Measurements of four-lepton production in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector

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On behalf of ATLAS Collaboration

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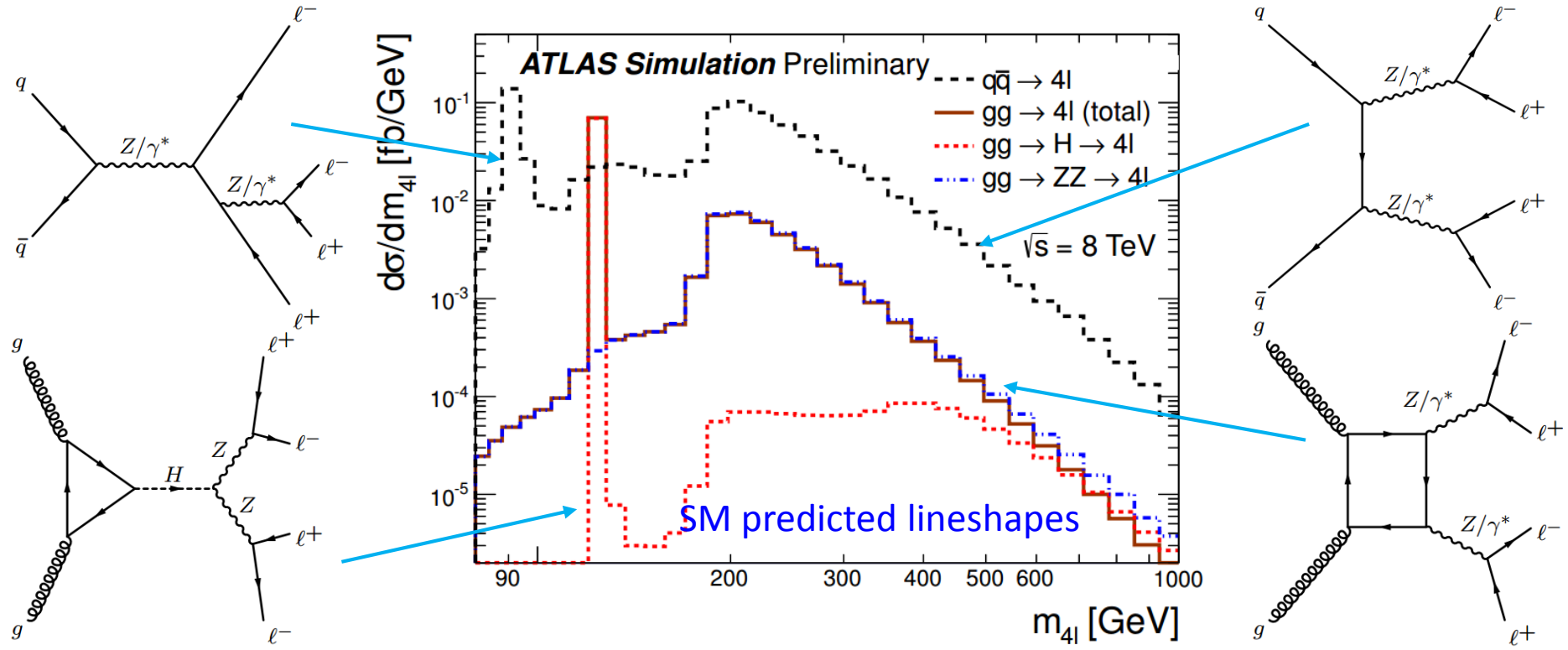
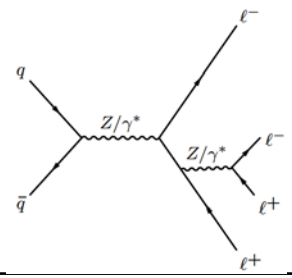
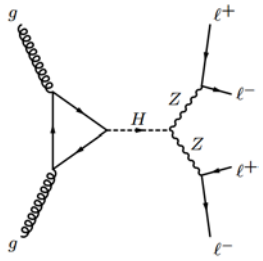
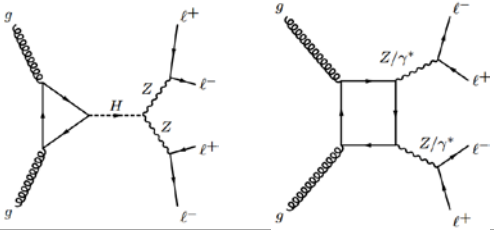
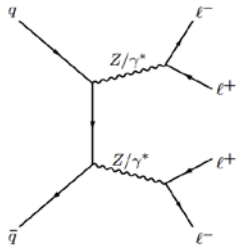
Introduction

- Very rich physics with 4l production at the LHC
  - Produced in resonant Z- and H-bosons, as well as continuum ZZ productions from qq, gg, and qg initial states
  - An important channel to test SM gauge sector and Higgs sector
  - Sensitive to new physics



Four-lepton measurements

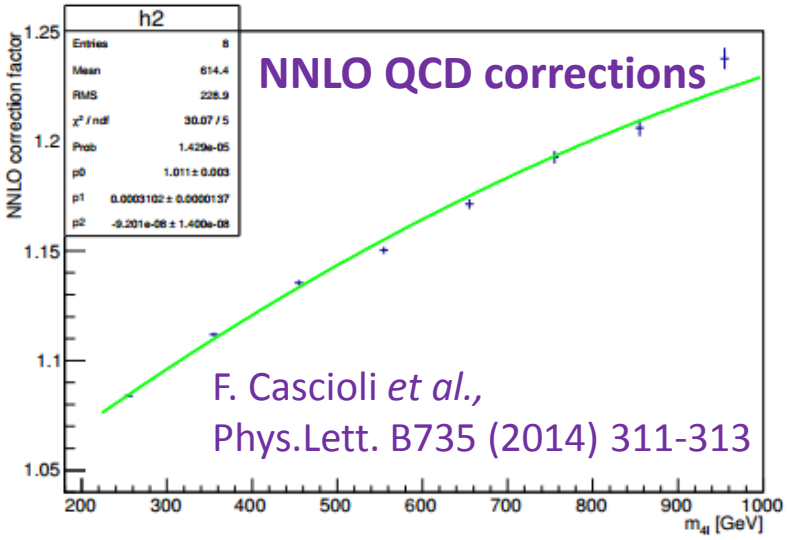
Single Z resonance 	ATLAS: Phys. Rev. Lett. 112, 231806 CMS: JHEP 12 (2012) 034	m_{4l}[80, 100] GeV
H→ZZ→4l 	Higgs discovery ATLAS: Phys.Lett. B716 (2012) 1-29 CMS: Phys. Lett. B 716 (2012) 30	m_{4l}[120, 130] GeV
off-shell Higgs 	ATLAS: arXiv:1503.01060 CMS: Phys. Lett. B 736 (2014) 64	ATLAS: m_{4l} > 350 GeV CMS: m_{4l}> 400 GeV
on shell ZZ 	ATLAS: ATLAS-CONF-2013-020 CMS: Phys. Lett. B 740 (2015) 250	ATLAS: m_Z [66, 116] GeV CMS:m_Z [60, 120] GeV

