Searches for $t\bar{t}$ Resonances and Dark Matter at CMS

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On behalf of the CMS Collaboration

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Outline

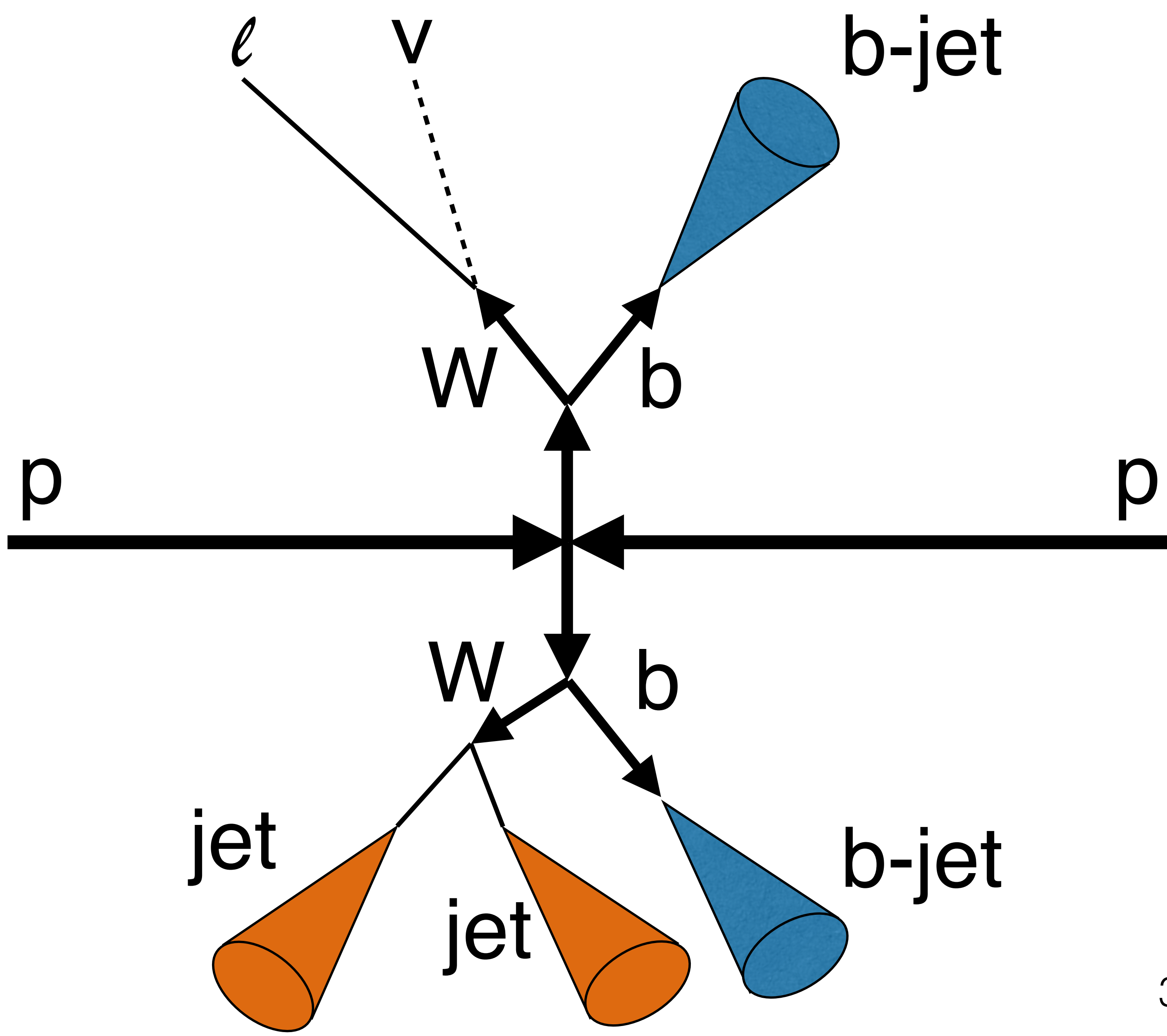
- Talk will focus on an upcoming search for a $t\bar{t}$ resonance and present search results for the dark matter with associated top quarks
  - Overview several new t-tagging techniques
  - Discuss an upcoming $Z' \rightarrow t\bar{t}$ search
  - Present the current top+DM results
- Briefly discuss future analysis of 13TeV data

Process	Channels	Top Tagging	CMS PAS
$Z' \rightarrow t\bar{t}$	lvlvbb	No	B2G-13-008
	lvjjbb	Yes	B2G-13-008
	jjjjbb	Yes	B2G-13-008
$t\bar{t}$+DM	lvlvbb	No	B2G-13-004
	lvjjbb	No	B2G-14-004
t+DM	jjb	No	B2G-12-022

