

CMS top-like BSM and boosted techniques

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for the CMS collaboration

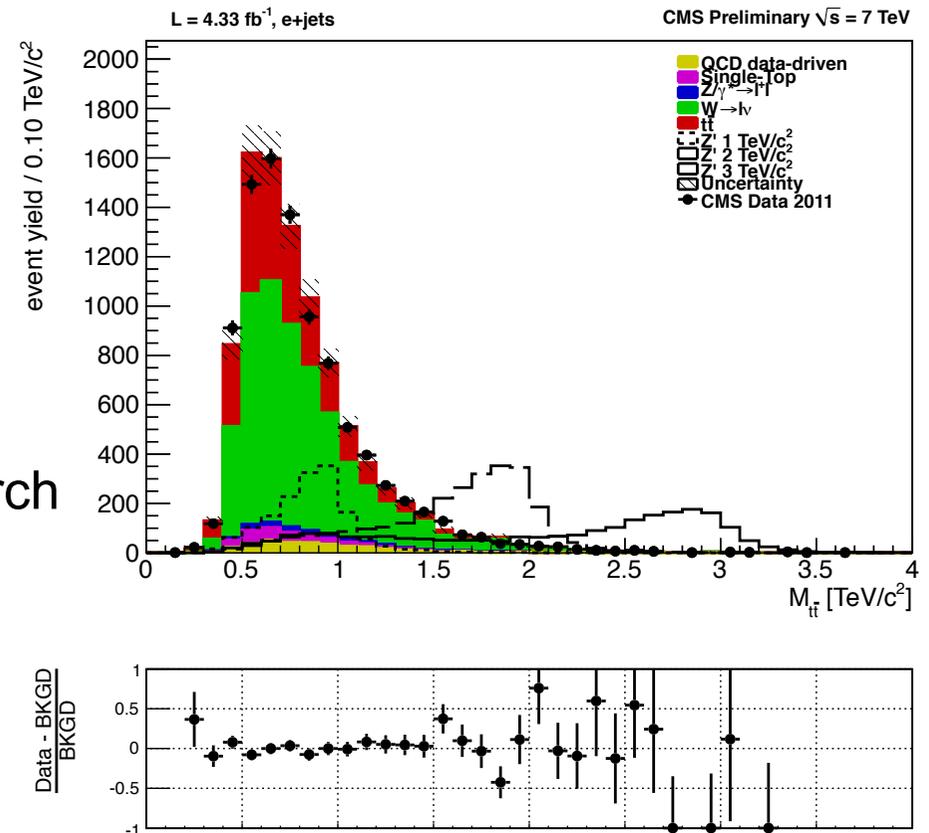
at Implications of LHC results for TeV-scale physics
(26-30 March 2012)

Bibliography

- A Search for resonances in semileptonic top pair production ([CMS PAS TOP-11-009](#))
- Search for heavy narrow resonances decaying to $t\bar{t}$ (μ +jets) ([PAS EXO-11-055](#))
- Search for Z' to $t\bar{t}$ in high-mass (e +jets) channel ([PAS EXO-11-092](#))
- Search for Z' to $t\bar{t}$ (boosted tops) ([EXO11006](#))
- Jet Substructure Algorithms ([PAS JME-10-013](#))
- Search for Randall-Sundrum Gravitons Decaying into a Jet plus E_T^{miss} ([PAS EXO-11-061](#))
- Other CMS top-like BSM results not covered in this talk:
 - Search for the pair production of a fourth-generation up-type quark (t') in events with a lepton and at least 4 jets ([PAS EXO-11-099](#))
 - Search for t' to bW ([EXO11050](#))
 - Search for a Vector-like Quark with Charge $2/3$ in $t + Z$ Events from pp Collisions at $\sqrt{s} = 7$ TeV ([10.1103/PhysRevLett.107.271802](#))
 - Inclusive Search for a Fourth Generation of Quarks ([PAS EXO-11-054](#))

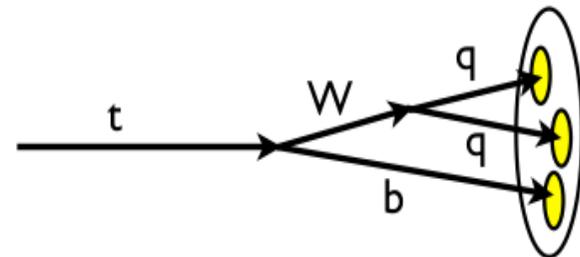
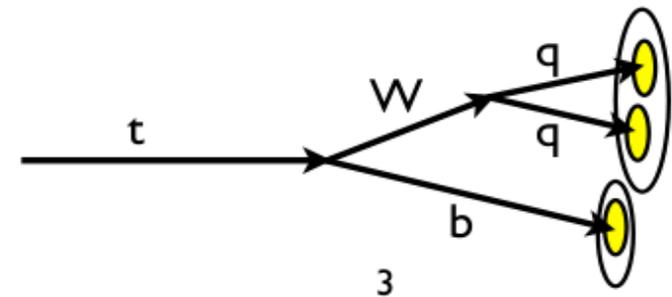
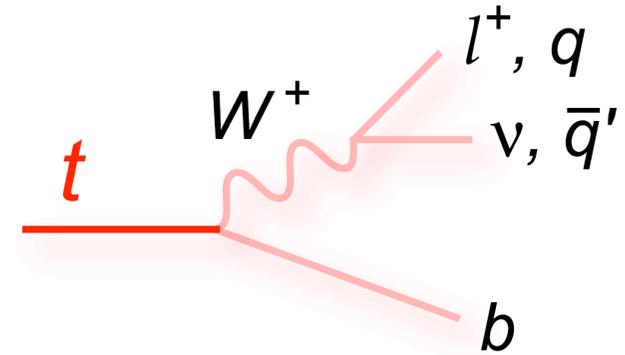
Motivation and signal models

- Top is special in BSM models, since mass of order EWSB scale
- BSM models with enhanced $t\bar{t}$ production
 - Technicolor
 - Topcolor
 - Randall-Sundrum, ADD
- Main experimental signature:
 - Bump or enhancement in $t\bar{t}$ invariant mass $m_{t\bar{t}}$
- Benchmarks for model independent search
 - Narrow-width (1%) Z' (smaller than experimental resolution in $m_{t\bar{t}}$)
 - Intermediate-width (10%) Z'
 - Intermediate-width (~20%) KK-gluon
 - Enhancement of the spectrum (no bump in $m_{t\bar{t}}$)



Categories

- Low mass regime
 - isotropic event topology
 - standard top selection
 - combinatorial event reconstruction
 - b-tagging
- Intermediate mass regime
 - partially merged hadronic top decays
 - neither high nor low mass work well
 - b-tagging works
- High mass regime
 - relativistic (boosted) top quarks
 - hadronic decay products (jets) merge
 - need to break them into sub-jets
 - no b-tagging



Outline of the talk

Search for BSM physics in the $m_{t\bar{t}}$ distribution

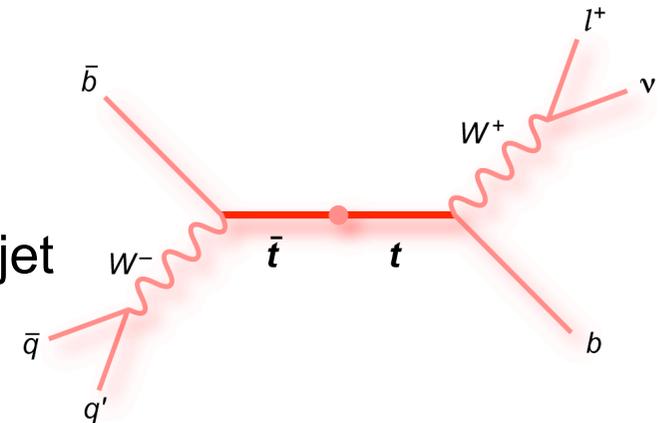
- Low mass semileptonic search
- High mass semileptonic search
- High mass fully hadronic search

Boosted techniques

- Boosted leptonic tops
- Boosted hadronic Ws
- Boosted hadronic tops
- Other fields of applications

