Top quark production in association with additional particles at CMS

Phenomenology 2021 Symposium

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

$t\bar{t}$+X production at CMS

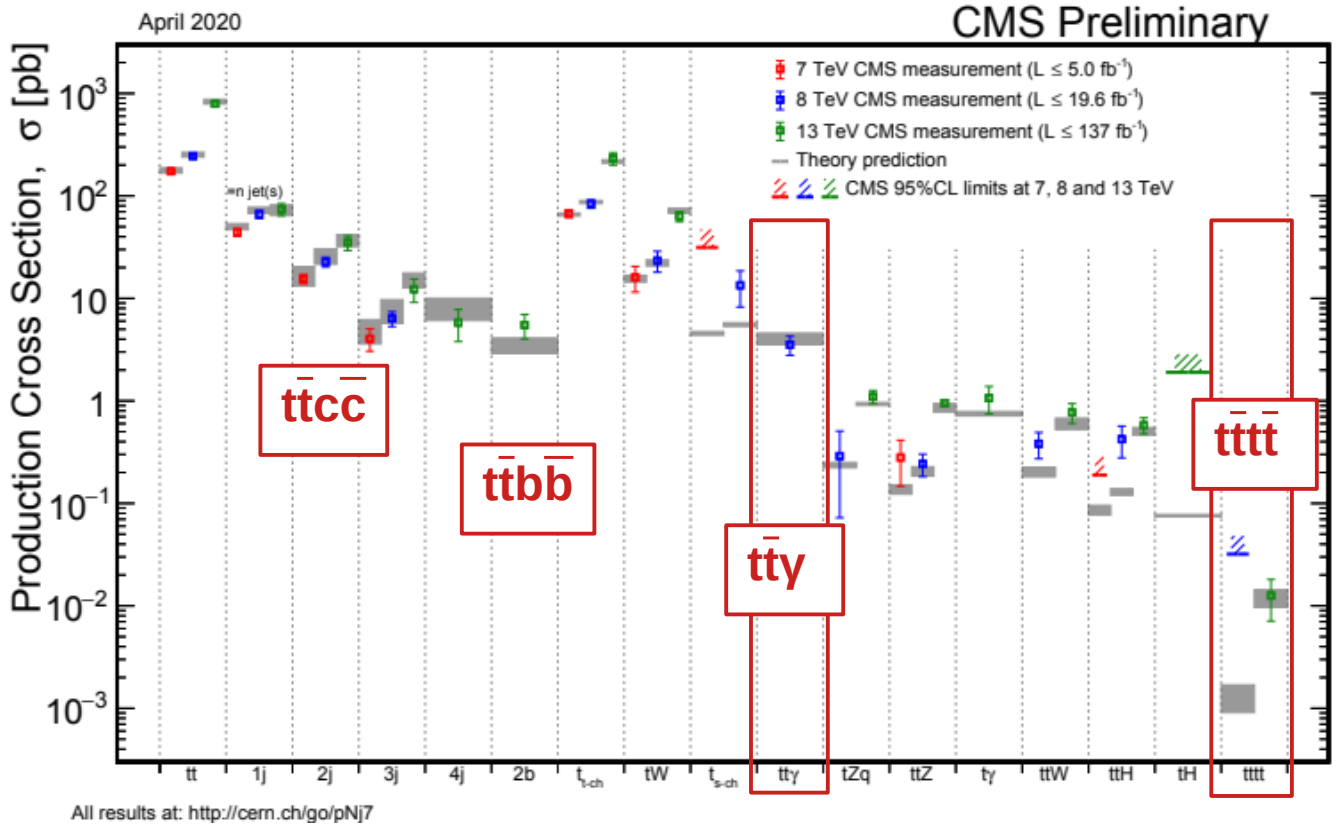
LHC run 2

- CMS collected almost 140 fb^{-1} of pp collision data at 13 TeV

Most top associated processes in precision era

- Studying new final states → extremely challenging background handling
- Going differential → exploration of new kinematic regimes

Focus of this talk: Standard model measurements

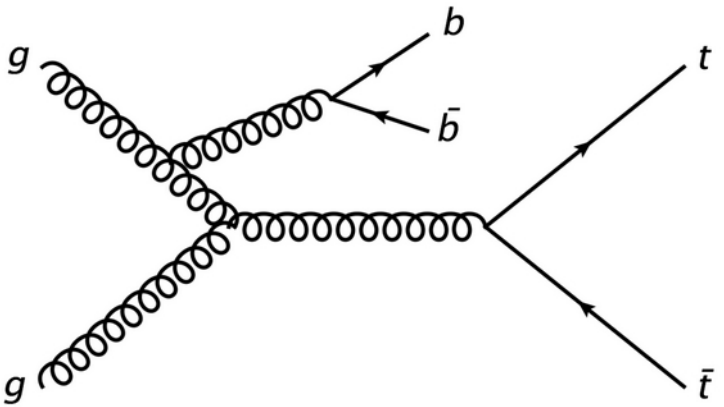


$t\bar{t}+b\bar{b}$ measurements

Large background to $t\bar{t}H(H\rightarrow b\bar{b})$ and $t\bar{t}t\bar{t}$

Improve modeling of $t\bar{t}$

Strong test for QCD



Final states

- All hadronic
- Semileptonic
- Dileptonic

Challenges

- b-jet identification → flavor tagging
- Many permutations for (b) jet assignment

PLB 803 (2020) 135285

$t\bar{t}+b\bar{b}$ in all hadronic final state

Target signal with 4 light jets and 4 b jets

Large branching fraction

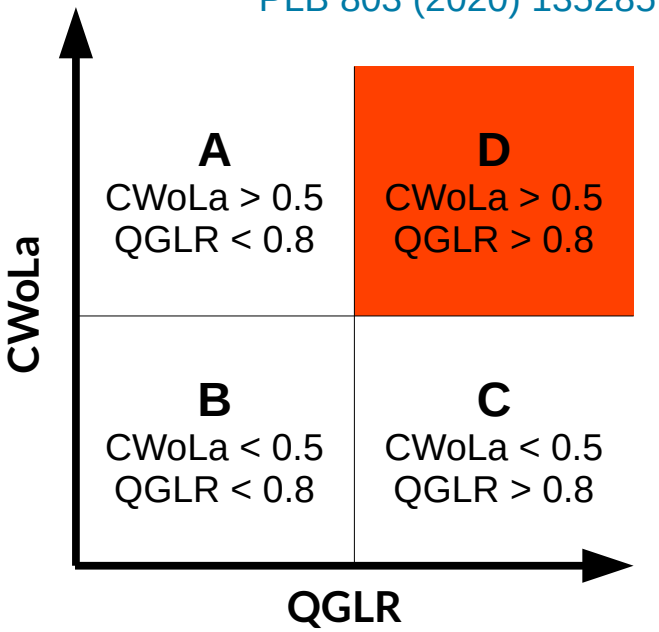
Difficult jet assignment

- BDT trained on permutations

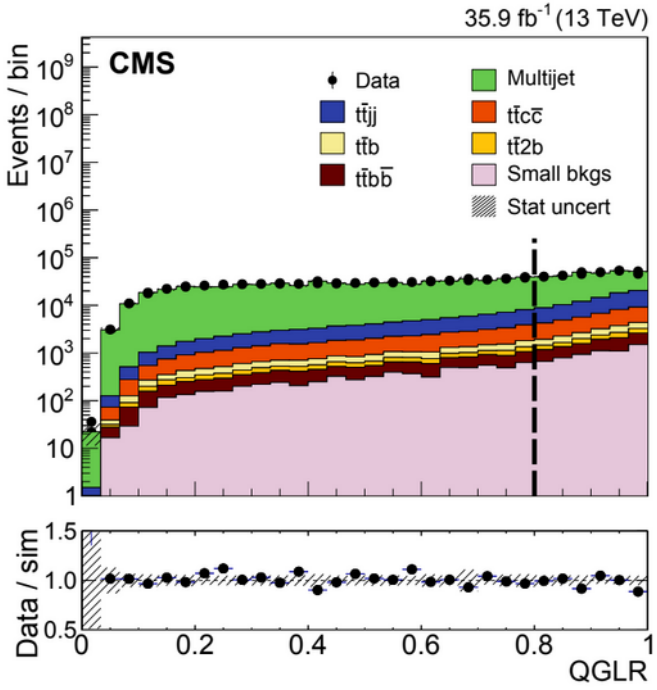
Large multijet background

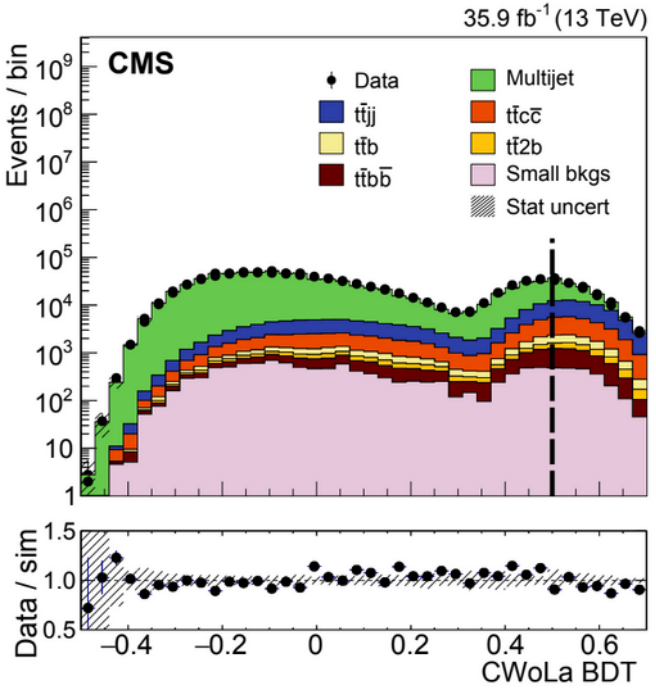
- Data driven ABCD method

$$D = C \cdot \frac{A}{B}$$



Quark gluon likelihood ratio (QGLR) **vs.** **Classification without labels (CWoLa)**





