Measurement of the semileptonic tt+γ production cross section at 8 TeV

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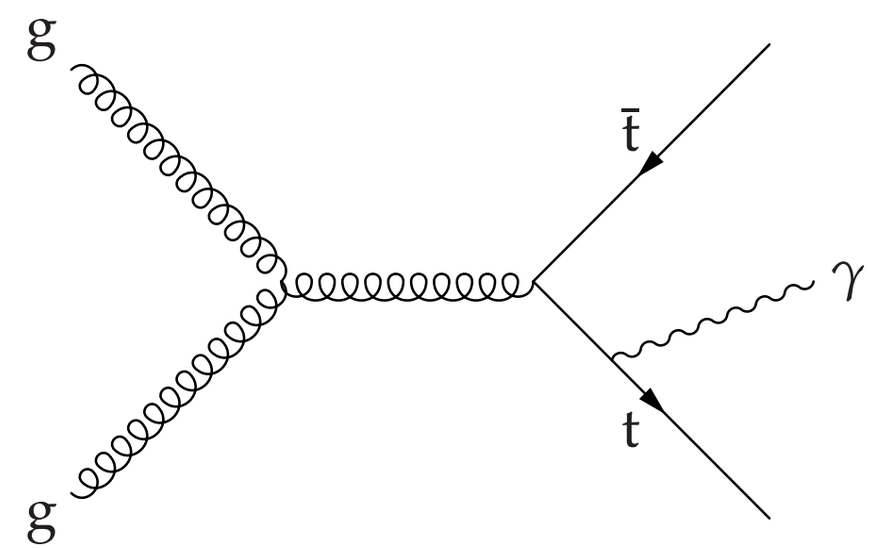
submitted to JHEP

Overview

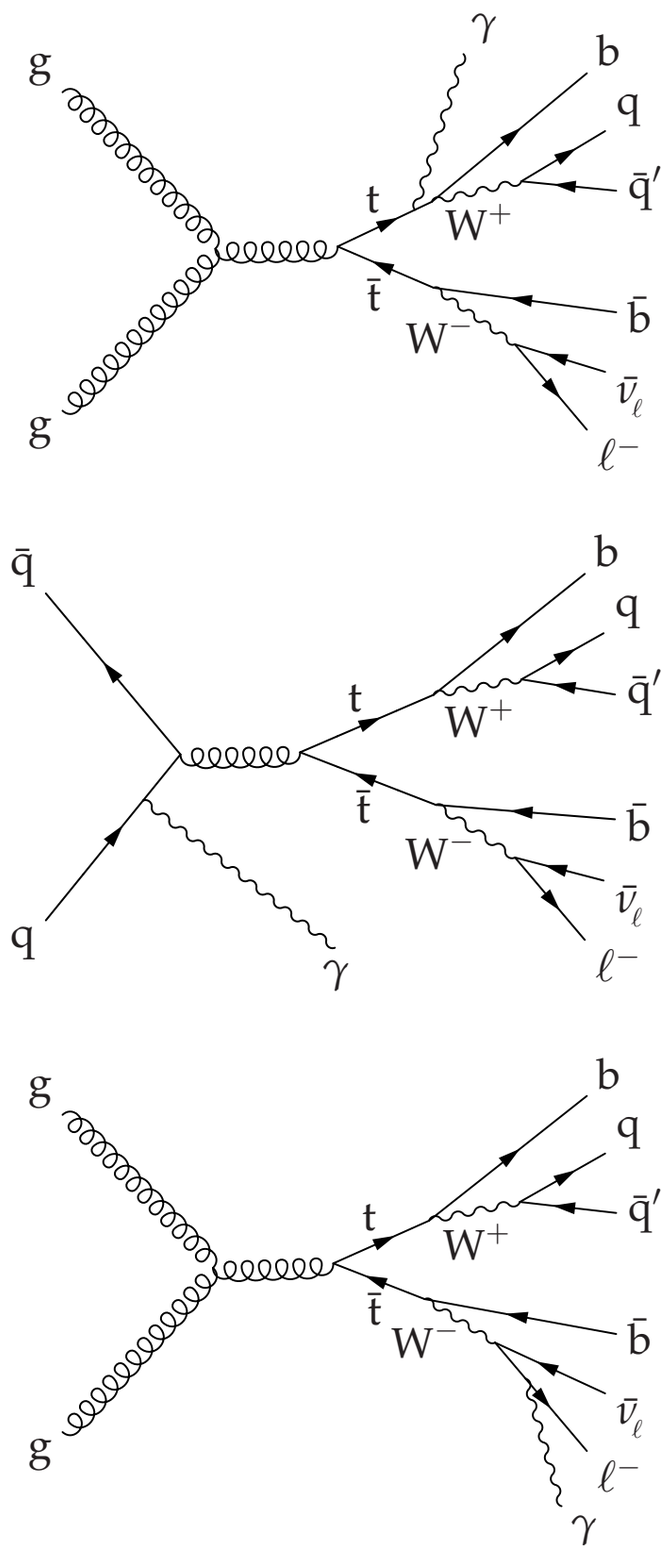
- Associated production of top quarks provides an interesting check of the standard model and window where new physics could show up
  - Provides measurements which are directly sensitive to the couplings of the top quark



