SM@LHC 2015: Electroweak Summary

Jeffrey Berryhill
Joao Guimaraes da Costa
Guido Montagna

Talks this week

Title	Presenter	Tr
State-of-the-art of theory predictions for Drell-Yan processes	SCHWINN, Christian	
W/Z and DY differential measurements (pT, eta, y, phi*)	ILTEN, Philip	
W/Z differential: Z AFB, angles and mass	GROSSI, Giulio Cornelio	
Theory review on diboson production	RATHLEV, Dirk	
Precision multiboson phenomenology: status and prospects	RAUCH, Michael	
Diboson production and anomalous TGCs	BRIGLJEVIC, Vuko	
EWK Hot Topic from ATLAS	KOUSKOURA, Vasiliki	
Precise electroweak predictions for V+multijet production	POZZORINI, Stefano Augusto	
W/Z + jets production	NEUMEISTER, Norbert	
VBF/VBS/triboson production and anomalous aQGC	Dr. LIANG, Zhijun	
EWK Hot Topic from CMS	CALDERON TAZON, Alicia	

Total Duration of Selected: **3h20m**

Inclusive W and Z predictions (Schwinn)

Progress towards wishlist

Process	State of the Art	Desired
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD and @ NNLO QCD+EW NNLO+PS

N^{3}LO QCD Very recent result: (Anastasiou et al. 15)

total cross section for $gg \to H$ at N^{3}LO in expansion around threshold $\Rightarrow$ appears feasible for DY

NNLO+PS First steps:

- Combinations of NNLO V and NLO $V + j$ in parton shower (UN^{2}LOPS, Höche/Li/Prestel 14; NNLOPS, Karlberg/Re/Zanderighi 14)
- General framework proposed (Alioli et al. 13)

NNLO QCD+EW approx. schemes for dominant corrections

- Implementation of NLO EW in QCD parton showers (Bernaciak/Wackeroth 12, Barzé et al. 12/13)
- Pole approximation in resonance region (Dittmaier/Huss/CS 14)

Inclusive W and Z predictions (Schwinn)

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(Anastasiou et al. 15)

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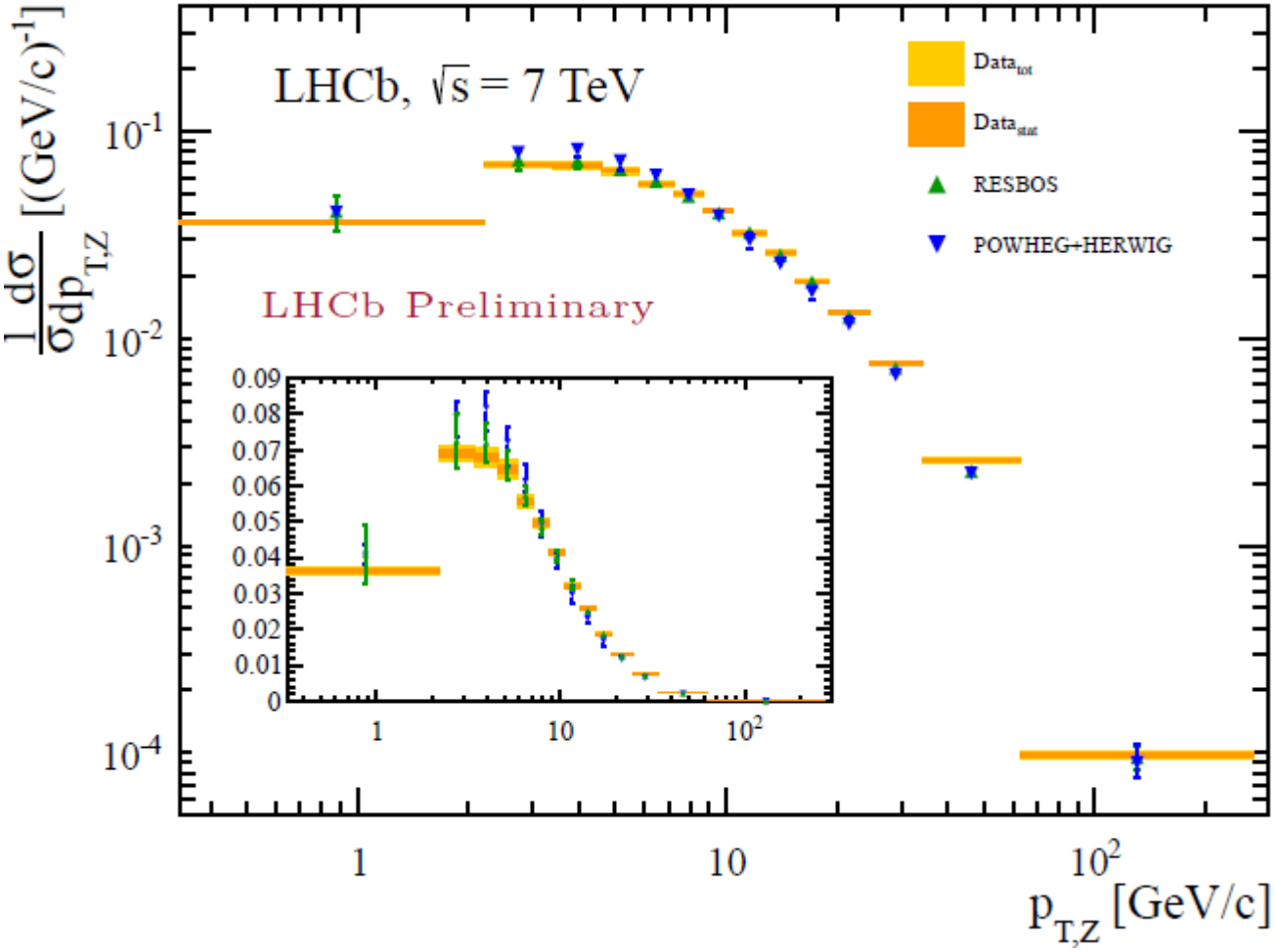
NNLO QCD+EW approx. schemes for

- Implementation of NLO EW in C
  (Bernaciak/Wackeroth 12, Barzé et al. 12/13)
- Pole approximation in resonance

W and Z differential cross sections (Ilten)

- large number of results available
  - not yet a complete set, but hopefully soon
  - missing 8 TeV results from ATLAS and LHCb
- results between the three experiments appear consistent
- differential uncertainties down to as low as 1%
- p_{T} spectra (W and Z) well measured
  - important for precision W mass measurements
  - useful for tunes, checking fixed order and p_{T} resummation
- very precise tests with W/Z ratios and COM ratios of ratios
  - strong constraints on PDFs

W and Z differential cross sections (Ilten)



