VLQ searches and hadronic final states - CMS

Antimo Cagnotta (Univ. & INFN Napoli) on behalf of CMS collaboration

Contents

- Introduction to BSM searches
- $T \rightarrow tH \quad (H \rightarrow \gamma\gamma)$ B2G-21-007 (submitted to JHEP, arxiv 2302.12802)
- Pair production TT/BB B2G-20-011 (accepted by JHEP, arxiv 2209.07327)
- Diboson pairs in all-jet final state B2G-20-009 (accepted by Phys. Lett. B, arxiv 2210.00043)
- Conclusions

BSM searches

- **New Physics searches** → look for new particles predicted by beyond SM theories
- rare final states or high-centre-of-mass energy $\sqrt{s}$ needed !

Vector-Like Quarks

- Vector-like quarks (VLQ): colored 1⁄2-spin particles, left and right components are symmetric
- VLQ masses do not depend on Yukawa couplings
- Predicted by many theoretical models
- Can be produced at LHC
  - **Pair production** via Strong interaction
    - σ does not depend on VLQ Γ and EW coupling
  - **Single production** via EW interaction
    - heavier masses can be probed

Hadronic final states

- Decays to heavy SM objects, **H/W/Z/Top**:
  High $\sqrt{s}$ → large Lorentz boost
- **Large BR** in hadronic decays
  → **large background** (multijet)
- Focus on diboson final state

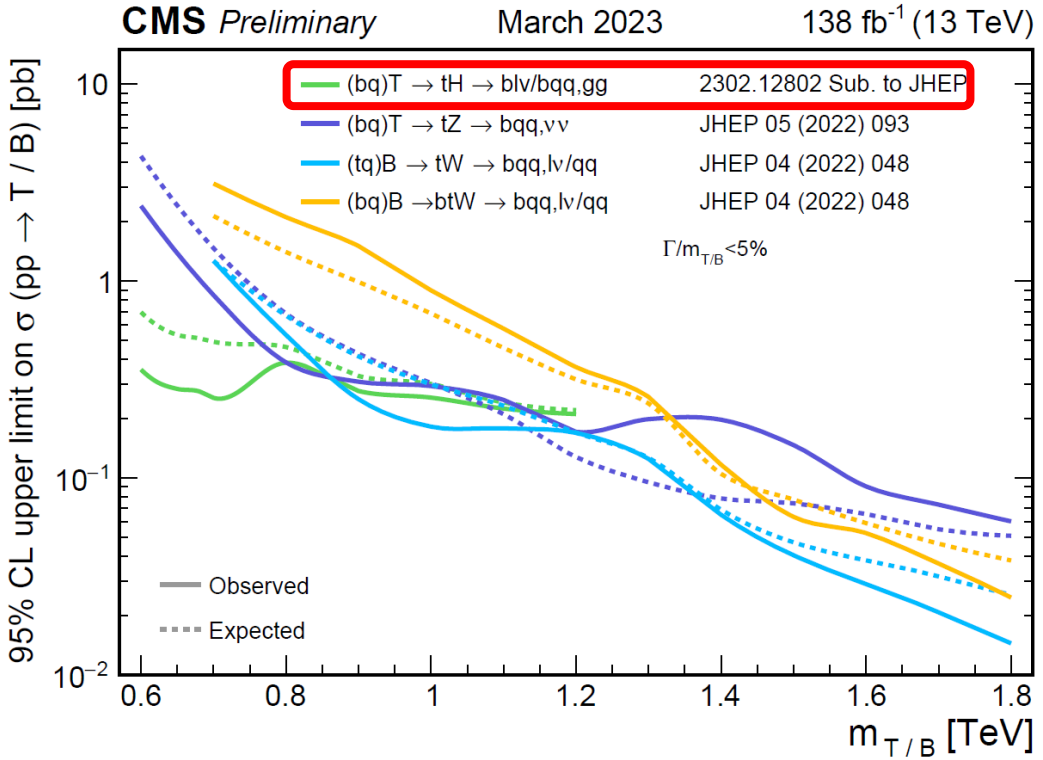
Leptonic final states in Halil and Nicolas' talks

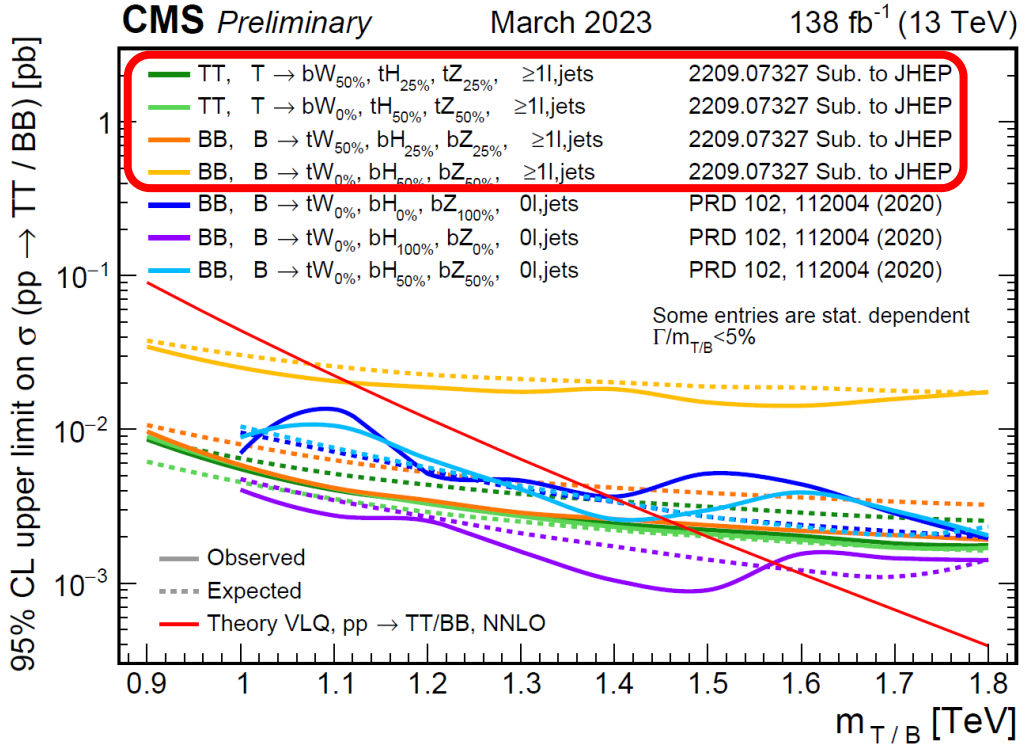
→ can be produced by

- **spin-0 *Rad*** and **spin-2 G_{bulk}** in the Randall–Sundrum model with warped extra dimensions
- **spin-1** vector boson resonances **(W′ and Z′)** appearing in composite Higgs and little Higgs models

Vector-Like Quarks (VLQs)

- In minimal models, VLQs exist as either singlets (T and B) or as a doublet (T, B), each with different **B**ranching **F**ractions:
  - singlet → **50 %** ($T \to bW$, $B \to tW$),
    25% ($T \to tH$ and $\to tZ$, $B \to bW$ and $\to bZ$)
  - doublet → **50%** ($T \to tH$ and $\to tZ$, $B \to bW$ and $\to bZ$)





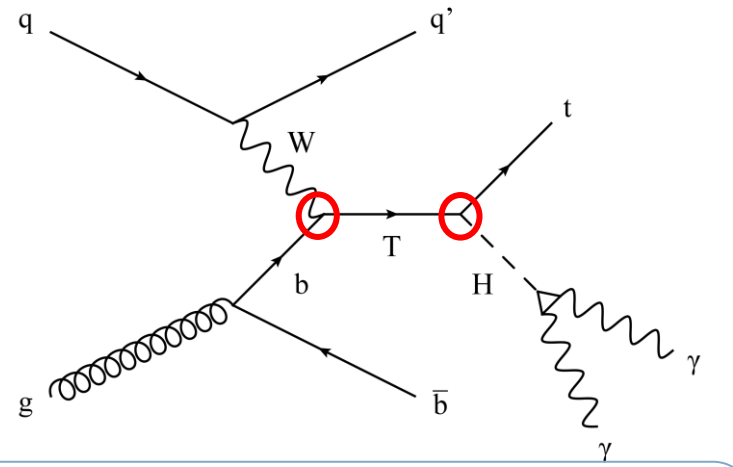
In this presentation

$T \rightarrow tH \ \ (H \rightarrow \gamma\gamma)$

Submitted to JHEP

- EW single production of an isospin singlet VLQ T
- NWA → $\Gamma \approx 1\% \ of \ M_T$ (valide up to $\frac{\Gamma}{M_T} \approx 10 - 15\%$)
- Search in tH final state
  - diphoton reconstruction of H
  - $t \rightarrow Wb$ separatly considered: $\boldsymbol{W \rightarrow lv}$ and $\mathbf{W \rightarrow q\bar{q}'}$
- Selection :
  - 2 prompt photons
  - **leptonic events** → 1 electron/muon
  - **hadronic events** → 2 jets