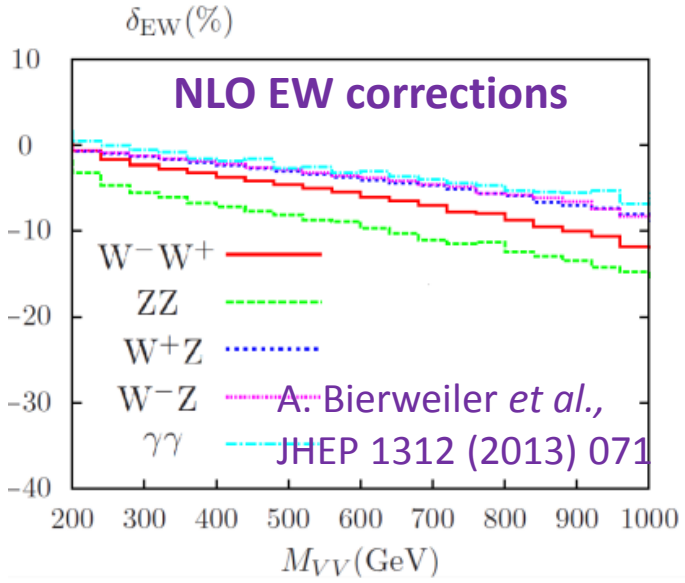
Analysis overview

- Physics goals:
  - Measure the 4l (4e, 4μ, 2e2μ) production cross section (integrated and differential) inclusively (Z/H/ZZ) from [80, 1000] GeV
  - Determine the signal strength of the gg→ZZ in high mass region m_{4l} > 180 GeV
- Dataset used: 20.3 fb^{-1} at 8 TeV
- Signal modeling:
  - qq→ZZ and on-shell Higgs (ggF and VBF): Powheg(NLO QCD)+ Pythia8, with higher-order corrections (NNLO QCD and NLO EW)
  - On-shell Higgs (VH and ttH): Pythia8
  - VBF ZZ and off-shell Higgs (and interference): Madgraph
  - gg→(H*→)ZZ: MCFM(LO QCD) + Pythia8
- Background (~5% of the total event yields):
  - Z+jets, $t\bar{t}$ are estimated with data
  - WZ, Zγ, tZ, $t\bar{t}V$, VVV (V=W, Z), DPI ZZ are estimated with Monte Carlo (MC)

High order corrections

- NNLO QCD and NLO EW corrections are used for
  - **qq→ZZ**, for normalization and for m_{4l} spectrum correction
  - **On-Shell Higgs production** for normalization





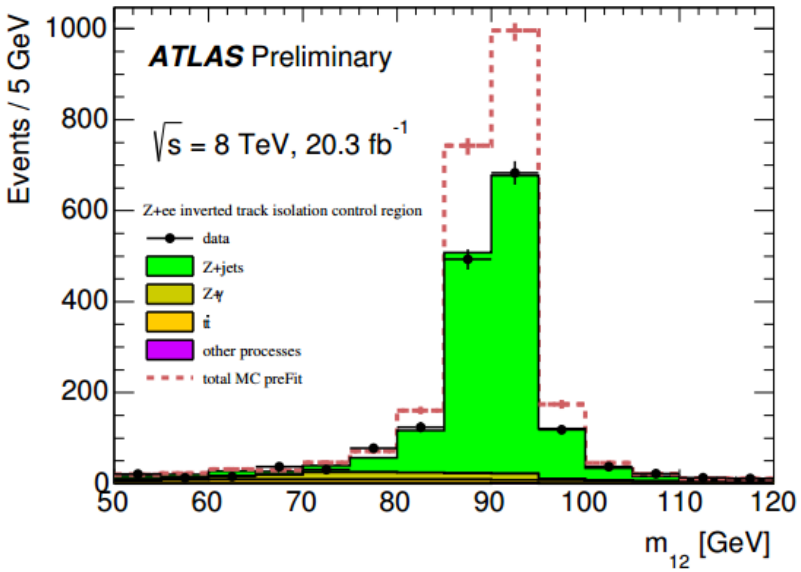
- Non-resonant gg→(H*)→ZZ:
  - NNLO QCD corrections are also available for the off-shell Higgs production
  - Only LO calculations available for gg→ZZ continuum process
  - LO cross section from MCFM is used to normalize the gg process

