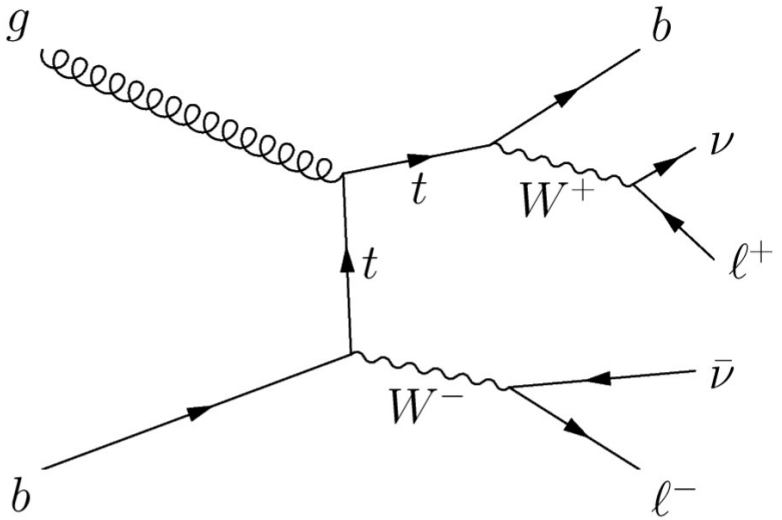
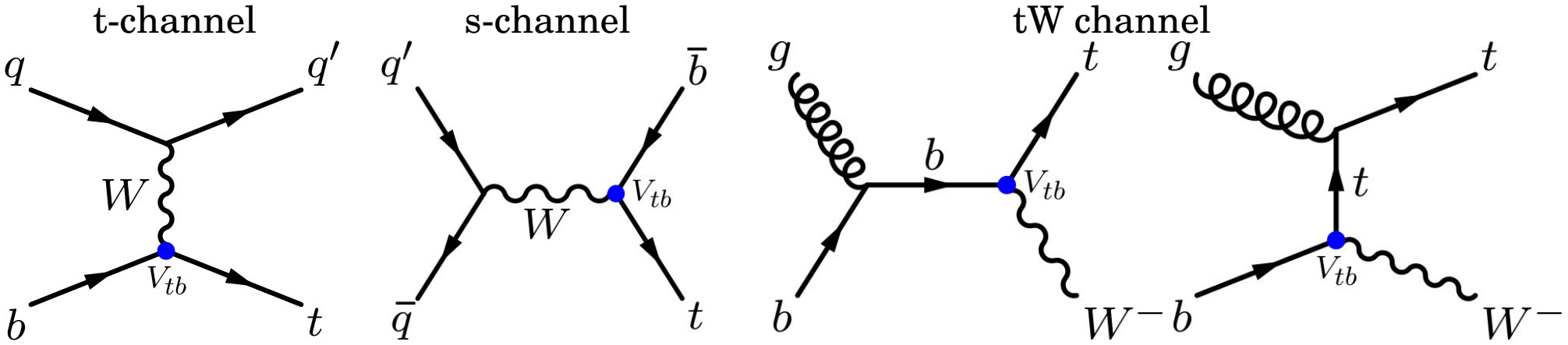
First observation of single top quark production in tW channel from CMS

Danny Noonan
University of Kansas



US LHC Users Organization Annual Meeting
November 6-8, 2013

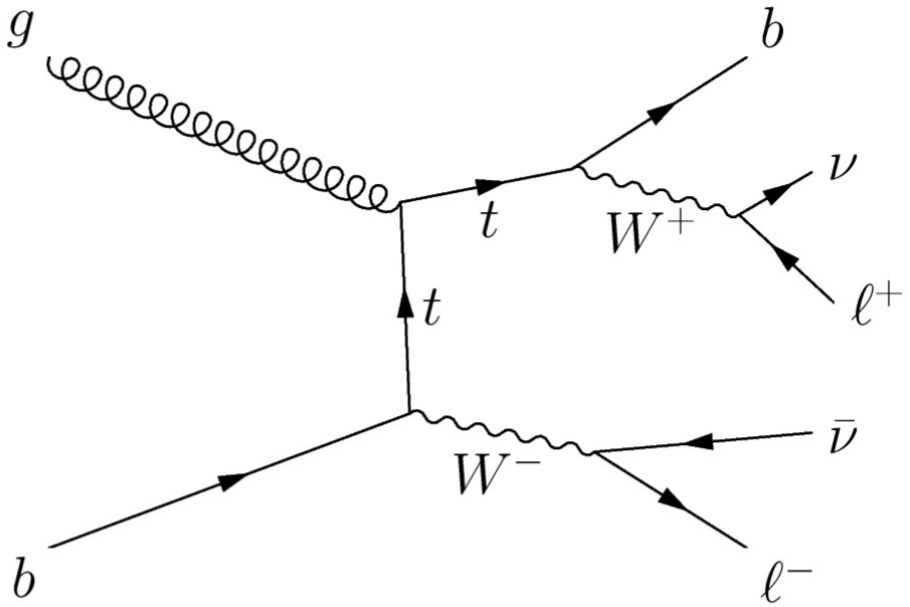
Single Top Production



- Electroweak top quark production
  - Possible channel for new physics
- Direct measurement of V_{tb}
- LHC provides first chance for measuring tW production channel

σ(pb)	t-channel	s-channel	tW channel
Tevatron - 1.96 TeV	2.08	1.05	0.22
LHC - 7 TeV	65.9	4.56	15.6
LHC - 8 TeV	87.2	5.55	22.2