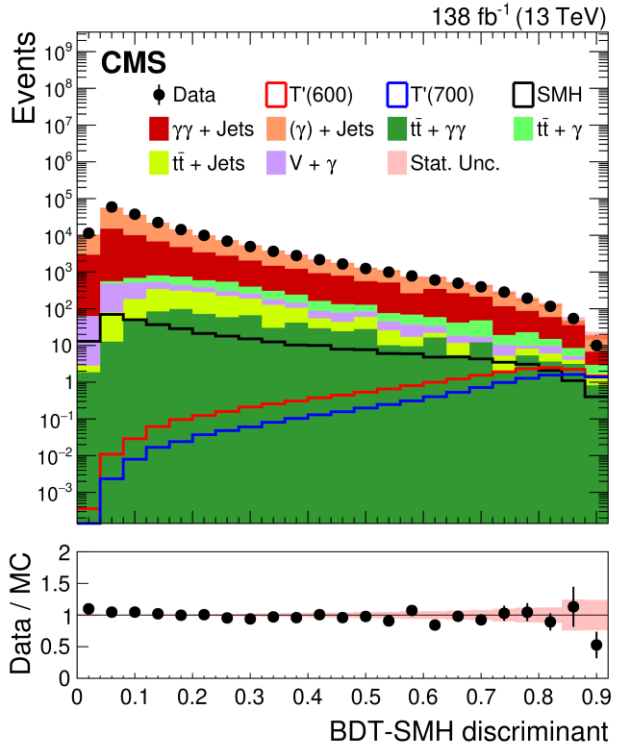
} + 1 b-tagged jet

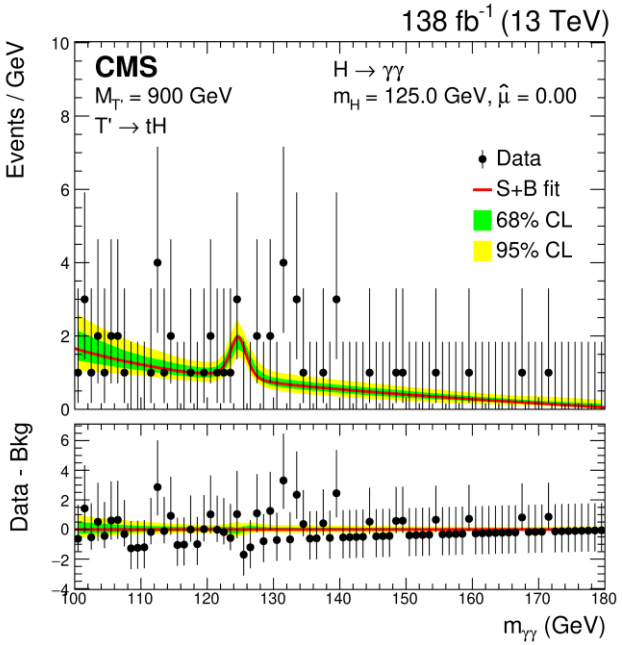


Coupling of T to the third-generation quarks ($\boldsymbol{\kappa_T}$)

$T \rightarrow tH \ \ (H \rightarrow \gamma\gamma)$

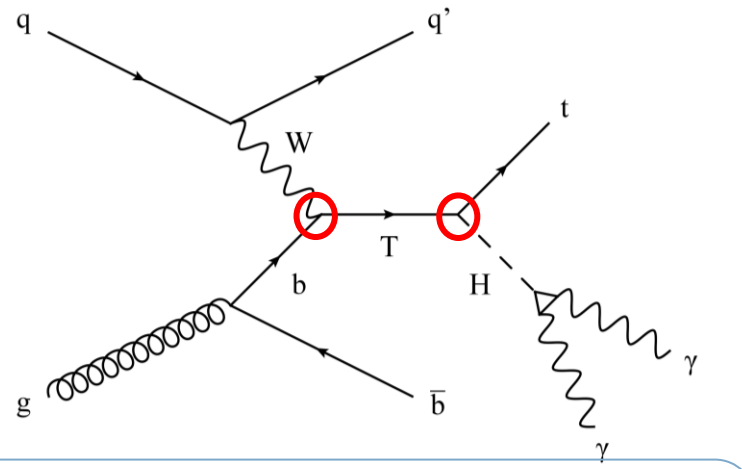
- Background composition :
  - **Leptonic category**: Drell-Yan processes
  - **Hadronic category**: QCD and $\gamma(\gamma) + jets$
  - both categories: dominant background $\boldsymbol{ttH}$, among the SM Higgs (SMH) production processes
  - BDT-SMH implemented separately **for each category**
  - Additional **BDT (BDT-NRB)** suppresses Non-Resonant Backgrounds in the **hadronic category**
- Signal extraction via fit to m_H:
  - Exploits $\boldsymbol{m_{\gamma\gamma}}$ **resolution of 1-2%**
  - Searches for a peak in the invariant mass of the reconstructed photons
- No significant excess found in data



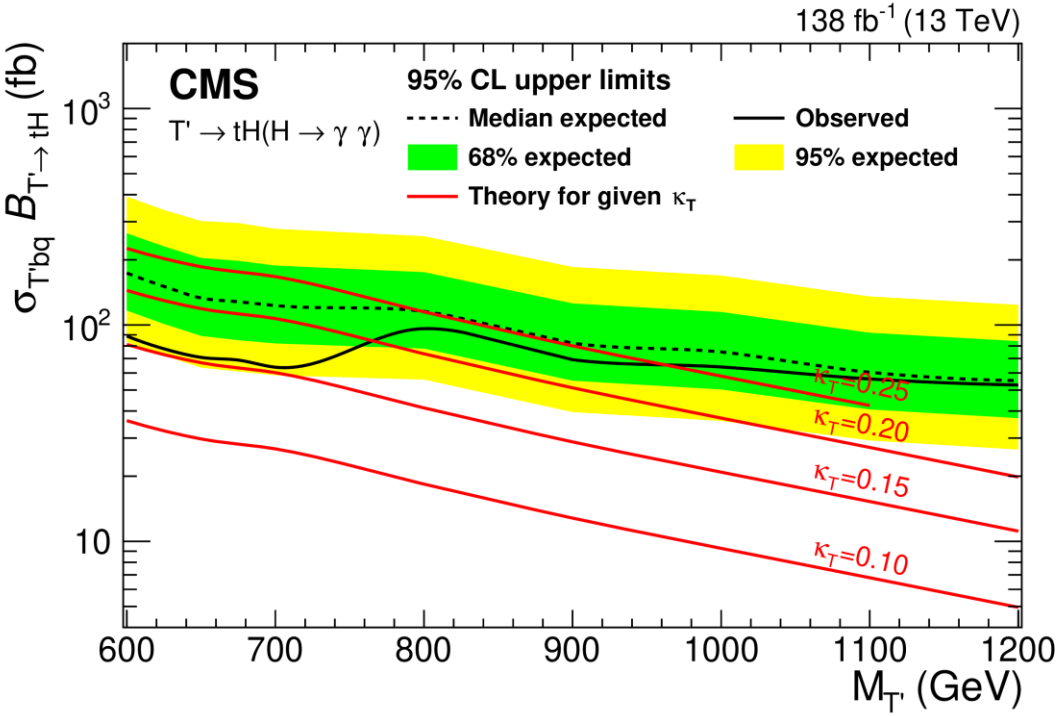


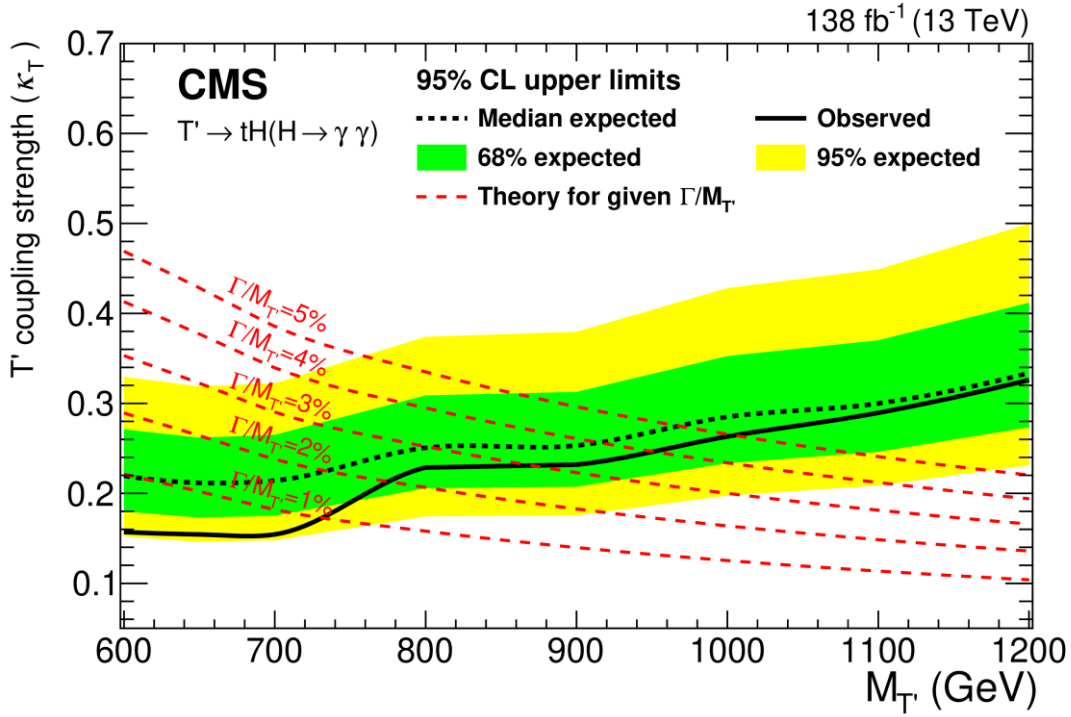
$T \rightarrow tH \ (H \rightarrow \gamma\gamma)$

- With $\kappa_T = 0.25$ and a width of $\Gamma/M_T < 5\%$, the search has successfully excluded the EW production of a singlet T' VLQ up to a mass of 960 GeV at a 95% CL



Coupling of T to the third-generation quarks (κ_T)

