

# Probing the SM: Top quarks and beyond

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*LIP Lisbon*

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- ✓ Top quarks as window to New Physics
- ✓ Top-Higgs associated production
- ✓ Top quark signatures in SUSY
- ✓ Top and Dark Matter



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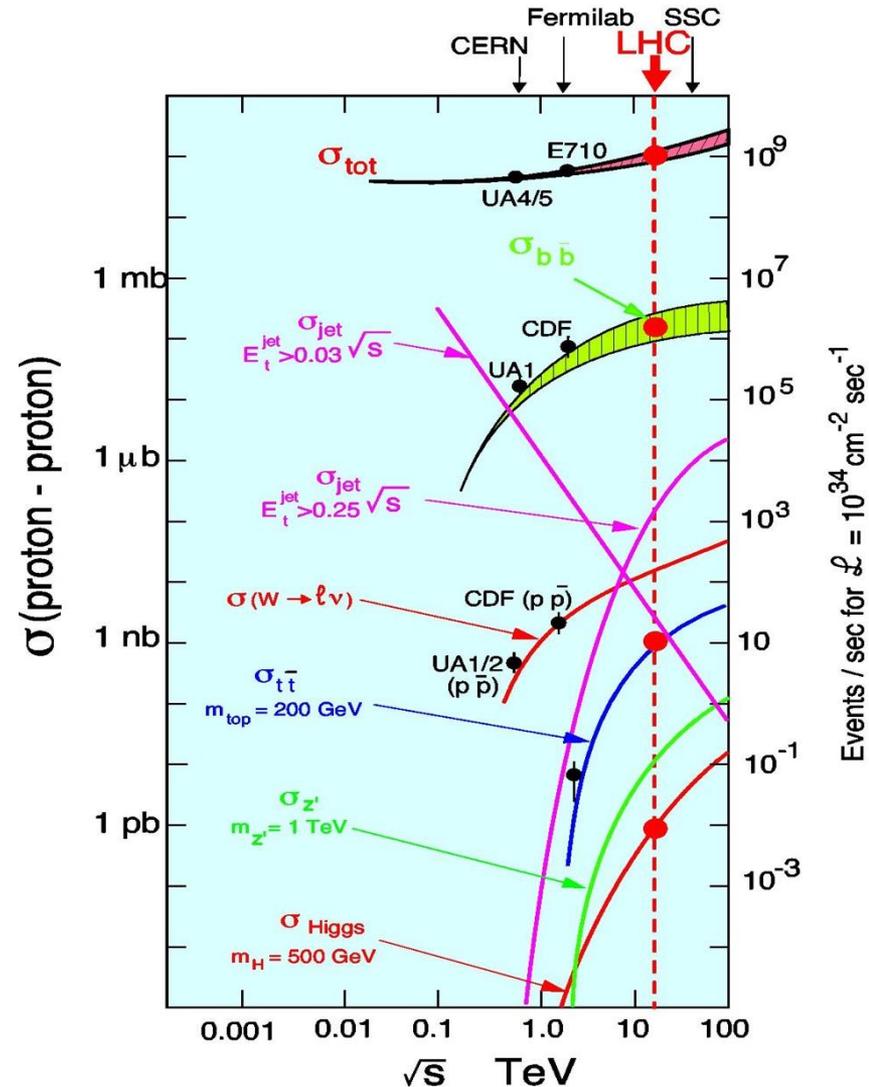


**FCT**

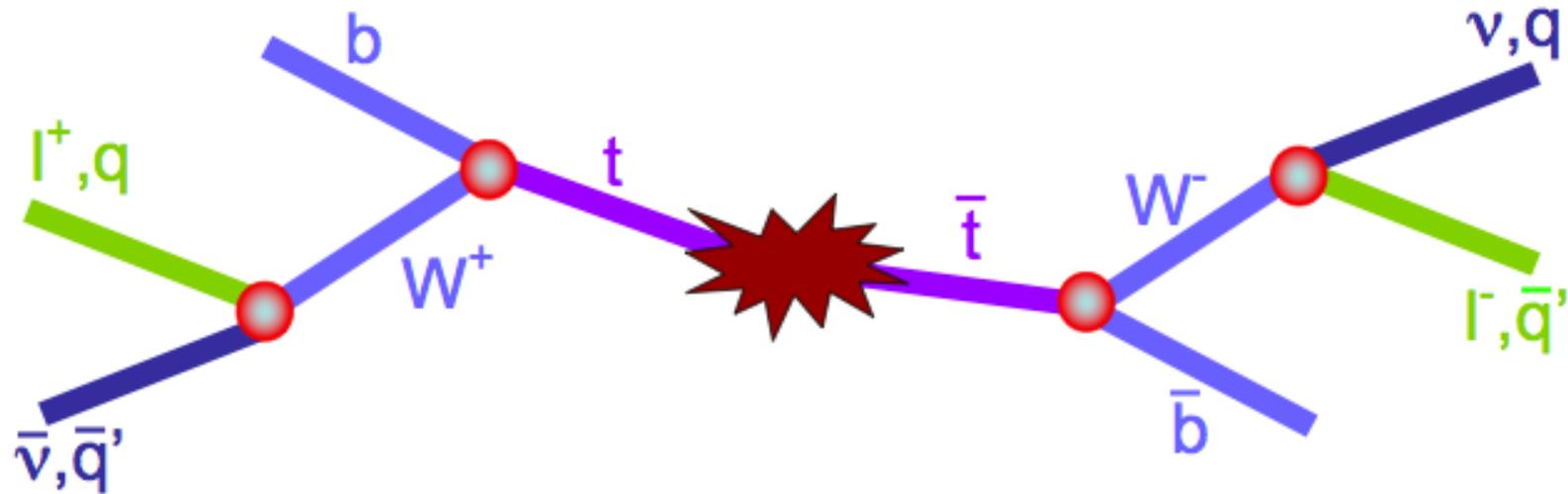
Fundação para a Ciência e a Tecnologia  
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# Top cross section at 7/8 vs 13 TeV

- LHC collisions started at 7/8 TeV
- LHC design is at 14 TeV
- Top cross section drops faster than background processes at lower  $\sqrt{s}$ 
  - top  $\sigma(7\text{TeV}) = 172 \text{ pb}$
  - top  $\sigma(8\text{TeV}) = 246 \text{ pb}$
  - top  $\sigma(13\text{TeV}) = 832 \text{ pb}$
- Background is more “flat”



# Interesting physics with Top quark



## PRODUCTION

Cross section  
Resonances  $X \rightarrow tt$   
Fourth generation  $t'$   
Spin-correlations  
New physics (SUSY)  
Flavour physics (FCNC)

...

## PROPERTIES

Mass  
Kinematics  
Charge  
Lifetime and width  
W helicity  
Spin

...

## DECAY

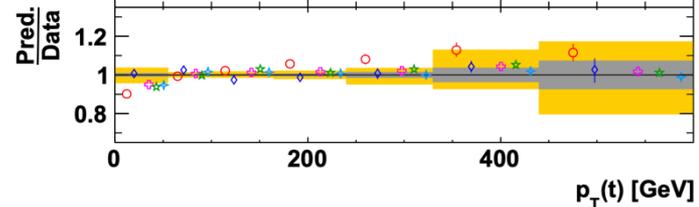
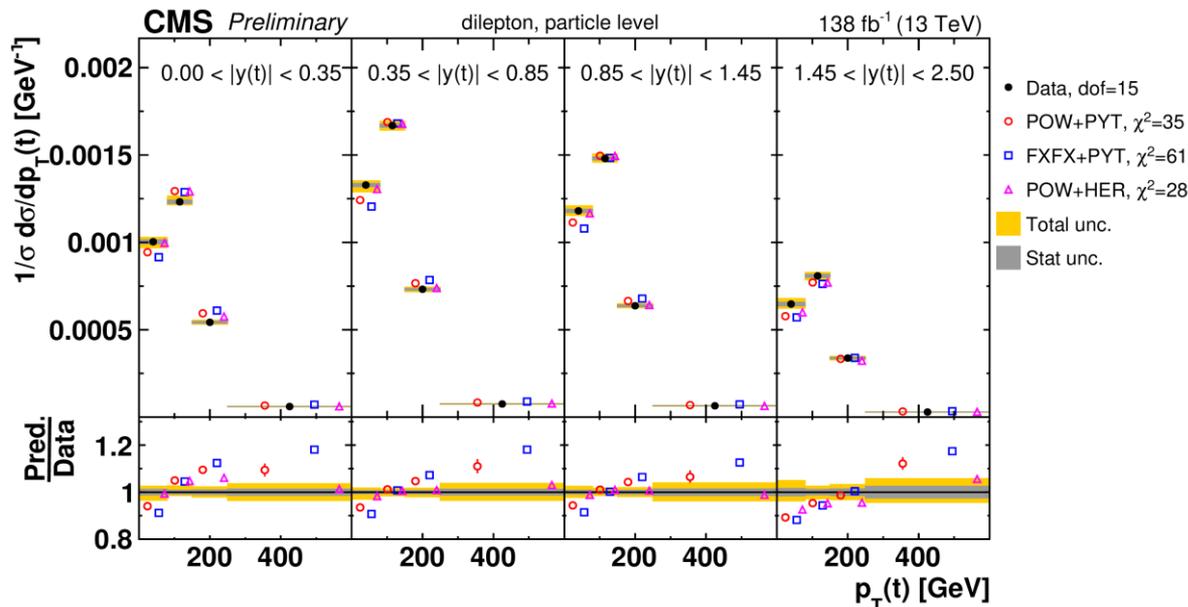
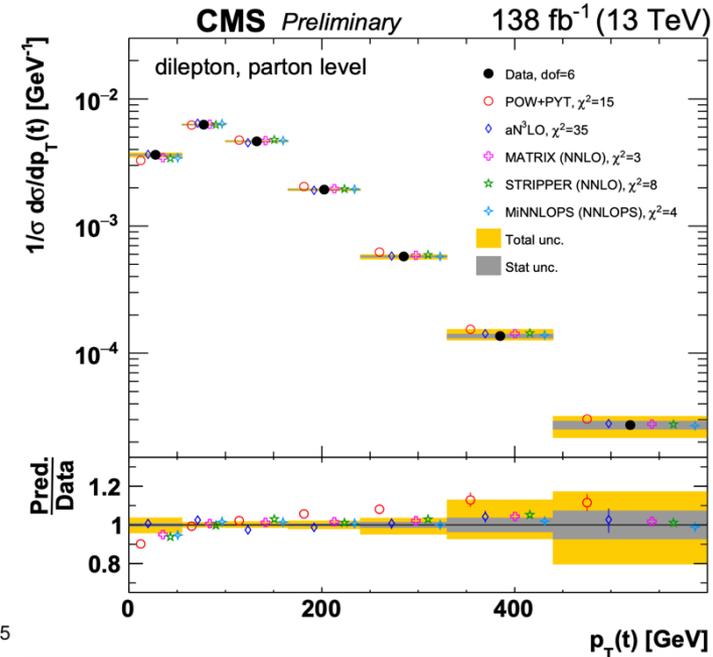
Branching ratios  
Charged Higgs (non-SM)  
Anomalous couplings  
Rare decays  
CKM matrix elements  
Calibration sample @LHC

...

# Multi-differential cross section

TOP-20-006

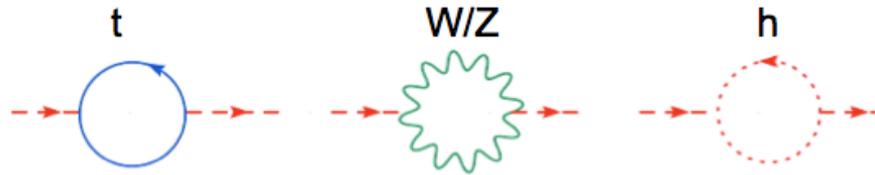
- Multi-differential cross section as a function of top and tbar kinematics, decay products and additional jets
- Sensitive to SM parameters  $m_t$  and  $\alpha_S$
- Total uncertainty reduced by a factor of  $\sim 2$  wrt previous analyses



# Top quarks as window to BSM physics

Top quark affects stability of Higgs mass

Contributions grow with  $\Lambda$ :



$$m^2 = m_0^2 + g^2 \Lambda^2$$

Cancellation?

## Solutions:

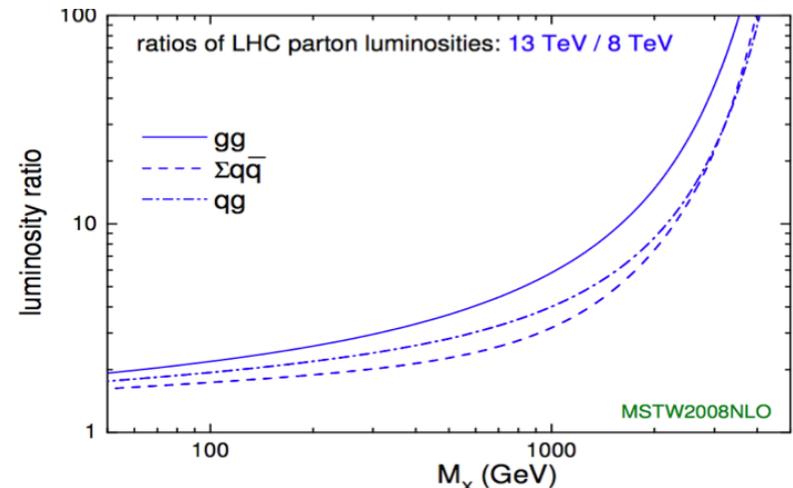
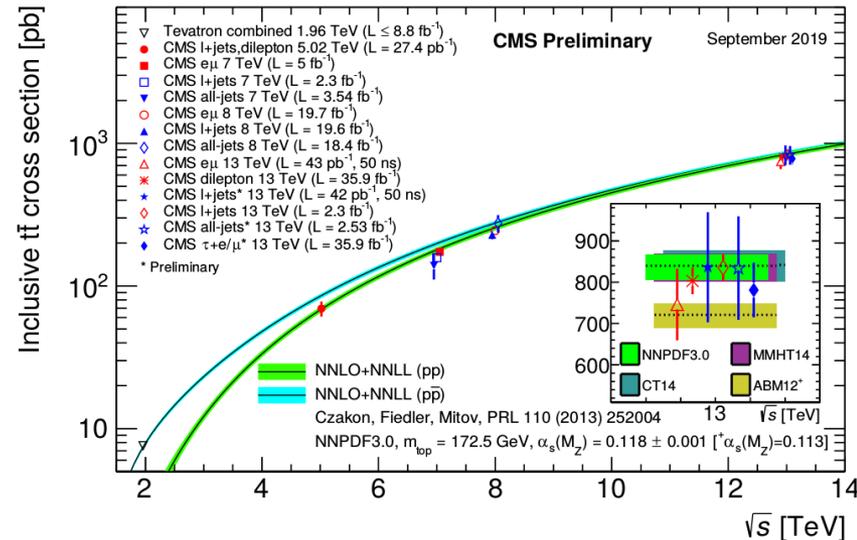
- **Naturalness:** There is no problem
- **Weakly-coupled model at TeV scale**
  - New particles to cancel SM divergences
  - Top partners: new scalar/vectors coupled to top, exotic top decays
- **Strongly-coupled model at TeV scale**
  - $t\bar{t}$  resonances, bound states, 4-top production, etc.
- **New space-time structure**
  - Introduce extra space dimensions to lower Planck scale cutoff to  $\sim 1\text{TeV}$
  - KK excitations

# Role of top quark physics

- Top quark physics after the Higgs discovery

- Heavy particle, preferential coupling?
- Special role in EWSB mechanism?
- Does it play a role in non-SM physics?
- Are the couplings affected?
- Main background for many NP searches

- Monitoring of production mechanism
- Is there any sign of NP in top production/decay?

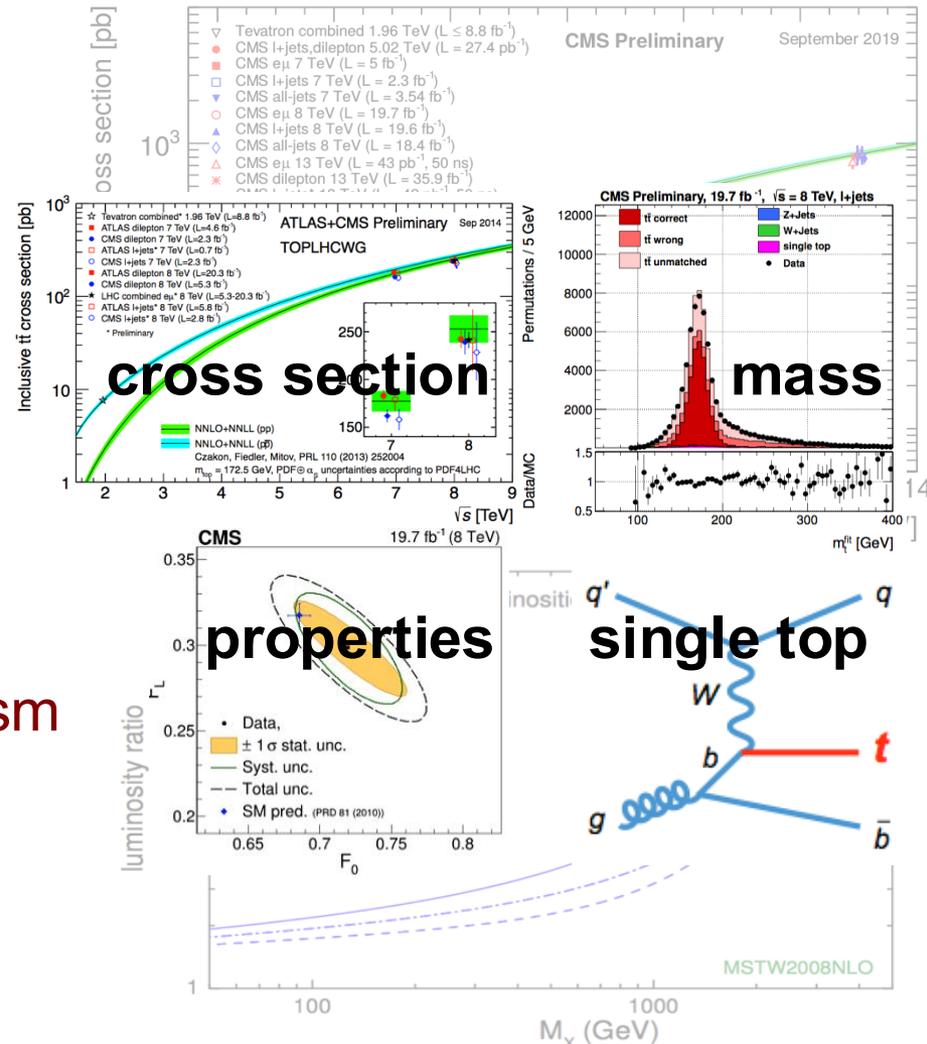


# Role of top quark physics

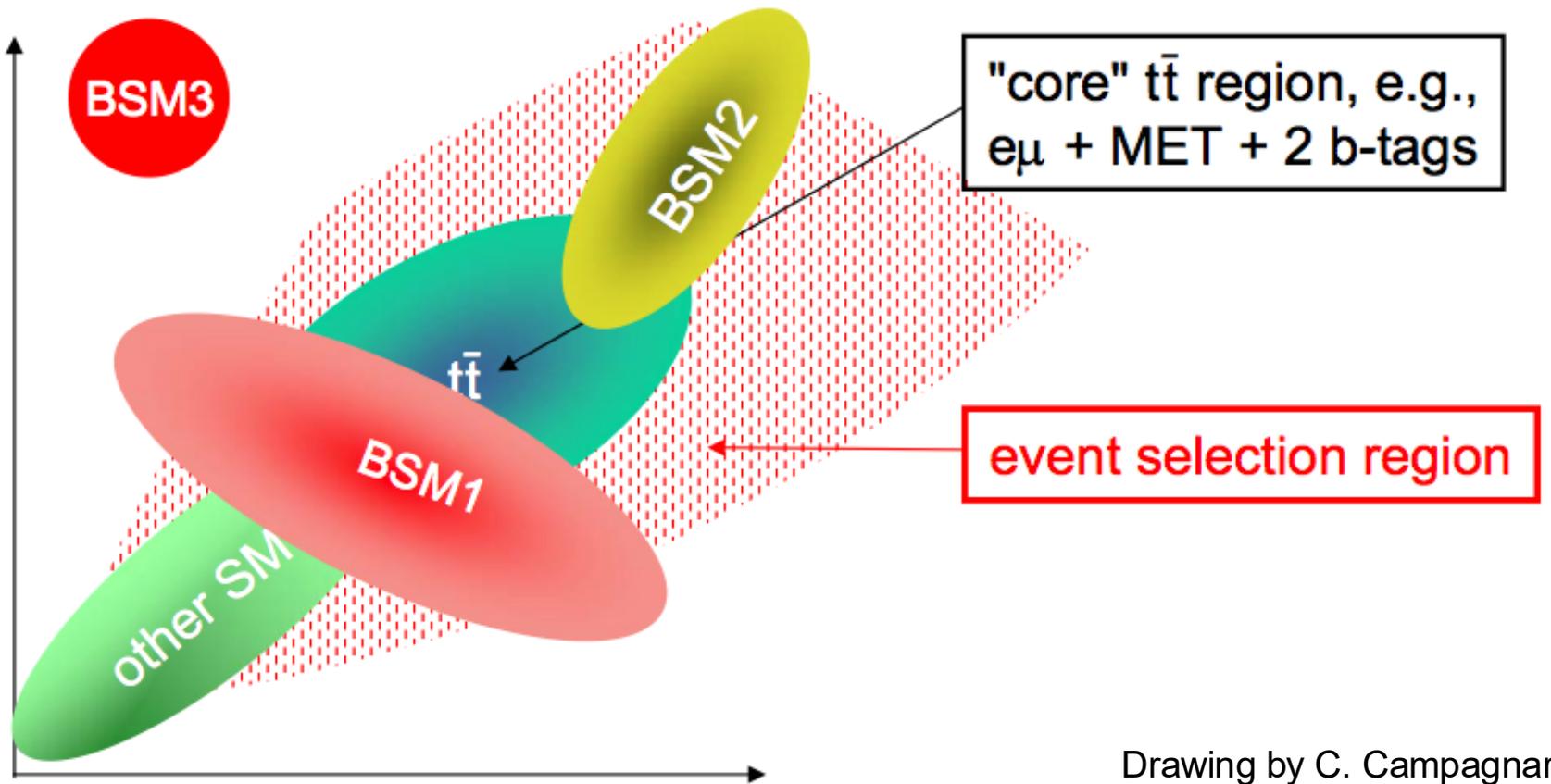
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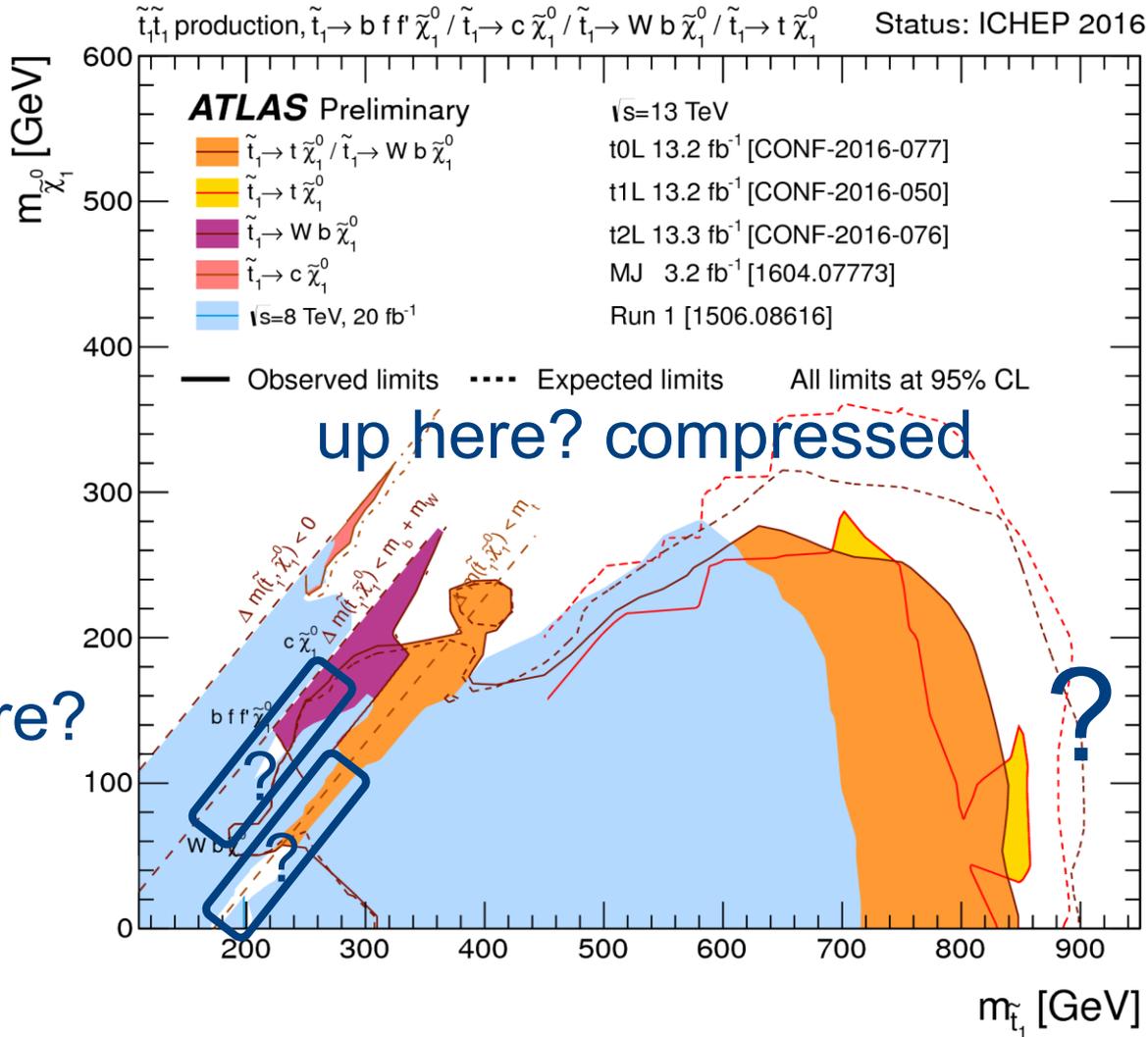
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- Is there any sign of NP in top production/decay?



