Search for ttbar resonances and dark matter at CMS

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DIS 2015

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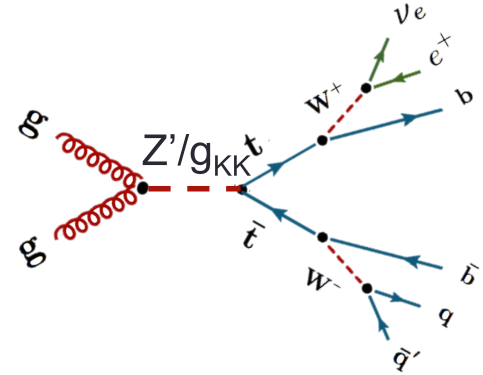
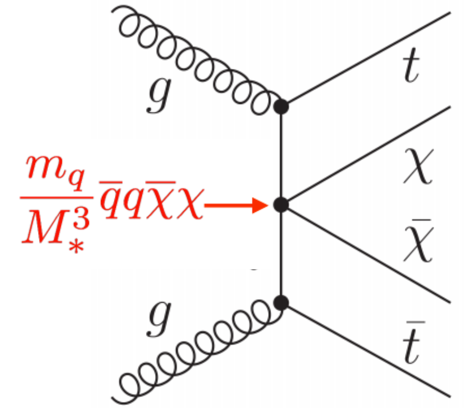
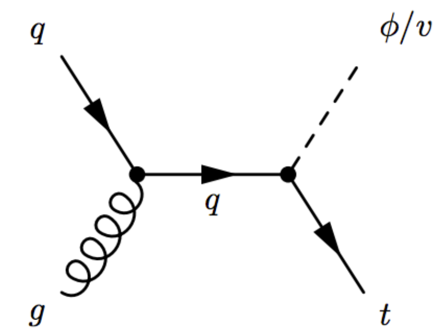
Outline

- Massive new resonances decaying to ttbar
  - Appear in many BSM models: Z' Bosons, Kaluza-Klein excitations of gluons…
  - Can be seen as extra resonant contributions on top of SM ttbar predictions → Searching ttbar invariant mass provides model-independent method for BSM searches
- Top quarks can also play a critical role in Dark Matter searches
  - Four-fermion contact scalar interaction proportional to quark mass → coupling to light quarks suppressed
  - Previous monojet+DM exclusions → light quarks flavor changed to top quarks in interaction with DM

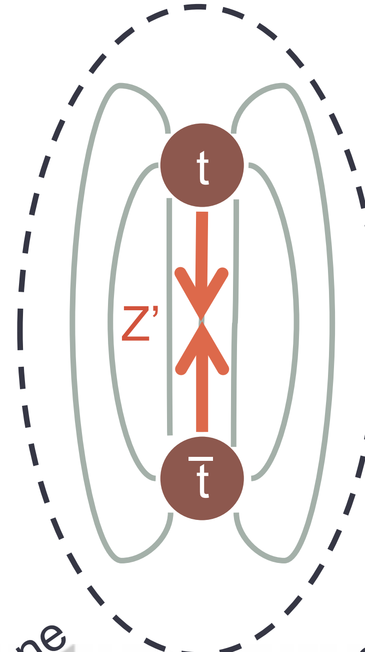


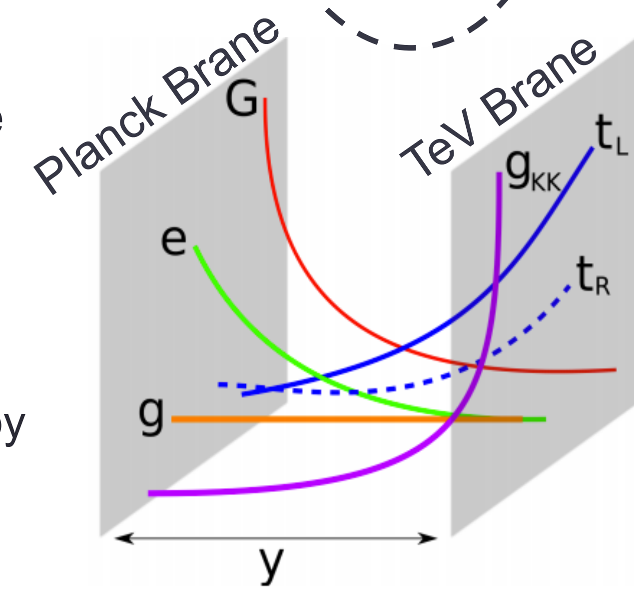




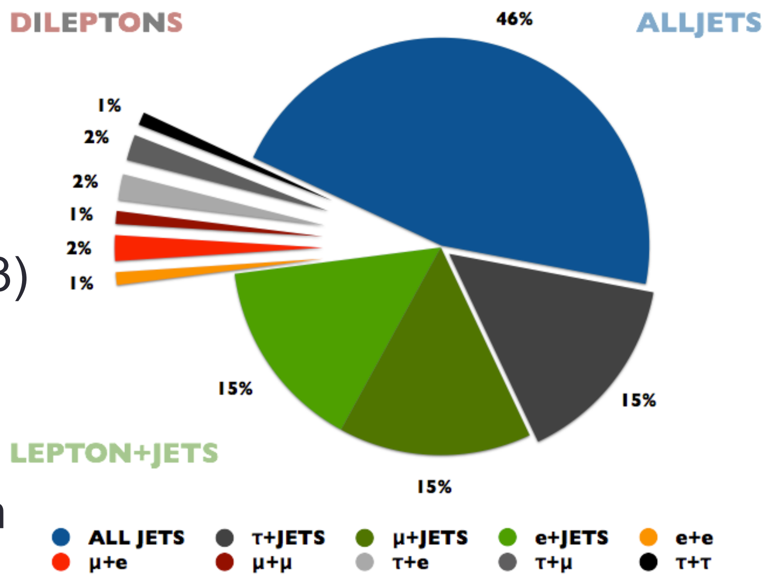
The Standard Model & Beyond

- The SM is far from a "theory of everything"
  - Gravity?
  - Hierarchy problem
  - Dark Matter/Dark Energy
  - Matter/Antimatter asymmetry
  - >19 arbitrary numerical constants
  - Fine tuning problem
- Therefore, there are many motivations for searching for physics Beyond the Standard Model (BSM)
  - Topcolor attempts to explain the huge mass of the top quark through dynamical EWSB
    - In terms of QFT, the SM is a broken symmetry of: $SU(3)_1 \times SU(3)_2 \times SU(2)_L \times U(1)_{Y1} \times U(1)_{Y2}$
  - Kaluza-Klein excitations of gluons
    - Our universe is a 5-D anti-de Sitter space bounded by two 3+1-D "Branes"





