Observation of W-Associated Single Top Production at 8TeV

(Submitted to Phys. Rev. Lett. and arXiv:1401.2942)

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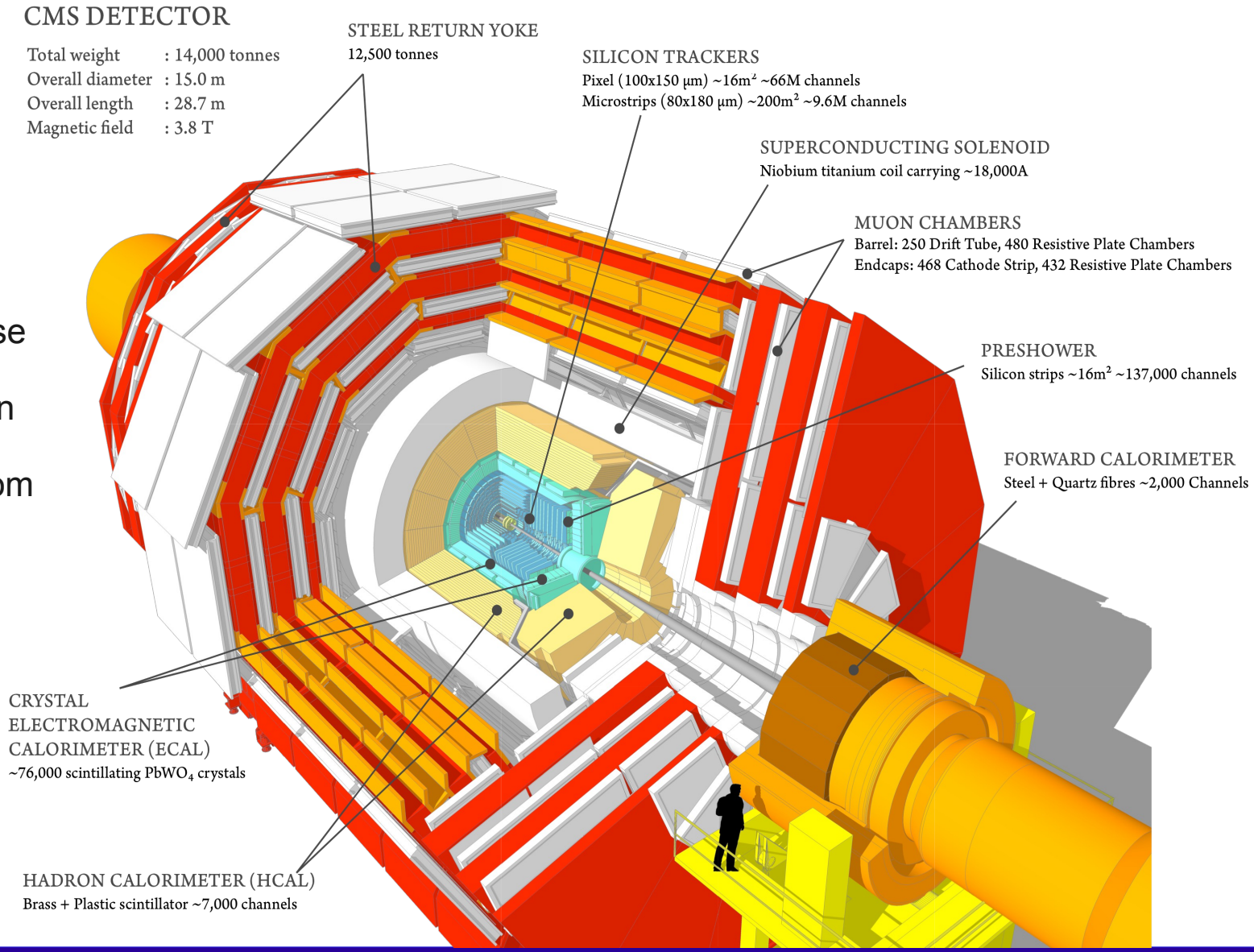
On behalf of the CMS Collaboration

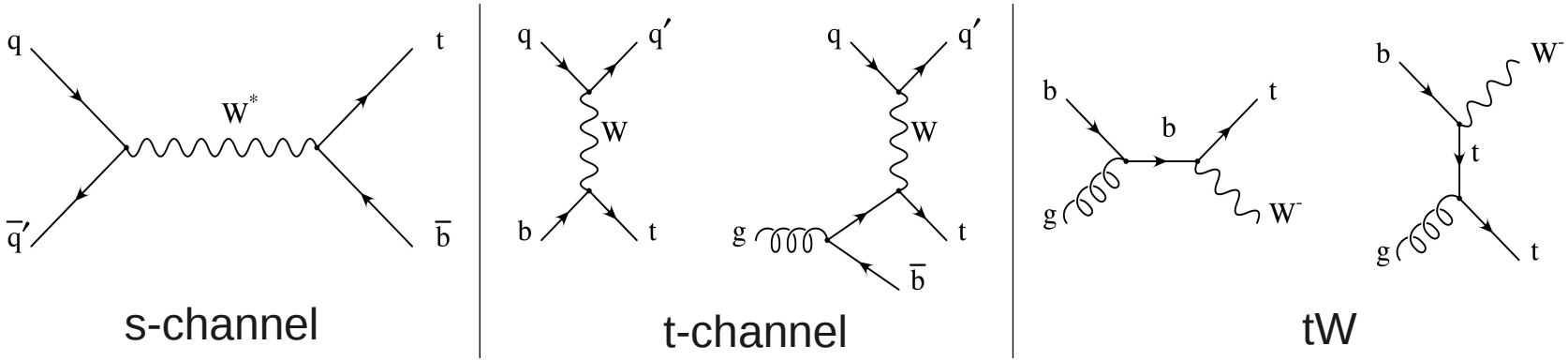
Compact Muon Solenoid (CMS)

- One of two general purpose detectors at the LHC
- 100 metres underground in Cessy, France
- More than 3000 people from 182 institutes across 42 countries.
- Superconducting solenoid operates at 3.8T at 4K



