Inclusive production of top quarks and W/Z bosons with jets at the LHC

Chunhui Chen
Iowa State University
On behalf of the ATLAS and CMS Collaboration

Rencontres du Vietnam 2014:
Physics at LHC and beyond
Quy-Nhon, Vietnam
August 10-17, 2014

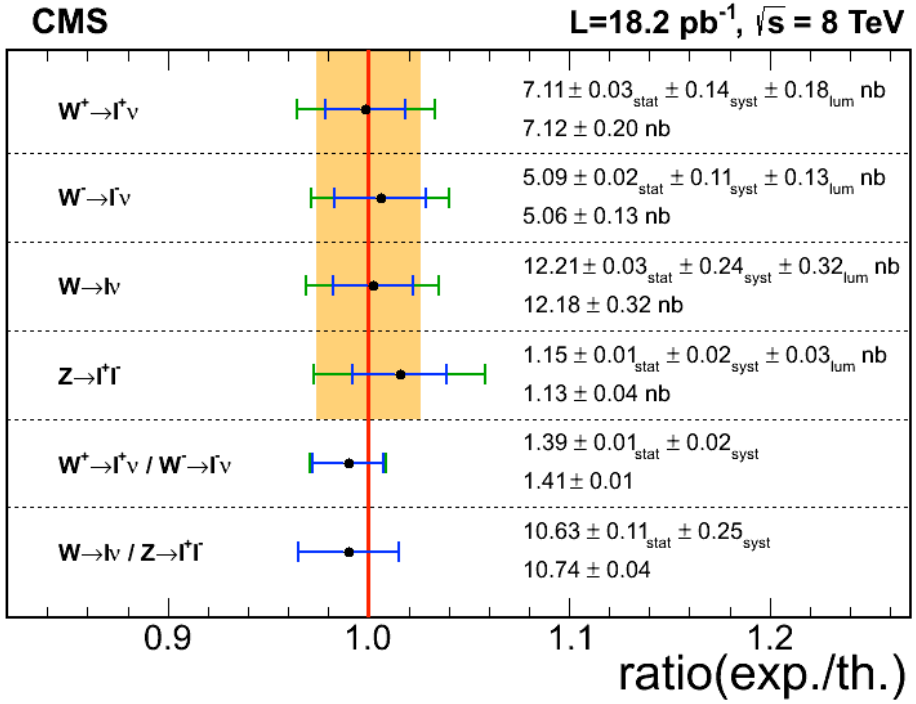
Outline

- Production of W/Z at LHC at 7 (~5fb^{-1}) and 8 TeV (~20fb^{-1})
  - ✓ Inclusive W/Z production
  - ✓ Production of W/Z + jets
  - ✓ Production of W/Z + heavy flavor
  - ✓ Other selected topics
- Top production at LHC at 7 and 8 TeV
  - ✓ Top pair production
  - ✓ Top pair production + jets, heavy flavors, W/Z bosons
  - ✓ Single top production
- Emphasis on most recent measurements
  - ✓ Some (many) measurements are not covered:
    - EW production of Z, high mass DY production etc
  - ✓ Very little experimental analysis details

W/Z production at LHC

Inclusive W/Z production at LHC

- Precision physics to test standard model (SM)
  - ✓ W/Z productions are theoretically well understood, Constrain Parton density function (PDF)
- Benchmark process for detector calibration
  - ✓ Clean final states with leptons at LHC environment: Trigger, identification and resolution
- They are important background in searches of new physics (NP)



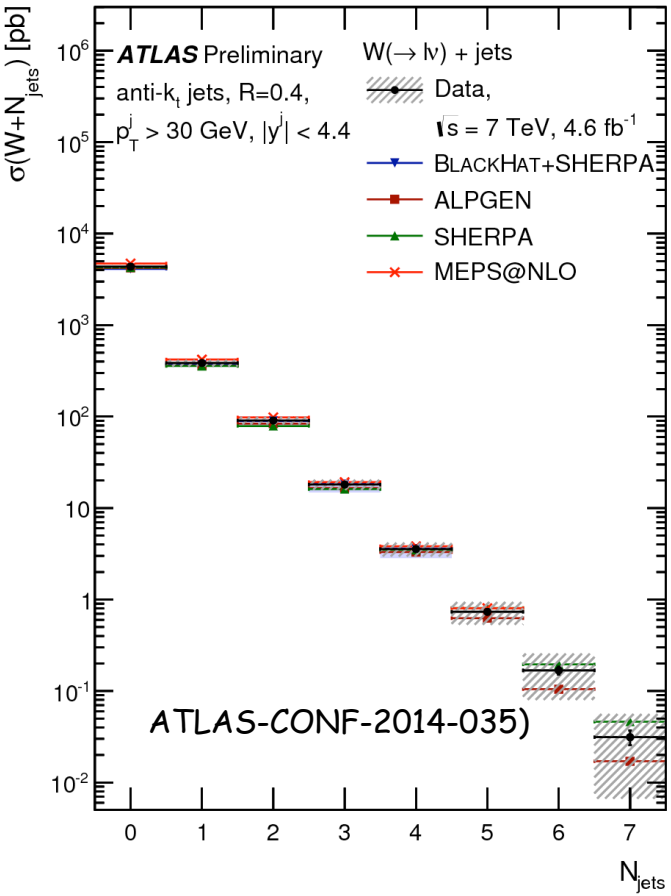
- Measurements at both 7 & 8TeV by LHC
- Many possible final states
  - ✓ Best to use leptonic final states
- Studies of kinematic distribution:
  - ✓ rapidity, MET …

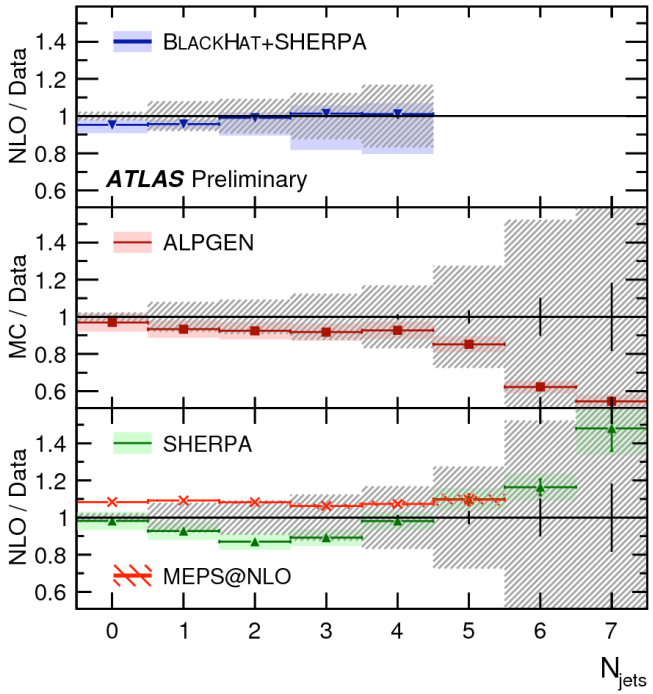
ATLAS, PRD,85,072004(2012)
CMS, JHEP,10,132(2011)
CMS, PRL,112,191802(2014)

- Stat uncertainties smaller than sys uncertainties
  - ✓ Sys error at percent level, dominated by luminosity uncertainty (~2-3%)
- Good agreement between electron and muon channels
- Good agreement between data and NNLO theoretical prediction

W/Z + jets production at LHC

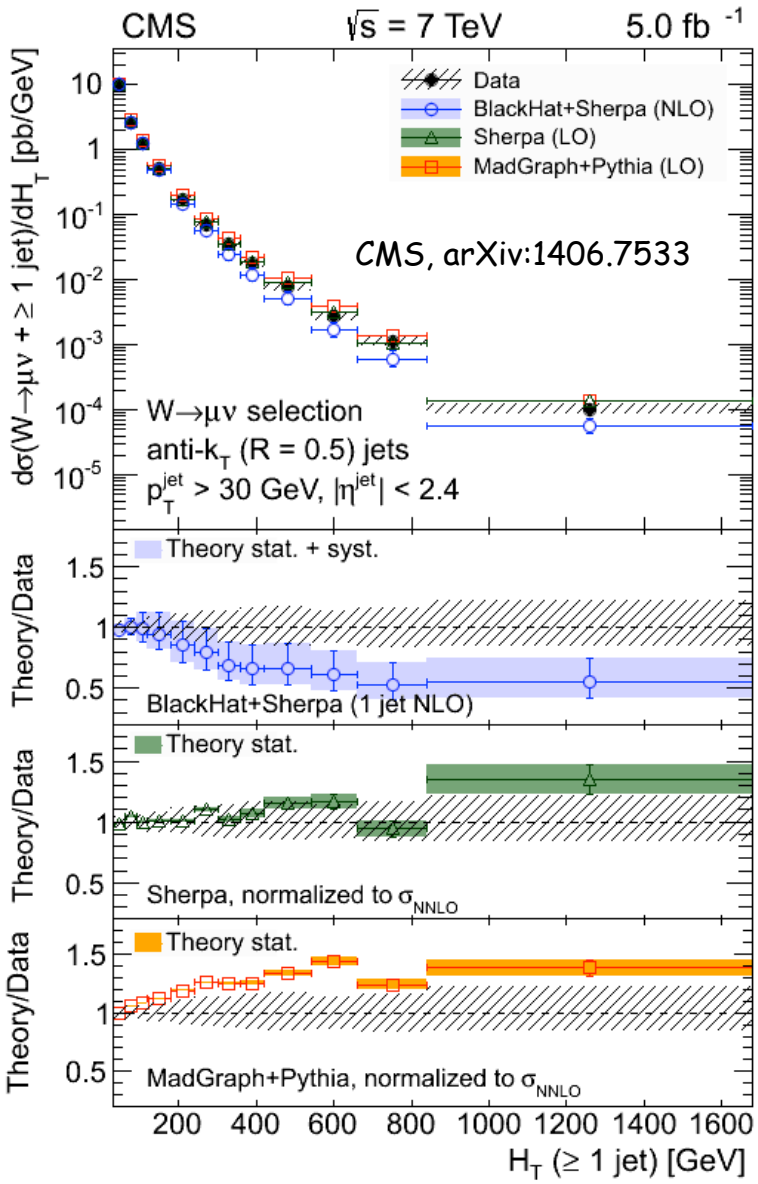
- Similar analysis as inclusive W/Z production with an additional jet requirement
  - ✓ Different jet cone size between ATLAS (0.4) and CMS (0.5)
- Detailed comparison on a high statistics sample and in a large kinematics range
  - ✓ precious information to validate/tune the predictions.
  - ✓ Tested variables: 1st , 2nd, 3rd 4th-leading jet p_T and η, H_T, S_T (Sum p_T including or not lepton and neutrino), angular separation of jets, invariant mass of lead-subleading jets. Inclusive and exclusive distributions…

