Search for Heavy Resonances and LFV in CMS

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On behalf of the CMS Collaboration

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53rd Rencontres de Moriond 2018: Electroweak Interactions and Unified Theories - La Thuile, Italy

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Outline

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- Focus on recently released searches for heavy resonances and lepton flavor violation (LFV)
  - Overview tagging approaches
  - Present 7 heavy resonances searches:
    - $X\to ZV$, $X\to HV(H)$, $X\to t\bar{t}$, $X\to tb$, $X\to \ell\ell$, $X\to \ell\nu$, and $X\to e\mu$

Process	Final State(s)	Boosted Object Tagging	Luminosity (fb^{-1})	CMS PAS	Publication
$X\to ZV$	$\ell\ell qq$	Yes	35.9	B2G-17-013	Preparing for JHEP
$X\to HV$ $X\to HH$	$\tau\tau qq$ $\tau\tau bb$	Yes	35.9	B2G-17-006	Preparing for JHEP
$X\to t\bar{t}$	$\ell\nu qq$ bqqbqq	Yes	2.6	B2G-16-015	JHEP 07 (2017) 001
$X\to tb$	$\ell\nu bb$	No	35.9	B2G-17-010	PLB Phys. Lett. B 777 (2017) 39
$X\to \ell\ell$	ee/μμ	No	35.9	EXO-16-047 & EXO-18-006	Preparing for JHEP
$X\to \ell\nu$	eν	No	35.9	EXO-16-033	Preparing of JHEP
$X\to e\mu$	eμ	No	35.9	EXO-16-058	arXiv:1802.01122 Submitted to JHEP

Boosted Object Tagging

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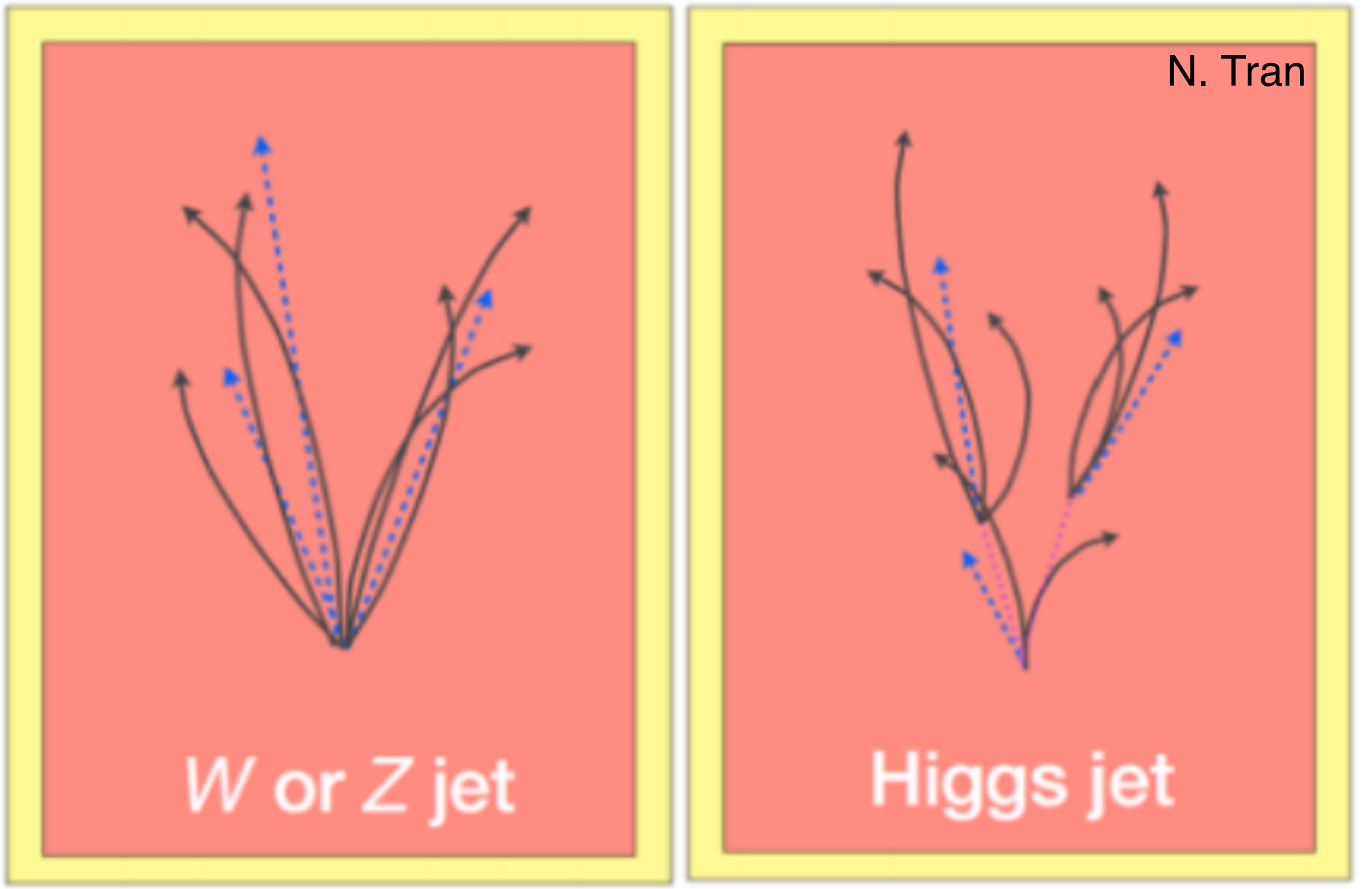
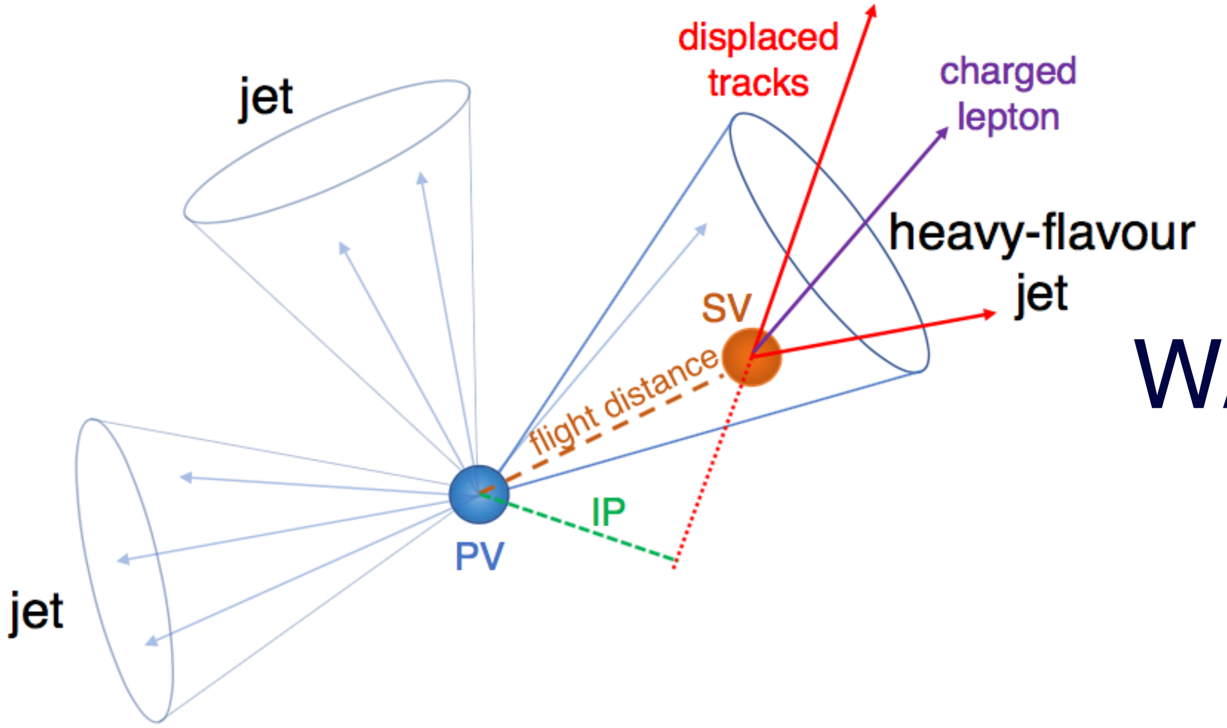
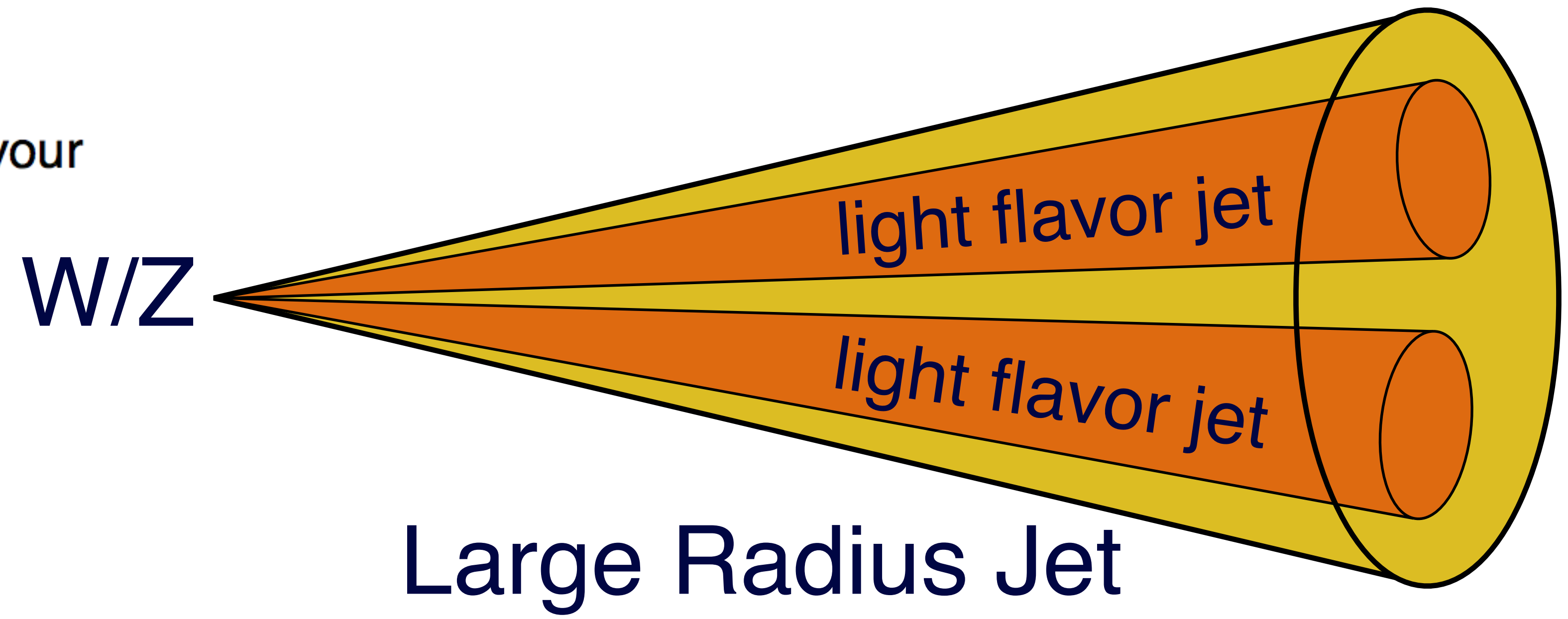
- Possible to reconstruct boosted hadronicly decaying heavy gauge and Higgs bosons
- Tagging methods use large footprint jets and sub-structure techniques
  - N-subjettiness (τ_{21}) is used to evaluate the compatibility of a large radius jet of having 2 sub-jets
- Analysis also use a b-jet discriminate to identify jets originating from b-quarks

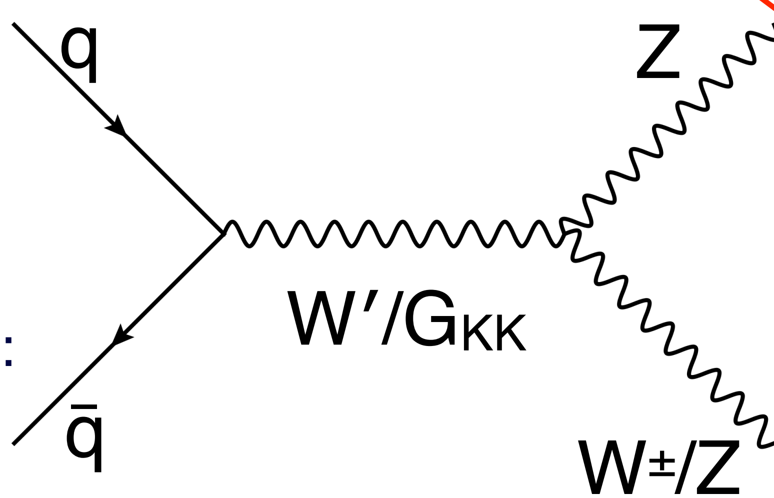


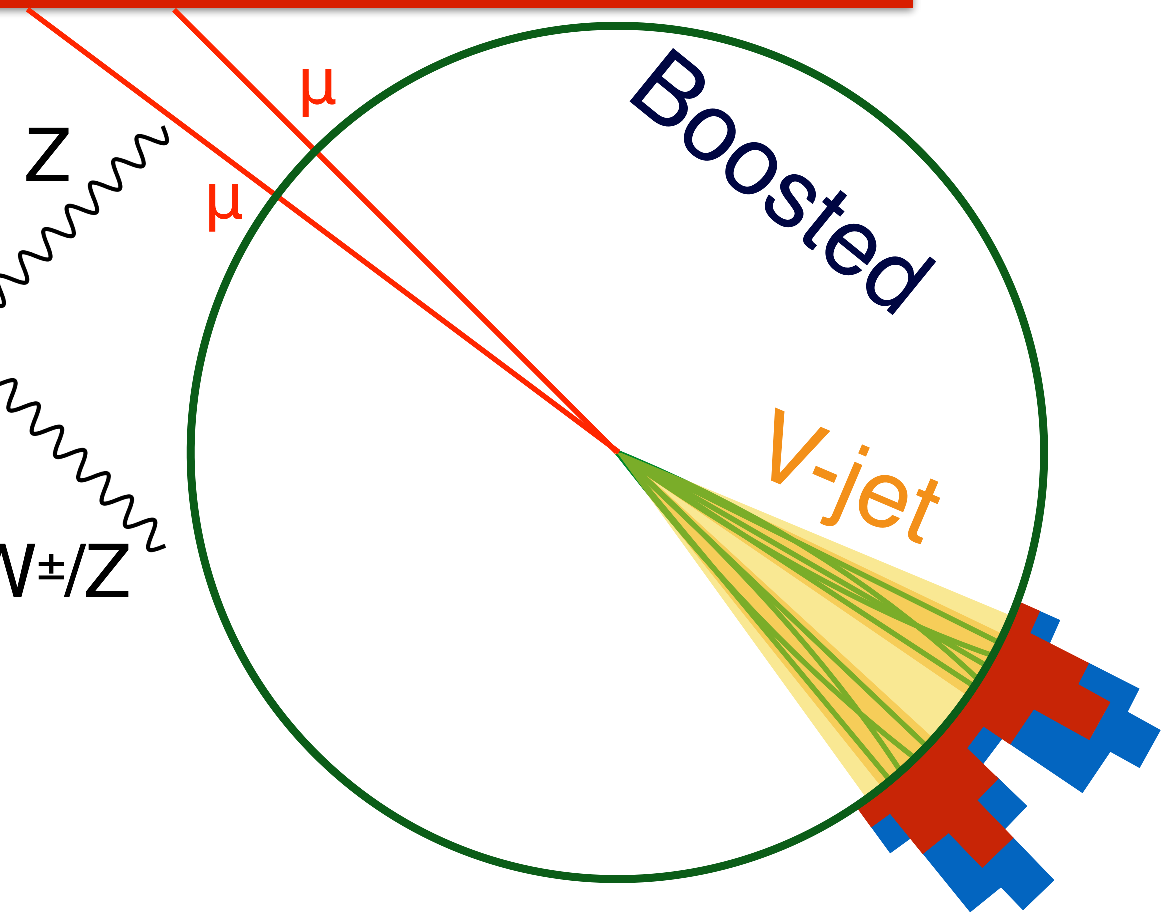


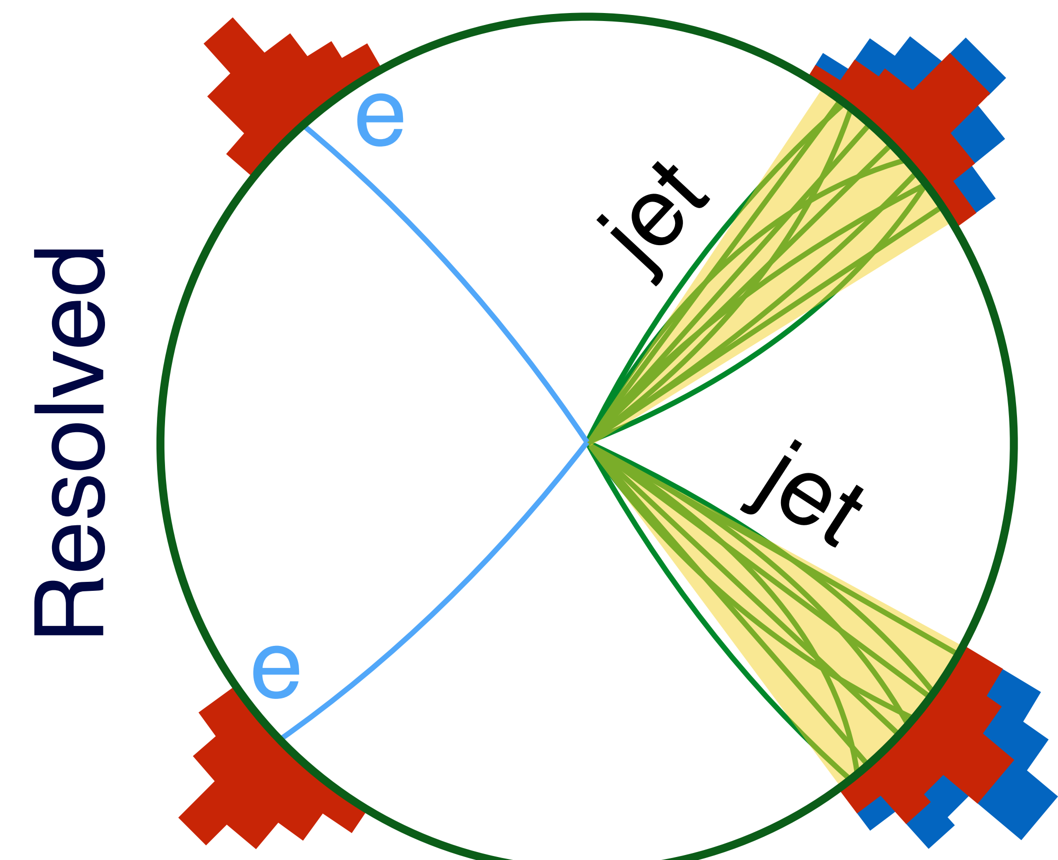


X→ZV→llqq Search

- Searches for a narrow diboson resonance
  - W′ boson in the heavy vector triplet (VHT) model: W′→ZW→llqq
  - Bulk graviton (G_{KK}) in the Randall–Sundrum (RS) scenario: G_{KK}→ZZ→llqq
- Boosted Z→ll ID with M_{ll} window
- Boosted V(W/Z)→jj tagging M_{jj} mass window
- High mass analysis covers 850 GeV to 4.5 TeV
  - Loose Isolation Requirement
    - Corrected Tracker Isolation
  - Lepton flavor (e/μ) and τ_{21} used for categorization (low and high purity)
- Low mass analysis starts at 400 GeV
  - 2 Isolated Leptons
  - Allows two separate jets
    - Still allows the merged case
    - A total of 8 different search categories

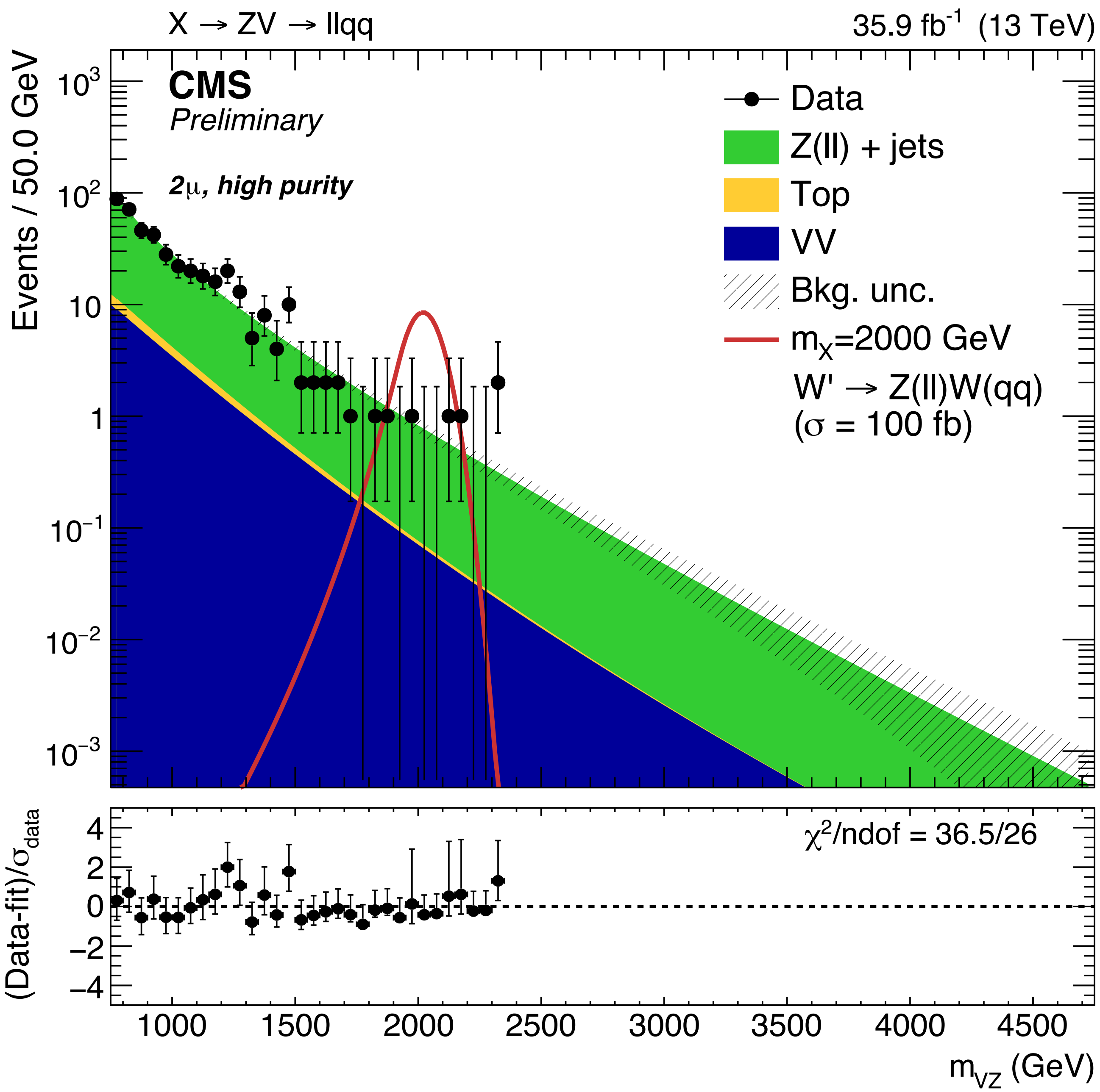




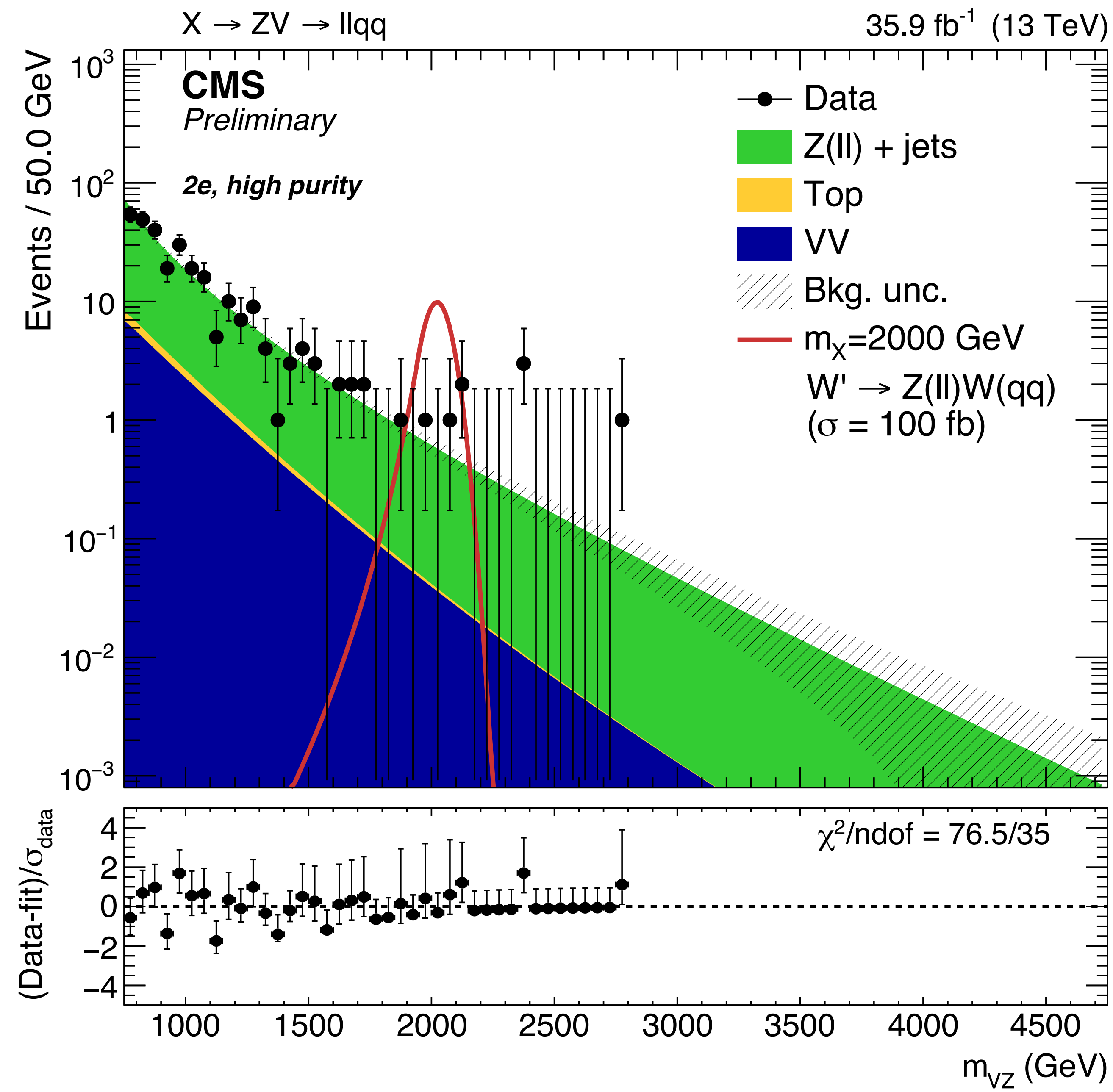


X→llqq Results

2 Muon High Purity SR



2 Electron High Purity SR



- Excess at 1.2 TeV has a local significance of 2.5σ
- Excess is not observed in other 7 categories

$X \to HV(H) \to \tau\tau qq(bb)$

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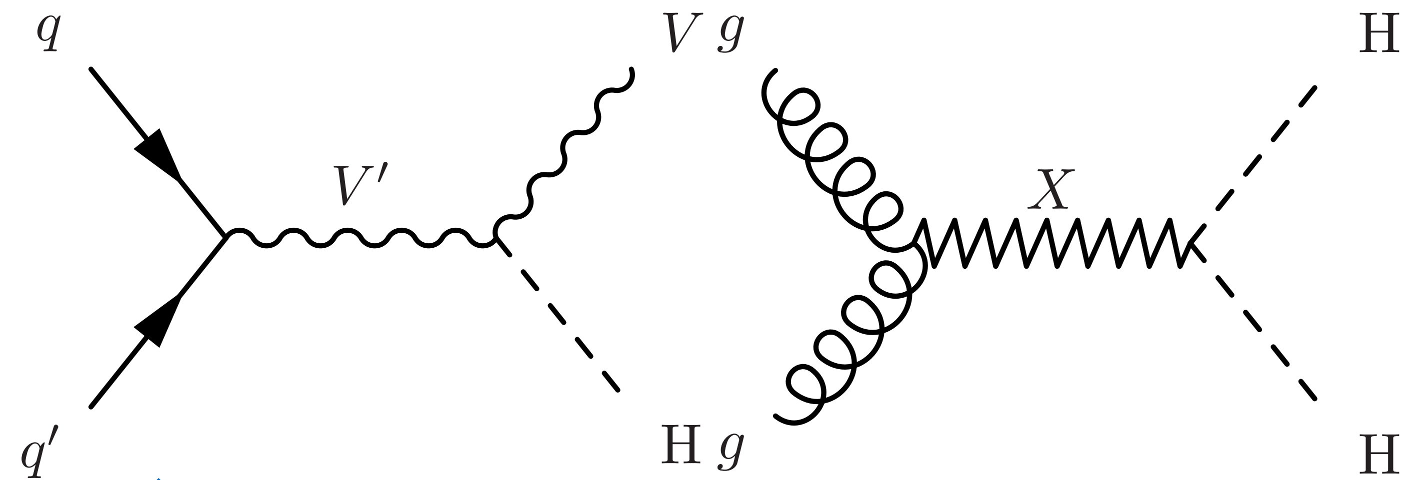
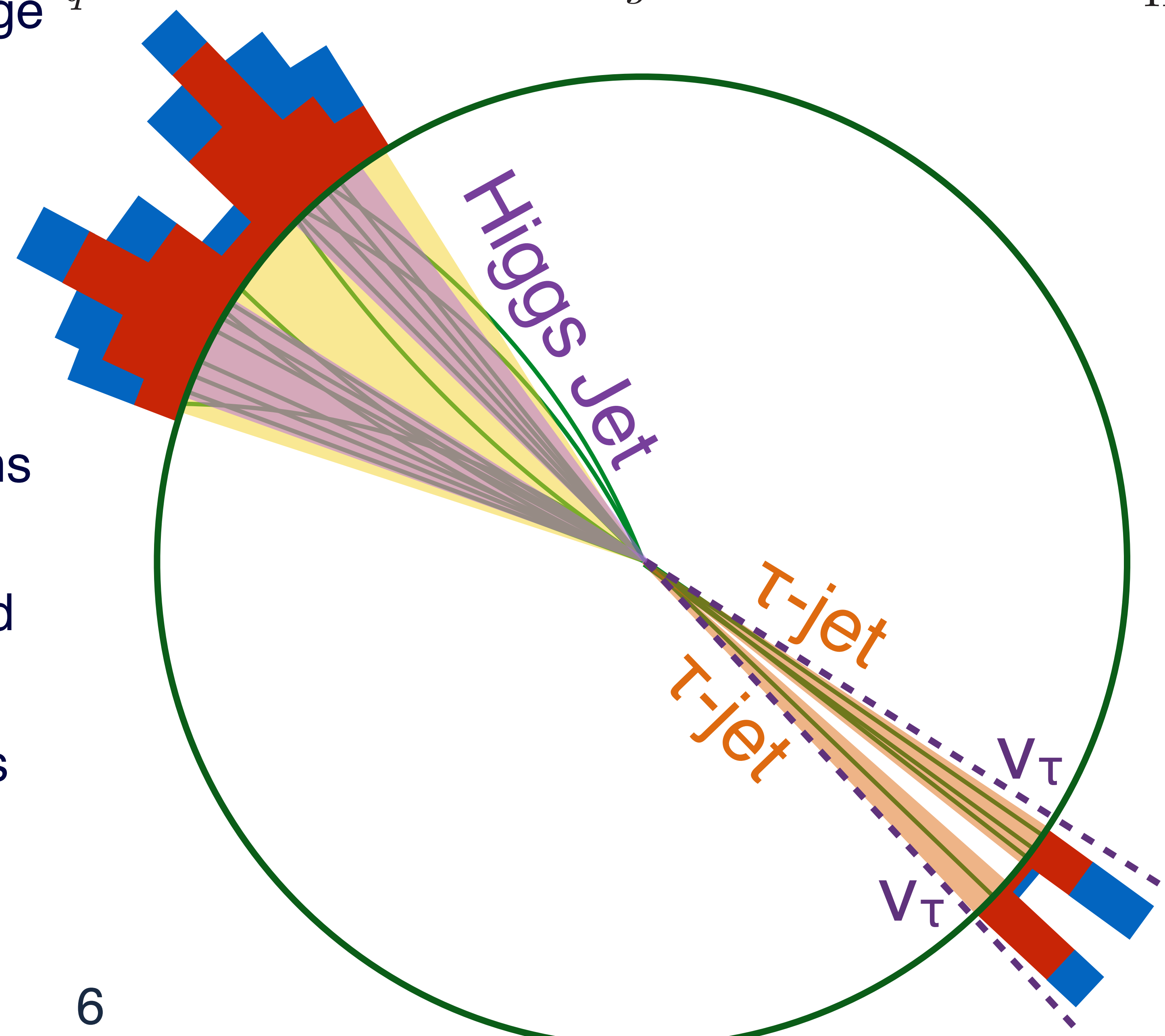
- Searches for narrow heavy resonances
  - VHT $Z' \to ZH \to qq\tau\tau$
  - VHT $W' \to WH \to qq\tau\tau$
  - Bulk Radion: $X \to HH \to bb\tau\tau$
- Resonance search in the 0.9 to 4 TeV range
- Require $H \to \tau_h\tau_h$ or $H \to \ell\tau_h$
  - $M_{\tau\tau}$ Selection
- M_{jj} window cut for W, Z, and H bosons
  - Sub-jet b-tagging used on Higgs jets
- τ_{21} used to form high and low purity regions for W- and Z-jets
- M_{jj} and τ_{21} along with the number of τ_h and sub-jet b-tags used for categorization
  - A total of 12 different search categories