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$t\bar{t}+b\bar{b}$ in all hadronic final state

Binned maximum likelihood fit to 2D distribution

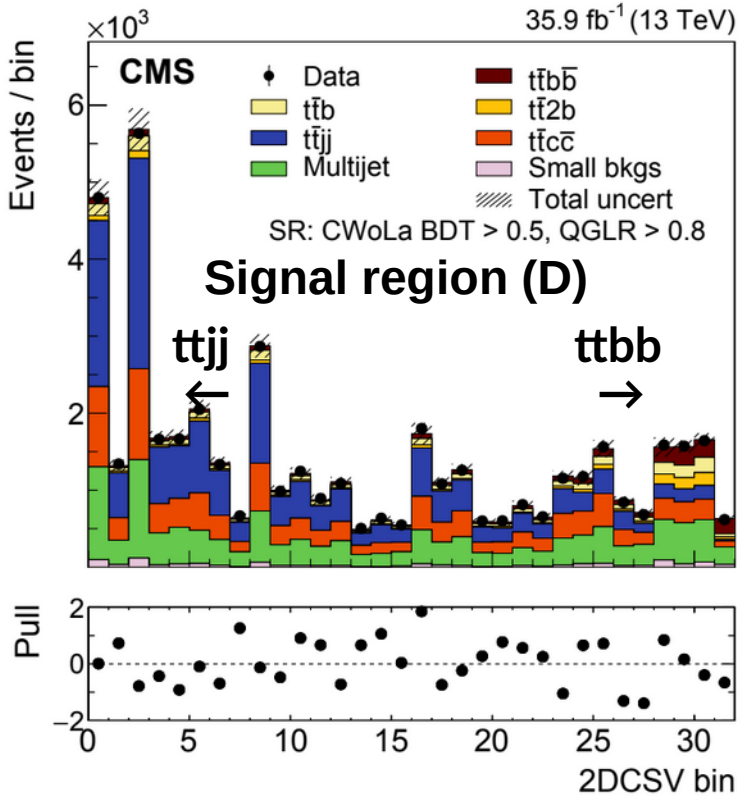
- Largest vs. second largest b-tagging score of “additional jets”
- Simultaneous fit in all regions (ABCD)

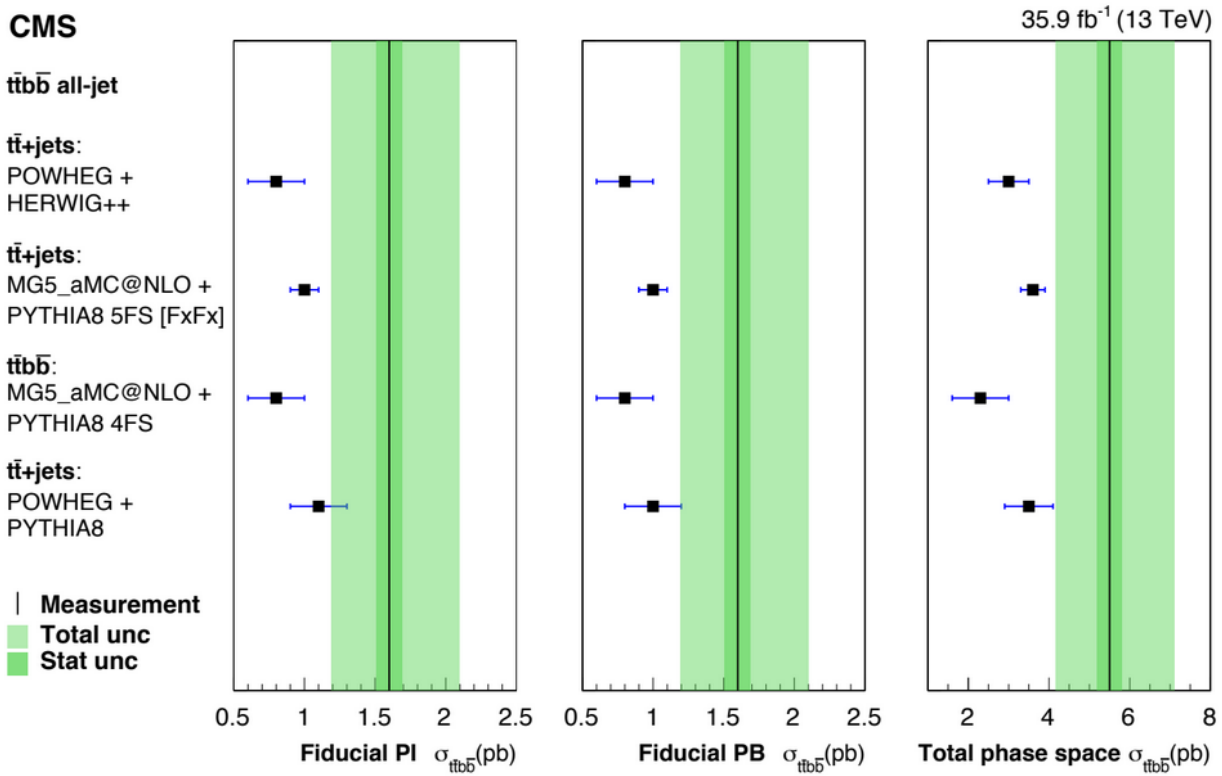
Leading uncertainties

- Simulated sample size, QGL modeling

$$\sigma_{t\bar{t}b\bar{b}} = 5.5 \pm 0.3(\text{stat})^{+1.6}_{-1.3}(\text{syst})\ \text{pb}$$