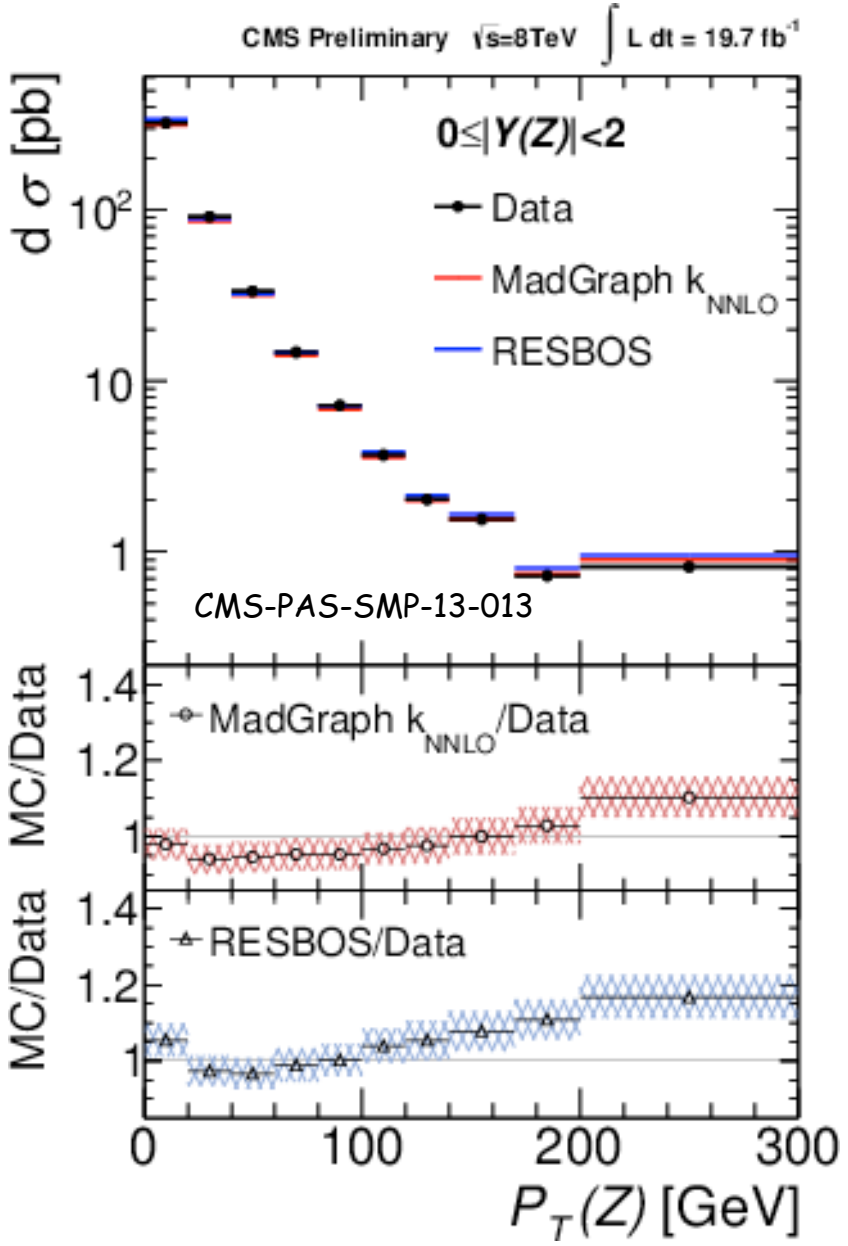




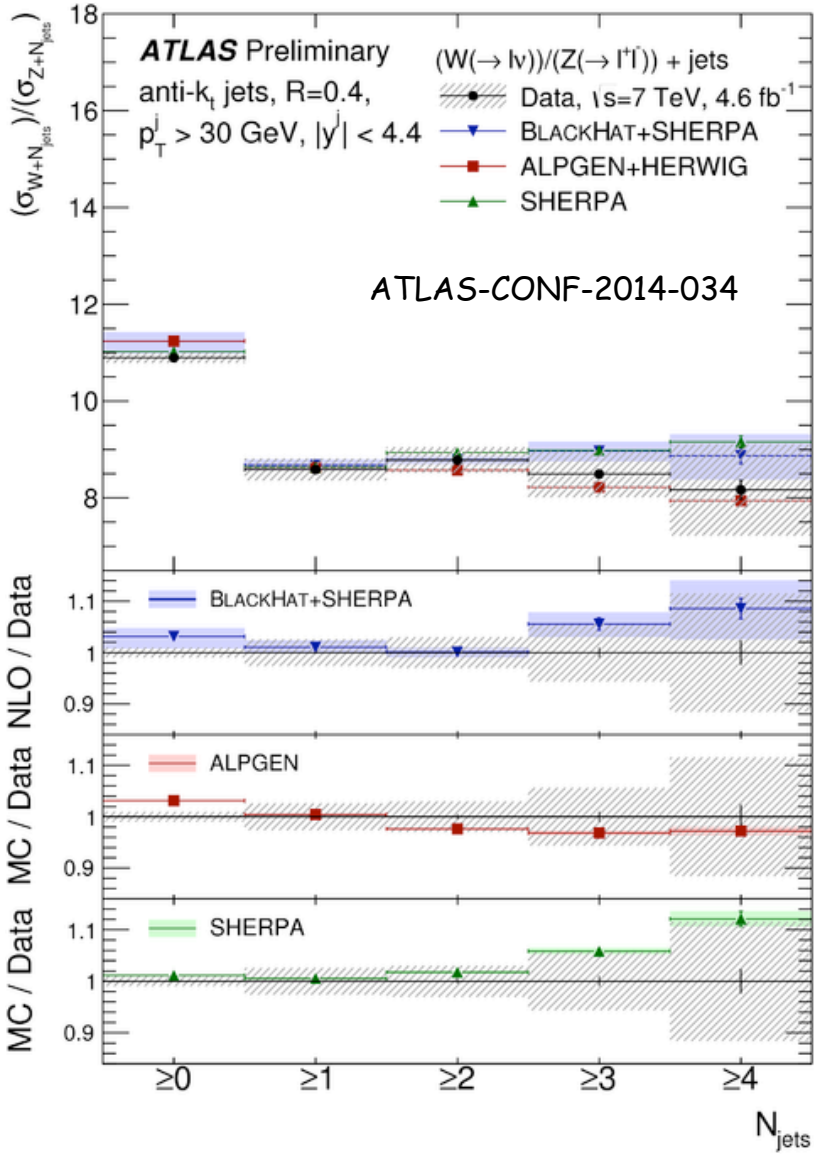
Jet multiplicity well reproduced up to ≥7 jets on 5 order of magnitudes !.

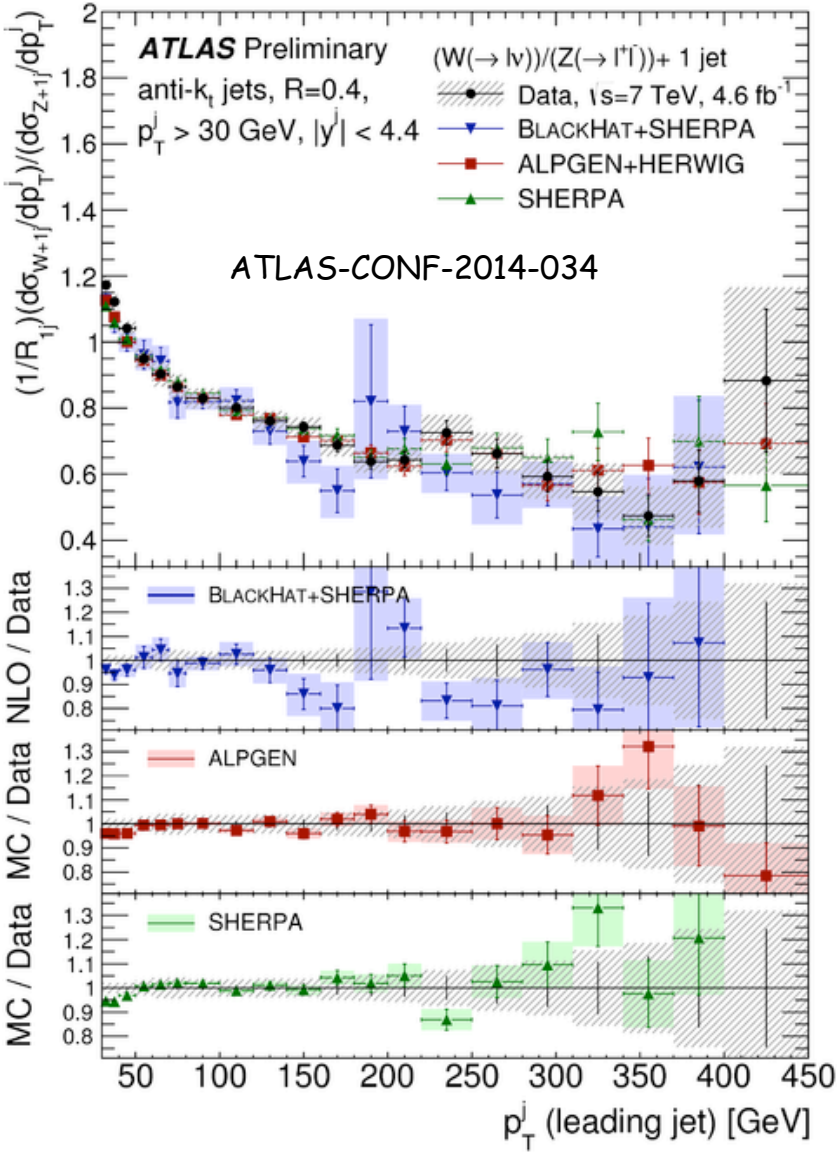
W/Z + jets production at LHC





W/Z + jets production ratio at LHC





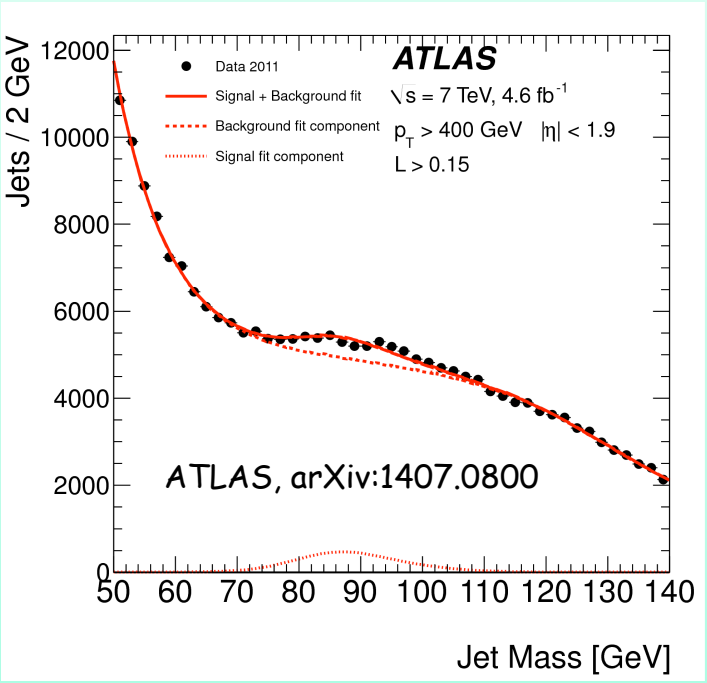
Ratio measurement allows to reduce experimental sys error

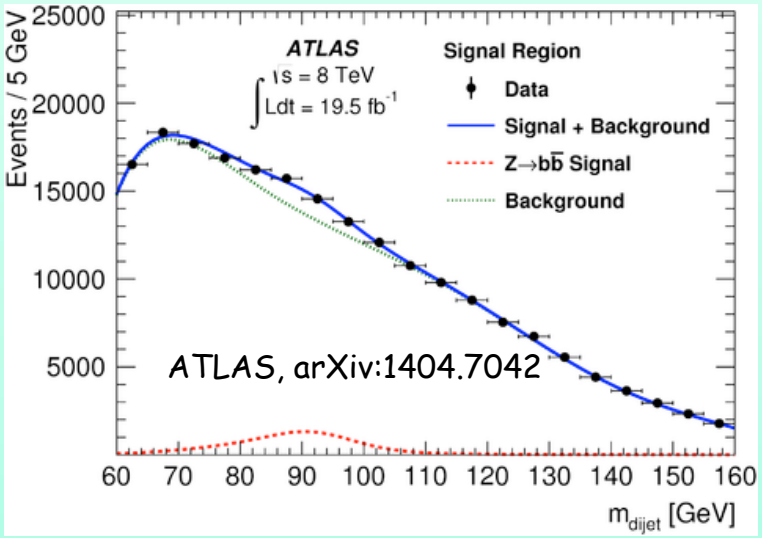
Production of high p_T hadronic W/Z

- High p_T hadronic W/Z production cross section (7TeV)
  - ✓ Reconstruct hadronic product inside single jets & identify signal using jet mass
  - ✓ Suppress multijet production using jet substructure in jet rest frame: PRD 85(2012),034007

$$\sigma_{W+Z} = 8.5 \pm 0.8\ (\text{stat.}) \pm 1.5\ (\text{syst.})\ \text{pb}$$

5.1±0.5 pb (MCFM)





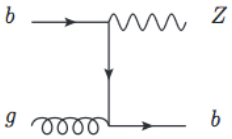
- Z->bbbar cross section (8TeV)
  - ✓ Combine 2 b-tagging jets to form a Z candidate with p_T>200GeV
  - ✓ Separate signal and background using a Neutral Network analysis

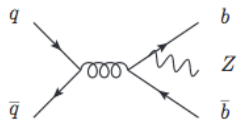
$$\sigma^{\text{fid}}_{Z\to b\bar{b}} = 2.02 \pm 0.20\ (\text{stat.}) \pm 0.25\ (\text{syst.}) \pm 0.06\ (\text{lumi.})\ \text{pb} = 2.02 \pm 0.33\ \text{pb}$$

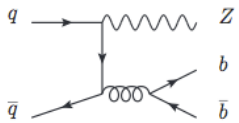
$$\text{POWHEG}: \quad \sigma^{\text{fid}}_{Z\to b\bar{b}} = 2.02\ ^{+0.25}_{-0.19}(\text{scales})\ ^{+0.03}_{-0.04}(\text{PDF})\ \text{pb}$$

$$\text{aMC@NLO}: \quad \sigma^{\text{fid}}_{Z\to b\bar{b}} = 1.98\ ^{+0.16}_{-0.08}(\text{scales}) \pm 0.03(\text{PDF})\ \text{pb}$$

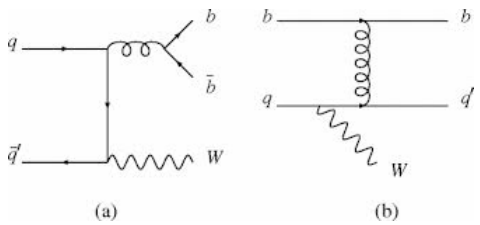
W/Z + b(b) production at LHC



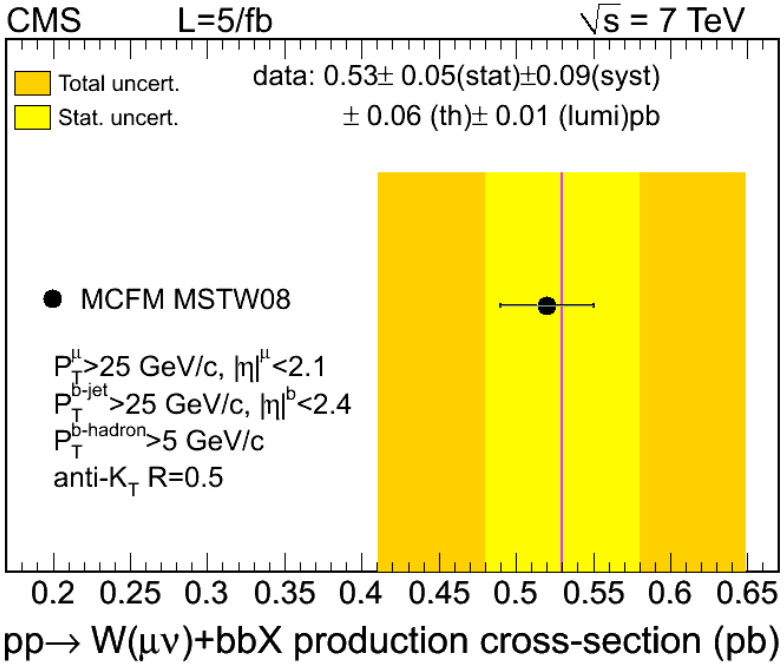


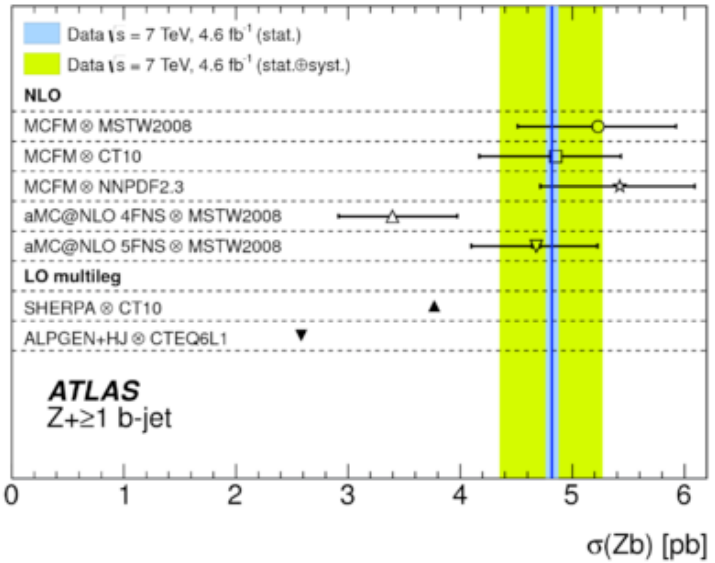


- Measurement done with 7TeV data
- Signal extracted by fitting flavor-sensitive variables:
  - ✓ NN output, secondary vertex mass
- Differential measurement available
- Measurement consistent with theory
  - ✓ Still large experimental uncertainty
    - b-jet tagging efficiency, b-jet template shape