- Measuring the tt+γ production cross section
  - Allows for probing the electroweak coupling of the top quark
  - Directly sensitive to the top quark charge
  - Any deviations from the SM prediction could be hints at new physics

tt+γ Cross Section Measurement

- Measuring the production cross section of tt+γ production using 19.7 fb^{-1} of data collected by the CMS experiment at a center of mass energy of 8 TeV



- Performed in the lepton+jets final state (e or μ)
- Fiducial cross section is measured relative to inclusive tt production
- arXiv:1706.08128 submitted to JHEP

Selection

- Selection is split into two levels:
  - **Top quark selection**: events with a top quark pair signature
  - **Photon selection**: passing the top quark selection and have at least one photon present

- **Top quark selection:**
  - Require exactly 1 lepton (e or mu)
    - Veto events with additional leptons passing loose requirements
  - At least 3 jets, one of which is b-tagged
  - $p_T^{miss} > 20$ GeV

- **Photon Selection:**
  - At least one photon, $p_T > 25$ GeV, $|\eta| < 1.44$, isolated from other activity in event

Top quark pair production

- Measurement is performed as a ratio of tt+γ to tt production cross sections

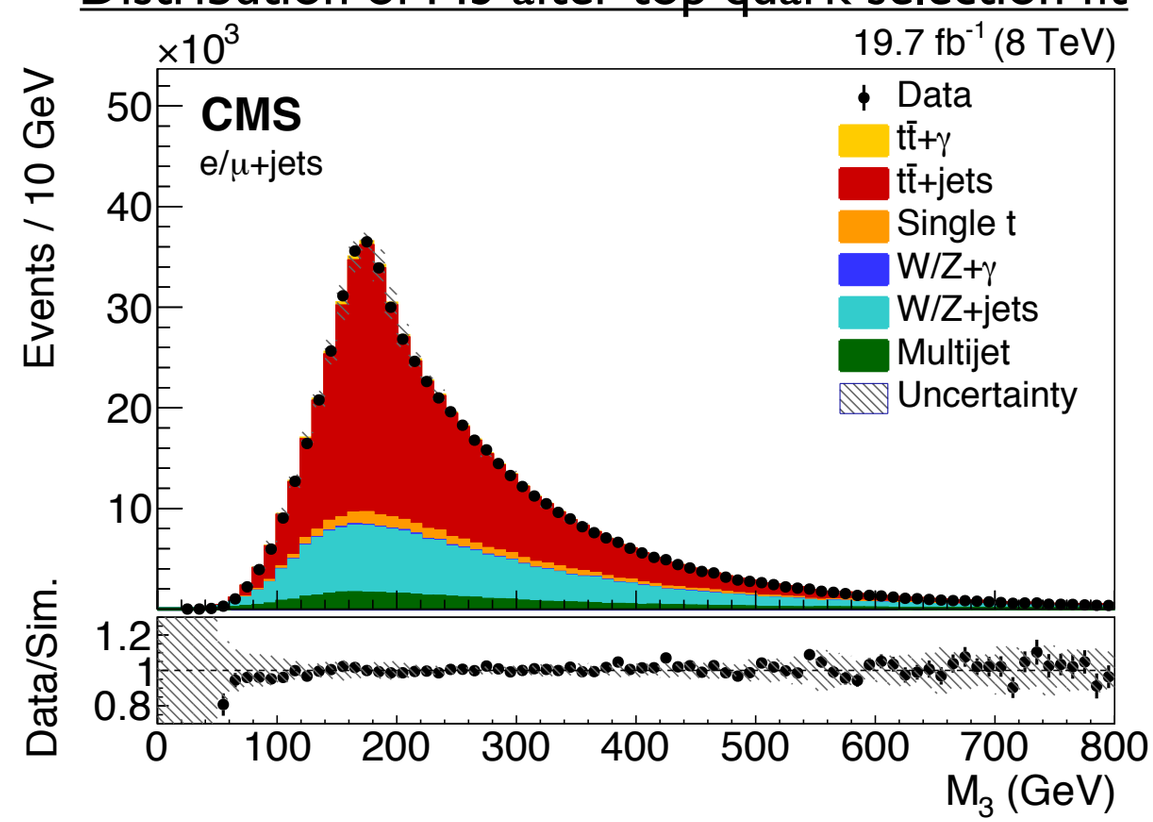
$$R = \frac{\sigma^{\text{fid}}_{t\bar{t}+\gamma}}{\sigma_{t\bar{t}}} = \frac{N_{t\bar{t}+\gamma}}{\epsilon^{t\bar{t}+\gamma}} \cdot \frac{\epsilon^{t\bar{t}}_{\text{top}} A^{t\bar{t}}_{\text{top}}}{N_{t\bar{t}}}$$

  - Need to measure both the number of tt+γ events (after photon selection) and number of top quark pair events at top quark selection level
  - Fit to M3 variable (mass of 3-jet combination with highest summed p_T) used to extract N_{tt}

e+jets: N_{tt} = 162200 ± 1600 (stat)

***μ*+jets**: N_{tt} = 219100 ± 1900 (stat)

Distribution of M3 after top quark selection fit



Backgrounds

- After photon selection, backgrounds can be split into two categories
  - Top pair events with fake photons
  - Non-top processes with real photons (W+γ, Z+γ)
- Each of these backgrounds is estimated using fits to different variables:
  - M3 is used to distinguish top from non-top processes
  - Photon charged hadron isolation can be used to separate prompt from nonprompt photons