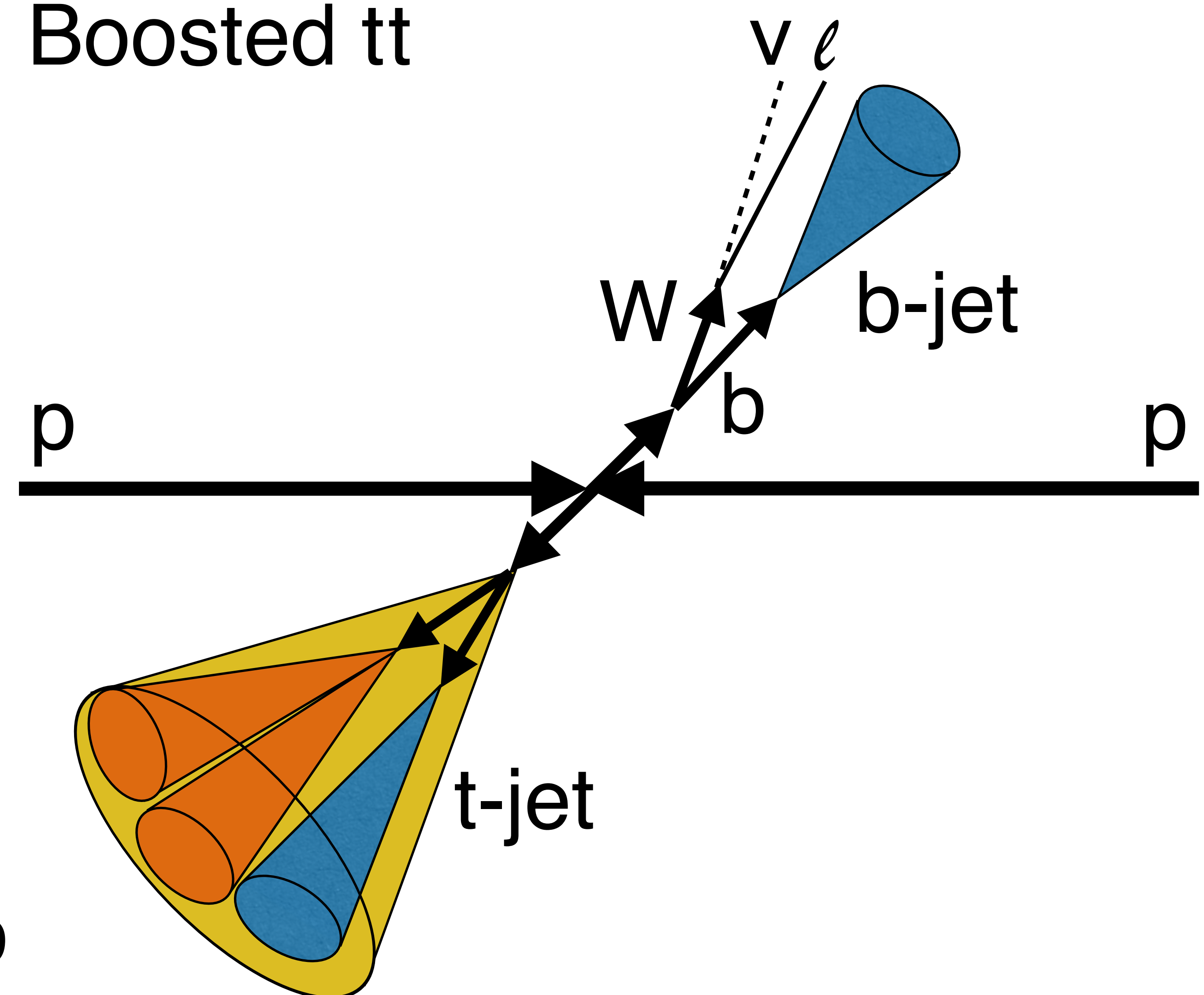
Boosted Tops

- New Event Topology
- Different triggering and reconstruction strategies

Non-Boosted $t\bar{t}$



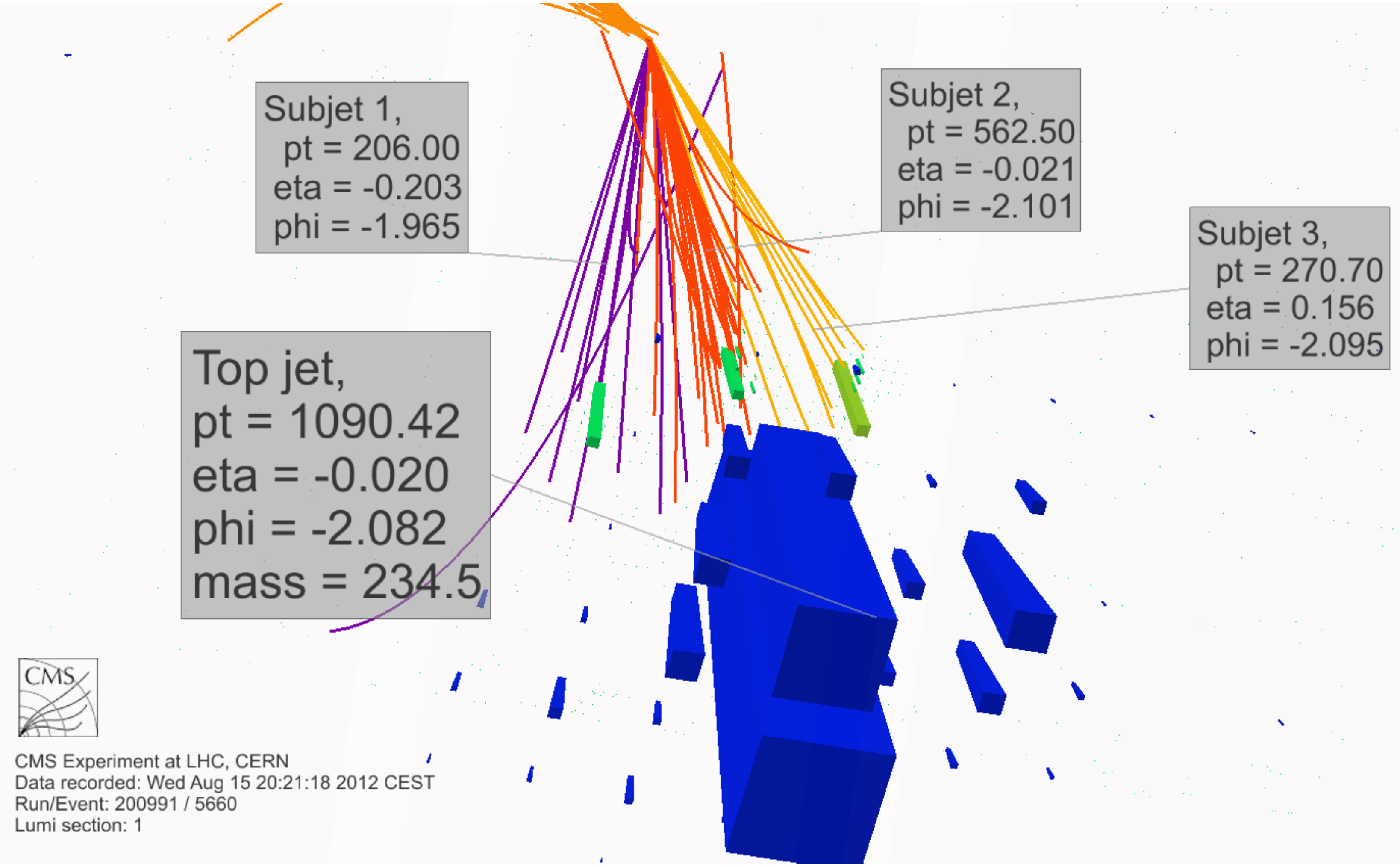
Boosted $t\bar{t}$



- Non-isolated lepton trigger
- Jet p_T cleaning

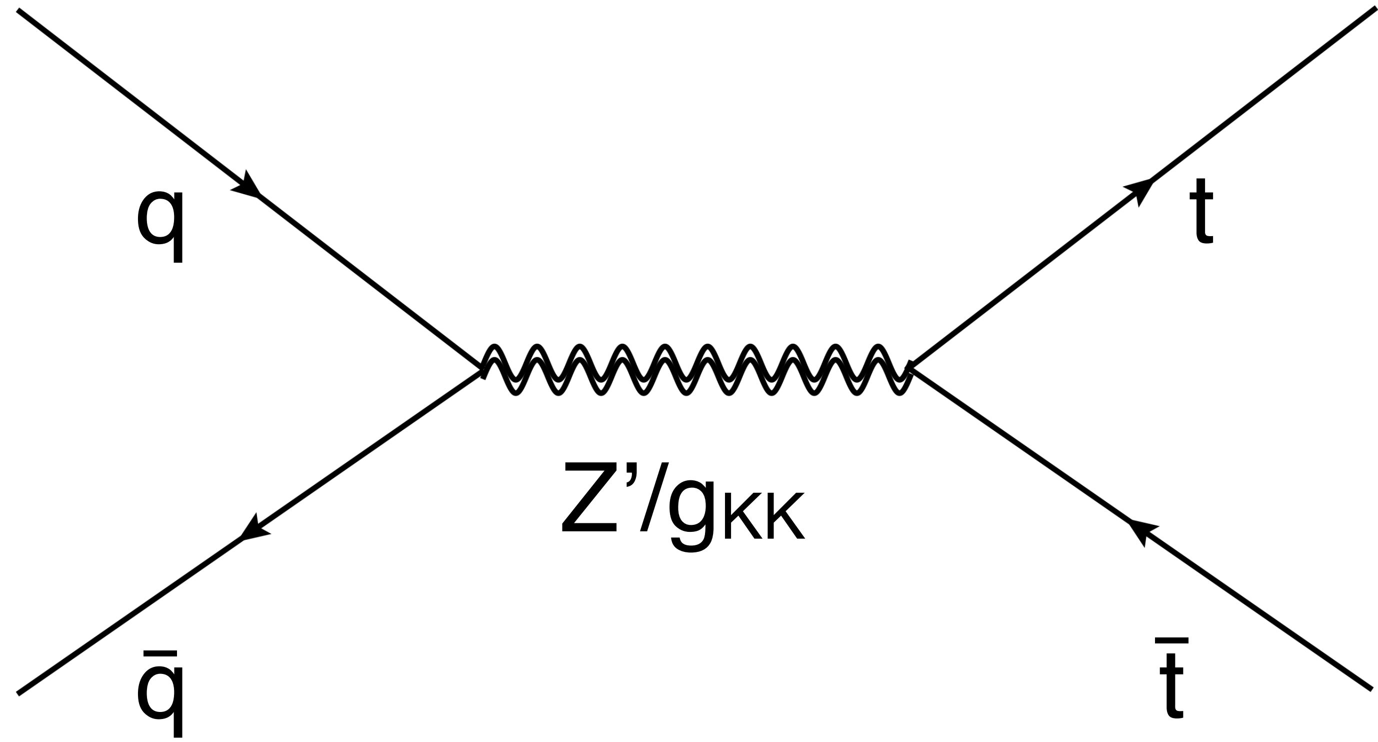
T-tagging

- Two different t-taggers are used in analyses
- A large cone (CA15) HEP t-tagger algorithm for somewhat boosted tops
- A narrower (CA8) CMS t-tagger algorithm for very boosted tops



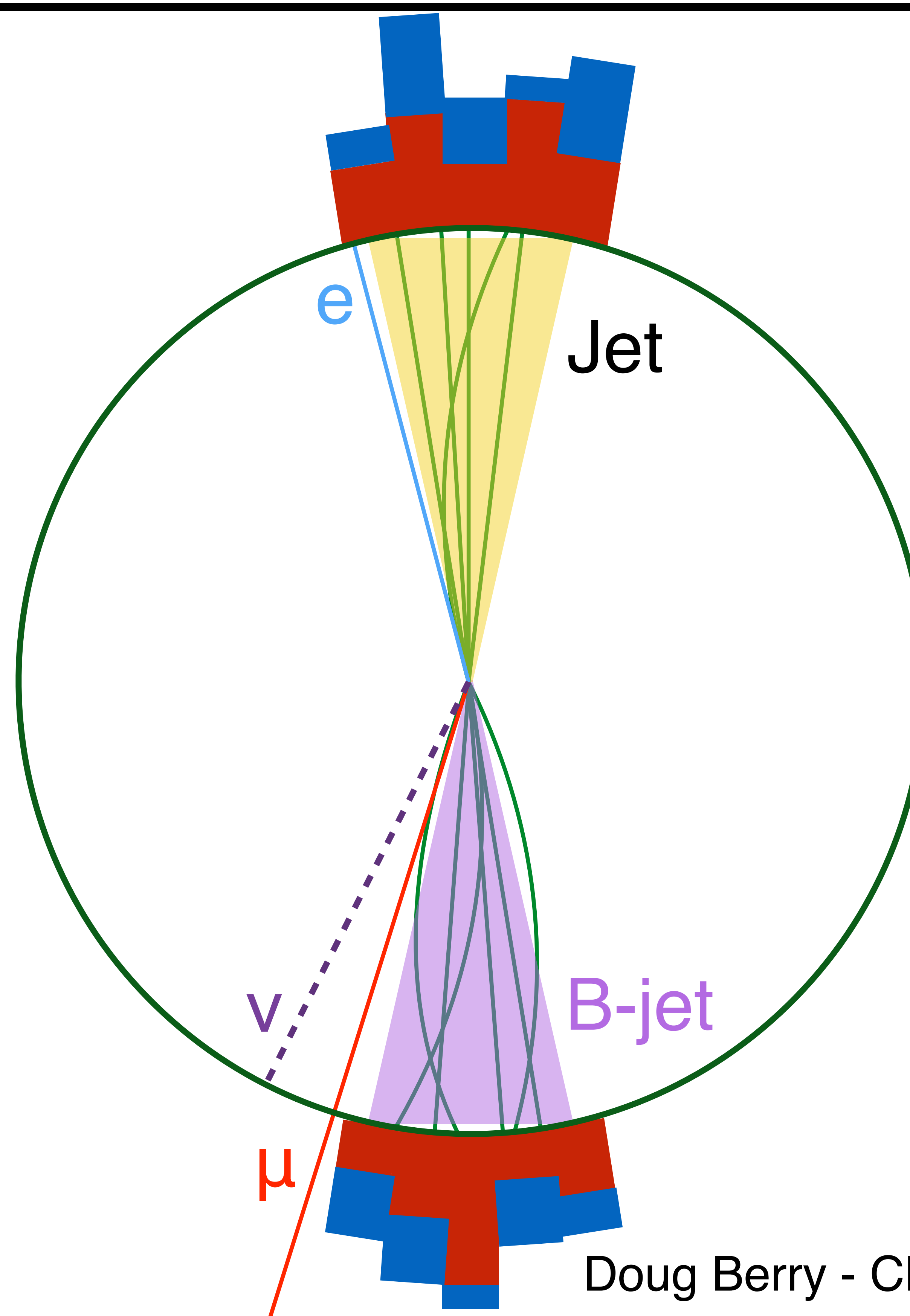
New $Z' \rightarrow t\bar{t}$ Search

- The $Z' \rightarrow t\bar{t}$ analysis searches for a generic resonance decaying to $t\bar{t}$ pairs
  - Search looks in three different final states that contain two, one, or zero leptons (e or μ)
  - Search sets explicit limits for a Z' boson and g_{KK}
  - The analysis is very effective at excluding heavy resonances decaying to $t\bar{t}$ pairs



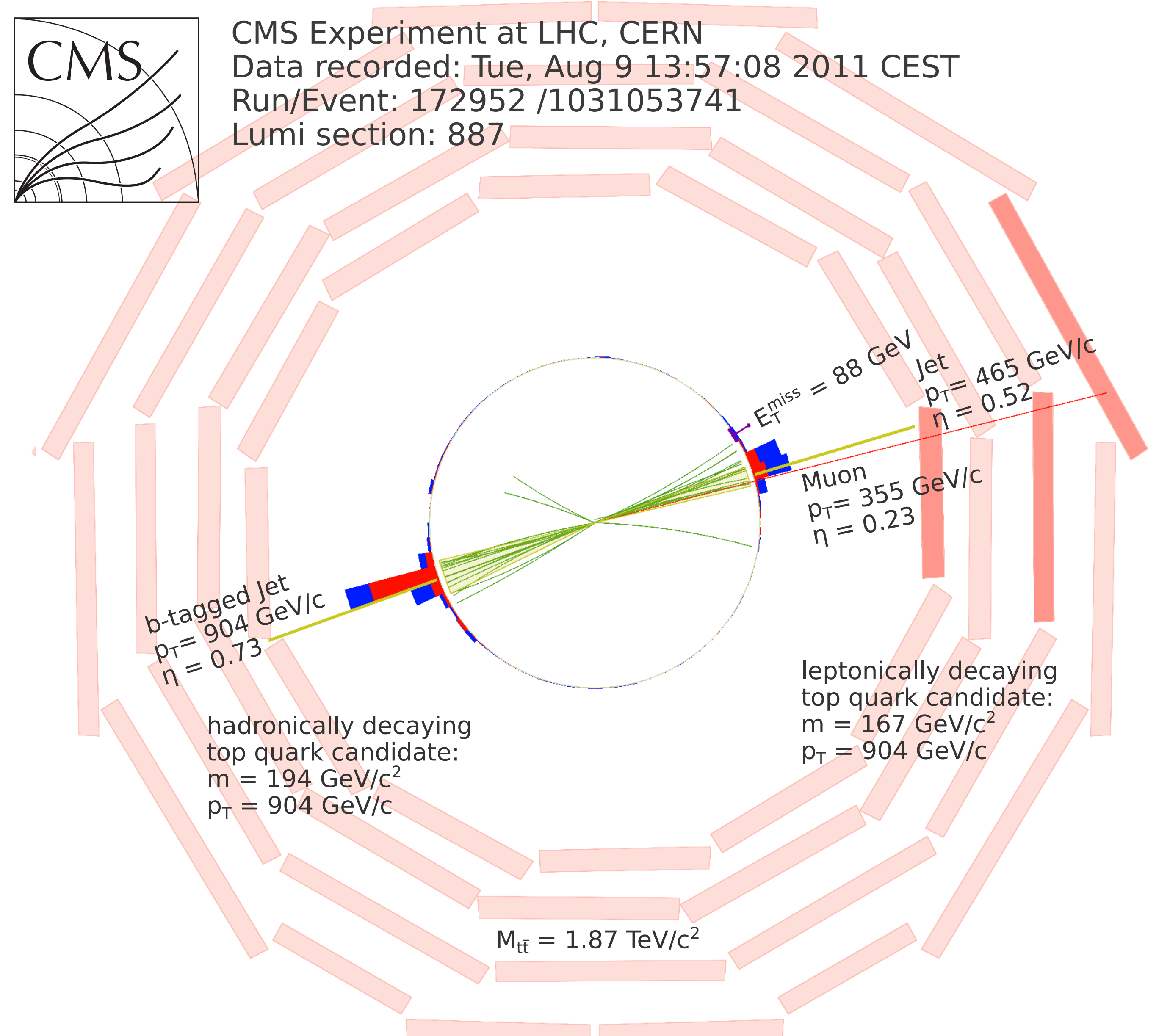
Dilepton Channel

- Requires two leptons and two jets in the final state
- Require one or two b-tags
- Leptons are not well separated from b-jets
- 2D-isolation cut removes multi-jet background
- MET cut removes multi-jet and Z/γ* background
- 3 categories in total