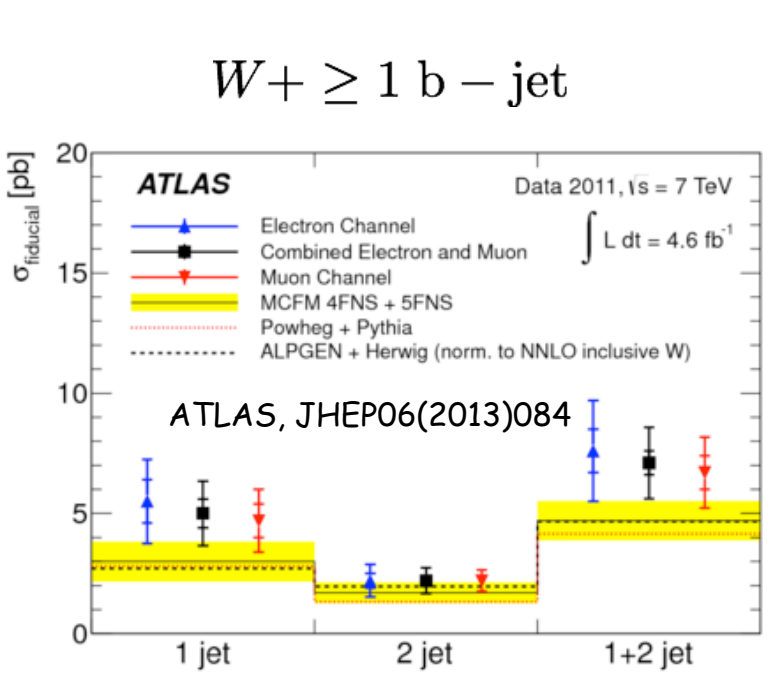


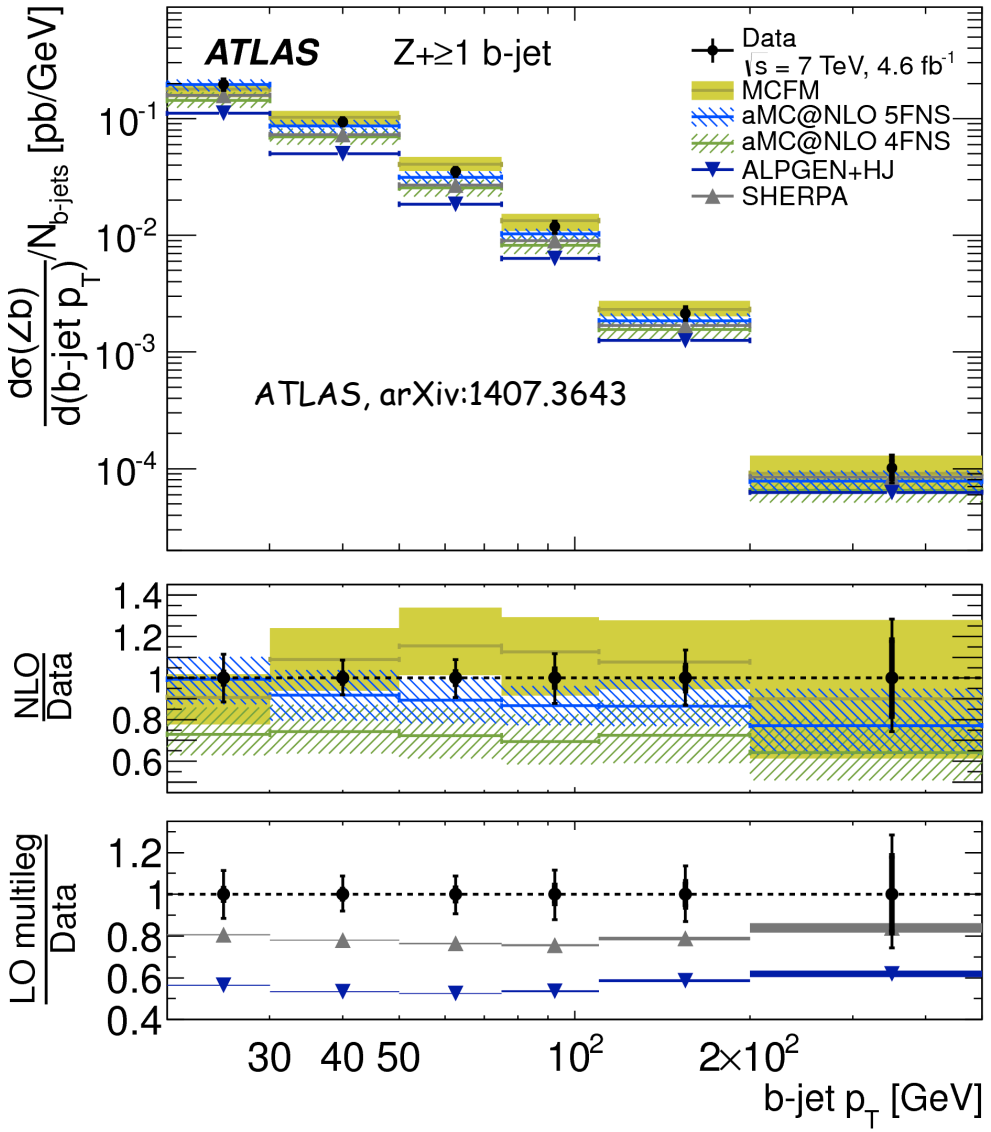
ATLAS, arXiv:1407.3643
ATLAS, JHEP06(2013)084
CMS, arXiv:1312.6608





W/Z + b(b) production at LHC

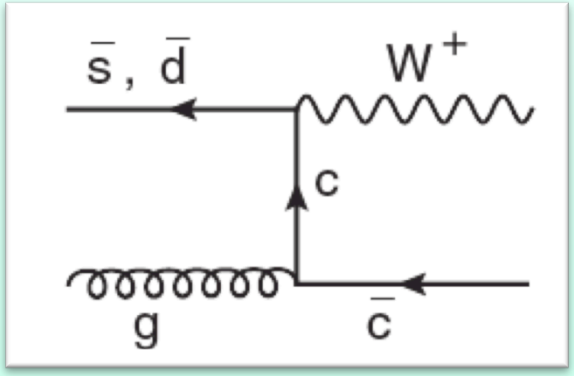


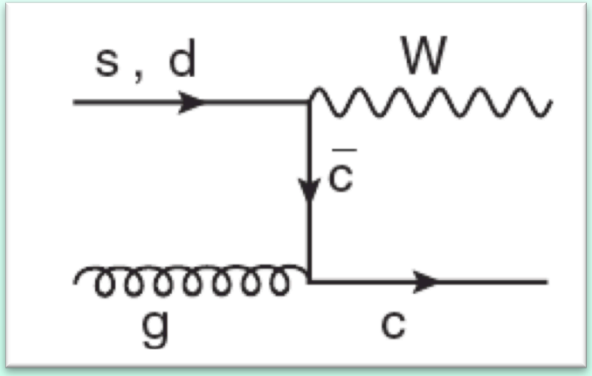


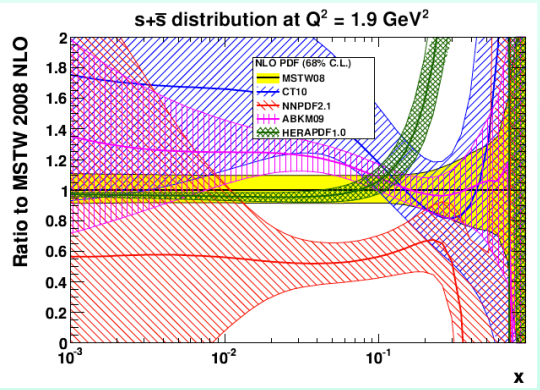
Other measurements:
ATLAS, arXiv:1407.3643
ATLAS, JHEP06(2013)084
CMS, arXiv:1312.6608
CMS, JHEP06(2014)120
CMS, JHEP12(2013)39

W + charm production at LHC

- W boson production associated with single charm: scattering of gluon and a down type quark (LO)







- Directly sensitive to s quark distribution in PDF
  - ✓ Contribution from d quark ~ 10% (Cabbibo suppressed)
  - ✓ Different PDF assume different s quark suppression with respect to d quark

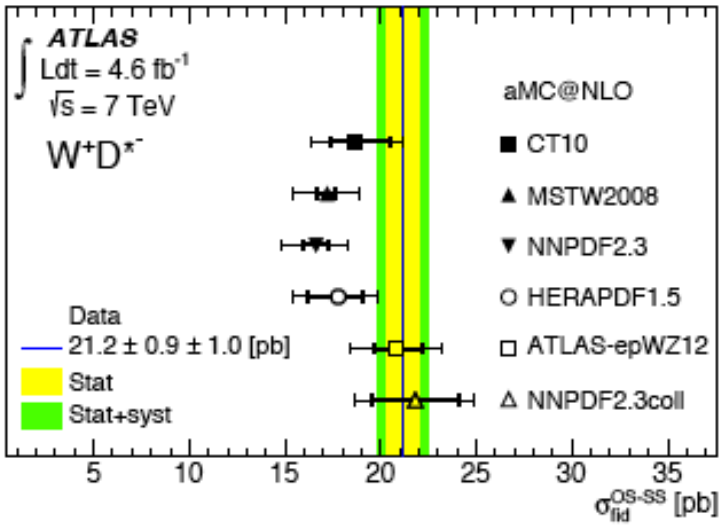
- Signal reconstruction
  - ✓ Similar W reconstruction as other analysis
  - ✓ Reconstruction of charm meson in D^{*+} and D^+ modes

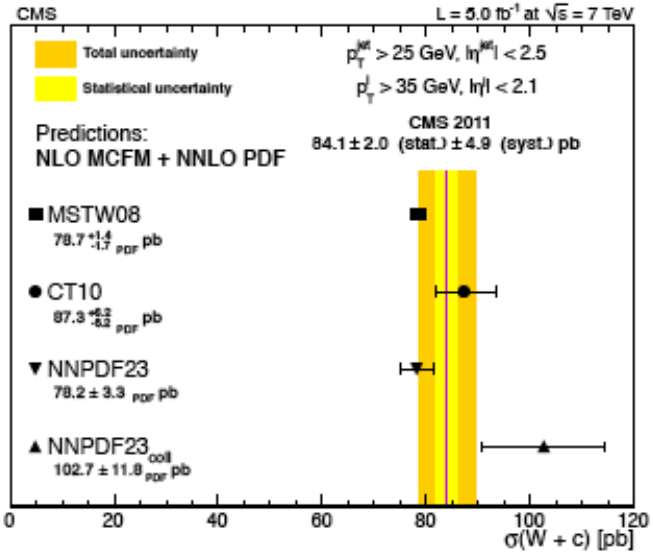
$$D^{*+} \to D^0\pi^+(D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^-\pi^+) \text{ and } D^+ \to K^-\pi^+\pi^+$$

  - ✓ Identify c-jet using soft (low p_T) muon tagging inside jets
  - ✓ Select signal as opposite (OS) – same (SS) sign
    - Automatically subtract Wcc and Wbb background
    - Cancel combinatorial background

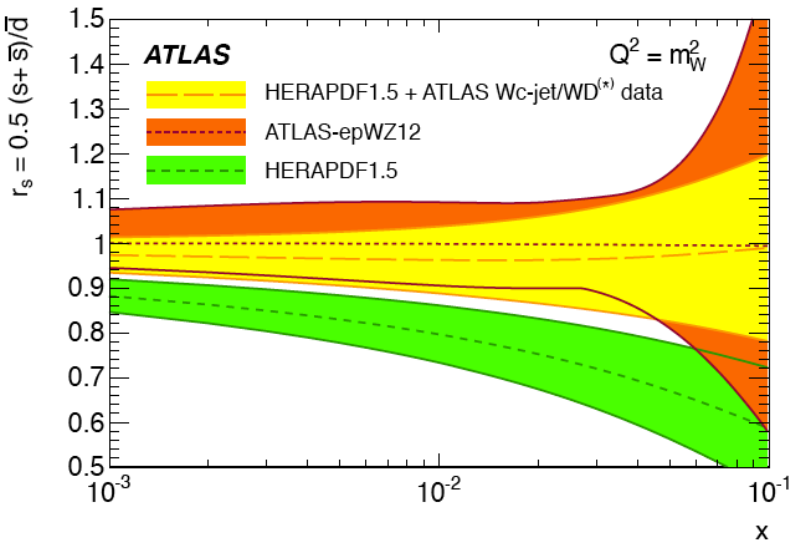
ATLAS, JHEP05(2014)068
CMS, JHEP02(2014)013

