Electroweak Physics (di-boson) measurements with the ATLAS detector

Vasiliki Kouskoura (BNL)

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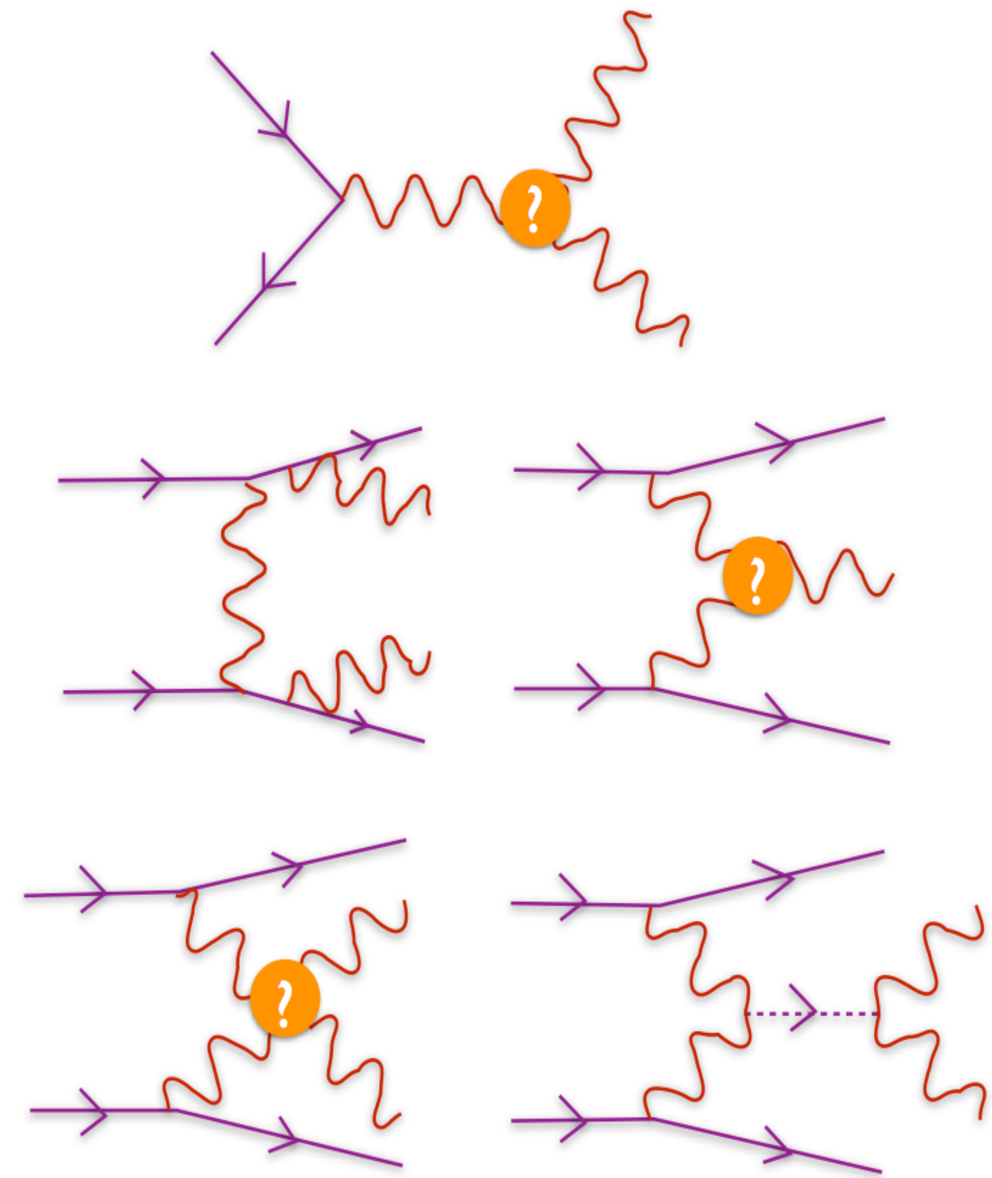
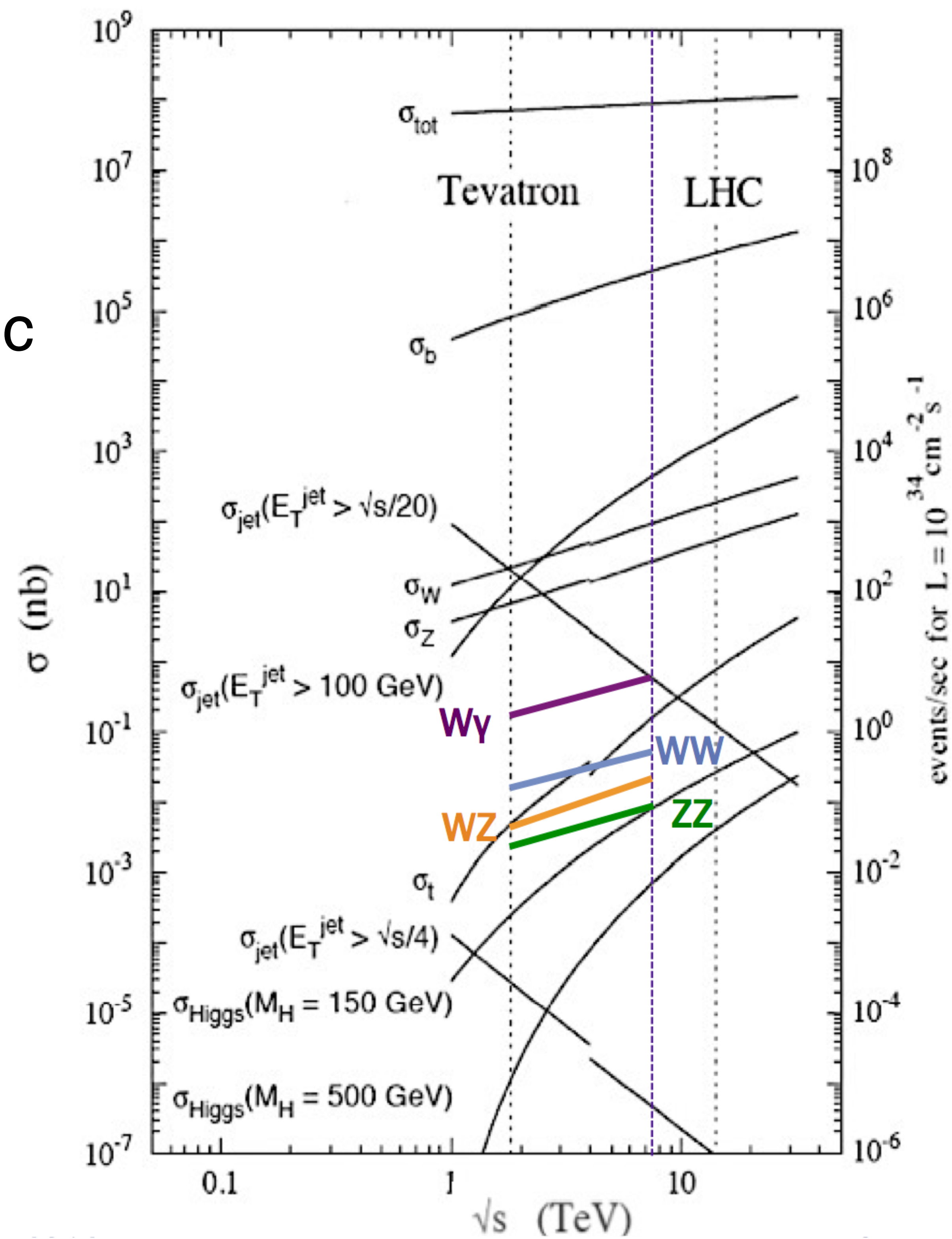
Physics motivation

- Di-boson processes
  - important tests of the Electroweak (EW) Sector of the Standard Model (SM) at high energy regimes
  - sensitivity to new heavy particles
  - irreducible background to Higgs measurements
- Anomalous Triple/Quartic Gauge Couplings (aTGC/aQGC)
  - self-couplings fundamental predictions of the SM
  - probe for new physics through deviations of measured cross sections from predictions



Di-boson production at the LHC

- Measurement of di-boson processes involving combinations of W, Z and γ
  - W/Zγ, ZZ, WZ, $W^{\pm}W^{\mp}$, $W^{\pm}W^{\pm}$
- Measured mainly through their leptonic final states
  - Relatively low backgrounds
  - Low branching ratios
    - *BR(W→ℓν) = 0.108, BR(Z→ℓℓ) = 0.03366*
- Small cross sections O(1-100pb)
- Gluon contribution up to ~10% depending on the channel



Signatures

- Leptons and photons
  - *High-p_T* ***isolated*** electrons/muons and photons
- Z bosons
  - Invariant mass in windows around the Z pole
- W bosons
  - Large missing E
    - *Calculated from jets, leptons and calorimetric clusters*
  - Transverse mass selection

Signatures

- Leptons and photons
  - *High-p*
- Z bosons
  - Invariant mass in windows around the Z pole
- W bosons
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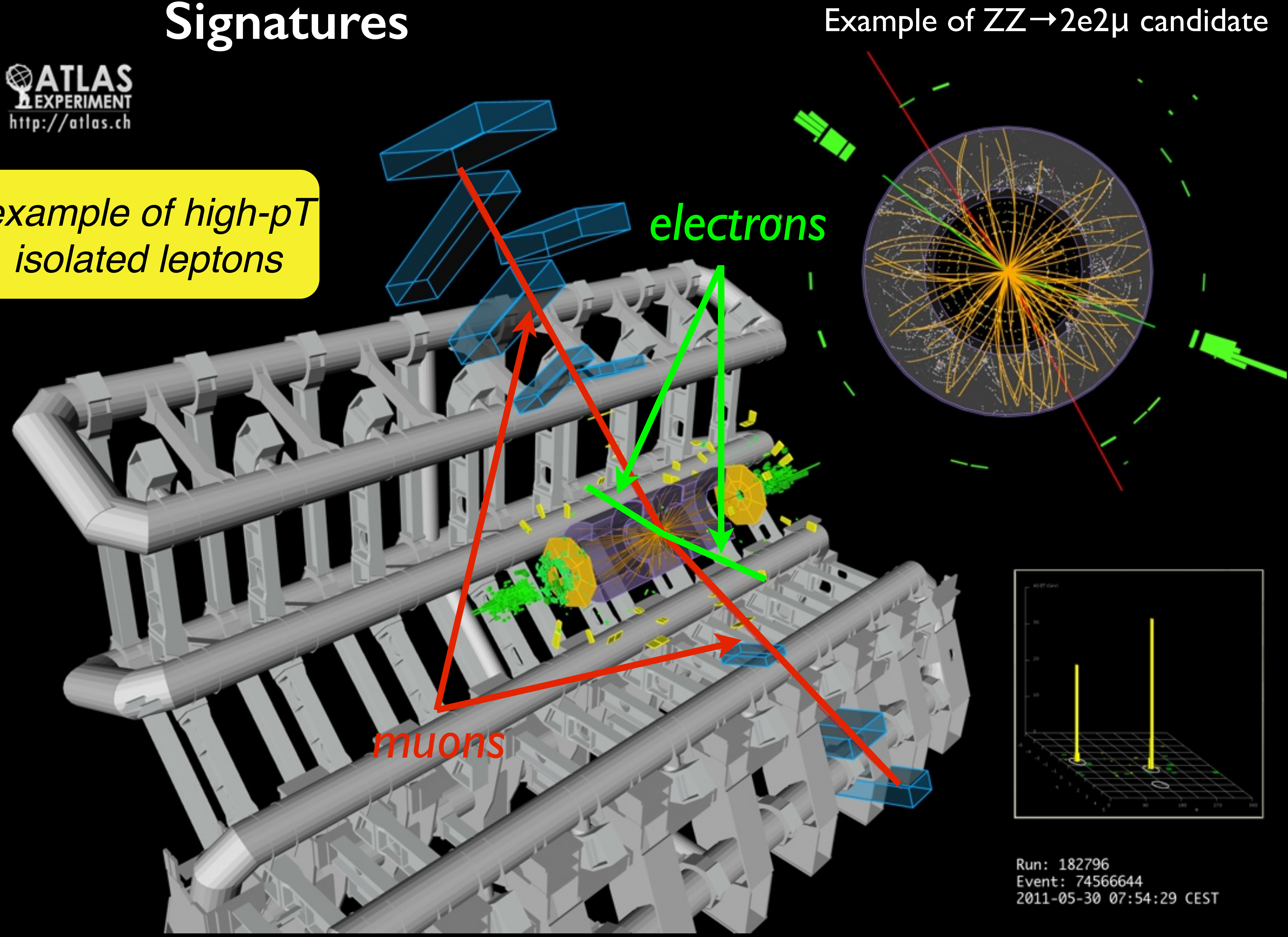
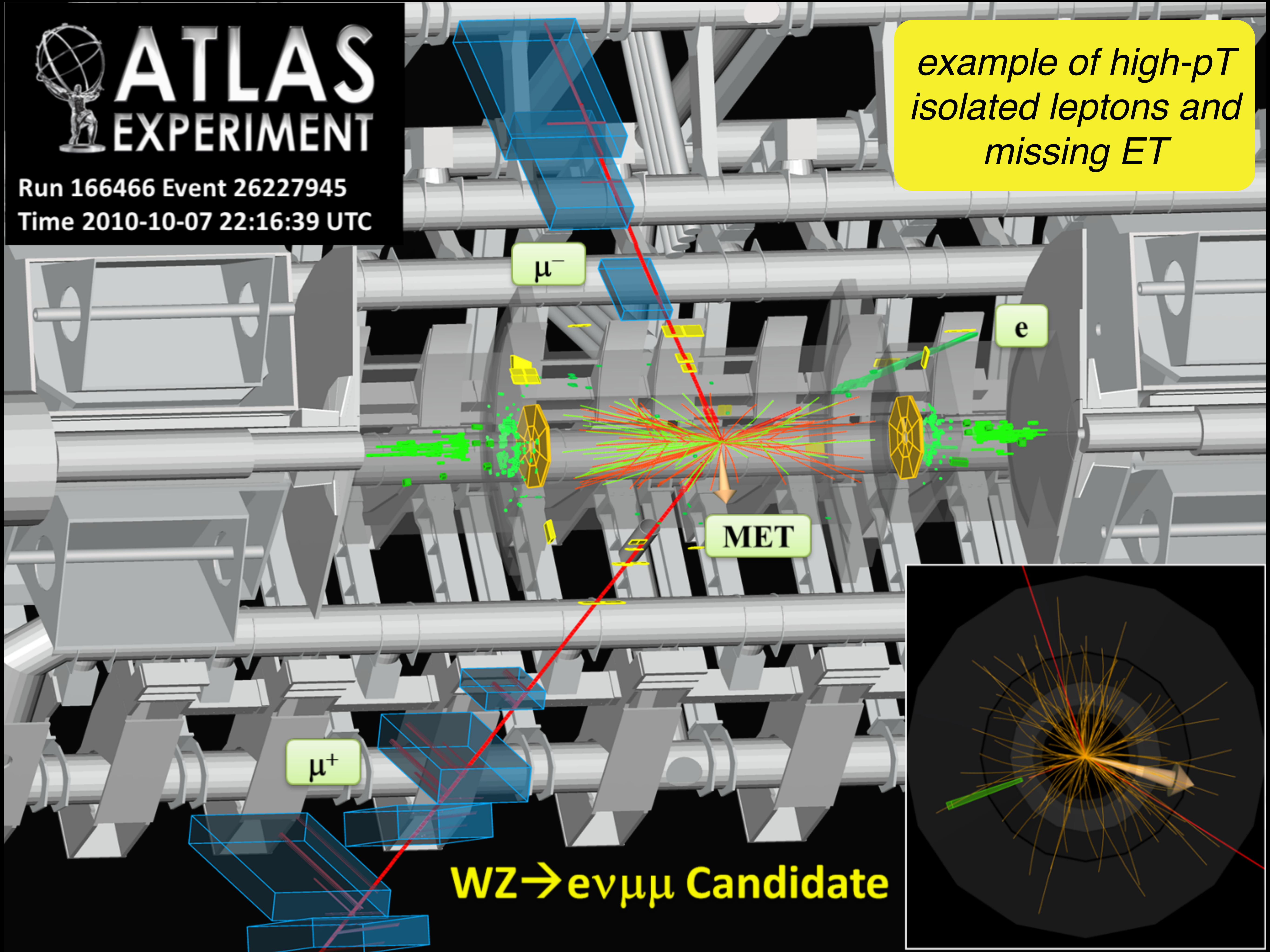
Signatures



