Search for Standard Model Production of Four Top Quarks at CMS

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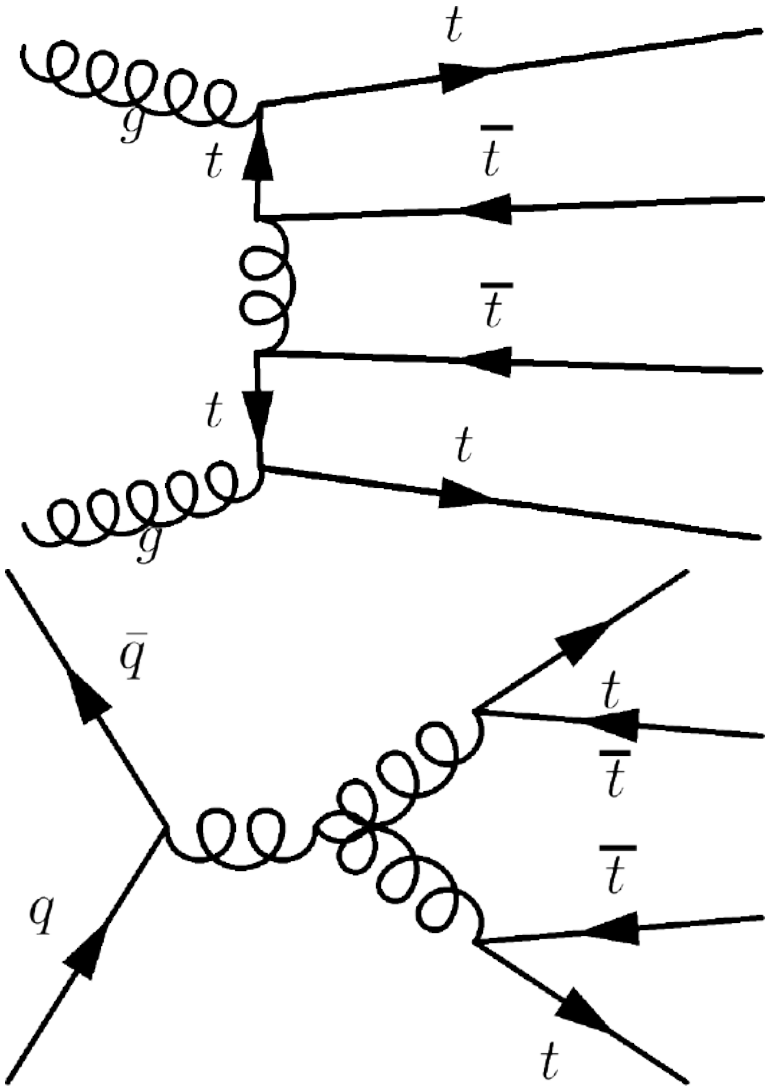
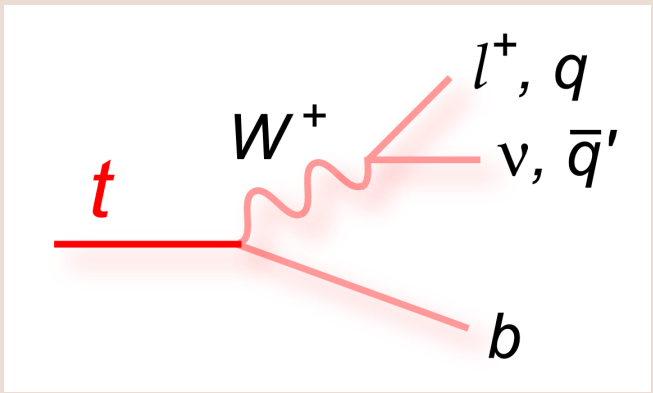
Four Top Production as probe of BSM Physics

- $t\bar{t}t\bar{t}$ is extremely rare in the SM
- Test of high-scale perturbative QCD at femtobarn cross section scale
- Many BSM models point to top-philic processes
- Enhancement of $t\bar{t}t\bar{t}$ cross section would be a clear sign of BSM physics
- Constraining SM $t\bar{t}t\bar{t}$ cross section extends sensitivity of top-philic BSM searches

Four Top Events



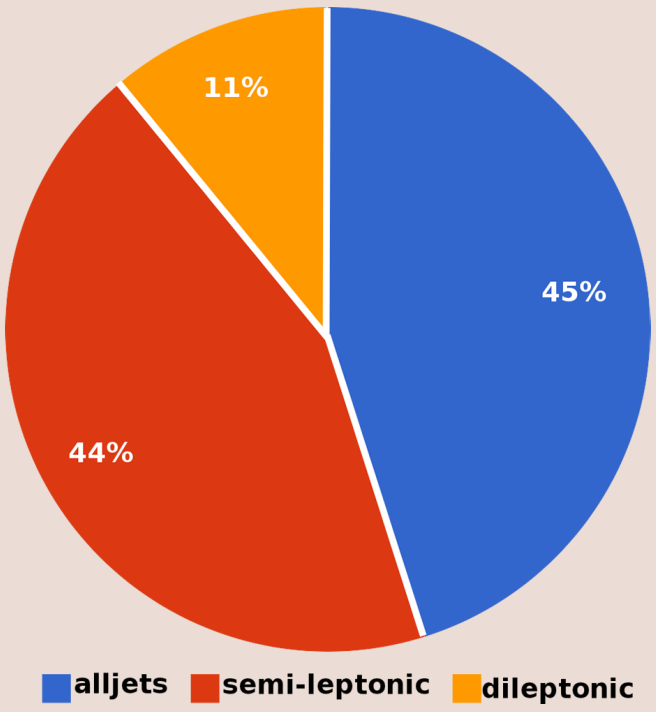
Top Quark Decay Path



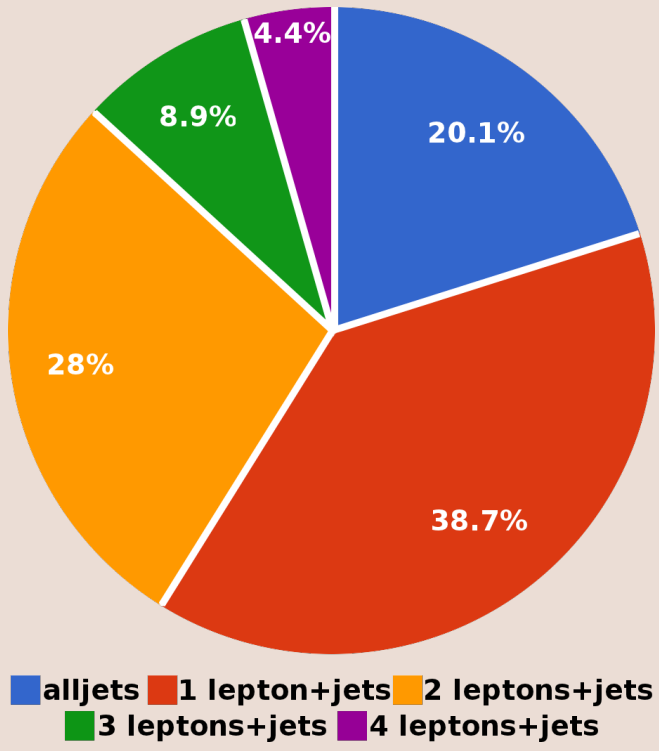
Assuming $B(t \to bW) = 1$, final states classified by decay of W-bosons

$t\bar{t}t\bar{t}$ vs. $t\bar{t}$

$t\bar{t}$ Branching Ratio



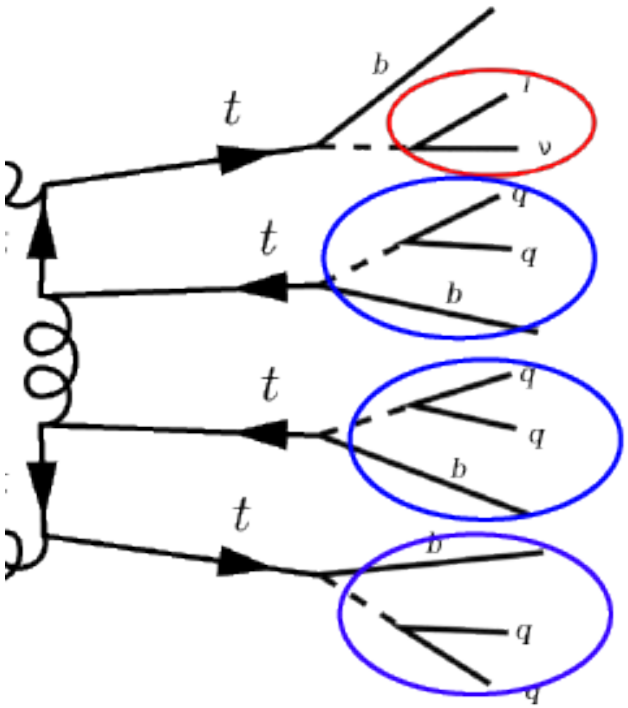
$t\bar{t}t\bar{t}$ Branching Ratio



$$\sigma^{SM}_{t\bar{t}t\bar{t}} \approx 1fb \text{ vs. } \sigma^{SM}_{t\bar{t}} \approx 253pb \text{ at } \sqrt{s} = 8\,TeV$$