Low mass semileptonic search

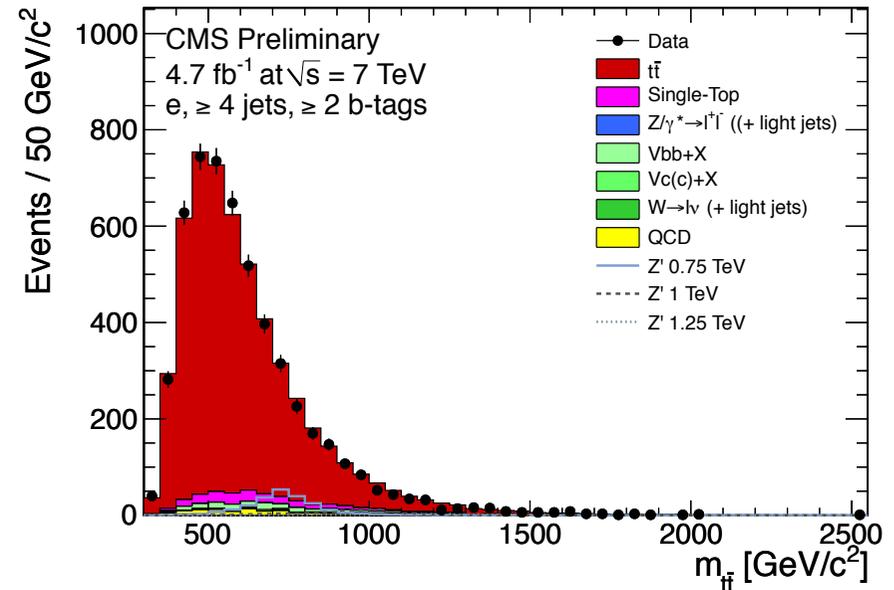
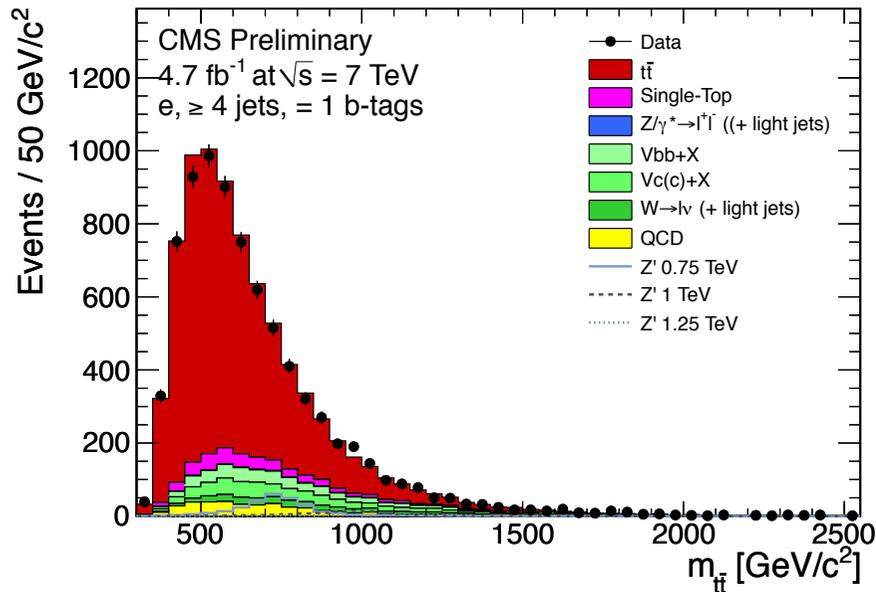
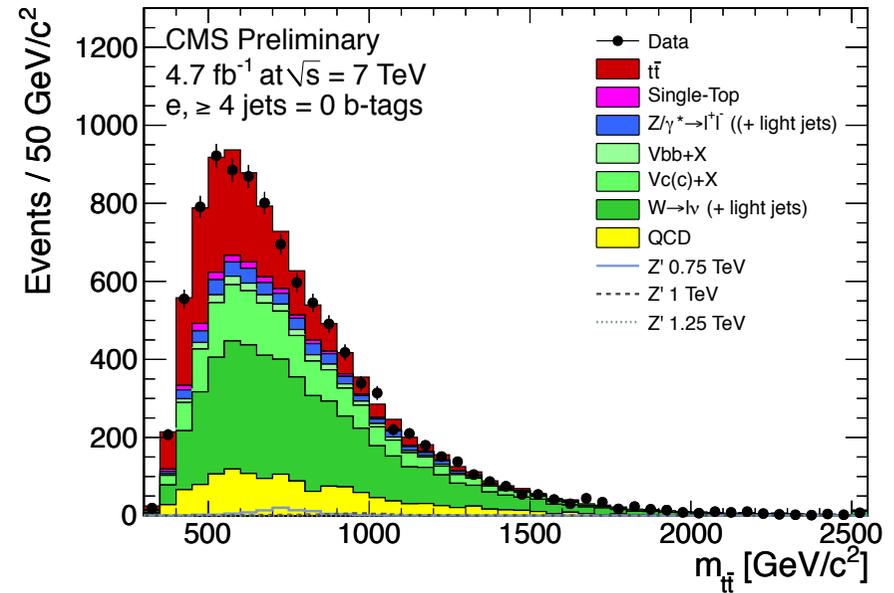
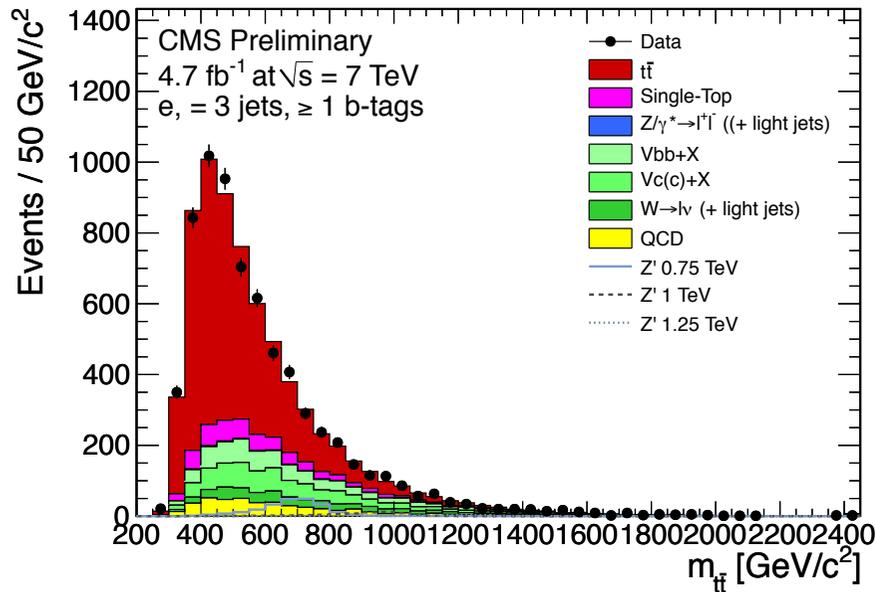
- Event selection identical to $t\bar{t}$ cross section measurement
 - One lepton: μ ($p_T > 20$ GeV) or e ($p_T > 30$ GeV)
 - Particle-based relative lepton isolation ($\Delta R < 0.4$): 0.125 (μ) or 0.1 (e)
 - Veto second lepton: μ ($p_T > 10$ GeV) or e ($p_T > 15$ GeV)
 - $E_T^{\text{miss}} > 20$ GeV
 - 3 or ≥ 4 jets ($p_T > 70, 50$ GeV)
 - 0, 1 or ≥ 2 jets b-tagged
- Event reconstruction
 - Reconstruct leptonic top from lepton, E_T^{miss} and jet
 - Reconstruct hadronic top from 2-3 jets
 - Select hypothesis based on χ^2 (m_{top} , $p_T(t\bar{t})$, ..)
- Backgrounds
 - QCD from data: normalization from template fit in low E_T^{miss} region
 - All other backgrounds ($t\bar{t}$, W +heavy flavor, W +light flavor) from MC
 - however, MC templates can morph according to systematic uncertainties, to a large degree, data driven as well



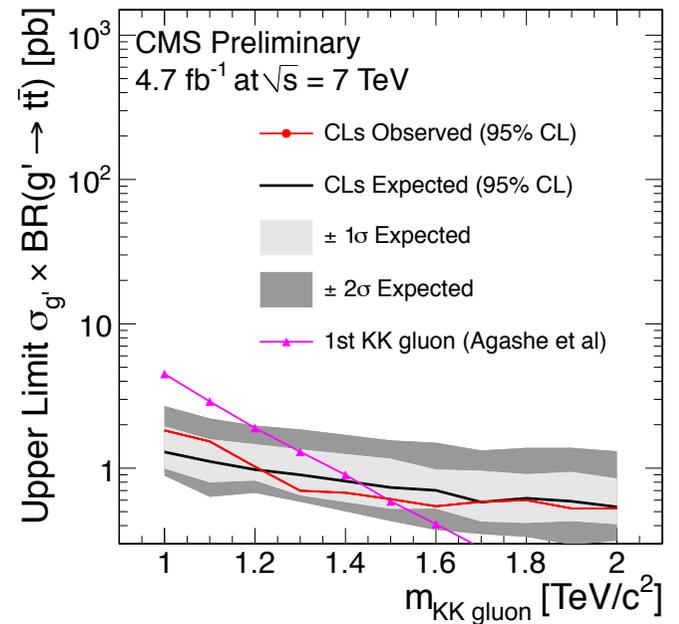
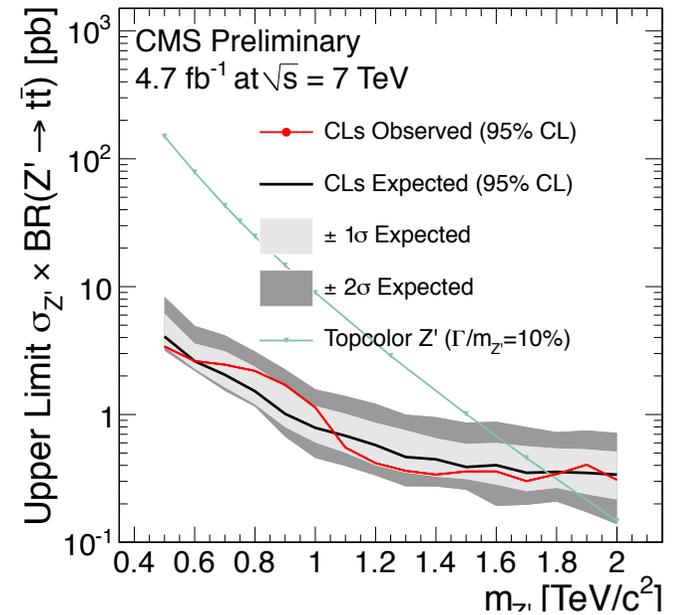
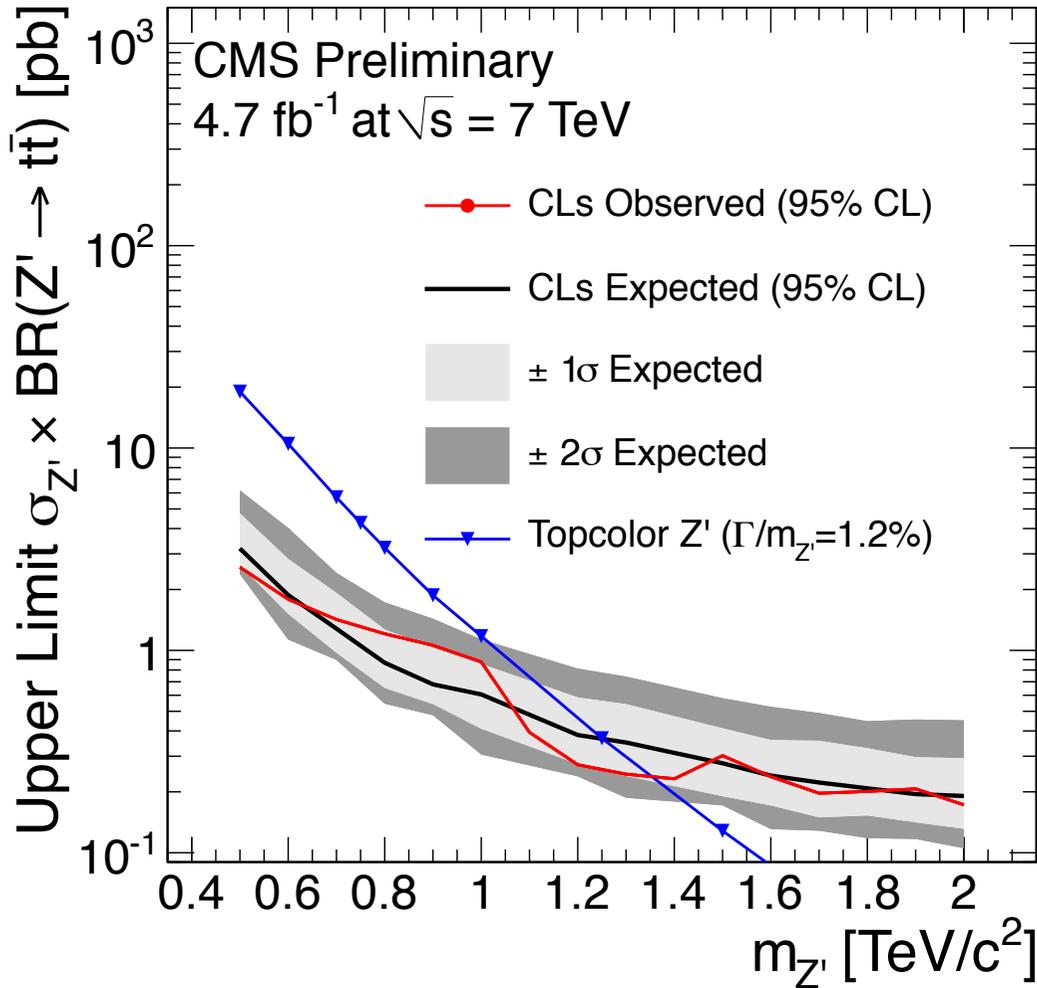
Low mass semileptonic – uncertainties

