EXOTIC SEARCHES in CMS

Jeremi Niedziela (DESY)
for CMS Collaboration

Outline

Searches for BSM particles decaying to Higgs, top and Gauge bosons (B2G)

- Search for **W' bosons** decaying to a top and a bottom quark in leptonic final states B2G-20-012
- Search for a **heavy resonance** decaying into a **top quark and a W boson** in the lepton+jets final state B2G-21-055 B2G-20-010

Exotica (EXO)

- Search for prompt production of a GeV scale **resonance** decaying to a **pair of muons** EXO-21-005
- Search for **dark matter** particles produced in W^+W^- events with transverse momentum imbalance EXO-21-012

INTRODUCTION

Why search for new physics at LHC?

- dark Matter,
- dark Energy,
- baryon asymmetry in the Universe,
- origin of neutrino masses,
- gravity and quantum mechanics,
- fine-tuning of the Higgs mass,
- hierarchy of fermion masses,
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And what could explain it?

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This talk

Presented results (unless stated otherwise):

- **proton-proton** collisions at $\sqrt{s}$ =13 TeV,
- full LHC **Run 2** data,
- luminosity: **138 fb^{-1}**.

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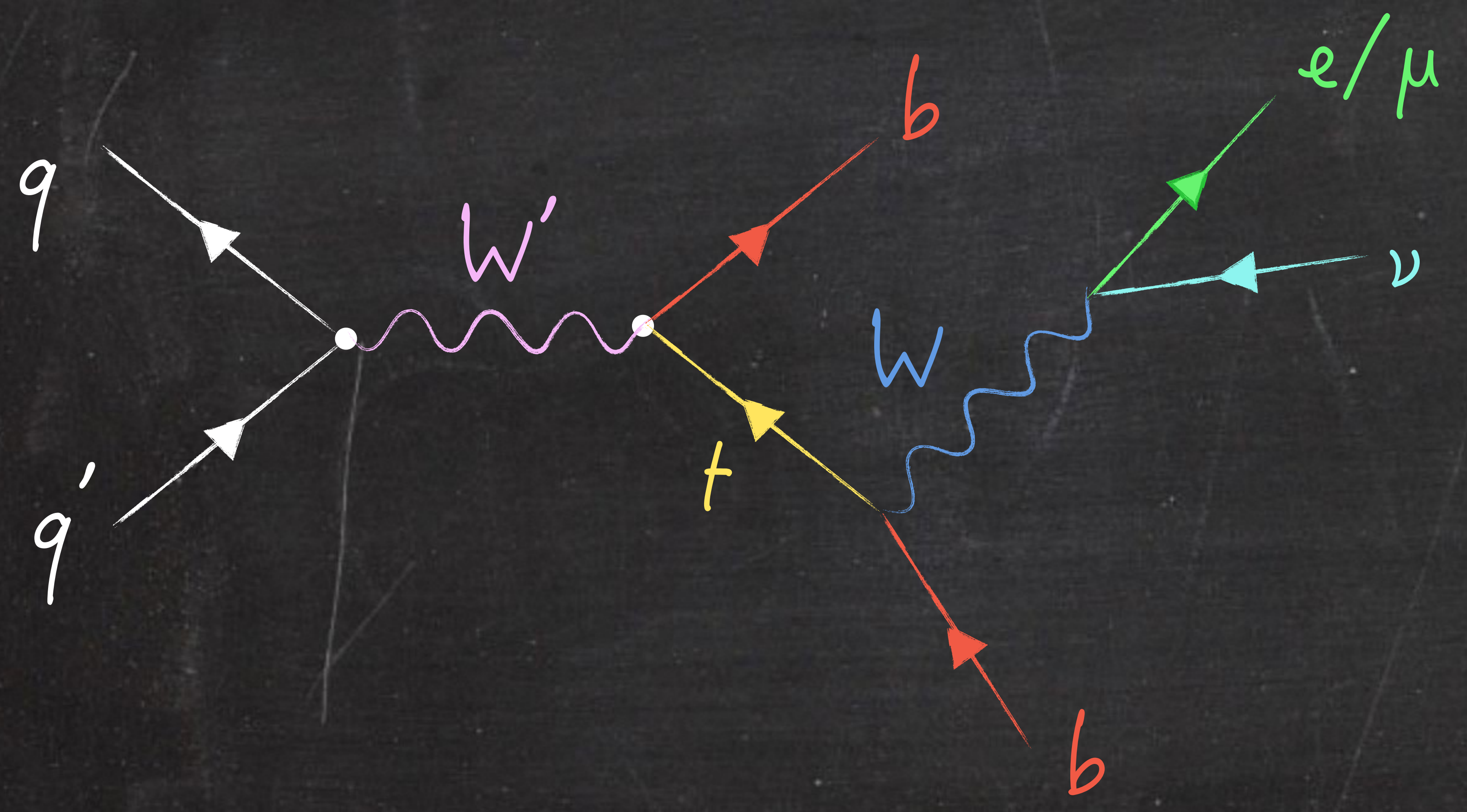
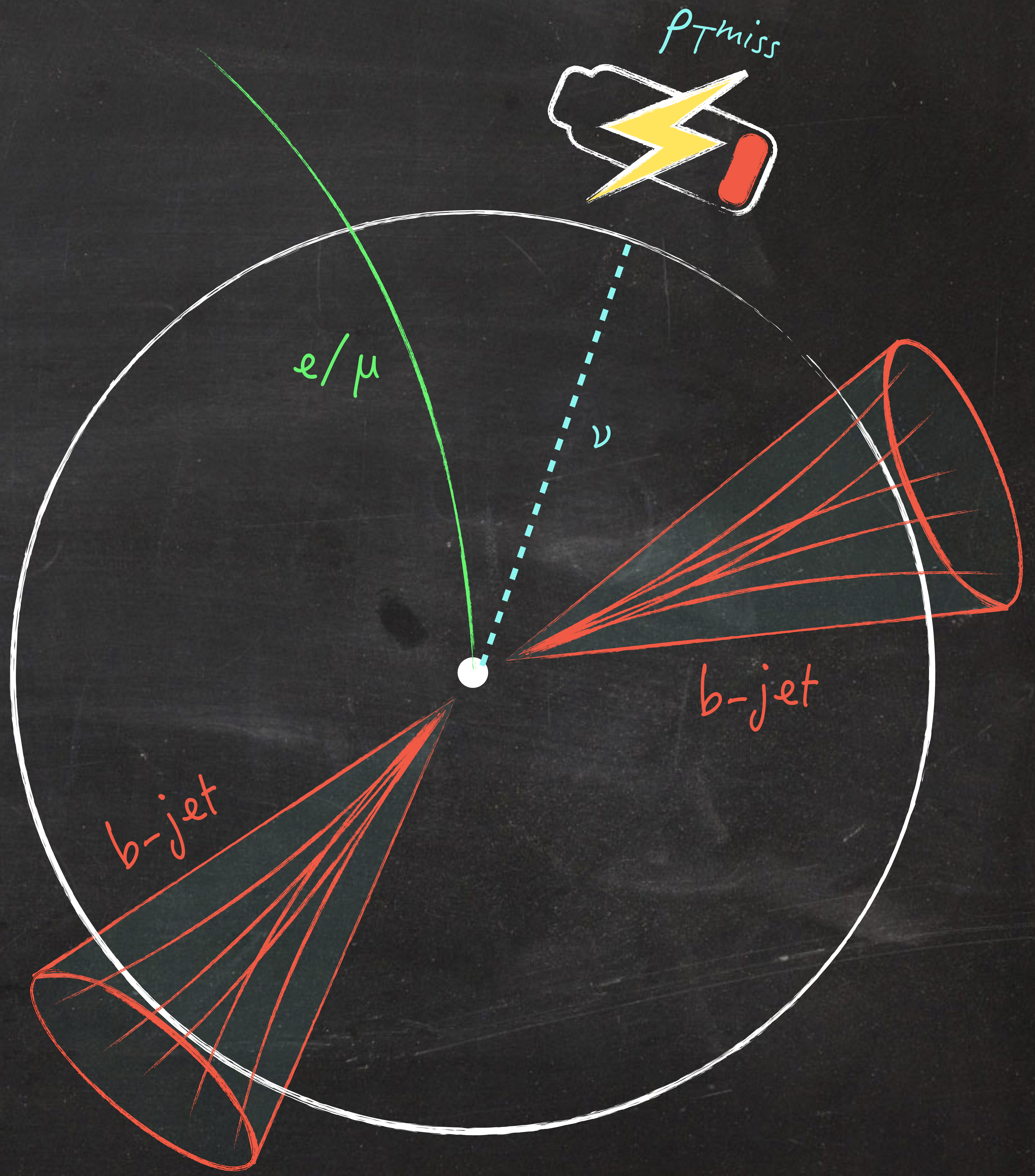
W' SEARCH

- target: **multi-TeV mass** range (2-6 TeV considered)
  → completing previous searches (< 3 TeV)
- top quark → distinct signature
- different width (1, 10, 20, 30%) and chirality assumptions
  → interpretations for **wide range of models**





Analysis details

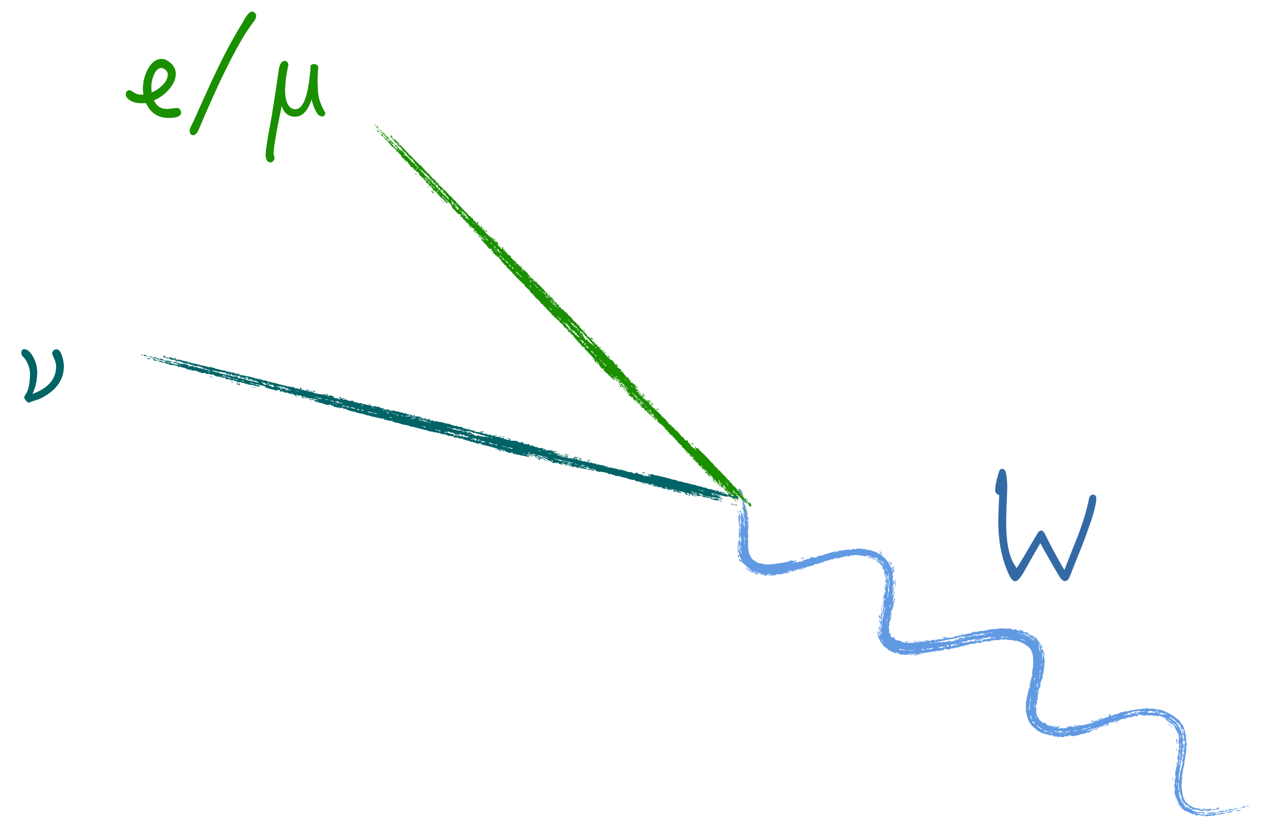
- backgrounds: W+jets, QCD, $t\bar{t}$, single top
- signal/control regions: number of b-tagged top/W' jets

W' search

B2G-20-012

reconstruct W

Assume: $p_T^{\nu} = p_T^{miss}$, $m_l = 0$ → use lepton 4-vector → **Find p_Z^{ν}, such that** $m_{\nu l} = m_W$



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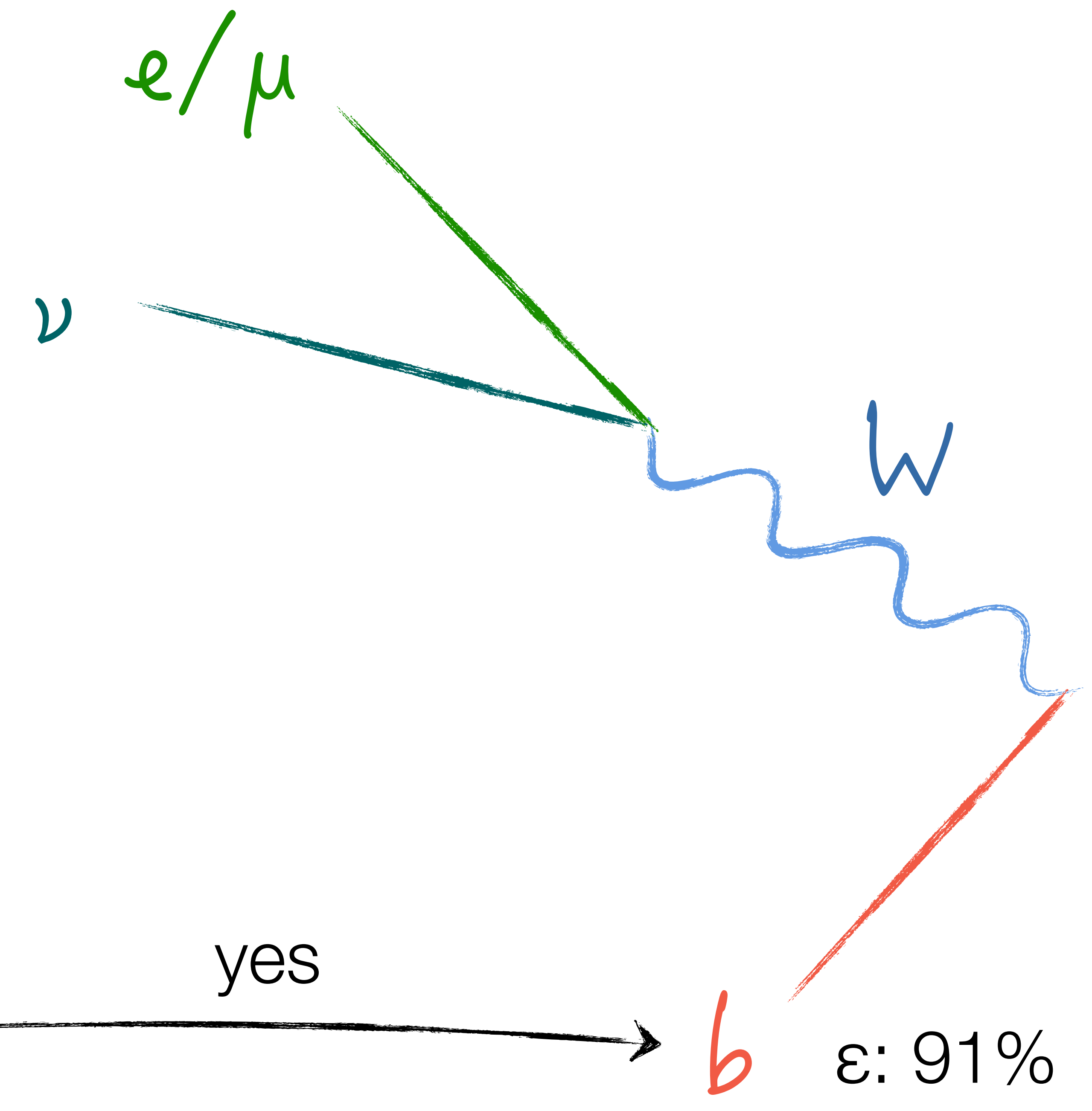

ε: 91%

find b-jet originating **from top**

- **smallest $|m_{jet,W} - m_{top}|$**
- **smallest ΔR(jet, lepton)**
- **sub-leading jet**

→ **same jet ≥2 criteria?**

yes → b

no → **mass criterion decides** → b

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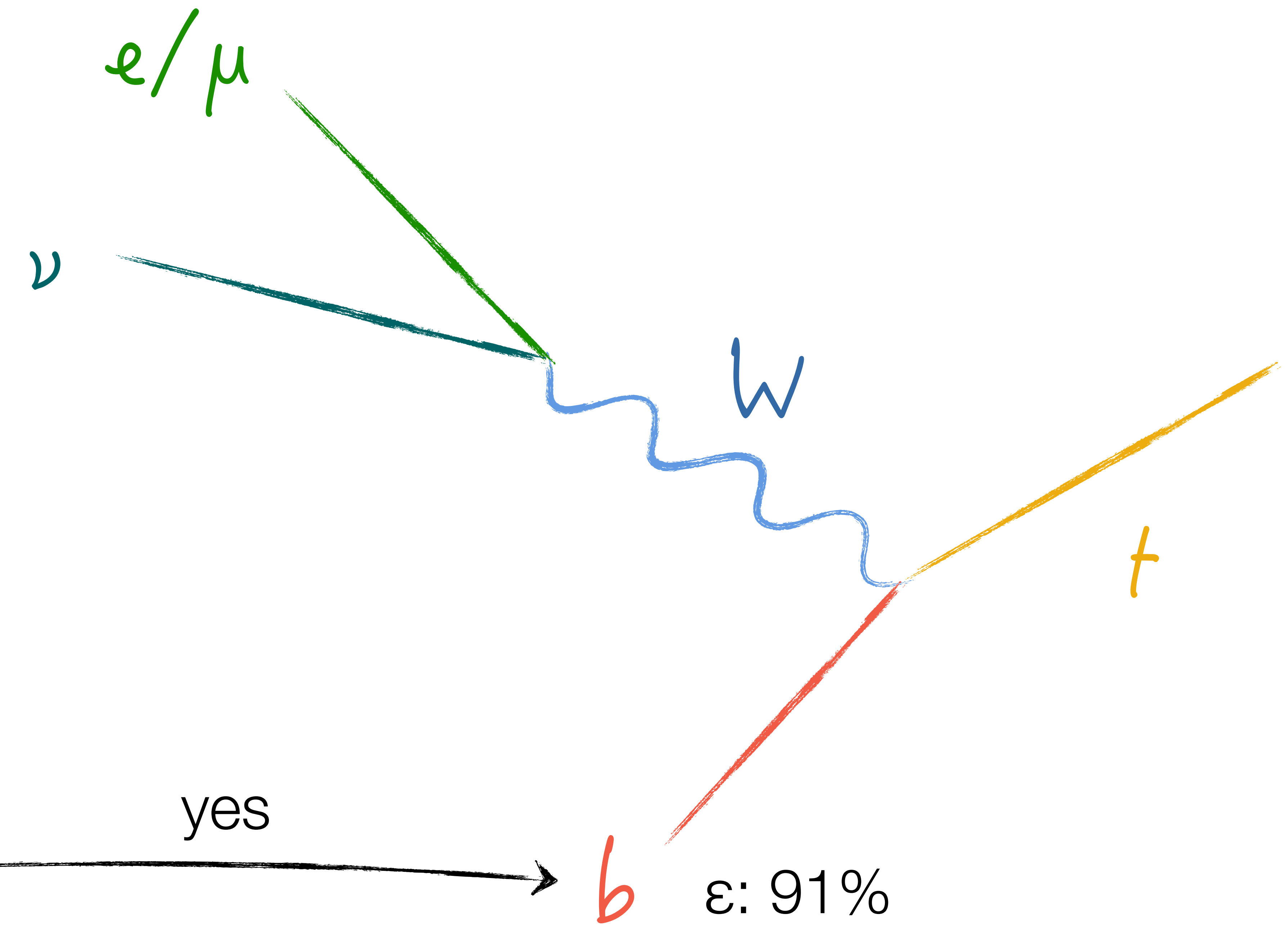

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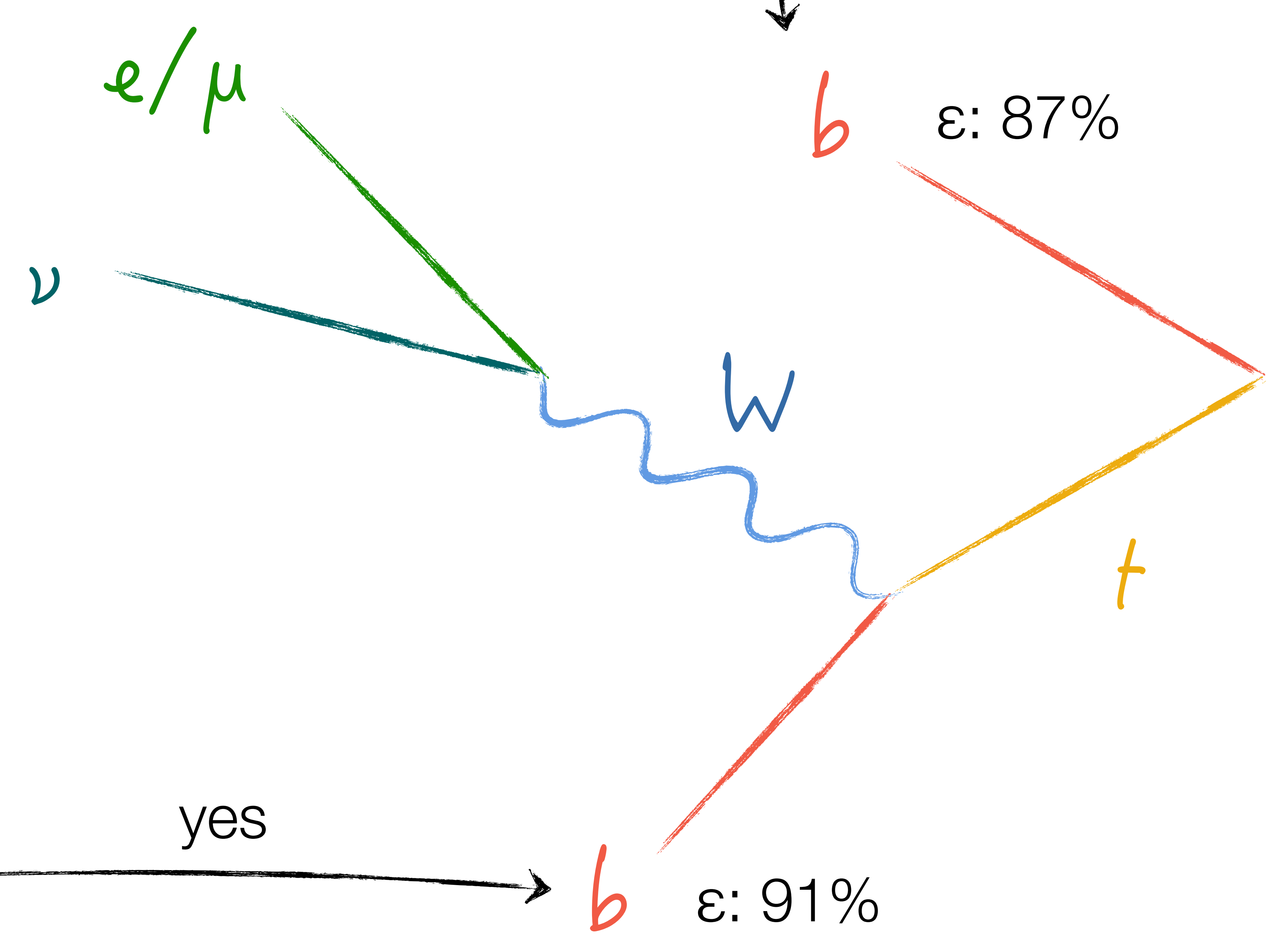

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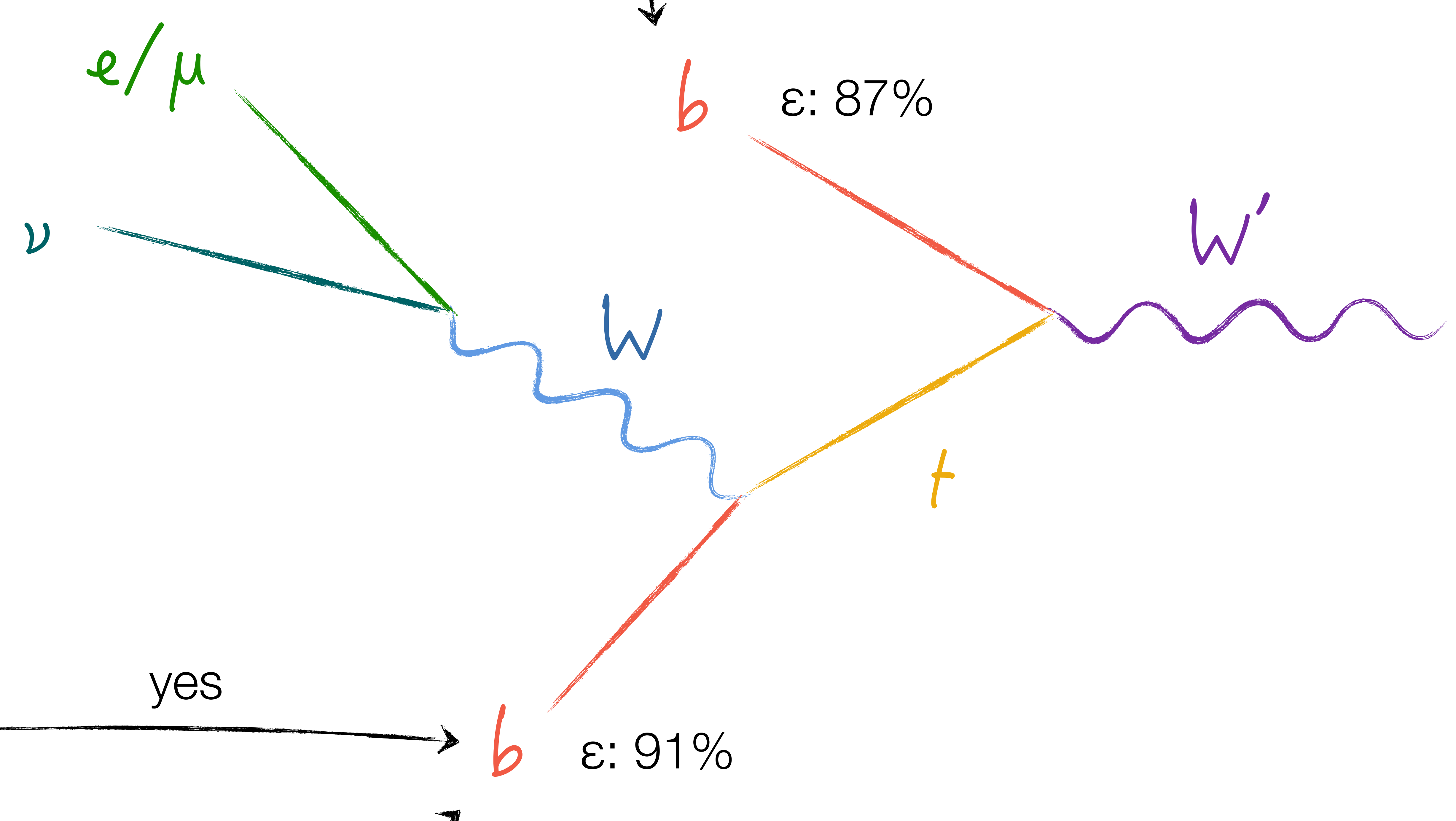

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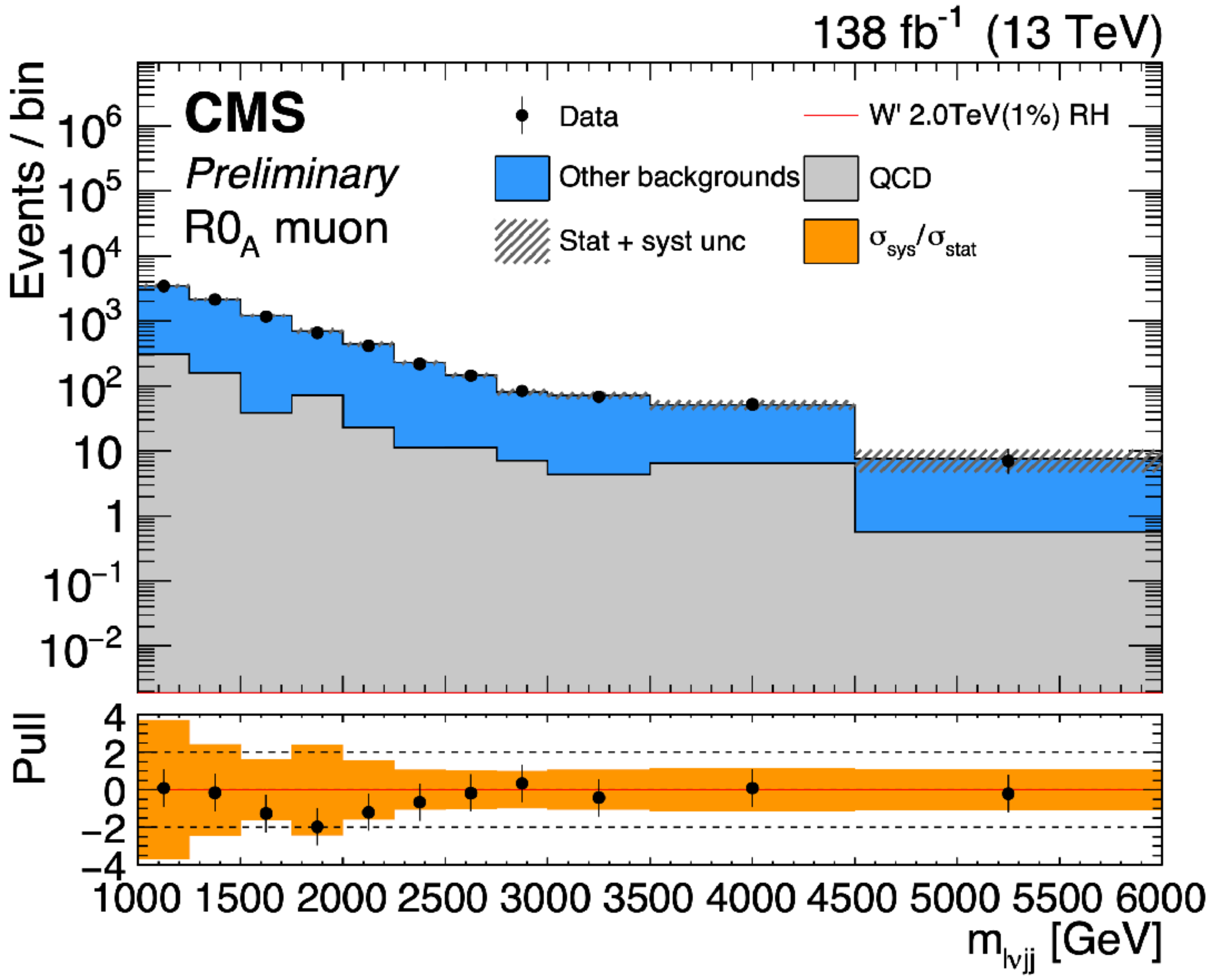

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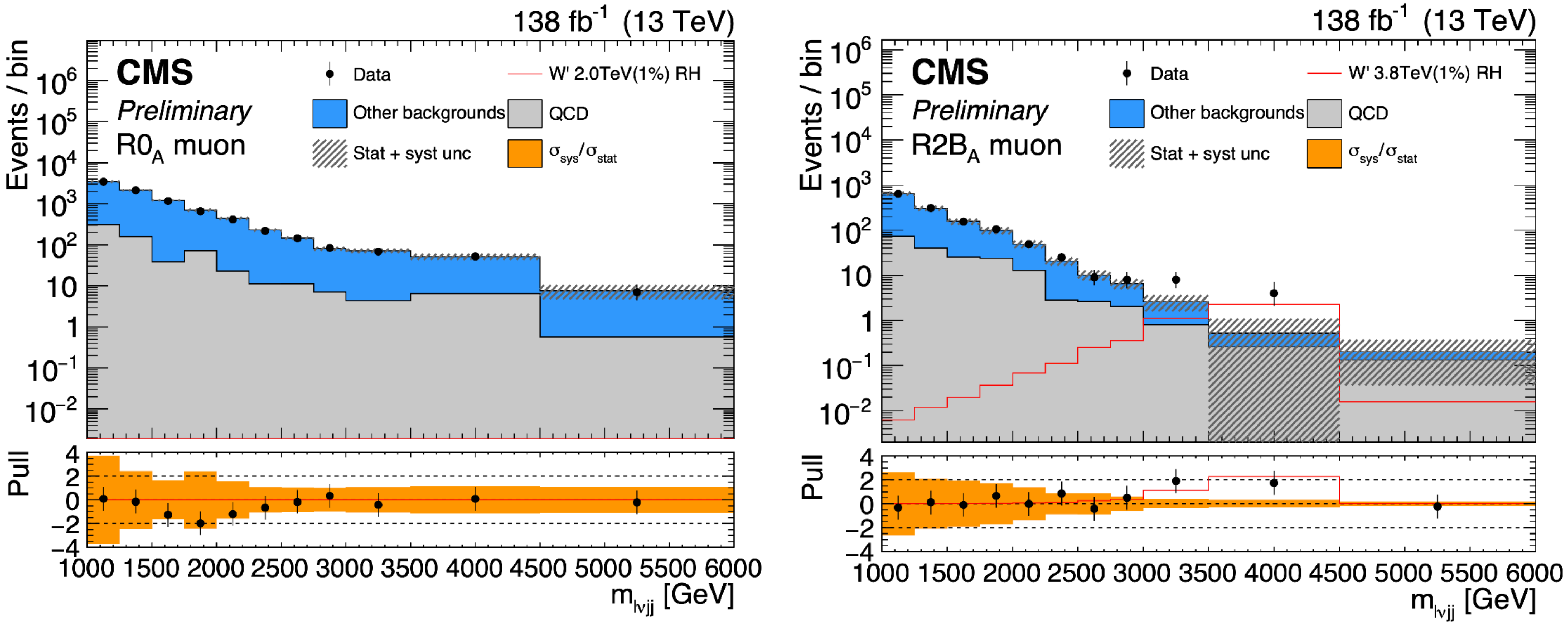

