Top quark associated production at CMS

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on behalf of the CMS collaboration

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Top quark associated production

- Top quark decay: dominated by $t \rightarrow Wb$ (V_{tb} coupling)
- Associated production gives access to top-boson and to BSM couplings

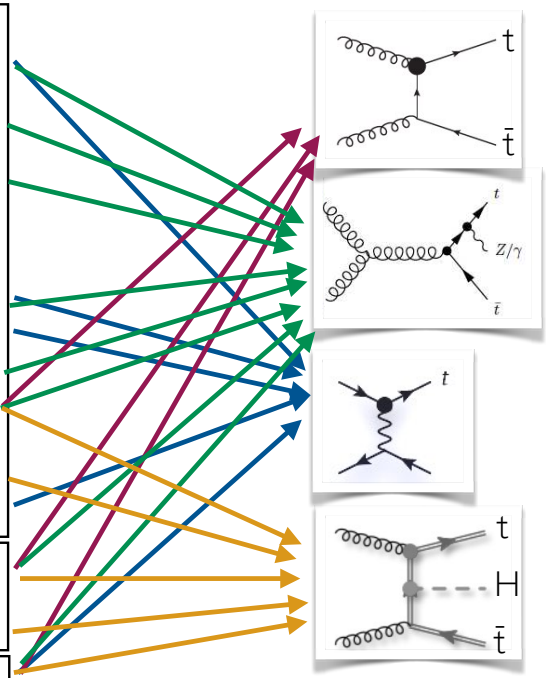
LPCC LHC Physics Centre at CERN

Operators and processes

$$O_{\varphi Q}^{(3)} = i\tfrac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu\tau^I Q)$$
$$O_{\varphi Q}^{(1)} = i\tfrac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$
$$O_{\varphi t} = i\tfrac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$
$$O_{\varphi b} = i\tfrac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{b}\gamma^\mu b)$$
$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$
$$O_{bW} = y_b g_w(\bar{Q}\sigma^{\mu\nu}\tau^I b)\varphi W^I_{\mu\nu}$$
$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu}t)\tilde{\varphi}B_{\mu\nu}$$
$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}$$
$$O_{t\varphi} = (\varphi^\dagger\varphi)(\bar{Q}t\tilde{\varphi})$$
$$O_{\varphi tb} = i(\varphi^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu b)$$

$$O_G = g_s f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$
$$O_{\varphi G} = g_s^2\left(\varphi^\dagger\varphi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

4-fermion ops



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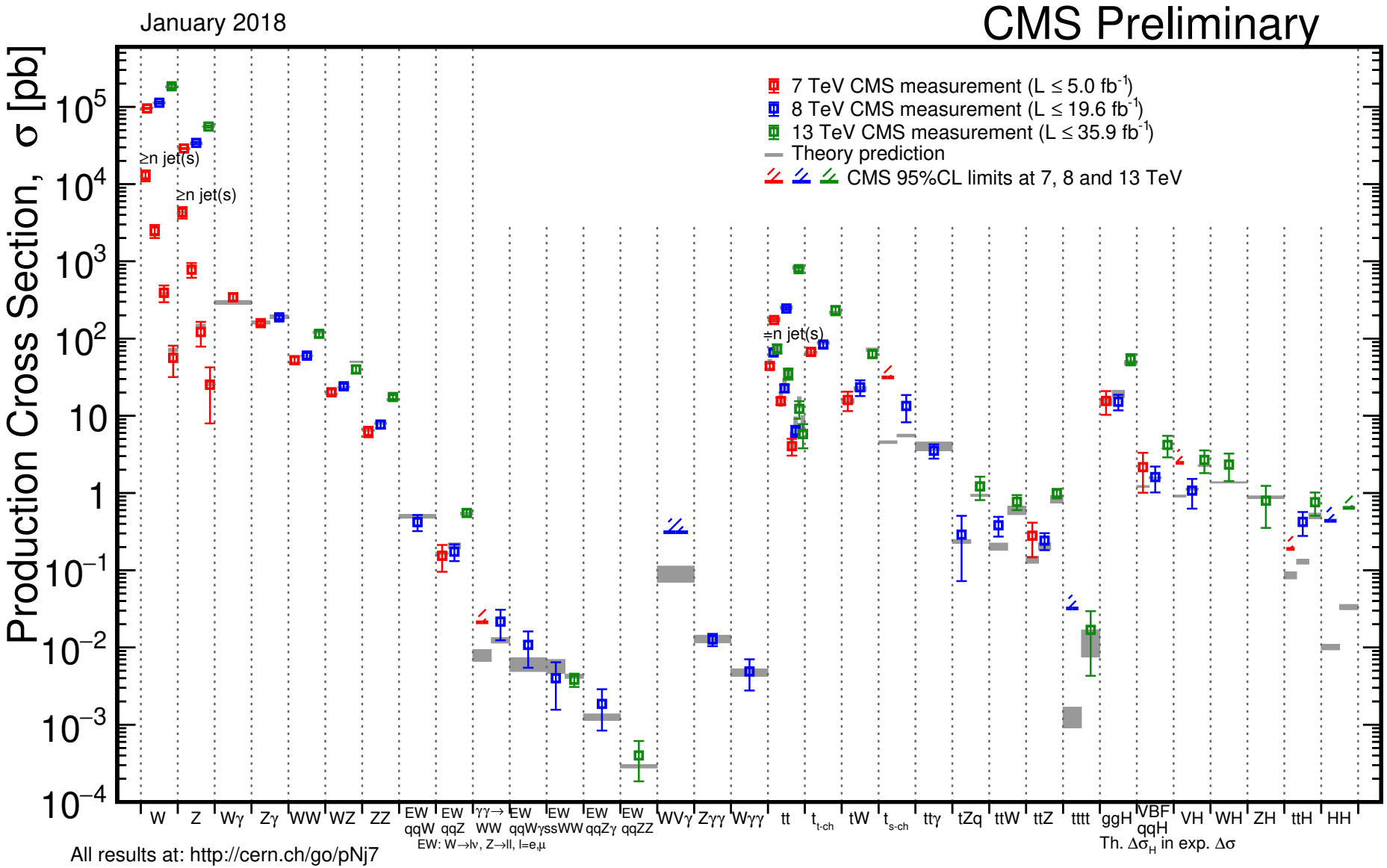

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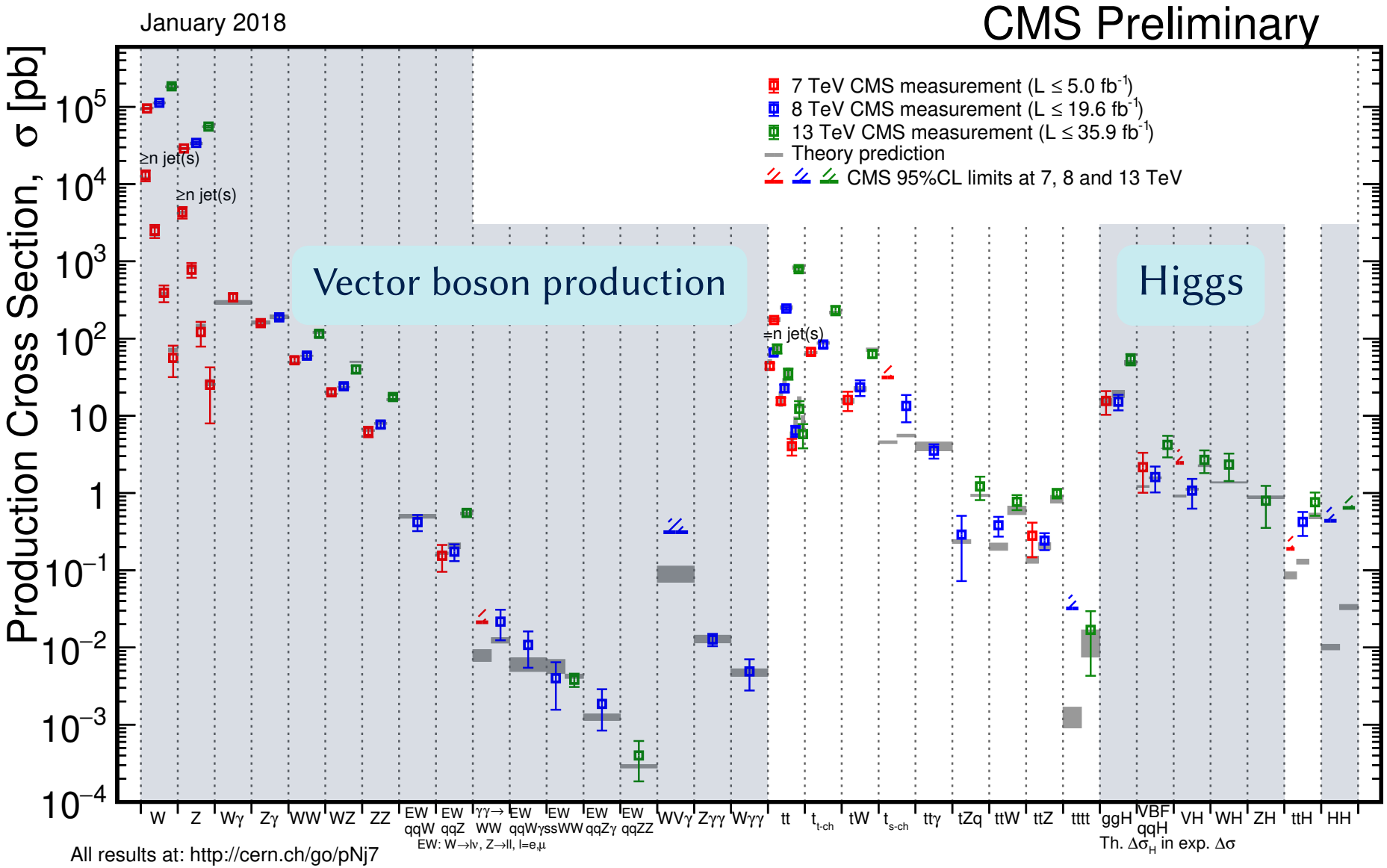

