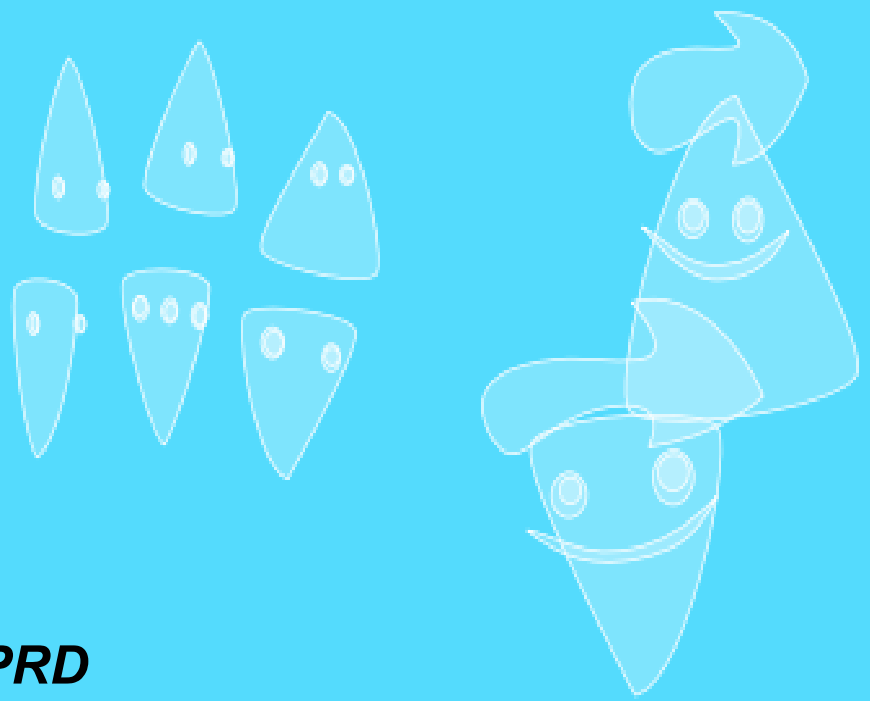
Emmy Noether-Programm
Deutsche Forschungsgemeinschaft DFG

Universität Hamburg

Searches for Vector-Like Top Partners at CMS



arXiv:1509.04177 [hep-ex], accepted by PRD

CMS Compact Muon Solenoid

Ivan Marchesini, Physics at the Terascale 2015, Hamburg
on behalf of the CMS collaboration

SM4 and its exclusion

- **Number of generations** in the SM: **free parameter**. A priori simple SM4 extension, with additional fourth generation analogous to the 3 observed ones, is possible

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \boxed{\begin{pmatrix} t' \\ b' \end{pmatrix}} \qquad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \boxed{\begin{pmatrix} \nu_4 \\ l_4^- \end{pmatrix}}$$

- SM4 is appealing: e.g. CKM matrix gains two complex phases, allowing **larger CP violation**, one of the three Sakharov ingredients to explain observed **baryon asymmetry**

- Considered disfavoured several times, with more or less conclusive arguments:
  - **LEP: number of light neutrinos** =3, additional fourth neutrino should be very heavy $m_\nu > m_Z/2$. Unnatural?
  - **electroweak fits**: exclusion based on limited assumptions (e.g. degenerate new families), hence not fully conclusive, see 2007 paper ***http://journals.aps.org/prd/abstract/10.1103/PhysRevD.76.075016***

- Final word: **Higgs discovery**. SM Higgs BR strongly modified by SM4, which is not observed. **SM4 with simple Higgs sector is ruled out**.

$$\sigma(gg \longrightarrow H) \cdot \mathrm{Br}(H \longrightarrow \gamma\gamma)\big|_{\mathrm{SM4}}$$

$$\approx (0.09 \ldots 0.2)\, \sigma(gg \longrightarrow H) \cdot \mathrm{Br}(H \longrightarrow \gamma\gamma)\big|_{\mathrm{SM}}$$

$H \to \gamma\gamma$ suppression in SM4

Vector-like quarks

- Vector-like heavy quarks:
  - **spin 1/2, colored**
  - left and right components transform in the same way under $SU(3)_c \times SU(2)_L \times U(1)_Y$

- Why are they called "vector"-like?

$$j_L^\mu = \bar{f}_L \gamma^\mu f'_L \qquad j_R^\mu = 0$$

$$j^\mu = j_L^\mu + j_R^\mu = \bar{f}\gamma^\mu(1-\gamma^5)f'$$

$$V - A$$

SM chiral quarks

$$j_L^\mu = \bar{f}_L \gamma^\mu f'_L \qquad j_R^\mu = \bar{f}_R \gamma^\mu f'_R$$

$$j^\mu = j_L^\mu + j_R^\mu = \bar{f}\gamma^\mu f'$$

$$V$$

VLQs

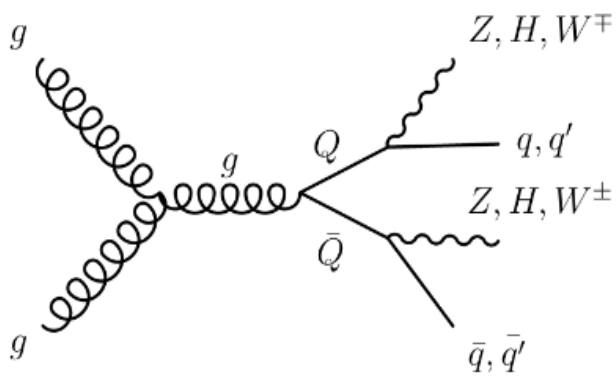
- Mass term independent from symmetry breaking mechanism:

