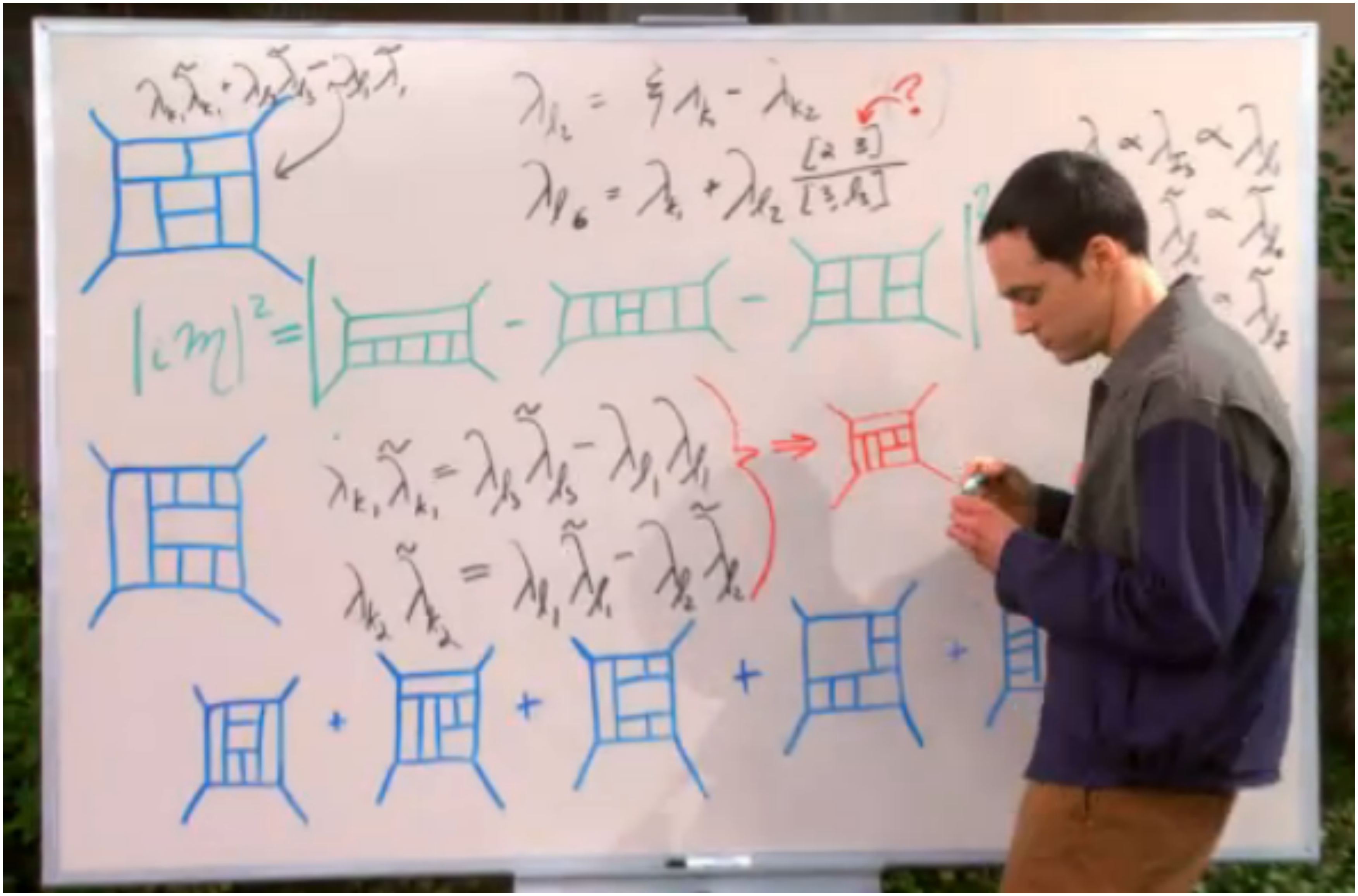
NNLO QCD + NLO EWK wishlist

- 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

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)