example of high-pT isolated leptons

Signatures

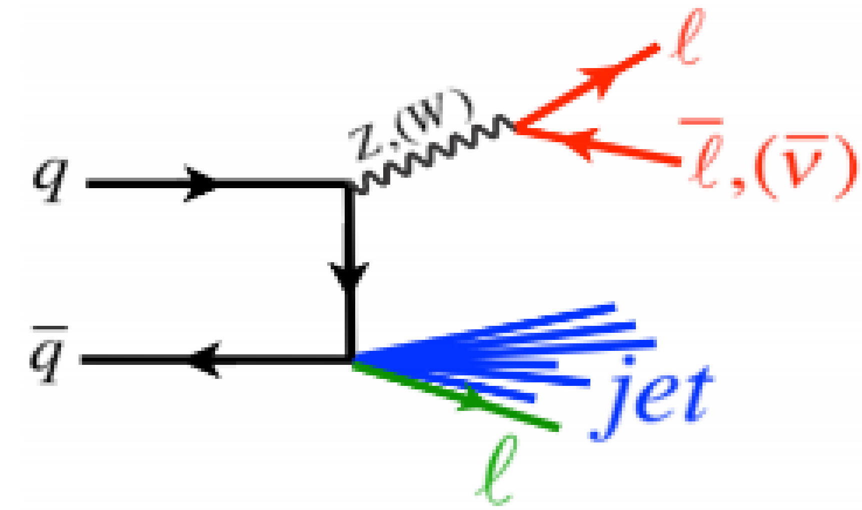
- Leptons and photons
  - *High-p*
- Z bosons
  - Invariant mass in windows around the Z pole
- W bosons
  - Large missing E_T to account for the neutrino
    - *Calculated from jets, leptons and calorimetric clusters*
  - Transverse mass selection


ATLAS EXPERIMENT
Run 166466 Event 26227945
Time 2010-10-07 22:16:39 UTC
example of high-pT isolated leptons and missing ET
μ⁻
e
MET
μ⁺
WZ→eνμμ Candidate

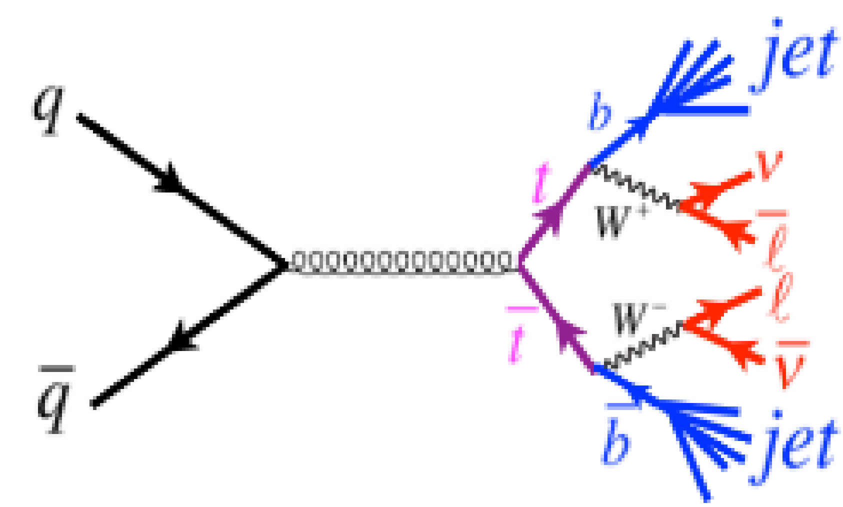
Backgrounds

Estimated with data driven methods

- V + jets characteristics:
  - High-pT leptons from boson decays
  - Leptons from heavy flavor decays
  - Jets misidentified as leptons/photons
  - Particles outside the detector acceptance



- ttbar and single top characteristics:
  - Prompt isolated leptons from W decays
  - Large missing E_T



Estimated from MC

- Di-boson processes
  - Background to each other

How do we measure cross sections?

- ***"Cut and Count"*** analysis: ***observed events***

$$N_{obs} = N_{sig} + N_{bkg}$$

- **Background** estimation

$$N_{bkg}$$

- Measurement of **fiducial cross section**
  - In a phase space defined by the detector's acceptance and our selection requirements

$$N_{sig} = \mathcal{L} \cdot \sigma^{fid} \cdot C$$

$$\sigma_{fid} = \frac{N_{obs} - N_{bkg}}{C \cdot \int \mathcal{L} dt}$$

$$\sigma_{tot} = \frac{N_{obs} - N_{bkg}}{A \cdot C \cdot BR \cdot \int \mathcal{L} dt}$$

- Extrapolate to **total phase space**
- Optionally provide differential cross sections in fiducial volumes
  - Distributions "unfolded" from detector effects

$$A = \frac{N^{fid}_{MC,gen}}{N^{tot}_{MC,gen}}$$

acceptance correction for kinematic and geometric selection criteria

$$C = \frac{N^{Selected}_{MC,reco}}{N^{fid}_{MC,gen}}$$

correction for detector effects

Zγ/Wγ production

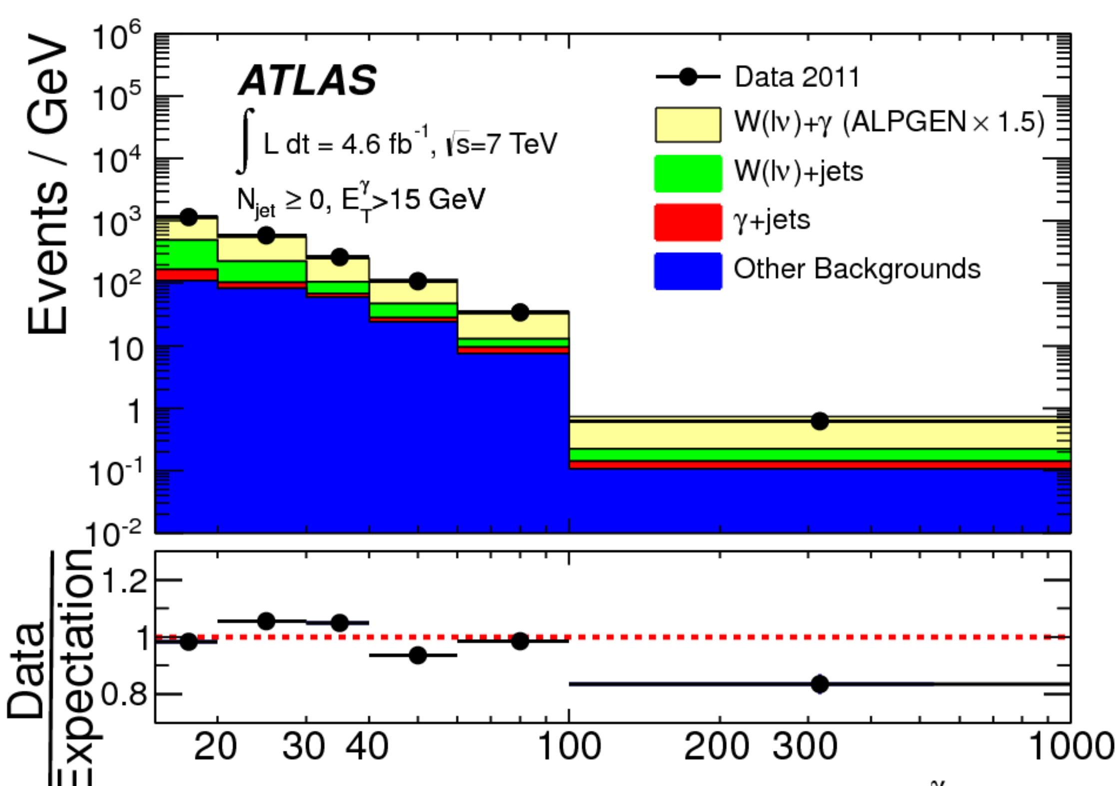
Phys. Rev. D 87, 112003 (2013)

- Measured final states
  - $\ell^{\pm}\nu\gamma$, $\ell^{\pm}\ \ell^{\mp}\ \gamma$, $\nu\nu\gamma$ $(\ell{:}e,\mu)$
- Backgrounds
  - W/γ+jets for the $\ell^{\pm}\nu\gamma$
  - Z+jets for the $\ell^{\pm}\ell^{\mp}\gamma$
  - Z/γ+jets, W→eν for the $\nu\nu\gamma$

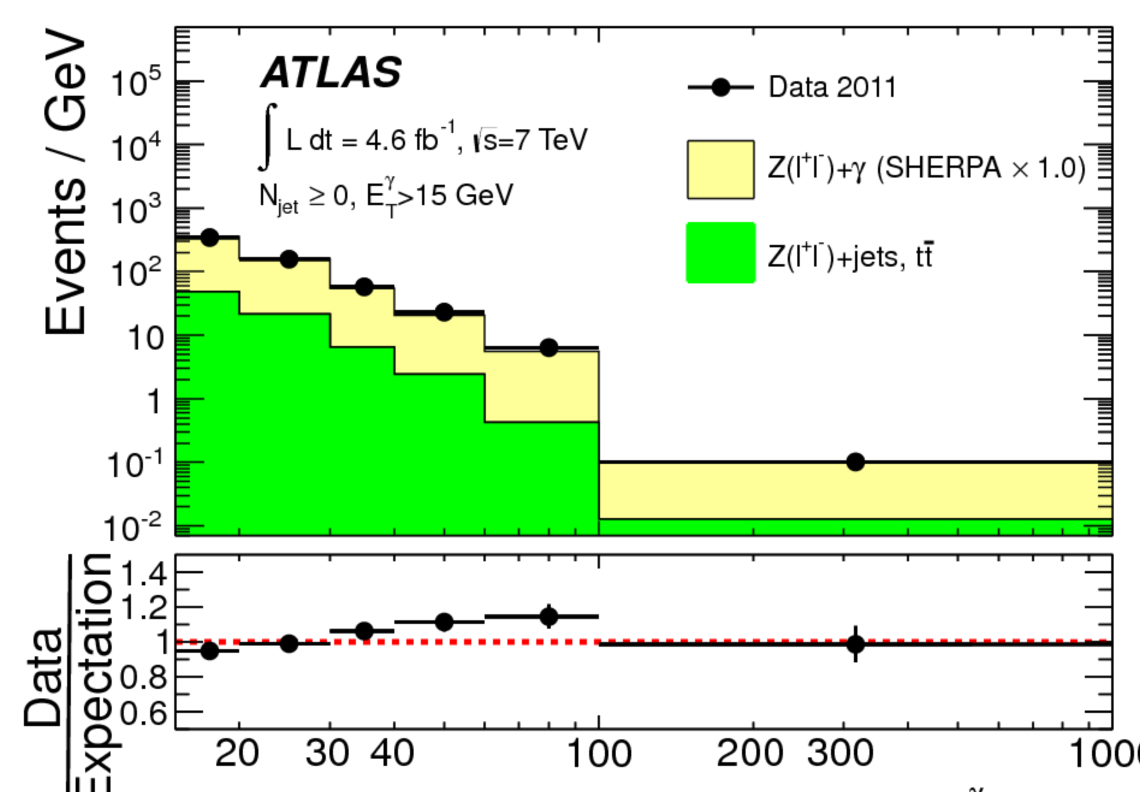
  } *data driven estimate*
- Dominant systematic uncertainties
  - Photon ID, jet/EM energy scale and resolution and background normalization

Event selection

- ☑ isolated high-p_T lepton, isolated high-p_T photon and E_T^{miss} + Z-veto $\ell^{\pm}\nu\gamma$
- ☑ isolated high-p_T leptons with $M_{\ell\ell}$ > 40 GeV and isolated high-p_T photon $\ell^{\pm}\ell^{\mp}\gamma$
- ☑ isolated high-E_T photon and E_T^{miss} $\nu\nu\gamma$
- ΔR (ℓ, γ) > 0.7 to suppress FSR
- jet-veto p_T > 30 GeV for exclusive measurements



