Single Top Production in CMS

Outline:

- Single Top at the LHC
- t-channel analysis
- tW channel analysis
- Conclusions

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On behalf of the CMS Collaboration

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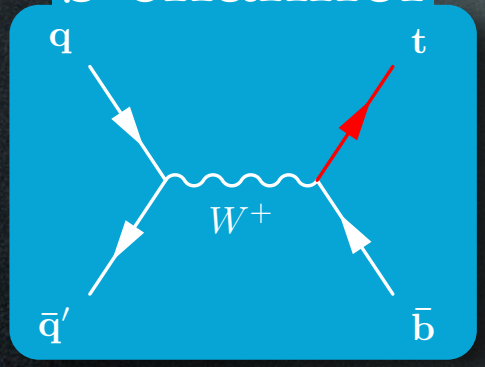
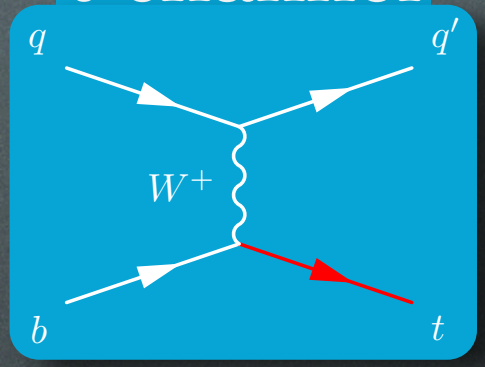
Introduction

- Three single top production channels:

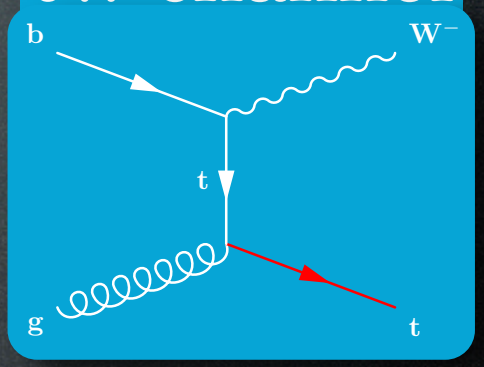
s-channel



t-channel



tW channel



- Weak interaction production (Wtb, btW) and decay vertices (tWb)
- Access to CKM matrix element V_{tb}
- Sensitive to new physics
- Top cross-sections at the LHC (and Tevatron)

Top mass = 173 GeV

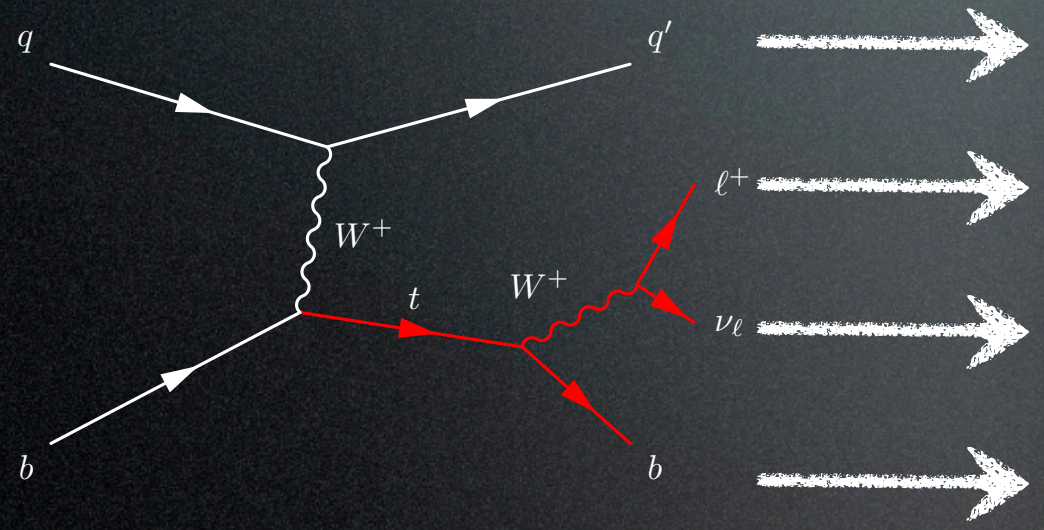
N. Kidonakis arxiv.org/pdf/1205.3453v1 (2012)

Cross sections (pb)	s-channel	t-channel	tW channel	top pairs
Tevatron: ppbar@1.96TeV	1.05	2.08	0.22* *arxiv.org/pdf/0909.0037	7.08
LHC: pp @ 7 TeV	4.56	65.9	15.6	163
LHC: pp @ 8 TeV	5.55	87.2	22.2	234

CMS PAS TOP-11-021

Single top t-channel

- Highest single top production cross-section at the LHC (and Tevatron)
- Systematics dominated measurement
- Only leptonic W decays considered (e, μ final states):
  - **Lepton + jets** topology:



→ **Light quark jet (large $|\eta_{j'}|$)**

ℓ^+ → **Isolated lepton (μ or e)**

ν_ℓ → **Missing Transverse Energy (ν_e or ν_μ)**

→ **Central high p_t b-jet**

  - Potential extra b-jet, broad $|\eta|$ and low p_t
- Main backgrounds:
  - W+jets, top pairs, QCD multi-jets

t-channel Lumi
1.2 fb^{-1}(μ)
1.6 fb^{-1}(e)

t-channel Event Selection

- Selection:
  - Exactly 1 isolated muon (electron)
  - Exactly 2 jets
  - Exactly 1 b-tagged jet

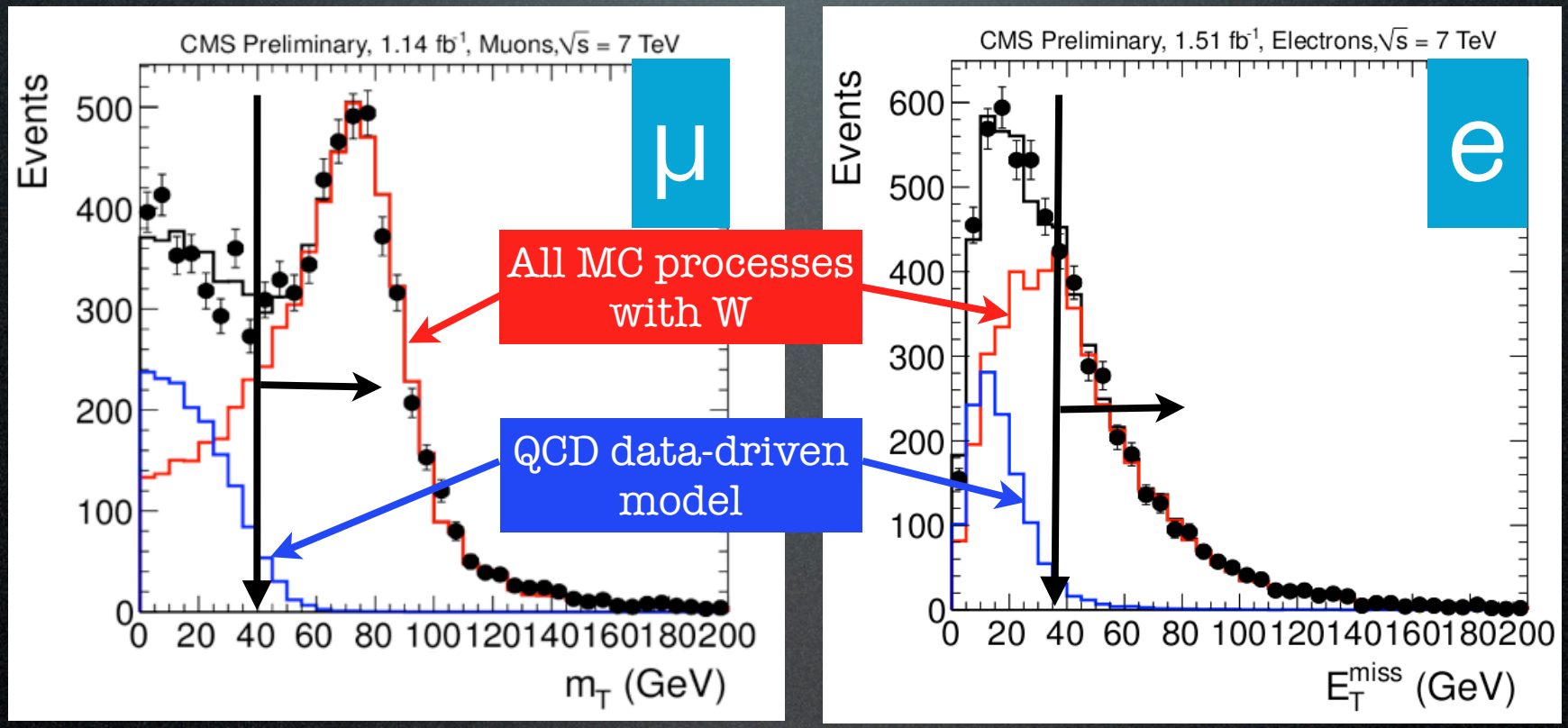
  2j1btag
- Background estimation and control samples:
  - QCD multi-jet — **Reversed Iso/ID**
  - W+light flavor — **2j0btag**
  - Top pairs — **3j2btag**
  - W+heavy flavor — **2j1btag sideband**
- Reconstruction:
  - W transverse mass $m_{T,W}$
  - Top invariant mass m_{lvb}

  for μ: $m_{T,W}$ >40GeV
  for e: E_T^{miss}>35 GeV
- Signal region (2j1btag):

  130GeV < m_{lvb} < 220GeV

t-channel QCD background

- Data-driven QCD multi-jet estimate:
  - QCD model from reversed iso/ID control region
  - QCD yield from 2j1btag fit of $m_{T,W}$ for muons and E_t^{miss} for electrons