The frontier



Meta-PDFs:arXiv:1401.0013

- Take NNLO (or NLO) PDFs

NNLO	*Initial scale*	a_S	*Error type*	*Error sets*
CT10	*1.3*	*0.118*	*Hessian*	*50*
MSTW'08	*1.0*	*0.1171*	*Hessian*	*40*
NNPDF2.3	*1.414*	*0.118*	*MC*	*100*

- Choose a meta-parametrisaton of PDFs at initial scale of 8 GeV (away from thresholds) for 9 PDF flavors (66 parameters in total)

$$f(x, Q_0; \{a\}) = e^{a_1} x^{a_2} (1-x)^{a_3} e^{\sum_{i\geq 4} a_i \left[T_{i-3}(y(x))-1\right]}$$

- Generate MC replicas for all 3 groups and merge with equal weights, finding meta parameters for each of the replicas by fitting PDFs in x ranges probed at LHC
- Construct 50 eigenvectors using Hessian method (throw away 16 least important)
- These 50 eigenvectors provide a very good representation of the PDF uncertainties for all of the 3 PDF error families above

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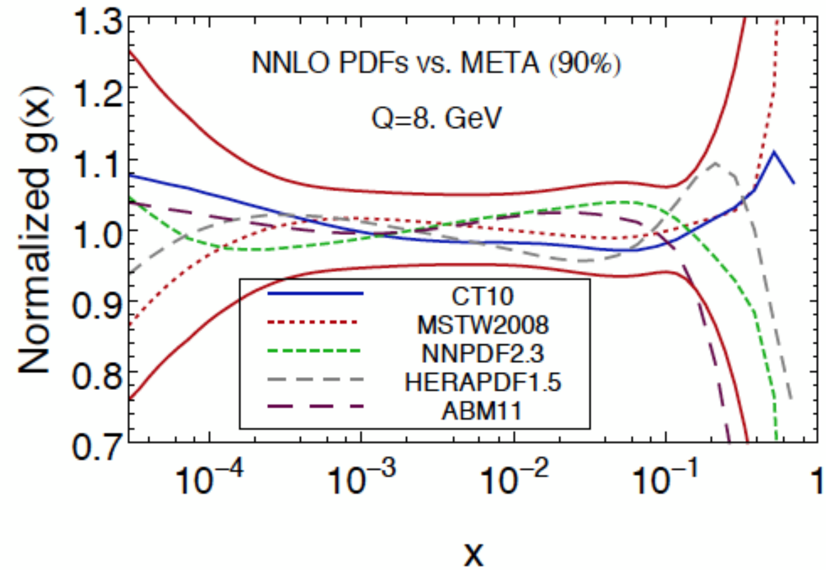
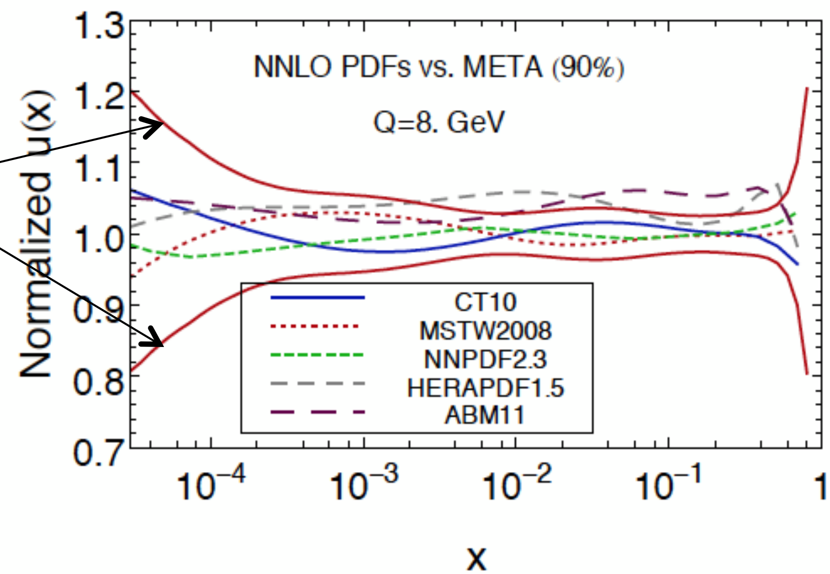
meta-PDFs