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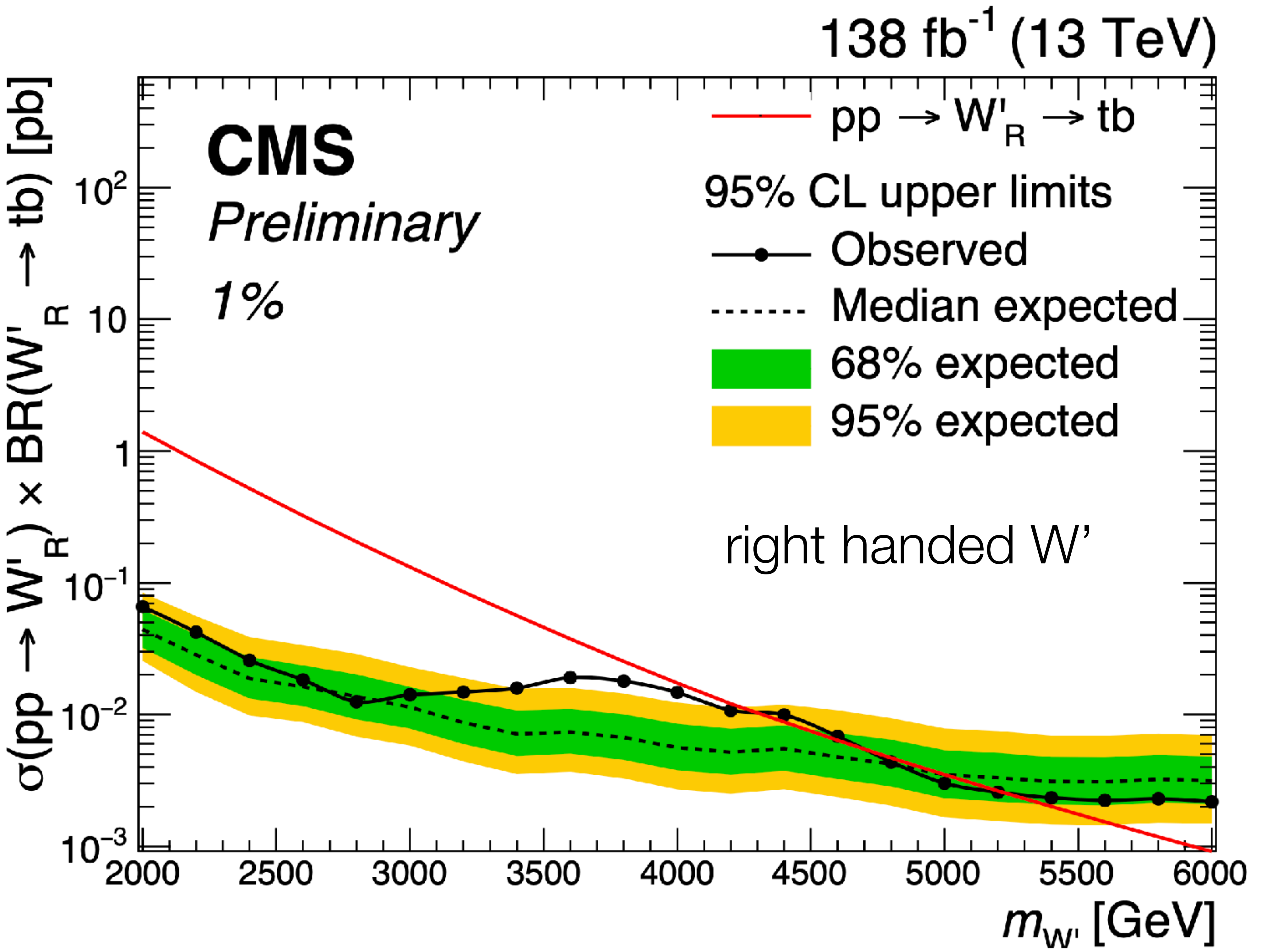
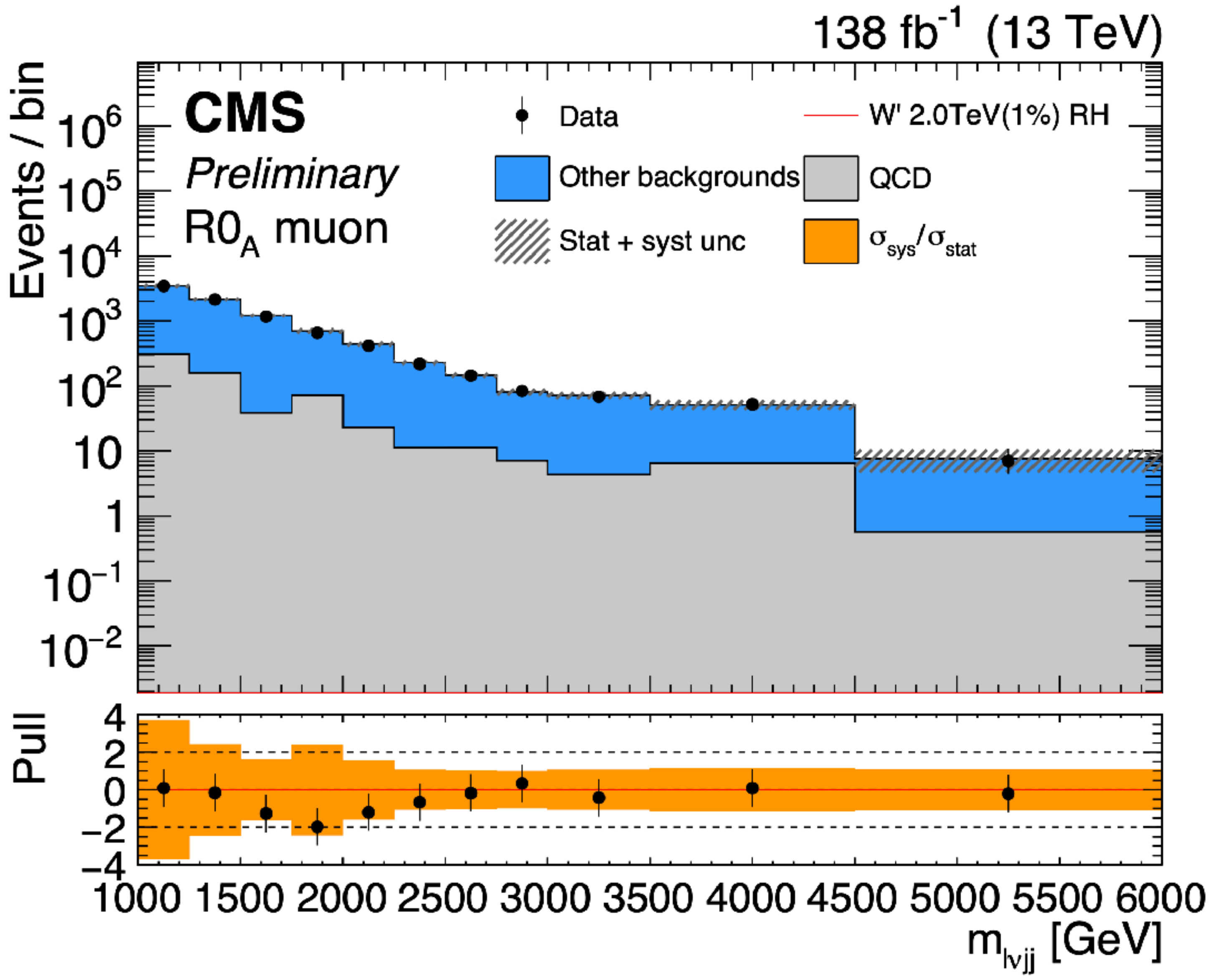
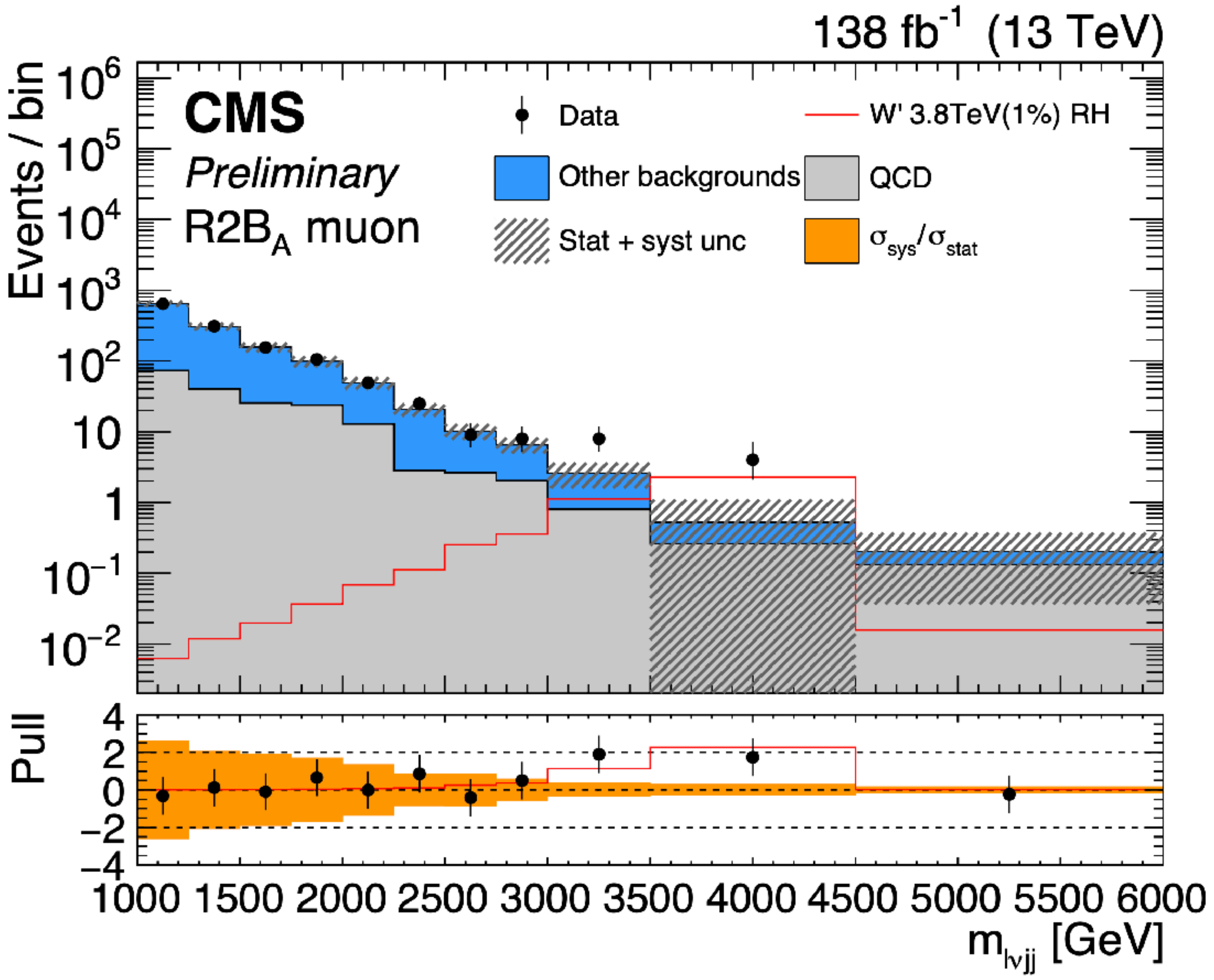
- **simultaneous fit** in all signal regions for e/μ final states,
- limits on RH and LH W', with different widths.

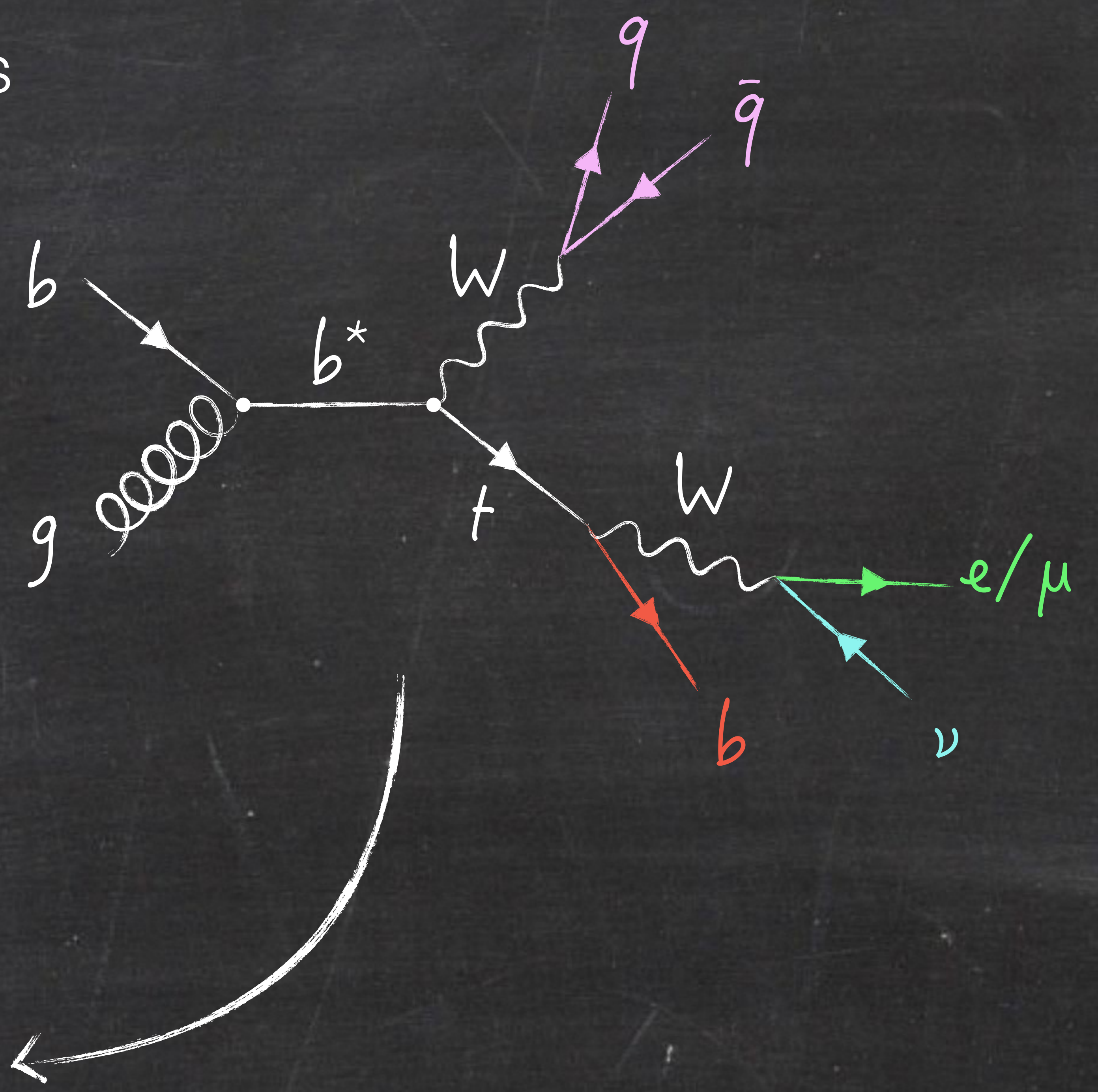


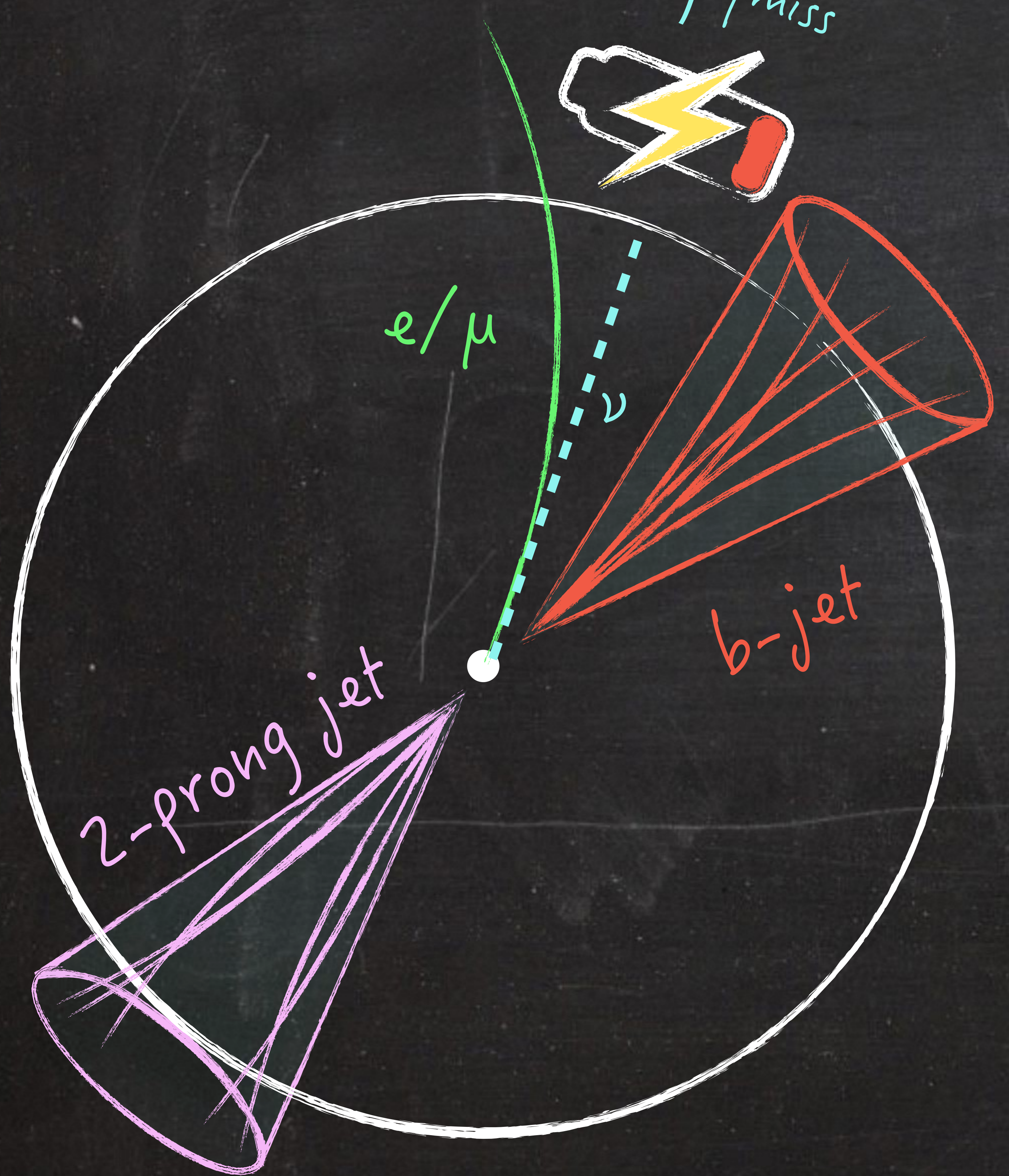


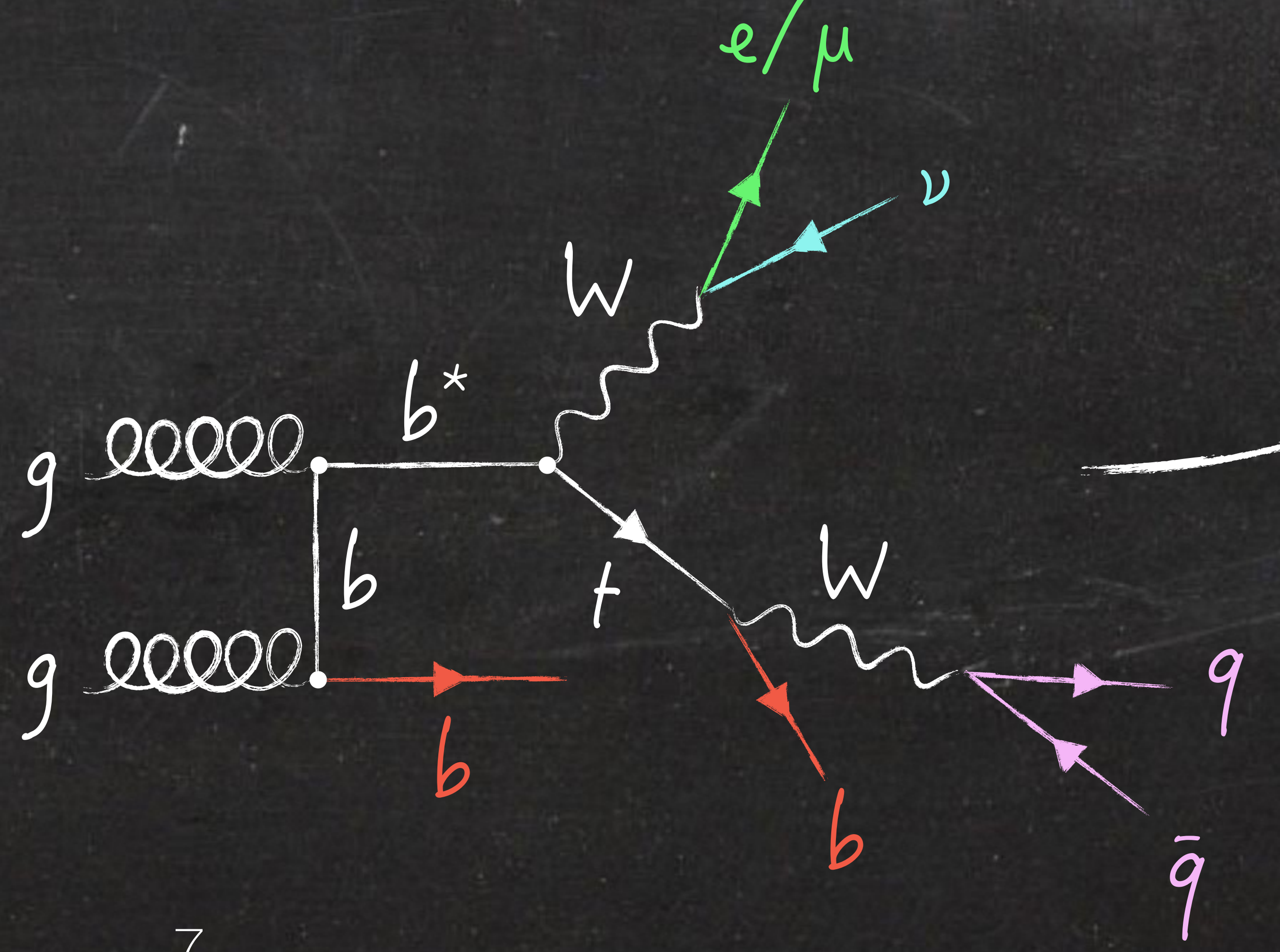


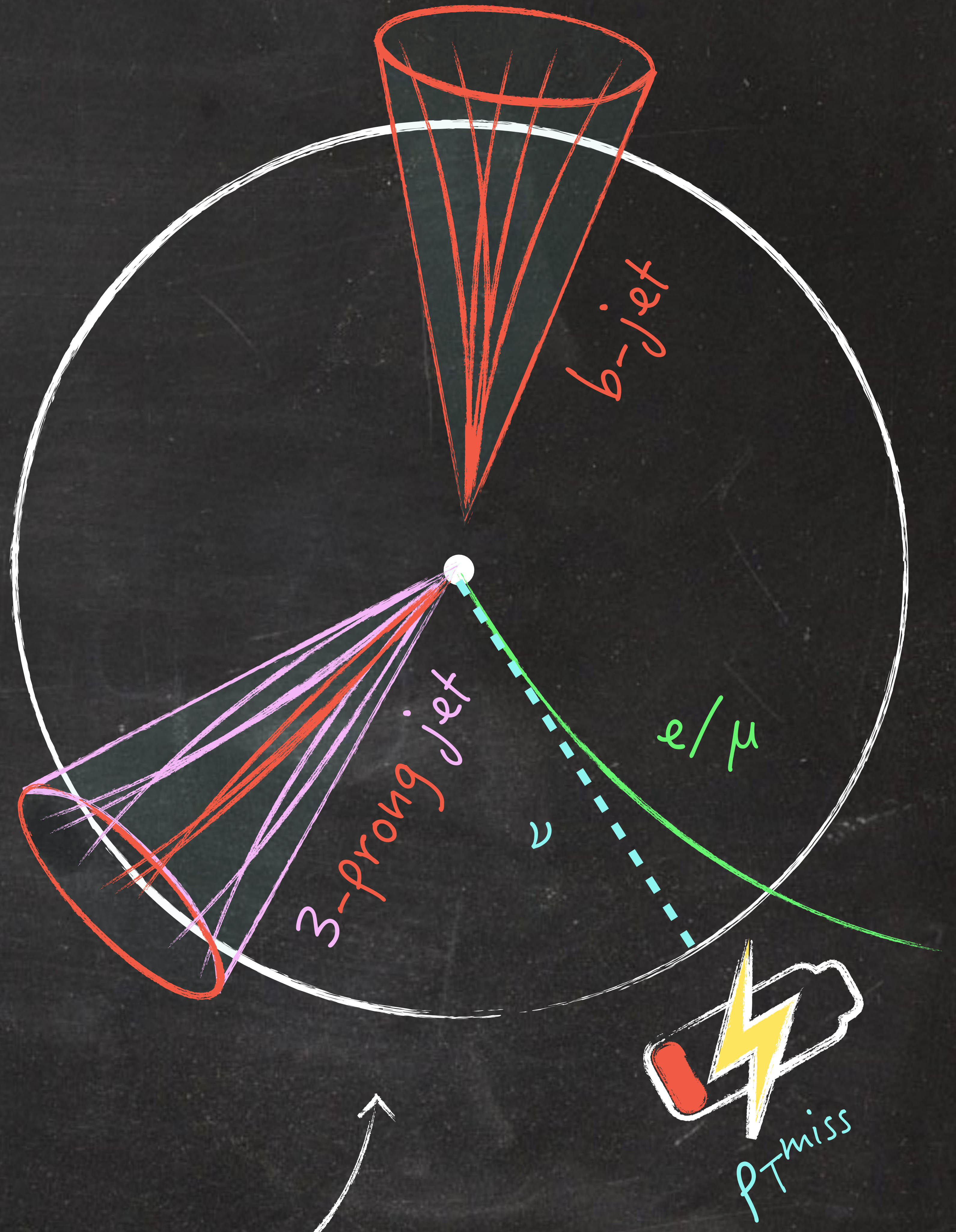
Heavy tW resonance

- **excited b-quarks** in compositeness models ≈**few TeV**
- for $m_{b^*} > 700$ GeV decays to **tW dominant**
- high p_T top and W → **collimated** objects
- RH, LH and VL scenarios studied









Heavy tW resonance

B2G-20-010

B2G-21-005

Analysis details & Results

- backgrounds: $t\bar{t}$, QCD, W+jets, single top, VV,
- signal/control regions:
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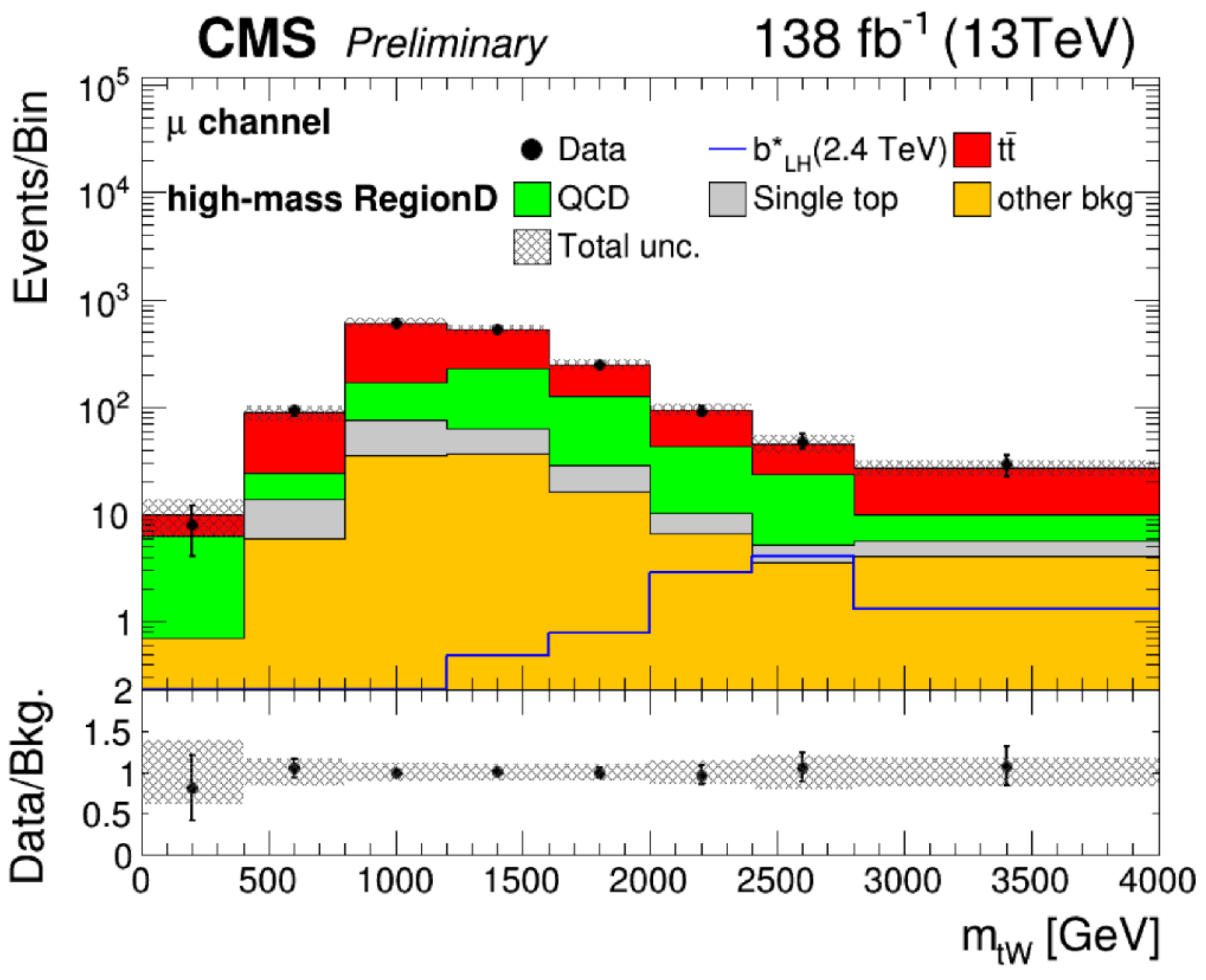

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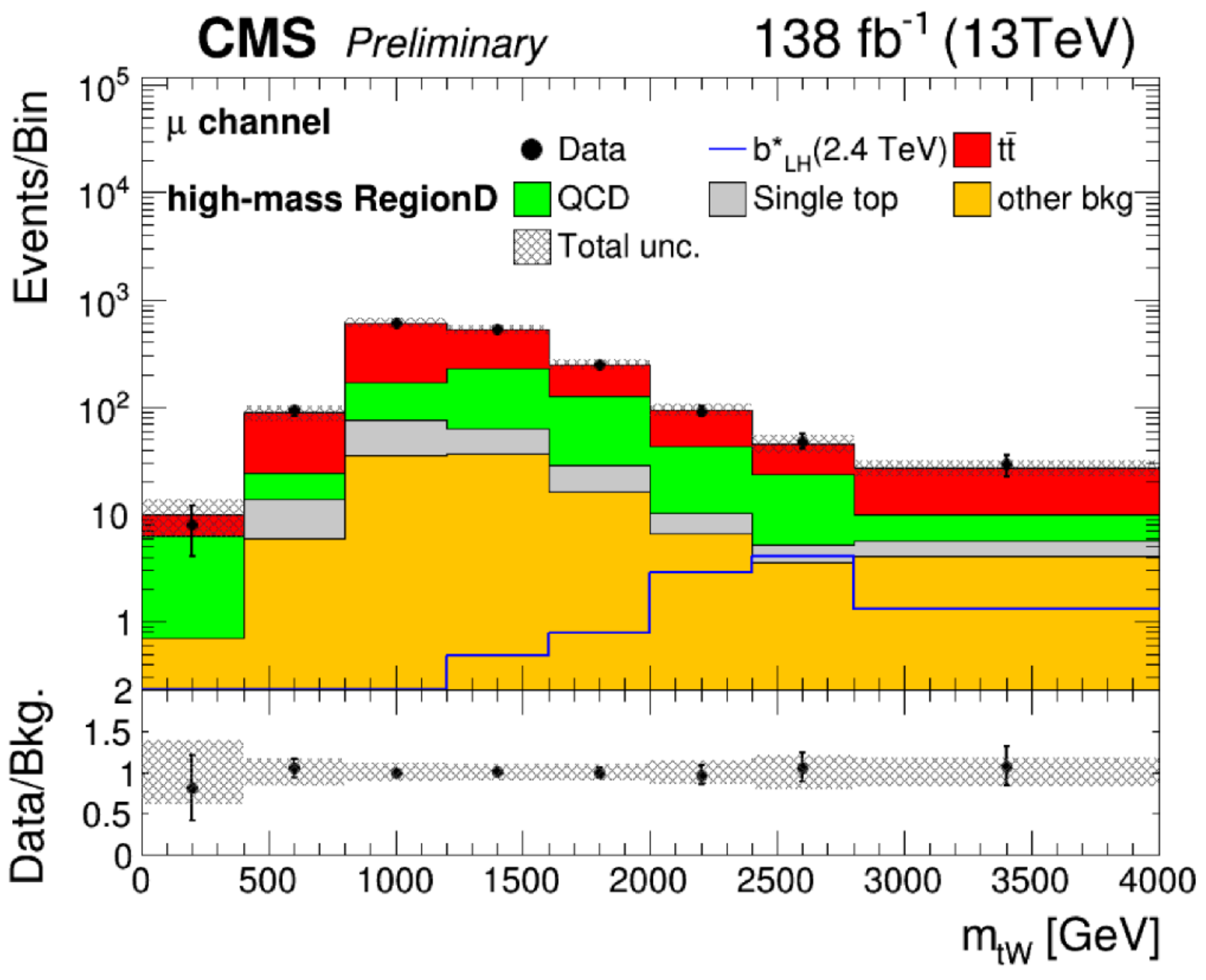