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X→ττqq(bb) Results

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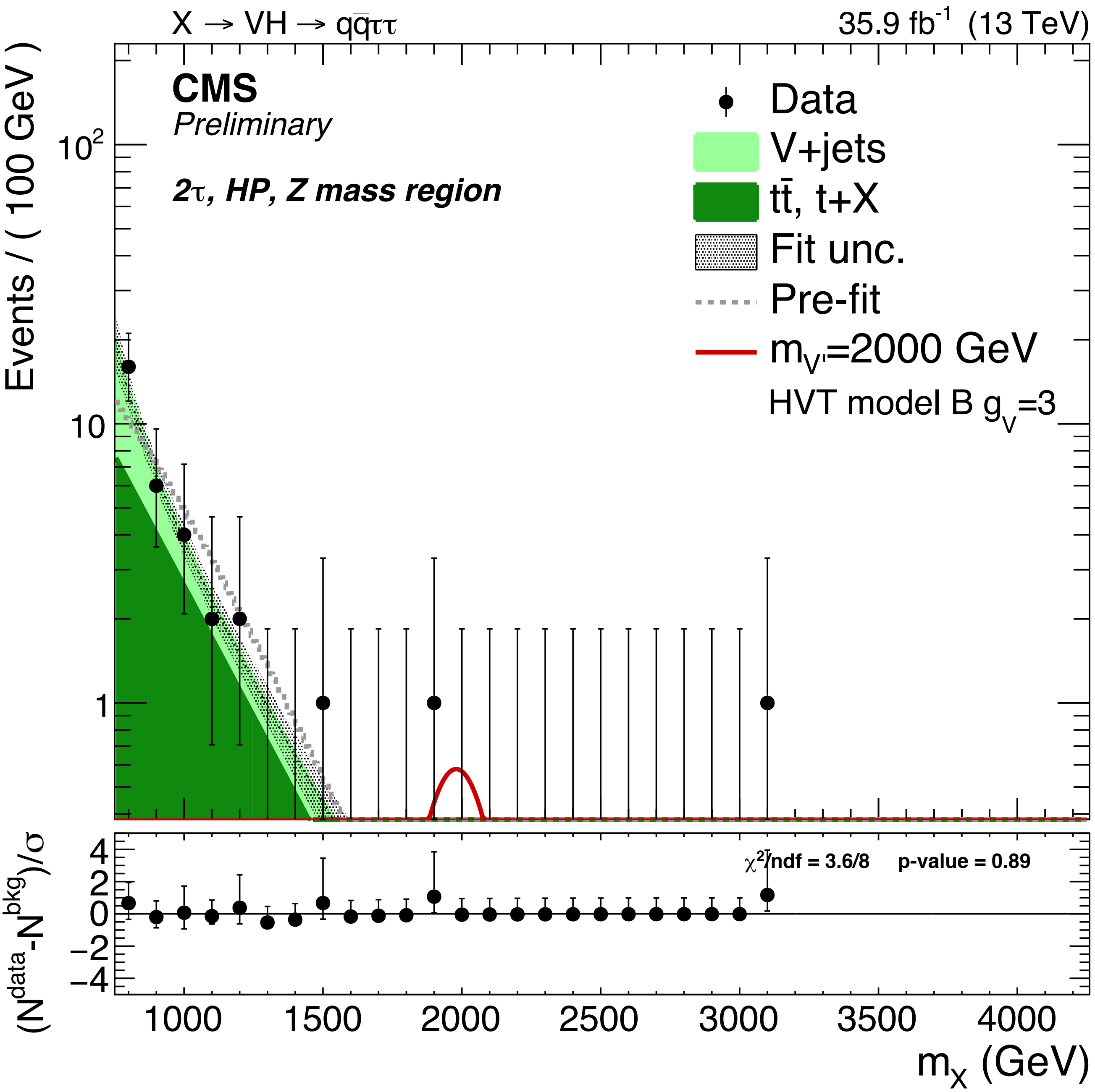
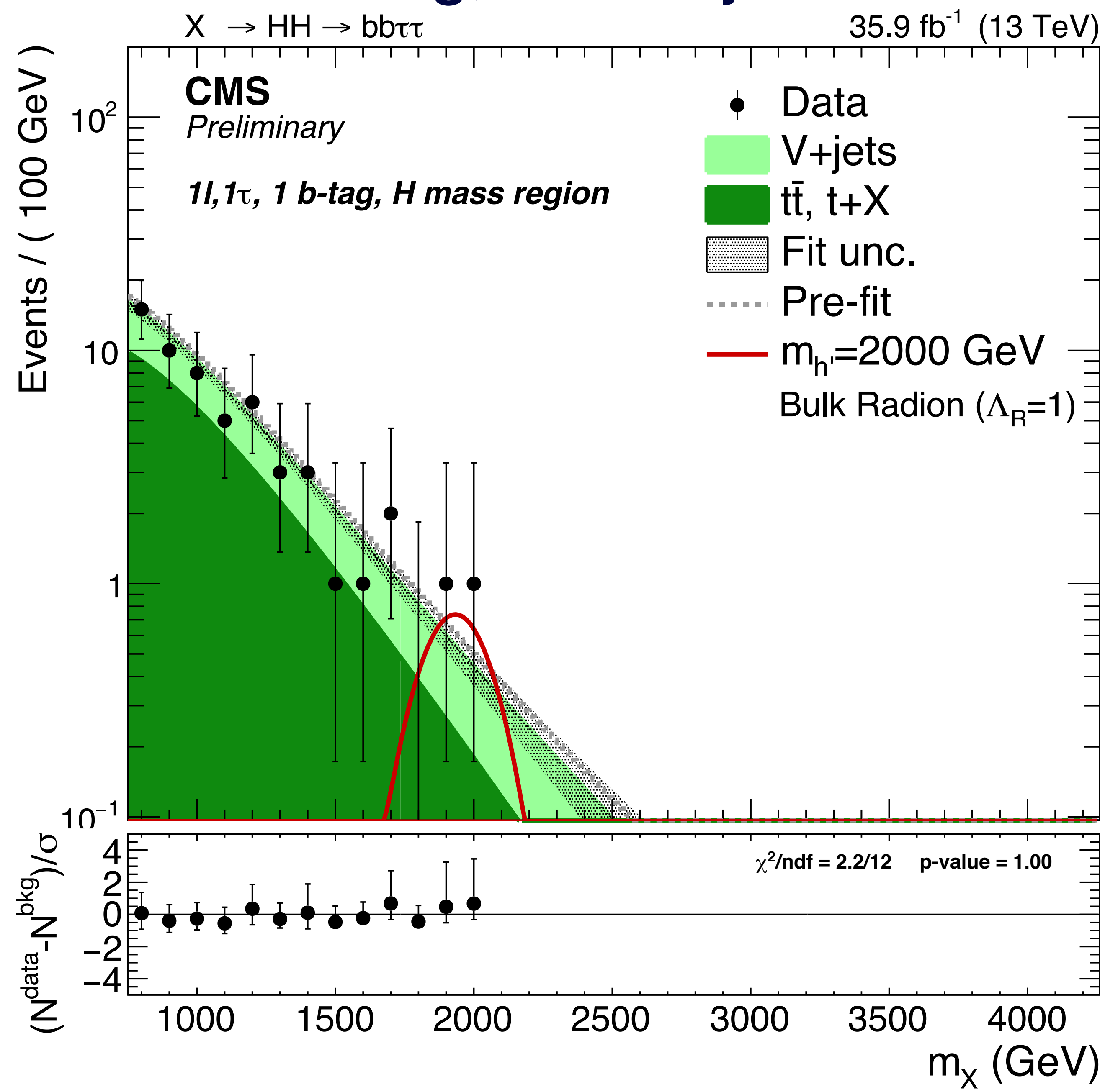
2 Taus and a high purity Z-jet

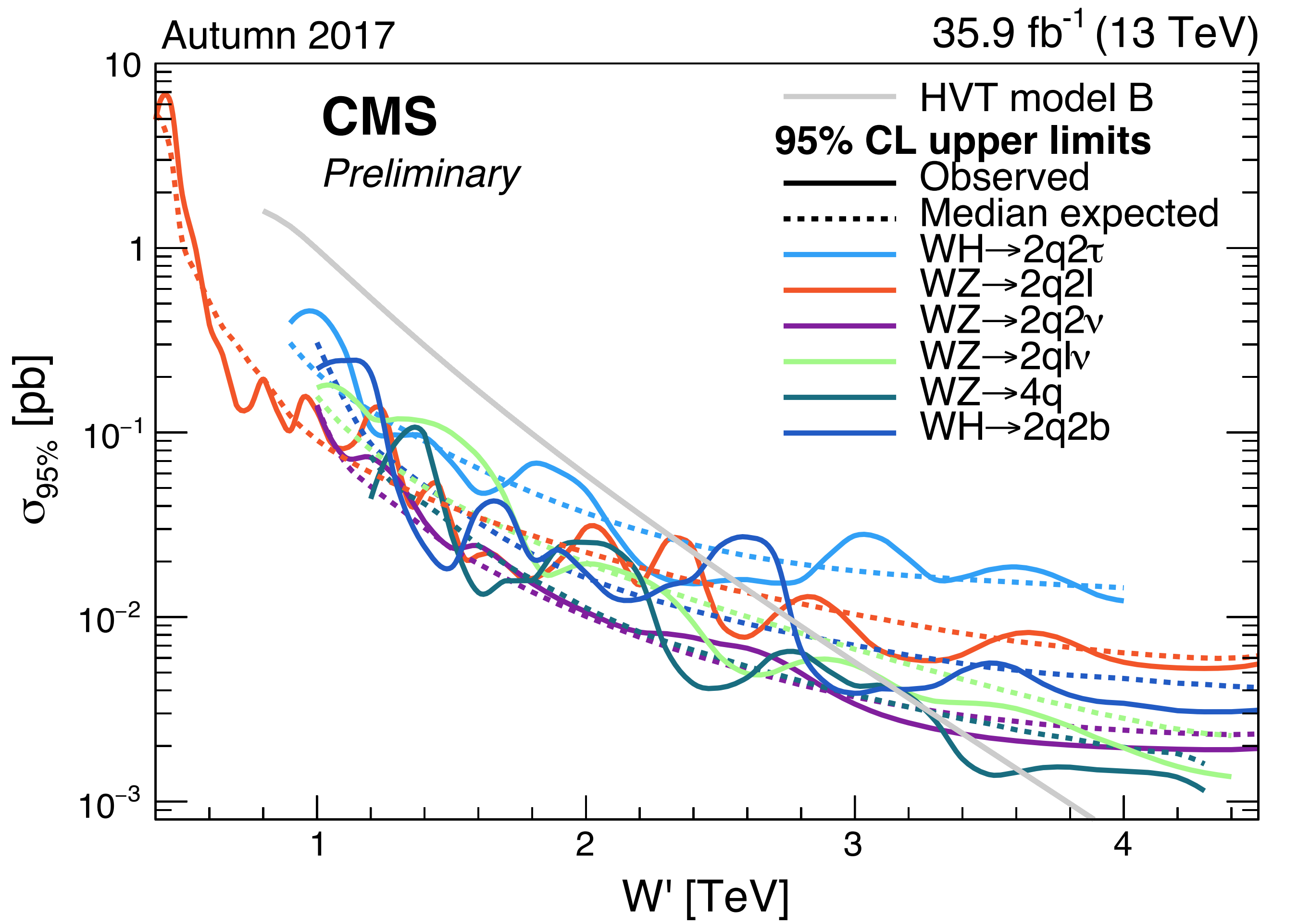


1 lepton (e/μ), 1 tau, 1 sub-jet b-tag, and H-jet



X→ττqq(bb) and X→llqq Results

Model	Expected Exclusion	Observed Exclusion
W′→WZ→llqq (gv=1)	2.4 TeV	2.3 TeV
W′→WZ→llqq (gv=3)	2.6 TeV	2.3 TeV
G_{KK}→ZZ→llqq ($\tilde{\kappa}$=0.5)	0.96 TeV	0.93 TeV
W′→HW→ττqq (gv=1)	2.0 TeV	1.8 TeV
W′→HW→ττqq (gv=3)	2.3 TeV	2.5 TeV
Z′→HZ→ττqq (gv=1)	1.5 TeV	1.6 TeV
Z′→HZ→ττqq (gv=3)	1.7 TeV	1.7 TeV
Radion→HH→ττbb (Λ_R=1 TeV)	2.4 TeV	2.5 TeV



$Z'/g_{KK} \rightarrow t\bar{t}$ and $W'_R \rightarrow tb$ Searches

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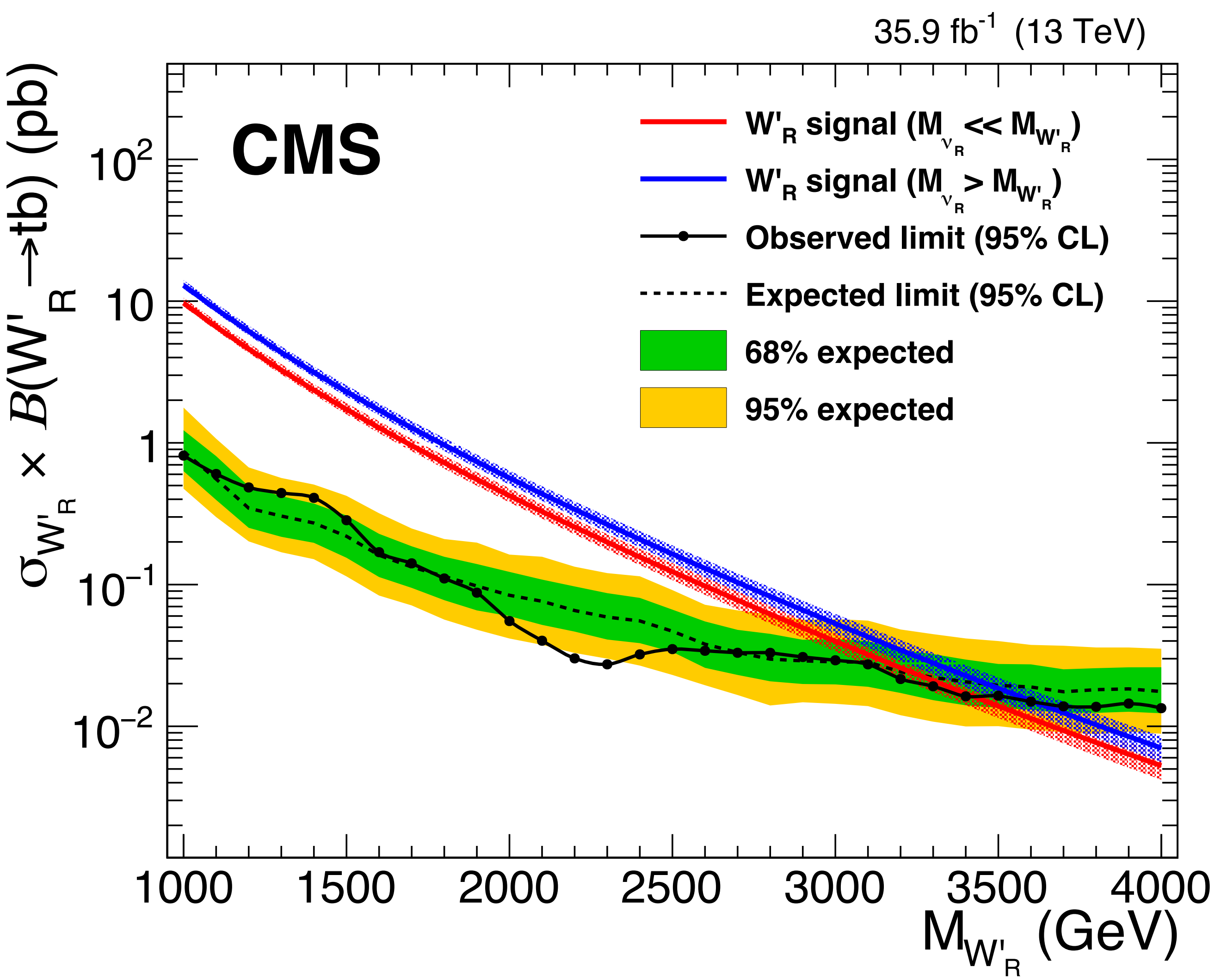
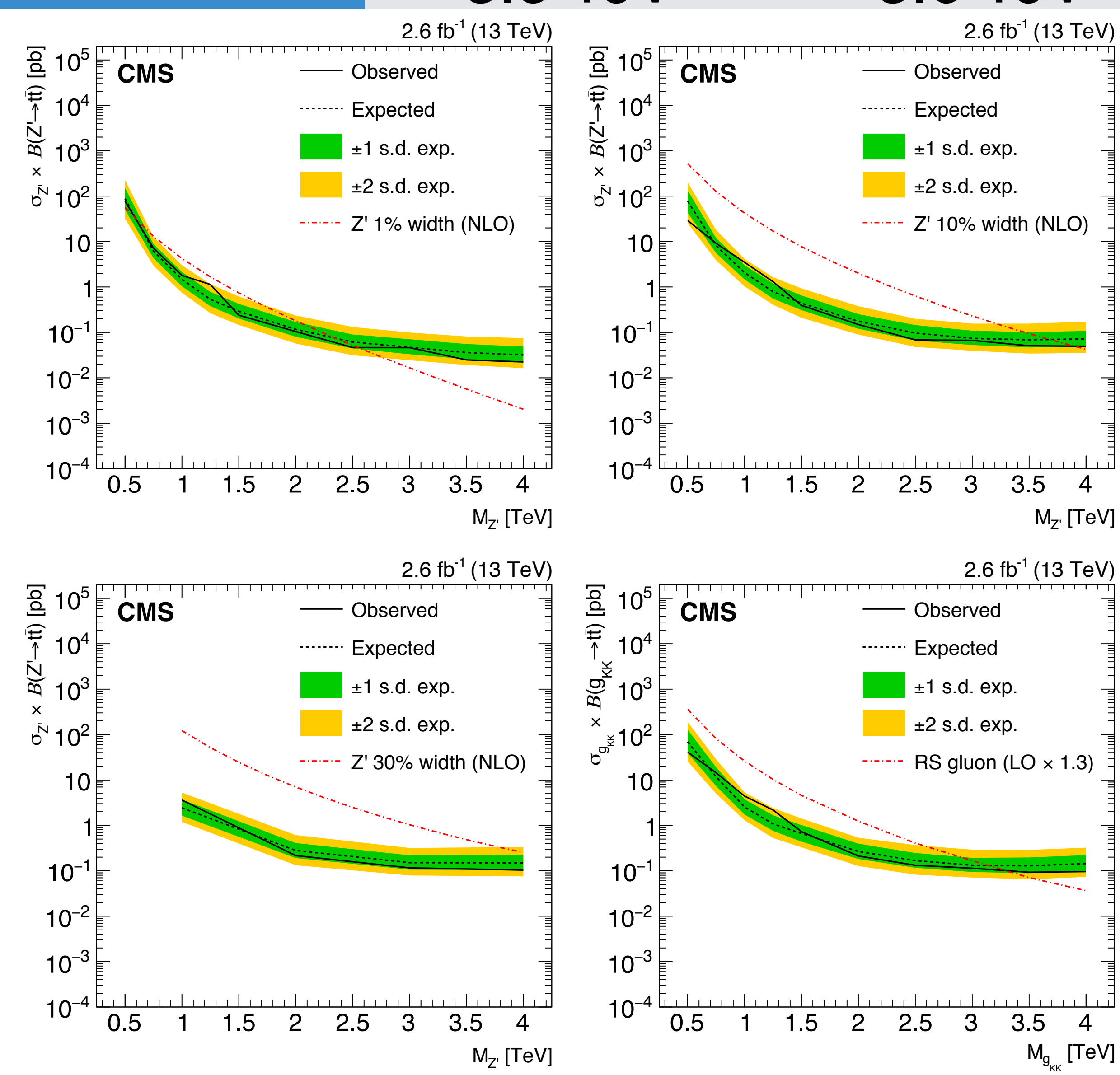
- Searches for $t\bar{t}$ and tb resonances publish in April (JHEP) and August (PLB), respectively
- Uses b- and t-tagging techniques
  - 3-body top decay becomes single large radius jet
- $Z' \rightarrow t\bar{t} \rightarrow bqqbqq$ or $\ell\nu bbqq$
- $W'_R \rightarrow tb \rightarrow \ell\nu bb$
- Searches constrain g_{KK}, Topcolor Z′ (3 widths), and W'_R

Model	Expected Exclusion	Observed Exclusion
Z′ (Γ/M=1%)	2.3 TeV	2.5 TeV
Z′ (Γ/M=10%)	3.6 TeV	3.9 TeV
Z′ (Γ/M=30%)	4.0 TeV	4.0 TeV
g_{KK}	3.1 TeV	3.3 TeV
W'_R ($M_{W'_R} >> M_{\nu_R}$)	3.3 TeV	3.4 TeV
W'_R ($M_{W'_R} < M_{\nu_R}$)	3.5 TeV	3.6 TeV





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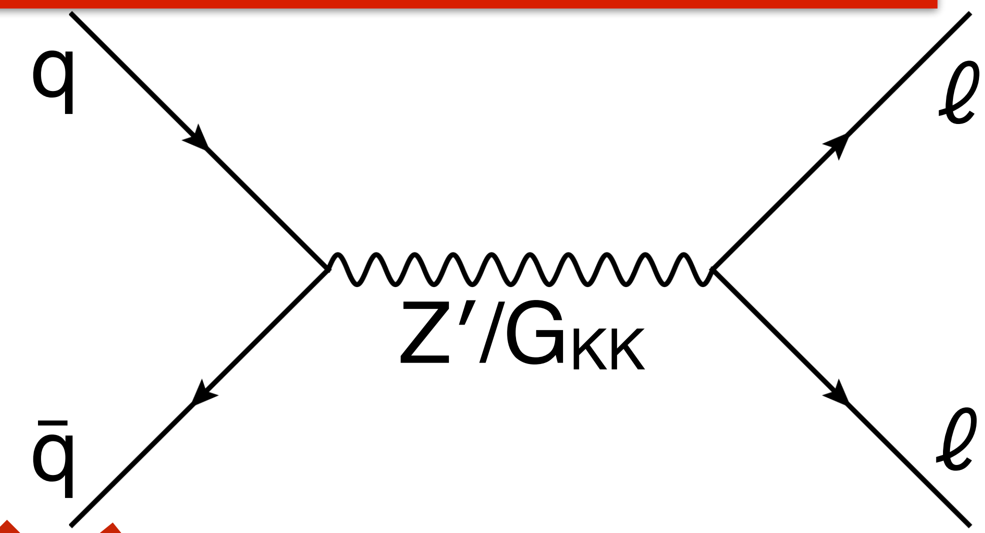
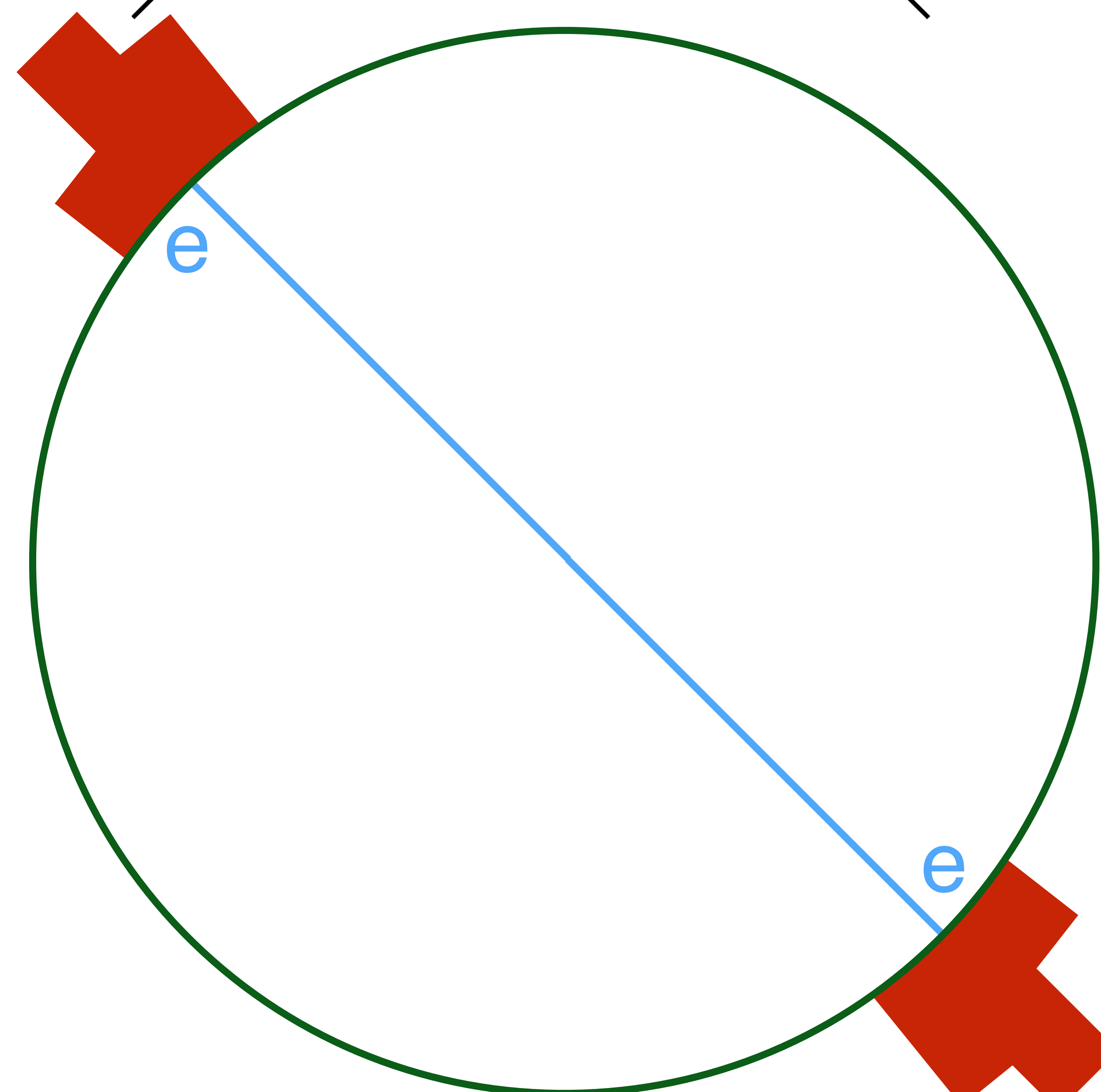
Heavy Resonances Decaying to Lepton Final States

$Z' \to \ell\ell$ Search

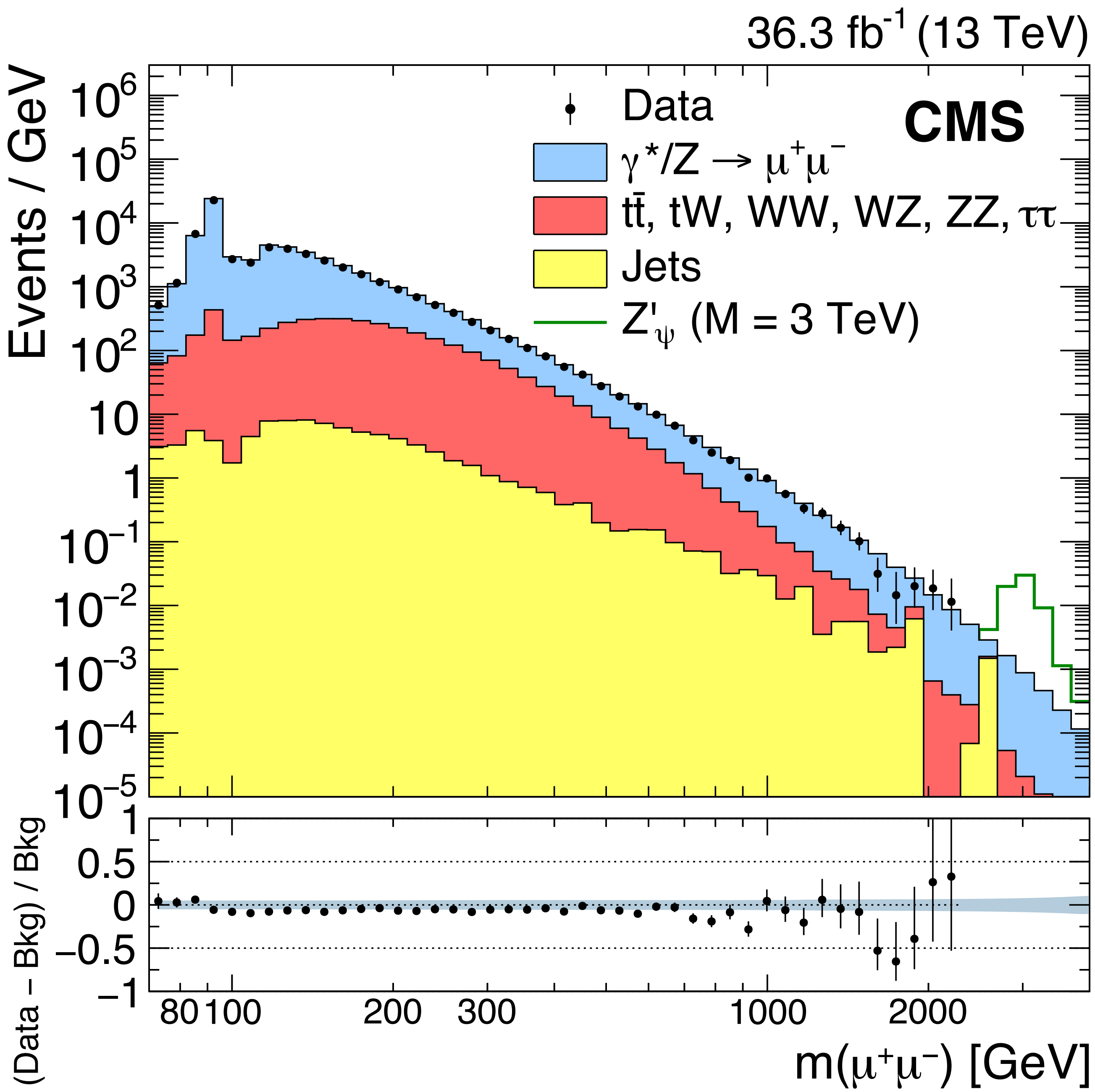
- Searches for a narrow width resonance decaying to lepton pairs
- Resonance found in many different models
  - Z'_{SSM}, Z'_{ψ}, Z'_{LR}, G_{KK}
- Search range covers 0.2 to 5.5 TeV
- Two high p_T same flavor leptons (e/μ)
  - Leptons must pass isolation criteria
- Dedicated high p_T muon and electron IDs
- Di-electron events require at least one electron in the barrel
  - No opposite charge requirement
- Only highest invariant mass $\ell\ell$ pair is considered



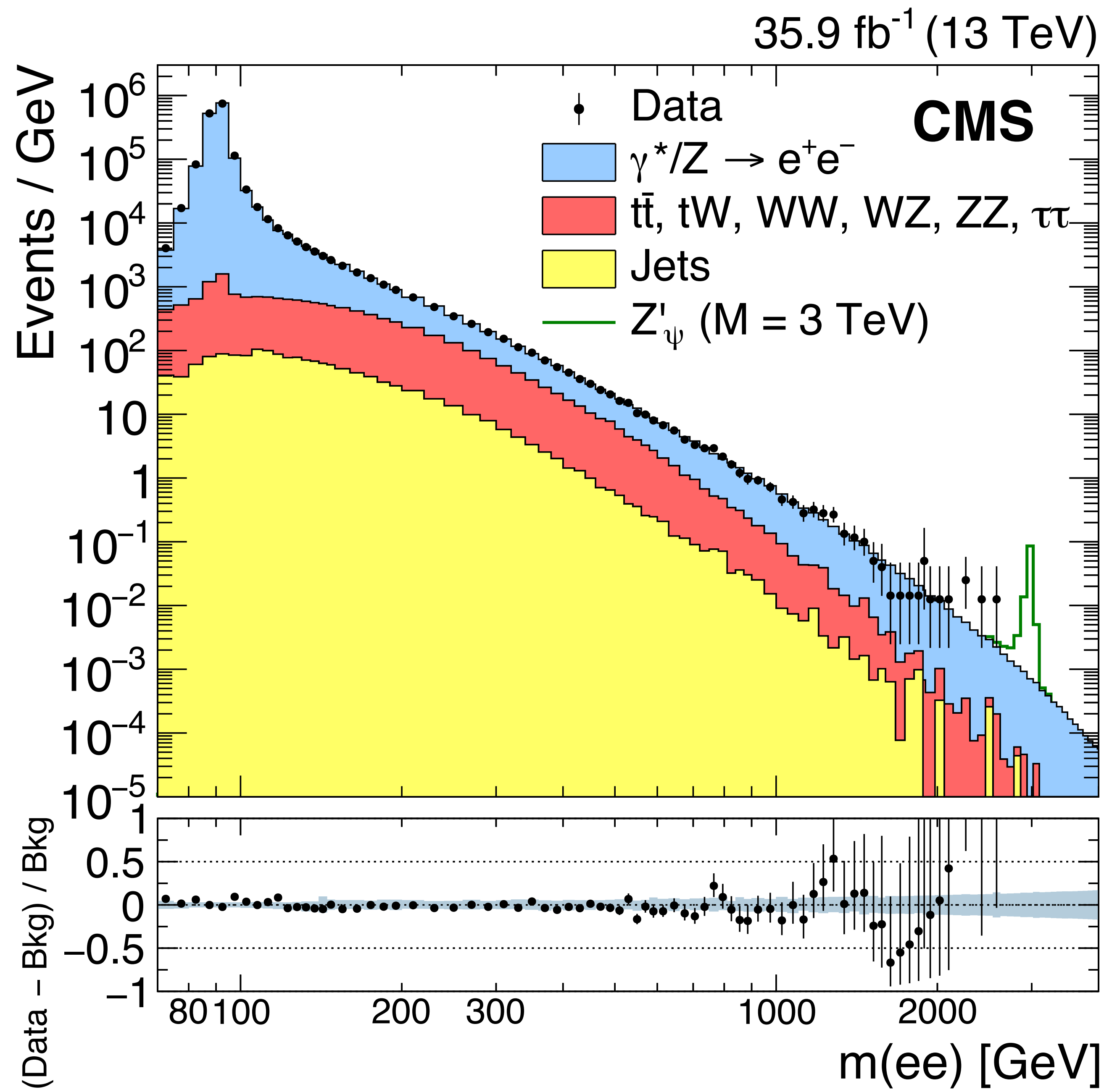


Z′→ℓℓ Results

Muon Channel



Electron Channel



- Excess at 1.3 TeV has a local significance of 2.5σ
- When taking the elsewhere effect into account, the global significance reduces to 0.9σ