$\ell^{\pm}\nu\gamma$

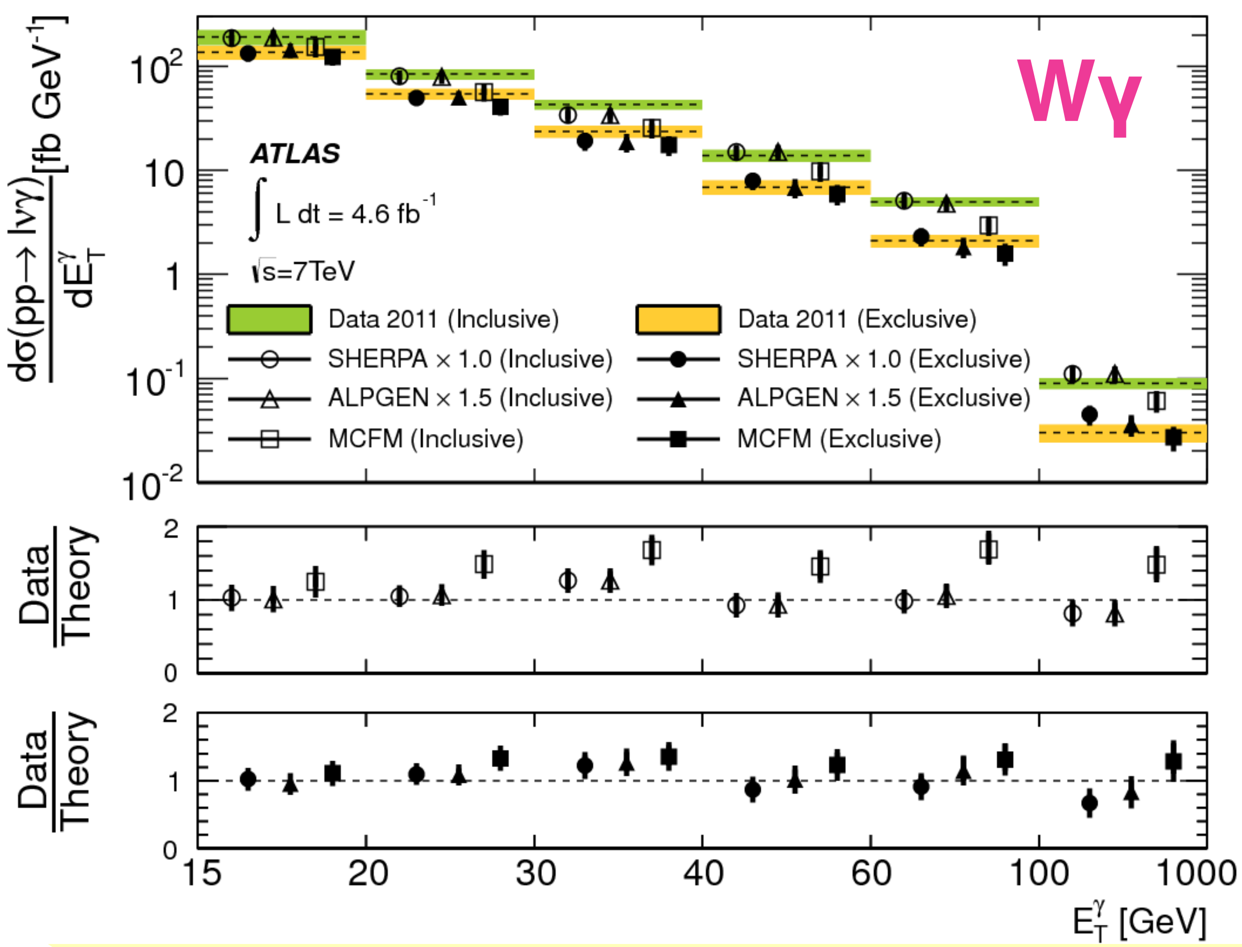


$\ell^{\pm}\ell^{\mp}\gamma$

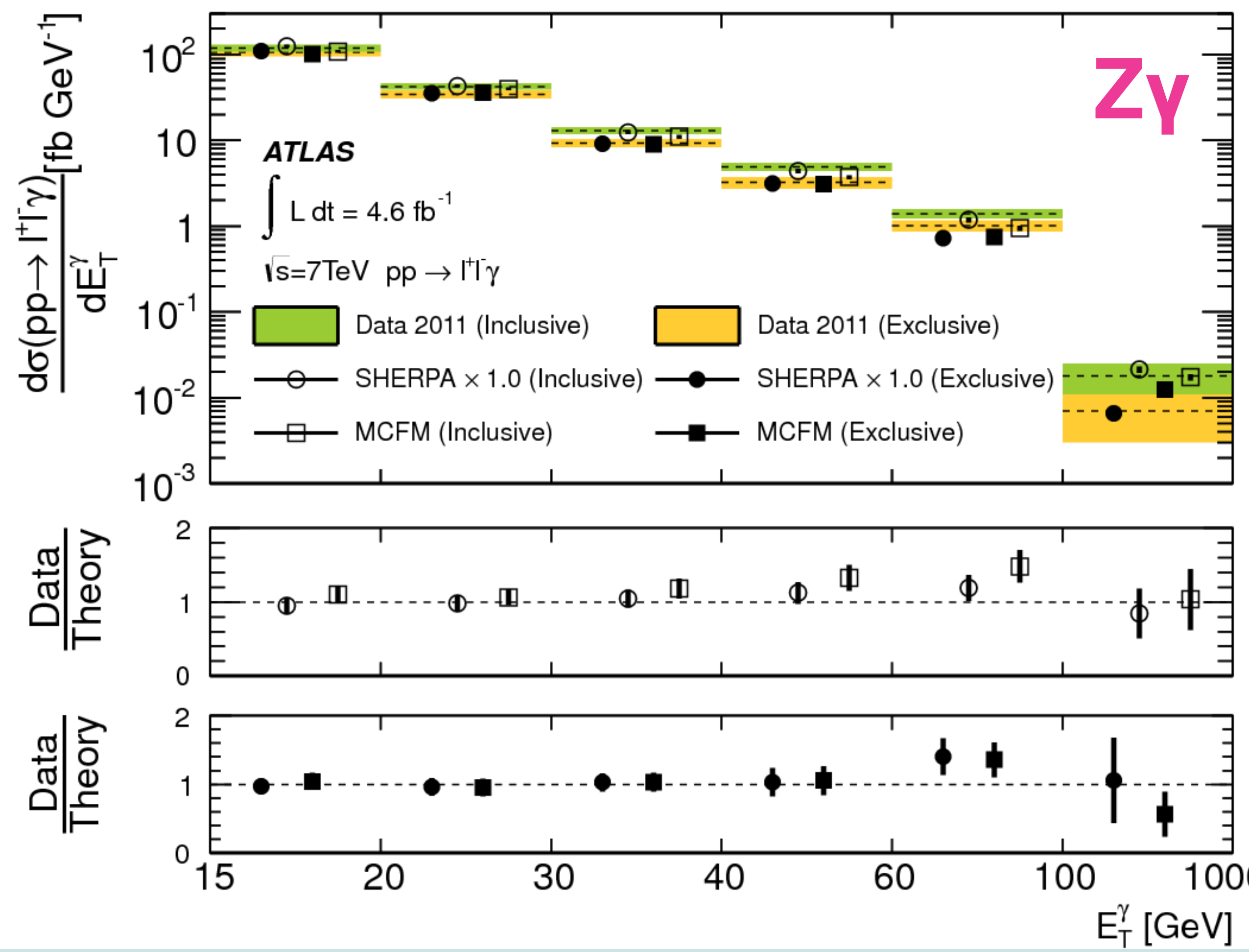
Zγ/Wγ production

Phys. Rev. D 87, 112003 (2013)

- Inclusive Wγ measurement above NLO theoretical prediction (MCFM) by 1-2σ
  - Worse discrepancy at high E_T^γ and jet multiplicity



- Fair agreement for Zγ

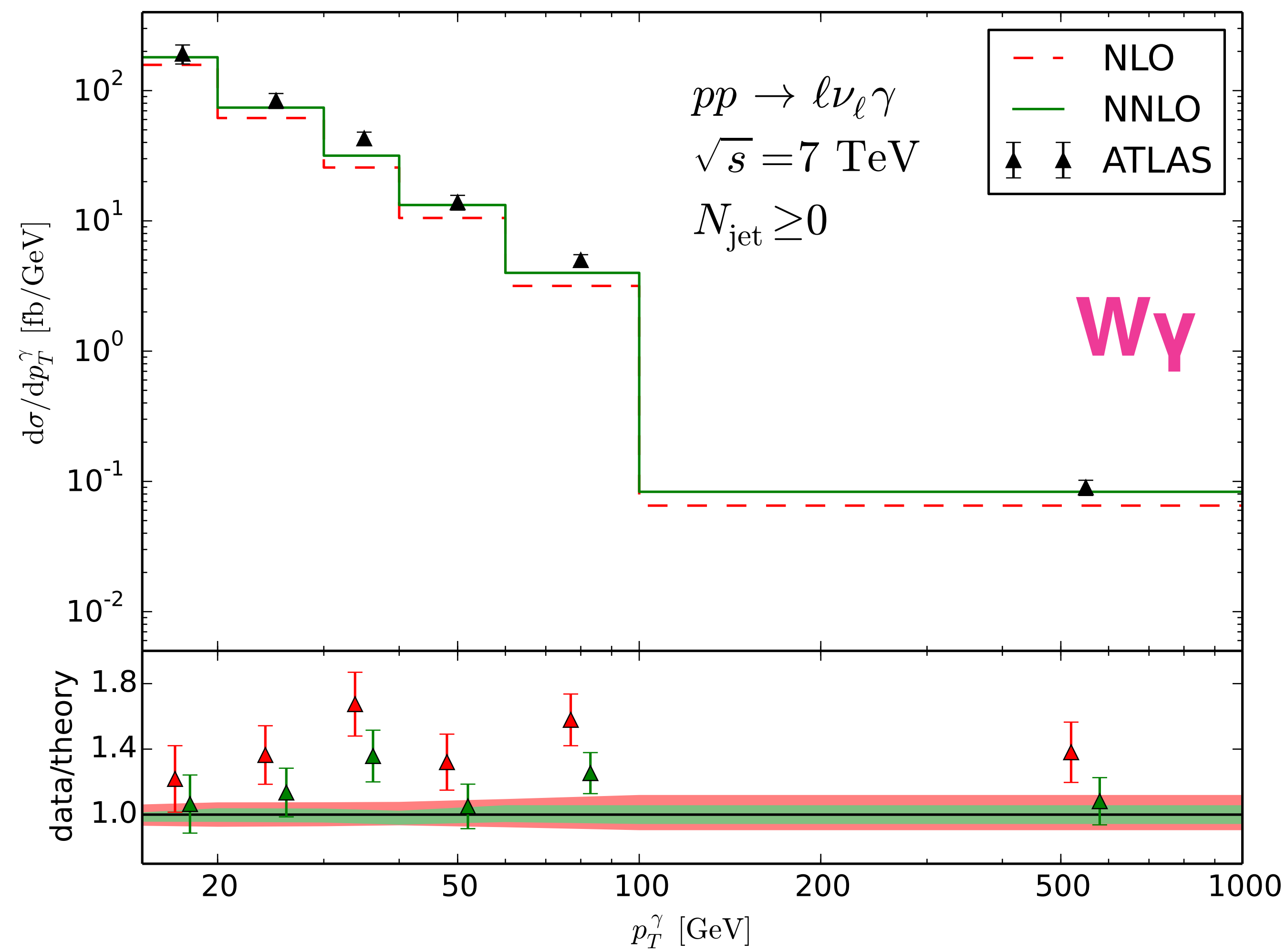


	Measurement [pb]	Theory (MCFM) [pb]
$W\gamma \to \ell\nu\gamma$	2.77±0.03(stat)±0.33(syst)±0.14(lumi)	1.96±0.17
$Z\gamma \to \ell\ell\gamma$	1.31±0.02(stat)±0.11(syst)±0.05(lumi)	1.18±0.05
$Z\gamma \to \nu\nu\gamma$	0.133±0.013(stat)±0.020(syst)±0.005(lumi)	0.156±0.012

Zγ/Wγ production

Phys. Rev. D 87, 112003 (2013)

- New NNLO QCD corrections have sizable effect; provide better agreement with the measurement
  - Corrections for Wγ: ~ 19% - 26%
  - Corrections for Zγ: ~ 8% - 18%



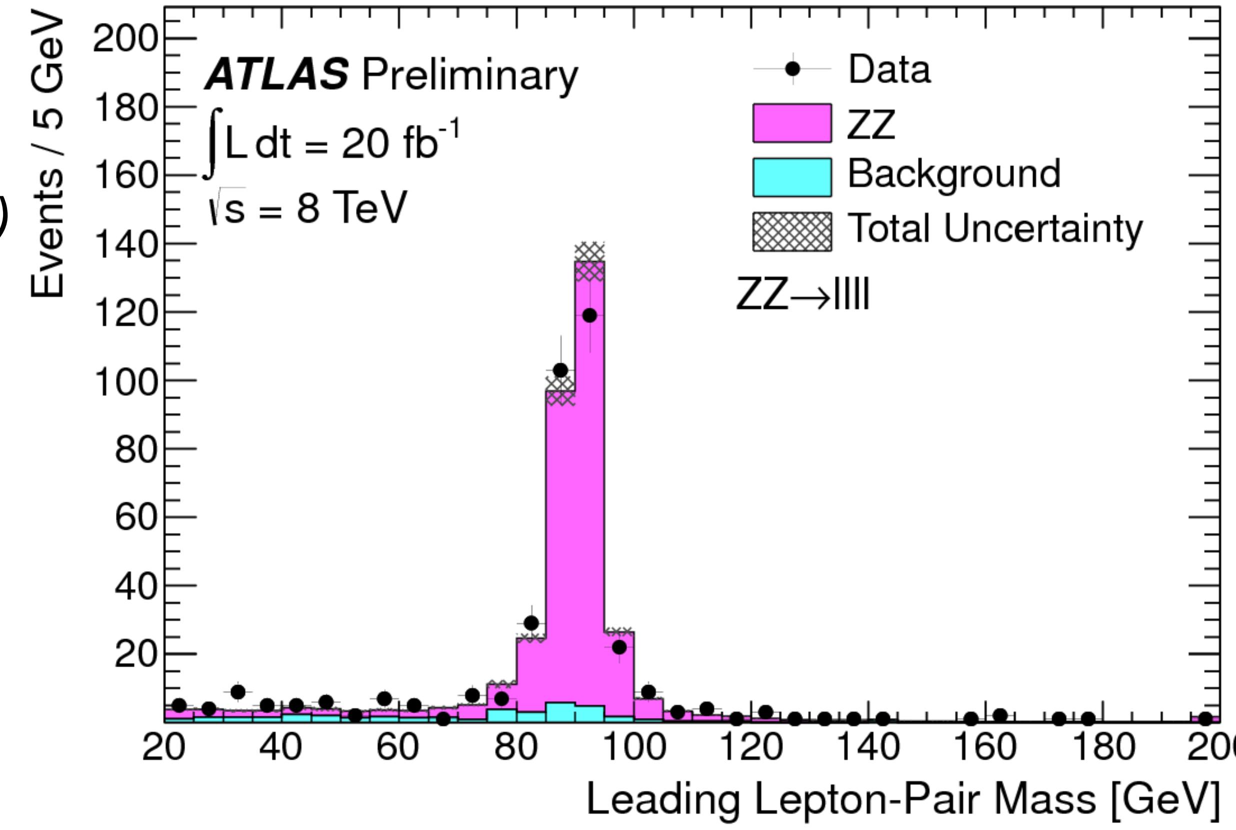
- *arXiv: 1504.01330v1 [hep-ph]*
- *arXiv: 1407.1618v1 [hep-ph]*
- *Phys. Lett. B731 (2014) 204*

	LO [pb]	NLO [pb]	NNLO [pb]	Measurement [pb]
$\sigma Z\gamma \to \ell\ell\gamma$	$0.8149^{+8.0\%}_{-9.3\%}$	$1.222^{+4.2\%}_{-5.3\%}$	$1.320^{+1.3\%}_{-2.3\%}$	1.31±0.02(stat)±0.11(syst)±0.05(lumi)
$\sigma W\gamma \to \ell\nu\gamma$	$0.8726^{+6.8\%}_{-8.1\%}$	2.058±6.8%	2.453±4.1%	2.77±0.03(stat)±0.33(syst)±0.14(lumi)

ZZ production

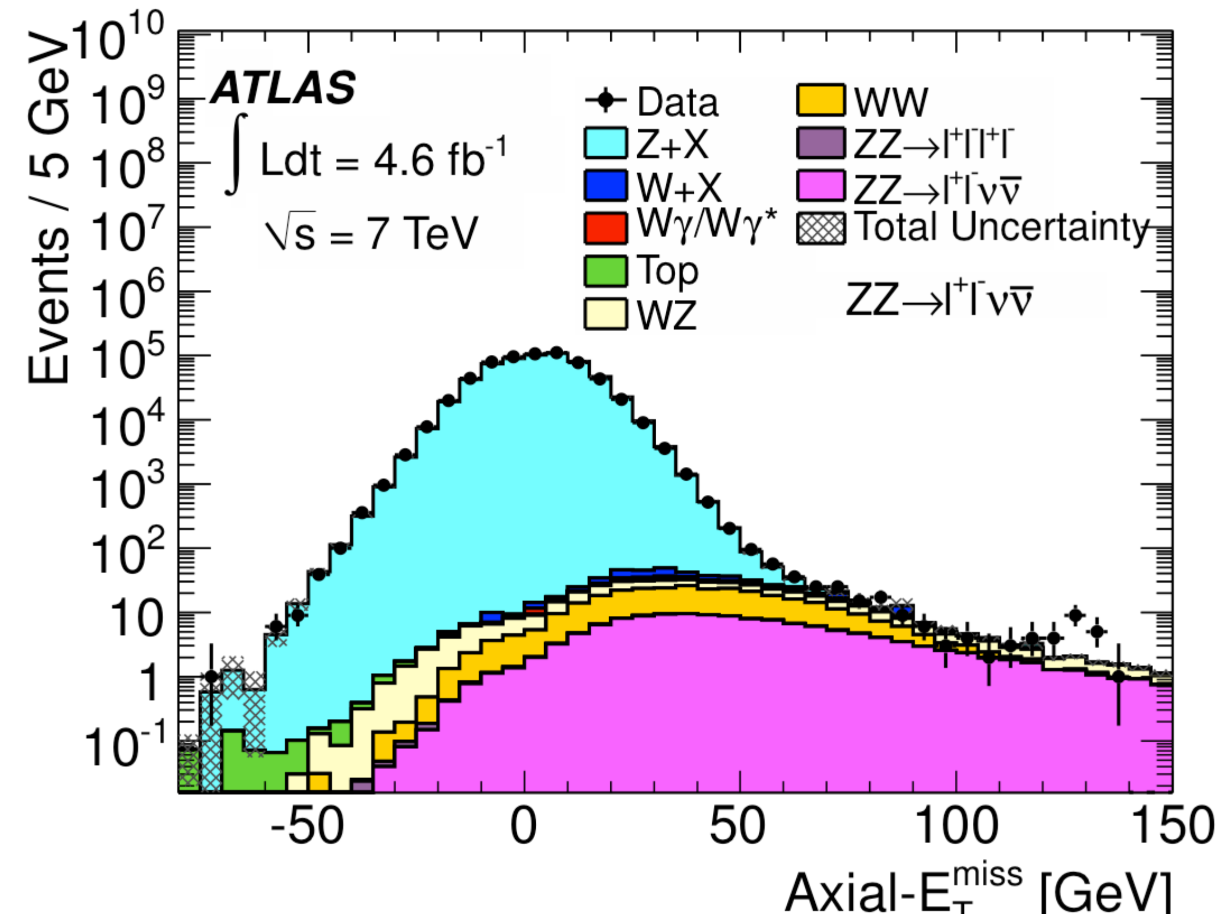
JHEP03(2013)128, ATLAS-CONF-2013-020

- Measured final states
  - $\ell^{\pm}\ell^{\mp}\ell^{\pm}\ell^{\mp}$ (ℓ:e,μ) and $\ell^{\pm}\ell^{\mp}\nu\nu$ (7 TeV only)
- Backgrounds
  - W/Z+jets, Top, WW, WZ
  - Estimated with data-driven methods



