Searches for Dark Matter in Heavy-Flavor Final States at CMS

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On behalf of the CMS Collaboration

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SUSY2016: The University of Melbourne

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Outline

- Dark matter constitutes 84.5% of the mass of the universe
  - It is possible that dark matter can be produced directly by the LHC
  - Searches for heavy flavor plus dark matter have lower backgrounds than conventional searches
    - Additionally, DM plus heavy flavor searches can offer more aggressive limits in certain models

Process	Channel	CMS-PAS	Lumi
DM+bb	MET+bb	B2G-15-007	2.17 fb^{-1}
DM+t	MET+bjj	EXO-16-017	2.3 fb^{-1}
DM+tt	MET+lvbjj	EXO-16-005	2.2 fb^{-1}

DM+Bottom Search

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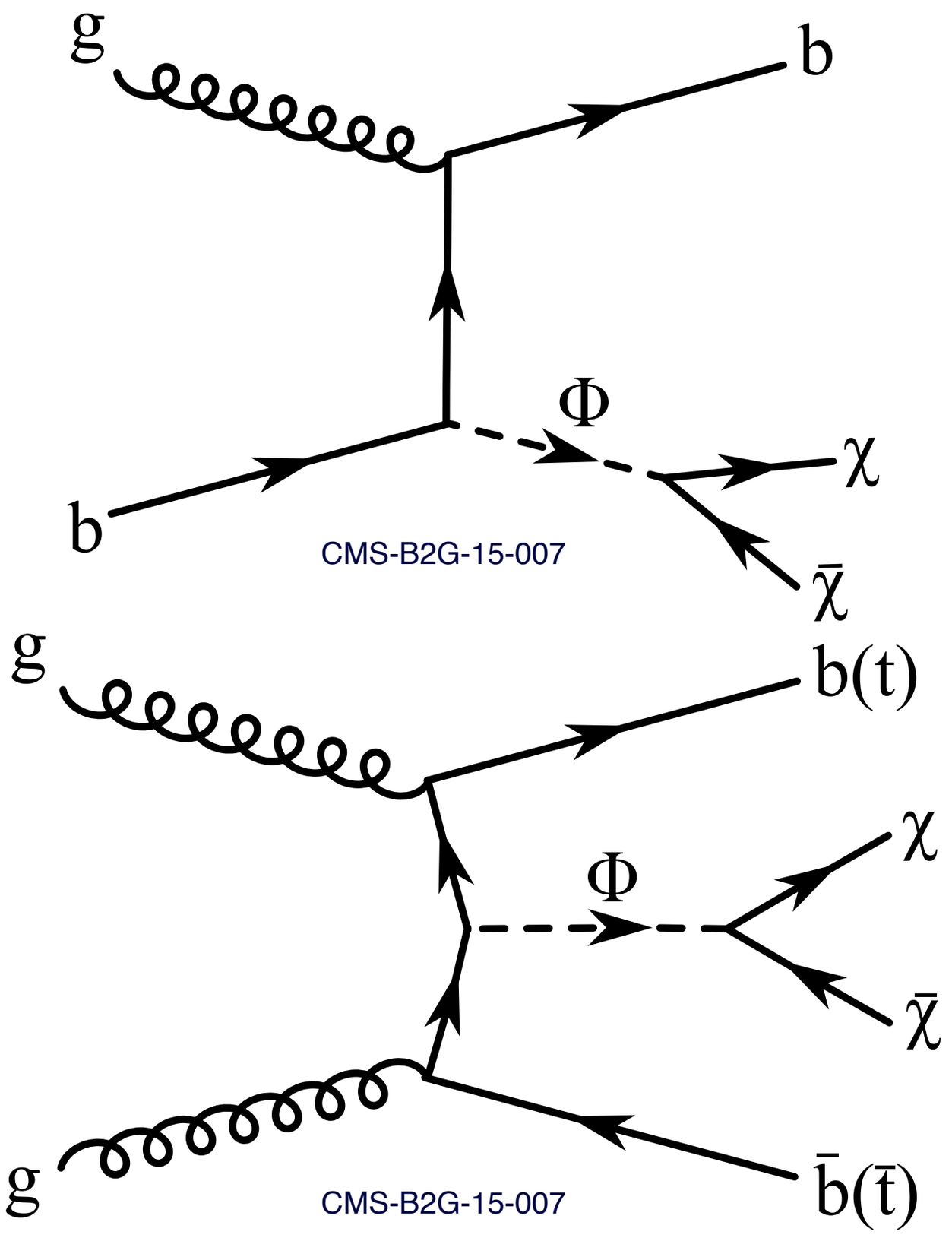
- Search for dark matter that couples to a spin-0 mediator
- Samples generated based on the ATLAS-CMS Dark Matter Forum
  - Unitary coupling between mediator and the dark matter
  - Yukawa-like coupling between the mediator and the quarks
- Channel produces moderate p_T b-jets
- Search is sensitive to both DM +$b\bar{b}$ and DM+$t\bar{t}$ channels



DM+Bottom Selection

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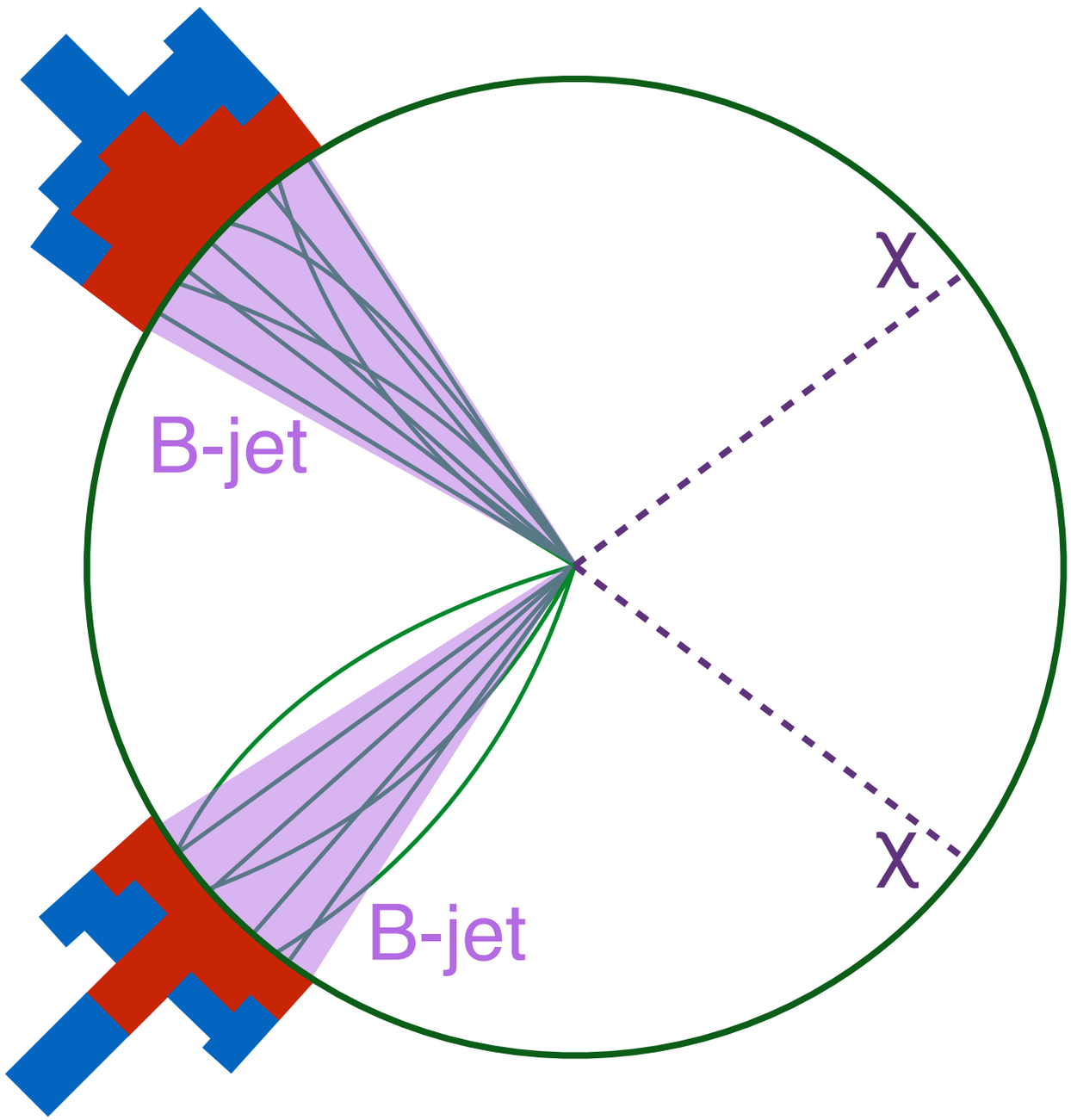
- Large MET
- Veto on e, μ, and τ leptons and photons
- Minimum Δϕ cut between jets and MET
- Two exclusive signal regions require either 1 or 2 b-jets
- 10 exclusive control regions used to normalize the background samples



Hadronic Recoil

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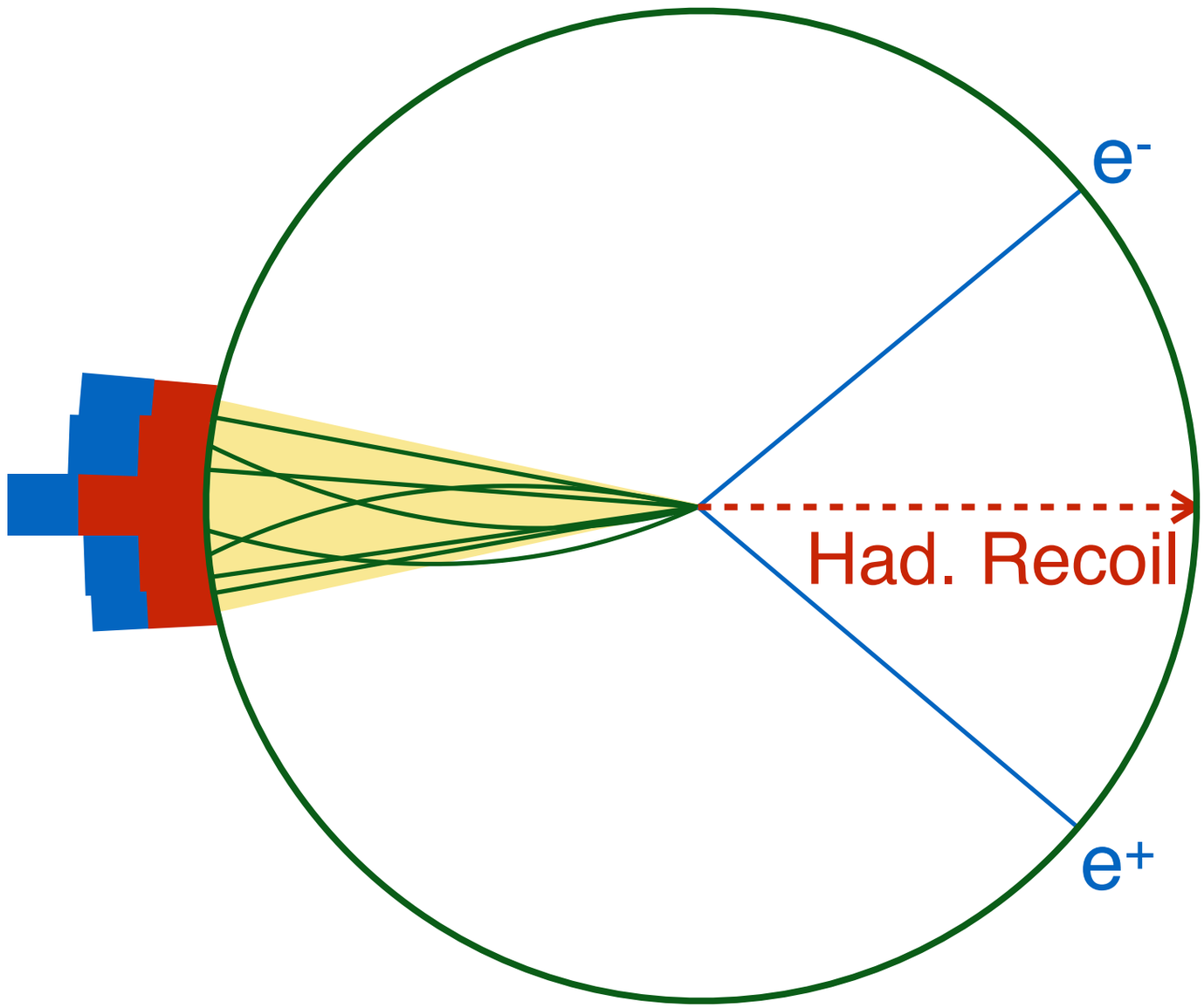
- Hadronic recoil (U) is used to simulate MET in the control regions
- The hadronic recoil is calculated by removing leptons and photons from the MET calculation
- The selection on U in the control region is the exact same as the selection on MET in the signal region

Z+jet→ee+jet Event



DM+Bottom Control Regions

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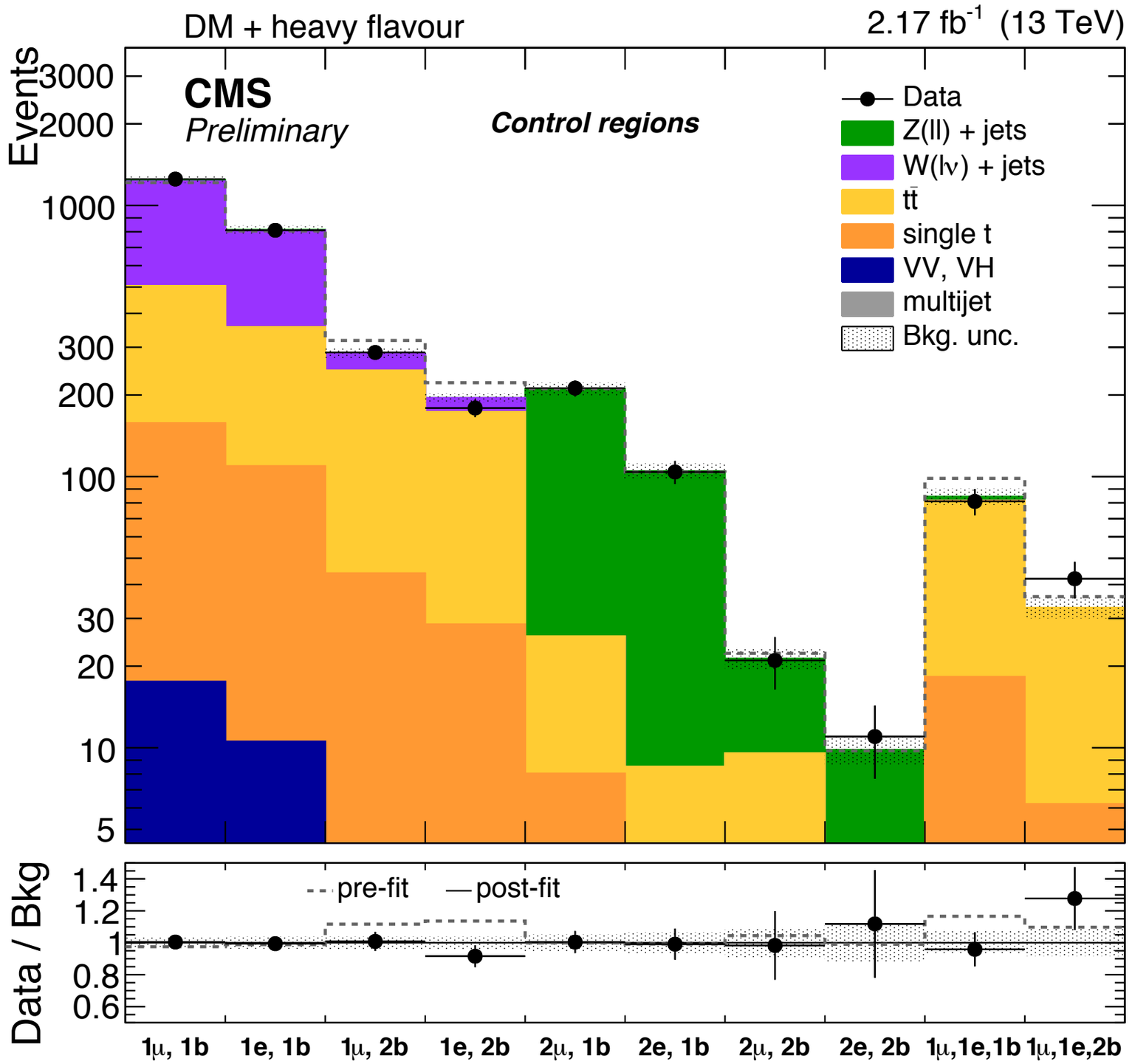
- Control regions are based on:
  - 1 or 2 b-tags
  - Lepton Flavor (e/μ) and multiplicity (1 or 2)
    - M_W cut in single lepton region
    - M_Z cut in 2 matching lepton region
- All control regions have $U > 250$ GeV



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DM+Bottom MET Spectrum

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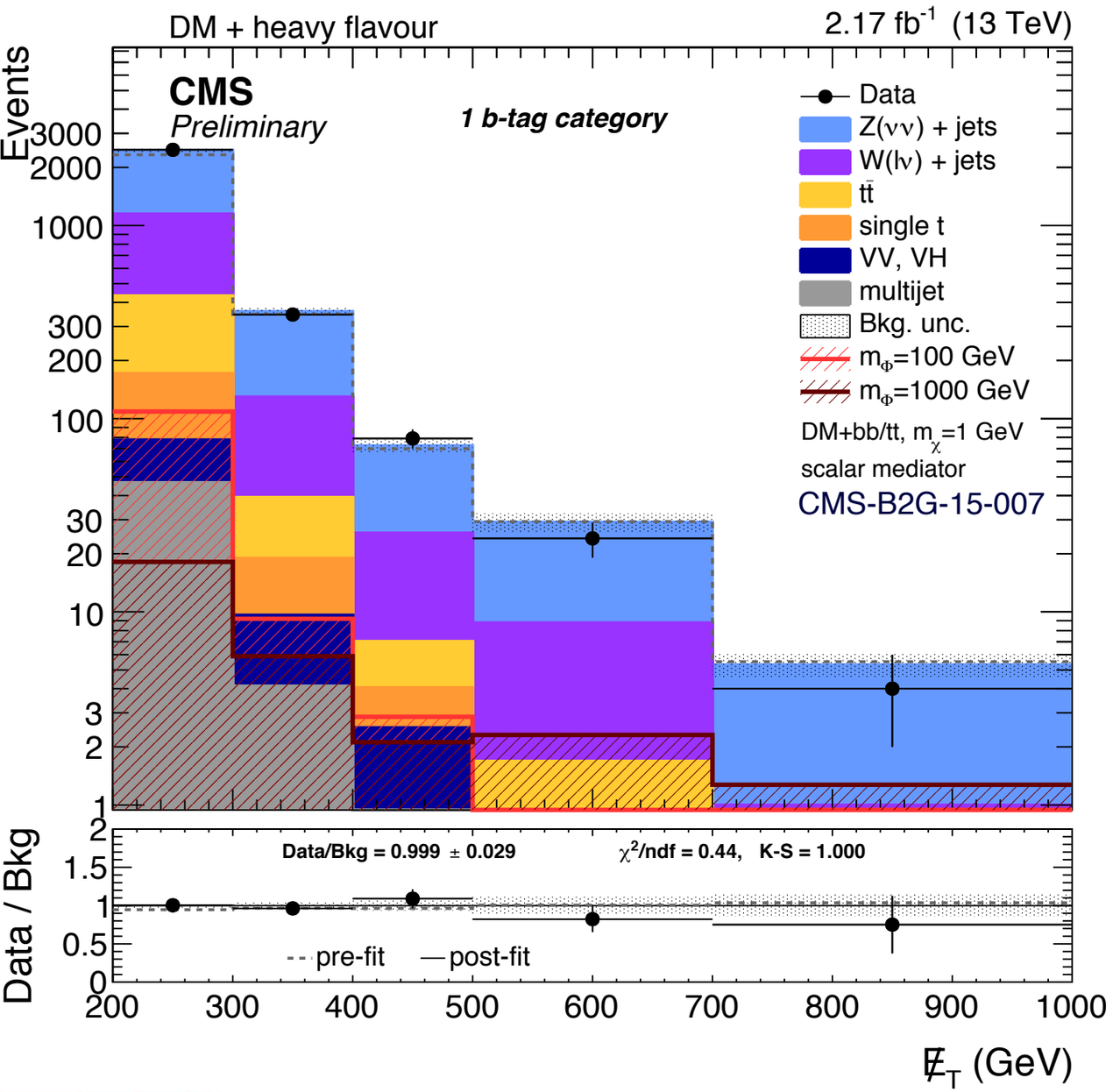
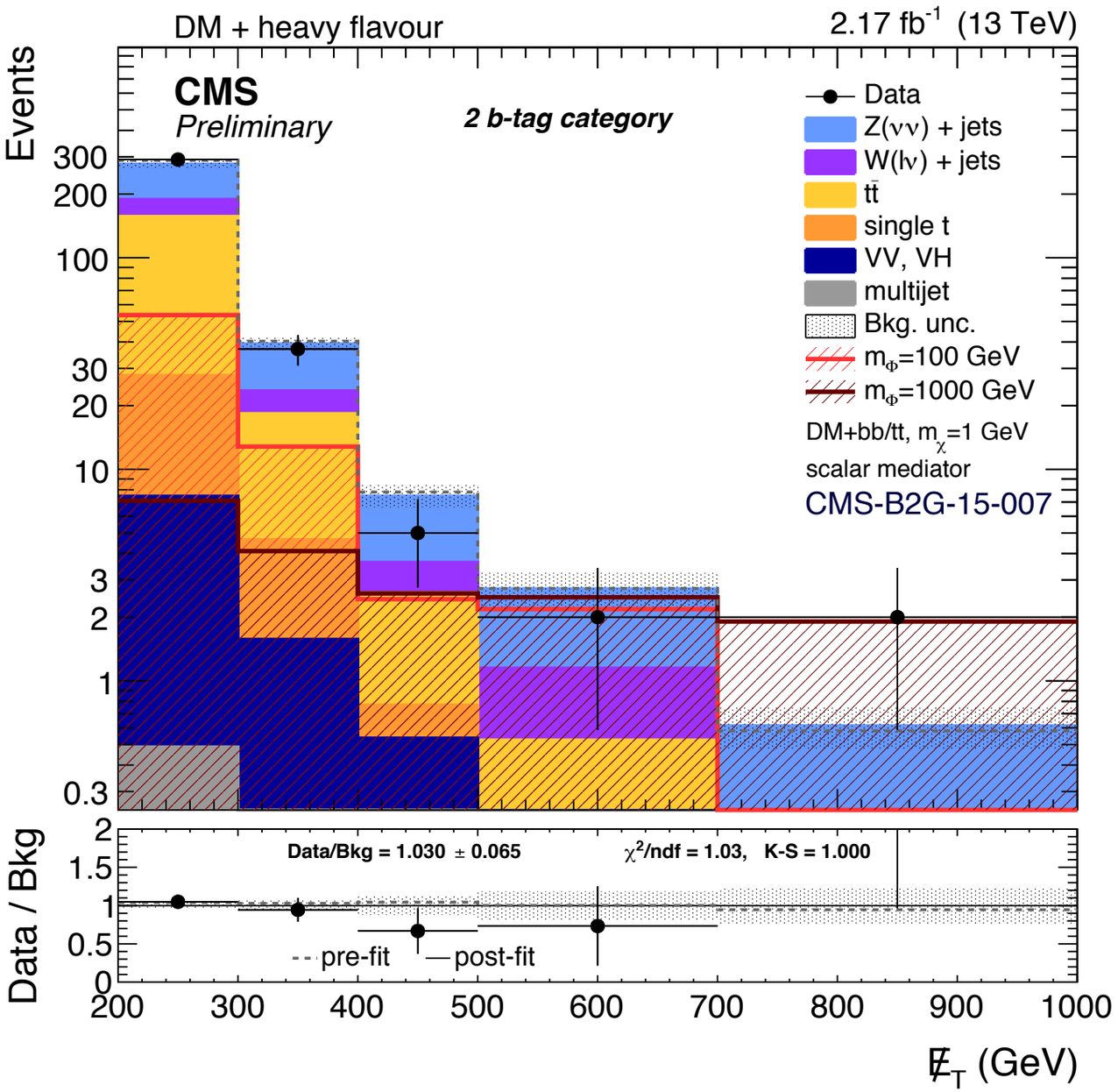
- Good agreement is seen in the MET spectrum for data and MC in the signal region