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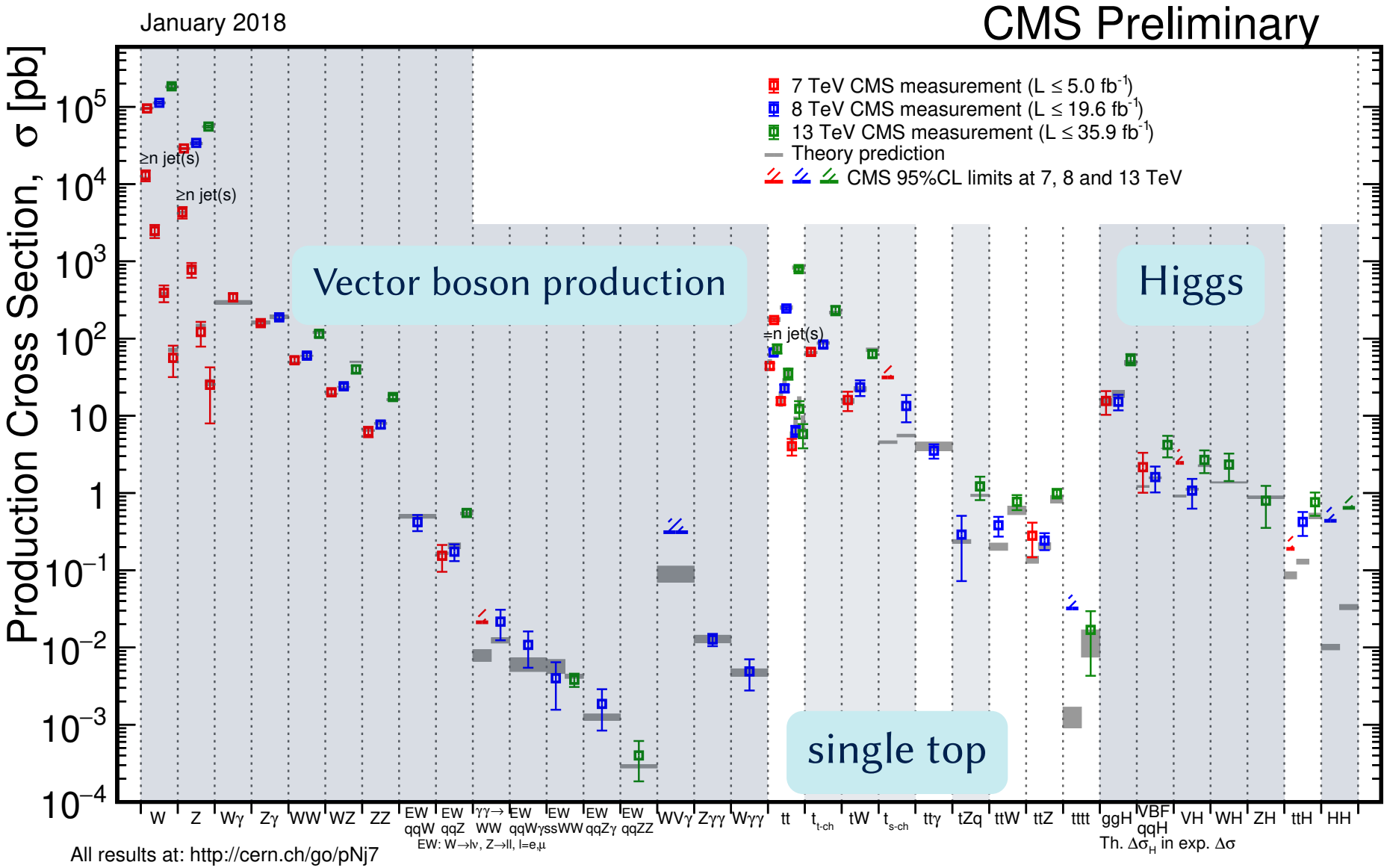

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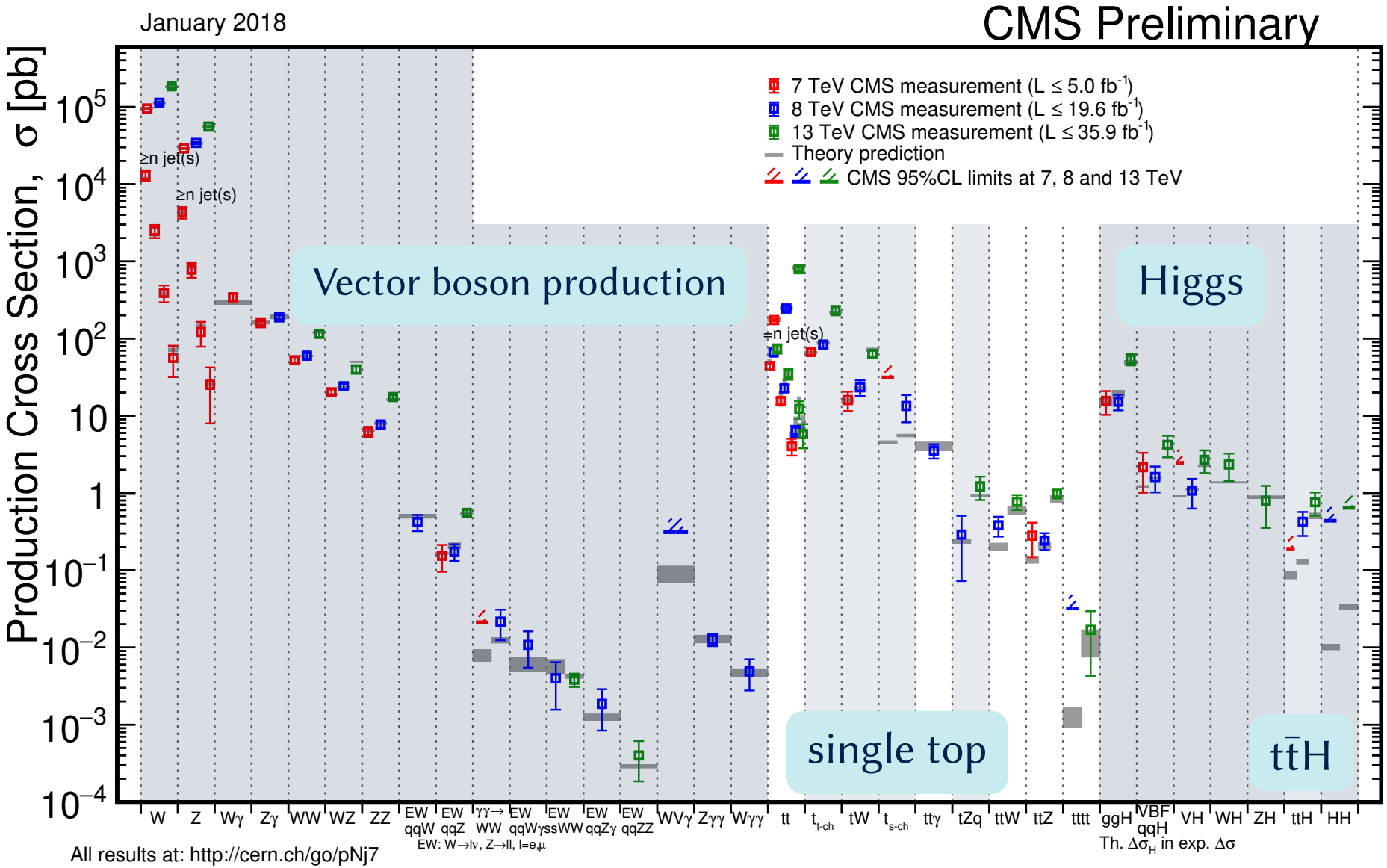

