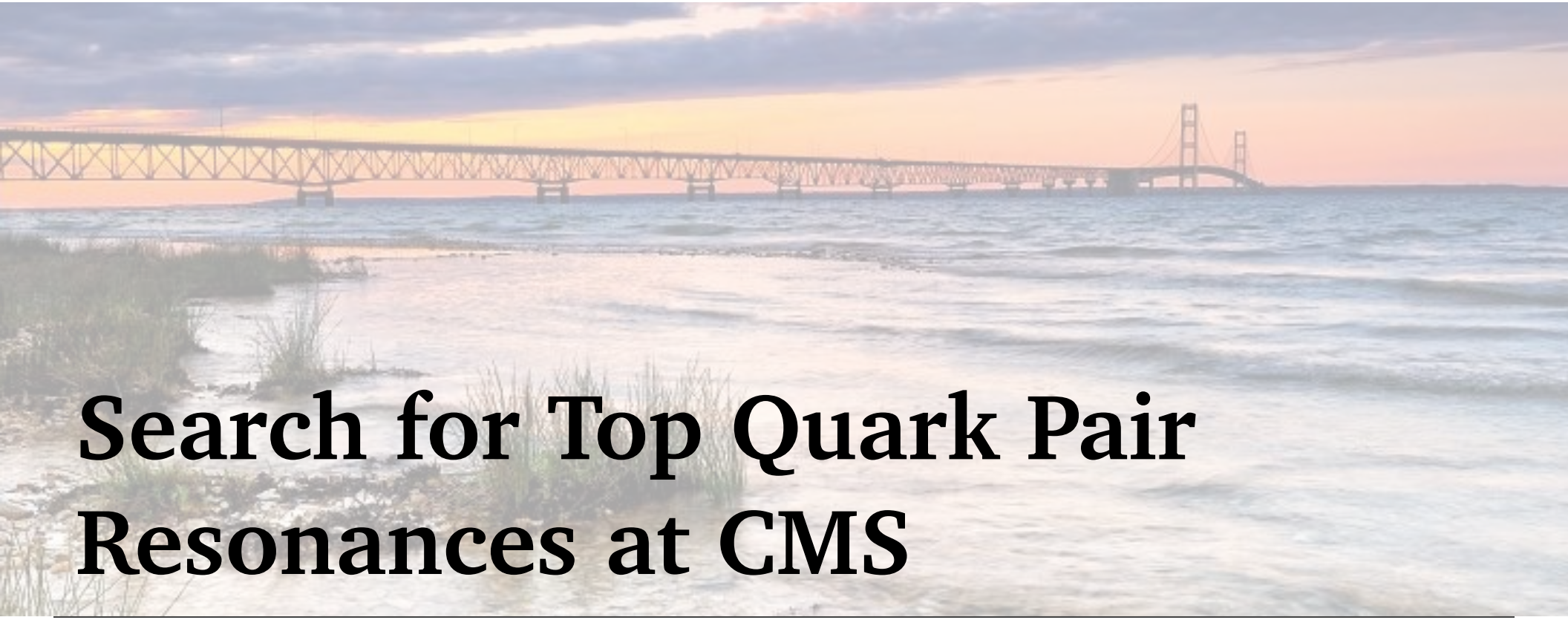


Search for Top Quark Pair Resonances at CMS

Justin Pilot, *University of California — Davis*
on behalf of the CMS Collaboration

APS Meeting of the Division of Particles & Fields
University of Michigan, Ann Arbor, MI

6 August 2015

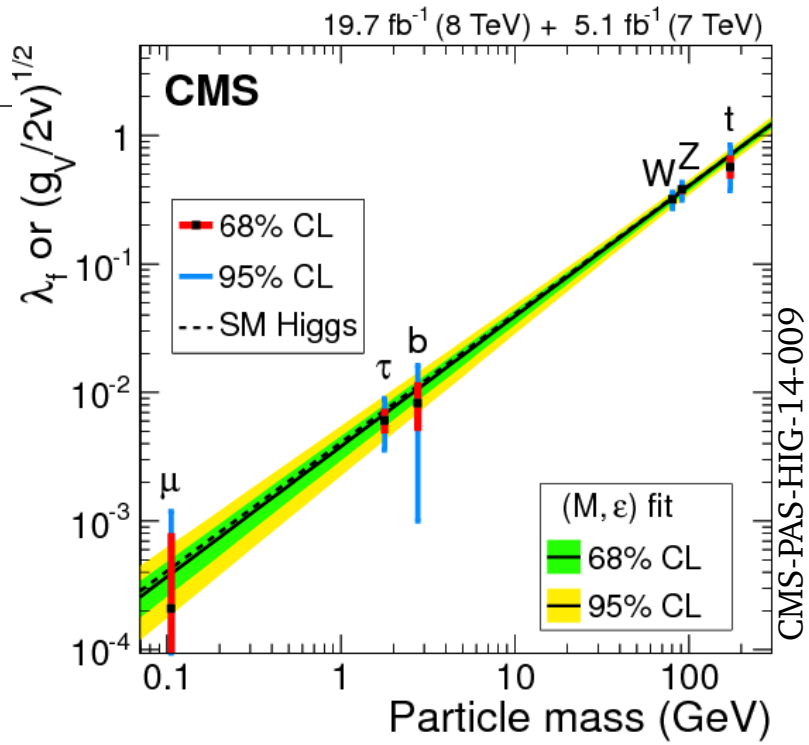
Motivation

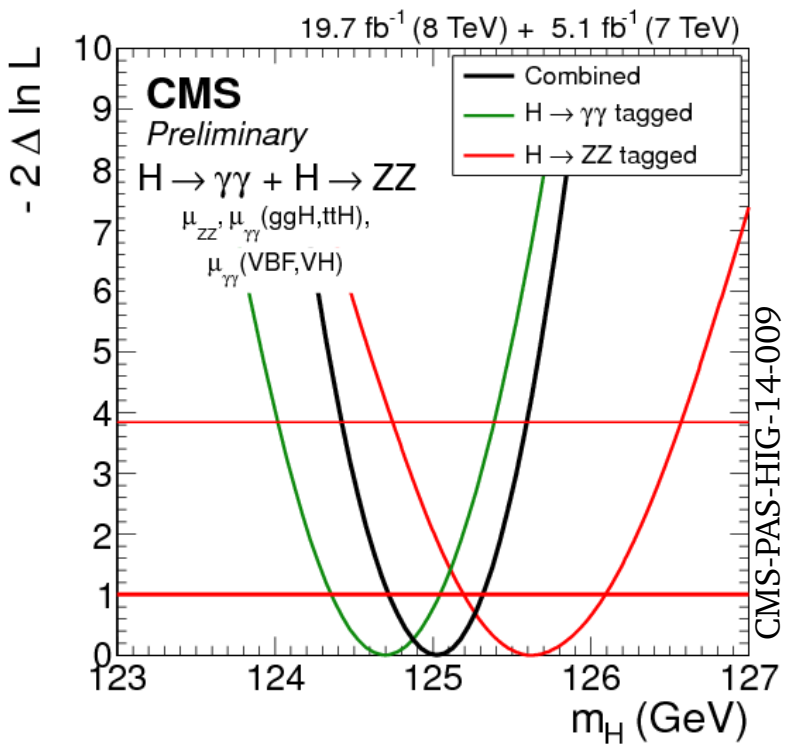
- Higgs boson discovery provided missing piece of the Standard Model

- We know there are further questions to be answered
  - What about fine tuning; what can provide a solution to the hierarchy problem??

- Several new physics models have been proposed
  - Composite Higgs
  - Extra dimensions
  - SUSY

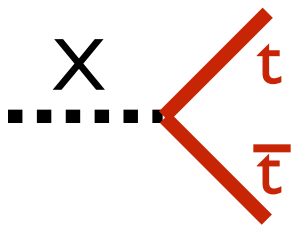
  - Predict new particles in the 1-3 TeV range

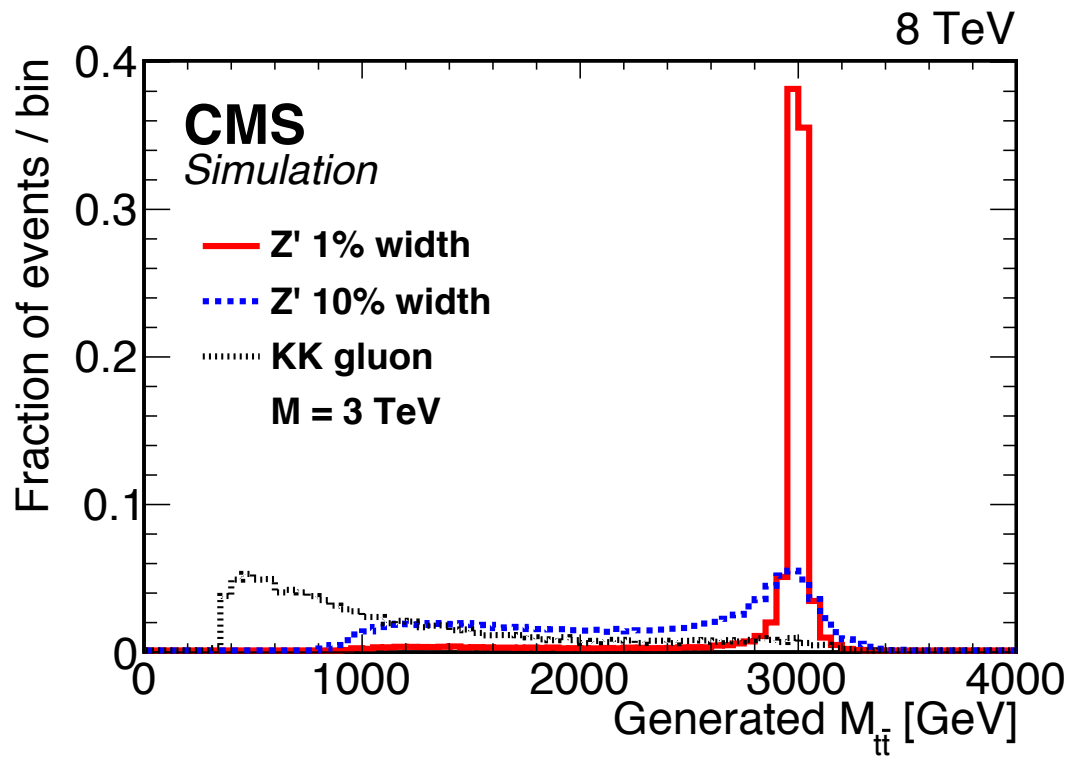




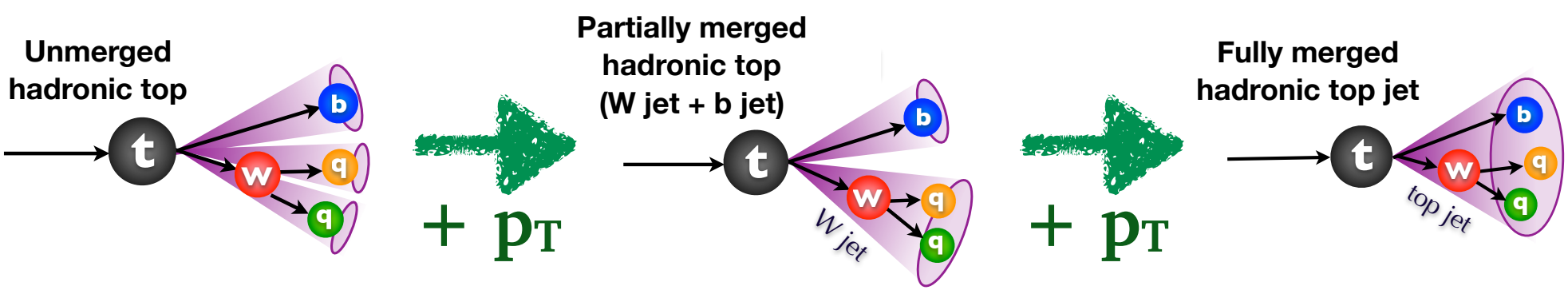
Outline

- We present a search for new heavy resonances decaying to top quark pairs
  - CMS combination of channels recently submitted to PRD (http://arxiv.org/abs/1506.03062)



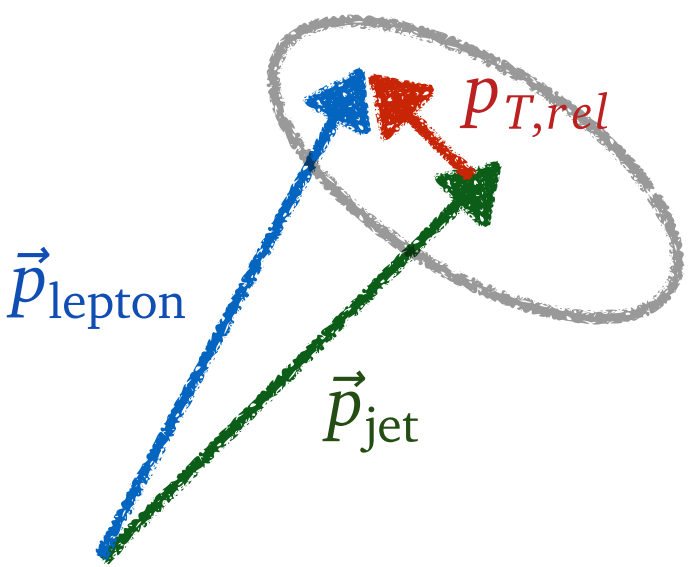


- Use the reconstructed top pair invariant mass to search for structures in the 1 TeV to 3 TeV mass range
  - As mass increases, decay products more boosted → special reconstruction techniques needed!

