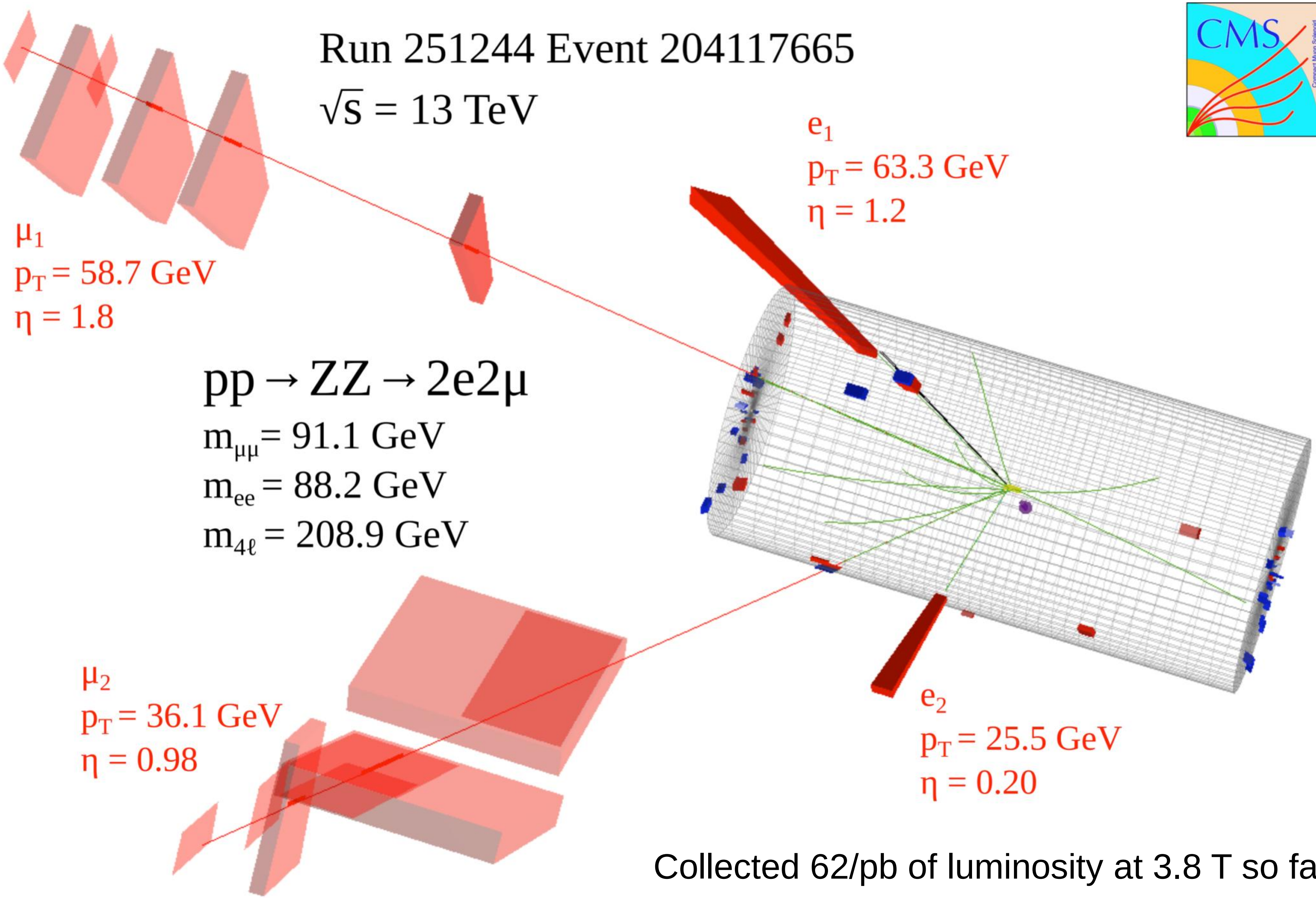
Multiboson production at CMS

P. Dudero (TTU) on behalf of the CMS Collaboration

EPS-HEP, Vienna, Austria 24 Jul. 2015

A recently identified ZZ→ 4ℓ event in Run 2

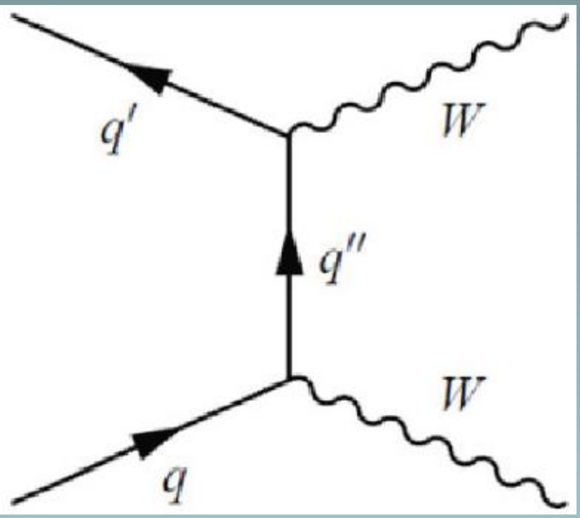


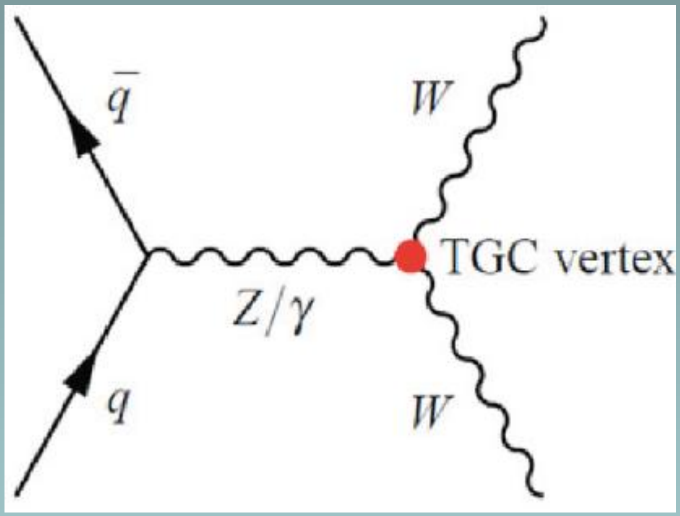
Collected 62/pb of luminosity at 3.8 T so far

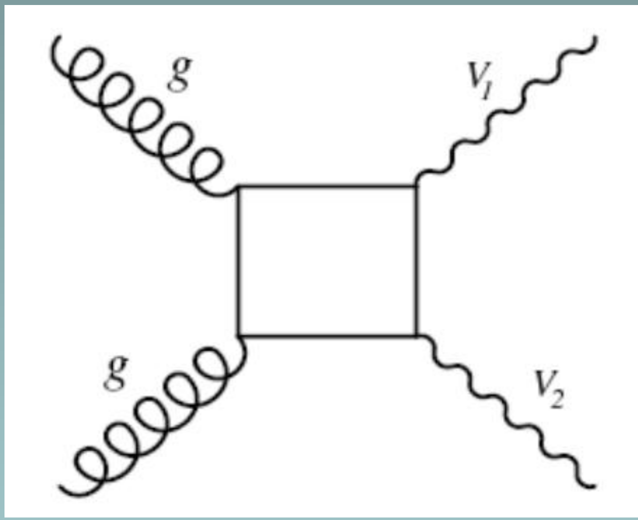
Channel Overview

	$WW \rightarrow \ell\nu\ell\nu$	$Z\gamma \rightarrow \nu\nu\gamma$	2γ + jets
Coordinates	CMS-PAS-SMP-14-016	CMS-PAS-SMP-14-019	CMS-PAS-SMP-14-021
Related Analyses	Previous 8TeV measurement (3.5/fb) **CMS-PAS-SMP-12-013** Higgs search (4.9+19.4/fb) [**PAS**] [**PAPER**]	Monophoton search for ADD "branons" **[PAS][arxiv]**	Inclusive diphoton measurement **[PAS][Paper]**
Release Date	March 17, 2015	July 23, 2015	July 21, 2015
Journal submission	Submitted to EPJC [**arxiv**]	planned	planned
∫ L dt, √s	19.4 fb^{-1} (8 TeV)	19.6 fb^{-1} (8 TeV)	5.0 fb^{-1} (7 TeV)
Anomalous Coupling*	aTGC for HWW/ZWW/γWW	aTGC for Zγγ/ZZγ	N/A

* See Senka's talk for details







WW → 2ℓ2ν

(CMS-PAS-SMP-14-016)

WW → 2ℓ2ν Overview

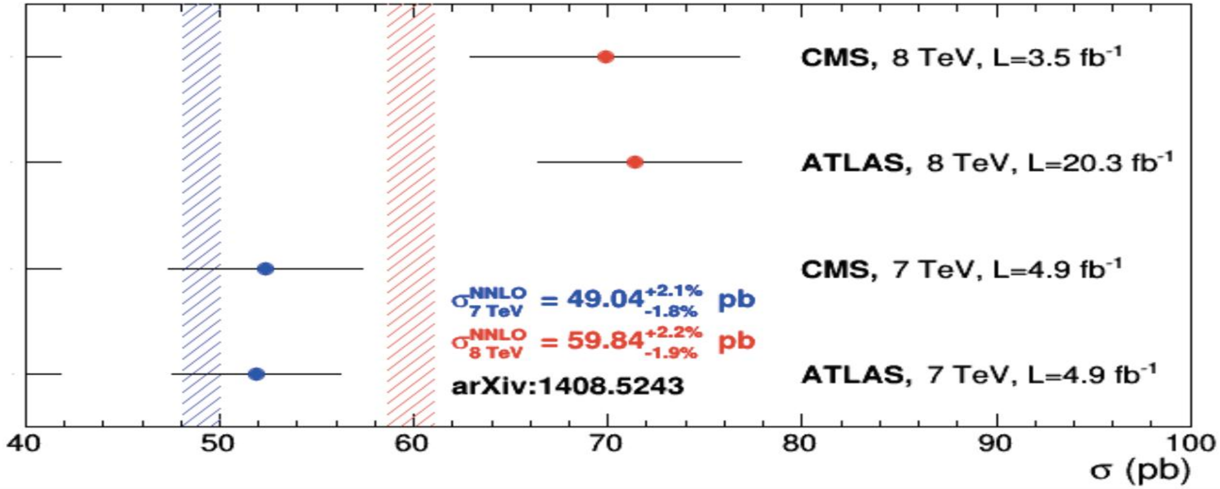
Signature

$e^+e^-,\ \mu^+\mu^-,\ \text{or}\ \ e^\pm\mu^\mp$ + 0,1 jets + MET

Previous Measurements

CMS-PAS-SMP-12-013

- 8 TeV, 3.5 fb^{-1}, found σ(WW → 2ℓ2ν) = (22±13)% higher than NLO prediction



Improvements

- NNLO calculation is ~7% higher [1408.5243]
- Switched from LO MC (Madgraph) to NLO MC (Powheg)
- Employed WW pT resummation reweighting [1407.4481]
- Included H(125) → WW in background