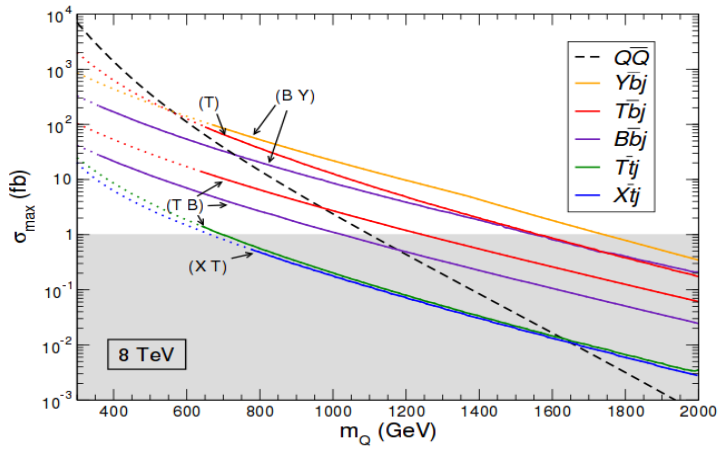
$$L_{mass} = -M(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$$

- Appealing:
  - naturally solve the **hierarchy problem** and are predicted by several theories (little Higgs models, composite Higgs models, extra dimensions)
  - modest impact on SM Higgs production and decay modes, **not ruled out**

VLQs phenomenology

- Run I: focus on **pair-production through strong interaction**





- **Single-production**: dominant for large VLQ masses, being explored in Run II

- Here focus on **T(+2/3) searches**:
  - analyses typically target one specific decay mode: **bW, tH, tZ**
  - results provided for all possible BRs

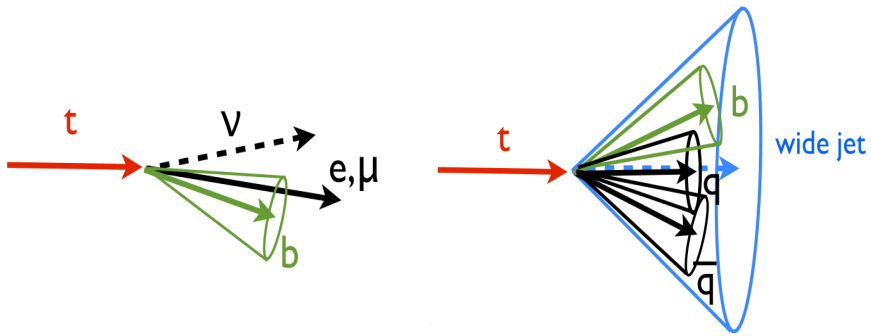
- B and X searches covered separately by CMS

$T(+2/3)$	$W^+b,\ Ht,\ Zt$
$B(-1/3)$	$W^-t,\ Hb,\ Zb$
$X(+5/3)$	W^+t
$Y(-4/3)$	W^-b

Boosted regime

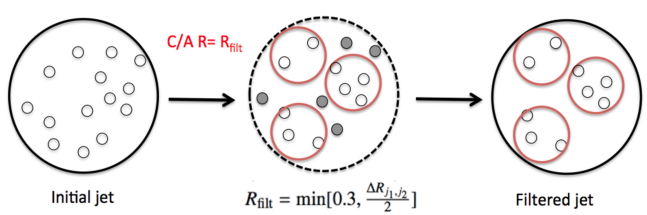
[JHEP 06 (2015) 080]

- **Classical selection methods fail**:

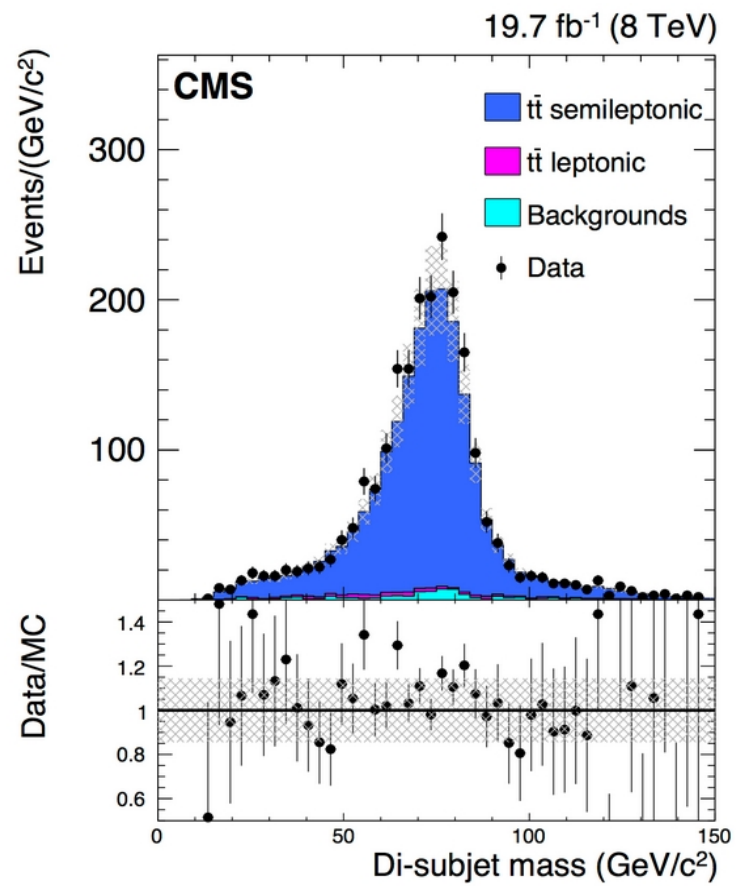


→non-isolated leptons
→hadronic decay products from heavy particles **merged into large fat-jets**

- **Jet mass**: fundamental observable to identify merged jets
  - → **grooming** (pruning, trimming, filtering, ...): remove soft/large angle radiation, protect from pile-up