DM+Bottom Limits

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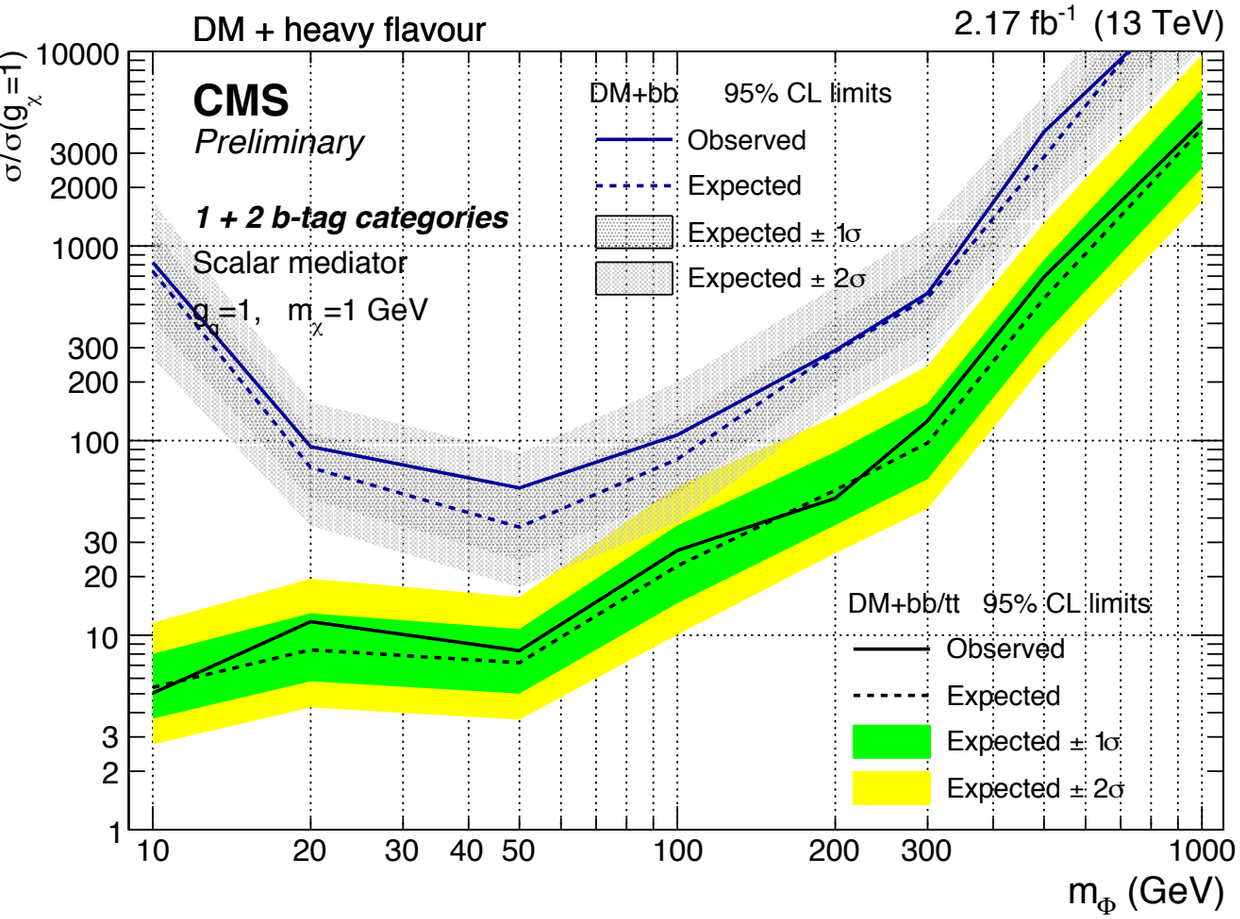
- Limits are extracted from the result of the simultaneous fit in the 2 signal and 10 control regions
- Limits are calculated using the asymptotic CL_s approach



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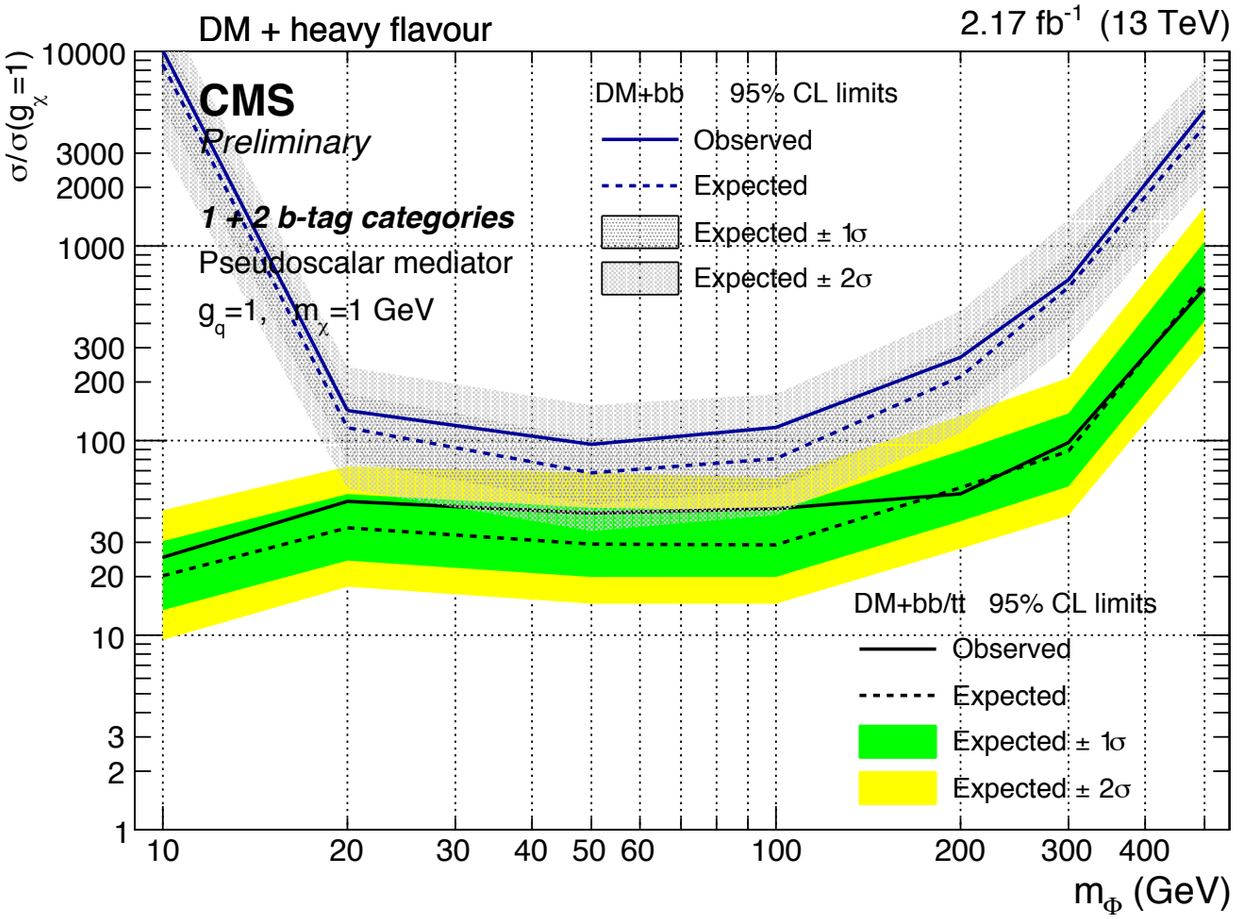

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DM+Monotop Search

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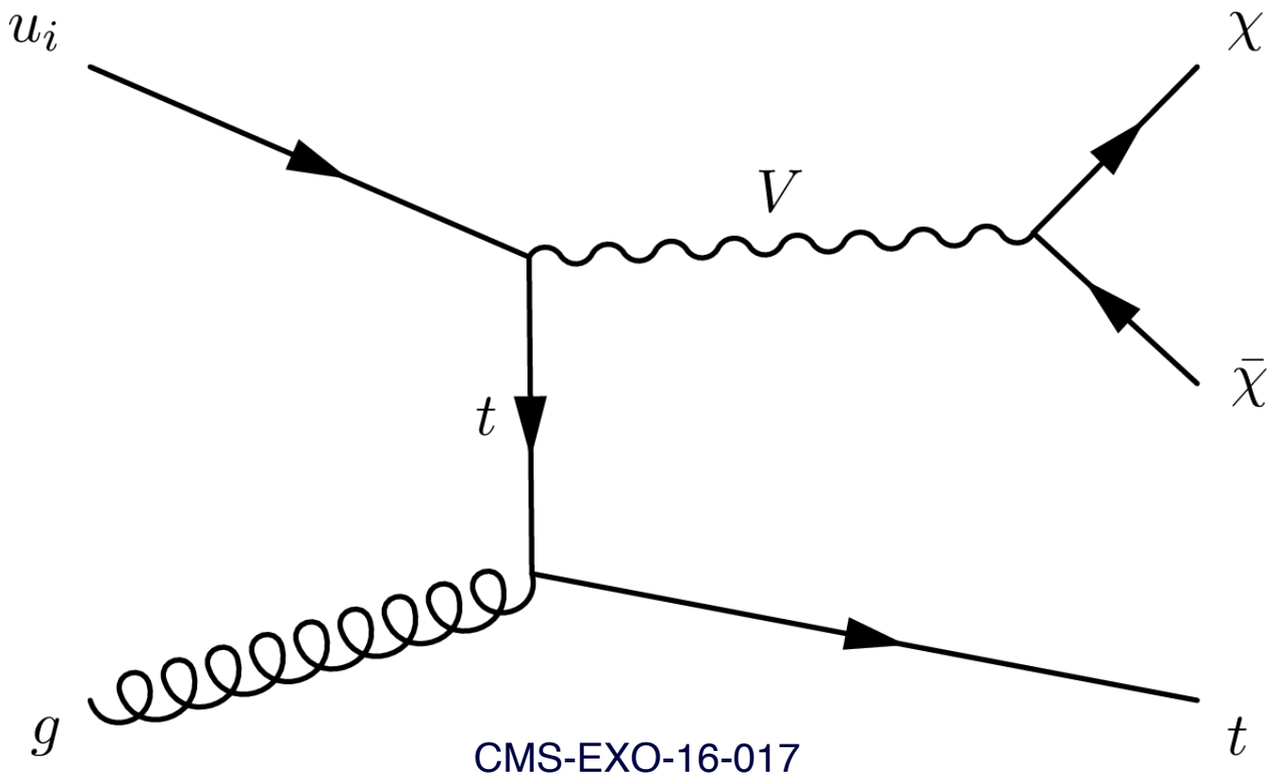
- Non-resonant production creates a top quark and dark matter via a FCNC
- Search is optimized for a boosted top quark
- Search range of 300 GeV < M_V < 1.5 TeV



CMS-EXO-16-017

DM+Monotop Selection

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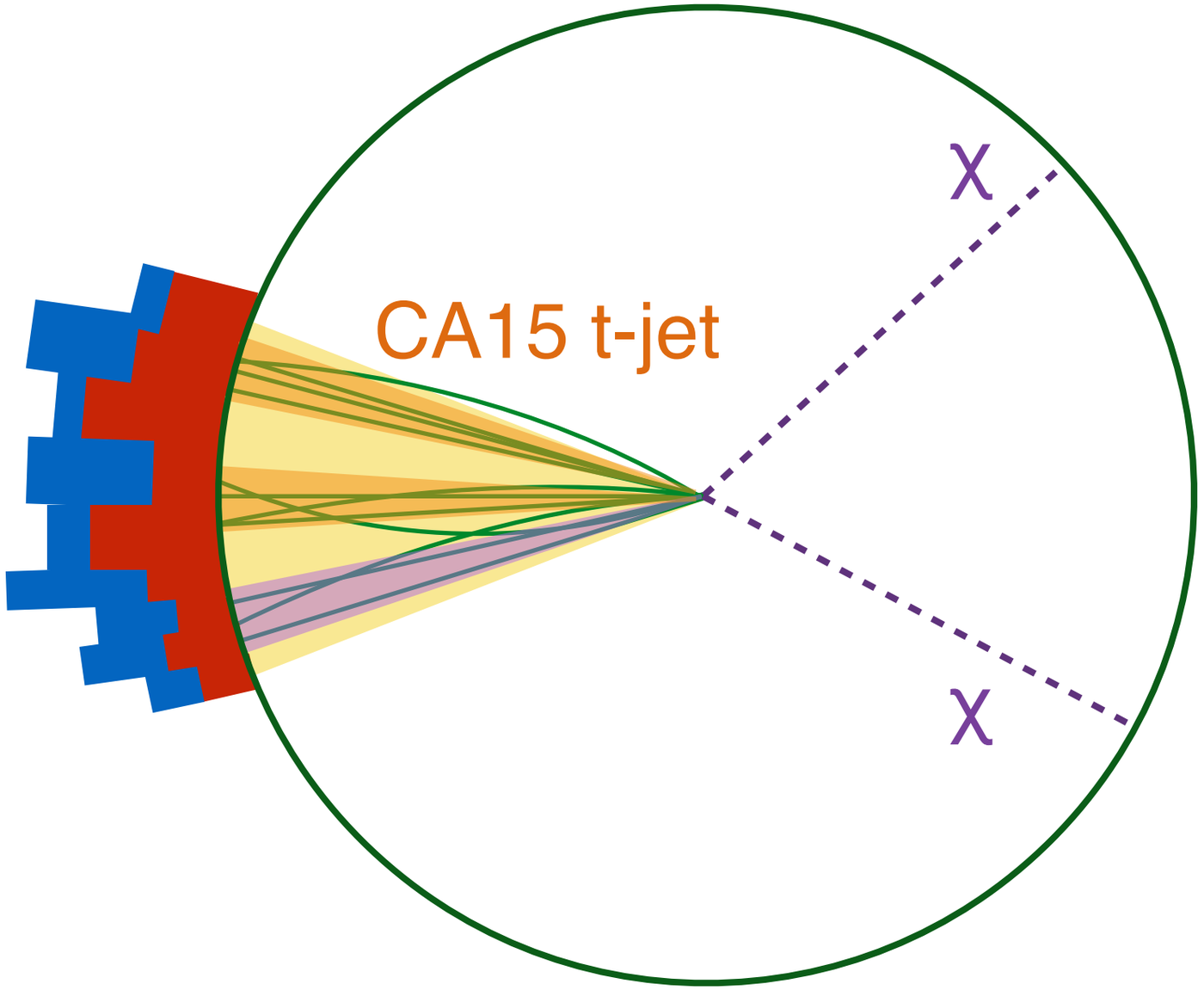
- Large MET Selection
- Exactly 1 top-tagged high p_T CA15 jet
- One sub-jet b-tag
  - Veto stand alone b-jets
- Veto leptons (e, μ, and τ) and photons
- Δϕ cut between MET and AK4 jets



DM+Monotop Top Tagging

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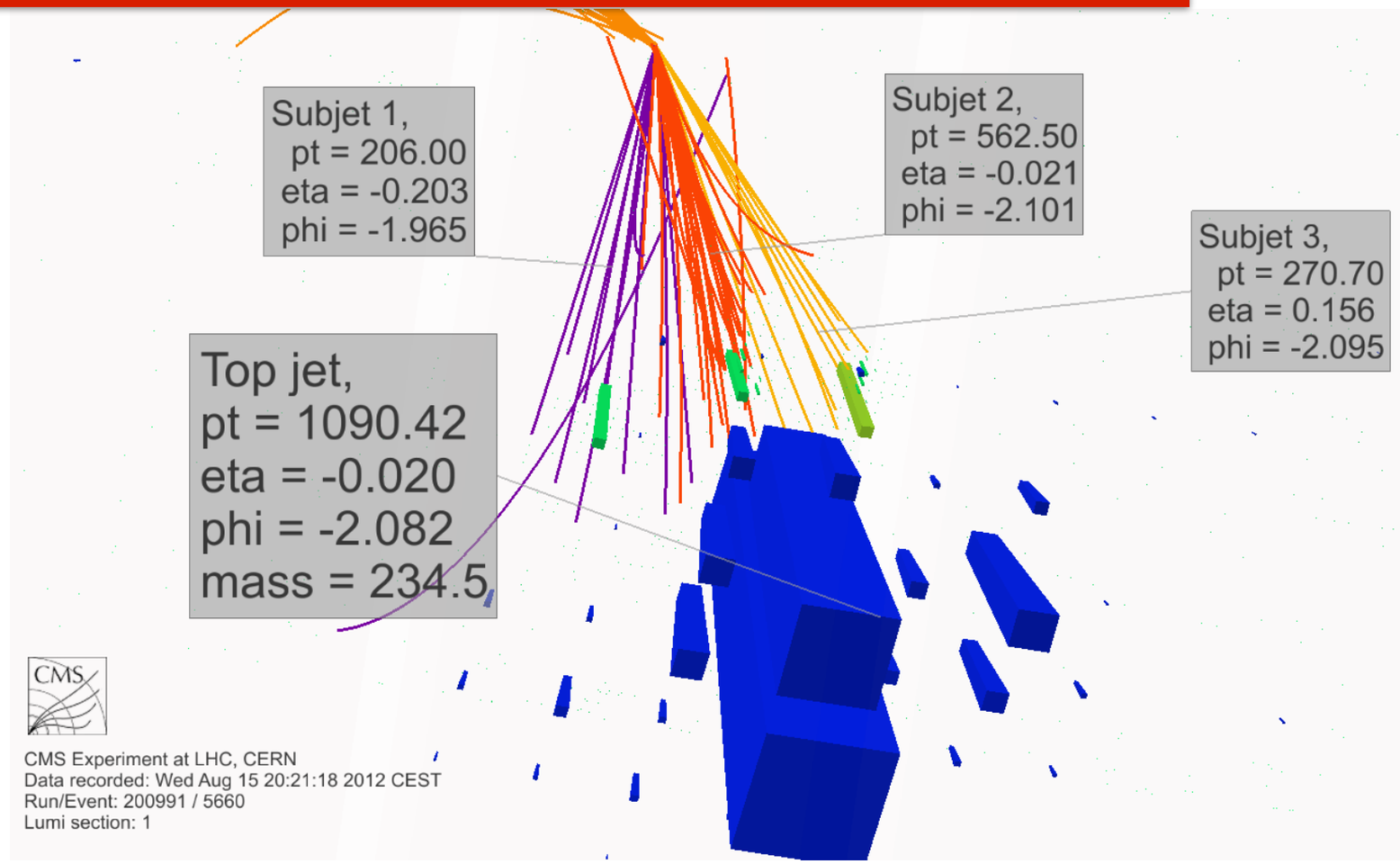
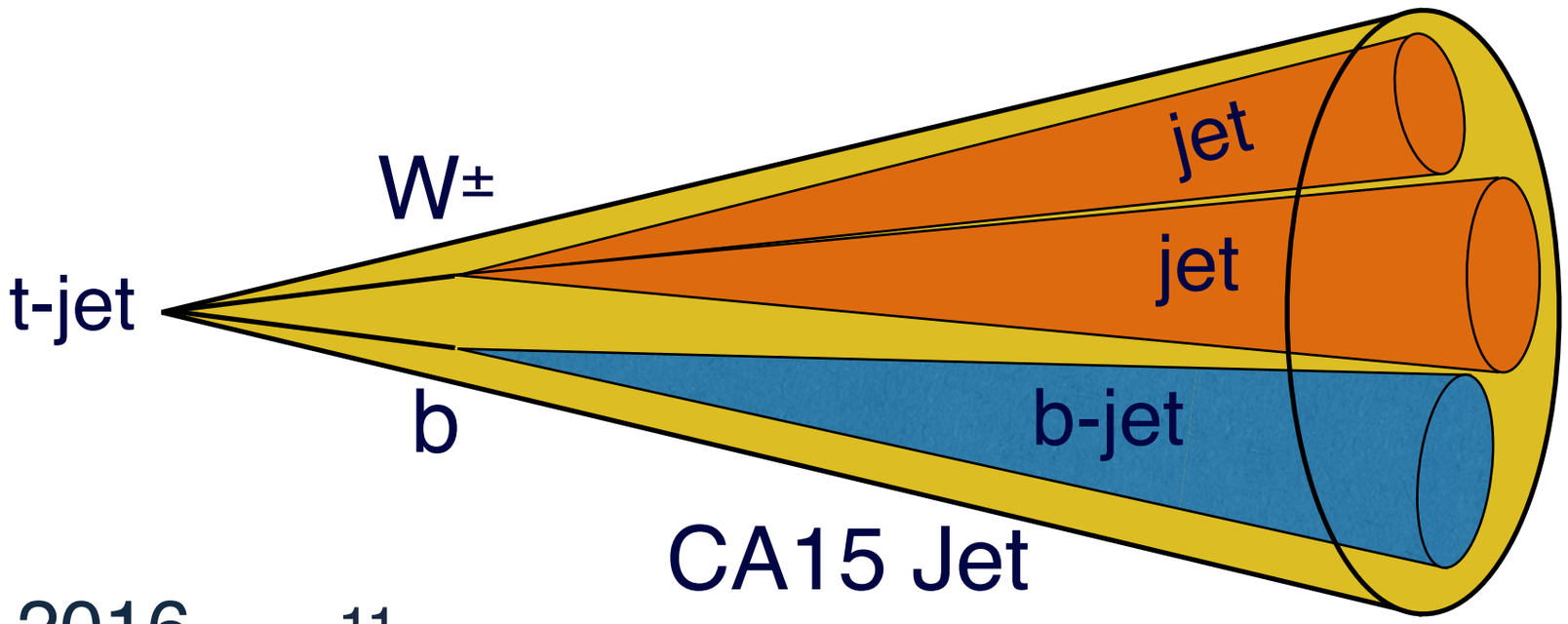
- CA15 jet
  - $p_T > 250$ GeV and $|\eta| < 2.5$
  - Groomed (soft-drop) jet mass used
    - 110 GeV < M_{SD} < 210 GeV
  - AK4 sub-jet b-tag (CSV > 0.76)
  - $\tau_{32} = \tau_3/\tau_2 < 0.61$





DM+Monotop Control Region

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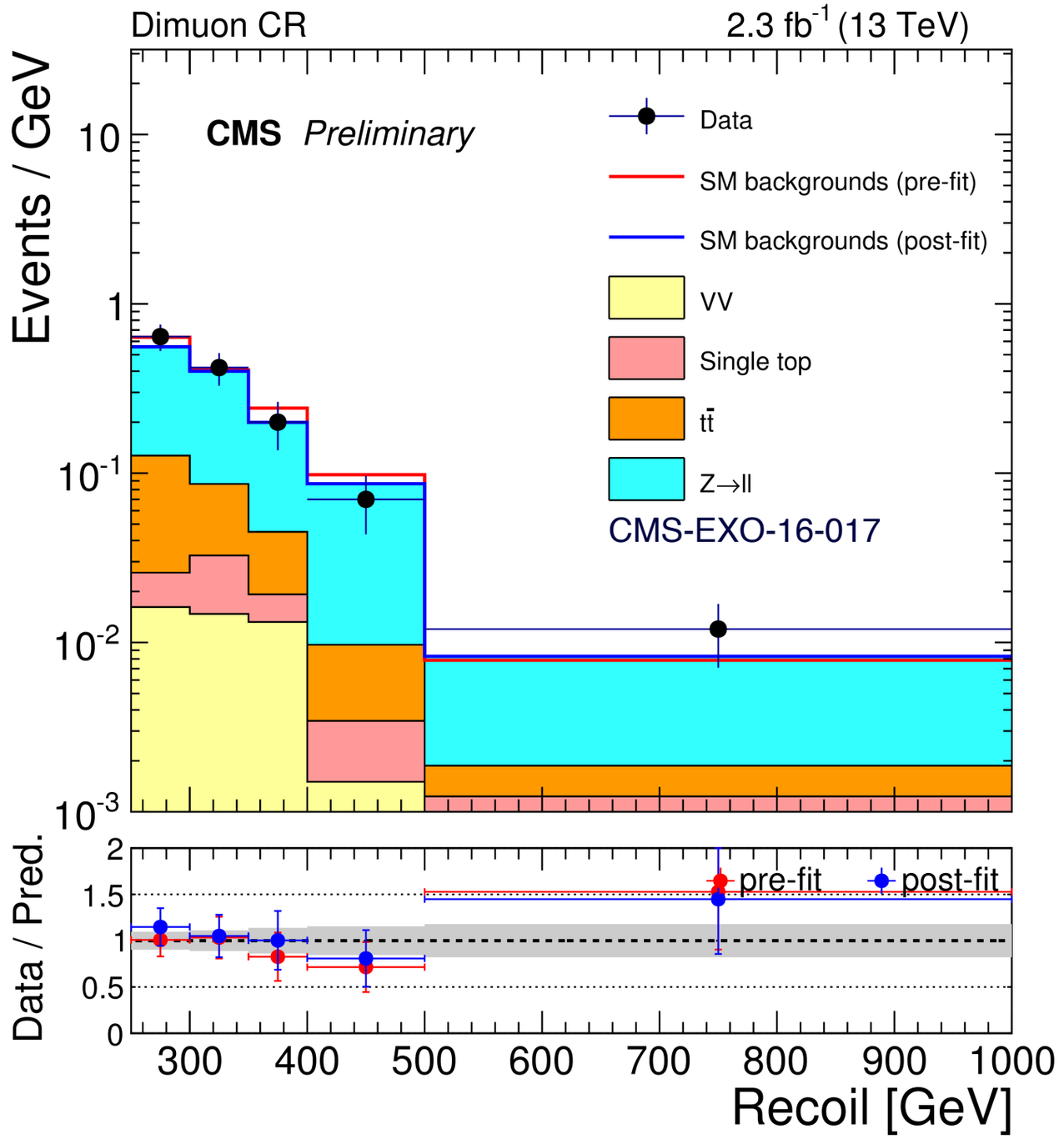
- The signal extraction requires fitting the Z+jets, W+jets, and $t\bar{t}$ backgrounds
  - The normalizations are fit from 7 different control regions
  - Hadronic recoil is used to simulate MET in the control region
  - *U* is fit across all 7 control regions and the signal region
- Single top, di-boson, and QCD multi-jet are obtained from MC simulation