WW → 2ℓ2ν Selection

Selection

Variable	Different-flavor	Same-flavor
Opposite-sign charge requirement	Applied	Applied
p_{T}^{ℓ} [GeV]	> 20	> 20
$\min(\text{proj. } E_{T}^{\text{miss}}, \text{proj. } trackE_{T}^{\text{miss}})$ [GeV]	> 20	> 20
DY MVA	-	> 0.88 in 0-jet (> 0.84 in 1-jet)
$\lvert m_{\ell\ell} - m_{Z}\rvert$ [GeV]	-	> 15
$p_{T}^{\ell\ell}$ [GeV]	> 30	> 45
$m_{\ell\ell}$ [GeV]	> 12	> 12
Additional leptons ($p_{T}^{\ell} > 10$ GeV)	veto	veto
Top-quark veto	applied	applied
Number of reconstructed jets	< 2	< 2

Backgrounds

- Z/γ*/DY/resonances (same flavor category)
- ZZ→2 ℓ2ν (mℓℓ is resonant)
- WZ→3ℓν (one ℓ escapes, peaking and non-peaking)
- ttbar →2l2ν2b, tW →2ℓ2ν1b (mℓℓ is non-resonant)
- W+jets, dijets (nonprompt leptons)
- Higgs (125) → WW → 2ℓ2ν

WW → 2ℓ2ν Selection

Selection

Variable	Different-flavor	Same-flavor
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p_T^{ℓ} [GeV]	> 20	> 20
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Backgrounds

- **Z/γ*/DY/resonances** **(same flavor category)**
- **ZZ→2 ℓ2ν** **(mℓℓ is resonant)**
- WZ→3ℓν (one ℓ escapes, peaking and non-peaking)
- ttbar →2l2ν2b, tW →2ℓ2ν1b (mℓℓ is non-resonant)
- W+jets, dijets (nonprompt leptons)
- Higgs (125) → WW → 2ℓ2ν (small irreducible background)

WW → $2\ell 2\nu$ Selection

Selection

Variable	Different-flavor	Same-flavor
Opposite-sign charge requirement	Applied	Applied
p_T^ℓ [GeV]	> 20	> 20
min(proj. E_T^{miss}, proj. $trackE_T^{miss}$) [GeV]	> 20	> 20
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Backgrounds

- Z/γ*/DY (same flavor category)
- ZZ→2 $\ell 2\nu$ ($m_{\ell\ell}$ is resonant)
- **WZ→$3\ell\nu$ (one ℓ escapes, peaking and non-peaking)**
- ttbar →2l2ν2b, tW →$2\ell 2\nu$1b ($m_{\ell\ell}$ is non-resonant)
- W+jets, dijets (nonprompt leptons)
- Higgs (125) → WW → $2\ell 2\nu$

WW → 2ℓ2ν Selection

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- Higgs (125) → WW → 2ℓ2ν

WW → 2ℓ2ν Cross Sections

$$\sigma_{W^+W^-} = \frac{N_{\text{data}} - N_{\text{bkg}}}{\mathcal{L} \cdot \epsilon \cdot (3 \cdot \mathcal{B}(W \to \ell\overline{\nu}))^2}$$

- $N_{data} - N_{bkg}$ (yields in backup)
- L = luminosity, 19.4 fb^{-1}
- ε = acceptance x efficiency (in backup)
- B (W→ ℓν)= branching ratio to leptons, 10.80 ± 0.09%

Per-channel cross sections

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	$65.1 \pm 5.5\,(\text{stat.}) \pm 8.3\,(\text{exp.}) \pm 8.0\,(\text{th.}) \pm 1.7\,(\text{lum.})$

Inclusive cross section, channels combined : $\sigma(pp \to WW)$

$$\sigma_{W^+W^-} = 60.1 \pm 0.9\,(\text{stat.}) \pm 3.2\,(\text{exp.}) \pm 3.1\,(\text{th.}) \pm 1.6\,(\text{lum.})\,\text{pb} = 60.1 \pm 4.8\,\text{pb}.$$

The result is **well within one standard deviation** of the SM NNLO theoretical prediction of: $59.8^{+1.3}_{-1.1}$ pb

Measurement is dominated by the DF 0-jet category, which has the most events and the best S/B. Precision is dominated by the jet counting uncertainty

WW → 2ℓ2ν Fiducial Cross Sections

$$\sigma_{sig}^{fid.} = \frac{N_{data} - N_{bkg.}}{\epsilon_{sig}^{fid.} \mathcal{L} \left(3 \cdot \mathcal{B}(\mathrm{W} \to \ell\overline{\nu})\right)^2 \left(1 + f_{non-fid./fid.}\right)}.$$

- $\epsilon_{sig}^{fid.}$ = acceptance x efficiency
- $f_{non-fid./fid.}$ = fraction of events reco'ed inside fid. volume that were generated outside (s/b <<1)

- Fiducial volumes close to the default
- Reduces the theoretical uncertainties
- Leptonic τ decays excluded from signal

Fiducial volume: 0 jets at particle level within |η|<4.7, and…

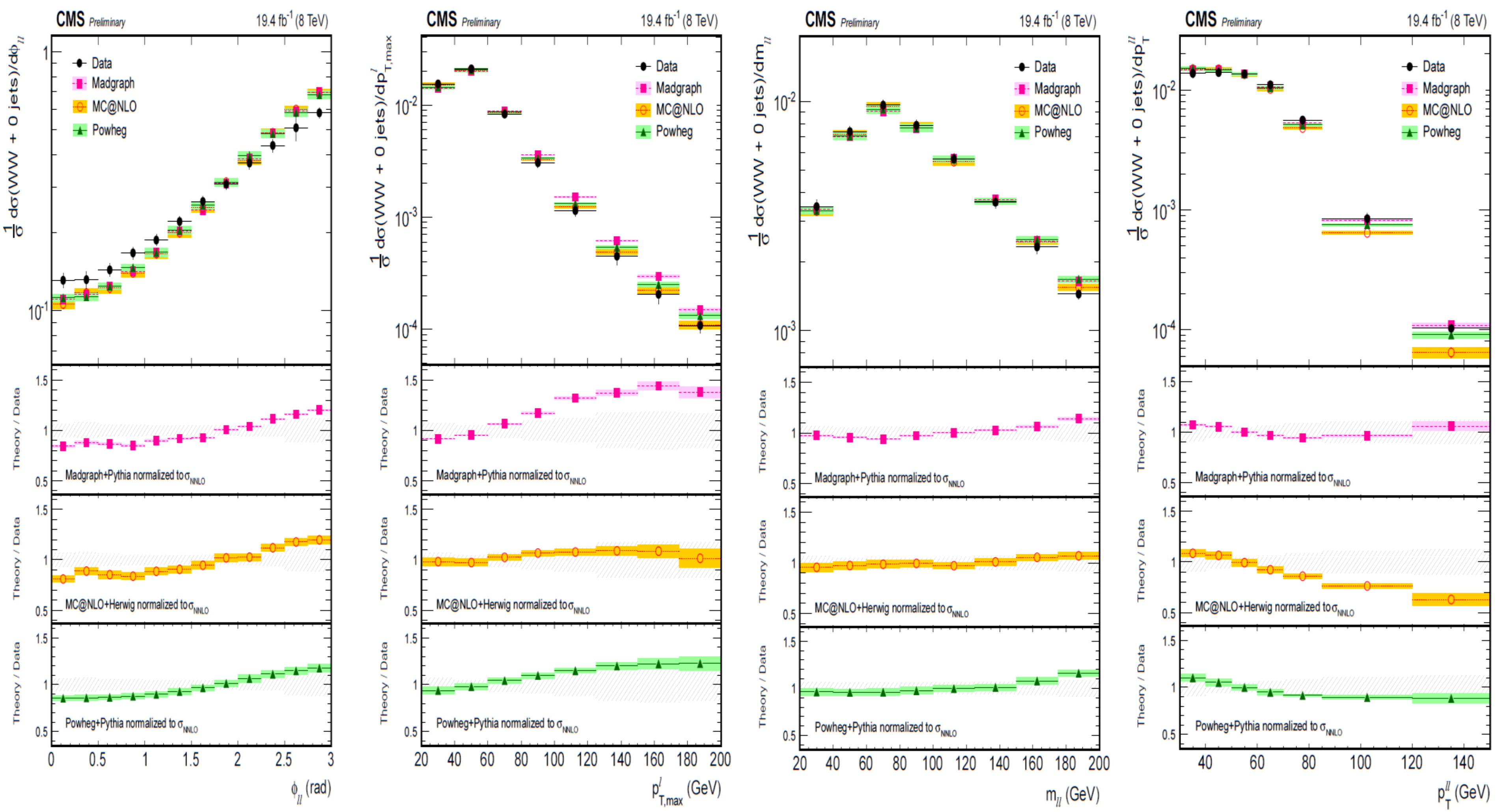
p_T^{jet} threshold (GeV)	σ_{0jet} measured (pb)	σ_{0jet} predicted (pb)
20	$36.2 \pm 0.6\,(\mathrm{stat.}) \pm 2.1\,(\mathrm{exp.}) \pm 1.1\,(\mathrm{th.}) \pm 0.9\,(\mathrm{lum.})$	$36.7 \pm 0.1\,(\mathrm{stat.})$
25	$40.8 \pm 0.7\,(\mathrm{stat.}) \pm 2.3\,(\mathrm{exp.}) \pm 1.3\,(\mathrm{th.}) \pm 1.1\,(\mathrm{lum.})$	$40.9 \pm 0.1\,(\mathrm{stat.})$
30	$44.0 \pm 0.7\,(\mathrm{stat.}) \pm 2.5\,(\mathrm{exp.}) \pm 1.4\,(\mathrm{th.}) \pm 1.1\,(\mathrm{lum.})$	$43.9 \pm 0.1\,(\mathrm{stat.})$

