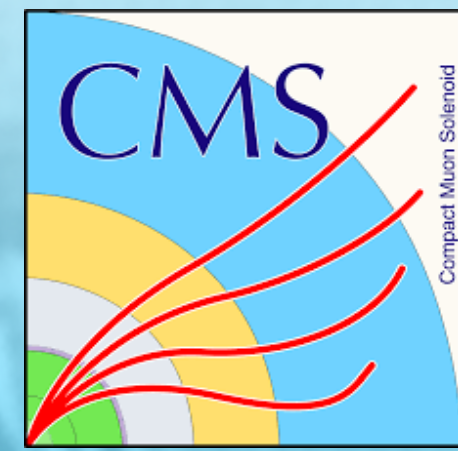




Universität  
Zürich<sup>UZH</sup>



**Raffaella Tramontano on behalf of the CMS Collaboration**  
**LHCDays2024 - Hvar Croatia**  
**05-10-2024**

# **Beyond the Standard Model Searches with the CMS experiment**

# BSM @ CMS overview in time

Run2

Run3

2024: The legacy reviews

Latest news

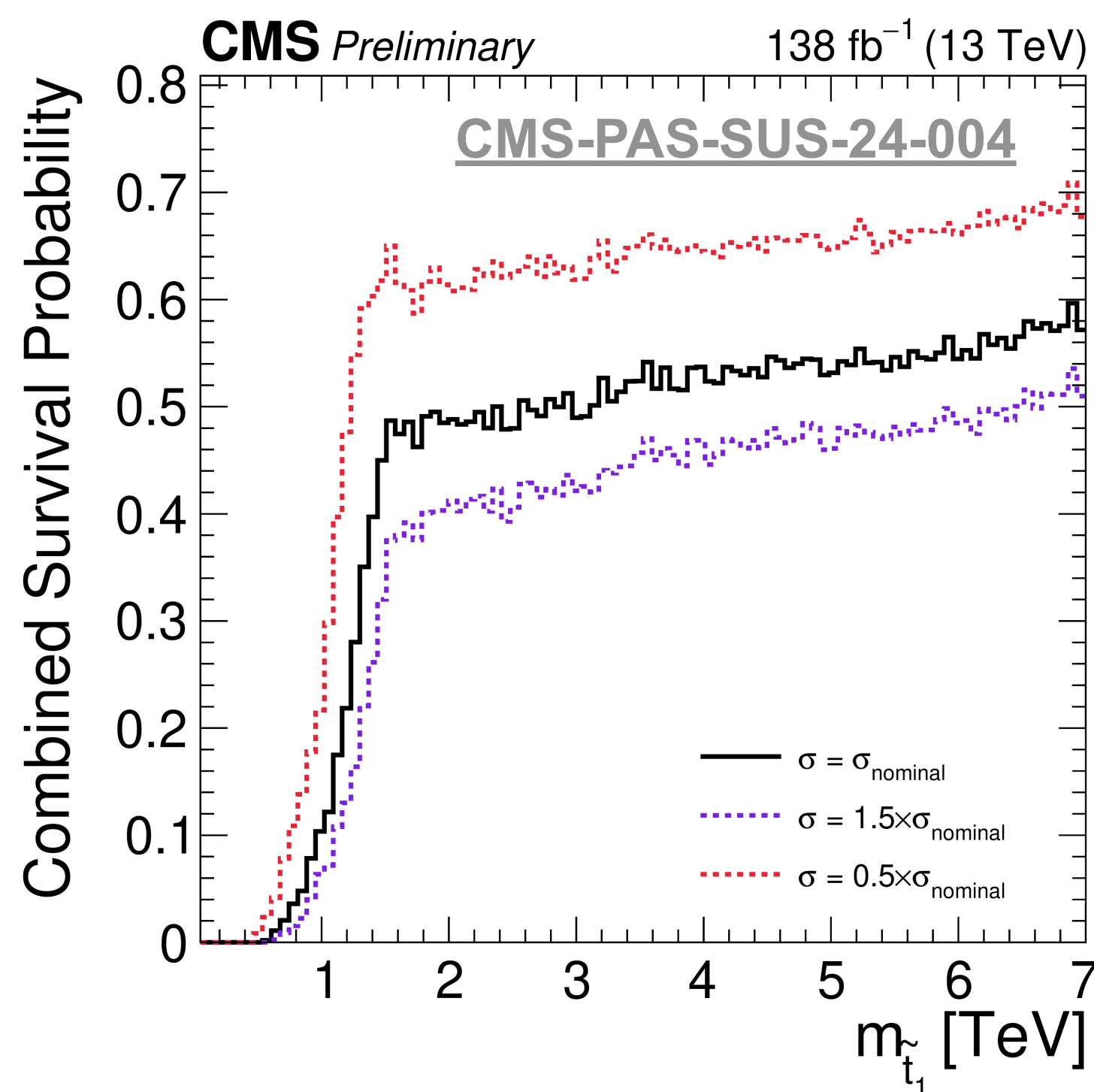
Sneak peaks...

[Physics of Dark Sectors in CMS](#)

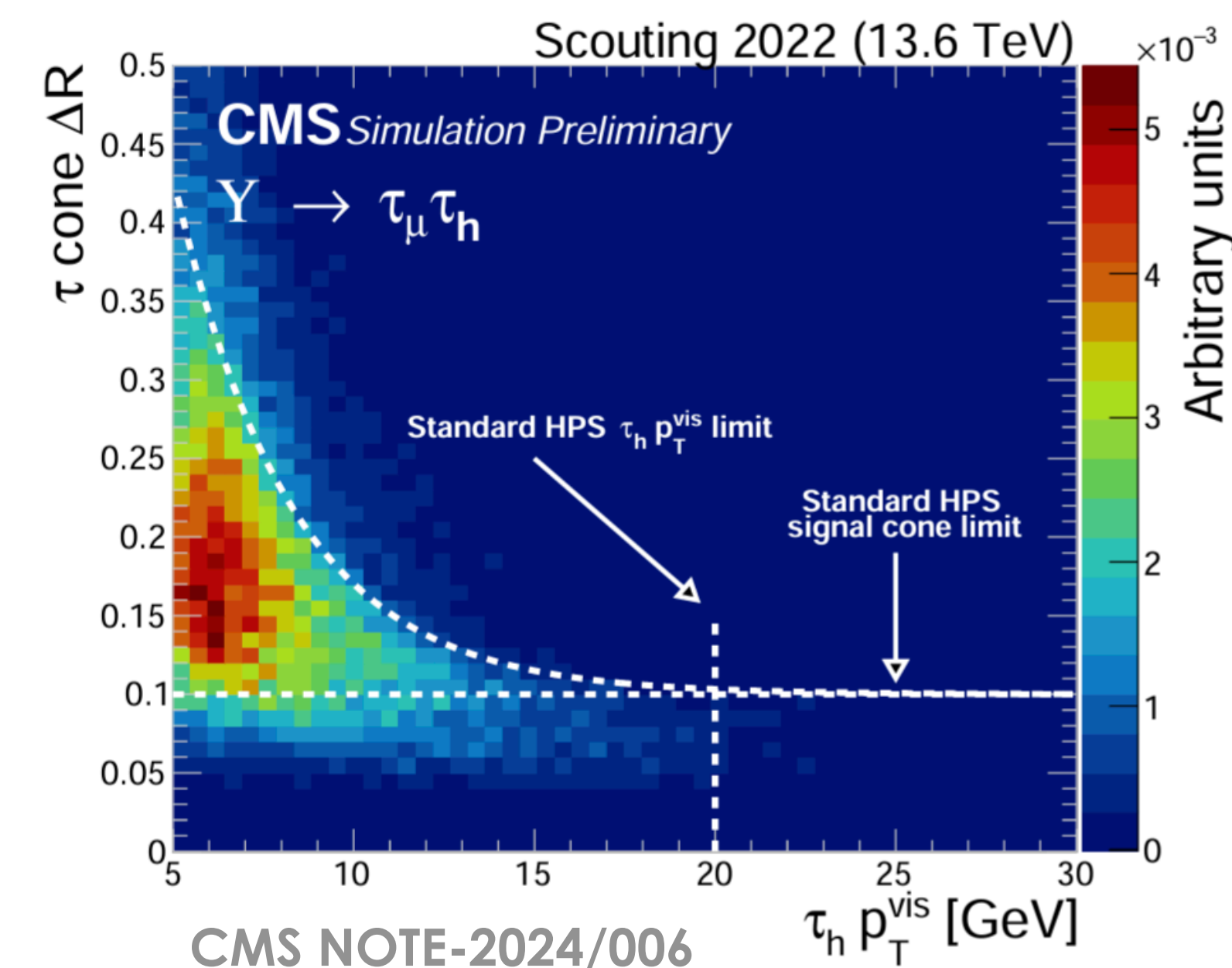
[Review of searches for vector-like quarks, vector-like leptons, and heavy neutral leptons in proton-proton collisions at 13 TeV at the CMS experiment](#)

[Enriching the physics program of the CMS experiment via data Scouting and data Parking](#)

A selection of  
The latest CMS BSM results



What's cooking  
in Run3?



# Beyond the Standard @ CMS



## Model(s)

- Extended Higgs (in [Alexandre's Talk](#))
- SUSY (in Tomek's Talk)
- Composite/bounded quark states
- ...

## Signatures

- Anomalous detector signatures
- Long Lived Signatures

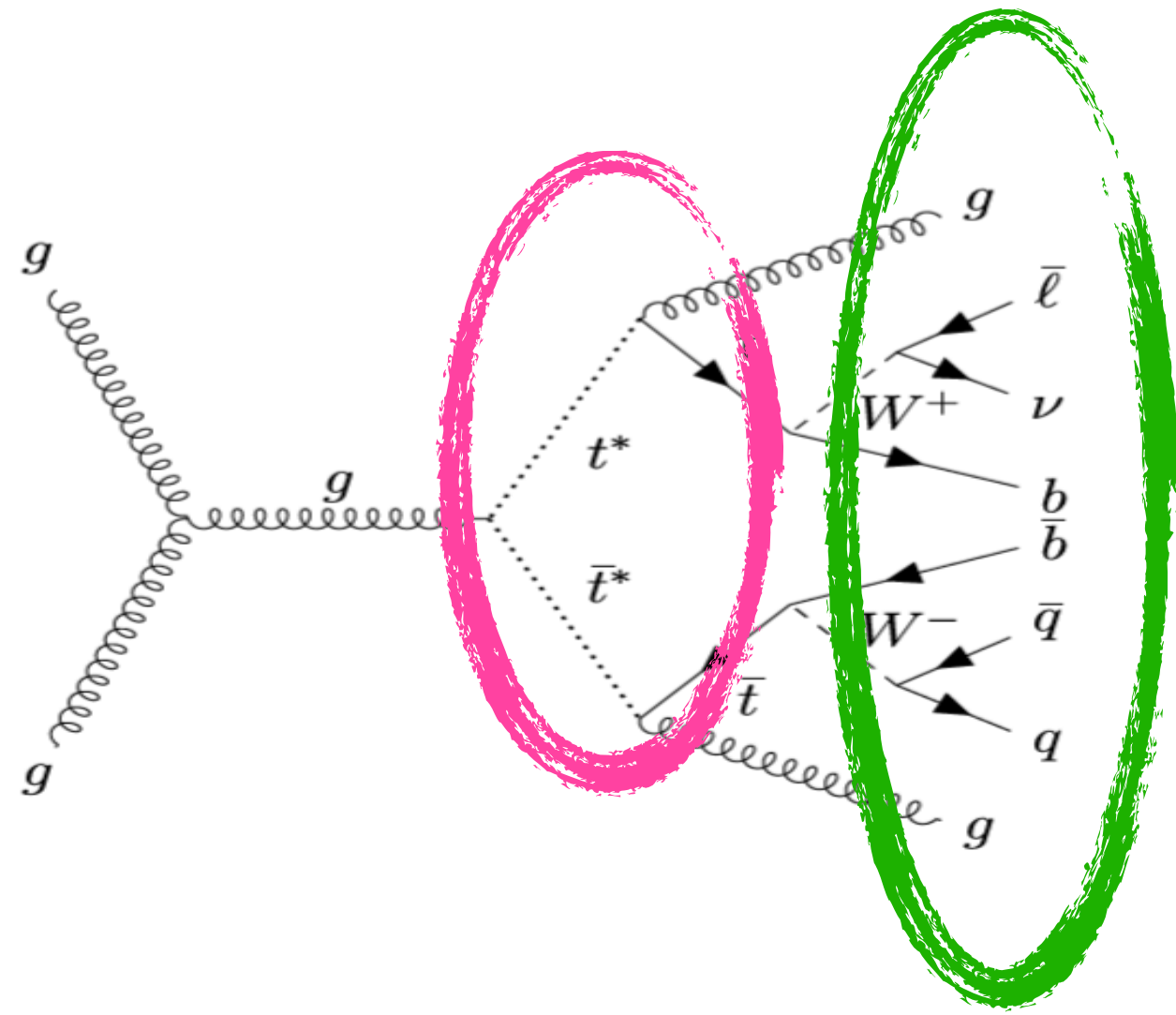
## Tools

- Deep Multivariate information
- Novel trigger strategies
- Novel data-taking strategies

## Corners

- Granular phase spaces
- Going left
- The multi-TeV range

# Infinitesimal compositeness - excited quarks



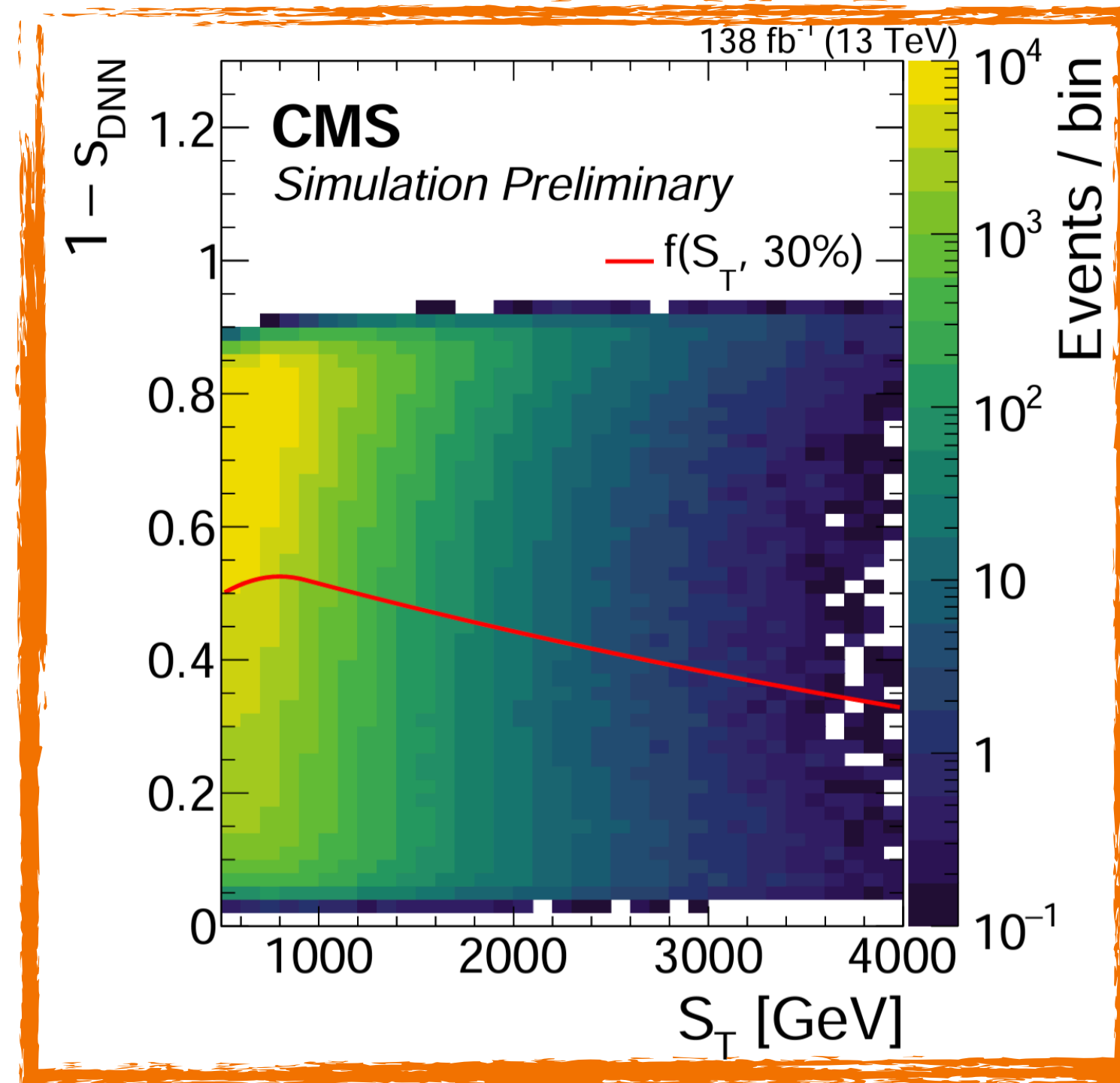
Excited quark states imply substructure

Upcycled Run2 analysis:

- 35.6 fb<sup>-1</sup> to 138 fb<sup>-1</sup>
- **Looser selection on leptons**

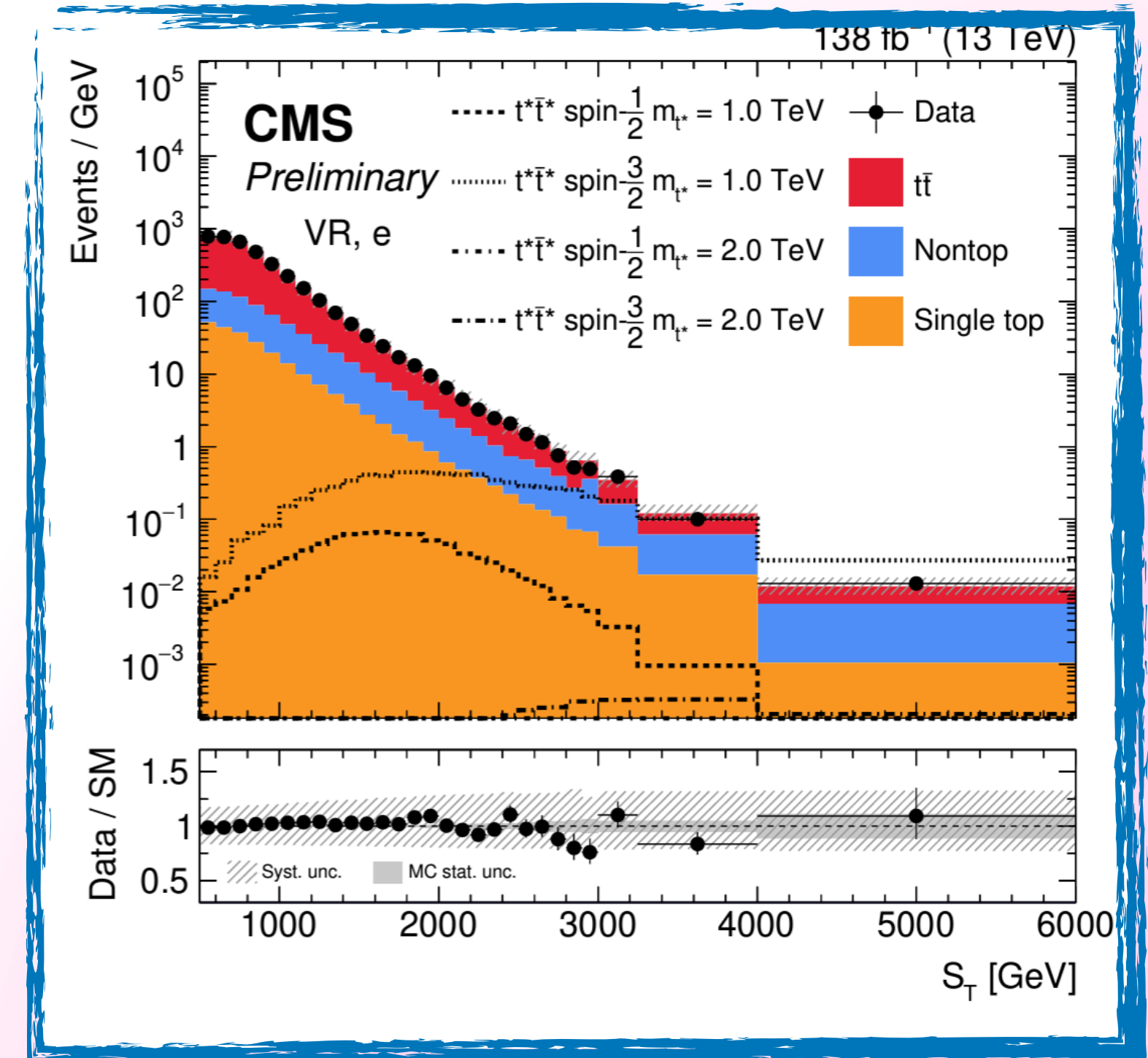
## Selection

DNN with two-tier decorrelation from kinematic variables



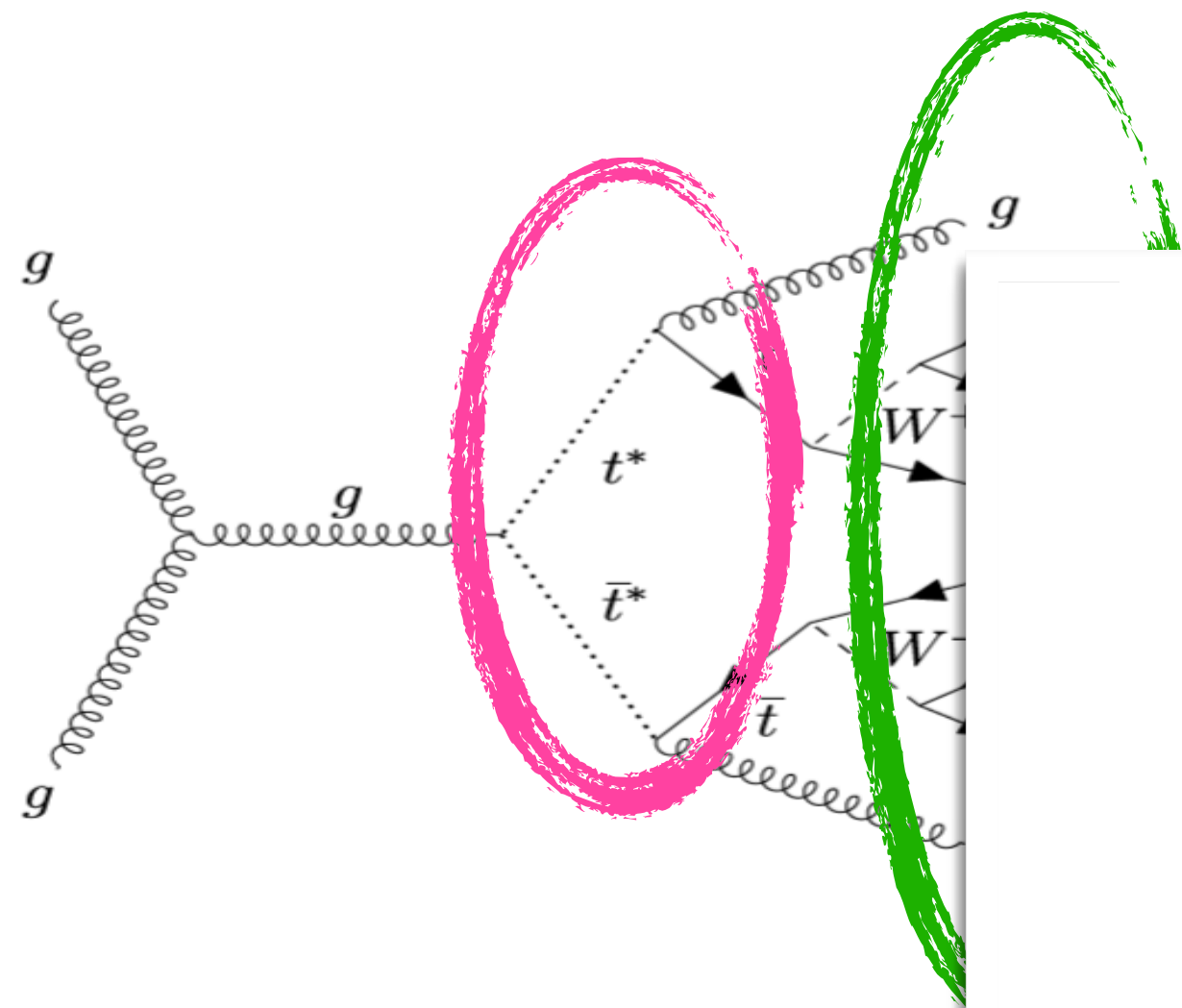
Statistical analysis:  
From t\* system to

$$S_T = p_T^{\ell} + p_T^{\text{miss}} + \sum_i p_{T,i}^{\text{jet}},$$



Signal has higher  $S_T$

# Infinitesimal compositeness - excited quarks

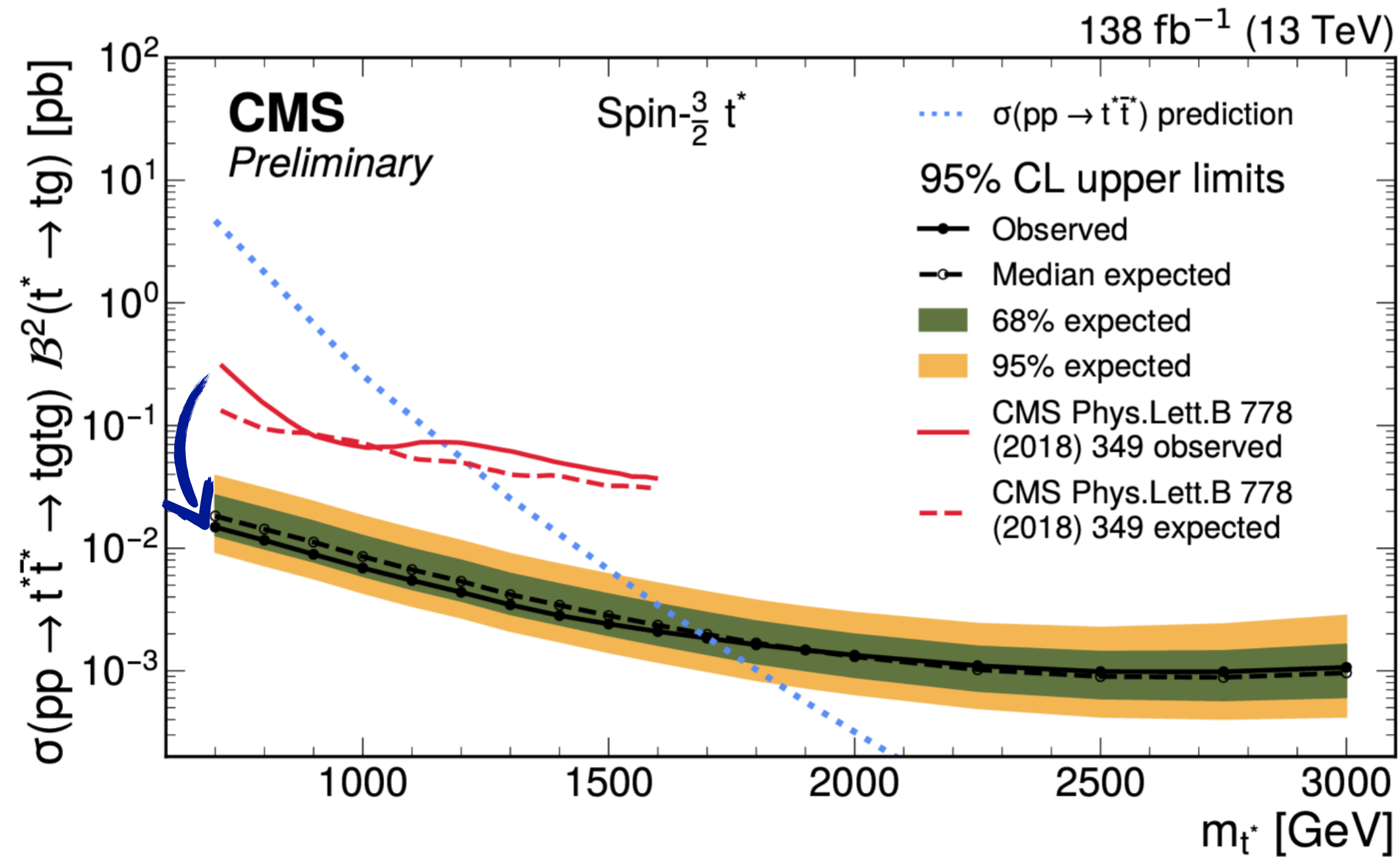


Excited quark states imply substructure

Upcycled Run2 analy

- 35.6 fb<sup>-1</sup> to 138 fb<sup>-1</sup>
- Looser selection on

Selection



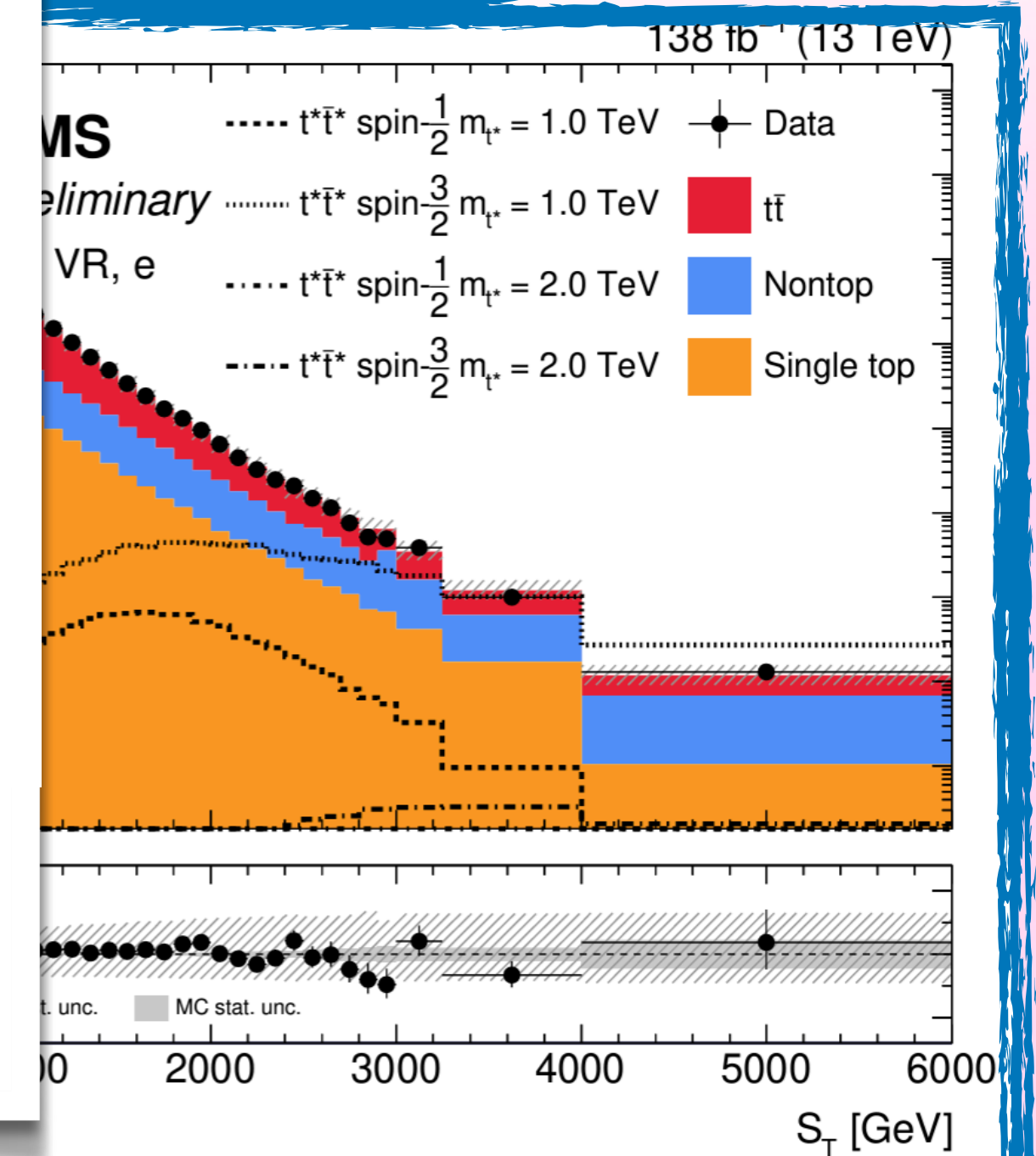
Doubled up mass range

Largely improved sensitivity

$S_T$  [GeV]