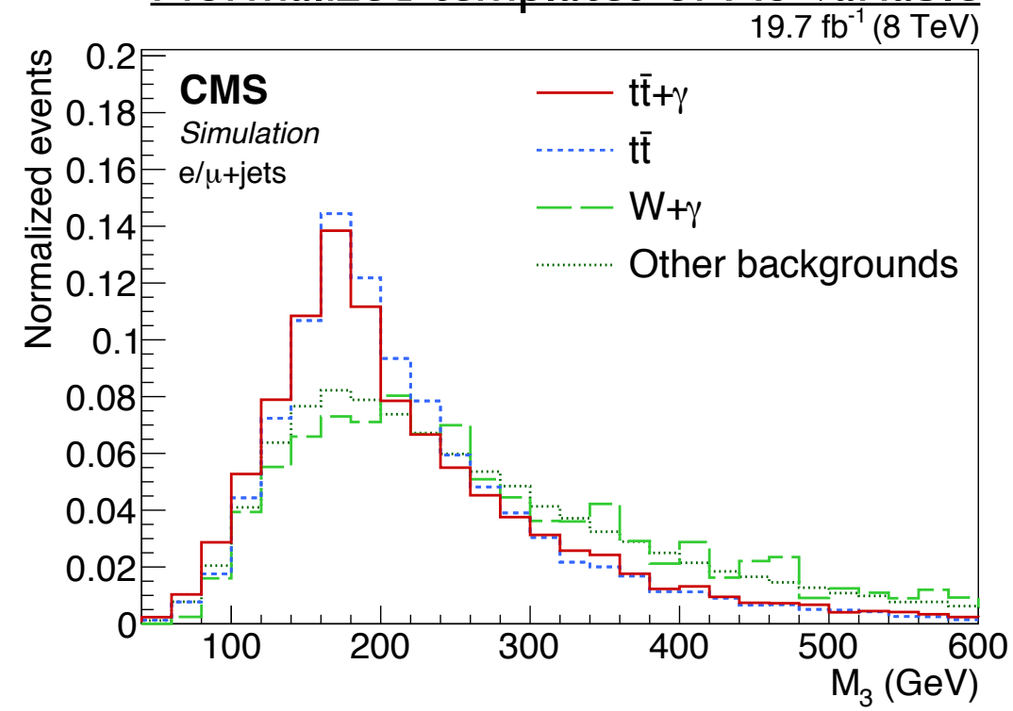
Top quark purity

- Top quark purity (π_{tt}), defined as fraction of events coming from top pair events, measured with fit to M_3 distribution
  - Measured after the photon selection is applied
  - Templates for top events (tt or tt+γ), W+γ, and other backgrounds taken from simulation

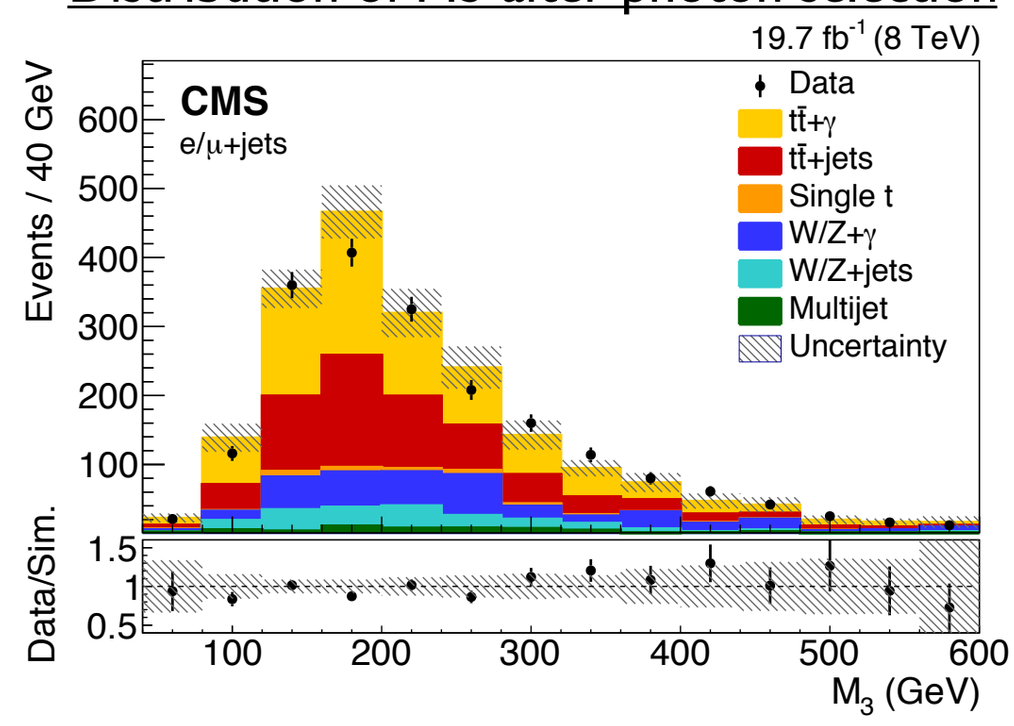
e+jets: π_{tt} = 0.70 ± 0.08 (stat)

