Perspectives on multi-boson + jets physics

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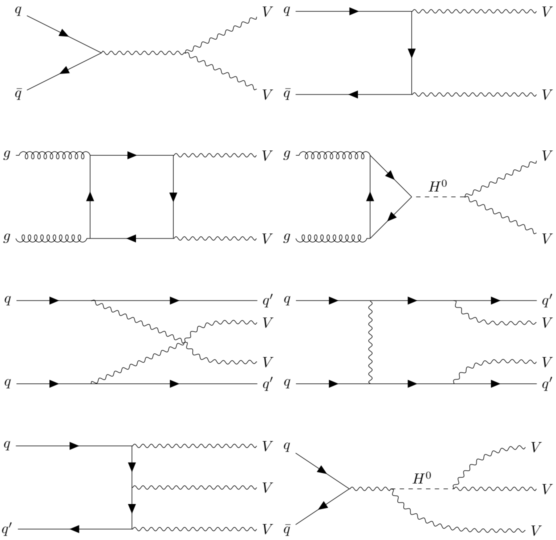
ATLAS/CMS MC workshop

03 May 2017

Overview

- fully leptonic $VV+$ jets
- semileptonic $VV+$ jets
- loop-induced VV
- electroweak $VVjj$
- $VVV+$ jets
- $V+\gamma+$ jets



fully leptonic $VV+$ jets

Fully leptonic $ZZ+$ jets: out-of-the-box generator comparisons

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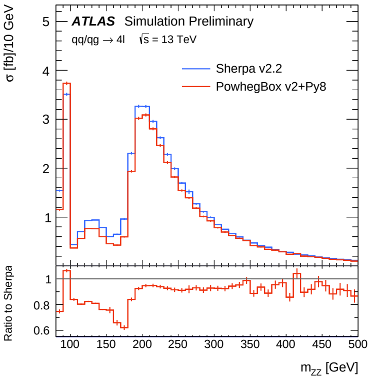

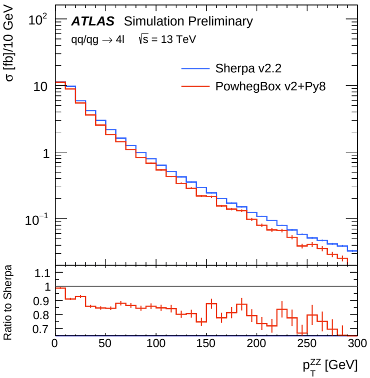

- ➜ SHERPA 2.2 + OPENLOOPS: $4\ell + 0, 1j$@NLO$+2, 3j$@LO (NNPDF3.0nnlo)
- ➜ POWHEGBOX + PYTHIA8: $4\ell + 0j$@NLO (CT10nlo)
- ➜ $p_{\mathrm{T}}^{\ell} > 20/15/10$ GeV, 50 GeV $< m_{\ell\ell} <$ 106 GeV, J/ψ veto, sliding-mass selection

Fully leptonic $ZZ+$ jets: electroweak effects

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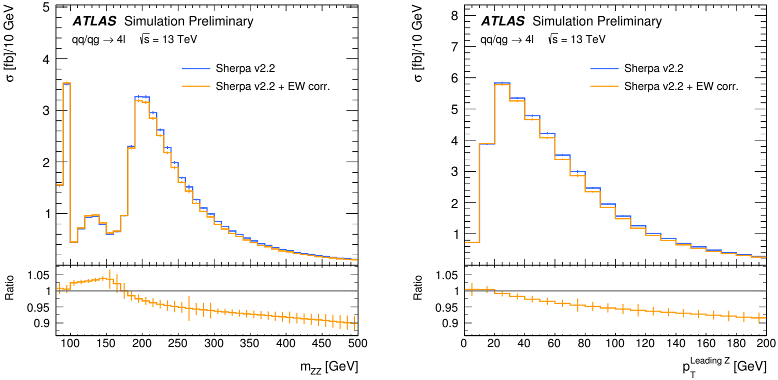

- ➜ SHERPA 2.2 + OPENLOOPS: $4\ell + 0, 1j$@NLO+$2, 3j$@LO (NNPDF3.0nnlo)
- ➜ + NLO electroweak corrections [Biedermann, Denner, Dittmaier, Hofer, Jäger, arXiv:1601.07787, arXiv:1611.05338]

