

Beyond the Standard Model searches in the top final state

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The University of Alabama**

TOP 2023 — Traverse City, MI — September 27, 2023

Outline

- What is “Beyond the SM with top in the final state”
- Tools of the trade
- Bird’s eye view
 - VLQs
 - Resonances (W' , b^*)
 - 2HDM
- Prospectives for the future

Outline

Top as a BSM probe

LFV

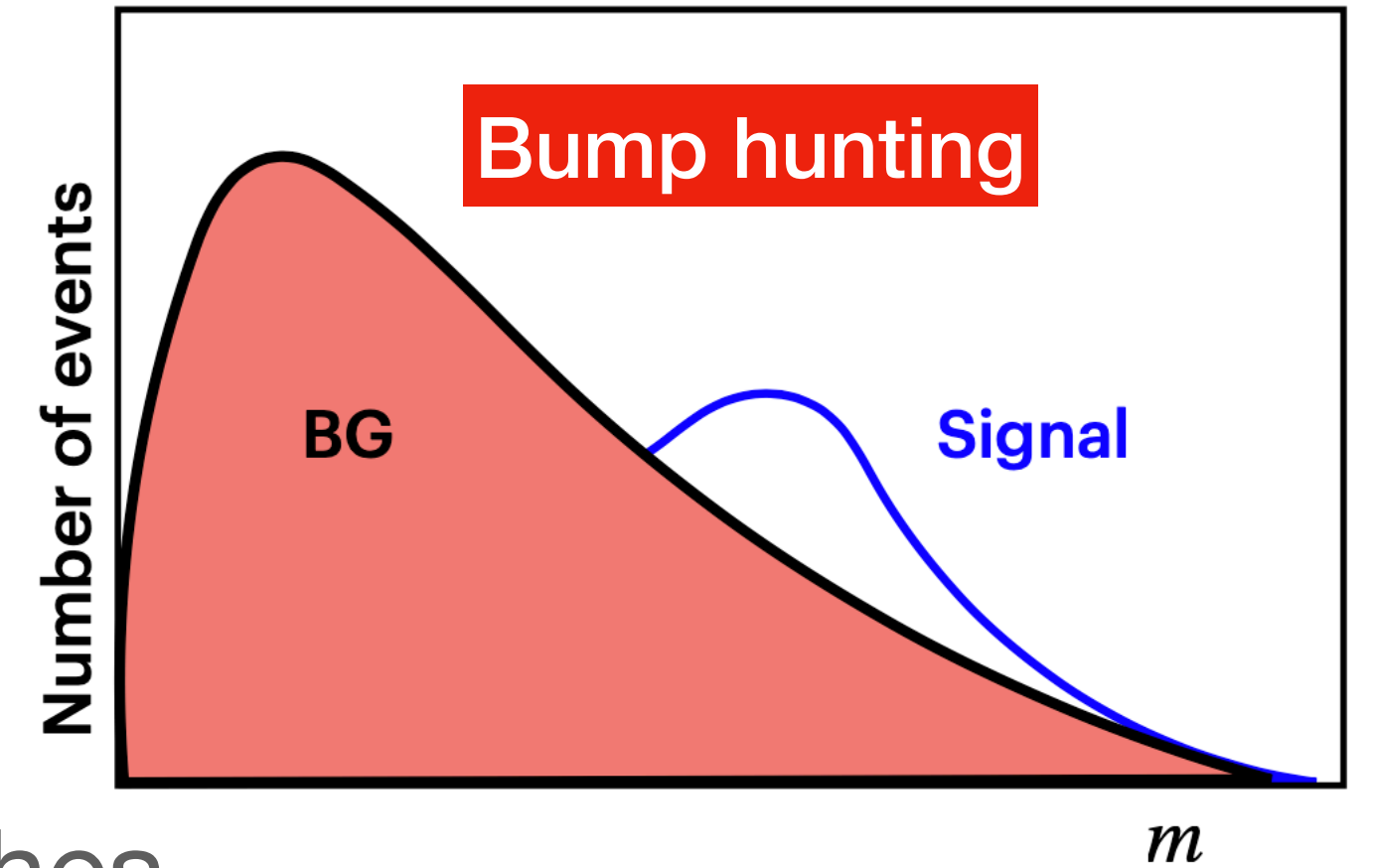
Rare processes

EFT

Boosted top measurements

Low mass searches

Very wide resonances



BSM from precision measurements

Scouting

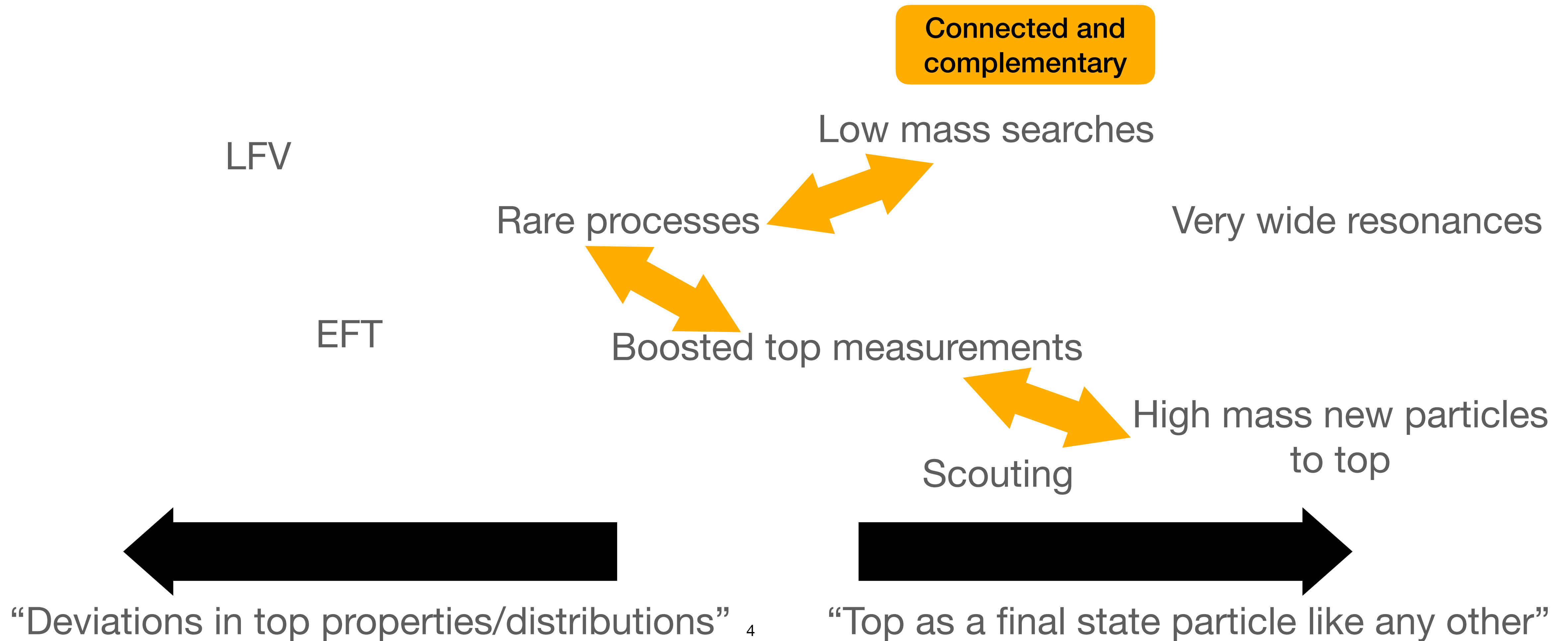
Bump hunting

High mass new particles
to top

“Deviations in top properties/distributions” ₃

“Top as a final state particle like any other”

Outline



Outline

LFV

Low mass searches

Focus of this talk

Rare processes

Very wide resonances

EFT

Boosted top measurements

High mass new particles
to top

Scouting



“Deviations in top properties/distributions” ⁵

“Top as a final state particle like any other”

The tools of the trade

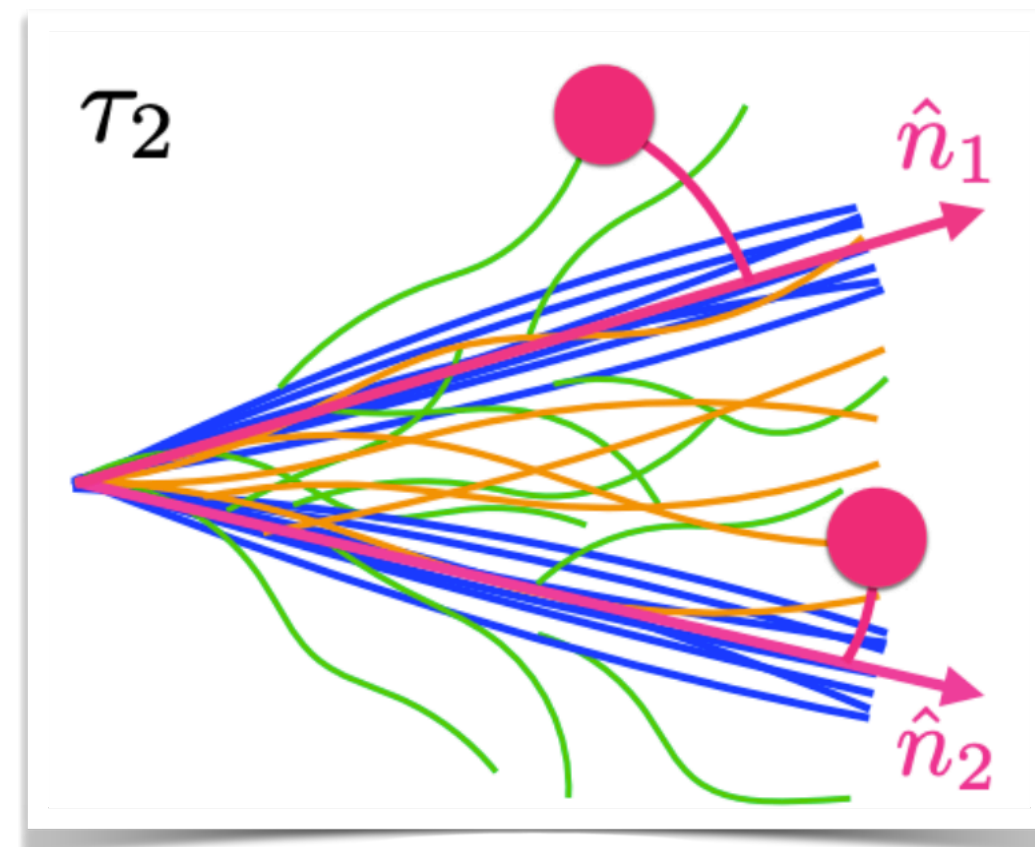
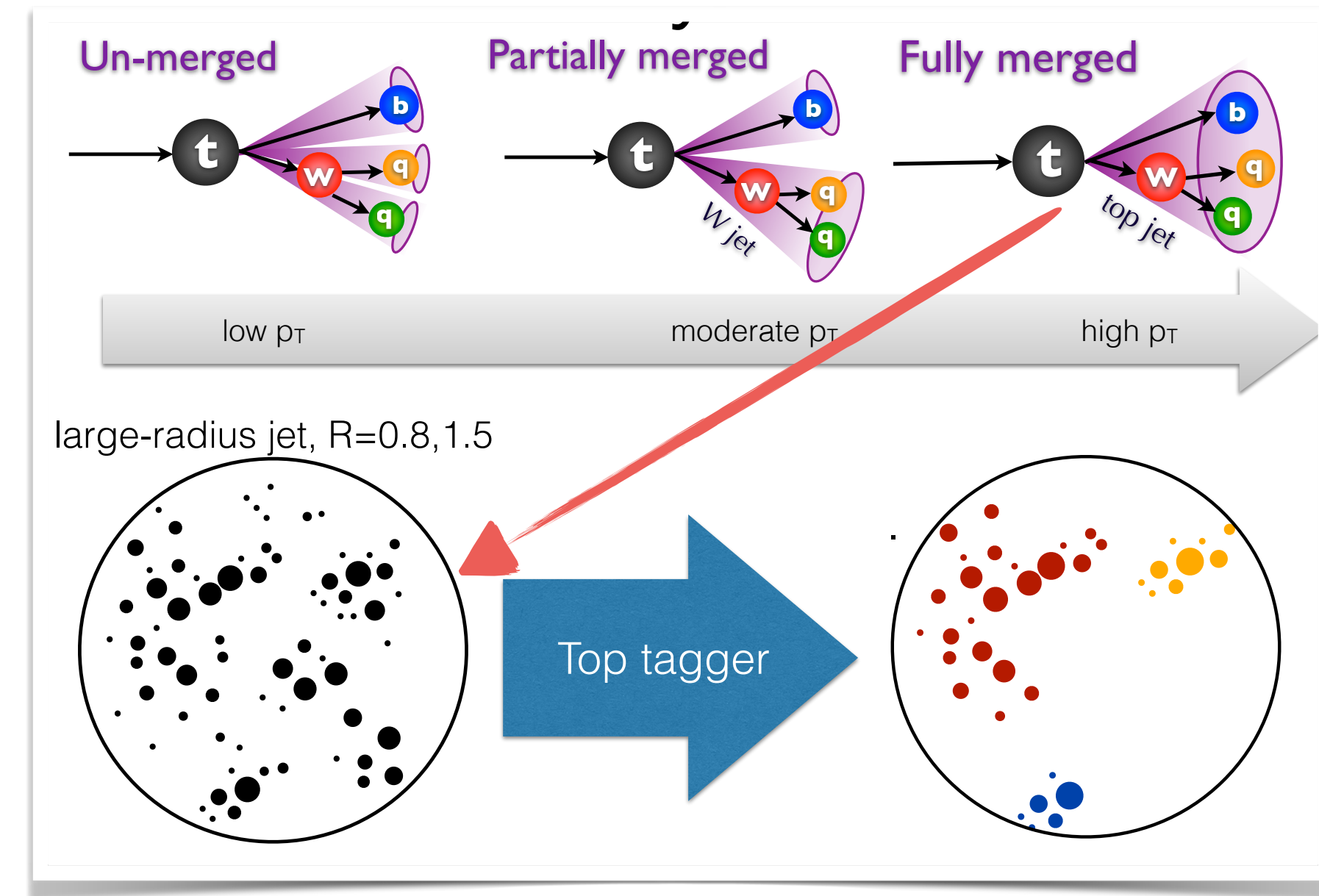
Boosted top:
experimental tools overview

Emanuele Usai
on behalf of the **CMS** and **ATLAS** collaborations
prepared with the help of **Johannes Erdmann**

ATLAS EXPERIMENT UH Universität Hamburg Emmy Noether-Programm Deutsche Forschungsgemeinschaft DFG CMS

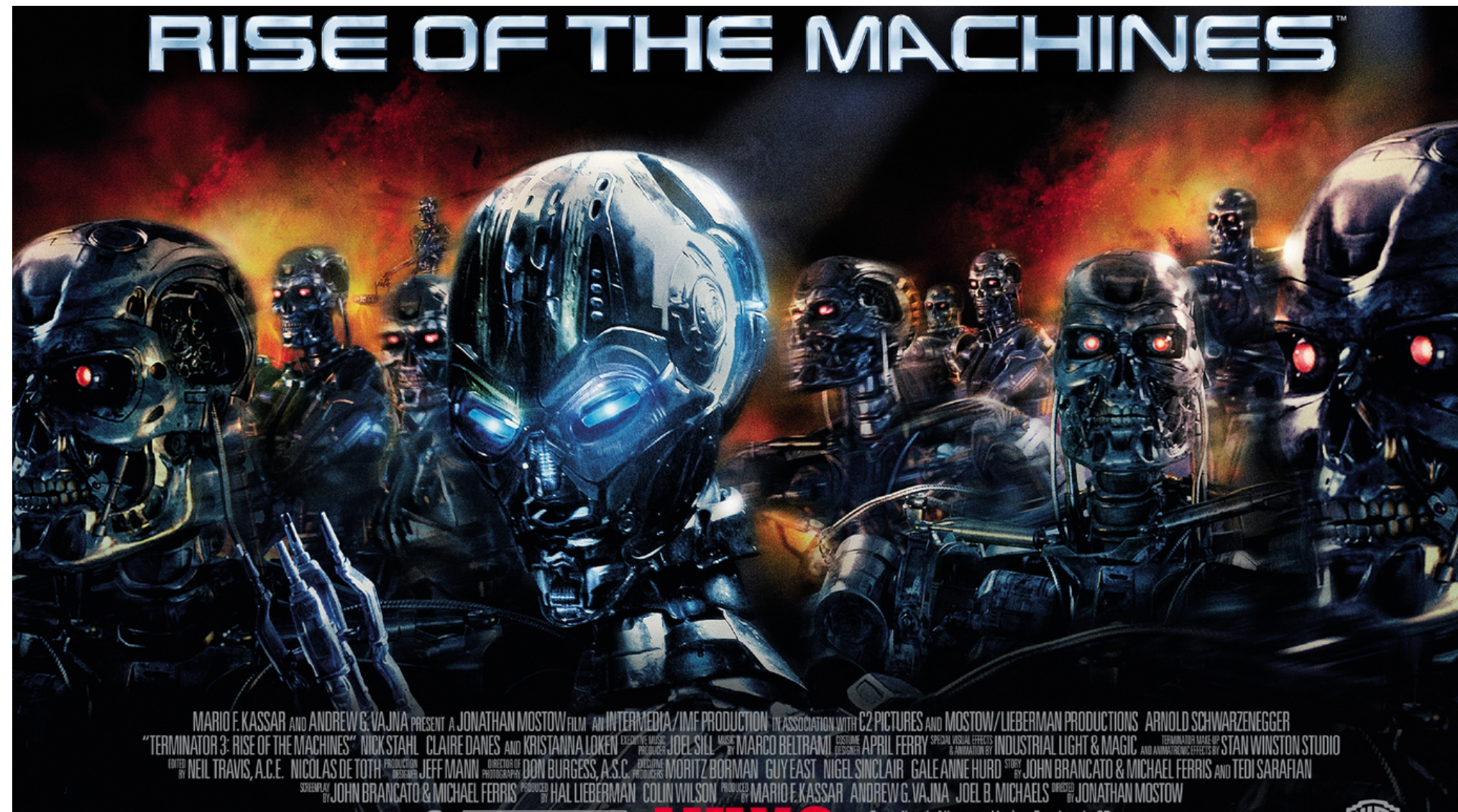
top 2014 7th International Workshop on Top Quark Physics

Cannes, October 1st, 2014

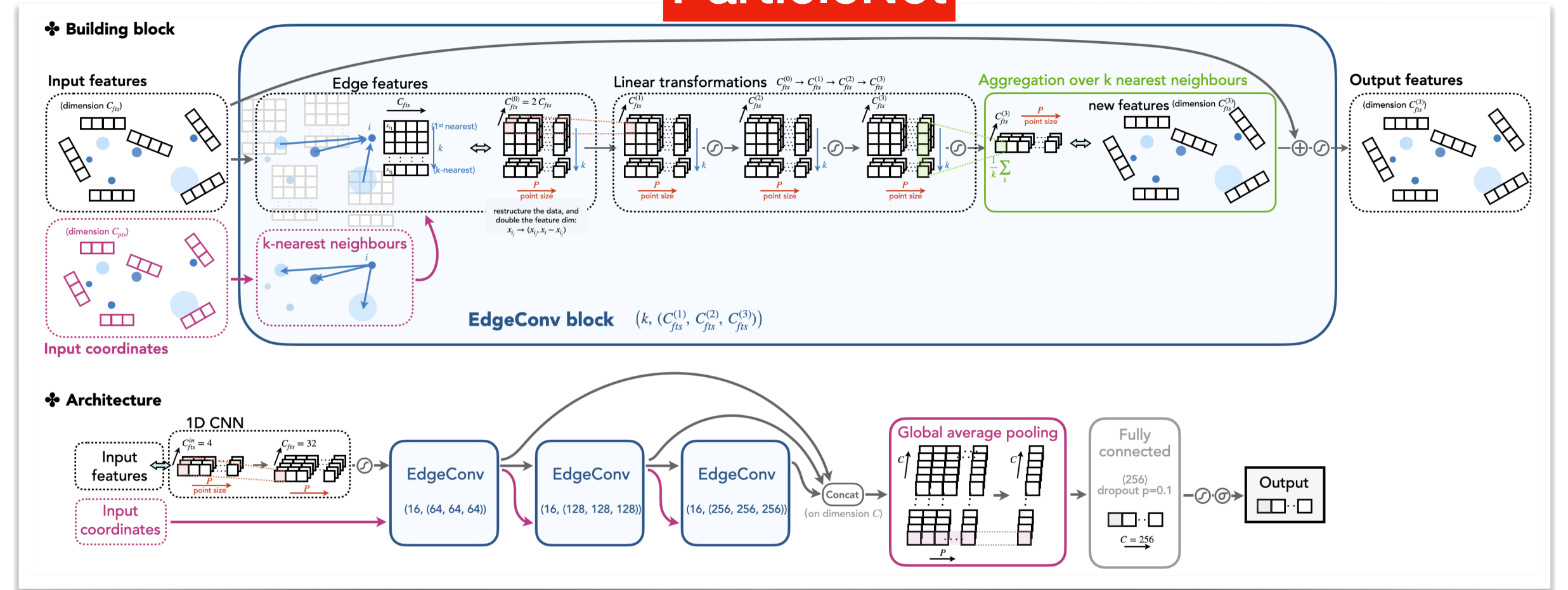


- Particle flow candidates for computation of substructure Pileup mitigation:
 - PUPPI [CMS, JINST 15 (2020) P09018]
- Soft drop for groomed jet mass
- N-Subjettiness ratios for 2- and 3-prong tagging
- Subjet b tagging for t and H jets