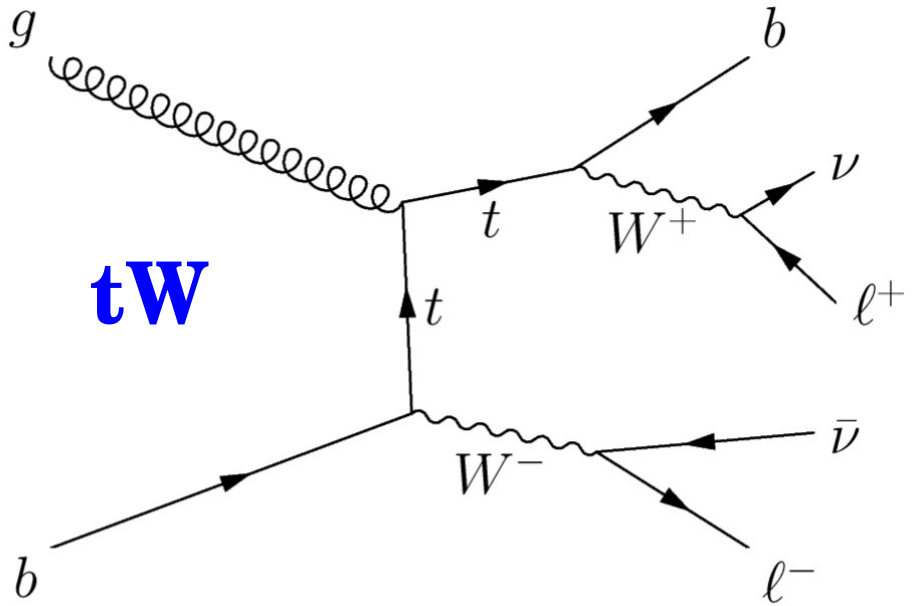
tW Dilepton Signature



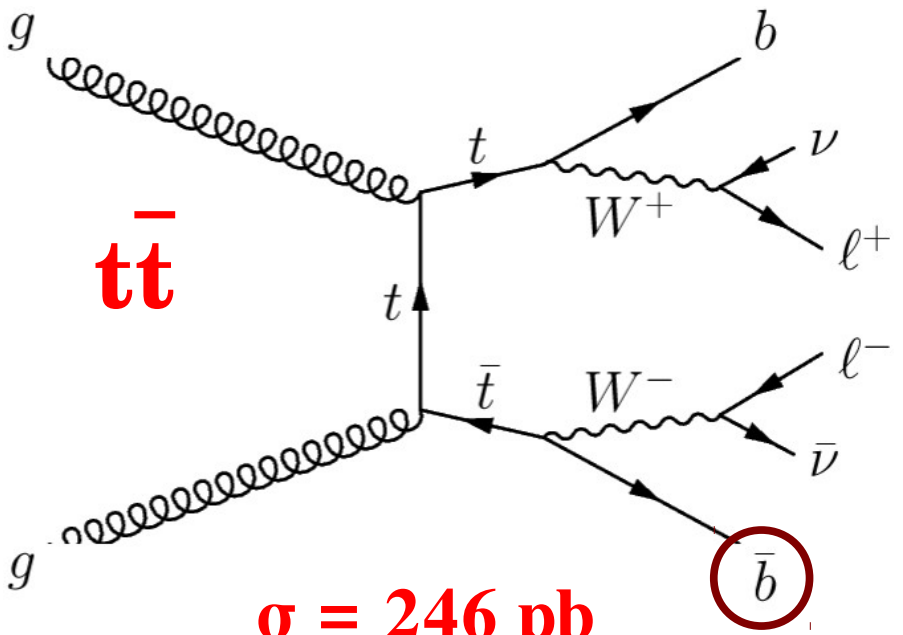
- Top decays into W boson and bottom quark
- Dilepton decay channel:
  - **Two leptons**
  - **B-quark (jet)**
  - **Two neutrinos (Missing E_T)**

tW Dilepton Signature

- Very similar to dilepton ttbar production



σ = 22.2 pb



σ = 246 pb

Only difference is one extra b-quark in the final state

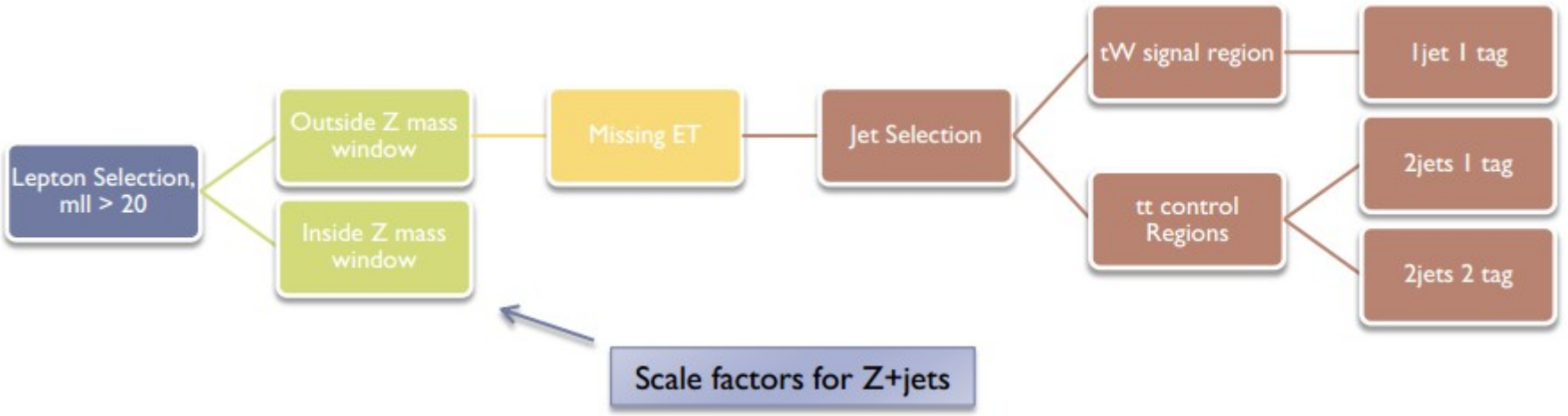
Event Selection

- **Data:** Analysis uses 12.2 fb^{-1} of data recorded by the CMS detector at 8 TeV
- **Event Selection**:
  - Dilepton triggers (eμ/μμ/ee)
  - Two oppositely charged leptons with $p_T > 20$ GeV
  - $m_{\ell\ell} > 20$ GeV (all channels) and veto if $81 < m_{\ell\ell} < 101$ GeV (in ee and μμ channels)
  - Missing $E_T > 50$ GeV in ee and μμ channels
  - One b-tagged jet (CSV) with $p_T > 30$ GeV
- **Backgrounds**:
  - Largest is $t\bar{t}$ (245 pb), followed by Z+jets, and then diboson (WW, WZ, ZZ)

Signal and Control Regions

Three regions are used in the analysis:

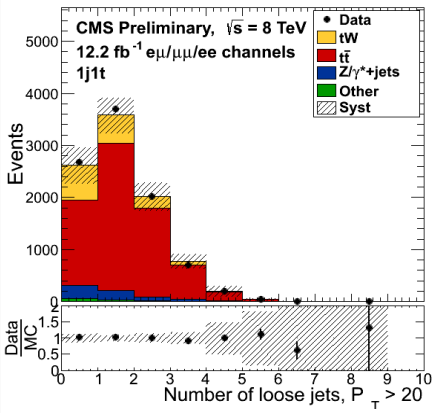
- **Signal region**: Exactly 1 jet, b-tagged (**1j1t**); largely tW and $t\bar{t}$, with some Z+jets (~15-20% tW, ~75% $t\bar{t}$, ~5% Zjets)
- **$t\bar{t}$ control regions**: Exactly 2 jets, with either 1 b-tagged (2j1t) or both b-tagged (2j2t); dominated by $t\bar{t}$

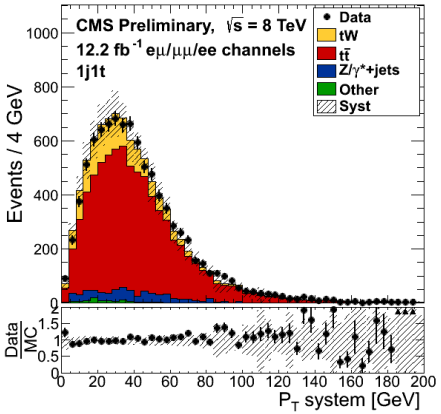


Boosted Decision Tree (BDT)

- Trained to distinguish tW signal from $t\bar{t}$ background
- 13 input variables used
  - Having some separation power between signal and background
  - Being well modeled in MC (in various control regions)

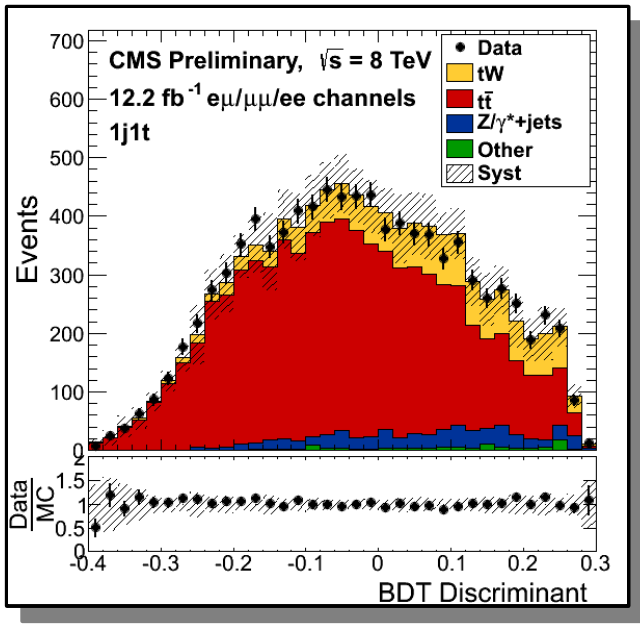
Variable	Description
Nloosejets	Number of loose jets, $p_T > 20$ GeV, $\|\eta\| < 4.9$
NloosejetsCentral	Number of loose jets, $p_T > 20$ GeV, $\|\eta\| < 2.4$
NbtaggedLoosejets	Number of loose jets, $p_T > 20$ GeV, CSVM btagged
$p_{T,sys}$	Vector sum of p_T of leptons, jet, and E_T^{miss}
H_T	Scalar 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

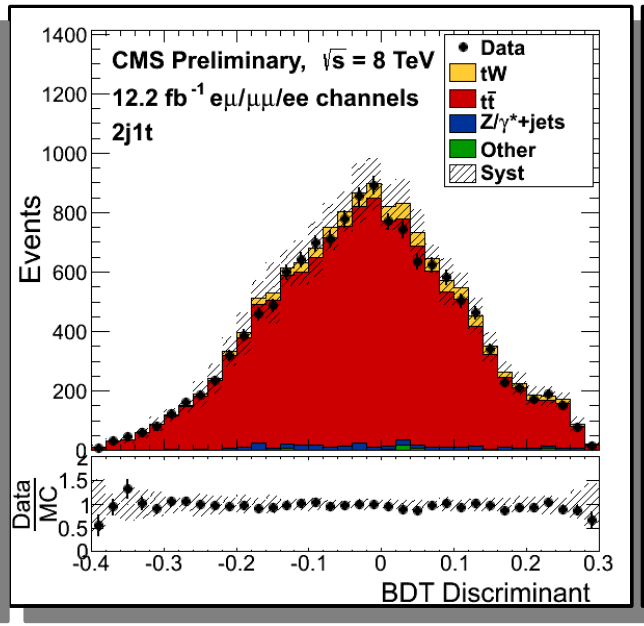


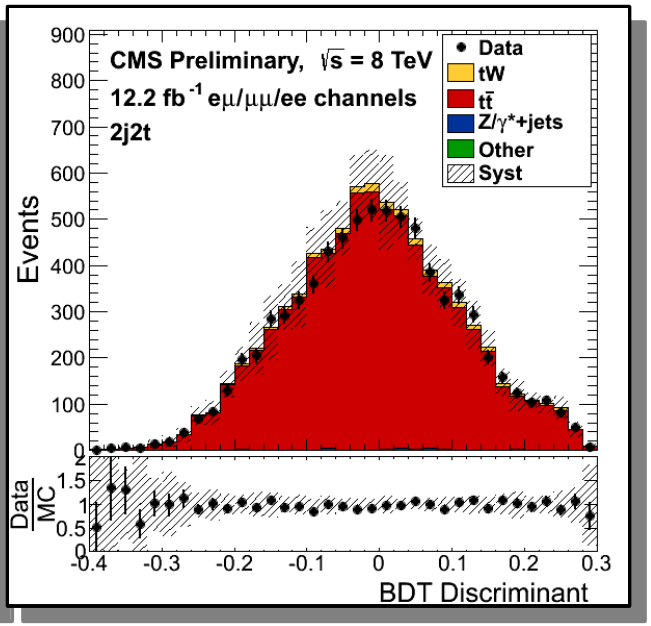


BDT Discriminant Fit

- Likelihood fit to BDT discriminant
  - Simultaneous fit across all **three dilepton channels** (eμ/μμ/ee) and **three regions** (1j1t signal region, 2j1t and 2j2t control regions)
- Templates for signal and background taken from MC
- Systematic uncertainties taken into account based on change to template, added into the fit as nuisance parameters