Fully leptonic $ZZ+$ jets: generator comparisons

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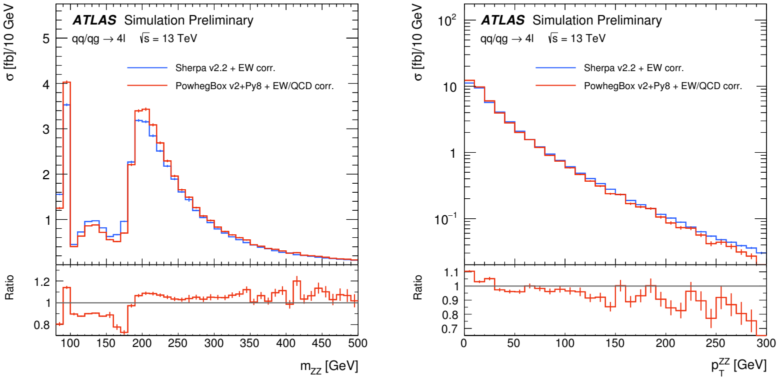


- SHERPA 2.2 + OPENLOOPS: $4\ell + 0, 1j$@NLO$+2, 3j$@LO (NNPDF3.0nnlo)
- POWHEGBOX + PYTHIA8: $4\ell + 0j$@NLO (CT10nlo)
- both + NLO electroweak corrections [Biedermann, Denner, Dittmaier, Hofer, Jäger, arXiv:1601.07787, arXiv:1611.05338]
- POWHEG rescaled using nNLO fO QCD k-factor [Grazzini, Kallweit, Rathlev, arXiv:1507.06257]