- Measured excess of 1-2 σ





$t\bar{t}+c\bar{c}$ in dilepton final states

First measurement of $t\bar{t}+c\bar{c}$ cross section

Complementary information to $t\bar{t}+b\bar{b}$

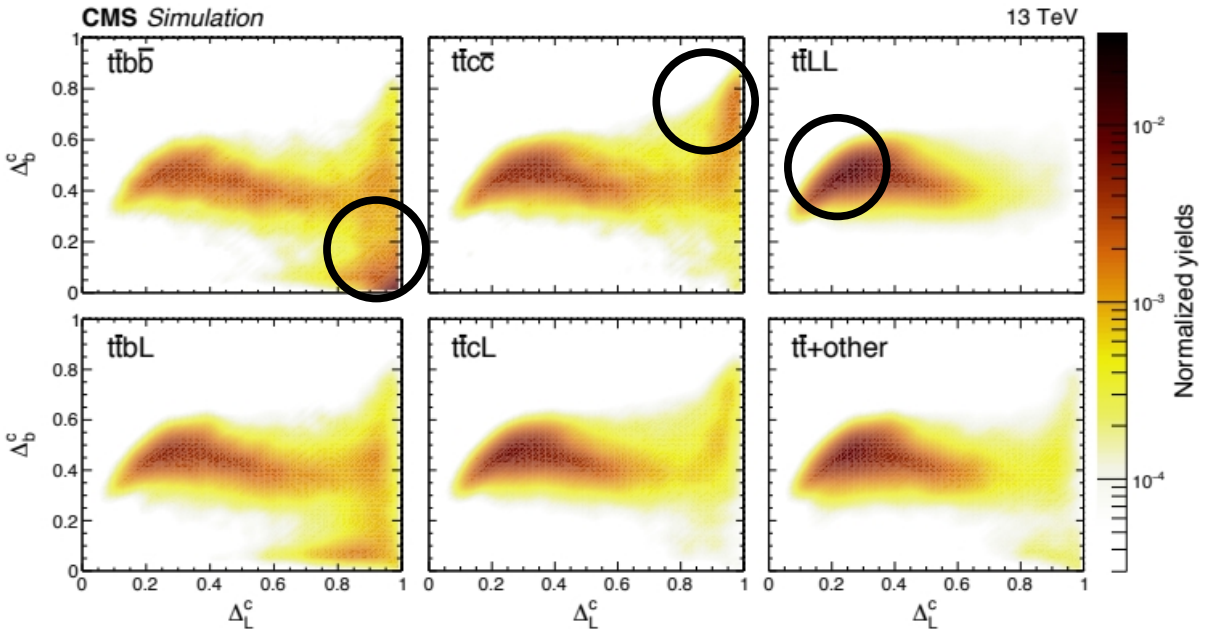
Dileptonic final state with ≥ 4 jets

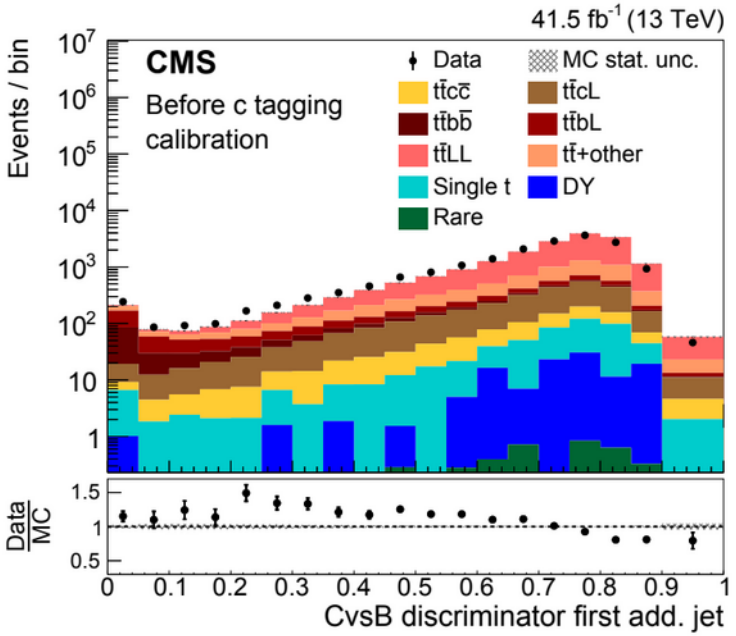
NN for jet assignment

Use of dedicated charm taggers

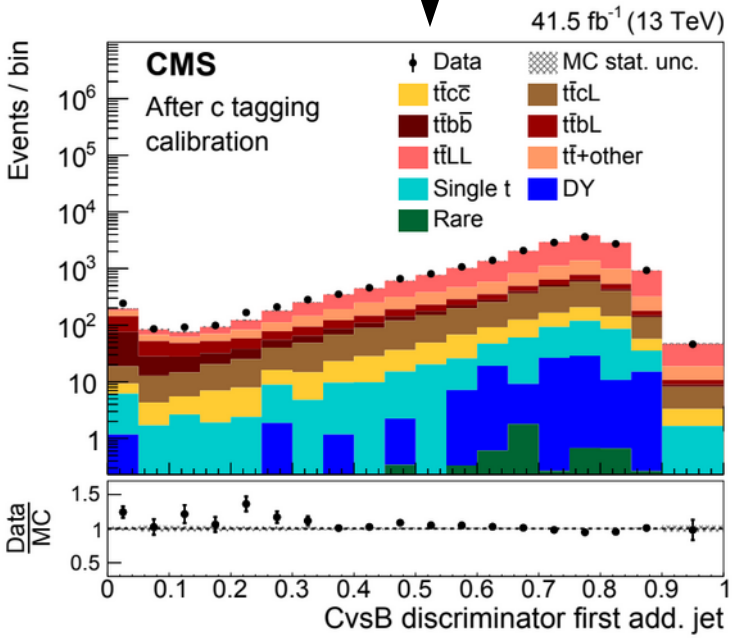
$$\Delta_b^c = \frac{P(t\bar{t}c\bar{c})}{P(t\bar{t}c\bar{c}) + P(t\bar{t}b\bar{b})}, \qquad \Delta_L^c = \frac{P(t\bar{t}c\bar{c})}{P(t\bar{t}c\bar{c}) + P(t\bar{t}LF)}$$

- Calibrated in tt, W+c and DY+jets topologies via iterative fit





calibration

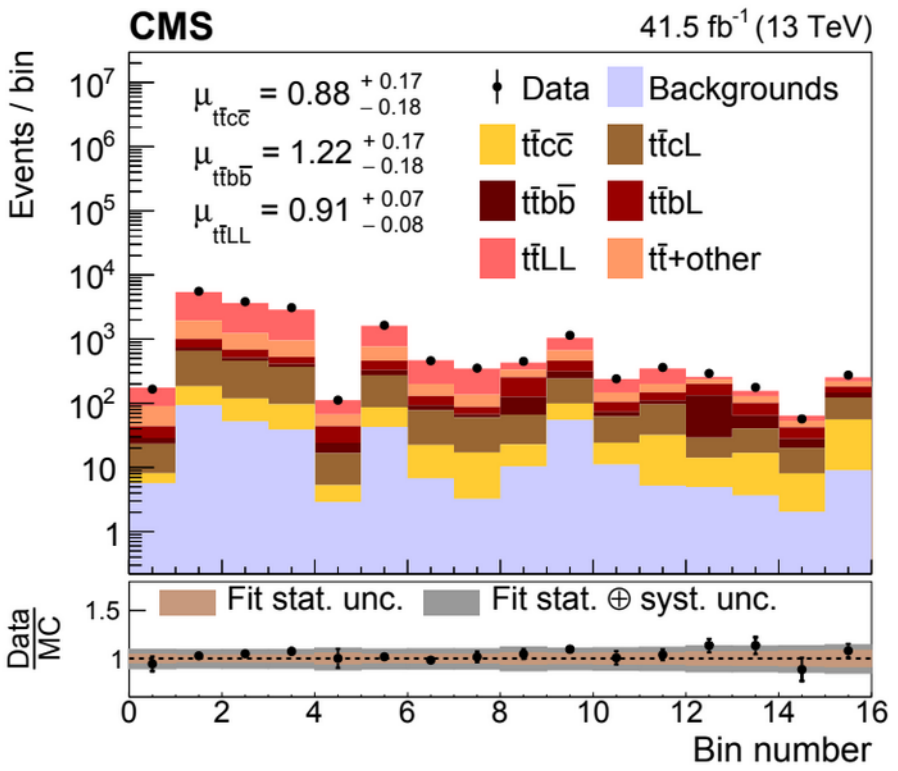


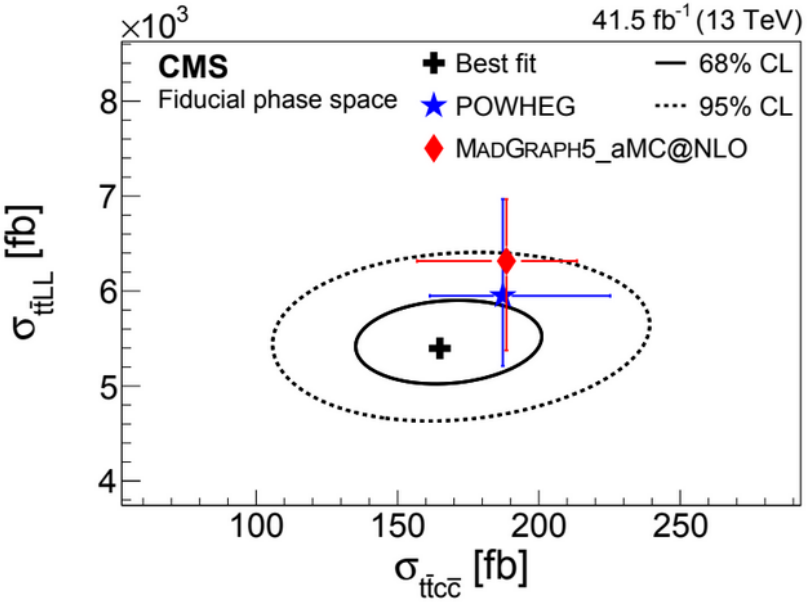
$t\bar{t}+c\bar{c}$ – results

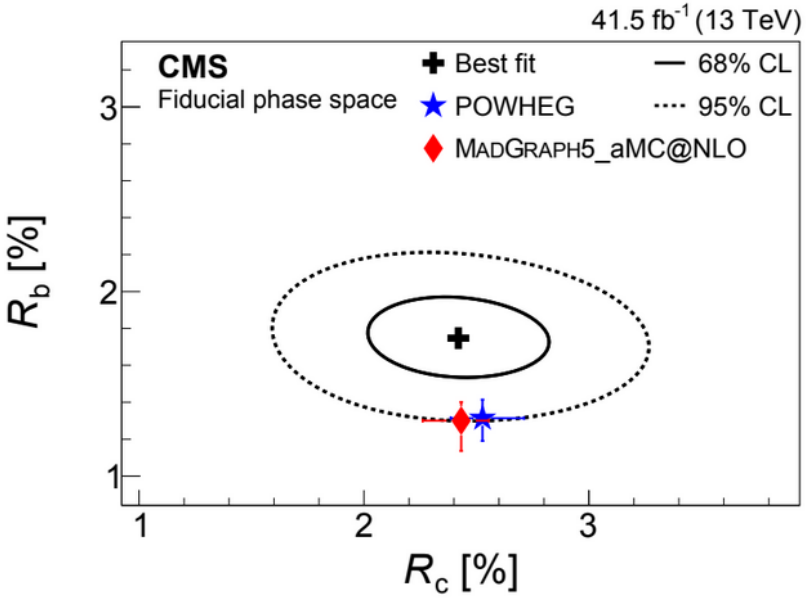
Multidimensional binned maximum likelihood fit
- 2D histogram unrolled into 1D distribution with 16 bins
- $t\bar{t}b\bar{b}$, $t\bar{t}c\bar{c}$ and $t\bar{t}$LF

Leading uncertainty
- c-tagging calibration
- Jet energy scale
- QCD ME scales

Results consistent with $t\bar{t}b\bar{b}$ measurements

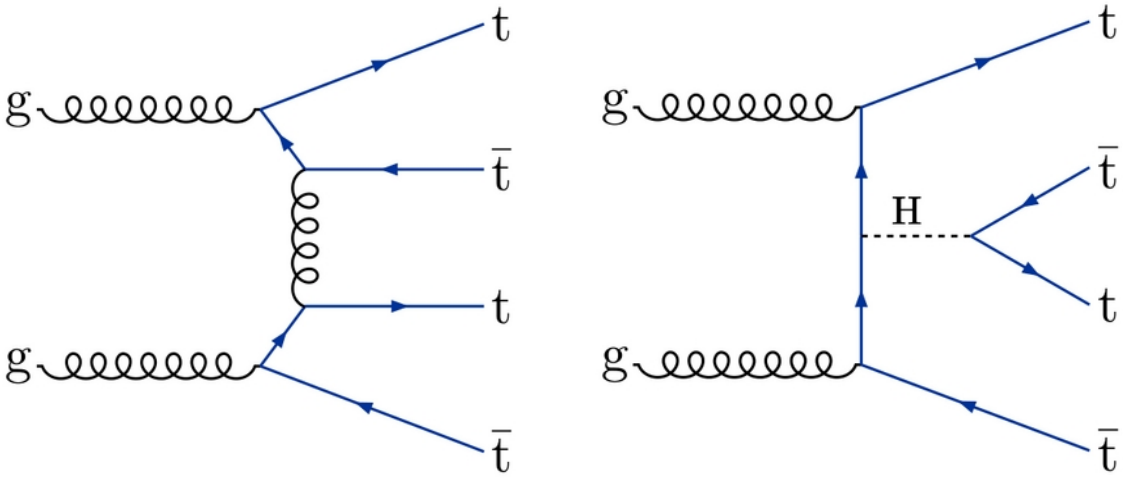






Eur. Phys. J. C (2020) 80:75

$t\bar{t}t\bar{t}$



Constrain top Yukawa coupling y_t

Sensitive to BSM physics (2HDM, DM, EFT, ...)

