Rare processes with top quarks at CMS

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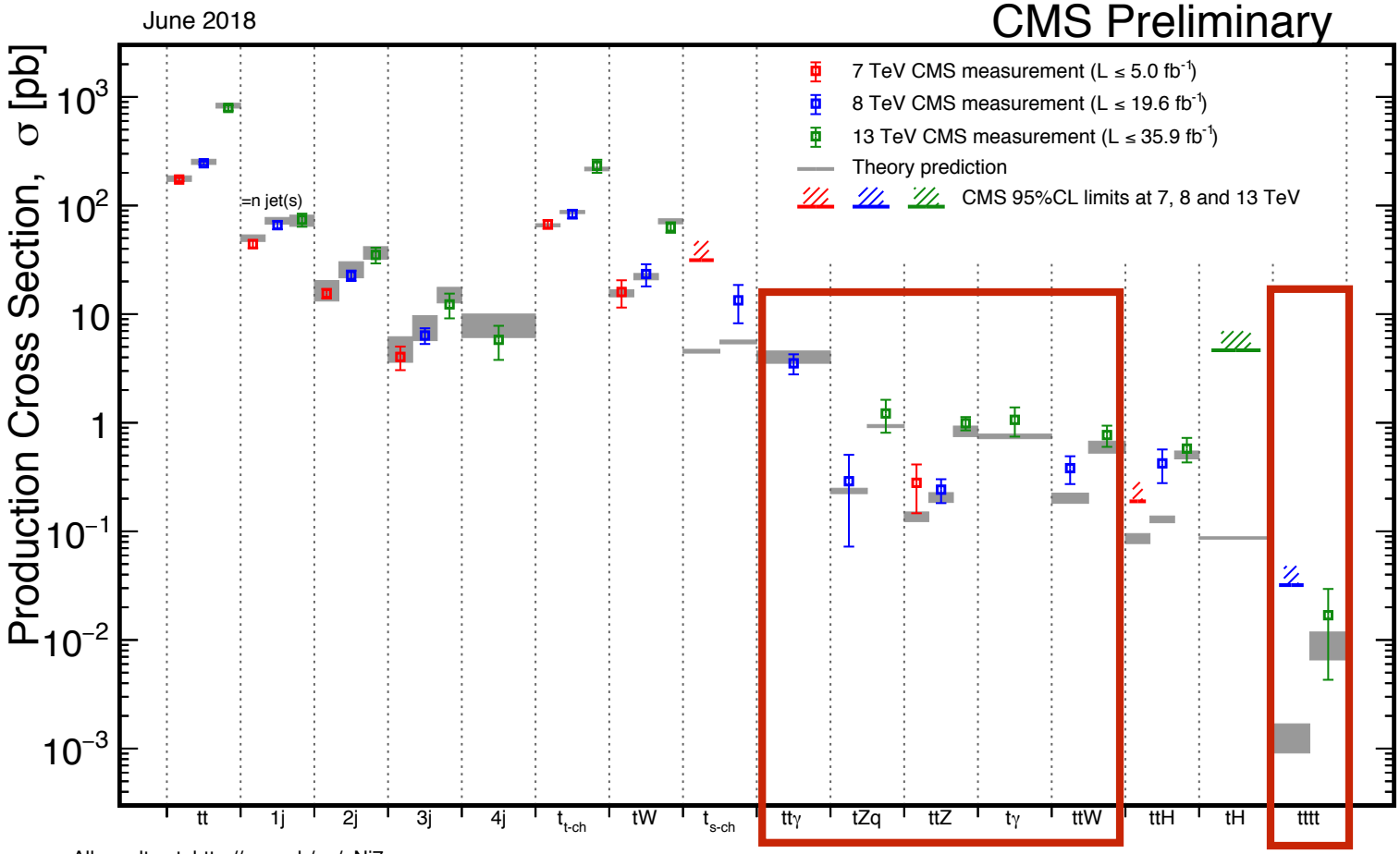
Introduction

Processes with top quarks produced at low rate in the SM

- **tt + W/Z** (13 TeV), **tt + γ** (8 TeV)
- **t + Z** (13 TeV), **t + γ** (13 TeV, NEW)
- **Four top quarks** (13 TeV)

Latests results

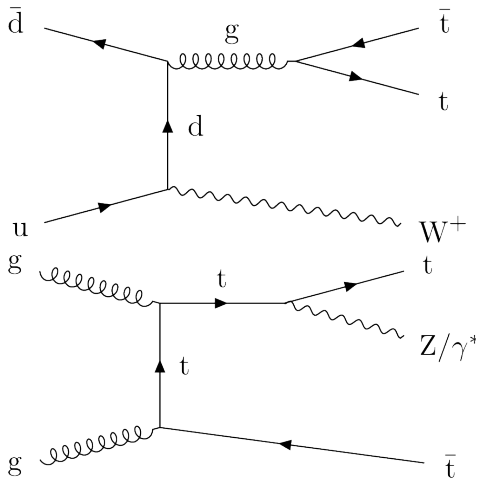
- Rich phenomenology of anomalous couplings of top and vector bosons (top-boson, FCNC, triple gauge coupling…): *see talk from A. Grohsjean*



All results at: http://cern.ch/go/pNj7

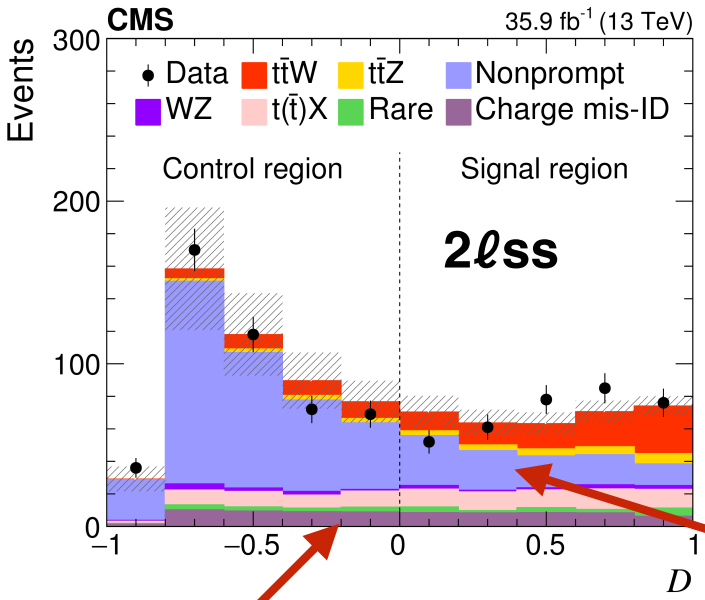
$t\bar{t}$+W/Z

arxiv:1711.02547, submitted to JHEP

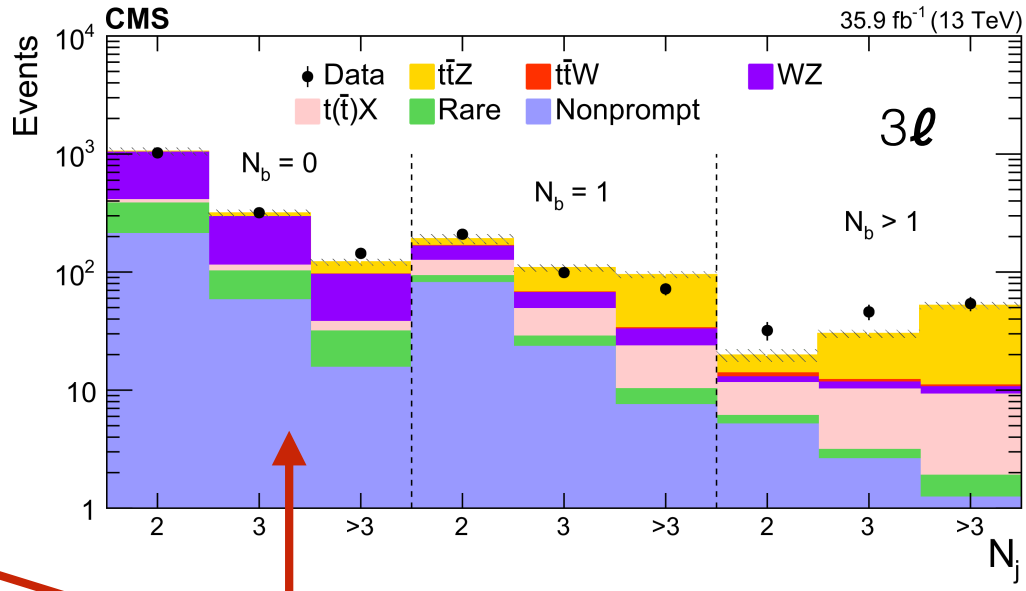


- A test of top quark - vector boson coupling,
- Irreducible background to ttH multi-lepton searches