more ZZ

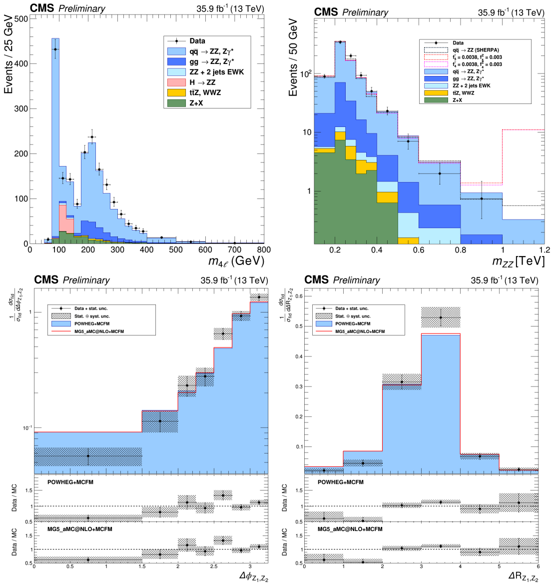
SMP-16-017

POWHEGBOX+PYTHIA8
$qq \rightarrow ZZ + 0j$@NLO
$qg \rightarrow ZZ + 0j$@LO

MCFM+PYTHIA8
$gg \rightarrow ZZ + 0j$@LO

MG5_AMC@NLO+PYTHIA8

SHERPA



more *ZZ*

SMP-16-017

POWHEGBOX+PYTHIA8

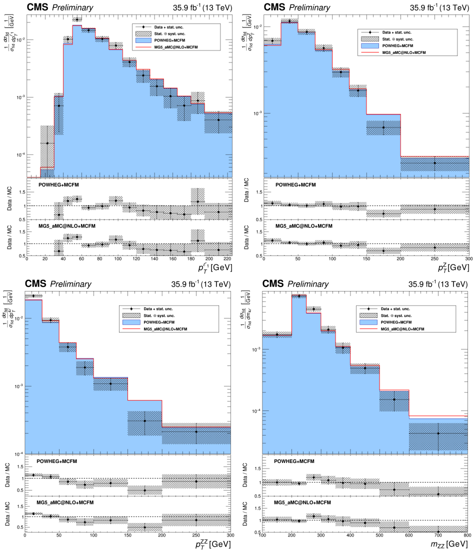
$qq \to ZZ + 0j$@NLO

$qg \to ZZ + 0j$@LO

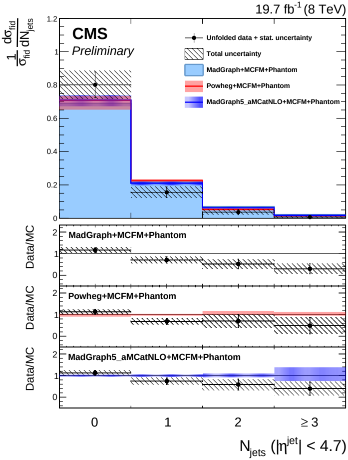
MCFM+PYTHIA8

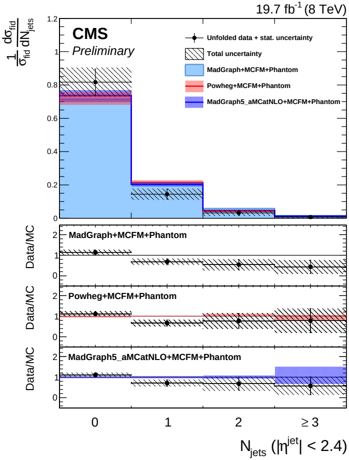
$gg \to ZZ + 0j$@LO

MADGRAPH+PYTHIA8



more $ZZ+$ jets





SMP-15-012

POWHEGBOX
+MCFM
+PYTHIA8
$4\ell + 0j$@NLO

MADGRAPH+PYTHIA8
$4\ell + 0, 1, 2j$@LO

MG5_AMC@NLO+PYTHIA8
$4\ell + 0, 1j$@NLO

Fully leptonic $WZ+$ jets: generator comparisons

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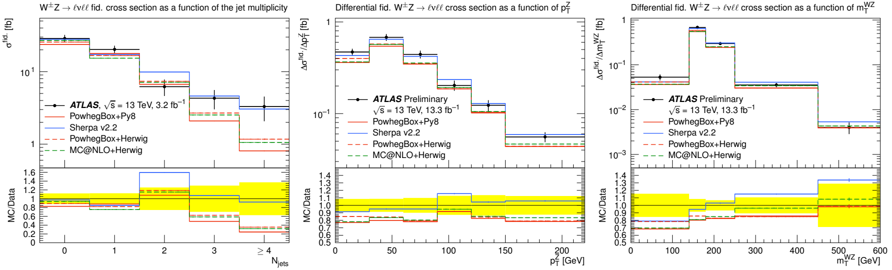

➜ SHERPA 2.2 + OPENLOOPS: $3\ell\nu + 0, 1j$@NLO$+2, 3j$@LO (NNPDF3.0nnlo)

➜ POWHEGBOX + PYTHIA8/HERWIG++: $3\ell\nu + 0j$@NLO (CT10nlo)

➜ MC@NLO 4.0 + HERWIG++/JIMMY: $3\ell\nu + 0j$@NLO (CT10)

➜ $p_T^\ell(Z) > 15$ GeV, $p_T^\ell(W) > 20$ GeV, $|\eta_\ell| < 2.5$

Fully leptonic $WW+$ jets: generator comparisons

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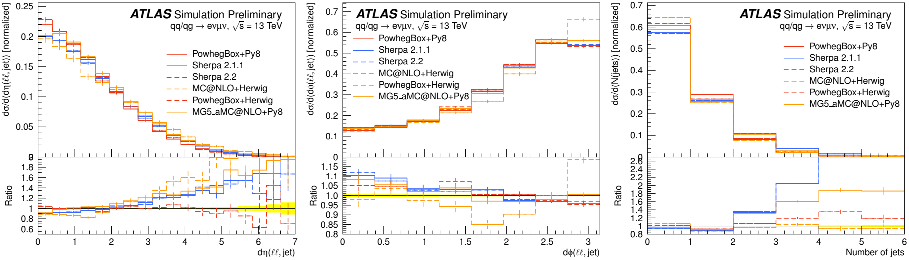

- SHERPA 2.2 + OPENLOOPS: $2\ell 2\nu + 0, 1j$@NLO$+2, 3j$@LO (NNPDF3.0nnlo)
- SHERPA 2.1.1 + OPENLOOPS: $2\ell 2\nu + 0, 1j$@NLO$+2, 3j$@LO (CT10nlo)
- POWHEGBOX + PYTHIA8/HERWIG++: $2\ell 2\nu + 0j$@NLO (CT10nlo)
- MC@NLO 4.0 + HERWIG++/JIMMY: $2\ell 2\nu + 0j$@NLO (CT10)
- MG5_AMC@NLO + PYTHIA8: $2\ell 2\nu + 0, 1j$@NLO (NNPDF3.0)
- $p_T^\ell > 25(20)$ GeV, $m_{\ell\ell} > 10$ GeV, $p_T^{miss} > 20$ GeV, $p_T^j > 25$ GeV

semileptonic $VV+$ jets

Semileptonic $VV+$ jets: generator comparisons

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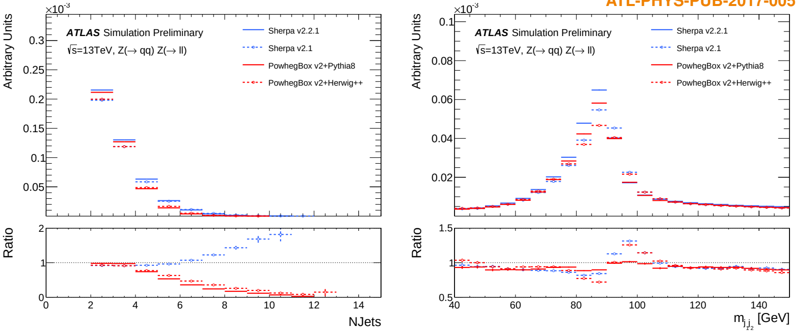