- The meta-PDFs provide both an average of the chosen PDFs, as well as a good estimation of the total PDF uncertainty



meta-PDF uncertainty band



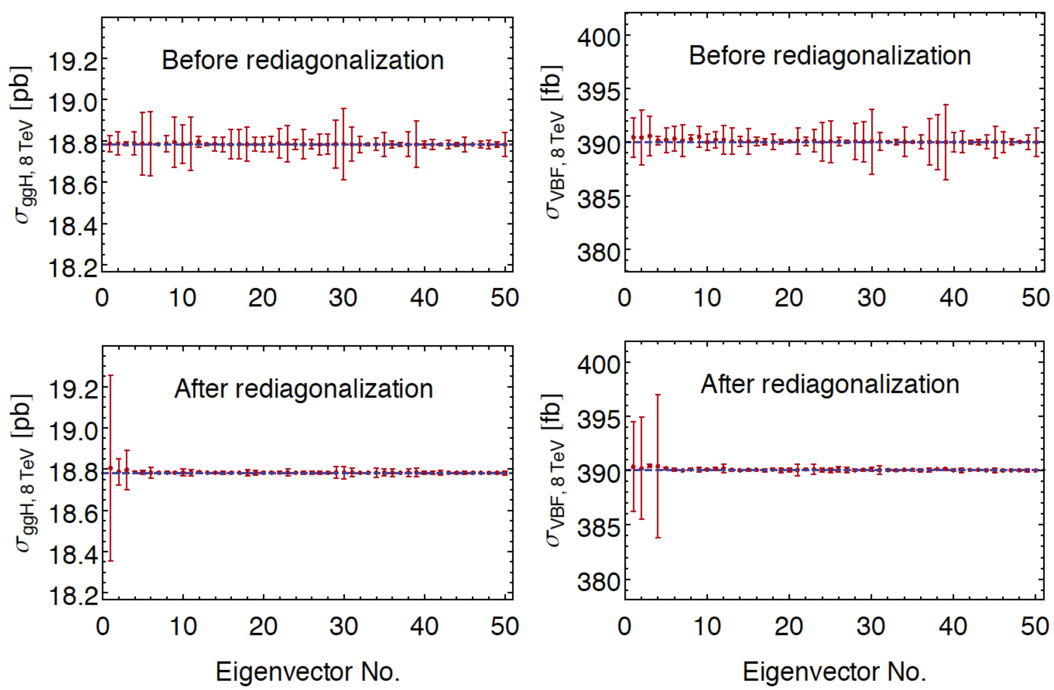
Higgs observables

- Select global set of Higgs cross sections at 8 and 14 TeV (46 observables in total; more can be easily added if there is motivation)

production channel	$\sigma(inc.)$	$\sigma(\lvert y_H \rvert > 1)$	$\sigma(p_{T,H} > m_H)$	scales
$gg \to H$	iHixs1.3 [32] at NNLO	MCFM6.3 [33] at LO	—	m_H
$b\bar{b} \to H$	iHixs at NNLO	—	—	m_H
VBF	VBFNLO2.6 [34] at NLO	same	same	m_W
HZ	VHNNLO1.2 [35] at NNLO	CompHEP4.5 [36] at LO	CompHEP at LO	$m_Z + m_H$
$HW^\pm$	VHNNLO at NNLO	—	—	$m_W + m_H$
HW^+	CompHEP at LO	same	same	$m_W + m_H$
HW^-	CompHEP at LO	same	same	$m_W + m_H$
$H + 1jet$	MCFM at LO	same	same	m_H
$Ht\bar{t}$	MCFM at LO	CompHEP at LO	CompHEP at LO	$2m_t + m_H$
HH	Hpair [37] at NLO	—	—	$2m_H$