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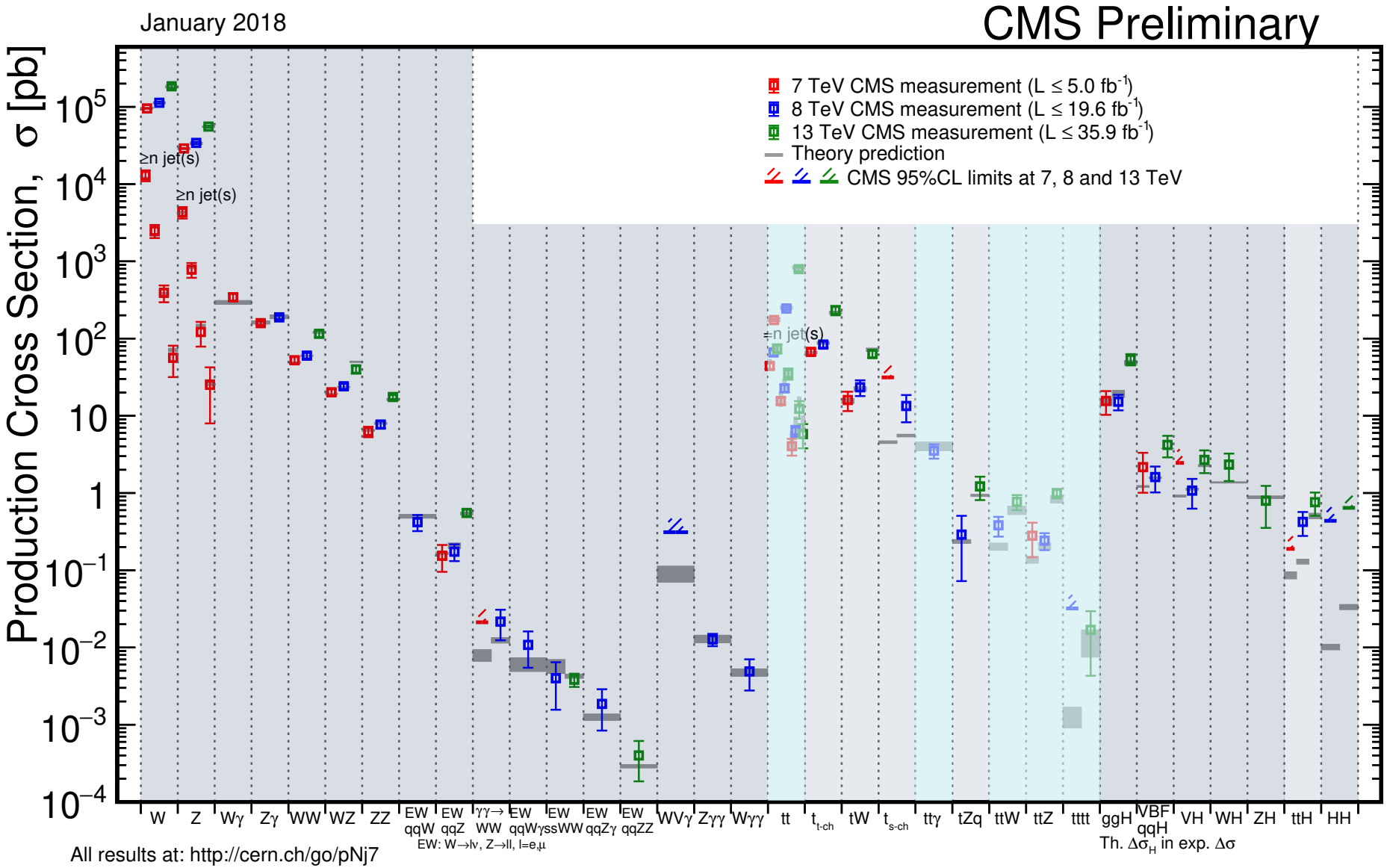
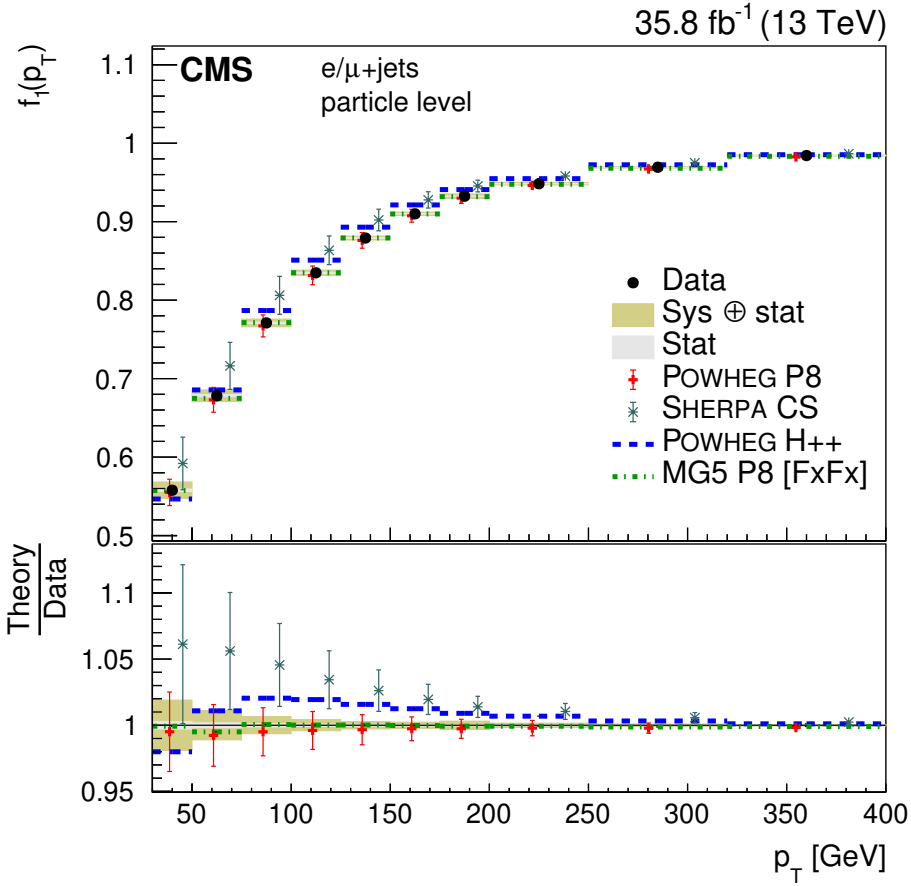


$pp \to t\bar{t} + \text{jets}$ ($t\bar{t} \to \ell + \text{jets}$) at $\sqrt{s} = 13$ TeV

arχiv:1803.08856 accepted by Phys. Rev. D

- ℓ + jets, background-subtracted (from non-b-tagged data, except for single top) and unfolded to particle level
- Differential cross-section measurements as a function of top quark, top decay product, and additional jet kinematic variables
- Overall reasonable agreement with POWHEG+PYTHIA8, larger differences with SHERPA with the Catani-Seymour parton shower
- Useful input for further tuning of parton shower models