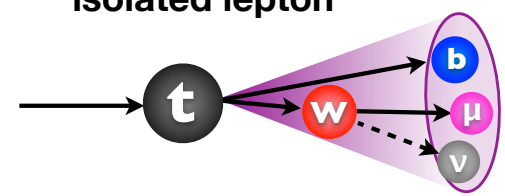


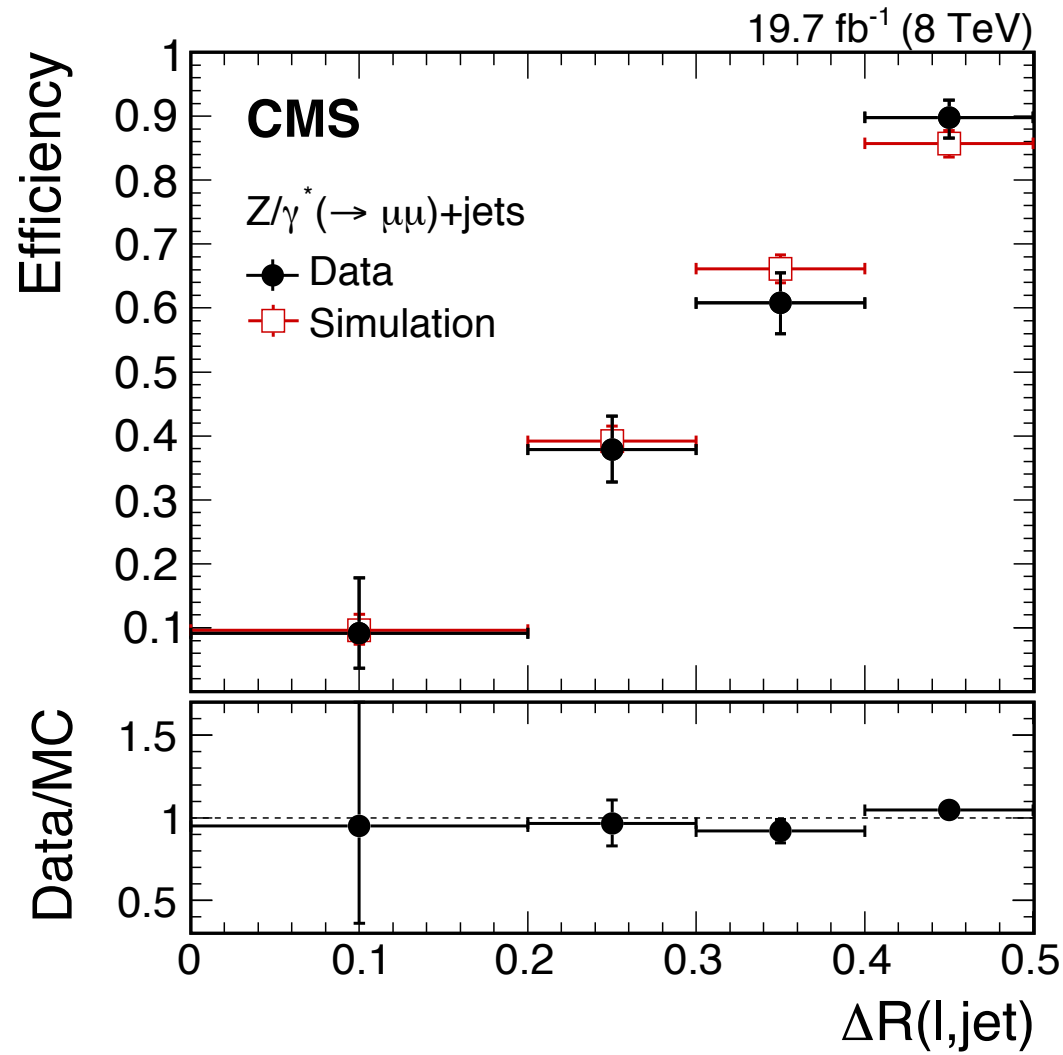
Top Quark Identification

- For lepton+jets mode, need to efficiently identify non-isolated leptons
  - Standard isolation requirements will remove large fraction of signal acceptance
  - Use component of p_T transverse to jet axis ($p_{T,rel}$)
  - Efficiencies measured and validated in data/simulation comparisons



Leptonic top with non-isolated lepton





Top Quark Identification

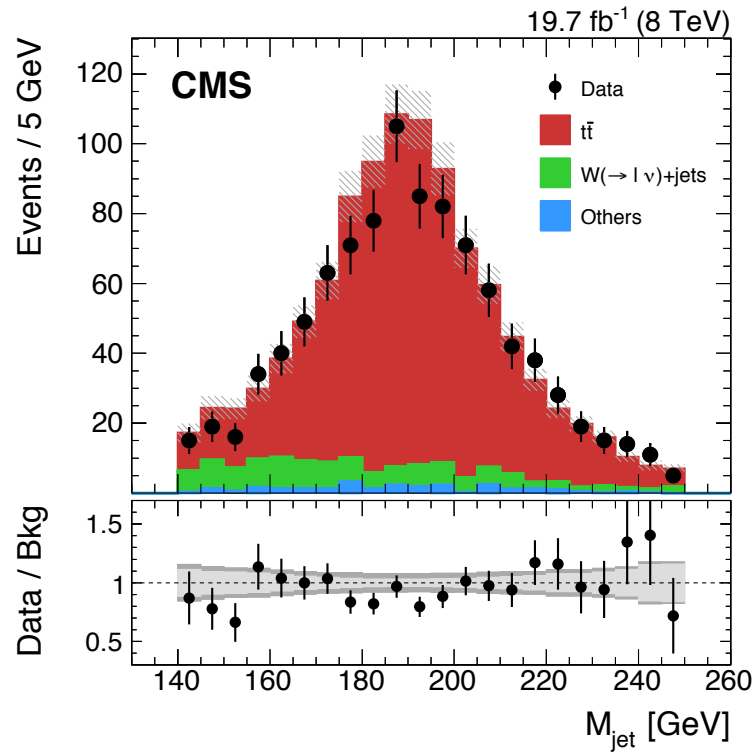
- For hadronic mode, use jet substructure algorithms to identify merged decay products

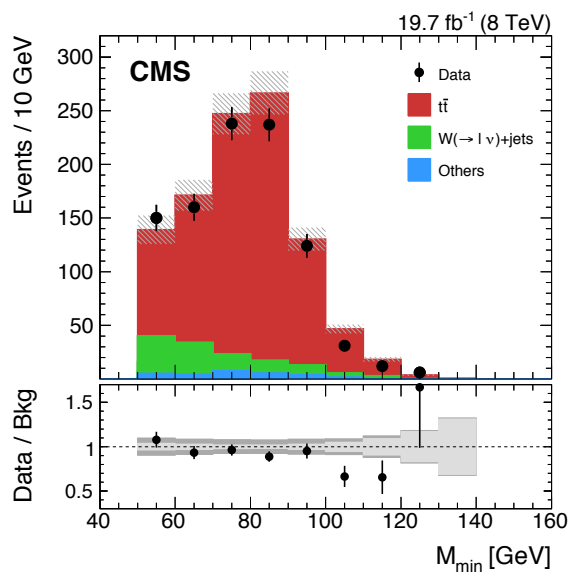
$$\Delta R \sim \frac{2m}{p_T}$$

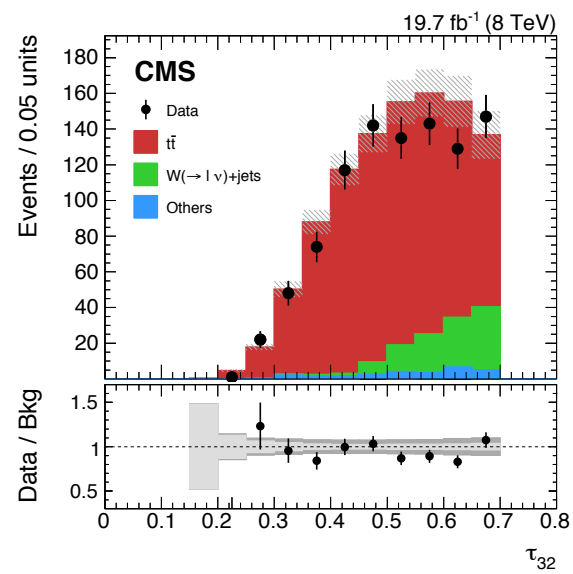
  - Large-radius jets (R=0.8, 1.5)
    - W jets — $p_T > \sim 200$ GeV
    - Top jets — $p_T > \sim 400$ GeV

- "CMS Top Tagger" (R=0.8)
  - Jet mass, N subjets, min. di-subjet mass, N-subjettiness τ_{32}
- "HEP Top Tagger" (R=1.5)
  - Subjet mass combinations

- Also utilize subjet b-tagging for increased purity



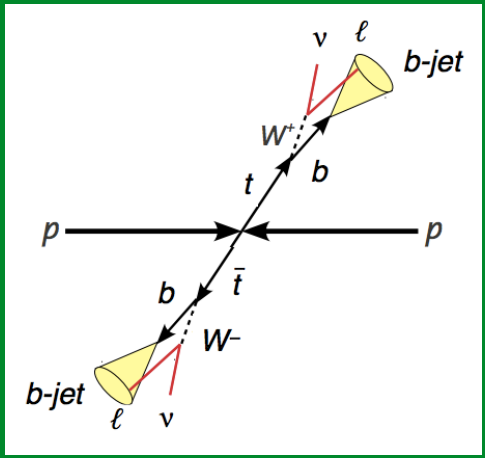




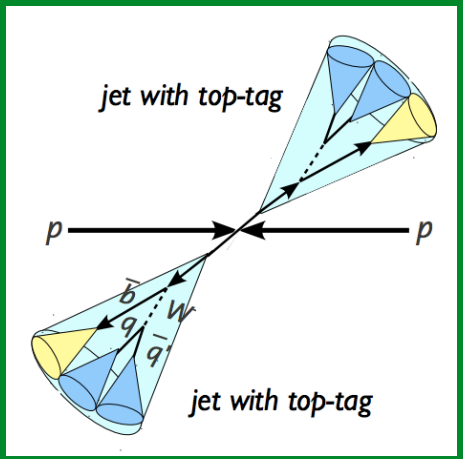
Outline

- Several final state topologies considered; combined in final results

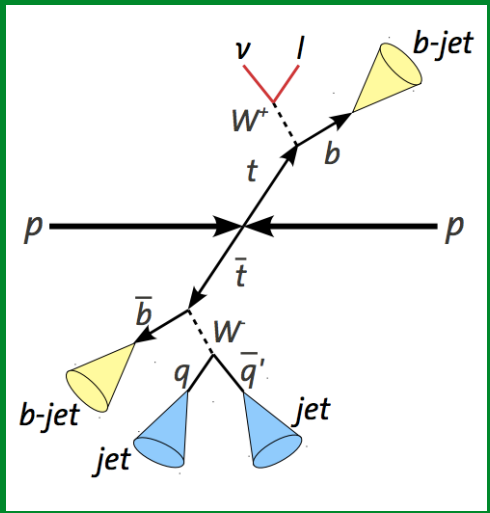
Dilepton



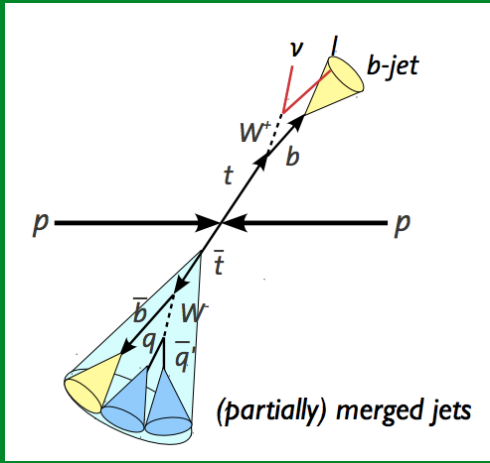
All-Hadronic



Lepton+jets (Resolved)