# Study characteristics

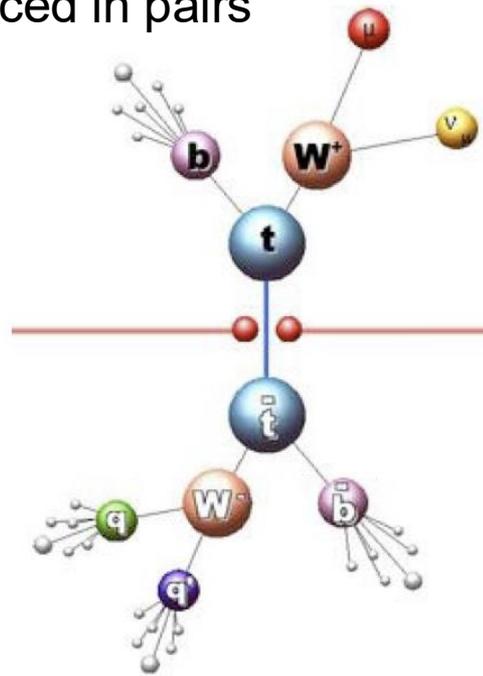


# Regions hard to explore

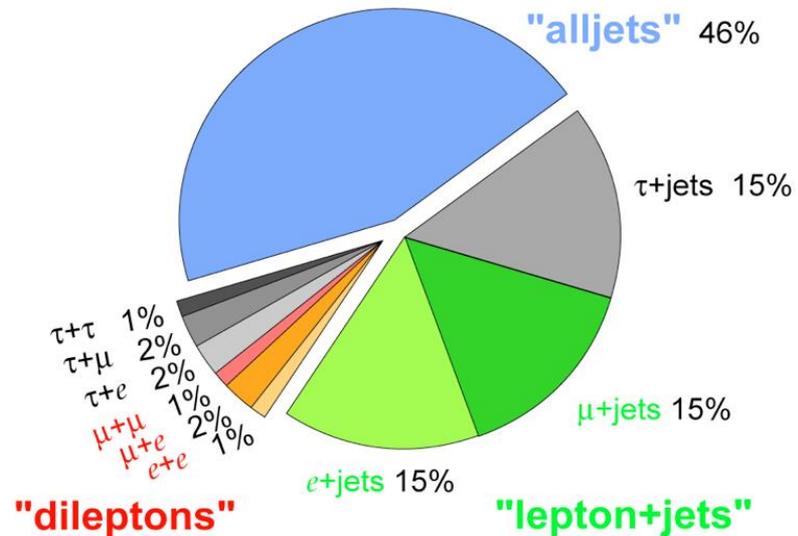


# Top quark decays

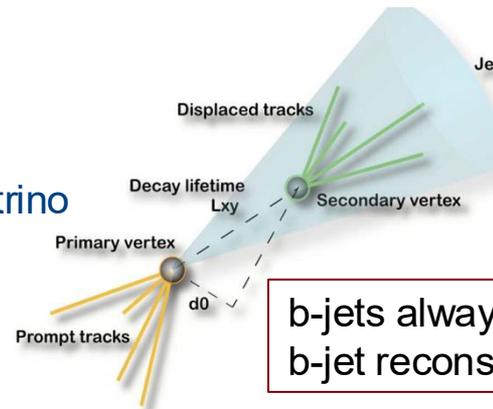
Top quarks (mostly) produced in pairs



Top Pair Branching Fractions



- Dilepton ( $ee$ ,  $\mu\mu$ ,  $e\mu$ ):
  - BR~5%, 2 leptons+2 b-jets+2 neutrinos
- Lepton ( $e$  or  $\mu$ ) + jets
  - BR~30%, one lepton+4jets (2 from b)+1 neutrino
- All hadronic
  - BR~44%, 6 jets (2 from b), no neutrinos



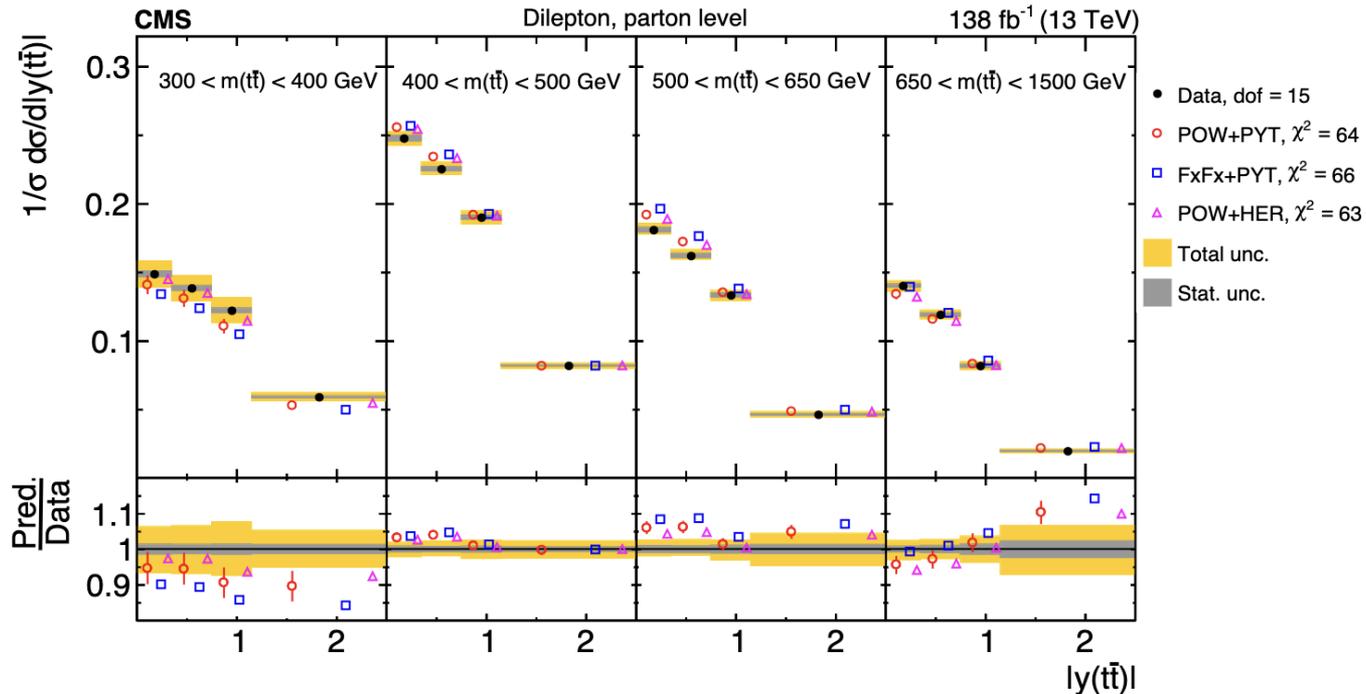
b-jets always present  
b-jet reconstruction plays important role

# Differential cross section

arXiv:2402.08486

- Measure differential cross section
  - Test perturbative QCD
  - Test BSM scenarios (Z' decays, etc)
- Cross sections measured as a function of  $p_T$ ,  $\eta$ , invariant mass of the final state leptons, top quarks,  $t\bar{t}$  system, etc.
- Good agreement with expectations

$$\frac{1}{\sigma_{t\bar{t}}} \frac{d\sigma_{t\bar{t}}}{dX}$$



# Probing the $Wtb$ vertex

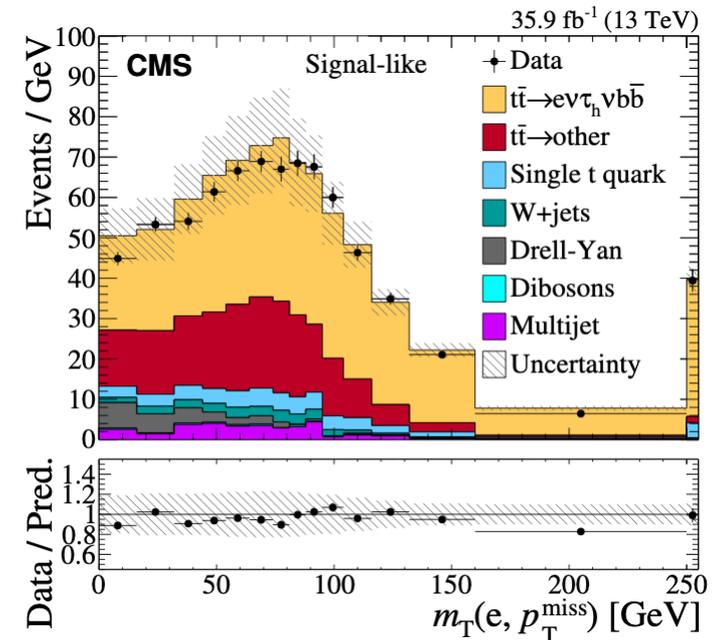
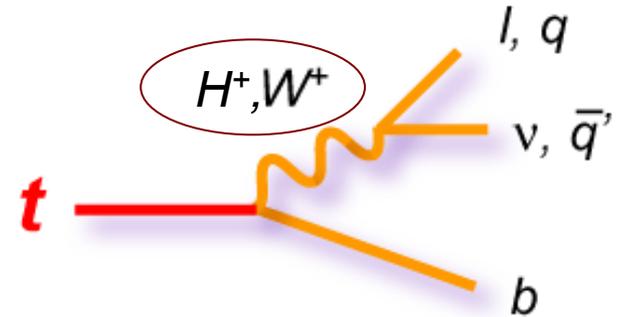
PRD 85(2012)112007, PLB 739(2014)23, JHEP 02(2020)191

## Dileptons with taus

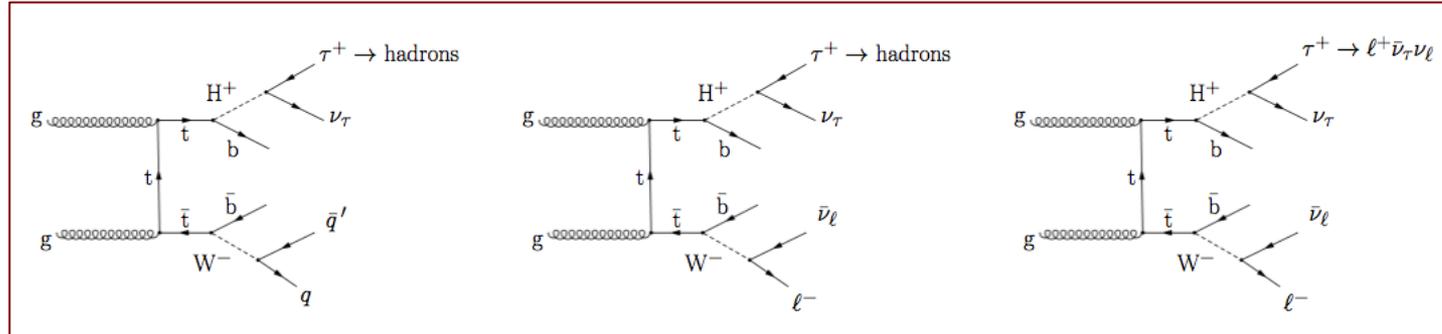
- cross section measurement including  $\tau$ s
- Includes only 3<sup>rd</sup> generation quarks/leptons
- Syst unc: tauld, fakes

Channel	Signature	BR
Dilepton( $e/\mu$ )	$ee, \mu\mu, e\mu + 2b$ -jets	4/81
Single lepton	$e, \mu + \text{jets} + 2b$ -jets	24/81
All-hadronic	$\text{jets} + 2b$ -jets	36/81
<b>Tau dilepton</b>	<b><math>e\tau, \mu\tau + 2b</math>-jets</b>	<b>4/81</b>
Tau+jets	$\tau + \text{jets} + 2b$ -jets	12/81

- If top quark plays special role in EWK symmetry breaking, couplings to  $W$  may change
- Charged Higgs may alter coupling to  $W$
- Search for final states with **taus**: charged Higgs

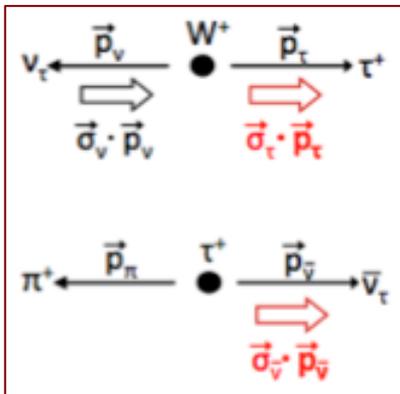


# Looking at tau decays

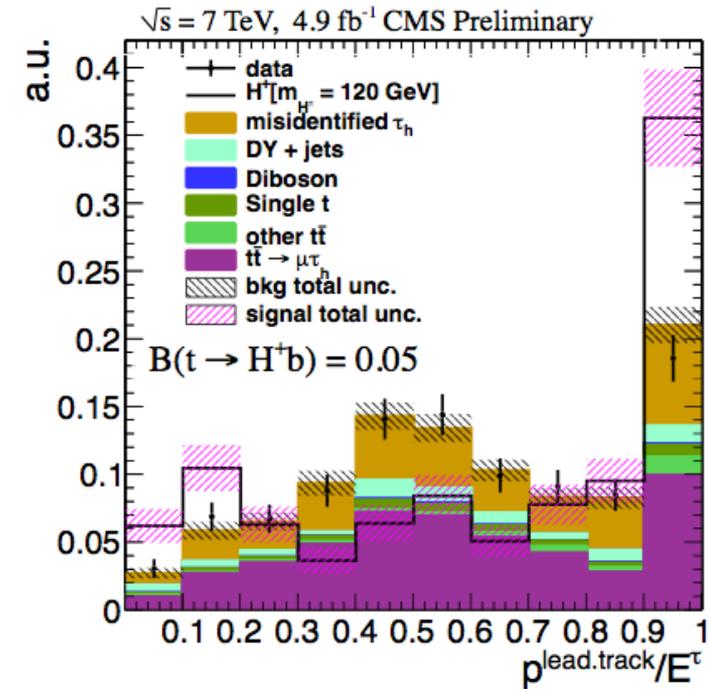
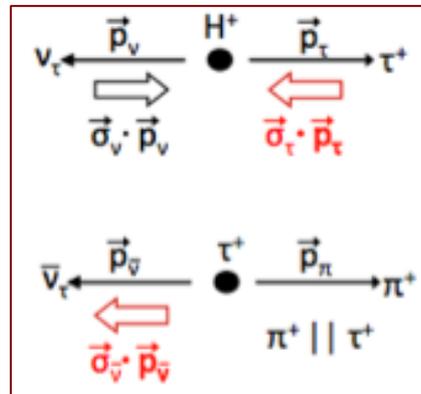


SM

BSM



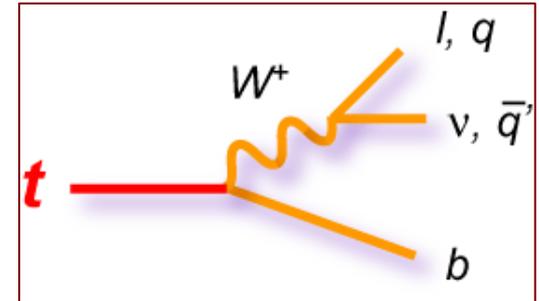
VS



# W boson branching fractions

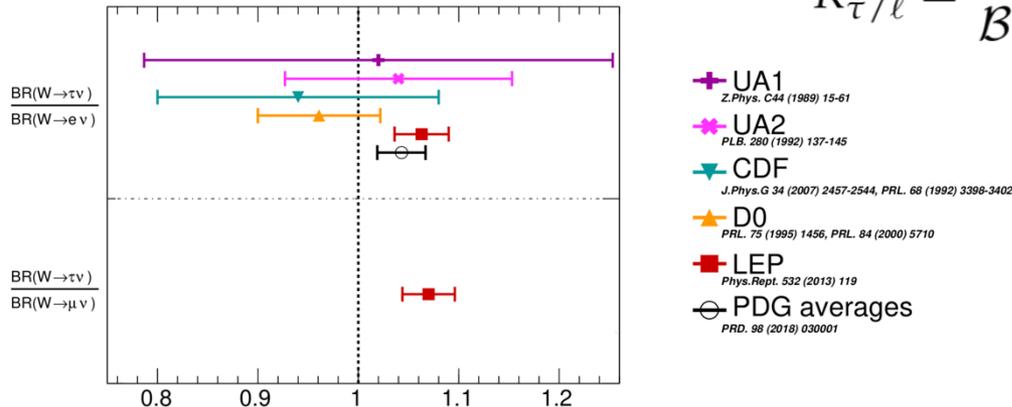
- Precise measurement of the W boson BRs (electrons, muons, taus)

- Use events with WW and W+jets
- Multiple categories used
- Maximum likelihood simultaneous fitting of templates to data in each category



- Most precise determination of  $B(W \rightarrow l\nu)$  from LEP has  $2.6\sigma$  deviation from LFU

$$R_{\tau/\ell} = \frac{2\mathcal{B}(W \rightarrow \tau\bar{\nu}_\tau)}{\mathcal{B}(W \rightarrow e\bar{\nu}_e) + \mathcal{B}(W \rightarrow \mu\bar{\nu}_\mu)} = 1.066 \pm 0.025$$



# Lepton Flavour Universality

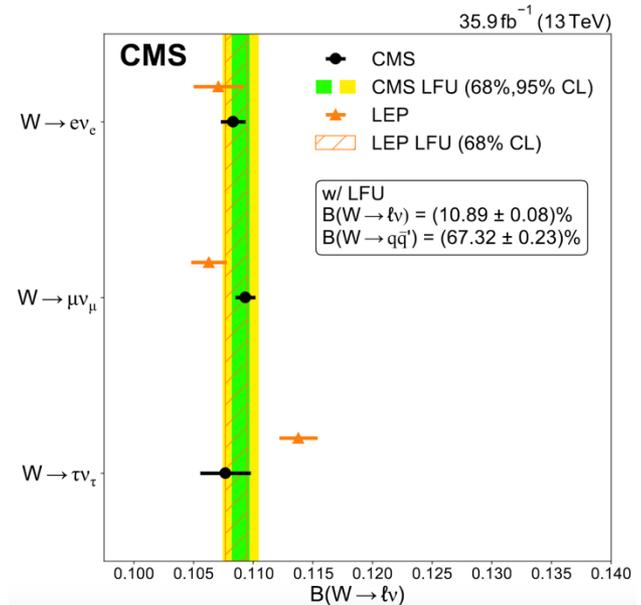
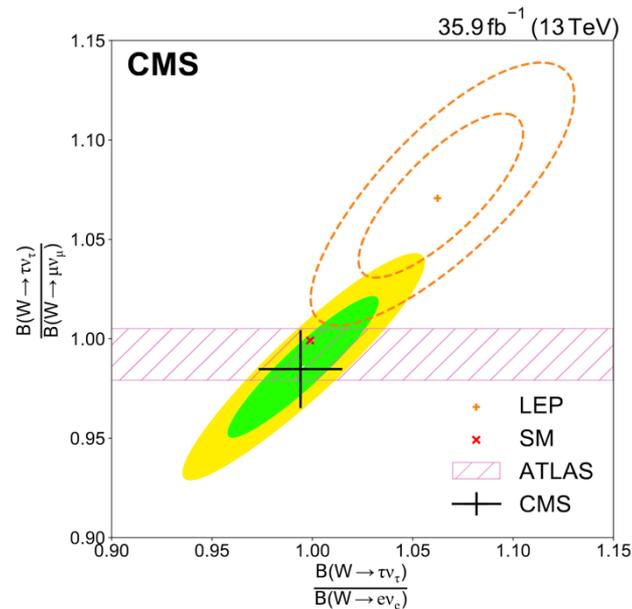
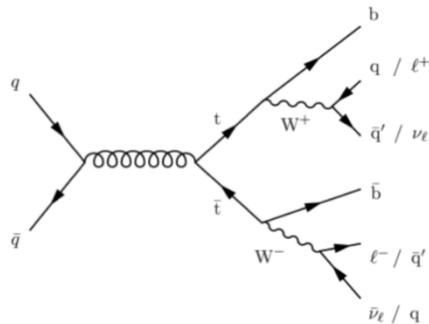
arXiv:2201.07861

## Resolving an old discrepancy from LEP

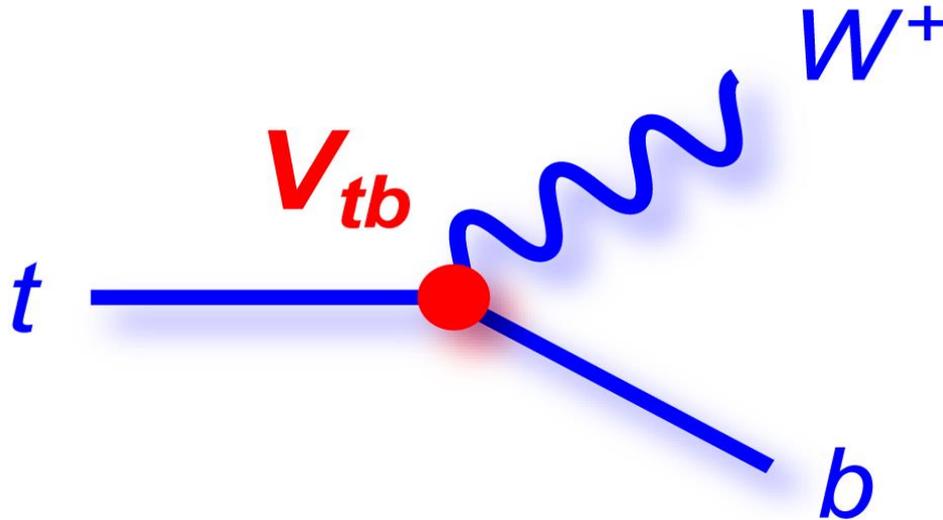
Strategy :  
Use W bosons  
from top quarks