Event selection

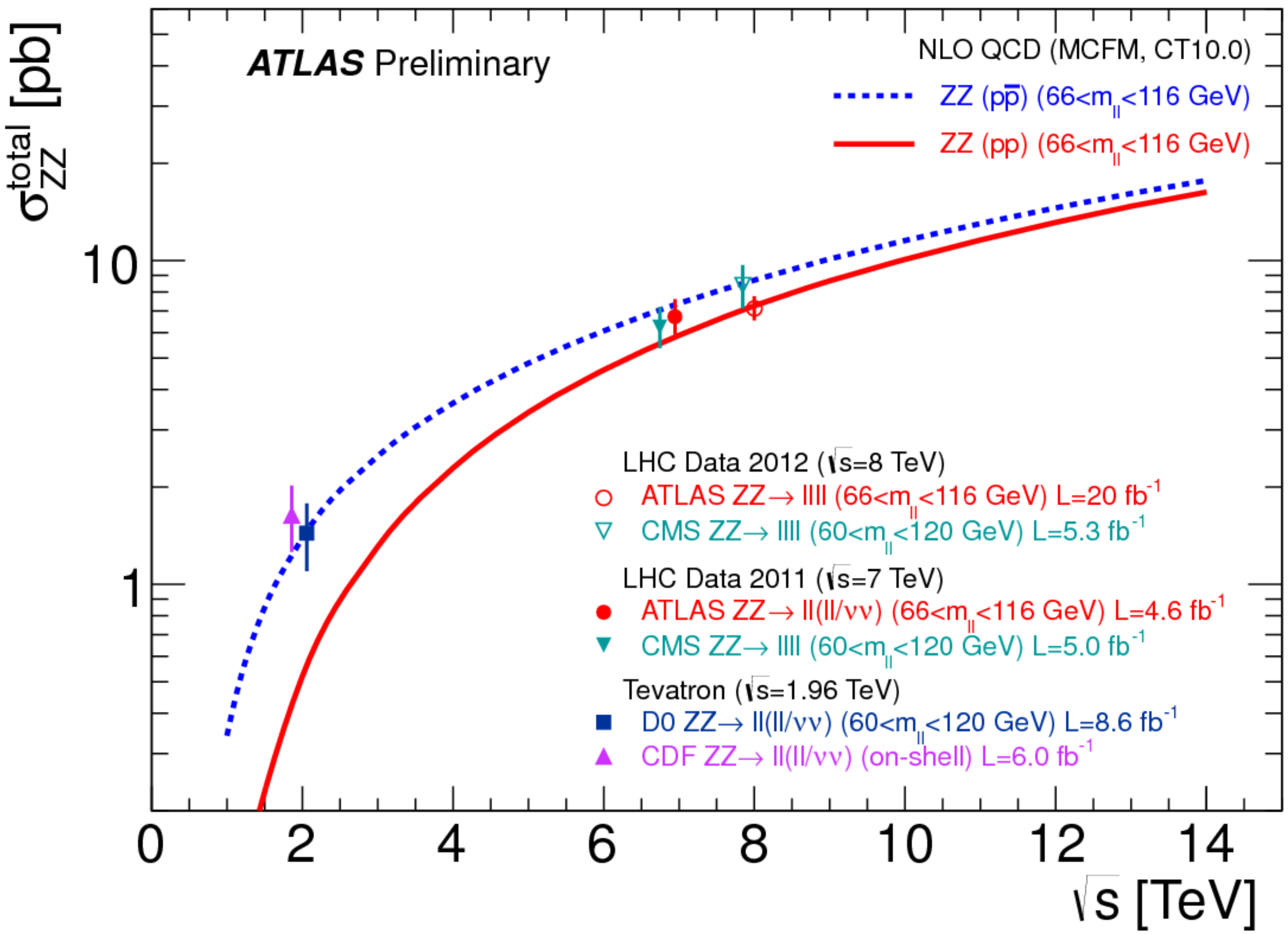
- ☑ 4 (or 2) isolated high-p_T leptons
- ☑ (4ℓ): enhanced muon acceptance $|\eta|<2.7$ and electron acceptance $|\eta| < 3.16$
- ☑ ($2\ell2\nu$): axial-E_T^{miss*} > 75 GeV to suppress Z+jets background



*the projection of the E_T^{miss} along the direction opposite to the $Z\rightarrow\ell\ell$ candidate in the transverse plane

ZZ production

JHEP03(2013)128, ATLAS-CONF-2013-020



- **Statistical** uncertainties dominate
- Systematic uncertainties
  - Reconstruction efficiencies
  - Background estimate
  - Luminosity

$\sqrt{s}$	$\int \mathcal{L}\mathrm{dt}\ [\mathrm{fb}^{-1}]$	Measurement [pb]	Theory (MCFM) [pb]
7 TeV	4.6	$6.7 \pm 0.7(\mathrm{stat})^{+0.4}_{-0.3}(\mathrm{syst}) \pm 0.3(\mathrm{lumi})$	$5.89^{+0.22}_{-0.18}$
8 TeV	20.3	$7.1^{+0.5}_{-0.4}(\mathrm{stat}) \pm 0.3(\mathrm{syst}) \pm 0.2(\mathrm{lumi})$	$7.2^{+0.3}_{-0.2}$

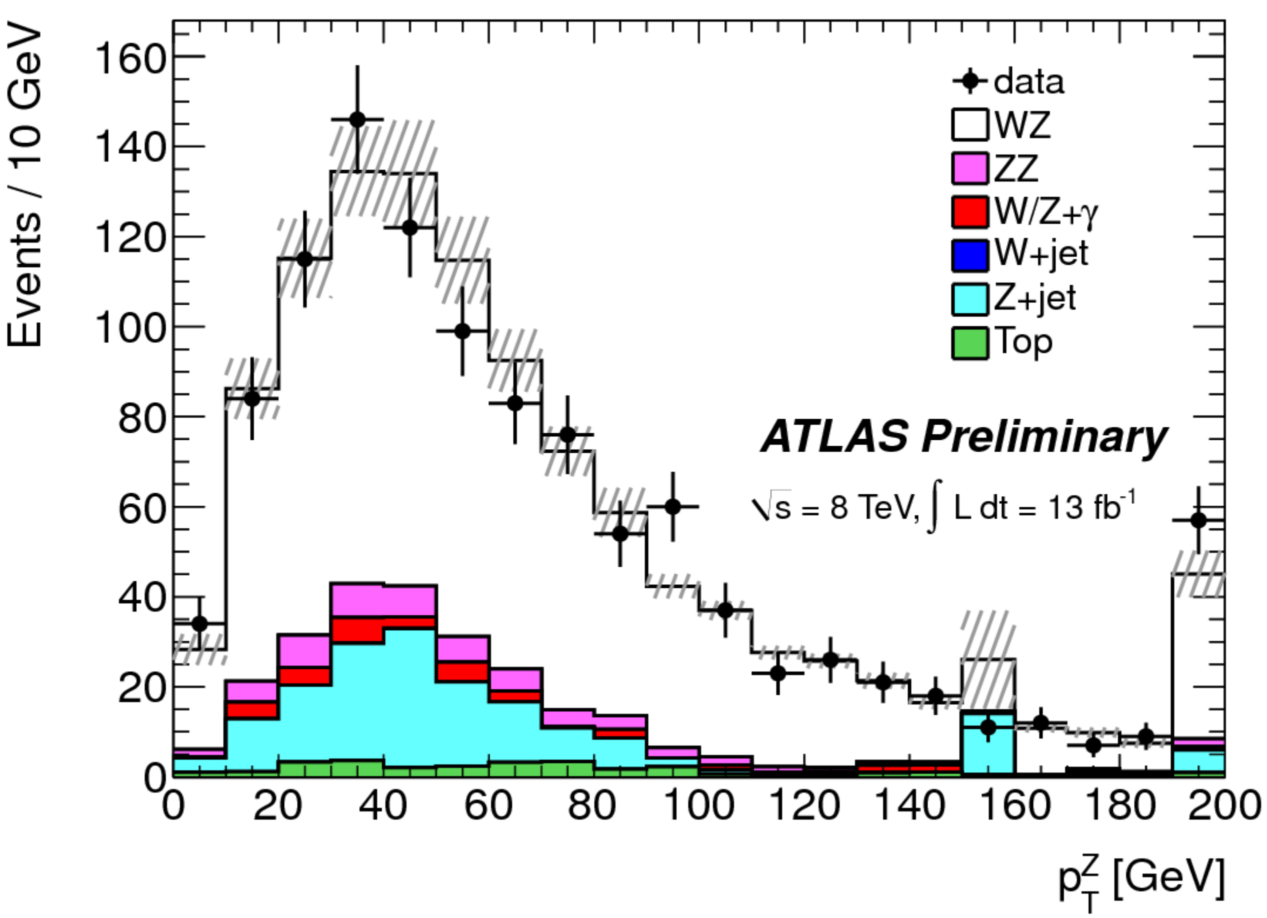
W±Z production

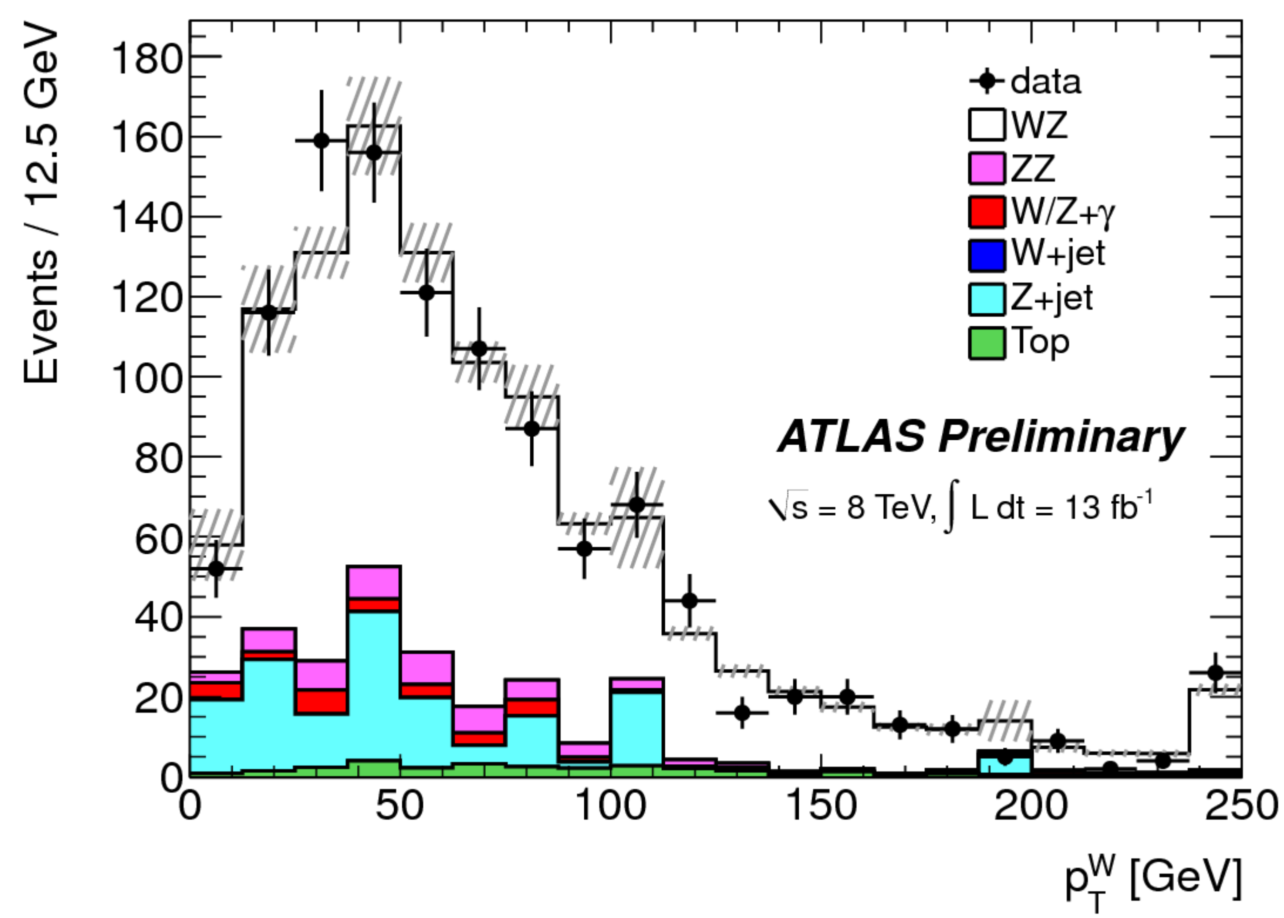
Eur,Phys. J. C. (2012), 72:2173, ATLAS-CONF-2013-021

- Measured final states
  - $\ell^{\pm}\nu\ \ell^{\pm}\ell^{\mp}$ (ℓ:e,μ)
- Backgrounds
  - Z+jets (~15%), Top (~4%) (data driven)
  - ZZ (~5%) and W/Z + γ (~3%) (MC estimate)

Event selection

- 3 isolated high-p_T leptons and E_T^{miss}
- tight Z-mass window $|M_{\ell\ell}-M_{PDG}| < 10$ GeV
- tight isolation and identification criteria on the W-lepton