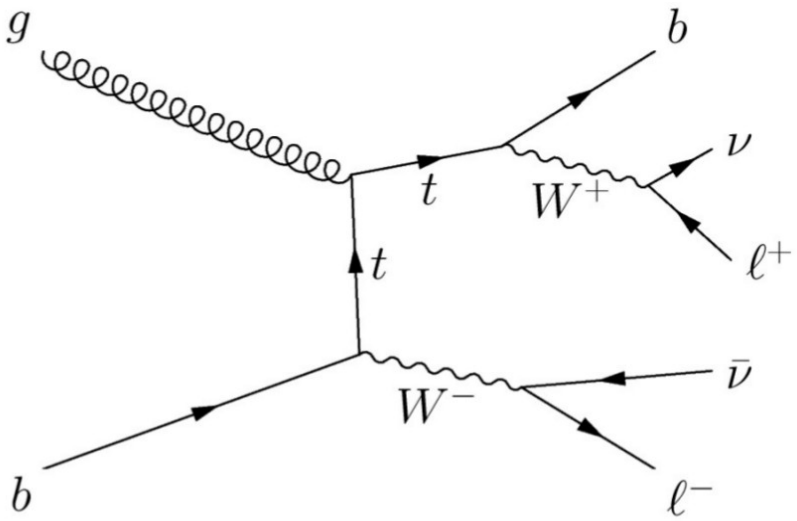
Single Top Production

- Three main production modes of a single top quark: t-channel, s-channel and associated production with a W boson (tW).
- Tevatron has observed the t-channel and (very recently!) the s-channel (arxiv:1402.5126), but tW was not accessible due to the small production cross-section.
- CMS and ATLAS have presented evidence for tW at 7TeV (see backup slides)



tW Associated Production

- Associated production of a single top quark with a W boson



Standard Model
$\sigma = 22.2 \pm 0.6 \pm 1.4$ pb

NLO+NNLL value: N. Kidonakis PhysRevD 82 (2010) 054018

Why is it interesting?

- Previously unseen
- Strong interference with $t\bar{t}$
- Direct measurement of $|V_{tb}|$. Sensitivity to new physics
- Background for several SUSY and Higgs searches

Event Signature:

- Two oppositely charged, isolated leptons (electrons and muons)
- Exactly one jet from a b-quark decay.
- Substantial missing E_T (two neutrinos)

arXiv:1401.2942, submitted to PRL

Backgrounds

- $t\bar{t}$ production is dominant background
  - σ = 245 pb at NNLO, ~10 times larger than tW.
  - Very similar final states – only difference is one additional b-jet
  - Mixes with tW signal at NLO
- Other sources of background can be largely reduced through event selection
  - Z/γ^* + jets is second largest background
  - Small contributions from diboson, W+jets and other single top processes.

Analysis Flow

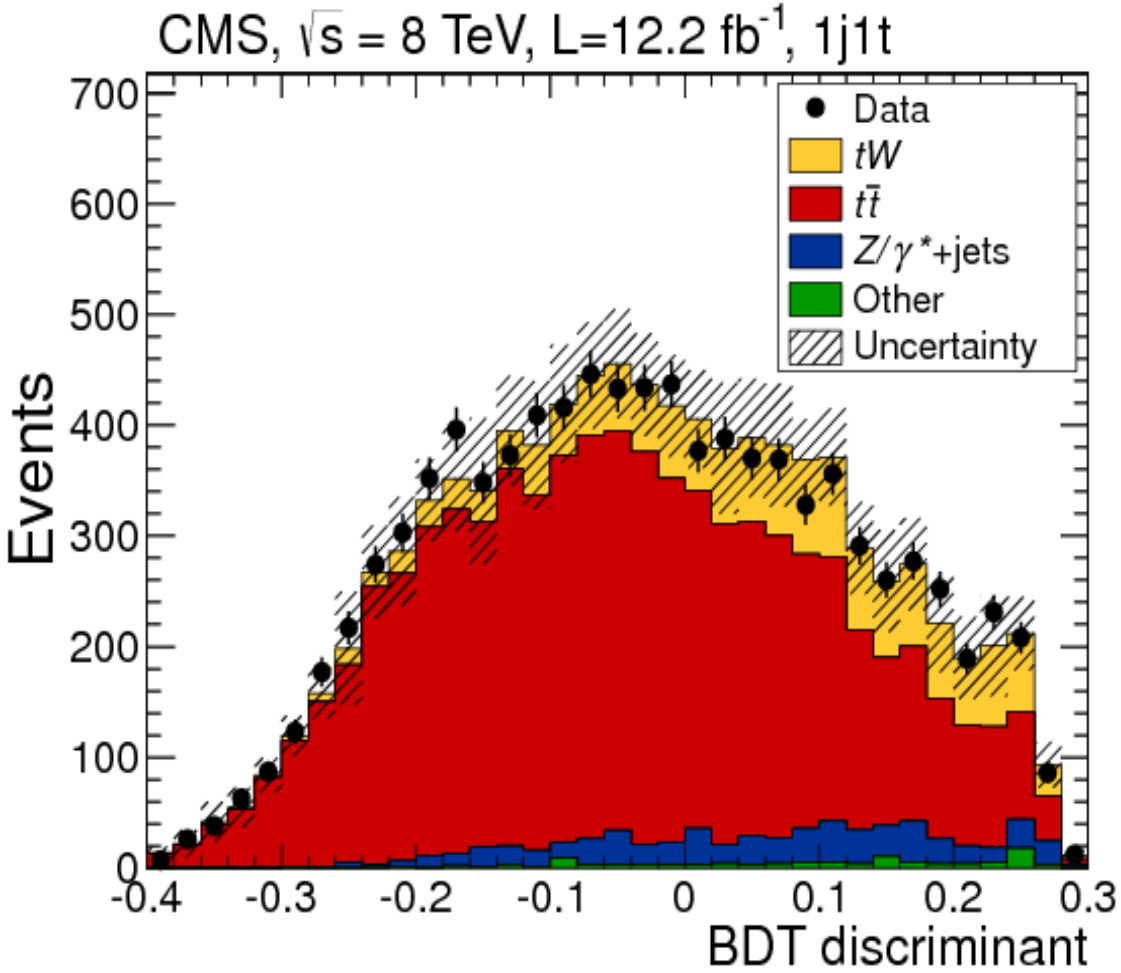
- Di-electron, di-muon or electron-muon triggers applied.
- Lepton Selection
  - Exactly two isolated, oppositely charged leptons. Events with additional low p_T leptons are vetoed.
- Lepton pair invariant mass:
  - m_{ll} > 20 GeV to remove low-mass Drell-Yan (all channels)
  - Veto Z-mass window (81 < m_{ll} < 101 GeV) in ee and mumu channels to remove Z backgrounds. Vetoed events used to model this background in the signal region.
- Further reduce Z/γ^* + jets background in ee and mumu channels by requiring missing E_T > 50 GeV.
- One signal region (1 b-tagged jet - 1j1t) and 2 control regions (2 jets, 1 and 2 b-tags – 2j1t and 2j2t). Control regions are enriched in $t\bar{t}$ background. Used to constrain $t\bar{t}$ background and extract b-tagging efficiencies.

