Bundesministerium für Bildung und Forschung

Universität Hamburg
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Search for heavy resonances decaying to $t\bar{t}$ and tb

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on behalf of the CMS Collaboration

BOOST 2013

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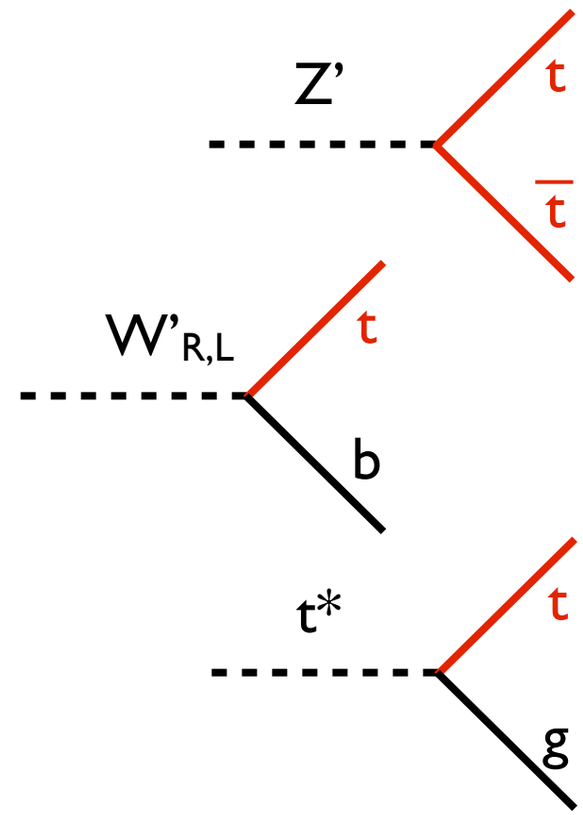
Overview

The top-quark and new physics

- high mass of the top quark is still intriguing
- special rôle of the top in new physics models
- Tevatron forward-backward asymmetry still unresolved issue

[see also: talk by Rebekka Höing]

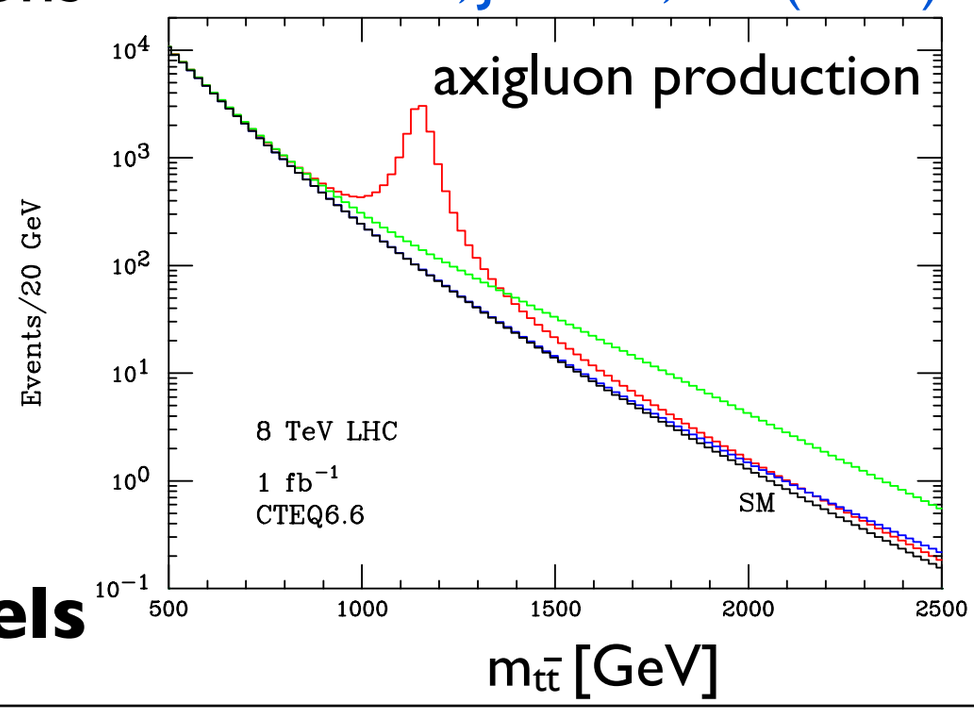


Top quark resonances in BSM Models

- extended gauge sectors: Z', W' and G' bosons
- top-color condensates
- warped extra dimensions: Kaluza-Klein excitations
- compositeness
- ...

⇒ rich final states, numerous channels

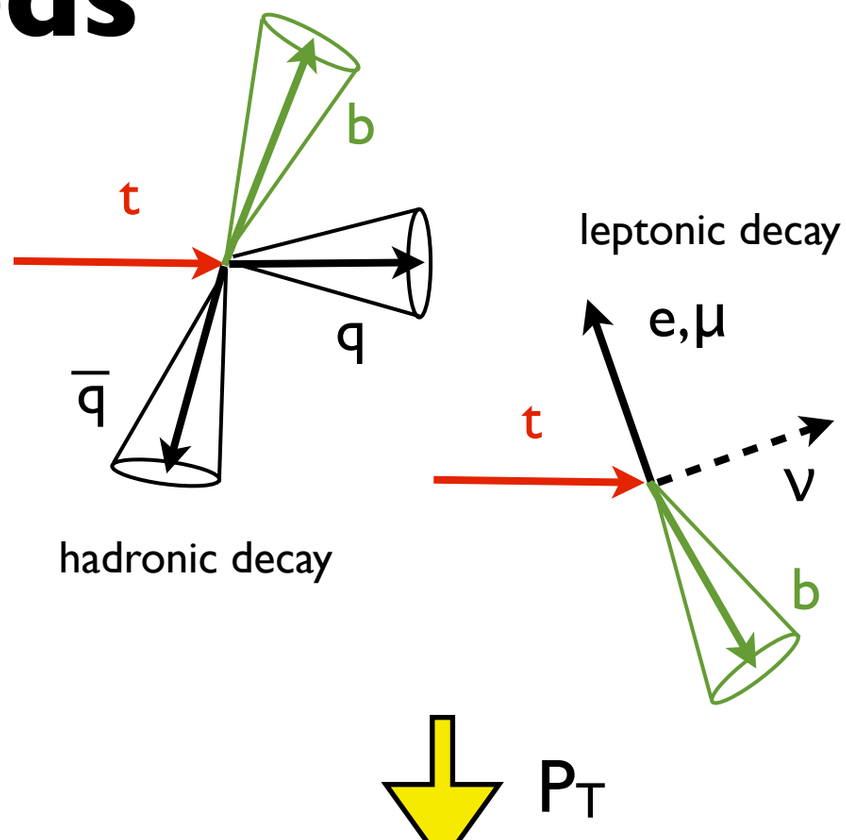
Y. Bai et al, JHEP03,003 (2011)



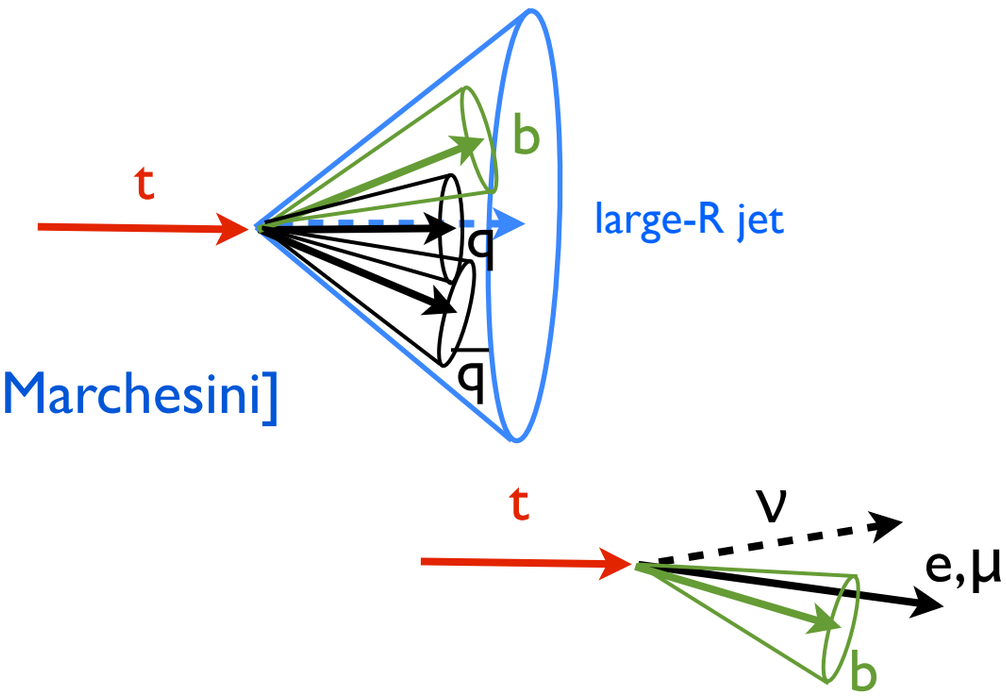
Analysis Methods

strategies for different mass regimes

- low mass resonances (< 1 TeV)
  - resolved final state objects
  - many jets, isolated leptons
  - solve combinatorics for resonance mass reconstruction, using known masses as constraints



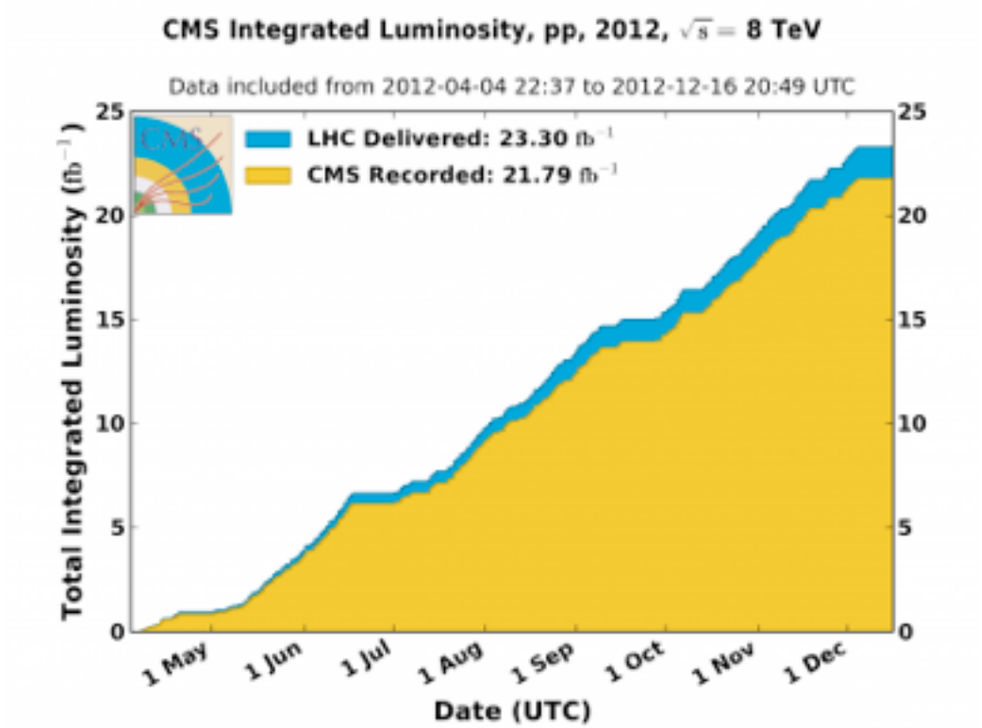
- high mass resonances (> 1 TeV)
  - merged final state objects
  - less jets, non-isolated leptons
  - special requirements: top tagging, b-tagging in dense environments [talk by Ivan Marchesini]
  - unambigious selection of top quark helps in the reconstruction of the resonance mass

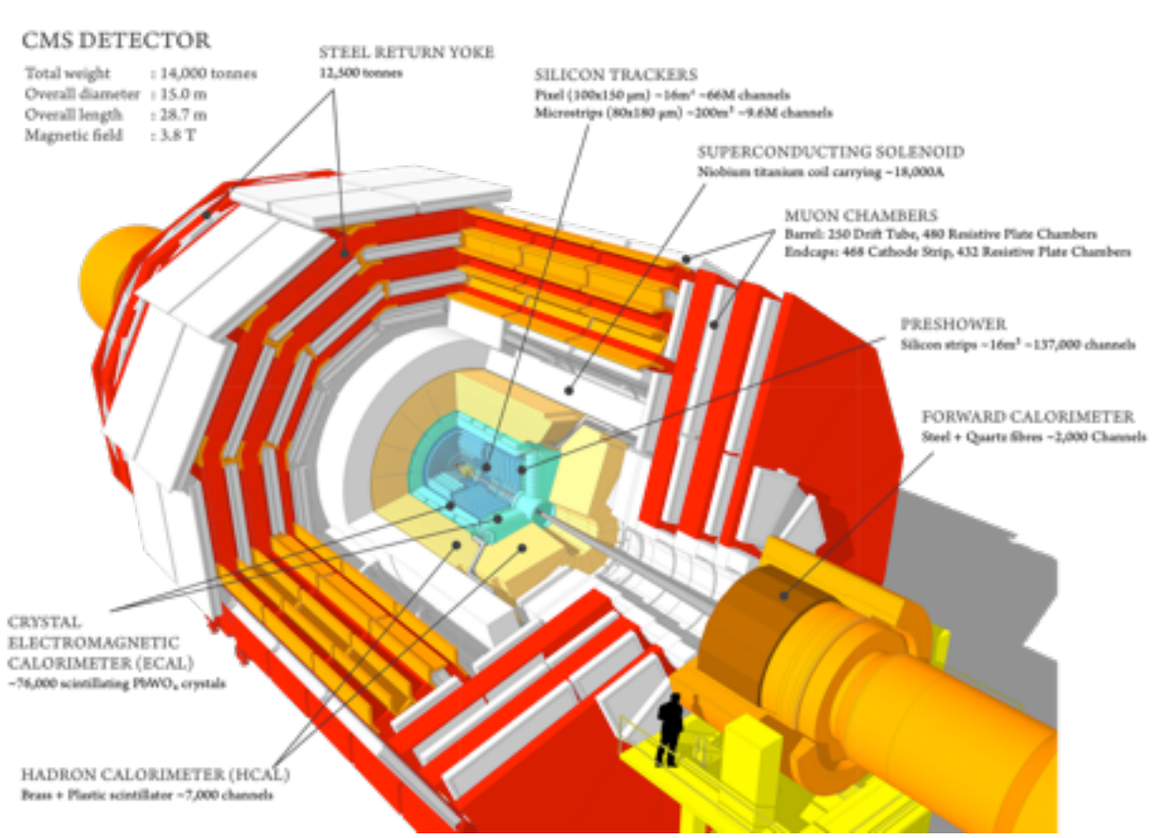


Analyses Overview

Analyses of the full 2012 dataset at $\sqrt{s}$ = 8 TeV

- resonances decaying to t+jet in lepton+jets (t* search) [CMS PAS B2G-12-014]
- narrow t+b resonances in lepton+jets (W' search) [CMS PAS B2G-12-010]
- resonances in the $t\bar{t}$ invariant mass spectrum in lepton+jets (resolved and boosted Z' searches) [CMS PAS B2G-12-006]
- resonances in the $t\bar{t}$ invariant mass spectrum in all-hadronic channel (boosted Z' search) [CMS PAS B2G-12-005]



