



# Top quark physics at the Compact Muon Solenoid

Freya Blekman  
on behalf of the CMS collaboration



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Vrije Universiteit Brussel, Belgium

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Specific thanks to the CMS top physics group and convenors for their hard work over the last few months and aid in preparation of this talk



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# The building blocks of matter

LEPTONS			
Charge			
0	Electron neutrino Mass: >0	Muon neutrino Mass: >0	Tau neutrino Mass: >0
1	Electron Mass: 0.511	Muon Mass: 105.7	Tau Mass: 1,777
QUARKS			
Charge			
2/3	Up Mass: 5	Charm Mass: 1,500	Top Mass: 175,000
-1/3	Down Mass: 8	Strange Mass: 160	Bottom Mass: 4,250

Shown lepton and quark sizes proportional to mass

Top quark is heavy!!!

Probe new physics  
No hadronisation

Masses are in millions of Electron Volts [MeV/c<sup>2</sup>]



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# Top quark and new physics

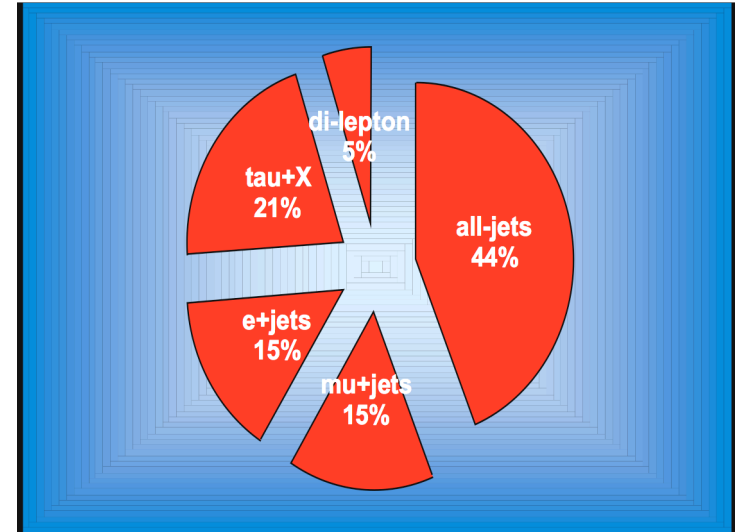
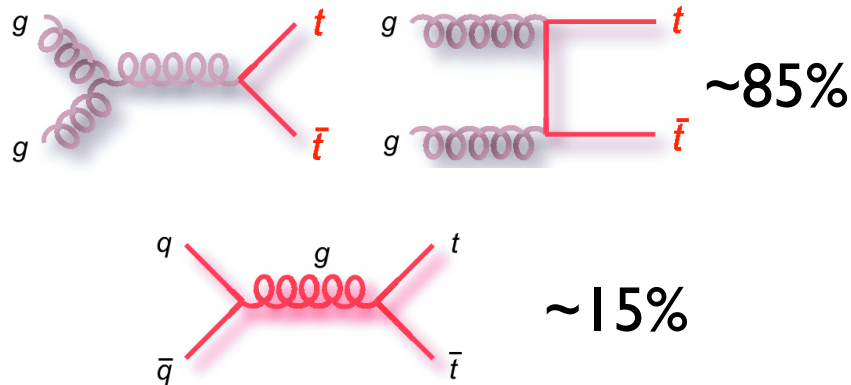
- Precise SM measurements
  - Heaviest known elementary particle (large Yukawa coupling)
    - Constraints on Higgs mass
    - Unique window on bare quarks due to short lifetime
  - Probe for QCD at scale  $>$  gauge bosons
- A window to new physics
  - New physics - many models couple preferentially to top
  - New particles may decay to top
  - Non-standard couplings
- In many new physics scenarios (e.g. SUSY) top is dominant BG
- Great tool to calibrate detector
  - Jet energy scale, b-jet efficiency

Top pair production rate  
Top mass  
Single top production rate  
 $B(t \rightarrow Wb)$   
 $|V_{tb}|$   
W helicity  
Top polarization  
Anomalous couplings  
Spin correlations  
Rare decays  
Top width

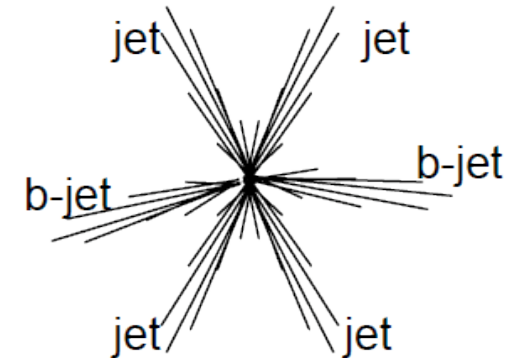
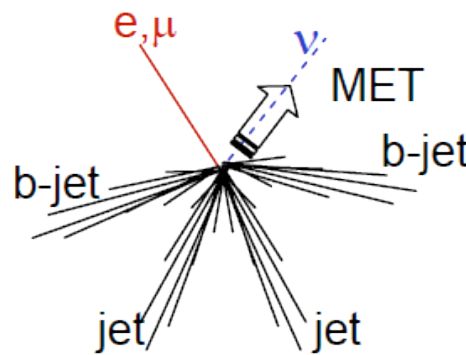
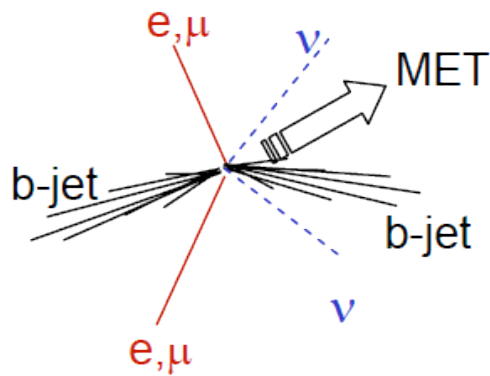
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# Top pair production and decay

- Pair production in 7 TeV pp collisions:



- $BR(t \rightarrow Wb) \approx 1$  in Standard Model
- Analysis strategy depends on W decay modes



# Compact Muon Solenoid

## CMS Detector

- Pixels ✓
- Tracker ✓
- ECAL ✓
- HCAL ✓
- Solenoid ✓
- Steel Yoke ✓
- Muons ✓

**STEEL RETURN YOKE**  
~13000 tonnes

**SUPERCONDUCTING SOLENOID**  
Niobium-titanium coil carrying ~18000 A

**HADRON CALORIMETER (HCAL)**  
Brass + plastic scintillator

**SILICON TRACKER**  
Pixels (100 x 150  $\mu\text{m}^2$ )  
~1m<sup>2</sup> 66M channels  
Microstrips (50-100 $\mu\text{m}$ )  
~210m<sup>2</sup> 9.6M channels

**CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)**  
76k scintillating PbWO<sub>4</sub> crystals

**PRESHOWER**  
Silicon strips  
~16m<sup>2</sup> 137k channels

**FORWARD CALORIMETER**  
Steel + quartz fibres

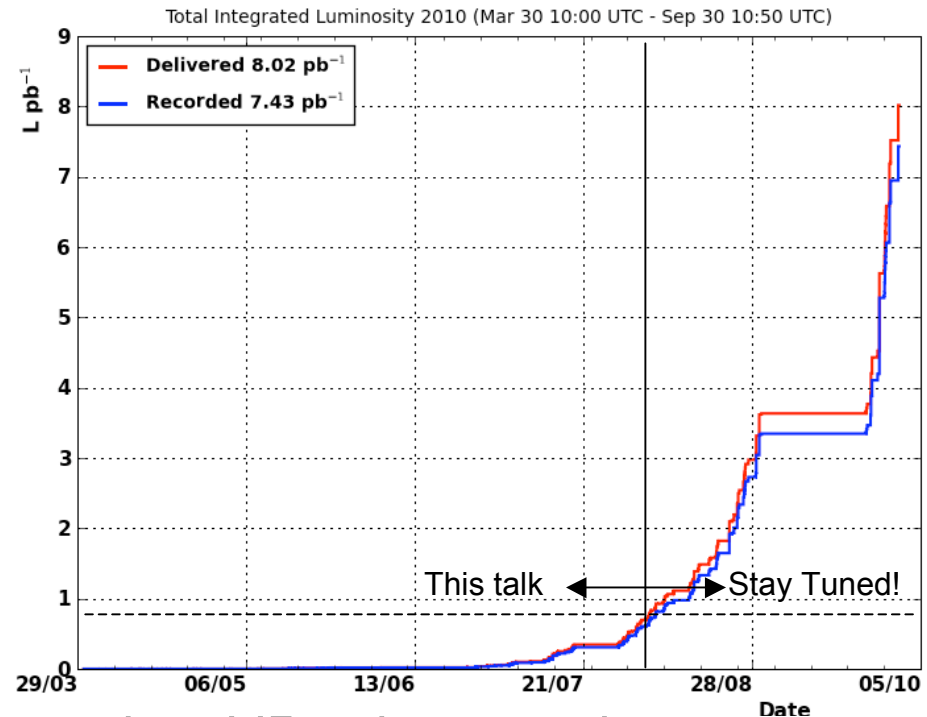
**MUON CHAMBERS**  
Barrel: 250 Drift Tube & 500 Resistive Plate Chambers  
Endcaps: 450 Cathode Strip & 400 Resistive Plate Chambers

Total weight : 14000 tonnes  
Overall diameter : 15.0 m  
Overall length : 28.7 m  
Magnetic field : 3.8 T



# Data and MC samples

- Results presented:
  - $L = 0.84 / \text{pb}$
- Much larger sample ( $>7 / \text{pb}$ ) in hand
  - Working hard on updated results!
- Monte Carlo samples
  - $t\bar{t} + \text{jets}$ ,  $W/Z + \text{jets}$ : Madgraph, matching ME with parton showers
    - $V + b\bar{b}/c\bar{c} + \text{jets}$  matrix elements included
  - Cross sections normalized to inclusive (N)NLO cross sections
    - $\sigma(t\bar{t}, \text{NLO}) = 157 \text{ pb}$  (MCFM),  $m_{\text{top}} = 172.5 \text{ GeV}$
    - $\sigma(W \rightarrow l\nu, \text{NNLO}) = 31314 \text{ pb}$  (FEWZ)
  - QCD: PYTHIA (filtered at gen level)

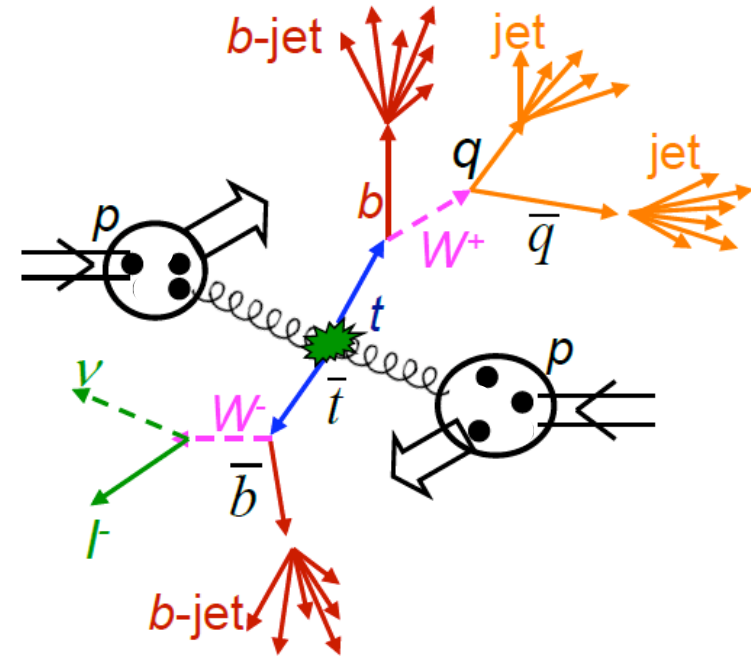


# Lepton+jets: Event selection

- Considered modes:
  - e+jets
  - mu+jets
- Single lepton triggers
- Exactly one isolated lepton
  - Muons:  $p_T > 20 \text{ GeV}, |\eta| < 2.1$ 
    - Rel. Isolation  $< 0.05$
  - Electrons:  $p_T > 30 \text{ GeV}, |\eta| < 2.4$ 
    - Rel. Isolation, conversion veto

$$\text{Rel.isol.} = \frac{\sum_{R<0.3} p_T^{\text{track}} + \sum_{R<0.3} p_T^{\text{ECAL}} + \sum_{R<0.3} p_T^{\text{HCAL}}}{p_T(\text{lepton})}$$

- Missing  $E_T$  (MET)
  - Not used in event selection, but to reconstruct transverse Mass



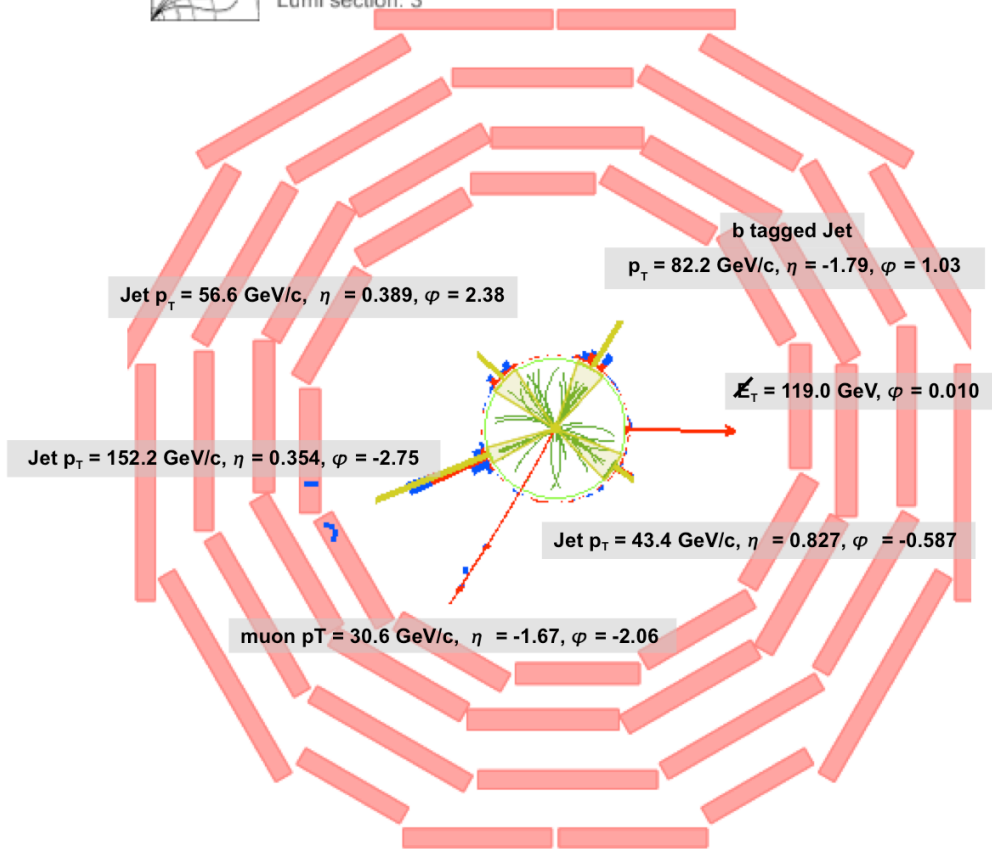
- Jets
  - Anti-Kt (R=0.5)
  - $P_t > 30 \text{ GeV}, |\eta| < 2.4$
  - Expect  $\geq 4$  jets for  $t\bar{t}$



# mu+jets candidate

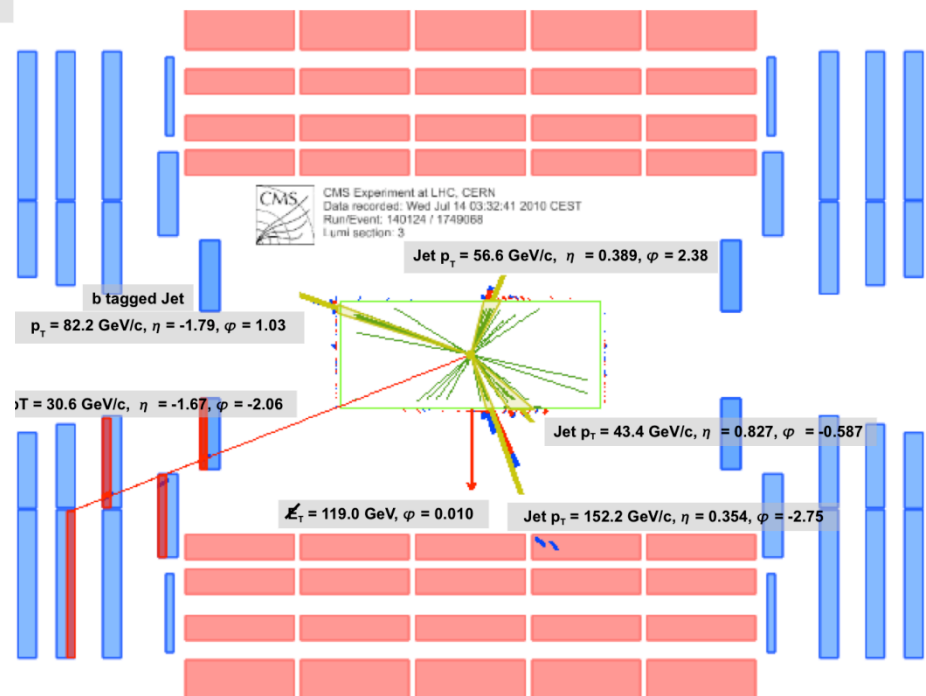


CMS Experiment at LHC, CERN  
 Data recorded: Wed Jul 14 03:32:41 2010 CEST  
 Run/Event: 140124 / 1749068  
 Lumi section: 3