Full run 2 data: 137 fb^{-1}

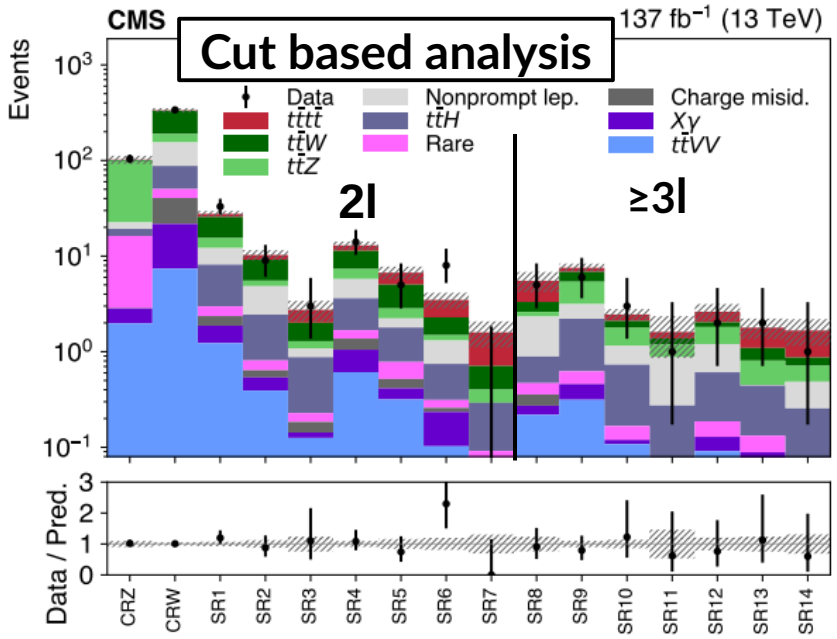
2 same sign leptons or ≥ 3 lepton

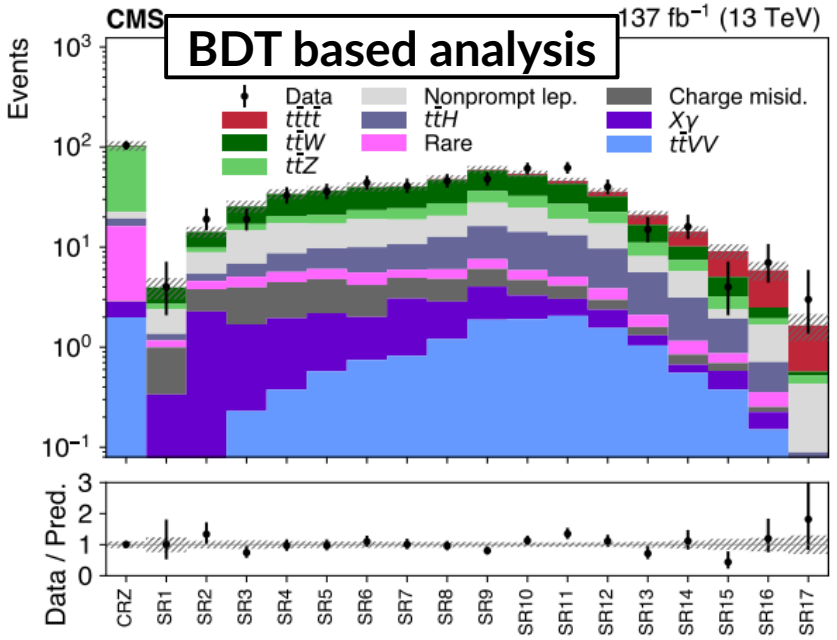
- Hadronic activity H_T > 300 GeV
- Missing energy p_T^{miss} > 50 GeV
- ≥2 jets and ≥2 b jets

Data driven background estimation

- Nonprompt: Tight-to-loose ratio
- Charge misid.: Misid. probability

Binned maximum likelihood fit





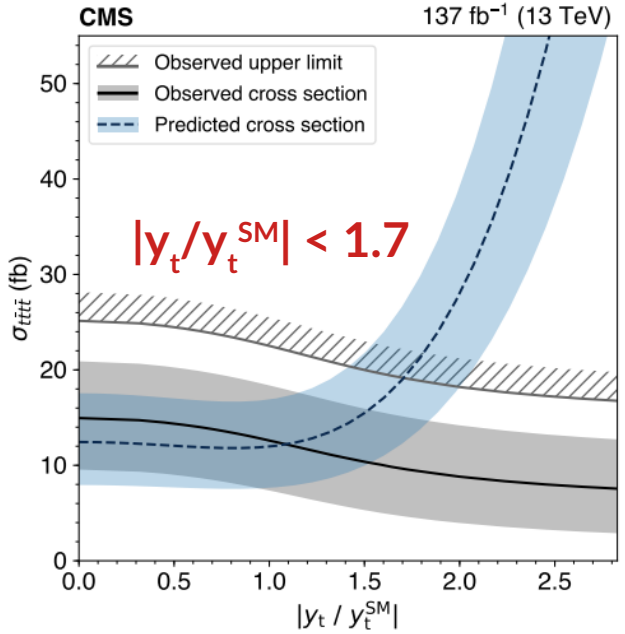
$t\bar{t}t\bar{t}$

Both analysis strategies agree (Cut based & BDT)

Observed significance of 2.5σ and 2.7σ

New CMS limit on top Yukawa coupling y_t !

- By varying $t\bar{t}H$ backrgound



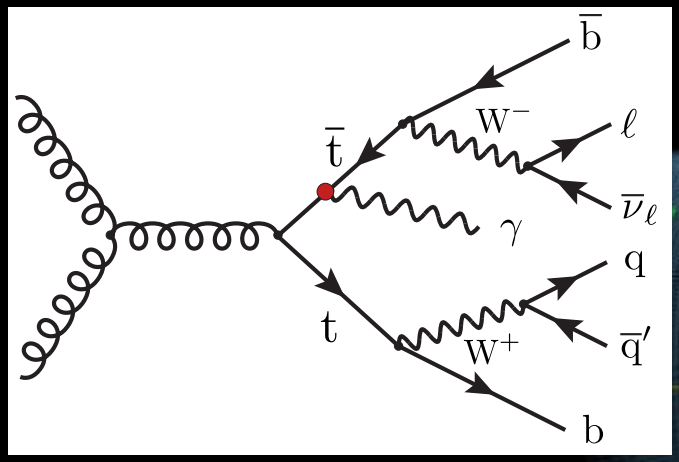
Source	Uncertainty (%)	Impact on $\sigma(t\bar{t}t\bar{t})$ (%)
Integrated luminosity	2.3–2.5	2
Pileup	0–5	1
Trigger efficiency	2–7	2
Lepton selection	2–10	2
Jet energy scale	1–15	9
Jet energy resolution	1–10	6
b tagging	1–15	6
Size of simulated sample	1–25	< 1
Scale and PDF variations†	10–15	2
ISR/FSR (signal)†	5–15	2
$t\bar{t}H$ (normalization)†	25	5
Rare, $X\gamma$, $t\bar{t}VV$ (norm.)†	11–20	< 1
$t\bar{t}Z$, $t\bar{t}W$ (norm.)†	40	3–4
Charge misidentification†	20	< 1
Nonprompt leptons†	30–60	3
$N_{\text{jets}}^{\text{ISR/FSR}}$	1–30	2
$\sigma(t\bar{t}\,b\bar{b})/\sigma(t\bar{t}\,jj)$†	35	11

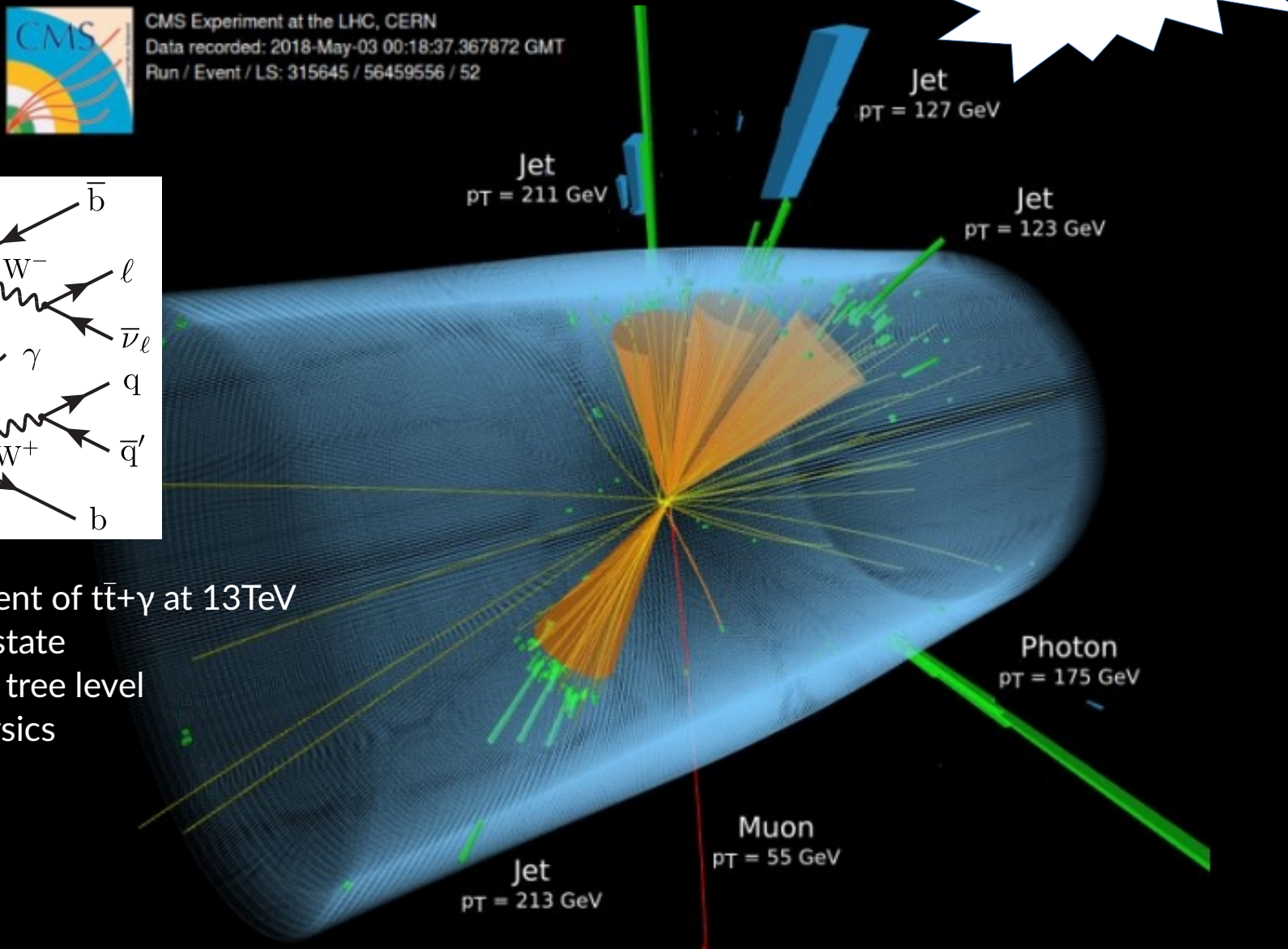
- Limits on new particles
  - **$m < 2m_t$:** neutral scalar (ϕ) and neutral vector (Z')
  - **$m > 2m_t$:** Heavy scalar (H) and pseudoscalar (A)
- Simplified dark matter models