Z→μμ control region using *U*

DM+Monotop Muon Control Region

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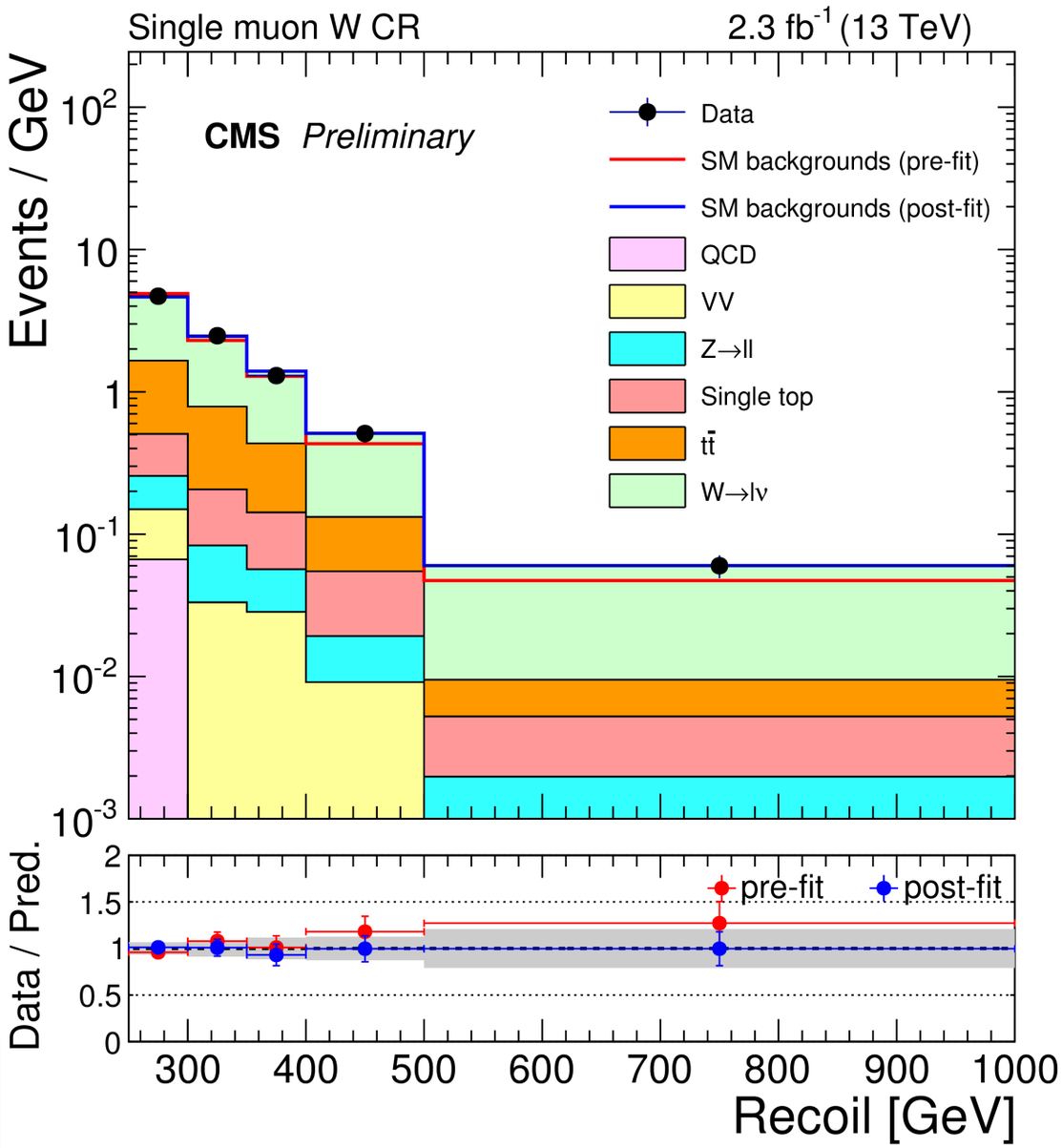
- Single muon hadronic recoil spectrum in the W and $t\bar{t}$ control regions
  - W+jets control region veto events with b-tags
    - Additional MET cut in electron channel
  - $t\bar{t}$ control regions requires a medium and loose b-tagged jet



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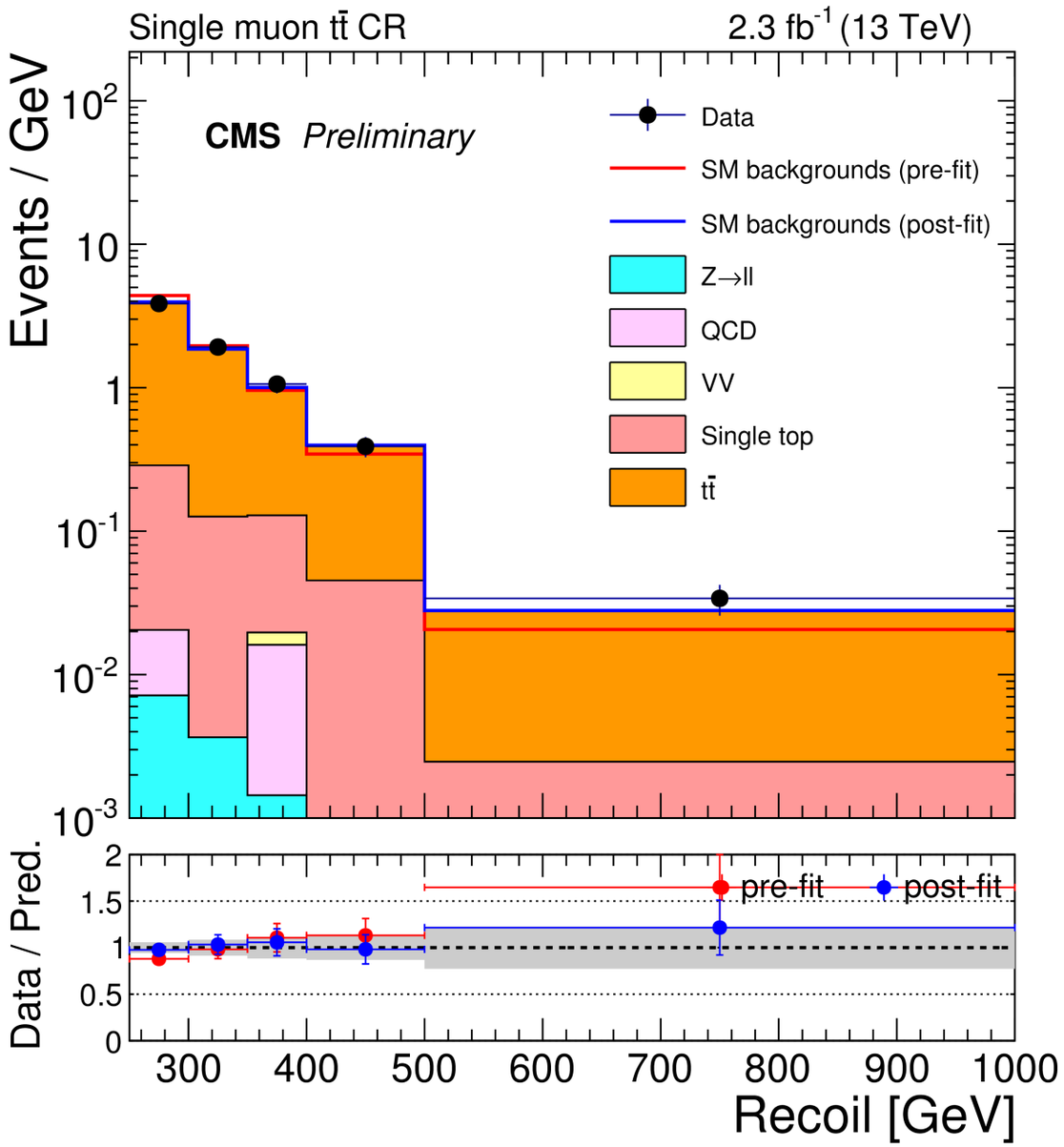

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DM+Monotop Top Recoil

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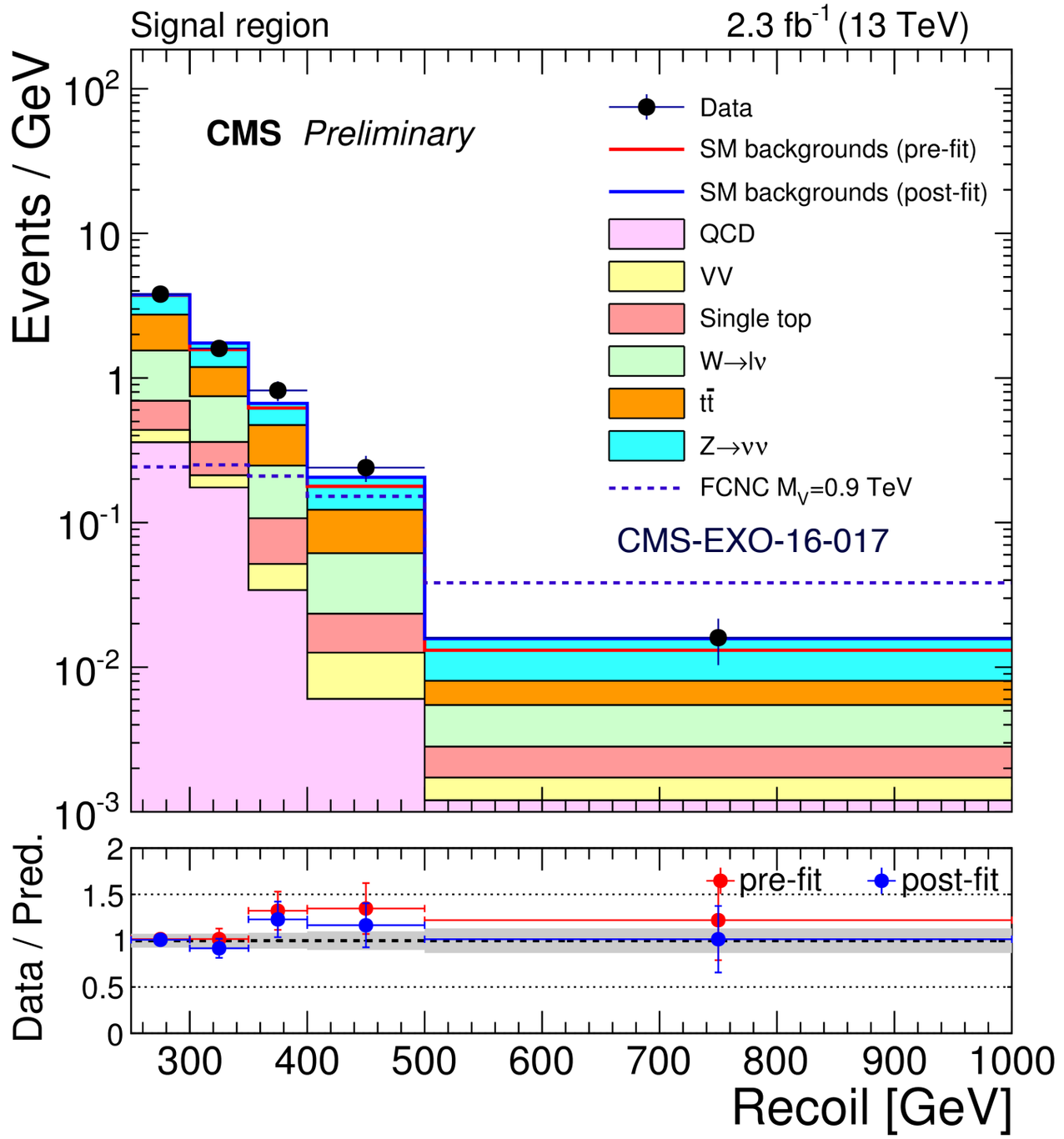
- The *U* spectrum in the signal region shows agreement with the background only hypothesis
  - W→lν, $t\bar{t}$, Z→νν, and γ+jets normalized to post fit values
  - QCD, VV, and Single top normalized to MC values
  - Last bin contains overflow events
  - Red line is pre likelihood fit
  - Blue line is post likelihood fit



DM+Monotop Limits

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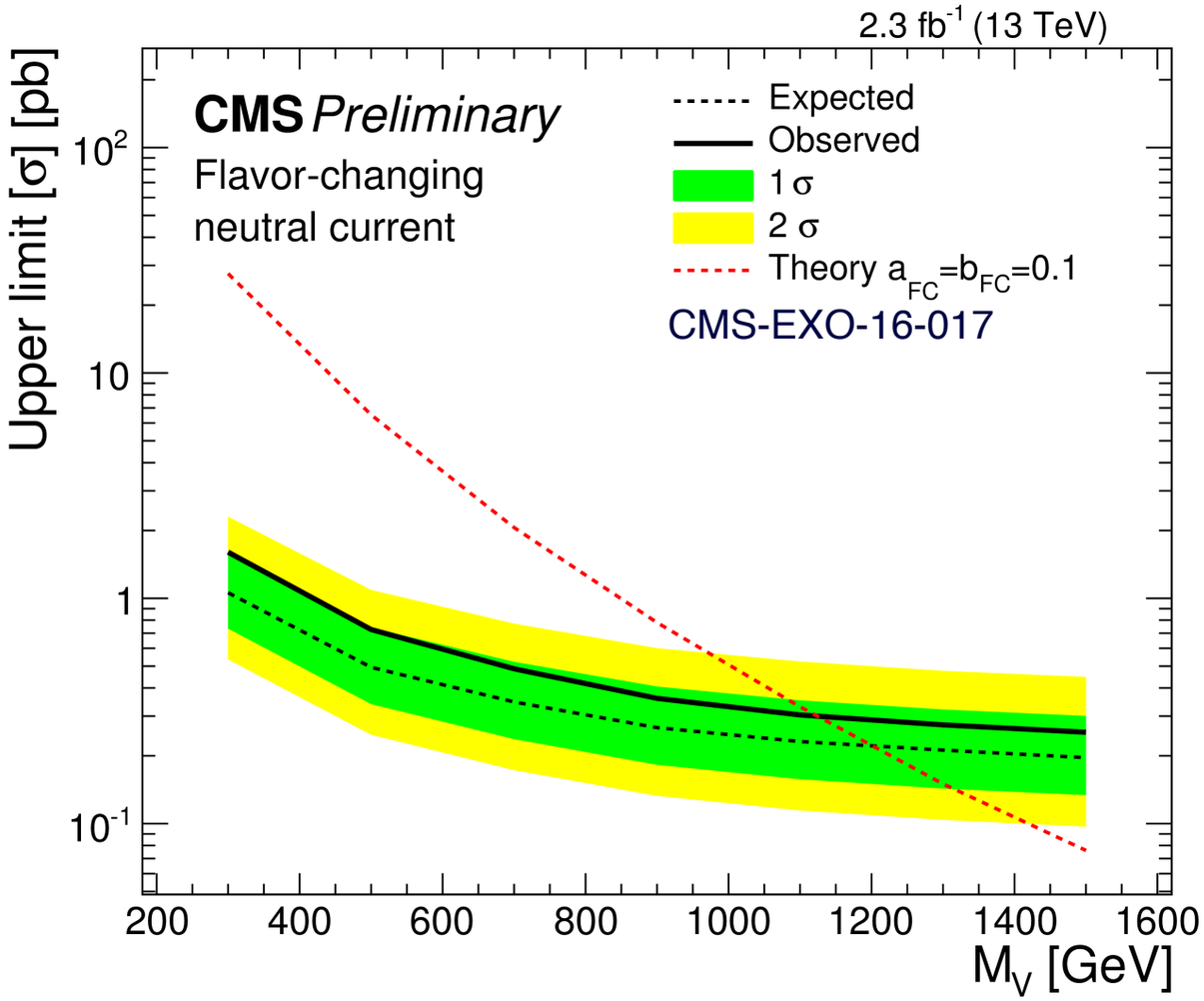
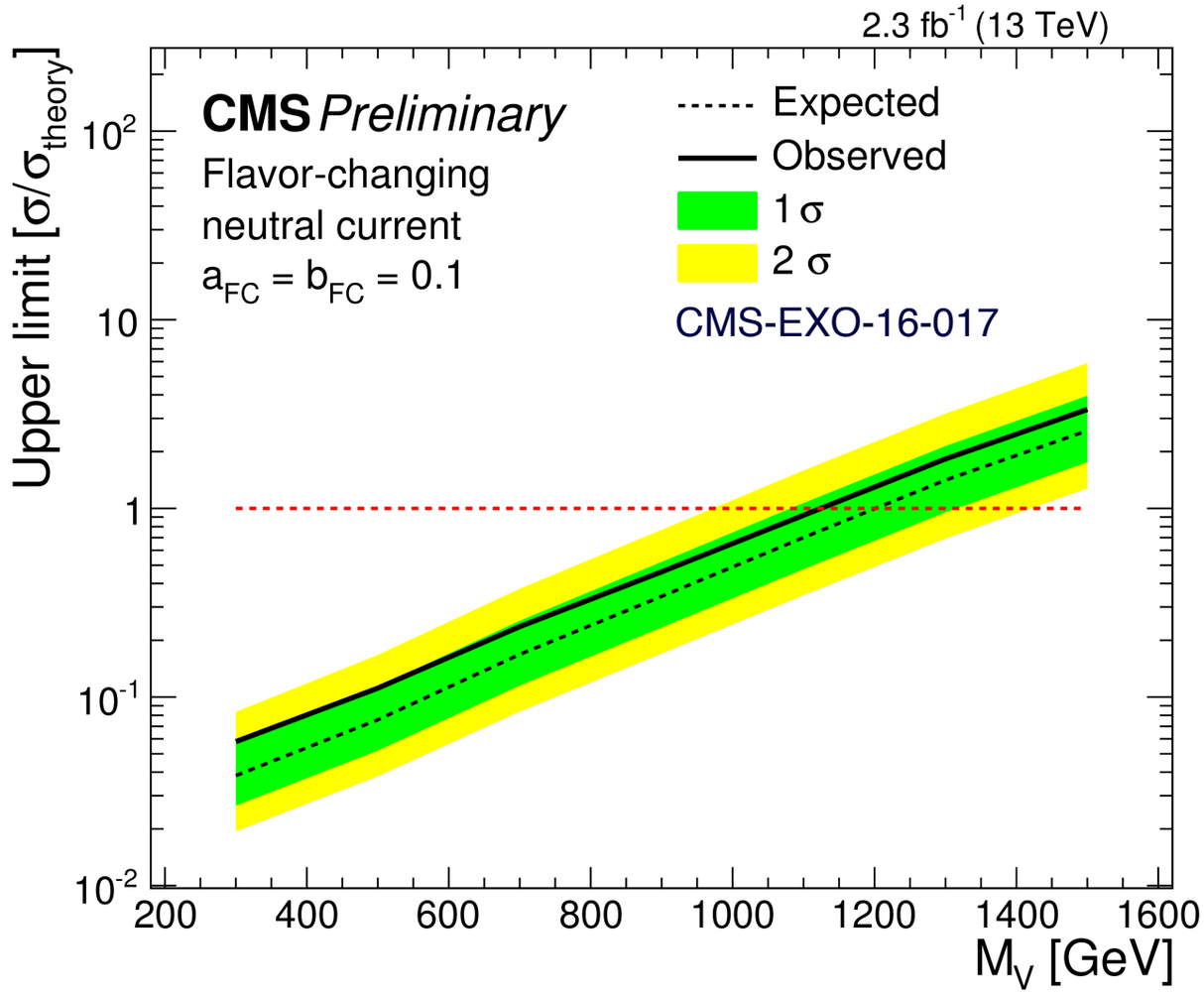
- Limits are set from the hadronic recoil spectrum in the signal region using the asymptotic CL_s approach





$$a_{\mathrm{FC}}^{1} = (a_R + a_L)/2$$

$$b_{\mathrm{FC}}^{1} = (a_R - a_L)/2$$

DM+$t\bar{t}$ Search (Upcoming)

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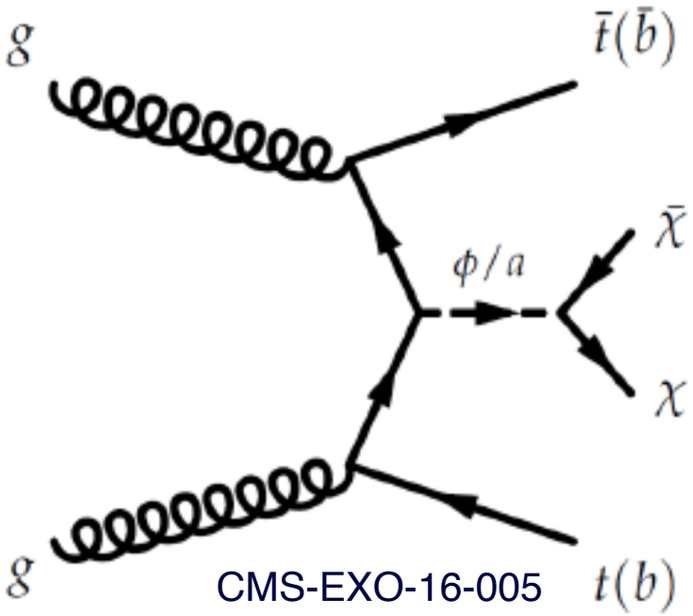
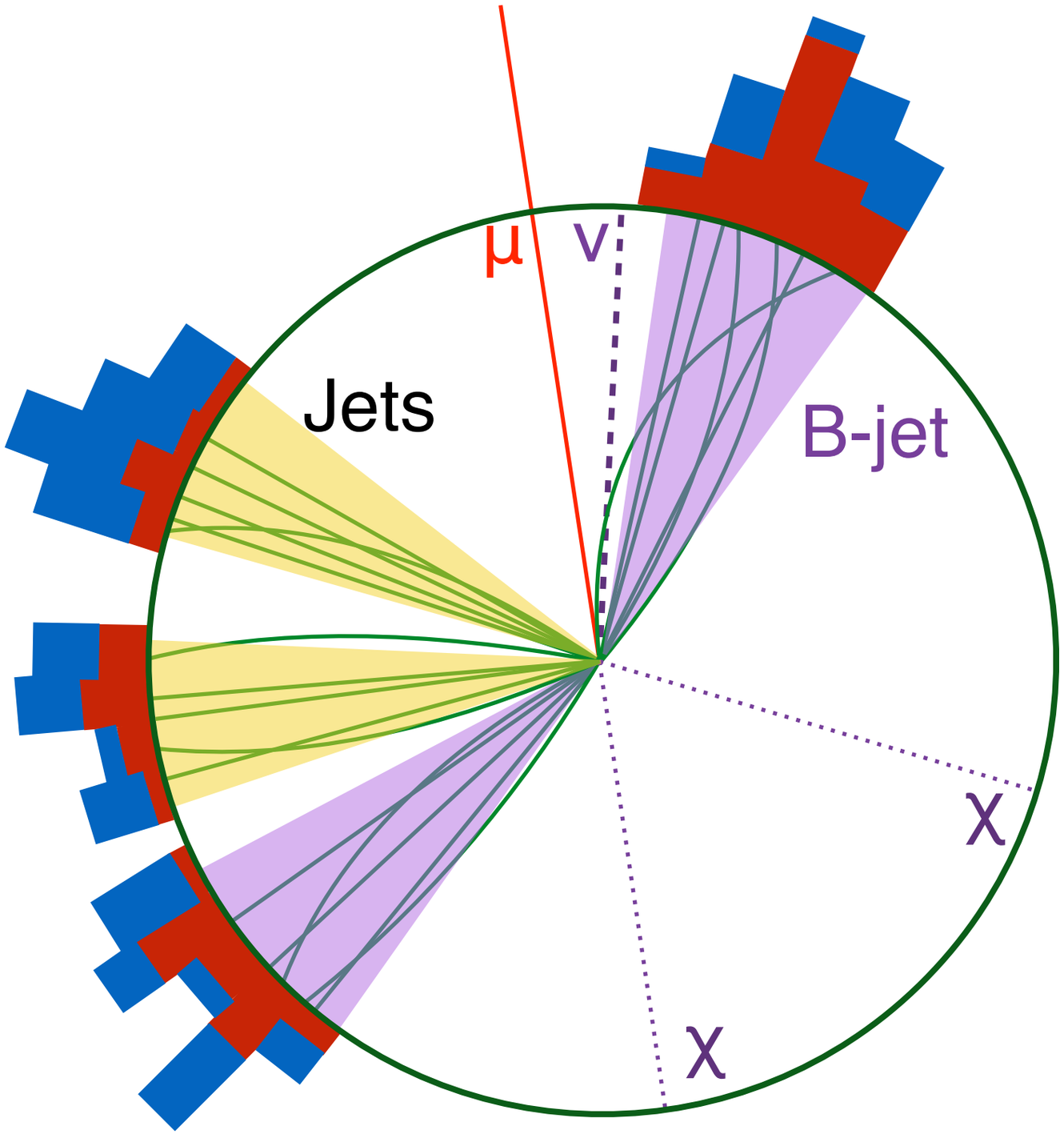
- On going search for DM+$t\bar{t}$
- New search uses simplified model
- Search will cover 13TeV Data
- Search will cover both
  - Semi-leptonic resolved final state
  - Boosted semi-leptonic and all hadronic final states



CMS-EXO-16-005



Summary

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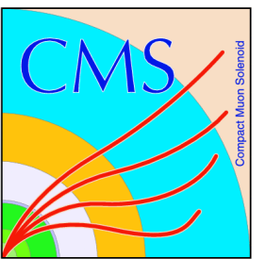
- Two DM plus heavy flavor searches have been presented
  - The DM+bottom quark search excludes a scaler mediator down to $5\times\sigma/\sigma_{g_x,g_q=1}$ and a pseudo-scalar down to $26\times\sigma/\sigma_{g_x,g_q=1}$
  - The DM+monotop search excludes a massive flavor changing neutral current in the range 300 GeV < M_V < 1100 GeV
- Search of DM+$t\bar{t}$ in currently being developed and will search in both semi-leptonic and all hadronic channels
  - All hadronic search will cover the boosted topology
  - Semi-leptonic search will cover both the boosted and resolved topologies



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Backup

DM+bb: Data and MC Samples

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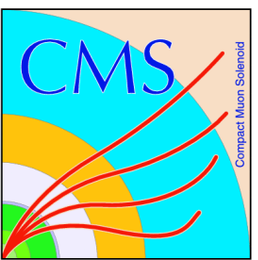
- DM+bb and DM+tt samples generated in MADGRAPHv5 and shower matching via PYTHIA8
- $t\bar{t}$ and tW samples generated with POWHEG interfaced with PYTHIA
- S and t-channel single top samples generated with aMC@NLO
- Inclusive W and Z samples were generated with aMC@NLO
- All DiBoson samples generated with aMC@NLO
- W+Jets, Drell-Yan+Jets, and QCD samples generated in MADGRAPHv5 and shower matching via PYTHIA8