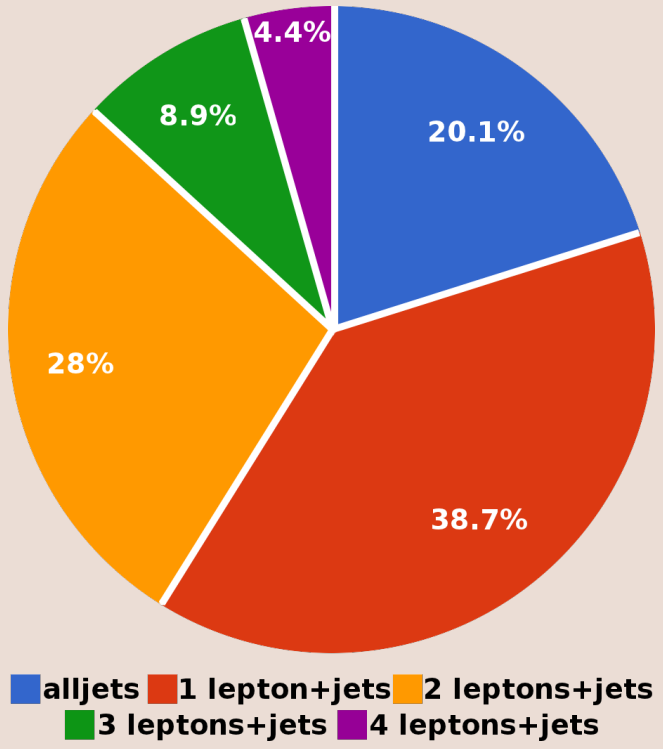
Five orders of magnitude difference in cross section

Single Lepton Four Top Events



Leptonic Top - Hadronic Tops

$t\bar{t}t\bar{t}$ Branching Ratio

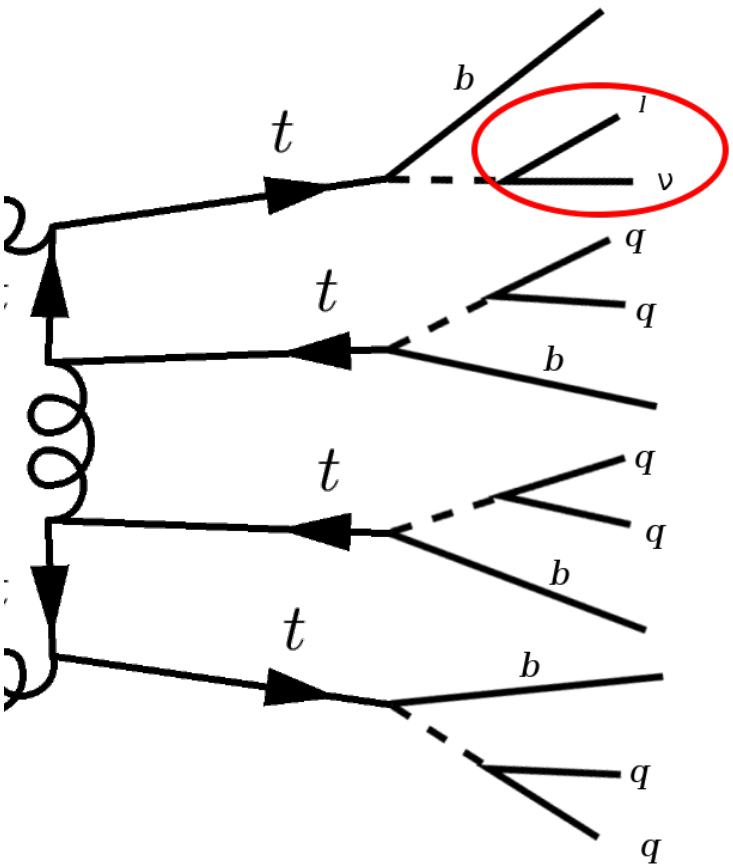


Analysis Strategy

Identify semi-leptonic top decay and search for two hadronic tops

Event Selection - Leptons

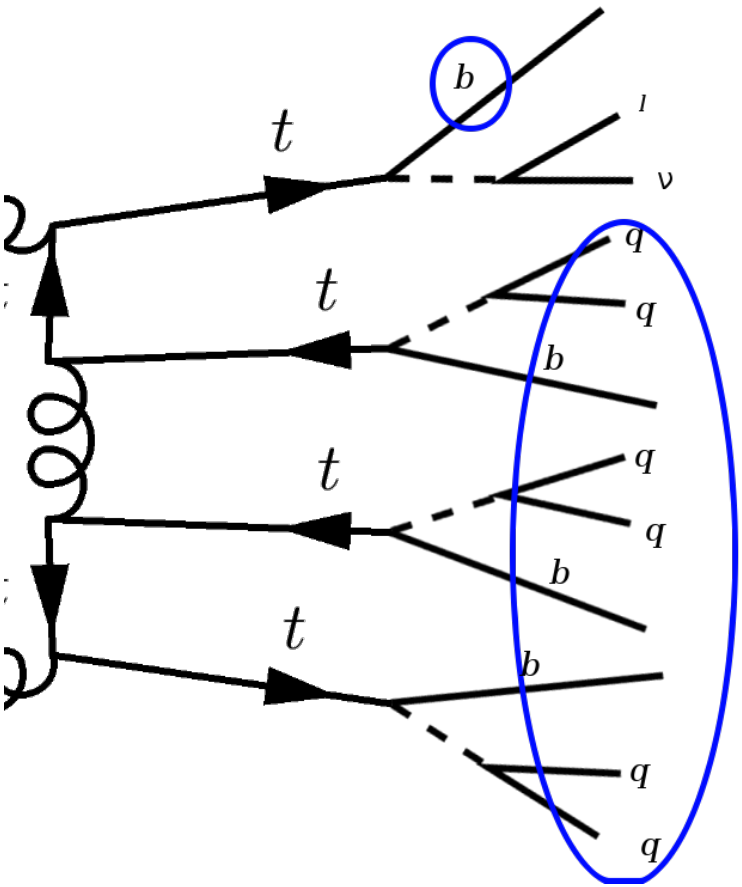
One isolated charged lepton (e/mu) and missing transverse momentum $\geq$ 30 GeV



- Leptons come from a W which comes from a high mass object
- Leptons from W decay likely isolated from jets

Event Selection - Jet Activity

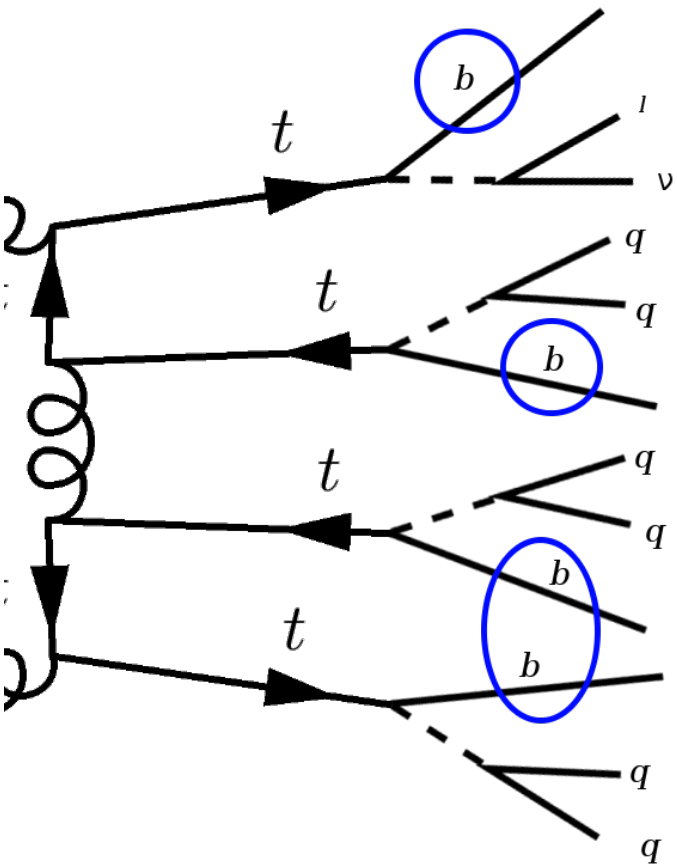
nJets ≥ 6 with $H_T \geq 400$ GeV



- Jet multiplicity very high in $t\bar{t}t\bar{t}$
  - 10 final state partons
- Require enough jets to reconstruct 2 hadronic tops
- $H_T = \Sigma_{jets} p_T$