Publications

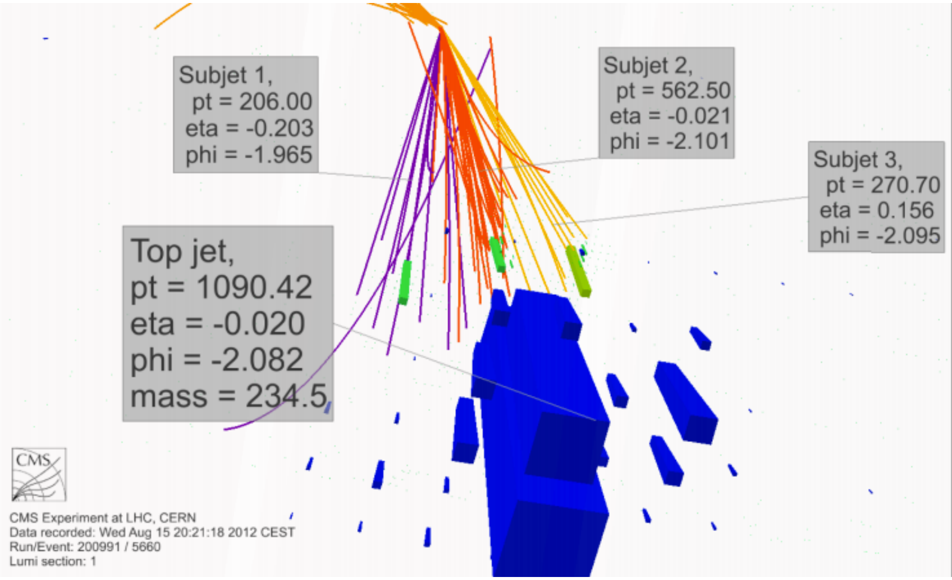


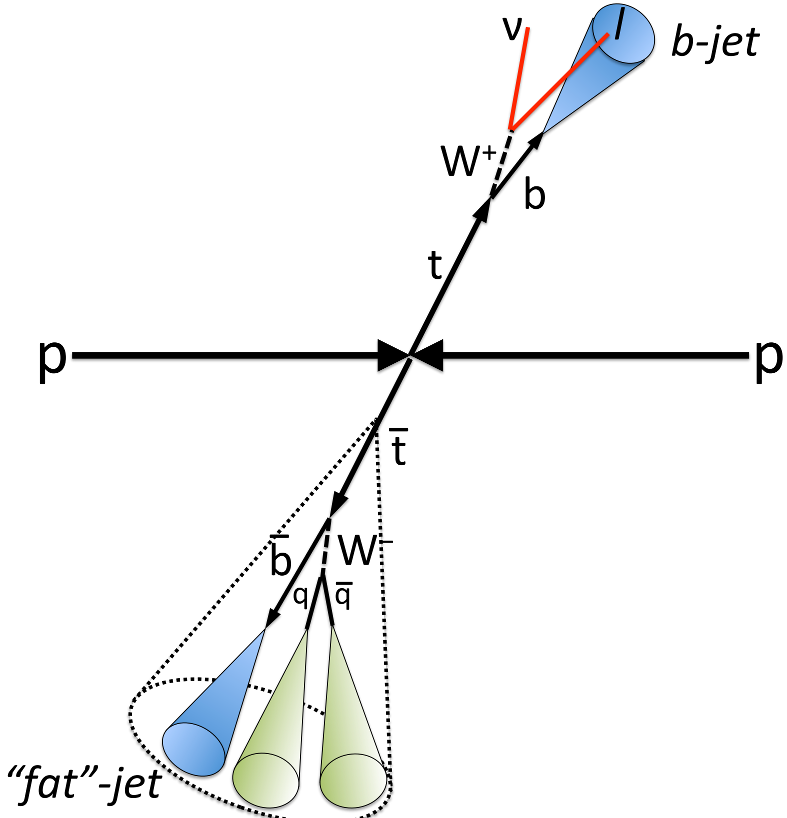
- Previous version of combined Z' search published in PRL
  - hep-ex/1309.2030, Phys.Rev.Lett. 111 (2013) 21, 211804
  - Narrow Z' – 2.1 TeV, Wide Z' – 2.6 TeV, g_{KK} – 2.4 TeV lower limits @ 95% C.L
- Updated Z' search (*CMS-PAS-B2G-13-008*) on the same dataset:
  - New triggering strategy in lepton+jets channel
  - Inclusion of top-quark tagging in lepton+jets channel (previously only all hadronic)
  - All hadronic channel now includes low-mass signal region using new HEP top-tagger, subjet b-tagging
- Dark Matter + ttbar
  - *CMS-PAS-B2G-13-004*, dilepton
  - *CMS-PAS-B2G-14-004*, hep-ex/1504.03198, submitted to JHEP
- Dark Matter + top (monotop)
  - *CMS-PAS-B2G-12-022,* Phys. Rev. Lett. 114 (2015) 101801

Boosted Tops for Z' Search

CMS-PAS-B2G-13-008

- Non-resolved topology
- Non-isolated leptons
- Jet-Lepton Cleaning
- New triggering/ reconstruction techniques



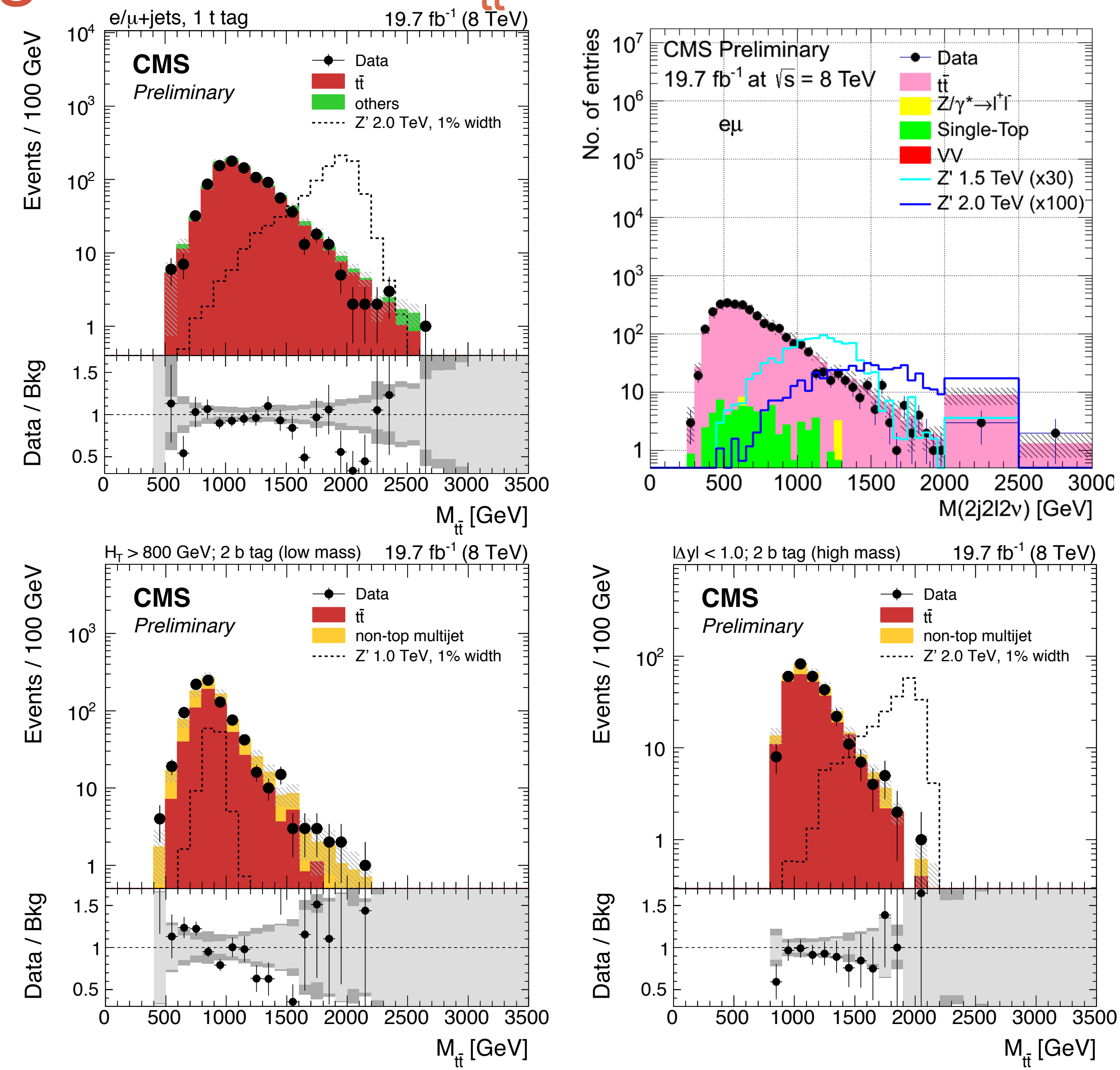


- Top-Quark Tagging
- "Fat" jet substructure analyzed to find hadronically decaying top quarks
- Very good bkg reduction

hep-ph/0806.0848, Phys.Rev.Lett. 101 (2008) 142001 ; CMS-PAS-JME-13-007

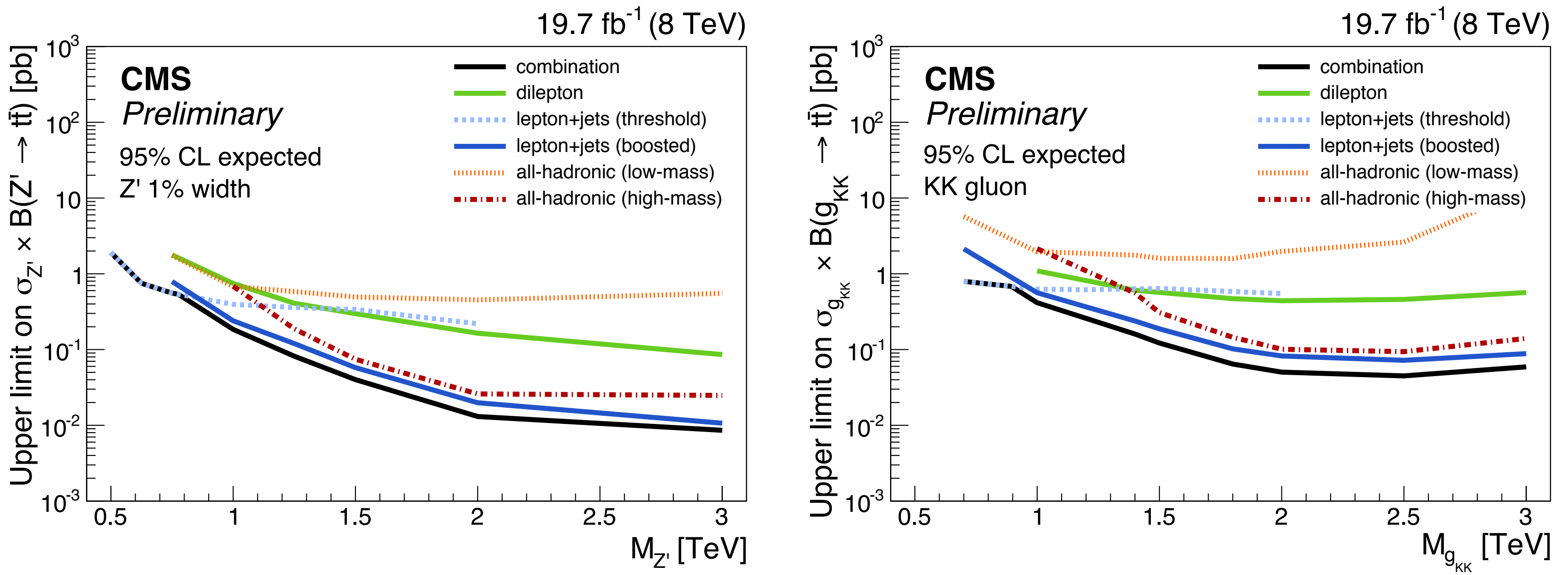
Event Categorization & $M_{t\bar{t}}$ Distributions