The tools of the trade

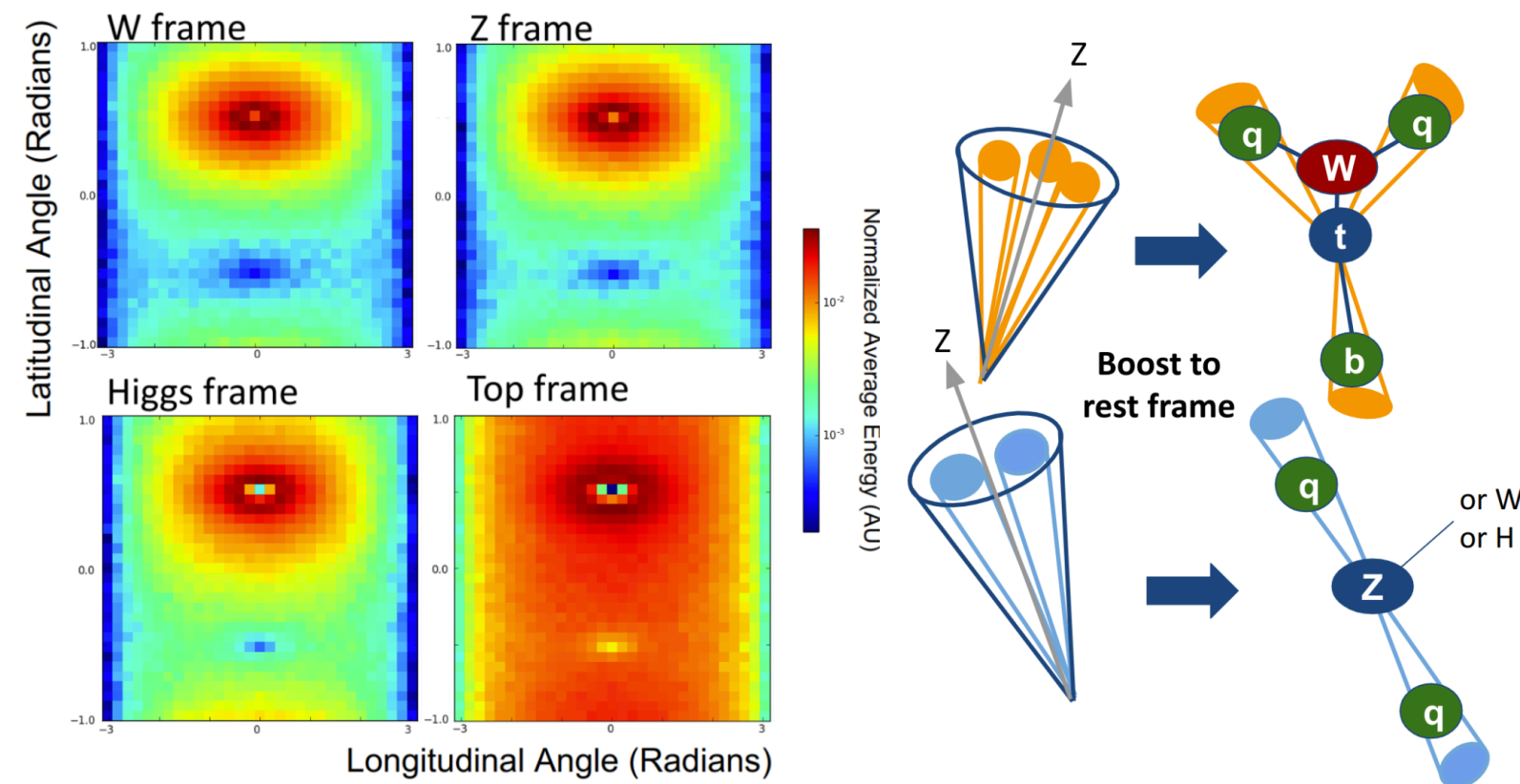


ParticleNet



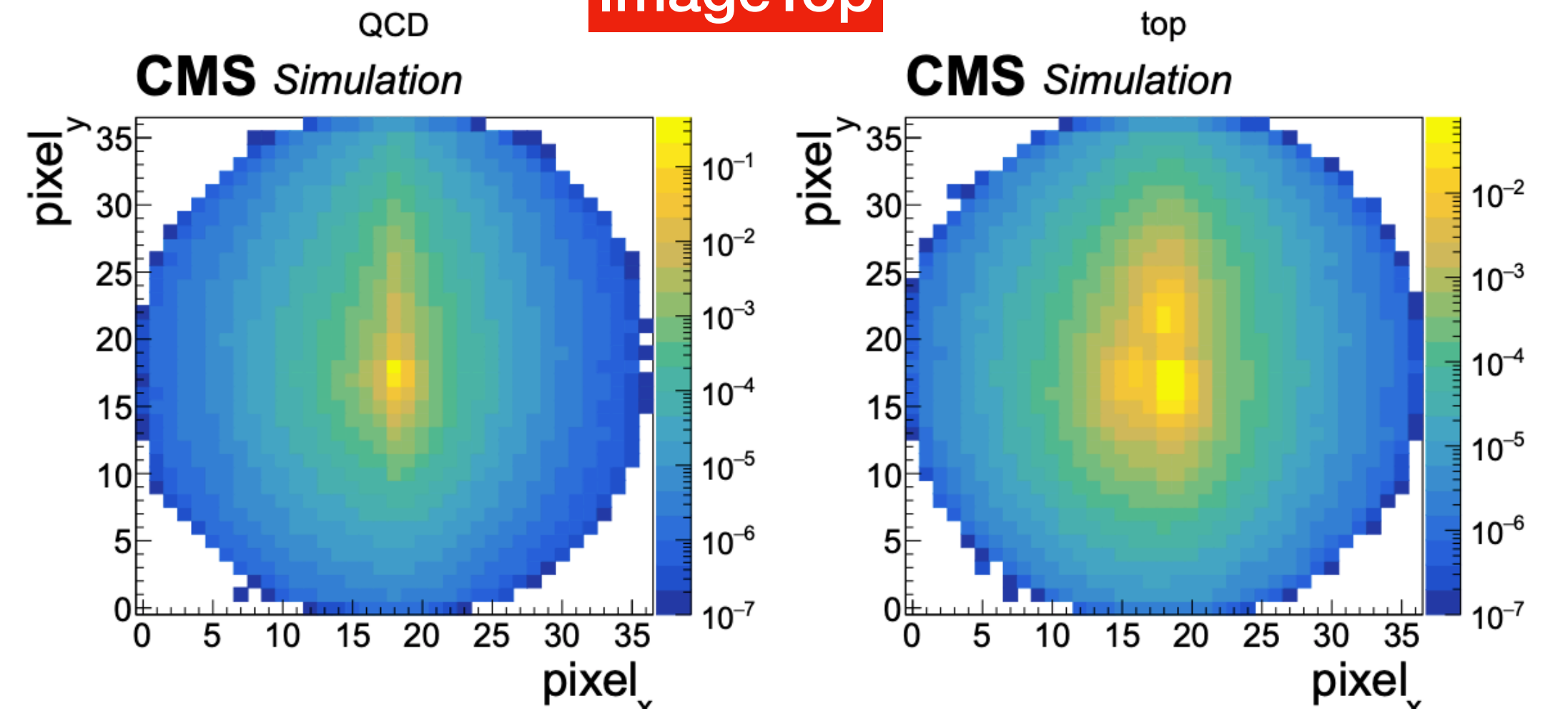
Phys. Rev. D 101, 056019 (2020)

Boosted Event Shape Tagger



CERN-THESIS-2023-040

ImageTop

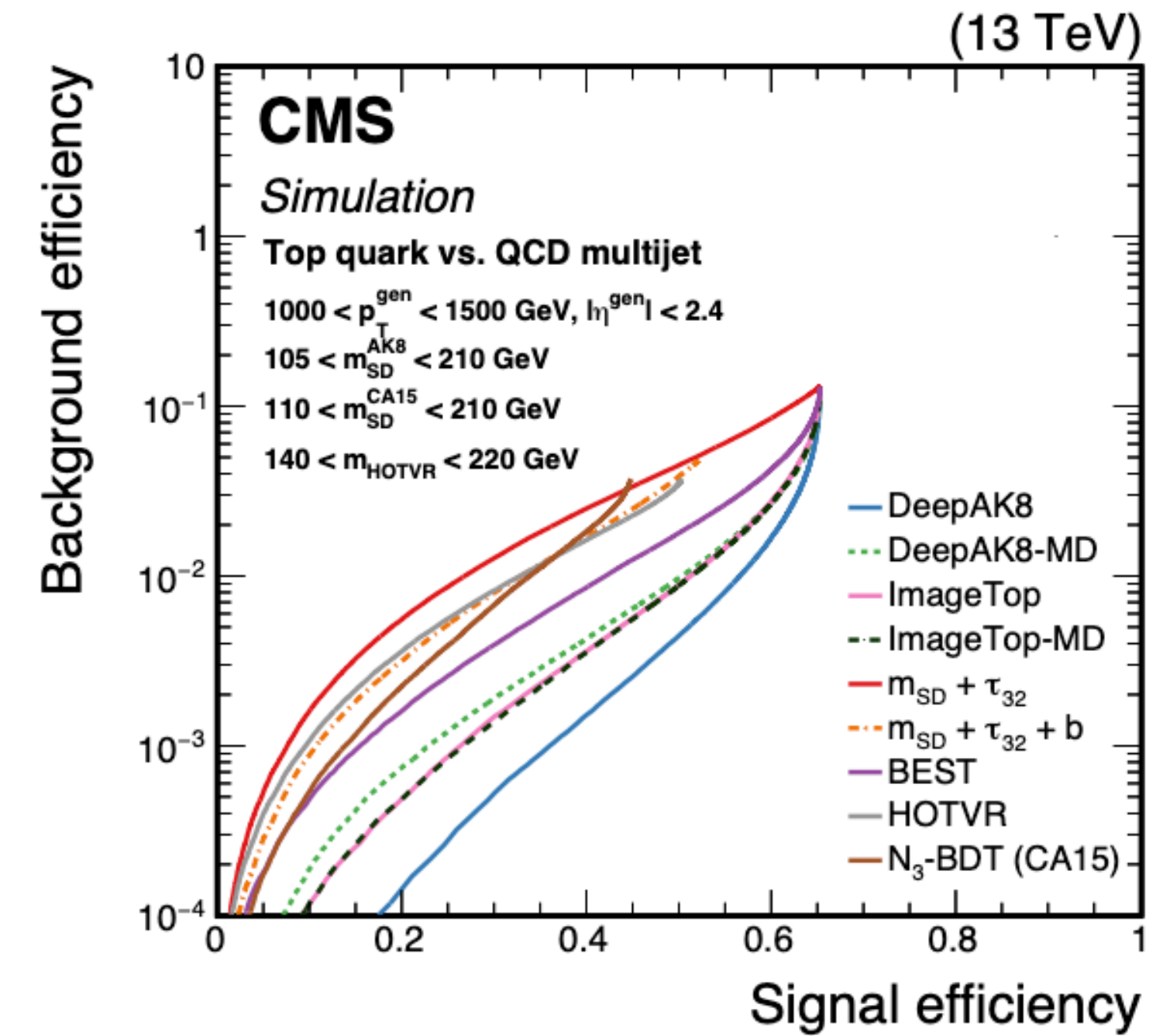
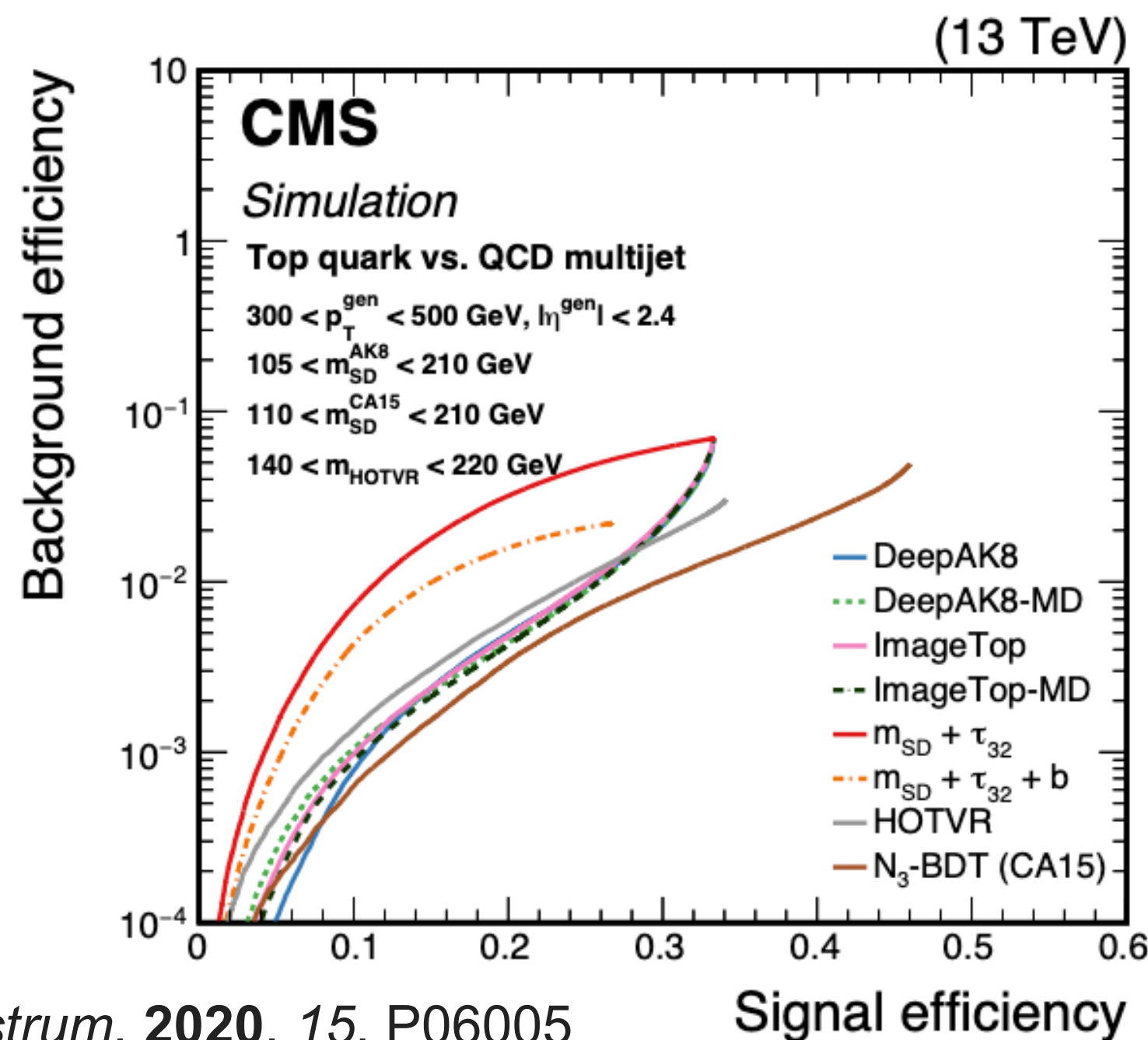
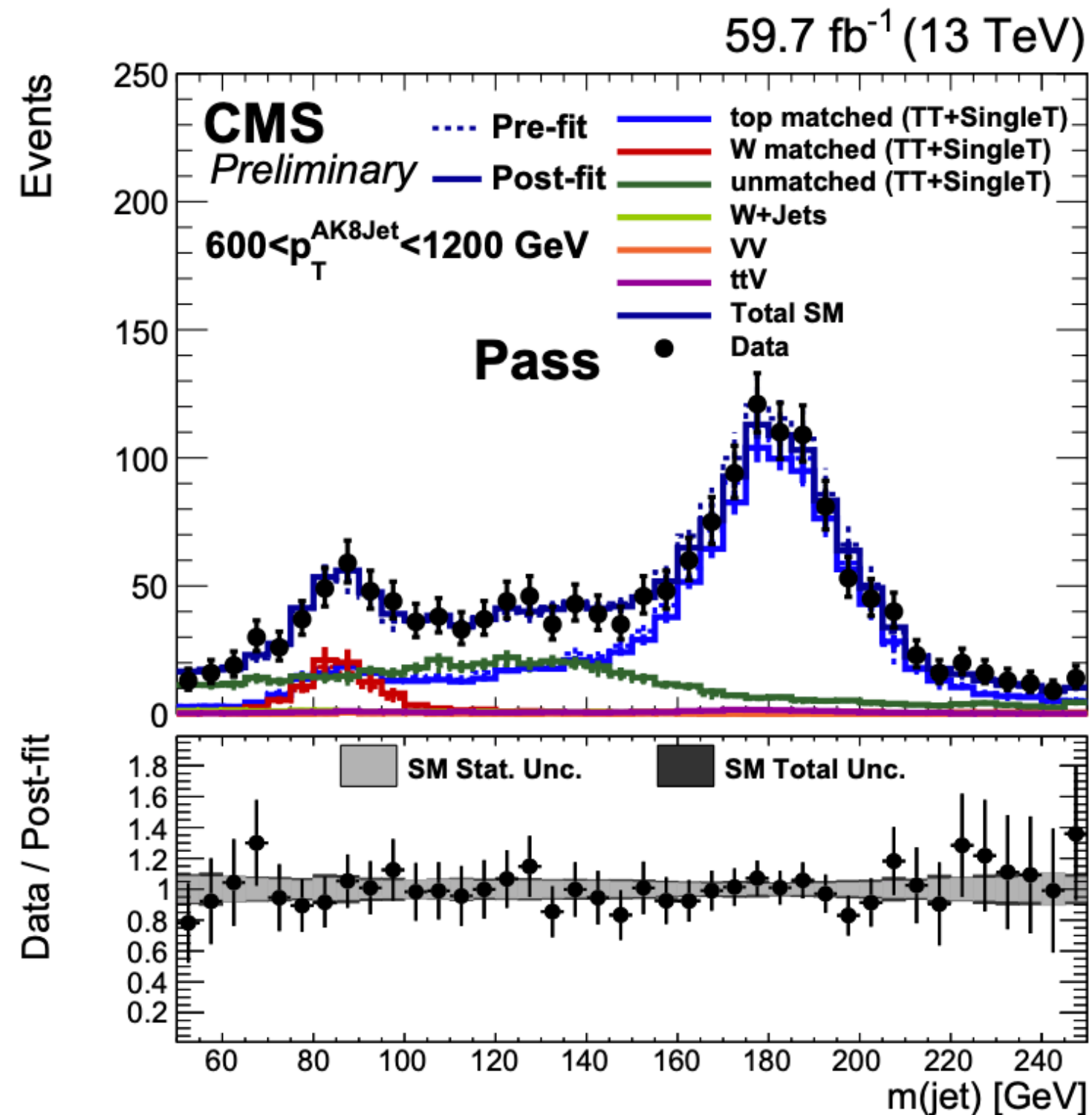
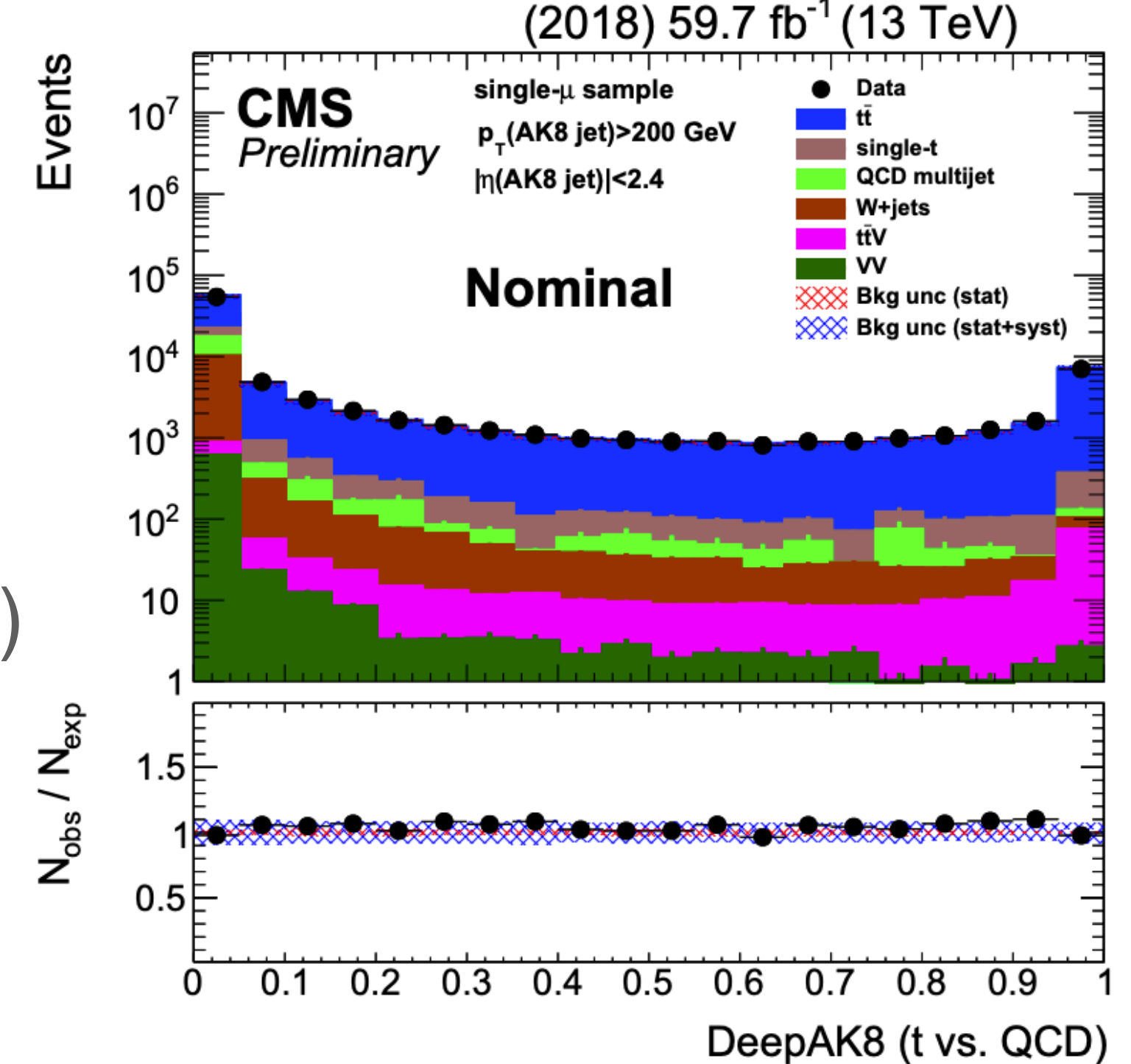