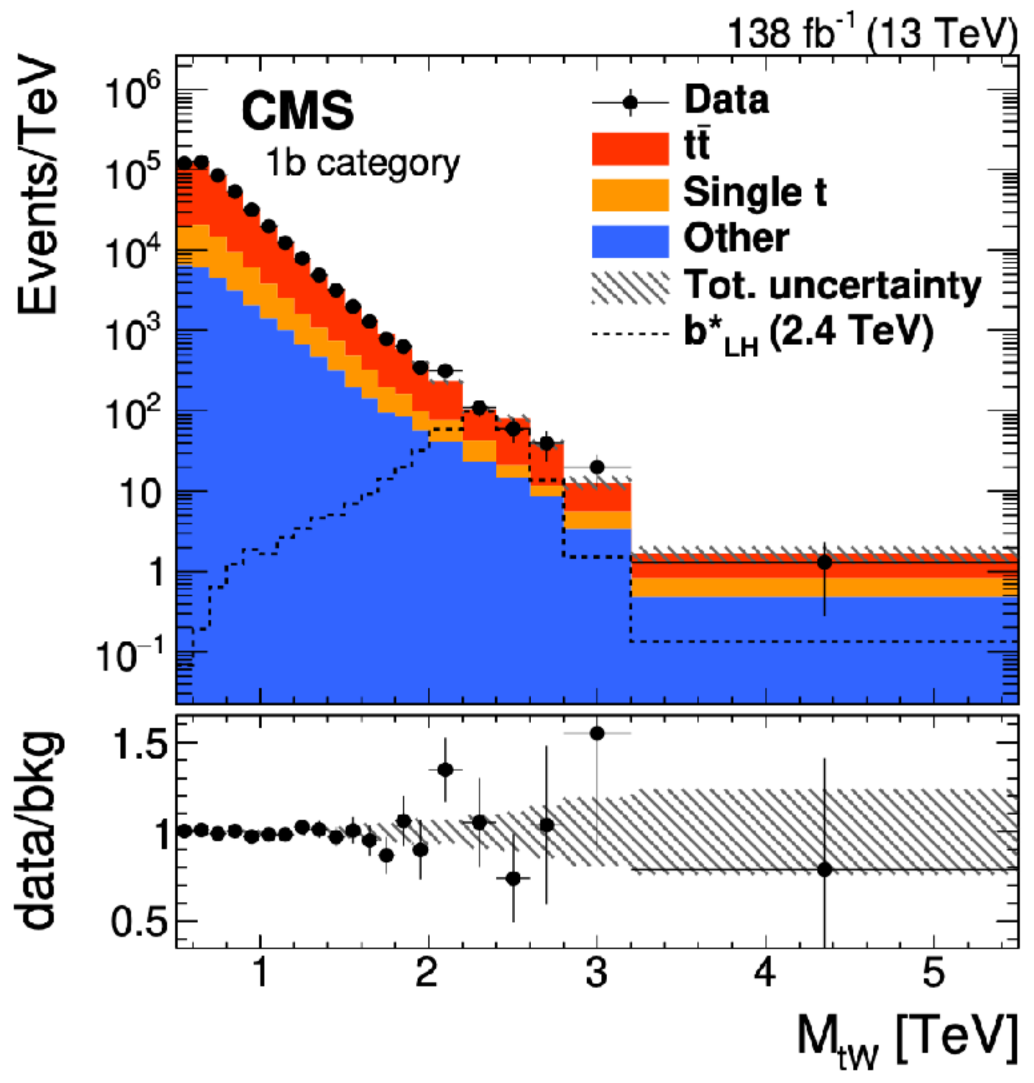

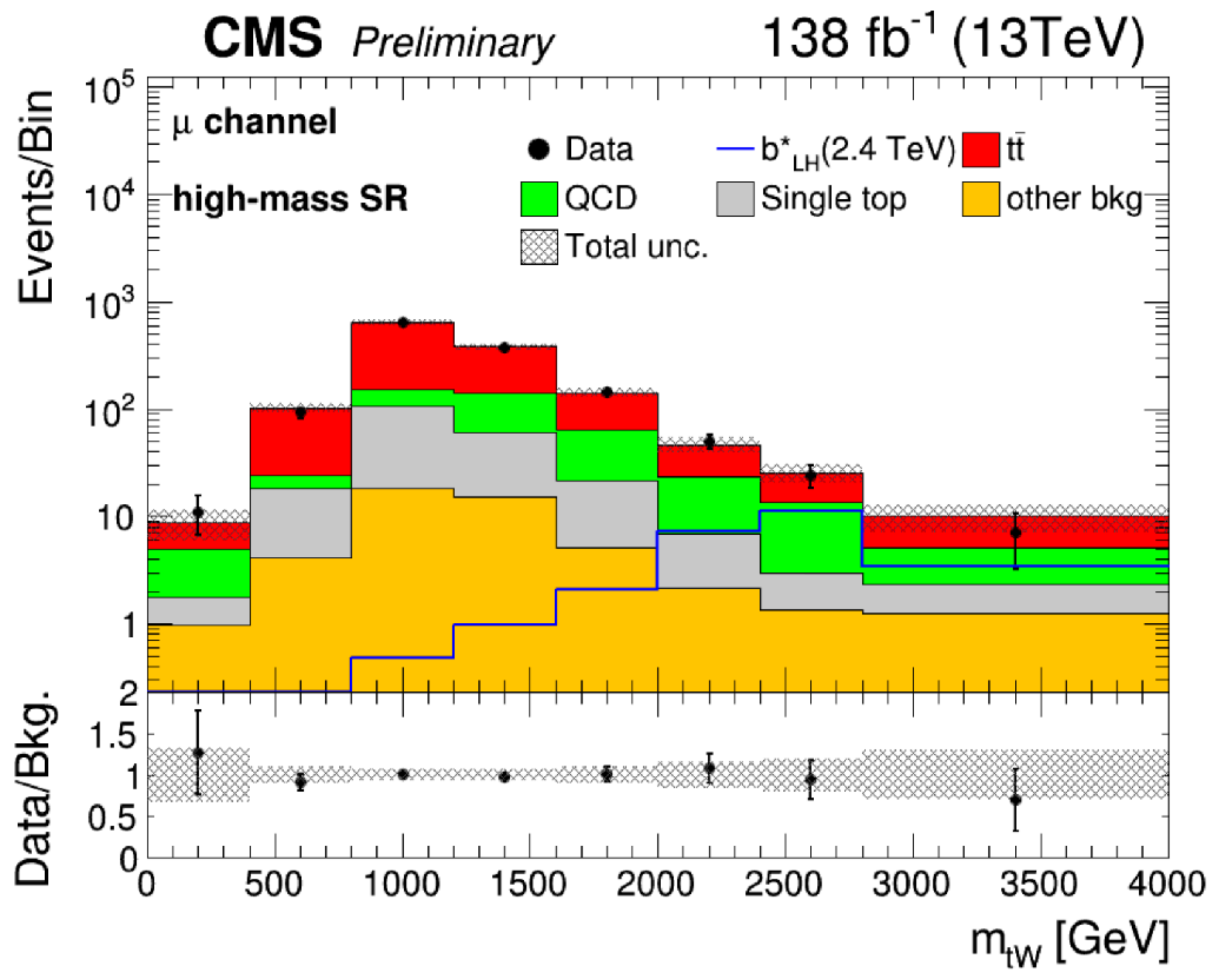

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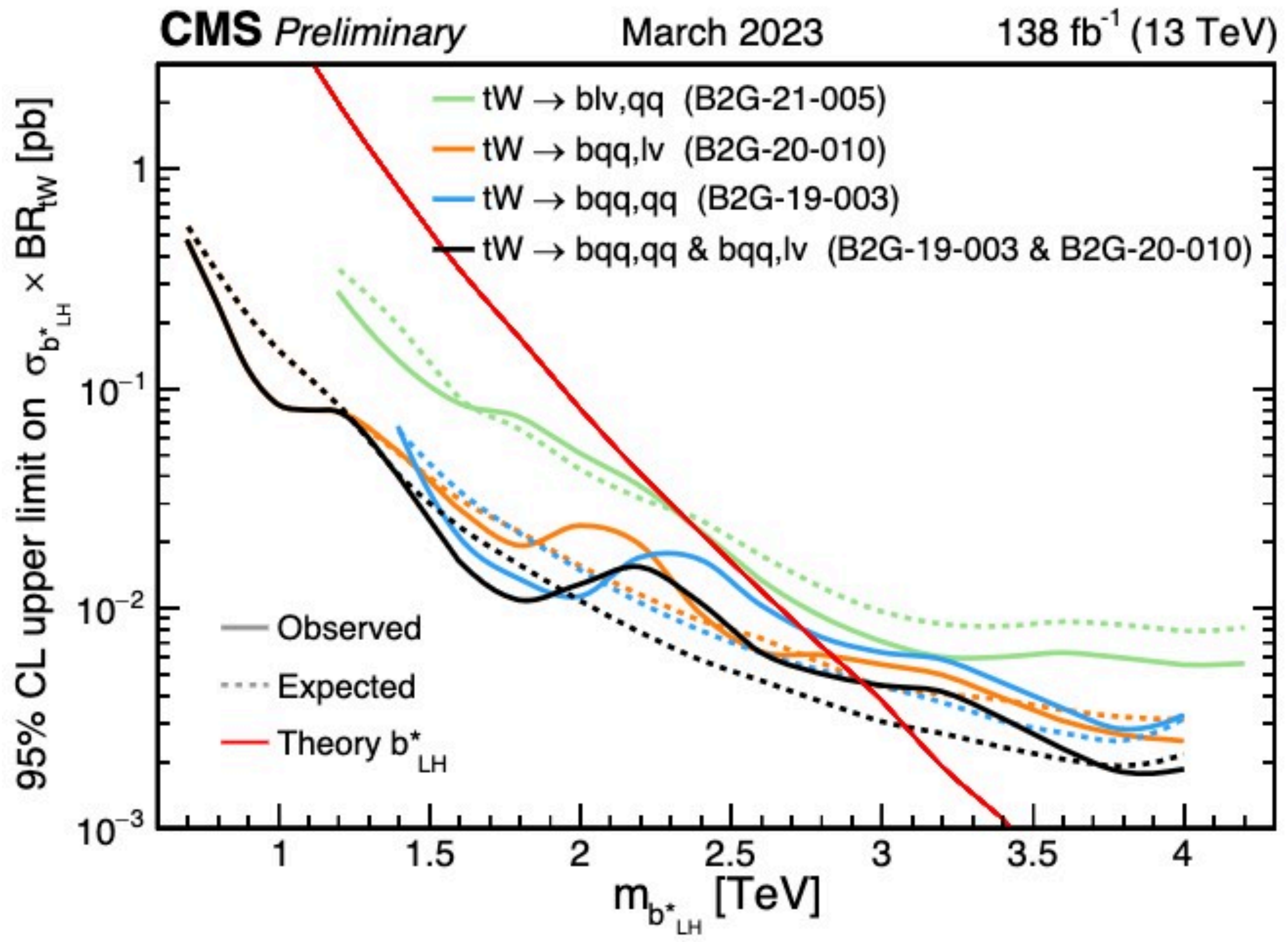
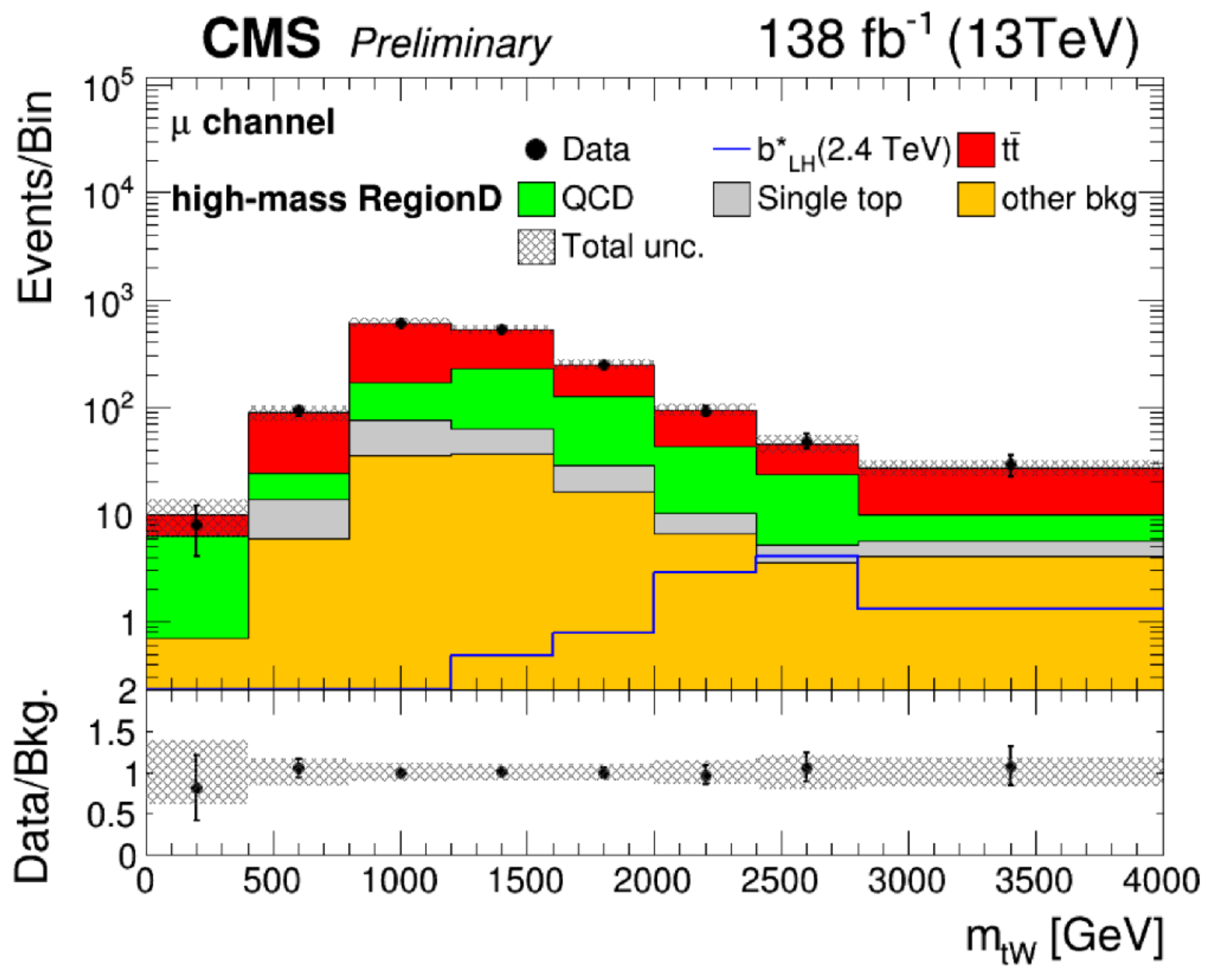
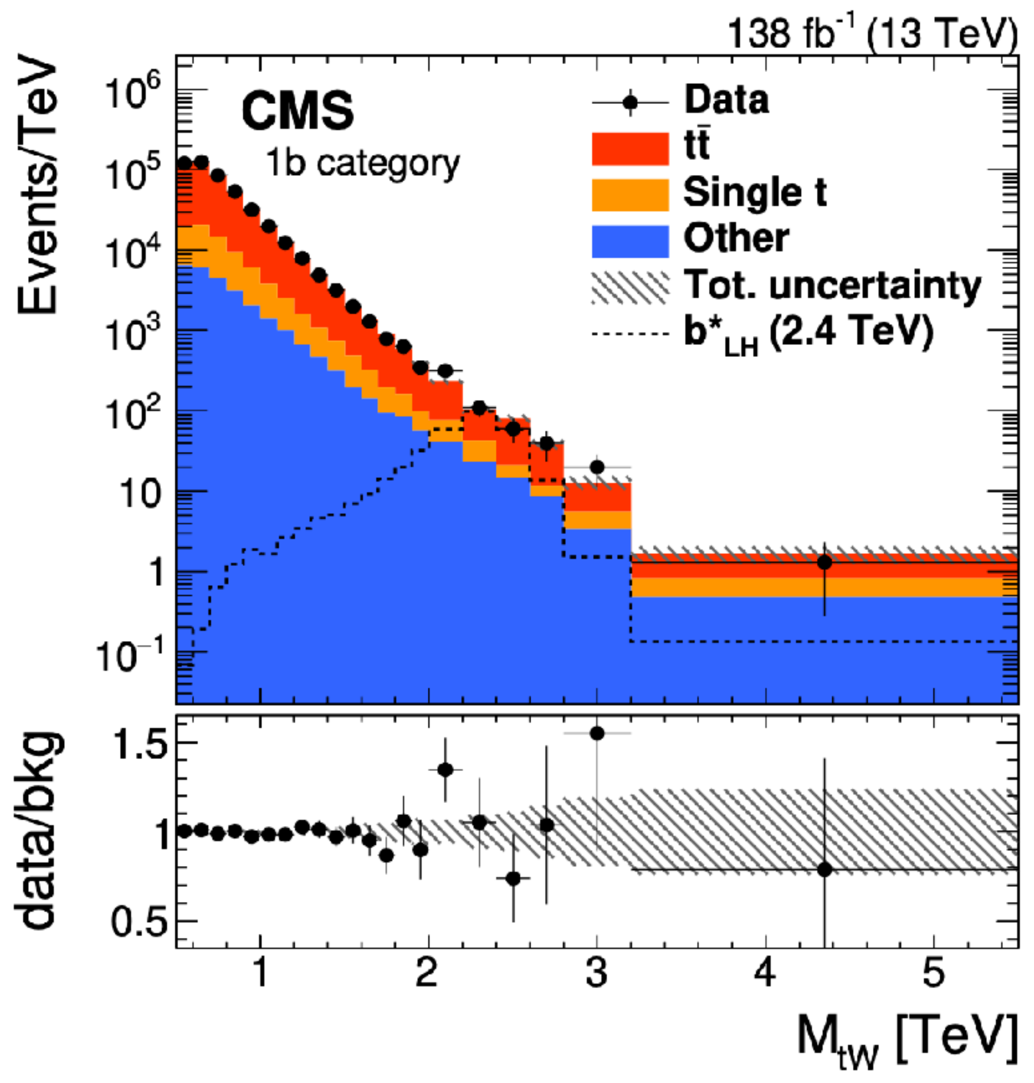
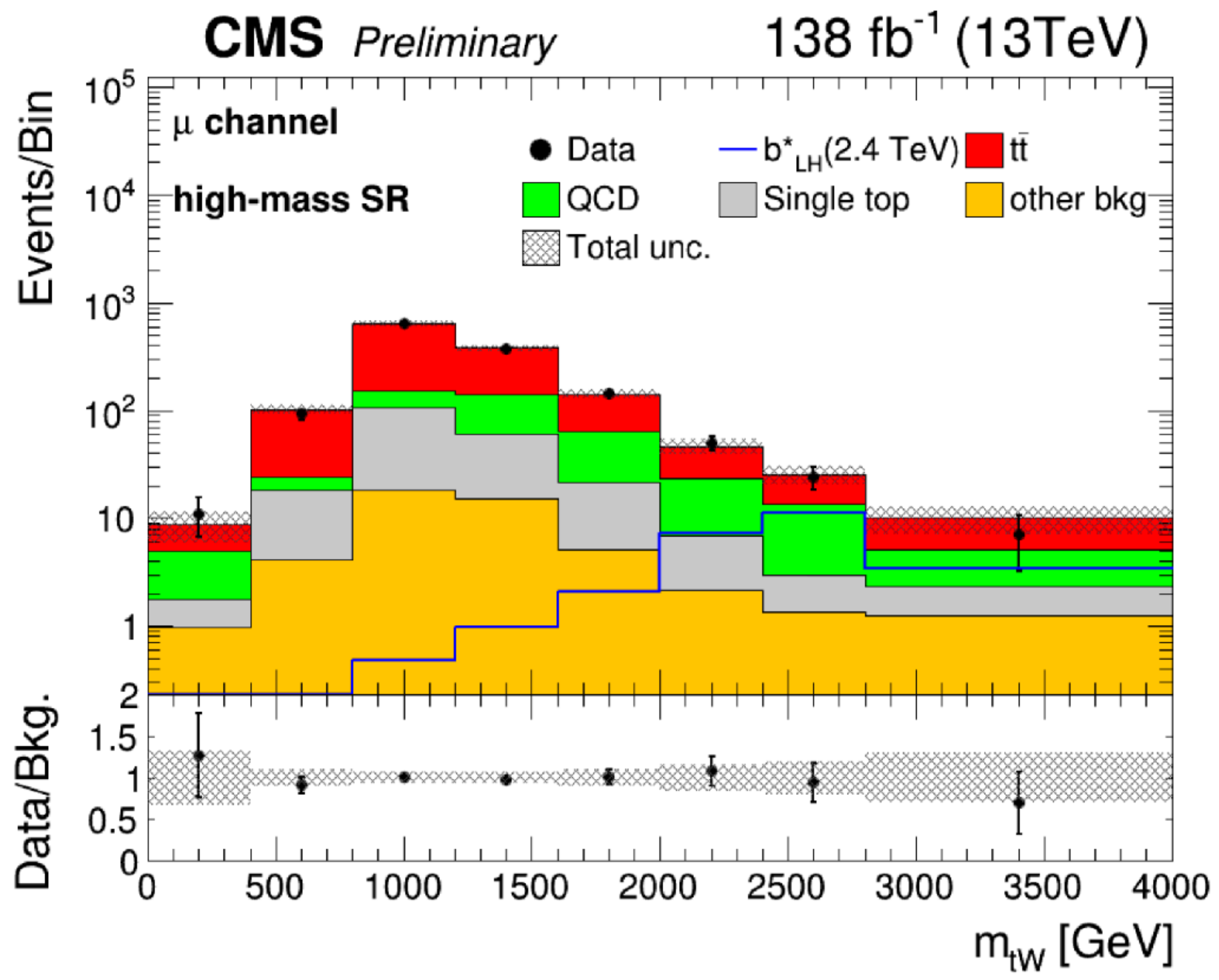
- depending on the signal hypothesis and final states, **excited b-quarks excluded up to 3.0-3.2 TeV.**



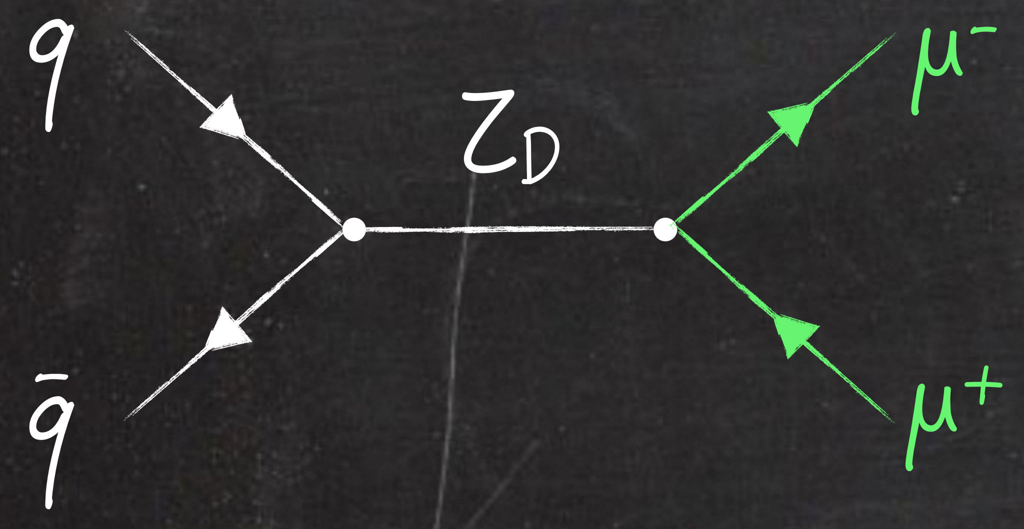


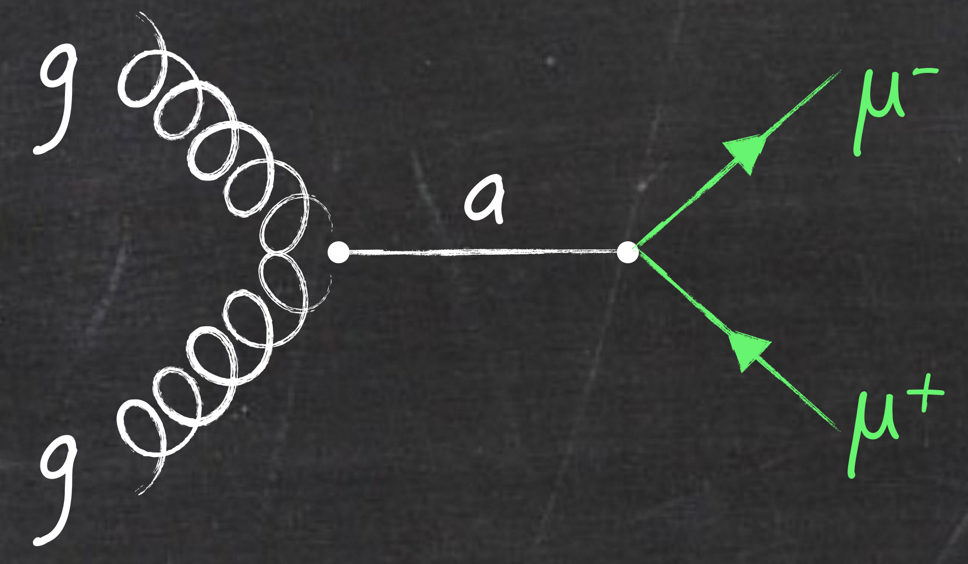


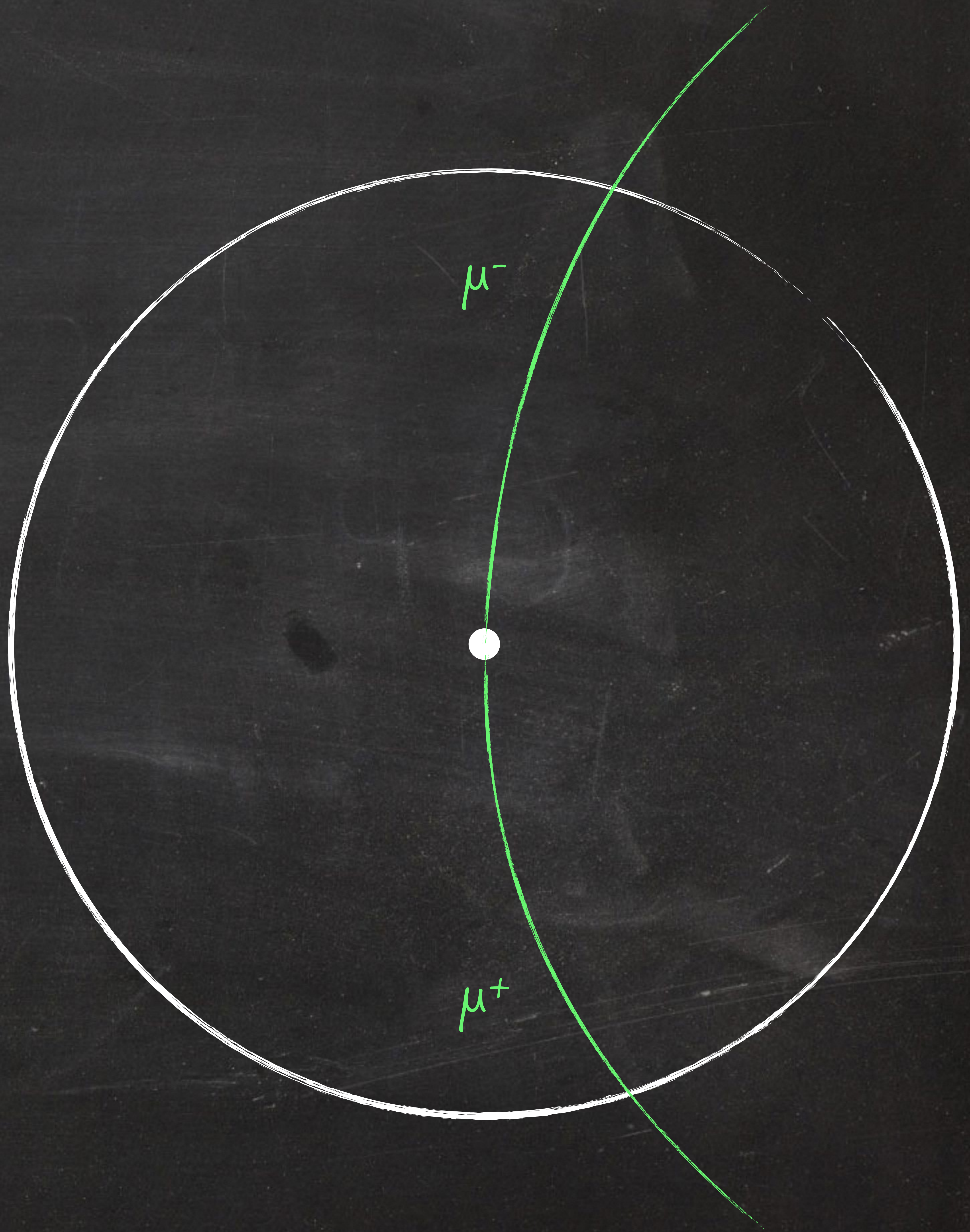


Low-mass dimuons

- final state: **2 opposite sign muons**
- extension of high-mass searches
  - mass range: 1.1-2.6 GeV and 4.2-7.9 GeV
    (excluding region of J/ψ, ψ’ and Υ(1S) resonances)
- example theoretical scenarios
  - dark photons Z_D, with kinetic mixing ε
  - two Higgs doublet models with extra scalar a (2HDM+S)







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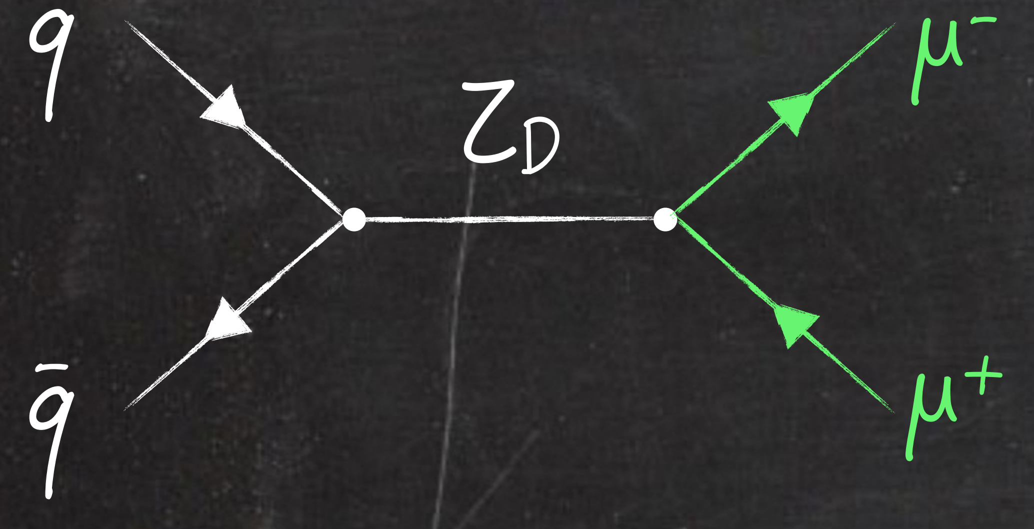

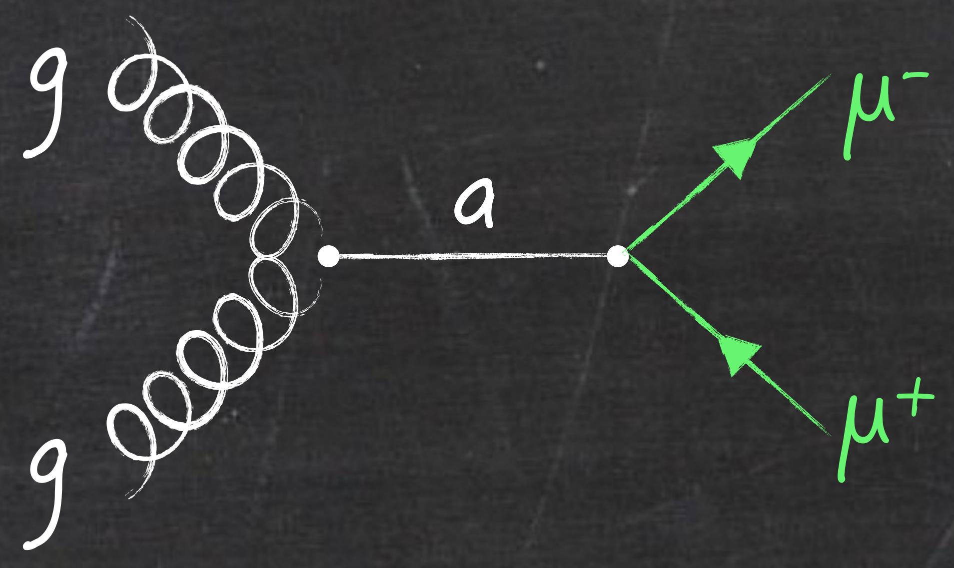

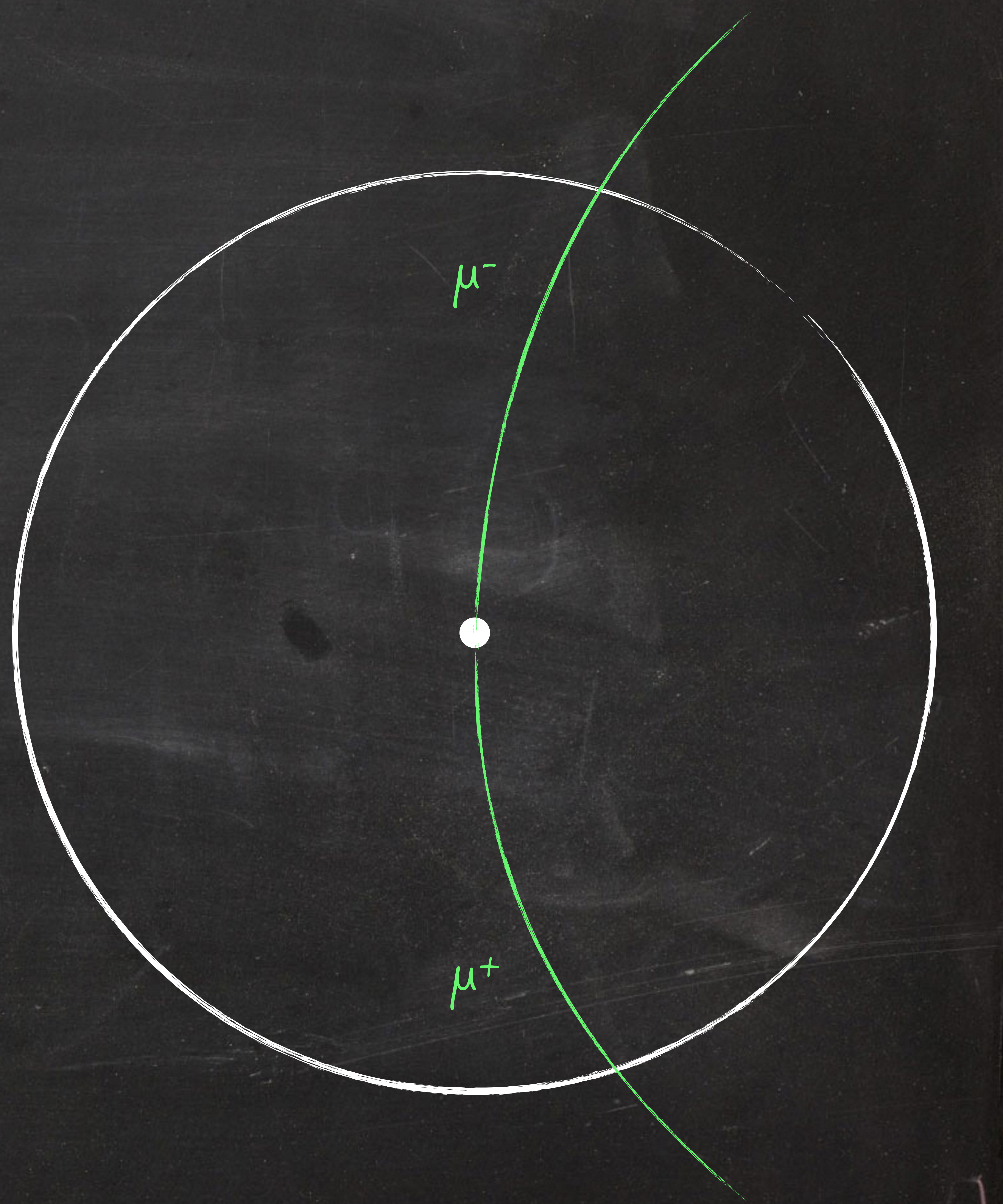

Analysis details

- dedicated **scouting trigger** stream
  - muon p_T as low as **3 GeV**
  - storing **reduced event** information

Low-mass dimuon scouting

EXO-21-005

Scouting trigger

- at HLT: **≥2 muons p_T > 3 GeV**,
- ≈**4-8 kB/event** (standard event size ≈1 MB),
- **2 kHz event rate** (standard dimuon triggers: 0.45 kHz),
- integrated luminosity: **96.6 fb^{-1}**,

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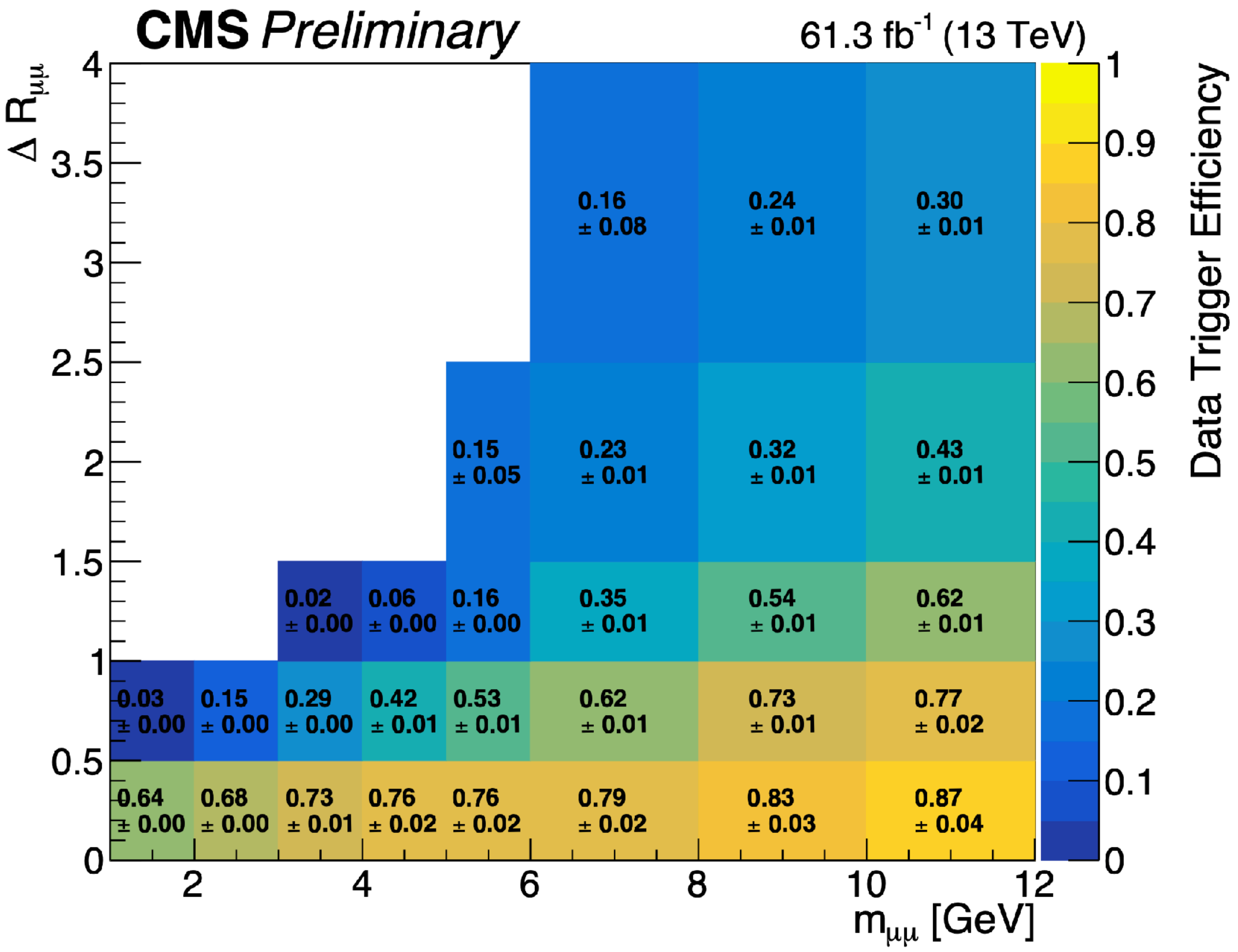

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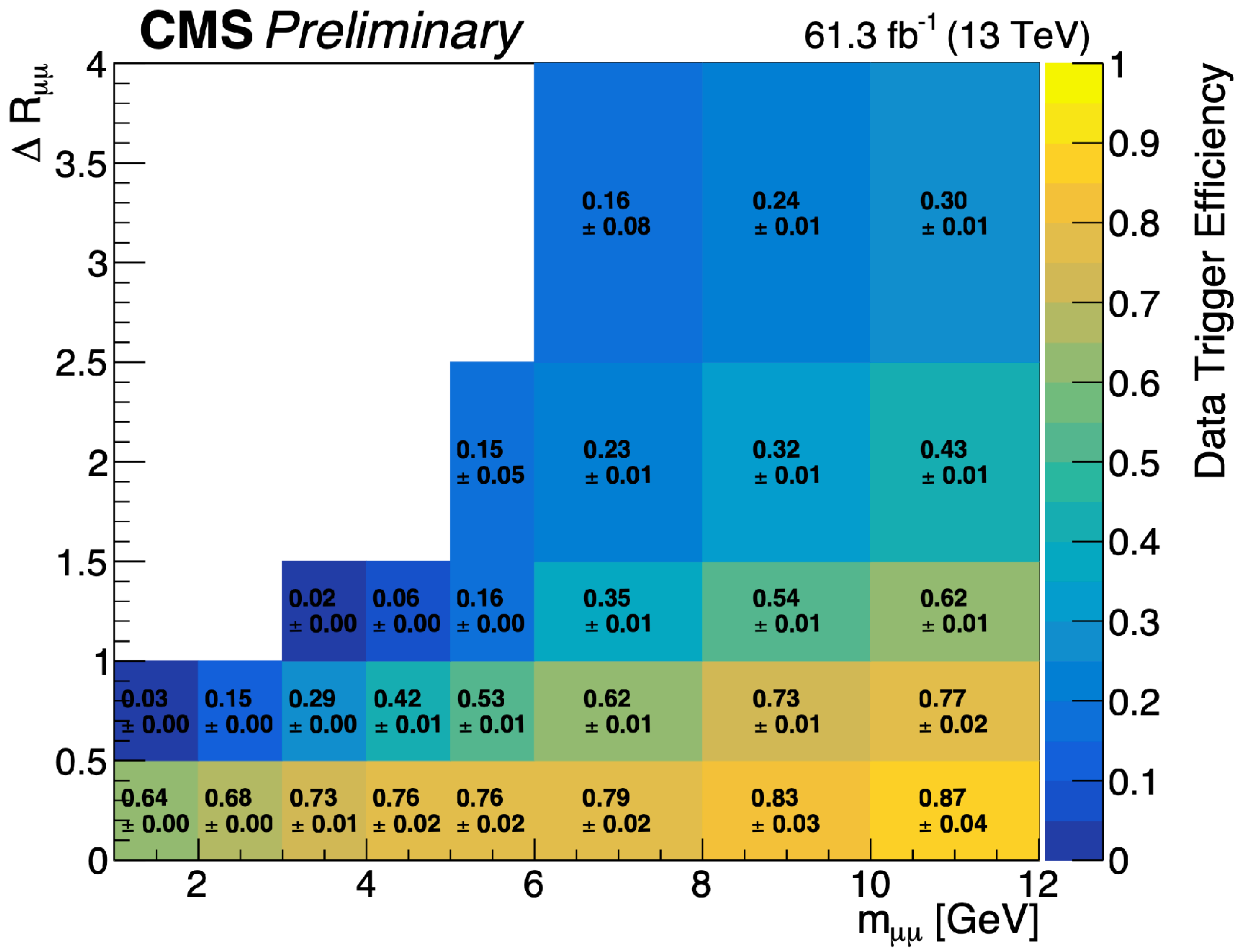
Offline analysis

- $p_T > 4$ GeV, $|\eta| < 1.9$ (assure **optimal dimuon mass resolution**),
- **muons identified** with a MVA technique, based on:
  - tracks quality,
  - isolation,
  - vertex information.



