LHC Standard Model Results 1
or
Poking the Standard Model

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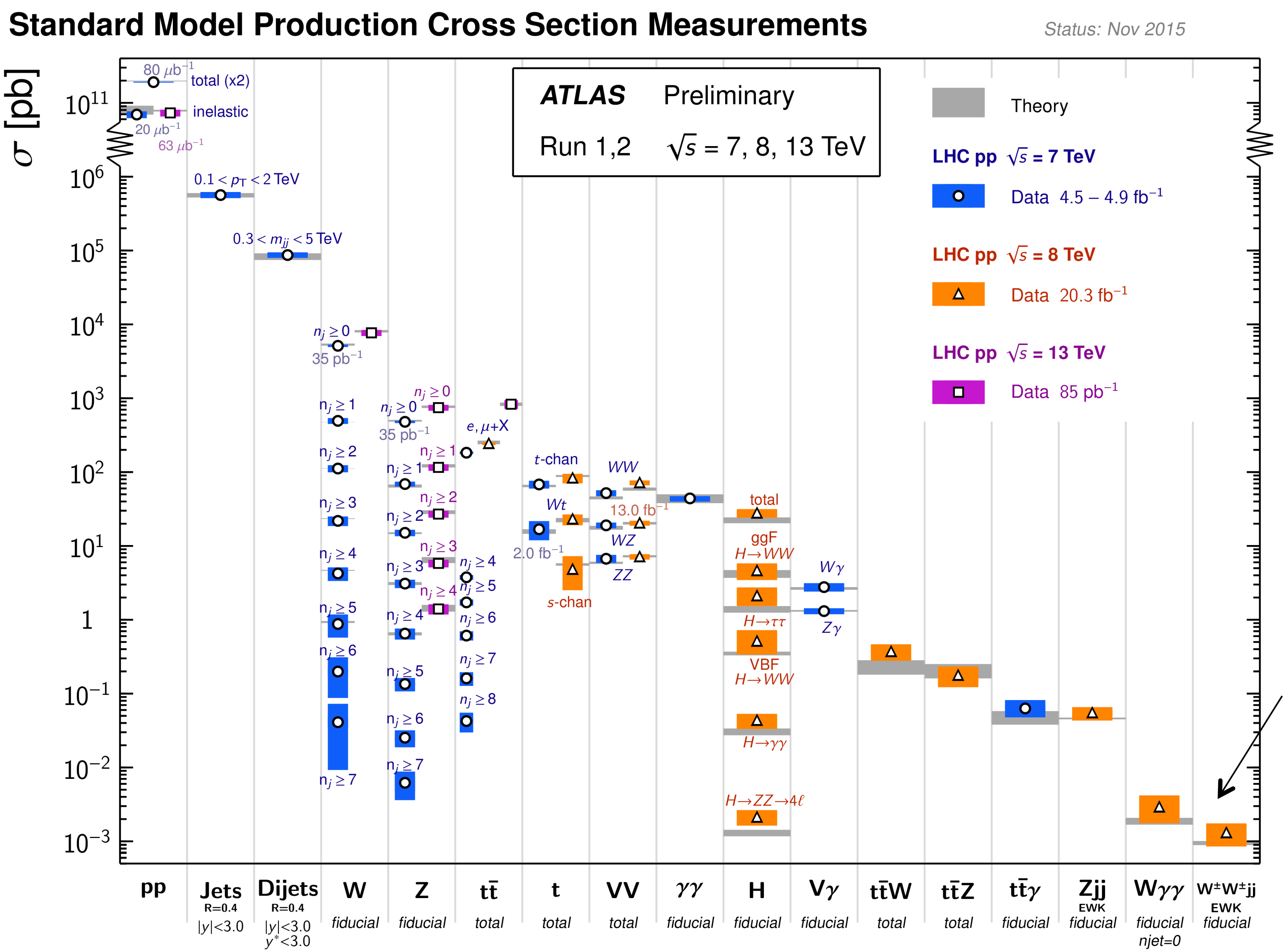
Stress Testing the Standard Model at the LHC
Kavli Institute for Theoretical Physics
May 23, 2016

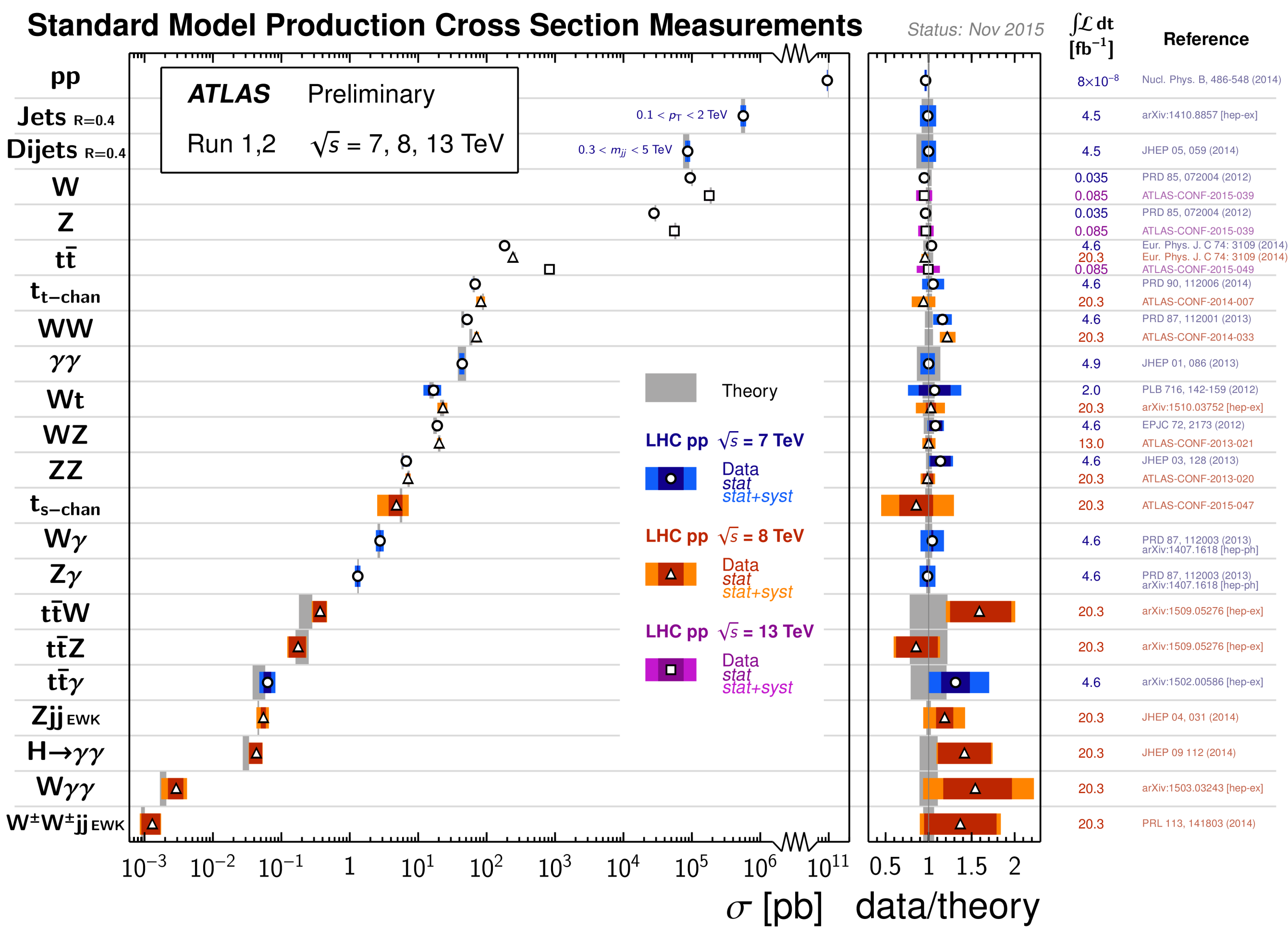
(SM) Physics from Runs 1 and 2



probing fb cross sections

Physics from Runs 1 and 2

…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 SM predictions available to test data vs theory. <u>We need to have the data in a form to allow for precision comparisons to the SM.</u>

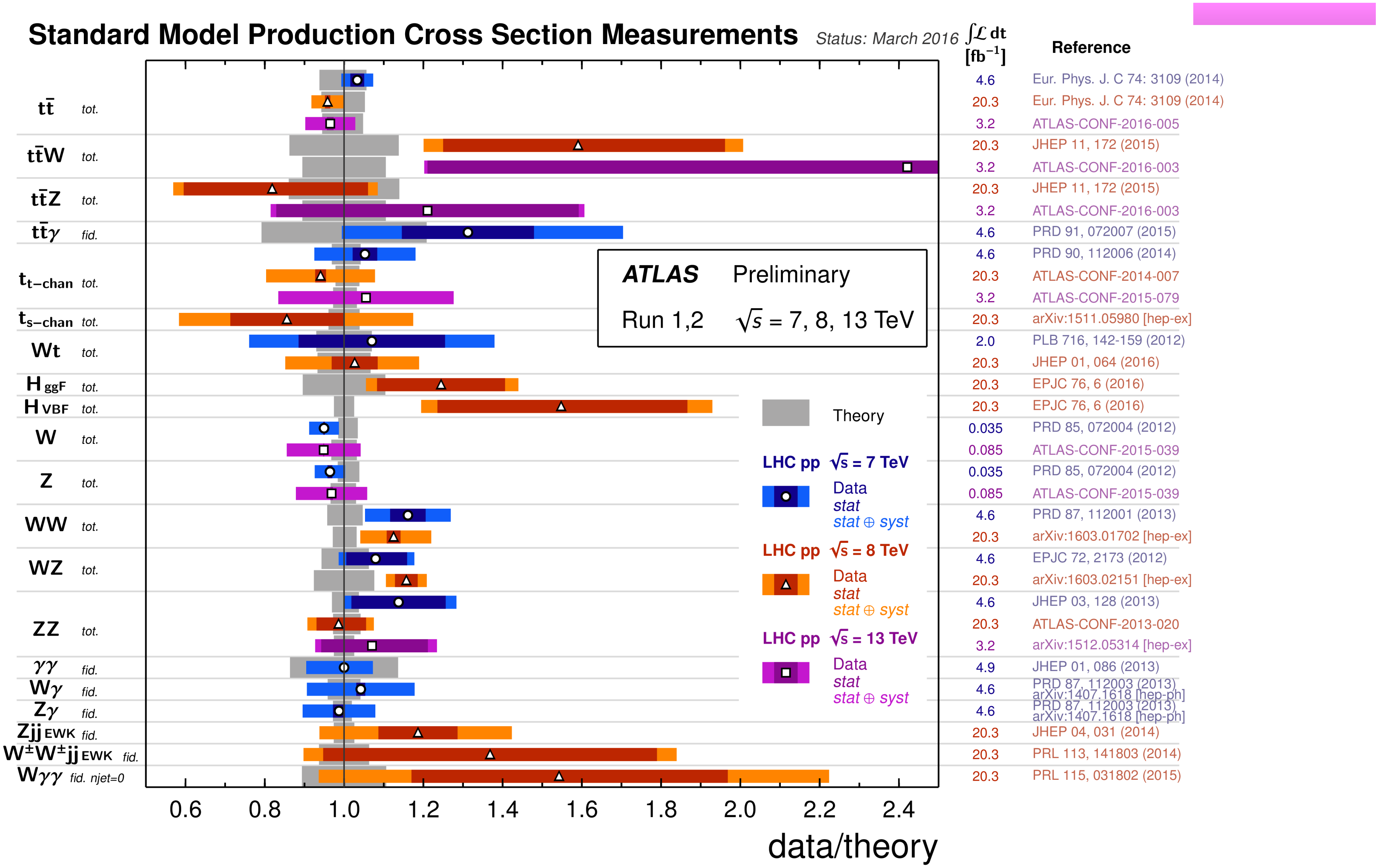


We also need a better understanding of the gluon distribution, especially at high x

↓

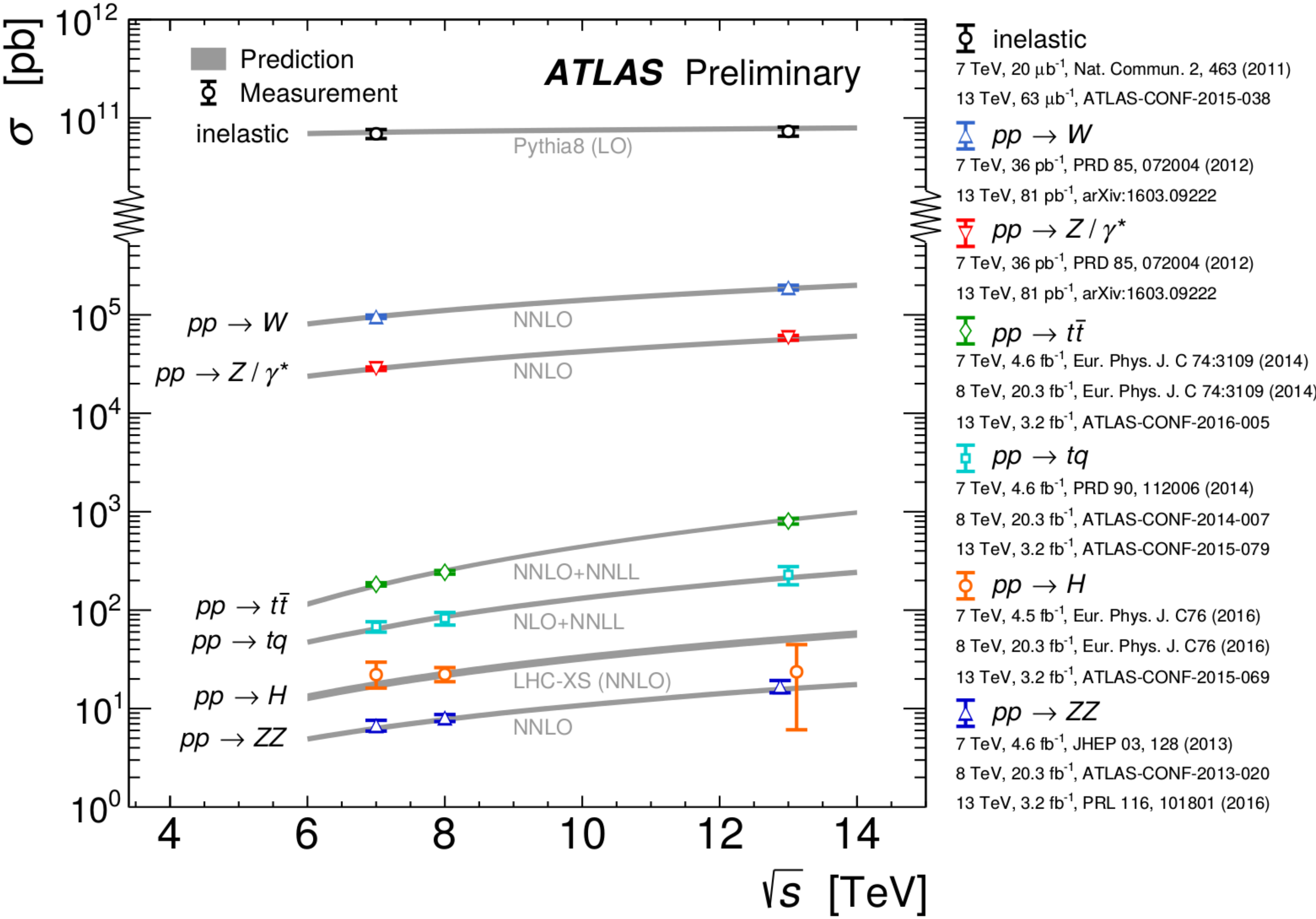
a theme

…in some more detail



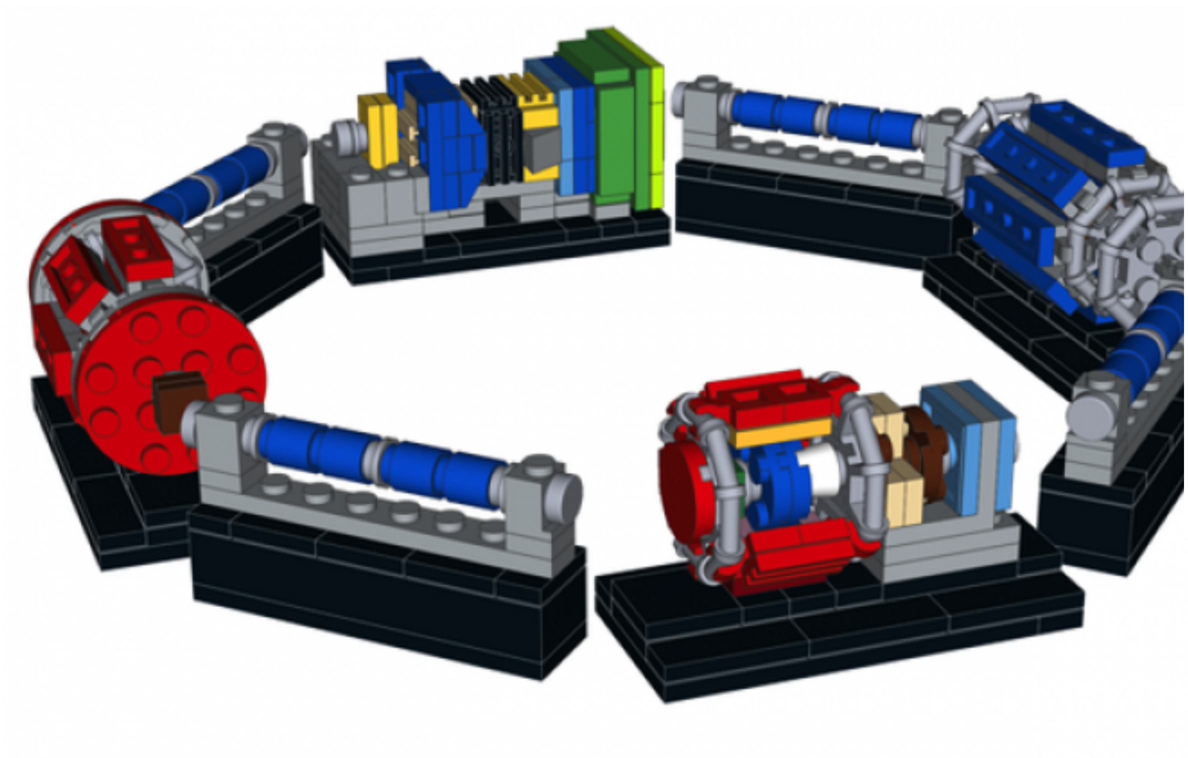
There are deviations from the SM predictions; however, given the errors, both theoretical and experimental, nothing to write home about…or make a reservation for Stockholm

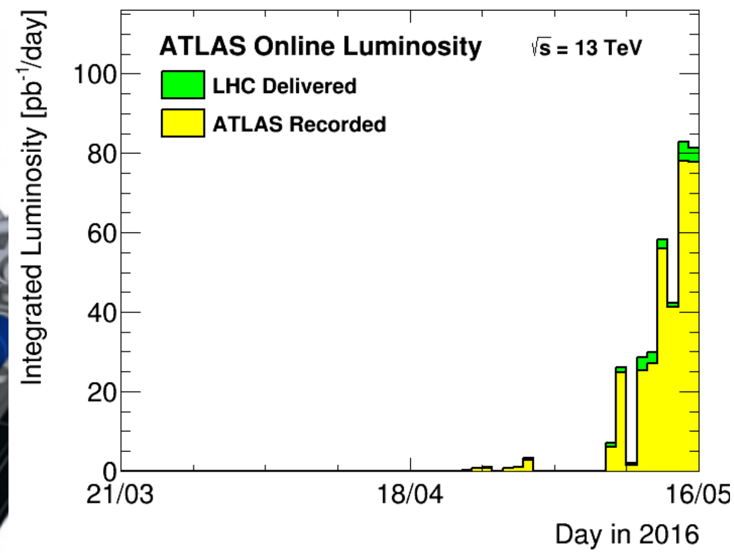
The increase in cross section from 8 to 13 TeV is welcome

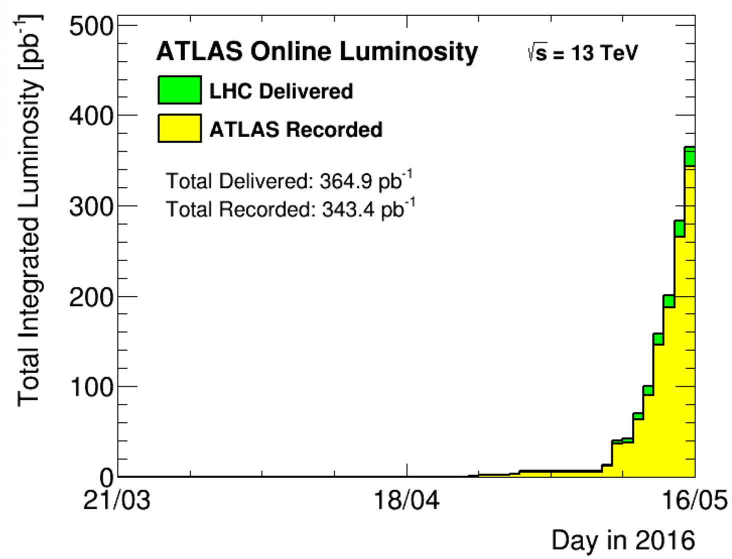


…but most results will be at 7 and 8 TeV since that is where most of the precision physics has been done to date.

The LHC is up and running again at 13 TeV

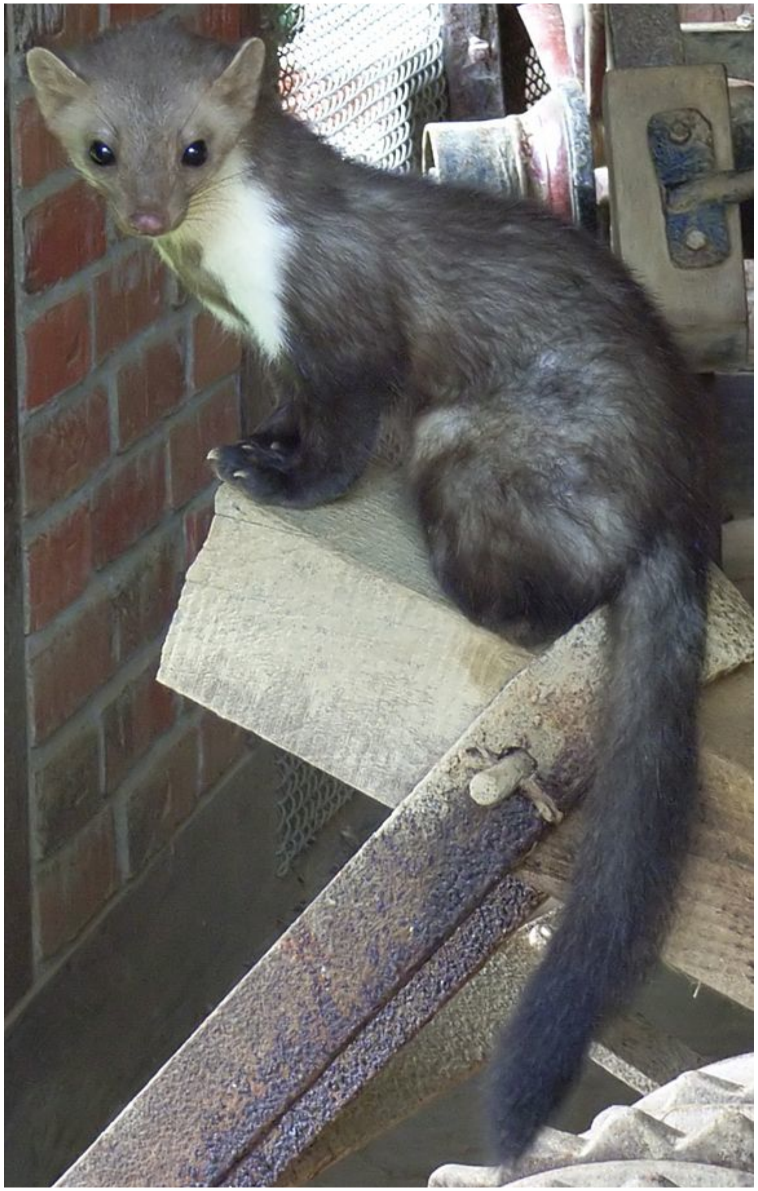




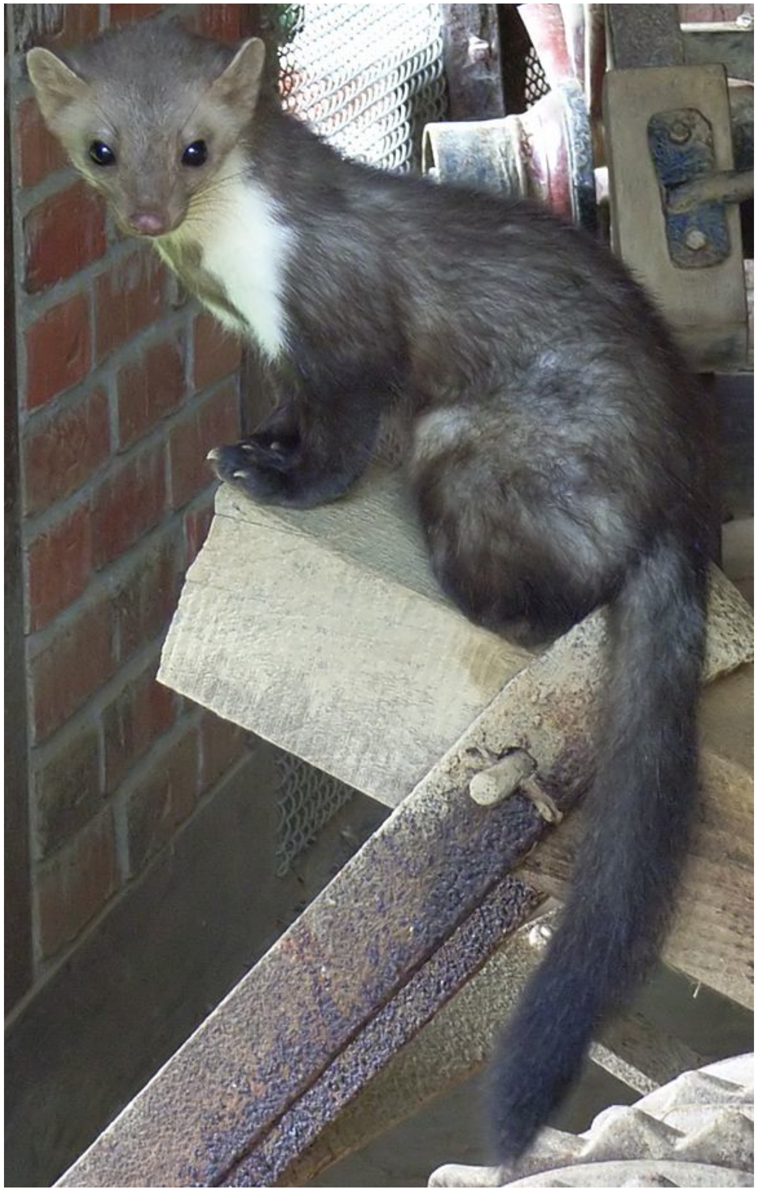


…after a brief mis-hap

Obligatory joke about la fouine



Obligatory joke about la fouine



I will note that Linux Kernel 4.6 has been designated as ‘charredweasel’. Expect a new sub-release 4.6.1: charred fouine’.