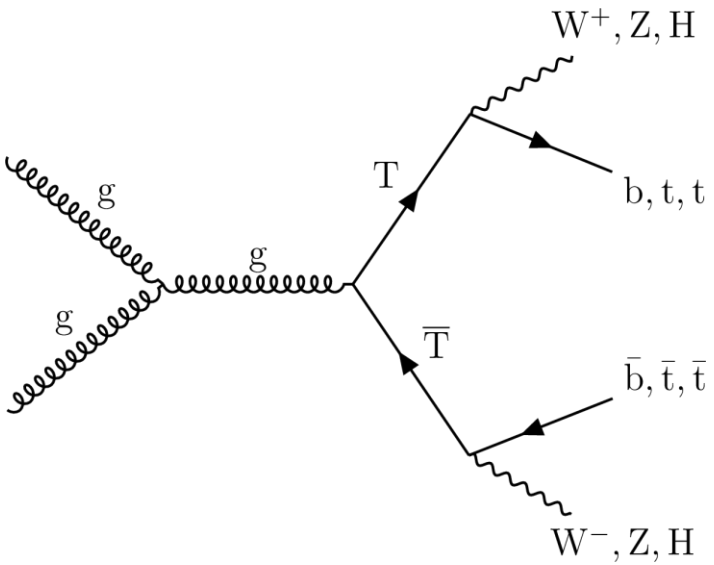


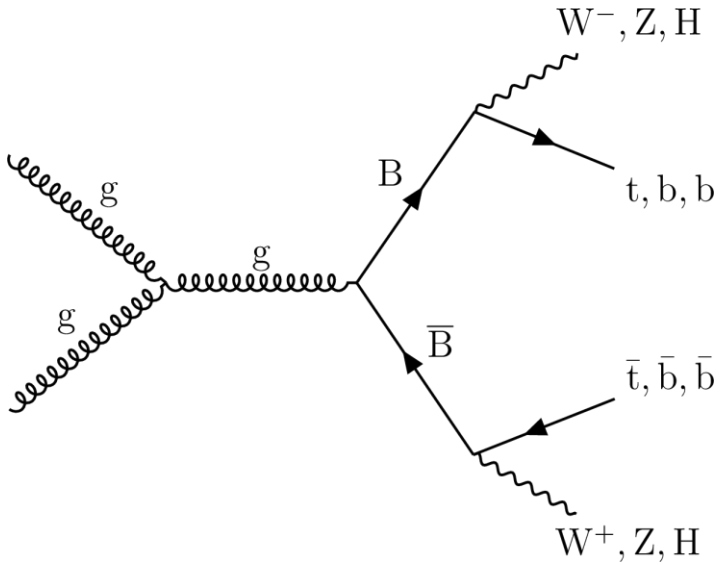


Pair production TT/BB

Accepted by JHEP

- Assumptions:
  - Only one flavor of VLQ is present in this search
- Three final states considered
  - **single-lepton channel (1 ℓ)**
  - **same-sign charge (SS) dilepton channel (2 ℓ)**
  - **multilepton channel with at least three leptons ($\geq$ 3 ℓ)**

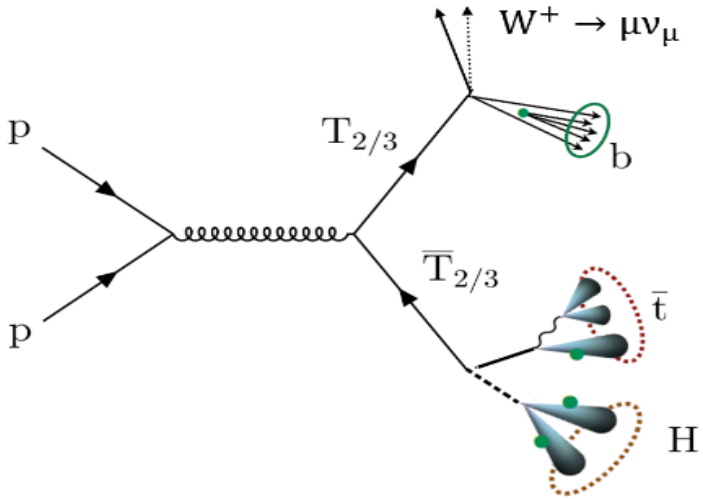




Pair production TT/BB

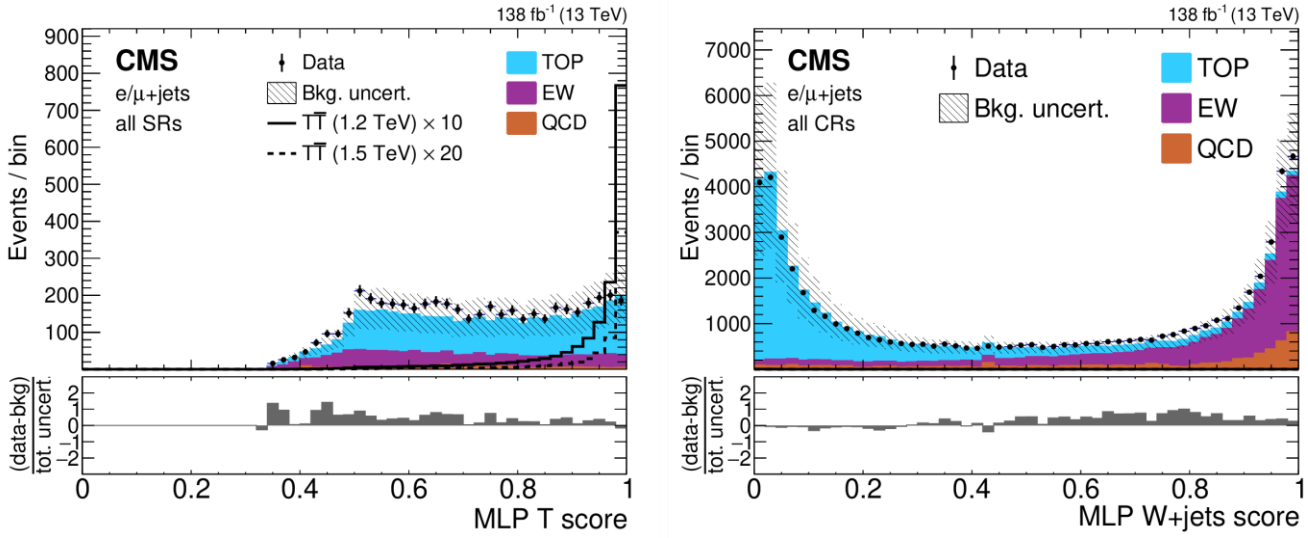
Single-lepton channel

- Provides broad sensitivity to all $T\bar{T}$ decays, as well as to $B \to tW$
- A VLQ pairs decay produce $2\ top\ or\ bottom\ quarks$ and $2\ W, Z, or\ H$ bosons
- Final state: **1 top** or **W** decays in $\to l\nu$, while the other products decay hadronically in $\geq$ **3 large-radius jets (AK8)**



- $\ell + \boldsymbol{MET} = \boldsymbol{W}$ or ***b*-jet** $+\boldsymbol{W} = \boldsymbol{t}$
- $(\boldsymbol{W}/\boldsymbol{t} + AK8), (AK8 + AK8) = VLQ\ pairs$
- MLP trained to separate SR and CR

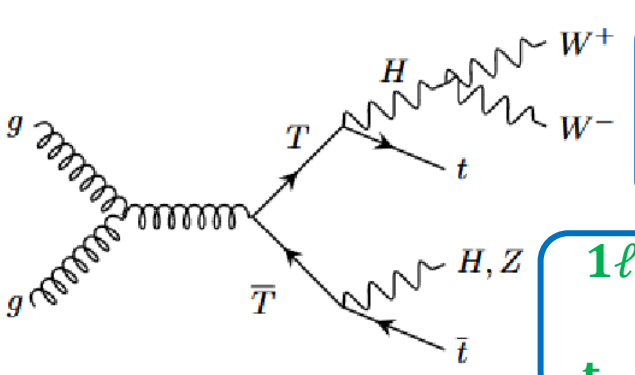
  → 2 independent model for TT and BB



Pair production TT/BB

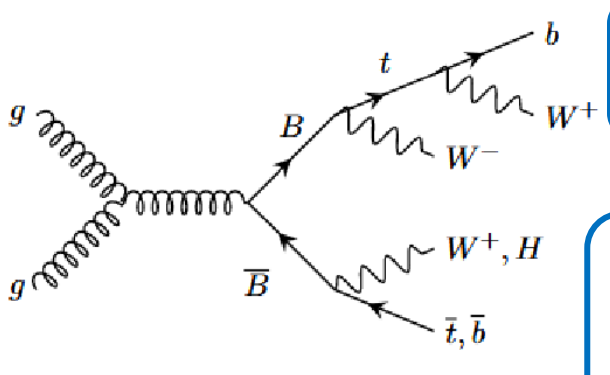
Same-Sign charge (SS) dilepton channel

- sensitive to $T \rightarrow tH$ (with $H \rightarrow WW$) and $B \rightarrow tW$ decays