Event passes all cuts  
 of full selection

- 1 high-momentum muon
- significant  $\text{MET} > 100 \text{ GeV}$
- $m_T(W) = 104 \text{ GeV}/c^2$
- 4 high- $p_T$  jets, one of which with good  $b$ -tag

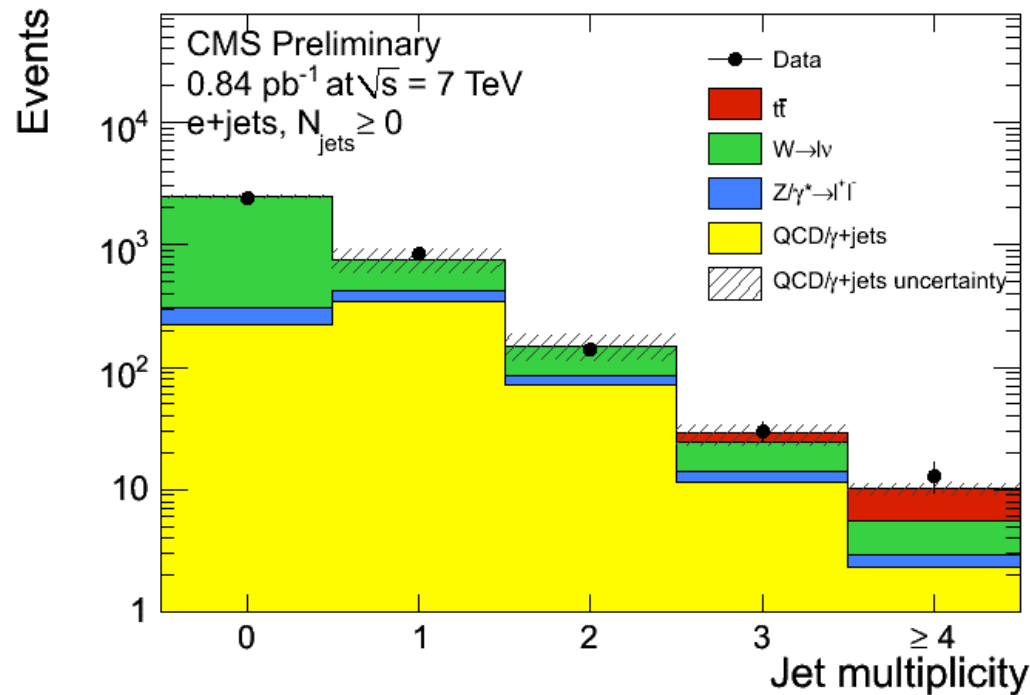


reconst. top mass around  $210 \text{ GeV}/c^2$   
 masses of 2 untagged jets (3 possible comb.): 104, 105, 151  $\text{GeV}/c^2$



# Electron+Jets - before b-tagging

Jet multiplicity	t $\bar{t}$	single top	W+jets	Z+jets	QCD	Sum MC	Data
$N_{\text{jets}} \geq 0$	$12 \pm 2$	$3.4 \pm 0.4$	$2619 \pm 317$	$180 \pm 21$	$658 \pm 73$	$3472 \pm 326$	3434
$N_{\text{jets}} \geq 1$	$12 \pm 2$	$3.1 \pm 0.4$	$419 \pm 77$	$92 \pm 11$	$436 \pm 62$	$962 \pm 99$	1022
$N_{\text{jets}} \geq 2$	$11 \pm 2$	$1.9 \pm 0.3$	$74 \pm 18$	$19 \pm 5$	$85 \pm 22$	$191 \pm 29$	183
$N_{\text{jets}} \geq 3$	$8.9 \pm 1.8$	$0.70 \pm 0.14$	$13 \pm 4$	$3.3 \pm 1.0$	$14 \pm 5$	$40 \pm 7$	43
$N_{\text{jets}} \geq 4$	$4.8 \pm 1.2$	$0.21 \pm 0.06$	$2.6 \pm 1.1$	$0.60 \pm 0.23$	$2.3 \pm 1.1$	$11 \pm 2$	13



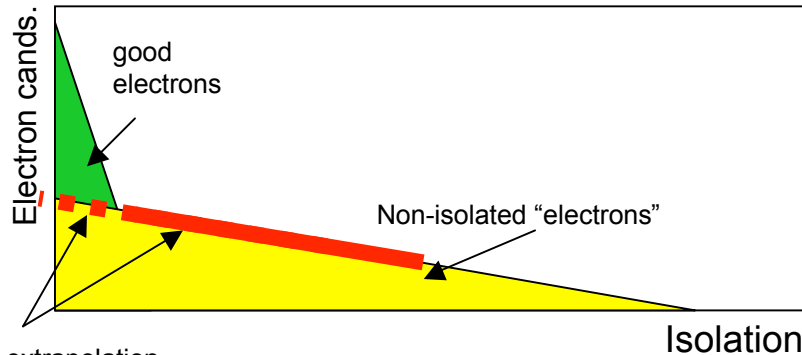
Quoted: Systematic uncertainties

- Jet energy scale (known to 10%)
- Luminosity (known to 11%)
- Cross section unc. (scale, PDF)

Ref: CMS-PAS-TOP-10-004



# Electron+jets: QCD electron isolation extrapolation

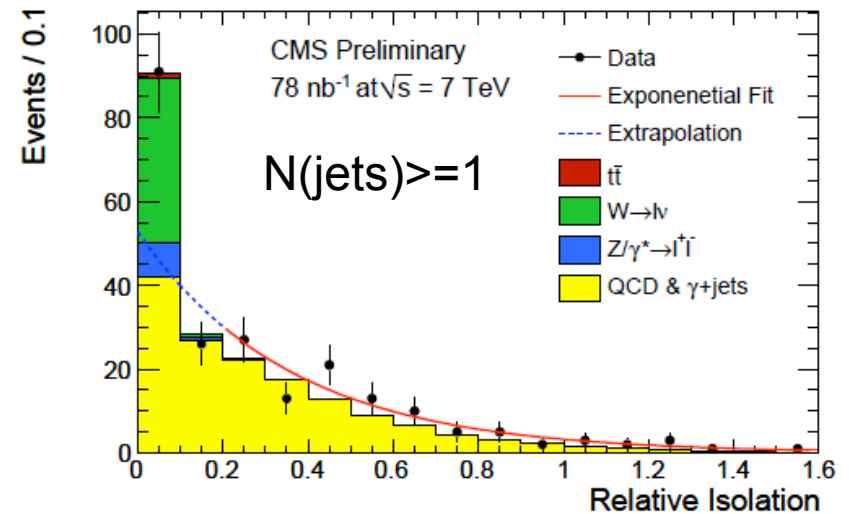
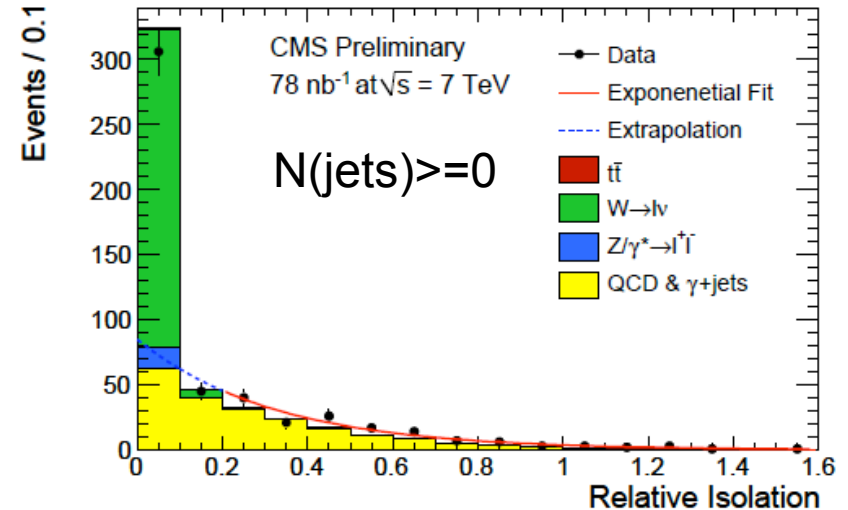


Fit + extrapolation

- Fit function to isolation distribution in non-isolated (QCD dominated) region
- Extrapolate to isolated (W-like) region

Isolation extrapolation method ( $e$ +jets)

Fit Range	$N_{\text{QCD}}^{\text{est.}} (\geq 0\text{-jet})$	$N_{\text{QCD}}^{\text{est.}} (\geq 1\text{-jet})$
0.1–1.6	$67 \pm 9$	$40 \pm 6$
0.2–1.6	$73 \pm 13$	$46 \pm 9$
0.3–1.6	$71 \pm 17$	$45 \pm 12$
Average $N_{\text{QCD}}^{\text{est.}}$	$70 \pm 35$	$44 \pm 22$
Prediction $N_{\text{QCD}}^{\text{MC}}$	$63 \pm 7$	$42 \pm 6$

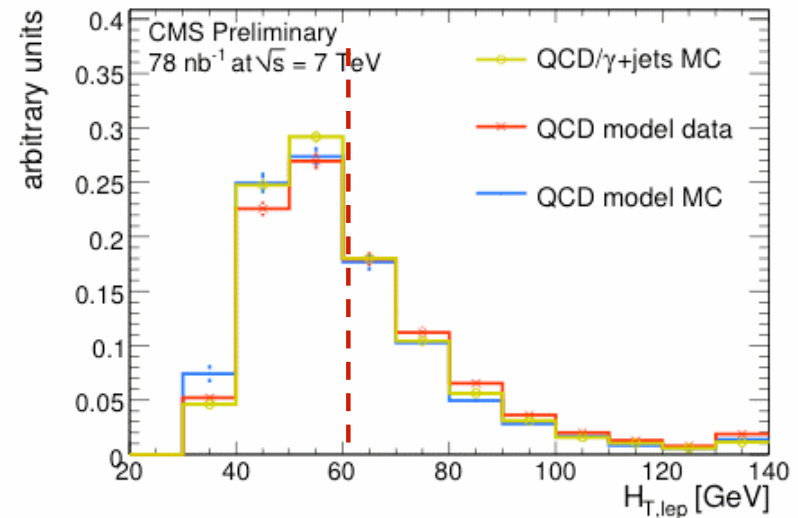
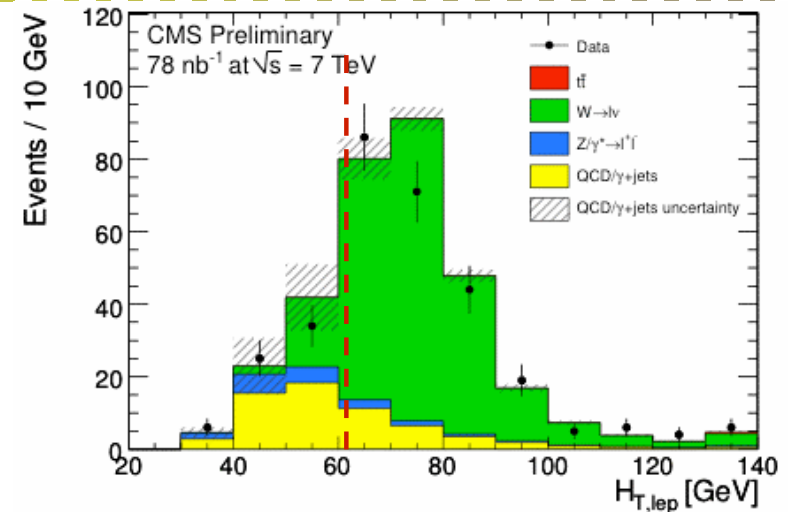


# Electron+jets: QCD template fit

- First tests of data-driven background model, using low jet multiplicity events
- e+jets: Fit sum of templates in low MET or HT(lep) region
  - QCD template from multijet sample (near-miss electrons or large EM jets)
- Predict N(QCD) in signal region

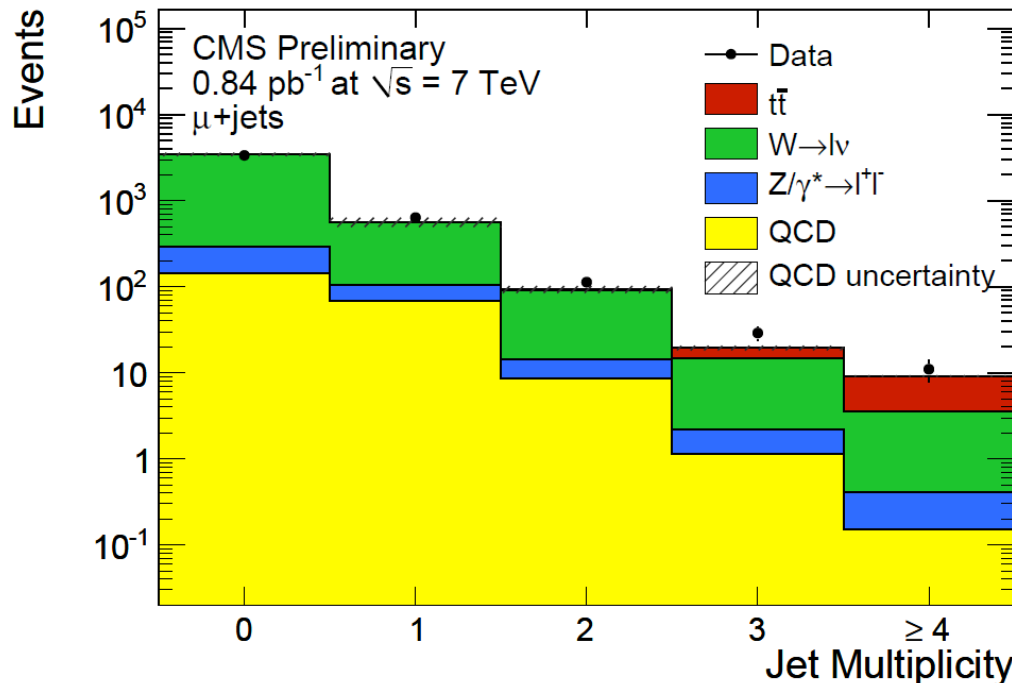
N(jets) $\geq 0$	QCD MC	QCD estimate
MET $>25$ GeV	12.2 $\pm$ 0.2	19 $\pm$ 7
HT(lep) $>60$ GeV	26.0 $\pm$ 0.3	39 $\pm$ 11

N(jets) $\geq 1$	QCD MC	QCD estimate
MET $>25$ GeV	5.3 $\pm$ 0.1	8 $\pm$ 5
HT(lep) $>60$ GeV	12.4 $\pm$ 0.2	10 $\pm$ 4



# Muon+jets before b-tagging

Jet multiplicity	t $\bar{t}$	single top	W+jets	Z+jets	QCD	Sum MC	Data
$N_{\text{jets}} \geq 0$	$13 \pm 3$	$4.2 \pm 0.4$	$3708 \pm 448$	$192 \pm 29$	$223 \pm 25$	$4140 \pm 450$	4142
$N_{\text{jets}} \geq 1$	$13 \pm 3$	$3.9 \pm 0.4$	$552 \pm 106$	$42 \pm 12$	$79 \pm 17$	$690 \pm 108$	789
$N_{\text{jets}} \geq 2$	$13 \pm 2$	$2.3 \pm 0.3$	$92 \pm 24$	$7.1 \pm 4.4$	$10 \pm 3$	$124 \pm 25$	153
$N_{\text{jets}} \geq 3$	$10 \pm 2$	$0.82 \pm 0.15$	$16 \pm 5$	$1.3 \pm 0.9$	$1.3 \pm 0.5$	$29 \pm 5$	40
$N_{\text{jets}} \geq 4$	$5.6 \pm 1.4$	$0.24 \pm 0.06$	$3.1 \pm 1.2$	$0.25 \pm 0.18$	$0.15 \pm 0.07$	$9.3 \pm 1.9$	11