- Measure **ttW with 2ℓss events**: use kinematics in 3 BDT categories
- Use charge asymmetry



- **ttZ with 3ℓ,4ℓ** : counting events classified by jets/b-jets multiplicity



- **Charge mismeasurement** (ee channel only): estimated from DY events in data (20% uncertainty)
- **Non-prompt lepton background**: measured relaxing isolation in a QCD data sample (30% uncertainty)

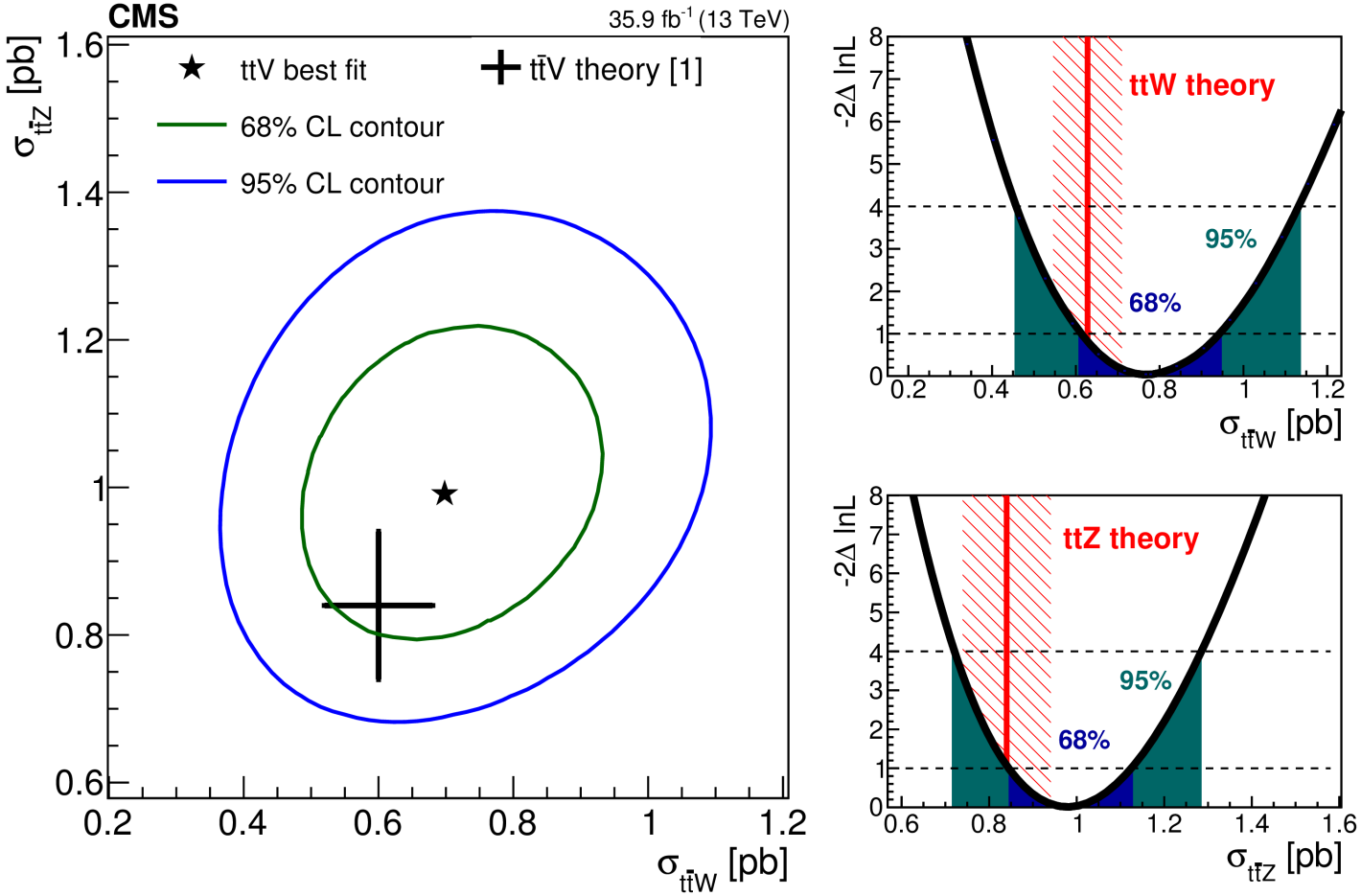
$t\bar{t}$+W/Z

arxiv:1711.02547, submitted to JHEP

- **Main systematics**: lepton identification / trigger selections, non-prompt background
- **ttW** with 2ℓss: **4.5σ** (5.3σ) **observed** (expected)
- **ttZ** with 3ℓ/4ℓ: »**5σ**

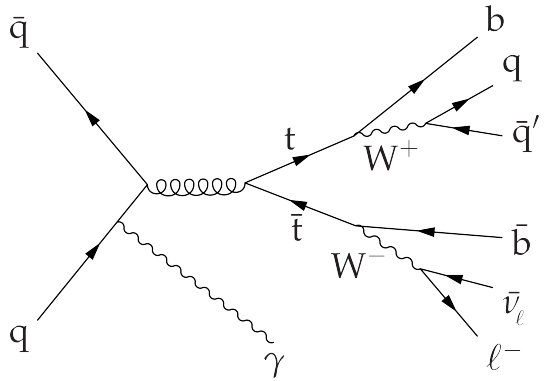
$$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}W}) = 0.77^{+0.12}_{-0.11}\,(\mathrm{stat})^{+0.13}_{-0.12}\,(\mathrm{syst})\,\mathrm{pb},$$

$$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}Z}) = 0.99^{+0.09}_{-0.08}\,(\mathrm{stat})^{+0.12}_{-0.10}\,(\mathrm{syst})\,\mathrm{pb}.$$



