# Searches for vector-like quarks at CMS experiment

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# Overview

- Theoretical motivation for vector-like quarks
- Production and decay modes
- Overview of the CMS search program
- Searches on single production
- Searches on pair production
- Future prospects for VLQ searches at the HL-LHC
- Conclusion

**References:**


1. EXO-23-006 (Submitted to Phys. Rept.)

1. B2G-21-007 (10.1007/JHEP09(2023)057)
2. B2G-19-001 (submitted to PRD)
3. B2G-21-014 (submitted to PRD),
4. B2G-20-011 (10.1007/JHEP07(2023)020 )
5. FTR-22-002

# Motivation

- After the discovery of Higgs boson, the SM is complete as a low-energy effective theory
  - Describe all fundamental particles and their interactions
- At high energies, quantum loop corrections to the Higgs boson self-energy tend to diverge.
  - We are still left with the “hierarchy problem”
- Various physics theories beyond the SM theories (Little Higgs, Composite Higgs etc.) predict additional particles, provides a feasible solution

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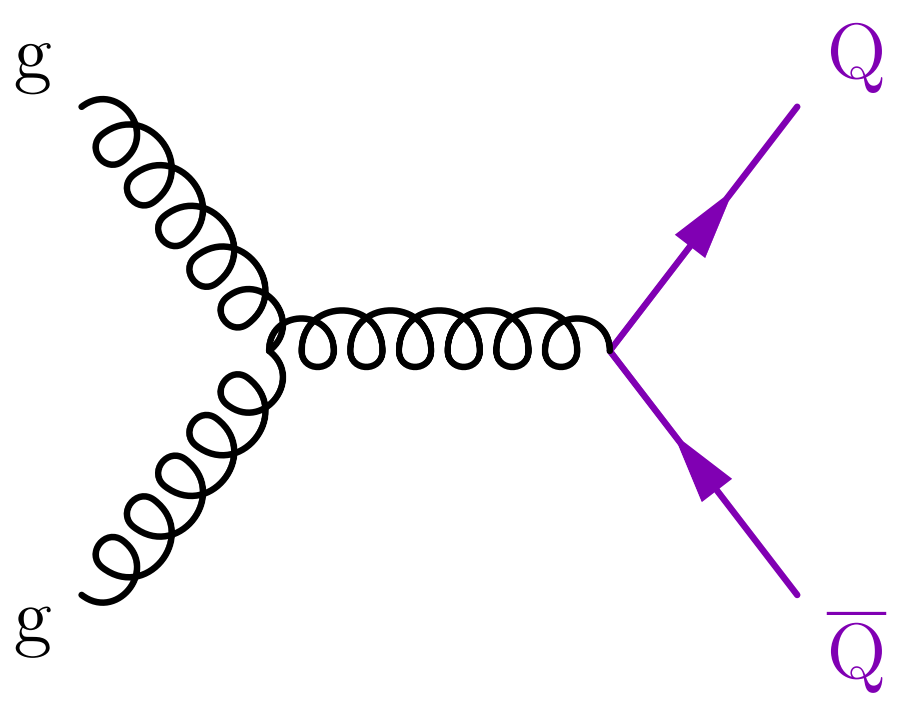
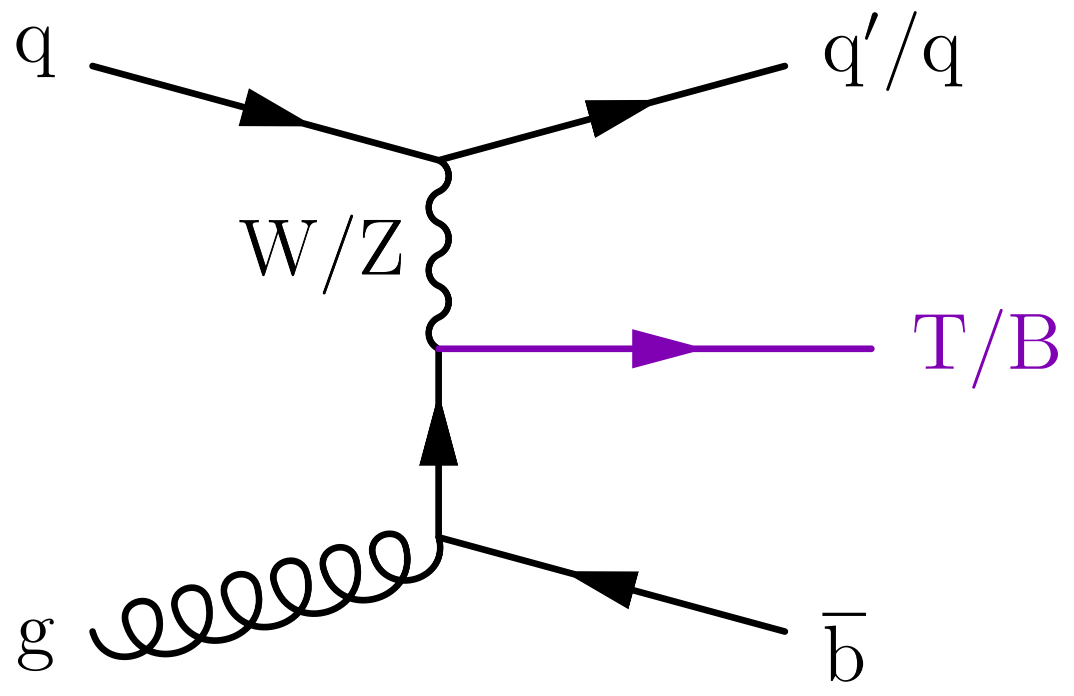
- Such a new particles are a **vector-like quarks**
- As singlets, **T and B are introduced with electrical charges of +2/3 and –1/3**
- Doublets and triplets incorporate two additional particles: $X_{5/3}$ **(charge +5/3) and** $X_{4/3}$ **(charge –4/3).**
- The dominant decay modes of the VLQs are to third-generation SM quarks
- Time to utilize precise SM measurement tools to probe these BSM physics

# VLQ production @ LHC

**Strong**



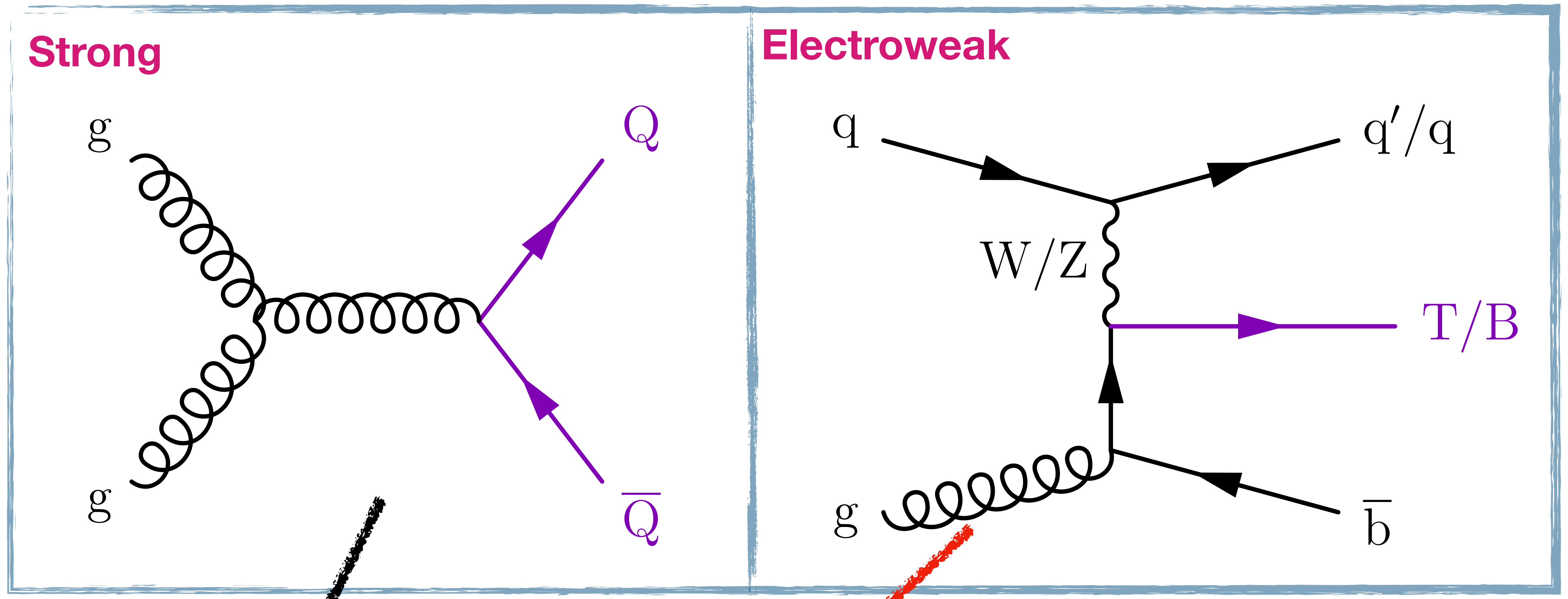

**Electroweak**

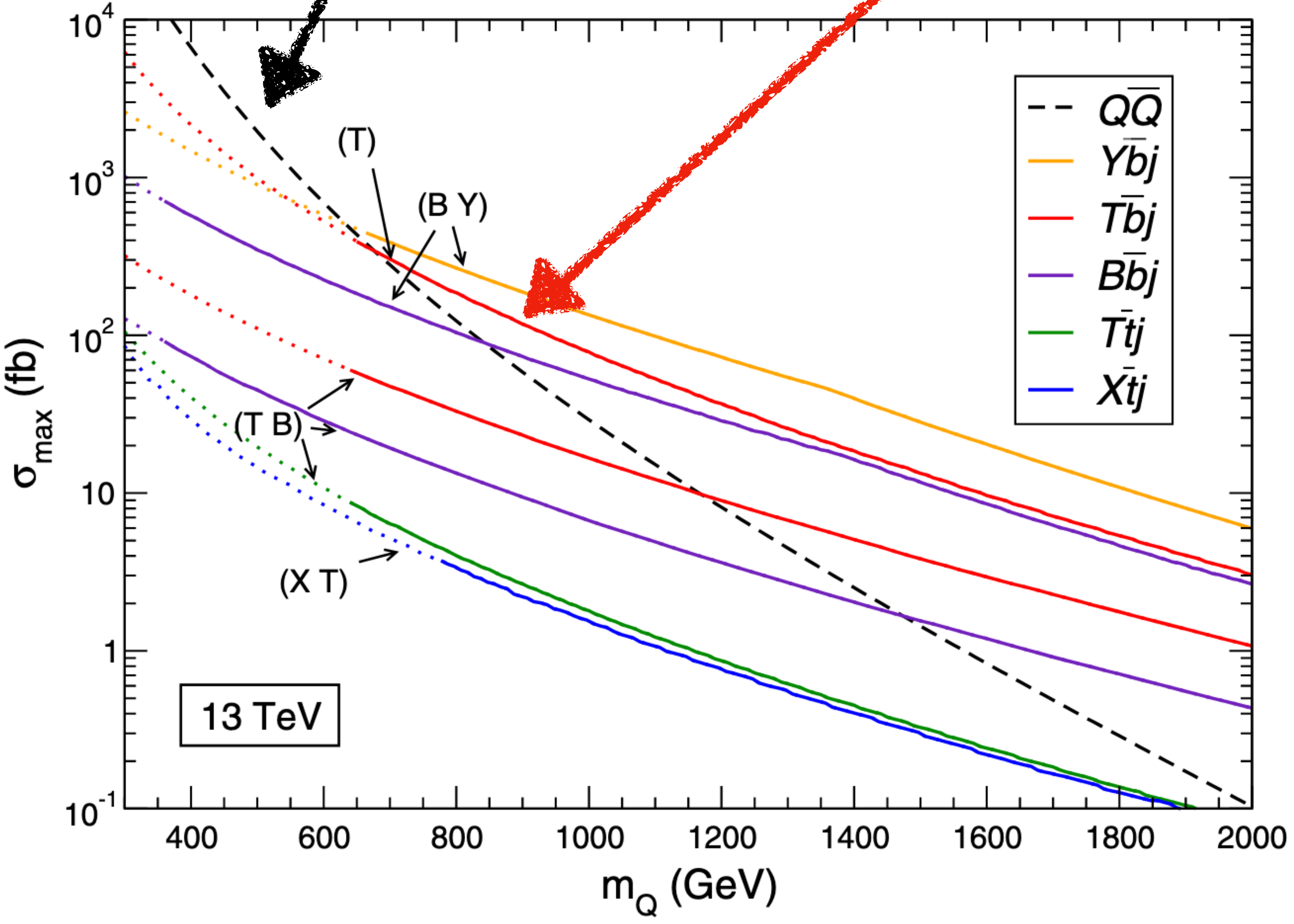



## Strong production

- Production depends in strong coupling constant ($\alpha_s$) and the mass of $\mathrm{T}$ ( $\mathrm{M_T}$ )
- Cross section is only depend on $\mathrm{T}$ mass, less model dependent.

# VLQ production @ LHC




Phys Rev D.88.094010

## Strong production

- Production depends in strong coupling constant ($\alpha_s$) and the mass of T ( $M_T$ )
- Cross section is only depend on T mass, less model dependent.