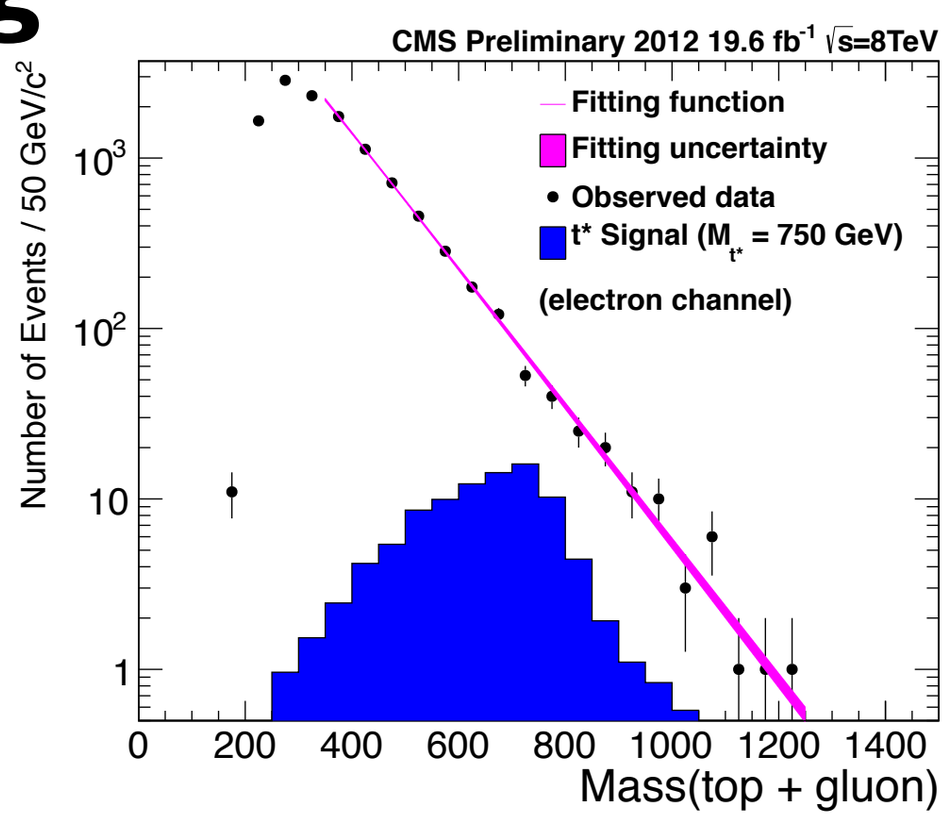


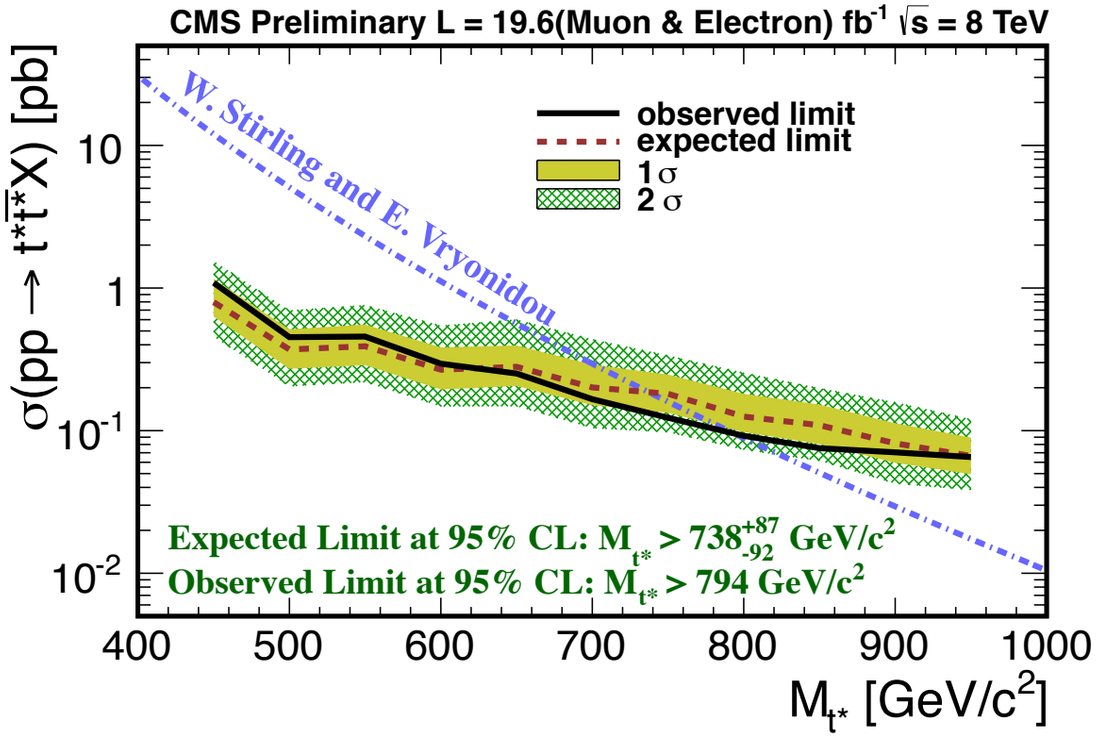
[CMS PAS B2G-12-014]

$t^* \rightarrow t + g$

pair production of excited top quarks

- rich final state: $t\bar{t}$ + ≧ 2 jets
  - analysis performed in lepton+jets channel
  - select isolated lepton + ≧ 6 jets
  - at least on b-tagged jet
- mass reconstruction: using the constraint
  M_{t+g} = m(lνbg) = m(qqbg)
- background: obtained from a fit to the obtained mass spectrum, signal distribution taken from simulation
- no excess observed: excluded spin-3/2 t* resonances below 790 GeV at 95% C.L.



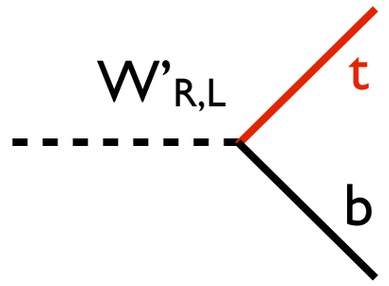


[CMS PAS B2G-12-010]

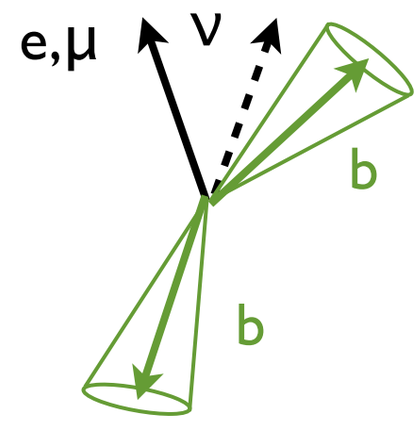
t+b Resonances

search for production of W'→t+b

- consider left- and right-handed W's
  - W'_L: interference with SM W production
  - W'_R: leptonic decay involves ν_R with unknown mass: different branching ratios depending on $M_{\nu R}$



- semi-leptonic analysis:
  - one isolated lepton (e, μ), P_T > 50 GeV
  - 2 jets: P_{T1} > 120 GeV, P_{T2} > 40 GeV
  - one b-tag

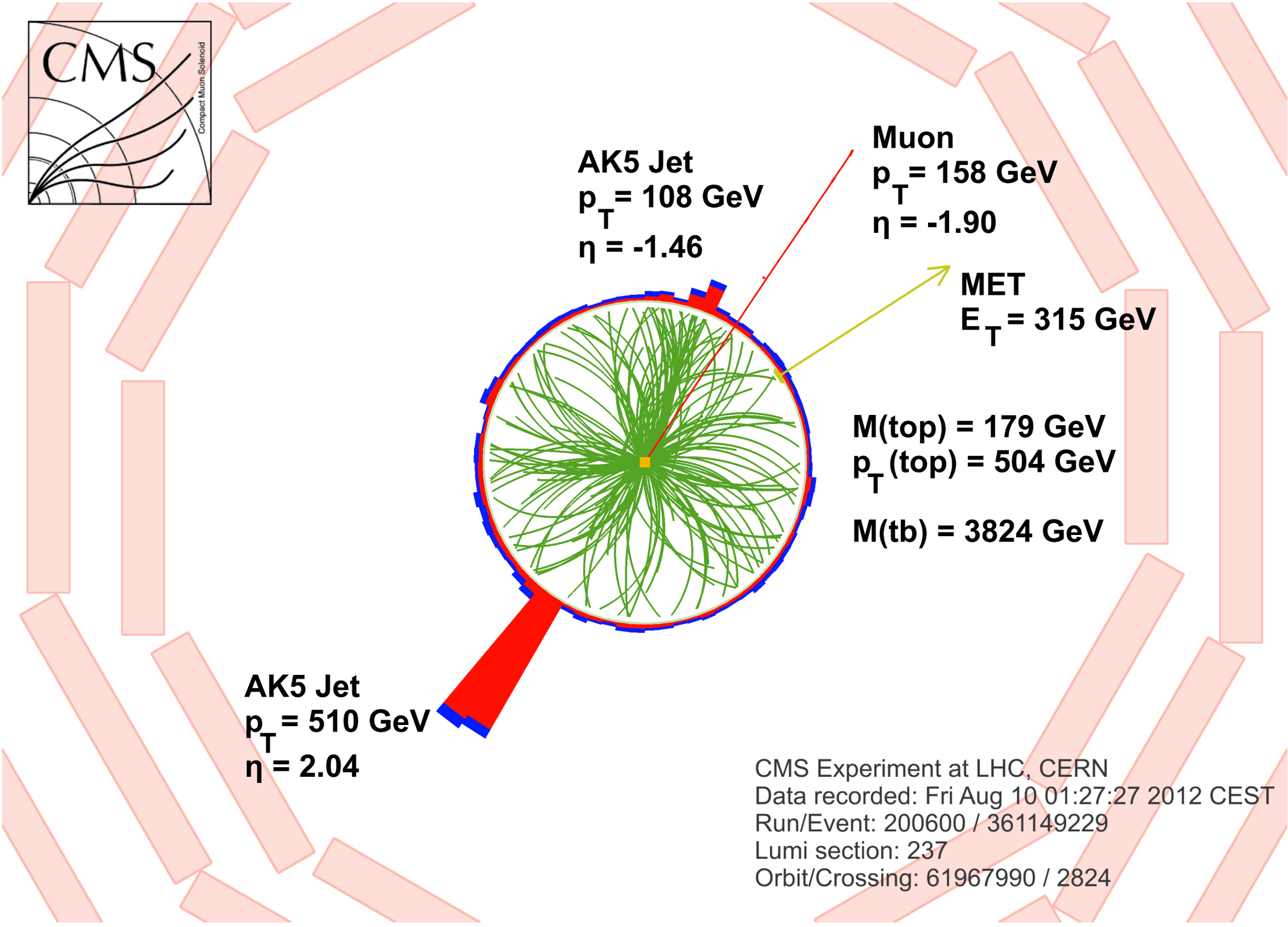


- mass reconstruction:
  - W reconstruction from P_T^{miss} + lepton
  - top reconstruction: combine W with jets, take hypothesis closest to m_{top}
  - M(tb): combine top with remaining highest P_T jet

- background reduction
  - P_T^{top} > 85 GeV
  - $P_T(j_1+j_2)$ > 120 GeV
  - 130 < m_{top} < 210 GeV

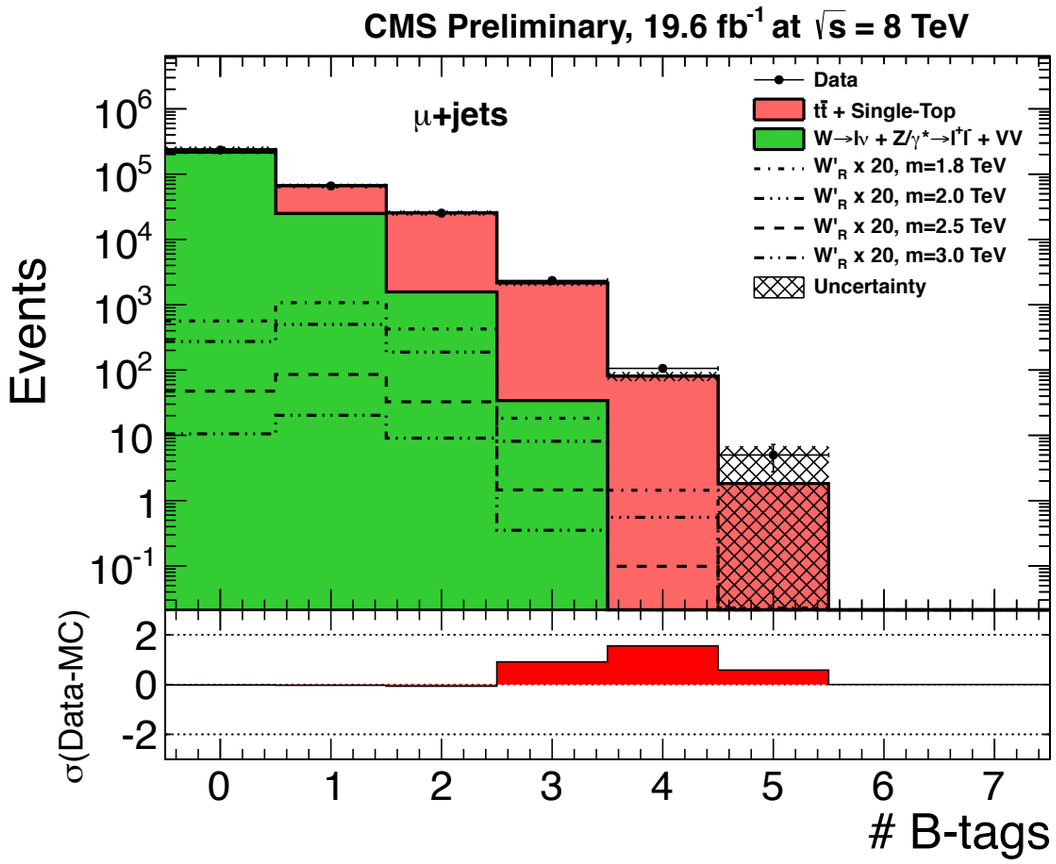
[CMS PAS B2G-12-010]

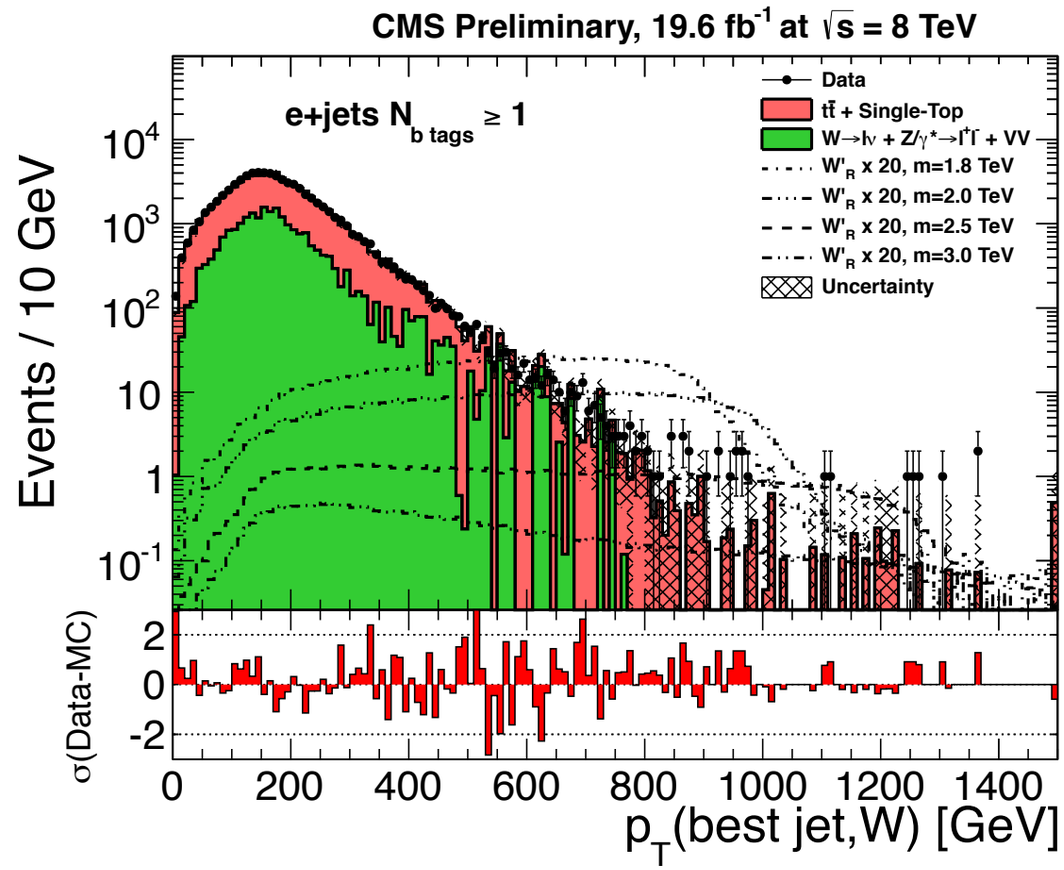
t+b Candidate Event



[CMS PAS B2G-12-010]

t+b: Background Verification





Verification of the W+jets background

- use 0 b-tag sample, little signal contamination
- reconstructed M(t+jet) shape well described by simulation, small differences taken as systematic uncertainty

Top P_T spectrum

- original distribution not well described by simulation
- weights derived using a signal-depleted control region ($N_{jets} \geqq 4$, $N_{b\text{-}jets} \geqq 2$, $400 < M(tb) < 750$ GeV)
- good agreement after reweighting