HCb

ar consistent

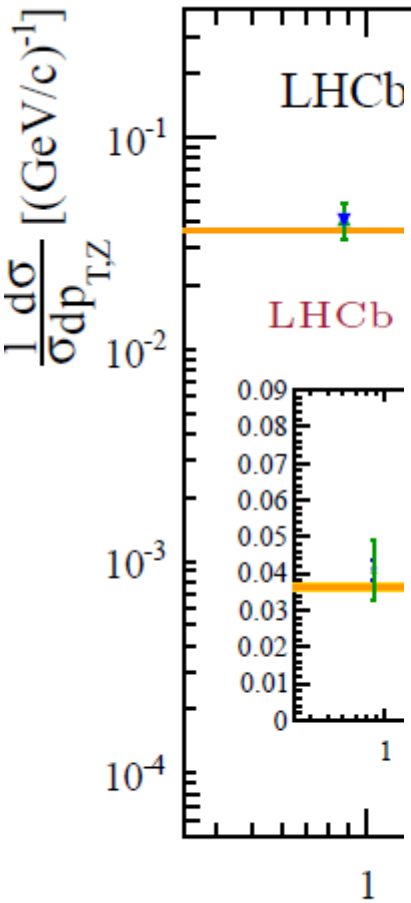
1%

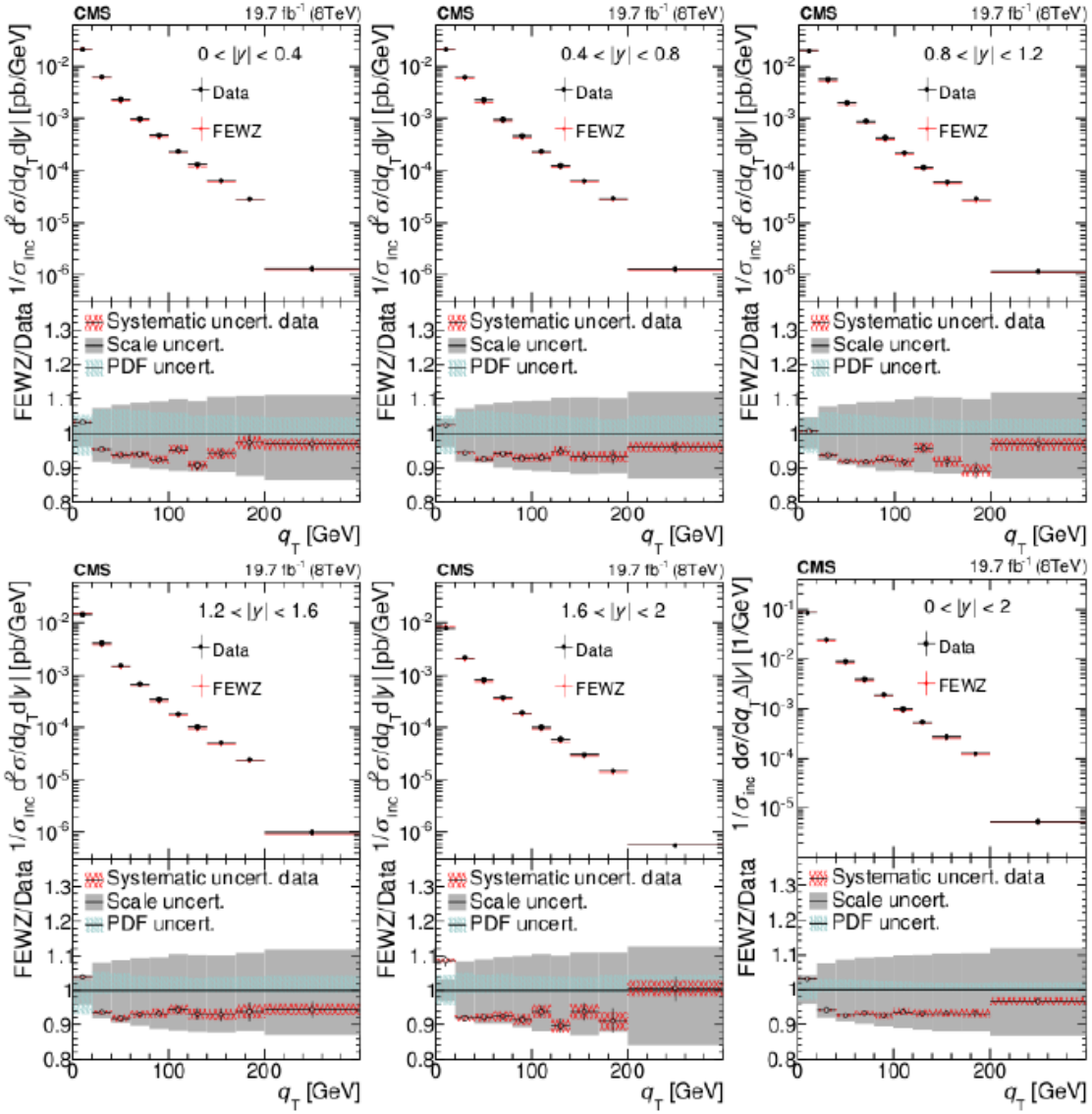
ents

p_T resummation

M ratios of ratios

W and Z differential cross sections (Ilten)





tent

nation

of ratios

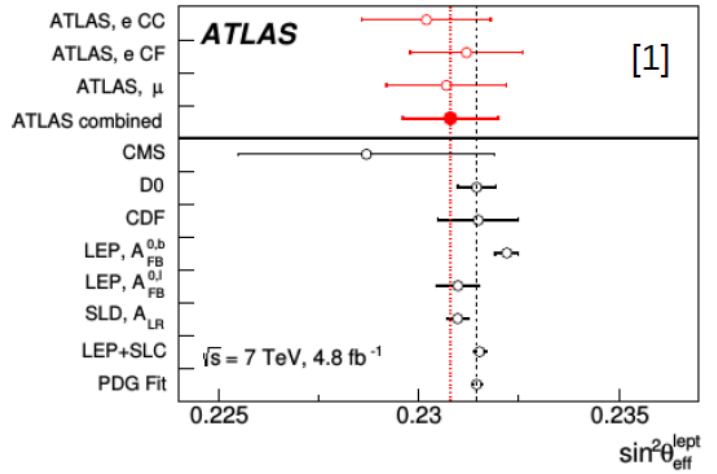
Z angular distributions (Grossi)

- ATLAS submitted a publication of their 7 TeV weak mixing angle measurement

ATLAS combined result

$\sin^2\theta_W^{eff} = 0.2308 \pm 0.0005(\text{stat.}) \pm 0.0011(\text{syst.})$

Forward electron usage helped a lot
Large PDF errors looming

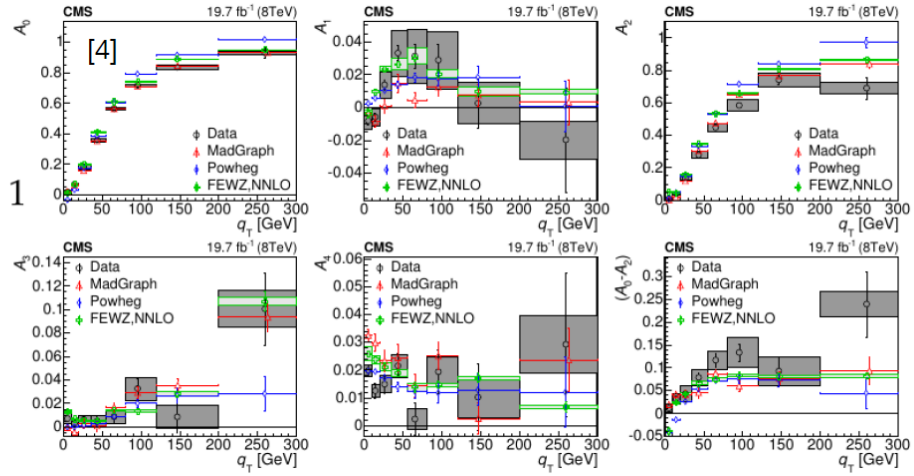


- CMS submitted a publication of 8 TeV angular coefficients in Z production

First LHC study of Z polarization coefficients vs. qT

Reveals many disagreements of NLO and NNLO with data

$|y| < 1$



V+jets production theory (Pozzorini)

NLO QCD+EW for V+multijets

- EW corrections crucial at the TeV scale
- large QCD radiation calls for EW+QCD corrections for multi-jet final states

NLO QCD+EW automation

- applicable to any $2 \to 2, 3, 4$ SM process
- various nontrivial physics features (EW-QCD interplay, decays, "overlapping" processes, jet/photon definition, ...)