Event Selection - B-jet Multiplicity

nBTaggedJets ≥ 2



- HIGHLY suppresses non top quark backgrounds
- Additional b-Jet multiplicity highly discriminating between $t\bar{t}$ and $t\bar{t}t\bar{t}$

Discriminating Variables - $BDT_{trijet2}$

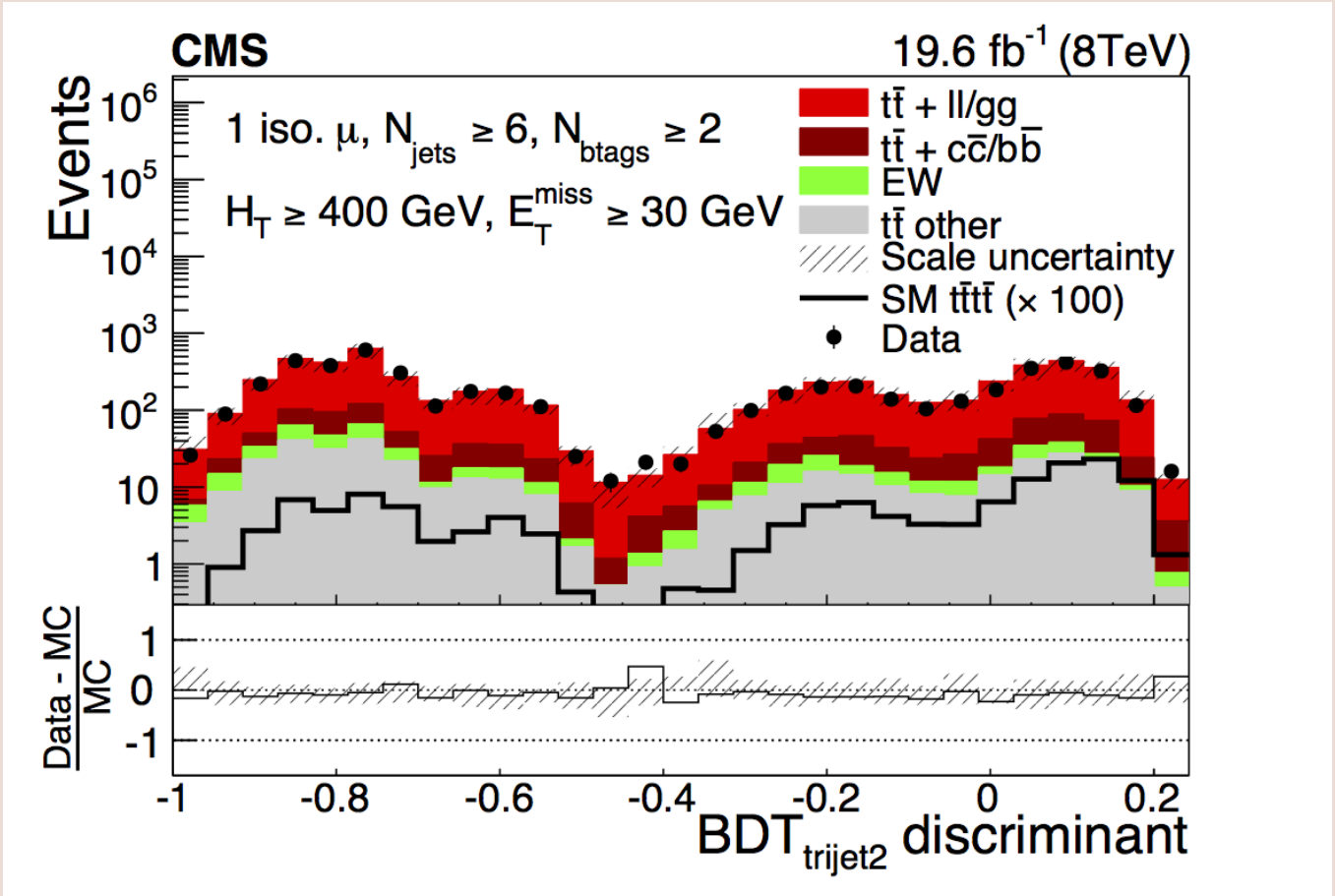
$BDT_{trijet2}$

MVA discriminator for second hadronic top

- BDT is trained to select trijet combinations
- Jets are combinatorially passed through BDT
- Closest pair in ΔR defined as coming from W
- B-tagging discriminant of third jet passed to BDT
- Second highest ranked trijet combination selected
  - MVA Discriminant $\rightarrow$ $BDT_{trijet2}$

Discriminating Variables - $BDT_{trijet2}$

$BDT_{trijet2}$



Discriminating Variables - Reduced Event Variables

Reduced Event

Collection of objects in the event with the jets contributing to the two leading hadronic top tri-jets removed

- H_T^{RE}
  - Hadronic activity in Reduced Event
  - From signal jets in $t\bar{t}t\bar{t}$
  - Softer spectrum in background
- M^{RE}
  - Invariant mass of jets in the Reduced Event
  - Signal has at least one more top quark of mass

Discriminating Variables - Jet Activity

- nJets
- nBTaggedJets
- H_T^b
  - Scalar sum of b-tagged jet E_T
- H_T/H_p
  - H_p is the scalar sum of total jet momenta
- H_T^{ratio}
  - Ratio of the leading four jets H_T to the H_T of the remaining jets
- p_T of both the 5th and 6th leading jets

Event Level BDT

- The 10 variables from the previous slides are supplied to an Event Level BDT
- Further categorized in $nJets = 6$, $nJets = 7$ and $nJets > 7$
- $nJets = 6$ category is used to constrain $t\bar{t}$ in the limit calculation

Template Fit

Simultaneous Maximum Likelihood Fit

- BDT output shapes are fitted in categories with a simultaneous maximum likelihood fit
- Categories for both the $\mu + jets$ and $e + jets$ channels input to the fit
- Systematic uncertainty in the cross section for $t\bar{t}$ is expected to dominate and is considered in the fit

Luminosity	$t\bar{t}$ scaleUp	$t\bar{t}$ scaleDown	$t\bar{t}$ PDFUp	$t\bar{t}$ PDFDown
2.6%	+2.5%	−3.4%	+2.5%	−2.6%

Table: Dominant Systematic Uncertainties on $\sigma_{t\bar{t}}$

Limits

The modified frequentist CL_s approach is adopted, calculating limits at the 95% confidence level on $\frac{\sigma_{signal}}{\sigma^{SM}_{t\bar{t}t\bar{t}}}$

Channel	Exp. $\frac{\sigma_{signal}}{\sigma^{SM}_{t\bar{t}t\bar{t}}}$	Obs. $\frac{\sigma_{signal}}{\sigma^{SM}_{t\bar{t}t\bar{t}}}$	Exp.(fb)	Obs.(fb)
$\mu + jets$	35.6 ± 18	33.9	46.3 ± 23	44
$e + jets$	36.1 ± 16	36.1	47.0 ± 20	47
combined	24.6 ± 13	24.7	32 ± 17	32

Table: Limits on SM Four Top production

Limit of $\sigma^{SM}_{t\bar{t}t\bar{t}} = 32fb$ set at the 95% confidence level

JHEP 11 (2014) 154 (arXiv:1409.7339)

(Recent ATLAS results comparable arxiv:1505.04306)