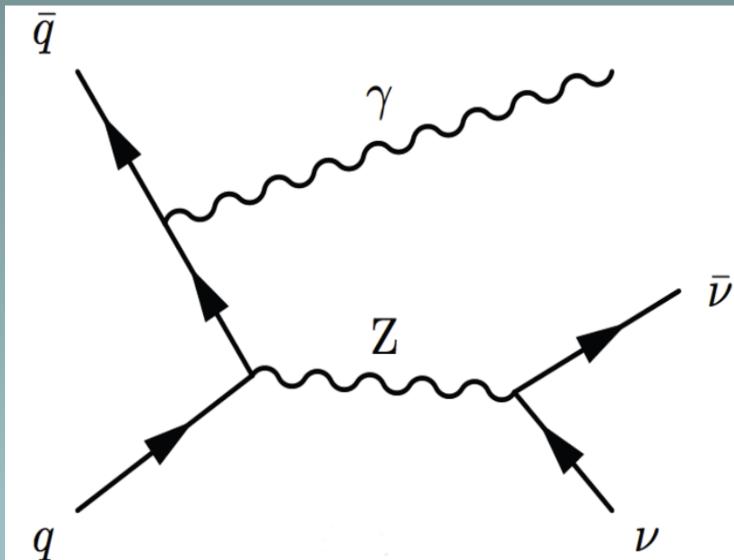
Fiducial volume: 0 jets + DF prompt leptons (1e, 1μ) at particle level with pT >20 GeV before FSR , |η|<2.5

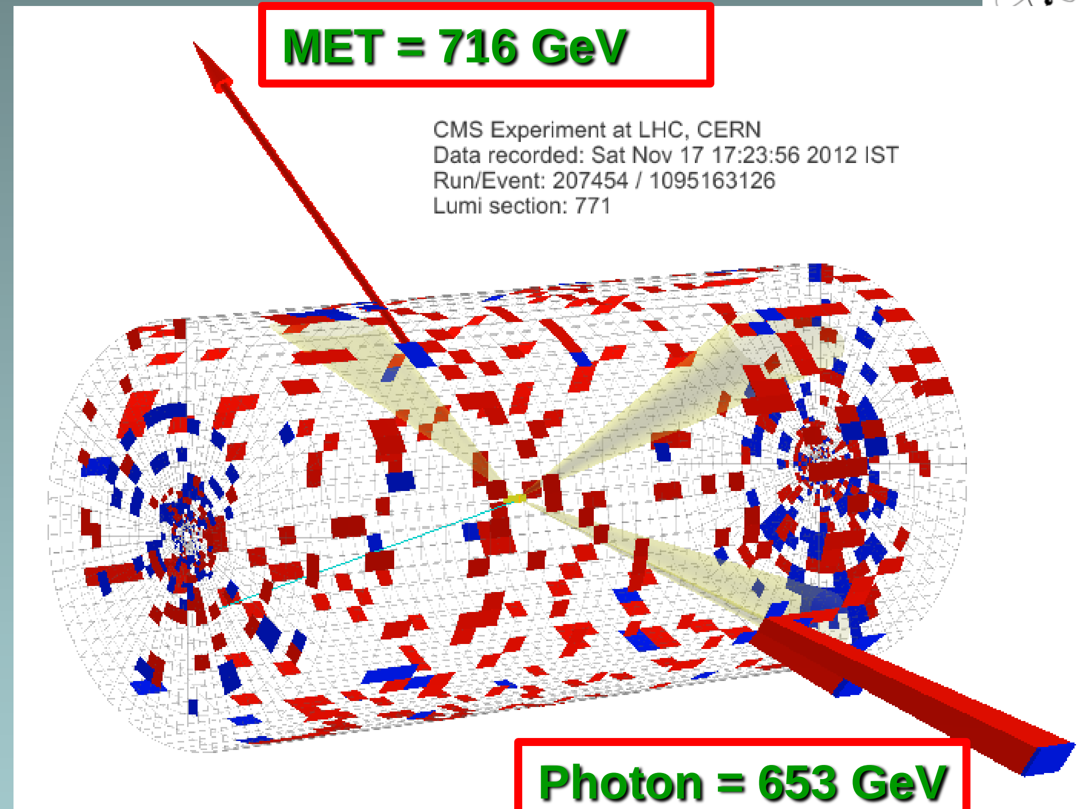
p_T^{jet} threshold (GeV)	$\sigma_{0jet,\mathrm{W}\to\ell\nu}$ measured (pb)	$\sigma_{0jet,\mathrm{W}\to\ell\nu}$ predicted (pb)
20	$0.223 \pm 0.004\,(\mathrm{stat.}) \pm 0.013\,(\mathrm{exp.}) \pm 0.007\,(\mathrm{th.}) \pm 0.006\,(\mathrm{lum.})$	$0.228 \pm 0.001\,(\mathrm{stat.})$
25	$0.253 \pm 0.005\,(\mathrm{stat.}) \pm 0.014\,(\mathrm{exp.}) \pm 0.008\,(\mathrm{th.}) \pm 0.007\,(\mathrm{lum.})$	$0.254 \pm 0.001\,(\mathrm{stat.})$
30	$0.273 \pm 0.005\,(\mathrm{stat.}) \pm 0.015\,(\mathrm{exp.}) \pm 0.009\,(\mathrm{th.}) \pm 0.007\,(\mathrm{lum.})$	$0.274 \pm 0.001\,(\mathrm{stat.})$

WW → 2ℓ2ν Differential Cross Sections

- Comparisons with Madgraph+Pythia, Powheg+Pythia, & MC@NLO+Herwig provided
- All normalized to NNLO prediction , Statistical and systematic uncertainties included



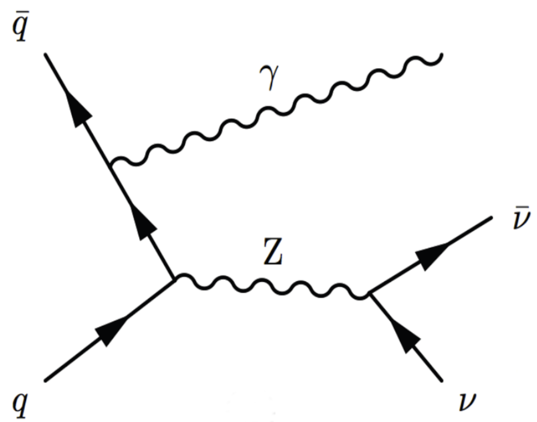


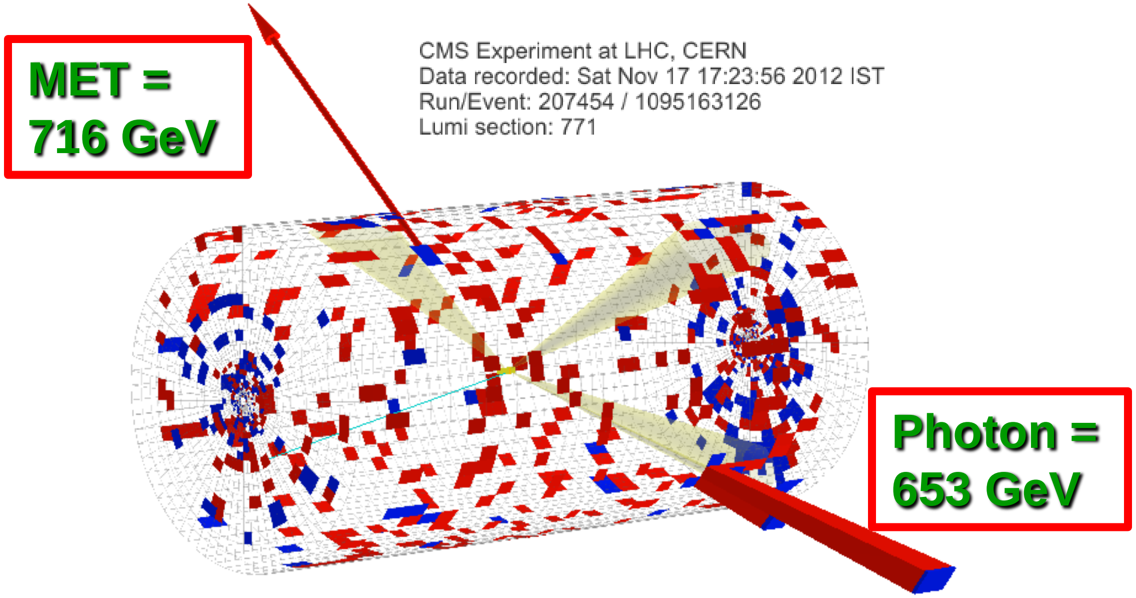


$Z\gamma \rightarrow \nu\nu\gamma$

(CMS-PAS-SMP-14-019)

$Z\gamma \to \nu\nu\gamma$ Overview





Signature

Monophoton (from ISR) + large MET

Irreducible Background to BSM searches (EXO-12-047, 1410.8812)

Large Extra dimensions ($Z \to \nu\nu$ becomes Graviton/branon production
and dark matter ($Z \to \nu\nu$ becomes $X \to \chi\chi$)

Uses the same HL triggers, datasets, analysis strategies

$Z\gamma \rightarrow \nu\nu\gamma$ Selection & Backgrounds

Selection

- High-pT photon trigger (>150 GeV)
- Low pT Photon (70)-MET (100) trigger
- Photon E_T>145, $|\eta| < 1.44$, pass “medium” ID, isolation (reduces jet fakes)
- non-overlapping lepton veto pT > 10GeV (kill leptonic processes)
- Njet <= 1, jet pT > 30 GeV, dR>0.5 (reduce MET from mismeasured jets)
- MET > 140, $\Delta\varphi$(MET,γ) > 2 (reduce γ + jet, mismeasured photon)

Non-collision MET backgrounds

- Detector noise filters (mis-timed lasers, HCAL HPD discharges, etc.)
- intra-cluster time difference < 5ns (ECAL APD spikes)
- collision timing 3ns window cut (Bremming cosmic and halo muons)
- halo MIP event tagging veto (Bremming halo muons)

Mismeasured objects: MHT Minimization

Try to redistribute the MET back to the visible objects and balance

Use the minimized MET and the χ^2 to discriminate real from fake MET

$\widetilde{\not{E}}_T > 120\,\mathrm{GeV}$ reduces γ + jets

$Z\gamma \rightarrow \nu\nu\gamma$ Background Estimation

Remaining Backgrounds		
In decreasing order of importance		**Estimation method**
$W\gamma \rightarrow \ell\nu\gamma$	(ℓ escapes)	From LO Madgraph, norm to NLO σ from MCFM (validated in data control region)
$W \rightarrow e\nu$	(e fakes γ, missing pixel match)	estimate fake rate from tag/probe of $Z \rightarrow ee$ in data and MC
jets$\rightarrow\gamma$ + MET	(jet fakes γ, mismeasured)	estimate fake rate from data sample with jets, small MET
Showering halo muons		Estimated fraction of halo in signal timing window from ECAL timing distribution
γ + jet	(mismeasured jet)	From Pythia (with k=1.3)
$\gamma\,\gamma$	(mismeasured γ)	From Pythia