[CMS PAS B2G-12-010]

t+b Results

M(tb) spectrum

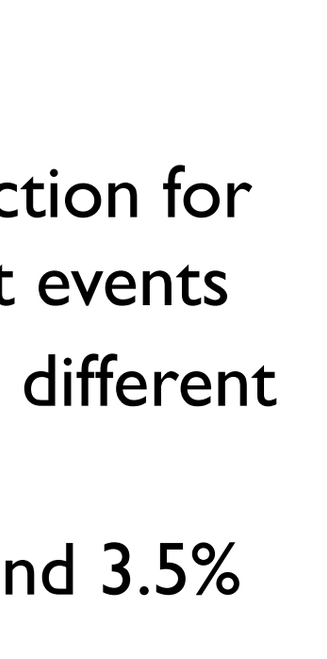
- data consistent with SM prediction for $t\bar{t}$, single top, Z+jet and W+jet events
- visible peaks for W' signals for different mass hypothesis
- signal selection efficiency around 3.5%

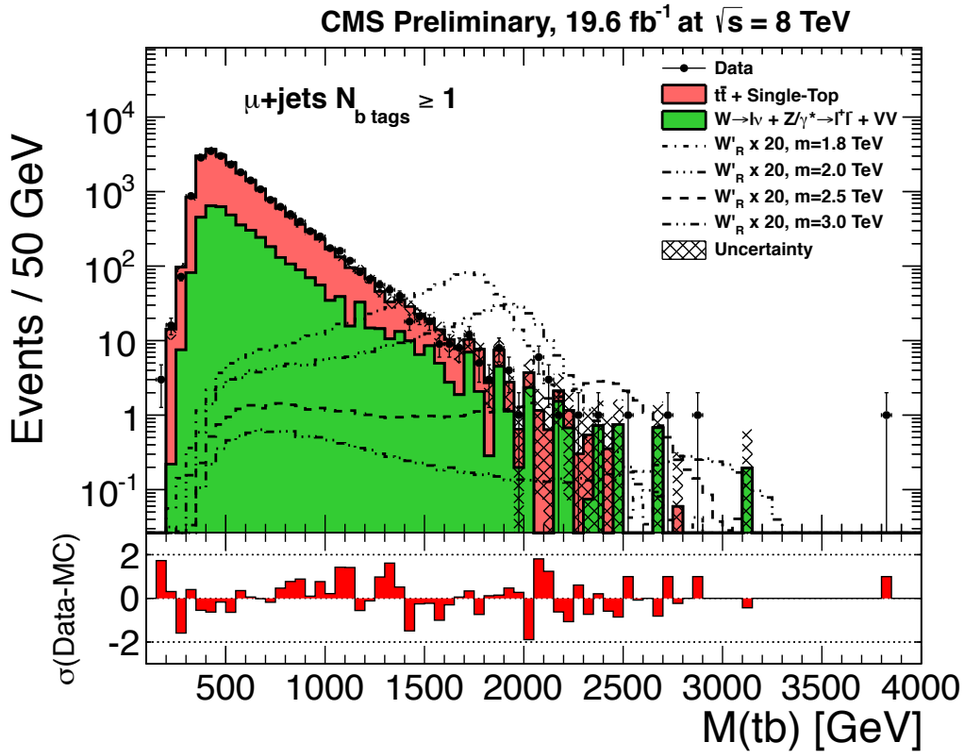
limits

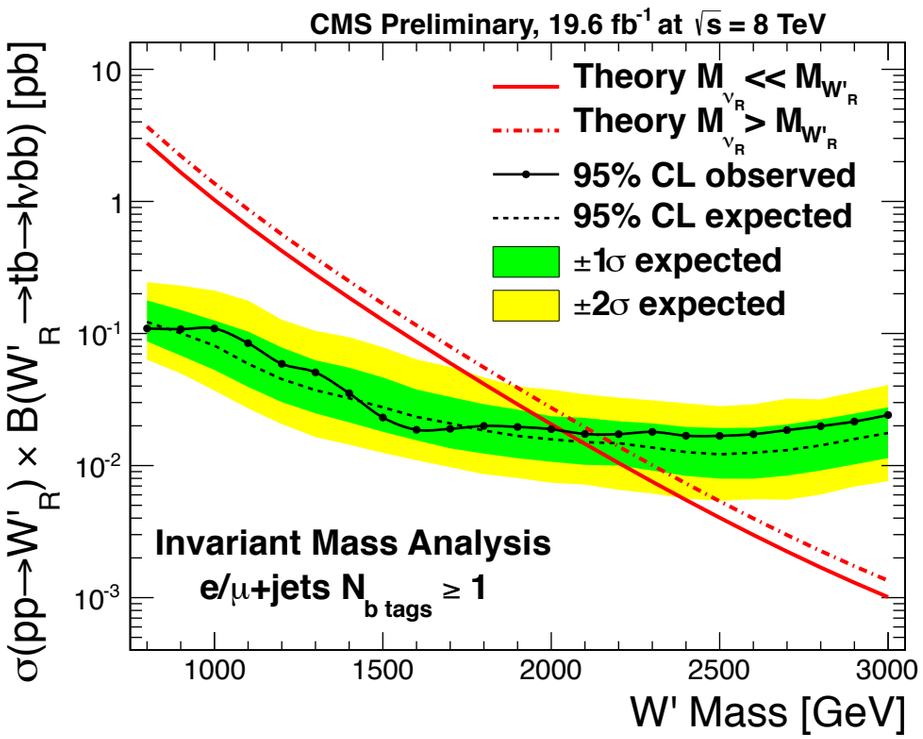
- $\sigma \times BR < 0.1$ pb at 1 TeV
- $\sigma \times BR < 0.02$ pb above 1.5 TeV
- $M(W'_R) > 2.03$ TeV (2.09 TeV expected) at 95% C.L.

all-hadronic analysis

- difficult because of huge background
- good progress using advanced tagging techniques

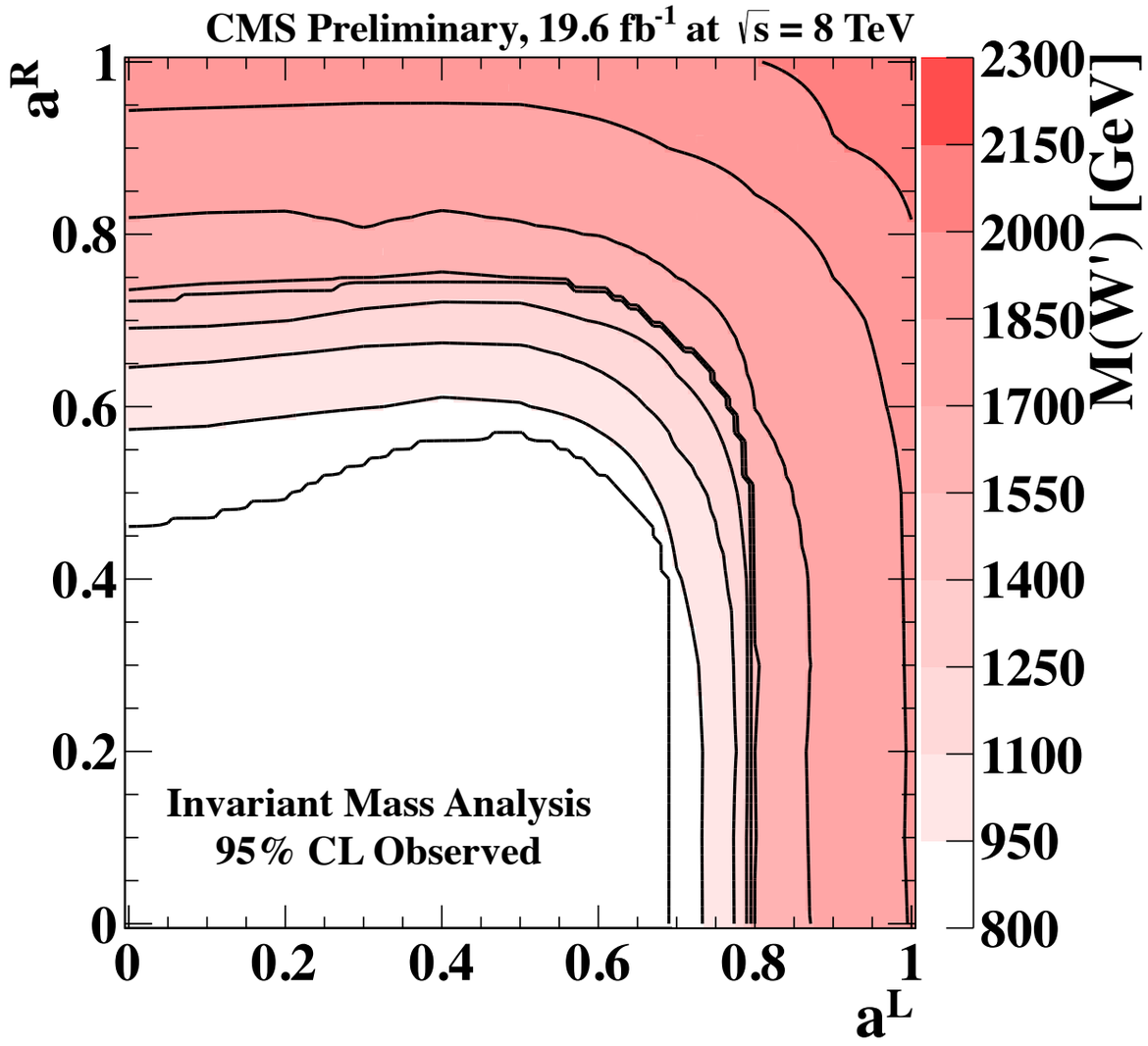


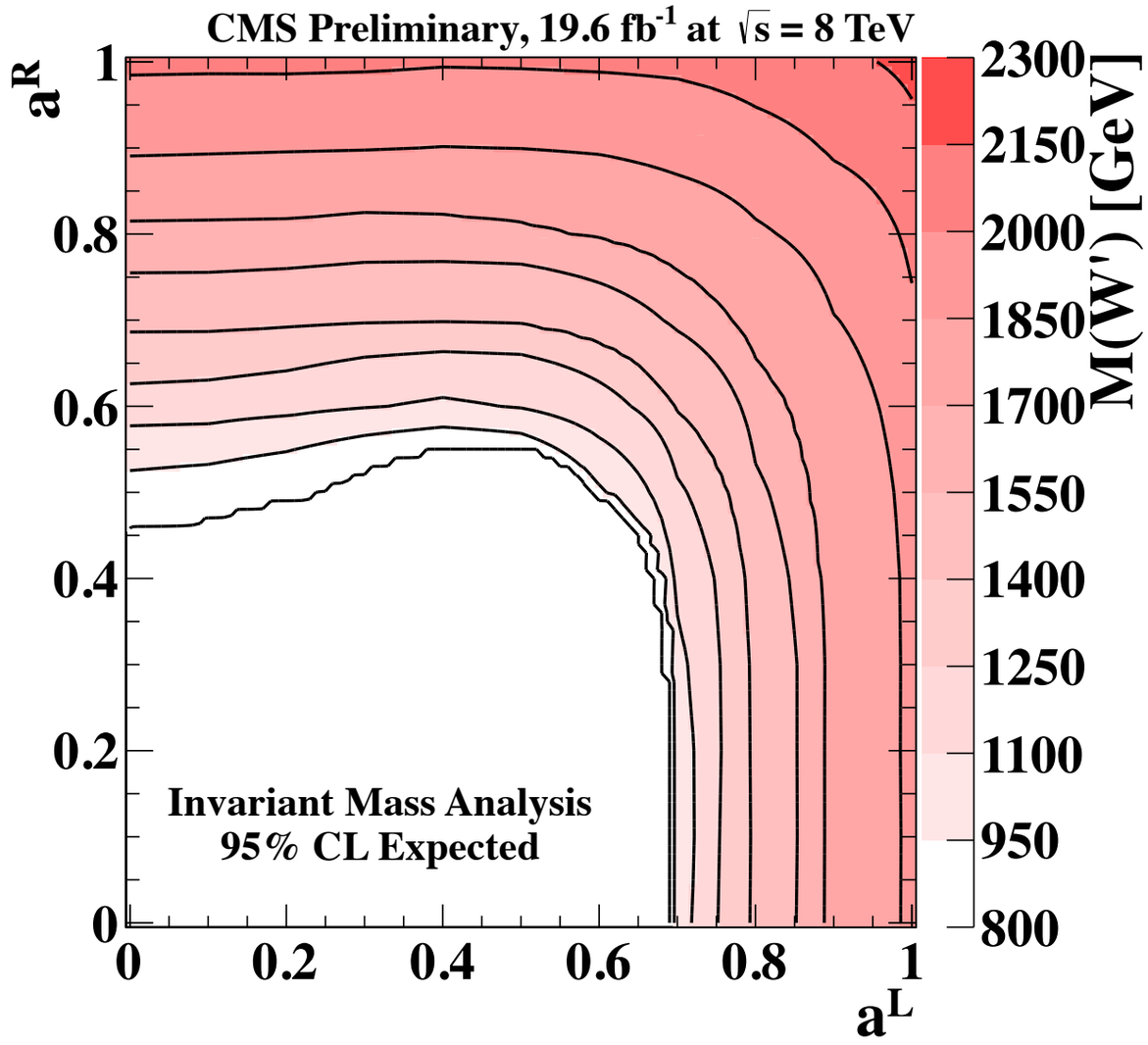




[CMS PAS B2G-12-010]

t+b Resonances





Contour plots of M(W') in the (a^L, a^R) plane

- contours where the 95% C.L. limit equals the predicted cross section

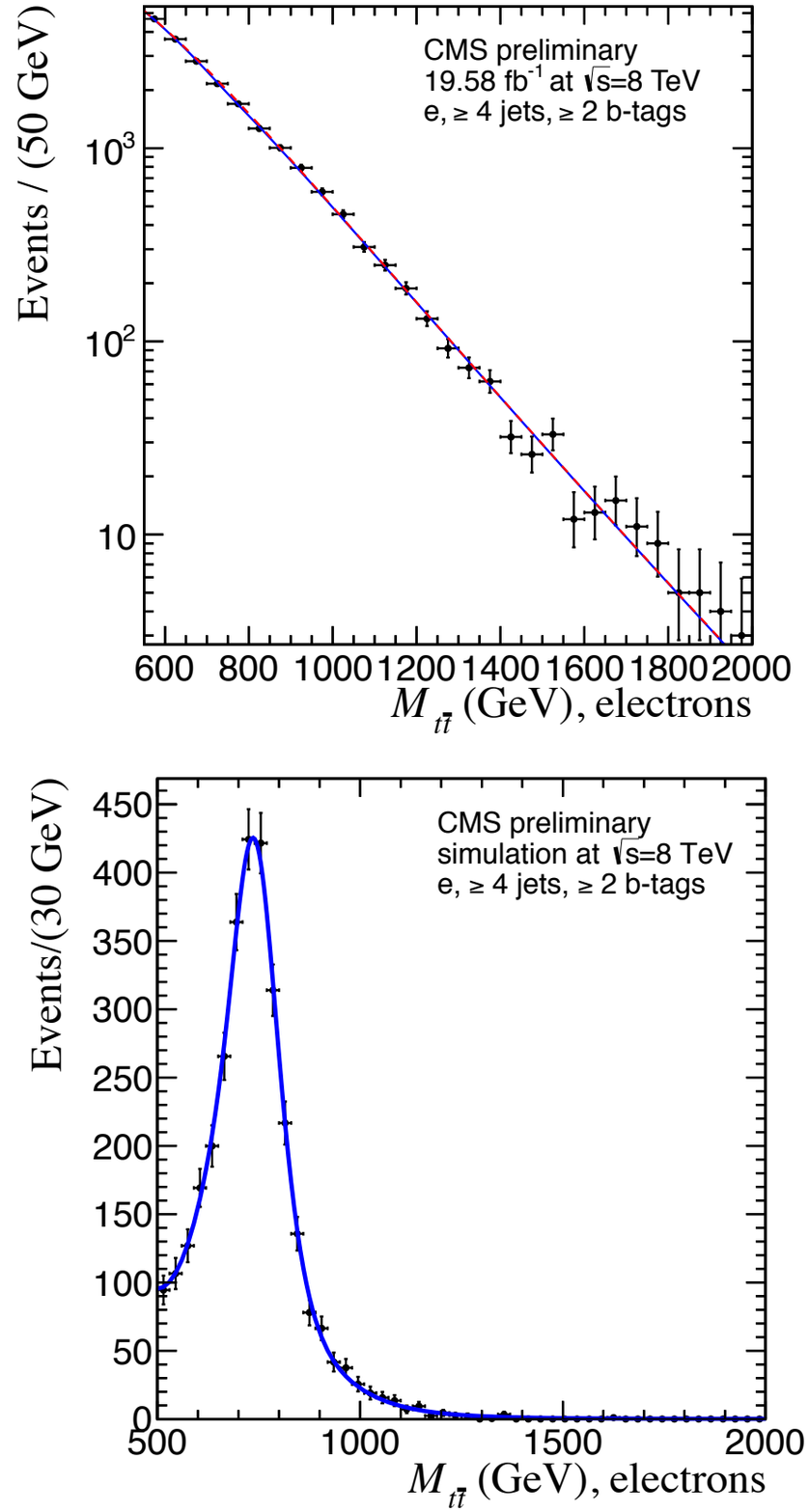
$$\mathcal{L} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_w \overline{f}_i \gamma_\mu \left(a^R_{f_i f_j}(1+\gamma^5) + a^L_{f_i f_j}(1-\gamma^5) \right) \mathrm{W}'^{\mu} f_j + \mathrm{H.c.}$$