Gap fraction $f_1(p_T)$: fraction of events with < 1 additional jet above p_T



see also the talks by Juan and Javier for more details about this analysis

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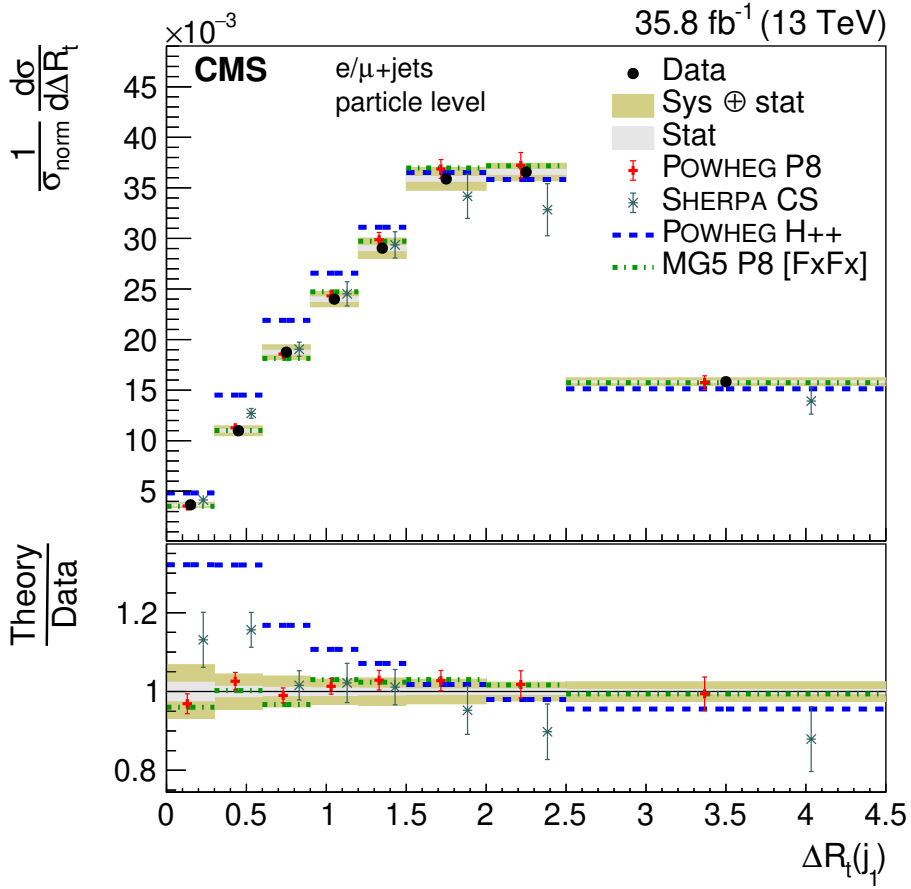
ΔR between the leading additional jet and the closest top quark



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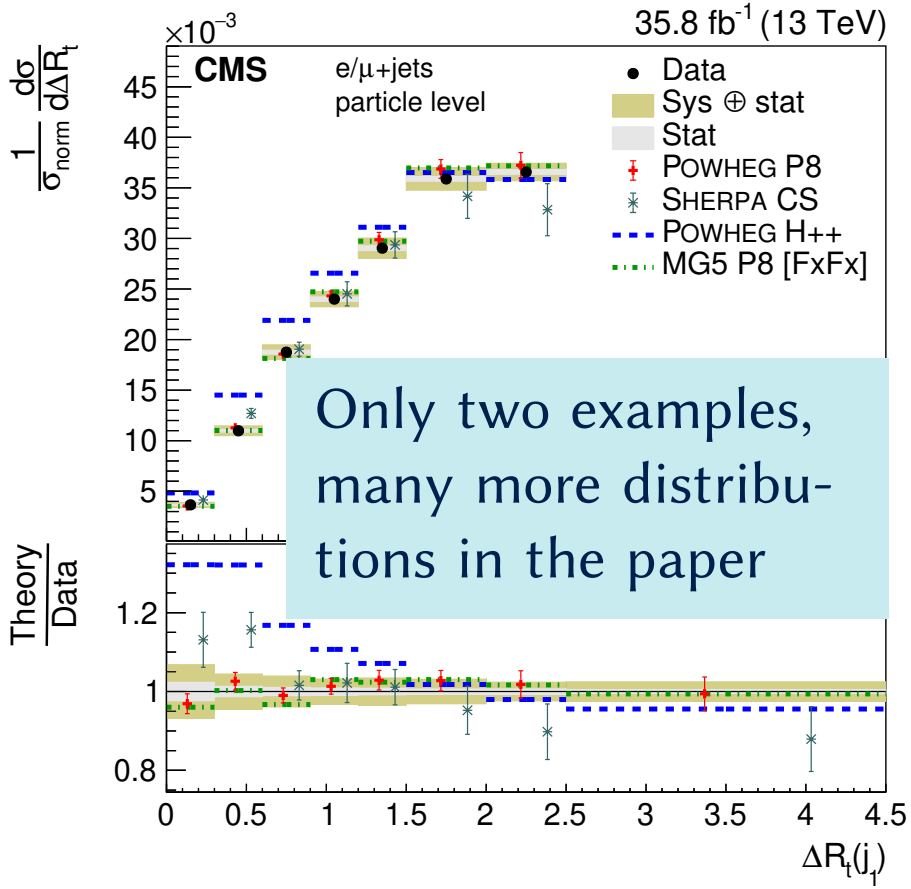

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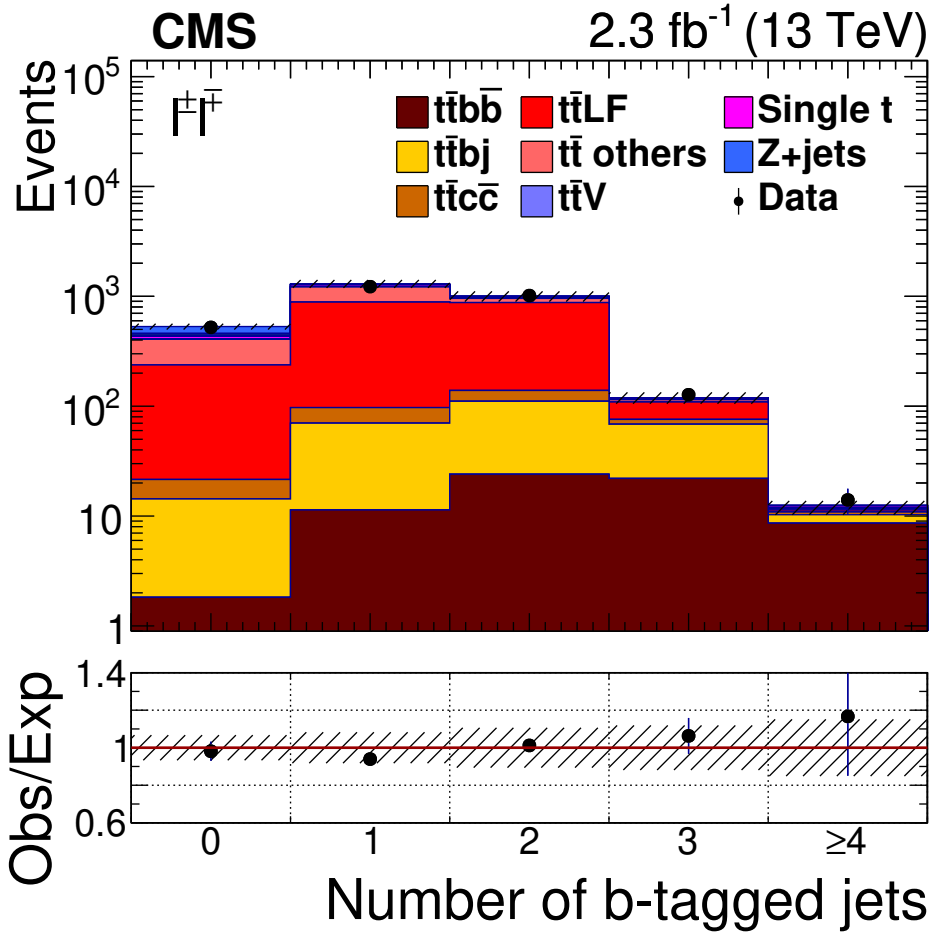
$pp \to t\bar{t}$ + b-jets ($t\bar{t} \to$ dilepton) at $\sqrt{s} = 13$ TeV