Lepton+jets (Boosted)

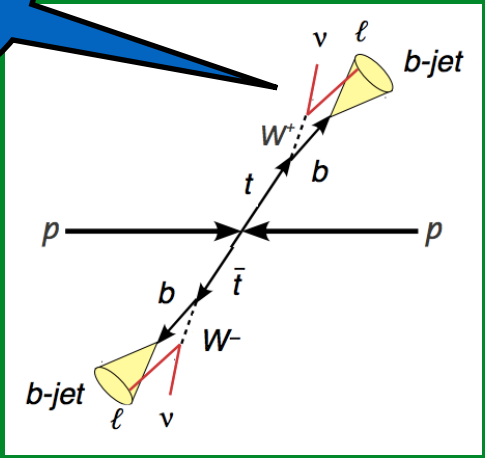


Outline

- Several final state topologies considered; combined in final results

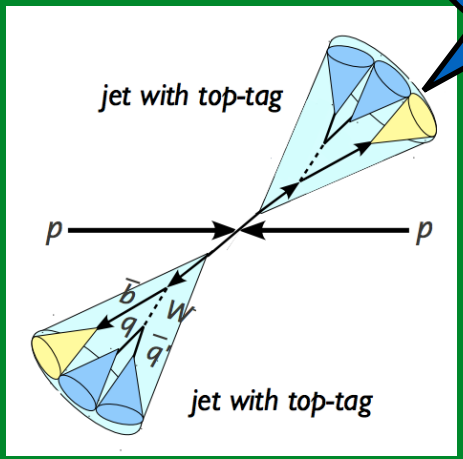
Non-iso. leptons

Dilepton

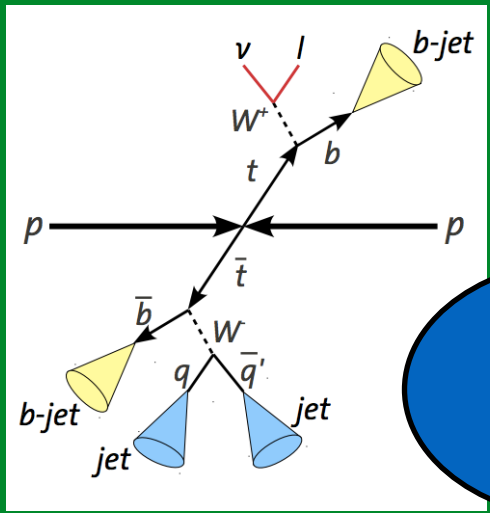


All-Hadronic

Top tagging

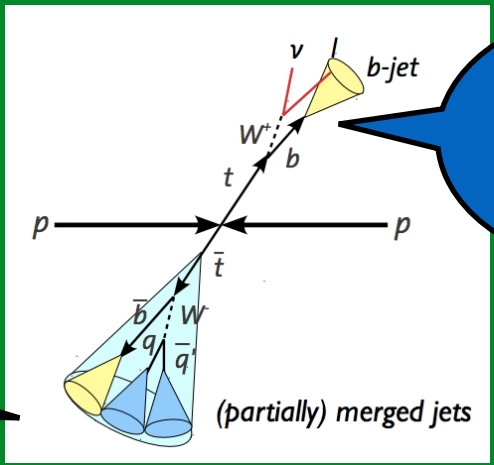


Lepton+jets (Resolved)



W, top tagging

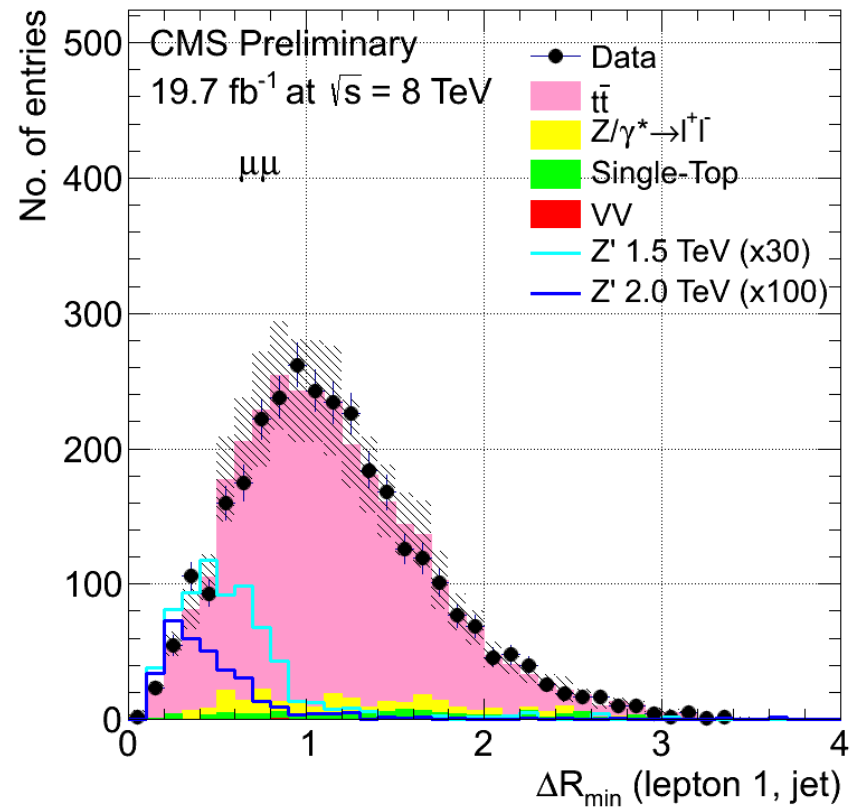
Lepton+jets (Boosted)

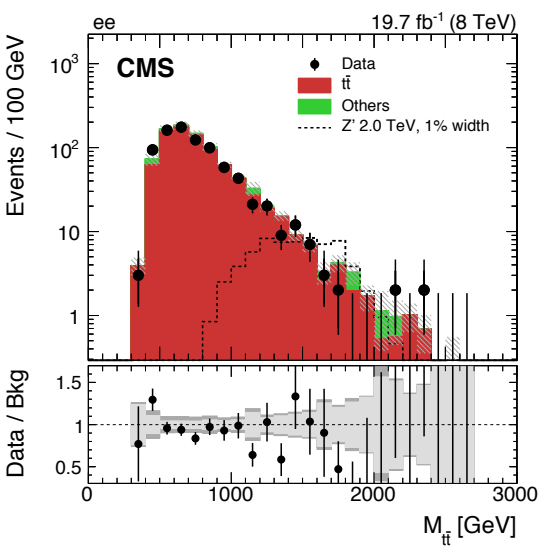


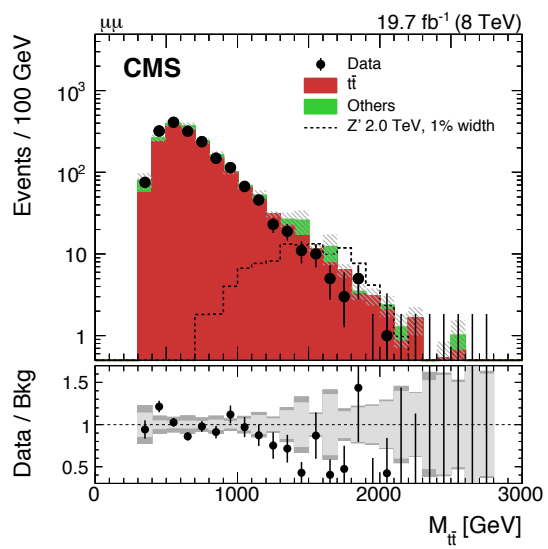
Non-iso. leptons

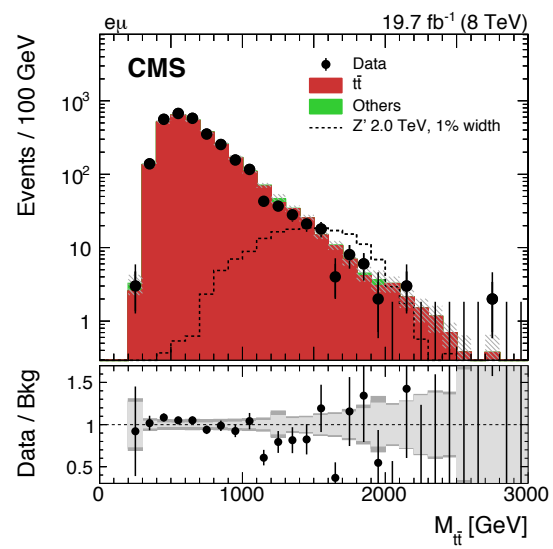
Dilepton Channel

- Select 2 non-isolated leptons, 2 jets, and missing E_T
  - ΔR distribution used to extract ttbar normalization
- Events divided into categories based on b-tagging
  - 1 tight b-tagged jet
  - 2 loose b-tagged jets
- Mass is computed from two leptons, two jets, and missing E_T from neutrinos



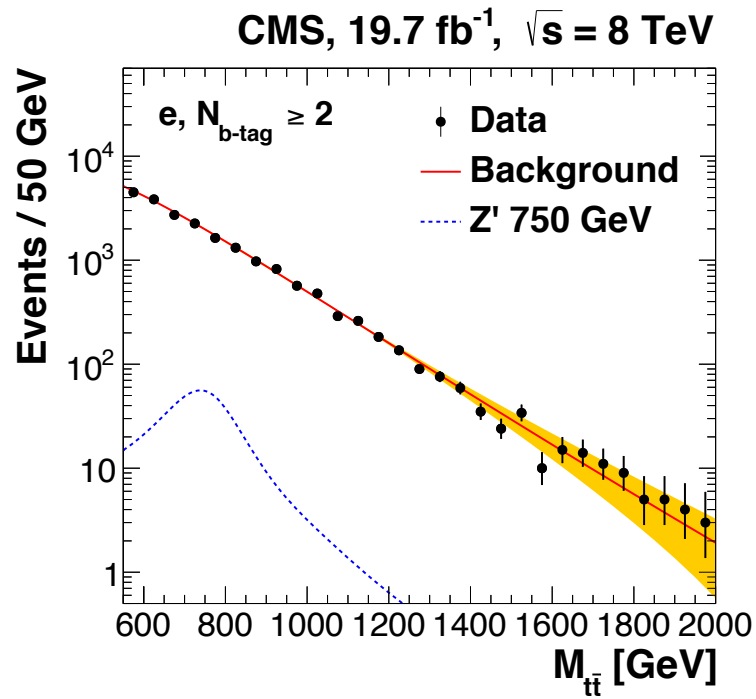


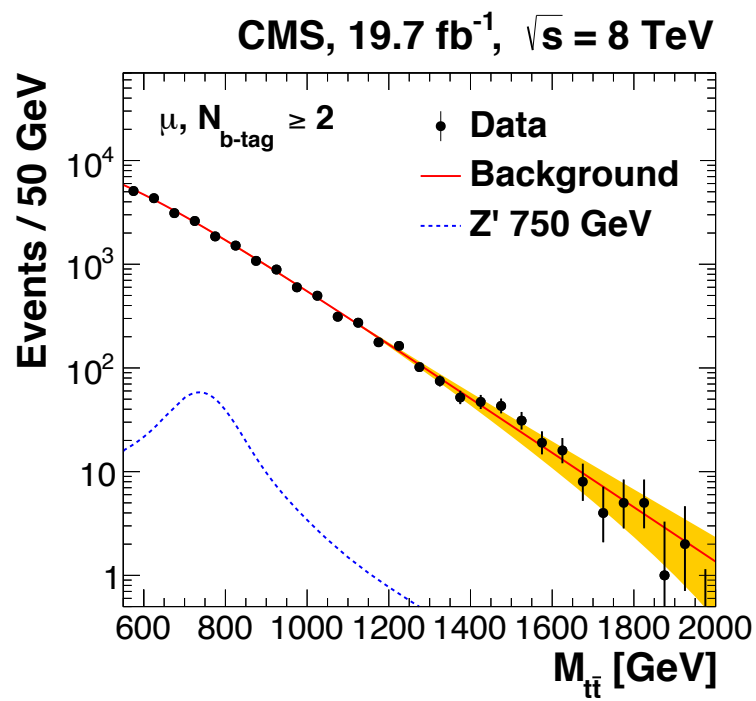




Lepton+Jets Channel (Resolved)