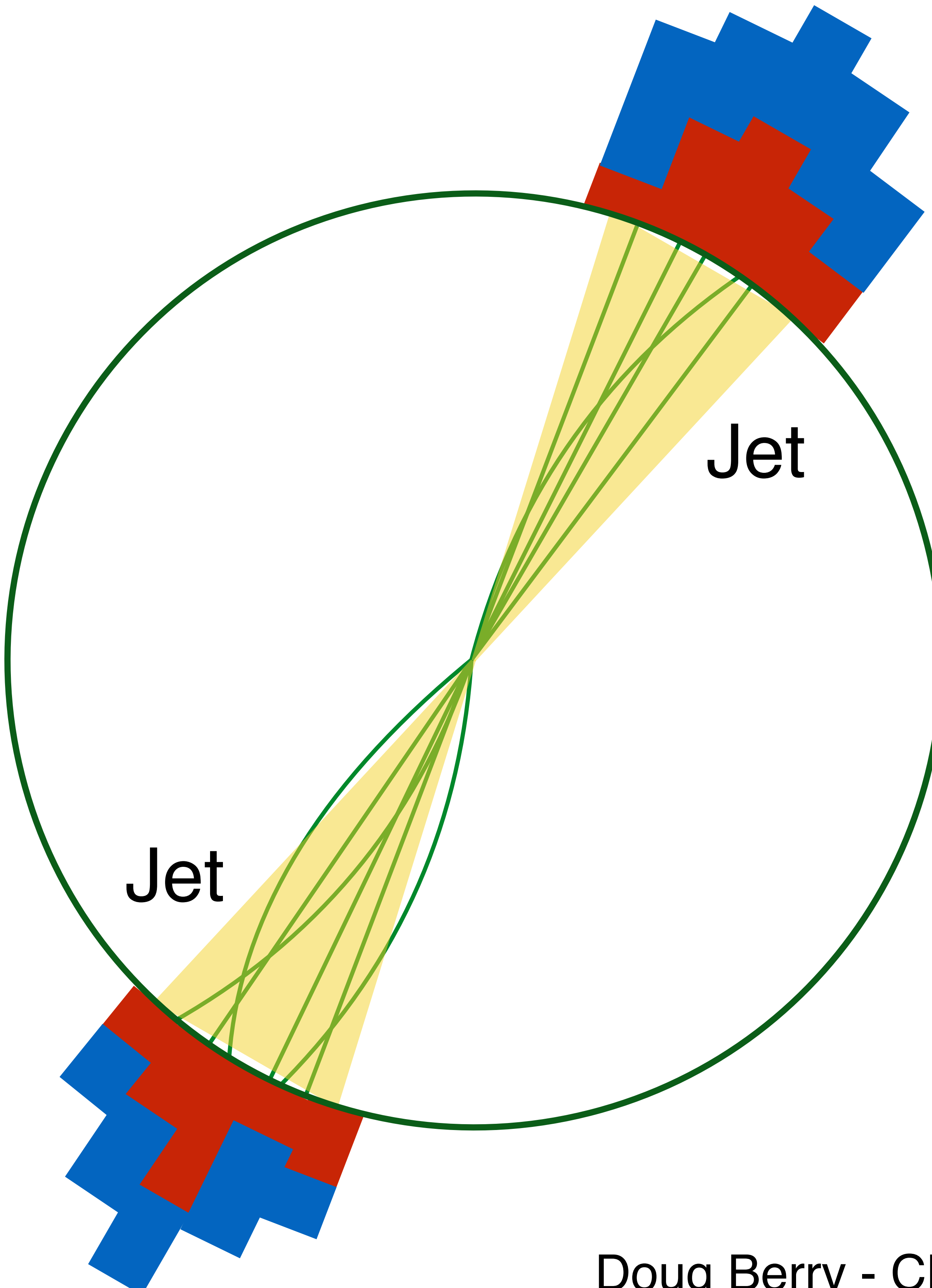
Lepton+Jets Channel

- Requires exactly one lepton and two high p_T jets
- 2D-isolation cut is applied to the lepton
- MET and lepton p_T+MET cut reduces multi-jet background
- MET may not be collinear with the leading jet or lepton
- χ^2 minimization technique is used to reconstruct the $t\bar{t}$ system
- T-tagging and b-tagging are used for categorization and increased analysis sensitivity
- Total of 6 categories



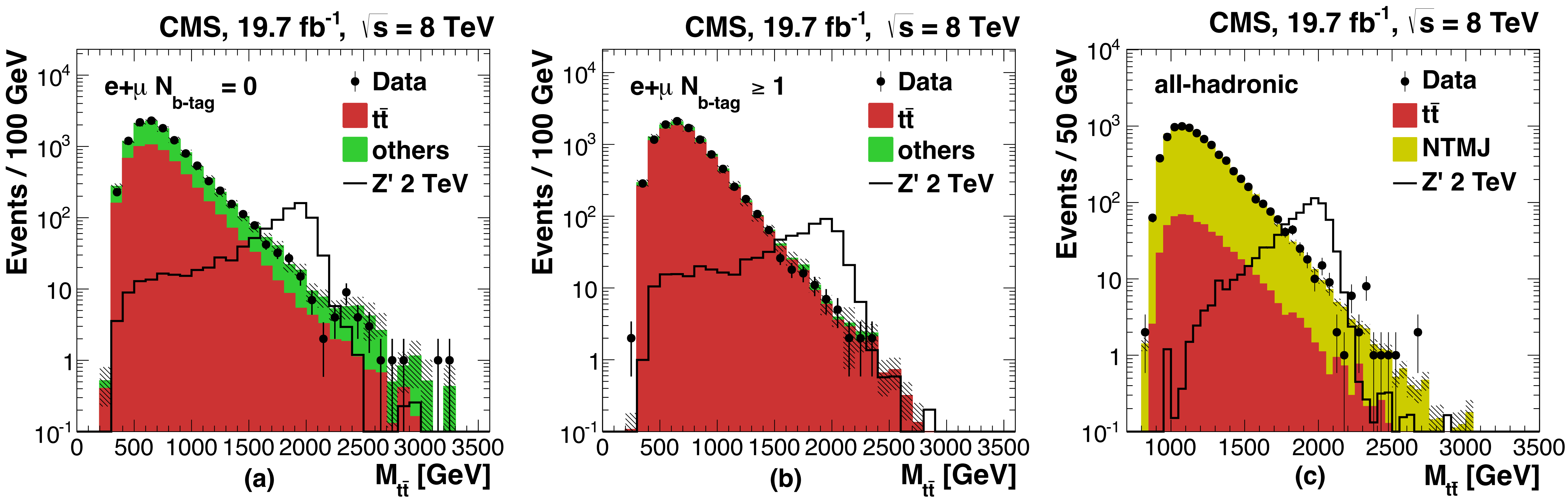
All-Hadronic

- The Lorentz boost of the top quarks causes this channel to become a dijet analysis
- Two exclusive t-tagging algorithms are used (HEP and CMS), optimized to different kinematic regimes
- In addition to t-tagging, sub-jet b-tagging, H_T, and $|\Delta y|$ are used for categorization
- 12 categories in total



Previous Z’→$t\bar{t}$ Results

- Previous Z’→$t\bar{t}$ results were published in Phys. Rev. Lett. 111 (2013) 211804 (hep-ex:1309.2030)
- The new analysis adds the dilepton and the hadronic HEP t-tagged channels
- Also the new analysis adds t-tagging in the semi-leptonic channel and sub-jet b-tagging in the all hadronic channels



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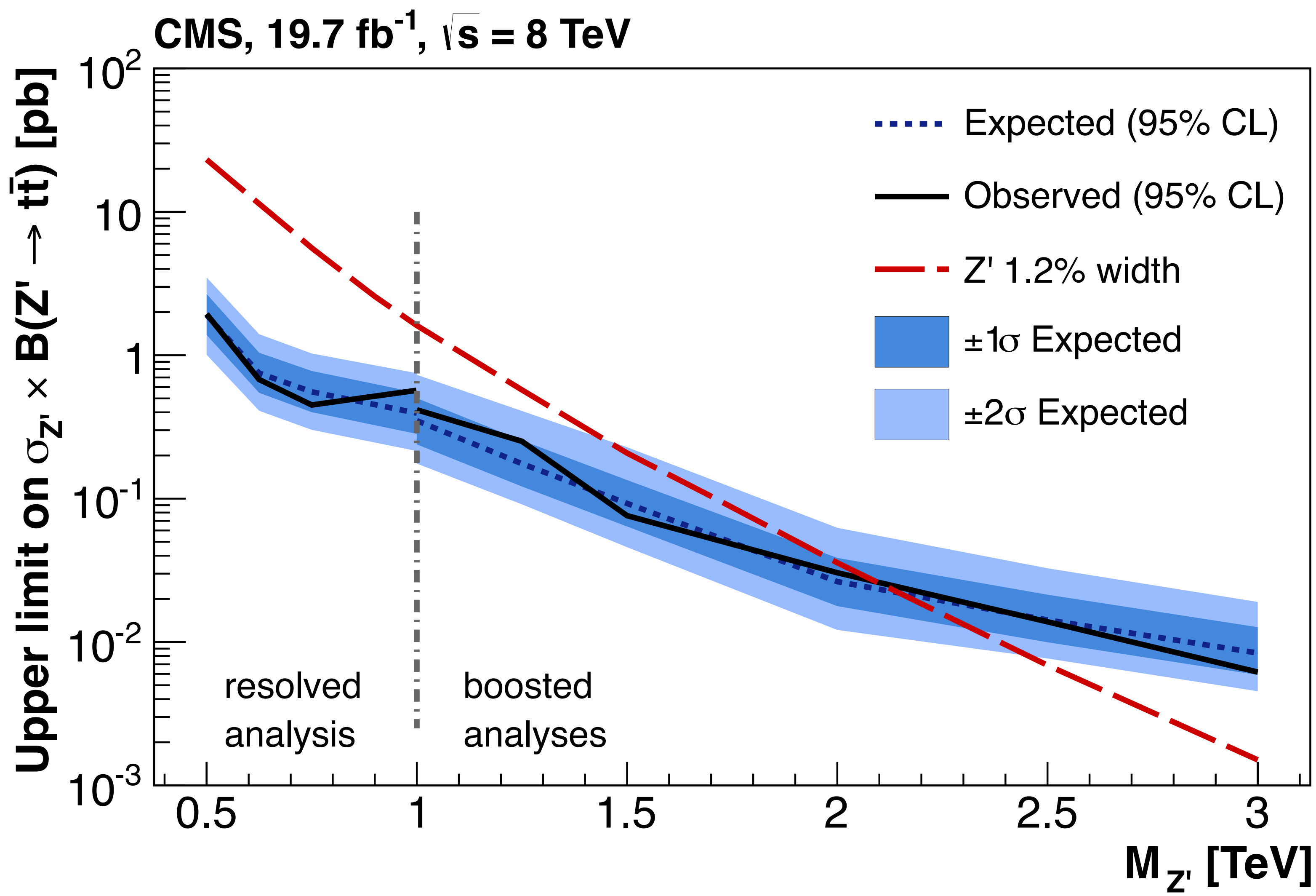
Previous Z'→$t\bar{t}$ Limits

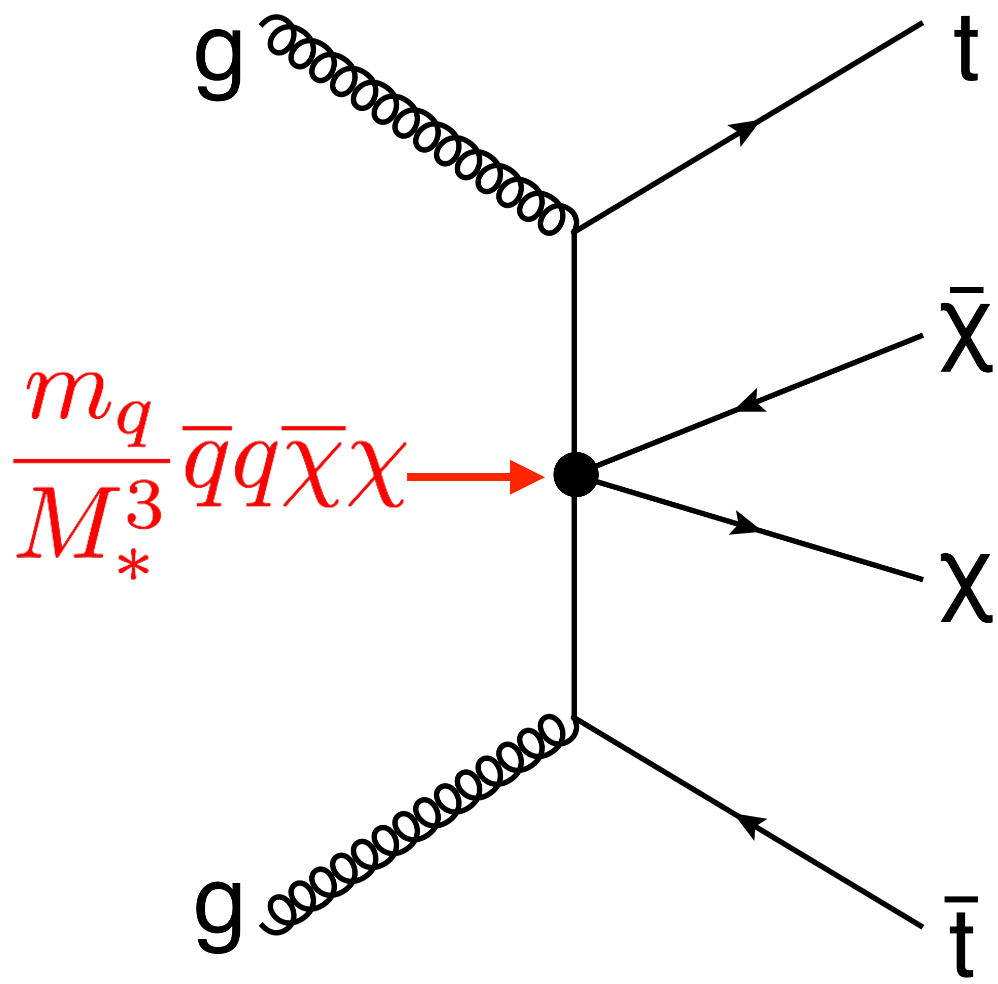
- The new analysis has an expected 50% improvement in cross-section exclusion and an expected ~10% improvement in mass exclusion depending on model