***μ*+jets**: π_{tt} = 0.68 ± 0.06 (stat)

Normalized templates of M3 variable



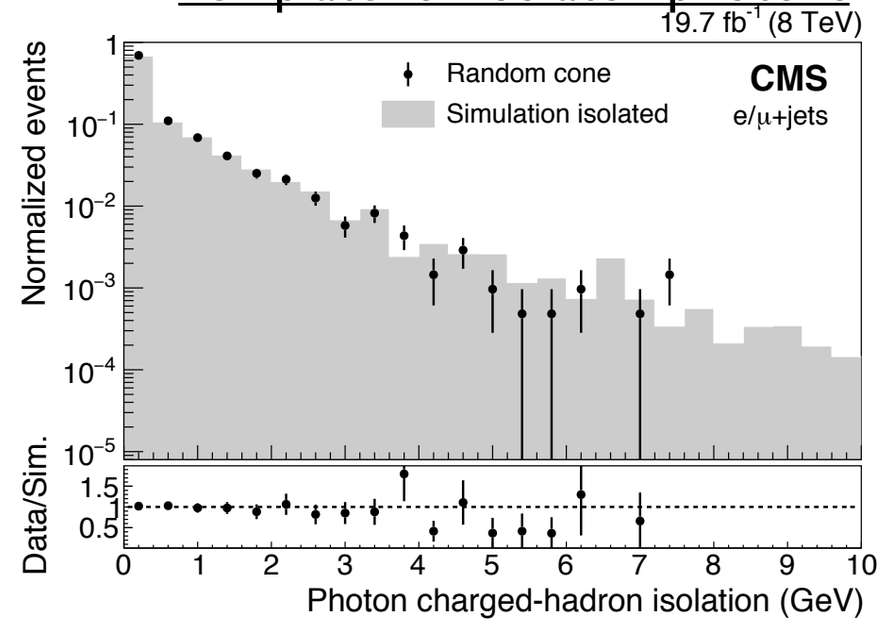
Distribution of M3 after photon selection



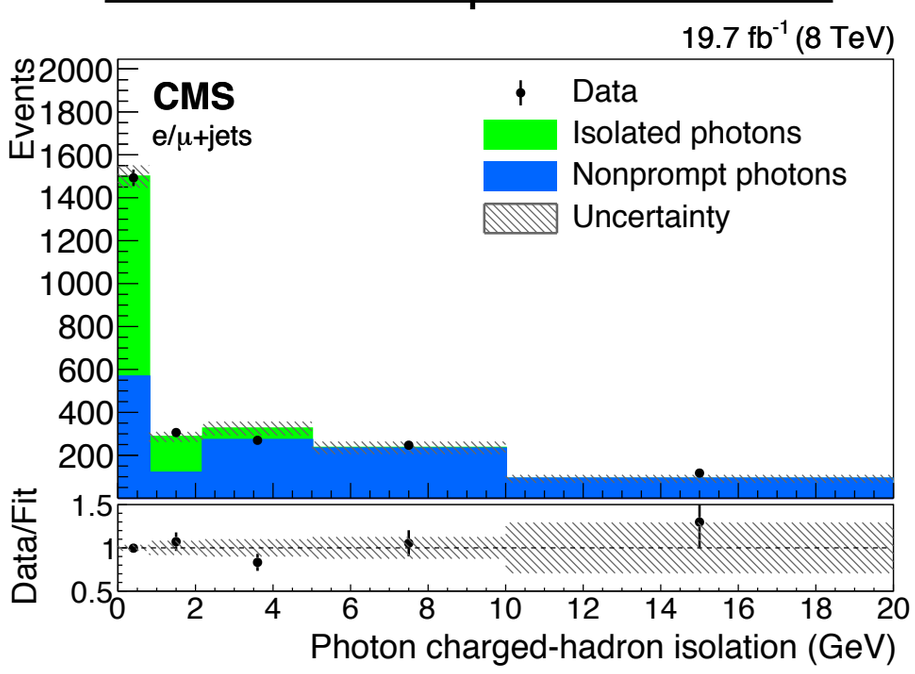
Photon purity

- Photon purity(π_γ), fraction of events coming from prompt photons, measured through a fit to the photon isolation
  - Prompt photons (or also misidentified electrons) will be isolated
  - Hadronic/nonprompt photons will be less isolated
- Templates for both derived from data
  - Isolated photons template taken from measuring isolation in random cone
  - Nonprompt template taken from inverting selection requirements on photon shower shape ($\sigma_{\eta\eta}$)