Main event selection

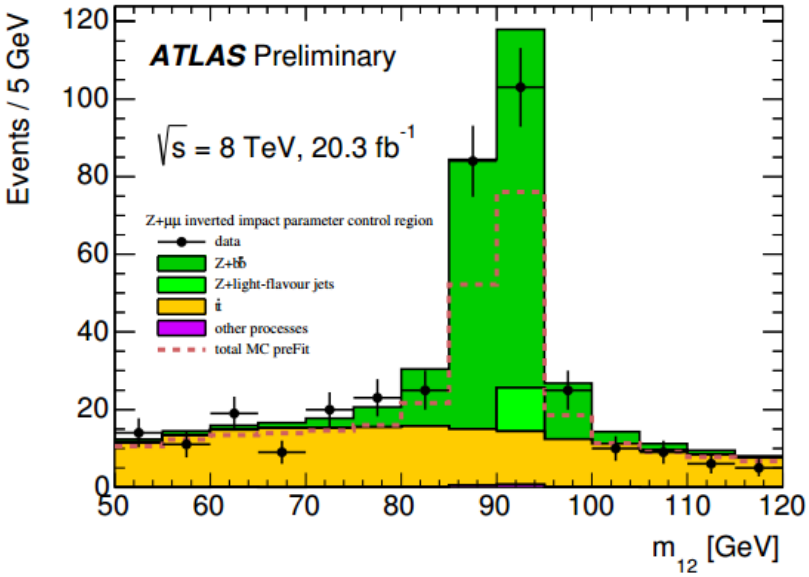
- Two pairs of same-flavor opposite-charge leptons (quadruplet):
  - Electrons: $E_T > 7$ GeV and $|\eta| < 2.47$
  - Muons: $p_T > 6$ GeV and $|\eta| < 2.7$
  - Passing isolation and impact parameter requirements
- Kinematic selection:
  - The three leading leptons in the quadruplet have $p_T >$ 20, 15, and 10 (8 for muon) GeV
  - Leading di-lepton pair: $50 < m_{12} < 120$ GeV
  - Sub-leading di-lepton pair: $12 < m_{34} < 120$ GeV
  - Dilepton pair $p_T > 2$ GeV
- Mass window: $80 < m_{4l} < 1000$ GeV

Fake background estimation

- Two types of reducible (fake) background:
  - Z(→ll) + μμ: fake muons from Z+ heavy flavor jets, $t\bar{t}$
  - Z(→ll) + ee: fake electrons from Z+ light flavor jets, $t\bar{t}$
- Perform simultaneously fit in background control regions
- The fitted scale factors in the control regions are extrapolated to the signal region using efficiencies obtained from simulation



ll+ee control region with inverted track isolation requirement

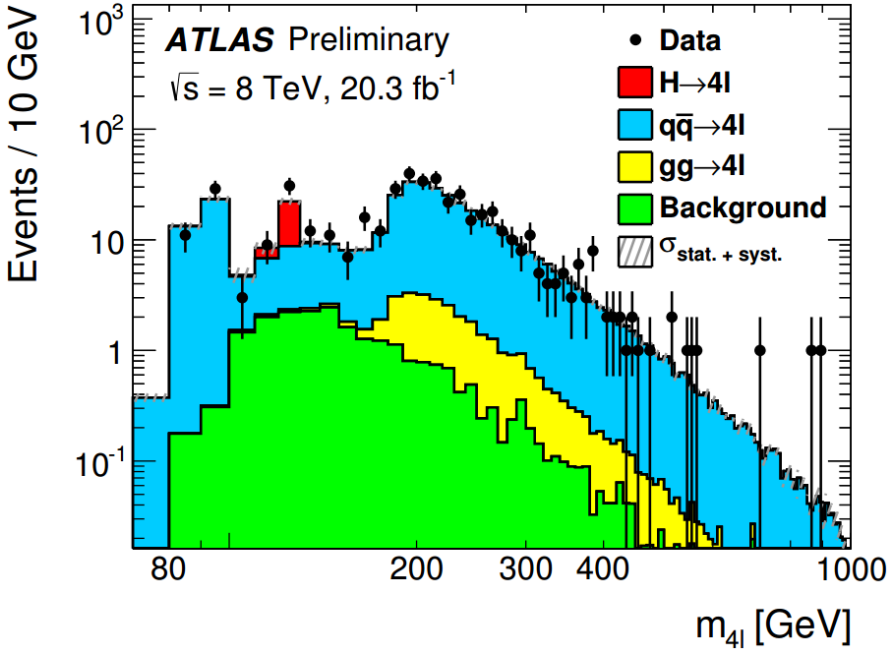


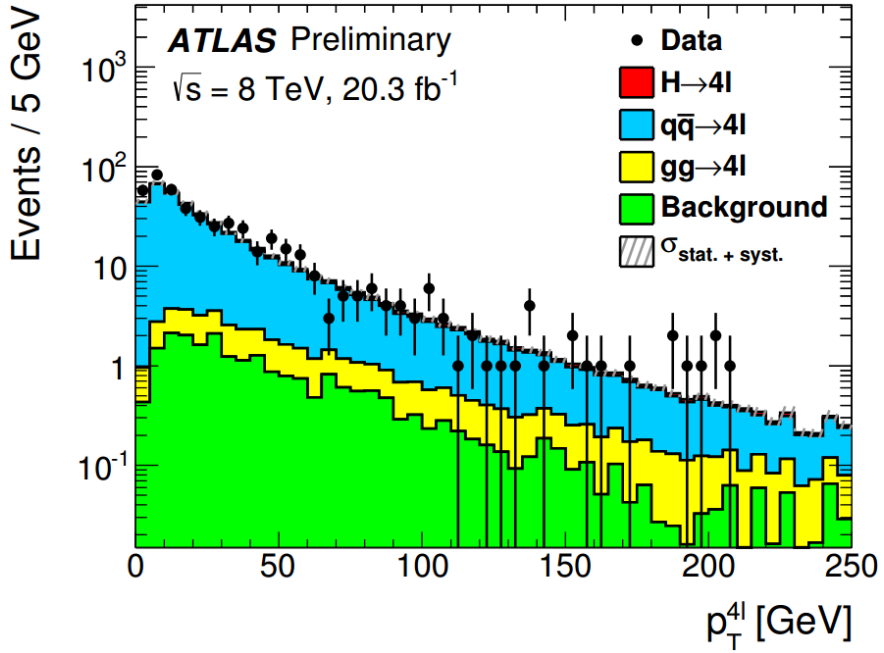
ll+ μμ control region with inverted impact parameter requirement

Observed and predicted events

- Observed and predicted 4l events:

Channel	N^{Data}	$N^{Total}_{expected}$	N^{signal}_{non-gg}	N^{signal}_{gg}	N^{MC}_{τ}	N_{bkg}
$4e$	85	80 ± 4	68.4 ± 3.4	6.24 ± 0.31	1.28 ± 0.06	3.6 ± 0.5
4μ	156	150.2 ± 2.9	128.2 ± 2.5	11.00 ± 0.21	2.18 ± 0.09	9.0 ± 1.5
$2e2\mu$	235	205 ± 5	172 ± 5	16.0 ± 0.4	3.08 ± 0.13	13.6 ± 2.1
Total	476	435 ± 9	369 ± 9	33.3 ± 0.8	6.54 ± 0.14	26.2 ± 3.6





Cross section extraction

- The cross section is firstly extracted from the experimental phase space defined by the event selection criteria (fiducial phase-space)
  - A correction factor **C_{4l}** is defined to account for the trigger and reconstruction efficiencies between simulation and data in the fiducial phase-space

$$\sigma_{4\ell}^{fiducial} = \frac{N_{obs} - N_b}{\mathcal{L} \cdot C_{4\ell} \cdot K_\tau} \qquad K_\tau = 1 + \frac{N_\tau^{\mathrm{MC}}}{N_{\mathrm{sig}}^{\mathrm{MC}}}$$

contribution from τ-lepton decays (<2%)

- Then extrapolated to an extended phase-space:
  - 80 < m4l < 1000 GeV, $m_{l^+l^-}$> 4 GeV, $p_T^{Z_{1,2}}$> 2 GeV, with 4 leptons each with p_T > 5 GeV and $|\eta|$ < 2.8
  - The extrapolation factors (acceptance) **A_{4l}** are evaluated using MC

$$\sigma_{4\ell}^{phase-space} = \frac{N_{obs} - N_b}{\mathcal{L} \cdot A_{4\ell} \cdot C_{4\ell} \cdot K_\tau}$$

Channel	$4e$	4μ	$2e2\mu$
$C_{4\ell}$	53.3%	82.2%	67.7%
$A_{4\ell}$	41.6%	50.3%	42.2%

- A Likelihood fit is performed to extract the cross sections

Systematic uncertainties

The overall background estimation uncertainty is 12%, and the impact on the measured cross sections is < 1%

C_{4l} uncertainties

Sources	$\Delta C_{4\ell}/C_{4\ell}$		
	$4e$	4μ	$2e2\mu$
e experimental	4.8%	0	2.3%
μ experimental	0	1.8%	0.9%
PDF, μ_R, μ_F, PS	0.1%	0.1%	0.2%
Higher-order corrections	0.6%	0.2%	0.3%
Combined uncertainty	4.9%	1.9%	2.5%

A_{4l} uncertainties

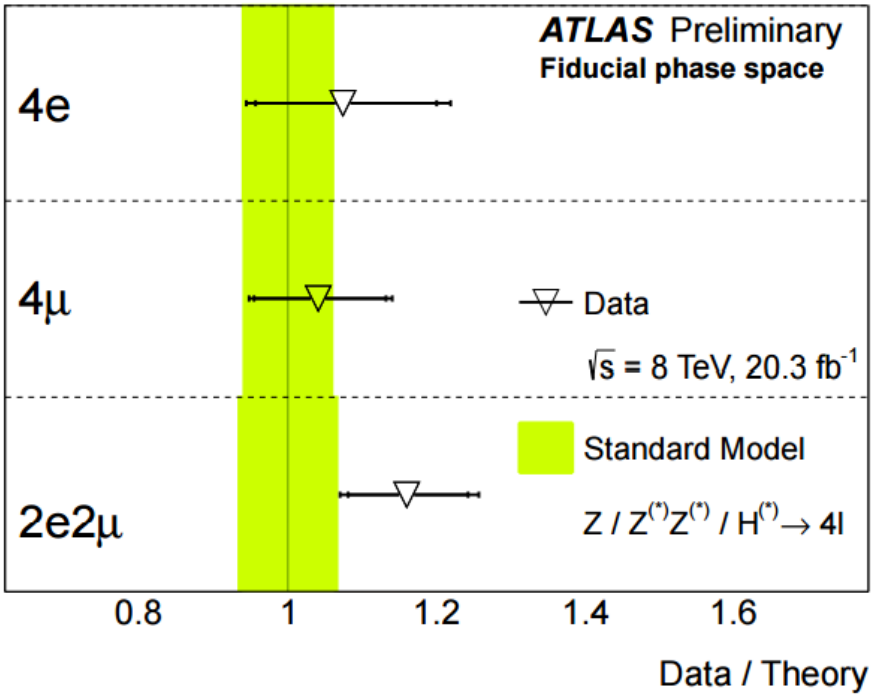
	$\Delta A_{4\ell}/A_{4\ell}$		
Sources	$4e$	4μ	$2e2\mu$
PDF, μ_R, μ_F, PS	1.2%	1.0%	1.6%
Higher-order corrections	4.0%	3.0%	3.9%
	$\Delta(A_{4\ell} \times C_{4\ell})/(A_{4\ell} \times C_{4\ell})$		
PDF, μ_R, μ_F, PS	1.4%	1.1%	1.7%
Higher-order corrections	4.6%	3.2%	4.2%

Largest uncertainties:
Electron identification (4.1%)
Theoretical uncertainty in the NNLO QCD corrections(4.6%)