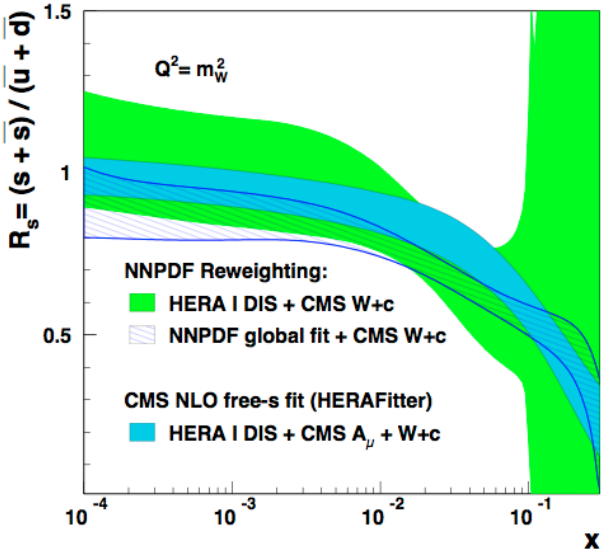
W + charm production at LHC





Fit s-quark PDF: HERAPDF including W+c data





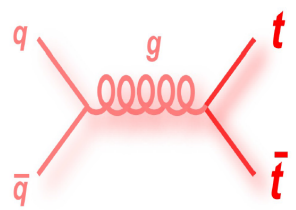
ATLAS, JHEP05(2014)068
CMS, JHEP02(2014)013

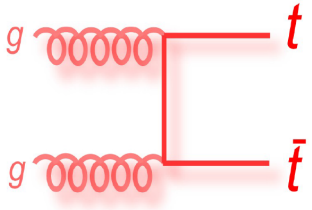
Top production at LHC

Top pair production

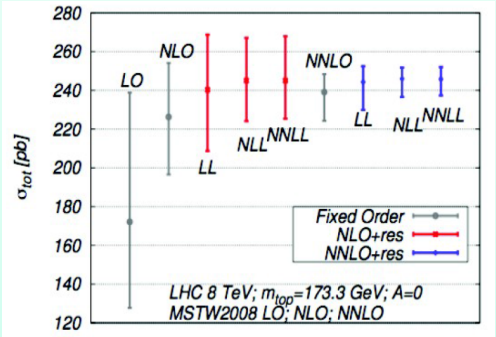
- Large top quark production at LHC:

Example diagrams:

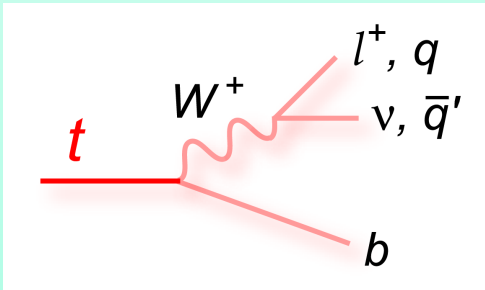


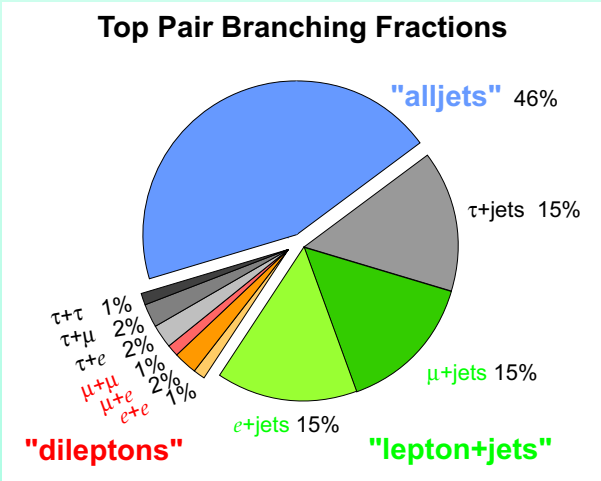


	σ_{gg}/σ_{tot}
Tevatron	$\approx 15\%$
LHC 7 TeV	$\approx 85\%$
LHC 14 TeV	$\approx 90\%$



- Precision test of QCD calculation
  - ✓ Improved theoretical calculation: NLO to NNLO+NNLL QCD
  - ✓ Less than 10% uncertainty for cross section (~3% from scale & ~5% from PDF)
    - Eg: arXiv:1303.6254, 1303.7215
- Important data sample for detector calibration
- Crucial SM background in many NP searches

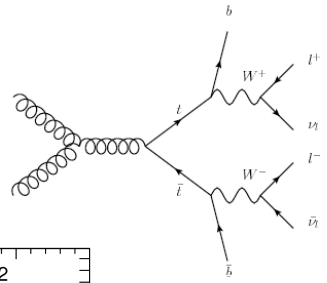




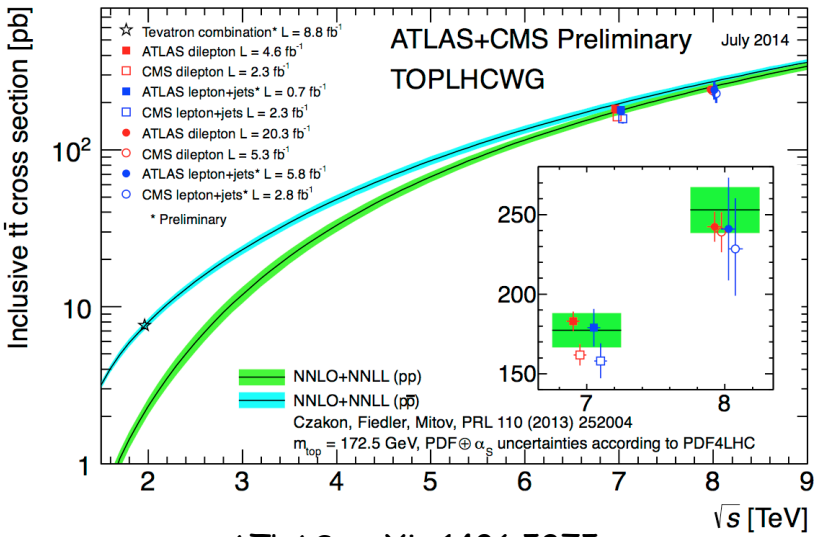
- Top pair signature (based on W decay):
  - ✓ Dileptons: Low branching ratio (Br) and low background (Bg)
  - ✓ Lepton+jet: compromise between Br and Background
  - ✓ All jets: High Br and Background
  - ✓ Others: tau final states

Top pair production

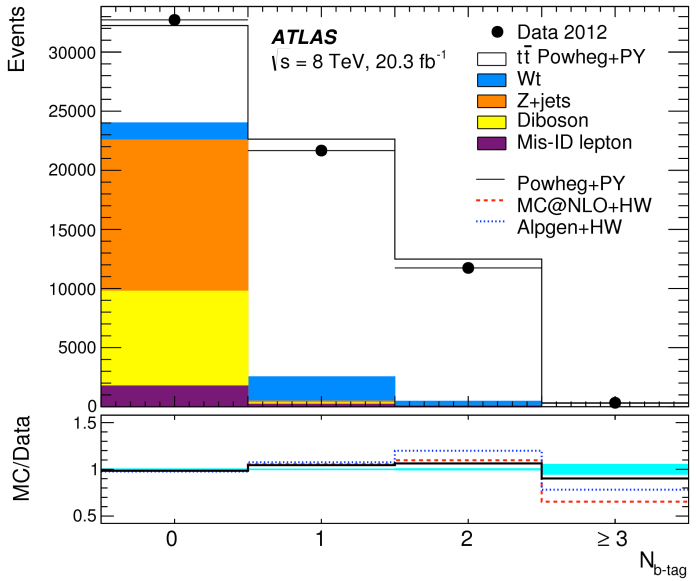
- Dilepton final state: best channel to measure top pair cross section
  - ✓ 2 isolated high pT lepton and large missing ET
  - ✓ Counting b jets to determine the cross section
    - Fit b jet efficiency with the cross section



	7TeV		8TeV	
Error	ATLAS	CMS	ATLAS	CMS
Total	3.5%	4.2%	4.5%	5.5%
Stat	1.7%	1.5%	0.7%	0.8%
Sys	2.3%	3.2%	2.3%	4.7%
Lumi	2.0%	2.2%	3.1%	2.6%



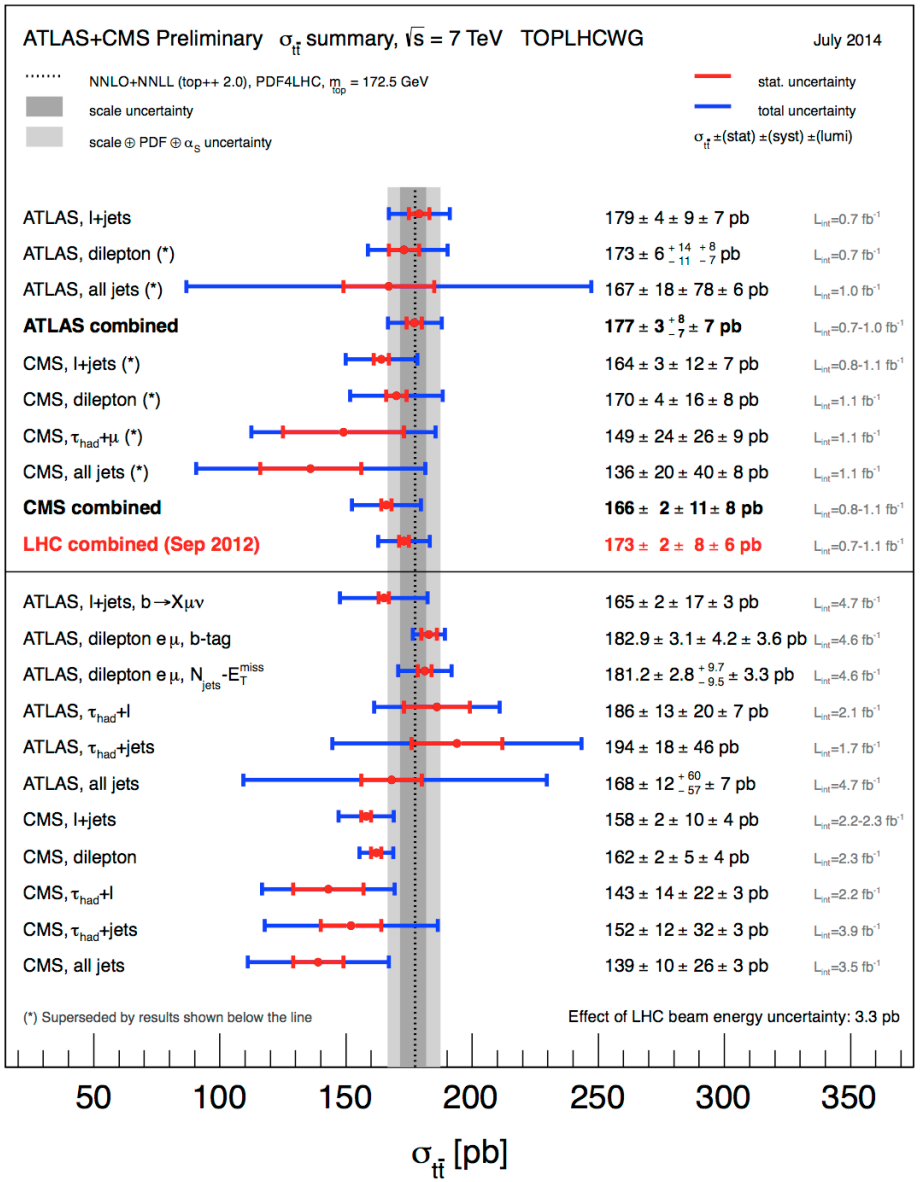
ATLAS, arXiv:1406.5375
CMS, JHEP02(2014)024
CMS, JHEP11(2012)067

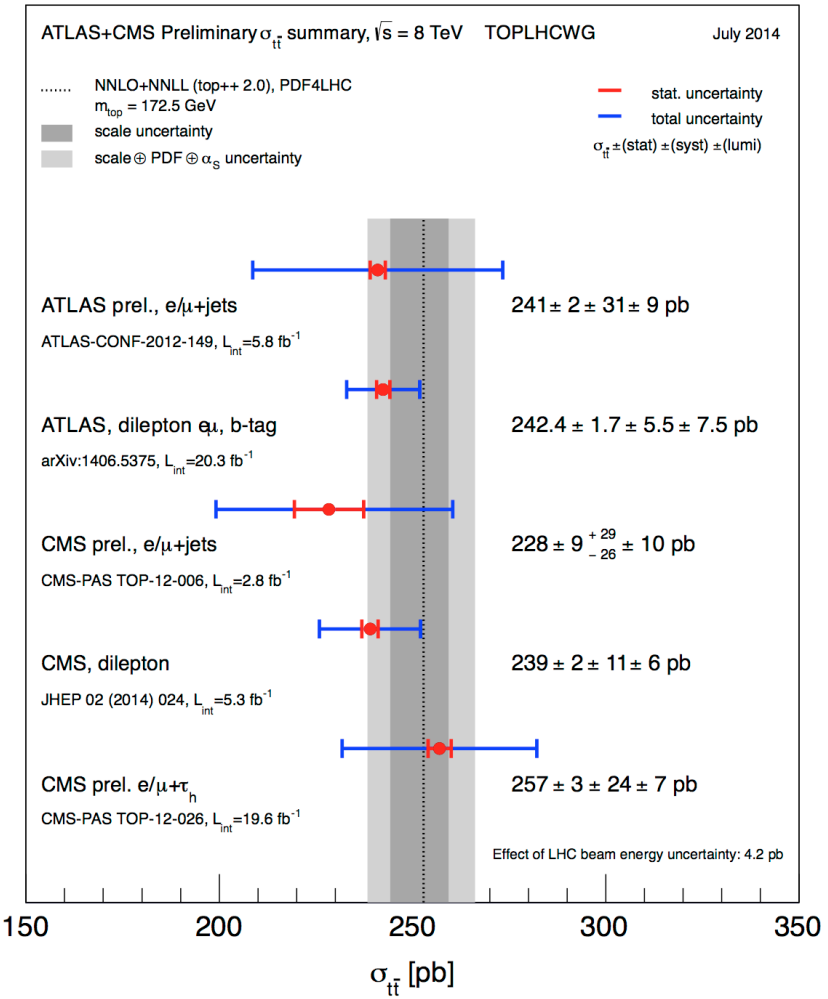


$$N_1 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu} 2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\mathrm{bkg}}$$
$$N_2 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu} C_b{\epsilon_b}^2 + N_2^{\mathrm{bkg}}$$