J. Instrum. 2020, 15, P06005

The tools of the trade

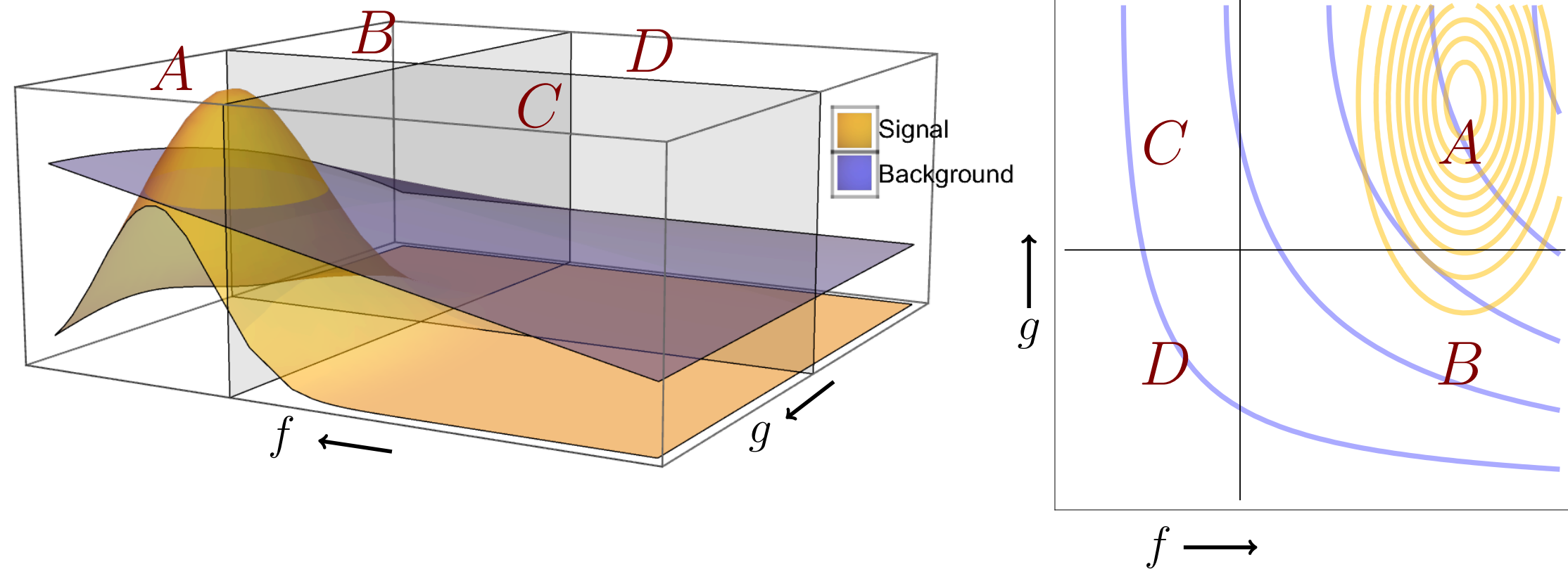
DeepAK8

- Use of low-level inputs (Particle-flow candidates, secondary vertices)
- Up to 100 PF candidates 40 features/candidate
- Up to 5 secondary vertices, 14 features per secondary vertex



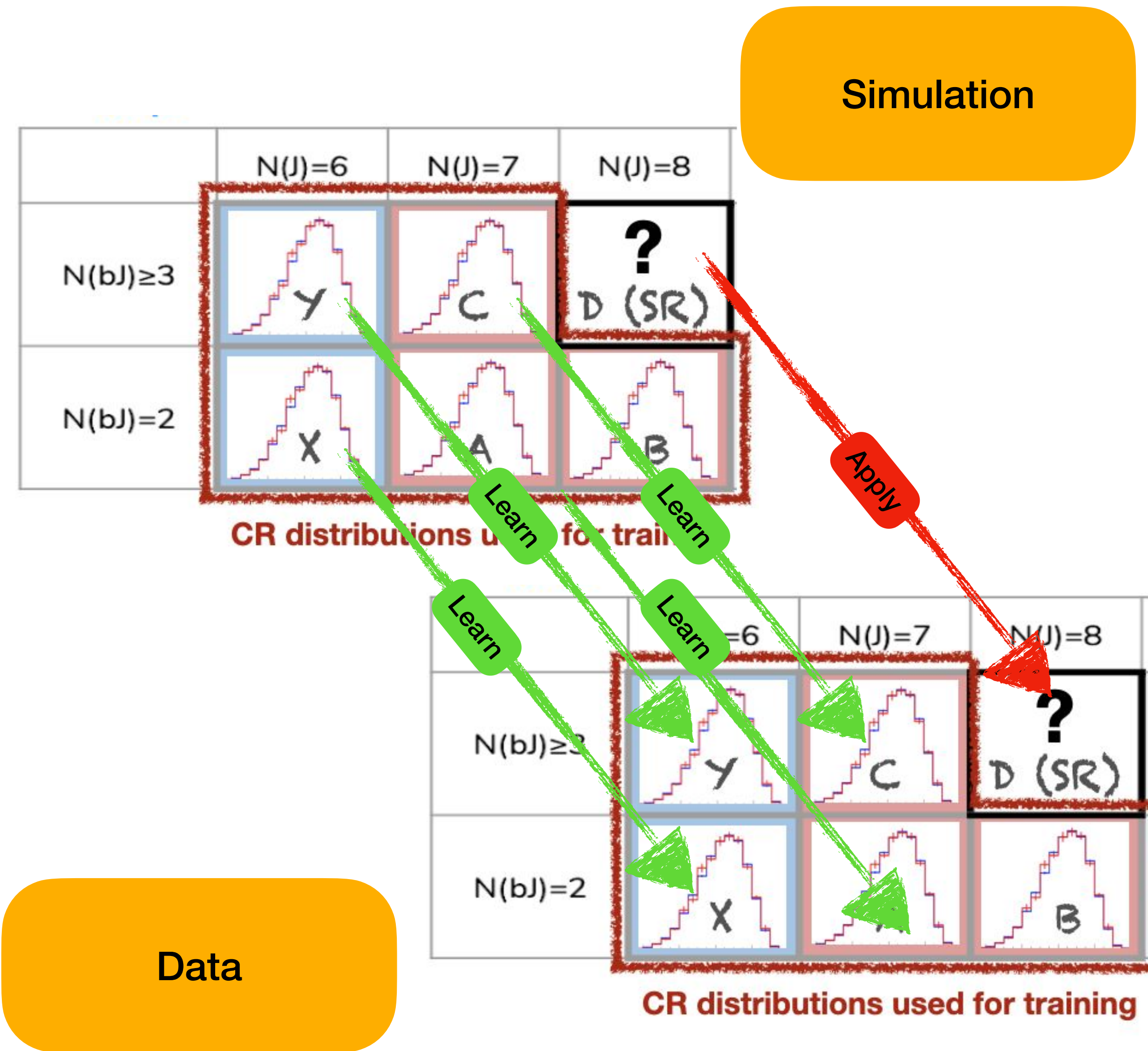
The tools of the trade

$$N_A = \frac{N_B N_C}{N_D}$$



Phys. Rev. D 103, 035021 (2021)

- Reduce systematics impact with data-driven techniques
 - ABCDnn
 - Train autoregressive flow
 - Learn transition MC \rightarrow Data in control region
 - Apply transformation to signal region



arXiv:2008.03636

[PLB 844 \(2023\) 138076](#)

Bird's eye view — models

Vector-like quarks

$T' \rightarrow tH, tZ$ $B' \rightarrow tW$

Supersymmetric
Models

$\tilde{g}\tilde{g} \rightarrow t\bar{t}t\bar{t}\tilde{\chi}_1^0, \tilde{t}_1\tilde{t}_1 \rightarrow t\bar{t}\tilde{\chi}_1^0\chi_1^0$