Many more Ws  
than at LEP

	CMS	LEP
$\mathcal{B}(W \rightarrow e\bar{\nu}_e)$	$(10.83 \pm 0.01 \pm 0.10)\%$	$(10.71 \pm 0.14 \pm 0.07)\%$
$\mathcal{B}(W \rightarrow \mu\bar{\nu}_\mu)$	$(10.94 \pm 0.01 \pm 0.08)\%$	$(10.63 \pm 0.13 \pm 0.07)\%$
$\mathcal{B}(W \rightarrow \tau\bar{\nu}_\tau)$	$(10.77 \pm 0.05 \pm 0.21)\%$	$(11.38 \pm 0.17 \pm 0.11)\%$
$\mathcal{B}(W \rightarrow h)$	$(67.46 \pm 0.04 \pm 0.28)\%$	
with LU		
$\mathcal{B}(W \rightarrow \ell\bar{\nu})$	$(10.89 \pm 0.01 \pm 0.08)\%$	$(10.86 \pm 0.06 \pm 0.09)\%$
$\mathcal{B}(W \rightarrow h)$	$(67.32 \pm 0.02 \pm 0.23)\%$	$(67.41 \pm 0.18 \pm 0.20)\%$



# How does a top quark decay?



- almost always  $t \rightarrow Wb$  (i.e.  $V_{tb} \sim 1$ )
- lifetime is short, and it decays before hadronizing
- the  $W$  is real:
  - can decay  $W \rightarrow l\nu$  ( $l=e, \mu, \tau$ ),  $BR \sim 1/9$  per lepton
  - can decay  $W \rightarrow qq$ ,  $BR \sim 2/3$

# Cross section in the R measurement

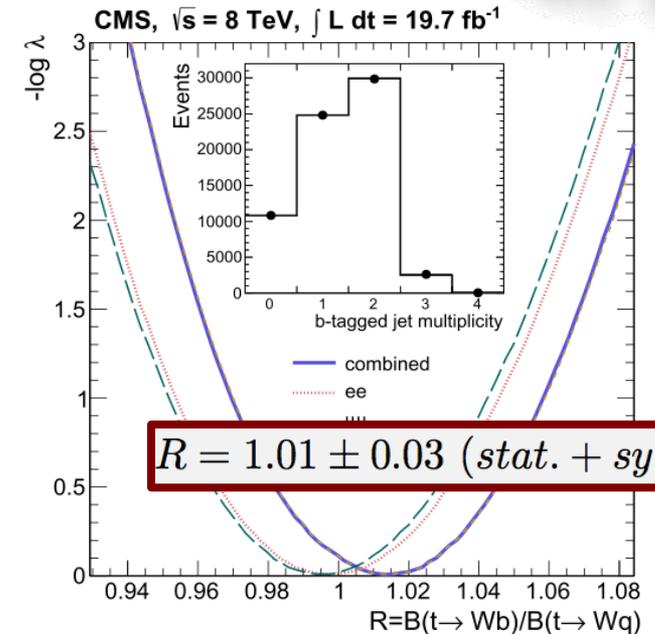
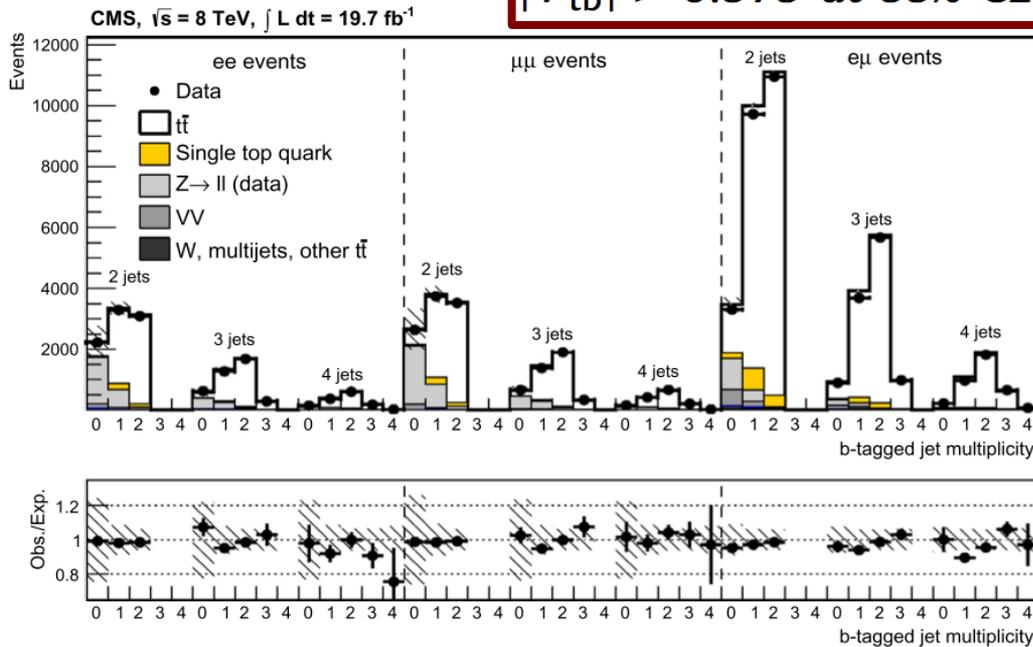
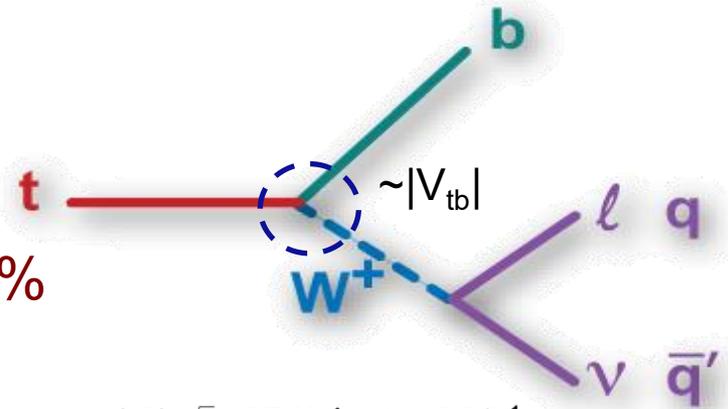
N.Cim. B125(2010)983, PLB 736(2014)33

- Measure R:
- Dilepton final state

$$R \equiv \frac{BR(t \rightarrow Wb)}{BR(t \rightarrow Wq)} \approx |V_{tb}|^2$$

$$\sigma(t\bar{t}) = 238 \pm 1 \text{ (stat.)} \pm 15 \text{ (syst.) pb} \pm 6\%$$

$$|V_{tb}| > 0.975 \text{ at 95\% CL}$$



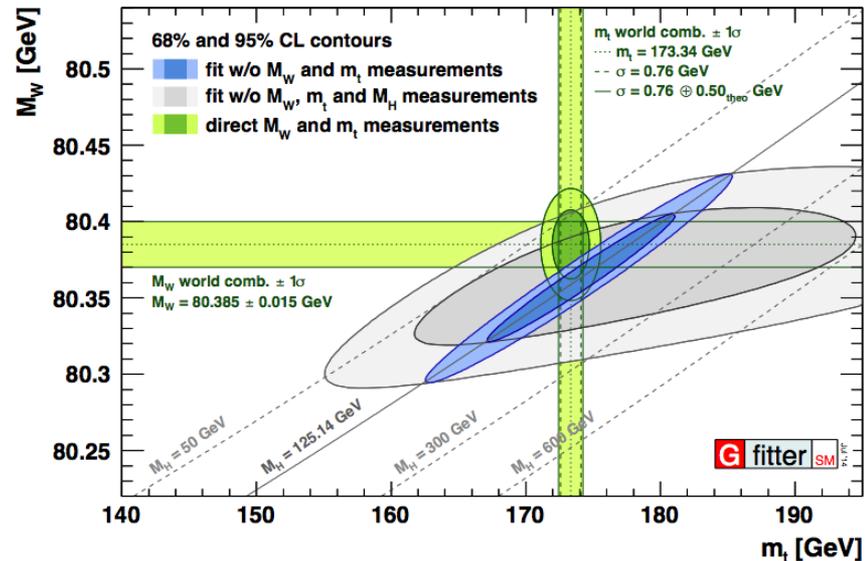
$$R = 1.01 \pm 0.03 \text{ (stat. + syst.)}$$

# Top quark mass

- Top quark mass is a fundamental parameter of the SM



- Precise measurement needed for checking consistency of the SM

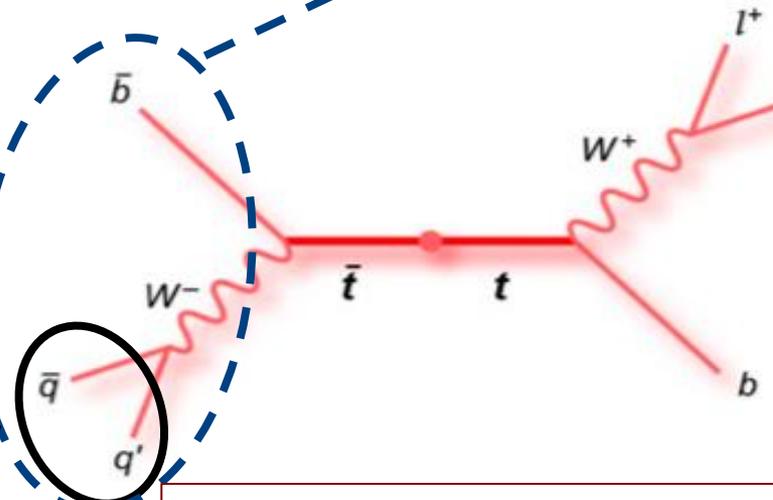
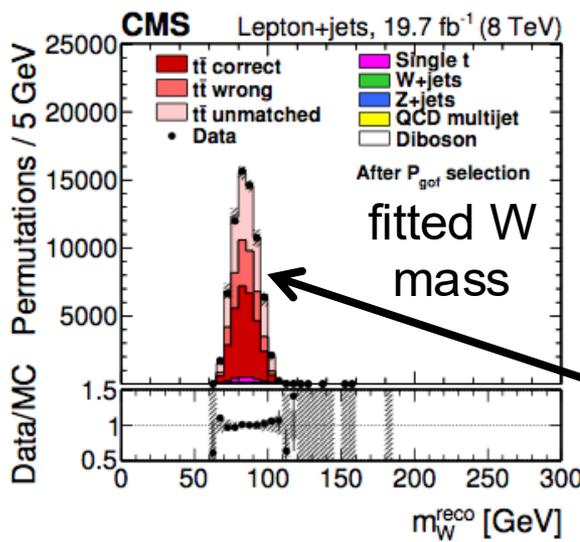
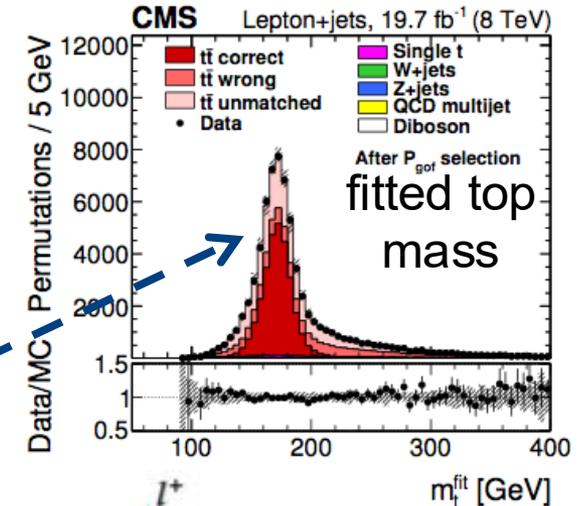


- Top is the only fermion with the mass of the order of EWSB scale
- Discovered Higgs boson fits well with precise determinations of  $m_W$  and  $m_{\text{top}}$
- Other properties (EWK coupling, production asymmetries, etc.) are predicted by SM
- Precise measurements could reveal breakdown of SM

# Precise mass measurement

arXiv:1509.04044, EPJC78(2018)891

- Select lepton+jet final state
  - Best channel to measure  $m_{\text{top}}$
  - well defined final state (1 lepton, 1  $\nu$ , 2b  $W_{qq'}$ )
- Select  $t\bar{t}$  events: hadronic decays ( $m_{\text{top}}$ ,  $m_W$ )
- Kinematic fit: constrain  $W$  mass, top-antitop masses
  - In-situ JES calibration
- Measure  $m_{\text{top}}$  and JSF



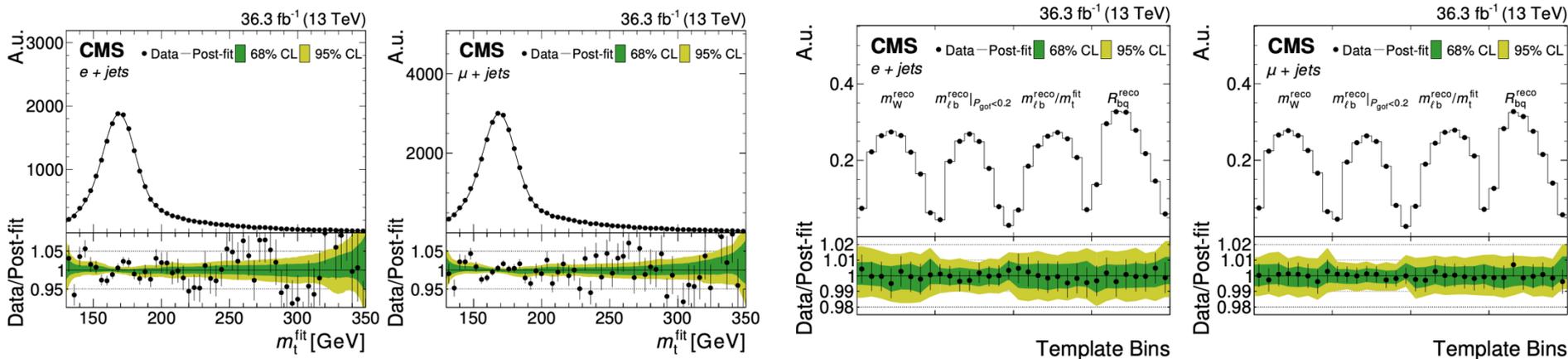
$\pm 0.3\%$

$$m_t = 172.44 \pm 0.13 \text{ (stat+JSF)} \pm 0.47 \text{ (syst) GeV}$$

# Top quark mass

arXiv:2302.01967

- Updated measurement (l+jets ch.)
- Likelihood method ( $m_t^{\text{fit}}$ ,  $m_W^{\text{reco}}$ ,  $m_{l_b}^{\text{reco}}/m_t^{\text{fit}}$ ,  $R_{\text{bq}}^{\text{reco}}$ )
- In-situ constraints via nuisance parameters
- Main systematics: b-flavour component of JEC, FSR



$$m_t = 171.77 \pm 0.38 \text{ GeV} \quad \pm 0.22\%$$

⇒ most precise measurement to date

# Top quark mass results

arXiv:2402.08713, Phys.Rep. 1115(2025)116

The European Physical Journal  
**EPJ C**  
 volume 74 · number 4 · april · 2014  
 Particles and Fields

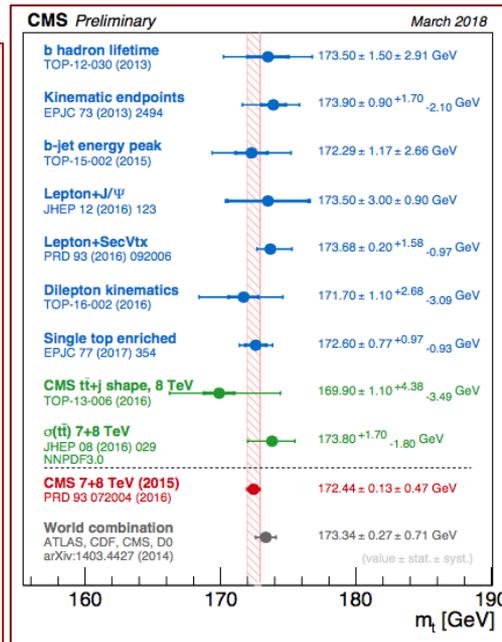
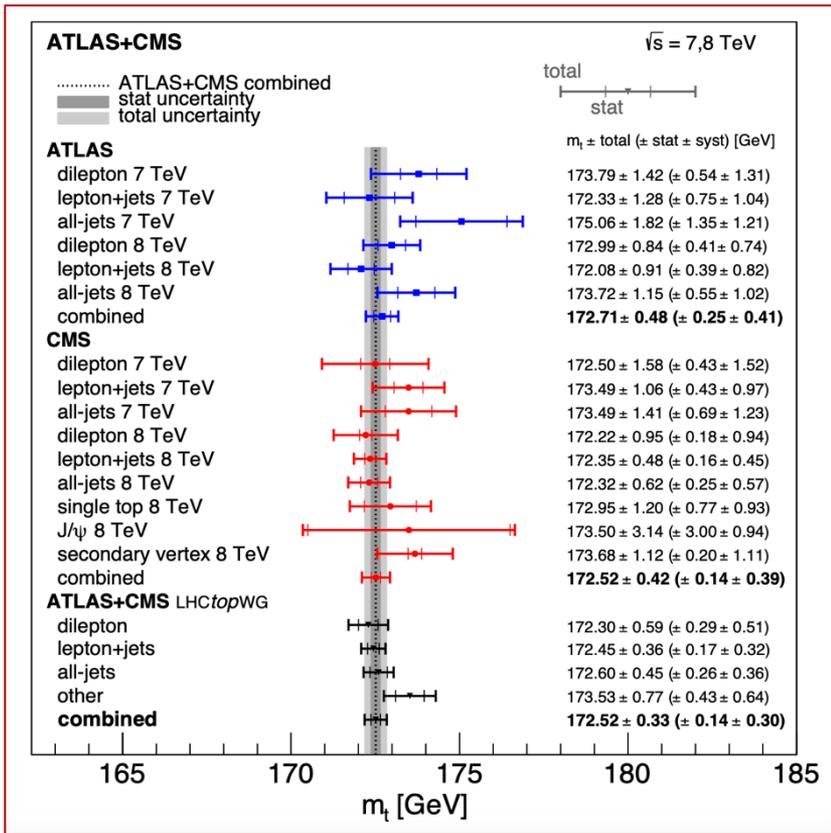
Recognized by European Physical Society

**CMS,  $\sqrt{s} = 7$  TeV**

CMS 2010, dilepton JHEP 07 (2011) 049, L=36 pb <sup>-1</sup>	$175.50 \pm 4.60 \pm 4.52$ GeV (value ± stat ± syst)
CMS 2011, dilepton EPJC 72 (2012) 2202, L=0.9 fb <sup>-1</sup>	$172.50 \pm 0.43 \pm 1.48$ GeV (value ± stat ± syst)
CMS 2011, lepton+jets JHEP 12 (2012) 105, L=5.0 fb <sup>-1</sup>	$173.49 \pm 0.27 \pm 1.03$ GeV (value ± stat ± syst)
CMS 2011 all-jets This analysis, L=3.54 fb <sup>-1</sup>	$173.49 \pm 0.69 \pm 1.21$ GeV (value ± stat ± syst)
CMS combination up to L=5.0 fb <sup>-1</sup>	$173.54 \pm 0.33 \pm 0.96$ GeV (value ± stat ± syst)
Tevatron combination Phys. Rev. D 86 (2012) 092003, up to L=5.8 fb <sup>-1</sup>	$173.18 \pm 0.56 \pm 0.75$ GeV (value ± stat ± syst)

Overview of the CMS top-quark measurements, including the latest results of the all-jets channel. The shaded band shows the combined CMS result. The combined Tevatron average is also shown. From The CMS Collaboration: Measurement of the top-quark mass in all-jets events in pp collisions at  $\sqrt{s} = 7$  TeV.

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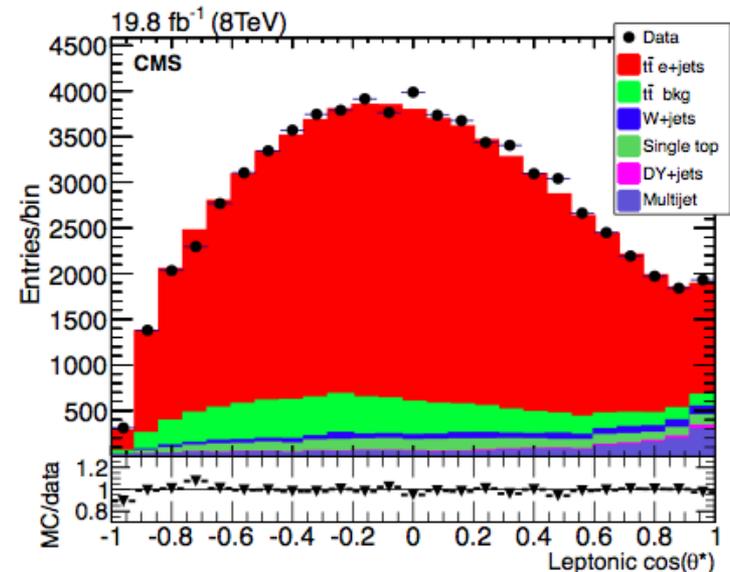
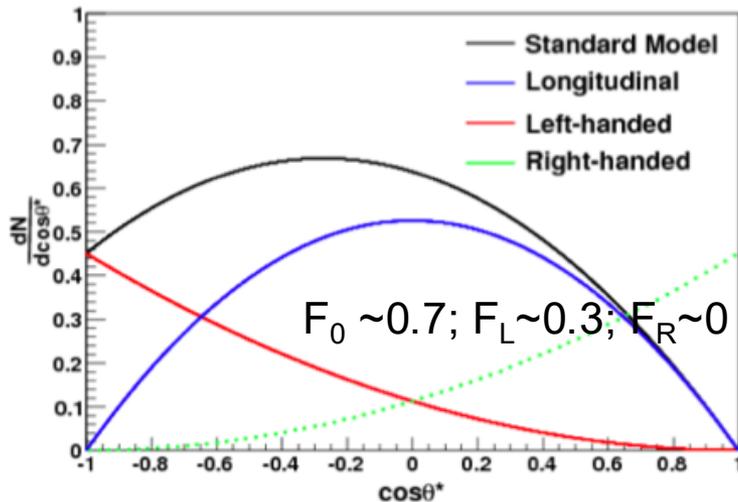
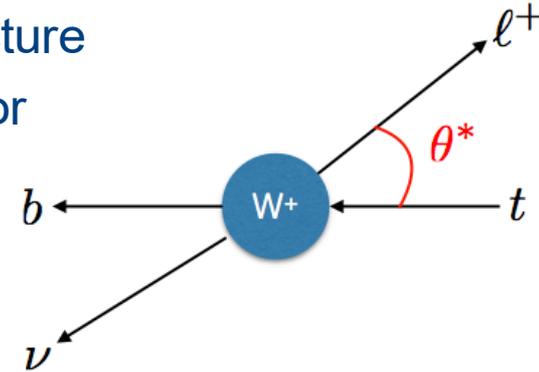
<0.2% uncertainty

$$m_t = 172.52 \pm 0.14 (\text{stat}) \pm 0.30 (\text{syst}) \text{ GeV}$$

# W boson polarization

arXiv:1612.02577, PRD 93(2016)052007

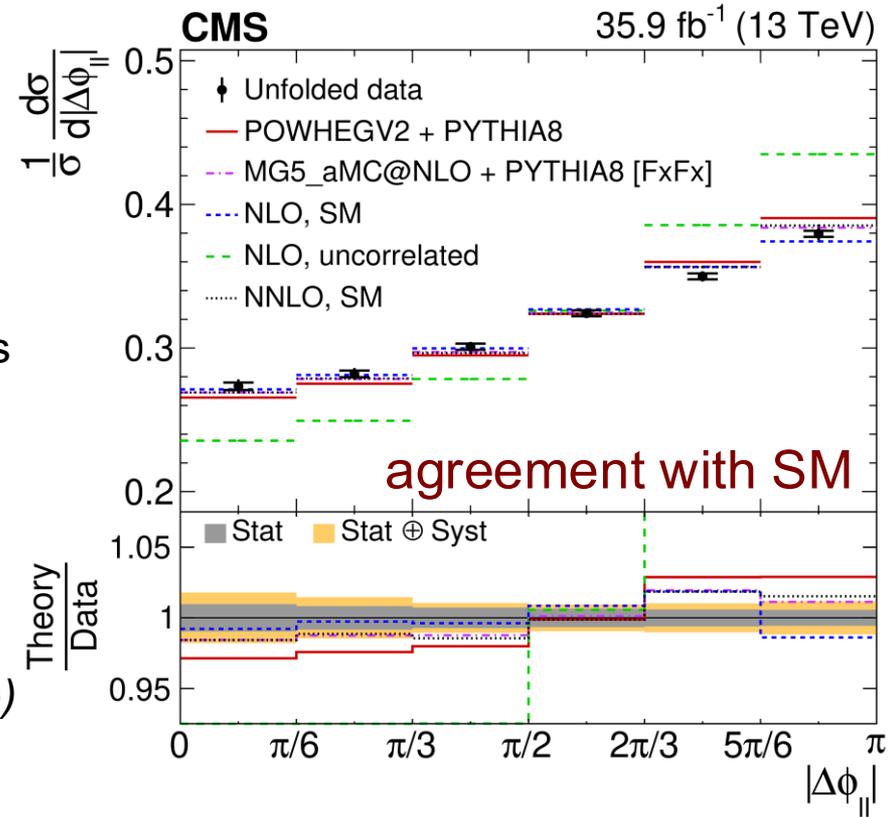
- Properties of  $Wtb$  vertex in SM is characterized by V-A structure
- W bosons can be produced with **left-handed**, **right-handed**, or **longitudinal** polarization
  - Fractions of polarization states are well predicted
- Can probe by measuring the angular distributions of the W boson decay products
- **New physics could alter the polarization**