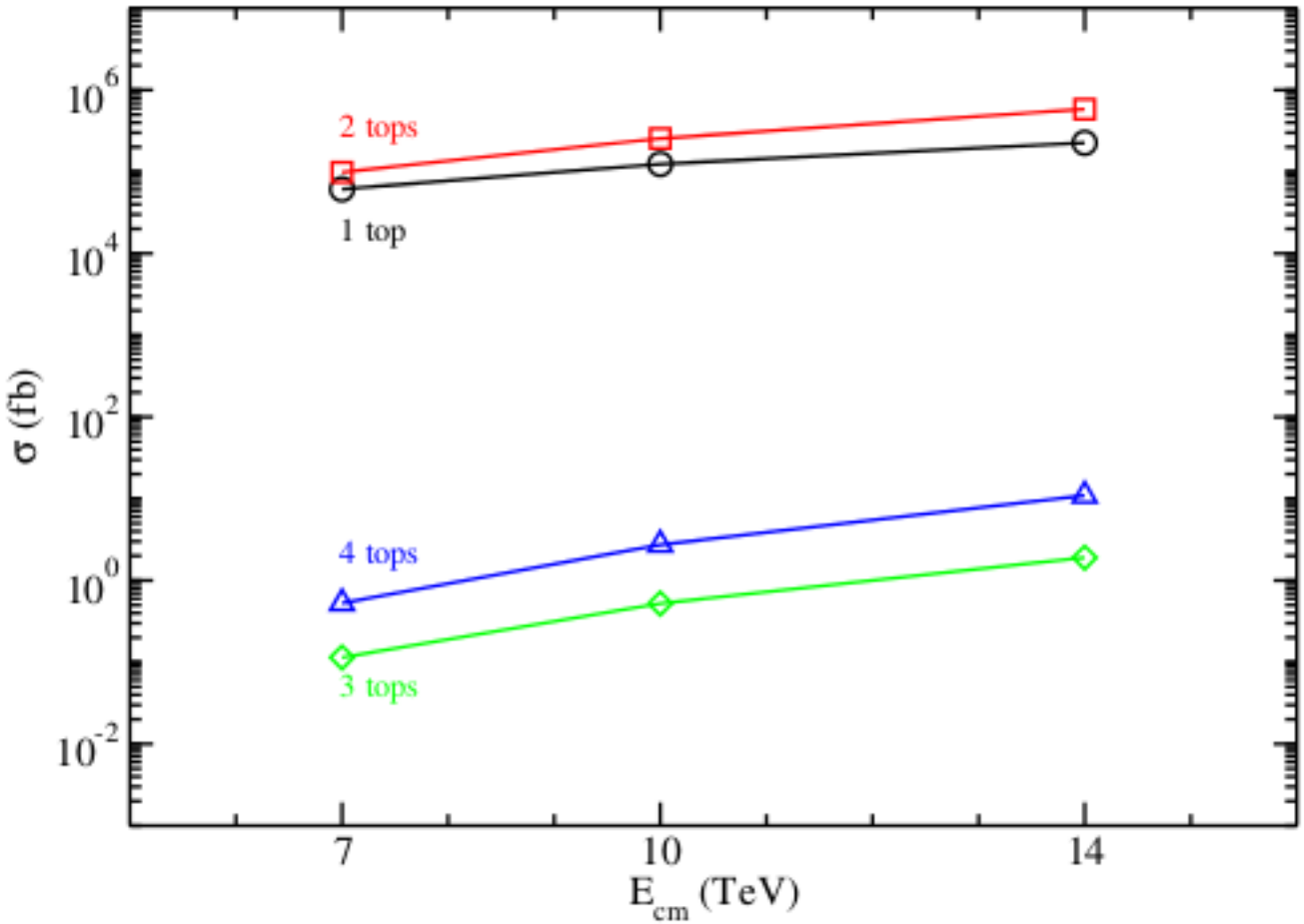
Final Thoughts

- Analysis strategy focused on extra hadronic activity in $t\bar{t}t\bar{t}$ as compared to $t\bar{t}$ quite successful
- Multi-variate techniques key in differentiating between similar processes
- $\sigma^{SM}_{t\bar{t}t\bar{t}}$ expected to rise relatively faster at $\sqrt{s} = 13$ TeV and $\sqrt{s} = 14$ TeV than $\sigma_{t\bar{t}}$
  - $\sigma^{SM}_{t\bar{t}t\bar{t}}(13\,TeV) = 9.201$ fb $^{+31\%}_{-26\%}$ (scale) $^{+5.5\%}_{-5.9\%}$ (PDF)
  - $\sigma^{SM}_{t\bar{t}t\bar{t}}(14\,TeV) = 15.33$ fb $^{+26\%}_{-25\%}$ (scale) $^{+3.95\%}_{-3.81\%}$ (PDF)
- Adding in other final states (di-lepton) will improve sensitivity of measurement