(Quasi-)
model-independent
Resonances

$Z' \rightarrow tt, W' \rightarrow tb$
res \rightarrow VLQ+t

Leptoquarks

$LQ\bar{L}\bar{Q} \rightarrow t\mu t\mu, t\tau t\tau$

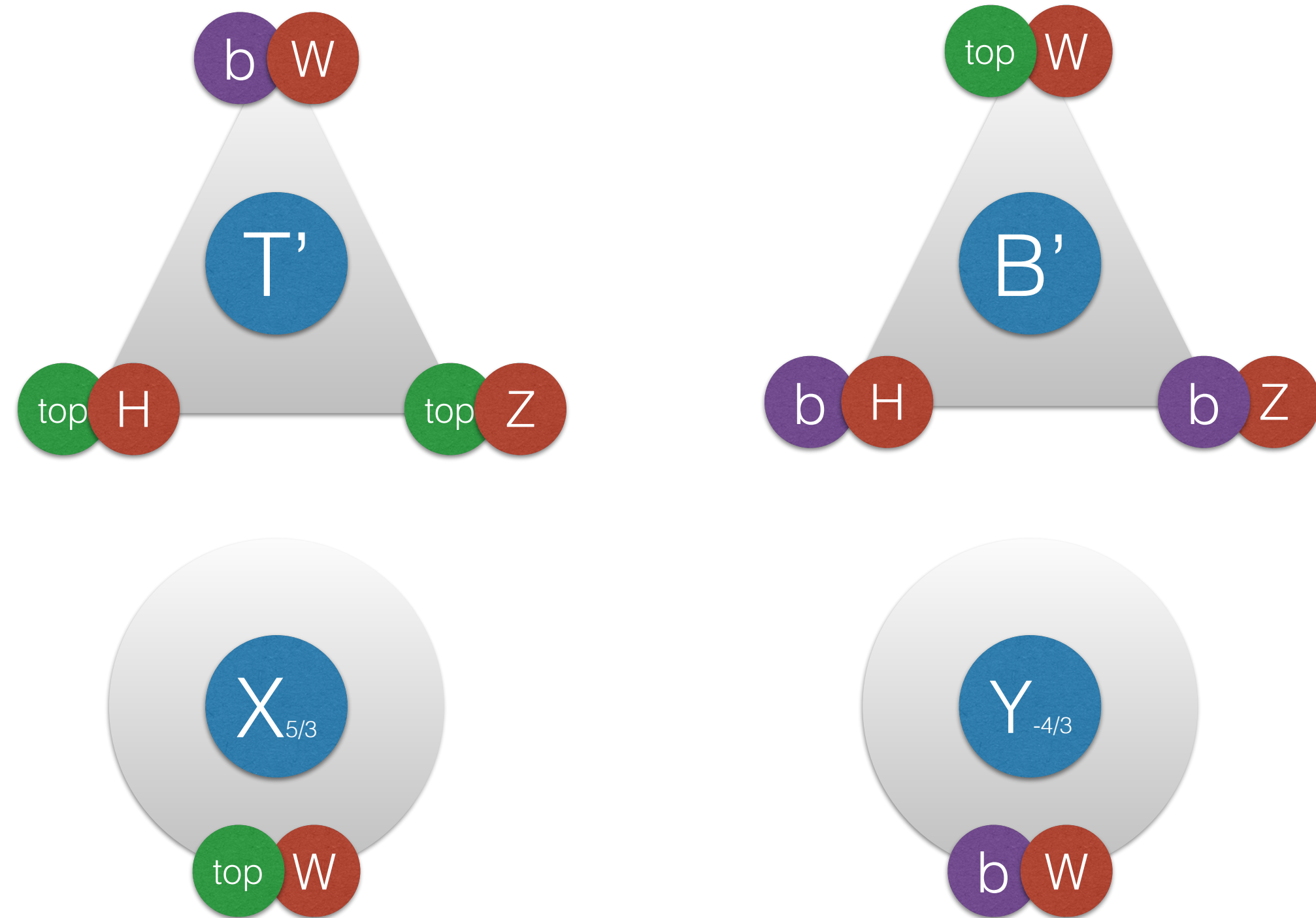
Higgs doublet
Models

$pp \rightarrow H/A$ $t \rightarrow ttq$

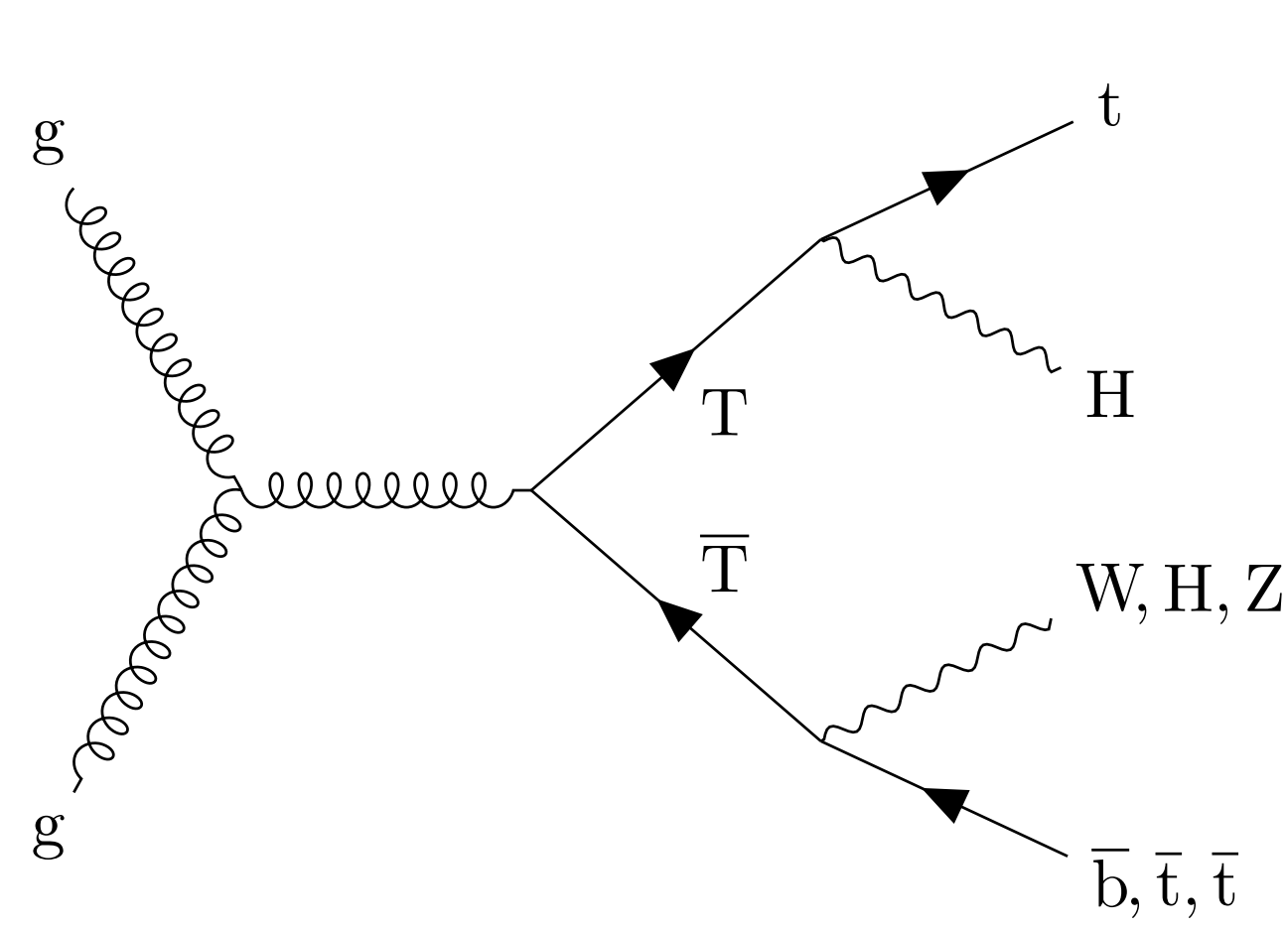
Excited quarks

$b^* \rightarrow tW$

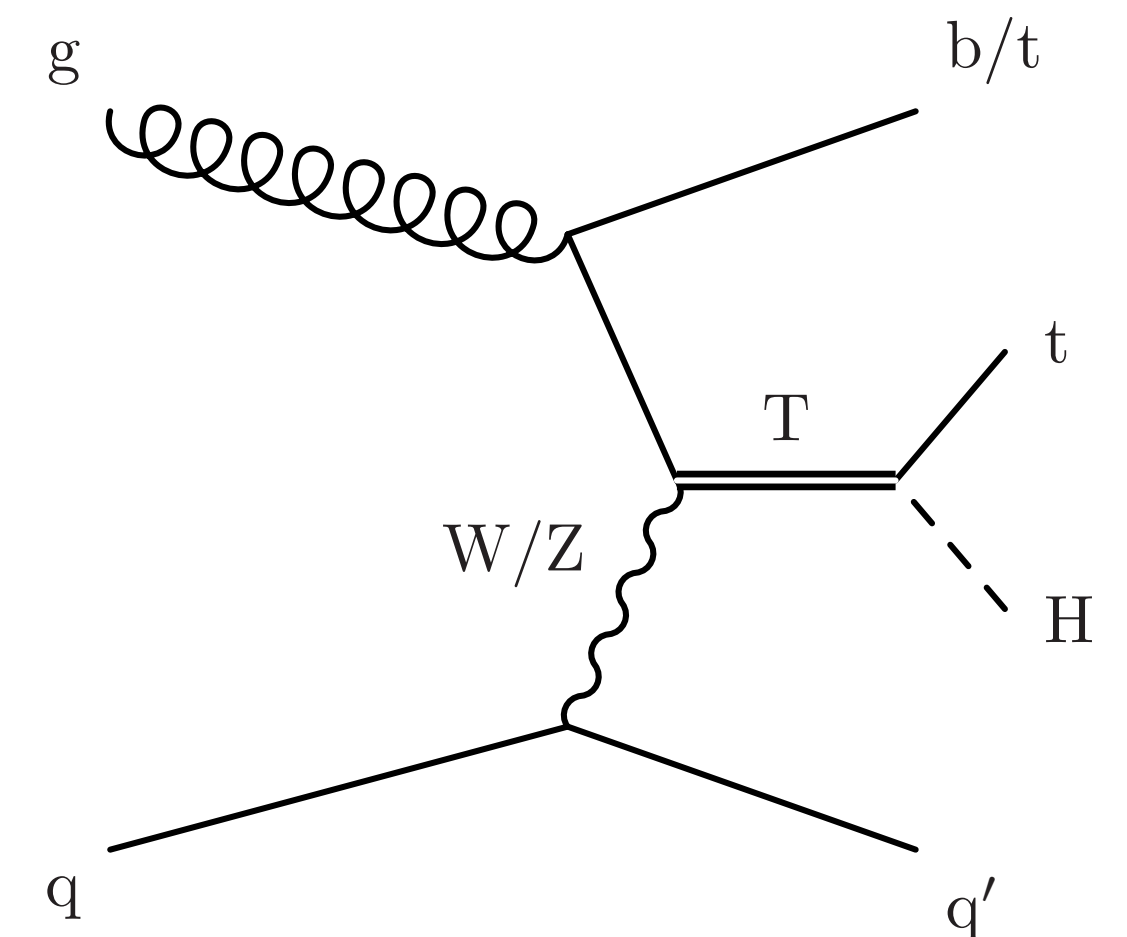
Vector-like quarks



Pair production

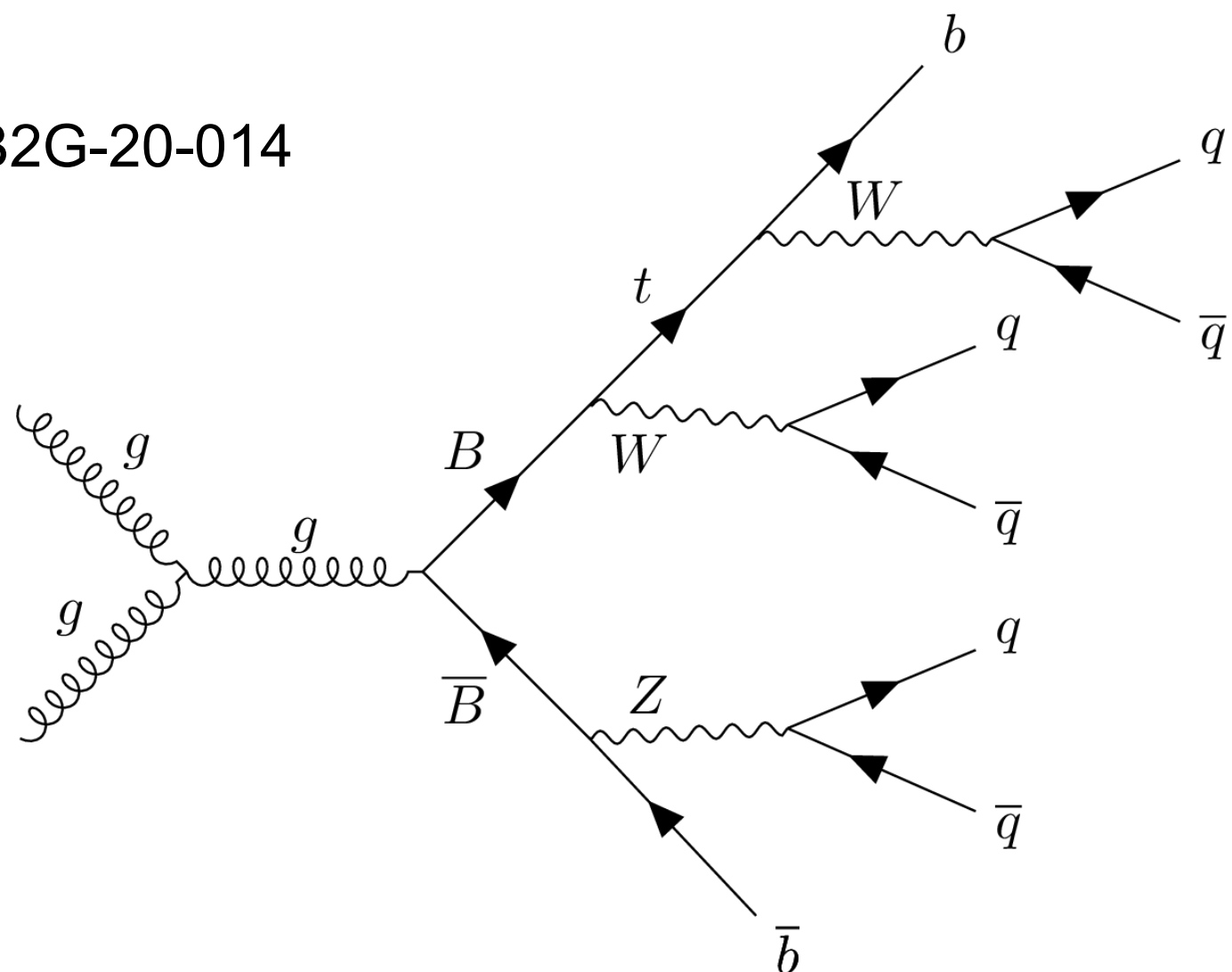


Single production



Pair Production of B' VLQ, 2 leptons and Hadronic Final State

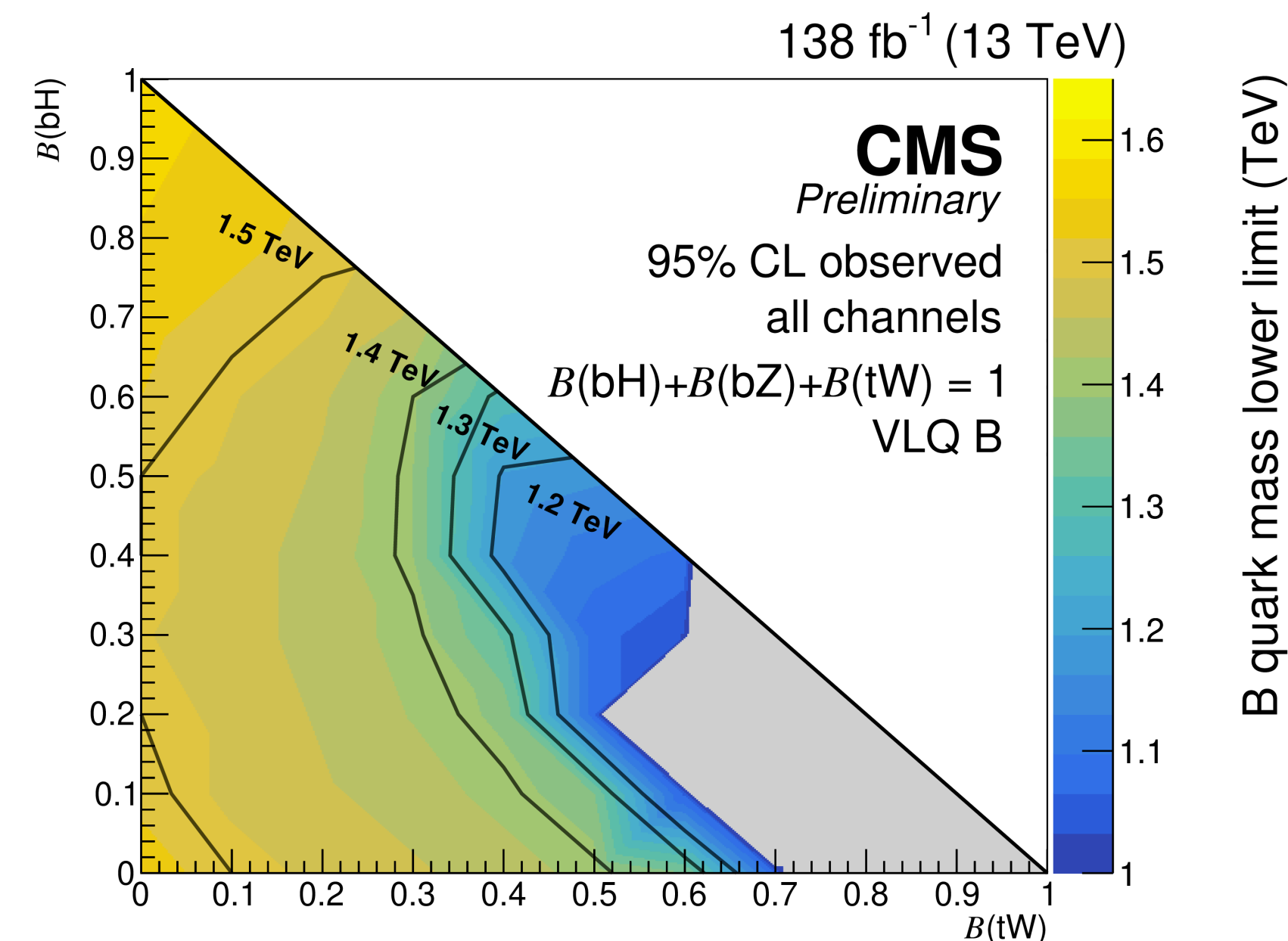
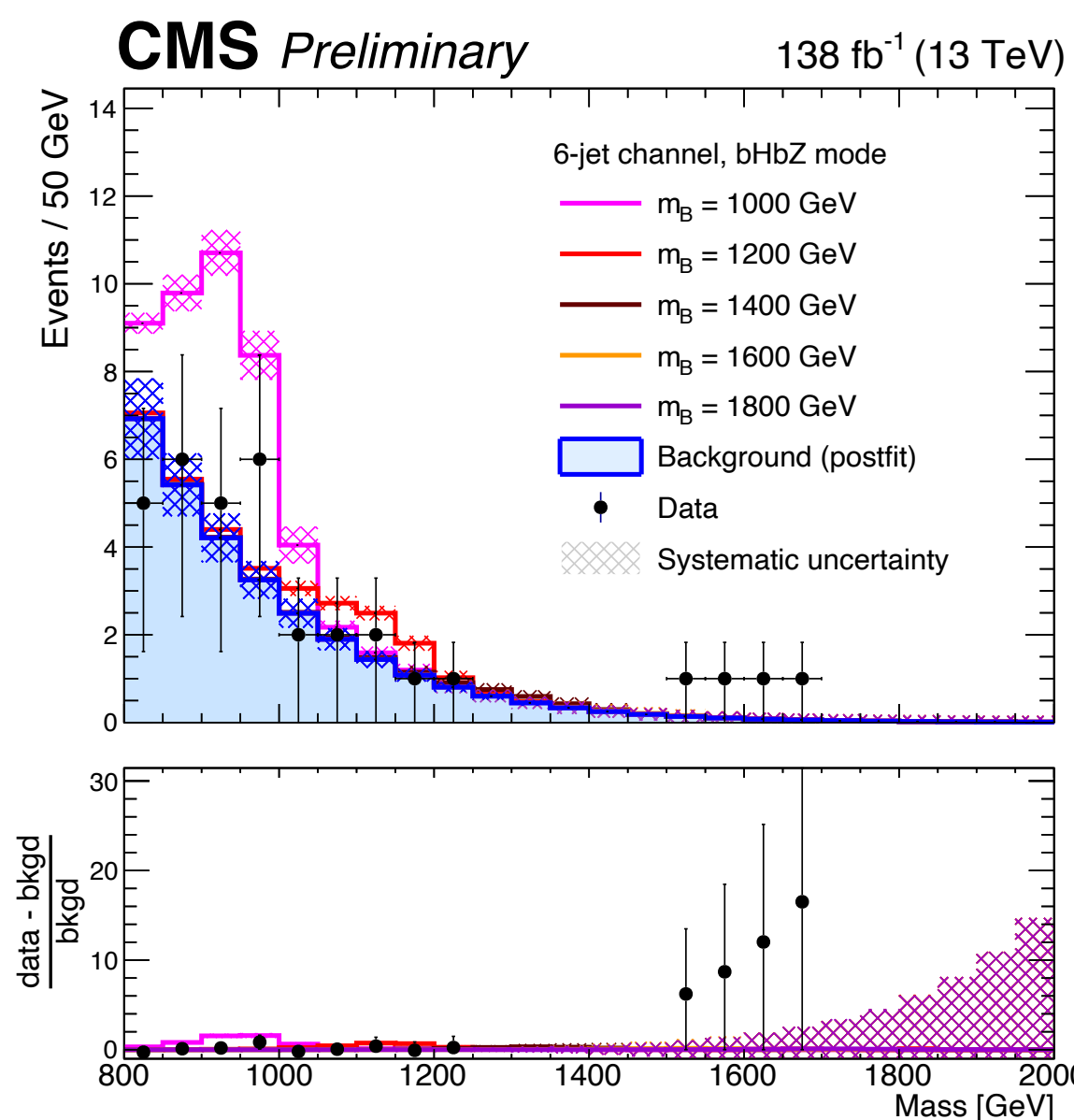
CMS-PAS-B2G-20-014



- Fully hadronic and semileptonic final states independently using orthogonal datasets
 - 4-6 jet hadronic events (fully hadronic)
 - 3-4 jet + 2 Opposite sign leptons for semileptonic events (di-leptonic)
- Allow for merged H, Z, W, t jets
 - 1 AK8 / 2 AK4 (H, Z, W)
 - 1 AK8 / 2 AK4 / 3 AK4 (t)
 - DeepFlavor tagging

$$\chi_{\text{mod}}^2 = \frac{(\Delta m_{\text{VLQ}} - \overline{\Delta m_{\text{VLQ}}})^2}{\sigma_{\Delta m_{\text{VLQ}}}^2} + \frac{(m_1 - \overline{m_1})^2}{\sigma_{m_1}^2} + \frac{(m_2 - \overline{m_2})^2}{\sigma_{m_2}^2}$$

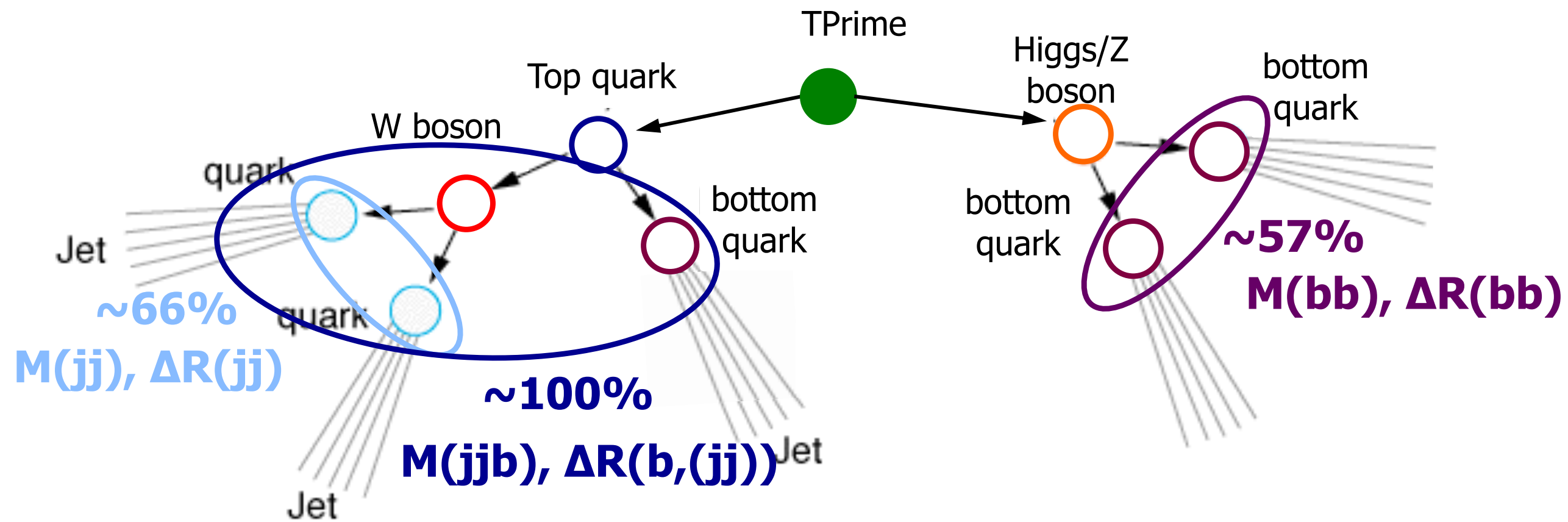
Most stringent limits on M_B



Vector-like quarks

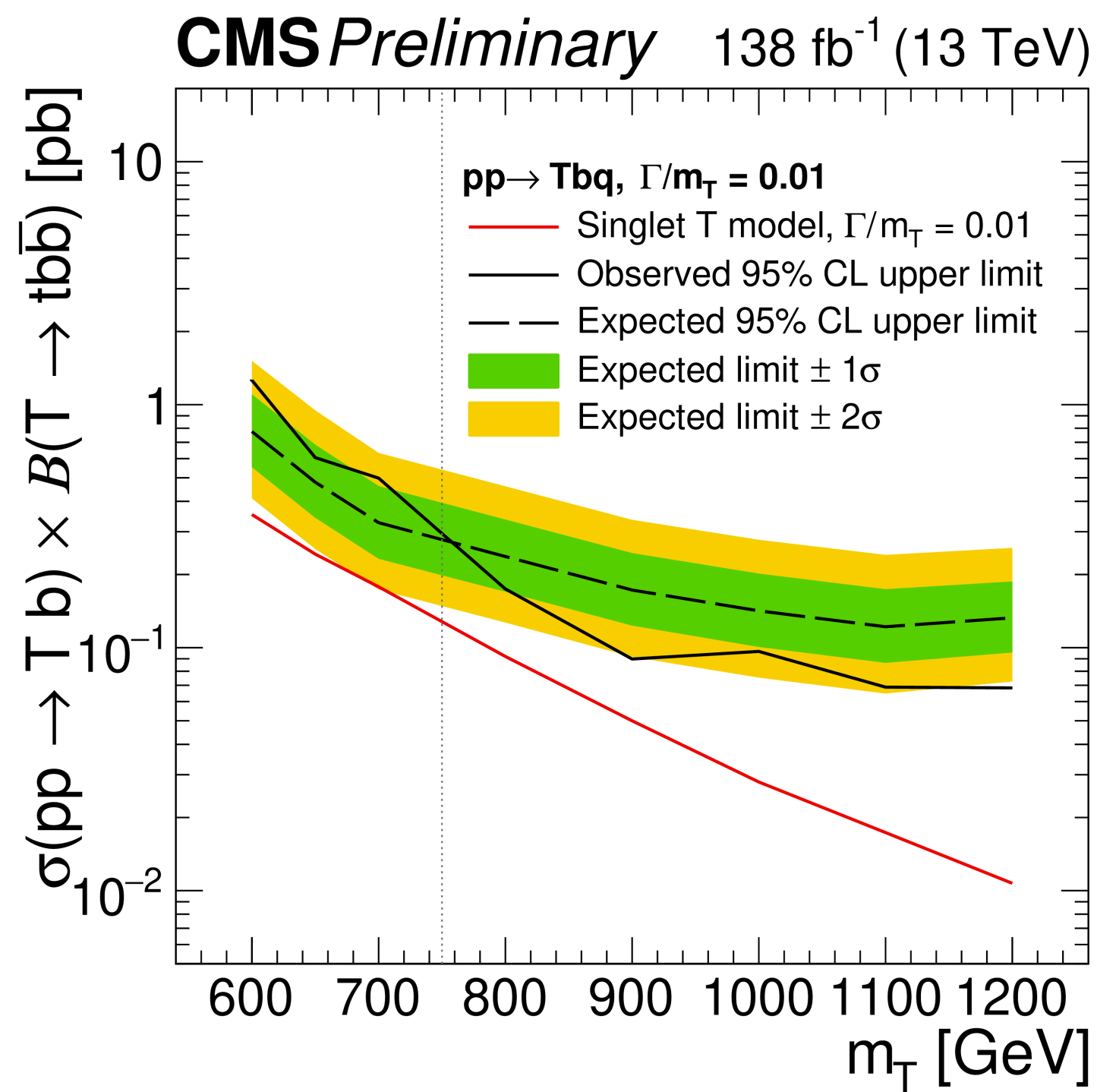
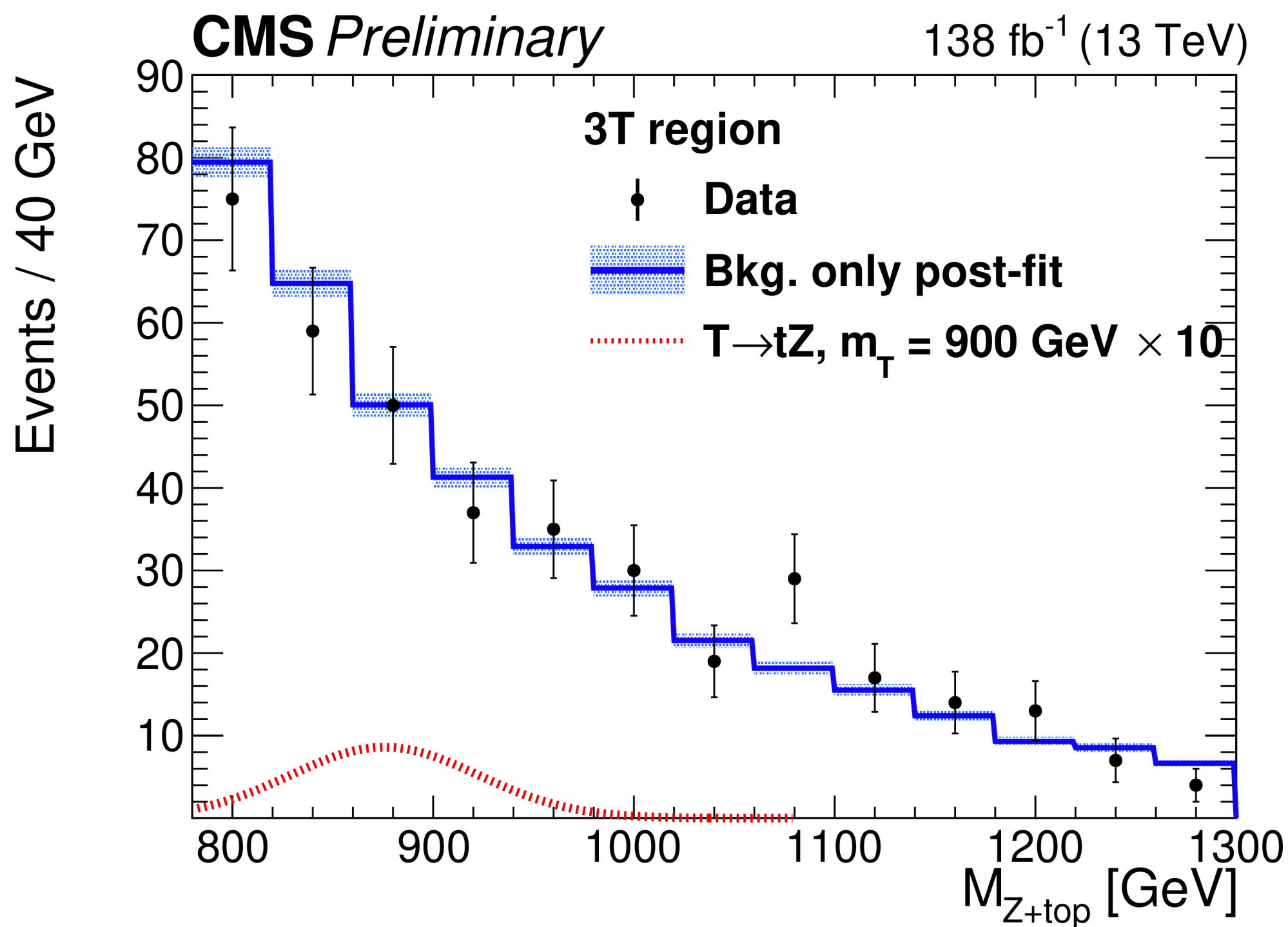
single $T \rightarrow tH/Z(bb)$ in the resolved all-hadronic channel