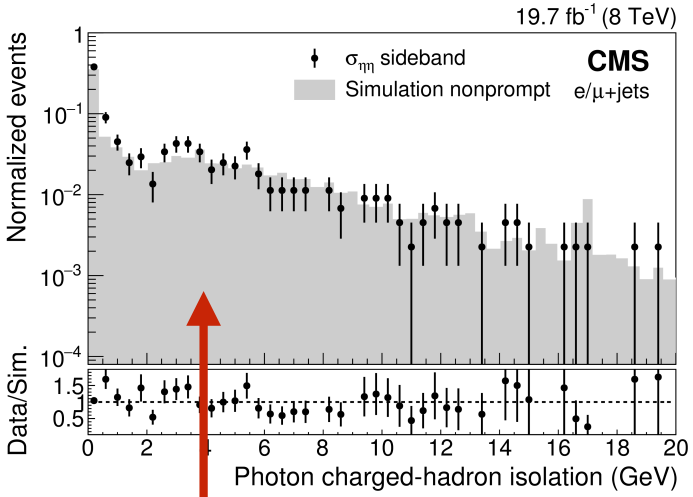
$t\bar{t}+\gamma$

JHEP 10 (2017) 006



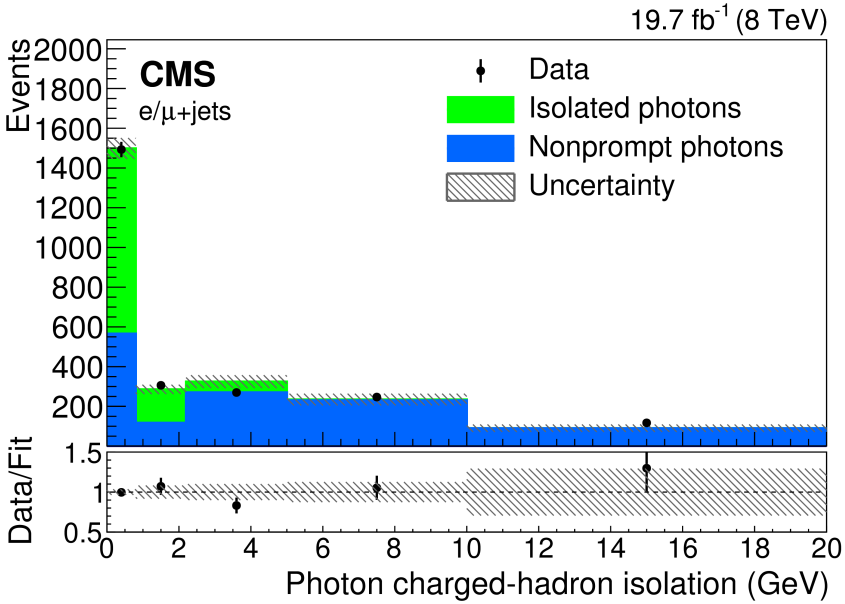
Target semi-leptonic final states

- Measure **tt+γ over tt ratio**
- **Normalize** the number of **ttbar** events (including tt+γ) with a **fit of the 3-jet mass**



Background template from **cluster shape sideband**

- Increase purity with **photon shower shape** cut
- Extract the signal with a fit of **charged-hadron isolation**
- **Signal** template from **random cone** method (same η, random Φ)



Measure prompt photon purity >**50%**

$t\bar{t}+\gamma$

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- Normalize **relative ttγ, Vγ and fake photon contributions** with a **likelihood** exp(-χ2):

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

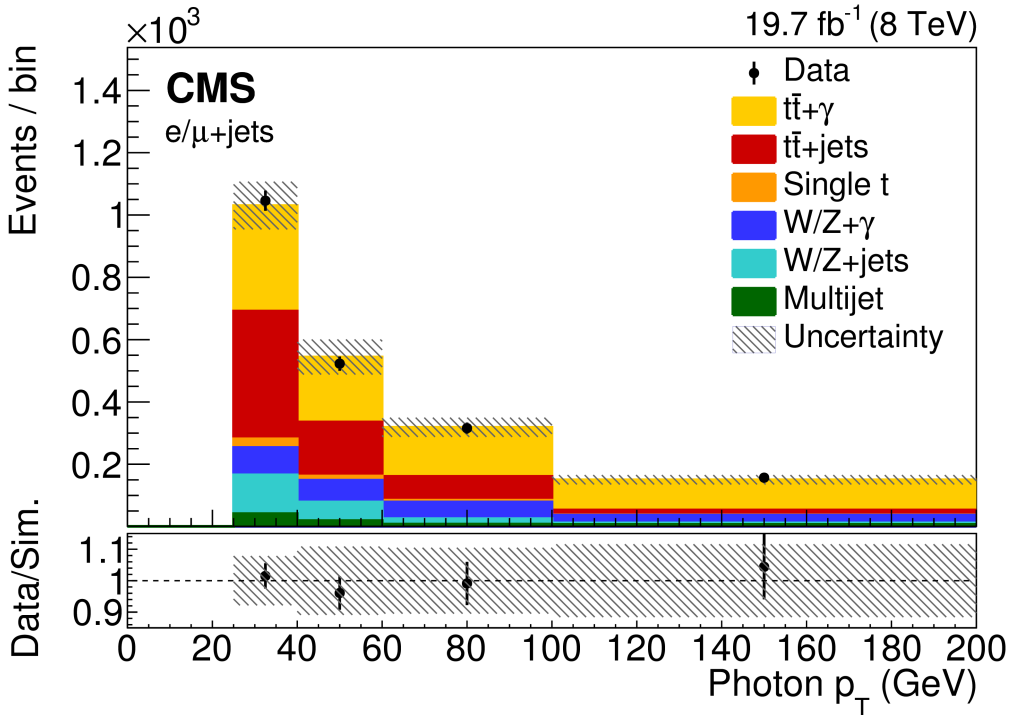
- Main **systematic uncertainties**:

Source	Uncertainty (%)
Statistical likelihood fit	15.5
Top quark mass	7.9
JES	6.9
Fact. and renorm. scale	6.7

- **Fiducial volume** at generator level as close as possible to reconstructed level, to minimize unfolding effects

Results:

Category	R	$\sigma^{\mathrm{fid}}_{t\bar{t}+\gamma}$ (fb)	$\sigma_{t\bar{t}+\gamma}\,\mathcal{B}$ (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)



Single top + Z (tZq)

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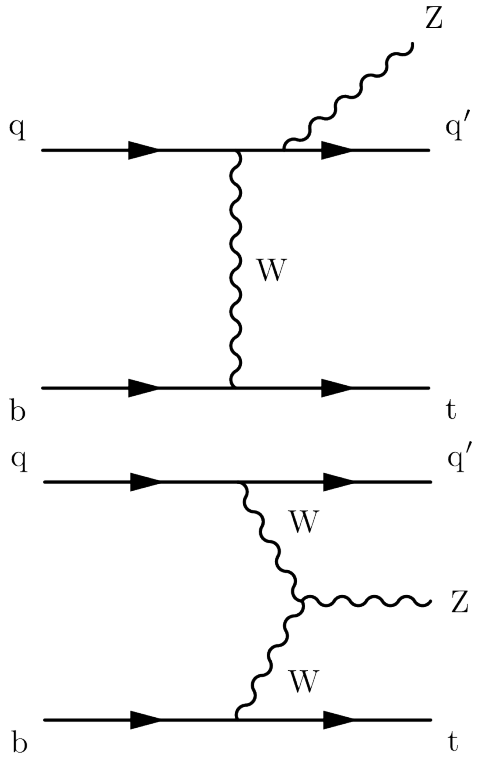
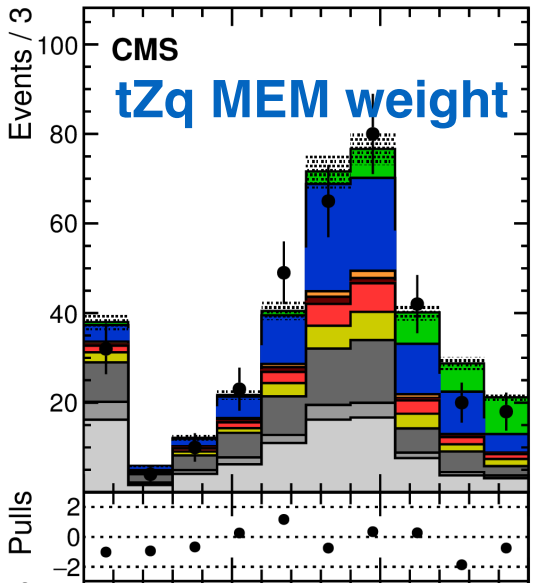


