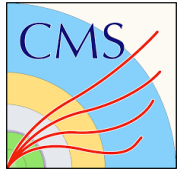
Recontres de Blois 2023

News from the Top at CMS

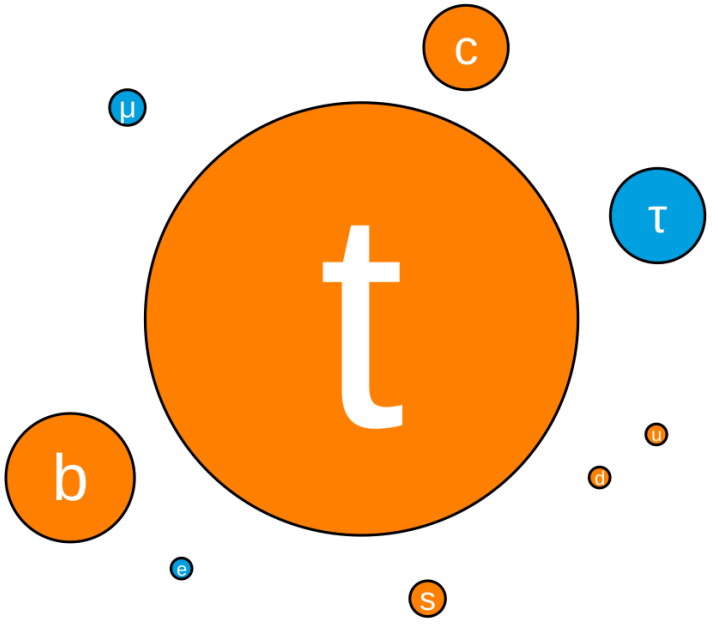
Laurids Jeppe on behalf of the CMS collaboration

16.05.2023 | laurids.jeppe@desy.de



The top quark and us

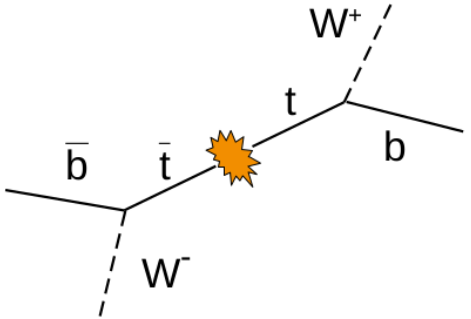
- Heaviest known elementary particle
  - Bare quark – decays before hadronizing
  - Largest Yukawa coupling to Higgs
  - Coloured particle – access to QCD parameters
- Gateway to new physics!
  - Couplings to new Higgs-like particles
  - Access to flavour-violating processes in production and decay



- **Understanding the top is crucial for SM and BSM physics!**

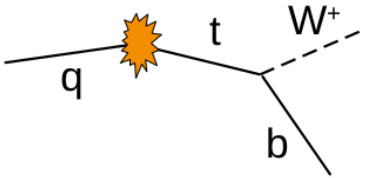
Top quark production at the LHC

- Top quarks are produced in many different configurations



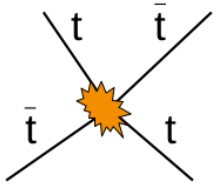
Top quark pairs ($t\bar{t}$)

σ ~ 800 pb



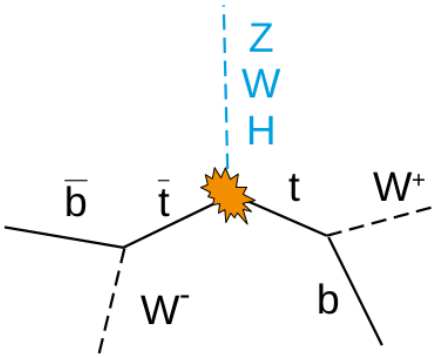
Single top production

σ ~ 300 pb



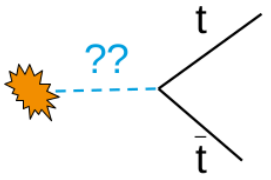
Rare SM processes

σ ~ 0.01 pb



Associated top production

σ ~ 0.1 pb



BSM top processes?

Overview of recent CMS results

- Top quarks are produced in many different configurations

- Differential $t\bar{t}b\bar{b}$ measurement
- First $t\bar{t}$ cross section at 13.6 TeV

Top quark pairs ($t\bar{t}$)

σ ~ 800 pb

- Four top production

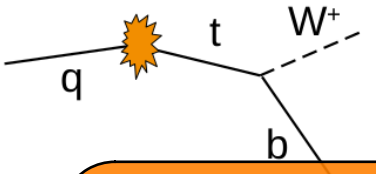
Rare SM processes

σ ~ 0.01 pb

- EFT in multilepton $t\bar{t}$+X events

Associated top production

σ ~ 0.1 pb

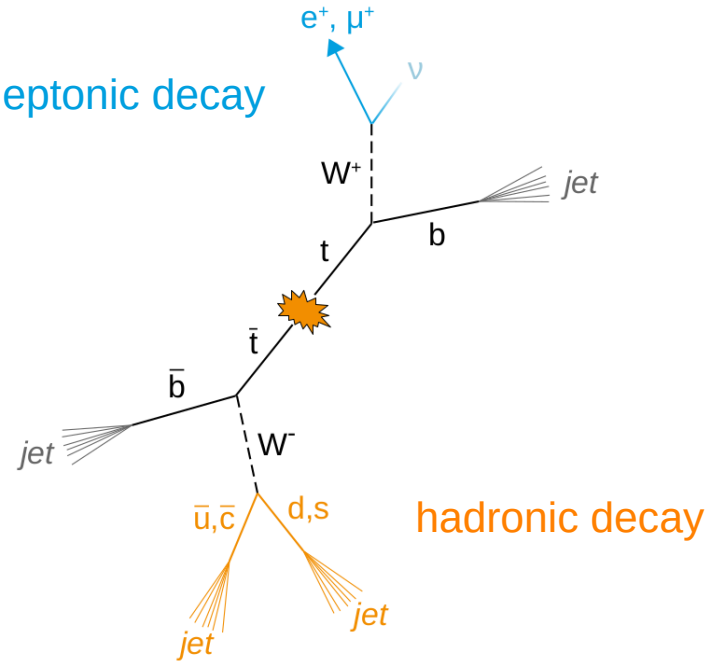


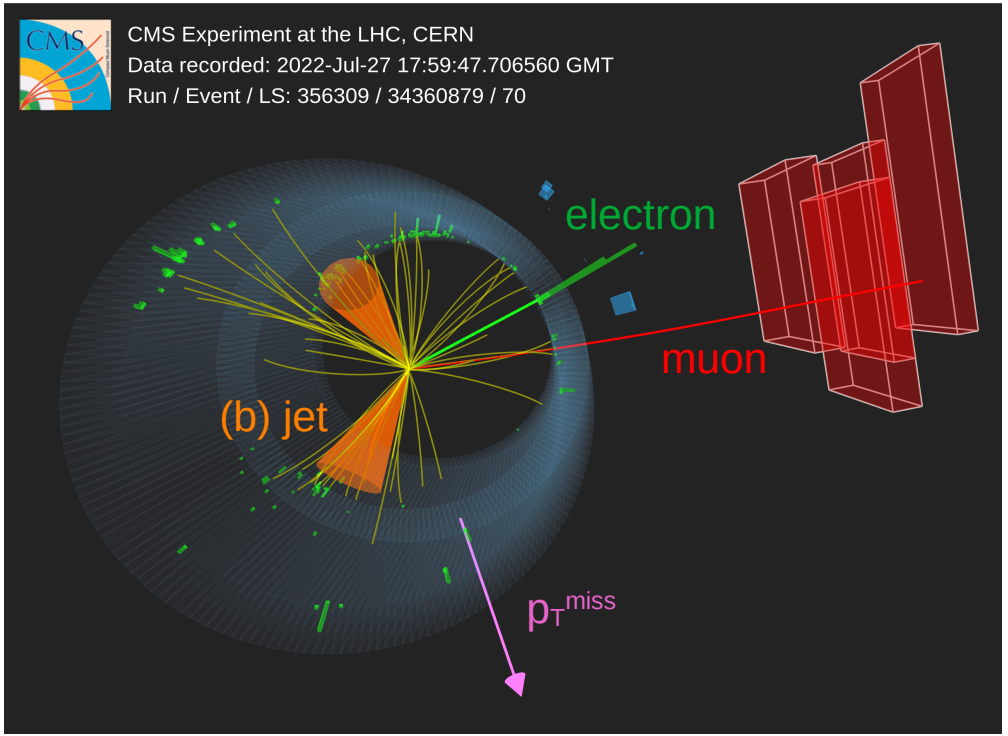
- Flavour-changing neutral currents
- Charged lepton flavour violation

BSM top processes?