CMS-PAS-B2G-19-001



Strongest xsec limits for all-had resolved final state

1260 to 68 fb for T masses from 600 to 1200 GeV



$$\chi_{H/Z}^2 = \left(\frac{m_{H/Z}^{meas} - m_{H/Z}^{MC}}{\sigma_{H/Z}^{MC}} \right)^2,$$

$$\chi_W^2 = \left(\frac{m_W^{meas} - m_W^{MC}}{\sigma_W^{MC}} \right)^2,$$

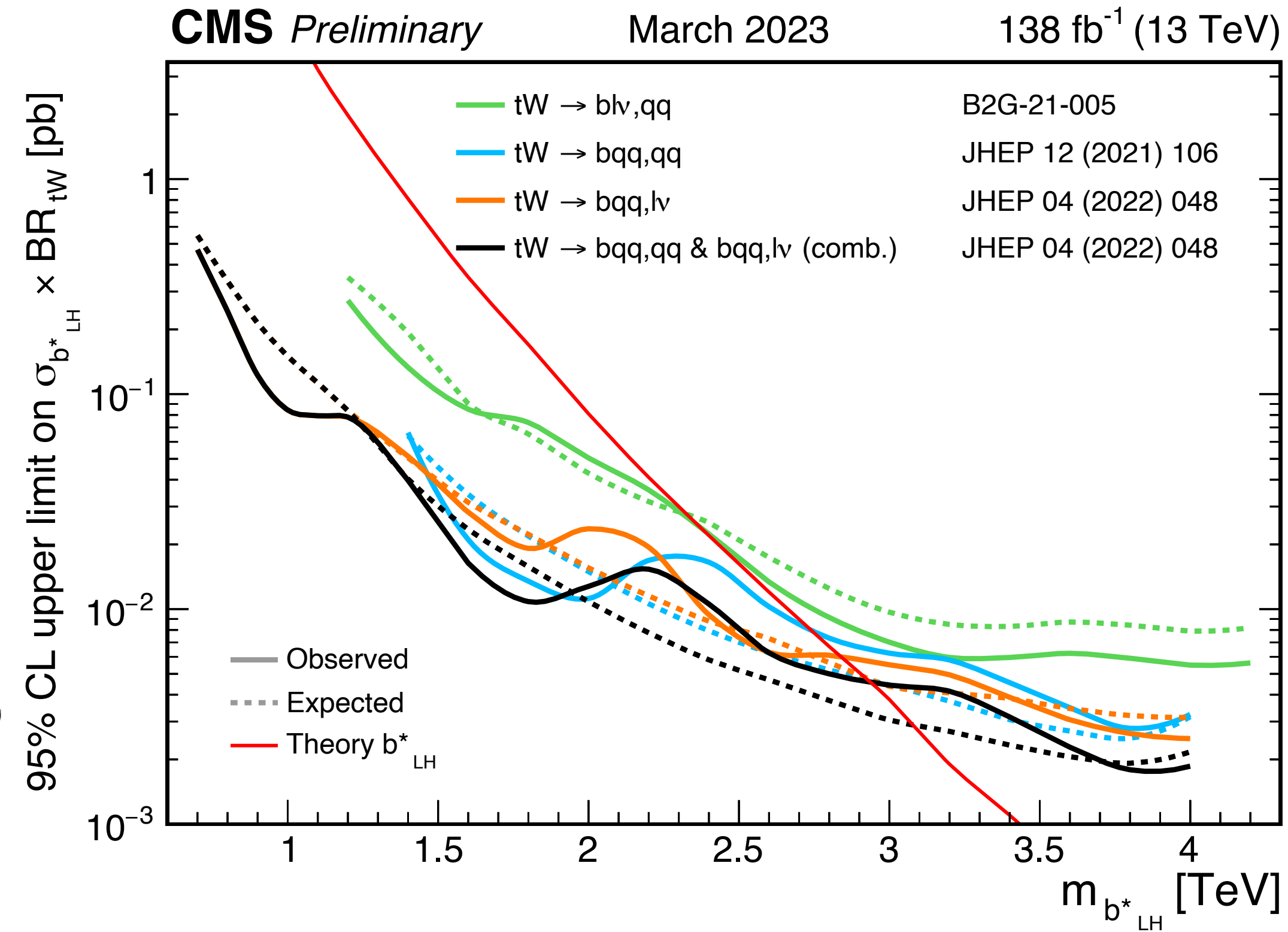
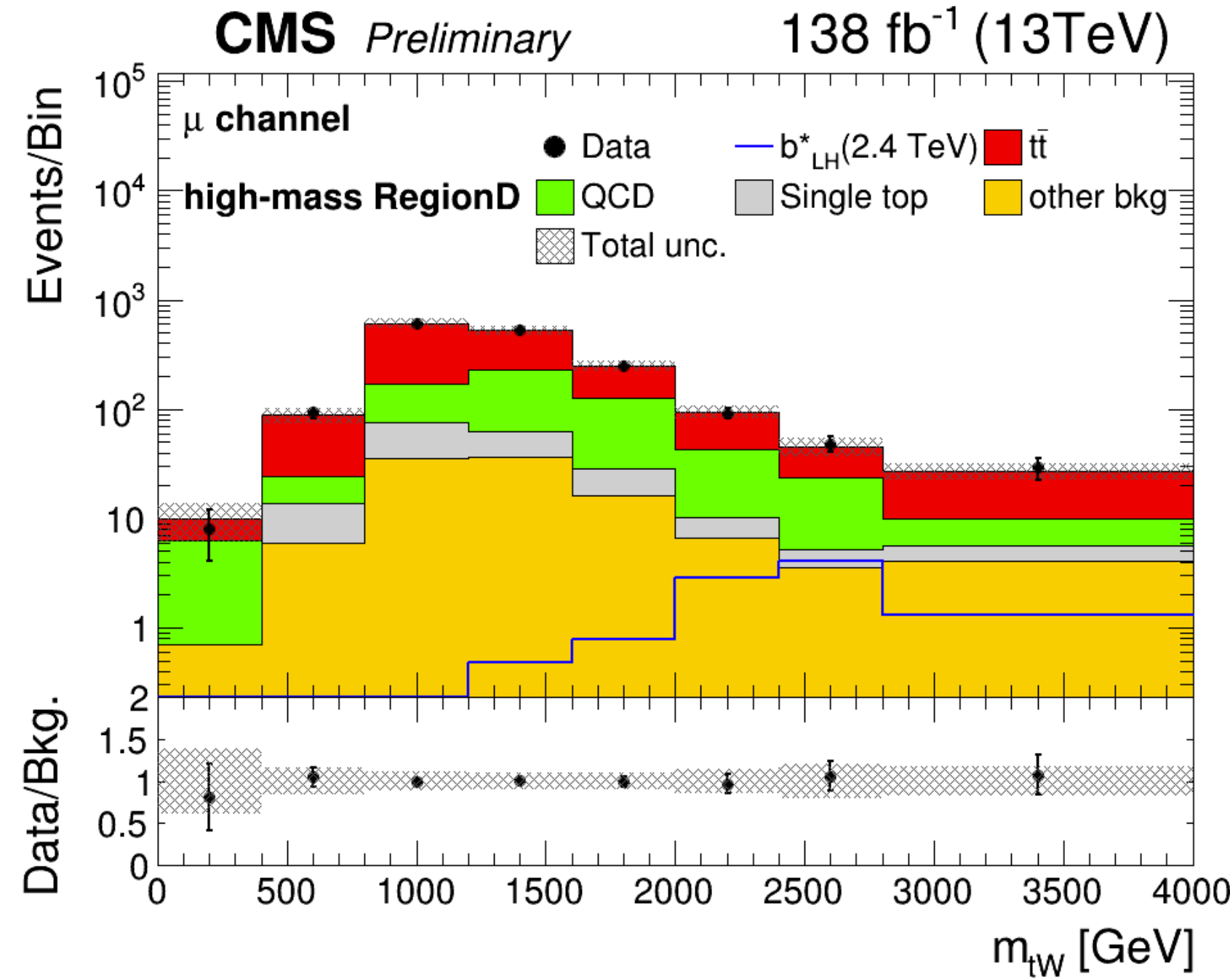
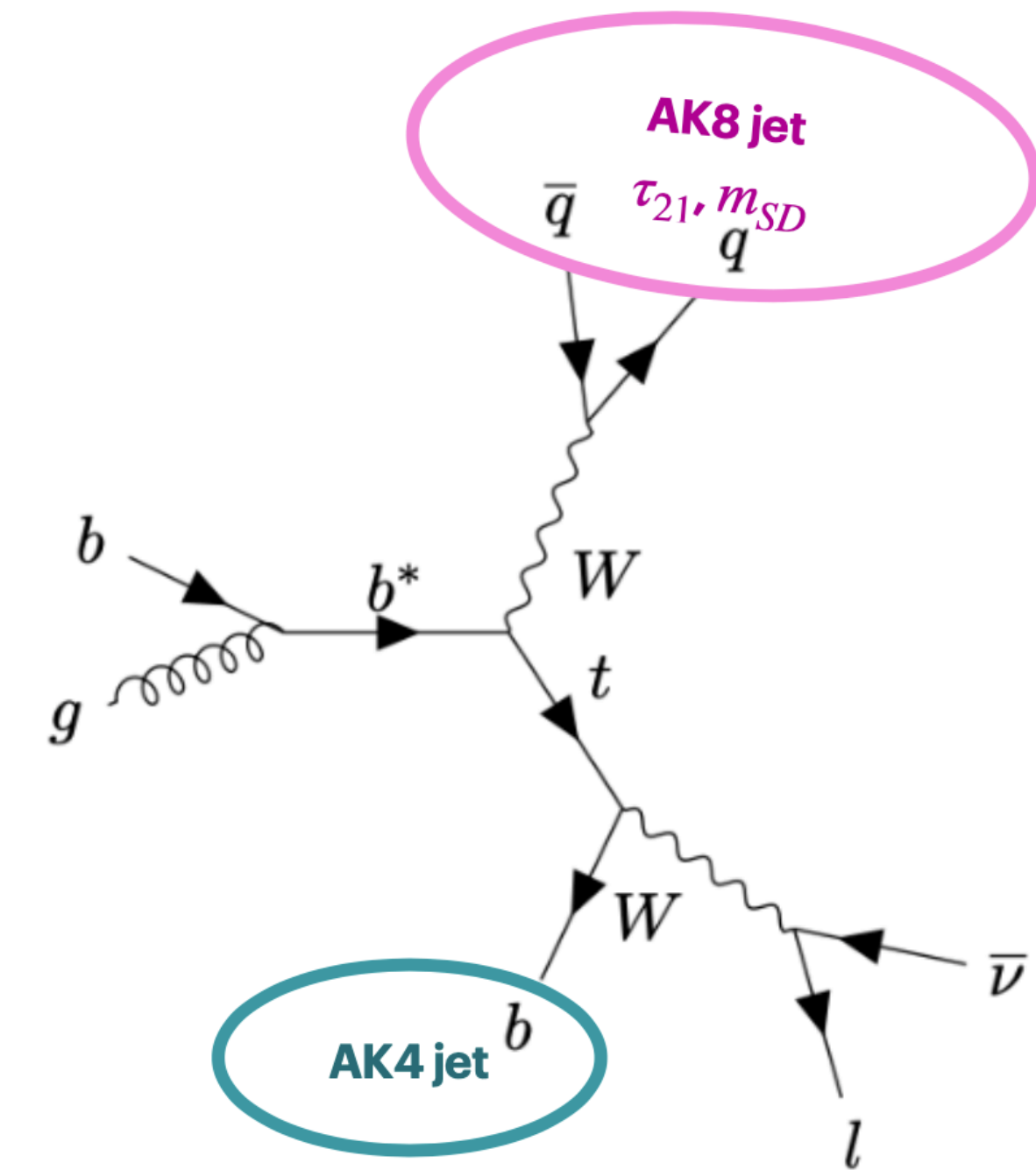
$$\chi_t^2 = \left(\frac{m_t^{meas} - m_t^{MC}}{\sigma_t^{MC}} \right)^2,$$

Excited quarks

NEW

$b^* \rightarrow tW, 1 \text{ lepton}$

CMS-PAS-B2G-21-005



- boosted $t \rightarrow$ non-isolated lepton, $p_{T,miss}$, and AK4 b jet
- boosted $W \rightarrow$ large radius jet with 2 pronged structure $\tau_{21} < 0.4$ and $65 < m_{SD} < 105 \text{ GeV}$
- One isolated lepton
- $\Delta R(bjet, Wjet) > 0.8$

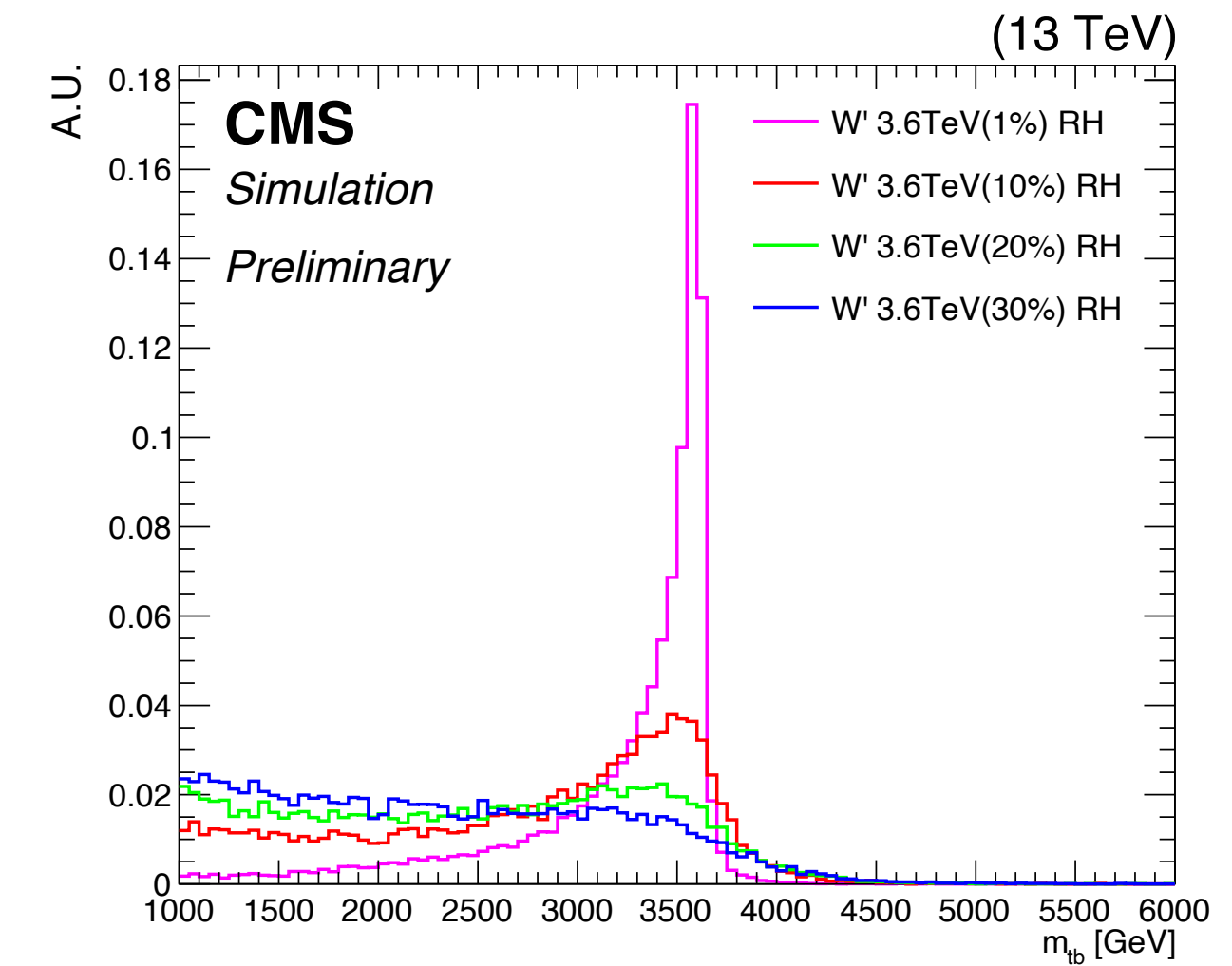
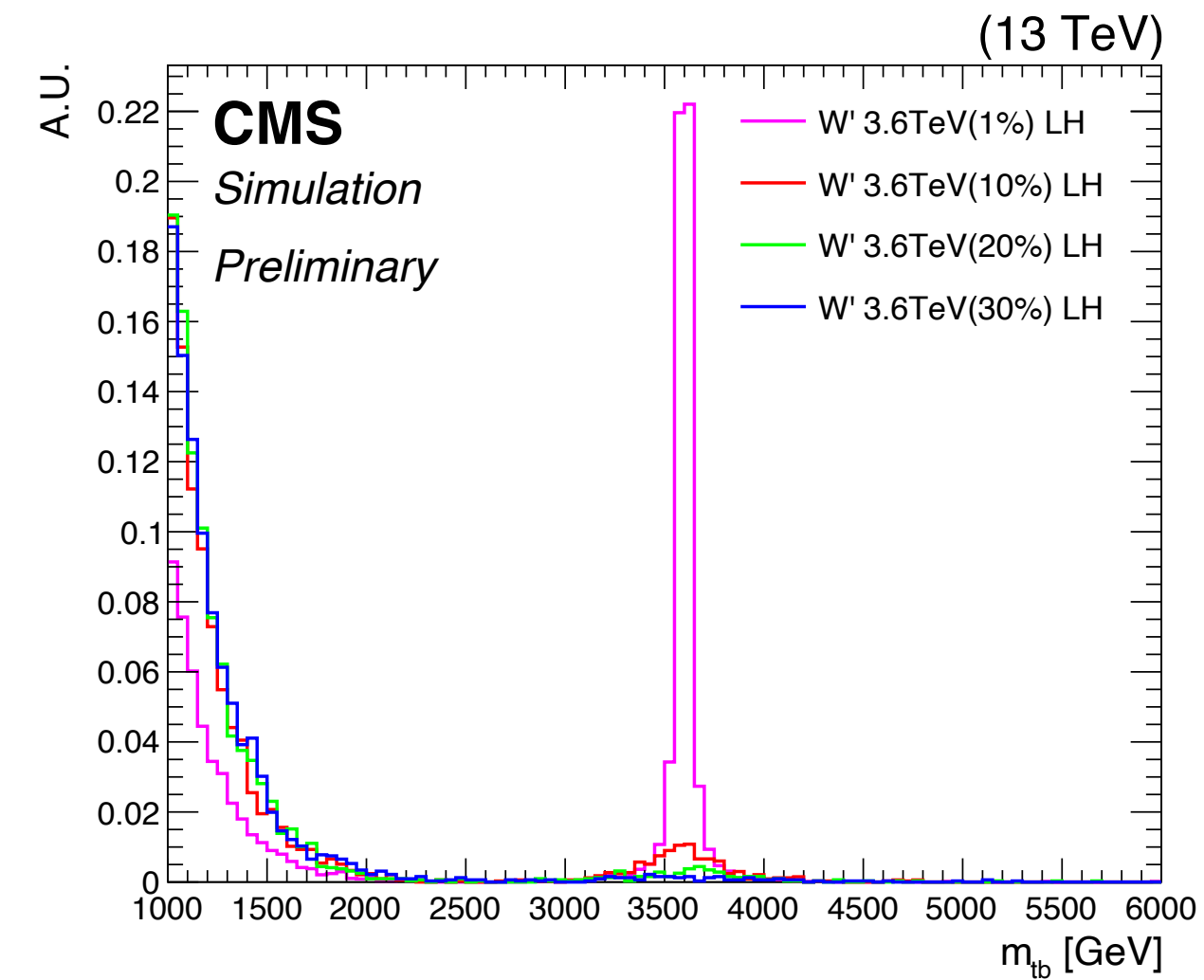
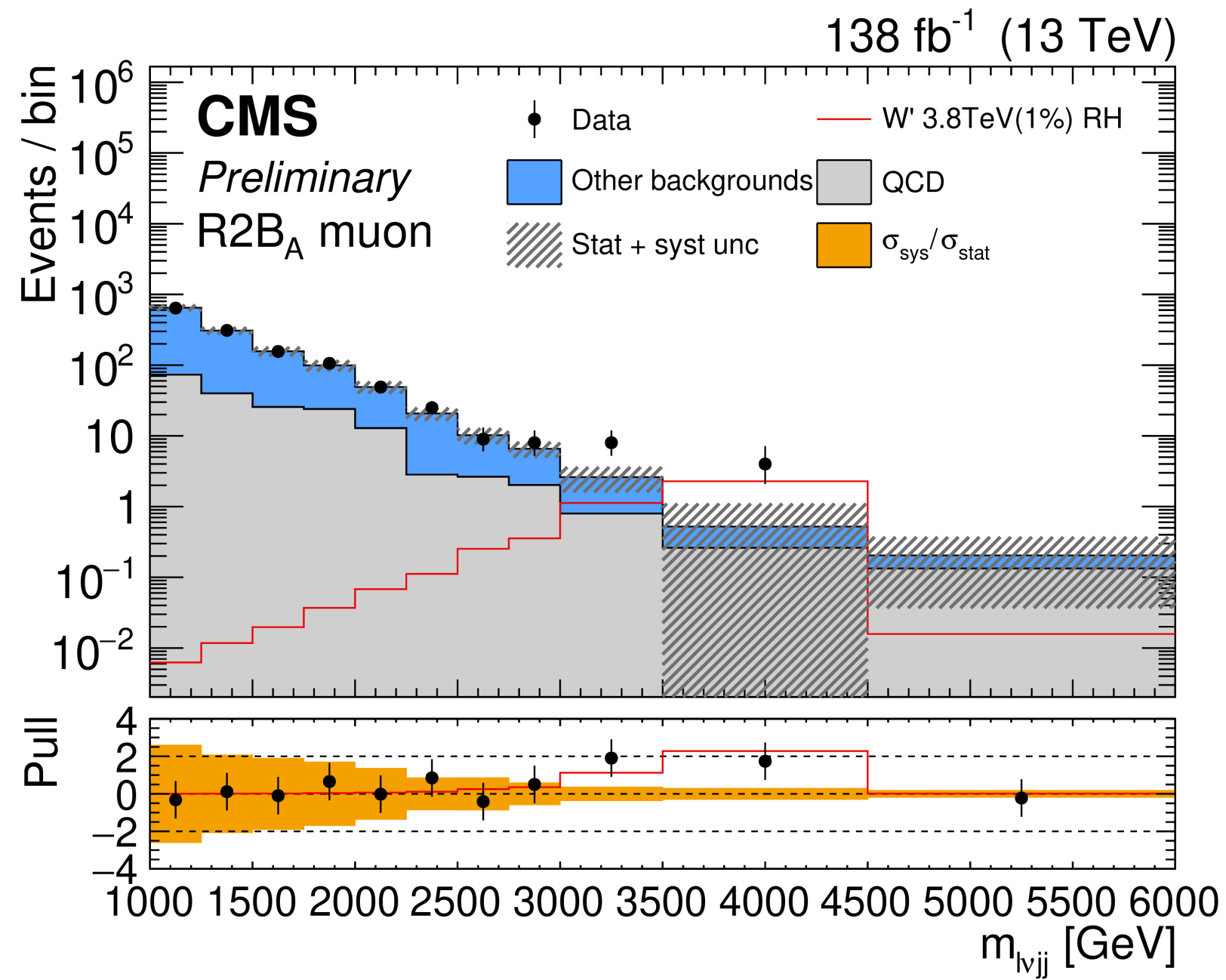
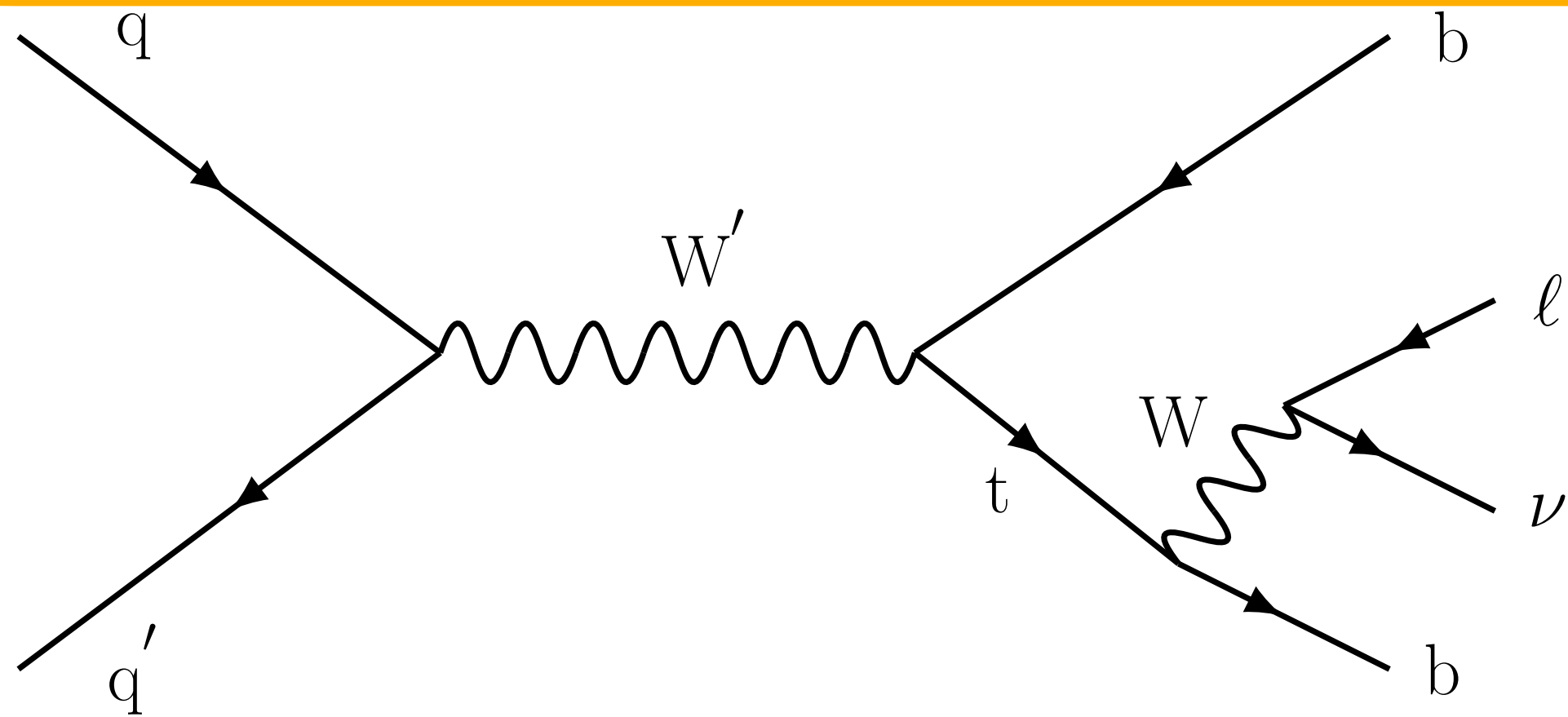
First result with leptonic top decay (full Run2)