$1\ell + 1\nu + 1\,W - jet$ and jets from t

$1\ell + 1\nu$ + jet from H or $t \rightarrow bW, W \rightarrow 1\ell + 1\nu$



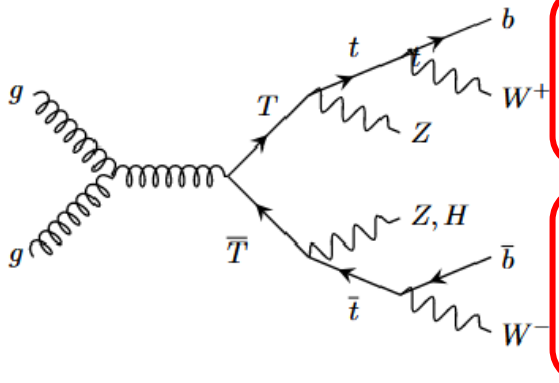
$1\ell + 1\nu + 1$ b − jet

$1\,W - jet$

$1\ell + 1\nu + 1$ b − jet

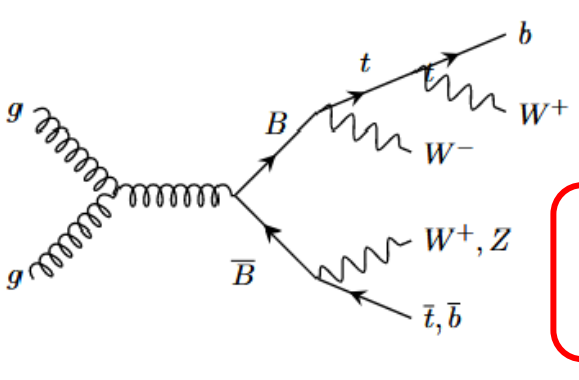
Multilepton channel with at least three leptons

- sensitive to $T \rightarrow tZ$ and $B \rightarrow tW$ decays



2ℓ from Z + 1ℓ from W $+1$b − jet

0 to $3\ \ell$ from $W/Z/H$ $+1$b − jet

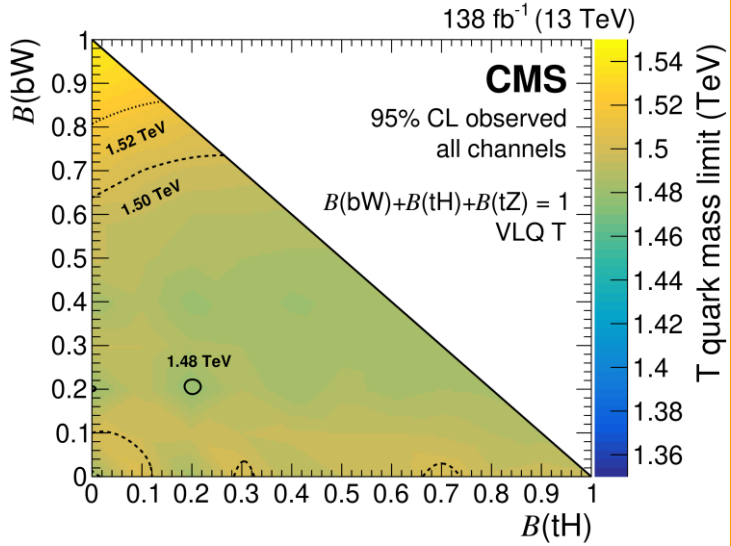


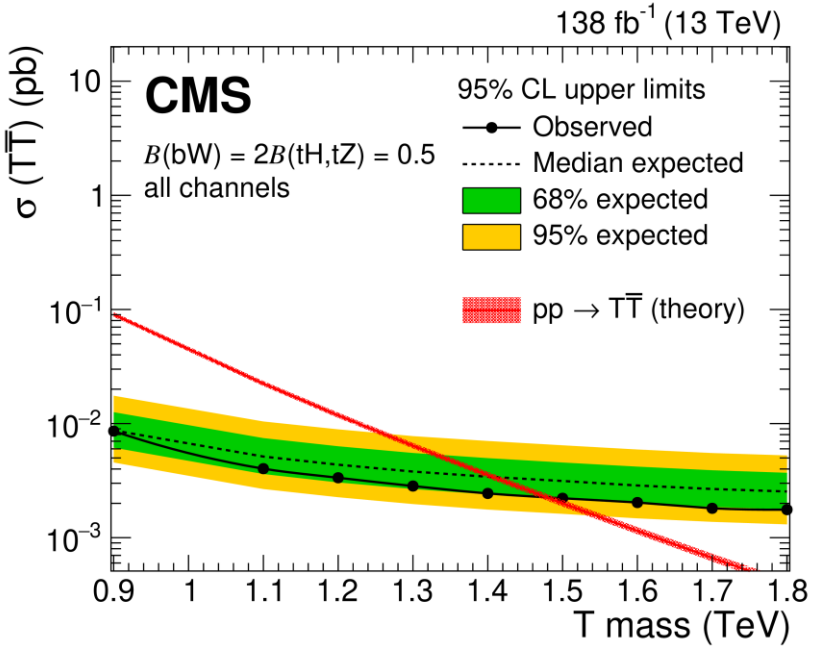
$1 - 2\ell$ from $2W$ $+1$ b − jet

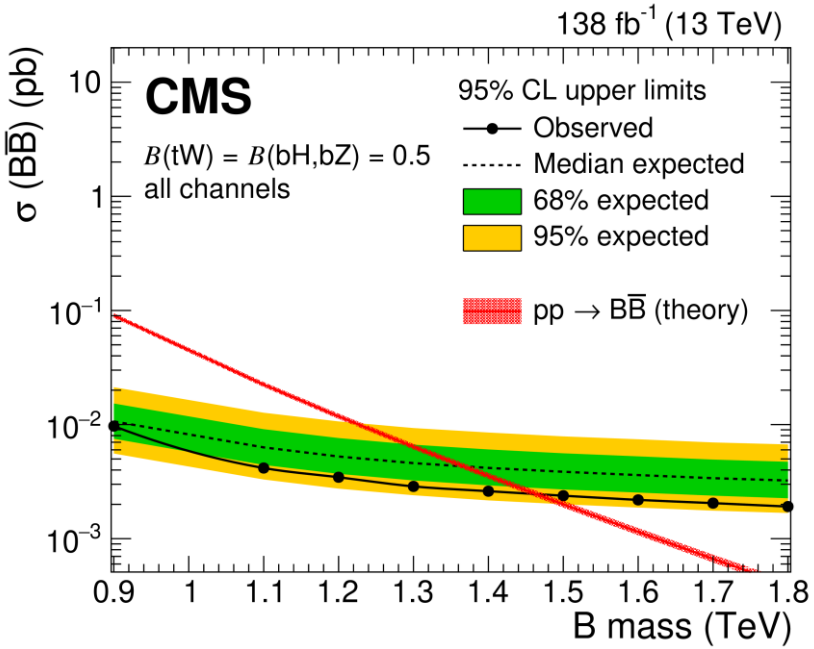
$1 - 2\ell$ from $2W$ or Z $+1$ b − jet

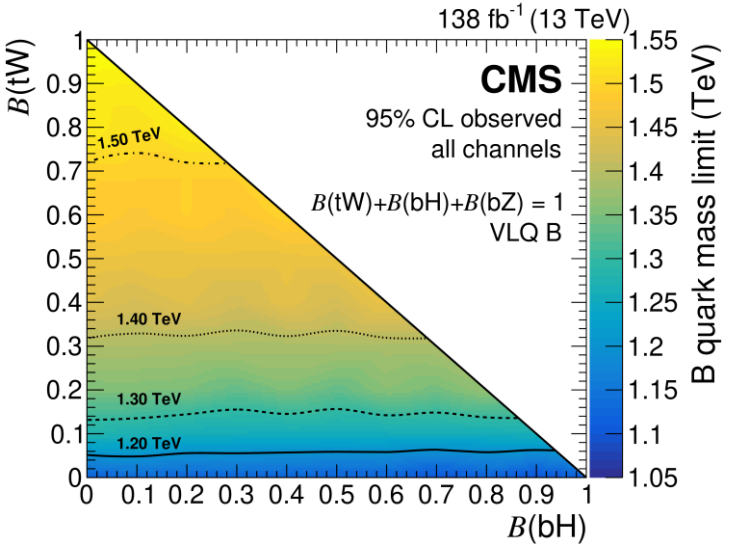
Pair production TT/BB

- Simultaneous fit using template histograms from multiple different discriminating variables in all three channels
- From the scan, we exclude T quarks with masses below $1.48–1.54$ TeV and B quarks with masses below $1.12–1.56$ TeV, depending on the branching fraction. T masses below 1.48 TeV are excluded in any scenario.