Next steps

- full NLO SM predictions
- how to disentangle W+multijets from VBF and WW/WZ, tj, Wt, tt production$\times$decays?
- NLO QCD+EW matching and multi-jet merging

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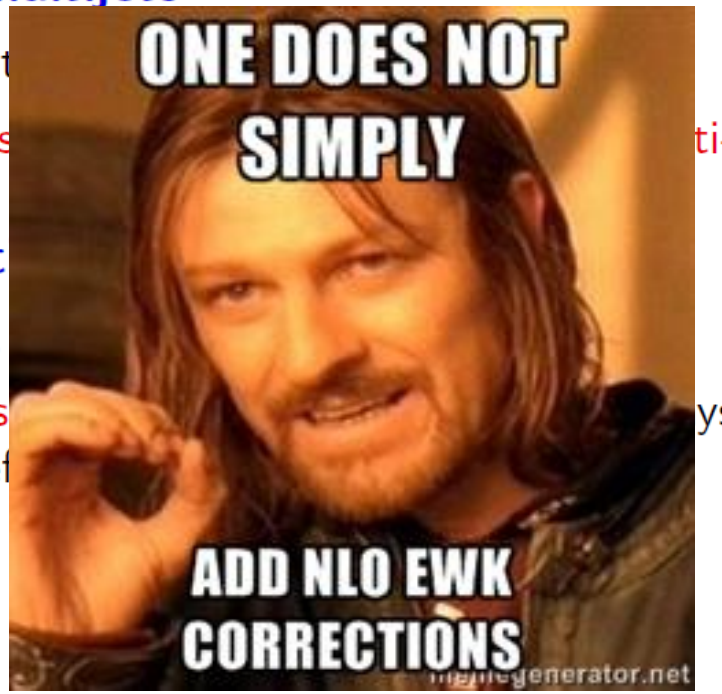

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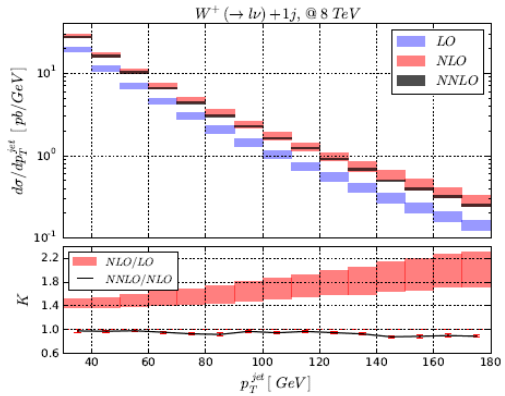
V+jets production theory (Pozzorini)

NNLO QCD corrections starting to be available

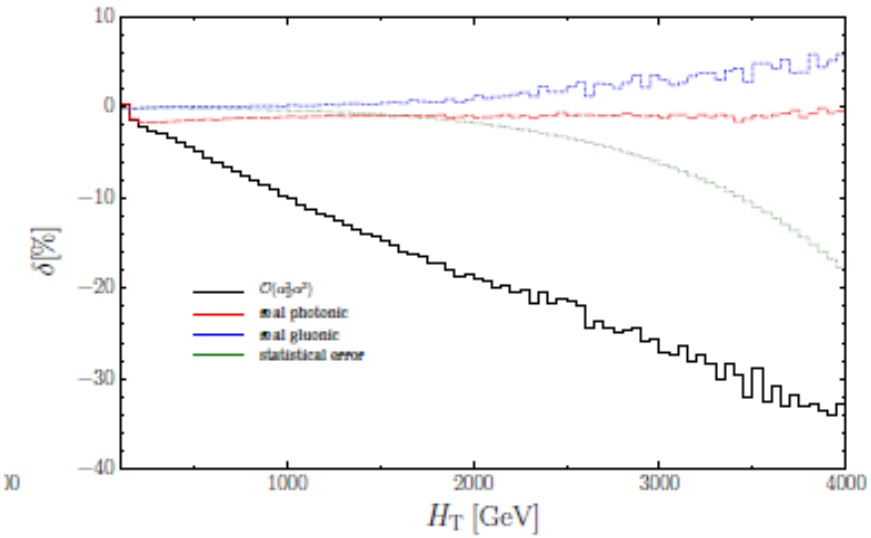
BUT beware
-20-30% electroweak corrections at the TeV scale
expected at 13 TeV:

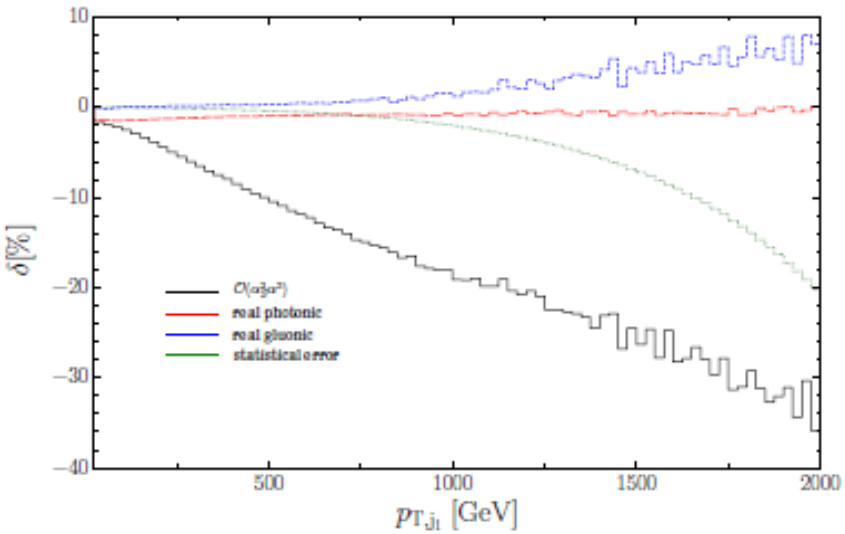
$W+1$ jet at NNLO

[Boughezal, Focke, Liu, Petriello '15]



$\Rightarrow$ $\mathcal{O}(1\%)$ **scale uncertainty**





V+jets production theory (Pozzorini)

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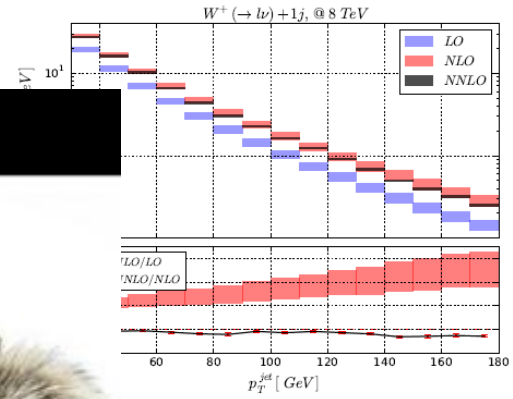
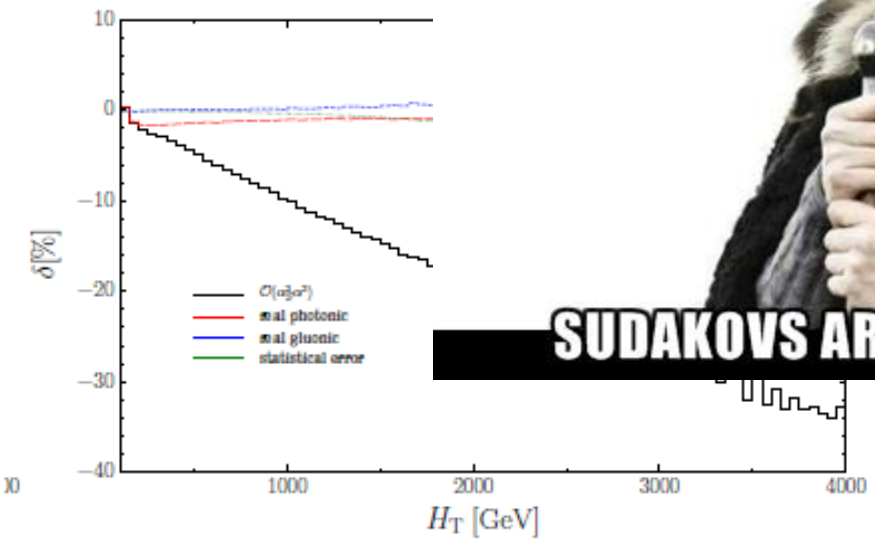
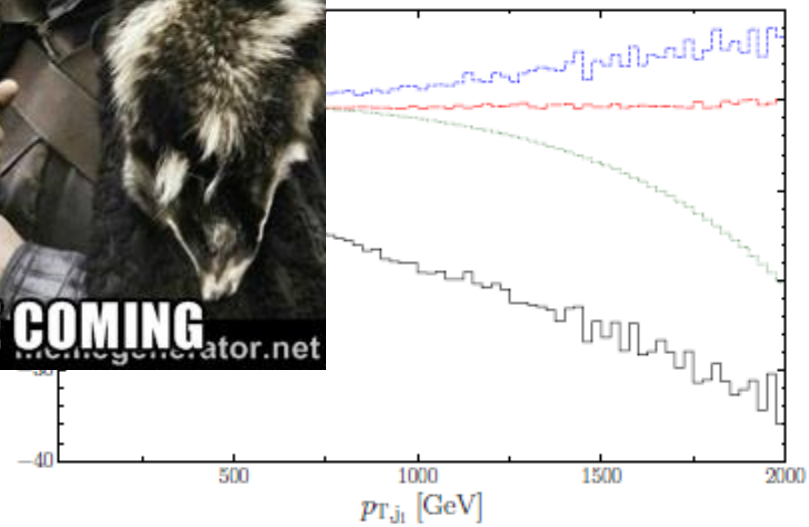
$W + 1$ **jet at NNLO**