- SHERPA 2.2 + OPENLOOPS: $V(\to \ell\ell)V(\to qq) + 0, 1j$@NLO+$2, 3j$@LO (NNPDF3.0nnlo)
- SHERPA 2.1.1 + OPENLOOPS: $V(\to \ell\ell)V(\to qq) + 0j$@NLO+$1, 2, 3j$@LO (CT10nlo)
- POWHEGBOX + PYTHIA8/Herwig++: $2\ell 2j + 0j$@nLO (CT10nlo)

Semileptonic $VV+$ jets: generator comparisons

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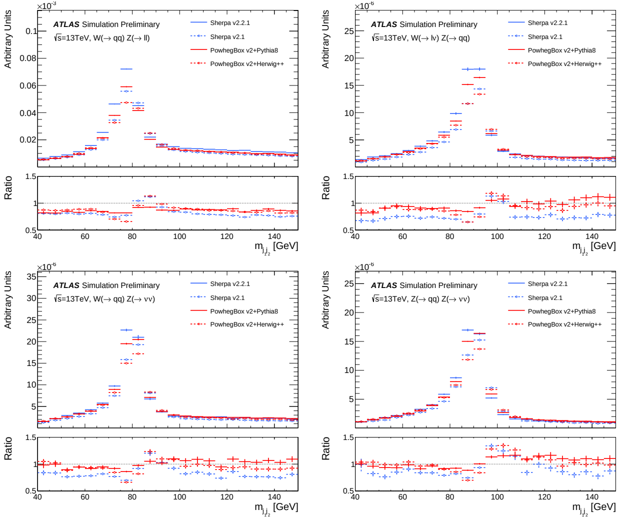

loop-induced *VV*

Loop-induced *VV*: generator comparisons

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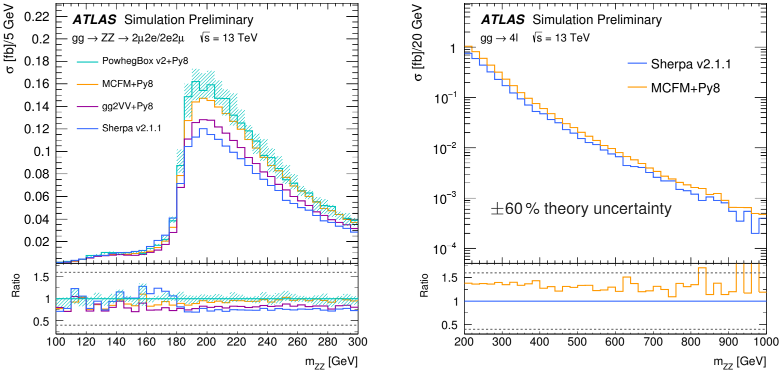

POWHEGBOX + PYTHIA8:	$gg \to 4\ell + 0j$@NLO	(NNPDF3.0nlo,	$\mu = m_{VV}$)
gg2VV 3.1.6 + PYTHIA8:	$gg \to 4\ell + 0j$@LO $\times 1.7$	(CT10,	$\mu = m_{VV}$)
MCFM8 + PYTHIA8:	$gg \to 4\ell + 0j$@LO $\times 1.7$	(CT10nnlo,	$\mu = m_{VV}/2$)
SHERPA 2.1.1 + OPENLOOPS:	$gg \to 4\ell + 0,1j$@LO $\times 1.7$	(CT10nlo,	$\mu = m_{VV}/2$)

Loop-induced *VV*: generator comparisons

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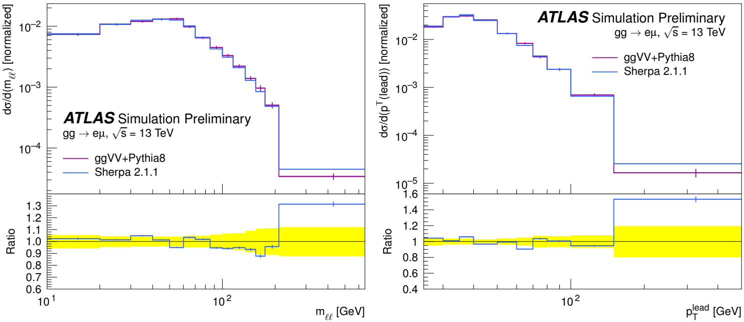
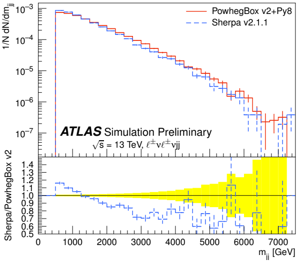
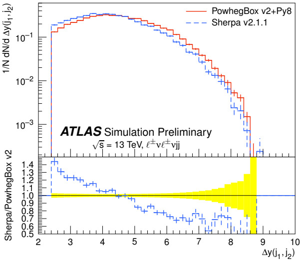