- Suppress fake W leptonic decay events with $m_{T,W}$ and E_t^{miss} cut

t-channel W+heavy flavor

- Event yield in signal region after $\mathbf{m_{lvb}}$ cut:

MC Simulation

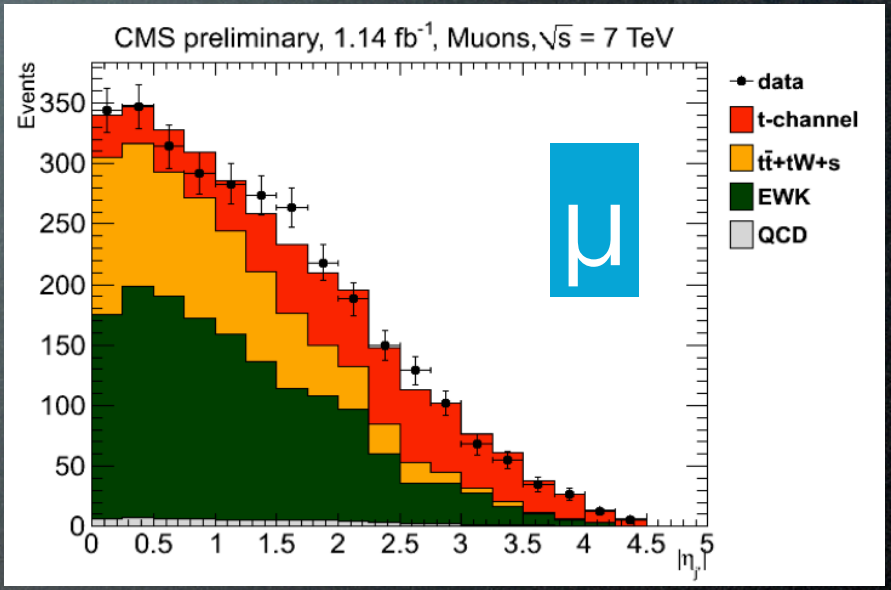
data-driven

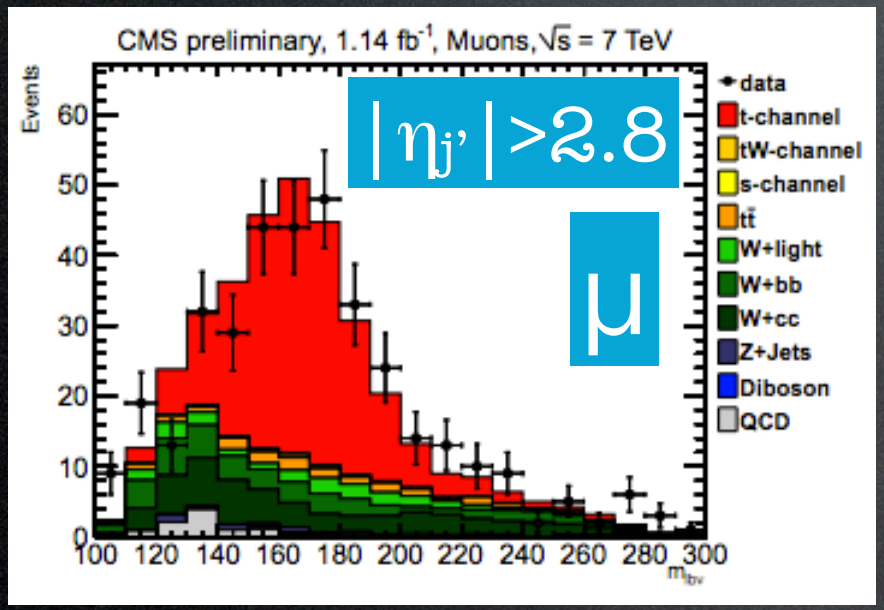
Process	muon yield	electron yield
t-channel	604.1 ± 2.6	332.9 ± 2.1
tW channel	107.0 ± 1.0	70.13 ± 0.89
s-channel	25.38 ± 0.46	14.70 ± 0.38
$t\bar{t}$	637.1 ± 5.4	472.7 ± 5.0
W + light partons	90.0 ± 6.9	48.2 ± 5.5
$Wc(\bar{c})$	437 ± 14	213.8 ± 9.9
$Wb(\bar{b})$	528 ± 15	244 ± 10
Z + jets	81.5 ± 2.7	11.35 ± 0.90
Dibosons	23.54 ± 0.36	11.03 ± 0.26
QCD	76.1 ± 2.9	61.2 ± 3.3
Total	2610 ± 22	1480 ± 17
Data	3108	1581