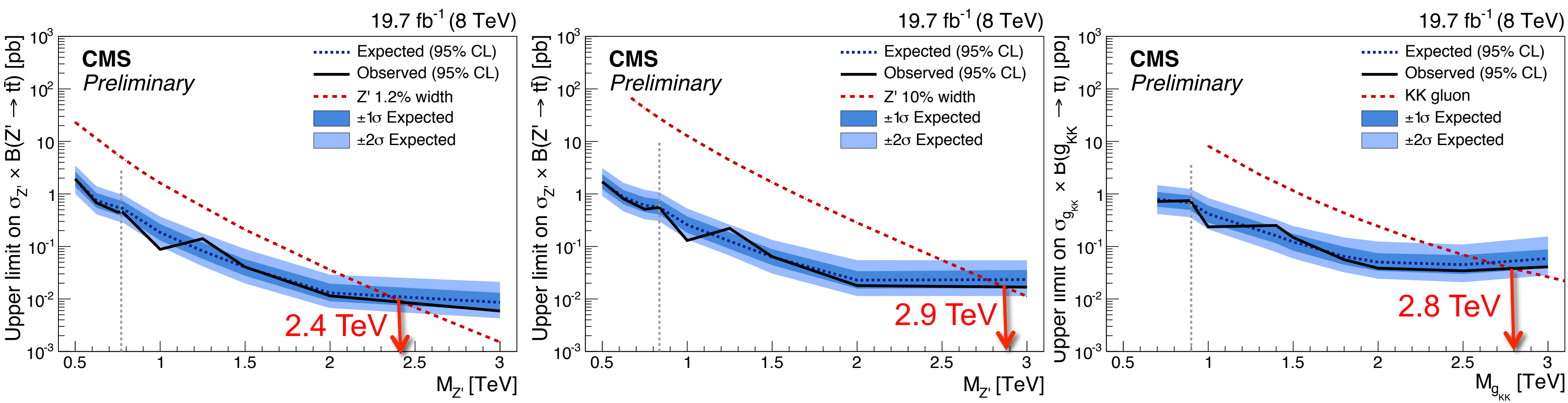
- Lepton+Jets
  - 6 Categories (3 for each {e,μ} channel)
  - 1 t-tag, 0 t-tag 1 b-tag, 0 t-tag 0 b-tag
- All Hadronic
  - High-Mass: 6 Categories
    - |Δy| < 1.0, |Δy| > 1.0
      - 0,1,2 subjet b-tags
  - Low-Mass: 6 Categories
    - H_T > 800 GeV, H_T < 800 GeV
    - 0,1,2 b-tagged CA15 jets
- Dilepton
  - ee,eμ,μμ



Combined ttbar Resonance Limits

Binned Likelihood
Statistical Analysis
across all channels
simultaneously, 95% C.L.



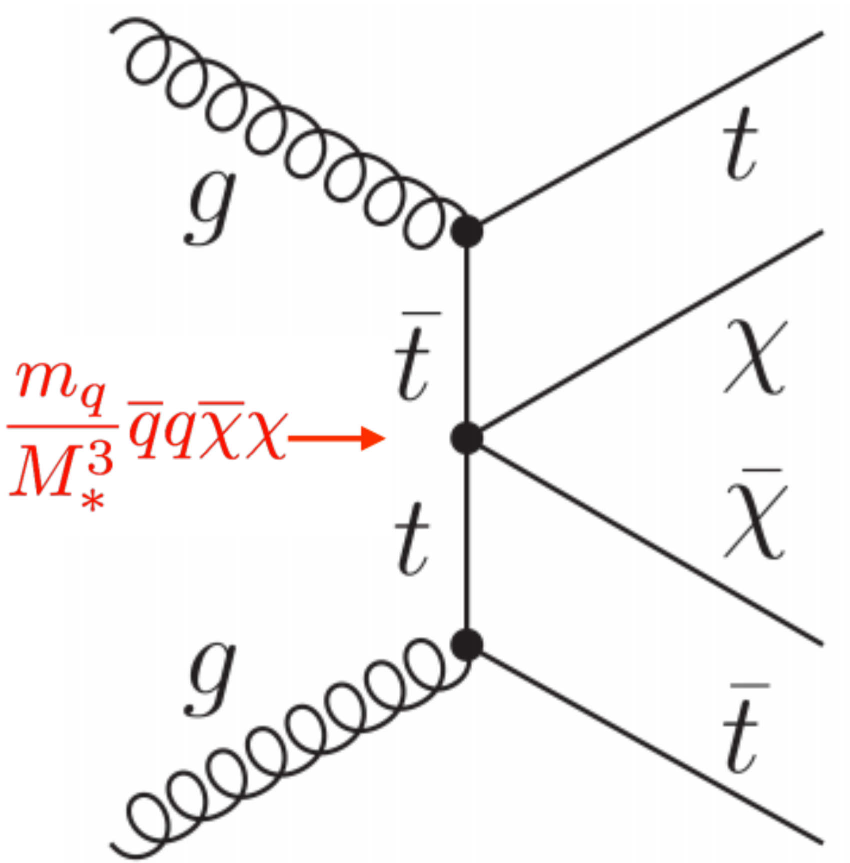


- Combined analysis provides the most stringent constraints on resonant ttbar production to date!

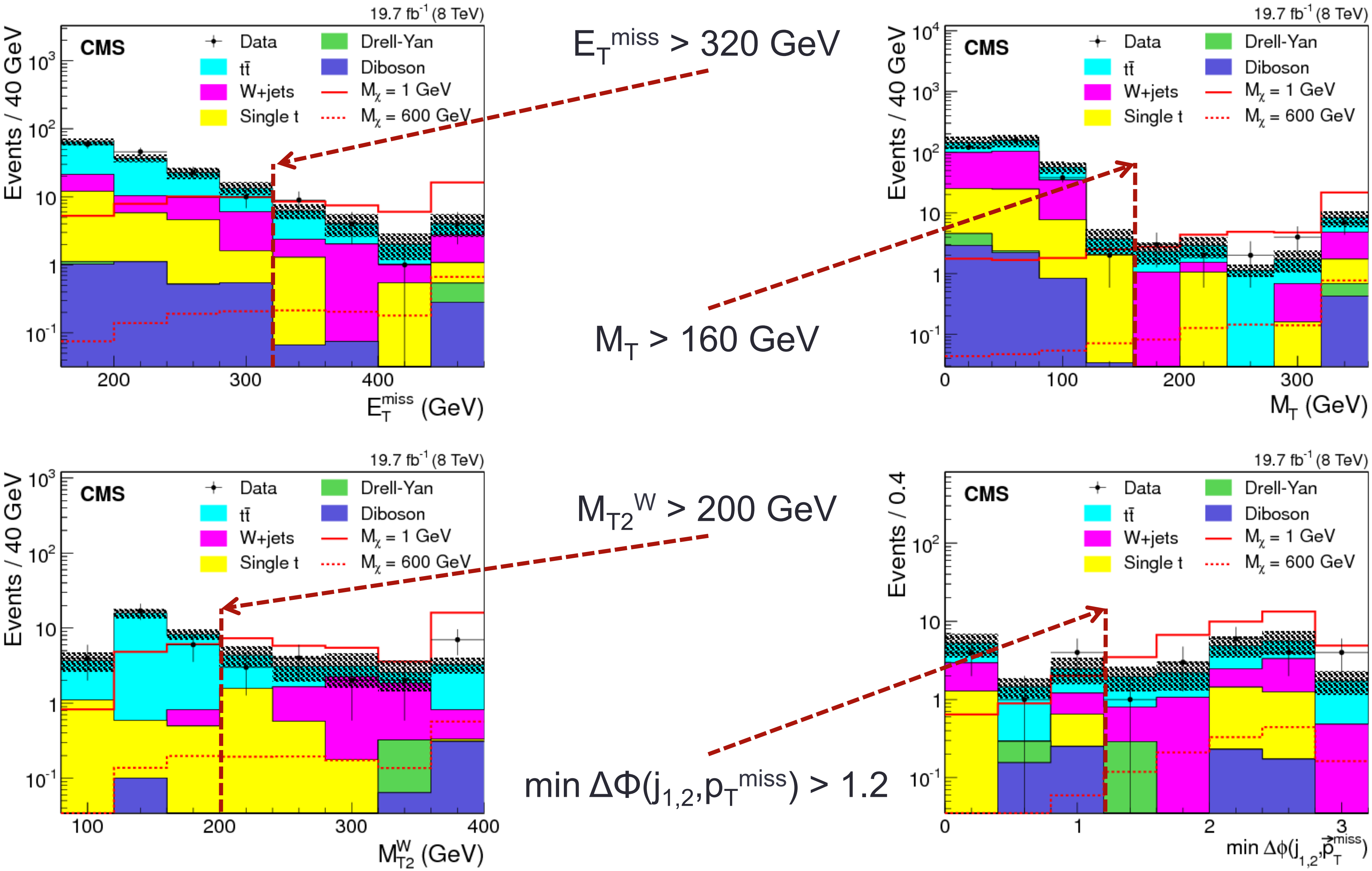
Dark Matter + ttbar Search

hep-ex/1504.03198, submitted to JHEP

- EFT prefers higher mass quarks
- Focus on semileptonic decay mode of ttbar
  - Look for large E_T^{miss} from undetected dark matter
  - Look for at least 3 jets from ttbar decay
  - Look for exactly one isolated electron (muon)
  - Reduce backgrounds via:
    - M_T – kinematically constrained to M_W
    - M_{T2}^W – reduce dilepton decay in which 1 lepton unreconstructed