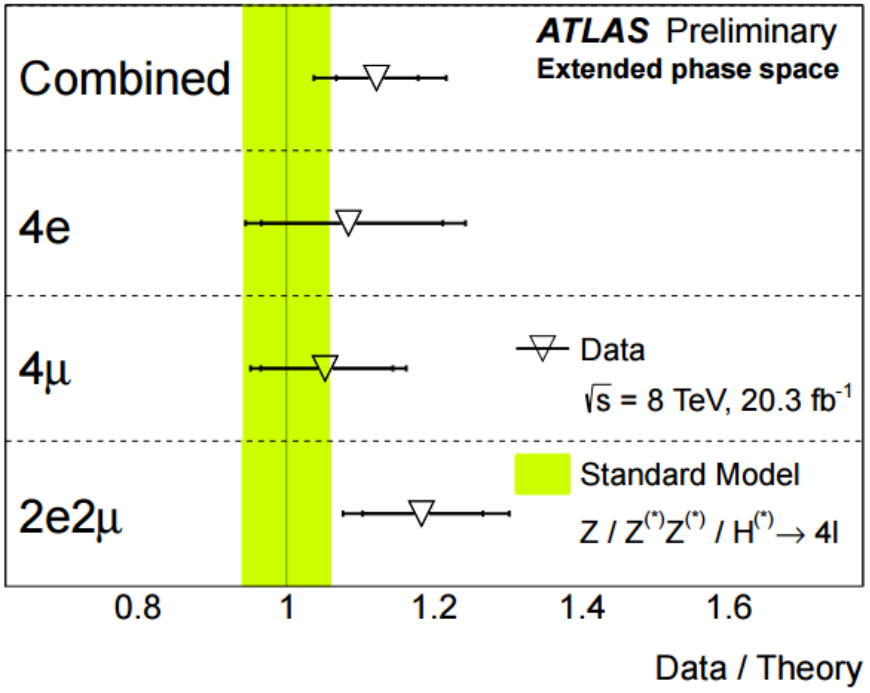
Cross section results

	Fiducial Cross Section [fb]	SM Predictions [fb]
σ^{fid}_{4e}	$7.4^{+0.9}_{-0.8}$ (stat) $^{+0.4}_{-0.3}$ (syst) $^{+0.2}_{-0.2}$ (lumi)	6.9 ± 0.6
$\sigma^{fid}_{4\mu}$	$8.7^{+0.8}_{-0.7}$ (stat) $^{+0.2}_{-0.2}$ (syst) $^{+0.3}_{-0.2}$ (lumi)	8.3 ± 0.7
$\sigma^{fid}_{2e2\mu}$	$15.9^{+1.1}_{-1.1}$ (stat) $^{+0.5}_{-0.4}$ (syst) $^{+0.5}_{-0.4}$ (lumi)	13.7 ± 1.2

Cross Section in the extended phase space [fb]	
Combined $\sigma^{ext-PS}_{4\ell}$	73^{+4}_{-4} (stat) $^{+4}_{-4}$ (syst) $^{+2}_{-2}$ (lumi)
SM Predictions	65 ± 4



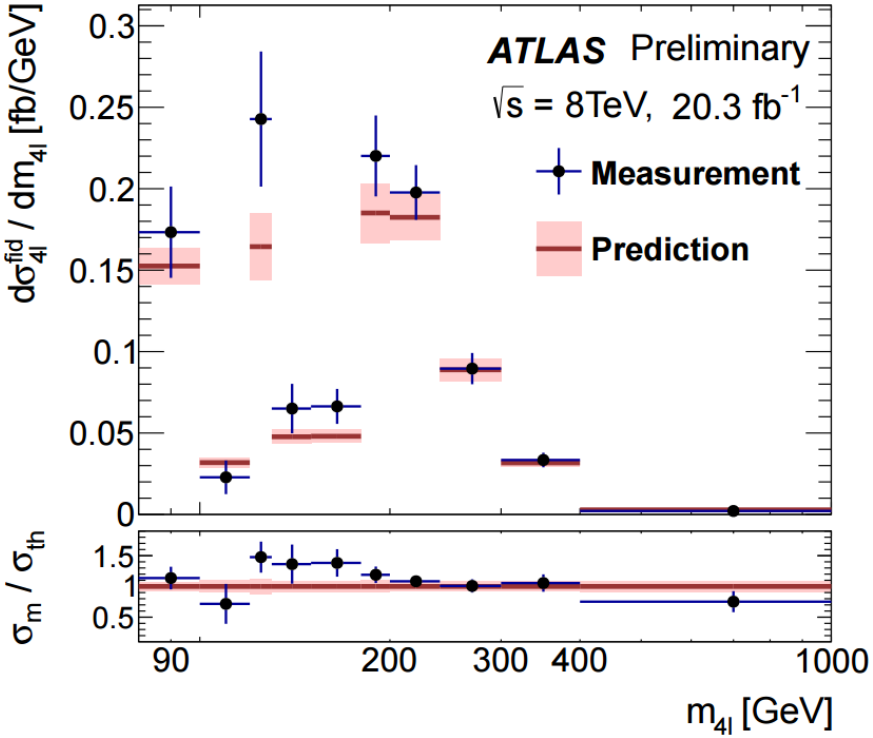
Fiducial cross sections

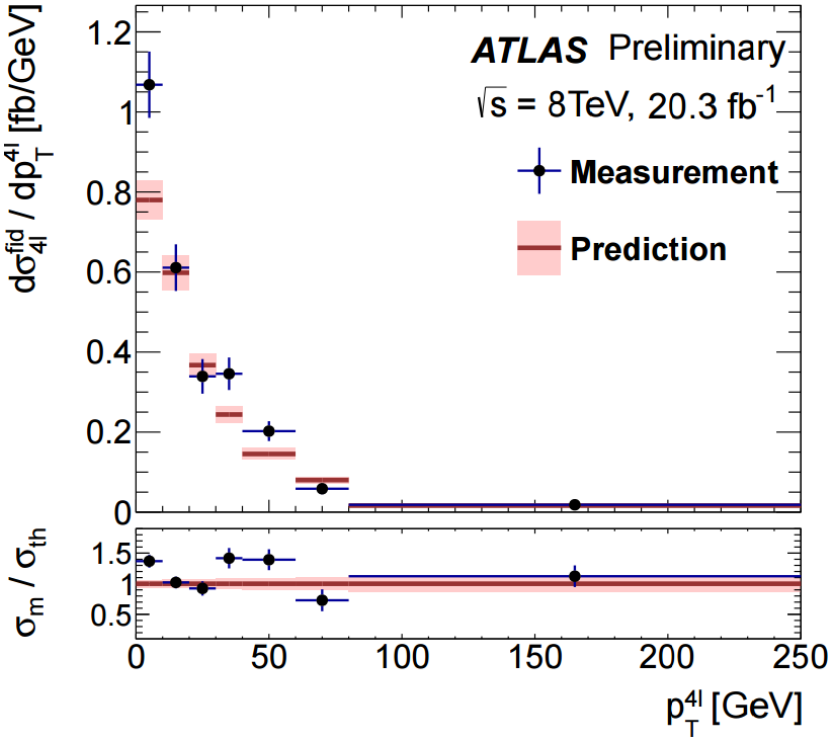


Cross sections in the extended phase-space

Differential cross sections

- Differential cross sections are extracted via the unfolding procedure
  - Convert the measured distributions into the underlying true distributions enabling comparisons with theoretical predictions