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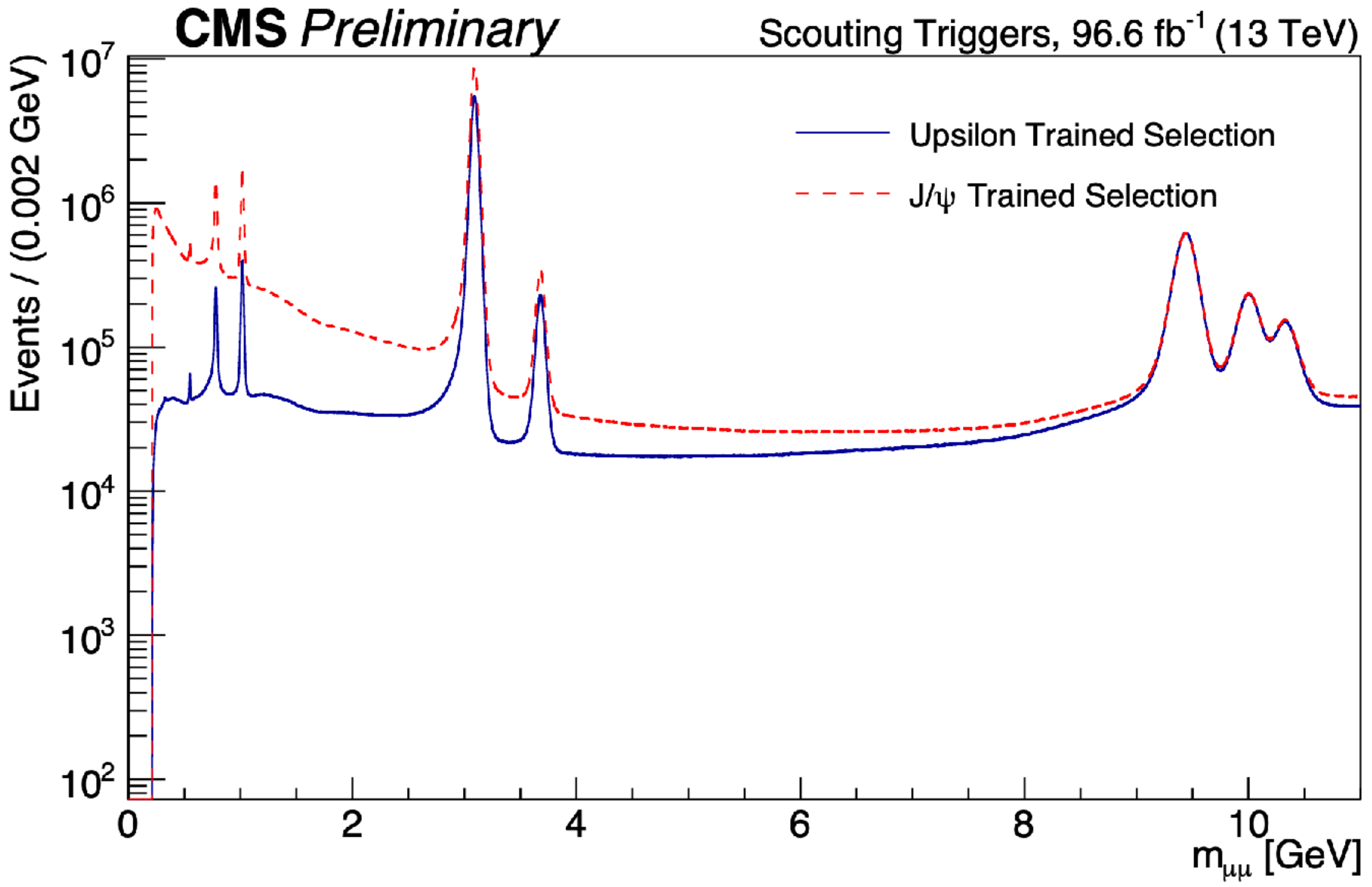
EXO-21-005

Signal extraction & background estimation

Fit to dimuon m_{inv} distribution:

- signal: double Crystal Ball + Gaussian, parameters from known resonances,
- background: empirical functions (e.g. polynomial times exponential).



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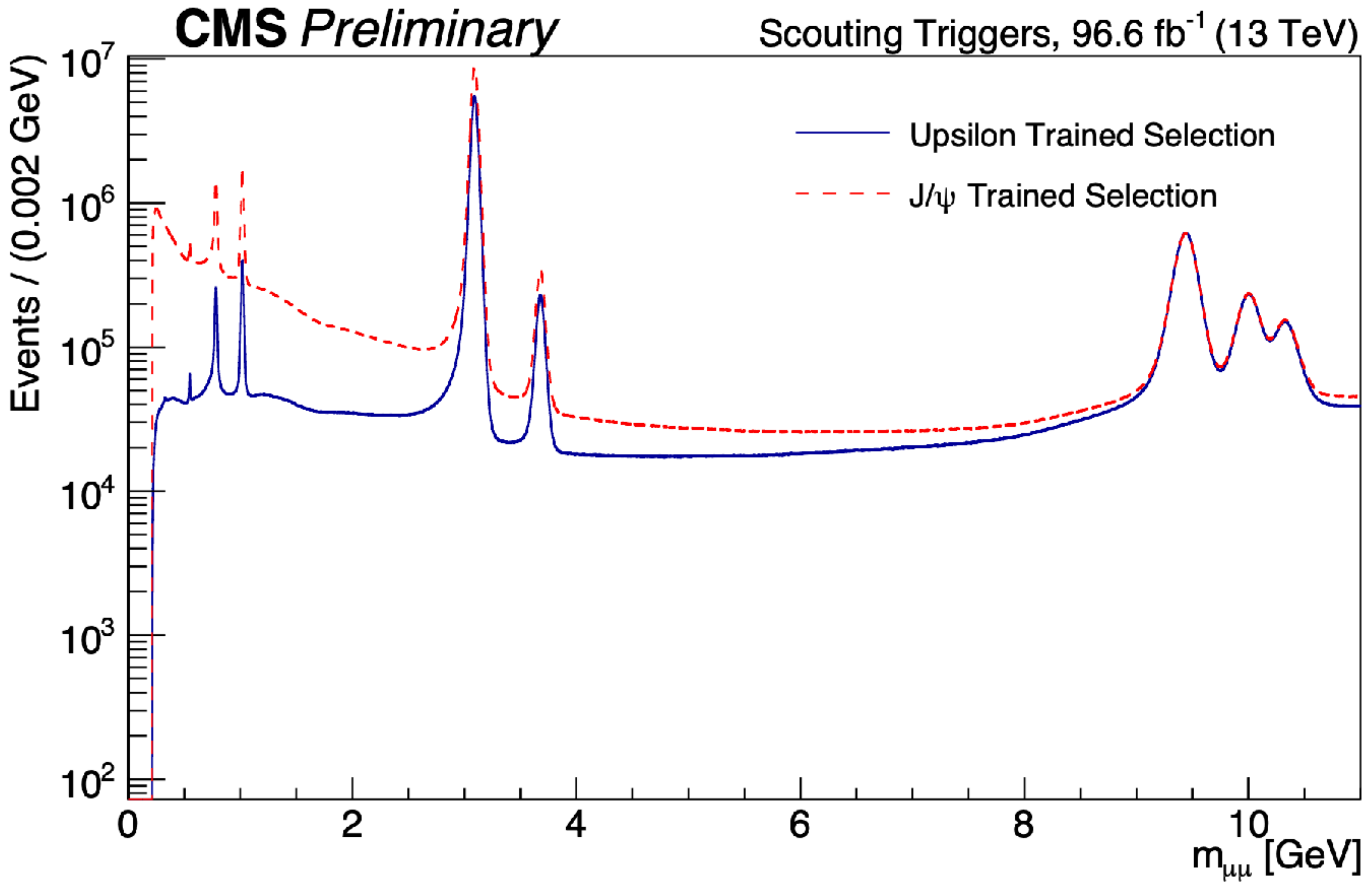

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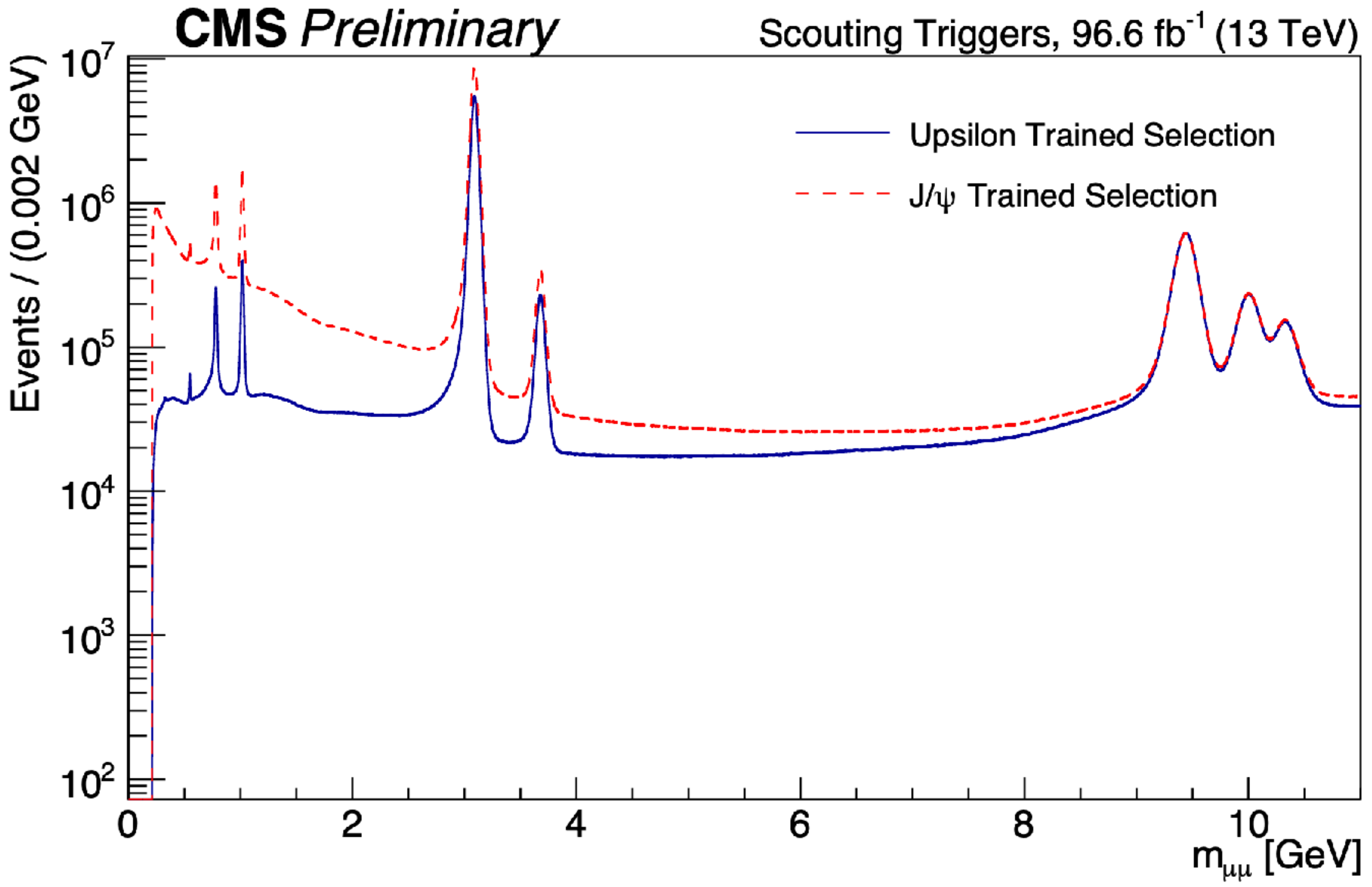
→ side note: 3.1σ LHCb excess at 2.42 GeV,



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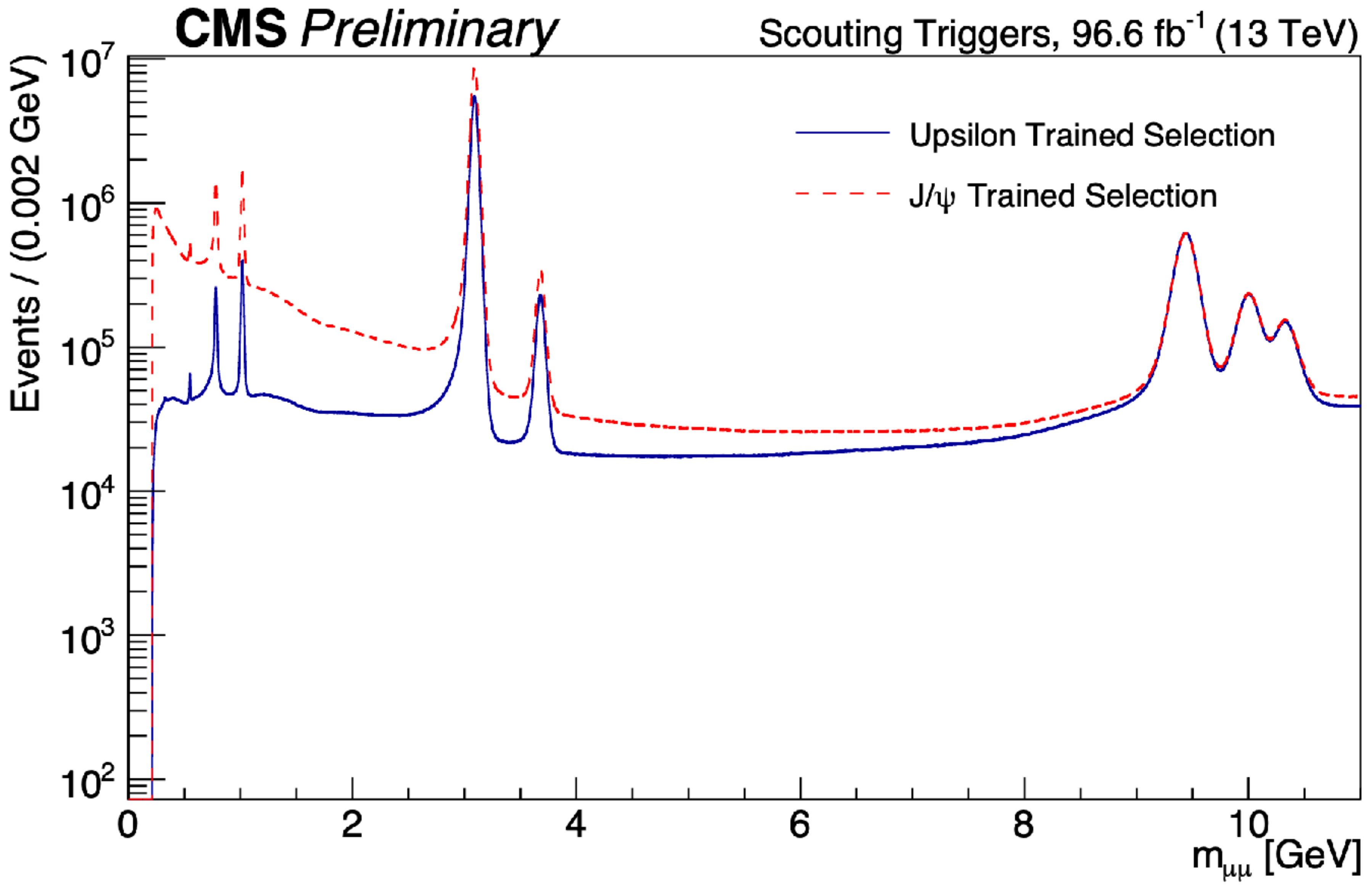

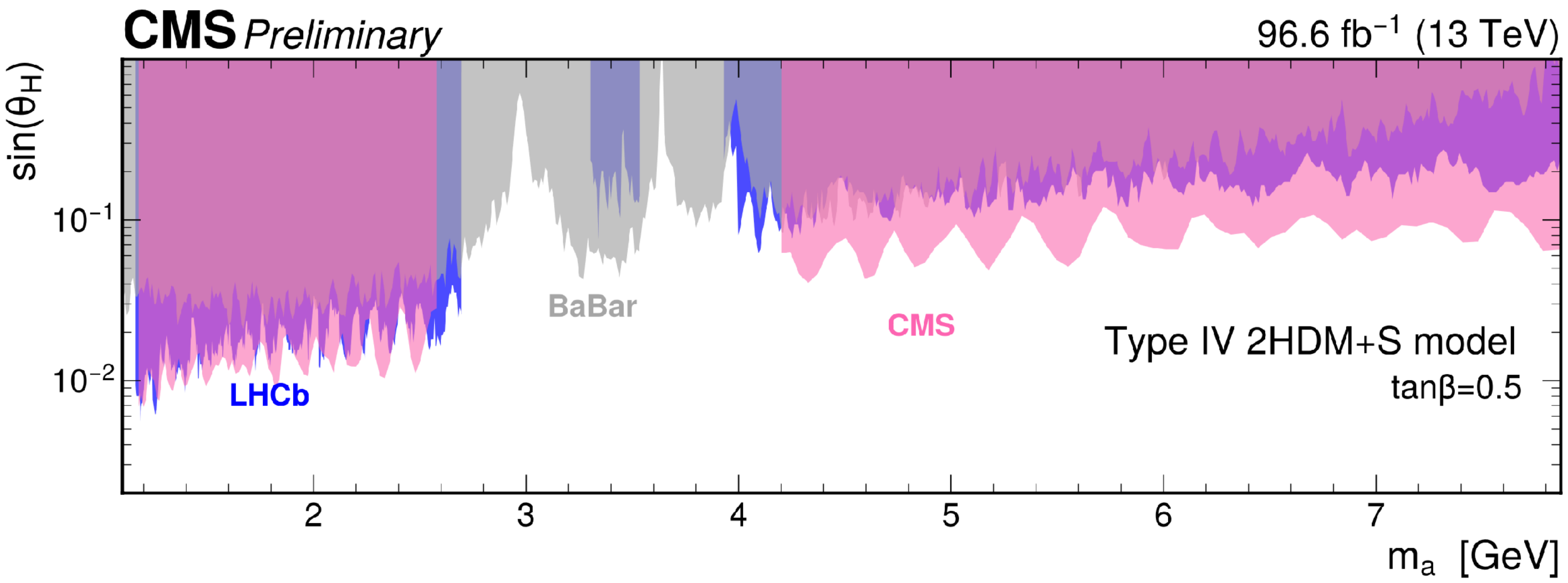

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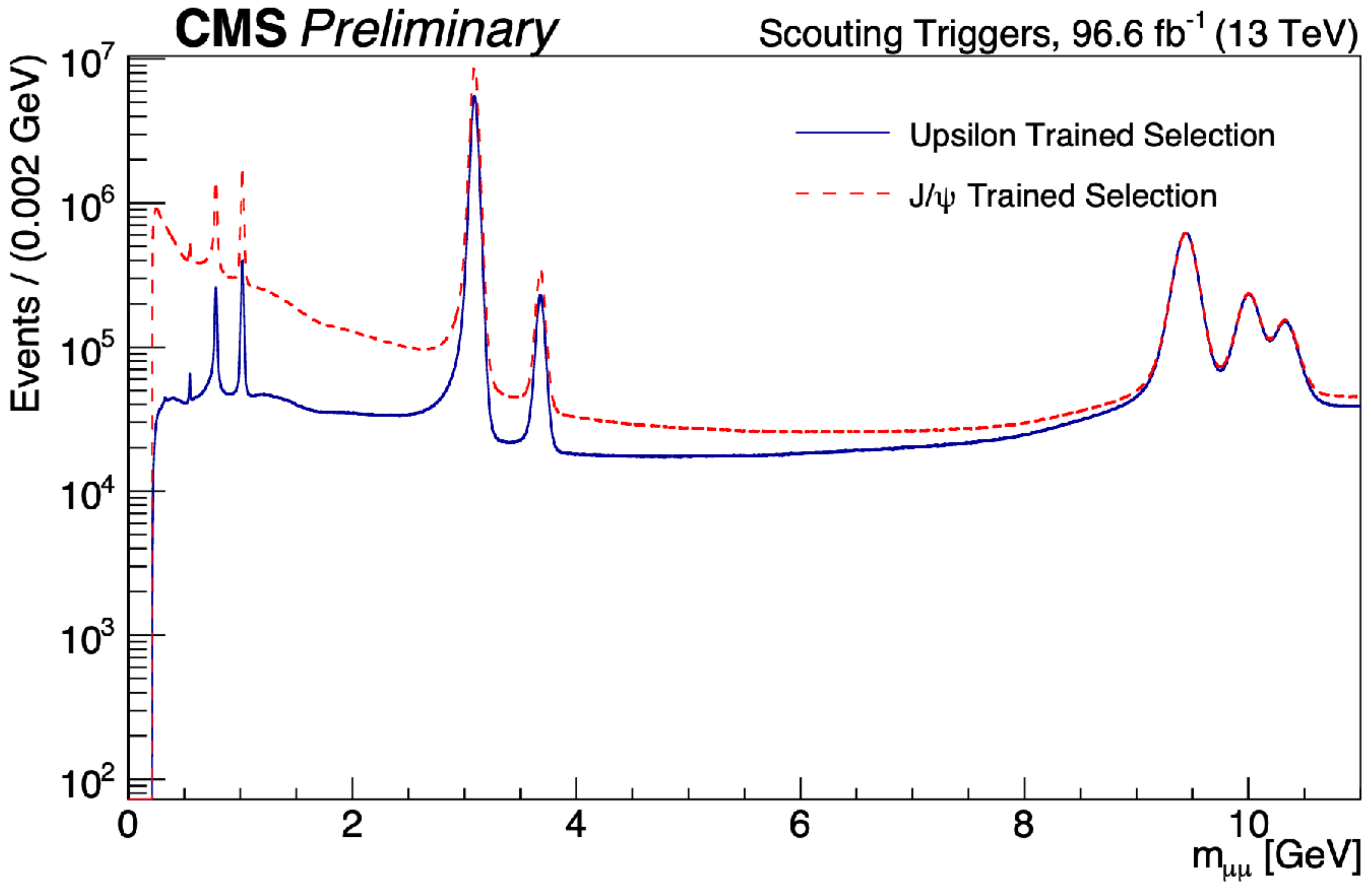

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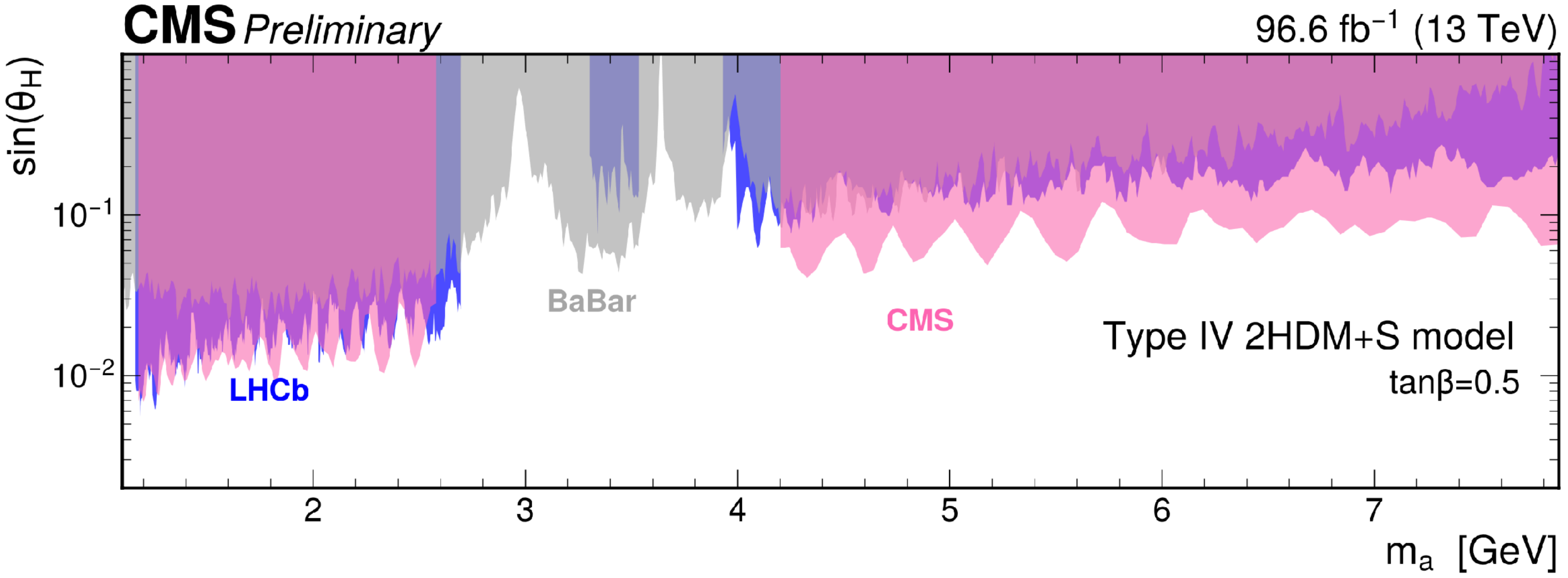
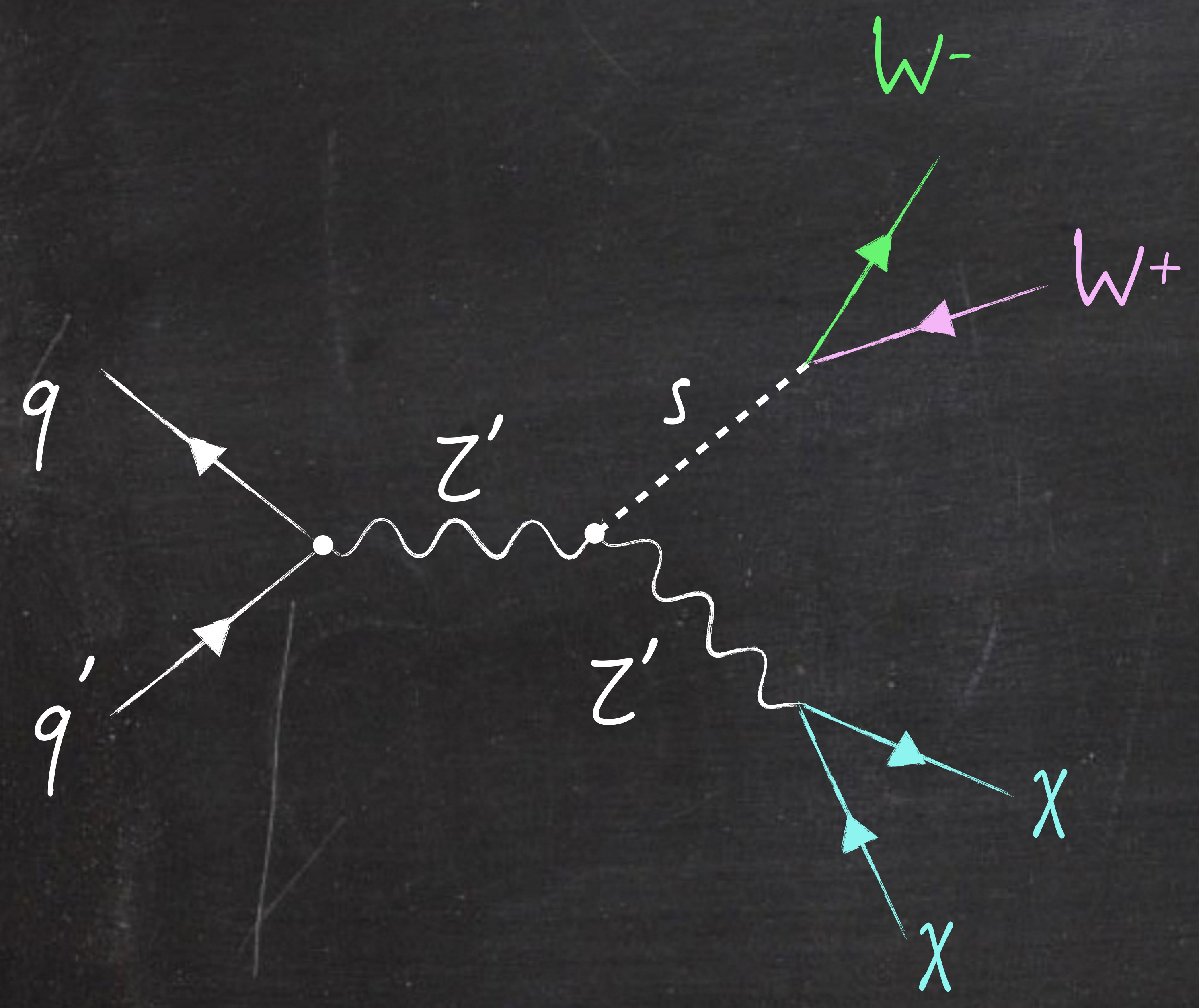
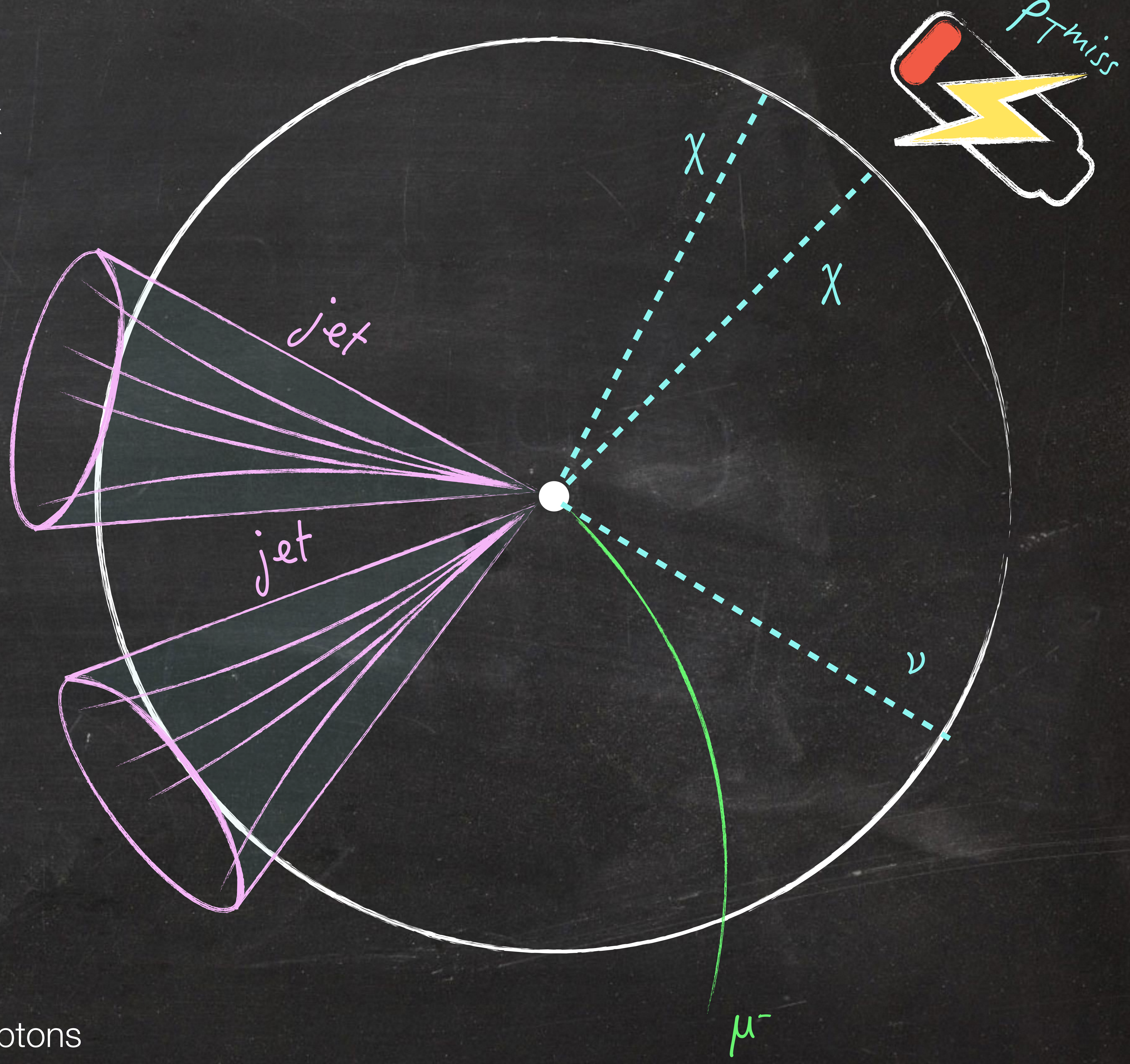


Dark Higgs

- models with dark Higgs s, Z' boson and DM candidates χ
- m_s > 160 GeV → decays to WW dominant
- di-leptonic & semi-leptonic channels



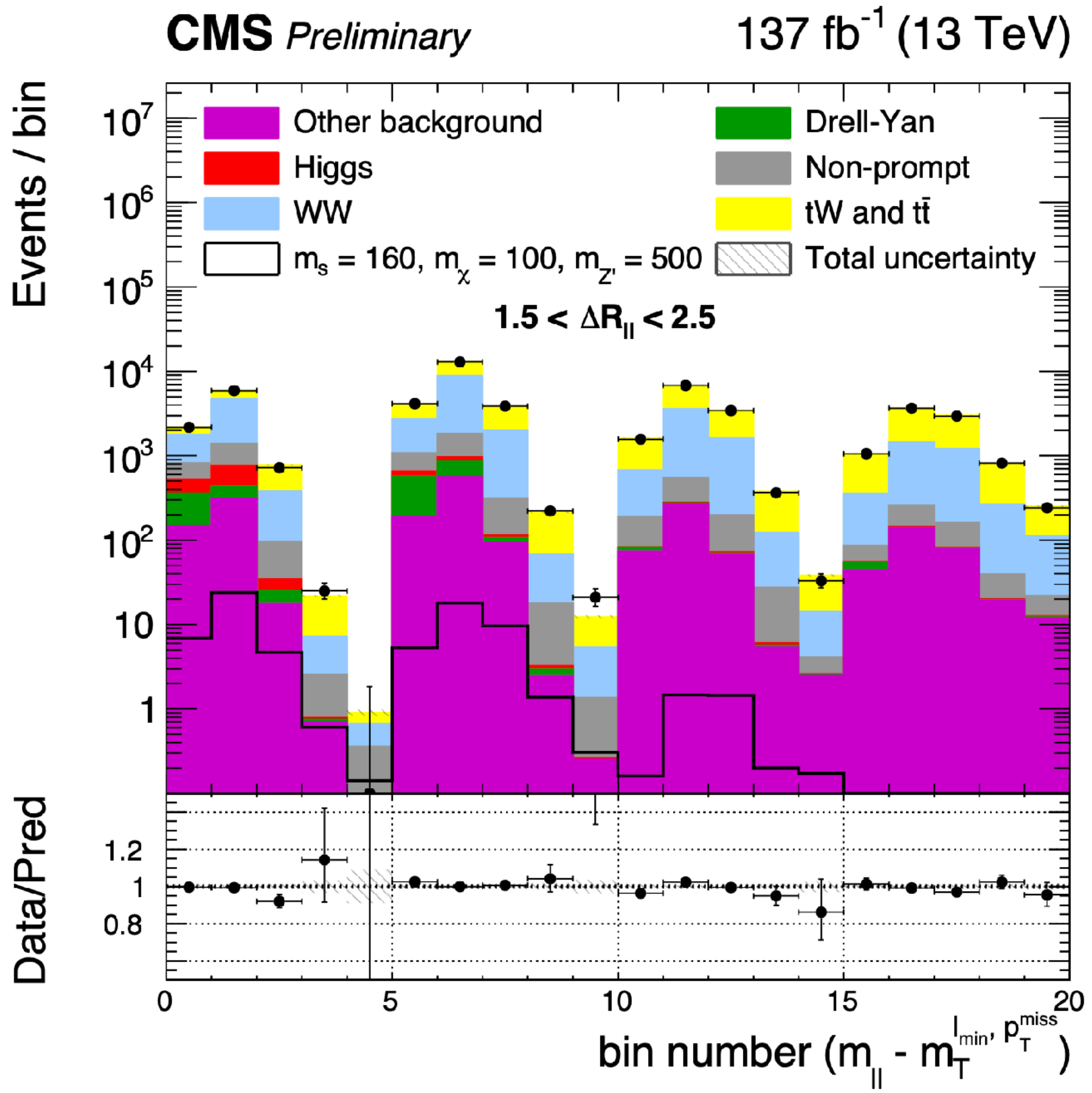


Analysis details

- luminosity: 137 fb^{-1} (2016-2018)
- backgrounds: WW, Z→μμ, W+jets, tW, $t\bar{t}$
- signal/control regions: e.g. same sign vs. opposite sign leptons

Dark Higgs

EXO-21-012



Analysis details

- di-leptonic channel:
  - main variable: m_T of **trailing lepton** $\oplus$ **p_T^{miss}** system,
  - 2D fit to m_{ll} vs. $m_T^{lmin,pTmiss}$,
- semi-leptonic channel:
  - **BDT** based on 13 most discriminative variables (e.g. p_T^{jj}, $\Delta\eta_{l,jj}$, p_T^{miss}).