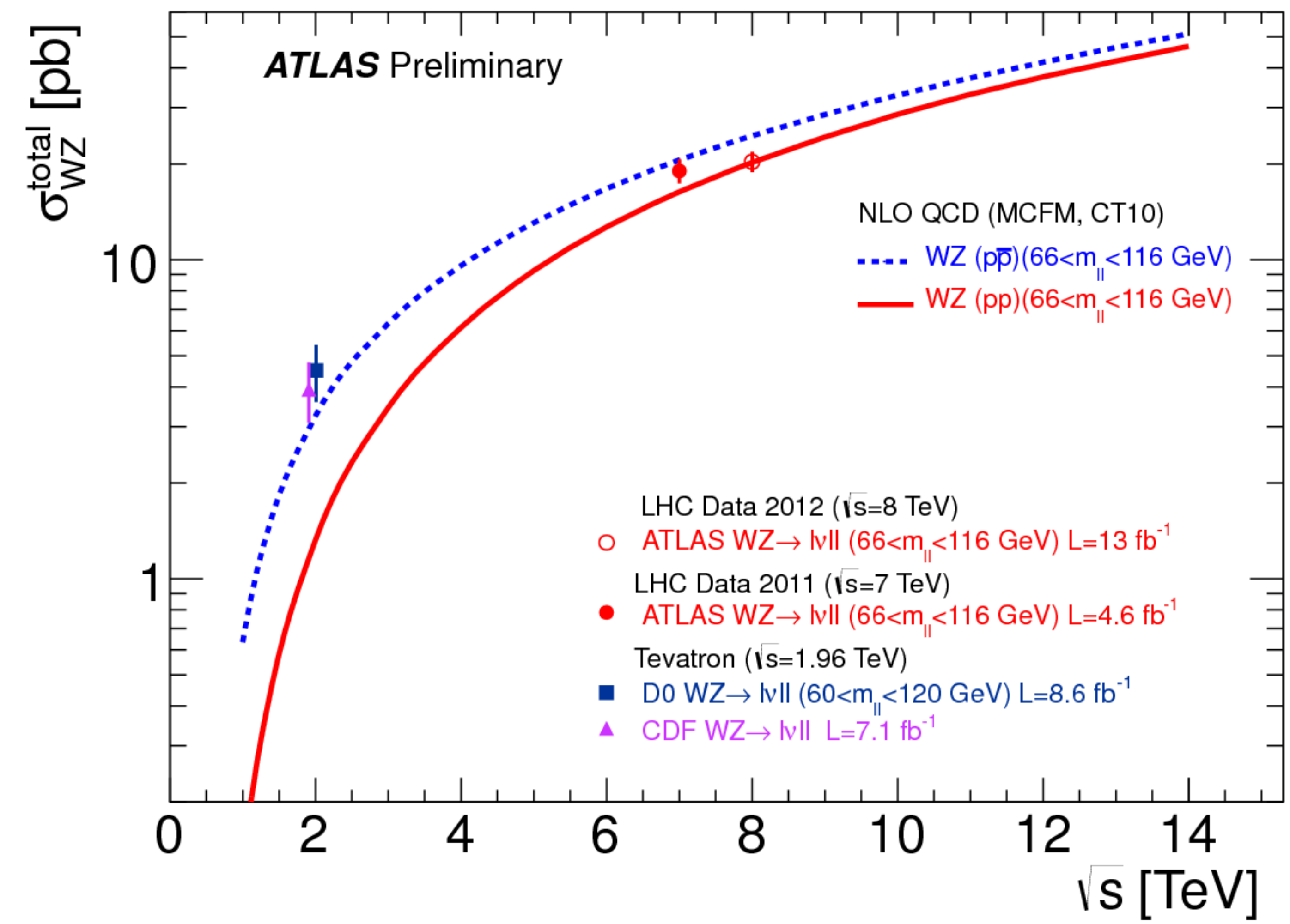




$W^{\pm}Z$ production

Eur,Phys. J. C. (2012), 72:2173, ATLAS-CONF-2013-021

- Compatible with SM expectation from MCFM
- Systematic uncertainties dominate at 8 TeV measurement
  - Data-driven background estimate
  - Reconstruction efficiencies
  - Luminosity



$\sqrt{s}$	$\int \mathcal{L}dt$ [fb^{-1}]	Measurement [pb]	Theory (MCFM) [pb]
7 TeV	4.6	$19.0^{+1.4}_{-1.3}$(stat)$^{+0.9}_{-0.9}$(syst)$^{+0.4}_{-0.4}$(lumi)	$17.6^{+1.1}_{-1.0}$
8 TeV	13	$20.3^{+0.8}_{-0.7}$(stat)$^{+1.2}_{-1.1}$(syst)$^{+0.7}_{-0.6}$(lumi)	20.3±0.8

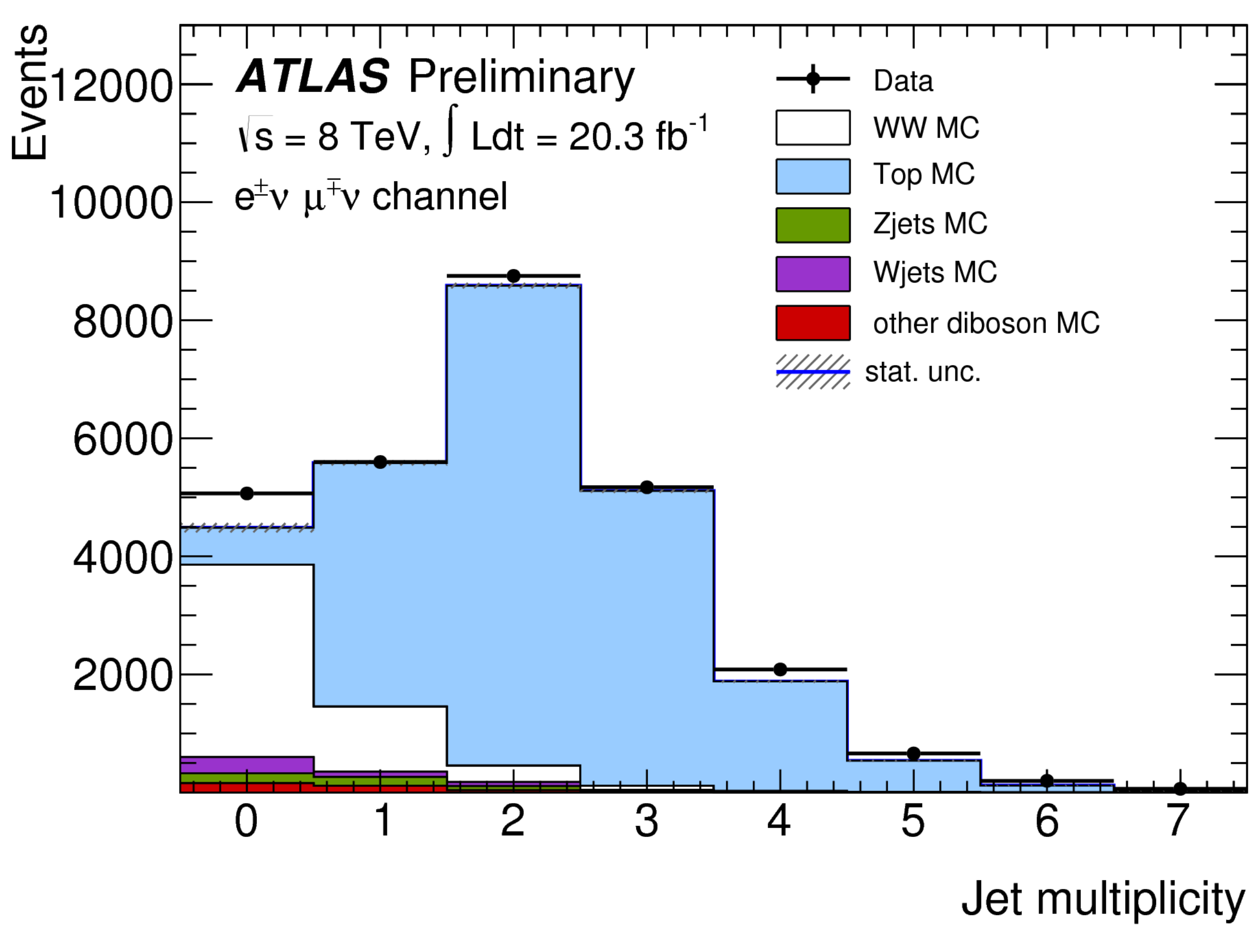
$W^{\pm}W^{\mp}$ production

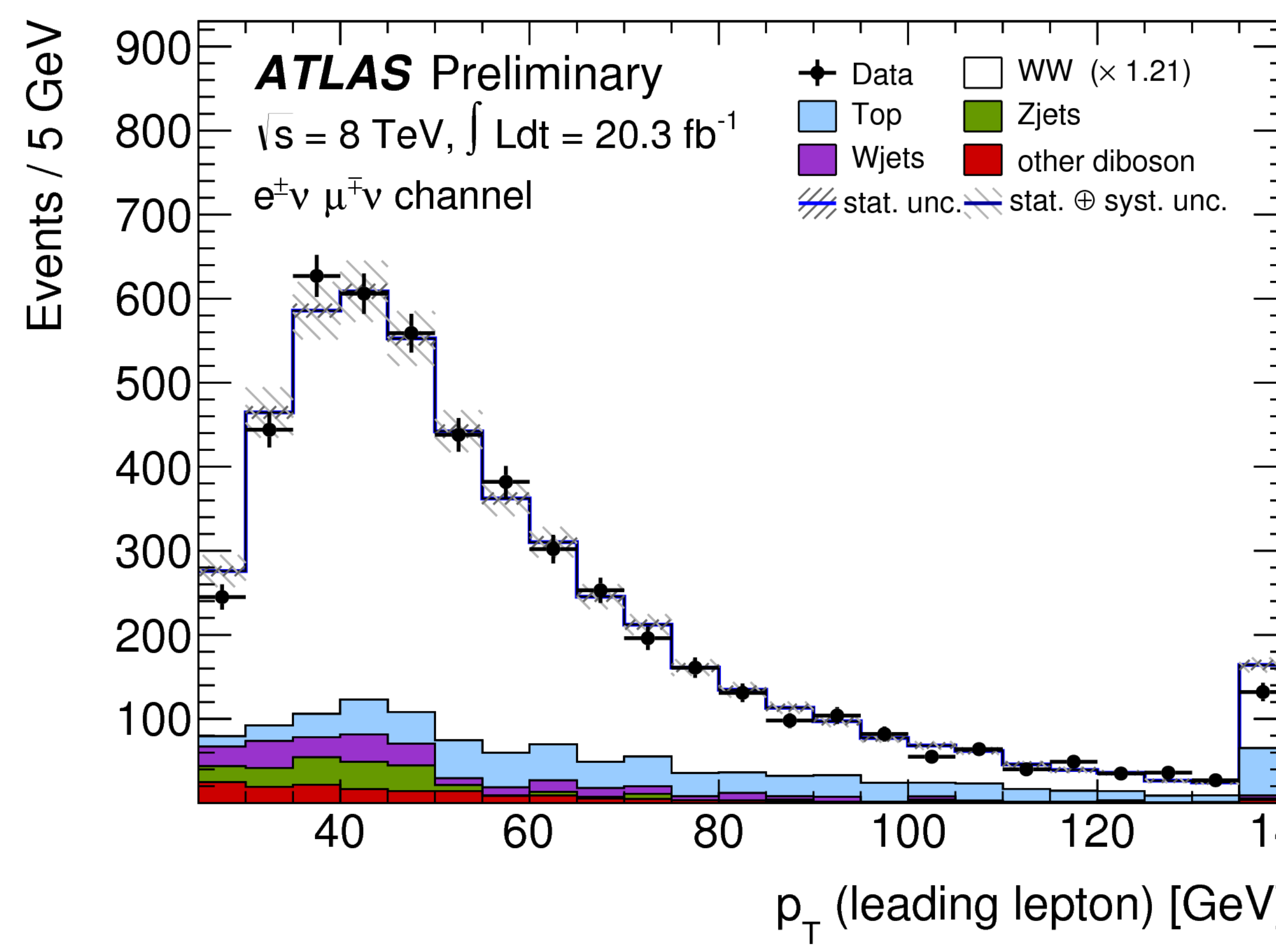
Phys.Rev.D 87, 112001 (2013), ATLAS-CONF-2014-033

- Measured final states
  - * $\ell^{\pm}\nu\ell^{\mp}\nu$ (ℓ:e,μ) in 0-jet bin
- Backgrounds
  - * Top (~15%), Drell-Yan (~5%), W+jets (~5%) (data driven)
  - * various di-bosons (MC estimate)

Event selection

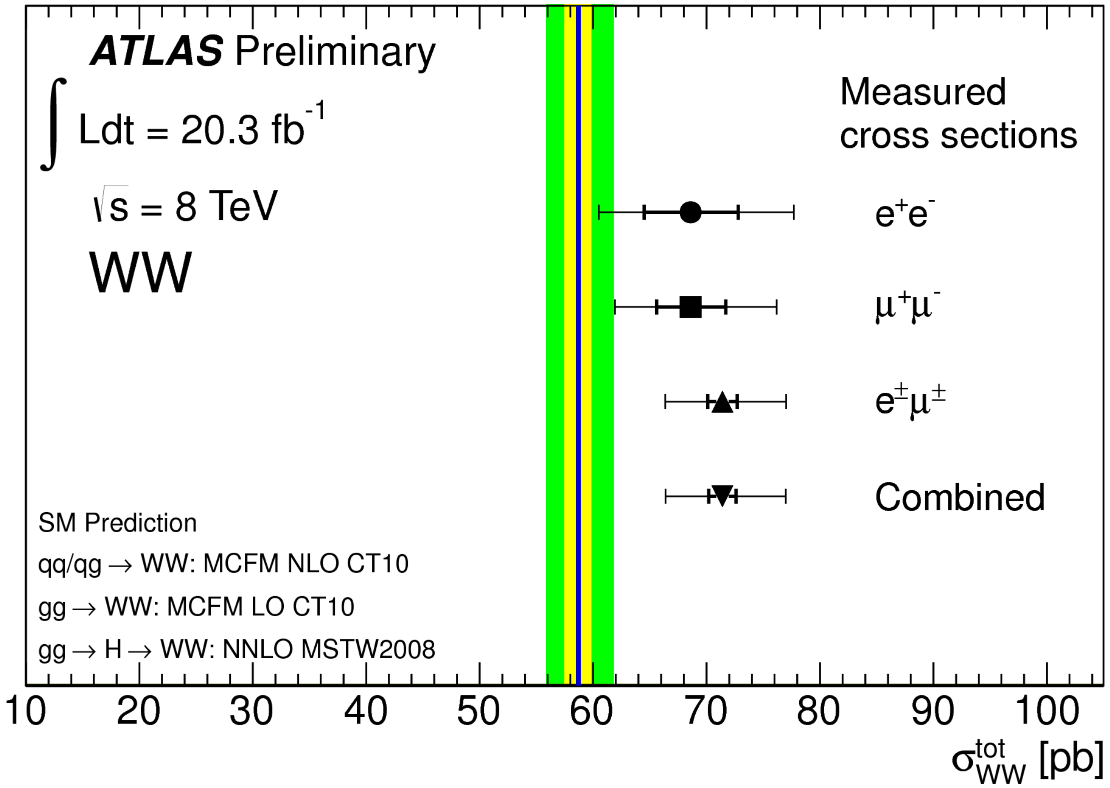
- ☑ 2 isolated high-p_T leptons and E_T^{miss}
- ☑ hard jet-veto to reject ttbar and single top events
- ☑ Z-veto $|m_Z - m_{\ell\ell}| > 15$GeV to suppress Drell-Yan background in same flavor channels