- 'Standard' reconstruction of one object corresponding to one parton from top decay
  - 1 isolated lepton
  - 4 jets
    - At least one b-tag
- Chi-squared algorithm used to reconstruct masses
- Background is fit to a functional form; templates used for signal discrimination
- Analysis loses sensitivity at ~1 TeV due to boosted nature of decays

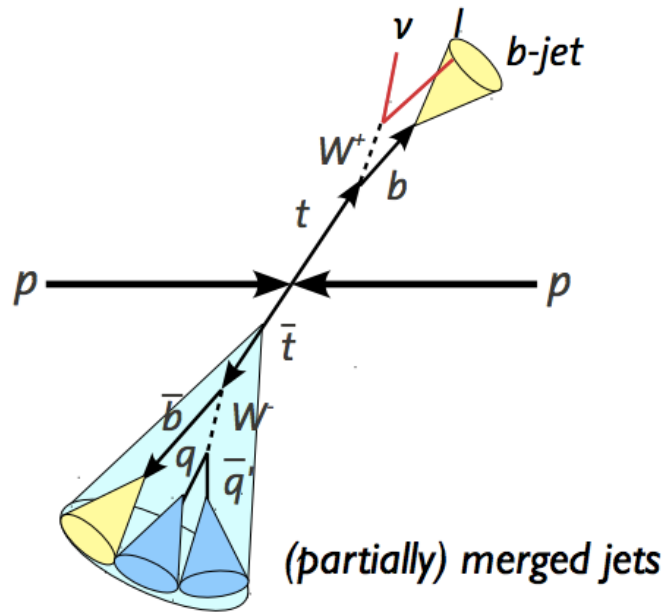




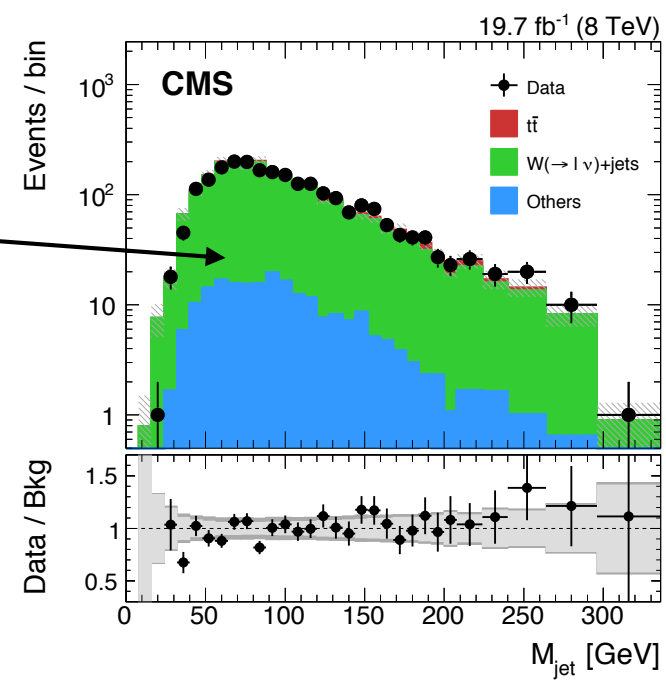
Lepton+Jets Channel (Boosted)

- Maintains sensitivity to resonances above 1 TeV through use of non-isolated leptons, top-tagging algorithms

- 1 electron or muon
- At least two jets, p_T > 150, 50 GeV
  - Can select both partially and fully merged hadronic top decays
- Missing E_T



- Events categorized based on number of CMS top-tagged jets and number of b-tagged jets
  - Mistag rate determined from W+jets control region



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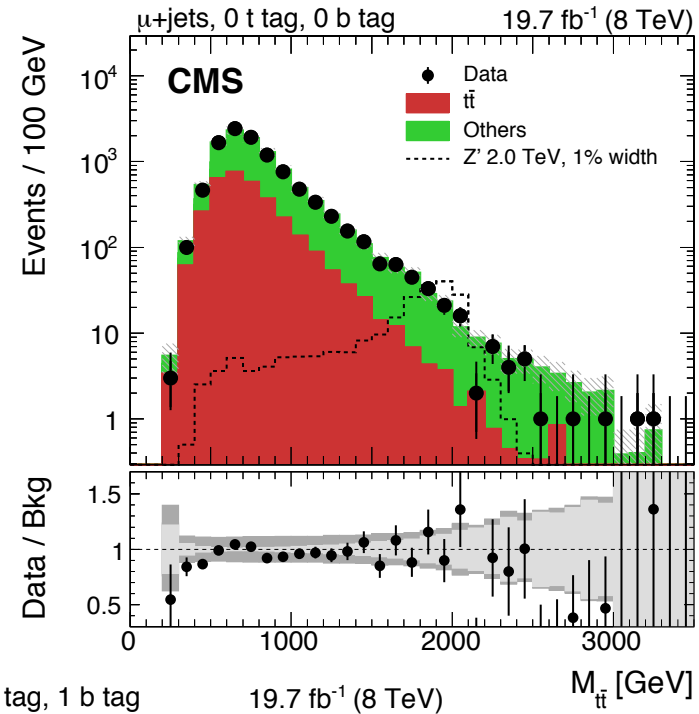

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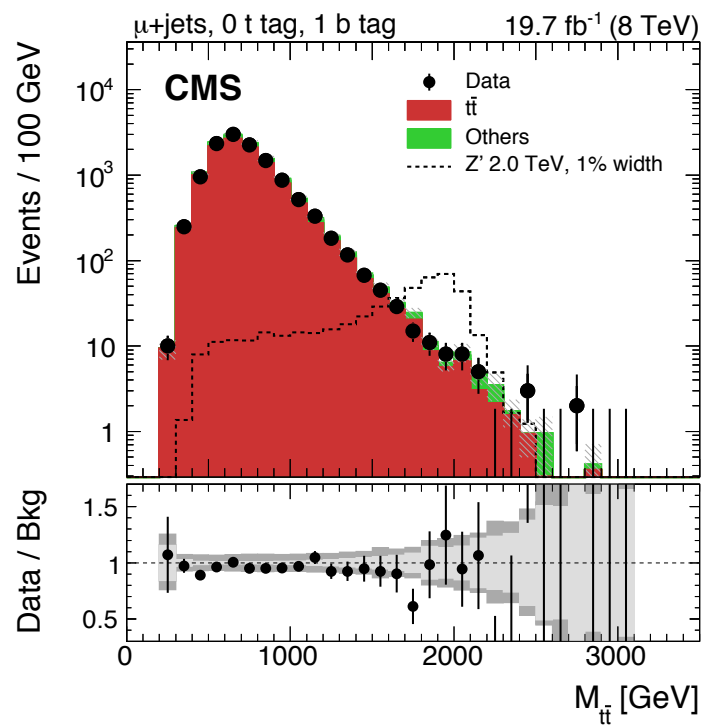
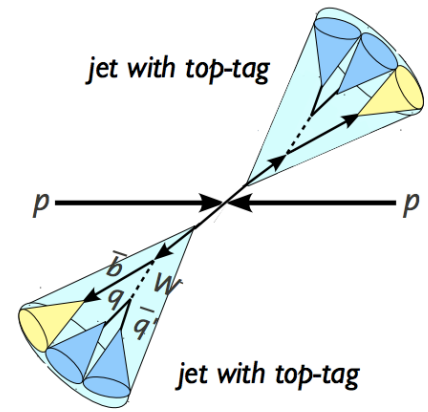
- Signal regions have high top purity

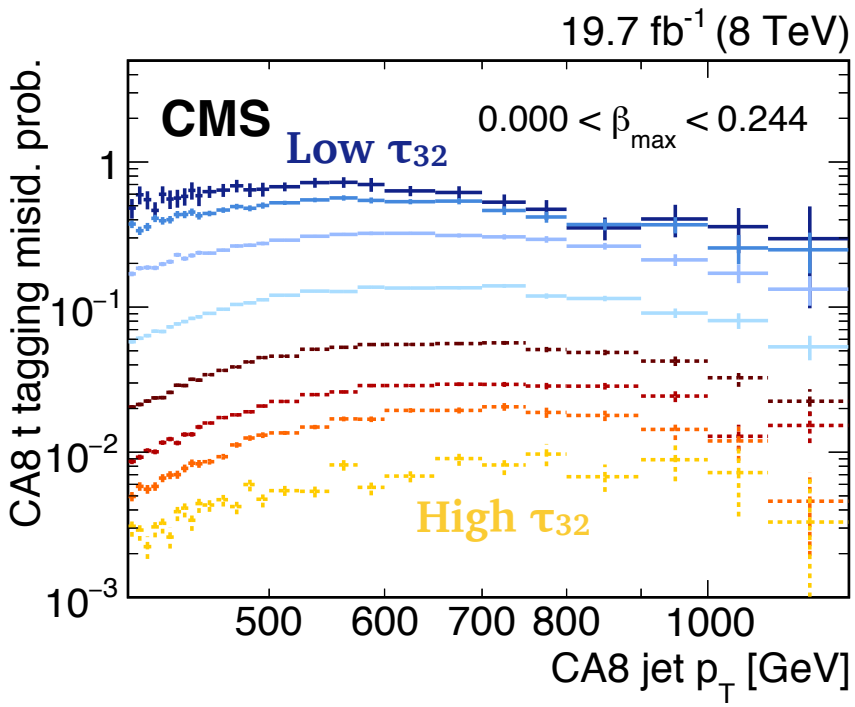


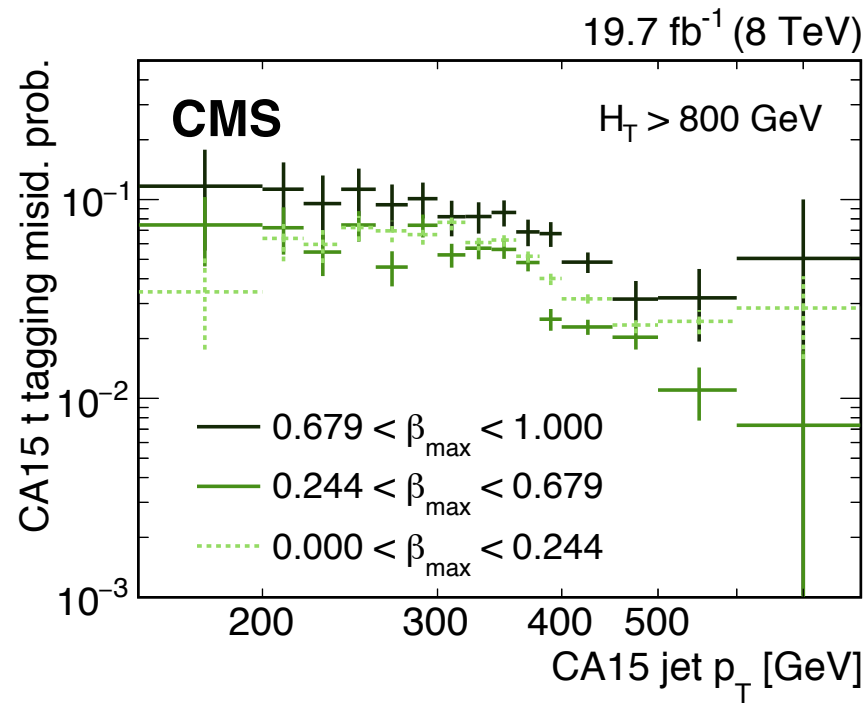
All-Hadronic Channel

- Two selections for optimization across mass range:
  - Low mass — two R = 1.5 jets, p_T > 200 GeV, HEP top-tagged
  - High mass — two R = 0.8 jets, p_T > 400 GeV, CMS top-tagged