## Electroweak production

- Only one heavy particle is produced, relatively heavy VLQ masses can be explored
- Cross section dependent on the couplings of the VLQ to third-generation quarks, $\kappa_T$
- The coupling $\kappa_T$ can significantly change based on the choice of the VLQ mass and width

**Makes the study of the both production mode important**

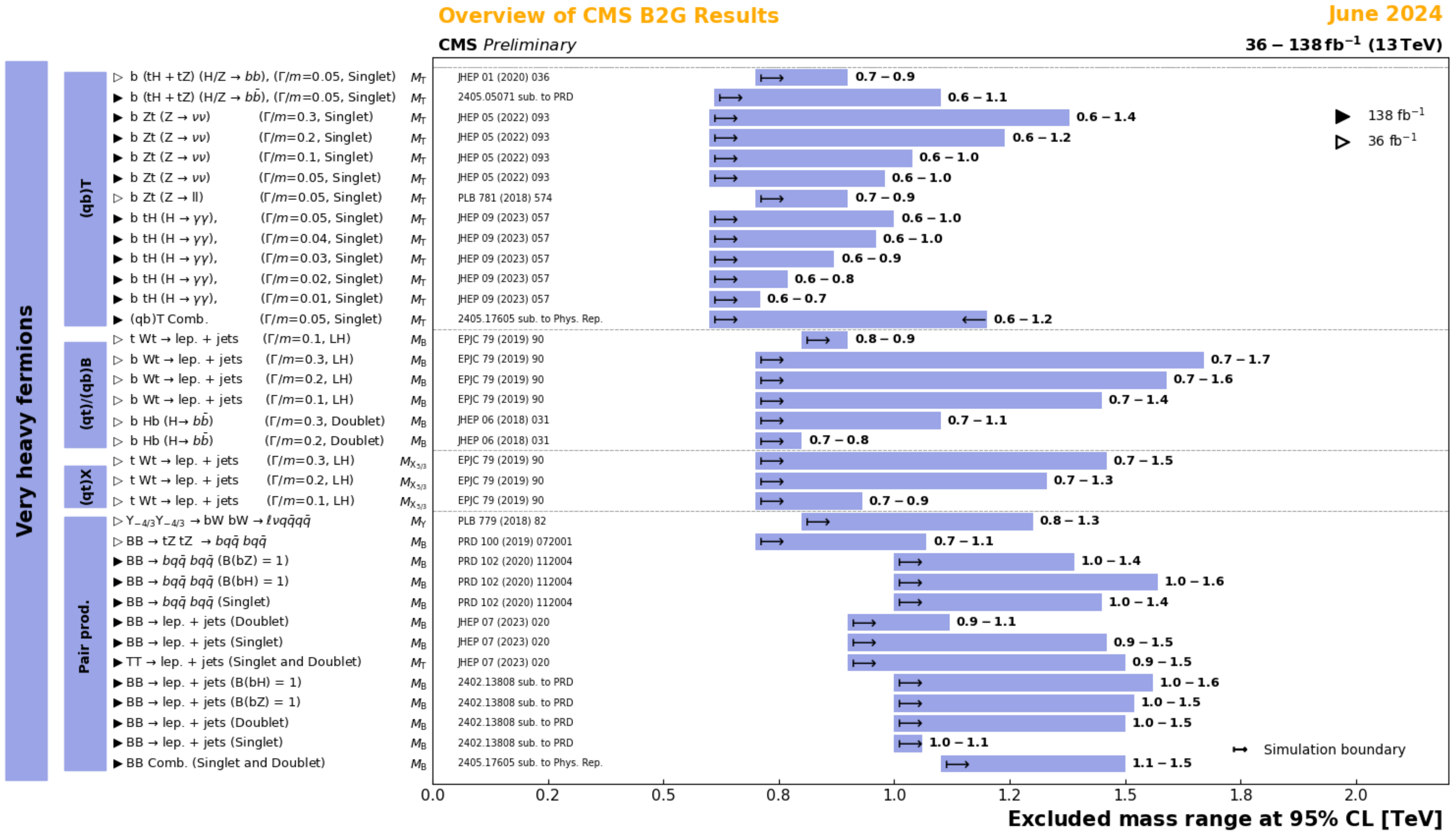
# Overview of the CMS search program

| Production mode | Decay mode | Channel |
|---|---|---|
| $T\bar{T}$ | bW, tH, tZ | $0\ell, 1\ell$, OS $2\ell$, SS $2\ell, 3\ell$ |
| $B\bar{B}$ | tW, bH, bZ | $0\ell, 1\ell$, OS $2\ell$, SS $2\ell, 3\ell$ |
| $X_{5/3}\bar{X}_{5/3}$ | tW | $1\ell$, SS $2\ell$ |
| $Y_{4/3}\bar{Y}_{4/3}$ | bW | $1\ell$ |
| T | tZ | $bqq\,\ell\ell$, $bqq\,bb$, $bqq\,\nu\nu$ |
| | tH | $bqq\,\gamma\gamma$, $bqq\,bb$ |
| | bW | $b\,\ell\nu$ |
| B | bH | $b\,bb$ |
| | tW | $bqq\,\ell\nu$, $b\ell\nu\,qq$, $bqq\,qq$ |
| $X_{5/3}$ | tW | $bqq\,\ell\nu$, $b\ell\nu\,qq$, $bqq\,qq$ |
| $Y_{4/3}$ | bW | $b\,\ell\nu$ |

Pair production

Single production

- Run II : $\sqrt{s} = 13\,\text{TeV}$ $\int Ldt = 138\,\text{fb}^{-1}$
- **Dedicated analysis for each production modes and VLQs of all flavors.**

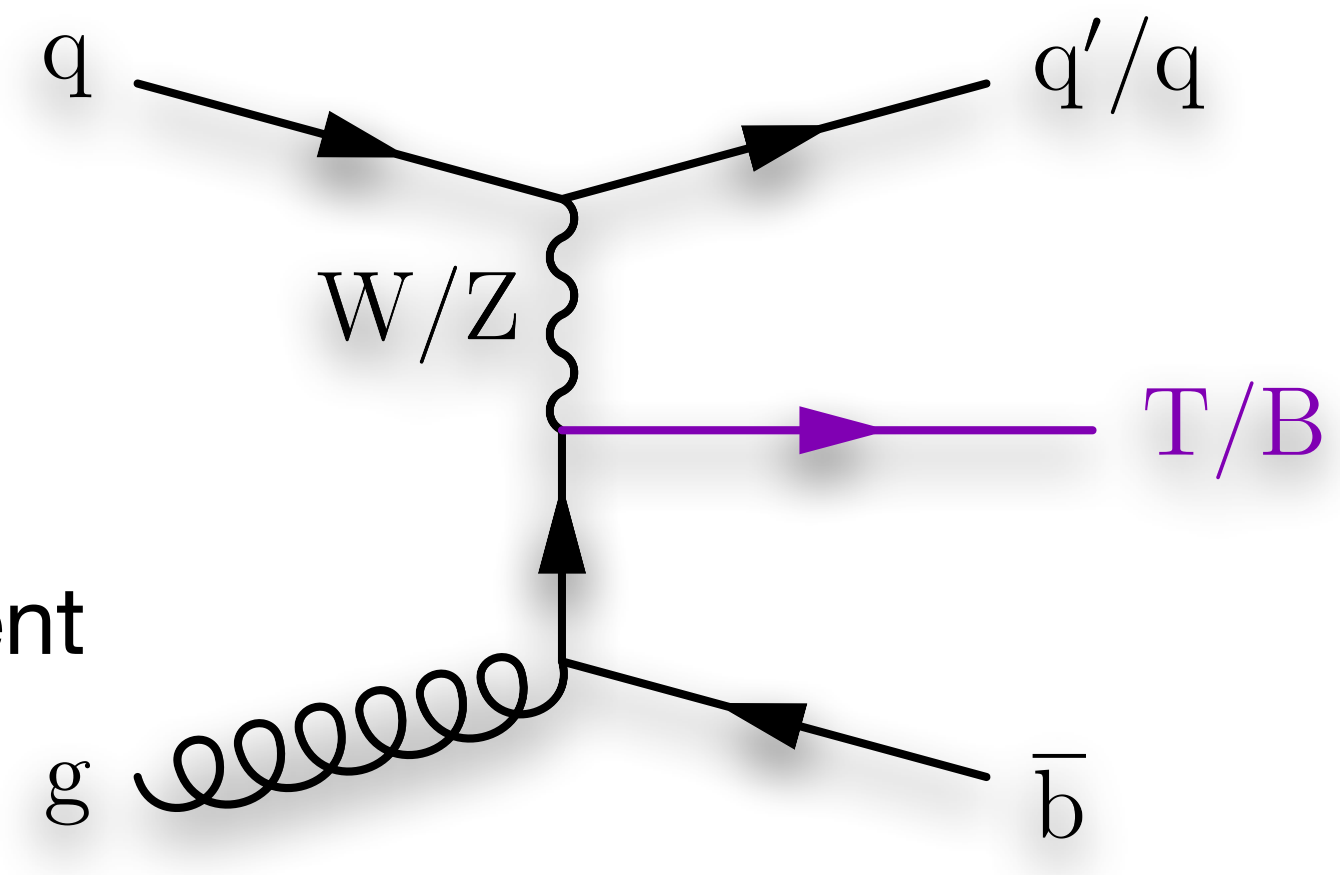



**Combination of Analyses: (Released in May 2024)**

- searches targeting pair production $B\bar{B}$ events.
- searches focusing on single $T$ events.

# Single production

- Under the **Narrow Width Approximation** ($\Gamma/M_{T'} < 10 - 15\,\%$) the cross section become only function of $\kappa_T$.
- Analyses are designed using different width approximations: **Narrow Width Approximation** and **width approximations of 10, 20, and 30%**, considering different values for $\kappa_T$ .




| | | |
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| T | tZ | $bqq\,\ell\ell$, $bqq\,bb$, $bqq\,\nu\nu$ |
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| | bW | $b\,\ell\nu$ |
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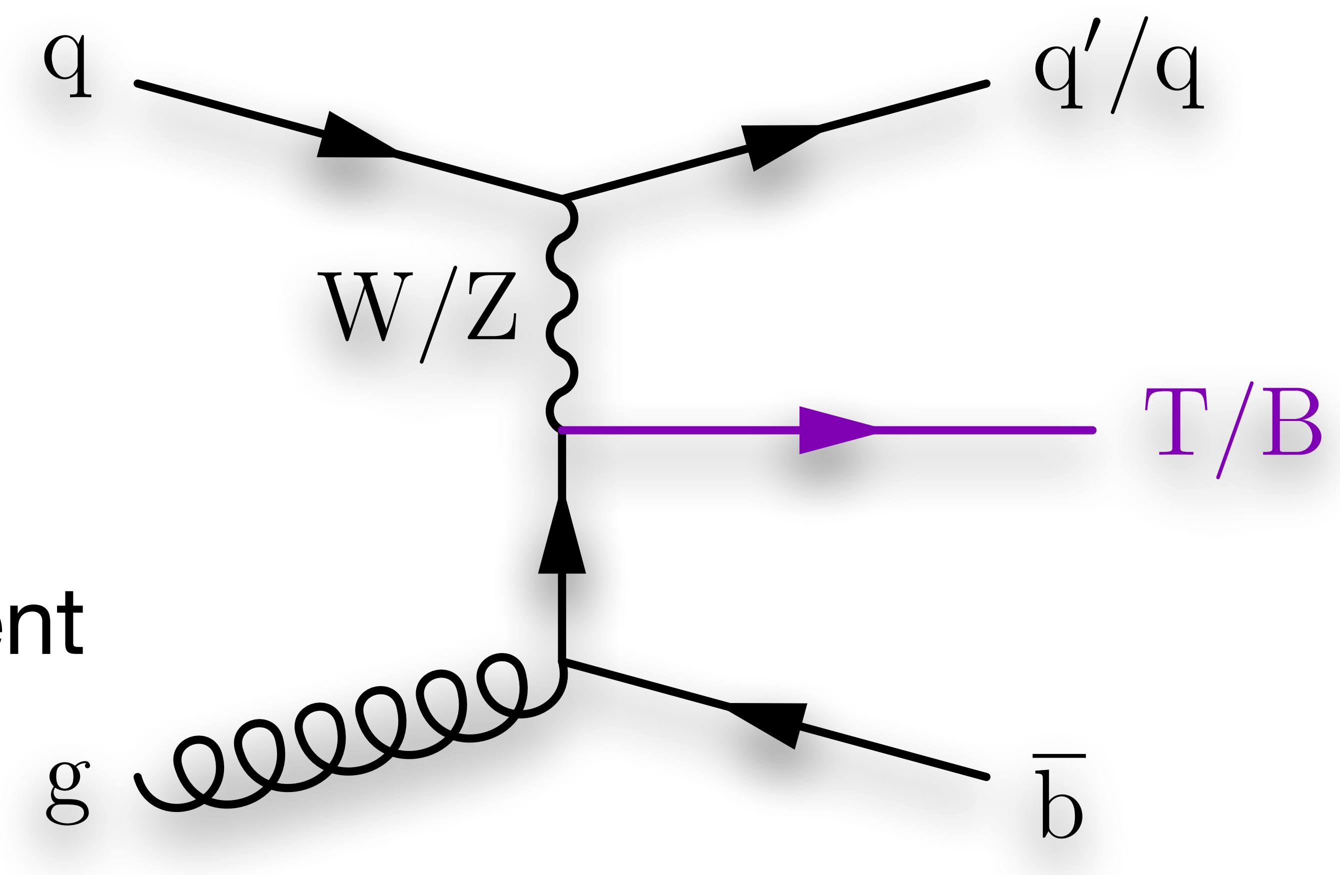


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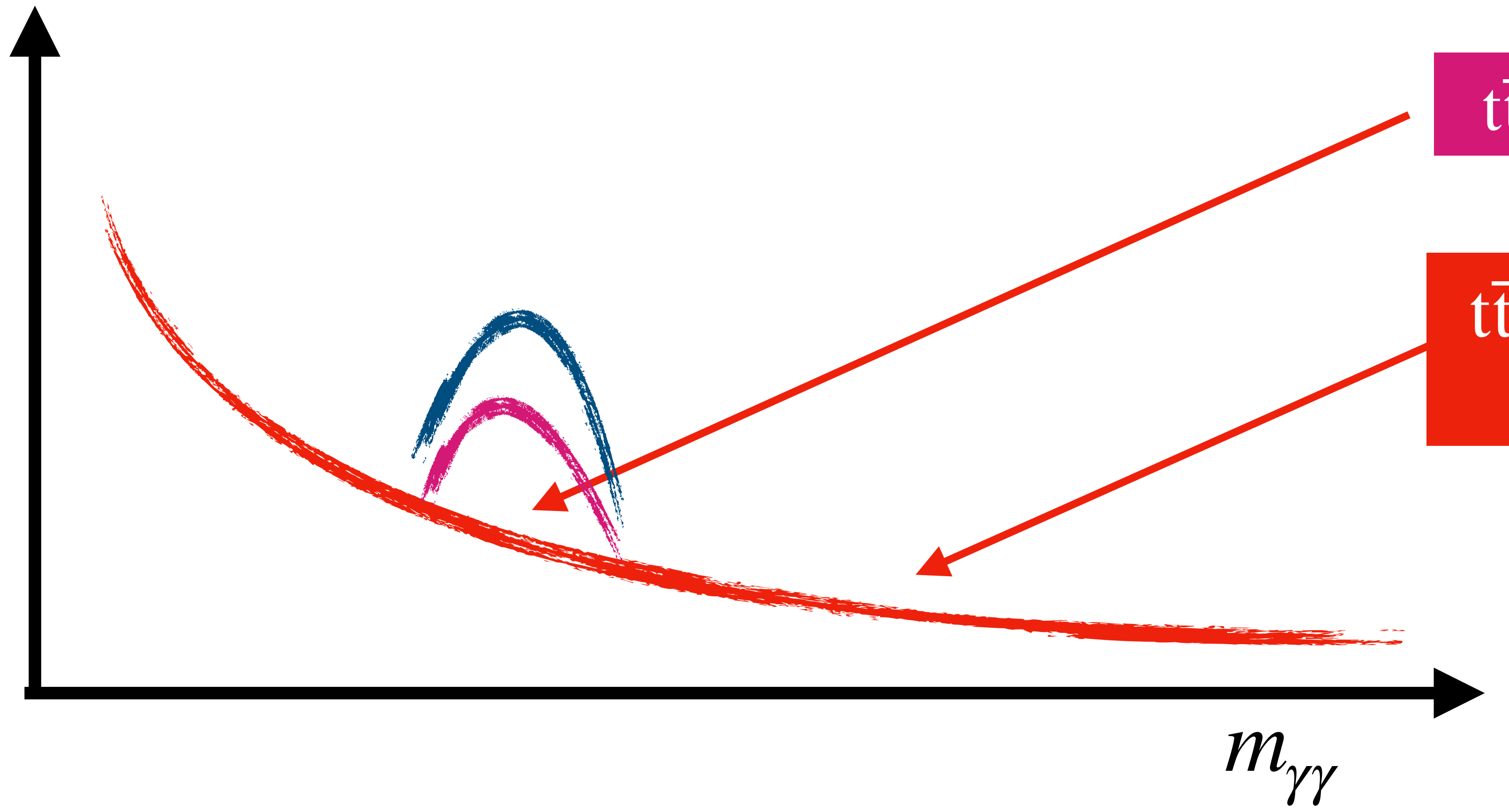
Single production