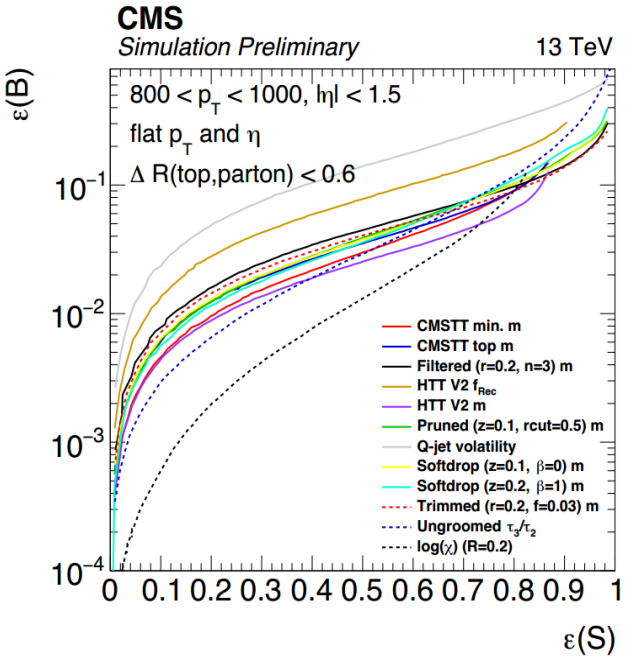
filtering, merged W candidates



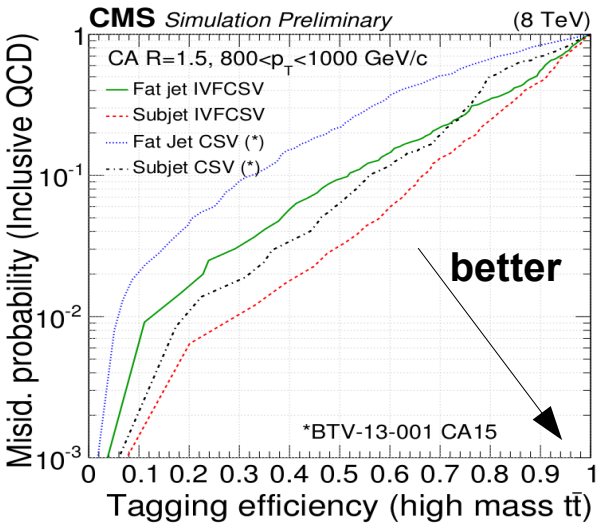
Substructure tools

[CMS DP-2014/031, DP-2015/043]

- **Top/Higgs/W/Z-tagging**:
  - **jets mass + substructure** requirements (2 or 3-body structure of the fat-jet)
  - sofisticated **top-tagging** algorithms: HepTopTagger, CMSTopTagger
  - large **optimization efforts**, several tools tested for Run 2:
    - n-subjettiness
    - shower deconstruction
    - ...



- **Boosted b-tagging**:
  - largely **orthogonal from substructure**
  - b-tagging sequence **applied to individual subjets**
  - combined to top-tagging: up to **factor 10 gain in QCD rejection**, keeping 70% efficiency



Run 1 subjet b-tagging

Run 2 subjet b-tagging

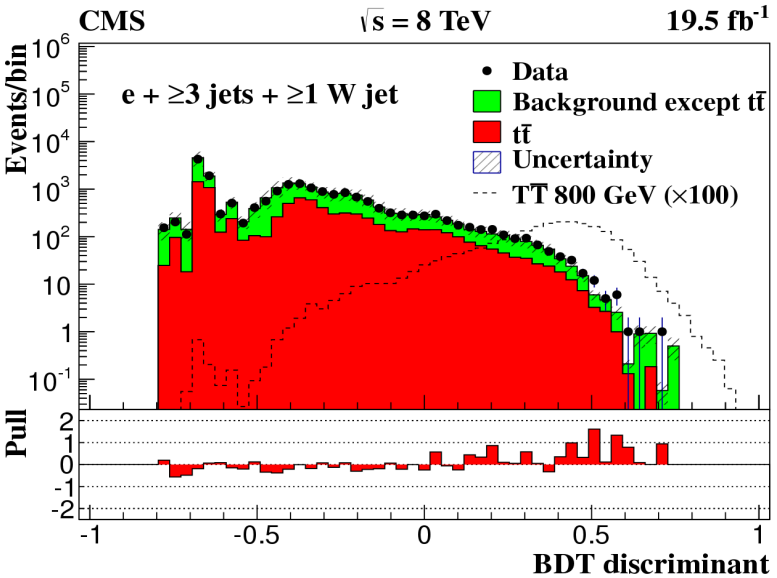
Individual Analyses

T in leptonic final states

[Phys. Lett. B 729 (2014) 149]

Single lepton (e, μ):
multivariate analysis
substructure

- two event categories: with or without **W-tag**
- **top-tagging**
- **boosted decision tree BDT**:
  - multiplicity/p_T of reconstructed objects (lepton, jets, tagged jets...)
  - N of b-, W- and top-tags



BDT single-electron channel

Multilepton (e, μ):
- **counting experiment**
- event categories:
  - two/three leptons
  - opposite/same-sign di-leptons

Combined inclusive search:
- sensistive to **all T decay modes**
- observed (expected) mass limits for 100% BR:
  - tZ: **782 (813) GeV**
  - tH: **706 (770) GeV**
  - bW: **700 (785) GeV**

T→bW, single lepton

- **Single lepton + 4 AK5 jets**:

TT→bWbW→μ+ν+4jets, e+ν+4jets

- **Recover merged W decays**:
  - W-tagger based on **pruning** and CA8 jets
  - 2 pruned subjets counted as 2 jets

- **2 b-tagging** requirements:
  - reduce combinatorics

- **Kinematic fit**:

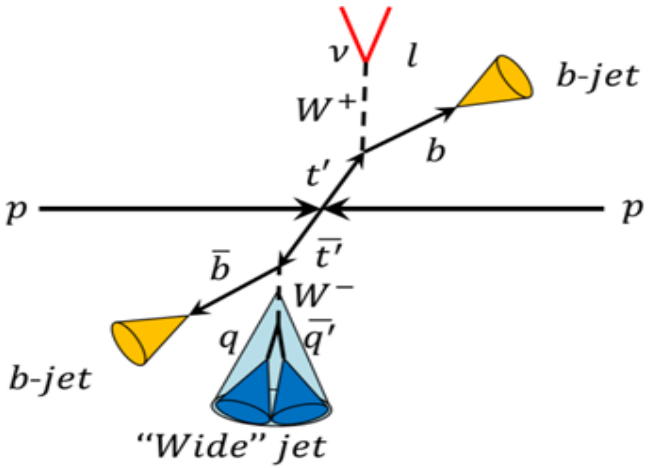
$$m(lep\ \nu) = M_W$$
$$m(qq) = M_W$$
$$m(lep\ \nu b) = m\ (qqb)$$

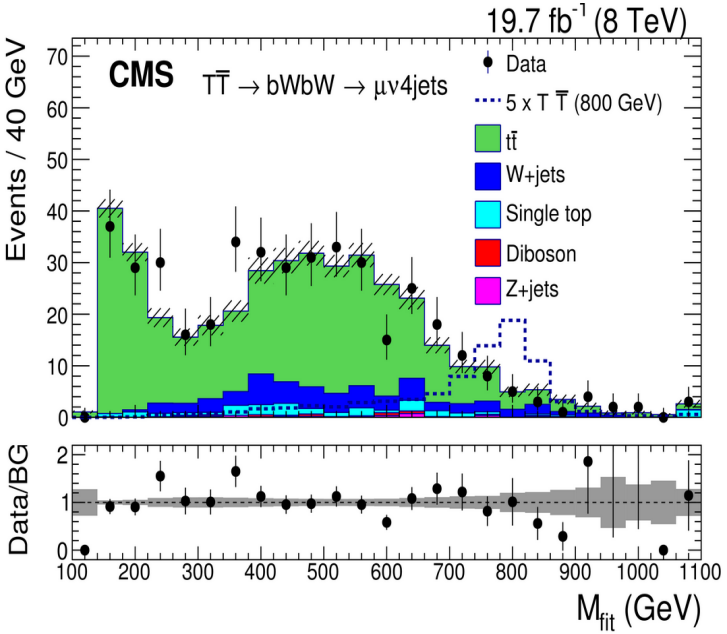
- **Observables**:
  - fitted mass T and S_T

$$S_T = p_T^{\ell} + E_T^{miss} + p_T^{J_1} + p_T^{J_2} + p_T^{J_3} + p_T^{J_4}$$

- Very sensitive to bW decays:

100% T→bW, obs (exp) limit: **912 (851) GeV**

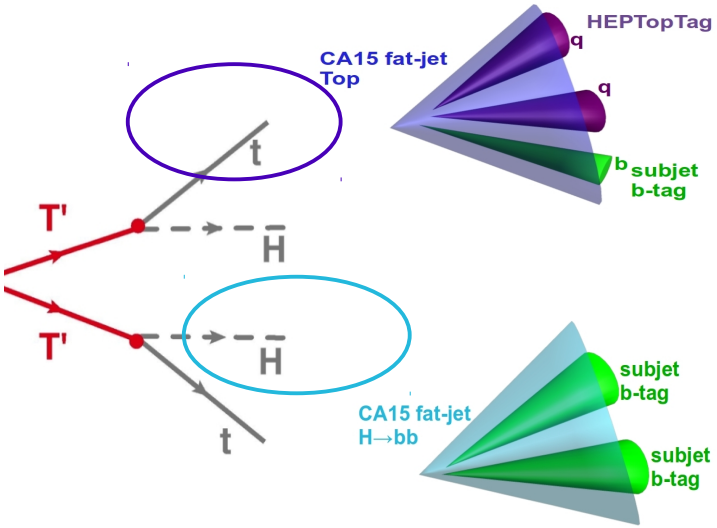




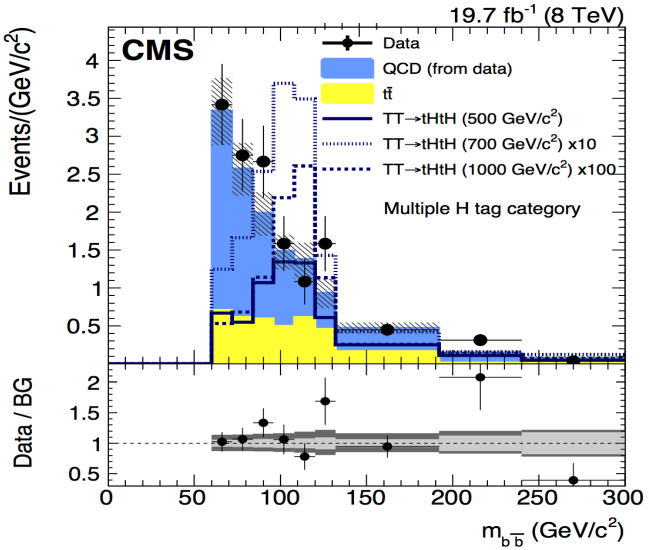
Fully hadronic T→tH, H→bb

[JHEP 06 (2015) 080]

- **Large use of substructure**:
  - HEPTopTagger+subjet b-tagging
  - Higgs-tagger based on subjet b-tagging
- Increase acceptance:
  - ≥ 1 top-tag and ≥ 1 Higgs-tag
- Exploit purity when multiple Higgs-tags: ==1, ≥2 Higgs-tags categories
- Two observables **combined in Likelihood**: H_T^{sub} **and** M_{higgs}, where H_T^{sub} is evaluated from subjets of selected fat jets with p_T > 150 GeV
- Use of substructure: QCD background reduced to the level of ttbar
- Obs (exp) limit of 745 (773) GeV, for 100% BR T→tH