Results

- Excess of events is observed above a background-only hypothesis

$$\begin{aligned}&\text{Observed Significance: } 6.0\sigma\\&\text{Expected Significance: } 5.4^{+1.5}_{-1.4}\sigma\\&\text{Cross Section: } 23.4^{+5.5}_{-5.4}\text{ pb}\end{aligned}$$

- V_{tb} matrix element estimated
  - Under assumption that $|V_{tb}| \gg |V_{td}|, |V_{ts}|$

$$|V_{tb}| = \sqrt{\frac{\sigma_{tW}}{\sigma_{tW}^{th}}} = 1.03 \pm 0.12(exp.) \pm 0.04(th.)$$

- Assuming $0 \leq |V_{tb}| \leq 1$, get a limit at 95% C.L. of $|V_{tb}| > 0.78$

Summary

First observation of tW associated production

Observed Significance: 6.0 σ

Expected Significance: $5.4^{+1.5}_{-1.4}$ σ

Measured Cross Section: $23.4^{+5.5}_{-5.4}$ pb

Theoretical Cross Section: 22.2 ± 0.6 ± 1.4 pb

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

More details on the analysis can be found in CMS-PAS-TOP-12-040:

http://cds.cern.ch/record/1563135

Thank You

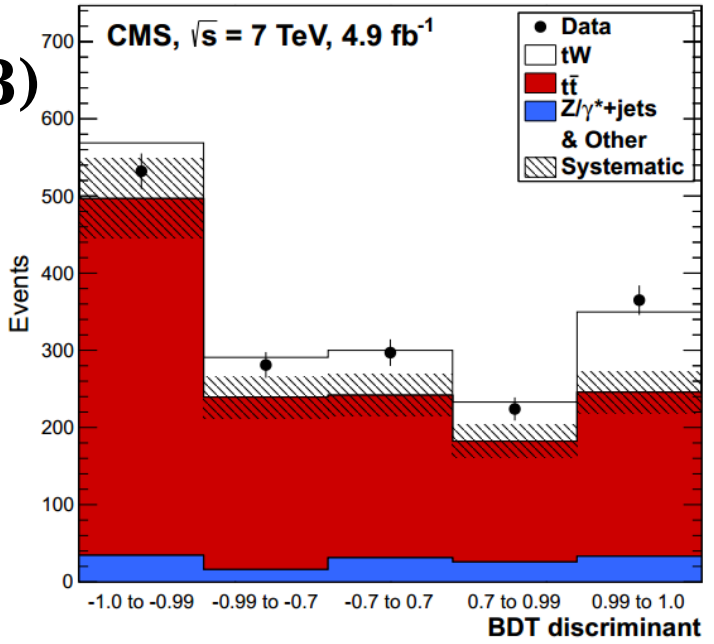
Backup Slides

Previous tW Results

- Tevatron wasn't able to see this channel
- Both ATLAS and CMS saw evidence for tW channel production in 7 TeV data

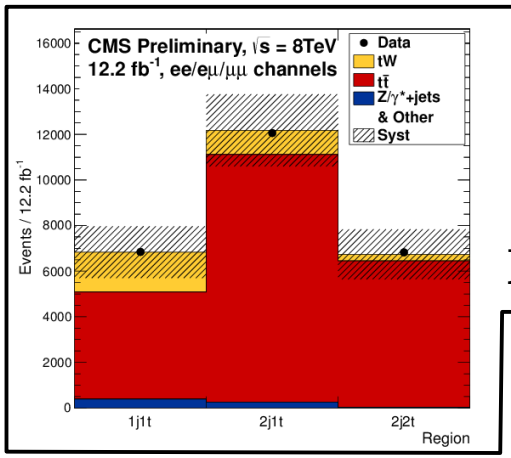
CMS: Phys. Rev. Lett. 110, 022003 (2013)
4.0 σ signficance,
Cross section of 16 +5 -4 pb

ATLAS: Phys. Lett. B716 (2012)
3.3 σ signficance,
Cross section of 16.8±2.9±4.9 pb



Cross Checks

- Two cross check analyses done: cut-based and fit to $p_{T,sys}$ distribution
- Same event selection and control regions, with two added cuts:
  - Veto on events with extra b-tagged loose jets (p_T>20 GeV)
  - Cut on H_T in eμ channel (H_T > 160 GeV)



Cut-based

Observed Significance: 3.6 σ

Expected Significance: $2.8^{+0.9}_{-0.8}$ σ

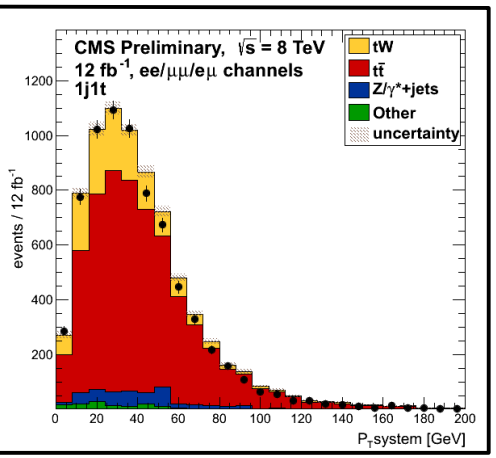
Measured Cross Section: $33.9^{+8.6}_{-8.6}$ pb

$p_{T,sys}$ fit

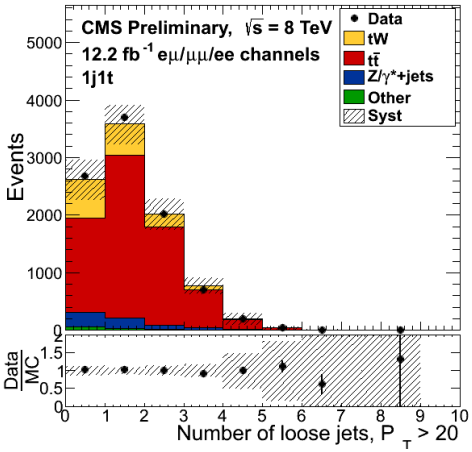
Observed Significance: 4.0 σ

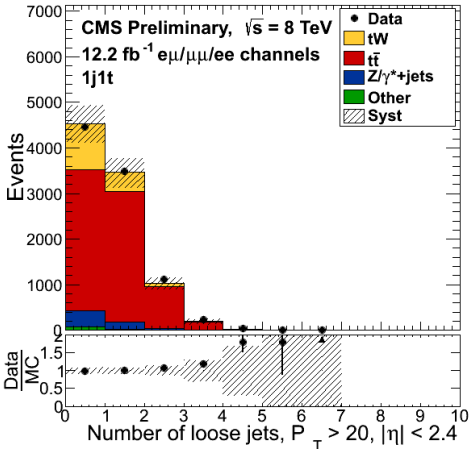
Expected Significance: $3.2^{+0.4}_{-0.9}$ σ