Z′/G_KK→ℓℓ Limits

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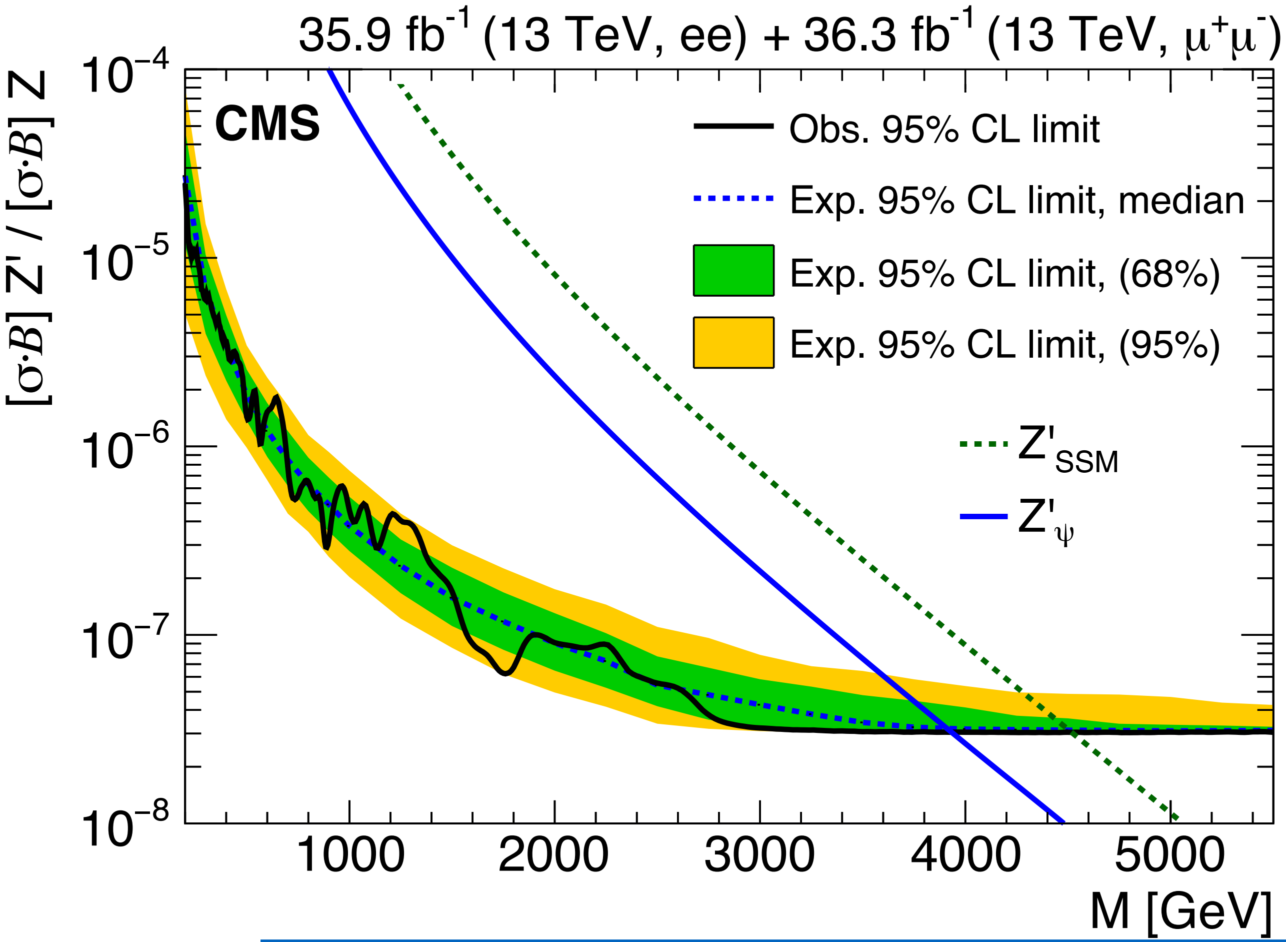
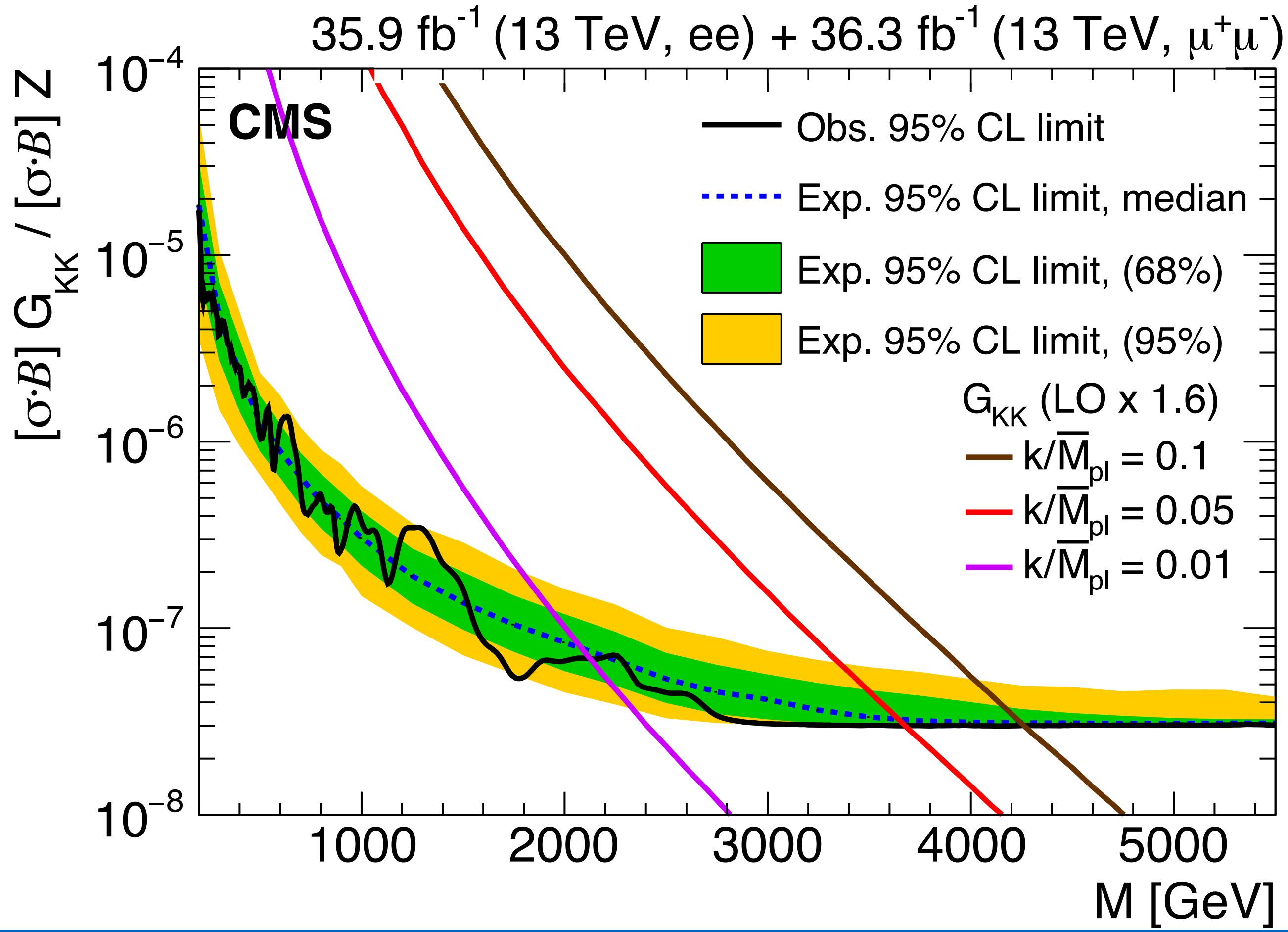
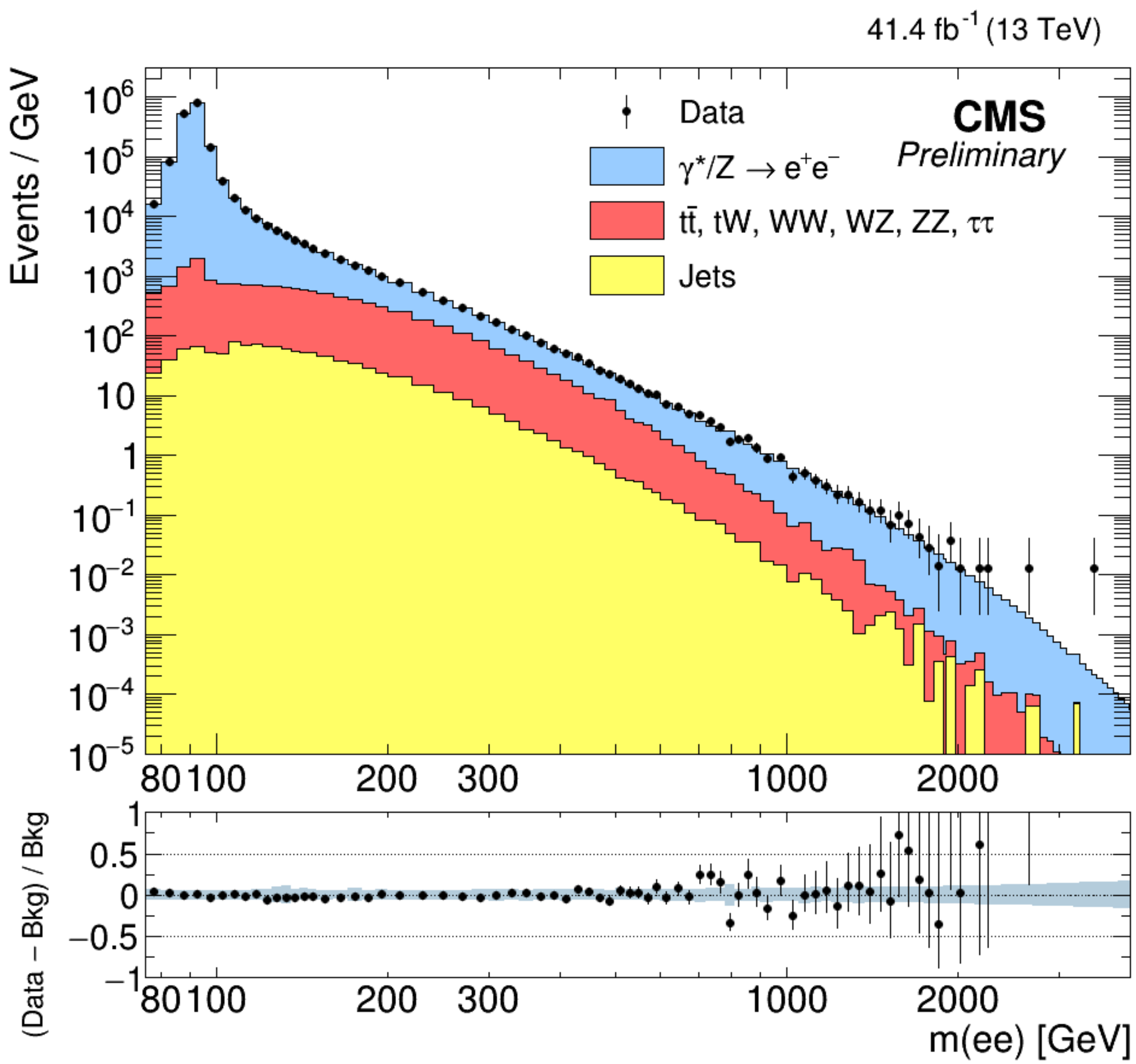
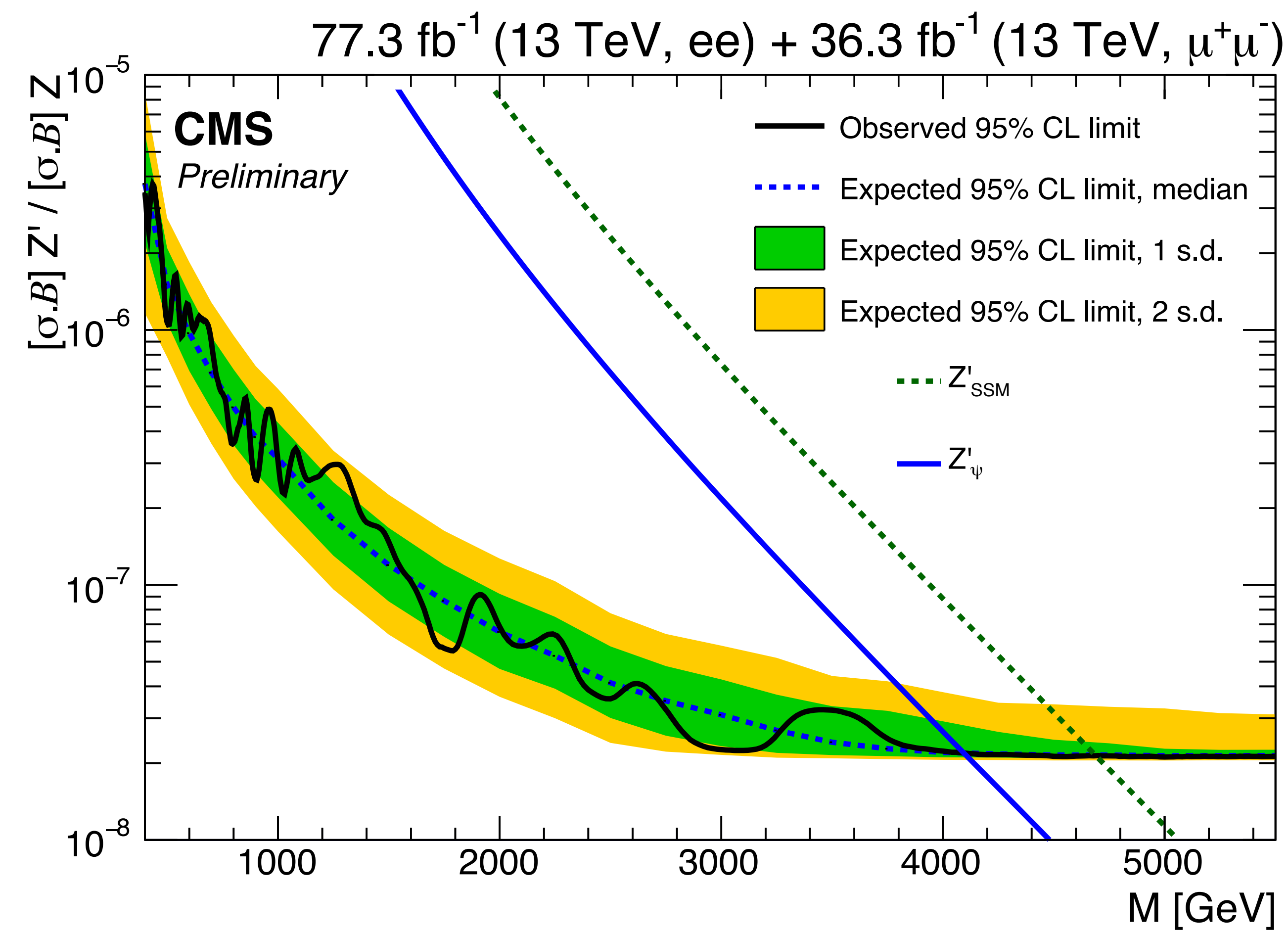




Model	Expected Exclusion	Observed Exclusion
Z'_{SSM}	4.50 TeV	4.50 TeV
Z'_{ψ}	3.90 TeV	3.90 TeV
G_{KK} ($\tilde{\kappa}$=0.1)	4.25 TeV	4.25 TeV
G_{KK} ($\tilde{\kappa}$=0.05)	3.65 TeV	3.60 TeV
G_{KK} ($\tilde{\kappa}$=0.01)	2.10 TeV	2.05 TeV

2017 Results!

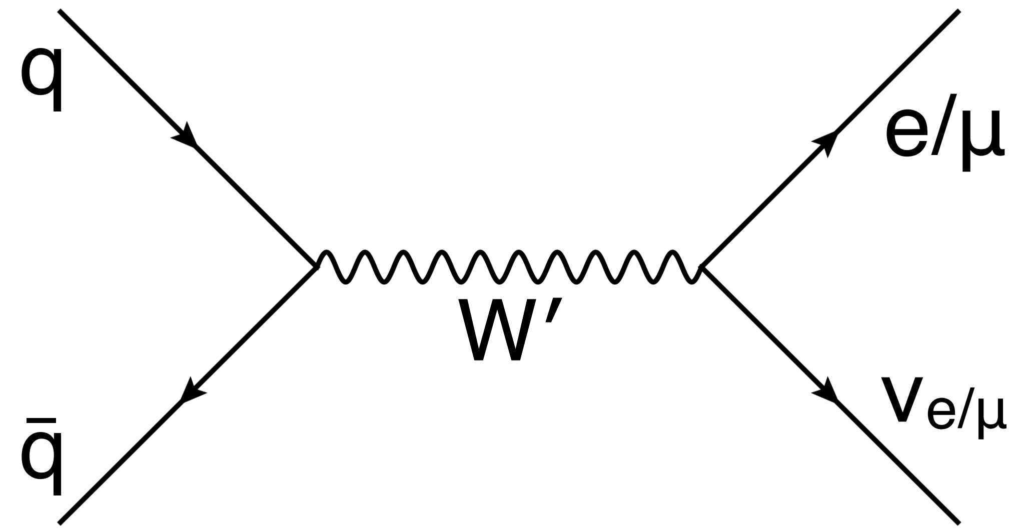


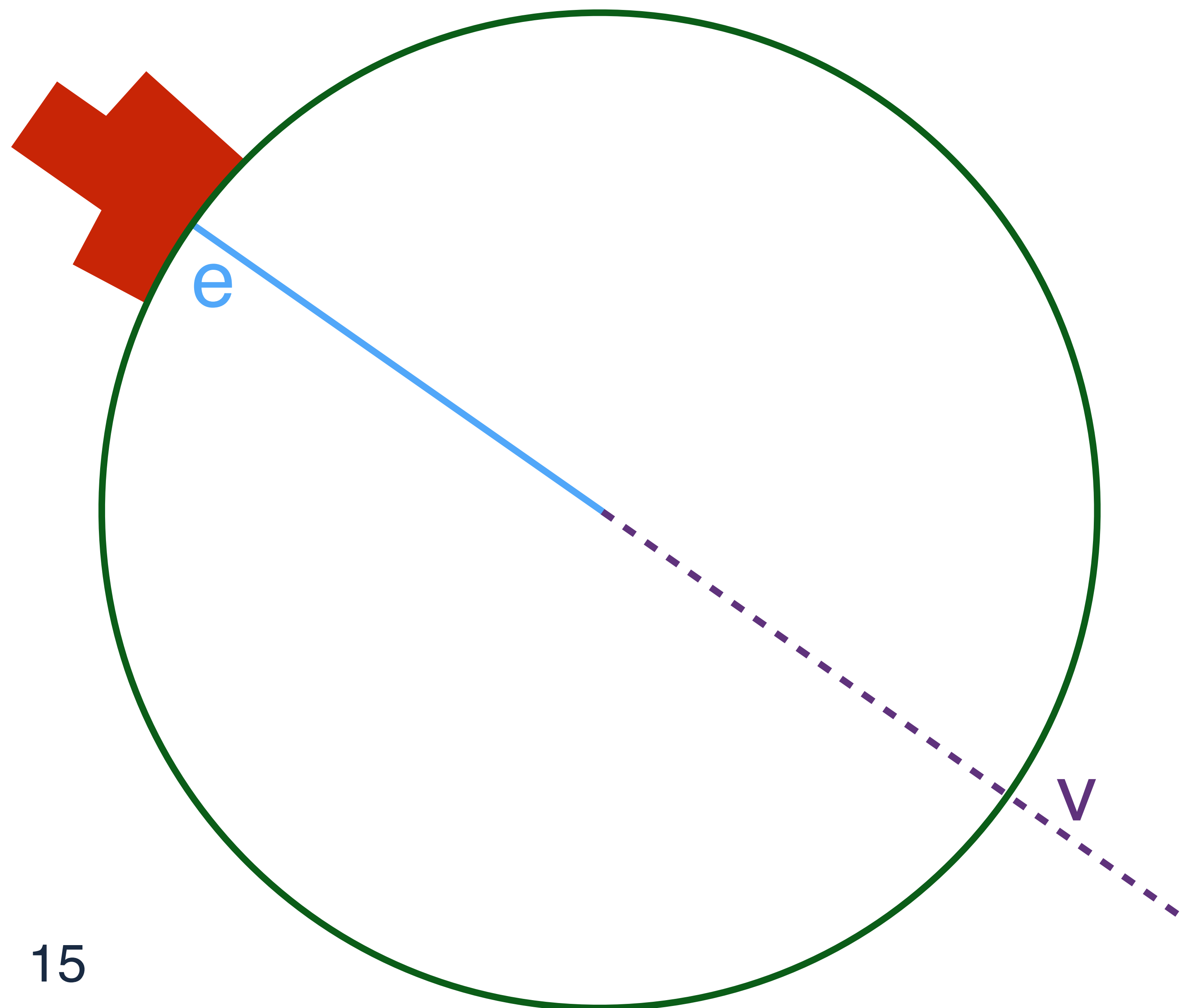


- No excess seen in 2017 electron channel
- Other interpretations in backup slides
- Can extend the Z′ exclusion to 4.7 and 4.1 TeV for the Z'_{SSM} and Z'_{ψ}, respectively

W′→ℓν Search

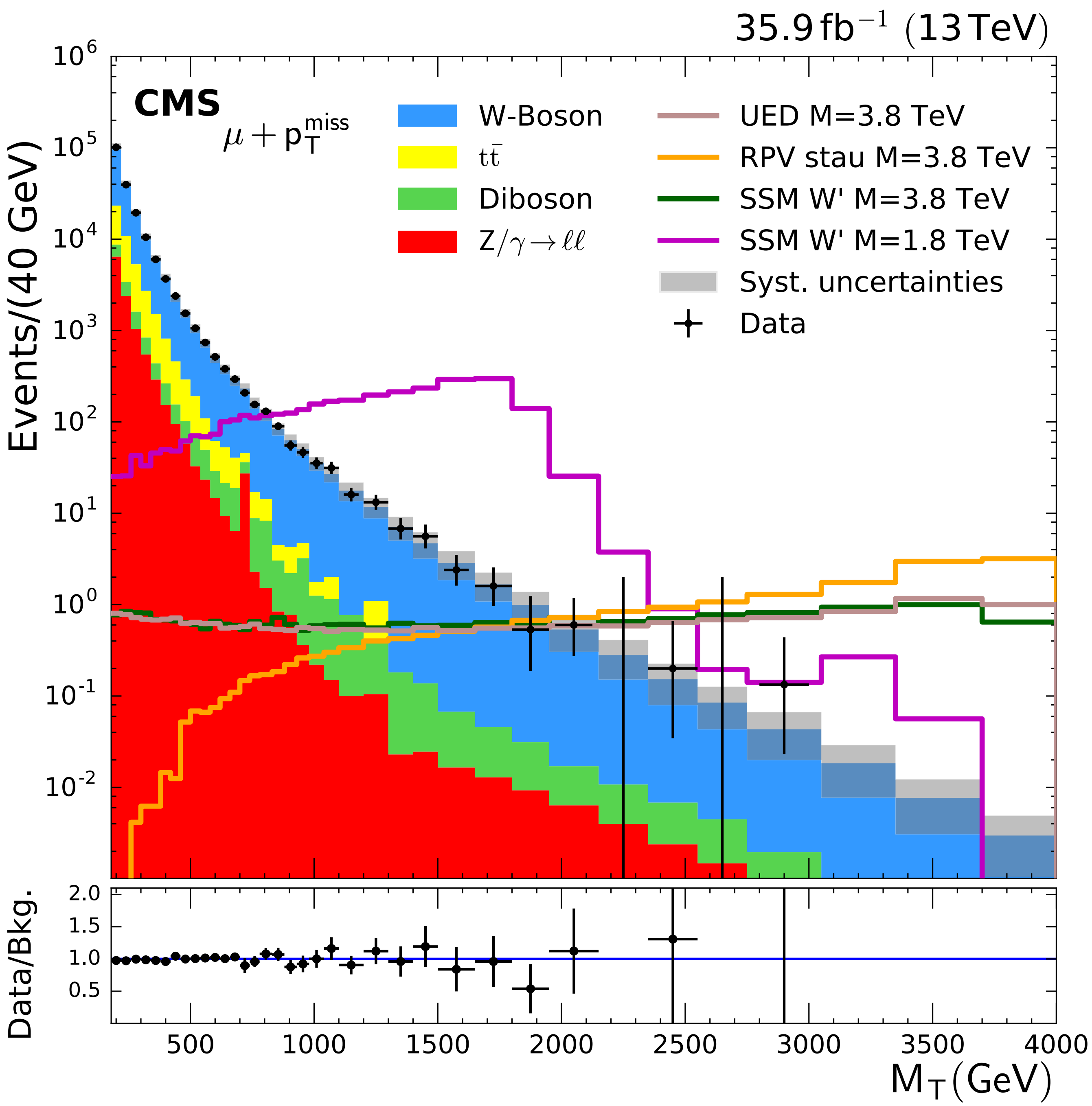
- Search for new physics in the ℓ+MET transverse mass spectrum
  - $M_T = \sqrt{2p_T^l\, p_T^{\text{miss}}\,(1-\cos[\Delta\phi(l,\vec{p}_T^{\,\text{miss}})])}$
- W′ is modeled from the SSM using couplings that range from $g_{W'}/g_W=0.01$ to $g_{W'}/g_W=3$
- Search range covers 0.2 to 5 TeV in transverse mass
- Single high p_T lepton
  - Lepton must pass isolation criteria
  - High p_T muon and electron identification
- Large MET
  - Large Δφ between lepton and MET
    - Selection on p_T/MET ratio



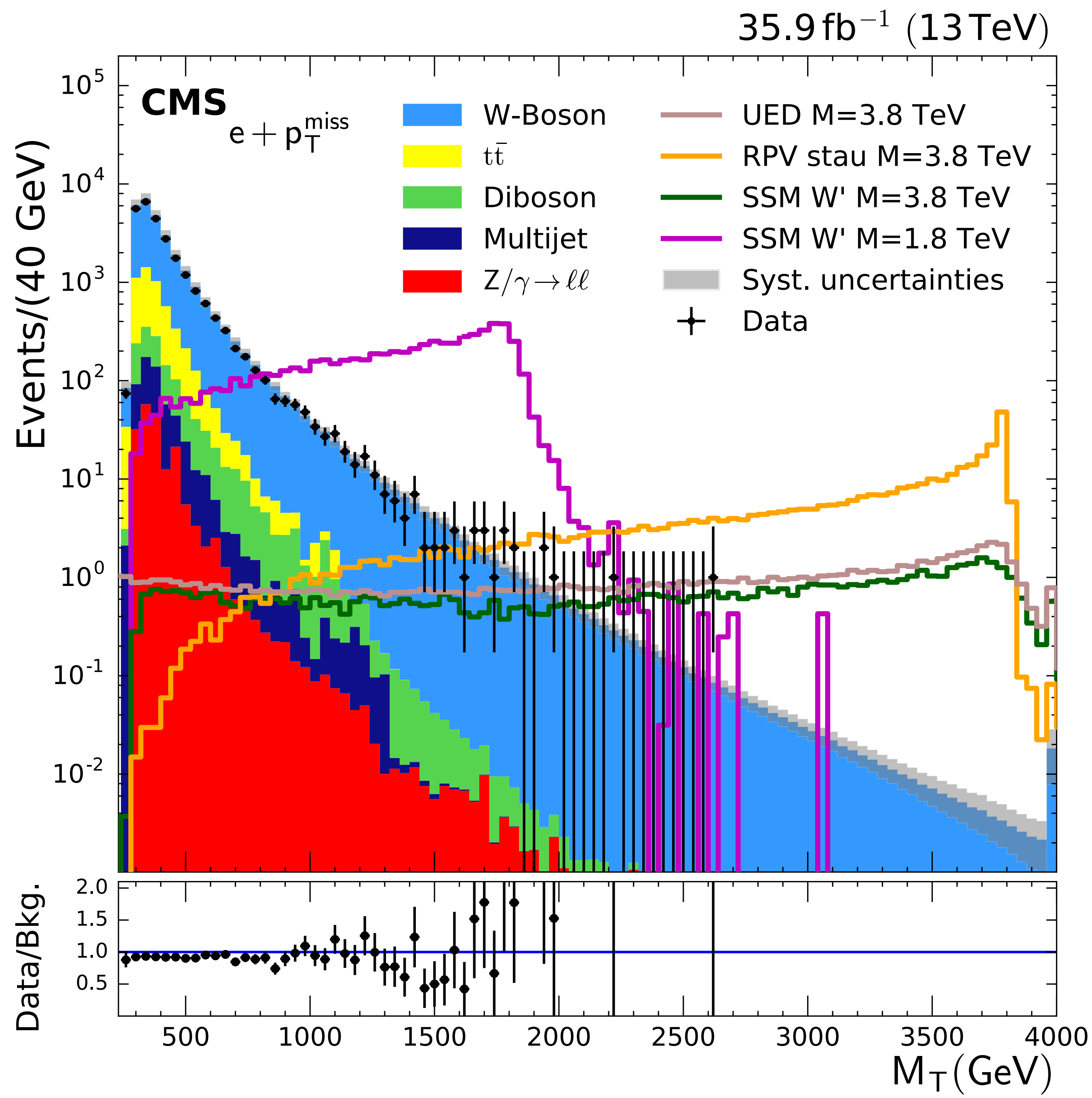


W′→ℓν Results

Muon Channel



Electron Channel



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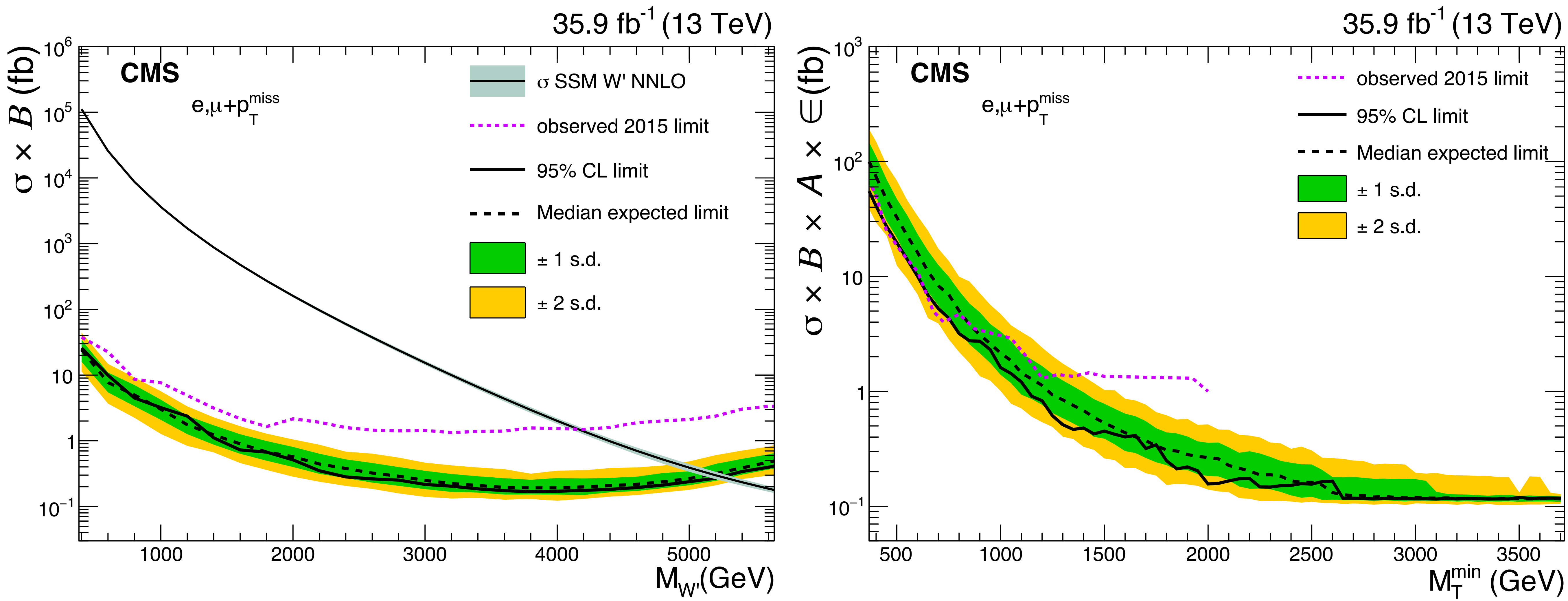
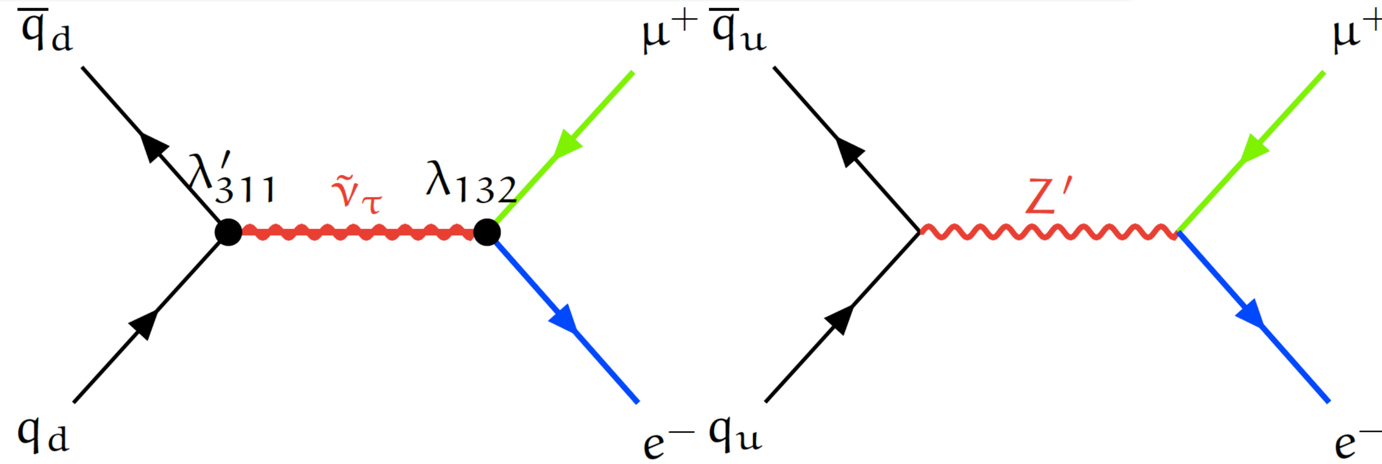
W′→ℓν Limits

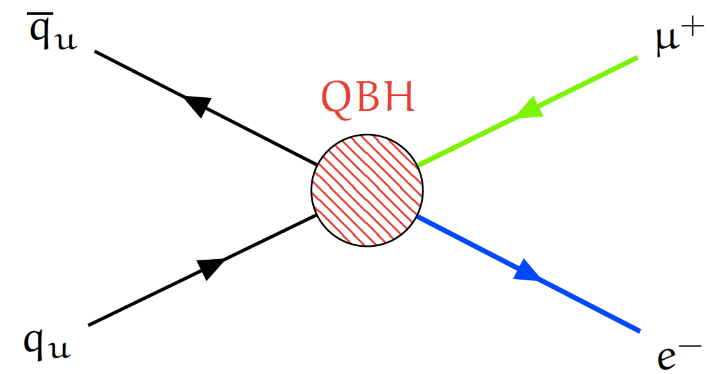


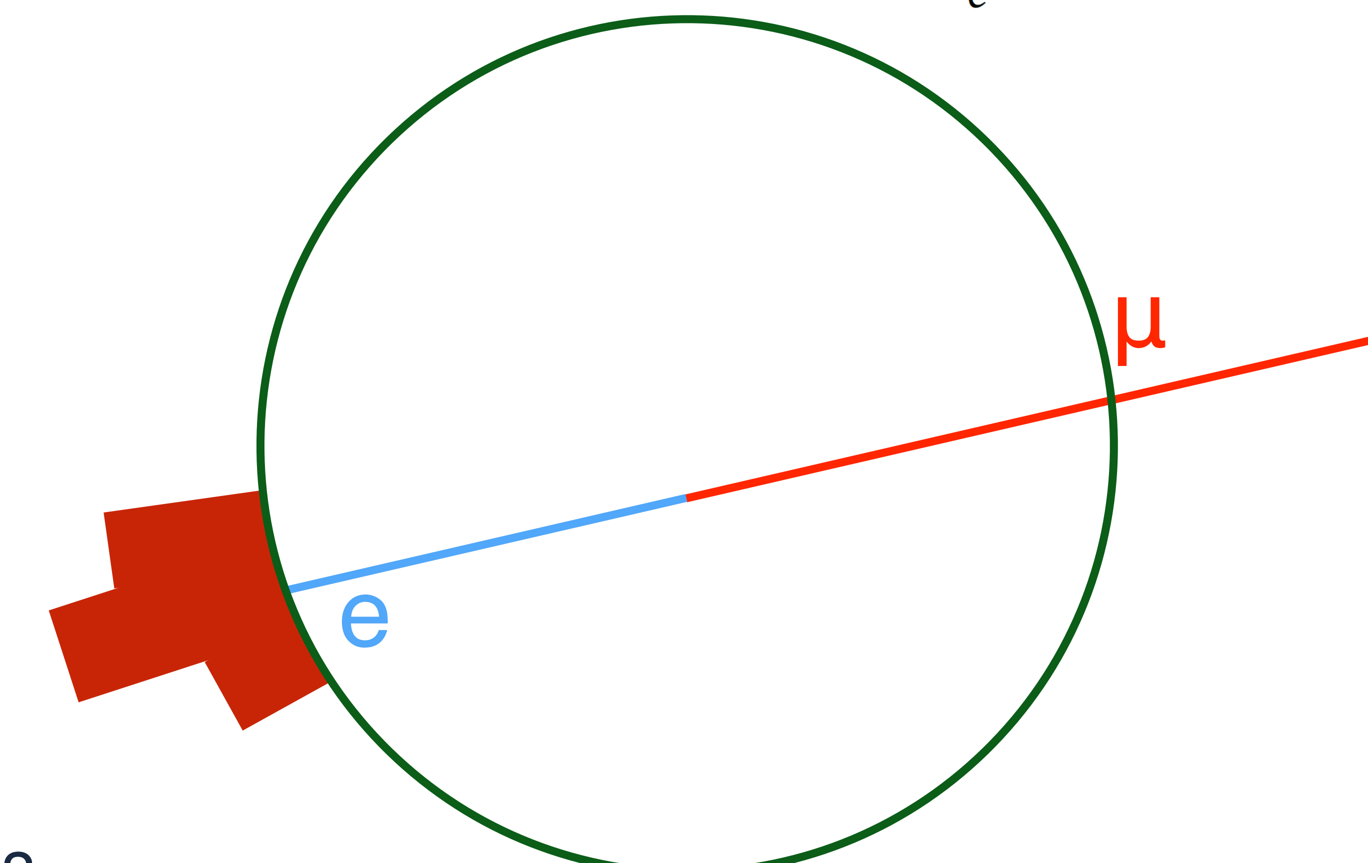
- W'_{SSM} is excluded up to 5.2 TeV assuming SM couplings
- Model independent W′ limits vary between 50 and 0.1 fb^{-1}
- Exclusion limits for other models are available in the backup slides

X→eμ Search

- Search for new physics in eμ invariant mass spectrum
- $Z'/\tilde{\nu}_\tau$/QBH→eμ
  - τ sneutrinos ($\tilde{\nu}_\tau$) can be the lightest supersymmetric particle (LSP) in RPV SUSY models
  - Z′ in LFV models from P. Langacker
  - Quantum Black Holes from N. Arkani-Hamed, S. Dimopoulos, and G. Dvali (ADD) model
    - Spin-0, colorless, neutral, and violate lepton flavor
- Search range covers 0.1 to 4.0 TeV
- One high p_T muon and electron
  - Both Isolated
  - No charge requirement
  - High p_T ID for both electrons and muons
  - Electrons within a $\Delta R < 0.1$ of the muon are vetoed from the event selection
  - Only highest invariant mass eμ pair is considered