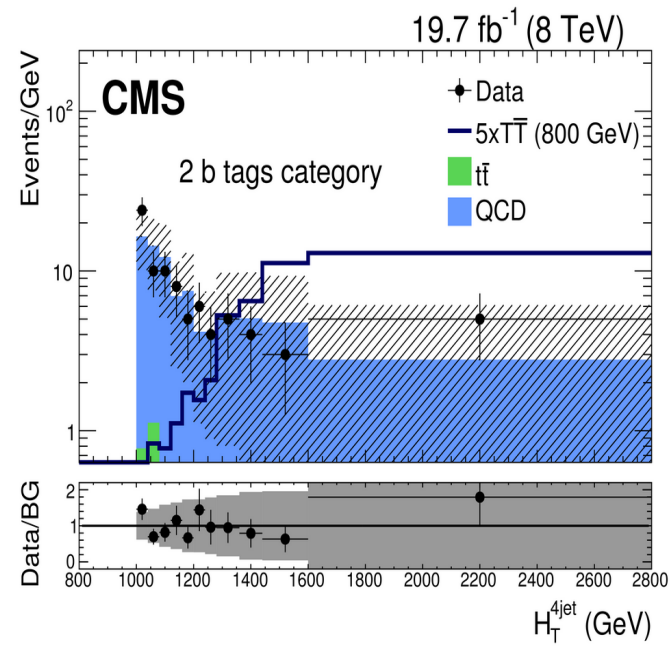
Higgs-candidate mass



Fully hadronic T→bW

- **Substructure**:
  - W-tagger based on pruning+mass drop
- **TT→bWbW**: 2 W tags + 2 AK5 jets
- 1 and 2 **b tag categories**
- Reconstruct two T candidates:
  - combine W with b-candidates
  - choose pairing giving closest T masses
- Additional requirements:
  - M_T > 200 GeV
  - two T in opposite hemispheres
  - relative mass difference < 0.1
- Limits from $H_T^{4jet} = p_T\ jet1 + p_T\ jet2 + p_T\ jet3 + p_T\ jet4$
- 100% BR T→bW, obs (exp) limit: **705 (667) GeV**

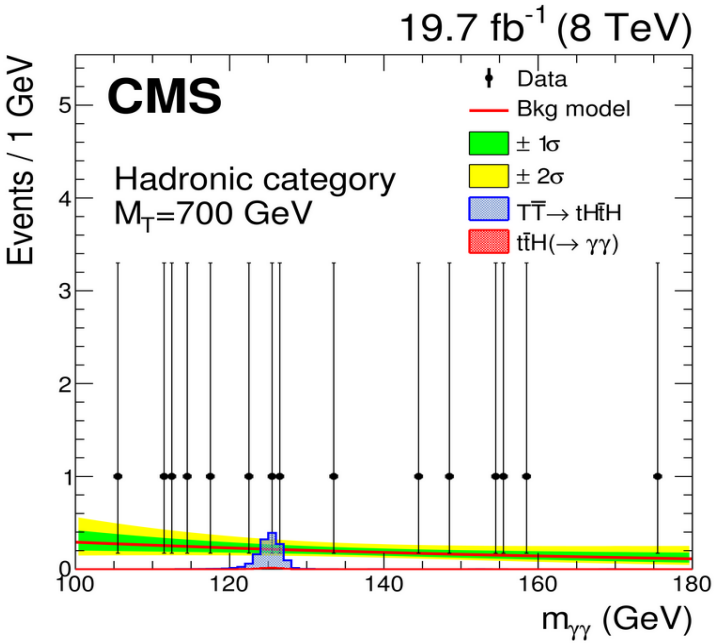
H_T^{4jet} *observable*



T→tH, H→γγ

- Search technique:
  - at least one T→tH, with H→γγ. **Observable: $m_{\gamma\gamma} = m_{Higgs}$**
  - two channels: **leptonic** and **hadronic**

Variable	Hadronic channel	Leptonic channel
$p_T(\gamma_1)$	$> \frac{3}{4} m_{\gamma\gamma}$ GeV	$> \frac{1}{2} m_{\gamma\gamma}$ GeV
$p_T(\gamma_2)$	35 GeV	25 GeV
n_{jets}	≥ 2	≥ 2
H_T	≥ 1000 GeV	≥ 770 GeV
leptons	0	≥ 1
b tags	≥ 1	-



- By construction, the analysis is sentitive exclusively to tH decays, with an obs (exp) limit of **540 (607) GeV**, for 100% BR T→tH

Combination

Combination strategy

- Event lists cross-checked
  - negligible overlaps, with the exception of the two single lepton searches

- **Single lepton** analyses: **inclusive** and **optimized for bW decays**
  - overlapping selection, no sense to introduce vetoes
  - replace the inclusive single lepton analysis with the optimized search when setting limits for T→bW decays, with BR(bW) up to 80%
  - combine with the multi-lepton part of the inclusive analysis