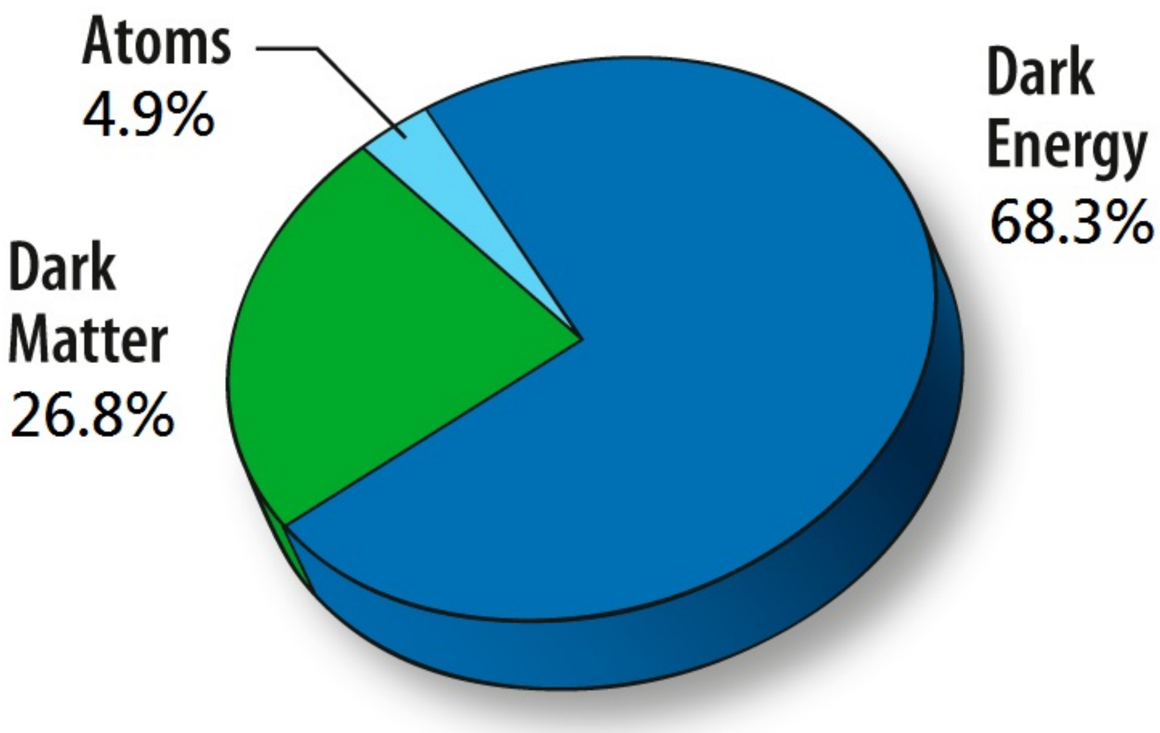


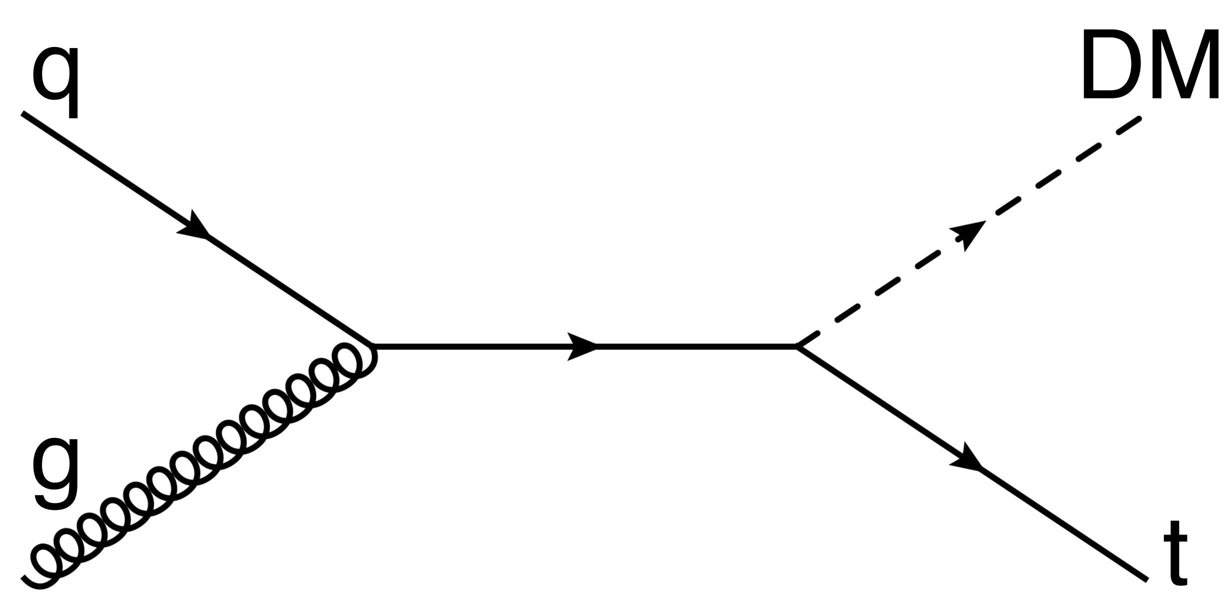
Signal	Expected Limit	Observed Limit
Z' Width=1.2%	2.1 TeV	2.1 TeV
Z' Width=10%	2.7 TeV	2.6 TeV
RS g_{KK}	2.5 TeV	2.4 TeV

Dark Matter + Tops

- Current Dark Matter + Top searches look for Dark Matter in events with one or two top quarks
- The tt+DM analyses search in the dilepton and semi-leptonic channels
- The t+DM analysis searches in the all hadronic channel