Uncertainty	Variation	Type
Luminosity	4.5%	rate
Electron efficiency (trigger + ID + isolation)	3%	rate
Muon efficiency (trigger + ID + isolation)	3%	rate
$t\bar{t}$ cross section	15%	rate
Single top cross section	30%	rate
W/Z+jets yield	50%	rate
Drell-Yan yield	30%	rate
W/Z+c+X	100%	rate
W/Z+b+X	100%	rate
Muon multijet yield	50–75%	rate
Electron multijet yield	45–70%	rate
Jet energy scale	p_T, η dependent	shape
Jet energy resolution	6–20% per jet	shape
b tagging efficiency (b jets $p_T < 670$ GeV)	1.6–8% per jet	shape
b tagging efficiency (c jets $p_T < 670$ GeV)	Twice that for b jets	shape
b tagging efficiency ($p_T > 670$ GeV)	Twice that at 670 GeV	shape
Mistagging rate	11%	shape
Factorisation scale for W events	$\pm 1\sigma$ generator parameters	shape
$t\bar{t}$ modelling	$\pm 1\sigma$ generator differences	shape
Factorisation scale for $t\bar{t}$ events	$\pm 1\sigma$ generator parameters	shape
Matching scale for $t\bar{t}$ events	$\pm 1\sigma$ generator parameters	shape
Multiple collisions	8% inelastic cross section	shape

Low mass semileptonic – distributions

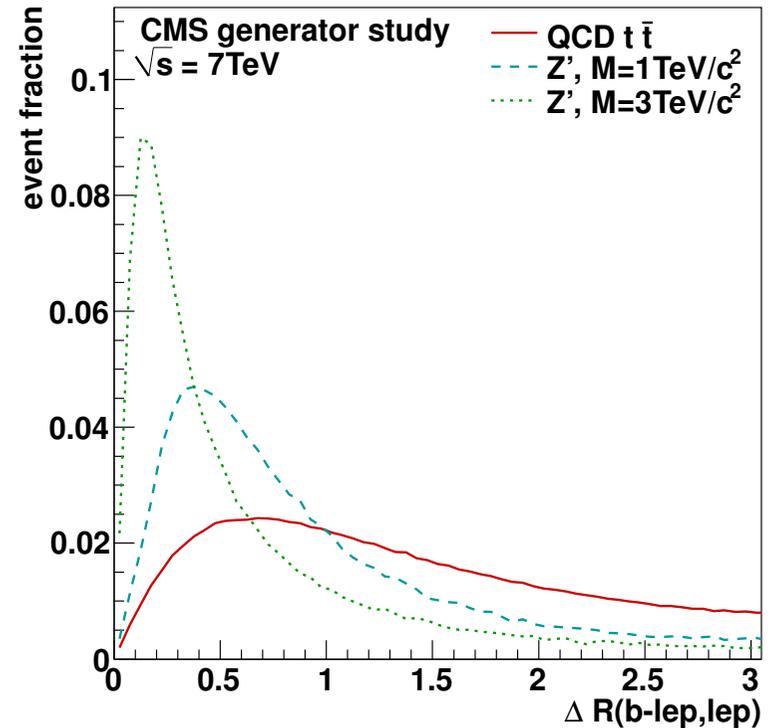


Low mass semileptonic – limits



Boosted leptonic tops – isolation

- Main issue for boosted leptonic tops is the isolation
 - Lepton isolation needed to suppress QCD background
 - Typically defined through energy in fixed cone (e.g. $\Delta R < 0.4$) around lepton
 - For boosted top quarks the b-jet comes close to lepton
- Solution:
 - 2D cut: $\Delta R(\ell, \text{closest jet}) > 0.5$
OR $p_T^{\text{rel}}(\ell, \text{closest jet}) > 25 \text{ GeV}/c$



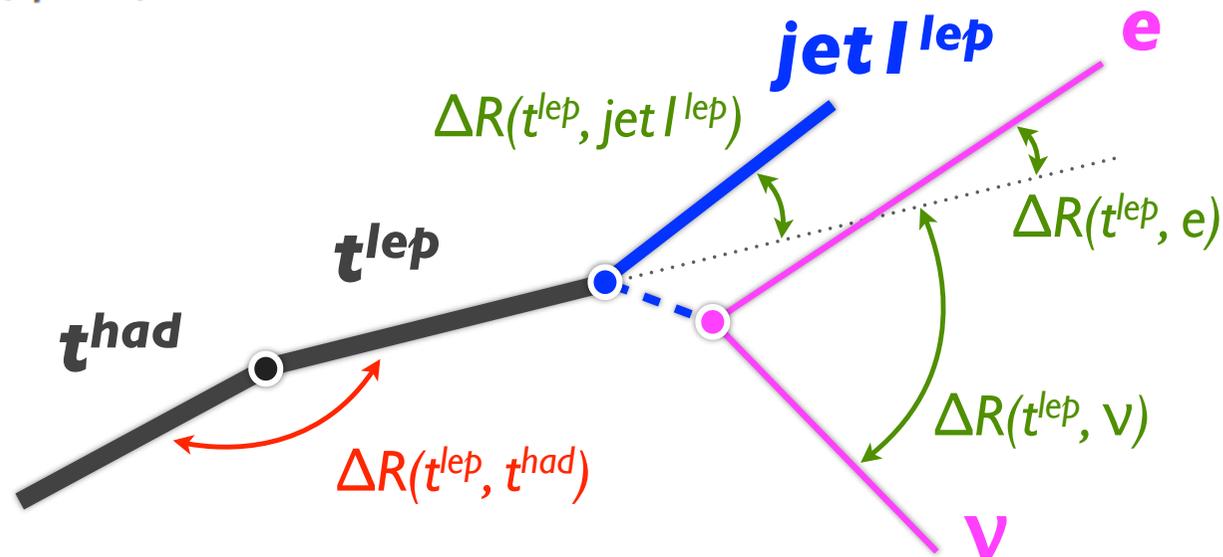
Boosted leptonic tops – event reco

- Hypothesis selection for boosted leptonic tops
 - Based on geometric separation of top decay products

$$\Delta R_{\text{sum}} = \Delta R(b_l, t_l) + \Delta R(\nu, t_l) + \Delta R(l, t_l)$$

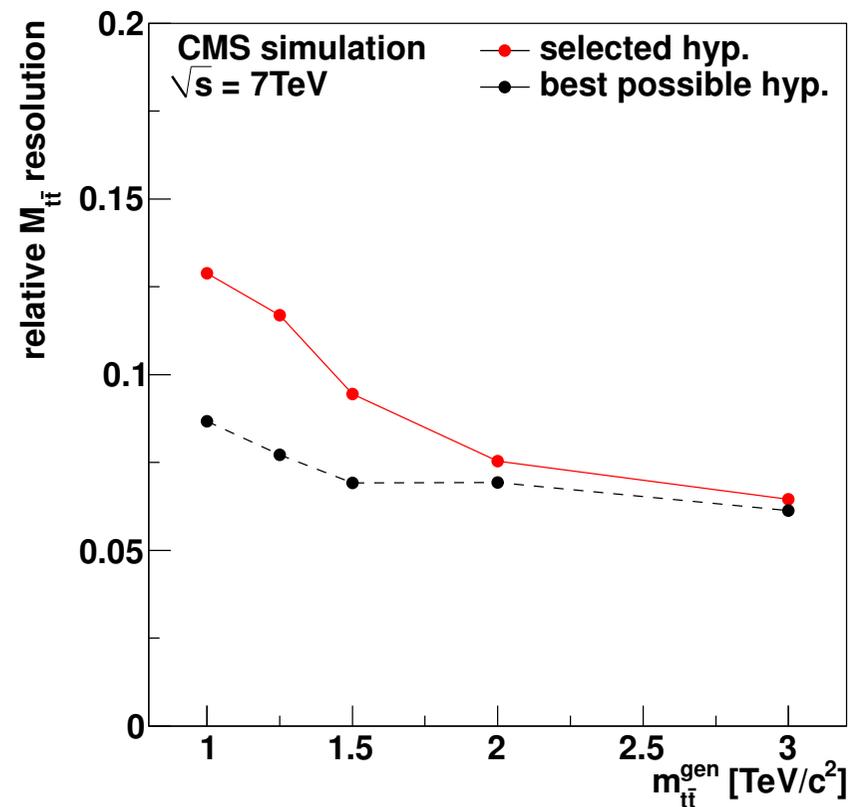
- No need to make hypothesis on number of jets from hadronic top
- Hadronic top jets associated through distance to leptonic top

$$\Delta R(t_\mu, t_h)$$



Boosted leptonic tops – performance

- Performance of event reconstruction by geometric separation
 - Close to best possible association (from parton-jet matching in MC)
 - Works best in highly boosted regime