Dataset
MET/Run2015D-PromptReco-v4
MET/Run2015D-05Oct2015-v1
MET/Run2015C 25ns-05Oct2015-v1
SingleMuon/Run2015D-PromptReco-v4
SingleMuon/Run2015D-05Oct2015-v1
SingleMuon/Run2015C 25ns-05Oct2015-v1
SingleElectron/Run2015D-PromptReco-v4
SingleElectron/Run2015D-05Oct2015-v1
SingleElectron/Run2015C 25ns-05Oct2015-v1



DM+bb: Selection

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- MET > 90 GeV or MHT > 90 GeV trigger
- MET > 200 GeV
- $N_{Jets} < 4$
- Veto isolated e, μ, and γ with $p_T > 10$ Gev, with τ $p_T > 18$ GeV
- $\Delta\phi_{(j,MET)} > 0.5$

- Signal Region 1 (2 jets)
  - 1 medium b-jet $p_T > 50$ GeV
  - 1 jet $p_T > 30$ GeV
- Signal Region 2 (3 jets)
  - 2 jets with $p_T > 50$ GeV
  - 1 additional jet with $p_T > 30$ GeV
  - 2 jets need to pass medium b-tag

Working point	CSV cut	mis-tag probability
CSVL (Loose)	> 0.605	≈ 10%
CSVM (Medium)	> 0.890	≈ 1%
CSVT (Tight)	> 0.970	≈ 0.1%

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DM+bb: Signal Efficiency

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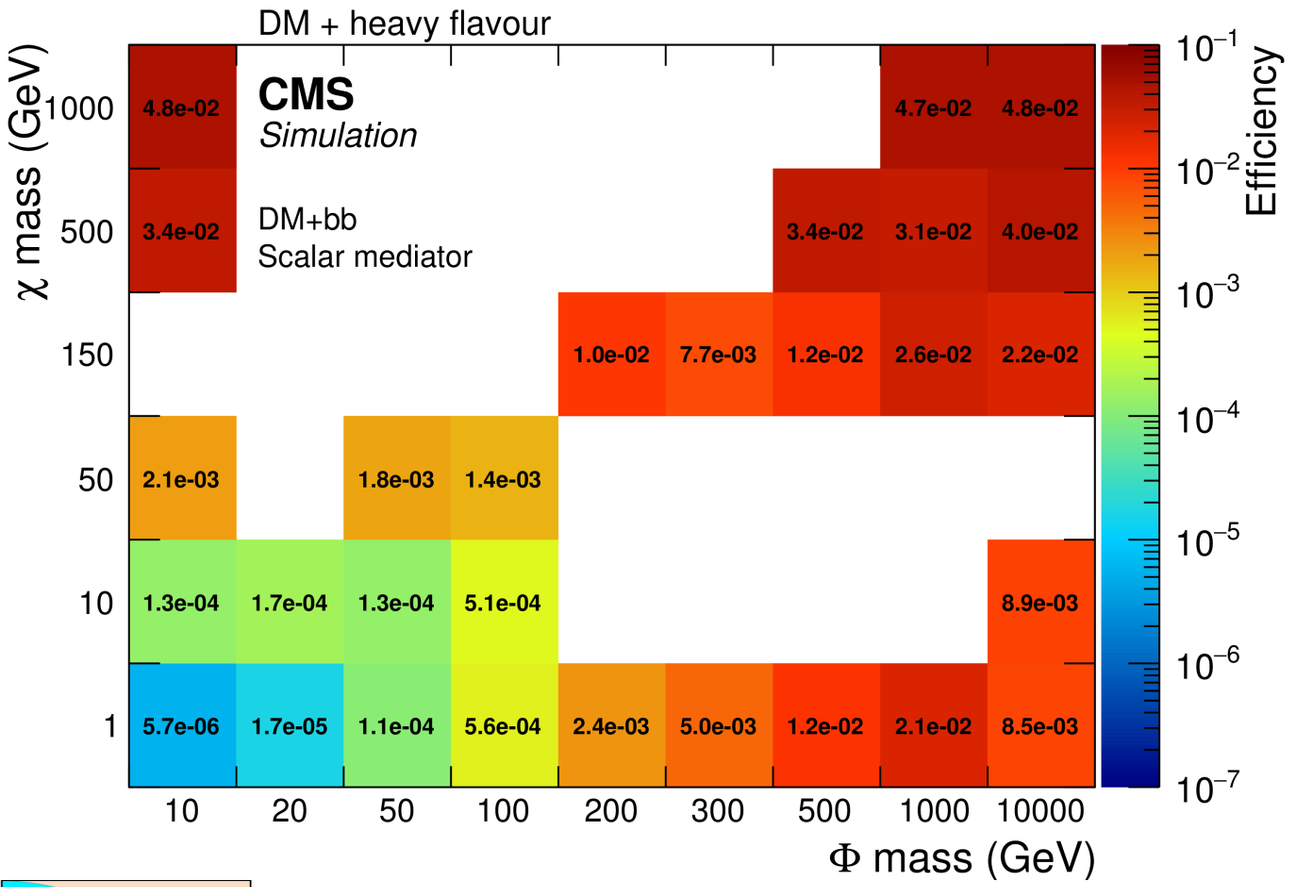
- Signal efficiency from DM+bb MC for a scaler (left) and pseudoscalar (right) mediator



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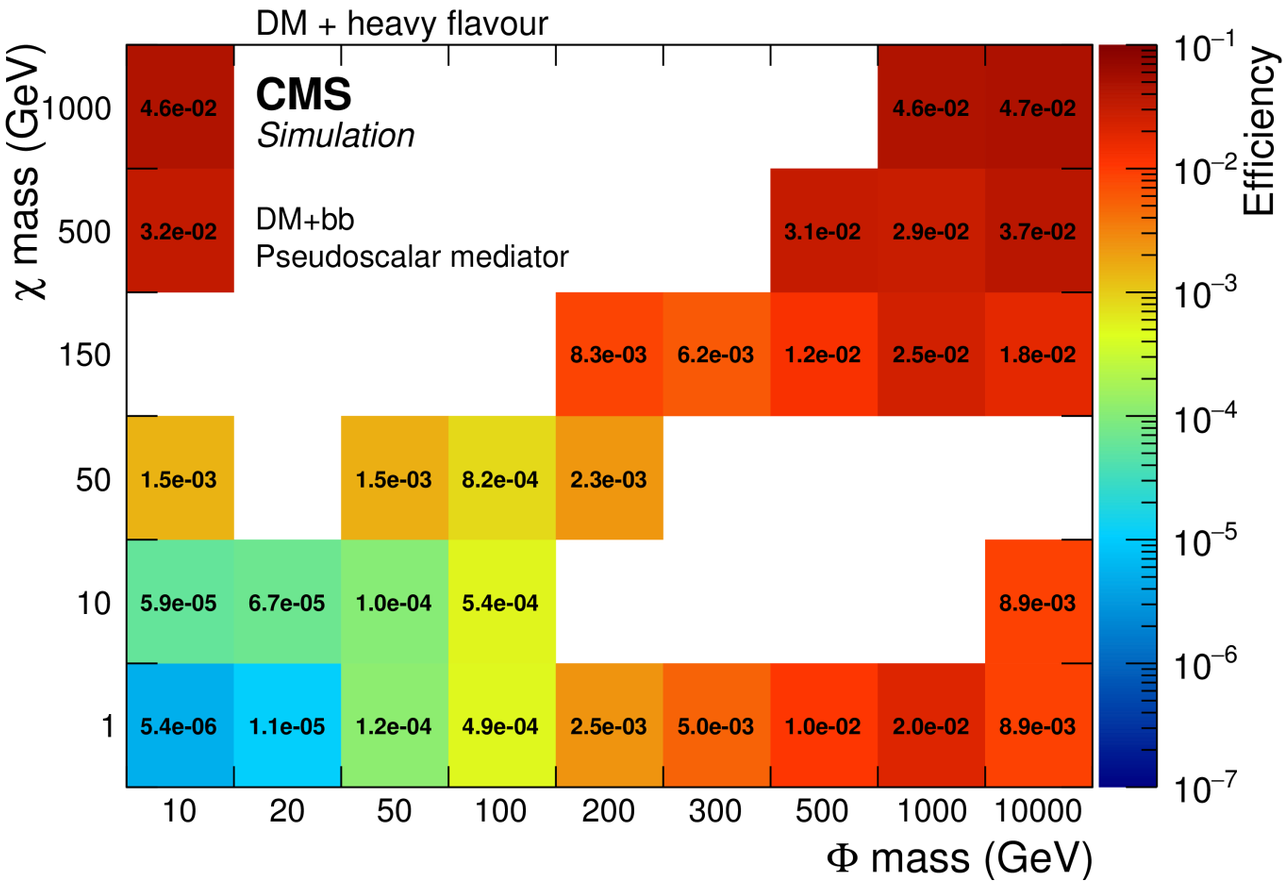

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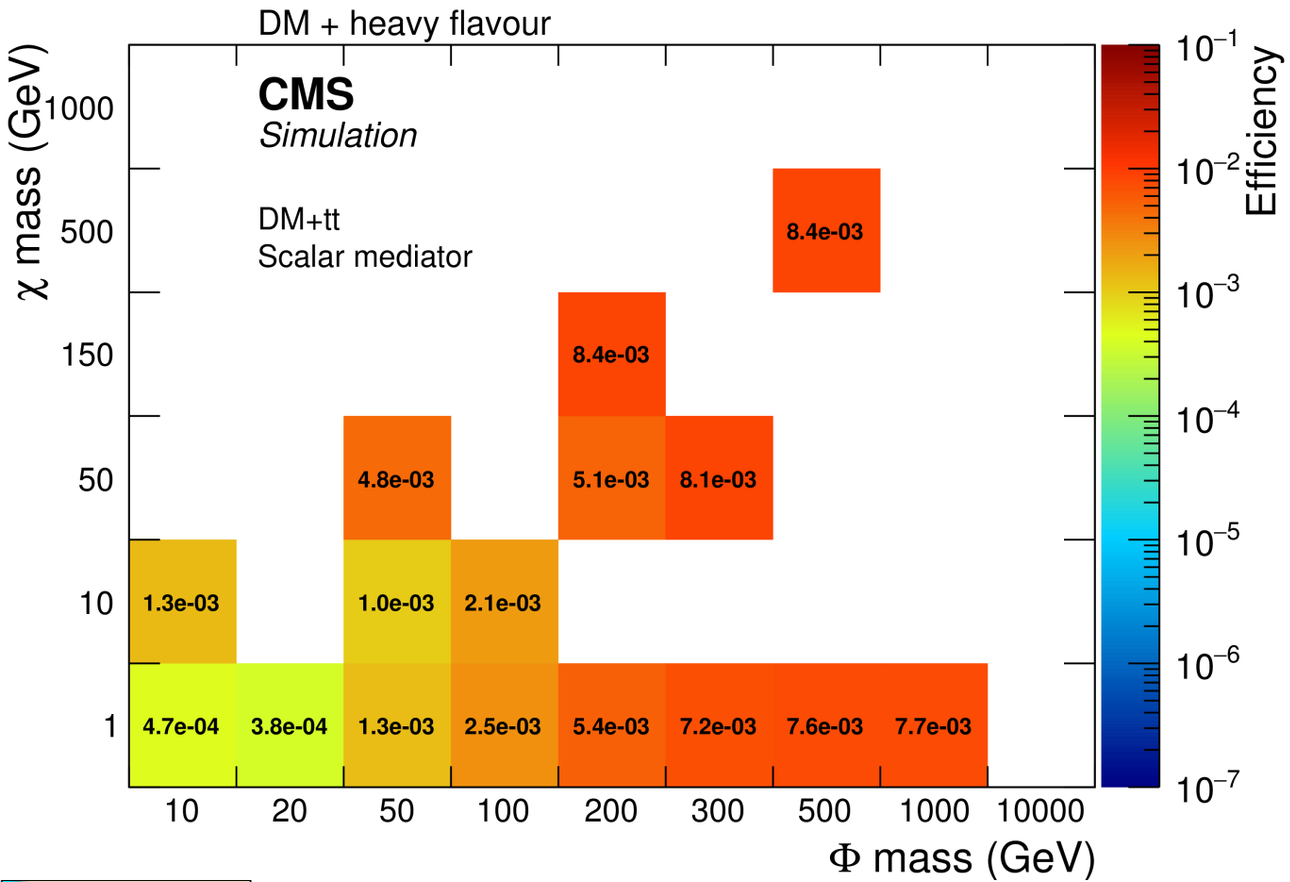
DM+bb: Signal Efficiency

UIC UNIVERSITY OF ILLINOIS AT CHICAGO

- Signal efficiency from DM+tt MC for a scaler (left) and pseudoscalar (right) mediator



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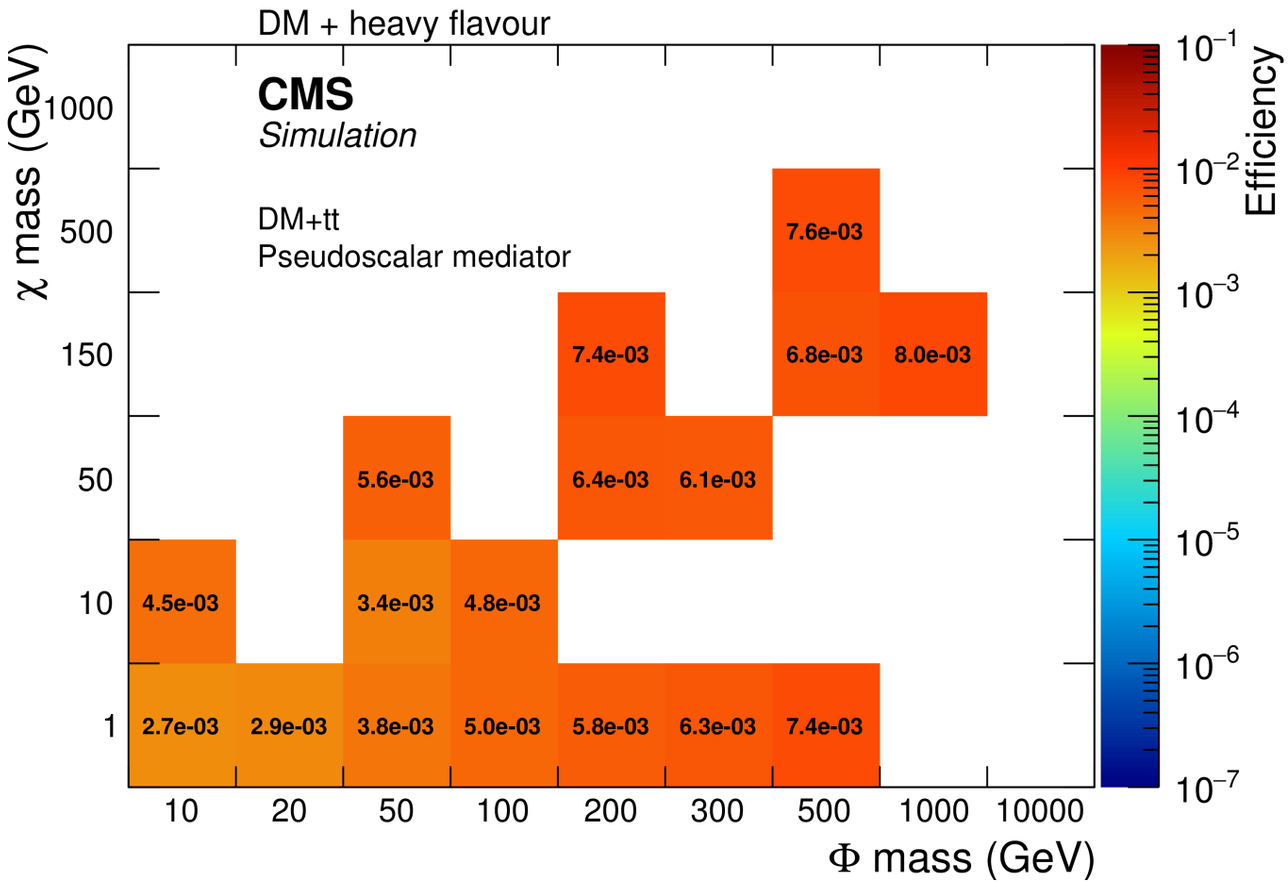

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DM+bb: Mediator Distribution

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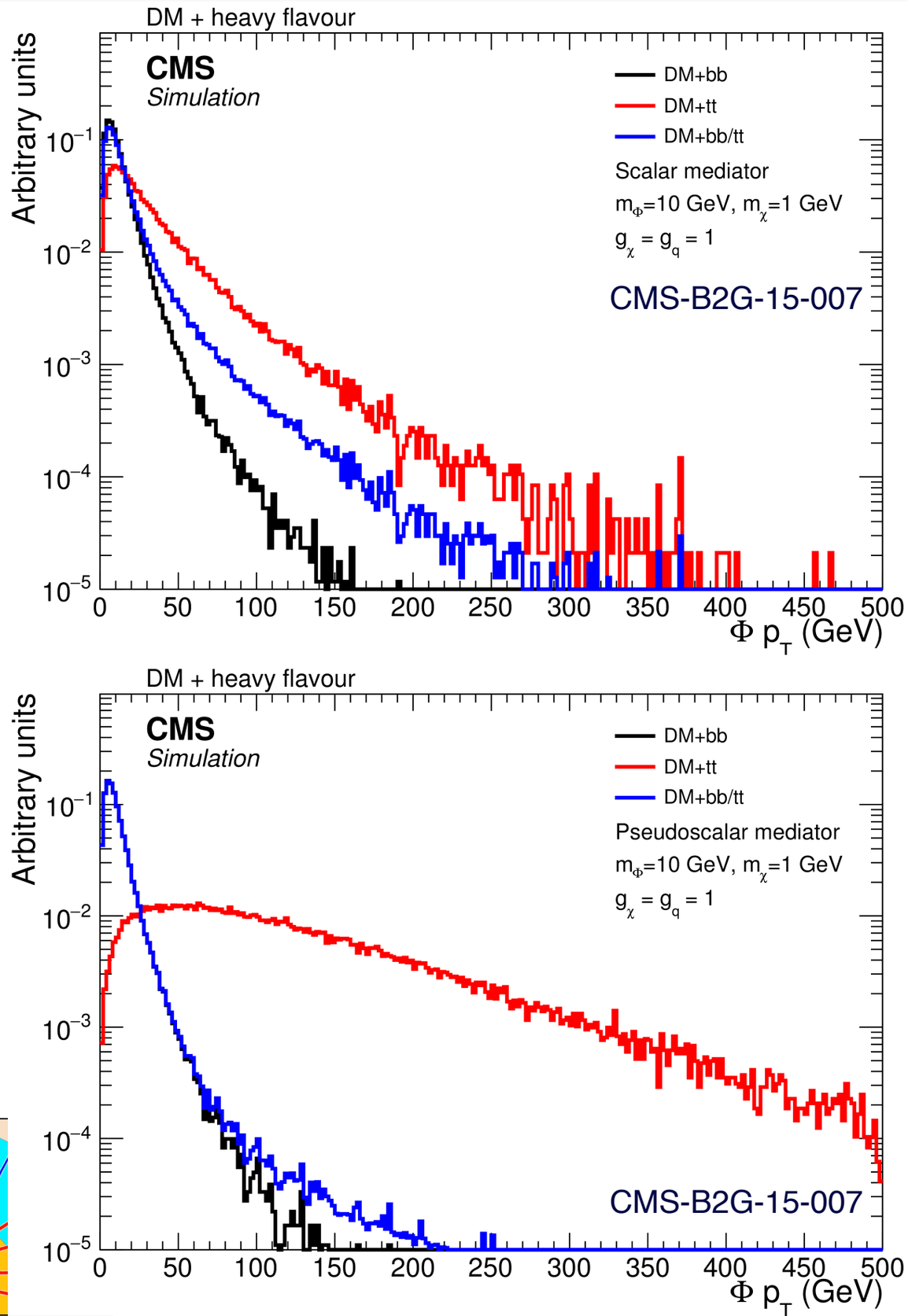