# Spin correlation

PRD 100(2019)072002, ATLAS-CONF-2018-027

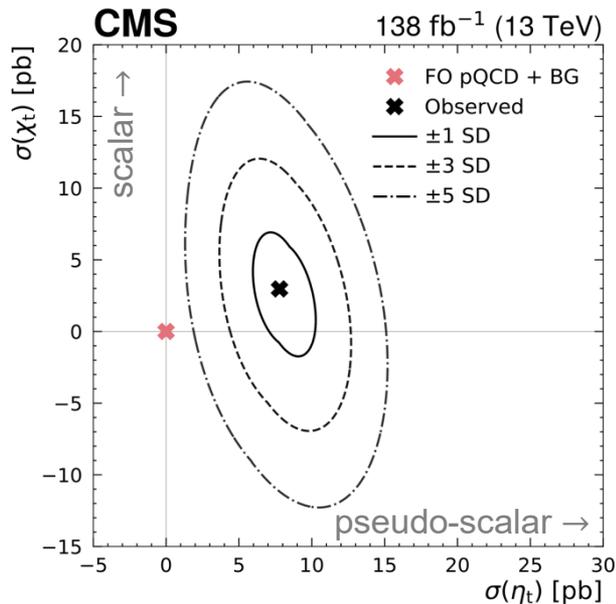
- Top quark produced are not polarized
  - ...but spins between quark and anti-quark are correlated
- Top quark decays before spins decorrelate
  - It decays before hadronization ( $\tau \sim 10^{-25}$  s)  $\Rightarrow$  spin information transmitted to decay products
  - No need to reconstruct full  $t\bar{t}$  system
- Spin correlation depends on production mode
- It may differ from SM expectations
  - Decays to charged Higgs and b quark ( $t \rightarrow H^+ b$ )
  - Other BSM scenarios



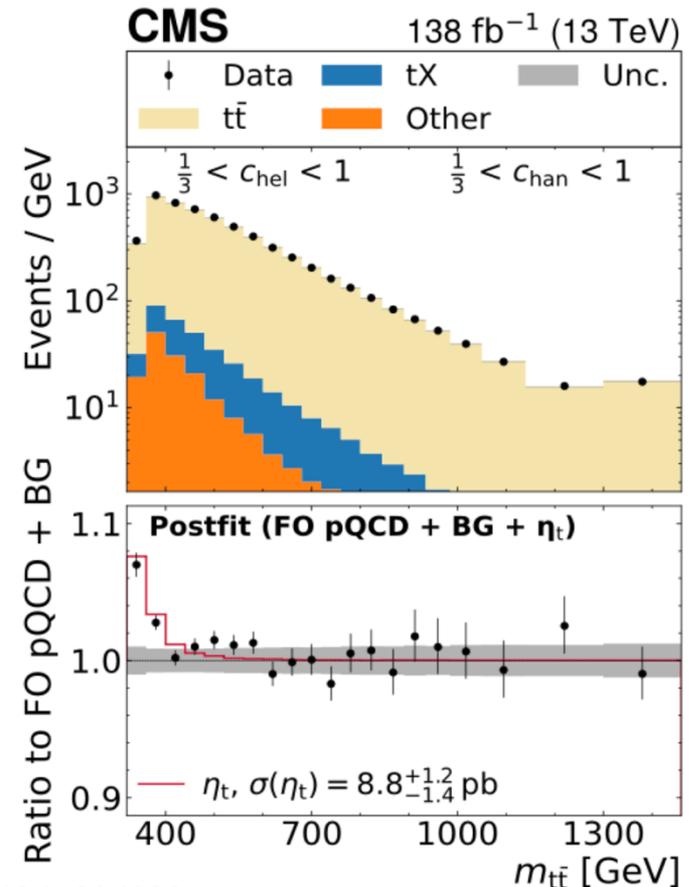
# Pseudoscalar excess at $t\bar{t}b\bar{a}$ threshold

arXiv:2503.22382

- In the search for H/A resonance into  $t\bar{t}b\bar{a}$ :  $H/A \rightarrow t\bar{t}$  observed **excess of data at threshold**
  - Dilepton decays of top quarks
  - Signal extracted via 3D profile likelihood fit
  - Experimentally challenging (1% of incl.xsec)
- $t\bar{t}b\bar{a}$  bound states near  $t\bar{t}b\bar{a}$  threshold predicted by SM



**Excess compatible with pseudo-scalar hypothesis**



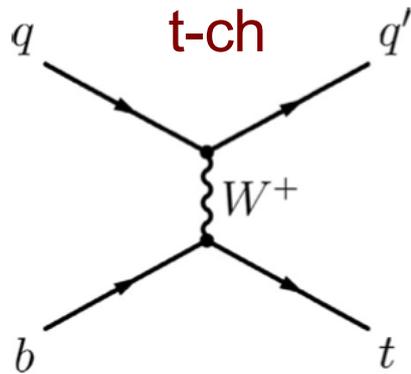
$\sigma_{theo} = 6.4$  pb (PRD 104, 034023)

$$\sigma(\eta_t) = 8.8 \pm 0.5 \text{ (stat)}^{+1.1}_{-1.3} \text{ (syst)} \text{ pb} = 8.8^{+1.2}_{-1.4} \text{ pb}$$

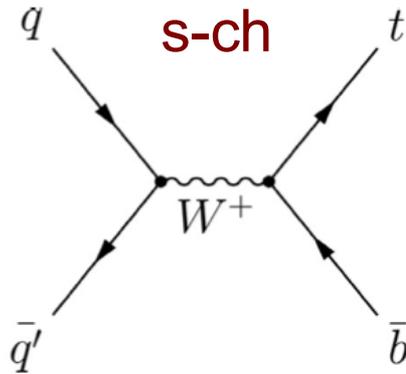
# How else is Top produced?

PRD102(2009)182003, PRD81(2010)054028

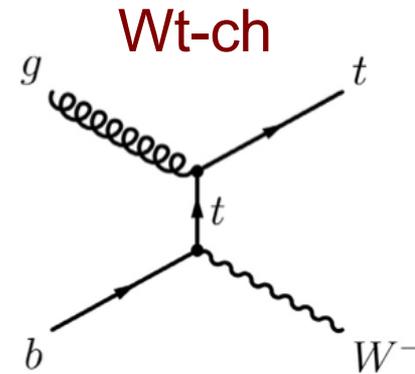
- Single top quark production



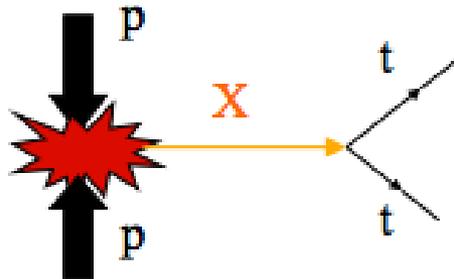
$\sigma(13\text{TeV}) = 217 \text{ pb}$



10 pb



72 pb



**Resonance Production?**  
**Top Color-Assisted Technicolor**  
**OR**  
**?????**

# Probing top quark production

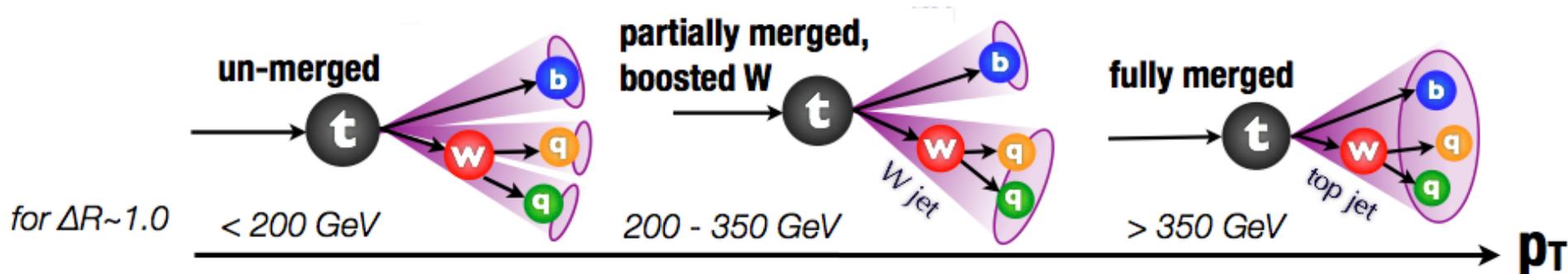
- Differential measurements

- Testing QCD, measuring properties, searching for new physics, ...
- Function of kinematics, global variables, associated production

- Increased sensitivity: top quark pairs produced at rest

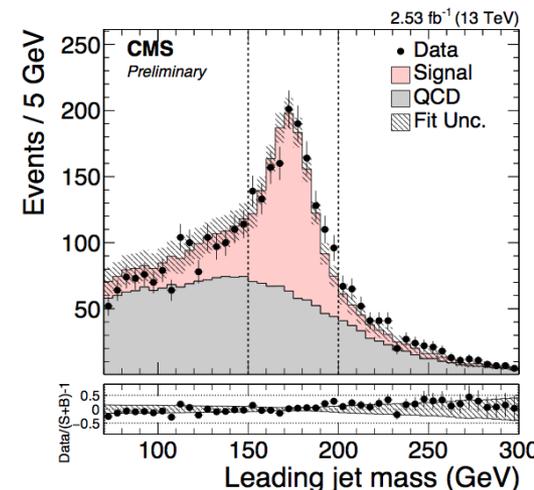
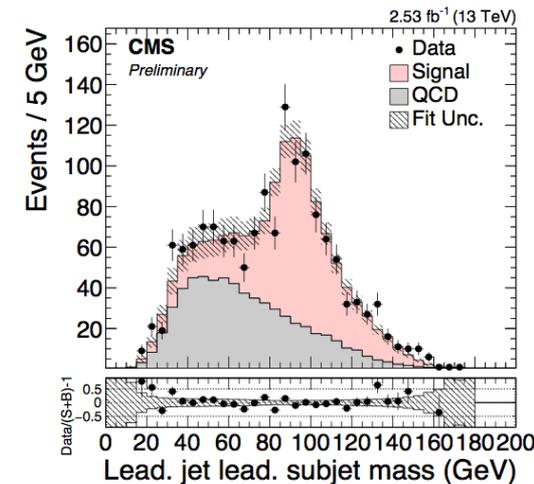
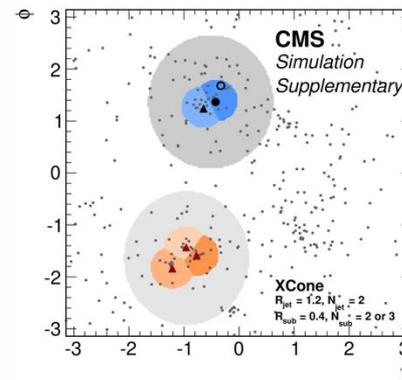
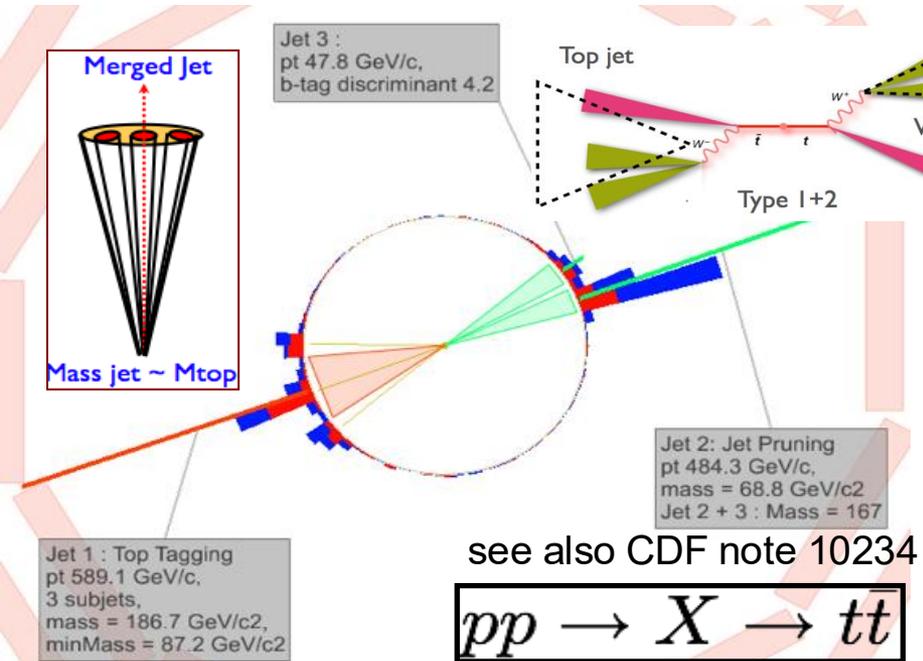
□  $\sigma(M_{t\bar{t}} > 1 \text{ TeV at } 13 \text{ TeV}) = 8 \times \sigma(M_{t\bar{t}} > 1 \text{ at } 8 \text{ TeV})$

⇒ Unique opportunity to probe boosted production at 13 TeV



# Boosted topology

JHEP 1209(2012)029, TOP-16-013, PRL 124(2020) 202001



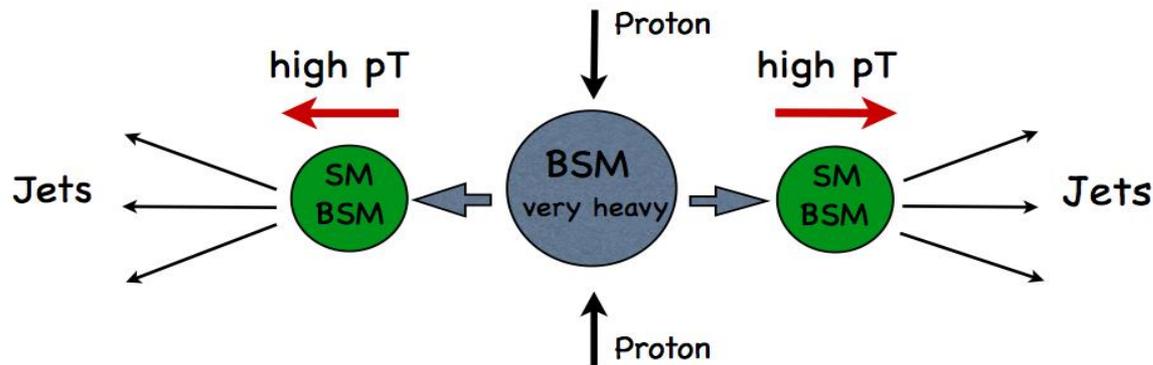
- At high energy, particles produced beyond threshold
- All-hadronic topology
  - Top  $p_T$  boosted, jets are collimated
  - Decay products and FSR collected in a “fat” jet
- Look at jet substructure
- Measure mass (no neutrinos)

# Boosted topology

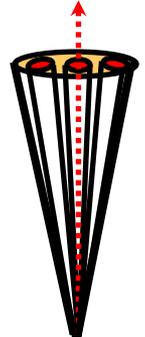
- In many models there is high potential to discover new physics in the top sector in search for heavy resonances

$$pp \rightarrow X \rightarrow t\bar{t}$$

- Simple approach to merge neighboring jets



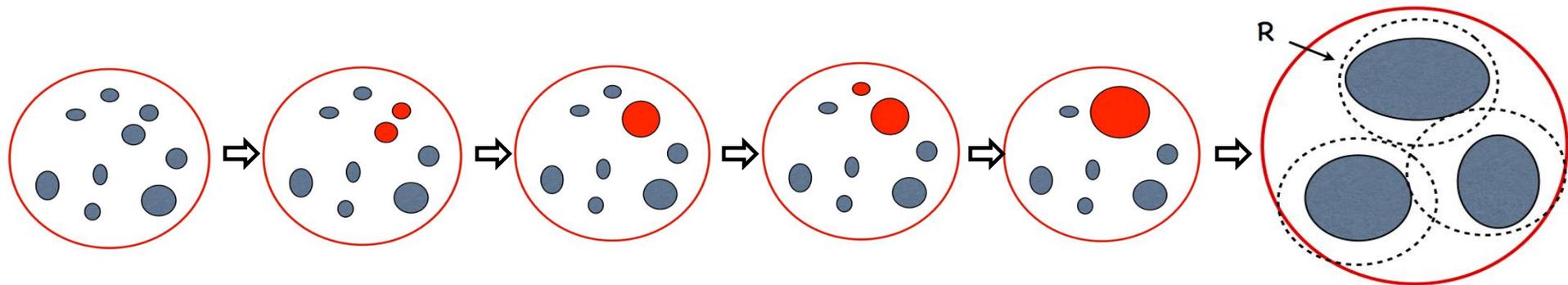
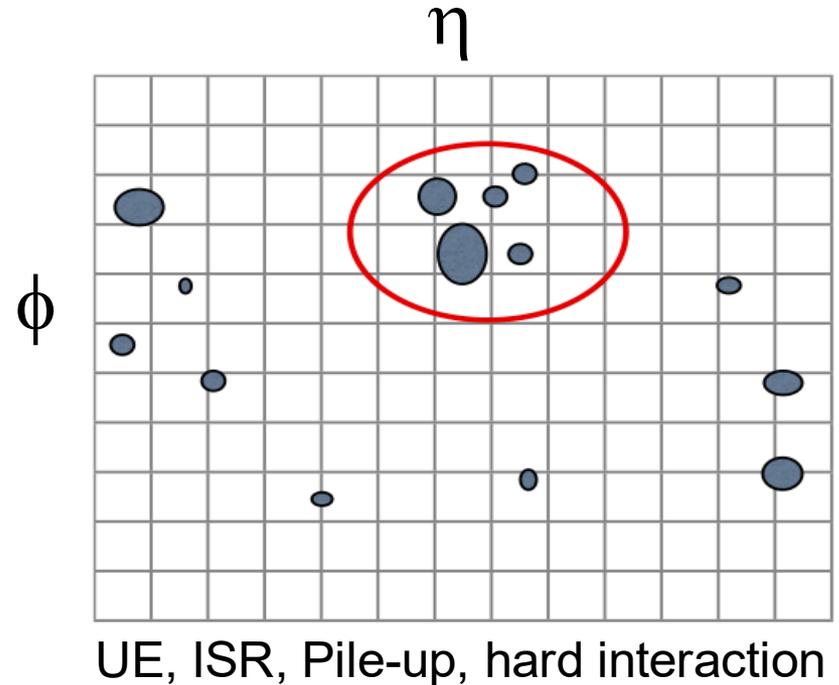
Merged Jet  
Mass jet  $\sim M_{\text{top}}$



- At LHC energy, EWK scale particles produced beyond threshold
- Jets are highly collimated
- Decay products and FSR collected in a fat jet

# Jet/Event selection

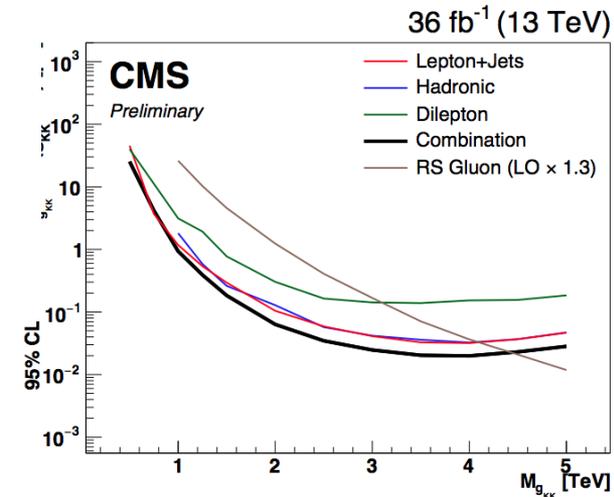
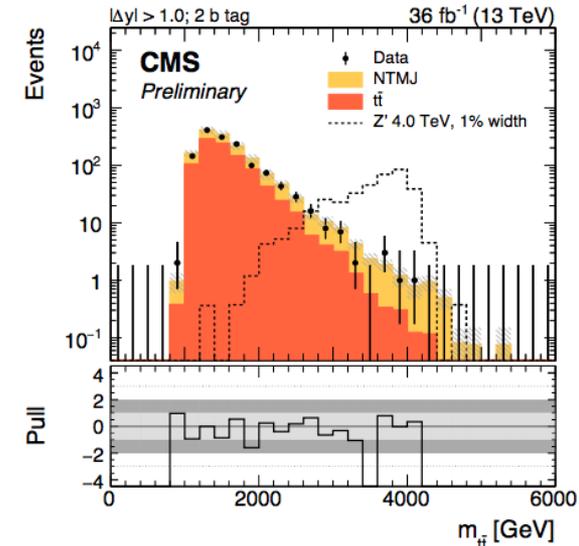
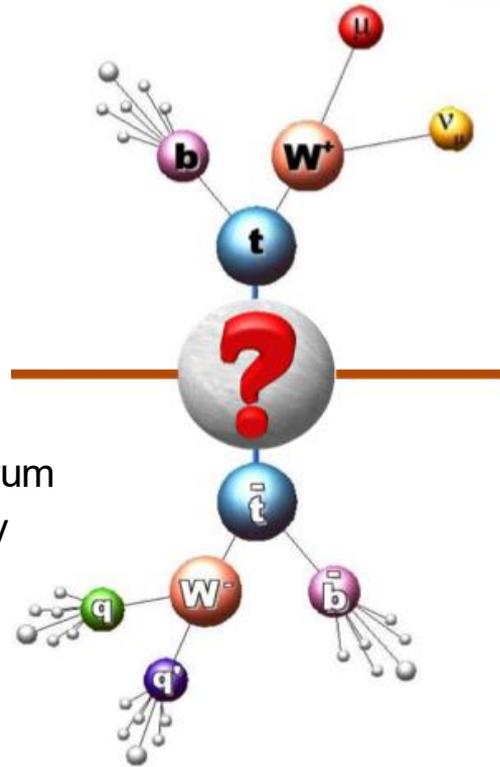
- Locate hadronic energy deposit in detector by choosing initial jet finding algorithm
- Impose jet selection cuts on fat jet
  - Recombine jet constituents with new algorithm
  - Filtering: recombine  $n$  sub-jets  $\min d(i,j)$
  - Trimming: recombine sub-jets with  $\min p_T$
- Minimum distance between jets is  $R$



# Top quark pair resonance

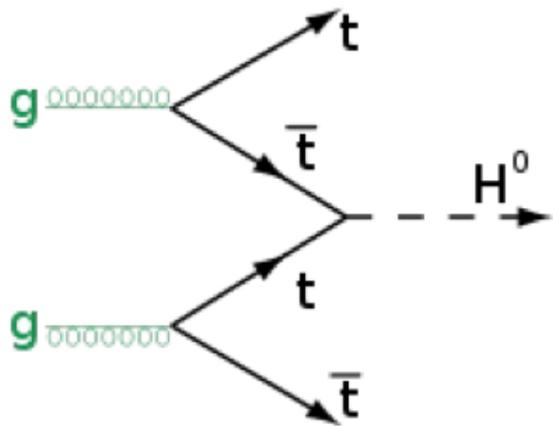
CMS-B2G-17-017, EPJC78(2018)565

- No resonance expected in SM
- Why is top so heavy?
  - new physics?
  - is third generation ‘special’?
- Search for massive neutral bosons decaying via a  $t\bar{t}$  quark pair
- Experimental check
  - search for bump in the inv. mass spectrum
  - progressive loss in reconstruction ability due to jet merging
  - reconstruct  $M_{t\bar{t}}$  in different categories ( $e/\mu$ ,  $n$ -jets,  $n$  b-tags)
  - $l$ +jet events: full event reconstruction
  - Subdivide in categories