[CMS PAS B2G-12-006]

$t\bar{t}$ Resonances (Low Mass)

Threshold lepton+jet analysis

- selection: isolated lepton and four or more jets with R=0.5, one or more b-tagged jets
  - reconstruct neutrino from missing transverse momentum
  - $t\bar{t}$-system: take solution which minimizes $\chi^2 = \chi^2_{lep} + \chi^2_{had} + \chi^2_{W,had} + \chi^2_{pt}$
- four categories: e/μ channels, N_{btag} = 1 or ≧ 2
- fit $m_{t\bar{t}}$ spectrum to data, parametrisation validated with simulated $t\bar{t}$ events
- templates for various signal hypothesis, superposition of Gaussian kernels
- fits performed simultaneously for all four categories
- absence of signal validated with pseudo-experiments



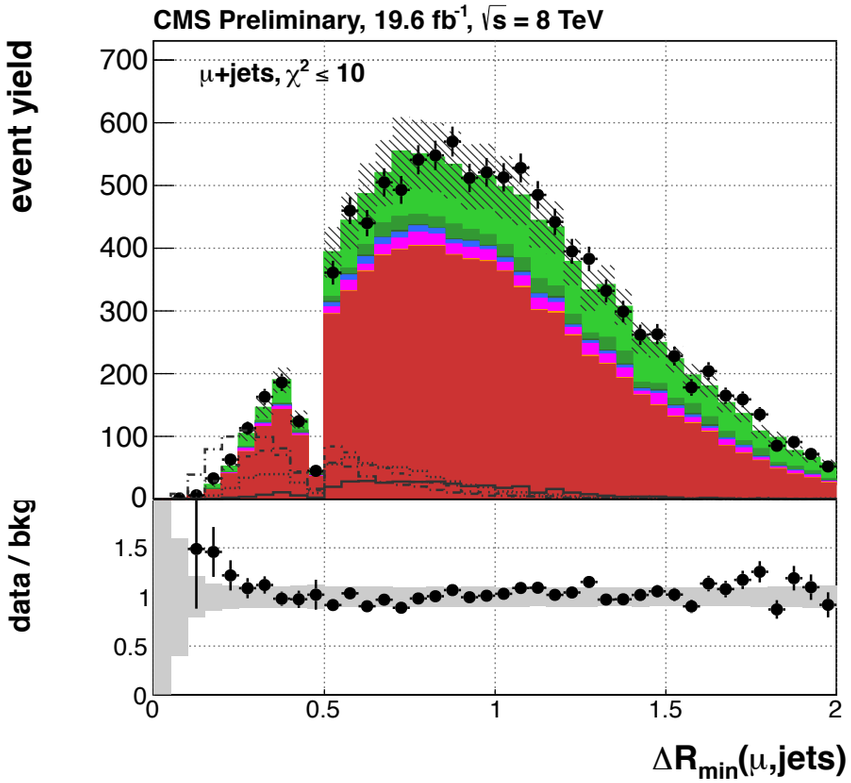
[CMS PAS B2G-12-006]

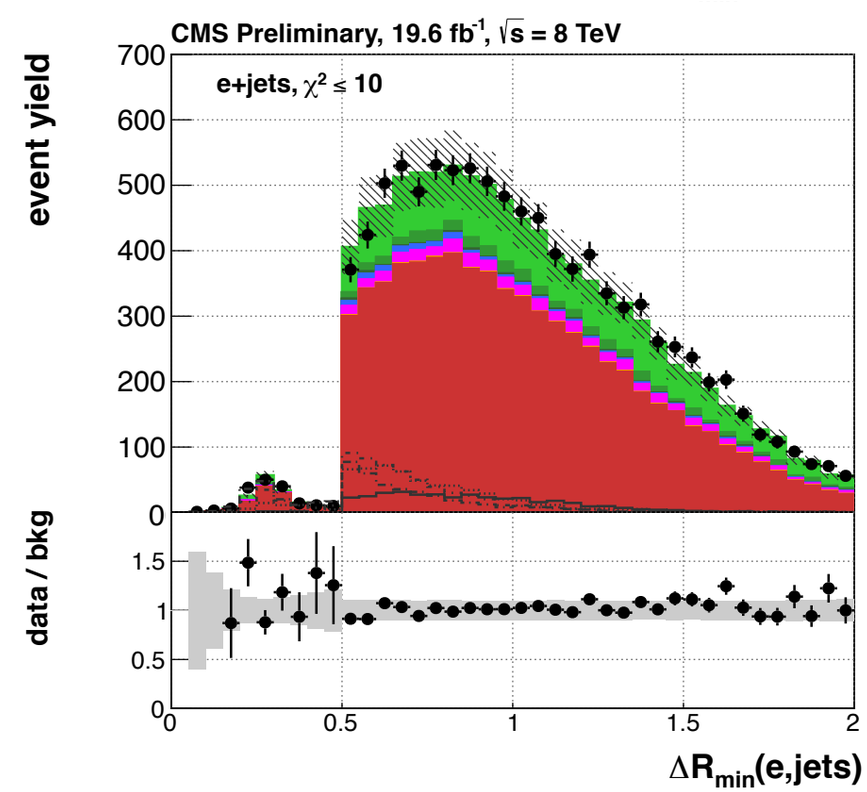
$t\bar{t}$ Resonances (High Mass)

Boosted lepton+jet analysis

- 2 or more jets with P_T > 150 and 50 GeV
  - ak5 jets, no substructure
- missing transverse momentum from neutrino, P_T^{miss} > 50 GeV
- $P_T^{miss} + P_T^{lep}$ > 150 GeV
- non-isolated lepton, $P_T^{e,\mu}$ > 35 and 45 GeV
- special selection using ΔR(lepton,jet) and p_T^{rel} to retain sensitivity in boosted region
- ΔR(lepton,jet) > 0.5 or p_T^{rel} > 25 GeV
- additional topological cut for the electron channel:

$$\left|\Delta\phi\left(\mathrm{e\ or\ j}, E_{\mathrm{T}}^{\mathrm{miss}}\right)\right| - 1.5 < \frac{1.5\ E_{\mathrm{T}}^{\mathrm{miss}}}{75\ \mathrm{GeV}}$$





[CMS PAS B2G-12-006]

Top Reconstruction

- reconstruction of the $t\bar{t}$-system

  assign jets to the leptonic or hadronic top candidate

  - allow for final states with 2 or more jets
  - assign jets to hadronic or leptonic decay
  - choose hypothesis with minimum

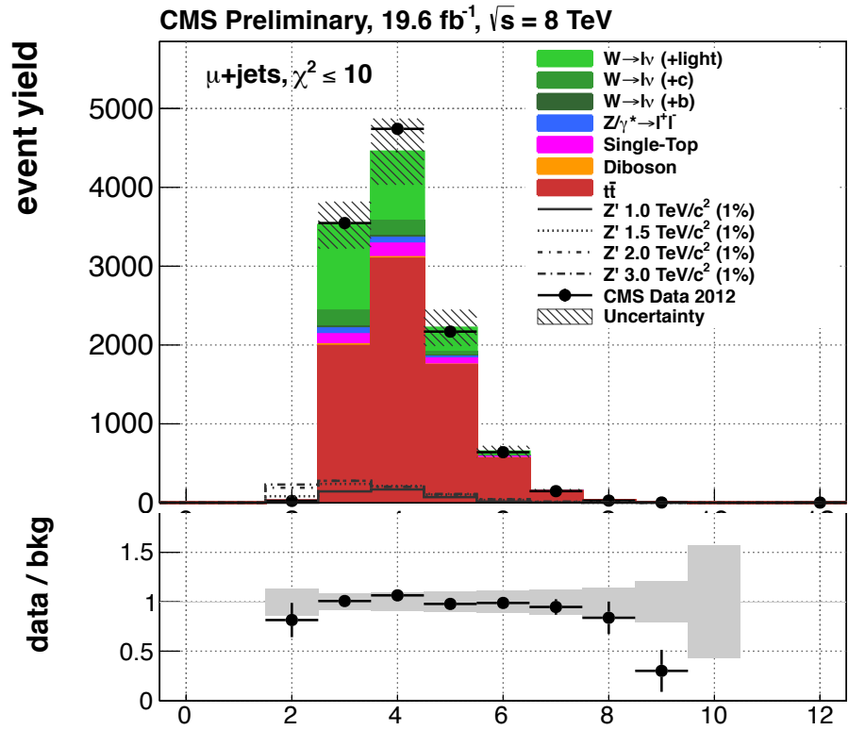
    $\chi^2 = \chi^2_{lep} + \chi^2_{had}$

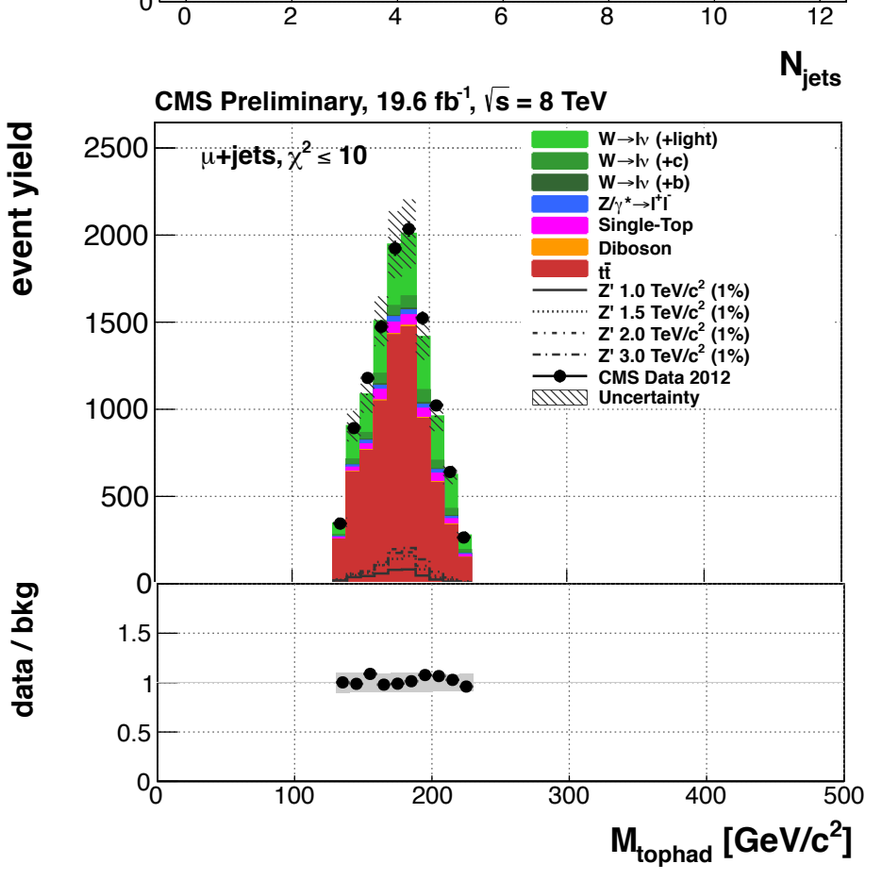
    optimized for boosted events
  - select events with $\chi^2 < 10$

    rejects large fraction of the W+jets background, while keeping the signal efficiency high (7-13% for 0.5-1.5 TeV)

- b-tagging

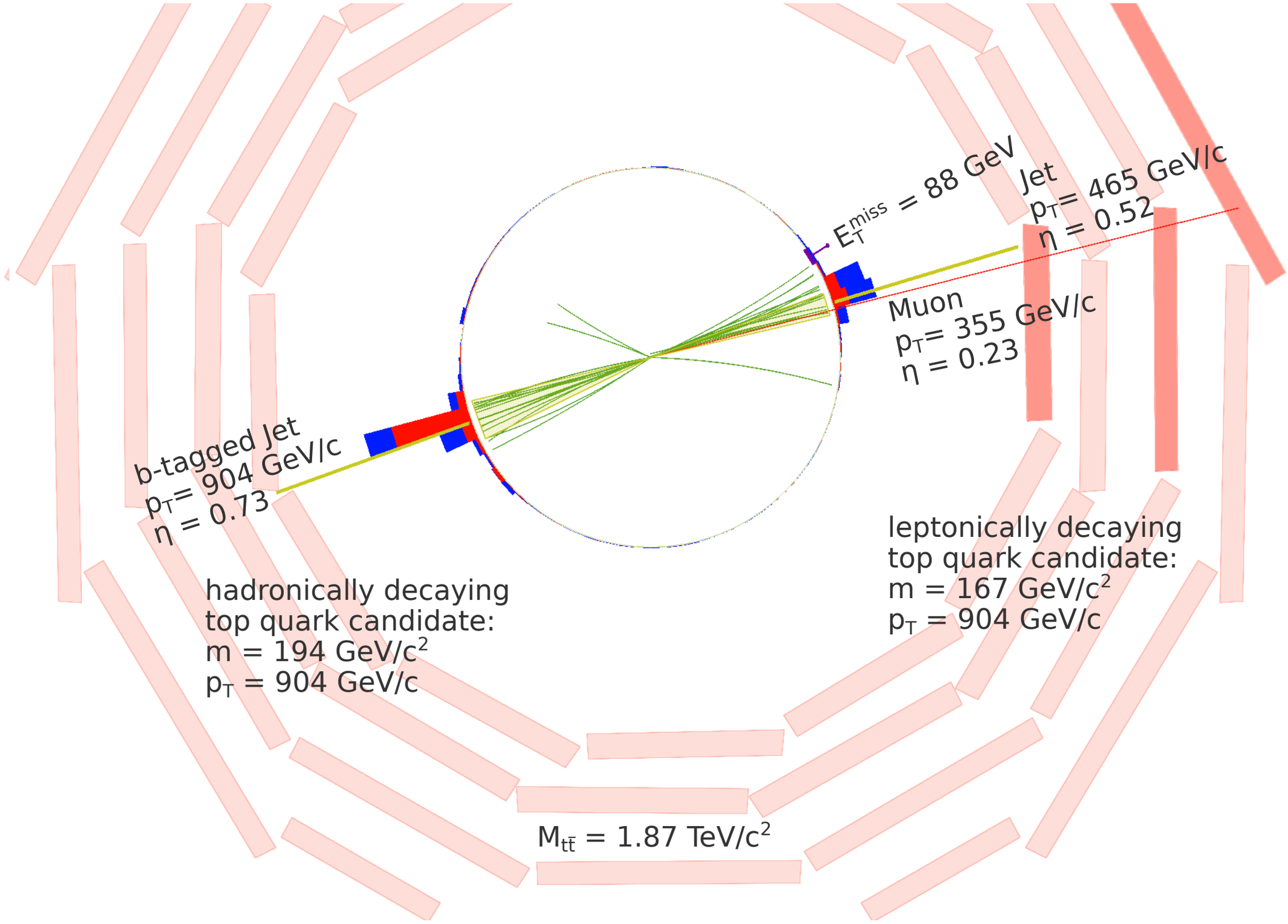
  split events according to number of b-tagged jets