- Measurement in good agreement with prediction
- Data/MC consider LHC beam energy uncertainty
  - ✓ 1.8% error for cross section
- ATLAS and CMS results at 7TeV ~ 2σ tension

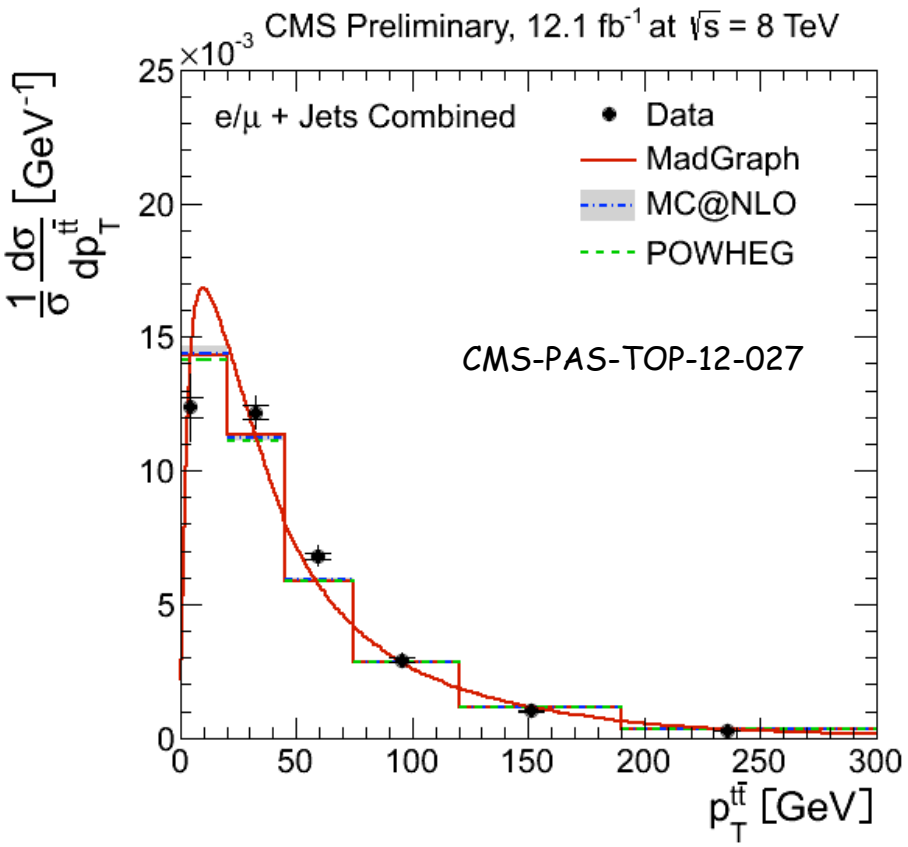
Top pair production

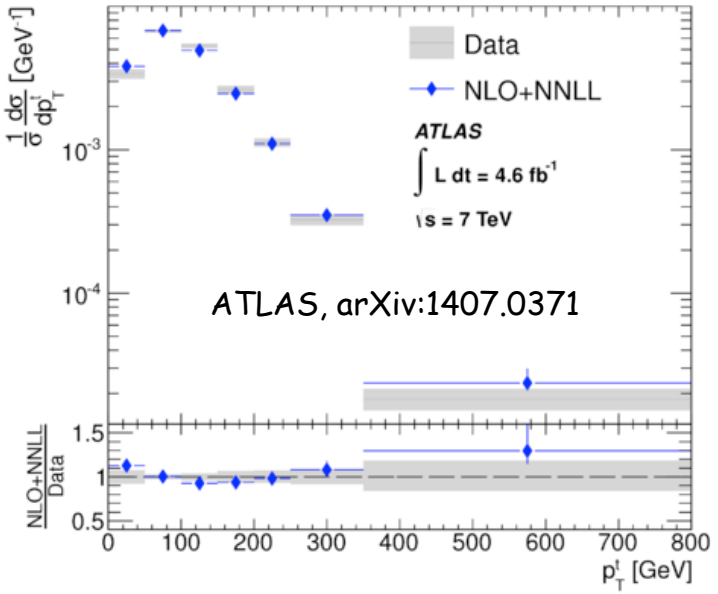


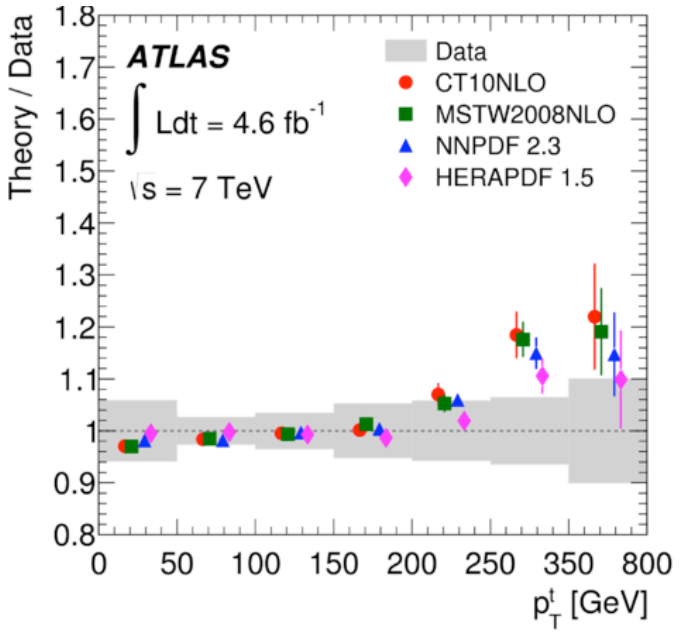


Differential top pair production

- Lepton + jet final state: full reco. of both tops
  - ✓ Kinematic variables: top p_T, top pairs system (total mass, average p_T & rapidity)



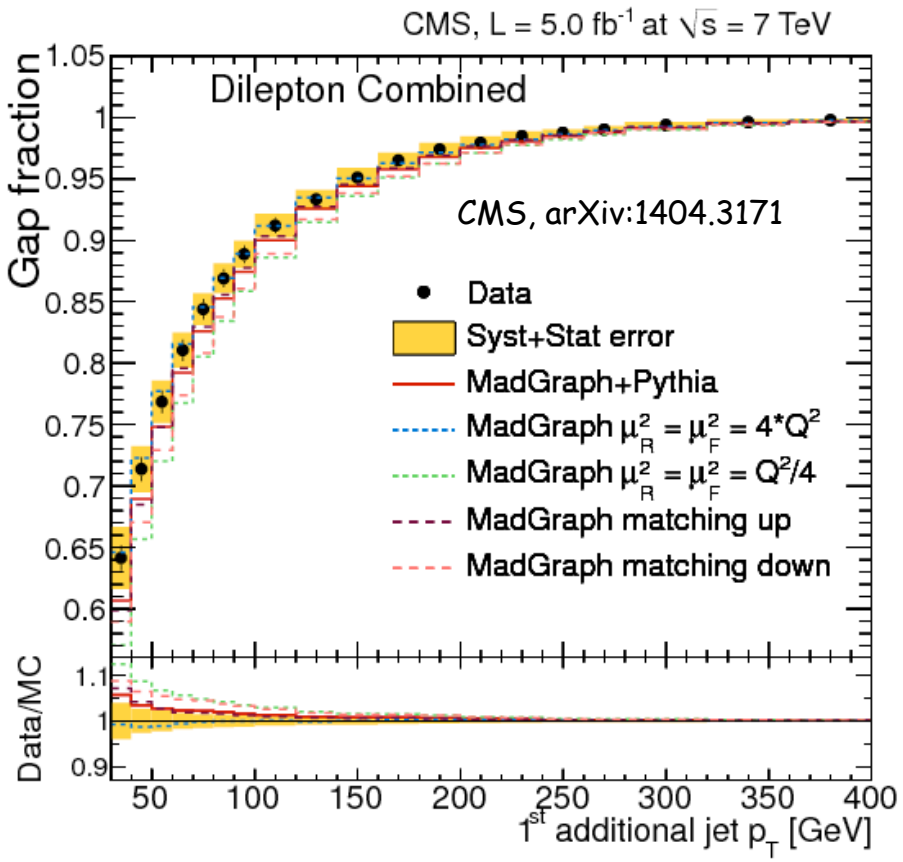


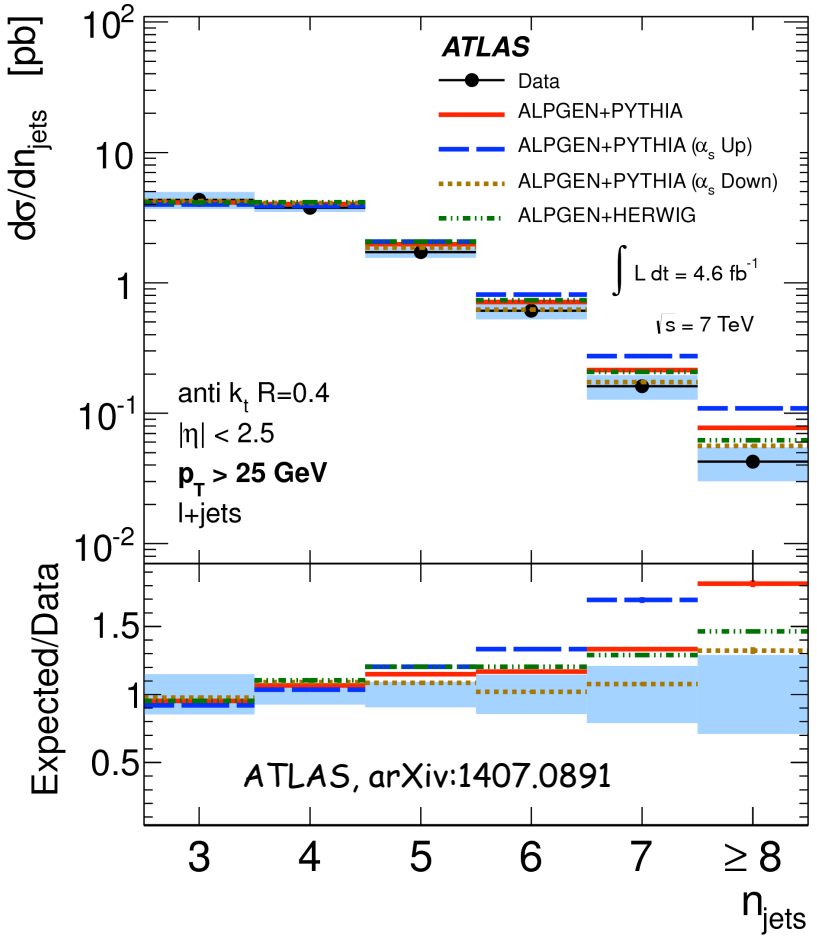


Good data/MC agreement at low p_T
Both ATLAS & CMS data lower than NLO QCD prediction at high p_T

Top pair + jets production

- Dilepton or lepton+jet final state: select 2 b-jets and count additional jets
  - ✓ Measure gap fraction: prob. to emit no additional jet
  - ✓ ATLAS and CMS use the results to constrain top mass sys error due to radiation





Top pair + HF / Top pair + W/Z

- Measure top pair + HF (b or c) production
  - ✓ Dilepton final state: Select 2 b-jets and examine additional jet
  - ✓ ATLAS: 7TeV with 4.7fb^{-1} data
    - Prediction: 3.4% (5.2%) by ALPGEN+HERWIG (POWHEG+HERWIG)

$$R_{\mathrm{HF}} = \frac{\sigma_{\mathrm{fid}}(t\bar{t}+\mathrm{HF})}{\sigma_{\mathrm{fid}}(t\bar{t}+\mathrm{j})} = 6.2 \pm 1.1(\mathrm{stat}) \pm 1.8(\mathrm{syst})\%$$

  - ✓ CMS: 7TeV with 5fb^{-1} and 8TeV with 19.6fb^{-1} data:

$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 3.6 \pm 1.1(\mathrm{stat.}) \pm 0.9(\mathrm{syst.})\% \quad (7\mathrm{TeV})$$
$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 2.3 \pm 0.3(\mathrm{stat.}) \pm 0.5(\mathrm{syst.})\% \quad (8\mathrm{TeV})$$

ATLAS, PRD89,072012(2014)
CMS, TOP-PAS-12-024
CMS, TOP-PAS-13-010

- Measure top pair + W/Z: X section ~200fb (NLO QCD)
  - ✓ Sensitive to additional contribution from NP effects
  - ✓ Experimental signature:
    - CMS : 2 SS leptons, 3 leptons, 4 leptons (counting)
    - ATLAS: 2 OS leptons (NN based on kinematics), 2 SS muons, 3 leptons (counting)