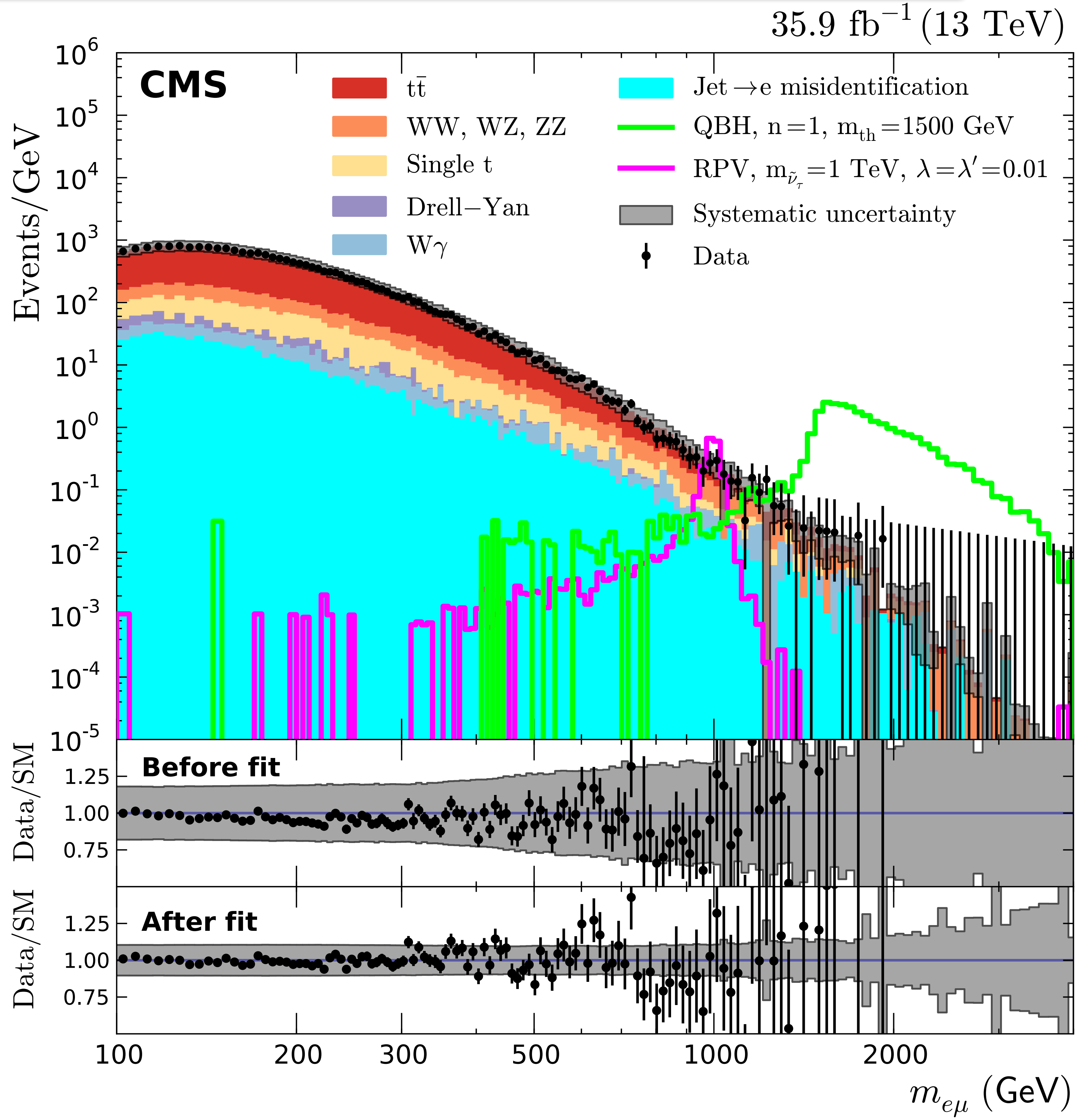




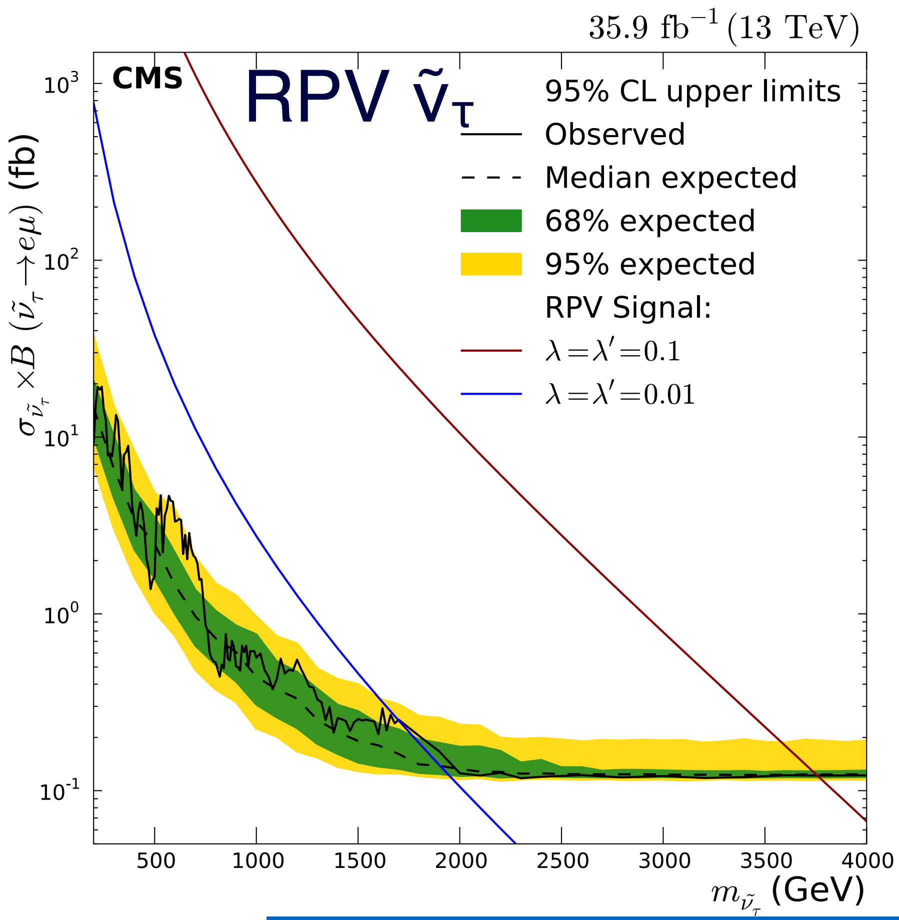


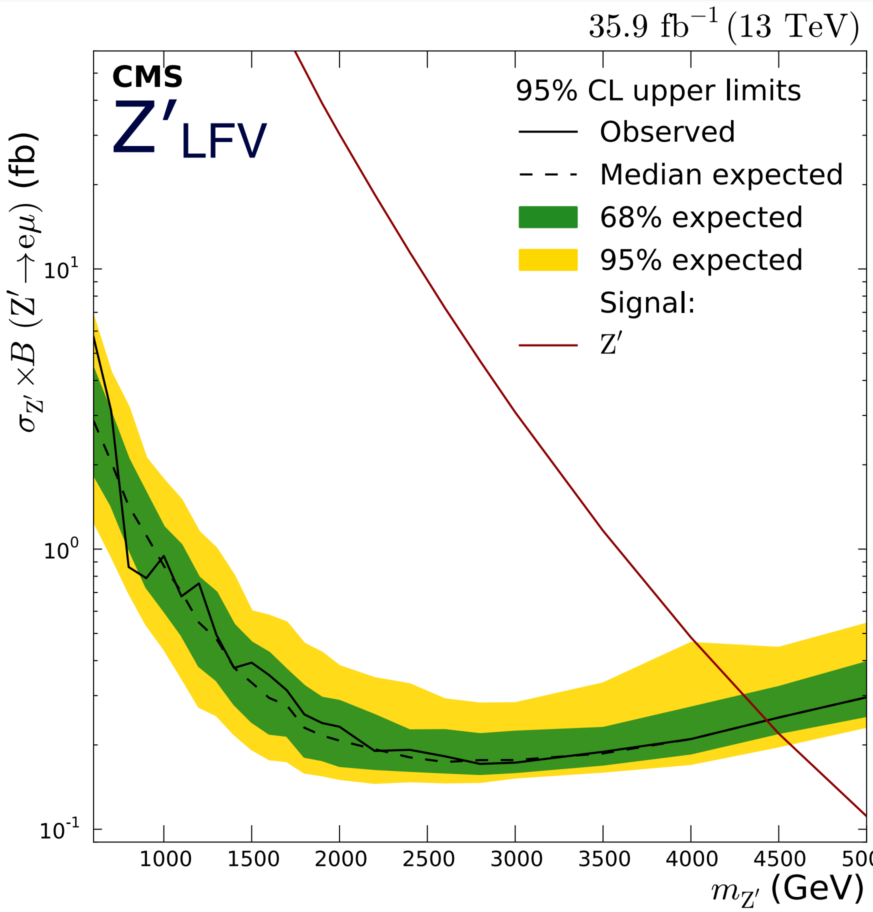
X→eμ Results

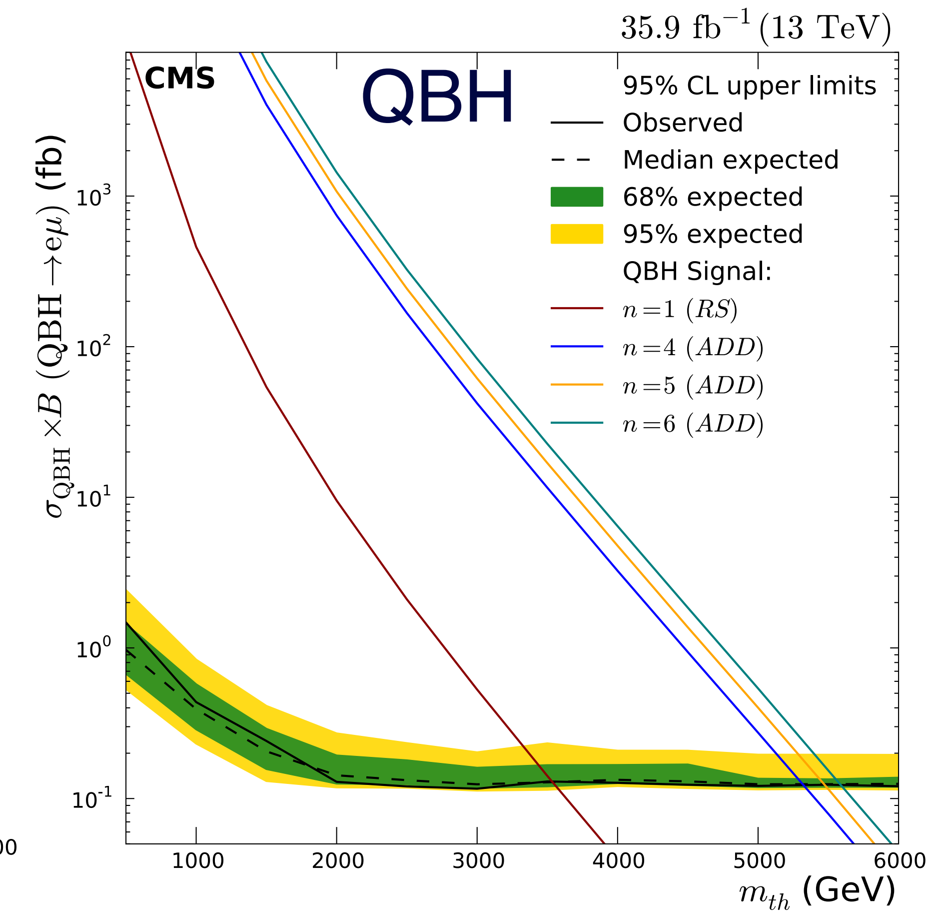
- Backgrounds containing electrons and muon are modeled in simulation
  - tt, diboson, single top, and Drell-Yan
- Backgrounds containing mis-identified electron and muons
  - W+γ is taken from simulation
  - W+Jets and QCD mutlijet backgrounds are estimated from data
  - Electron mis-identification rate is measured in electron control region
- Largest uncertainty is the shape variation in the $t\bar{t}$ eμ mass spectrum from uncertainties in the renormalization and factorization scales



X→eμ Limits







Model	Expected Exclusion	Observed Exclusion
RPV $\tilde{\nu}_\tau$ ($\lambda=\lambda'=0.1$)	3.8 TeV	3.8 TeV
RPV $\tilde{\nu}_\tau$ ($\lambda=\lambda'=0.01$)	1.9 TeV	1.7 TeV
Z′ (LFV)	4.4 TeV	4.4 TeV
QBH (n=1 RS)	3.6 TeV	3.6 TeV
QBH (n=4 ADD)	5.3 TeV	5.3 TeV
QBH (n=5 ADD)	5.5 TeV	5.5 TeV
QBH (n=6 ADD)	5.6 TeV	5.6 TeV

Summary

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- 7 recent searches for heavy resonances have been presented
    - $X\rightarrow ZV$, $X\rightarrow HV(H)$, $X\rightarrow t\bar{t}$, $X\rightarrow tb$, $X\rightarrow \ell\ell$, $X\rightarrow \ell\nu$, and $X\rightarrow e\mu$
    - Nearly all results cover the full 2016 dataset (35.9 fb^{-1})
        - $Z'\rightarrow ee$ channel covers the 2016+2017 dataset (77.3 fb^{-1})
    - Z'_{SSM}, W'_{SSM}, and Z'_{ψ} excluded to 4.7, 5.2, 4.1 TeV, respectively
    - Z'_{LFV} excluded to 4.4 TeV
    - HVT W'_{A}, W'_{B}, Z'_{A}, and Z'_{B} are excluded up to 2.3, 2.3, 1.8 and 2.5 TeV, respectively
    - G_{KK} excluded up to 4.5 TeV depending on $\tilde{\kappa}$
    - Bulk radion$_{(\Lambda_{R=1})}$ excluded up to 2.5 TeV
    - QBH excluded between 3.6 and 5.6 TeV depending on number of extra dimensions
    - Heavy resonance results can also interpreted as constraints on RPV $\tilde{\tau}$ and $\tilde{\nu}_{\tau}$, and on vector and axial vector mediated dark matter

Backup

Hierarchy Problem

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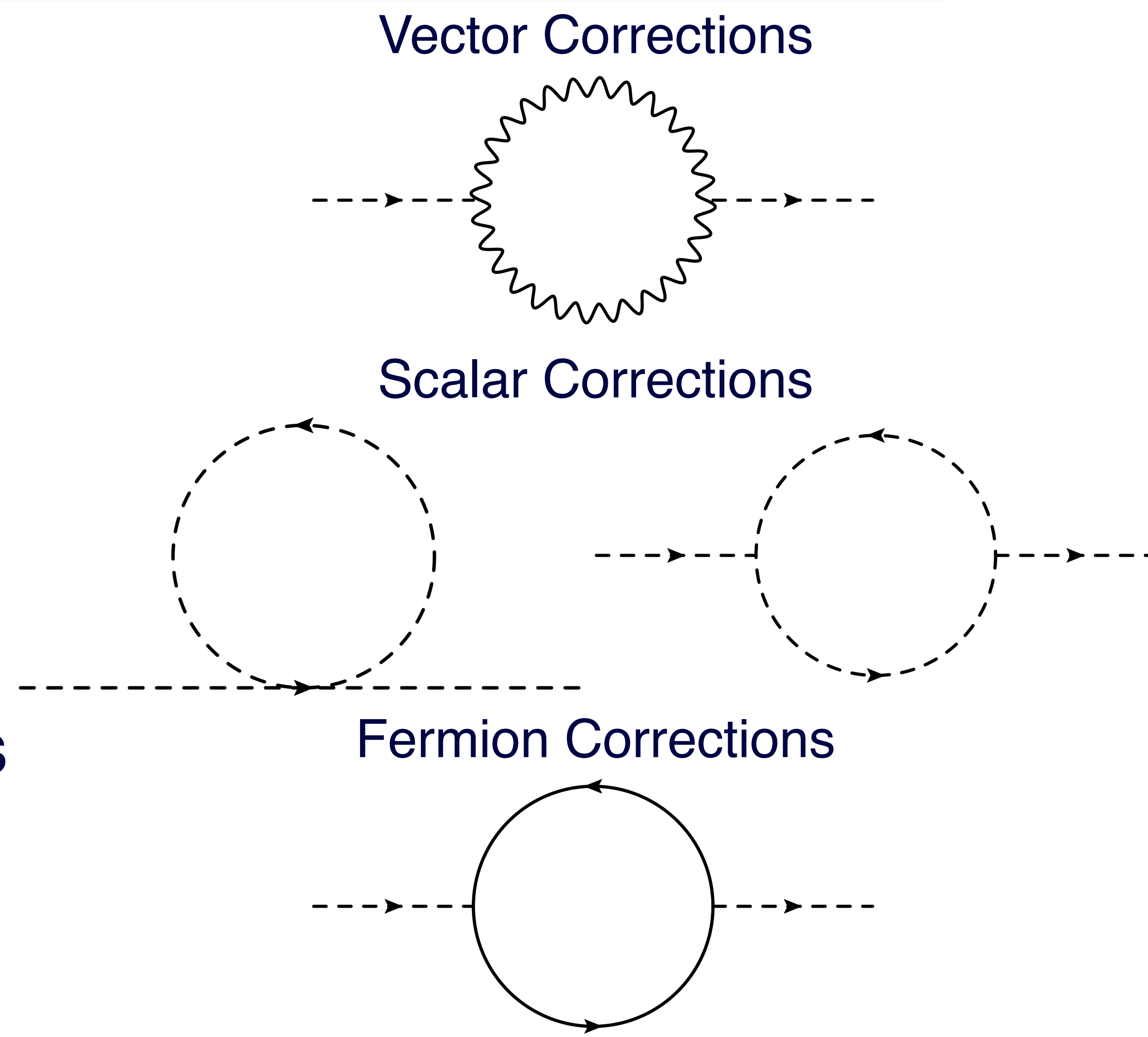
- The Higgs vev has a value near the electroweak scale
- The scalar mass squared receives quantum corrections up to some cut off scale Λ (10^{16} or 10^{19} GeV)
- Requires excessive fine tuning for the renormalized Higgs mass to be on the electroweak scale
- Some mechanism either cancels the corrections or lowers the cutoff scale Λ



$$\delta m_H^2 \approx \frac{3G_F}{4\sqrt{2}\pi^2}\left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2 + \ldots\right)\Lambda^2$$

$$m_H^2 = m_0^2 + \delta m_H^2$$

Extra Dimensions

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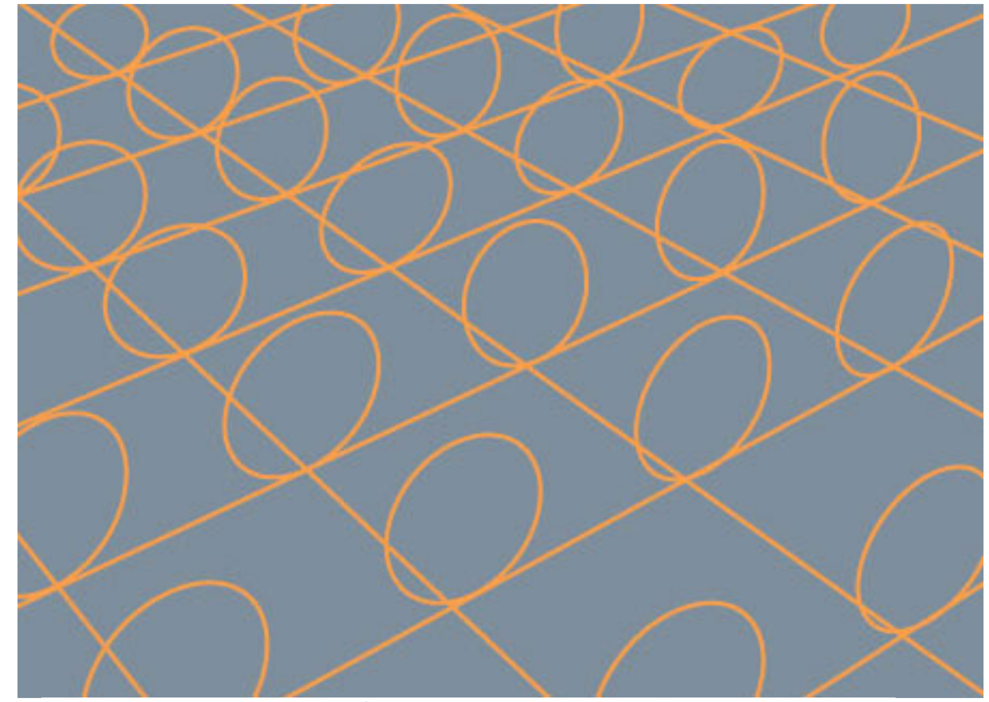
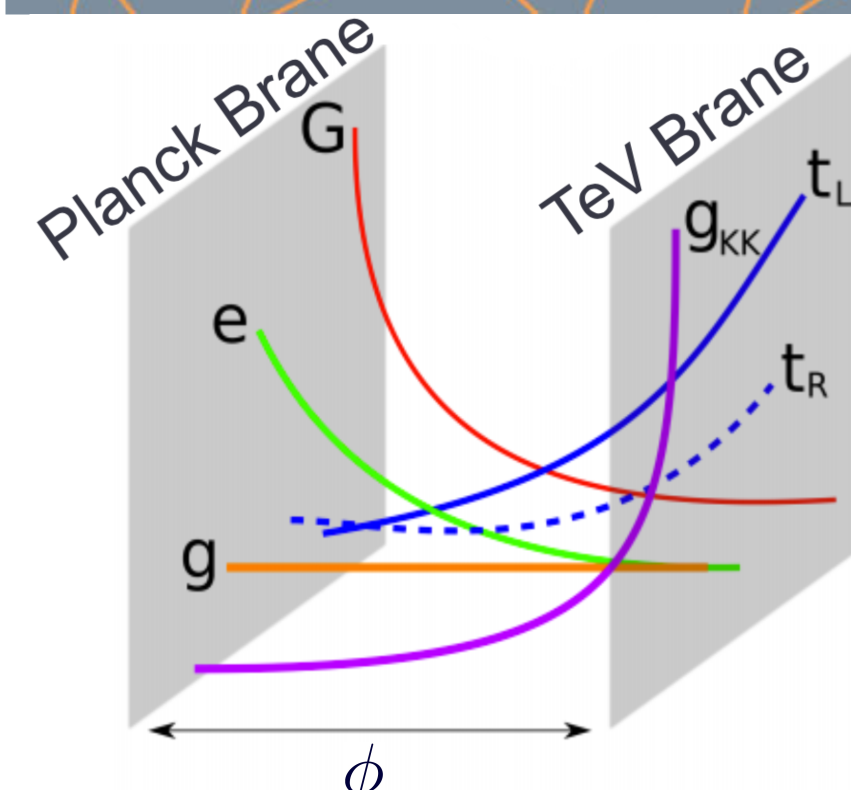
- There are many models that resolve the hierarchy problem by adding extra dimensions
- Some models add compactified extra dimensions
    - Universal Extra Dimensions
- Randall-Sundrum Models add a 5th highly warped dimension
- These models allow standard model particles to have Kaluza-Klein excitations



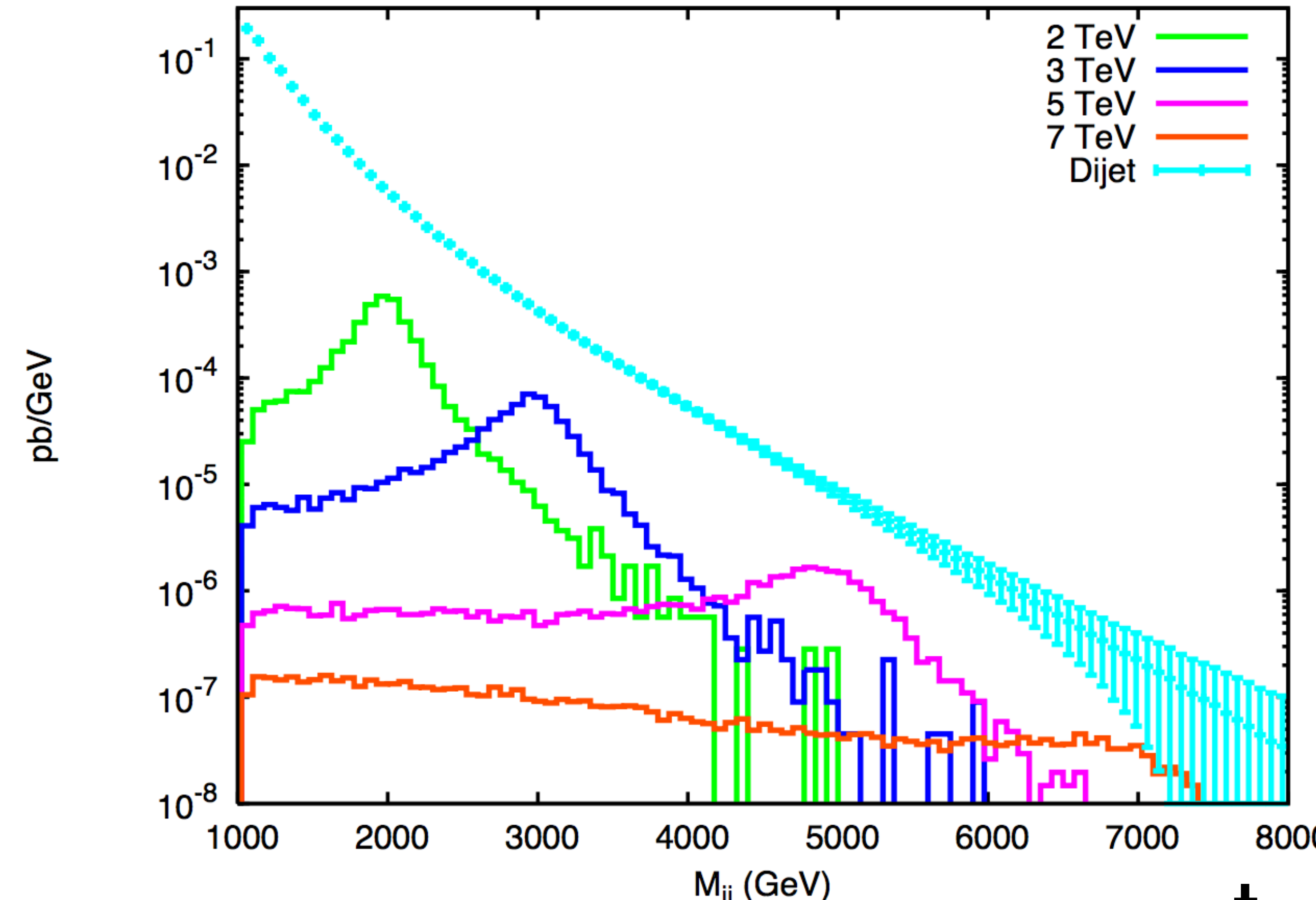


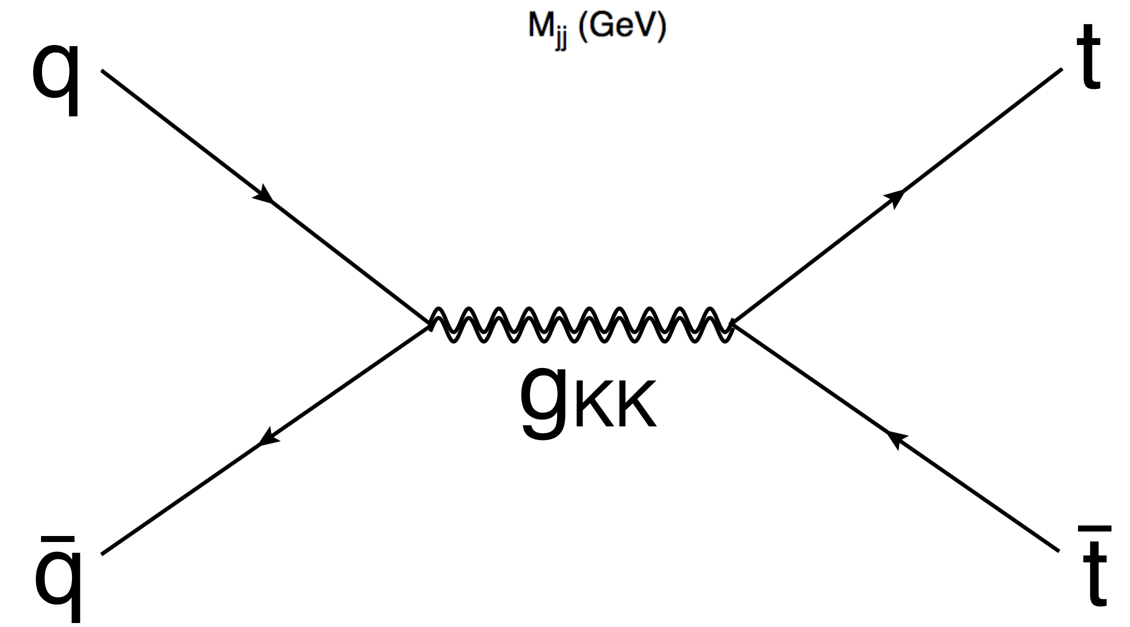
$$ds^2 = e^{-2kr_c\phi}\eta_{\mu\nu}dx^u dx^\nu + r_c^2 d\phi^2$$

KK Gluon Resonance Search

- KK Gluons (g_{KK}) are the most strongly coupled KK particle and have the highest production cross section
  - g_{KK} decay to top quarks
    - As do all gauge KK states
- Resonance peaks become smeared at high masses due to off-shell production

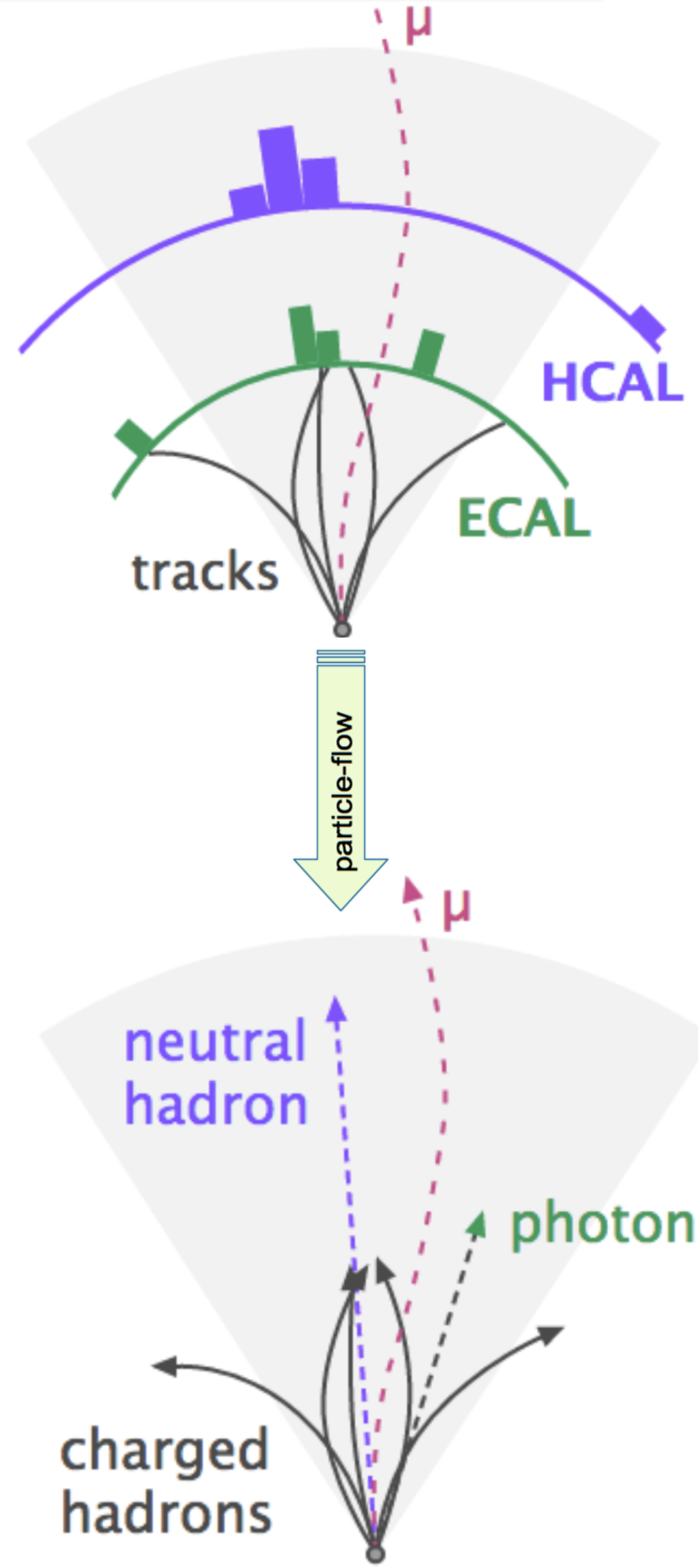
Ben Lillie, Lisa Randall, Lian-Tao Wang
arXiv:hep-ph/0701166





Particle Flow

- Particle flow reconstruction takes advantage of the high granularity of the tracker and calorimeters
- Iterative algorithm that reconstructs the best object first and then proceeds to the next objects
  - Muons are reconstructed from high quality tracks paired with hits in the muon chamber
  - Electrons are reconstructed from deposits in the electromagnetic calorimeter and tracks
  - Charged hadrons are reconstructed from hits in the HCAL matched to tracks
  - Neutral hadrons and photons are then created from the remaining calorimeter objects



Tagging

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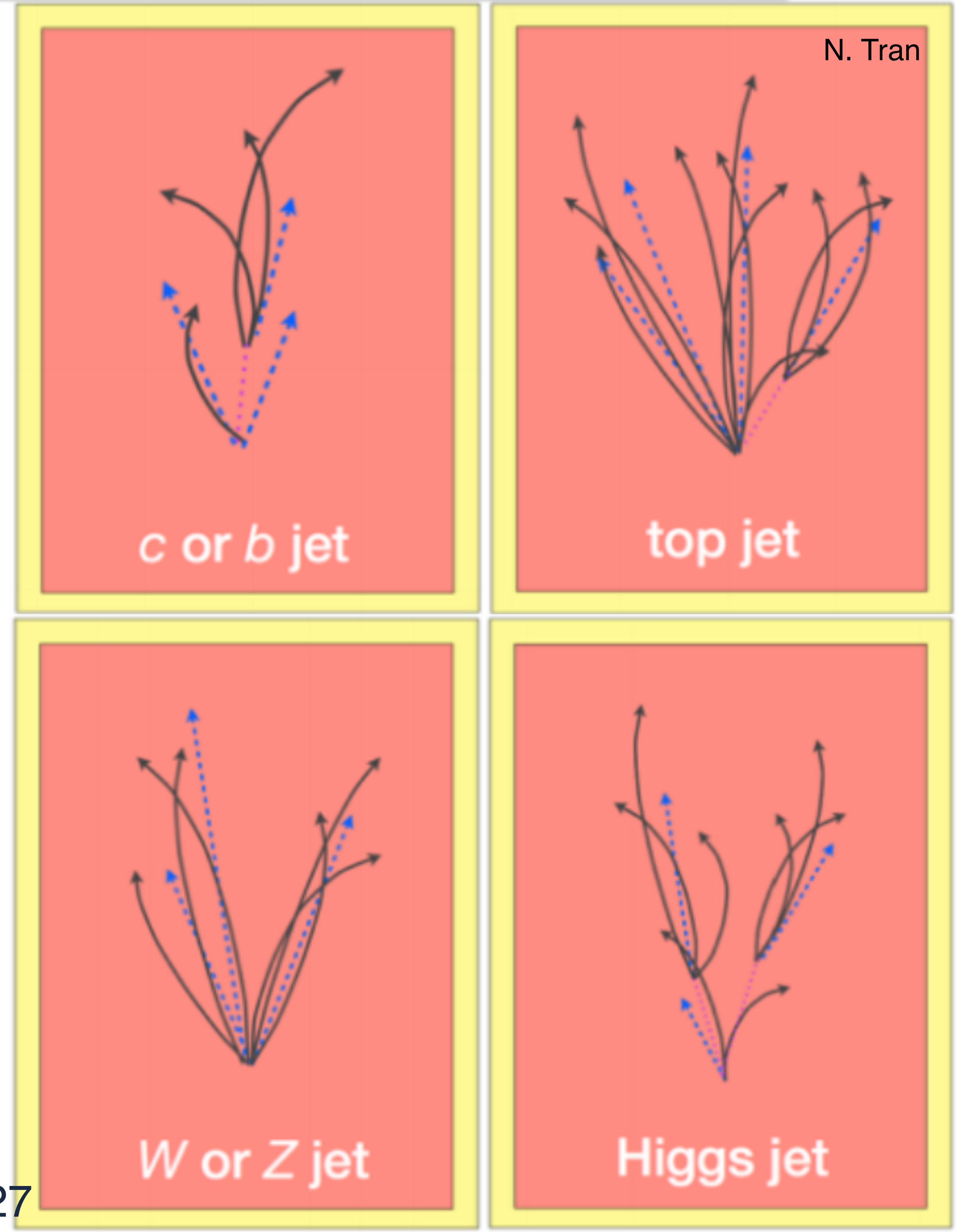
- Tagging is used to classify jets, or groups of jets, as likely originating from a particular type of particle
- b-tagging
    - Single pronged jet with a displaced vertex
- t-tagging
    - Three pronged jet with one displace vertex
    - Jet mass near top mass
- W/Z tagging
    - Two pronged jet
    - Jets mass near W/Z boson
- Higgs tagging
    - Two pronged jet with two displaced vertices
    - Jet mass near Higgs mass