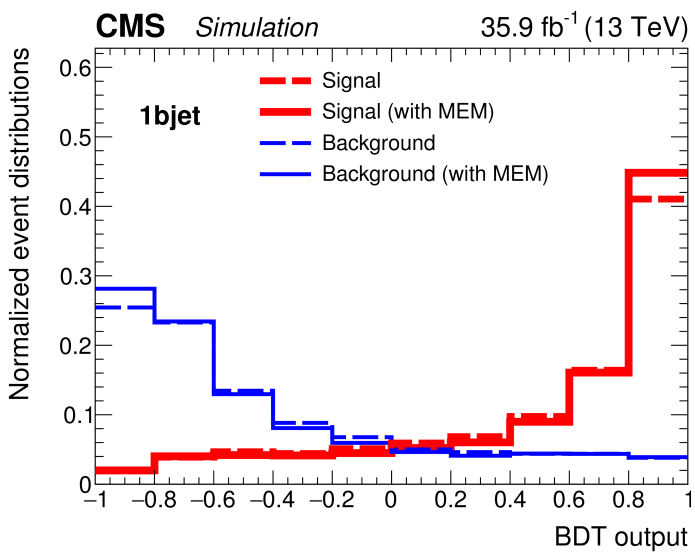
Analysis performed in **3ℓ final state (e or μ)**

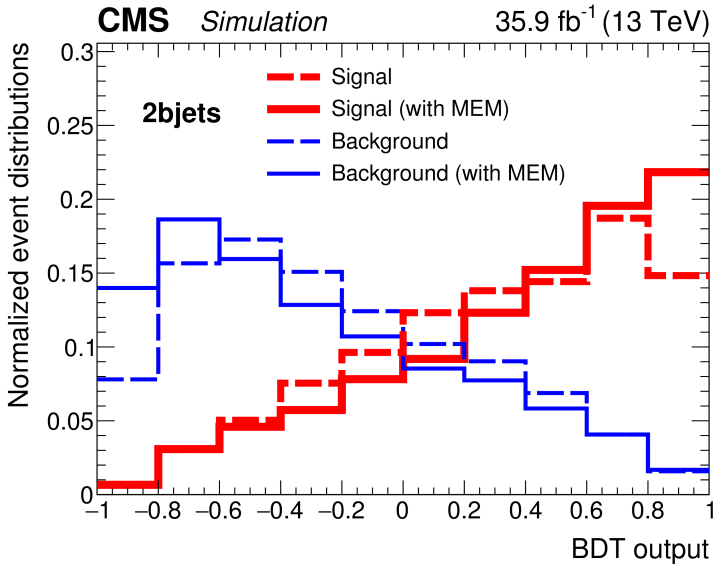
- Makes use of the **forward jet** in tZq to discriminate signal from background
- Build **BDT discriminants** using kinematic information
- Include **MEM weights** and MEM kinematic fit as input to the BDT

$$w_{i,\alpha}(\Phi') = \frac{1}{\sigma_\alpha}\int d\Phi_\alpha \cdot \delta^4\left(p_1^\mu + p_2^\mu - \sum_{k\geq 2} p_k^\mu\right) \cdot \frac{f(x_1,\mu_F)f(x_2,\mu_F)}{x_1 x_2 s} \cdot \left|\mathcal{M}_\alpha(p_k^\mu)\right|^2 \cdot W(\Phi'|\Phi_\alpha)$$

MEM improves the analysis significance **by 20%**







Single top + Z (tZq)

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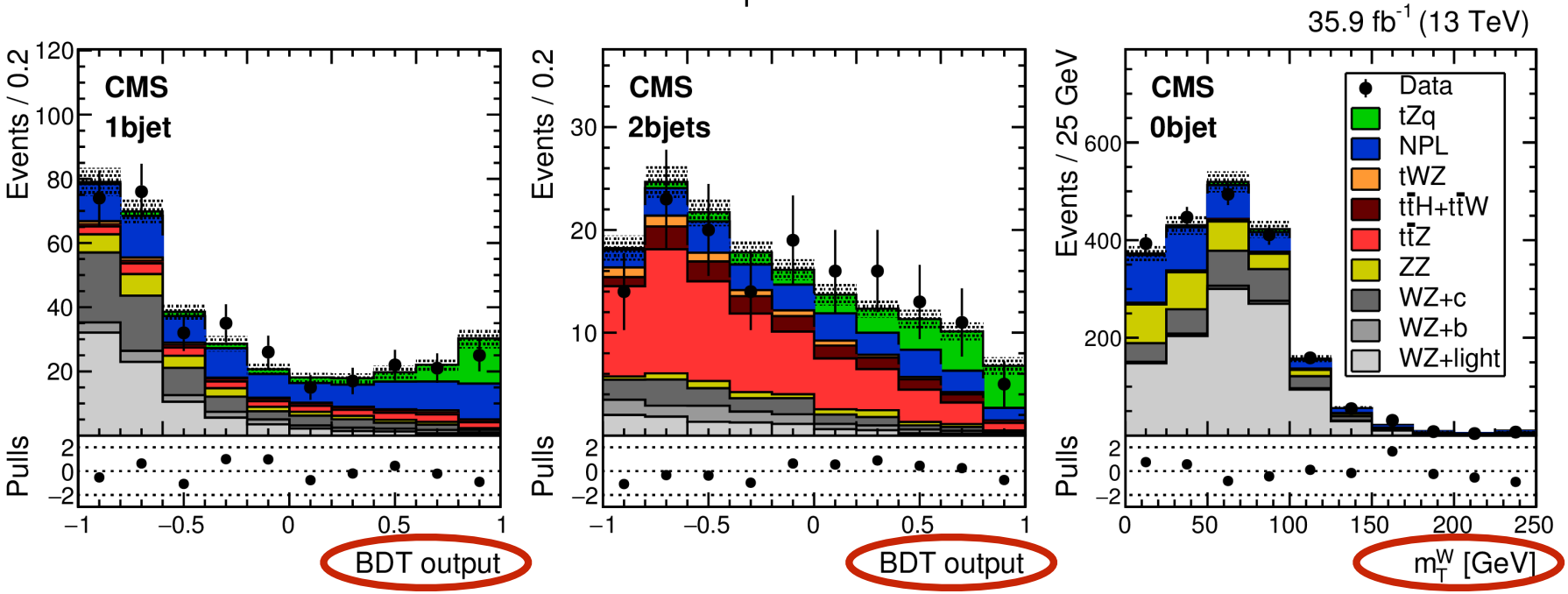
Signal extraction: simultaneous fit in 3 categories

1 b-jet + 1-2 non-b-jet : enriched in **tZq** signal
- Constrains tZq

2 b-jets + ≥0 non-b-jets: enriched in **ttZ**
- Constrains ttZ and tZq

0 b-jets + ≥1 non-b-jets: enriched in **WZ** and **fakes**
- **Measure fakes**
- **Constrains WZ**



Observation 3.7σ (3.2σ expected)

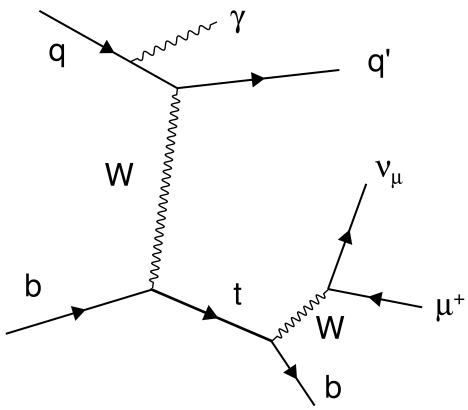
$$\sigma(pp \to tZq \to Wb\ell^+\ell^-q) = 123^{+33}_{-31}\,(stat)^{+29}_{-23}\,(syst)\,fb, \quad \text{for } m_{\ell^+\ell^-} > 30\,GeV$$

$$\sigma^{SM}(t\ell^+\ell^-q) = 94.2^{+1.9}_{-1.8}\,(scale) \pm 2.5\,(PDF)\,fb$$

Single top + γ (tγq)