CMS 7 TeV PRL 110 (2013) 172002

Channels used	Process	Cross section	Significance
2ℓ	$t\bar{t}V$	430^{+170}_{-150} (stat.) $\pm^{90}_{70}$ (syst.) fb	3.0
3ℓ	$t\bar{t}Z$	280^{+140}_{-110} (stat.)$^{+60}_{-30}$ (syst.) fb	3.3

CMS 8 TeV arXiv:1406.7830

Channels used	Process	Cross section	Significance
2ℓ	$t\bar{t}W$	170^{+90}_{-80} (stat) $\pm$ 70 (syst) fb	1.6
3ℓ+4ℓ	$t\bar{t}Z$	200^{+80}_{-70} (stat)$^{+40}_{-30}$ (syst) fb	3.1
2ℓ+3ℓ+4ℓ	$t\bar{t}W + t\bar{t}Z$	380^{+100}_{-90} (stat)$^{+80}_{-70}$ (syst) fb	3.7

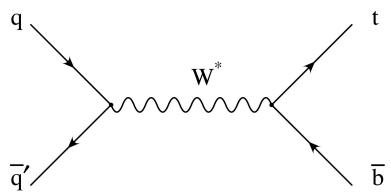
ATLAS-CONF-2014-038

Summary of combined simultaneous fit results

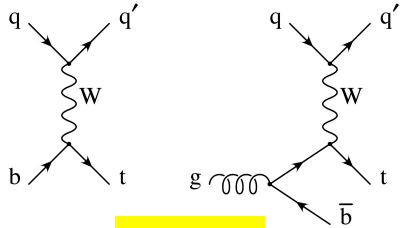
Process	Measured cross-sections	Observed σ
$t\bar{t}Z$	150^{+58}_{-54}(total) = 150^{+55}_{-50}(stat.) $\pm$ 21(syst.) fb	3.1
$t\bar{t}W$	300^{+140}_{-110}(total) = 300^{+120}_{-100}(stat.)$^{+70}_{-40}$(syst.) fb	3.1

Evidence of top pair production associated with W/Z on 3σ level, cross section consistent with SM Expectation.

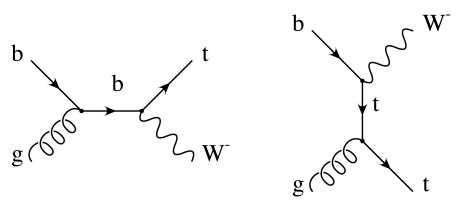
Single top production



s-channel

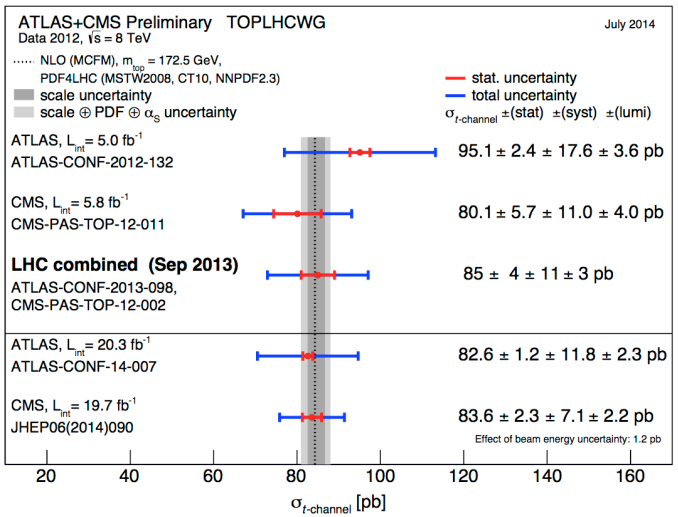


t-channel



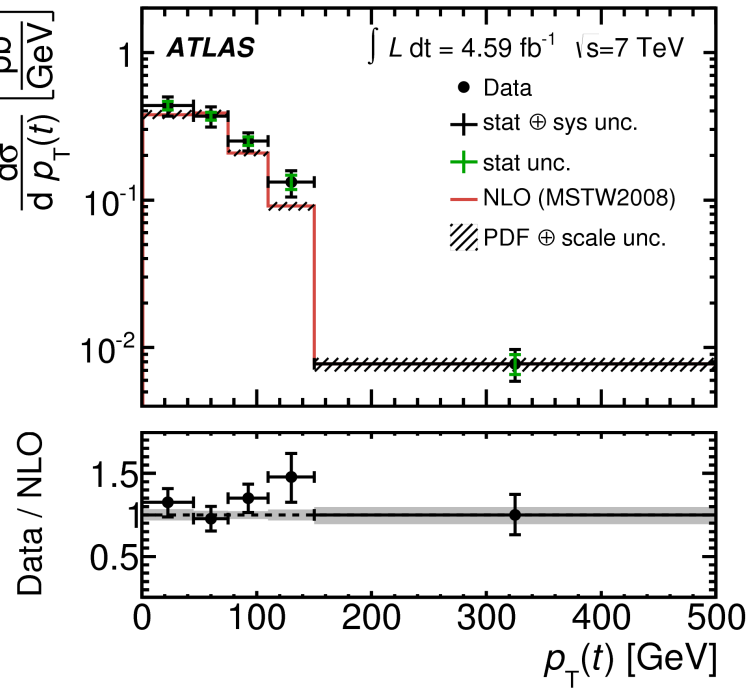
Wt-channel

- t-channel: high statistics at LHC
  - ✓ S/B ~ 2 after selection, precision measurement
  - ✓ Study kinematics distribution: p_T, rapidity
  - ✓ Top and anti-top measurement separately
  - ✓ Good agreement between data and theory



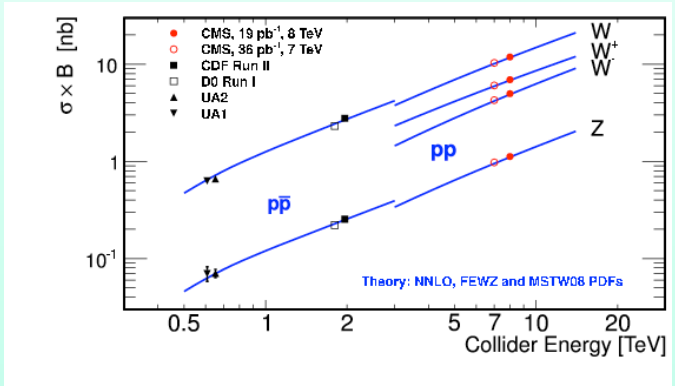
- Wt-channel: Evidence at 7TeV, observation at 8TeV
- s-channel: no evidence yet at LHC (set upper limit)

ATLAS, arXiv:1406.7844



Summary and outlook

- Many 7 & 8 TeV analysis have been done by ATLAS and CMS
  - ✓ Most measurements limited by sys errors
  - ✓ Good agreement between data and theory



- Only a small set of measurements reported here:
  - ✓ All public results are summarized online:

    https://twiki.cern.ch/twiki/bin/view/AtlasPublic
    https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

- Looking forward to 14TeV challenges
  - ✓ High production rate, high luminosities
    - More precise measurements (smaller stat error)
    - Many sys error can be reduce with more data
    - Detail studies of kinematic distribution in multi dimensional phase spaces
  - ✓ More challenge environment: high pileups
    - Clean and important data for detector calibration
  - ✓ Production of W/Z and top a prior for NP searches at the LHC
    - Proof of the understanding the detector
    - Irreducible background of searches for NP effects

Backup

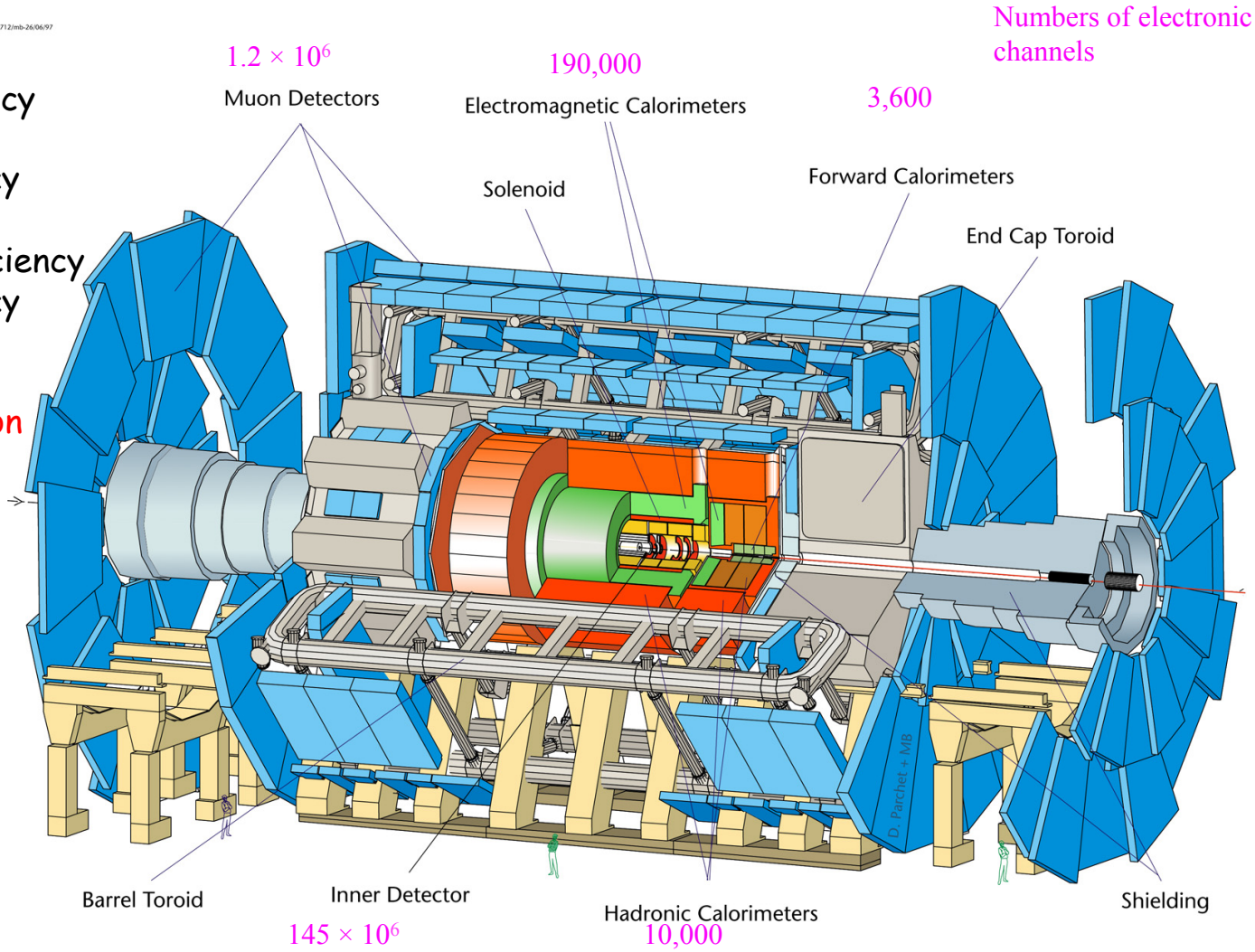
The ATLAS Detector

e: ~75 – 90% efficiency

muon: ~90% efficiency

b tagging: ~57% efficiency
~ 0.2% fake efficiency
from light jets

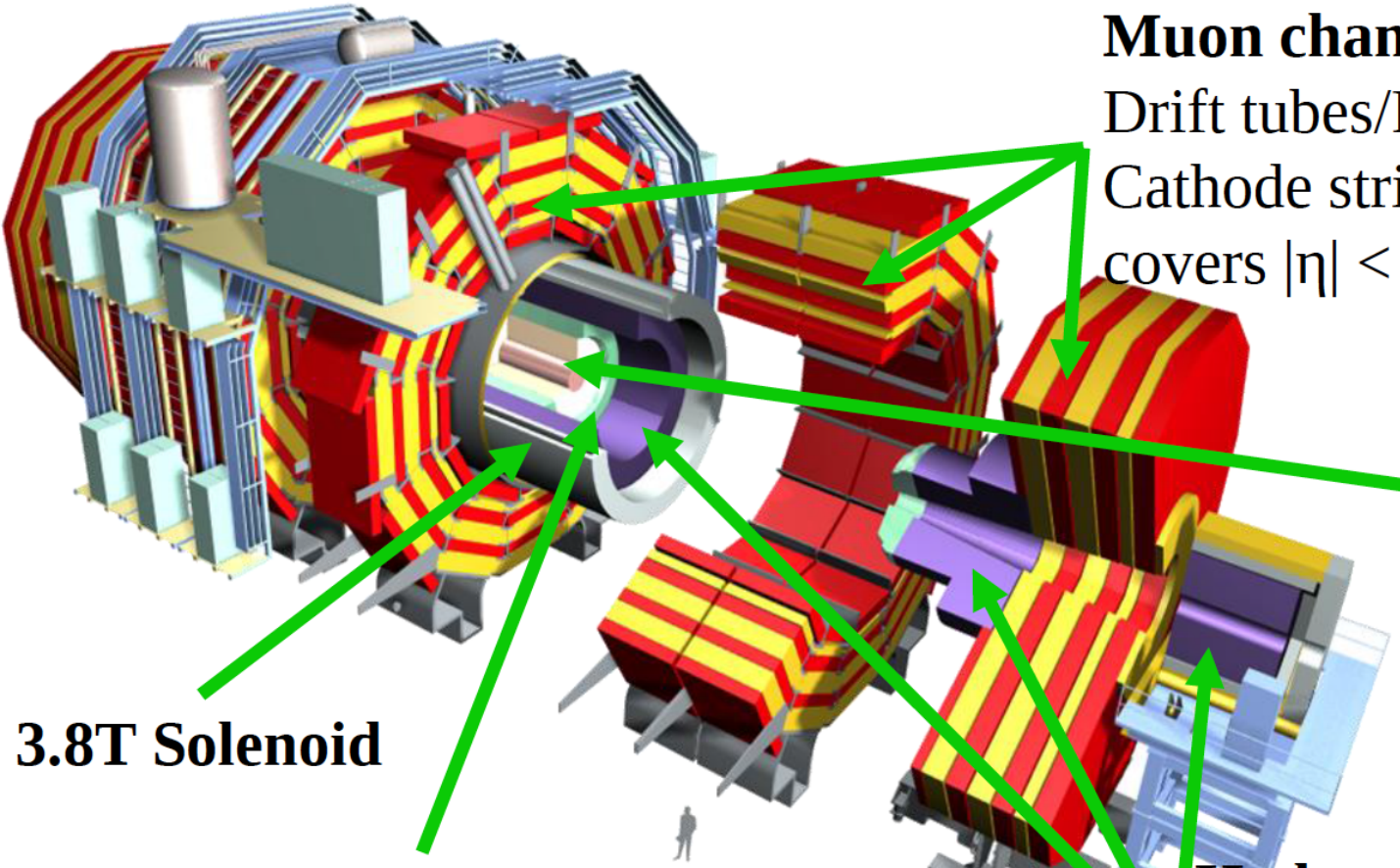
Efficiency & resolution dependents on the selection criteria