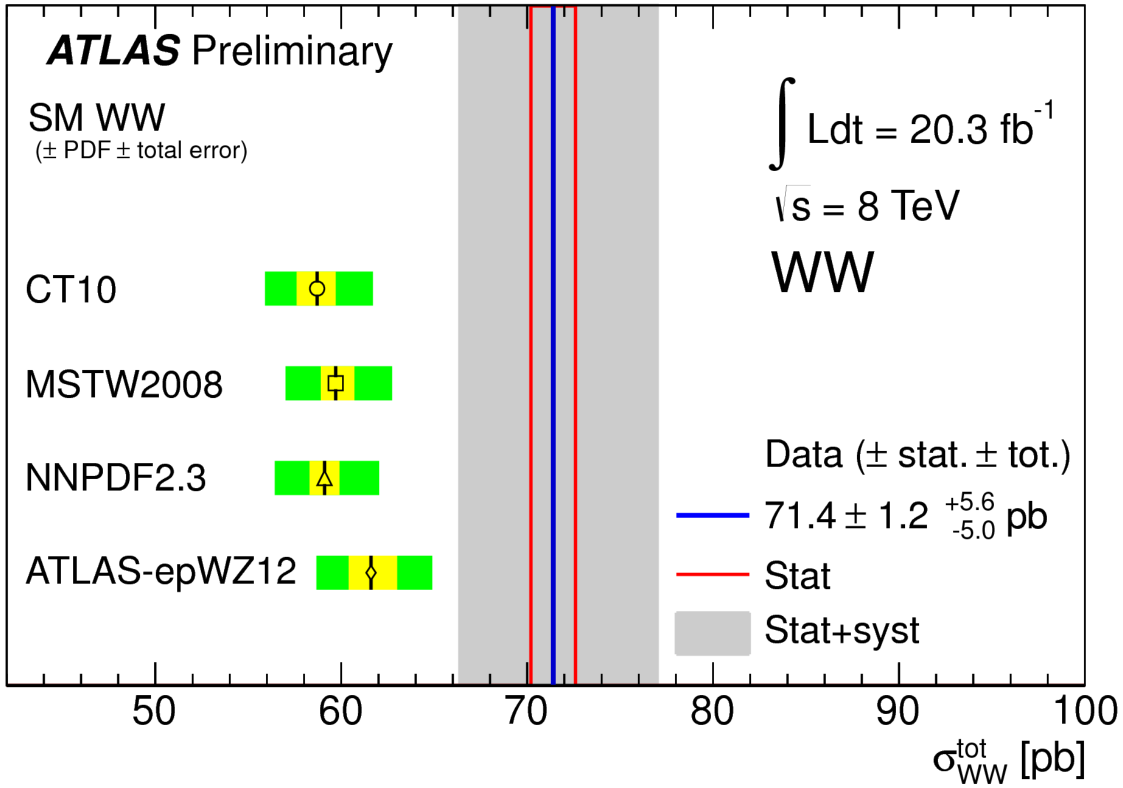




$W^{\pm}W^{\mp}$ production

Phys.Rev.D 87, 112001 (2013), ATLAS-CONF-2014-033





- Measured cross section higher than SM prediction (CT10 NLO pdf) by ~2.1σ
- NNLO corrections: Enhancement of cross section by ~10% *(arXiv:1408:5243)*
- NNLL resummation of large logs: Enhancement of cross section can partially explain the excess *(arXiv: 1407:4537, arXiv: 1407:4481)*

$\sqrt{s}$	$\int \mathcal{L}dt\ [\mathrm{fb}^{-1}]$	**Measurement [pb]**	**Theory (MCFM) [pb]**
7 TeV	4.6	51.9±2.0(stat)±3.9(syst)±2.0(lumi)	$44.7^{+2.1}_{-1.9}$
8 TeV	20.3	71.4±1.2(stat)$^{+5.0}_{-4.4}$(syst)$^{+2.2}_{-2.1}$(lumi)	$58.7^{+3.0}_{-2.7}$

$W^{\pm}W^{\mp}/W^{\pm}Z$ production in semileptonic final state

JHEP01(2015)049

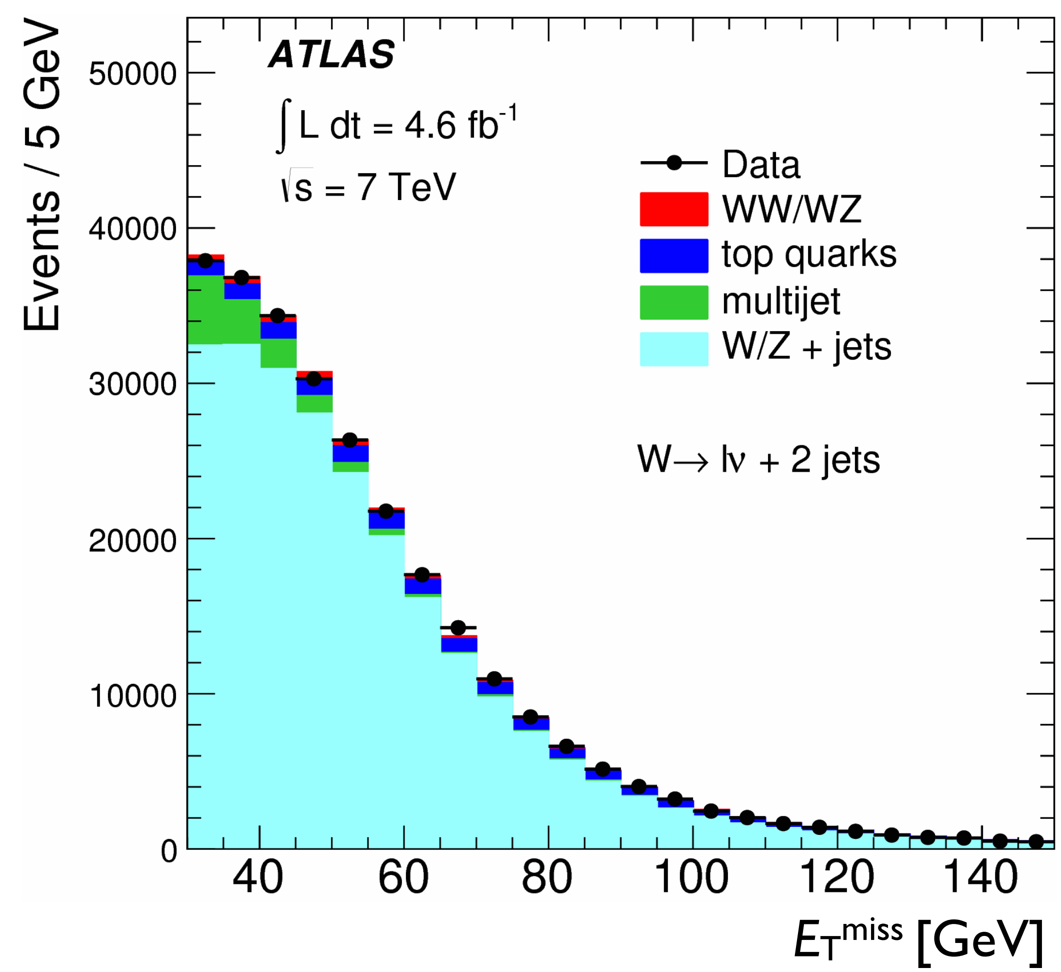
Event Selection

- single lepton triggers
- isolated high-p_T lepton, E_T^{miss} and two jets
- $p_T(e,\mu,jets) > 25$ GeV
- $E_T^{miss} > 30$ GeV
- $m_T(W) > 40$ GeV
- $\Delta\phi(E_T^{miss}, j) > 0.8$
- $\Delta\eta(j_1,j_2) < 1.5$
- 25 GeV < m_{jj} < 250 GeV

to suppress multijet bkg

to increase signal-to-bkg ratio

- Measured final states
  - $\ell^{\pm}\nu jj$ (ℓ: e,μ)



Background composition

- W/Z+jets (89%), multijet (~5%) - data driven estimate
- top (~4%) - MC estimate

	Electron channel	Muon channel
Total Background	~126000	~132500
Data	127650	134846

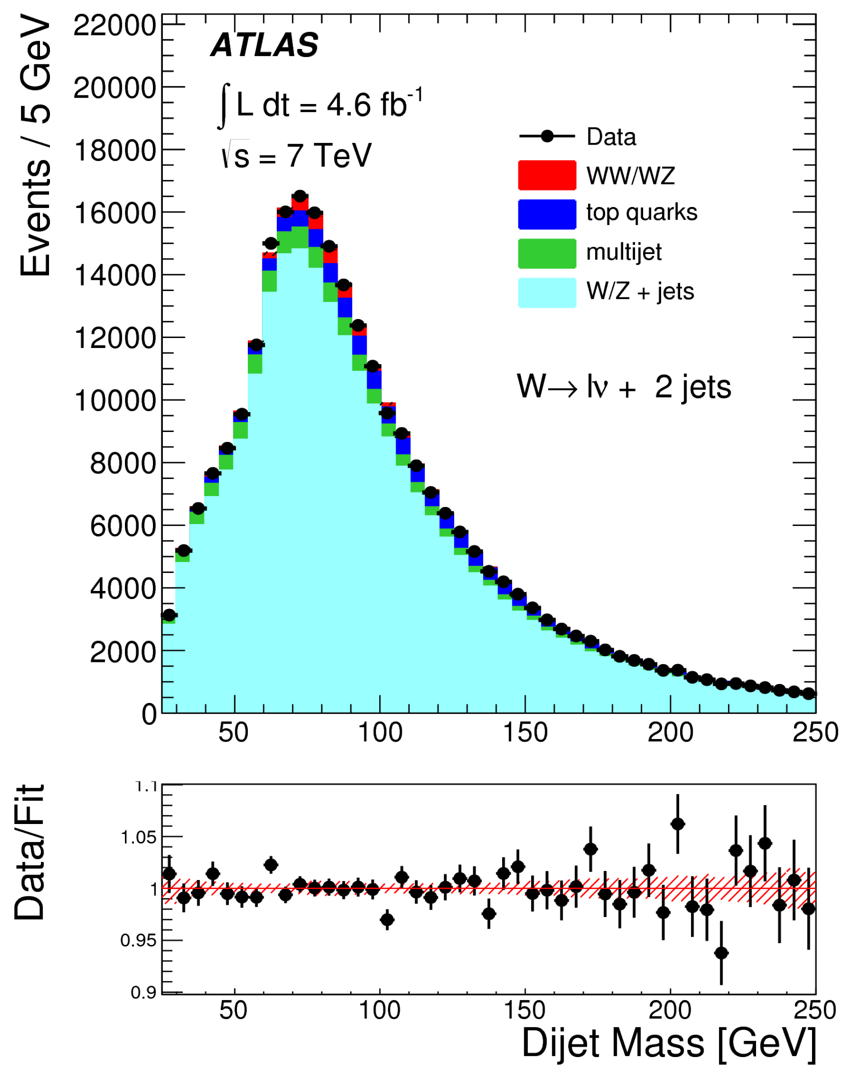
$W^{\pm}W^{\mp}/W^{\pm}Z$ production in semileptonic final state

JHEP01(2015)049

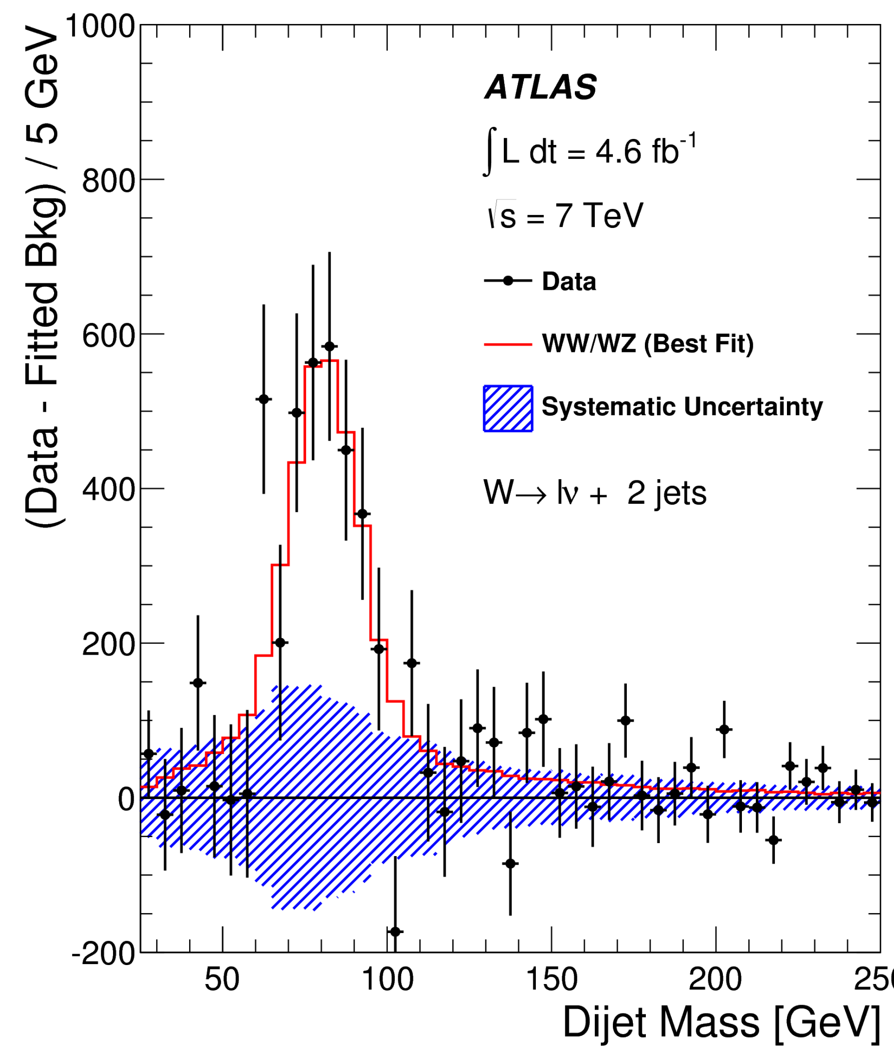
- fiducial cross section measurement and extrapolation to the total phase space
  - simultaneous maximum likelihood fit to m_{jj}