- Main background is QCD multijet production
  - Reduced through use of subjet b-tagging
  - Determined by inverting top-tagging algorithm requirements
    - Measure rate in QCD dijet events in data
    - Parameterized as function of jet p_T, N-subjettiness value, b-tag score
    - Validated through closure test





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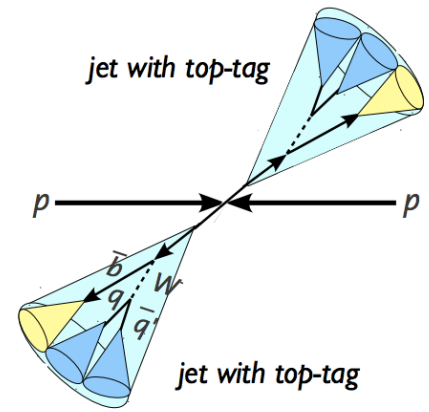

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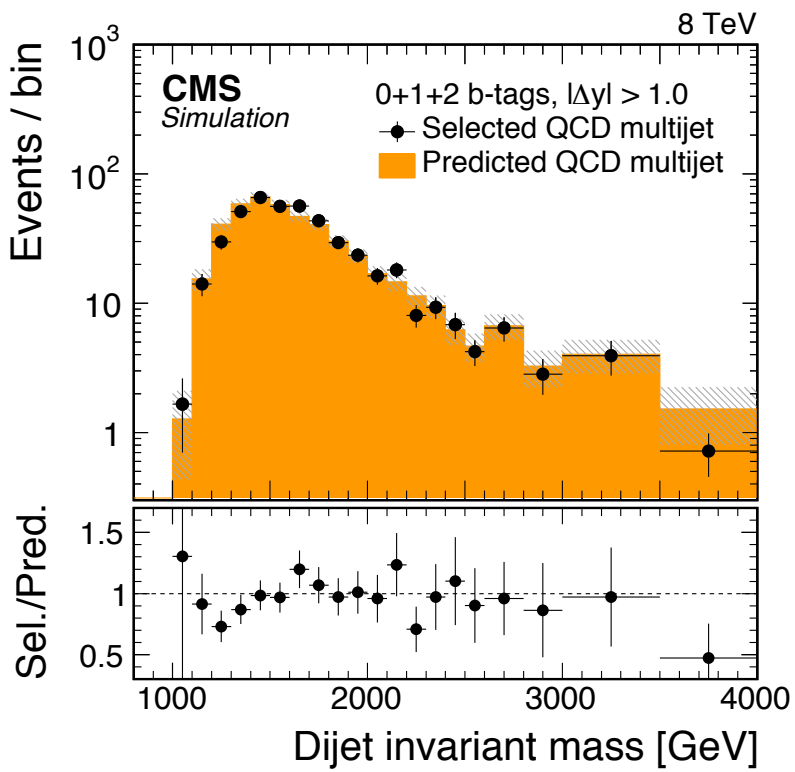
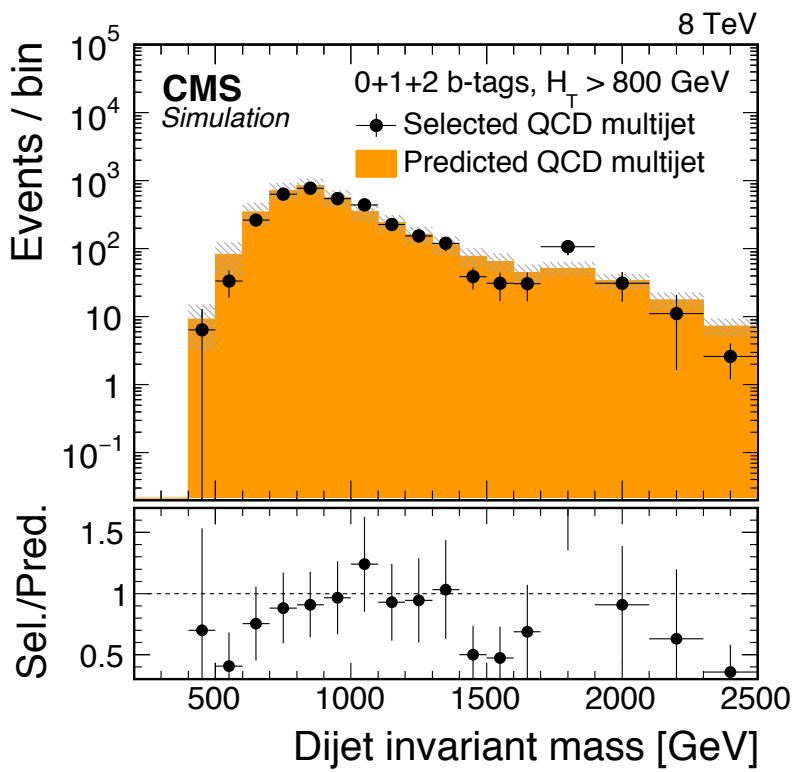
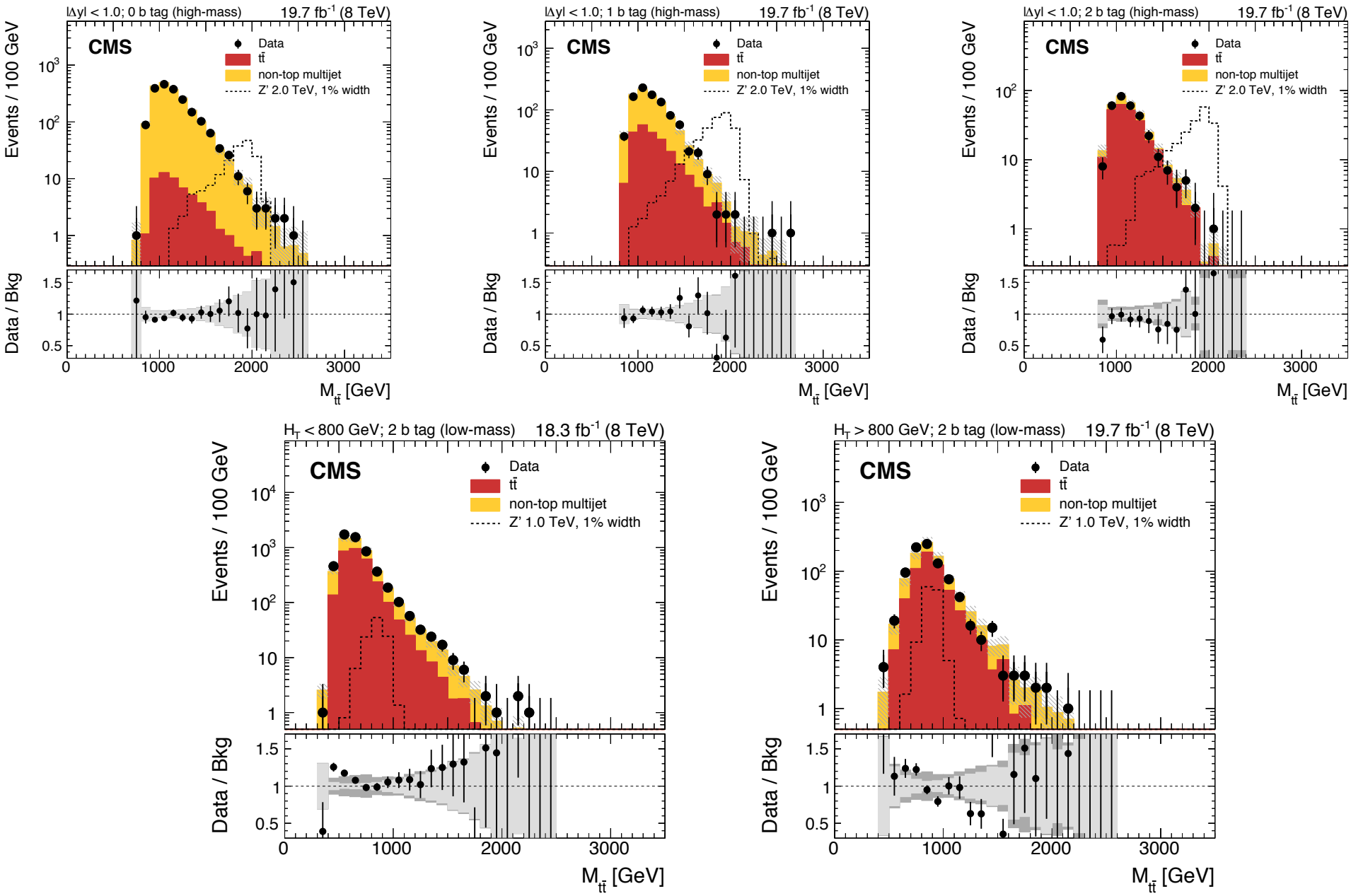




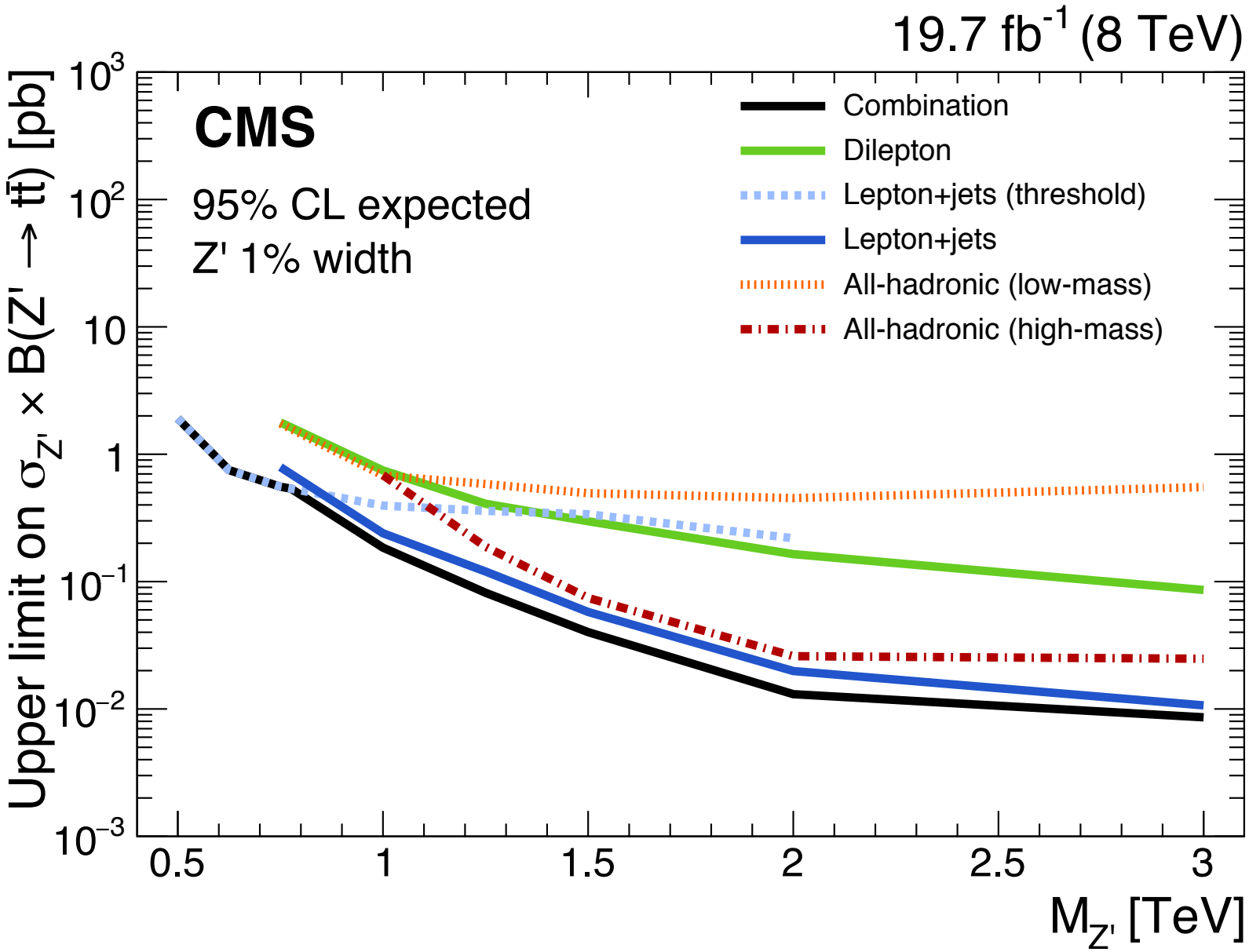
All-Hadronic Channel

- Events divided based on number of subjet b-tags, H_T, and jet rapidity difference