→ **Discuss in today's talk**

# Single production ($T \rightarrow tH \rightarrow bqq/b\ell\nu\ \gamma\gamma$)

- **Usage of well-established $H \rightarrow \gamma\gamma$ tools**
- Diphoton invariant mass ($m_{\gamma\gamma}$) as the main observable
- MVA is used to reject the SM Higgs and non-resonant backgrounds

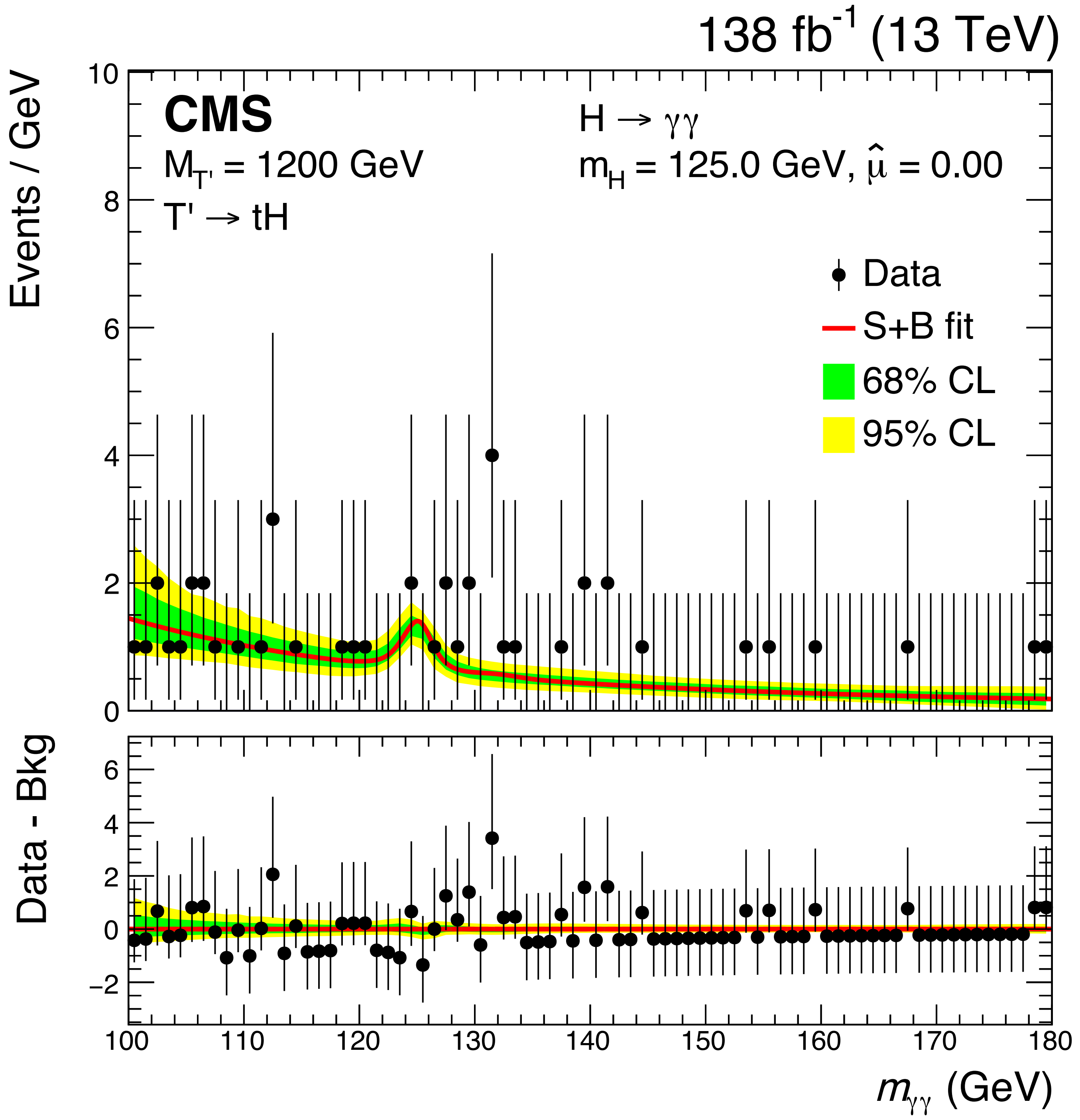


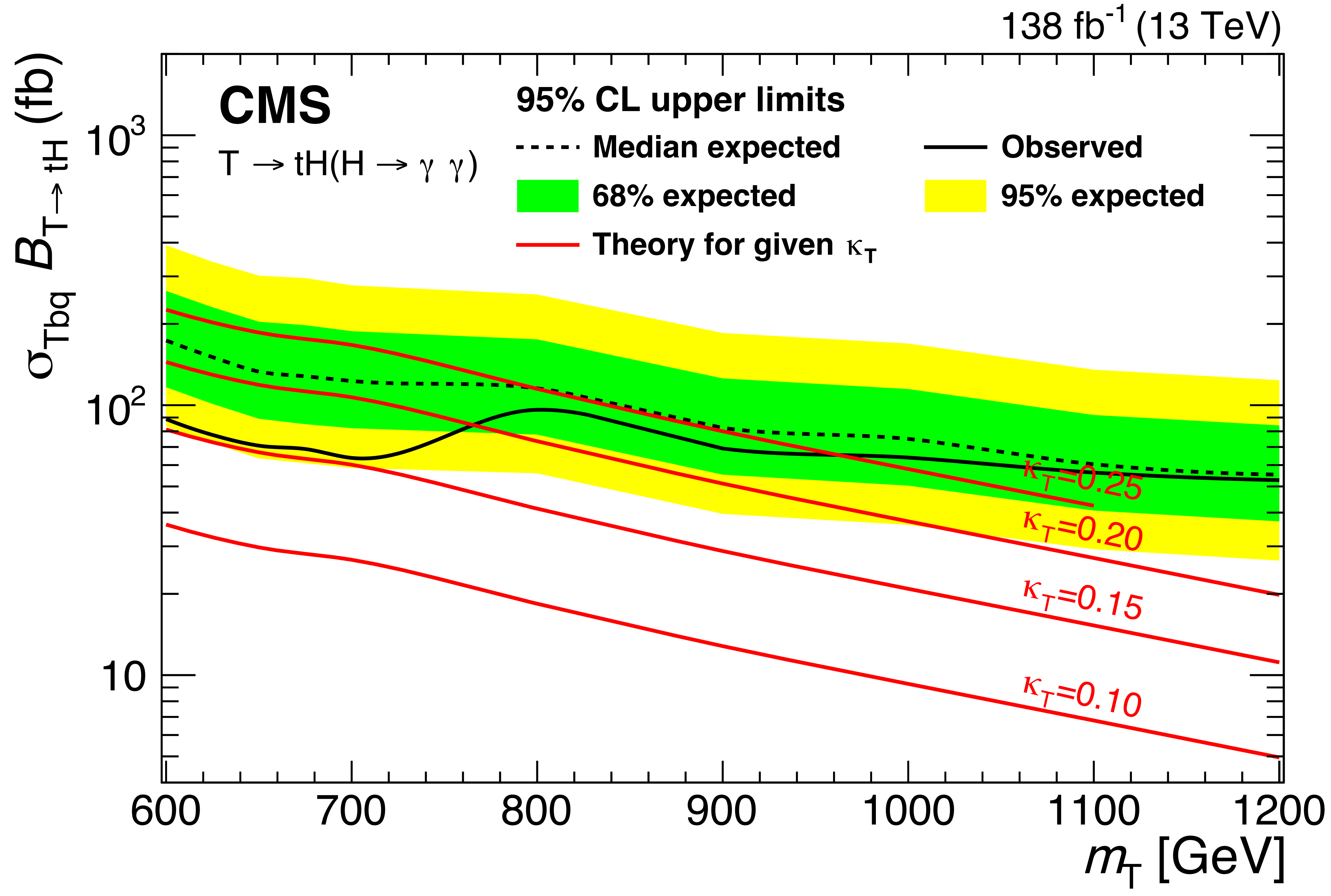

**Signal and SM Higgs Model:**

- Modeled from MC sample
- $m_{\gamma\gamma}$ distribution is fitted with a sum of gaussians

**Background Model:**

- Modeled from data for 100<$m_{\gamma\gamma}$<180 GeV
- **Functions used for background fit:** Exponentials, power laws, polynomials, and Laurent series




**Singlet T masses are excluded up to 960 GeV under NWA**

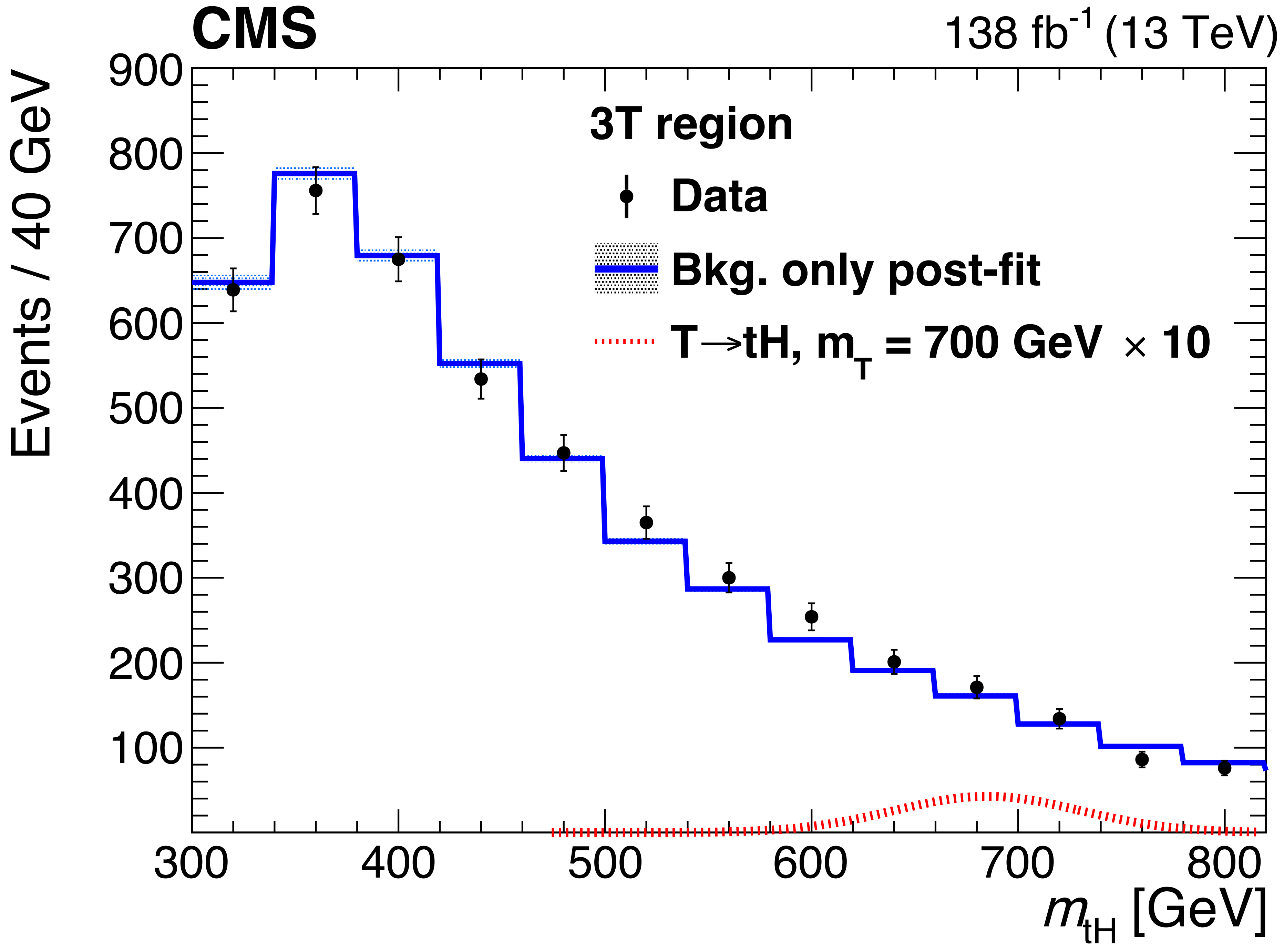
**Despite the low $H \rightarrow \gamma\gamma$ branching fraction (0.2%), provided the best constraints**

10.1007/JHEP09(2023)057

# Single production ($T \to tH/tZ \to bqq\ b\bar{b}$)

- T singlet with **narrow width approximation** in the mass range **[600,1200] GeV.**
- Observable: resonant peak in the reconstructed five-jet mass distribution
  - T quark candidates are reconstructed using a multistep $\chi^2$ minimization technique.
- Base line event selection: **≥ 6 jets** out of which ≥ 3 are b-tagged jets