dominant systematics

- W/Z+jets rate
- Jet energy resolution



dijet invariant mass after the likelihood fit



background-subtracted data

	Measurement [pb]	Theory (MC@NLO) [pb]
σ^{tot}	68±7(stat)±19(syst)	61.1±2.2

signal significance
3.4σ

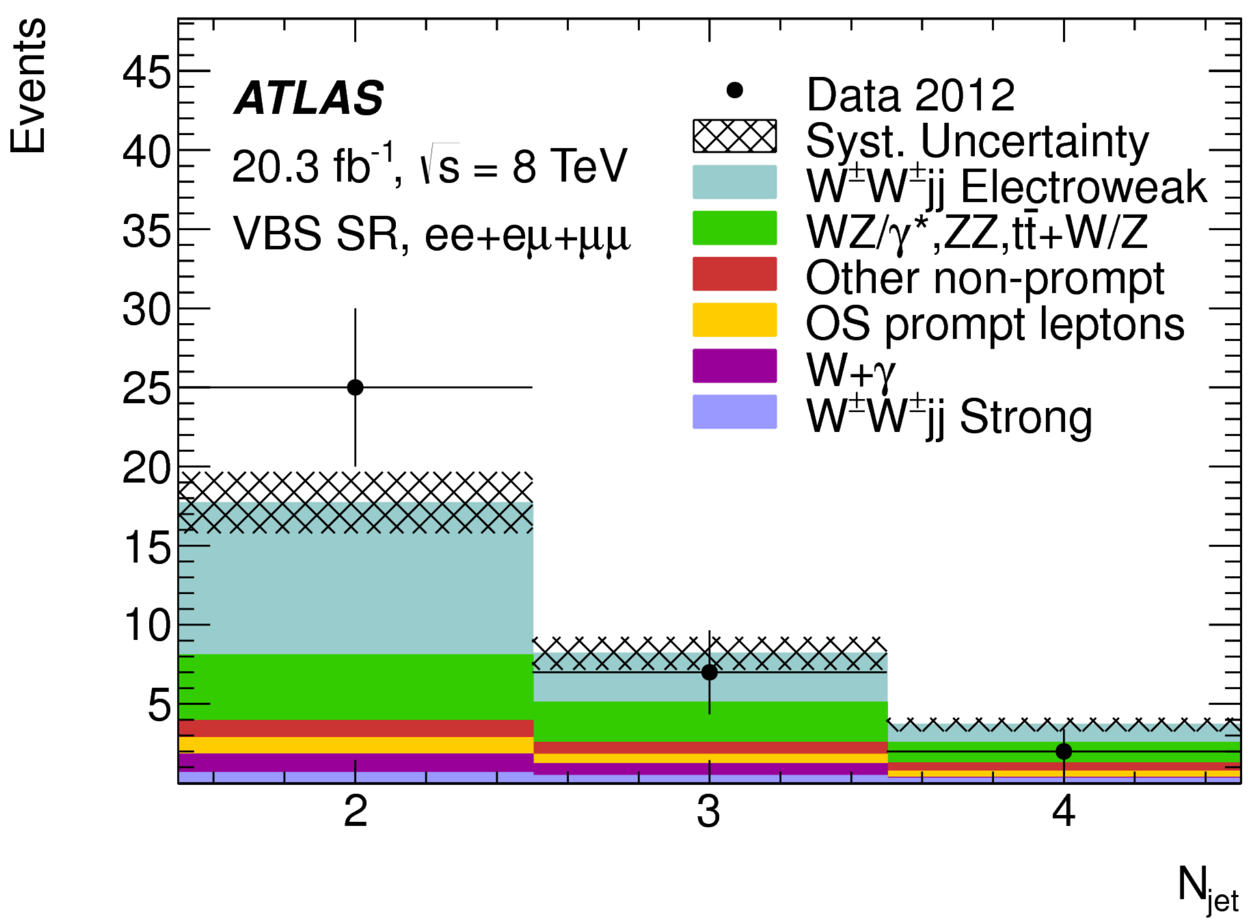
$W^{\pm}W^{\pm}$+2jets production

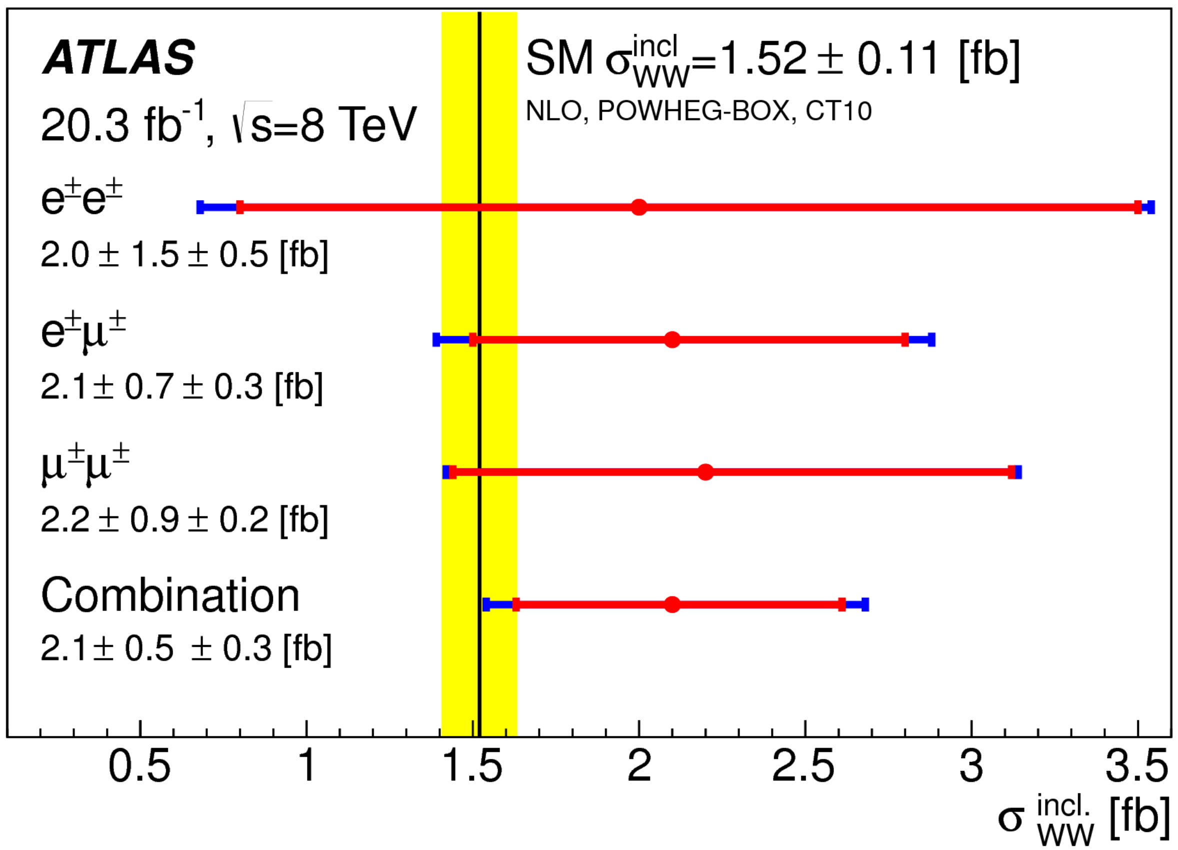
PRL 113, 141803 (2014)

More details on talk by K. Bachas

First evidence of VV→VV scattering

- Measured final states
  - $\ell^{\pm}\nu\ell^{\pm}\nu+jj$ (ℓ:e,μ)
- Backgrounds
  - WZ+ 2 jets, Wγ+ 2 jets - MC estimate
  - ttbar, single Z production through charge misidentification - data driven estimate