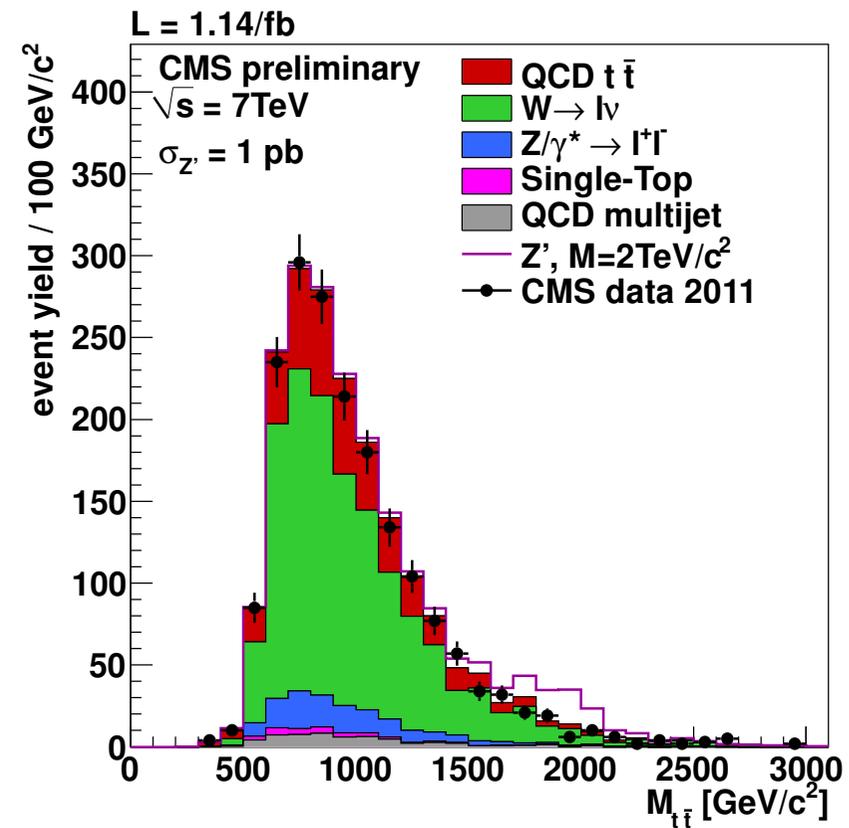
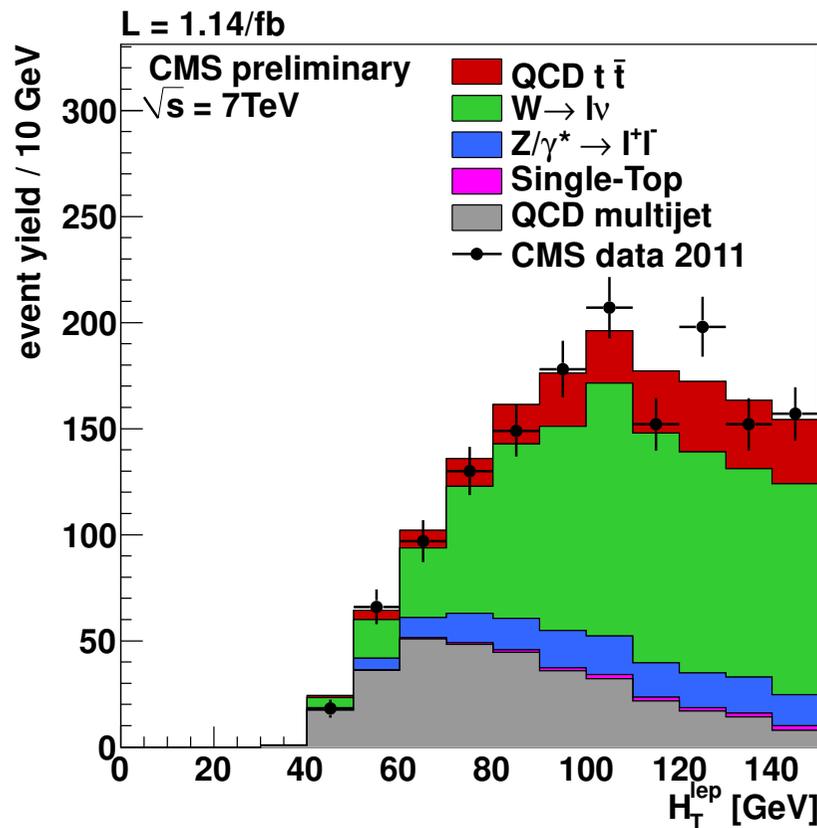


High mass semileptonic search

- Event selection:
 - One lepton: μ ($p_T > 35$ GeV) or e ($p_T > 70$ GeV)
 - 2D lepton isolation
 - 2 or more jets: $p_T > 250$ GeV and $p_T > 50$ GeV
 - Veto second lepton: μ ($p_T > 35$ GeV) or e ($p_T > 30$ GeV)
 - $H_T^{\text{lep}} \equiv E_T^{\text{miss}} + p_T^{\ell} > 150$ GeV
- Dominated by W+jets (no b-tagging or top-tagging)
- Backgrounds
 - QCD background shape from non-isolated region
 - Details for normalization of QCD and W+Jets on next slide

High mass semileptonic – μ +jets

- Background estimation for μ +jets:
 - Template fit (Bayesian marginalisation) for signal and background simultaneously with combined likelihood in H_T^{lep} and $m_{t\bar{t}}$
 - Low H_T^{lep} is signal depleted
 - Template morphing for shape-changing systematics



High mass semileptonic – e+jets

- Additional cuts to reduce QCD background with $E_T^{\text{miss}} > 50 \text{ GeV}$

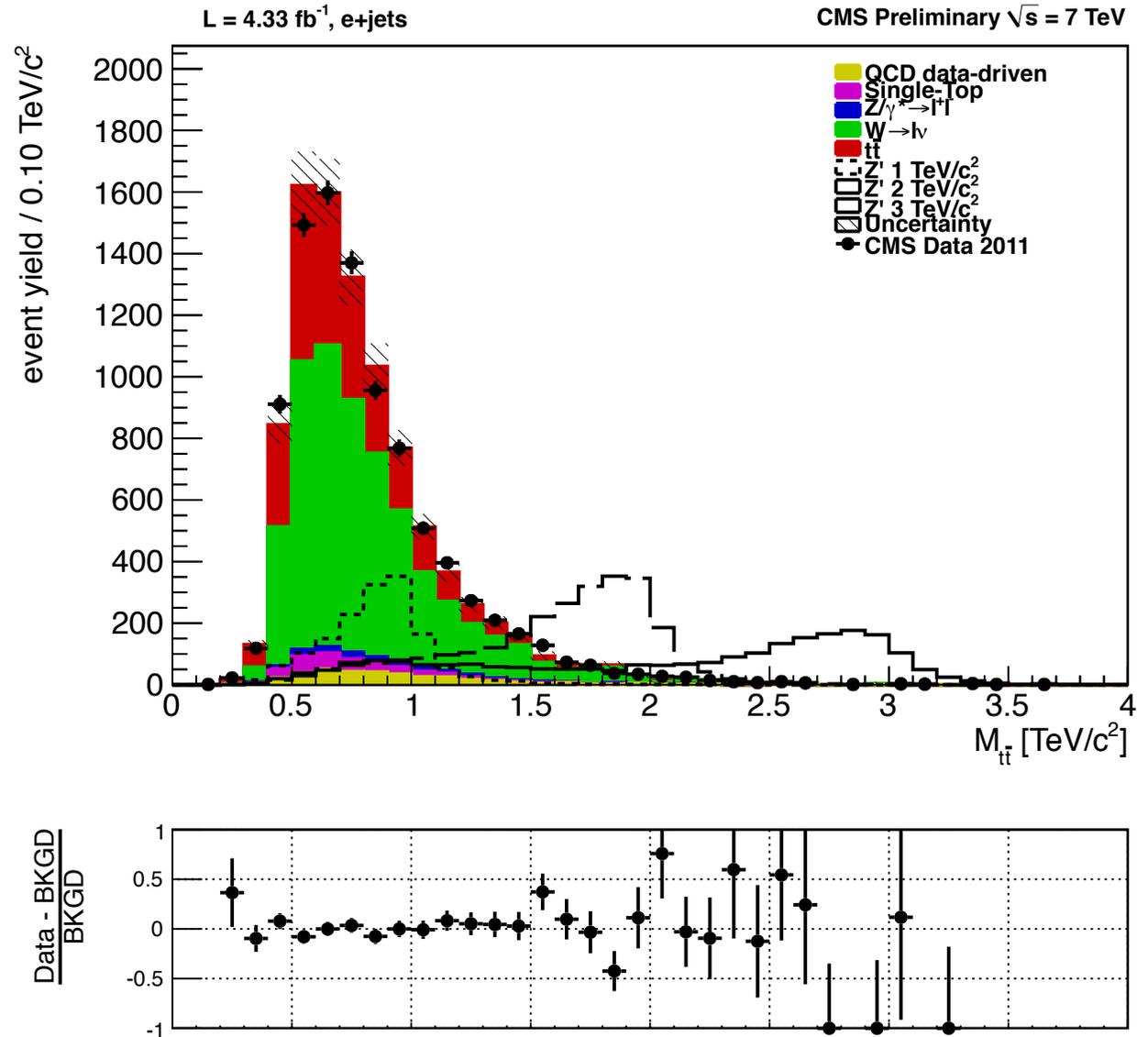
$$\Delta\phi(e, E_T^{\text{miss}}) < \frac{1.5}{75} E_T^{\text{miss}} + 1.5$$