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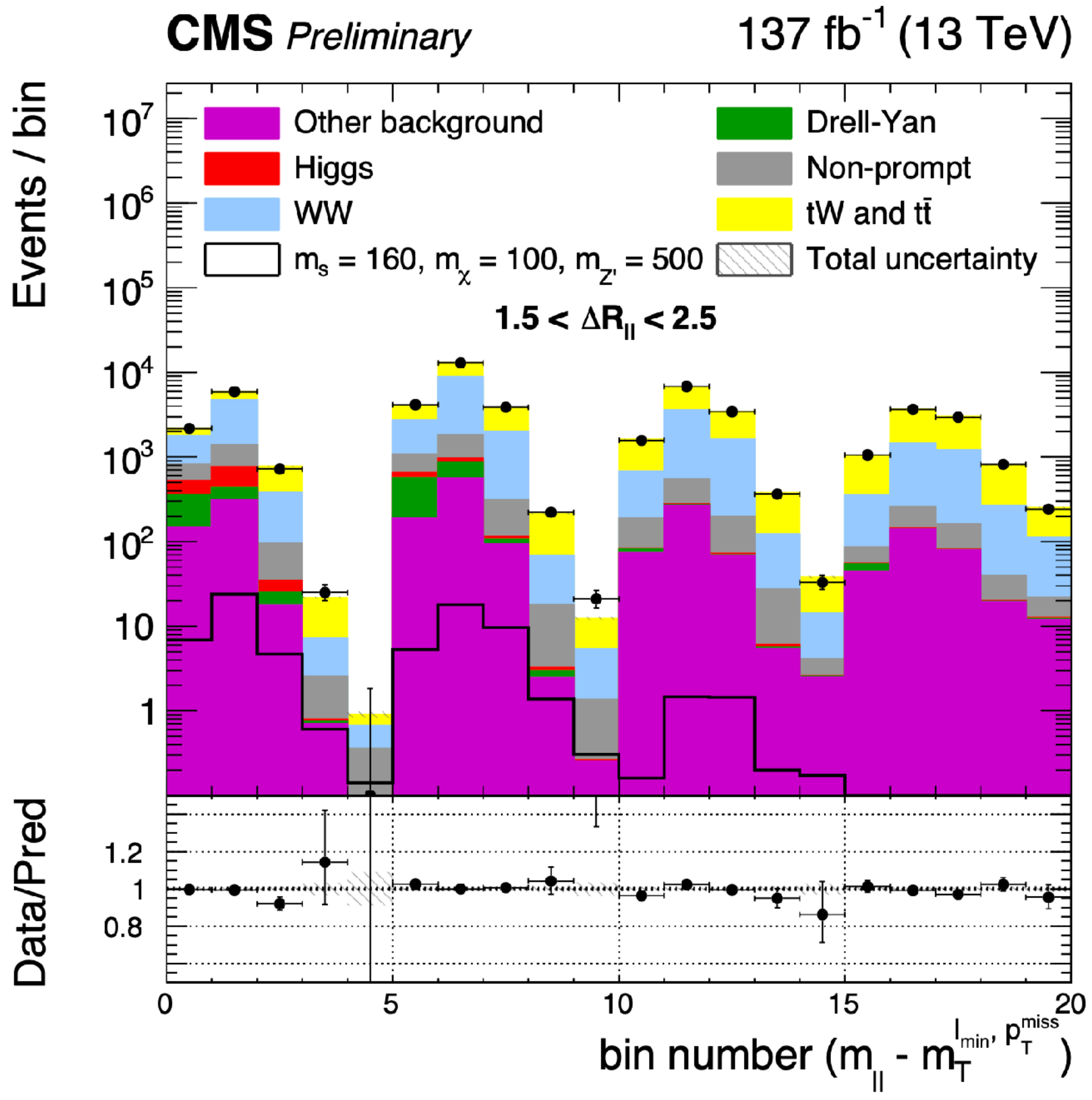
Dark Higgs

EXO-21-012



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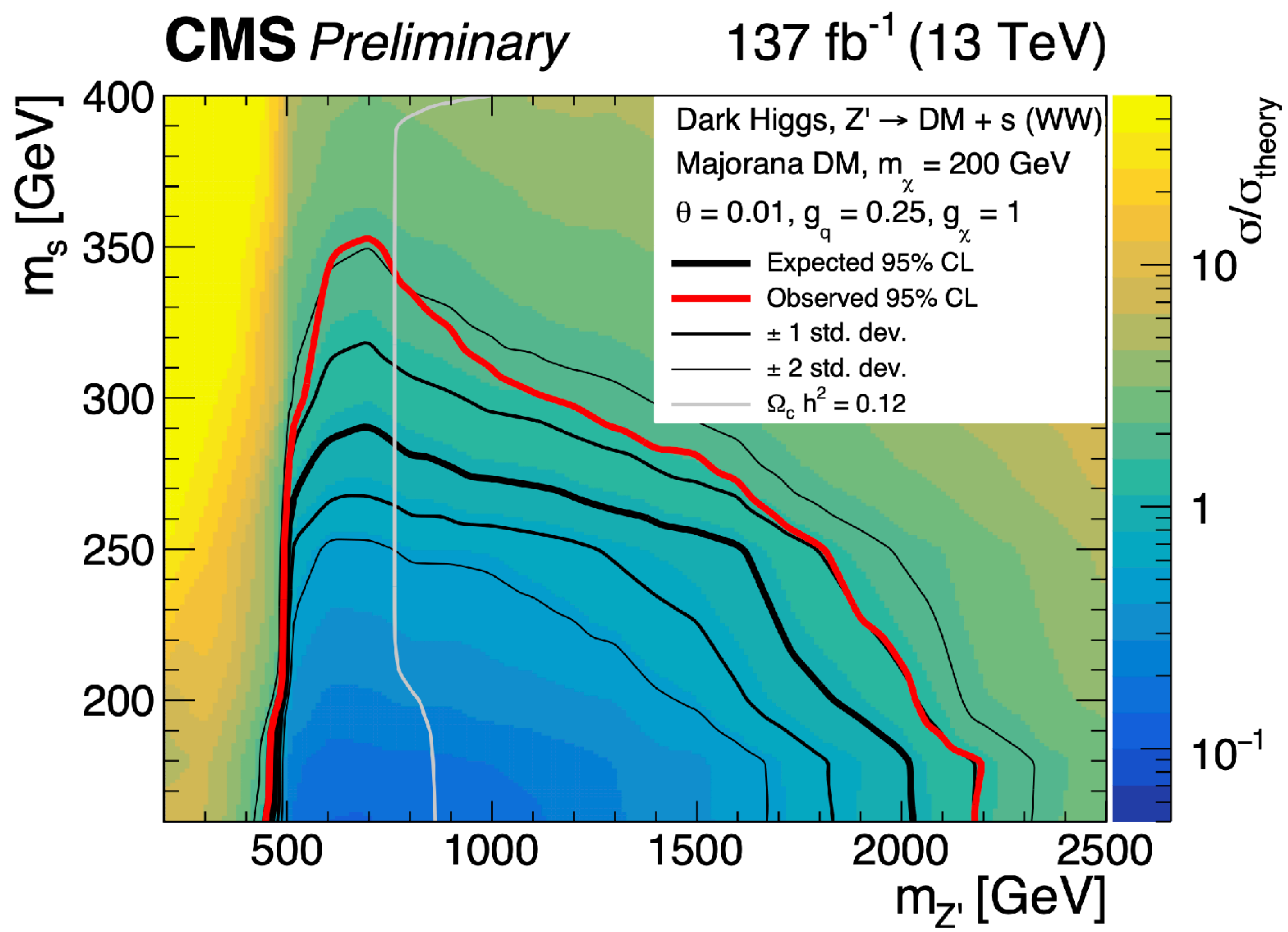

Results

- **simultaneous fit** to both channels,
- **no significant excess,**
- limits derived on **m_s vs. $m_{Z'}$** for different m_χ assumptions,
- for m_χ = 200 GeV, these are the **most stringent limits.**

Summary

W' search

- **small excess** (< 3σ) at 3.4-4.4 TeV,
- best described by RH narrow width W'.

Heavy tW resonance

- consistent with SM,
- excited **b-quarks excluded** up to 3.0 - 3.2 TeV.

Low-mass dimuon scouting

- **small excess** at 2.41 GeV (local 3σ), consistent with the LHCb excess at 2.42 GeV,
- limits on dark photons and 2HDM+S.

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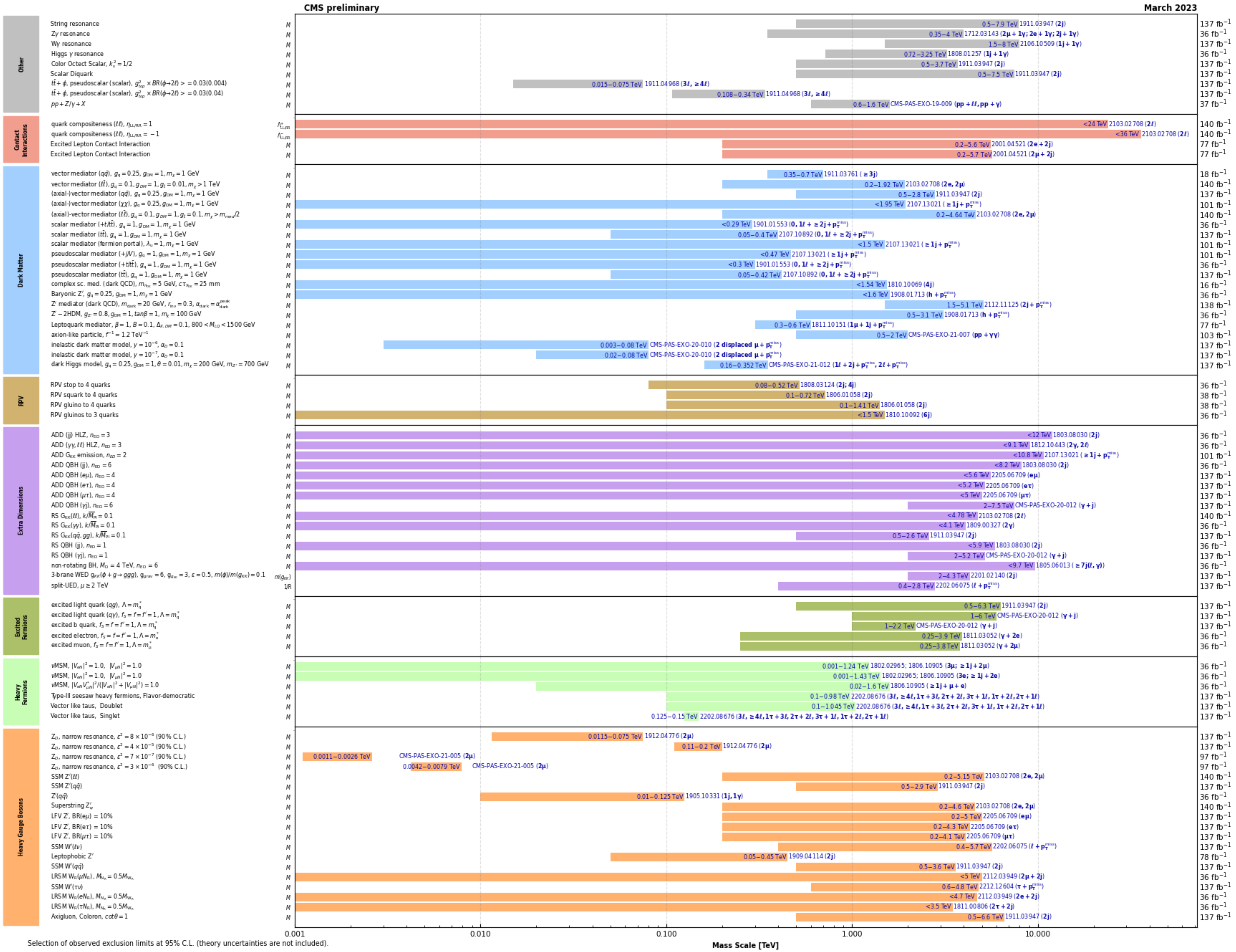
Backup

EXO Results



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W' search

B2G-20-012

Trigger

- muons,
- electrons,
- photons → helps for very high energy electrons
- jets → +8% efficiency,

number of b-jets	jet_{top} b-tagged	$jet_{W'}$ b-tagged	label
0	X	X	R0B
Signal-enriched regions			
1	✓	X	RT
1	X	✓	RW'
≥2	✓	✓	R2B

Selections

- isolation requirements (I_{mini}) → reduce number of leptons from hadronic decays,
- events with additional e/μ discarded → reduce $t\bar{t}$ background,
- p_T^{miss} > 120 GeV → suppress QCD background,
- AK4 jets: ≥2 required (>300 GeV and >150 GeV):
  - for top quark and W' candidates,
  - jet ID with DeepJet to reduce light quark an gluon jets,
- AK8 jets: ≥2 required:
  - for loose selection,
  - veto hadronic tops from SM backgrounds.

$$I_{\text{mini}} = \frac{\Sigma_I(R)}{p_T^{lep}}, \text{with } R = \frac{10\,\text{GeV}}{\min(\max(p_T^{lep}, 50\,\text{GeV}), 200\,\text{GeV})},$$

W' search

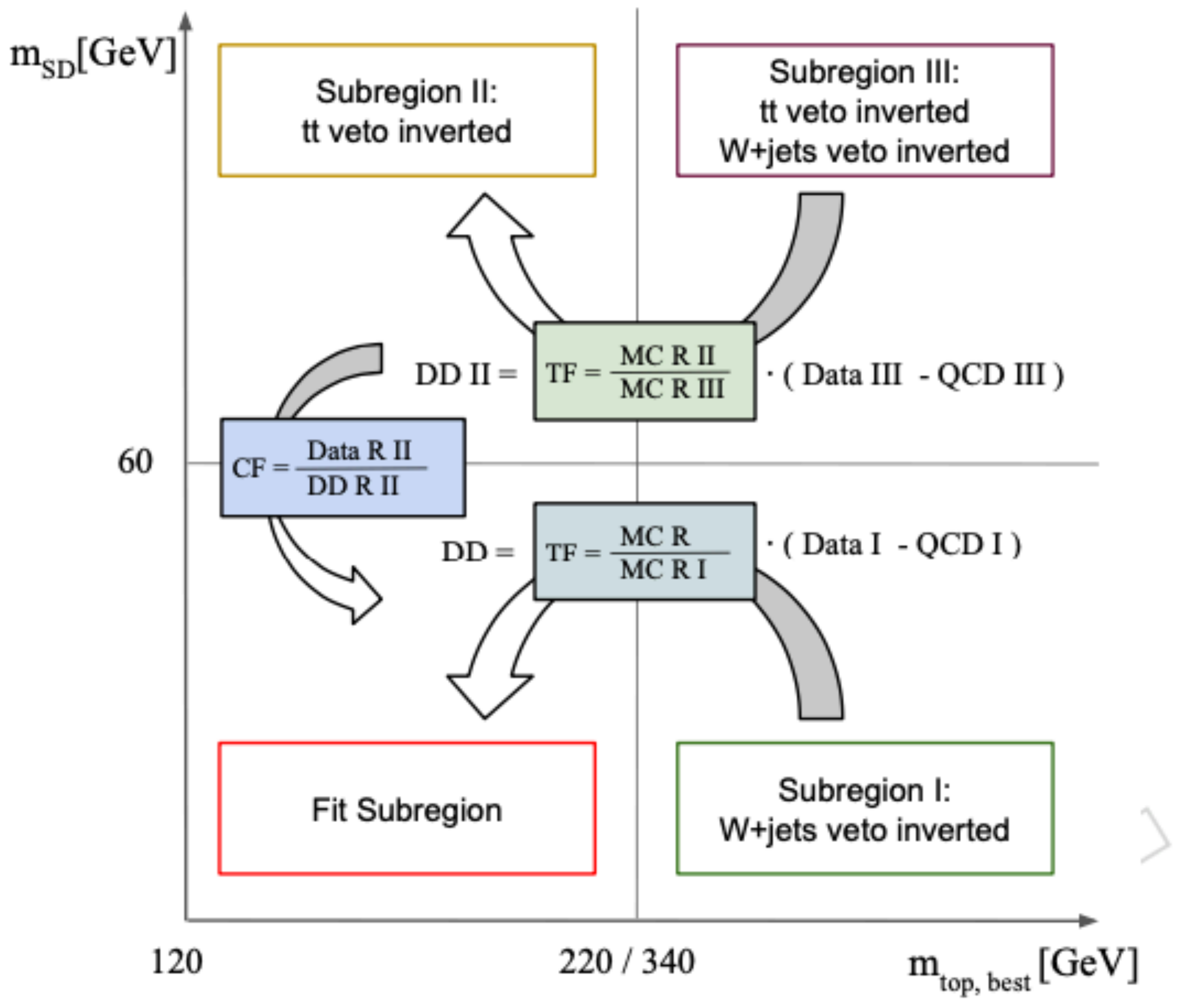
B2G-20-012

Regions definition

- regions: depending on which selected W' and t jets are b-tagged,
- subregions based on:
  - $m_{SD,AK8}$ of the AK8 jet with smallest $\Delta R(jet_{W'}, jet_{AK8})$. Soft-drop declustering removes soft wide-angle radiation from a jet,
  - the mass of the reconstructed top quark m_{top}.

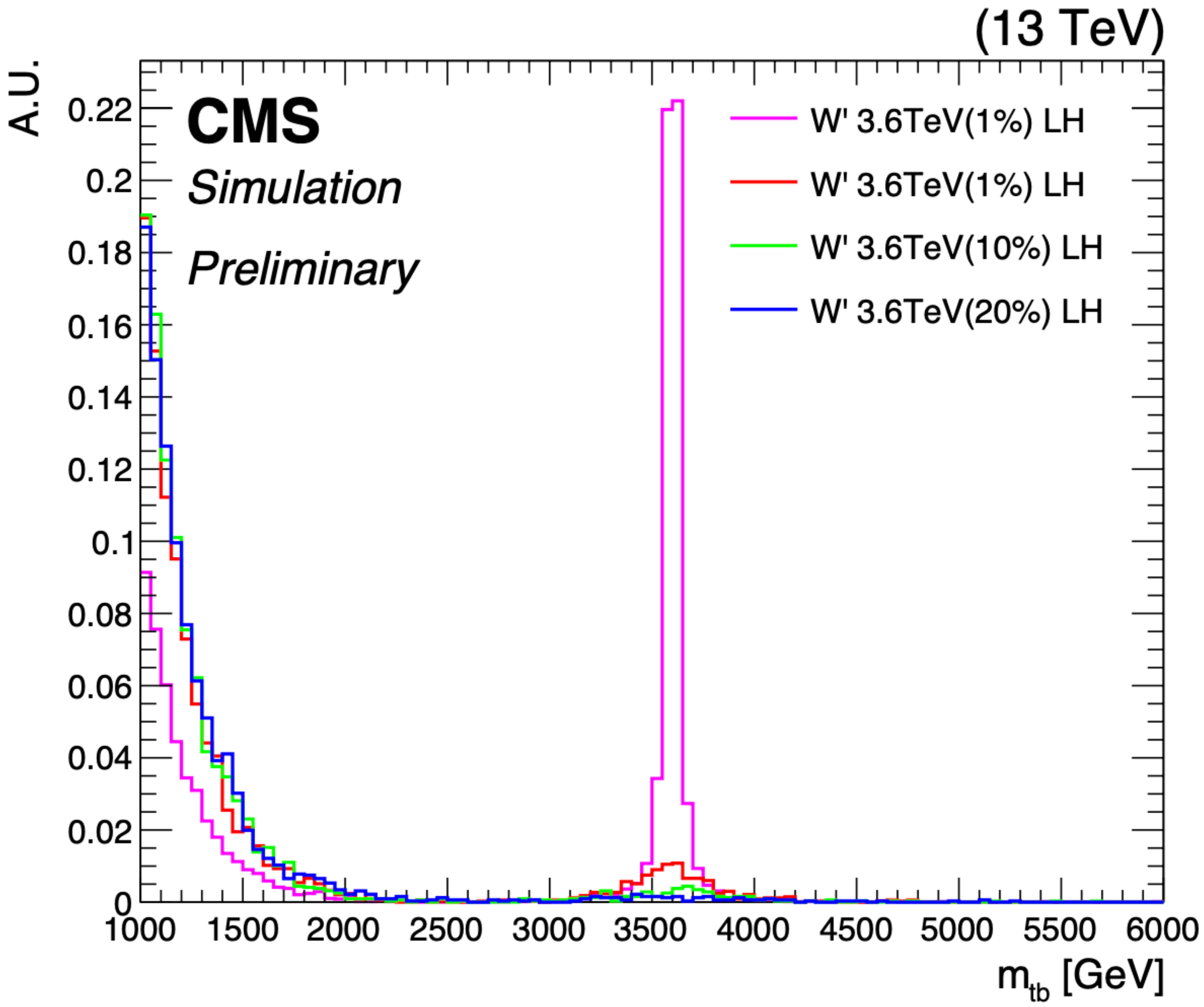
Background estimation

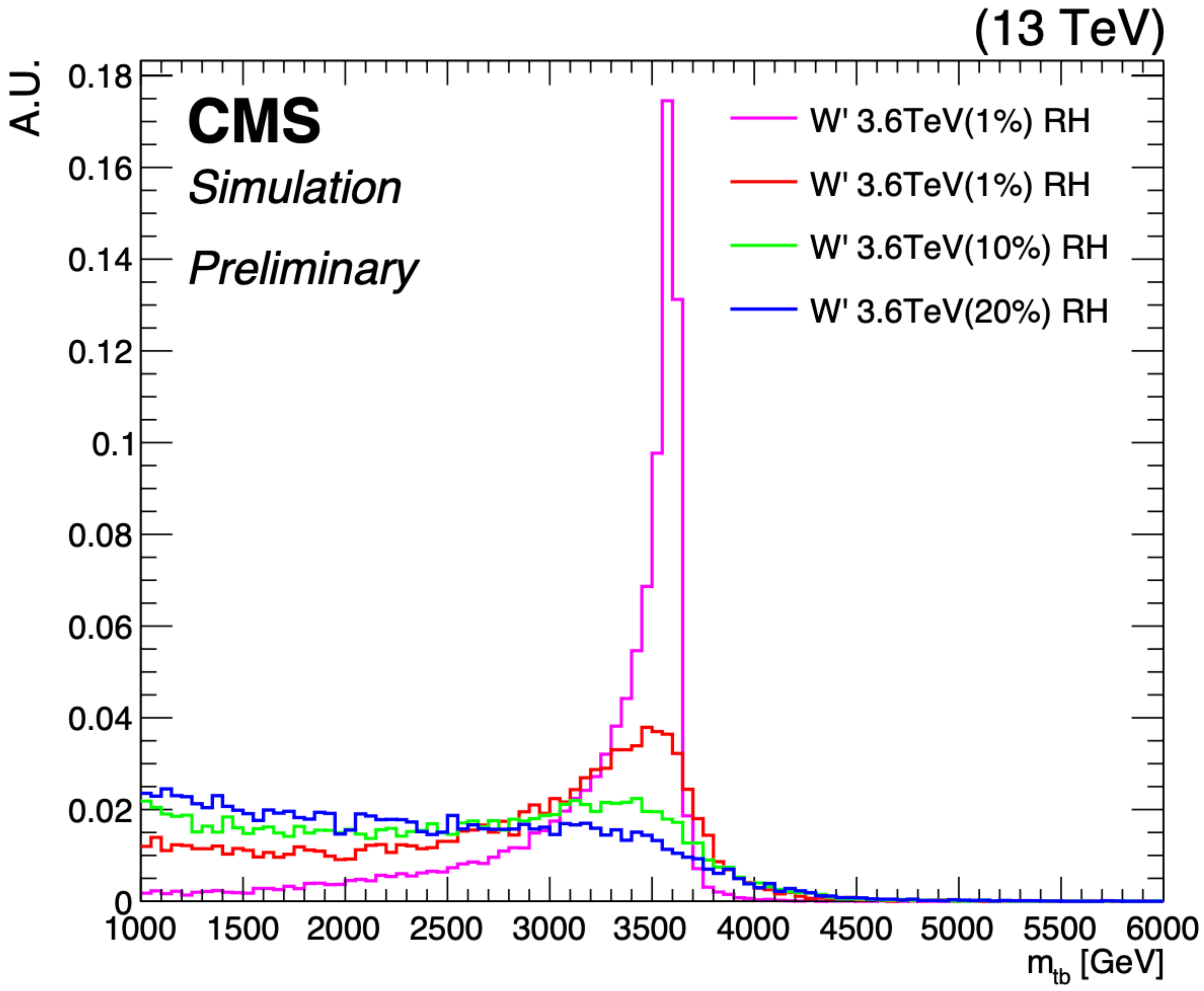
- distribution of background extracted from data,
- overall shape and normalization found from control regions,
- simulation used to determine transfer functions to signal regions,
- function fitted: $a \cdot \exp(b \cdot m_{W'}) + c \cdot m_{W'} + d$,
- statistical uncertainty of the fit propagated to the prediction,
- some regions used to estimate systematic effects (differences in $m_{W'}$ spectra due to selections, or different background composition).



W' search

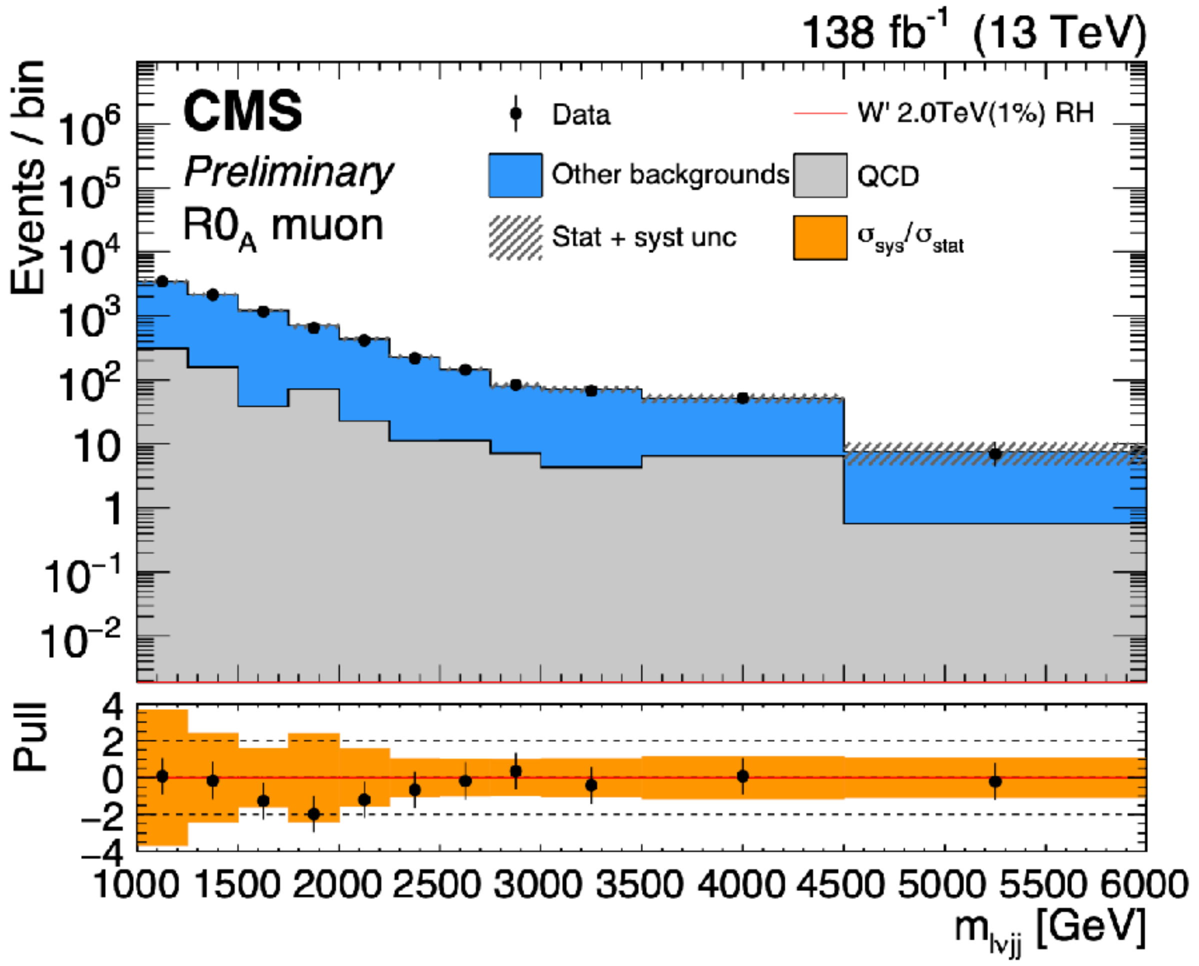
B2G-20-012

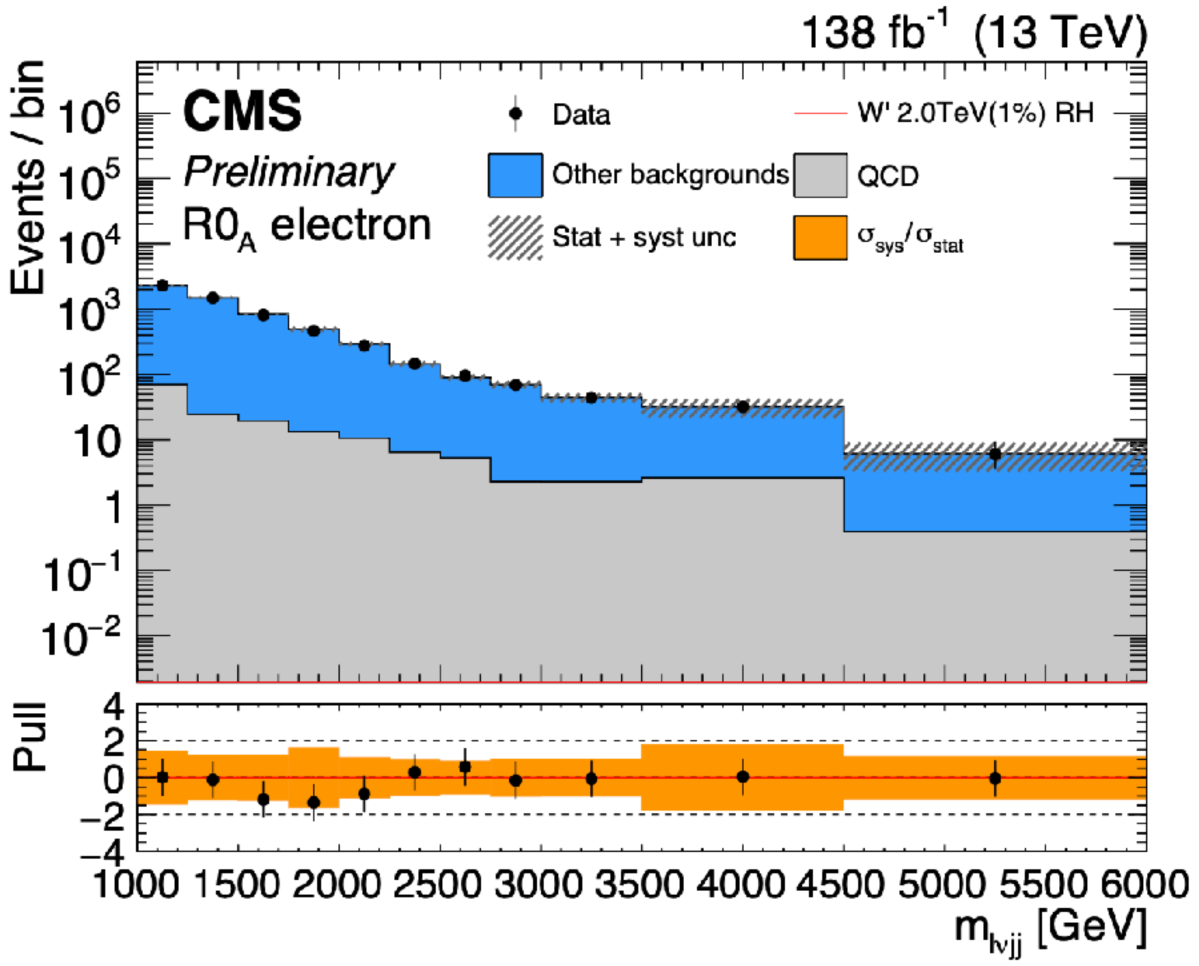


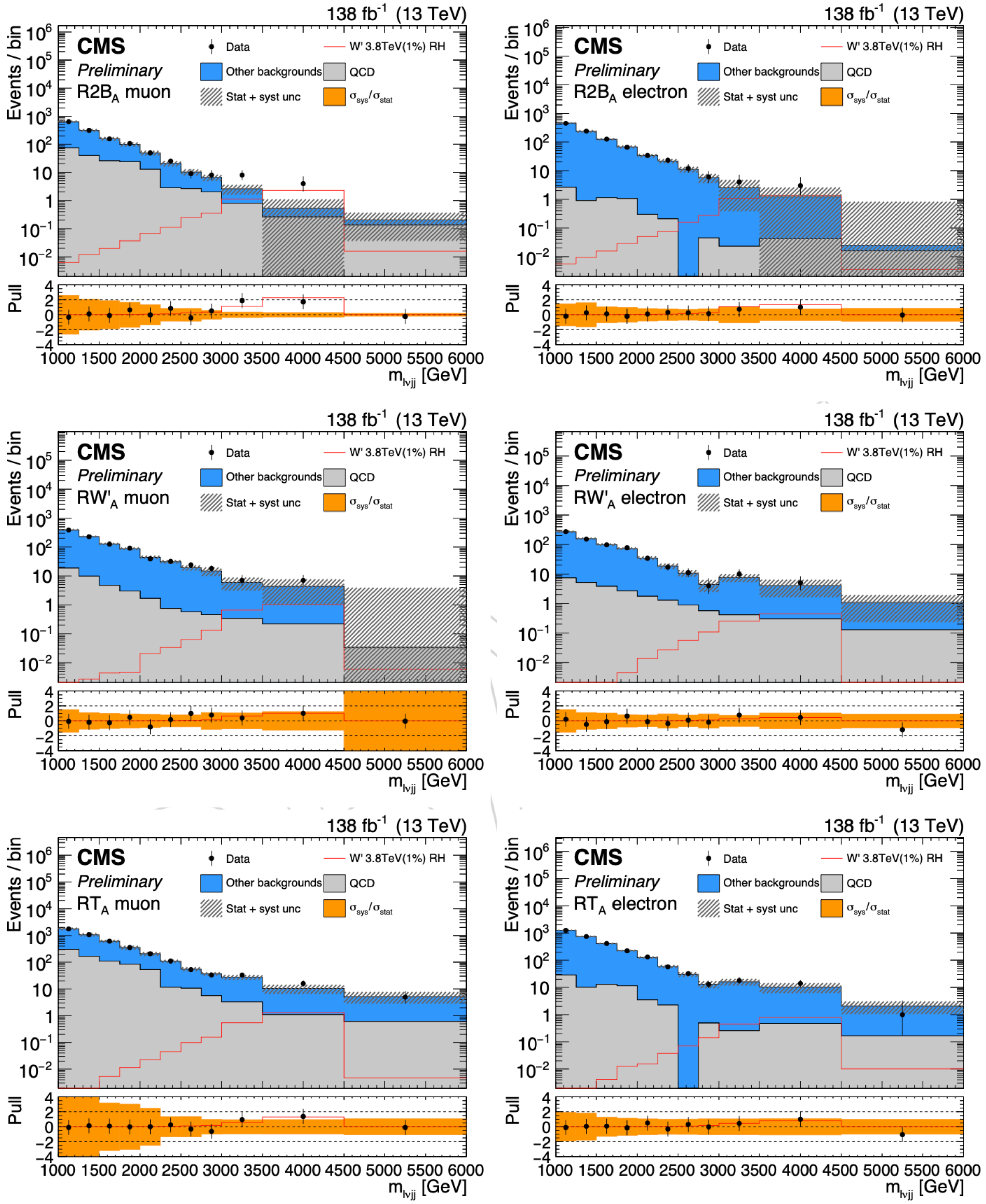


W’ search

B2G-20-012







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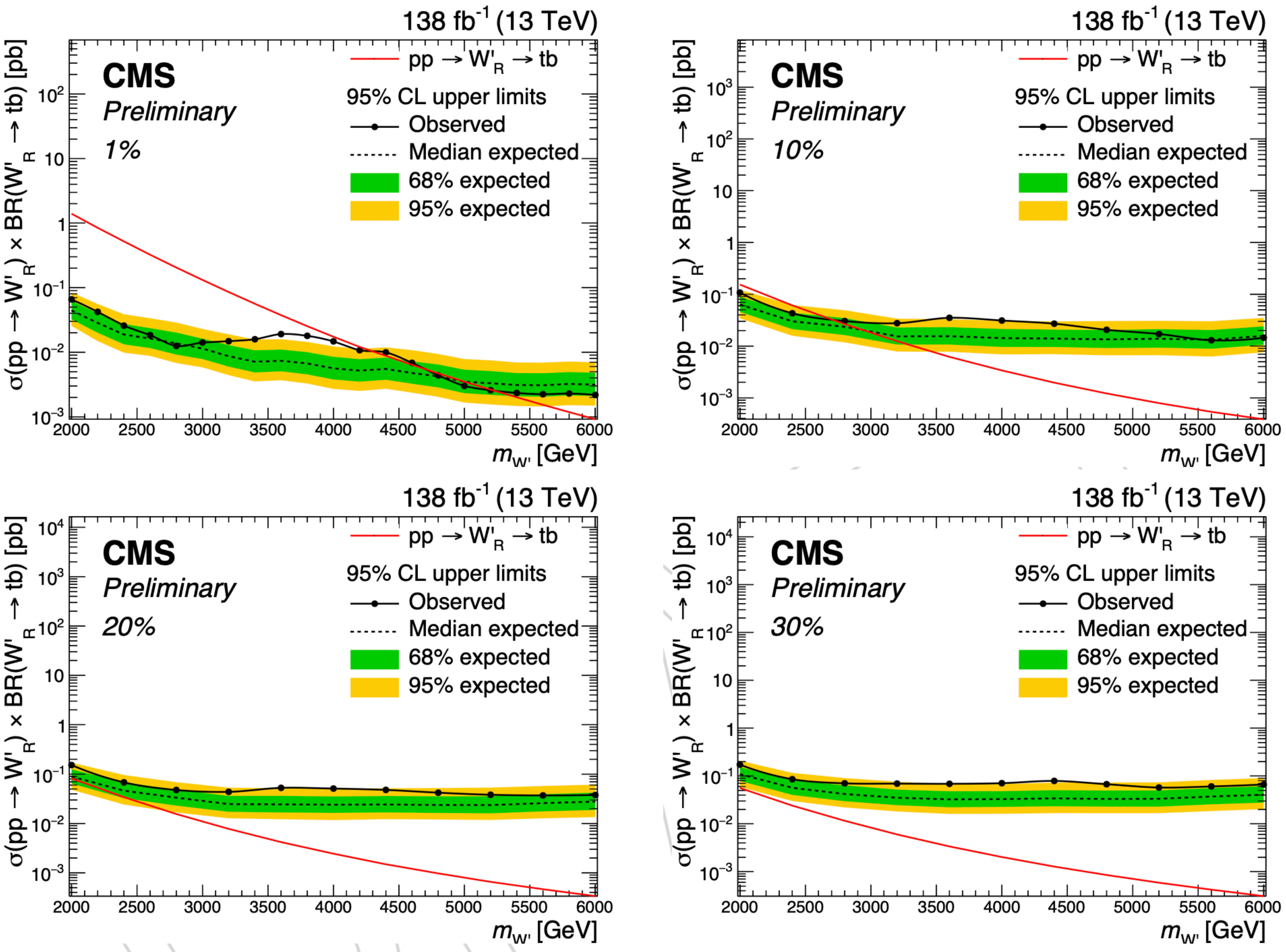
W’ search