Measurement of the inclusive and differential $t\bar{t}+\gamma$ cross section and EFT interpretation in the single lepton channel at sqrt(s) = 13 TeV

CMS-PAS-TOP-18-010

New!





- First CMS measurement of $t\bar{t}+\gamma$ at 13TeV
  - Semileptonic final state
- Probes $t\gamma$ coupling at tree level
- Sensitive to BSM physics
  - e.g. EFT, ...

$t\bar{t}+\gamma$ inclusive and differential measurement

Signal (genuine) photon:

- photon from ISR, top or top decay products

Electron misidentified as photon:

- Enriched control regions included in the fit
- Also for $W\gamma$ and $Z\gamma$

Nonprompt photons from hadron decay:

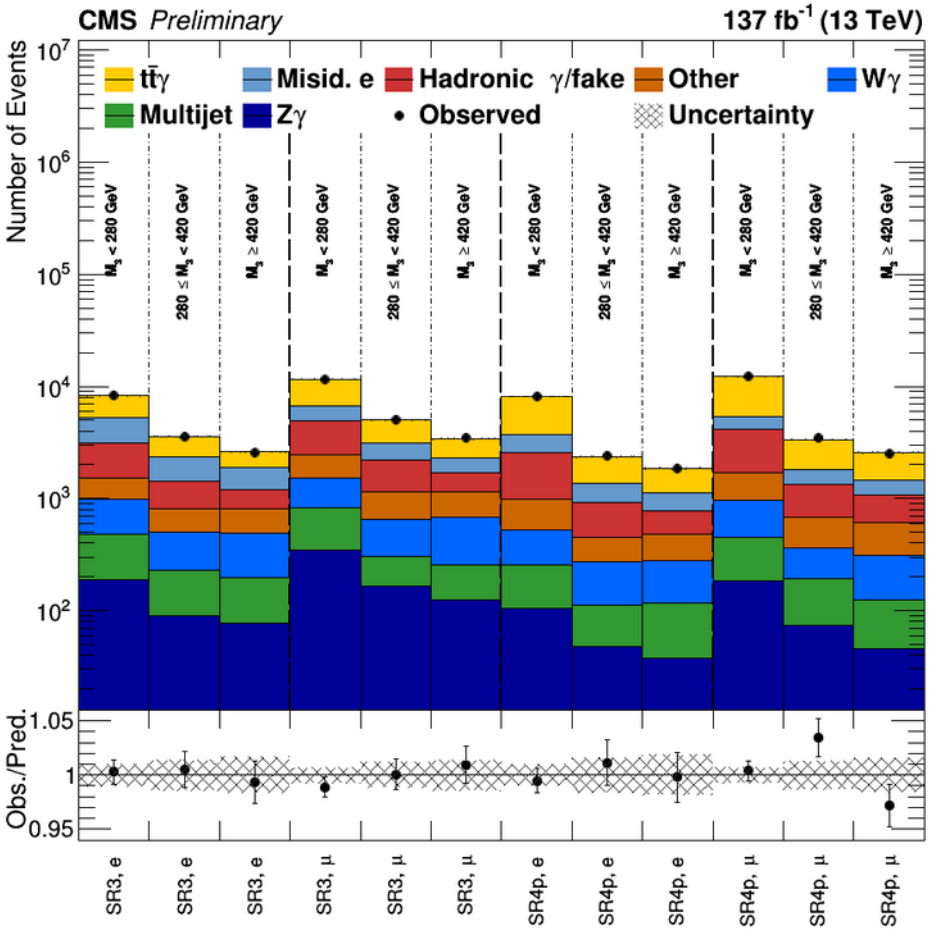
- ABCD method (Shower shape and isolation)

Nonprompt leptons from QCD multijet:

- Template from data (loosened lepton isolation)
- Normalization from measured transfer factor

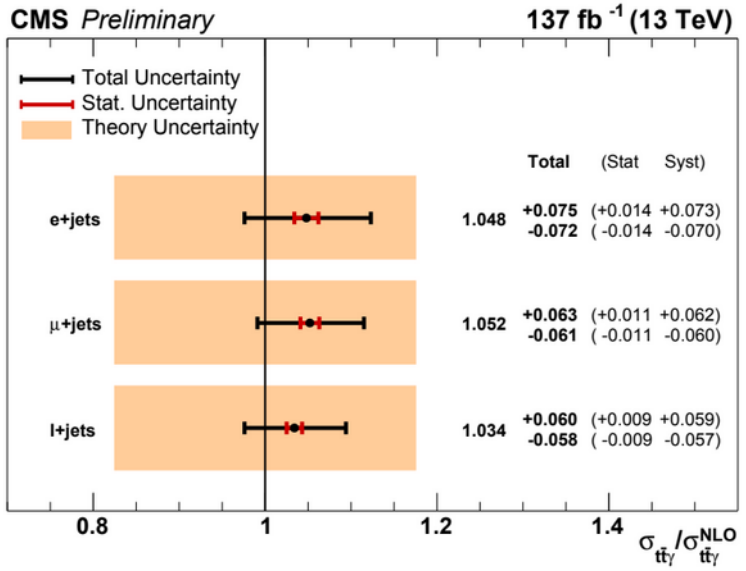
Simultaneous binned likelihood fit

- 12 signal regions
- 34 control regions



$t\bar{t}+\gamma$ – results

Inclusive



Extracted inclusive cross section:

$$\sigma_{\mathrm{tt}\gamma} = 800 \pm 46(\mathrm{syst}) \pm 7(\mathrm{stat})$$

5.8% uncertainty → more precise than theory!