$$\Delta\phi(e, E_T^{\text{miss}}) > -\frac{1.5}{75} E_T^{\text{miss}} + 1.5$$

$$\Delta\phi(j_1, E_T^{\text{miss}}) < \frac{1.5}{75} E_T^{\text{miss}} + 1.5$$

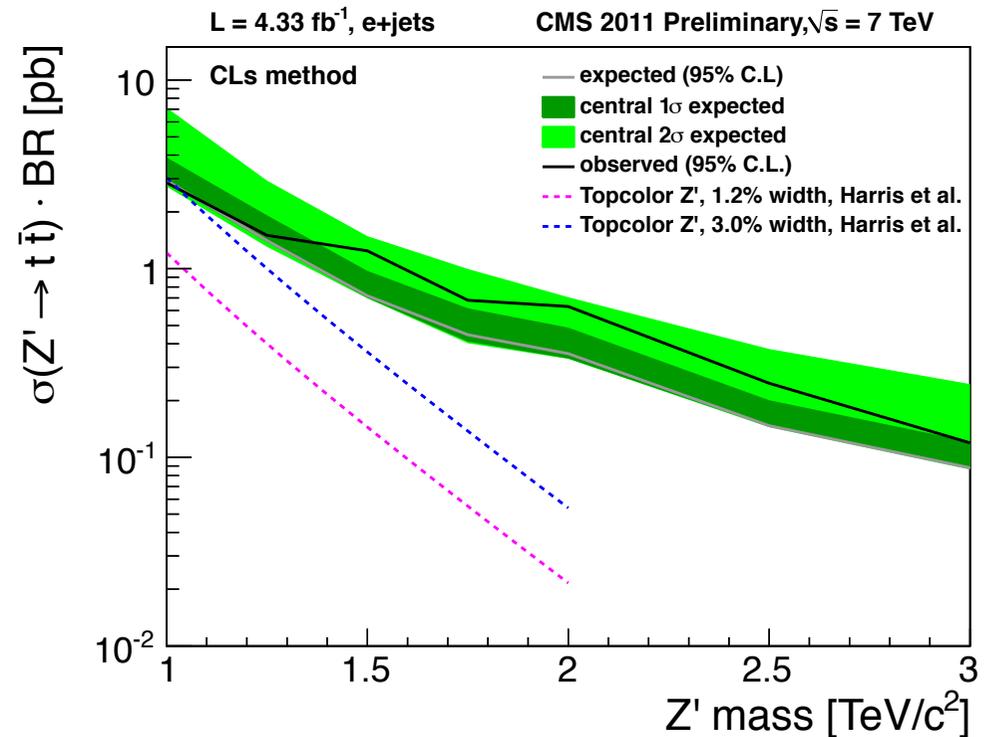
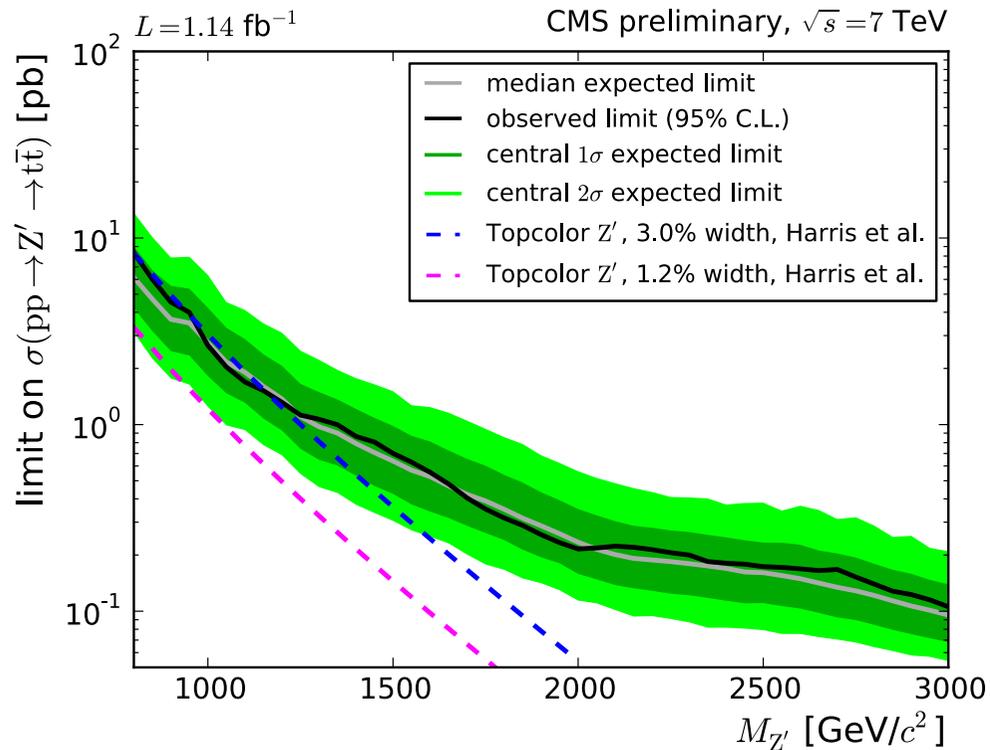
$$\Delta\phi(j_1, E_T^{\text{miss}}) > -\frac{1.5}{75} E_T^{\text{miss}} + 1.5$$

- Background estimation for e+jets:
 - 1D template fit
 - Backgrounds from MC with large systematic error (30%)
 - Template morphing for shape-changing systematics



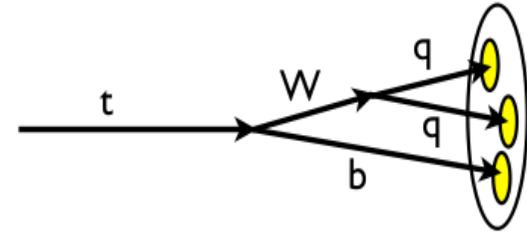
High mass semileptonic – limits

- μ +jets analysis with 1.14/fb
 - powerful analysis
 - being updated
- e+jets analysis with 4.33/fb
 - new result

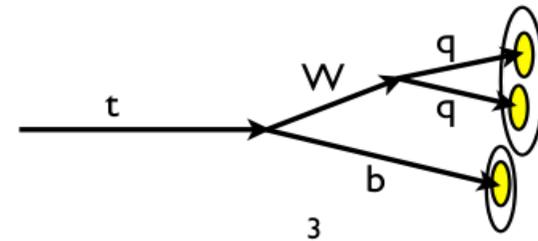


Boosted hadronic tops+Ws – categories

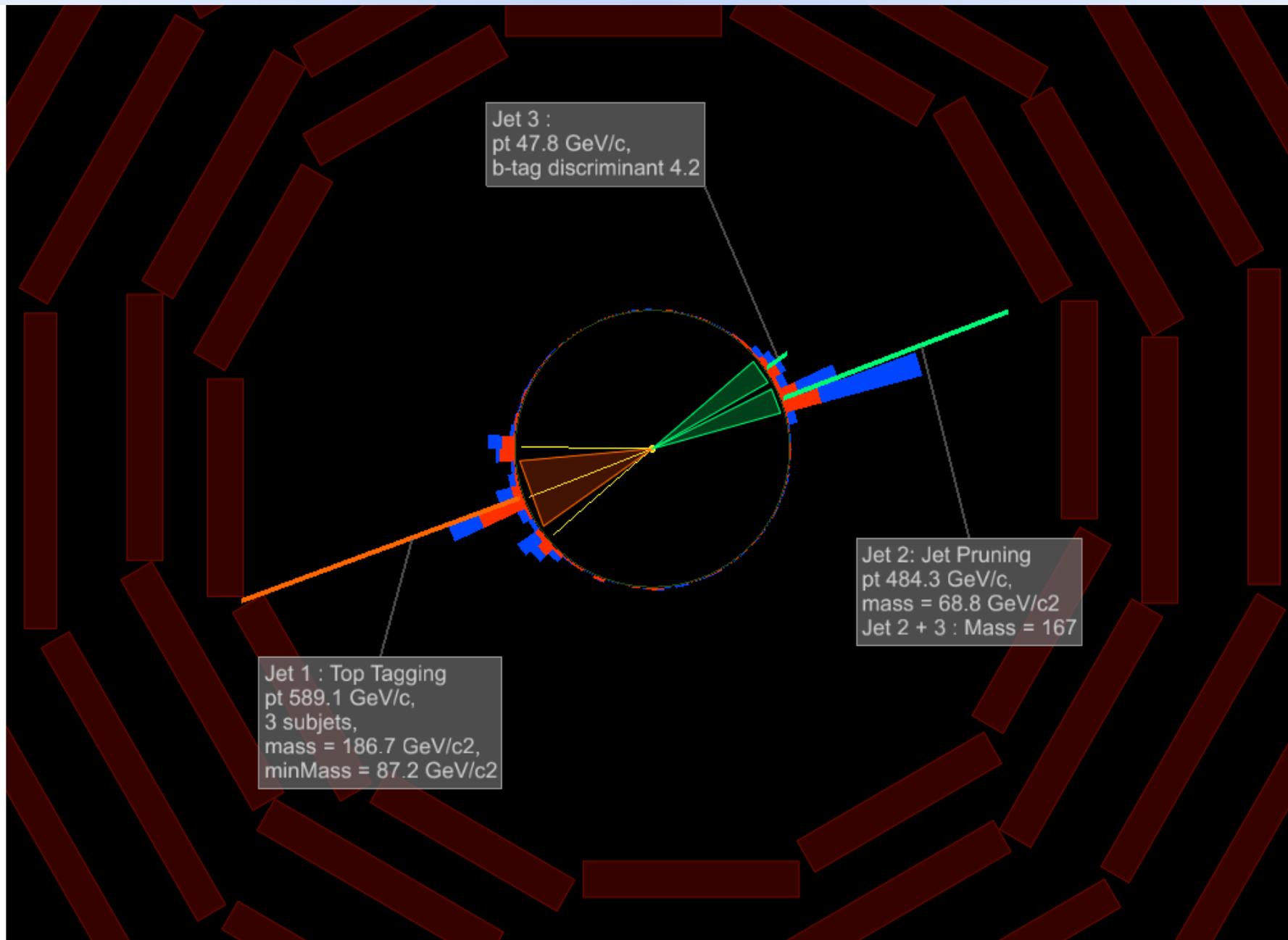
- Type 1 (single jet):
 - all three jets from top merged into single jet
 - top-tagging



- Type 2 (double jet):
 - two jets from W are contained in a single jet + b-jet separately
 - W-tagging