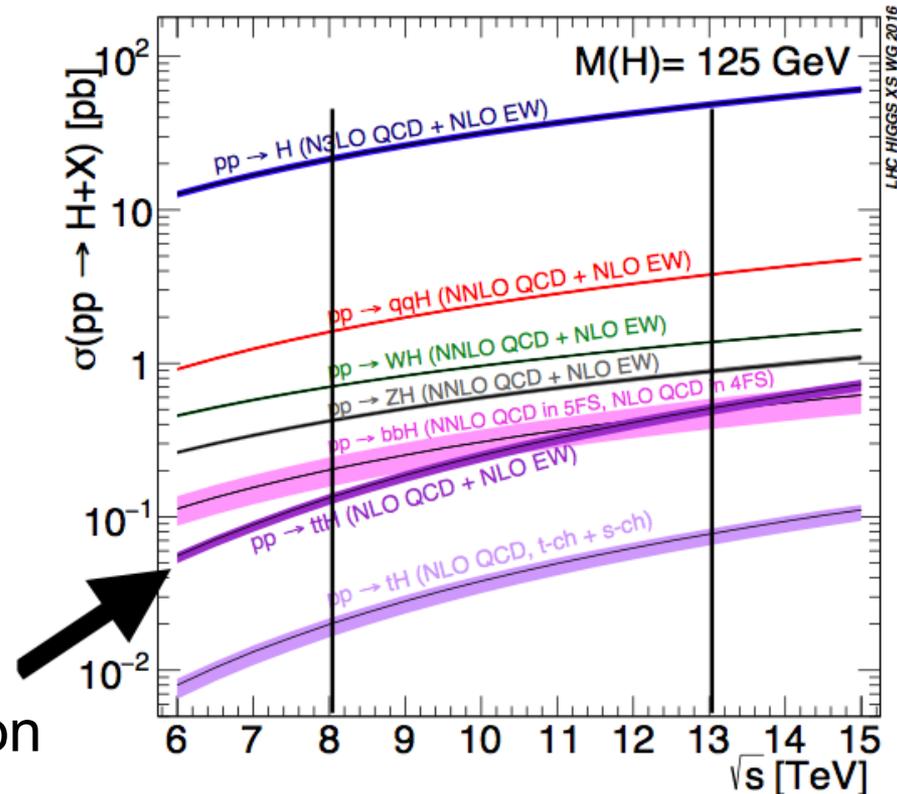
# ttbar+Higgs

- ttbar produced in association with H
  - ttbar is a “clean” tag
- direct measurement of Higgs couplings



Cross section for ttH at the LHC:  
 0.13 pb (8 TeV)  
 0.61 pb (14 TeV)

ttH ~1% of total Higgs cross section



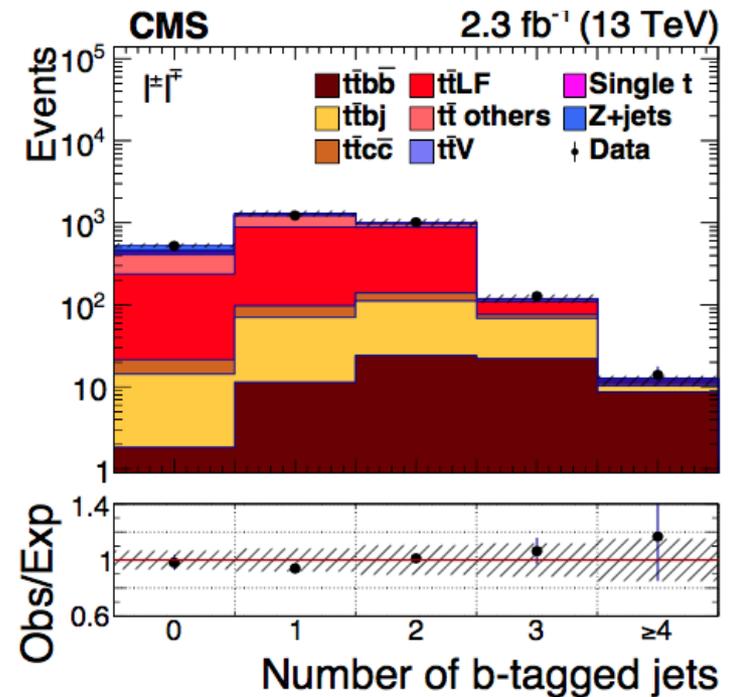
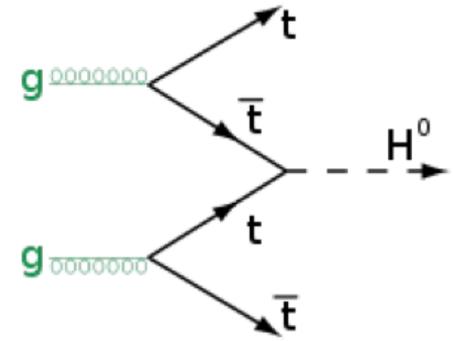
# ttbar+heavy flavour

arXiv:1411.5621, PLB776(2018)355

- Study rate of ttbb:  $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$
- Anomalous tt+jets could signal BSM final states
- First direct measurement of typical bkg to top-Higgs coupling
  - Irreducible non-resonant bkg from ttbb
- Improved theoretical understanding of ttH(bb) crucial to ttH and NP searches

$$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj} = 0.022 \pm 0.003 \text{ (stat)} \pm 0.005 \text{ (syst)}$$

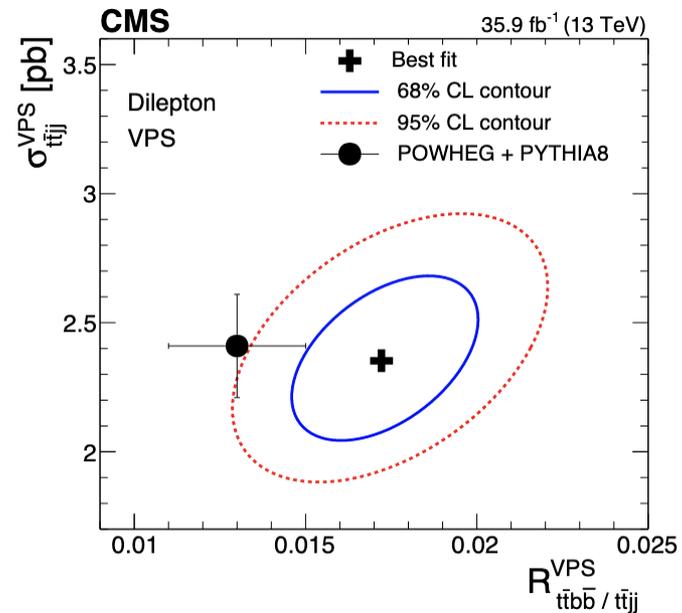
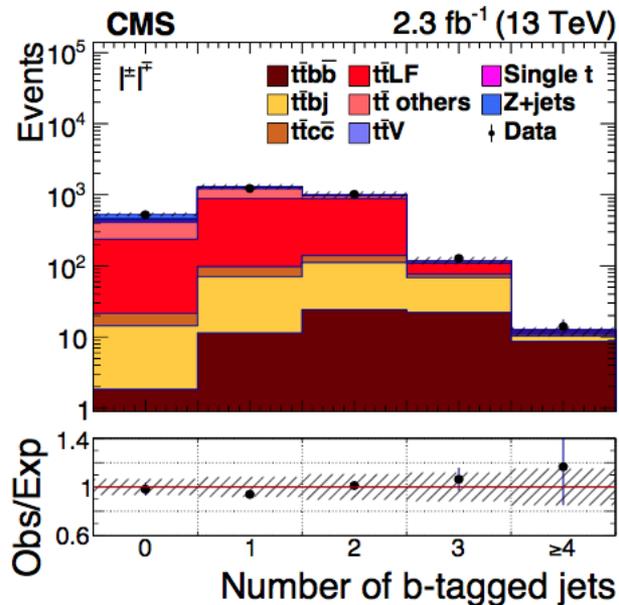
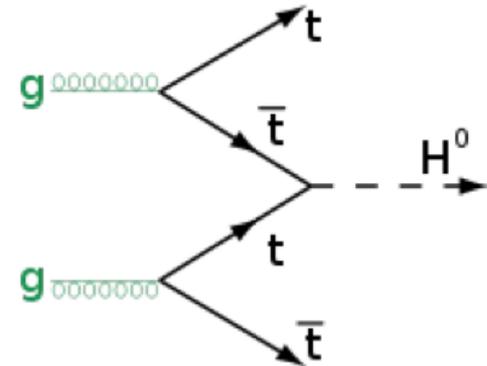
$$\sigma(\text{ttbb}) = 4.0 \pm 0.6 \text{ (stat)} \pm 1.3 \text{ (syst) pb}$$



# ttbar+heavy flavour

arXiv:1411.5621, PLB776(2018)355

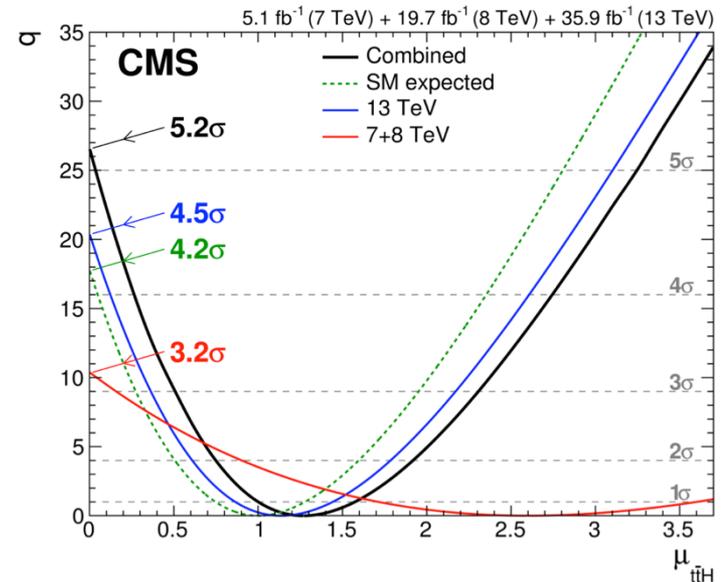
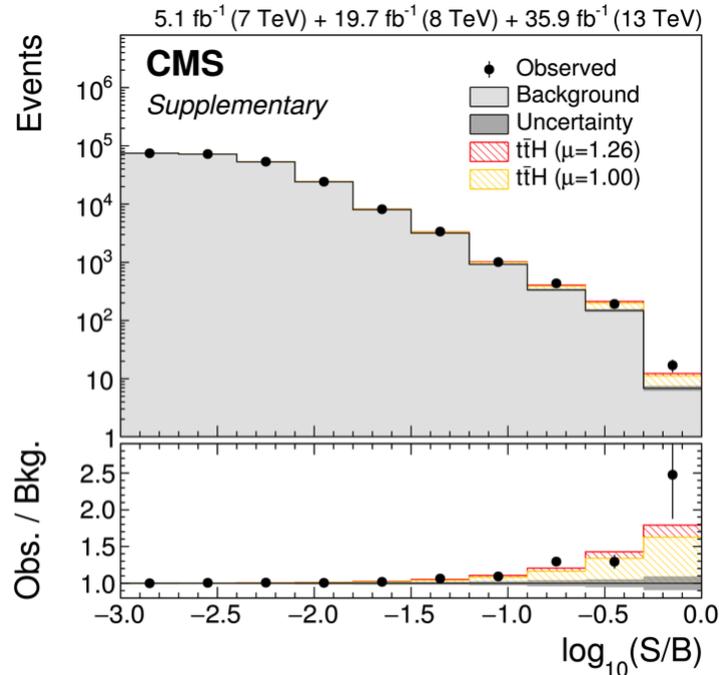
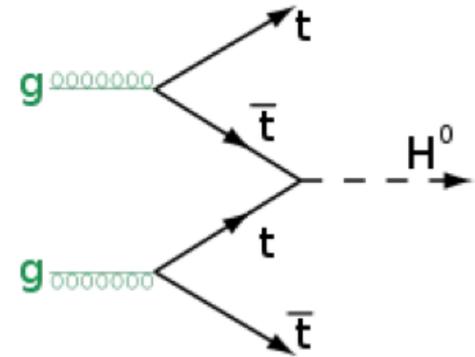
- Study rate of ttbb:  $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$
- Anomalous tt+jets could signal BSM final states
- direct measurement of bkg to top-Higgs coupling
  - Irreducible non-resonant bkg from ttbb
- Improved theoretical understanding of ttH(bb) crucial to ttH and NP searches



# Higgs couplings to top quarks

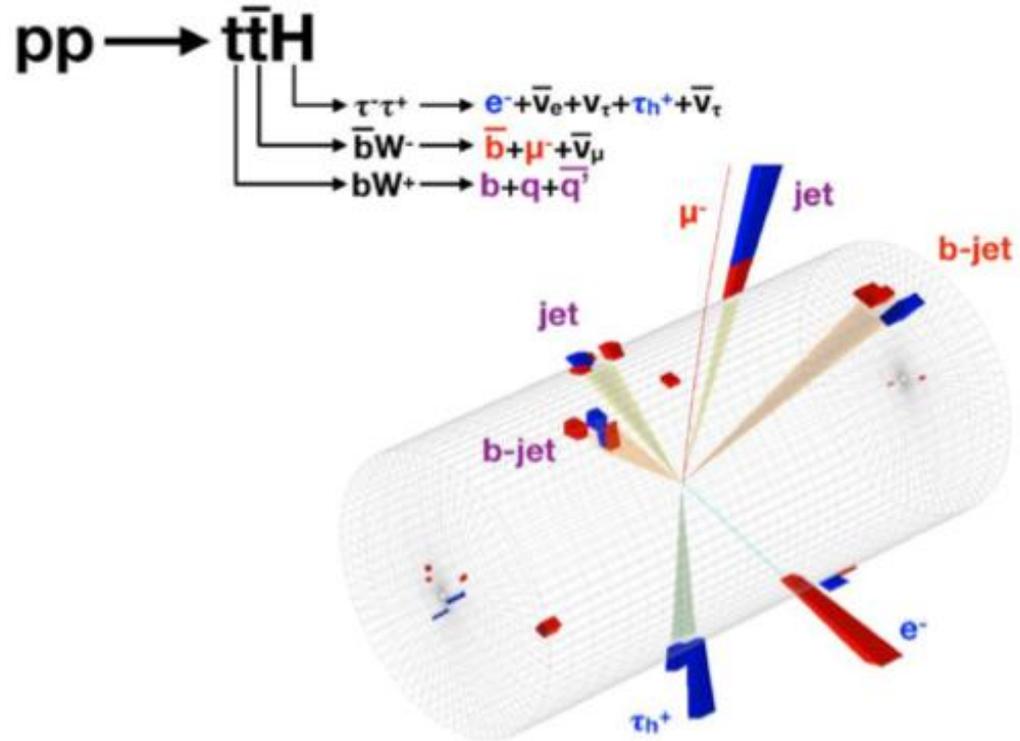
PRL 120(2018)231801, arXiv:1806:00242

- Direct study of Top-Higgs Yukawa coupling
- Explore all accessible Higgs decay modes
- Independent analysis of different final states (WW, ZZ,  $\gamma\gamma$ ,  $\tau\tau$ , bb)



# Event selection

- Improve sensitivity thanks to progress in data analysis strategies that use advanced algorithms
- Analysis workflow more efficient thanks to compressed data format

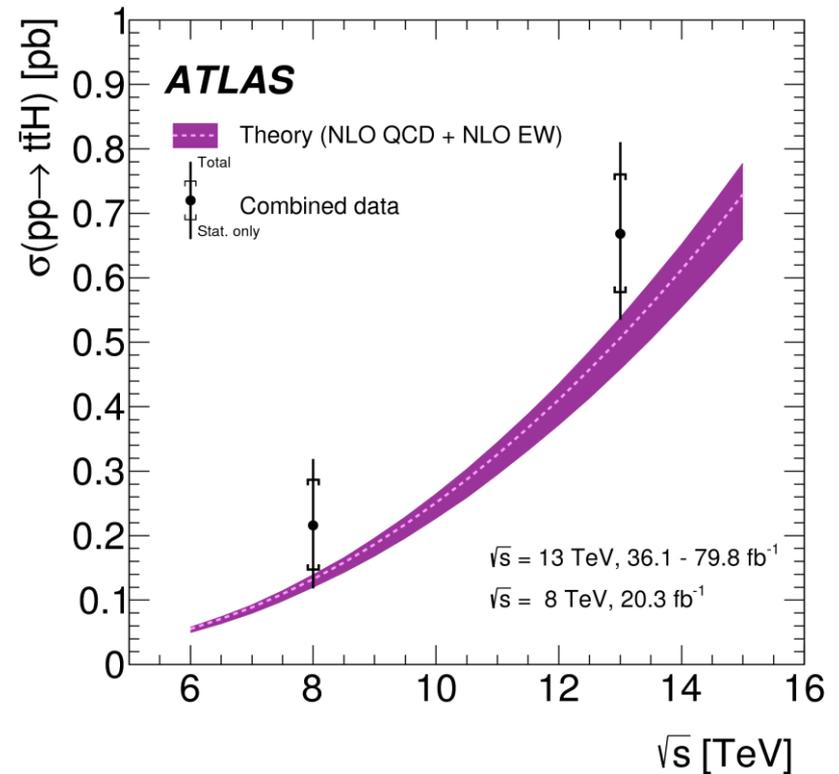
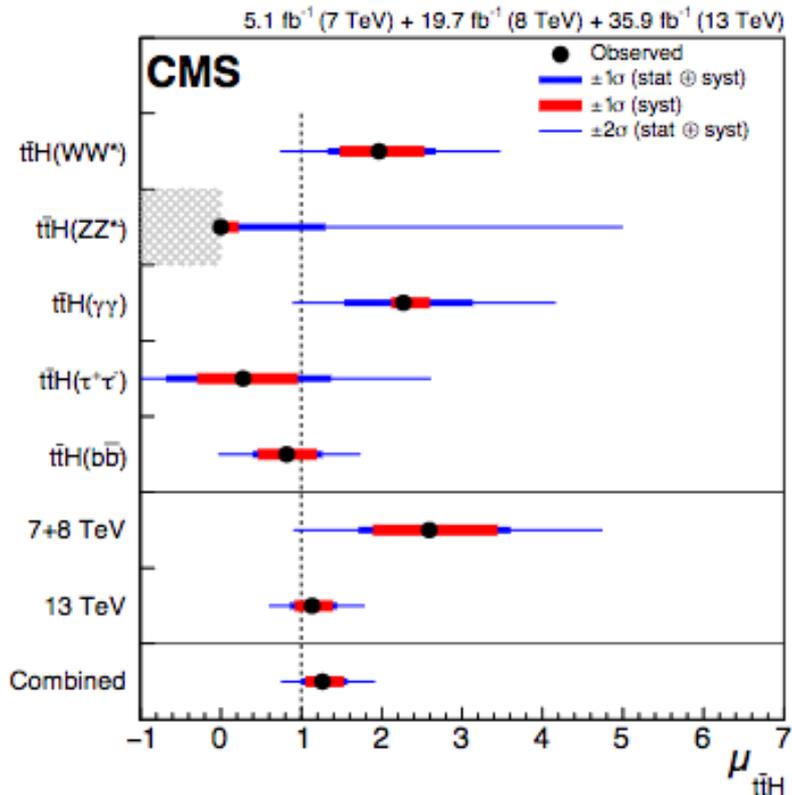


# Observation of ttH

PRL 120(2018)231801, arXiv:1806:00242

- Use several event categories
- Establishes directly tree-level coupling to an up-type quark

$$\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26}$$

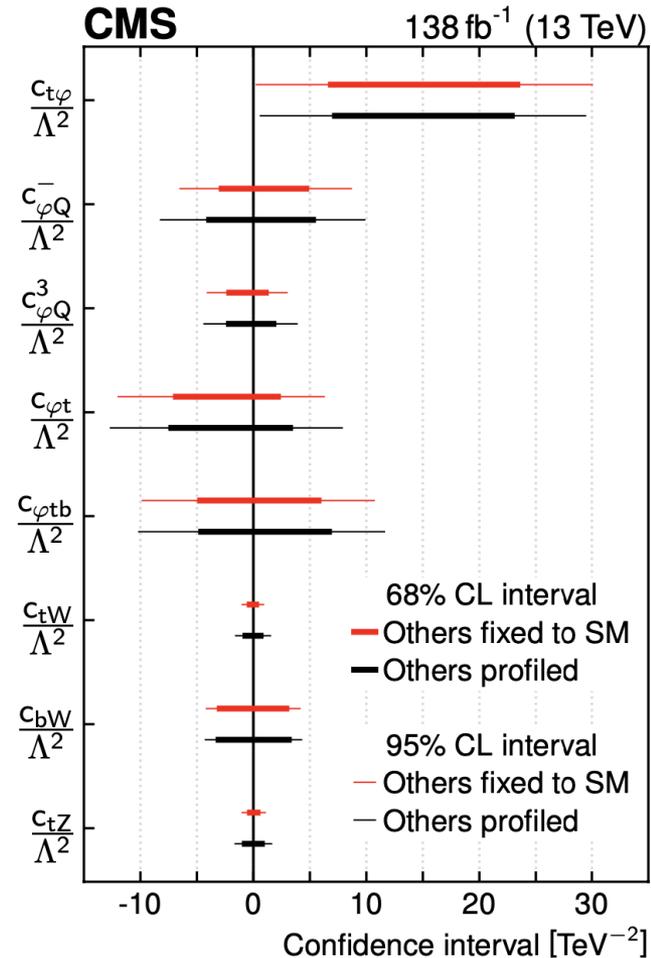
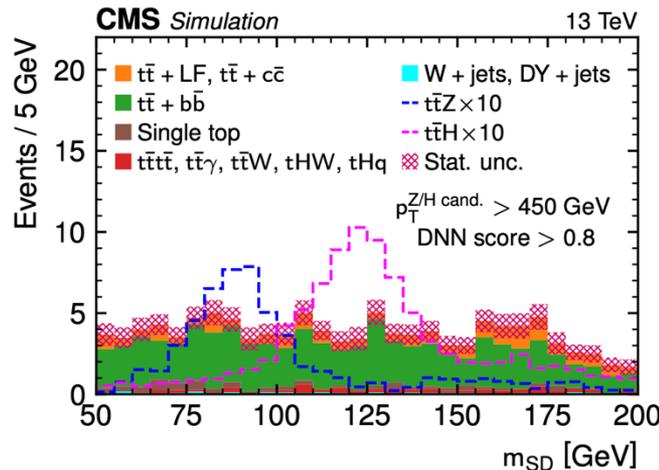
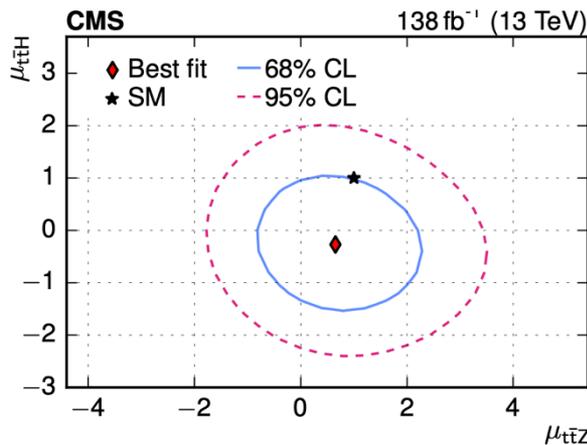
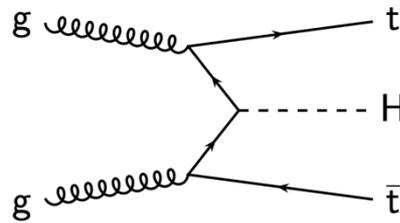
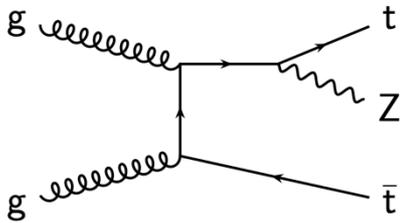