Top quark decays

- Different decay channels give access to the full breadth of physics objects at CMS!



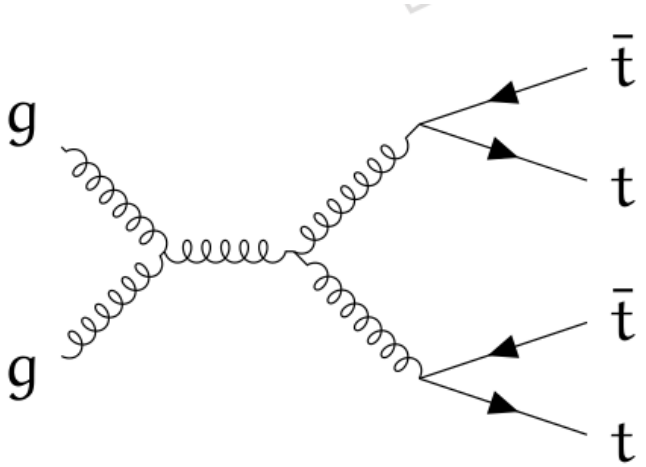


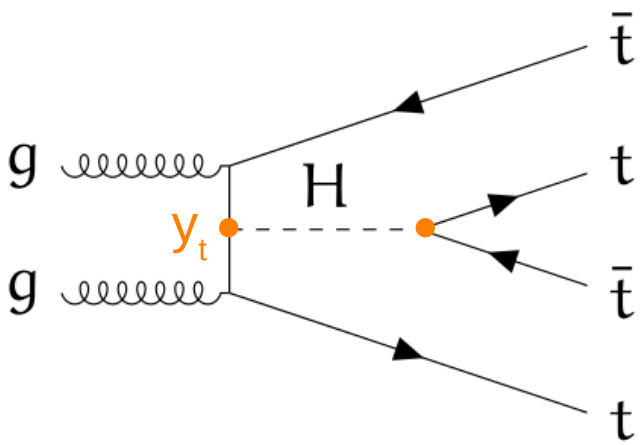
https://cds.cern.ch/record/2827339

[1] arXiv:2212.03259

Four top production

- Rare SM process: $\sigma_{\mathrm{SM}} = 13.4^{+1.0}_{-1.8}\,\mathrm{fb}$ at NLO+NLL [1]
- Direct access to crucial SM parameters, e.g. top Yukawa coupling…

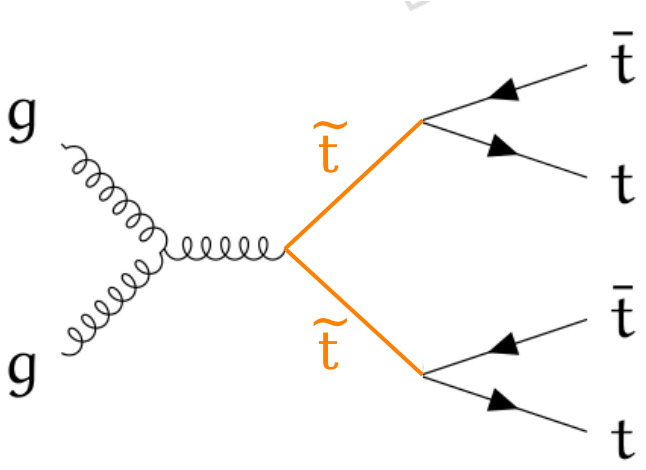


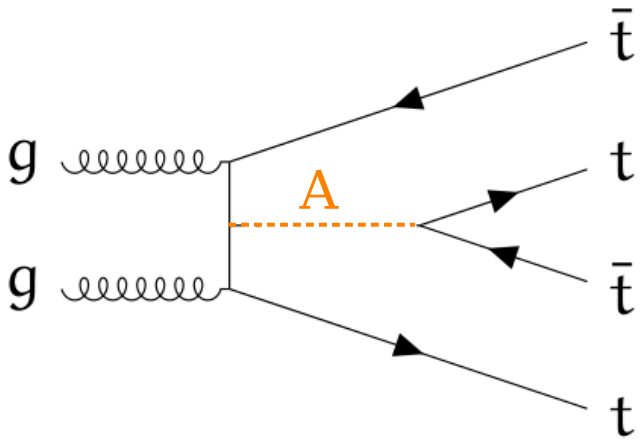


[1] arXiv:2212.03259

Four top production

- Rare SM process: $\sigma_{\mathrm{SM}} = 13.4^{+1.0}_{-1.8}\,\mathrm{fb}$ at NLO+NLL [1]
- Direct access to crucial SM parameters, e.g. top Yukawa coupling…
- … but also BSM, e.g. SUSY or additional Higgs bosons



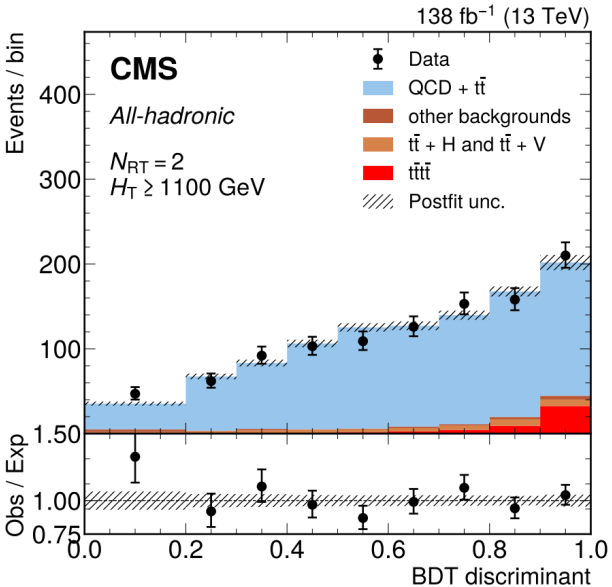


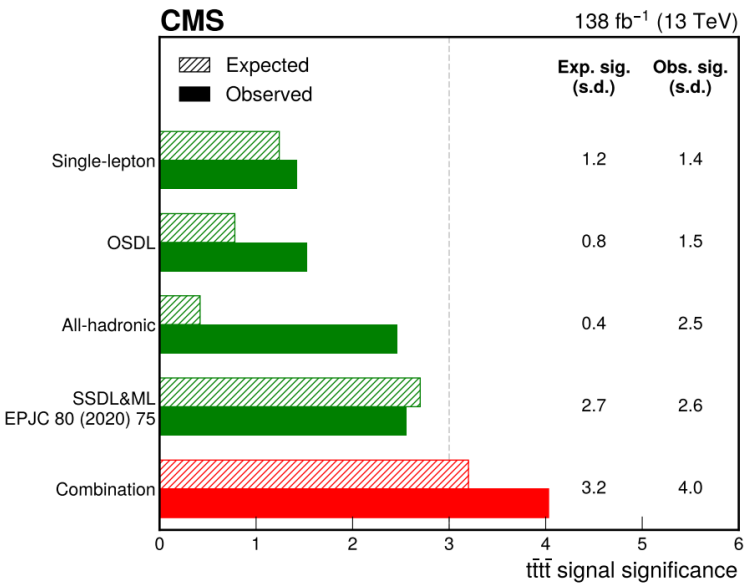
Four top production - ≤2ℓ

arXiv:2303.03864
submitted to PLB

- Measure in channels with ≤ 2 leptons
  - 2 leptons – opposite charge
  - 1 lepton
  - all-hadronic ← first measurement in this channel!