Template for isolated photons



Results of fit to photon isolation



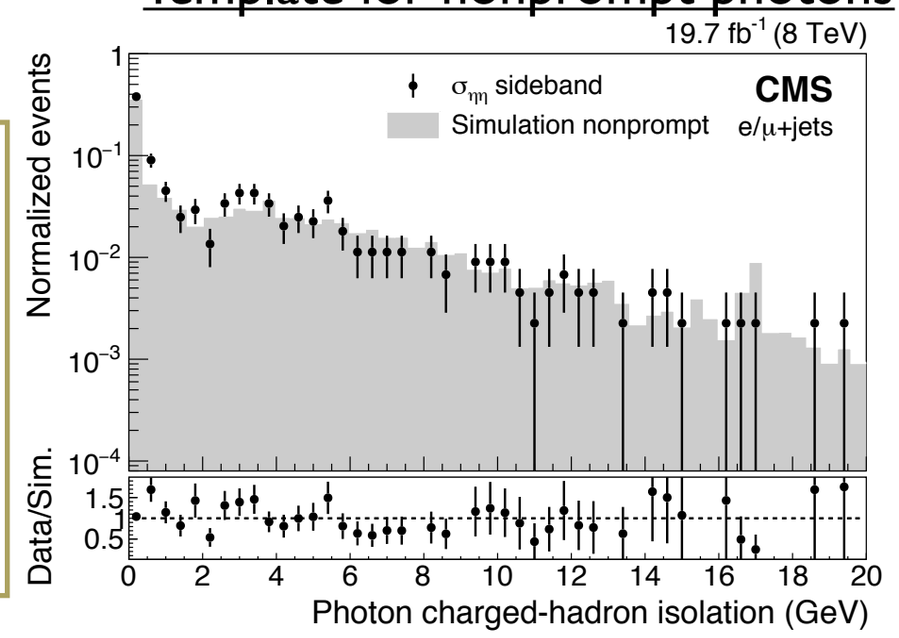
e+jets:

$\pi_\gamma = 0.57 \pm 0.06$ (stat)

***μ*+jets**:

$\pi_\gamma = 0.53 \pm 0.06$ (stat)

Template for nonprompt photons



$N_{tt+\gamma}$ Measurement

- Combine the information from the top quark purity, photon purity, and number of events observed in data into a χ^2 function
  - Fit to rates of signal and primary background contributions (V+γ and nonprompt photons)
  - Maximizing Likelihood function $\mathcal{L} = e^{-\chi^2/2}$

$$\chi^2 = \frac{(\pi_\gamma^{\rm data} - \pi_\gamma^{\rm MC})^2}{\sigma^2_{\pi_\gamma}} + \frac{(\pi_{t\bar{t}}^{\rm data} - \pi_{t\bar{t}}^{\rm MC})^2}{\sigma^2_{\pi_{t\bar{t}}}} + \frac{(N^{\rm data} - N^{\rm MC})^2}{\sigma^2_N}$$

$\pi_\gamma^{\rm data(MC)}$: photon purity in data (MC), with uncertainty σ_{π_γ}
$\pi_{t\bar{t}}^{\rm data(MC)}$: top purity in data (MC), with uncertainty $\sigma_{\pi_{t\bar{t}}}$
$N^{\rm data(MC)}$: number of events in data (MC), with uncertainty σ_N

e+jets:	***μ*+jets**:
$N_{tt+\gamma}$ = 338 ± 53 (stat)	$N_{tt+\gamma}$ = 442 ± 69 (stat)

Uncertainties

- For each systematic, measurement is repeated with each parameter varied within uncertainties
- Largest uncertainty from:
  - Statistical uncertainty in fit
  - Top quark mass: ±1 GeV change in mass used in simulation (m_t=172.5 GeV)
  - Jet energy scale uncertainties
  - Scale uncertainties, doubling and halving scale used in simulation ($\mu_R=\mu_F=Q=\mathrm{sqrt}(m_t^2+\sum p_T^2)$)

Source	Uncertainty (%)
Statistical likelihood fit	15.5
Top quark mass	7.9
JES	6.9
Fact. and renorm. scale	6.7
ME/PS matching threshold	3.9
Photon energy scale	2.4
JER	2.3
Multijet estimate	2.0
Electron misid. rate	1.3
Z+jets scale factor	0.8
Pileup	0.6
Background normalization	0.6
Top quark $p_T$reweighting	0.4
b tagging scale factor	0.3
Muon efficiency	0.3
Electron efficiency	0.1
PDFs	0.1
Muon energy scale	0.1
Electron energy scale	0.1
Total	20.7