# ttH/Z with boosted Z/H

arXiv:2208.12837

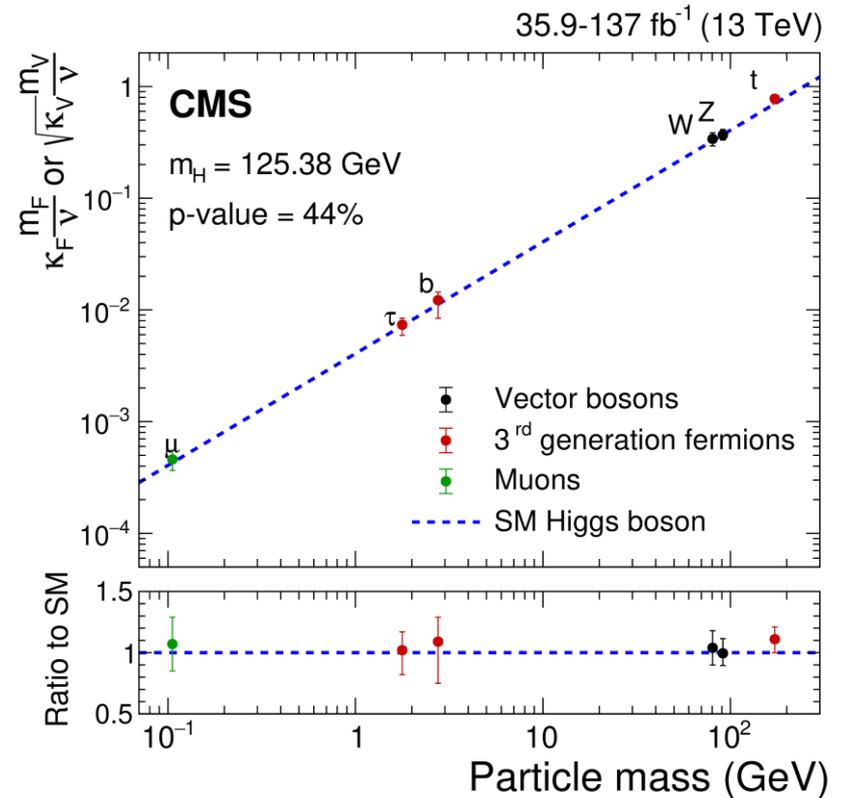
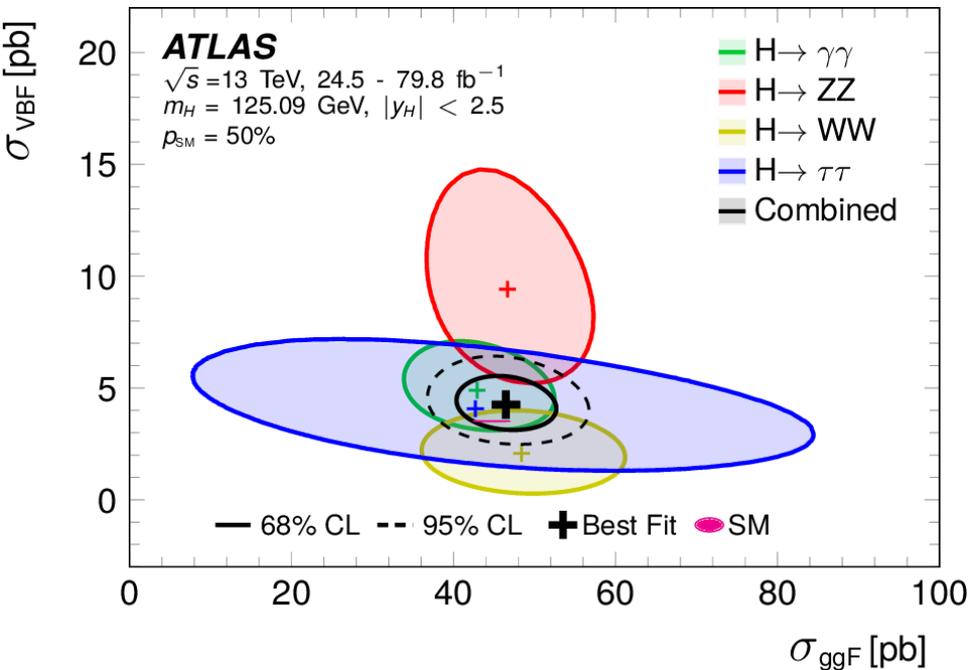
## Search for tt+ boosted Z/H → bb

- Direct access to top-Z and top-H couplings
- Signal strengths and differential cross section
- Search for EFT effects



# Consistency with SM

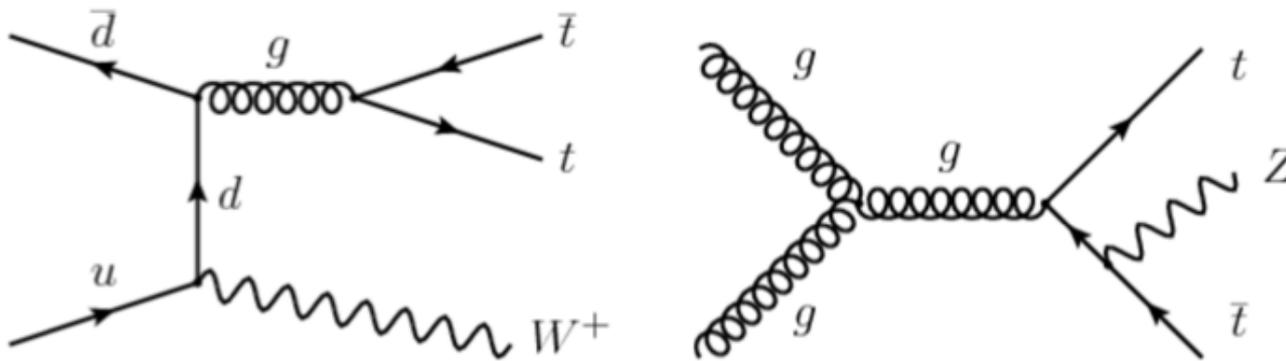
JHEP 08(2016)45, CMS-HIG-15-002, ATLAS-CONF-2015-044



VBF+VH: boson in production  
 ggF+ttH: fermions in production

# ttV production ( $V=\gamma, W, Z$ )

- Large datasets give access to rare tt+W and tt+Z processes
- ttZ: direct probe of top-Z coupling (new physics?)
- ttW: important background to NP searches

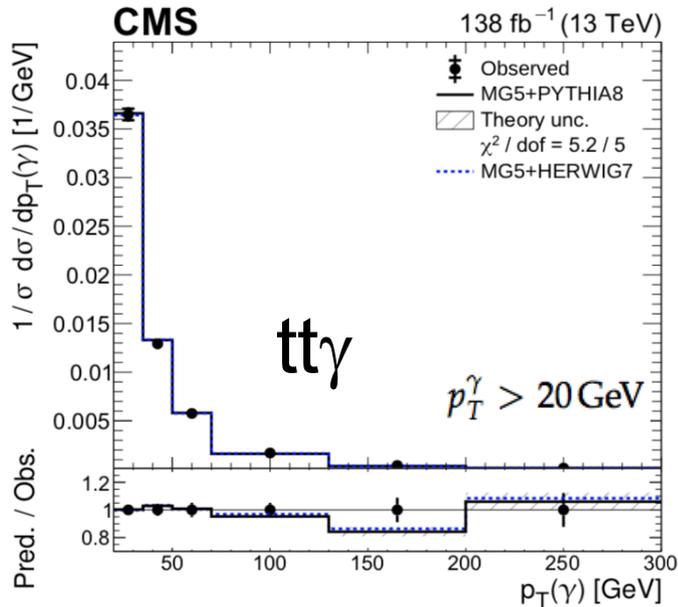


- Use multi-lepton final states
  - 2 same-sign charge leptons, 3 or 4 lepton final states

# ttV production (V=γ,W,Z)

arXiv:1808.02913, JHEP08(2018)011, arXiv:2201.07301

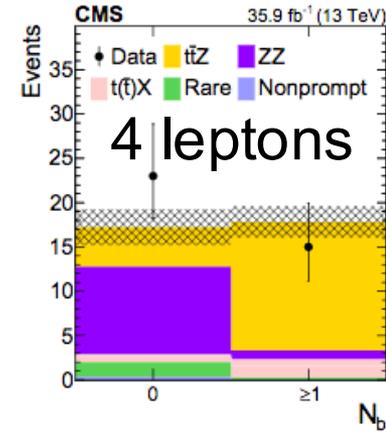
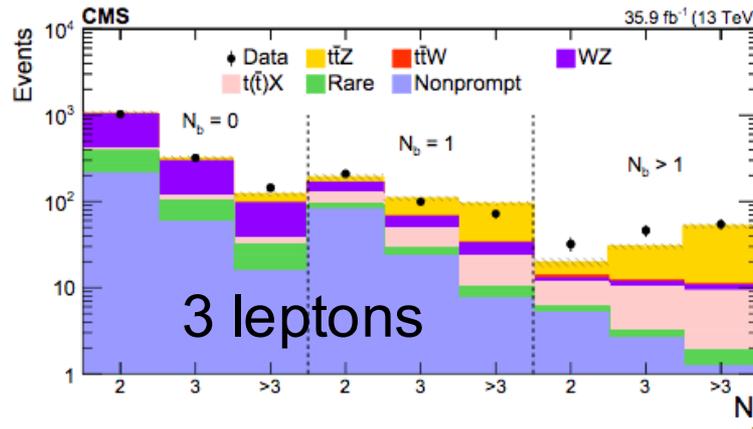
- Measurements gives access to EW couplings of the top



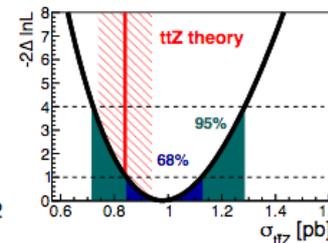
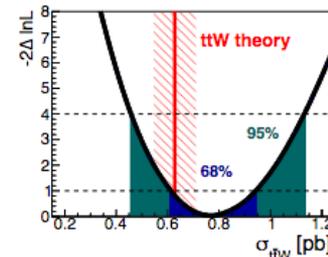
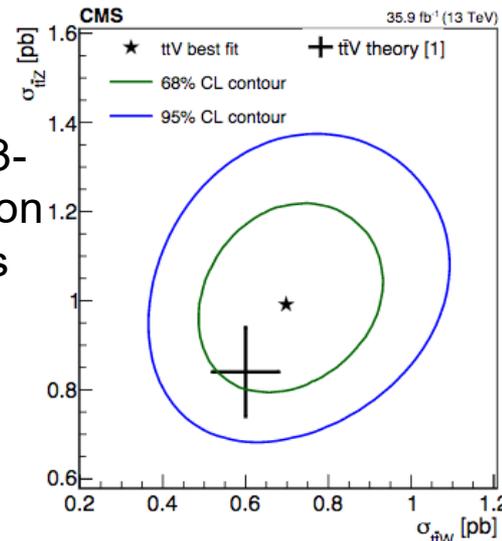
Measure:

$$\sigma_{\text{fid}}(pp \rightarrow t\bar{t}\gamma) = 173.5 \pm 2.5 \text{ (stat)} \pm 6.3 \text{ (syst)} \text{ fb}$$

⇒ Consistent with SM predictions



Combine 3- and 4-lepton final states



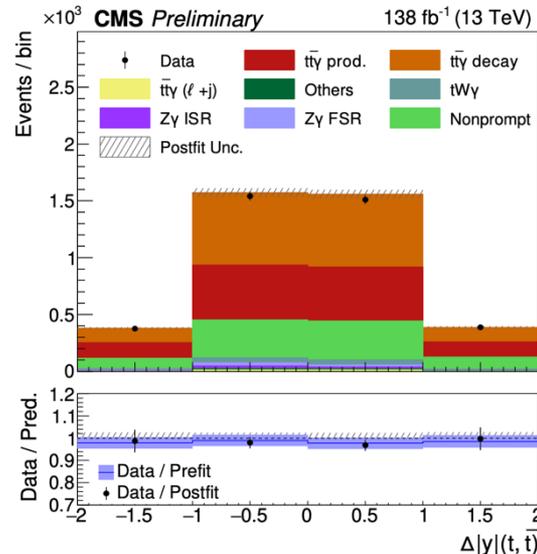
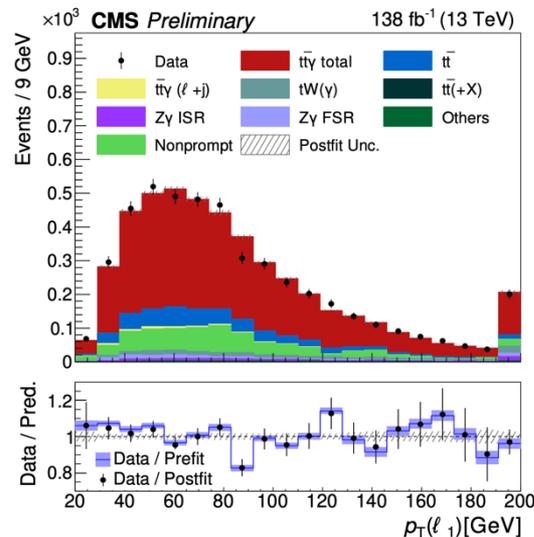
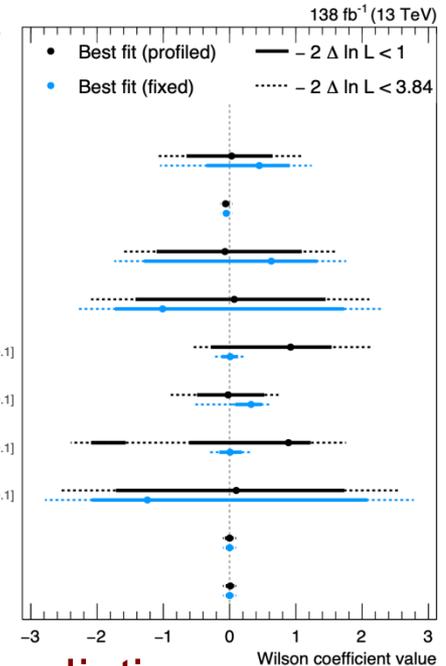
# Associated production: $t\bar{t}\gamma$ , $t\bar{t}Z$

CMS-TOP-23-002, arXiv:2507.17498

- $t\bar{t}$  + isolated photon
- Direct access to  $t\bar{t}\gamma$  coupling
- Measure:
  - $t\bar{t}\gamma$  inclusive and differential cross section
  - $R = \sigma(t\bar{t}\gamma) / \sigma(t\bar{t})$ : further enhancement in sensitivity
  - Charge asymmetry  $A_C = \frac{\sigma(\Delta|y| > 0) - \sigma(\Delta|y| < 0)}{\sigma(\Delta|y| > 0) + \sigma(\Delta|y| < 0)}$

- $t\bar{t}$  + Z, WW/ZZ multilepton final states
- Probe lepton flavour structure w/different quark generations
- Study dim-6 EFT operators

**CMS**

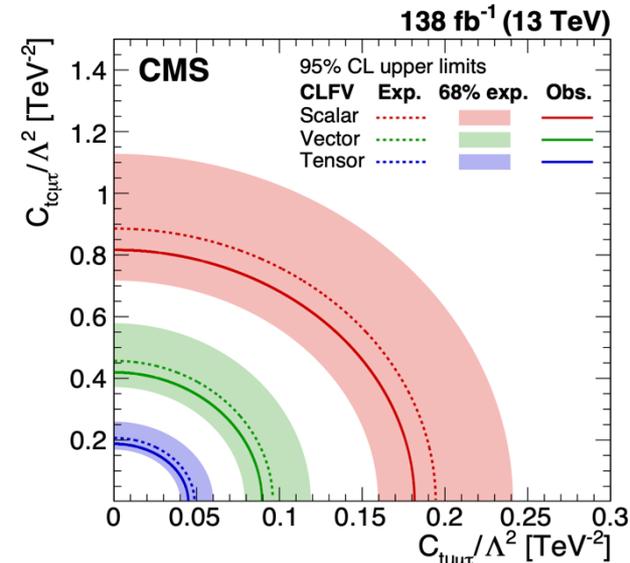
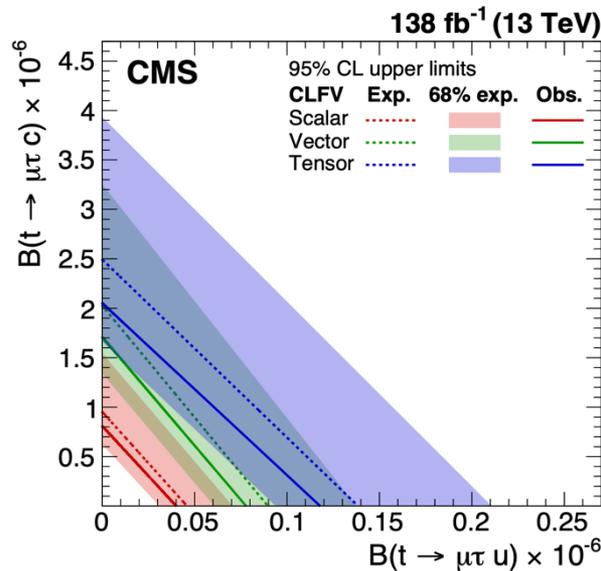
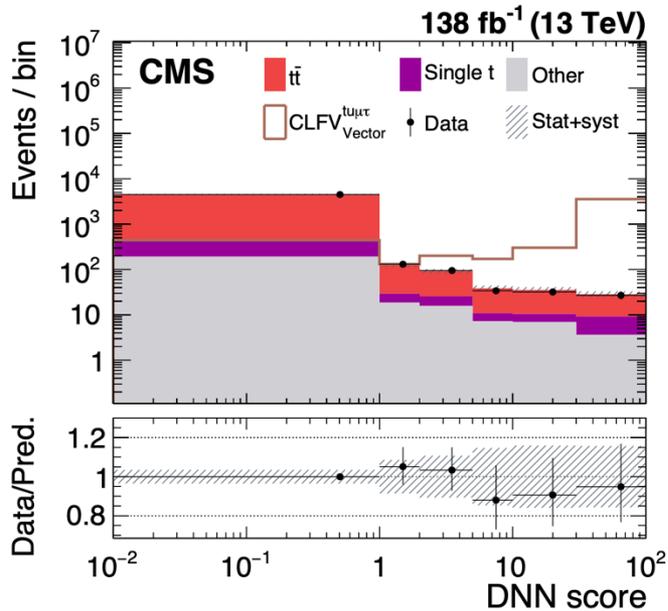
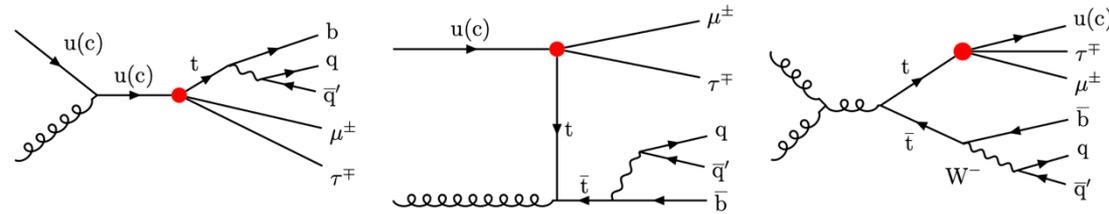


⇒ measurements are consistent with SM predictions

# Lepton Flavour Violation

arXiv:2504.08532

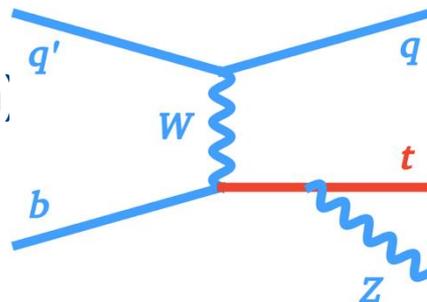
- Top quark(s) production followed by cLFV decay:  $B(t \rightarrow \mu \tau q)$ 
  - Final state with:  $\mu$ ,  $\tau_h$ , multiple jets
- Set most stringent upper limits on Wilson coefficients related to cLFV interactions



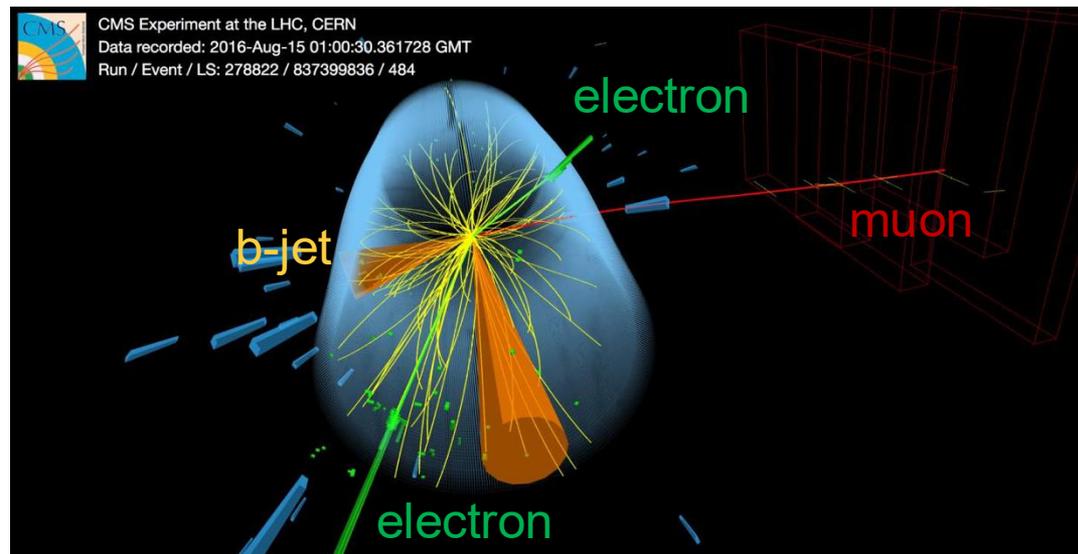
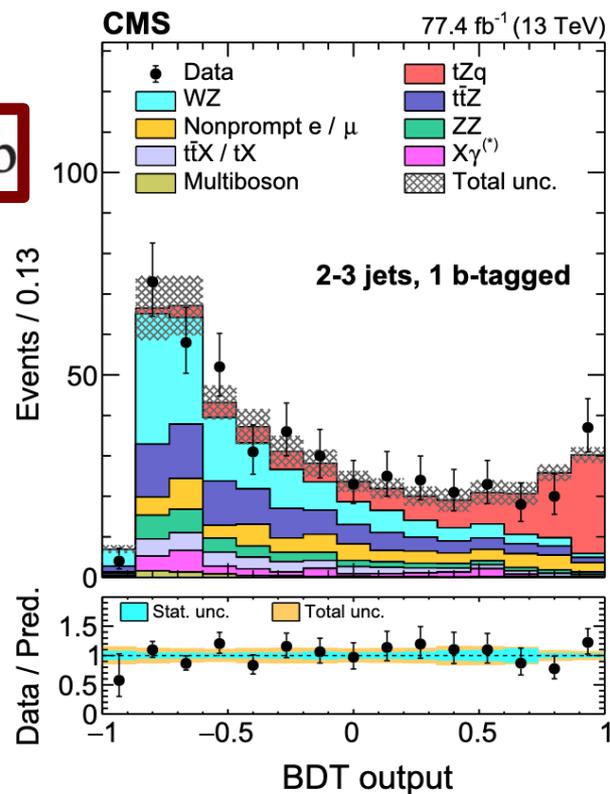
# Top-Z coupling

PRL 122(2019)132003

- Small production rate (~50 times smaller than that of the Higgs boson) and large backgrounds



$$\sigma(pp \rightarrow tZq \rightarrow t\ell^+\ell^-q) = 111 \pm 13(\text{stat})_{-9}^{+11}(\text{syst}) \text{ fb}$$