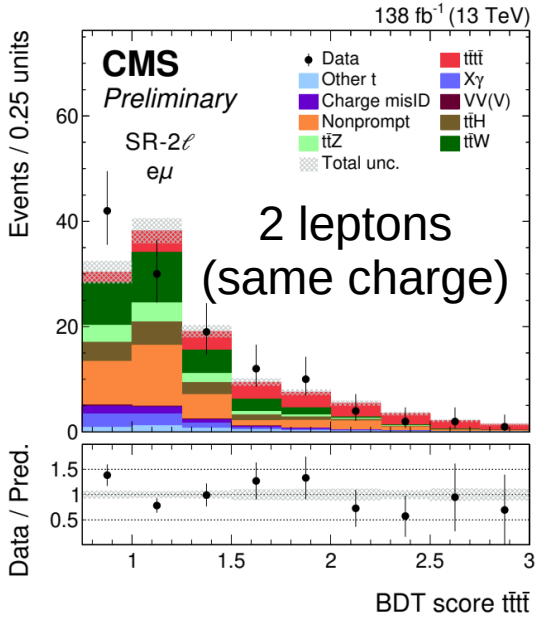
- Categorize in jet & b jet multiplicity
- All-hadronic channel: use Deep Neural Network (DNN) to predict QCD background

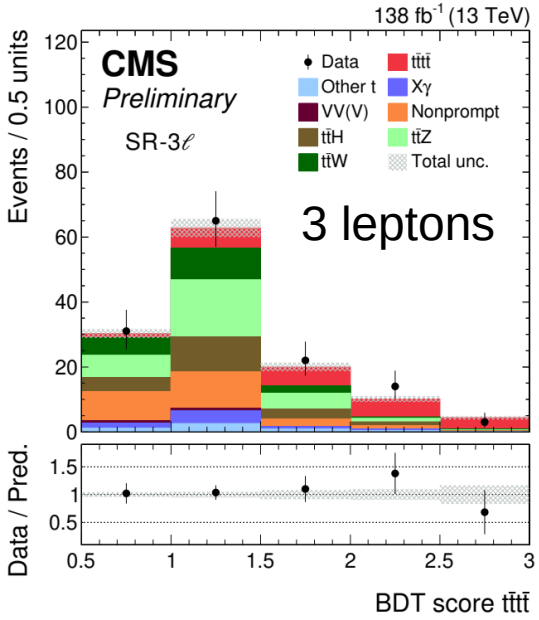


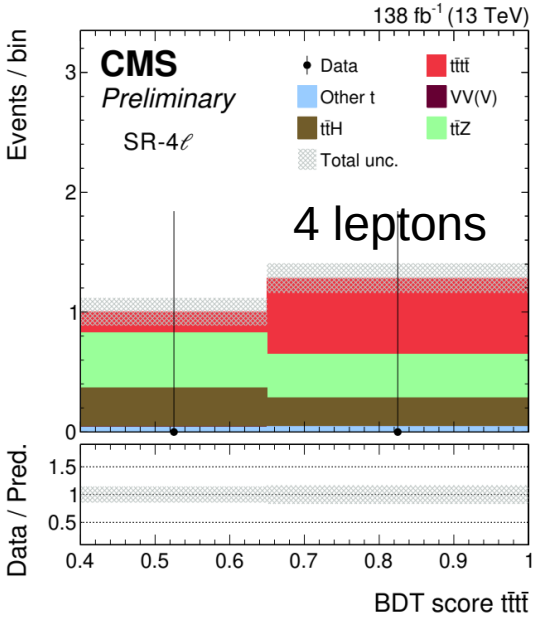


Four top production - multilepton

- Complementary measurement with multilepton final states
  - Channels split by number of leptons
  - Number of jets / b-jets → 3 Signal regions + 5 control regions to constrain backgrounds
  - Use Boosted Decision Tree (BDT) to further separate signal and background

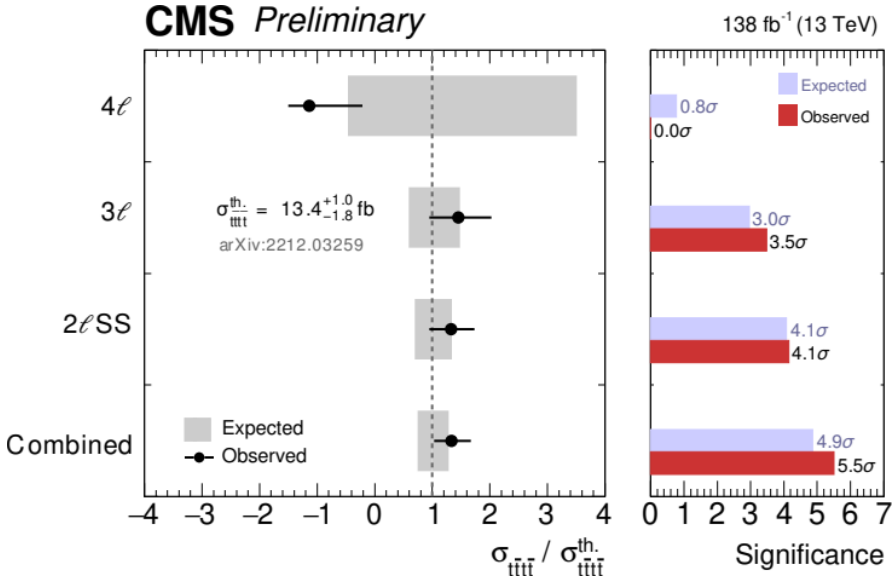


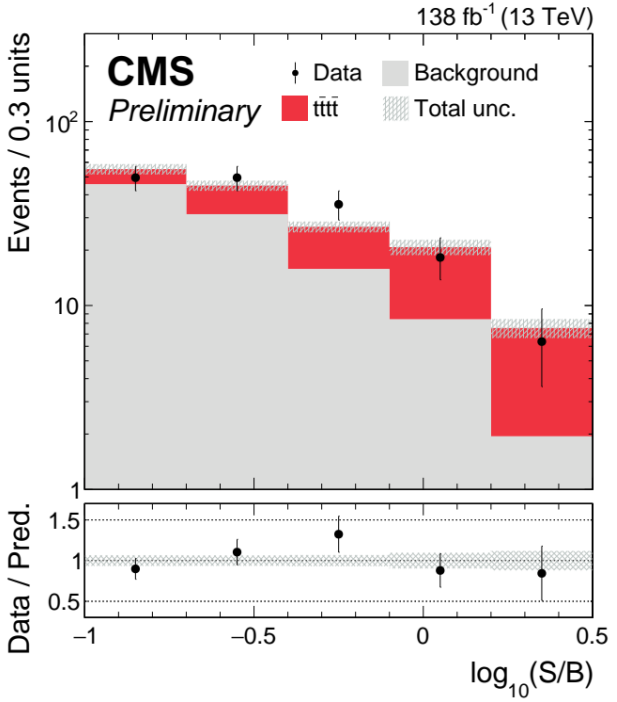




Four top production - observation

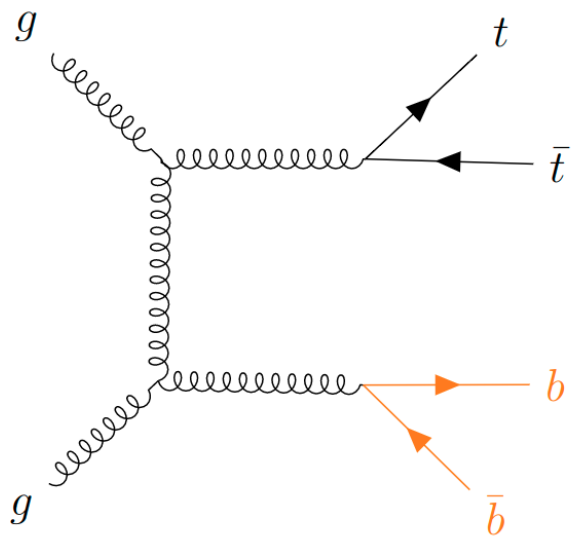
- Cross section result: $\sigma = 17.9^{+3.7}_{-3.5}\,(\mathrm{stat})\,^{+2.4}_{-2.1}\,(\mathrm{syst})\,\mathrm{fb}$
- 5 s.d. over background-only hypothesis – observation of four top production!
- Compatible with $\sigma_{\mathrm{SM}} = 13.4^{+1.0}_{-1.8}\,\mathrm{fb}$ within 1 s.d.