46 m long, Overall weight: 7000 Tons

Excellent reconstruction efficiency and resolution:
Electron, muon, track, jets, b-tagging & missing transverse energy

The CMS detector



Muon chambers
Drift tubes/RPC in barrel
Cathode strip/RPC in endcaps
covers $|\eta| < 2.4$

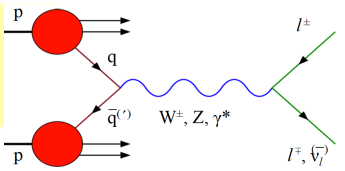
Inner tracker
Silicon pixels
Silicon strips

3.8T Solenoid

Electromagnetic Calorimeter
76k $PbWO_4$ crystals

Hadronic Calorimeter
Brass/scintillator/wls fiber
Iron/quartz fiber

W/Z reconstruction at LHC



- Signal reconstruction:
  - ✓ One isolated high p_T lepton &missing transverse energy (MET)

$$W \to \ell\nu \quad (\ell = e, \mu)$$

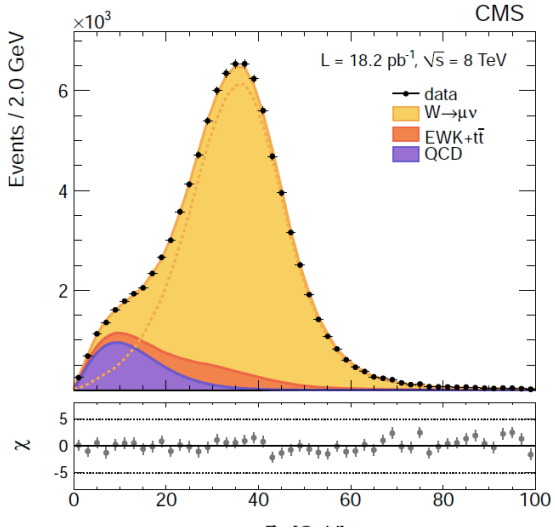
  - ✓ Two (isolated) high p_T leptons:
    - 60(66) < m_{ll} < 120(116) GeV for ATLAS(CMS)

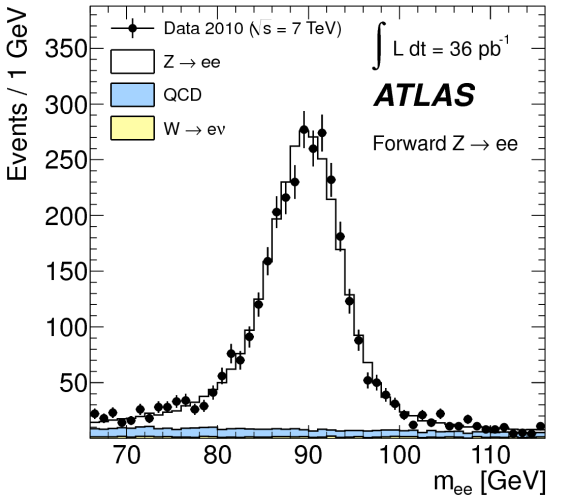
$$Z \to \ell\ell \quad (\ell = e, \mu)$$

- Background:
  - ✓ EWK: Drell-Yan, diboson, W->τν, Z->ττ
  - ✓ top production
  - ✓ QCD: fake leptons from multijet production

- Signal Extraction: fit MET for W and m_{ll} for Z
  - ✓ Signal template from MC & EWK and top bg fixed to MC
  - ✓ QCD template from control data sample
    - Invert lepton identification criteria

CMS, PRL,112,191802(2014)





ATLAS, PRD,85,072004(2012)

- Calculation of the total cross section:

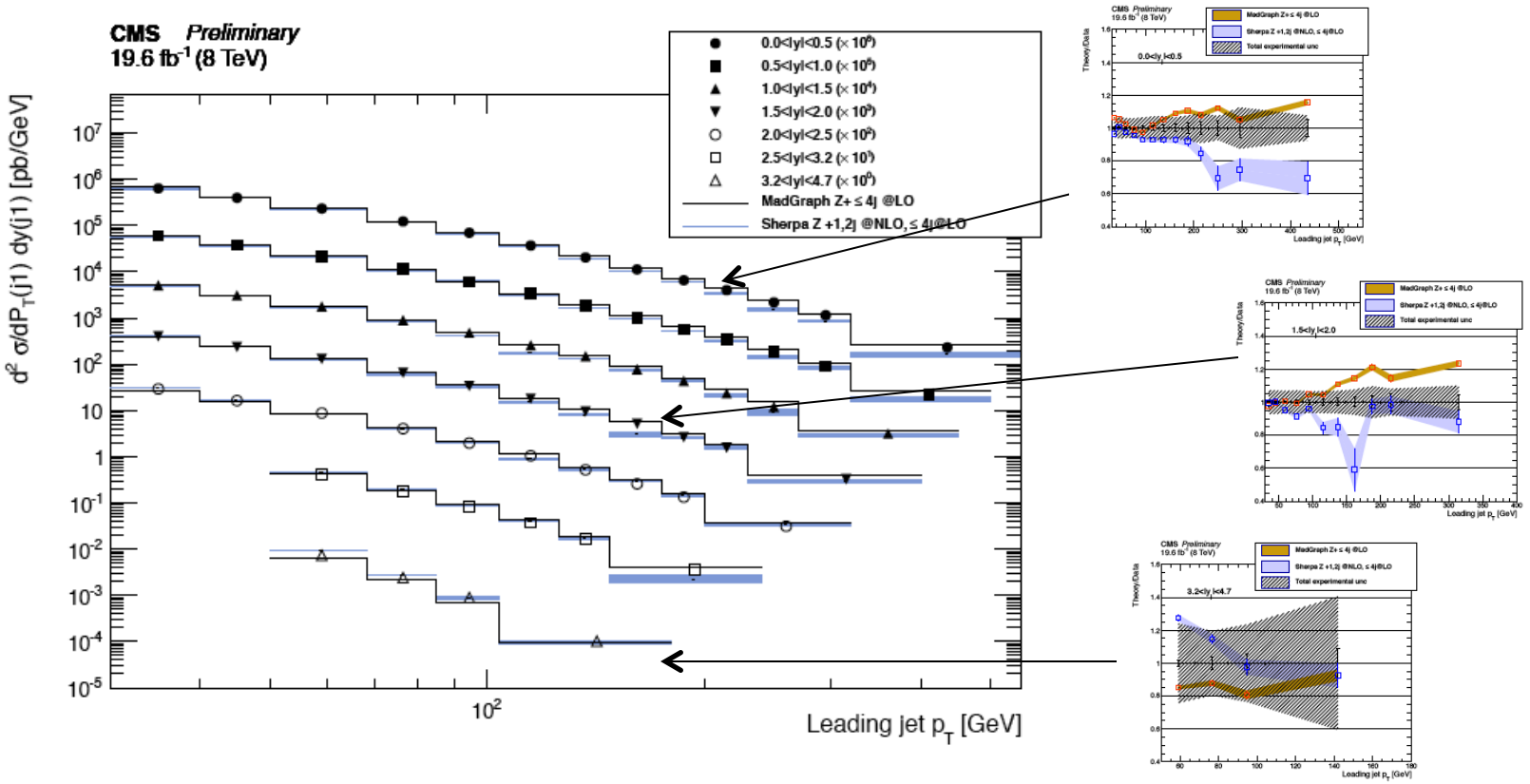
$$\sigma = \frac{N_{\text{observed}} - N_{background}}{C_{W/Z} \times A_{W/Z} \times Br(W/Z \to \ell\nu\ell\ell) \times \text{Luminosity}}$$

Efficiency

Acceptance

W/Z + jets production at LHC

CMS-PAS-SMP-14-009



- First double differential measurement Z+jet with jet up to $|\eta|<4.7$ – $30 < p_T < 550$ GeV
- Largest experimental uncertainty from JES
- Predictions: MadGraph norm. NNLO / Sherpa2 (NLO 1j,2j /LO<=4j)
- Reasonable description from Sherpa2, some regions to investigate

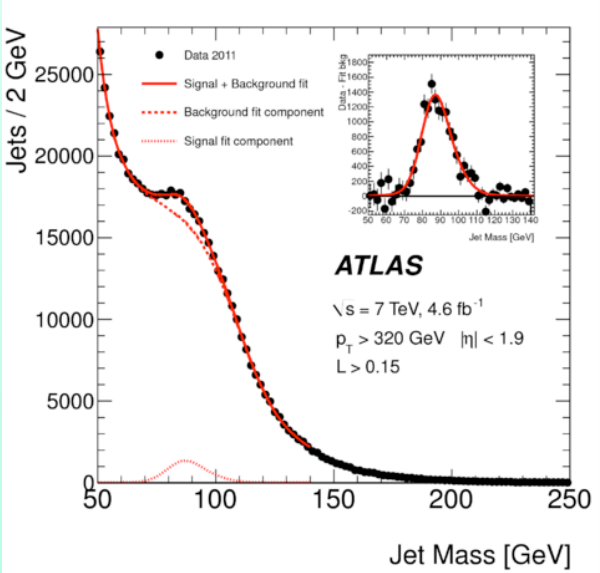
Production of high p_T hadronic W/Z

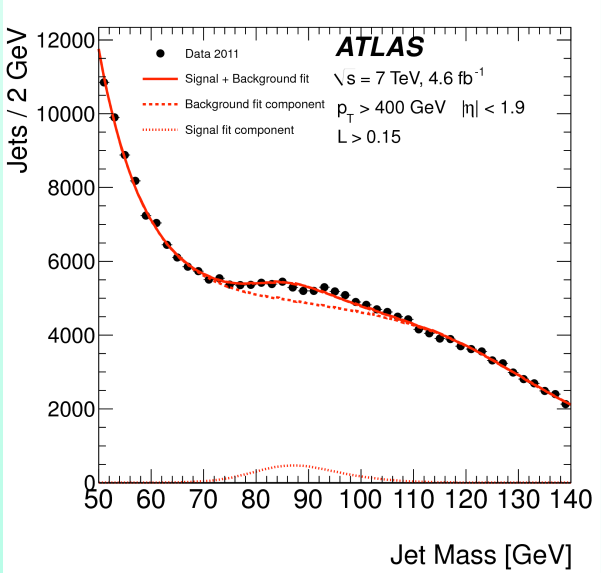
- High p_T hadronic W/Z production cross section (7TeV)
  - ✓ Reconstruct hadronic product inside single jets & identify signal using jet mass
  - ✓ Suppress multijet production using jet substructure in jet rest frame
    - W/Z jet: back-to-back 2 body topology, QCD jet: isotropic distribution
    - LH using shape variable: thrust-minor, sphericity, aplanarity

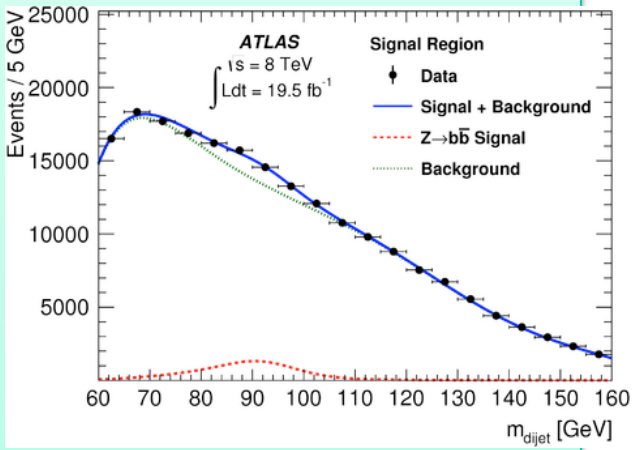
ATLAS, arXiv:1407.0800

$$\sigma_{W+Z} = 8.5 \pm 0.8\ (\text{stat.}) \pm 1.5\ (\text{syst.})\ \text{pb}$$

5.1±0.5 pb (MCFM)







- Z->bbbar cross section (8TeV)
  - ✓ Combine 2 b-tagging jets to form a Z candidate with p_T>200GeV
  - ✓ Separate signal and background using a Neutral Network analysis
    - η_{dijet} and $\Delta\eta$(dijet , balance jet)
  - ✓ Simultaneous fit to dijet mass in signal and control region (constrain background shape)