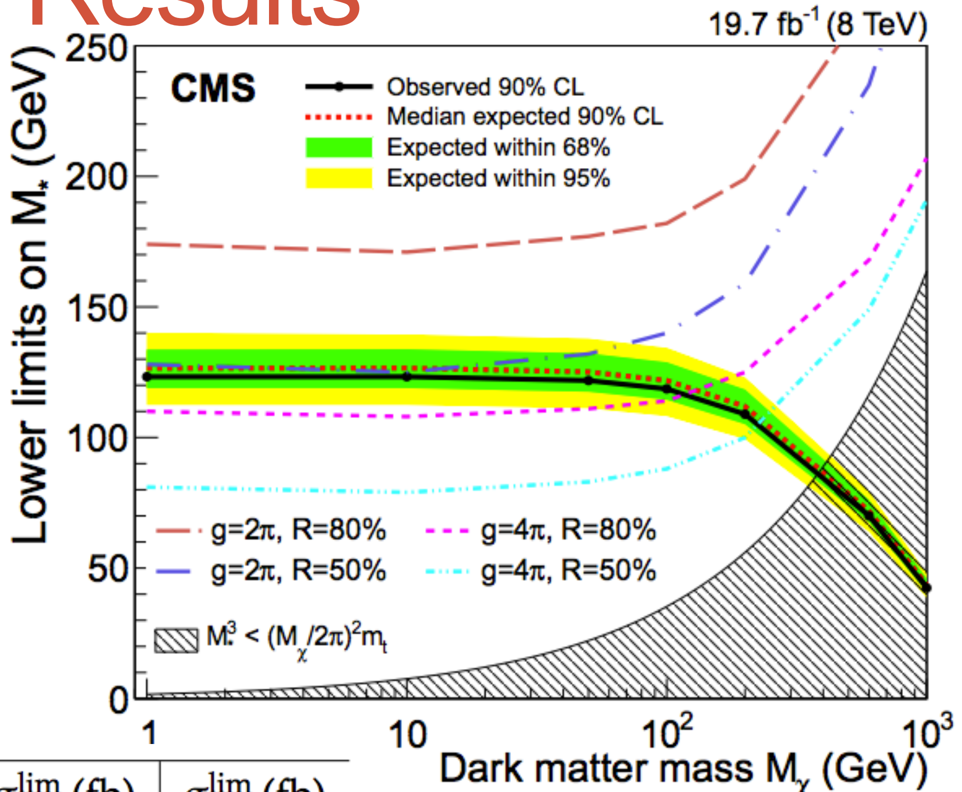


Dark Matter + ttbar Control Plots



Dark Matter + ttbar Results

Source	Yield (±stat ±syst)
$t\bar{t}$	$8.2 \pm 0.6 \pm 1.9$
W	$5.2 \pm 1.8 \pm 2.1$
Single top	$2.3 \pm 1.1 \pm 1.1$
Diboson	$0.5 \pm 0.2 \pm 0.2$
Drell–Yan	$0.3 \pm 0.3 \pm 0.1$
Total Bkg	$16.4 \pm 2.2 \pm 2.9$
Signal	$38.3 \pm 0.7 \pm 2.1$
Data	18



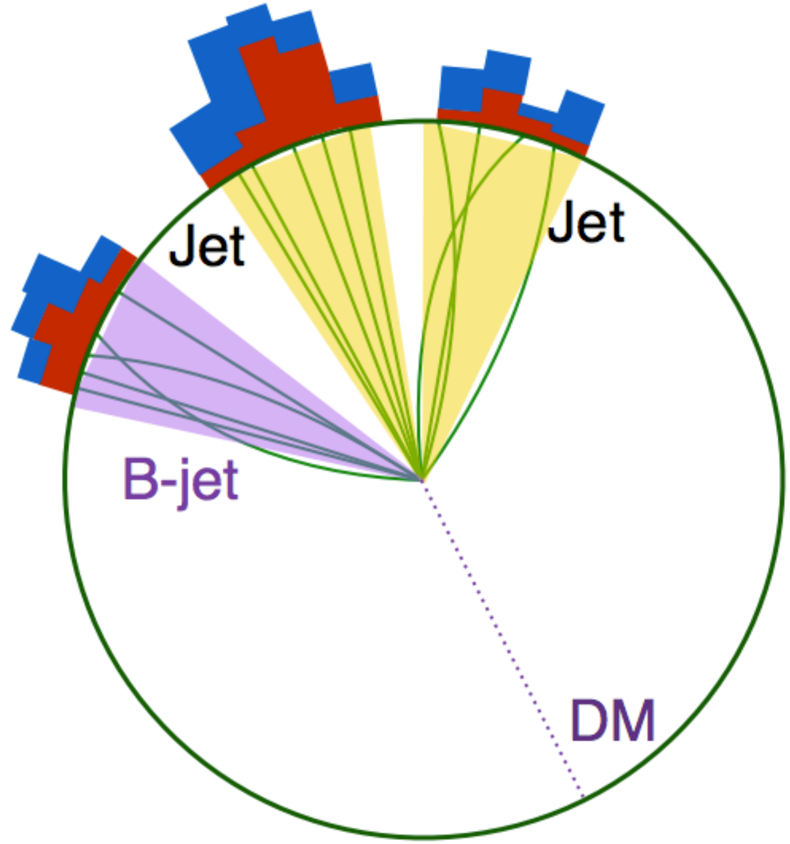
M_χ (GeV)	Signal efficiency (%) (±stat ±syst)	$\sigma_{\text{exp}}^{\text{lim}}$ (fb)	$\sigma_{\text{obs}}^{\text{lim}}$ (fb)
1	$1.01 \pm 0.02 \pm 0.05$	47^{+21}_{-13}	55
10	$1.01 \pm 0.02 \pm 0.05$	46^{+21}_{-13}	54
50	$1.20 \pm 0.02 \pm 0.06$	39^{+18}_{-11}	45
100	$1.46 \pm 0.02 \pm 0.07$	32^{+14}_{-9}	37
200	$1.73 \pm 0.02 \pm 0.08$	27^{+12}_{-8}	32
600	$2.40 \pm 0.03 \pm 0.11$	19^{+9}_{-6}	23
1000	$2.76 \pm 0.04 \pm 0.13$	17^{+8}_{-5}	20

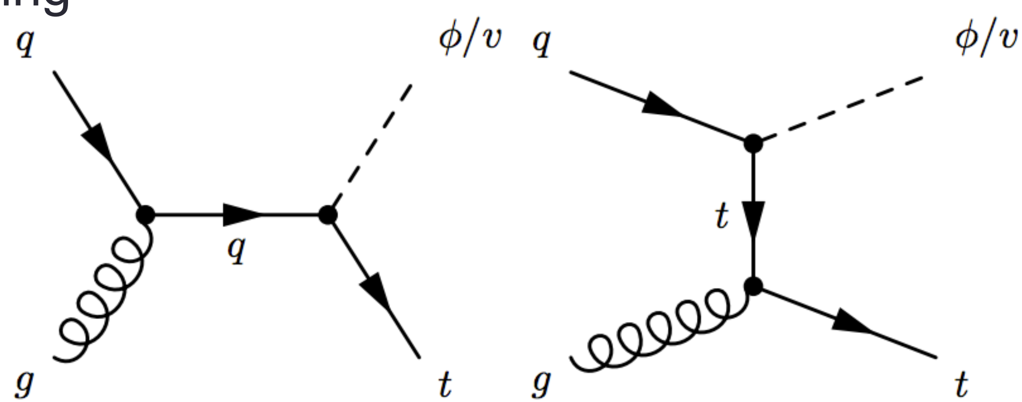
- 90% C.L. limits using modified CL_s method

Monotop Search

CMS-PAS-B2G-12-022,
Phys. Rev. Lett. 114 (2015) 101801
(hep-ex/1410.1149)