Associated $t\bar{t}b\bar{b}$ production

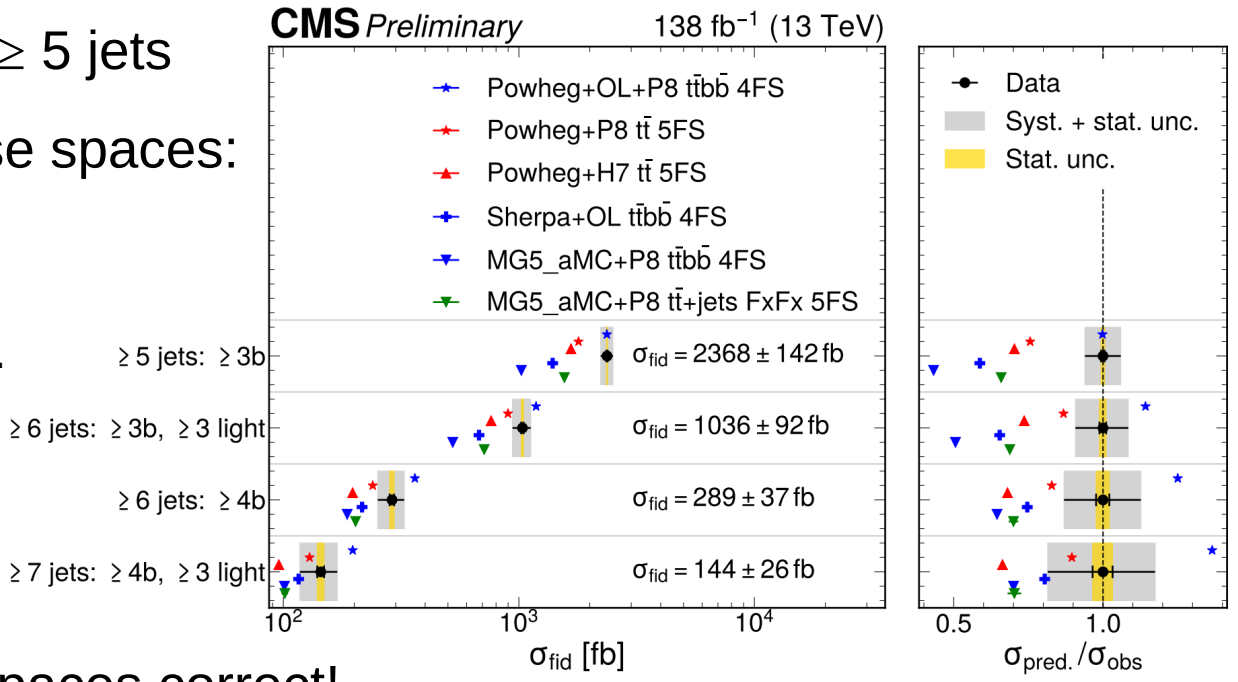
- Important process for deeper understanding of QCD
- Notoriously hard to model correctly → large uncertainties
  - Problem: non-negligible b mass << top mass
- Significant background for many measurements:
  - Irreducible background for $t\bar{t}H(H\rightarrow b\bar{b})$, also in four top production
- Measure inclusive and differential cross sections
- Compare to state-of-the-art predictions at NLO



Inclusive $t\bar{t}b\bar{b}$ cross sections

- Lepton+jets decay of $t\bar{t} \rightarrow 1\ell$, ≥ 5 jets
- Measure in four different phase spaces:
  - ≥5 jets, ≥3 b → $t\bar{t}b$
  - ≥6 jets, ≥4 b → $t\bar{t}b\bar{b}$
  - ≥6 jets, ≥3 b, ≥3 light
  - ≥7 jets, ≥4 b, ≥3 light

  } add. jets

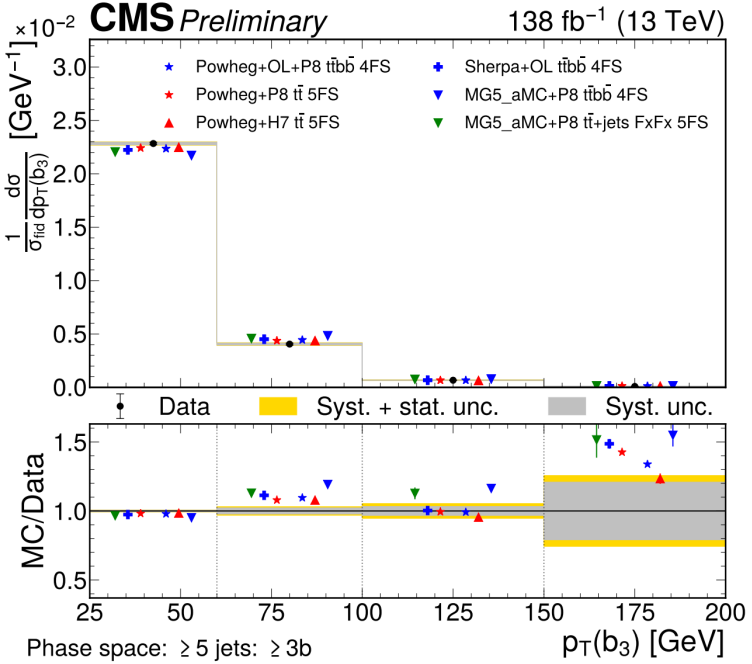


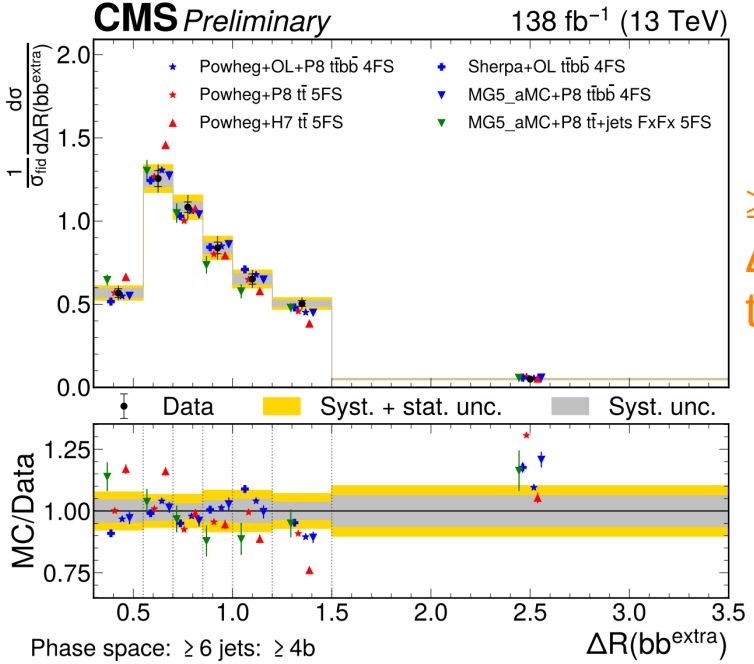
- Fiducial cross section:
  No prediction gets all phase spaces correct!
- ~6% precision in inclusive phase space
  – most precise $t\bar{t}b\bar{b}$ measurement so far!

Differential $t\bar{t}b\bar{b}$ cross sections

- Cross section measured as a function of many kinematic properties of the add. jets
  - DNN used to identify “additional” (not top-decay) b jets
- Unfolded to stable particle level using maximum likelihood fit

≥5 j, ≥3 b
p_T of the third b

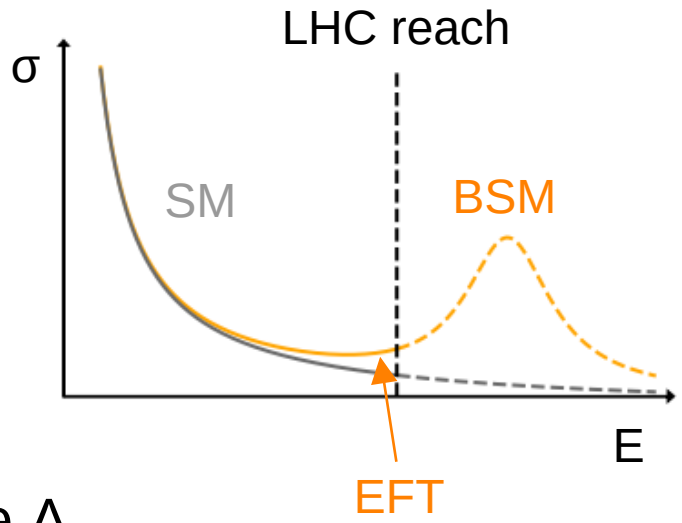




≥6 j, ≥4 b
ΔR between the add. bs

Effective Field Theory

- New physics might lie beyond the energies reachable by the LHC
  - ➔ Use indirect searches!
- Model-independent description: Effective Field Theory (EFT)
- SM ≈ lowest order of expansion in BSM scale Λ



$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + O(\Lambda^{-4})$$

All allowed dim-6 operators

- ➔ Measure Wilson coefficients c_i!