Bottom Quark Decay

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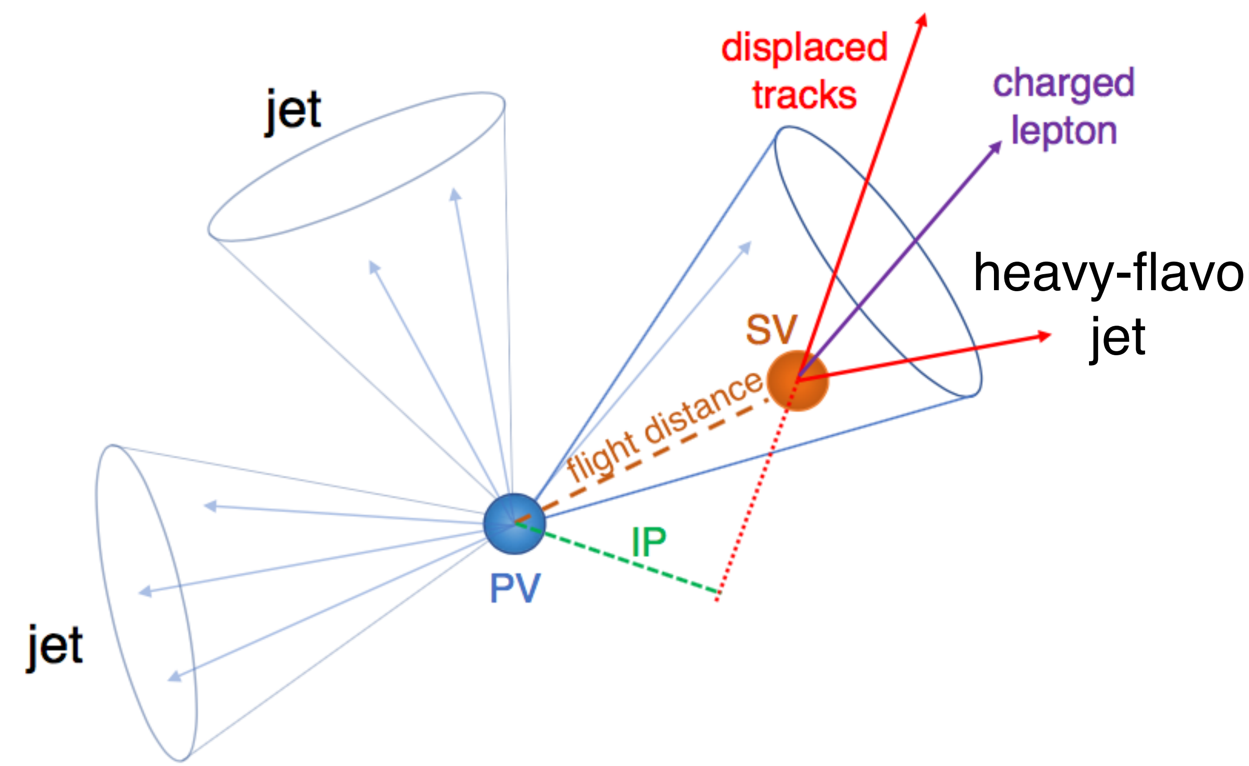
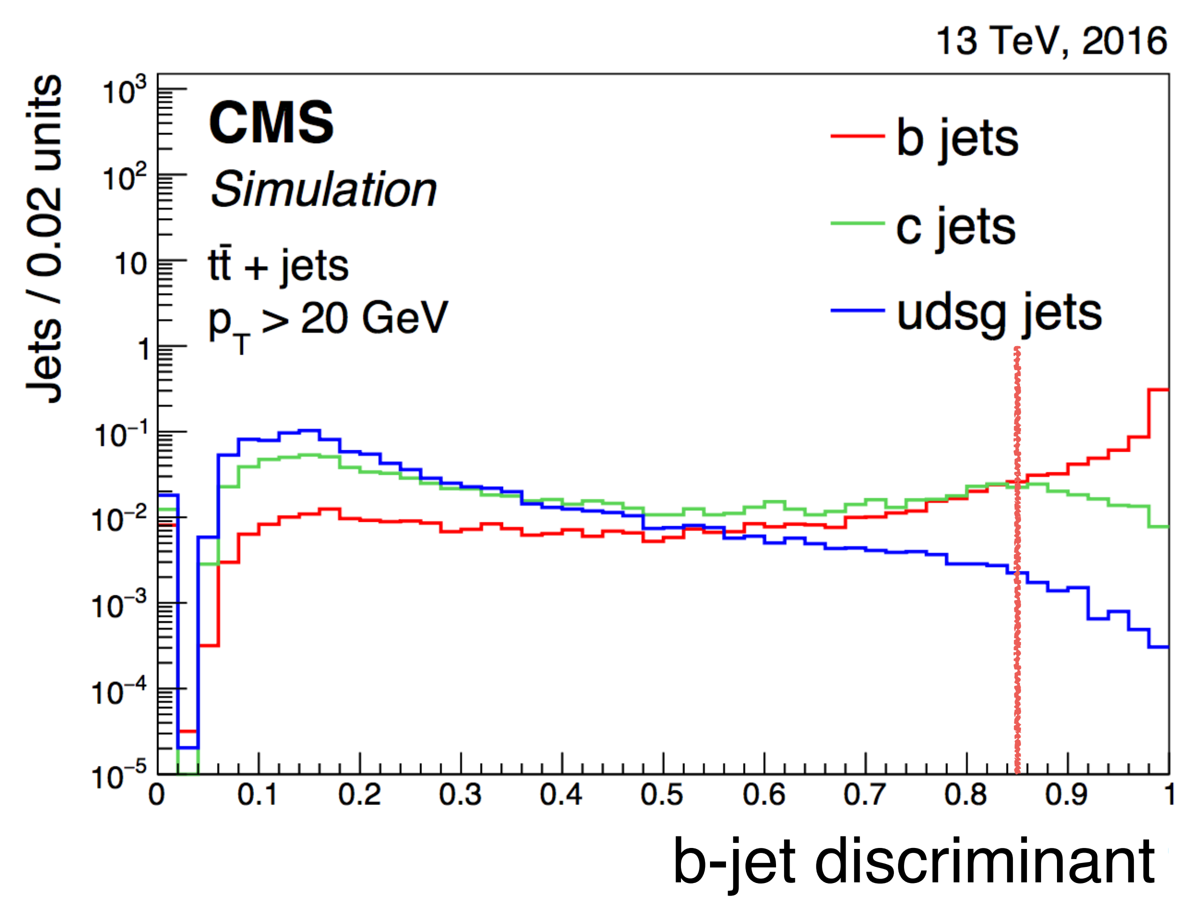
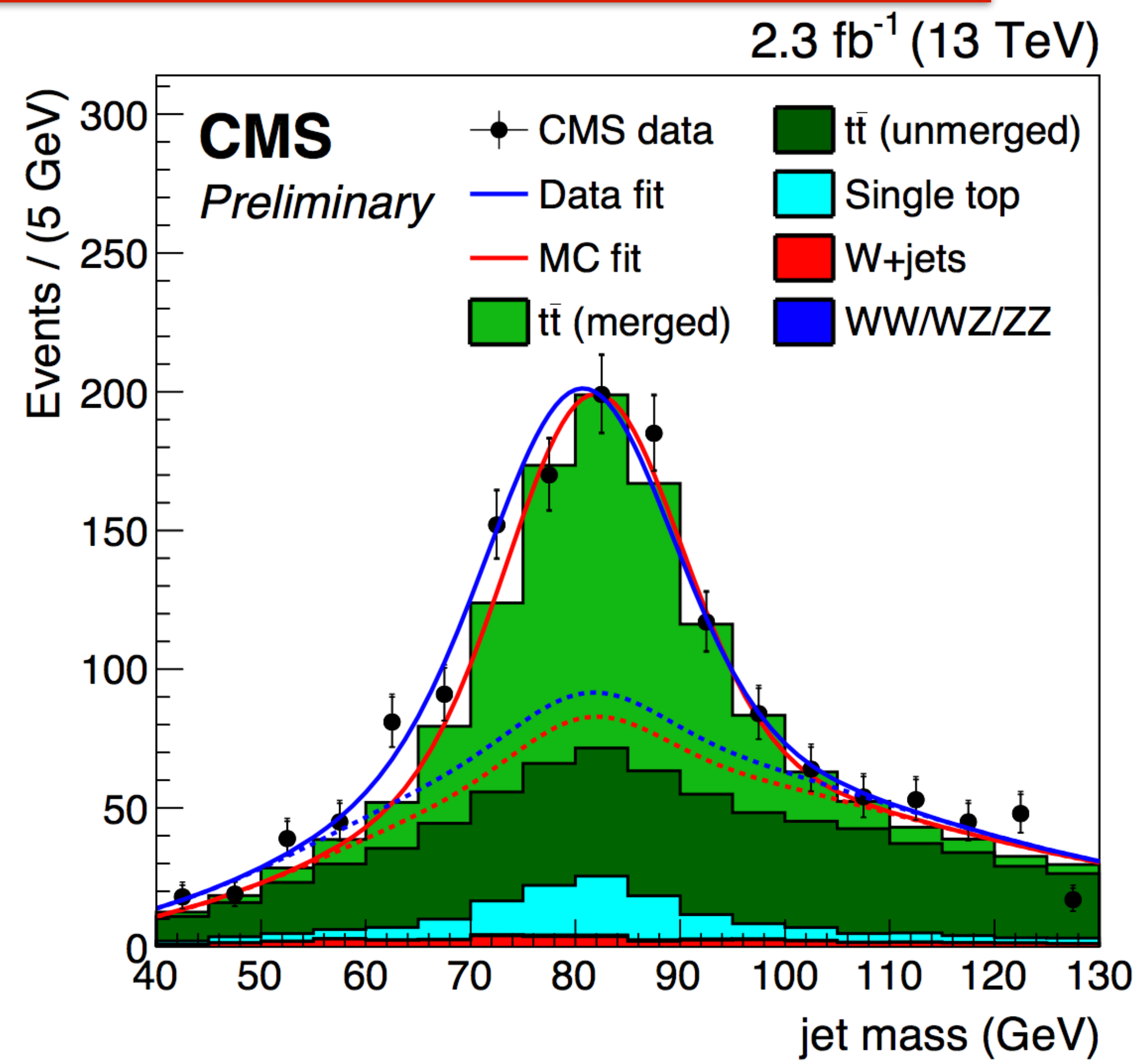
- Jets that originate from a b-quark have an origin that is displaced from the beam spot
- A neural network is used to discriminate between jets originating for b versus those from c quarks and light flavor (u, d, s quarks)
- Presented analyses generally use 'medium' working point (~0.85)
  - b-tag efficiency of ~70%
  - ~1% mis-tag rate

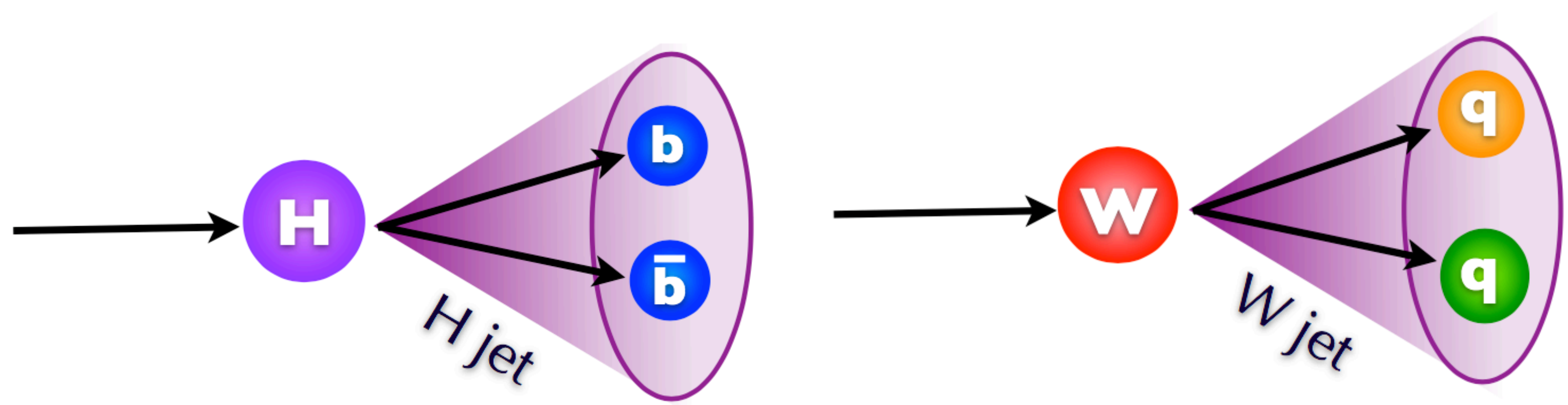




Heavy Boson Tagging

- Heavy boson tagging looks for large radius jets that have 2 sub-jets
- W/Z tagging requires the invariant mass of the sub-jets to be in the W/Z mass window
  - τ_{21} discriminator
- H tagging requires the invariant mass of the sub-jets to be in the Higgs mass window
  - Has a requirement on the sub-jets b discriminant score





X→ZV: Jet Kinematics

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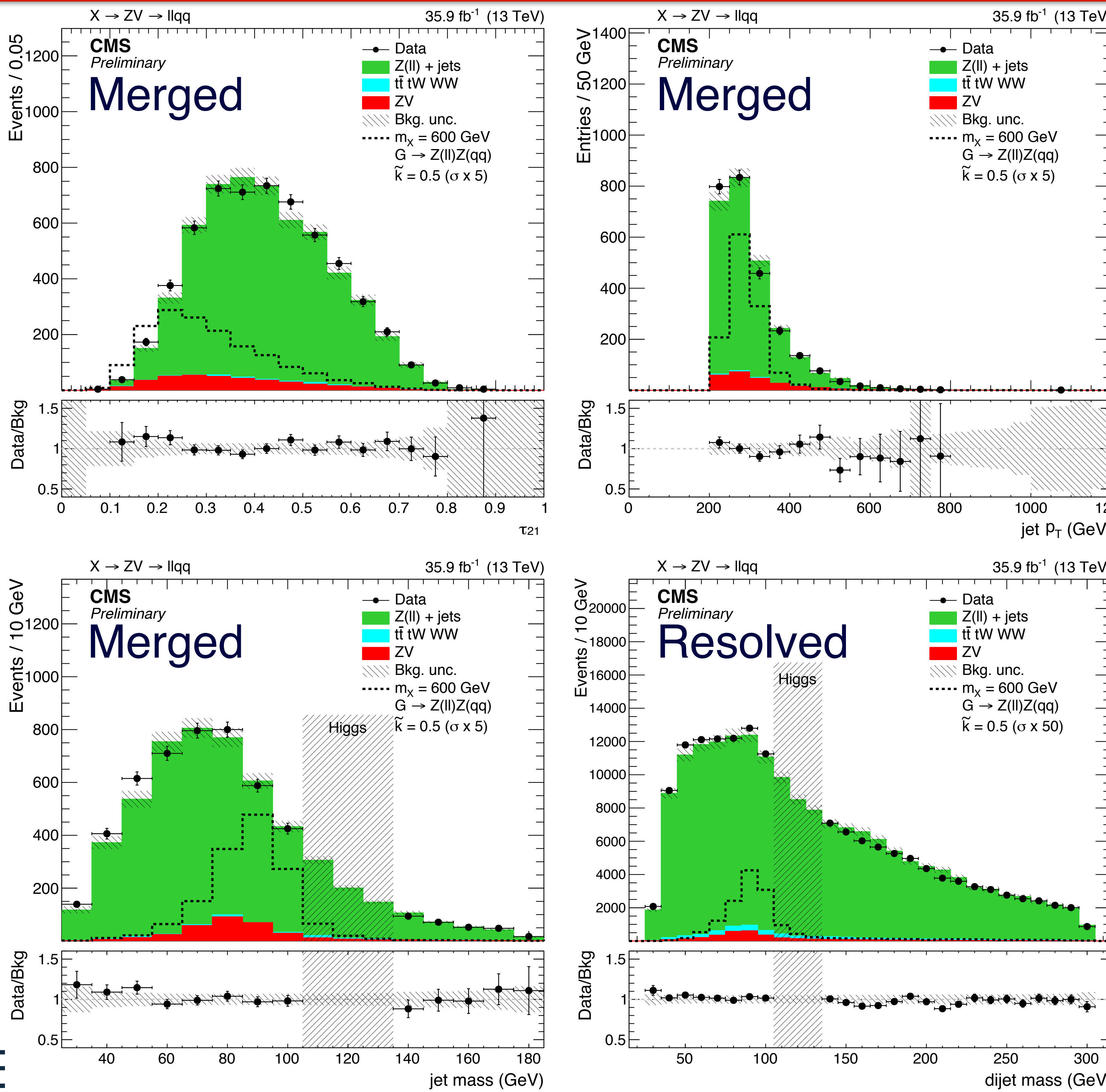
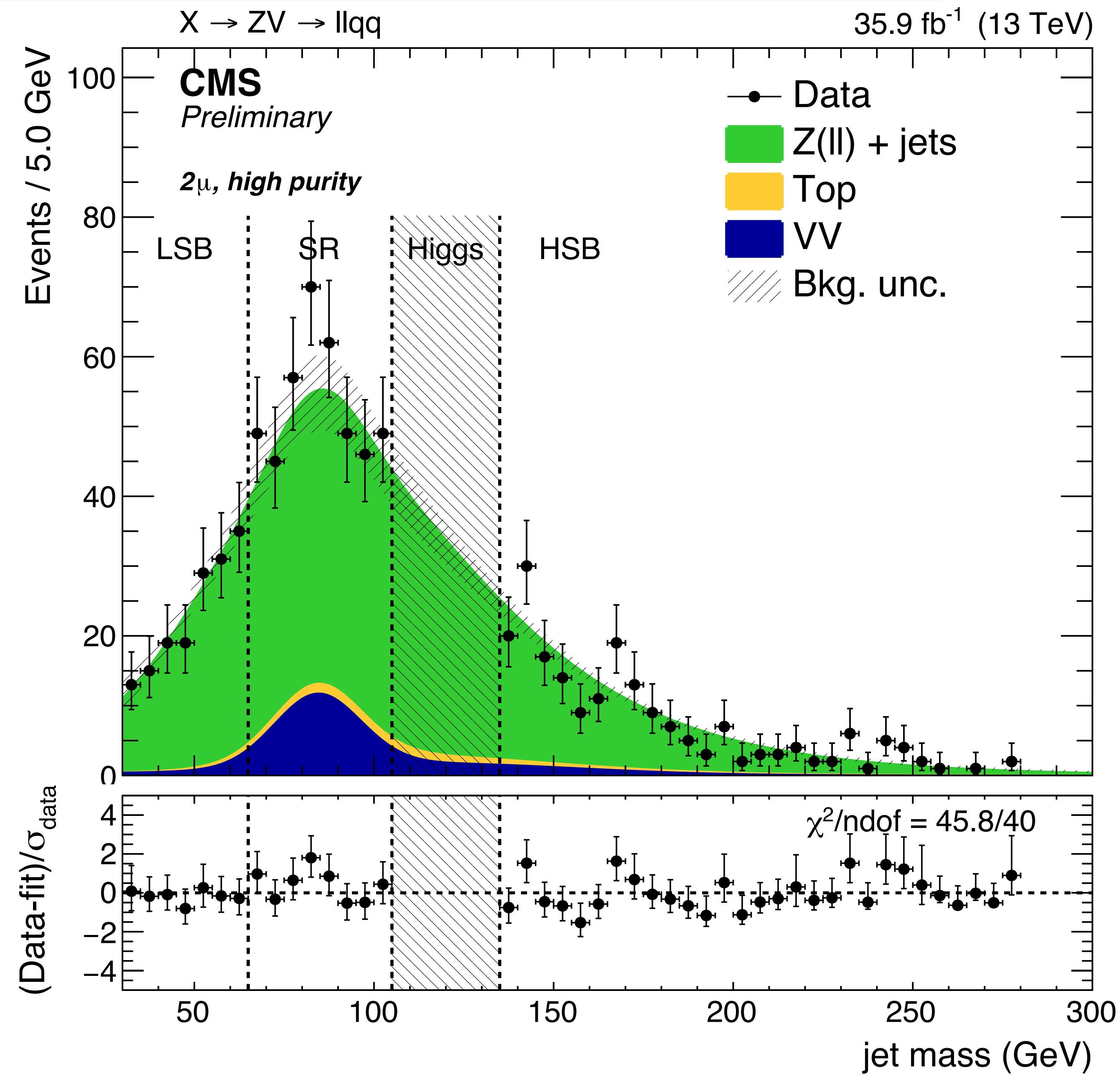


D. E

X→ZV: Background Estimation (High Mass)

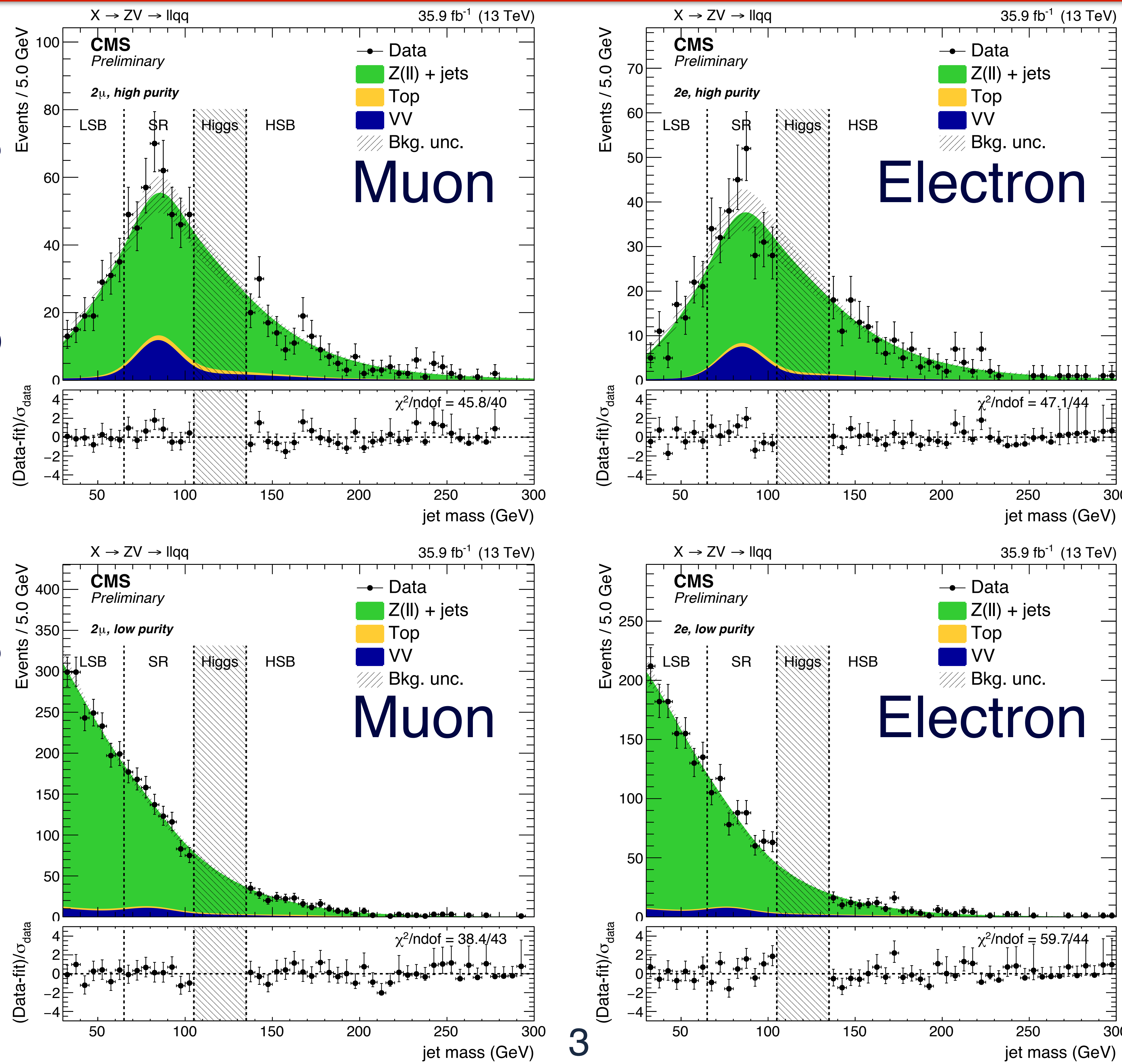
- Background from Z+Jets, diboson, and $t\bar{t}$
- Z+jets background modeled in two control regions
  - M_{jj} is used to define low and high side-band regions
  - Background shapes modeled using analytic functions
  - Statistical uncertainty and alternative shape hypotheses are used as systematic uncertainties
- Diboson and $t\bar{t}$ background taken from simulation



X→ZV: Background Shapes (High Mass)

High Purity

High Purity



Low Purity

Low Purity

X→ZV: Background Estimation (Low Mass)

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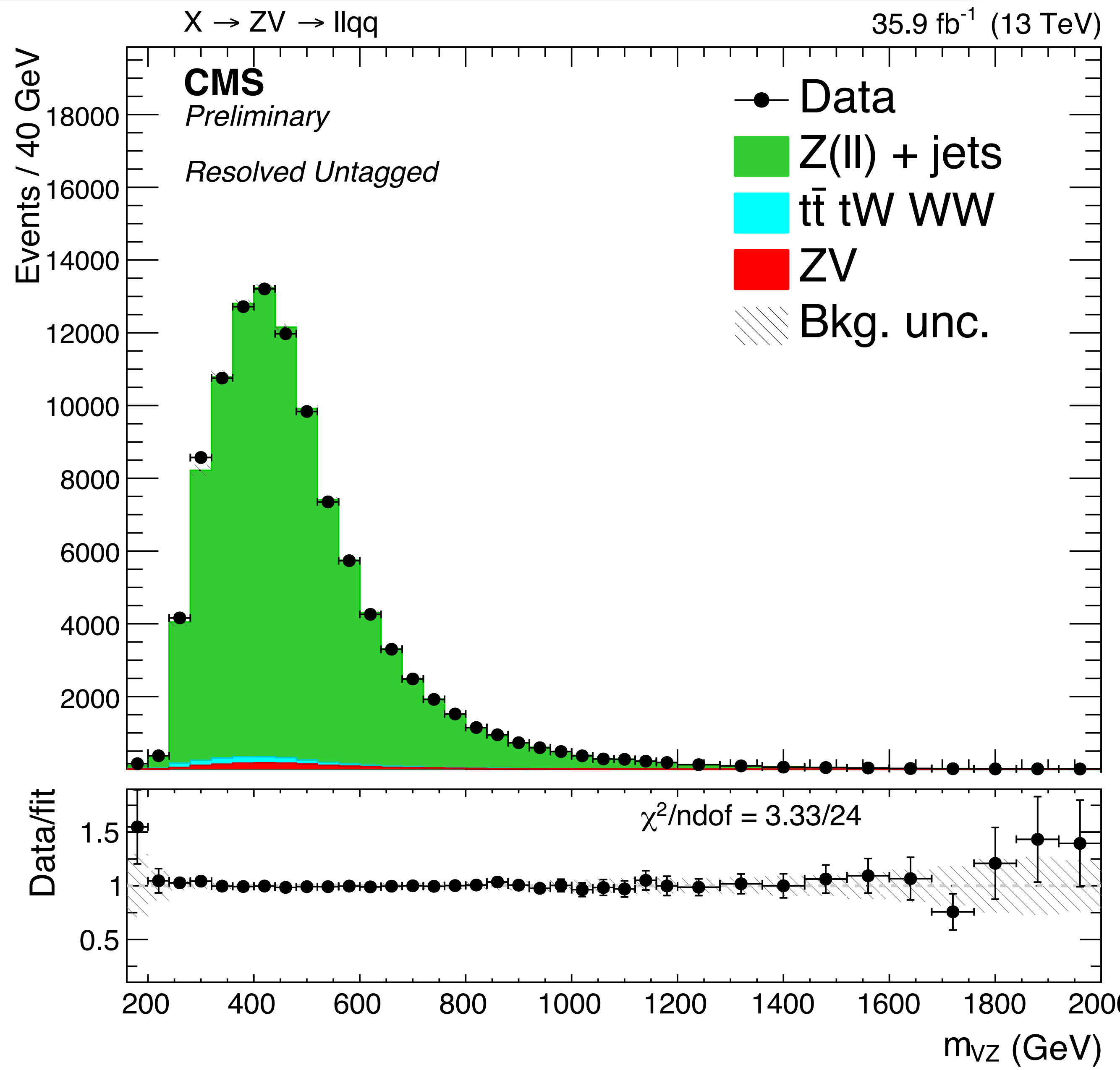
- Z+Jets background shape taken from simulation
  - M_{jj} is used to define low and high side-band regions
  - Low VV mass region also used as side band
- Non-Z background modeled in eμ control region
- Diboson background taken from simulation
- Differences between data and simulation in control regions taken as a systematic uncertainty



X→ZV: Background Shapes (Low Mass)

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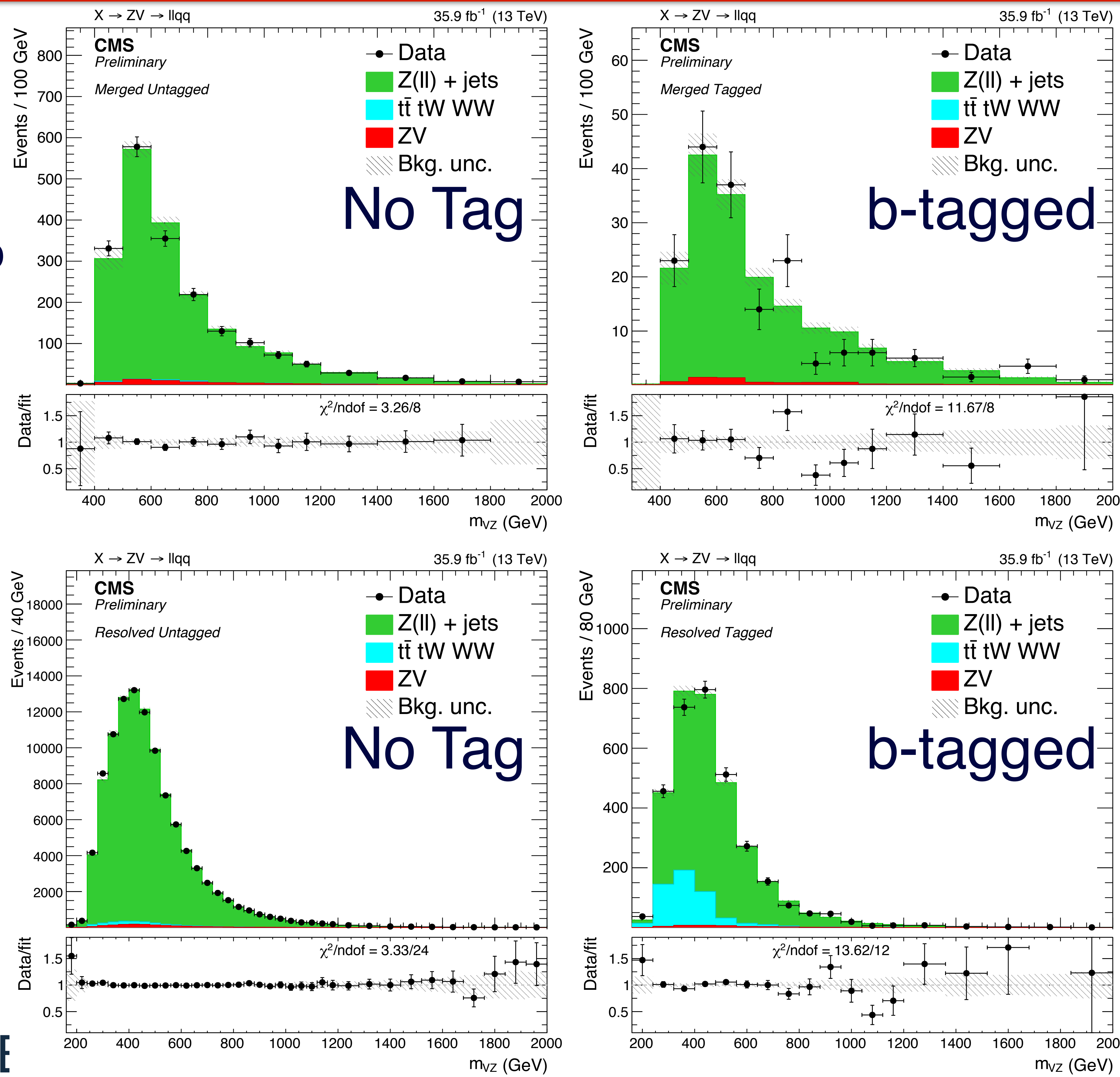
Merged

Resolved



Merged

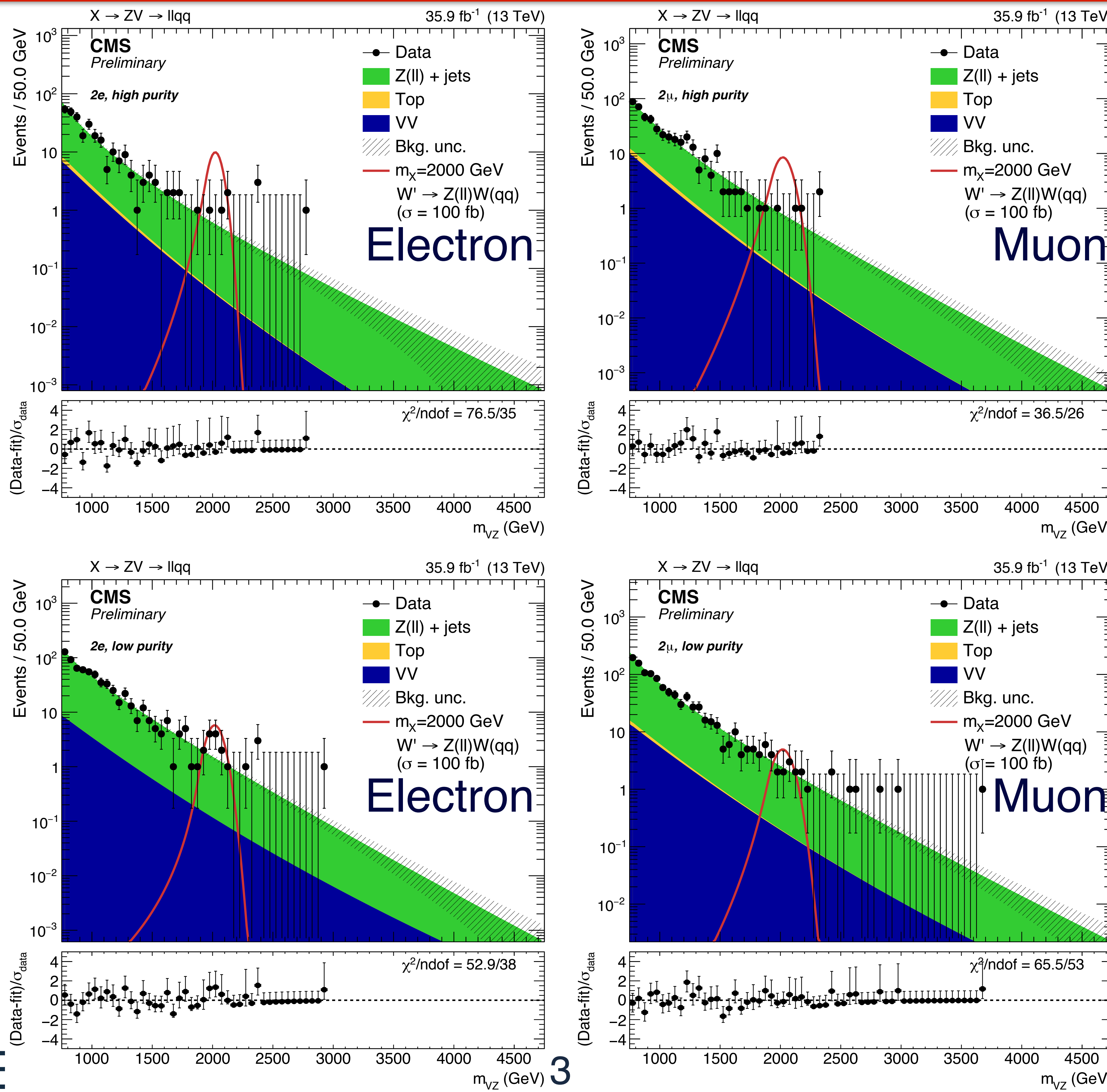
Resolved

D. E

X→ZV: Results (High Mass)

High Purity

Low Purity

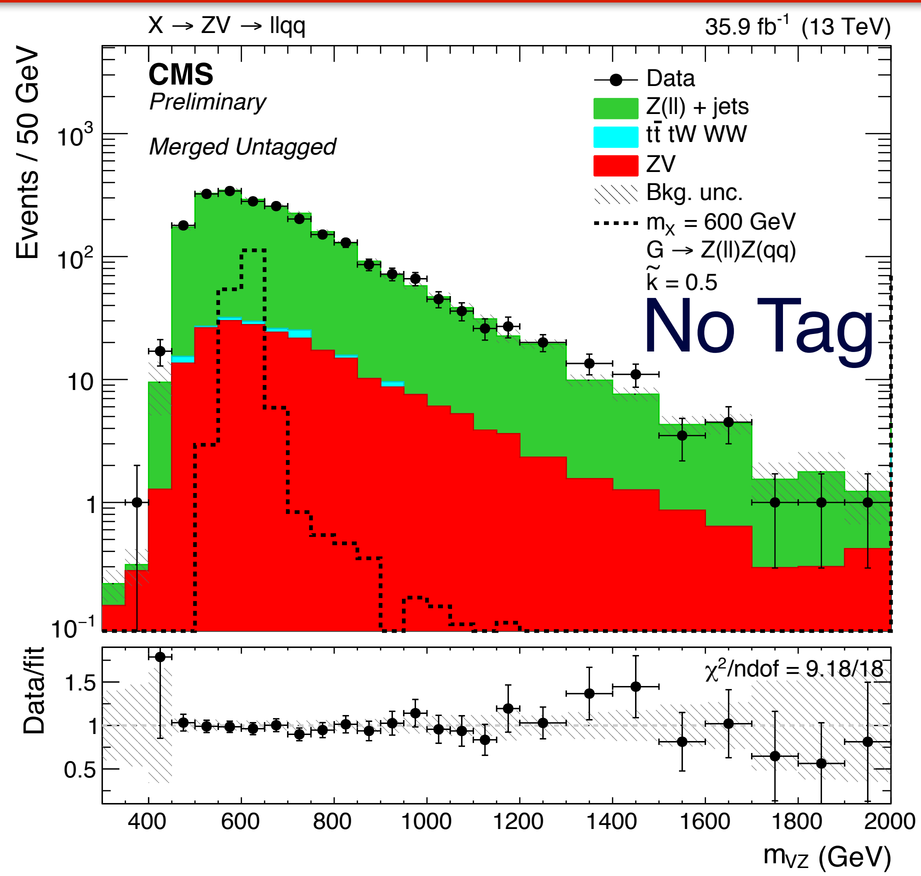


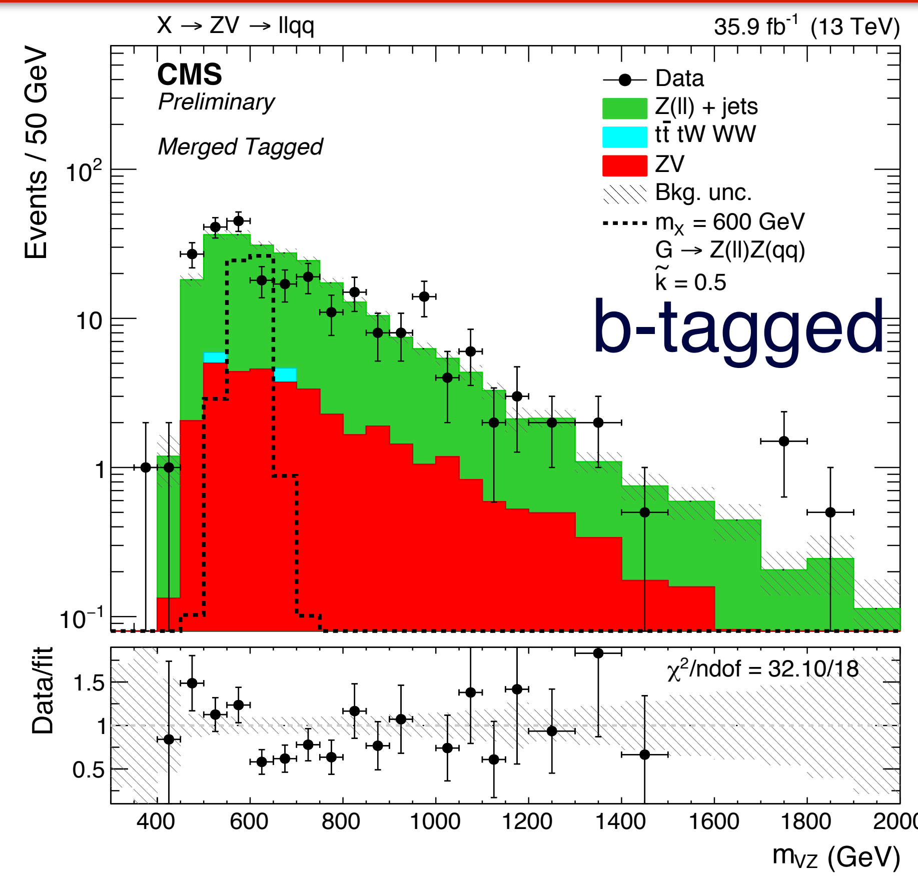
High Purity

Low Purity

X→ZV: Results (Low Mass)