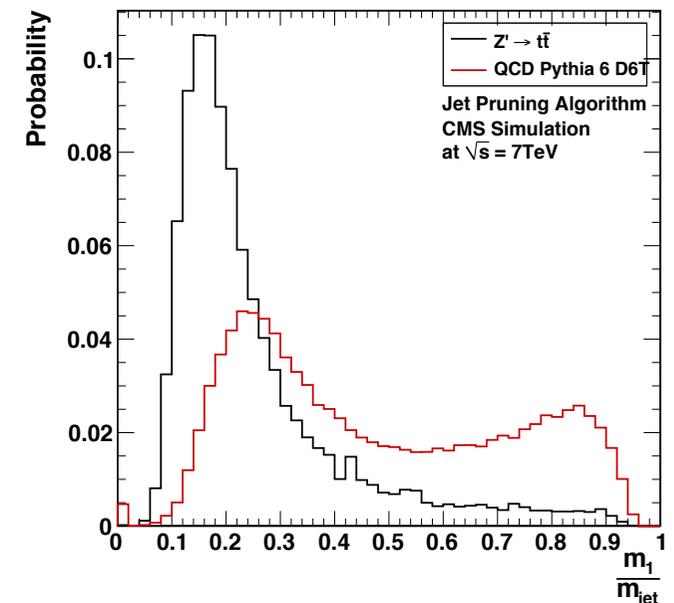
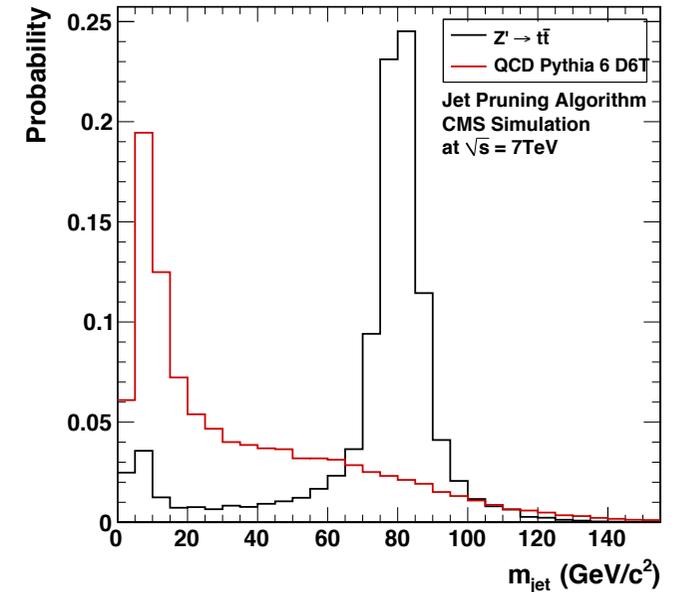


Boosted hadronic tops+Ws – example



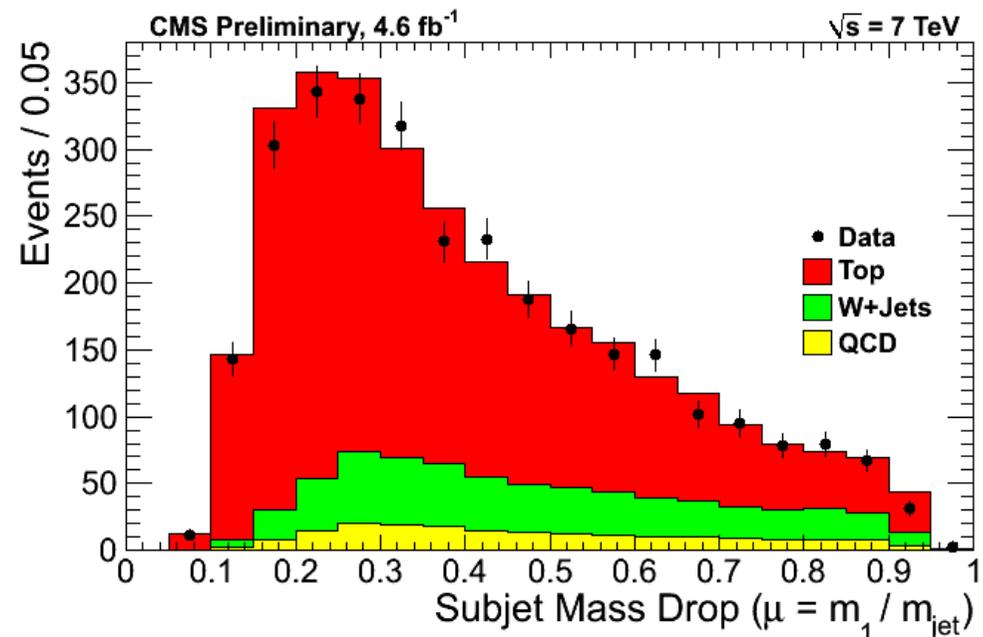
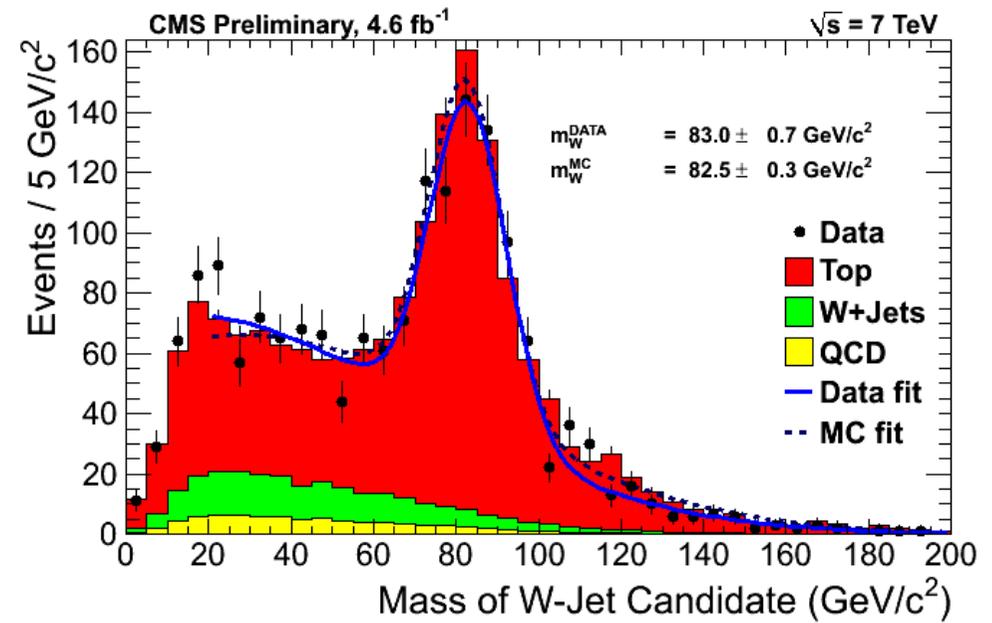
Boosted hadronic Ws – tagging

- Jet pruning
 - Ellis, Vermillion, Walsh (arXiv:0903.5081)
 - Improves mass resolution by removing soft, large angle particles
- Cluster jets with Cambridge Aachen (CA) with $R=0.8$
- Undo last step of jet clustering to find two subjets
- Tag Ws by
 - Butterworth et al. (arXiv:0802.2470)
 - Pruned jet mass $60 < m_{\text{jet}} < 130 \text{ GeV}/c^2$
 - Mass drop $\mu \equiv \frac{m_{\text{leading subjet}}}{m_{\text{jet}}} < 0.4$



Boosted hadronic Ws – performance

- Look for merged Ws in low mass semileptonic $t\bar{t}$ events
- Use W peak from W-tagged jets to determine
 - substructure energy correction for MC
= 1.02 ± 0.01
 - W-tagging efficiency correction for MC
= 0.97 ± 0.03
- Madgraph+Pythia Z2 works well



Boosted hadronic tops – tagging

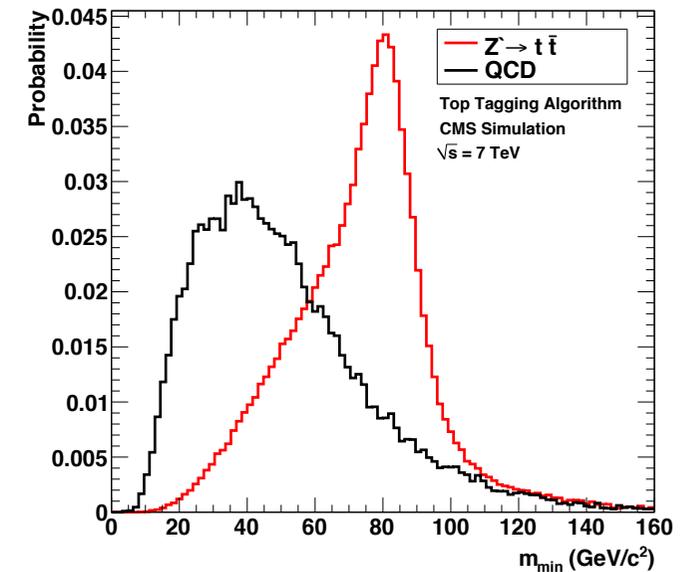
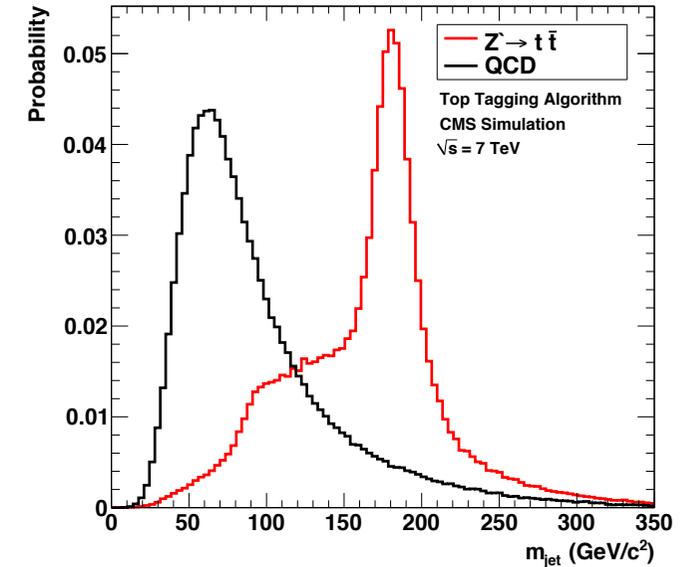
- JHU Top Tagger (Kaplan, Rehermann, Schwartz, and Tweedie, arXiv: 0806.0848), tweaked by CMS
- Cluster jets with CA R=0.8
- Retrace two steps of clustering sequence back to find subjets
- Variables:

- Jet mass ($\sim m_{\text{top}}$)
- Number of subjets
- Min pairwise mass ($\sim m_W$)

$$140 < m_{\text{jet}} < 250 \text{ GeV}/c^2$$

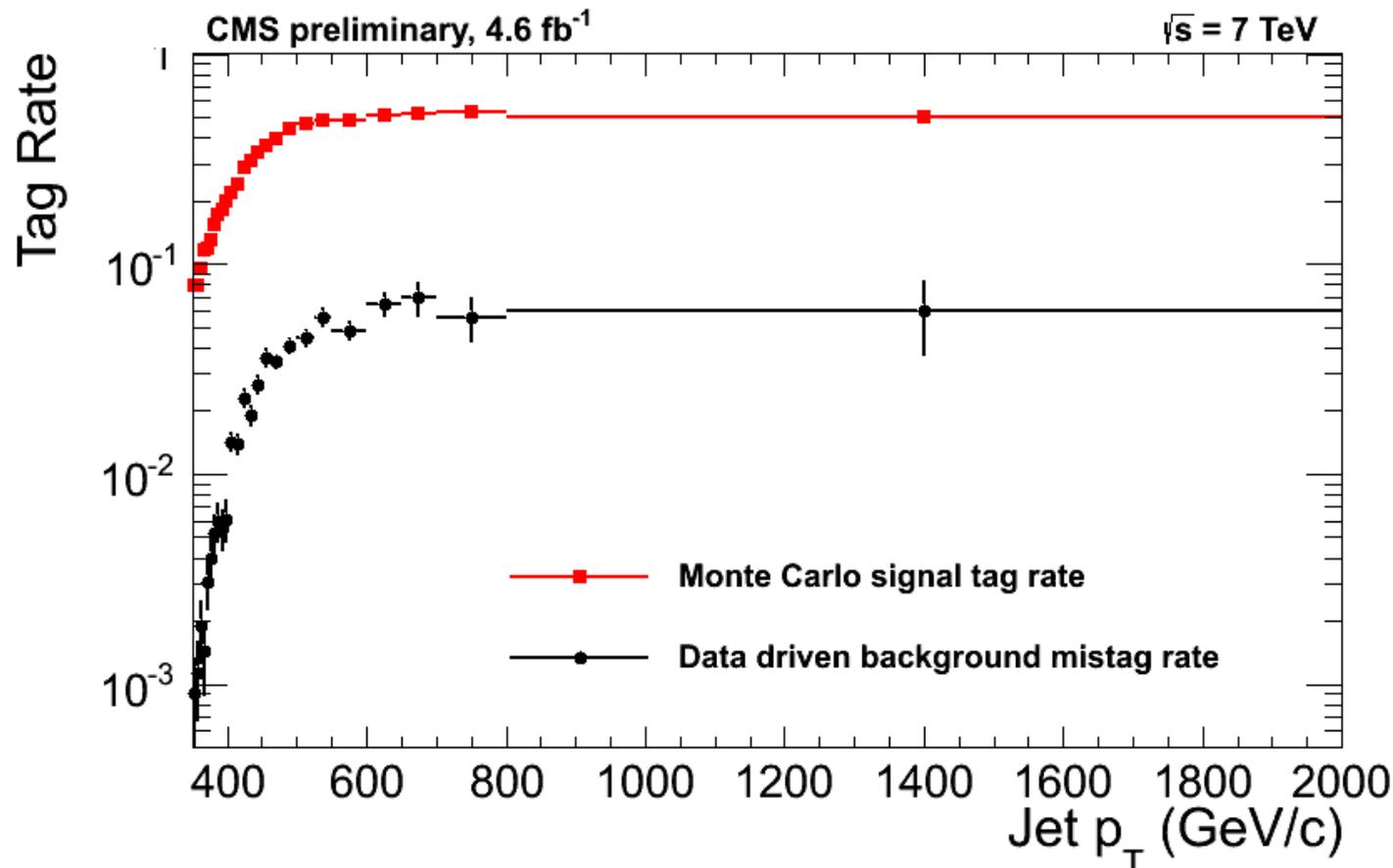
$$N_{\text{subjets}} \geq 3$$

$$m_{\text{min}} > 50 \text{ GeV}/c^2$$



Boosted hadronic tops – performance

- Signal efficiency (incl. trigger) from MC with scale factor discussed before
- Mistag probability estimated from data in signal-depleted sideband with $t\bar{t}$ -like kinematics (type 1+2):
 - Tag one side top (type 2) with inverted massdrop requirement
 - Probe jet (type 1) on other side



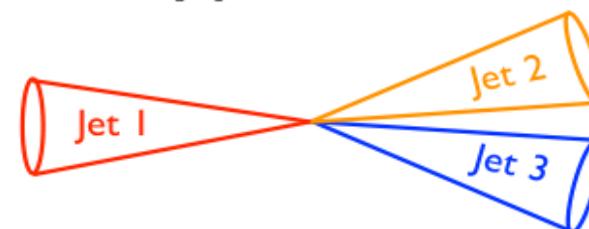
High mass fully hadronic search

- Event selection
 - Type 1+1
 - ≥ 2 jet with $p_T > 350$ GeV
 - 2 jets top-tagged
 - Type 1+2
 - ≥ 3 jets with $p_T > 350, 200, 30$ GeV
 - 1st jet top-tagged
 - 2nd jet W-tagged
 - 2nd+3rd jet invariant mass in 140-250 GeV

Type 1+1

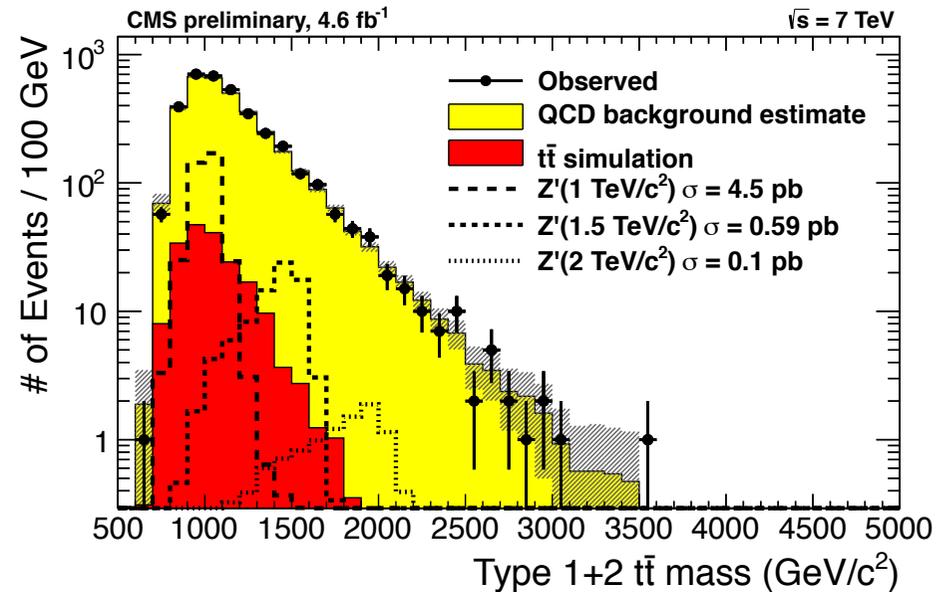
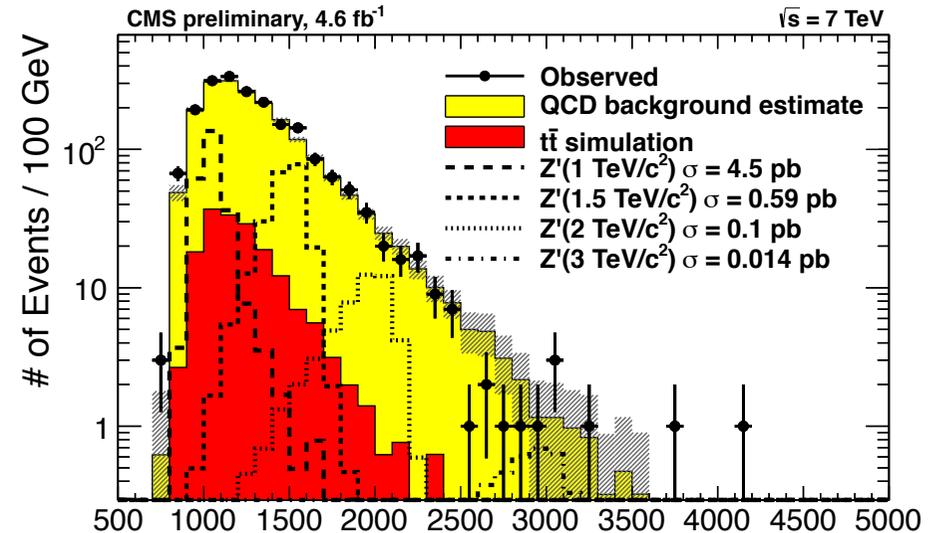