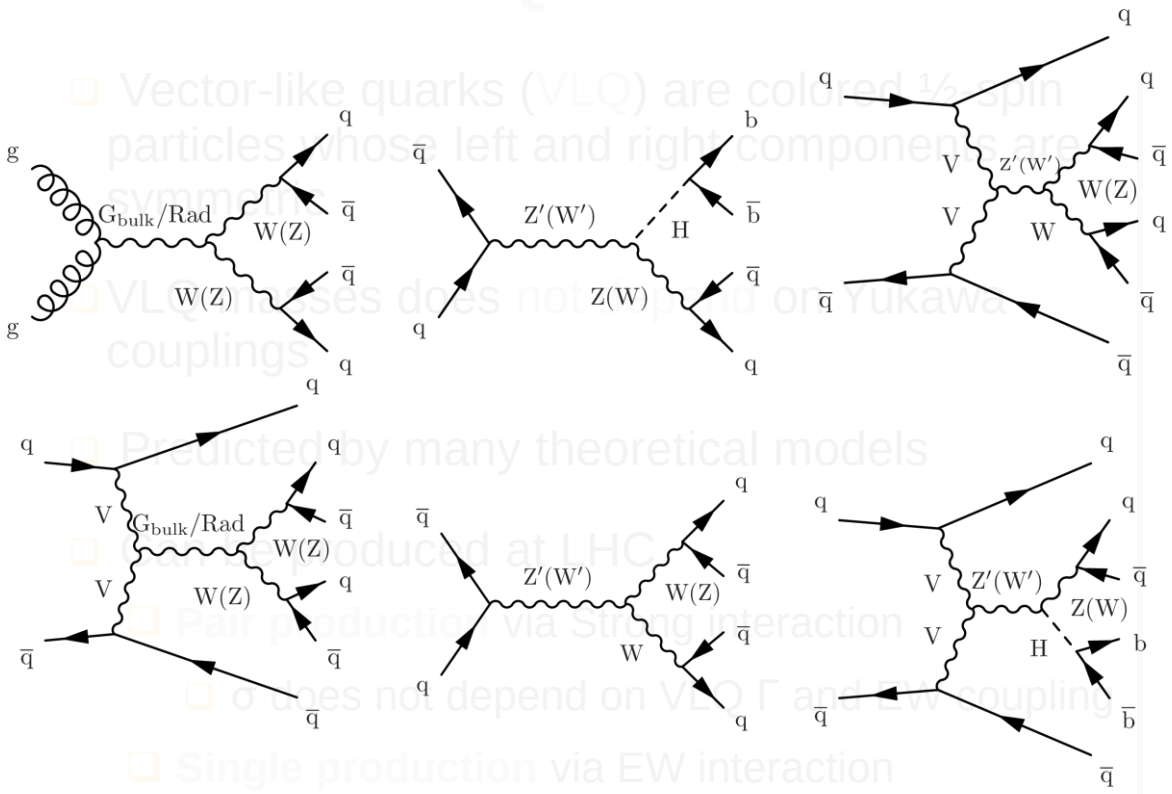






BSM searches

- **New Physics searches** → extend the SM discovering new particles
- rare final states or high-centre-of-mass energy $\sqrt{s}$ needed !



Hadronic final states

- Decays to heavy SM objects, **H/W/Z/Top**:
  High $\sqrt{s}$ → large Lorentz boost
- **Large BR** in hadronic decays
  → **large background** (multijet)
- Focus on diboson final state

Leptonic final states in Halil and Nicolas' talks

→ can be produced by

- **spin-0 *Rad*** and **spin-2 G_{bulk}** in the Randall–Sundrum model with warped extra dimensions
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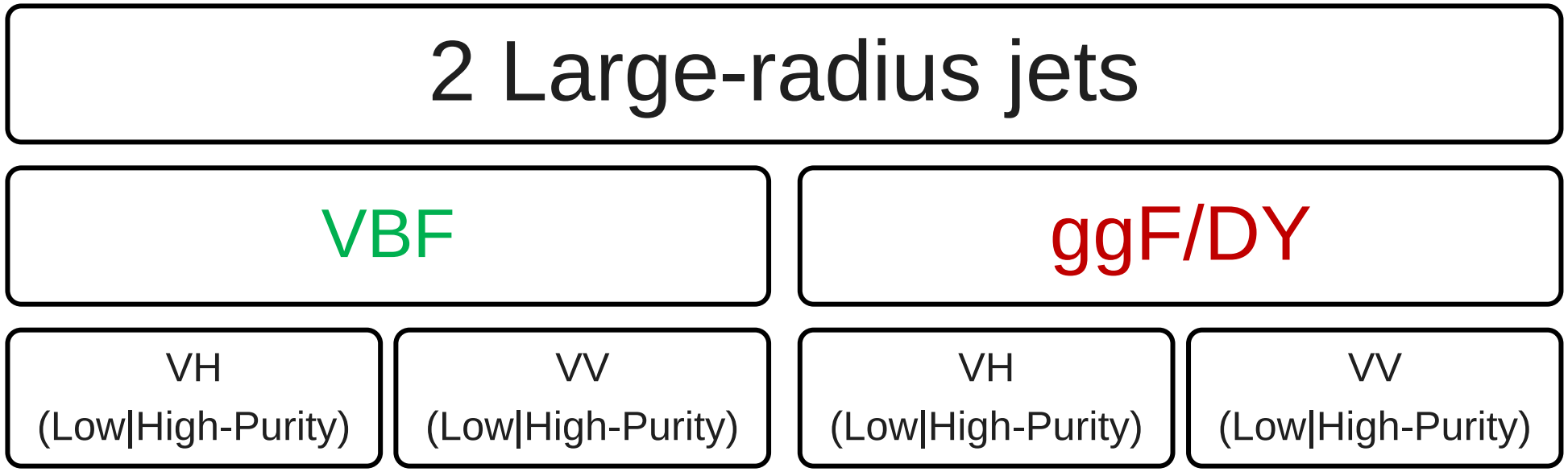
Diboson pairs in all-jet final state

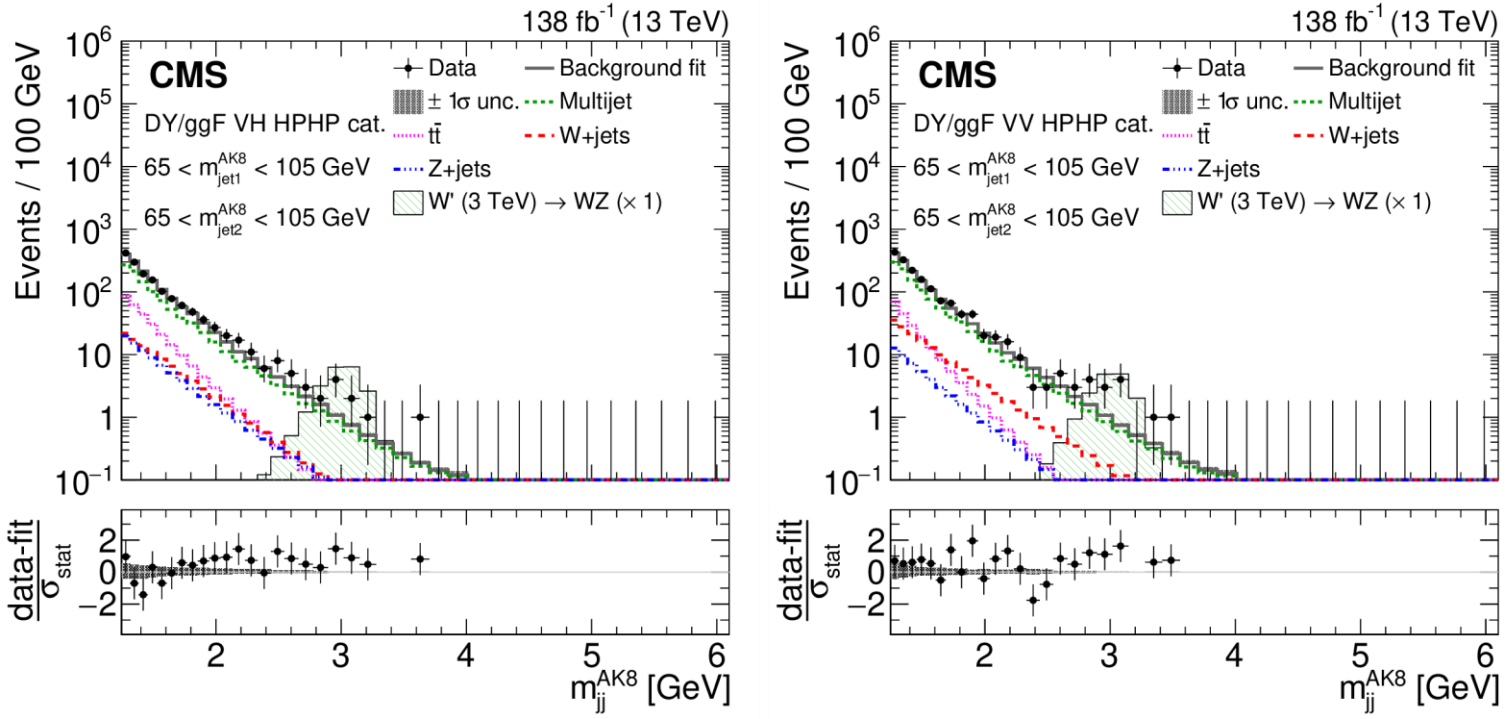
Accepted by Phys. Lett. B

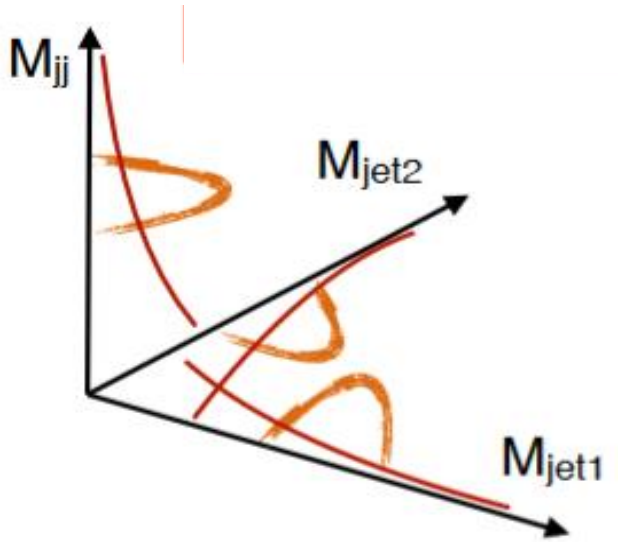
- Search for new heavy resonances decaying in diboson pairs
- Resonances produced via gluon fusion (ggF), Drell–Yan (DY), or vector boson fusion (VBF) are targeted in final state made up by 2 large-radius jets (AK8)
- Large-radius jets selection → “groomed” mass and deepAK8 tagger
- Several regions are determined based on the misID of the deepAK8 tagger



Diboson pairs in all-jet final state

- Background composition
  - Non-resonant background (Multijet)
    - Dominant background
    - Forward folding ensures smooth, full spectrum
  - Partially resonant
    - Resonant in m_{jet1} or m_{jet2}, non-resonant in m_{jj}
    - Model separately ttbar and V+jets