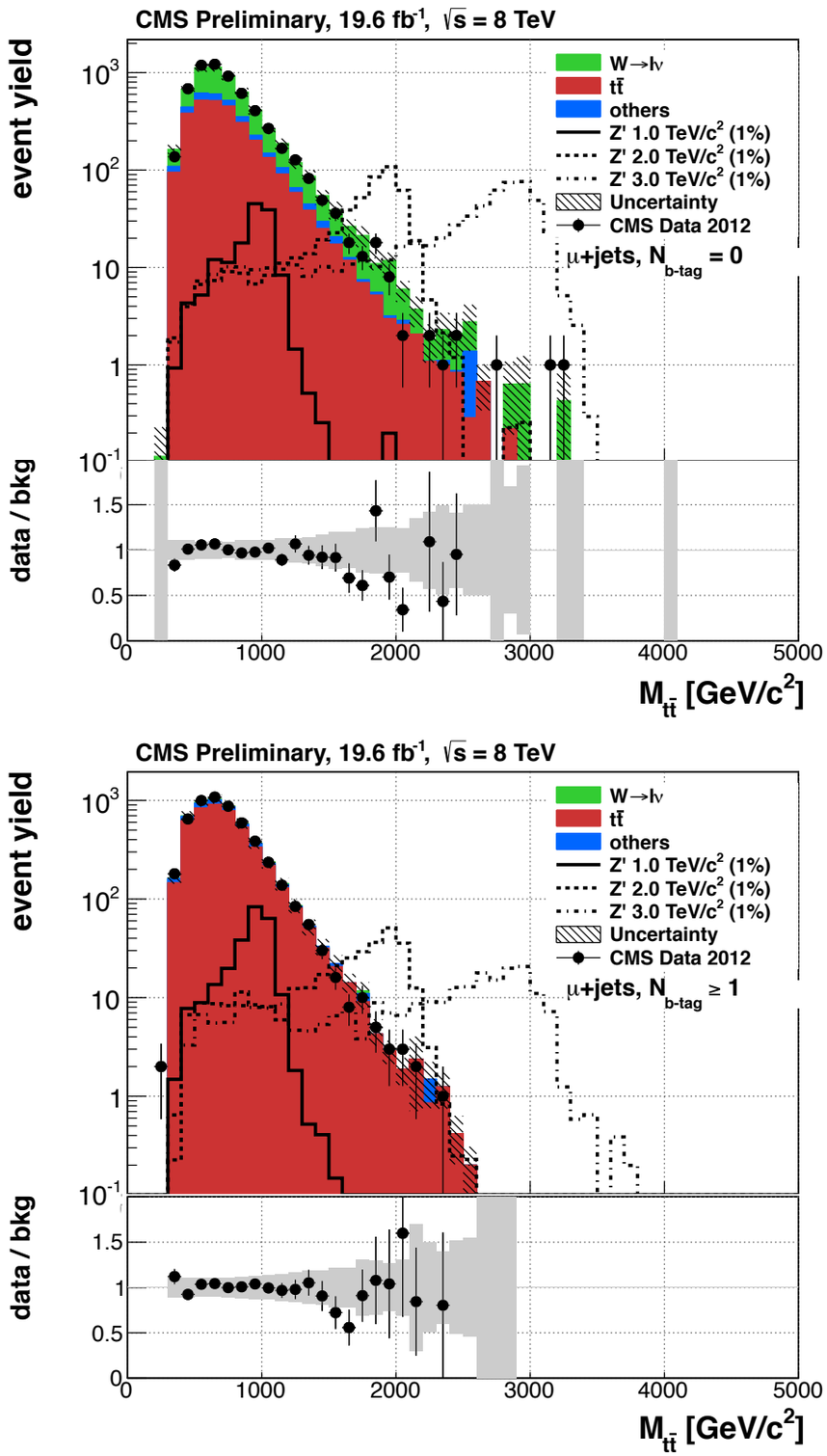
[CMS PAS B2G-12-006]

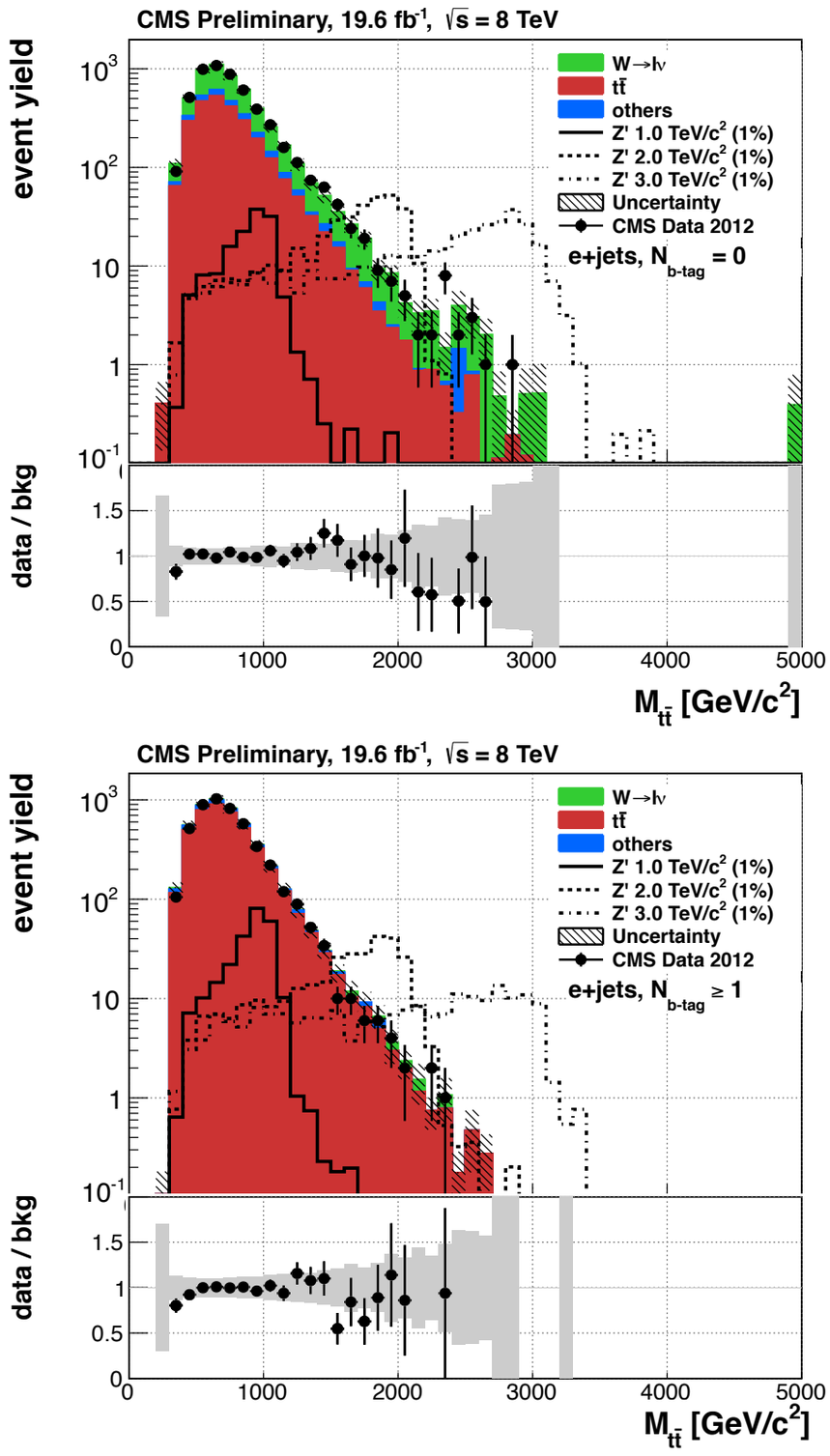
Candidate Event



[CMS PAS B2G-12-006]

Mass Reconstruction





Spectra of the reconstructed mass of the $\bar{t}t$-system

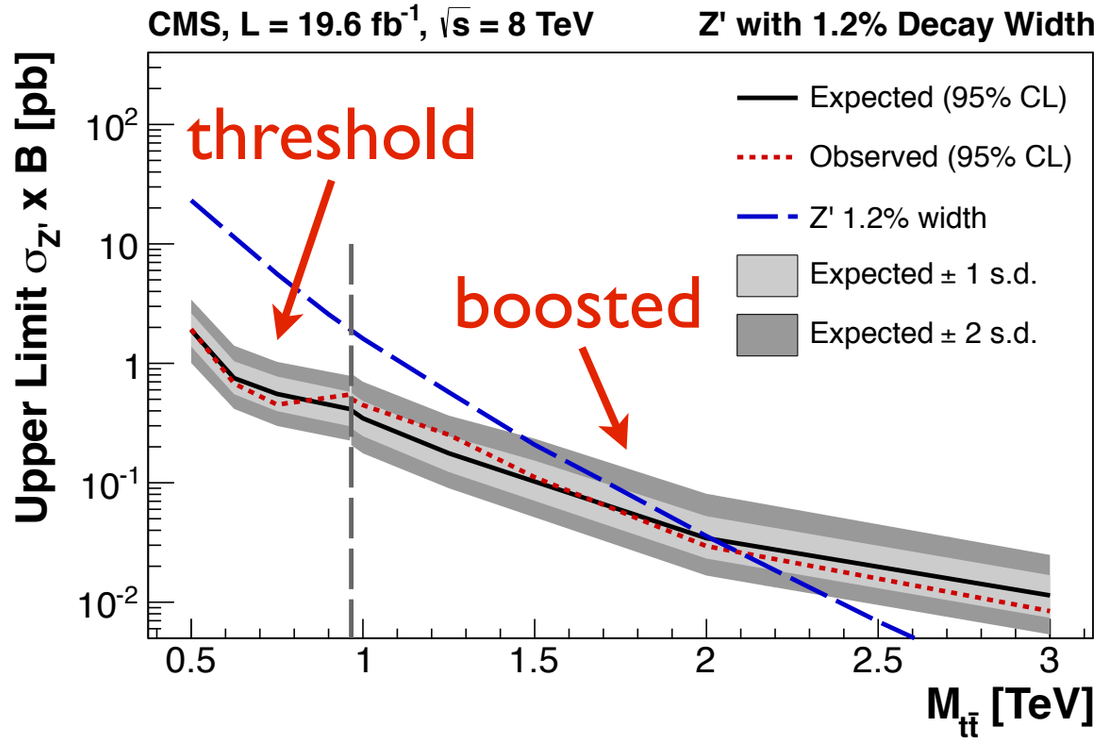
- four categories: e/μ, $N_{b\text{-}tag}$ =0 / ≧1
- Dominant uncertainties
  - variation of ren., fac. and matching scales in $\bar{t}t$ and W+jets samples
  - PDF
  - JES

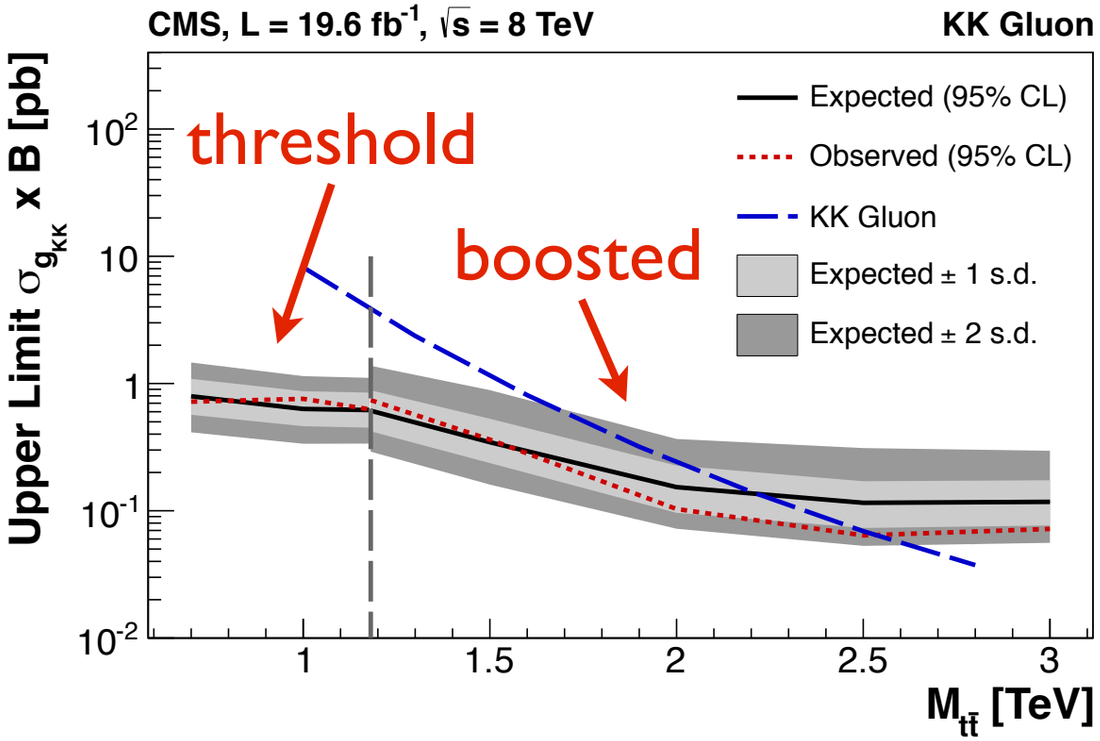
[CMS PAS B2G-12-006]

$t\bar{t}$ Resonances: Limits

Combined low and high mass

- extended coverage 0.5 - 3 TeV in m_{tt} through combining two analyses
- threshold analysis higher sensitivity at < 1 TeV, boosted analysis takes over at ~1 TeV
- narrow (wide) Z' models excluded at 95% CL for masses below 2.1 (2.7) TeV
- mass limit for KK gluons: 2.5 TeV
- upper limit of 0.03 pb on cross section × BR for masses > 2 TeV for narrow resonances



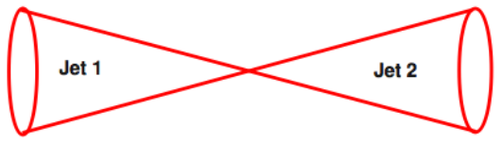


[CMS PAS B2G-12-005]

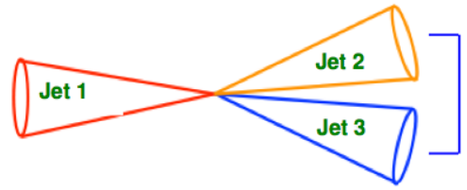
$t\bar{t}$ Resonances: All-hadronic

All-hadronic analysis

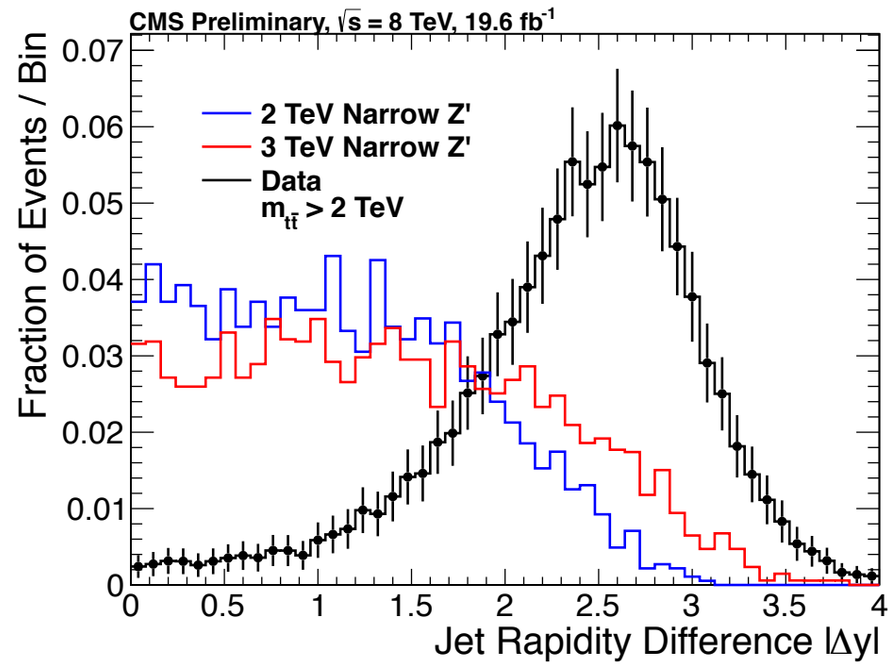
- 2-jet selection, CA jets with R=0.8
  - $P_T^{jet} > 400$ GeV
  - $|\Delta\Phi| > \pi/2$
  - $|\Delta y| < 1$
- sensitivity of 1+1 events one order of magnitude better than 1+2 events
- require top tag on both jets
- reconstruction of $t\bar{t}$-system in fully merged final-states
- main background: QCD
  - determined from data
  - cross check misidentification rate with 1+2-type events