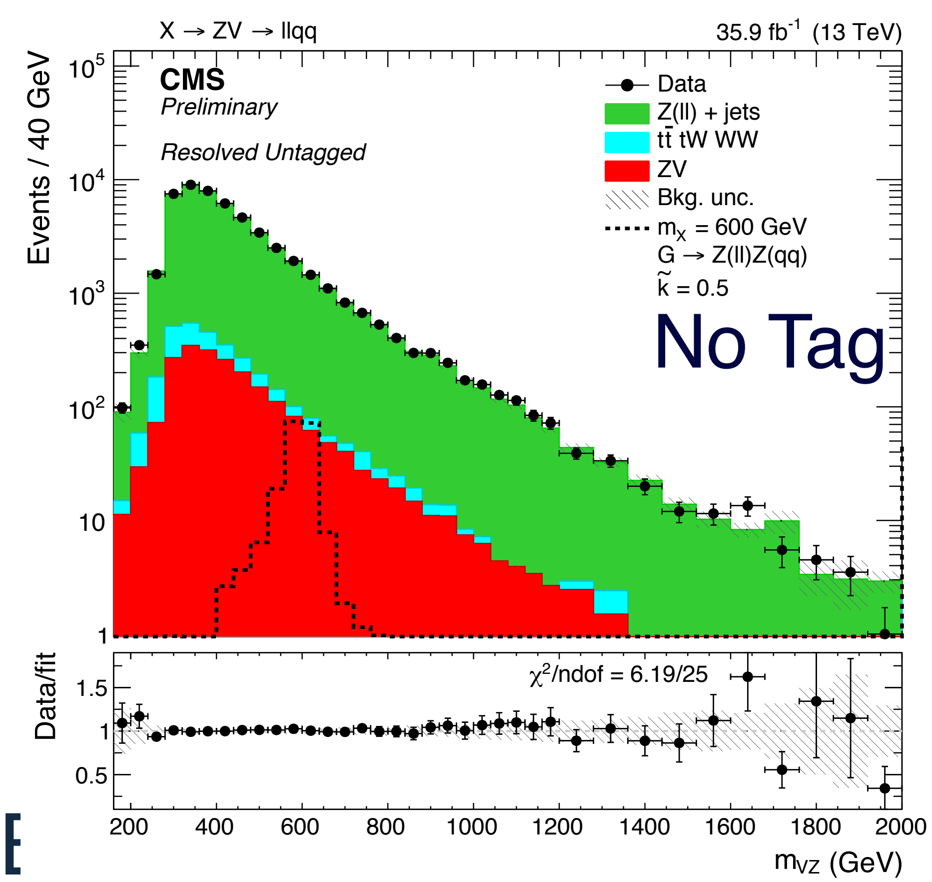
Merged

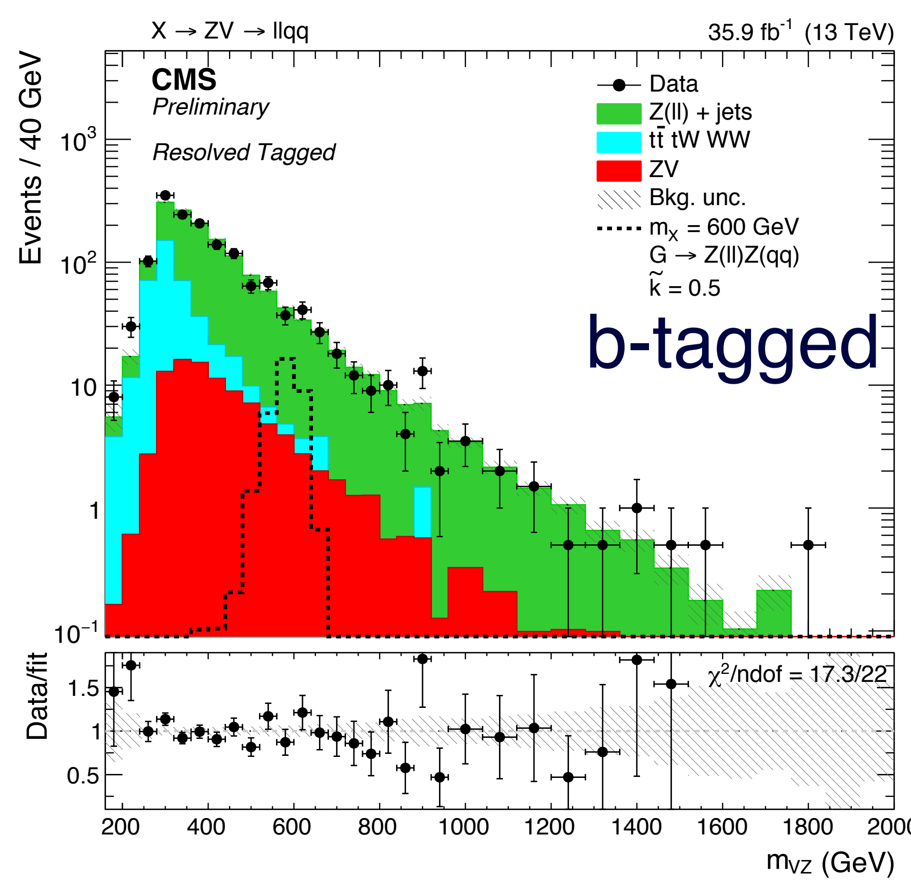




Merged

Resolved





Resolved

X→ZV: Systematic Uncertainties

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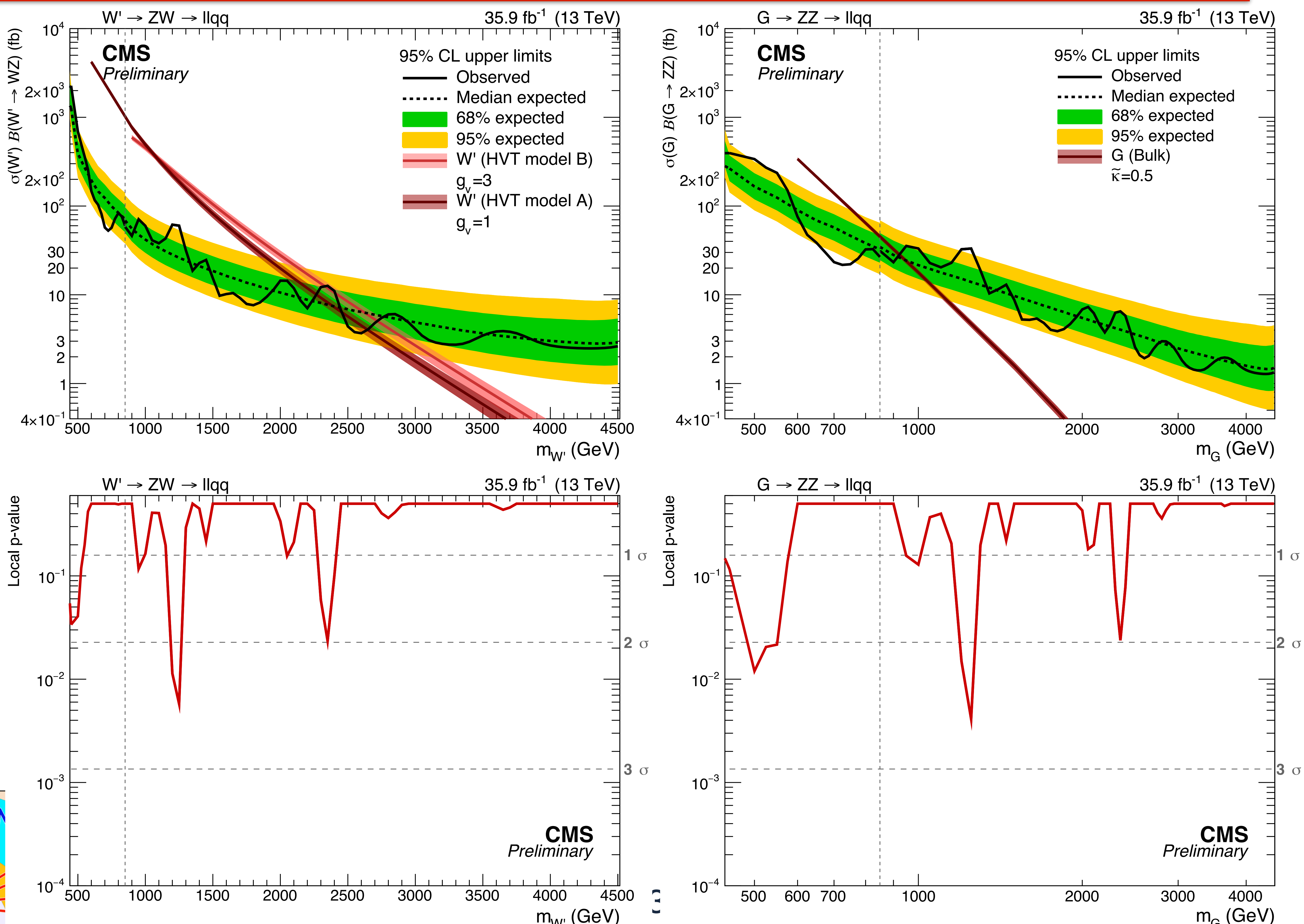
	High-mass		Low-mass		Low-mass	
	Merged		Merged		Resolved	
Source	Background	Signal	Background	Signal	Background	Signal
electron trigger and ID	2.0–3.0%		2.0%		2.0%	
muon trigger and ID	1.5–3.0%		1.5%		1.5%	
electron energy scale	-	1.0%	0.8%	0.1–0.5%	1.3%	1.2–2.5%
muon momentum scale	-	0.5–2%	0.6%	0.1–0.4%	1.4%	0.2–2.0%
jet energy scale	0.1–0.5%	0.1%	1.0%	0.3–0.6%	1.3%	0.6–1.8%
jet energy resolution	-	-	0.6%	0.1%	0.2%	0.1–0.2%
b tag SF untagged	-	-	0.2%	0.3–0.4%	0.1%	0.6%
b tag SF tagged	-	-	2.0%	2.0–2.3%	3.8%	4.1–4.3%
mistag SF untagged	-	-	0.5%	0.5–0.6%	0.4%	0.2–0.4%
mistag SF tagged	-	-	1.5%	0.4–0.6%	4.3%	0.5–1.4%
SM VZ production	12%	-	12%	-	12%	-
SM t quark production	5%	-	4% (eμ)	-	4% (eμ)	-
V identification (τ_{21})	-	11–23%	6% (VZ)	6%	-	-
V identification (extrapolation)	-	2.5–20%	-	2.6–6%	-	-
V mass scale	0.5–2.5%	1.0–2%	0.2% (VZ)	0.5–1.1%	-	-
V mass resolution	5.5%	5–6%	5.6% (VZ)	5.7–6%	-	-
Z+jets normalization	9–15%	-	-	-	-	-
pileup	0.5–4%	0.4%	0.5%	0.1–0.3%	0.1%	0.3–0.5%
PDFs	0.3–1.5%	0.5%	-	1.5–1.6%	-	0.3–1.1%
QCD scale	2% (VZ), 15% (Top)	1.0–3%	-	0.1–0.3%	-	0.2–0.3%
luminosity	2.5%		2.5%		2.5%	

X→ZV: Limits and PValues



X→ττqq(bb) Background Estimation

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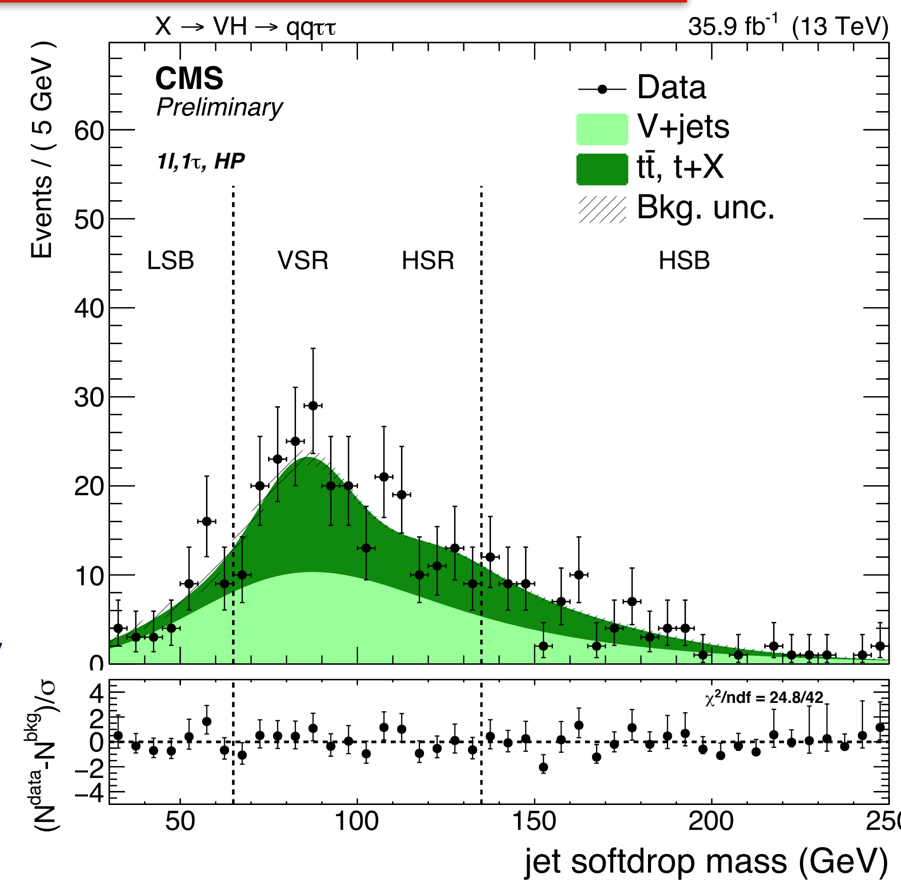
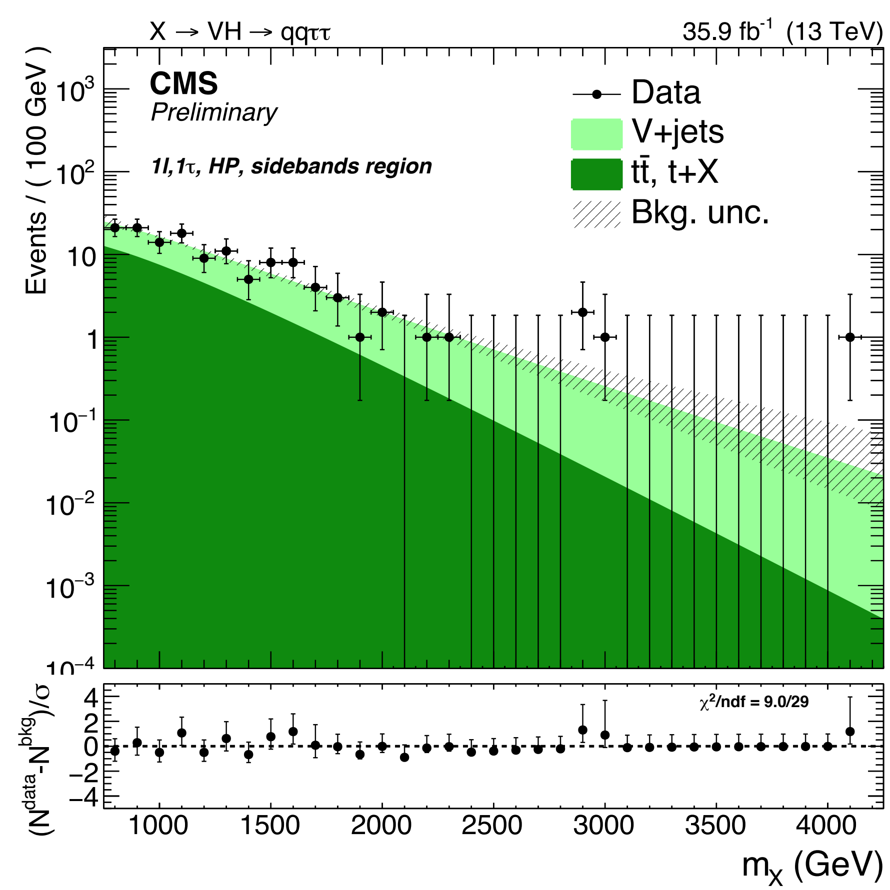
- Primary background are $t\bar{t}$, W/Z+jets production
  - Single top, diboson, and QCD multijet production are secondary backgrounds
- $t\bar{t}$ and single top background normalization determined from b-tag control region
- W/Z+Jets background normalization determined by looking in the low and high m_{jj} sideband regions
  - An analytic function is fit using the sideband data and is used to normalize the W/Z+Jet background in the signal region
  - An alternative function is also fit, and the difference, along with statistical uncertainty, is take as a systematic





X→ττqq(bb) Single Lepton Results

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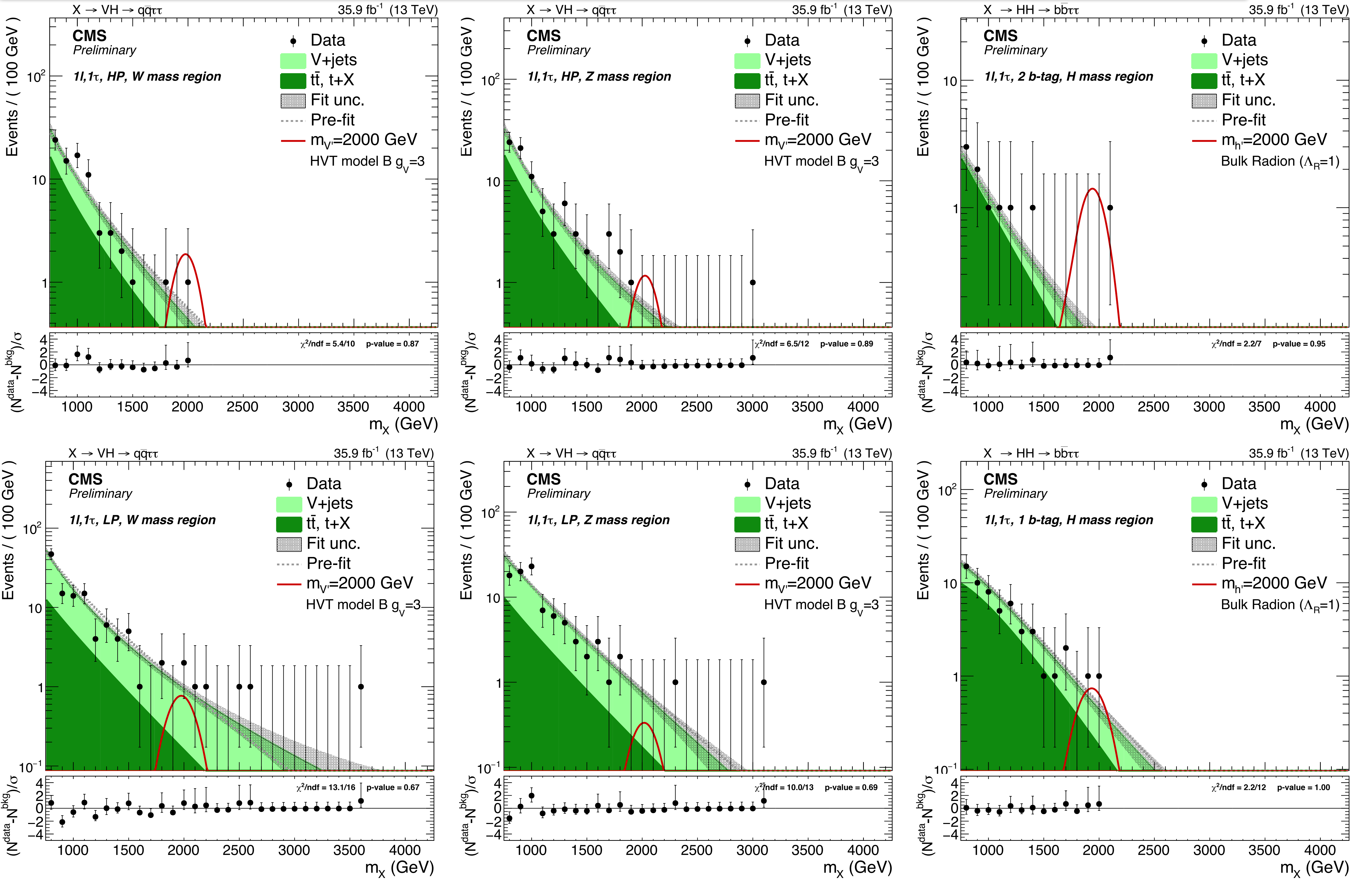
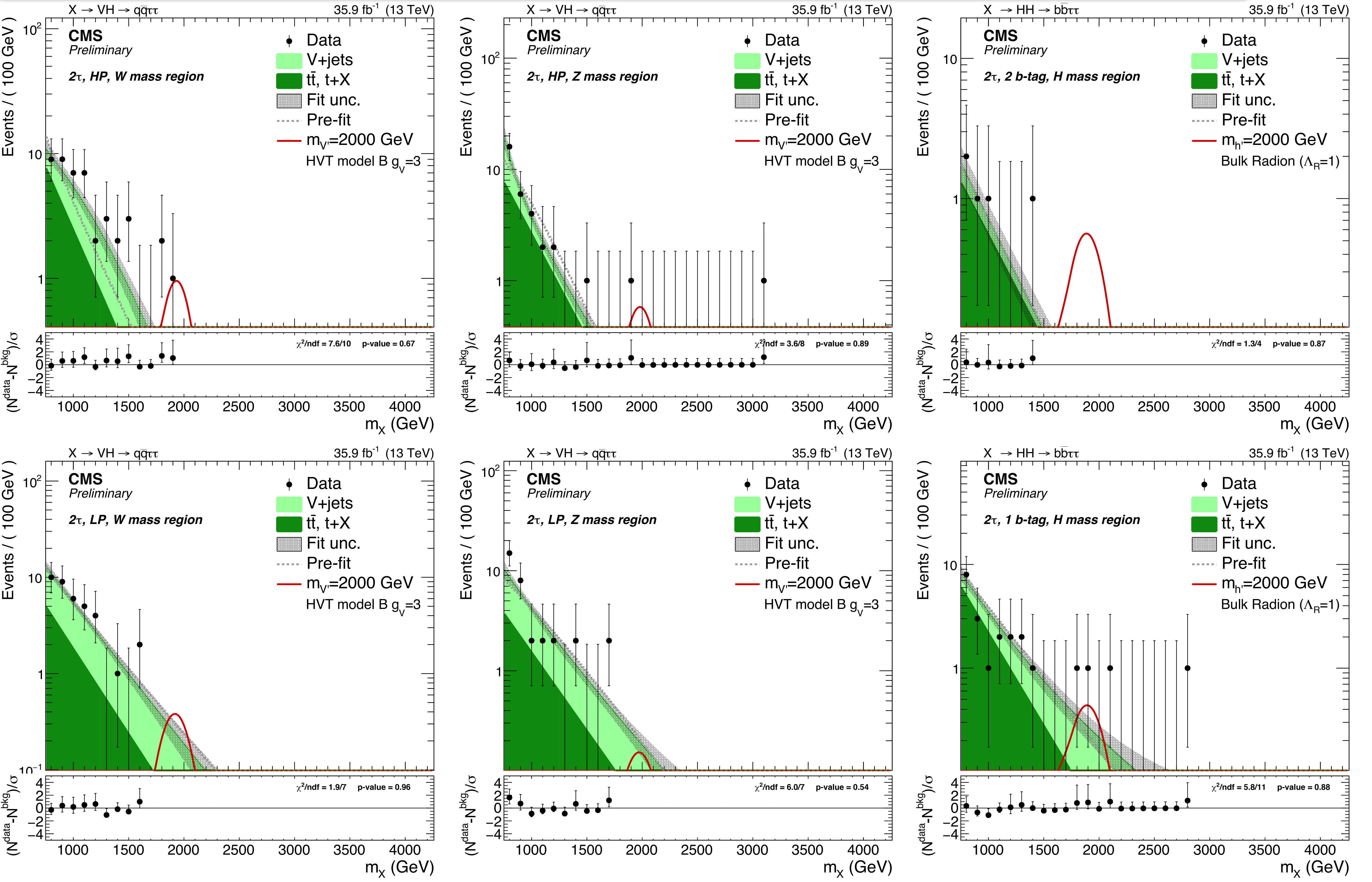


X→ττqq(bb) All Hadronic Results



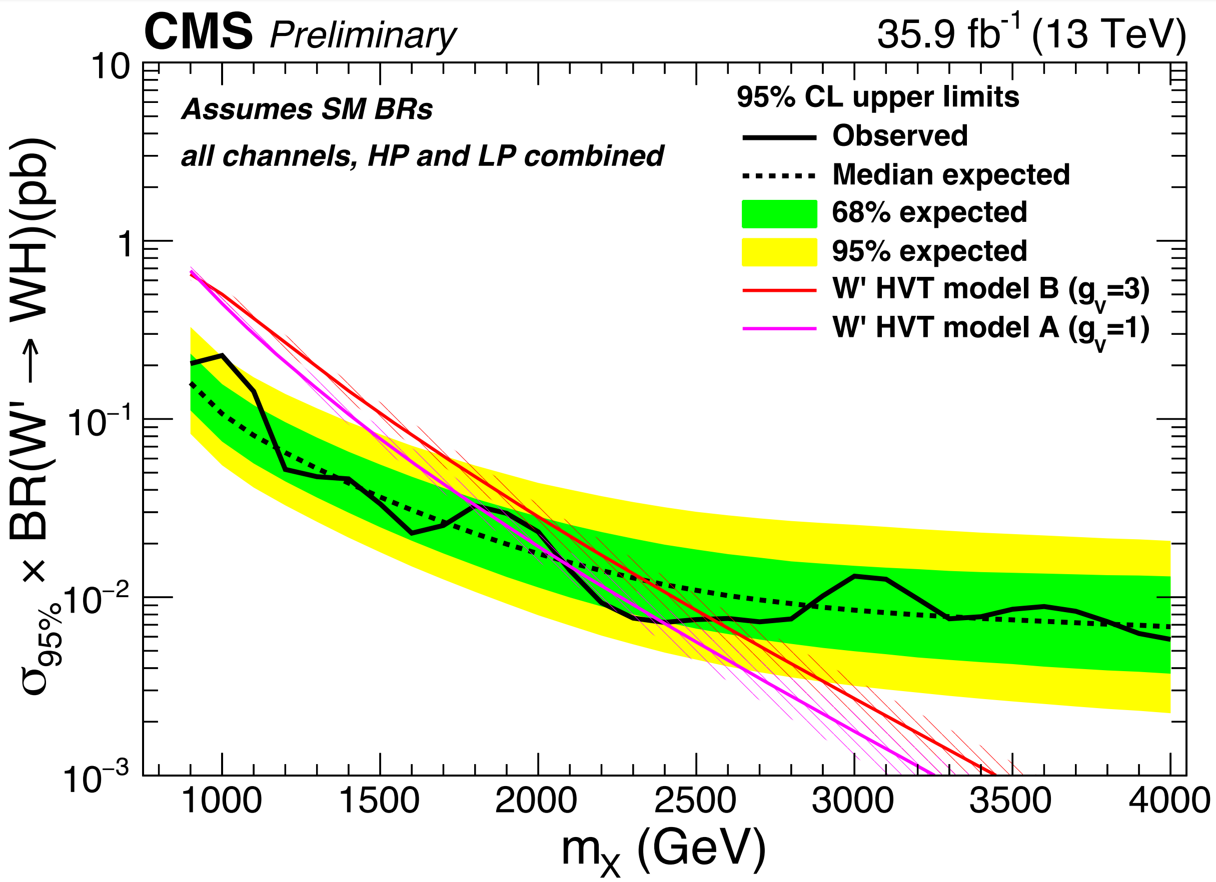
X→ττqq(bb) Yields

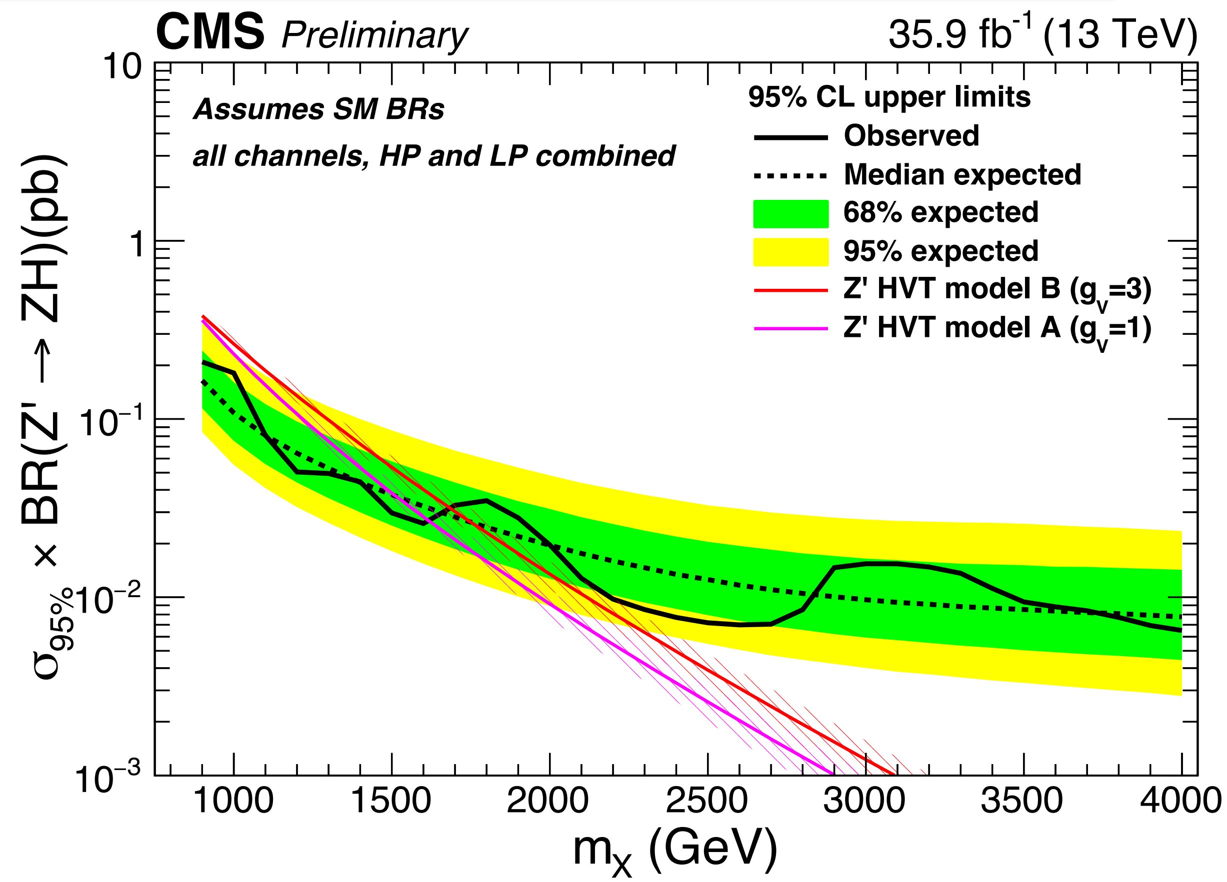
Category			V+jets (± fit)(± alt)	Top	Total exp. events	Obs. events
W region	HP	$\ell\tau_h$	$37.9 \pm 6.5 \pm 12.2$	37.8 ± 0.6	75.7 ± 13.8	78
		$\tau_h\tau_h$	$13.0 \pm 3.2 \pm 0.2$	16.0 ± 1.8	29.0 ± 3.7	45
	LP	$\ell\tau_h$	$105.3 \pm 6.8 \pm 9.0$	34.2 ± 0.9	139.5 ± 11.4	120
		$\tau_h\tau_h$	$27.0 \pm 3.3 \pm 3.0$	12.3 ± 0.6	39.3 ± 4.5	37
Z region	HP	$\ell\tau_h$	$39.9 \pm 6.1 \pm 7.9$	42.4 ± 1.0	82.3 ± 10.0	82
		$\tau_h\tau_h$	$13.7 \pm 3.0 \pm 2.5$	18.0 ± 1.8	31.6 ± 4.3	33
	LP	$\ell\tau_h$	$73.5 \pm 4.8 \pm 6.1$	29.1 ± 1.9	102.6 ± 8.0	92
		$\tau_h\tau_h$	$19.1 \pm 2.3 \pm 2.5$	10.4 ± 0.8	29.5 ± 3.5	33
H region	2 b-tag	$\ell\tau_h$	$2.4 \pm 0.9 \pm 0.4$	6.9 ± 0.6	9.2 ± 1.2	10
		$\tau_h\tau_h$	$1.1 \pm 0.6 \pm 0.0$	3.8 ± 1.8	4.9 ± 1.9	5
	1 b-tag	$\ell\tau_h$	$29.3 \pm 3.5 \pm 6.6$	37.3 ± 1.2	66.6 ± 7.5	56
		$\tau_h\tau_h$	$11.5 \pm 2.2 \pm 2.6$	15.4 ± 1.7	26.9 ± 3.8	23

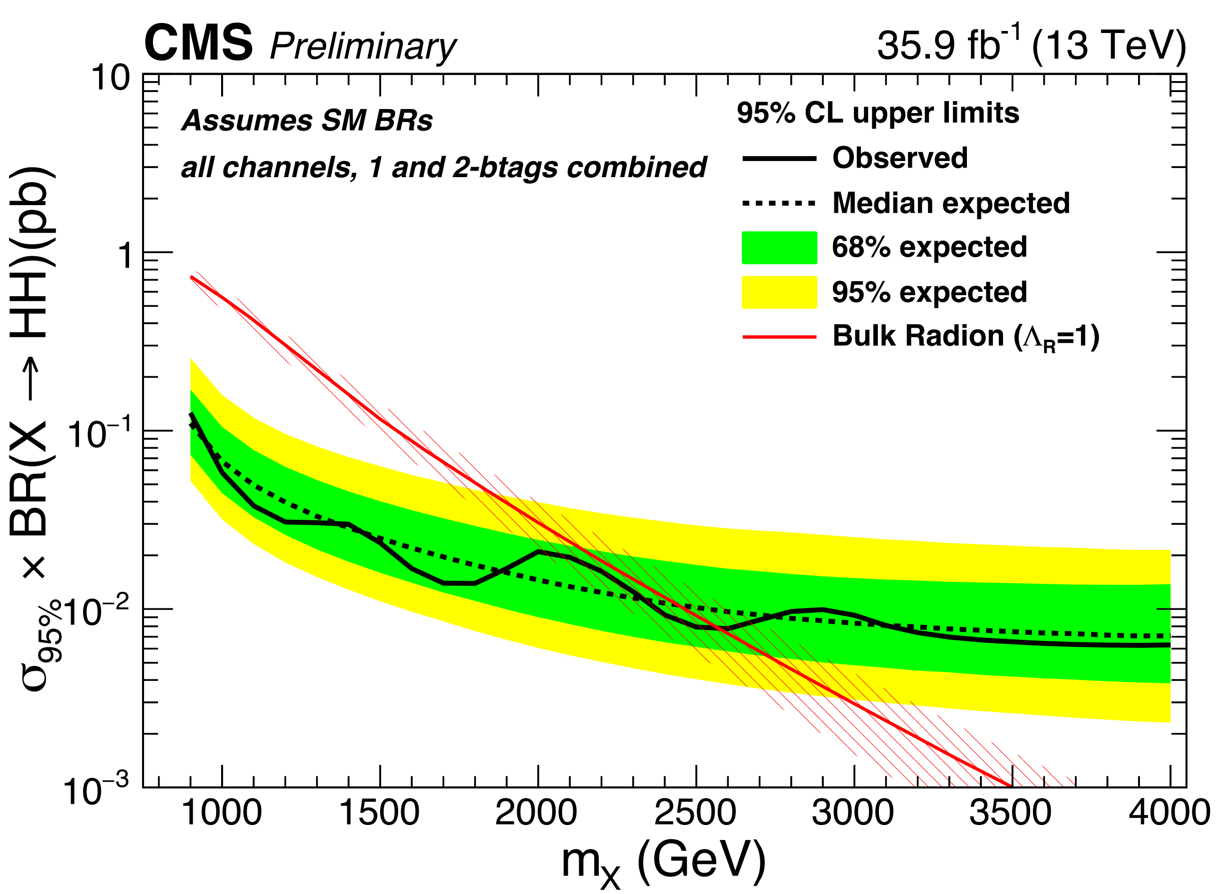
X→ττqq(bb) Systematics

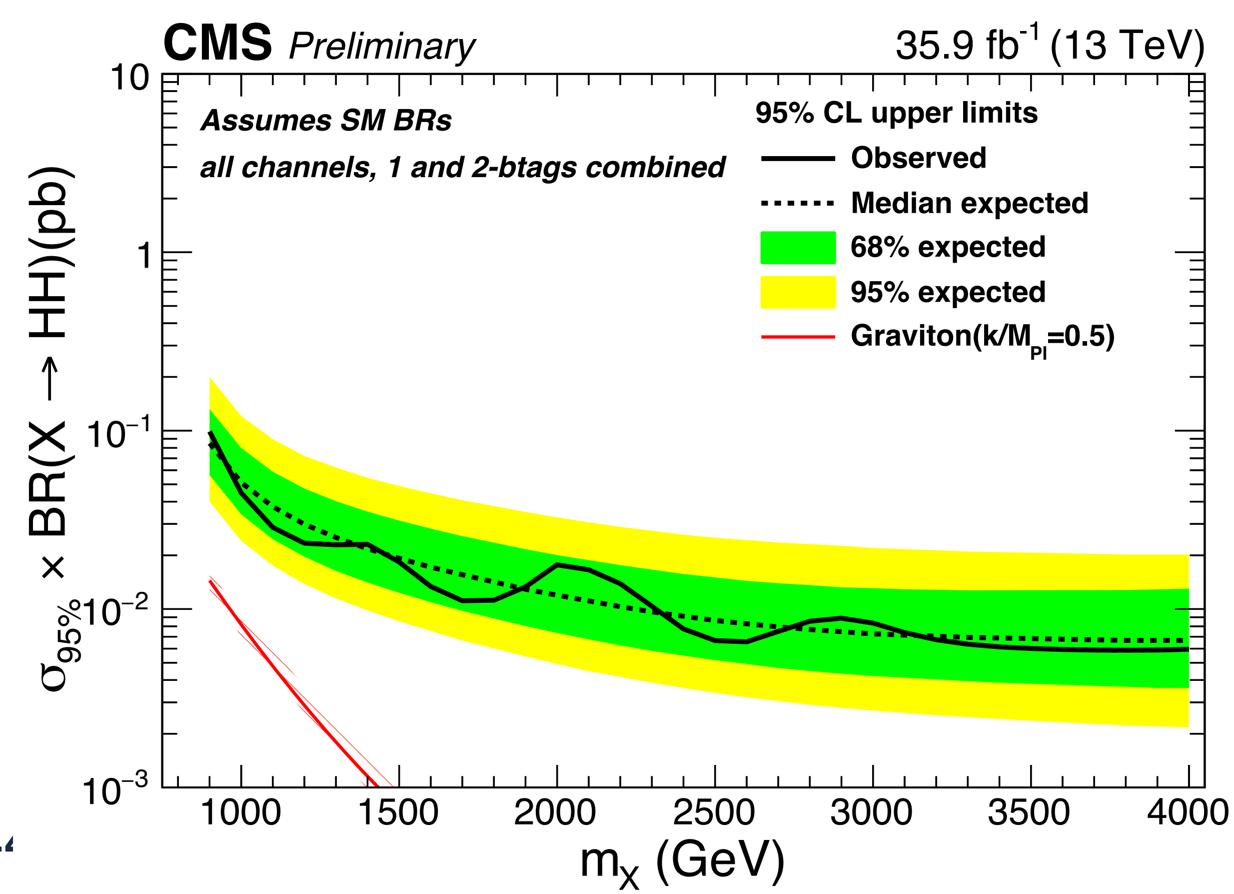
	shape	V+jets	$t\bar{t}$, t+X	Signal
α-function	✓	✓	-	-
Bkg. normalization		11–60%	2–38%	-
Top scale factors		-	5–14%	-
jet energy scale	✓	-	-	✓
jet energy resolution	✓	-	-	✓
jet mass scale		-	-	1%
jet mass resolution		-	-	8%
V tagging		-	-	6%(HP)–11%(LP)
V tagging extr.		-	-	8%–18%(HP), 2%–8%(LP)
b-tagging		-	-	3–7% (1b), 3.7–5.4% (2b)
b-tagged jet veto		-	3%	1%
trigger		-	-	2%
leptons Id, Iso		-	-	2%
τ Id		-	-	6–8% ($\ell\tau_h$), 10–13% ($\tau_h\tau_h$)
τ Id pt extr.	✓	-	-	0.5–18% ($\ell\tau_h$), 0.2–30% ($\tau_h\tau_h$)
τ energy scale	✓	-	-	1% ($\ell\tau_h$), $5-3\%$ (τ_h)
pile-up		-	-	0.5%
QCD scales†		-	-	2.5%–12.5%, 10%–19%
PDF scale†		-	-	6%–37% ,10%–64%
PDF acceptance		-	-	0.5%–2%
luminosity		-	-	2.6%