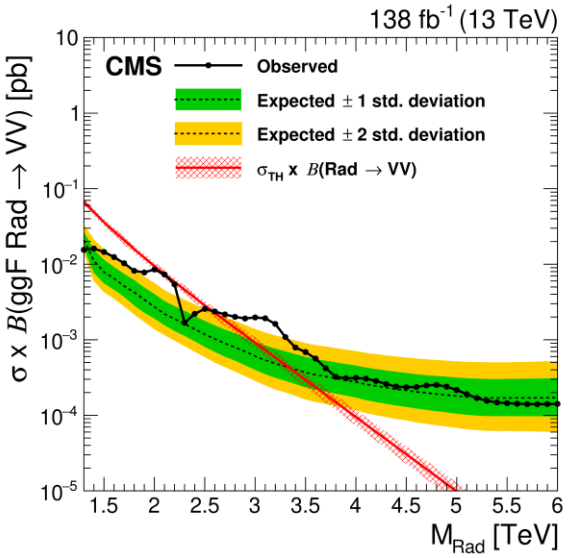


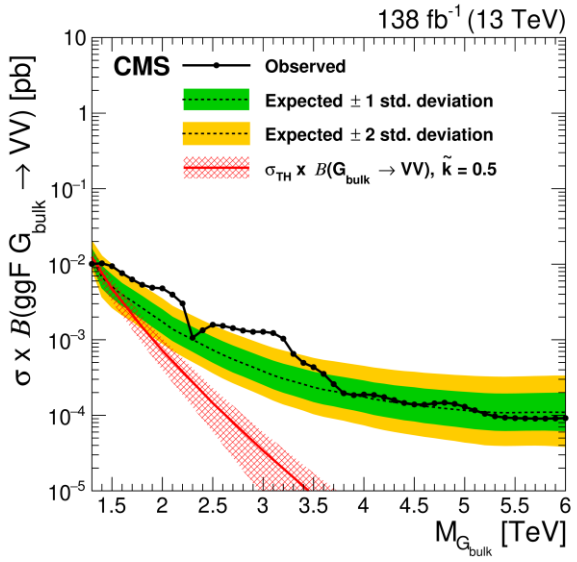
- 3D maximum likelihood fit of signal and background templates to data in (m_{jj}^{AK8}, m_{jet1}^{AK8}, m_{jet2}^{AK8}) space is conducted in all regions
- Excess observed:
  - DY/ggF VH category: **1.7–3.2 TeV** range
  - DY/ggF VV category: around **2 and 3 TeV**

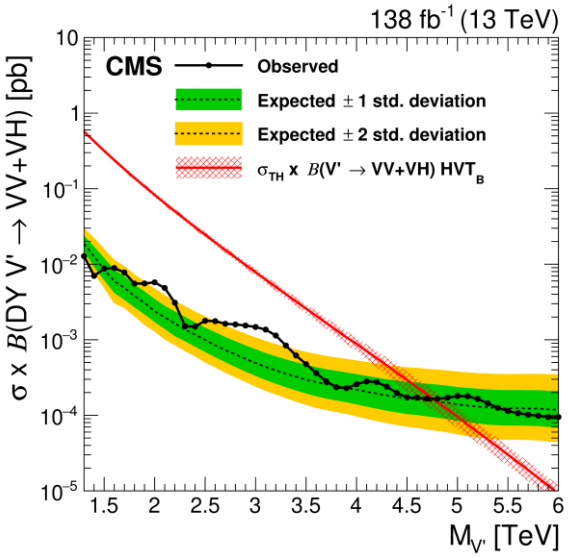
Global significance of **2.3σ**

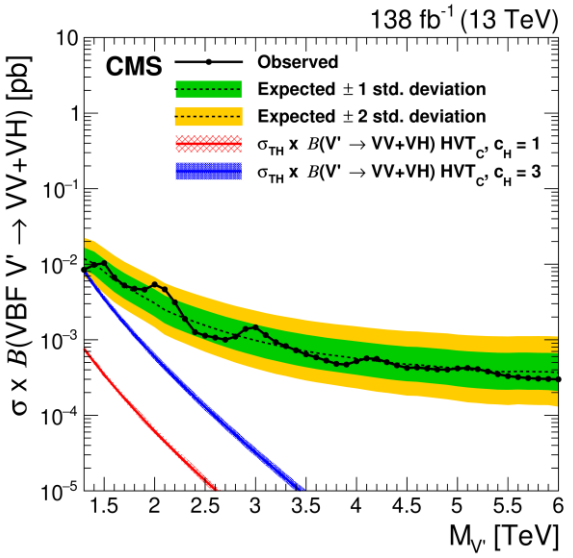
Diboson pairs in all-jet final state

- Upper limits on the production cross section at 95% CL are set
- A global significance of 2.3σ is found under $W' \rightarrow WZ$ hypothesis at 2.1 and 2.9 TeV mass
- Searches in the semileptonic final states did not observe any excesses in the same mass range









Conclusions

- An overview of recent results in BSM searches is presented
  - VLQs
    - T→tH (γγ) the most sensitive to date for mass up to 1.1 TeV with this production mechanism
    - TT production strongest limits to date with all decays mode and the BB production strongest limit in tW decay
  - Hadronic final state
    - a diboson pair production in all hadronic final state with an excess found in data is presented. However, searches in the semileptonic final states did not observe any excesses in the same mass range

Unleash the power of Run 3 results!

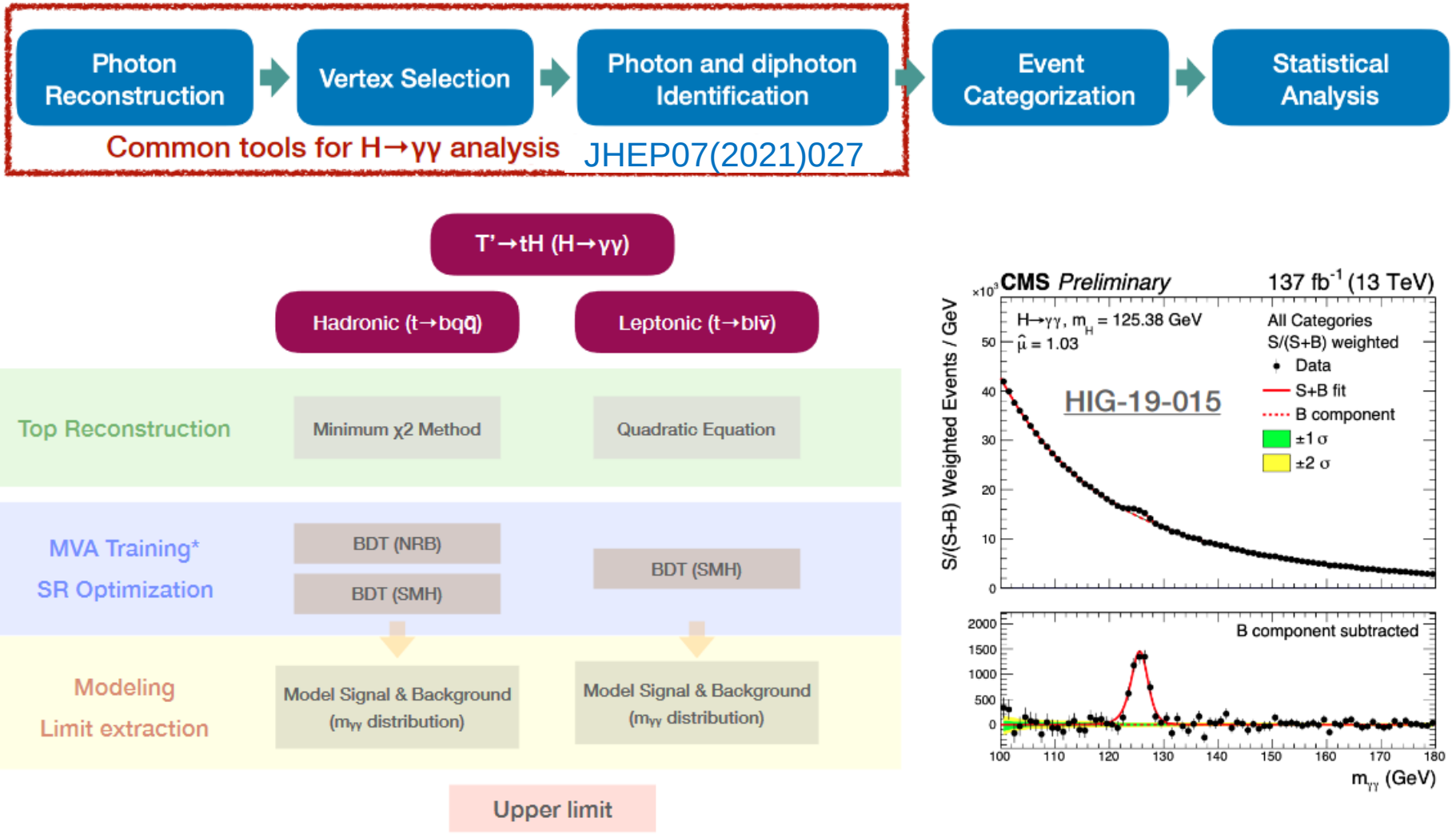
backup

VLQ

	SM	Singlets	Doublets	Triplets
	$\begin{pmatrix} u \\ d \end{pmatrix}\begin{pmatrix} c \\ s \end{pmatrix}\begin{pmatrix} t \\ b \end{pmatrix}$	(t') (b')	$\begin{pmatrix} X \\ t' \end{pmatrix}\begin{pmatrix} t' \\ b' \end{pmatrix}\begin{pmatrix} b' \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ t' \\ b' \end{pmatrix}\begin{pmatrix} t' \\ b' \\ Y \end{pmatrix}$
$SU(2)_L$	2 and 1	1	2	3
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	2/3 -1/3	7/6 1/6 -5/6	2/3 -1/3
$\mathcal{L}_Y$	$-\frac{y_u^i v}{\sqrt{2}}\bar{u}_L^i u_R^i$ $-\frac{y_d^i v}{\sqrt{2}}\bar{d}_L^i V_{CKM}^{i,j} d_R^j$	$-\frac{\lambda_u^i v}{\sqrt{2}}\bar{u}_L^i U_R$ $-\frac{\lambda_d^i v}{\sqrt{2}}\bar{d}_L^i D_R$	$-\frac{\lambda_u^i v}{\sqrt{2}} U_L u_R^i$ $-\frac{\lambda_d^i v}{\sqrt{2}} D_L d_R^i$	$-\frac{\lambda_i v}{\sqrt{2}}\bar{u}_L^i U_R$ $-\lambda_i v \bar{d}_L^i D_R$