Realistic wishlist for NLO

- 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. $pp \to VVb\bar{b}$,	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

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

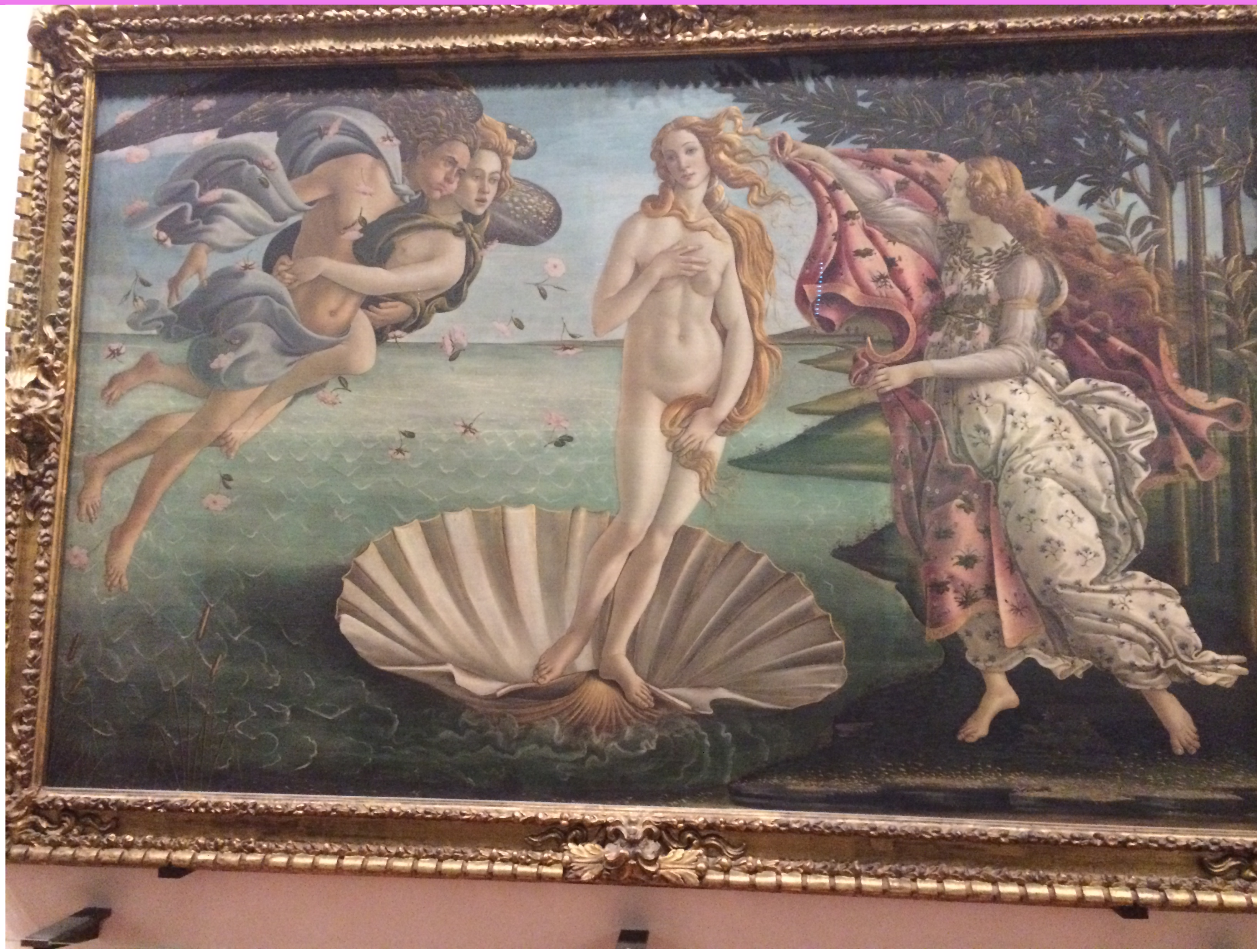
- From the 2013 proceedings
  - arxiv:1405.1067
- NB: The counting of orders is done relative to LO QCD independent of the absolute power of α_s in cross section
- $\alpha \sim \alpha_s^2$ so that NNLO QCD and NLO EW effects are naively of the same size
- $d\sigma$ represents full differential cross sections
- The list is very ambitious, but possible to do over the remainder of the LHC running

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

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

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

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



…which have been around longer than we realized

Wishlist: Higgs sector

status 2014 — (underline) 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 one more year?	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 differential VBF at NNLO with projection to Born	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

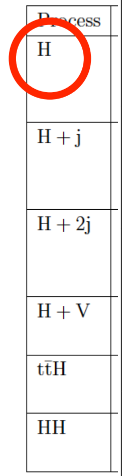
Table 1: Wishlist part 1 – Higgs (V = W, Z)

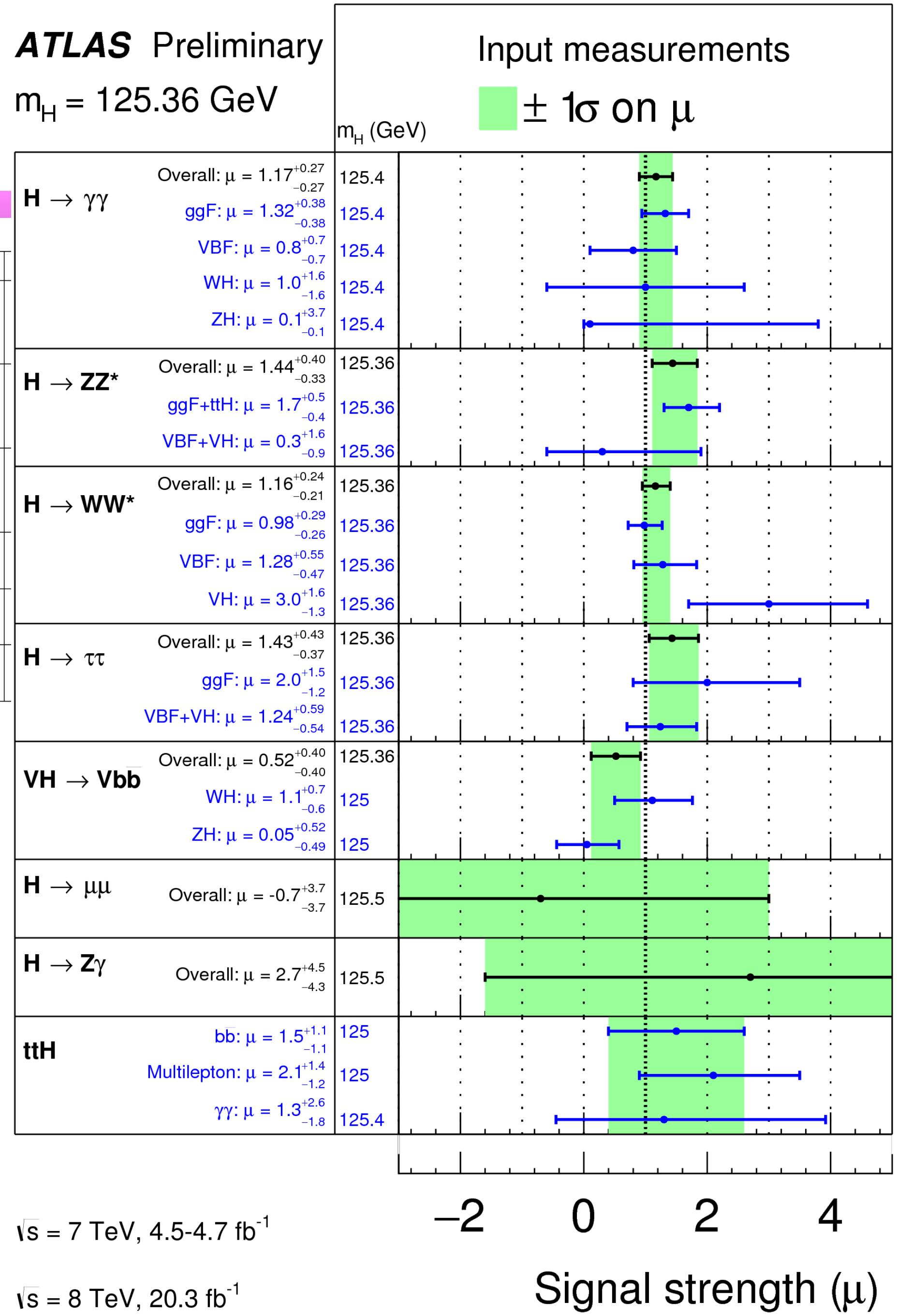
Higgs sector

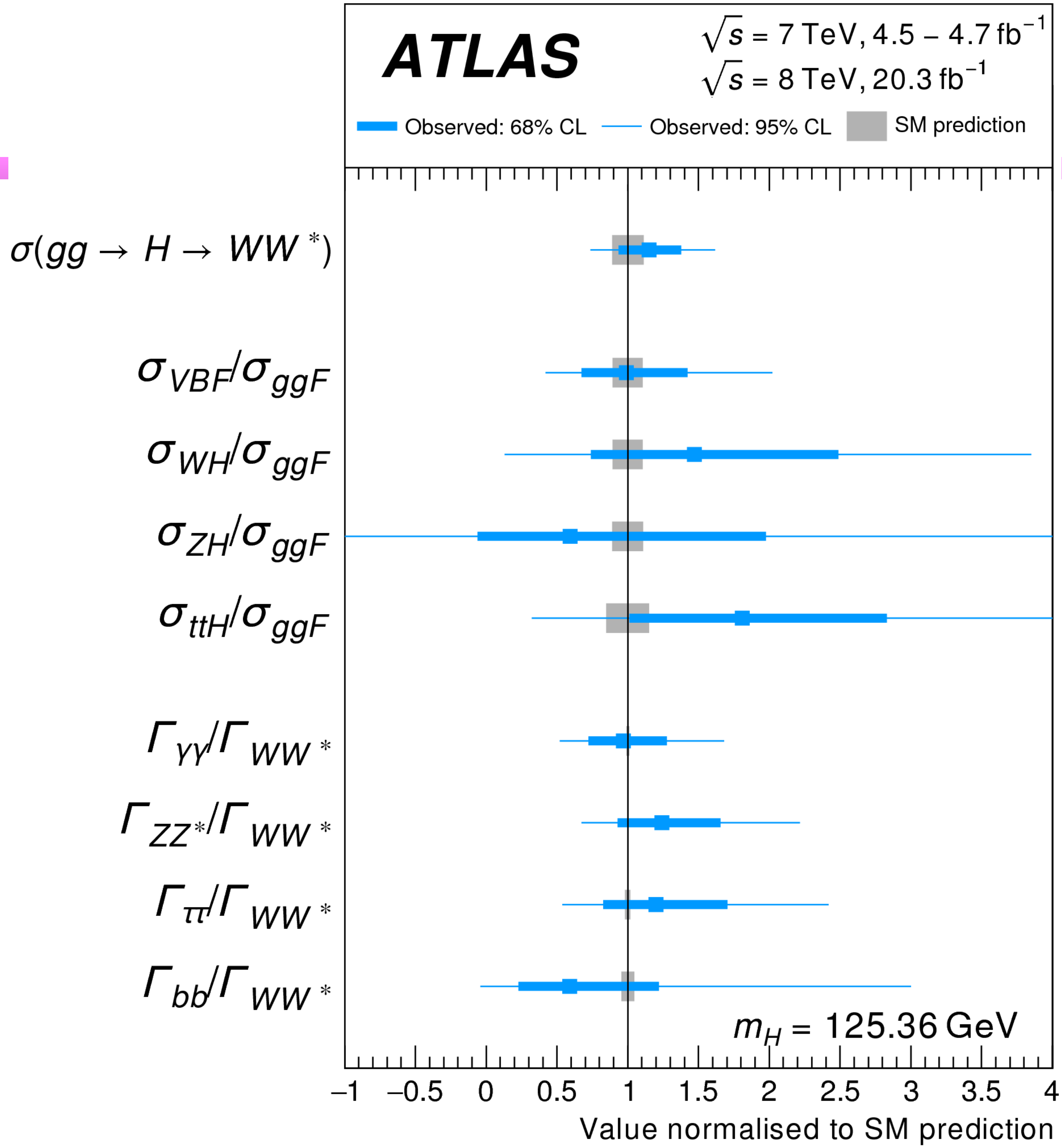
- We currently know the production cross section for gg fusion to NNNLO QCD in the infinite m_t limit, including finite quark mass effects at NLO QCD and NLO EW.
- Current ATLAS experimental uncertainties are of the order of 20-40%->consistency with SM at that level
- NB: signal strength parameters make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





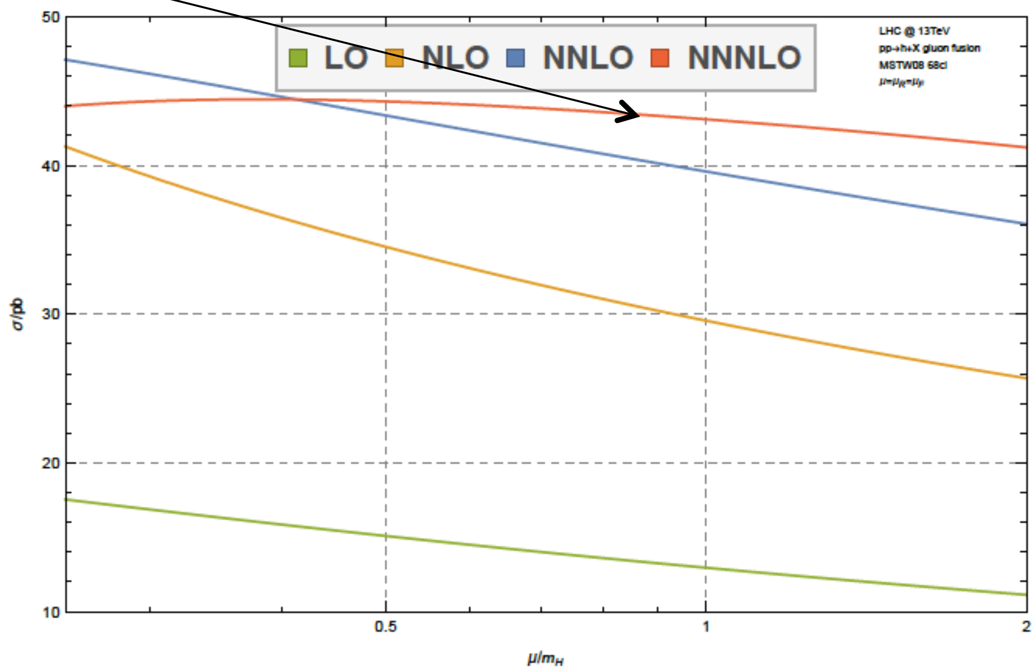


ATLAS
$\sqrt{s}$ = 7 TeV, 4.5 – 4.7 fb^{-1}
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Observed: 68% CL
Observed: 95% CL
SM prediction
$\sigma(gg \to H \to WW^*)$
$\sigma_{VBF}/\sigma_{ggF}$
σ_{WH}/σ_{ggF}
σ_{ZH}/σ_{ggF}
$\sigma_{ttH}/\sigma_{ggF}$
$\Gamma_{\gamma\gamma}/\Gamma_{WW^*}$
$\Gamma_{ZZ^*}/\Gamma_{WW^*}$
$\Gamma_{\tau\tau}/\Gamma_{WW^*}$
$\Gamma_{bb}/\Gamma_{WW^*}$
m_H = 125.36 GeV
–1 –0.5 0 0.5 1 1.5 2 2.5 3 3.5 4
Value normalised to SM prediction

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 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

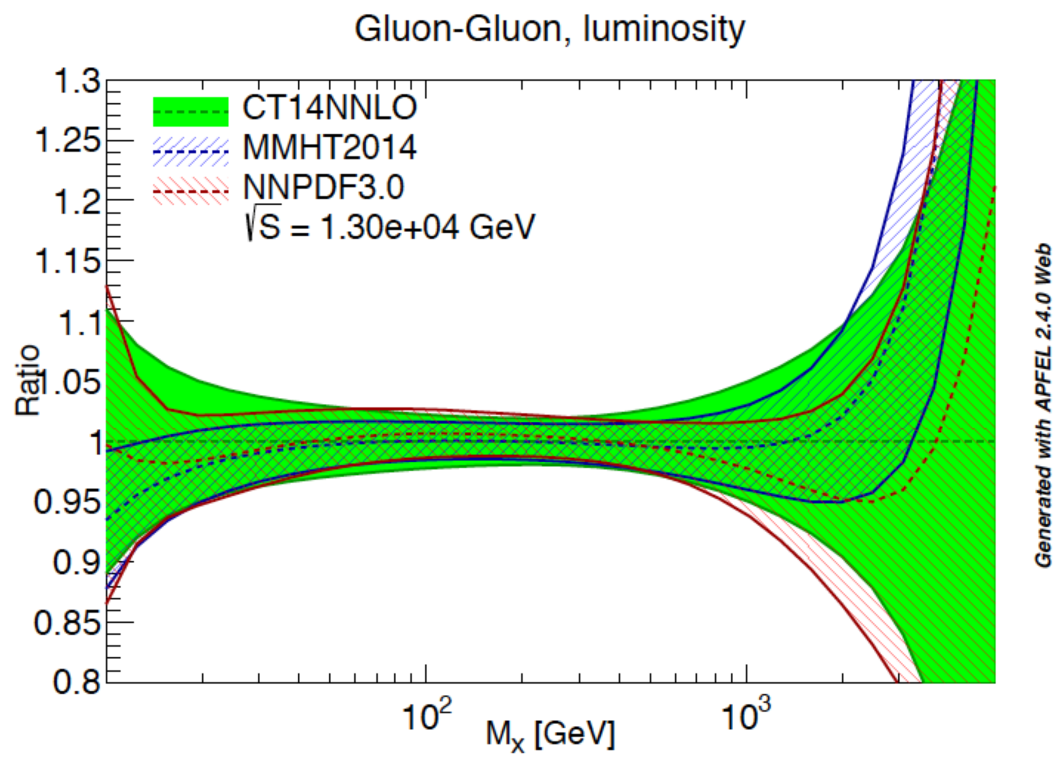
Process	known	desired	details
H	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ NLO	$d\sigma$ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW finite quark mass effects @ LO	$d\sigma$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



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

PDFs: the next generation

- NNPDF3.0
- MMHT14
- CT14
- HERAPDF2.0
- 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 NNLO, and comparable to the α_s 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

See Maria's, Pavel's talks

A comparison of ggF at NNLO (at 8 TeV)

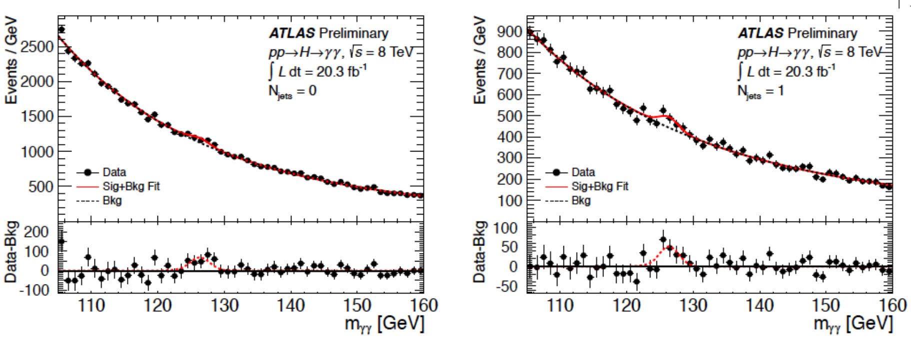
scale = m_H	**CT14**	**MMHT2014**	**NNPDF3.0**
8 TeV	18.66 pb -2.2% +2.0%	18.65 pb -1.9% +1.4%	18.77 pb -1.8% +1.8%
13 TeV	42.68 pb -2.4% +2.0%	42.70 pb -1.8% +1.3%	42.97 pb -1.9% +1.9%

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.

Higgs sector

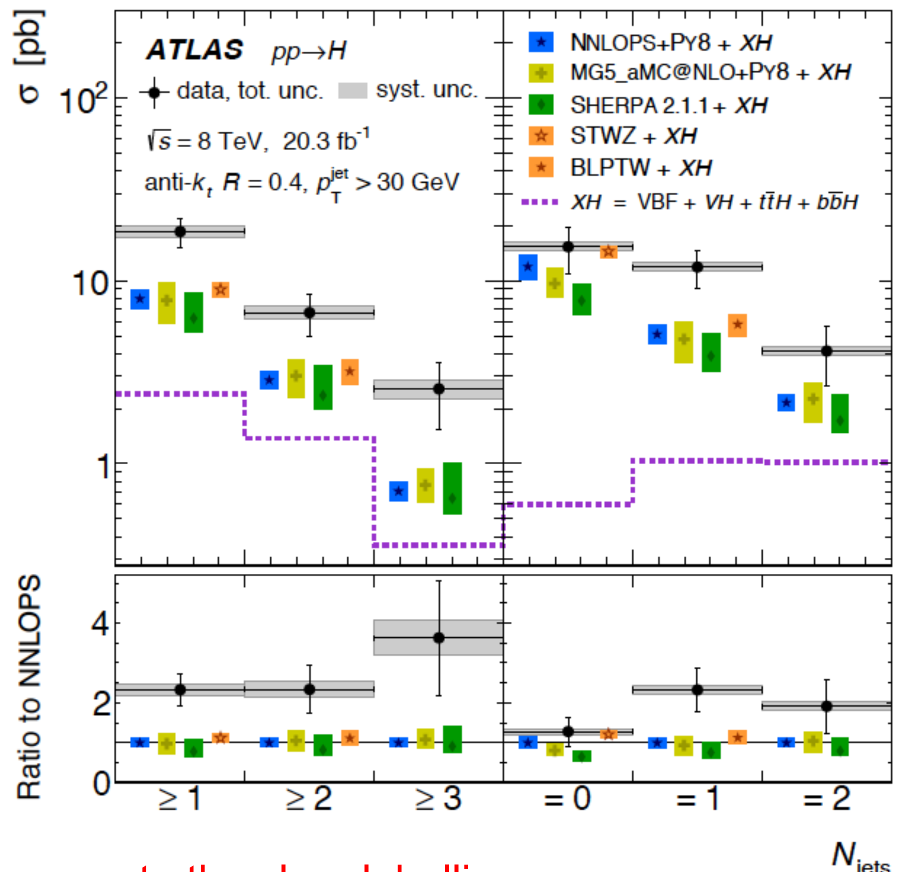
- First attempts to measure differential Higgs+jets measurements made in diphoton (ZZ*) channel at ATLAS
  - JHEP 1409(2014)112; (Phys. Lett. B738(2014)234)
- Combination with ZZ*
  - arXiv:1504.05833

Process	known	desired	details
H	$d\sigma$ @ 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