EFT in $t\bar{t}$+leptons

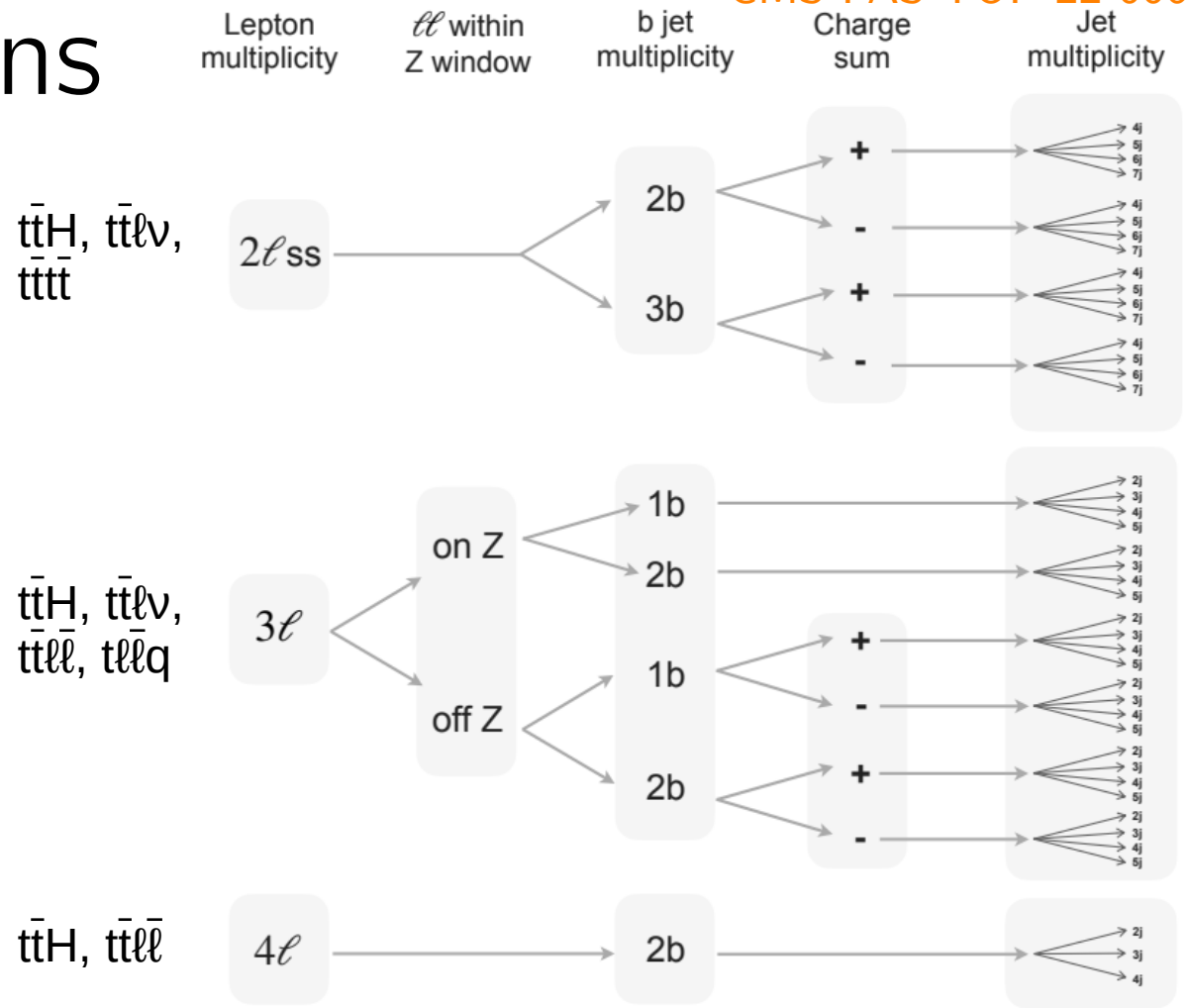
- Measure EFT operators in events with tt + additional leptons
- Regions with 2 same-sign, 3 and 4 leptons

Lepton multiplicity	
$t\bar{t}H$, $t\bar{t}\ell\nu$, $t\bar{t}t\bar{t}$	2ℓ ss
$t\bar{t}H$, $t\bar{t}\ell\nu$, $t\bar{t}\ell\bar{\ell}$, $t\ell\bar{\ell}q$	3ℓ
$t\bar{t}H$, $t\bar{t}\ell\bar{\ell}$	4ℓ

EFT in $t\bar{t}$+leptons

CMS-PAS-TOP-22-006

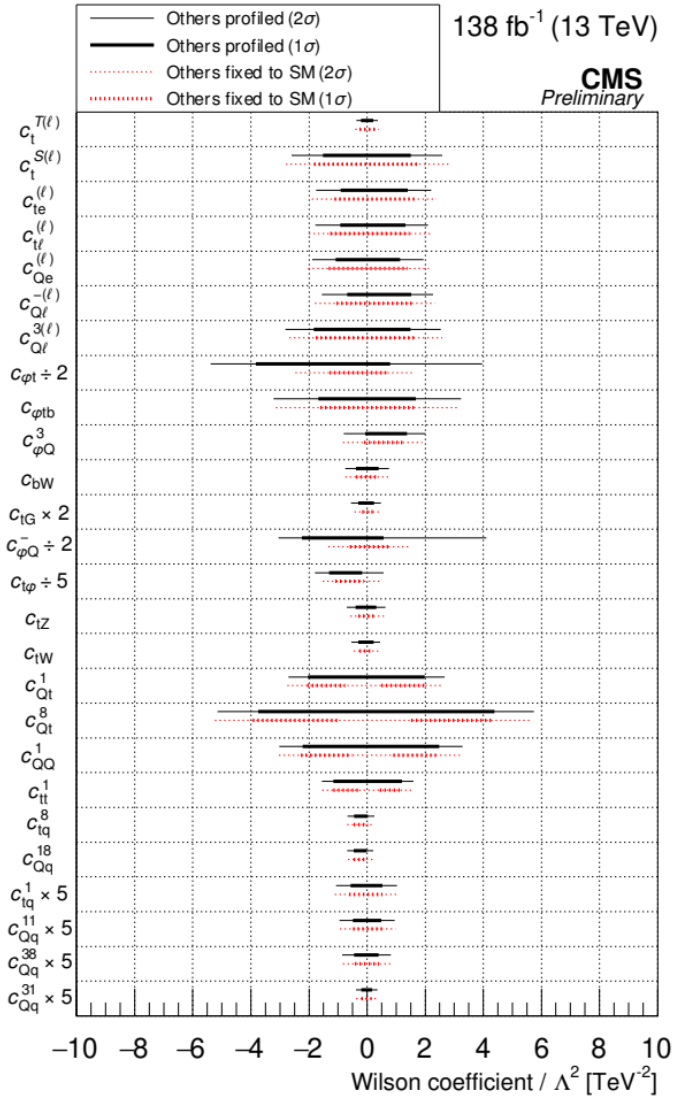
- Measure EFT operators in events with tt + additional leptons
- Regions with 2 same-sign, 3 and 4 leptons
- Further categorize by:
  - Presence of Z candidate
  - Number of b jets
  - Lepton charges
  - Number of jets



EFT in $t\bar{t}$+leptons

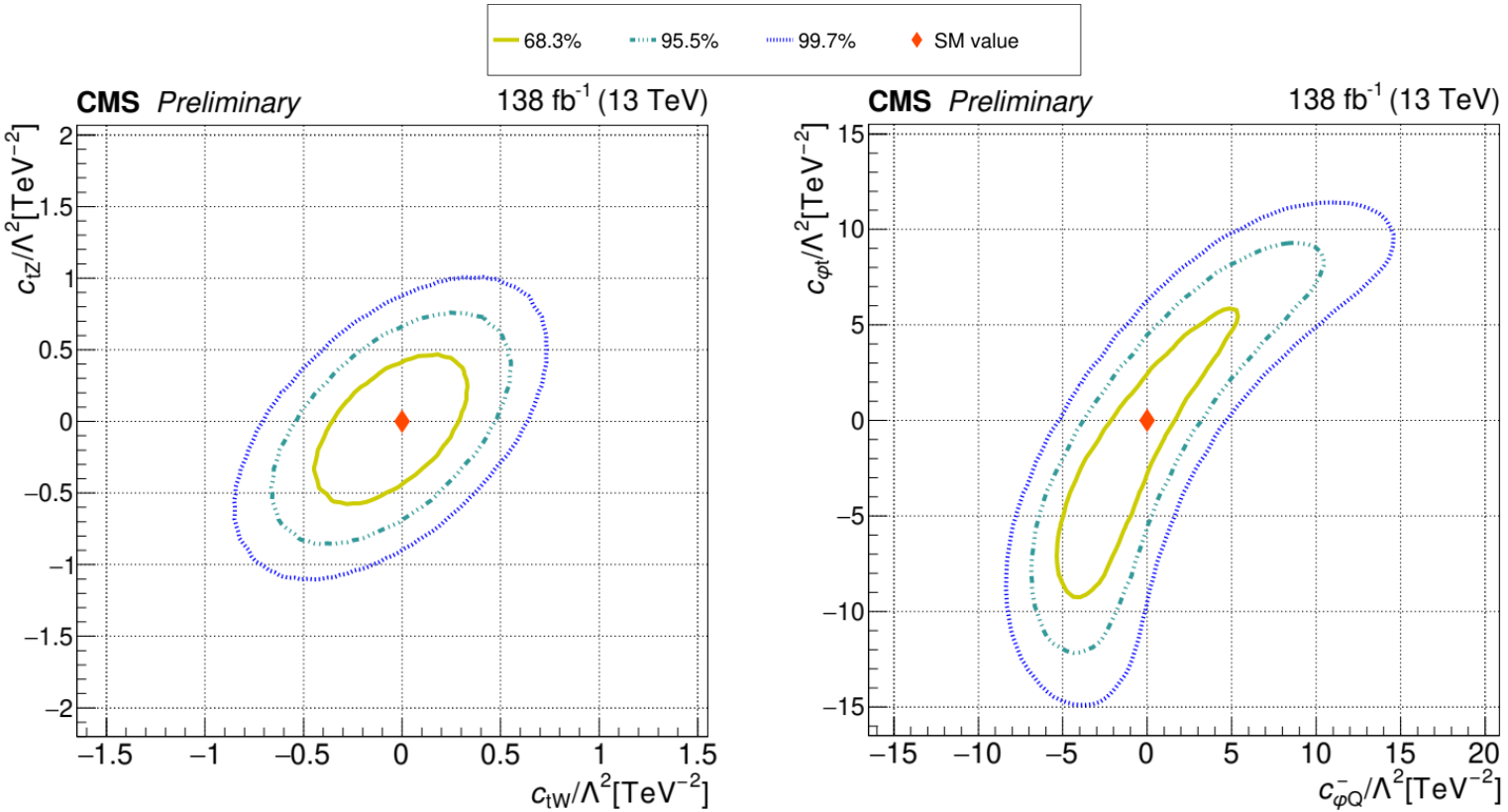
- Choose sensitive observable in each region
  - E.g. $p_T(\ell+\text{jet})$, $p_T(Z)$...
- Fit either only one coefficient (red) or all at the same time (black)
- No deviation from SM observed