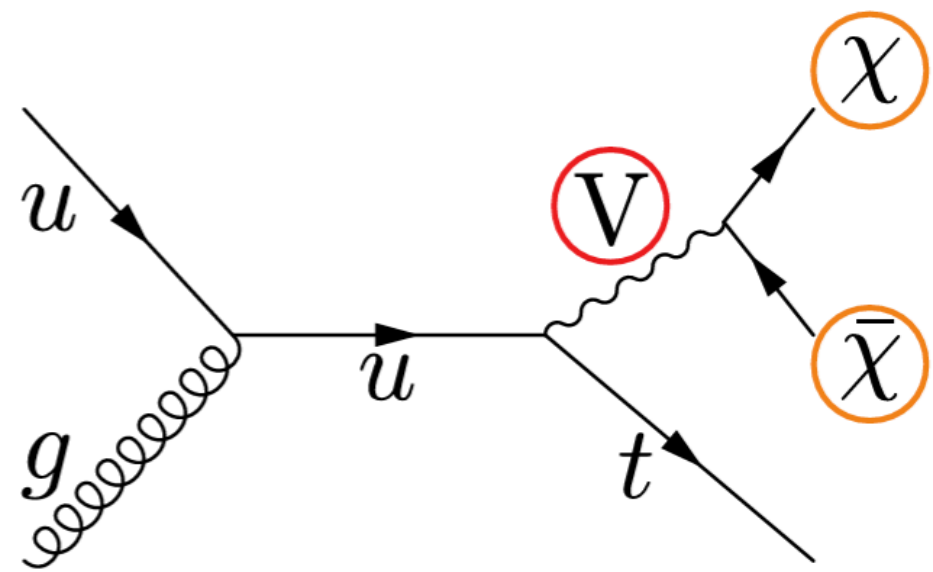
Statistical analysis:  
From  $t^*$  system to

$$= p_T^{\ell} + p_T^{\text{miss}} + \sum_i p_{T,i}^{\text{jet}},$$



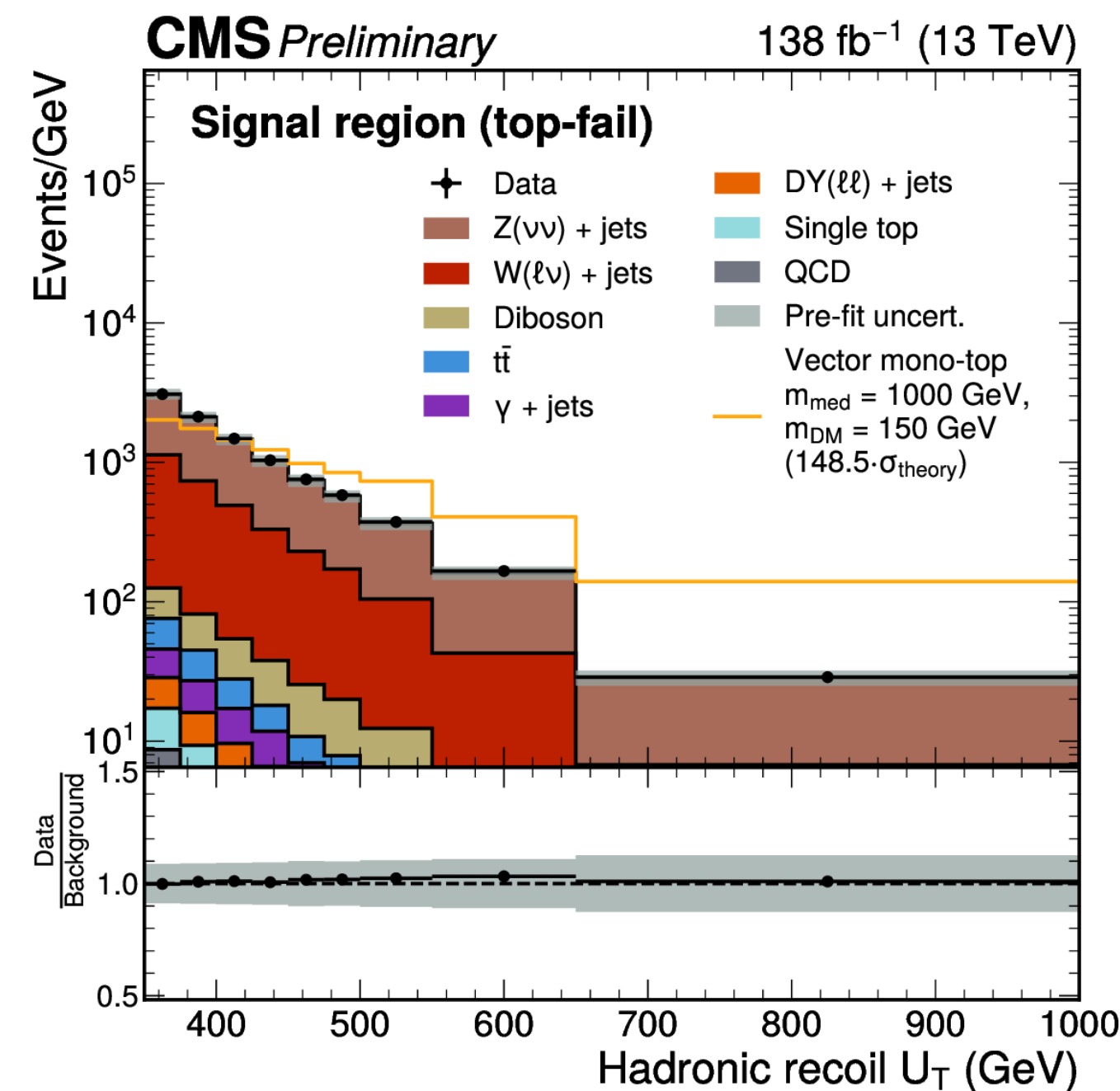
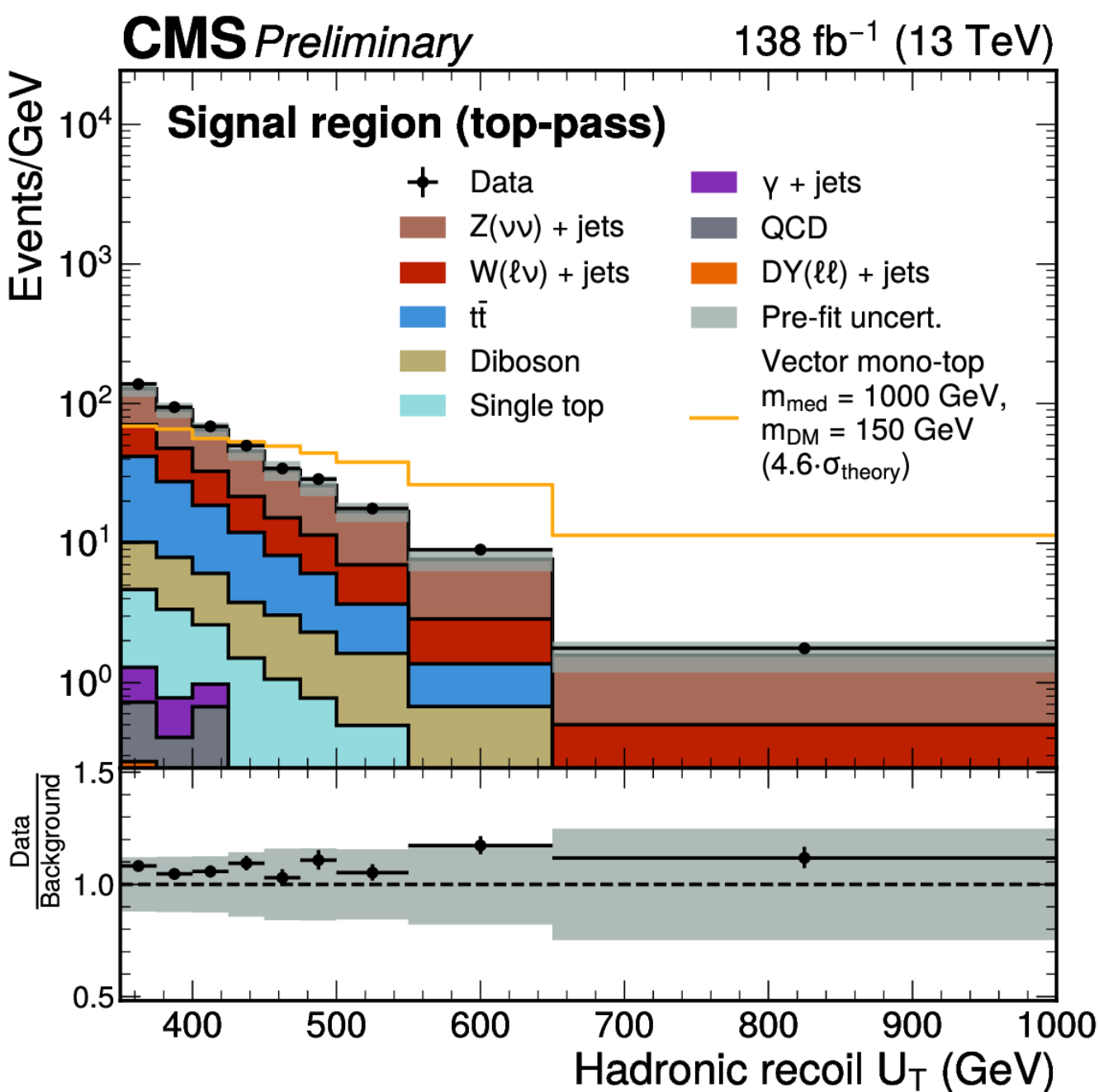
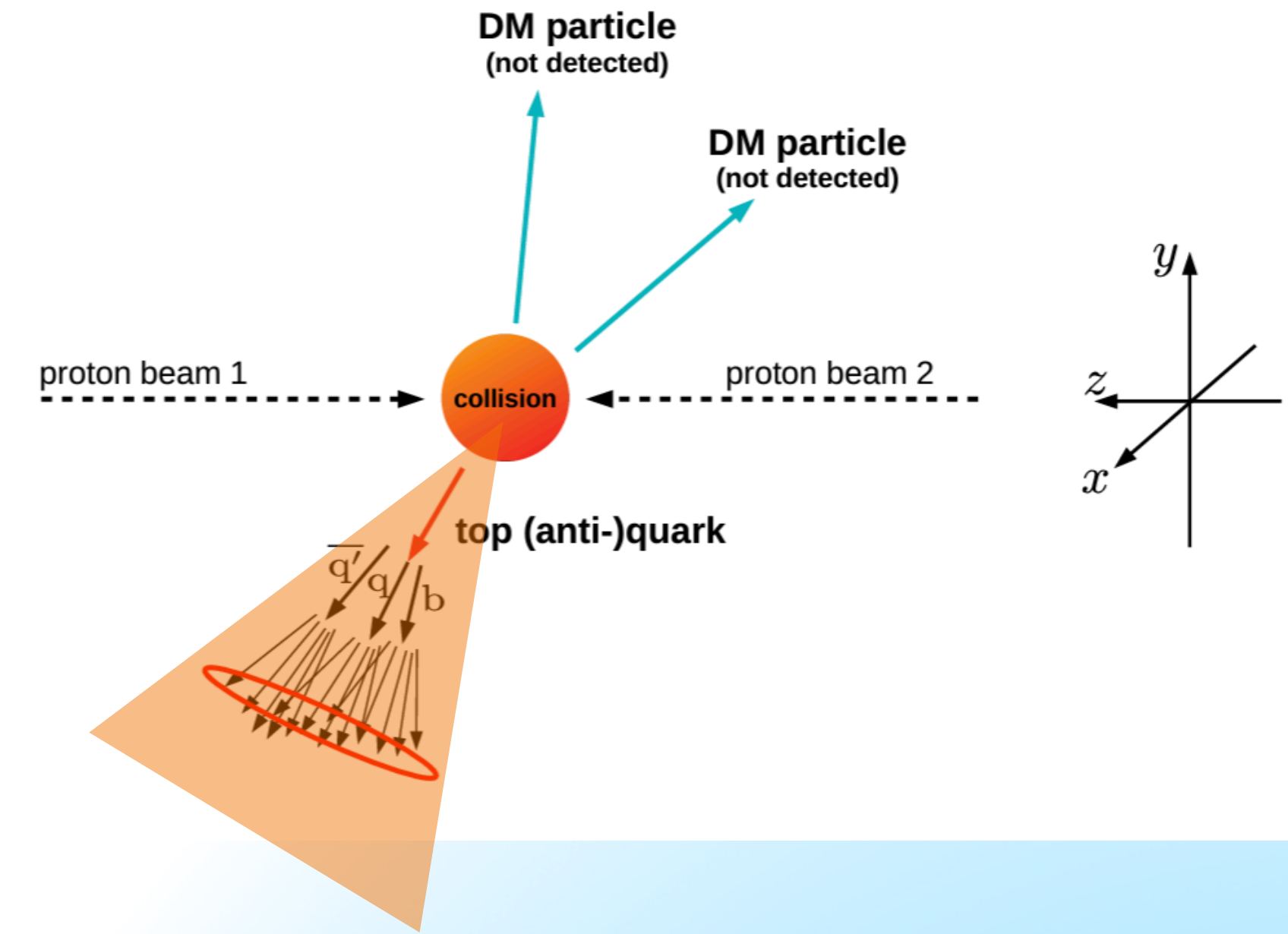
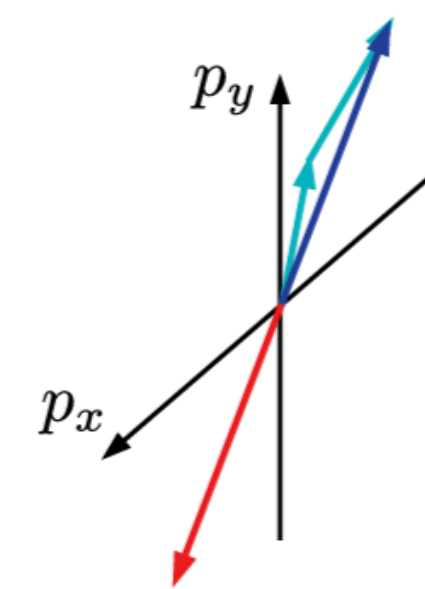
Signal has higher  $S_T$

# The wide and boosted - mono-top models



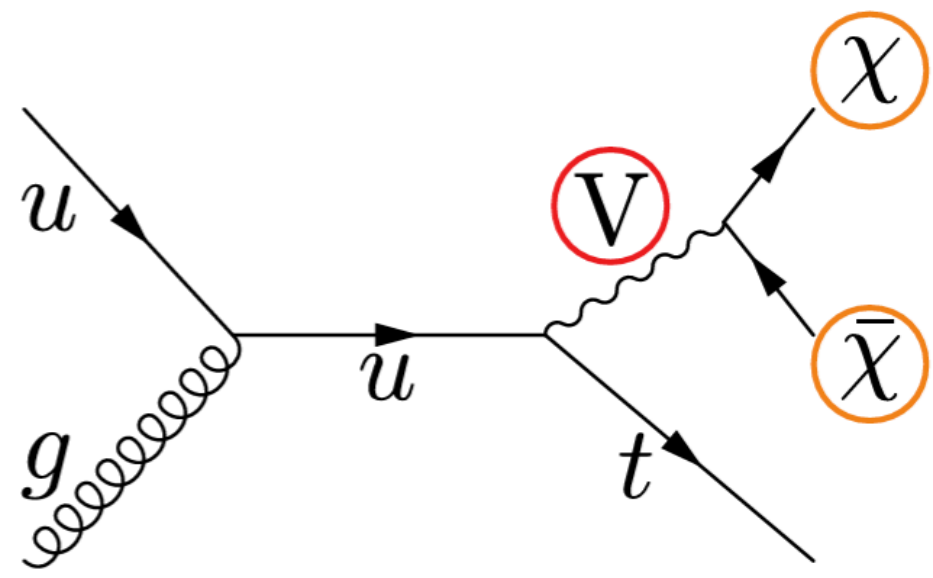
- Top quark recoils vs invisible

$$\vec{E}_T = - \sum_i \vec{p}_{T,i}$$



- High energy hadronization:
- **AK15 Jet final state**
- ParticleNet Graph NN to identify top hadronic over QCD bkg

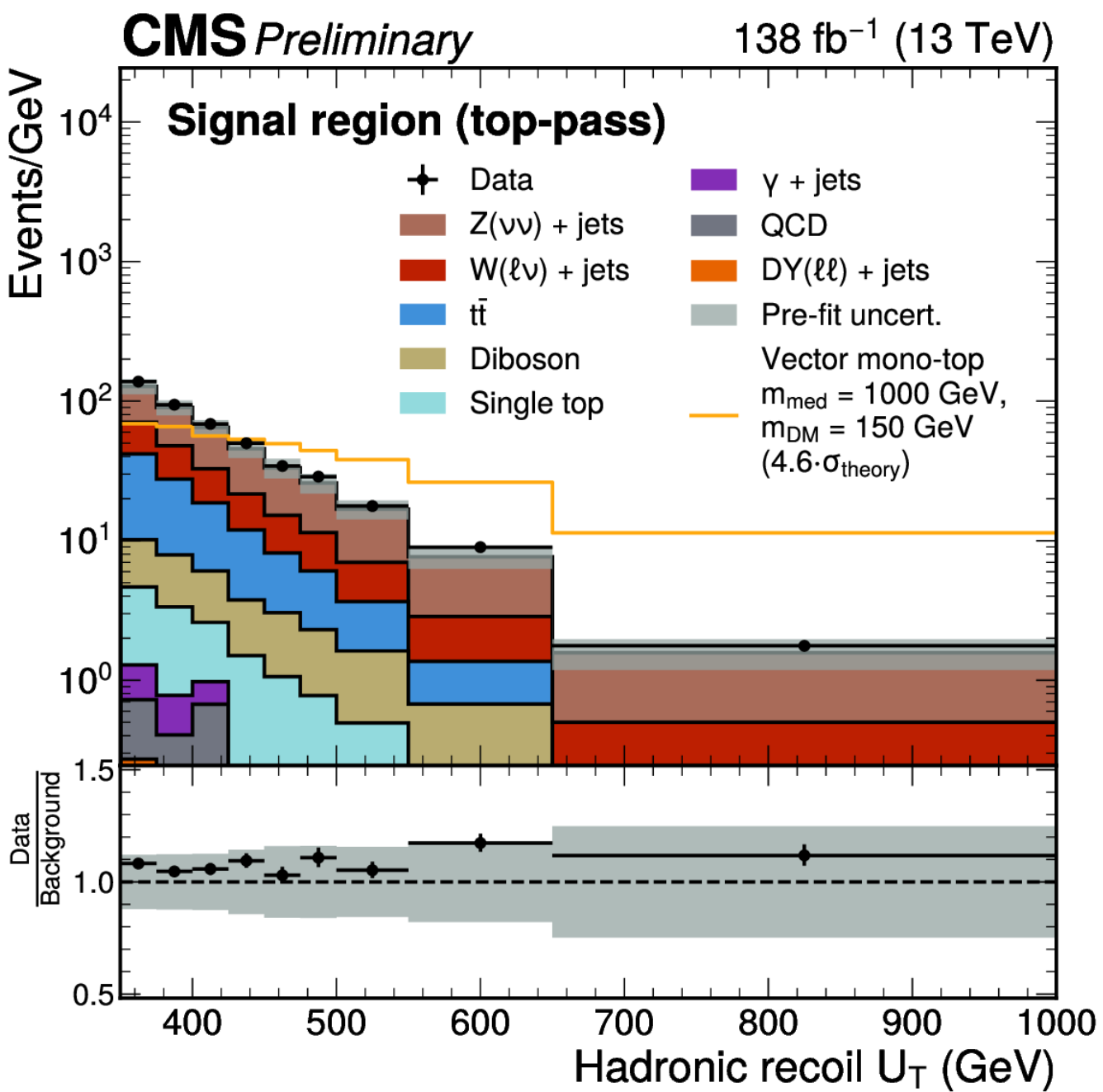
# The wide and boosted - mono-top models