$W' \rightarrow tb$ with lepton



CMS-PAS-B2G-20-012

probes $\Gamma/m_{W'}$ of 1, 10, 20, and 30%, for the first time

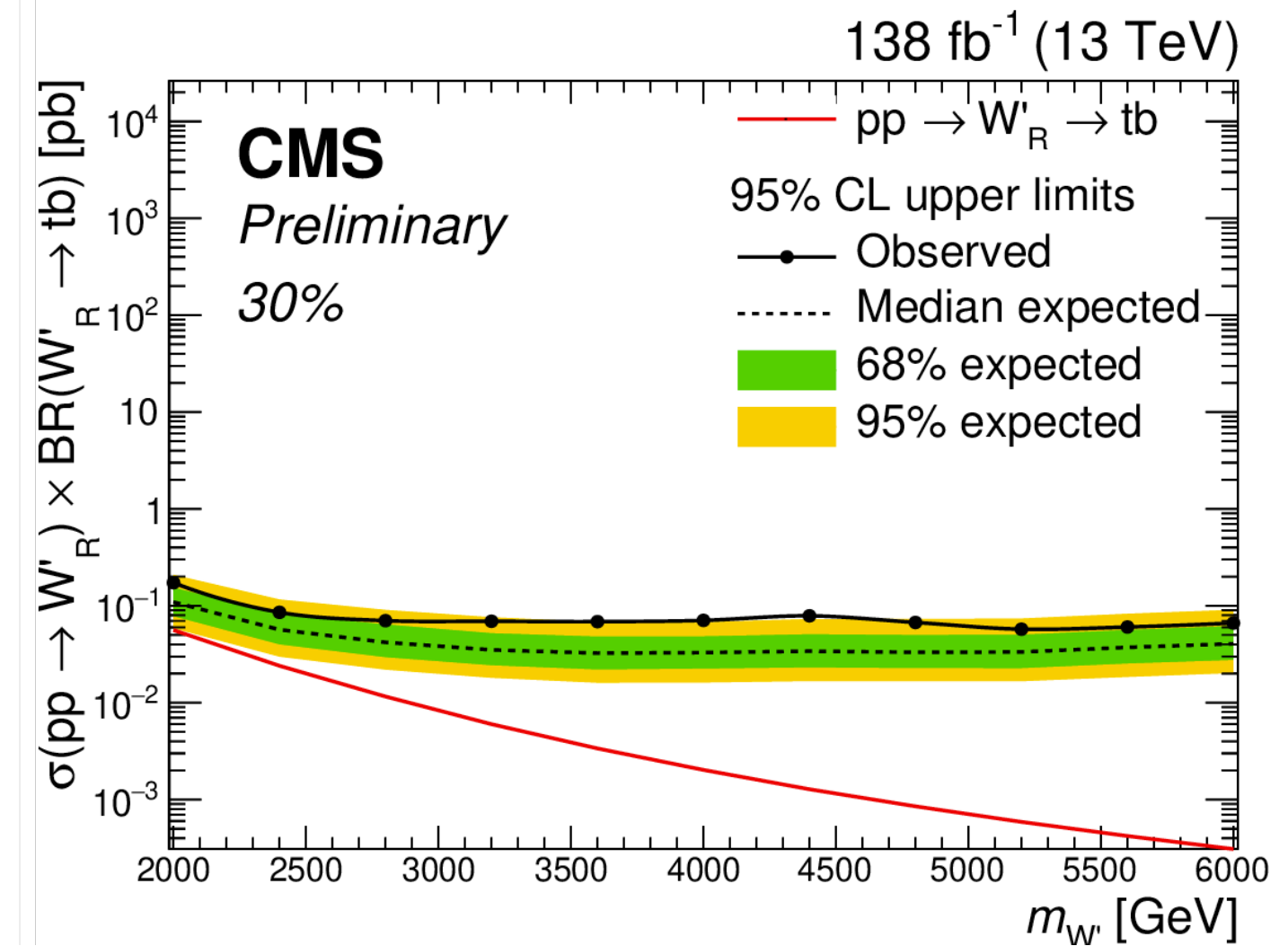
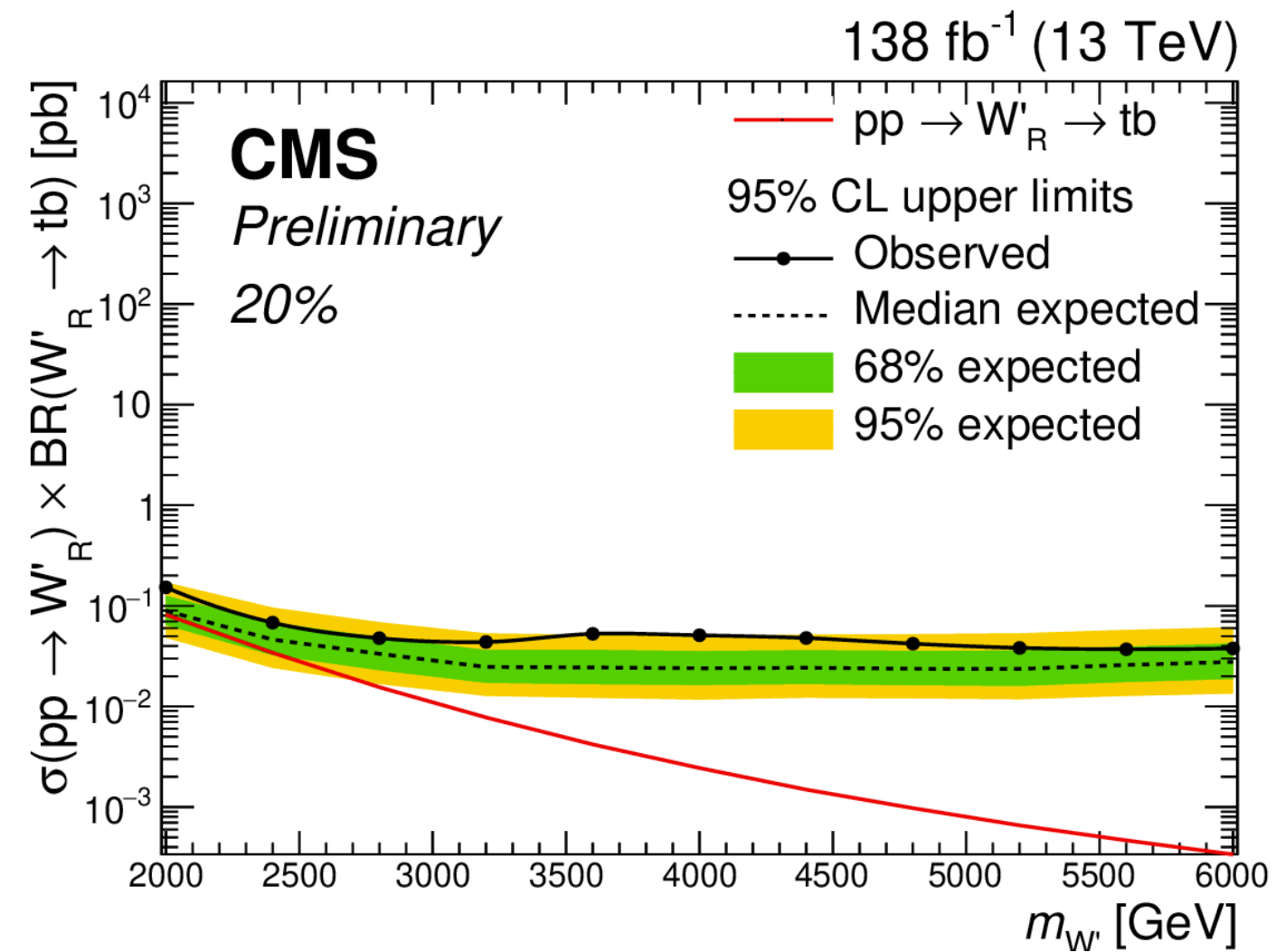
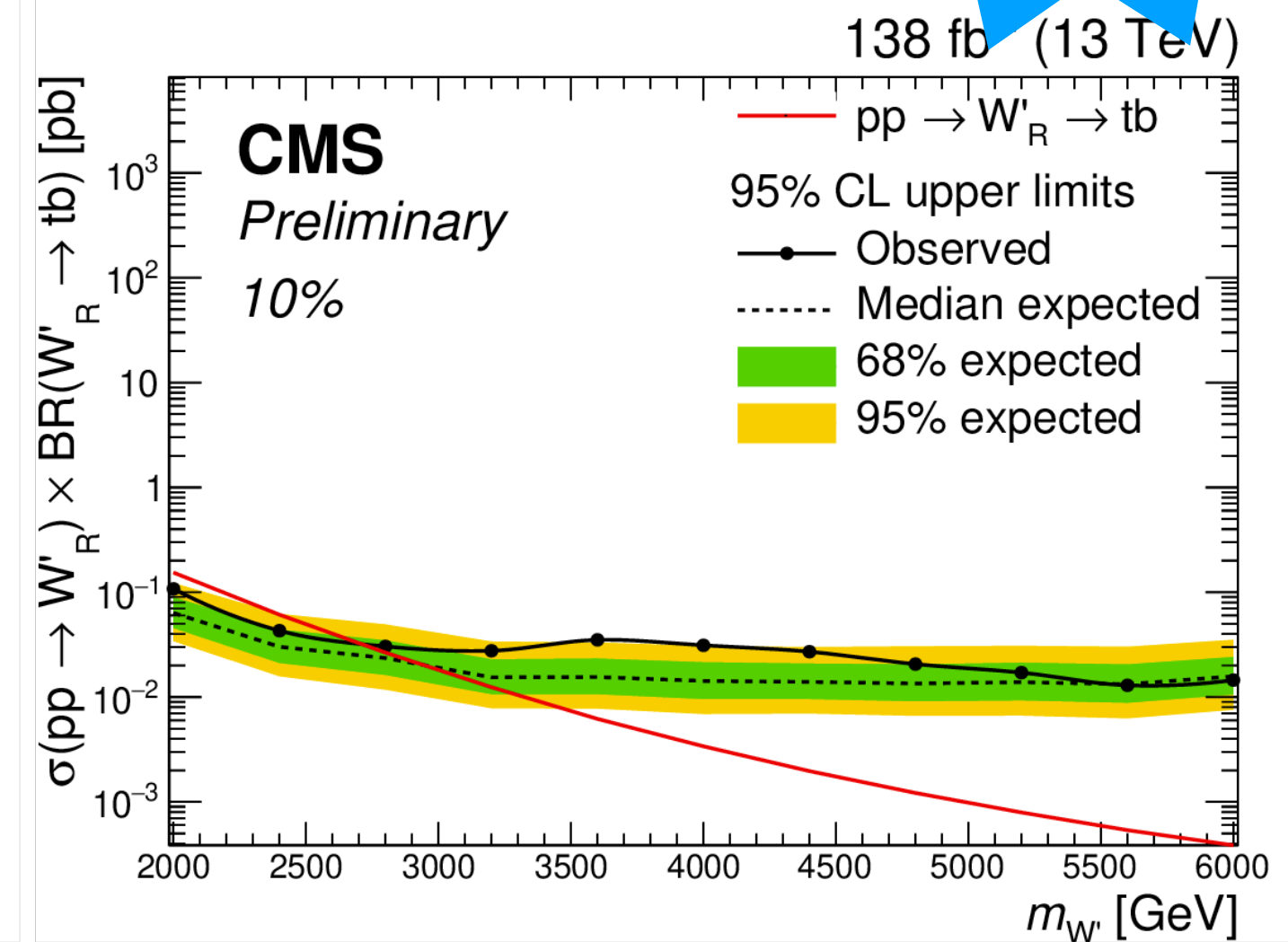
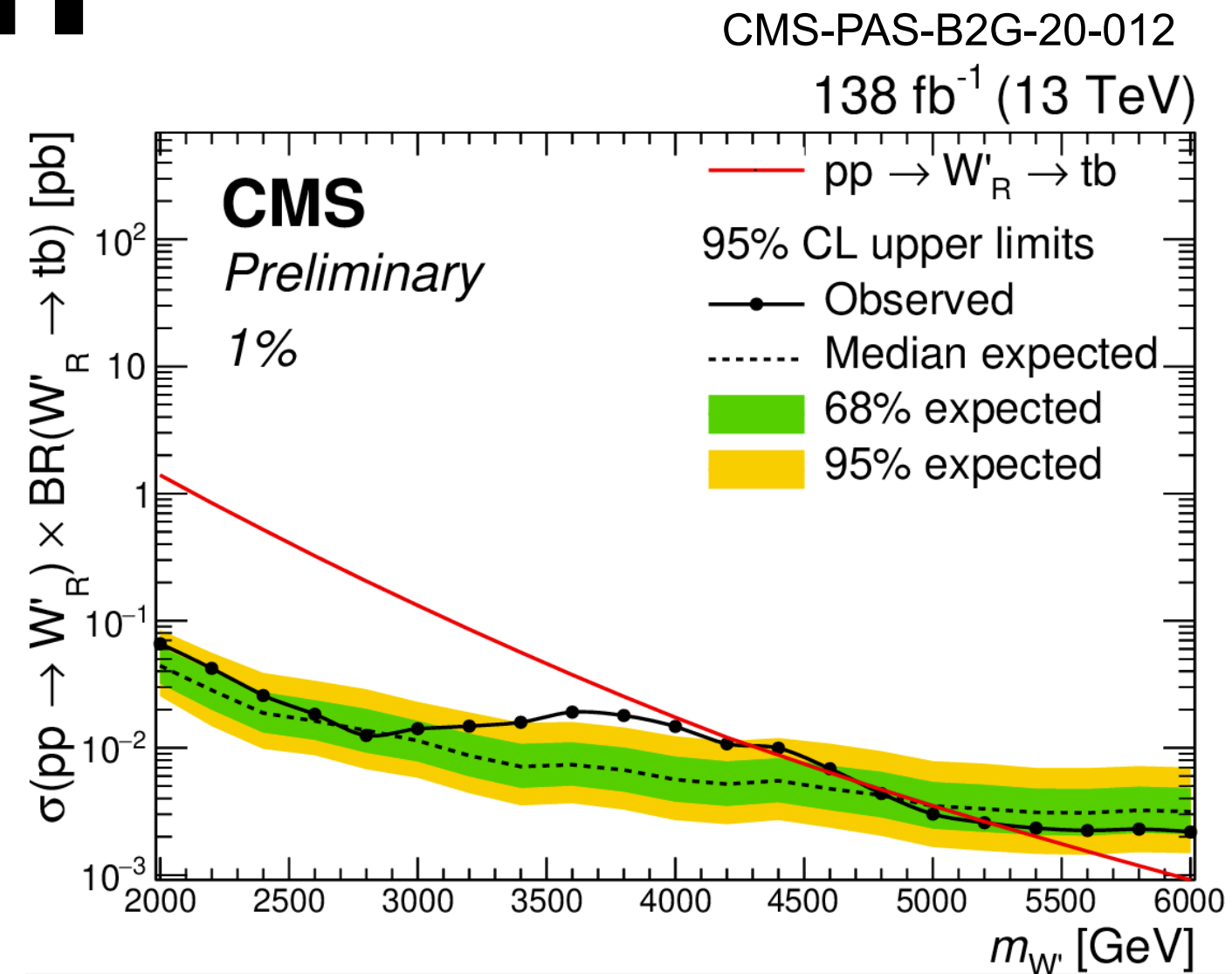
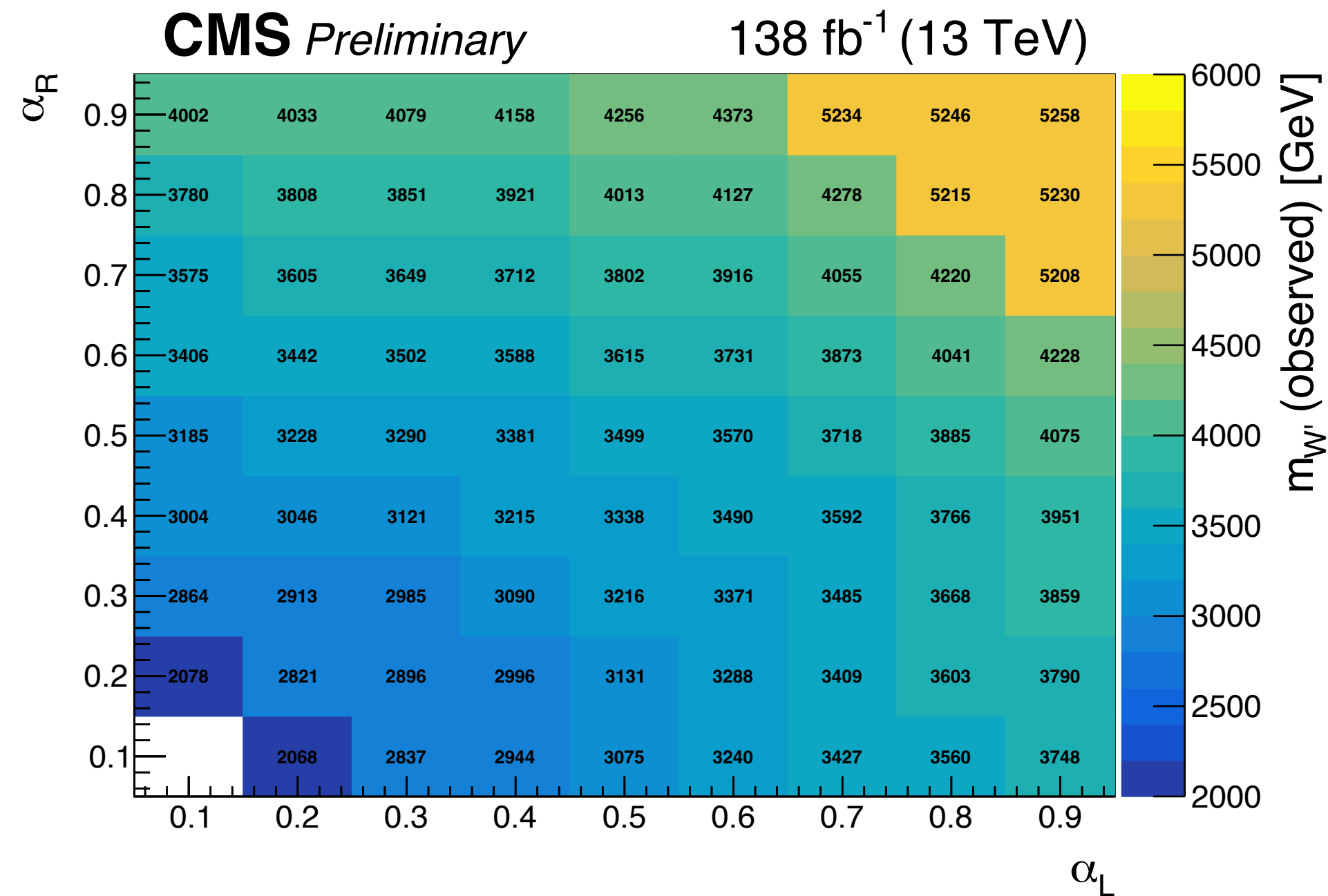


- DeepJet for b tagging
- AK8 with SoftDrop for hadronic top veto
- ABCD method for background
- Reconstructed

Resonances

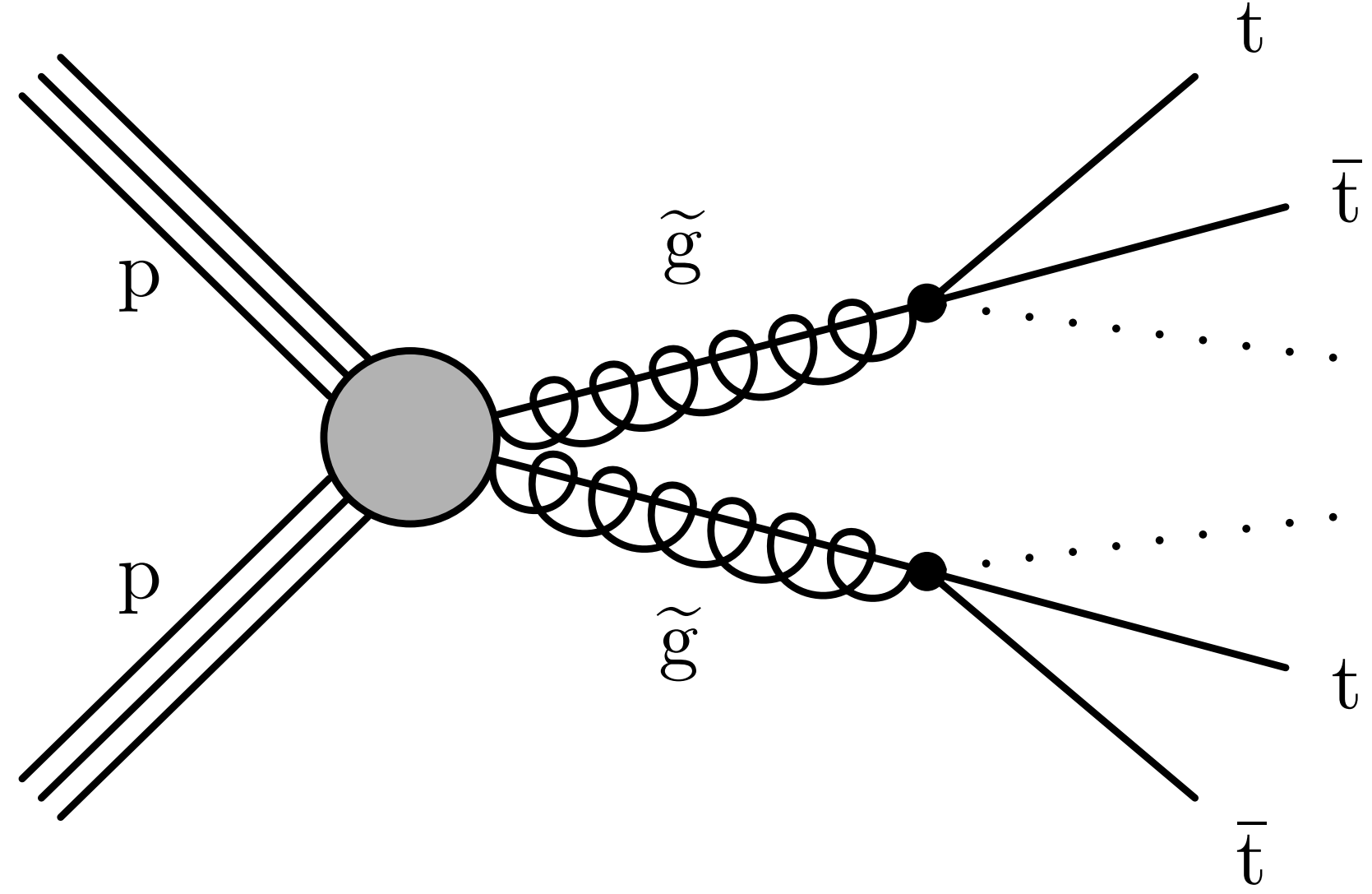
$W' \rightarrow tb$ with lepton

excess at 3.8 TeV 1% width
 local significance of 2.6 s.d.
 global significance 2.0 s.d.