**Five-jet invariant mass distributions**




**No statistically significant excess observed over the background expectations.**

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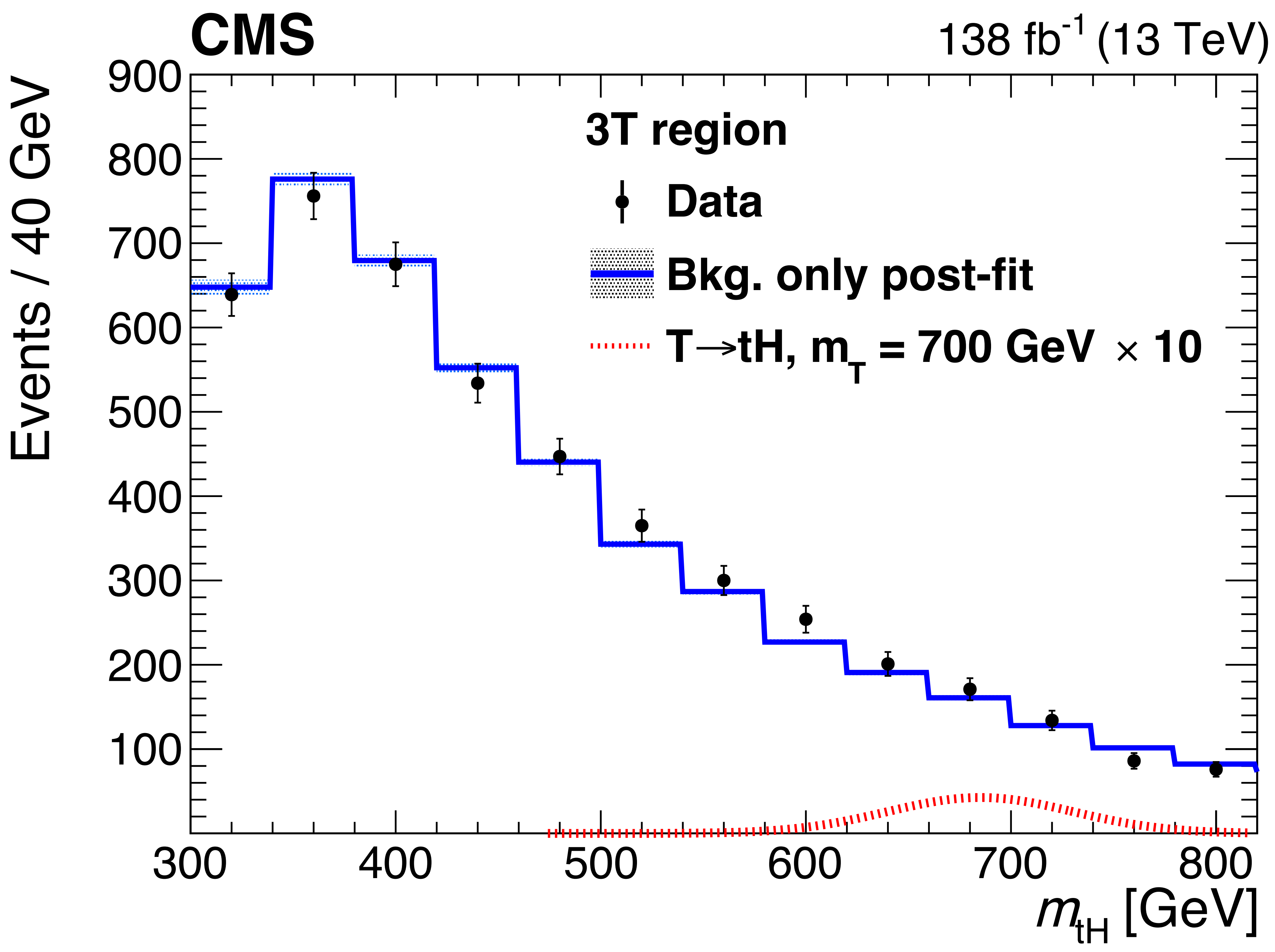
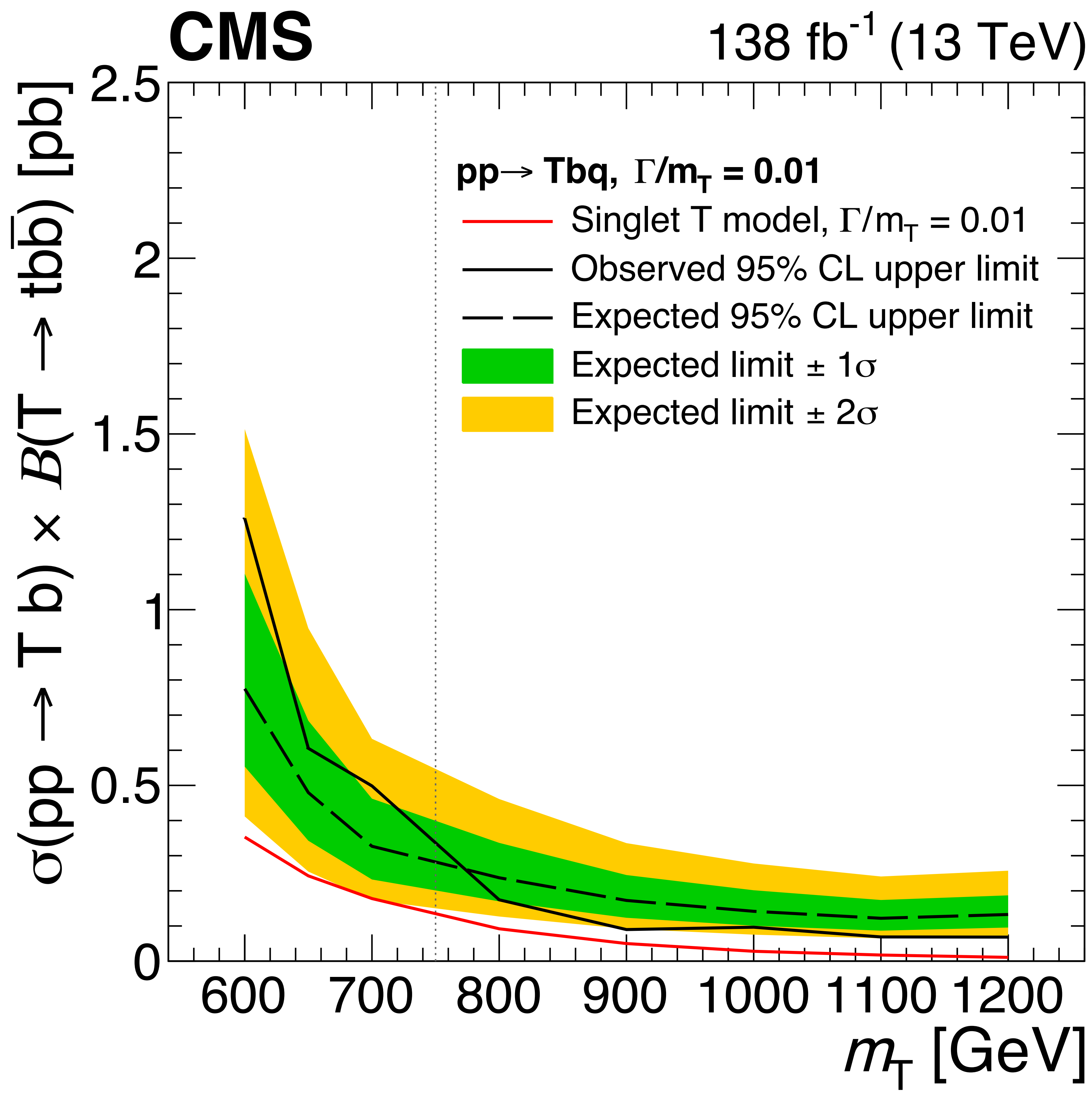



**No statistically significant excess observed over the background expectations.**

**Upper limits on the cross sections for single T quark production (tH and tZ)**

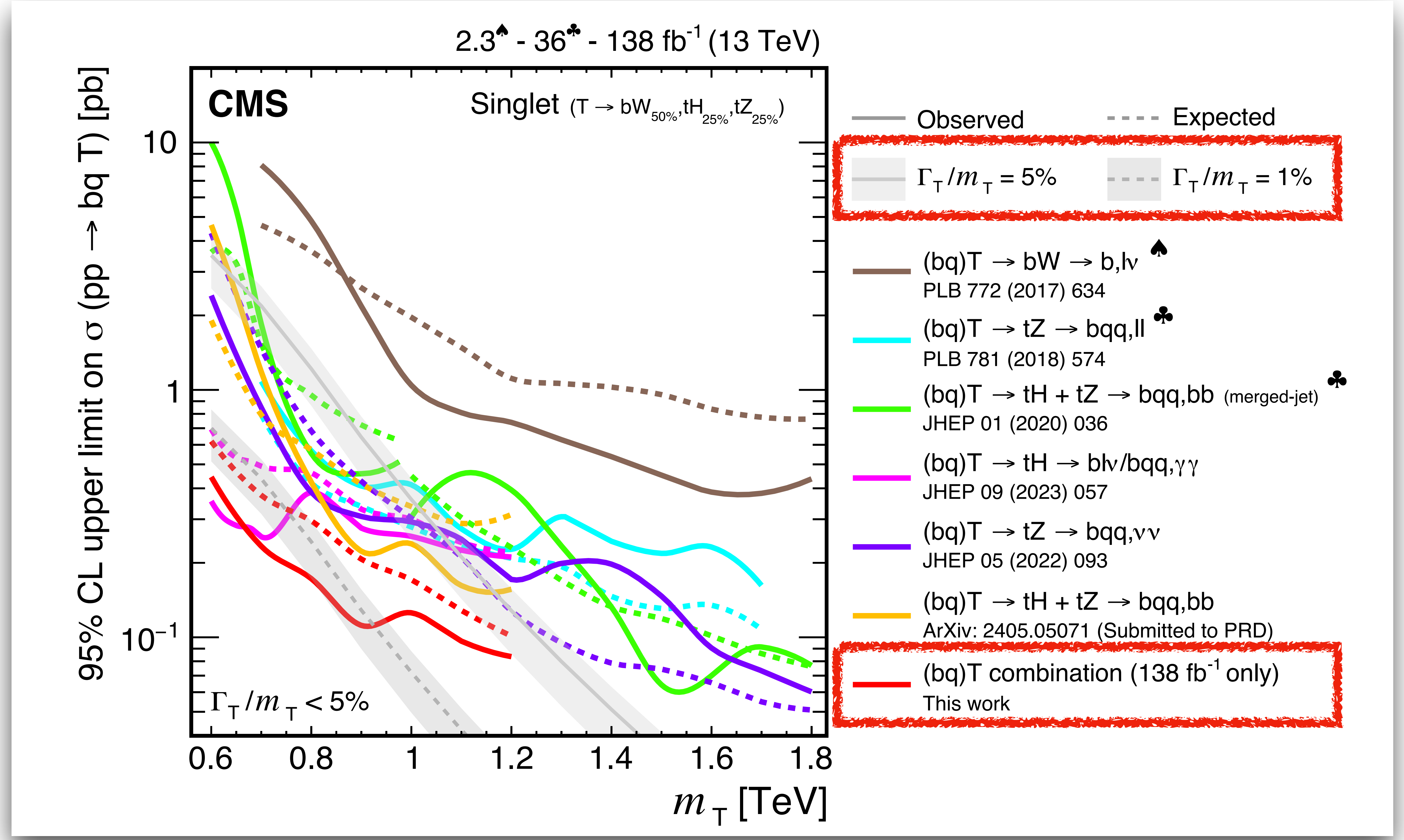



**Obtained a stronger limit by a factor of three than 10.1007/JHEP01(2020)036**

B2G-19-001, submitted to PRD

# Single production ( T )

**Upper limits on single T quark production crossection obtained by different analyses under NWA**




**Statistical combination:**

For NWA

$T \to tZ$

$tZ \to bqq\,\nu\nu$

$tZ \to bqq\,bb$

$T \to tH$

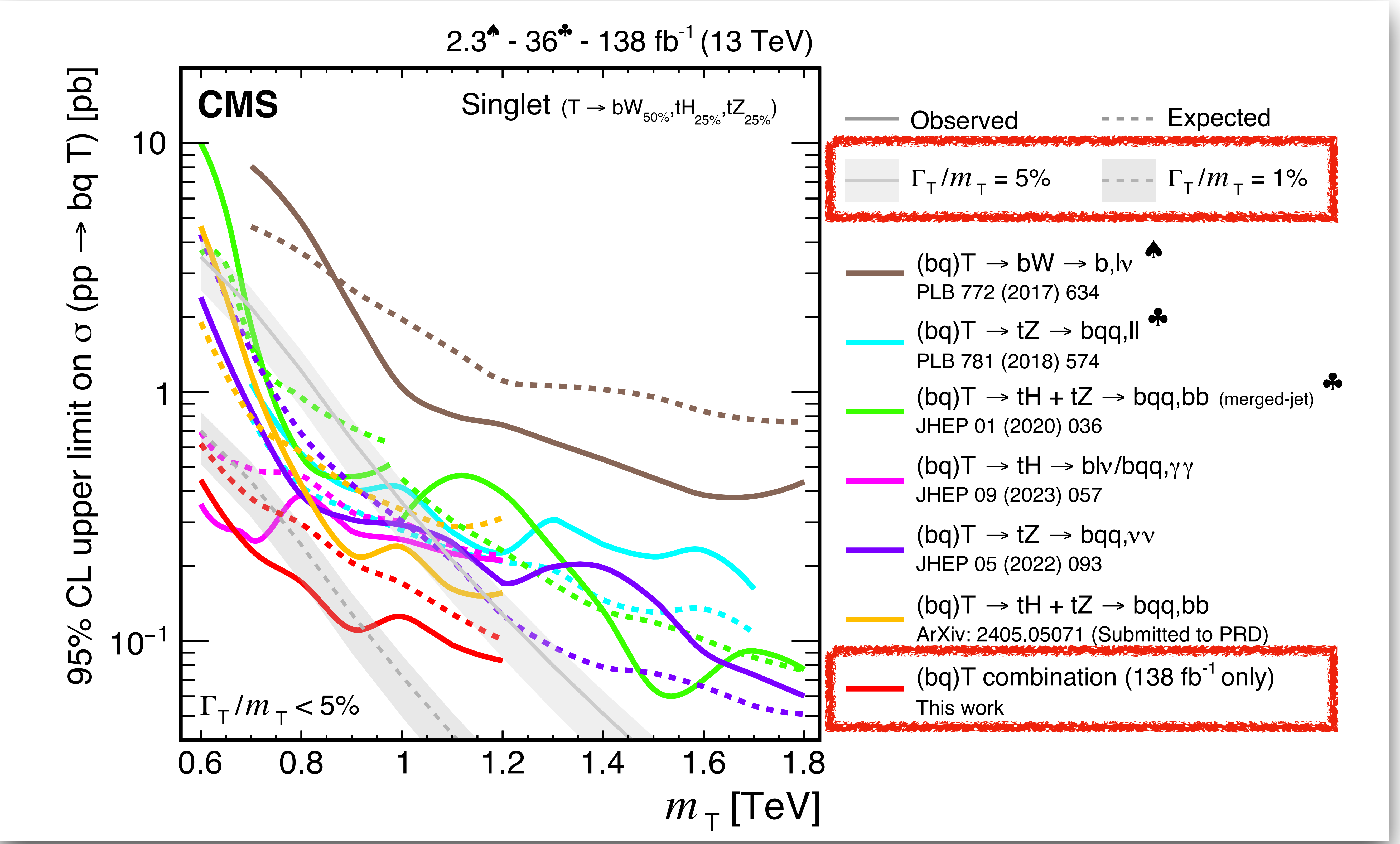
$tH \to bqq\,bb$

$tH \to bqq\,\gamma\gamma$

EXO-23-006 (Submitted to Phys. Rept.)