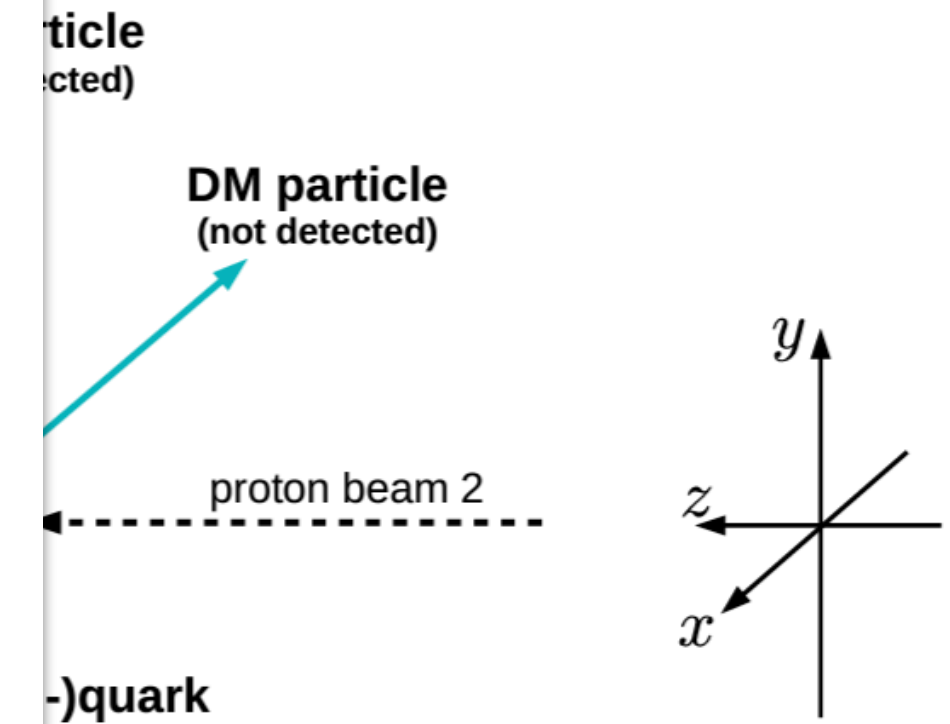
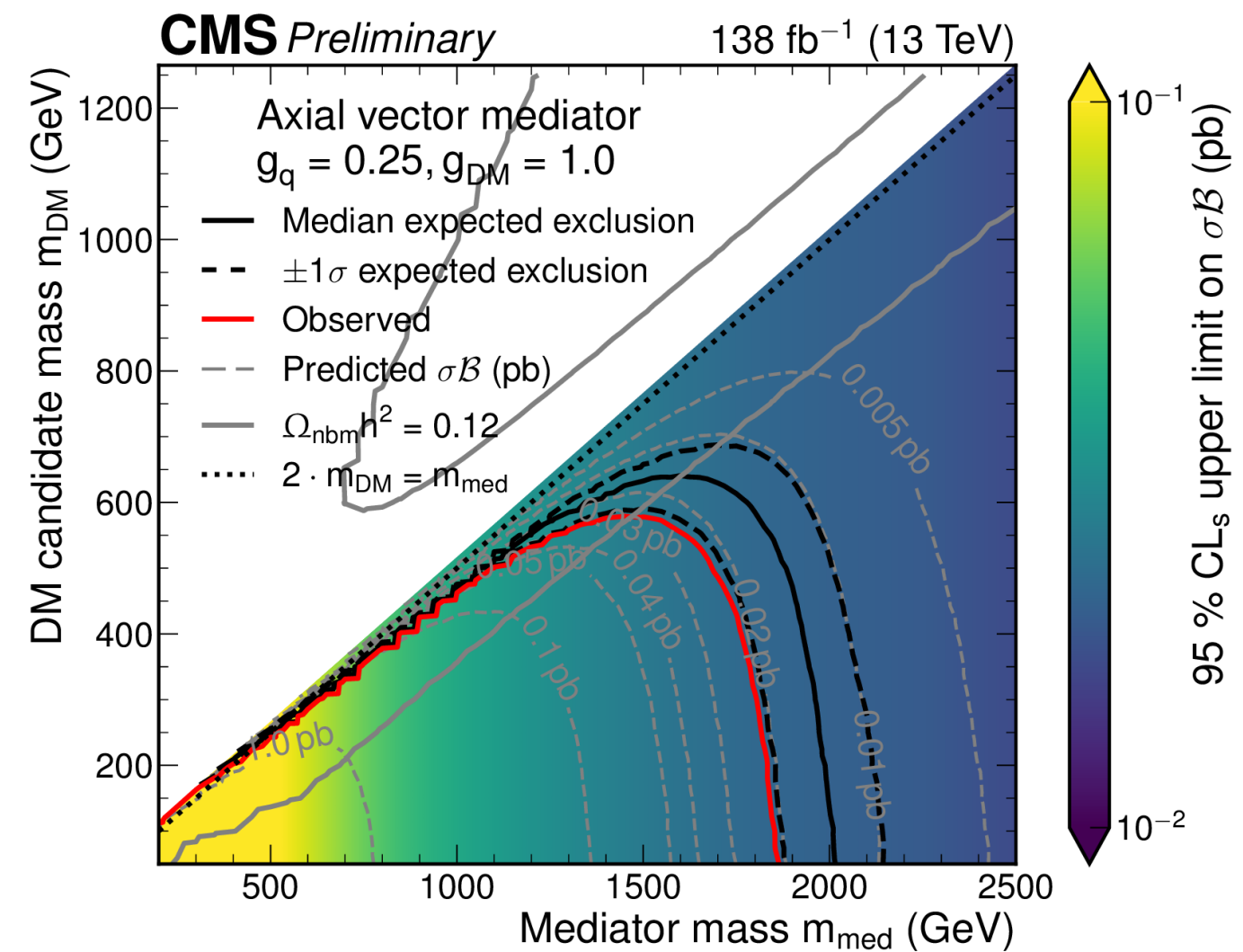
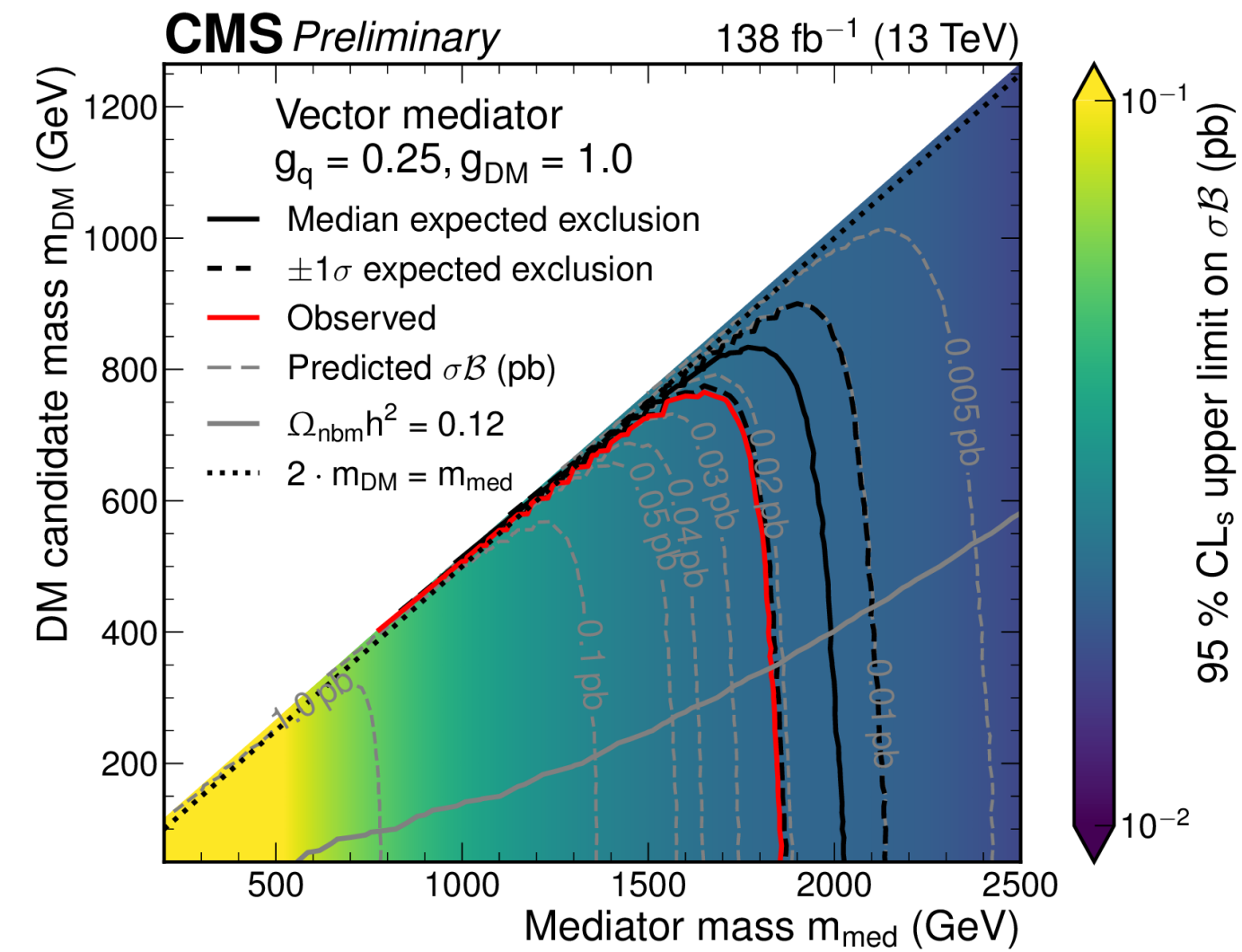
• Top

Exclusions depend on  $V$  and  $\chi$  masses

Compared to DM relic density measurements



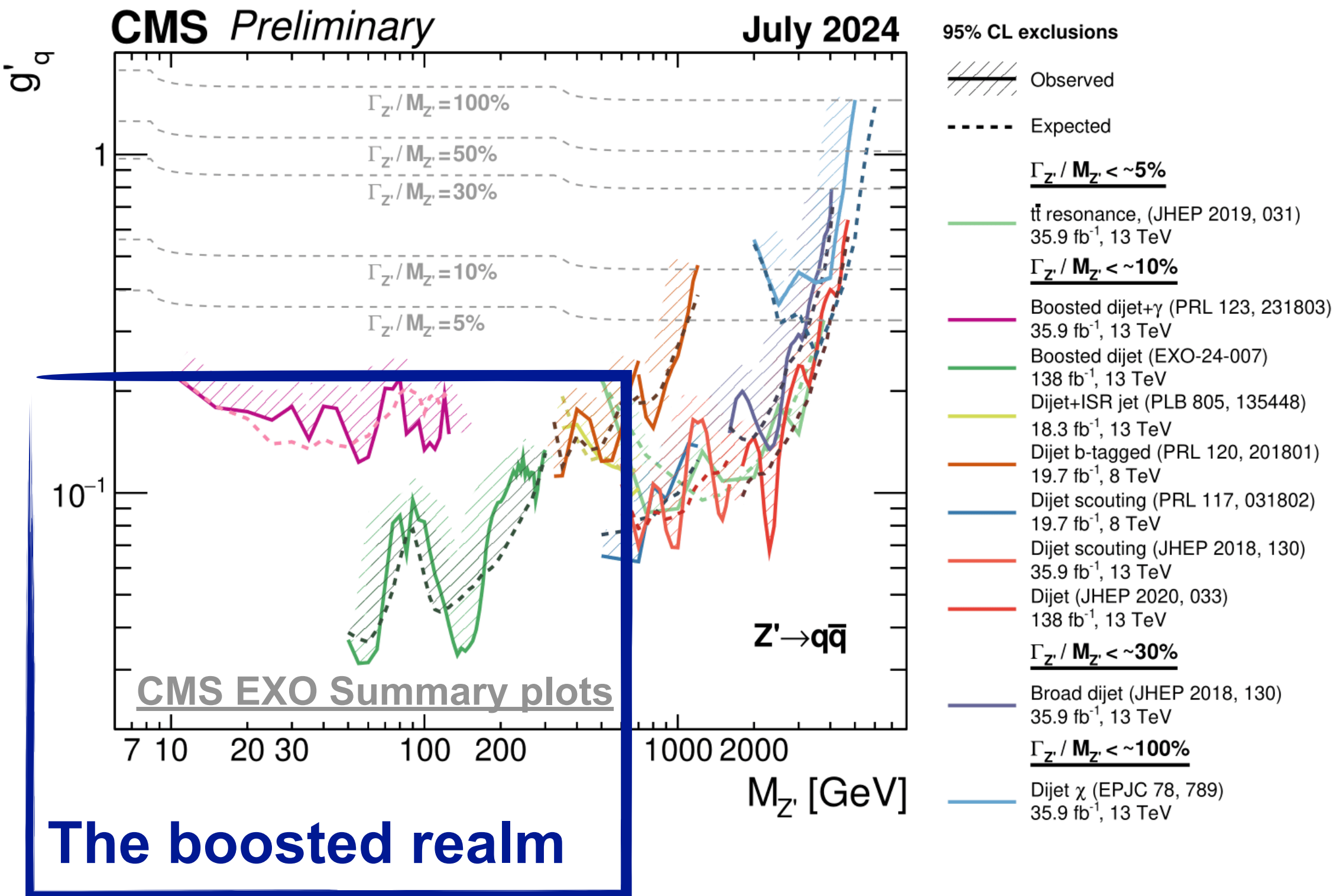
Raffaella Tramontano



ation:

to identify  
D bkg

# The light and boosted - di-jet + ISR



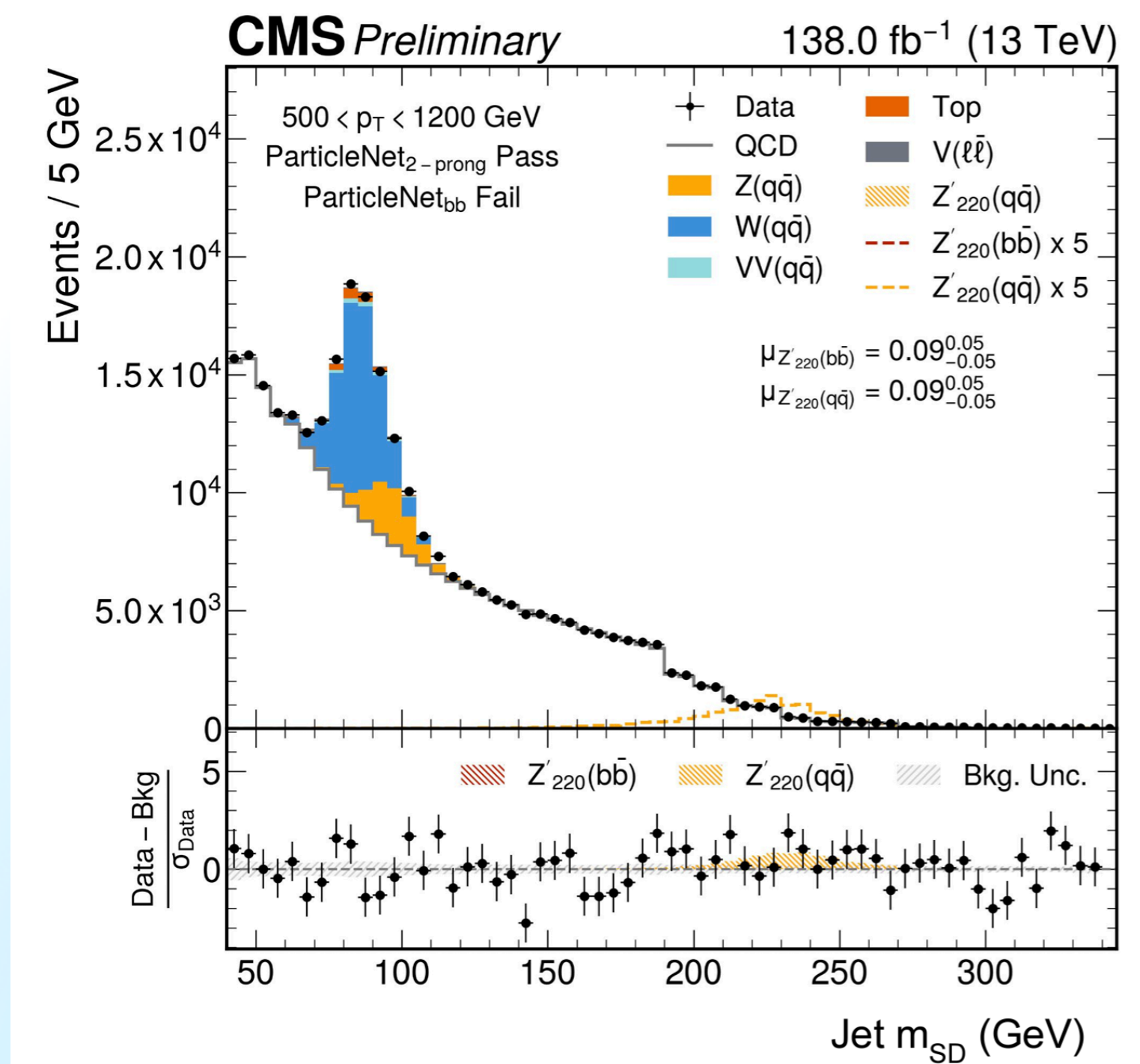
ParticleNet selection:  
2-pronged Fat Jet tagger

Dedicated Ralphabet for  
Mass shaping

Bump hunt  
In the Fat Jet mass  $m_{SD}$

ISR Jet

Fat Jet (AK8)



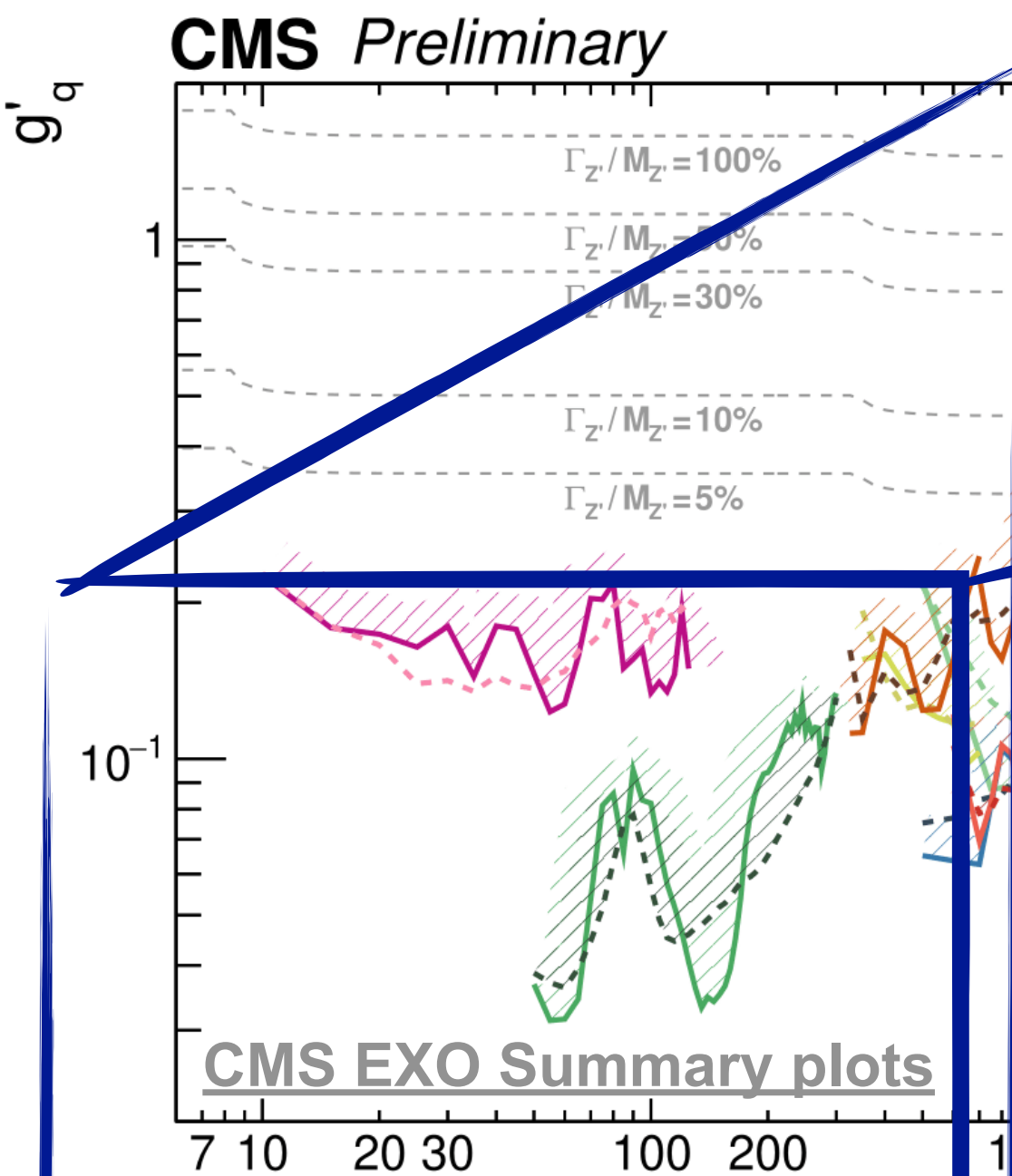
QCD bkg overwhelming and poorly predictable

Boost the signature:

- access low-mass
- higher bkg control



# The light and boosted structures - di-jet + ISR

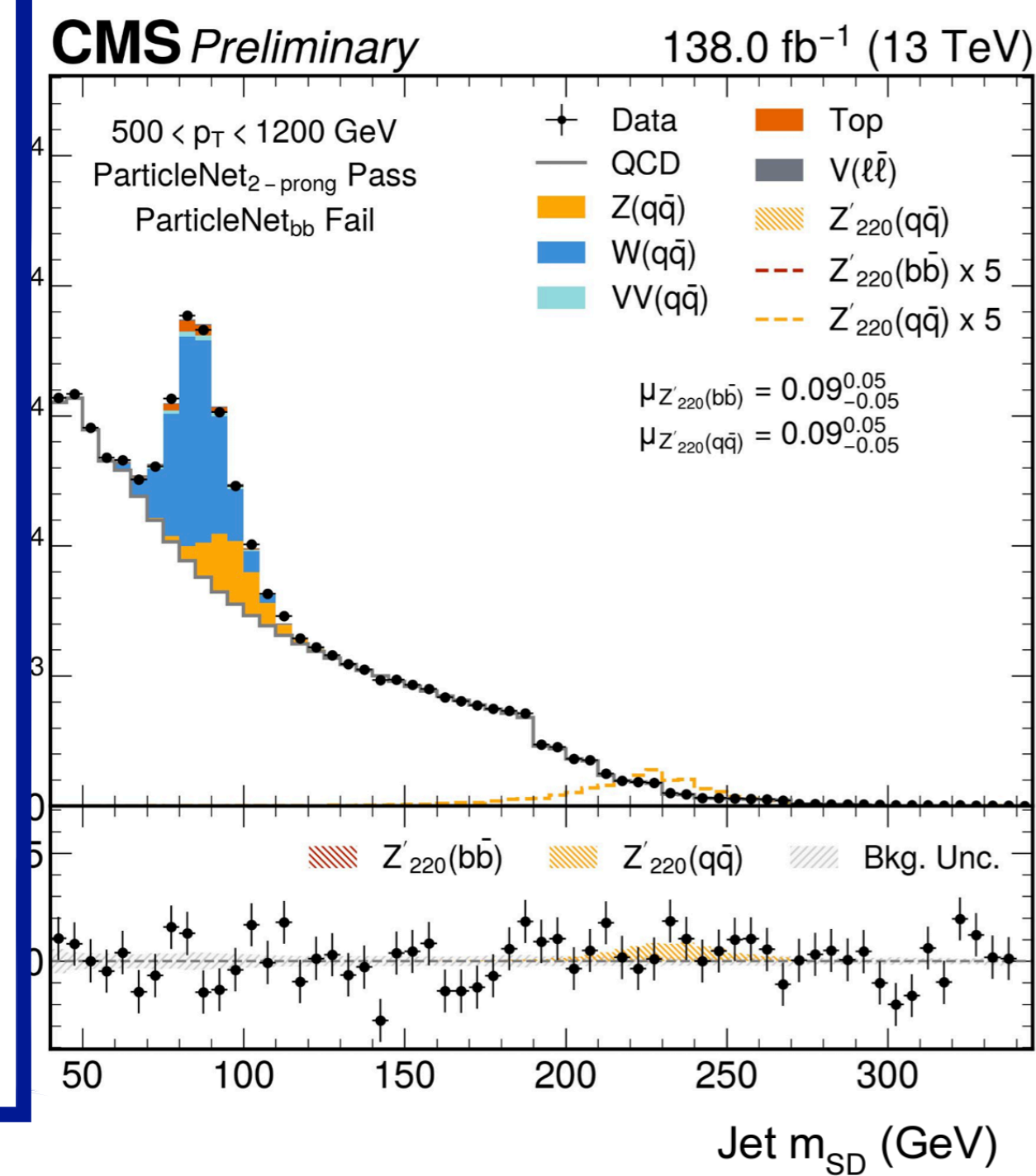
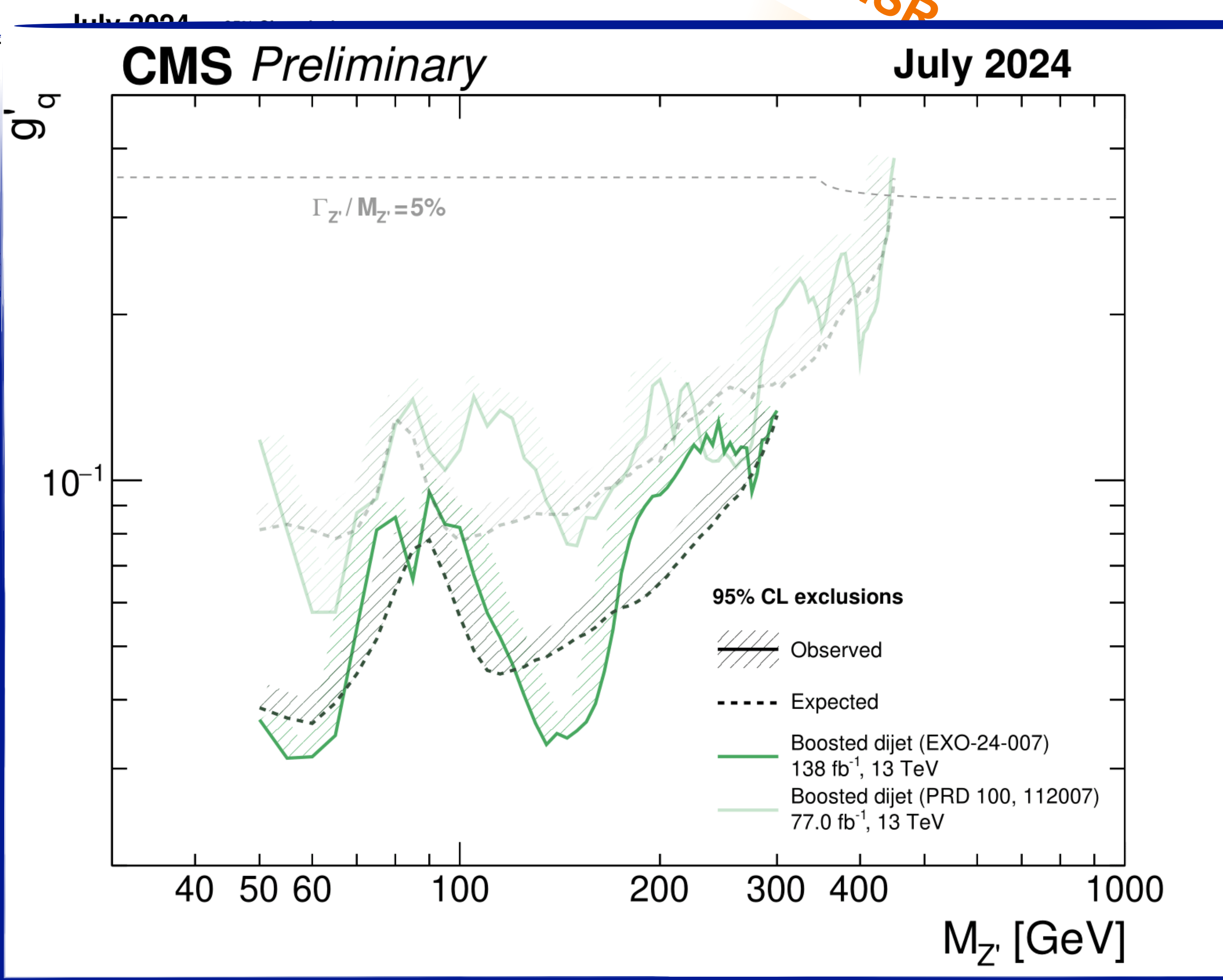


The boosted realm

QCD bkg overwhelming

Boost the signature:

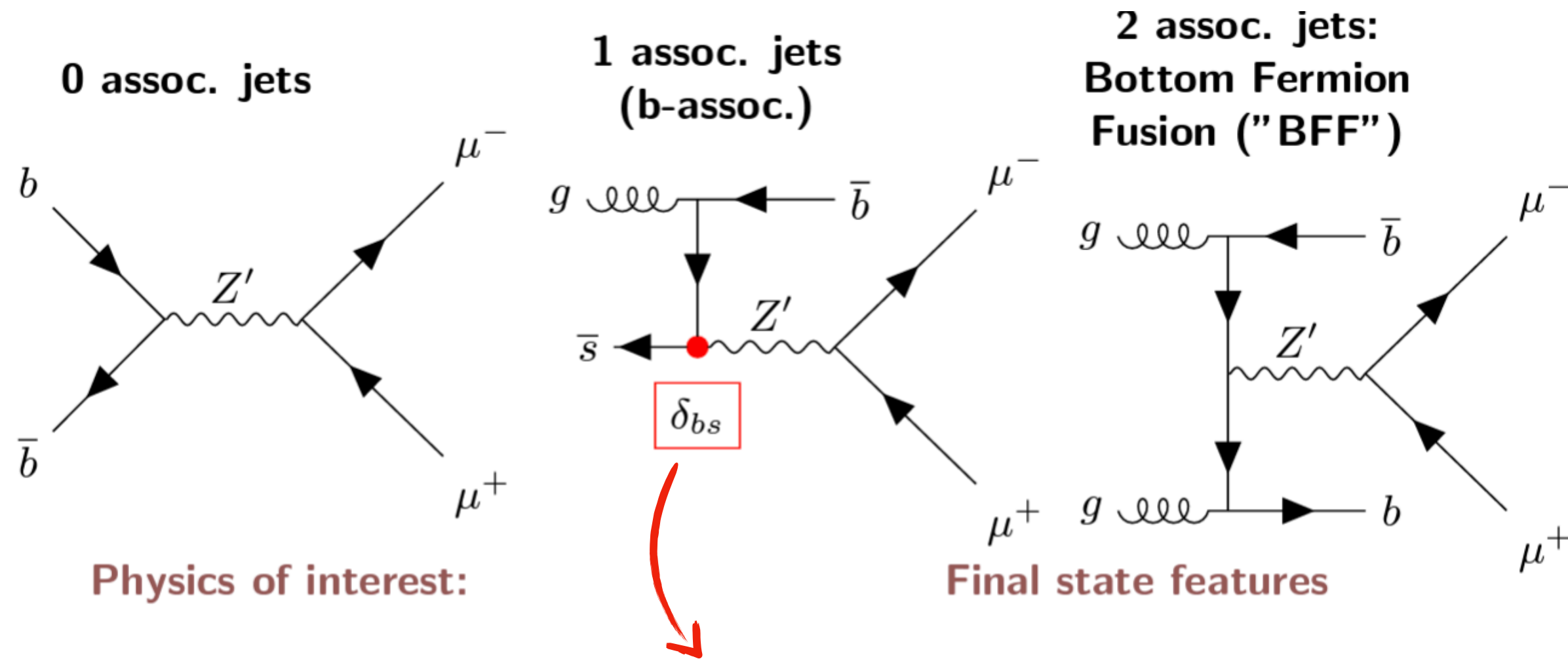
- access low-mass
- higher bkg control



# Enhance by granularity: di-lepton + b-jets

## Lepton Flavor Violation ABCD

### Bottom fermion fusion $Z'$ in dimuon final states



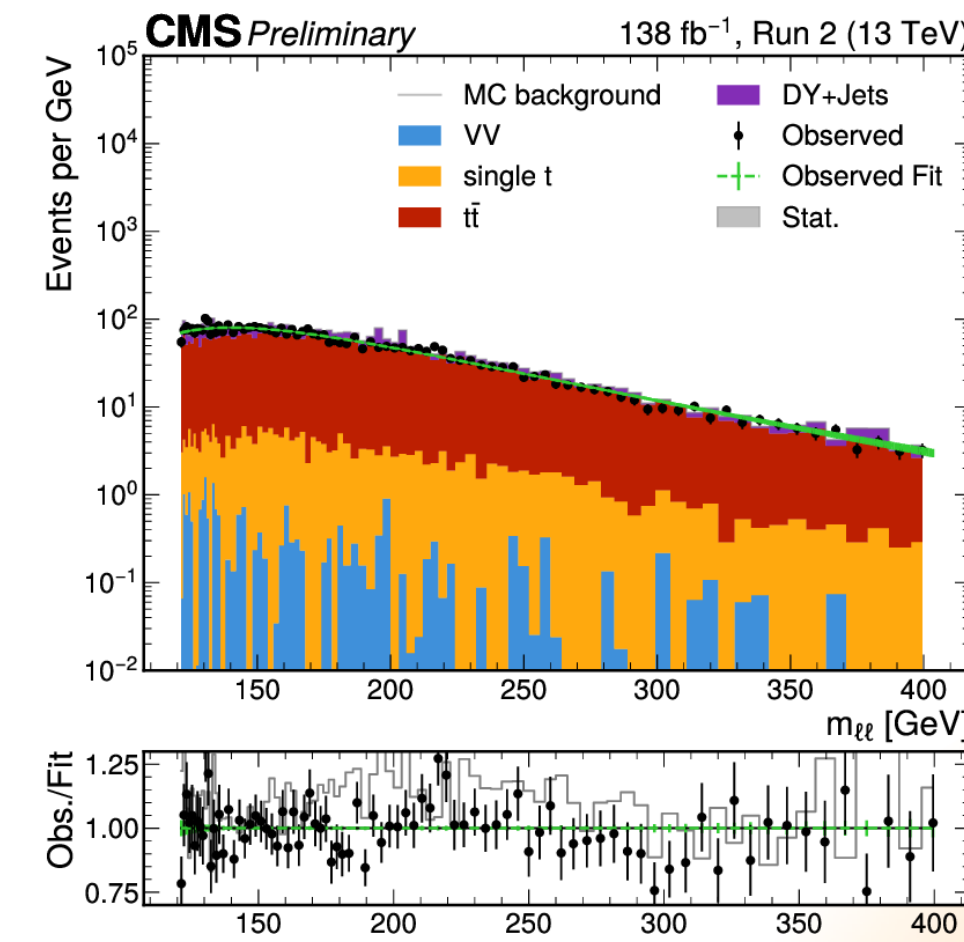
Generation specific couplings motivated by flavor anomalies ( $R_D^*$ )