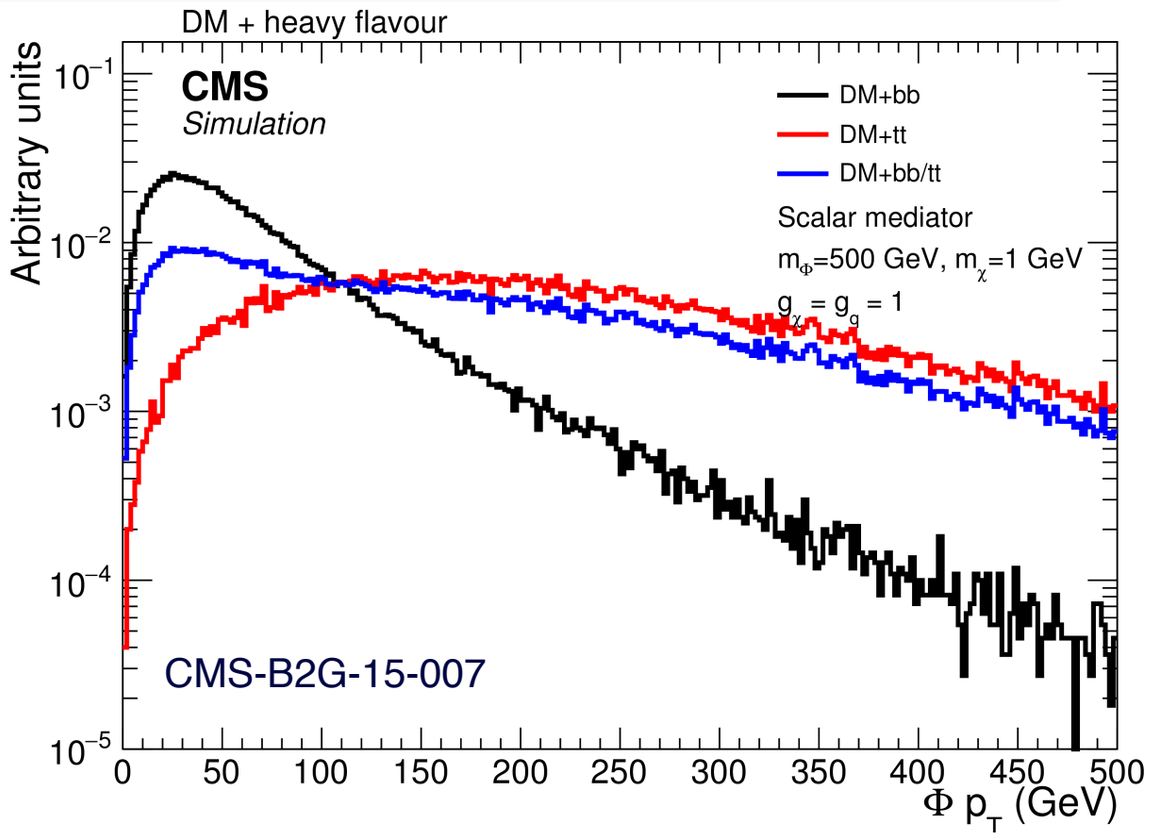

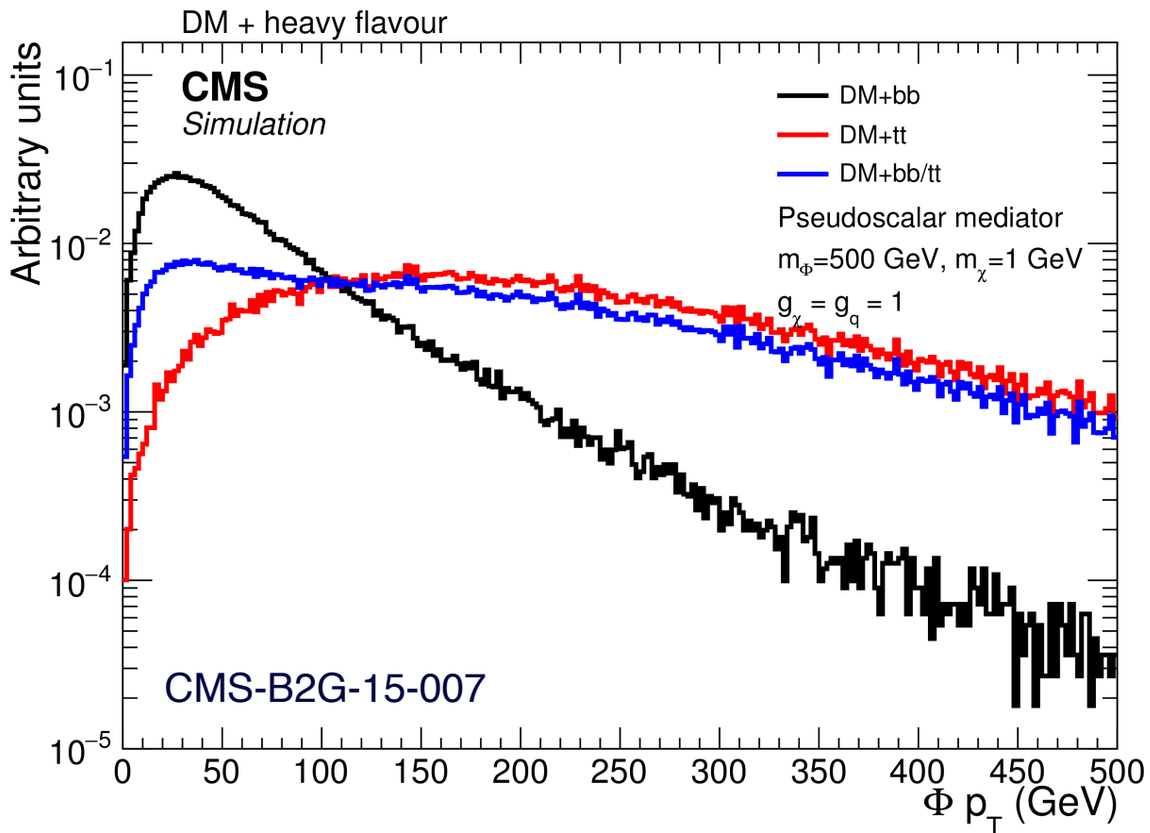

DM+bb: B-jet Distribution

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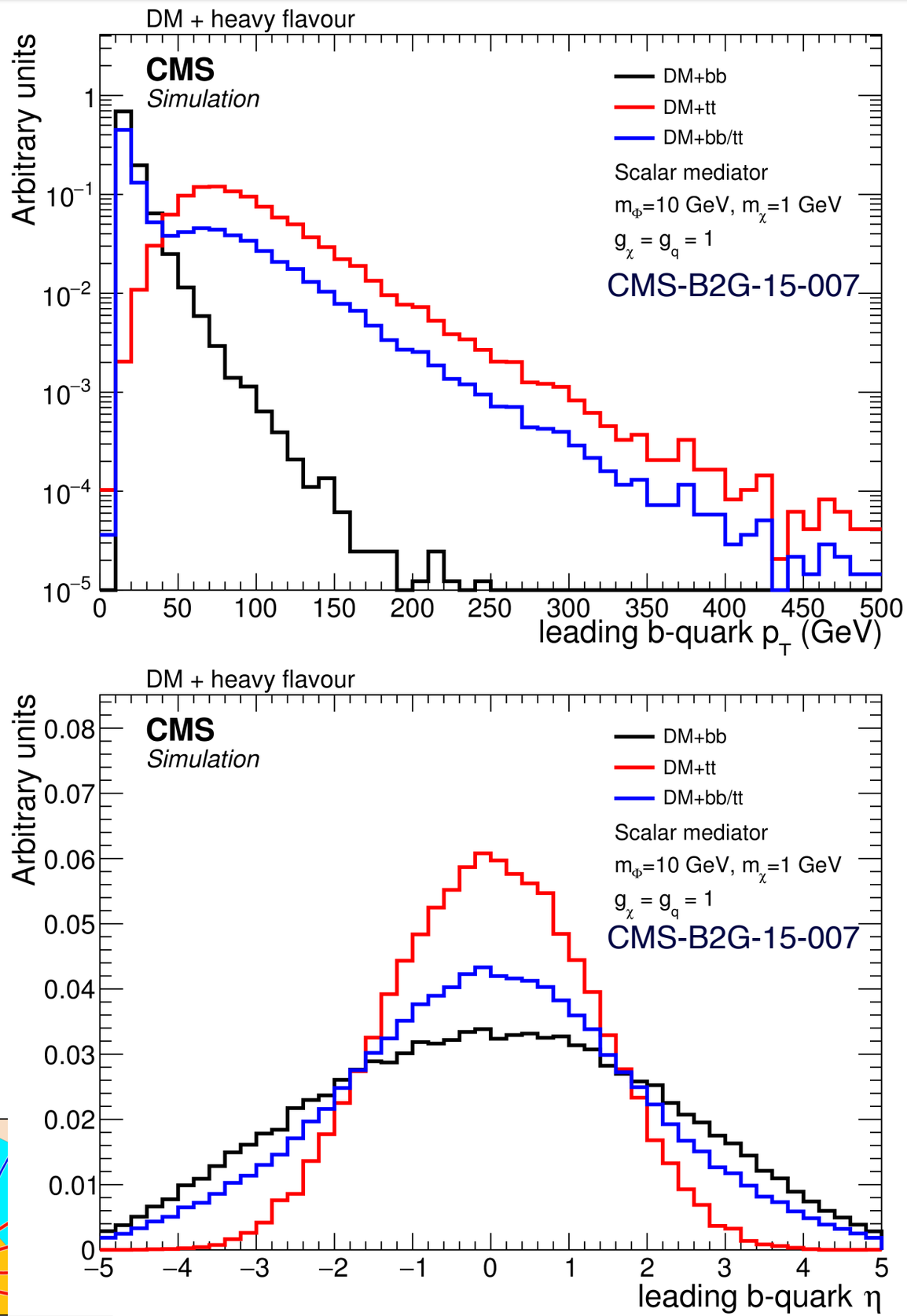

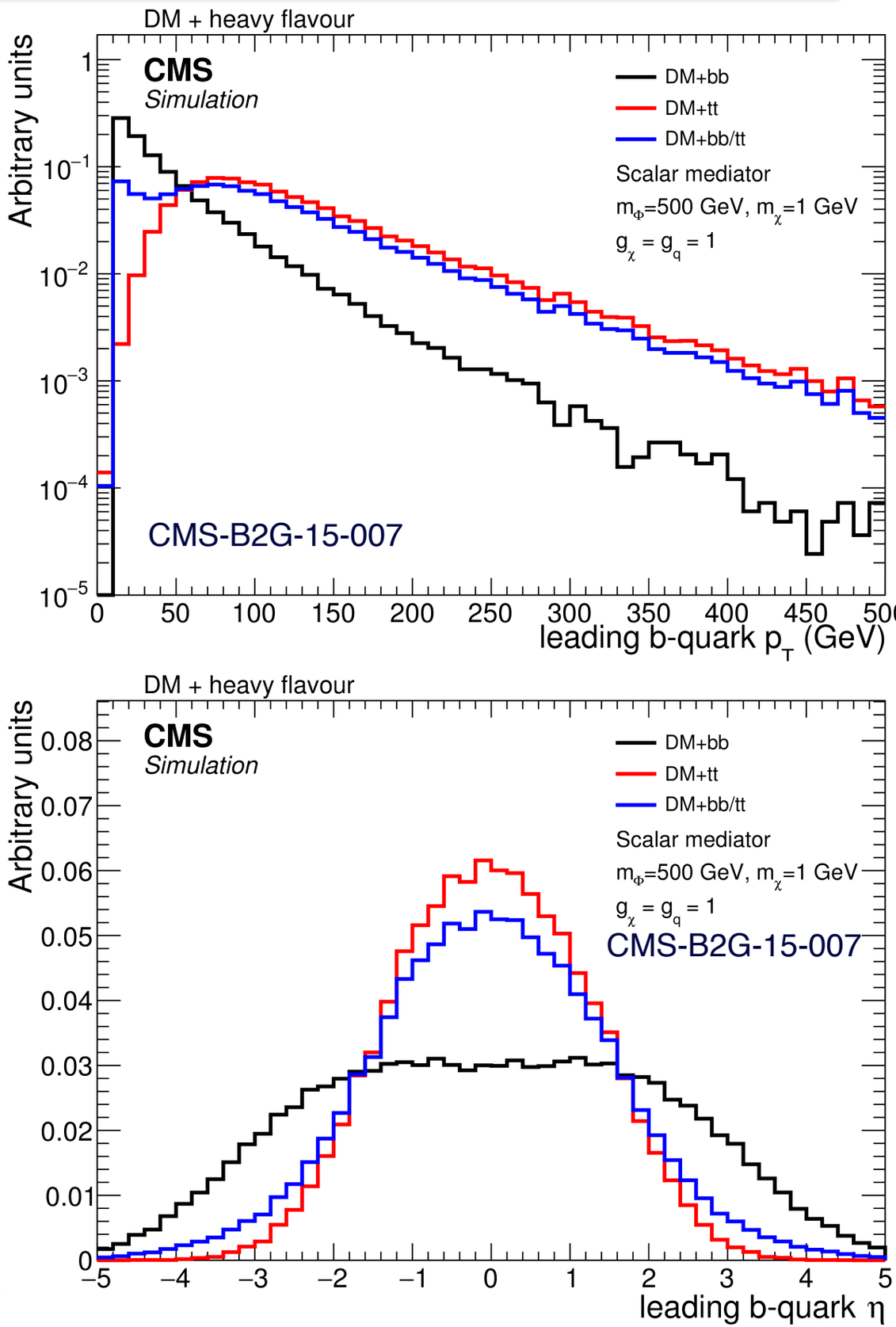

DM+bb: B-jet Distribution

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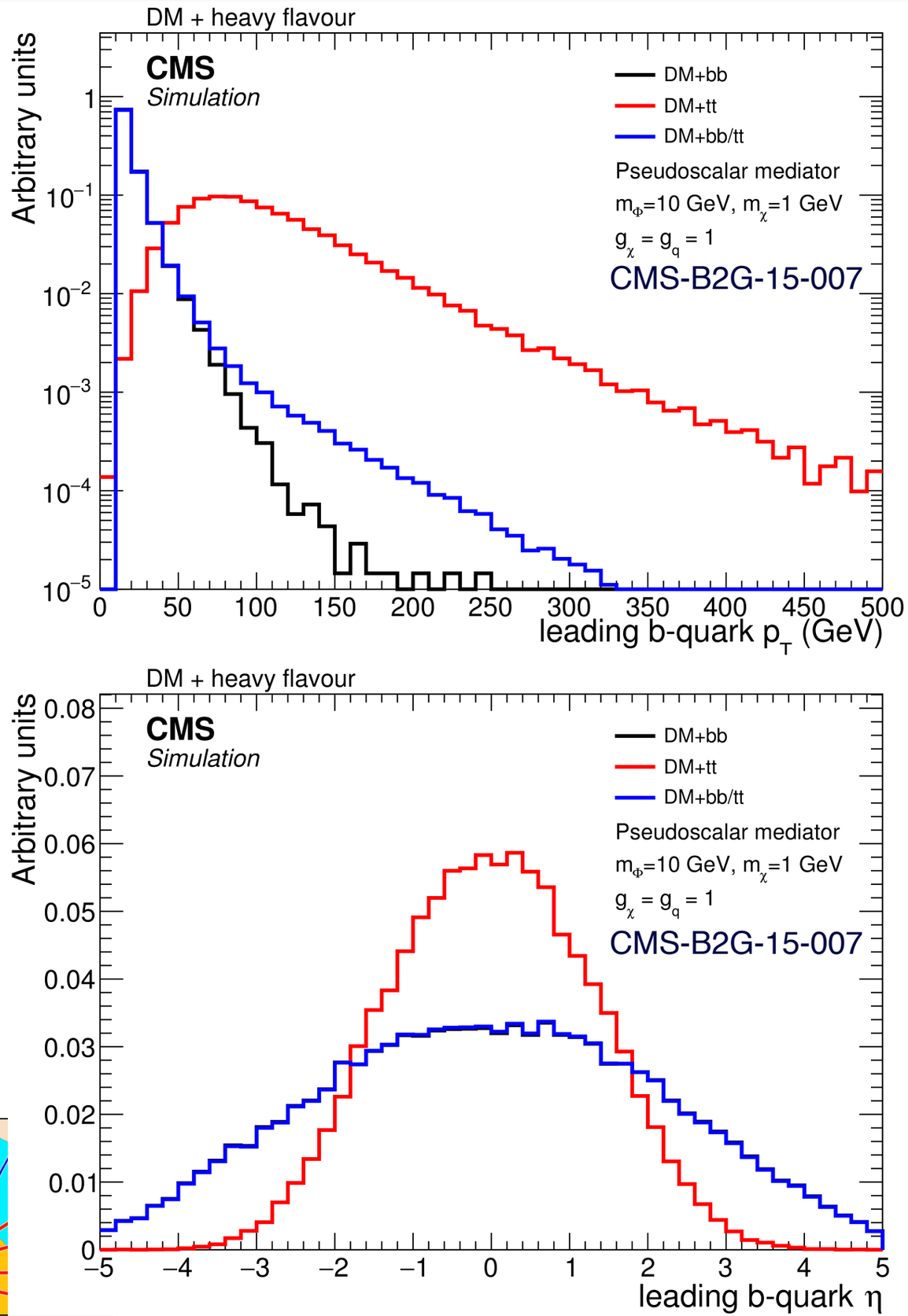

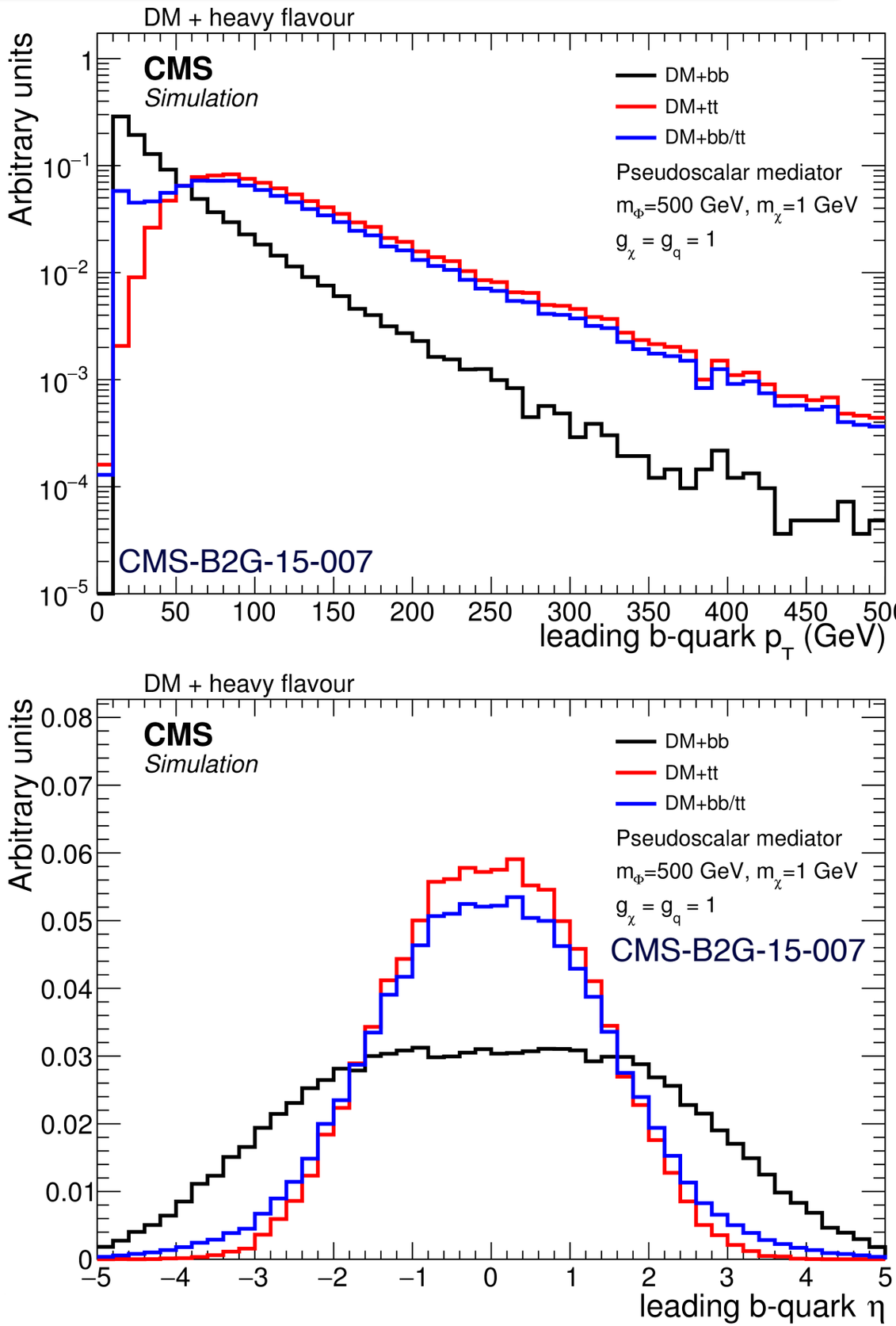

DM+bb: W→μν Control Region

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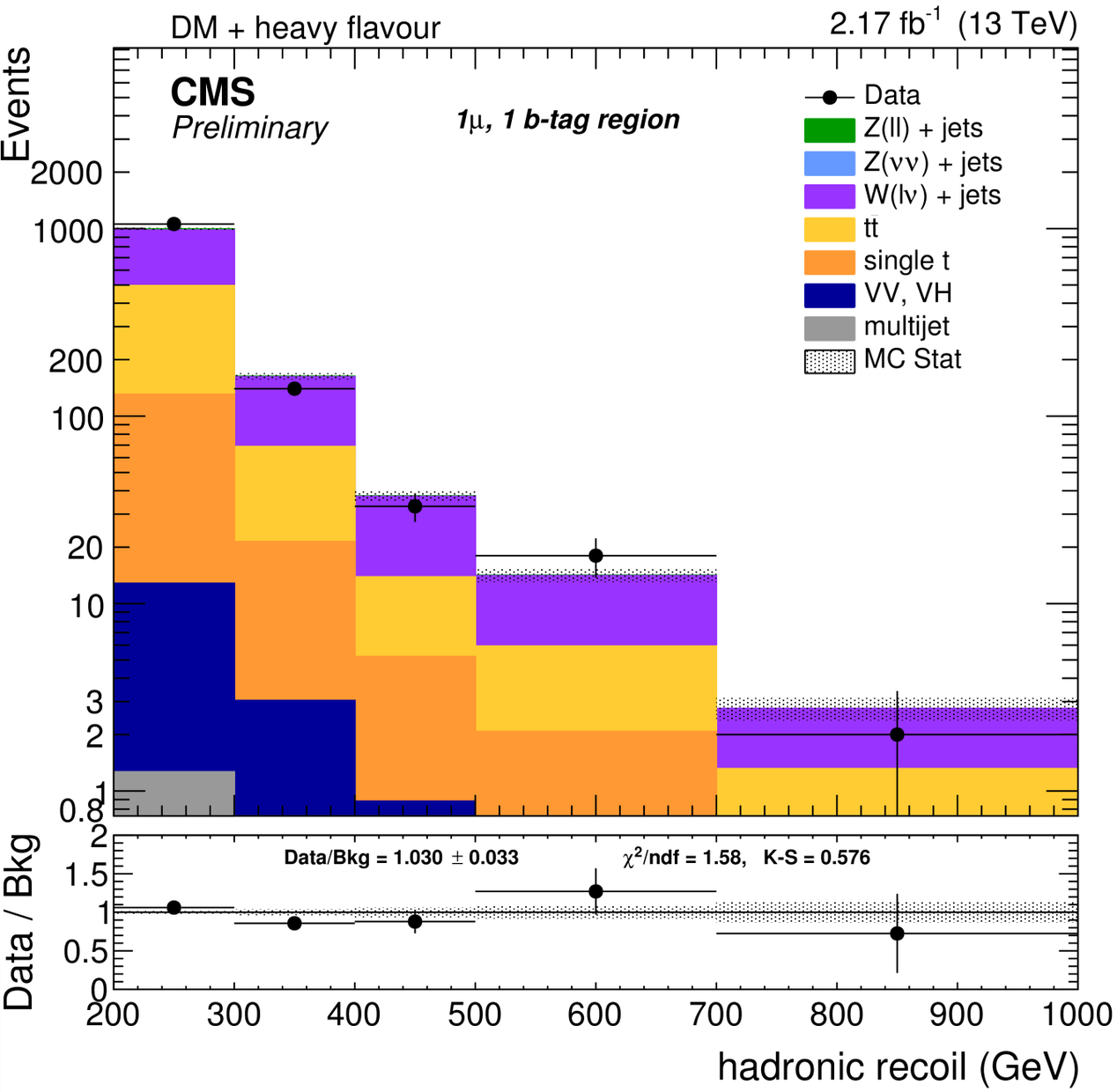
- One Isolated muon that passes the tight criteria
- Additionally, 50 GeV < M_T < 160 GeV



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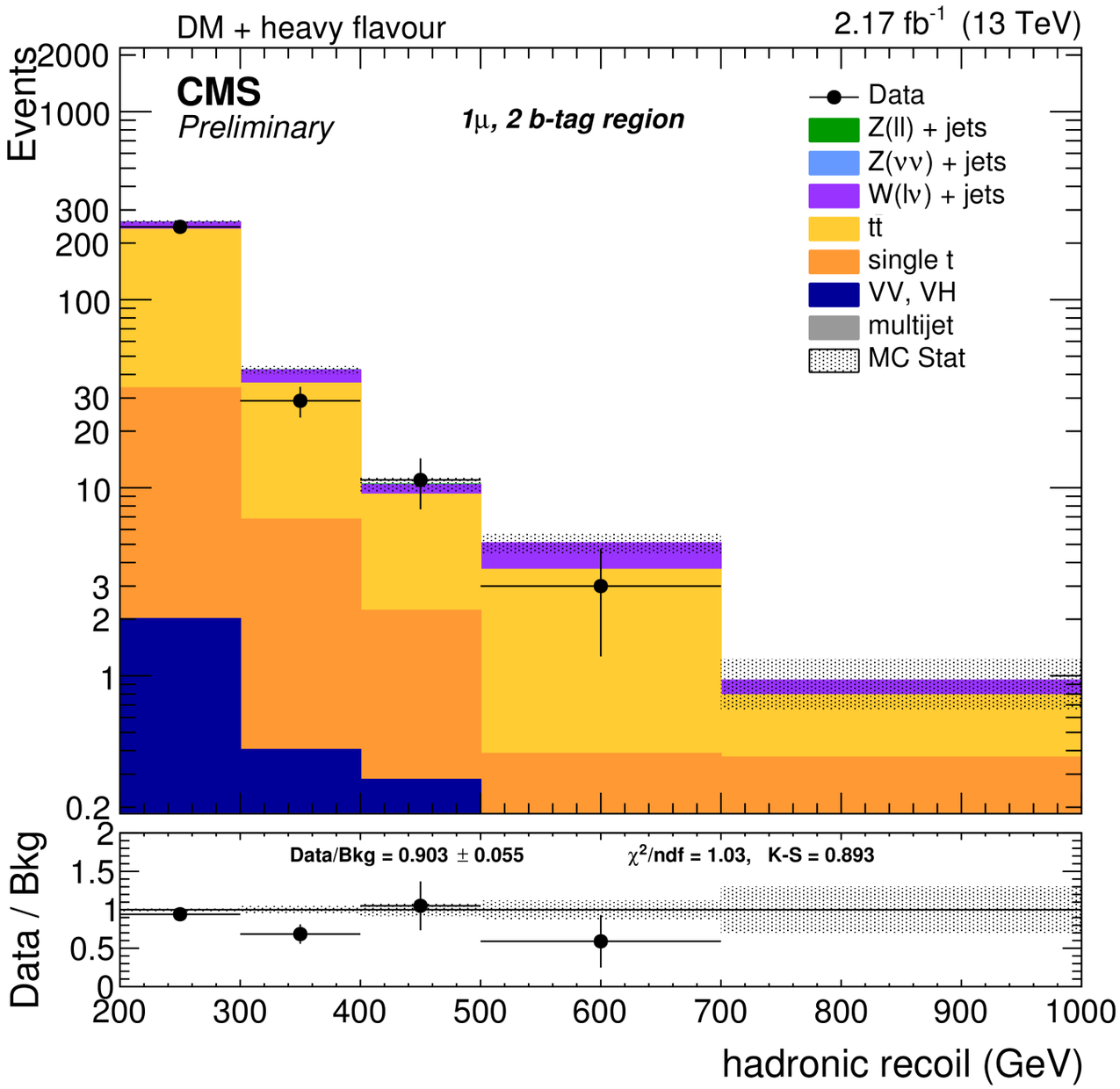

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DM+bb: W→ev Control Region

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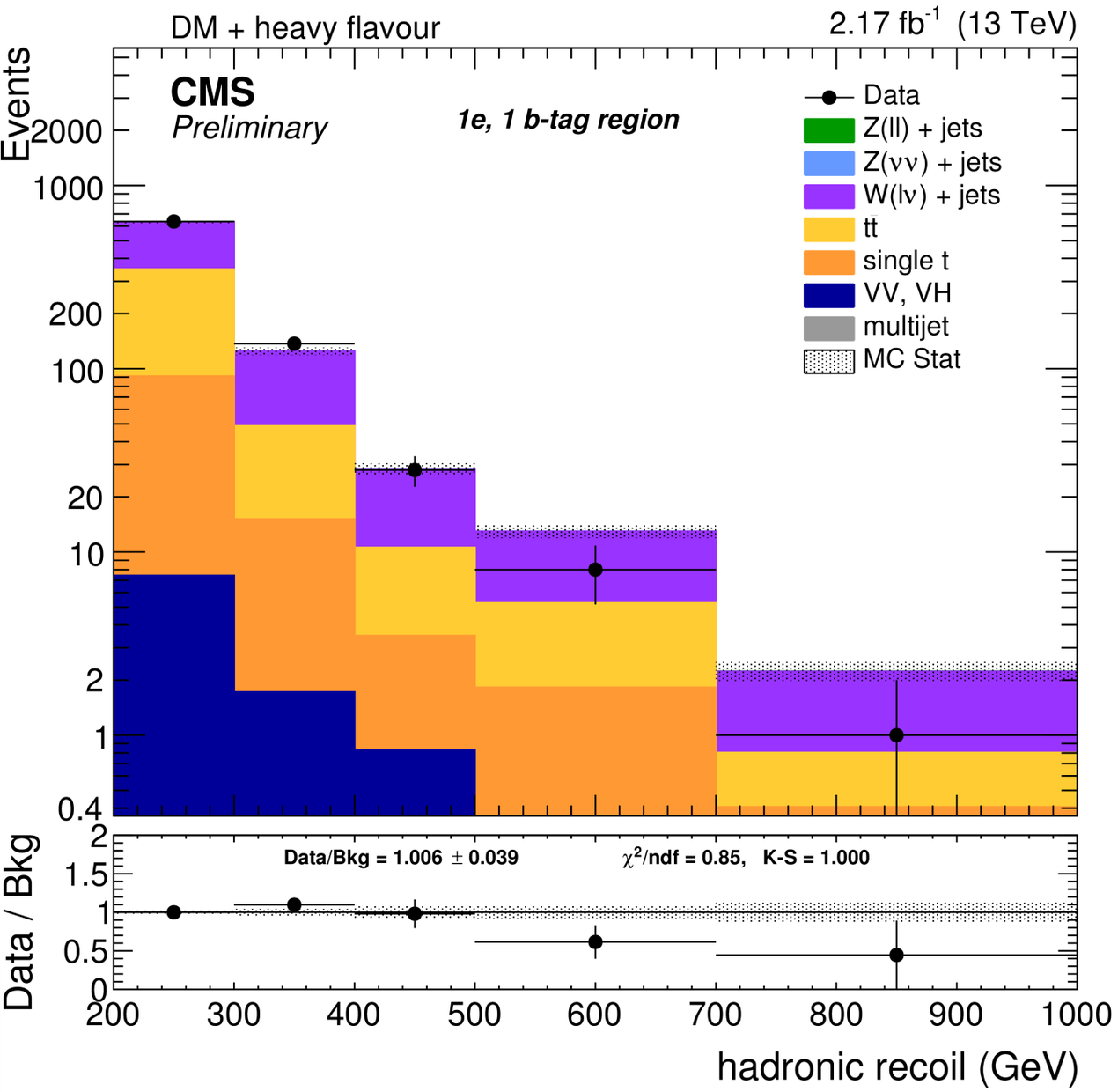
- One Isolated electron that passes the tight criteria
- Additionally, 50 GeV < M_T < 160 GeV