# Single production ( T )

**Upper limits on single T quark production crossection obtained by different analyses under NWA**




**Statistical combination:**

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| | |
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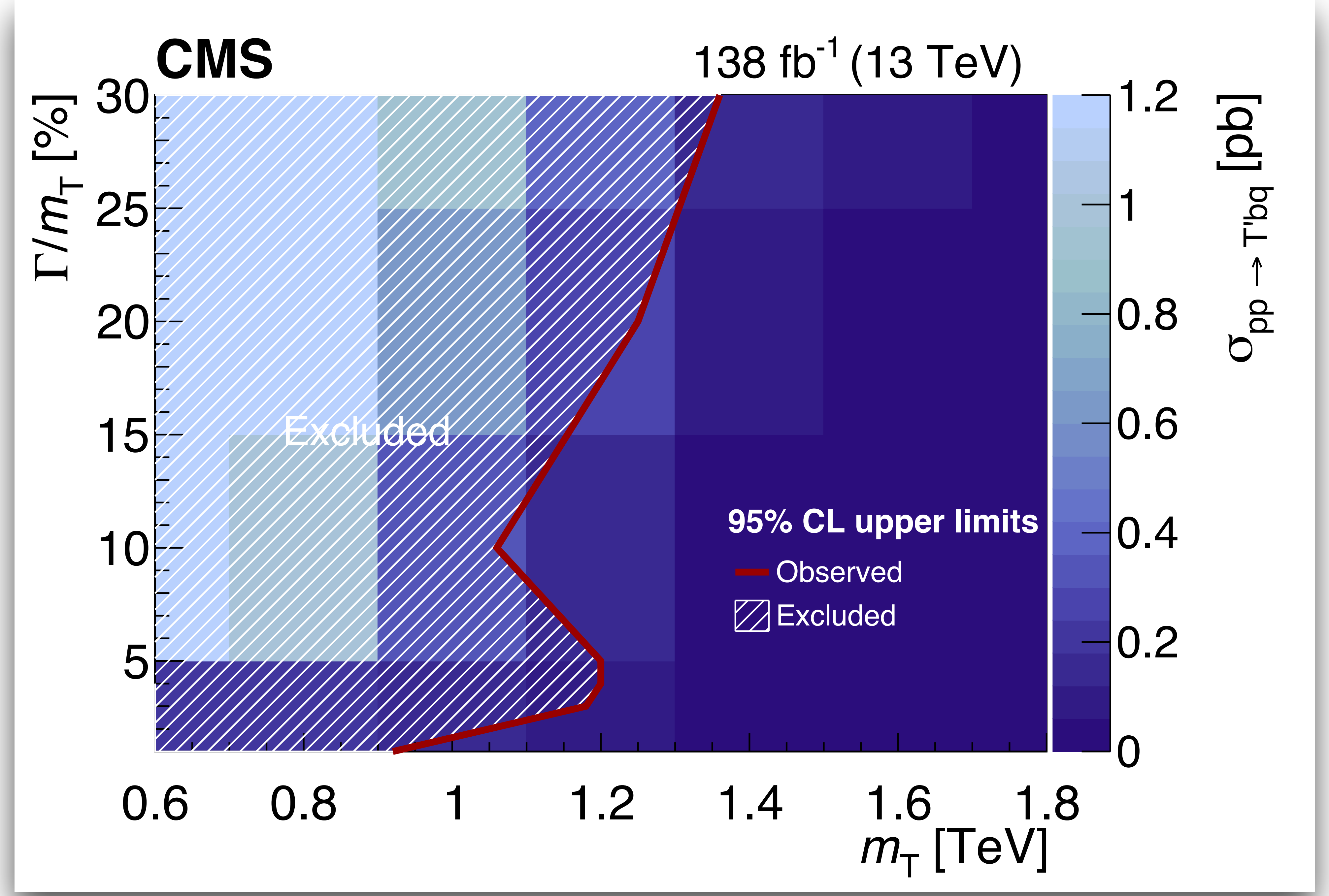


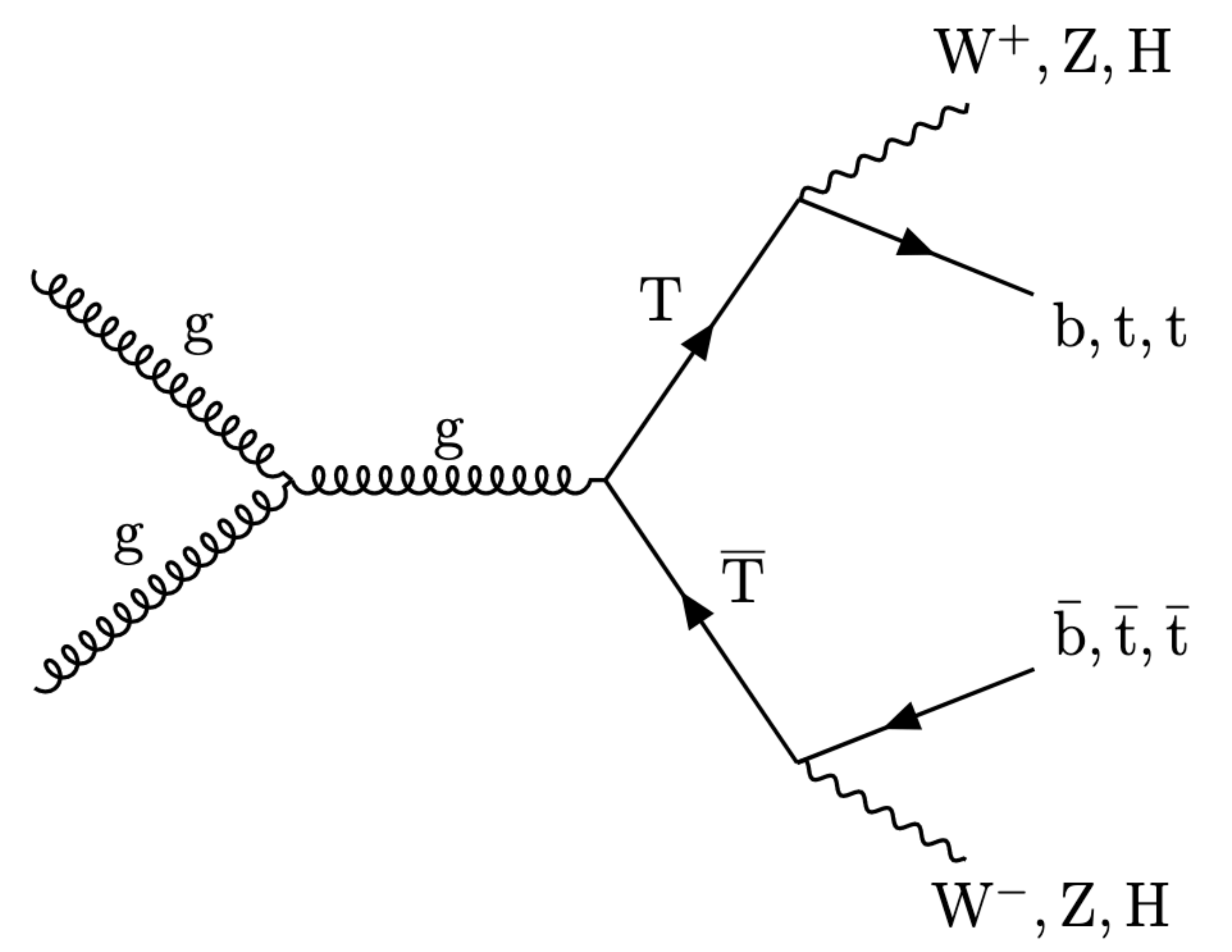

**Combination improved the limit compared to the individual analysis**

**For decay width of $\Gamma/m_T = 5, 10, 20$ and $30\%$, T quark is excluded up to a mass of 1.20, 1.06, 1.25, and 1.36 TeV**

EXO-23-006 (Submitted to Phys. Rept.)

# Pair production

- Pair production of $\mathrm{T}$, $\mathrm{B}$, $\mathrm{X}_{5/3}$ and $\mathrm{Y}_{4/3}$ quarks via. gluon fusion has been studied
- Exploit the presence of t quarks and W, Z, or Higgs bosons in the decay chain




## All-hadronic final state

- Boosted event shapes tagger/DEEPAK8 algorithm are used in identifying large-radius jets
  - light-quark/gluon, b quark, t quark, and W, Z, and Higgs boson jets

## Three final states containing charged electrons or muons

- **Single lepton channel**
  - Sensitive to all TT decay modes, as well as $\mathrm{B} \to \mathrm{tW}$.
- **Same-sign dilepton channel**
  - Primarily sensitive to $\mathrm{T} \to \mathrm{tH}$ ($\mathrm{H} \to \mathrm{WW}$) decays
- **Multilepton channel**
  - Primarily sensitive to contributions from T → tZ and $\mathrm{B} \to \mathrm{tW}$

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| $\mathrm{T\overline{T}}$ | bW, tH, tZ | $0\ell$, $1\ell$, OS $2\ell$, SS $2\ell$, $3\ell$ |
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| $\mathrm{X}_{5/3}\overline{\mathrm{X}}_{5/3}$ | tW | $1\ell$, SS $2\ell$ |
| $\mathrm{Y}_{4/3}\overline{\mathrm{Y}}_{4/3}$ | bW | $1\ell$ |

Pair production

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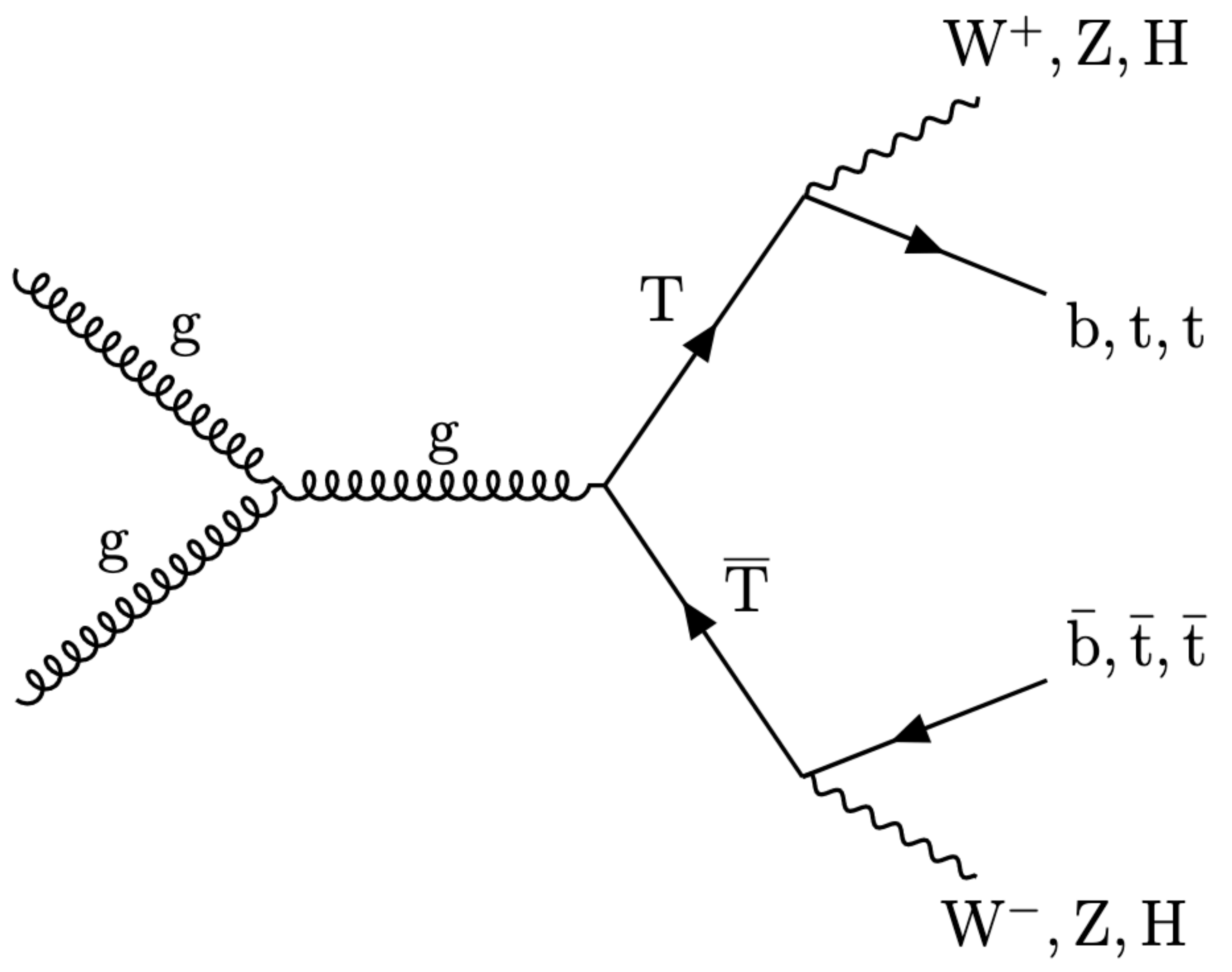


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| $X_{5/3}\overline{X}_{5/3}$ | tW | $1\ell$, SS $2\ell$ |
| $Y_{4/3}\overline{Y}_{4/3}$ | bW | $1\ell$ |

Pair production

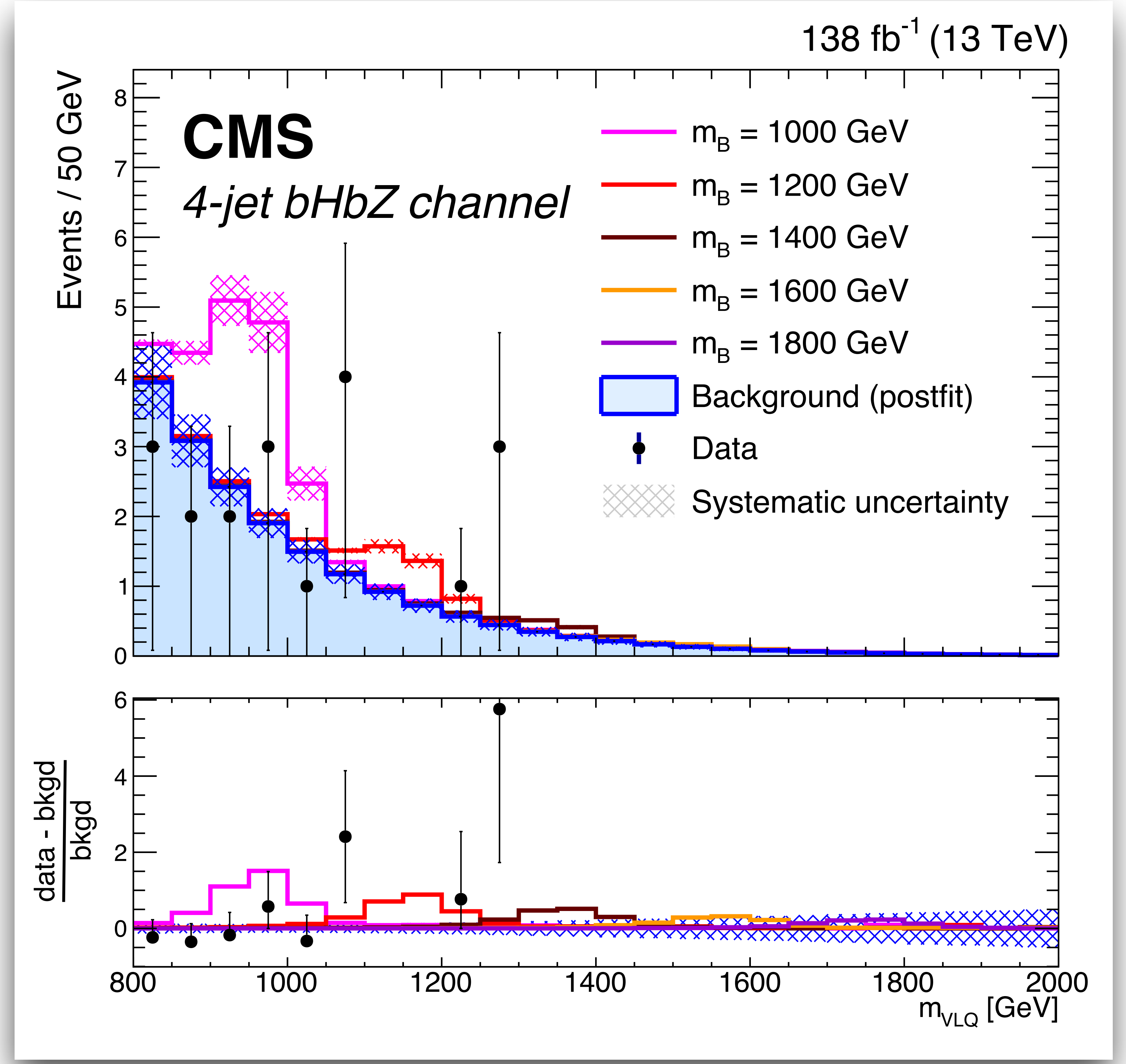
→ Discuss briefly in today's talk

# Pair production ($B\bar{B}$)

- Search of $\mathrm{B}$ in the mass range **[1000,1800] GeV.**
- Reconstructed $\mathrm{m_{VLQ}}$ distribution is used as the observable.
- A modified $\chi^2$ metric, to associate an event to a given decay mode and assign jets to a parent particle.