$Z'$  not coupled to  $e$ :

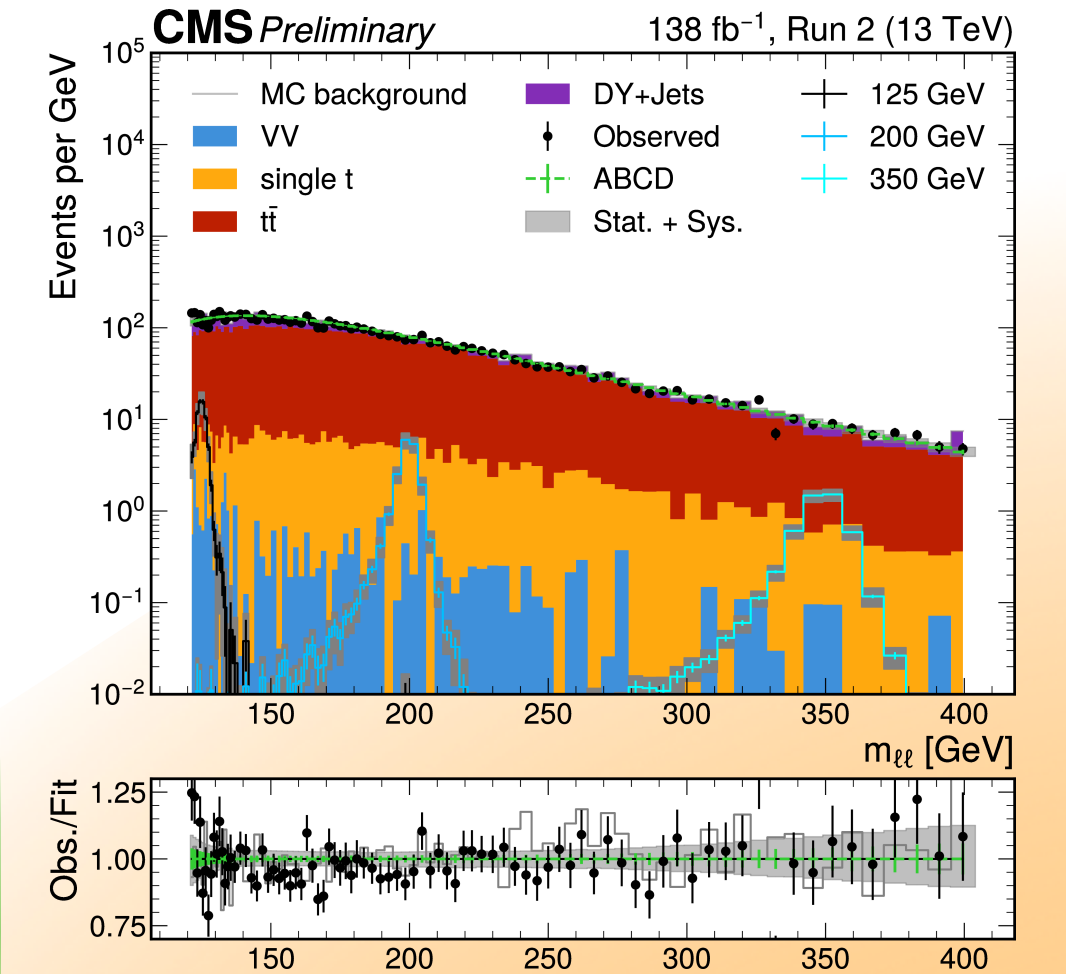
$N_b$	$N_{\text{jets}}^{\text{all}}$	$\mu\mu$	$ee$
$\geq 1$	2	$SR_{b+j/b}^{\mu\mu}$	$CR_{b+j/b}^{ee}$
0	2	$CR_{j+j}^{\mu\mu}$	$CR_{j+j}^{ee}$
1	1	$SR_b^{\mu\mu}$	$CR_b^{ee}$
0	1	$CR_j^{\mu\mu}$	$CR_j^{ee}$

Used as CR

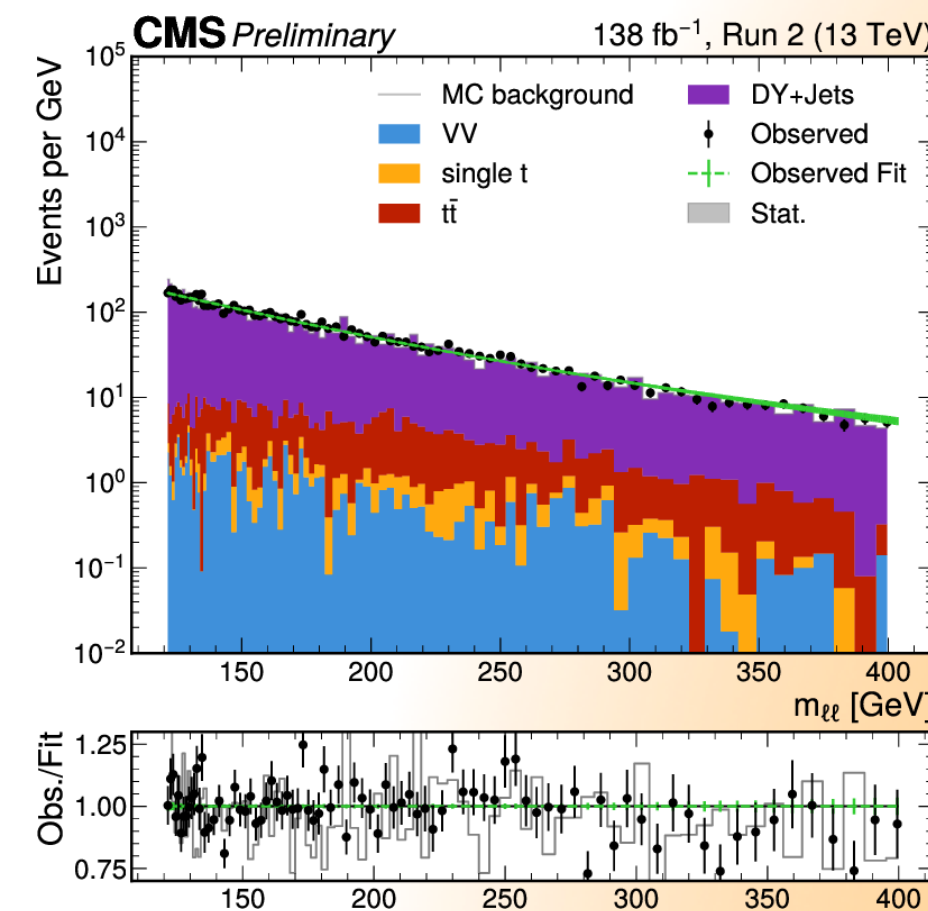
### D: Di-electron + bjet + j



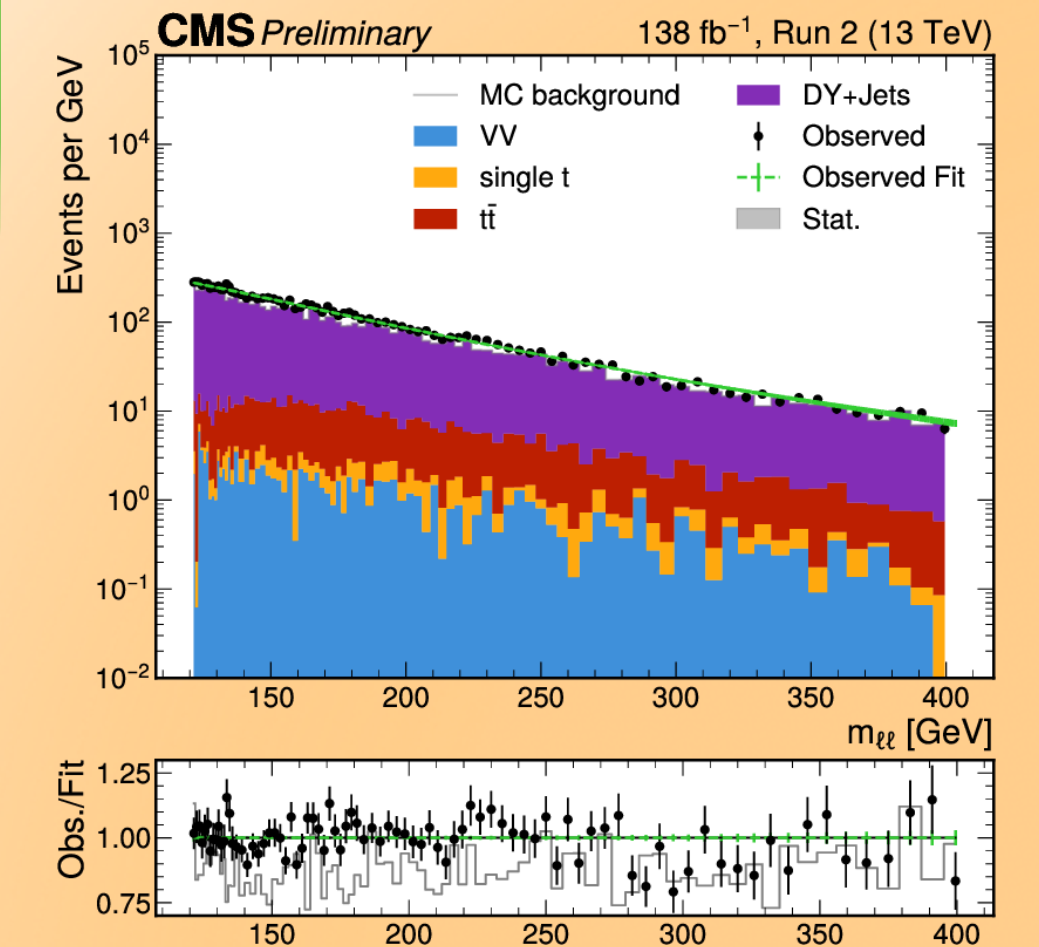
### SR : Di-muon + b-jet + j



### C: Di-electron + 2j



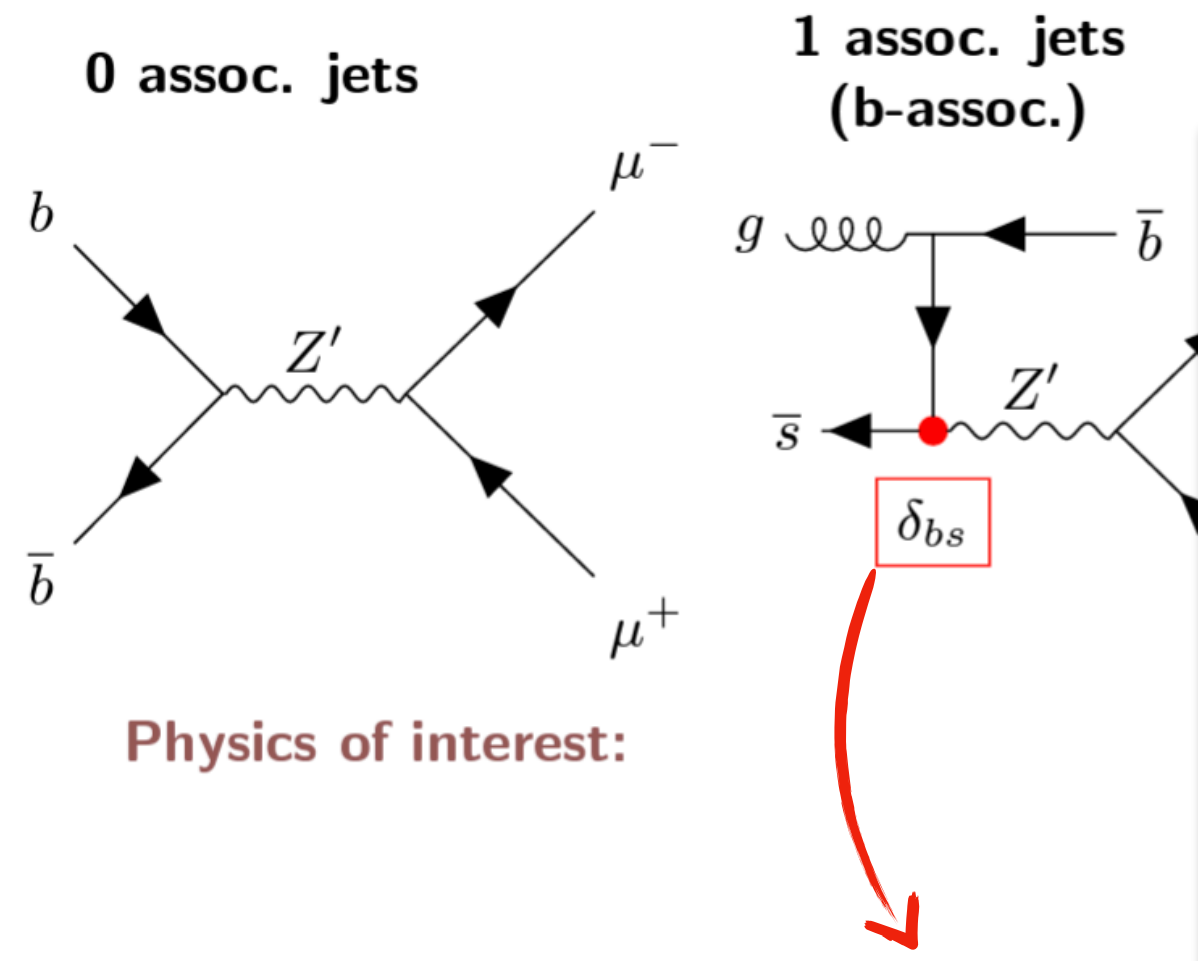
### B: Di-muon + 2j



# Enhance by granularity: di-lepton + b-jets

## Lepton Flavor Violation ABCD

### Bottom fermion fusion $Z'$ in dimuon final states



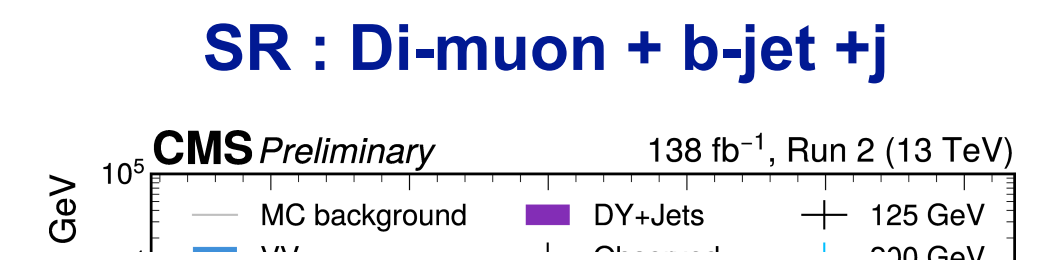
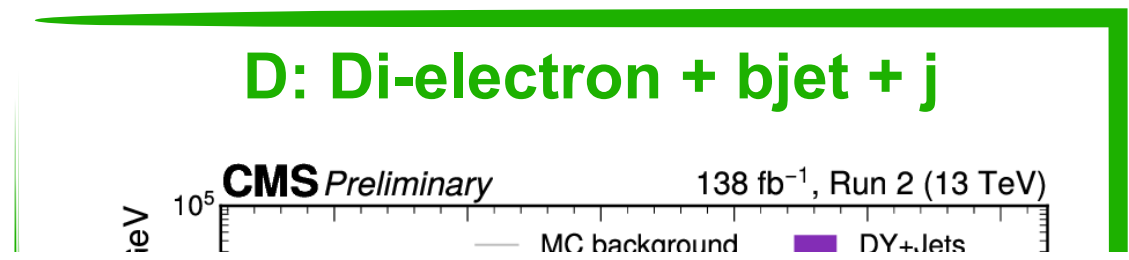
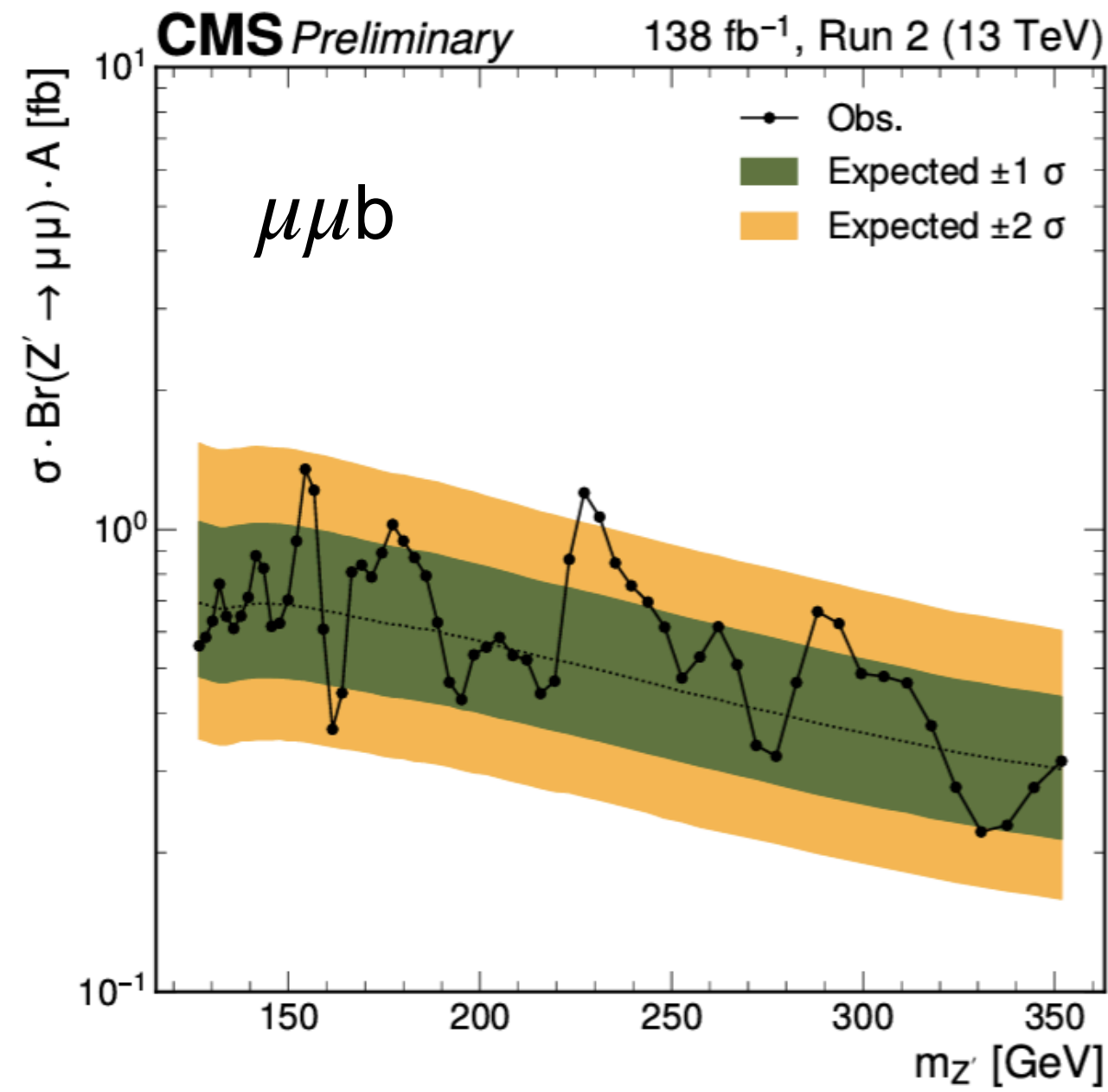
Generation specific couplings motivated by flavor

$Z'$  not c

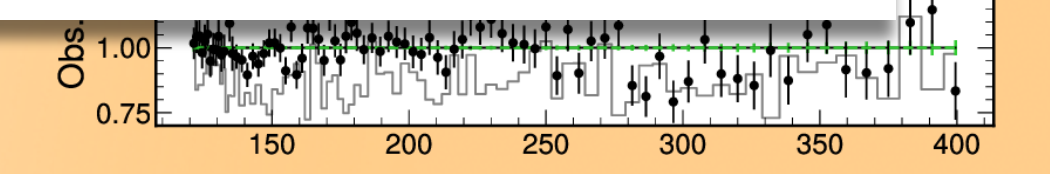
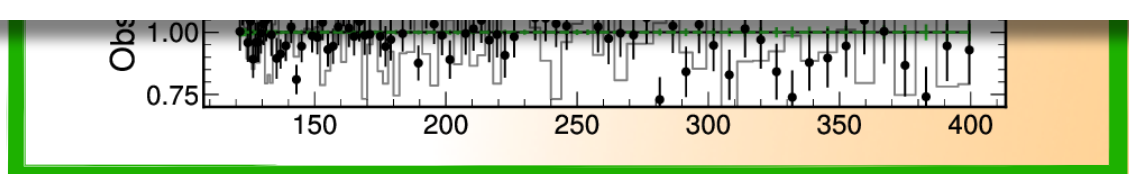
$N_b$	$N_{\text{jets}}^{\text{all}}$	$\mu\mu$	
$\geq 1$	2	$SR_{b+j/b}^{\mu\mu}$	CR
0	2	$CR_{j+j}^{\mu\mu}$	CR
1	1	$SR_b^{\mu\mu}$	CR
0	1	$CR_j^{\mu\mu}$	CR

Used as CR

2 assoc. jets:  
Bottom Fermion

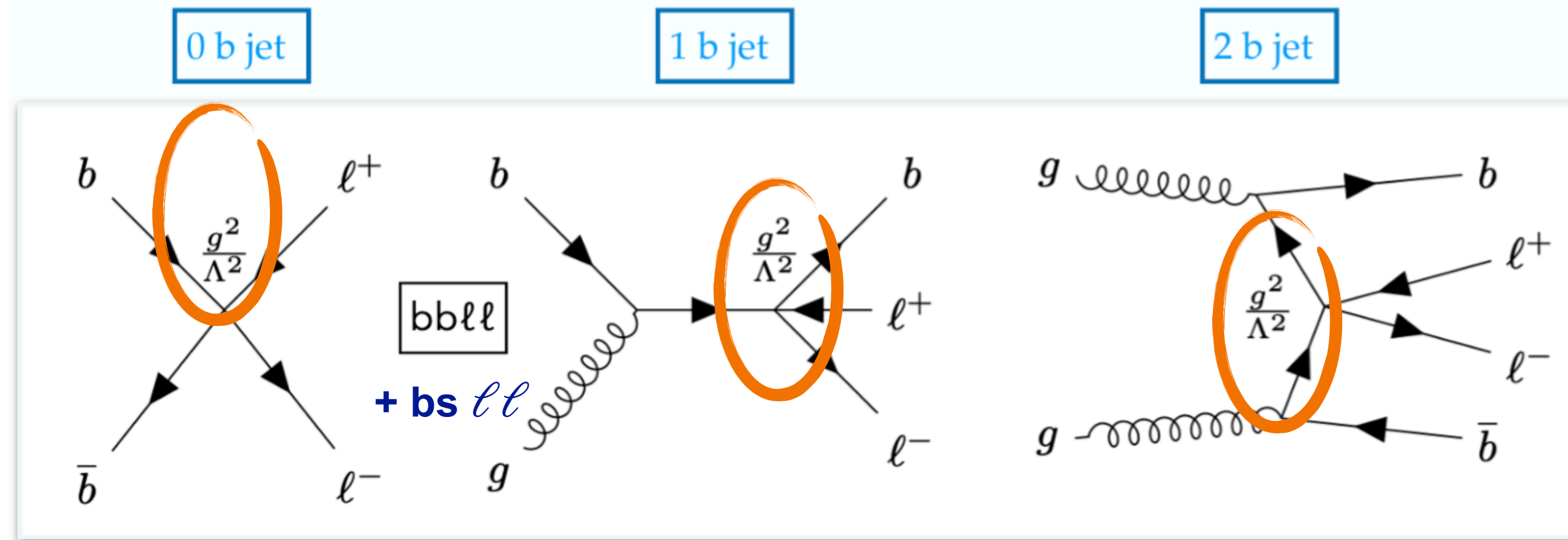


First result in associated channels  
Complementary to existing search in light quark production