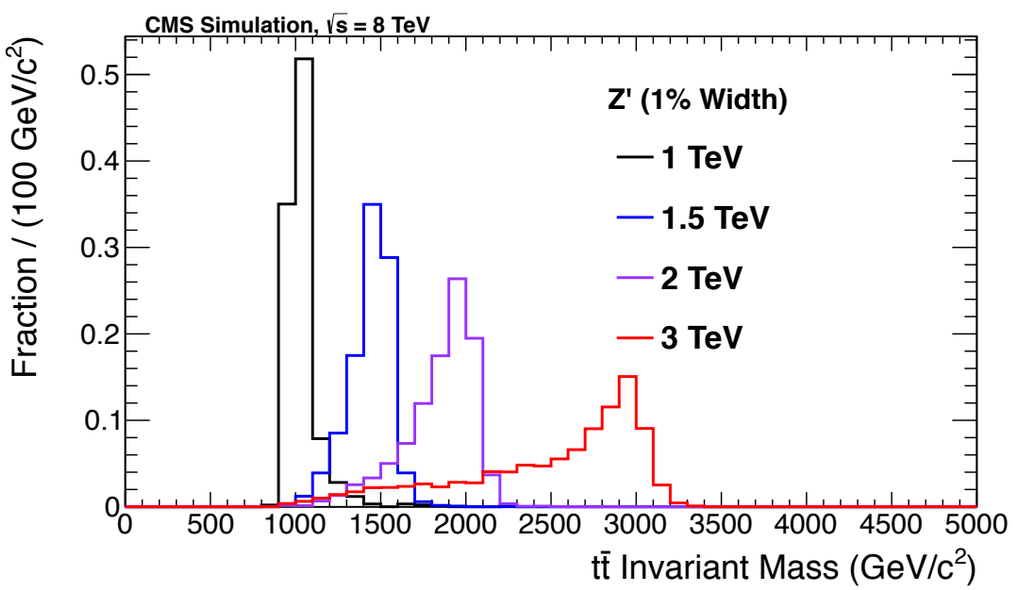


type 1+1



type 1+2





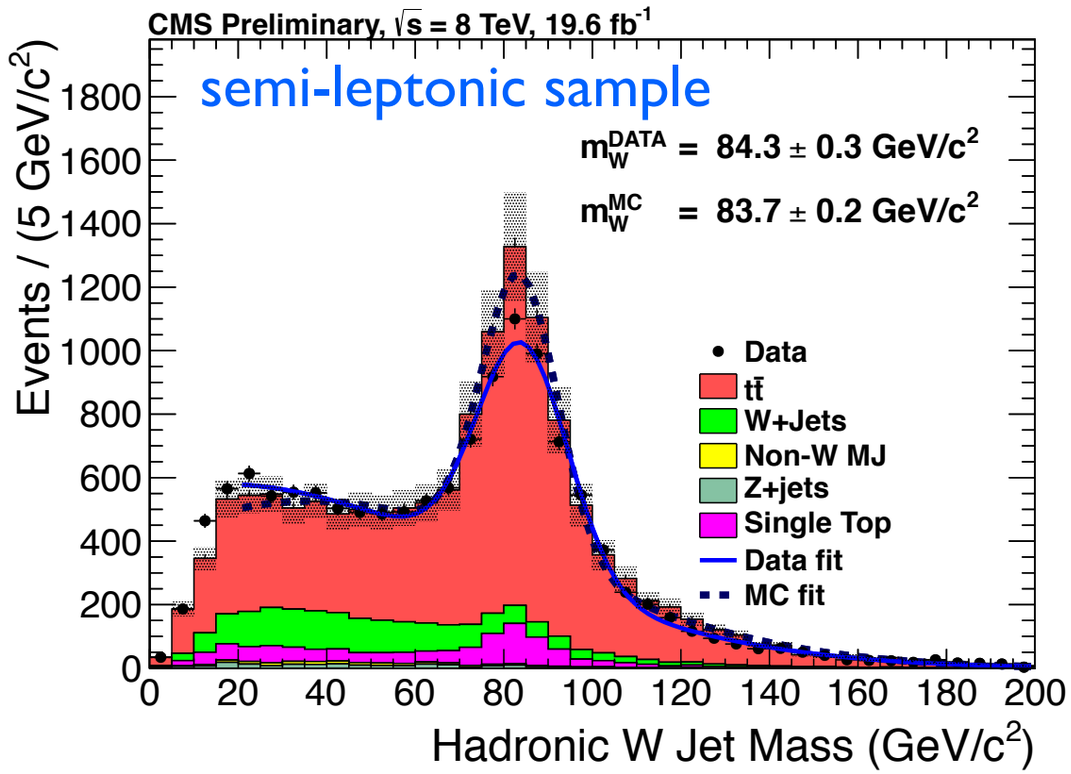
[CMS PAS B2G-12-005]

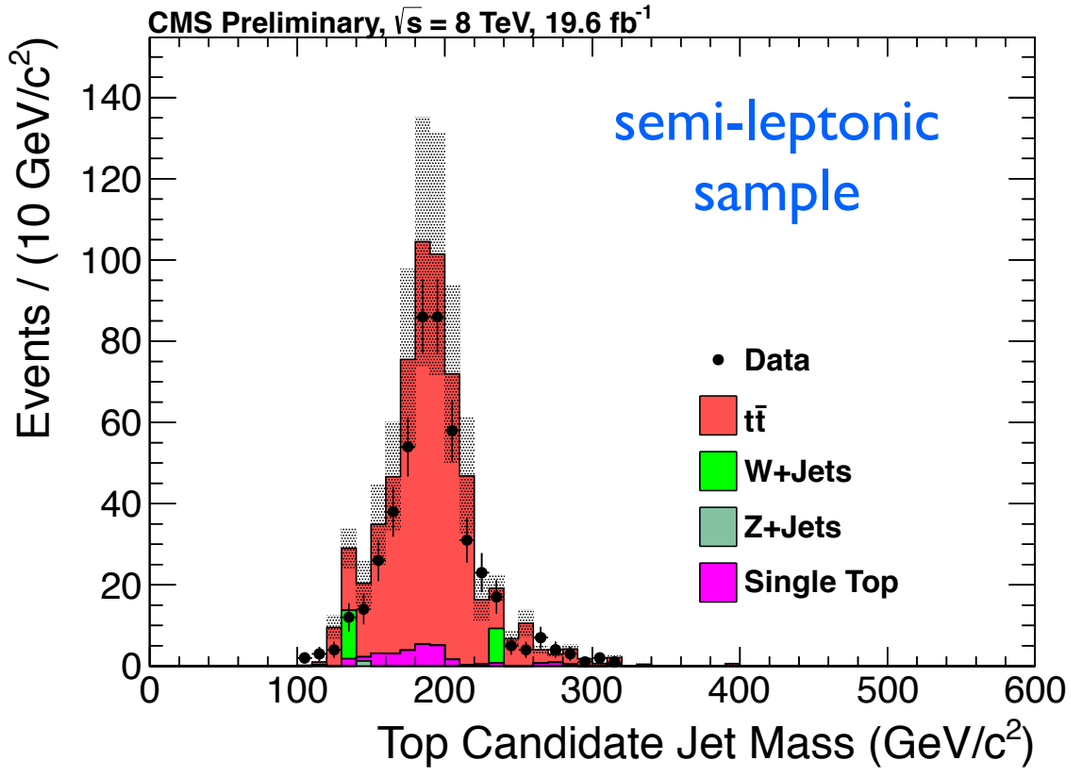
Top Tagging in CMS

more in Emanuele Usai's talk

Top- and W-tagging in all-hadronic final states

- W-tagger: pruned CA8 jets
  - 2 subjets, mass drop μ > 0.4
- CMS top tagger:
  invariant mass of subjets from CA8 jets
  - robust algorithm (pile-up, calibration,...)
  - good efficiency (~40% at high P_T) with small mistag rate (3-7%, depending on P_T)
- top tagging efficiency measurement in μ+jets sample
  - data/MC ration of 0.93 ± 0.04

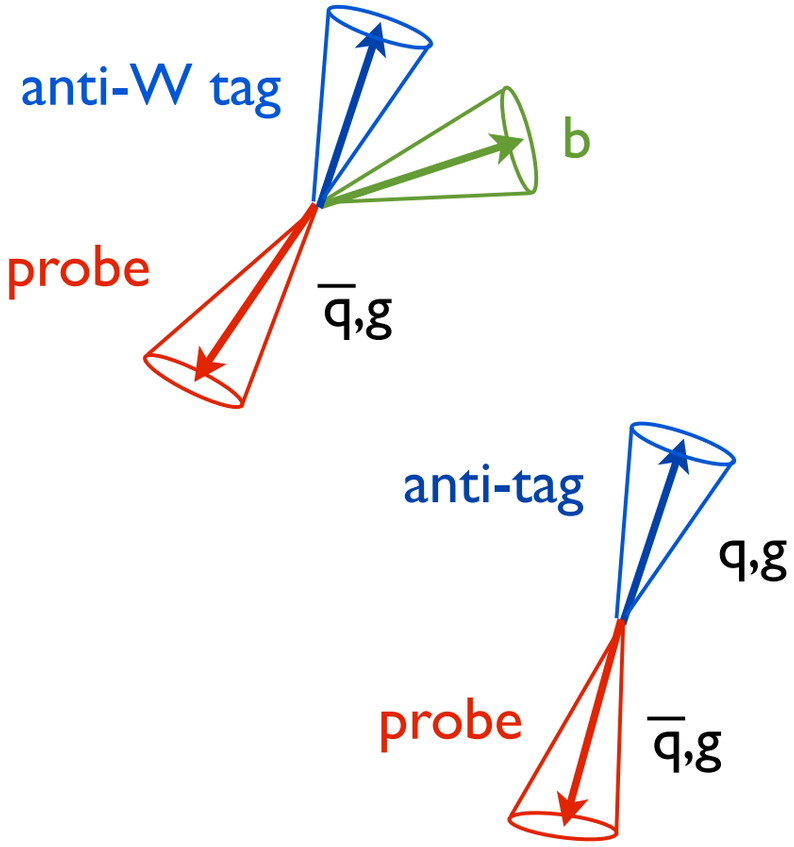


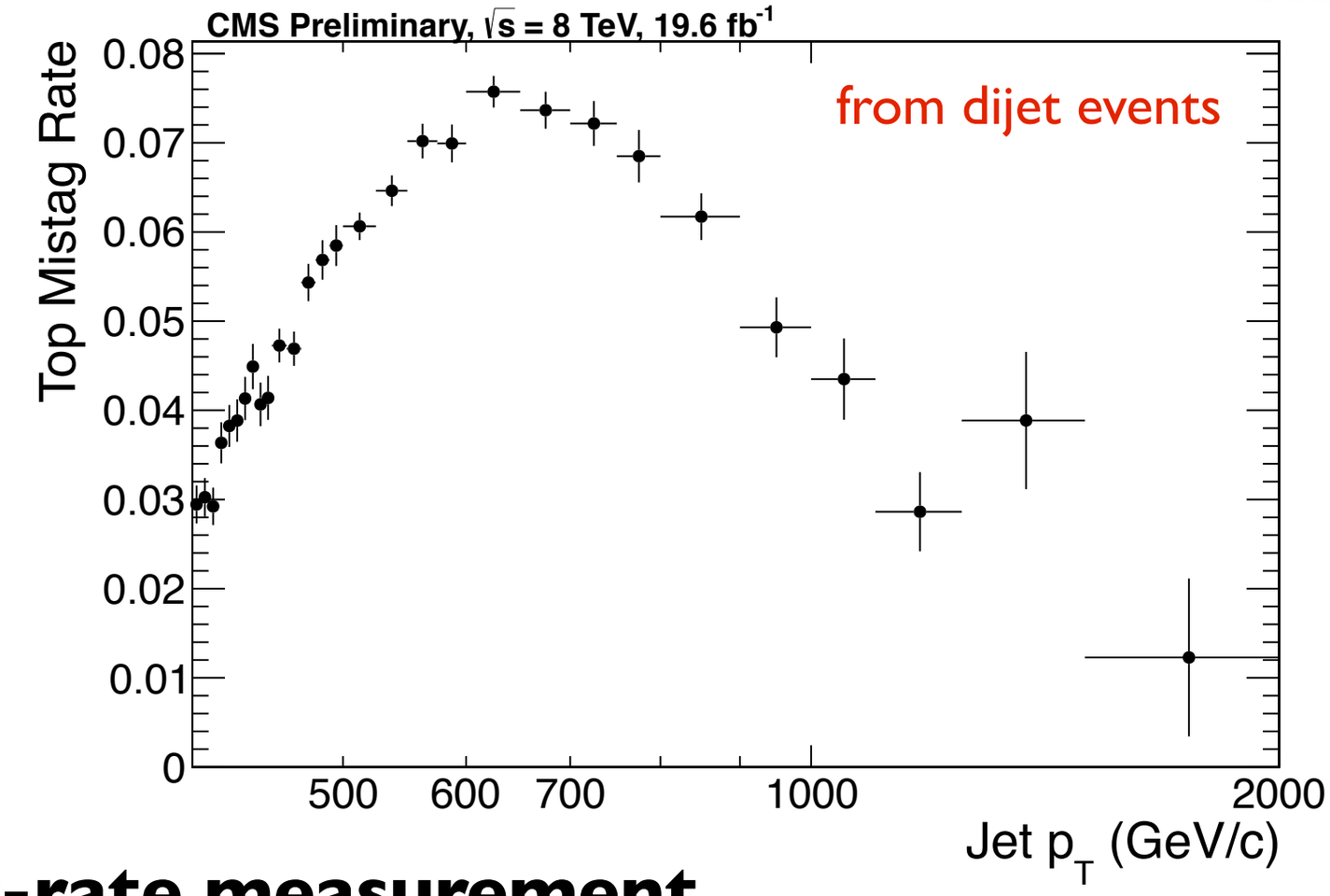


[CMS PAS B2G-12-005]

more in Emanuele Usai's talk

Misidentification Rate



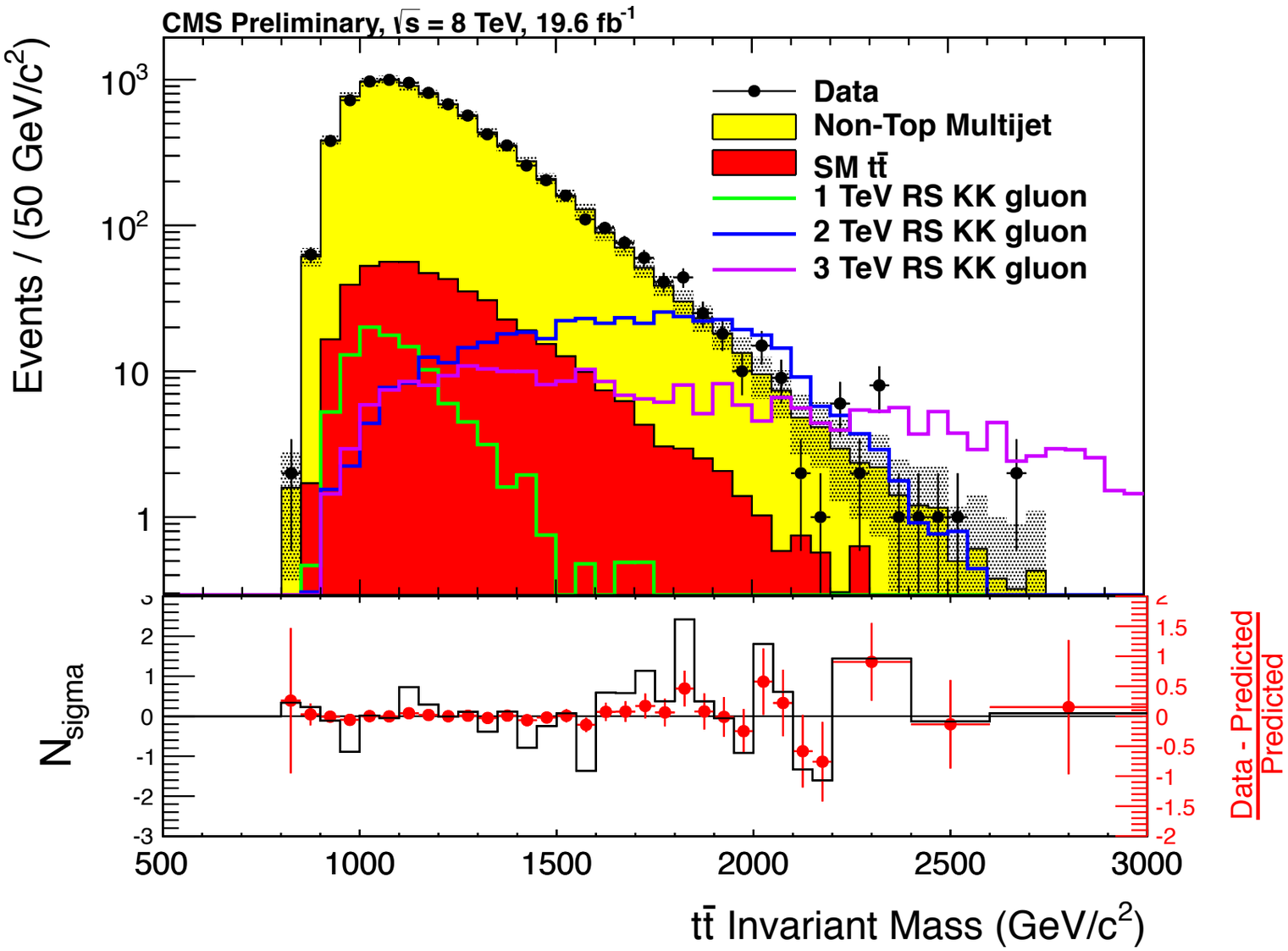


Top-tagging mistag-rate measurement

- dijet event selection
- Invert minimum-pairwise mass requirement on one jet
  → control region with small $t\bar{t}$ contamination (subtracted)
- top-tagging mistag rate measured on the other jet
- good agreement between semi-resolved and fully merged samples, higher statistics at high P_T when using fully merged events