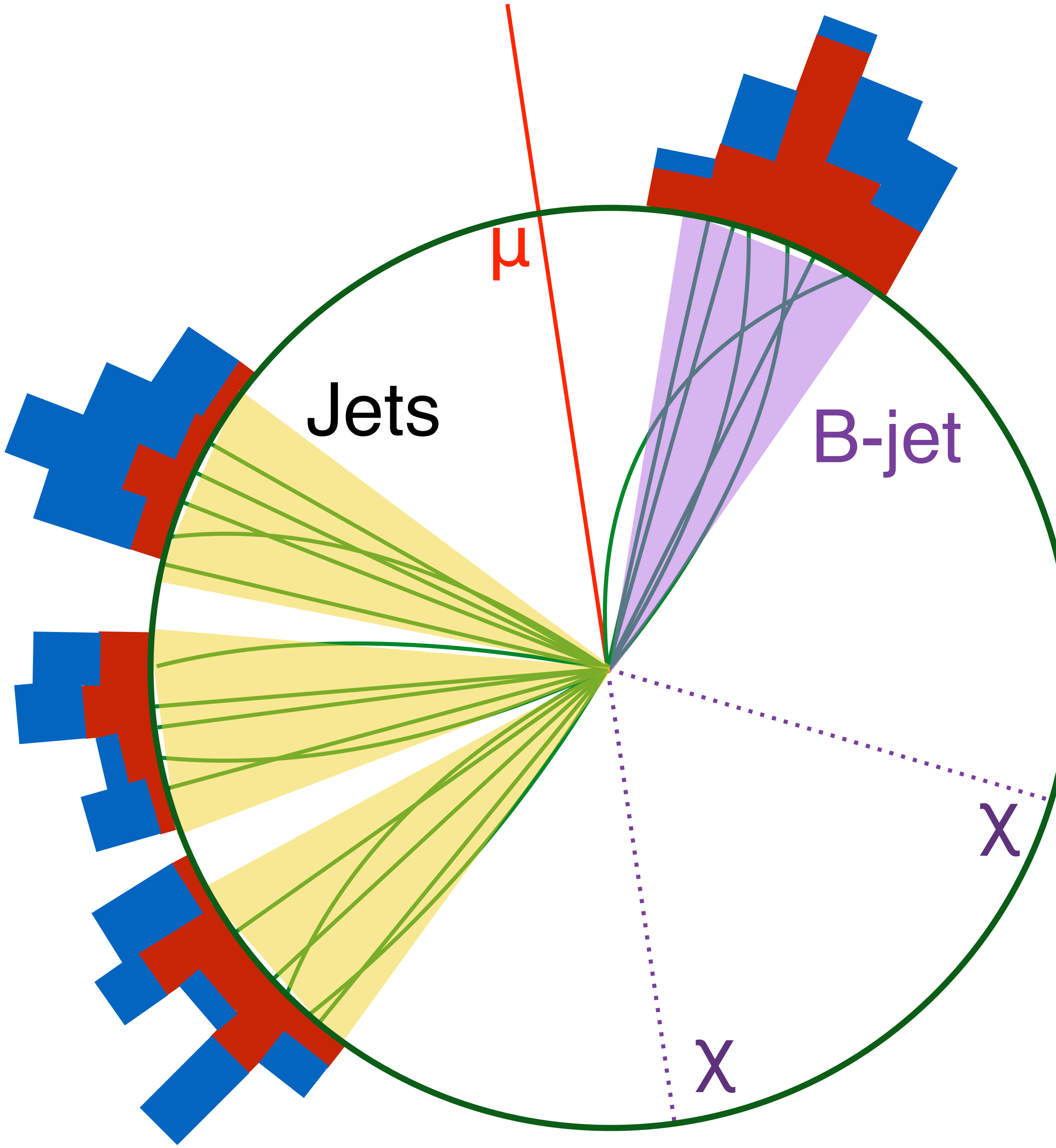






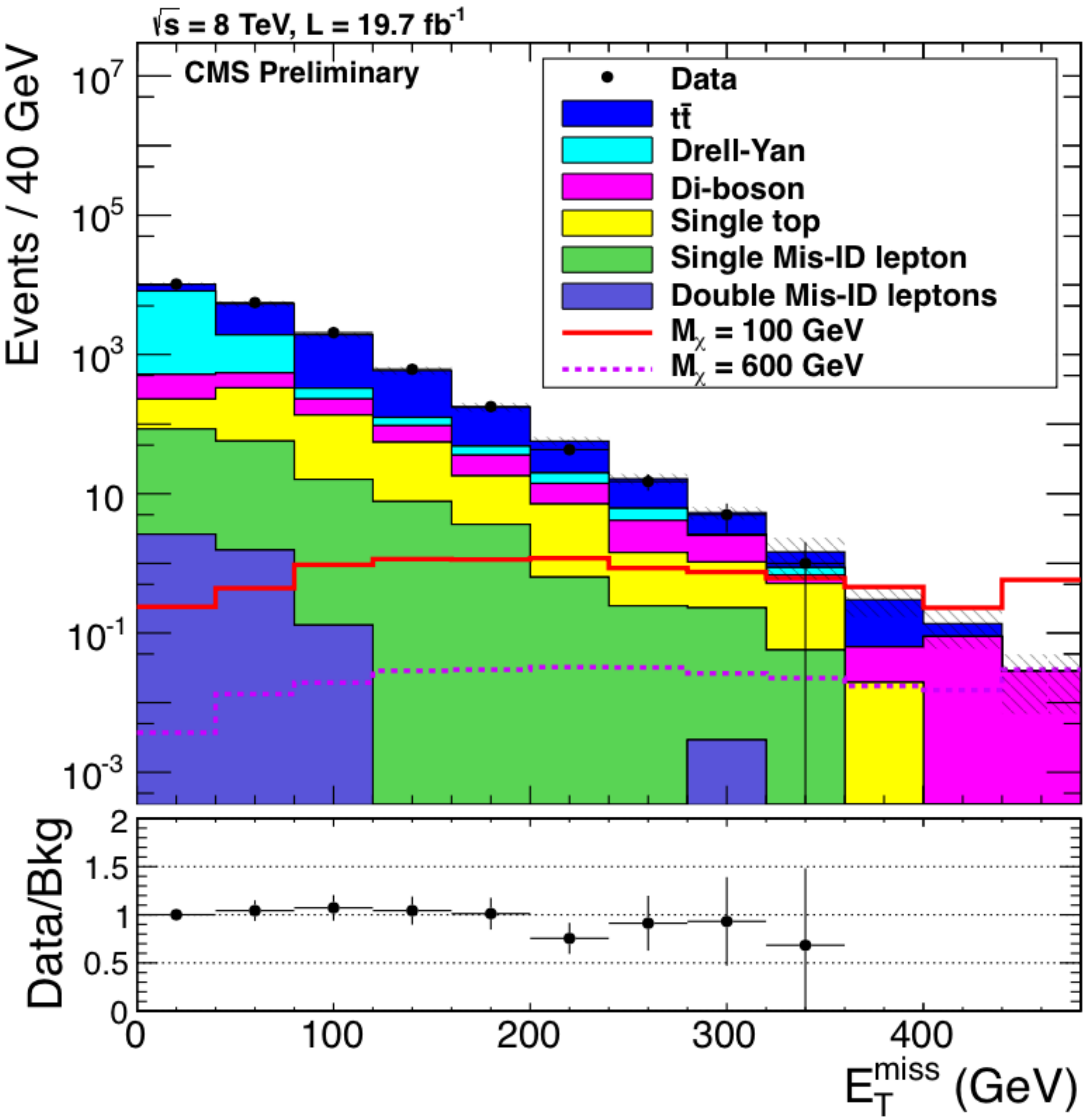
$t\bar{t}$+DM

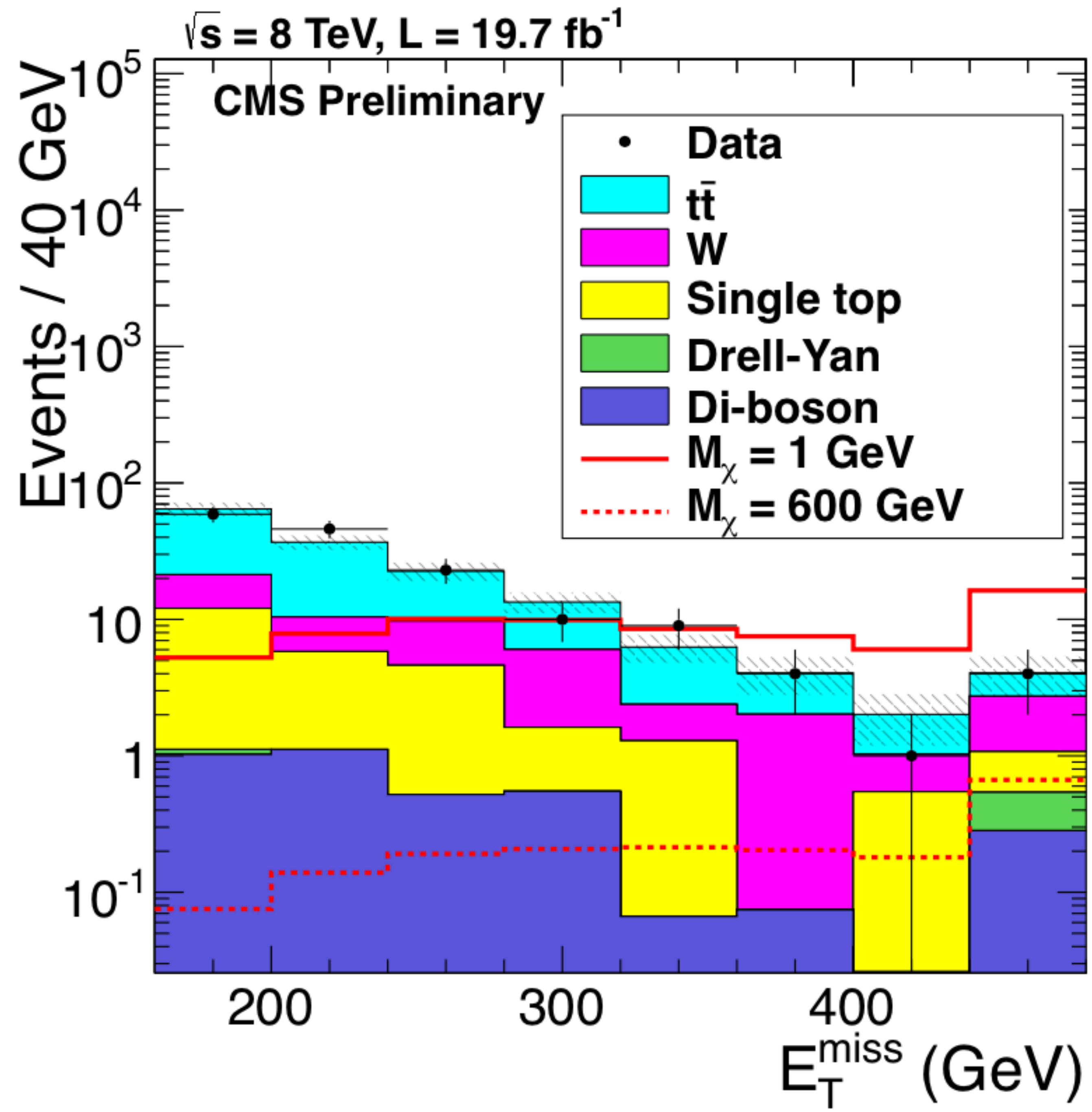
- Dilepton Channel (B2G-13-004)
  - Two isolated leptons and two Jets
  - Lepton invariant mass cut, Z-veto, $\Delta\phi_{ll}$ cut
  - Cut on H_T and very large MET
- Semi-Leptonic Channel (B2G-14-004)
  - One lepton and at least 3 jets (1 b-jet)
  - Large MET cut
  - Kinematic cuts on m_T^W and m_{T2}^W
  - $\Delta\phi$ between MET and jets



tt+DM MET Distribution

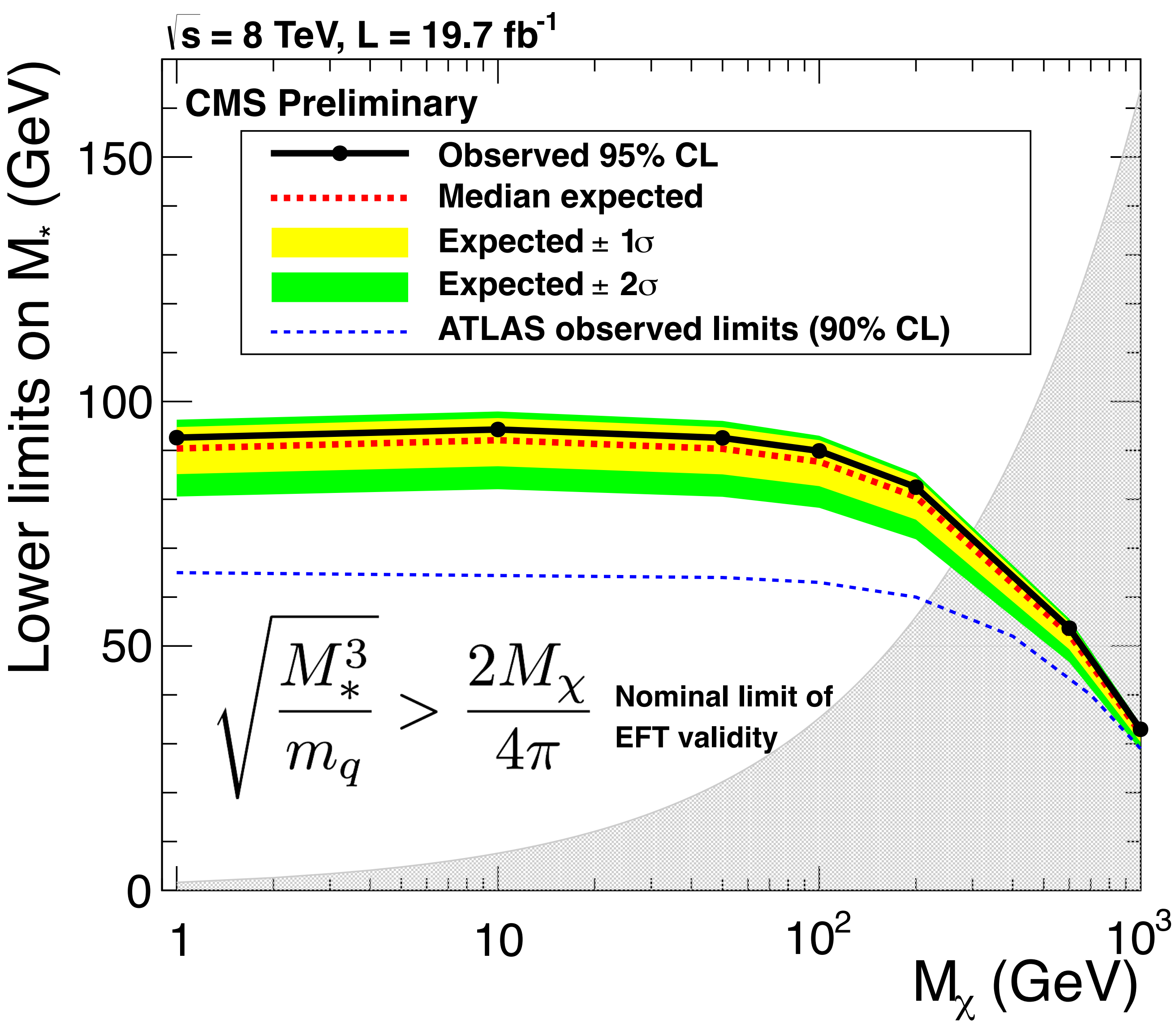
- The MET distributions for the dileptonic channel (left) and semi-leptonic channel (right).