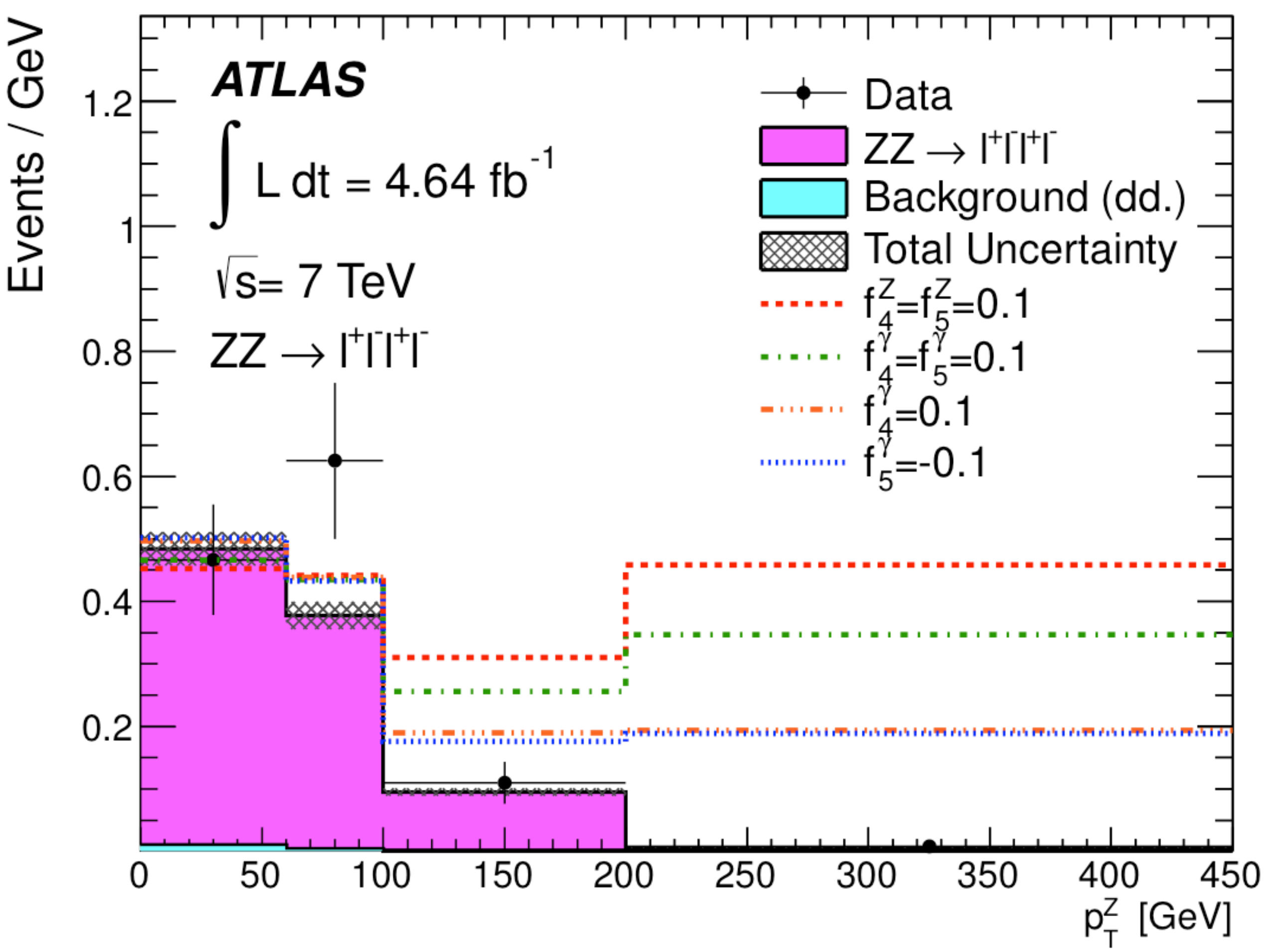


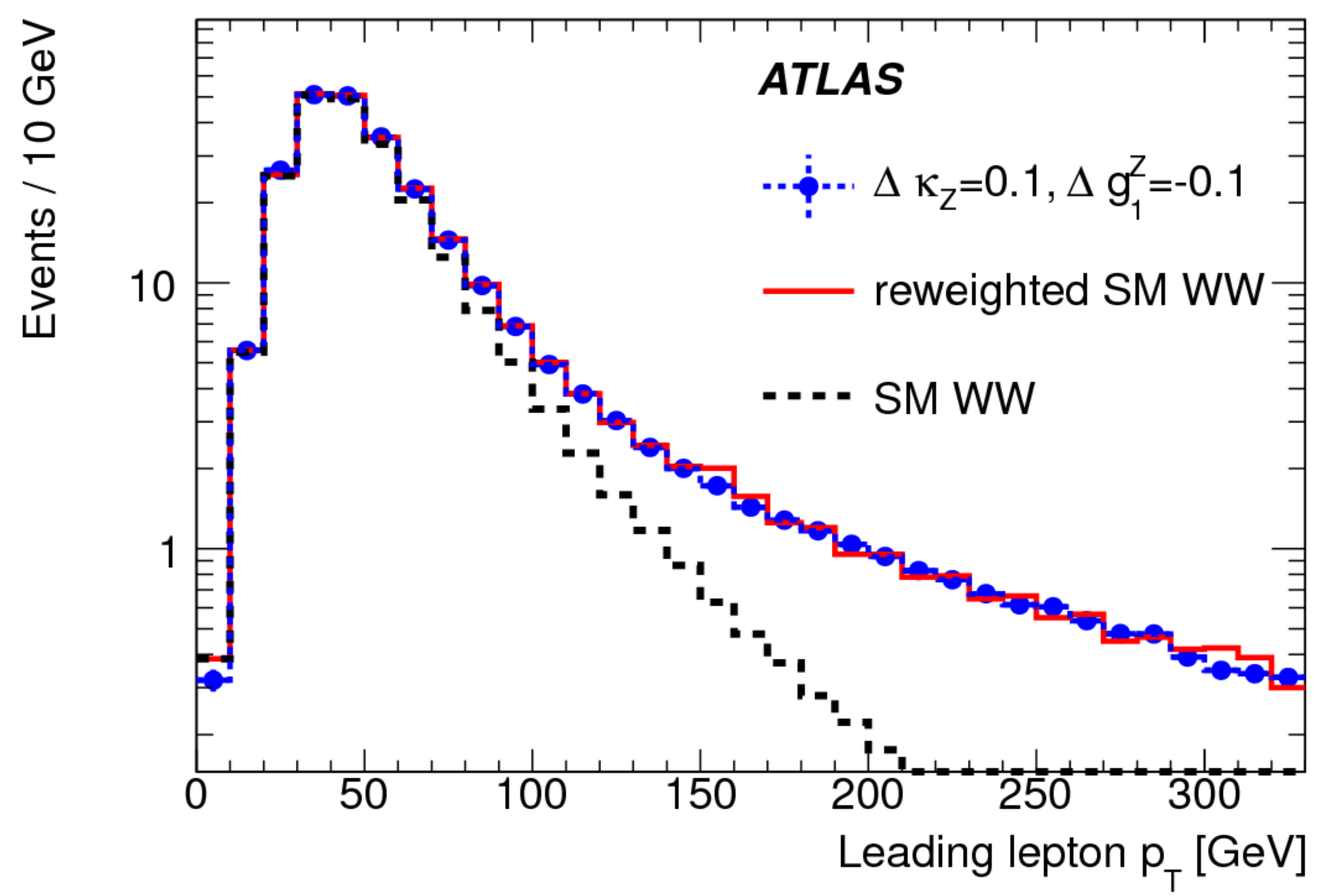
dominant systematics

- Jet energy scale
- WZ+jets normalization

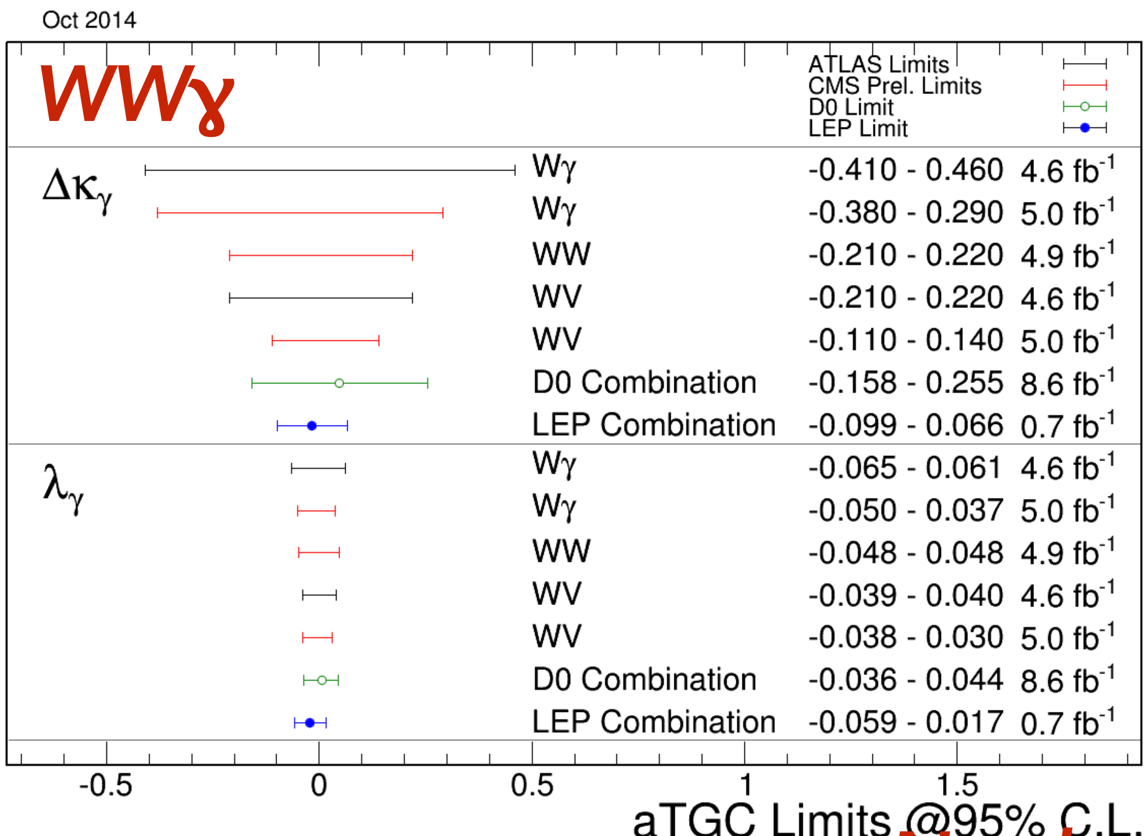
Anomalous gauge boson couplings

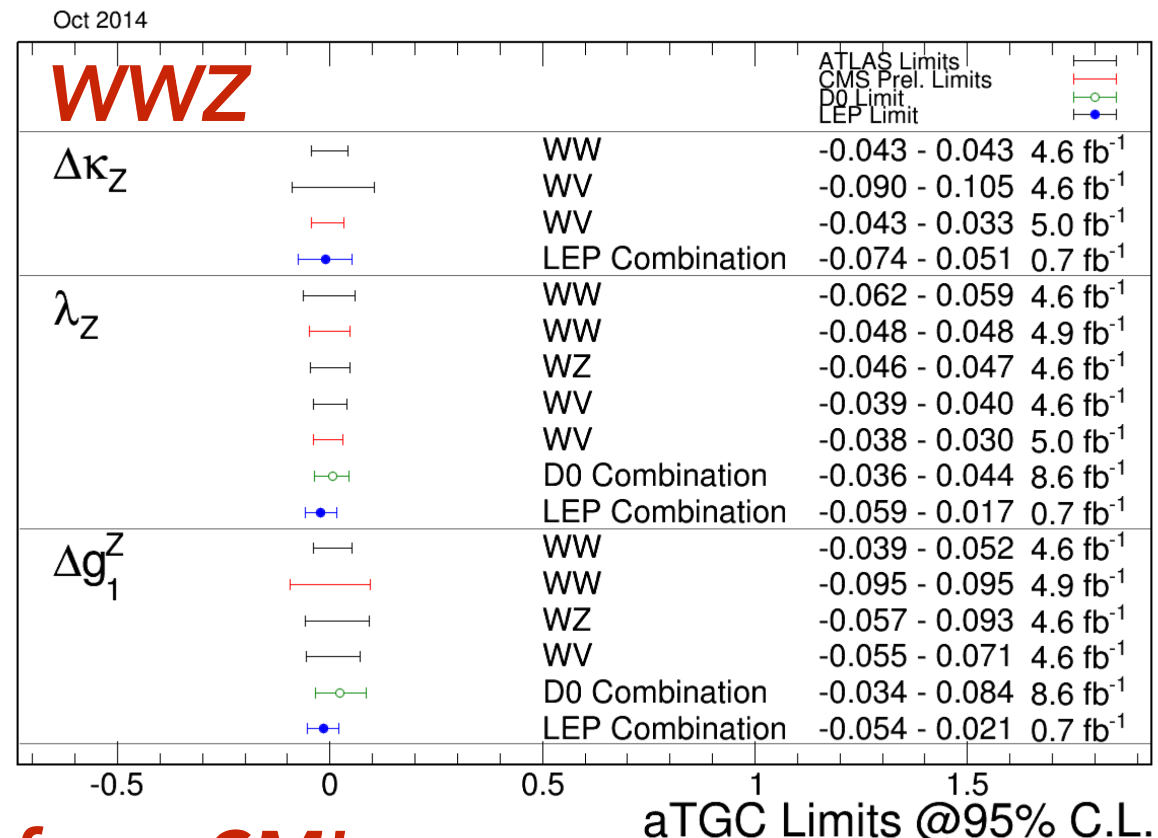
- Self interactions of gauge bosons are predicted by the SM (non-abelian nature of the EWK)
- Anomalous couplings can manifest themselves with **increased cross sections** and **modification of kinematic distributions**
- Effective Lagrangians approach to parametrize the anomalous couplings as deviations from SM (SM+higher order operators)



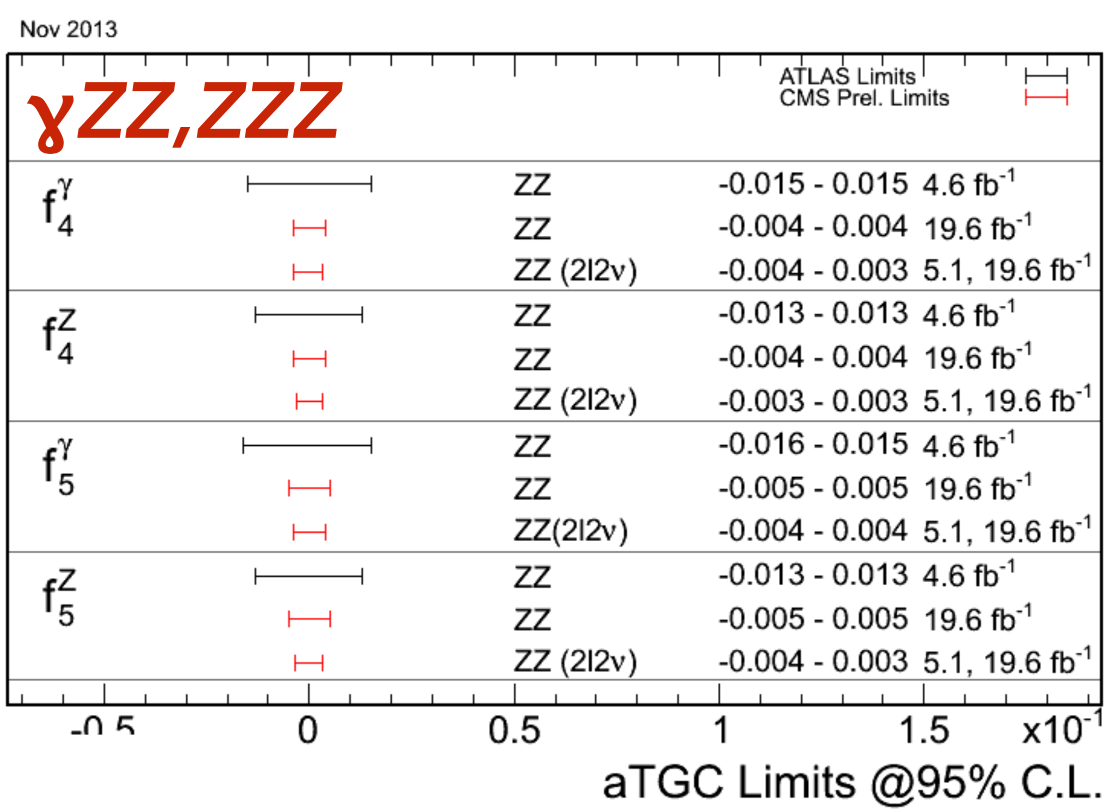


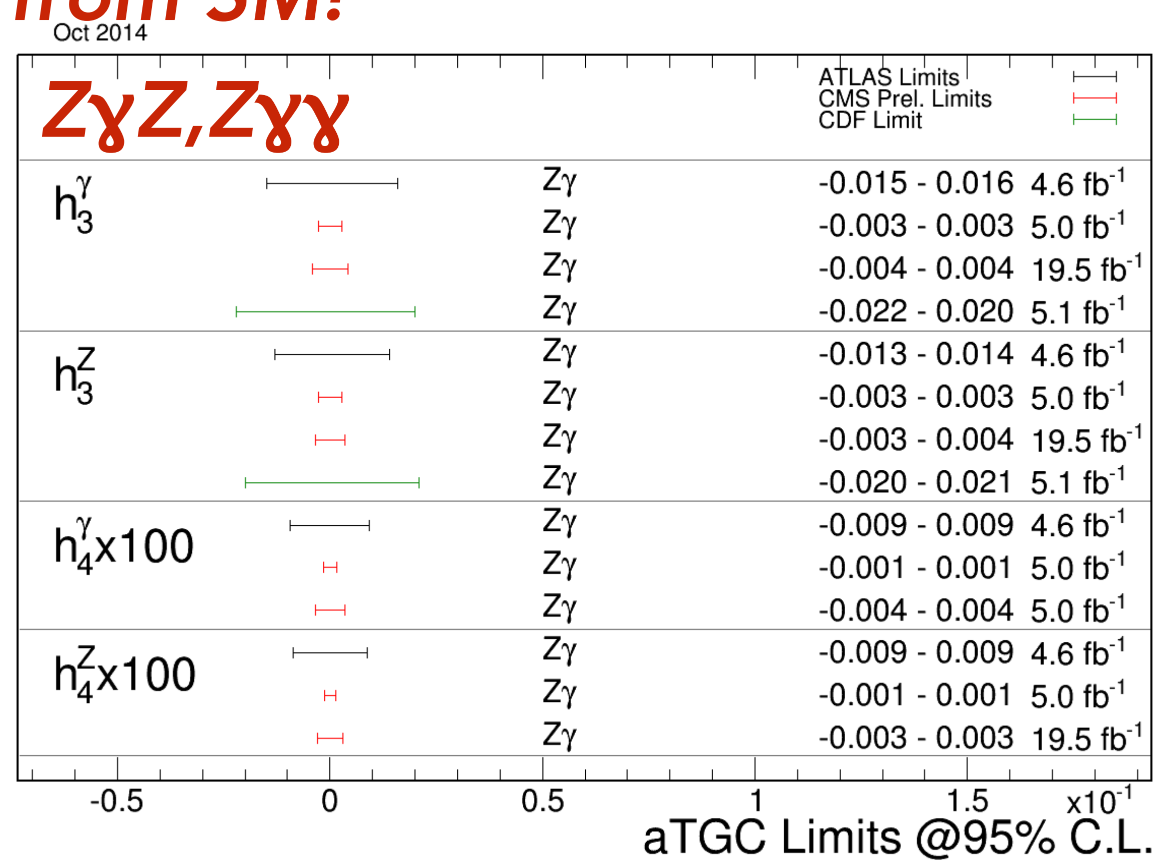
Summary of aTGC Limits





No deviations from SM!

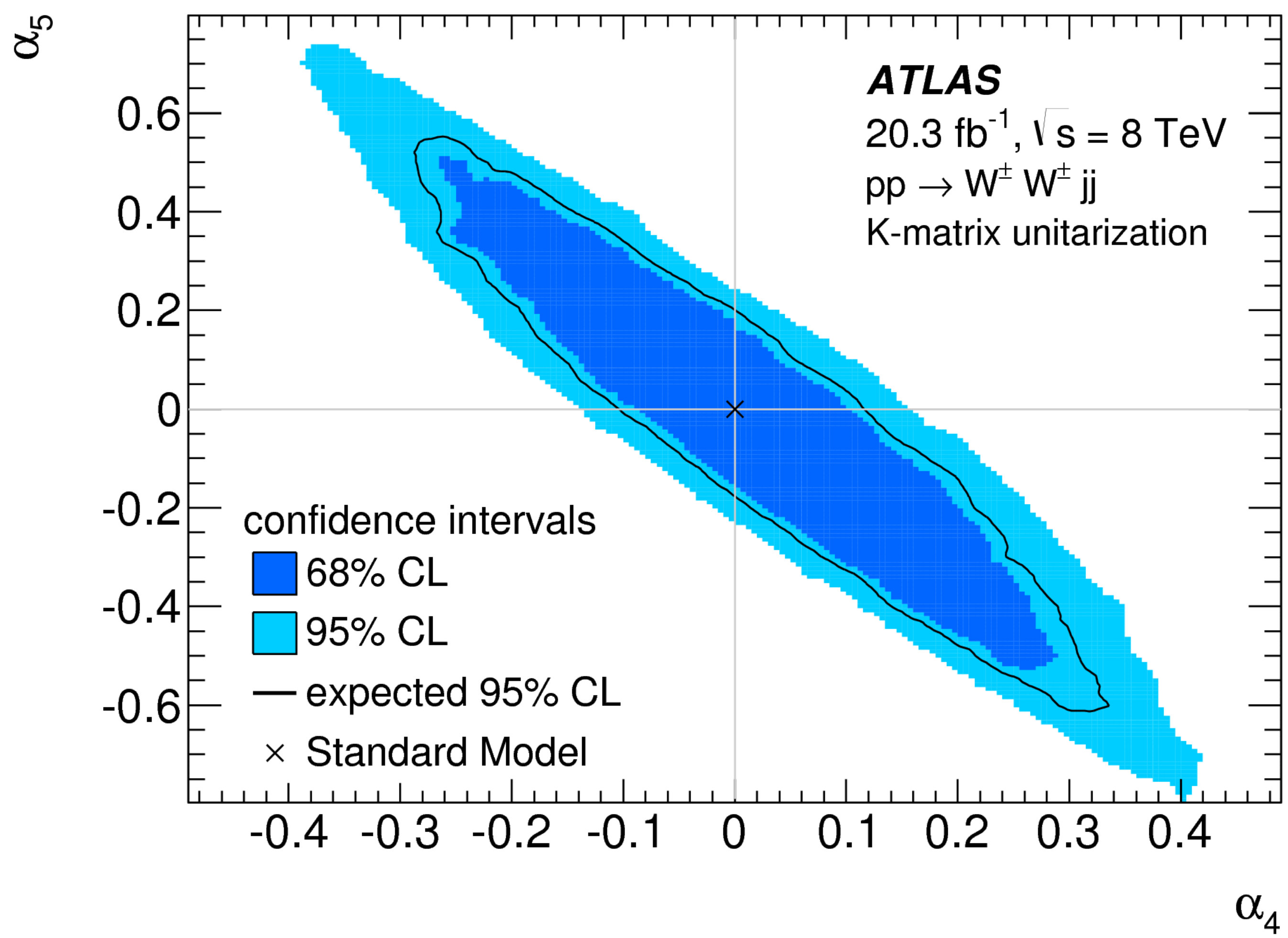




First limits on aQGC

More details on talk by K. Bachas

- Measurement of VBS allows limit setting on anomalous quartic couplings



Conclusions

- Very good understanding of the physics processes with high precisions
- Excellent performance of the ATLAS detector
  - Di-boson measurements of fiducial, total and differential cross sections with 7 and 8 TeV
  - Exclusion limits on aTGC, no deviations from the SM, expected sensitivity will increase at higher centre-of-mass energies
  - Evidence of the same sign WW+2 jets EW production (3.6σ significance)
  - First limits on aQGC through VBS

- Looking forward for Run-2 and beyond for more precise measurements and probes for new physics!

back up

MC simulation

- Wγ/Zγ
  - lνγ: Alpgen+Herwig(PS)+Jimmy(UE)
  - llγ, ννγ: Sherpa
  - Z(ll):Pythia, ttbar:Powheg, WW,Top:MC@NLO
- ZZ
  - Powheg+Pythia and gg2ZZ
  - Z/W+jets, Z/Wγ: Alpgen
  - ttbar: MC@NLO, single Top: AcerMC(MC@NLO)
  - WZ (WW): Herwig(Powheg), Z/Wγ Madgraph
- WZ
  - MC@NLO+Herwig+Jimmy(7TeV), Powheg(8TeV)
  - Z/W+jets, DY: Alpgen, WW: MC@NLO, ZZ: Powheg
  - multijet: PythiaB, ttbar: MC@NLO, W/Z+γ, ttbar+W/Z: Madgraph
- WW
  - MC@NLO+Herwig+Jimmy and gg2WW(7TeV), Powheg+Pythia(8TeV)
  - Z/W/γ+jets, DY, Wγ: Alpgen, WZ/ZZ: Herwig(7TeV), Powheg(8TeV)
  - ttbar: MC@NLO, single Top: AcerMC
- WV semileptonic
  - diboson:MC@NLO+Herwig+Jimmy
  - W/Z+jets: Alpgen+Herwig+Jimmy
  - ttbar:MC@NLO+Herwig+Jimmy, single Top:MC@NLO
  - ZZ:Herwig, Wγ: Madgraph
- ssWW+2jets
  - Sherpa
  - WZ/γ+jets, ZZ+jets: Sherpa
  - ttbar+W/Z:Madgraph
  - Wγ:Alpgen

$W^\pm W^\pm$+2jets production

PRL 113, 141803 (2014)

parameter	observed limit	expected limit
a4	-0.139, 0.157	-0.104, 0.116
a5	-0.229, 0.244	-0.180, 0.199

	Measurement [fb]	Theory [fb] (PowhegPythia8)	signal significance
Inclusive	2.1±0.5(stat)±0.3(syst)	1.96±0.17	4.5
EW-only	1.3±0.4(stat)±0.2(syst)	1.18±0.05	3.6

aTGC parameters

Vertex	Parameters	channel
$WW\gamma$	λ	WW, $W\gamma$
WWZ	λ_Z	WW, WZ
$ZZ\gamma$	h	$Z\gamma$
$Z\gamma\gamma$	h	$Z\gamma$
$Z\gamma Z$	f_4	ZZ
ZZZ	f_4	ZZ