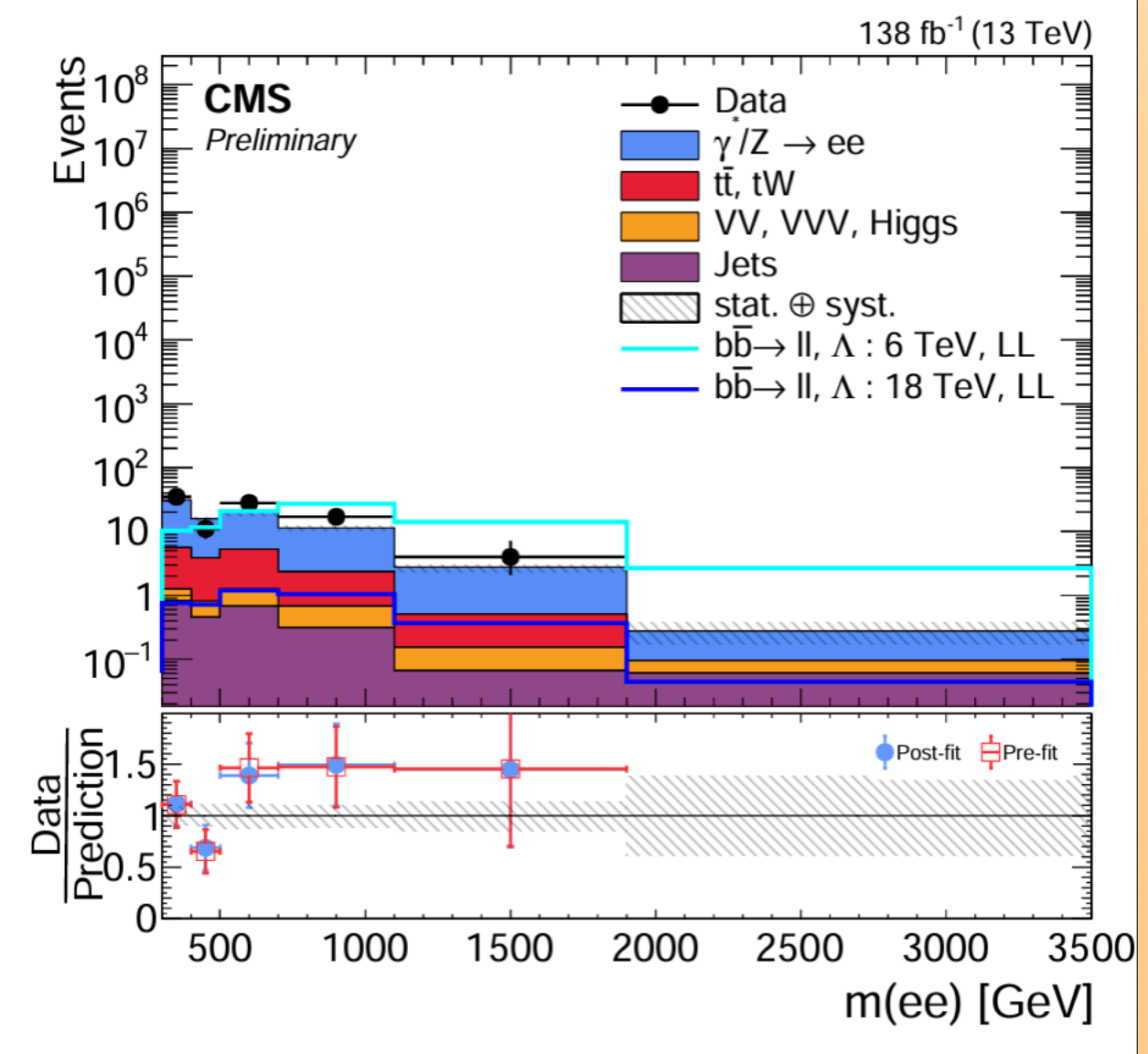
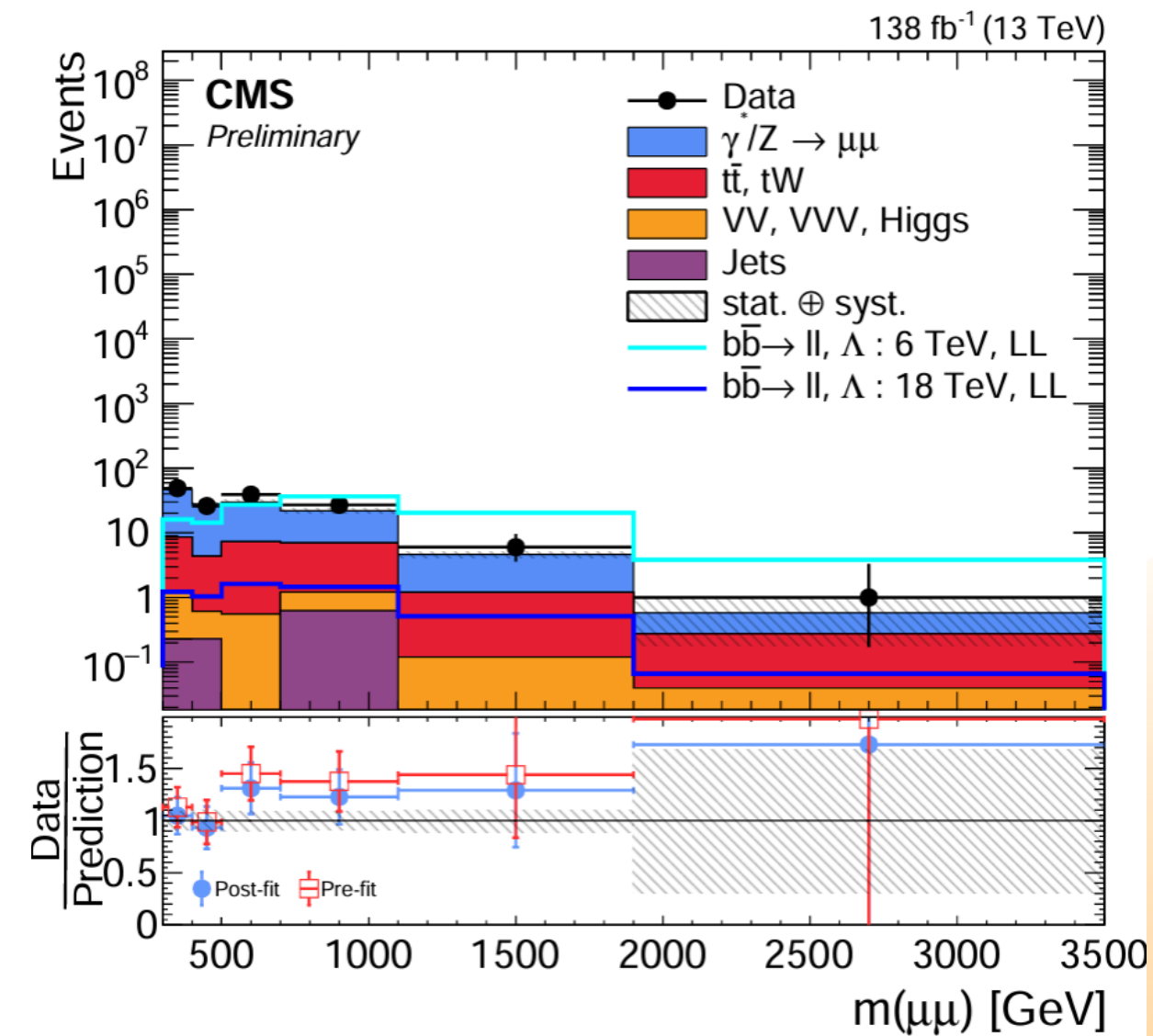
# Enhance by granularity: di-lepton + b-jets

No signal detected in probed mass ranges → EFT indirect search



## Strategy:

- Test perturbative effects of  $\Lambda \sim O(10 \text{ TeV})$  on lower mass range
  - In several chirality structures
- Independent treatment for  $ee$  and  $\mu\mu$  channel
- Test of lepton flavor violation in the three  $bb$  fusion channels
  - Check  $R$  vs number of jets



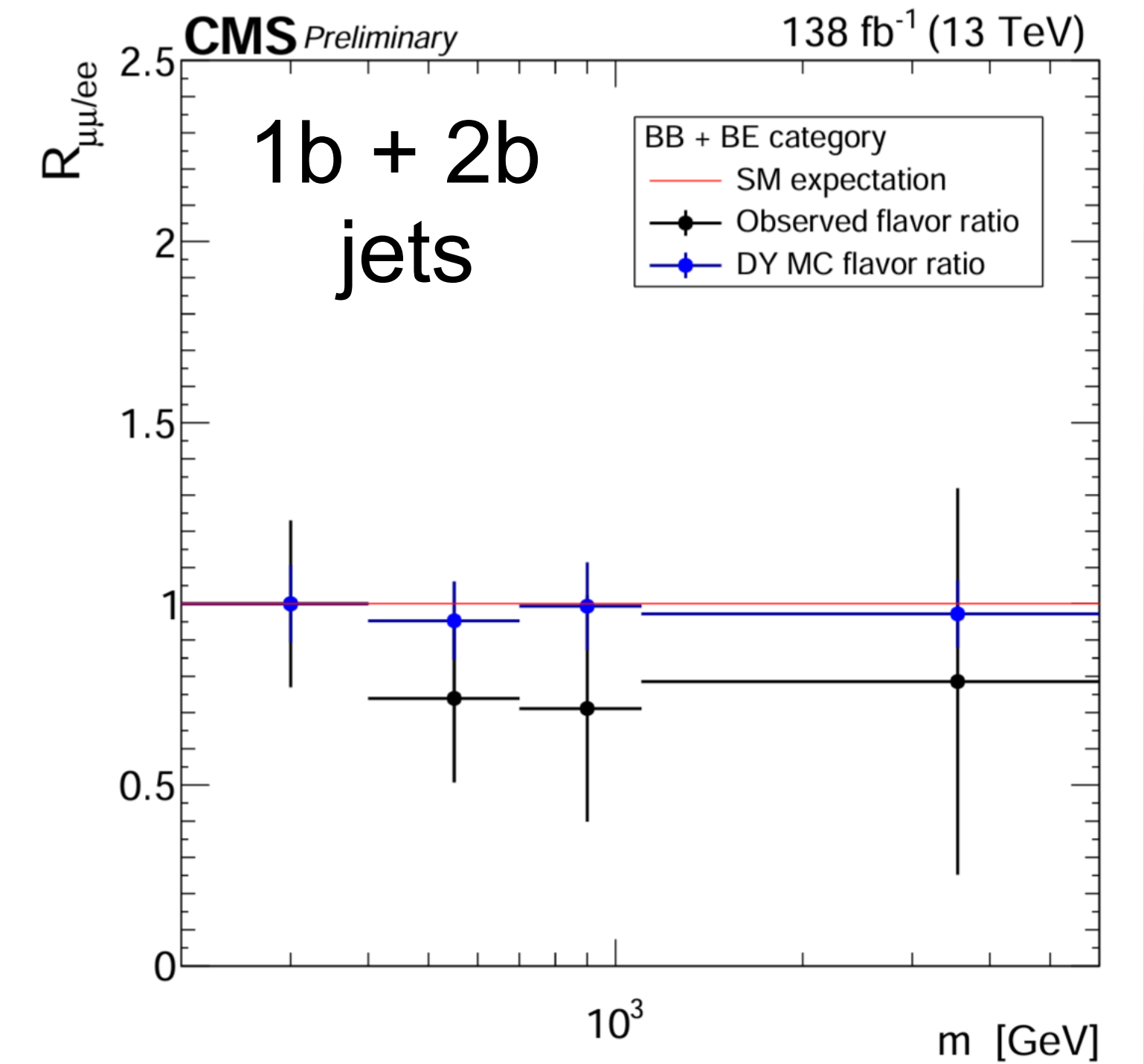
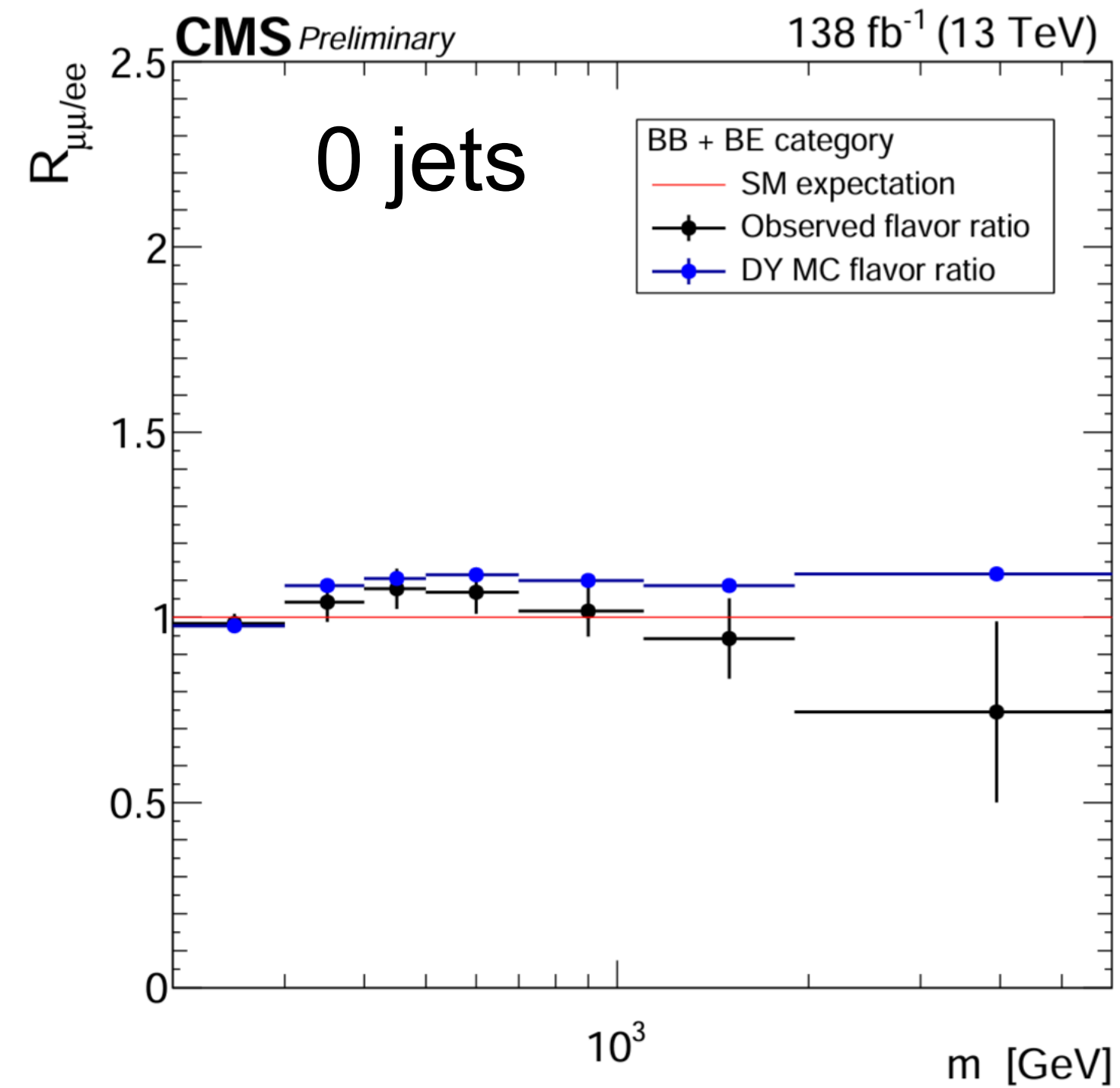
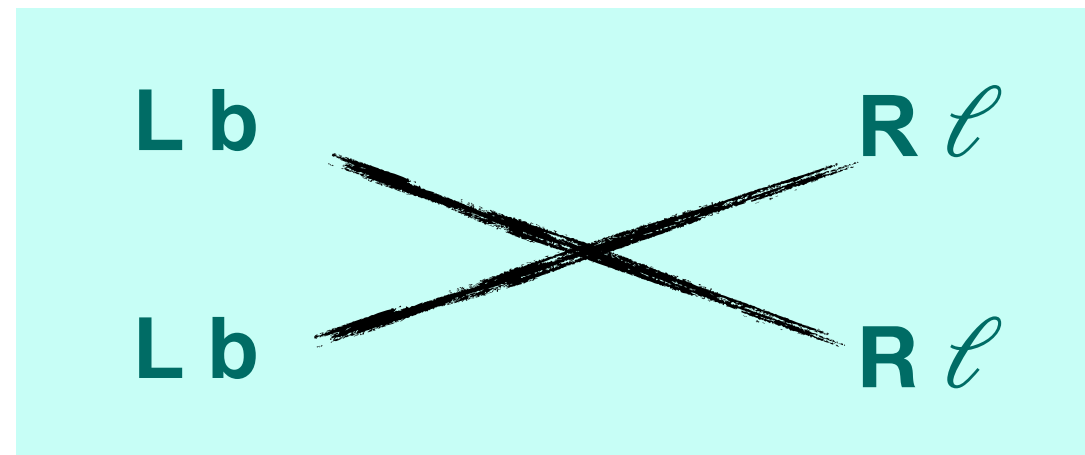
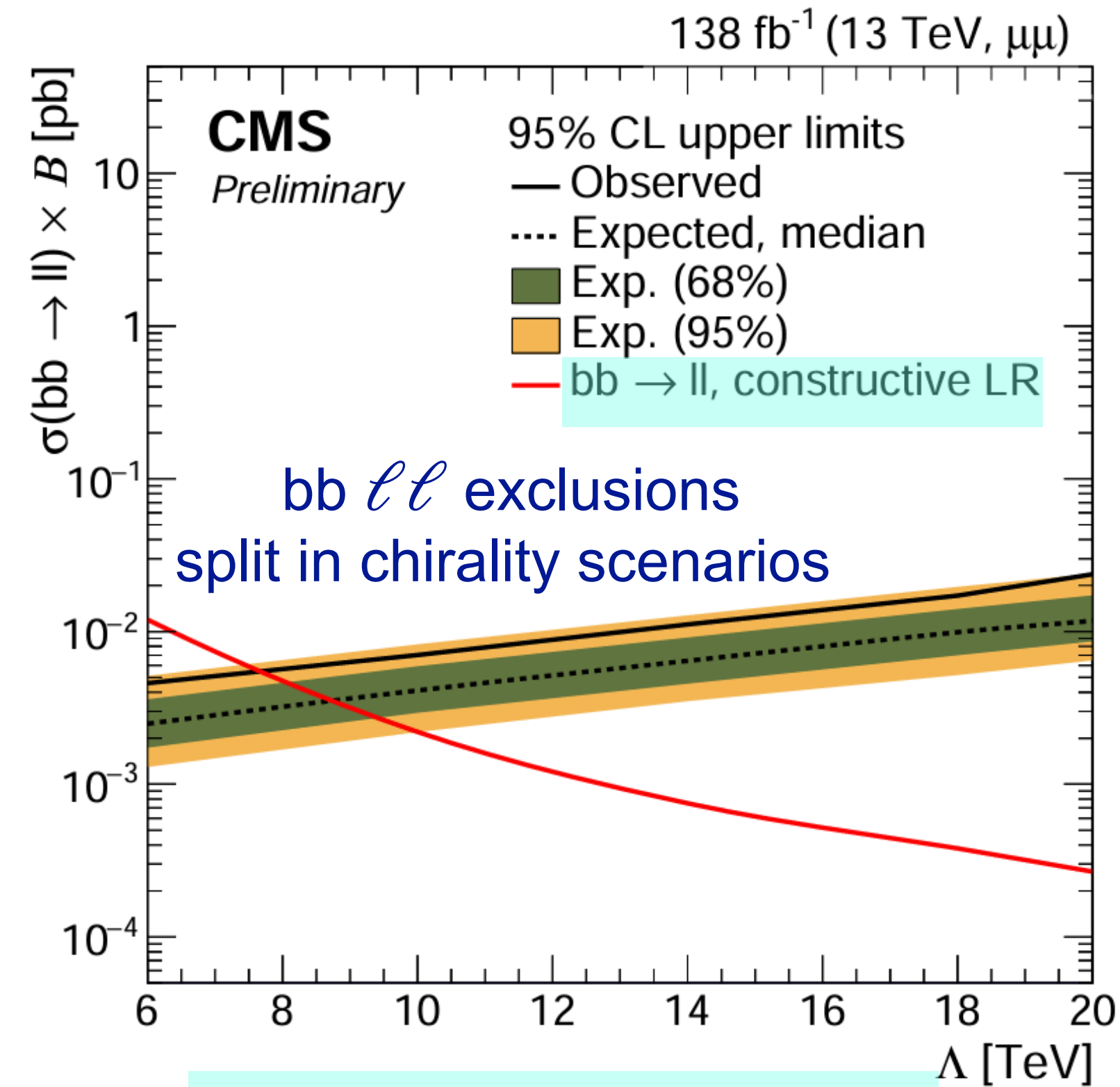
Unfolding detector and resolution effects  
To compute

$$R_{\mu\mu/ee} = \frac{d\sigma(q\bar{q} \rightarrow \mu\mu)/dm_{\mu\mu}}{d\sigma(q\bar{q} \rightarrow ee)/dm_{ee}}$$

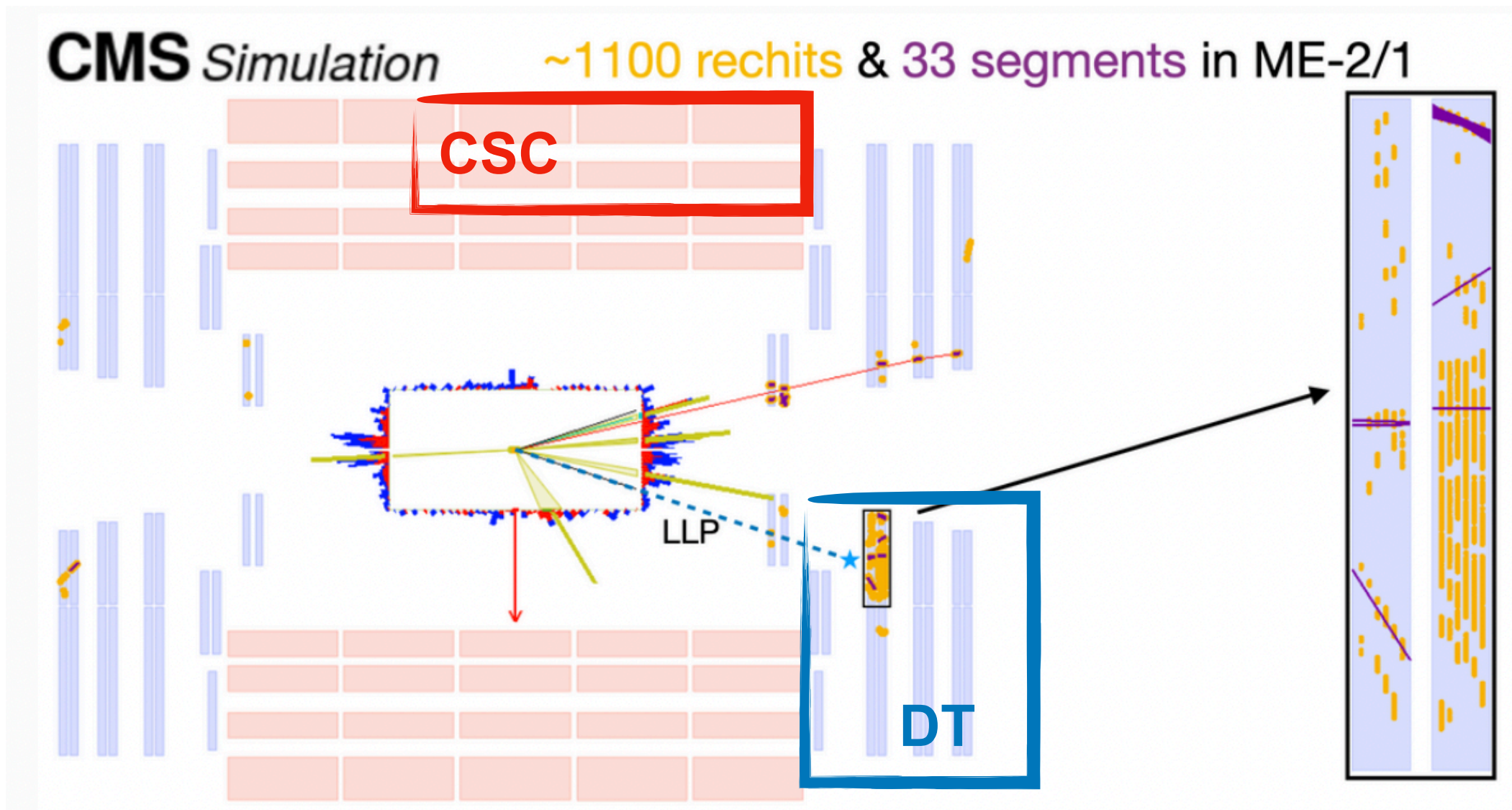
# Enhance by granularity: di-lepton + b-jets

limits on  $\Lambda$  on  $bb \ell\ell$ ,  $\Lambda/g^*$  for +  $bs \ell\ell$

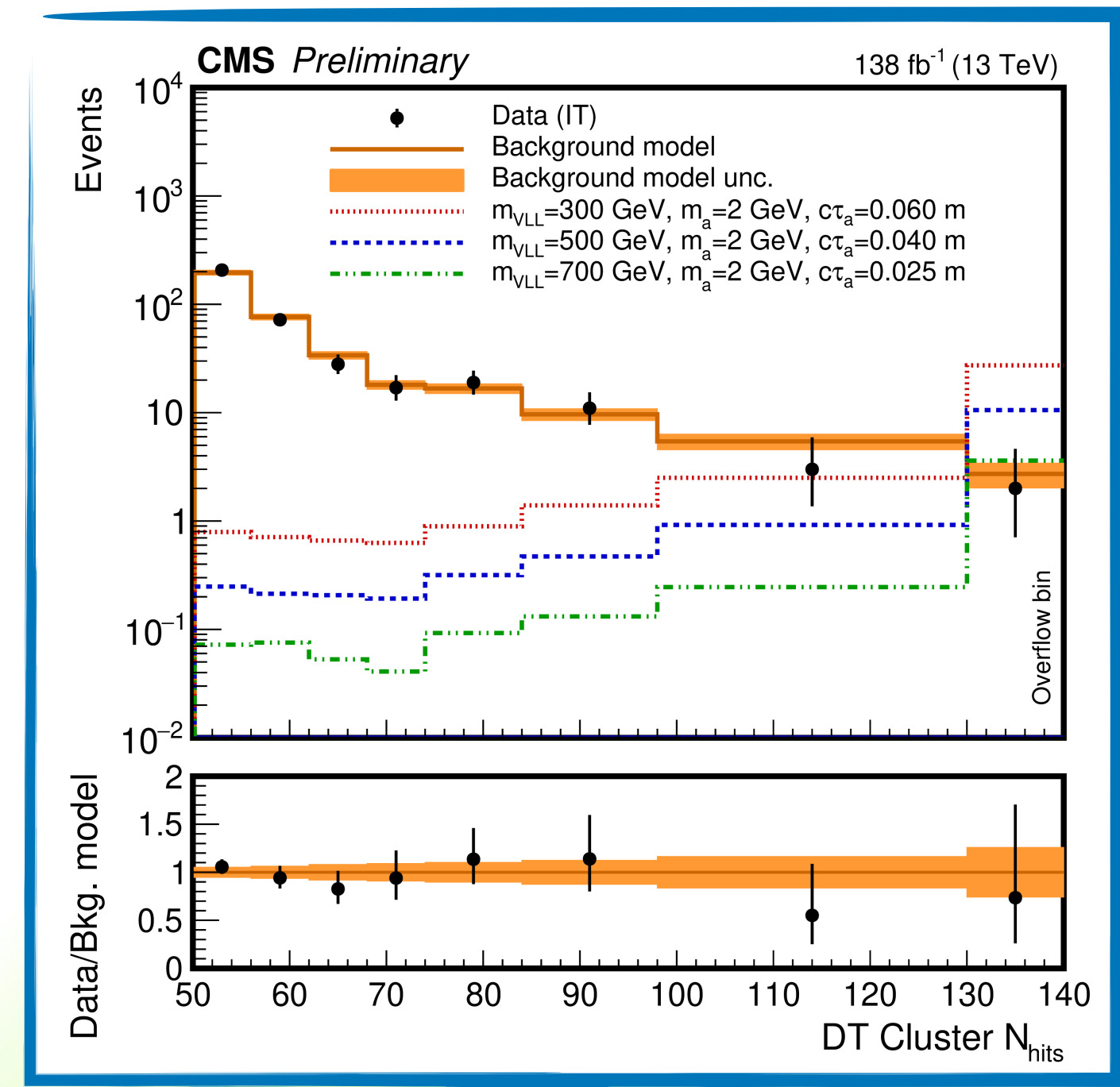
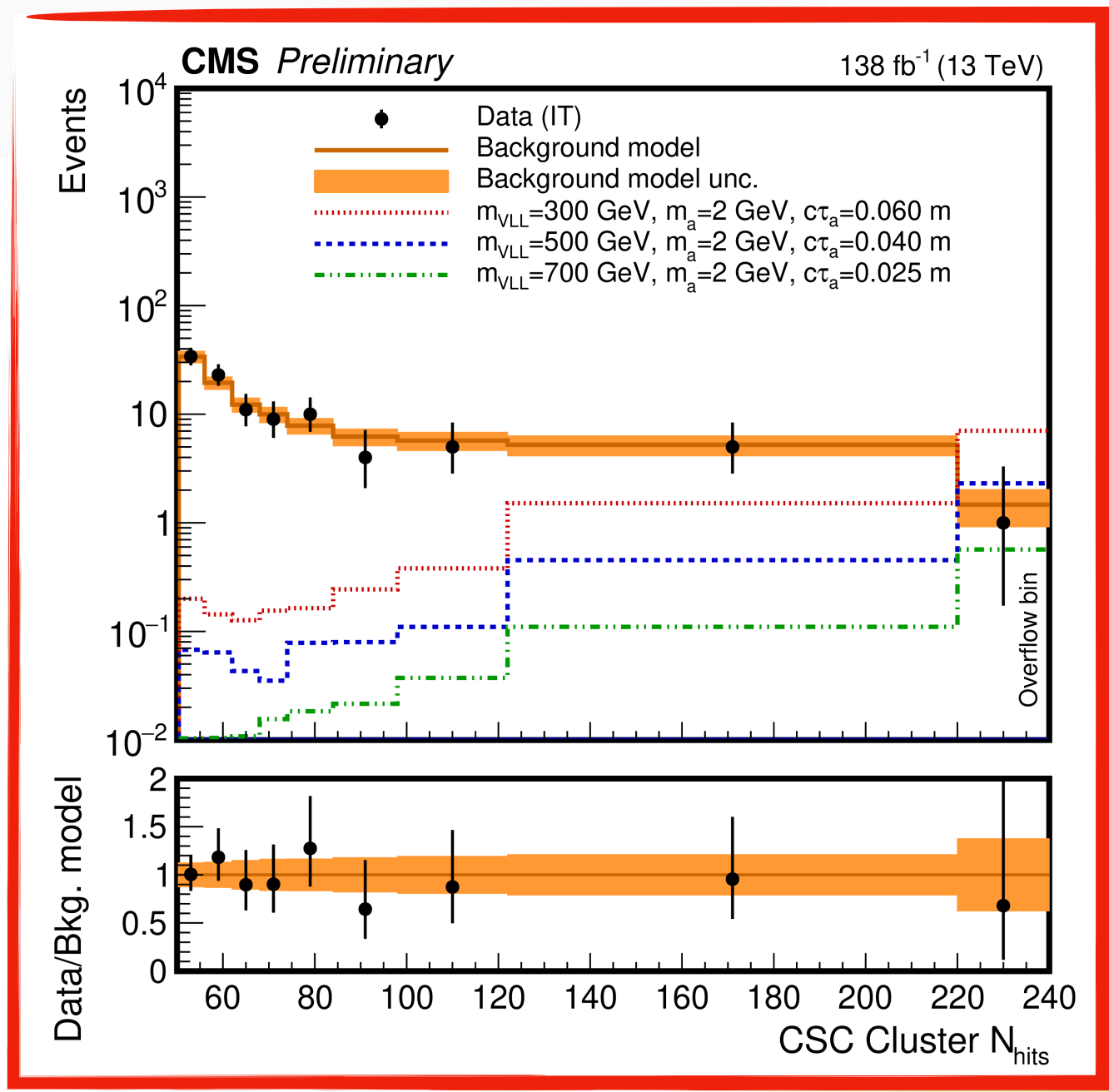
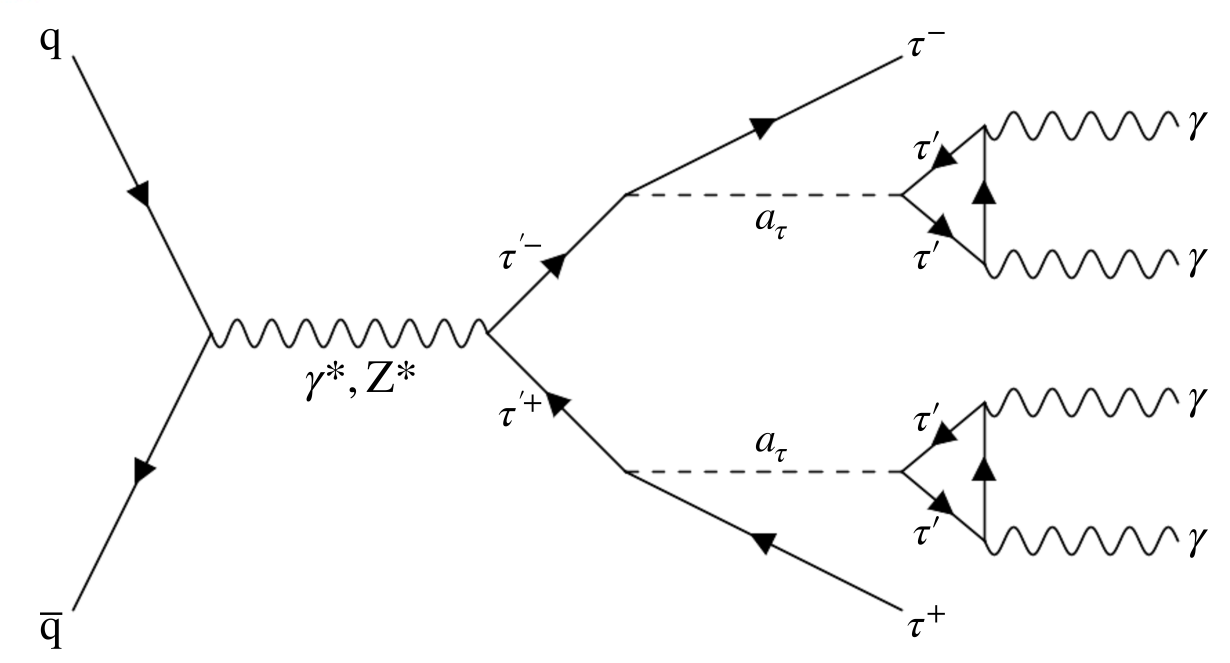
Test of LFV