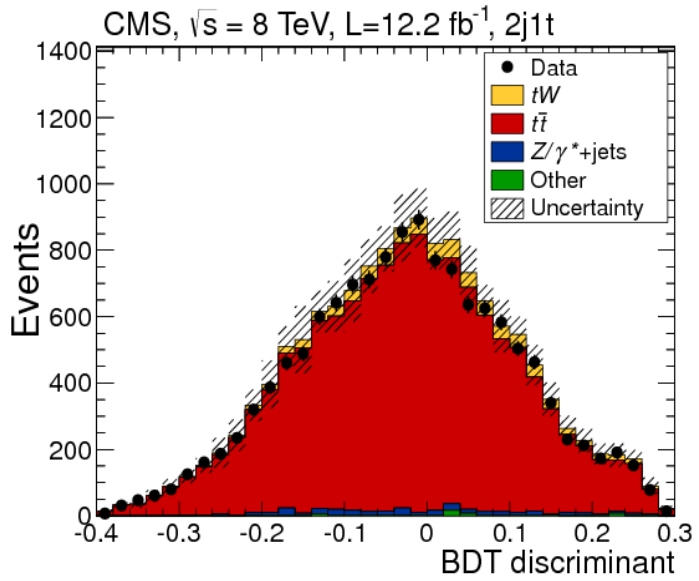
Boosted Decision Tree

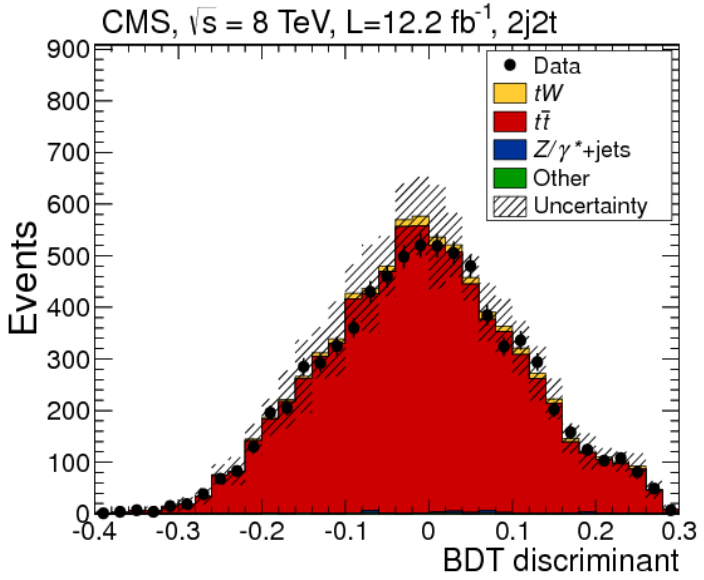
- BDT trained to discriminate tW signal and $t\bar{t}$ background.
- 200k MC events passing full signal 1j1t region cuts in both tW and $t\bar{t}$ dilepton samples.
- 13 variables used for BDT, chosen based on separation power and data/MC agreement in the control regions.

Variable	Description
Nloosejets	Number of loose jets, $p_T > 20$ GeV, $\|\eta\| < 4.9$
NloosejetsCentral	Number of loose jets, $p_T > 20$ GeV, $\|\eta\| < 2.4$
NbtaggedLoosejets	Number of loose jets, $p_T > 20$ GeV, CSVM btagged
$p_{T,sys}$	Vector sum of p_T of leptons, jet, and E_T^{miss}
H_T	Scalar sum of p_T of leptons, jet, and E_T^{miss}
Jet p_T	p_T of the leading, tight, b-tagged jet
Loose jet p_T	p_T of leading loose jet, defined as 0 for events with no loose jet present
$p_{T,sys}/H_T$	Ratio of $p_{T,sys}$ to H_T for the event
Msys	Invariant mass of the combination of the leptons, jet, and E_T^{miss}
centralityJLL	Centrality of jet and leptons
$H_{T,leptons}/H_T$	Ratio of scalar sum of p_T of the leptons to the H_T of full system
p_T-jll	Vector sum of p_T of jet and leptons
E_T^{miss}	Missing transverse energy in the event

BDT Discriminant Distribution







Systematics

- Theory dominated
  - ME/PS matching in $t\bar{t}$
  - Normalisation scale (Q^2)
  - Top quark mass
- Luminosity, lepton scale factors and $t\bar{t}$ cross-section treated as rate uncertainties, all others shape uncertainties.

Systematic uncertainty	$\Delta\sigma$ (pb)	$\Delta\sigma/\sigma$
ME/PS matching thresholds	3.3	14%
Renormalization/factorization scale	2.9	12%
Top-quark mass	2.2	9%
Fit statistical	1.9	8%
Jet energy scale	0.9	4%
Luminosity	0.7	3%
Z+jets data/simulation scale factor	0.6	3%
tW DR/DS scheme	0.5	2%
$t\bar{t}$ cross section	0.4	2%
Lepton identification	0.4	2%
PDF	0.4	2%
Jet energy resolution	0.2	1%
b-tagging data/simulation scale factor	0.2	<1%
$t\bar{t}$ spin correlations	0.1	<1%
Pileup	0.1	<1%
Top-quark p_T reweighting	0.1	<1%
E_T^{miss} modeling	0.1	<1%
Lepton energy scale	0.1	<1%
Total	5.5	24%

Statistical Method

- Likelihood fit to BDT discriminant in all three regions of all channels.
- Signal and background templates are taken from MC, with systematic uncertainties taken into account as variations on these templates.
  - Systematics included in the fit as nuisance parameters.

Significance

- Maximum likelihood method used
- Pseudo-experiments cast with signal strength set to 0
- p-value is the fraction of pseudo-experiments with a defined likelihood function larger than that for the data.

Cross Section

- Profile likelihood fit
- Cross section and 68% confidence level estimated
- Theory uncertainties not included in the fit, added in by hand afterwards.