ATLAS, arXiv:1404.7042

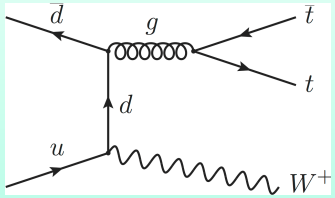
$$\sigma^{\text{fid}}_{Z\to b\bar{b}} = 2.02 \pm 0.20\ (\text{stat.}) \pm 0.25\ (\text{syst.}) \pm 0.06\ (\text{lumi.})\ \text{pb} = 2.02 \pm 0.33\ \text{pb}$$

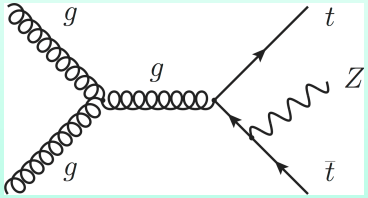
$$\text{POWHEG}: \quad \sigma^{\text{fid}}_{Z\to b\bar{b}} = 2.02\ ^{+0.25}_{-0.19}(\text{scales})\ ^{+0.03}_{-0.04}(\text{PDF})\ \text{pb}$$

$$\text{aMC@NLO}: \quad \sigma^{\text{fid}}_{Z\to b\bar{b}} = 1.98\ ^{+0.16}_{-0.08}(\text{scales}) \pm 0.03(\text{PDF})\ \text{pb}$$

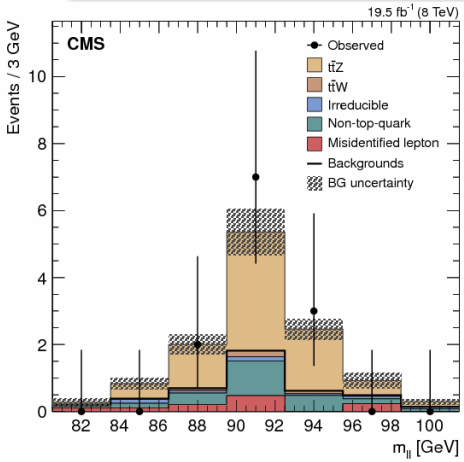
Top pair + W/Z production

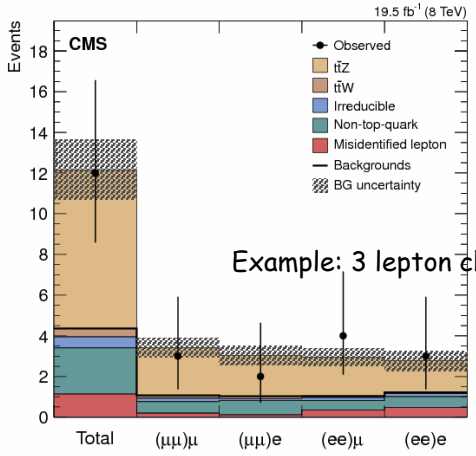
- Cross section ~200fb estimated by NLO QCD



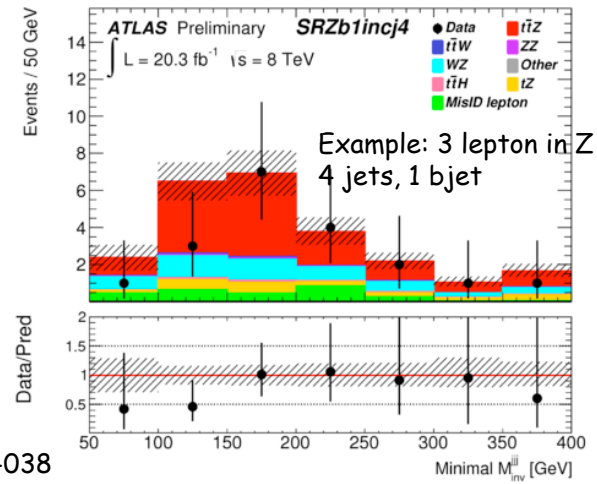


- Experimental signature:
  - ✓ CMS : 2 SS leptons, 3 leptons, 4 leptons (counting)
  - ✓ ATLAS: 2 OS leptons (NN based on kinematics), 2 SS muons, 3 leptons (counting)





Example: 3 lepton channel



Example: 3 lepton in Z mass region
4 jets, 1 bjet

CMS 7 TeV PRL 110 (2013) 172002

Channels used	Process	Cross section	Significance
2ℓ	$t\bar{t}V$	430^{+170}_{-150} (stat.) $\pm^{90}_{70}$ (syst.) fb	3.0
3ℓ	$t\bar{t}Z$	280^{+140}_{-110} (stat.)$^{+60}_{-30}$ (syst.) fb	3.3

CMS 8 TeV arXiv:1406.7830

Channels used	Process	Cross section	Significance
2ℓ	$t\bar{t}W$	170^{+90}_{-80} (stat) $\pm$ 70 (syst) fb	1.6
3ℓ+4ℓ	$t\bar{t}Z$	200^{+80}_{-70} (stat)$^{+40}_{-30}$ (syst) fb	3.1
2ℓ+3ℓ+4ℓ	$t\bar{t}W$ + $t\bar{t}Z$	380^{+100}_{-90} (stat)$^{+80}_{-70}$ (syst) fb	3.7

ATLAS-CONF-2014-038

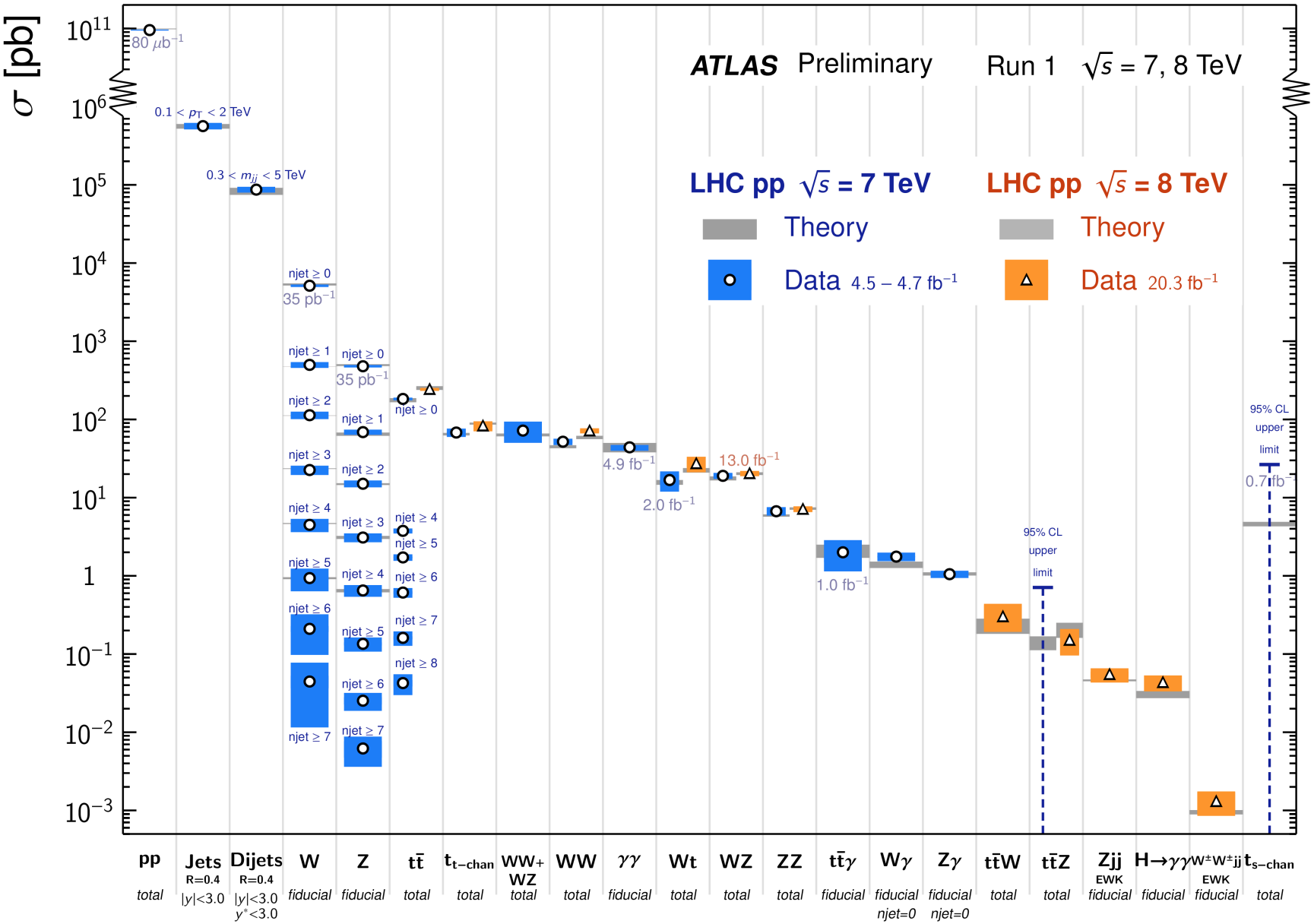
Summary of combined simultaneous fit results

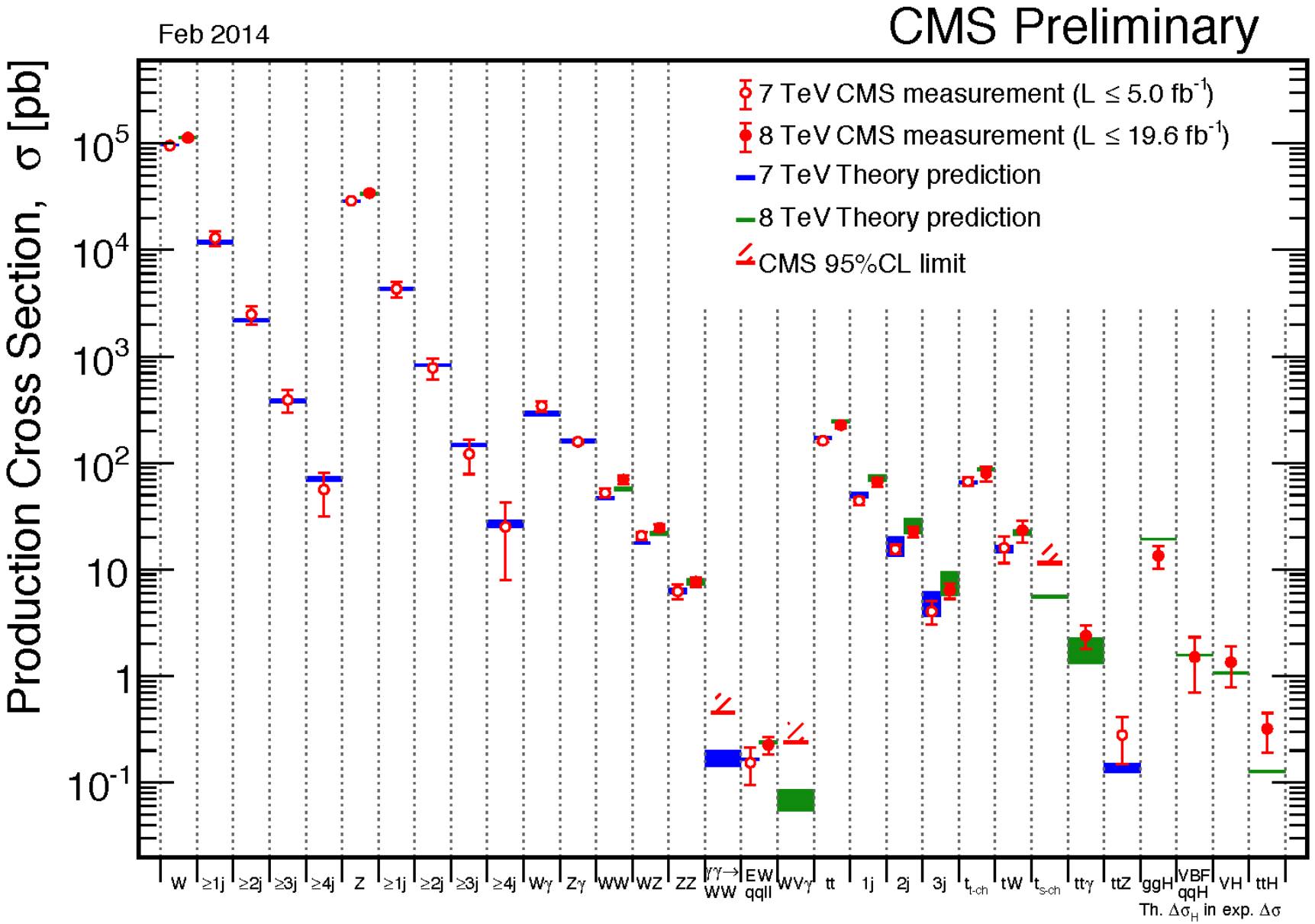
Process	Measured cross-sections	Observed σ
$t\bar{t}Z$	150^{+58}_{-54}(total) = 150^{+55}_{-50}(stat.) $\pm$ 21(syst.) fb	3.1
$t\bar{t}W$	300^{+140}_{-110}(total) = 300^{+120}_{-100}(stat.)$^{+70}_{-40}$(syst.) fb	3.1

Evidence of top pair production associated with W/Z on 3σ level, cross section consistent with SM Expectation.

Standard Model Production Cross Section Measurements

Status: July 2014




CMS Preliminary
Feb 2014
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
7 TeV Theory prediction
8 TeV Theory prediction
CMS 95%CL limit
W
≥1j
≥2j
≥3j
≥4j
Z
≥1j
≥2j
≥3j
≥4j
Wγ
Zγ
WW
WZ
ZZ
γγ→WW
EW qqll
WVγ
tt
1j
2j
3j
t t-ch
tW
t s-ch
ttγ
ttZ
ggH
VBF qqH
VH
ttH
Th. Δσ_H in exp. Δσ