# Muon detector showers - VLL via LLPs



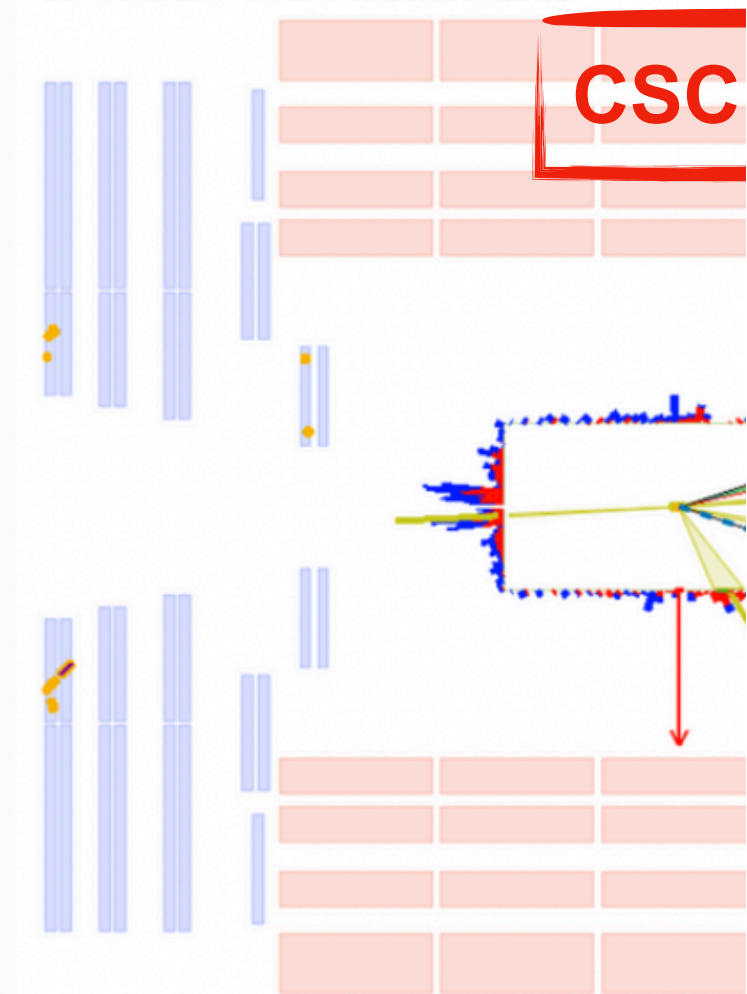
high-multiplicity  
MDS



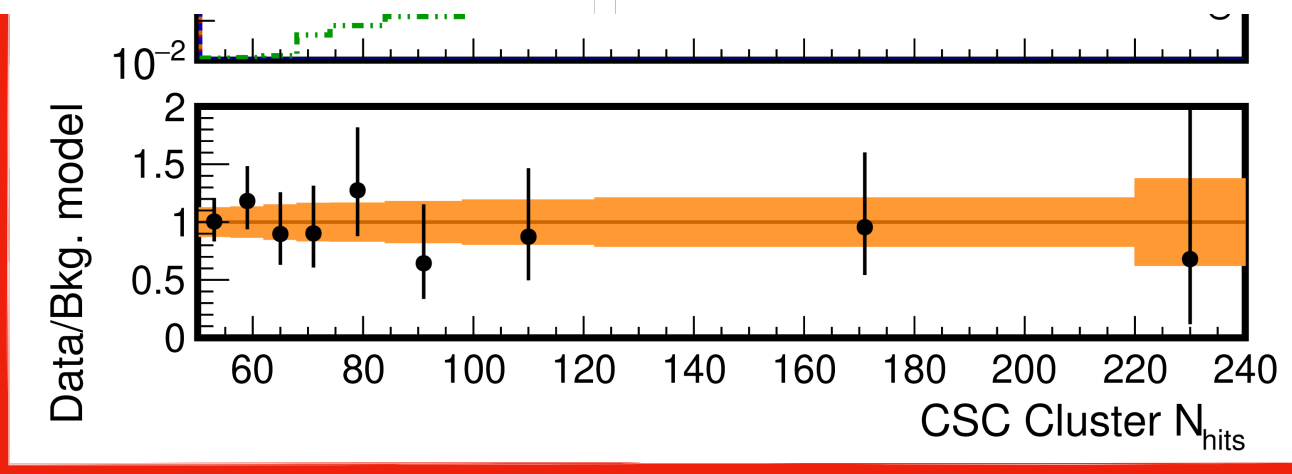
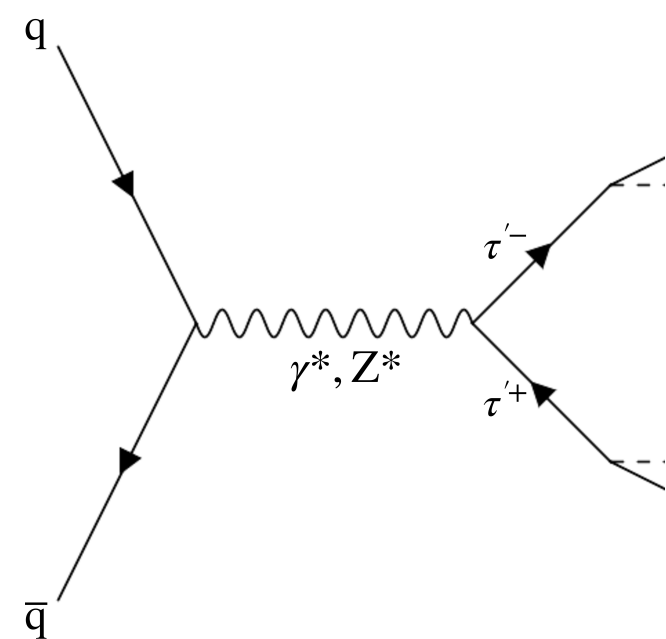
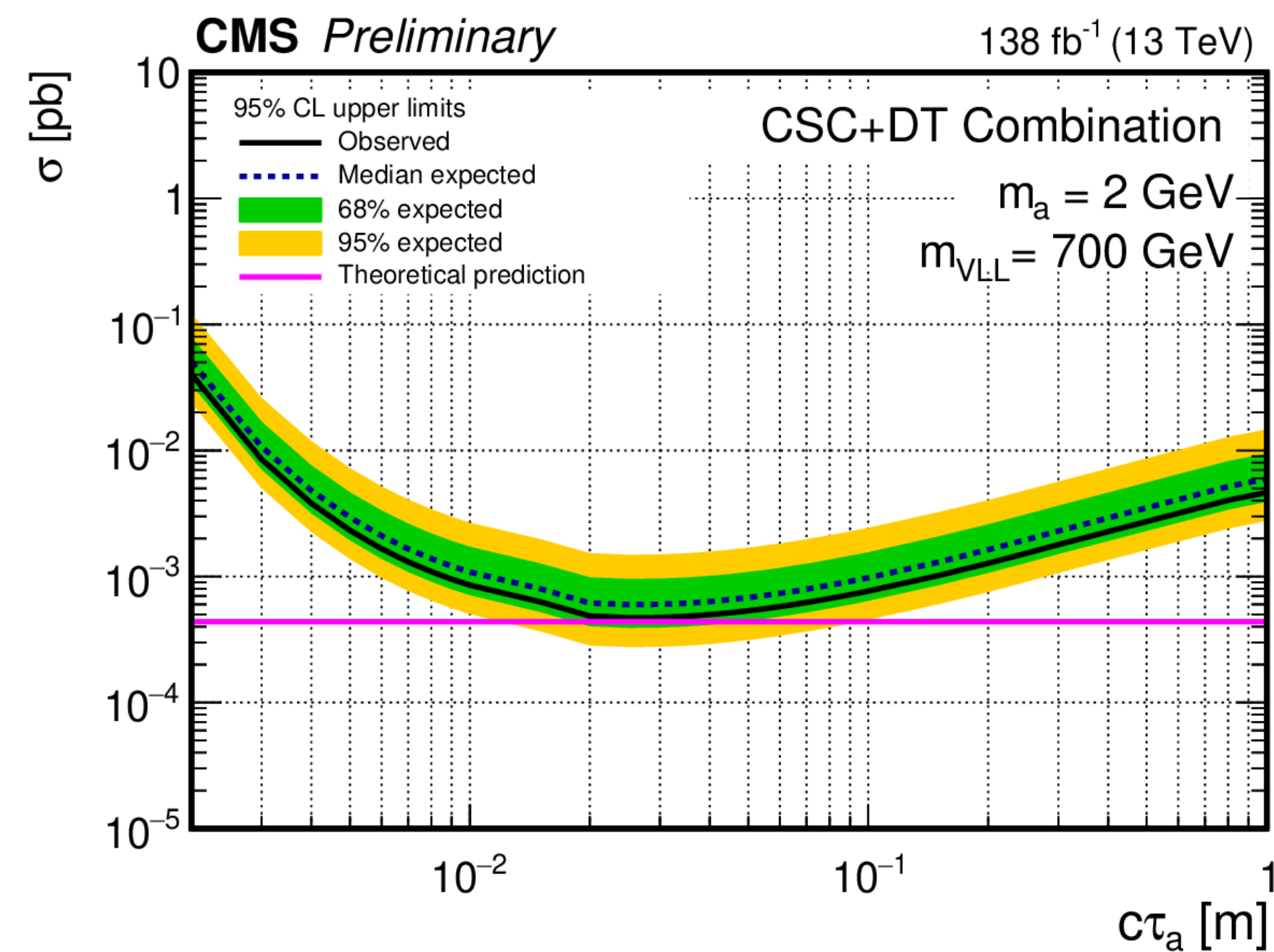
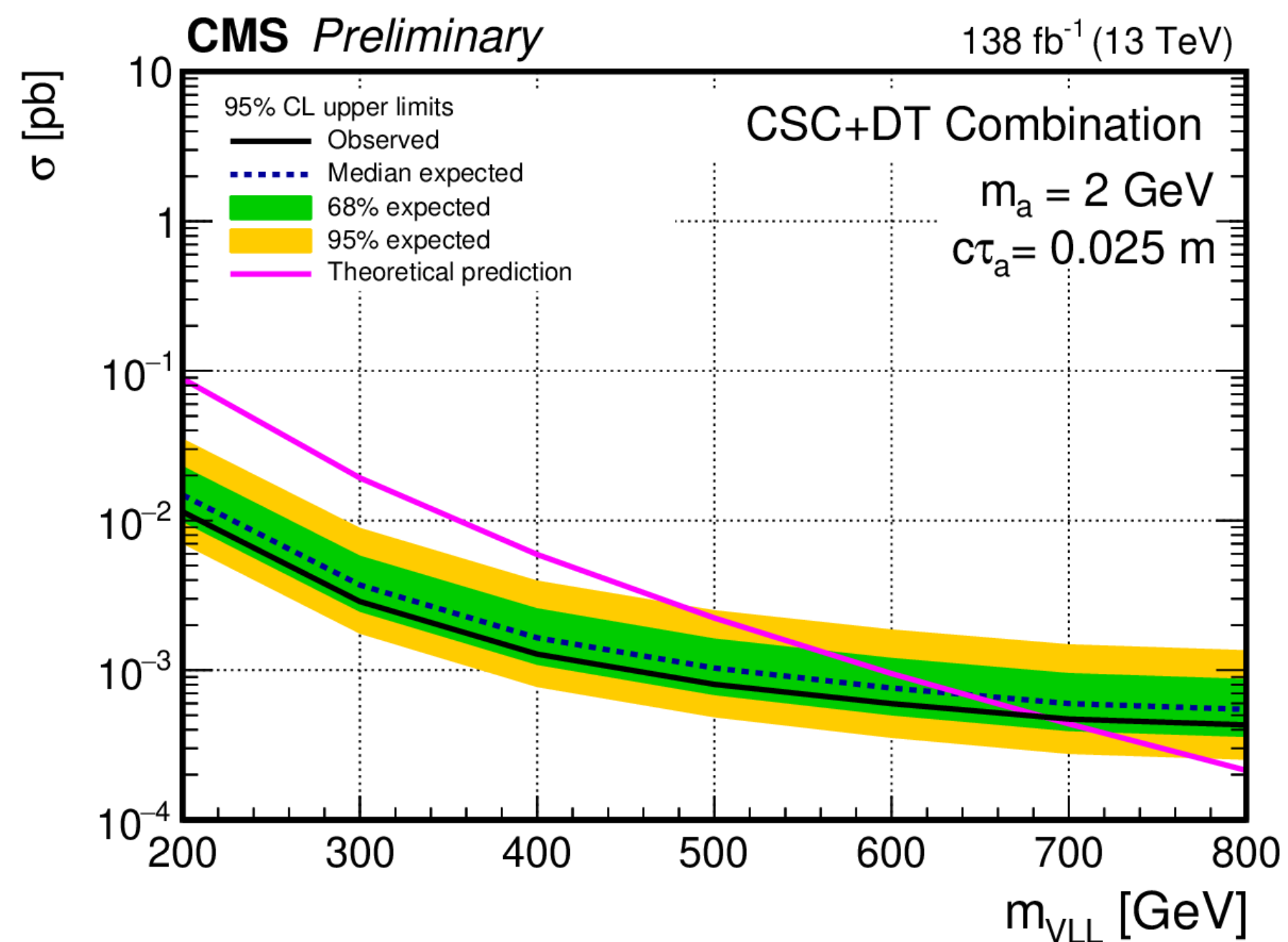
**Novel signature for  
Muon dedicated detectors!**

# Muon detector showers - VLL via LLPs

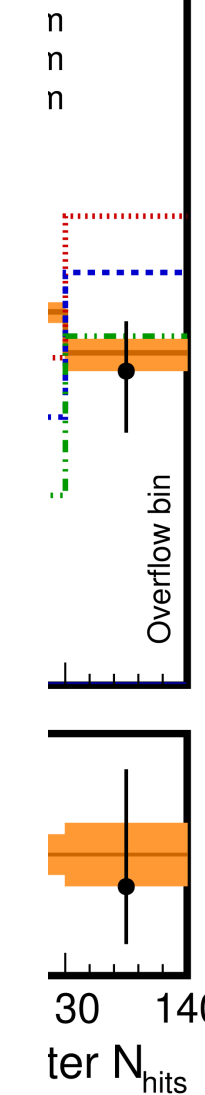
CMS Simulation



Exclusions depend on both the pseudoscalar mass and lifetime



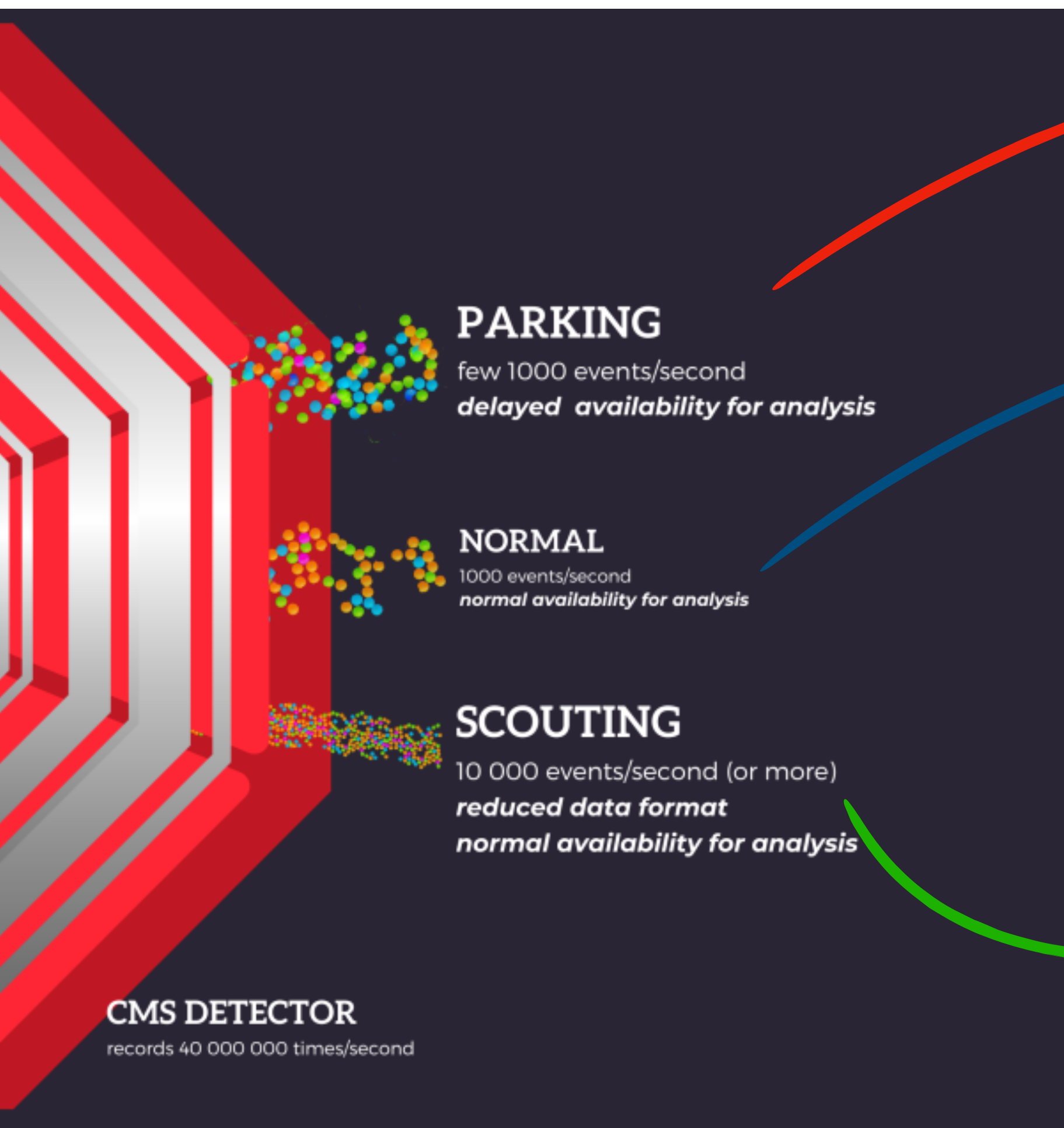
CMS Preliminary 138 fb<sup>-1</sup> (13 TeV)  
 Data (IT)



**MUON dedicated detectors!**

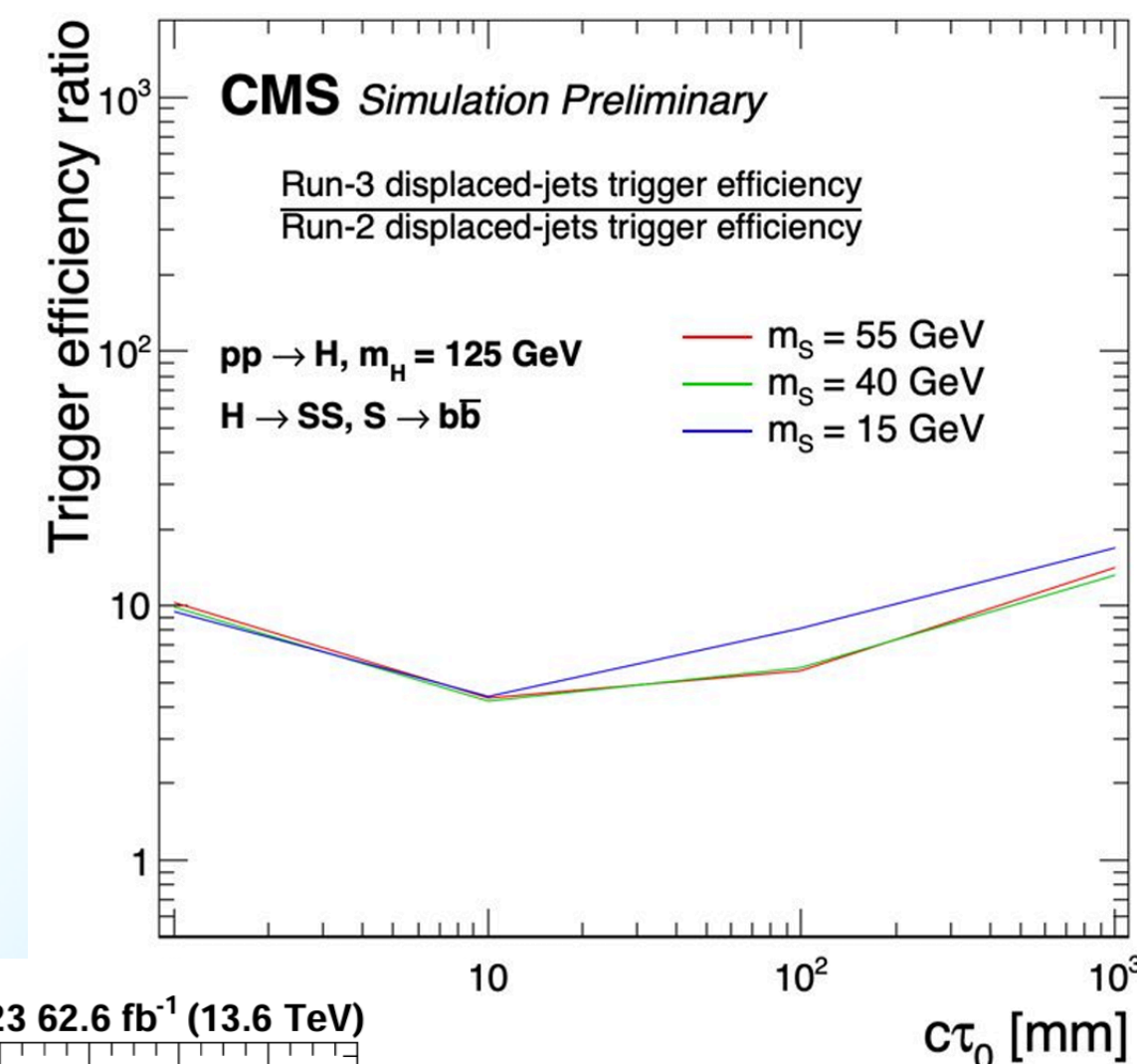
# Data streamline frontiers for Run3

Pivoted for specific physics cases in Run2 -> expanded to larger scopes in Run3

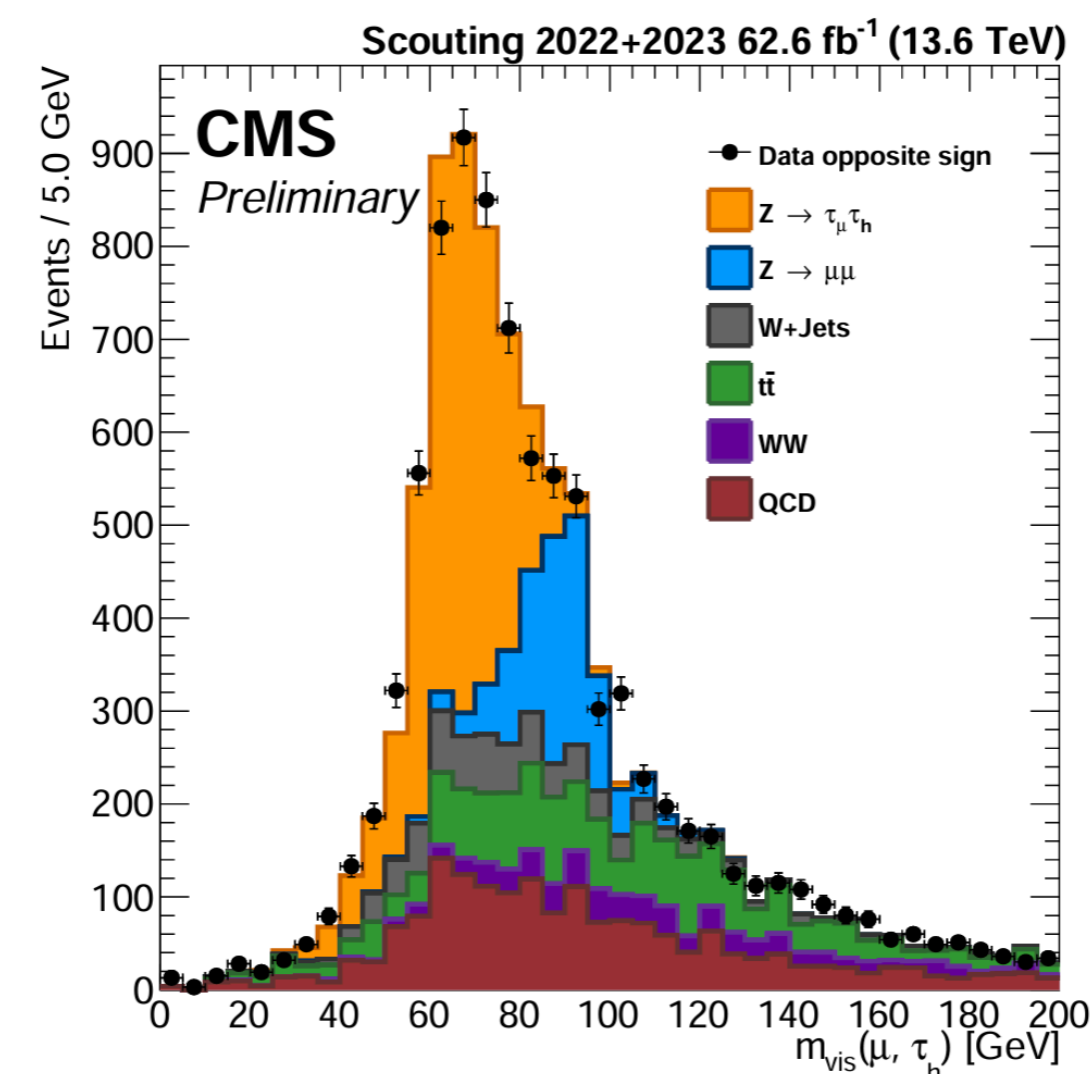


Delayed reco: can be used with time consuming algorithms

Normal stream:  
novel dedicated triggers



Run3:  
PF candidates scouting



Z →  $\tau\tau$  observed  
in scouting data!