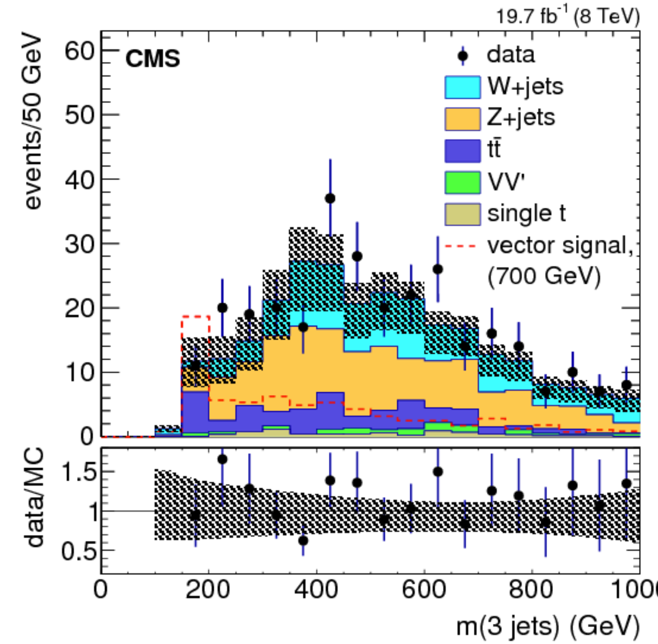
- Search for hadronic top quark decay recoiling against DM
- Large E_T^{miss}
- Veto against isolated leptons
- Veto against more than 3 jets
- b-tagging categorization
  - Improve background modeling



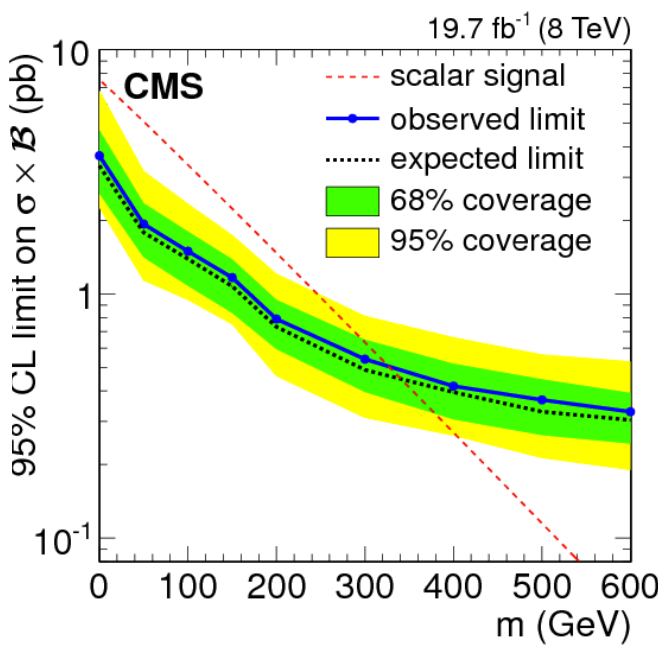


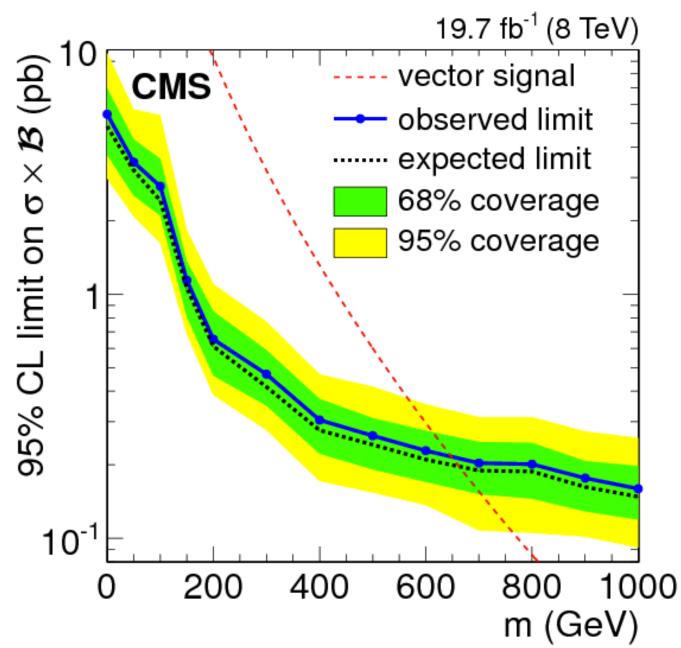
t+DM Results

- Limits set by CL_s technique @ 95% C.L.
- Scaler DM excluded below 327 GeV (343 GeV expected)
- Vector DM excluded below 655 GeV (668 GeV expected)



	No b tag	One 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
Multijet	6(±39)	1(±9)
Total background	140±36	28±16
Signal	2±6	3±11
Data	143	30





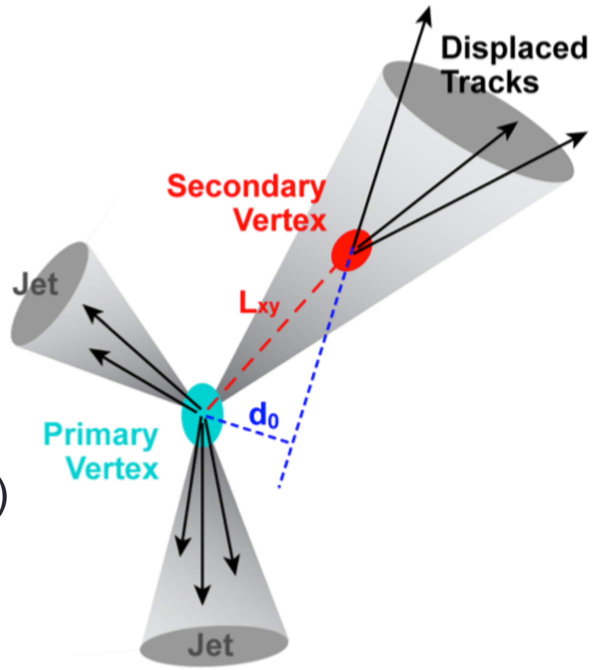
Summary

- Analyses performed performed in 19.7 fb^{-1} of data recorded at $\sqrt{s}$ = 8 TeV at the CMS experiment
- Model-independent search for resonant ttbar production:
  - 30-40% improvement w.r.t. previously published results on same dataset (top-tagging, trigger)
  - Narrow Z' resonances excluded at 95% C.L. below 2.4 TeV, Wide Z' below 2.9 TeV, KK Gluons below 2.8 TeV
  - Combined result is most stringent limit on resonant ttbar production to date
- Dark matter production in association with top quarks:
  - Cross sections larger than 20 to 55 fb are excluded at 90% CL for dark matter particles with the masses ranging from 1 to 1000 GeV
  - Monotop+DM excluded below 327 (655) GeV for scalar (vector) DM

BACKUP SLIDES

Object Identification

- Muons are required to be a Global Muon (reconstructed from muon system) and a PF Muon
  - >96% reconstruction efficiency, minimal misid (only muons make it to muon system)
- Electrons are identified using a BDT MVA of several discriminating variables
  - >95% (98% in barrel) reconstruction efficiency for prompt electrons
- Jets are clustered from particles not labeled as isolated leptons or “pileup”
  - b-tagging identifies jets with displaced vertices consistent with heavy flavor decays (CKM suppression)
  - top-tagging uses jet substructure to identify jets coming from boosted hadronically decaying top quarks
    - moderate efficiency for massive resonance signals (~20%) with good background discrimination
- MET is the negative vector sum of all particle $\vec{p}_T$ originating from primary vertex



Jet Clustering

- Particles not identified as isolated leptons or pileup are clustered into jets using two algorithms

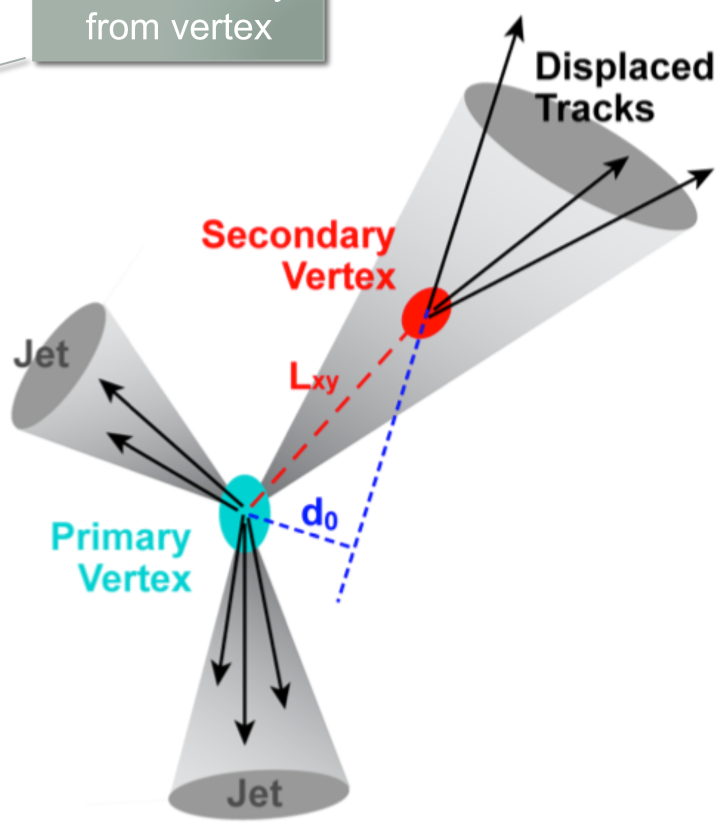
$$d_{ij} = \min(k_{Ti}^{2p}, k_{Tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = k_{Ti}^{2p}$$