(a) $N_{\text{jets}} = 0$ (b) $N_{\text{jets}} = 1$

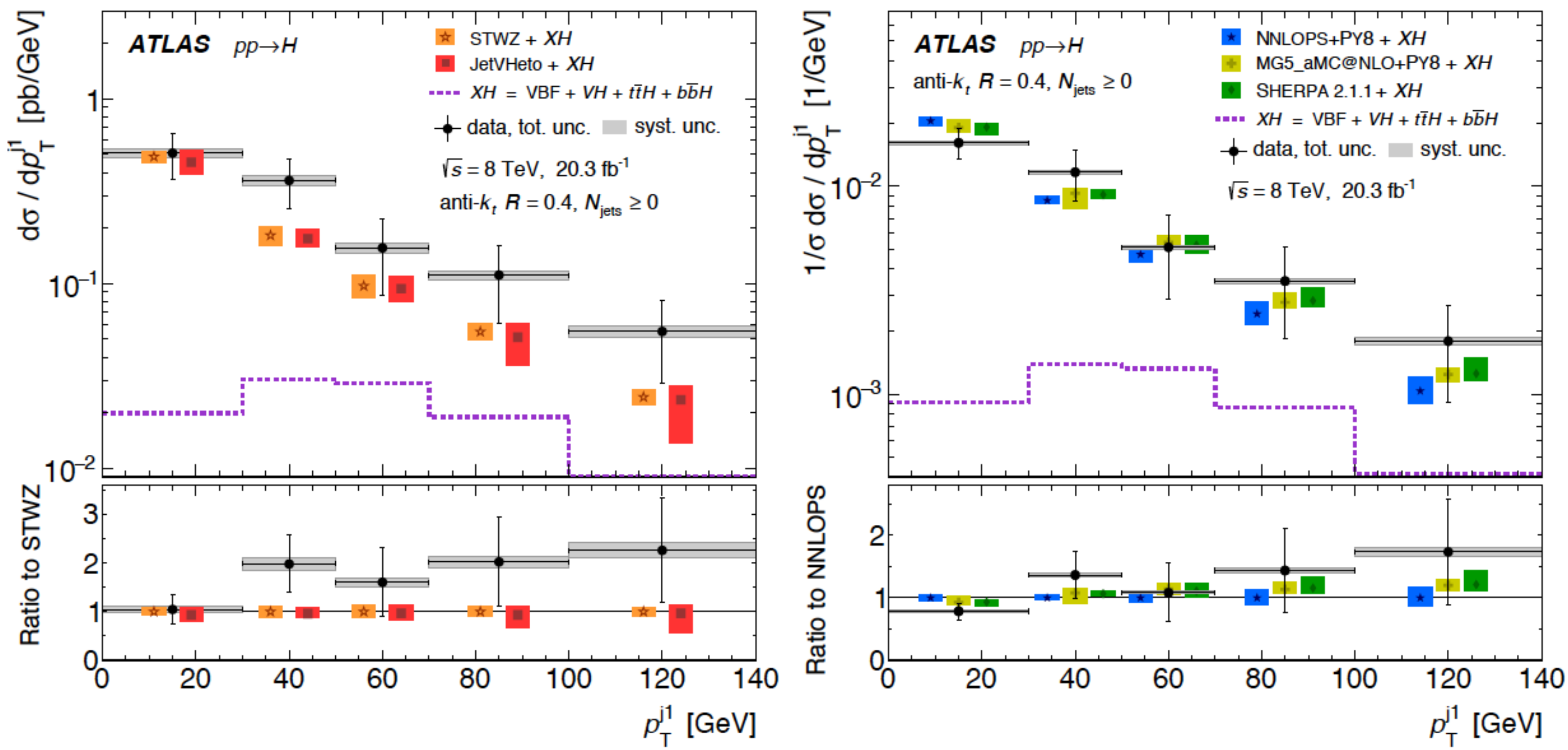
(c) $N_{\text{jets}} = 2$ (d) $N_{\text{jets}} \geq 3$



note the clear labelling

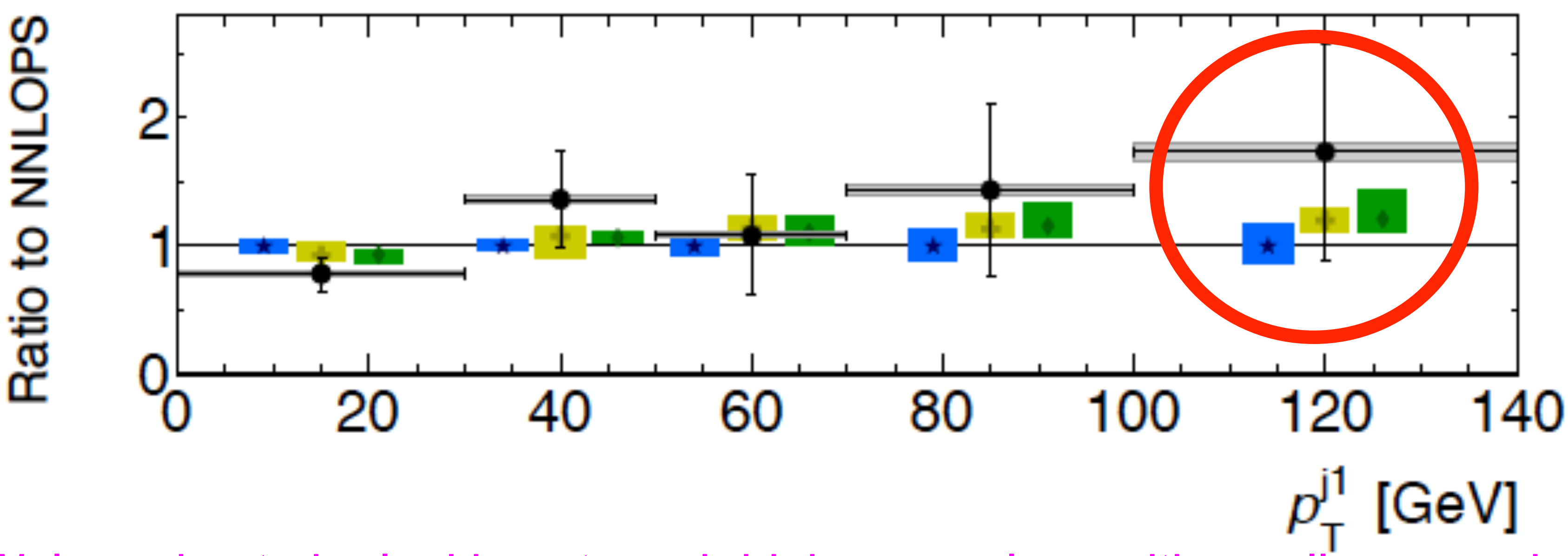
ATLAS Higgs+>=1 jet

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



ATLAS Higgs+>=1 jet

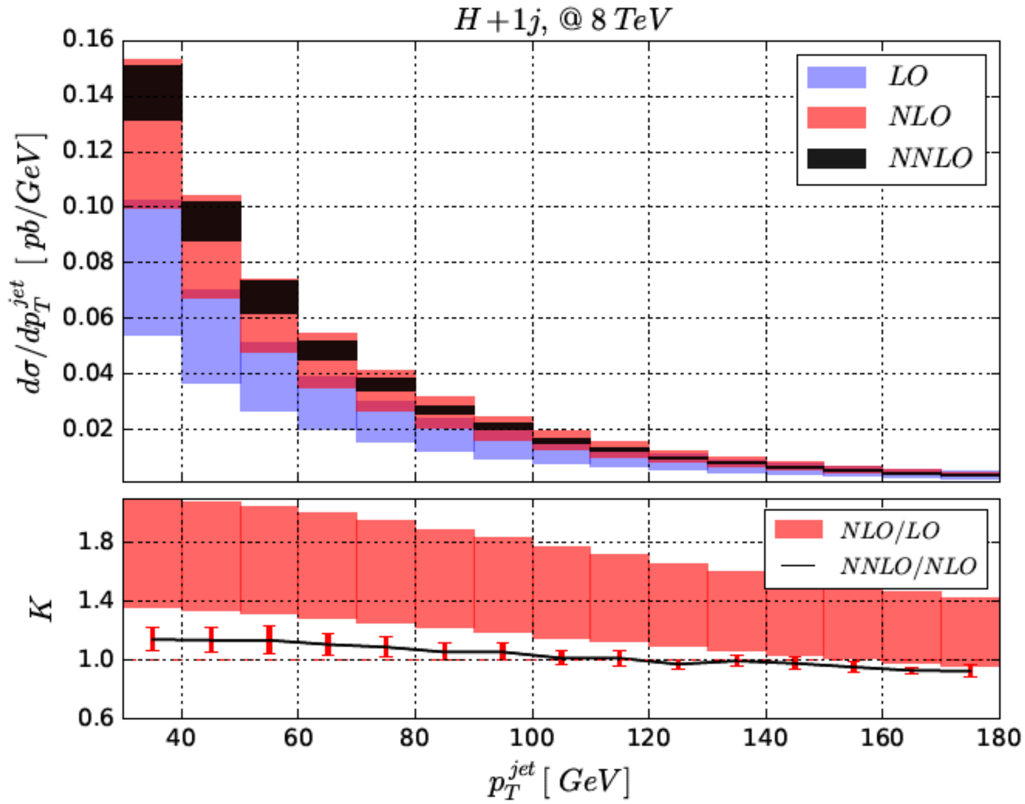
- Comparisons to a wide number of resummation/ME+PS predictions…**but not to fixed order**!
- **Les Houches:compare each predictions to each other, to fixed NLO/NNLO in detailed framework**
  - **wide variety of observables relating to Higgs+jets; Rivet routine available; ntuplereader modification available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



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 13 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
  - codes with multiple subtraction techniques agree with each other
  - MCFM-NNLO and NNLOJET, bringing H+>=1 jet at NNLO to the masses
  - 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

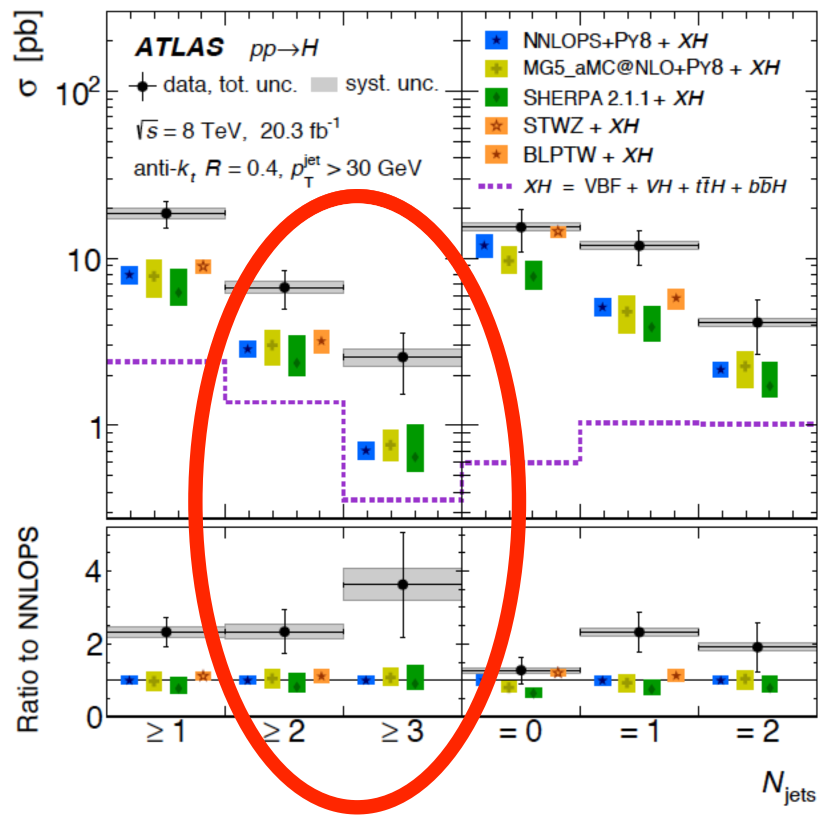


Can n-jettiness be successfully used for other processes, for example Higgs+>=2 jets at NNLO (once appropriate virtual terms are known)?

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
  - VBF differential known to NNLO using the projection-to-Born method; would like explicit calculation to verify
- 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

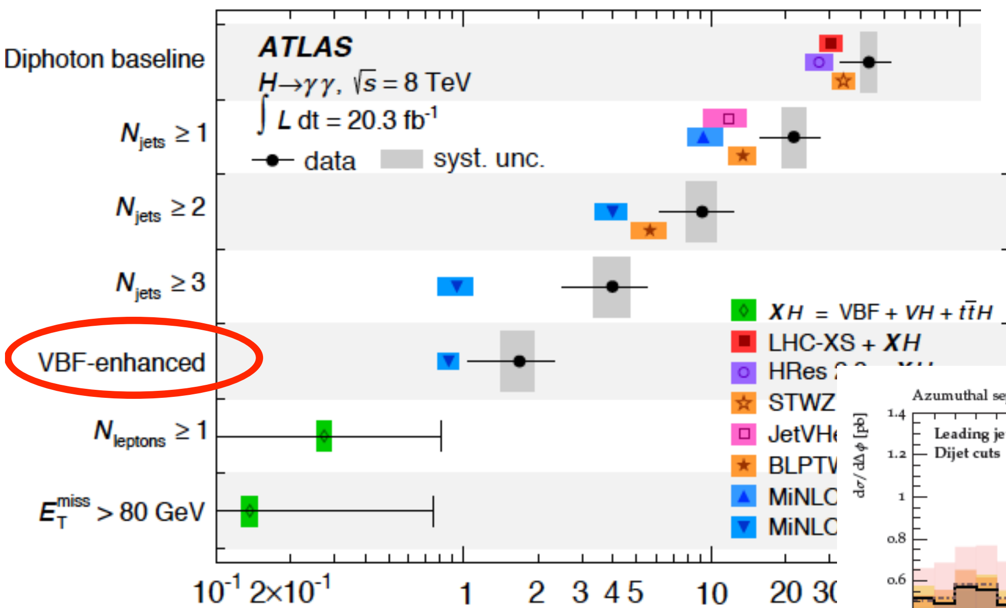
Process	known	desired	details
H	dσ @ NNLO QCD dσ @ NLO EW finite quark mass effects @ NLO	dσ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	dσ @ NNLO QCD (g only) dσ @ NLO EW finite quark mass effects @ LO	dσ @ NNLO QCD + NLO EW finite quark mass 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			
$t\bar{t}$H			
HH			



interesting that the (statistically limited) results seem to show a jettier final state than predicted…
but, statistics…and CMS does not see excess

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

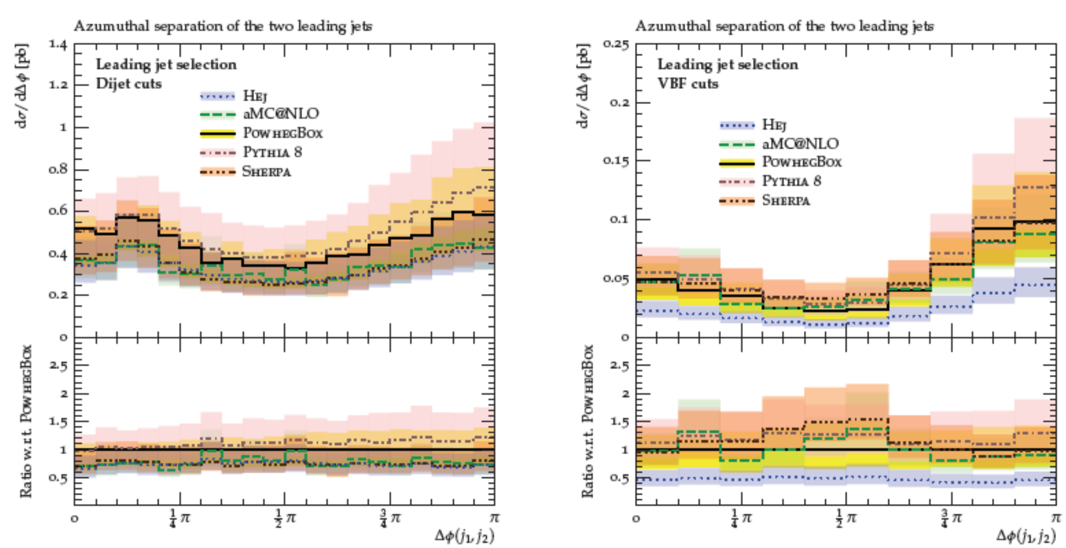


Fig. III.29: Azimuthal separation of the tagging jets before (left) and after (right) the application of the VBF selection cuts in the leading jet selection as predicted by the different generators. The individual sources of uncertainties used to generate the respective bands are described in Sec. 6.2.

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.

Les Houches 2015 study: gluon-gluon fusion

- The production of a Higgs boson through gg fusion is an excellent testing ground for such comparisons because of
  - the intrinsic importance of the process
  - the enhanced rate for additional jets in the ggF process

- The expectations prior to the study are:
  - outside of Sudakov regions, the influence of parton showers should be mild
  - cross sections that are fairly inclusive should not be subject to large jet veto logs
  - …thus, for observables such as the lead jet distribution for H+>=1 jet, we do not expect there to be any significant resummation corrections, originating either in parton showering or in explicit resummation calculations
- These may not, I believe, be the typical expectations of the ATLAS/CMS Higgs groups, or even of many theorists

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- There will be a quiz afterwards

Study

To allow for as standardized a comparison as possible, a group of generation parameters were agreed upon. MMHT2014 NLO PDFs (and the NNLO version for the NNLO calculations) were to be used, with a central value of $\alpha_s(m_Z) = 0.118$, and variations thereof of ± 0.0015. Variations of scale choice are allowed; however, they should reproduce a scale of $\frac{1}{2}m_h$ in the zero-jet limit.

Alas, in some cases, there are deviations from these standards. These will be noted where present, and the impact on the comparisons will be discussed. The Higgs boson was left undecayed. Jets were reconstructed with the anti-k_T jet clustering algorithm using $R = 0.4$, and a transverse momentum constraint of 30 GeV was imposed, along with a rapidity cut of $\eta(j) < |4.5|$. To provide a common framework for the display of the results, a Rivet routine [**?**] was created and distributed to each group providing a prediction.

Madgraph5_aMC@NLO uses a scale that devolves to m_H, rather than $m_H/2$ at low p_T; thus it is typically below the other MEPS predictions

Note that it is not enough to say that two calculations agree within their scale uncertainty bands, unless you know specifically how the individual choices of scale compare to each other. Scale logs are common to all of the calculations being compared.

Tools

- **Fixed order**
  - gosam Higgs+>=1,2,3 jets at NLO → $\mu_0 = \frac{1}{2}\sqrt{m_h^2 + \sum p_{T,j_i}^2}$
  - BFGLP H+>=1 jet at NNLO → $\mu_0 = \frac{1}{2}\sqrt{m_h^2 + \sum p_{T,j_i}^2}$
  - MiNLO applied to gosam Higgs+jets ntuples; events are read in by Sherpa, which applies MiNLO prescription, event by event → $\mu_{\rm core}^{\rm MINLO} = \frac{1}{2}\hat{H}_T' = \frac{1}{2}\left(\sqrt{m_h^2 + p_{T,h}^2} + \sum_i p_{T,i}\right)$
  - ~NNLO H+>=1 jet calculation, using LoopSim procedure applied to gosam ntuples
  - Sherpa inclusive H NNLO (fixed order) → $\mu_R = \mu_F = m_H/2$
- **Resummed**
  - HqT combines exact fixed order for Higgs for high p_T with resummation at low p_T → $\mu_R = \mu_F = Q = m_H/2$
  - ResBos2 resums soft gluon radiation at all orders using CSS formalism; also includes for first time resummation of Higgs+jet final state → $\mu_R = Q = m_H/2$
  - Jet veto resummation uses SCET carrying out the calculation to NNLL'+NNLO → scale choices equivalent to FO NNLO with $m_H/2$
  - HEJ describes hard, wide angle emissions to all order and multiplicities using all-order resummation → $\alpha_s^{n+2} = \alpha_s^2(m_h)\cdot\alpha_s^n(\mu_R)$ (with μ_R → $H_T/2$)

Tools

- ME+PS
  - Powheg NNLOPS uses H+jet MiNLO predictions → $\mu_R = \mu_F = m_H/2$
  - Sherpa NNLOPS is performed with UN^{2}LOPS method → $\mu_R = \mu_F = m_H/2$
  - Madgraph5_aMC@NLO has 0, 1 and 2 jets at NLO; central merging scale = 35 GeV → $\mu_R = \mu_F$~transverse energy of Higgs boson after partons clustered to pp->hj configuration; m_H for pp->h
  - Herwig 7.1 merges 0,1 and 2 jets at NLO and 3,4 jets at LO; merging scale of 30 GeV → scales determined through clustering; core scale defined as $\mu_R = \mu_F = m_H/2$
  - Sherpa MEPS@NLO merges 0,1,2,3 jets at NLO with merging cut of 20 GeV → $\mu_{core} = m_H/2$; μ_F and parton shower scales set to μ_{core}; μ_R set through CKKW

Scale variations for all calculations typically performed by varying scales a factor of 2 around central scale, or equivalent, requiring that μ_R and μ_F do not vary from each other by more than a factor of 2

Study

- Comparisons always have central values compared on the left, scale uncertainty bands on the right
- For the sake of brevity for this talk, I will only be sharing a few results
- For better visibility, the predictions are typically divided into 3 groups based on simulation type and/or claimed accuracy
- …so for example, the upper plot may contain NNLO predictions, the middle plot ME+PS predictions, and the lower plot (fixed order) NLO predictions

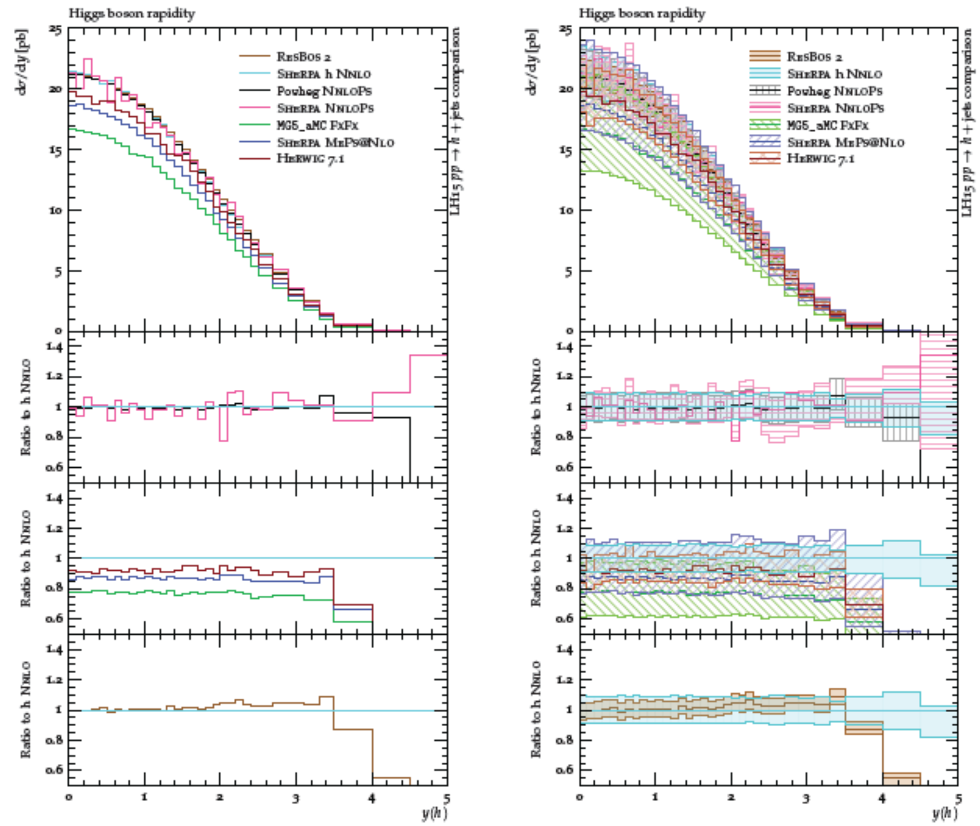
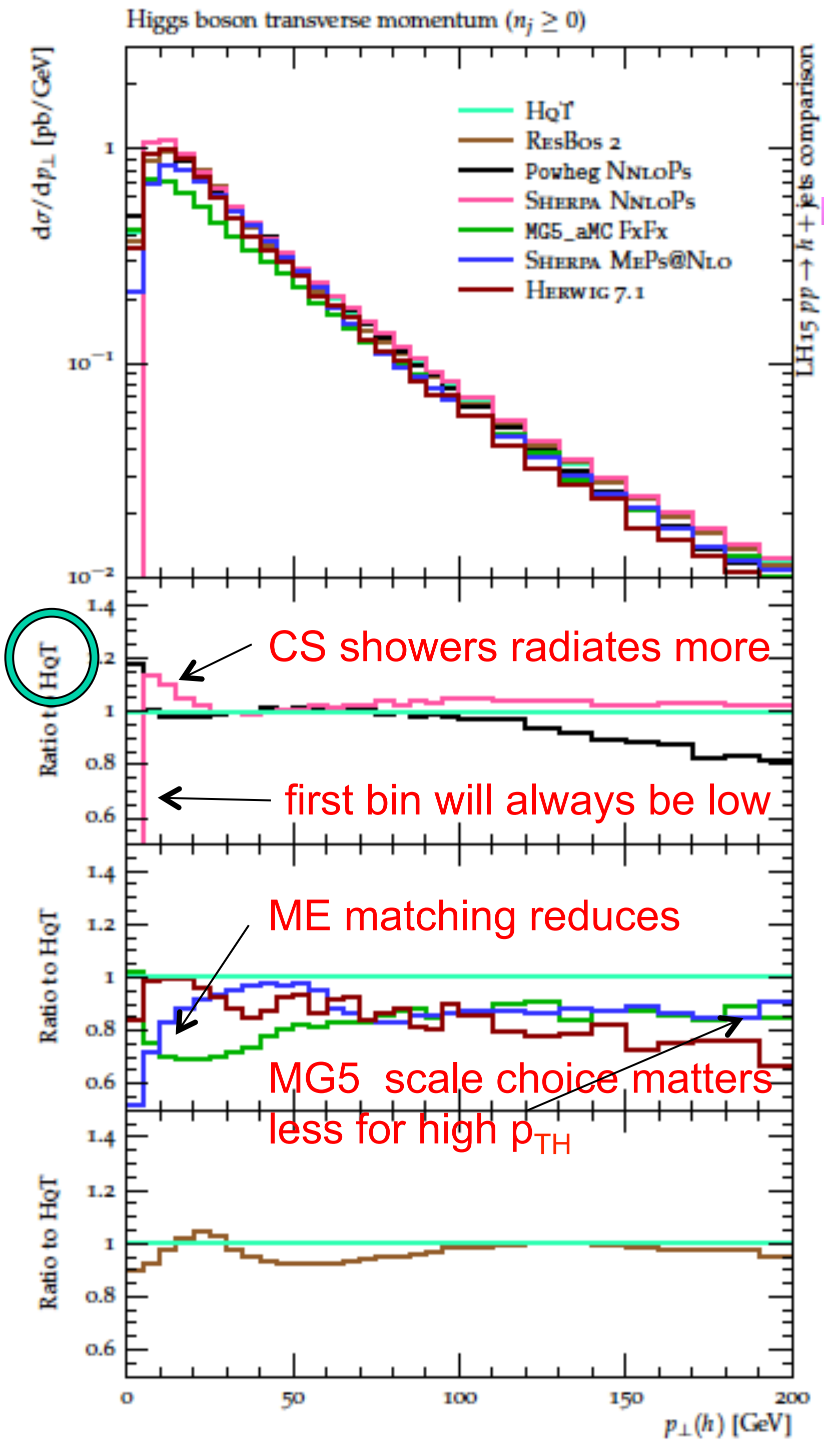
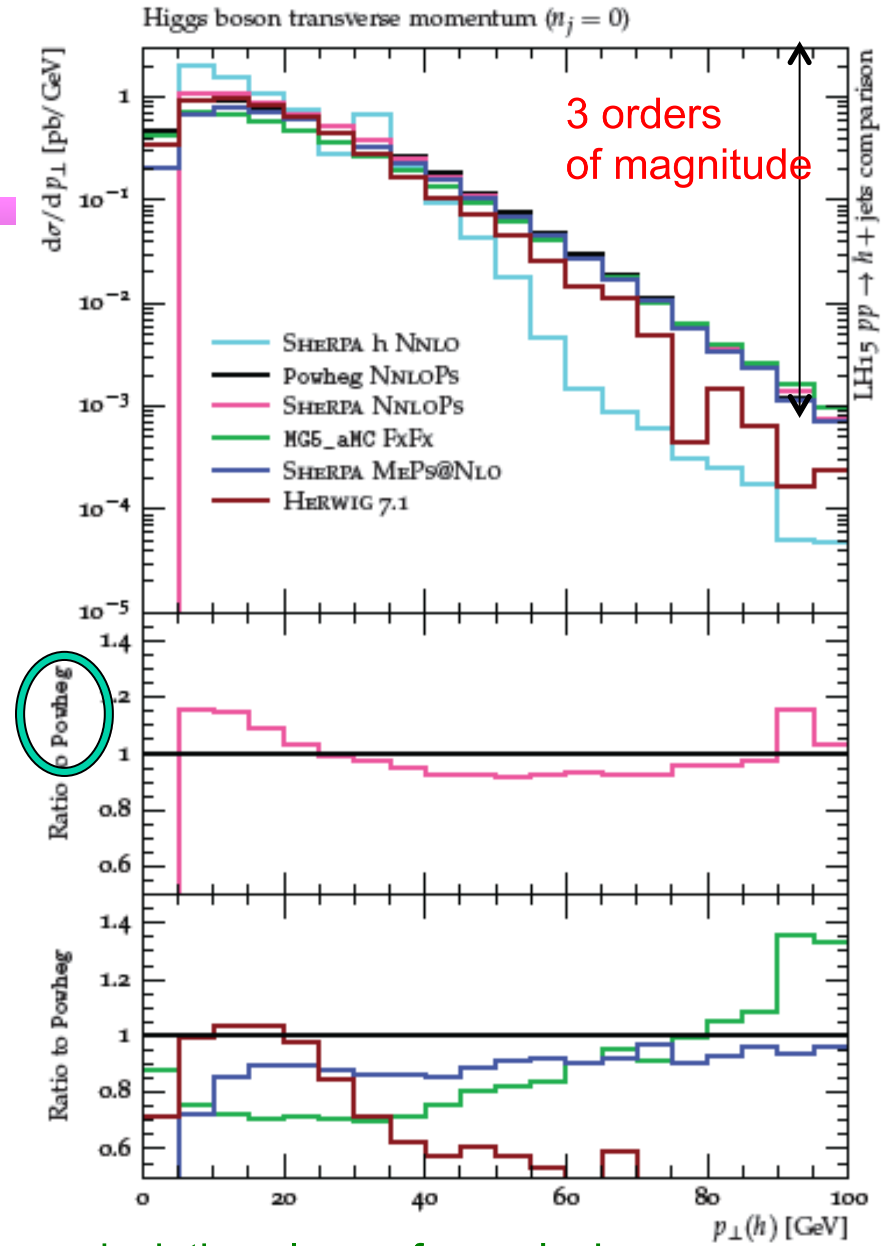