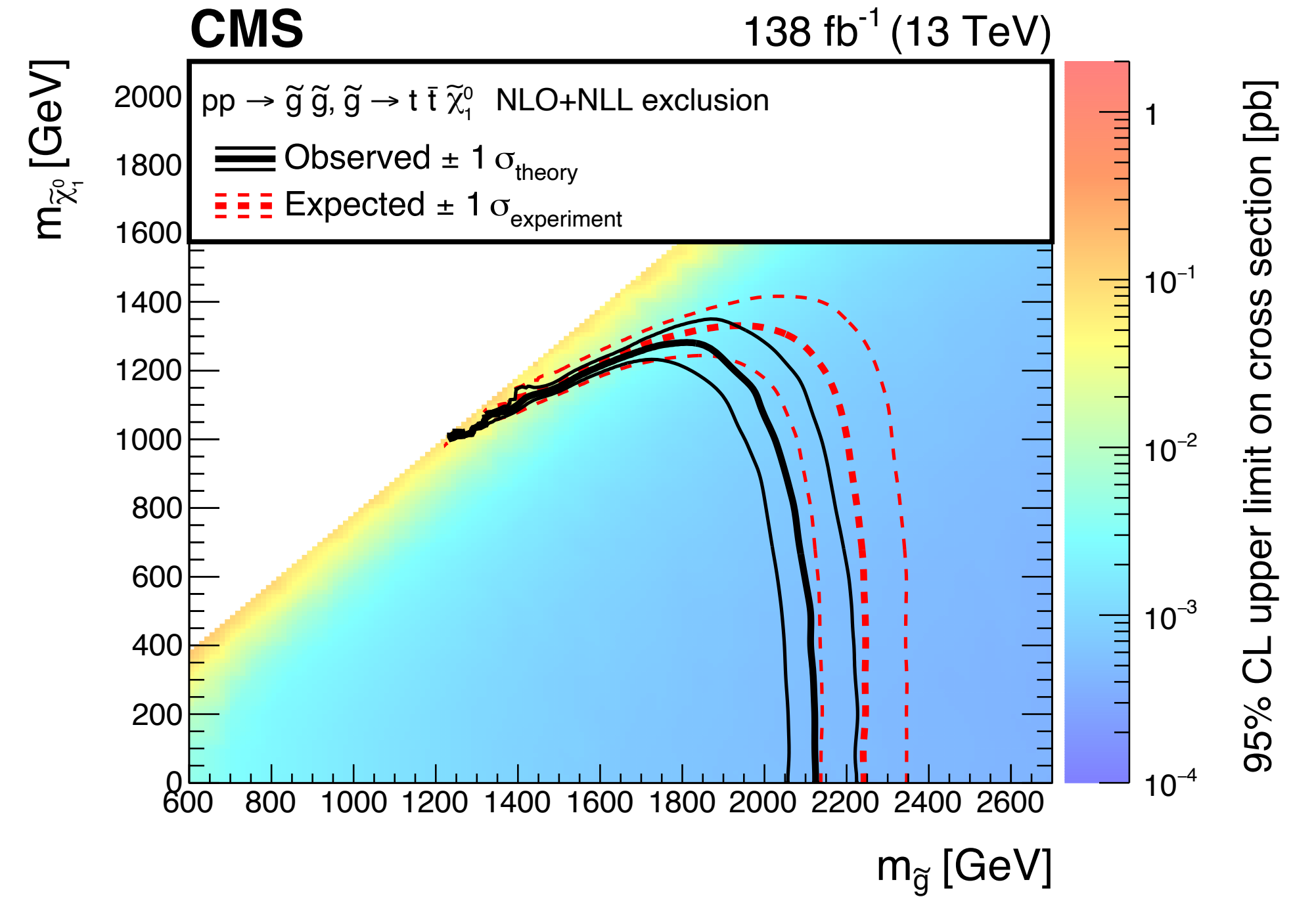


SUSY

$$\tilde{g}\tilde{g} \rightarrow t\bar{t}t\bar{t}\tilde{\chi}_1^0, \text{ 1 lepton}$$

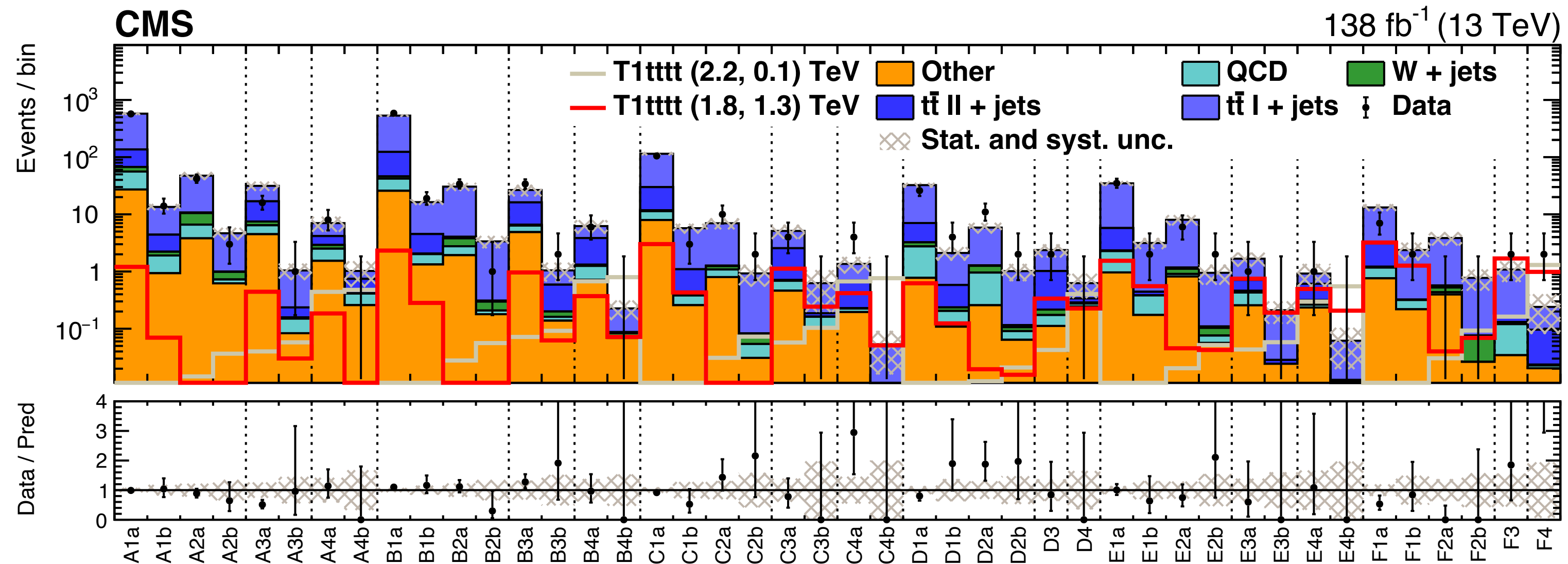


arXiv:2211.08476, accepted to JHEP



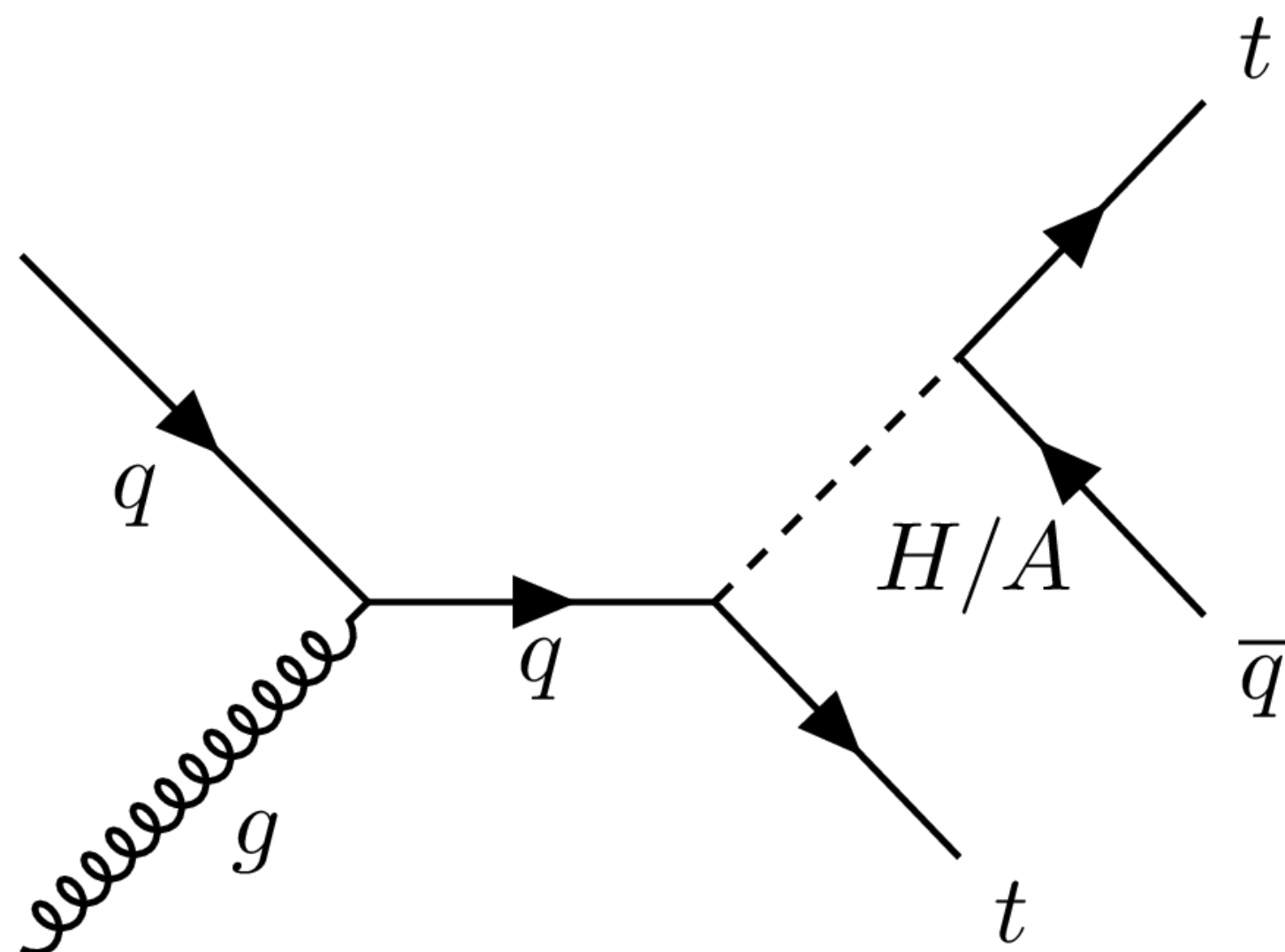
Challenging 4 tops + $p_{T,miss}$ final state

- DeepJet + resolved top tagger



Extra Higgs bosons $pp \rightarrow H/A \ t \rightarrow ttq$, 2 leptons same sign

CMS-PAS-TOP-22-010



$$\frac{\rho_{ij}}{\sqrt{2}} \bar{u}_{iL} (H + iA) u_{jR} + \text{h.c.}$$

$\rho_{tc} \rightarrow ttc$ final state $\rho_{tu} \rightarrow ttu$ final state

Signal Extraction with BDT

Input features of the BDT

$$\begin{aligned}
 & p_T(\ell_i): i=1,2; H_T, p_T^{\text{miss}} \\
 & CvsB(j_i), CvsL(j_i): i=1,2,3 \\
 & m_{\ell\ell}, m_{\ell\ell}(j_i): i=1,2,3 \\
 & \Delta R(j_n, j_m), m(j_n, j_m): 1 \leq n < m \leq 3 \\
 & \Delta R(j_n, l_m), m(j_n, l_m): n=1,2,3; m=1,2
 \end{aligned}$$

Same sign dilepton condition suppresses most of SM bkg

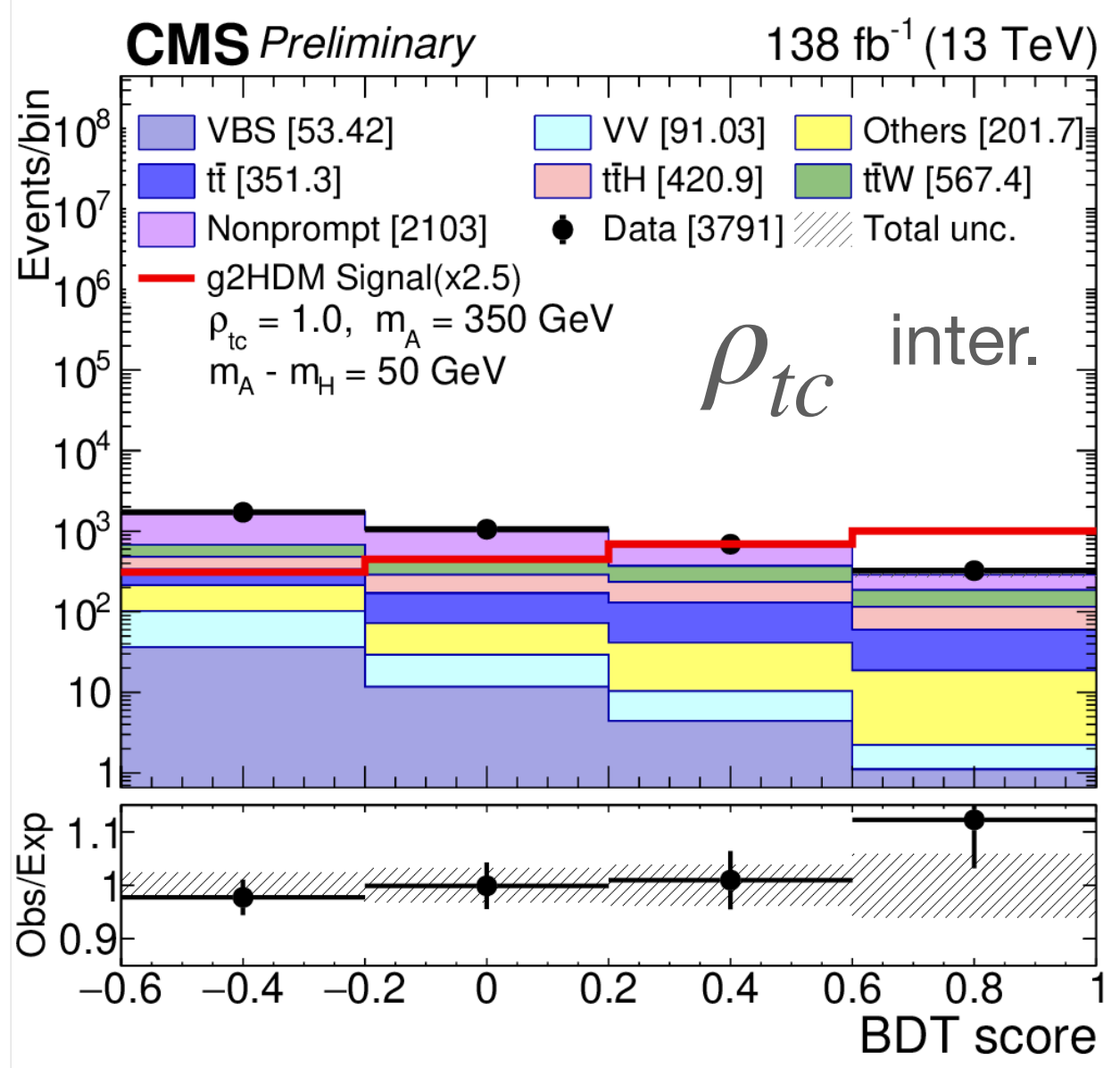
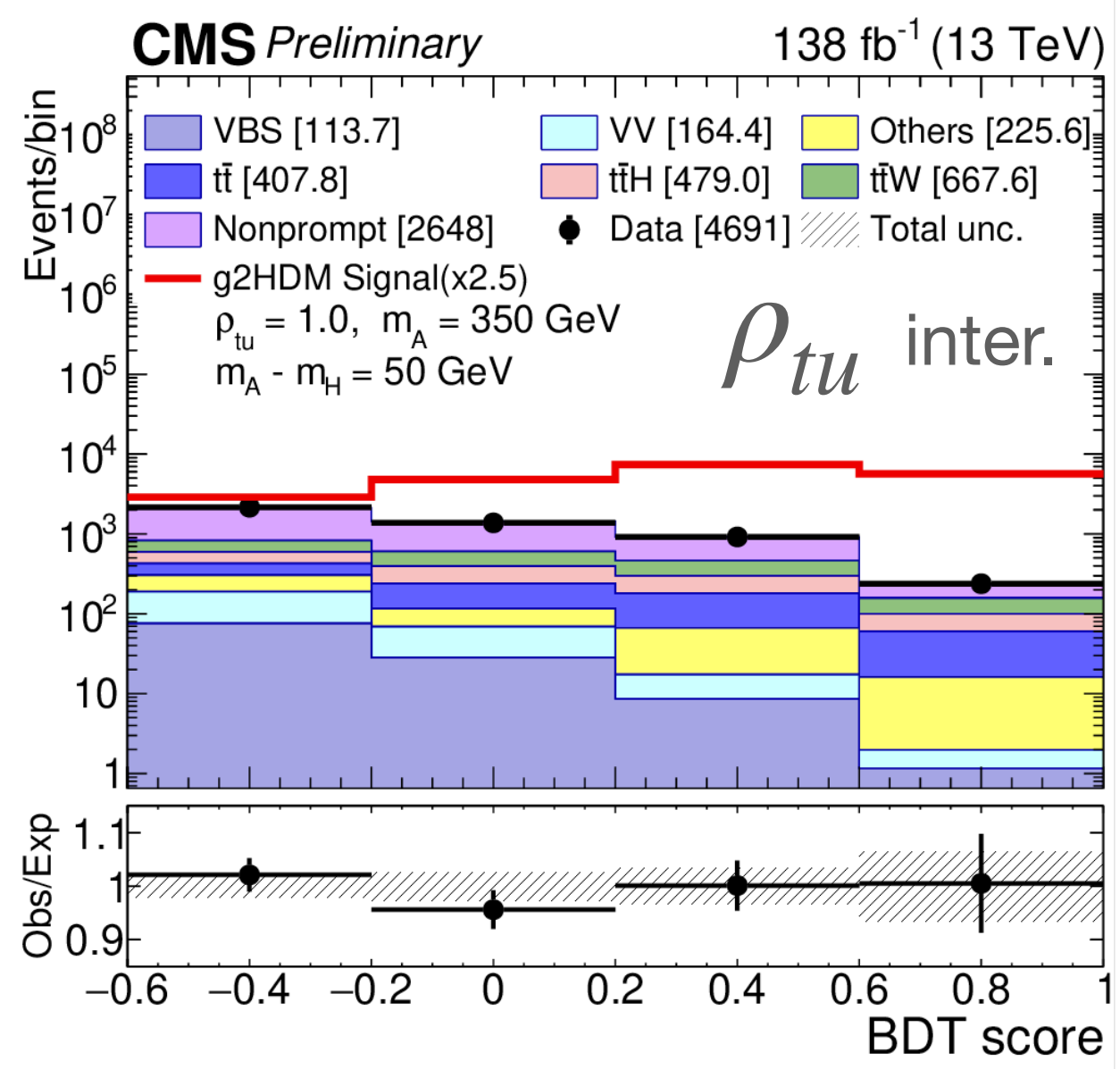
Dominant backgrounds

1. Nonprompt lepton
2. ttX process
3. Charge misID event

$m_A - m_H = 50 \text{ GeV} \rightarrow$ Interference!