  - anti-κ_T (p=-1) with a distance parameter of 0.5
    - Used to reconstruct the jets in the ttbar decay system
  - Cambridge-Aacheen (p=0) with a distance parameter of 0.8
    - Used for the CMS Top Tagging algorithm
- Jets are required to pass a minimal jet quality criteria:
  - number of constituent particles > 1
  - fraction of jet energy coming from either electrons, neutral hadrons, or photons < 0.99
  - if $|\eta| < 2.4$, charged hadron energy fraction > 0
  - if $|\eta| < 2.4$, charged multiplicity > 0

Combined Secondary Vertex

- Likelihood ratio technique combines several low correlation discriminating variables:
  - vertex category (real, “psuedo”,”no vertex”)
  - flight distance significance in transverse plane
  - vertex mass
  - number of tracks at the vertex
  - ratio of energy carried by tracks at vertex w.r.t. whole jet
  - η of tracks at vertex w.r.t. jet axis
  - 2D IP significance of first track that raises invariant mass above charm threshold @ 1.5 GeV
  - number of tracks in jet
  - 3D IP significance for each track in the jet

Tracks more than 2σ away from vertex



Triggers

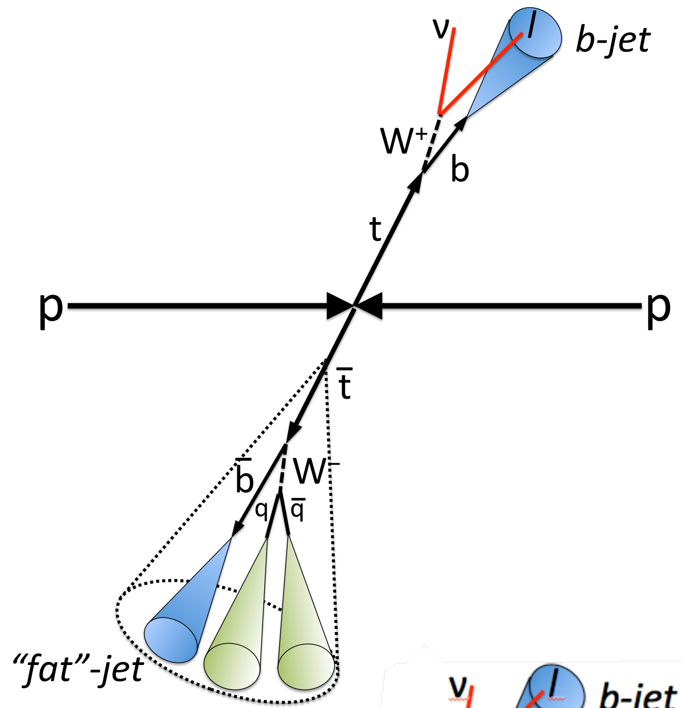
- Muon+Jets Channel
  - Single muon w/p_T > 40 GeV, no isolation requirement on muon
  - Trigger efficiencies and scale factors measured in Z→ℓℓ using a tag-and-probe method
- Electron+Jets Channel
  - Single electron w/p_T > 30 GeV, one jet w/p_T > 100 GeV, second jet w/p_T > 25 GeV; no isolation requirement on electron
    - Slightly inefficient (~90%) for signals with M > 1.5 TeV
  - Single jet w/p_T > 320 GeV
    - Shows high efficiency for signals above 1.5 TeV
    - Adds ~10% more efficiency!
  - Use logical 'OR'
- All Hadronic: two signal regions (high/low mass)
  - High mass: Scalar sum of jet p_T > 750 GeV
  - Low mass: Four jets w/p_T > 50 GeV
- Dilepton:
  - Muon: same as Muon+Jets trigger
  - Electron: Single electron w/p_T > 80 GeV

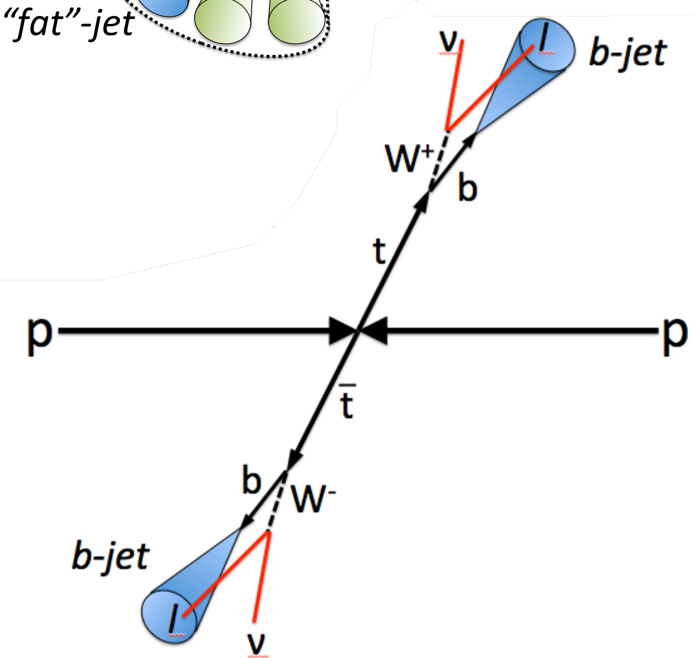
Signal Regions

- Lepton+Jets
  - Exactly 1 high p_T muon or electron [p_T > 45 GeV (muon), 35 GeV (electron)], can be non-isolated
  - At least 2 high p_T jets [$p_{T,1}$ > 150 GeV, $p_{T,2}$ > 50 GeV]
  - E_T^{miss} > 50 GeV
  - $H_T^{lep} = E_T^{miss} + p_T^{lep}$ > 150 GeV
  - 2D Cut: $\Delta R_{l,j}$ > 0.5 or $p_{T,rel(l,j)}$ > 25 GeV
  - Triangular Cut (e+jets):

$$-\frac{1.5}{75GeV}E_T^{miss}+1.5<\Delta\phi\{(e\ or\ j),E_T^{miss}\}<\frac{1.5}{75GeV}E_T^{miss}+1.5$$

- All Hadronic (high mass)
  - Exactly 2 CMS top-tagged jets w/p_T > 400 GeV, $|\Delta\Phi|$ > 2.1
- All Hadronic (low mass)
  - Exactly 2 HEP top-tagged jets w/p_T > 200 GeV
- Dilepton
  - Exactly 2 opposite sign leptons
    - 12 GeV < M_{ll} < 76 GeV || M_{ll} > 106 GeV if same flavor
  - At least 2 jets [$p_{T,1}$ > 100 GeV, $p_{T,2}$ > 50 GeV]
  - 2D Cut: $\Delta R_{l,j}$ > 0.5 or $p_{T,rel(l,j)}$ > 15 GeV
  - E_T^{miss} > 50 GeV if same flavor





Cross-Sections

Backgrounds

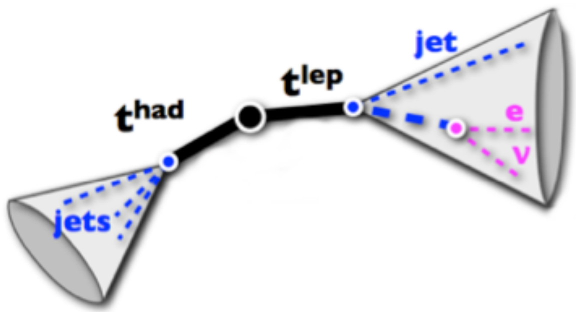
Process	σ (pb)	
$t\bar{t}$	245.8	(NNLO)
$t\bar{t}$, $700 < M_{t\bar{t}} < 1000$	18.19	(NNLO)
$t\bar{t}$, $1000 < M_{t\bar{t}}$	3.44	(NNLO)
W+1jet	6663	(NNLO)
W+2jets	2159	(NNLO)
W+3jets	640	(NNLO)
W+4jets	264	(NNLO)
single top, s-channel	3.79	(approx. NNLO)
single top, t-channel	56.4	(approx. NNLO)
single top, tW-channel	11.1	(approx. NNLO)
single antitop, s-channel	1.76	(approx. NNLO)
single antitop, t-channel	30.7	(approx. NNLO)
single antitop, tW-channel	11.1	(approx. NNLO)
Z+1jet	666	(NNLO)
Z+2jets	215	(NNLO)
Z+3jets	60.7	(NNLO)
Z+4jets	27.4	(NNLO)
WW	54.8	(NLO)
WZ	33.2	(NLO)
ZZ	8.1	(NLO)