- First comprehensive analysis of all 26 relevant operators with full Run 2 data!
- Improved limits w.r.t previous CMS result



EFT in $t\bar{t}$+leptons

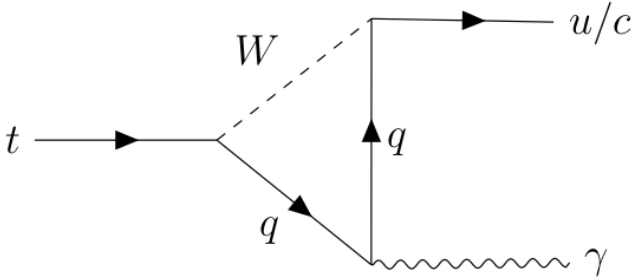
- Also derive 2D limits for different combinations of operators



FCNC in tqγ

- Flavour-changing neutral currents (FCNC) strongly suppressed for tops in the SM

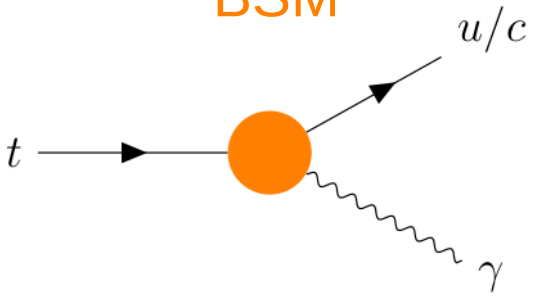
SM



$$\mathcal{B}(\mathrm{t} \to \mathrm{u/c} + \gamma) \approx 10^{-14}$$

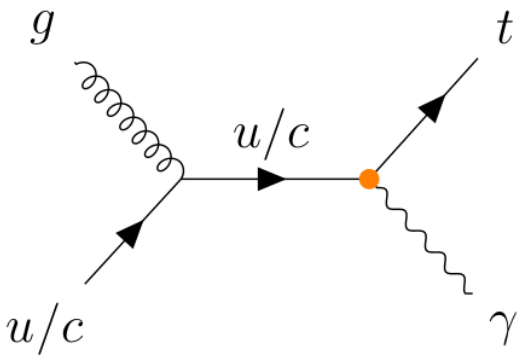
- Common BSM scenarios predict significant enhancement
  - e.g. 2HDM, R-parity violating SUSY
- Search for tqγ coupling using EFT approach

BSM

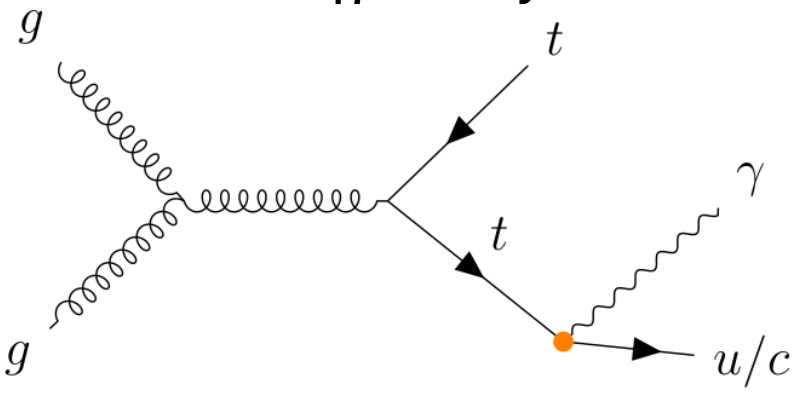


FCNC in tqγ - strategy

FCNC t+γ production



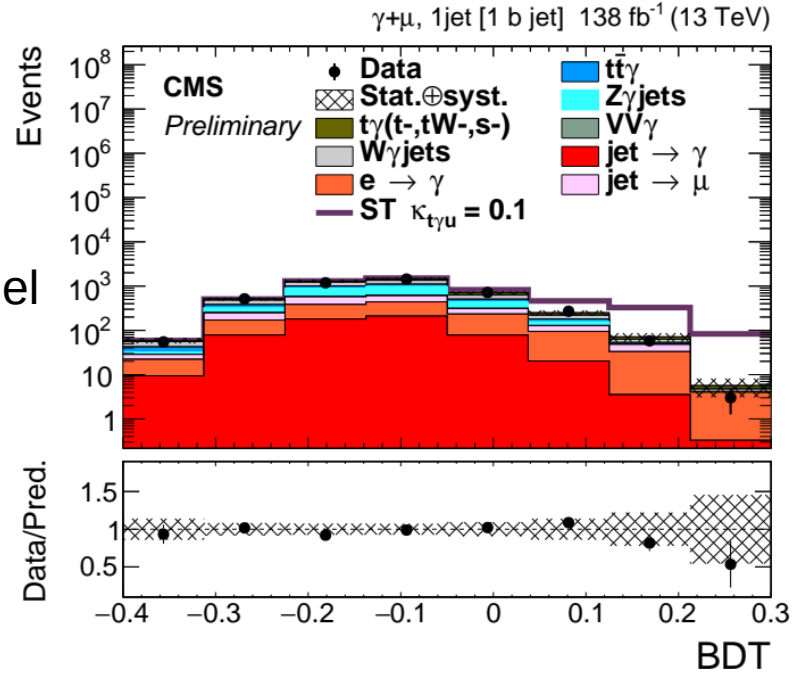
FCNC t→qγ decay in $t\bar{t}$



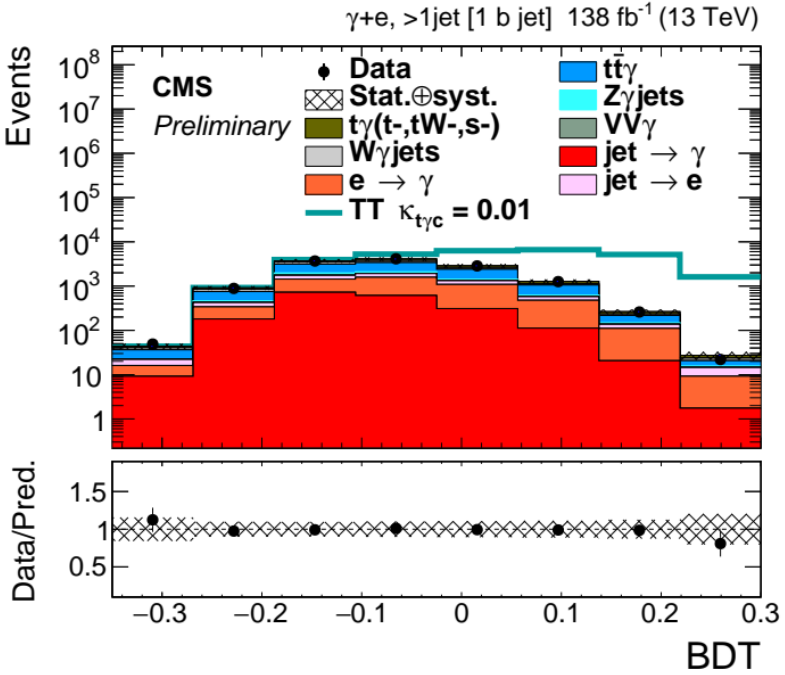
- Leptonic top decay → final state 1ℓ, p_T^{miss}, 1 photon
- Two signal regions: = 1 jet and ≥ 2 jets
- Use BDT to distinguish signal and background