# Search for $t\bar{t}$ structures

QCD (with perturbative and EW corrections) against

NP

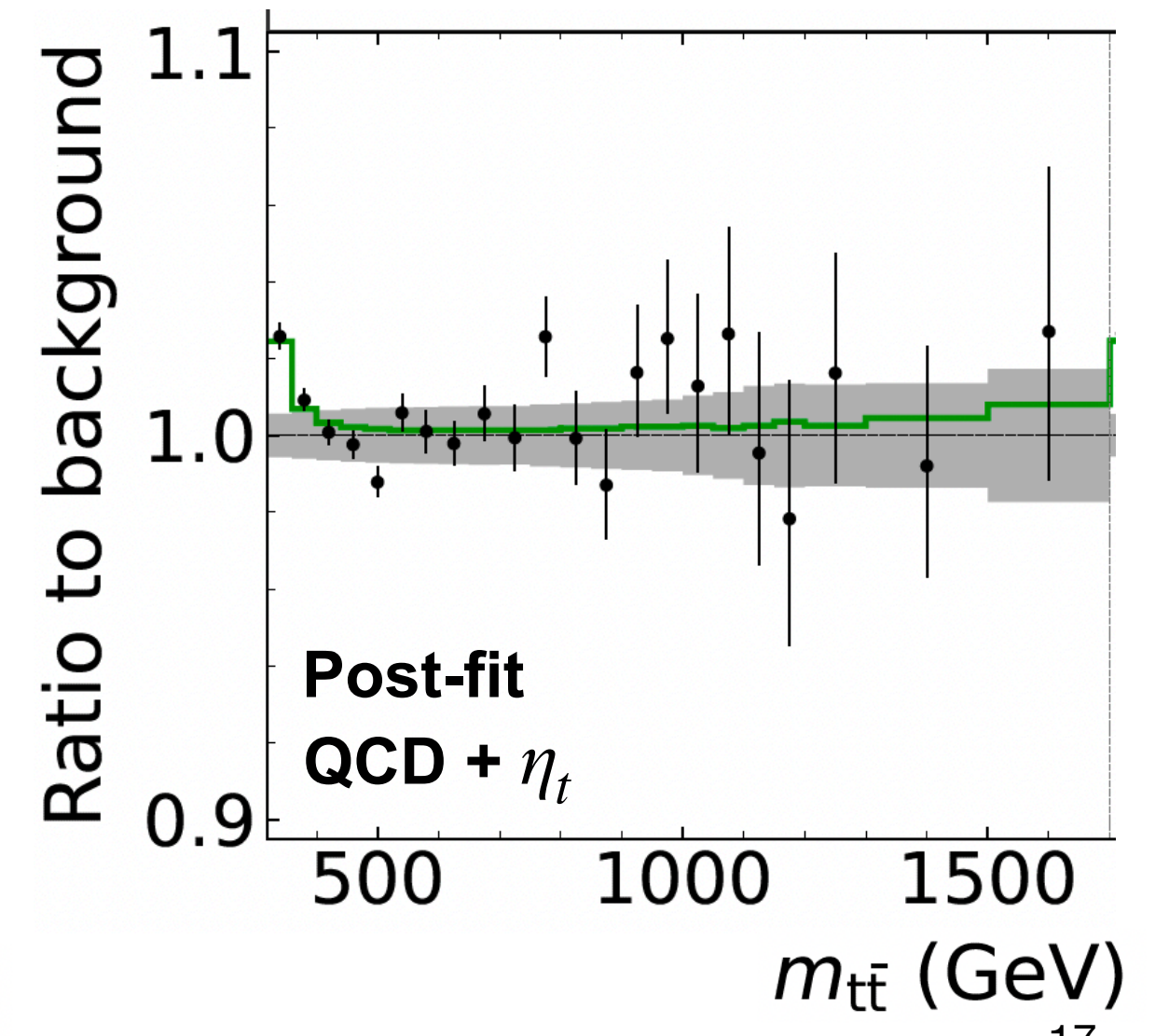
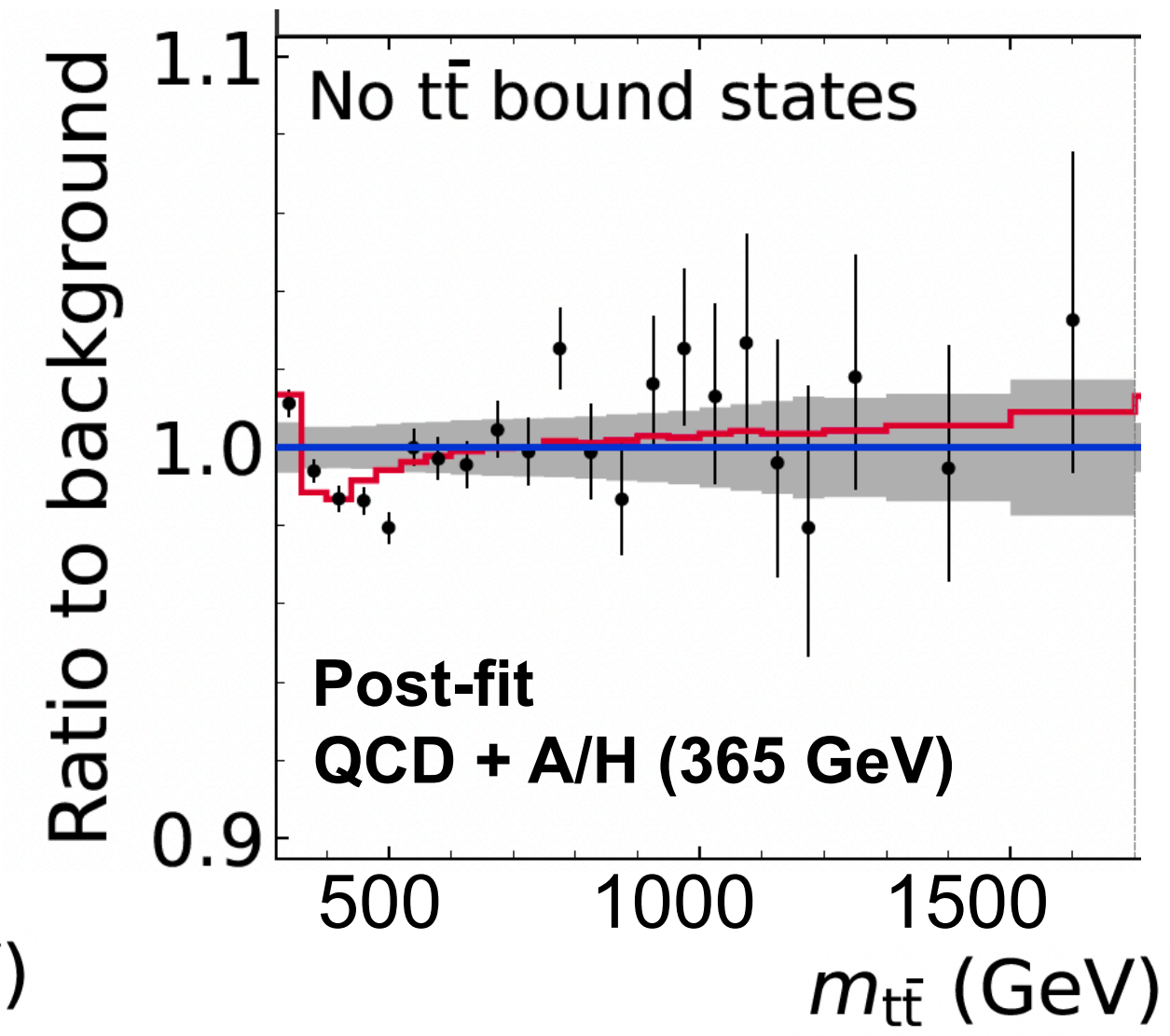
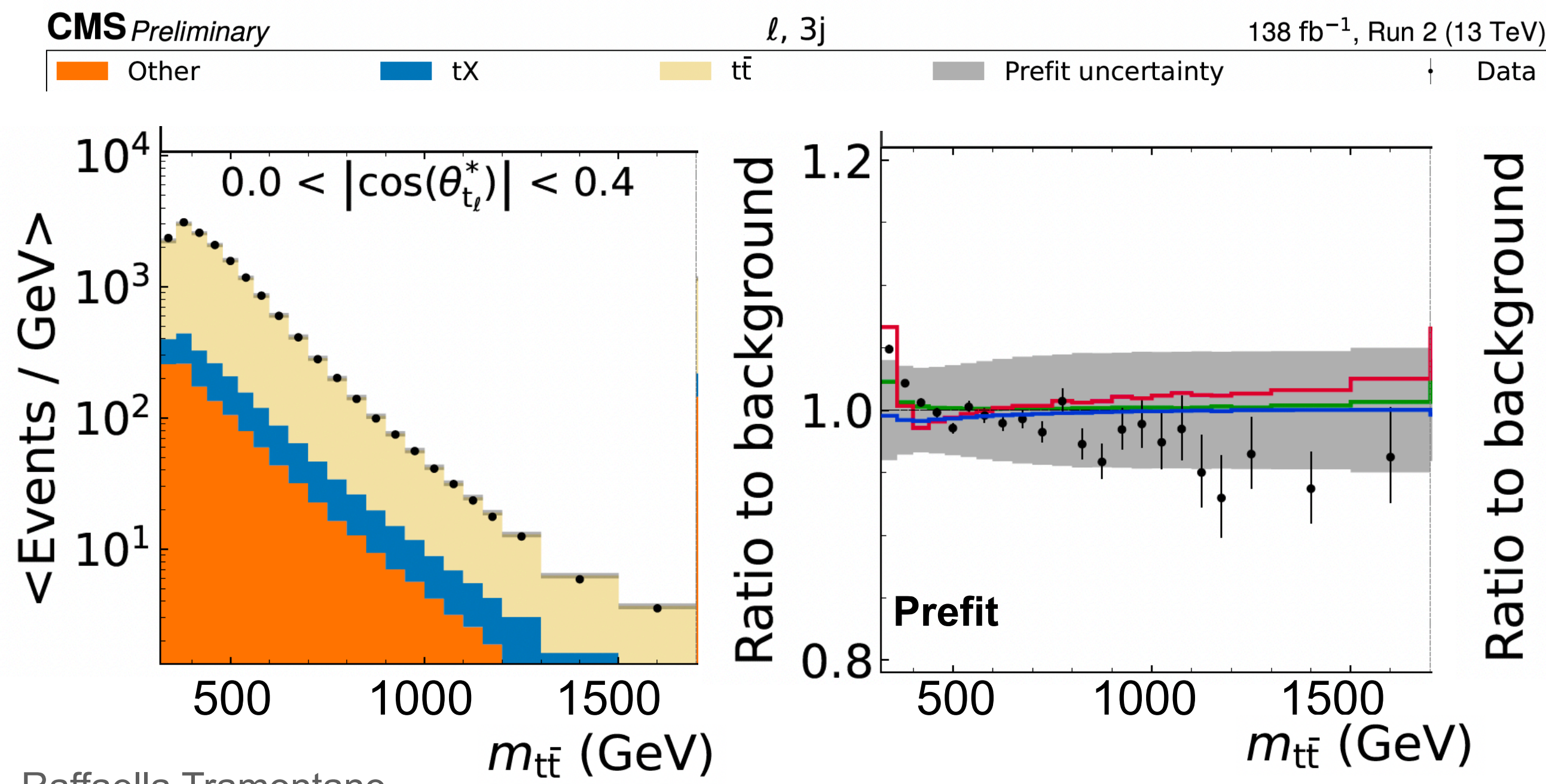
$\phi$  scalar (**H**) or  
pseudoscalar (**A**) boson

Non relativistic QCD

$\eta_t$ :  $t\bar{t}$  bound state

## Strategy:

- Two channels:
  - $\ell + > 3$  jets
  - $\ell\ell + > 2$  jets
- $t$ : fully reconstructed kinematics (algebraic)
- $t\bar{t}$  spin dependent variables for selection/categorization
- Check  $m_{t\bar{t}}$  for discrepancies from QCD only

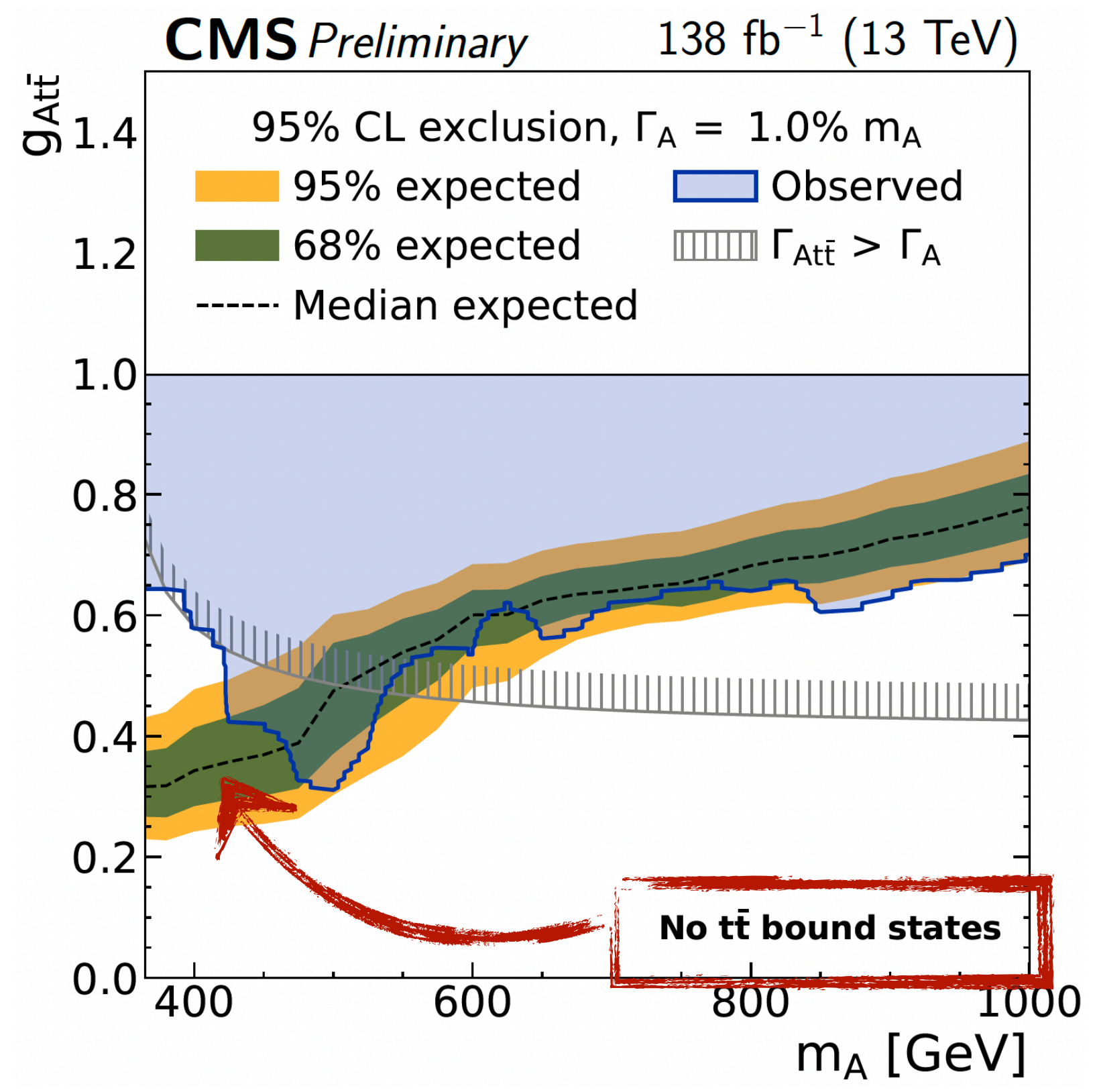
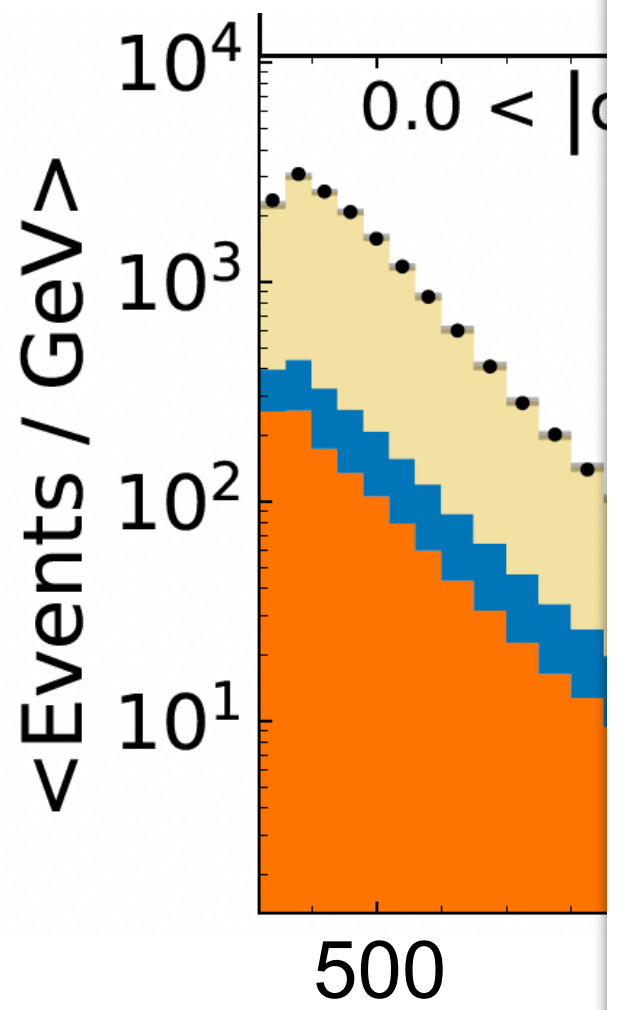


# Observation of a new structure @ top-antitop threshold

QCD (with p

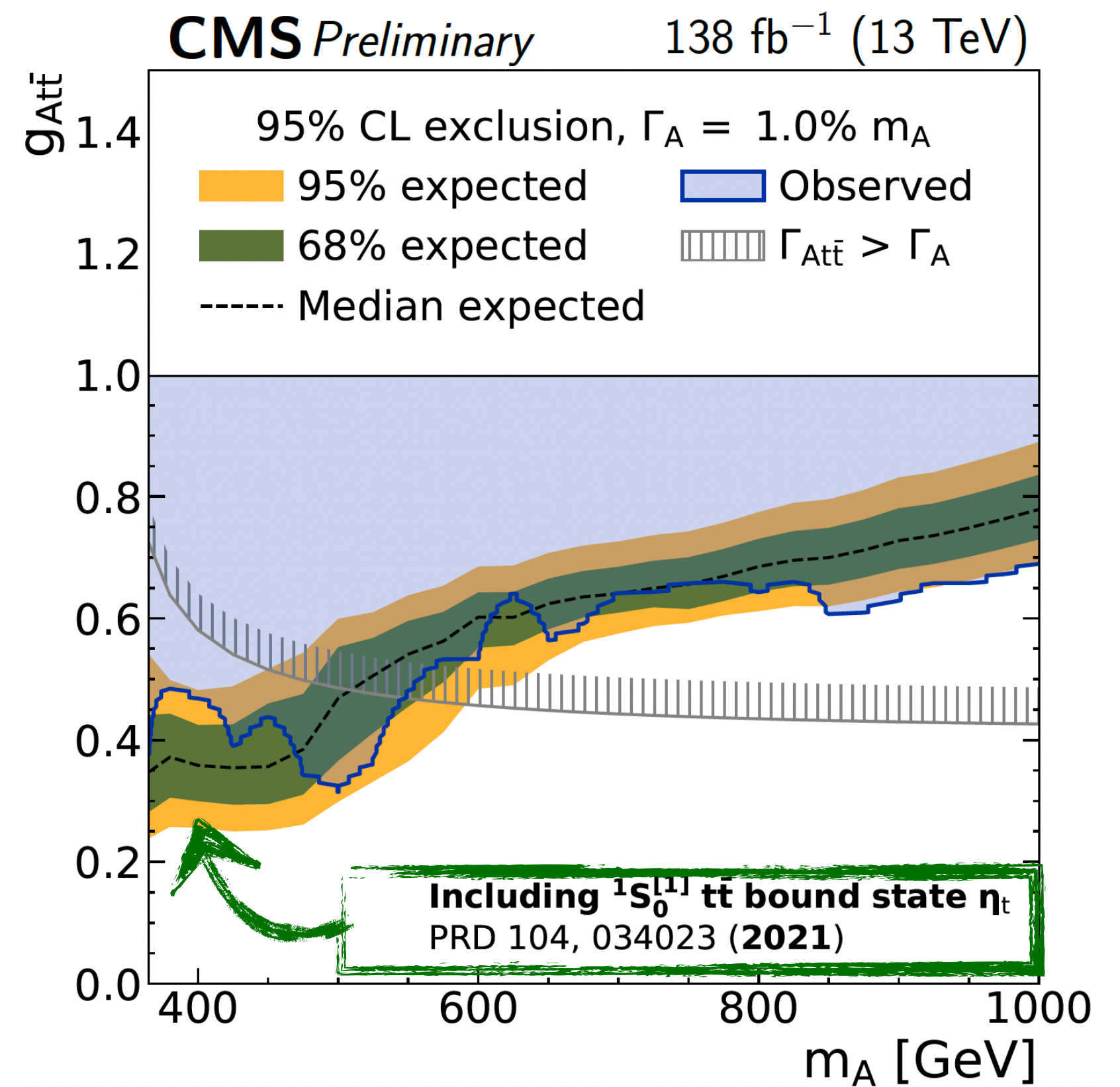
$\phi$  scal  
pseudosca

CMS Preliminary  
Other



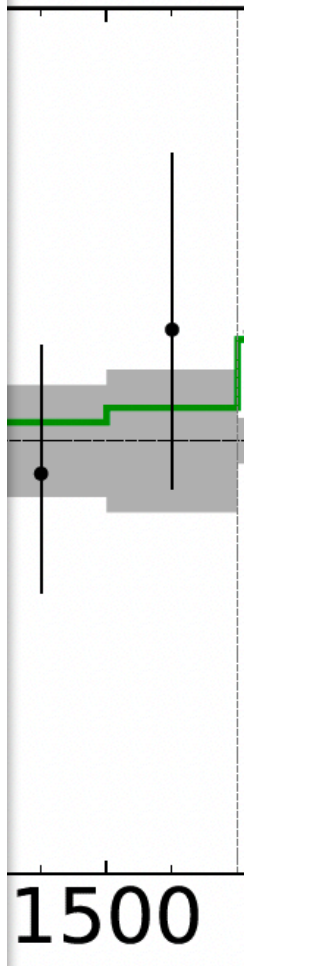
Deviation from pQCD is observed  
> 5 $\sigma$  significance

Close to  $t\bar{t}$  production threshold (~350 GeV)  
Favours pseudoscalar hypothesis over scalar



When plugged in with QCD,  
no other significant deviation observed

only



# Conclusion

- Beyond the SM physics calls for **original** approaches
- Today: (Non exhaustive) review of tailored approaches in
  - **Models**
  - **Tools**
  - **Signatures**
  - **Corners**
- **Hints (or maybe not only hints)** of possible BSM physics
- Run2 and early Run3 data: perfect **playground**
  - Novel probes
  - High stats -> high granularity
  - Novel Models

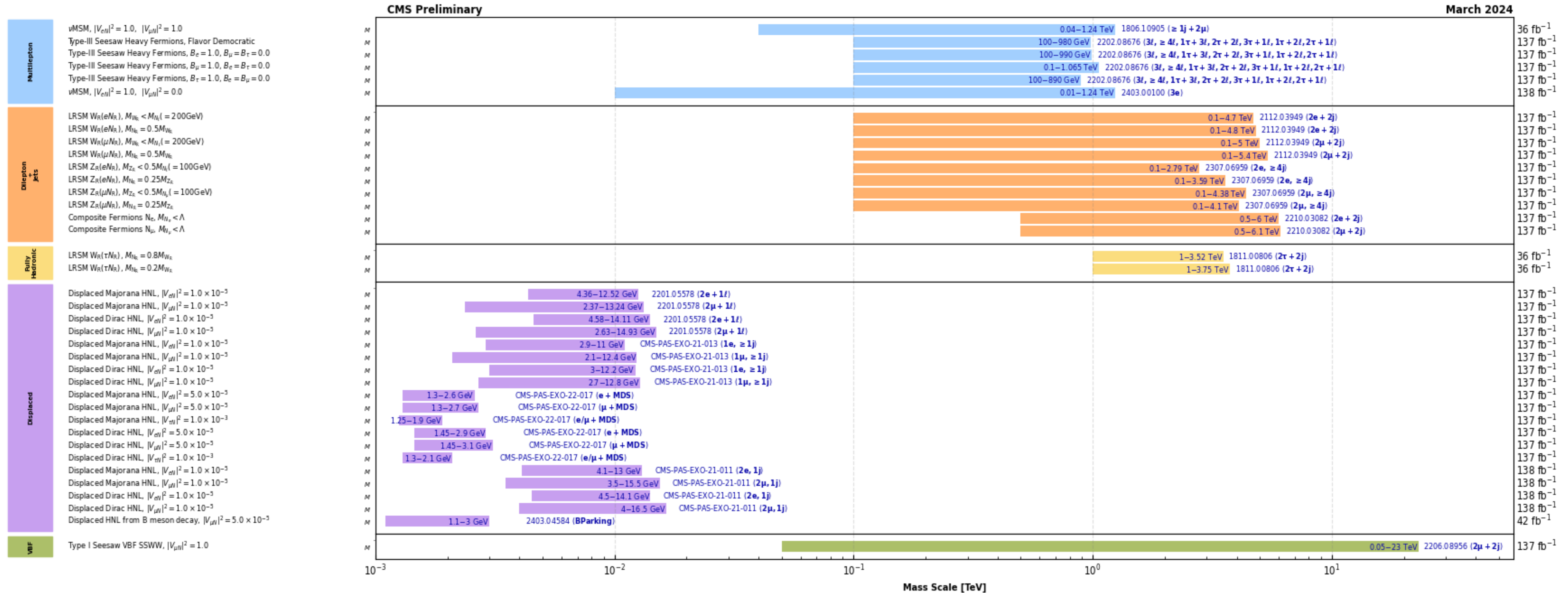
**Towards HL-LHC and future colliders**

CMS BSM public results pages:  
Exotic Searches (EXO)  
BSM to SM bosons and top (B2G)  
Supersimmetry (SUS)