Fig. IV.7: The inclusive Higgs boson rapidity without (left) and with (right) uncertainties. To enhance visibility, the NNLOPs, multijet merged and analytic q_T-resummation predictions are grouped together and shown with respect to the same reference curve in the upper, lower and middle ratio plots, respectively. The reference prediction is taken from the NNLO-accurate description of inclusive h production.





deviations larger for exclusive case; Sudakov effects dominate low p_T region, resummation effects at higher p_T through jet veto

Modulo scale choices, neither the addition of parton showers, or resummation a la STWZ or ResBos2 (resum for H+jet) seems to noticeably affect the lead jet p_T cross section; unfolded data can be directly compared to fixed order (+NP)

Sherpa and Powheg NNLOPS agree with hj NNLO except at high p_T; Sherpa goes up and Powheg down; Sherpa uses $m_H/2$, Powheg CKKW/MiNLO

MEPS agrees with hj NNLO at low p_T; 10-20% lower at high p_T due to scale choice

Note agreement between NLO and NNLO

STWZ and ResBos2 agree with hj NNLO at low p_T; greater at high p_T due to different (common) scale choice ($m_H/2$); fixed, not dynamic like others

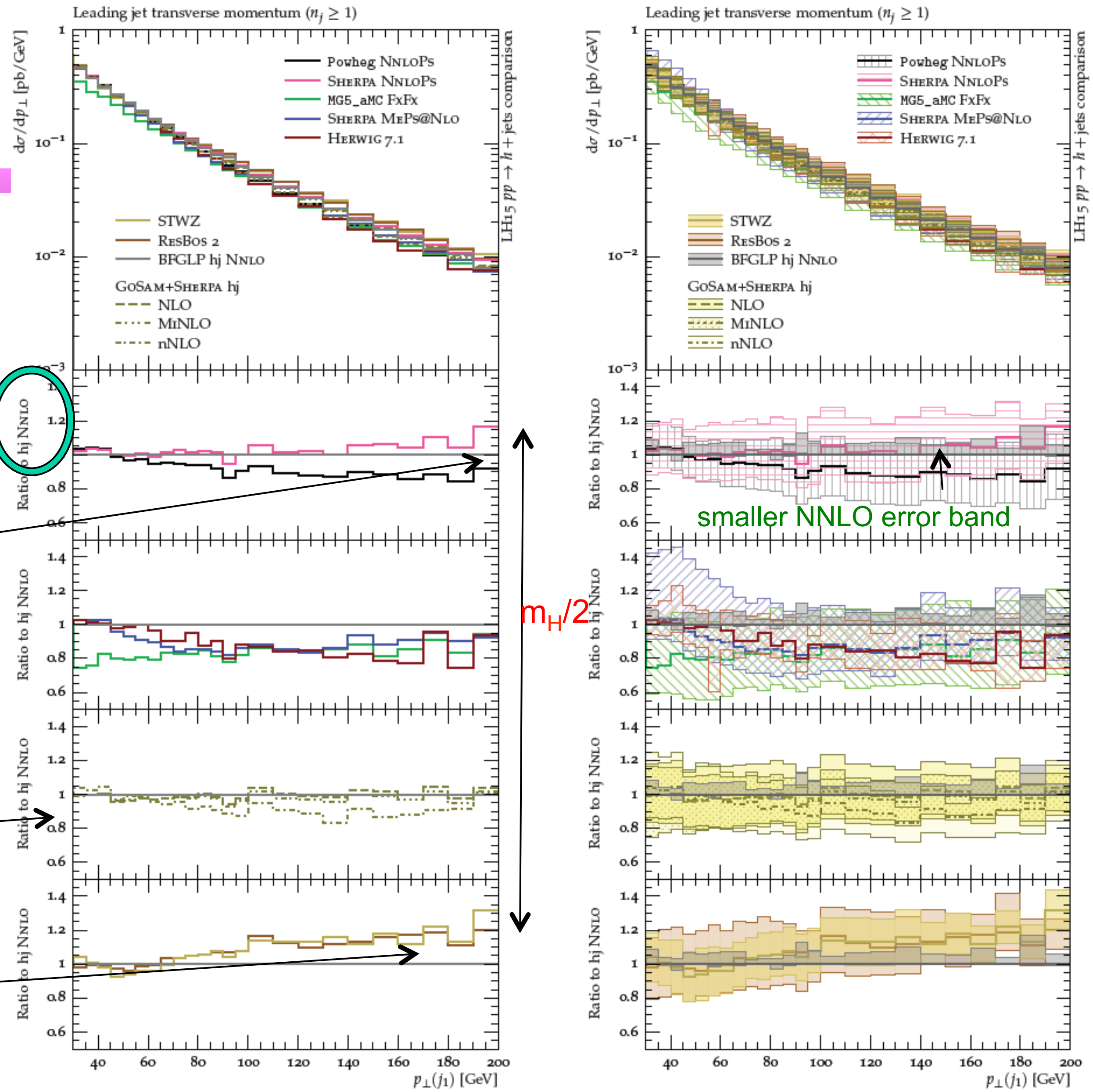


Fig. IV.14: The leading jet transverse momentum distribution for $h + \geq 1$-jet production, to the right (left) shown with (without) the uncertainty bands provided by the various calculations. The part below the main plot contains four ratio plots taken wrt. the NNLO result of the BFGLP group following the same strategy for grouping the predictions as before (NNLOPs versus NLO ME+PS versus fixed-order and resummation results).

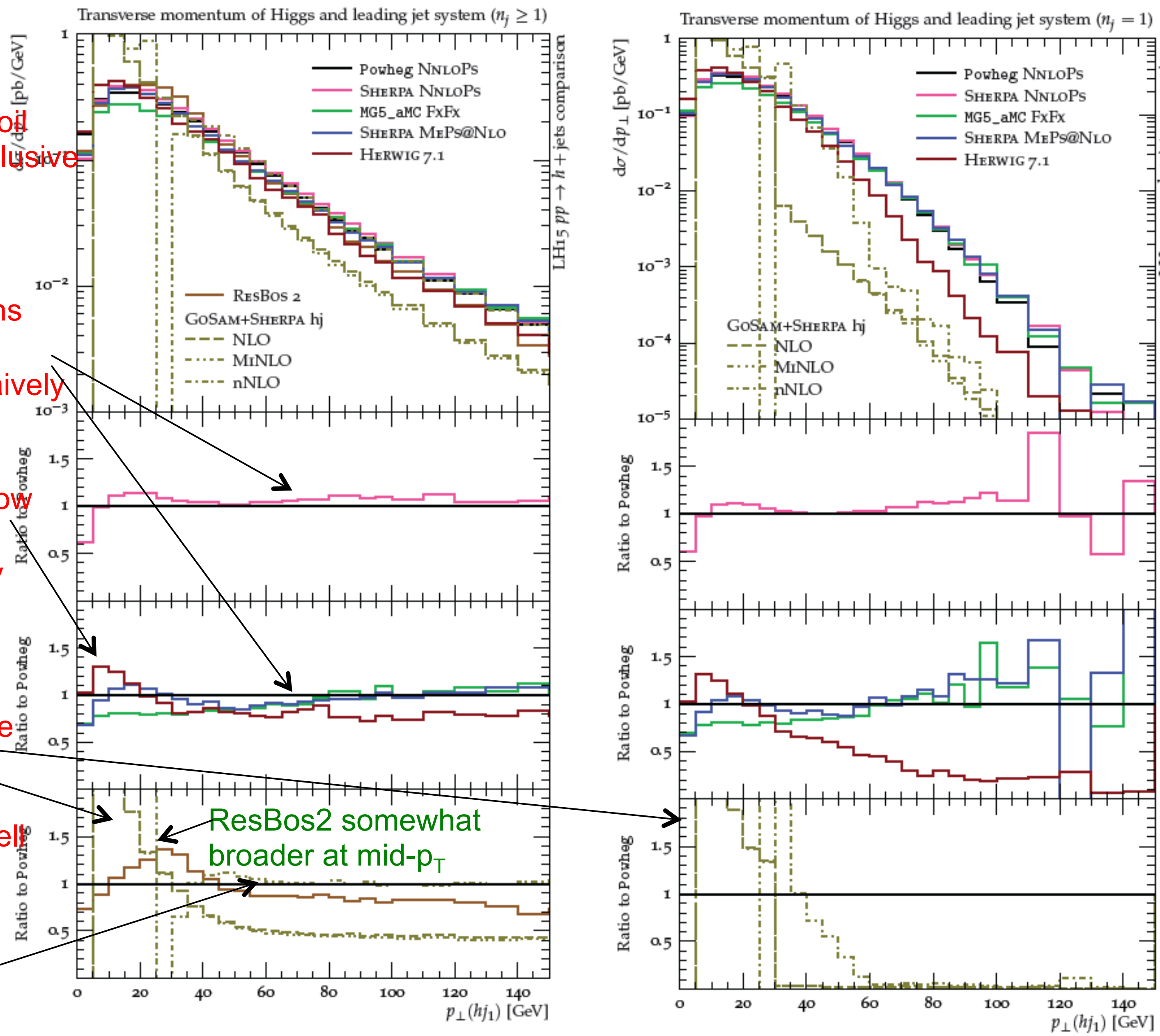
both variables examine recoil effects, hard+soft for the inclusive case, soft radiation only for exclusive case

note comparable descriptions from NNLO PS and ME+PS approaches; not perhaps naively expected

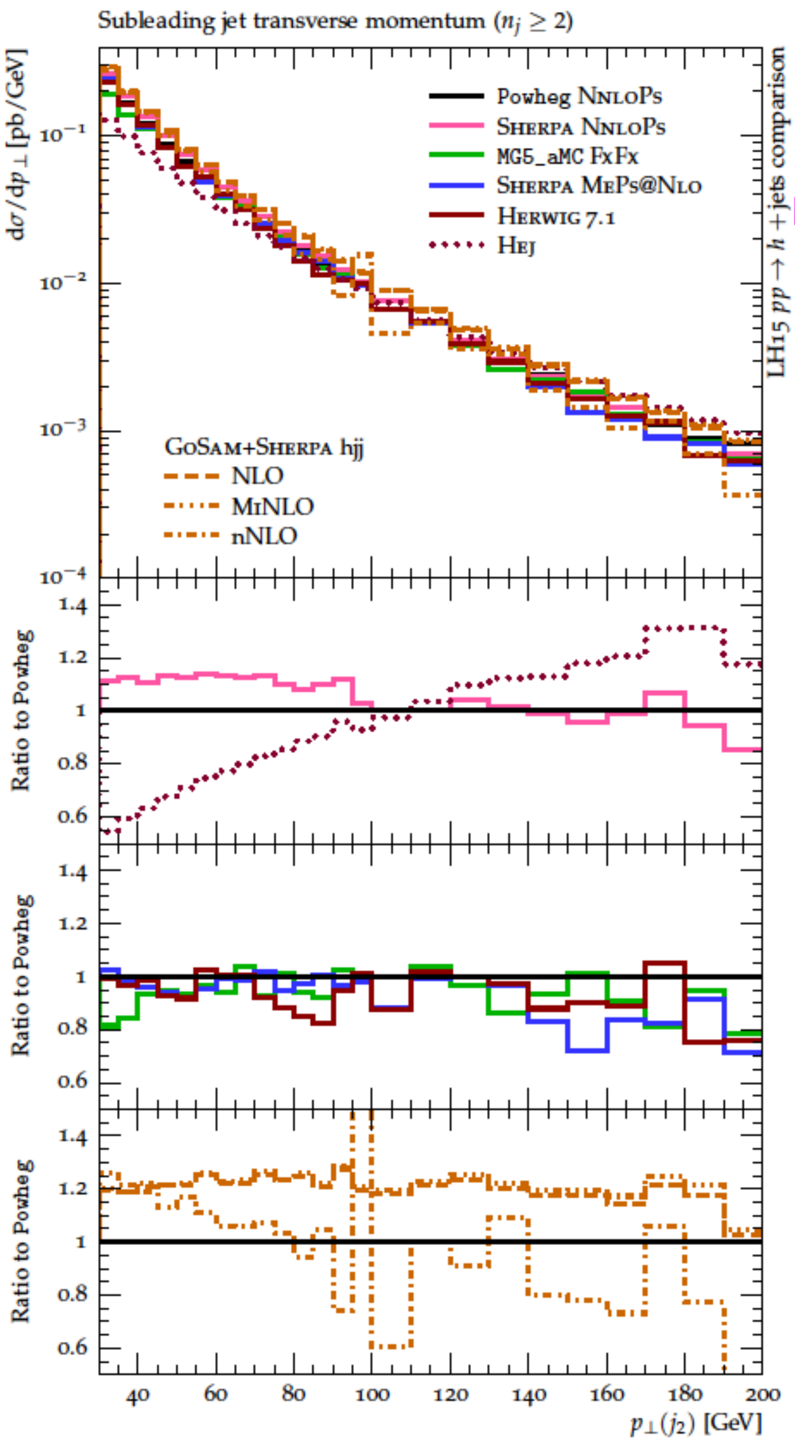
deviations of order 30% below jet p_T threshold, better agreement above,especially for inclusive case

fixed order fails at low p_T (and in general for exclusive case)

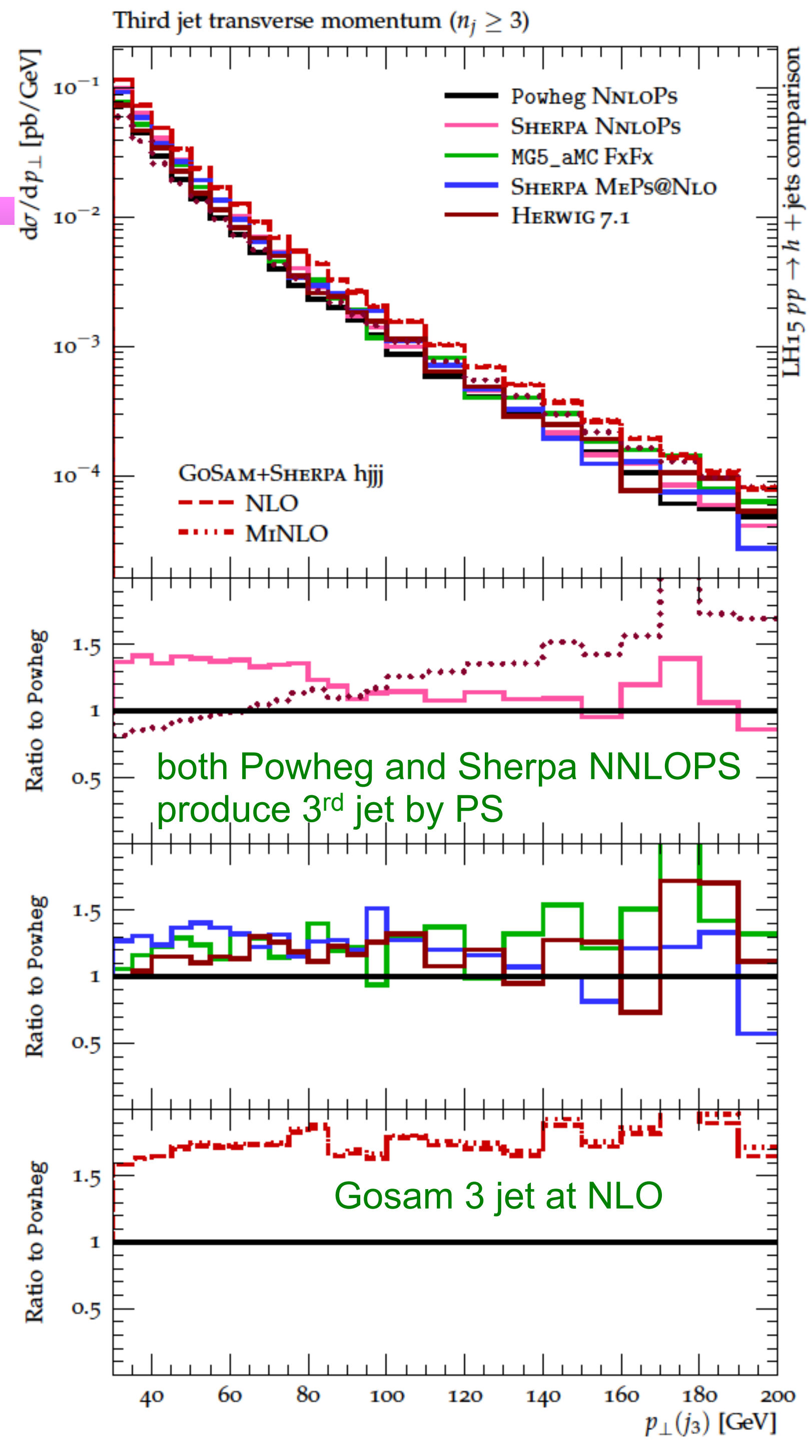
LoopSim seemingly does well in the high p_T tail; adequate description of 2^{nd} and 3^{rd} jet sufficient for fixed order to describe this variable?



NB: ResBos 2 explicitly resums H+jet; at lower p_T is NLL accurate, better accuracy than other predictions; also includes effects if $\ln(1/R^2)$ terms



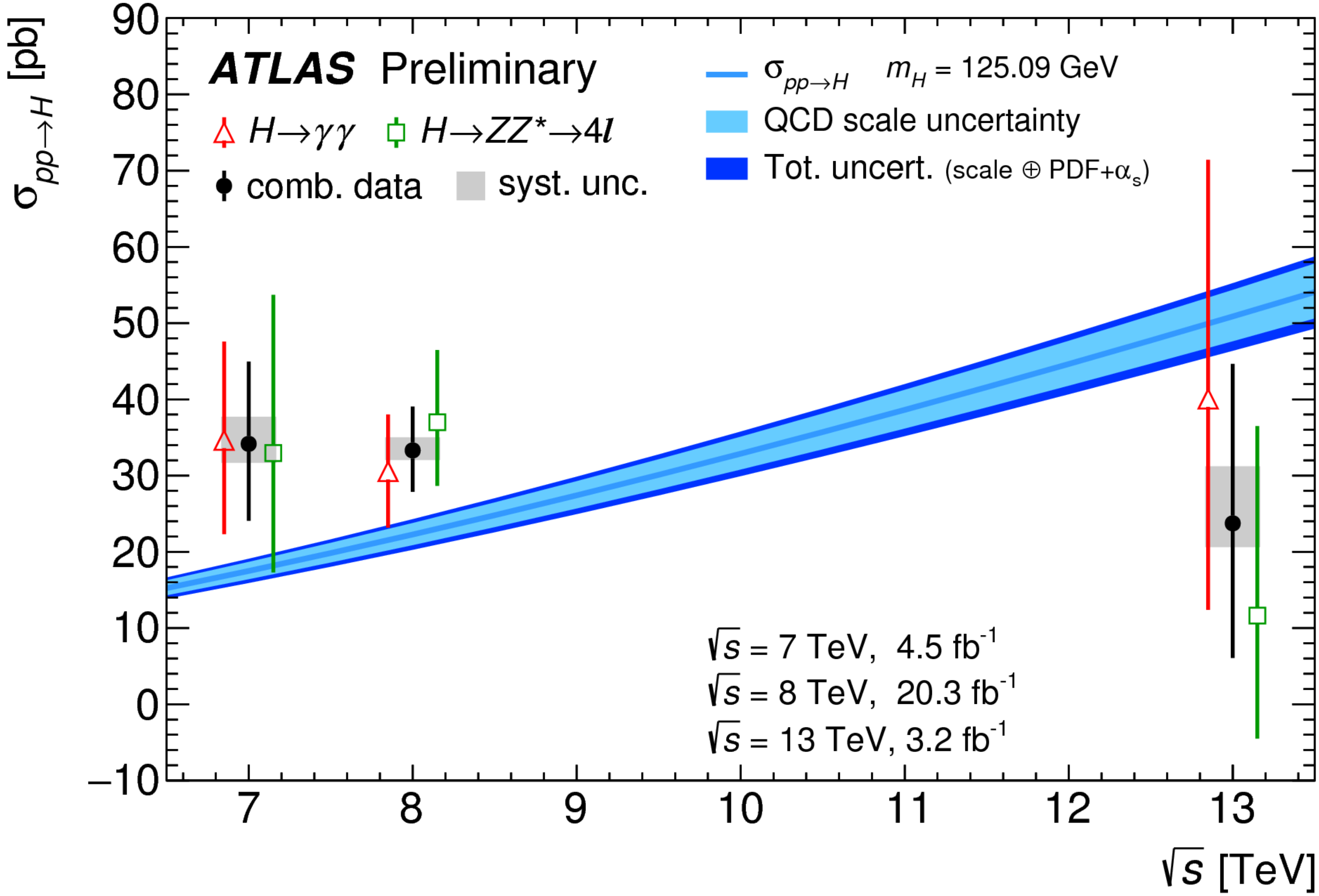
Similar conclusions regarding jet2 and jet3 modulo scale choices and higher order effects



Summary for Les Houches Higgs study

- Many more observables in the Les Houches document; even more on website
  - see arxiv:1605.04692
- The contribution described here contains the most detailed comparison of predictions for Higgs observables
  - in most case, better agreement than at least I would have expected
- One of the purposes of this study was to show (1) the power of inclusive observables, (2) that observables such as the lead jet p_T for H+>=1 jet are inclusive, and (3) that fixed order predictions are often the best for comparison to those inclusive observables
- This study is specifically for the Higgs, but it holds for other final states as well
- This is on the quiz

13 TeV, so far



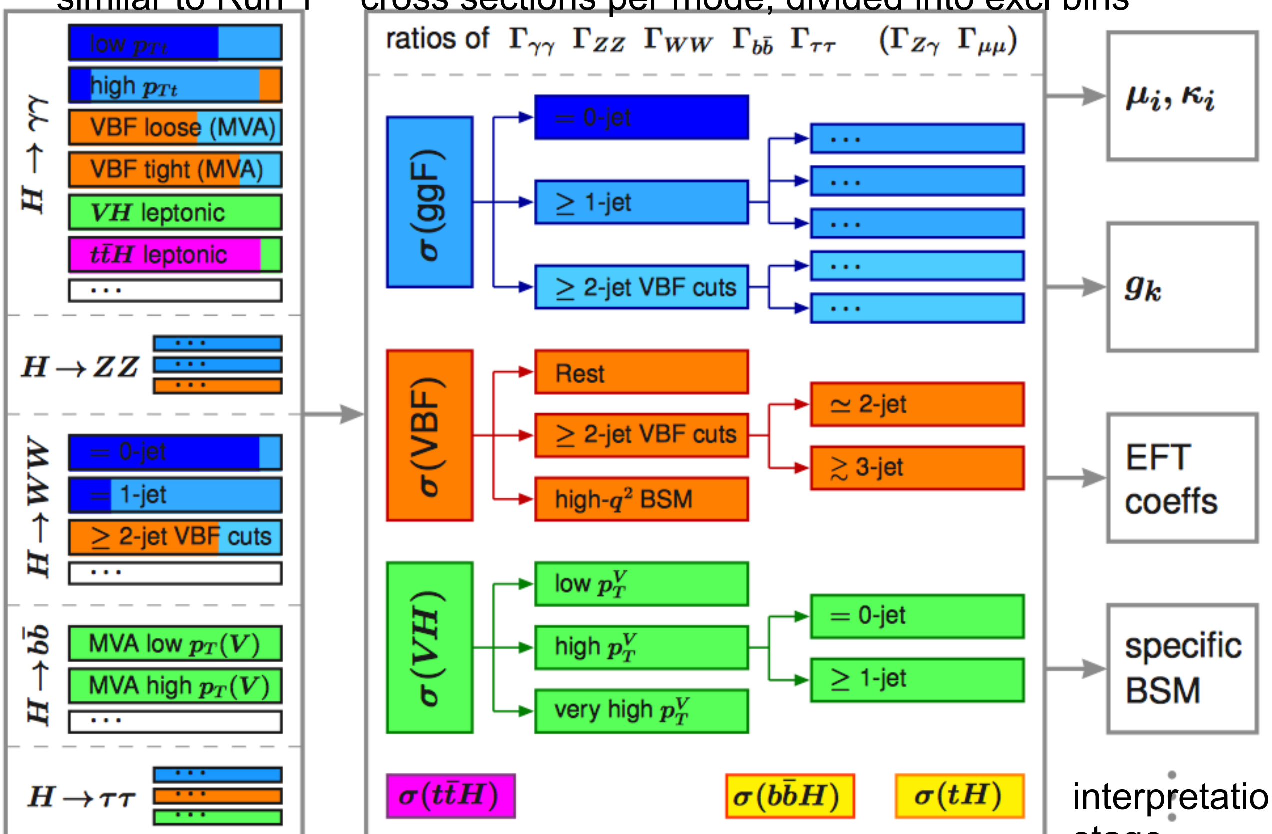
ATLAS Preliminary
$H \rightarrow \gamma\gamma$
$H \rightarrow ZZ^* \rightarrow 4l$
comb. data
syst. unc.
$\sigma_{pp \rightarrow H}$ m_H = 125.09 GeV
QCD scale uncertainty
Tot. uncert. (scale ⊕ PDF+α_s)
$\sqrt{s}$ = 7 TeV, 4.5 fb^{-1}
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
$\sqrt{s}$ = 13 TeV, 3.2 fb^{-1}
$\sigma_{pp \rightarrow H}$ [pb]
$\sqrt{s}$ [TeV]
90
80
70
60
50
40
30
20
10
0
−10
7
8
9
10
11
12
13

Simplified template cross sections

- For several of the Higgs(+jets) channels, we have measured fiducial cross sections in Run 1; that will happen even more in Run 2. But in most cases, we quoted measured signal strength and multiplicative coupling modifiers. We'd like to evolve the signal strength measurements to simplified template cross sections in Run 2.

Les Houches 2015
(and YR4)

similar to Run 1 cross sections per mode, divided into excl bins



interpretation stage

Fig. III.4: Schematic overview of the simplified template cross section framework.