Thank You

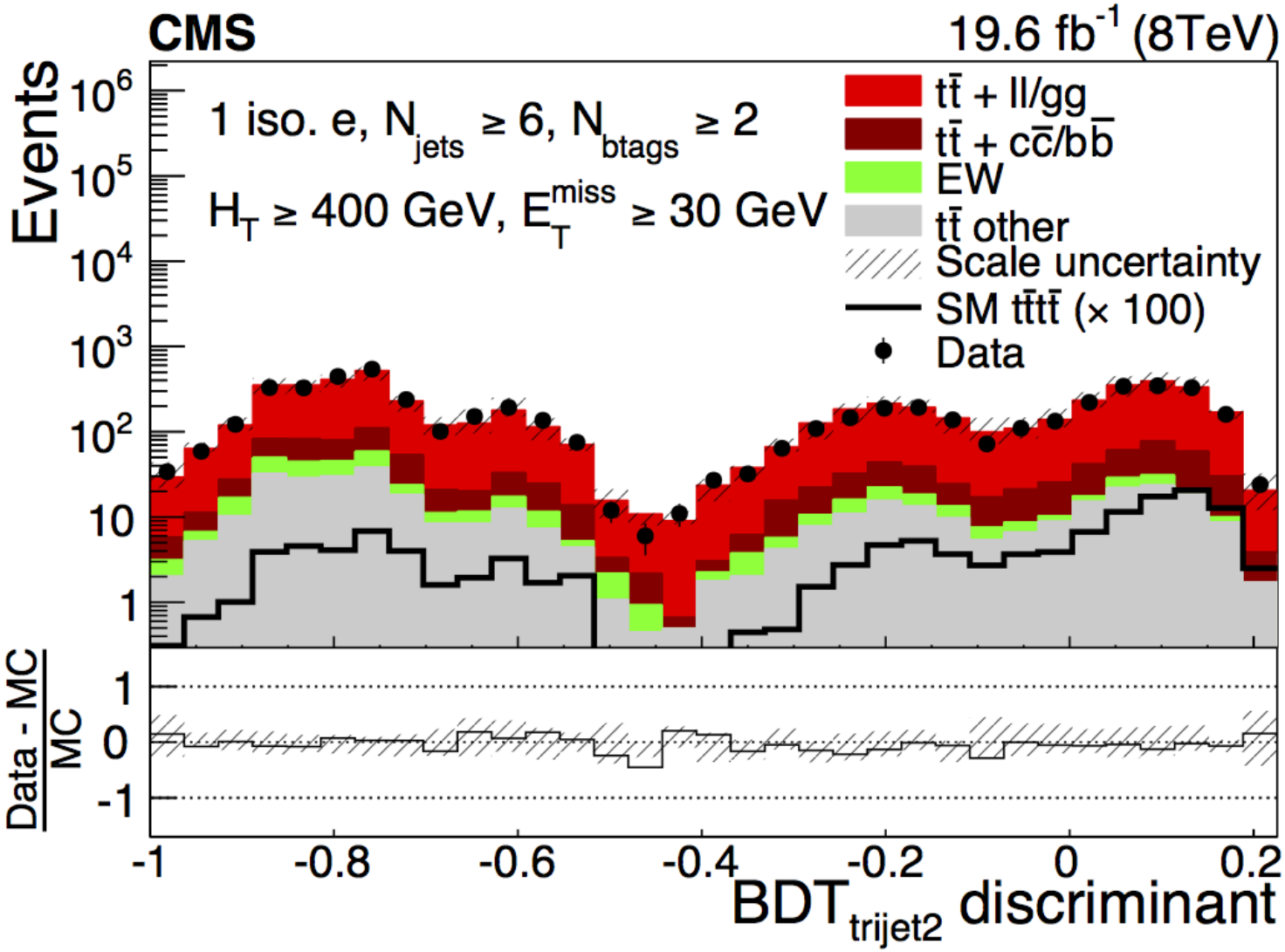
Backup

LO Multi-Top Cross Sections at the LHC

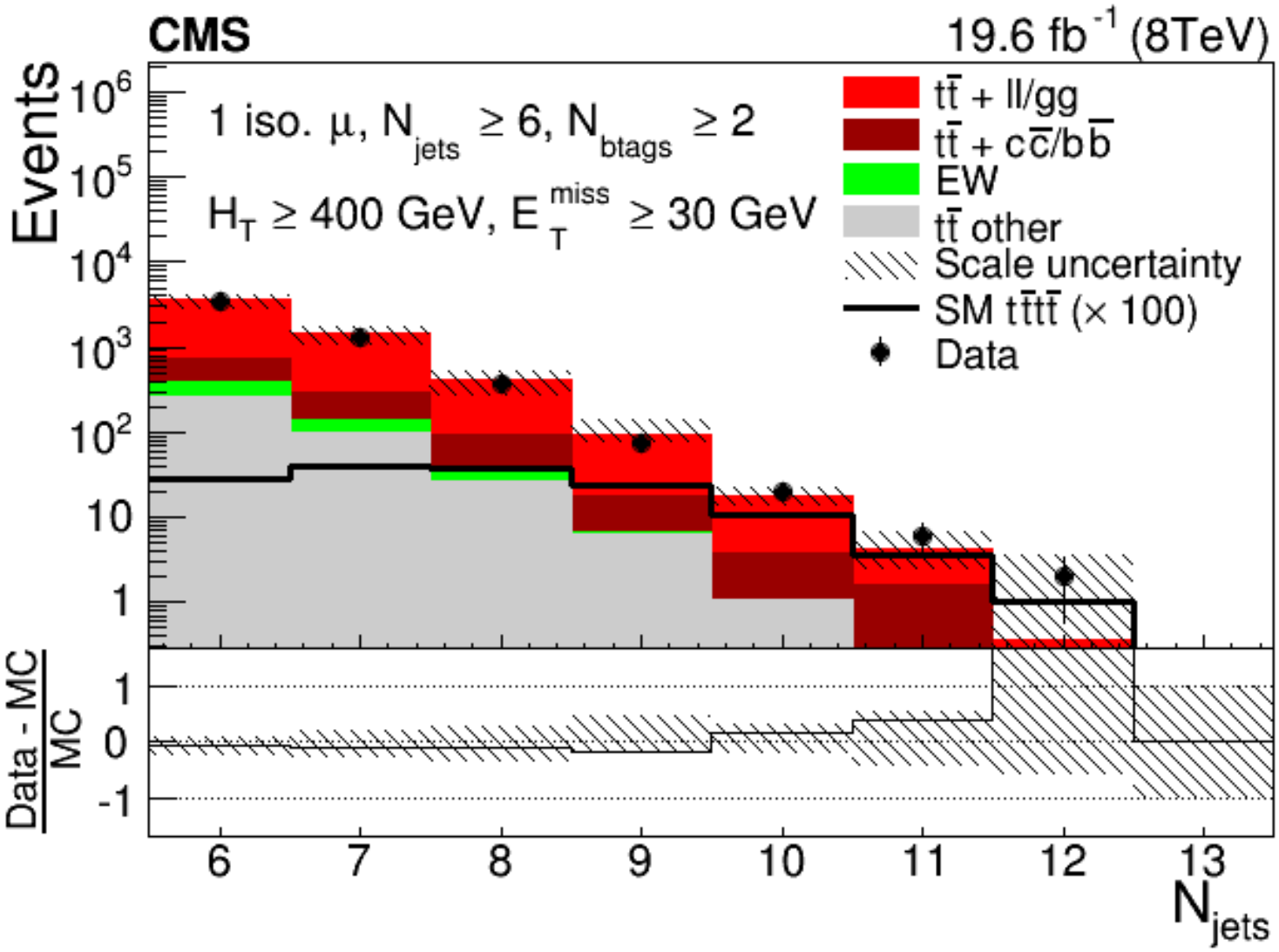


Barger, Keung and Yencho
(http://arxiv.org/pdf/1001.0221v3.pdf)