[Boughezal,Focke,Liu,Petriello '15]



(1%) **scale uncertainty**





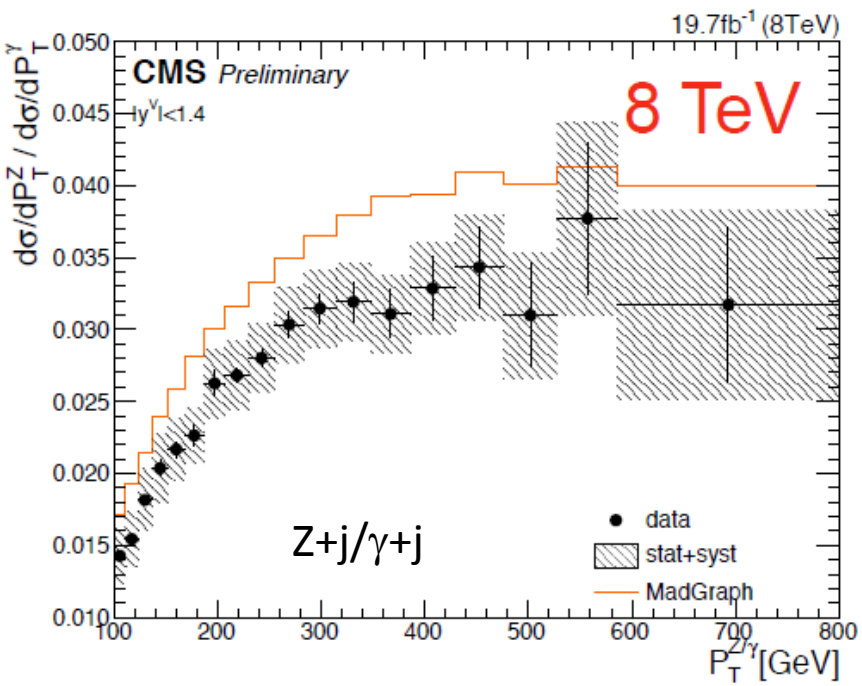
V+jets production results (Neumeister)

Huge number of results obtained, many less than a year old!

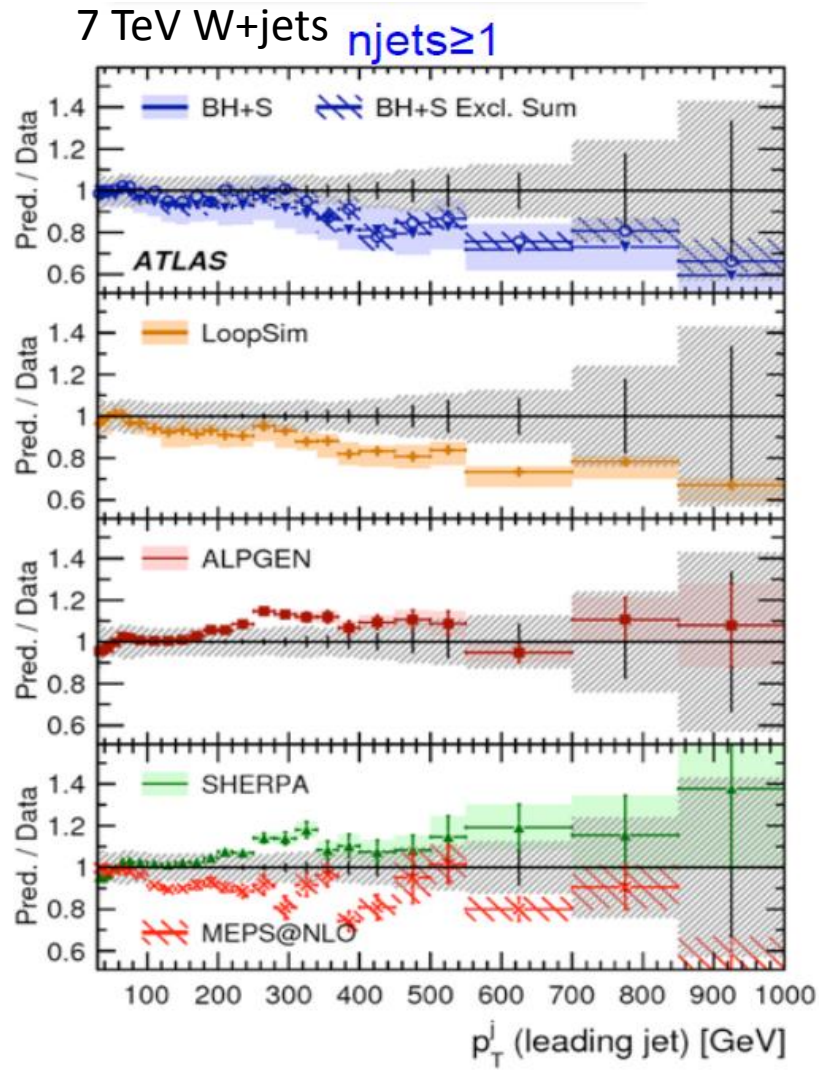
No major excursions of data from predictions; but many measurements that MC theorists can dig into.

In general the NLO calculations merged with PS yield the best description of data and are becoming a standard

- Leading edge calculations, performs better as expected, but with known limitations due to the lack of PS
- In some cases LO+PS gives a better prediction



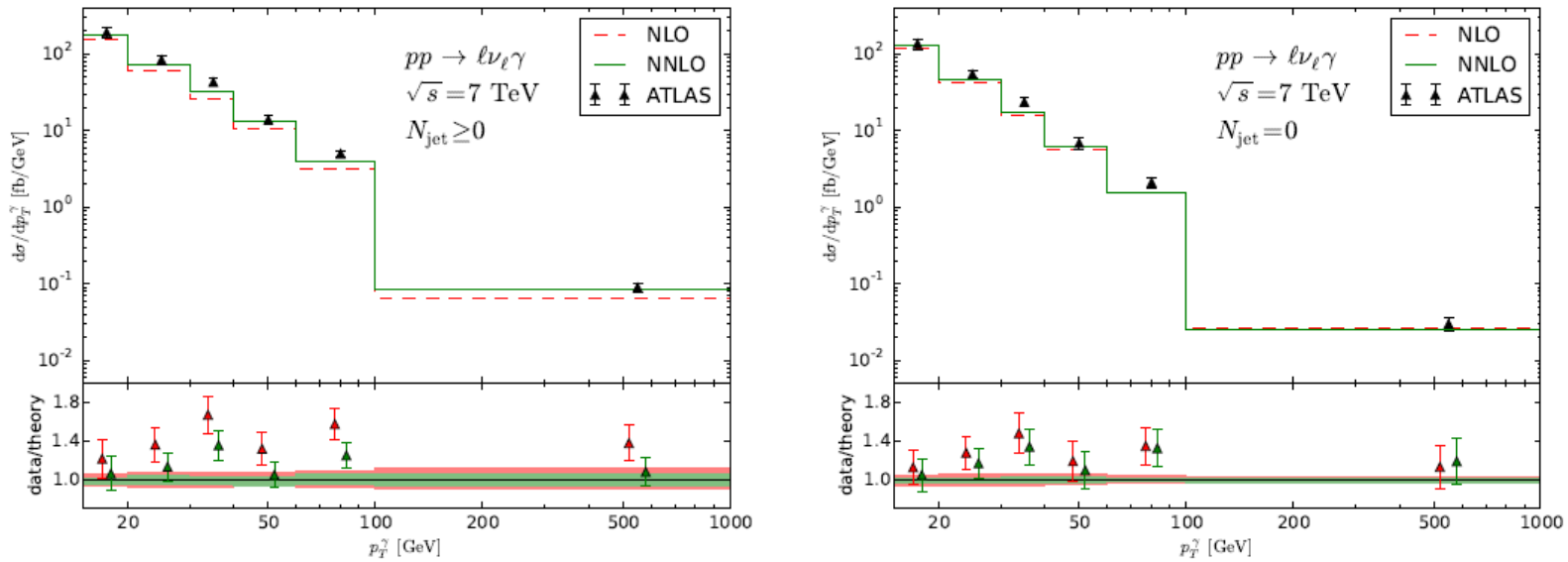
7 TeV W+jets



Diboson production theory (Rathlev)