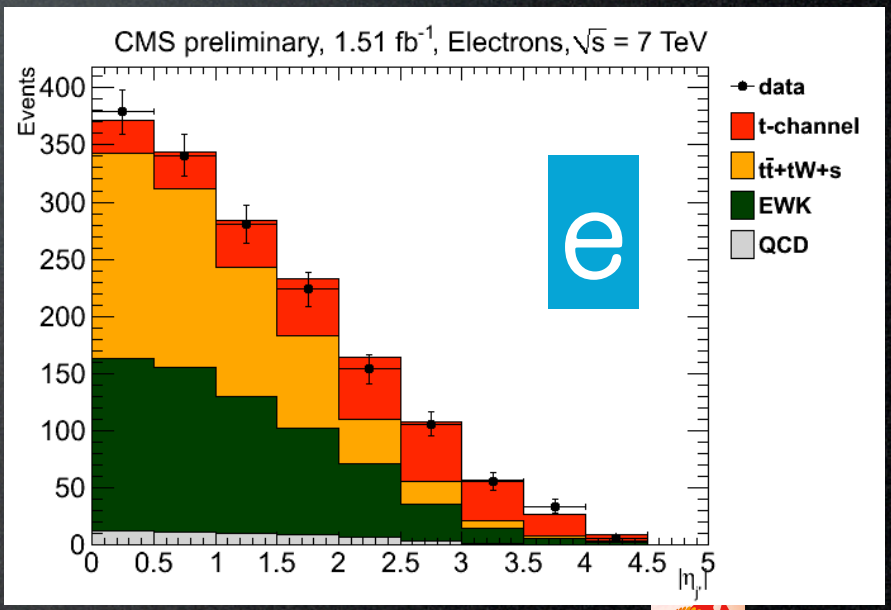
- W+heavy flavor mostly responsible for the data excess:
- In situ $|\eta_{j'}|$ distribution extracted from the m_{lvb} sidebands by subtracting all other processes from data
- W+heavy flavor + di-boson fit as EWK component of the signal region $|\eta_{j'}|$ fit

t-channel Signal Extraction

- Maximum Likelihood Fit to $|\eta_{j'}|$
- Simultaneous fit in μ and e channels
- Signal model is taken from simulation
- QCD fixed to the data-driven estimate, W+HF in situ
- Fit results cross-checked in signal and control regions







t-channel Results

- All systematics are folded into the statistical evaluation
- Main systematic uncertainties:
  - JES (9%), W+HF extraction (7%), b-tagging (3%)
  - Theoretical uncertainties: Q^2 scale (7% t-channel, 4% top pairs)
- Cross section results per channel and combined:

$$\sigma_{t-\mathrm{ch.}} = 76.9 \pm 6.6(\mathrm{stat.}) \pm 11.4(\mathrm{syst.}) \pm 3.7(\mathrm{lumi.})\ \mathrm{pb} \quad \text{(muons)}$$

$$\sigma_{t-\mathrm{ch.}} = 59.3 \pm 8.2(\mathrm{stat.}) \pm 11.9(\mathrm{syst.}) \pm 2.8(\mathrm{lumi.})\ \mathrm{pb} \quad \text{(electrons)}$$

$$\sigma_{t-\mathrm{ch.}} = 70.2 \pm 5.2(\mathrm{stat.}) \pm 10.4(\mathrm{syst.}) \pm 3.4(\mathrm{lumi.})\ \mathrm{pb} \quad \text{(combined)}$$

- Theoretical value:

$$\sigma^{\mathrm{th}}_{t-\mathrm{ch.}} = 64.57^{+2.09}_{-0.71}\,(\mathrm{scale})^{+1.51}_{-1.74}\,(\mathrm{PDF})\ \mathrm{pb}$$

N. Kidonakis
Phys. Rev. D83 (2011) 091503

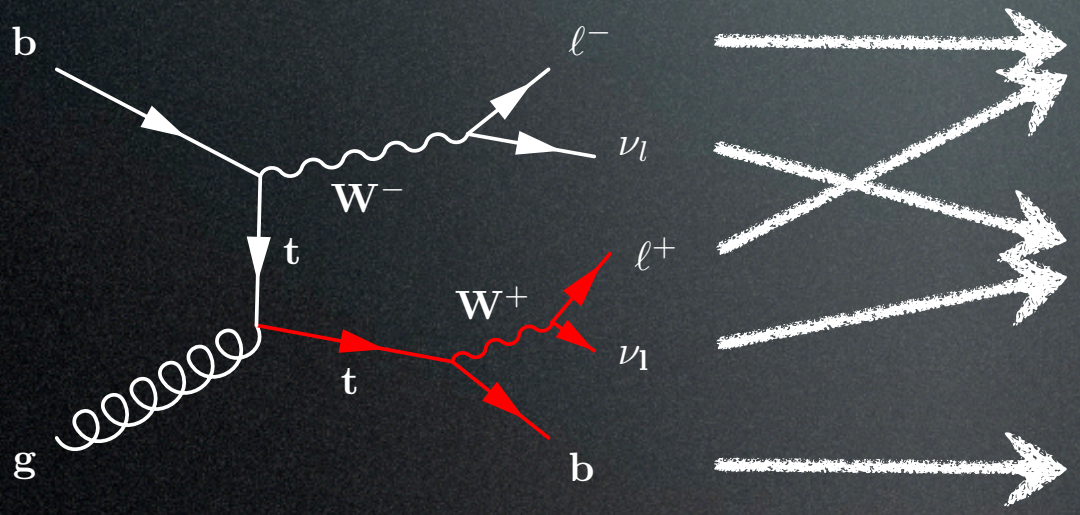
- CKM matrix element $|V_{tb}|$ in the assumption $|V_{td}|, |V_{ts}| \ll |V_{tb}|$