$Z\gamma$ signal simulated at LO with Madgraph and normed to NNLO σ

$Z\gamma \to \nu\nu\gamma$ Fiducial Cross Section

$$\sigma \times \mathcal{B} = \frac{N_{\rm data} - N_{\rm bg}}{A \times \epsilon \times L},$$

$$A \times \epsilon = (A \times \epsilon)_{\rm sim} \times \rho$$

- $N_{data} - N_{bg}$ (see below)
- L = luminosity, 19.6 fb^{-1}
- A x ε = acceptance x efficiency
- ρ = MC/data correction factor

➔ A x ε denominator is

# of events passing PT > 145 GeV, |η| < 1.4

➔ Scale factor (ρ) = 0.94 ± 0.06

Process	Estimate
$W(\to \ell\nu) + \gamma$	103 ± 21
$W \to e\nu$	60 ± 6
jet $\to \gamma$ MisID	45 ± 14
Beam halo	25 ± 6
Others	36 ± 3
Total background	268 ± 26
$Z(\to \nu\bar{\nu}) + \gamma$	345 ± 43
Data	630

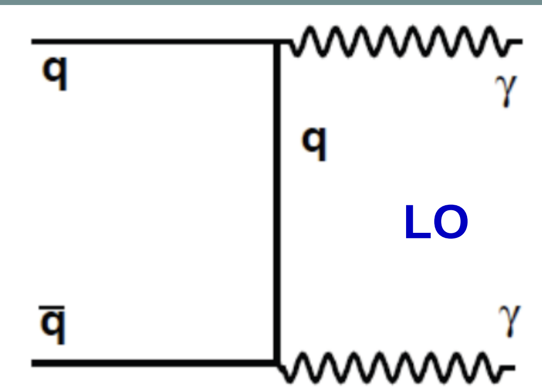
➔ Measured cross section for PT > 145 GeV, |η| < 1.4 is

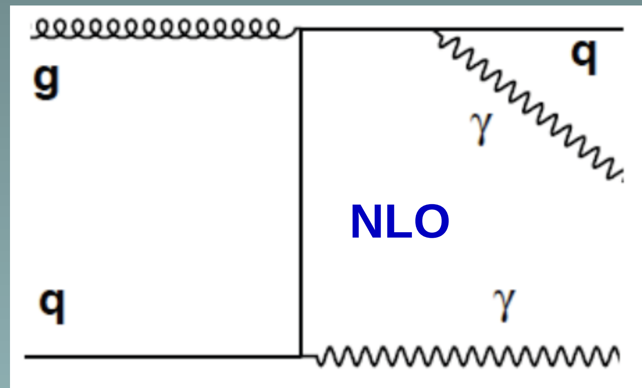
52.7 ± 2.1 (stat) ± 6.4(syst) ± 1.4(lumi) fb

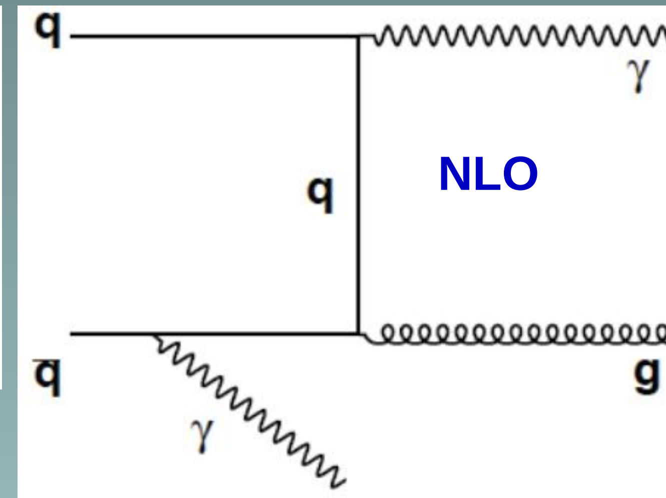
➔ NNLO theory cross section from Grazzini et.al

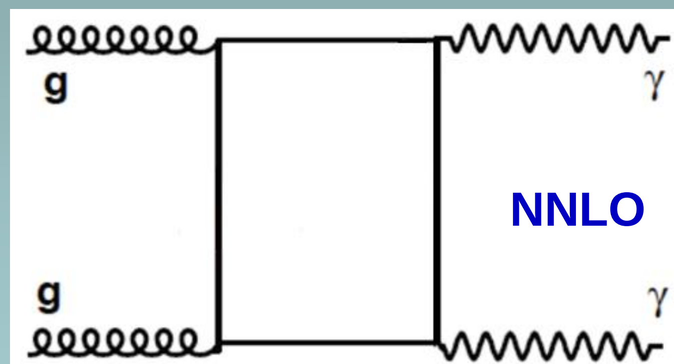
50.0 + 2.4 – 2.2 fb

where uncertainty is the scale uncertainty









γγ + jets @ 7 TeV

(CMS-PAS-SMP-14-021)

γγ + jets Overview

Extension of the previous analysis (SMP-13-001, EPJC, QCD@LHC 2013)

Signature

Two prompt isolated photons + jets

Primary Background

Two NON-prompt merged photons from neutral meson decay in jets

Strategy

- **Same** data,γ selection,template methods
- **Jets** pT>25 GeV, |η|<4.7, $\Delta R_{\gamma j} > 1.0$, PU
- **photon isolation** is the discriminator
- Build **data-driven templates** for sig,bkg
- **Fit the isolation distribution** in data, extracting prompt diphoton purity
- **Unfold** to gen-level quantities correcting for selection efficiency
- **Compare** the results to theory

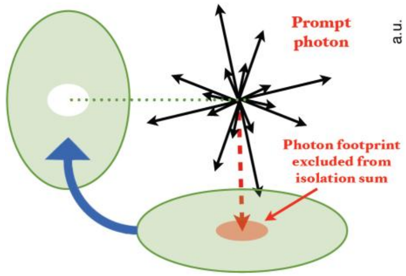
Motivation

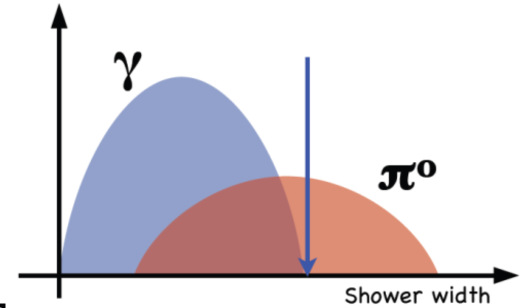
Background to VBF Higgs → γγ,
Probe of QCD
Sensitive to new physics (GMSB)

Differential variables

- ✦ **inclusive 1-jet bin:**
  - Jet pT
  - Jet-photon separations:
    - ΔR (leading photon, jet)
    - ΔR (trailing photon, jet)
    - ΔR (closer photon, jet)
    - ΔR (far photon, jet)
- ✦ **inclusive 2-jet bin:**
  - Jet pT
  - Jet separation
  - Di-jet invariant mass
  - Δφ γγ / jj
  - Zeppenfeld variable
- ✦ **number of jets**

γγ + jets Construction of templates





Random cone

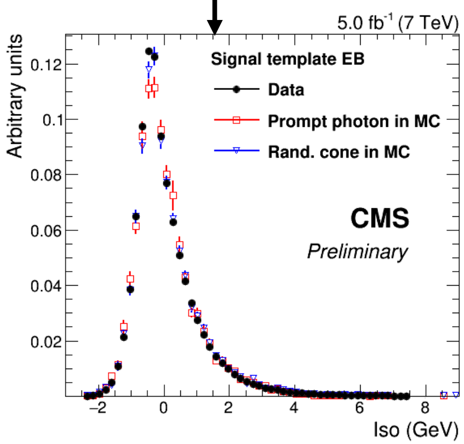
Selection

Shower shape sideband

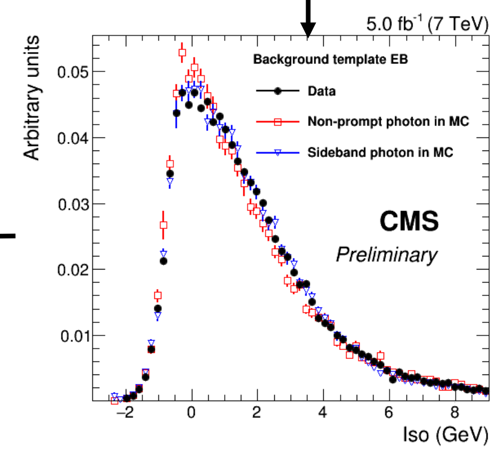
Prompt template

Diphoton events

Fakes template



Purity fits in the differential variable



γγ + jets Switch to 2D!

$$\mathcal{L}_{2D}(Iso_1, Iso_2) =$$

$$= pp \cdot T_{pp}(Iso_1, Iso_2) + pf \cdot T_{pf}(Iso_1, Iso_2) + fp \cdot T_{fp}(Iso_1, Iso_2) + ff \cdot T_{ff}(Iso_1, Iso_2)$$

- Isolation sums for the two photons are not factorizable
- PU correlates them, even after area subtraction
- Build separate **2D** templates according to combinations

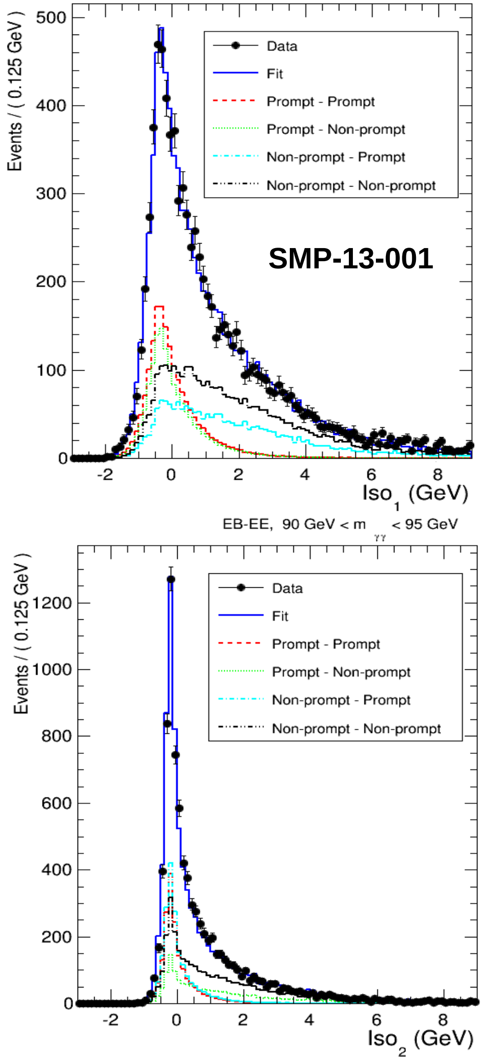
pp = prompt-prompt, pf = prompt-fake,

fp = fake-prompt, ff = fake-fake

- **pp**: use two random cones in the same event
- **pf, fp**: use one random cone in event with sideband photon
- **ff** : merge two events containing a sideband photon each

Extract raw signal (pp) event yield from a four-component likelihood fit in each bin of each variable separately for barrel-barrel, barrel-endcap and endcap-endcap combinations

Wow, that's a lot of fits!!