Predictions are the sum of the qq → ZZ and gg →(H→)ZZ processes:

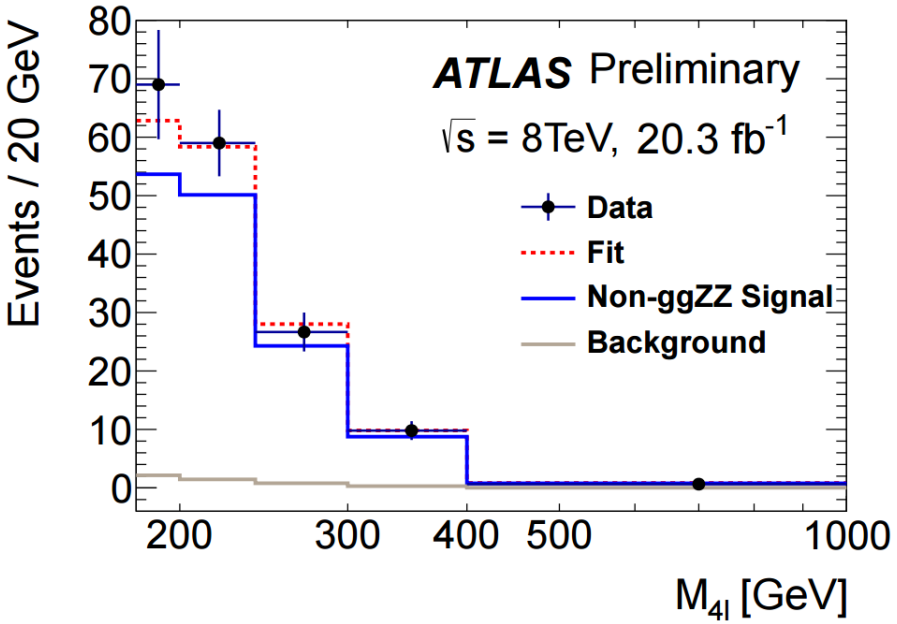
non-resonant gg: LO

on-shell Higgs and qq productions: NNLO QCD and the NLO EW

Determination of gg signal strength

- LO Predictions on non-resonant gg→ZZ 4l process
- Measure the non-resonant gg→ZZ 4l signal strength with respect to LO prediction from data:
  - Using events in the high mass region: $m_{4l} > 180$ GeV
  - Signal strength: $\mu_{gg} = \sigma(data)/\sigma(LO)$
- A likelihood fit on m_{4l} is performed to extract μ_{gg} :
  - Contribution from non-ggZZ process is fixed to the best theory knowledge
- Measured result:

$\mu_{gg} = 2.4 \pm 1.0(stat.) \pm 0.5(syst.) \pm 0.8(theory)$



Post-fit m_{4l} spectrum

Summary

- The inclusive 4l production cross sections are measured in ATLAS at 8 TeV with 20.3 fb^{-1} data
  - In fiducial and extended phase-space
  - Unfolded distributions as function of m_{4l} and $p_T(4l)$

Cross Section in the extended phase space [fb]	
Combined $\sigma_{4\ell}^{ext-PS}$	73^{+4}_{-4} (stat) $^{+4}_{-4}$ (syst) $^{+2}_{-2}$ (lumi)
SM Predictions	65 ± 4