CMS PAS TOP-17-016 (June 2018)

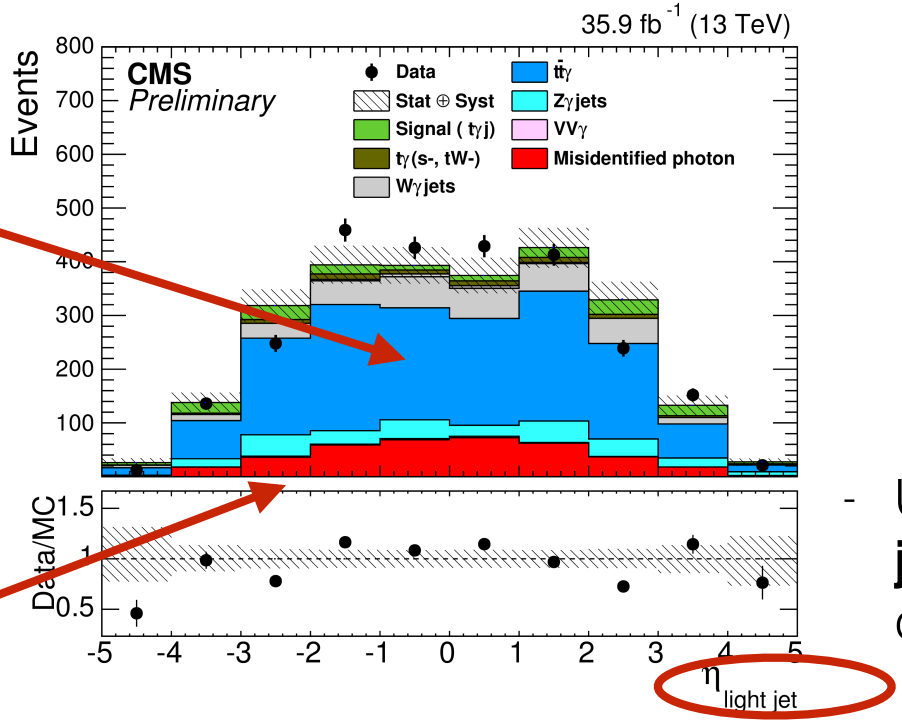
NEW



Target **muonic** top quark decay

- At least two jets, with only **one tagged as b-jet**

- **Dominant background tt+γ**



- Uses the **forward jet** to increase discrimination

Estimate **non-prompt photon** background with a **fake ratio method**

- relax photon requirement,
- measure probability to mis-identify a non-prompt as a prompt photon

Single top + γ (tγq)

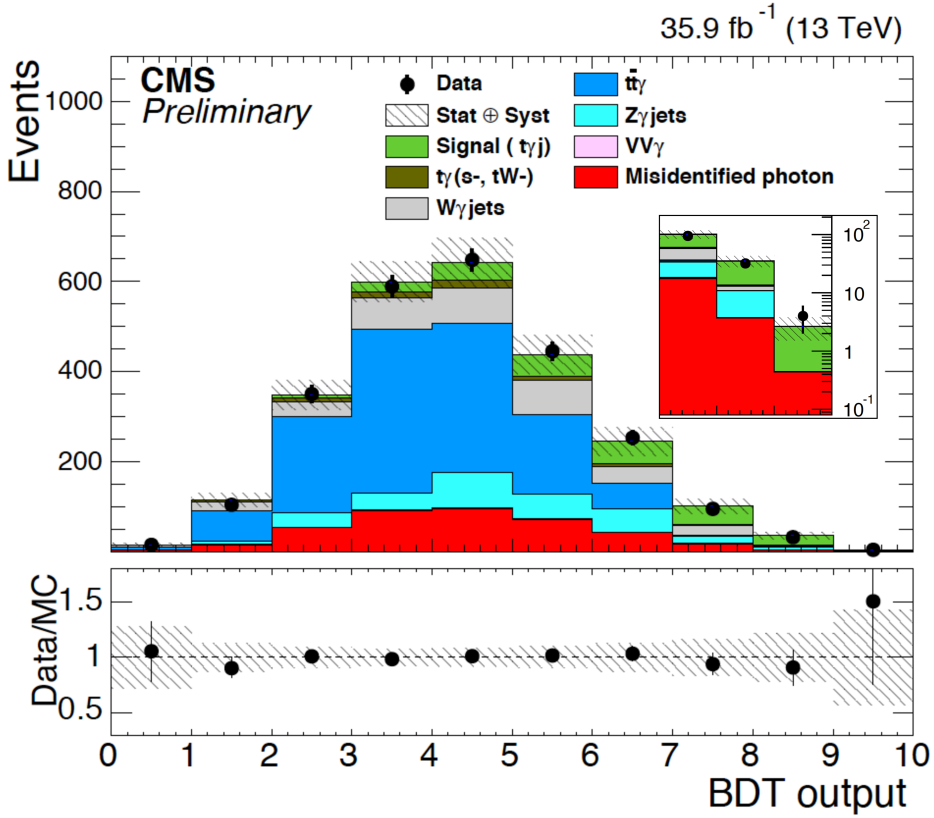
CMS PAS TOP-17-016 (June 2018)

NEW

- Build a **BDT** discriminant using kinematics
  - Most important variable **forward jet η**
  - Template for **tt+γ obtained from data** control region with additional b-jet
  - Non-prompt from fake ratio method

- **Simultaneous fit** of **tγq and tt+γ regions**

First evidence for tγq:
Observation 4.4σ (3.0σ expected)



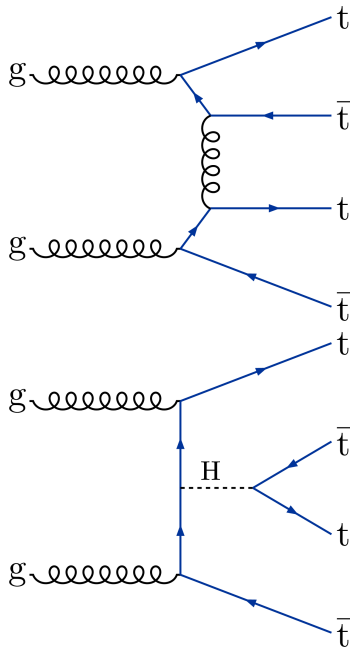
Dominated by systematics: jet energy scale, b-tagging, tγq modeling

$$\mathcal{B}(t\to \mu\nu b)\sigma(t\gamma j) = 115 \pm 17(\text{stat})^{+33}_{-27}(\text{syst})\ \text{fb}$$

The SM predicted cross section is 81 ± 4 fb

Four top quarks ($t\bar{t}t\bar{t}$)