## Quoted systematic uncertainties:

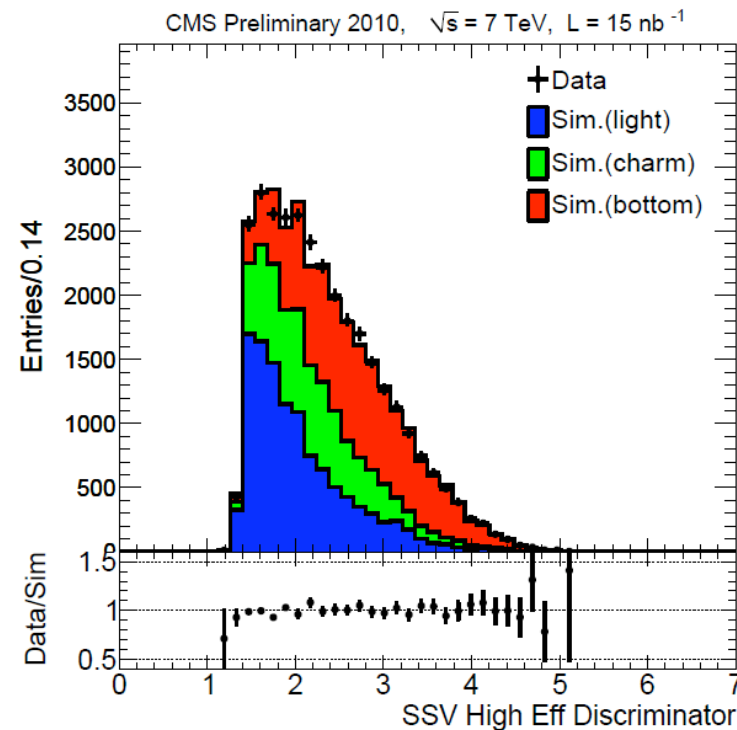
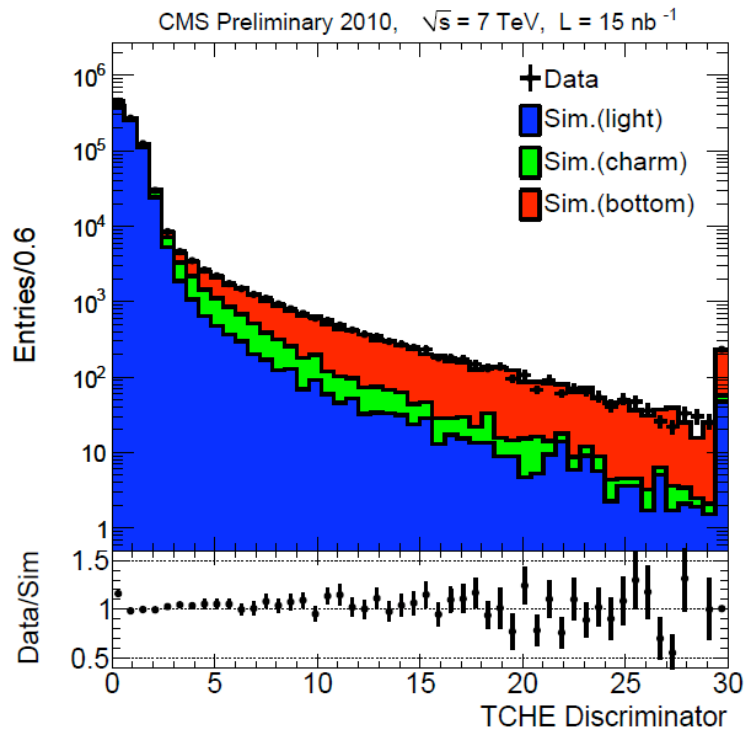
- Jet energy scale (known to 10%)
- Luminosity (known to 11%)
- Cross section unc. (scale, PDF)

Ref: CMS-PAS-TOP-10-004



# Identification of b-quark jets

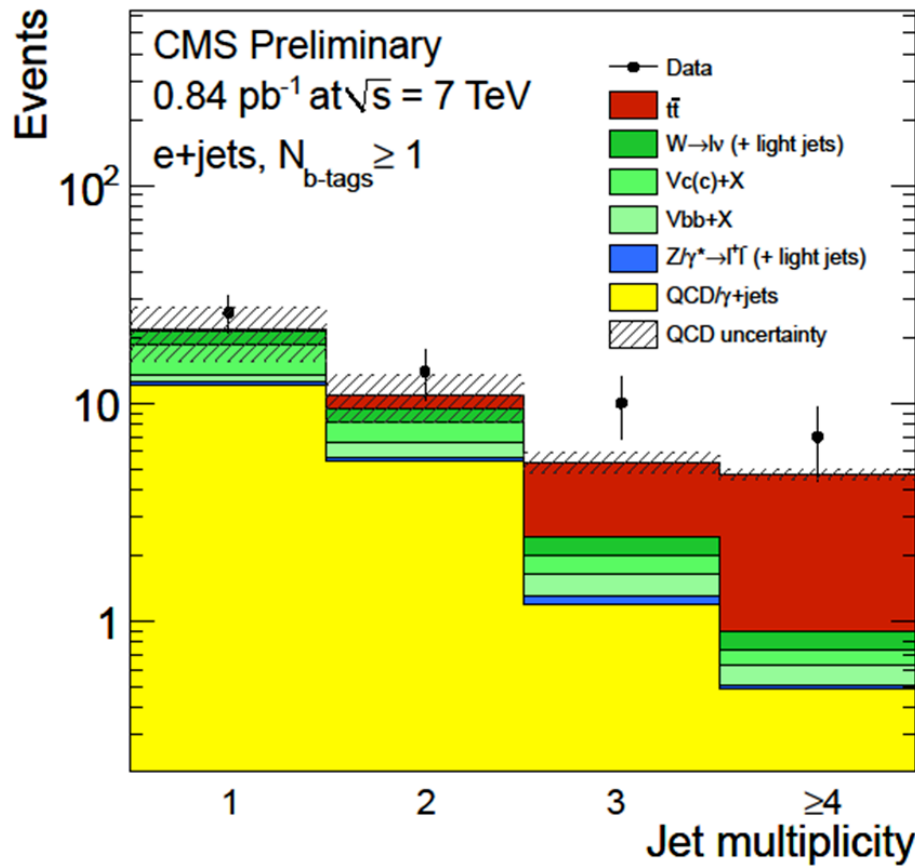
- “Track counting” tagger
  - Uses IP significance of n-th track as discriminator
- Secondary vertex tagger
  - Uses discriminator based on 3D flight distance



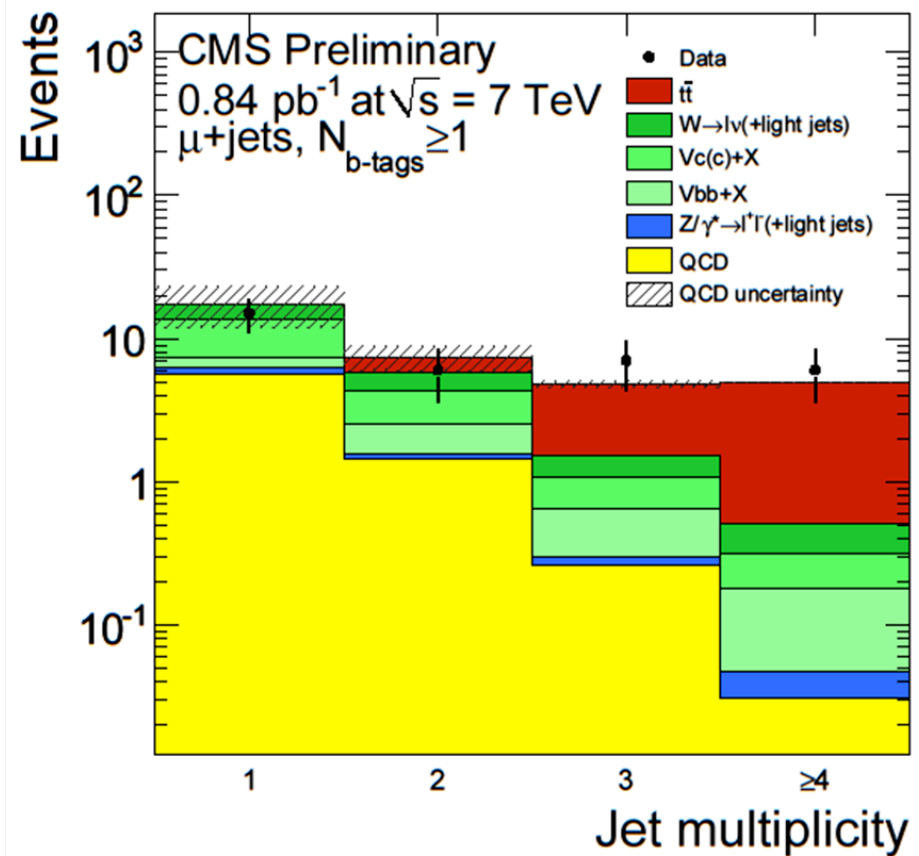
- General data/MC agreement good.
  - Small differences are taken into account as scale factors at this stage

# e/mu+jets+ vertex b-tag

- e+jets

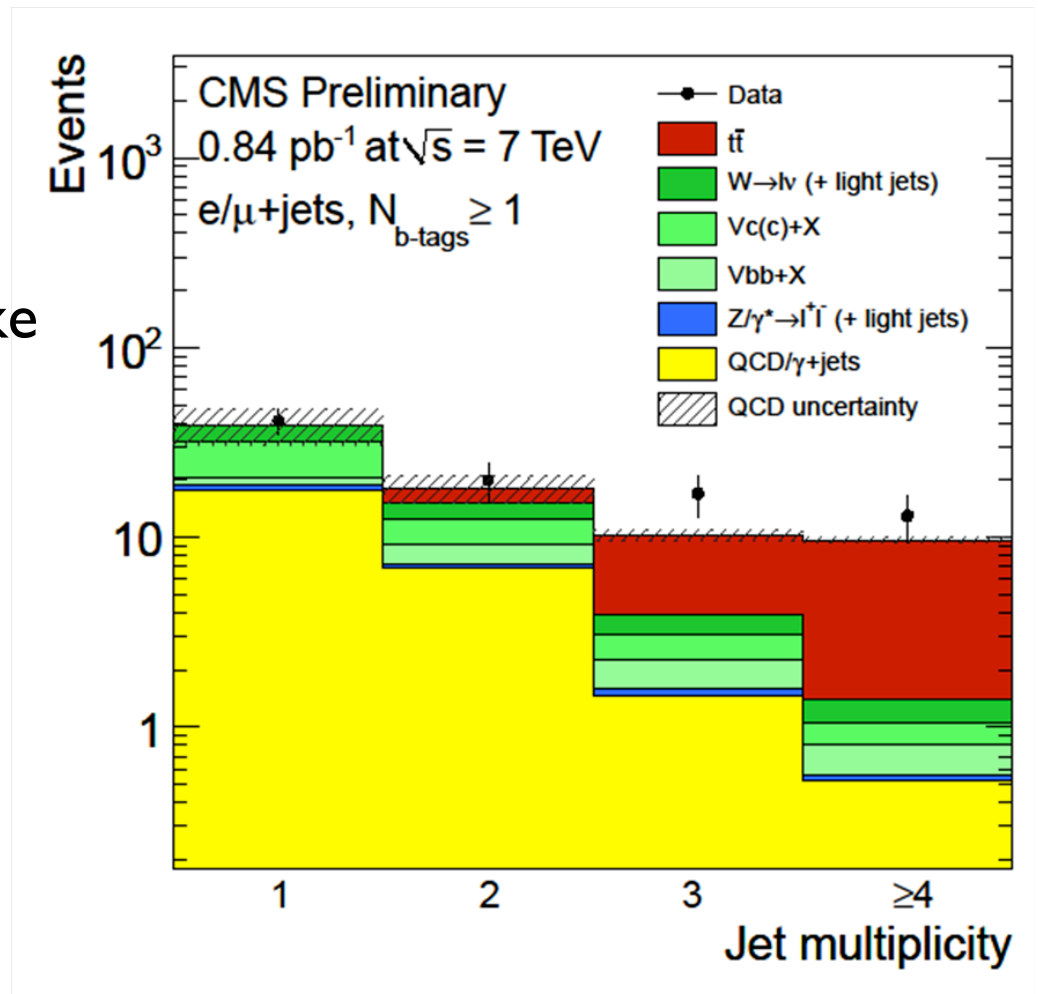


- mu+jets



# e/mu+jets with vertex b-tagging

- e/mu+jets combined
- Secondary vertex tagger (working point with  $\sim 1\%$  fake rate)
- For  $N(\text{jets}) \geq 3$ :
  - Observed  $N(\text{data})=30$
  - Predicted background  $N(\text{BG,MC})=5.3$
  - Predicted signal  $N(\text{ttbar,MC})=15$



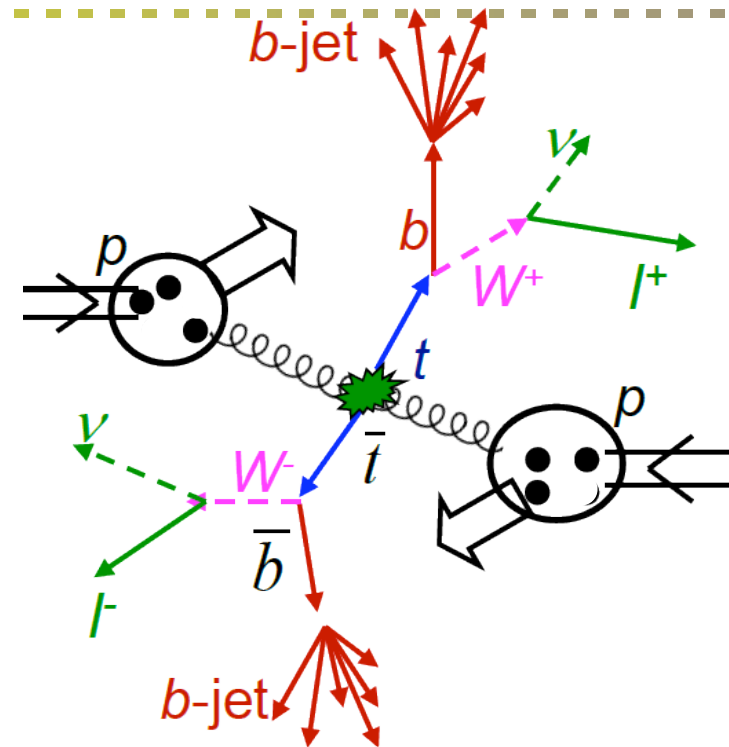


# Dilepton: Event selection

- Single lepton triggers
  - mu+X (Pt>9 GeV), e+X (Pt>15 GeV)
- Two isolated, opposite charge leptons (ee, mumu, emu)
  - pT>20 GeV, |eta|<2.5(mu), 2.4(e)
  - Rel. isolation < 0.15


$$\text{Rel.isol.} = \frac{\sum_{R<0.3} p_T^{\text{track}} + \sum_{R<0.3} p_T^{\text{ECAL}} + \sum_{R<0.3} p_T^{\text{HCAL}}}{p_T(\text{lepton})}$$

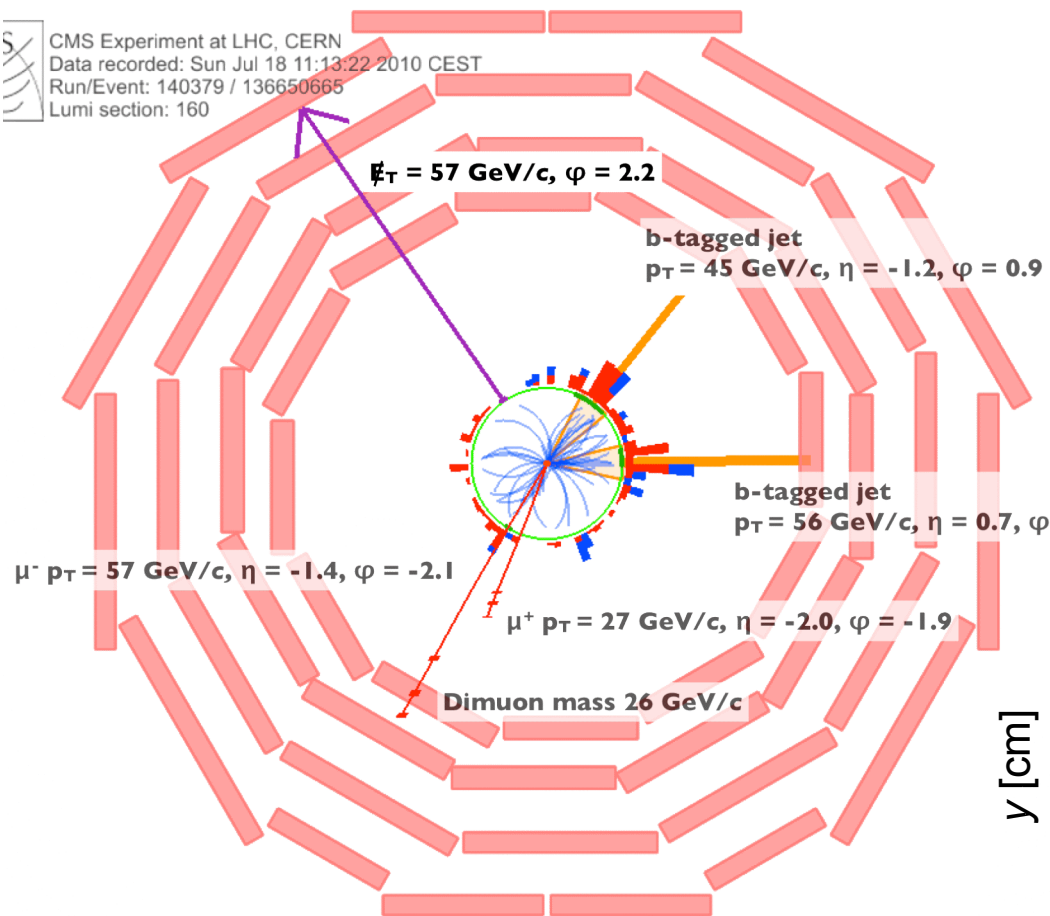
- Z-boson veto (ee, mumu)
  - |M(l1)-M(Z)|>15 GeV
- Missing Et (MET)
  - Using calorimeter & tracking
  - MET>30(20) GeV in ee, mumu (emu)