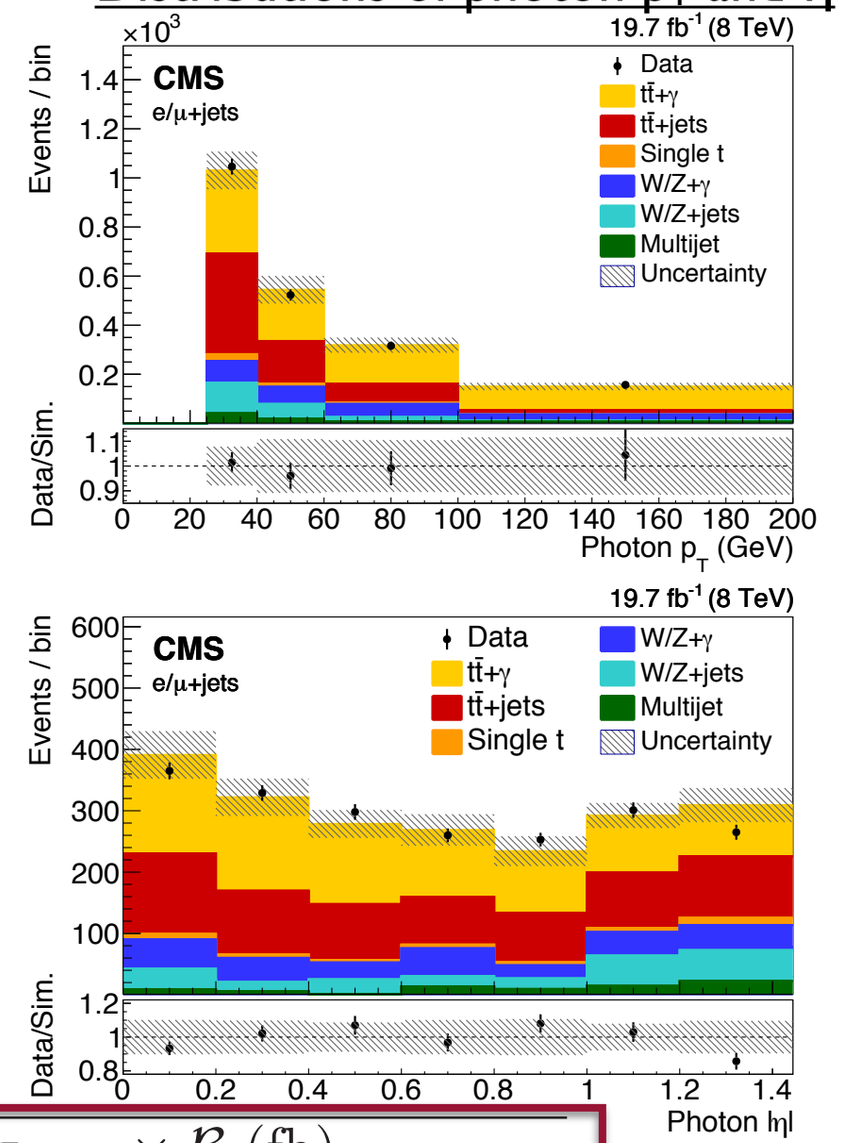
Results

$$R = \frac{\sigma^{\text{fid}}_{t\bar{t}+\gamma}}{\sigma_{t\bar{t}}} = \frac{N_{t\bar{t}+\gamma}}{\epsilon^{t\bar{t}+\gamma}} \cdot \frac{\epsilon^{t\bar{t}}_{\text{top}} A^{t\bar{t}}_{\text{top}}}{N_{t\bar{t}}}$$

- Cross section measured in fiducial region of ℓ+jets final state of the top decay with photon having p_T>25 GeV & |η|<1.44
- Efficiencies and acceptances are taken from simulation
- Cross section can be extracted by multiplying R by measured value of tt cross section

$$\sigma_{t\bar{t}} = 244.9 \pm 1.4\,(\text{stat})^{+6.3}_{-5.5}\,(\text{syst}) \pm 6.4\,(\text{lumi})$$

Distributions of photon p_T and η



Category	R	$\sigma^{\text{fid}}_{t\bar{t}+\gamma}$ (fb)	$\sigma_{t\bar{t}+\gamma} \times \mathcal{B}$ (fb)
e+jets	$(5.7 \pm 1.8) \times 10^{-4}$	138 ± 45	582 ± 187
μ+jets	$(4.7 \pm 1.3) \times 10^{-4}$	115 ± 32	453 ± 124
Combination	$(5.2 \pm 1.1) \times 10^{-4}$	127 ± 27	515 ± 108
Theory	–	–	592 ± 71 (scales) ± 30 (PDFs)

Summary

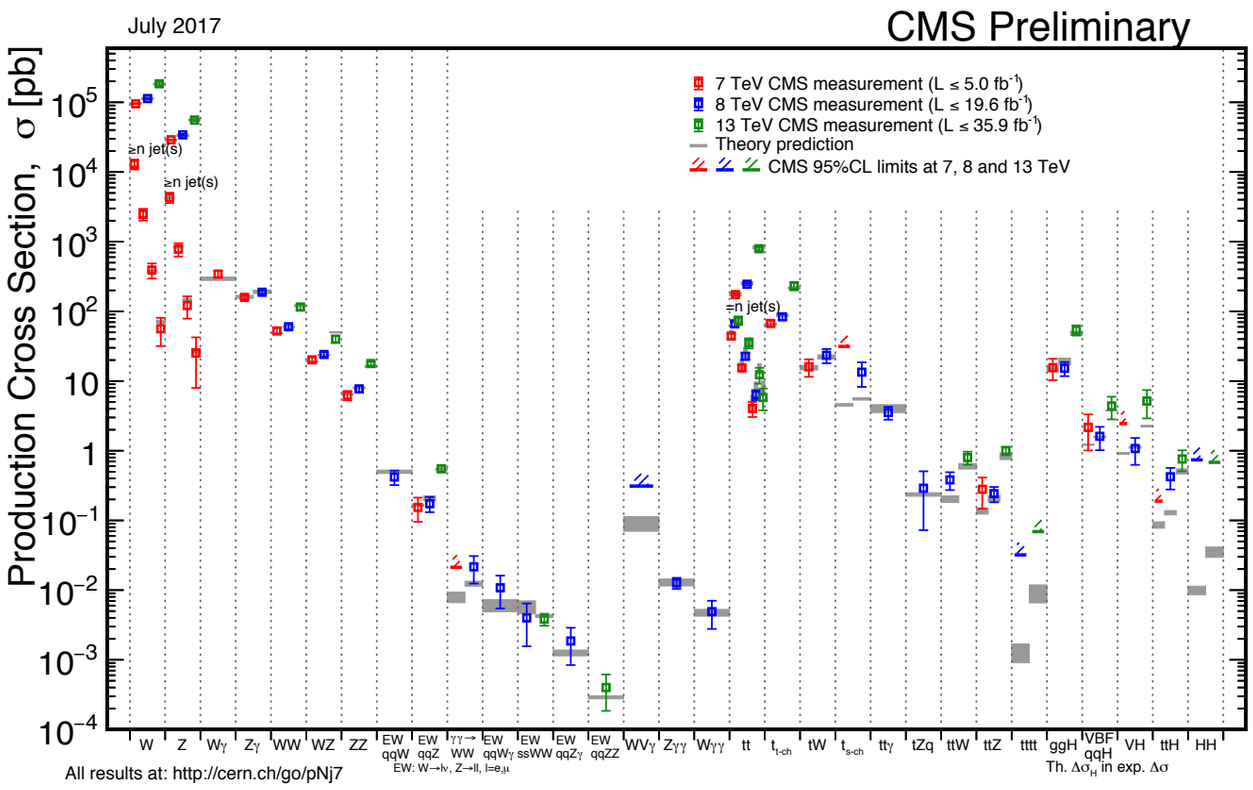
- Measurement of the associated production of top quark-antiquark pair with a photon in the semileptonic final state presented
- Using 19.7 fb^{-1} of data collected at center-of-mass energy of 8 TeV
- Ratio of the tt+γ to tt production cross sections measured to be