B2G-20-012

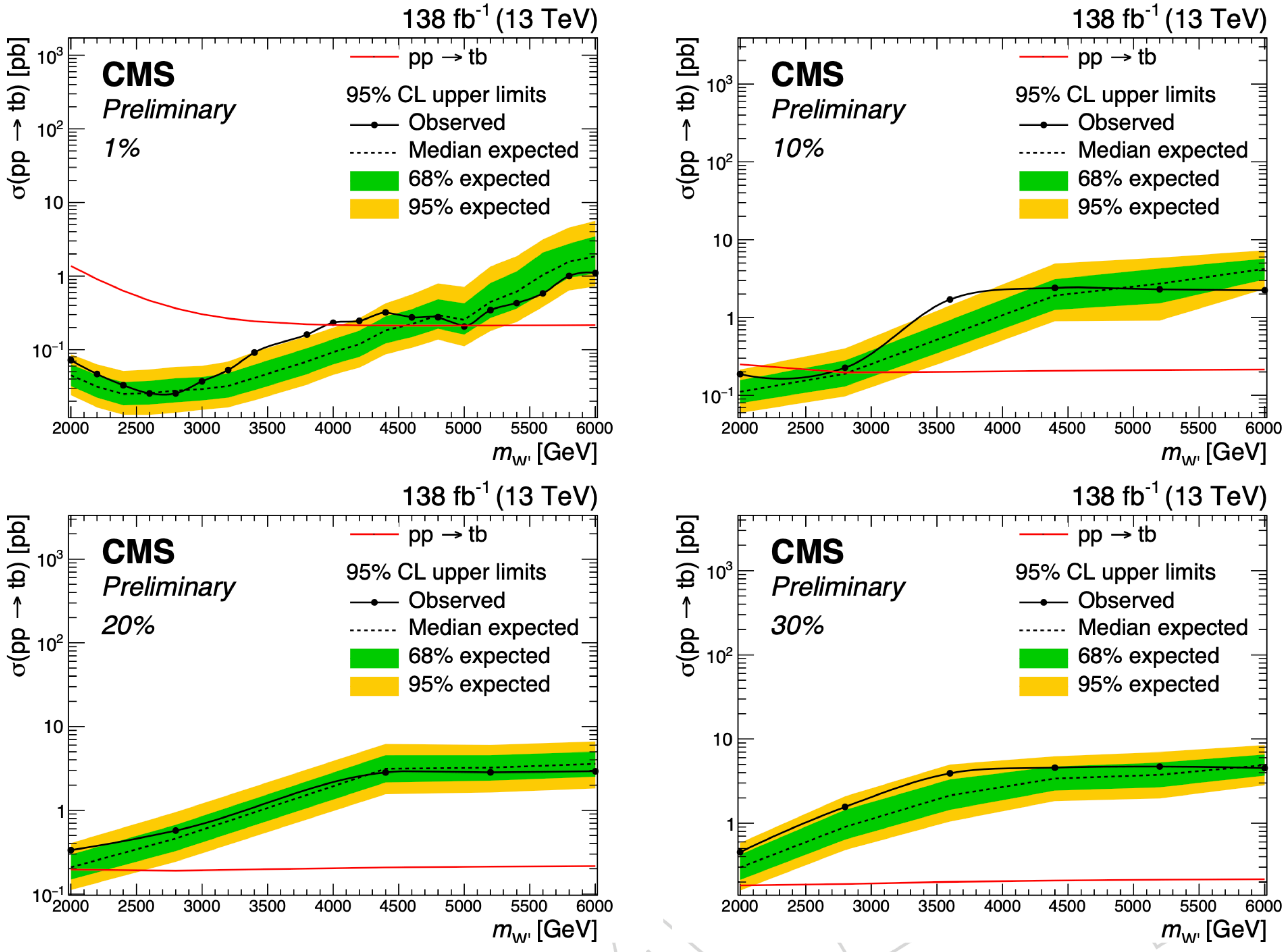
right handed W’



W' search

B2G-20-012

left handed W'

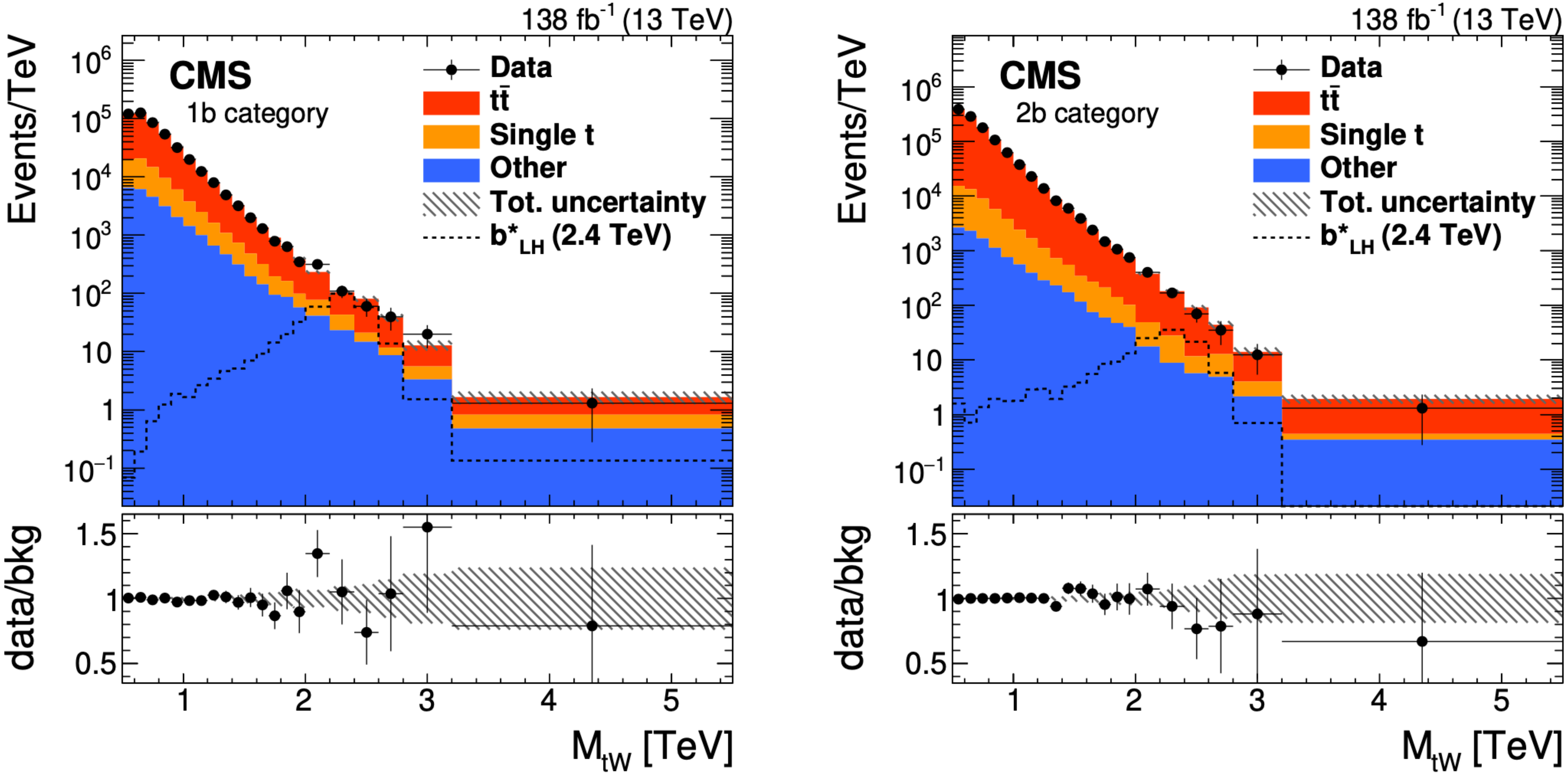


Heavy tW search

B2G-20-010

Trigger

- ≥1 muon,
- ≥ 2 electron,
- photons



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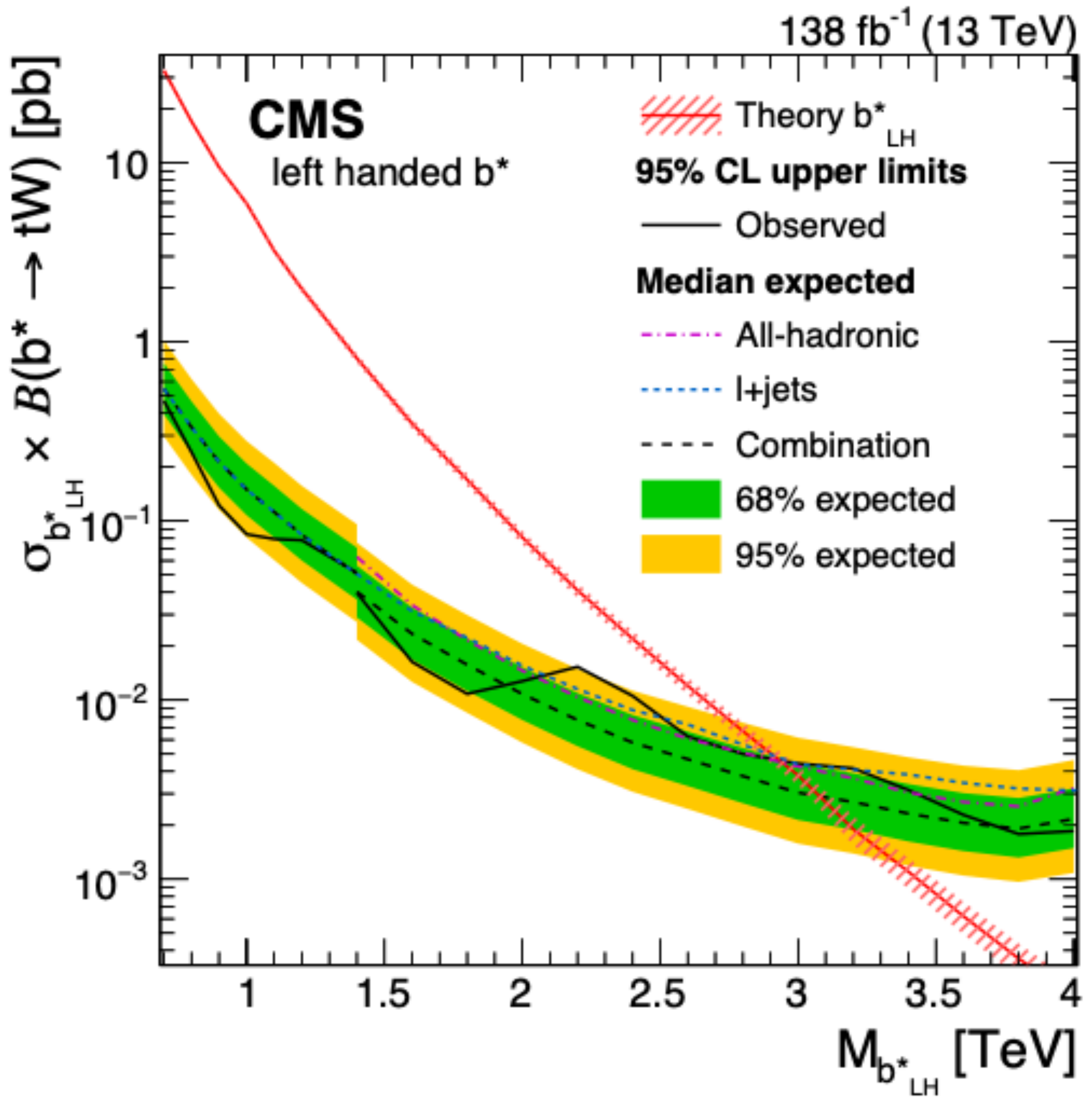
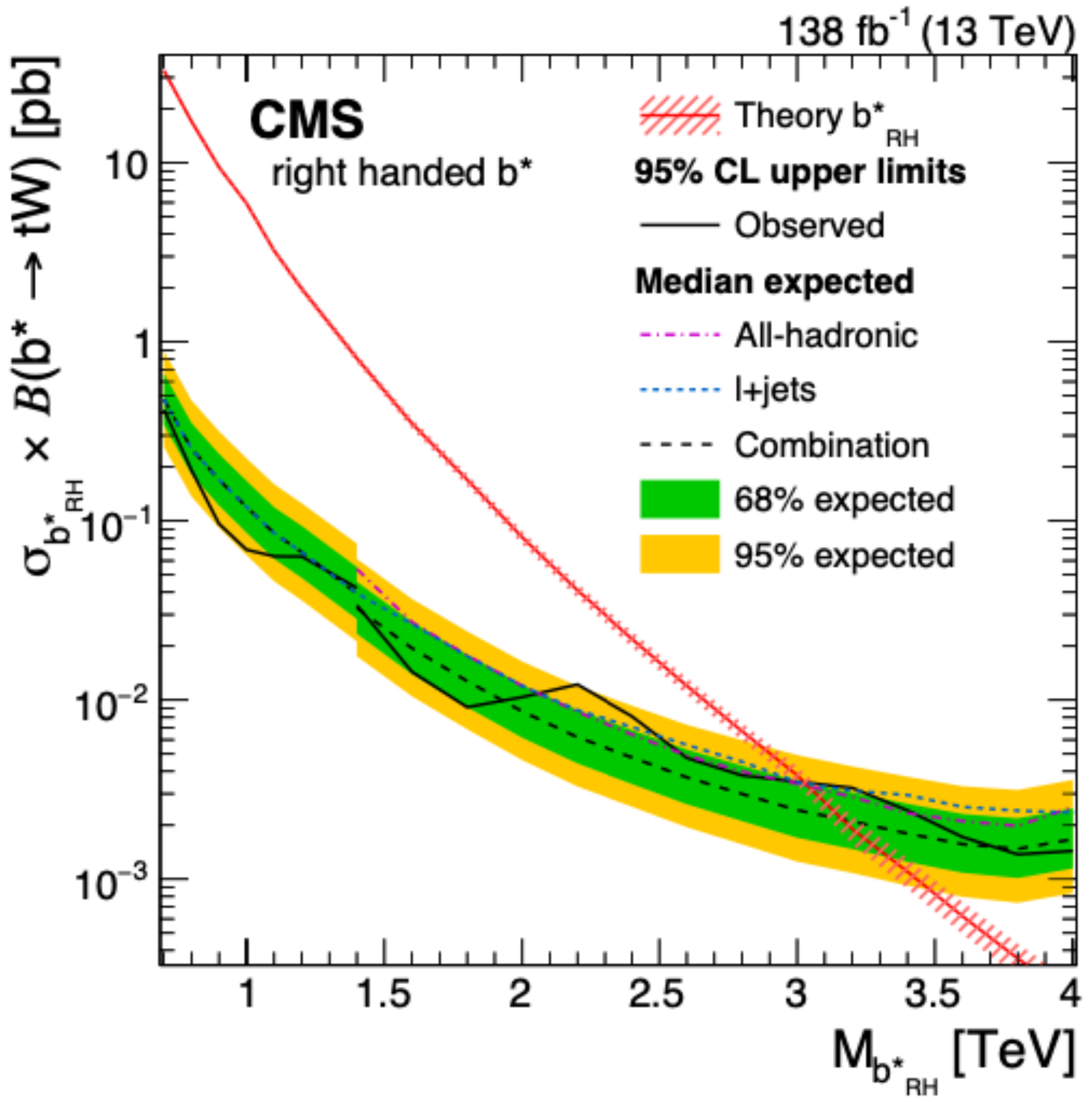
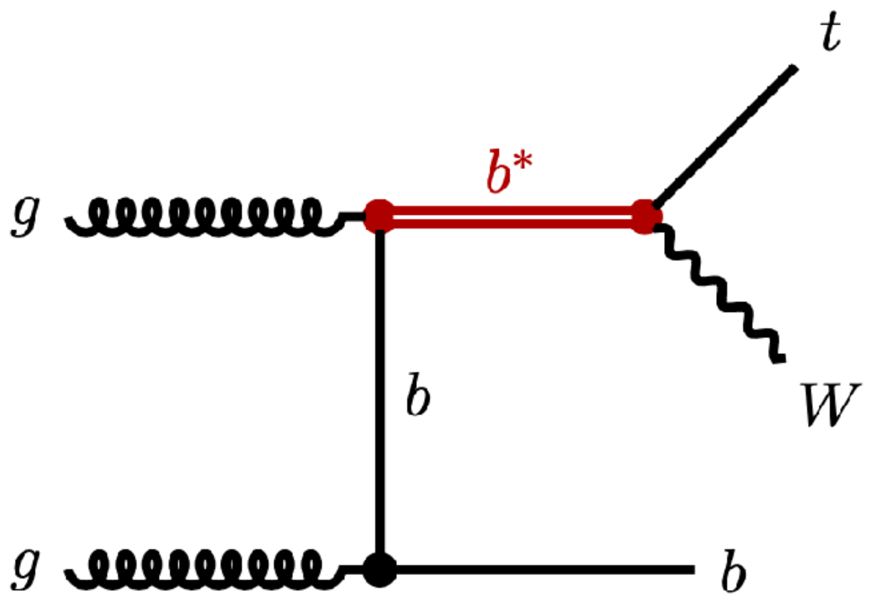
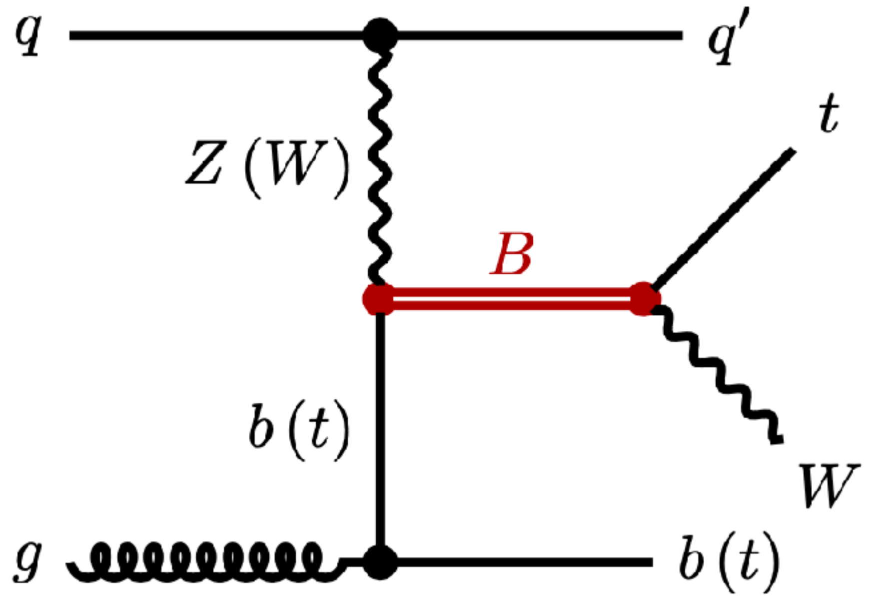
Heavy tW search