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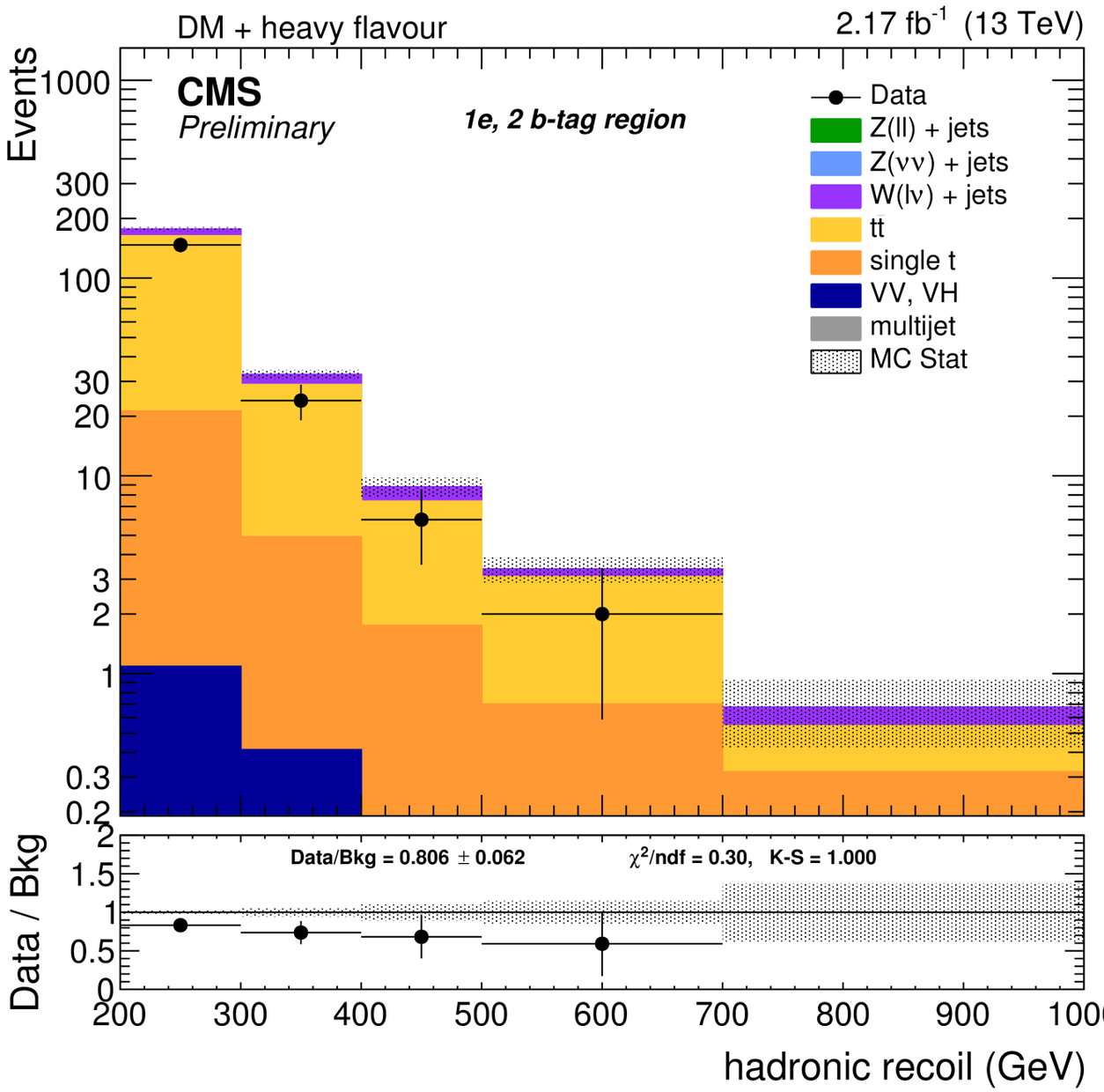

CMS-B2G-15-007

DM+bb: Z→μμ Control Region

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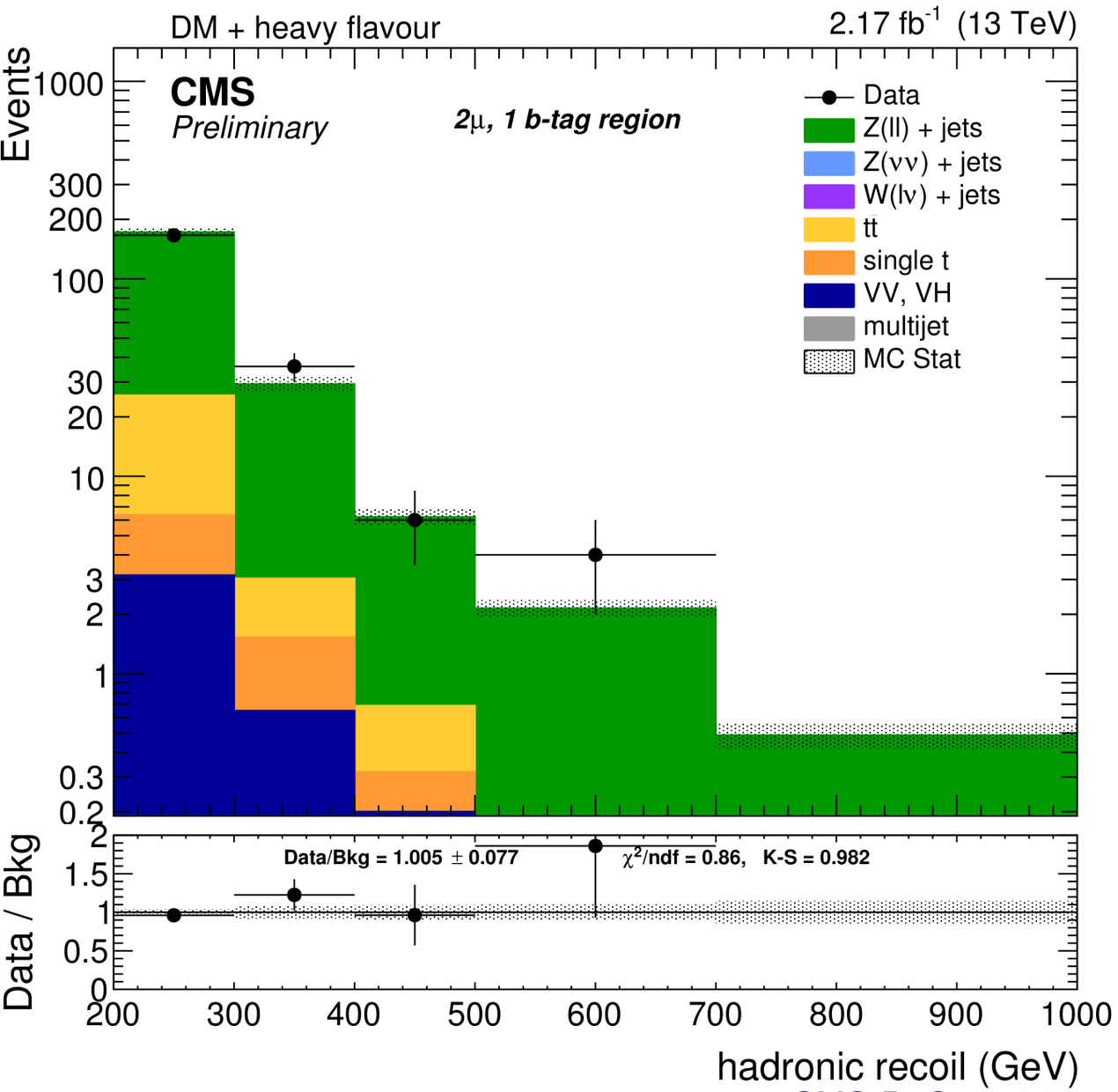
- Control region requires two isolated muons with a 70 GeV < $M_{\mu\mu}$ < 110 GeV
  - Lead muon must pass high isolation criteria
  - Sub-leading muon must pass loose isolation criteria



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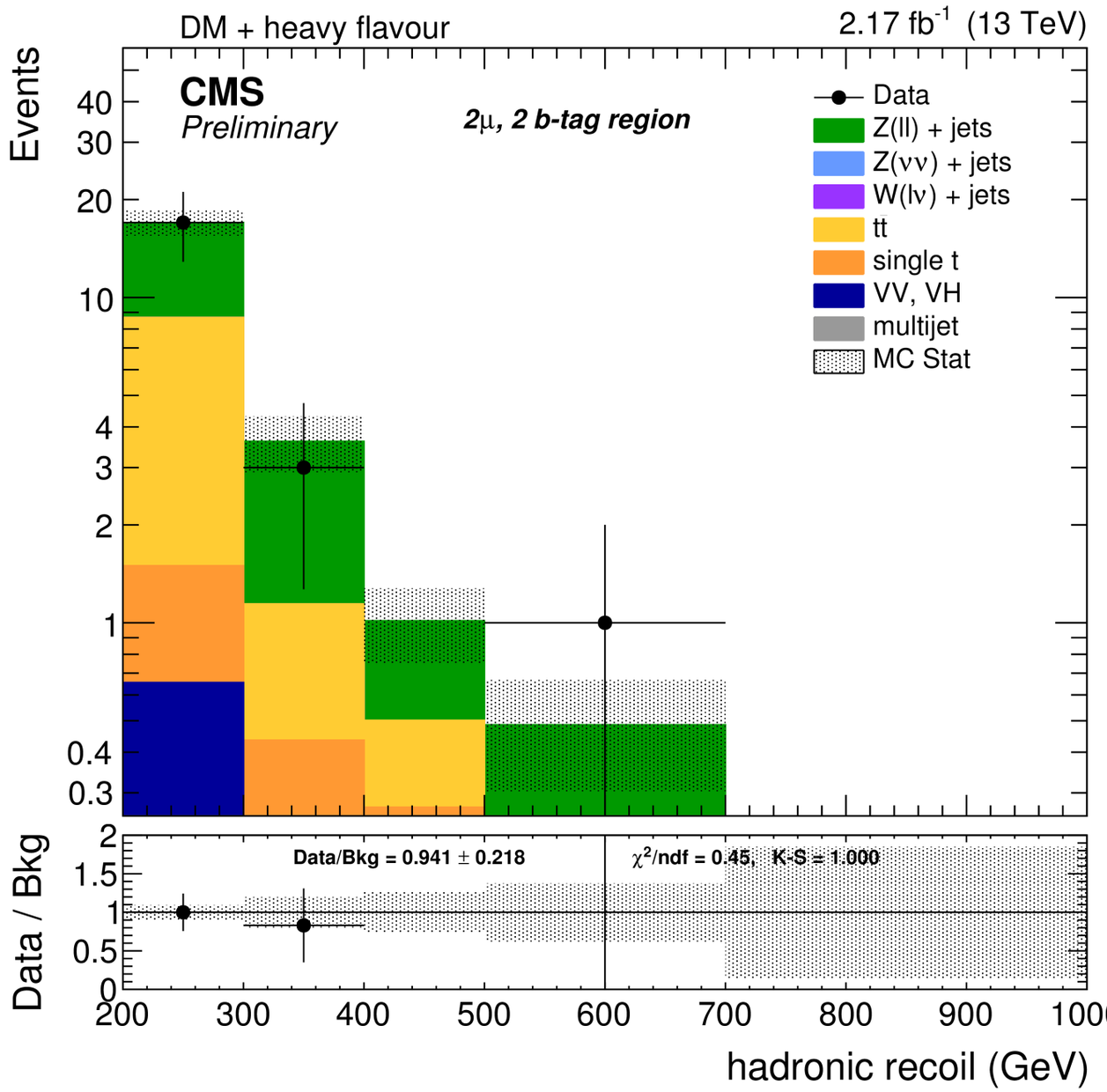

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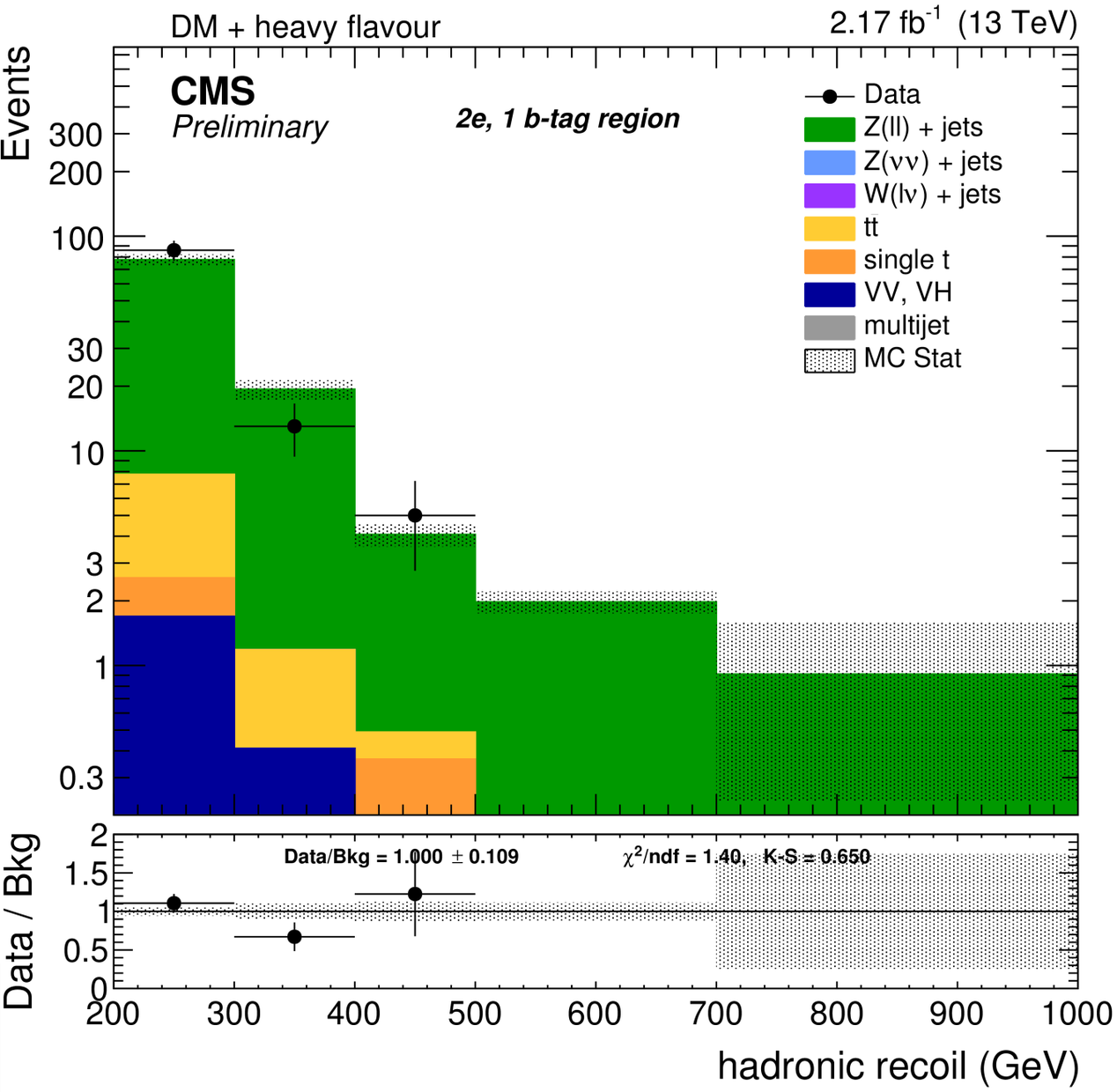
DM+bb: Z→ee Control Region

UIC UNIVERSITY OF ILLINOIS AT CHICAGO

- Control region requires two isolated electrons with a 70 GeV < M_{ee} < 110 GeV
  - Lead electron must pass high isolation criteria
  - Sub-leading electron must pass loose isolation criteria



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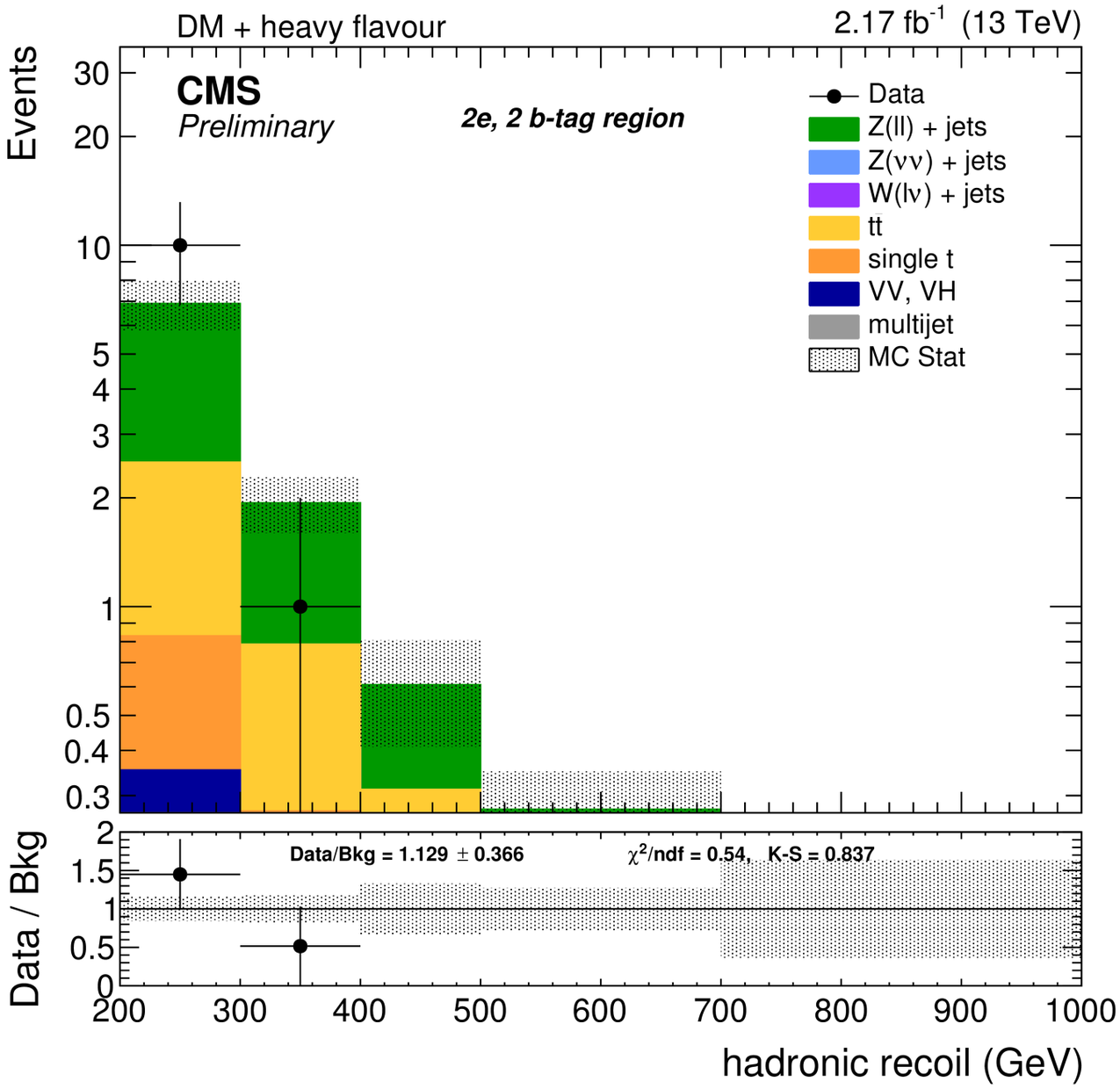

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DM+bb: 1e, 1μ Control Region

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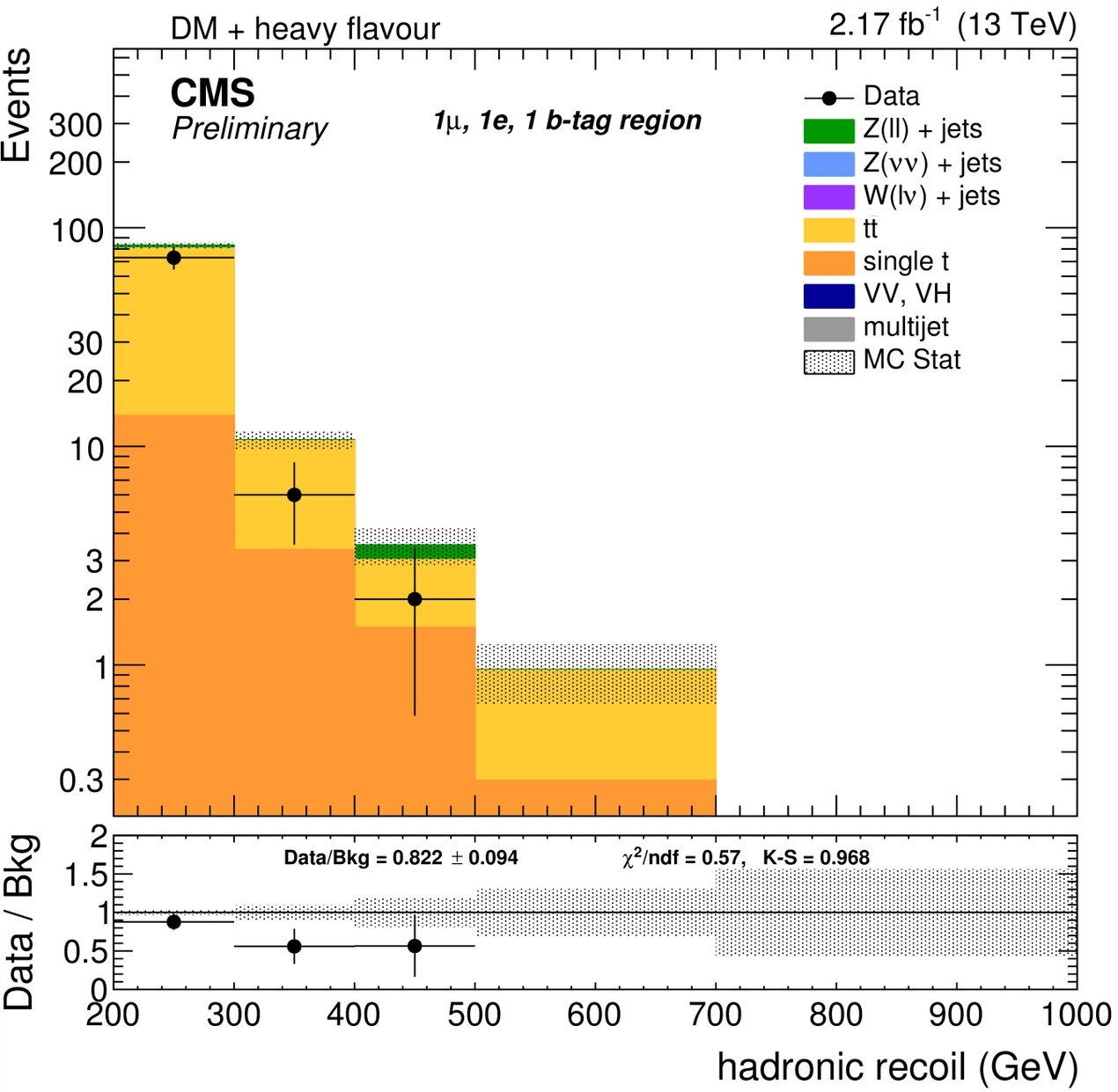
- This control regions accepts opposite sign different flavor leptons
  - Lead lepton must pass the tight isolation criteria
  - Sub-leading lepton must pass the loose isolation criteria
- It is used to control the $t\bar{t}$ and single top background