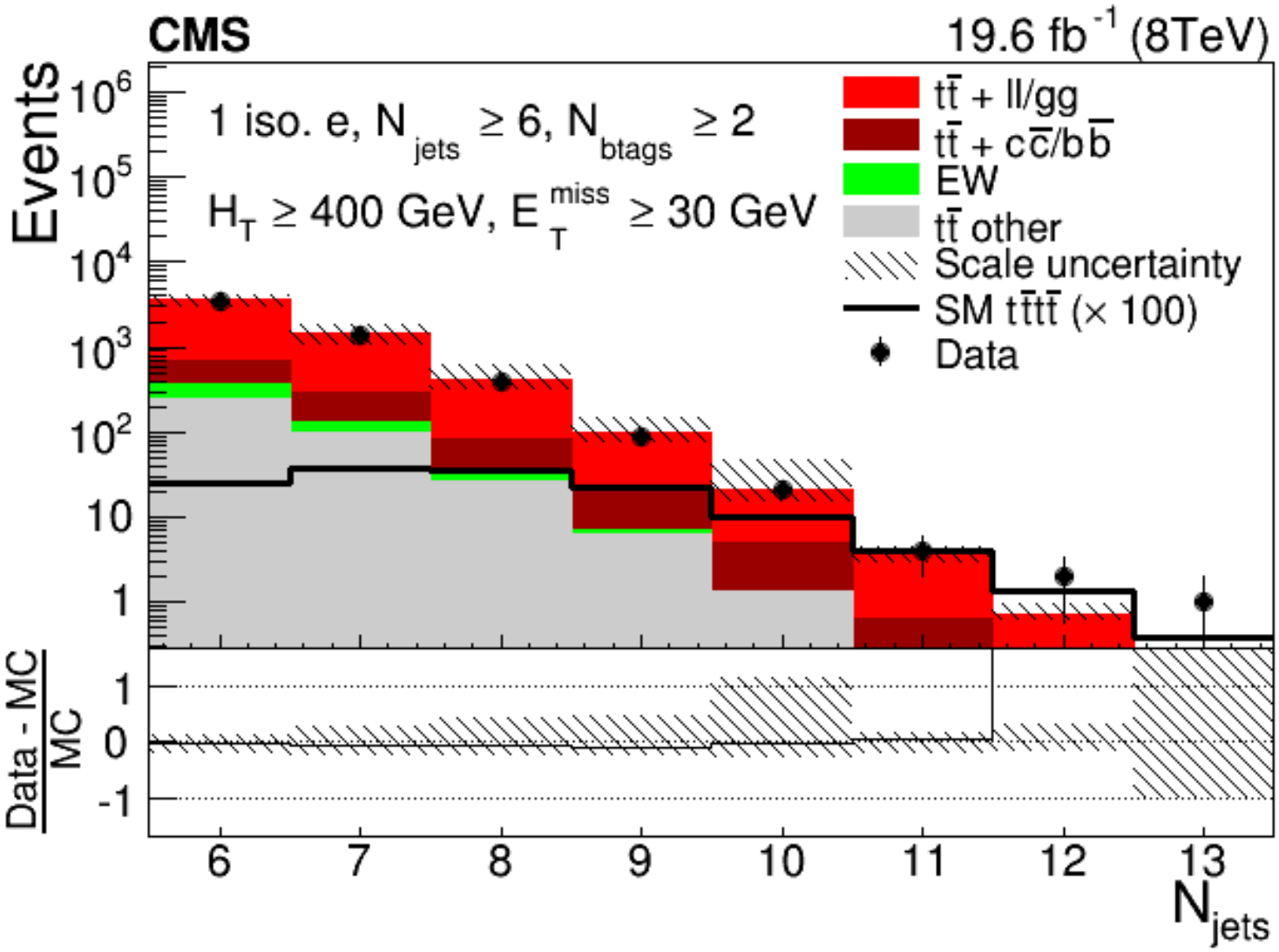
Multitopness - electron



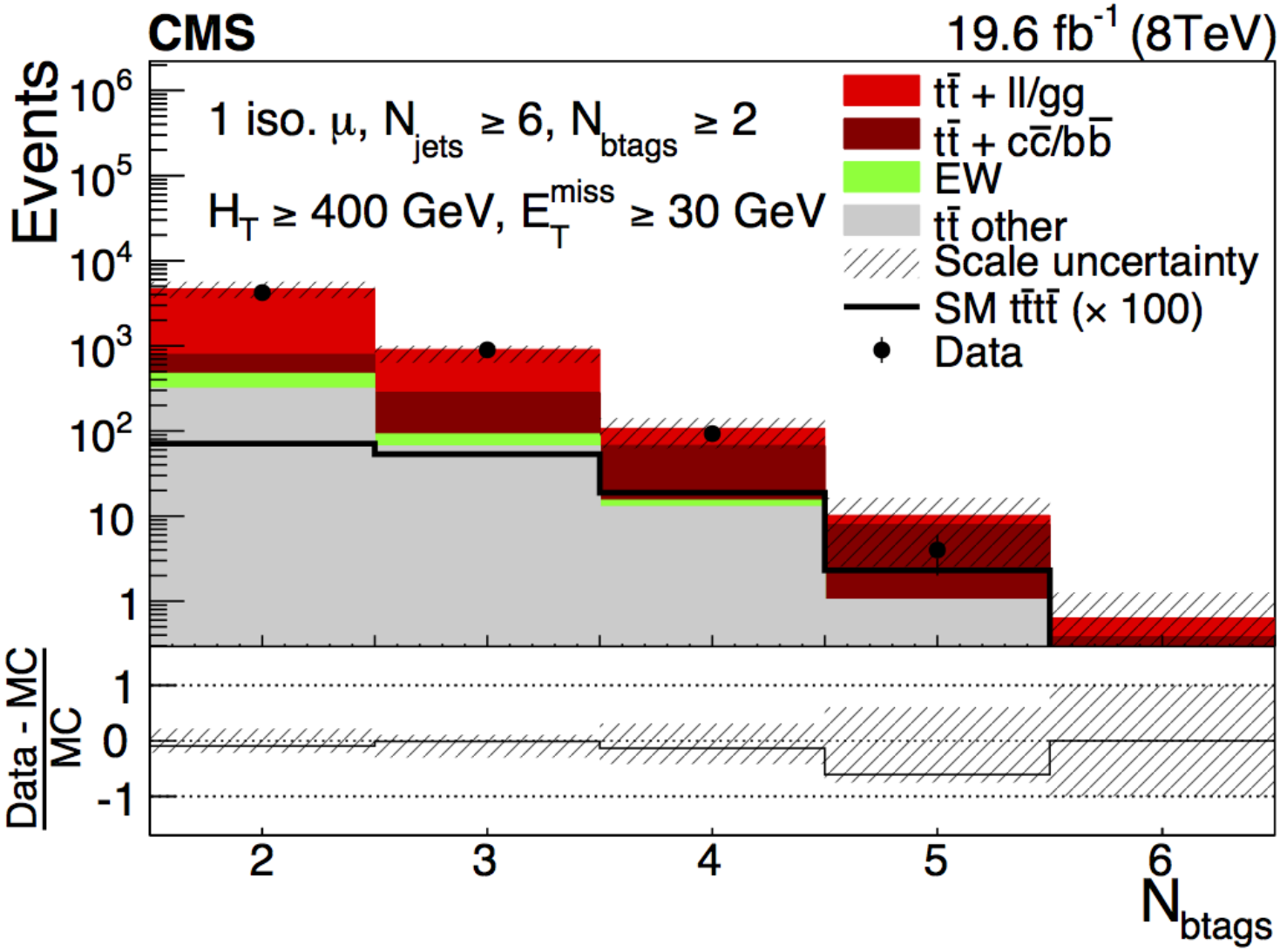
nJets - muon


CMS
19.6 fb^{-1} (8TeV)
1 iso. μ, $N_{jets} \geq 6$, $N_{btags} \geq 2$
$H_T \geq 400$ GeV, $E_T^{miss} \geq 30$ GeV
$t\bar{t}$ + ll/gg
$t\bar{t}$ + $c\bar{c}$/$b\bar{b}$
EW
$t\bar{t}$ other
Scale uncertainty
SM $t\bar{t}t\bar{t}$ (× 100)
Data
Events
Data - MC / MC
N_{jets}

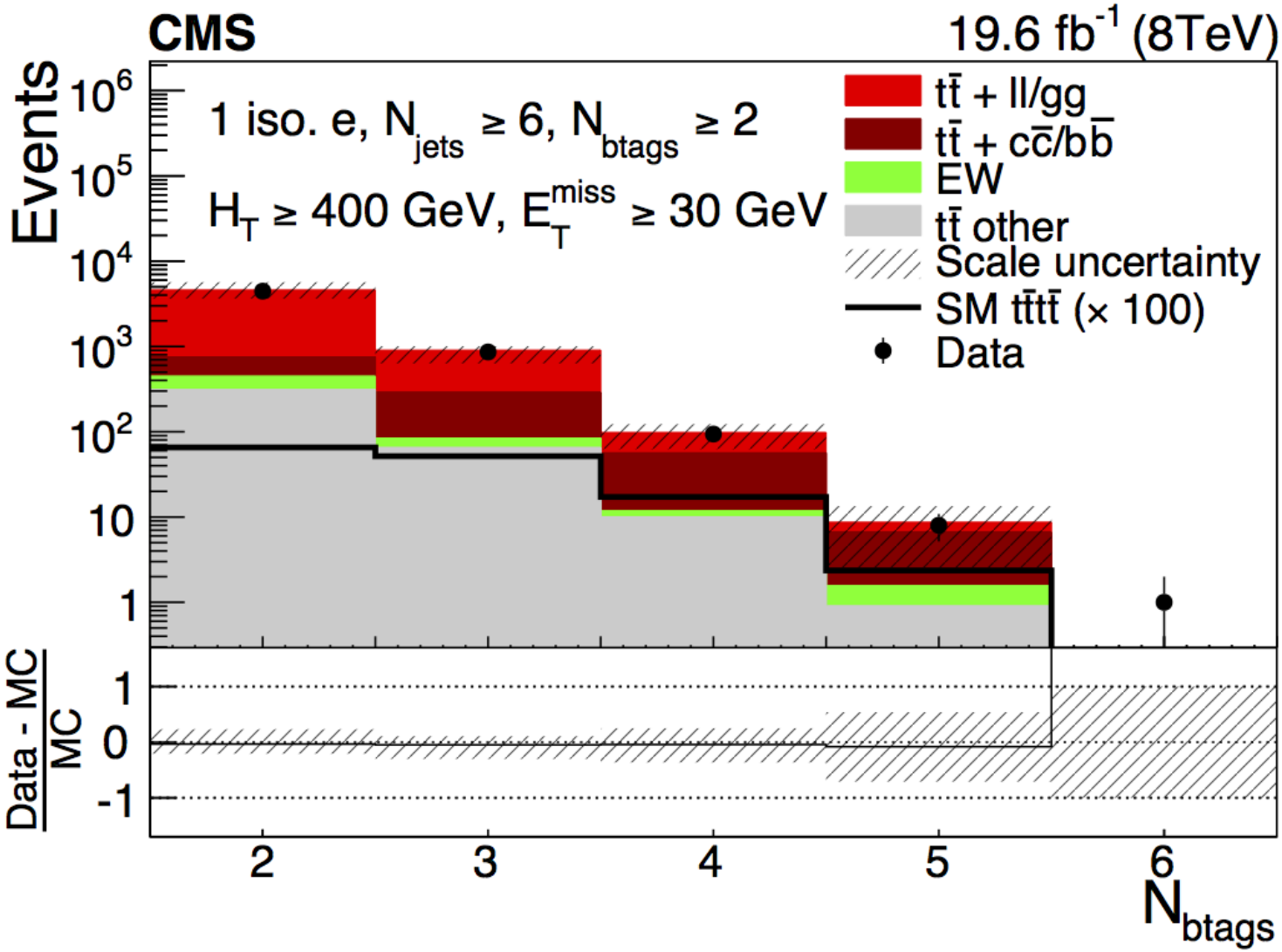
nJets - electron



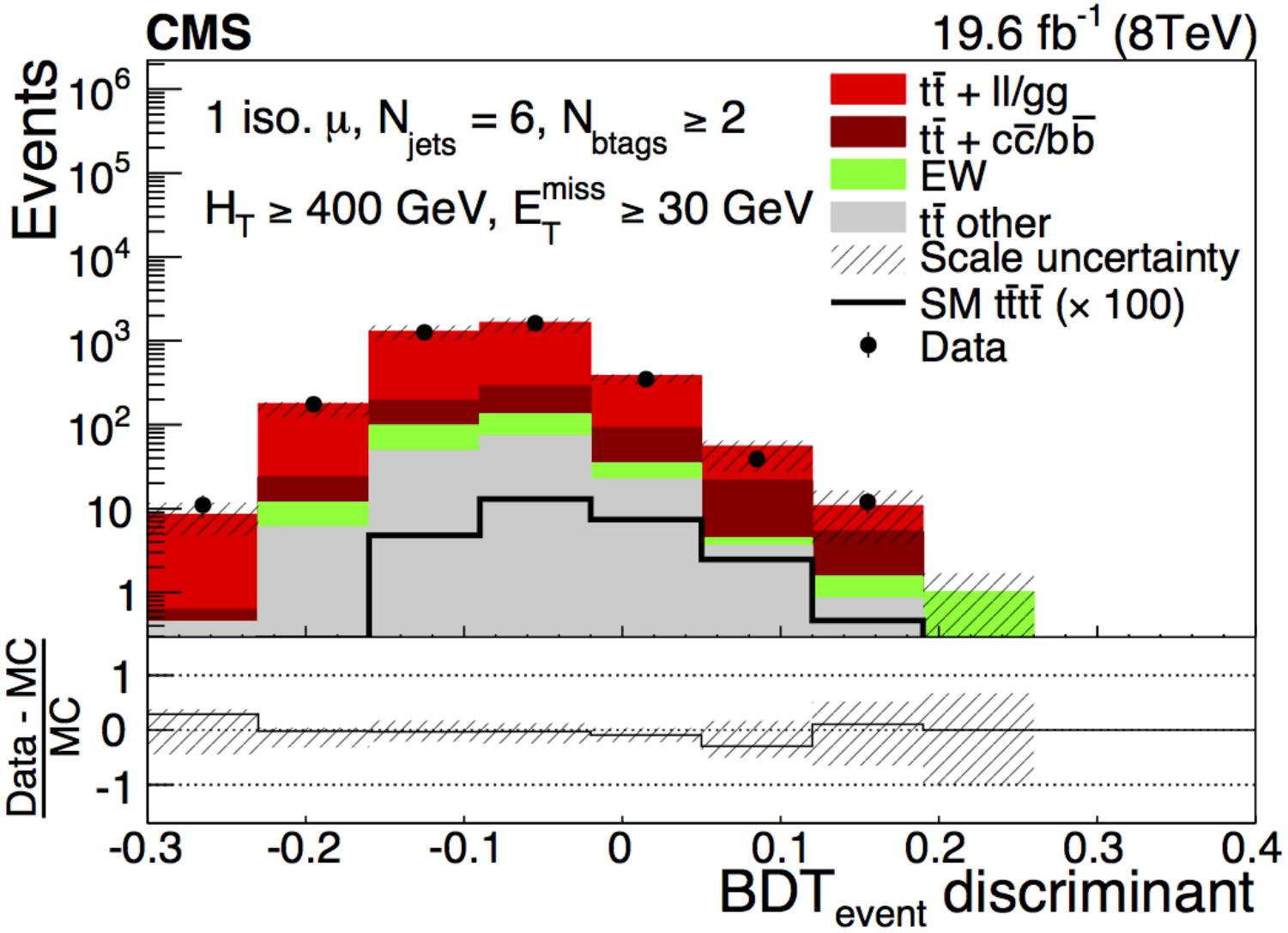
nTags - muon


CMS
19.6 fb-1 (8TeV)
1 iso. μ, Njets ≥ 6, Nbtags ≥ 2
HT ≥ 400 GeV, ETmiss ≥ 30 GeV
tt̄ + ll/gg
tt̄ + cc̄/bb̄
EW
tt̄ other
Scale uncertainty
SM tt̄tt̄ (× 100)
Data
Events
Data - MC / MC
Nbtags