$\gamma\gamma$ + jets Results

Compare results to

- Sherpa (LO) scaled to the inclusive NNLO calculation (k=1.17)
- aMC@NLO rescaled to inclusive NNLO (k=0.88)
- GOSAM NLO parton-level calculation, not scaled to NNLO

$$\sigma_{data}^{1-jet} = 7.4 \pm 0.2\,(\text{stat.}) \pm 1.0\,(\text{syst.}) \pm 0.2\,(\text{lumi})\ \text{pb}$$

$$\sigma_{data}^{2-jet} = 2.3 \pm 0.1\,(\text{stat.}) \pm 0.4\,(\text{syst.}) \pm 0.1\,(\text{lumi})\ \text{pb}$$

$$\sigma_{\text{SHERPA}}^{1-jet} = 5.9^{+1.9}_{-1.3}\,(\text{scale+stat.})\ \text{pb} \qquad \sigma_{\text{SHERPA}}^{2-jet} = 1.7^{+0.8}_{-0.5}\,(\text{scale+stat.})\ \text{pb}$$

$$\sigma_{a\text{MC@NLO}}^{1-jet} = 8.3^{+1.2}_{-1.2}\,(\text{scale+pdf+stat.})\ \text{pb} \qquad \sigma_{a\text{MC@NLO}}^{2-jet} = 2.5^{+0.4}_{-0.4}\,(\text{scale+pdf+stat.})\ \text{pb}$$

$$\sigma_{\text{GoSAM}}^{1-jet} = 5.8^{+0.9}_{-0.8}\,(\text{scale+stat.})\ \text{pb} \qquad \sigma_{\text{GoSAM}}^{2-jet} = 1.9^{+0.4}_{-0.4}\,(\text{scale+stat.})\ \text{pb}$$

Good data/theory agreement for Sherpa and aMC@NLO

Differential cross sections in the backup

Conclusions

- Results of 3 recently released analyses studying multiboson production at the CMS detector at 8 TeV have been presented
  - Comparisons with several MC generators are provided

All results are consistent with the Standard Model

- Keep your eyes peeled for more results in the weeks and months to come
  - New multiboson events are already identified in Run 2
- More talks at EPS from CMS (and Theory) about the topic:
  - **Exclusive W+W- production measured with the CMS experiment and constraints on Anomalous Quartic Gauge Couplings** (Manfred Jietler)
  - **Measurement of anomalous triple and quartic gauge couplings at CMS** (Senka Duric)
  - **Di-vector Boson Production in Association with Multiple Jets at the LHC** (QCD & Hadronic physics – presenting NLO QCD corrections of $pp \rightarrow W^+W^-$+jets)

BACKUP

WW → 2ℓ2ν Background Estimation

- **Top**: estimate from data by counting $N_{top\text{-}tagged}$ events and applying corresponding efficiency $\varepsilon_{top\text{-}tagged}$ measured separately
- **W+Jets**: estimate from a "tight-loose" (i.e., "real-fake") dilepton control sample in data, and apply efficiency ε_{loose} measured separately
- **Z+Jets**: estimate by measuring N_{events} in tight window around the Z pole from data, and extrapolating out using simulation
- **Wγ*:** estimate from simulation, but normalized to data sample with three reconstructed leptons (one lepton from γ* decay escapes)
- Other backgrounds from simulation.

WW → 2ℓ2ν 0-jet distributions

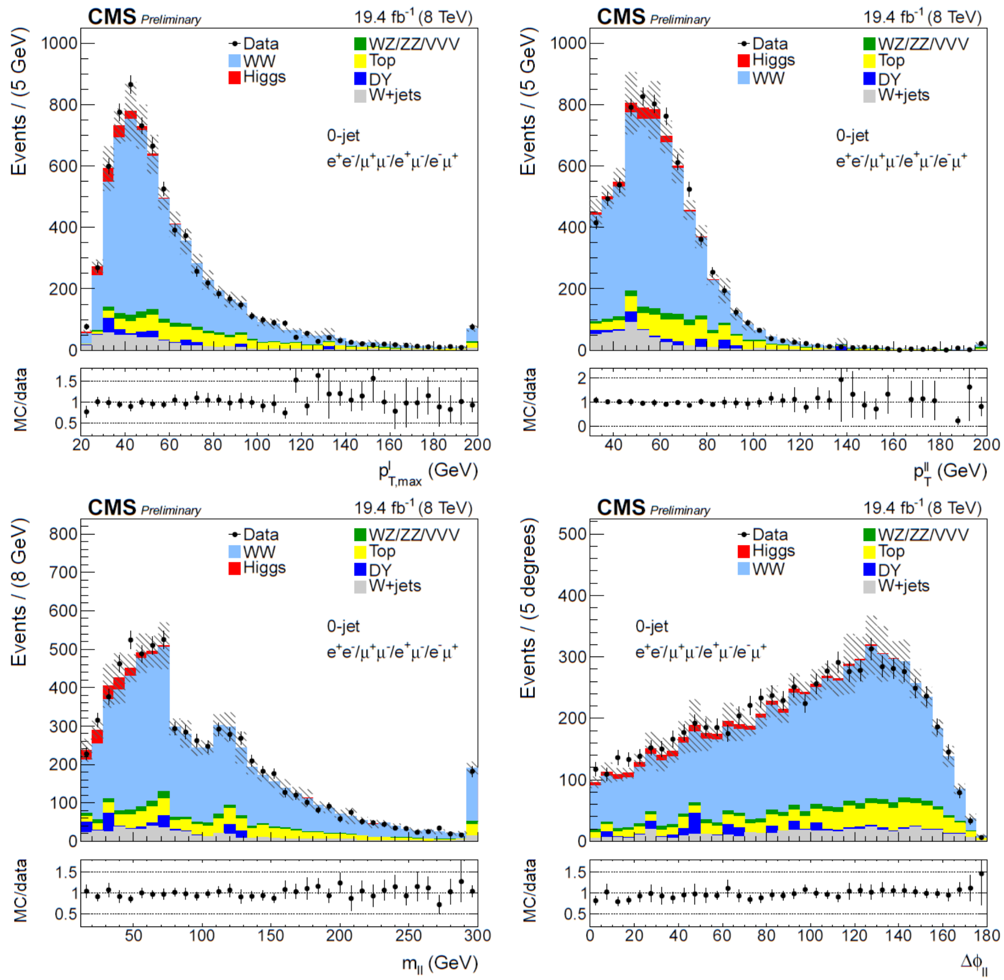


Figure 1: The data and MC distributions for the 0-jet category of the leading lepton p_{T}, $p^{\ell}_{T,\,\max}$; the p_{T} of the dilepton system, $p^{\ell\ell}_{T}$; the dilepton invariant mass, $m_{\ell\ell}$; and the azimuthal angle between the two leptons, $\Delta\phi_{\ell\ell}$. The hatched areas represent the total systematic uncertainty in each bin. The error bars in the ratio plots are calculated considering both the statistical uncertainty from the limited size of the data sample as well as the systematic uncertainties in the background estimation and signal efficiency. The last bin includes the overflow.

WW → 2ℓ2ν 1-jet distributions

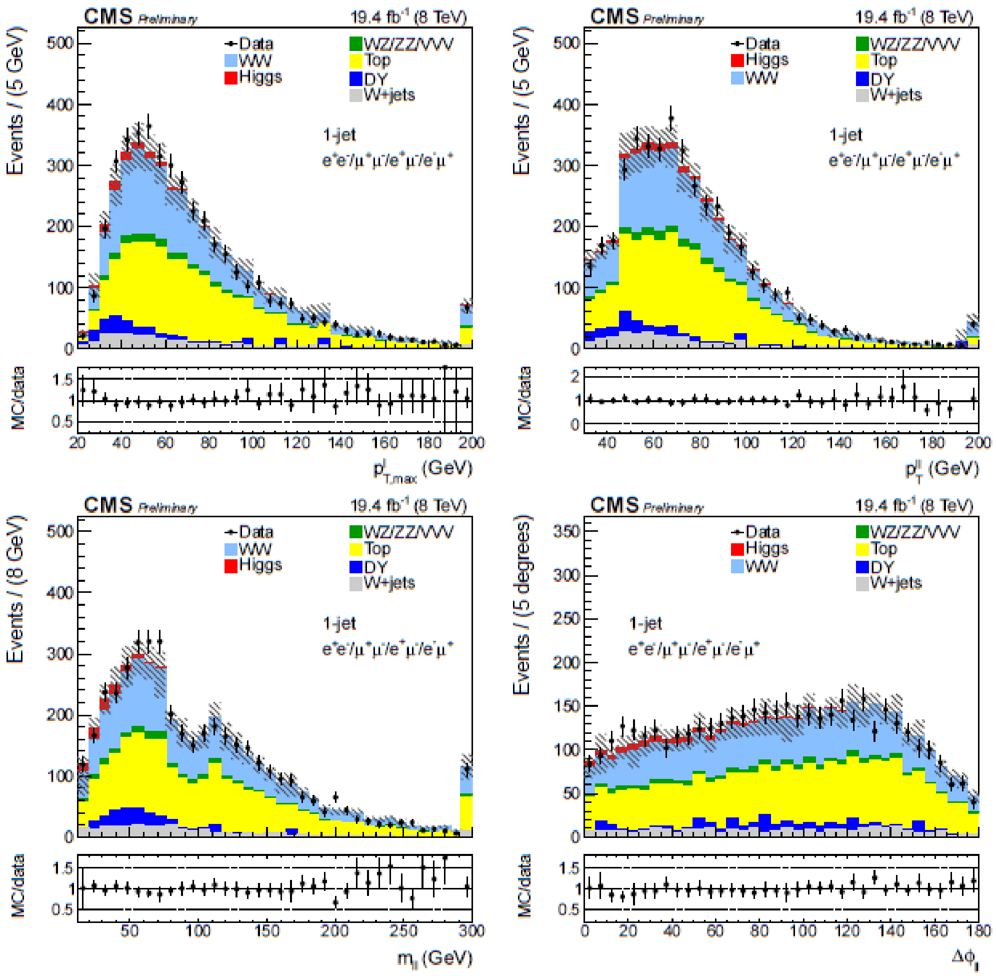


Figure 2: The data and MC distributions for the 1-jet category of the leading lepton p_T, $p^{\ell}_{T,\,\max}$; the p_T of the dilepton system, $p_T^{\ell\ell}$; the dilepton invariant mass, $m_{\ell\ell}$; and the azimuthal angle between the two leptons, $\Delta\phi_{\ell\ell}$. The hatched areas represent the total systematic uncertainty in each bin. The error bars in the ratio plots are calculated considering both the statistical uncertainty from the limited size of the data sample as well as the systematic uncertainties in the background estimation and signal efficiency. The last bin includes the overflow.