Results

Submitted to Phys. Rev. Lett.
arXiv:1401.2942

- **6.1σ** excess of events over expected background is observed, compared to simulation only expected **$5.4^{+1.5}_{-1.4}\sigma$**
- Measured cross-section is **$23.4^{+5.5}_{-5.4}$ pb**.
- V_{tb} estimation: SM: 22 ± 0.6 ± 1.4 pb

$$|V_{tb}| = 1.03 \pm 0.12 \text{ (exp.)} \pm 0.04 \text{ (th.)}$$

- Assuming SM $0 \leq |V_{tb}| \leq 1$, a lower bound at 95% CL:

$$|V_{tb}| > 0.78$$

Assumes:
$|V_{tu}| = |V_{ts}| = 0$
SM-like interactions

- ATLAS sensitivity:

Observed: 4.2σ
Expected: 4.0σ
Cross section: 27.2±5.8 pb

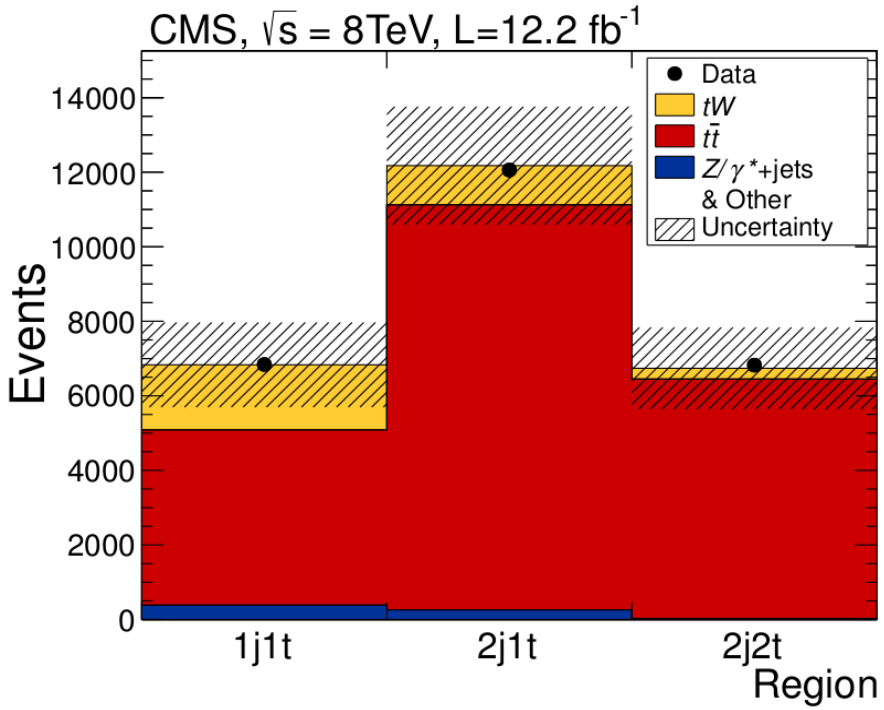
ATLAS-CONF-2013-100

Cross Check Analyses I
Cut and Count

- Cross check of BDT's robustness
- Same event selection and control regions, with additional cuts
  - Veto events with any additional b-tagged jets
  - H_T > 160 GeV in eμ channel
- Fit directly to event counts

Observed Significance: 3.6σ
Expected Significance: $2.8^{+0.9}_{-0.8}\sigma$
Measured Cross Section: $33.9^{+8.6}_{-8.6}$ pb

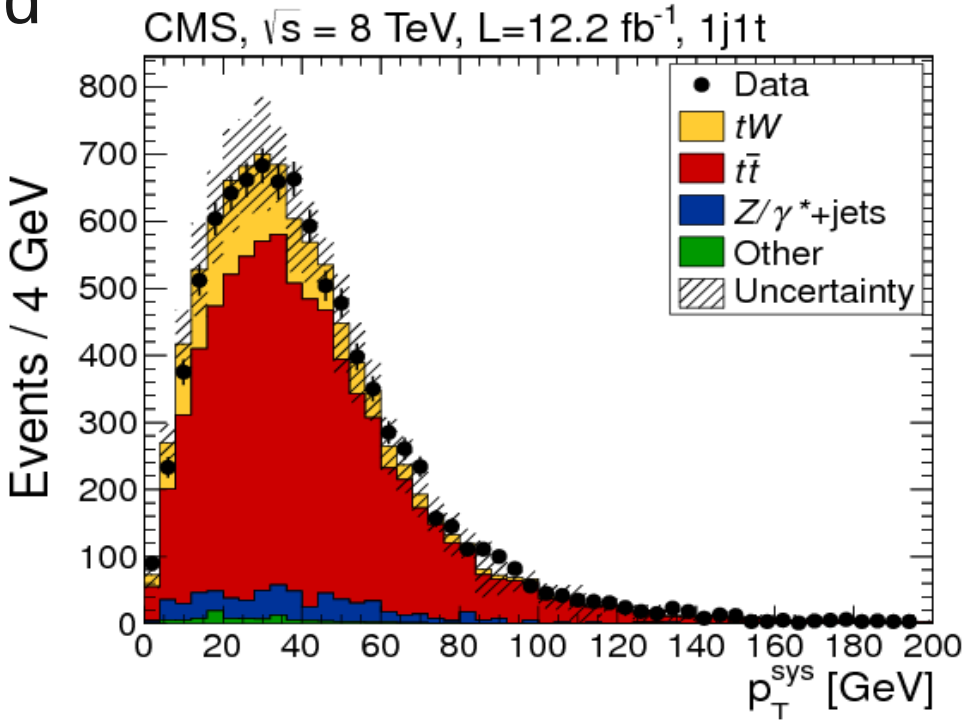
Cut and count alone provides evidence of tW



Cross Check Analysis II
$p_{T,sys}$ Fit

- Same cuts as cut and count cross check
- Fits the transverse momentum of the system – the vector sum of the p_T of the two leptons, jet and MET.
- Improved sensitivity compared to cut and count

Observed Significance: 4.0σ
Expected Significance: $3.2^{+0.4}_{-0.9}\sigma$
Measured Cross Section: $24.3^{+8.6}_{-8.8}$ pb