# Backup

# EXO Summary-HNL

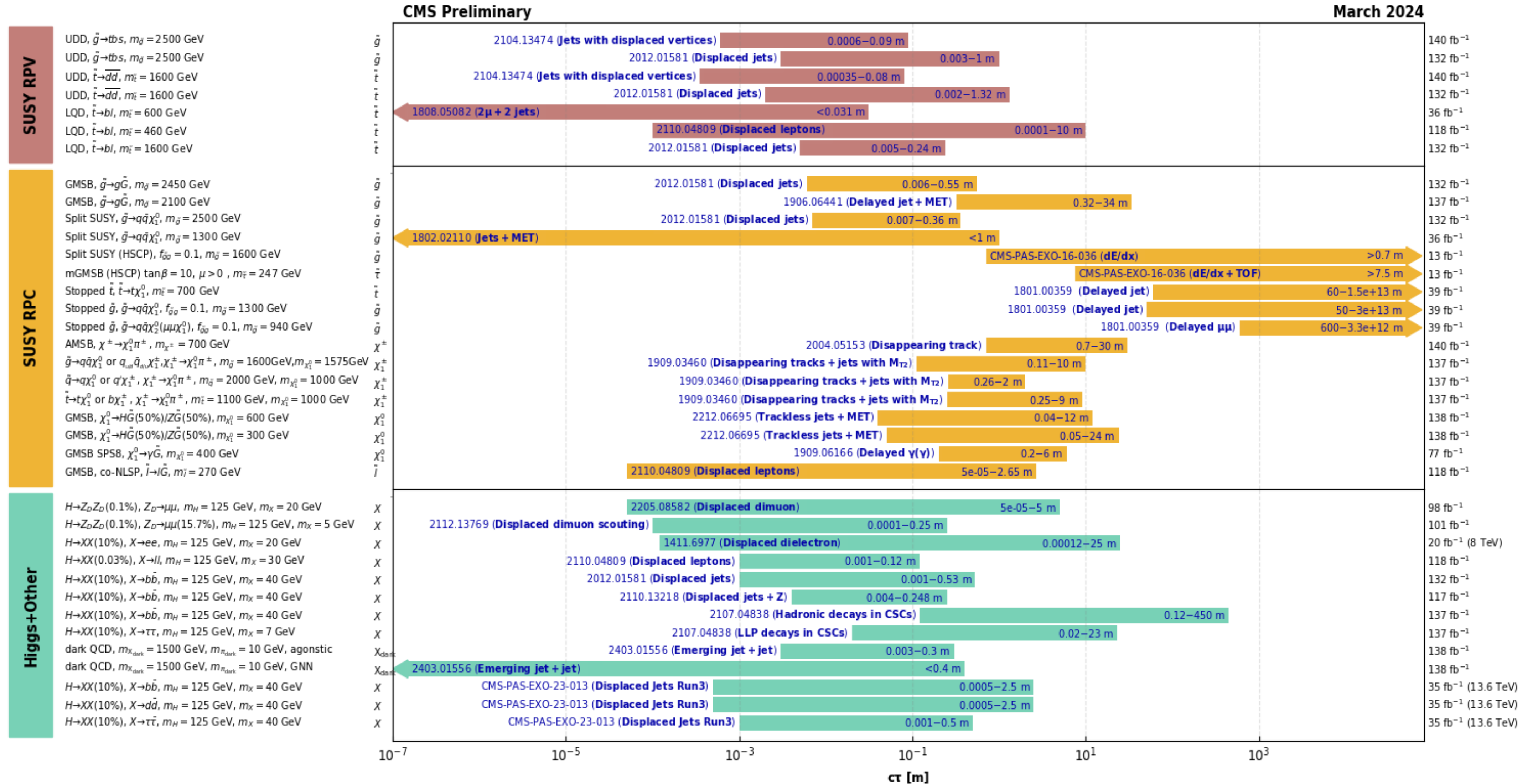
## Overview of CMS HNL results



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

# EXO Summary-LLP

## Overview of CMS long-lived particle searches



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

# B2G Summary

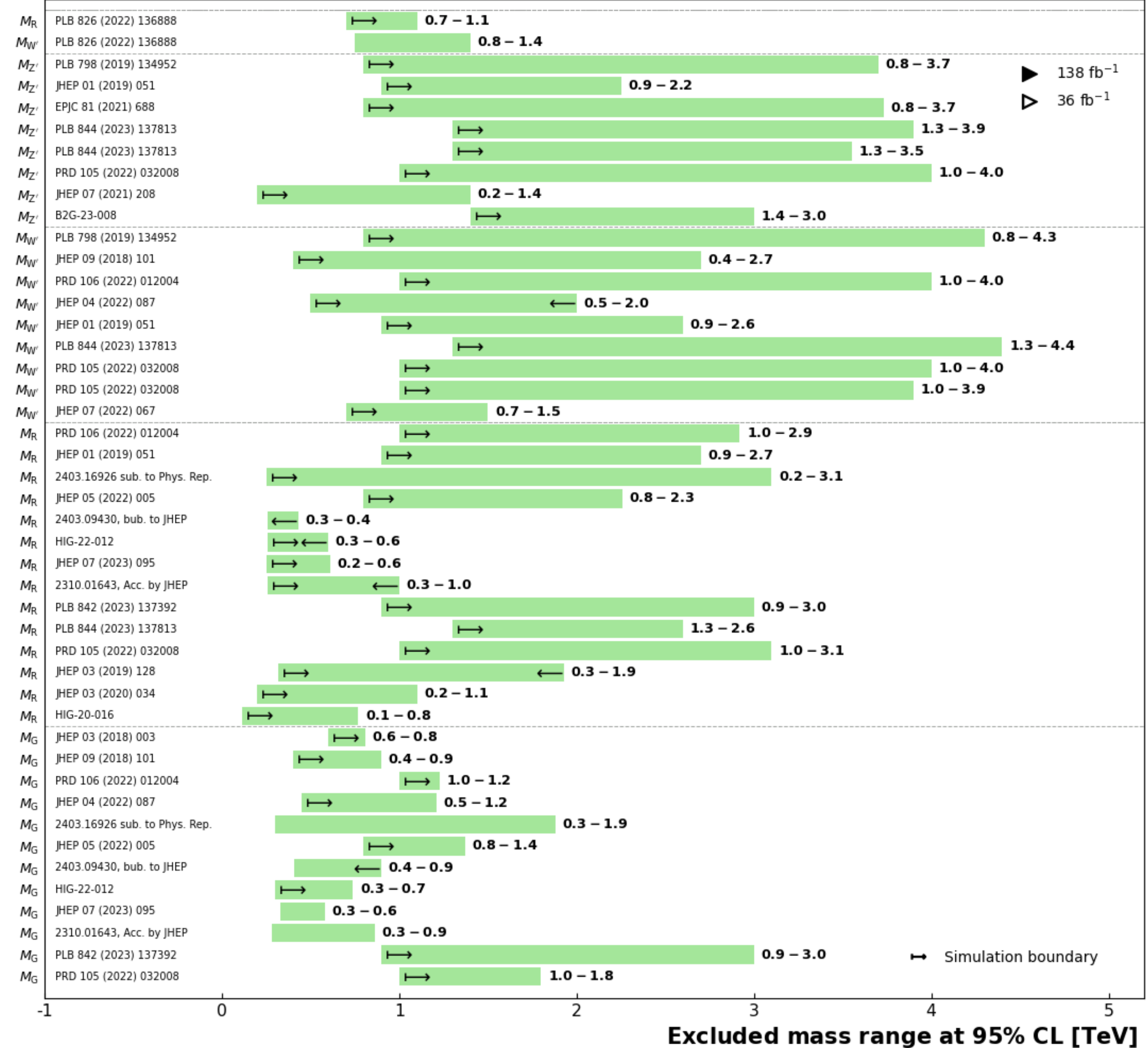
## Overview of CMS B2G Results

June 2024

CMS Preliminary

36 – 138 fb<sup>-1</sup> (13 TeV)

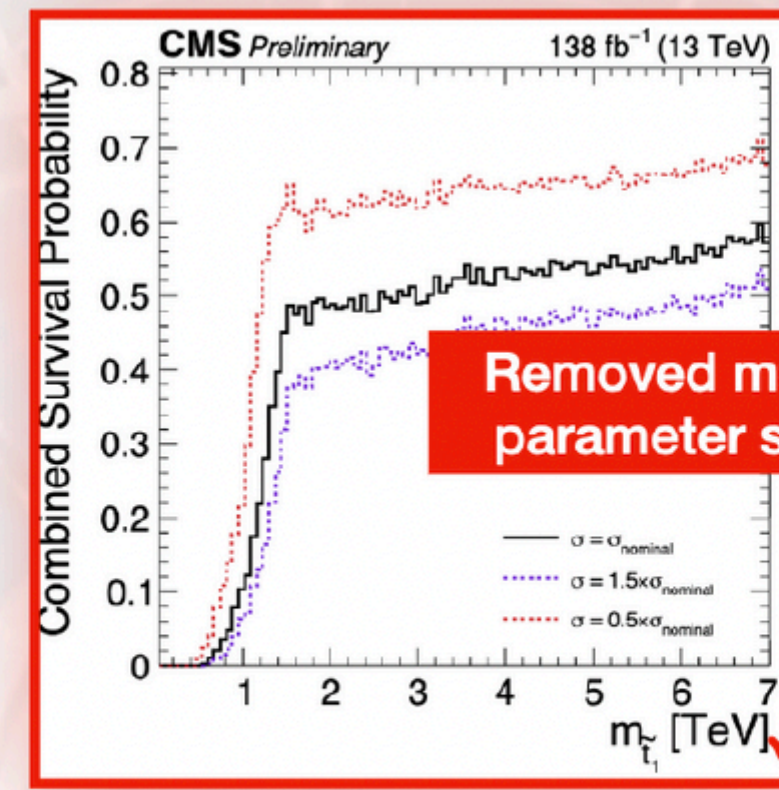
- WW/HH/HH/VV resonances**
- HST**
    - ▶ R → q $\bar{q}$ γ → Wγ (g<sub>m</sub> = 0.1, Λ = 4M<sub>X</sub>)
    - ▶ W' → q $\bar{q}$ γ → Wγ (g<sub>m</sub> = 0.1, Λ = 4M<sub>X</sub>)
    - ▷ Z' (2016 combination)
    - ▷ Z' → ZH → q $\bar{q}$ τ $\bar{\tau}$
  - Z', HVT B**
    - ▶ Z' → ZH → (ll, νν)b $\bar{b}$
    - ▶ Z' → ZH → q $\bar{q}$ q $\bar{q}$
    - ▶ Z' → WW → q $\bar{q}$ q $\bar{q}$
    - ▶ Z' → WW → lνq $\bar{q}$
    - ▶ Z' → ll
    - ▶ Z' → ZH → llνν, cc/4q
  - W', HVT B**
    - ▷ W' (2016 combination)
    - ▷ W' → WZ → llq $\bar{q}$
    - ▶ W' → WZ → ννq $\bar{q}$
    - ▶ W' → WZ → llq $\bar{q}$
    - ▷ W' → WH → q $\bar{q}$ τ $\bar{\tau}$
    - ▶ W' → WZ → q $\bar{q}$ q $\bar{q}$
    - ▶ W' → WH → lνq $\bar{q}$
    - ▶ W' → WZ → lνq $\bar{q}$
    - ▶ W' → lν
  - Radion, Λ<sub>R</sub> = 3 TeV**
    - ▶ R → ZZ → ννq $\bar{q}$
    - ▷ R → HH → q $\bar{q}$ τ $\bar{\tau}$
    - ▶ R → HH (combination)
    - ▶ R → HH → b $\bar{b}$ WW (lep.) merged-jet
    - ▶ R → HH → b $\bar{b}$ WW (lep.)
    - ▶ R → HH → ττγγ (not in HH Comb.)
    - ▶ R → HH → multi-leptons
    - ▶ R → HH → γγb $\bar{b}$
    - ▶ R → HH → b $\bar{b}$ b $\bar{b}$  merged-jet
    - ▶ R → VV → q $\bar{q}$ q $\bar{q}$
    - ▶ R → WW → lνq $\bar{q}$
    - ▷ R → ZZ
    - ▷ R → WW
    - ▶ R → WW
  - Bulk G, κ/M<sub>pl</sub> = 0.5**
    - ▷ G → ZZ → llνν
    - ▷ G → ZZ → llq $\bar{q}$
    - ▶ G → ZZ → ννq $\bar{q}$
    - ▶ G → ZZ → llq $\bar{q}$
    - ▶ G → HH (combination)
    - ▶ G → HH → b $\bar{b}$ WW (lep.) merged-jet
    - ▶ G → HH → b $\bar{b}$ WW (lep.)
    - ▶ G → HH → ττγγ (not in HH Comb.)
    - ▶ G → HH → multi-leptons
    - ▶ G → HH → γγb $\bar{b}$
    - ▶ G → HH → b $\bar{b}$ b $\bar{b}$  merged-jet
    - ▶ G → WW → lνq $\bar{q}$



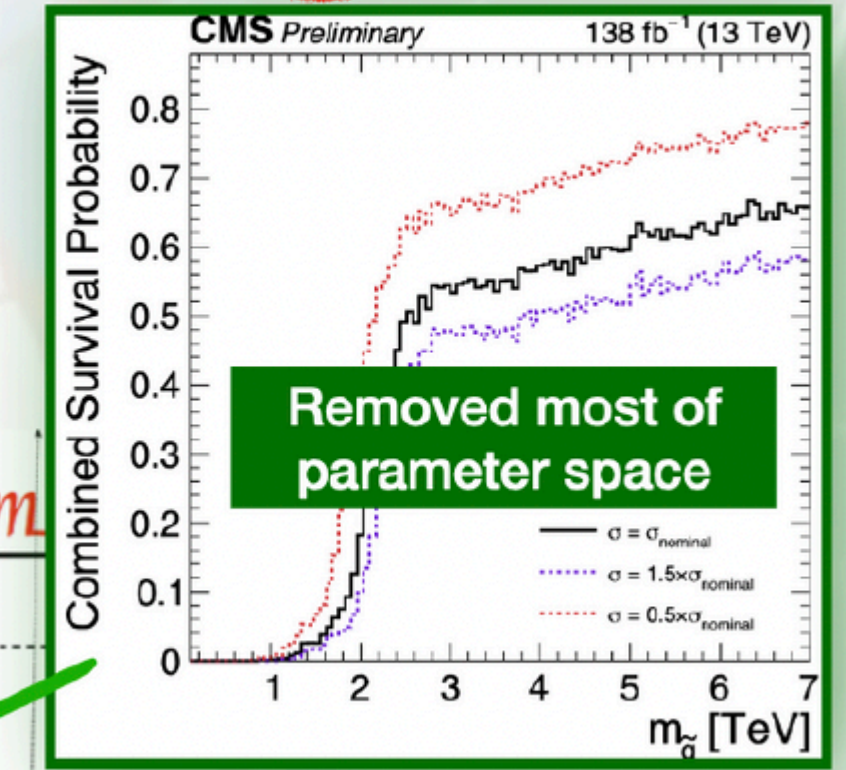
# Phenomenological MSSM interpretation of CMS searches

M. Pierini's talk @ICHEP2024

- Performed first statistical combination of SUSY searches with full Run2 luminosity
- In the framework of phenomenological MSSM (pMSSM): 19 free parameters
- Useful tool to identify weak spots in our program
- Gives us a big picture under realistic assumptions (e.g., on relative branching ratios)
  - quantified as fraction of tested models that survive the exclusion



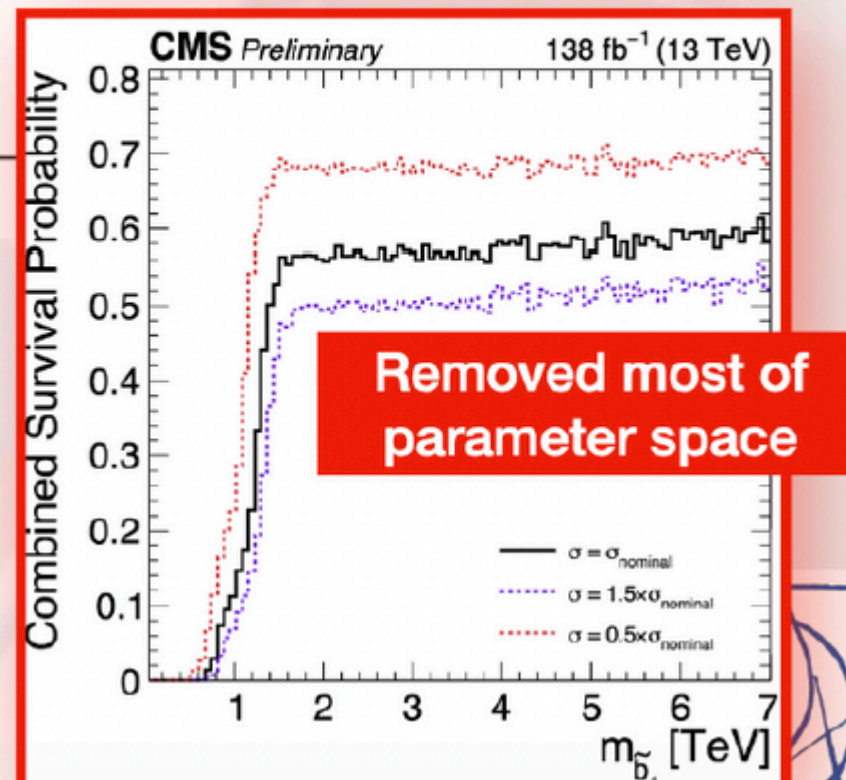
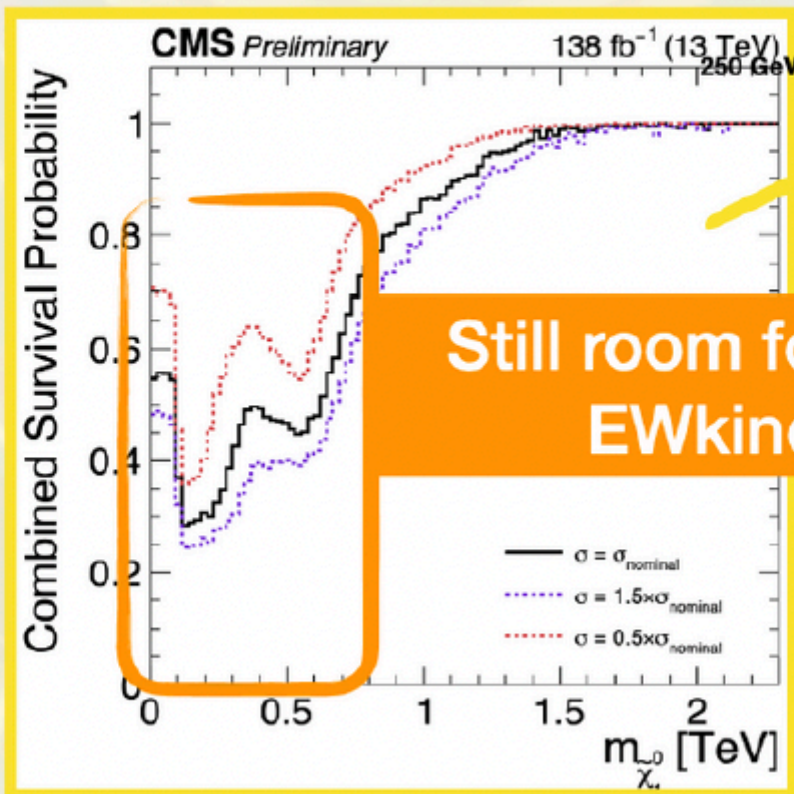
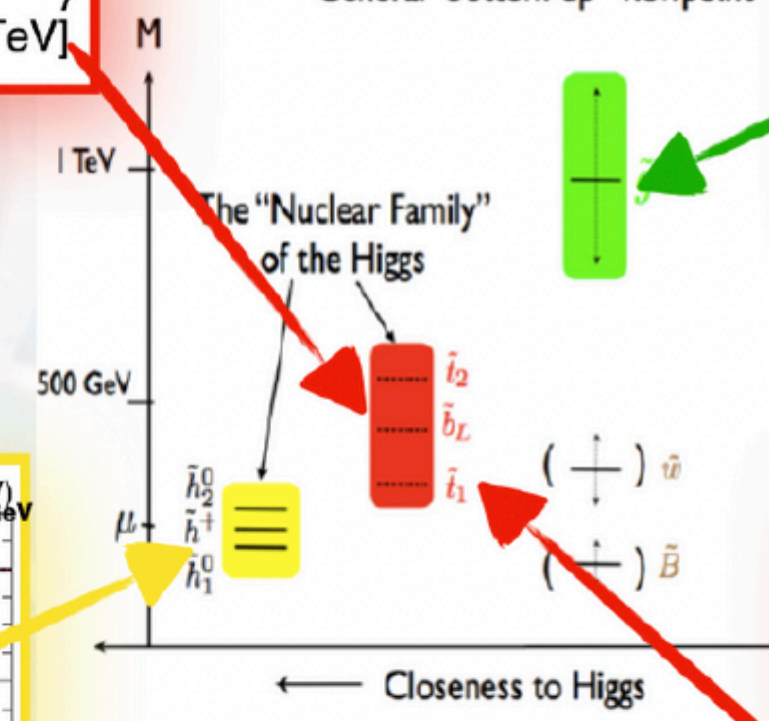
**CMS-PAS-SUS-24-004** New



Removed most of parameter space

Removed most of parameter space

*A Natural Spectrum*  
General "bottom-up" viewpoint



Still room for light EWkinos

Removed most of parameter space



# $t\bar{t}$ comparison with ATLAS

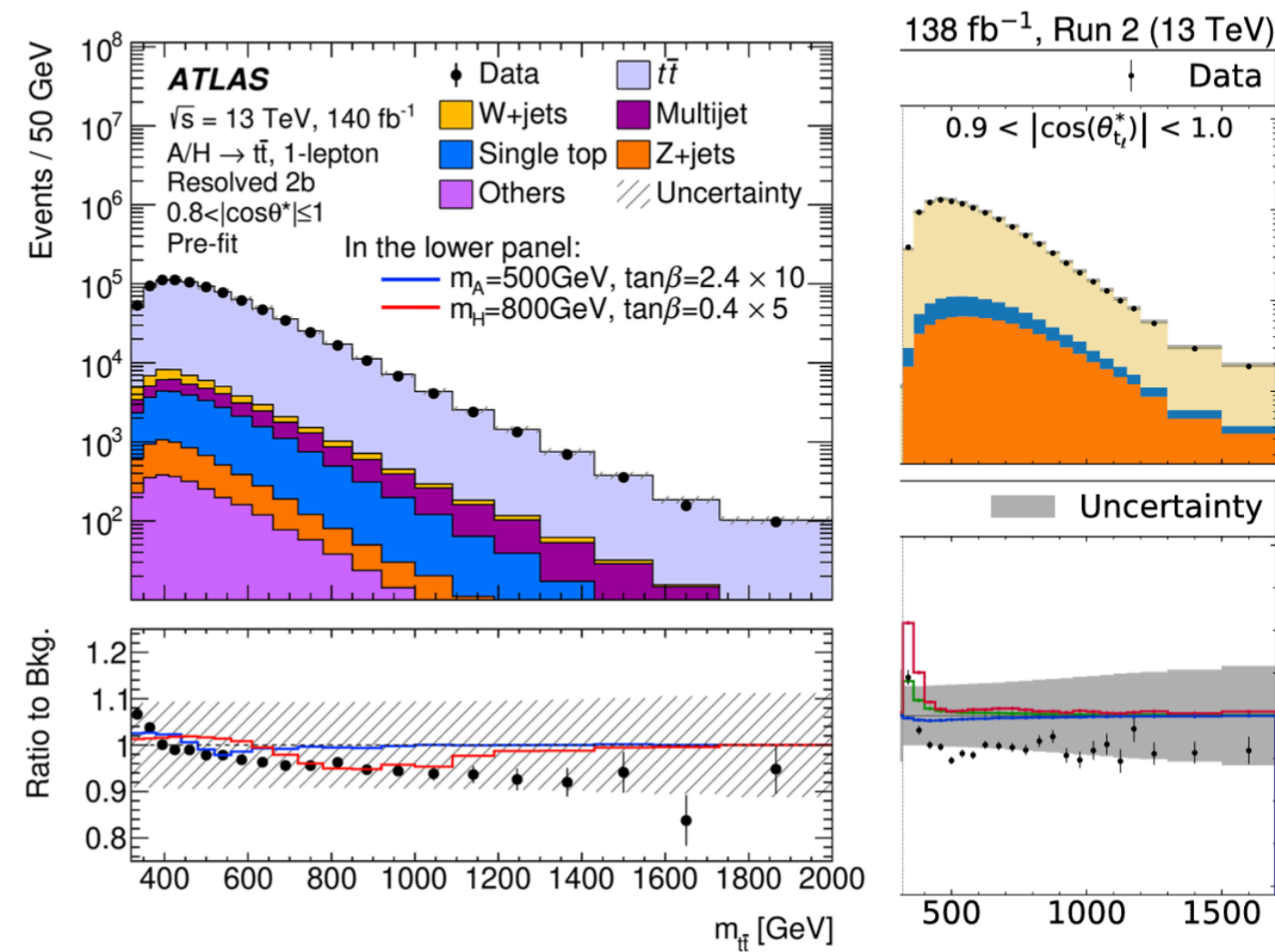
## Comparison with ATLAS - $\ell j$

- 1 $\ell$ , 2b,  $\geq 4$  jets category for both ATLAS and CMS  $\rightarrow$  compare pre-fit

E.g. high  $|\cos\theta^*|$  :

Similar excess in data in low  $m_{t\bar{t}}$  bins!

Also in  $\ell\ell$  (backup)



13.09.2024

Approval talk of HIG-22-013 | Laurids Jeppe

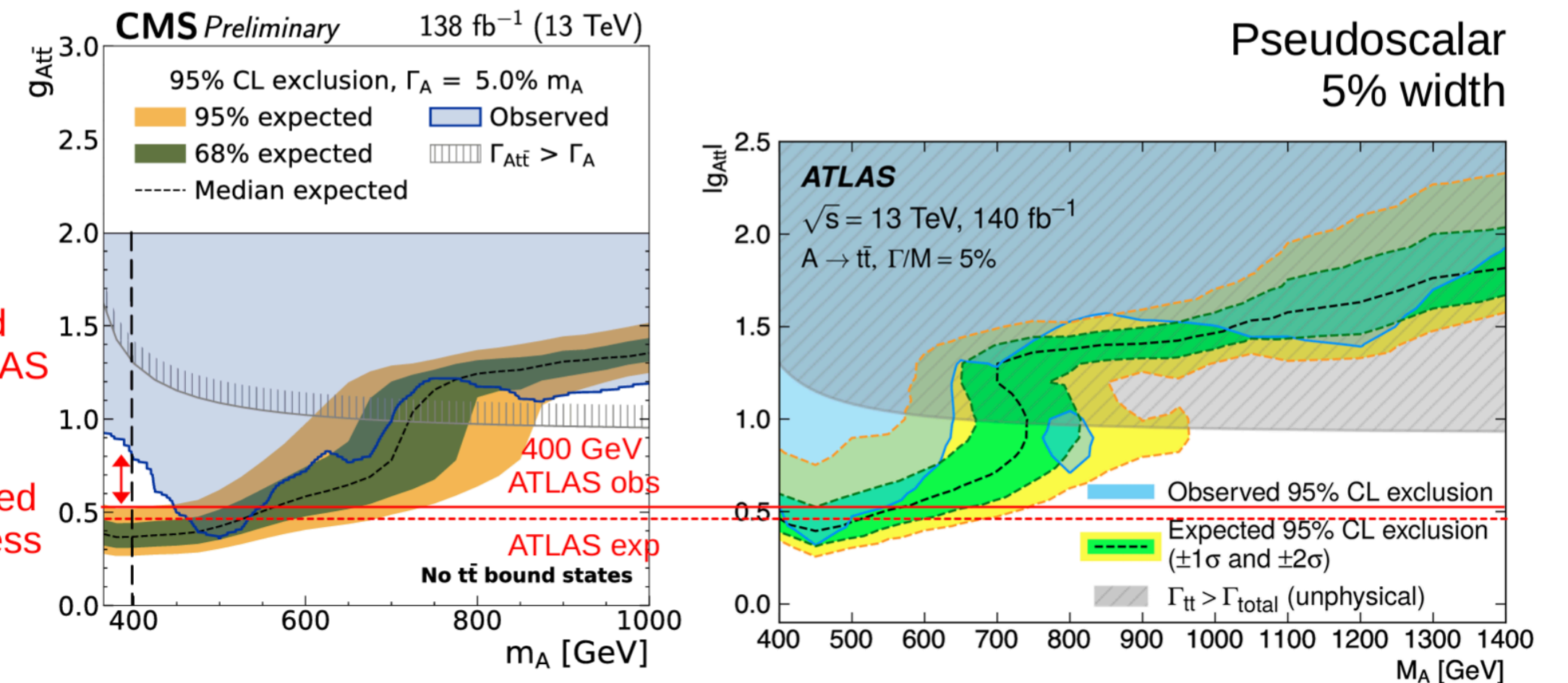
43 DE

## Comparison with ATLAS

- ATLAS has published a Run 2 result for  $A/H \rightarrow t\bar{t}$ : JHEP08 (2024) 013
- They see **no excess** and make **no mention of toponium** /  $t\bar{t}$  bound states  $\rightarrow$  need to understand the differences!

No observed excess for ATLAS

ATLAS expected limits slightly less sensitive



13.09.2024

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40 DESY.