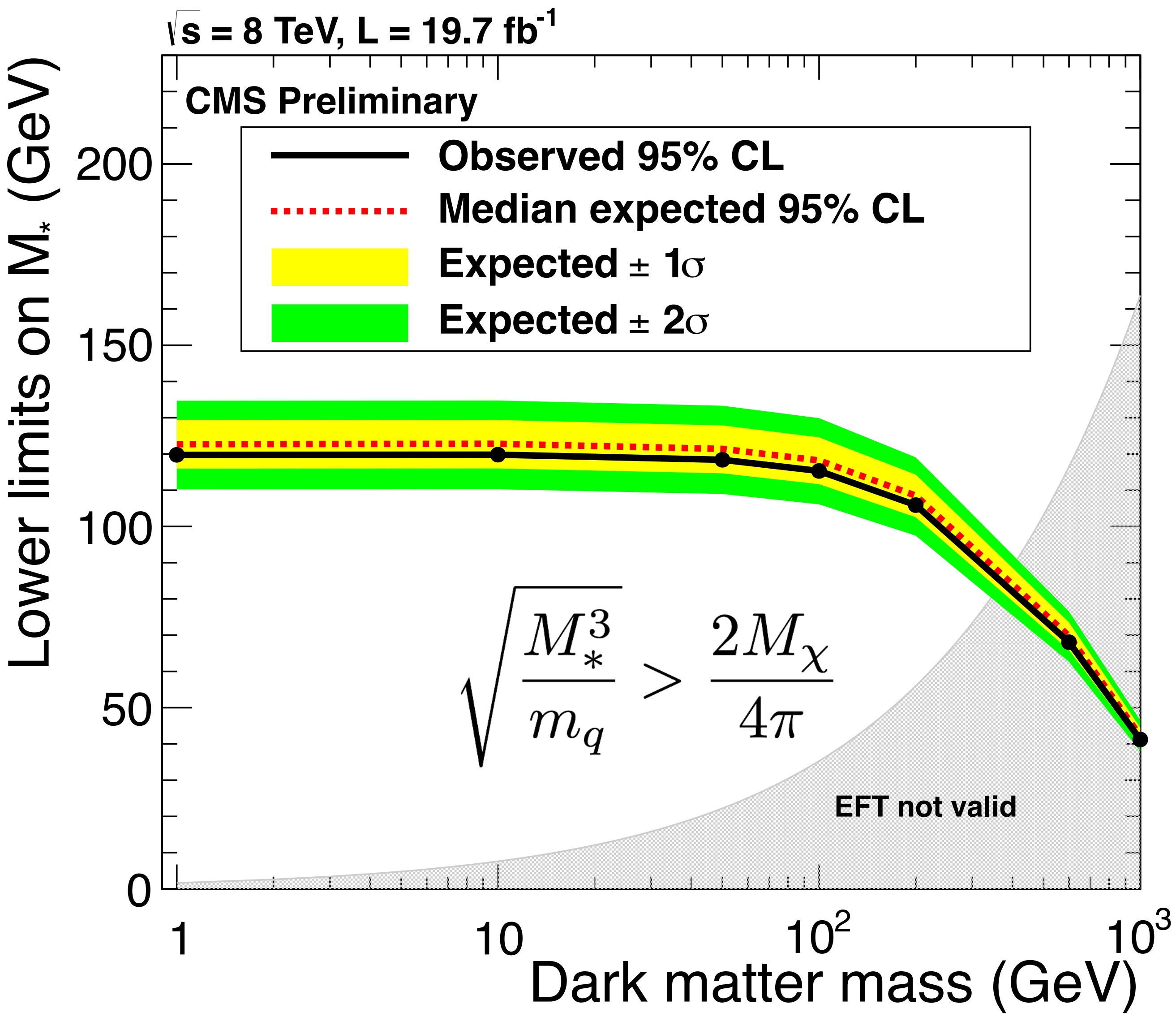




$t\bar{t}$+DM Results

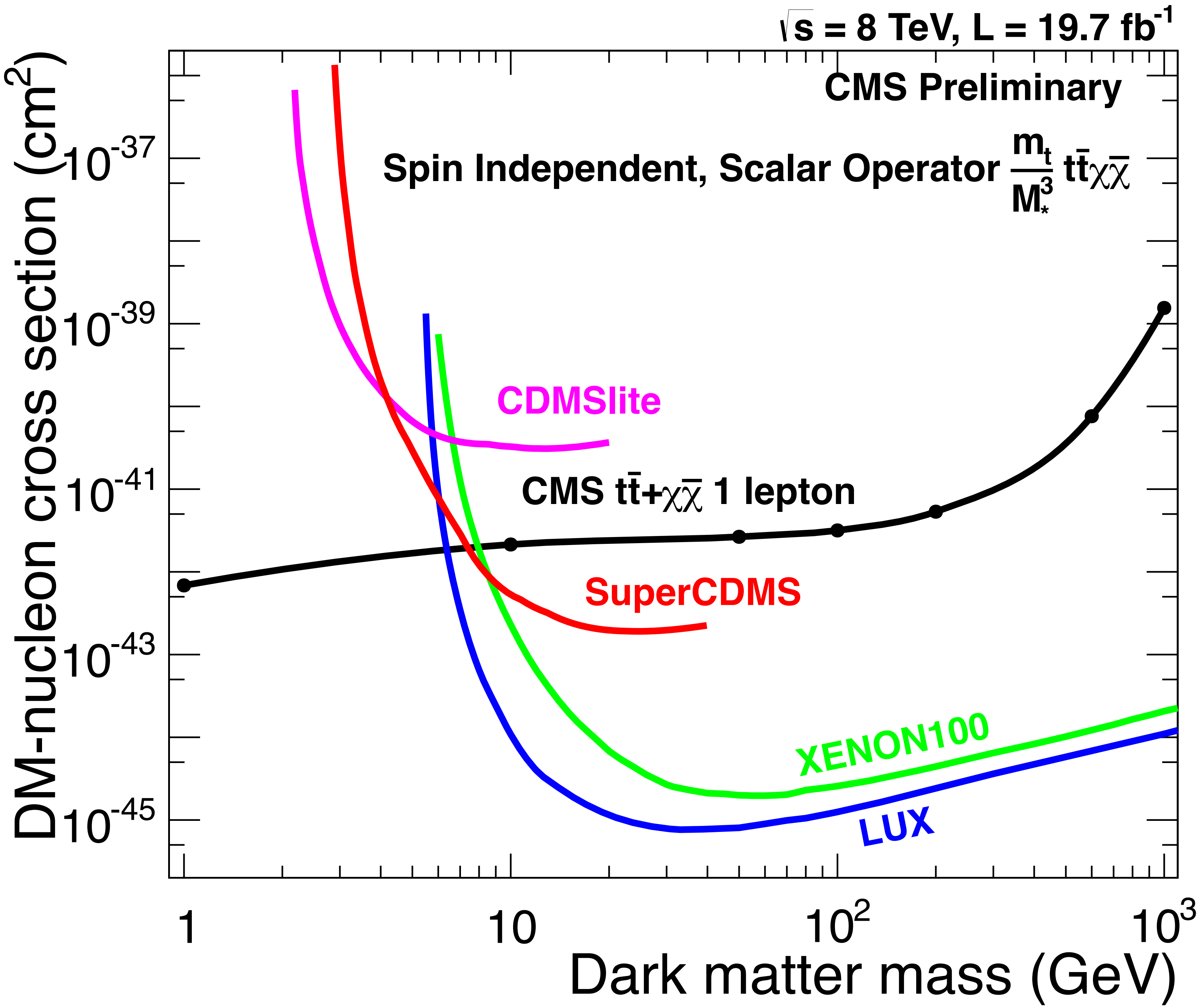
- The upper CL 95% limits for the fully leptonic channel (left) and the semi-leptonic channel (right) $t\bar{t}$+DM searches





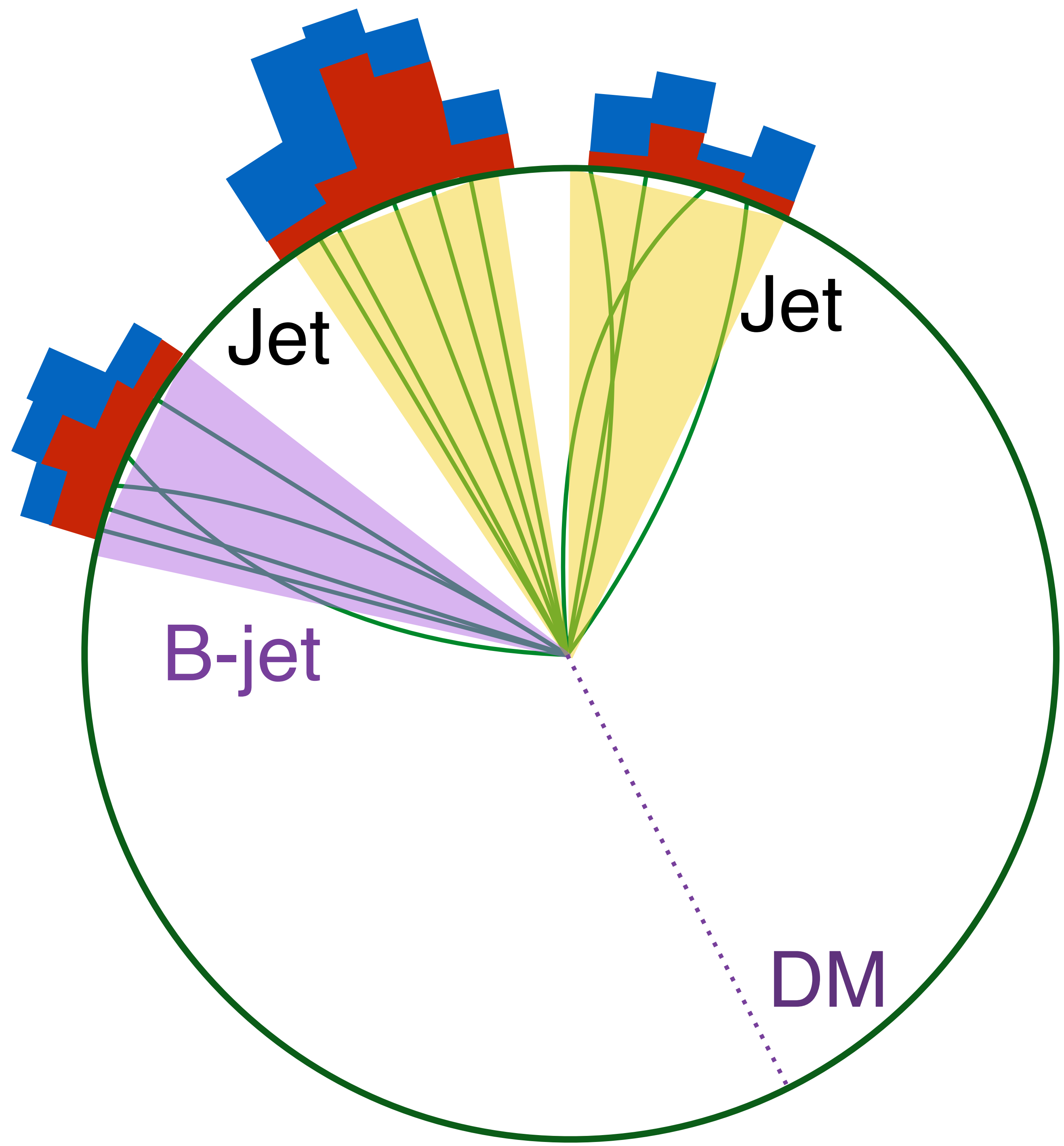
$t\bar{t}$+DM Results Continued

- The 90% CL limit on the dark matter-nucleon spin-independent scattering cross section as a function of the dark matter mass for a scalar operator



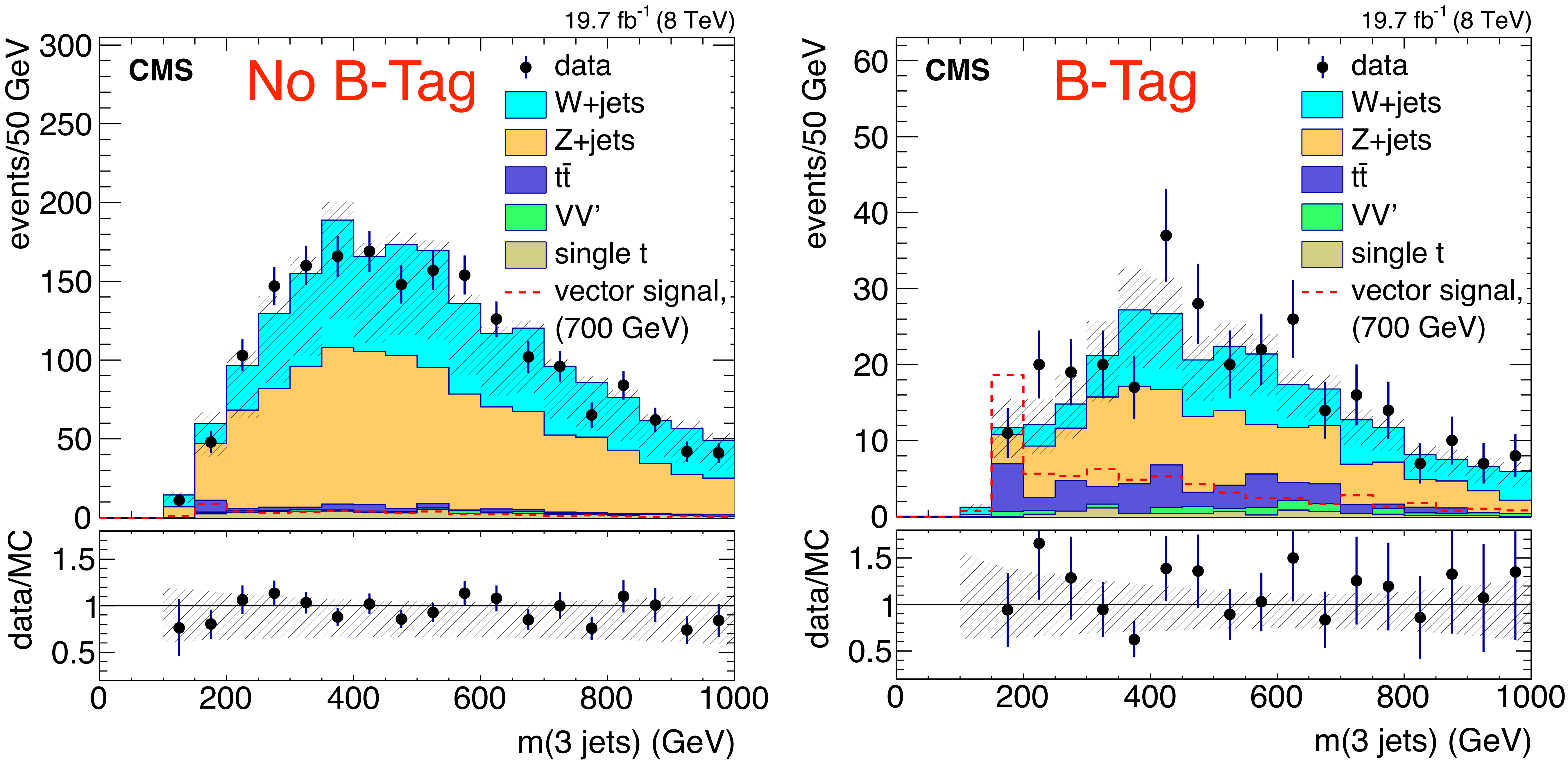
t+DM

- Mono Top DM Search
  - Three jets with one b-tag
  - Large MET cut
  - Veto against isolated leptons
  - Veto against more than three jets.
  - B-tagging categorization is used for increased sensitivity
  - Submitted to PRL (arXiv: 1410.1149)



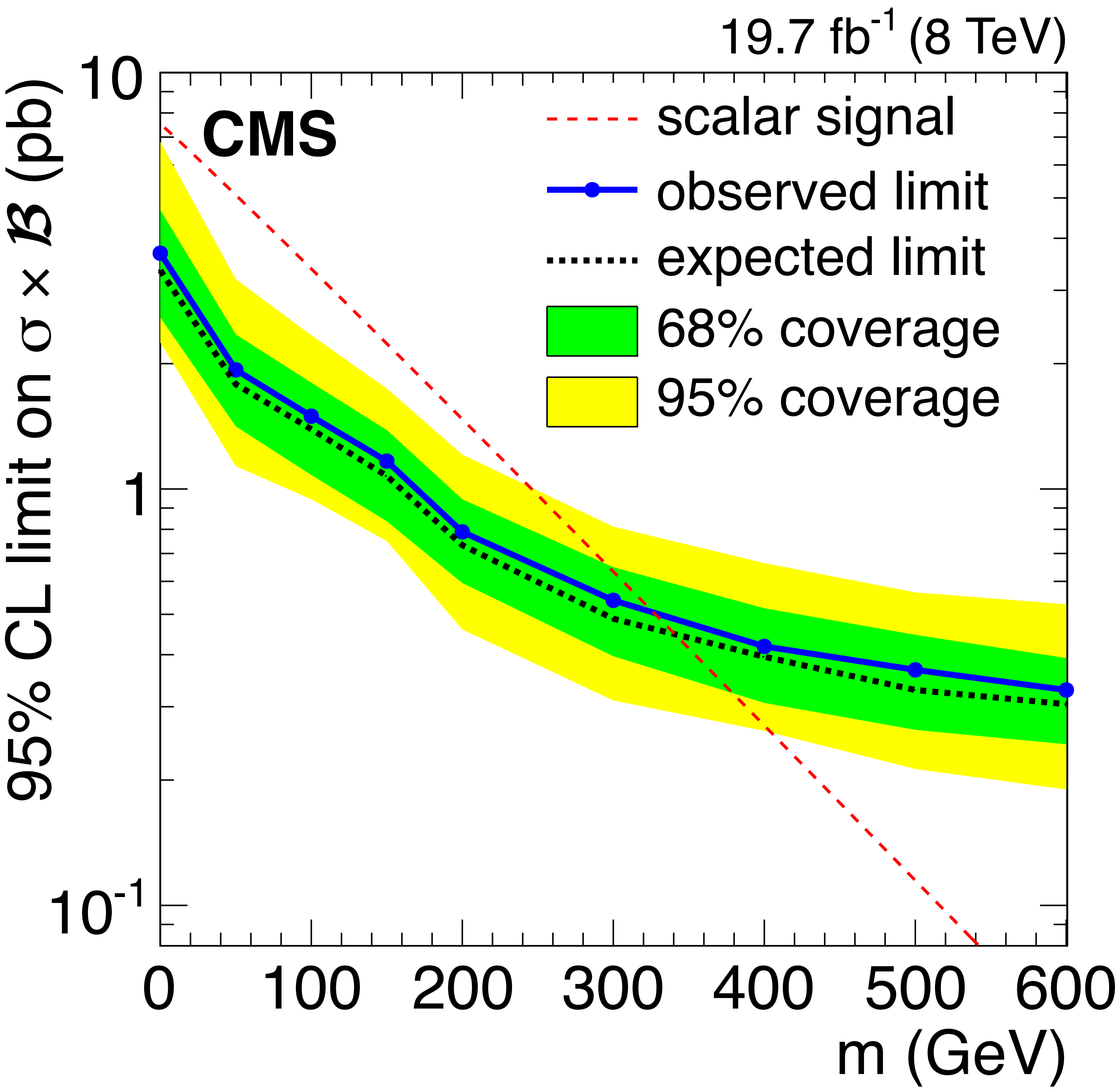
t+DM M_{jjj} Distribution

- The triple-jet invariant mass distribution for the hadronic t+DM analysis is well modeled by Monte Carlo