Data set diagonalization (arXiv:0904.2424)

- There are 50 eigenvectors, but can re-diagonalize the Hessian matrix to pick out directions important for the Higgs observables listed on previous page; with rotation of basis, 50 eigenvectors become 6



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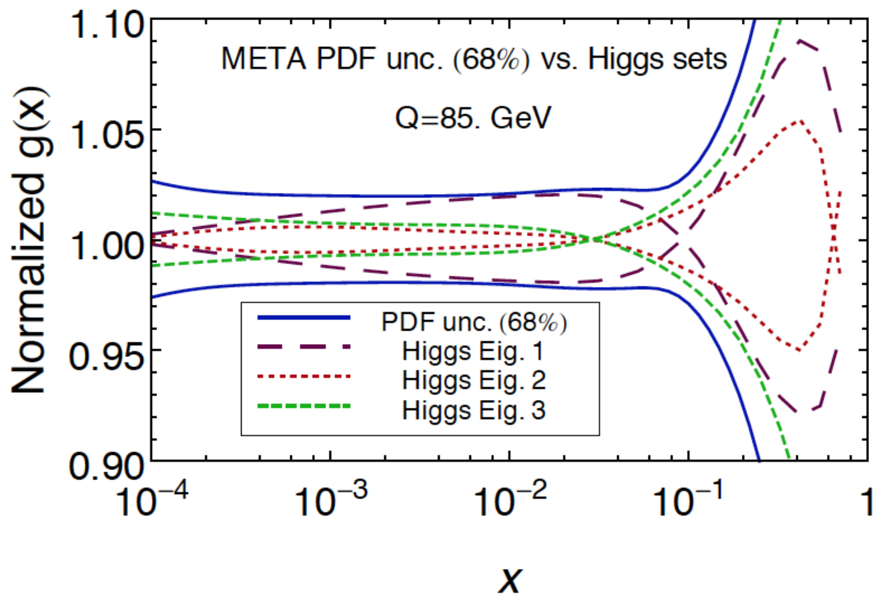
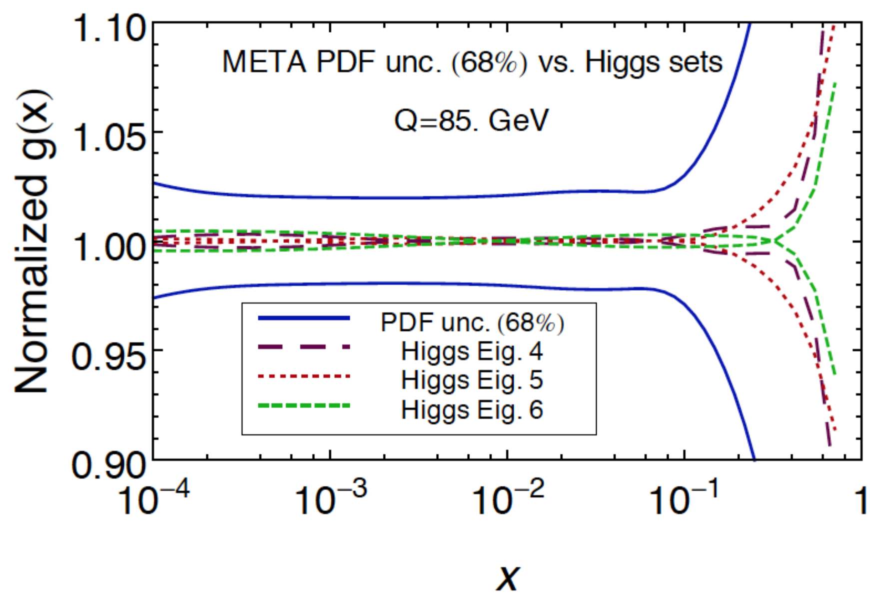
P. Nadolsky
(in progress)