$$|V_{tb}| = \sqrt{\frac{\sigma_{t-\mathrm{ch.}}}{\sigma^{\mathrm{th}}_{t-\mathrm{ch.}}}} = 1.04 \pm 0.09\,(\mathrm{exp.}) \pm 0.02\,(\mathrm{th.})$$

CMS PAS TOP-11-022

Single top tW channel

- tW associated production observable at LHC for the first time!
- Interesting topology (background to Higgs->WW searches)
- Only leptonic (e, μ) decays of W considered:
  - **Di-lepton** topology:



Two isolated leptons (ee, μμ, eμ)

E_t^{miss} from the two neutrinos

One b-jet from top decay b quark

- No chance to fully reconstruct W or top
- Main backgrounds:
  - Top pairs, Z+jets, all other processes very small

tW Lumi
2.1 fb^{-1}(all)

tW channel Event Selection

- Selection (3 final states ee, μμ, eμ):
  - Exactly 2 isolated leptons
  - Exactly 1 b-tagged jet

  All states

  - Z mass veto ($m_{ll} < 81$ GeV, $m_{ll} > 101$ GeV)
  - $E_T^{miss} > 30$ GeV

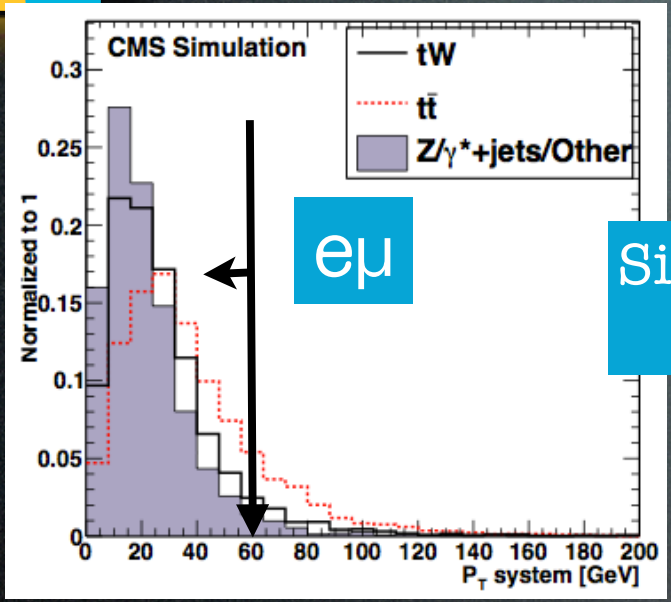
  ee/μμ

- Two variables inspired by LO tW process description:
  - $\vec{p}_T^{\,system} = \vec{p}_{T,\ell 1} + \vec{p}_{T,\ell 2} + \vec{p}_{T,jet} + \overrightarrow{E_T}^{miss}$
  - $H_T = p_{T,\ell 1} + p_{T,\ell 2} + p_{T,jet} + E_T^{miss}$
- Final cuts:
  - $H_T > 160$GeV