Sensitivity

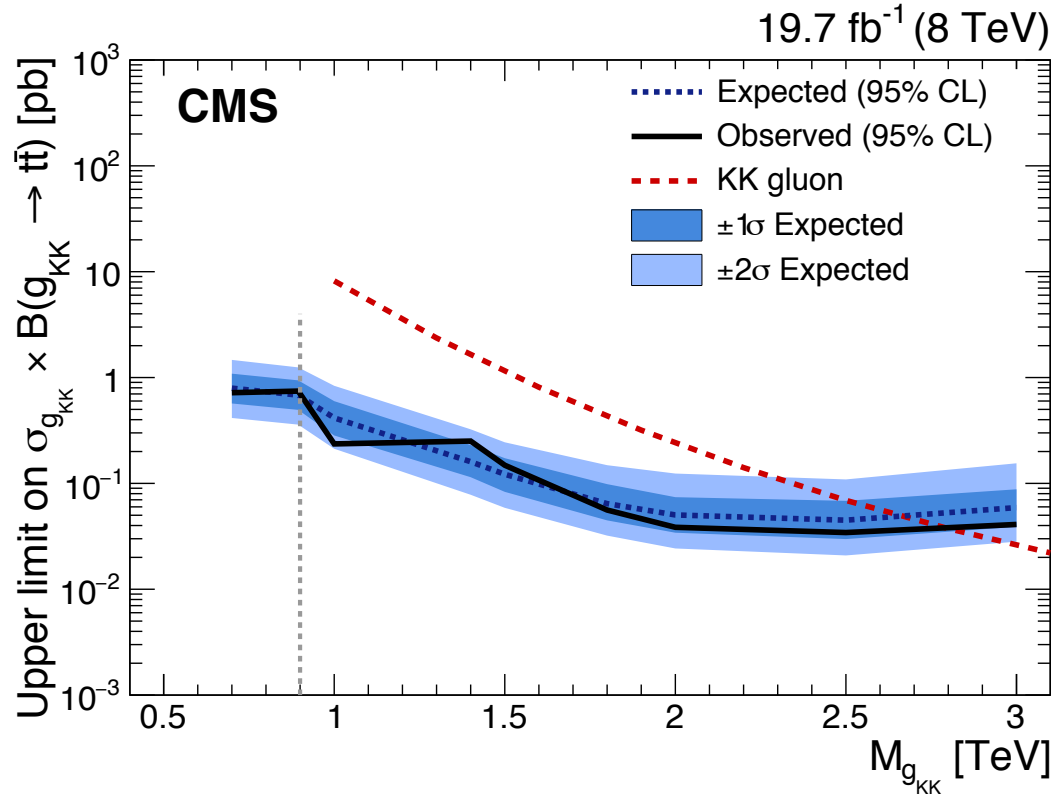
- Boosted analysis selections critical for high-mass regime!



Results

- We observe no significant deviations from the expected SM and set limits on three physics models:
  - Generic Z' resonance (1%, 10% width)
  - Randall-Sundrum KK gluon (~16% width)

- Observed limits exclude masses up to 2.9 TeV!

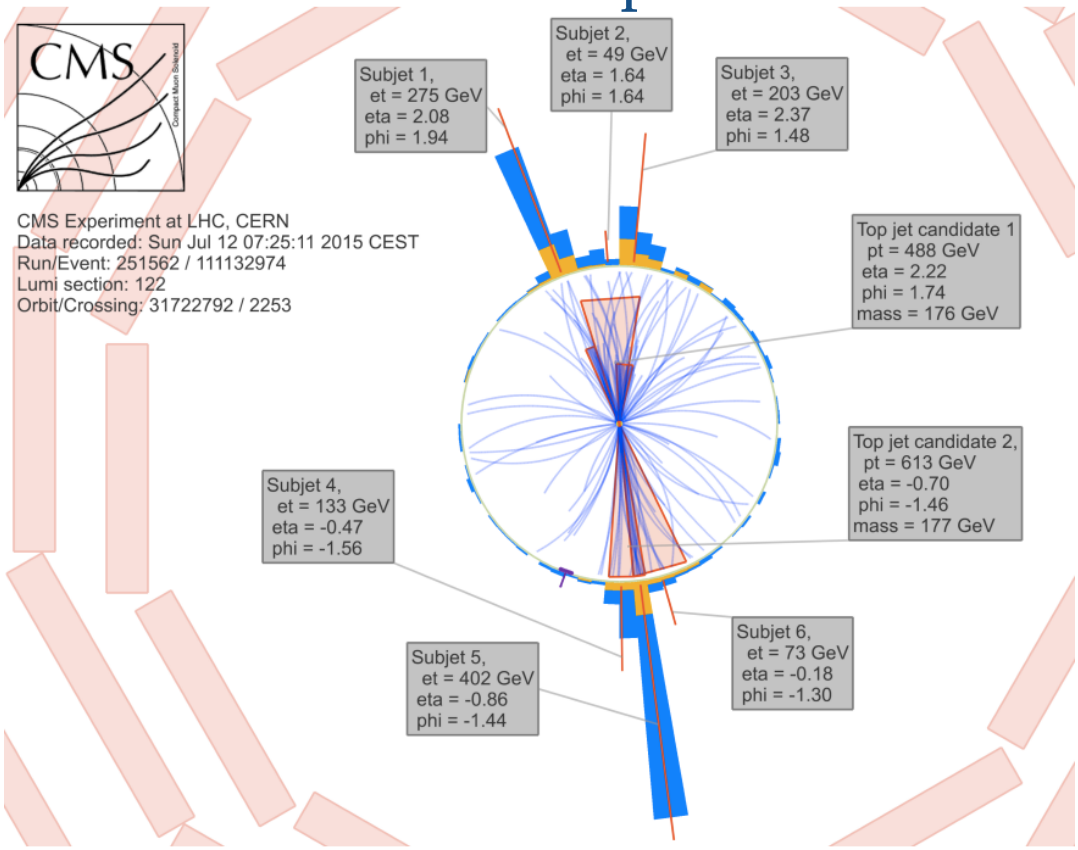


	Mass limit [TeV]							
	Dilepton channel		Lepton+jets channel		All-hadronic channels		Combined	
	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
$Z', \Gamma_{Z'}/M_{Z'} = 1.2\%$	1.4	1.5	2.2	2.3	2.1	2.1	2.4	2.4
$Z', \Gamma_{Z'}/M_{Z'} = 10\%$	2.1	2.2	2.7	2.8	2.5	2.5	2.8	2.9
RS KK gluon	1.8	2.0	2.5	2.5	2.4	2.3	2.7	2.8

Conclusions

- We performed a search for heavy resonances decaying to top quark pairs
  - Combination of several event topologies
- Critical reliance on specialized object reconstruction methods
  - Lepton (non-)isolation
  - Top-tagging algorithms
- No deviation from SM expectation is observed, we exclude masses up to 2.4 to 2.9 TeV depending on physics model
- Results available, paper submitted to PRD
  - http://arxiv.org/abs/1506.03062
  - CMS-B2G-13-008
- We look forward to what Run 2 holds for this search
  - Thank you for your attention!

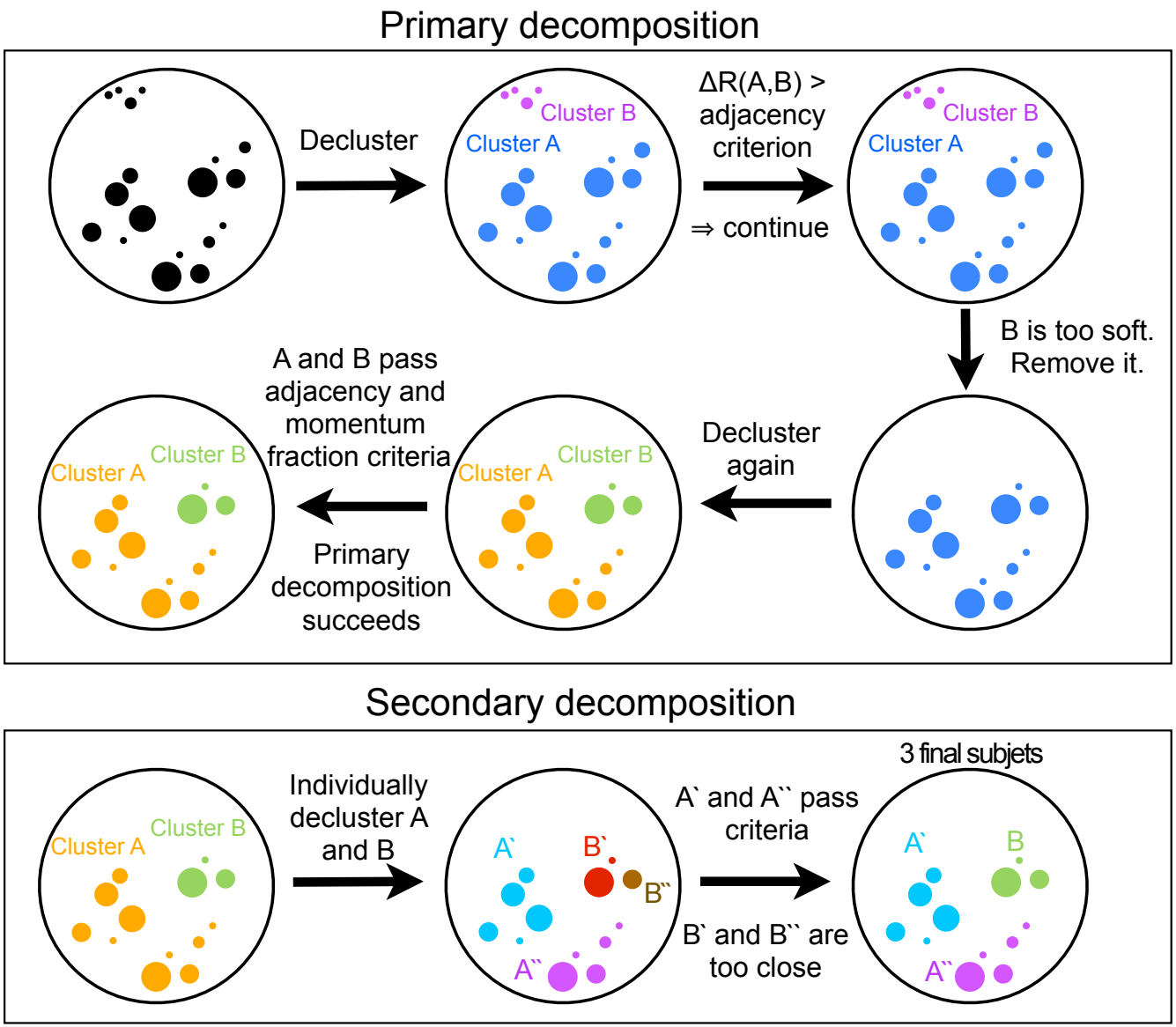
13 TeV Boosted Top Candidate!