It's possible to define a few eigenvectors which completely encompass the PDF and α_s uncertainties for CT10, MSTW08 and NNPDF2.3 for Higgs production for 8-14 TeV

Re-diagonalized eigenvectors

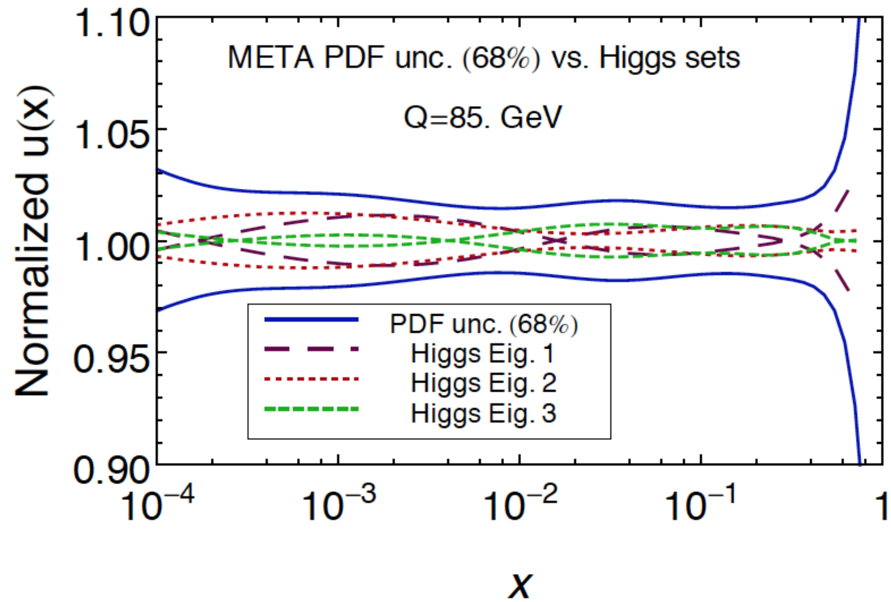
- Eigenvectors 1-3 cover the gluon uncertainty
- Note that eigenvector 1 saturates the uncertainty for most of the gg->Higgs range