PhysLett**B776**(2018)355

- interesting test of QCD calculations, and also important as a background to other top associated processes (especially $t\bar{t}H$ with $H \to b\bar{b}$)
- Event selection: $t\bar{t} \to$ dilepton with at least 4 jets, at least 2 b-tagged
- b-tagging discriminant distribution in simulation corrected from data
- dominant uncertainty: b-jet (mis-)tagging calibration

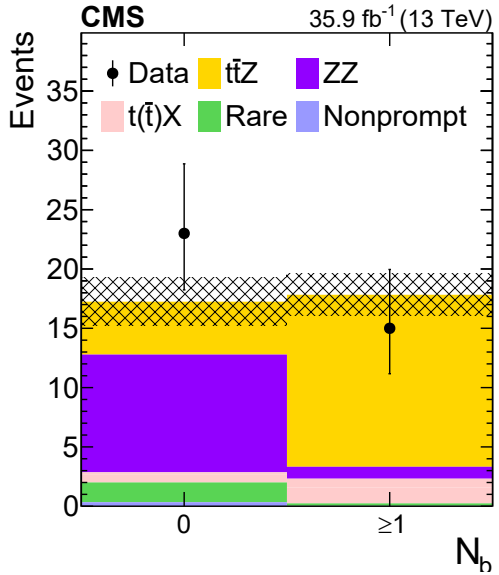


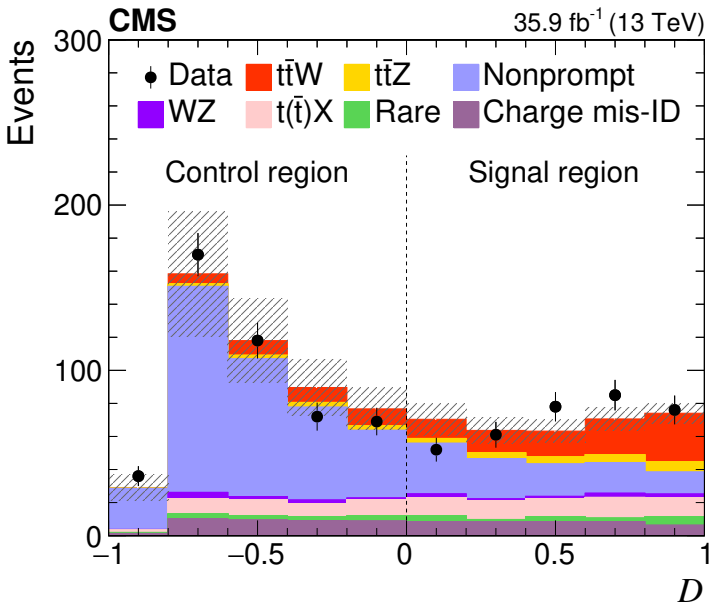
Phase space		$\sigma_{t\bar{t}b\bar{b}}$ [pb]	$\sigma_{t\bar{t}jj}$ [pb]	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$
Visible	Measurement	$0.088 \pm 0.012 \pm 0.029$	$3.7 \pm 0.1 \pm 0.7$	$0.024 \pm 0.003 \pm 0.007$
	SM (POWHEG)	0.070 ± 0.009	5.1 ± 0.5	0.014 ± 0.001
Full	Measurement	$4.0 \pm 0.6 \pm 1.3$	$184 \pm 6 \pm 33$	$0.022 \pm 0.003 \pm 0.006$
	SM (POWHEG)	3.2 ± 0.4	257 ± 26	0.012 ± 0.001

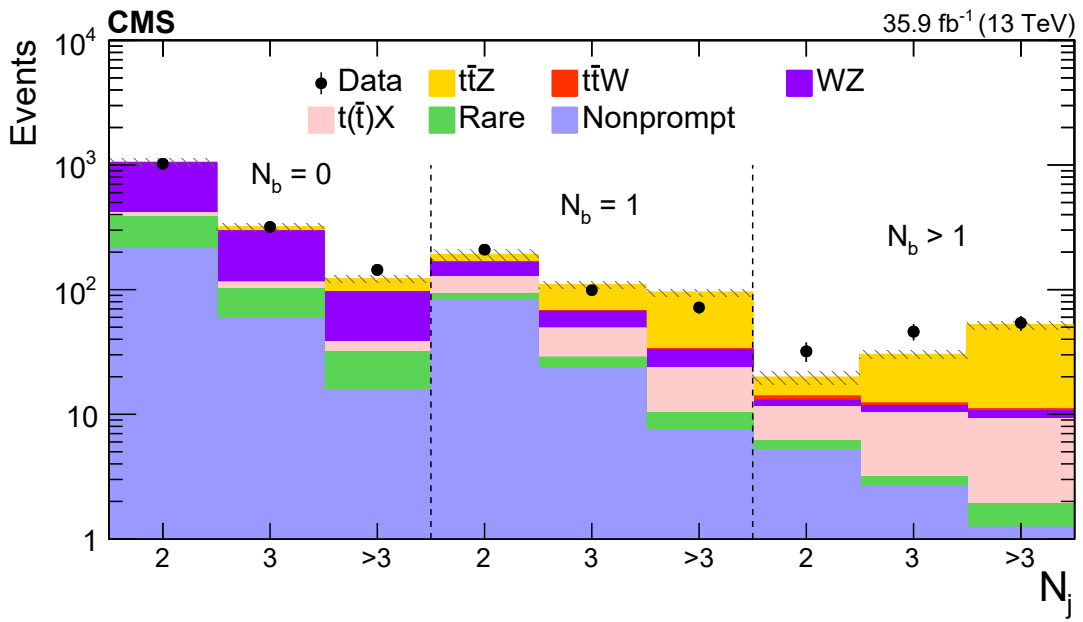
$pp \to t\bar{t} + W/Z$ cross-sections at $\sqrt{s} = 13$ TeV

arχiv:1711.02547 submitted to JHEP

- (same-sign) dilepton, three-lepton and four-lepton categories
- Kinematic BDT (2ℓ) and (b-)jet multiplicity categories
- Data-driven non-prompt and charge-misidentified lepton background, WZ from control region