Backup Material

CMS Top Tagger

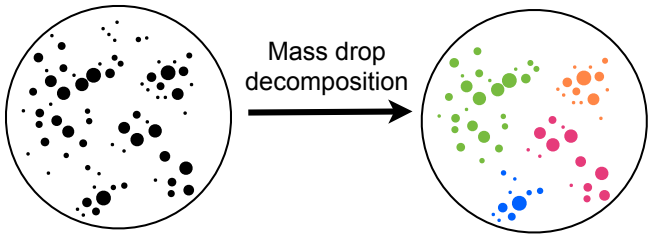
Example: CMS Top Tagger decomposition



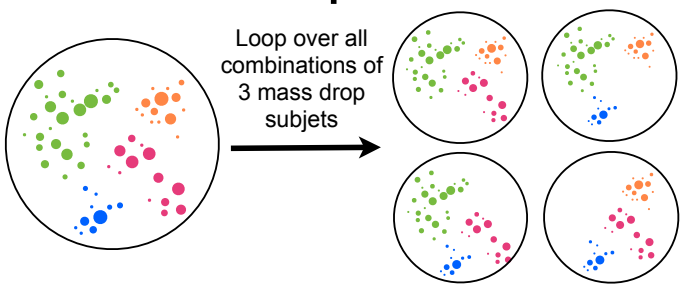
HEP Top Tagger

HEP Top Tagger details

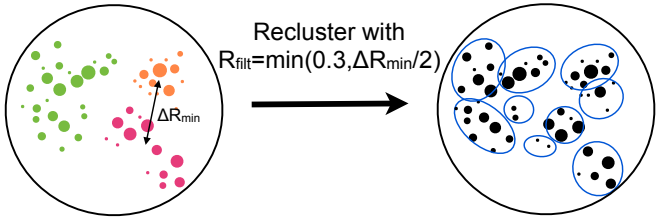
Step 1:



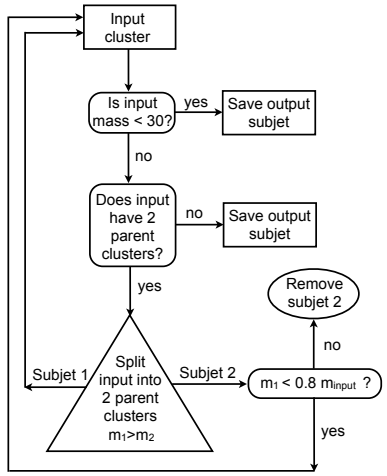
Step 2:



Step 3:



HEP Top Tagger
Mass drop decomposition



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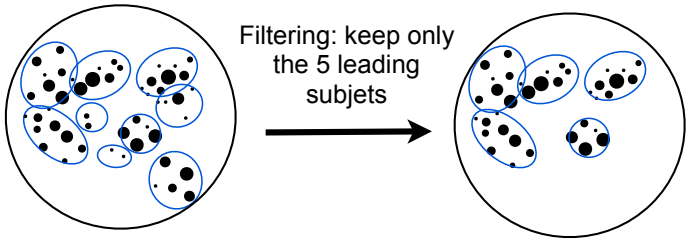

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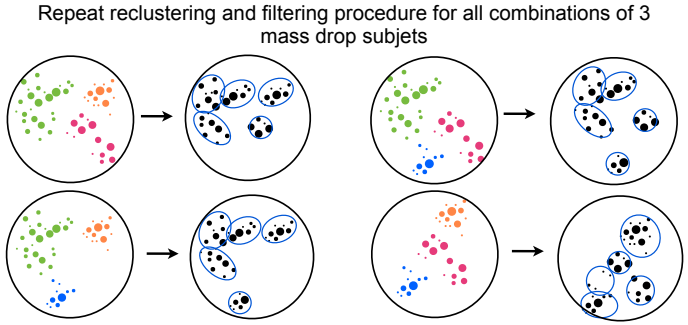

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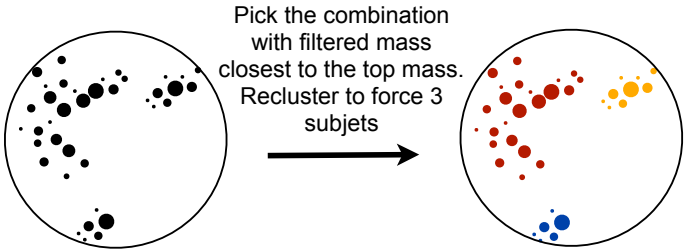


HEP Top Tagger

HEP Top Tagger - W mass selection

Bi-dimensional distribution based on the ratio of subjet pairwise masses

$$R^2_{\min}(1+(\frac{m_{12}}{m_{13}})^2) < 1-(\frac{m_{23}}{m_{123}})^2 < R^2_{\max}(1+(\frac{m_{12}}{m_{13}})^2)$$

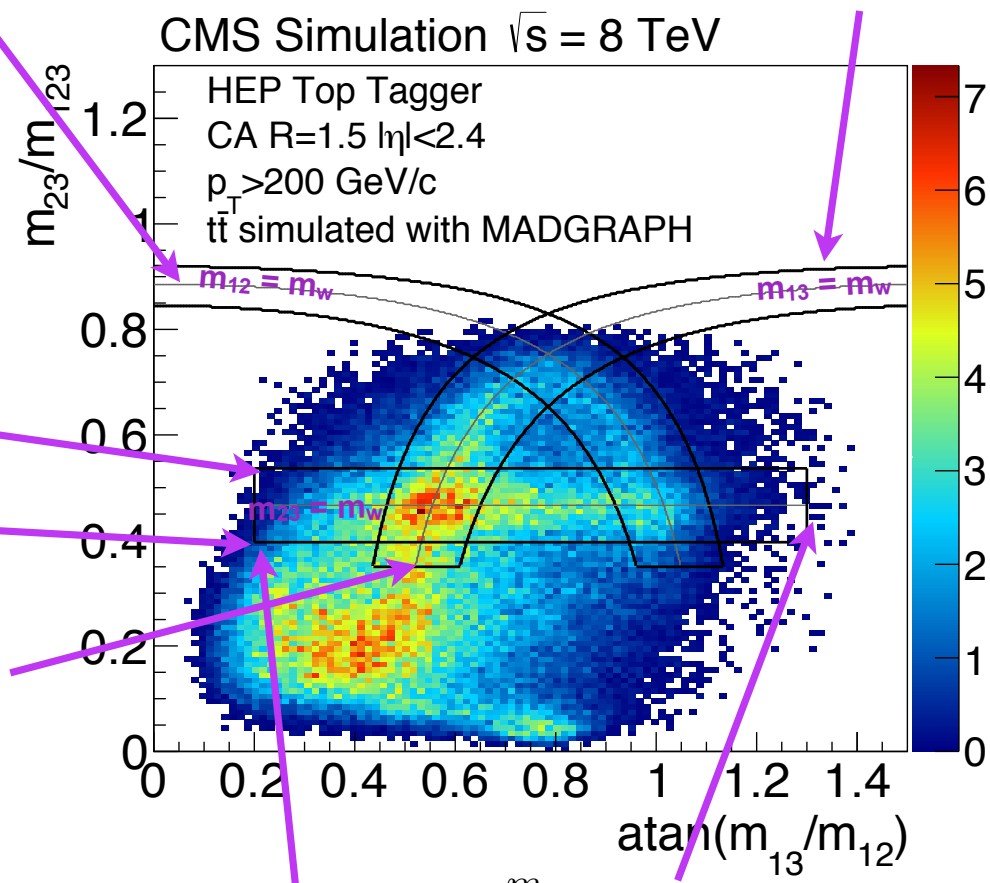
$$R^2_{\min}(1+(\frac{m_{13}}{m_{12}})^2) < 1-(\frac{m_{23}}{m_{123}})^2 < R^2_{\max}(1+(\frac{m_{13}}{m_{12}})^2)$$

$$R_{\min} < \frac{m_{23}}{m_{123}} < R_{\max}$$

$$R_{\max} = (1+f_W)\times m_W/m_t$$

$$R_{\min} = (1-f_W)\times m_W/m_t$$

$$\frac{m_{23}}{m_{123}} > 0.35$$



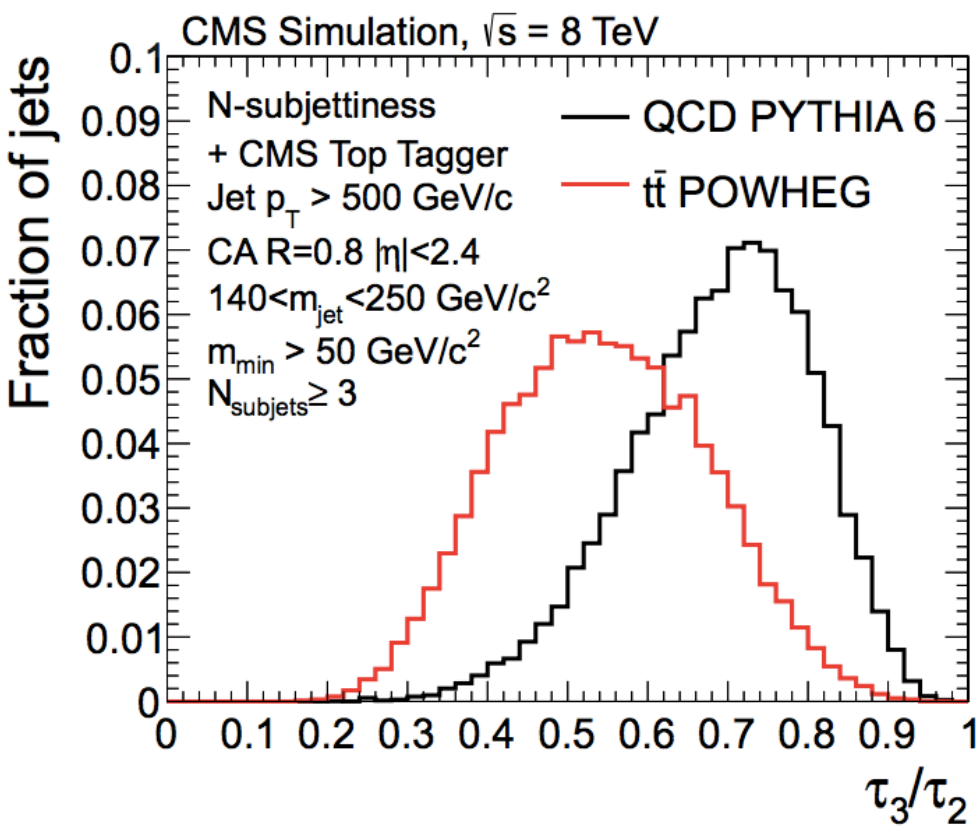
$$0.2 < \arctan\frac{m_{13}}{m_{12}} < 1.3$$