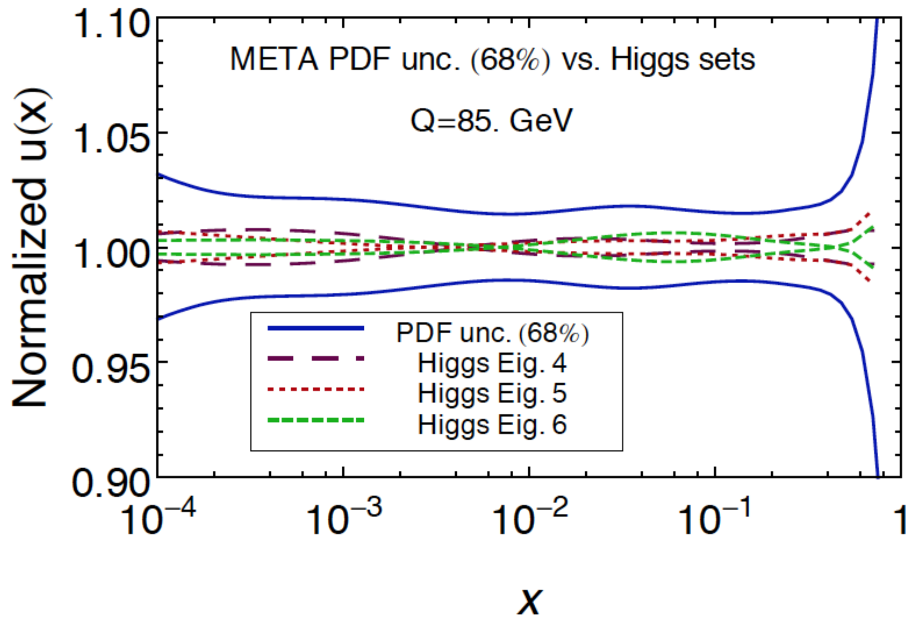




Re-diagonalized eigenvectors

- Up quark uncertainties a bit more distributed





arXiv:1004.4624

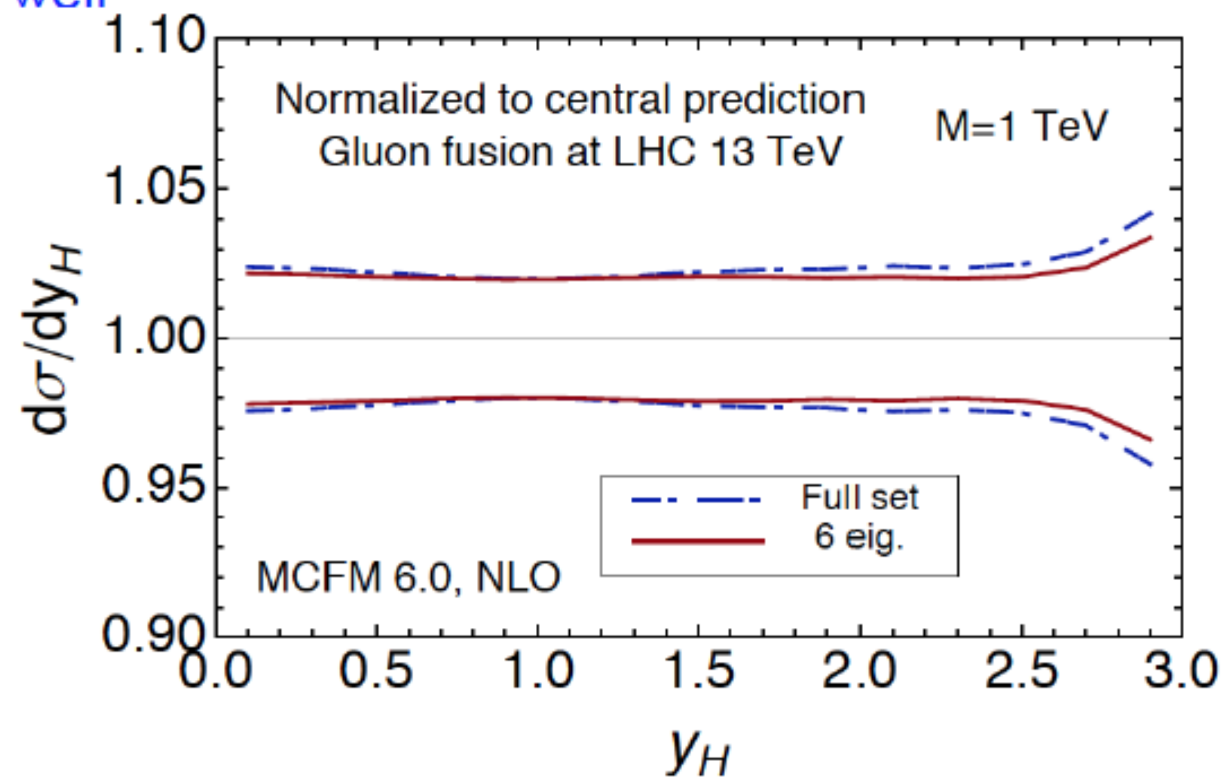
- Treat α_s input as another eigenvector; α_s and PDF uncertainties can be added in quadrature ($\alpha_s(m_Z)$=0.118+/0.0012)
- So 7 eigenvectors to represent all PDF+α_s uncertainty for all 3 global PDFs