- significant progress on the NNLO QCD corrections to diboson production

Wγ is agreeing better with ATLAS data



- $gg \to VV'$ at NLO now feasible (formally NNNLO)
- NLO EW corrections are being automated
  - partial results already available
  - phenomenologically relevant
- standard theory precision for all diboson processes will soon be NNLO QCD + NLO EW
- midterm goal: provide a single code to compute all VV' processes at NNLO QCD

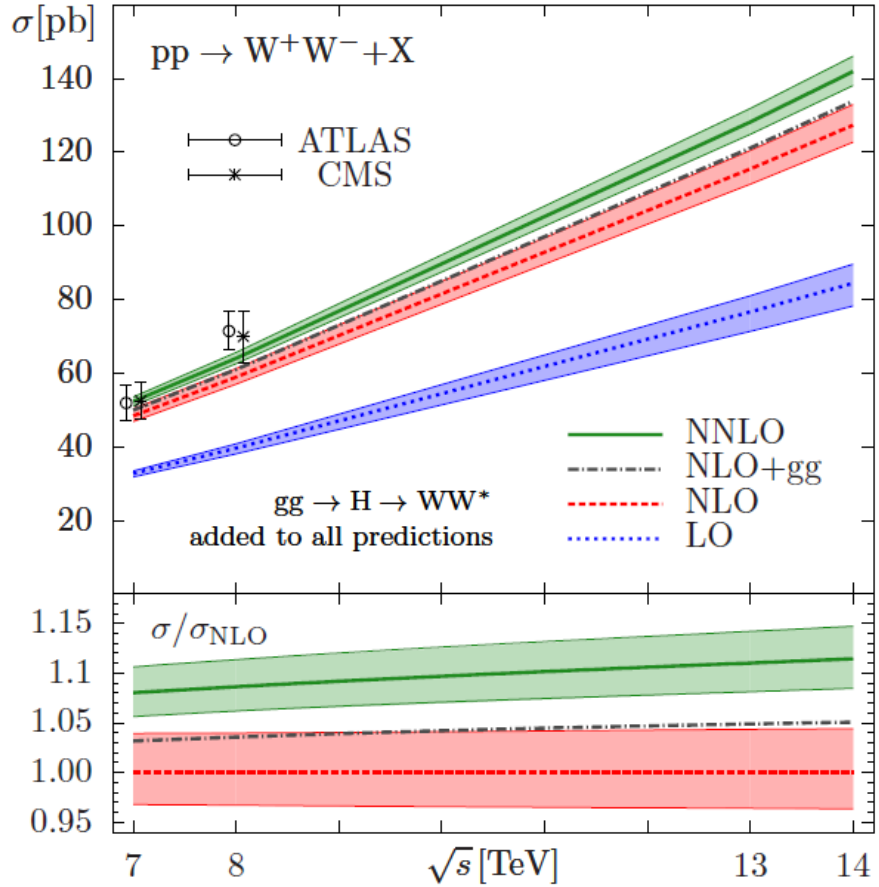
Diboson production theory (Rathlev)

W^+W^-: the inclusive cross section

[Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, D. R., Tancredi; 1408.5243]

NNLO WW in closer agreement with CMS and ATLAS 8 TeV data

TBC: N3LO gg contribution, jet veto effects



- NNLO corrections range from 9% to 12%
- gg fusion contribution is about 35% of the NNLO correction

Diboson production results (Brigljevic)

Complete inventory of cross sections and couplings at 7 TeV;
Wγ still uncovered at 8 TeV

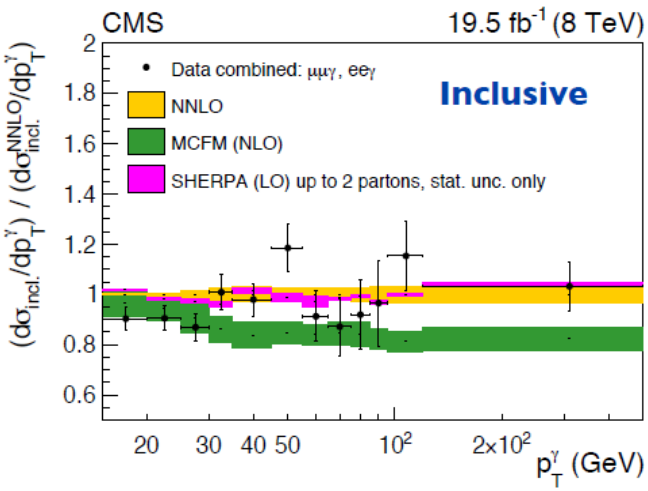
Recent updates (from Summer 2014)

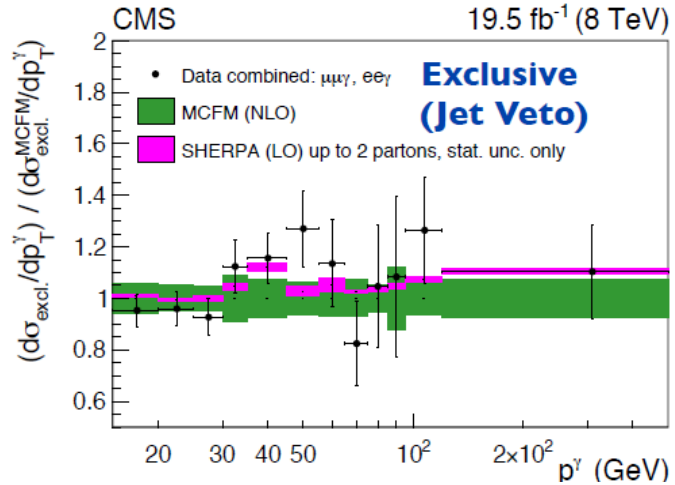
Channel (final state)	ATLAS		CMS	
	7 TeV	8 TeV	7 TeV	8 TeV
Wγ(ℓνγ)	xs,dx,ac		xs,ac	
Zγ(ℓℓγ)	xs,dx,ac		xs,ac	xs,dx,ac
Zγ(ννγ)	xs,ac		xs,ac	
WW(ℓνℓν)	xs,dx,ac	xs	xs,ac	xs,dx,ac
WZ(3ℓν)	xs,dx,ac	xs	xs	xs
ZZ(4ℓ)	xs,dx,ac	xs	xs,ac	xs,dx,ac
ZZ(2ℓ2ν)	xs,dx,ac		xs,ac	xs,ac
WV(ℓνjj)	xs,ac		xs,ac	

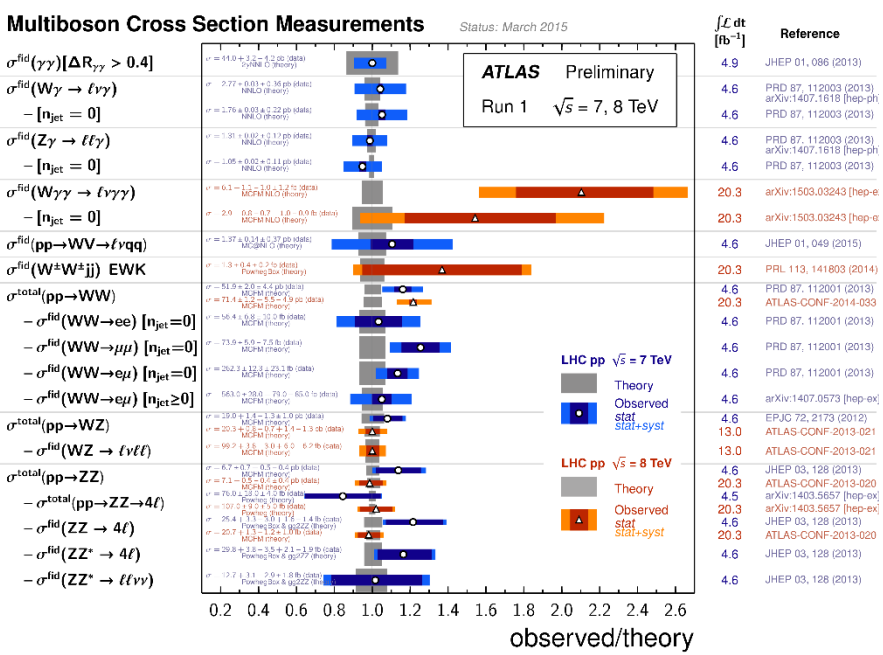
xs: cross section, ac: limits on aTGCs, dx: differential cross sections