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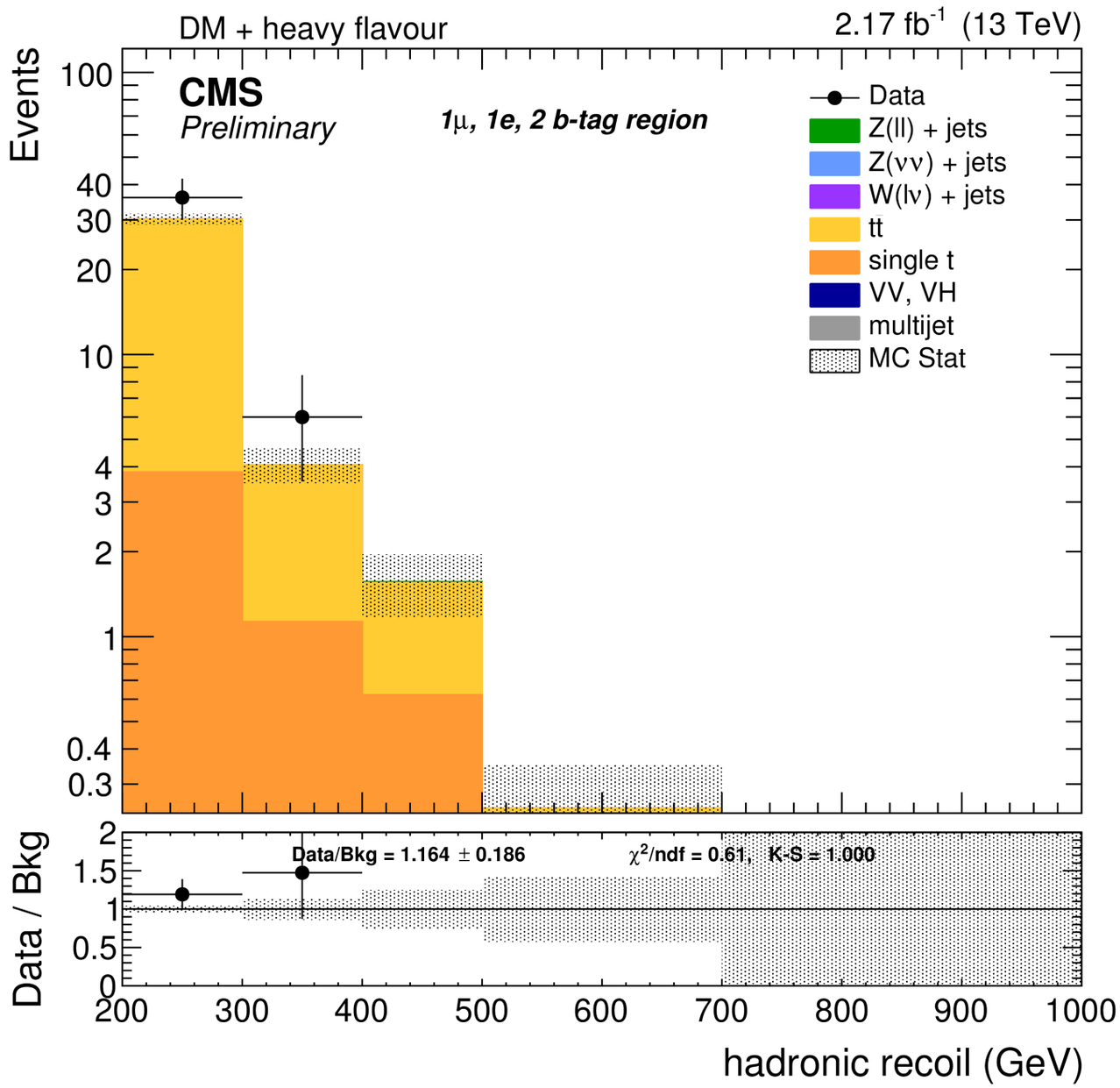

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DM+bb: Systematics

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	process	2ℓ	1ℓ	$1\mu, 1e$	SR1	SR2
MET resolution	all	1%	1%	< 1%	1%	1%
MET scale	all	< 1%	< 1%	< 1%	< 1%	< 1%
JES	VV, ST, multijet	1%	1%	2%	< 1%	1%
b-tagging	all	7%	9%	7%	8%	11%
lepton trigger, id, iso	all	4%	3%	3%	3%	3%
trigger	all		< 1%		< 1%	
pile-up	all	2%	1%	1%	1%	< 1%
Fact. scale	all	4%	3%	4%	4%	4%
Ren. scale	all	7%	6%	12%	5%	6%
EWK corr.	V+jets	4%	2%	< 1%	5%	3%
PDF	all	1%	1%	1%	1%	1%
luminosity	VV, ST, multijet			2.7%		
Other bkg cross section	VV, ST			15%		
Multijet cross section	multijet			50%		

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DM+bb: Limits

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DM+bb Scalar Mediator

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m_χ (GeV) \ m_Φ (GeV)	10	15	20	50	100	200	300	500	1000
1	824	-	93	57	107	291	572	$3.8 \cdot 10^3$	$2.3 \cdot 10^4$
10	$2.7 \cdot 10^3$	$1.8 \cdot 10^3$	-	54	61	-	-	-	-
50	-	-	-	$1.2 \cdot 10^4$	$7.1 \cdot 10^3$	-	-	-	-
100	-	-	-	-	-	-	-	-	-
150	-	-	-	-	-	$7.2 \cdot 10^4$	$2.7 \cdot 10^4$	$4.7 \cdot 10^3$	$2.8 \cdot 10^4$
500	$8.0 \cdot 10^6$	-	-	-	-	-	-	$5.0 \cdot 10^6$	$6.9 \cdot 10^5$

DM+bb Pseudoscalar Mediator

CMS-B2G-15-007

m_χ (GeV) \ m_Φ (GeV)	10	15	20	50	100	200	300	500	1000
1	$1.0 \cdot 10^4$	-	143	96	117	268	671	$5.0 \cdot 10^3$	$3.1 \cdot 10^4$
10	-	340	-	74	60	-	-	-	-
50	$1.1 \cdot 10^4$	-	-	$7.0 \cdot 10^3$	$2.9 \cdot 10^3$	360	-	-	-
100	-	-	-	-	-	-	-	-	-
150	-	-	-	-	-	$2.8 \cdot 10^4$	$7.3 \cdot 10^3$	$5.9 \cdot 10^3$	$2.4 \cdot 10^4$
500	$3.3 \cdot 10^6$	-	-	-	-	-	-	-	-

Combined DM+bb,tt Scalar Mediator

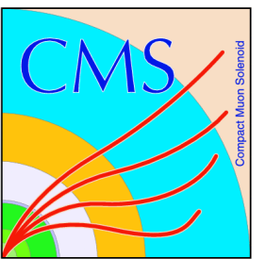
CMS-B2G-15-007

m_χ (GeV) \ m_Φ (GeV)	10	15	20	50	100	200	300	500	1000
1	5.0	-	11	8.3	27	50	126	704	$5.1 \cdot 10^3$
10	455	-	-	13	52	-	-	-	-
50	-	-	-	$2.6 \cdot 10^3$	-	-	-	-	-
100	-	-	-	-	-	-	-	-	-
150	-	-	-	-	-	$1.8 \cdot 10^4$	-	-	-
500	-	-	-	-	-	-	-	$8.0 \cdot 10^5$	-

Combined DM+bb,tt Pseudoscalar Mediator

CMS-B2G-15-007

m_χ (GeV) \ m_Φ (GeV)	10	15	20	50	100	200	300	500	1000
1	26	-	47	42	45	53	98	578	-
10	660	-	-	22	38	-	-	-	-
50	-	-	-	$1.3 \cdot 10^3$	-	67	-	-	-
100	-	-	-	-	-	-	-	-	-
150	-	-	-	-	-	$9.3 \cdot 10^3$	-	914	$6.6 \cdot 10^3$
500	-	-	-	-	-	-	-	$2.8 \cdot 10^5$	-



DM+bb: DM+tt Limits

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DM+tt Scalar Mediator

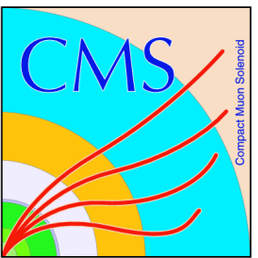
		m_Φ (GeV)								
$\sigma/\sigma(g_\chi, g_q = 1)$		10	15	20	50	100	200	300	500	1000
m_χ (GeV)	1	5.0	-	12	9.0	31	55	136	776	$5.6 \cdot 10^3$
	10	442	-	-	12	49	-	-	-	-
	50	-	-	-	$2.9 \cdot 10^3$	-	47	81	-	-
	100	-	-	-	-	-	-	-	-	-
	150	-	-	-	-	-	$1.9 \cdot 10^4$	-	-	-
	500	-	-	-	-	-	-	-	$1.3 \cdot 10^6$	-

CMS-B2G-15-007

DM+tt Pseudo Scalar Mediator

		m_Φ (GeV)								
$\sigma/\sigma(g_\chi, g_q = 1)$		10	15	20	50	100	200	300	500	1000
m_χ (GeV)	1	26	-	42	54	60	59	105	633	-
	10	$1.1 \cdot 10^3$	-	-	22	49	-	-	-	-
	50	-	-	-	$1.4 \cdot 10^3$	-	71	163	-	-
	100	-	-	-	-	-	-	-	-	-
	150	-	-	-	-	-	$1.1 \cdot 10^4$	-	$1.0 \cdot 10^3$	$7.1 \cdot 10^3$
	500	-	-	-	-	-	-	-	$3.5 \cdot 10^5$	-

CMS-B2G-15-007



DM+bb: Limits Continued

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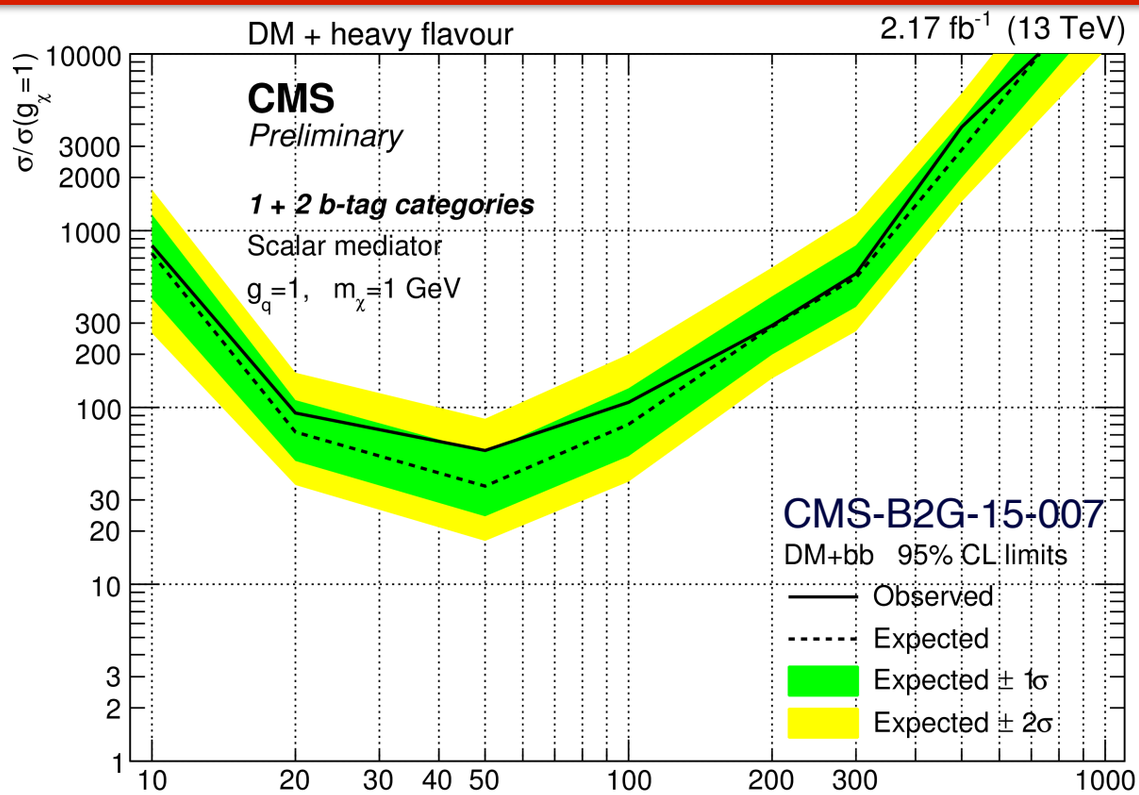

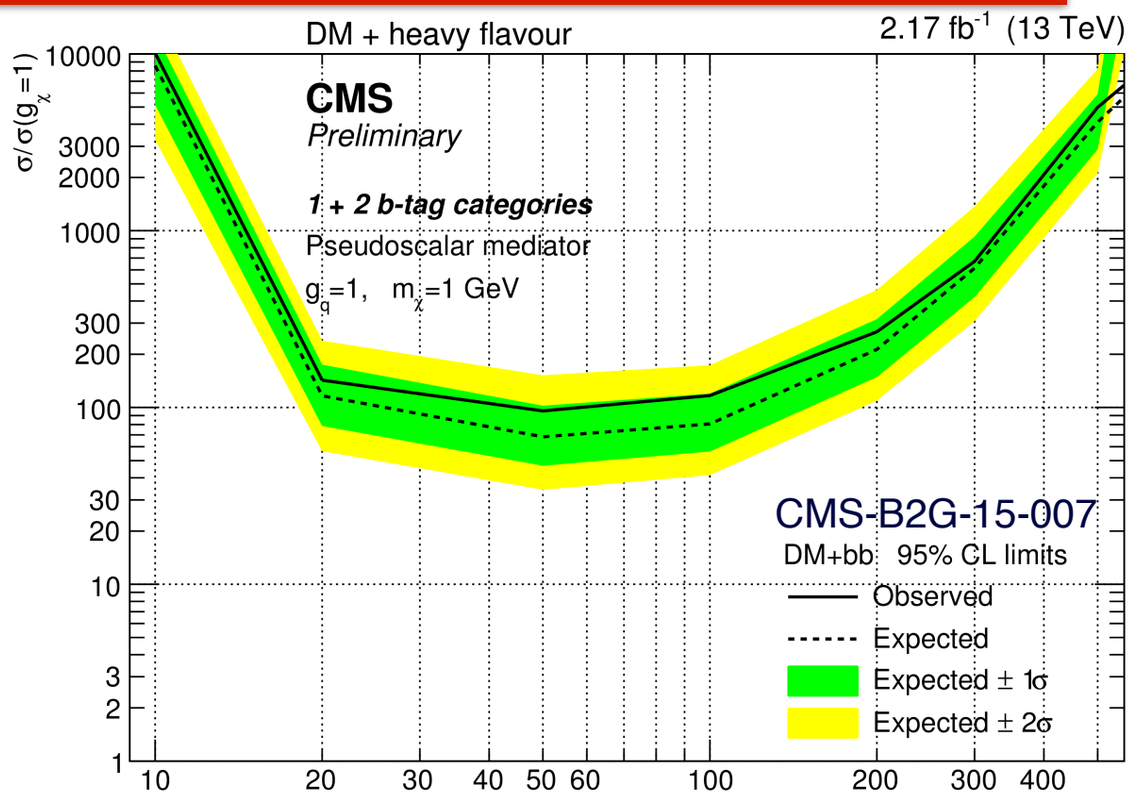

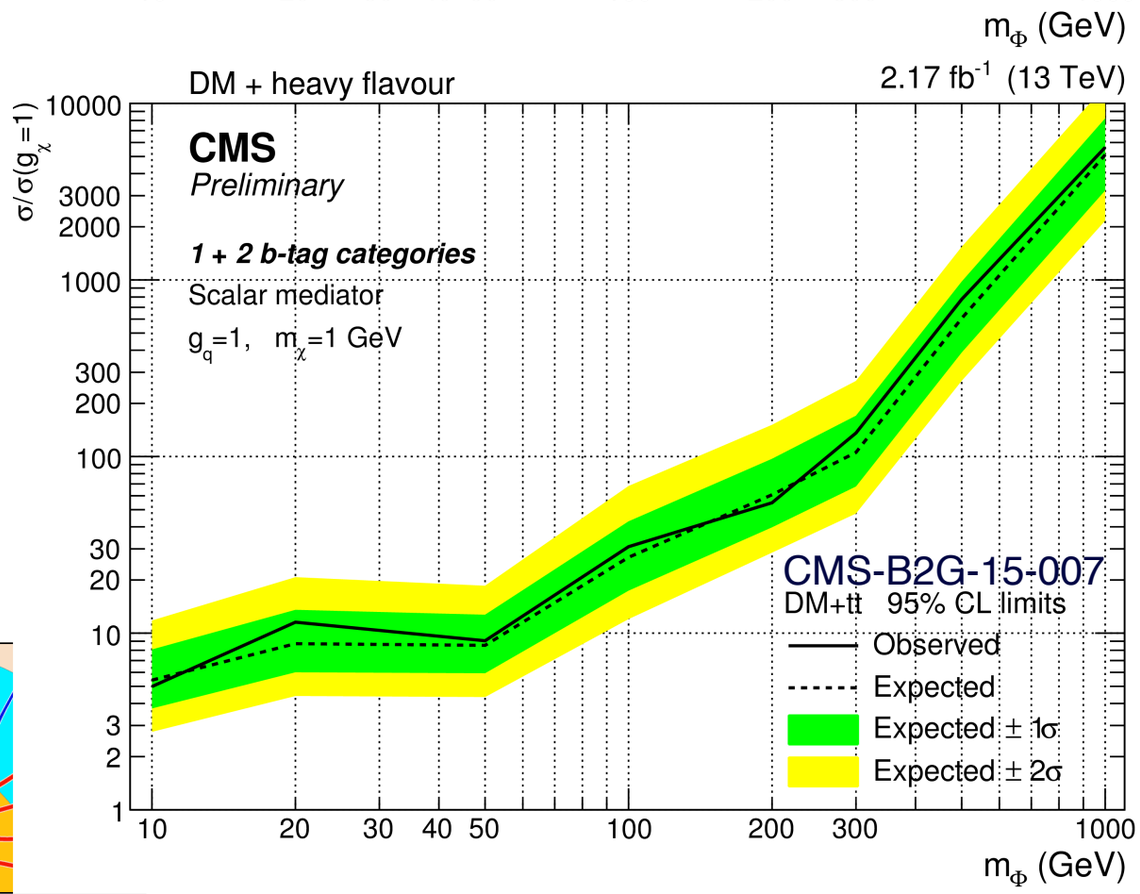

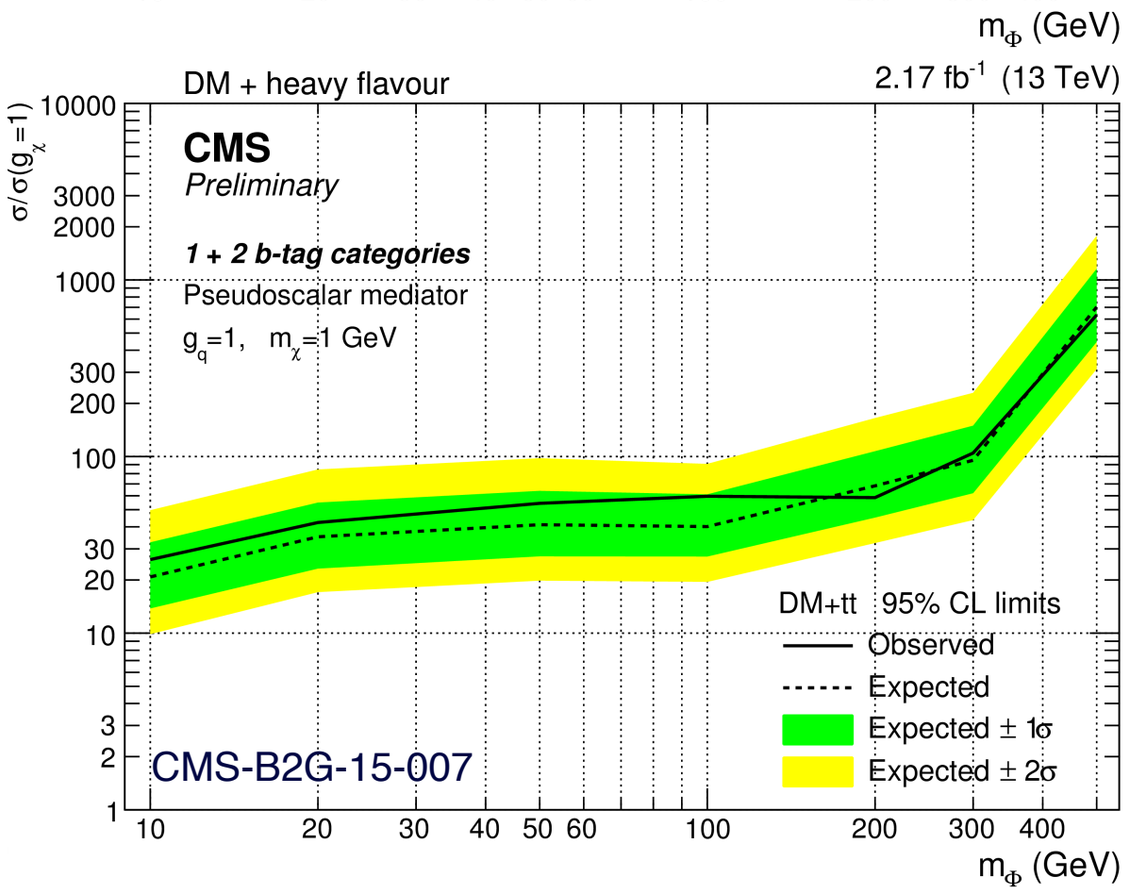

DM+Monotop: Data and MC Sample

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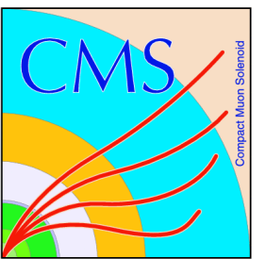
- DM+Monotop samples are generated in MADGRAPHv5 with PYTHIA8 used for parton showering
- $t\bar{t}$ and tW samples generated with POWHEG interfaced with PYTHIA
- S and t-channel single top samples generated with aMC@NLO
- All DiBoson samples generated with aMC@NLO
- Z+Jets→νν generated in MADGRAPH
- W+Jets, Drell-Yan+Jets, γ+Jets, and QCD samples generated in MADGRAPHv5 and shower matching via PYTHIA8

Dataset
/MET/Run2015D
/SingleElectron/Run2015D
/SinglePhoton/Run2015D



DM+Monotop: Event Selection

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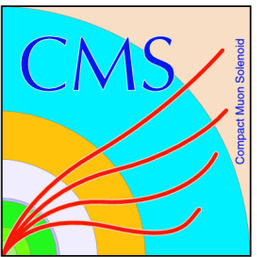
- MET > 90 GeV or MHT > 90 GeV trigger
- MET > 250 GeV
- 1 CA15 t-jet with a $p_T > 250$ GeV and $|\eta| < 2.5$
  - $\tau_{32} < 0.61$
  - 110 GeV $< M_{jet} <$ 210 GeV
    - AK4 sub-jet b-tag (CSV > 0.76)
- Veto isolated e/μ with $p_T > 10$ GeV, γ with $p_T > 15$ GeV, and τ with $p_T > 18$ GeV
- Veto b-tagged AK4 jets with $\Delta R > 2.0$
- $\Delta\phi(j_{AK4}, MET) > 1.1$