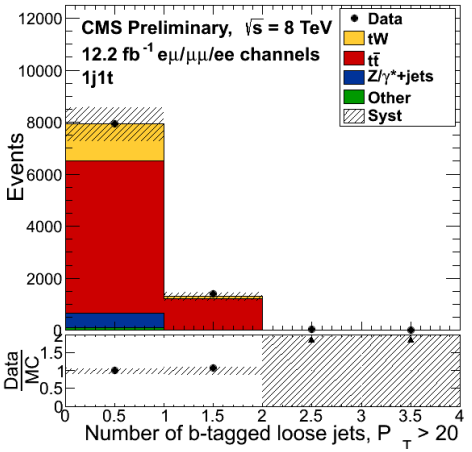
Measured Cross Section: $24.3^{+8.6}_{-8.8}$ pb

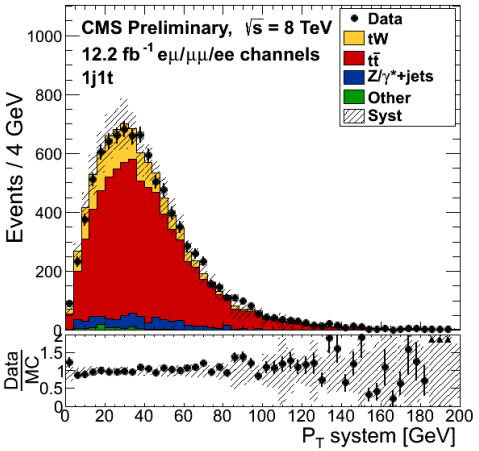


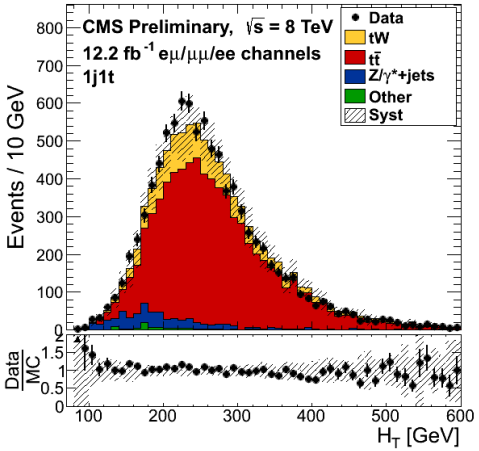
Additional Plots
Input Variable Distributions (1j1t)