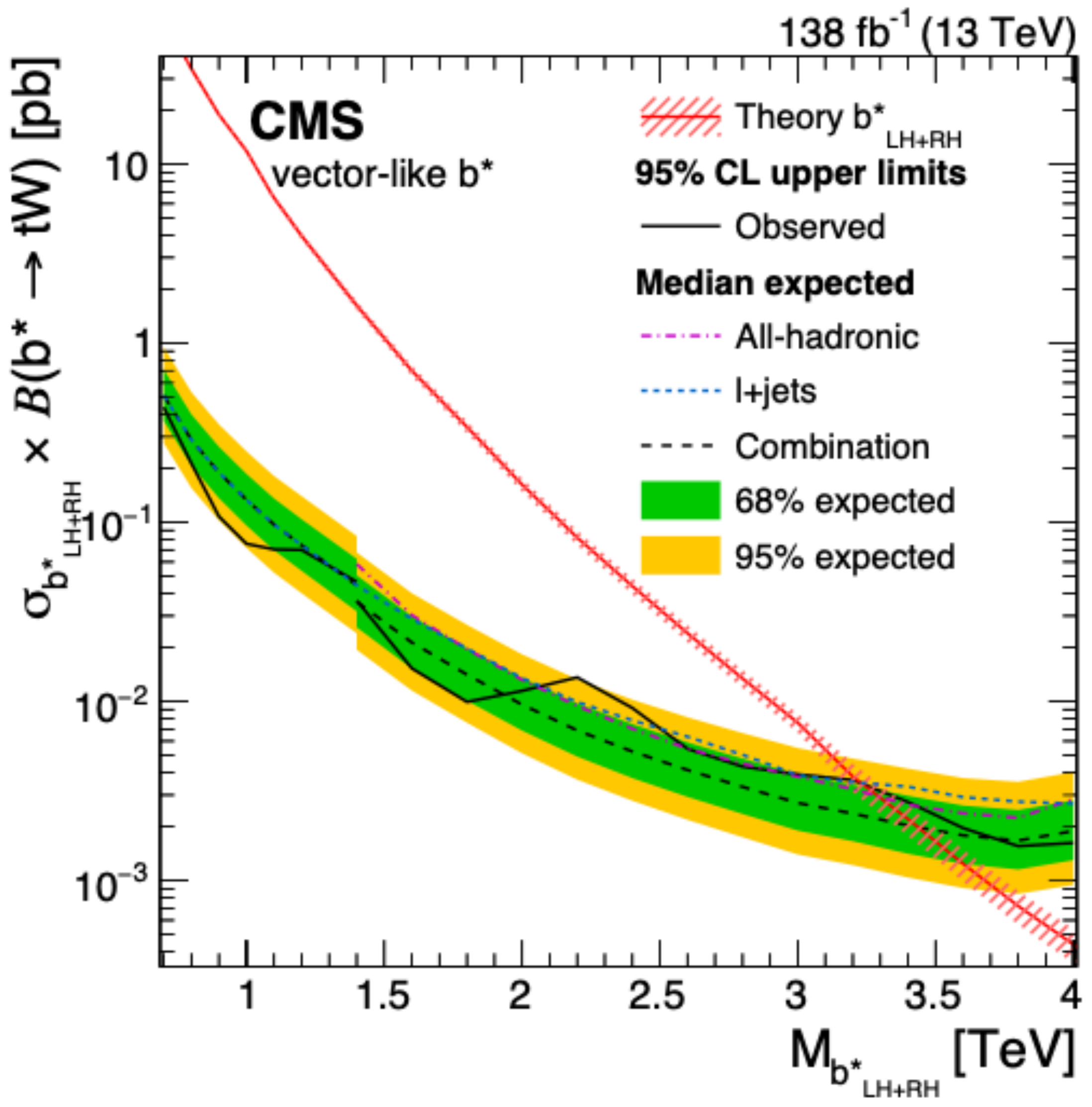
B2G-20-010

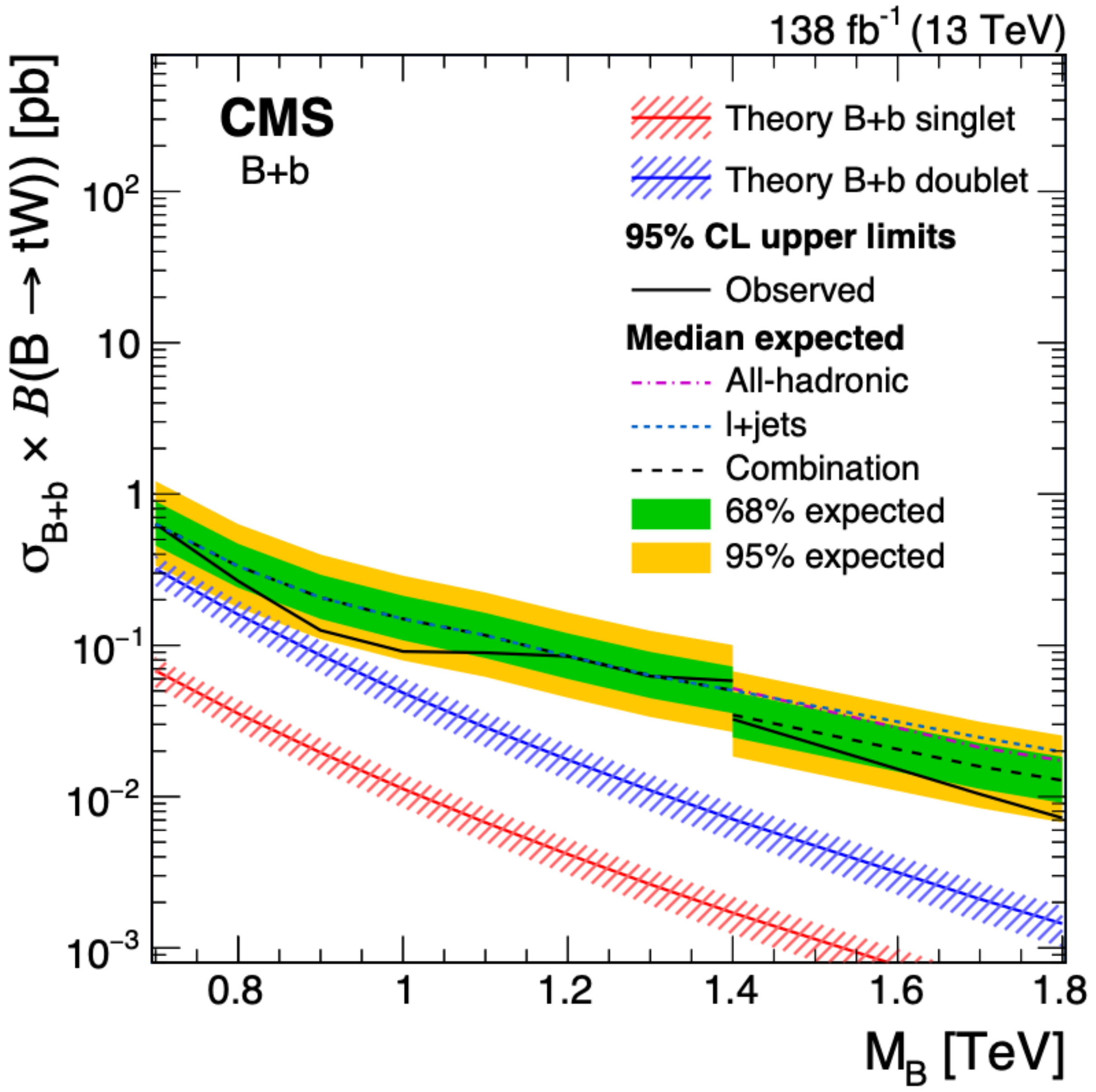


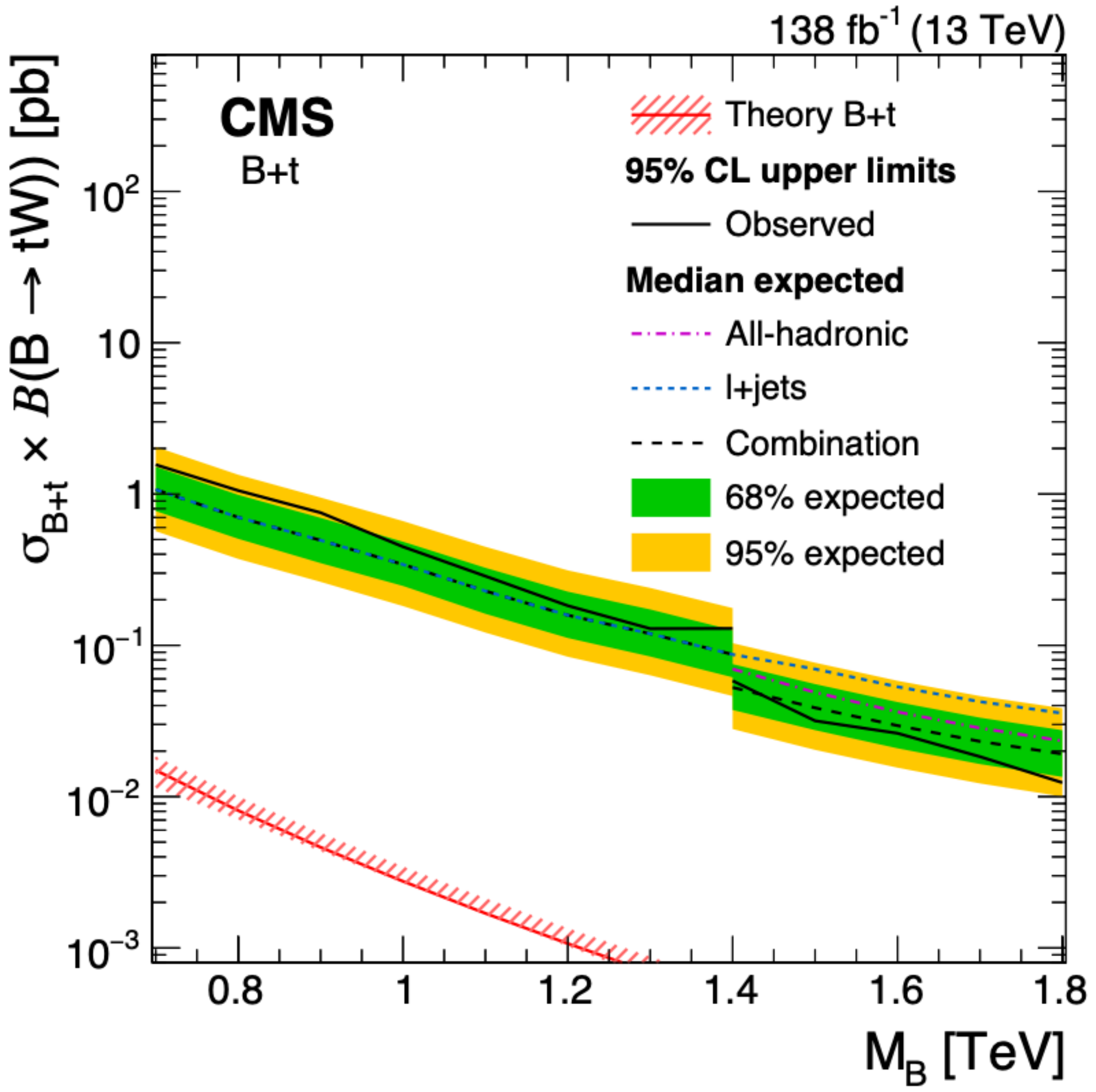






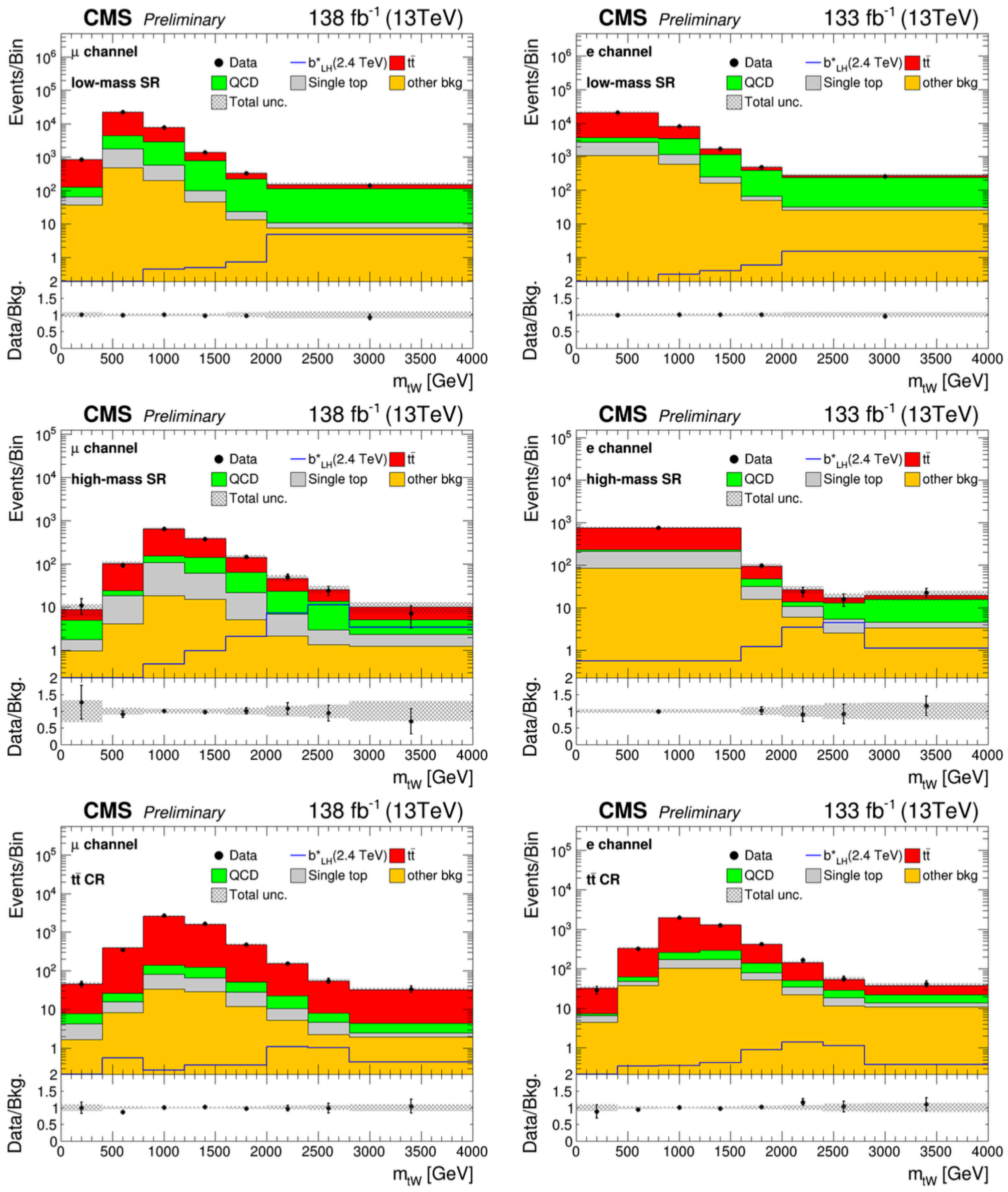


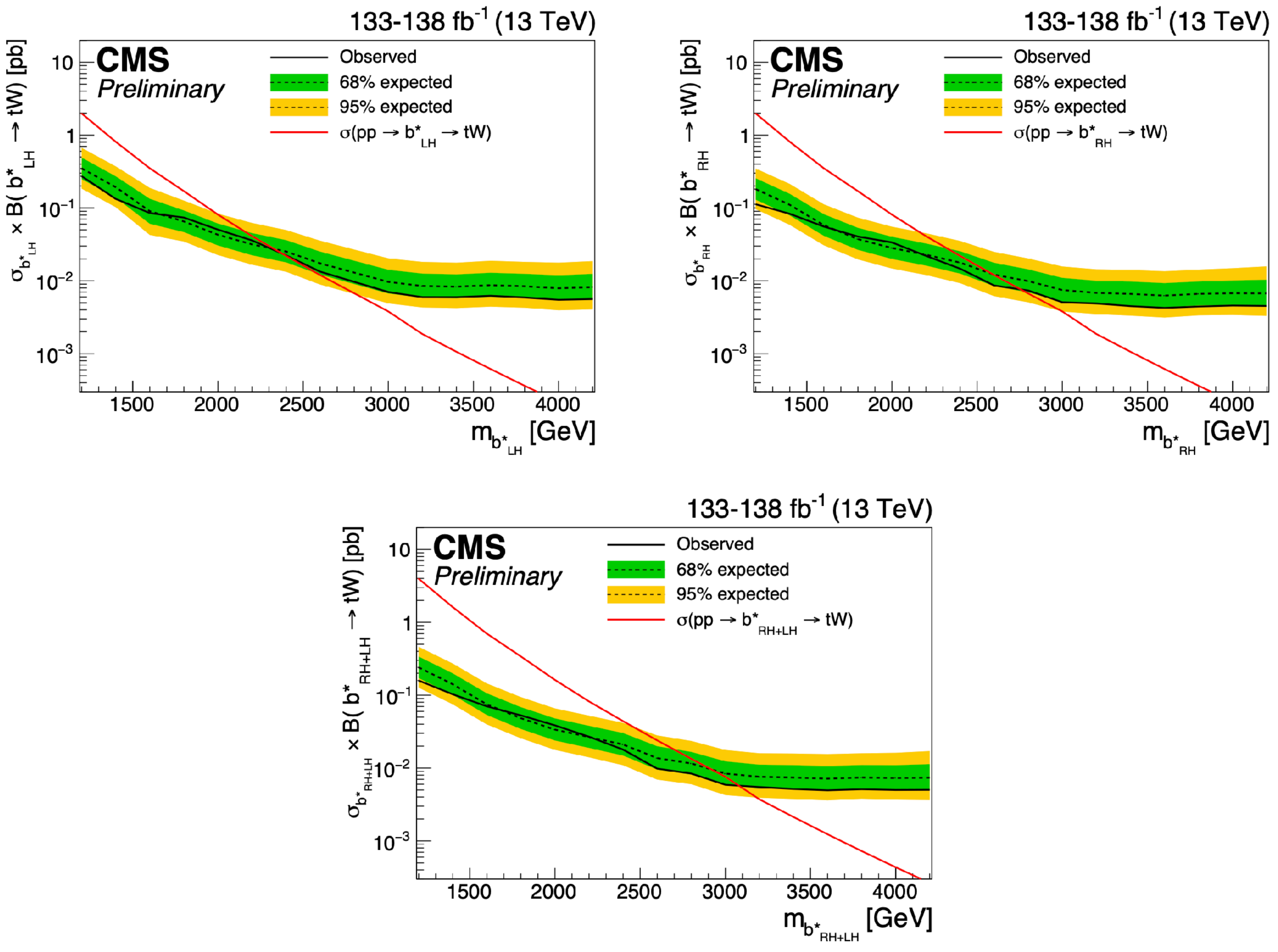




Heavy tW search

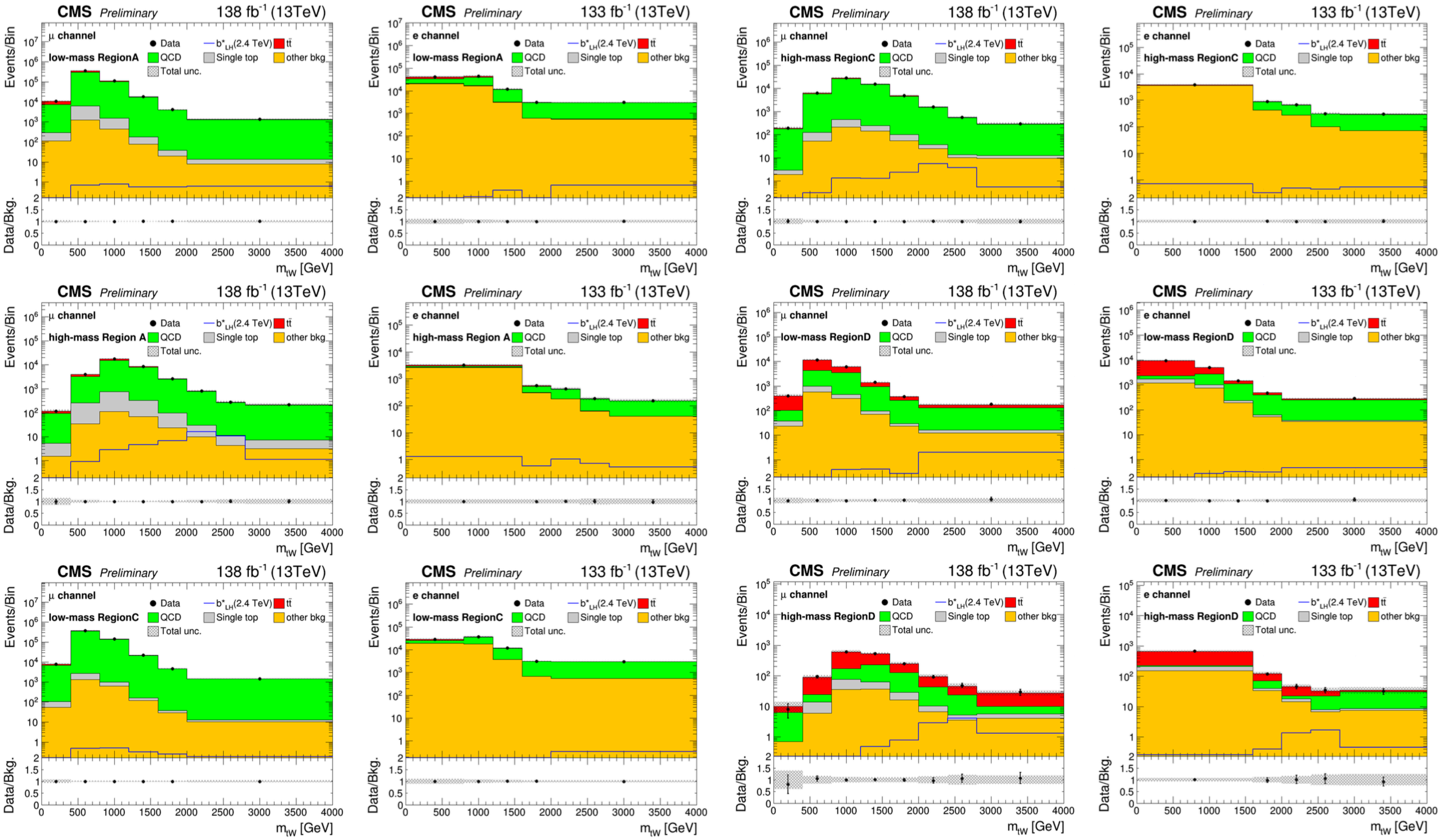
B2G-21-005





Heavy tW search

B2G-21-005



Heavy tW search

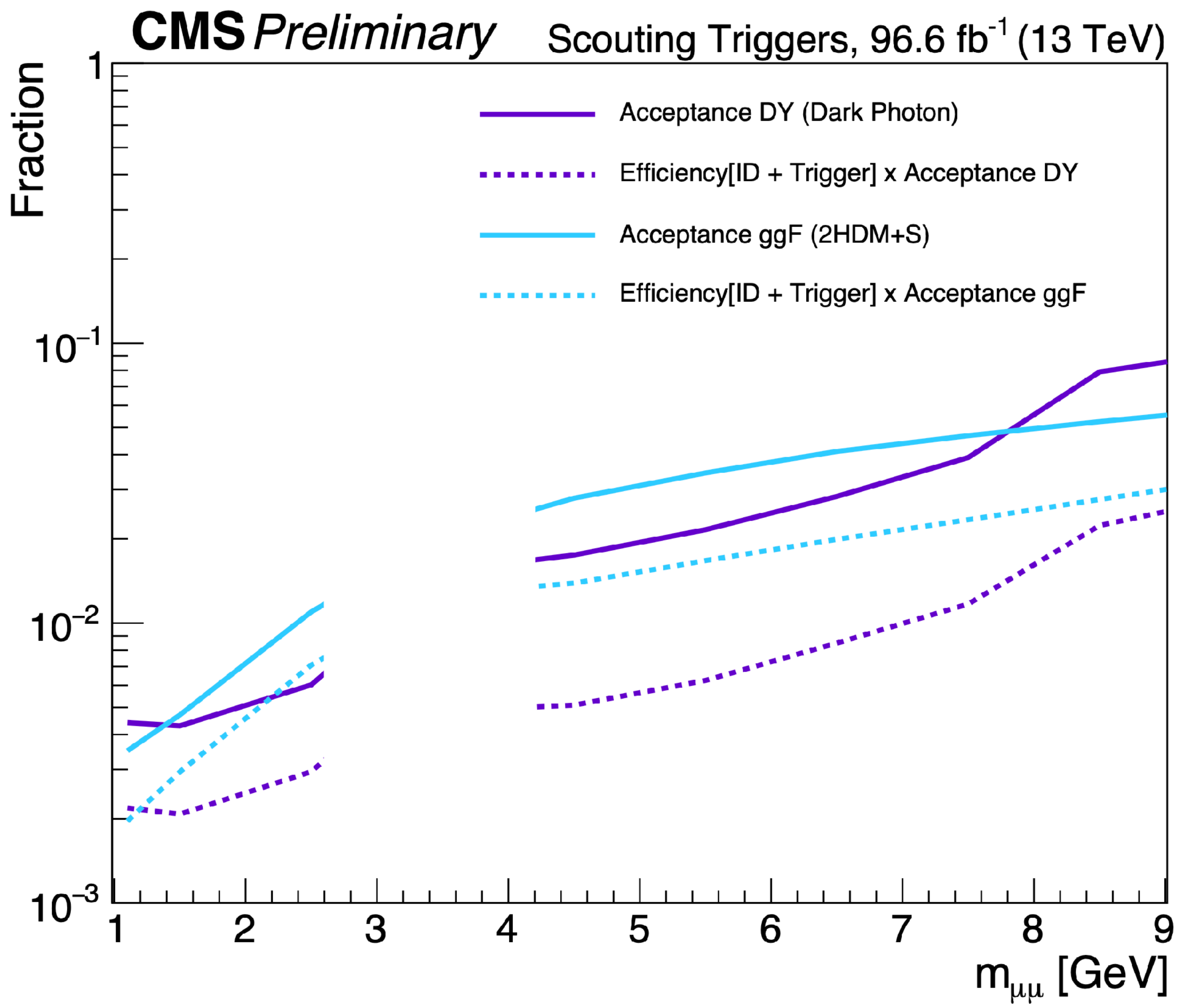
B2G-21-005

Signal/control regions

- dominant backgrounds: QCD & tt,
- QCD from data: ABCD method, several CRs, simultaneous maximum-likelihood fit with the SRs,
- tt determined from simulation:
  - tt-enriched CR used to constrain the uncertainties in the tt normalization and shape of the tt background in the m_{tW} distribution,
  - W tagging requirement → t tagging requirement on AK8 jets,
  - QCD background in tt CR small → taken from simulation,
- minor backgrounds from W+jets, diboson, top + W → shape from simulation, yields through nuisance paramaters in the fit.

LOW-MASS DIMUON SCOUTING

EXO-21-005

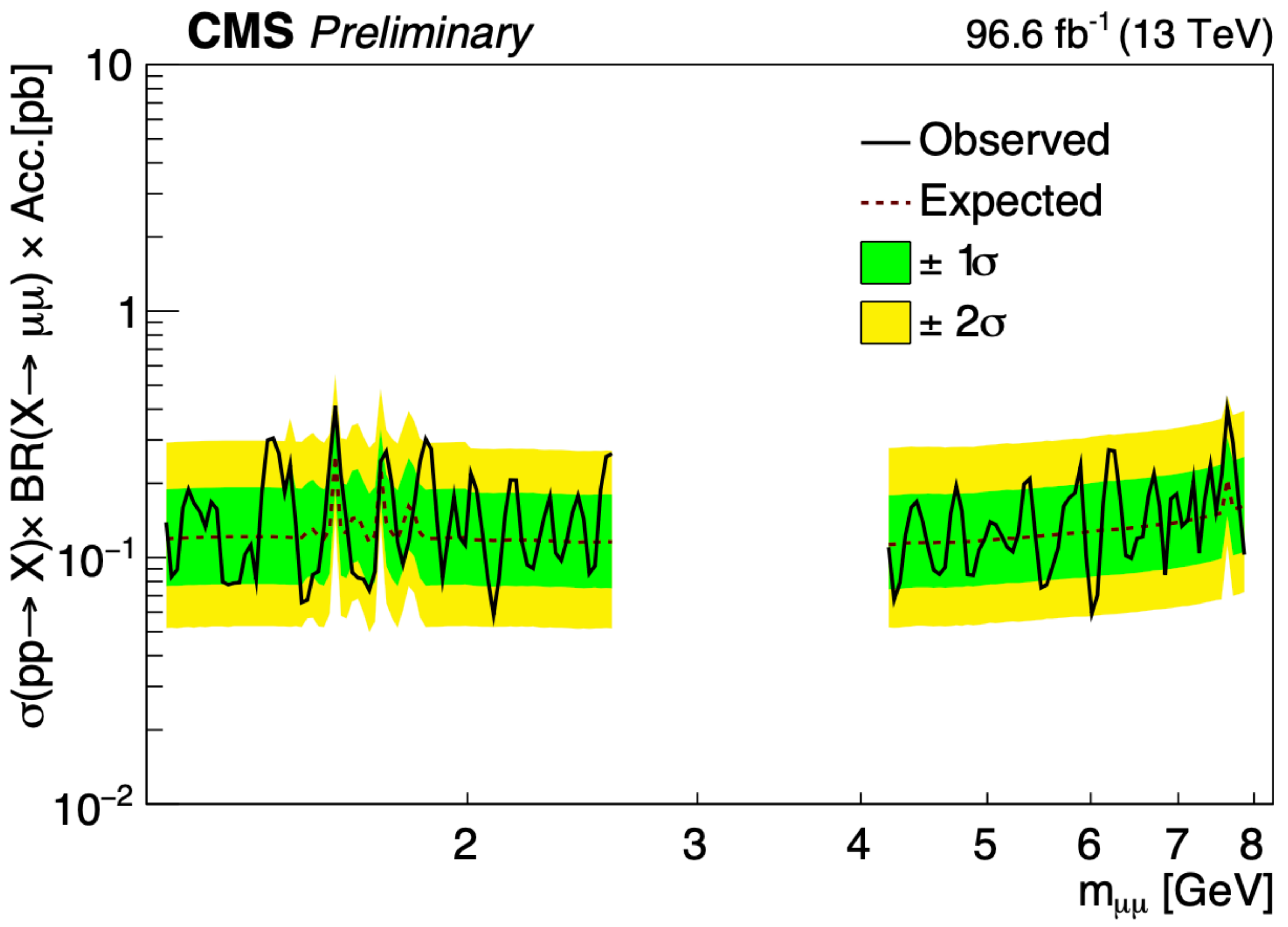


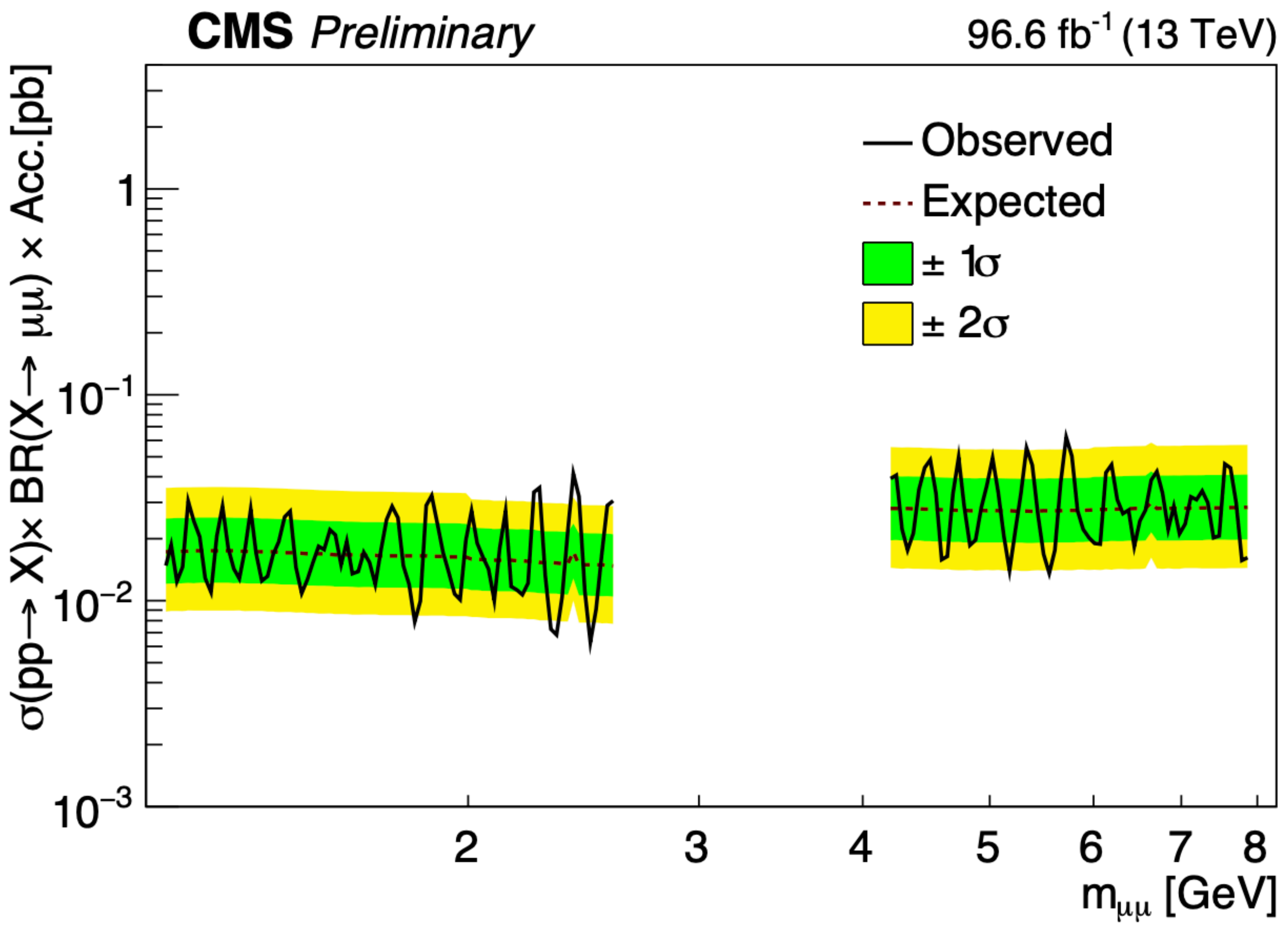
L1 seeds

OS	$p_{T,1}$	$p_{T,2}$	$\|\eta\|$	$m_{\mu\mu}$	$\Delta R_{\mu\mu}$
X	> 15 GeV	> 7 GeV	—	—	—
✓	> 4.5 GeV		< 2.0	∈[7, 18]	—
	> 4.0 (4.5) GeV		—	—	< 1.2
	—		< 1.5	—	< 1.4

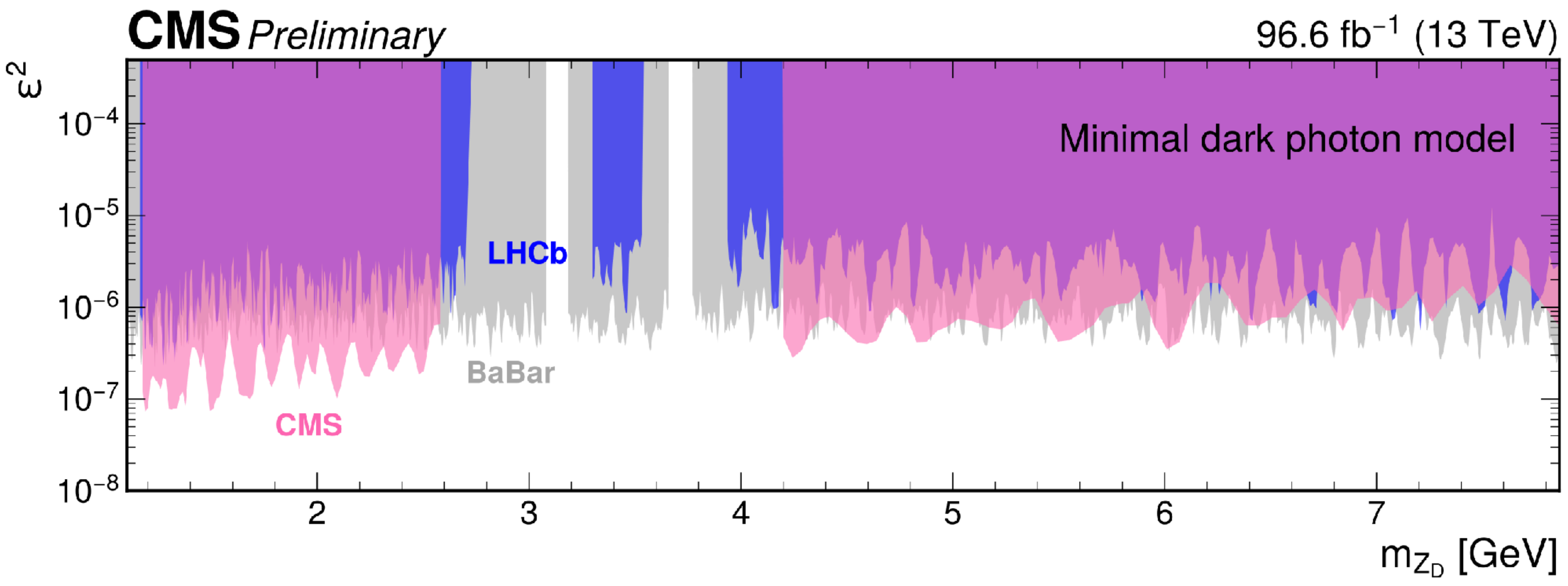
LOW-MASS DIMUON SCOUTING

EXO-21-005





Effect	$m_{\mu\mu} < 2.6$ GeV	$m_{\mu\mu} > 4.2$ GeV
Integrated luminosity	2.3–2.5%	
Mass resolution	20%	
Trigger efficiency	1–20%	
Muon ID efficiency	4–9%	12–20%
Vertex selection	—	3%
Efficiency application	8%	4%
D meson normalization TFs	20–25%	—



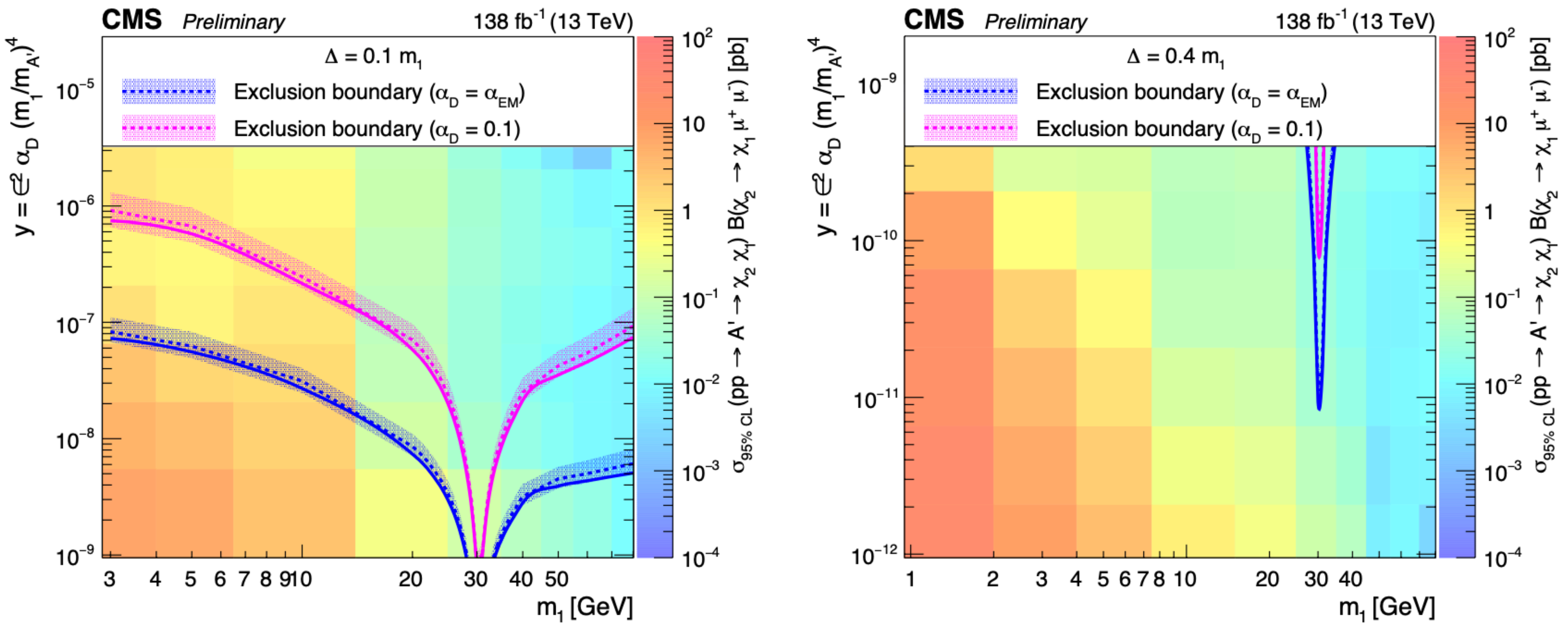
INELASTIC DM

Trigger

- triggering on MET (muons too soft)

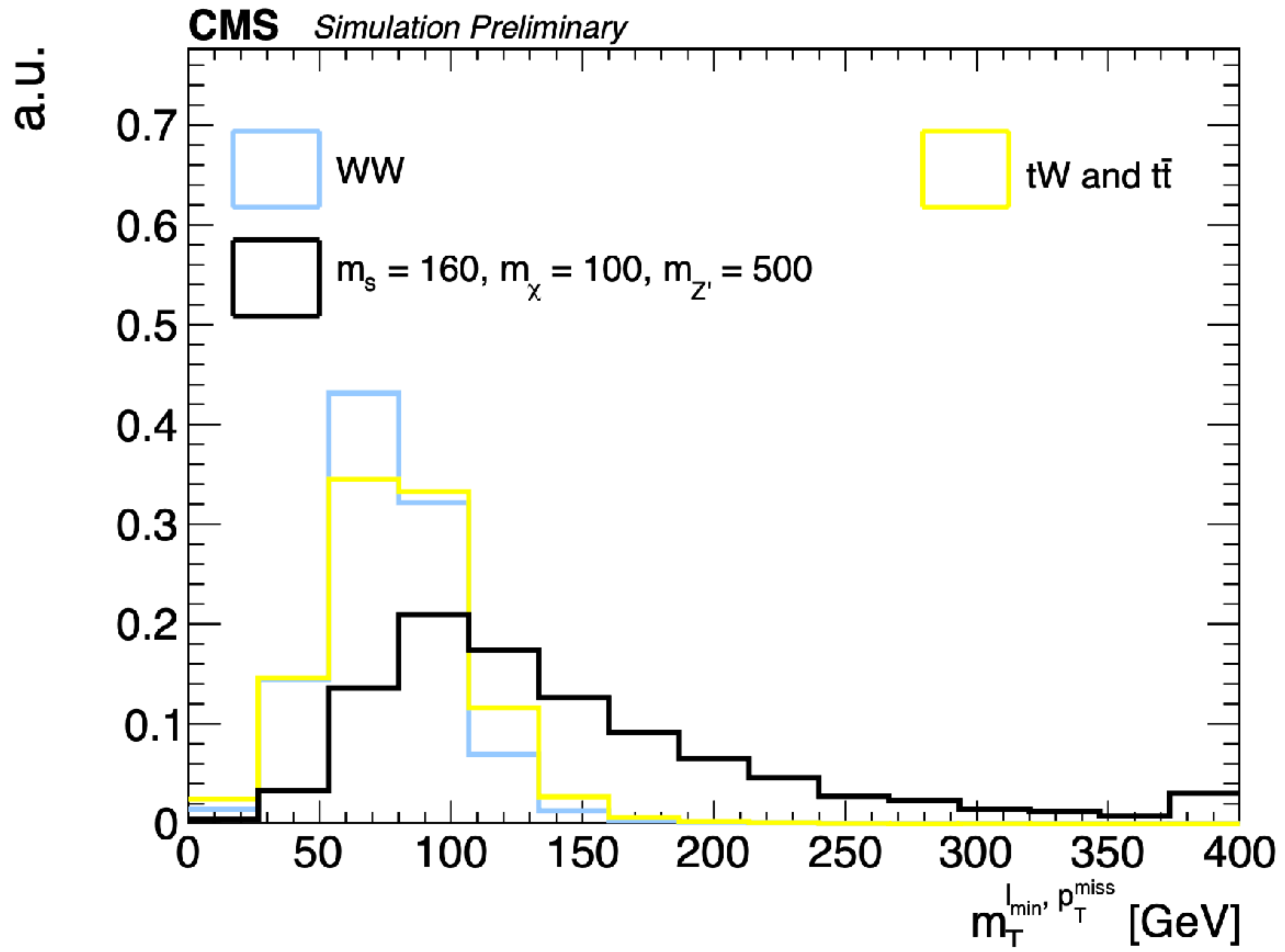
Backgrounds

- QCD (suppressed with Njets ≤ 2 requirement)
- top (suppressed by b-jets veto)
- W+jets

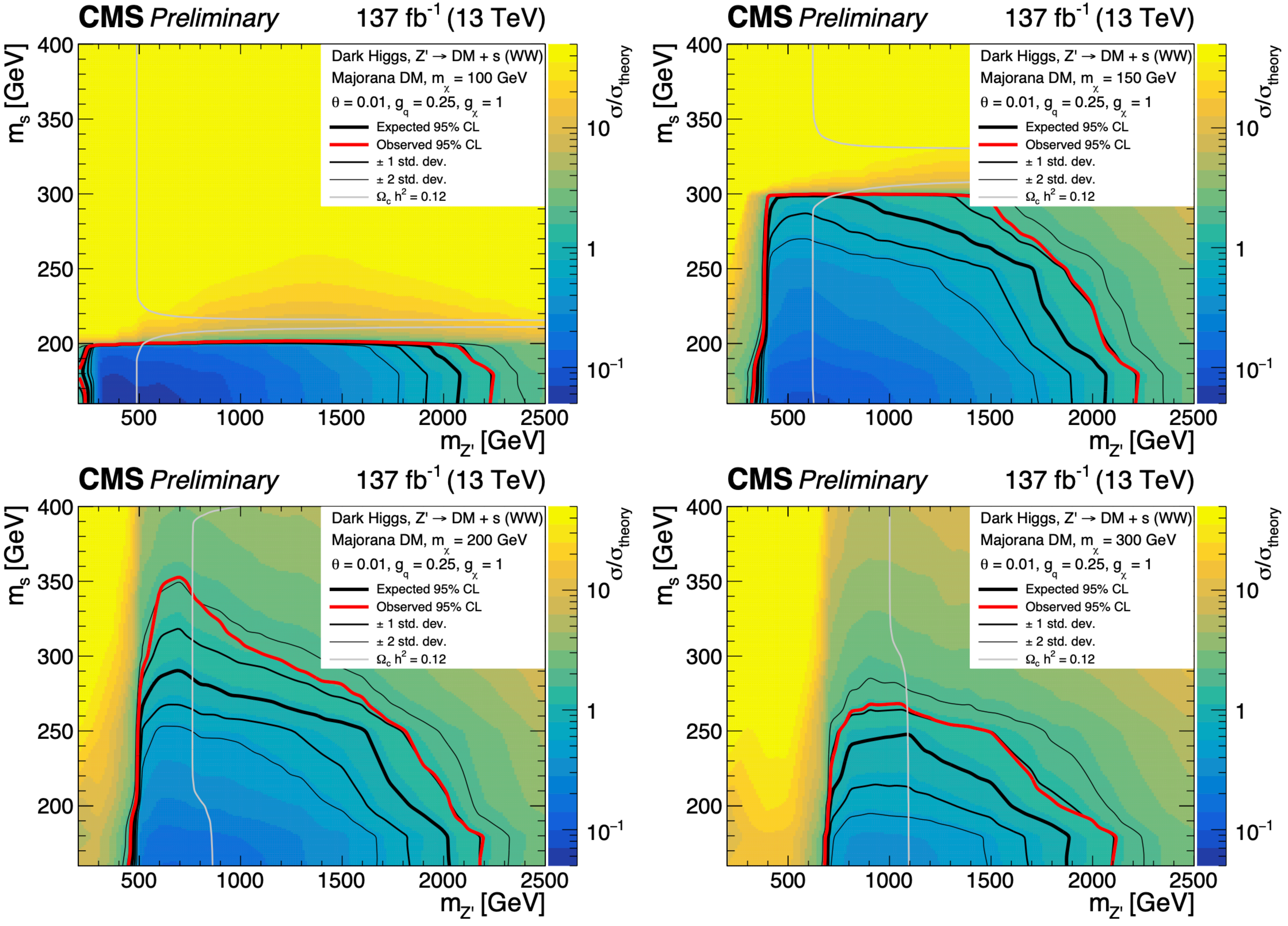


DARK HIGGS

EXO-21-012



$$m_{\mathrm{T}}^{\ell\,\mathrm{min},p_{\mathrm{T}}^{\mathrm{miss}}} = \sqrt{2 p_{\mathrm{T}}^{\ell\,\mathrm{min}} p_{\mathrm{T}}^{\mathrm{miss}} \left[1 - \cos\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\ell\,\mathrm{min}}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})\right]},$$