| Jet multiplicity | Leptonic category | Fully hadronic category |
| --- | --- | --- |
| 3 | bHbZ, bZbZ | — |
| 4 | bHbZ, bZbZ | bHbH, bHbZ, bZbZ |
| 5 | — | bHbH, bHbZ, bZbZ, bHtW, bZtW |
| 6 | — | bHbH, bHbZ, bZbZ, bHtW, bZtW |

$$\chi^2_{\mathrm{mod}} = \frac{(\Delta m_{\mathrm{VLQ}} - \overline{\Delta m_{\mathrm{VLQ}}})^2}{\sigma^2_{\Delta m_{\mathrm{VLQ}}}} + \frac{(m_1 - \overline{m_1})^2}{\sigma^2_{m_1}} + \frac{(m_2 - \overline{m_2})^2}{\sigma^2_{m_2}}$$


**Background estimation:**

- **Leptonic**: Drell–Yan dilepton production in association with jets
- **Hadronic**: Quantum chromodynamics multijet events
- Background estimations are done from the control samples in data

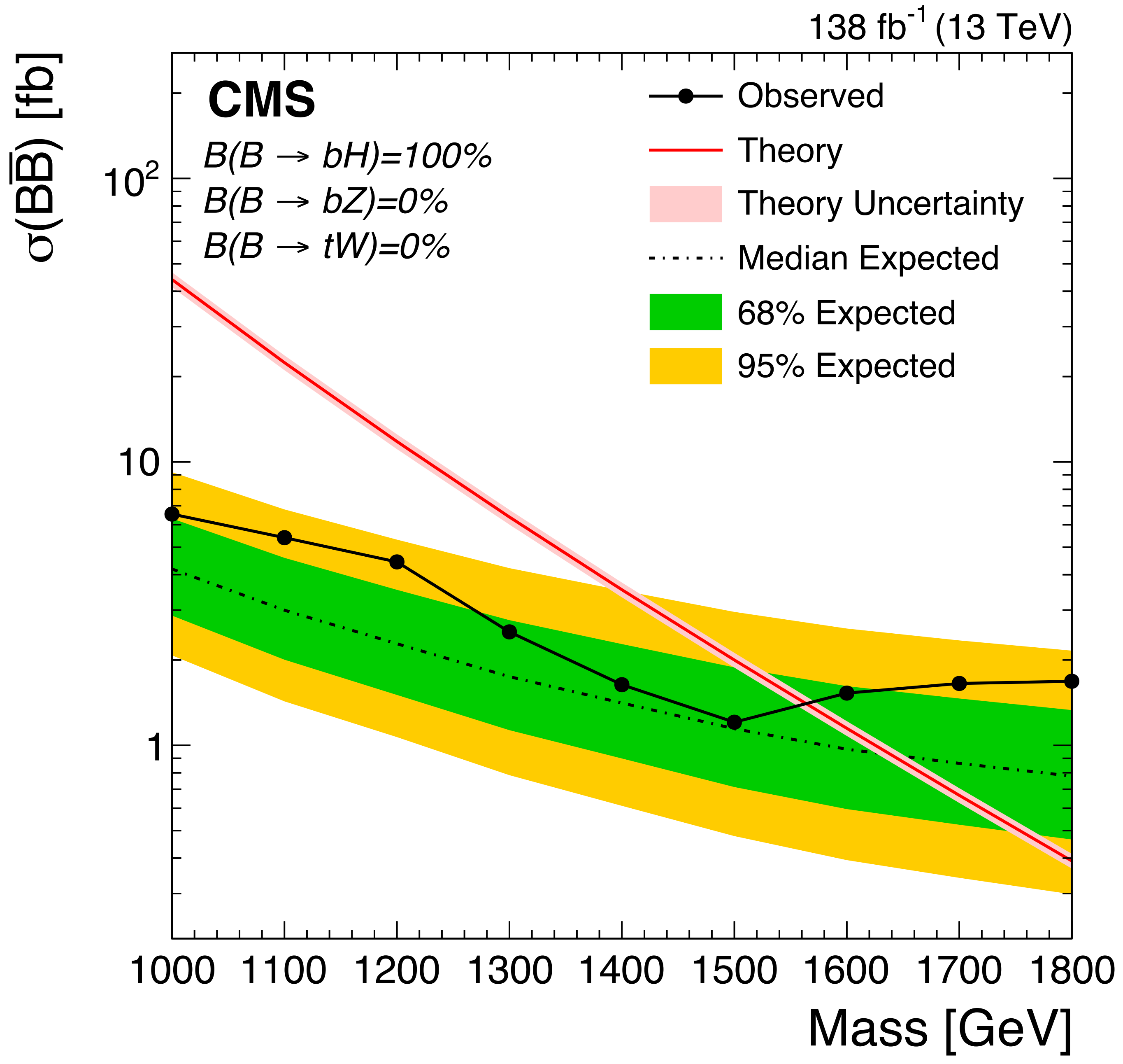
**Highly complex search, covering a larger number of possible final states**

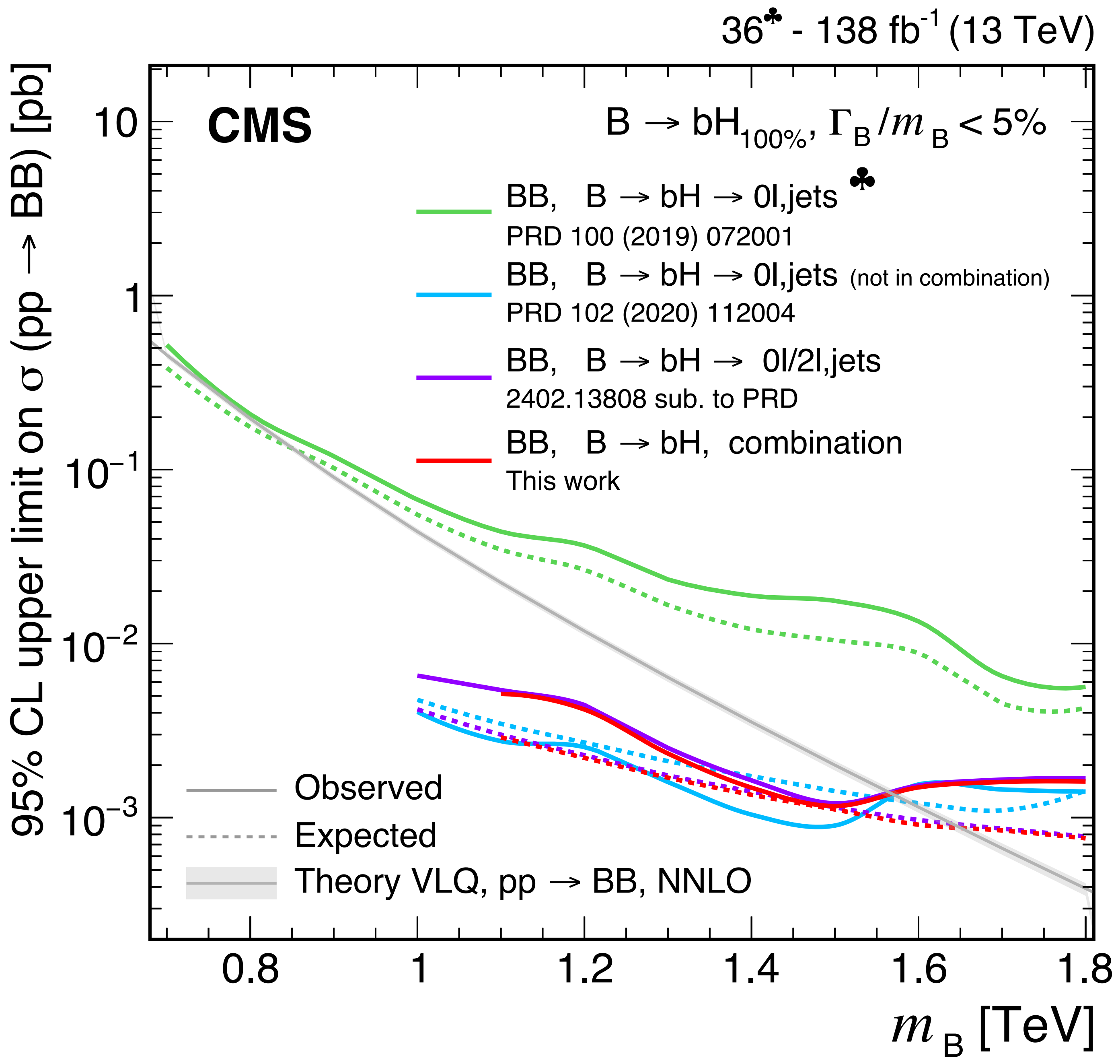
**No statistically significant excess over the background expectations.**

B2G-20-014 (submitted to PRD)

# Pair production ( $B\bar{B}$)

**Upper limits on pair B quark production crossection obtained by different analyses under different BR assumption.**




**Channels combined**

- Hadronic, single-lepton, dilepton (SS and OS), and multilepton

B2G-20-014 (submitted to PRD),
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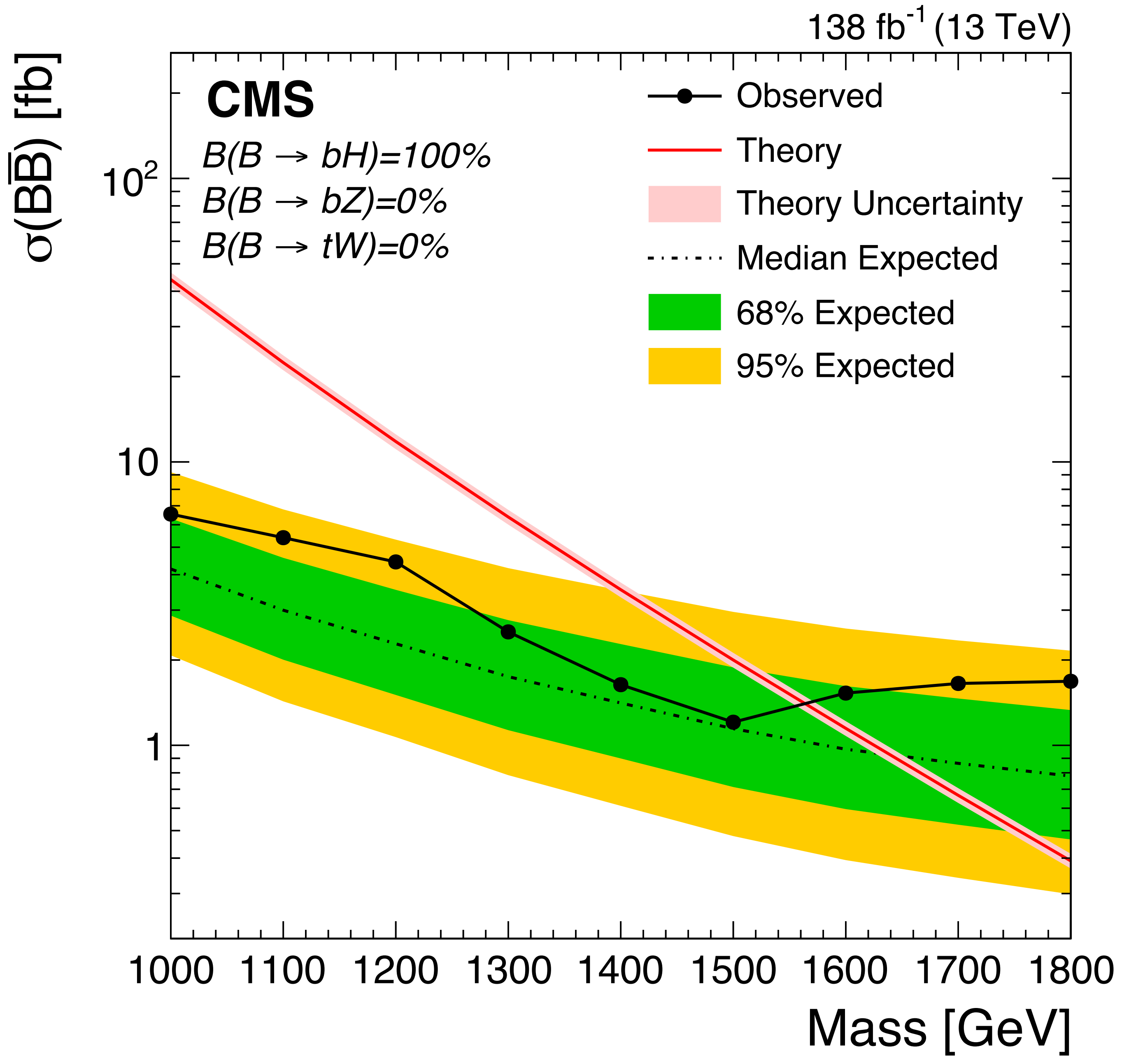
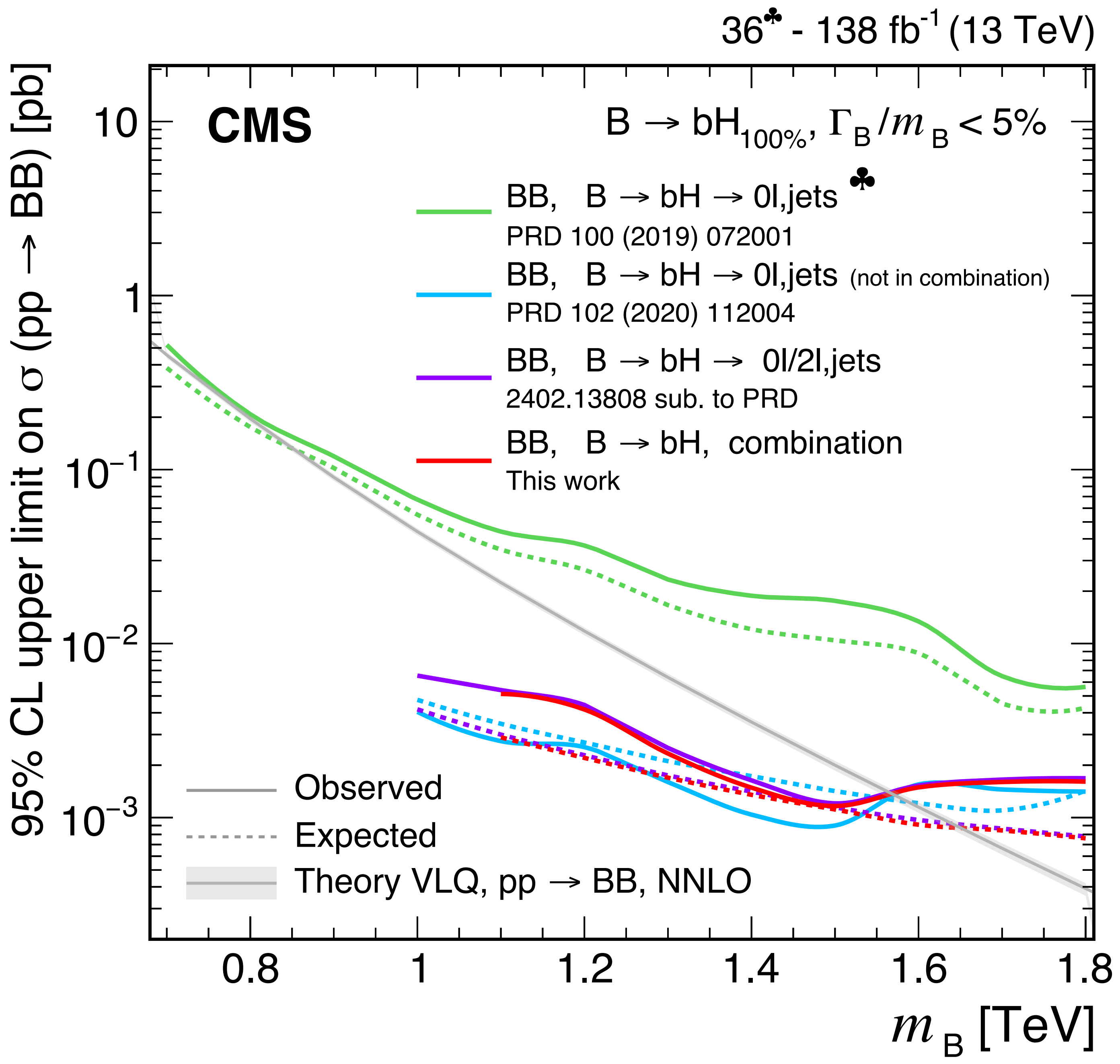
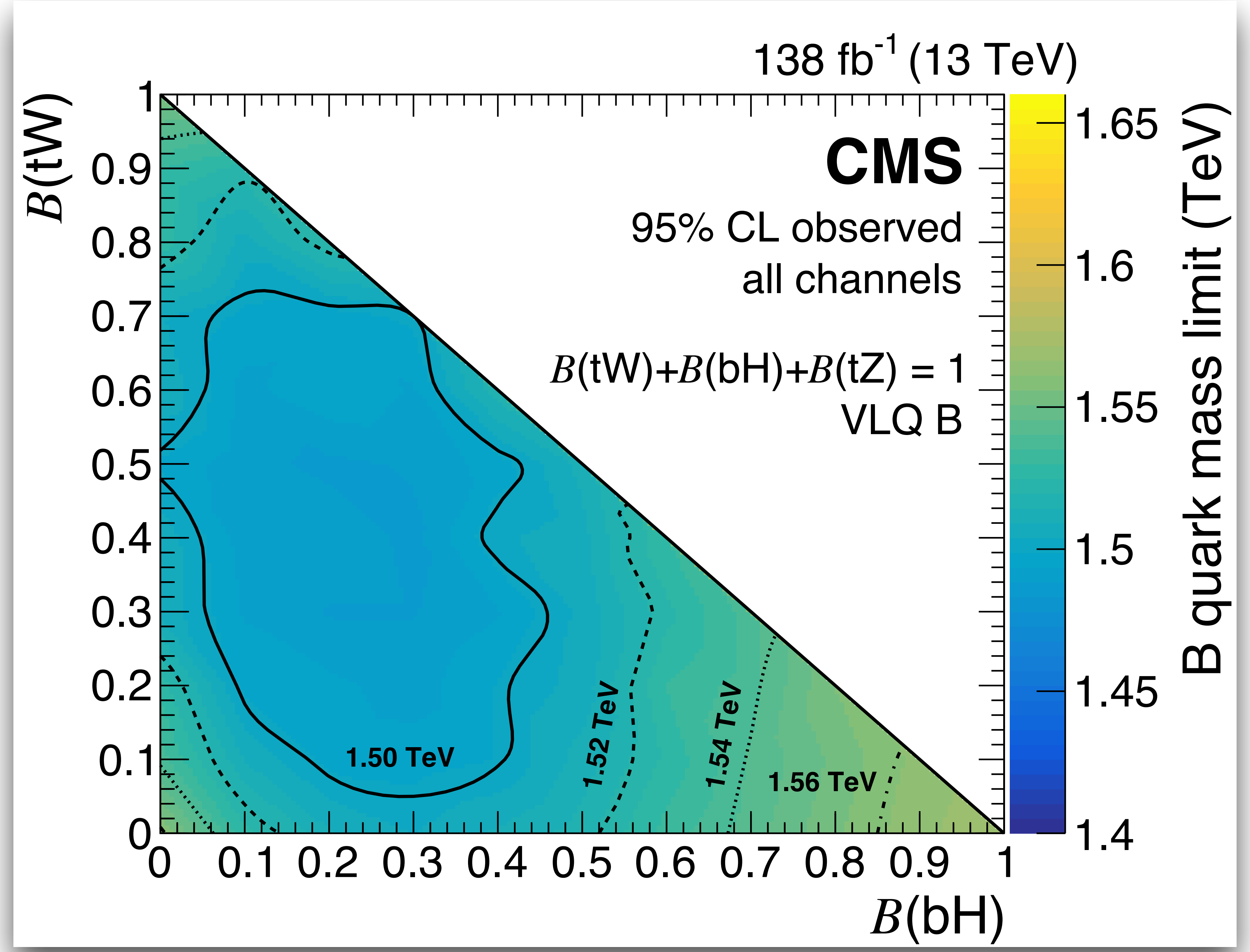