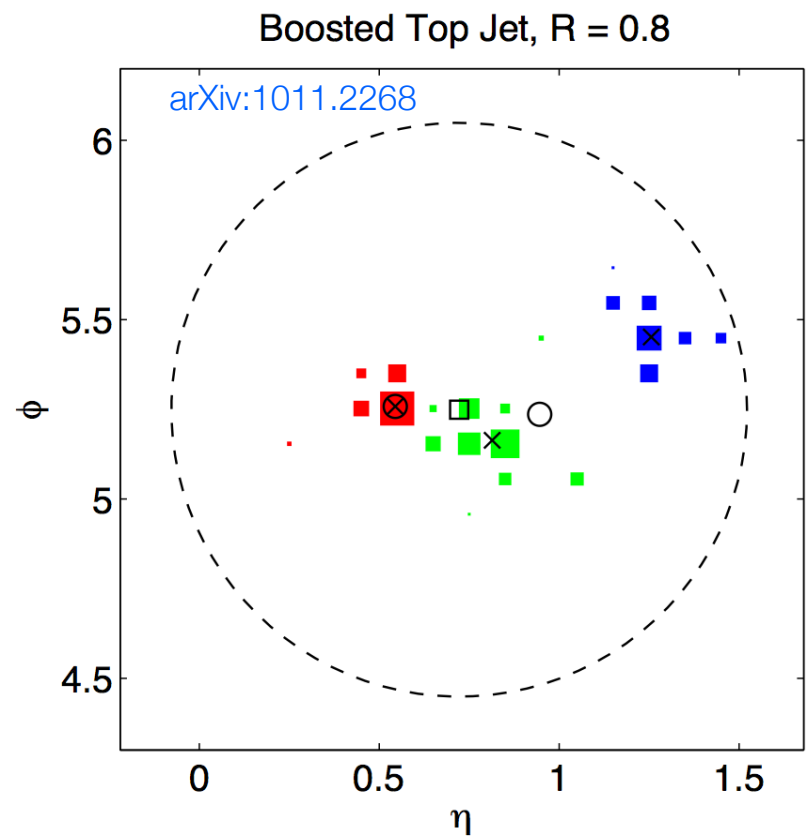
N-Subjettiness

J. Thaler, K Van Tilburg
arXiv:1011.2268

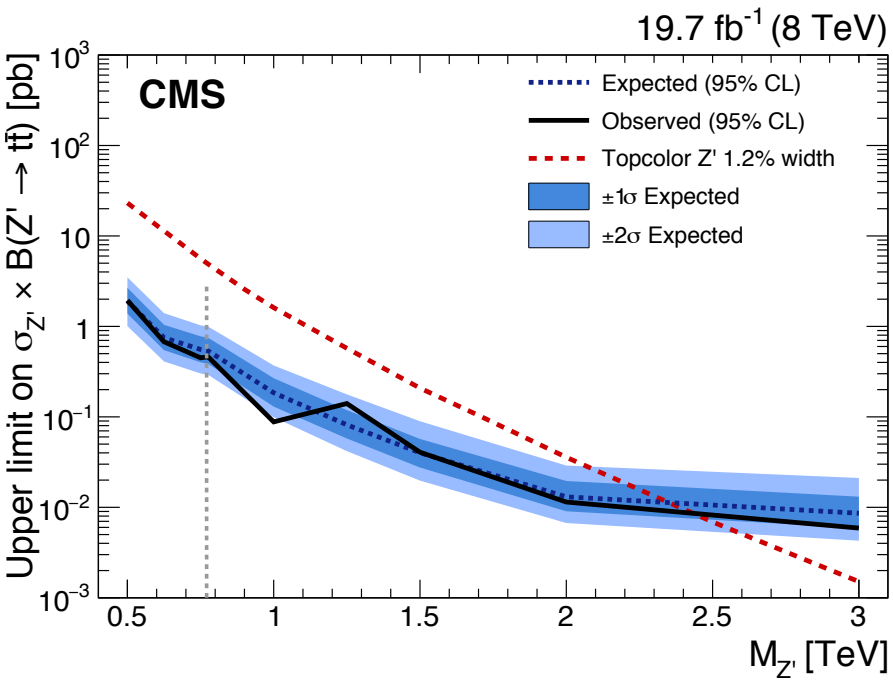
- A measure of the consistency of jet constituents with N number of subjets

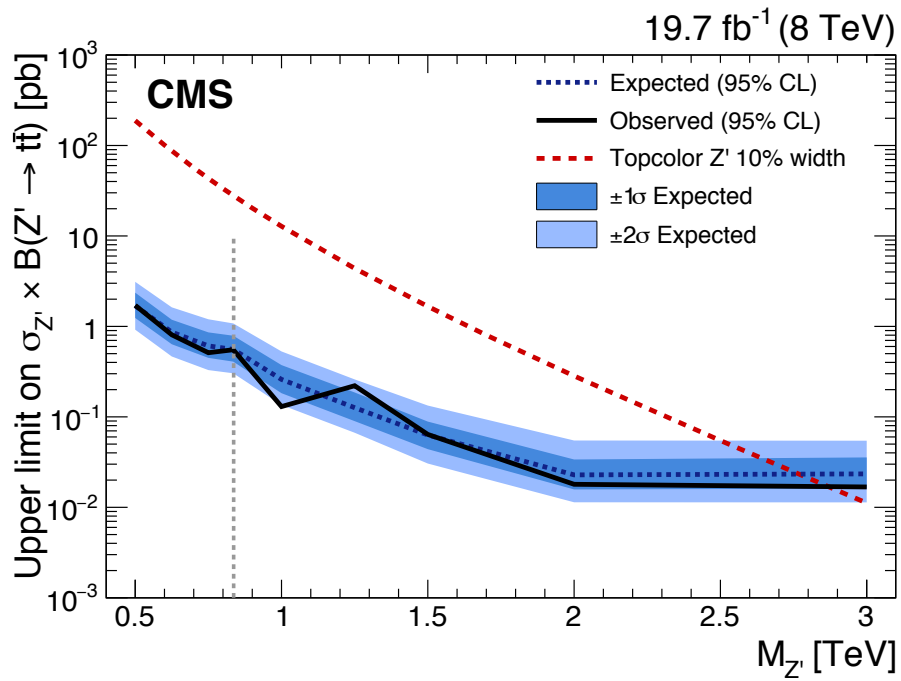
$$\tau_N = \frac{\sum_{i=1}^{n_{\text{constituents}}} p_{\mathrm{T},i} \min\{\Delta R_{1,i}, \Delta R_{2,i}, \ldots, \Delta R_{N,i}\}}{\sum_{i=1}^{n_{\text{constituents}}} p_{\mathrm{T},i} R}$$

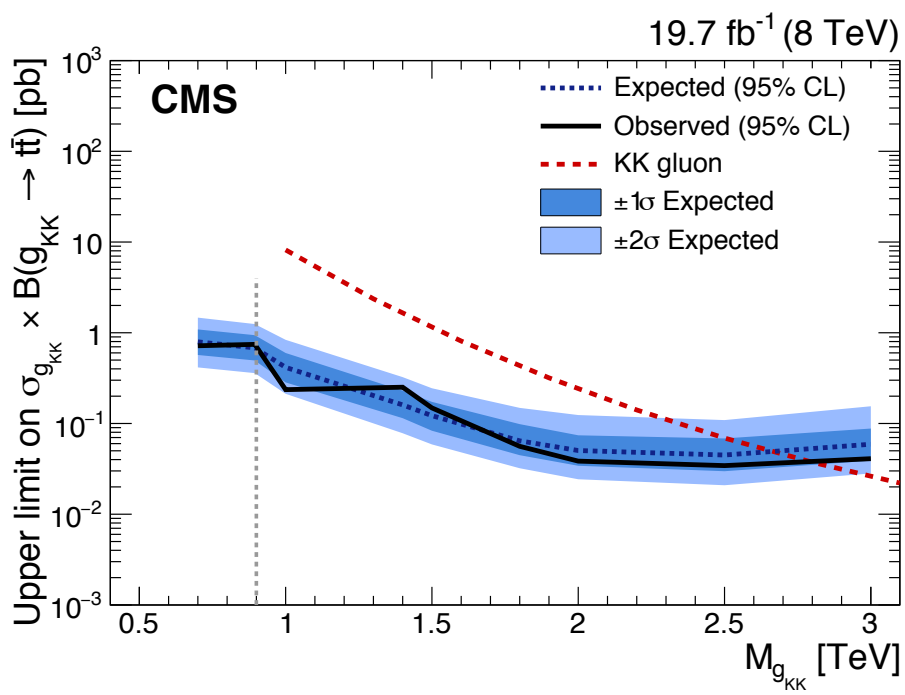




Other Models Results







Systematics

Source of uncertainty	Prior uncertainty	2ℓ	ℓ+jets	Had. channel high-mass	Had. channel low-mass
Integrated luminosity	2.6%	$\oplus$	$\oplus$	$\oplus$	$\oplus$
$t\bar{t}$ cross section	15%	$\oplus$	$\oplus$	$\oplus$	$\oplus$
Single top quark cross section	23%	$\oplus$	$\oplus$		
Diboson cross section	20%	$\oplus$	$\oplus$		
Z+jets cross section	50%	$\oplus$	$\oplus$		
W+jets (light flavor) cross section	9%		$\odot$		
W+jets (heavy flavor) cross section	23%		$\odot$		
Electron+jet trigger	1%		$\odot$		
H_T trigger	2%			$\oplus$	$\oplus$
Four-jet trigger	$\pm 1\sigma(p_T)$				$\odot$
Single-electron trigger	$\pm 1\sigma(p_T, \eta)$	$\odot$			
Single-muon trigger and id	$\pm 1\sigma(p_T, \eta)$	$\oplus$	$\oplus$		
Electron ID	$\pm 1\sigma(p_T, \eta)$	$\oplus$	$\oplus$		
Jet energy scale	$\pm 1\sigma(p_T, \eta)$	$\oplus$	$\oplus$	$\oplus$	$\oplus$
Jet energy resolution	$\pm 1\sigma(\eta)$	$\oplus$	$\oplus$	$\oplus$	$\oplus$
Pileup uncertainty	$\pm 1\sigma$	$\oplus$	$\oplus$	$\oplus$	$\oplus$
b tagging efficiency$^{(\dagger)}$	$\pm 1\sigma(p_T, \eta)$	$\oplus$	$\oplus$		$\oplus$
b tagging mistag rate $^{(\dagger)}$	$\pm 1\sigma(p_T, \eta)$	$\oplus$	$\oplus$		$\oplus$
CA8 subjet b tagging	unconstrained			$\odot$	
CA8 t tagged jet efficiency	unconstrained		$\oplus$	$\oplus$	
CA8 t-tagged jet mistag	$\pm 25\%$		$\odot$		
CA15 t-tagged jet efficiency	$\pm 1\sigma(p_T, \eta)$				$\odot$
QCD multijet background	sideband			$\odot$	$\odot$
PDF uncertainty	$\pm 1\sigma$	$\oplus$	$\oplus$	$\oplus$	$\oplus$
$t\bar{t}$ ren. and fact. scales	$4Q^2$ and $0.25Q^2$	$\oplus$	$\oplus$	$\oplus$	$\oplus$
W+jets ren. and fact. scales	$4Q^2$ and $0.25Q^2$		$\odot$		
W+jets matching scale μ	2μ and 0.5μ		$\odot$		
MC statistical uncertainty		$\odot$	$\odot$	$\odot$	$\odot$

$^{(\dagger)}$ AK5 and CA15 subjets

Likelihood Fit Results

Process	Best fit value	Prior uncertainty	Posterior uncertainty
$t\bar{t}$	0.99	15%	2.1%
W+jets (light flavor)	0.99	9%	5.0%
W+jets (c flavor)	1.06	23%	21%
W+jets (b flavor)	0.95	23%	18%
Single top quark	0.83	23%	22%
Z+jets	1.72	50%	36%
Diboson	1.02	20%	19%
CA8 t-tagged jets scale factor	0.94	unconstrained	3%
CA8 subjet b tagging scale factor	1.3	unconstrained	1.5

Cross Section Limits

	$Z', \Gamma_{Z'}/M_{Z'} = 1\%$			
$M_{Z'}$ (TeV)	Expected (pb)	Expected range ($\pm 1\sigma$) (pb)	Expected range ($\pm 2\sigma$) (pb)	Observed (pb)
0.75	0.61	0.89 — 0.43	1.3 — 0.32	0.86
1.0	0.18	0.27 — 0.13	0.37 — 0.099	0.088
1.25	0.082	0.12 — 0.058	0.18 — 0.042	0.14
1.5	0.04	0.057 — 0.028	0.089 — 0.02	0.041
2.0	0.013	0.02 — 0.009	0.029 — 0.0067	0.011
3.0	0.0086	0.013 — 0.0059	0.021 — 0.0043	0.0059
	$Z', \Gamma_{Z'}/M_{Z'} = 10\%$			
$M_{Z'}$ (TeV)	Expected (pb)	Expected range ($\pm 1\sigma$) (pb)	Expected range ($\pm 2\sigma$) (pb)	Observed (pb)
0.75	0.83	1.2 — 0.57	1.8 — 0.42	0.89
1.0	0.26	0.37 — 0.18	0.53 — 0.14	0.13
1.25	0.13	0.19 — 0.09	0.26 — 0.067	0.22
1.5	0.063	0.089 — 0.044	0.13 — 0.03	0.064
2.0	0.023	0.034 — 0.016	0.055 — 0.011	0.018
3.0	0.023	0.036 — 0.016	0.055 — 0.011	0.017
	RS KK gluon			
$M_{g_{KK}}$ (TeV)	Expected (pb)	Expected range ($\pm 1\sigma$) (pb)	Expected range ($\pm 2\sigma$) (pb)	Observed (pb)
0.7	1.7	2.5 — 1.2	3.8 — 0.84	3.5
1.0	0.42	0.6 — 0.28	0.84 — 0.21	0.24
1.4	0.16	0.23 — 0.11	0.32 — 0.078	0.25
1.5	0.12	0.17 — 0.083	0.24 — 0.059	0.15
1.8	0.064	0.098 — 0.045	0.15 — 0.032	0.056
2.0	0.05	0.074 — 0.034	0.12 — 0.024	0.038
2.5	0.045	0.068 — 0.03	0.11 — 0.021	0.034
3.0	0.059	0.088 — 0.039	0.15 — 0.028	0.041