gg2VV 3.1.6 + PYTHIA8:	$gg \to 2\ell 2\nu + 0j$@LO $\times 1.7$	(CT10,	$\mu = m(VV)$)
SHERPA 2.1.1 + OPENLOOPS:	$gg \to 2\ell 2\nu + 0,1j$@LO $\times 1.7$	(CT10nlo,	$\mu = m_{VV}/2$)

electroweak *VVjj*

Same-sign $2\ell 2\nu jj$: generator comparisons





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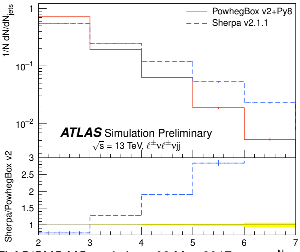


POWHEGBOX+PYTHIA8: $\ell^\pm\ell^\pm 2\nu jj + 0j$@NLO (NNPDF3.0nlo)

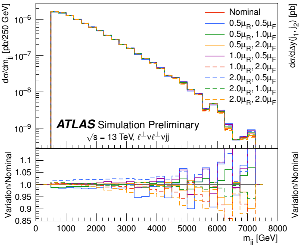
SHERPA 2.1.1: $\ell^\pm\ell^\pm 2\nu jj + 0j$@LO (CT10nlo)

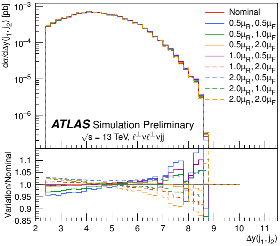
$p_T^\ell > 27$ GeV, $p_T^j > 30(35)$ GeV for $|\eta_j| < 4.5$ ($|\eta_j| < 2.4$)

$m_{jj} > 500$ GeV, $E_T^{\text{miss}} > 30$ GeV, $|\Delta y_{jj}| > 2.4$

b-jet veto, Z-boson veto, τ veto

Same-sign $2\ell 2\nu jj$: uncertainties





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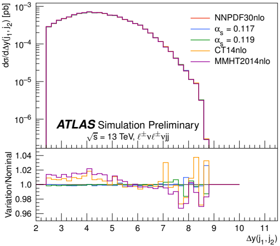

POWHEGBOX+PYTHIA8: $\ell^\pm \ell^\pm 2\nu jj + 0j$@NLO (NNPDF3.0nlo)

9-point scale variations of factorisation scale and renormalisation scale

100 replicas of NNPDF3.0nlo set (+ nominal of CT14nlo and MMHT2014nlo)

Opposite-sign $2\ell 2\nu jj$: generator comparisons

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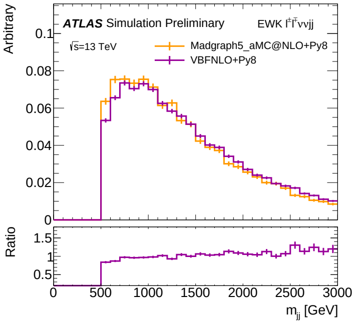

- ➜ MG5_aMC@NLO+Pythia8: $\ell^{\pm}\ell^{\mp}2\nu jj + 0j$@LO (NNPDF3.0lo)
- ➜ VBFNLO+Pythia8: $\ell^{\pm}\ell^{\mp}2\nu jj + 0j$@LO (NNPDF3.0lo)
- ➜ $p_T^{\ell_1} > 30$ GeV, $p_T^{\ell_2} > 20$ GeV, $|\eta_\ell| < 2.5$, $E_T^{miss} > 90$
- ➜ $N_{jets} \geq 2$ jets with $p_T > 25$ GeV and $|\eta| < 4.5$, $m_{jj} > 500$ GeV, $|\Delta\eta_{jj}| > 3$

Semileptonic *VVjj*: generator comparisons

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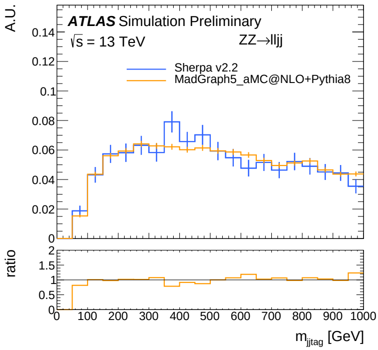

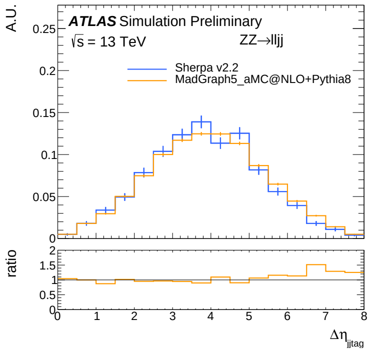

- SHERPA 2.2: *VVjj* + 0*j*@LO using factorised on-shell decays (NNPDF3.0nnlo)
- MG5_AMC@NLO+PYTHIA8: *VVjj* + 0*j*@LO using factorised on-shell decays (NNPDF3.0lo)
- 2 leptons with $p_T > 20$ GeV and $|\eta| < 2.5$
- at least 4 jets with $p_T > 20$ GeV and $|\eta| < 4.5$