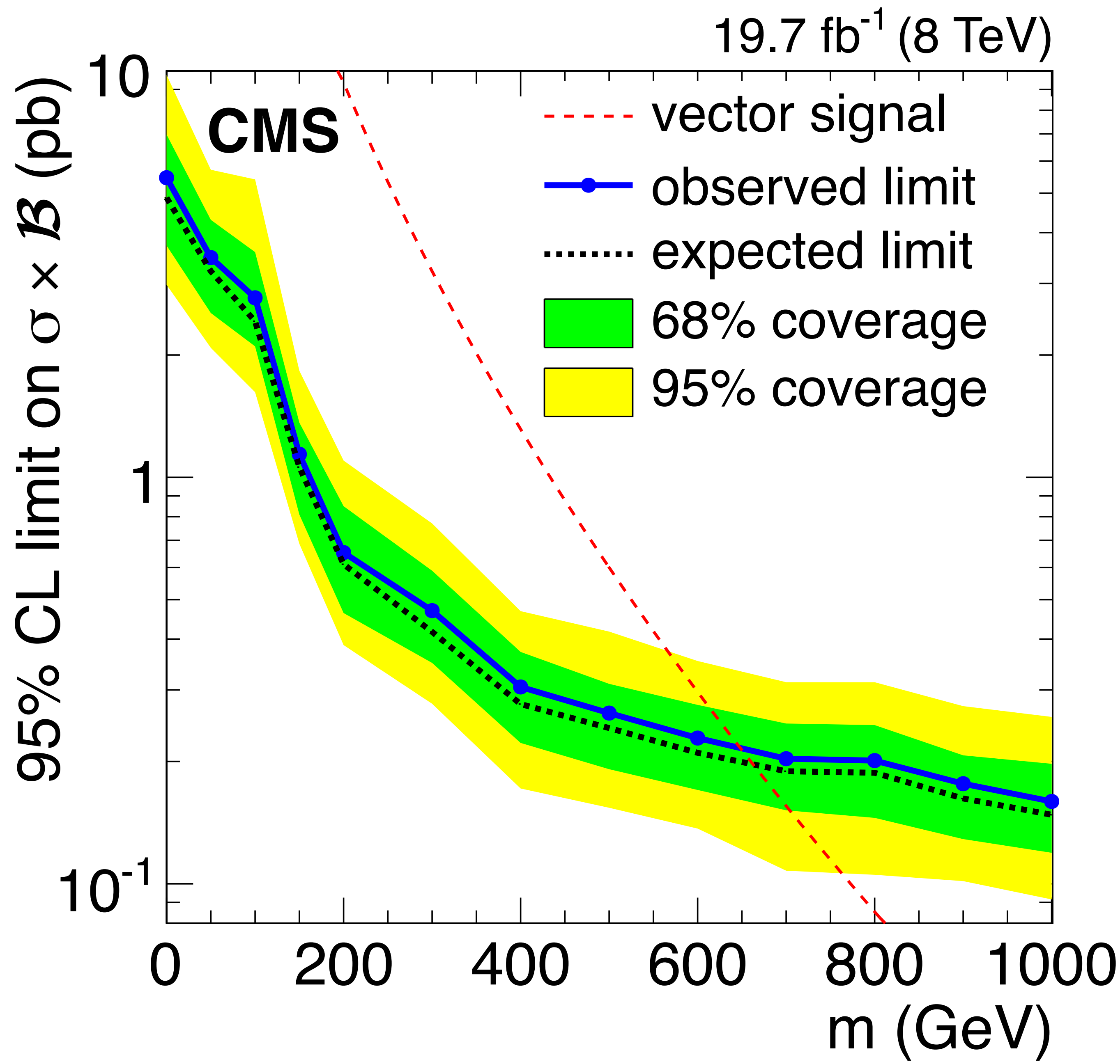


t+DM Results

Scaler DM exclude below
327 GeV (343 Expected)



Vector DM excluded below
655 GeV (668 Expected)



Strategies for 13 TeV

- Searches for a Z' and dark matter and will continue at 13 TeV
  - Increase in energy will improve both the Z' and DM production cross-section
  - New t-tagging strategies will be added to analysis
- New analysis channels will be added to the DM search:
  - tt+DM - Dileptonic, Semi-leptonic, and Fully Hadronic
  - t+DM - Resonant Production (Fully hadronic)
- Re-examine DM EFT requirements with respect to new energy scale:

$$M_{inv}(\chi\chi) < 4\pi\sqrt{\frac{M_*^3}{m_q}}$$

- Interpret results with different DM couplings

Summary and Conclusions

- Discussed the upcoming search of a $t\bar{t}$ resonance
    - The addition of the dilepton channel, t-tagging, and sub-jet b-tagging should result in significant improvements in sensitivity
- Presented most recent DM limits for CMS, which are competitive at low mass scales
    - Will add t-tagging and sub-jet b-tagging for increased sensitivity in the future
- Increased production cross sections at 13 TeV will allow for more stringent limits on Z', g_{KK}, and DM…
  or maybe something more exciting!

Backup

CMS and HEP t-taggers

- CMS t-tagger
  - Used on narrower CA8 jet.
  - Used on highly boosted jets (pT > 400 GeV)
  - Requires 3 sub-jets
  - M_{jet} is between 140GeV and 250GeV
  - Minimum par-wise mass must be greater than 50 GeV
  - $\tau_{3}/\tau_{2} < 0.7$
  - CSV medium working point used for sub-jet b-tagging

- HEP t-tagger
  - Large CA15 jet cone
  - Used only for moderately boosted tops (p_T > 200 GeV)
  - M_{jet} is between 140 GeV and 250 GeV
  - W mass selection in sub-jets
  - CSV medium working point used for sub-jet b-tagging.

$Z' \rightarrow t\bar{t}$ Dilepton Analysis Selection

- Two oppositely charged lepton pairs
- μμ Channel
  - Lead Muon: $p_T > 45$ GeV and $|\eta|<2.1$
  - Sub-lead Muon: $p_T > 20$ GeV and $|\eta|<2.1$
- μe Channel
  - Muon Selection: $p_T > 45$ GeV and $|\eta|<2.1$
  - Electron Selection: $p_T > 20$ GeV and $|\eta|<2.5$
- ee Channel
  - Lead Electron: $p_T > 85$ GeV and $|\eta|<2.5$
  - Sub-lead Electron: $p_T > 20$ GeV and $|\eta|<2.5$
- $M_{ll} > 12$ GeV
- Z Veto: 76 GeV $< M_{ll} <$ 106 GeV
- MET > 30 GeV in μμ and ee channels
- At least 2 Jets:
  - Lead $p_T > 100$ GeV with $|\eta|<2.5$
  - Sub-lead $p_T > 50$ GeV with $|\eta|<2.5$
- 2D Cut:
  - If $\Delta R_{l,j} < 0.5$: $p_{Trel(i,j)} > 15$ GeV
- Either one CSV medium b-tag or 2 CSV loose b-tags.
- Lead Lepton $\Delta R_{l,j} < 1.2$
- Sub-lead Lepton $\Delta R_{l,j} < 1.5$

$Z' \rightarrow t\bar{t}$ Lepton+Jet Analysis Selection

- Lepton Selection
  - Exactly 1 muon with $p_T > 45$ GeV and $|\eta| < 2.1$
  - Exactly 1 muon with $p_T > 35$ GeV and $|\eta| < 2.5$
- Jet Selection
  - Lead Jet $p_T > 150$ GeV and $|\eta| < 2.4$
  - Sub-lead Jet $p_T > 50$ GeV and $|\eta| < 2.4$
- Veto events with more than one CA8 jet
- MET > 50 GeV
- H_{Tlep} (MET + p_{Tlep}) > 150 GeV
- 2D Cut
  - If $\Delta R_{l,j} < 0.5$: $p_{Trel(i,j)} > 25$ GeV
- Triangular Cuts (electron channel)
  - $|\Delta\phi(j_{lead}$ and e$)-1.5| <$ 1.5/75GeV X MET

Z’→$t\bar{t}$ All Hadronic Selections

- CMS t-tag Selection
  - Fires HT750 Trigger
  - Jet pT > 400 GeV
  - 3 or 4 sub-jets
  - 140 GeV < Mjet < 250 GeV
  - Minimum pairwise sub-jet mass > 50 GeV
  - $\tau_3/\tau_2 < 0.7$
  - Events are categorized on number of CSV medium sub-jet b-tags and $|\Delta y| < 1.0$
- HEP t-tag Selection
  - Either $H_T > 800$ GeV or 4 jets with $p_T > 70$ GeV
  - 2 HEP t-tagged CA 15 jets with pT > 200 GeV and $|y| < 2.4$
  - Either 0, 1, or 2 CSV working point medium b-tagged sub-jets.

Top+DM Object Definitions

Electrons Tight

Variables	tight cuts
$\lvert d_0(\mathrm{vtx})\rvert$	< 0.02 cm
$\lvert d_z(\mathrm{vtx})\rvert$	< 0.1 cm
$\sigma_{i\eta i\eta}$	$< 0.01(\mathrm{barrel}), < 0.03(\mathrm{endcap})$
$\lvert\Delta\eta_{\mathrm{in}}\rvert$	$< 0.004(\mathrm{barrel}), < 0.03(\mathrm{endcap})$
$\lvert\Delta\phi_{\mathrm{in}}\rvert$	$< 0.03(\mathrm{barrel}), < 0.02(\mathrm{endcap})$
H/E	$< 0.12(\mathrm{barrel}, < 0.10(\mathrm{endcap})$
$\lvert 1/E - 1/p\rvert$	< 0.05
pfIso03/p_T	< 0.1
Matched conversion?	false
Missing hits	0

Jets Loose

PF Jet ID	Cuts
Neutral hadron fraction	< 0.99
Neutral EM fraction	< 0.99
Number of constituent	> 1
Below for $\lvert\eta\rvert < 2.4$ only	
Charged hadron fraction	> 0
Charged multiplicity	> 0
Charged EM fraction	< 0.99

Muons Tight

Variables	tight cuts
isGlobalMuon	true
isPFMuon	true
χ^2/d.o.f.	< 10
Number of muon hits	> 0
Number of pixel hits	> 0
Number of matched stations	> 1
Number of tracker layers	> 5
$d_{xy}(\mathrm{vtx})$	< 0.2 cm
$d_z(\mathrm{vtx})$	< 0.5 cm
pfIso04/p_T, $\Delta\beta$ corr.	< 0.12

$t\bar{t}$+DM Dilepton Selections

- One tight electron or muon with $p_T > 20$ GeV and $|\eta| < 2.5$ and $|\eta| < 2.1$, respectively
- Two loose jets with $p_T > 30$ GeV and $|\eta| < 5.0$
- $M_{ll} > 20$ GeV
- Z Veto: $76 < M_{ll} < 106$ GeV
- MET > 320 GeV
- $p_{Tj1} + p_{Tj2} < 400$ GeV
- $p_{Tl1} + p_{Tl2} > 120$ GeV
- $\Delta\phi_{ll} > 2.0$

Background Source	Yield
$t\bar{t}$	$0.87 \pm 0.18 \pm 0.27$
Single top	$0.48 \pm 0.46 \pm 0.09$
Di-boson	$0.32 \pm 0.09 \pm 0.05$
Drell-Yan	$0.19 \pm 0.14 \pm 0.03$
One Mis-ID lepton	$0.02 \pm 0.07 \pm 0.02$
Double Mis-ID leptons	$0.00 \pm 0.00 \pm 0.00$
Total Bkg	$1.89 \pm 0.53 \pm 0.39$
Data	1
Signal	$1.88 \pm 0.11 \pm 0.07$