$T \rightarrow tH \ \ (H \rightarrow \gamma\gamma)$

Submitted to JHEP



*Separate trainings are performed for three T' mass categories
[600, 625, 650, 675, 700] [800, 900, 1000] [1100, 1200]

Analysis uses H→γγ as a probe to tag T'

Define signal window: $m_{\gamma\gamma} \in [115, 135]$ GeV

$T \rightarrow tH \ (H \rightarrow \gamma\gamma)$

Submitted to JHEP

- Di-photon — Technical details on photons
  - Flashgg preselected diphoton
  - P_T (leading photon) > $M_{\gamma\gamma}$ / 3
  - P_T (subleading photon) > $M_{\gamma\gamma}$ / 4
  - Photon ID MVA score > -0.7
  - 100 GeV < $M_{\gamma\gamma}$ < 180 GeV
- Electron
  - P_T > 10 GeV
  - $|\eta|$ < 2.4 with [1.4442, 1.566] excluded
  - Loose cut-based electron ID
  - ΔR (electron and photon) > 0.4
  - ΔM (electron/photon and Z) > 5 GeV
- Muon
  - P_T > 10 GeV and $|\eta|$ < 2.4
  - Tight cut-based muon ID
  - Isolation < 0.25
  - ΔR (muon and photon) > 0.4
- Jets
  - P_T > 25 GeV and $|\eta|$ < 4.5
  - Tight ID (17/18) and Loose ID (16)
  - ΔR (jet, photon/lepton) > 0.4
  - For w-jets, $|\eta|$ < 3.0
- bJets
  - Loose working point of deepCSV
  - b-tagged discriminant is reshaped
- Triggers
  - 2016: HLT_Diphoton30_18_R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass90*
  - 2017: HLT_Diphoton30_22_R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass90*
  - 2018: HLT_Diphoton30_22_R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass90*

$T \rightarrow tH \ (H \rightarrow \gamma\gamma)$

Submitted to JHEP

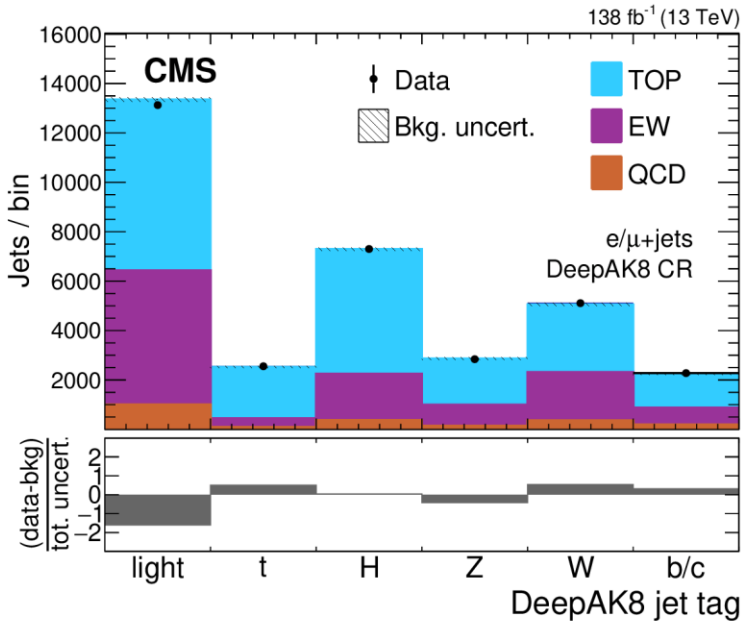
- Multivariate analysis technique
  - Distinguish VLQ signal from background events
  - Gradient boosted decision trees (BDT)
  - Separate trainings are performed for three T' mass categories [600, 625, 650, 675, 700] [800, 900, 1000] [1100, 1200]
- Leptonic channel
  - One BDT is trained for each T' mass category
  - Signal: VLQ
  - Background: $t\bar{t}H$, ggH, VH, VBF, tHq
- Hadronic channel
  - Two BDTs are trained for each T' mass category
  - Signal: VLQ
  - Non-resonant background (NRB): γγ+jets, data-driven QCD, $t\bar{t}\gamma\gamma$, $t\bar{t}\gamma$+jets, tγ+jets, $t\bar{t}$+jets, V+γ
  - SM Higgs background (SMH): $t\bar{t}H$, ggH, VH, VBF, tHq

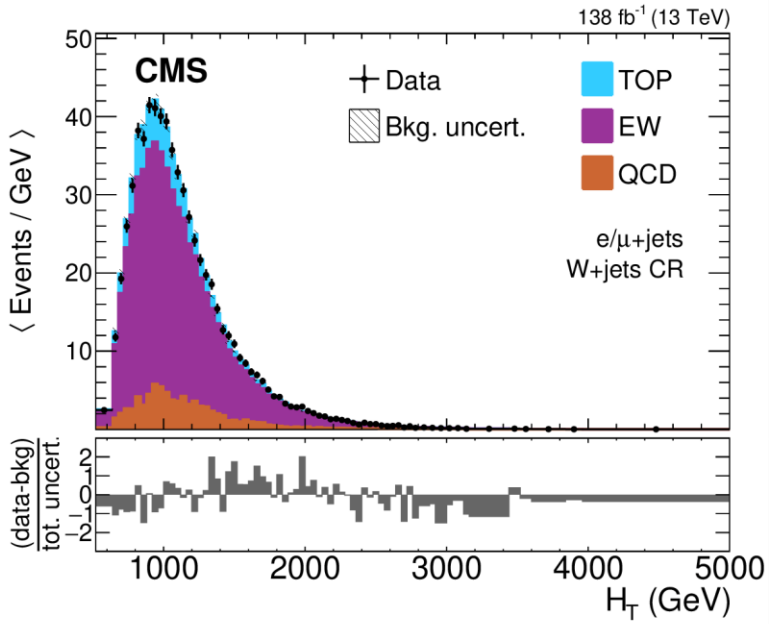
Training configuration
- Algorithm: Gradient BDT
- Decision trees: 1000
- Tree depth: 2
- Training samples: 50%
- Testing samples: 50%