Conclusions

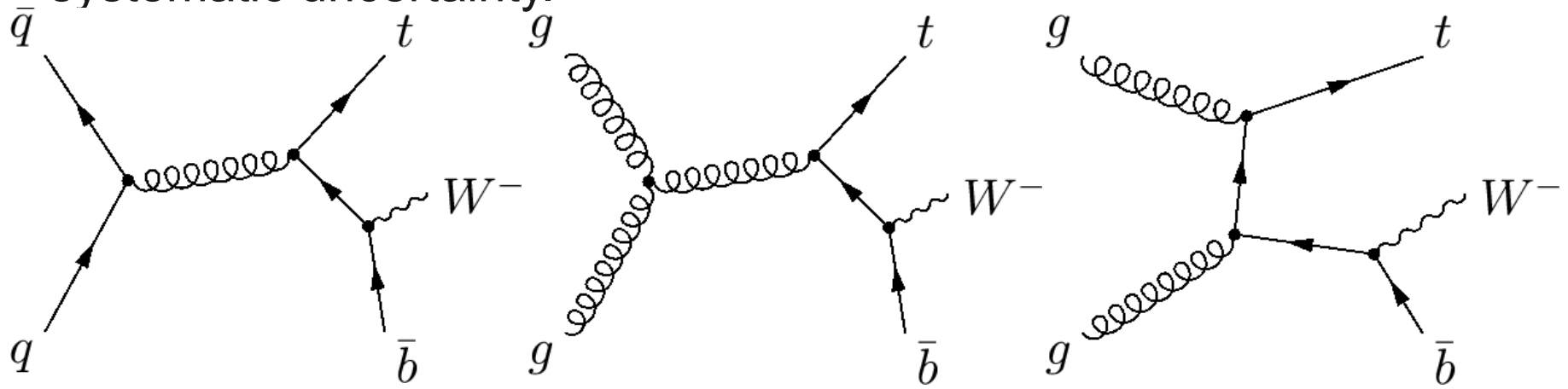
- CMS has previously provided evidence for tW associated production, which was not accessible at the tevatron, at 7TeV and has now provided the first observation using 8TeV proton-proton collisions.
- Separation of signal and $t\bar{t}$ background is the main difficulty.
- 6.1σ significance, $23.4^{+5.5}_{-5.4}$ pb.
- Two cross check analyses provided as test of BDT robustness. All are consistent and cross checks achieve evidence on their own.
- Available online (arXiv:1401.2942) and submitted to PRL.
- Systematic (not statistics) dominated.
- Future plan is to reduce uncertainty on measured cross-section at 8TeV by using larger statistics and improving theory uncertainties.
- tW cross-section grows the most of single top processes (~3.8) from 8 to 13TeV (Run-2 to begin in 2015), scaling favourably compared to $t\bar{t}$ (~4).
- Finally, many thanks to STFC for their studentship support and to Brunel University for their continued support in my ongoing work!

Brunel UNIVERSITY LONDON

Backup Slides

Diagram Removal/Diagram Subtraction

- tW signal mixes strongly with top quark pair production at NLO. Two schemes to avoid a problem:
  - Diagram Removal (DR) – remove doubly resonant diagrams from signal definition
  - Diagram Subtraction (DS) – subtract guage-invariant term to cancel $t\bar{t}$ contribution
- DR chosen for analysis, but the two are shown to be consistant within statistical uncertainties, and the difference is included as a systematic uncertainty.



7 TeV – Evidence of tW

- Dilepton channel, using 4.9 fb^{-1} 7 TeV data
- BDT with 4 variables, cut and count cross-check
- PRL110(2013)022003 – published 11th Jan 2013