Monte Carlo Corrections

- Several corrections are applied to MC samples
  - Pileup reweighting → Ensures pileup conditions match those in data
  - Lepton identification and triggering efficiency
    - Measured in $Z \rightarrow \ell\ell$ events using tag-and-probe method
    - Except electron channel trigger, measured in dilepton ttbar events
  - 2D cut efficiency is measured in a $Z \rightarrow \ell\ell$ +jets control sample
  - Jet Energy Corrections (JECs) are applied to both jet collections
    - L1 Pile Up: Removes dependence on pileup interaction → Subsequent corrections are lumi independent
    - L2 Relative Jet Correction: Removes η dependence on jet response
    - L3 Absolute Jet Correction: Ensures uniform jet response in p_T
    - L2L3 Residual: Applied to DATA only, corrects for small differences (<10%) left between DATA and MC
  - Jet Energy Resolution smearing is applied to MC events to account for known discrepancy between data and MC
  - Jet-lepton cleaning is performed (due to unisolated leptons possibly merging with jets)
  - b-tagging efficiency & mistag rate data/MC scale factors derived from bb events are applied to MC
  - top-tagging mistag rate SF is measured in W+jets control sample, efficiency SF is measured *in situ* during limit setting

Jet-Lepton Cleaning (lepton+jets)

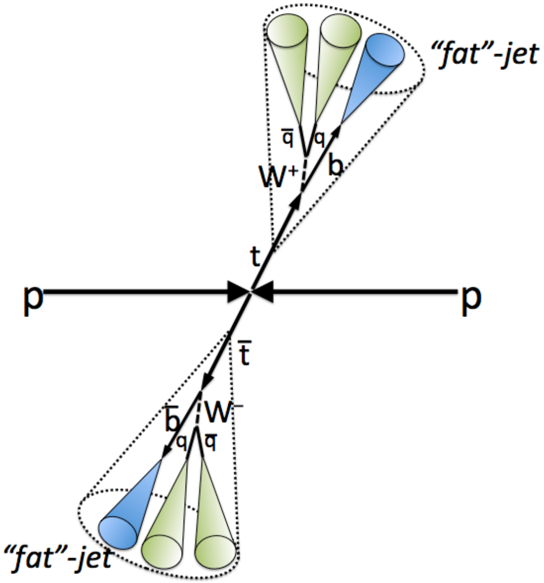
- Boosted topology → Merging of objects in event



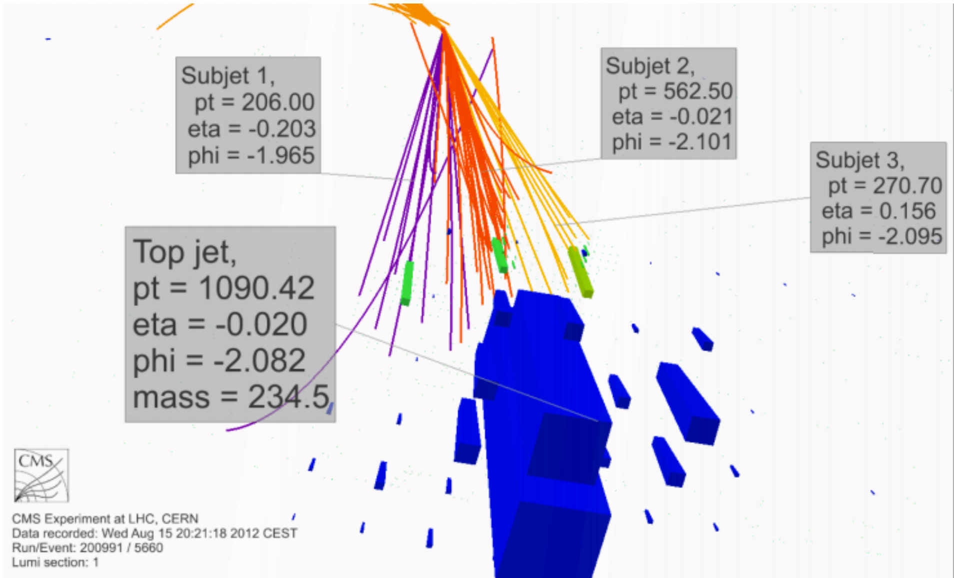
- Want to use non-isolated leptons that may have merged with a jet → Subtract lepton energy from jet it is inside ($\Delta R_{lep,jet} < 0.5$)
- Jet Energy Corrections are recalculated for new raw jet energy
- Only "fat" jets (for top-tagging) sufficiently away from the event lepton are considered ($\Delta R_{lep,jet} > 0.8$)

Top-Quark Tagging

hep-ph/0806.0848, Phys.Rev.Lett. 101 (2008) 142001 ; CMS-PAS-JME-13-007



- CMS Top Tagger & HEP Top Tagger
  - Reconstructs full hadronic top quark decay instead of top quark decay products
  - Run on "fat"-jets (R < 0.8, 1.5) clustered using Cambridge/Aachen jet clustering
    - Uses jet-substructure to identify jets consistent with hadronic top quark decay
- All-hadronic analysis:
  - 2 CMS Top Tagged jets
  - 2 HEP Top Tagged jets
- Lepton+Jets analysis:
  - 1 CMS Top Tagged jet



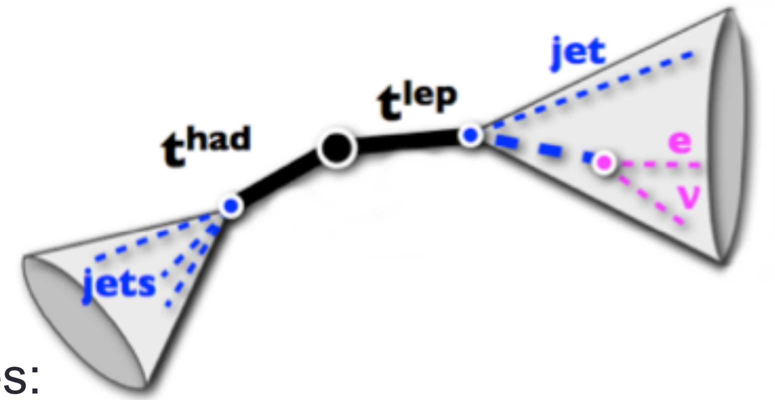
top-tagged Jet Decomposition

- Jets clustered with CA8 algorithm are iteratively "decomposed" as follows:
  - The pairwise clustering sequence which formed the jet is examined in reverse to find two subclusters
  - Continue if the subclusters satisfy: $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.4 - A \times p_T^C$,
    - A = 0.0004
    - If this is not satisfied, the decomposition fails
  - If each subcluster satisfies: $p_T^{\text{cluster}} > \delta_p \times p_T^{\text{hardjet}}$,
    - δ_p=0.05, Then the subcluster decomposition succeeds
  - Repeat on each passing subcluster until both subclusters pass, both subclusters fail, or the subcluster consists of single constituent
  - Primary decomposition declusters the hard jet to find two subclusters, A and B, which are well separated and contain a significant fraction of the hard jet momentum
    - If primary decomposition fails, only 1 subjet. Decomposition is attempted on A,B if it primary decomposition succeeded, yielding either 2,3, or 4 subjets

top-tagged Jets

- CA8 jets are iteratively decomposed into 1,2,3 or 4 subjets by reversing the clustering algorithm
- After the decomposition, a jet is deemed “top-tagged” if:
  - $N_{subjets} \geq 3$
  - $140 \text{ GeV} < m_{jet} < 250 \text{ GeV}$
  - $m_{min} > 50$ GeV, where m_{min} is the minimum pair-wise mass of the subjets
  - $\tau_{32} = \tau_3/\tau_2 < 0.7$, where τ_N is a jet-shape variable known as “N-subjettiness” which is designed to determine the consistency of the jet substructure with the decay of N quarks
- This CMS Top Tagging algorithm is shown to have decent efficiency at tagging boosted hadronic top quark decays, such as those contained in our signal, with a very small mistag rate → Greatly enhances the sensitivity of the analysis

Event Reconstruction



- Lepton+Jets:
  - Create a list of reconstruction hypotheses:
    - Determine neutrino momentum from W-mass constraint
      - 0,1,2 real solutions – use real part of imaginary solution
    - Select hypothesis with minimal

$$\chi^2 = [\frac{M_{lep} - \bar{M}_{lep}}{\sigma_{M_{lep}}}]^2 + [\frac{M_{had} - \bar{M}_{had}}{\sigma_{M_{had}}}]^2$$

  - Electron+Jets Channel Only: Leptonic top candidate transverse momentum, $p_T^{t,lep} > 140$ GeV
  - Require $\chi^2 < 50$
- All Hadronic:
  - Use sum of top-tagged jets
- Dilepton:
  - Use sum of leptons, 2 highest p_T jets, and E_T^{miss} (interpreted as sum of 2 neutrinos)