DM+Monotop: Di-Lepton Control Region

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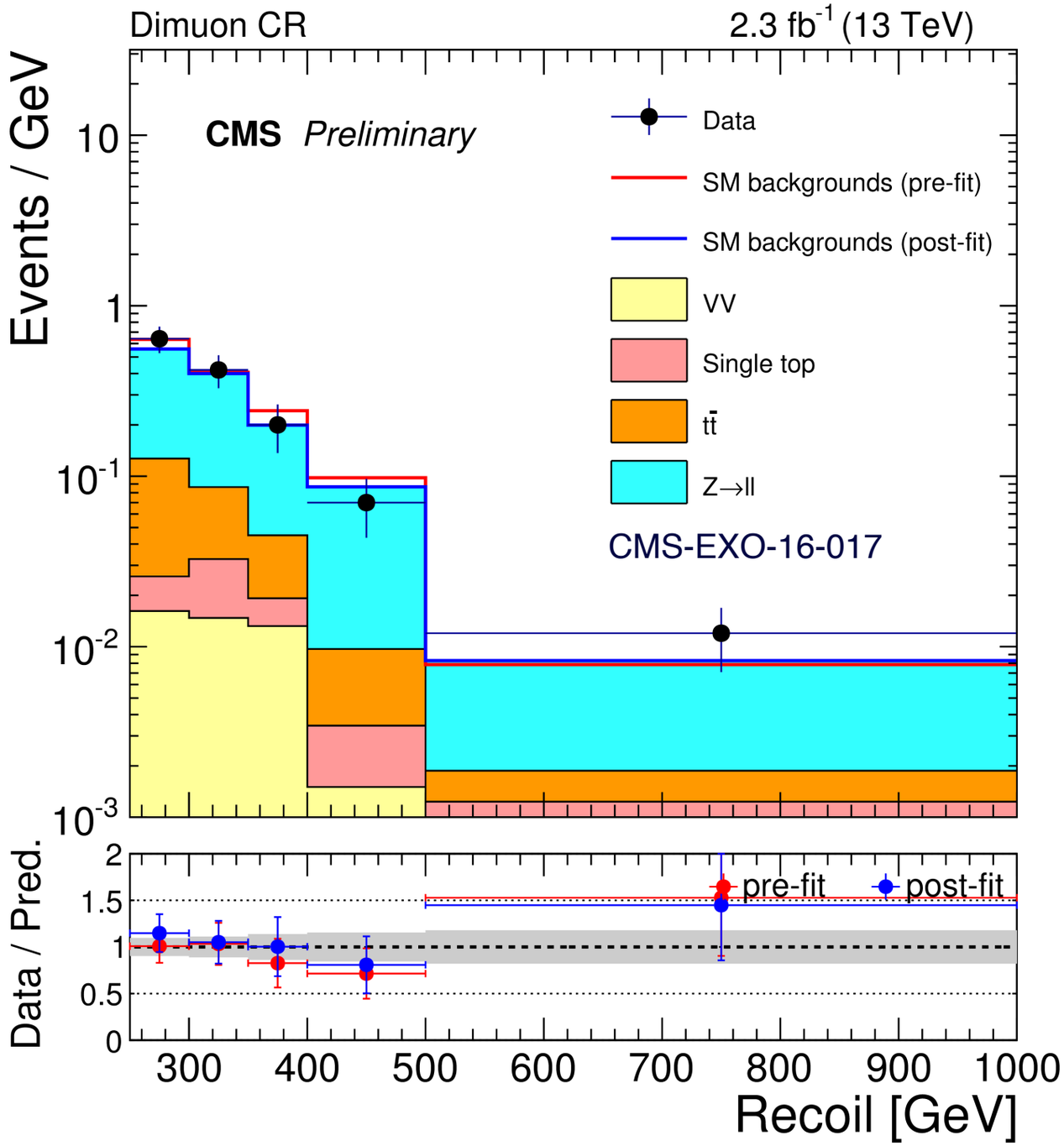
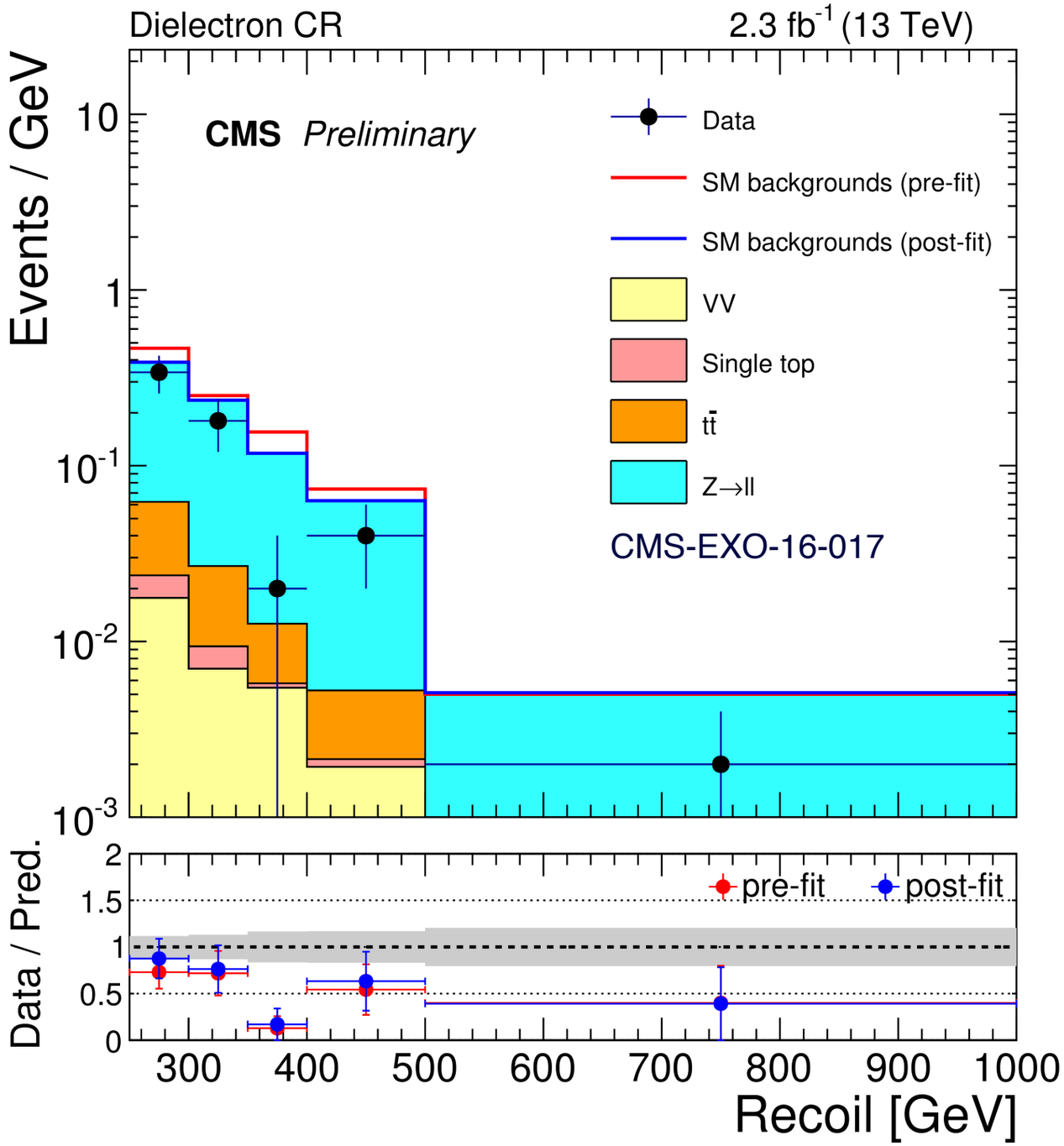
- *U* used instead of MET (*U* > 250 GeV)
- Two isolated muons (p_T >20 GeV and |η| < 2.4) or electrons (p_T >40 GeV and |η| < 2.5)





DM+Monotop: Single Lepton No B-Tag CR

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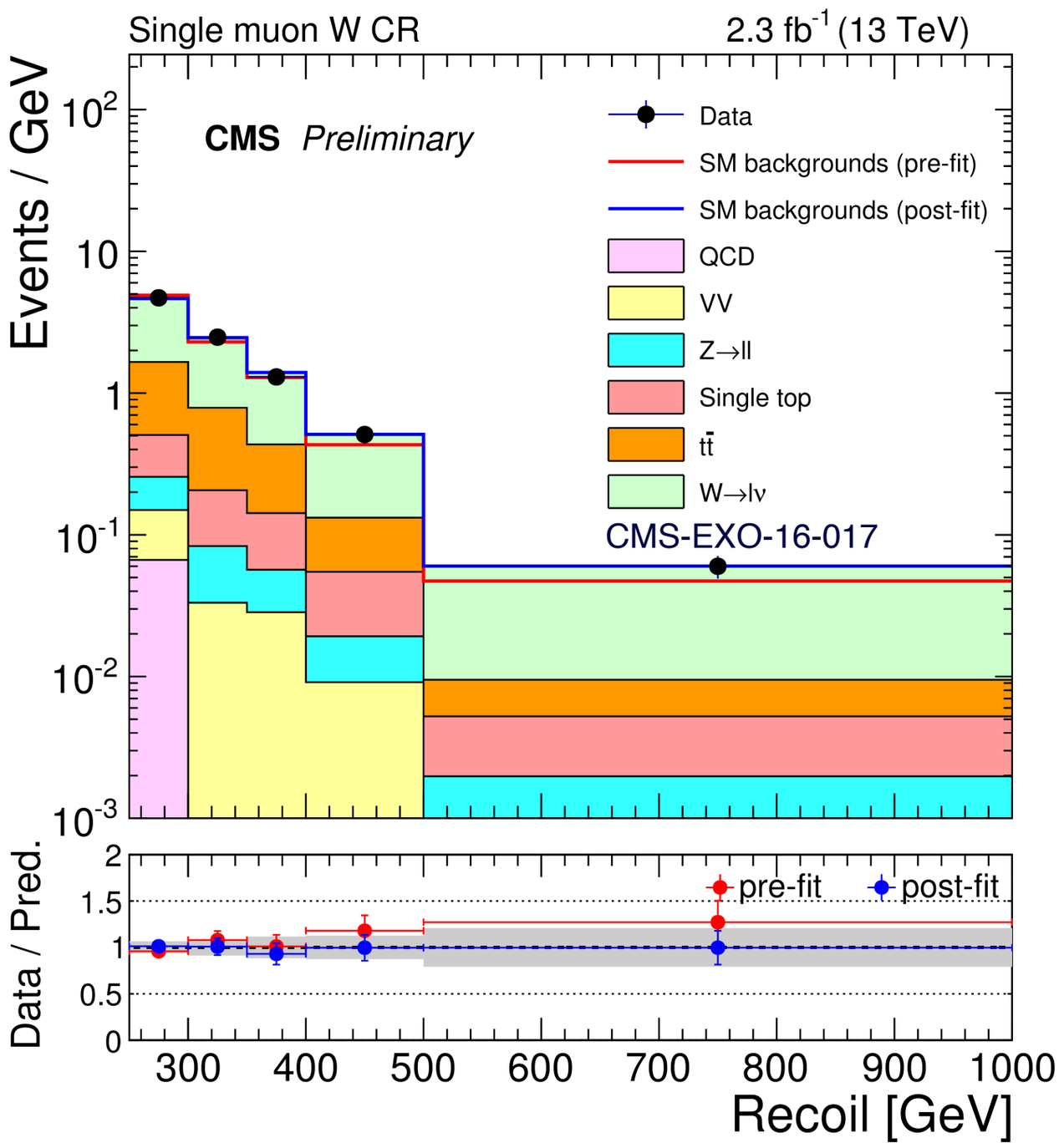
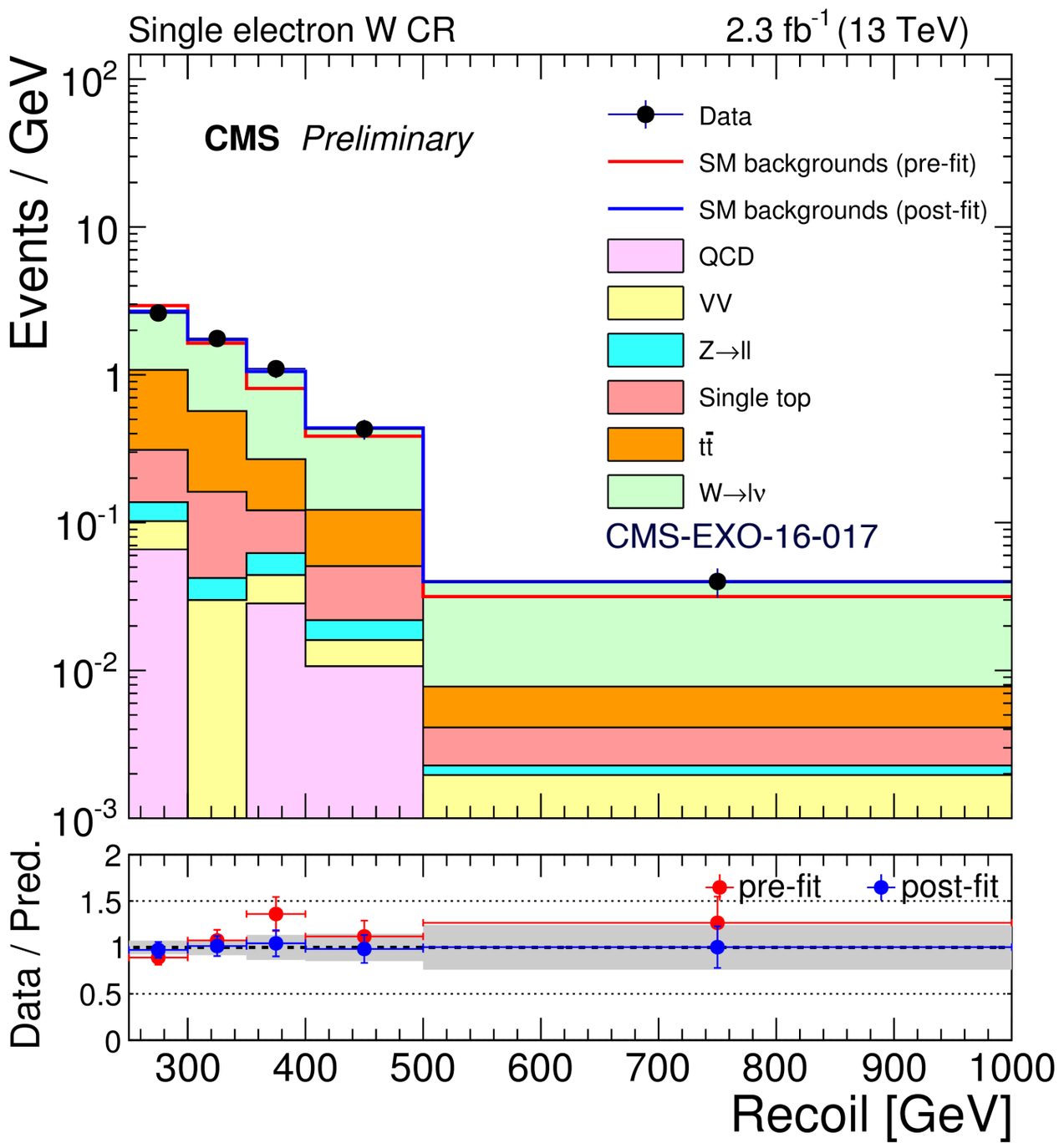
- Exactly one isolated tight lepton
- Additional lepton and photon veto
- Veto loose b-tags with ΔR(AK4,CA15) > 2
- No Δϕ(AK4,MET) cut

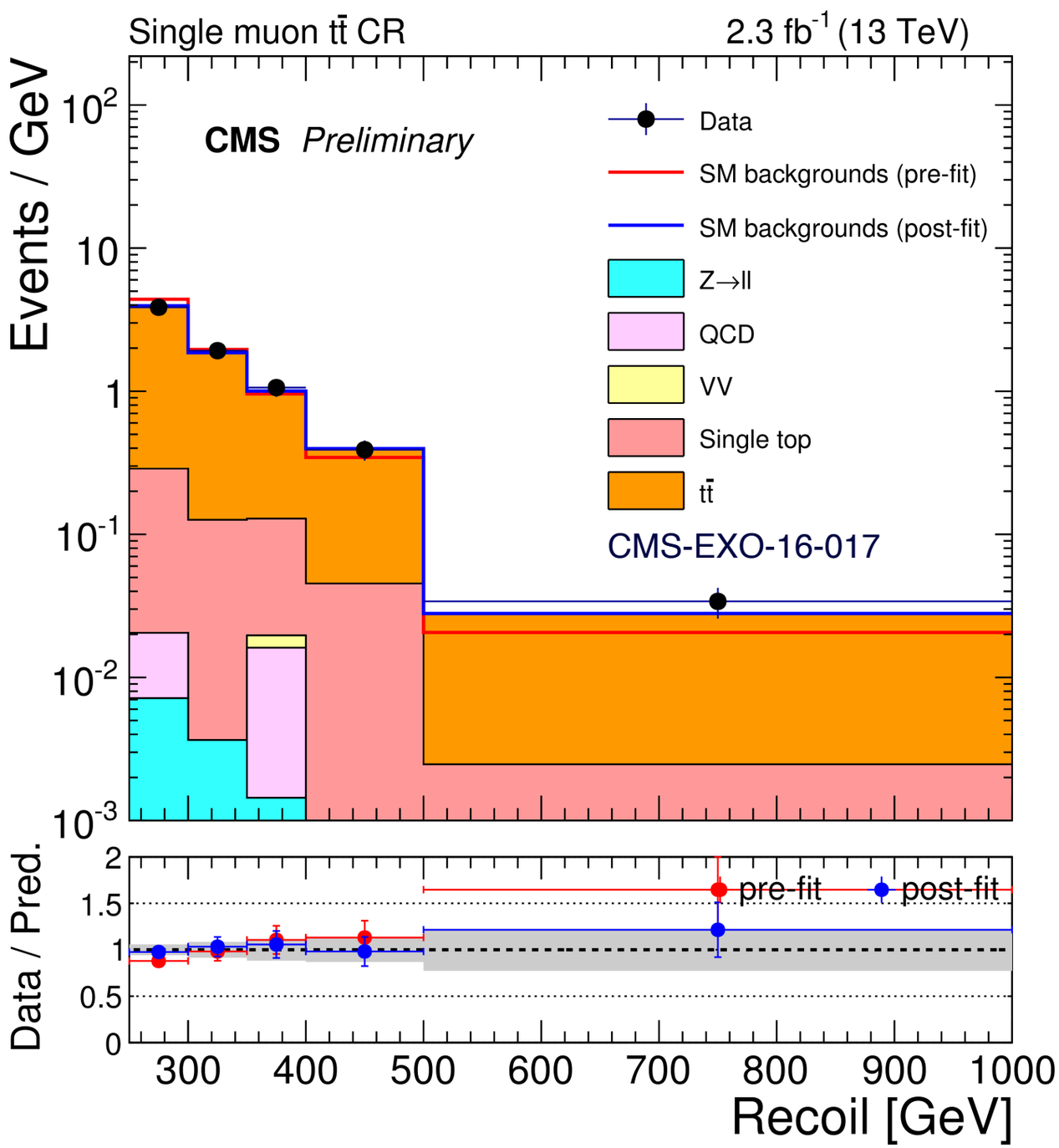


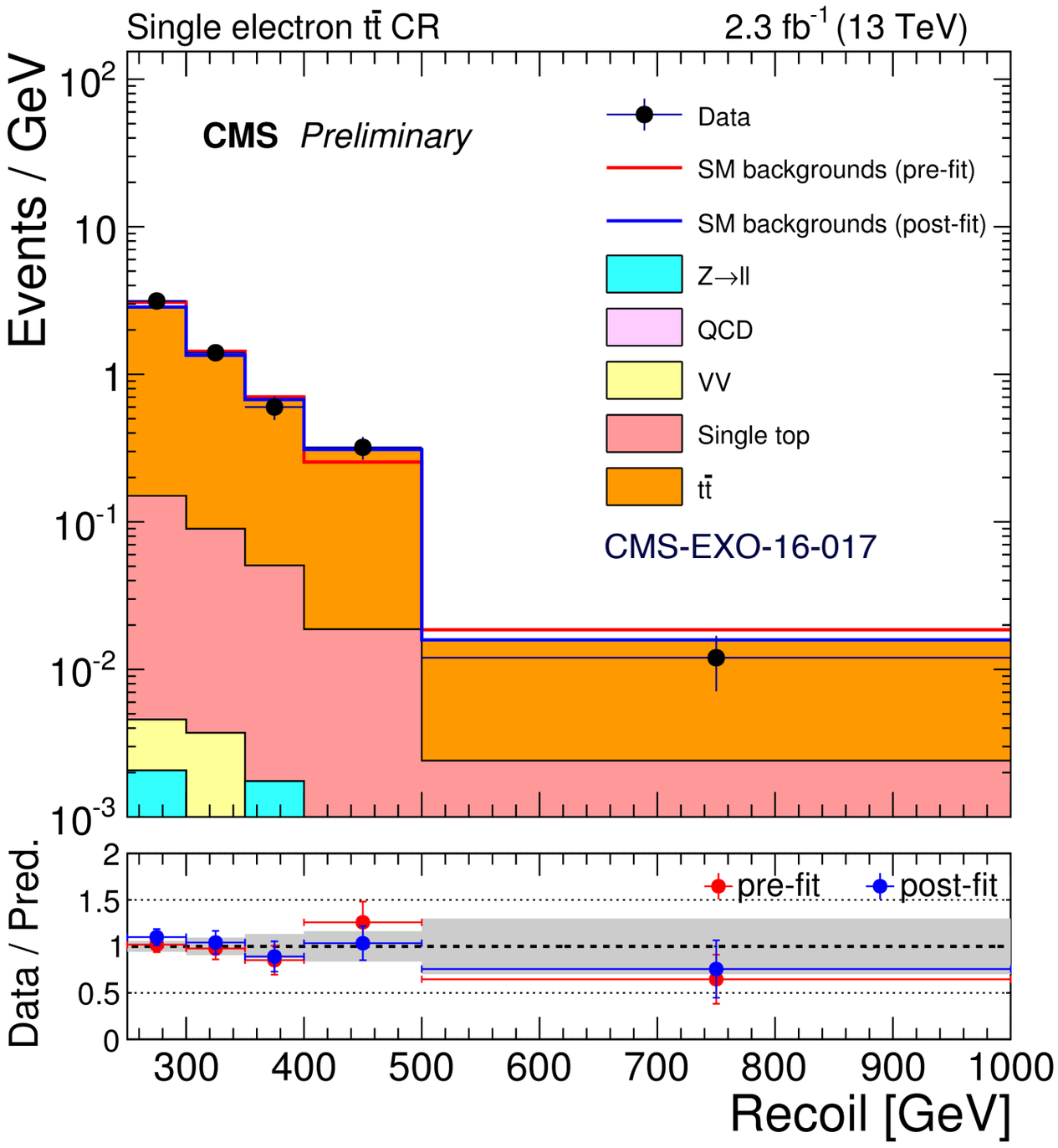


DM+Monotop: Single Lepton B-Tag CR

UIC UNIVERSITY OF ILLINOIS AT CHICAGO

- Exactly one isolated tight lepton
- Additional lepton and photon veto
- One loose b-tagged jet with ΔR(AK4,CA15) > 2
- No Δϕ(AK4,MET) cut





DM+Monotop: Photon Control Region

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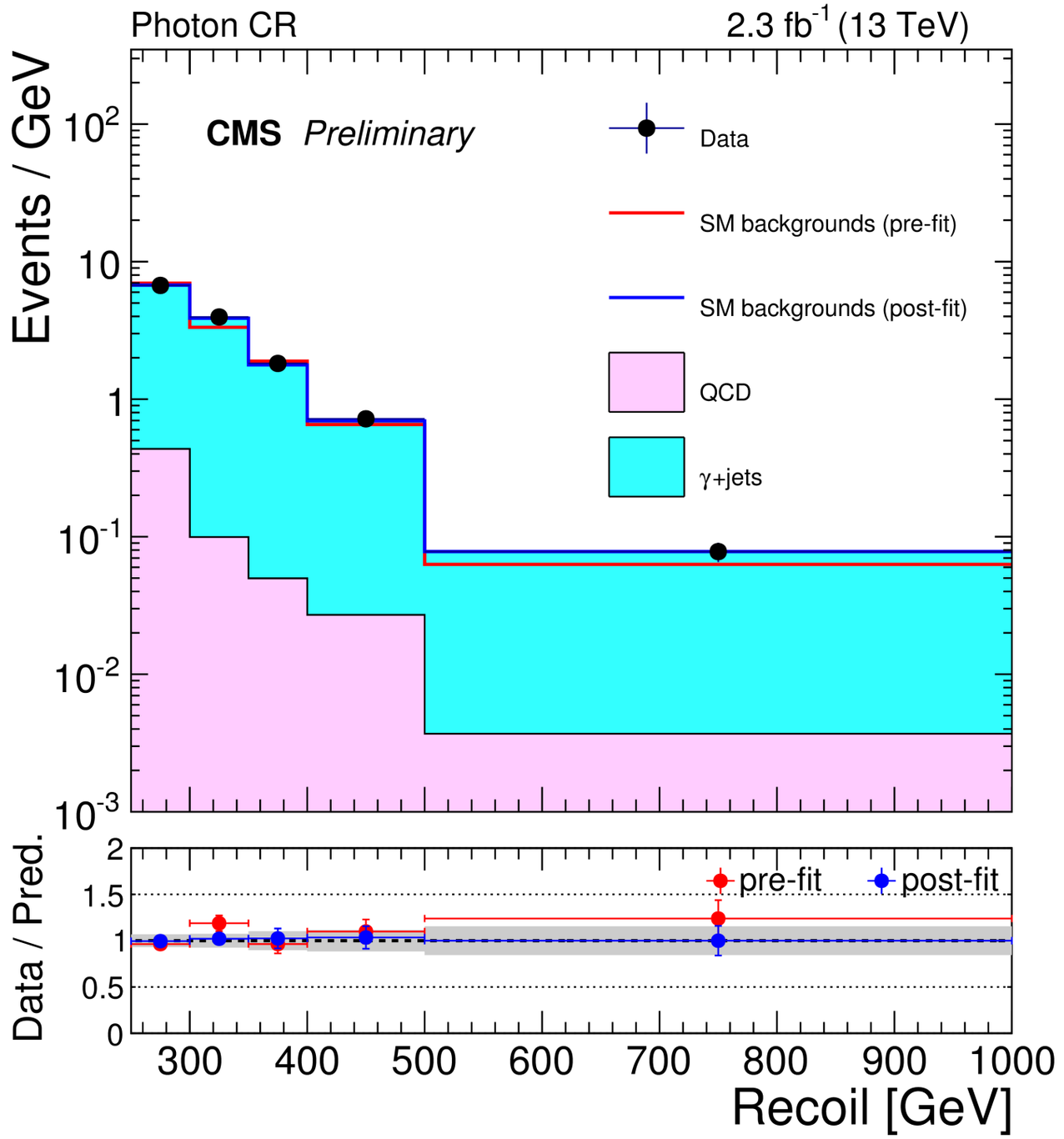
- Provides the dominate constrains on the $Z \rightarrow \nu\nu$
- Photon CR Selection
  - Passes photon trigger
  - High p_T photon (175 GeV)
  - One t-tagged CA15 jet
  - Lepton veto
  - $U > 250$ GeV
- Transfer Function

$$N_i^X = \frac{\mu_i^{Z\rightarrow\nu\nu}}{R^X}$$

  - N - Number of Signal Region Events
  - $\mu^{Z\rightarrow\nu\nu}$ - Yield in signal region
  - i - Bin Number
  - R^X - Transfer Function



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DM+Monotop: Event Yields

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	Z+Jets	W+Jets	$t\bar{t}$	Single-t	VV	QCD	γ+Jets
Signal	103.87	59.08	103.18	22.05	7.02	25.60	-
Single-μ (W)	12.46	349.57	113.66	31.01	9.32	3.70	-
Single-e ($t\bar{t}$)	4.76	222.00	80.36	24.98	5.75	7.10	-
Single-μ (W)	0.58	11.52	365.80	26.51	0.13	1.19	-
Single-e ($t\bar{t}$)	0.20	8.8	276.69	16.94	0.25	0.00	-
Dimuon	62.74	0.42	9.70	2.17	2.50	0.00	-
Dielectron	49.07	0.40	3.54	0.47	1.97	0.00	-
Photon	-	-	-	-	-	30.64	712.31

DM+Monotop: Limits

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FCNC mass [GeV]	Observed σ/σ_{Theory}	Expected σ/σ_{Theory}	Inclusive σ_{Theory} [pb]
300	0.05871	0.03949	41.4
500	0.1128	0.07759	9.78
700	0.2391	0.1730	3.09
900	0.4671	0.3518	1.17