$|m_A - m_H| \gg 50 \text{ GeV} \rightarrow$ no interference

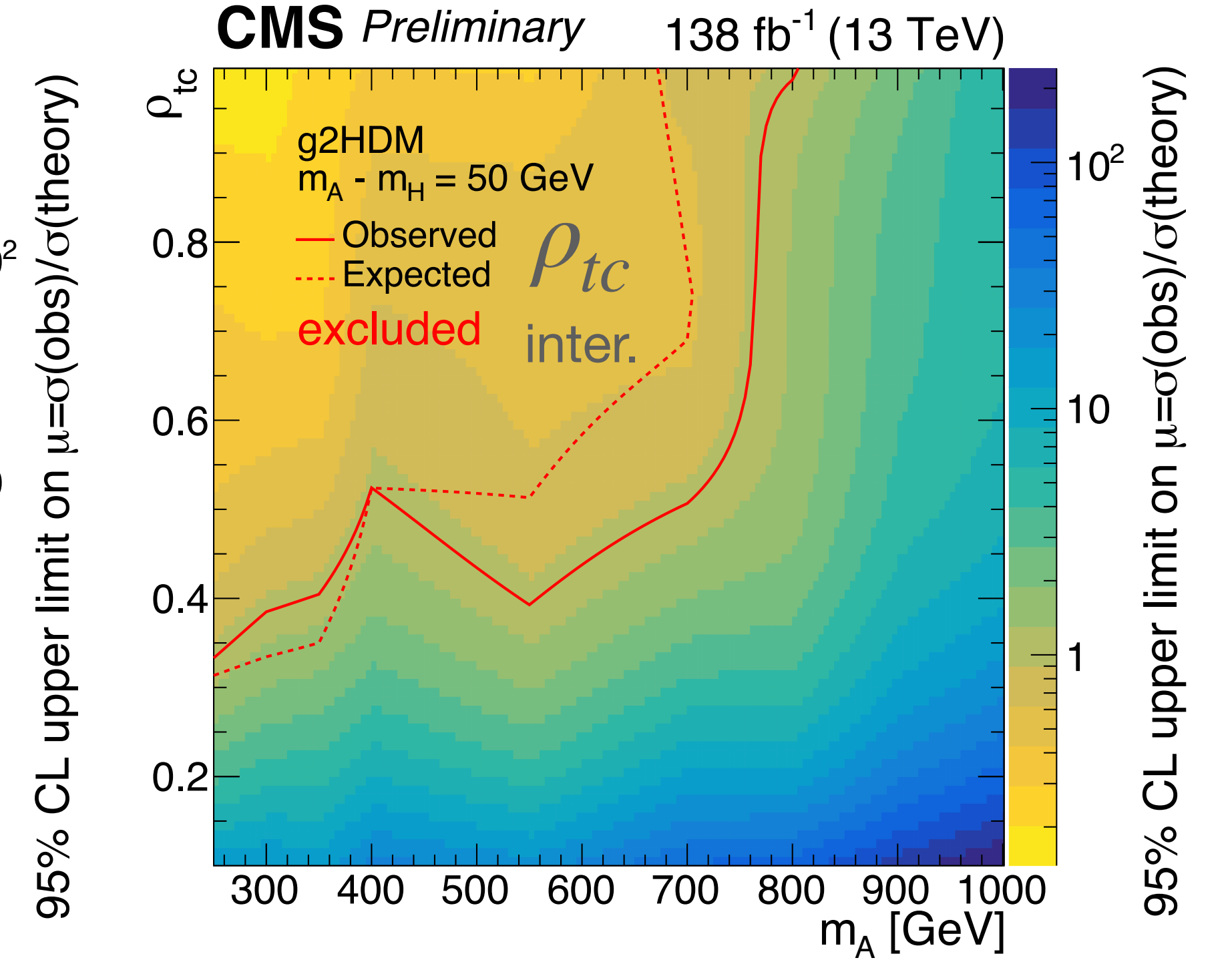
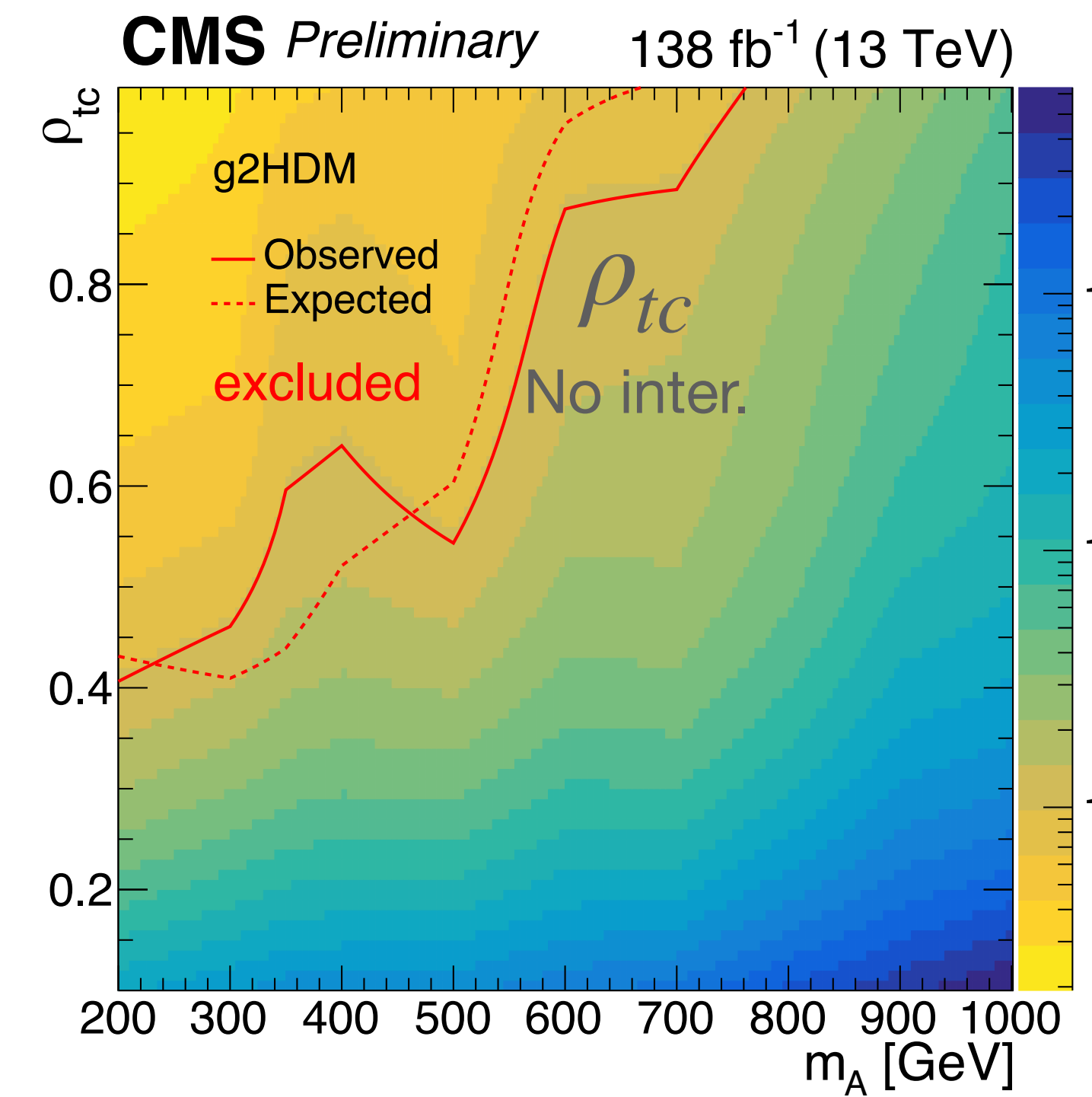
Extra Higgs bosons $pp \rightarrow H/A \rightarrow ttq, 2 \text{ leptons same sign}$ **NEW**



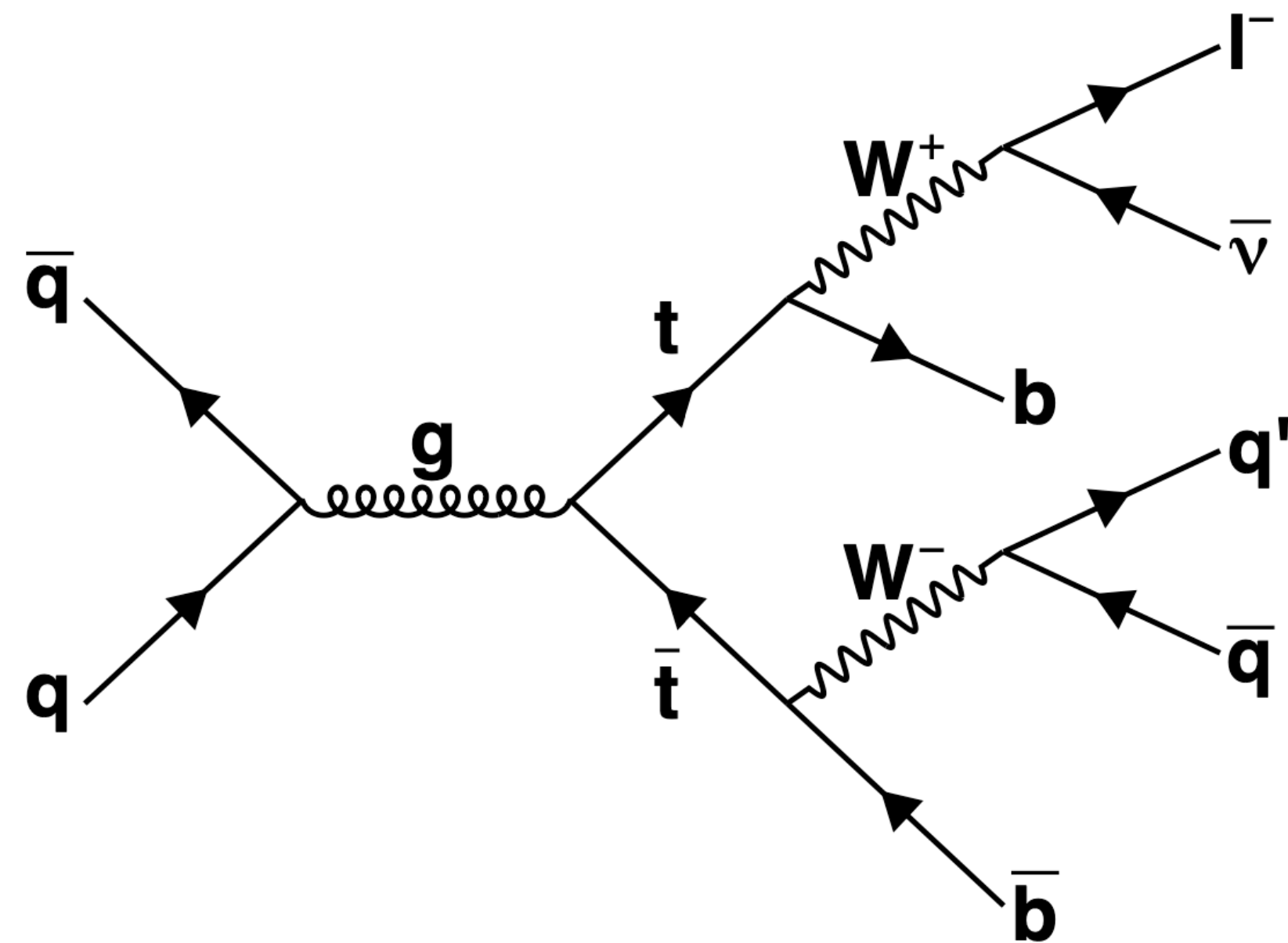
CMS-PAS-TOP-22-010

combination of $e^\pm e^\pm, \mu^\pm \mu^\pm,$ and $e^\pm \mu^\pm$ categories

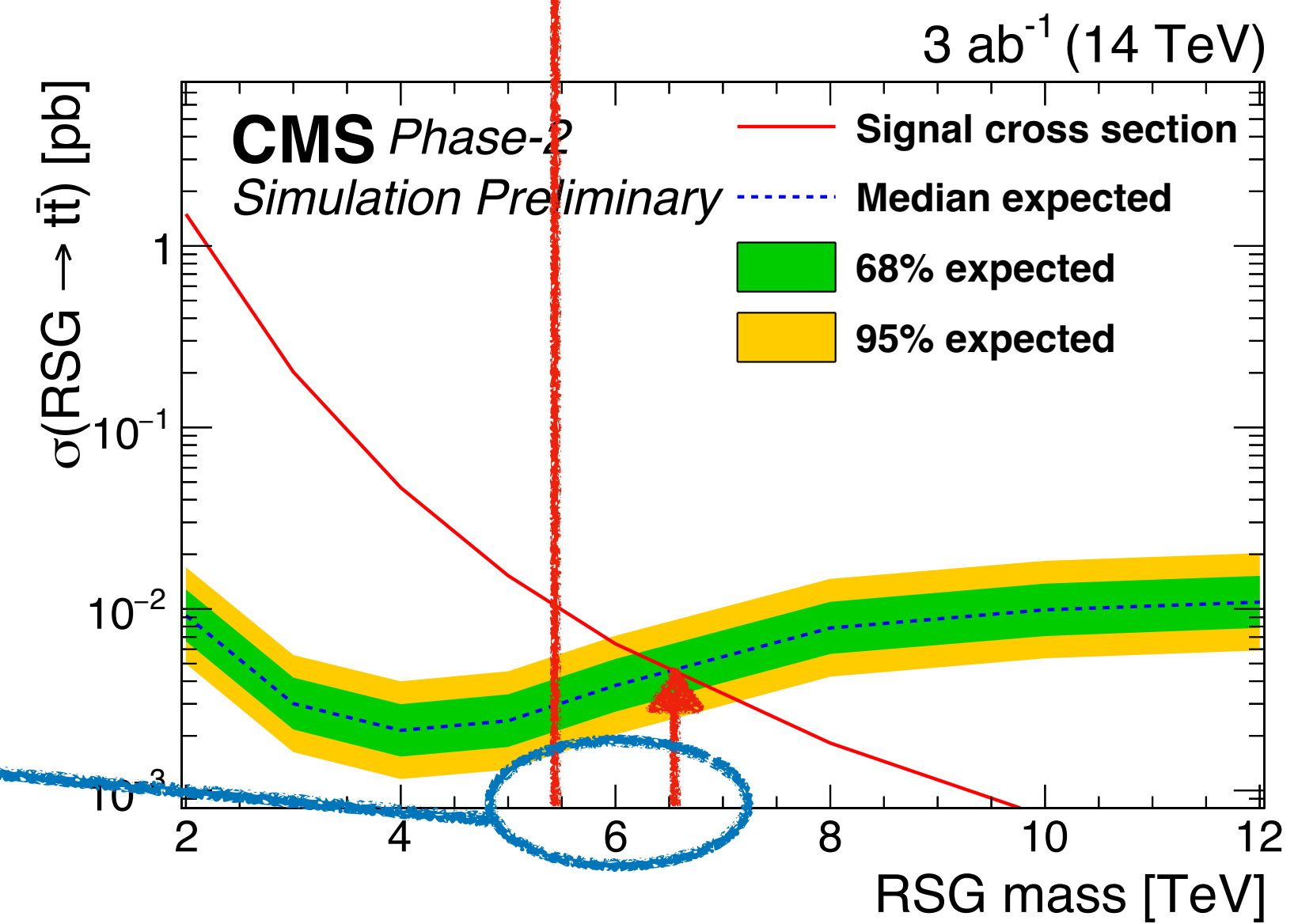
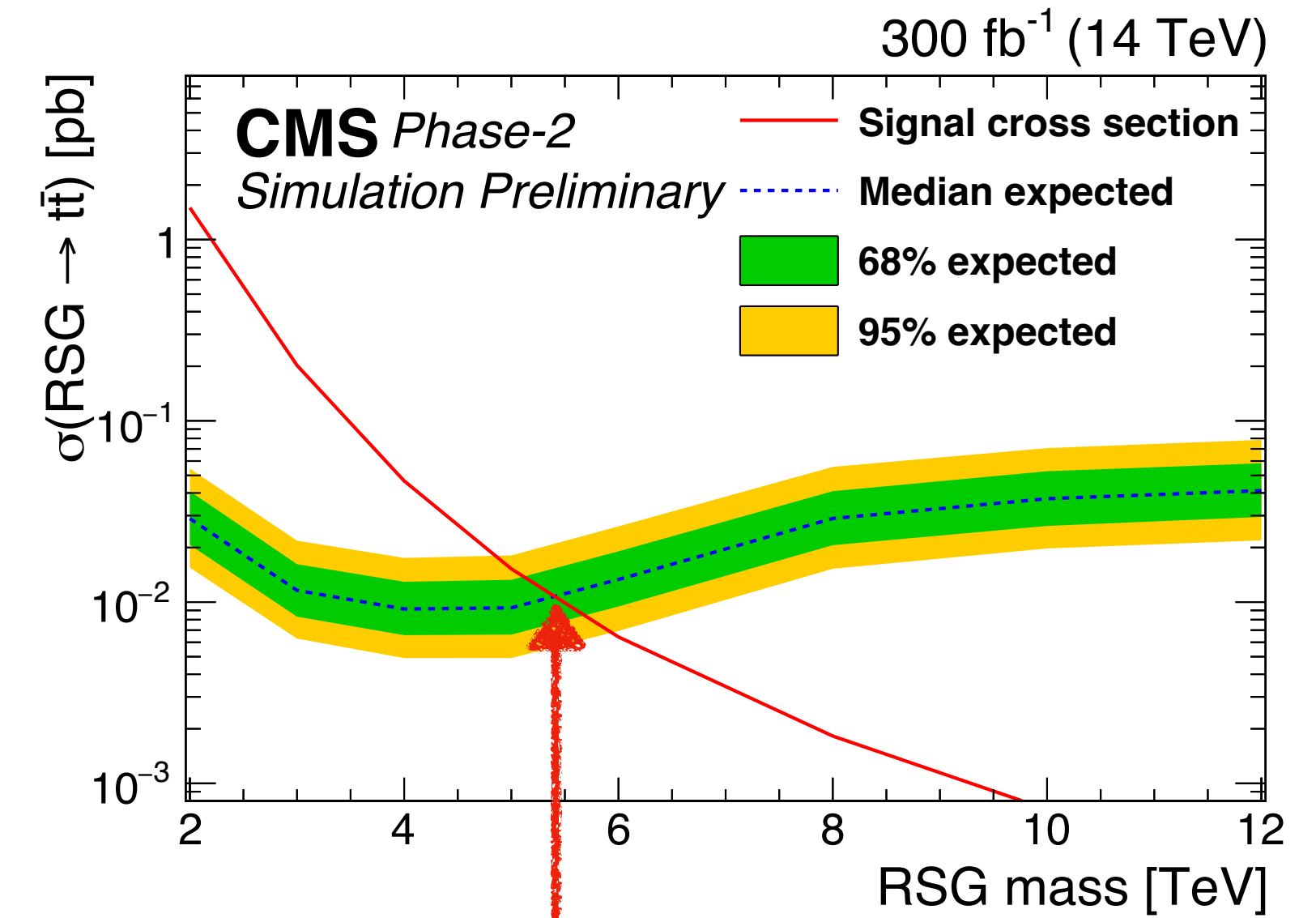
2HDM



Prospective for the future



10x increment in data



Prospective for the future

- Run 3 analyses are in progress
 - Most high mass searches COM-limited
 - No more low-hanging fruits
- Exceptional improvements in
 - Top tagging/ML
 - Background techniques
- Crucial contribution from theory community to find new ideas/channels

Backup

b^* , LQ , W' and Z'

Excited quarks

- ▶ $b^* \rightarrow tW \rightarrow bq\bar{q} q\bar{q}$ (LH+RH)
- ▶ $b^* \rightarrow tW \rightarrow bq\bar{q} q\bar{q}$ (RH)
- ▶ $b^* \rightarrow tW \rightarrow bq\bar{q} q\bar{q}$ (LH)
- ▶ $b^* \rightarrow tW \rightarrow bq\bar{q} \ell\nu$ (LH+RH)
- ▶ $b^* \rightarrow tW \rightarrow bq\bar{q} \ell\nu$ (RH)
- ▶ $b^* \rightarrow tW \rightarrow bq\bar{q} \ell\nu$ (LH)
- ▶ $b^* \rightarrow tW \rightarrow b\ell\nu q\bar{q}$ (LH+RH)
- ▶ $b^* \rightarrow tW \rightarrow b\ell\nu q\bar{q}$ (RH)
- ▶ $b^* \rightarrow tW \rightarrow b\ell\nu q\bar{q}$ (LH)

LQ

- ▷ $LQ\bar{L}\bar{Q} \rightarrow t\mu t\mu$
- ▷ $LQ\bar{L}\bar{Q} \rightarrow t\tau t\tau$
- ▷ $W' \rightarrow tb, \ell\ell$ (RH) $M_{V_i} > M_{W'}$

$W' \rightarrow tb$

- ▶ $W' \rightarrow tb, \ell\ell$, (LH)
- ▶ $W' \rightarrow tb, \ell\ell$, (RH)

$Z' \rightarrow tt$

- ▷ $Z' \rightarrow t\bar{t}$ ($\Gamma/M_{Z'}=30\%$)
- ▷ $Z' \rightarrow t\bar{t}$ ($\Gamma/M_{Z'}=10\%$)
- ▷ $Z' \rightarrow t\bar{t}$ ($\Gamma/M_{Z'}=1\%$)

Other

- ▷ $Z' \rightarrow tT \rightarrow tZt/tHt \rightarrow \ell\nu + \text{jets}$ ($M_T = 1.5$ TeV)
- ▶ $W' \rightarrow Tb/Bt$ ($M_{VLQ} = 2/3M_{W'}$)



VLQs

Very heavy fermions