[CMS PAS B2G-12-005]

$t\bar{t}$ Resonances: All-hadronic

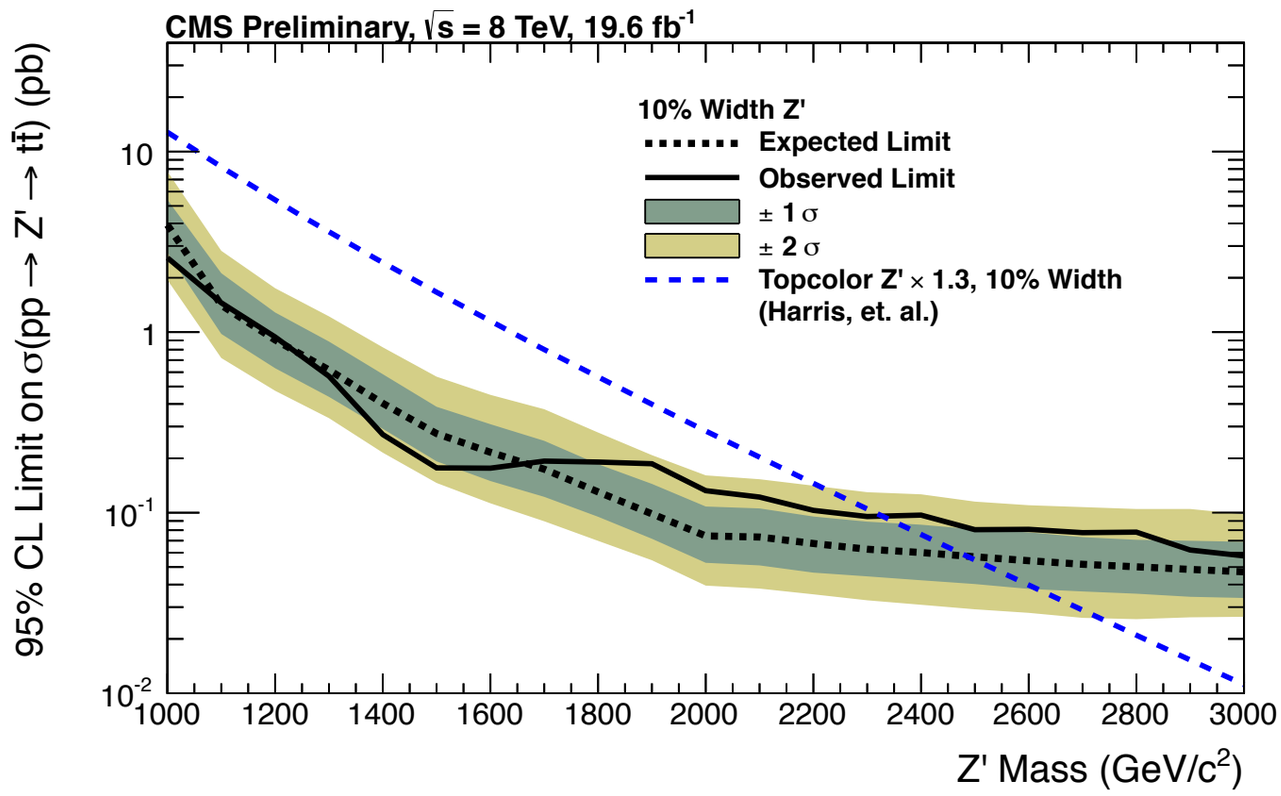


- $m_{t\bar{t}}$ distribution after likelihood maximization
- overwhelming background from QCD dijet production (could be reduced using advanced b-tagging techniques on subjets)
- broad resonances from KK gluon excitations

[CMS PAS B2G-12-005]

All-hadronic Results

- dominant uncertainties: JES, $t\bar{t}$ normalization+shape
- comparable limits to the lepton+jets analysis for M > 1.5 TeV
- exclusion limits on narrow and wide Z' and KK gluons of up to 2.3 TeV



Enhancement analysis:

Process	Events
SM $t\bar{t}$	507 ± 269
Non-Top Multijet	6602 ± 723
Total Background	7109 ± 771
Observed Data	6887
$t\bar{t}$ Efficiency	$(3.4 \pm 1.7) \cdot 10^{-4}$

with $\mathcal{S} = \dfrac{\int_{M_{t\bar{t}}>1\mathrm{TeV}/c^2} \frac{d\sigma_{SM+NP}}{dM_{t\bar{t}}} dM_{t\bar{t}}}{\int_{M_{t\bar{t}}>1\mathrm{TeV}/c^2} \frac{d\sigma_{SM}}{dM_{t\bar{t}}} dM_{t\bar{t}}}$.

derive constraints on a general enhancement in the invariant $m_{t\bar{t}}$ spectrum: $S < 1.79$ at 95% C.L.

Summary

Searches for resonances decaying to top quarks

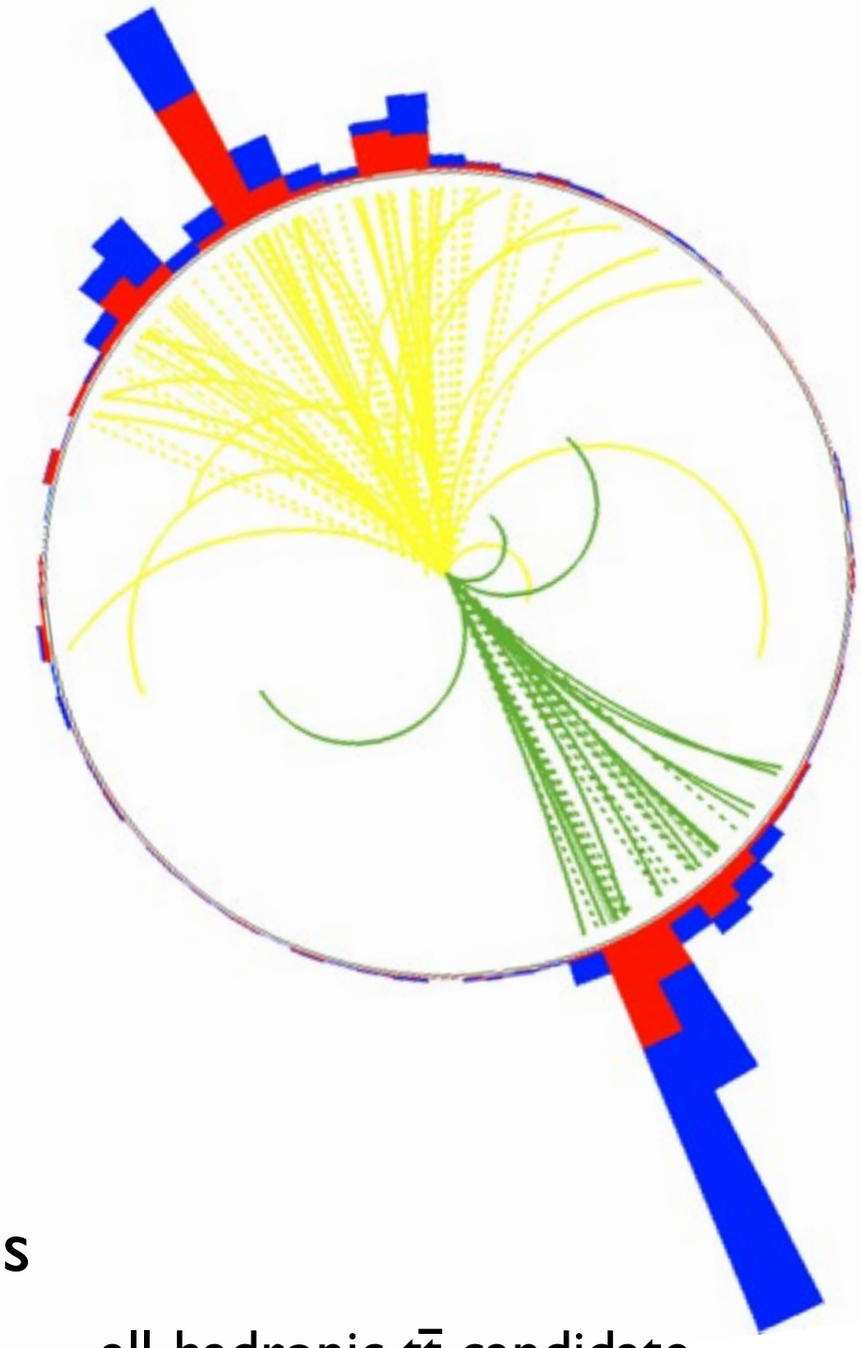
- exciting possibility to explore many new physics models
- very rich final states

Excellent performance of CMS

- analyses being released using the full 8 TeV data
- no signals so far, but new limits in so far unexplored regions

Boosted topologies

- higher mass regions accessible
- increasing importance for 13 and 14 TeV runs



all-hadronic $t\bar{t}$ candidate event recorded by CMS

Additional Material

[CMS PAS B2G-12-014]

t* Uncertainties

Uncertainties on the background shape: uncertainties of the fit parameters a, b, c

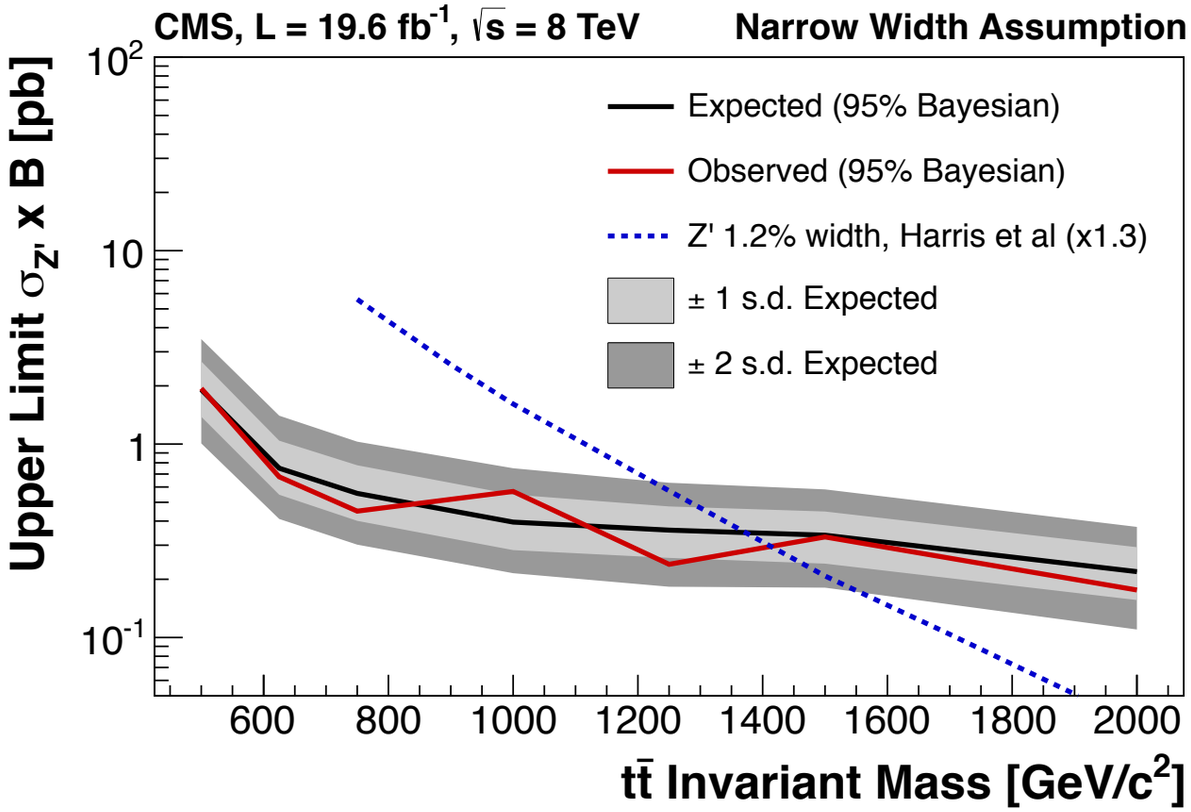
$$f(x) = \frac{a}{1 + e^{\frac{x-b}{c}}},$$

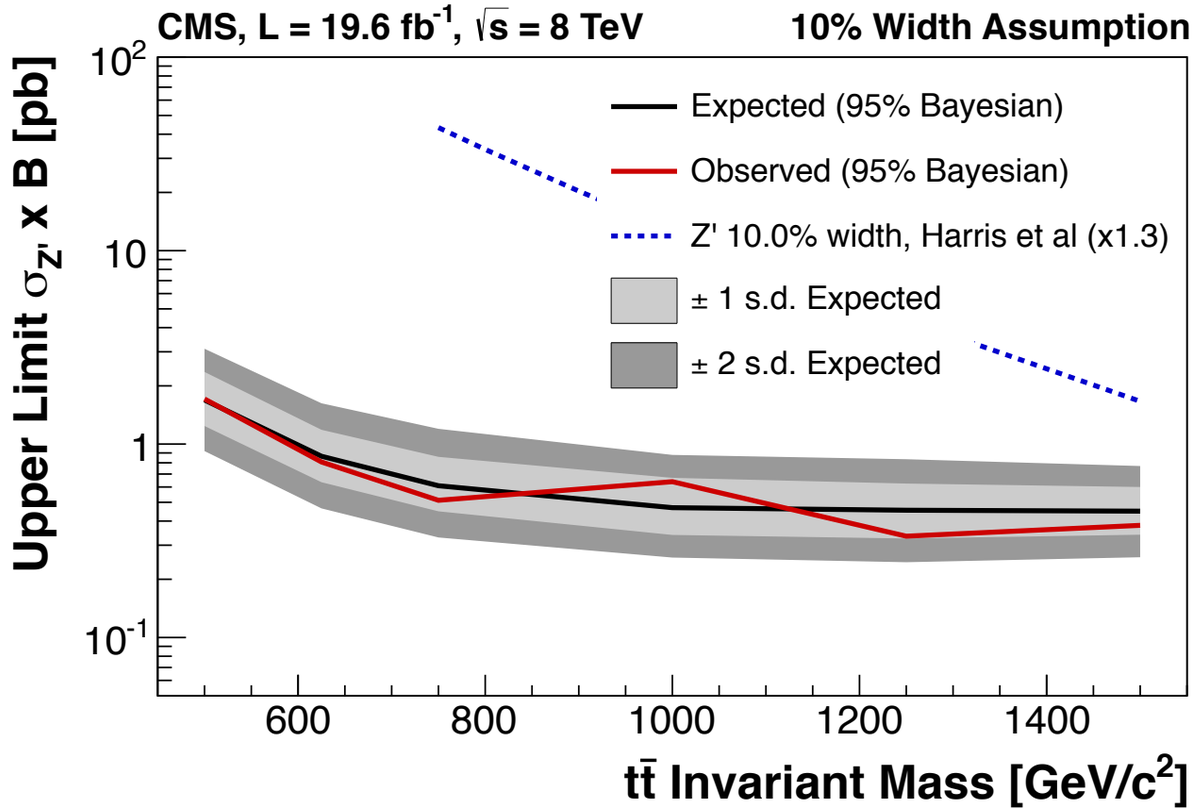
Uncertainties on the expected signal:

Source	Muon Channel	Electron Channel
Luminosity	4.4%	4.4%
JES	2.3–3.9%	2.2–4.1%
JER	0.1–0.6%	0.1–0.8%
Trigger Efficiency	1.0%	1.0%
Lepton Efficiency	0.9–1.3%	0.04%
b-tag SF	0.6–1.5%	0.8–1.4%
Pileup	0.02–0.7%	0.02–0.4%
PDF	0.3–1.9%	1.3–1.9%
MC Statistics	1.9%	2.0%

[CMS PAS B2G-12-006]

$t\bar{t}$ Resonances (Low Mass)