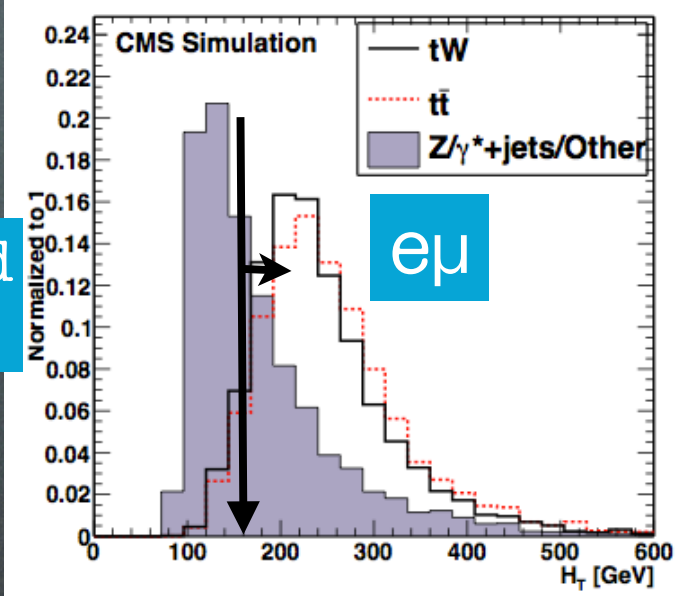
    eμ
  - $p_T^{system} < 60$GeV

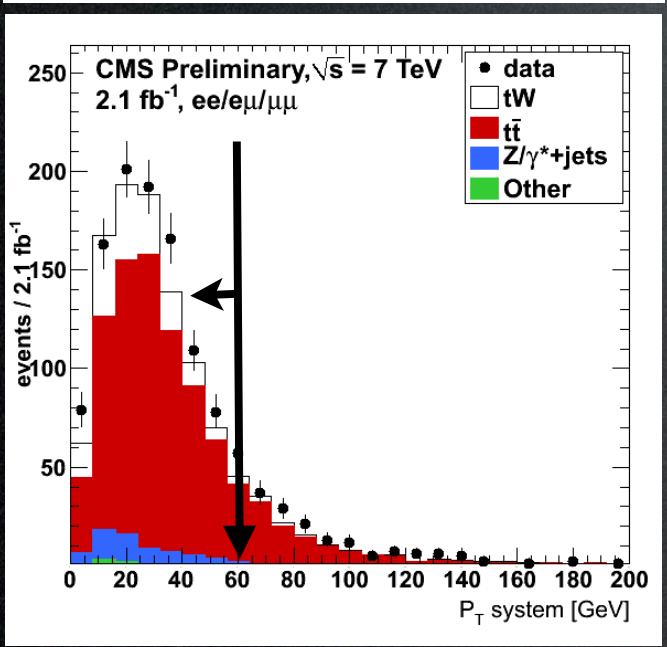
    All states
- Signal region defined by 1j1btag, other jet/b-tag multiplicities used as control regions to constrain top pair cross-section
- Z+jets (reverse Z mass veto) control region to get data-driven estimate