FCNC in tqγ - results

u → tγ
e channel



$$\mathcal{B}(\mathrm{t} \to \mathrm{u} + \gamma) < 0.95 \times 10^{-5}$$
$$\kappa_{\mathrm{tu}\gamma} < 6.2 \times 10^{-3}$$



$$\mathcal{B}(\mathrm{t} \to \mathrm{c} + \gamma) < 1.51 \times 10^{-5}$$
$$\kappa_{\mathrm{tc}\gamma} < 7.7 \times 10^{-3}$$

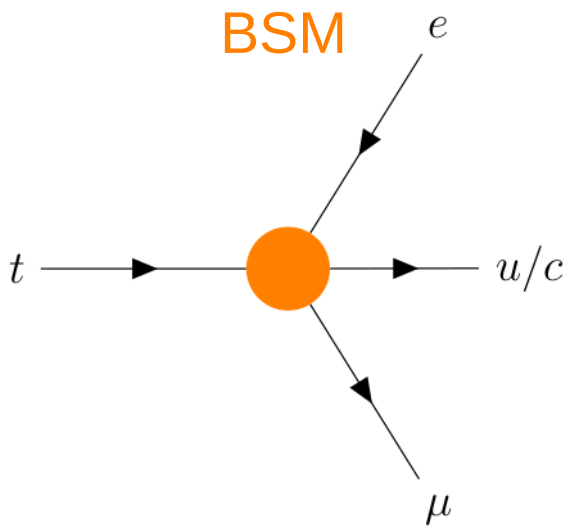
tt̄ → tc̄γ
μ channel

most stringent limit to date!

From neutral to charged currents

- Lepton flavour conservation is an accidental symmetry in the SM...
- … but: hints that it might be broken!
  - neutrino masses
  - flavour anomalies etc.

- Similar setup: model-independent search for tqeμ coupling
- Three operators considered: scalar-, vector-, tensor-like couplings

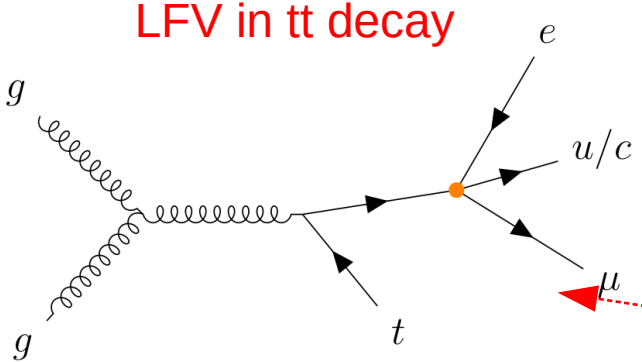


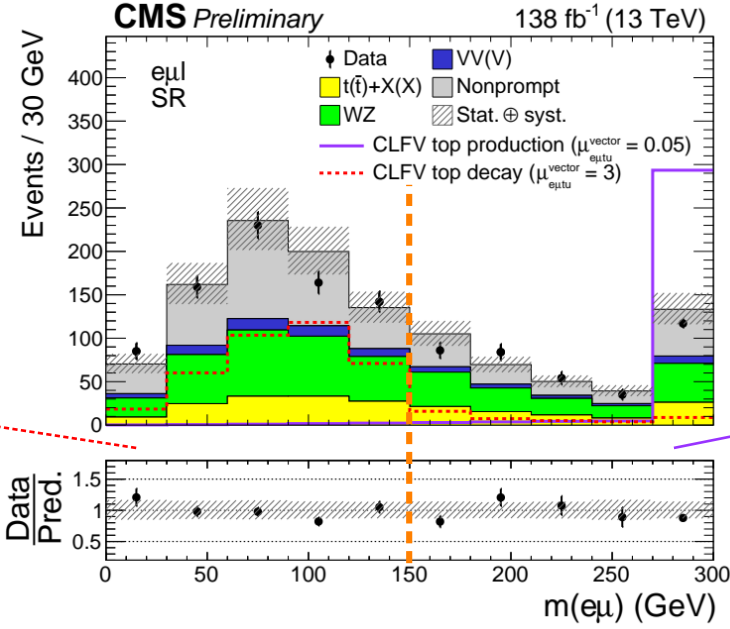
Charged LFV - strategy

- Leptonic top decay → final state: eμ + ℓ + ≥1 jet
- Use invariant eμ mass to define two signal regions

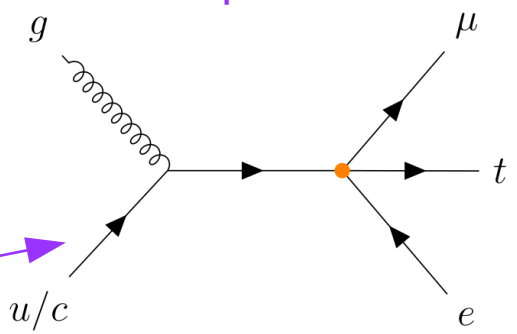
LFV SM top decay

LFV in $t\bar{t}$ decay



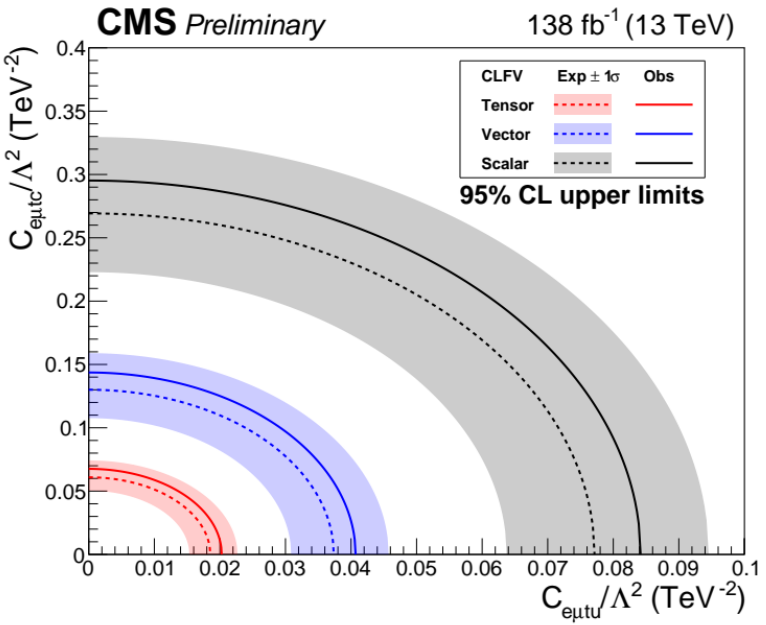


LFV in production

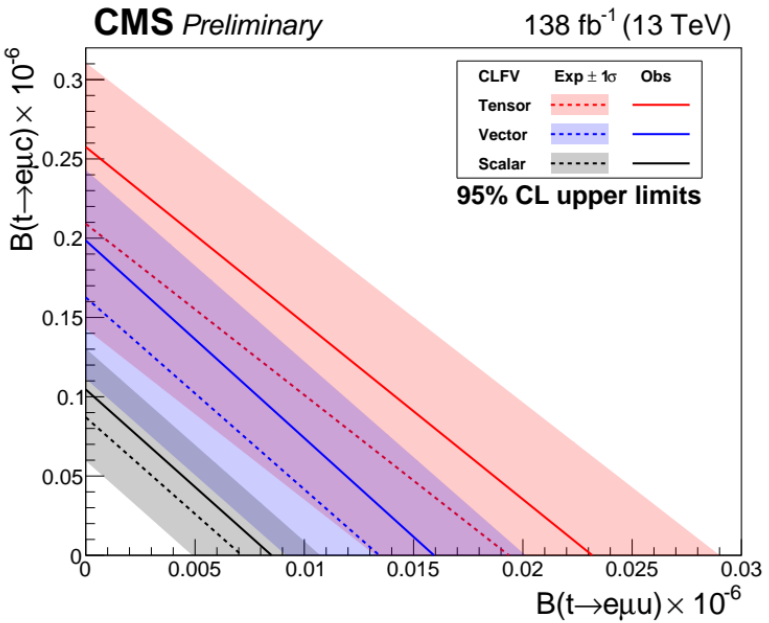


Charged LFV - results

- Use two BDTs in the two regions to enhance signal
- Set 2D limits on Wilson coefficients and branching ratios for u and c !