Neutrino Momentum Calculation

$$\mathbf{P}_W \cdot \mathbf{P}^W = (\mathbf{P}_l + \mathbf{P}_\nu) \cdot (\mathbf{P}^l + \mathbf{P}^\nu) = \mathbf{P}_l \cdot \mathbf{P}^l + \mathbf{P}_\nu \cdot \mathbf{P}^\nu + 2\mathbf{P}_l \cdot \mathbf{P}^\nu$$

Which simplifies to:

$$M_W^2 = M_l^2 + M_\nu^2 + 2(E_l E_\nu - \vec{p}_l \cdot \vec{p}_\nu)$$

$$\frac{M_W^2}{2} = E_l\sqrt{p_{T,\nu}^2 + p_{z,\nu}^2} - (p_{x,l}p_{x,\nu} + p_{y,l}p_{y,\nu} + p_{z,l}p_{z,\nu})$$
$$= E_l\sqrt{p_{T,\nu}^2 + p_{z,\nu}^2} - (p_{T,l}p_{T,\nu}\cos(\Delta\phi_{l,\nu}) + p_{z,l}p_{z,\nu})$$

Let $\alpha = \frac{M_W^2}{2} + p_{T,l}p_{T,\nu}\cos(\Delta\phi_{l,\nu})$ and rearrange the terms:

$$\alpha + p_{z,l}p_{z,\nu} = E_l\sqrt{p_{T,\nu}^2 + p_{z,\nu}^2}$$

Square both sides:

$$\alpha^2 + p_{z,l}^2 p_{z,\nu}^2 + 2\alpha p_{z,l}p_{z,\nu} = E_l^2(p_{T,\nu}^2 + p_{z,\nu}^2)$$

This is a quadratic equation which can be solved for the longitudinal component of the neutrino momentum:

$$p_{z,\nu} = \frac{\alpha p_{z,l}}{p_{T,l}^2} \pm \sqrt{\frac{\alpha^2 p_{z,l}^2}{p_{T,l}^4} - \frac{E_l^2 p_{T,\nu}^2 - \alpha^2}{p_{T,l}^2}}$$

Resonance Theoretical Model Information

- RSG/KK Gluon:
  - K. Agashe et al., “LHC Signals from Warped Extra Dimensions”, *Phys. Rev. D* **77** (2008) 015003, doi:10.1103/PhysRevD.77.015003, arXiv:hep-ph/0612015.
- Z’ Narrow and Wide:
  - R. M. Harris and S. Jain, “Cross Sections for Leptophobic Topcolor *Z′* decaying to top-antitop ”, *Eur. Phys. J. C* **72** (2012) 2072, doi:10.1140/epjc/s10052-012-2072-4, arXiv:hep-ph/1112.4928.

Statistical Analysis for Combined Search

- Binned likelihood statistical analysis is used
  - All channels (dilepton, lepton+jets, all hadronic) and all categories combined into single likelihood

$$L(\beta_k|data) = \prod_{i=1}^{N_{bins}} \frac{\mu_i^{n_i} \times e^{-\mu_i}}{n_i!}$$

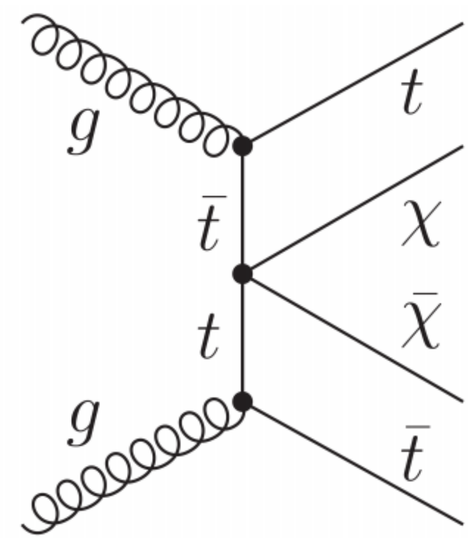
$$\int_0^{\hat{\beta}_{Z'}} d\beta_{Z'} \int d(\beta_K, \delta_u) L_p(\beta_{Z'}, \beta_k, \delta_u) \pi(\beta_{Z'}, \beta_k, \delta_u) = 0.95$$

✚ Fully Correlated
⊙ Not Correlated

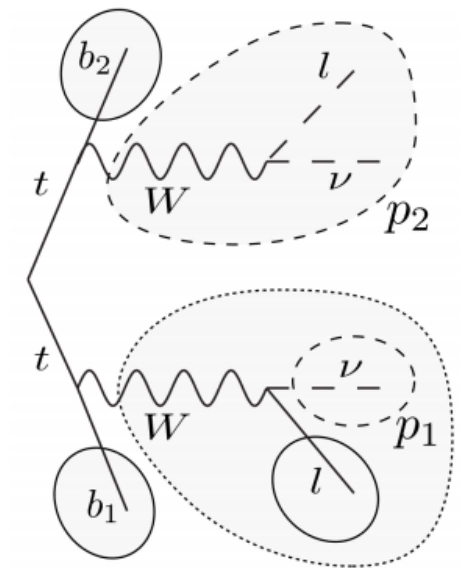
source	uncertainty	dilepton	lepton+jets	had. high mass	had. low mass
lumi	2.6%	✚	✚	✚	✚
tt x-sec	15%	✚	✚	✚	✚
jet energy scale	±1σ(p_T,η)	✚	✚	✚	✚
pileup uncertainty	±1σ	✚	✚	✚	✚
CMS Top Tag Eff.	unconstrained		✚	✚	
PDF Uncertainty	±1σ	✚	✚	✚	✚
tt Q^2 scale	$4Q^2$ and $0.25Q^2$	✚	✚	✚	✚
MC stat. unc.		⊙	⊙	⊙	⊙

Dark Matter + ttbar Search

hep-ex/1504.03198, submitted to JHEP



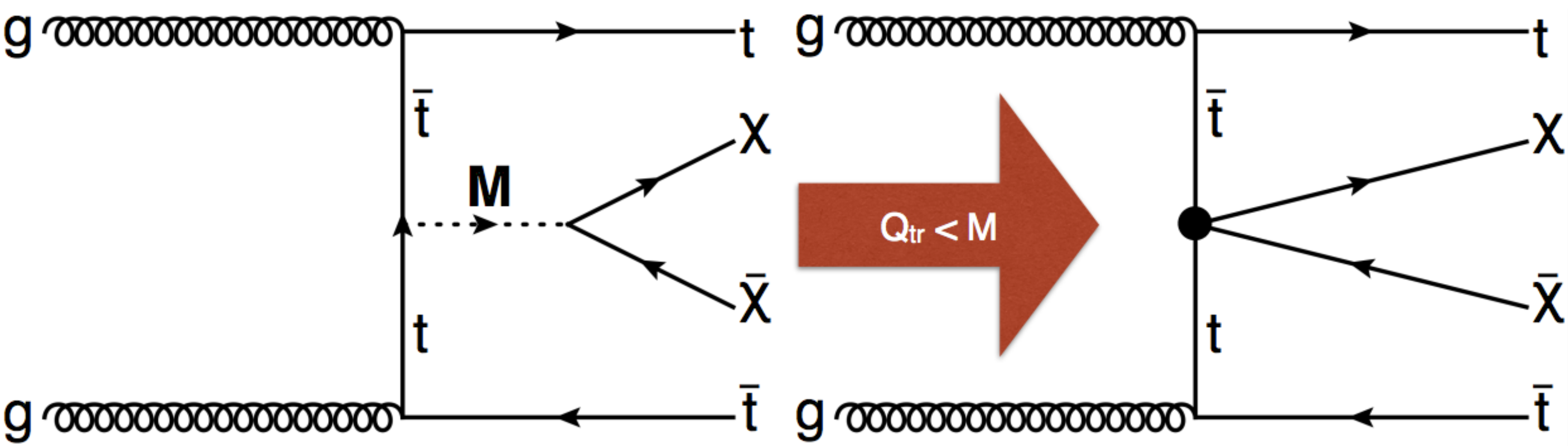
- Focus on semileptonic decay mode of ttbar
  - Single electron (muon) triggers with p_T thresholds of 27 (24) GeV
  - Exactly one isolated electron (muon)
  - At least 3 jets w/p_T > 30 GeV, $|\eta|$ < 4.0
    - At least one tagged as b-jet by CSVM
  - M_T > 160 GeV, $M_T=\sqrt{2 * E_T^{miss} * p_T^l(1-\cos(\Delta\Phi))}$ is kinematically constrained to $M_T < M_W$ for on-shell W-boson decay in tt and W+jets
  - M_{T2}^W > 200 GeV, M_{T2}^W is kinematic quantity to reduce dominant background with large M_T from events with an unreconstructed lepton



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

DM EFT Validity

- EFT is valid as long as momentum transfer is less than the mass of the mediating particle (M)



- Interaction scale (M_*) limit can be dreived from DM mass using kinematic constraints:

$$\sqrt{\frac{M_*^3}{m_q}} > \frac{M_\chi}{2\pi}$$