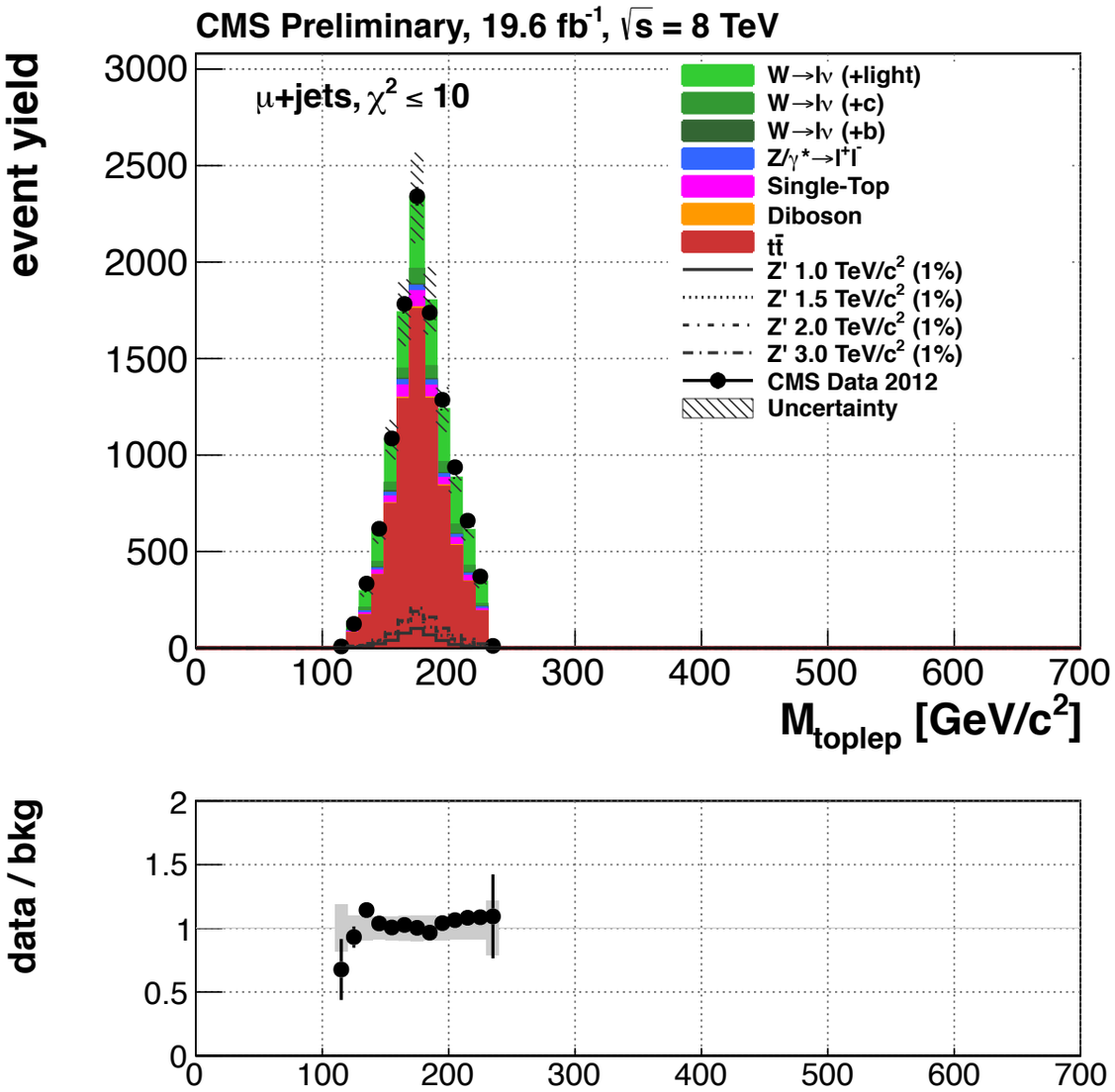


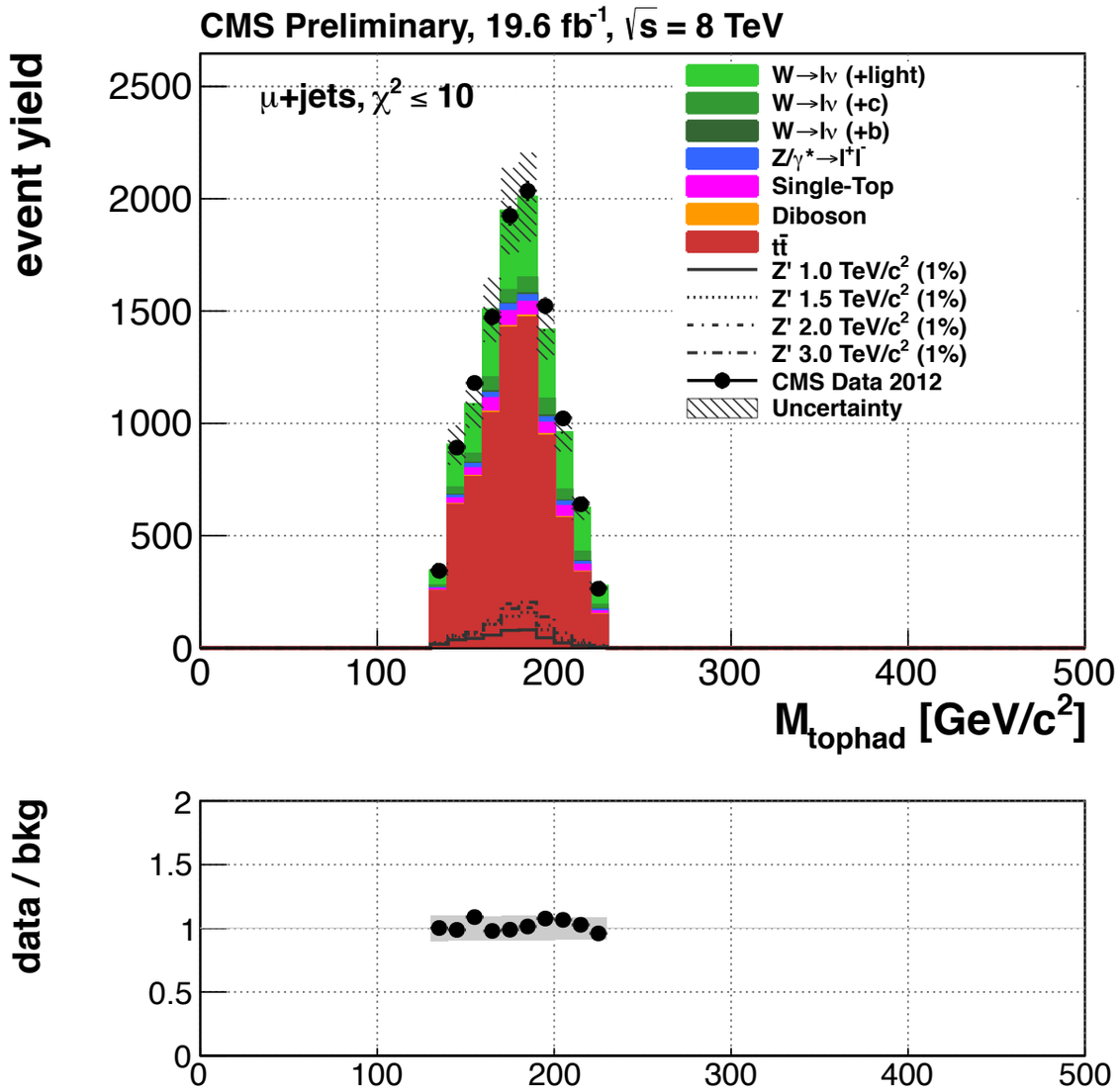


$t\bar{t}$-resonances: zoom-in of the obtained limits in the low-mass regime by the threshold analysis

[CMS PAS B2G-12-006]

$t\bar{t}$ Resonances (High Mass)

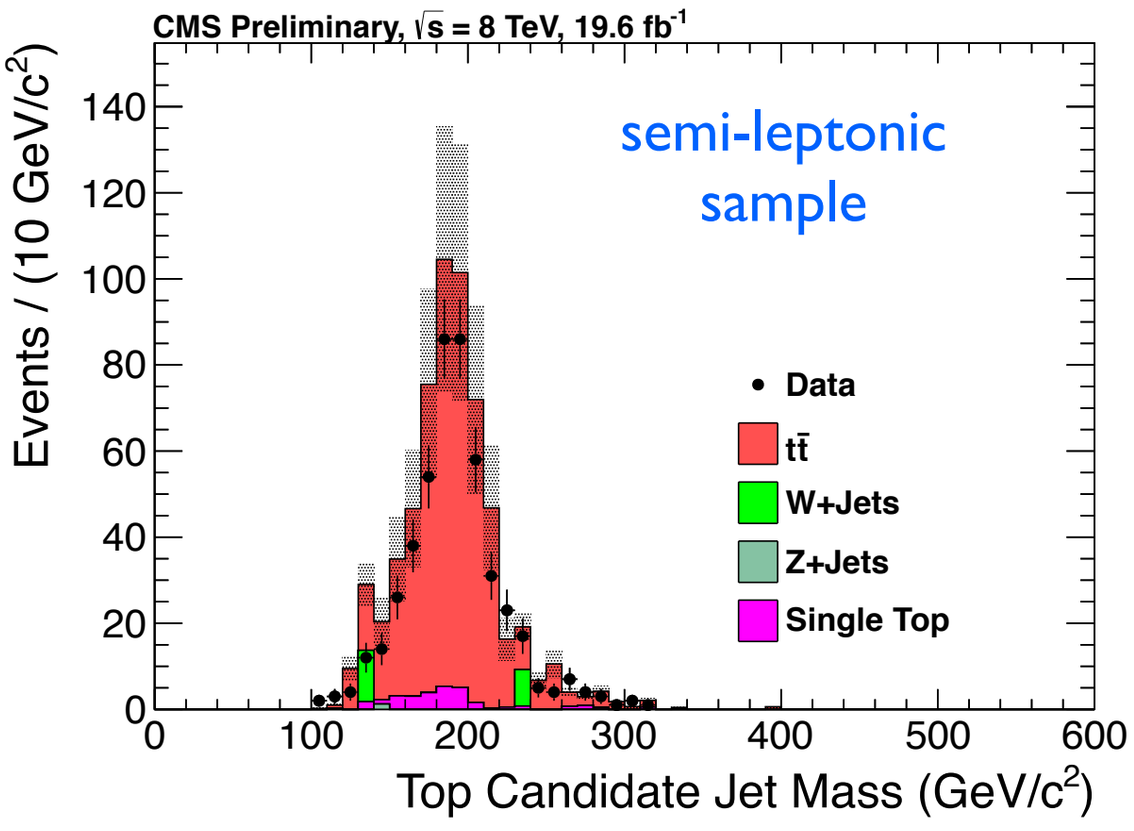


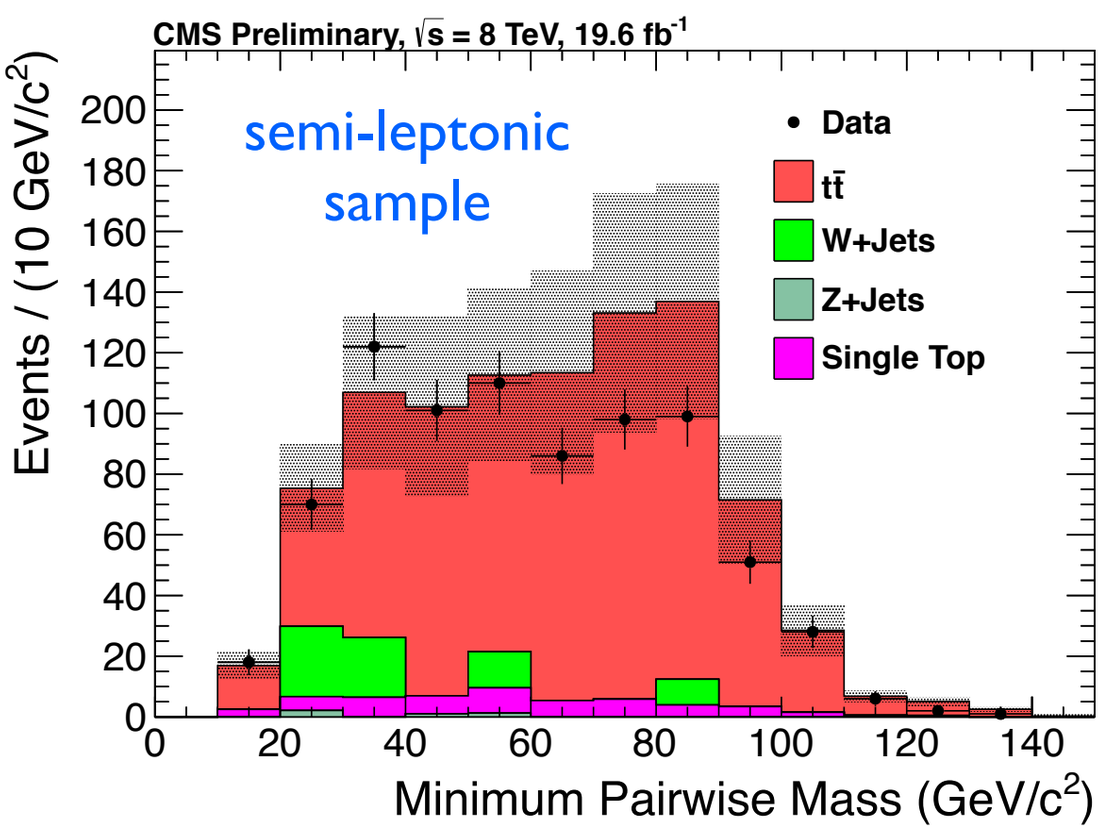


Reconstructed mass of the leptonic (left) and hadronic (right) top quark decay, after the full selection

[CMS PAS B2G-12-005]

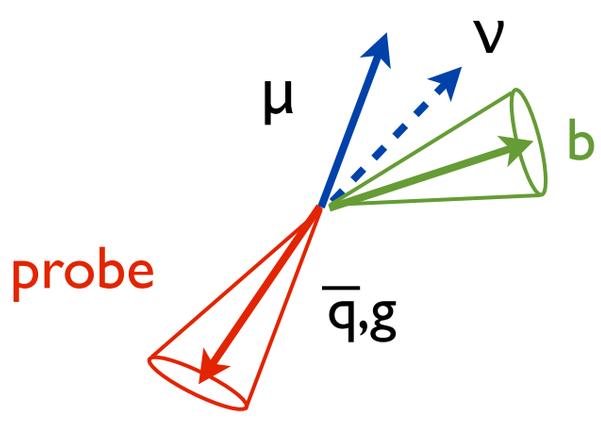
$t\bar{t}$ Resonances: all-hadronic





Top-tagging efficiency measurement:

- semi-leptonic control sample with one b-tagged jet
- determine efficiency and subjet scale factor for data and simulation
- good agreement found, ratio between data and simulation is 0.926 ± 0.039, applied as scale factor to tt and signal MCs



[CMS PAS B2G-12-005]

$t\bar{t}$ Resonances: all-hadronic

Systematic uncertainties:

	Process	$t\bar{t}$	NTMJ	RS KK gluon				
	Mass (TeV/c^2)			1	1.5	2	2.5	3
Systematic Source	**Variation**	**Effect of Systematic**						
Trigger Efficiency	2	2		2	2	2	2	2
Jet Energy Scale	$\sim \pm 5$	$^{+11}_{-15}$		$^{+15}_{-22}$	$^{+1.3}_{-3.5}$	$^{-4.5}_{-0.1}$	$^{-4.9}_{-0.1}$	$^{-3.0}_{-1.1}$
Jet Energy Resolution	$f(\eta)$			$^{-1.0}_{-0.3}$	$^{-0.4}_{+0.2}$	$^{-0.2}_{+0.3}$	$^{-0.4}_{+0.4}$	$^{-0.4}_{+0.3}$
Luminosity	± 4.4	4.4		4.4	4.4	4.4	4.4	4.4
Top Tagging Scale Factor	85.7 ± 7.8	8.4		8.4	8.4	8.4	8.4	8.4
NTMJ Determination	See Text		4.9					
NTMJ Closure Test	See Text		$^{+10.8}_{-8.7}$					
$t\bar{t}$ Cross Section	± 50	50						

	Process	Z′ (1% Width)				Z′ (10% Width)			
	Mass (TeV/c^2)	1	1.5	2	3	1	1.5	2	3
Systematic Source	**Variation**	**Effect of Systematic**							
Trigger Efficiency	2	2	2	2	2	2	2	2	2
Jet Energy Scale	$\sim \pm 5$	$^{+23}_{-26}$	$^{-1.9}_{-2.2}$	$^{-7.9}_{+2.4}$	$^{-14}_{+8.6}$	$^{+19}_{-23}$	$^{-0.9}_{-3.4}$	$^{-5.2}_{+2.1}$	$^{-7.5}_{+3.7}$
Jet Energy Resolution	$f(\eta)$	$^{+0.5}_{-0.1}$	$^{-0.3}_{+0.1}$	$^{-0.3}_{+0.1}$	$^{-0.5}_{+0.5}$	$^{+0.3}_{+0.1}$	$^{+0.0}_{+0.1}$	$^{-0.3}_{+0.2}$	$^{-0.4}_{+0.2}$
Luminosity	± 4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4
Top Tagging Scale Factor	85.7 ± 7.8	8.4	8.4	8.4	8.4	8.4	8.4	8.4	8.4
NTMJ Determination	See Text								
NTMJ Closure Test	See Text								
$t\bar{t}$ Cross Section	± 50								