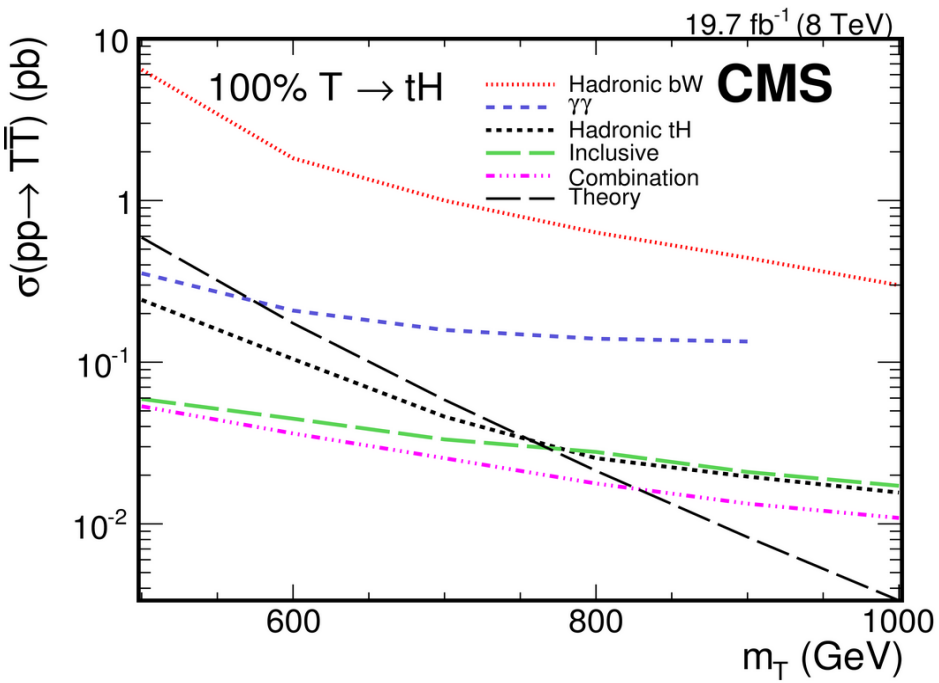
- Limit setting: based on the **Theta** framework, using **Bayesian limits**

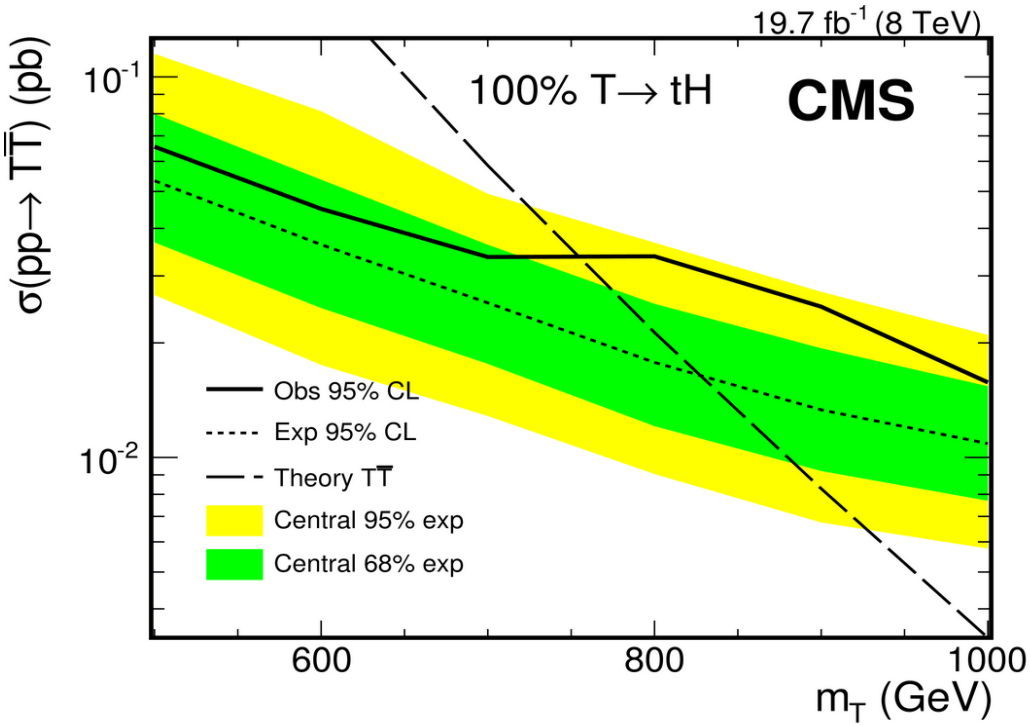
- Some uncertainties need to be **correlated** between analyses

Uncertainty	Single leptons	Inclusive leptons	Multiple leptons	All-had. $T \to bW$	All-had. $T \to tH$	$H \to \gamma\gamma$
Int. luminosity	☑	☑	☑	☑	☑	☑
Trigger	✓	✓	✓		✓	✓
Lepton ID	☑	☑	☑			☑
Photon ID						✓
Photon energy						✓
Pileup jet ID						✓
Jet energy scale	☑	☑	☑	☑	☑	☑
Jet energy resolution	☑	☑	☑	☑	☑	☑
Unclustered energy	✓					
b tag SF	☑	☑	☑	☑	☑	
b tag mistag SF	☑				☑	
t tagging SF					✓	
$t\bar{t}$ μR and μF scale	☑	☑	☑	☑	☑	
$t\bar{t}$ cross section	☑	☑	☑	☑	☑	
$t\bar{t}$ PDF	☑			☑	☑	
QCD background				✓	✓	
Other backgrounds	✓	☑	☑	✓		✓