X→ττqq(bb) Limits

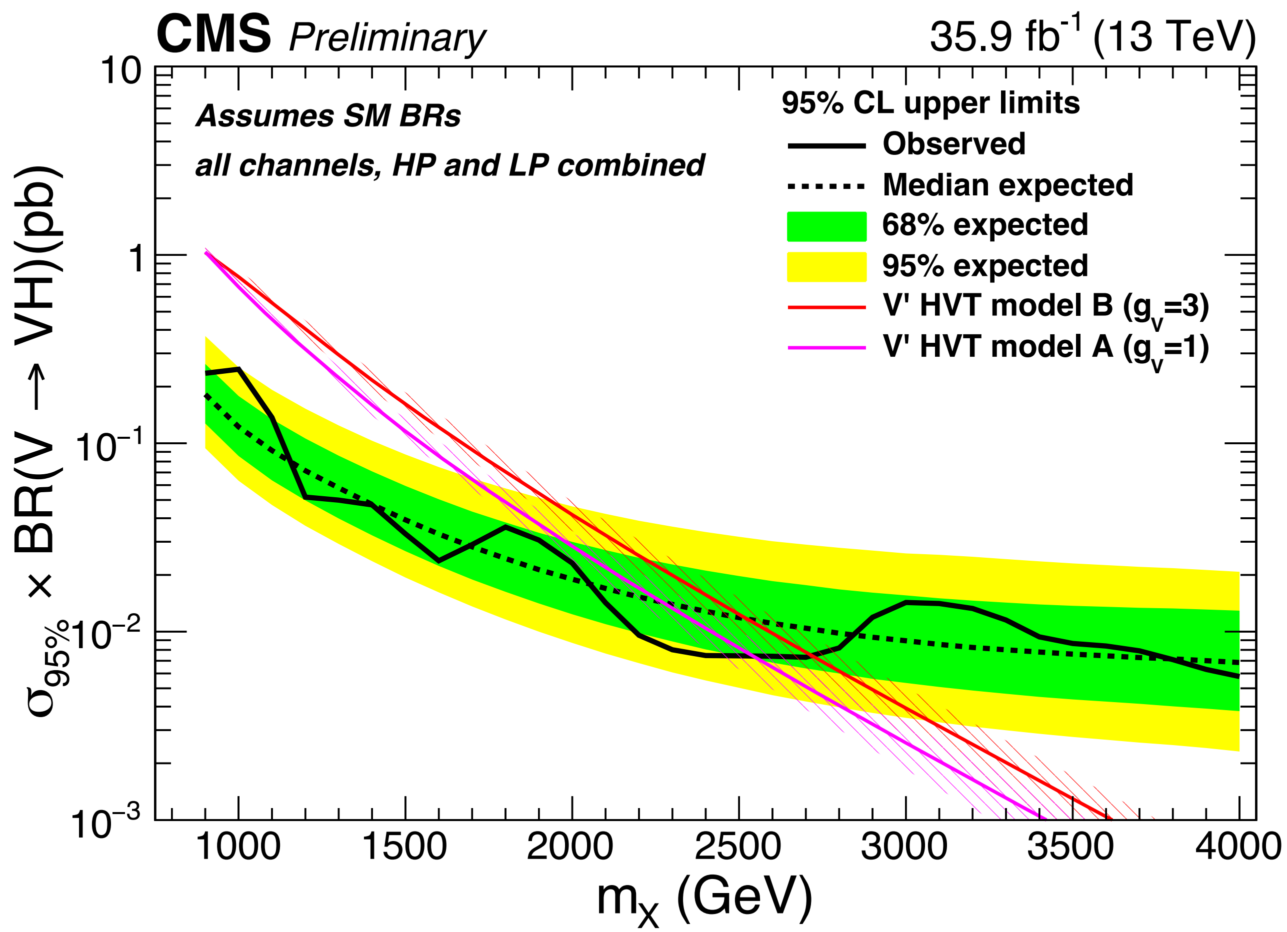


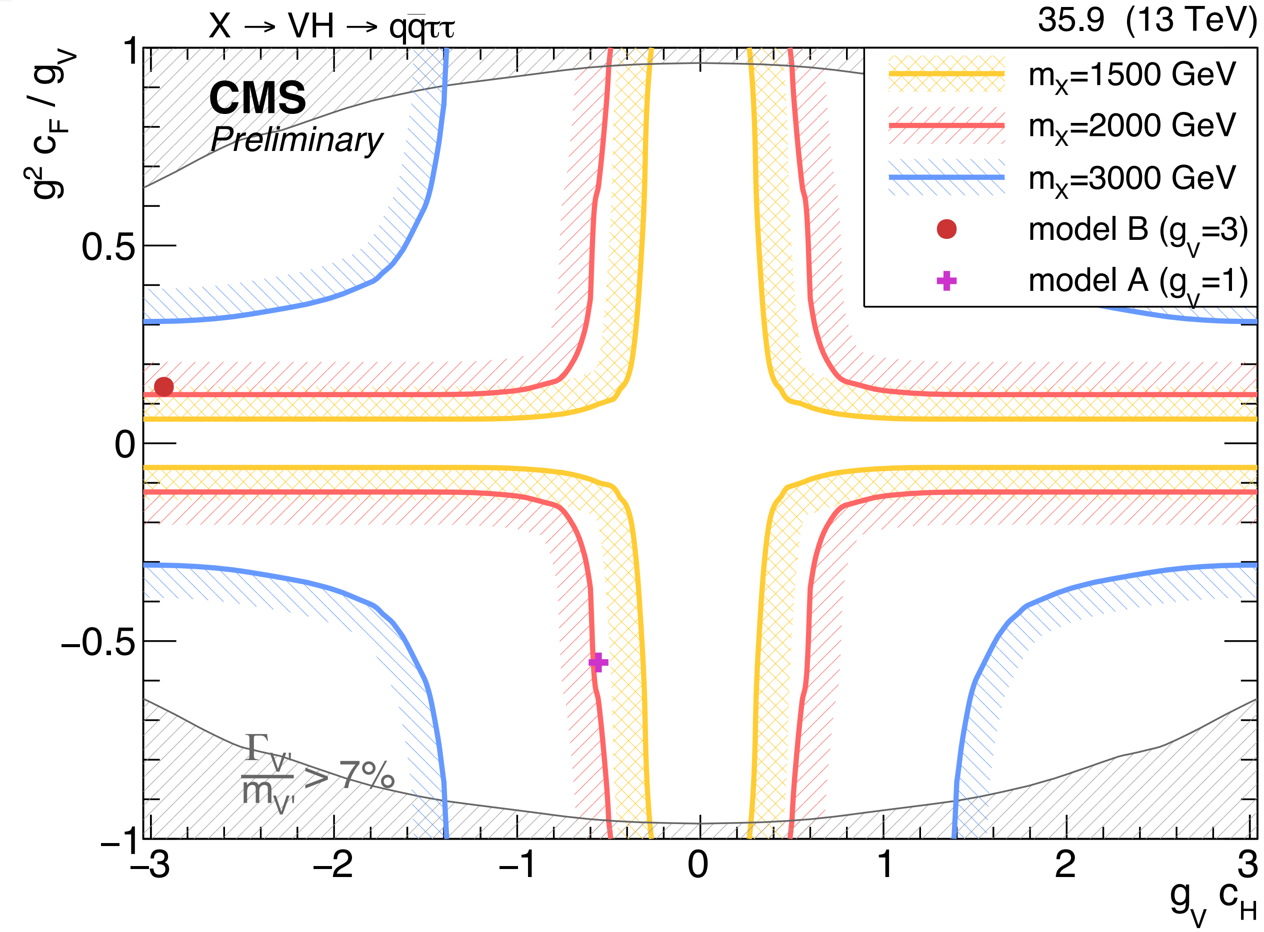






X→ττqq(bb) Limits





- Limits for a generic V′ boson in the HVT model
  - The W′ and Z′ search regions are combined
- Observed limits in the HVT parameter phase space $[g_V c_H, g^2 c_F / g_V]$ for three different masses: 1.5 2.0 and 3.0 TeV

$Z' \to \ell\ell$ Models

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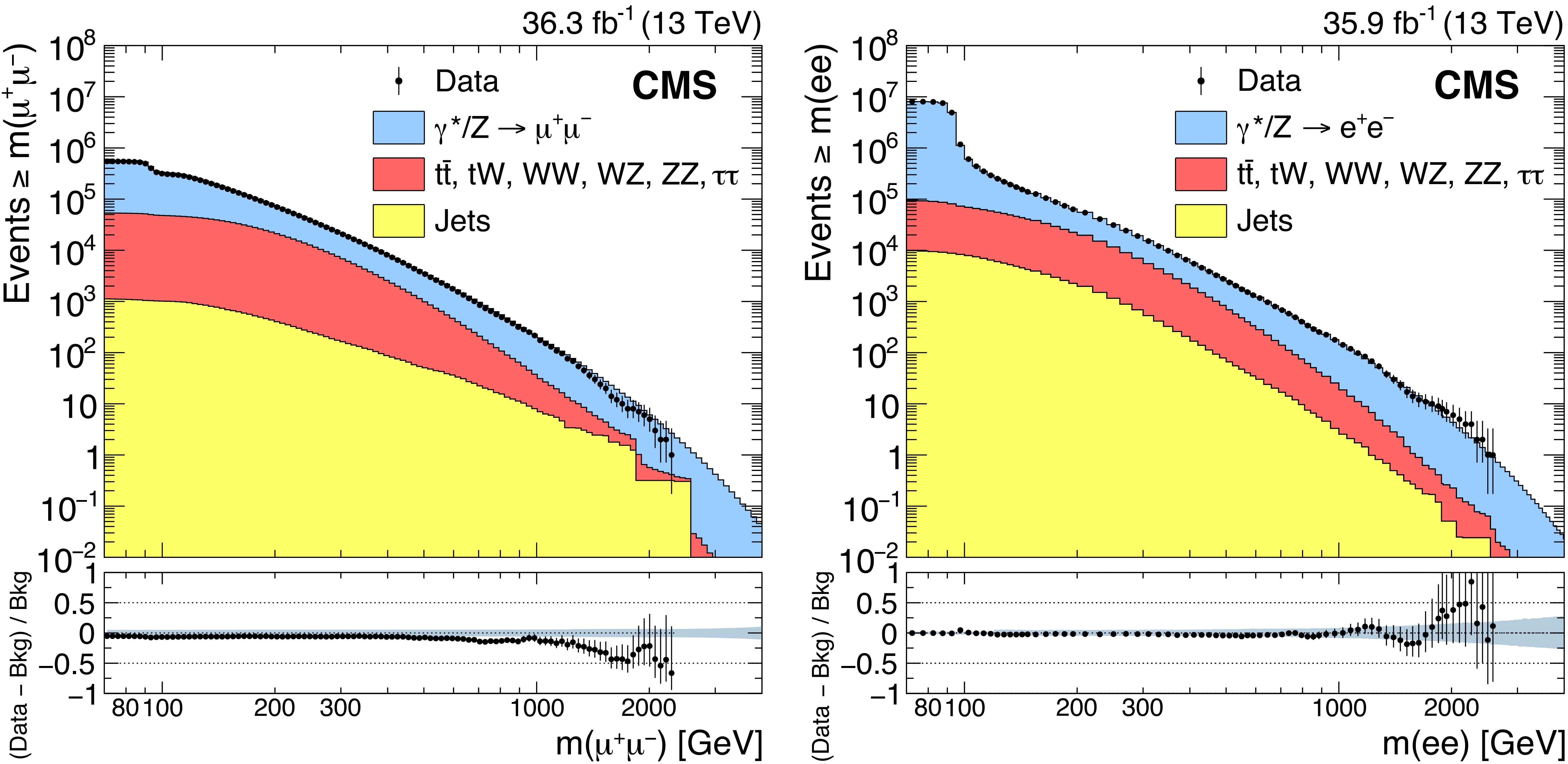
$U'(1)$ model	Mixing angle	$\mathcal{B}(\ell^+\ell^-)$	c_u	c_d	c_u/c_d	$\Gamma_{Z'}/M_{Z'}$
E_6						
$U(1)_\chi$	0	0.061	6.46×10^{-4}	3.23×10^{-3}	0.20	0.0117
$U(1)_\psi$	0.5π	0.044	7.90×10^{-4}	7.90×10^{-4}	1.00	0.0053
$U(1)_\eta$	-0.29π	0.037	1.05×10^{-3}	6.59×10^{-4}	1.59	0.0064
$U(1)_S$	0.129π	0.066	1.18×10^{-4}	3.79×10^{-3}	0.31	0.0117
$U(1)_N$	0.42π	0.056	5.94×10^{-4}	1.48×10^{-3}	0.40	0.0064
LR						
$U(1)_R$	0	0.048	4.21×10^{-3}	4.21×10^{-3}	1.00	0.0247
$U(1)_{B-L}$	0.5π	0.154	3.02×10^{-3}	3.02×10^{-3}	1.00	0.0150
$U(1)_{LR}$	-0.128π	0.025	1.39×10^{-3}	2.44×10^{-3}	0.57	0.0207
$U(1)_Y$	0.25π	0.125	1.04×10^{-2}	3.07×10^{-3}	3.39	0.0235
GSM						
$U(1)_{SM}$	-0.072π	0.031	2.43×10^{-3}	3.13×10^{-3}	0.78	0.0297
$U(1)_{T3L}$	0	0.042	6.02×10^{-3}	6.02×10^{-3}	1.00	0.0450
$U(1)_Q$	0.5π	0.125	6.42×10^{-2}	1.60×10^{-2}	4.01	0.1225

Z′→ℓℓ Cumulative Results (2016)



$Z' \to \ell\ell$ Yields (2016)

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m_{ee} range [GeV]	Observed yield	Total background	Z/γ^*	$t\bar{t}$ + other background	Jet mis-reconstruction
120–400	245 101	$252\,000 \pm 13\,000$	$199\,000 \pm 11\,000$	$47\,700 \pm 2\,100$	5800 ± 2900
400–600	4297	4430 ± 230	2890 ± 150	1400 ± 88	137 ± 69
600–900	943	986 ± 64	739 ± 49	221 ± 17	26 ± 13
900–1300	182	187 ± 14	156 ± 12	26.8 ± 2.3	3.9 ± 1.9
1300–1800	33	34.3 ± 3.4	30.9 ± 3.2	2.8 ± 0.5	0.6 ± 0.3
> 1800	9	7.5 ± 1.1	7.0 ± 1.1	0.30 ± 0.04	0.13 ± 0.07

$m_{\mu^+\mu^-}$ range [GeV]	Observed yield	Total background	Z/γ^*	$t\bar{t}$ + other background	Jet mis-reconstruction
120–400	244 277	$260\,000 \pm 14\,000$	$218\,000 \pm 11\,000$	$40\,900 \pm 3\,500$	800 ± 400
400–600	5912	6290 ± 350	4340 ± 230	1900 ± 160	50 ± 25
600–900	1311	1430 ± 80	1070 ± 60	340 ± 30	20 ± 10
900–1300	244	268 ± 15	220 ± 12	41 ± 4	7 ± 4
1300–1800	41	50 ± 3	42.6 ± 2.5	5.4 ± 0.9	2.1 ± 1.1
> 1800	8	12.1 ± 1.5	9.8 ± 0.7	1.1 ± 0.4	1.2 ± 0.6

$Z' \to \ell\ell$ Yields (2017)

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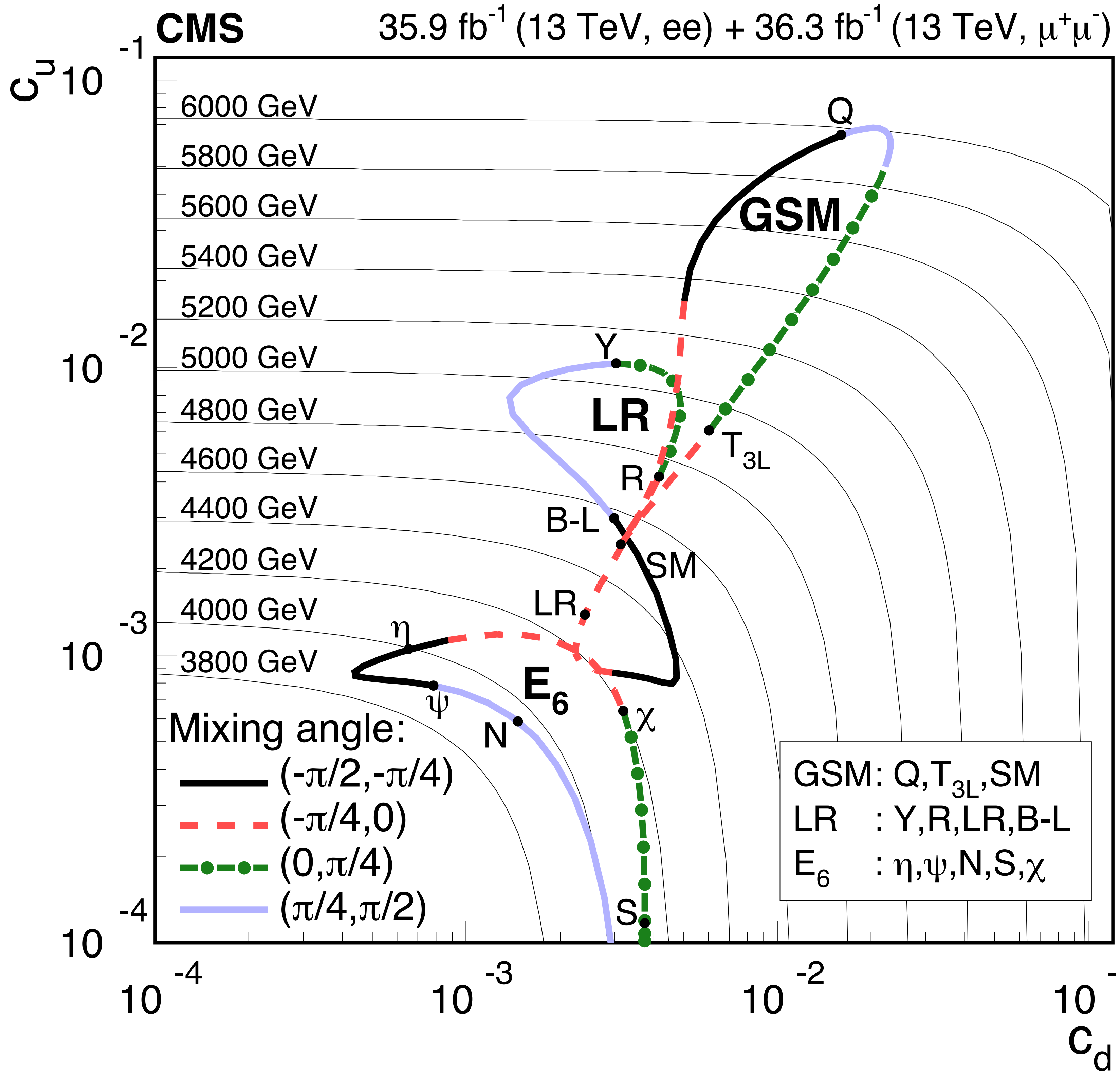
m_{ee} range [GeV]	Observed yield	Total background	DY	$t\bar{t}$ + other prompt bkgd	Multijet
120 – 400	271776	280587 ± 18317	222377 ± 15713	53192 ± 3977	5018 ± 2509
400 – 600	4868	4850 ± 330	3268 ± 217	1455 ± 129	127 ± 63.5
600 – 900	1106	1058 ± 78	829 ± 63	203 ± 18	25 ± 12.5
900 – 1300	193	203 ± 18	176 ± 16	24 ± 3	3.5 ± 1.75
1300 – 1800	44	38 ± 4	35 ± 4	2.2 ± 0.6	0.7 ± 0.35
> 1800	10	8.1 ± 1.2	7.8 ± 1.2	0.2 ± 0.0	0.1 ± 0.05

$Z' \rightarrow \ell\ell$ Limits

- Limits in the (cd, cu) plane obtained by recasting the combined limit at 95% CL on the Z′ boson cross section from dielectron and dimuon channels
- For a given Z′ boson mass, the cross section limit results in a solid thin black line. These lines are labelled with the relevant Z′ boson masses
- The closed contours representing the GSM, LR, and E6 model classes are composed of thick line segments
- Each point on a segment corresponds to a particular model, and the location of the point gives the mass limit on the relevant Z′ boson



Z′→ℓℓ Limits and PValues

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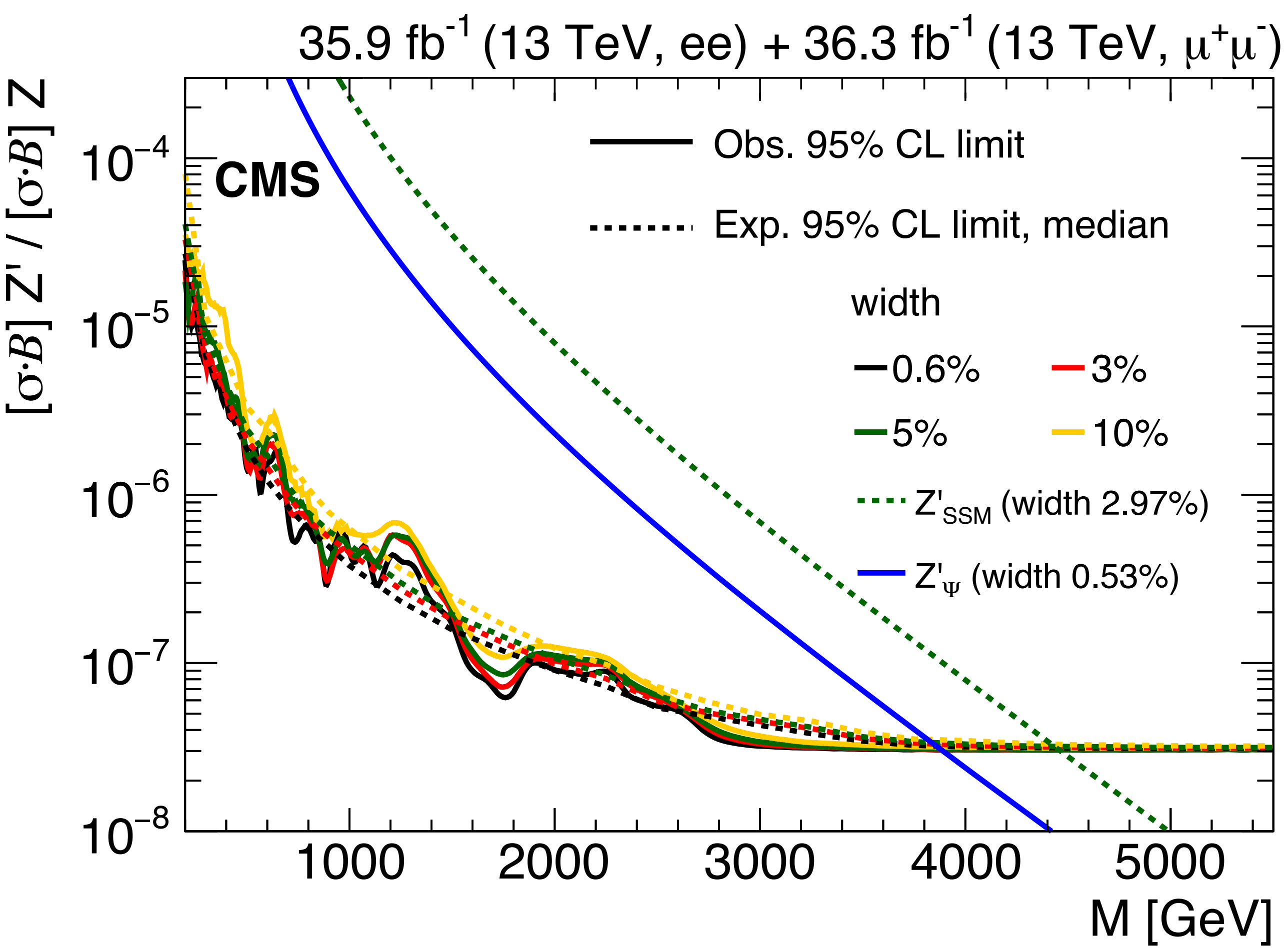

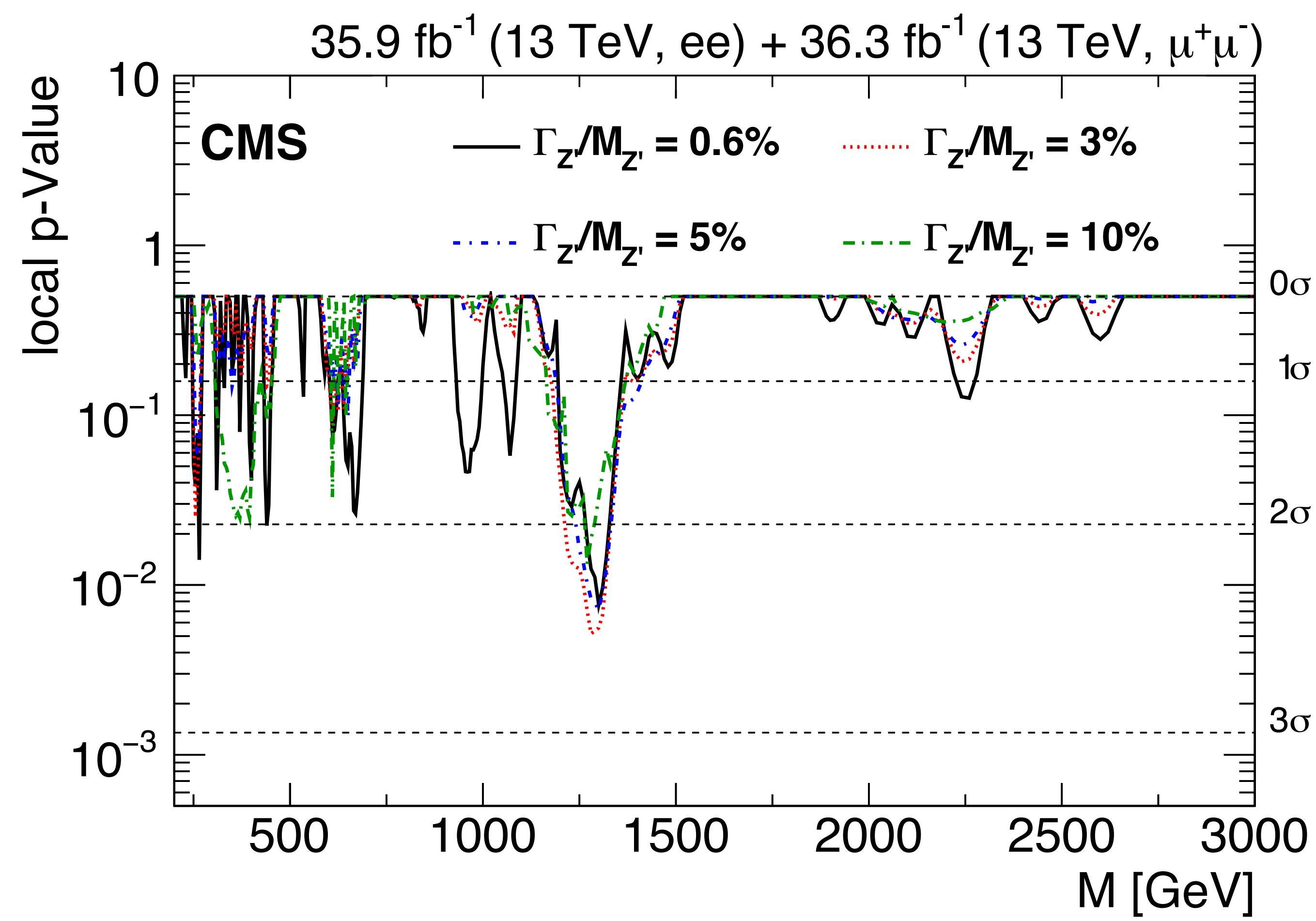

$Z \to \ell\ell$: Dark Matter Limits

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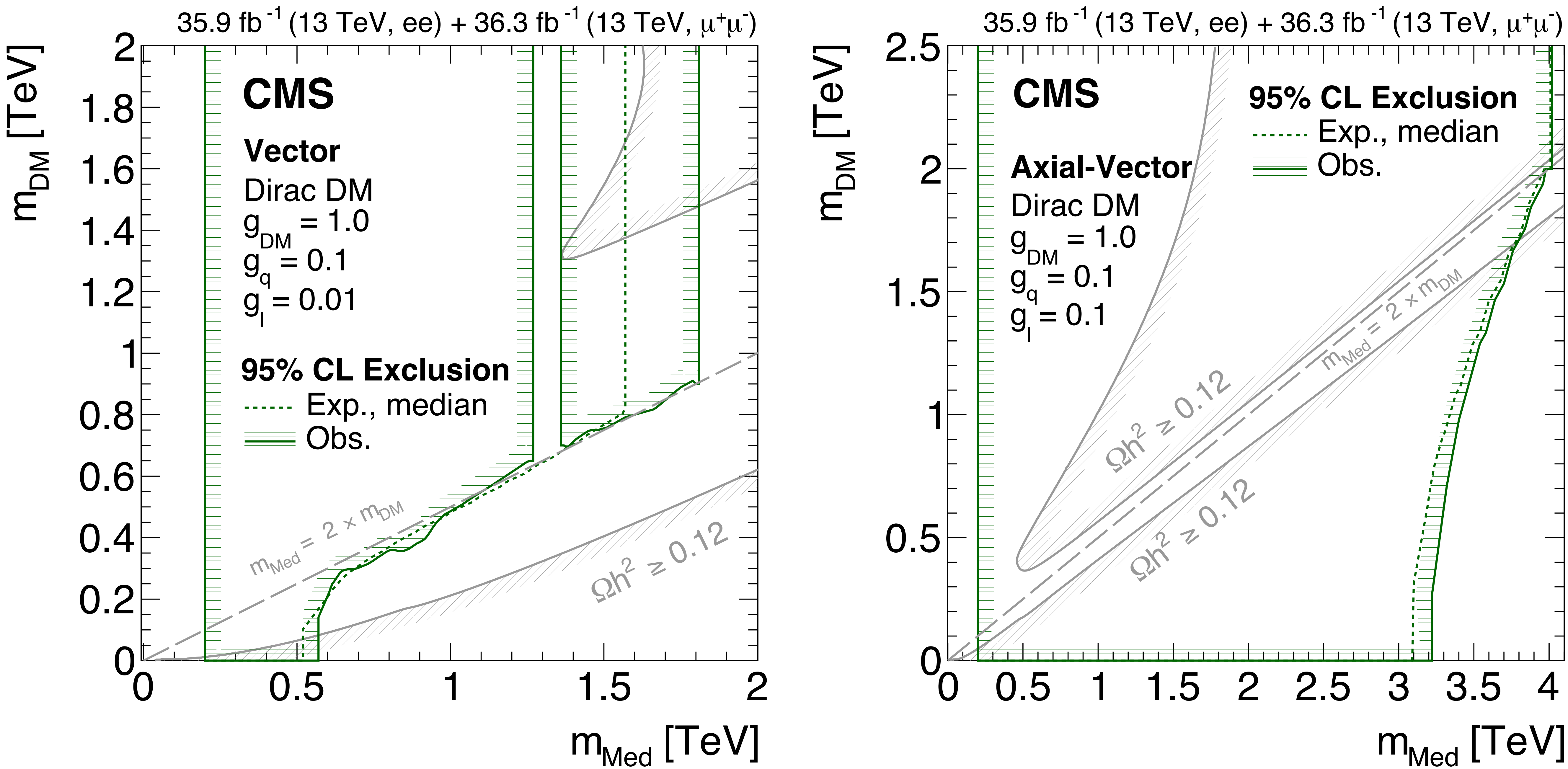
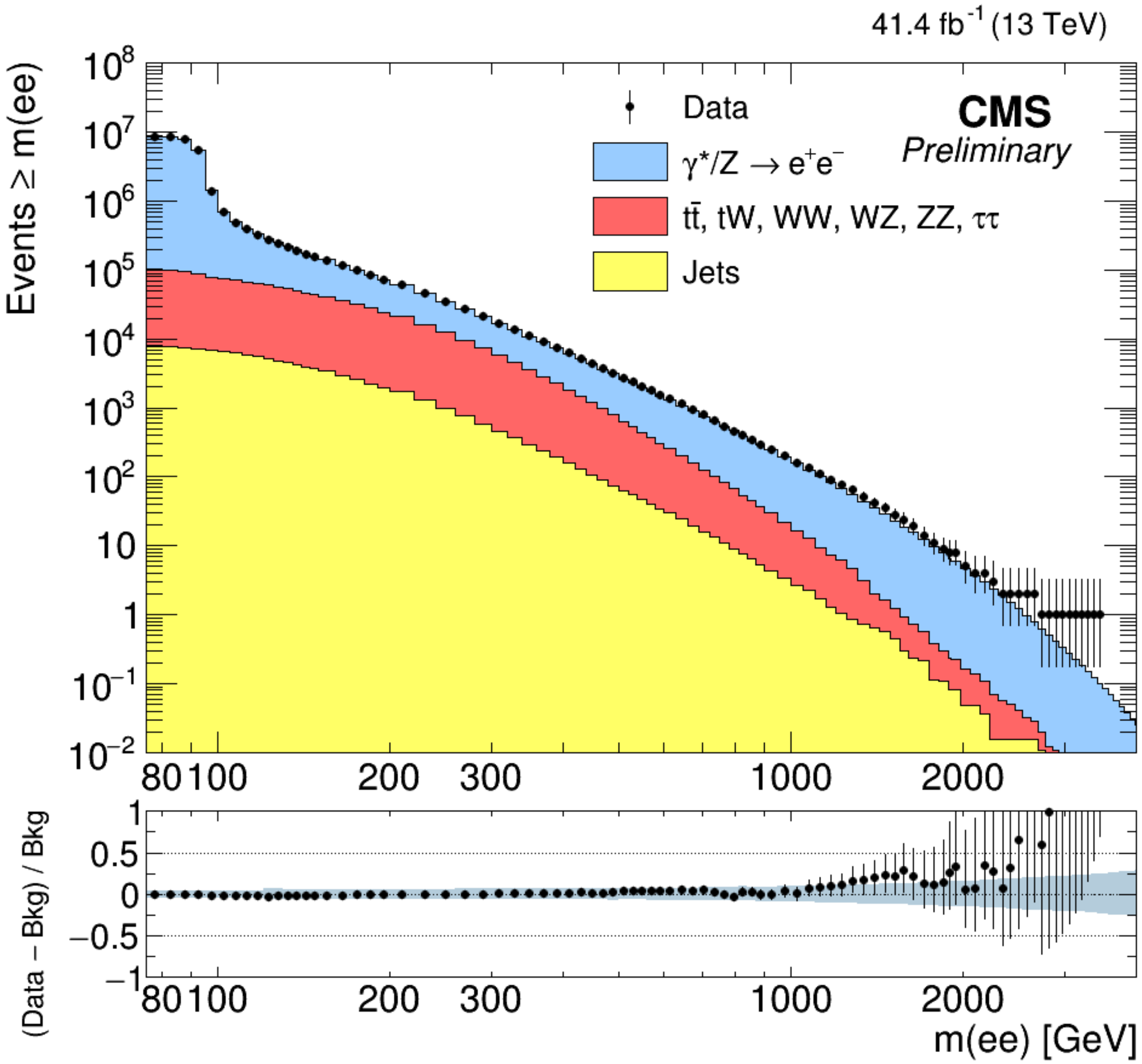
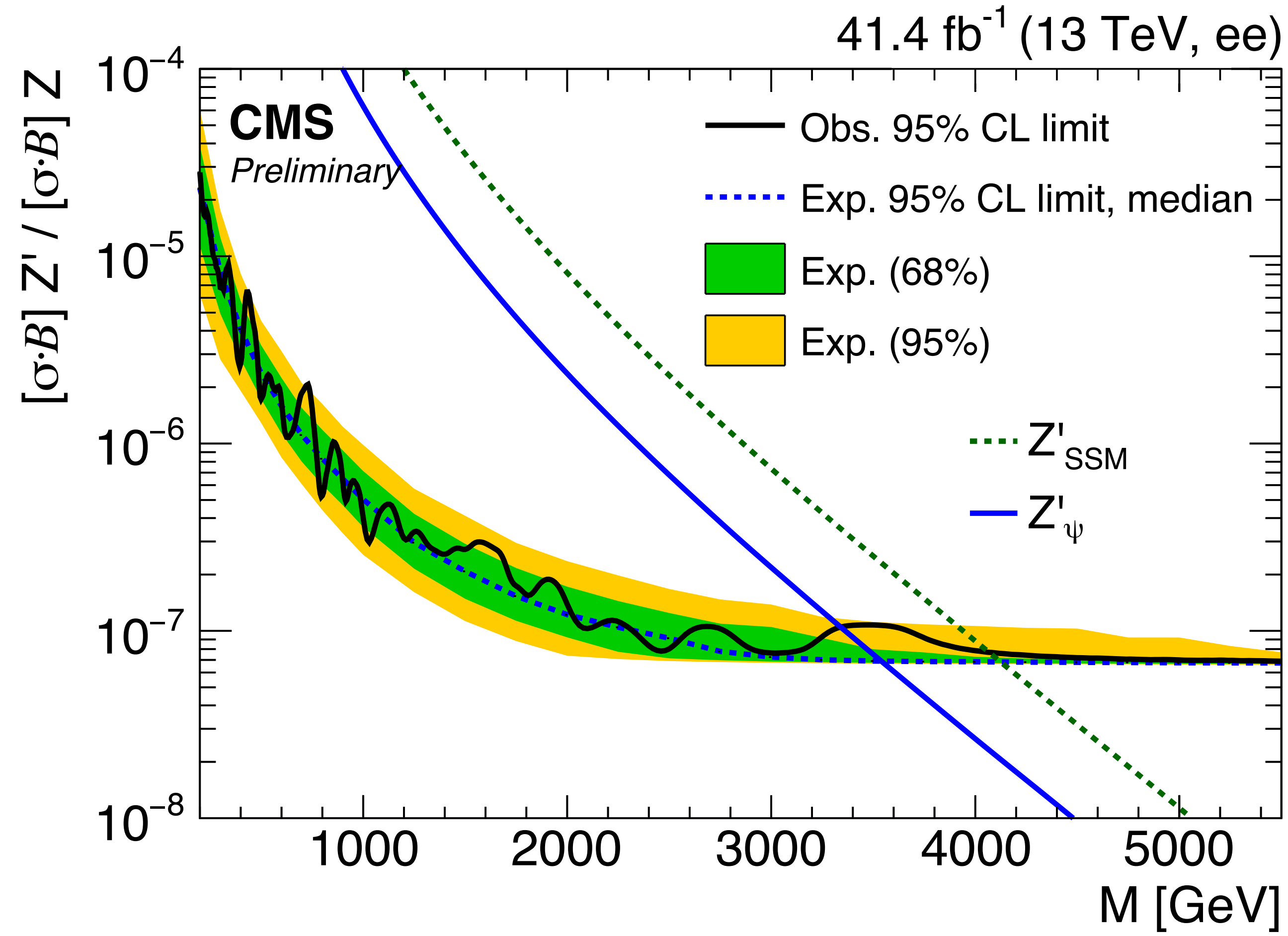