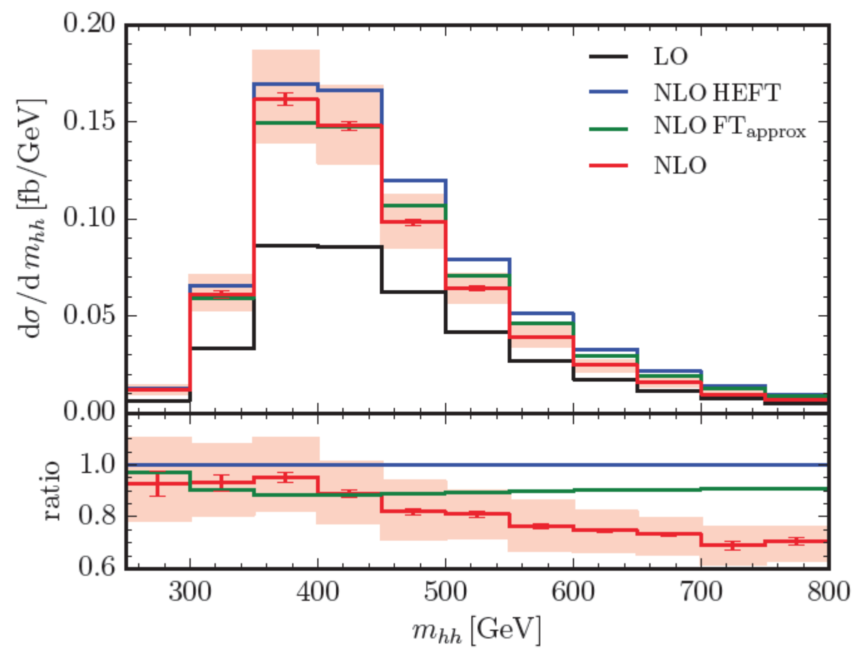
The primary goals of the STCS method are to maximize the sensitivity while minimizing the theory dependence.

This means:
-combination of decay channels
-measurement of cross sections rather than signal strengths
-cross sections are measured for specific production modes
…

Higgs sector

- Self-coupling of the Higgs one of the holy grails of extended running at the LHC
  - directly probes EW potential
- Now known at NLO in finite top mass limit
  - S. Borowka et al, arXiv: 1604.06447
- Strong deviations at high mass
- Experience may help with the calculation of finite m_t corrections for H+jet

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



Towards including m_t effects in hh

- HOW BIG ARE $1/m_t^2$ CORRECTIONS?
- Compute NLO with virtual corrections in HEFT limit and real corrections with exact m_t dependence (MadGraph5_aMC@NLO) (~-10% correction)
- Compute $1/m_t^{2n}$ corrections to NNLO and normalize to exact LO (~+5% correction)
- Different results from 2 approaches

S. Dawson
SM@LHC 2016

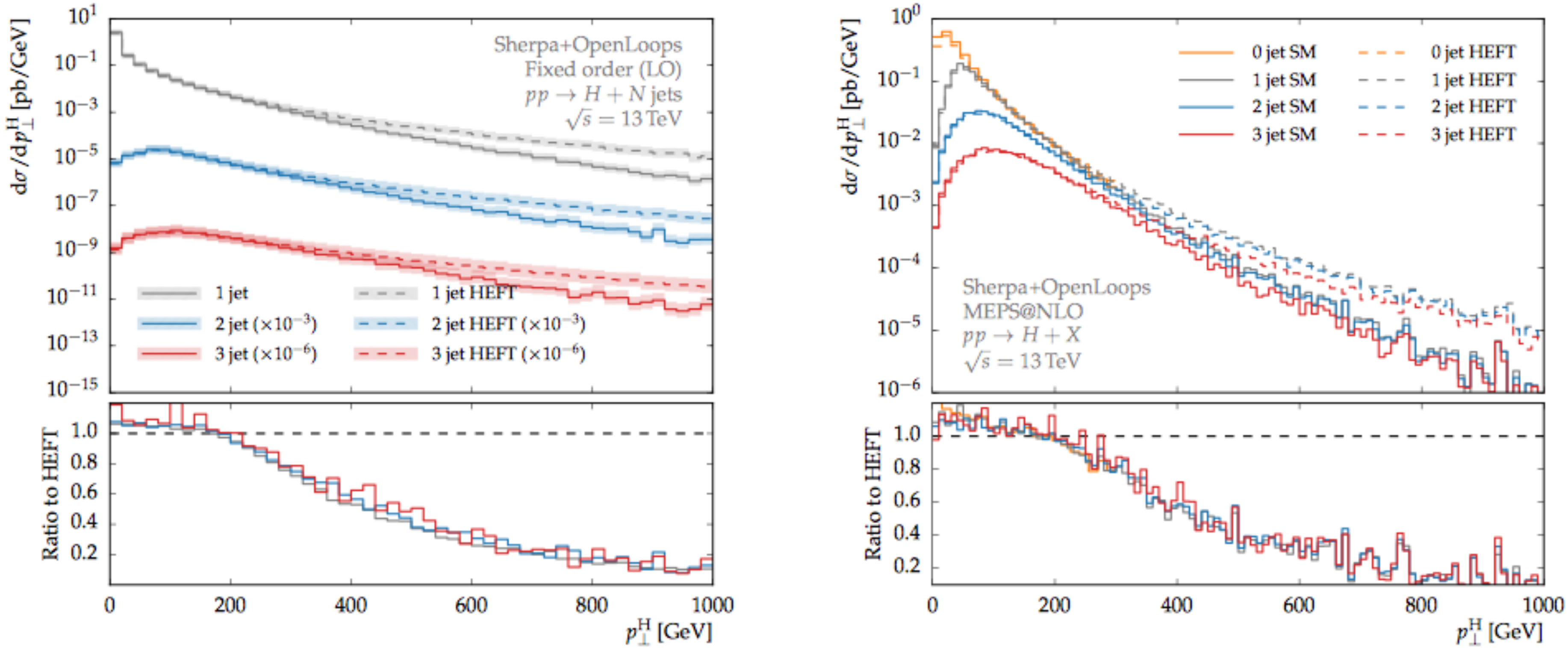
New: Exact top mass dependence

- 2-Loop virtual with exact mass dependence now known for gg →hh
  - WOW! Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke , arXiV: 1604.06447
- Result is 14% below HEFT result and does not fall in estimated error bands
- 14 TeV: HEFT NLO 38.29 fb $^{+18.1\%}_{-14.8\%}$
  EXACT NLO 32.80 fb $^{+13\%}_{-12\%}$

Will this work for H+jet as well?
Hopefully, we won't have to wait too long for the exact calculation

Higgs+jet: finite m_t corrections

right now we are assuming that we can factorize the LO finite m_t corrections for Higgs + n jets into the NLO (NNLO) cross sections: but of course, this is the region where we might also expect new physics, so we need to know the finite m_t cross section at NLO



S. Kuttimalai et al; Les Houches 2015

(a) LO fixed order calculation for up to three jets. The error bands indicate the uncertainties obtained from variations of the factorization and renormalization scales.

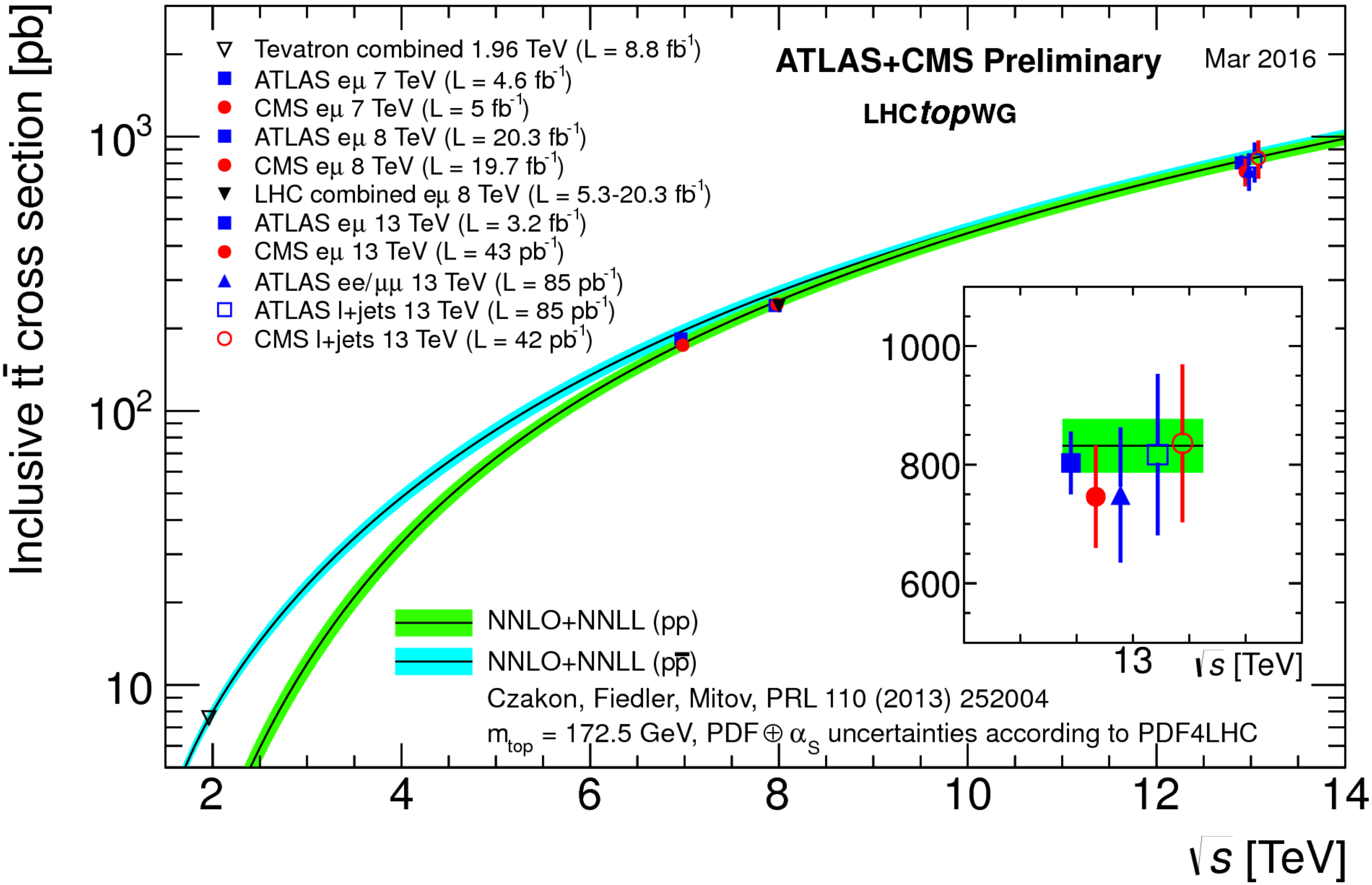
(b) Multijet merged calculation. We include the zero and one jet final states at NLO as well as the two jet final state at leading order. The individual curves show inclusive N-jet contributions.

heavy quarks, photons, jets

Process	known	desired	details
$t\bar{t}$	$\sigma_{\rm tot}$ @ 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

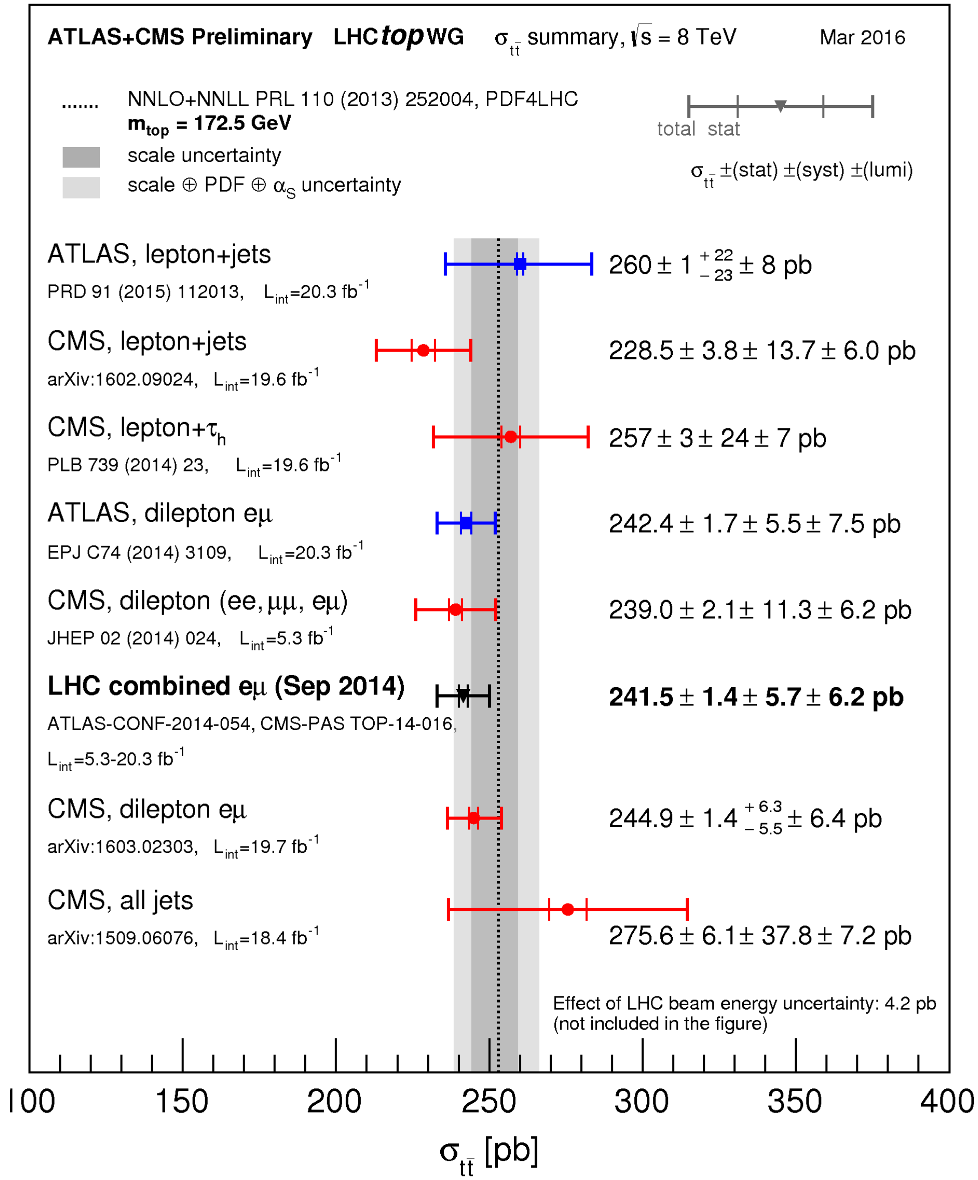
Table 2: Wishlist part 2 – jets and heay quarks

Top pair production



Top pair production

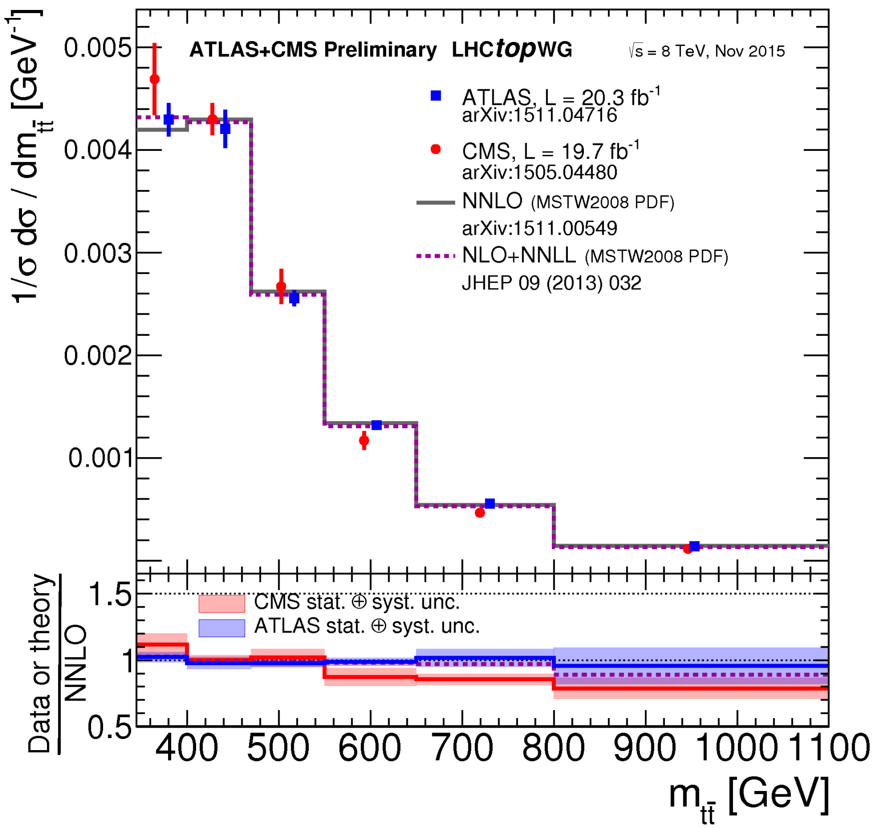
- Top production is important both as a possible venue for new physics as well as for more mundane purposes such as the determination of the gluon PDF at high x
- Currently, the dilepton final state is known to an experimental uncertainty of 4% and the uncertainty for the leptons+jets final state should 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

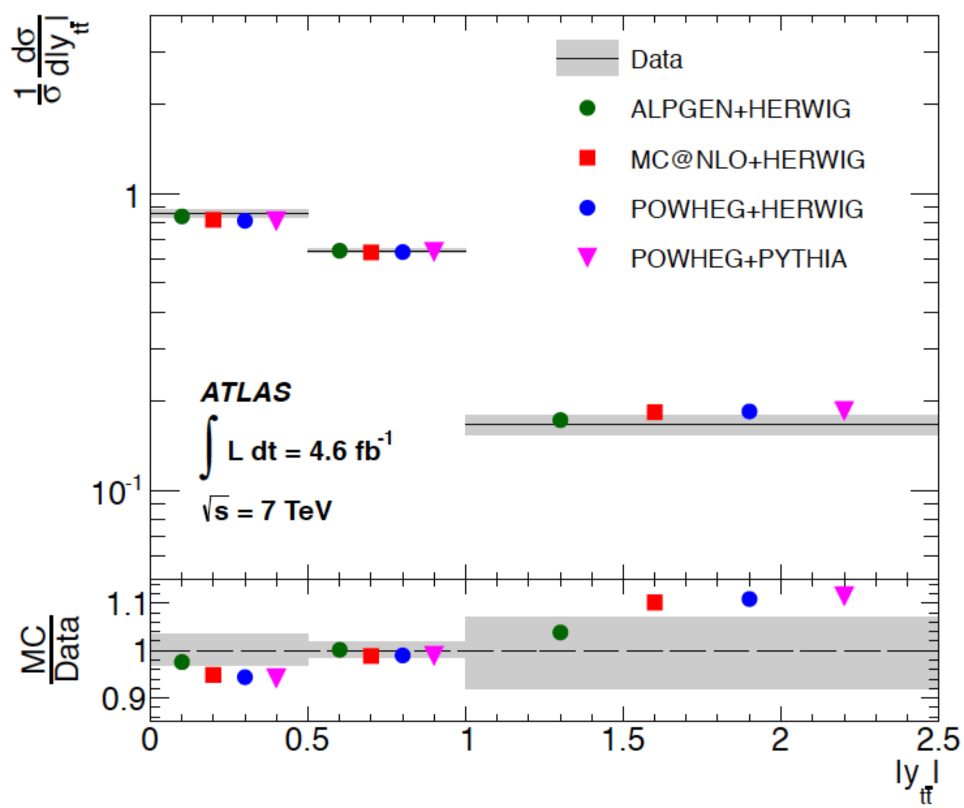


Mass and rapidity distributions

- gg channel is dominant; differential predictions at NNLO will help constrain high x gluon distribution, deviations may signal new physics; high mass tT=possible new physics
  - weaker gluon at high x than needed for jet production?
  - y_{tT} serves as a cross-check
- …but, NLO EW corrections also important

total cross sections have small impact in global PDF fits; need differential distributions

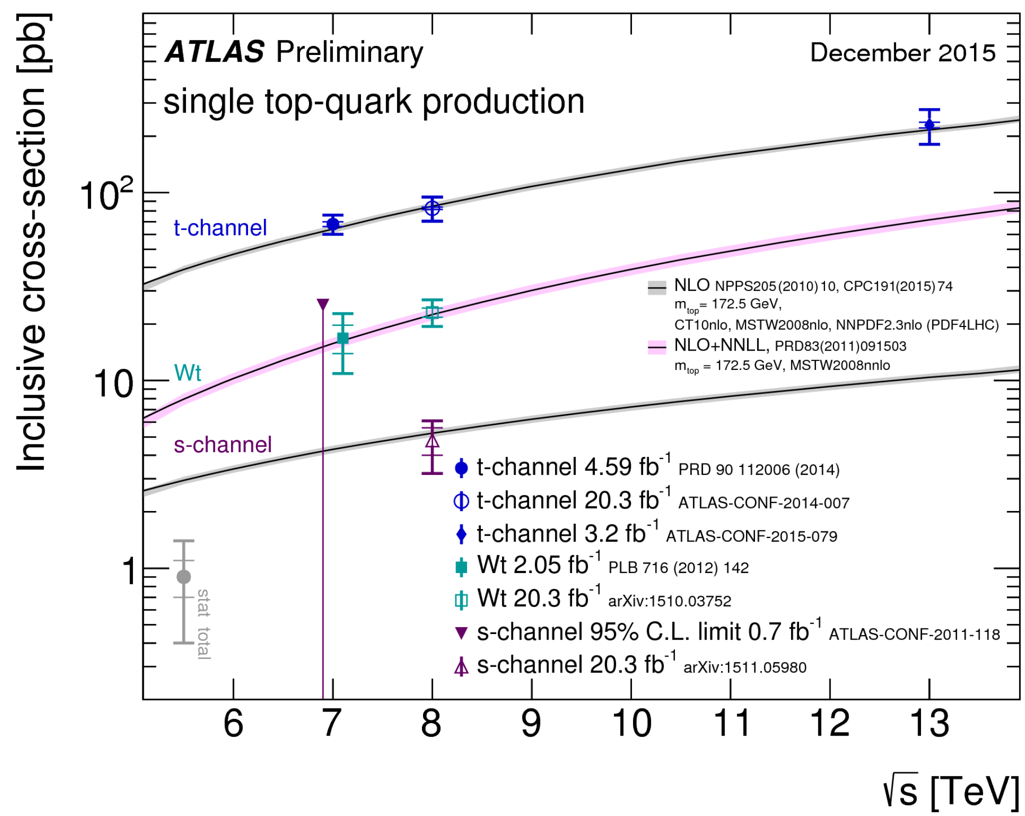




Single top

- 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

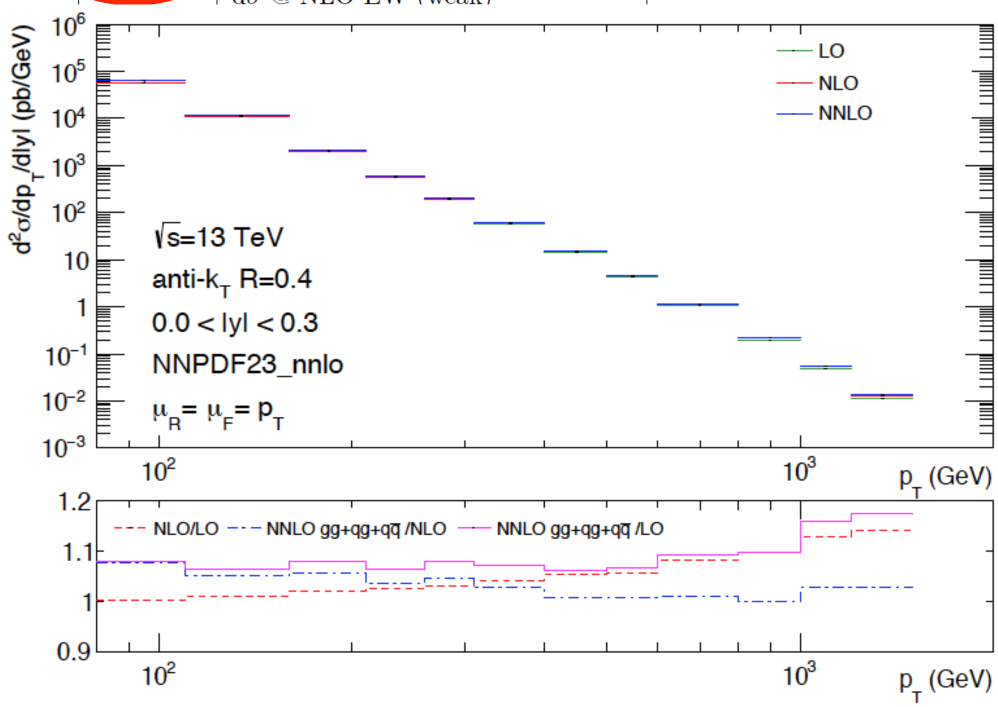
Process	State of the Art	Desired
$t\bar{t}$	σ_{tot}(stable tops) @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW
$t\bar{t}$ + j(j)	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
$t\bar{t}$ + Z	$d\sigma$(stable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



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
  - Multi-TeV range likely place for new physics
- Only process currently included in global fits not known at NNLO
  - only qq not public; all subprocesses known
  - calculation has been assimilated into the ~~Borg~~ NNLOJET
  - NNLOJET will also have H/Z+jet and ep->dijet, all at NNLO
- 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