$$R = \sigma^{\text{fid.}}_{t\bar{t}+\gamma}/\sigma_{t\bar{t}} = (5.2 \pm 1.1) \times 10^{-4}$$

- Cross section for tt+γ measured to be in agreement with SM prediction:

$$\sigma^{\text{fid.}}_{t\bar{t}+\gamma} = 127 \pm 27\,\text{fb}$$

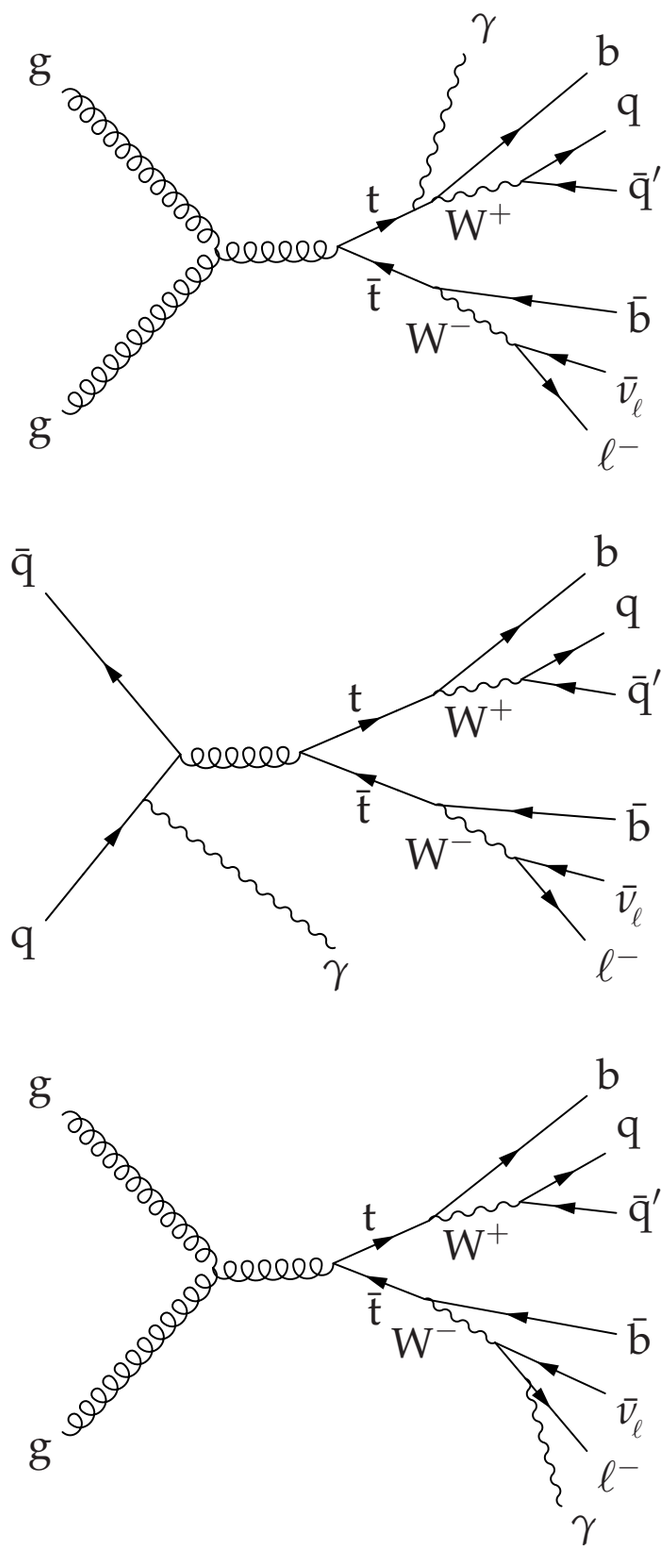
$$\sigma_{t\bar{t}+\gamma} \times \mathcal{B} = 515 \pm 108\,\text{fb}$$