- Jets
  - Anti-Kt (R=0.5)
  - Using calorimeter & tracking
  - pT>30 GeV, |mu|<2.4
  - Expect >=2 jets for ttbar

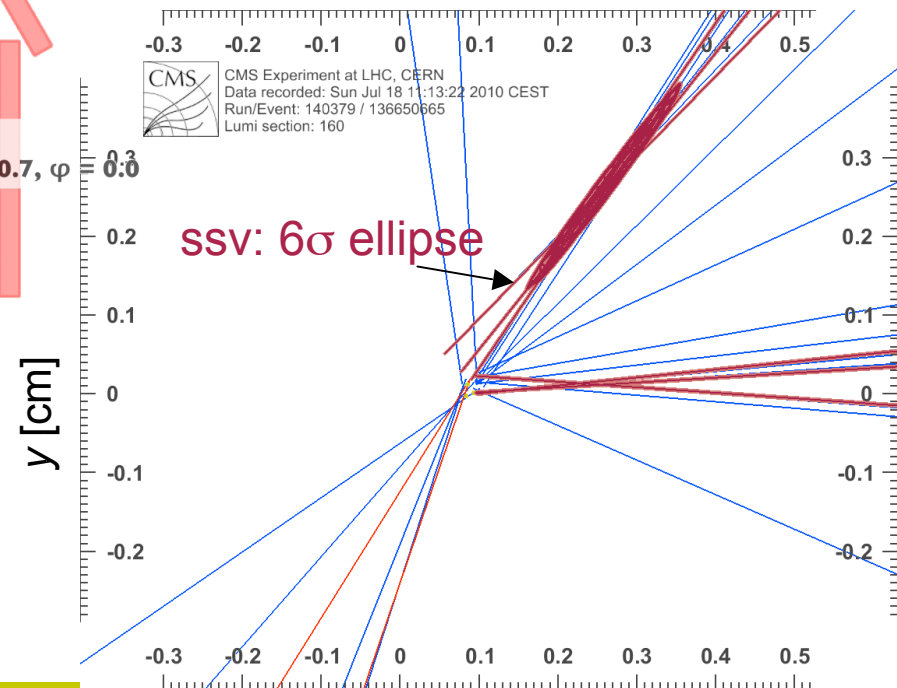
# Di- $\mu$ candidate event, 2 b-tags


 CMS Experiment at LHC, CERN  
 Data recorded: Sun Jul 18 11:13:22 2010 CEST  
 Run/Event: 140379 / 136650665  
 Lumi section: 160



## Selection:

2 muons with opposite charge  
 2 jets, both w/ good/clear *b*-tags  
 (and secondary vertices!)  
 significant Missing  $E_T$  ( $>50 \text{ GeV}$ )  
 Reconstructed mass:  $160\text{-}220 \text{ GeV}/c^2$



# Di-lepton event yields

- Z-veto,  $N(\text{jets}) \geq 1$

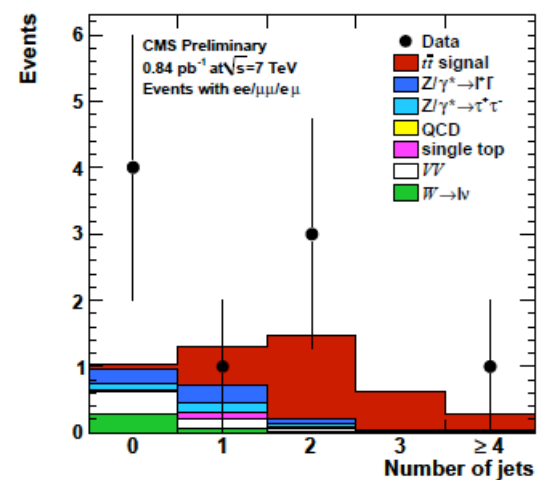
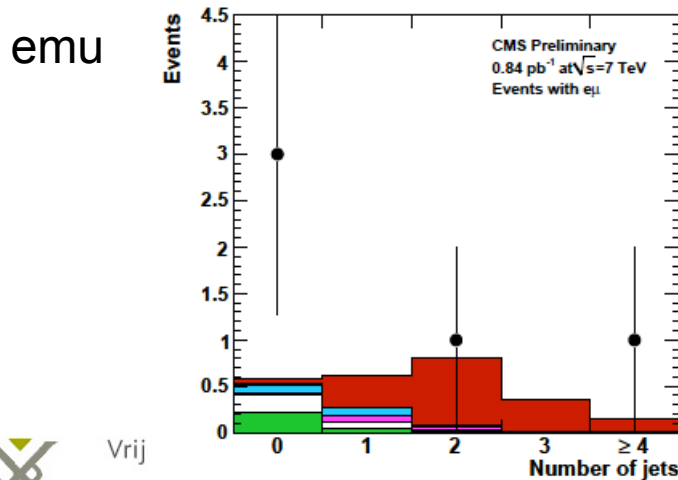
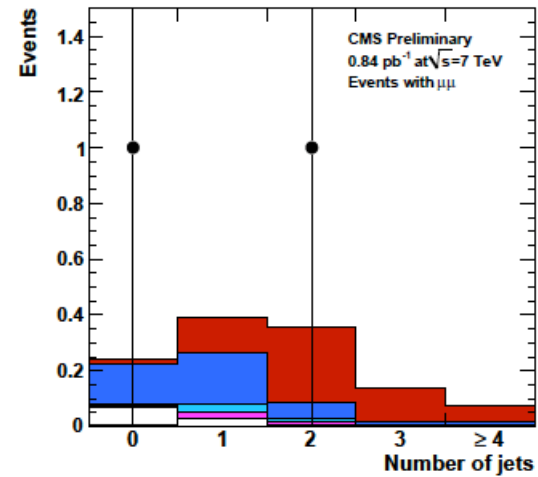
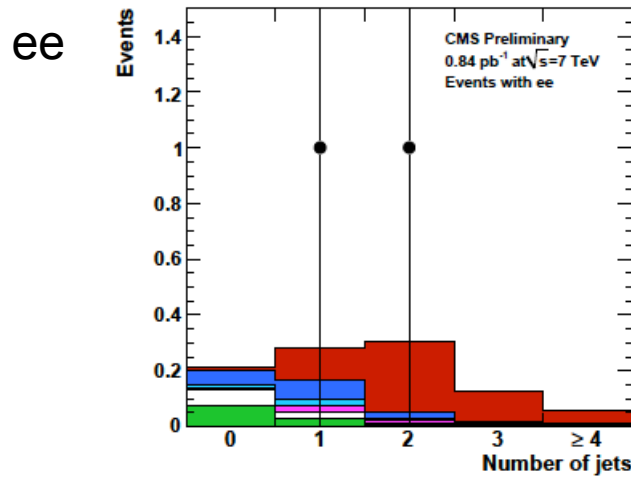
Sample	$ee$	$\mu\mu$	$e\mu$
Dilepton $t\bar{t}$	$0.63 \pm 0.09 \pm 0.12$	$0.70 \pm 0.11 \pm 0.13$	$1.70 \pm 0.26 \pm 0.32$
$VV$	$0.05 \pm 0.03$	$0.05 \pm 0.03$	$0.12 \pm 0.06$
Single top - $tW$	$0.04 \pm 0.02$	$0.05 \pm 0.03$	$0.12 \pm 0.06$
Drell-Yan $\tau\tau$	$0.08 \pm 0.04$	$0.13 \pm 0.07$	$0.19 \pm 0.09$
Drell-Yan $ee, \mu\mu$	$4.2 \pm 1.1$	$5.0 \pm 1.2$	$0.04 \pm 0.02$
Non-dilepton $t\bar{t}$	$0.02 \pm 0.01$	$0.003 \pm 0.002$	$0.03 \pm 0.02$
$W$ +jets	$0.06 \pm 0.03$	$0.000^{+0.002}_{-0.000}$	$0.07 \pm 0.04$
QCD multijets	$0^{+10}_{-0}$	$0^{+10}_{-0}$	$0^{+10}_{-0}$
Total simulated	$5.1 \pm 1.1$	$5.9 \pm 1.2$	$2.3 \pm 0.4$
QCD data-driven	$0.0^{+0.1}_{-0.0} \ ^{+0.1}_{-0.0}$	$0.0^{+0.2}_{-0.0} \ ^{+0.2}_{-0.0}$	$0.0^{+0.1}_{-0.0} \ ^{+0.1}_{-0.0}$
$W$ +jets data-driven	$0.2^{+0.2}_{-0.0} \ ^{+0.1}_{-0.0}$	$0.0^{+0.4}_{-0.0} \ ^{+0.2}_{-0.0}$	$0.0^{+0.4}_{-0.0} \ ^{+0.2}_{-0.0}$
Drell-Yan data-driven	$3.6 \pm 0.6 \pm 1.8$	$4.3 \pm 0.7 \pm 2.1$	N/A
Data	6	6	2

## Systematics:

- Signal and DY: 15% acc\*eff (conservative), 15% theory, 11% lumi
- Other backgrounds: 50% (conservative)
- Data-driven backgrounds: DY,  $W$ +jets: 50%; QCD: 100%

# Di-lepton: jet multiplicity

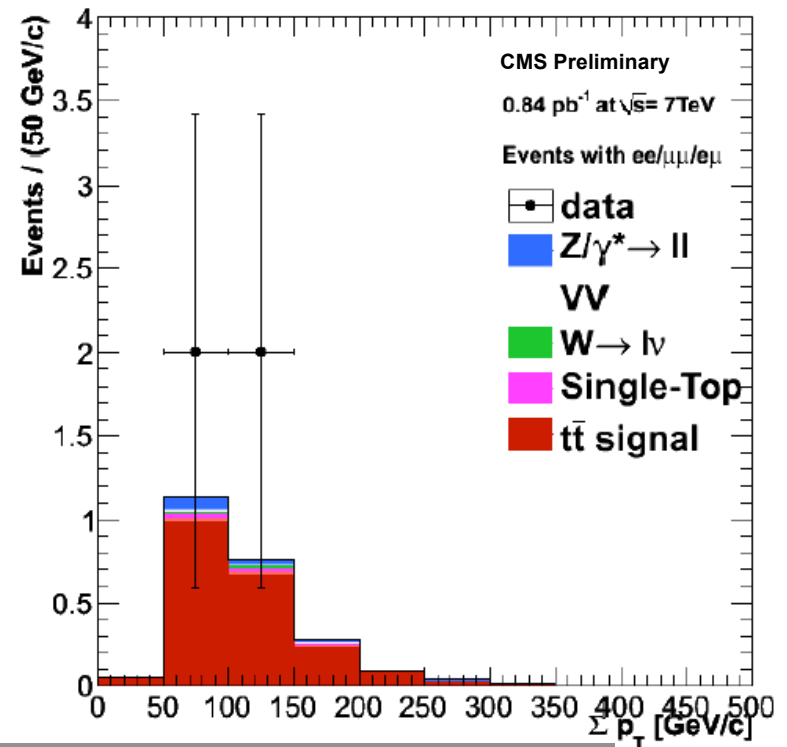
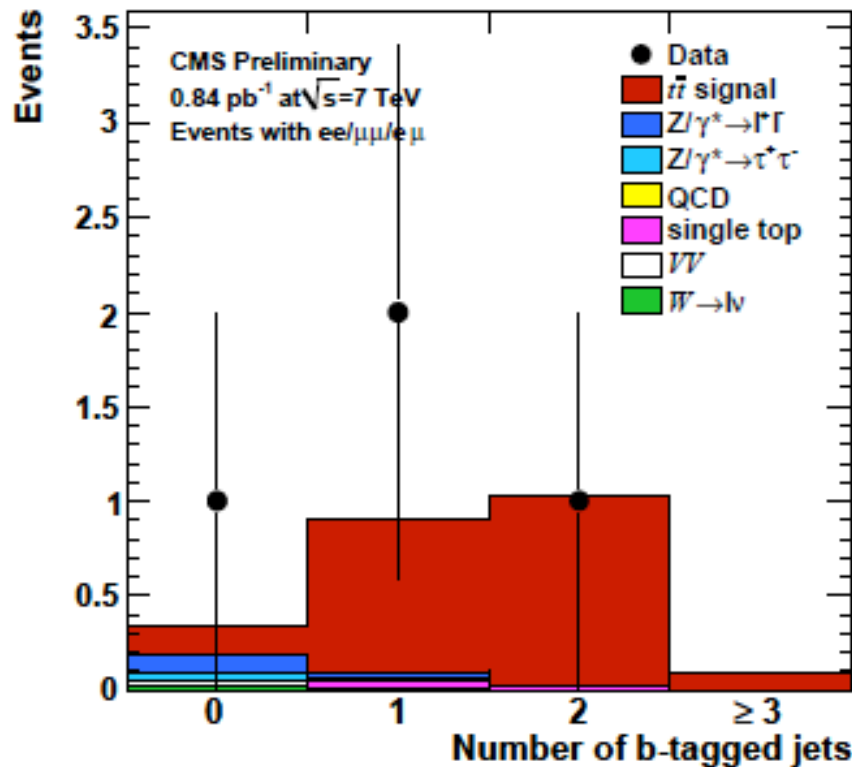
- N(jets), with Z-Veto, MET requirement applied



Vrij

# Di-lepton: all channels combined

- All cuts applied: Z-Veto, MET,  $N(\text{jets}) \geq 2$



Track-counting tagger

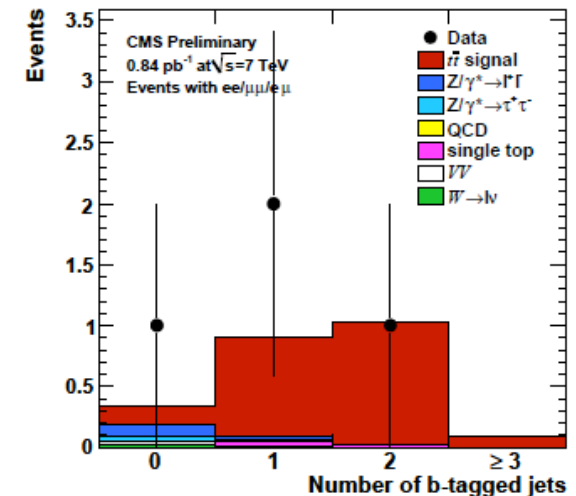
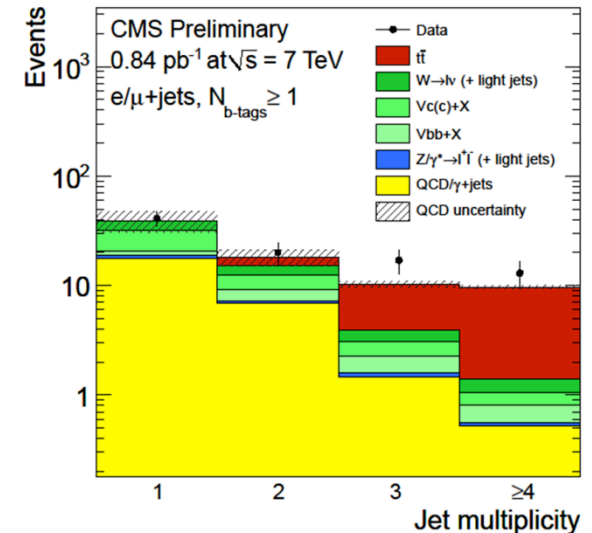
4 candidates observed  
<0.5 total background expected



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# Conclusion

- CMS top quark analyses on  $L=0.84$  /pb of LHC data presented
- Event yields consistent with simulation within statistical limits
  - Results consistent with SM predictions
  - Next iteration will employ data driven methods for major backgrounds
- Good performance CMS detector
  - B-tagging, Leptons, MET, jets
- Much larger sample in hand
  - First cross section measurements in very near future!