- Background normalization
- ISR/FSR
- Jet energy scale

In agreement with SM predictions

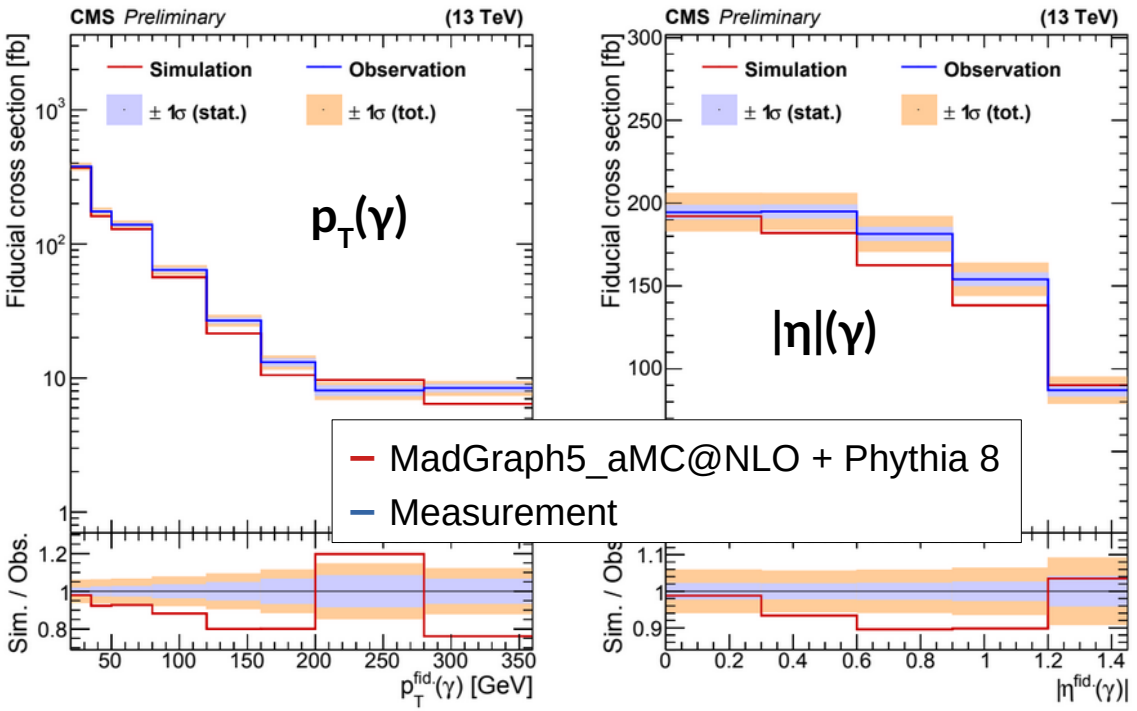
Differential

Fit repeated for each distribution

- $p_T(\gamma)$, $|\eta|(\gamma)$ and $\Delta R(l,\gamma)$

Unfolded to particle

- No regularization needed

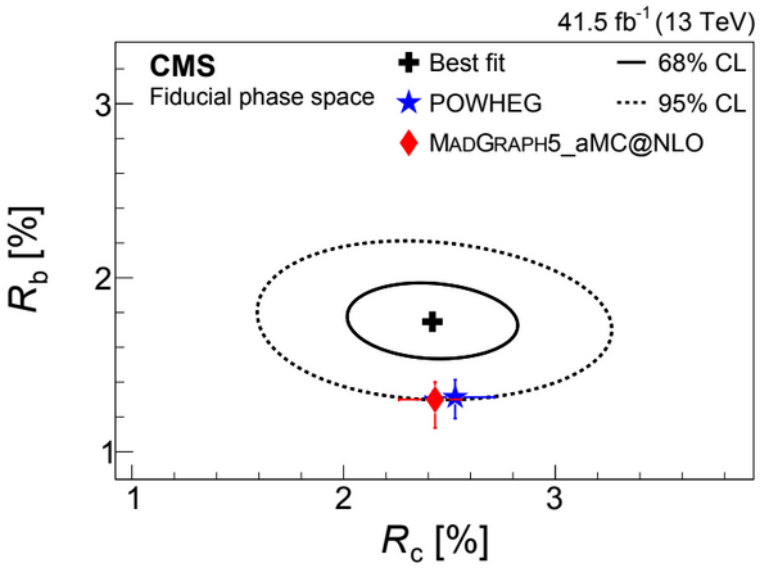


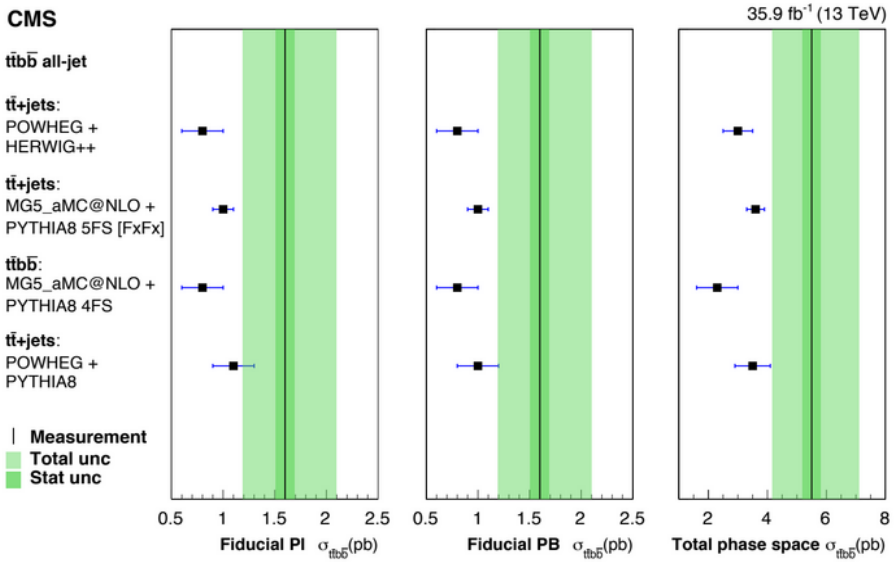
Summary

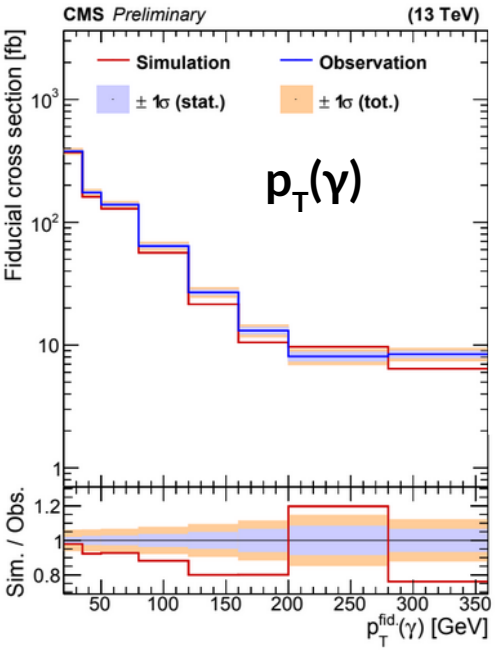
Presented most recent CMS results on $t\bar{t}$+X

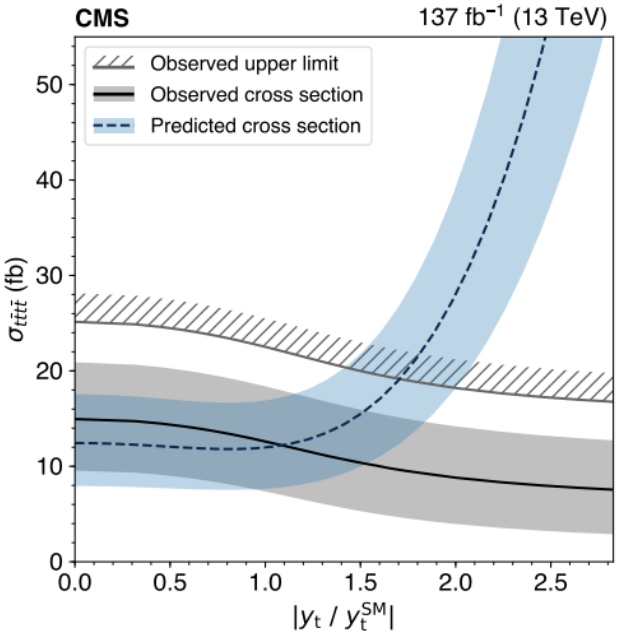
- Excess of $t\bar{t}+b\bar{b}$ measured in all channels
- First measurement of $t\bar{t}+c\bar{c}$
- Search for $t\bar{t}t\bar{t}$ production and study of its properties
- First CMS measurement of $t\bar{t}+\gamma$ at 13TeV

More to come soon!









Thanks !