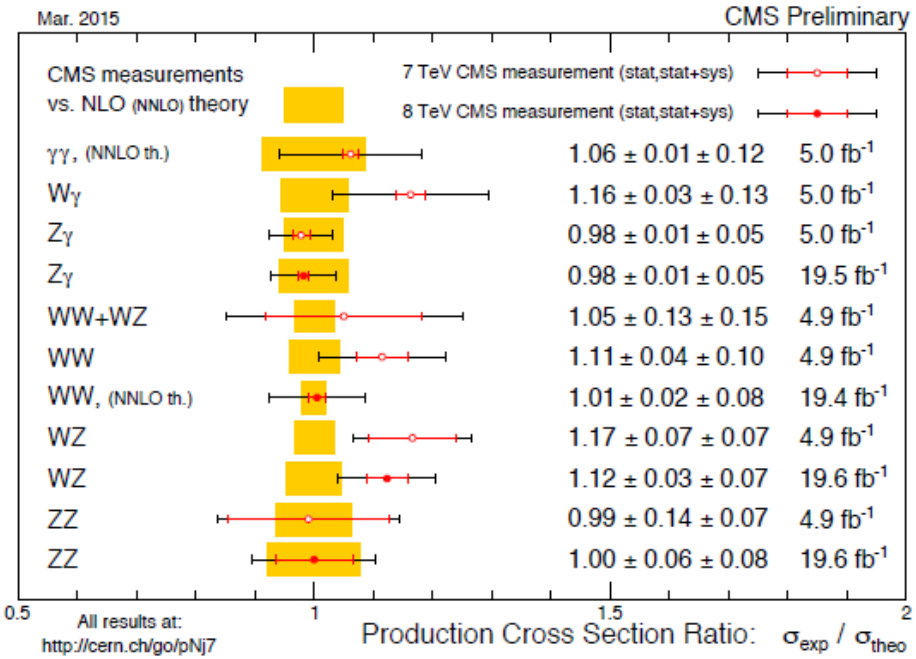
Diboson production results (Brigljevic)

NNLO agrees well with recent CMS Zγ cross section at 8 TeV









CMS WW cross section at 8 TeV (Calderon)

Exploring how to compute and bound errors for the jet veto continues

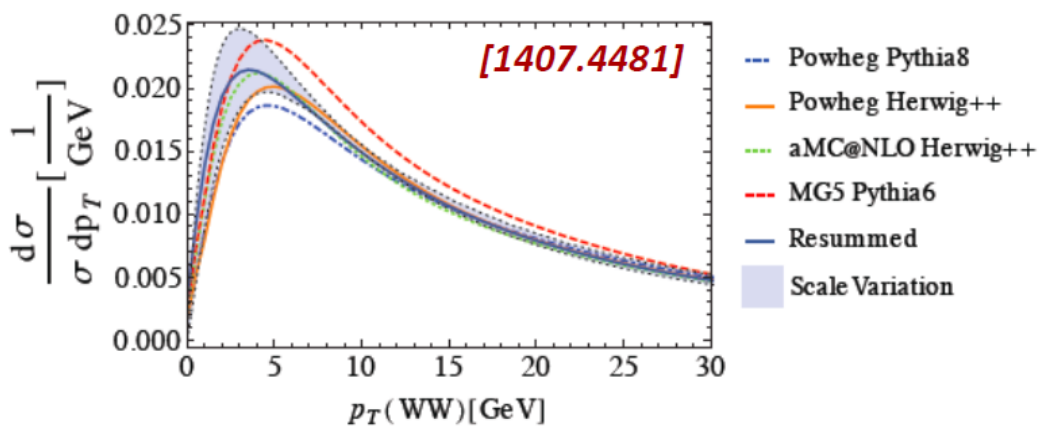
This procedure was largely consistent with Stewart-Tackmann, e.g.

Shifts xsec by -3.5% And about the same error as before

Stronger prescription from theory community needed for further progress

Higher order corrections

- Lots of theoretical interest in previous discrepancy, particularly w.r.t. jet-veto efficiency *[1407.4481] [1407.4537]*
- **The 0-jet (or 1-jet bin) veto applied** in this analysis makes the kinematical distributions particularly sensitive to higher-order QCD corrections.
  - Improve modelling of gluon resummation, by reweight p_T(WW) of the qq → WW MC to a NLO+NNLL p_T resummation calculation → **correlated with jet veto**
    - ~ 3.5% effect on the 0-jet cross section.
  - the resummation scale also provides a convenient handle to determine the acceptance uncertainty



CMS WW cross section at 8 TeV (Calderon)

New measurement in agreement with NNLO and across SF, OF, 0-jet, and 1-jet

Progress requires better understanding of leptons, backgrounds, luminosity, theory

- **Results per channel :**

Event category		W^+W^- production cross section (pb.)
0-jet category	Different-flavor	$59.7 \pm 1.1\,(\text{stat.}) \pm 3.3\,(\text{exp.}) \pm 3.5\,(\text{th.}) \pm 1.6\,(\text{lum.})$
	Same-flavor	$64.3 \pm 2.1\,(\text{stat.}) \pm 4.6\,(\text{exp.}) \pm 4.3\,(\text{th.}) \pm 1.7\,(\text{lum.})$
1-jet category	Different-flavor	$59.1 \pm 2.8\,(\text{stat.}) \pm 6.0\,(\text{exp.}) \pm 6.2\,(\text{th.}) \pm 1.6\,(\text{lum.})$
	Same-flavor	$65.1 \pm 5.5\,(\text{stat.}) \pm 8.3\,(\text{exp.}) \pm 8.0\,(\text{th.}) \pm 1.7\,(\text{lum.})$

- **Combined by performing a profile likelihood fit**

$$\sigma_{W^+W^-} = 60.1 \pm 0.9\,(\text{stat.}) \pm 3.2\,(\text{exp.}) \pm 3.1\,(\text{th.}) \pm 1.6\,(\text{lum.})\,\text{pb.}$$

- The result is below one standard deviation of the NNLO theoretical prediction of $59.8^{+1.3}_{-1.1}\,\text{pb}$

Multiboson production theory (Rauch)

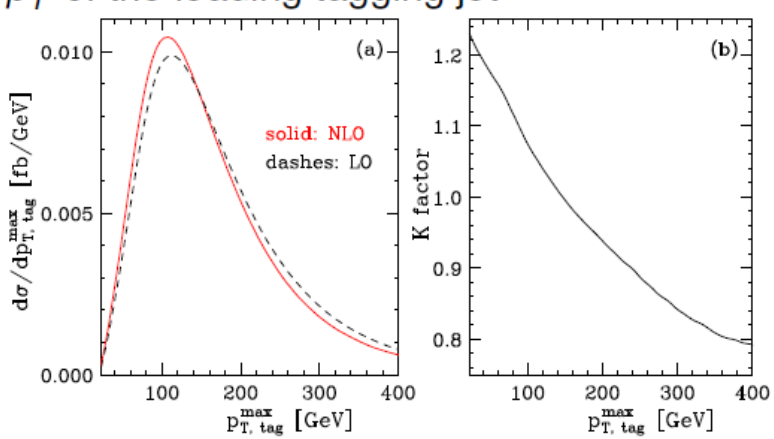
Vector-Boson Fusion/Scattering:

- modest NLO QCD corrections, small remaining scale uncertainties
- state-of-the-art: NLO QCD + parton shower
- enhance over irred. QCD background by VBF cuts
- $\leftrightarrow$ significant discrepancies in predicting central jet activity
  $\rightarrow$ needs further studies

Triboson production:

- large NLO QCD K factors due to new channels
- $\rightarrow$ merging with higher jet multiplicities
- fixed jet vetoes can induce large theory uncertainties