Eur. Phys. J. C 78 (2018) 140

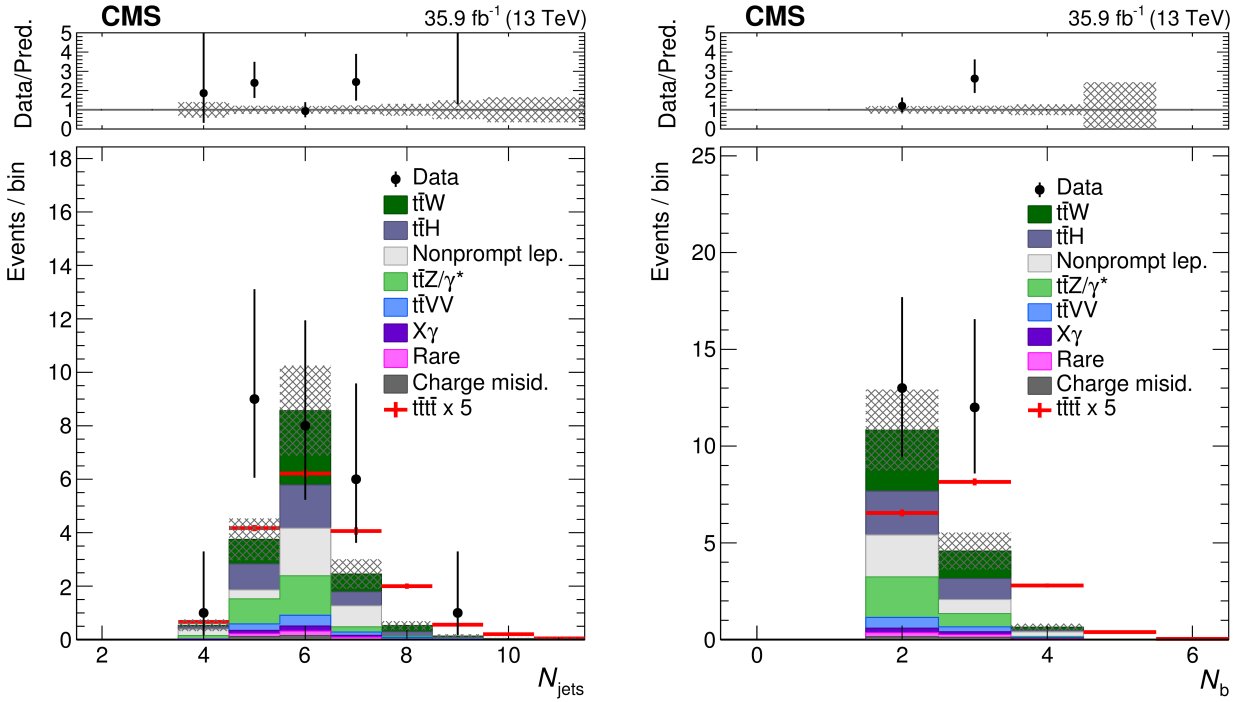


Analysis in **2ℓss and ≥3ℓ final state**

- **Take advantage of large multiplicity:**
  - Require HT>300 GeV
  - Categorize in the **number of jets and b-jets**
- Construct **ttZ and ttW control regions**

- **Charge misidentification** and **non-prompt leptons:** same techniques as in ttW/Z analysis
- **Main systematics**: lepton identification, QCD scale and pdf, ISR/FSR

N_ℓ	N_b	N_{jets}	Region
2	2	≤ 5	CRW
		6	SR1
		7	SR2
		≥ 8	SR3
	3	5, 6	SR4
		≥ 7	SR5
	≥ 4	≥ 5	SR6
≥ 3	2	≥ 5	SR7
	≥ 3	≥ 4	SR8
Inverted Z veto			CRZ

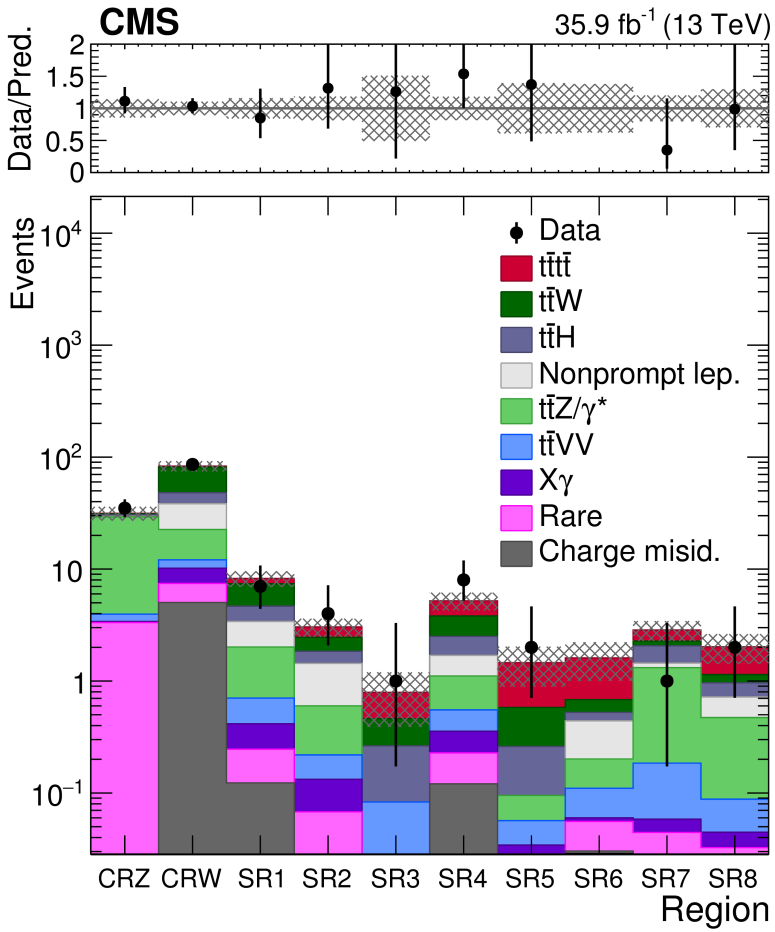


Four top quarks ($t\bar{t}t\bar{t}$)

Eur. Phys. J. C 78 (2018) 140

Observation 1.6σ (1.0σ expected)

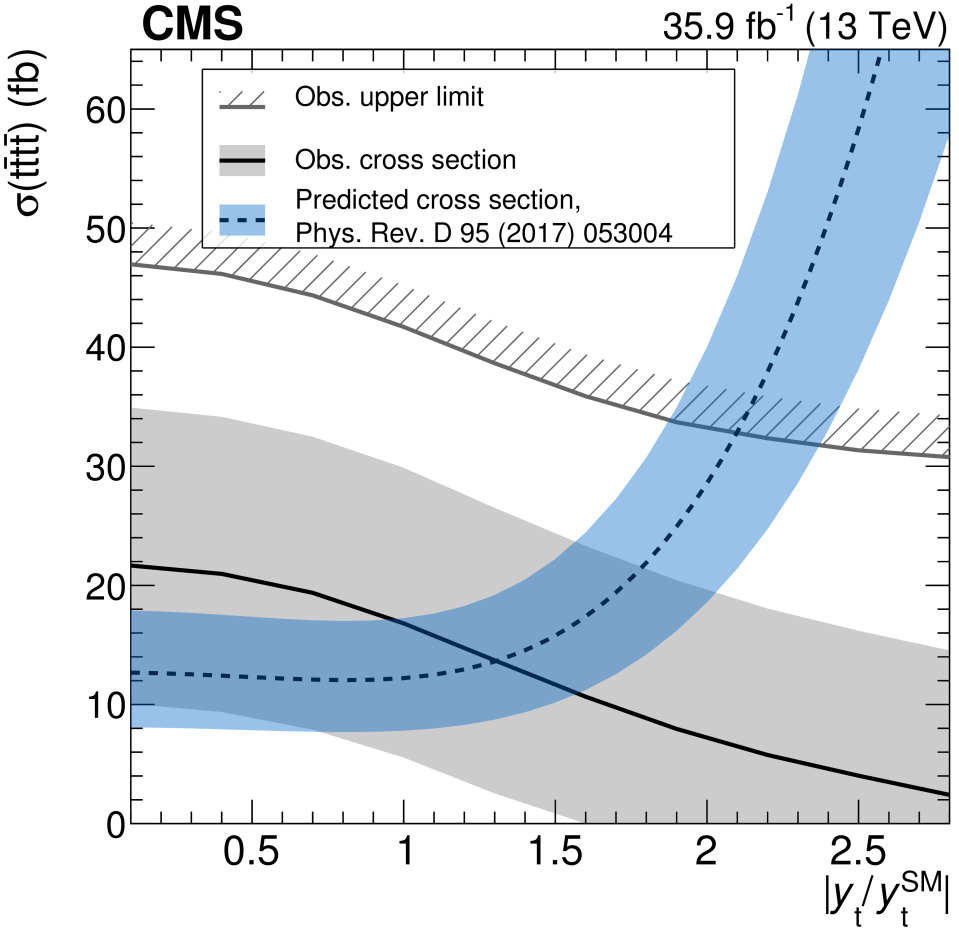
$t\bar{t}t\bar{t}$ cross section is measured to be $16.9^{+13.8}_{-11.4}$ fb,
NLO SM cross section of $9.2^{+2.9}_{-2.4}$ fb