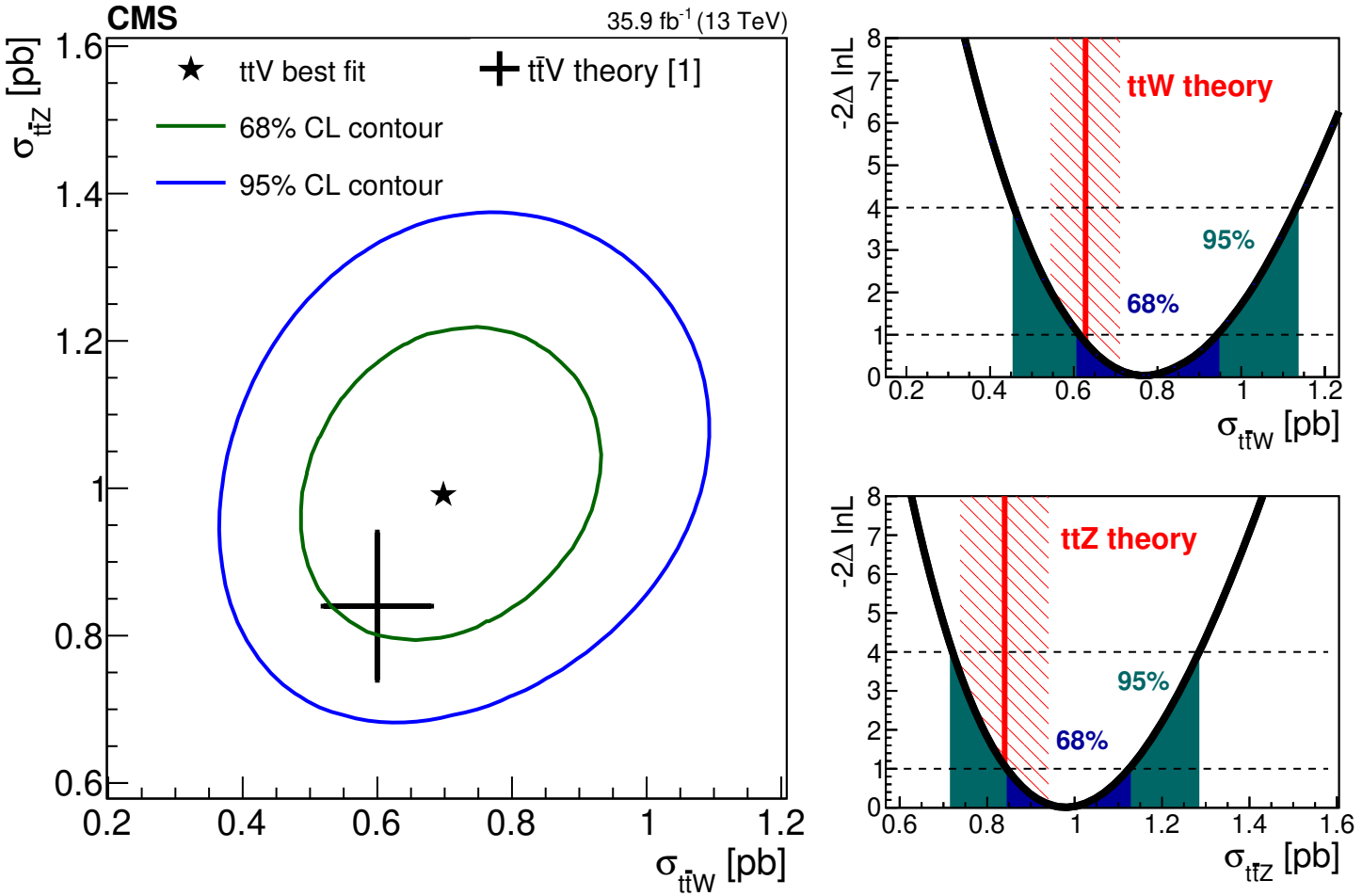




$pp \to t\bar{t} + W/Z$ cross-sections at $\sqrt{s} = 13$ TeV

arχiv:1711.02547 submitted to JHEP

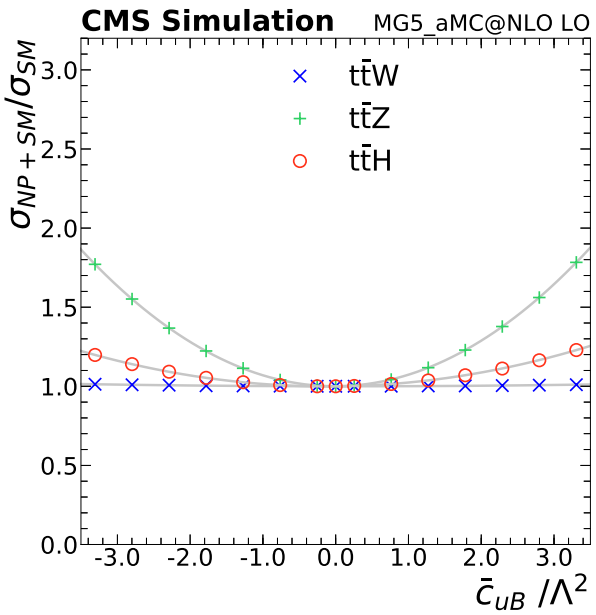
$$\sigma(pp \to t\bar{t}W) = 0.77^{+0.12}_{-0.11}\,(\text{stat.})\,^{+0.13}_{-0.12}\,(\text{sys.})\ \text{pb}$$
$$\sigma(pp \to t\bar{t}Z) = 0.99^{+0.09}_{-0.08}\,(\text{stat.})\,^{+0.12}_{-0.10}\,(\text{sys.})\ \text{pb}$$

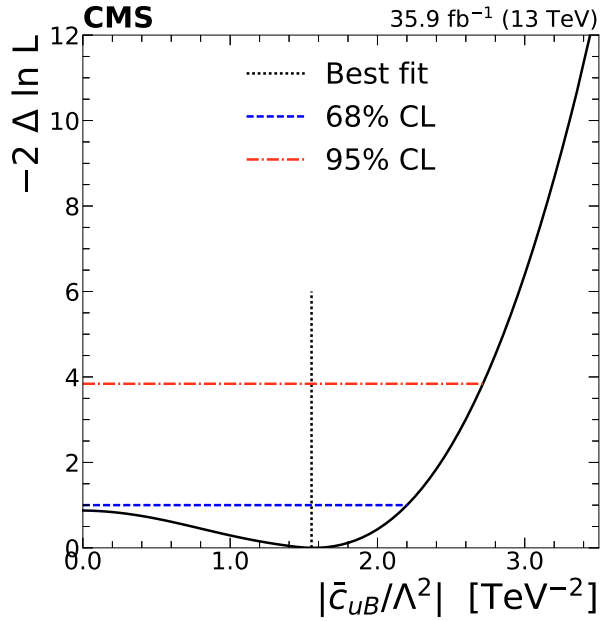


$pp \to t\bar{t} + W/Z$ cross-sections: EFT interpretation

arχiv:1711.02547 submitted to JHEP

- LO $t\bar{t}W$, $t\bar{t}Z$ and $t\bar{t}H$ cross-sections parameterized as a function of Wilson coefficients (in the HEL basis)
- Only considering operators that do not have a large impact on $t\bar{t}$, VV and H cross-sections (and rare backgrounds)
- One coefficient fit at a time





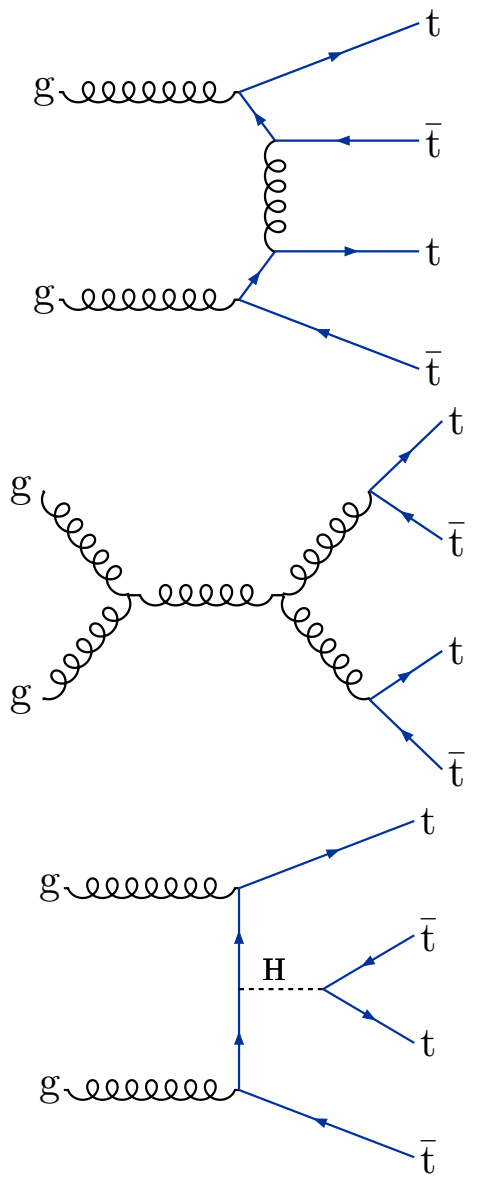
Wilson coefficient	Best fit [TeV^{-2}]	68% CL [TeV^{-2}]	95% CL [TeV^{-2}]
$\bar{c}_{uW}/\Lambda^2$	1.7	$[-2.4,-0.5]$ and $[0.4,2.4]$	$[-2.9,2.9]$
$\lvert\bar{c}_H/\Lambda^2 - 16.8\ \text{TeV}^{-2}\rvert$	15.6	$[0,23.0]$	$[0,28.5]$
$\lvert\tilde{c}_{3G}/\Lambda^2\rvert$	0.5	$[0,0.7]$	$[0,0.9]$
$\bar{c}_{3G}/\Lambda^2$	-0.4	$[-0.6,0.1]$ and $[0.4,0.7]$	$[-0.7,1.0]$
$\bar{c}_{uG}/\Lambda^2$	0.2	$[0,0.3]$	$[-1.0,-0.9]$ and $[-0.3,0.4]$
$\lvert\bar{c}_{uB}/\Lambda^2\rvert$	1.6	$[0,2.2]$	$[0,2.7]$
$\bar{c}_{Hu}/\Lambda^2$	-9.3	$[-10.3,-8.0]$ and $[0,2.1]$	$[-11.1,-6.5]$ and $[-1.6,3.0]$
$\bar{c}_{2G}/\Lambda^2$	0.4	$[-0.9,-0.3]$ and $[-0.1,0.6]$	$[-1.1,0.8]$