Results

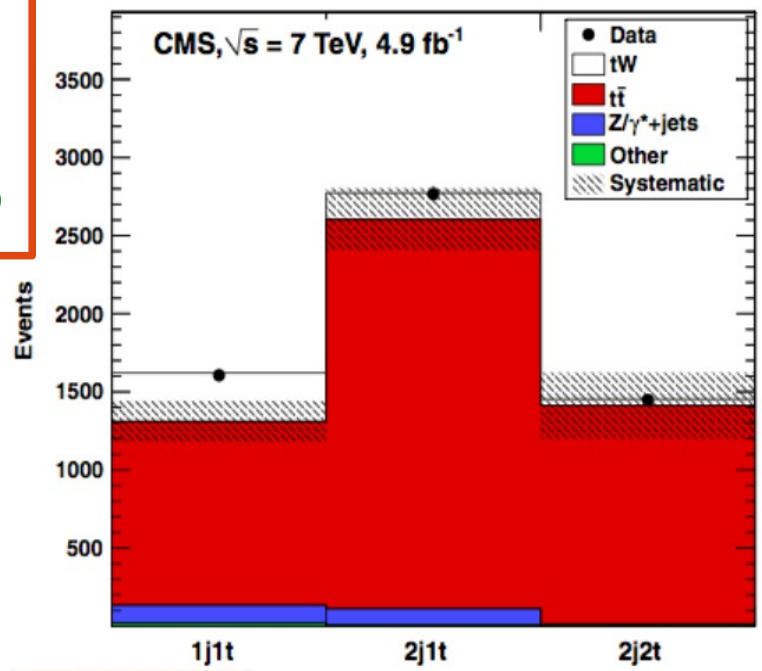
Observed: 4.0σ

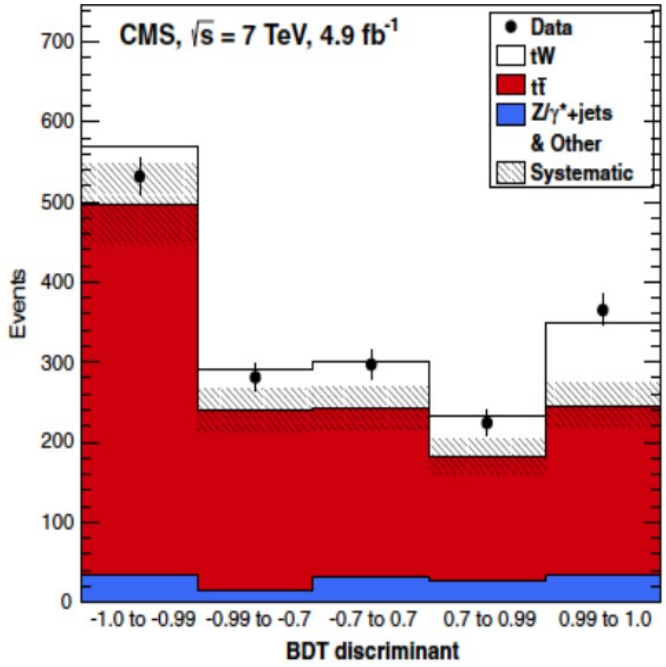
Expected: $3.6^{+0.8}_{-0.9}\sigma$

Cross Section: 16^{+5}_{-4} pb

SM Cross Section

$15.6 \pm 0.4^{+1.0}_{-1.2}$ pb





ATLAS: Evidence for tW at 7TeV

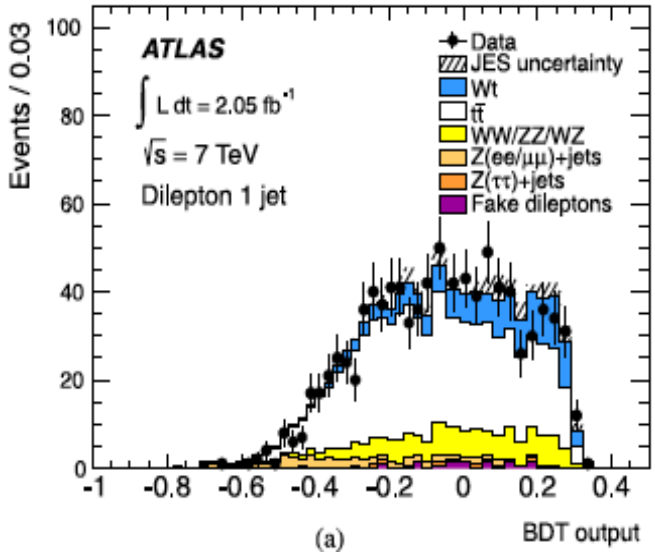
- Dilepton channel with 2.05 fb^{-1} 7TeV pp data
- Exactly 1 jet signal region. 22 variable BDT – p_t of the system is most powerful variable.
- Phys.Lett.B 716 (2012) 142-159

Results

Observed: 3.3σ

Expected: 3.4σ

Cross Section: 16.8 ± 2.9 ± 4.9 pb



Object Selections 1

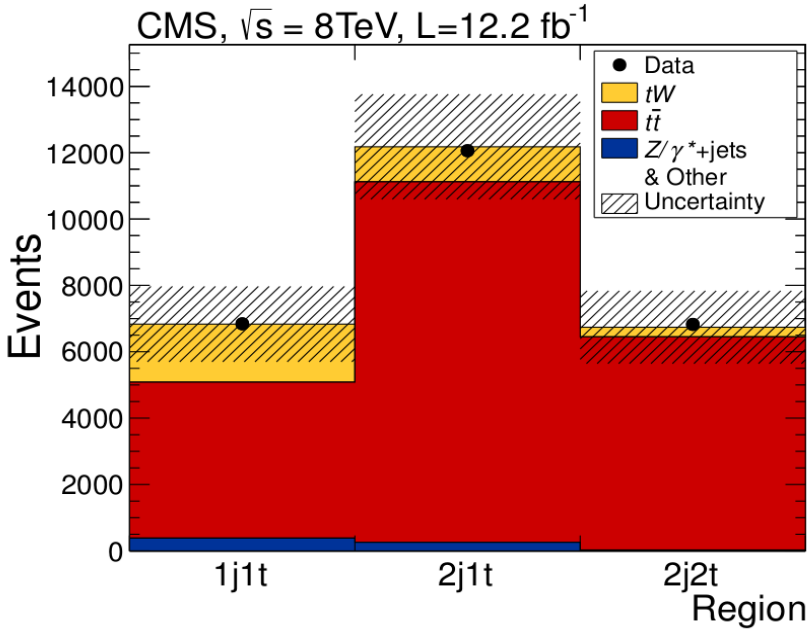
- **Electrons**
  - Gsf electrons, $p_T > 20$ GeV, $|\eta| < 2.5$, relIso < 0.15 ($\Delta R < 0.3$)
  - IP < 0.04cm from beam spot
- **Loose Electrons**
  - $p_T > 10$ GeV, $|\eta| < 2.5$
- **Muons**
  - PF, Global and Tracker muons, $p_T > 20$ GeV, $|\eta| < 2.4$, relIso < 0.20 ($\Delta R < 0.3$)
- **Loose Muons**
  - $p_T > 10$ GeV, $|\eta| < 2.4$

Object Selections 2

- **Jets**
  - PF anti-k_T jets, JEC applied
  - $p_T > 30$ GeV, $|\eta| < 2.5$
- **B-tagging**
  - Combined Secondary Vertex, medium working point
  - Reweighted with p_T dependent scale factors (MC only)
- **Loose Jets**
  - Failing above 'tight' criteria
  - $p_T > 20$ GeV, $|\eta| < 4.9$ (2.4 for 'central')
- **Missing Transverse Energy (MET)**
  - PF MET, type I corrected

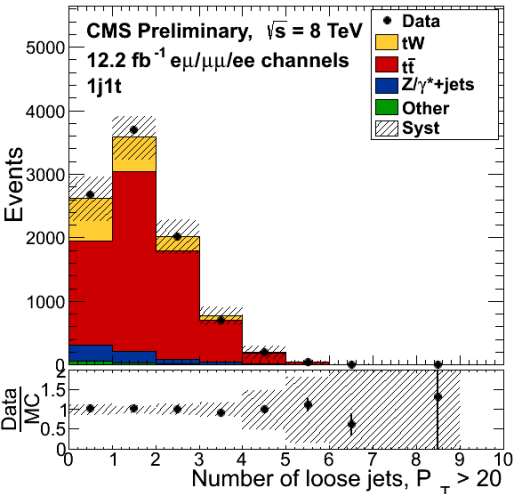
Signal and Control Regions

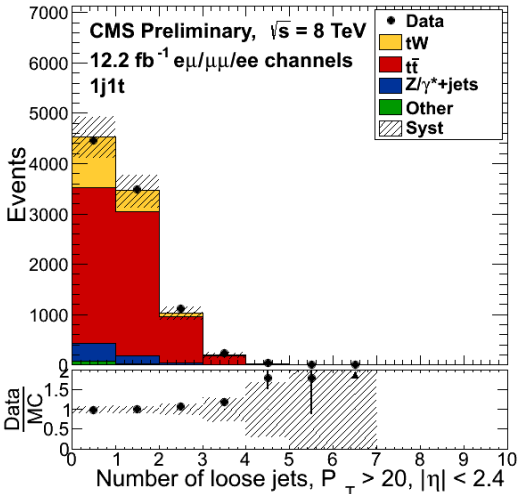
- Three regions are defined in the analysis:
  - **Signal Region:** Exactly 1, b-tagged jet (1j1t). (15-20% tW, 75% $t\bar{t}$, 5% Z+jets)
  - **$t\bar{t}$ Control Regions:** Exactly 2 jets, with either 1 (2j1t) or 2 b-tags (2j2t). Enriched in $t\bar{t}$: ~92% in 2j1t and ~97% in 2j2t.
- Z+jets control region (vetoed events within the Z-mass window) used to reweight Z+jets MC.