$2\ell\gamma jj$: generator comparisons

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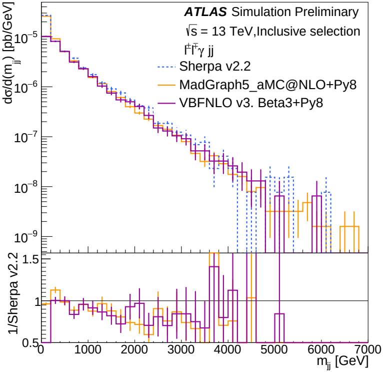
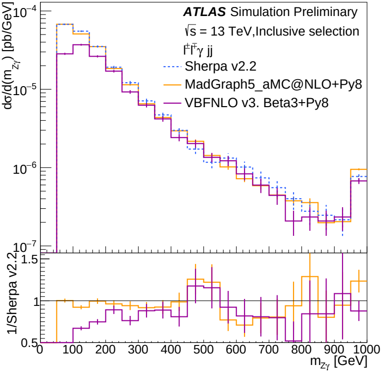
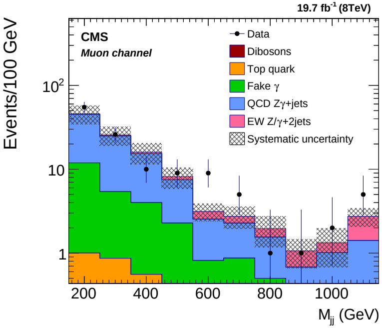




- all predictions $2\ell\gamma jj + 0j$@LO
- $N_\ell \geq 2$, $p_\mathrm{T}^\ell > 15$ GeV, $|\eta_\ell| < 2.5$, $m_{\ell\ell} > 40$ GeV
- $N_\gamma \geq 1$, $E_\mathrm{T}^\gamma > 15$ GeV, $|\eta_\gamma| < 2.5$, $N_\mathrm{jets} \geq 2$, $p_\mathrm{T}^j > 20$ GeV, $|\eta_j| < 5.5$

$Z\gamma jj$: detector-level comparisons



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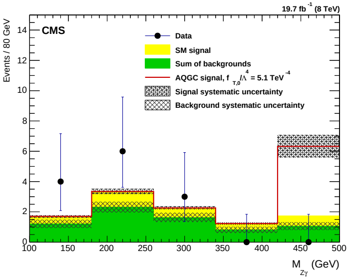


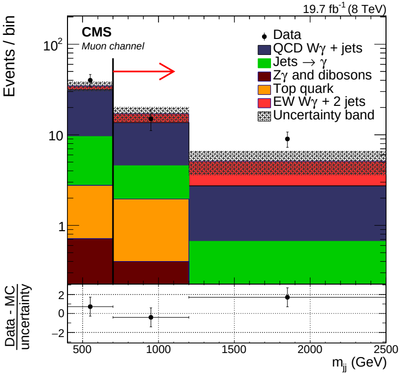
- MG5_AMC@NLO+PYTHIA6: QCD $Z\gamma + 0, 1, 2, 3j$@LO using MLM, EW $Z\gamma jj + 0j$@LO
- $p_T^j > 30$ GeV, $|\eta_j| < 4.7$, $p_T^\ell > 20$ GeV, $|\eta_\ell| < 2.4$, $|\eta_\gamma| < 1.4442$
- right plot: $m_{jj} > 400$ GeV, $|\Delta\eta_{jj}| > 2.4$, $p_T^\gamma > 60$ GeV

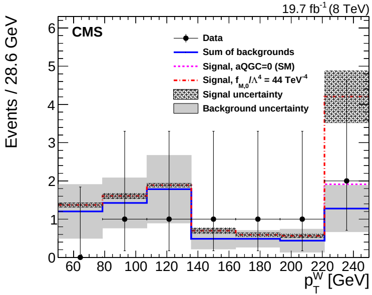
$W\gamma jj$: detector-level comparisons

MG5_aMC@NLO+PYTHIA6:

QCD $Z\gamma + 0, 1, 2, 3j$@LO using MLM

EW $Z\gamma jj + 0j$@LO





Single-lepton (e, μ) trigger	$\lvert M_{e\gamma} - M_Z \rvert > 10$ GeV (electron channel)
Lepton, photon ID and isolation	$p_T^{j1} > 40$ GeV, $p_T^{j2} > 30$ GeV
Second lepton veto	$\lvert \eta^{j1} \rvert < 4.7$, $\lvert \eta^{j2} \rvert < 4.7$
Muon (electron) $p_T > 25$ (30) GeV, $\lvert\eta\rvert < 2.1$ (2.4)	$\lvert \Delta\phi_{j1,\vec{p}_T^{miss}} \rvert > 0.4$, $\lvert \Delta\phi_{j2,\vec{p}_T^{miss}} \rvert > 0.4$ rad
Photon $p_T^{\gamma} > 22$ GeV, $\lvert\eta\rvert < 1.44$	b quark jet veto for tag jets
W boson transverse mass > 30 GeV	Dijet invariant mass $m_{jj} > 200$ GeV
$\lvert \vec{p}_T^{miss} \rvert > 35$ GeV	$\Delta R_{jj}, \Delta R_{j\gamma}, \Delta R_{j\ell}, \Delta R_{\ell\gamma} > 0.5$

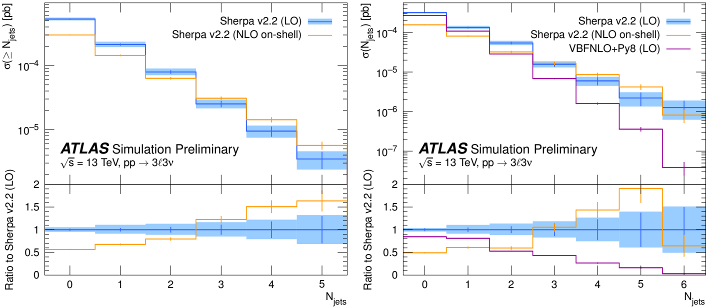
SMP-14-011

$VVV+$ jets

VVV: generator comparisons

Selection requirement	0 SFOS	1 SFOS	2 SFOS
Leptons	Exactly three charged leptons with $p_T > 20$ GeV		
p_T^{miss}	—	$p_T^{miss} > 45$ GeV	$p_T^{miss} > 55$ GeV
Same-flavour dilepton mass	$m_{\ell\ell} > 20$ GeV	—	
Angle between triboson and $\vec{p}_T^{miss}$	$\lvert\phi^{3\ell} - \phi^{\vec{p}_T^{miss}}\rvert > 2.5$		
Z-boson veto	$\lvert m_{ee} - m_Z\rvert > 15$ GeV	$\lvert m_Z - m_{SFOS}\rvert > 35$ GeV or $\lvert m_{SFOS} - m_Z\rvert > 20$ GeV	$\lvert m_{SFOS} - m_Z\rvert > 20$ GeV

- SHERPA 2.2+OPENLOOPS *VVV* + 0*j*@NLO +1, 2*j*@LO using factorised on-shell decays
- SHERPA 2.2 $3\ell3\nu$, +0, 1*j*@LO
- VBFNLO+PYTHIA8 $3\ell3\nu$ + 0*j*@LO



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VVV: generator comparisons

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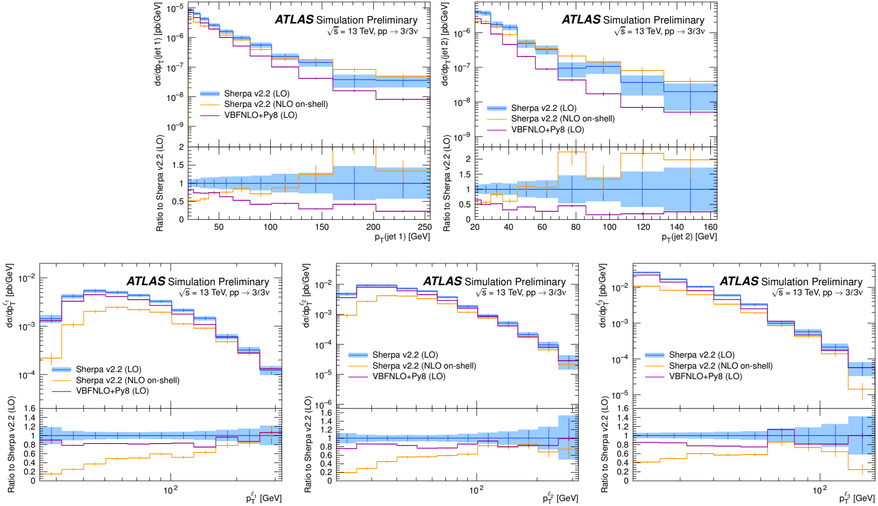
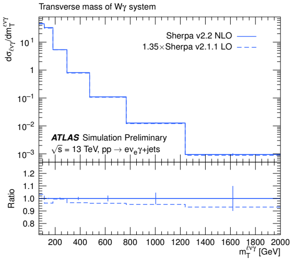