WW → $2\ell 2\nu$ Systematic Uncertainties

Table 1: Relative systematic uncertainties on the WW cross section measurement, in units of percent.

Source	Uncertainty (%)
Statistical uncertainty	1.5
Luminosity	2.6
Lepton efficiency	3.8
Lepton momentum scale	0.5
E_T^{miss} resolution	0.7
Jet energy scale	1.7
$t\bar{t}$+tW normalization	2.2
W + jets normalization	1.3
$Z/\gamma^* \to \ell^+\ell^-$ normalization	0.6
$Z/\gamma^* \to \tau^+\tau^-$ normalization	0.2
$W\gamma$ normalization	0.3
$W\gamma^*$ normalization	0.4
VV normalization	3.0
$H \to$ WW normalization	0.8
Jet counting theory model	4.3
PDFs	1.2
MC statistics	0.9
Total uncertainty	7.9

WW → 2ℓ2ν Event Yields

Event category		Signal efficiency (%)
0-jet category	Different-flavor	3.02 ± 0.02 (stat.) ± 0.22 (syst.)
	Same-flavor	1.21 ± 0.01 (stat.) ± 0.09 (syst.)
1-jet category	Different-flavor	0.96 ± 0.01 (stat.) ± 0.11 (syst.)
	Same-flavor	0.34 ± 0.01 (stat.) ± 0.04 (syst.)

Process	0-jet category		1-jet category	
	Different-flavor	Same-flavor	Different-flavor	Same-flavor
$qq \to W^+W^-$	3516 ± 271	1390 ± 109	1113 ± 137	386 ± 49
$gg \to W^+W^-$	162 ± 50	91 ± 28	62 ± 19	27 ± 9
W^+W^-	3678 ± 276	1481 ± 113	1174 ± 139	413 ± 50
$ZZ + WZ$	84 ± 10	89 ± 11	86 ± 4	42 ± 2
VVV	33 ± 17	17 ± 9	28 ± 14	14 ± 7
Top-quark	522 ± 83	248 ± 26	1398 ± 156	562 ± 128
$Z/\gamma^* \to \ell^+\ell^-$	38 ± 4	141 ± 63	136 ± 14	65 ± 33
$W\gamma^*$	54 ± 22	12 ± 5	18 ± 8	3 ± 2
$W\gamma$	54 ± 20	20 ± 8	36 ± 14	9 ± 6
$W + \text{jets}(e)$	189 ± 68	46 ± 17	114 ± 41	16 ± 6
$W + \text{jets}(\mu)$	81 ± 40	19 ± 9	63 ± 30	17 ± 8
Higgs	125 ± 25	53 ± 11	75 ± 22	22 ± 7
Total bkg.	1179 ± 123	643 ± 73	1954 ± 168	749 ± 133
W^+W^- + Total bkg.	4857 ± 302	2124 ± 134	3128 ± 217	1162 ± 142
Data	4847	2233	3114	1198

$Z\gamma \rightarrow \nu\nu\gamma$ Systematic Uncertainties

Source	$Z(\nu\nu)\gamma$ [%]
Photon and $\not{E}_T$ Energy Scale	+3.43, -5.01
jet and $\not{E}_T$ energy scale	+2.30,-2.36
Jet energy resolution	+1.20, -1.38
Unclustered ES	+1.9, -0.6
Pileup	0.3
Lumi	$\pm$2.6 %
PDFs $+\alpha_s$ (for k-factor)	$\sim$10
Scale factor	6.4

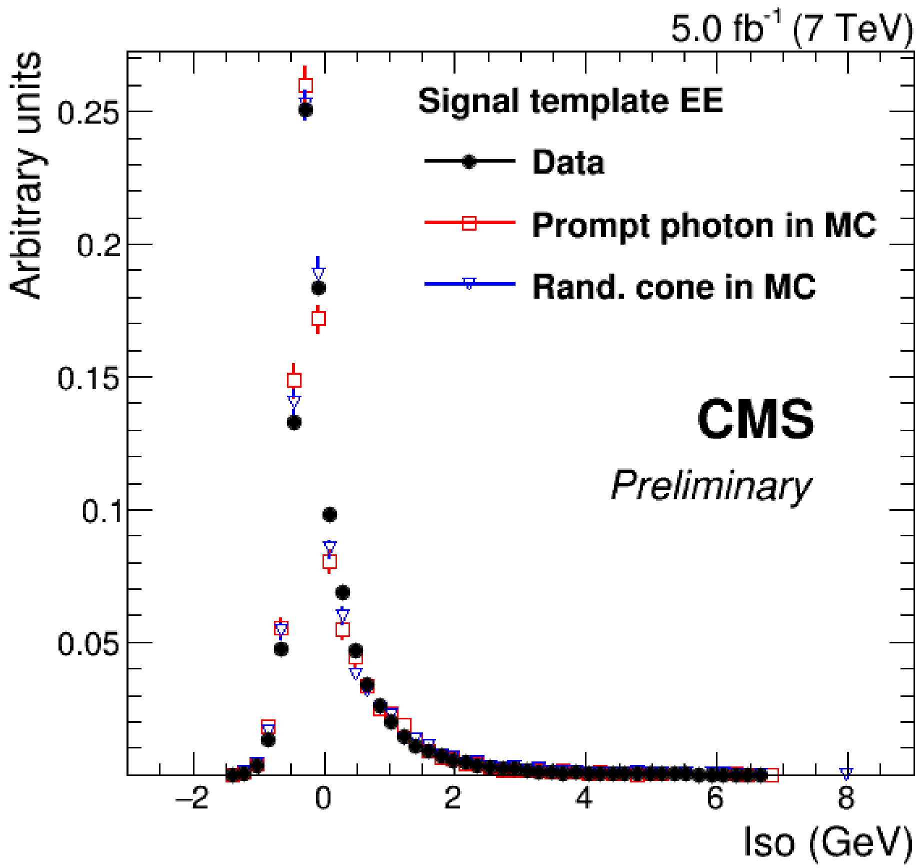
$\gamma\gamma$ + jets Photon Selection

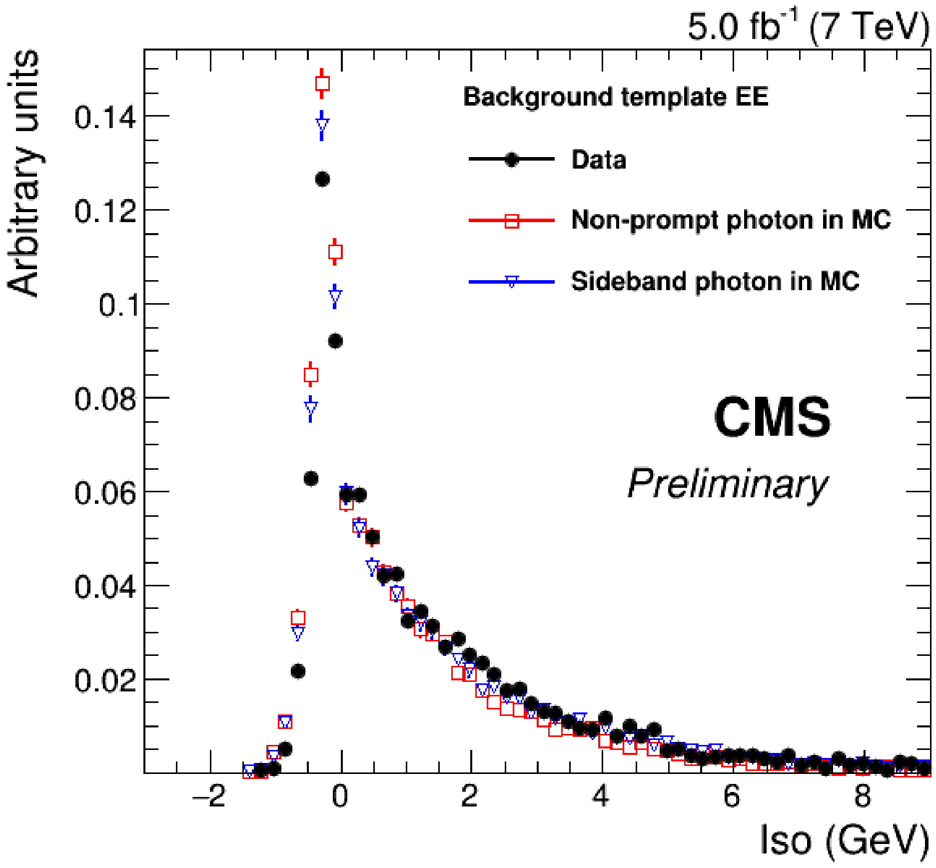
Variable	Requirement
Photon cluster + preshower energy	$E_{SC} + E_{SC}^{ES} > 20\,\mathrm{GeV}$
H/E	if ($R_9 > 0.9$): H/E < 0.082 (EB), 0.075 (EE) if ($R_9 < 0.9$): H/E < 0.075
$\sigma_{\eta\eta}$	$0.001 < \sigma_{\eta\eta} < 0.014$ (EB), 0.034 (EE)
ECAL isolation in a ΔR=0.3 cone	$\mathrm{Iso}_{\mathrm{ECAL}}^{0.3} < 4\,\mathrm{GeV}$ (only if $R_9 < 0.9$)
HCAL isolation in a ΔR=0.3 cone	$\mathrm{Iso}_{\mathrm{HCAL}}^{0.3} < 4\,\mathrm{GeV}$ (only if $R_9 < 0.9$)
TRK isolation in a ΔR=0.3 cone	$\mathrm{Iso}_{\mathrm{TRK}}^{0.3} < 4\,\mathrm{GeV}$ (only if $R_9 < 0.9$)