$t\bar{t}$+DM Dilepton Systematics

Source of systematic uncertainties	Relative error on total background (%)
Jet energy scale	15
$t\bar{t}$+jets top p_T reweighting	11
Jet energy resolution	5.3
$t\bar{t}$+jets Q^2	3.7
Pileup model	3.1
$t\bar{t}$+jets jet-parton matching	3.0
Cross section	2.7
Integrated luminosity	2.6
Electron energy scale	1.3
Misidentified lepton	1.3
Lepton identification efficiency	1.0
Trigger efficiency	0.3
Muon energy scale	0.2
Unclustered energy scale	0.2

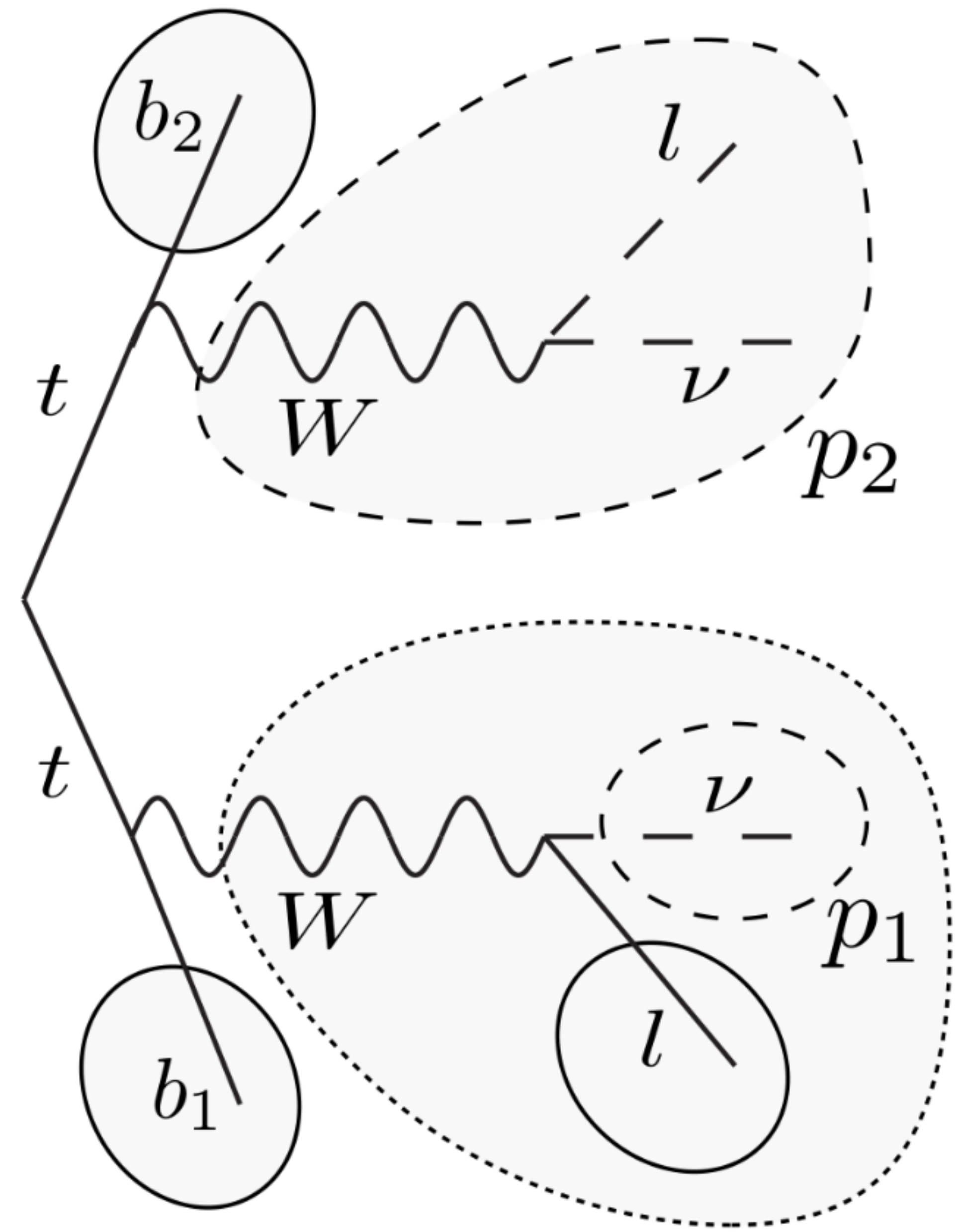
$t\bar{t}$+DM Semi-Leptonic Selections

- 1 tight electron or muon with $p_T > 30$ GeV and $|\eta| < 2.5$ and $|\eta| < 2.1$, respectively
- 3 jets with pT>30 GeV and $|\eta| < 4.0$.
- 1 b-tagged jet at CVS medium (0.679)
- MET > 320 GeV
- $M_T > 160$ GeV
- $\Delta\phi_{j1,MET}$ and $\Delta\phi_{j2,MET} > 1.2$
- $M_{T2}^W > 200$ GeV

Background Source	Yield
$t\bar{t}$	$8.2 \pm 0.6 \pm 1.9$
W	$5.2 \pm 1.7 \pm 0.6$
Single top	$2.3 \pm 1.1 \pm 1.1$
Di-boson	$0.5 \pm 0.2 \pm 0.2$
Drell-Yan	$0.3 \pm 0.3 \pm 0.1$
Total Bkg	$16.4 \pm 2.2 \pm 2.7$
Data	18
Signal	$38.3 \pm 0.7 \pm 2.1$

M_{T2}^{W} Definition

- M_{T2}^{W} was originally developed for supersymmetric stop searches
- It suppresses the $t\bar{t}$ background in events where both t-quarks decay leptonically, but one of the leptons is lost
- This increases the likelihood of the event passing the MET and M_T selections
- Further description can be found in: arXiv:1203.4813



$$M_{T2}^{W} = \min \left\{ \mathrm{m}_y \text{ consistent with: } \begin{bmatrix} \vec{p}_1^{\,T} + \vec{p}_2^{\,T} = \vec{E}_T^{miss}, p_1^2 = 0, (p_1 + p_l)^2 = p_2^2 = M_W^2, \\ (p_1 + p_l + p_{b1})^2 = (p_2 + p_{b2})^2 = m_y^2 \end{bmatrix} \right\}$$

$t\bar{t}$+DM Semi-Leptonic Systematics

Source of systematic uncertainties	Relative error on total background (%)
50% normalization error of other bkg in deriving SFs	10
Statistical error of SF_{W+jets}	1.5
$t\bar{t}$+jets jet-parton matching	8.2
$t\bar{t}$+jets Q^2	6.6
$t\bar{t}$+jets top p_T reweighting	3.9
Jet energy scale	4.0
Jet energy resolution	3.0
b-tagging correction factor (heavy flavor)	1.0
b-tagging correction factor (light flavor)	1.8
Pileup model	2.0

t+DM Selections

- 3 jets with $p_T > 60$, 60, and 40 GeV.
- 1 b-tagged jet at CSV medium (0.679).
- $M_{jjj} < 250$ GeV
- MET > 350 GeV
- Lepton Veto
  - Global muon $p_T > 10$ GeV, $|\eta| < 2.4$, and $Iso_{rel}^{0.4} < 0.2$
  - pT > 20 GeV, $|\eta| < 2.5$, and $Iso_{rel}^{0.3} < 0.2$

# of b tags	Zero CSVm b tag	One CSVm b tag
$t\bar{t}$	6±0±5	12±0±12
W+jets	18±9±7	3±1±2
Z+jets	103±33±9	11±10±1
Single top	2±1±1	1±1±1
VV	5±0±0	0±0±0
QCD	6	1
sum	140±36	28±16
Data	143	30

tDM Systematics

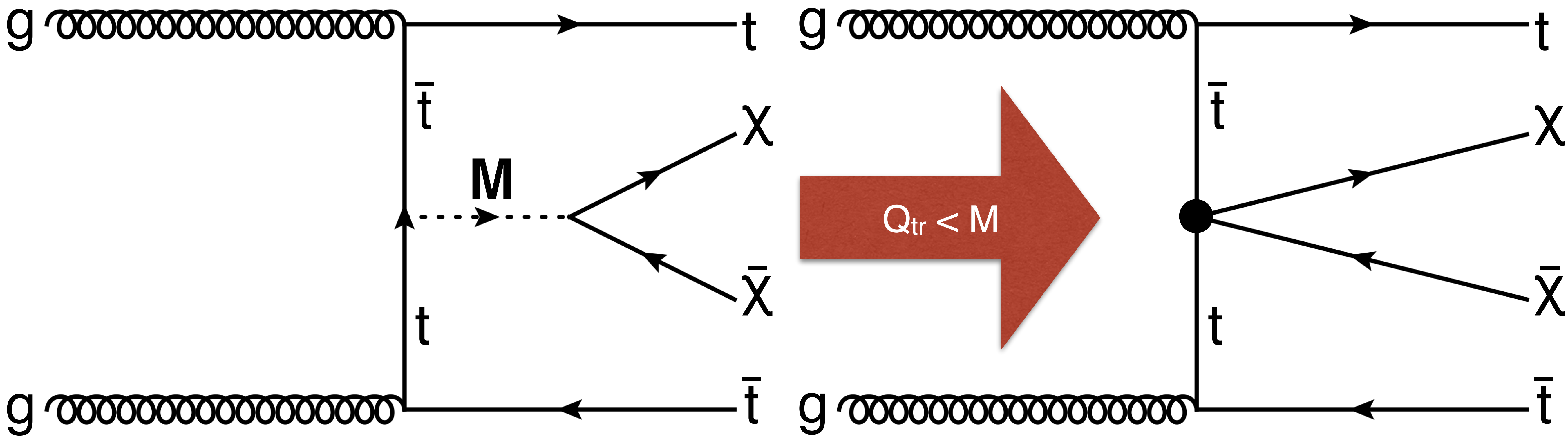
nuisance parameter	$N_{\mathtt{S}}^{0b(1b)}$	$N_{\mathtt{t\bar{t}}}^{0b(1b)}$	$N_{\mathtt{top}}^{0b(1b)}$	$N_{\mathtt{VV}}^{0b(1b)}$	$N_{\mathtt{W+jets}}^{0b(1b)}$	$N_{\mathtt{Z+jets}}^{0b(1b)}$	$N_{\mathtt{QCD}}$
$\mathcal{L}$	2.4%	2.4%	2.4%	2.4%	—	—	—
$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger scale	1.4%	1.4%	1.4%	1.4%	—	—	—
$\mathrm{PDF}_{\mathtt{S}}$	$\lesssim$ 12%	—	—	—	—	—	—
$\mathrm{PDF}_{\mathtt{t\bar{t}}}$	—	10(11)%	—	—	—	—	—
$\mathrm{PDF}_{\mathtt{top}}$	—	—	11(12)%	—	—	—	—
$\mathrm{PDF}_{\mathtt{VV}}$	—	—	—	6(8)%	—	—	—
JEC	$\lesssim$ 15%	14(22)%	44(56)%	7(25)%	—	—	—
JER	4(2)%	4(8)%	27(0)%	3(0)%	—	—	—
b tagging	6(2)%	10(15)%	0(0)%	2(14)%	—	—	—
Q^2-scale	—	35(76)%	—	—	—	—	—
$\mathrm{t\bar{t}}$ matching	—	50(44)%	—	—	—	—	—
$\mathrm{t\bar{t}}$ reweighting	—	41(41)%	—	—	—	—	—
Data-driven W+jets	—	—	—	—	67(85)%	—	—
Data-driven Z+jets	—	—	—	—	—	36(100)%	—
p_{QCD}^{1b}	—	—	—	—	—	—	17%
$N_{\mathtt{QCD}}$	—	—	—	—	—	—	0–10K

DM Couplings

- So far only the D1 coupling has been investigated
- Considering to expanding interpretations to include more couplings that are proportional to m_q
  - D1-D4
  - C1-C2
  - R1-R2

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

Dark Matter EFT Validity



- Effective field theory is valid as long as the momentum transfer of the interaction is less than the mass of the mediating particle (**M**).
- This reduce the interaction to a 4-point contact interaction.

Dark Matter EFT Continued

- Assuming $Q_{tr} < M$
- the coupling goes as

$$\frac{g_1 g_2}{Q_{tr}^2 - M^2} = -\frac{g_1 g_2}{M^2}\left(1 + \frac{Q^2}{M^2} + O\left(\frac{Q^4}{M^4}\right)\right) \simeq -\frac{g_1 g_2}{M^2}$$

- Effective coupling should match UV theory (D1)

$$M_* = \left(\frac{m_q M^2}{g_1 g_2}\right)^{\frac{1}{3}}$$

- From kinematics $Q_{tr} > 2M_\chi$
- and the strong coupling limit $\sqrt{g_1 g_2} < 4\pi$
- we get the final constraint $\sqrt{\frac{M_*^3}{m_q}} > \frac{M_\chi}{2\pi}$