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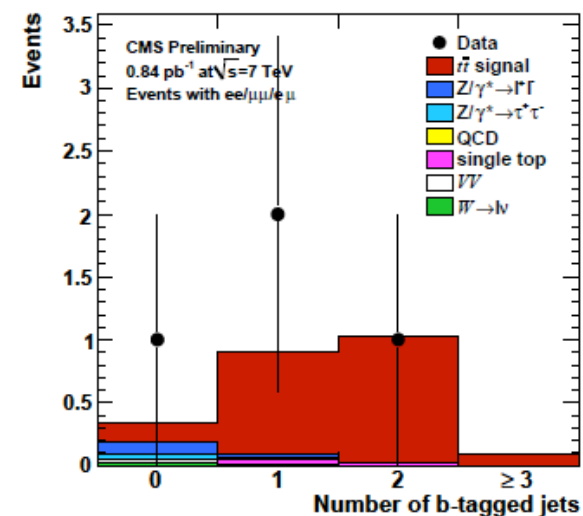
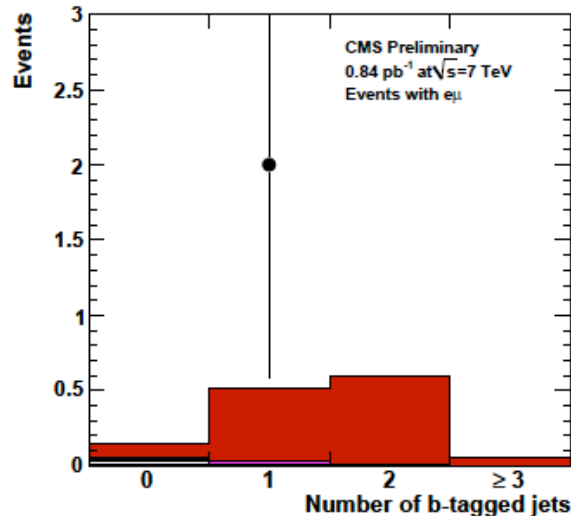
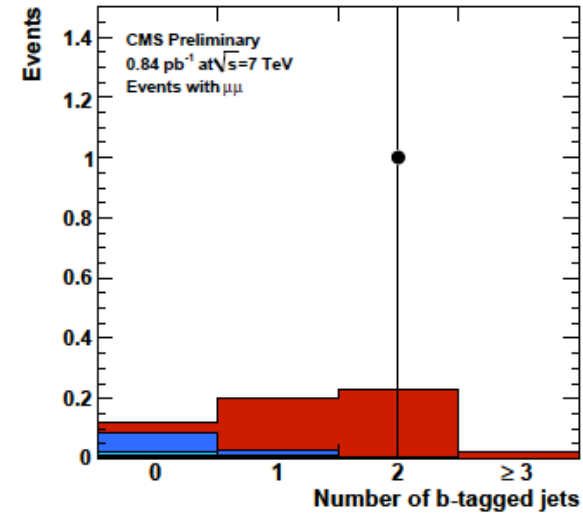
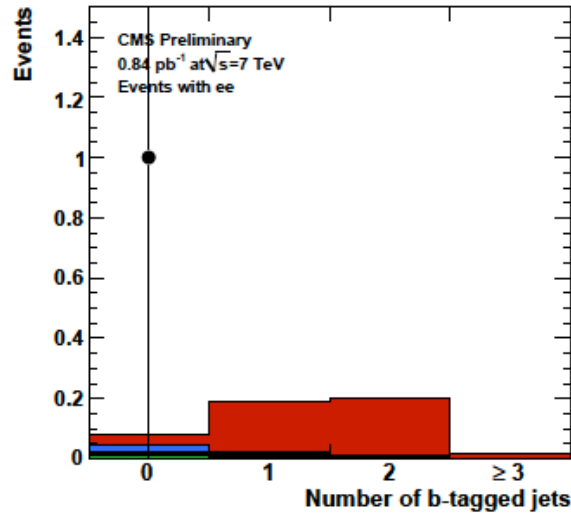
# Backup



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# b-tag multiplicity (full selection)

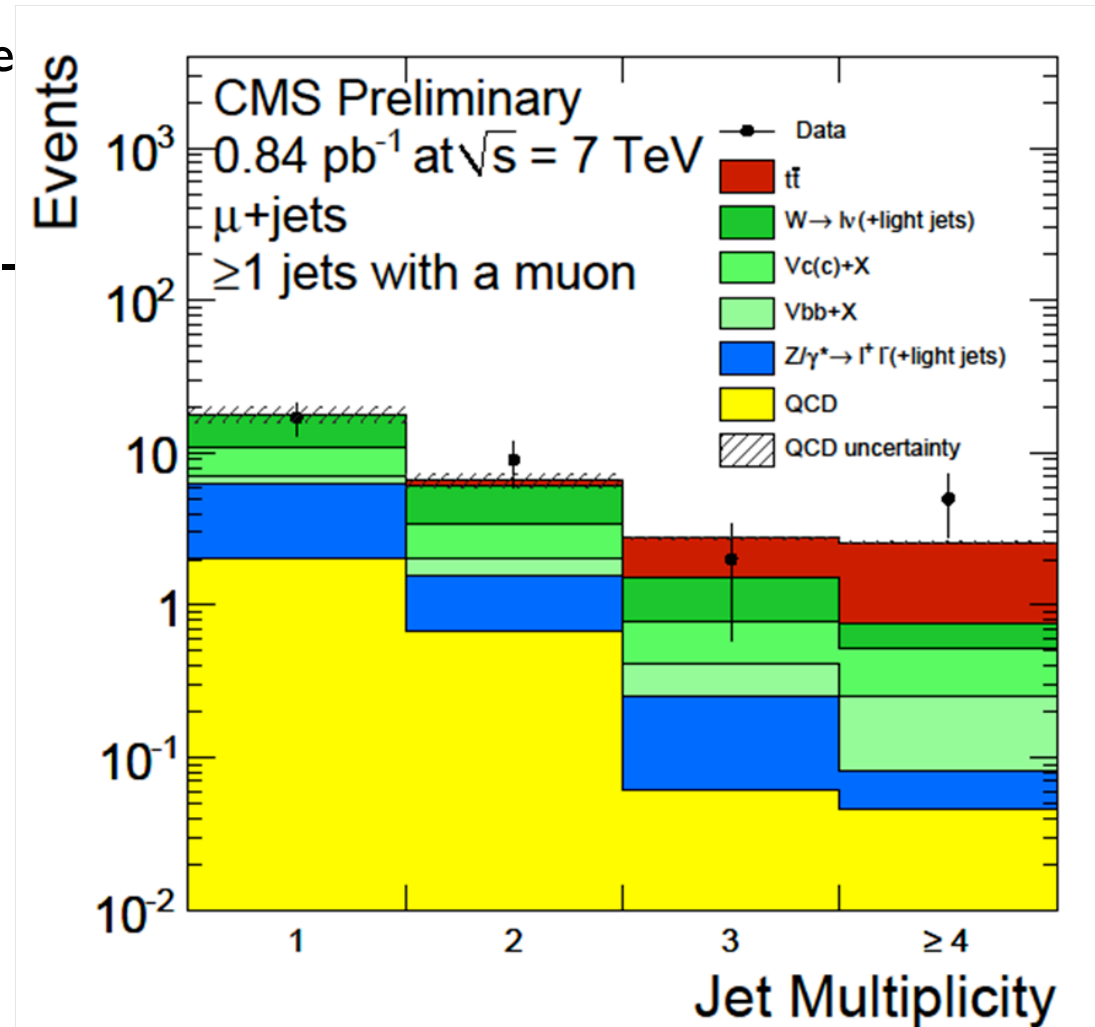
- With Z-veto, MET,  $N(\text{jets}) \geq 2$  cuts applied





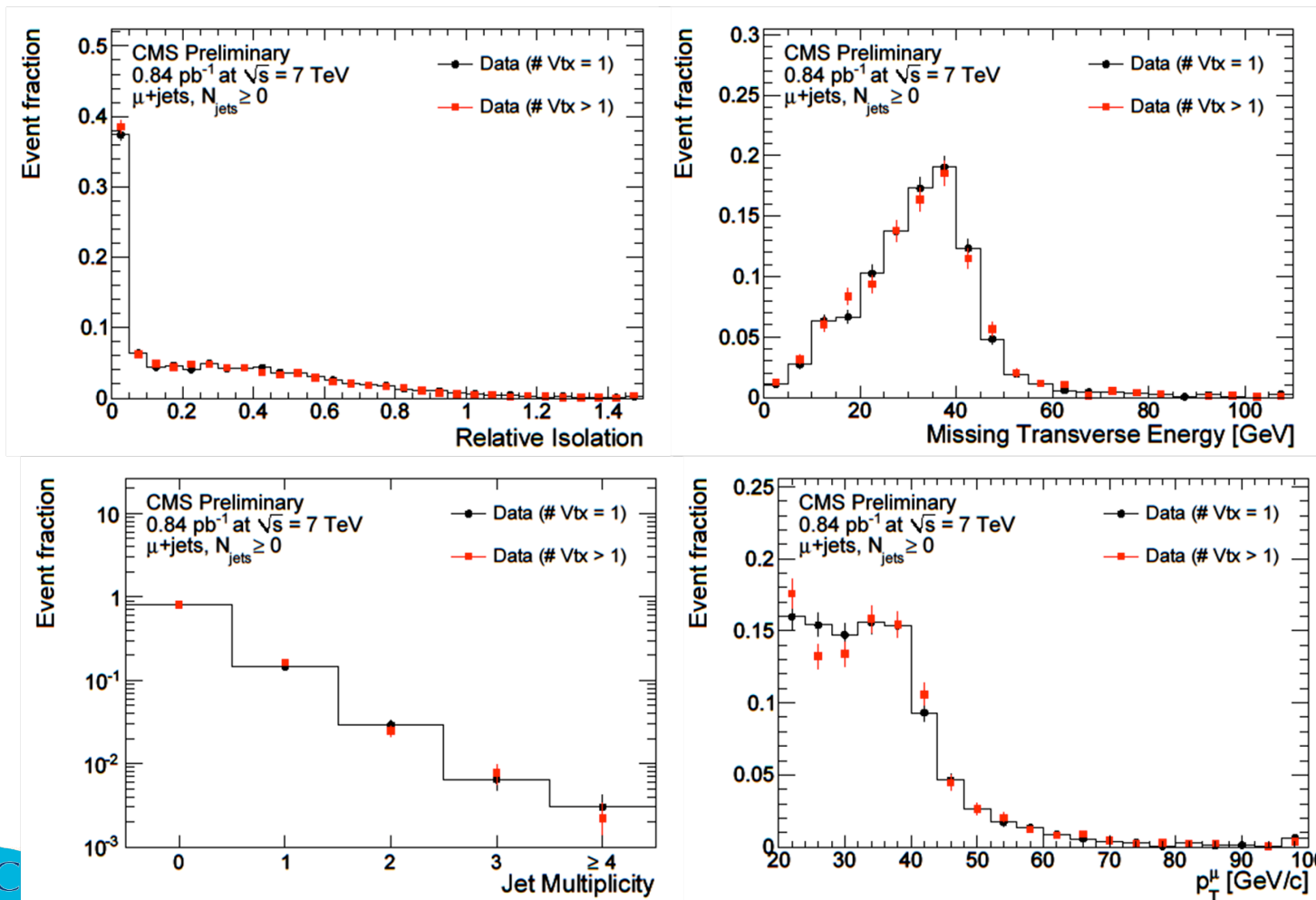
# Increasing b-content - soft $\mu$ tag

- “Muon-in-jet”
  - $\mu$ +jets: request at least one jet associated with a muon within  $dR < 0.4$
  - Sensitive to semileptonic b-decays in jets
- For  $N(\text{jets}) \geq 3$ , observe 7 events, consistent with  $t\bar{t}$  signal plus  $\sim 2.5$  background events

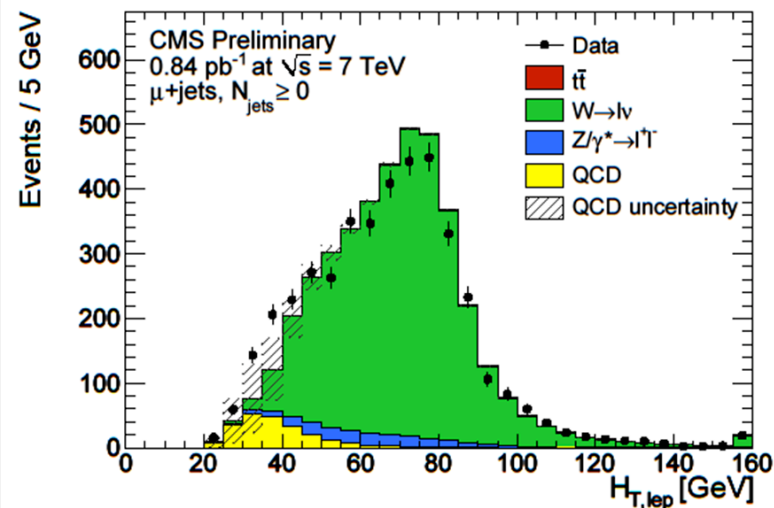
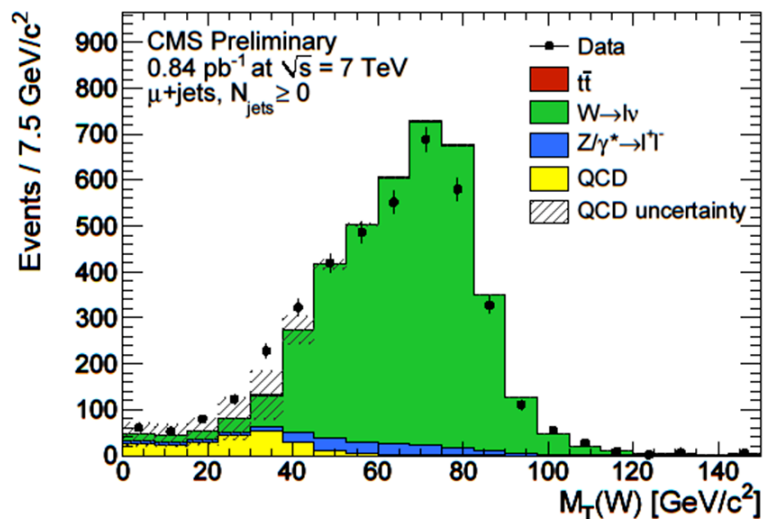
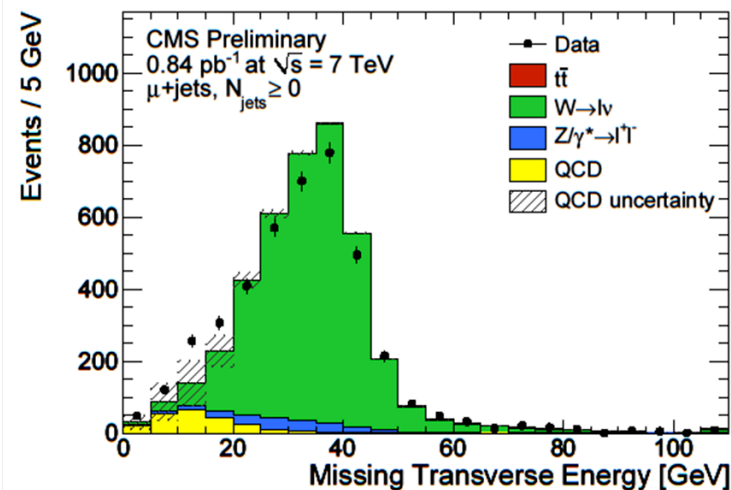
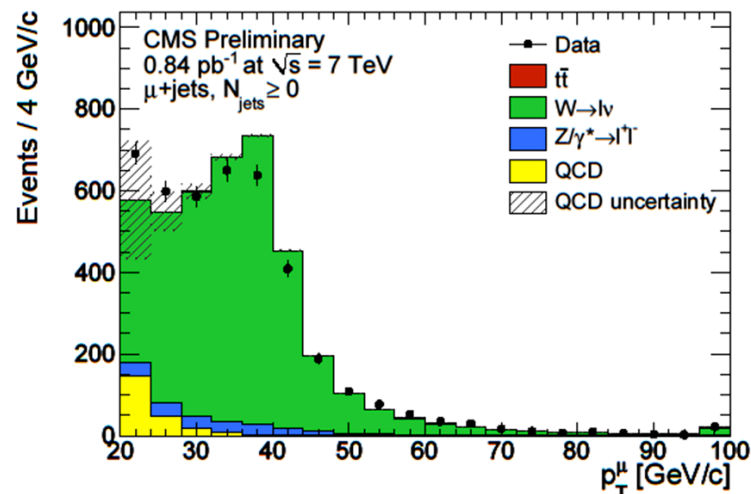


# Are we sensitive to Pile-up?

- LHC currently non-negligible pile-up,  $\langle N \rangle \sim 0.9$
- Simulation without pileup, so compare data with one vertex vs data with  $\geq 1$  vertex
- Sensitive distributions show no change within stat. limits.