Variable	Requirement
Matched pixel measurements	False
H/E	H/E < 0.05
$\sigma_{\eta\eta}$	$\sigma_{\eta\eta} < 0.011$ (EB), 0.030 (EE)

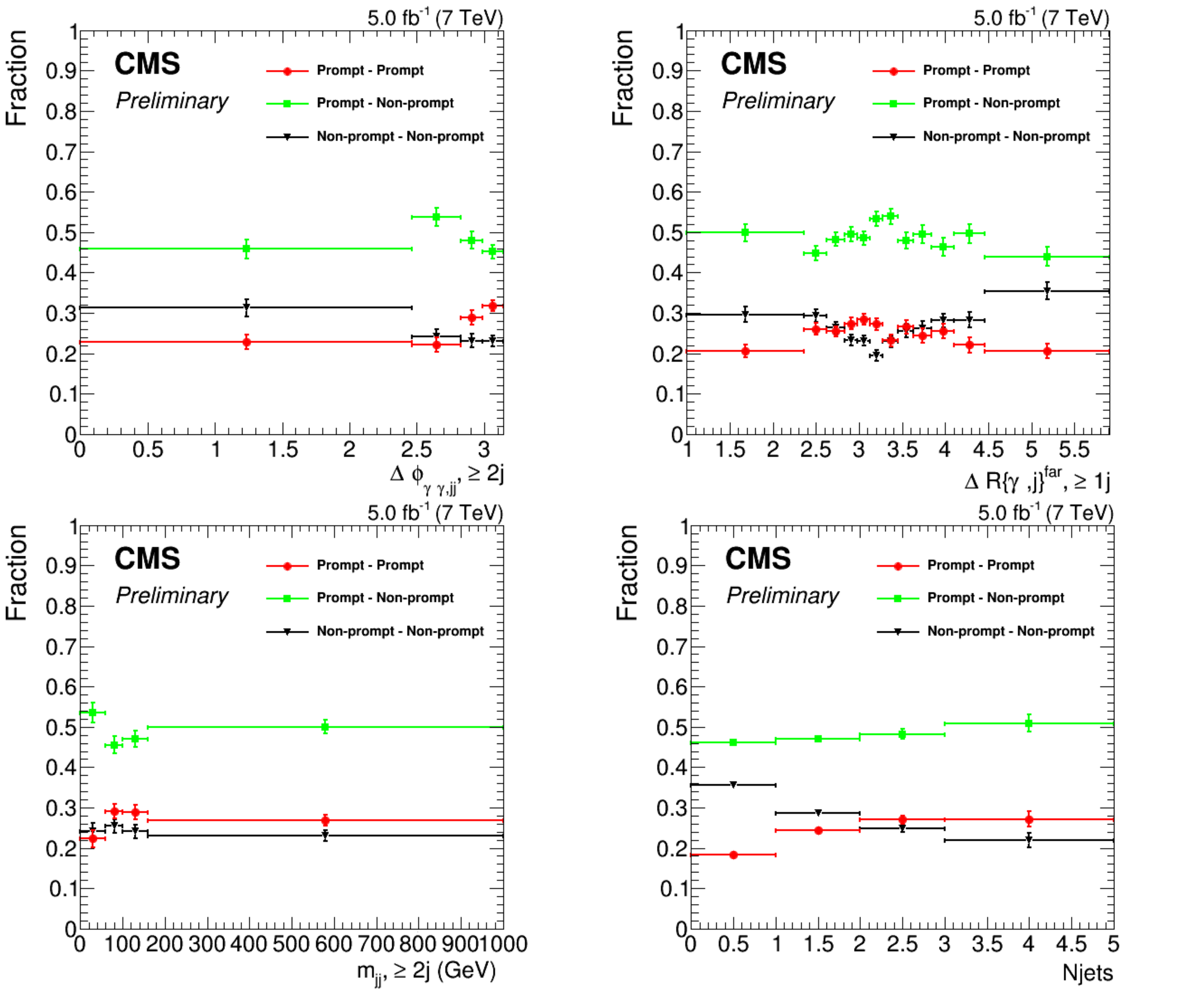
Event selection: $pT(\gamma_1) \geq 40\mathrm{GeV}$, $pT(\gamma_2) \geq 25\mathrm{GeV}$, $\Delta R(\gamma_1,\gamma_2) > 0.45$

γγ + jets EE templates





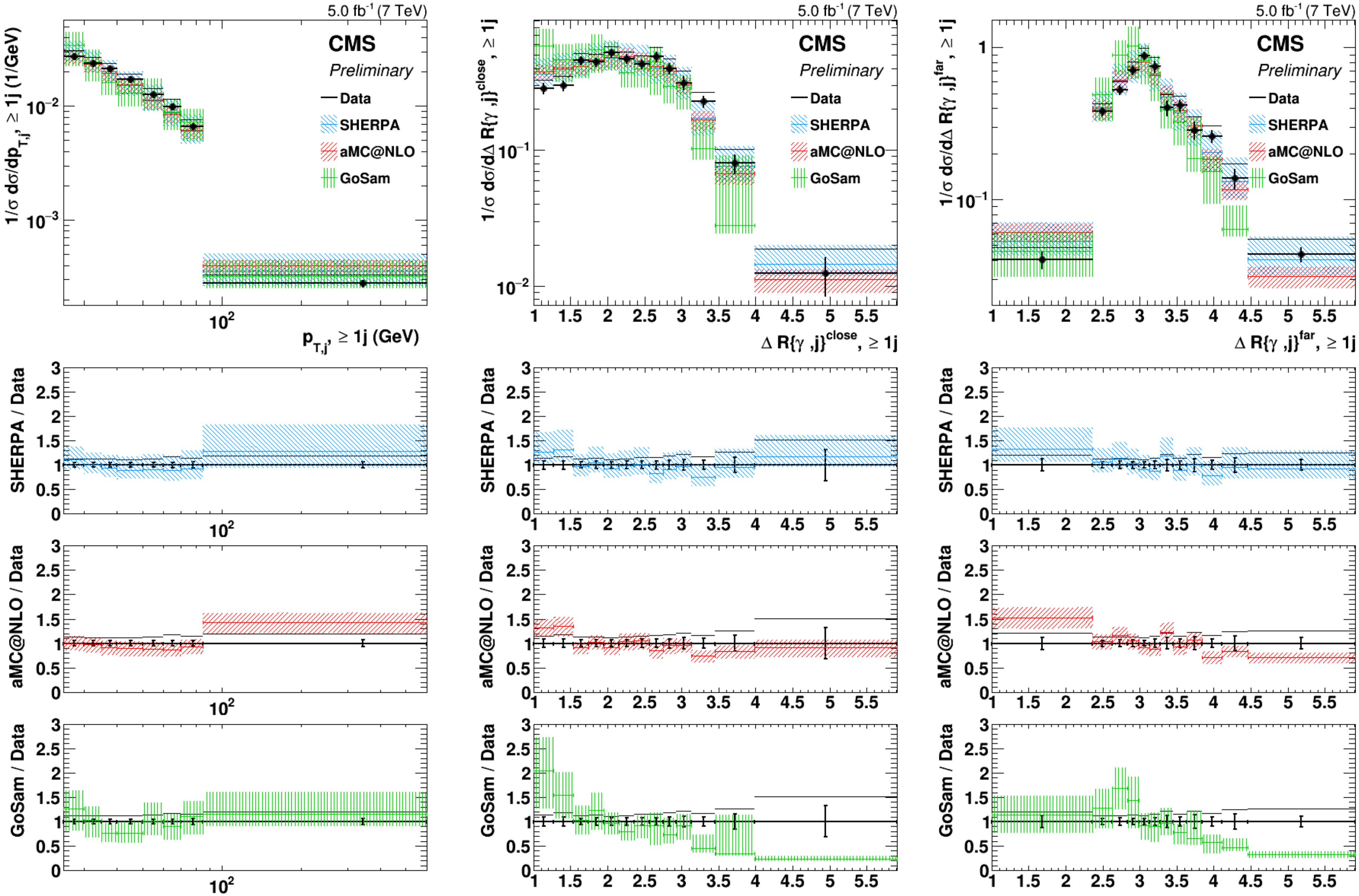
γγ + jets Purity Fractions



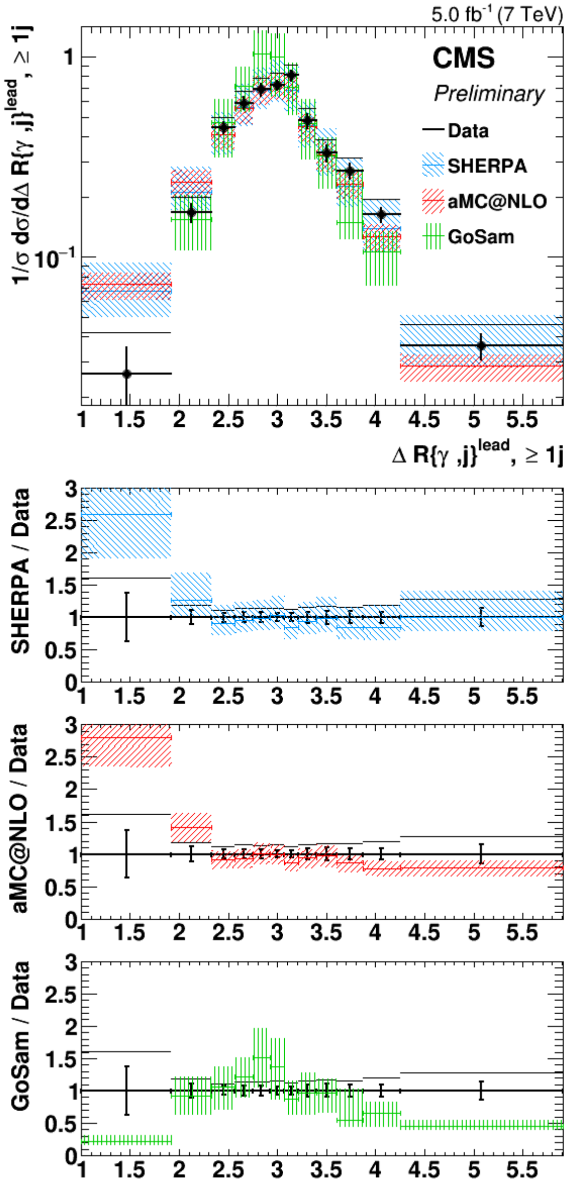
$\gamma\gamma$ + jets Systematic Uncertainties