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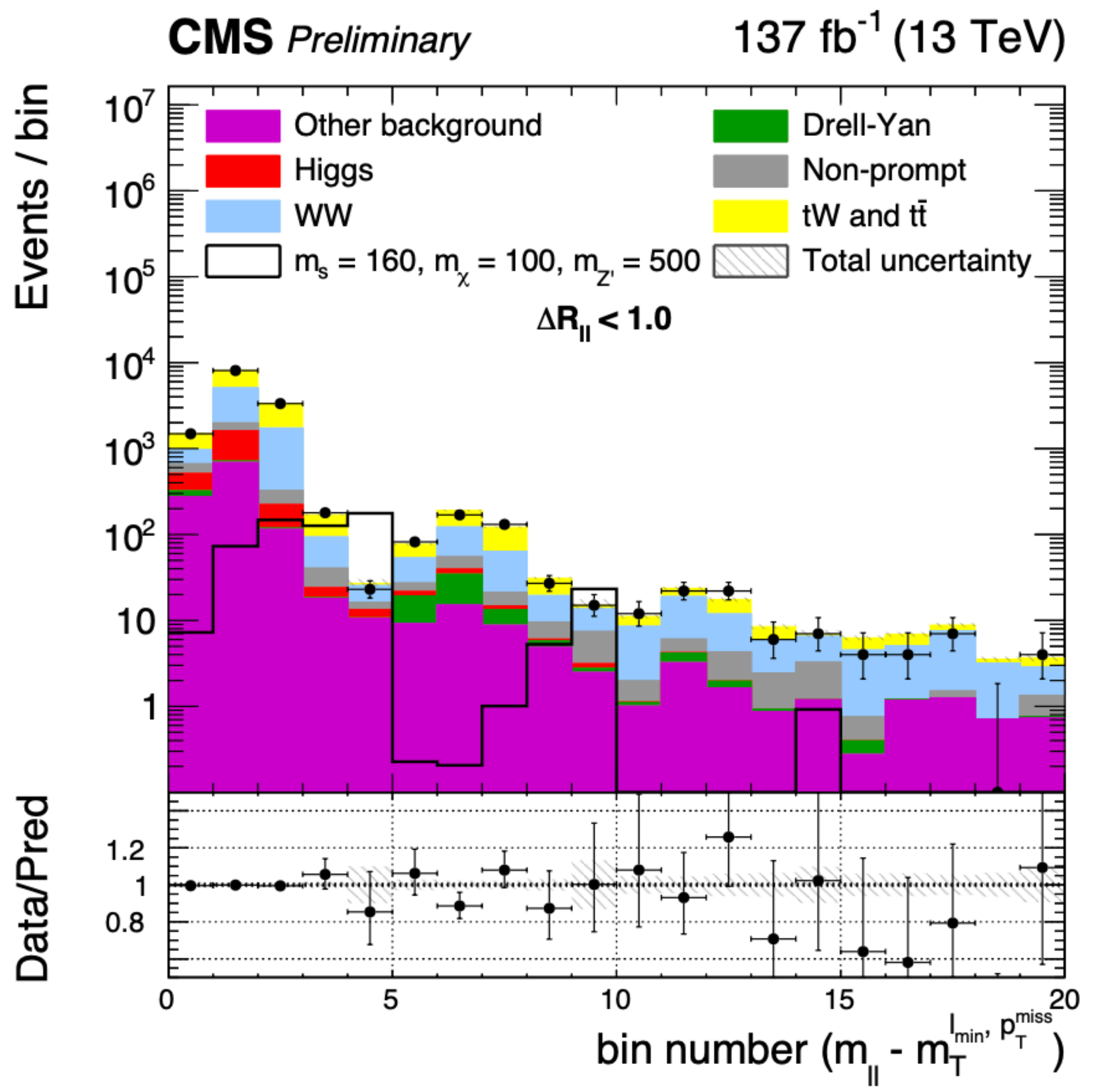
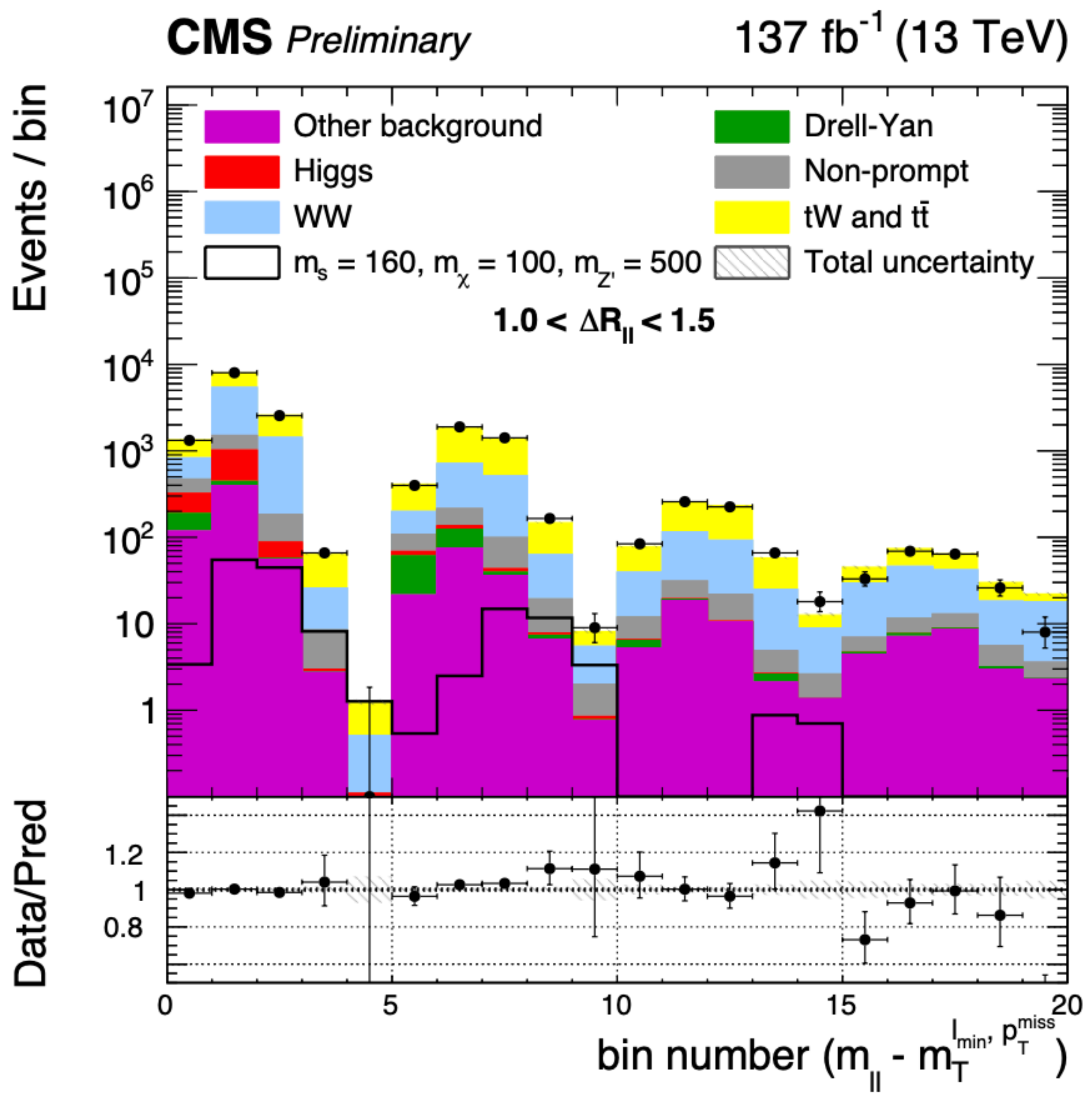
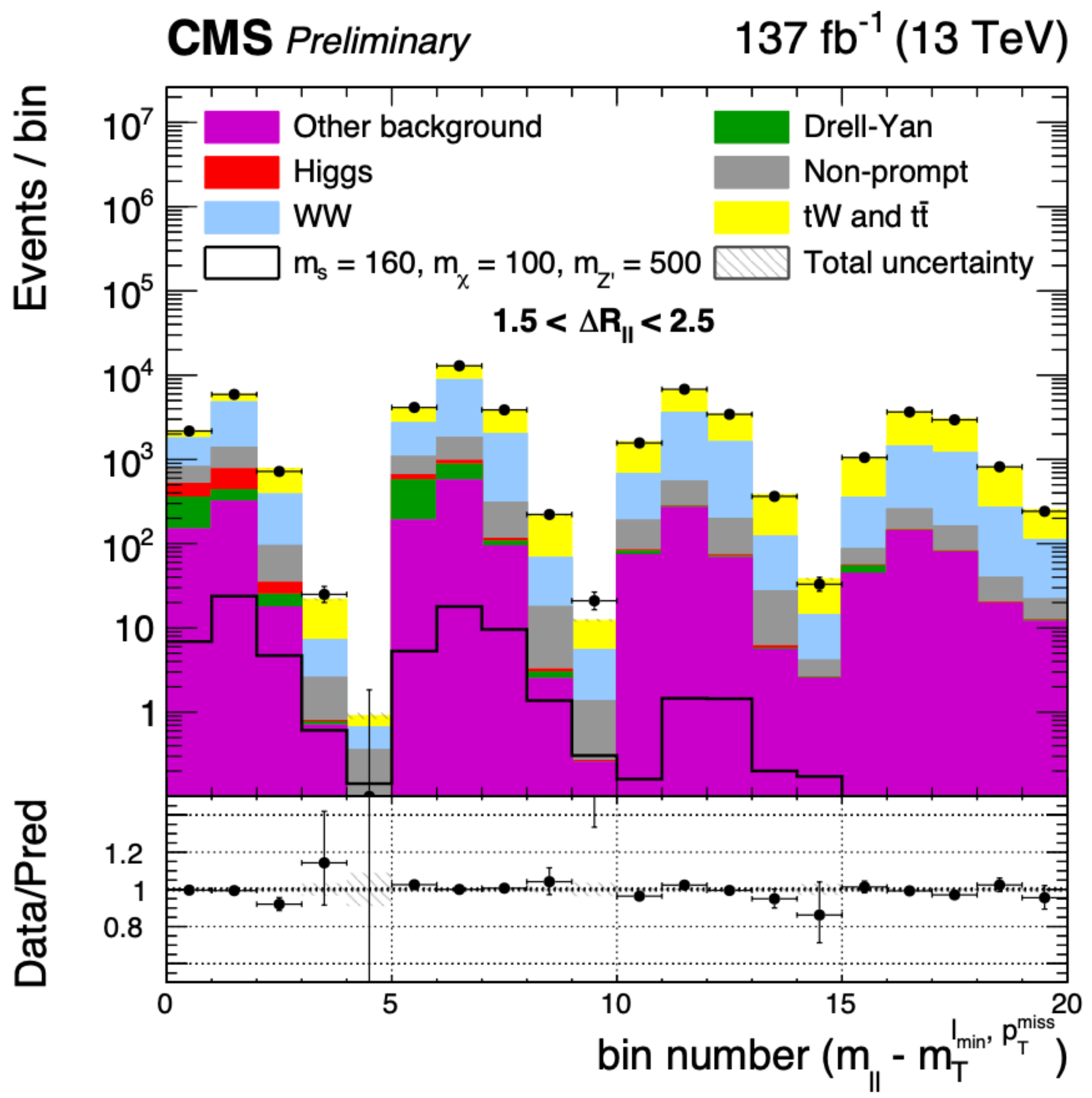
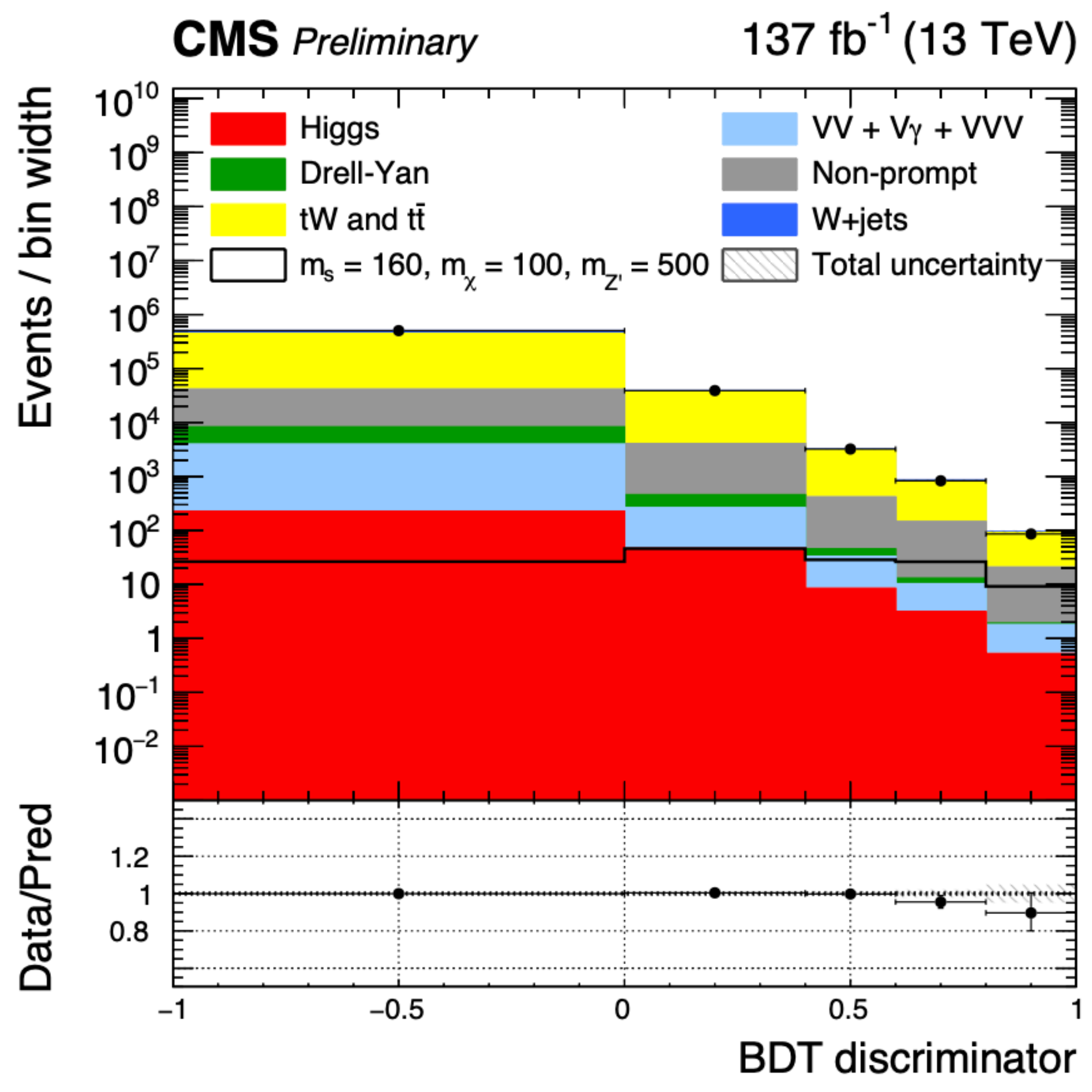
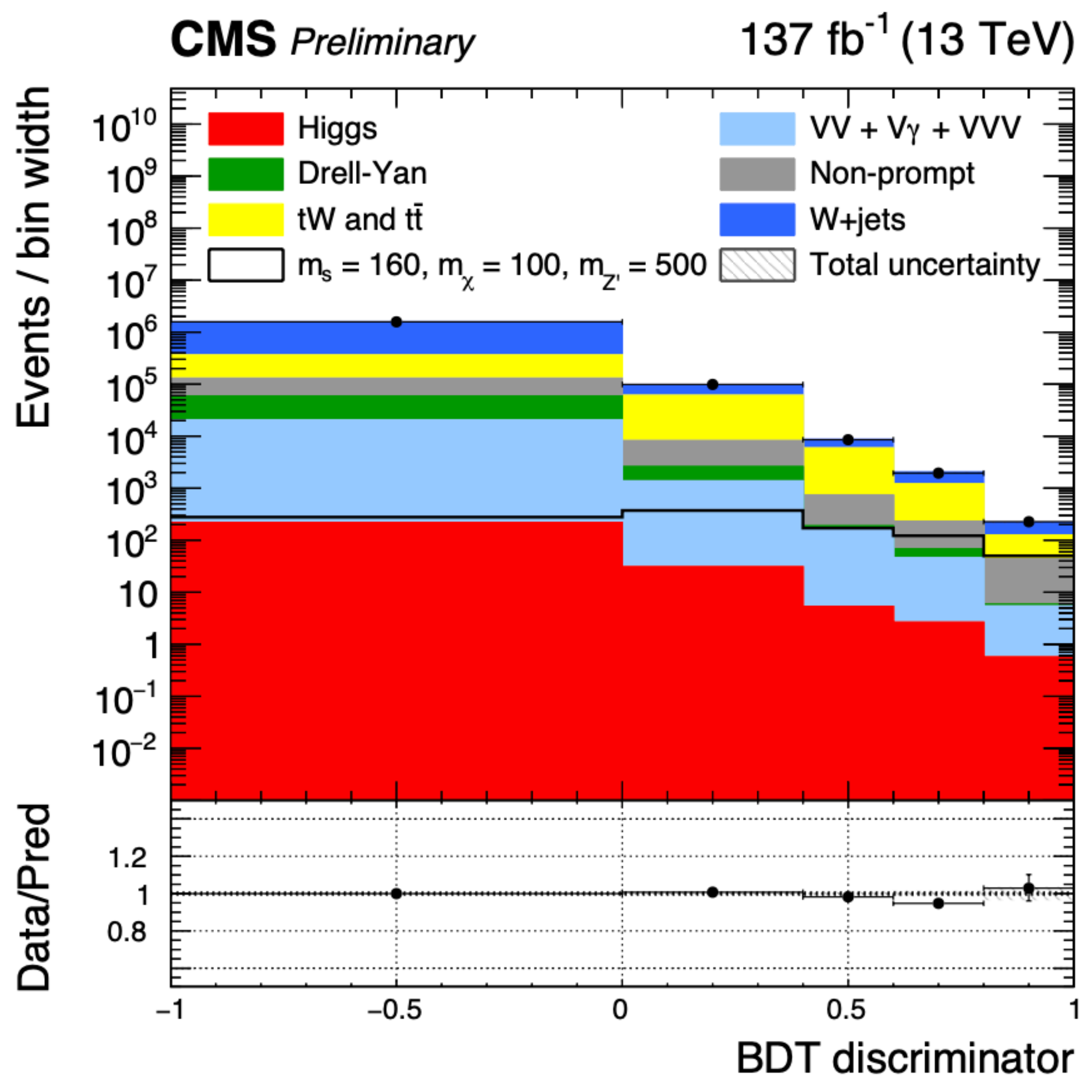
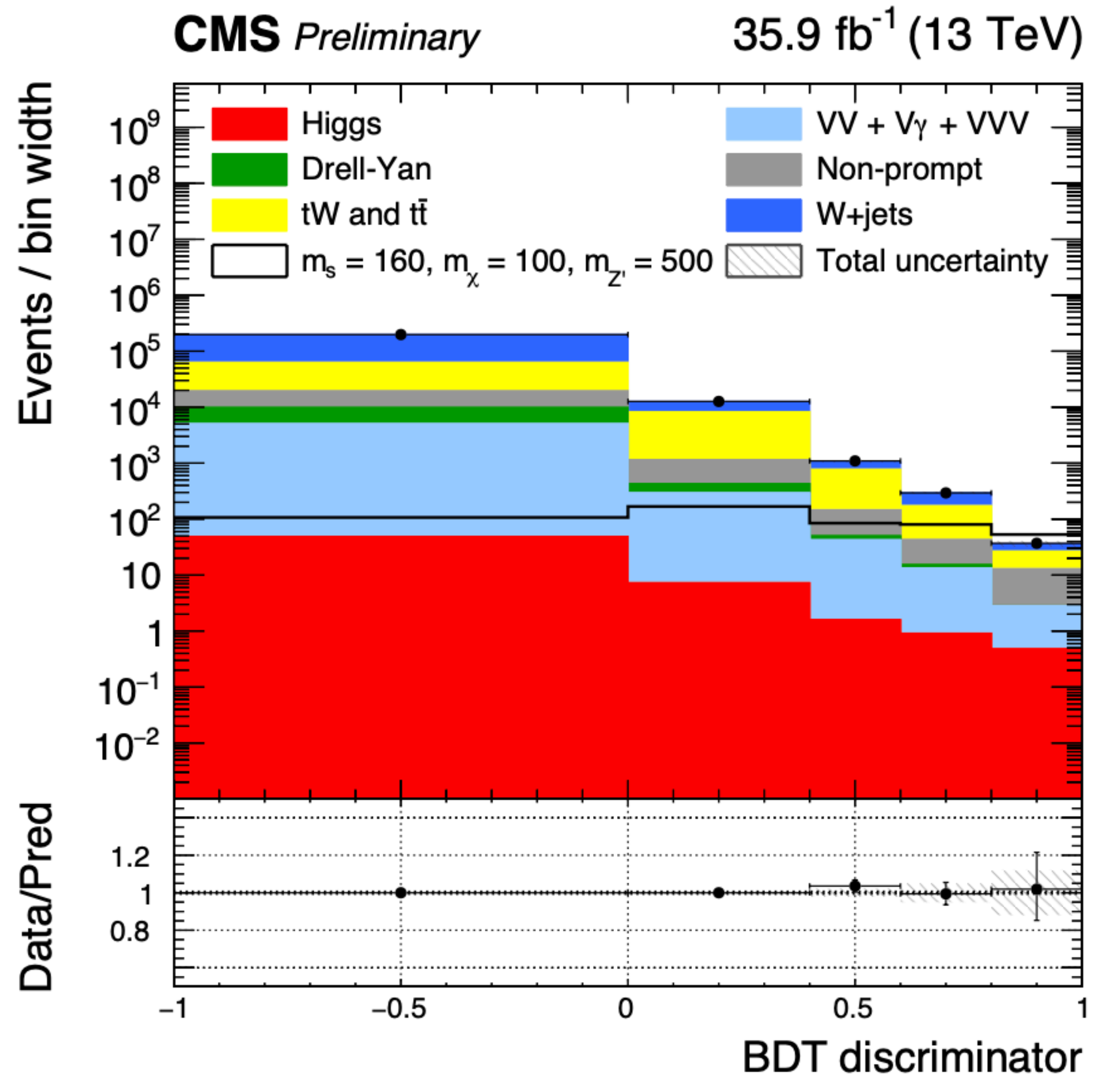


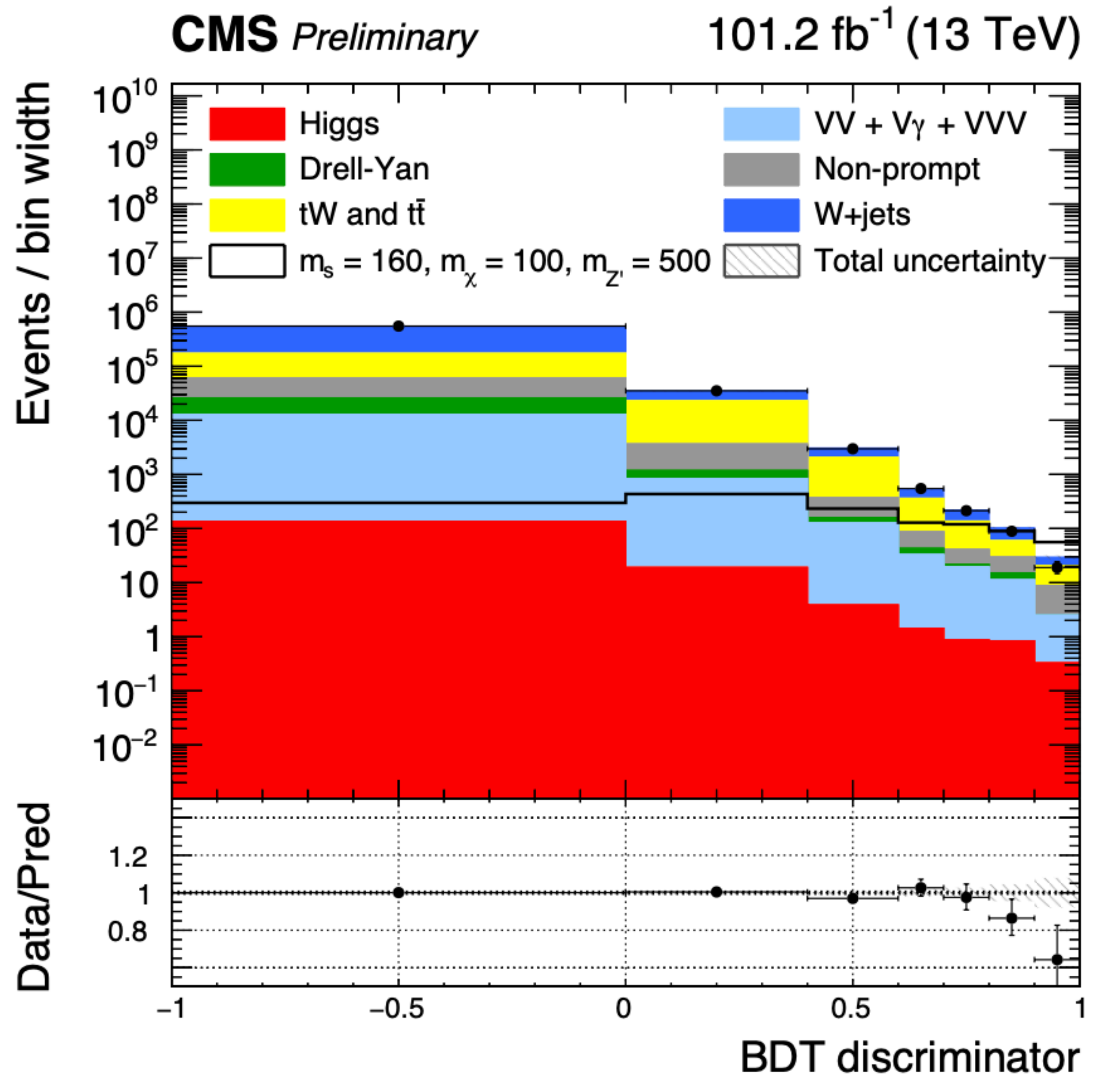












Dark Higgs

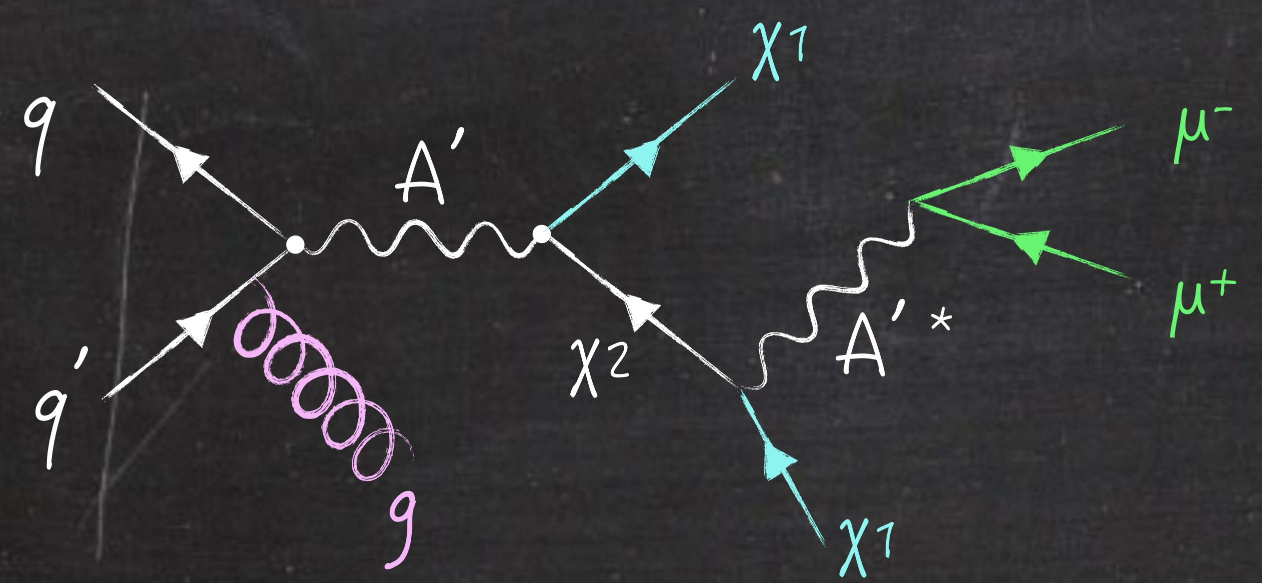
EXO-21-012

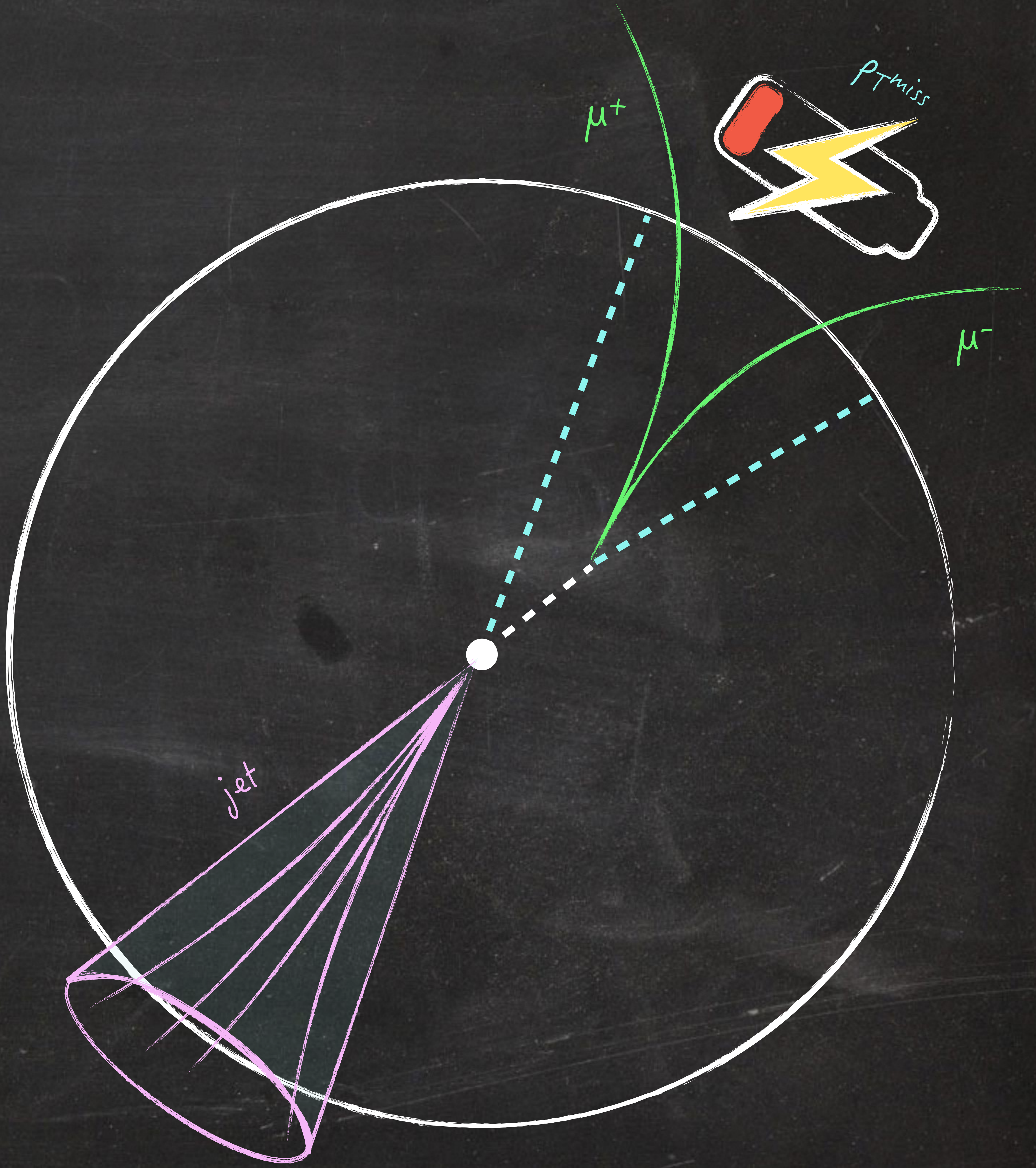
Signal/control regions

- normalization of background from observed CRs.
- main backgrounds:
  - WW & DY (di-leptonic channel),
  - W+jets (semi-leptonic channel),
  - tW & tt (both),
- one independent CR for each process:
  - tW and tt enriched region → reversing requirement on the number of b-tagged jets,
  - W^+W^- → reversing the ΔR_{ll}: $\Delta R_{ll} > 2.5$,
  - Drell–Yan → inverting the $m_T^{mll,pTmiss}$: $m_T^{mll,pTmiss}$ <50GeV,
  - W + jets → inverting the m_{jj}: $m_{jj} < 65$ GeV or mjj > 105 GeV,
- yields in CRs fitted simultaneously with SRs, background normalizations float freely.

Inelastic DM

- **first search** for inelastic DM at a hadron collider
  - ≥2 DM states χ_1 & χ_2 + dark photon A' with ε mixing
- **small** $\Delta = m_2 - m_1 \in [10, 40\%]\ m_1$:
  - **long lived** (easier to distinguish from backgrounds)
  - **low selection efficiency** (even 10^{-4} for low mass/large displacement)
  - large predicted **cross sections** (≈a few fb)
  - low p_T, low ΔR muons
- p_T^{miss} **collimated** with displaced muons



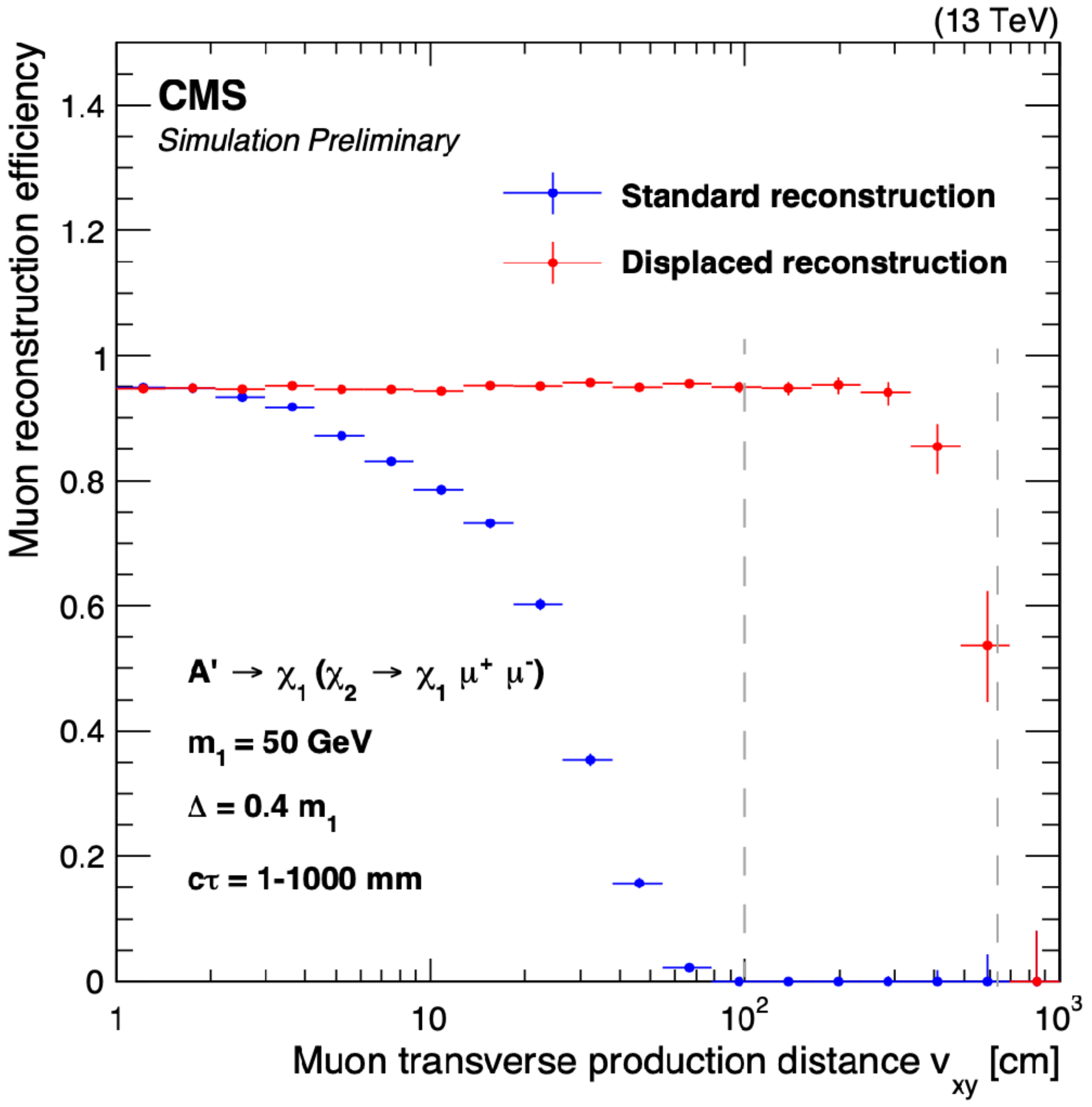


Analysis details

- backgrounds: QCD, single top, W+jets
- signal regions: depending on di-muon displacement
- control region: >2 jets
- cosmic muons rejected by ΔR < 0.9

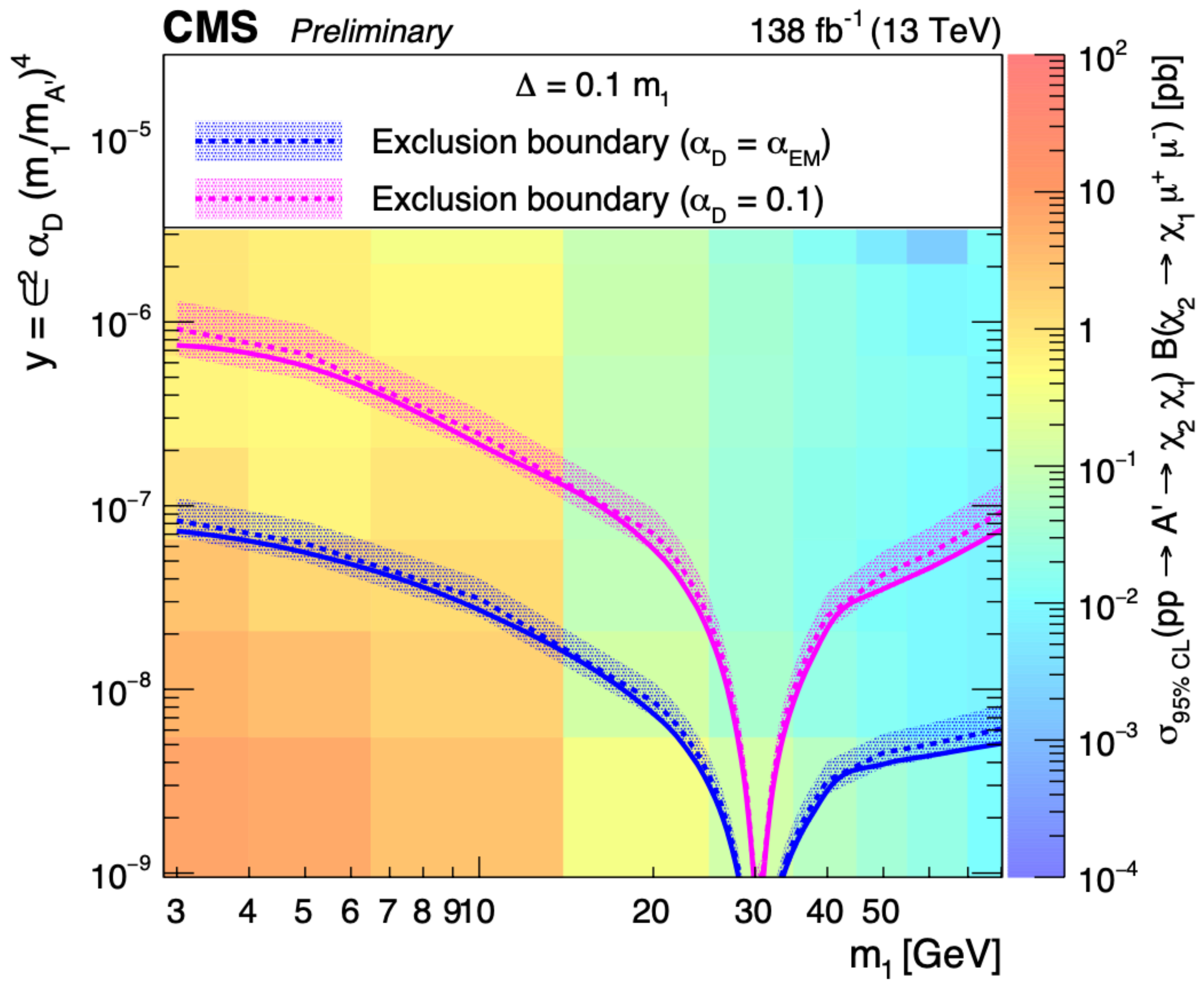
Search for **inelastic dark matter** in events with two displaced muons and missing transverse momentum

EXO-20-010



Specialized displaced standalone (dSA) muon reconstruction

- muon system only,
- cosmic muons algorithm for track seeding,
- **efficient for large displacement**, up to a few meters,
- small displacement muons **replaced** by standard PF algorithm,
- signal regions defined by number of dSA muons replaced by PF muons.



Results

- **ABCD method:** min-d_{xy} vs. relative isolation I_{PF} or $\Delta\phi_{\mu\mu}^{MET}$,
- data **consistent with the SM prediction**,
- **limits** in interaction strength y vs. m_1,
- sensitivity at m_1 = 30 GeV → $m_{A'}$ = 90 GeV increased due to kinetic mixing between A' and Z boson.