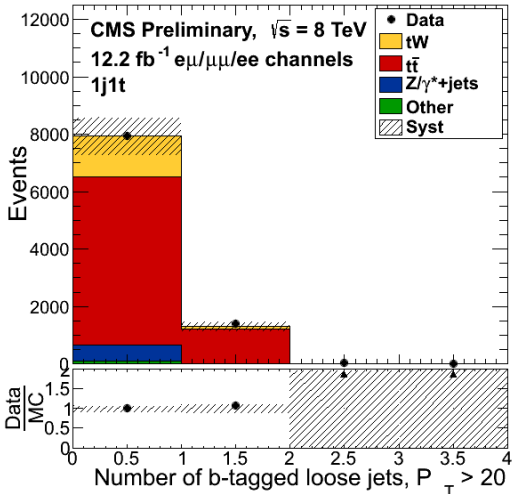


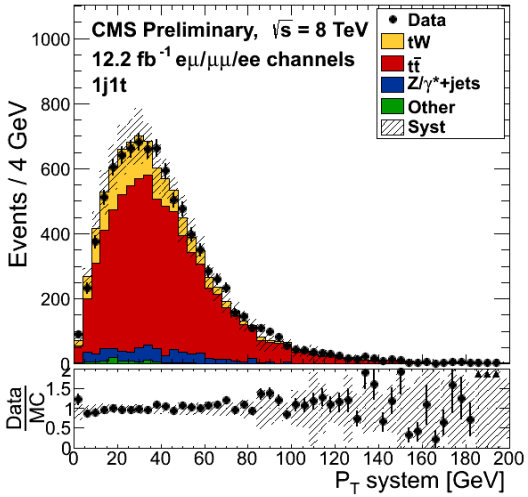
Input Variable Distributions I

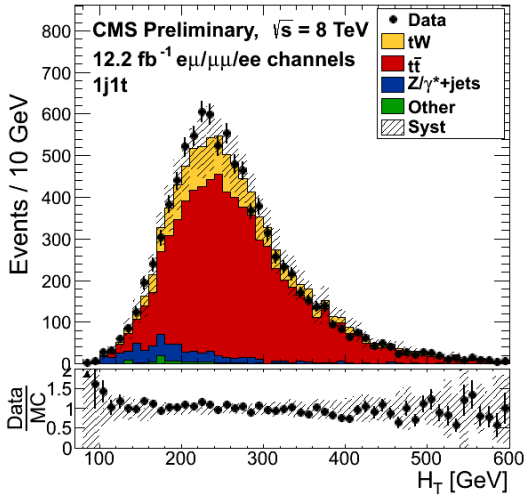
- Signal region BDT input variable distributions:

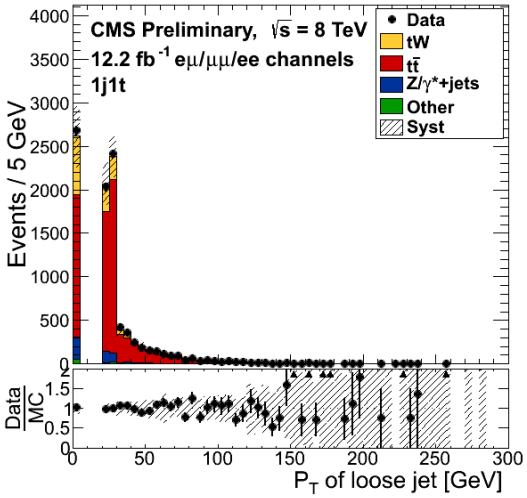


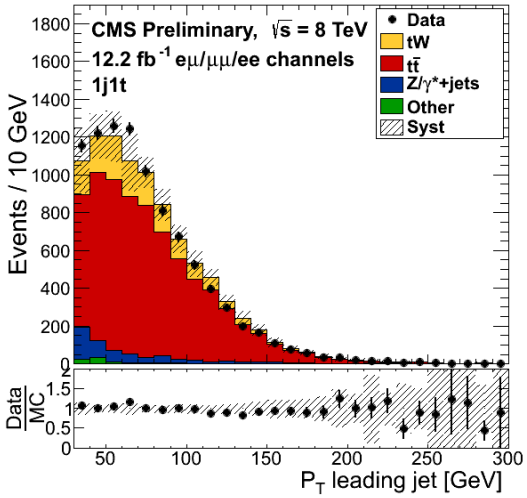




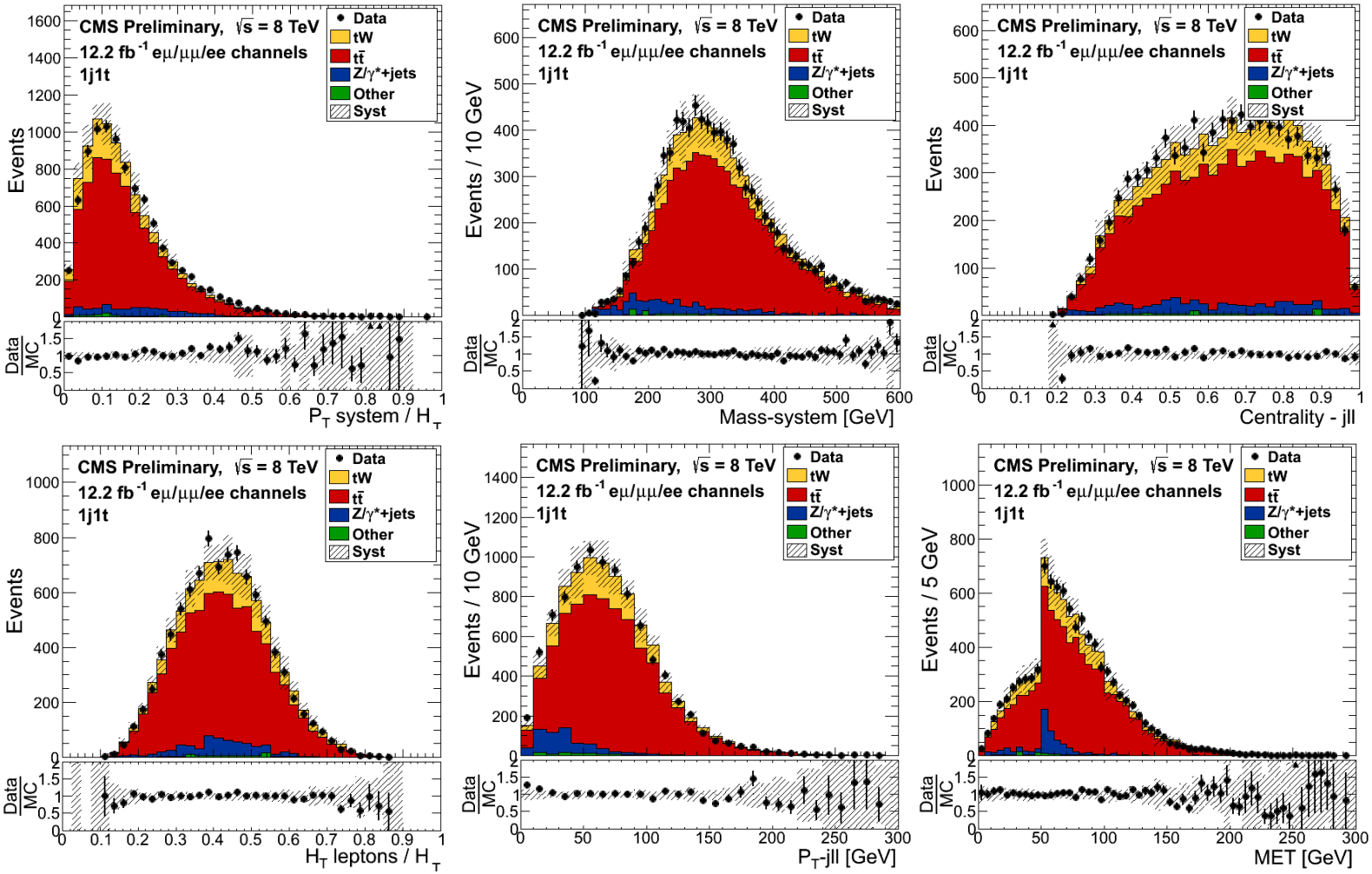




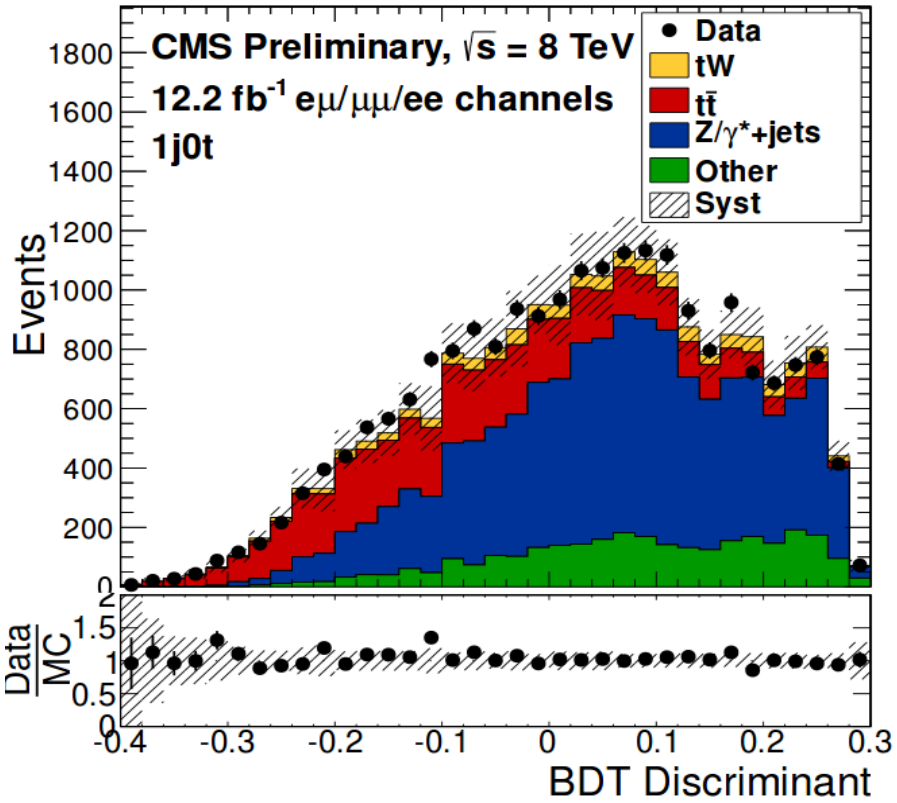


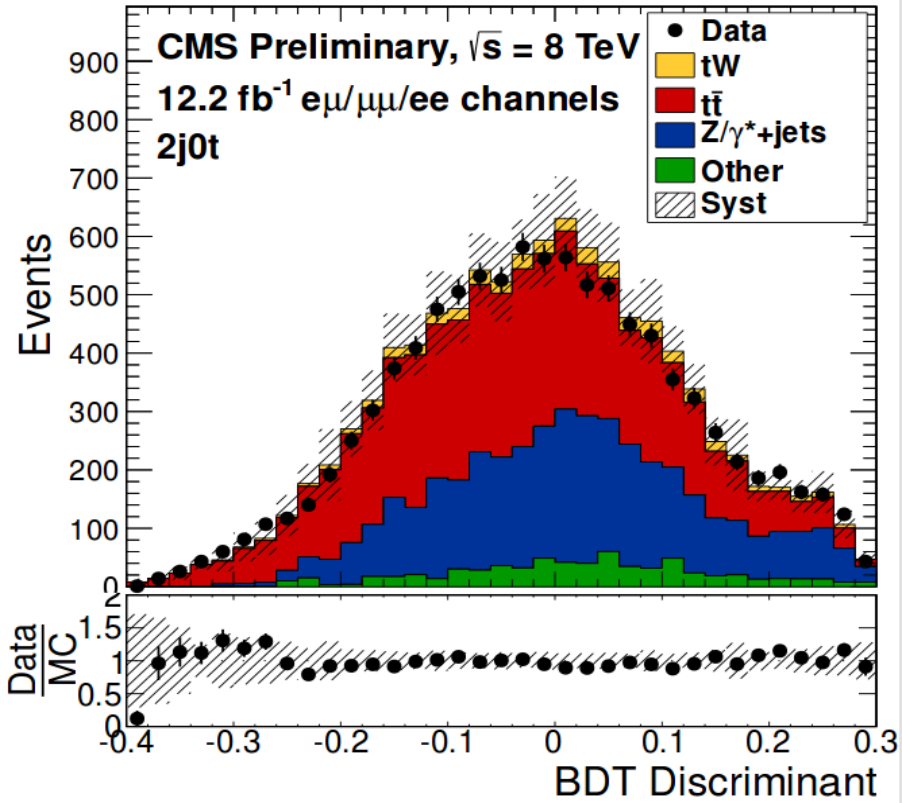


Input Variables Distributions II



BDT Discriminant in DY Dominated Control Region





Single top cross-sections at 13TeV