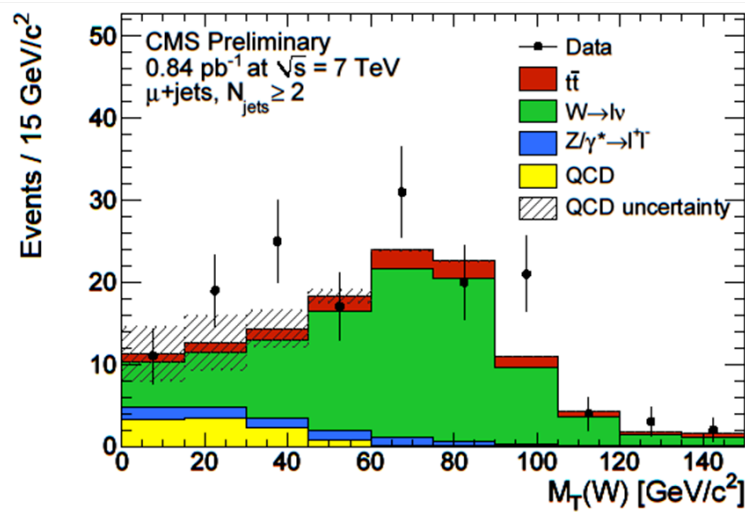
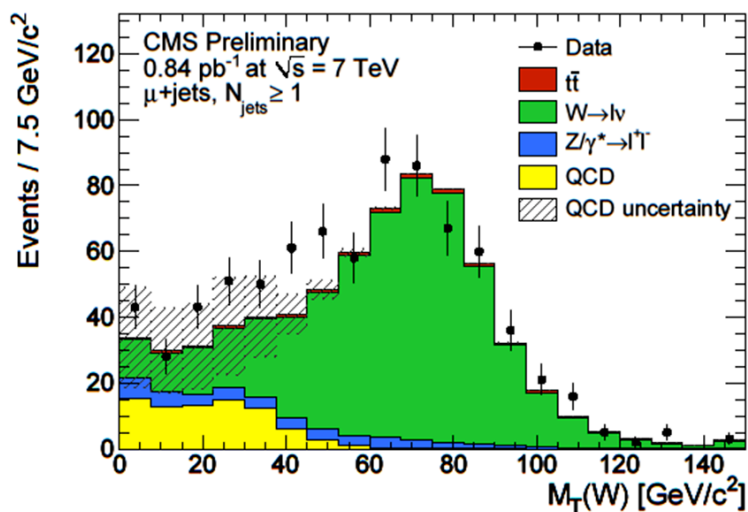
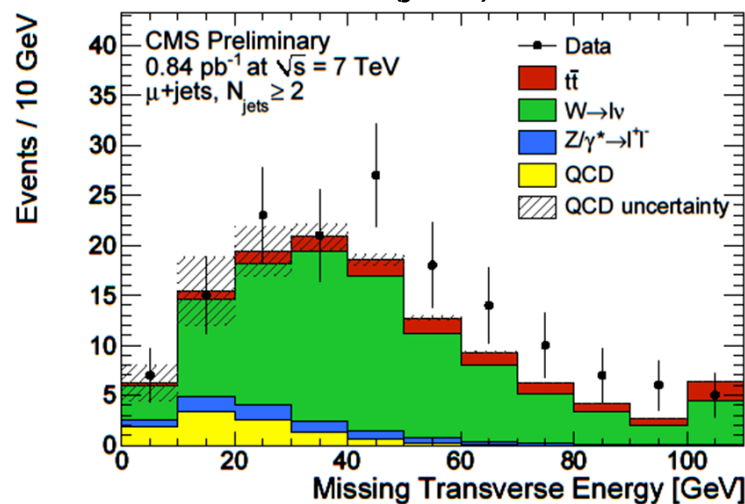
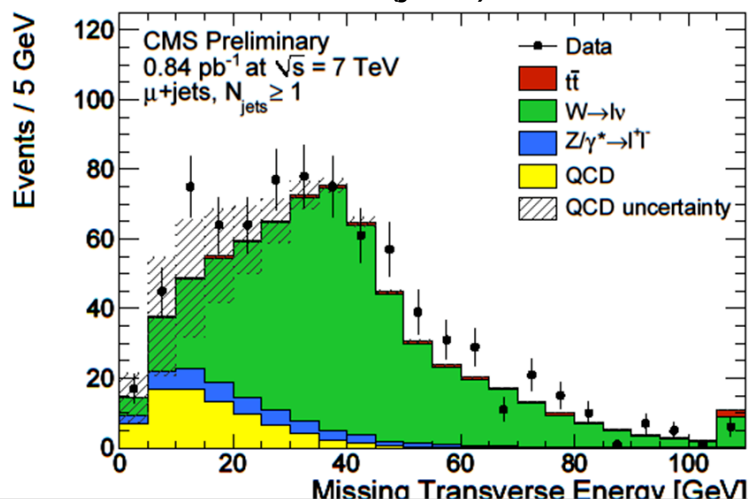
# $\mu$ +jets, $N(\text{jets}) \geq 0$



# $\mu + \text{jets}, N(\text{jets}) \geq 1, 2$

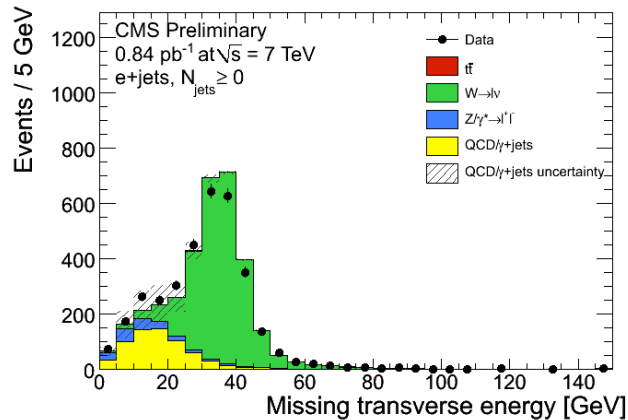
$N(\text{jets}) \geq 1$

$N(\text{jets}) \geq 2$

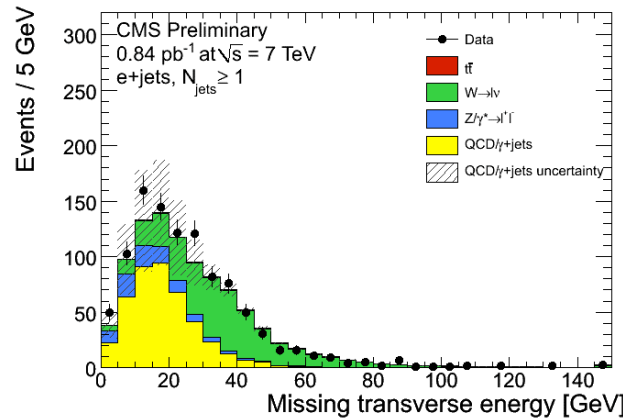


# e+jets: missing $E_T$ and transverse W mass

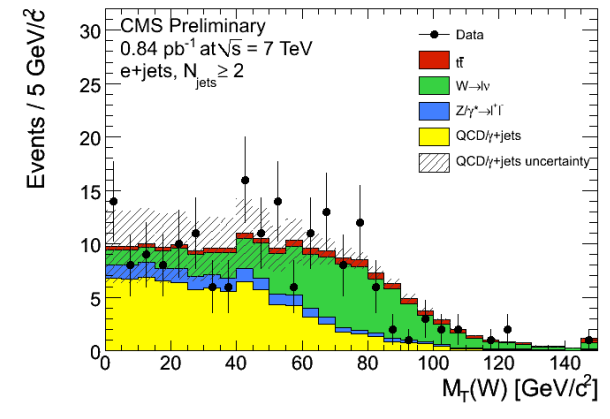
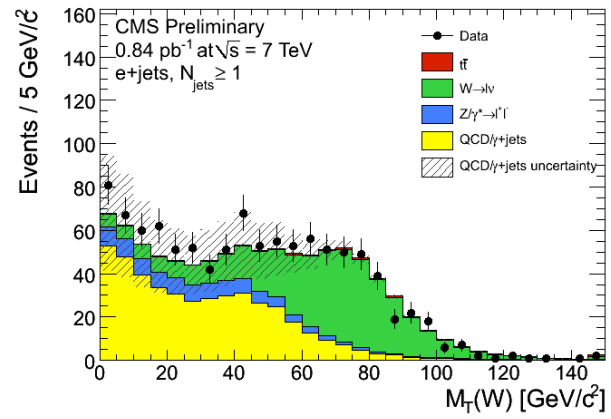
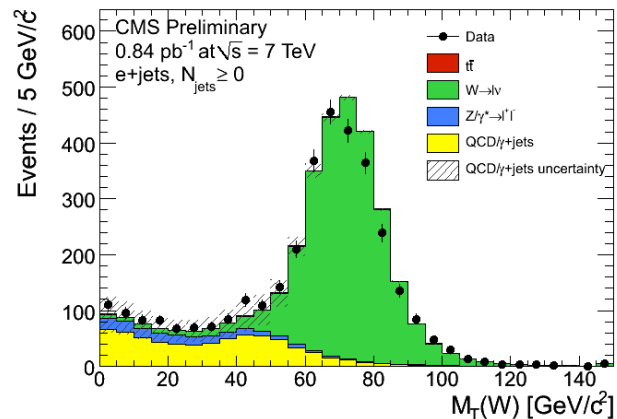
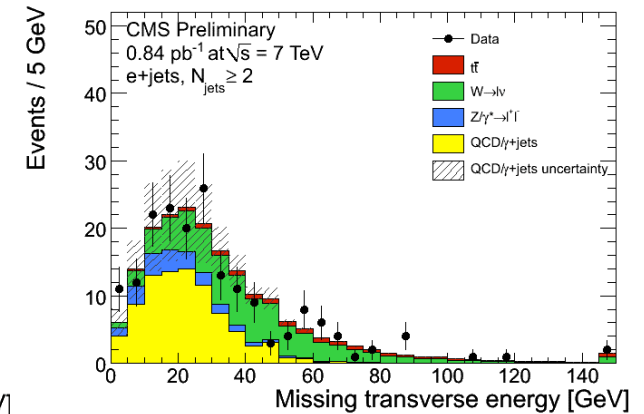
$N(\text{jets}) \geq 0$



$N(\text{jets}) \geq 1$



$N(\text{jets}) \geq 2$

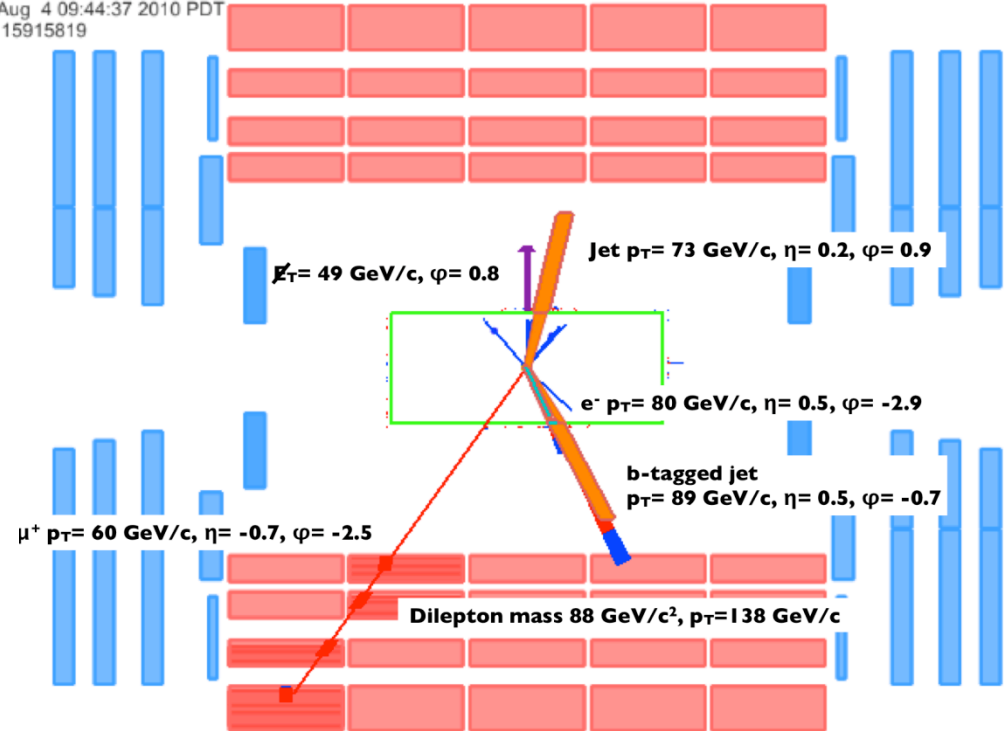


$M_T(W)$ : transverse W mass (calculated from lepton+MET)

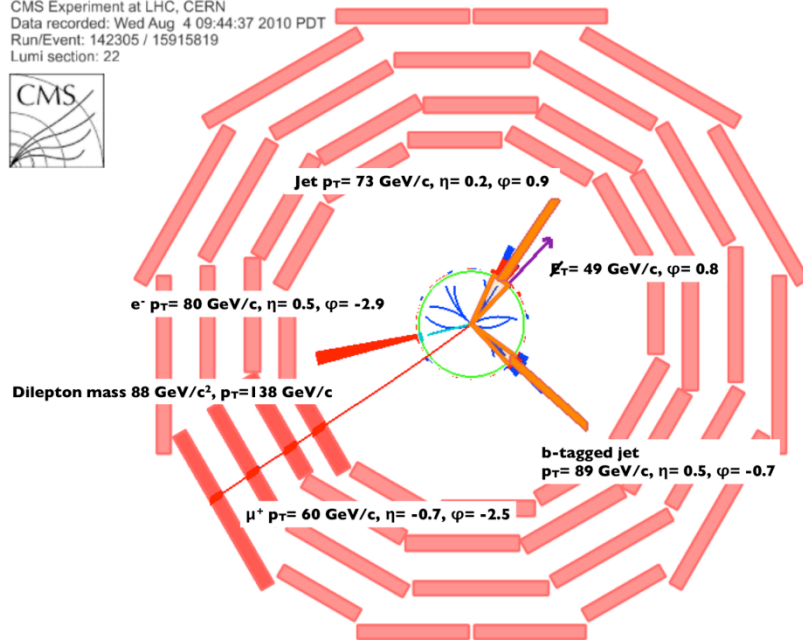
# e-mu candidate event

Muon Pt=60 GeV  
 Electron Pt=80 GeV  
 2 jets, 1 b-tag  
 MET=49 GeV

CMS Experiment at LHC, CERN  
 Data recorded: Wed Aug 4 09:44:37 2010 PDT  
 Run/Event: 142305 / 15915819  
 Lumi section: 22



CMS Experiment at LHC, CERN  
 Data recorded: Wed Aug 4 09:44:37 2010 PDT  
 Run/Event: 142305 / 15915819  
 Lumi section: 22

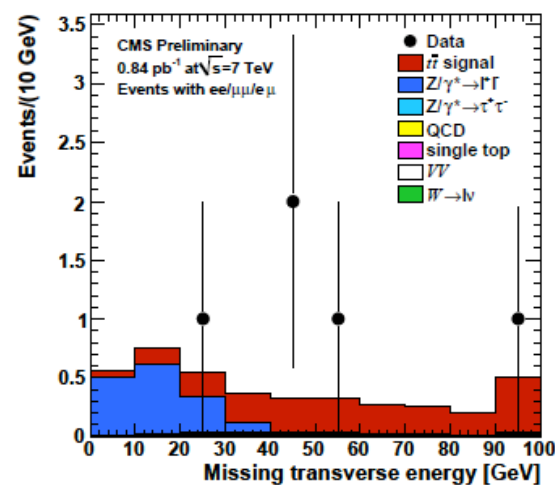
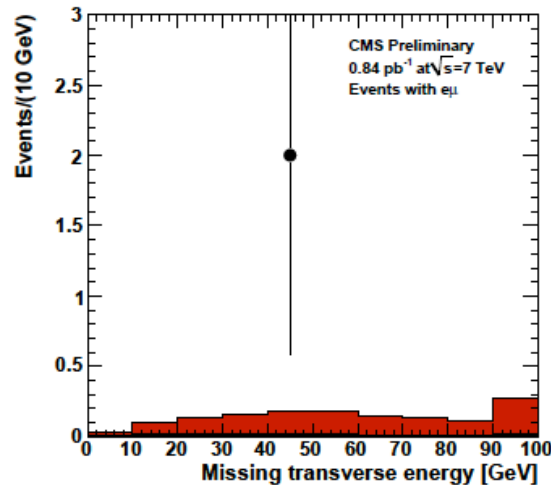
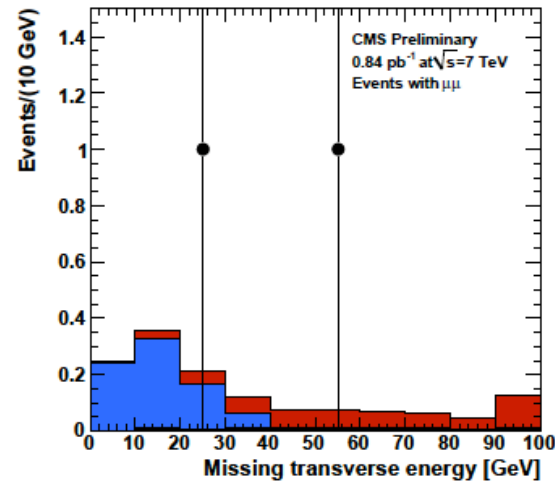
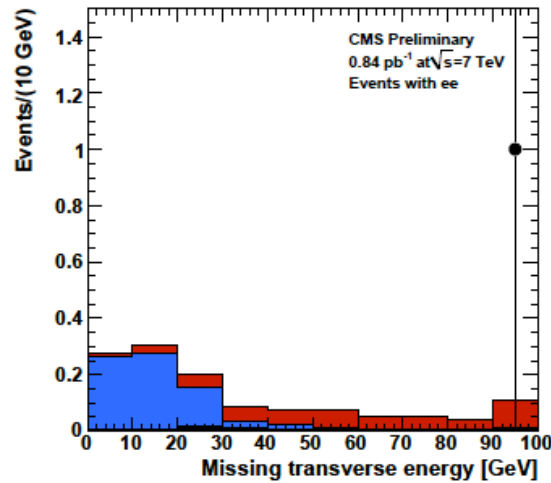