LHC	$\Delta\alpha_s(M_Z)$	GGH inc.	GGH 0j exc.	GGH 1j exc.	GGH 2j inc.	VBF inc.
LHC 8 TeV	$+1\sigma$	2.2%	1.6%	3.0%	4.8%	-0.23%
	-1σ	-2.2%	-1.6%	-2.8%	-4.8%	0.11%
LHC 14 TeV	$+1\sigma$	2.1%	1.4%	2.6%	4.5%	0.05%
	-1σ	-2.0%	-1.4%	-2.5%	-4.4%	-0.09%

❖ using PDF α_s series of the META PDFs

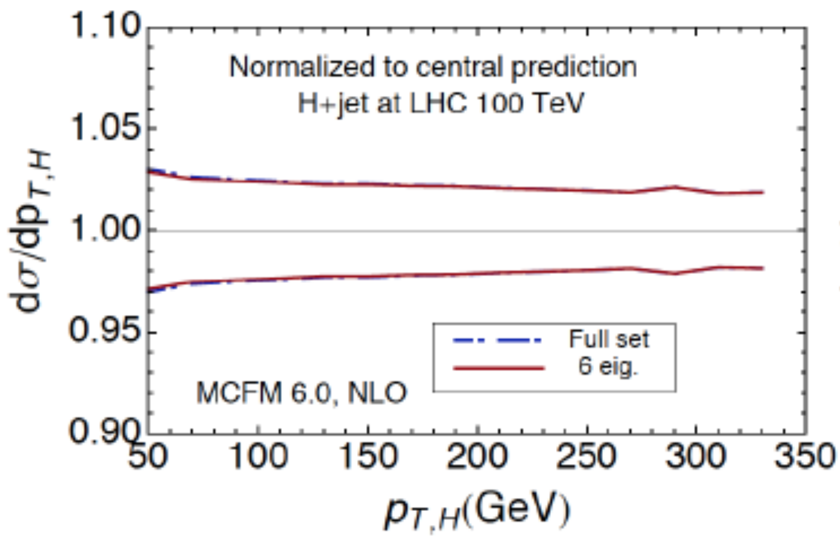
Try other distributions

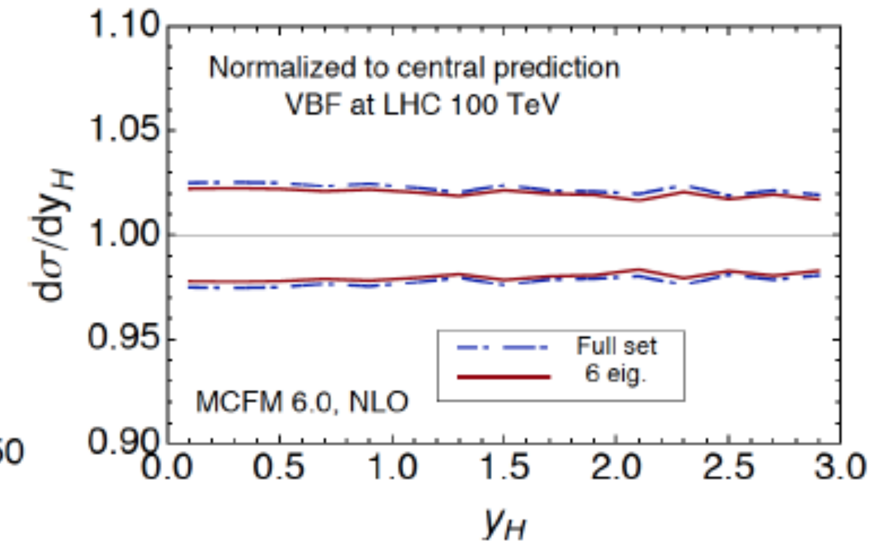
- Look at rapidity distribution for production of a 1 TeV mass state through gg fusion
- This was not an input to the re-diagonalization, but still works fairly well



Look at 100 TeV

- Again, these cross sections were not used in the re-diagonalization





what we left at Les Houches for the BSM session

Summary

- The new high precision Les Houches wishlist presents some real (and important) challenges for QCD and EW calculators
- The data taken in Run 2 requires the effort

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