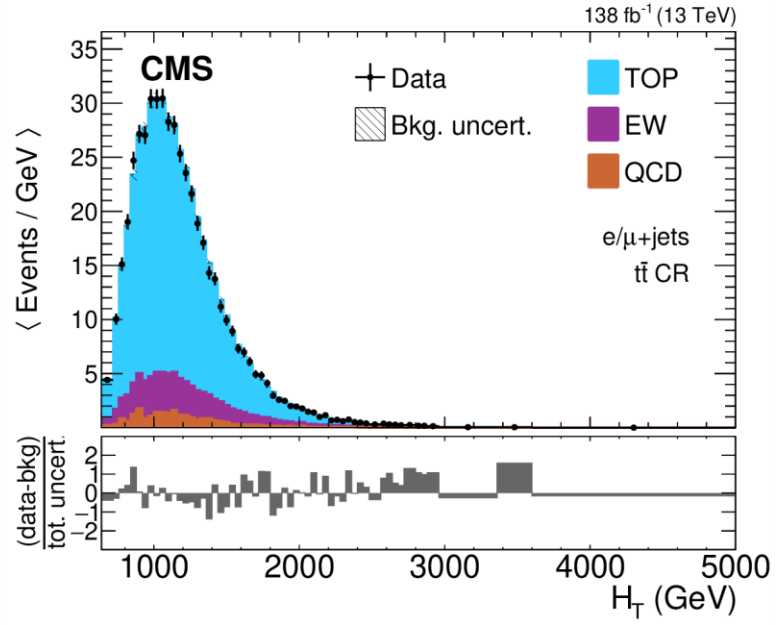
Pair production TT/BB

Accepted by JHEP

single-lepton channel



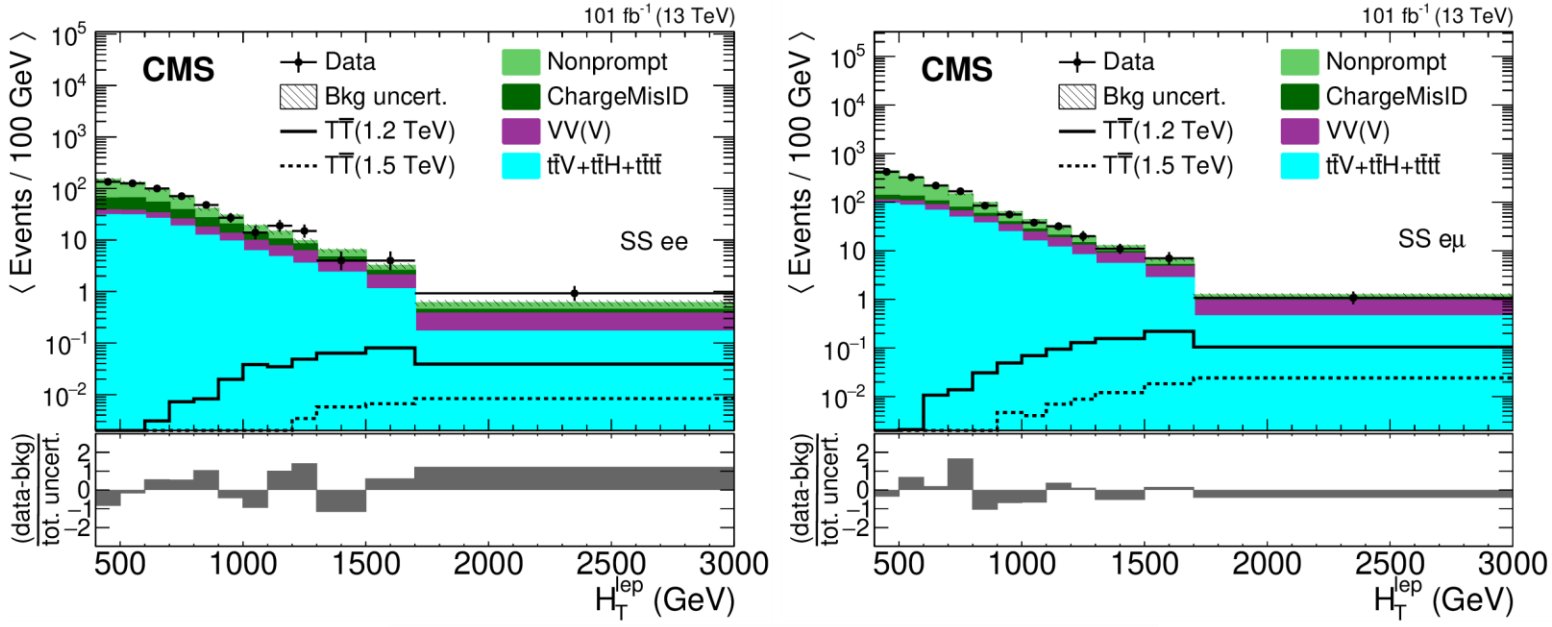


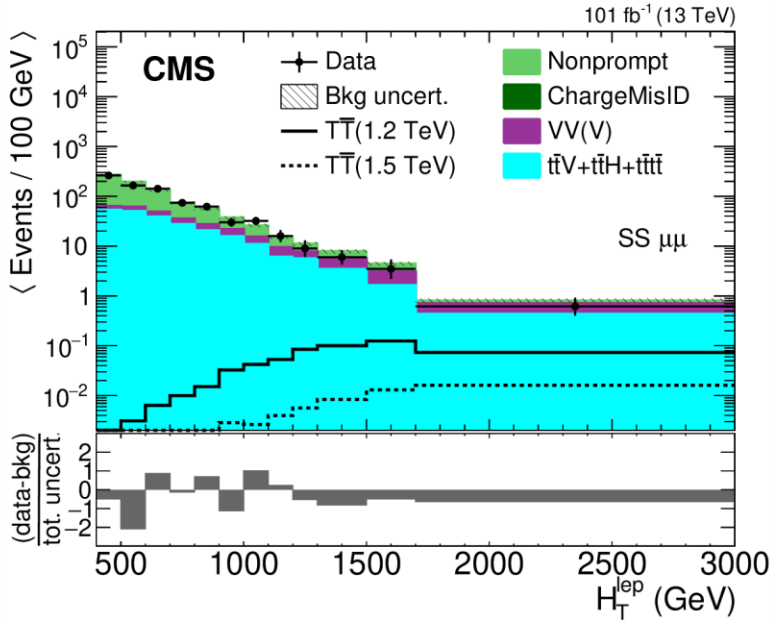


Pair production TT/BB

Accepted by JHEP

same-sign charge (SS) dilepton channel

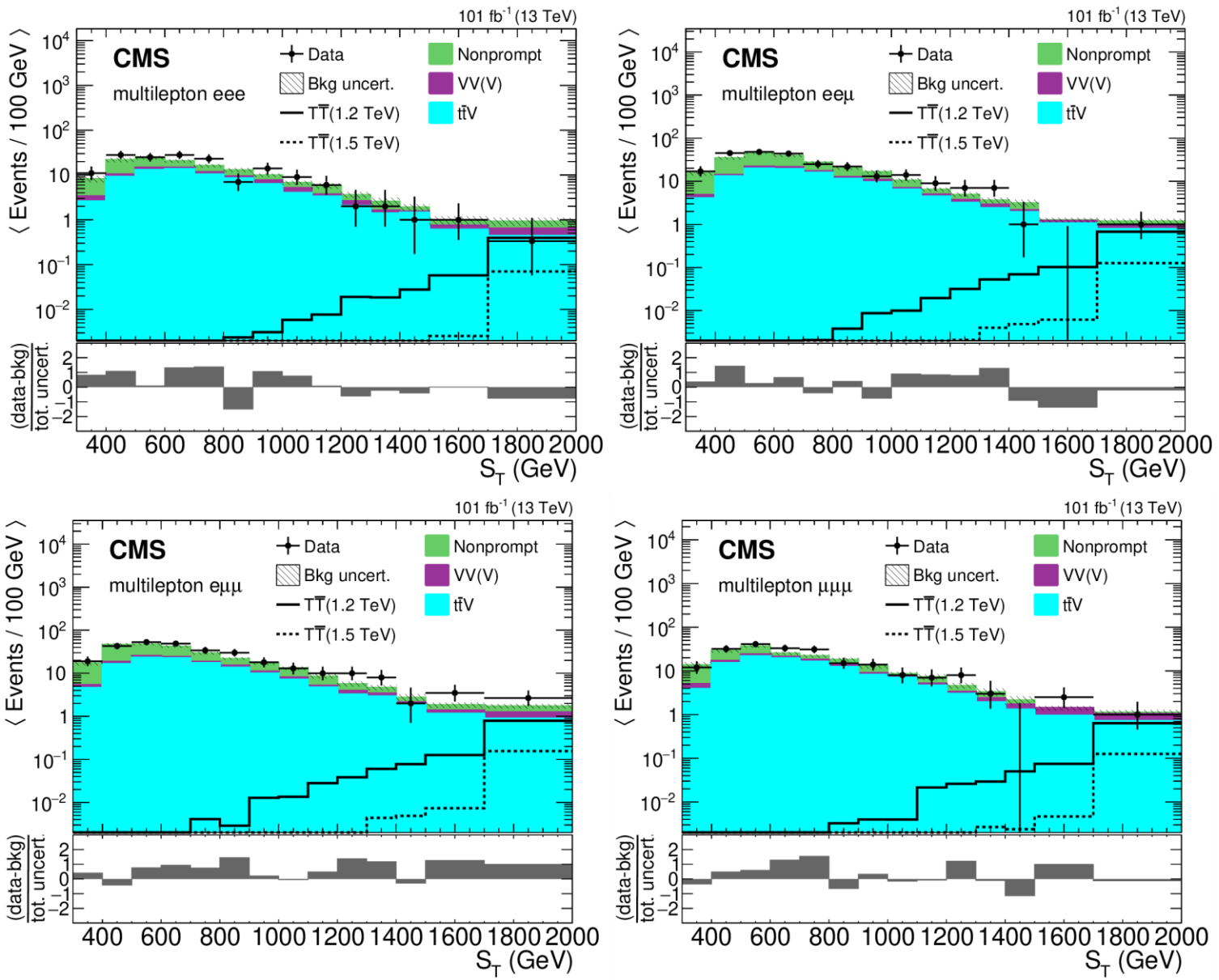




Pair production TT/BB

Accepted by JHEP

multilepton channel with at least three leptons

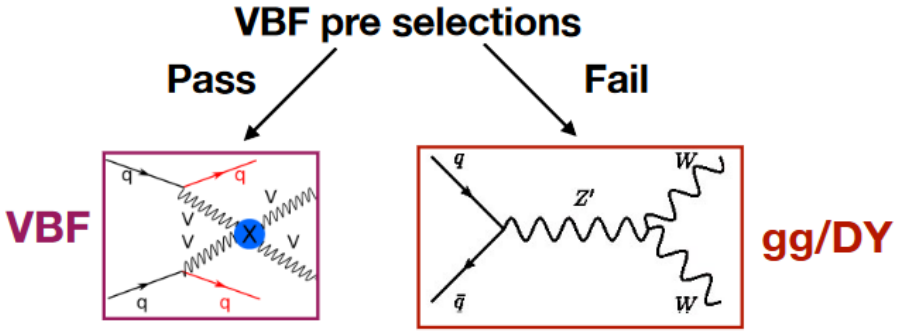


Diboson pairs in all-jet final state

Accepted by Phys. Lett. B

Event categorisation

- 2 orthogonal main categories
  - **VBF** & **gg/DY**



- Each of them divided in
  - **VH: H-tag enriched (H/Z→bb)** 2D MD-deepAK8 ZHbbvsQCD
    - HPHP, HPLP, LPHP
  - **VV: V-tag enriched (V→qq)** 2D MD-deepAK8 WvsQCD
    - HPHP, HPLP

- Subcategories defined by the purity (mistag rate) of the tagging:
  - HP = High Purity & LP = Low Purity

	HP	LP
V->qq tag	< 5 % mistag	5 - 20 % Mistag
H/Z->bb tag	< 2 % mistag	2 - 10 % mistag

Highest priority → Lowest priority

VH HPHP | VV HPHP | VH LPHP | VH HPLP | VV HPLP

- Working points and categories prioritization optimized for WW and ZH
- Checked Punzi Significance and expected limits (including SF)