# Flavor Changing Neutral Currents

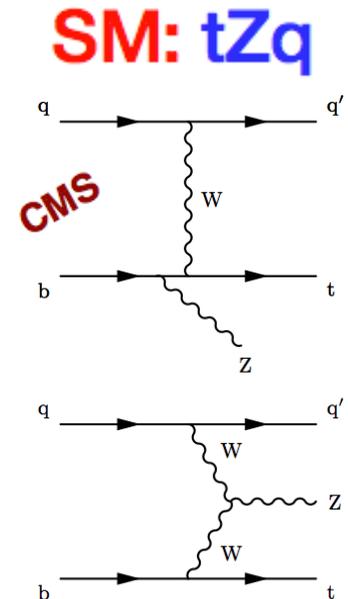
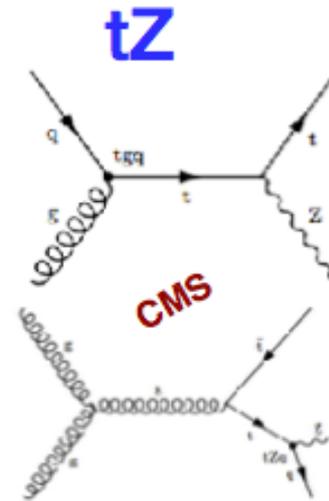
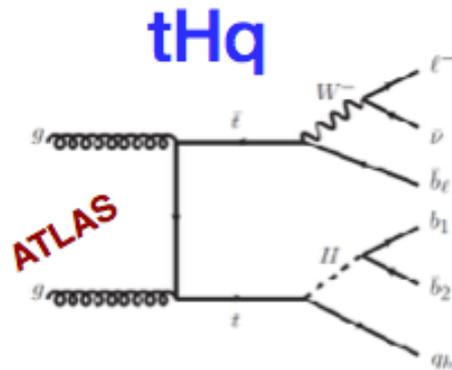
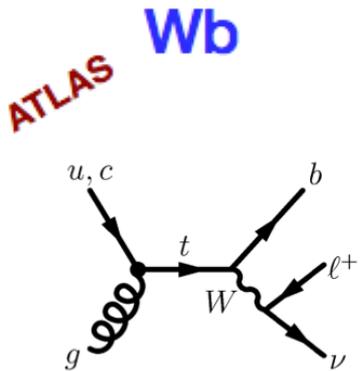
- FCNC: top couples to light quarks (u/c) and neutral bosons ( $\gamma, Z, H, g$ )
- Forbidden at tree level in SM
- Very small rates predicted
- Deviations would give hint for NP

Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \rightarrow Zu$	$7 \times 10^{-17}$	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \rightarrow Zc$	$1 \times 10^{-14}$	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \rightarrow gu$	$4 \times 10^{-14}$	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \rightarrow gc$	$5 \times 10^{-12}$	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \rightarrow \gamma u$	$4 \times 10^{-16}$	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \rightarrow \gamma c$	$5 \times 10^{-14}$	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \rightarrow hu$	$2 \times 10^{-17}$	$6 \times 10^{-6}$	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \rightarrow hc$	$3 \times 10^{-15}$	$2 \times 10^{-3}$	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

# Flavor Changing Neutral Currents

- Expect small signal from SM
- ...but signal may be large in BSM models

Final states:



Couplings:

$t \rightarrow ug$

$t \rightarrow cg$

$t \rightarrow uH$

$t \rightarrow cH$

$t \rightarrow ug, t \rightarrow cg$

$t \rightarrow uZ, t \rightarrow cZ$

$t \rightarrow tZ$

$$\sigma_{qg \rightarrow t} \times B(t \rightarrow Wb) < 3.4 \text{ pb}$$

$$\sigma_{qg \rightarrow t} \times B(t \rightarrow Wb) < 2.9 \text{ pb}$$

$$B(t \rightarrow Hc) < 0.40\%$$

$$B(t \rightarrow Hu) < 0.55\%$$

$$B(t \rightarrow Zu) < 0.022\%$$

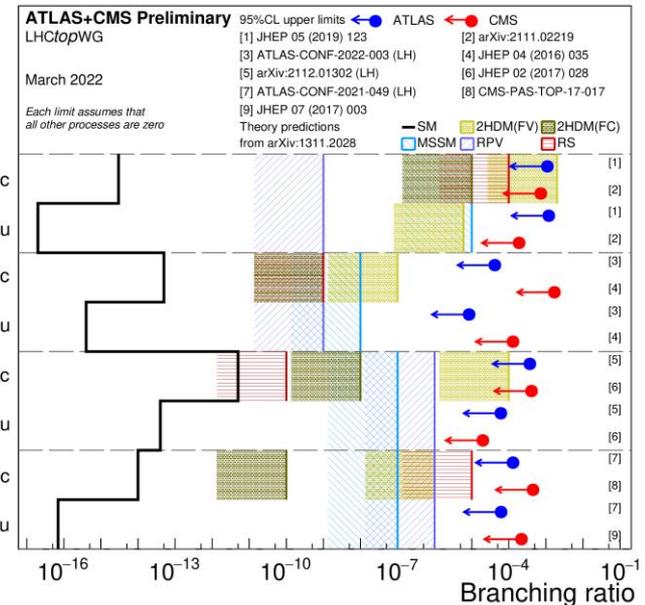
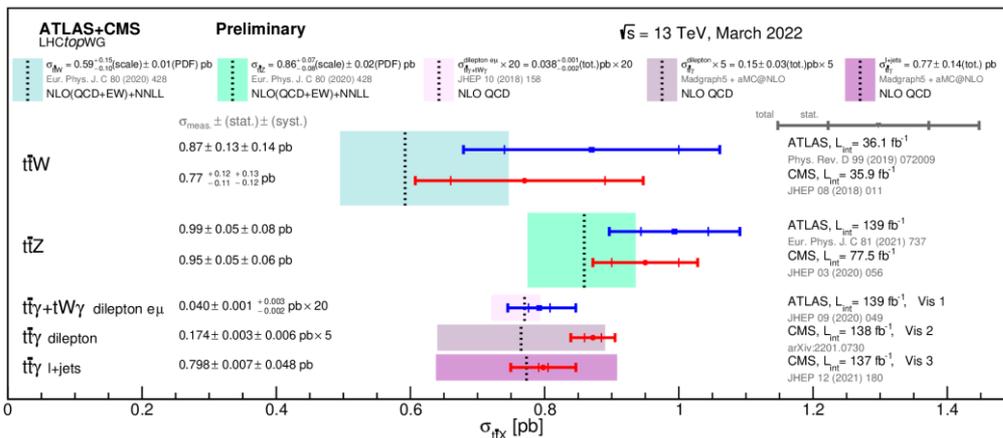
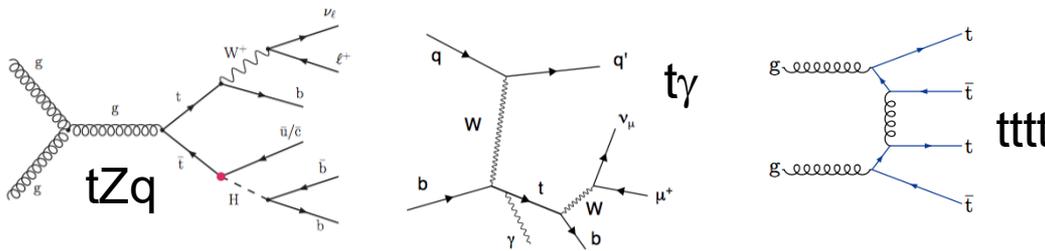
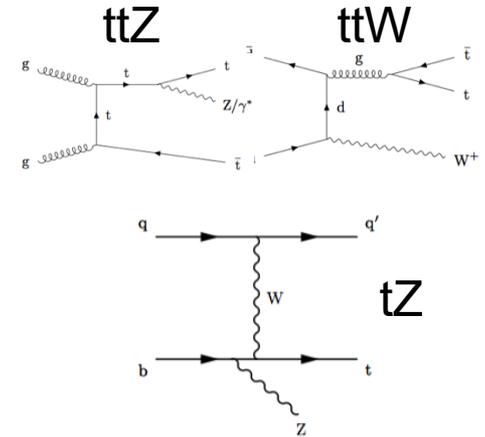
$$B(t \rightarrow Zc) < 0.049\%$$

$$\text{SM } \sigma(tZq) = 10^{+8-7} \text{ fb}$$

# Top quarks and rare decays

arXiv:1711.02547, PLB779(2018)358, EPJC78(2018)140, PRL 121(2018)221802

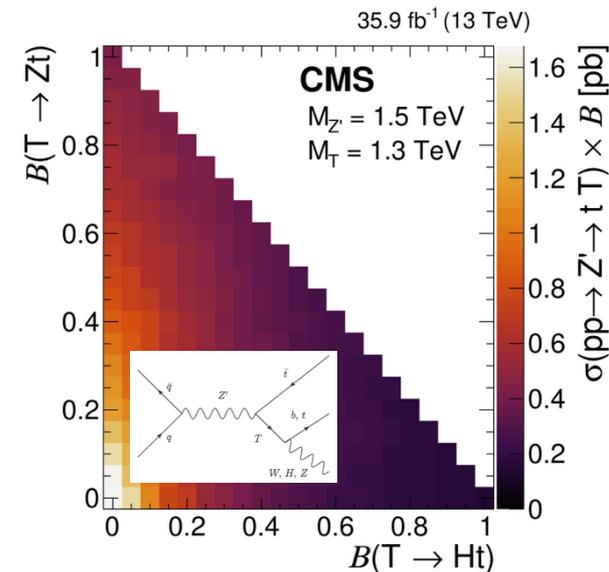
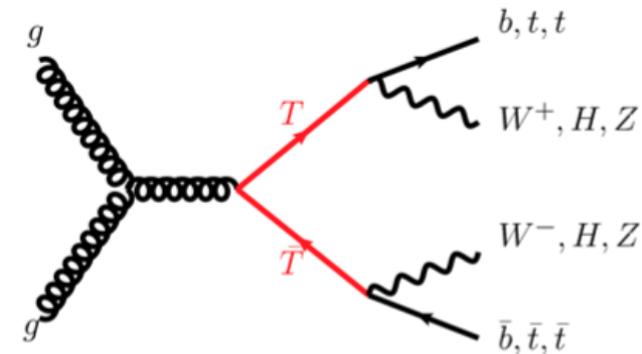
- Heaviest fundamental particle
- Study naked quark, decays before hadronization
- Strongly interacting with EWK sector and Higgs
- Anomalous couplings:  $Wtb$  vertex may include BSM terms



# Vector-like quarks

EPJC79(2019)364

- Predicted in many BSM models, aim to solve the hierarchy problem
  - Produced through strong interactions
  - left- and right-handed components with same quantum numbers
- VLQs can mix with SM quarks and modify the couplings to the Z/W/Higgs bosons
- Search for VLQ **single** and **pair production**
  - Most searches assume VLQs couple/decay to SM particles (bosons and 3<sup>rd</sup> generation quarks)
  - FCNC decays
- Busy events, a lot of top quarks, bottom quarks, leptons and jets in final state
  - Example: 2 tops in final state
  - use top/H/W/Z taggers to find hadronic decays



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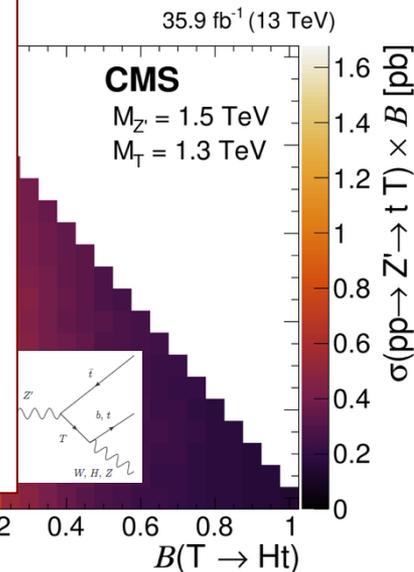
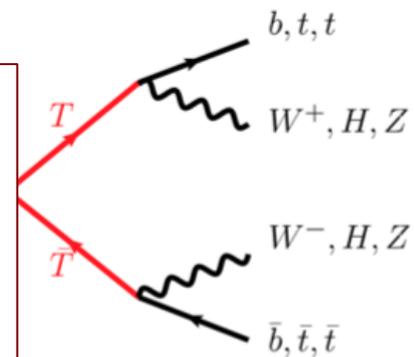
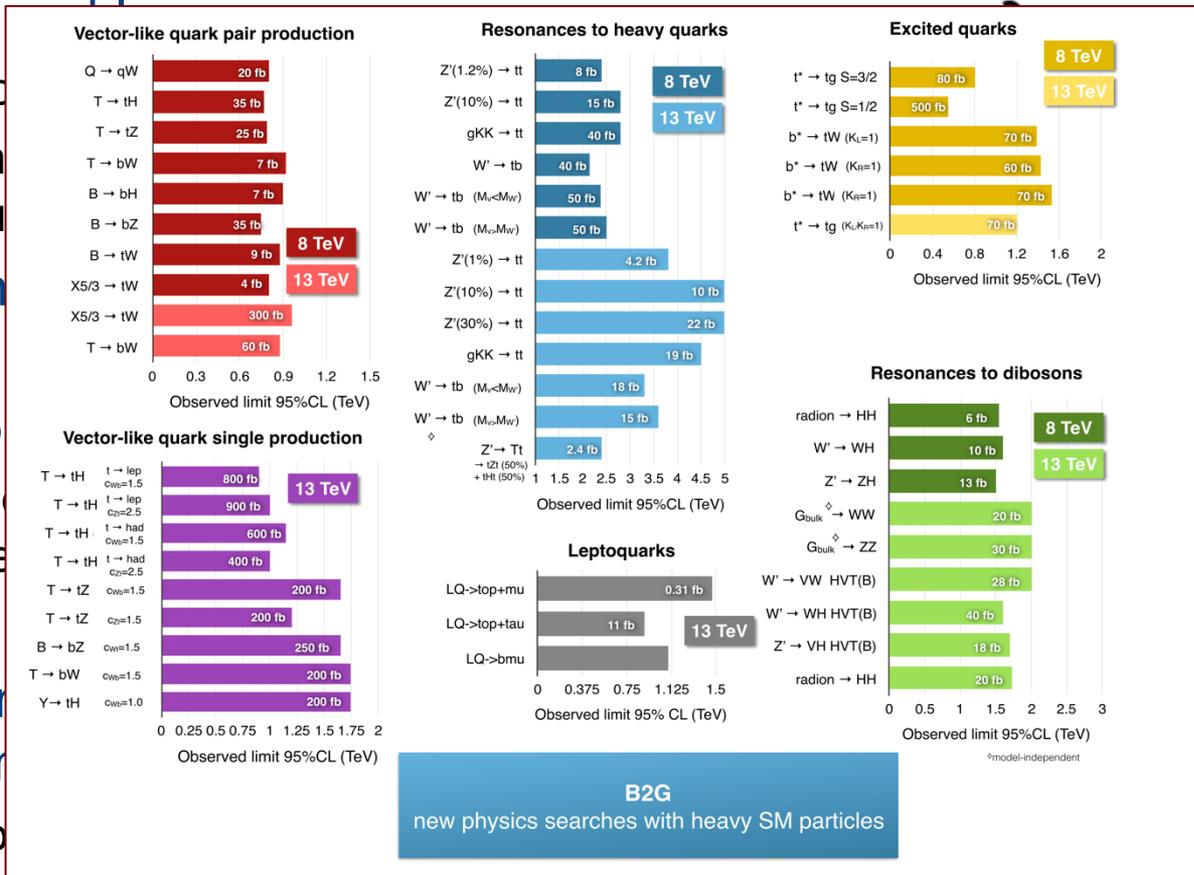
- Predicted in many BSM models, aim to solve the hierarchy problem

- Produced in pairs
- left- and right-handed quantum numbers

- VLQs can have anomalous couplings

- Search for FCNC
- Most sensitive to new particle production

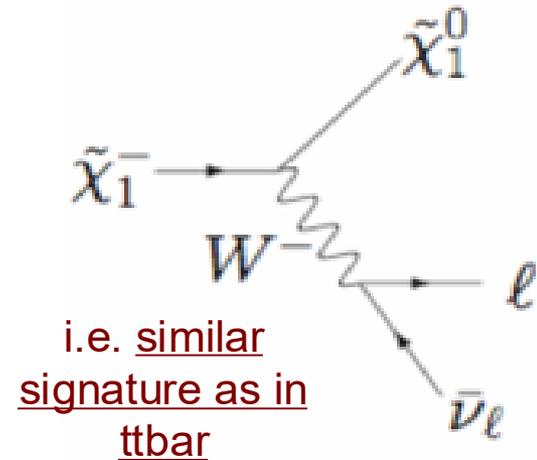
- Busy even if leptons are not produced
- Example:  $Z \rightarrow T \rightarrow Ht$
- use top/H/W/Z taggers to find hadronic decays



B2G  
new physics searches with heavy SM particles

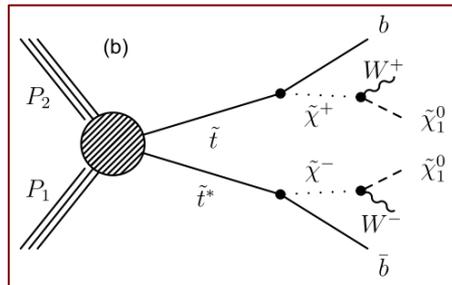
# Scalar top quark

- SUSY is one plausible extension of the SM
- due to the heavy top quark, mass splitting between  $\tilde{t}_1$  and  $\tilde{t}_2$  can be large, such that the lighter stop  $\tilde{t}_1$  can be even lighter than the top quark
- Decays dictated by mass spectrum of other SUSY particles



- Light stop:

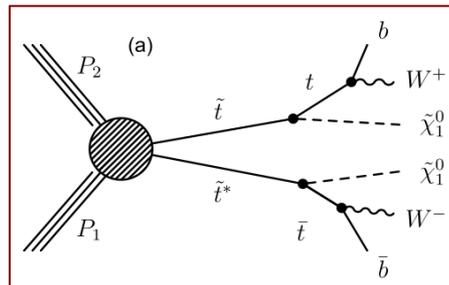
$$m_{\tilde{t}_1} \lesssim m_t$$



$$\tilde{t} \rightarrow b \tilde{\chi}^+ \rightarrow b W \tilde{\chi}_1^0$$

- Heavy stop:

$$\tilde{t} \rightarrow t \tilde{\chi}^0$$



$$\tilde{t} \rightarrow t \tilde{\chi}_1^0 \rightarrow b W \tilde{\chi}_1^0$$

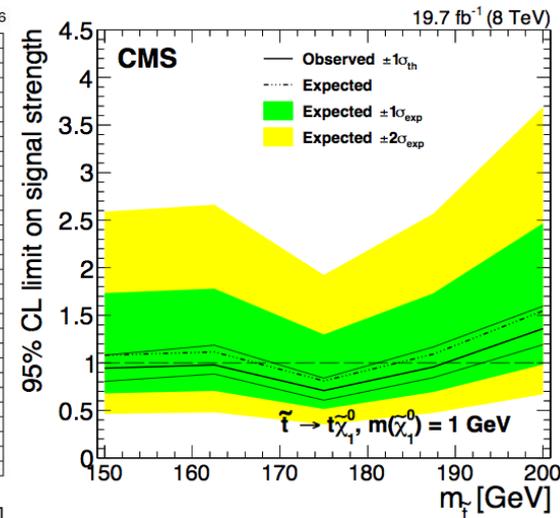
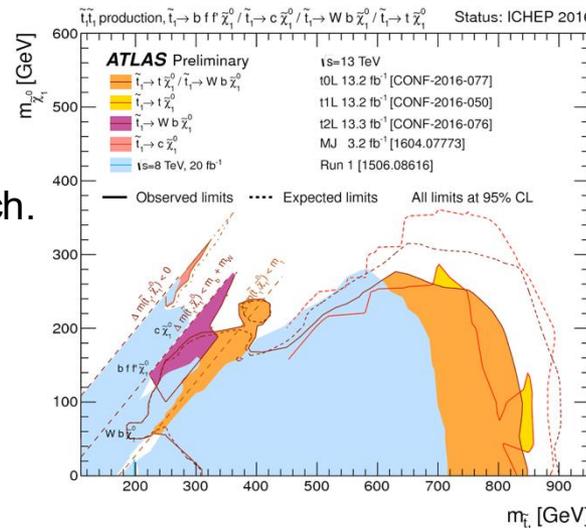
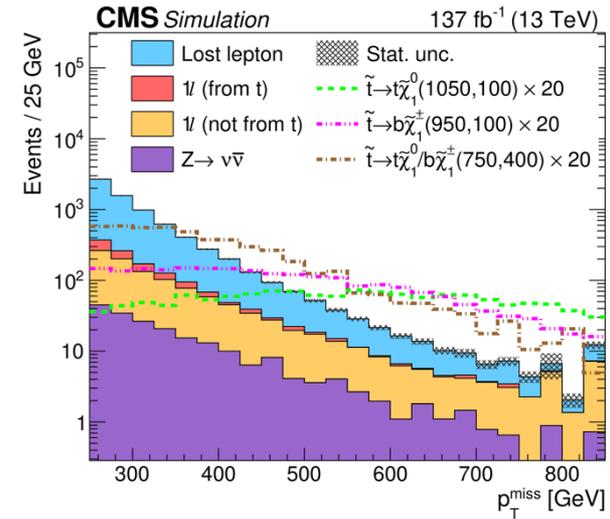
# Top and SUSY

arXiv:1603.02303, JHEP05(2020)032

- If SUSY exists and is responsible for solution of hierarchy problem, naturalness arguments suggest that SUSY partners of top quark (*stop*) may have mass close to  $m_{top}$  to cancel top quark loop contributions to Higgs mass

$$\begin{aligned} \tilde{t} &\rightarrow t \tilde{\chi}_1^0 \rightarrow b W \tilde{\chi}_1^0 && \text{"heavy"} \\ \tilde{t} &\rightarrow b \tilde{\chi}_1^+ \rightarrow b W \tilde{\chi}_1^0 && \text{"light"} \end{aligned}$$

- Small predicted cross section
  - for 175GeV: 40pb@8TeV
- Stop pair production:  $t\bar{t} \tilde{\chi}_1^0 \tilde{\chi}_1^0$ 
  - similar to  $t\bar{t}$  lepton+jet and dilepton ch.
  - additional MET from neutralinos
- change in  $t\bar{t}$  cross section