tW Reconstructed Variables

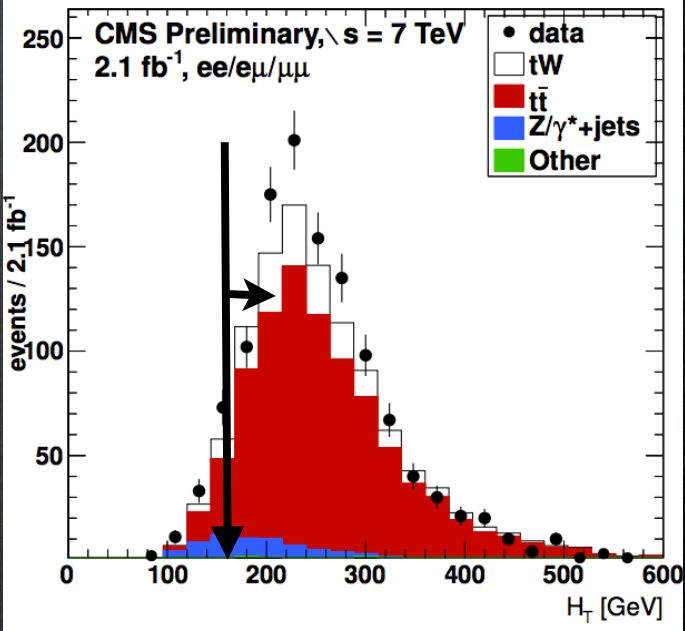


Signal/Background Separation



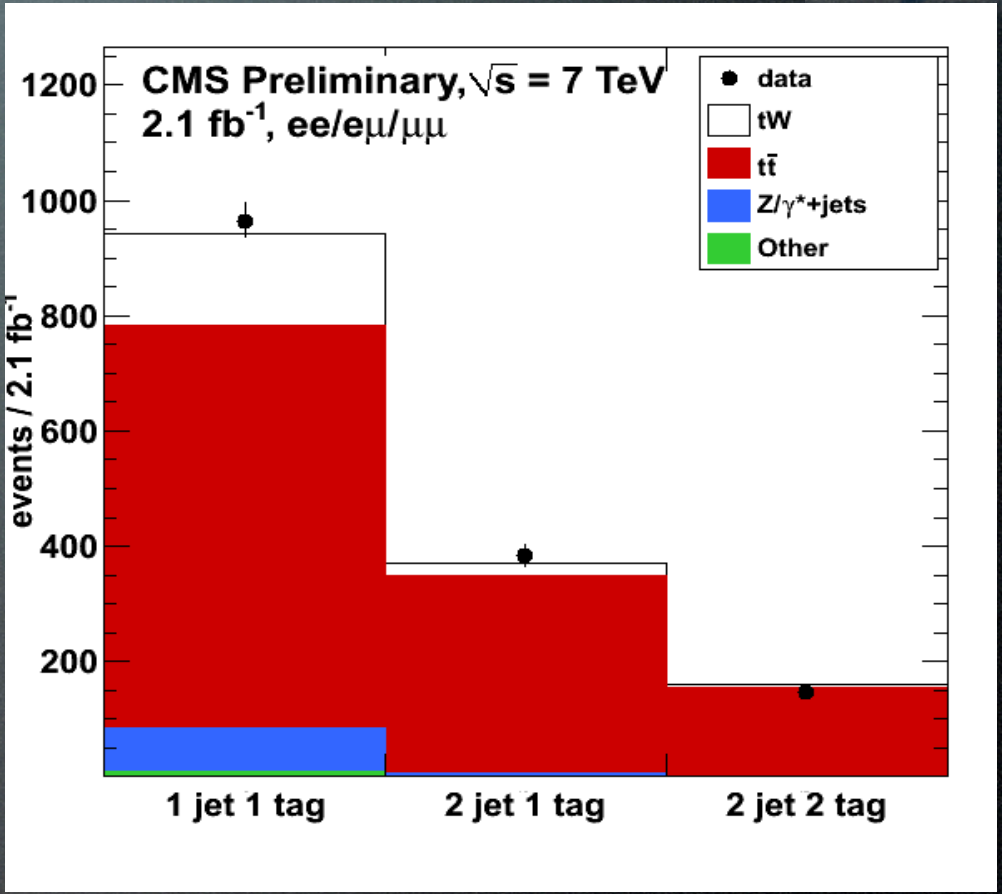


Data/MC distributions (all other cuts)



tW channel Analysis

- Data-driven estimate of Z+jets:
  - Invert Z mass veto and extract normalization for signal region
- Top pairs background estimate:
  - Two top pairs enriched control regions (2j1btag, 2j2btag)
  - Yield in these control regions to constrain top pair contamination in signal region
- Signal extracted using simultaneous fit to signal and control regions



tW Analysis Results

- Main systematic uncertainties:
  - b-tagging (10%), JES (2.5% tW signal,6% top pairs)
  - Theoretical: Q^2 scale (10% tW signal, 12% top pairs)

- With Poisson statistical model, combining all three channels and taking into account all systematic uncertainties:
  - Expected significance **1.8 +/- 0.9 σ** away from null-hypothesis
  - Observed significance **2.7 σ**
  - Measured value of the cross-section and 68% C.L. interval:
    - $\sigma_{tW} = 22\ ^{+9}_{-7}$ **(stat⊕sys) pb**
  - Theoretical value (m_{top}=173GeV):
    - $\sigma_{tW} = 15.6 \pm 0.4(\text{scale})^{+1.0}_{-1.2}(\text{PDF})$

N. Kidonakis
arxiv.org/pdf/1205.3453v1 (2012)

Conclusions

- Single top production has been studied in t- and tW channels at CMS
- First measurement of tW cross-section:
  - $\sigma_{tW} = 22\ ^{+9}_{-7}$ (stat⊕sys) pb
  - Expected significance: **1.8 +/- 0.9 σ** Observed: **2.7σ**
- Improved t-channel measurement, already dominated by systematics:

$$\sigma_{t-\mathrm{ch.}} = 76.9 \pm 6.6(\mathrm{stat.}) \pm 11.4(\mathrm{syst.}) \pm 3.7(\mathrm{lumi.})\ \mathrm{pb} \quad (\mathrm{muons})$$
$$\sigma_{t-\mathrm{ch.}} = 59.3 \pm 8.2(\mathrm{stat.}) \pm 11.9(\mathrm{syst.}) \pm 2.8(\mathrm{lumi.})\ \mathrm{pb} \quad (\mathrm{electrons})$$
$$\sigma_{t-\mathrm{ch.}} = 70.2 \pm 5.2(\mathrm{stat.}) \pm 10.4(\mathrm{syst.}) \pm 3.4(\mathrm{lumi.})\ \mathrm{pb} \quad (\mathrm{combined})$$

- $|V_{tb}|$ measurement with 10% uncertainty from t-channel analysis:

$$|V_{tb}| = \sqrt{\frac{\sigma_{t-\mathrm{ch.}}}{\sigma^{\mathrm{th}}_{t-\mathrm{ch.}}}} = 1.04 \pm 0.09\,(\mathrm{exp.}) \pm 0.02\,(\mathrm{th.})$$

- Both results are in agreement with Standard Model predictions
- Stay tuned for new results!