- Simplified vector mediator is excluded between 0.6 and 1.8 GeV, depending on m_{DM}
- Simplified axial-vector mediator is excluded between 3.0 and 4.0 TeV

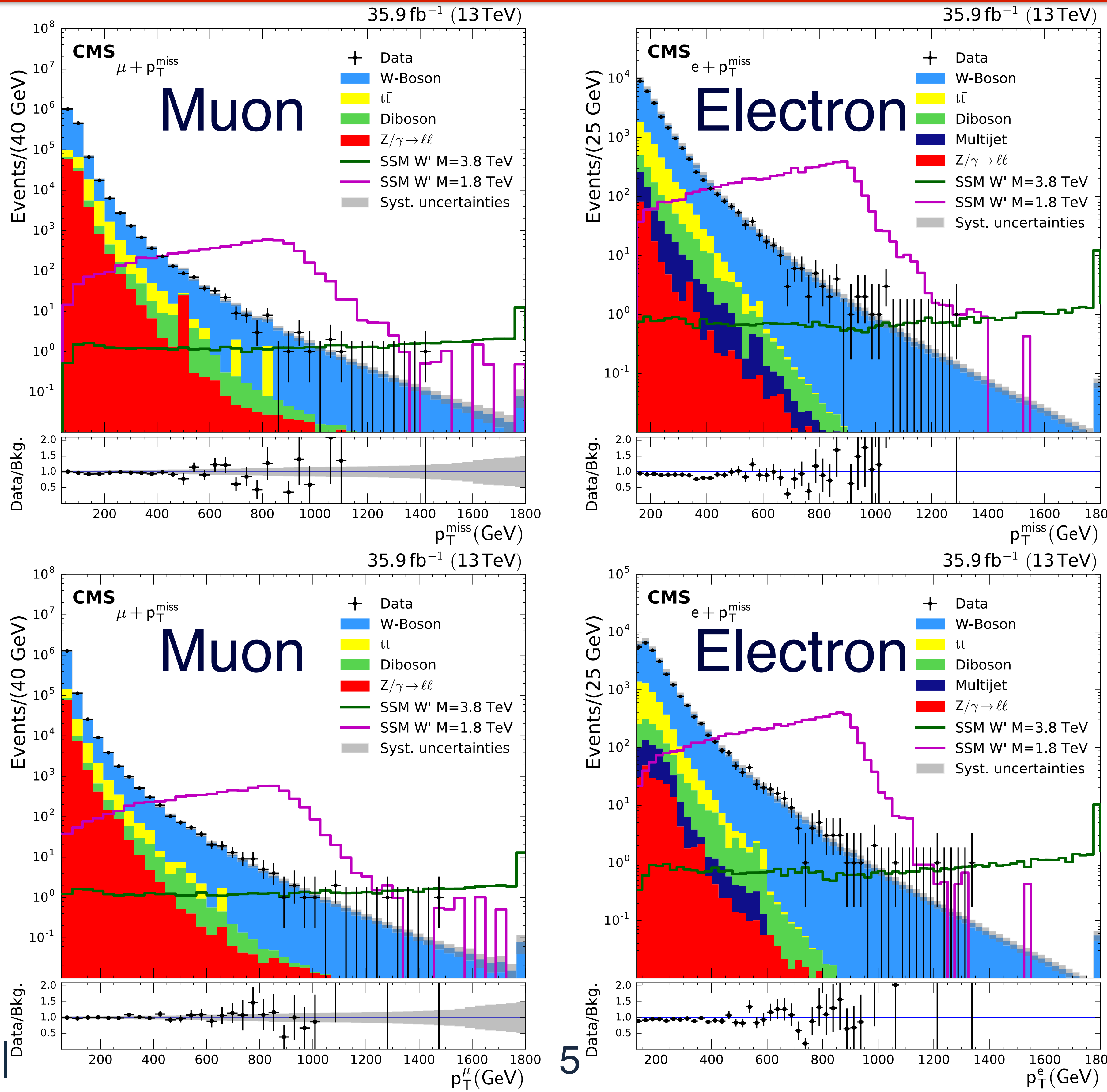
$Z' \to \ell\ell$ Results





W′→ℓν: Kinematics

MET



MET

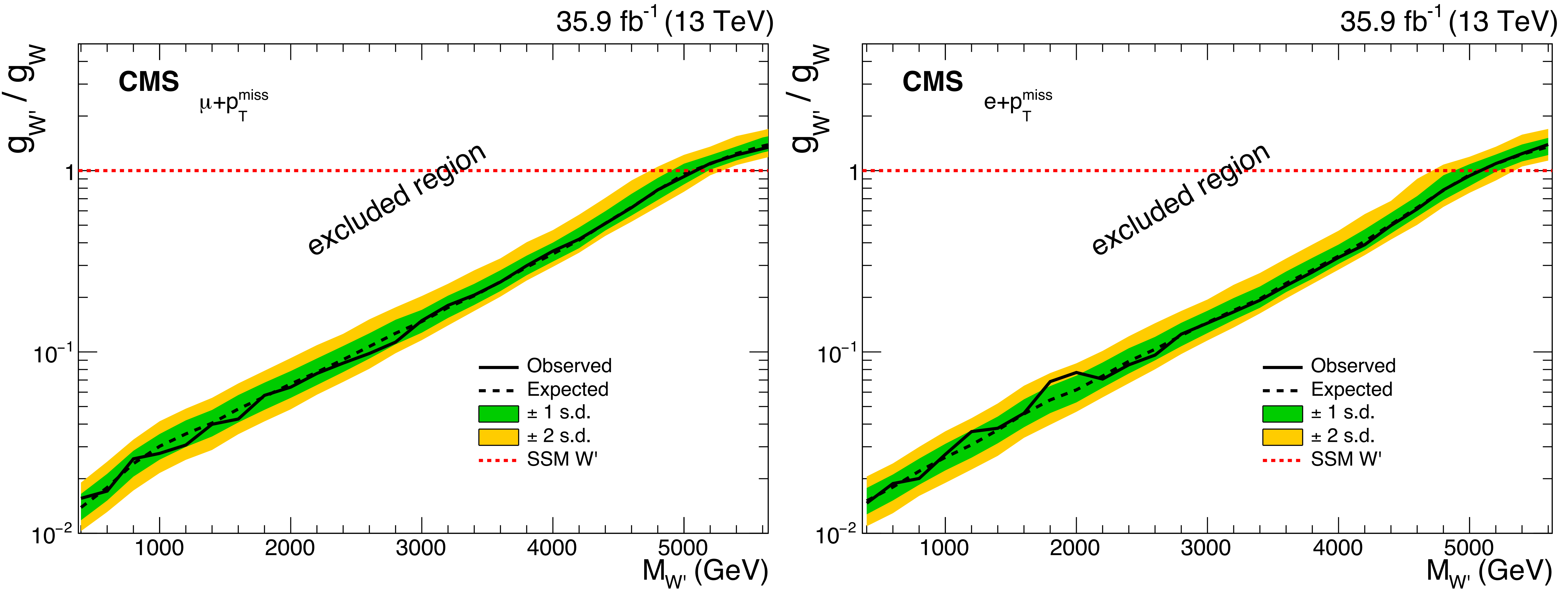
p_T

p_T

W′→ℓν: Yields

	$M_T > 1$ TeV	$M_T > 2$ TeV	$M_T > 3$ TeV	$M_T > 4$ TeV
Electron data	200	2	0	0
Sum of SM backgrounds	213 ± 28	5.00 ± 0.96	0.260 ± 0.077	0.0163 ± 0.0078
SSM W′ M = 1.8 TeV	5040 ± 770	25.9 ± 5.8	0.43 ± 0.44	0 ± 0
M = 2.4 TeV	1180 ± 200	560 ± 100	1.14 ± 0.44	0 ± 0
M = 3.8 TeV	53 ± 13	40 ± 11	23.9 ± 8.4	0.44 ± 0.25
M = 4.2 TeV	23.3 ± 7.3	17.6 ± 6.5	11.8 ± 5.4	3.4 ± 2.2
Muon data	208	4	0	0
Sum of SM backgrounds	217 ± 20	6.0 ± 1.2	0.27 ± 0.21	0.02 ± 0.02
SSM W′ M = 1.8 TeV	5345 ± 530	96 ± 14	2.5 ± 1.2	0 ± 0
M = 2.4 TeV	1282 ± 120	577 ± 85	2.4 ± 1.2	0.10 ± 0.05
M = 3.8 TeV	57 ± 6	42 ± 6	24 ± 12	2 ± 1
M = 4.2 TeV	25 ± 3	19 ± 3	12 ± 6	3.6 ± 1.8

W′→ℓν: Limits on $g_{W'}/g_W$



W′→ℓν: Split UED W_{KK} Limits

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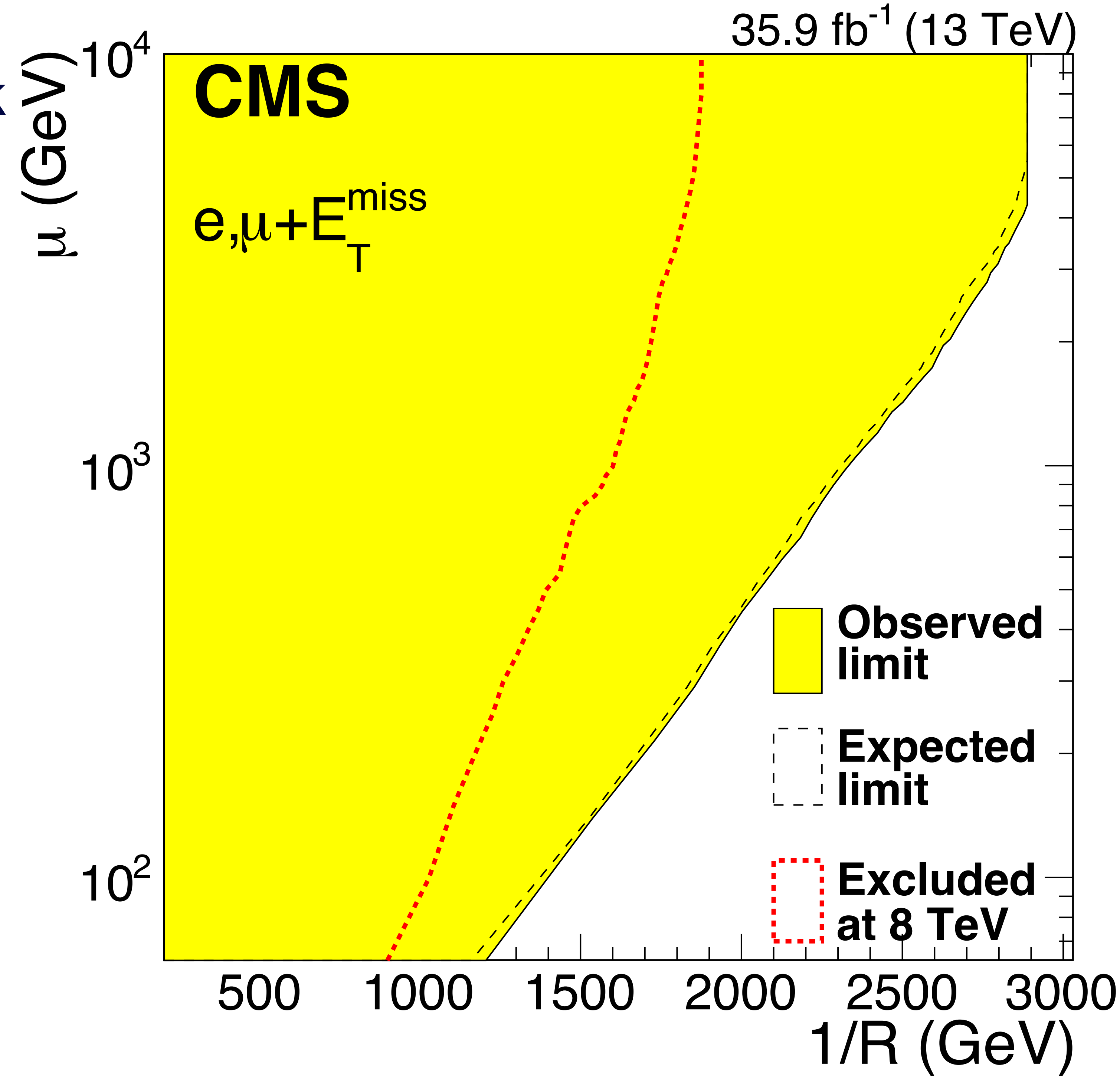
- The UED W_{KK} limits are parametrized in terms of the bulk mass parameter (μ) and the radius of the extra dimension (R)
- The lower limits on the W'_{SSM} can be directly translated into into bounds on the split-UED parameter space when n=2
- The limits on 1/R is 2.9 TeV when μ > 4 TeV
  - The limit drops to 1.2 TeV as μ is reduced
- Substantial improvement when compared to 8 TeV result



W′→ℓν: RPV τ̃ Limits

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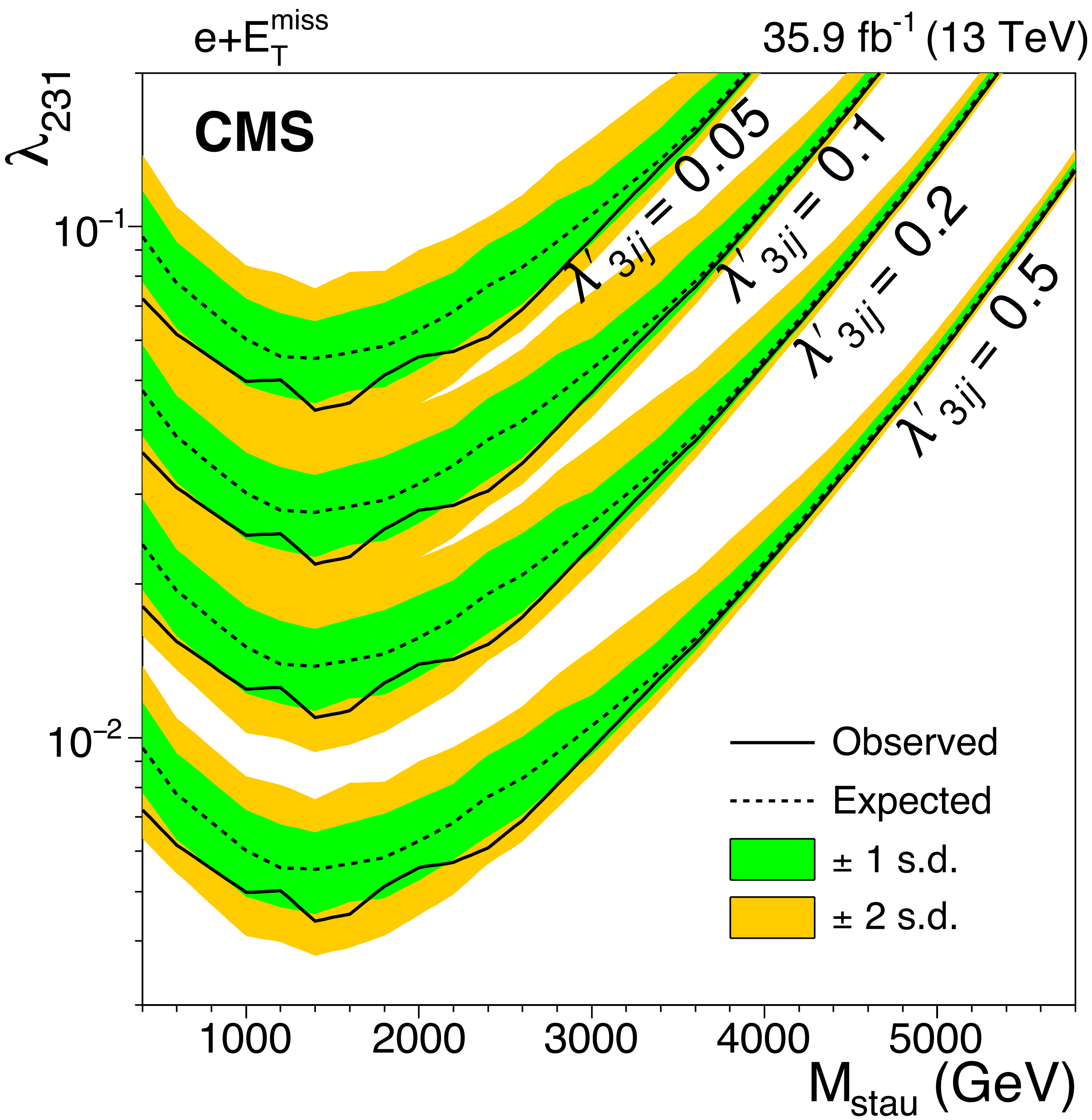
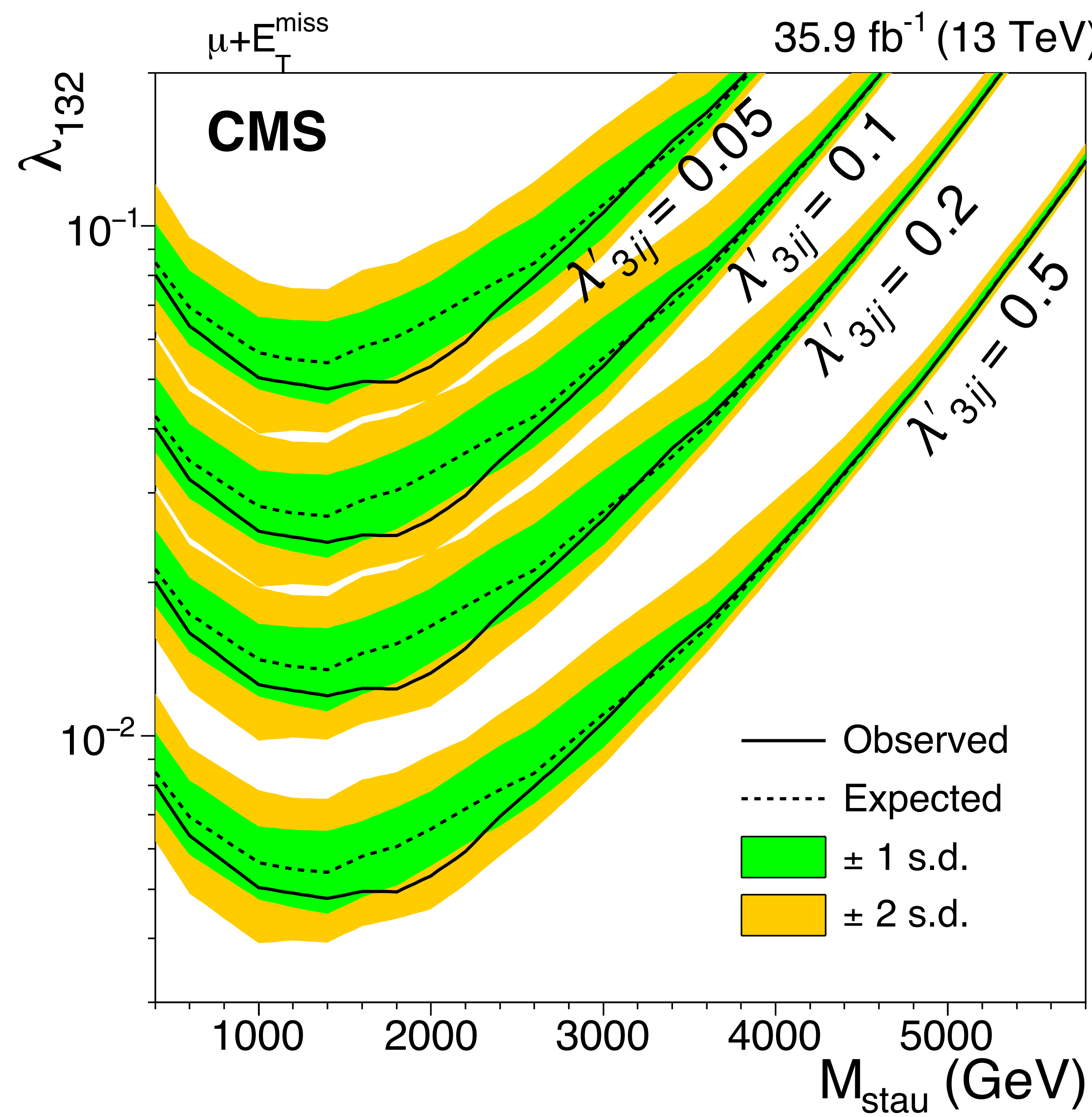
Muon Channel

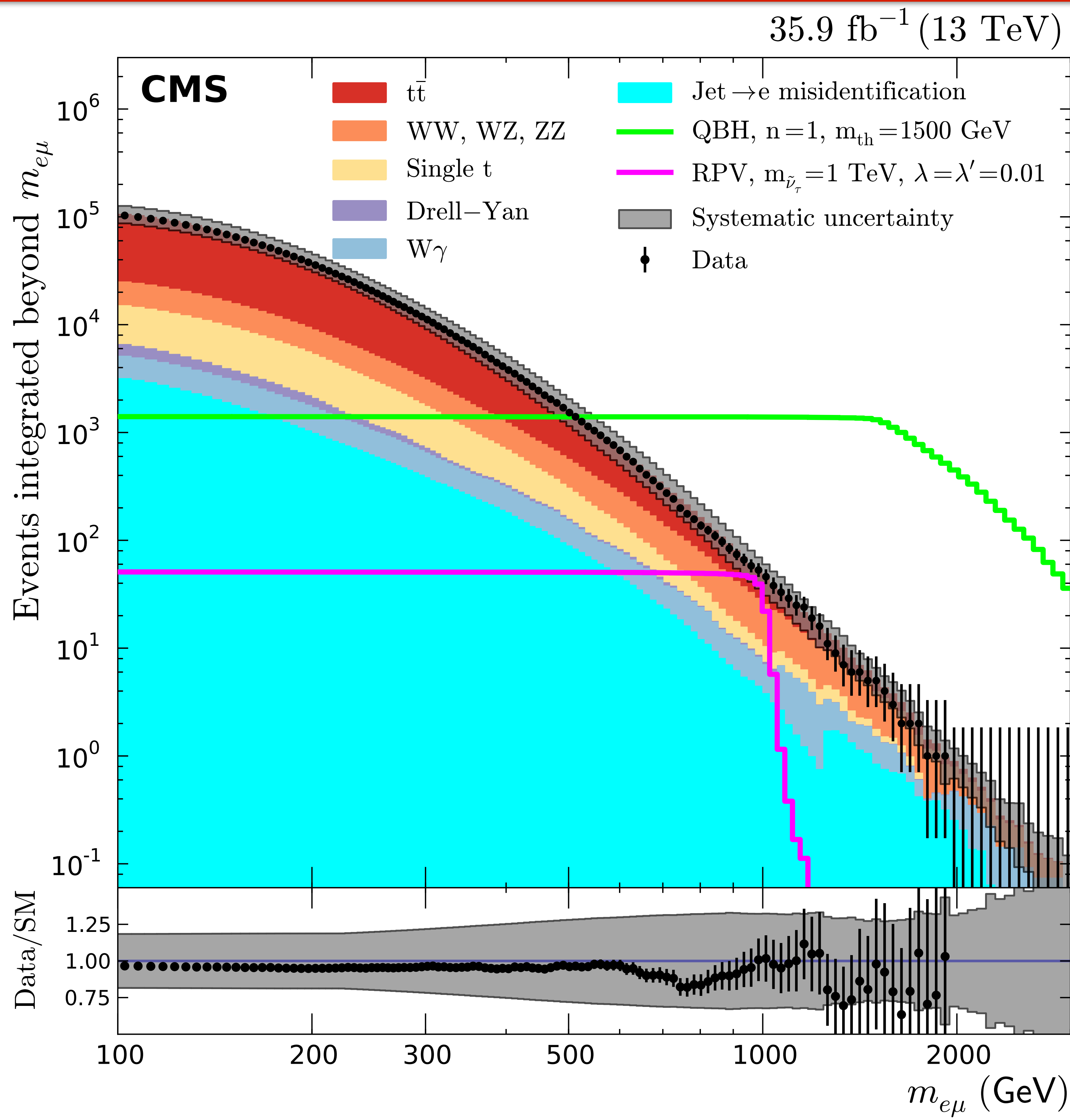


Electron Channel



- Due to the lack of off-shell production, the RPV τ̃ limits are significantly weaker at high mass

X→eμ: Cumulative Events



$X \to e\mu$: Yields

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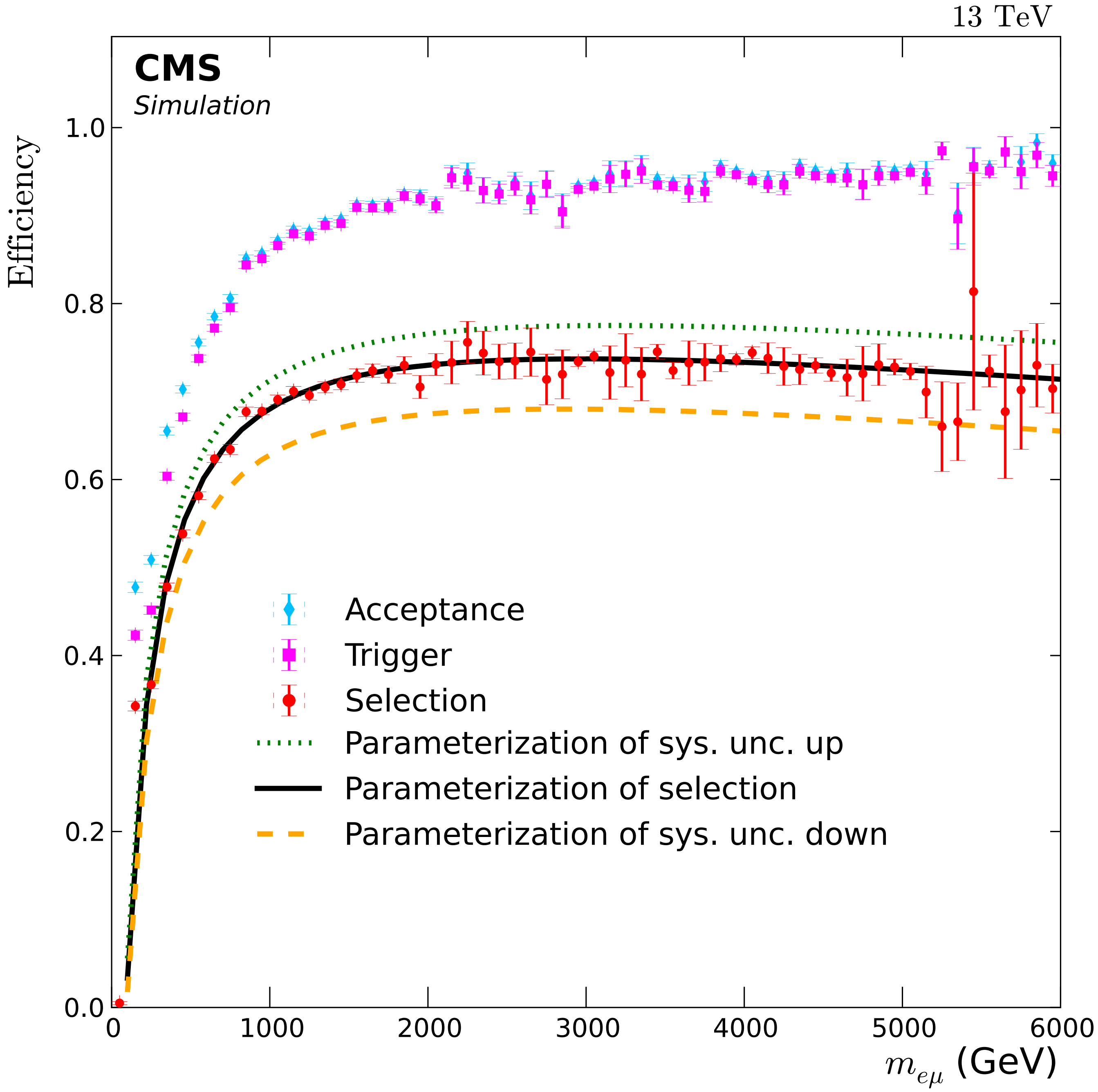
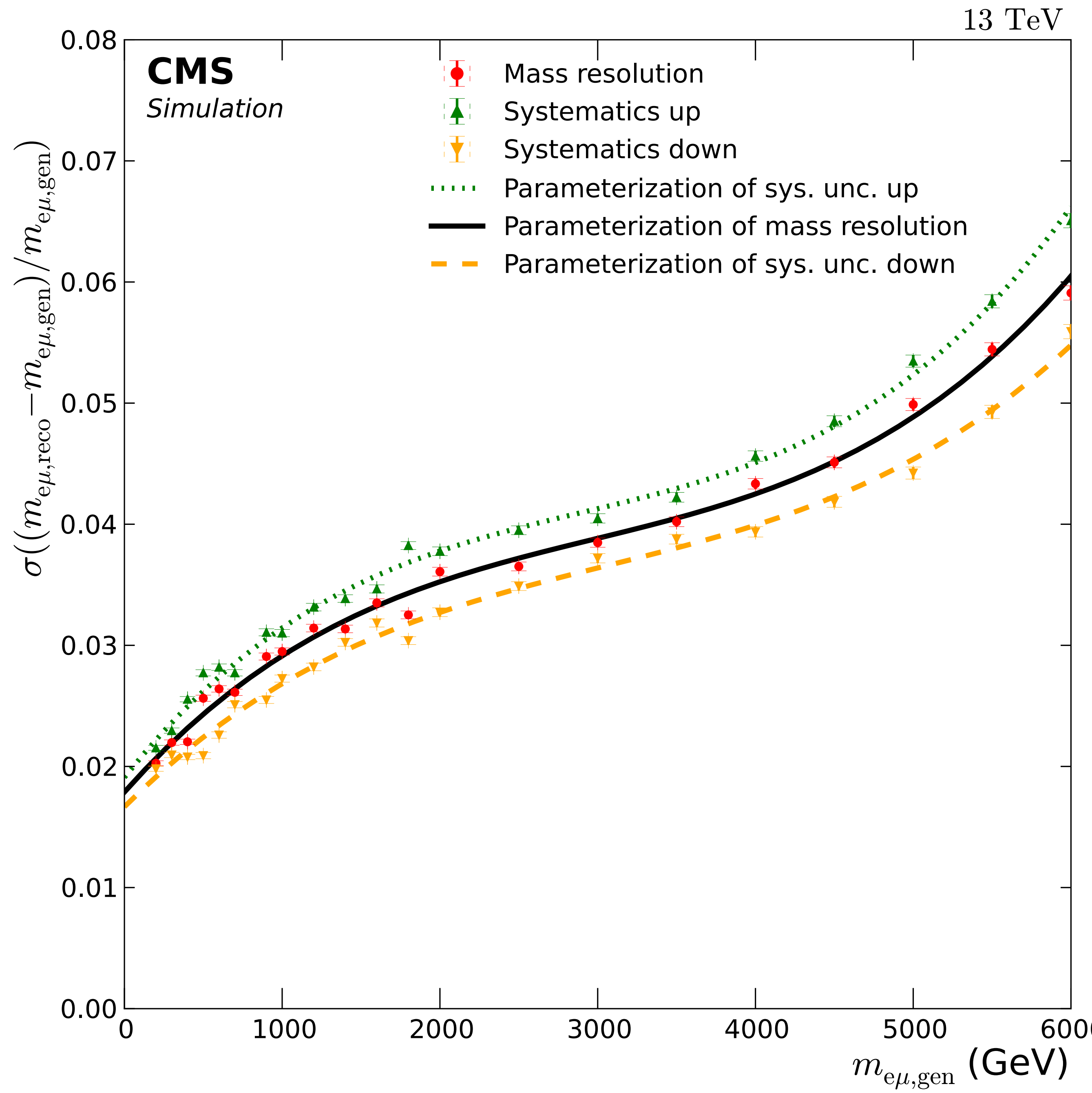
Mass range (GeV)	$m_{e\mu} < 500$	$500 < m_{e\mu} < 1000$	$1000 < m_{e\mu} < 1500$	$m_{e\mu} > 1500$
Jet→e misidentification	3601	82.8	2.92	0.849
Wγ	2462	56.2	2.76	0.562
Drell–Yan	2638	5.31	0.343	0.0145
Single t	9930	141	2.81	0.178
WW, WZ, ZZ	11126	239	13.0	2.03
$t\bar{t}$	96754	971	18.5	1.01
Total background	126513	1495	40.3	4.64
Systematic uncertainty	23495	420	13.5	1.28
Data	123150	1426	41	4

X→eμ: RPV Performance

RPV Selection Efficiency



RPV Signal Resolution



X→eμ: RPV λ′$_{311}$ Limits

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