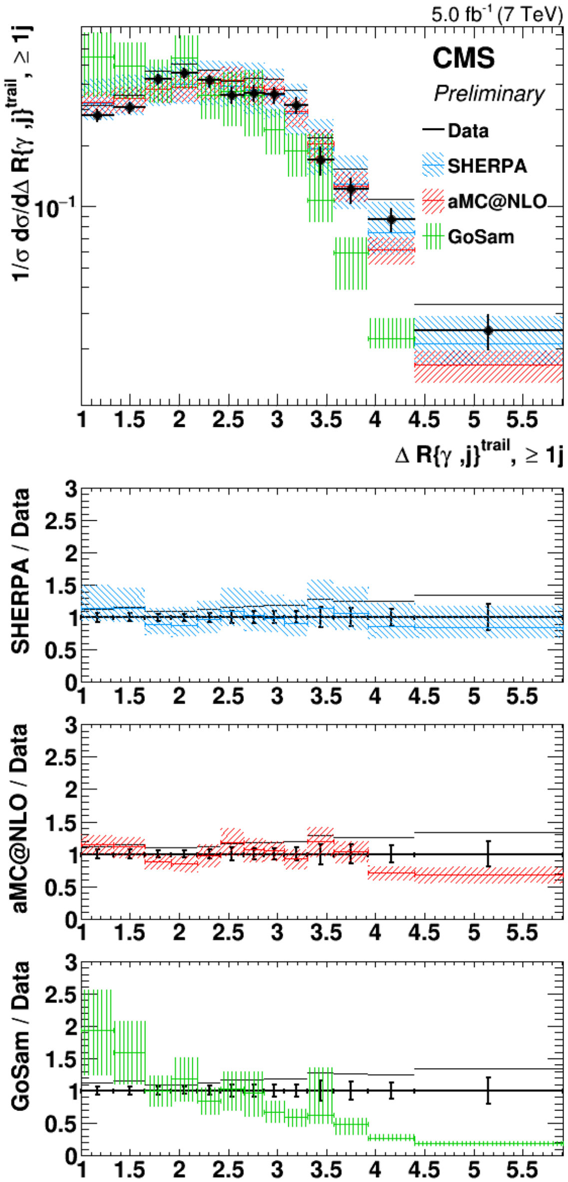
Source of uncertainty	
Prompt template shape (EB)	3%
Prompt template shape (EE)	4%
Non-prompt template shape (EB)	6%
Non-prompt template shape (EE)	9%
Effect of fragmentation component	1.5%
Template statistical fluctuation	3%
Jet energy scale and resolution	3-15%
Pileup description	1.5%
Unfolding response model	5%
Integrated luminosity	2.2%

γγ + jets Differential Cross Sections

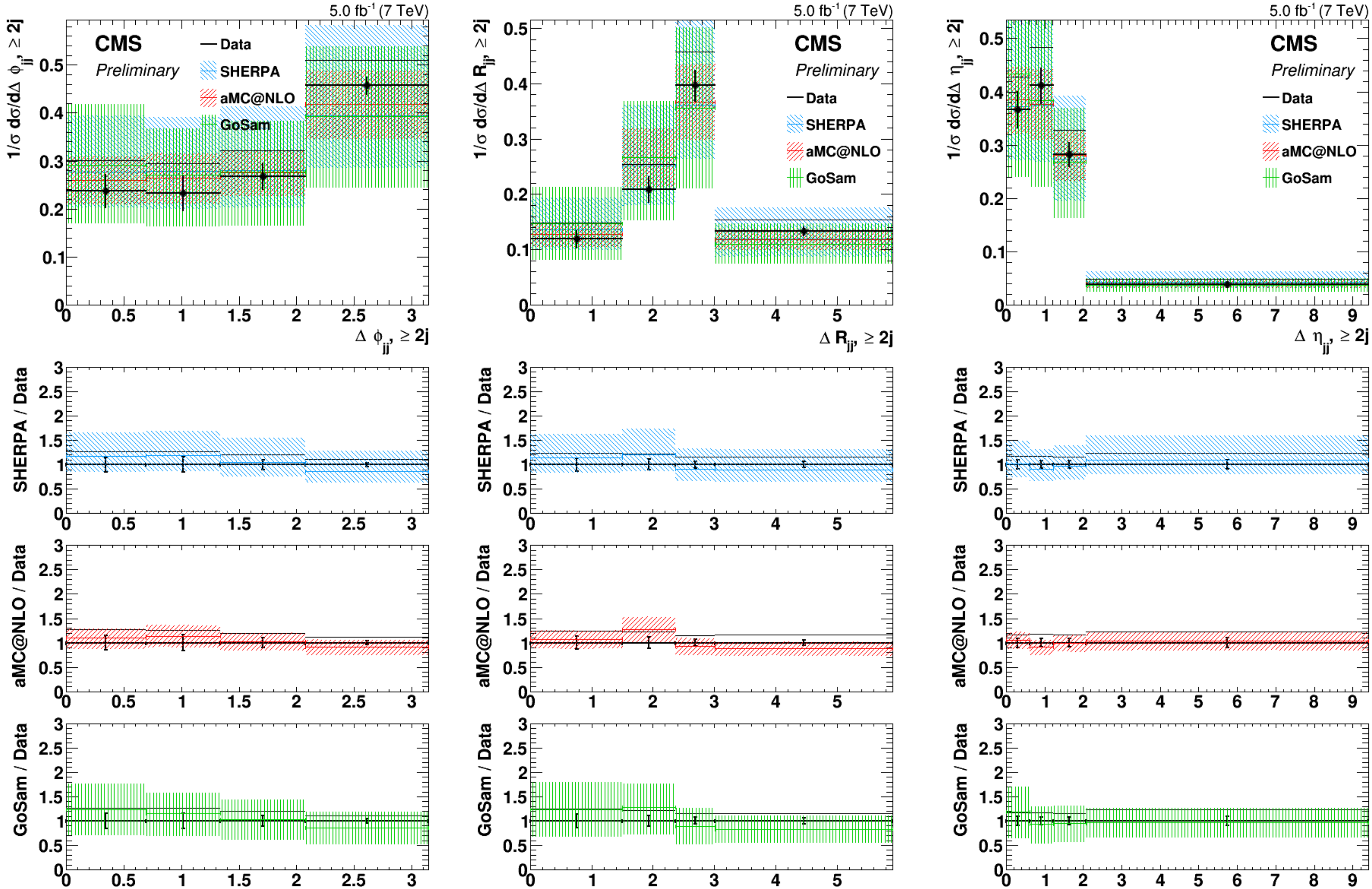


γγ + jets Differential Cross Sections

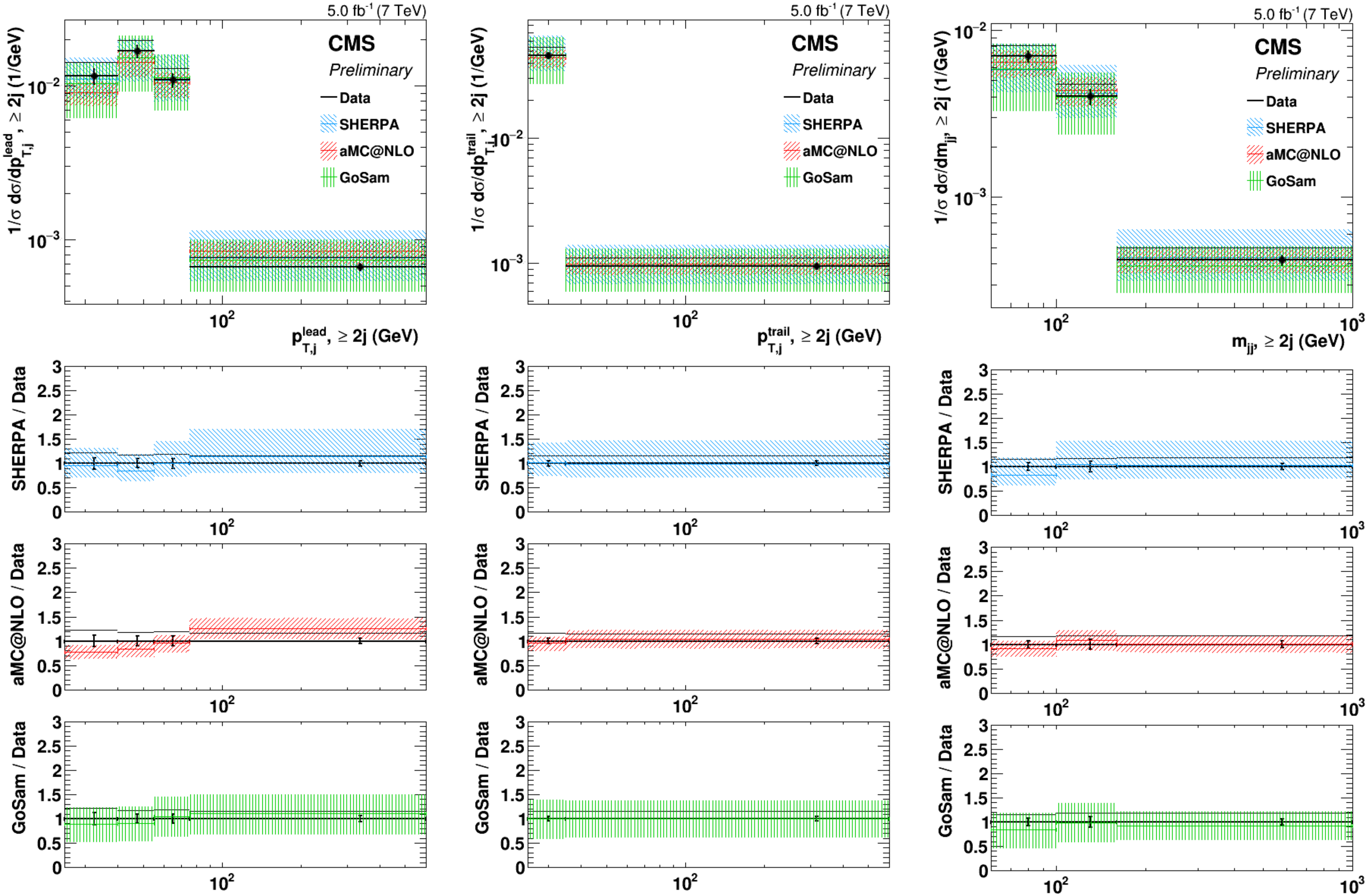




γγ + jets Differential Cross Sections



γγ + jets Differential Cross Sections



γγ + jets Differential Cross Sections