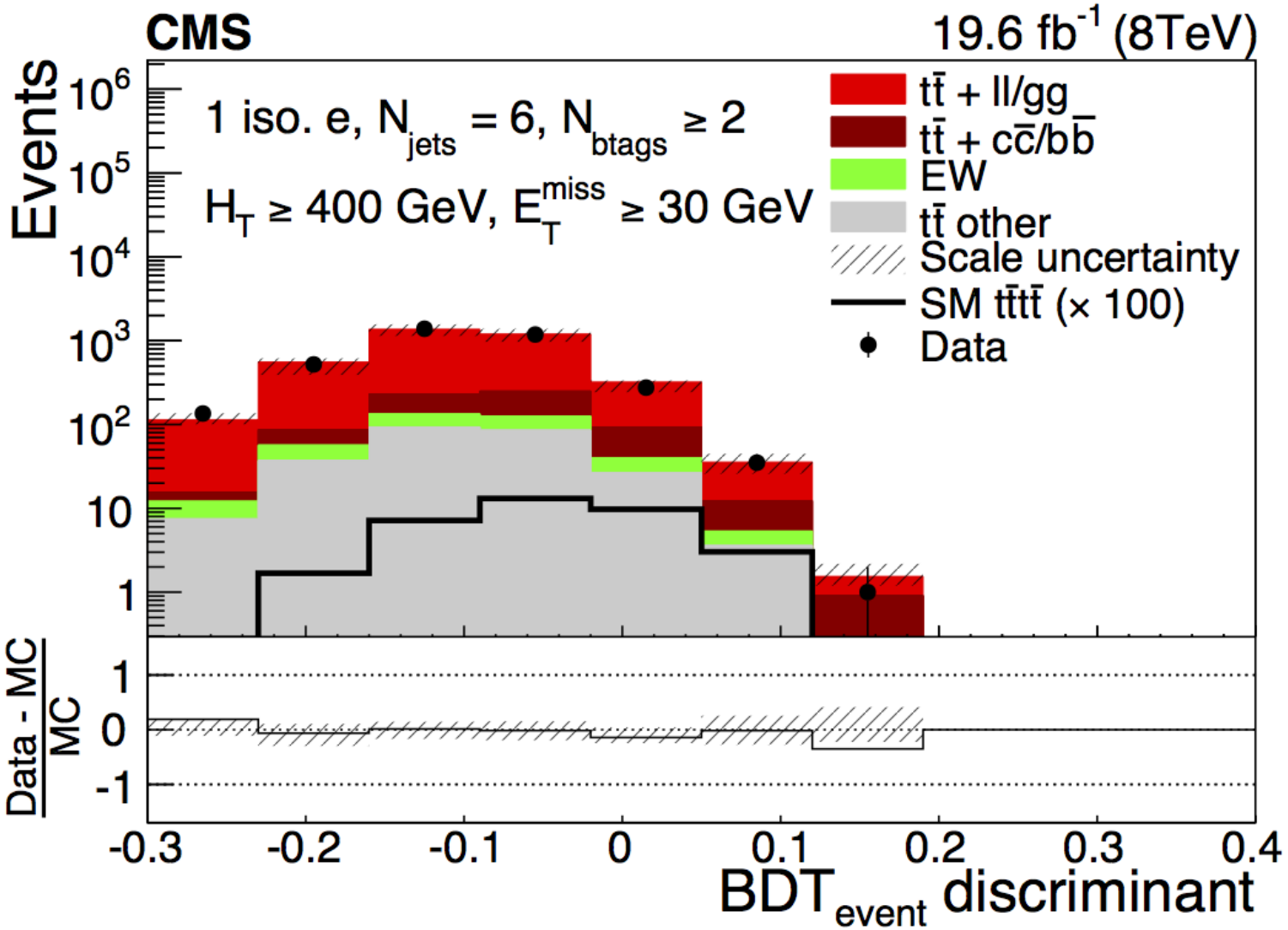
nTags - electron



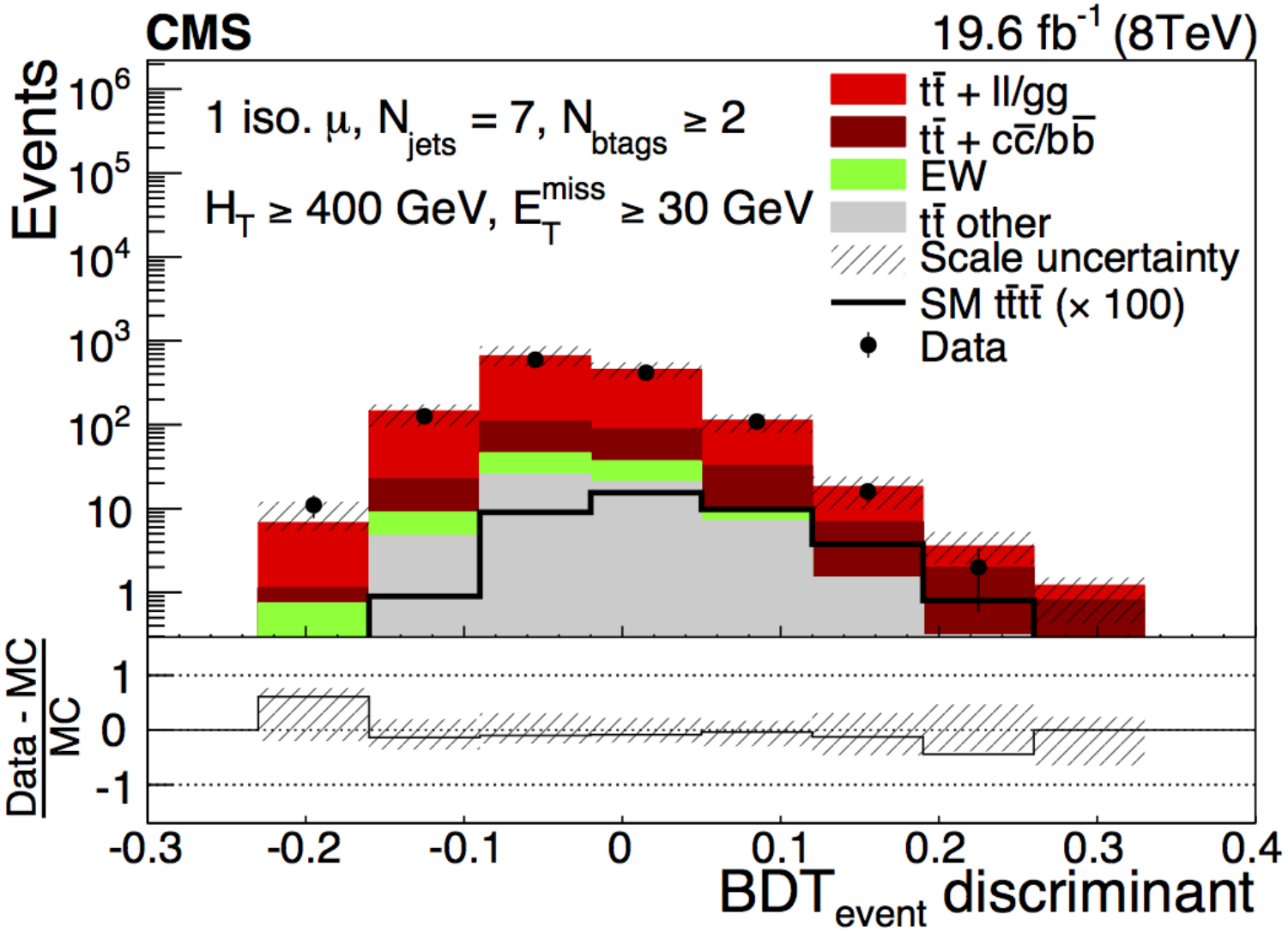
BDT - muon


CMS
19.6 fb^{-1} (8TeV)
1 iso. μ, N_{jets} = 6, N_{btags} ≥ 2
H_T ≥ 400 GeV, E_T^{miss} ≥ 30 GeV
tt̄ + ll/gg
tt̄ + cc̄/bb̄
EW
tt̄ other
Scale uncertainty
SM tt̄tt̄ (× 100)
Data
Events
Data - MC / MC
BDT_{event} discriminant