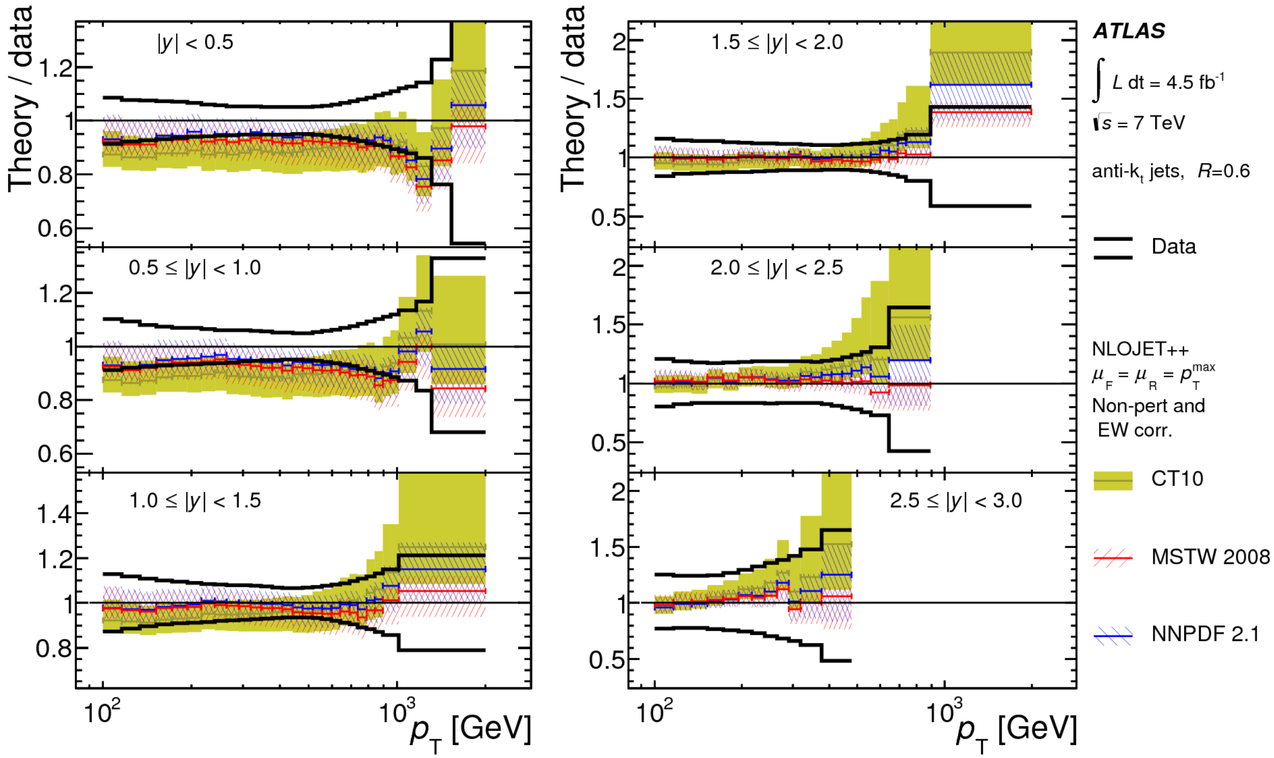


modest corrections, vanishing for high p_T

Dijets

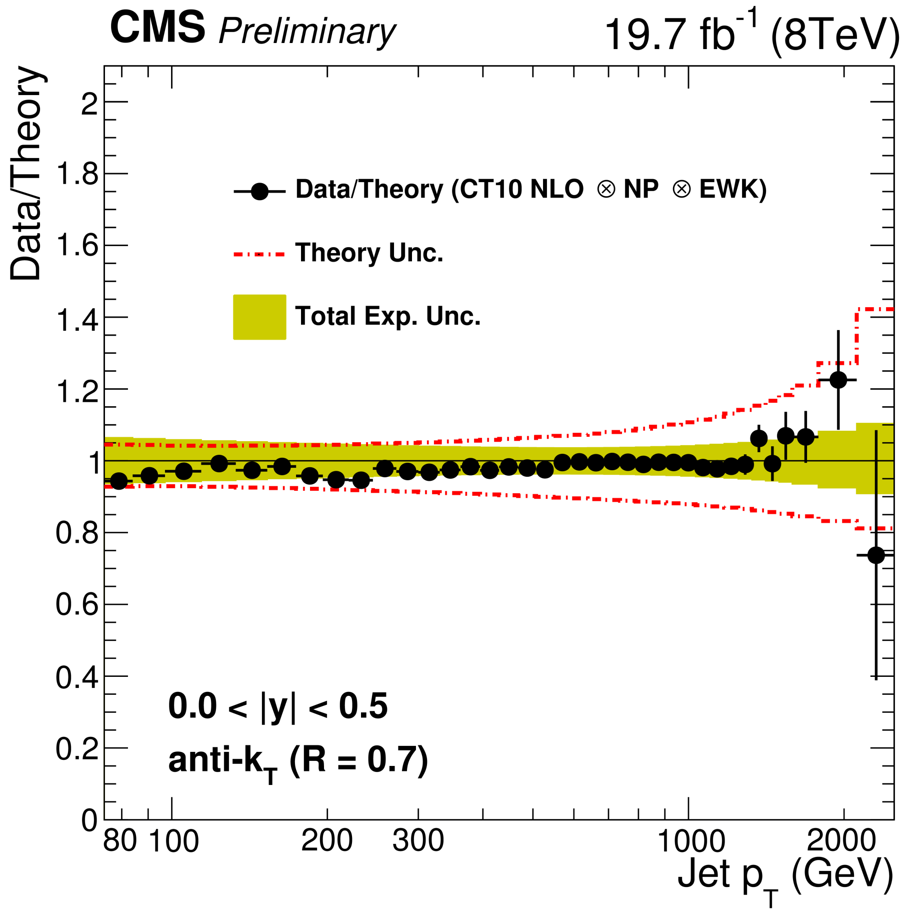
- One of key processes for perturbative QCD
  - covers largest kinematic range with jets produced in the multi-TeV range
  - EW effects very important in this range
- One advantage
  - new physics tends to be central
  - old physics (PDFs) has impact in forward region as well
  - important to include this data in global PDF fits

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

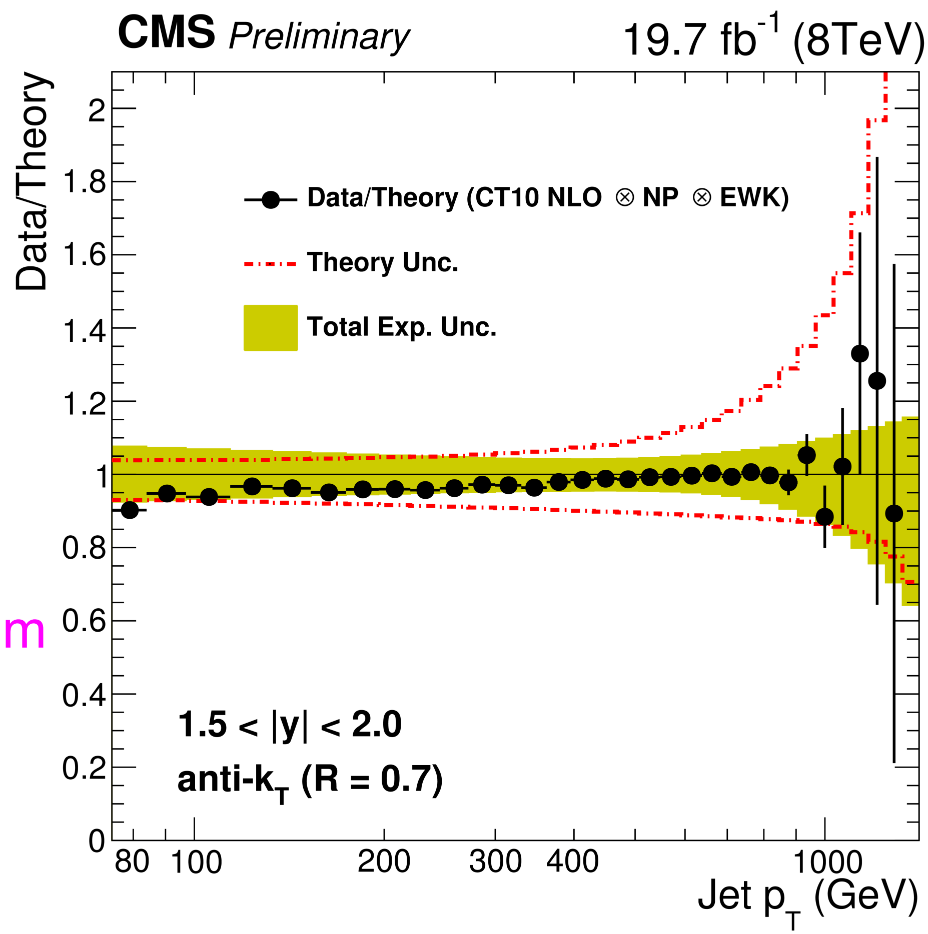


high x gluon too hard?

ets

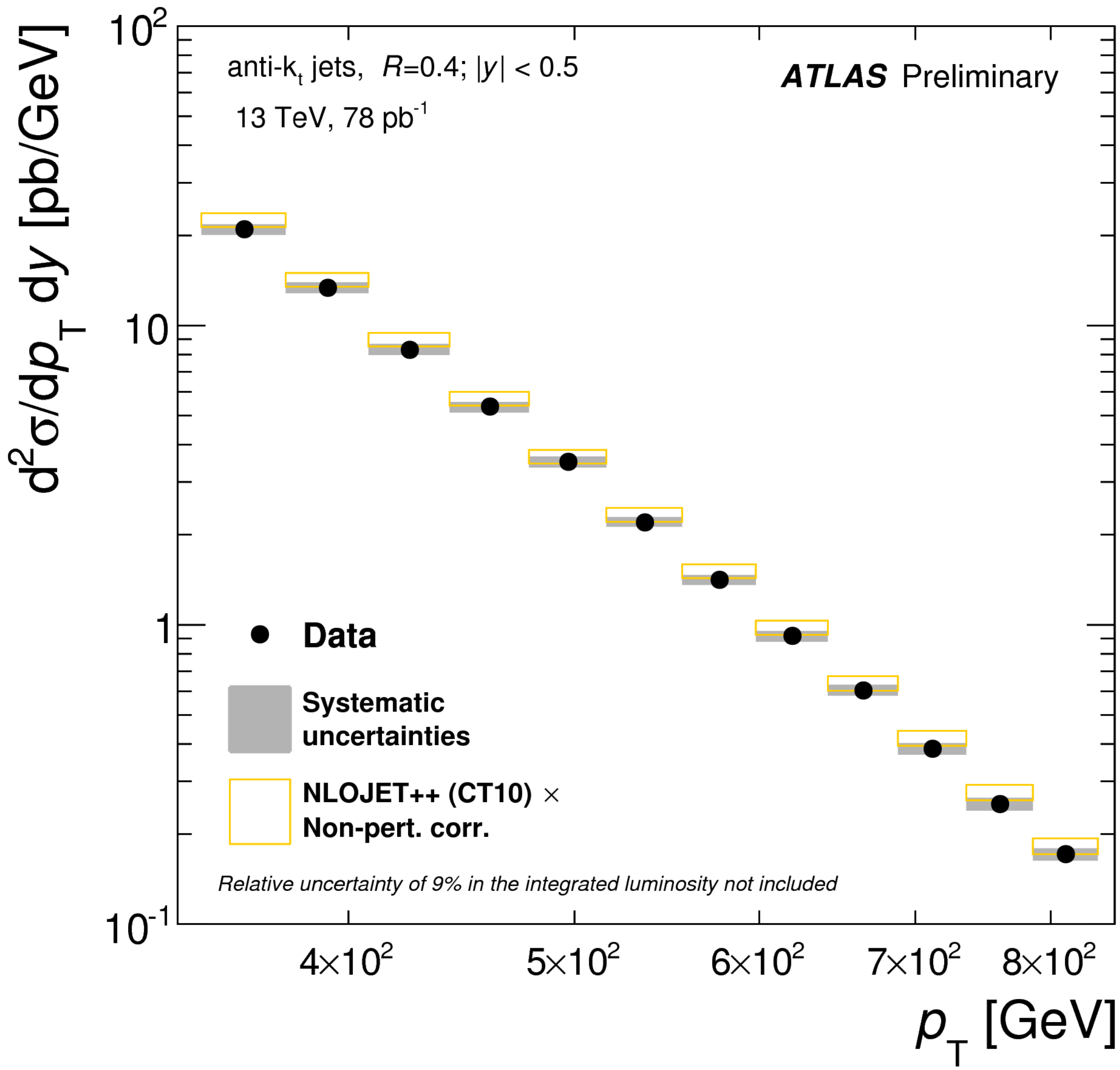


rocess	State of the Art	Desired
t	σ_{tot}(stable tops) @ NNLO QCD $d\sigma$(top decays) @ NLO QCD $d\sigma$(stable tops) @ NLO EW	$d\sigma$(top decays) @ NNLO QCD + NLO EW
t + j(j)	$d\sigma$(NWA top decays) @ NLO QCD	$d\sigma$(NWA top decays) @ NNLO QCD + NLO EW
t + Z	$d\sigma$(stable tops) @ NLO QCD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

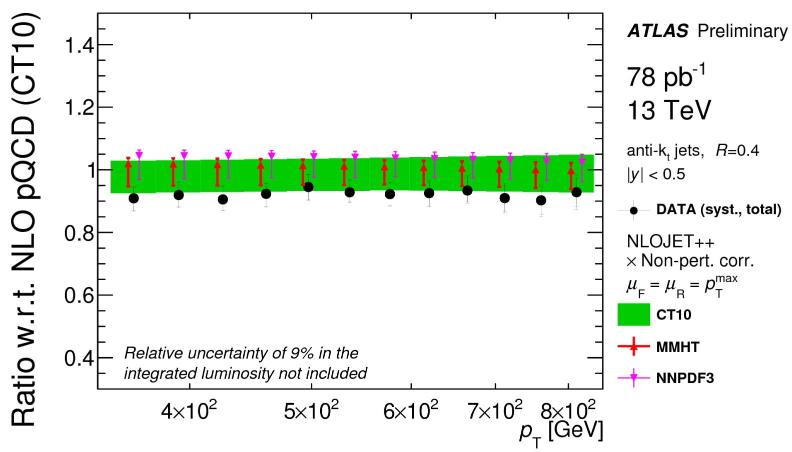


CMS seems happy with CT10 (so I'm happy)

On to 13 TeV



$d^2\sigma/dp_T\,dy$ [pb/GeV]
anti-k$_t$ jets, R=0.4; $|y|$ < 0.5
13 TeV, 78 pb^{-1}
ATLAS Preliminary
Data
Systematic uncertainties
NLOJET++ (CT10) × Non-pert. corr.
Relative uncertainty of 9% in the integrated luminosity not included
p_T [GeV]



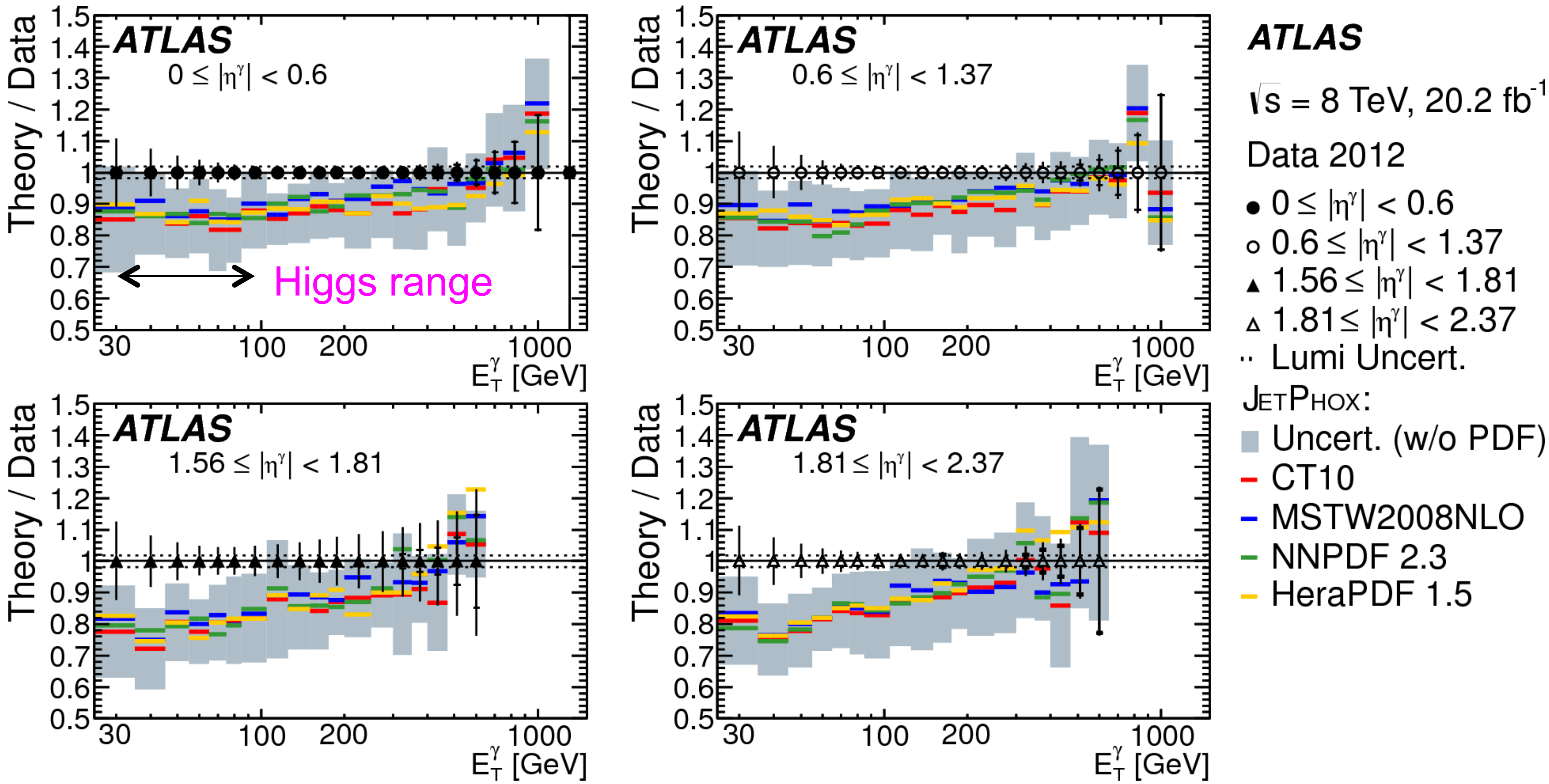
Ratio w.r.t. NLO pQCD (CT10)
ATLAS Preliminary
78 pb^{-1}
13 TeV
anti-k$_t$ jets, R=0.4
$|y|$ < 0.5
DATA (syst., total)
NLOJET++
× Non-pert. corr.
$\mu_F = \mu_R = p_T^{max}$
CT10
MMHT
NNPDF3
Relative uncertainty of 9% in the integrated luminosity not included
p_T [GeV]

Inclusive photons

- Useful for determination of the gluon distribution, especially at high x
  - good verification of the high x gluon distribution if new dijets physics suspected
- 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

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

theory tends to be smaller than data at low p_T; difficult to resolve by changing gluon



Vector bosons

Vector bosons

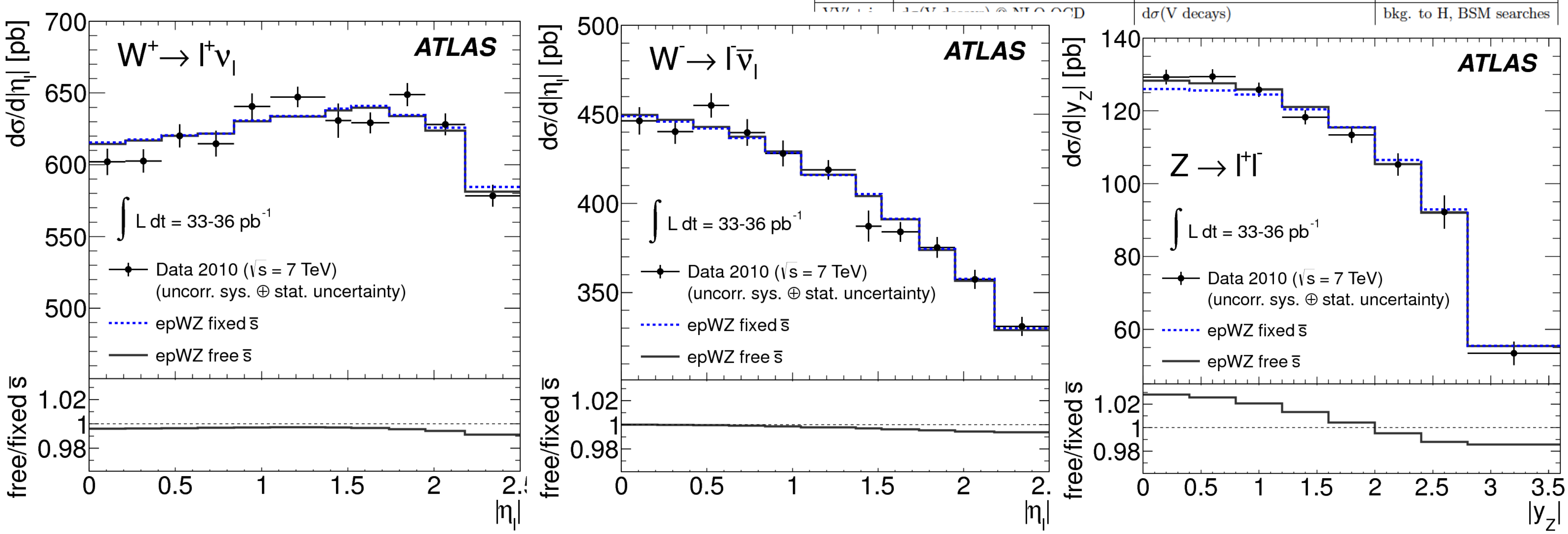
Process	known	desired	details
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
$\mathrm{V+j}$	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO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

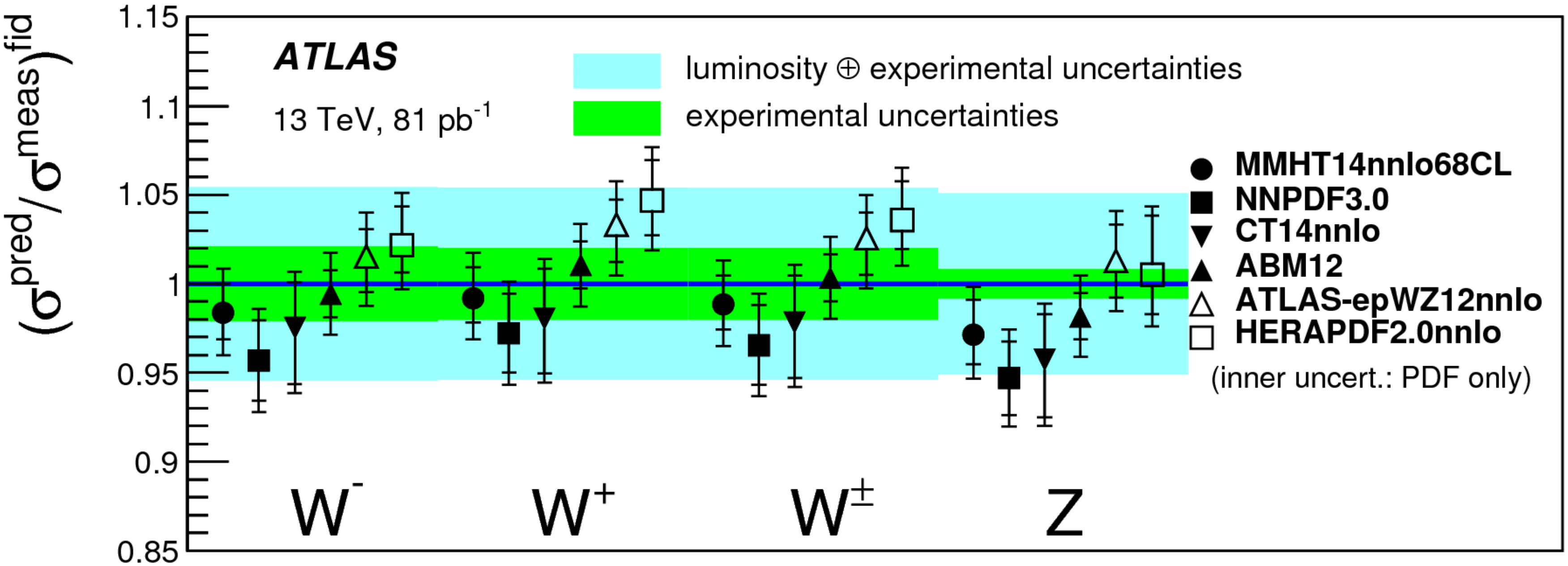
Vector boson production

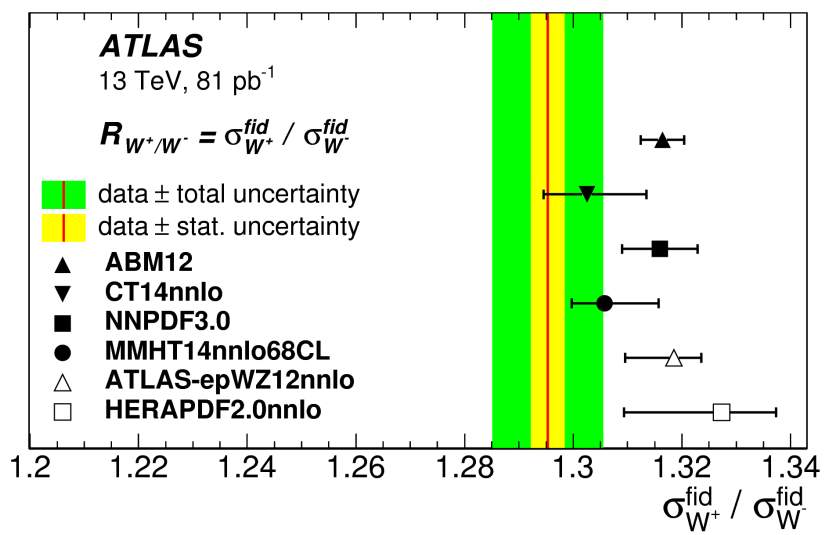
- Perhaps key collider benchmark process
- Known experimentally to 1-2% (excluding luminosity uncertainties)
- To take full advantage, would like to know process to NNNLO QCD and NNLO QCD+EW

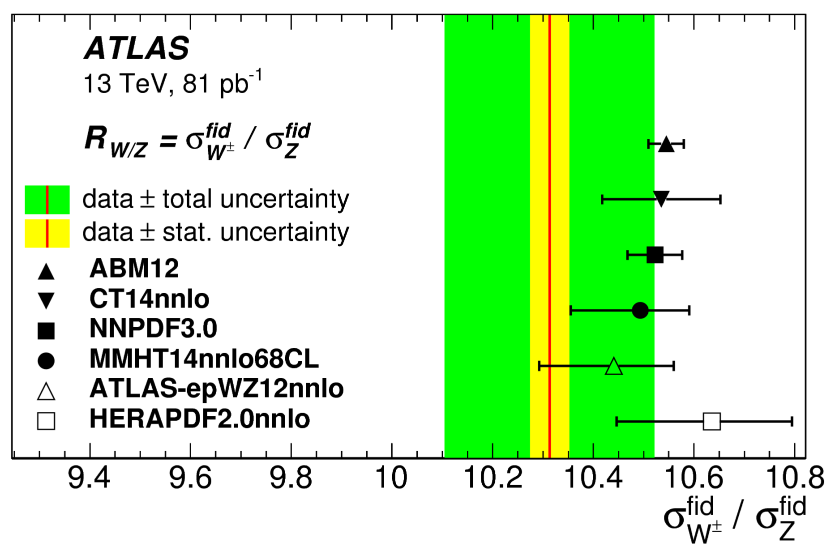
Process	known	desired	details
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
V + j	$d\sigma$(lept. V decay) @ NLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNLO QCD + NLO EW	Z + j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