Limits

E.g. for 100% BR T→tH, other BR in the back-up



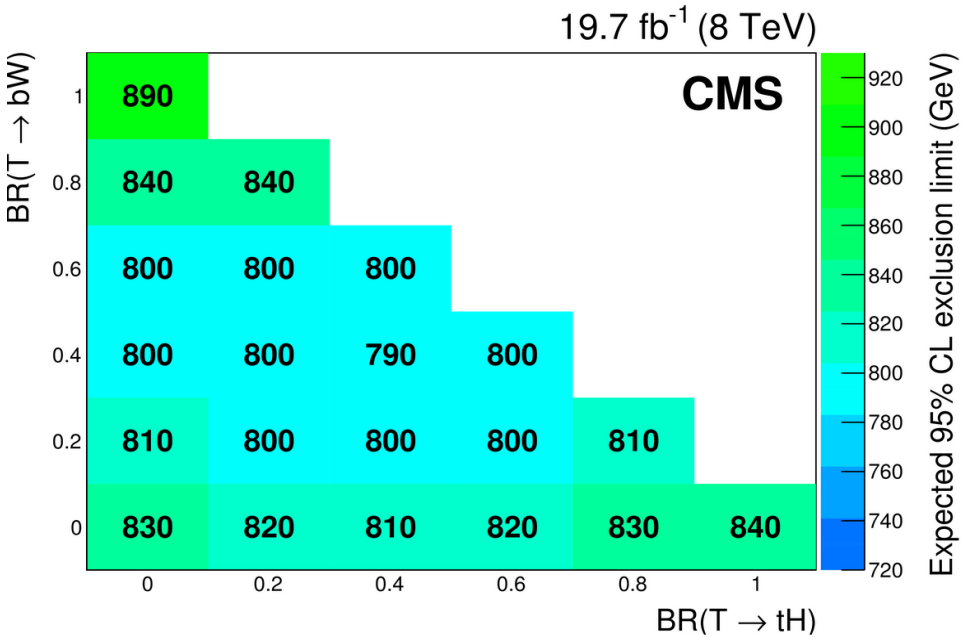


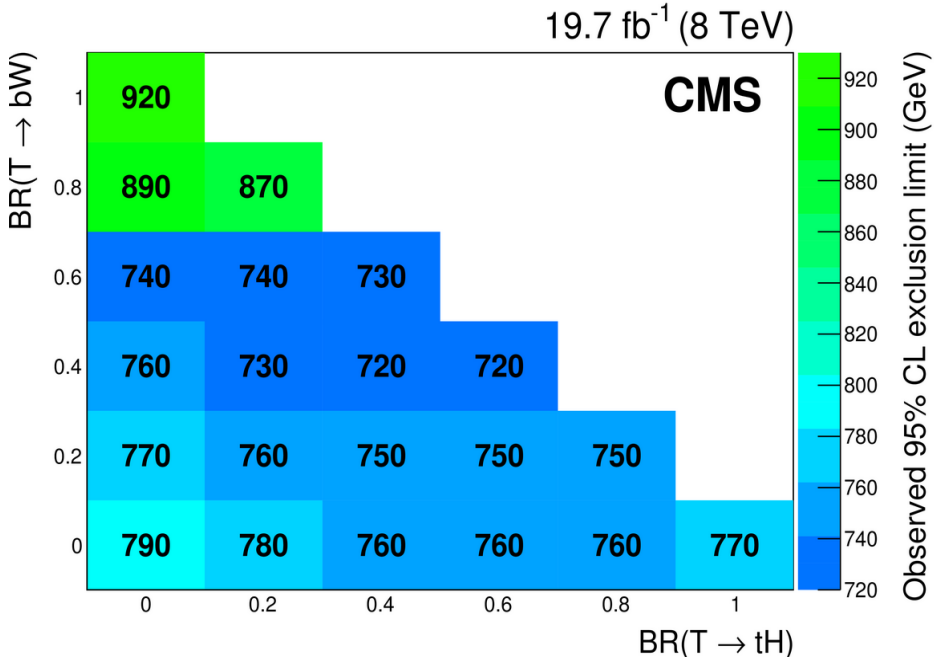
Expected limits:
impact of different analyses

Expected and observed limits:
final combination

Scan of branching fractions

Results provided for all possible BRs





Expected

Observed

Conclusions

- Performed a combination of searches for pair-produced T quarks:
  - 5 analyses
  - **O(20) observables/channels**

- Excellent **coverage of the entire phase space** of branching ratios of the T quark

- The expected limits are between 803 GeV and 897 GeV depending on the branching fraction of the T quark, with observed limits up to 912 GeV