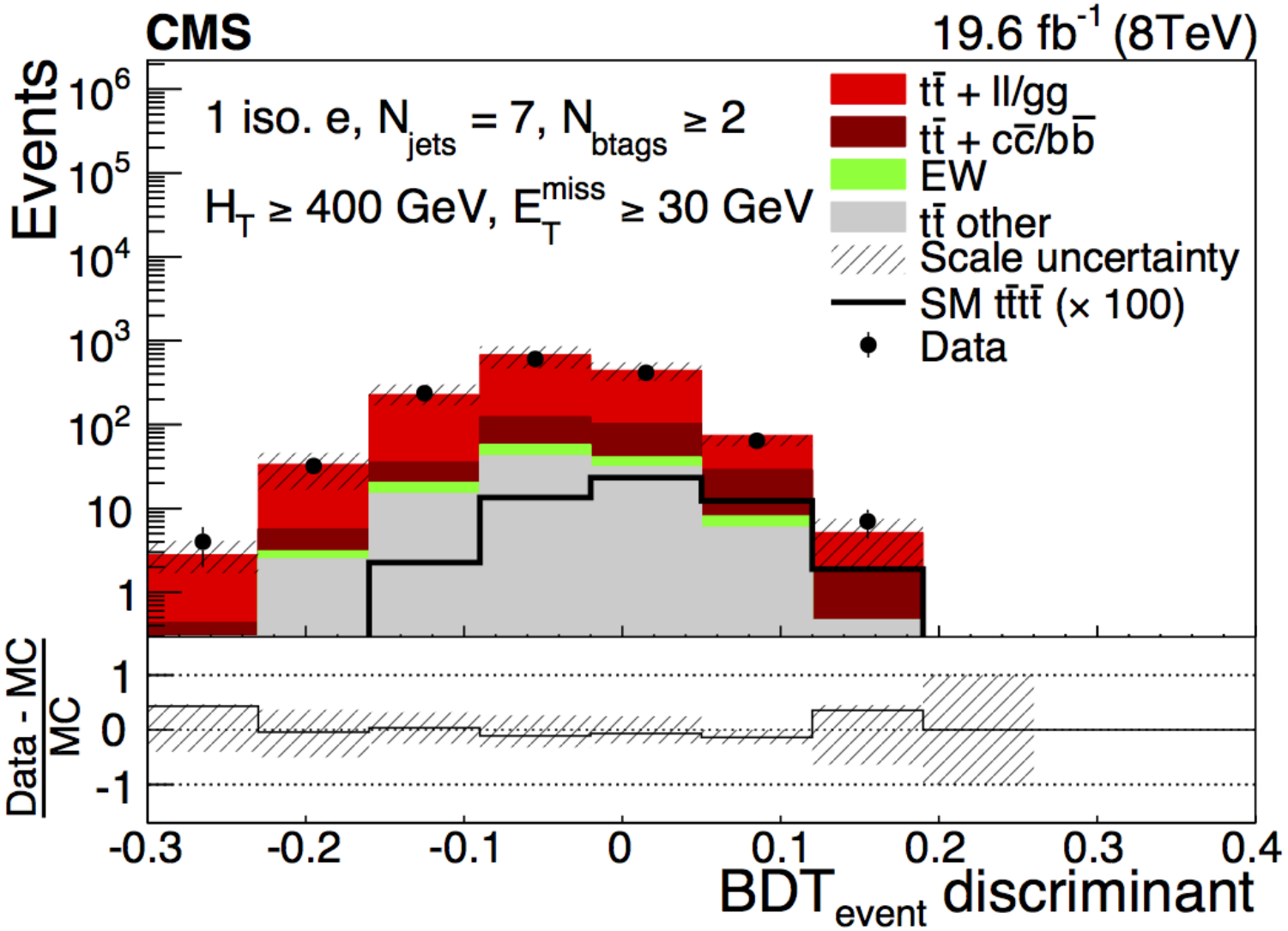
BDT - electron



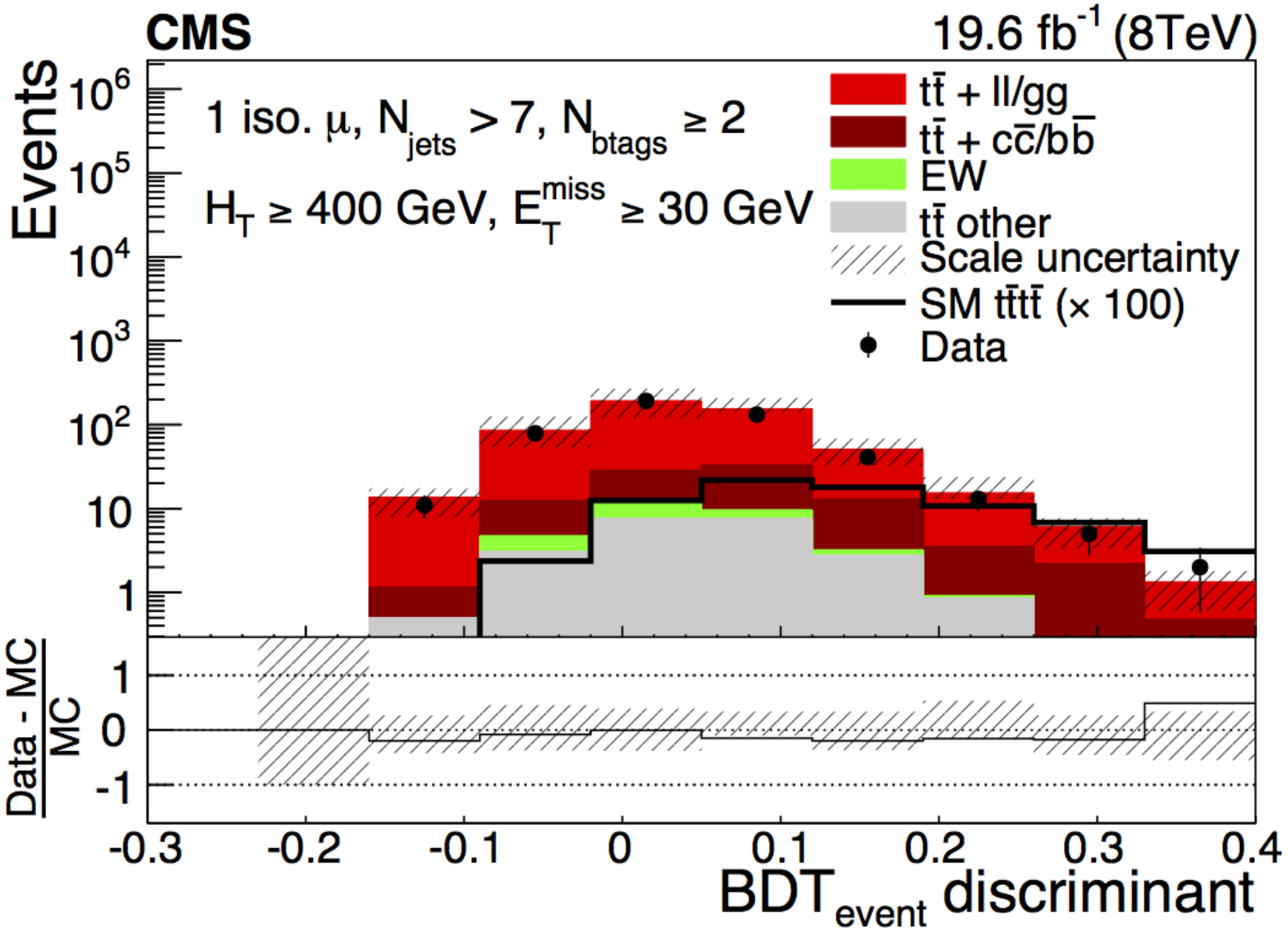
BDT - muon


CMS
19.6 fb^{-1} (8TeV)
1 iso. μ, N_{jets} = 7, N_{btags} ≥ 2
H_T ≥ 400 GeV, E_T^{miss} ≥ 30 GeV
tt̄ + ll/gg
tt̄ + cc̄/bb̄
EW
tt̄ other
Scale uncertainty
SM tt̄tt̄ (× 100)
Data
Events
Data - MC / MC
BDT_{event} discriminant

BDT - electron



BDT - muon


CMS
19.6 fb^{-1} (8TeV)
1 iso. μ, $N_{jets} > 7$, $N_{btags} \geq 2$
$H_T \geq 400$ GeV, $E_T^{miss} \geq 30$ GeV
$t\bar{t}$ + ll/gg
$t\bar{t}$ + $c\bar{c}$/$b\bar{b}$
EW
$t\bar{t}$ other
Scale uncertainty
SM $t\bar{t}t\bar{t}$ (× 100)
Data
Events
Data - MC / MC
BDT_{event} discriminant

BDT - electron