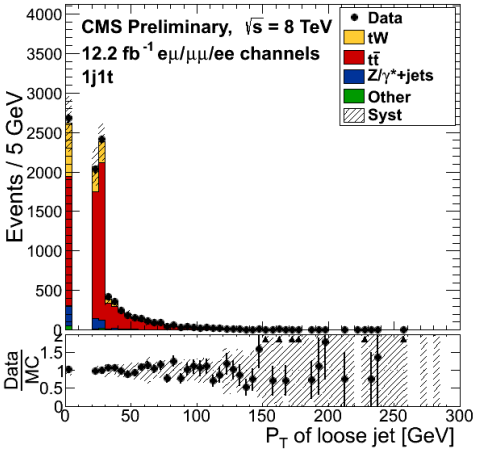


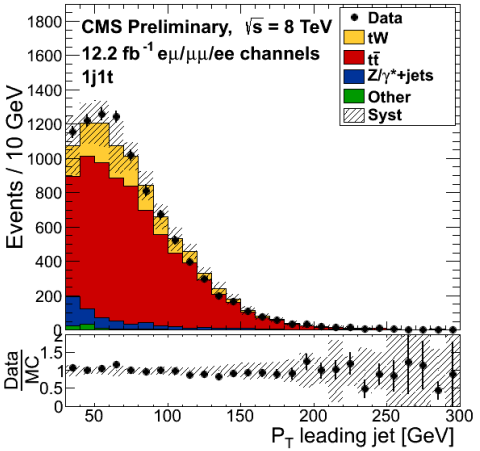




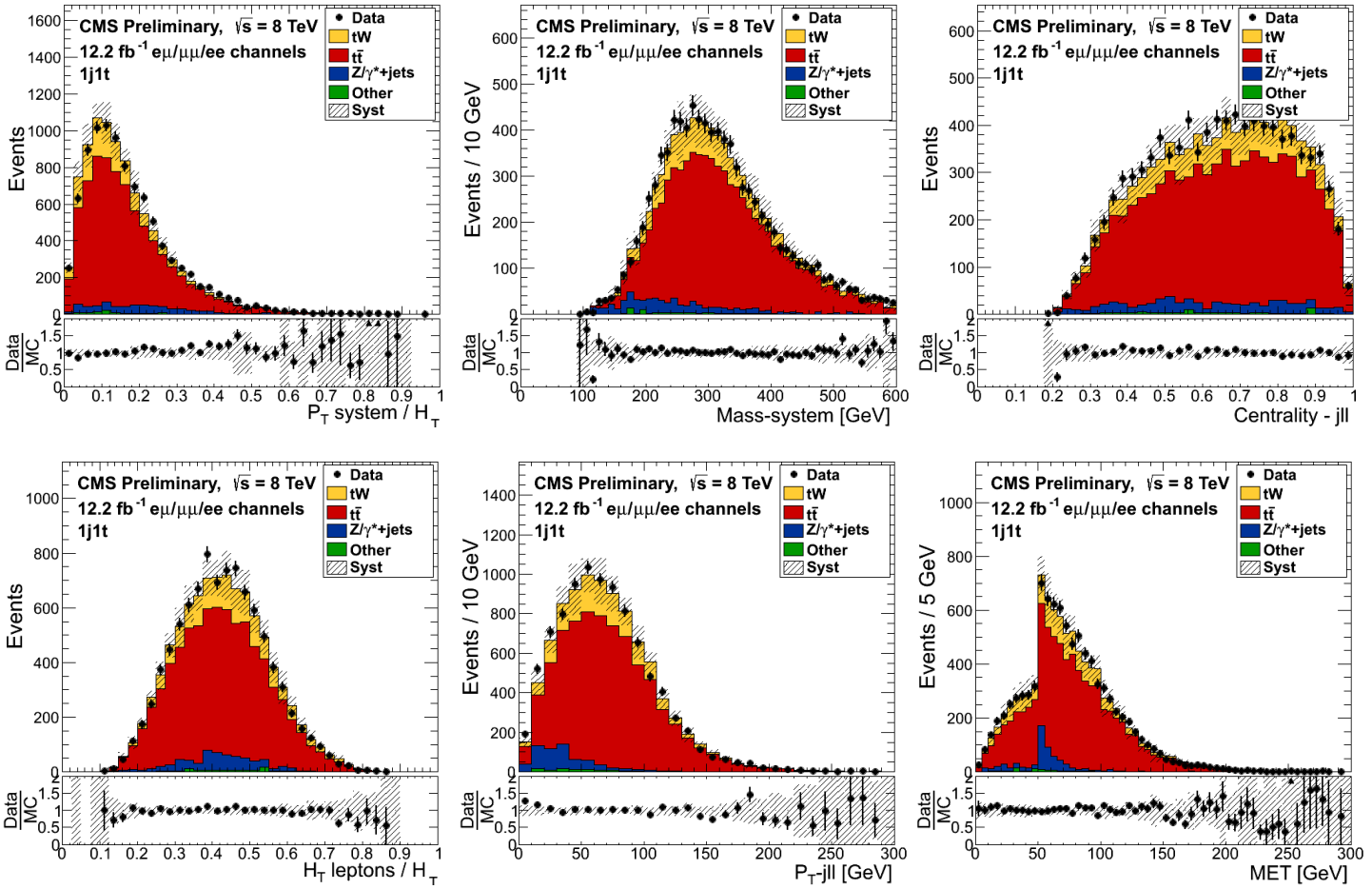






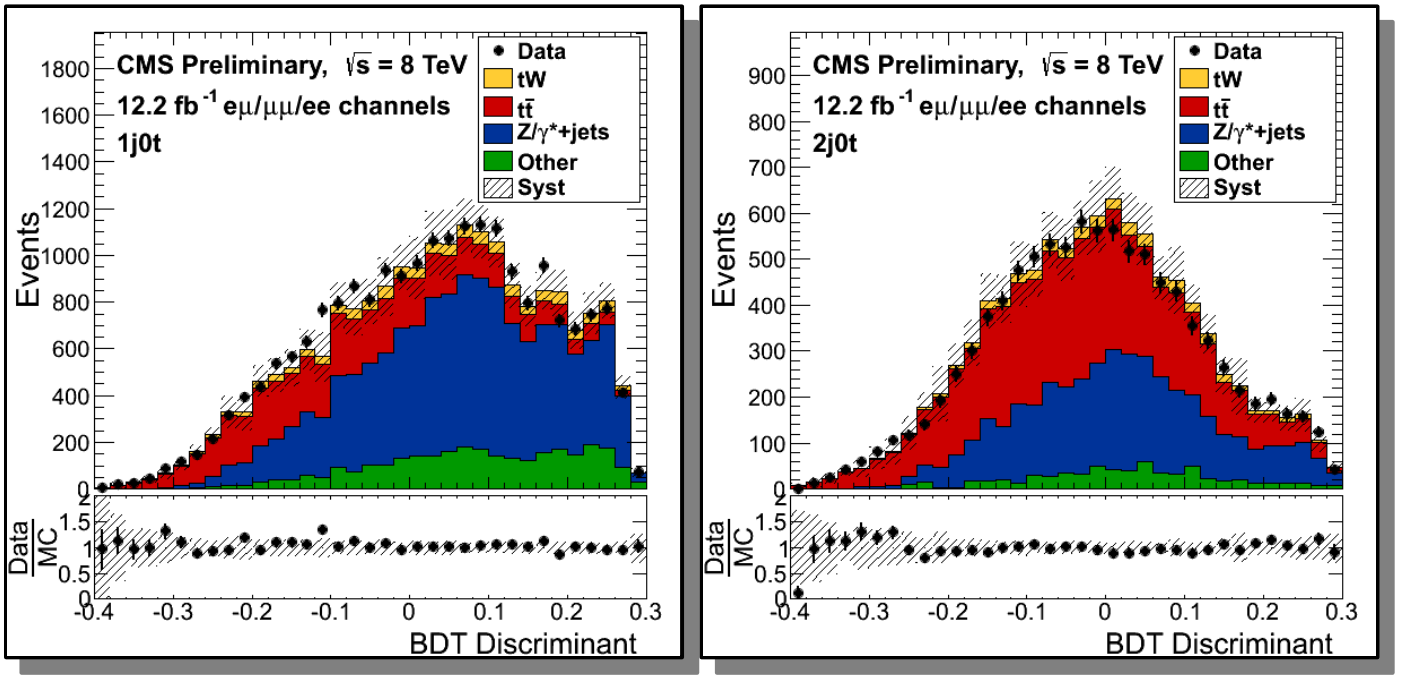


Additional Plots
Input Variable Distributions (1j1t)