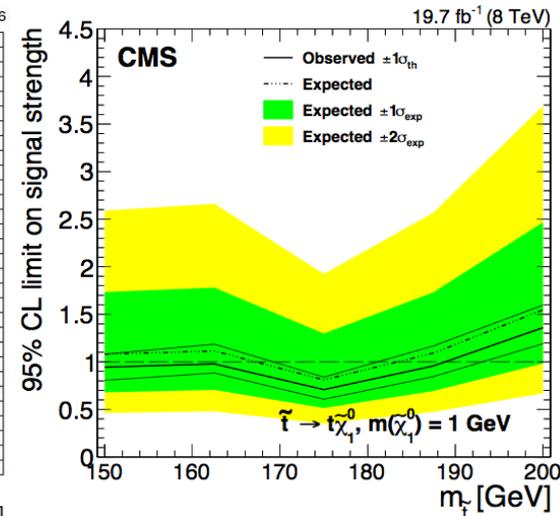
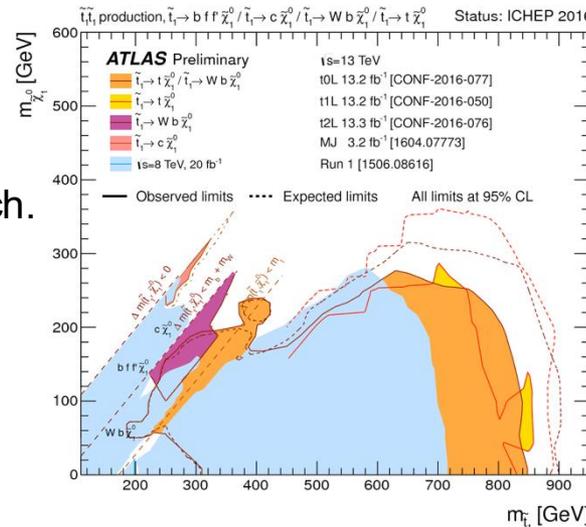
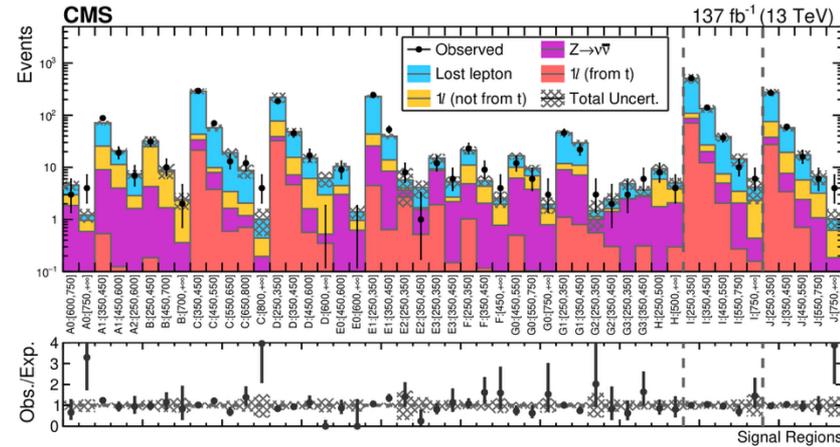
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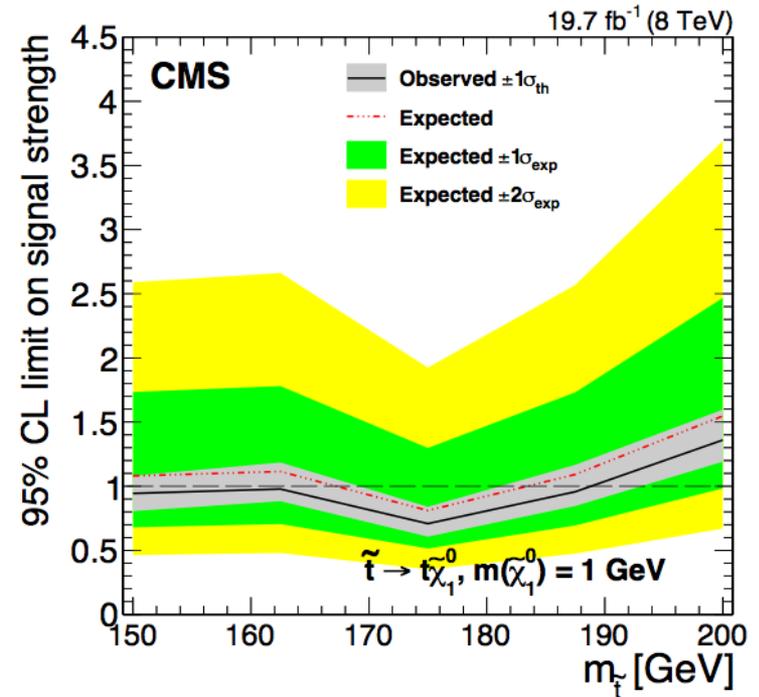
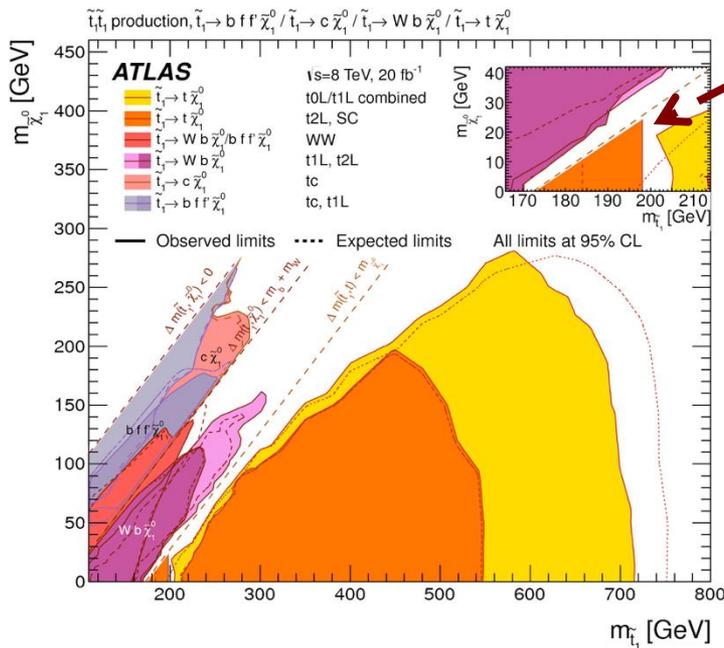
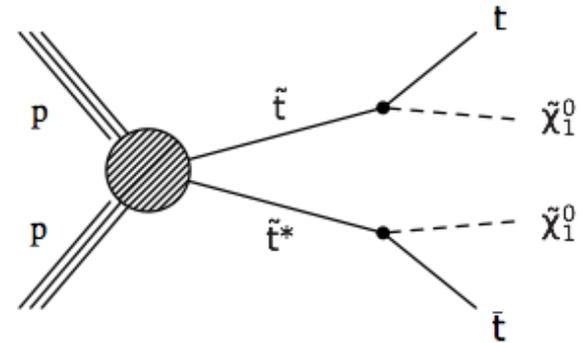
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# Top cross section: dileptons

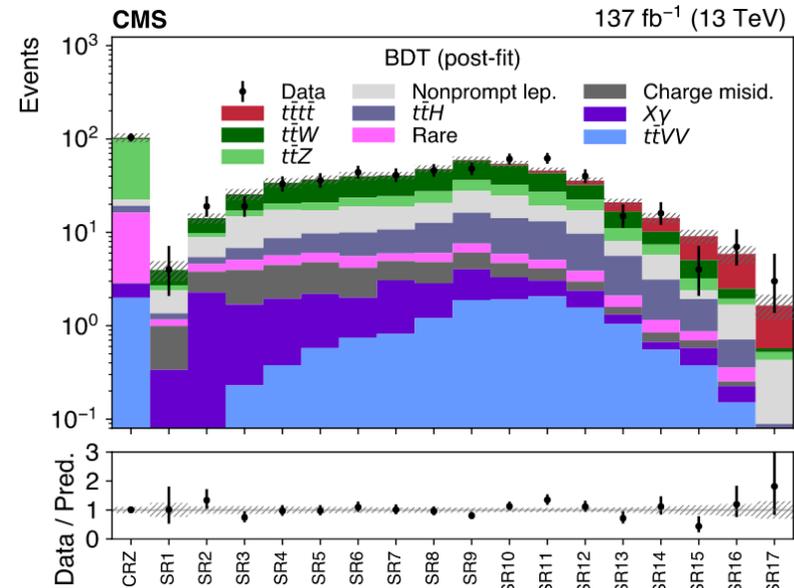
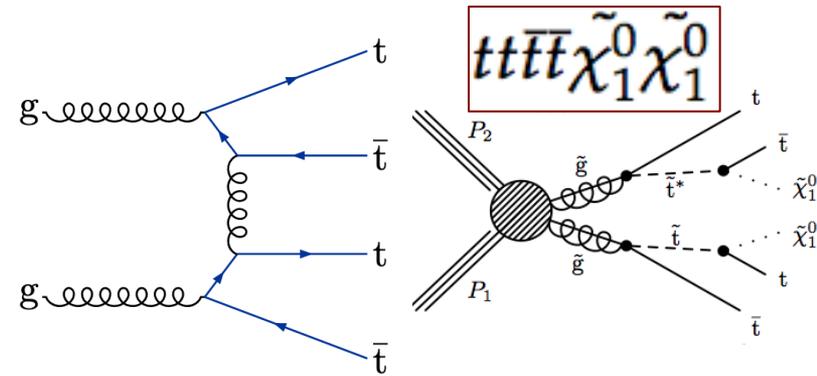
- Indirect searches
- SUSY models could produce final states very similar (with additional MET)
- For example: dilepton channel



# Multi-top production

arXiv:1605.03171, EPJC 80(2020)75, JHEP11(2021)118

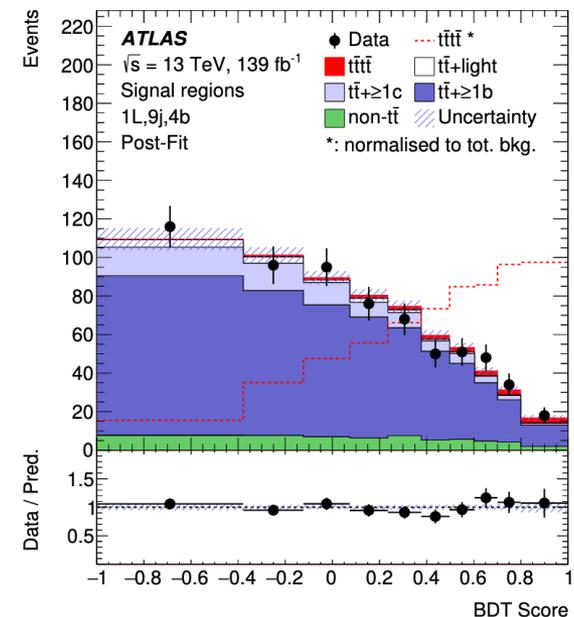
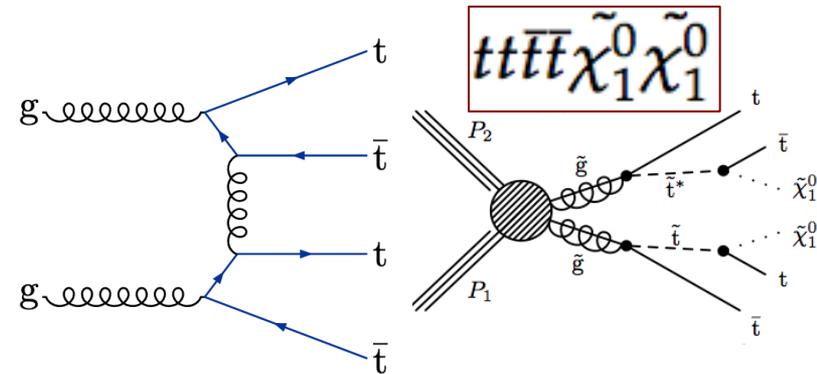
- Production of 4 tops is an attractive scenario in a number of new physics models
- The SM cross section is 12fb@13TeV
- Use dilepton and lepton+jets final states
- Combination of kinematical variables and BDT
- Search for same-sign dileptons, or >2 leptons
- Consider multiple **control-** and **search-regions** defined by MET, hadronic energy, number of (b-) jets, and  $p_T$  of the leptons in the events
- Measure cross section:  $\sigma = 12.6^{+5.8}_{-5.2} \text{ fb}$



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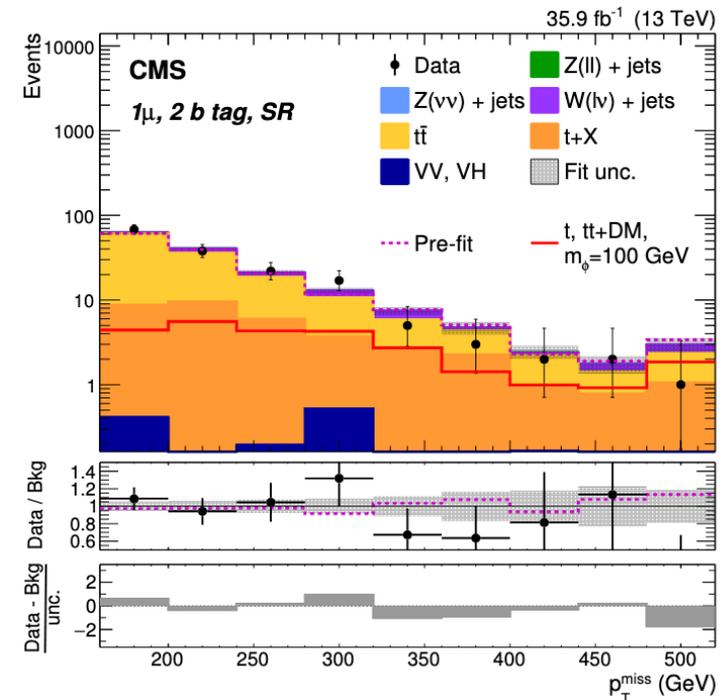
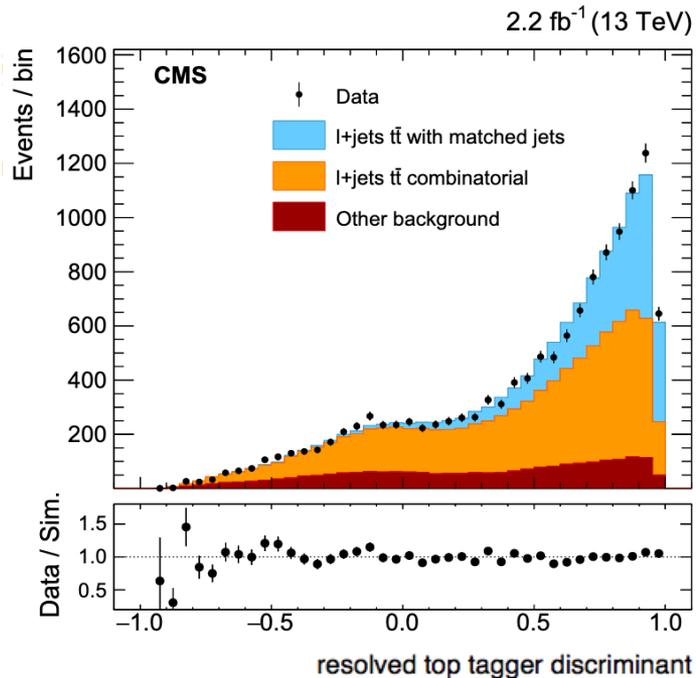
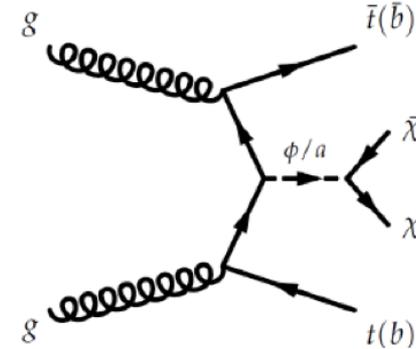
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- Measure cross section:  $\sigma = 12.6^{+5.8}_{-5.2}$  fb.
- Limits on Yukawa couplings:  $|y_t/y_t^{\text{SM}}| < 1.7$ .



# Dark Matter + $t\bar{t}$

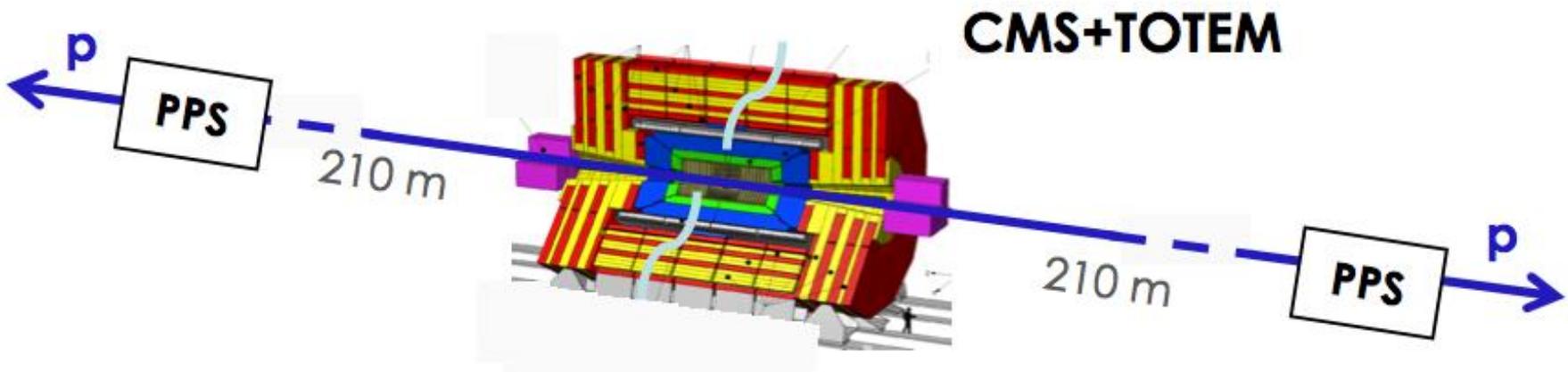
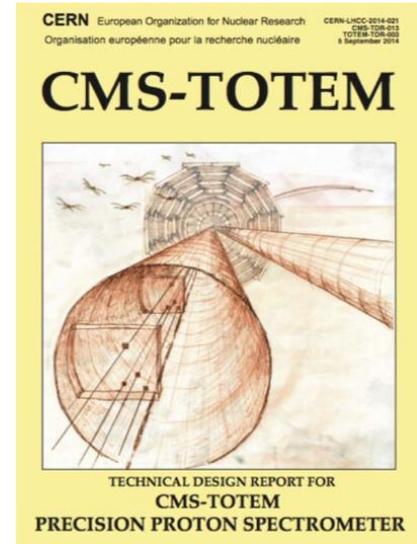
EPJC 77(2017)845, JHEP 03(2019)141

- Search for DM +  $t\bar{t}$  ( $\rightarrow l + \text{jets, all hadr.}$ )
- Shape of MET distribution
- Signature:  $t\bar{t}$  + MET
- Top-tagging categorization
- Signal events at large MET



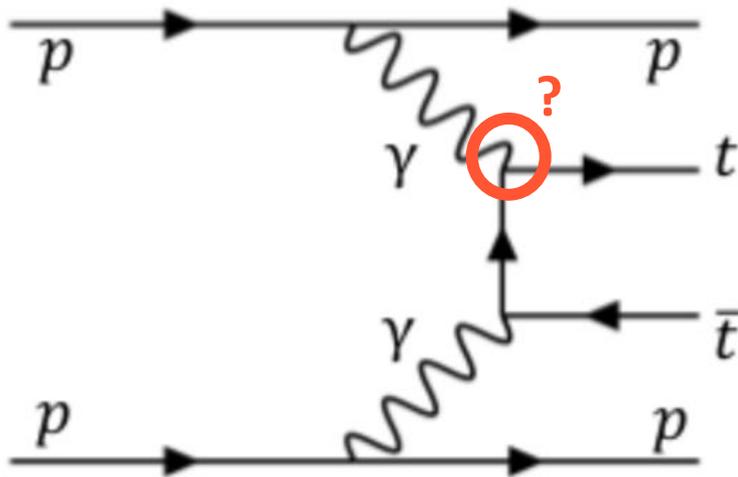
# Precision Proton Spectrometer

- Joint CMS and TOTEM project that aims at measuring the surviving **scattered protons** on both sides of CMS in standard running conditions
- **Tracking** and **timing** detectors inside the beam pipe at  $\sim 210\text{m}$  from IP5
- Approved (2014), exploratory phase in 2015, data taking started in 2016, pixels installed from 2017, full detectors in 2018



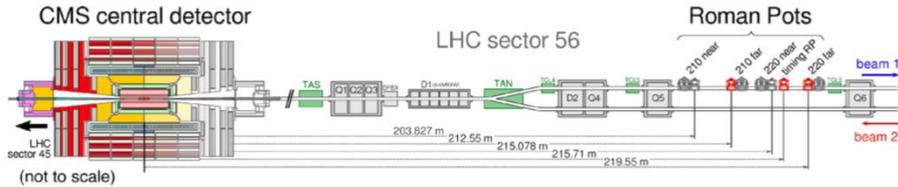
# Exclusive top quark production

- Reconstruction of  $t\bar{t}$  events is incomplete due to neutrinos (dileptons) etc.
- Exclusive production allows full reconstruction of  $t\bar{t}$  kinematics from the leading protons with **excellent momentum resolution**



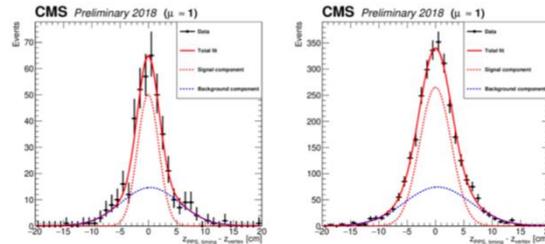
- Couplings of top quark to photons are small
- Process expected to be very sensitive to top quark anomalous couplings with the photon
- Anomalous production cross section or kinematical properties would provide **hints for New Physics**

# Physics with forward protons



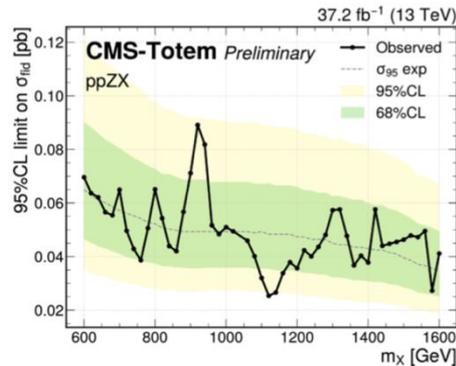
## [CMS-PAS-PRO-21-001](#)

CT-PPS collected more than  $110 \text{ fb}^{-1}$  of data during Run-2



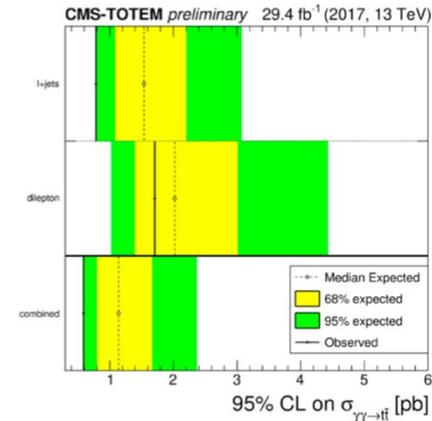
## [CMS-PAS-EXO-19-009](#)

Search for anomalous  $Z/\gamma^*$  central production with CT-PPS 2017 data (2% resolution on the missing mass)



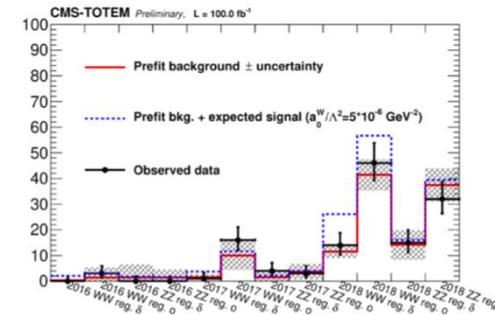
## [CMS-PAS-TOP-21-007](#)

Search for central exclusive production of top quark-antiquark pairs in proton-proton interactions (with tagged protons)



## [CMS-PAS-SMP-21-014](#)

Search for anomalous high-mass  $\gamma\gamma \rightarrow WW$  and  $ZZ$  with forward protons



# LHC: from searches to precision

- A hadron collider at full throttle
  - Reaching the energy limit
  - In Run3 (2022+), collisions at 13.6 TeV (?)
  - Large datasets ( $\sim 300/\text{fb}$  expected in Run3)
- Moving from searches to precision measurements and rare processes
  - Top quarks and rare decays
  - Higgs couplings and rare decays
  - Anomalous couplings etc.
- Preparing for High-Luminosity (2028 and beyond) with improved detectors
  - Several technological challenges ahead as complexity increases



# Summary

- Top quarks are valuable probes of SM
- Excellent consistency but **SM is incomplete**
  - Extensions foresee existence of additional bosons
  - Searches for BSM bosons ongoing
- Dominant background for New Physics searches
- Due to large mass, top quarks may couple to heavy objects
- Deviations from SM may indicate New Physics
- More data and improved algorithms will enhance the sensitivity
  - Higgs, multi-top, boosted objects, SUSY, Dark matter, etc.



# Theory cross sections: TeV vs LHC

Collider	$\sigma_{\text{tot}}$ [pb]	scales [pb]	PDF [pb]
Tevatron	7.164	+0.110(1.5%) −0.200(2.8%)	+0.169(2.4%) −0.122(1.7%)
LHC 7 TeV	172.0	+4.4(2.6%) −5.8(3.4%)	+4.7(2.7%) −4.8(2.8%)
LHC 8 TeV	245.8	+6.2(2.5%) −8.4(3.4%)	+6.2(2.5%) −6.4(2.6%)
LHC 14 TeV	953.6	+22.7(2.4%) −33.9(3.6%)	+16.2(1.7%) −17.8(1.9%)

Including NNLO+NNLL approximations  
PRL 110, 252004 (2013) (M. Czakon et al.)