…so far in Run 2



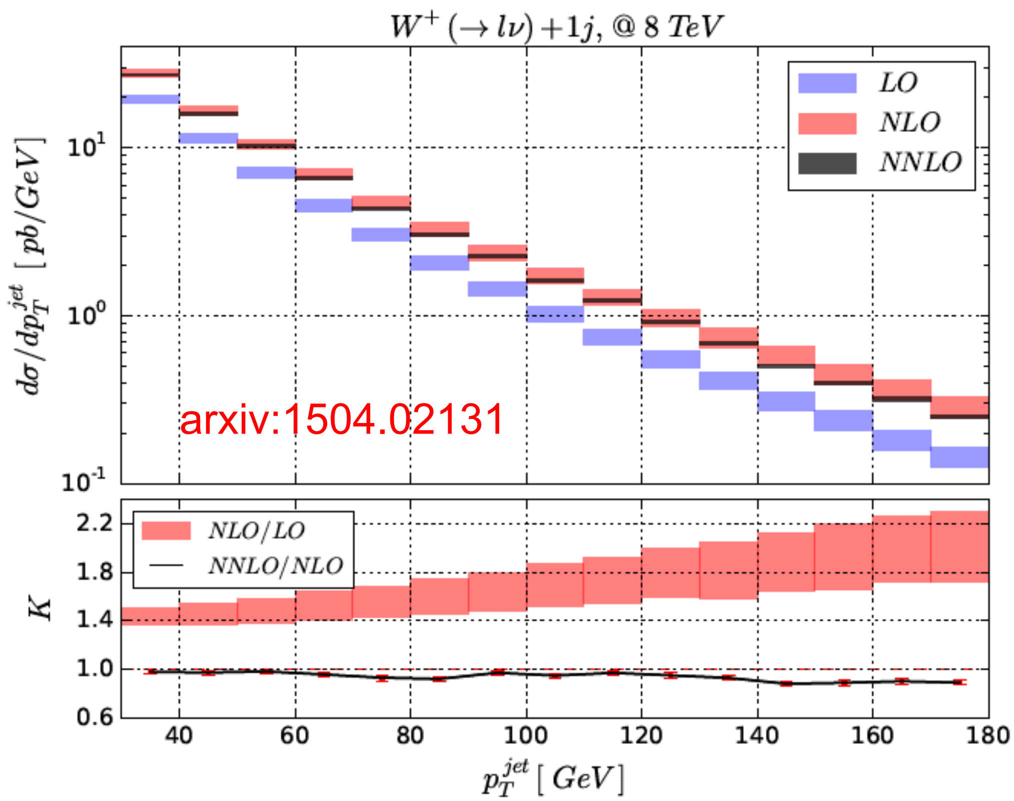




Vector bosons+jets

- 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/Z+>=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

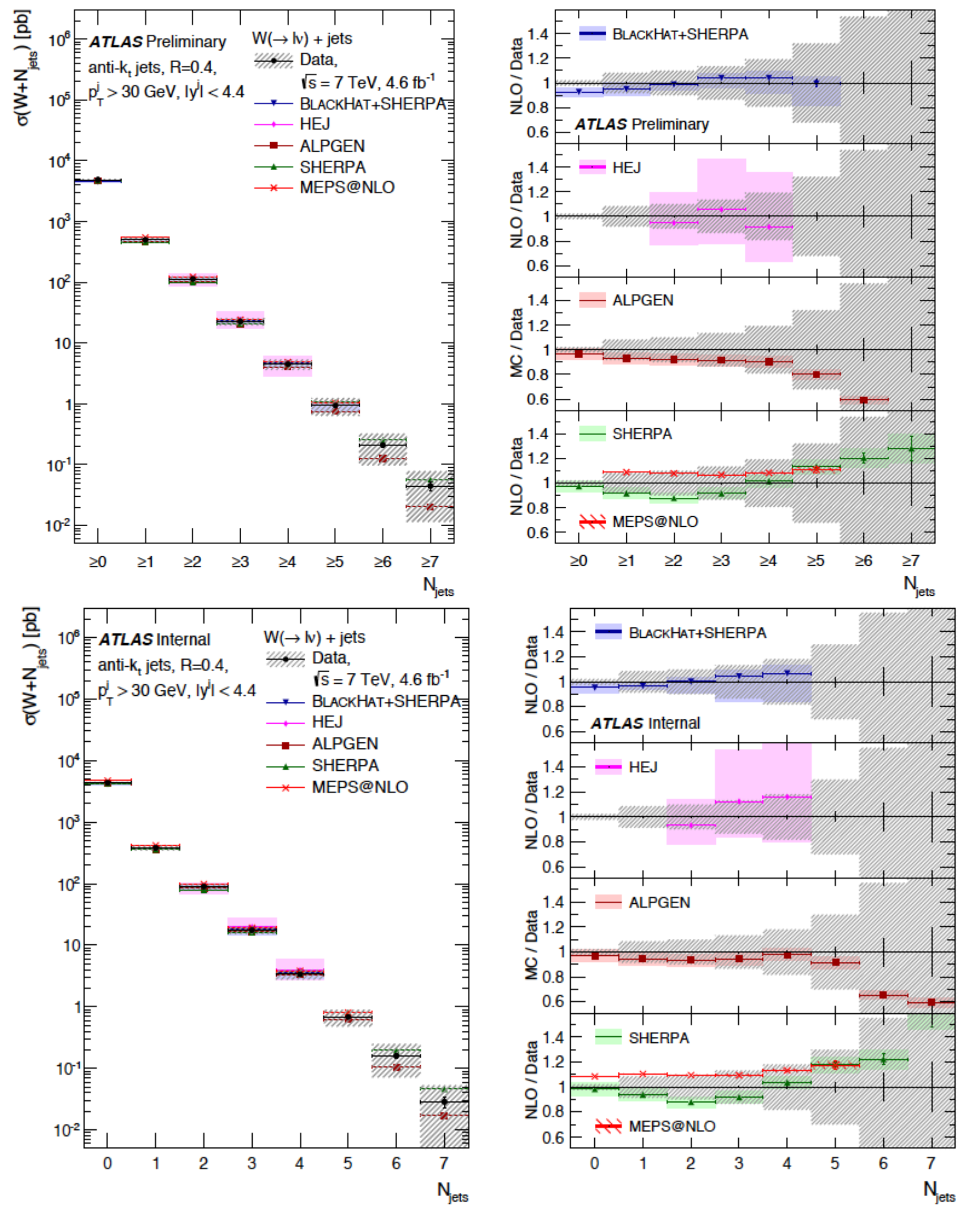
Process	known	desired	details
V	dσ(lept. V decay) @ NNLO QCD dσ(lept. V decay) @ NLO EW	dσ(lept. V decay) @ NNNLO QCD + NLO EW MC@NNLO	precision EW, PDFs
V + j	dσ(lept. V decay) @ NLO QCD dσ(lept. V decay) @ NLO EW	dσ(lept. V decay) @ NNLO QCD + NLO EW	Z + j for gluon PDF W + c for strange PDF
V + jj	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(V decays)	off shell leptonic decays



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

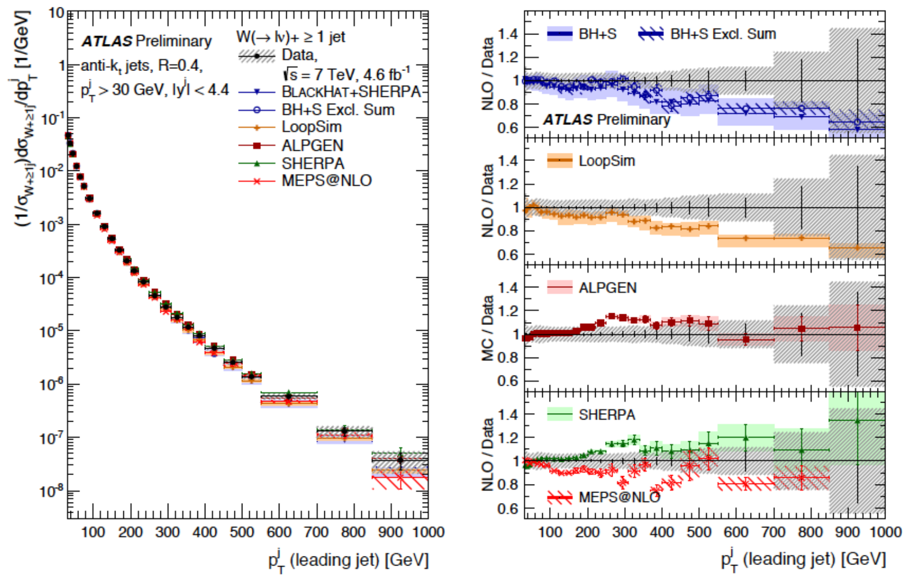
W+jets

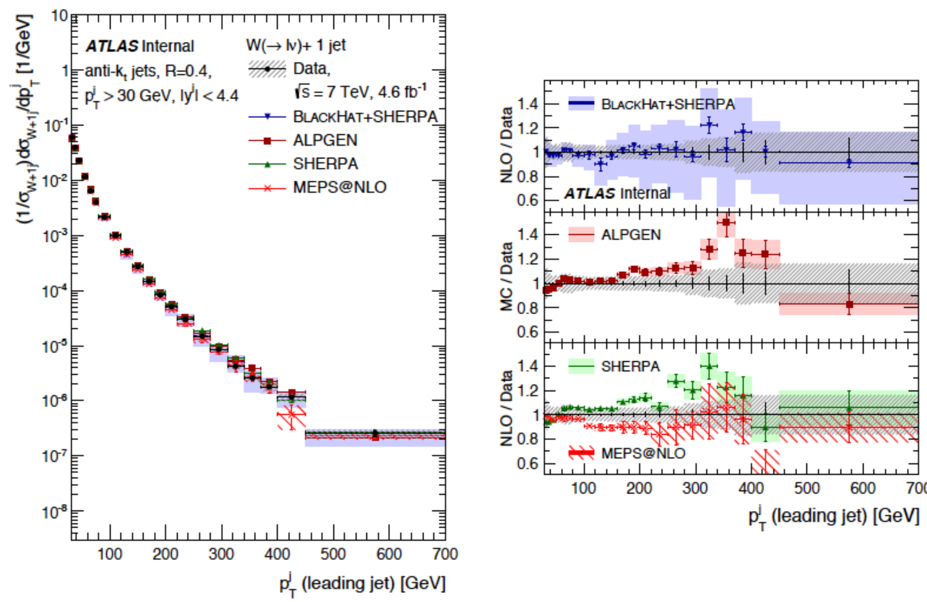
- ATLAS has measured up to 7 jets in the final state
  - both inclusive and exclusive final states
  - good agreement with Blackhat+Sherpa in general
    - with non-perturbative corrections
  - comparisons to a variety of predictions more thoroughly tests physics of process



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





Leading jet p_T

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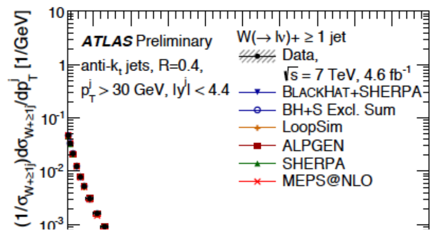
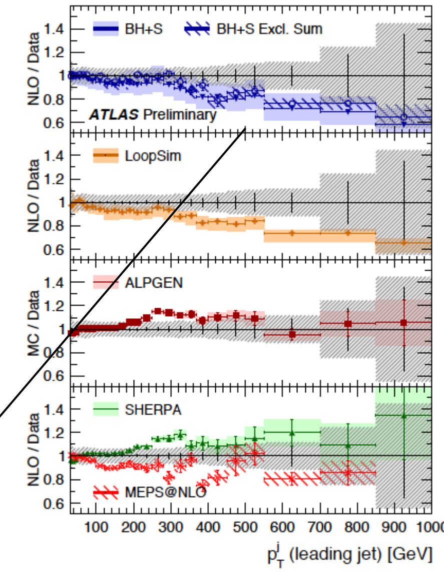
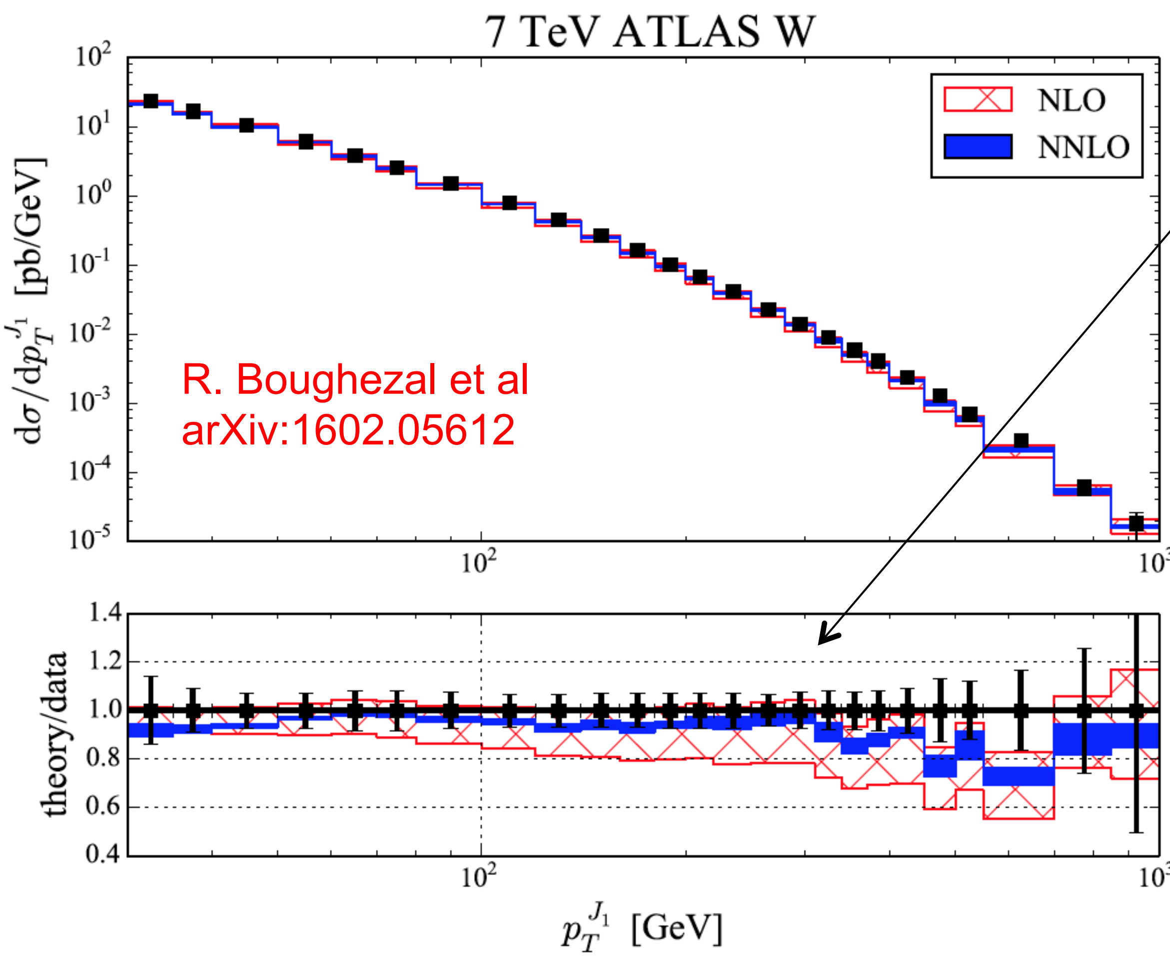
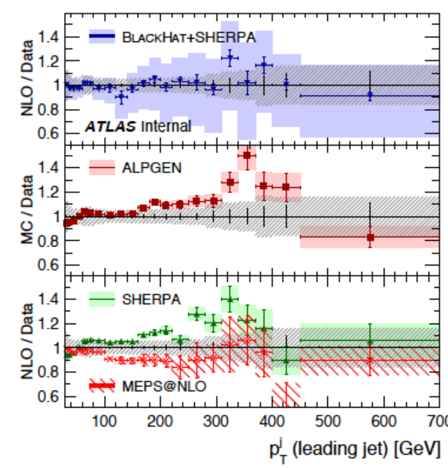
- a



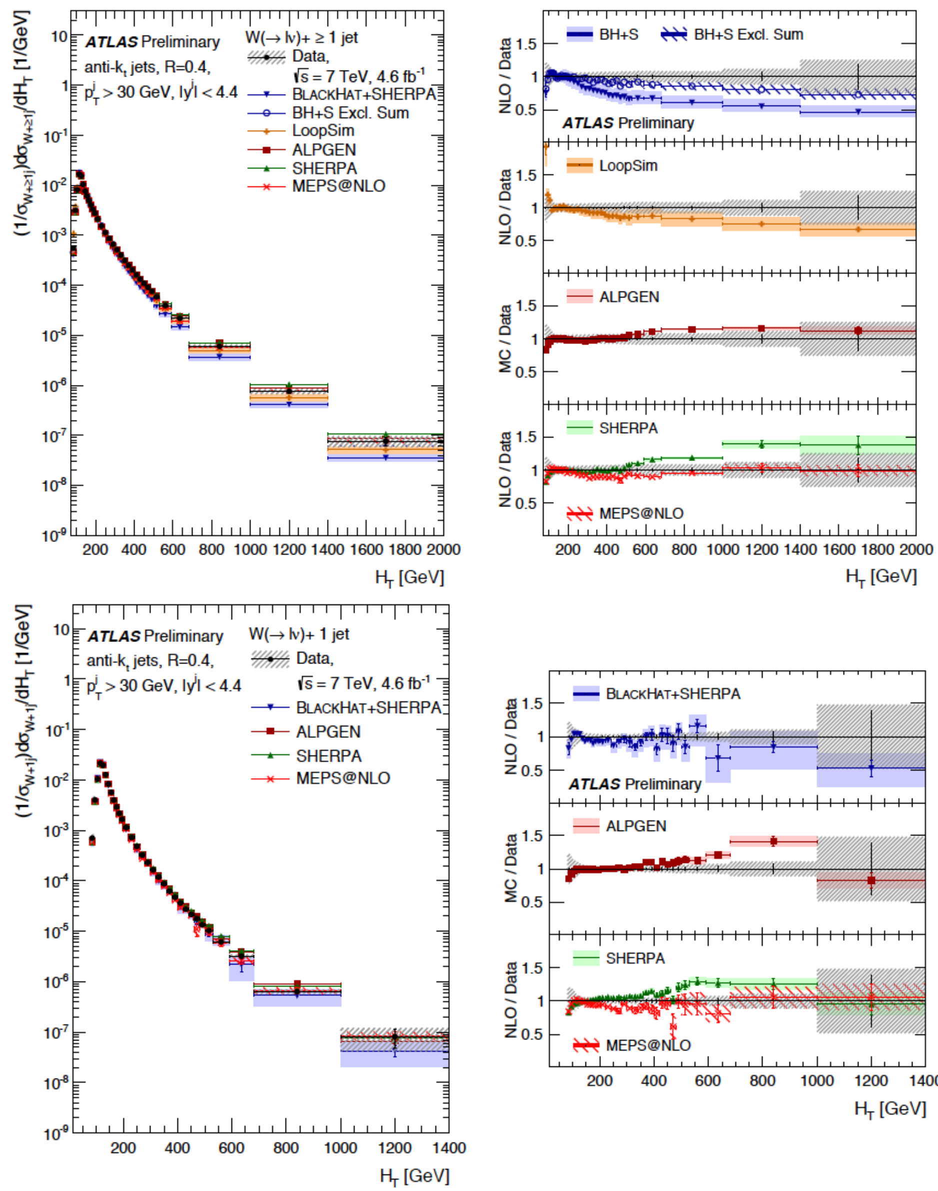






H_T

- 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
  - …now NNLO as well



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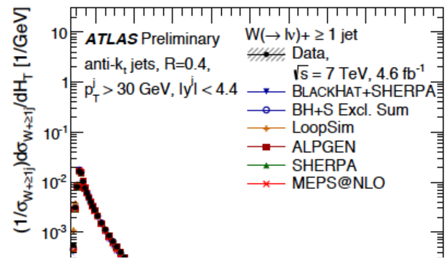
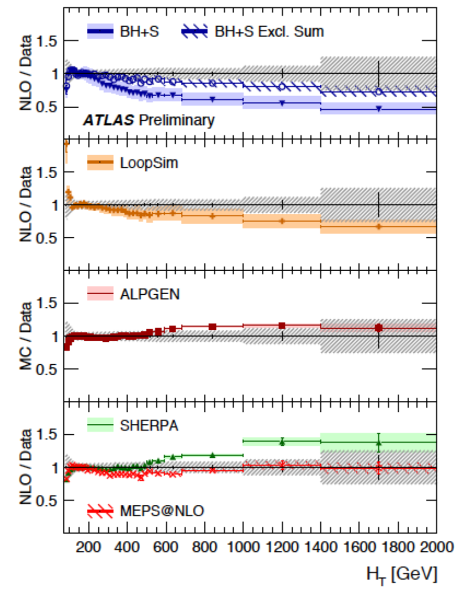
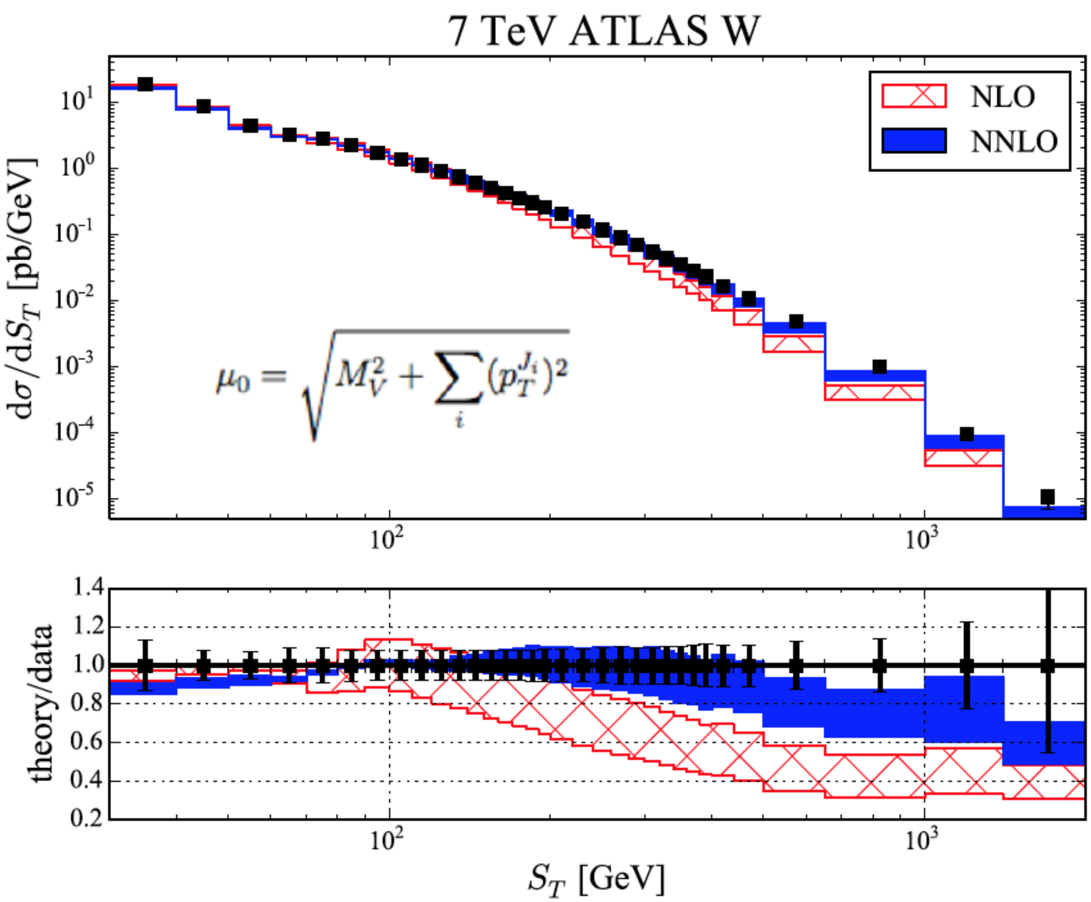
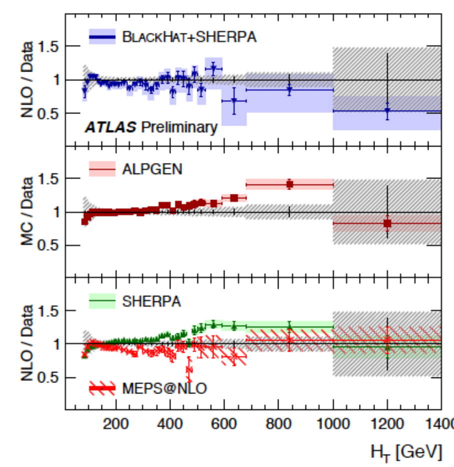
- Fc co (L ha da