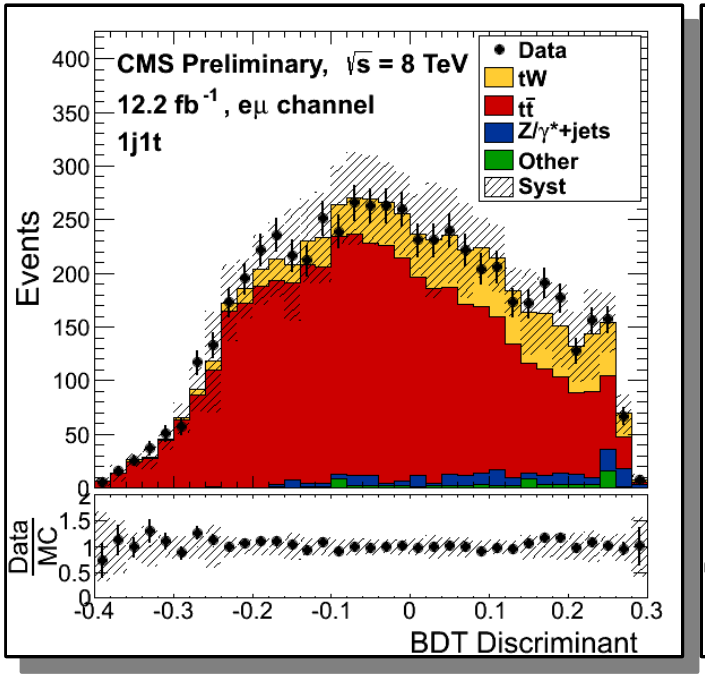


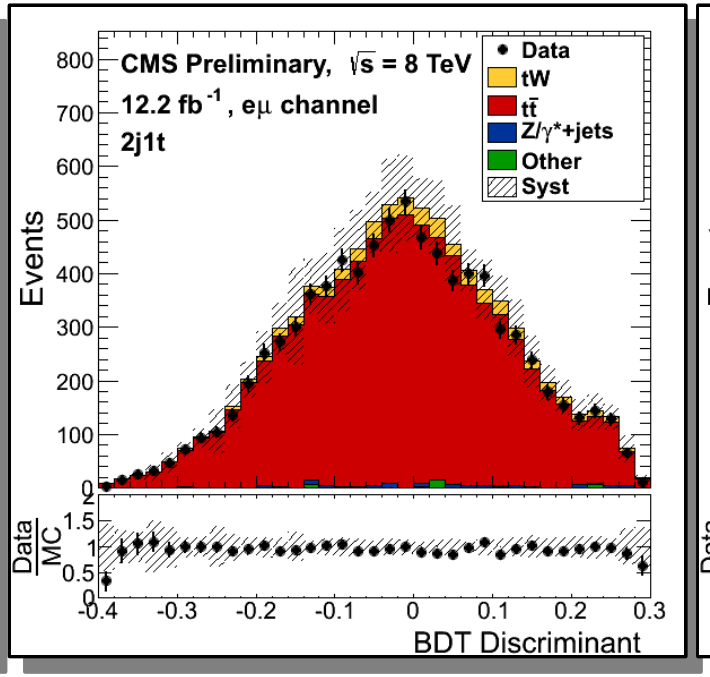
BDT Output

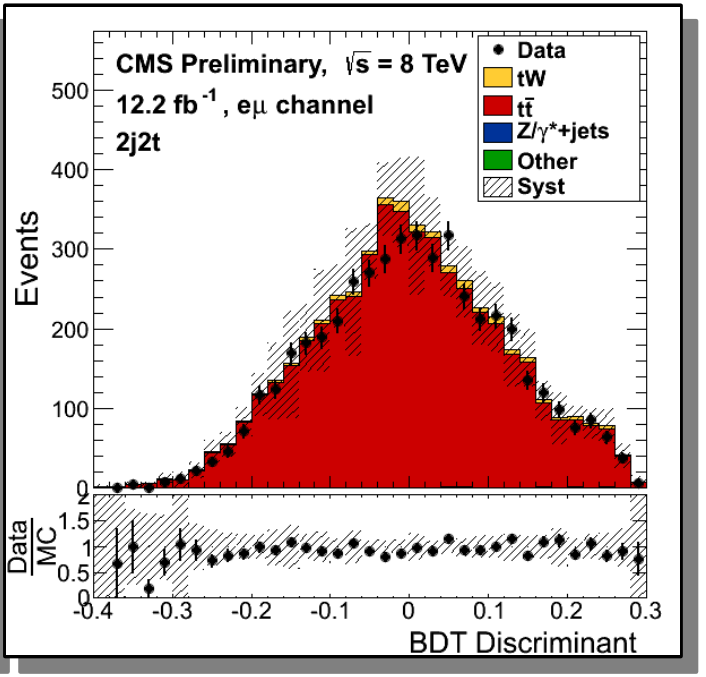
- Check the agreement between data and MC in two additional control regions: 1 untagged jet (1j0t) and 2 untagged jets (2j0t)