Type 1+2

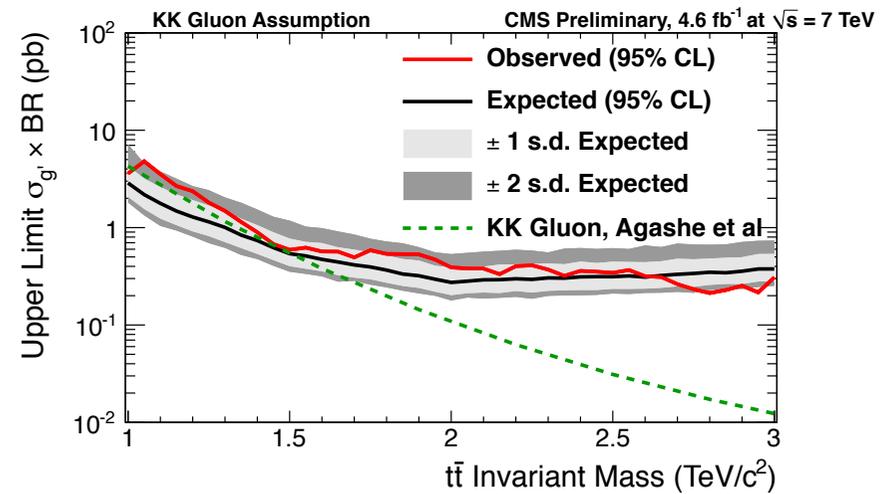
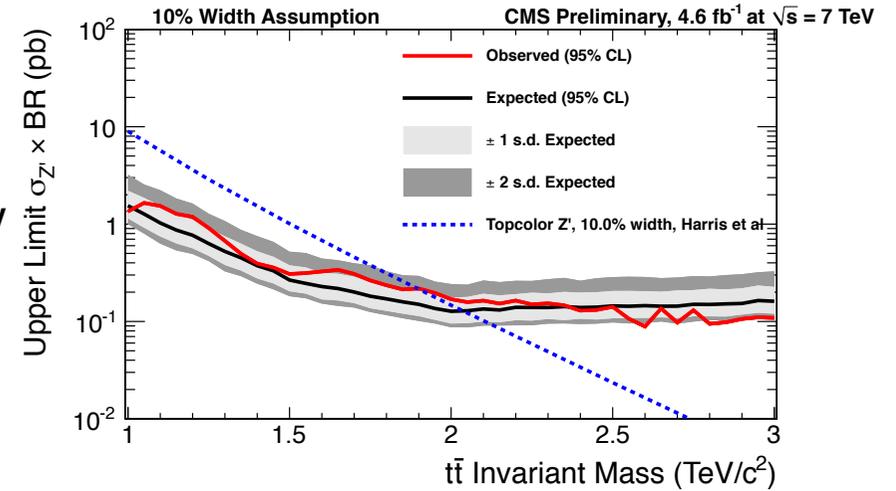
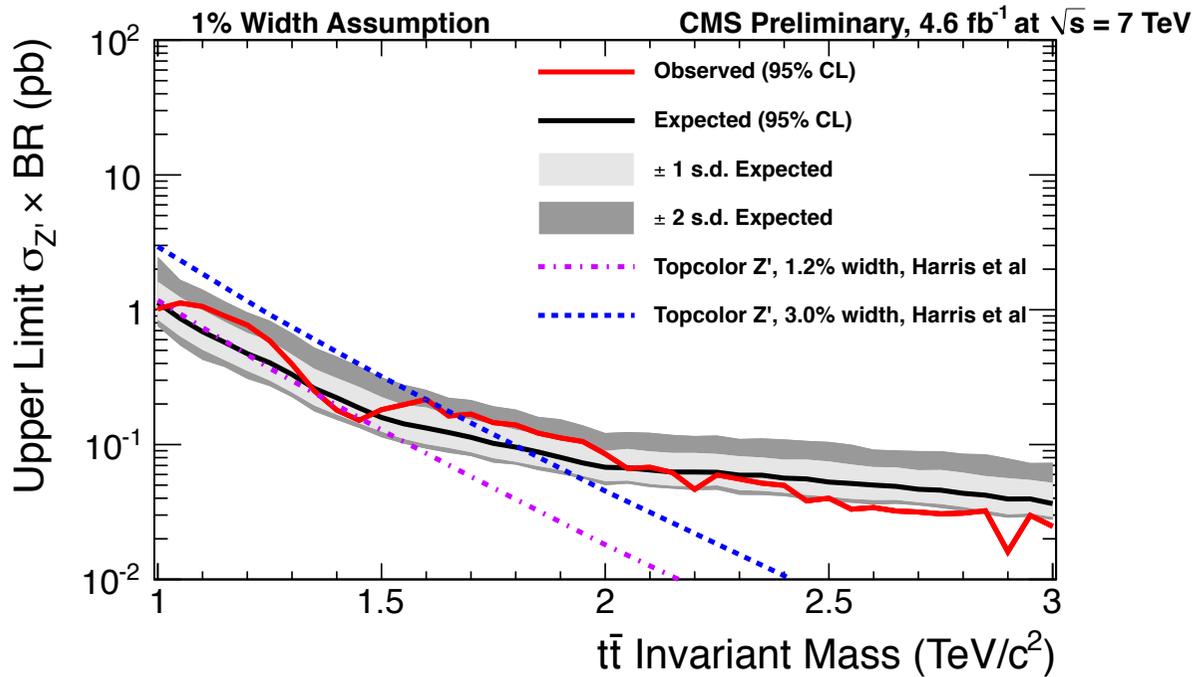


High mass fully hadronic – distributions

- Multijet background dominant (no lepton, no b-tag)
- Data driven background shape from pre-tagged samples
 - Background rate from mistag rate discussed before



High mass fully hadronic – limits



High mass fully hadronic – non-resonant

- Look also for non-resonant change in $m_{t\bar{t}}$ spectrum

- Set limit on

$$\mathcal{S} = \frac{\int_{1\text{TeV}}^{+\infty} \left(\frac{d\sigma_{SM+NP}}{dm_{t\bar{t}}} \right) dm_{t\bar{t}}}{\int_{1\text{TeV}}^{+\infty} \left(\frac{d\sigma_{SM}}{dm_{t\bar{t}}} \right) dm_{t\bar{t}}}$$

- Assume same efficiency as SM $t\bar{t}$ production

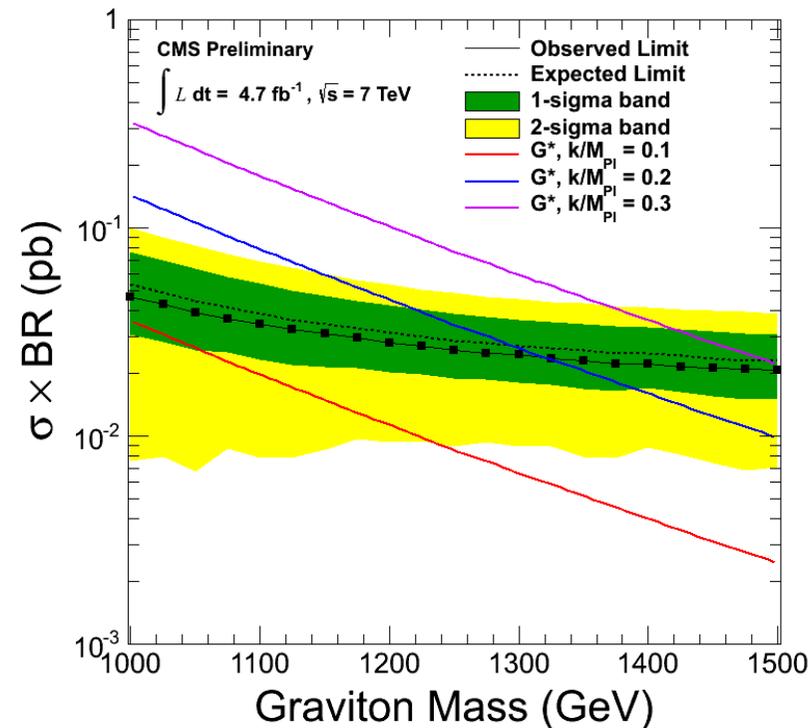
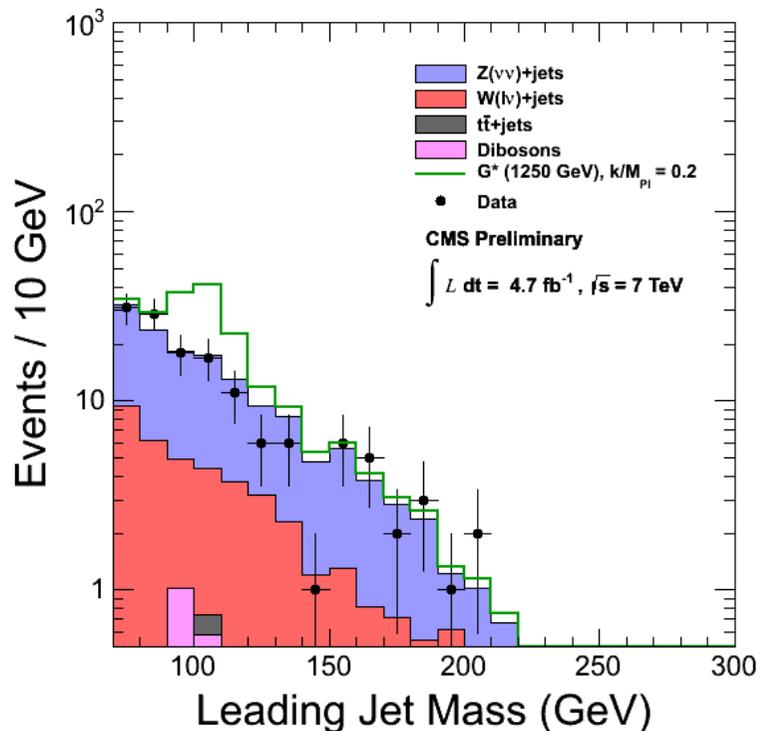
- Integrate $m_{t\bar{t}} > 1\text{TeV}/c^2$ and correct for smearing in $m_{t\bar{t}}$

	1+1	1+2
Expected SM $t\bar{t}$ events	194 ± 106	129 ± 80
Expected non-top multijet events	1546 ± 45	2271 ± 130
Total expected events	1740 ± 115	2400 ± 153
Observed events	1738	2423
$t\bar{t}$ efficiency	$(2.5 \pm 1.3) \times 10^{-4}$	$(1.6 \pm 1.0) \times 10^{-4}$

- Counting experiment gives CL_S 95% C.L. limit: $\mathcal{S} < 2.6$

Fields of application for boosted techniques

- Boosted H
 - e.g. $b\bar{b}$ final state (discussed in WG1)
- Boosted W/Z-bosons
 - WW-scattering in the SM (discussed in WG1)
 - Heavy resonances decaying into W/Z final states
 - e.g. $G^* \rightarrow ZZ \rightarrow q\bar{q}v\bar{v}$. : jet mass cut $m_{\text{jet}} > 70$ GeV to tag Z-boson
 - other final states in preparation



Conclusions

- Search for $t\bar{t}$ resonances intensive field of study in CMS, deploying leading edge techniques
- Already reached sub-picobarn limits (depending on the model)
 - individual searches rule out Z'/KKg below 1.2-2 TeV
- Boosted techniques allow to reach the highest momentum transfer regimes without loss through BR
- Outlook
 - Update of high mass μ +jets analysis
 - Combination of the channels and analysis techniques
 - Application of W -tagging in other searches with highly boosted W s/ Z s
 - Heavy resonances decaying to $WW/WZ/ZZ$