more EFT fit plots can be found on the results web page

Search for Standard Model $pp \to t\bar{t}t\bar{t}$ production

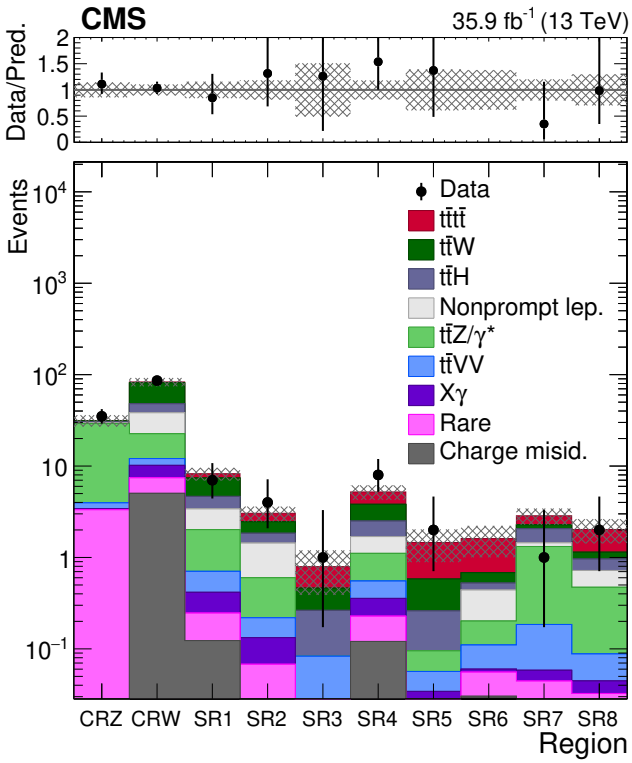
EurPhysJ**C78**(2018)140

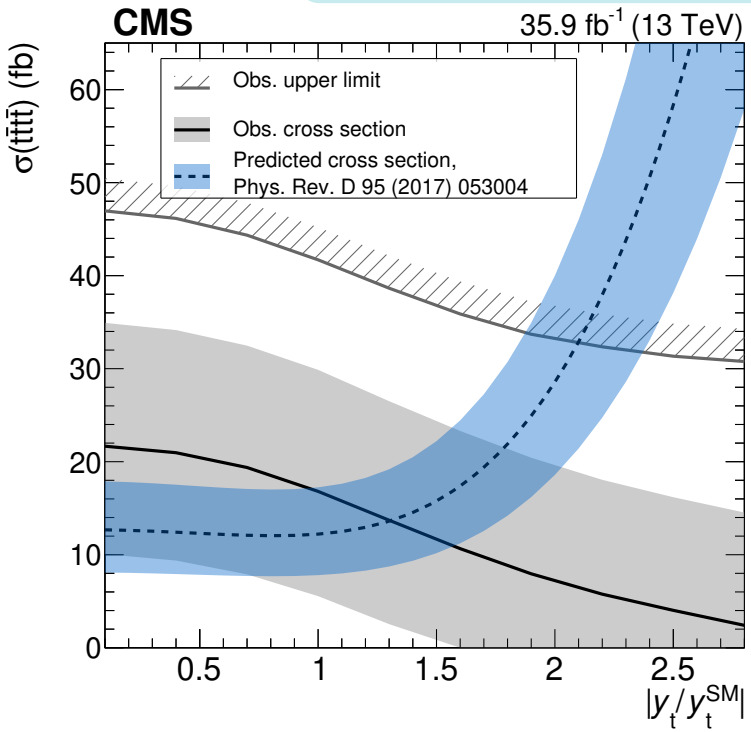
- Enhanced in many BSM theories, also sensitive to the top quark Yukawa coupling y_t
- Multilepton ($\ell^{\pm}\ell'^{\pm}$, 3ℓ, 4ℓ) final states
- 8 signal regions and $t\bar{t}W$, $t\bar{t}Z$ control regions based on the number of leptons, jets and b-tagged jets (and a $Z \to \ell^+\ell^-$ veto)
- Backgrounds from nonprompt and charge mis-identified leptons estimated using a "fake rate" method
- Improved description of $t\bar{t}W$ + jets and $t\bar{t}Z$ + jets backgrounds using corrections derived from $t\bar{t}$(dilepton) + jets and $t\bar{t}b\bar{b}/t\bar{t}jj$ measurements



Search for Standard Model pp → $t\bar{t}t\bar{t}$ production

EurPhysJ**C78**(2018)140





$\sigma(pp \to t\bar{t}t\bar{t}) = 16.9^{+13.8}_{-11.4}$ fb (NLO prediction: $9.2^{+2.9}_{-2.4}$ fb [MG5_aMC@NLO])

Signal significance: 1.6σ (1.0σ expected)

$\sigma(pp \to t\bar{t}t\bar{t}) < 41.7$ fb at 95% CL (background-only expected: $20.8^{+11.2}_{-6.9}$ fb)

$|y_t/y_t^{SM}| < 2.1$ with $\sigma_{SM} = 12.2^{+5.0}_{-4.4}$ fb

(from [PhysRev**D95**(2017)053004] with NLO/LO k-factor from [JHEP**07**(2012)111])

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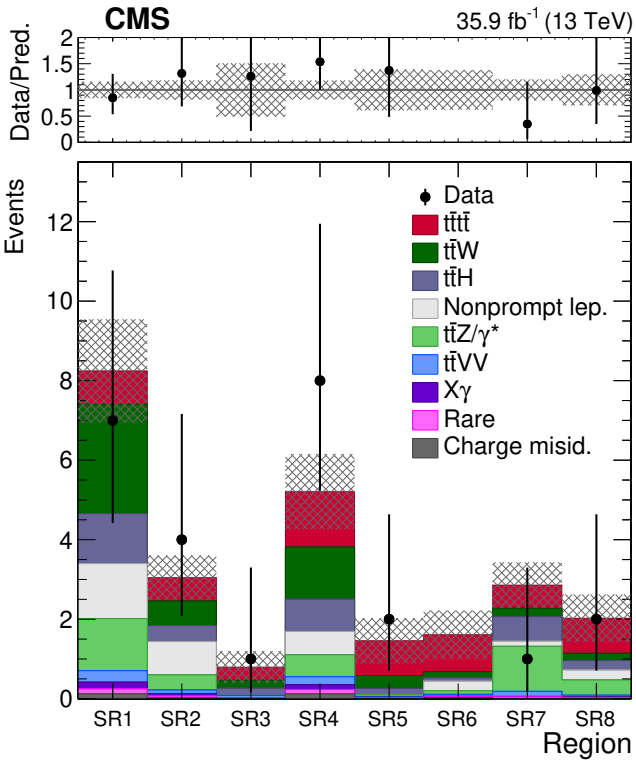

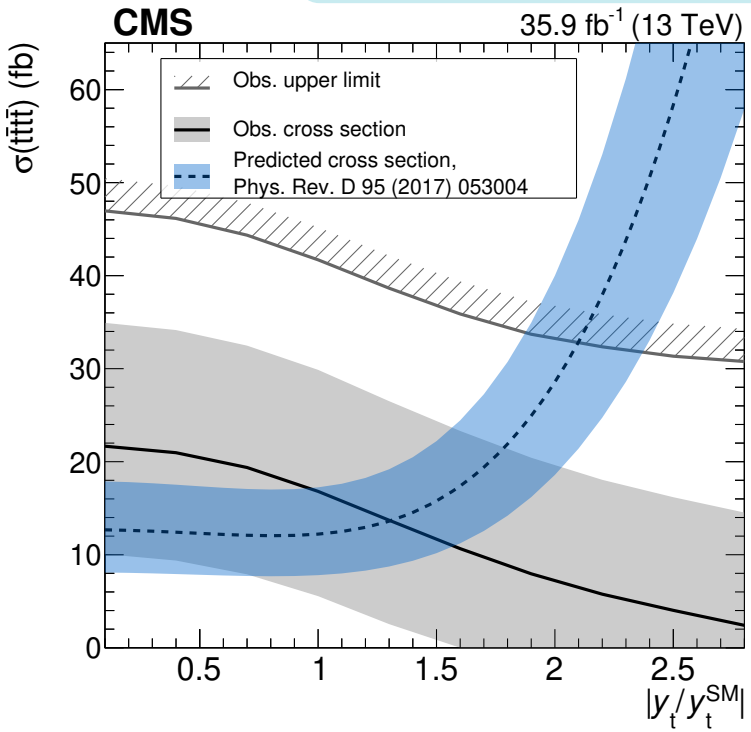

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Conclusions

- Top quark associated production provides an interesting opportunity to search for physics beyond the standard model by measuring SM couplings of the top quark and dimension-6 Wilson coefficients