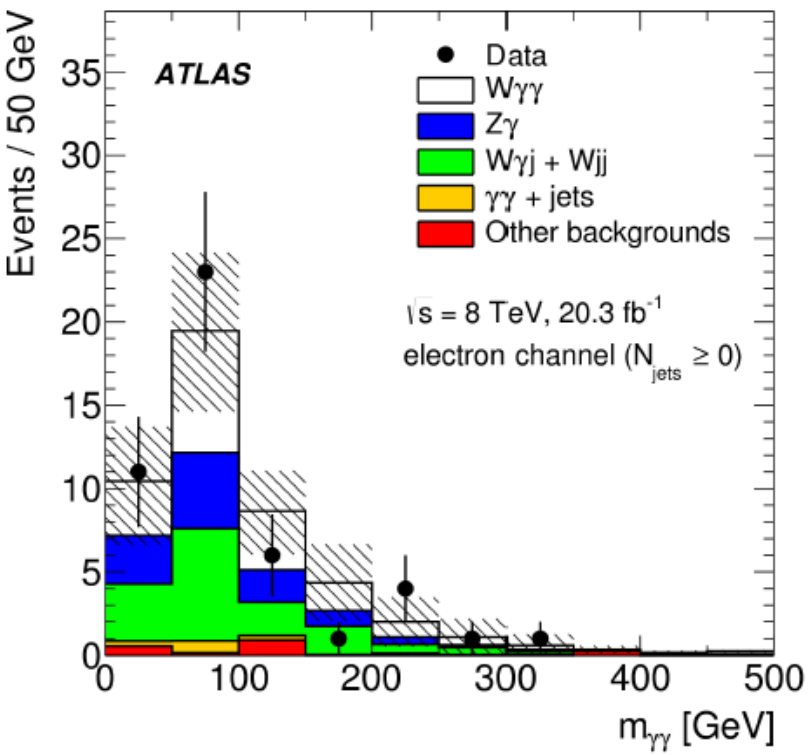
p_T of the leading tagging jet

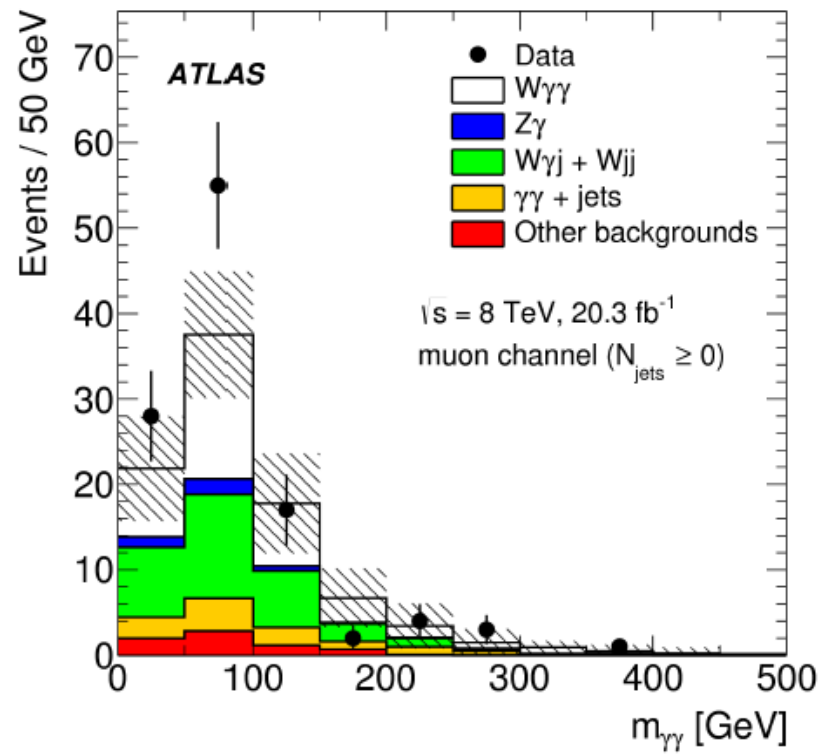


- K factor not constant over range of distribution
- $\rightarrow$ shape of distributions changes
- $\rightarrow$ simple rescaling with K factor not sufficient

ATLAS Wγγ evidence at 8 TeV (Kouskoura)

	Electron channel	Muon channel
Wγj + Wjj	$15.3 \pm 4.8_{(stat)} \pm 5.3_{(syst)}$	$30.5 \pm 7.7_{(stat)} \pm 6.8_{(syst)}$
γγ+jets	$1.5 \pm 0.6_{(stat)} \pm 1.0_{(syst)}$	$11.0 \pm 4.0_{(stat)} \pm 4.9_{(syst)}$
Total Background	$30.2 \pm 5.0_{(stat)} \pm 5.4_{(syst)}$	$52.1 \pm 8.9_{(stat)} \pm 8.4_{(syst)}$
Data	47	110





ATLAS Wγγ evidence at 8 TeV (Kouskoura)

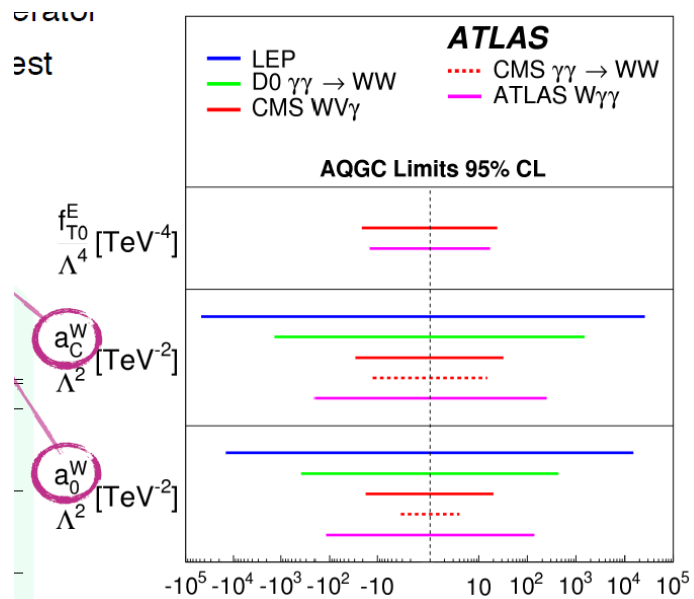
	σ^{fid}[fb]	σ^{MCFM}[fb]
μνγγ	$7.1^{+1.3}_{-1.2(stat)} \pm 1.5_{(syst)} \pm 0.2_{(lumi)}$	Inclusive
eνγγ	$4.3^{+1.8}_{-1.6(stat)}{}^{+1.9}_{-1.8(syst)} \pm 0.2_{(lumi)}$	2.90±0.16
ℓνγγ	$6.1^{+1.1}_{-1.0(stat)} \pm 1.2_{(syst)} \pm 0.2_{(lumi)}$	
μνγγ	$3.5 \pm 0.9_{(stat)}{}^{+1.1}_{-1.0(syst)} \pm 0.1_{(lumi)}$	Exclusive
eνγγ	$1.9^{+1.4}_{-1.1(stat)}{}^{+1.1}_{-1.2(syst)} \pm 0.1_{(lumi)}$	1.88±0.20
ℓνγγ	$2.9^{+0.8}_{-0.7(stat)}{}^{+1.0}_{-0.9(syst)} \pm 0.1_{(lumi)}$	

- ***dominant systematics*** on the measured cross section
  - 14% (incl.) and 23% (excl.) data-driven background estimate
  - 5% (incl.) and 7% (excl.) jet energy scale
  - 3% luminosity

3sigma first evidence for triboson production at LHC!