Mass hypothesis consistent with being a  $t\bar{t}$  event



# Di-lepton: missing transverse energy

- MET, with Z-veto,  $N(\text{jets}) \geq 2$  requirements applied



Vrije

# Dilepton Event Yields

- $L=0.84$  /pb: Using relaxed selection to gain maximum acceptance
  - No Z-veto, no MET, no N(jets) requirements

Process	$ee$	$\mu\mu$	$e\mu$
Dilepton $t\bar{t}$	$0.84 \pm 0.13 \pm 0.16$	$0.94 \pm 0.14 \pm 0.17$	$1.75 \pm 0.26 \pm 0.33$
$VV$	$0.23 \pm 0.12$	$0.25 \pm 0.13$	$0.35 \pm 0.18$
Single top - $tW$	$0.06 \pm 0.03$	$0.07 \pm 0.03$	$0.13 \pm 0.07$
Drell-Yan $\tau\tau$	$0.6 \pm 0.3$	$0.7 \pm 0.4$	$1.3 \pm 0.7$
Drell-Yan $ee, \mu\mu$	$298 \pm 74$	$343 \pm 86$	$0.1 \pm 0.1$
Non-dilepton $t\bar{t}$	$0.02 \pm 0.01$	$0.004 \pm 0.002$	$0.03 \pm 0.02$
$W$ +jets	$0.3 \pm 0.1$	$0.01 \pm 0.01$	$0.3 \pm 0.2$
QCD multijets	$0^{+10}_{-0}$	$0.00^{+10}_{-0}$	$0^{+10}_{-0}$
Total simulated	$300 \pm 74$	$345 \pm 86$	$4.0 \pm 0.8$
Data	305	294	6

## Systematics:

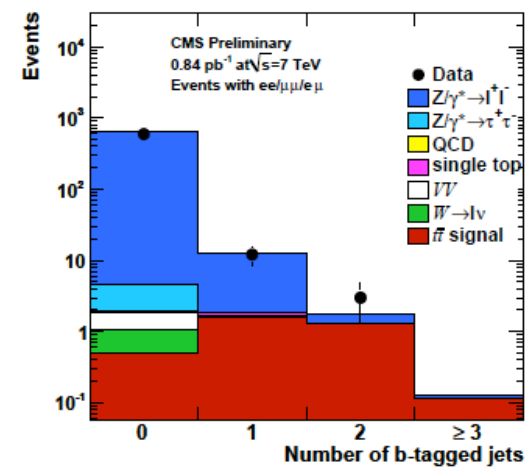
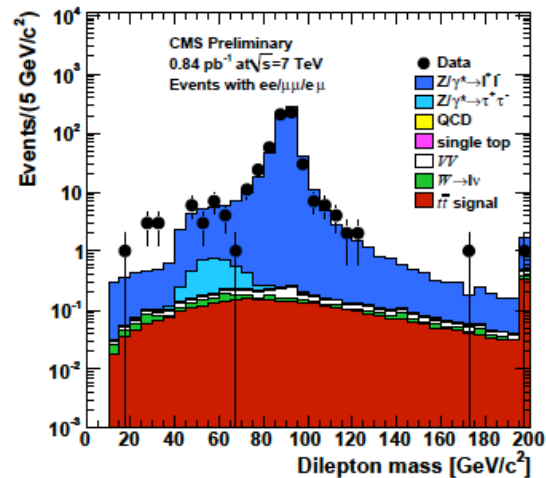
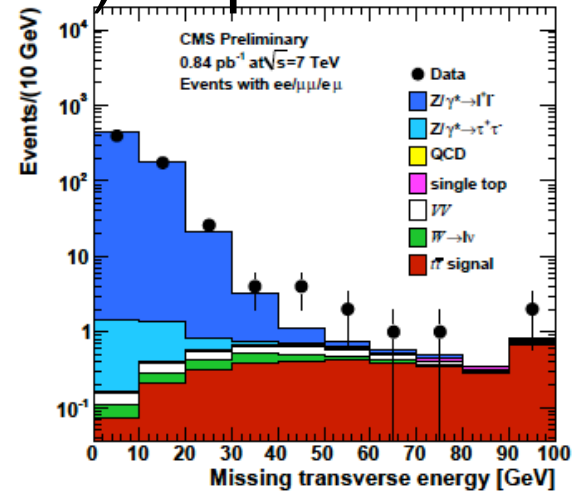
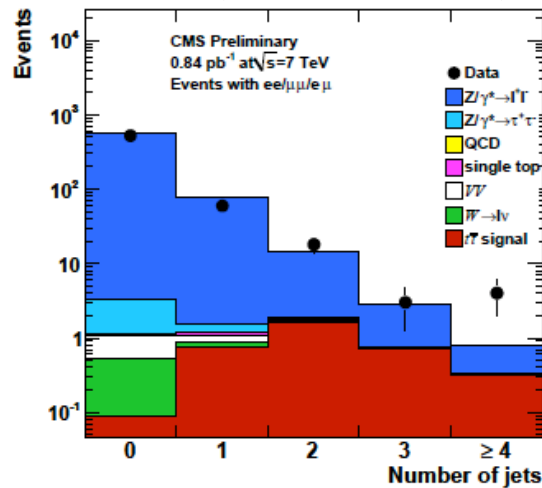
- Signal and DY: 15% acc\*eff (conservative), 15% theory, 11% lumi
- Other backgrounds: 50% (conservative)





# Data vs MC (relaxed selection)

- No Z-veto, no MET, N(jets) requirements



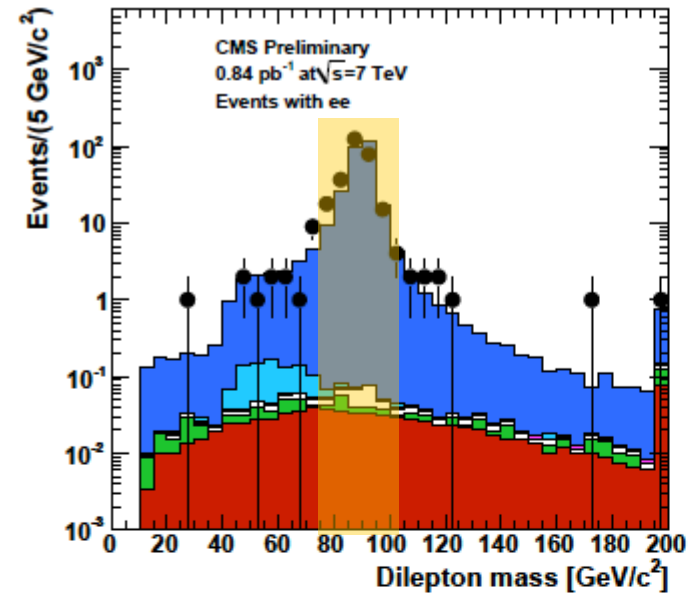
# Data driven Drell-Yan Background

Estimate Drell-Yan background outside  
Z-veto region from events inside:

ratio outside/inside from  
DY simulation

$$N_{\text{out}}^{ee,\text{data}} = R_{\text{out/in}}^{ee} \left( N_{\text{in}}^{ee,\text{data}} - \underbrace{0.5 N_{\text{in}}^{e\mu,\text{data}} k_{ee}}_{\text{correction for non-DY contribution in Z-veto region from } e\mu \text{ sample}} \right)$$

correction for non-DY  
contribution in Z-veto  
region from  $e\mu$  sample



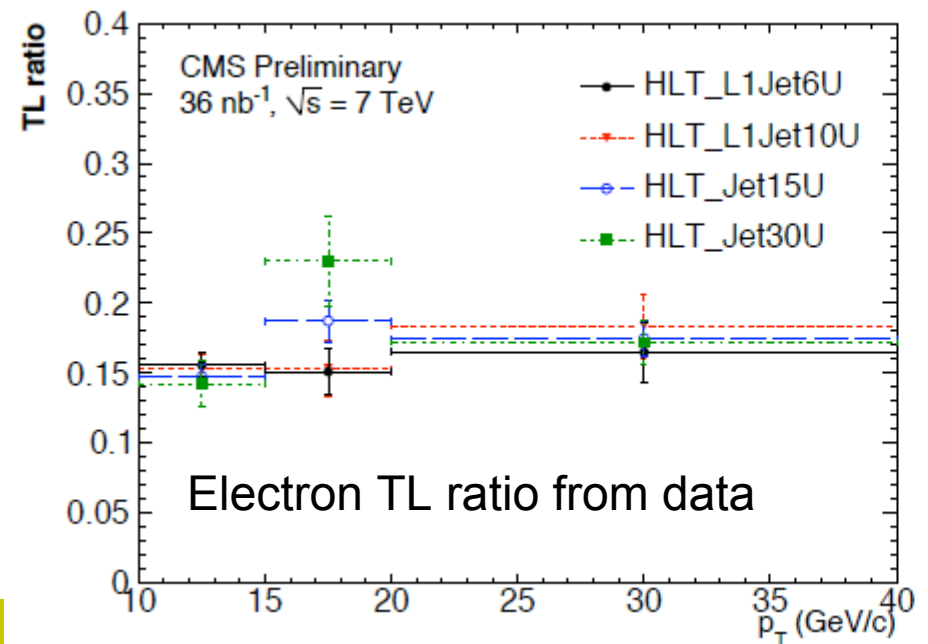
Sample	ID, ISO, Z-veto	with $N_{\text{jet}} \geq 1$	with $N_{\text{jet}} \geq 2$ and $\cancel{E}_T > 30$ GeV
<i>ee</i>			
DY in simulation	$26 \pm 6$	$4.2 \pm 1.1$	$0.04 \pm 0.01$
DY estimate in data	$26 \pm 1.6 \pm 13$	$3.6 \pm 0.6 \pm 1.8$	$0.4 \pm 0.2 \pm 0.2$
<i><math>\mu\mu</math></i>			
DY in simulation	$31 \pm 8$	$5.0 \pm 1.2$	$0.07 \pm 0.02$
DY estimate in data	$27 \pm 1.6 \pm 13$	$4.3 \pm 0.7 \pm 2.1$	$0.21^{+0.23}_{-0.21} \pm 0.11$

# Data-driven QCD, W+jets backgrounds

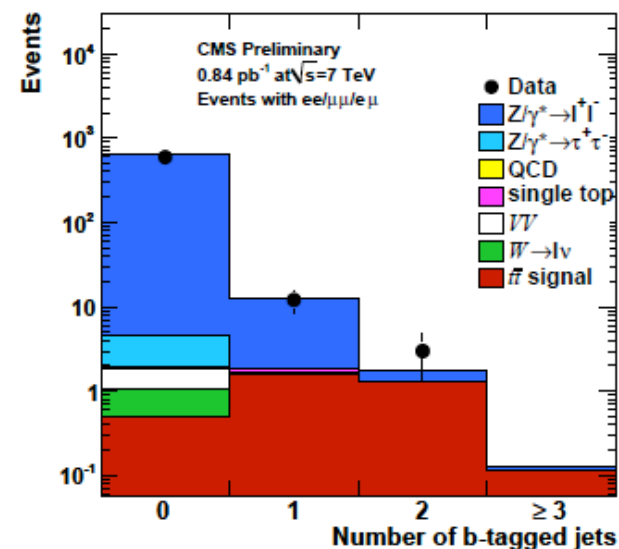
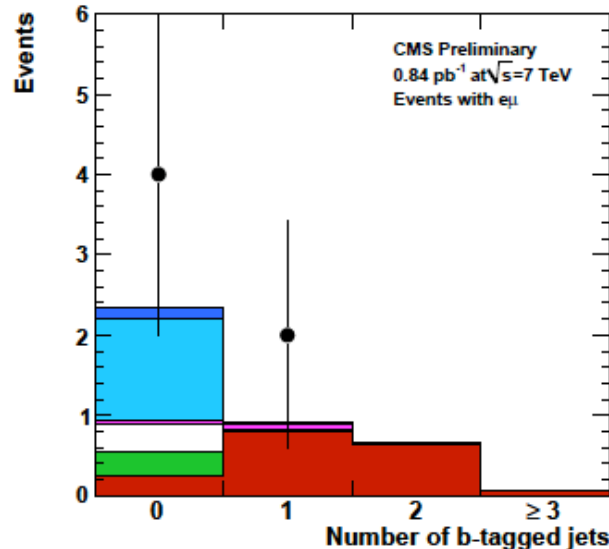
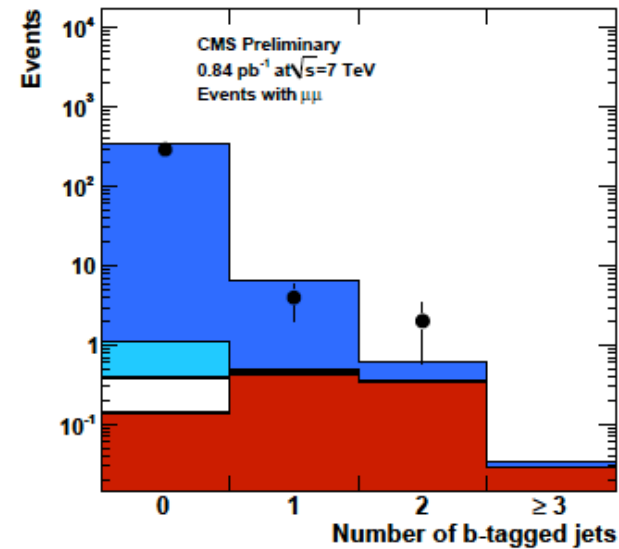
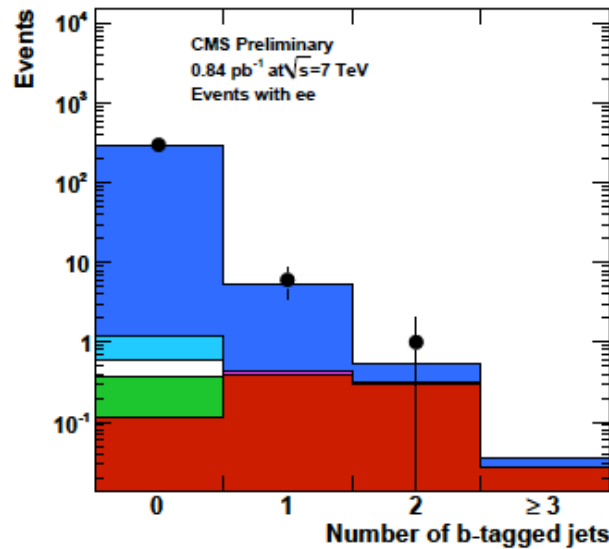
- “Fake” lepton backgrounds:
  - W+jets : one fake lepton
  - QCD: two fake leptons
- Determine a ‘tight-to-loose ratio’ (TL) in jet-triggered sample
- Apply to events where one (both) leptons pass loose, but fail tight lepton selection
- Weighed sum yields background estimate
- 50% systematics per “fake” lepton