$t\bar{t}+b\bar{b}$ in l+jets and dilepton final states

Lepton + jets

≥6 jets, ≥2 b jets

Assignment of additional jets

- Kinematic χ^2 fit

Dilepton

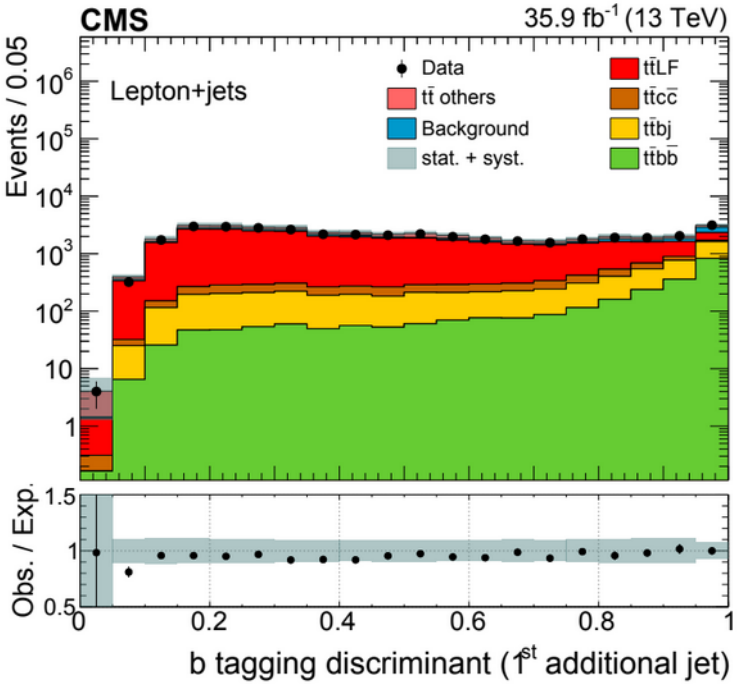
≥4 jets, ≥2 b jets

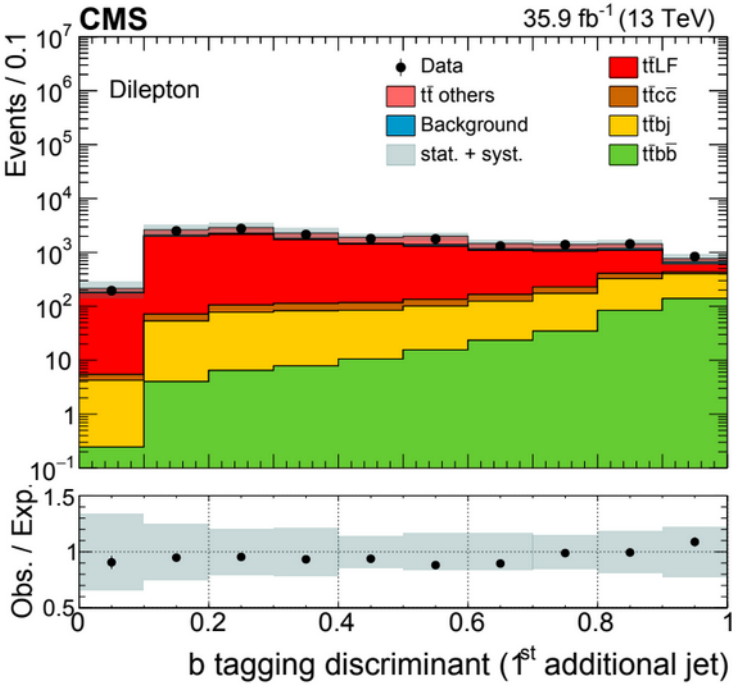
Assignment of additional jets

- Jets with 3rd and 4th highest b-tagging score

Measurement of σ_{ttbb}, σ_{ttjj} and $R_{ttbb/ttjj}$

Binned maximum likelihood fit on b-tagging discriminant of additional jets





$t\bar{t}+b\bar{b}$ in l+jets and dilepton final states

Lepton + jets

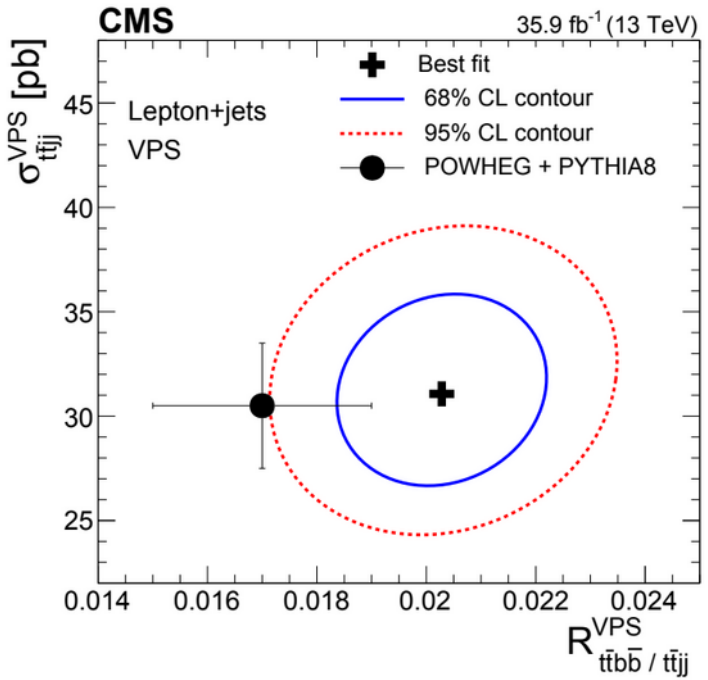
$$\sigma_{t\bar{t}b\bar{b}} = 4.7 \pm 0.2(\text{stat}) \pm 0.6(\text{syst})\ \text{pb}$$

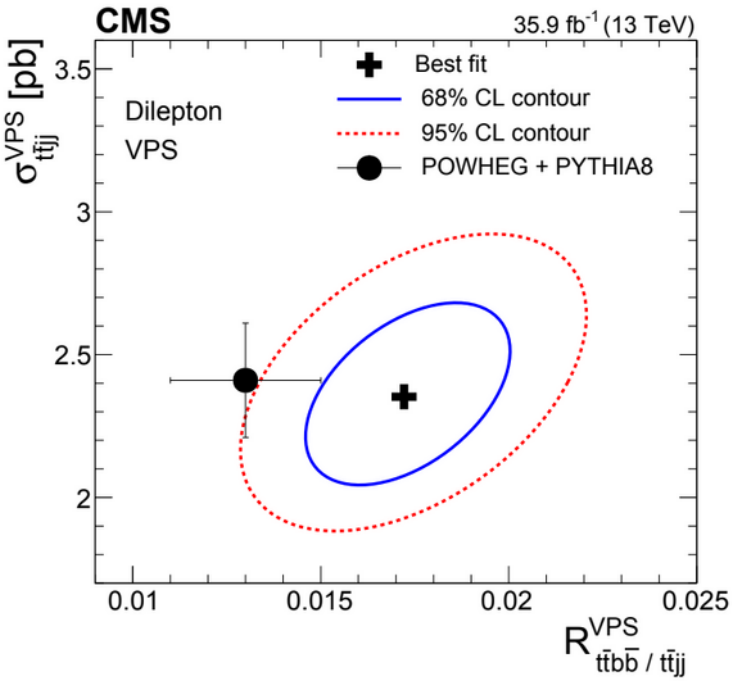
- Uncertainty of ~13%

Dilepton

$$\sigma_{t\bar{t}b\bar{b}} = 2.9 \pm 0.1(\text{stat}) \pm 0.5(\text{syst})\ \text{pb}$$

- Uncertainty of ~18%





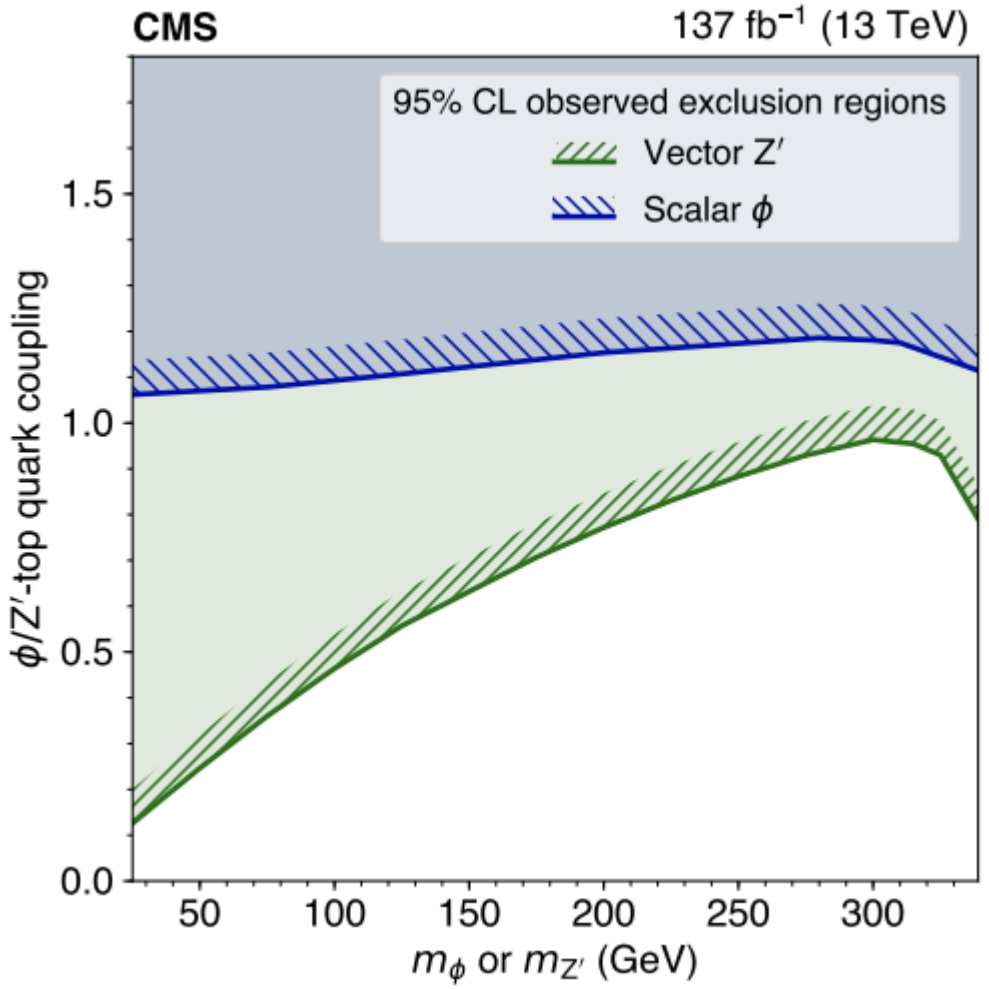
Again trend towards higher $t\bar{t}+b\bar{b}$ cross section measured

Dominant uncertainties

- Final state radiation, b-tagging, jet energy scale

Eur. Phys. J. C (2020) 80:75

tttt – neutral scalar (ϕ) and neutral vector (Z')