Constraint on Top-Higgs coupling κ_t

(looser than Higgs measurements)

$|y_t/y_t^{SM}| < 2.1$ at 95% confidence level



Conclusions and perspectives

Processes with top quarks produced at low rate in the SM

- **tt+W and tt+Z are observed at 13 TeV**
  - Processes very important to understand ttH signal extraction
  - Data is in agreement with SM at NLO
  - ttZ has a large signal: we can hope to perform differential measurements
- **tt + γ (8 TeV):**
  - First measurement at CMS, to be performed at 13 TeV
- **tZq at 13 TeV:**
  - **tZq is observed at CMS with 3.7σ** (3.2σ expected)
  - Matrix element method improves expected significance by 20%
  - Can improve further lepton identification and non-prompt estimate
- **tγq (13 TeV, NEW!):**
  - New measurement: **evidence of tγq at 4.4σ** (3.0σ expected)
- **Four top quarks** (13 TeV)
  - Takes advantage of ttH and ttW/Z analyses
  - This very rare process is not yet observed, but is very sensitive to new physics
  - **Allow to constrain top-Higgs coupling** (although less precisely than ttH) through virtual Higgs diagrams

Back-up slides

Matrix Element Method

MEM weight

Integration

Matrix Element
at LO

$$w_{i,\alpha}(\Phi') = \frac{1}{\sigma_\alpha} \int d\Phi_\alpha \cdot \delta^4\left(p_1^\mu + p_2^\mu - \sum_{k\geq 2} p_k^\mu\right) \cdot \frac{f(x_1,\mu_F) f(x_2,\mu_F)}{x_1 x_2 s} \cdot \left|\mathcal{M}_\alpha(p_k^\mu)\right|^2 \cdot W(\Phi'|\Phi_\alpha)$$

Phase-space
enforcing 4-momentum conservation

Parton distribution function

Transfer functions
relating pardon-level to reconstructed quantities

Interpretation: The **MEM weight** is the cross section, for a given hypothesis, evaluated at the phase space point of the event, convolved with the transfer functions

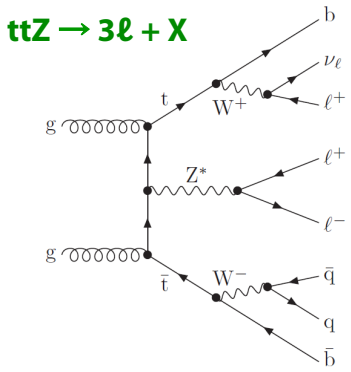
MEM likelihood ratio

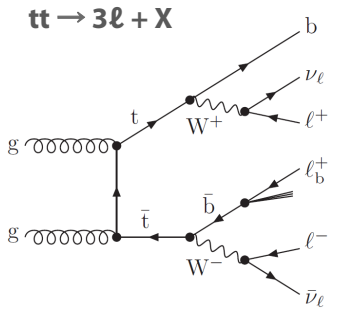
- **Neyman-Pearson Lemma:** Maximum **discrimination between two hypotheses** with a likelihood ratio

$$D_i = \frac{P(\boldsymbol{x}_i|S)}{P(\boldsymbol{x}_i|S) + P(\boldsymbol{x}_i|B)}$$