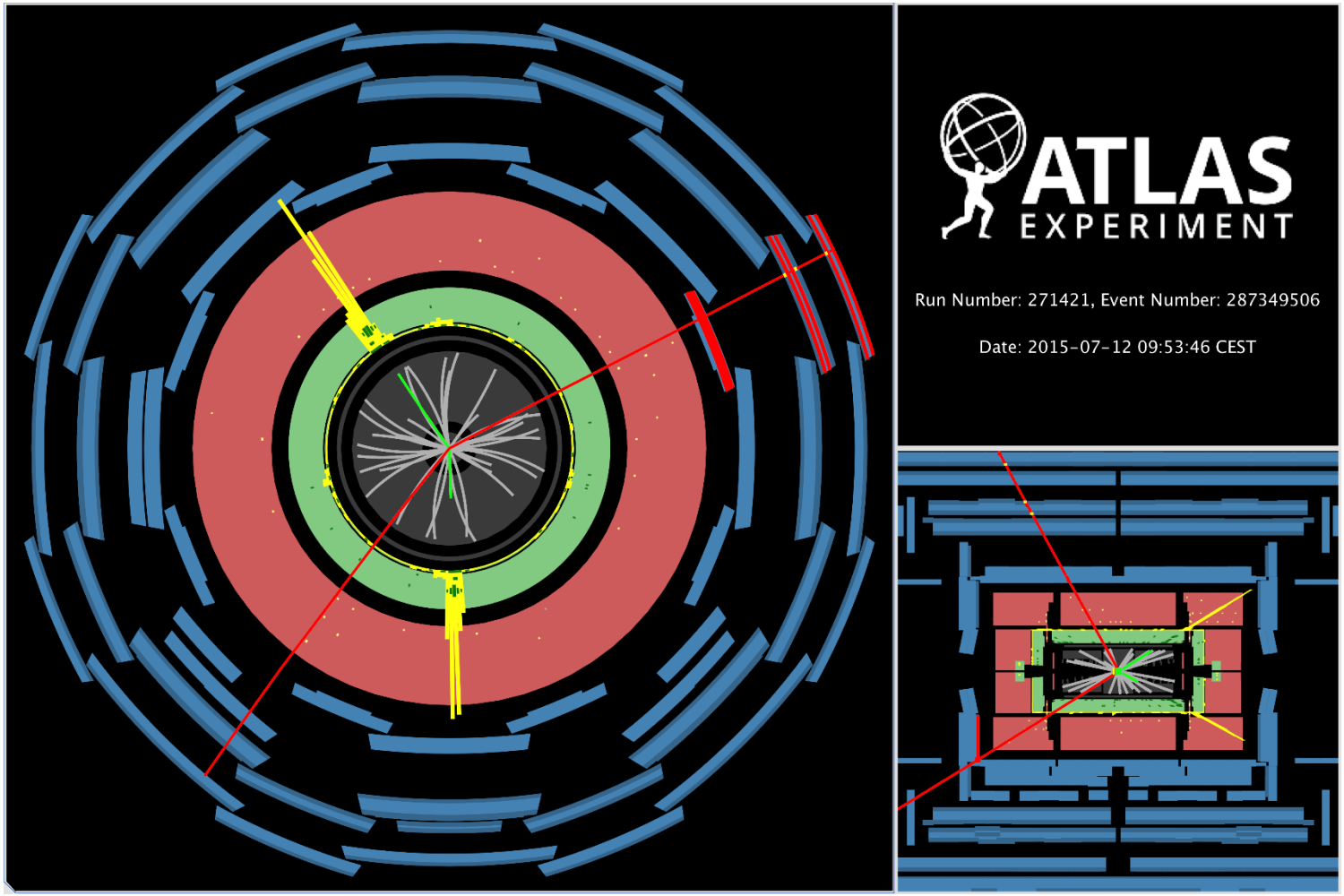
- First determination of the signal strength of the gluon-gluon fusion component in mass region above 180 GeV (with respect to the LO prediction)
  - $\mu_{gg} = 2.4 \pm 1.0(\text{stat.}) \pm 0.5(\text{syst.}) \pm 0.8(\text{theory})$

see more details at:
ATLAS-CONF-2015-031
Paper will come out shortly

ZZ→4l candidate at 13 TeV (1)

ZZ→eeμμ

m(ee) = 92 GeV, m(μμ)= 90 GeV, m(eeμμ) = 305 GeV

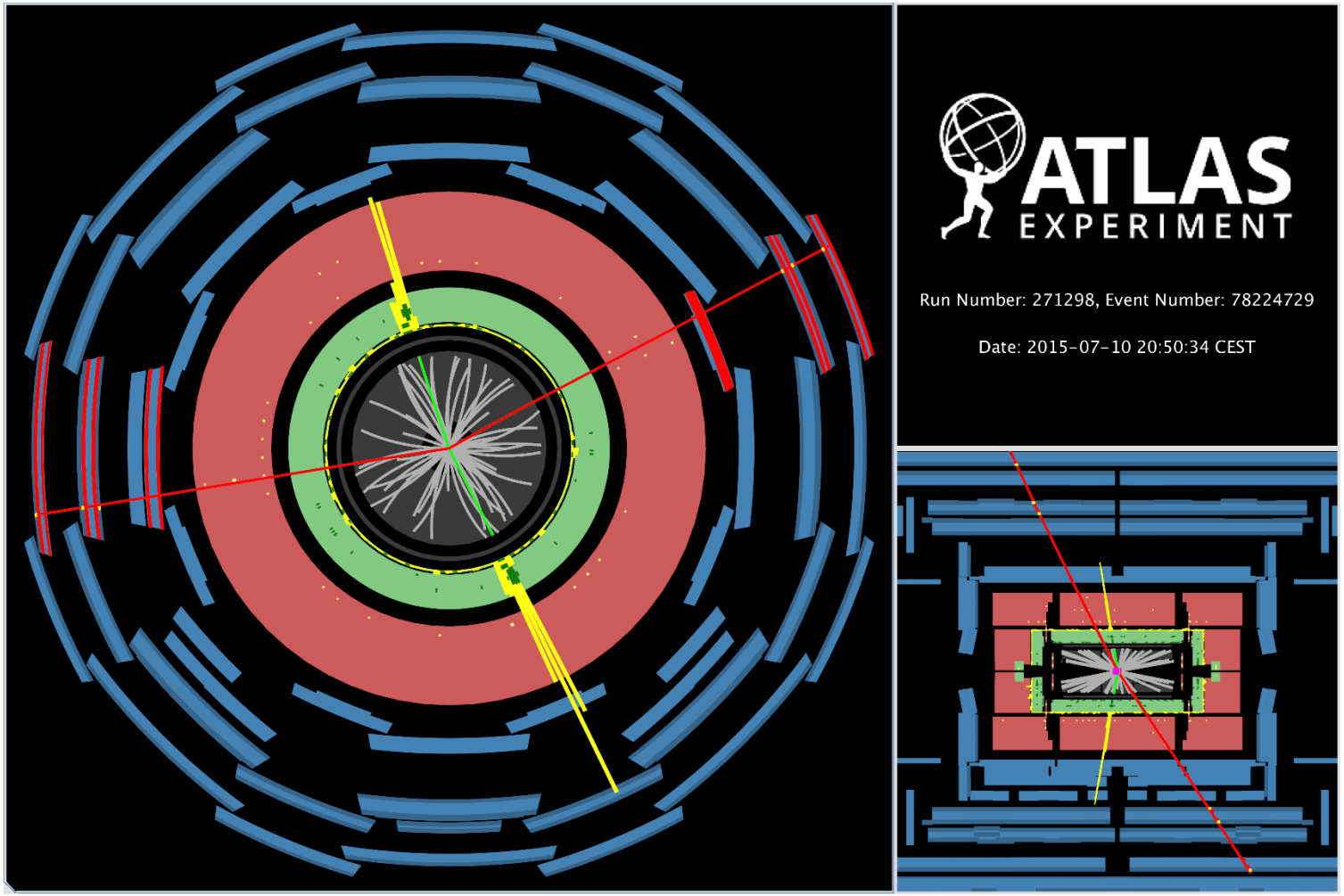


More details

ZZ→4l candidate at 13 TeV (2)