**Observed lower limits on the B quark mass:**




**Channels combined**

- Hadronic, single-lepton, dilepton (SS and OS), and multilepton

**In the pair production, B quark of masses below 1.49 TeV are excluded**

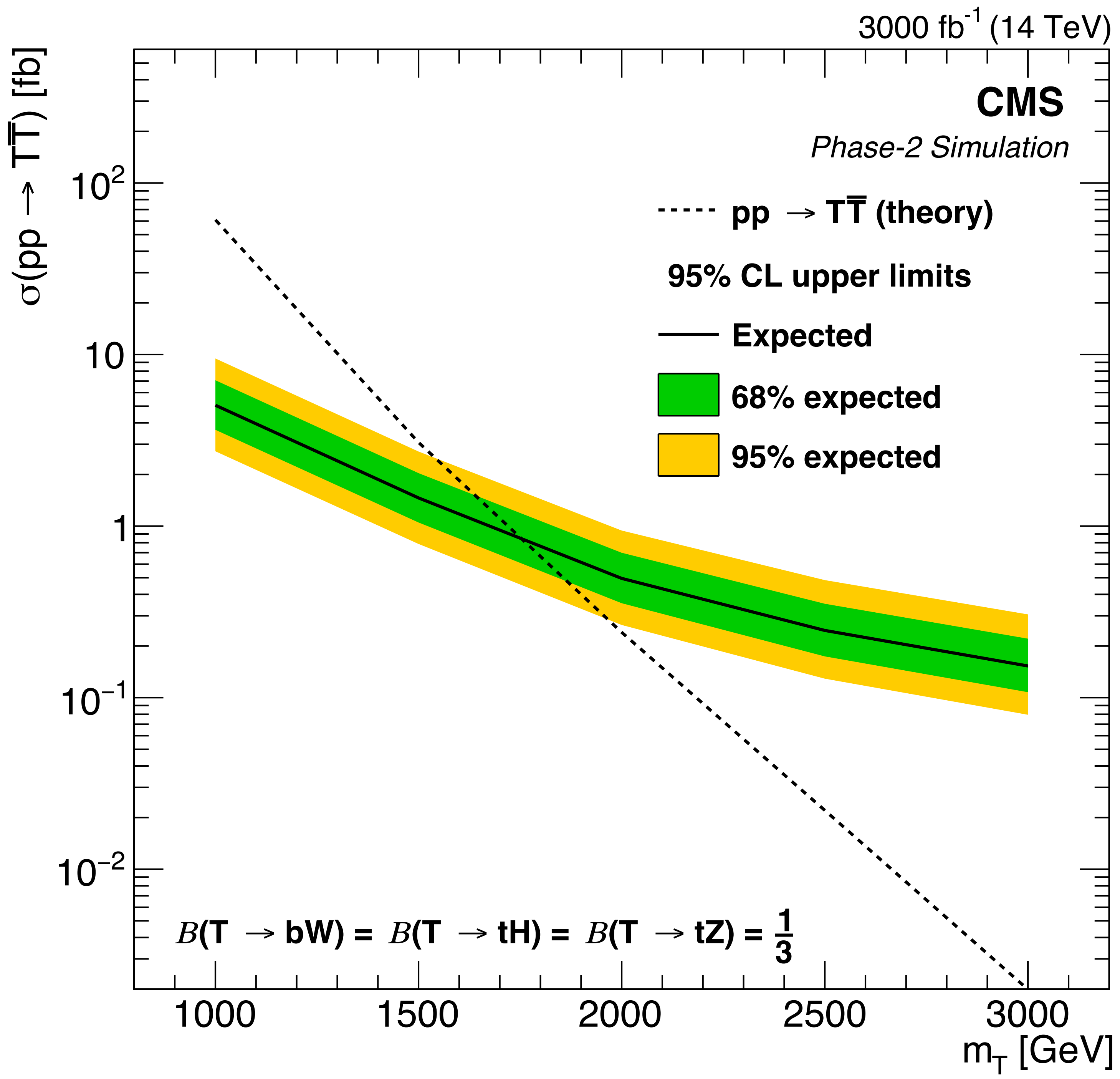
**Combination could extends exclusion limit across all scenarios of branching fractions**

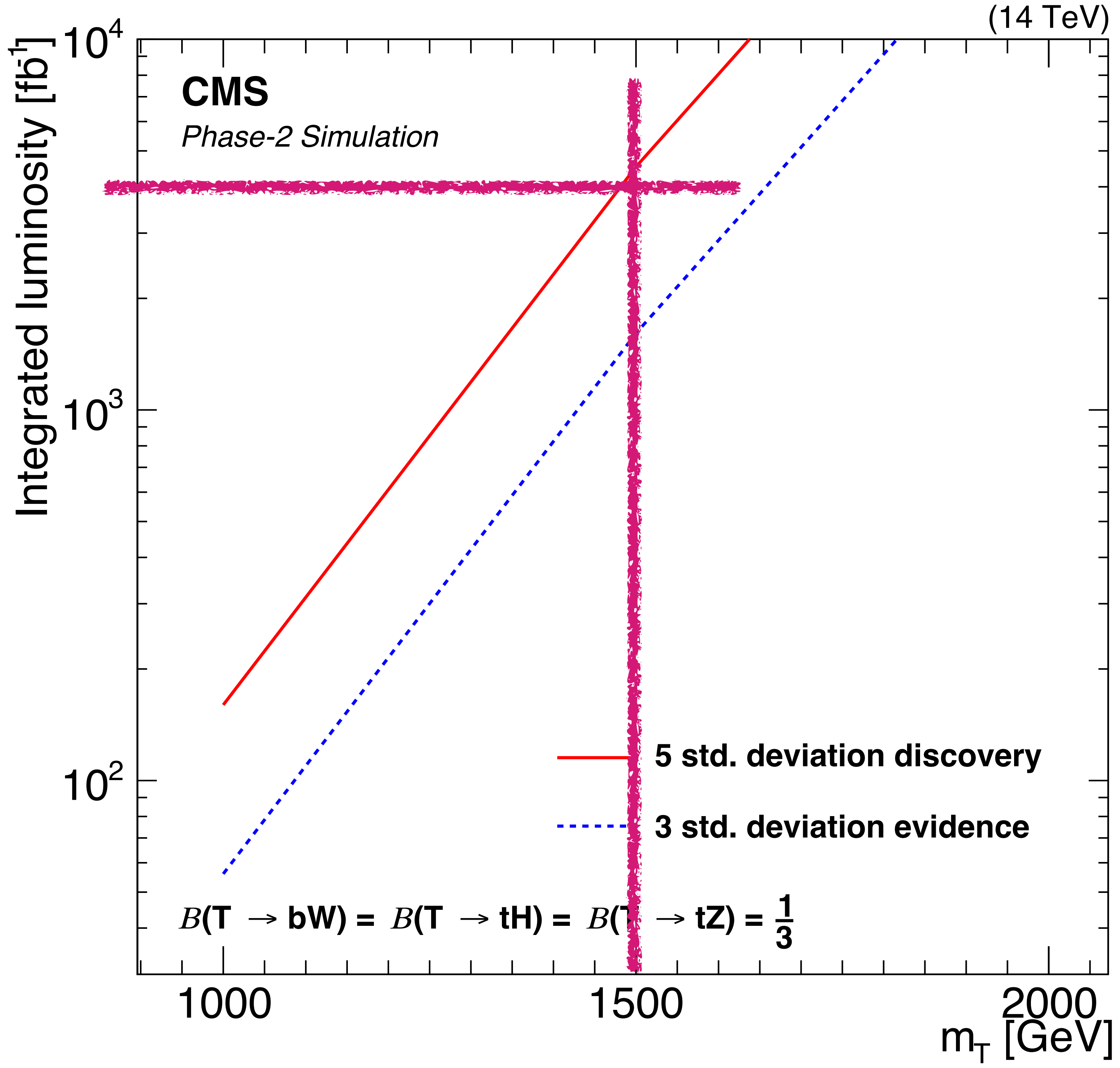
B2G-20-014 (submitted to PRD),
EXO-23-006 (Submitted to Phys. Rept.)

# Future prospects for VLQ searches at HL-LHC

- Physics capabilities of the Phase-2 upgrade of CMS for the **HL-LHC** have been studied
- Improved coverage and precision with new tracker detector
  - Identification of b quarks and hadronic decays of boosted particles within jets using track and vertex information.