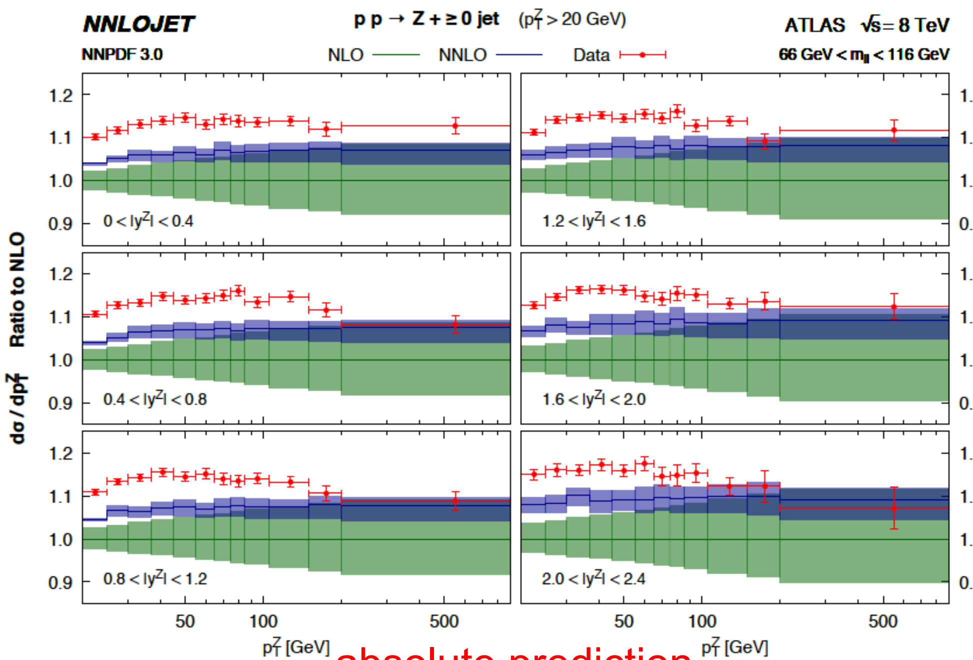




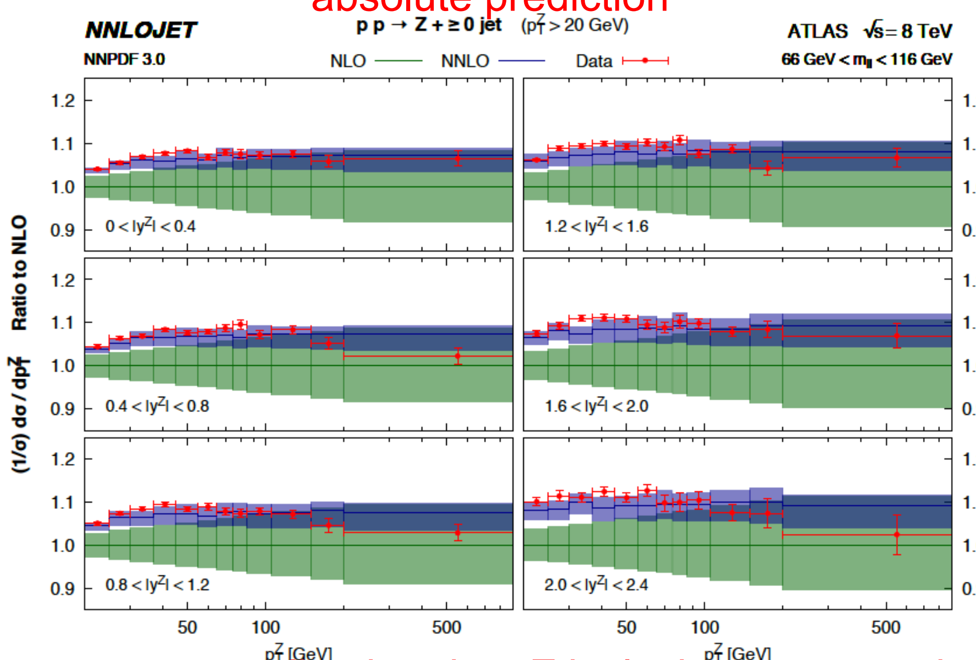


Z p_T

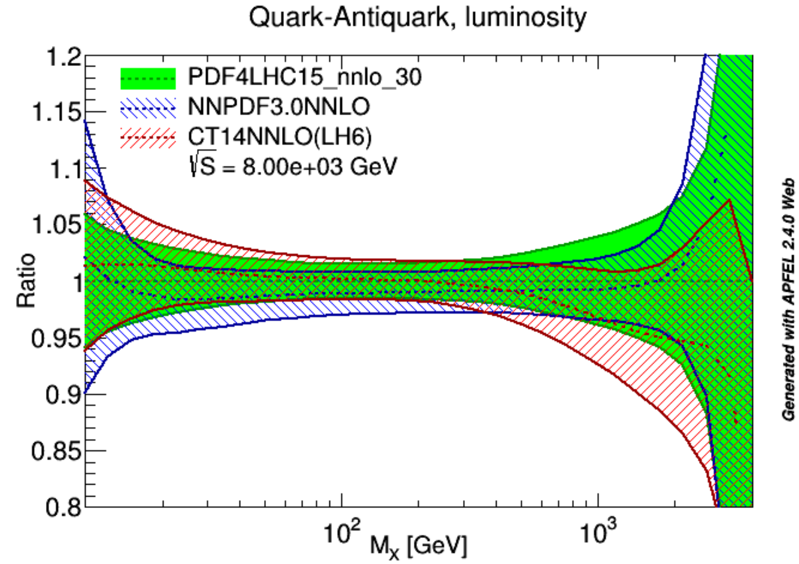
arXiv:1605.04295



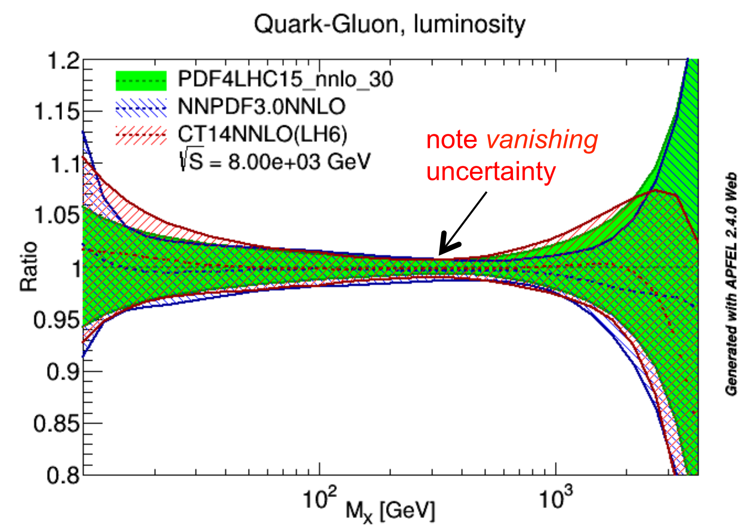
absolute prediction



normalized to data Z inclusive cross section



total cross section dominated by qQ



high p_T cross section dominated by qg

Vector boson pairs

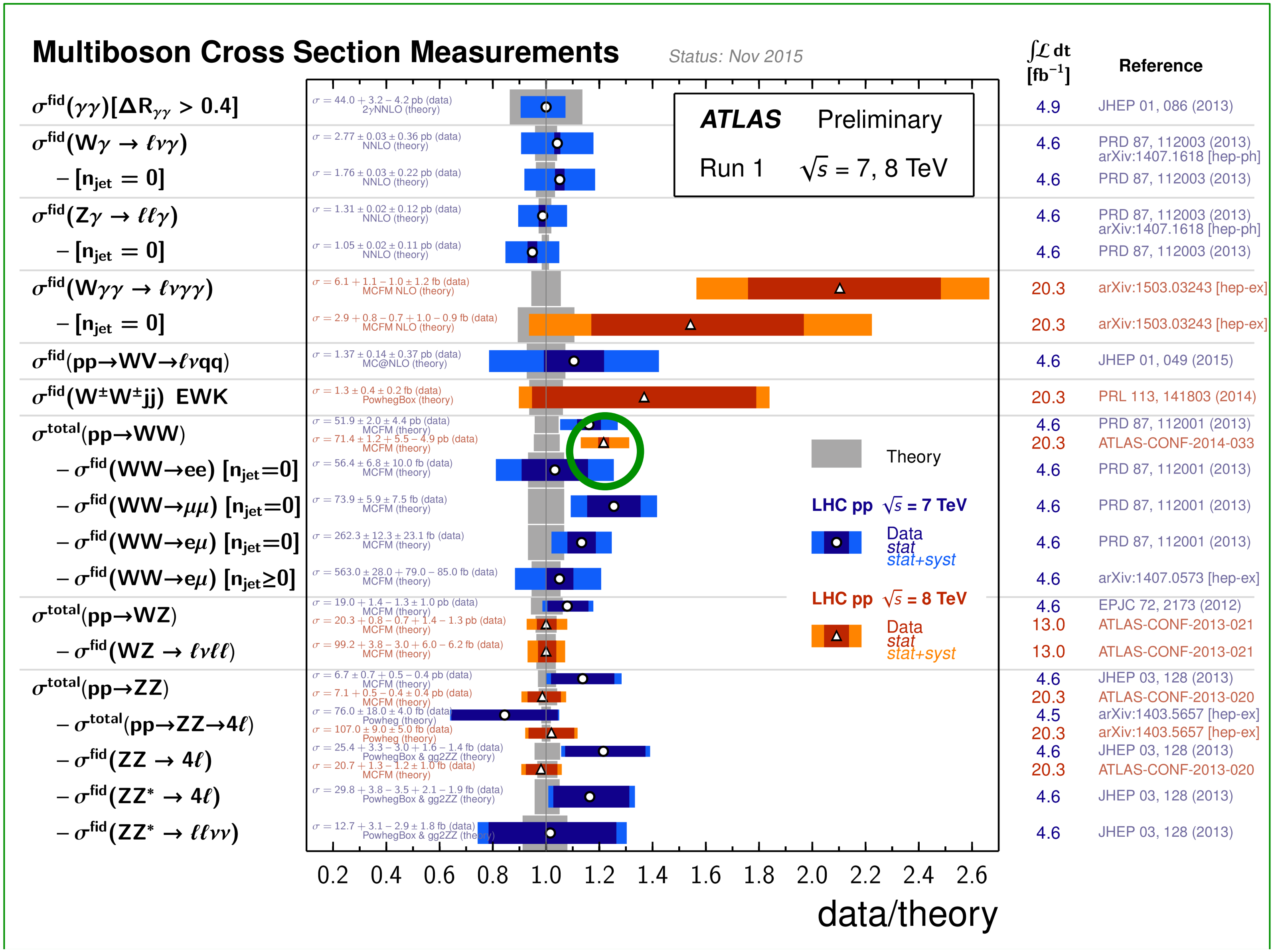
- Provides a handle on the determination of triple gauge couplings, and possible new physics
- Cross sections are known to NLO/ NNLO QCD (with V decays) and to NLO EW (with on-shell V's)
- WZ cross sections currently have a (non-luminosity) uncertainty of the order of 10%
  - will decrease in Run 2 of 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	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)

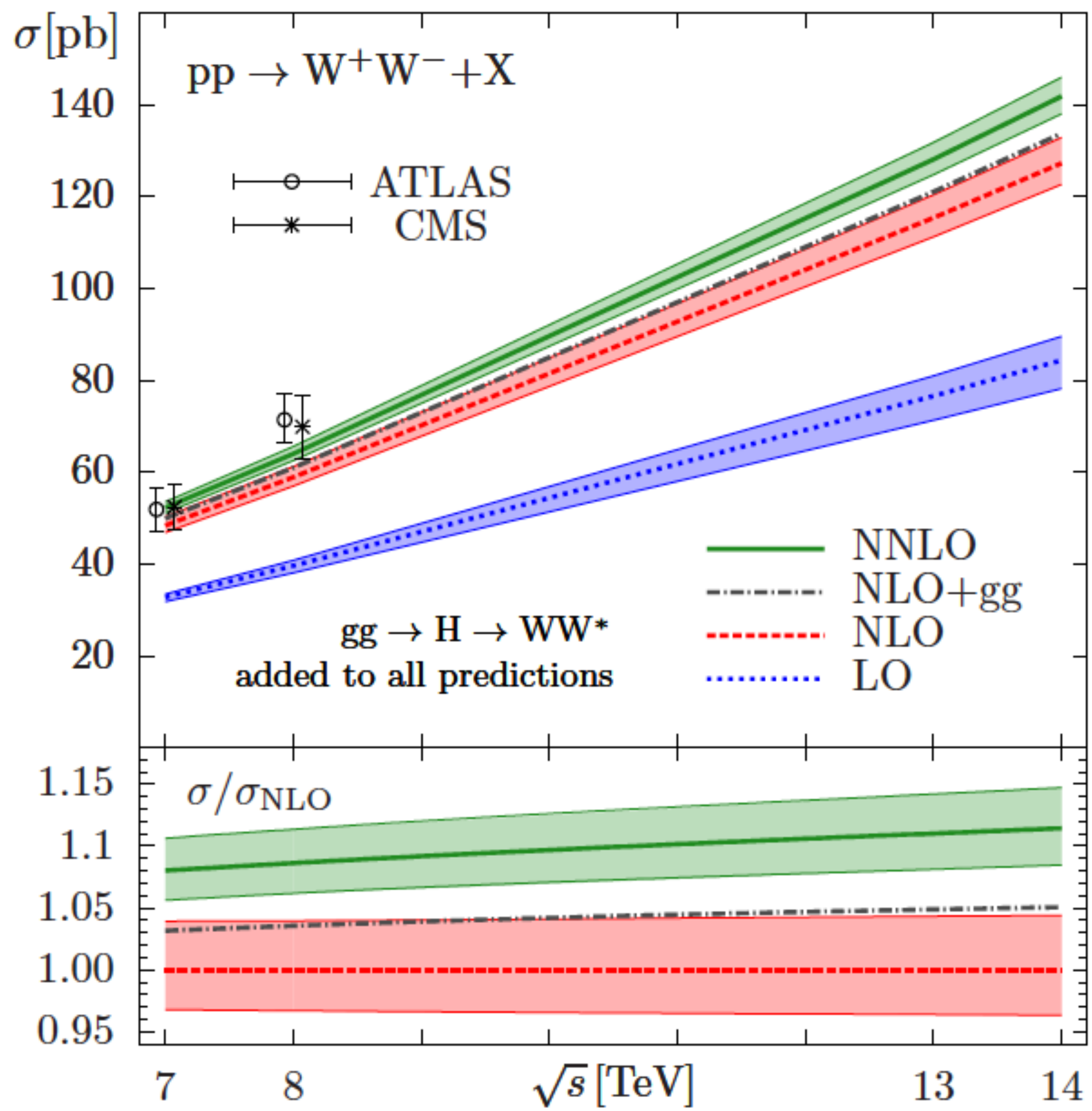
We also rely on theoretical predictions of VV* for Higgs measurements in that decay channel.

ATLAS diboson cross sections



…but arxiv:1408.5243

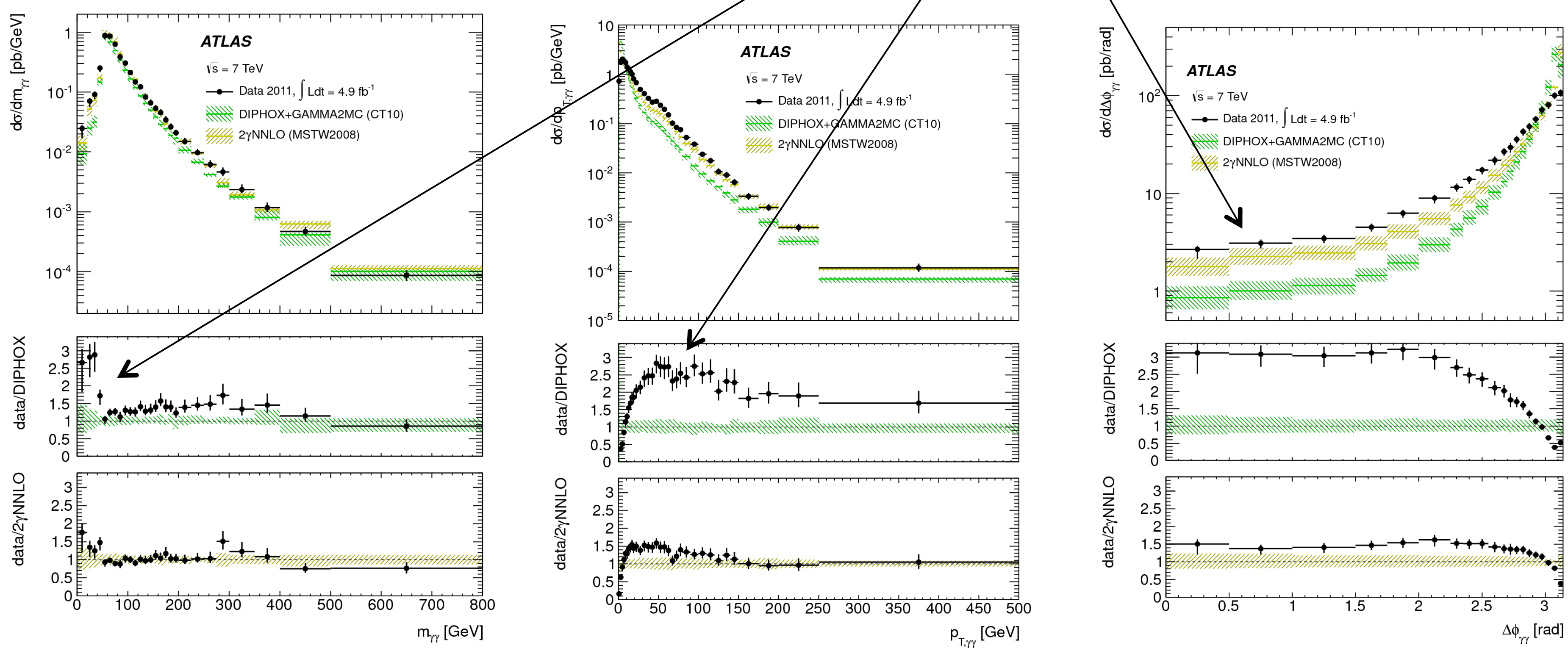
- NNLO calculation of WW production results in modest increase in size of cross section
- QCD issues with extrapolation of jet vetoed cross section to full cross section mean that uncertainty is larger than assumed in experimental papers
- Fiducial results agree with NNLO+NNLL
  - problem is in the extrapolation to full phase space
  - Powheg provides too large of an extrapolation from fiducial to full inclusive
  - **best to avoid such extrapolations; best to double-check with other predictions**



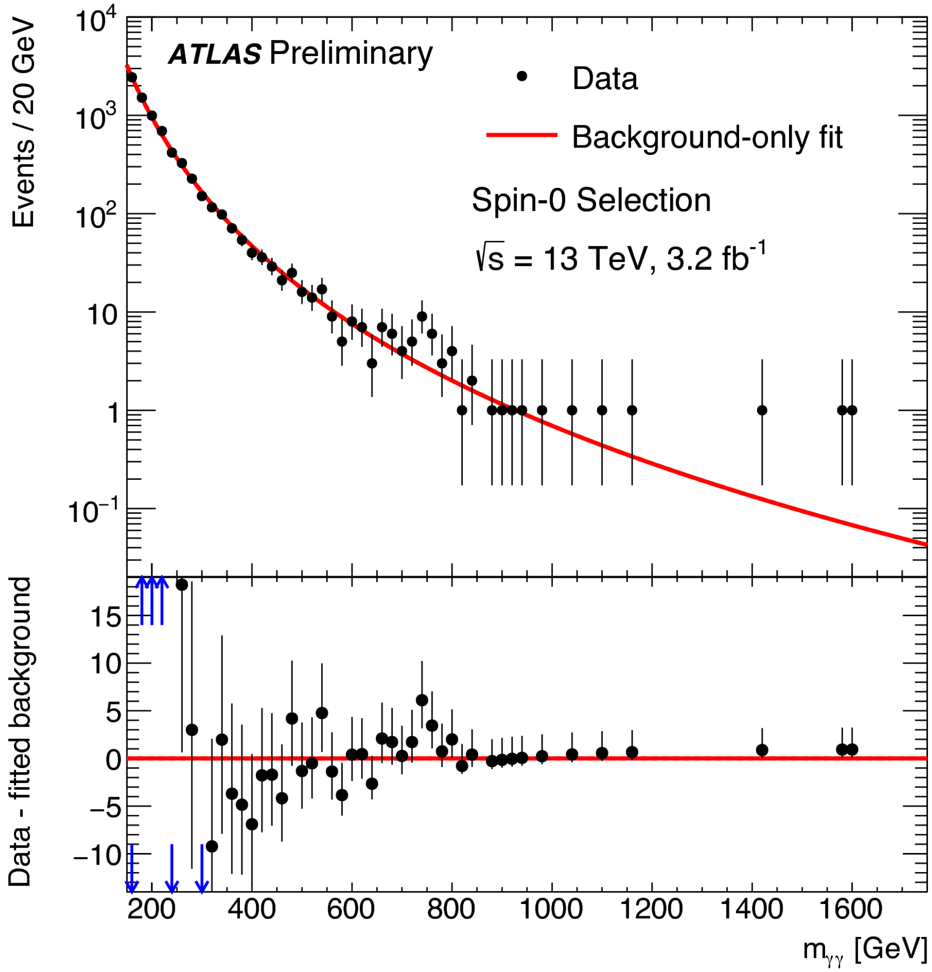
Diphoton production

- 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 $\gamma\gamma$

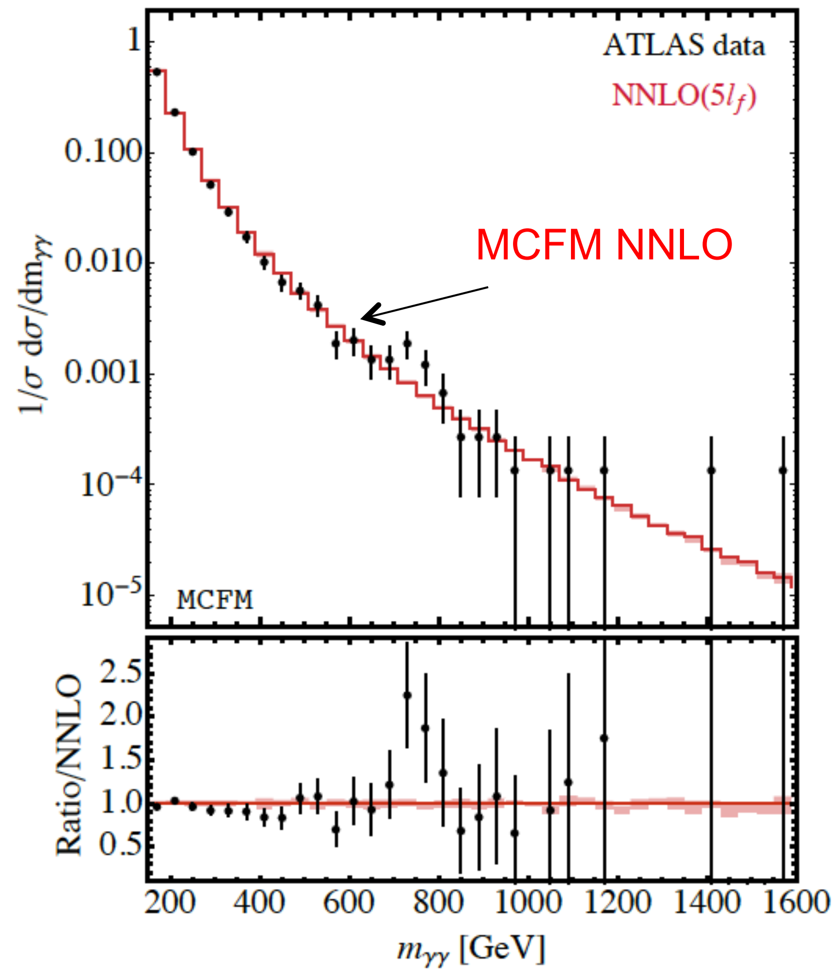
importance of higher multiplicity contributions clear in some corners of phase space



Some diphoton distributions are more interesting than others



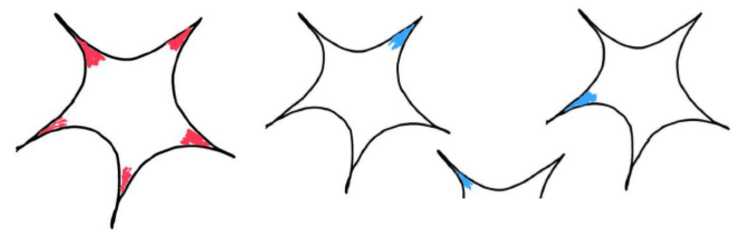
J. Campbell et al, arXiv:1603.02663

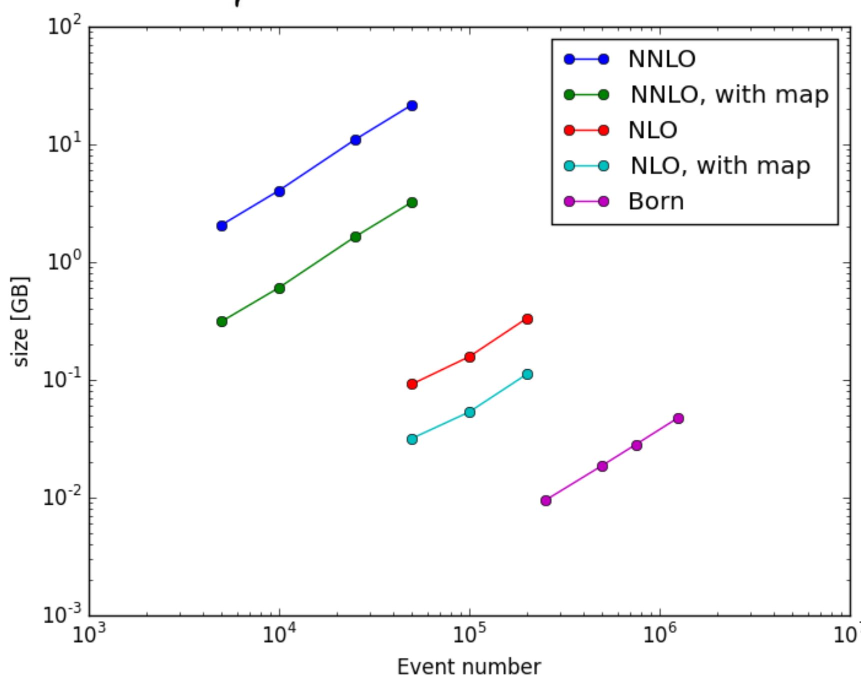


Distribution of NNLO results

- It's not enough to have a higher order result; it also has to be accessible to the user, whether experimentalist or theorist
- Stand-alone programs
  ->MCFM@NNLO
  ->NNLOJET
- Grid files in fastNLO and applgrid
- Possible ntuples a la Blackhat +Sherpa and gosam Higgs + jets for NLO
  - TB size is no problem
  - LH15 study (D. Maitre and G. Heinrich) using e+e- -> 3 jets at NNLO

can store all dipoles for real events, or store phase-space mappings needed to generate all of the kinematical configurations for the mappings
…at the expense of larger CPU time

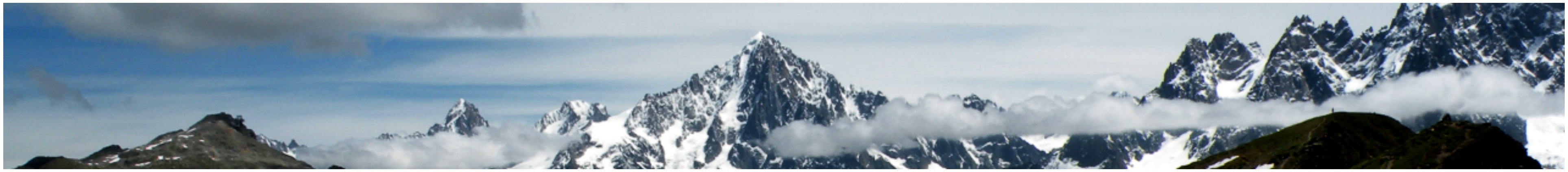




Summary

- Run 2 will be an exciting time for both experimentalists and theorists
- We need precise standard model predictions to best understand the data
- We need data that can be compared to theory in a straightforward way

~~Winter~~ Les Houches is coming



Les Houches 2017 June 5-23

Summary


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

Les Houches 2015: Physics at TeV Colliders
Standard Model Working Group Report

Conveners

Higgs physics: SM issues
J. Bendavid (CMS), M. Grazzini (Theory), K. Tackmann (ATLAS), C. Williams (Theory)

SM: Loops and Multilegs
S. Badger (Theory), A. Denner (Theory), J. Huston (ATLAS), J. Thaler (Jets contact)

Tools and Monte Carlos
V. Ciulli (CMS), R. Frederix (Theory), M. Schönherr (Theory)

Abstract

This Report summarizes the proceedings of the 2015 Les Houches workshop on Physics at TeV Colliders. Session 1 dealt with (I) new developments relevant for high precision Standard Model calculations, (II) the new PDF4LHC parton distributions, (III) issues in the theoretical description of the production of Standard Model Higgs bosons and how to relate experimental measurements, (IV) a host of phenomenological studies essential for comparing LHC data from Run I with theoretical predictions and projections for future measurements in Run II, and (V) new developments in Monte Carlo event generators.

Acknowledgements

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Les Houches 2015: Physics at TeV Colliders
Standard Model Working Group Report