- **CMS reaches generally similar sentitivity as ATLAS**

ATLAS
expected: 715-885 GeV
observed: 730-950 GeV

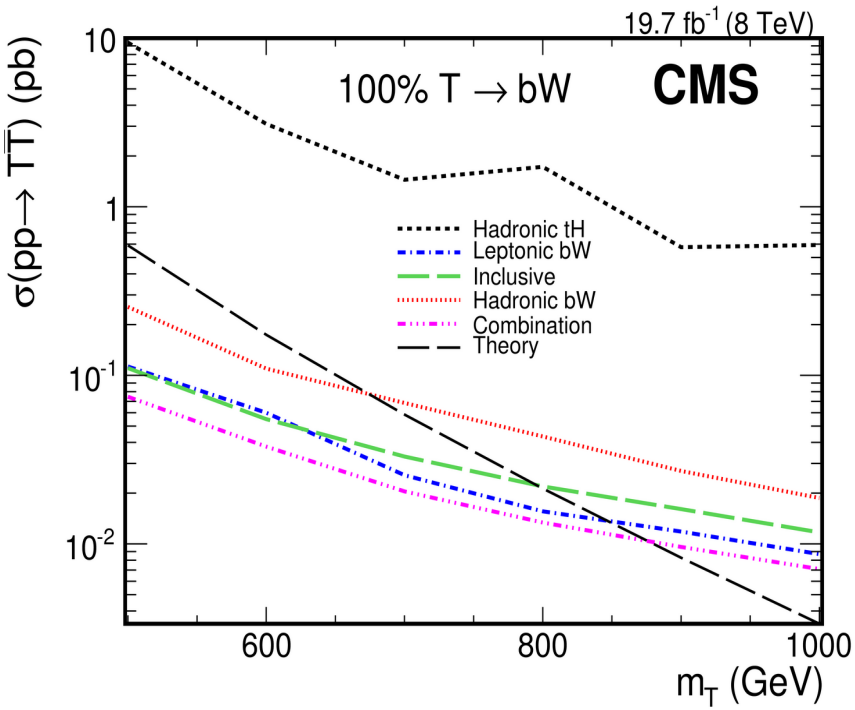
CMS

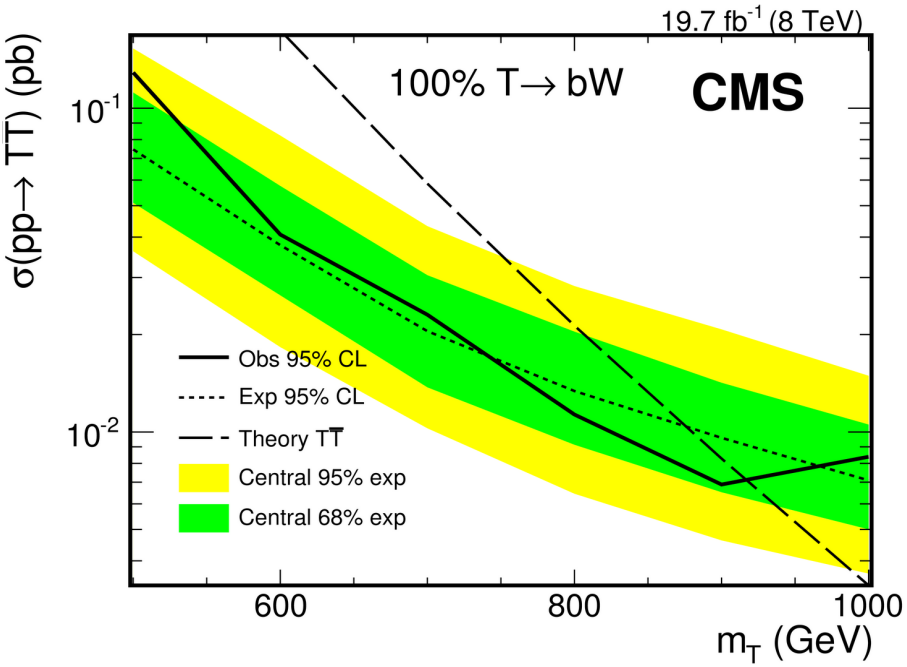
decay	exp (GeV)	obs (GeV)
bW	890	920
tH	840	770
tZ	830	790

Additional Slides

Limits

E.g. for 100% BR T→bW



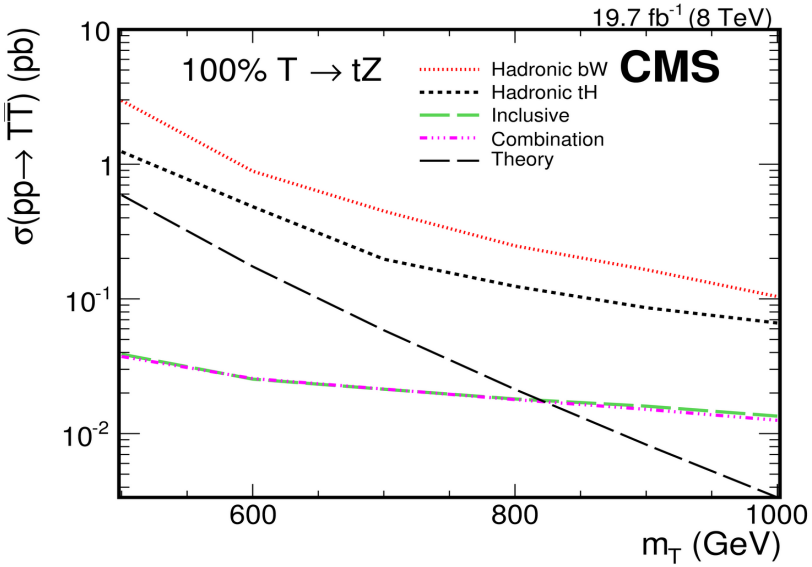


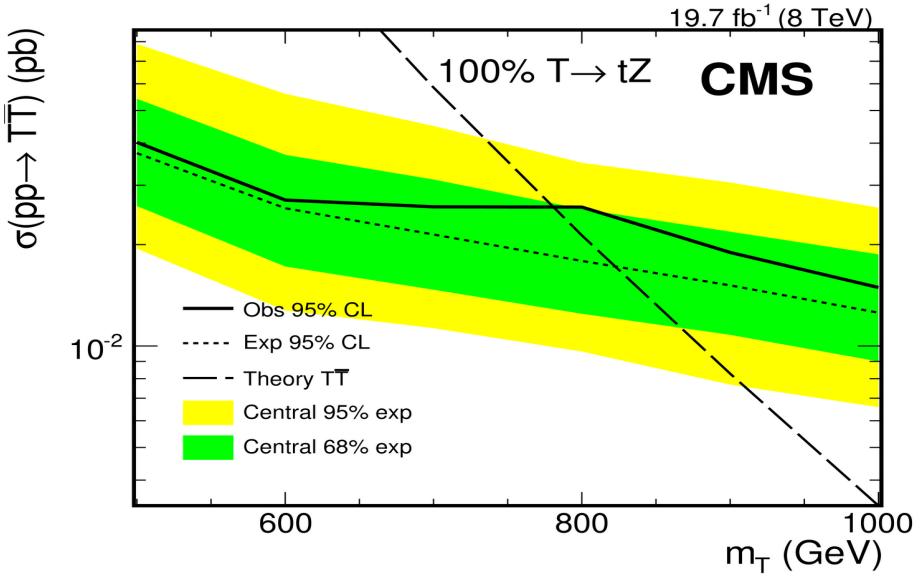
Expected limits:
impact of different analyses

Expected and observed limits:
final combination

Limits

E.g. for 100% BR T→tZ





Expected limits:
impact of different analyses

Expected and observed limits:
final combination