$$N_{nn}^{QCD} = \sum_{i,j} \frac{TL_i TL_j}{(1 - TL_i)(1 - TL_j)} N_{nn}^{ij}$$

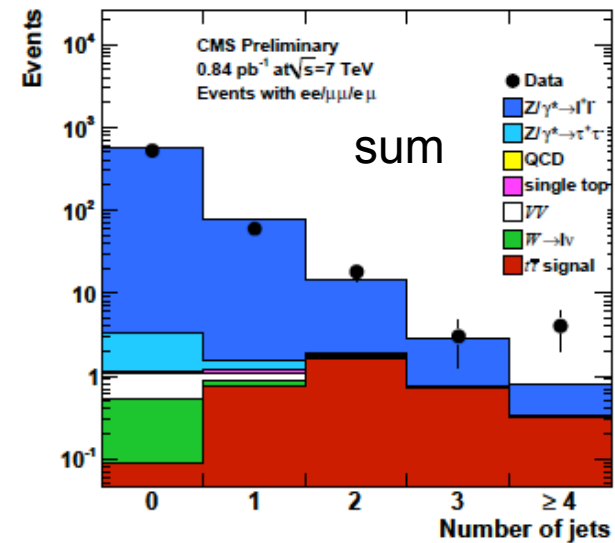
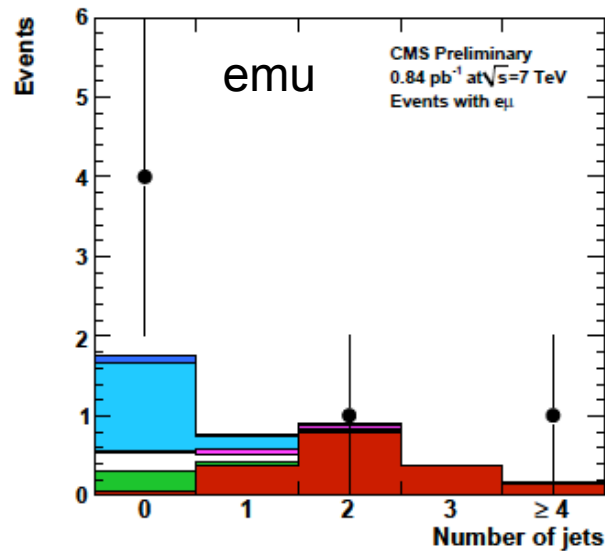
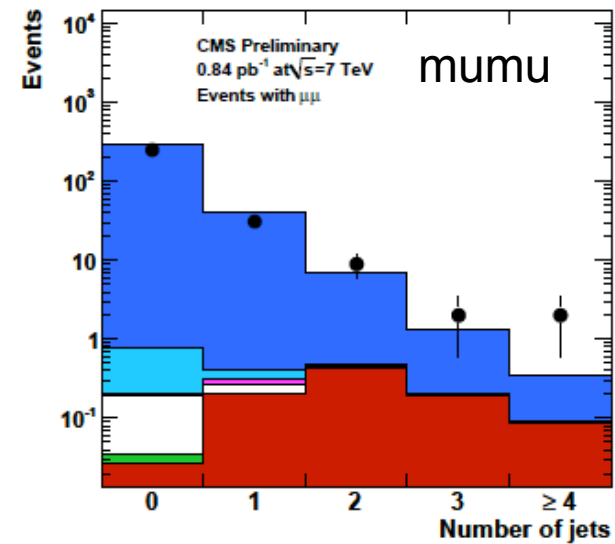
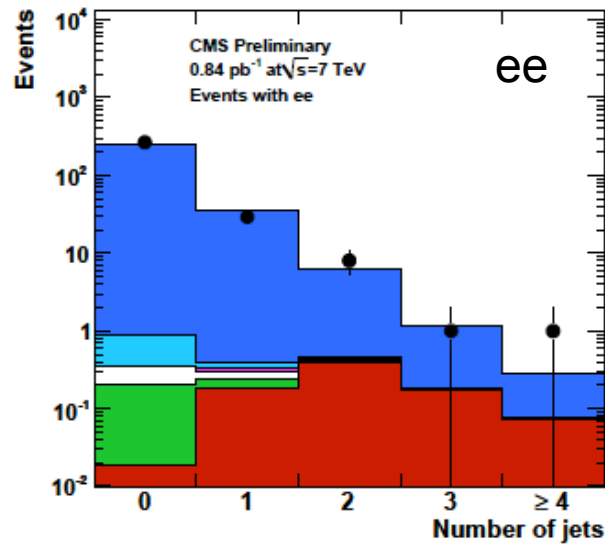
$$N_{nn}^{W Jets} = \sum_{i,j} \frac{TL_i}{(1 - TL_i)} N_{nn}^{ij}$$



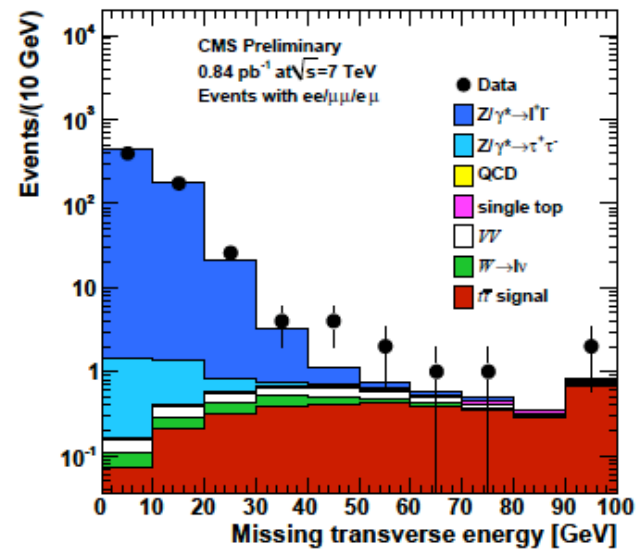
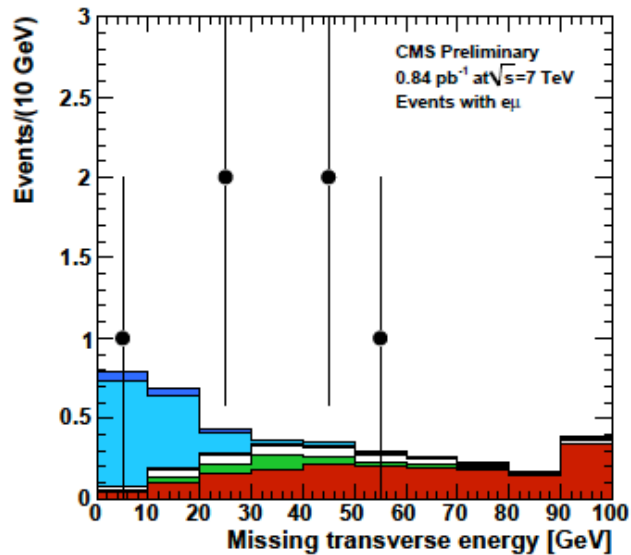
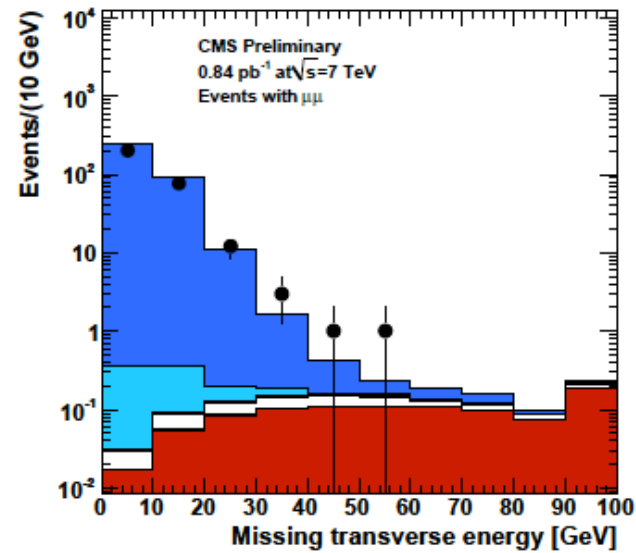
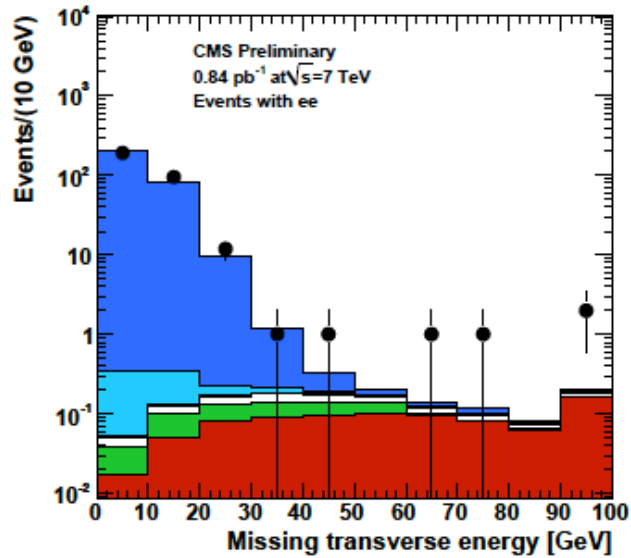
# b-tag multiplicity (relaxed sel.)



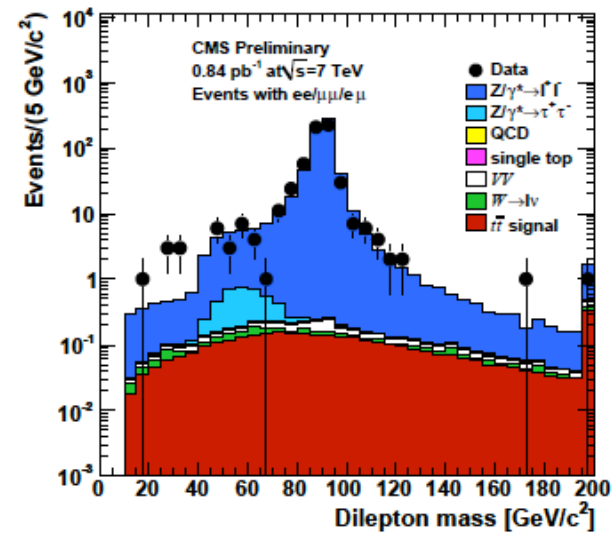
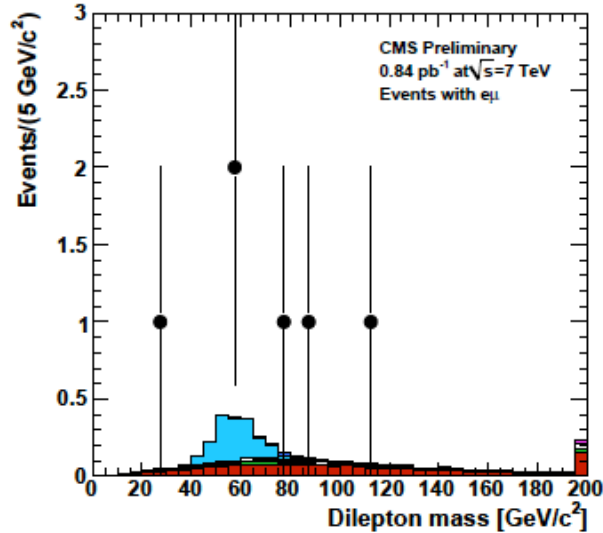
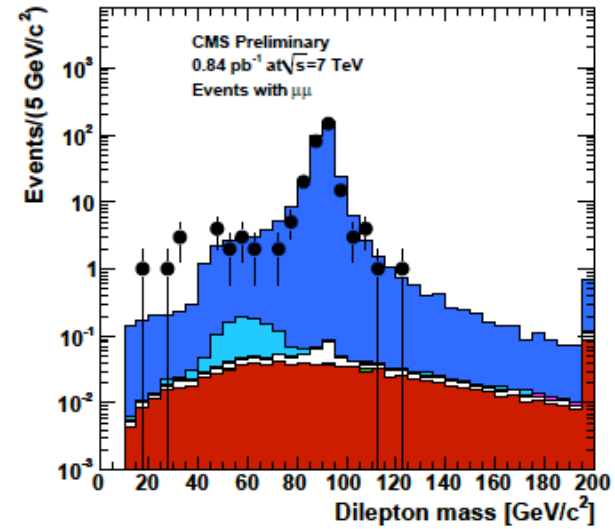
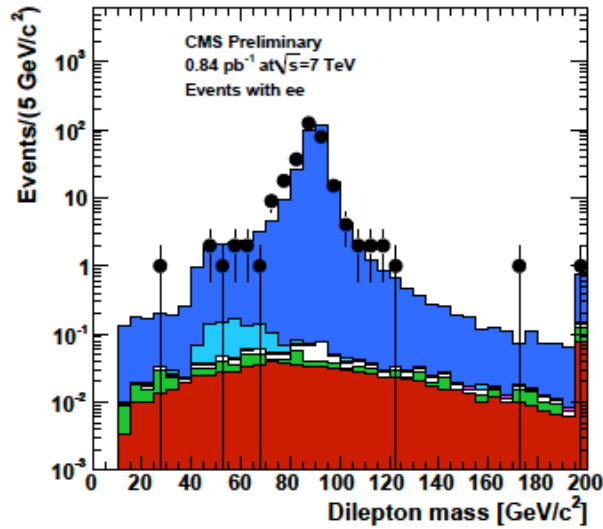
# Jet multiplicity (relaxed selection)



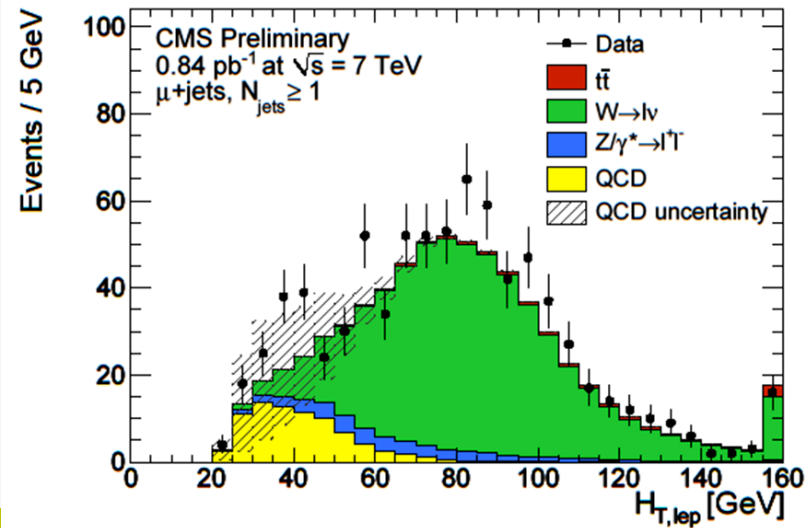
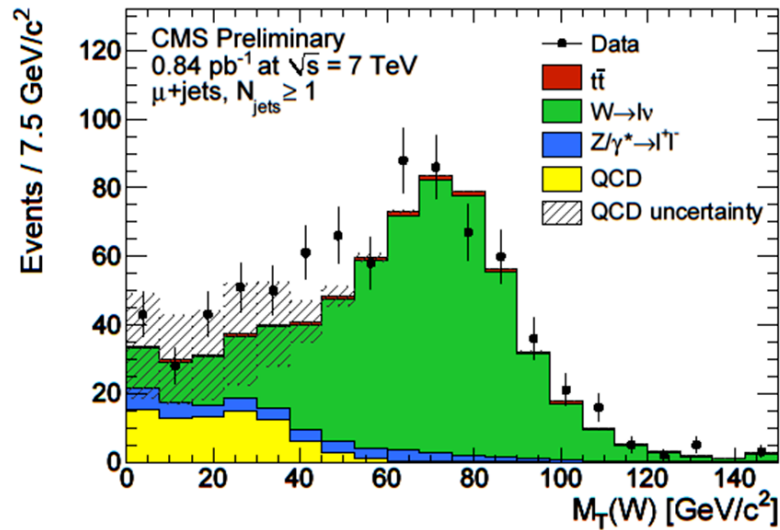
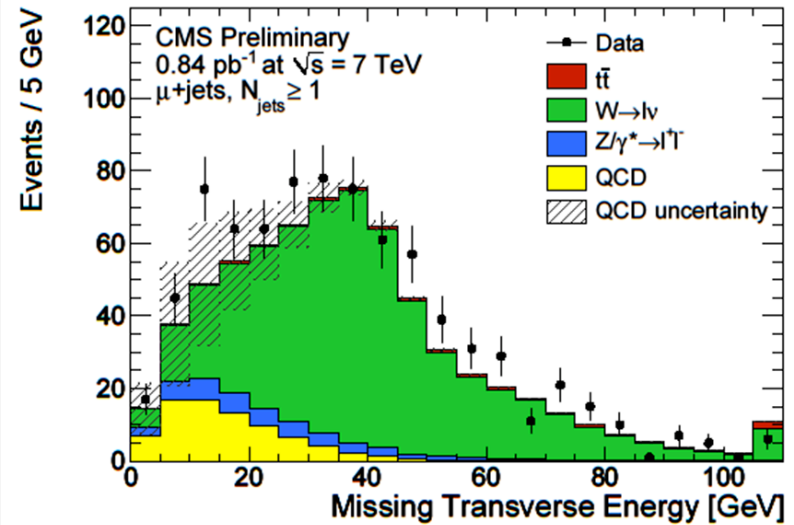
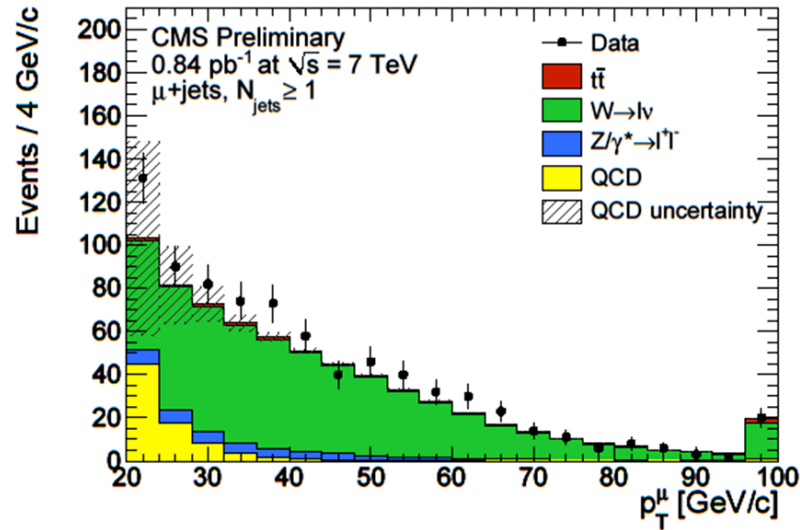
# Missing Transverse Energy (relaxed sel.)



# Dilepton invariant mass (relaxed sel.)



# mu+Jets, $\geq 1$ jets





# mu+Jets, $\geq 2$ jets