$V + \gamma +$ jets

$V + \gamma +$ jets: generator comparisons



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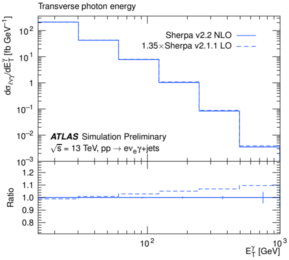
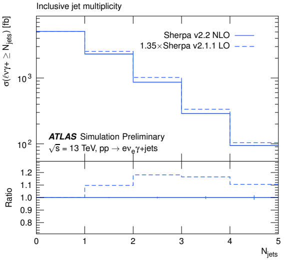
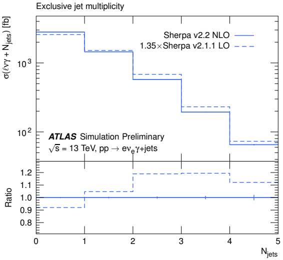
Electrons	$E_\mathrm{T} > 25\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.47$, $R^{\mathrm{dress}}_{e,\gamma} < 0.1$
Photons	$E_\mathrm{T} > 15\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.37$
Missing energy	$E_T^{\mathrm{miss}} > 35\,\mathrm{GeV}$
Jets	anti-k_t, $R = 0.4$, $p_\perp > 30\,\mathrm{GeV}$, $\lvert\eta\rvert < 4.4$
Overlap removal	$\Delta R(e, j) > 0.3$, $\Delta R(\gamma, j) > 0.3$, $\Delta R(e, \gamma) > 0.7$

SHERPA 2.2+OPENLOOPS: $\ell\ell, \ell\nu, \nu\nu + \gamma + 0, 1j$@NLO+$2, 3j$@LO

SHERPA 2.1.1: $\ell\ell, \ell\nu, \nu\nu + \gamma + 0, 1, 2, 3j$@LO







$V + \gamma +$ jets: generator comparisons

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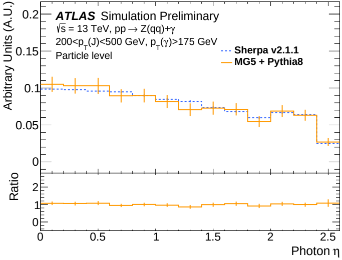
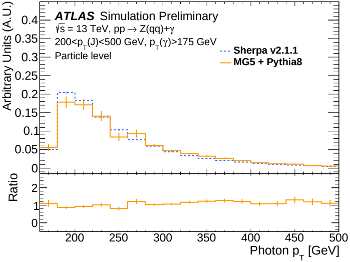


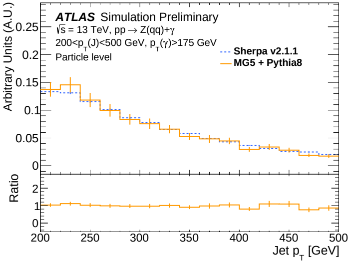


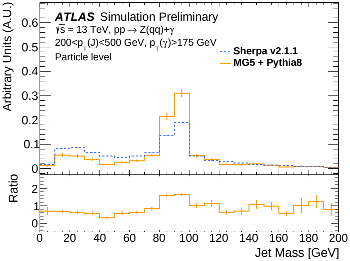
$|\eta_\gamma| < 2.5$

$|\eta_{j_1}| < 2.1$

(anti-k_t, $R = 1.0$)

$\Delta R_{j\gamma} > 1.0$





SHERPA 2.1.1

$V + \gamma + 0, 1, 2, 3j$@LO

MG5_AMC@NLO+PYTHIA8

$V + \gamma + 0, 1, 2, 3j$@LO

using factorised

on-shell decays

Summary and points for discussion

- lots of activity on the multi-V front
- state-of-the-art generators being employed and thoroughly validated
- hesitant to 'blindly' apply NNLO QCD k-factors to predictions without also considering NLO EW corrections at the same time
- sample preparation and event generation time can become quite challenging for these complex final states
- memory consumption for complex final states also becoming an issue

Backup

$V\gamma$: generator-level cuts

Cut	v2.1.1 LO ($p_\perp^\gamma$-sliced)	v2.1.1 LO ($m_{\ell\ell\gamma}$-sliced)	v2.2 NLO ($p_\perp^\gamma$-sliced)
$p_\perp^\gamma >$	10 GeV	40 GeV	7 GeV
$\Delta R(\gamma, \ell) >$	0.1	0.1	0.1
Photon isolation [50] $n =$	2	2	2
$\epsilon =$	0.025	0.025	0.1
$\delta =$	0.3	0.3	0.1
(for $\ell\ell\gamma$) $m_{\ell\ell} >$	10 GeV	40 GeV	10 GeV