- $\mathrm{T}$ quarks search in single-lepton channel to project the HL-LHC conditions
- DELPHES 3 fast simulation is used to simulate the Phase-2 CMS detector response.
- Performed using 2016 dataset, projected to HL-LHC conditions.
- Exclude a $\mathrm{T}$ mass up to $1.75\ \mathrm{TeV}$




**With 3000 $\mathrm{fb}^{-1}$ of data, the discovery of T quark with a $5\sigma$ significance may be achieved for masses up to ~1.5 TeV.**

FTR-22-002

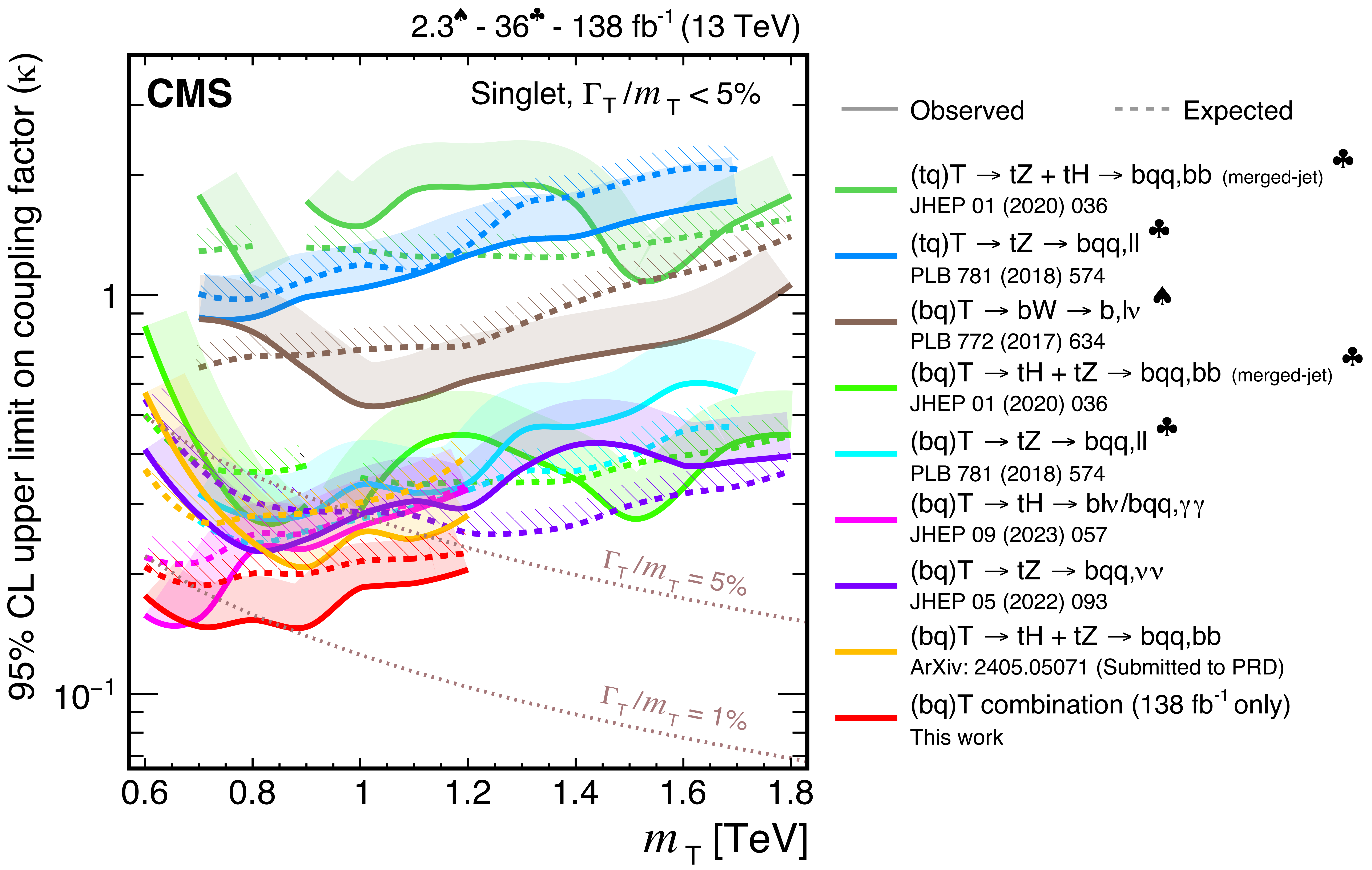
# Summary

- VLQs are a viable extension to the SM and we carry out a broad search program at CMS
- No statistically significant excess is observed in any of the searches for VLQ.
- There are still unexplored regions of parameter space
  - Nonminimal VLQ extensions such as decays of VLQs to scalar or pseudoscalar bosons
  - Exploring VLQ production modes such as electroweak pair production
  - Expanding the searches assuming a finite decay width.
- A detailed review of the VLQ searches has been released and submitted (May 2024) to **Phy. Rev.** for publication. EXO-23-006
- Continue efforts in innovating analysis techniques will further enhance the sensitivity
- Stay tuned for many more measurements from Run 3 and beyond!

Thank You

# Back Up

## Observed and expected 95% CL upper limits on the coupling strength $\kappa_T$ for single T quark production



# Pair production ($T\bar{T}$)

**Three final states containing charged electrons or muons**

**Single lepton channel:** 1 lepton, > 3 AK8 jets

- Train an MLP for discrimination tt, W+jets background, or VLQ signal events.

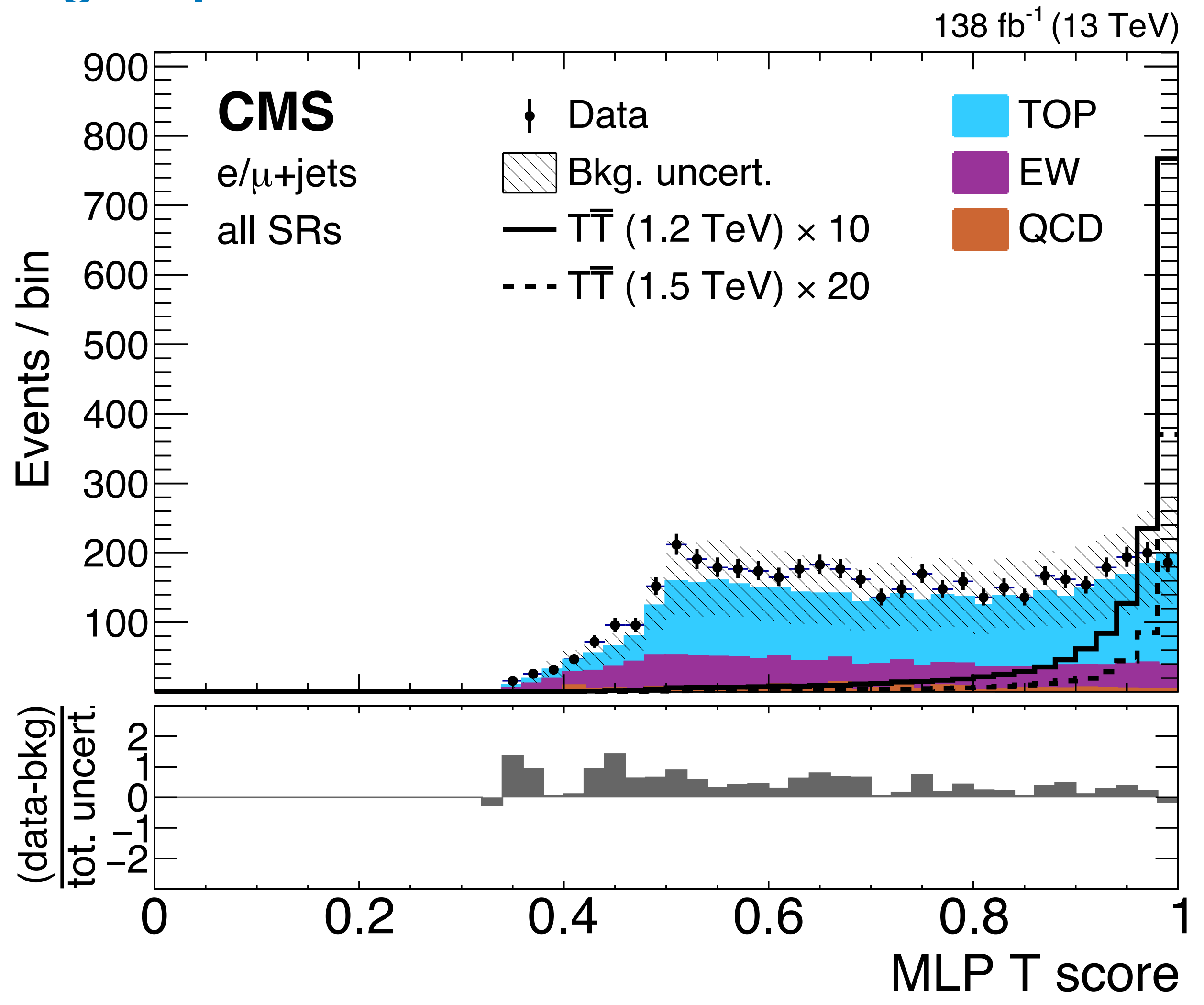
**Same-sign dilepton channel:** 2 SS leptons, > 4 AK4 Jets

- $H_T^{lep}$

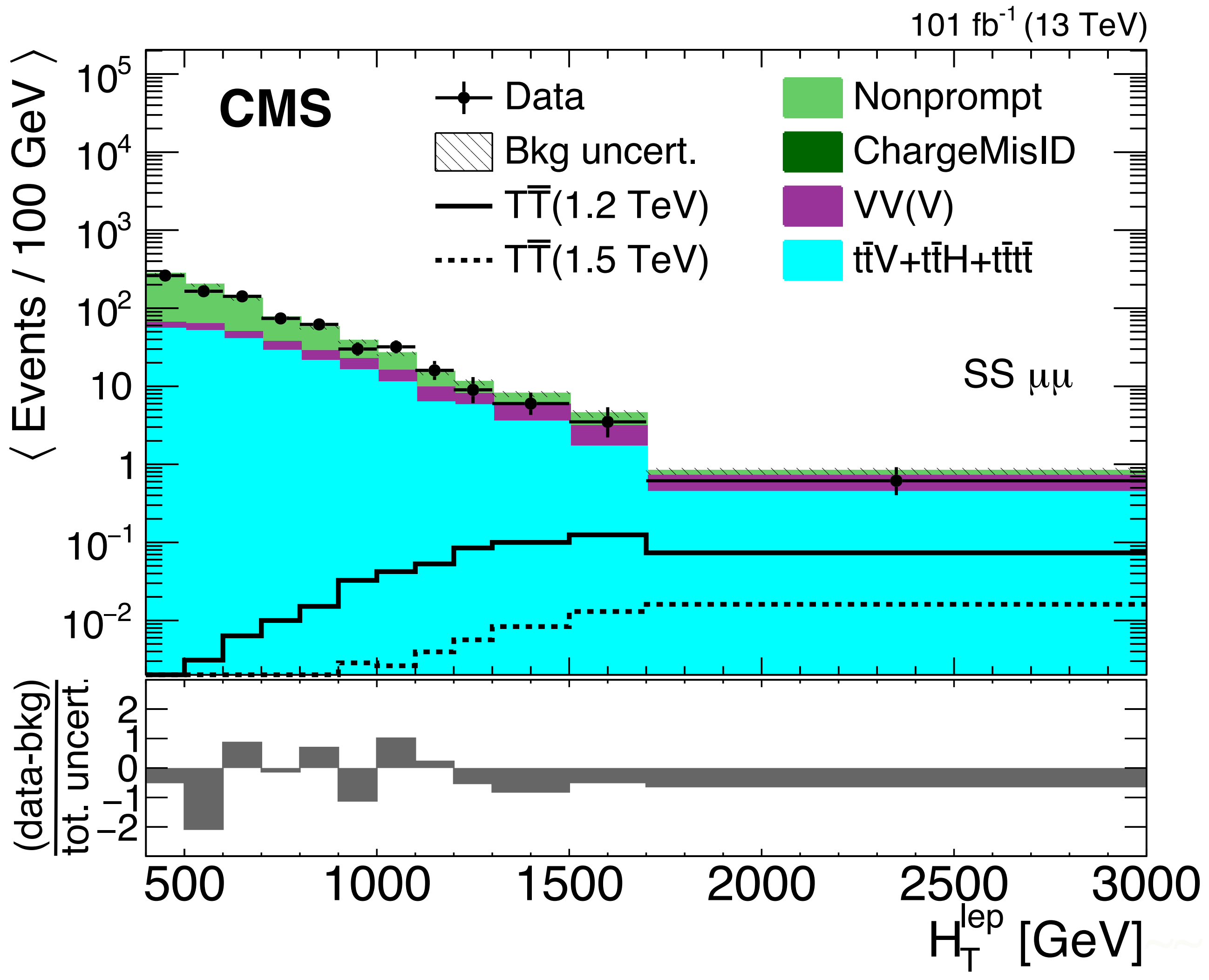
**Multilepton channel:** 3 leptons, > 3 AK4 Jets

- $S_T = \sum p_T^{jets} + \sum p_T^{leptons} + p_T^{miss}$

Single lepton

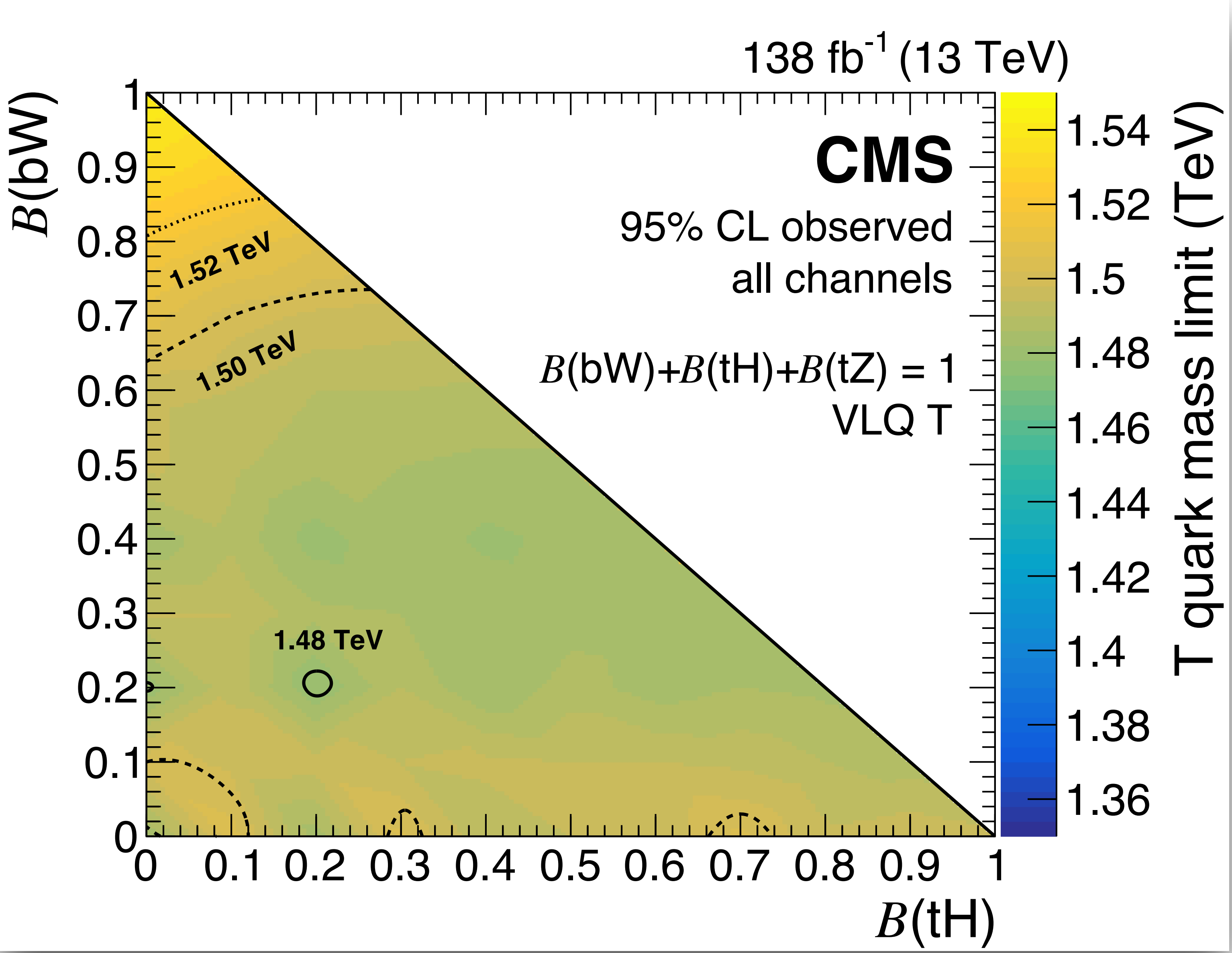



Same-sign dilepton




**Upper limits on pair $T$ quark production crossection obtained under different BR assumption.**

**No significant excess over the background expectations.**




**Pair production of $T$ quarks with masses below 1.48 - 1.54 TeV are excluded, depending on the BR.**

**The analysis does not discriminate between jets from b and $\bar{b}$ quark**

- the signal process can be interpreted as $Y_{4/3}\bar{Y}_{4/3}$ production.
- $Y_{4/3}$ quarks are excluded with masses below 1.48 - 1.54 TeV

10.1007/JHEP07(2023)020