Backup Slide

Signal Simulation

- tt+γ MC is simulated in Madgraph v5.1.3.30
- 2->7 production
  - Photon can come be radiated from top quark, decay products of top quark, or ISR
- Generator level photon cuts:
  - pT > 13 GeV
  - $|\eta| < 3.0$
  - $\Delta R = \sqrt{(\Delta\phi^2 + \Delta\eta^2)} > 0.3$, between generated photon and other generated particles
- Overlap removal:
  - Events are removed from tt MC which fall within the tt+γ signal definition to avoid double counting



Reconstructed Object Selection

Trigger:
- e+jets: pT>27 GeV, |η|<2.5
- μ+jets: pT>24 GeV, |η|<2.1

Electrons:
- p_T > 35 GeV
- |η|<2.5
- I_{rel} < 0.1
- Tight ID
- Loose: p_T > 20, |η|<2.5

Muons:
- p_T > 26 GeV
- |η|<2.1
- I_{rel} < 0.2
- Tight ID
- Loose: p_T > 10, |η|<2.5

Jets:
- anti-k_T, R=0.5 jets
- p_T > 30 GeV
- |η|<2.4
- Energy corrected for pileup

Photons:
- p_T > 25 GeV
- |η|<1.44 (ECAL barrel)
- Conversion rejection and identification requirements applied

B-tagging:
- Combined Secondary Vertex tagger
- "Medium" working point
- ~70% efficiency, 1-2% mistag rate

Fiducial Region Cuts

Cuts applied at generator level in MC

Electrons
- $p_T > 35$ GeV
- $|\eta|<2.5$

Muons:
- $p_T > 26$ GeV
- $|\eta|<2.1$

Jets:
- $p_T > 30$ GeV
- $|\eta|<2.4$

Photons:
- $p_T > 25$ GeV
- $|\eta|<1.44$ (ECAL barrel)

MET:
- $\sum p_T(\nu) > 20$ GeV

Require exactly one lepton, at least 3 jets (one coming from b), MET, and at least one photon

MC Event Categories

- Splitting MC events into 3 categories, based on where photon comes from
  - Genuine photons: events with a real, prompt photon
  - Misidentified electrons: reconstruction misidentifies a generated photon as an electron
  - Nonprompt/fake photons: reconstructed photon not matched to prompt photon or misidentified electron, or matched to generated non-prompt photon

Event Yields e+jets

Event Yields in the e+jets final state

Sample	Genuine photon	Misid. electron	Nonprompt photon	Total
$t\bar{t}+\gamma$	312 ± 17	0.2 ± 0.1	8.5 ± 0.9	321 ± 17
$t\bar{t}$	–	22 ± 3	215 ± 13	237 ± 14
W+γ	75 ± 25	–	–	75 ± 25
W+jets	–	–	60 ± 15	60 ± 15
Z+γ	14 ± 5	1.3 ± 1.1	$0.5^{+0.7}_{-0.5}$	16 ± 5
Z+jets	–	43 ± 28	11 ± 6	54 ± 30
Single t	11 ± 3	2.0 ± 1.3	16 ± 4	29 ± 7
QCD multijet	–	–	31 ± 18	31 ± 18
Total	412 ± 31	69 ± 29	342 ± 28	823 ± 52
Data	–	–	–	935

Event Yields in the μ+jets final state

Sample	Genuine photon	Misid. electron	Nonprompt photon	Total
$t\bar{t}+\gamma$	407 ± 23	0.4 ± 0.3	11 ± 1	418 ± 24
$t\bar{t}$	–	31 ± 5	291 ± 16	322 ± 17
W+γ	140 ± 41	–	9.0 ± 6.7	149 ± 45
W+jets	–	–	57 ± 14	57 ± 14
Z+γ	21 ± 7	–	1.4 ± 0.9	23 ± 7
Z+jets	–	–	9.6 ± 5.8	10 ± 6
Single t	12 ± 3	1.5 ± 1.3	25 ± 13	38 ± 14
QCD multijet	–	–	36 ± 20	36 ± 20
Total	580 ± 48	33 ± 5	440 ± 33	1053 ± 61
Data	–	–	–	1136

Likelihood Fit

$$\chi^2(SF_{t\bar{t}+\gamma}, SF_{V+\gamma}, SF_{jet\to\gamma}) = \frac{(\pi_\gamma^{\mathrm{data}} - \pi_\gamma^{\mathrm{MC}})^2}{\sigma^2_{\pi_\gamma}} + \frac{(\pi_{t\bar{t}}^{\mathrm{data}} - \pi_{t\bar{t}}^{\mathrm{MC}})^2}{\sigma^2_{\pi_{t\bar{t}}}} + \frac{(N^{\mathrm{data}} - N^{\mathrm{MC}})^2}{\sigma^2_N}$$

- Scale factors for tt+γ, V+γ, and nonprompt fake rates come into play in the MC predictions of the photon purity (π_γ^{MC}), top quark purity(π_{tt}^{MC}), and total number of events (N^{MC})
  - π_γ^{MC} = fraction of events in genuine photon or misid. electron categories
  - π_{tt}^{MC} = fraction of events coming from tt+γ or tt
  - N^{MC} = total number of MC events (effected by all three rates)

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$SF_{tt+\gamma}$

$SF_{V+\gamma}$

$SF_{jet\to\gamma}$