$t\bar{t}H$ multilepton: backgrounds

CMS HIG-17-004

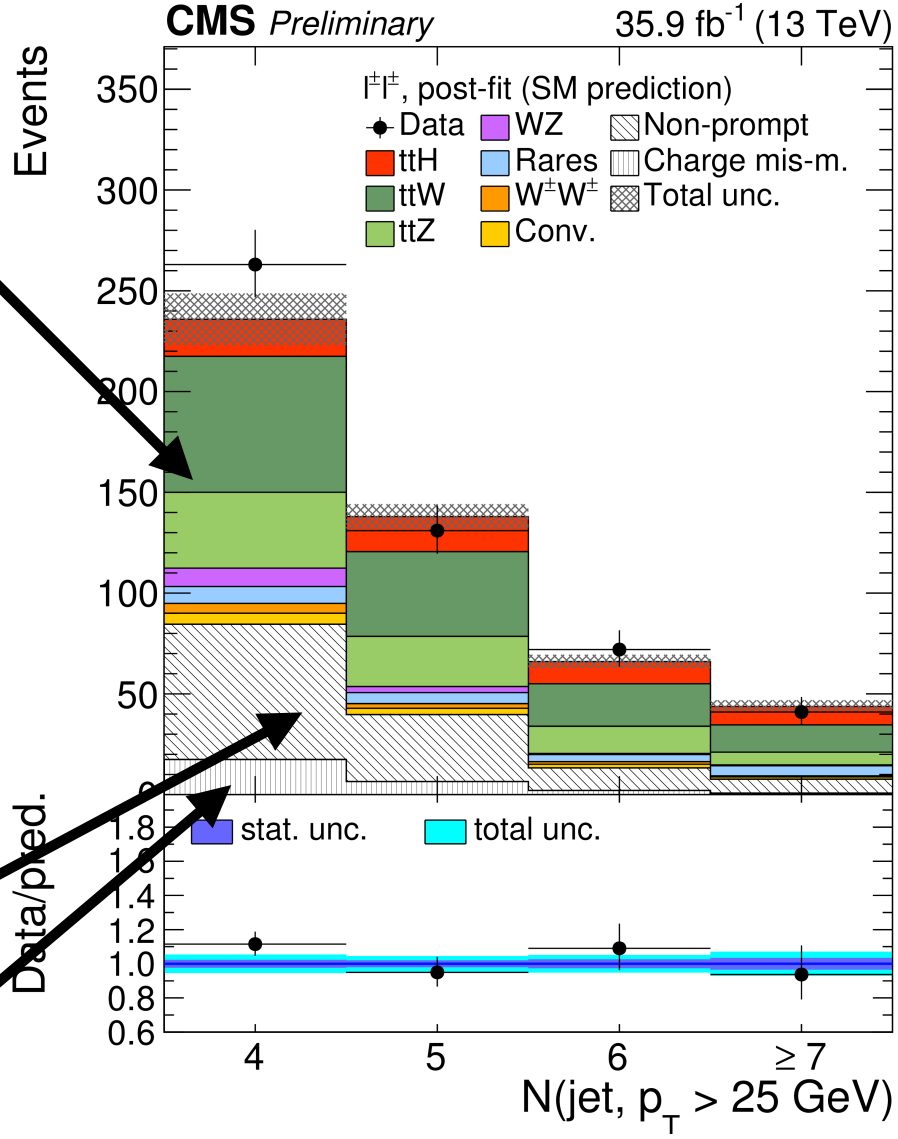




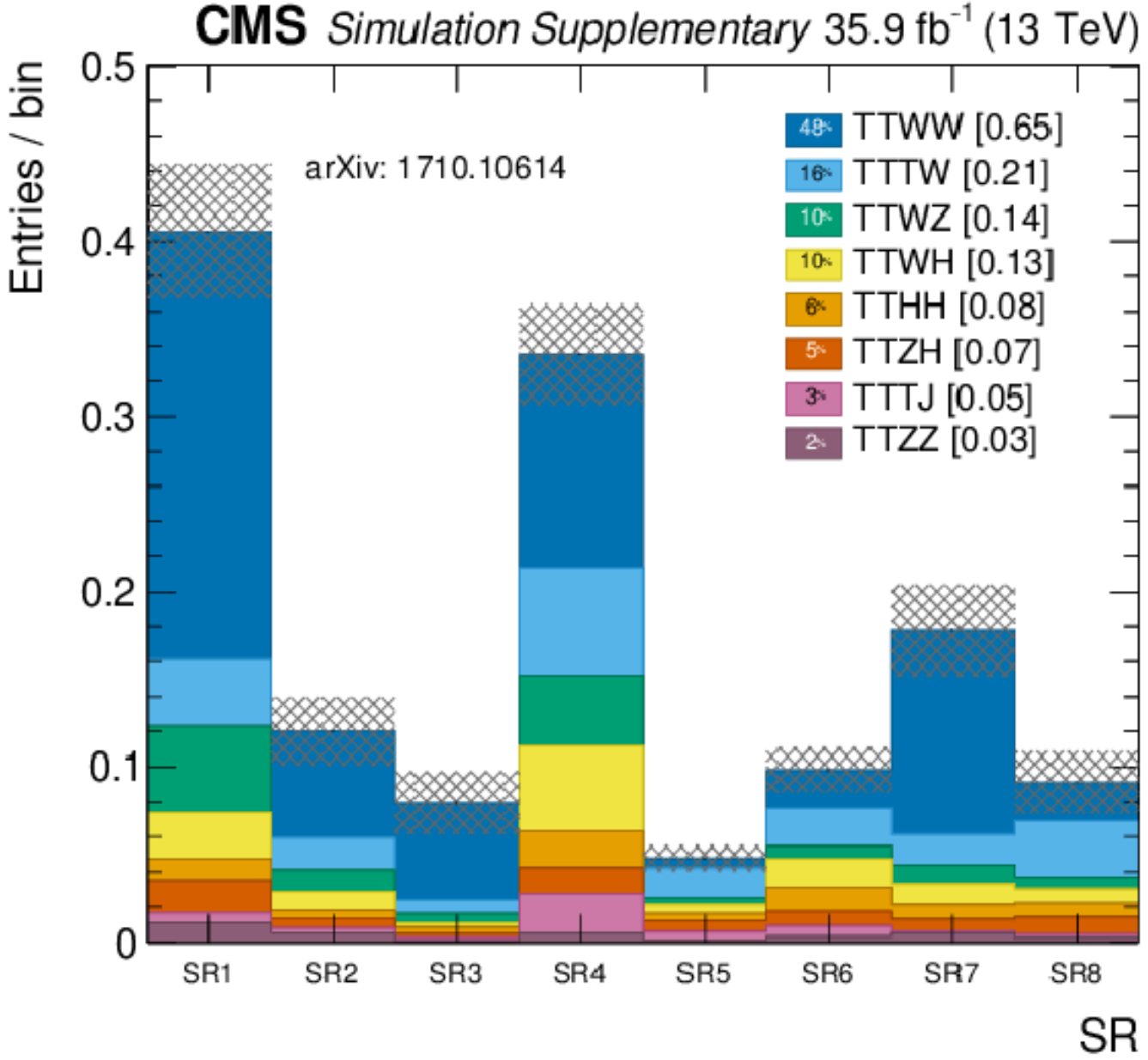
Irreducible: tt+W/Z/γ*
- from Monte Carlo,
- O(10%) uncertainty

Reducible: mainly tt+jets,
- shape obtained from data,
- O(30%) uncertainty

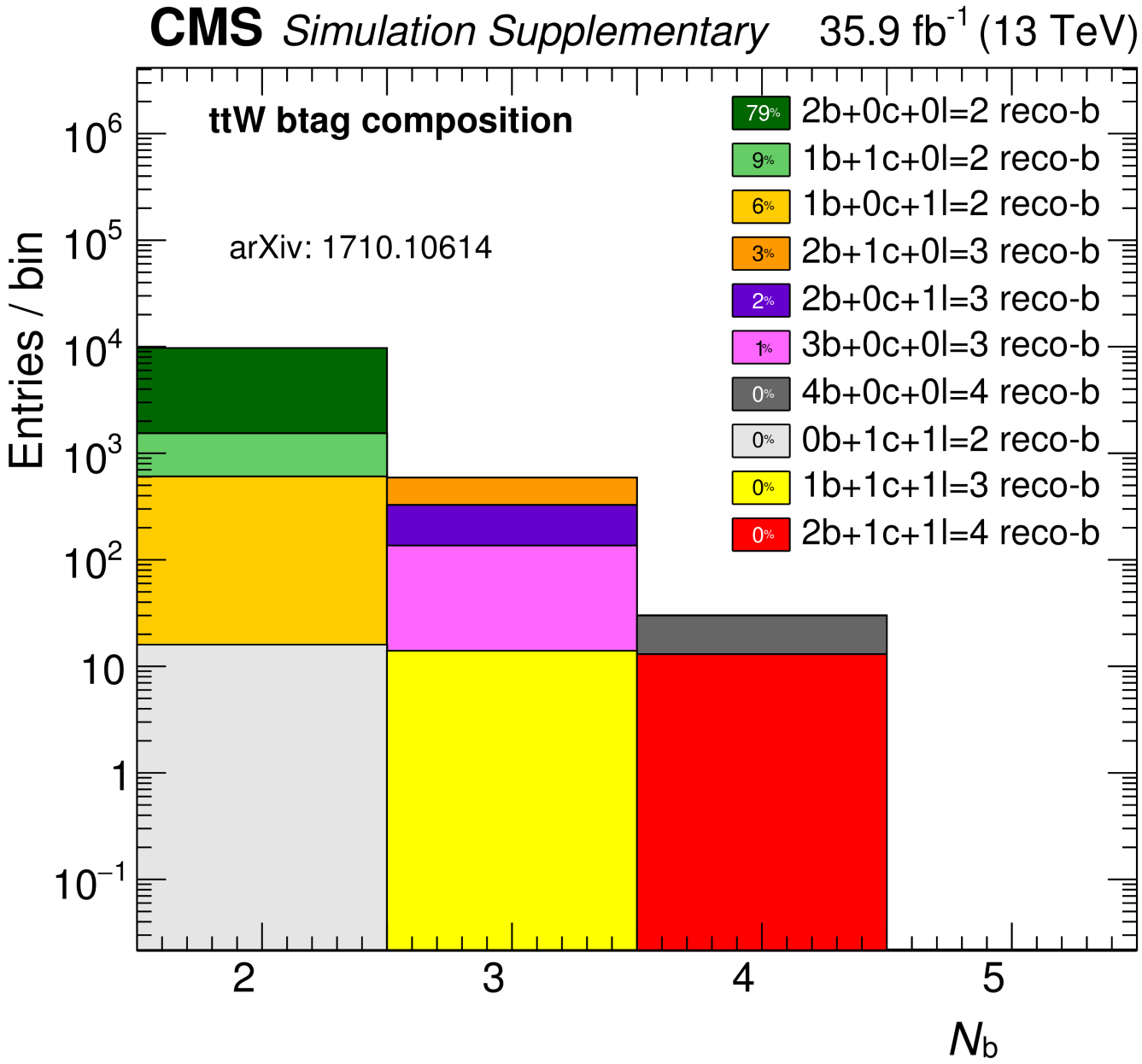
- **Jets faking leptons:** fake rate computed from QCD control region with loosened identification
- **Charge mis-assignment** (2ℓss only)**:** flip rate from Z→ℓ±ℓ± data



Four tops: rare backgrounds



Four tops: ttW composition



Rare top quark processes: summary