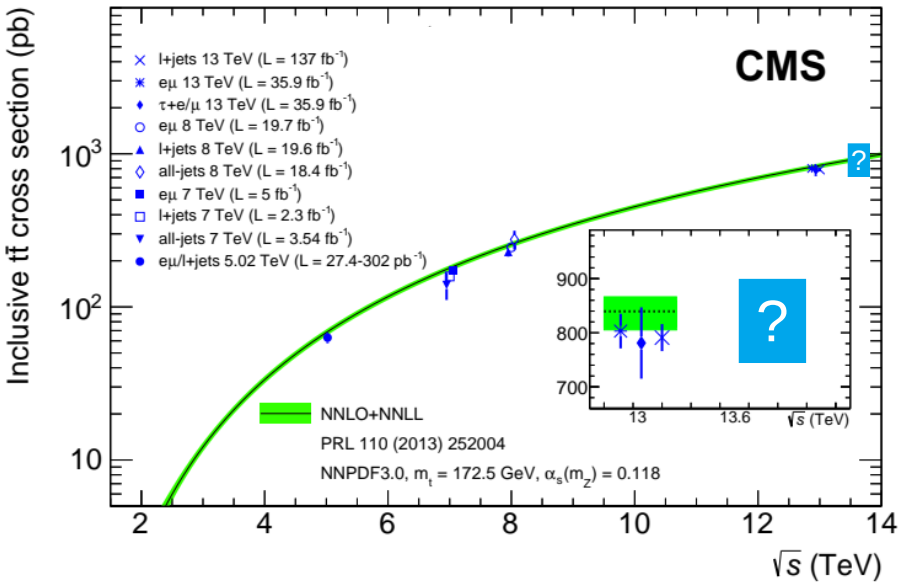
most stringent limits to date!



Towards the future: Run 3

arXiv:2303.10680
submitted to JHEP

- LHC Run 3 has started in July 2022
  - Additional statistics
  - Higher c.o.m energy – 13.6 TeV
- Good target for first measurement:
  inclusive $t\bar{t}$ cross section
  - Expected to rise by 10% from 13 to 13.6 TeV
- Early opportunity to…
  - Explore physics at the new energy frontier
  - Check CMS performance in Run 3!

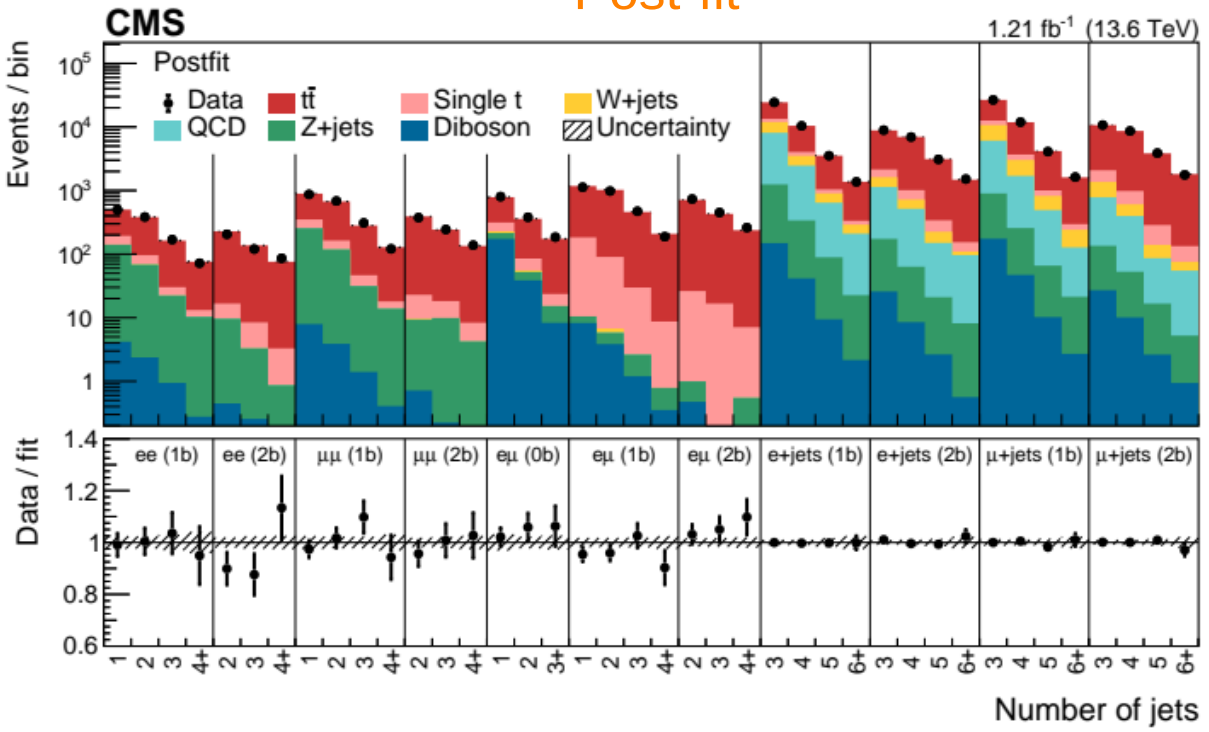


$t\bar{t}$ cross section at 13.6 TeV

arXiv:2303.10680
submitted to JHEP

- 1.21 fb^{-1} of luminosity
- Combine dilepton and lepton+jets channels
- Technique tailored to early data:
  - Fit in categories of lepton & b jet content
  - Constrain experimental nuisances in situ

Post-fit



Note: no b jet SF applied, no b tagging uncertainties

$t\bar{t}$ cross section at 13.6 TeV

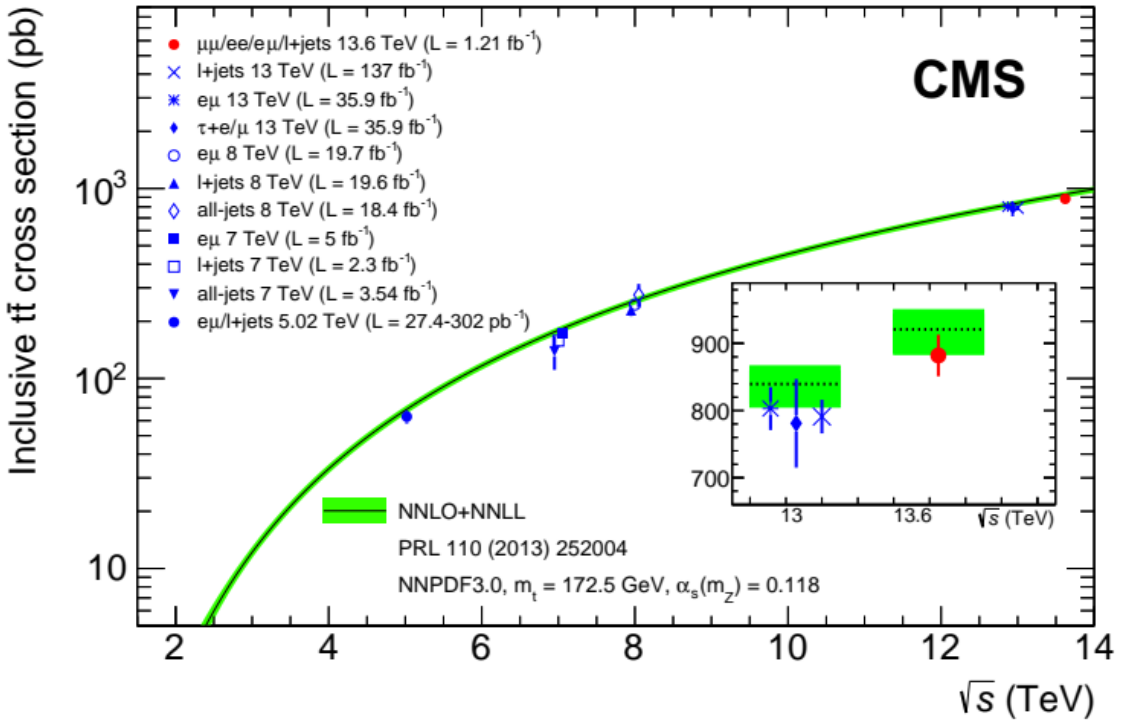
arXiv:2303.10680
submitted to JHEP

$$\sigma_{t\bar{t}} = 882 \pm 23(\text{stat} + \text{syst}) \pm 20(\text{lumi})\text{pb}$$

- ~ 3.5% total uncertainty!
- In agreement with theory:

$$\sigma_{t\bar{t}}^{\text{pred}} = 921^{+29}_{-37}\text{pb}$$

- First public physics result of the LHC in Run 3!



Summary & Outlook

- Top quarks are a key to both SM and BSM physics!
- Several new CMS results:
  - Observation of four top production
  - Most precise inclusive and differential $t\bar{t}b\bar{b}$ cross section measurement
  - Dedicated EFT, FCNC and LFV searches
  - First 13.6 TeV $t\bar{t}$ cross section measurement at the start of Run 3
- More results in the pipeline!
- Talk on top physics at ATLAS later this afternoon by Lucio Cerrito

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Backup