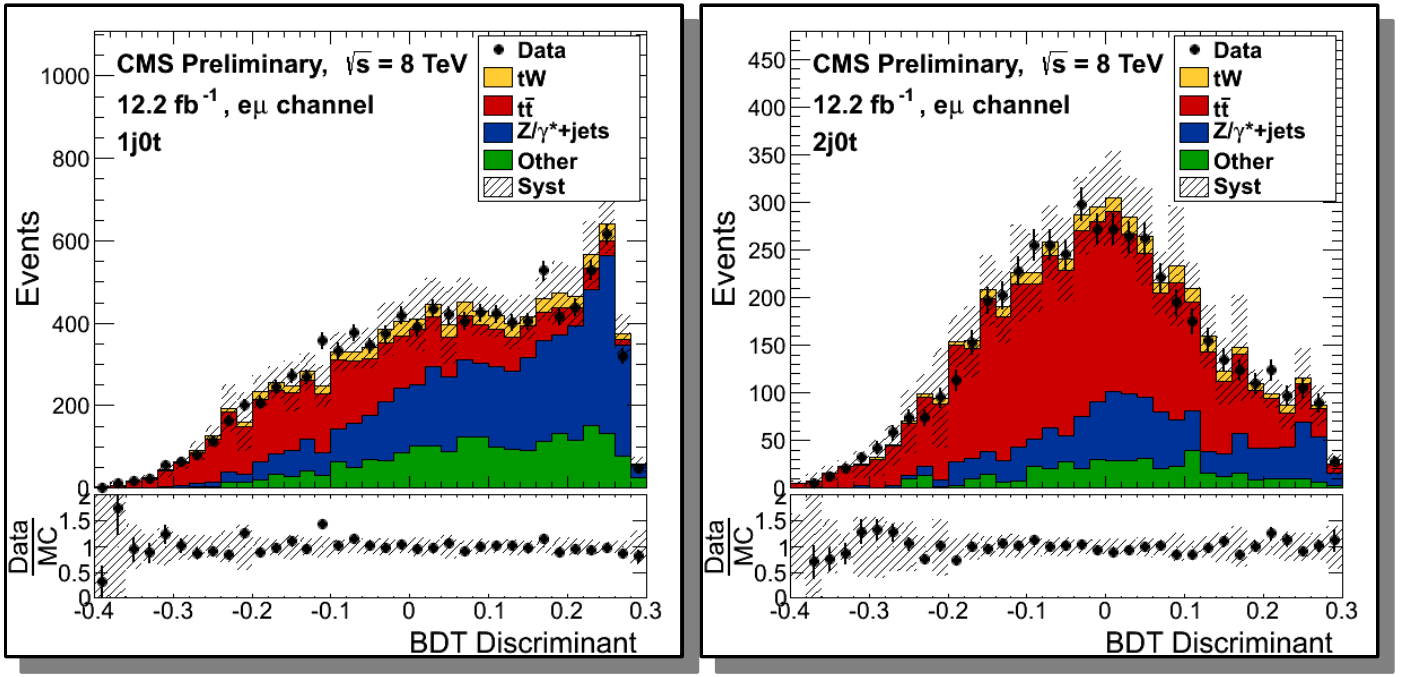
BDT Output emu channel







BDT Output


CMS Preliminary, √s = 8 TeV
12.2 fb-1, eμ channel
1j0t
Data
tW
tt̄
Z/γ*+jets
Other
Syst
Events
Data/MC
BDT Discriminant
CMS Preliminary, √s = 8 TeV
12.2 fb-1, eμ channel
2j0t
Data
tW
tt̄
Z/γ*+jets
Other
Syst
Events
Data/MC
BDT Discriminant

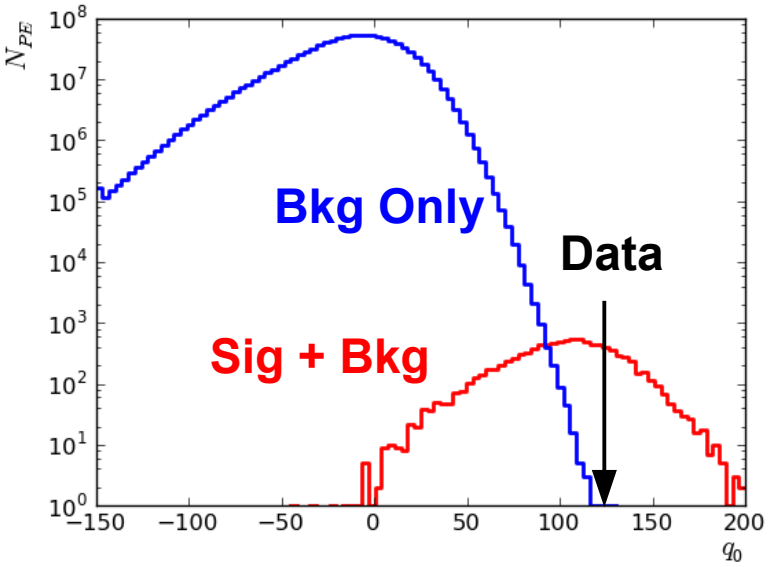
Systematics

- Effect of each systematic estimated based on contribution to uncertainty on cross section
  - Theory-based systematics are estimated based on setting nuisance parameters to +/- 1 sigma values
  - All other systematics are estimated by fixing the nuisance parameter to central value, and finding the change in the confidence interval
  - "Statistical" uncertainty found by fit with all nuisance parameters fixed and finding remaining uncertainty

Systematic Uncertainty	$\Delta\sigma$ (pb)	$\frac{\Delta\sigma}{\sigma}$
ME/PS matching thresholds	3.25	14%
Q^2 scale	2.68	11%
Top quark mass	2.28	10%
Statistical	2.13	9%
Luminosity	1.13	5%
JES	0.91	4%
$t\bar{t}$ cross section	0.87	4%
Z+jet data/MC scale factor	0.56	2%
tW DR/DS scheme	0.45	2%
PDF	0.33	1%
Lepton identification	0.31	1%
JER	0.27	1%
B-tagging data/MC scale factor	0.20	$< 1\%$
$t\bar{t}$ Spin Correlations	0.12	$< 1\%$
Top Pt Reweighting	0.12	$< 1\%$
Event pile up	0.11	$< 1\%$
$E_{\mathrm{T}}^{\mathrm{miss}}$ modeling	0.07	$< 1\%$
Lepton energy scale	0.02	$< 1\%$
Total	5.58	24%

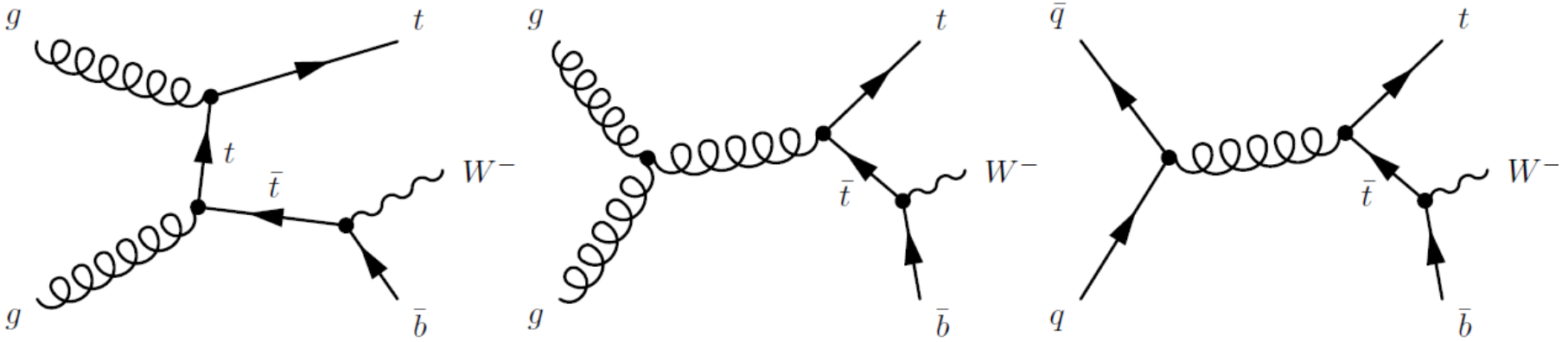
Significance

- Pseudo-experiments used for quantifying significance, using as the test-statistic:
  - $q_0 = \frac{\delta}{\delta\mu}\mathcal{L}(\mu = 0, \hat{\theta}_0|\text{data})$
  - μ is signal strength parameter, θ is set of nuisance parameters
  - Evaluated for background only and signal plus background hypothesis
  - Theory systematics included in toys, not fit



NLO QCD mixing

- tW signal mixes with pair production at NLO



  - **diagram removal (DR)**: remove double resonant diagrams
  - **diagram subtraction (DS)**: subtract gauge-invariant term to cancel contribution from $t\bar{t}$
- DR scheme used for definition of signal in this analysis
  - The two are consistent within statistical uncertainty and difference is accounted for as systematic uncertainty