- The measurements of these processes are challenging, but many are now feasible with an interesting precision, thanks to the large LHC run-2 data samples collected at $\sqrt{s} = 13\,\text{TeV}$

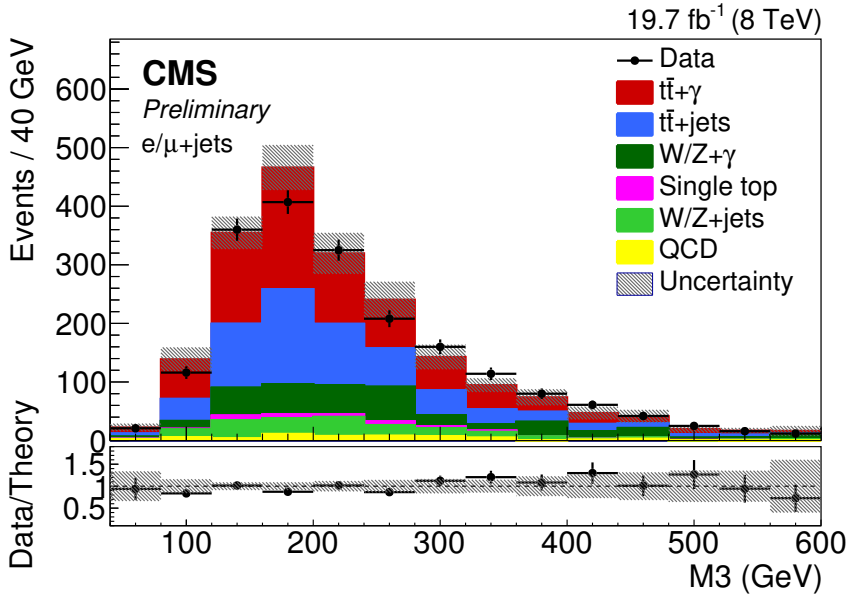
- Presented measurements of $t\bar{t}$ production in association with jets, b-jets, W and Z bosons and another $t\bar{t}$ pair. Most are based on only $36\,\text{fb}^{-1}$ (2016 data), and limited by statistics or systematic effects that can be further constrained with more data, so they will improve with the 2017 and 2018 data samples.

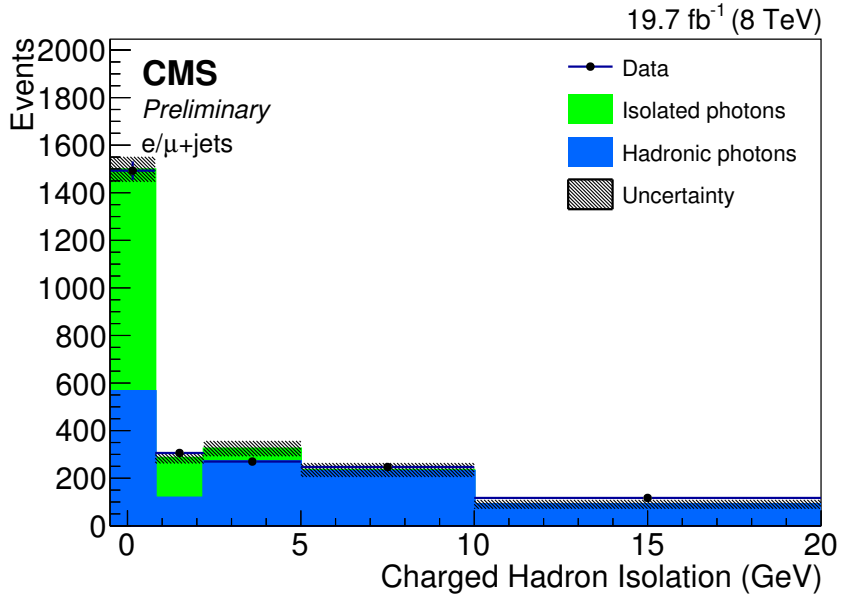
Additional material

$pp \to t\bar{t} + \gamma$ cross-section at $\sqrt{s} = 8$ TeV

CMS-PAS-TOP-14-008

- Fiducial region: photon $E_T > 25$ GeV, $|\eta| < 1.44$
- $t\bar{t}$+jets and V+γ backgrounds determined from fits to M3 (hadronic top mass) and photon isolation (with templates from data: random cone (PU) for isolated, photon η spread sideband for photons from jets)
- $e \to \gamma$ mis-ID rate corrected with $Z \to e^+e^-$
- $\sigma^{fid}_{t\bar{t}+\gamma}/\sigma_{t\bar{t}} = 5.2 \pm 1.1 \times 10^{-4}$(stat+syst)
  $\sigma^{fid}_{t\bar{t}+\gamma} = 127 \pm 27$(stat+syst) fb
- photon E_T and η distributions in good agreement with simulation





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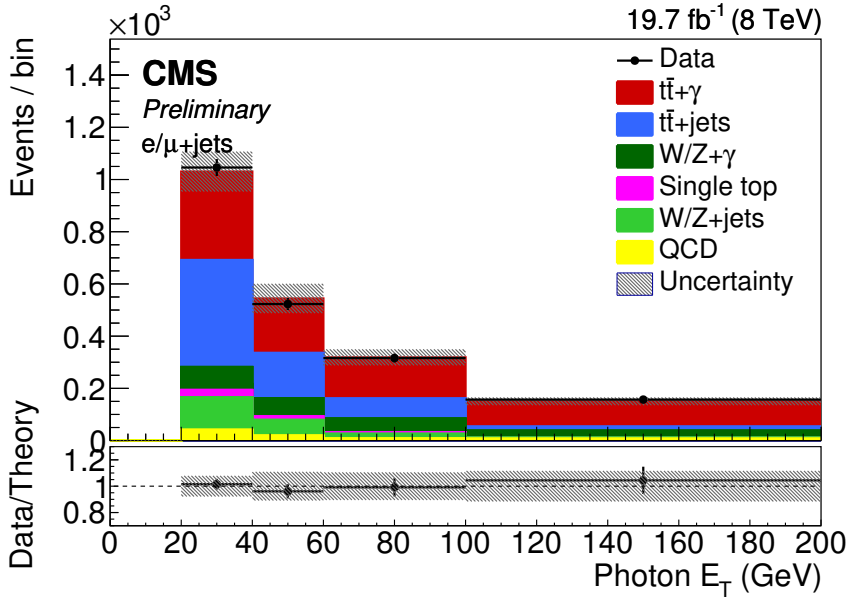

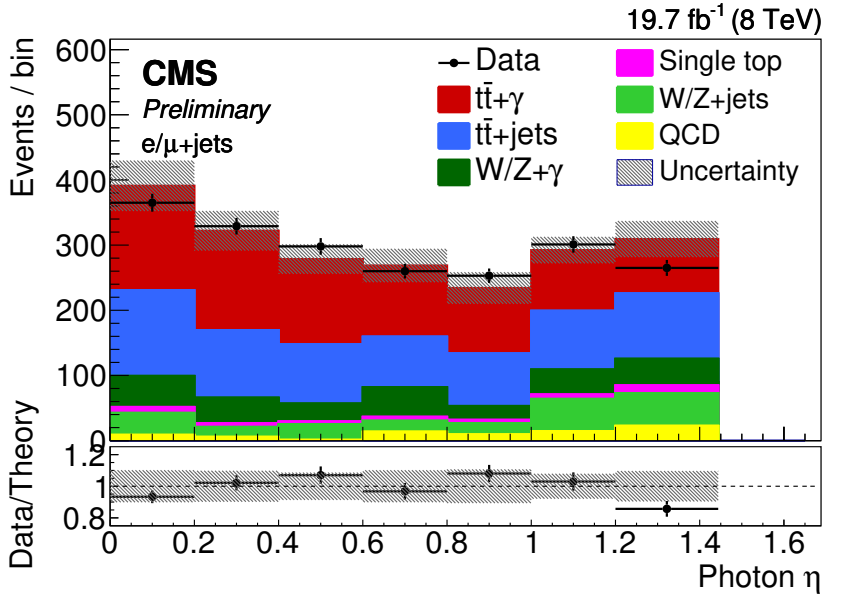

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