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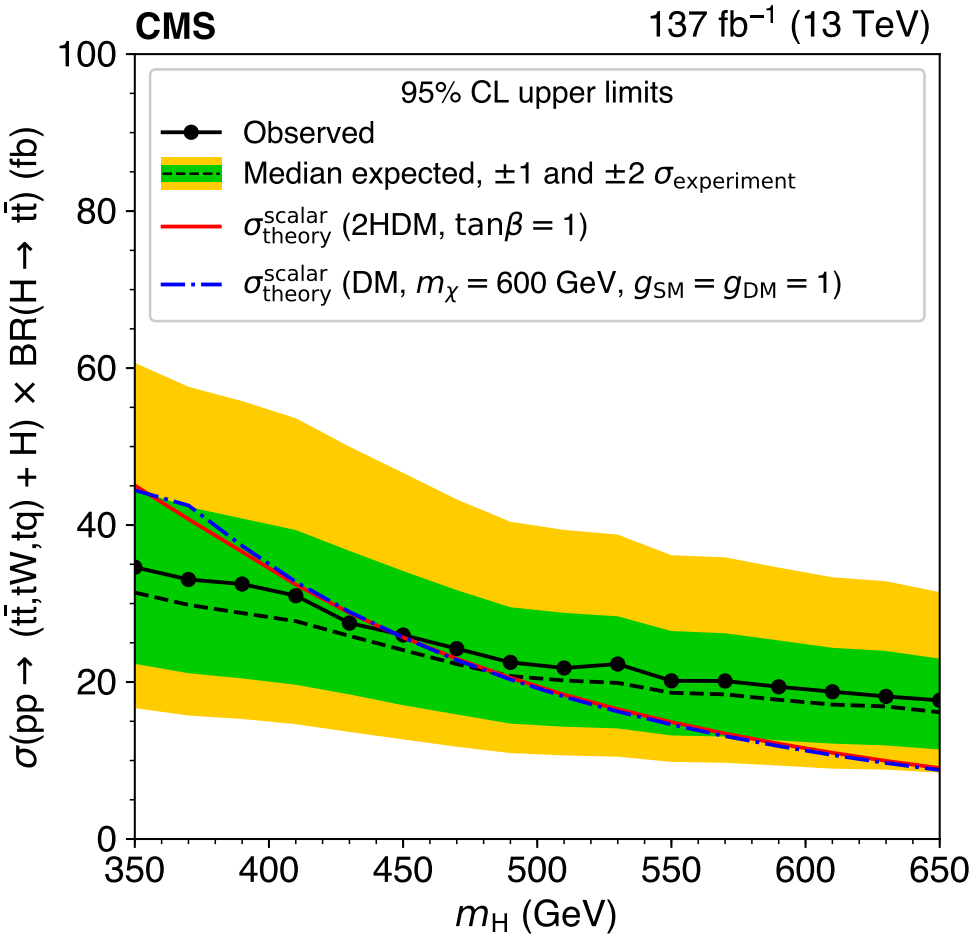
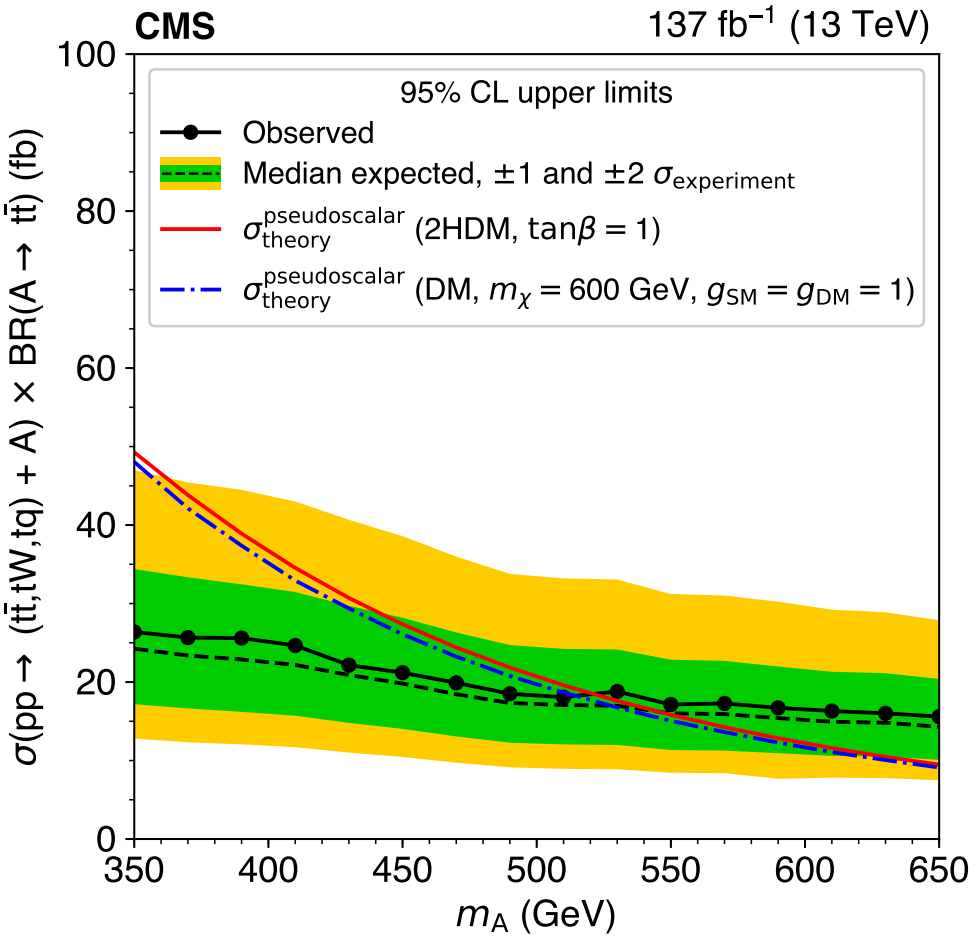
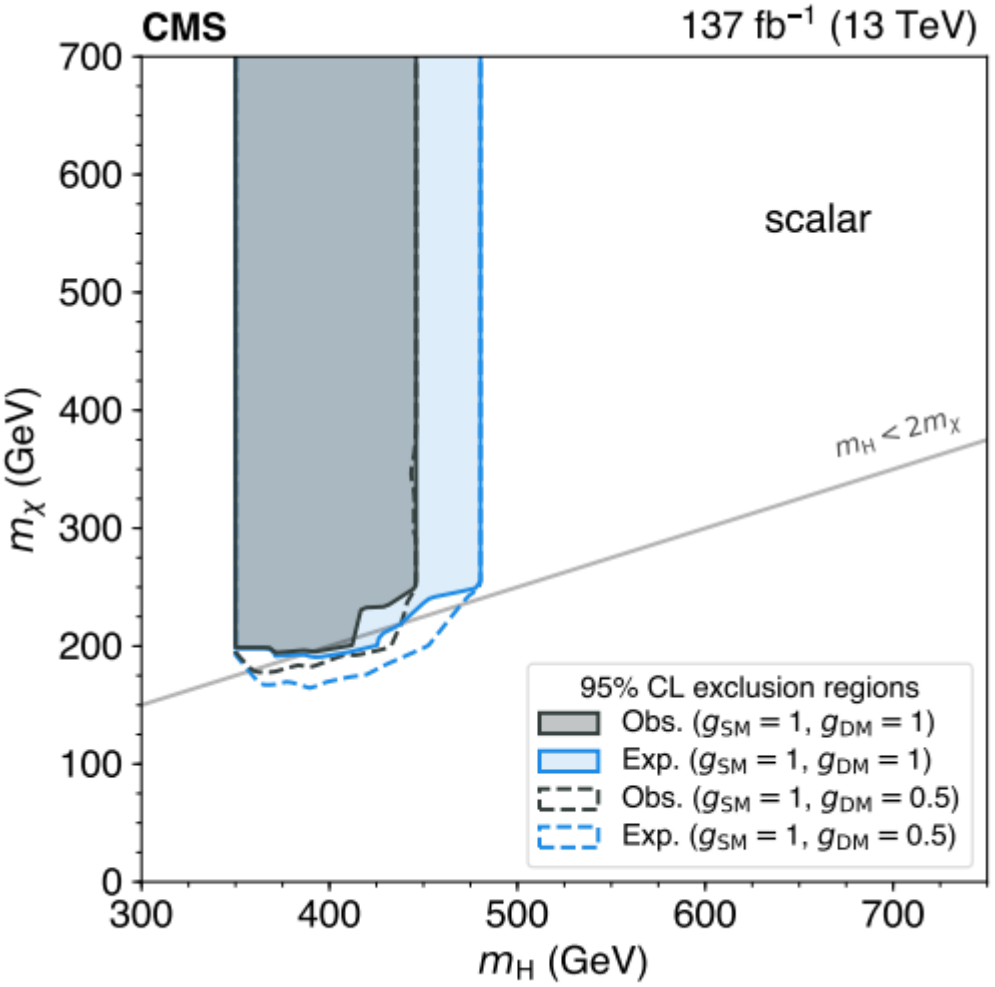
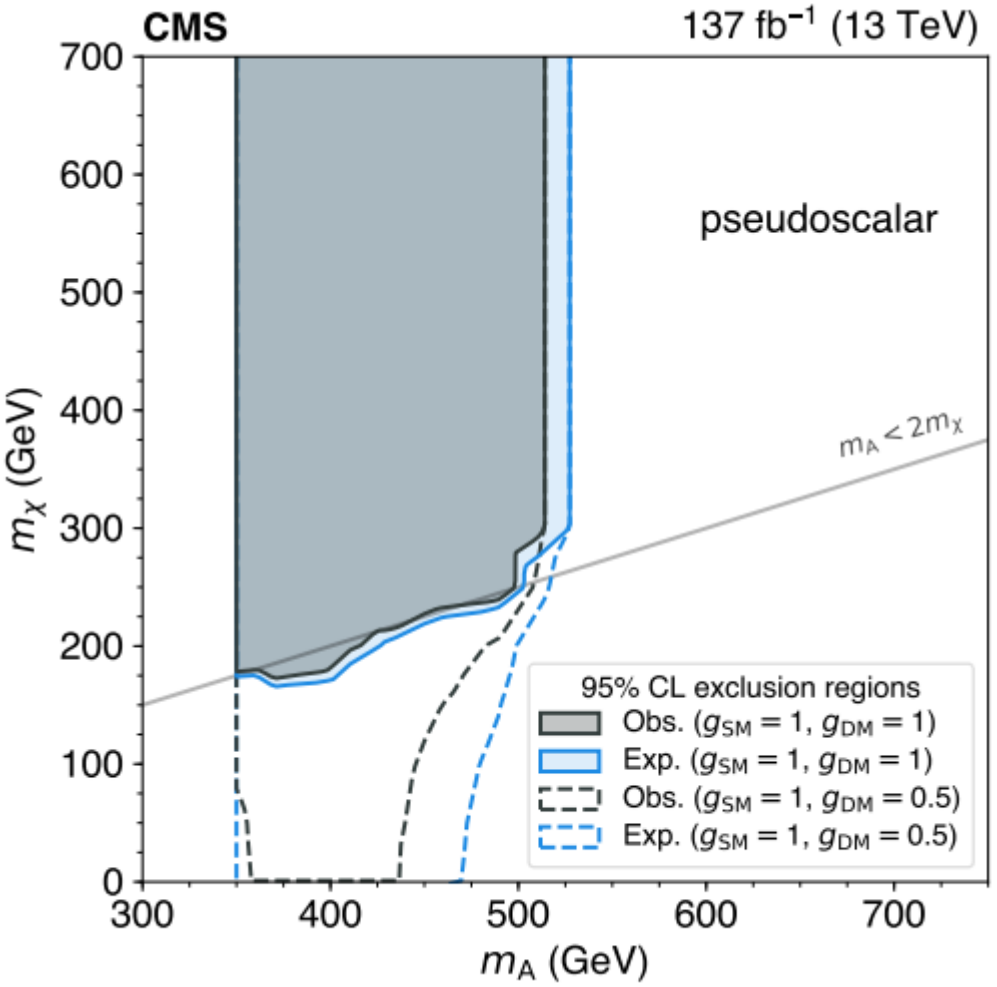
tttt – Heavy scalar (H) and pseudoscalar (A)





tttt – Dark matter model





tt+γ – response matrices