ZZ→μμee

m(μμ)= 94 GeV, m(ee) = 86 GeV, m(eeμμ) = 191 GeV



More details

backup

Fiducial phase-space

Lepton selection	
Muons:	$p_{\mathrm{T}} > 6$ GeV, $\lvert\eta\rvert < 2.7$
Electrons:	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.5$
Lepton pairing	
Leading pair:	SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Subleading pair:	The remaining SFOS with the largest $m_{\ell\ell}$
For both pairs:	$p_T^{\ell^+\ell^-} > 2$ GeV
Event selection	
Lepton kinematics:	$p_{\mathrm{T}} > 20, 15, 10(8\ if\ \mu)$ GeV
Mass requirements:	$50 < m_{12} < 120$ GeV $12 < m_{34} < 120$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1$ (0.2) for same- (different-) flavor leptons
J/ψ veto:	$m(\ell_i^+, \ell_j^-) > 5$ GeV
4ℓ mass range:	$80 < m_{4\ell} < 1000$ GeV

Detailed theory predictions

	Extended phase space [fb]		Fiducial volume [fb]	
$m_{4\ell}$ [GeV]	80-1000	180-1000	80-1000	180-1000
qq (NLO)	60.4 ± 3.6	24.7 ± 1.5	25.5 ± 1.5	19.1 ± 1.1
qq (NNLO)	61.2 ± 3.7	25.5 ± 1.5	26.2 ± 1.6	19.8 ± 1.2
gg (LO)	1.8 ± 0.8	1.6 ± 0.7	1.4 ± 0.6	1.3 ± 0.6
on-shell ggH	1.5 ± 0.2	0	1.1 ± 0.2	0
others	0.44 ± 0.03	0.20 ± 0.01	0.34 ± 0.02	0.18 ± 0.01

The “others” listed in the table include
on-shell VBF−H, VH, ttH and
off-shell VBF−H, VBF−ZZ and interference.

Detailed expectations of background

Expectations for the different background processes considered in this analysis

Process/Channel	4e	2e2μ	4μ
$t\bar{t}$	0.45 ± 0.24	1.3 ± 0.45	0.68 ± 0.19
Z + jets	0.60 ± 0.29	6.3 ± 1.4	5.3 ± 1.5
WZ	0.78 ± 0.11	1.31 ± 0.15	0.69 ± 0.11
$Z\gamma$	0.41 ± 0.13	1.34 ± 0.24	0
$t\bar{t}Z$	0.51 ± 0.15	1.48 ± 0.45	0.96 ± 0.32
VVV (V=W, Z)	0.22 ± 0.07	0.51 ± 0.16	0.35 ± 0.11
tZ	0.11 ± 0.02	0.26 ± 0.05	0.23 ± 0.05
ZH	0.45 ± 0.10	0.95 ± 0.10	0.62 ± 0.08
DPI	0.06 ± 0.06	0.19 ± 0.19	0.14 ± 0.14

Cross sections and uncertainties

	Fiducial Cross Section [fb]	SM Predictions [fb]
σ^{fid}_{4e}	$7.4^{+0.9}_{-0.8}$ (stat) $^{+0.4}_{-0.3}$ (syst) $^{+0.2}_{-0.2}$ (lumi)	6.9 ± 0.6
$\sigma^{fid}_{4\mu}$	$8.7^{+0.8}_{-0.7}$ (stat) $^{+0.2}_{-0.2}$ (syst) $^{+0.3}_{-0.2}$ (lumi)	8.3 ± 0.7
$\sigma^{fid}_{2e2\mu}$	$15.9^{+1.1}_{-1.1}$ (stat) $^{+0.5}_{-0.4}$ (syst) $^{+0.5}_{-0.4}$ (lumi)	13.7 ± 1.2

	Cross Section in the extended phase space [fb]	SM Predictions [fb]
σ^{ext-PS}_{4e}	$17.8^{+2.1}_{-2.0}$ (stat) $^{+1.5}_{-1.1}$ (syst) $^{+0.5}_{-0.5}$ (lumi)	16.4 ± 1.4
$\sigma^{ext-PS}_{4\mu}$	$17.3^{+1.5}_{-1.4}$ (stat) $^{+0.9}_{-0.7}$ (syst) $^{+0.5}_{-0.5}$ (lumi)	16.4 ± 1.4
Combined $\sigma^{ext-PS}_{4e+4\mu}$	$35.0^{+2.4}_{-2.3}$ (stat) $^{+1.9}_{-1.5}$ (syst) $^{+1.1}_{-1.0}$ (lumi)	32.9 ± 1.9
$\sigma^{ext-PS}_{2e2\mu}$	$37.7^{+2.7}_{-2.6}$ (stat) $^{+2.5}_{-2.0}$ (syst) $^{+1.1}_{-1.1}$ (lumi)	32.1 ± 2.0
Combined $\sigma^{ext-PS}_{4\ell}$	73^{+4}_{-4} (stat) $^{+4}_{-4}$ (syst) $^{+2}_{-2}$ (lumi)	65 ± 4

m_{4l} [GeV]	80-100	100-120	120-130	130-150	150-180	180-200	200-240	240-300	300-400	400-1000
$d\sigma_{4\ell}/dm_{4\ell}$ [ab/GeV]	173	22.8	243	65.1	66.4	220	198	89.6	33.4	2.14
Total Unc. [ab/GeV]	28	10.4	42	15.2	10.7	25	17	9.6	4.5	0.49
Stat. Unc. [ab/GeV]	27	10.2	41	14.9	10.5	24	16	9.4	4.4	0.48
Syst. Unc. [ab/GeV]	6	2.4	9	3.2	2.2	5	4	1.9	0.7	0.05