Observed xsec is 2sigma above NLO predictions

And also associated QGC constraints for high diphoton mass events, competitive with other channels



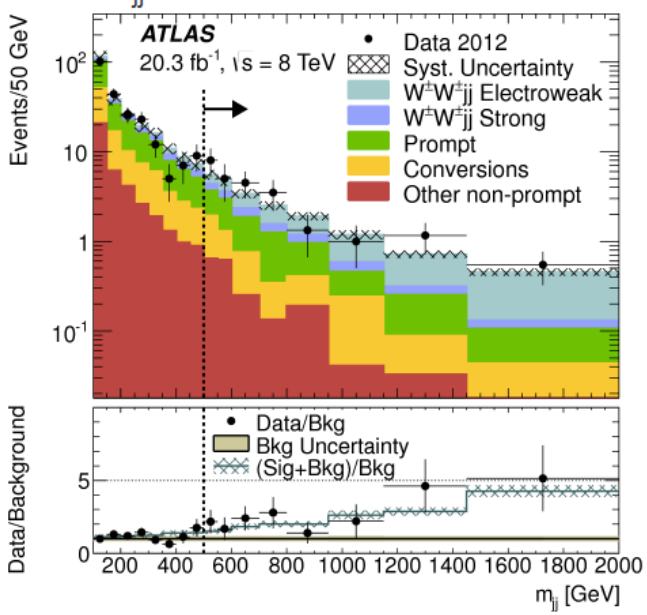
VBF/VBS/Triboson results (Liang)

First evidence for VBS process at the LHC

Electroweak $W^{\pm}W^{\pm}jj$ (ATLAS)

Inclusive QCD+EWK $W^{\pm}W^{\pm}jj$ measurement

- ❑ M_{ll}>20GeV
- ❑ $|M_{ee}-M_Z|$>10GeV
- ❑ M_{jj}>150GeV



Measured $\sigma_{EW+QCD}(W^{\pm}W^{\pm}jj)$=2.1 ± 0.5(stat) ± 0.3(syst) fb
Predicted $\sigma_{EW+QCD}(W^{\pm}W^{\pm}jj)$=1.52 ± 0.11fb
Observed with 4.5σ

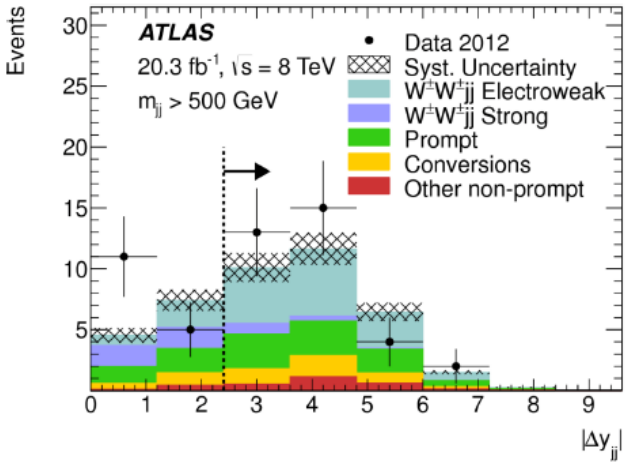
Object selection

- ❑ same sign di-leptons
- ❑ $p_{T,l}$>25 GeV
- ❑ Two high pT jets

EWK signal only measurement

- ❑ M_{ll}>20GeV
- ❑ $|M_{ee}-M_Z|$>10GeV
- ❑ M_{jj}>500 GeV
- ❑ $|\Delta\eta_{jj}|$ >2.4

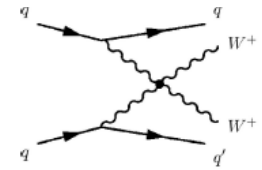
Measured $\sigma_{EW}(W^{\pm}W^{\pm}jj)$=1.3 ± 0.4(stat) ± 0.2(syst) fb
Predicted $\sigma_{EW}(W^{\pm}W^{\pm}jj)$=0.95 ± 0.06 fb
Observed with 3.6σ



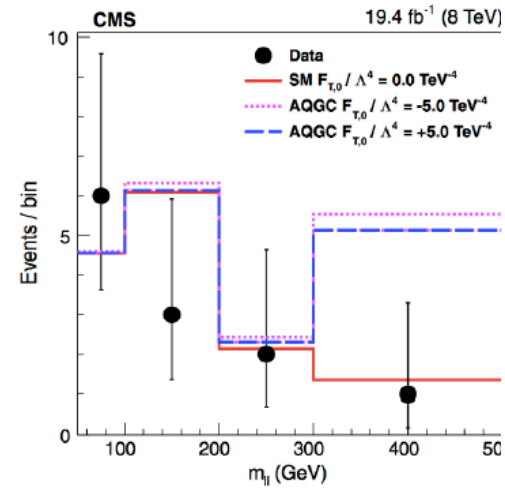
VBF/VBS/Triboson results (Liang)

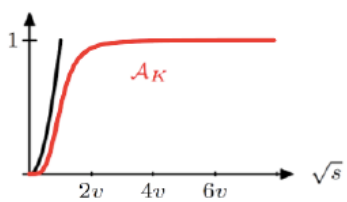
QGC limits probing 4W for the first time

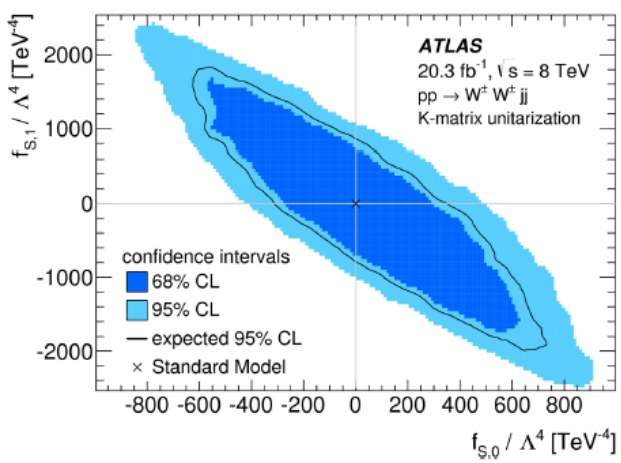
aQGCs limits from VBS process

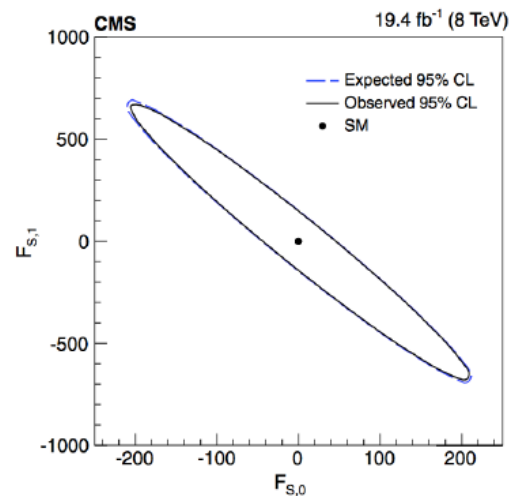


- FS0 and FS1 in Dim 8 EFT model is related to the Higgs field
- Naive EFT-predicted aTGC/aQGCs amplitudes
  - disrespect the gauge symmetry
  - and violate the unitarity once the √s goes sufficiently
- CMS result is not unitarized
- ATLAS use K matrix unitarization
  - Preserve unitarity in high sqrt(s)
  - Unitarization with the k-matrix approach (arxiv: 0806.4145)
  - K-matrix amplitude $|\mathcal{A}_K(s)|^2 \xrightarrow{s\to\infty} 1$









Some perspective: Seven predictive slogans I made in May 2012

- The best QCD is electroweak
- Putting nu out of business
- Your weak corrections are too strong
- Size 6 is the new size 4
- Some of my best friends are dijets
- You can tri it now
- Party like it's 1989

Some perspective: Seven predictive slogans I made in May 2012

- The best QCD is electroweak. Truer than ever, but not a very bold prediction.
- Putting nu out of business. Still potentially possible, but need progress in V+HF theory and experiment.
- Your weak corrections are too strong. Was not crucial at 8 TeV; almost certainly so at 13 TeV.
- Size 6 is the new size 4; Got our first glimpse with W+W+jj!
- Some of my best friends are dijets; lnujj important ingredient for TGC limits
- You can tri it now; Benvenuto W$\gamma\gamma$!
- Party like it's 1989; have not yet been able to fully exploit precision electroweak data

Questions and outlook

To what extent errors on precision electroweak measurements at LHC (MW, sin2thetaW) can be improved by theory or experiment (PDFs)

What are the next steps in VV/V+jets to improve agreement with data? NLO EWK? NNLO? NNLO+PS? What are the most urgent measurements needed to validate these technologies?

What is the right EFT basis going forward for dim6 operators?
Are POs even feasible here?
How can we best account for the effects of NLO EWK in the tails we seek anomalous TGCs?

VBF and VBS predictions are now being confronted with real data. What is the next step to test them beyond signal strength?
Is there any meaning to the dim8 EFT we use to benchmark VBS? Would simplified new particle models be better?