CMS PAS TOP-11-021
https://cdsweb.cern.ch/record/1430743

CMS PAS TOP-11-022
https://cdsweb.cern.ch/record/1385552

Back-up

Cross-section table

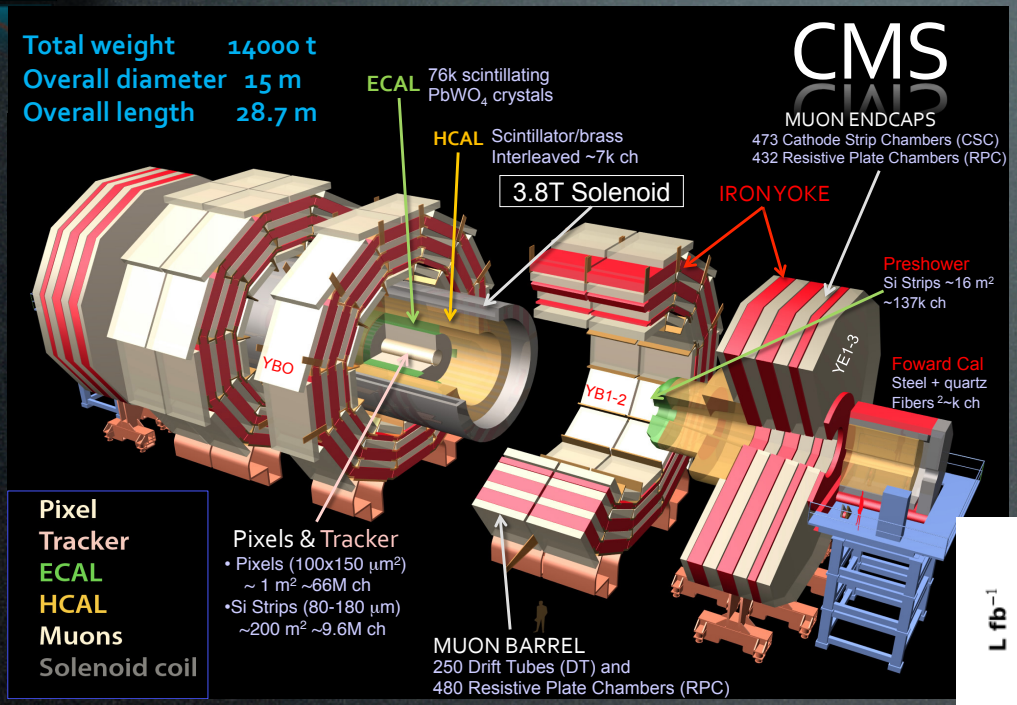
- With all uncertainties (first due to renormalization/factorization scale, second due to the parton distribution function)

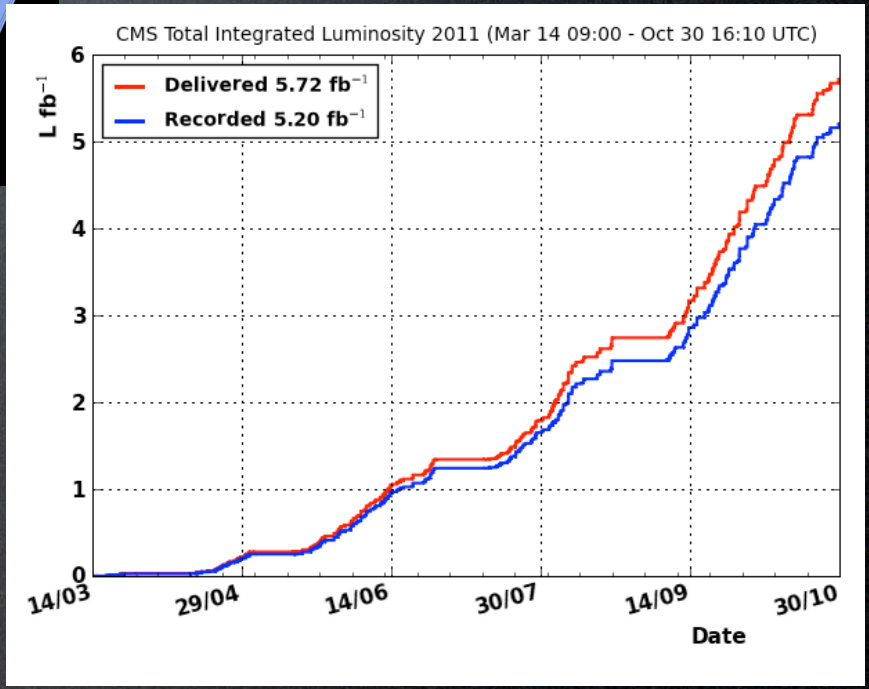
Cross sections (pb) [m_{top} = 173 GeV]	s-channel	t-channel	tW channel	top pair
Tevatron: ppbar@1.96TeV	$1.046^{+0.002}_{-0.01}{}^{+0.06}_{-0.056}$	$2.08\ ^{+0.00}_{-0.04} \pm 0.12$	0.22 ± 0.08	$7.08\ ^{+0.00}_{-0.24}{}^{+0.36}_{-0.27}$
LHC: pp @ 7 TeV	$4.56 \pm 0.07^{+0.18}_{-0.17}$	$65.9\ ^{+2.1}_{-0.7}{}^{+1.5}_{-1.7}$	$15.6 \pm 0.4\ ^{+1.0}_{-1.2}$	$163\ ^{+7}_{-5} \pm 9$
LHC: pp @ 8 TeV	$5.55 \pm 0.08 \pm 0.21$	$87.2\ ^{+2.8}_{-1.0}{}^{+2.0}_{-2.2}$	$22.2 \pm 0.6 \pm 1.4$	$234\ ^{+10}_{-7} \pm 12$

N. Kidonakis arxiv.org/pdf/0909.0037 (2009)

N. Kidonakis arxiv.org/pdf/1205.3453v1 (2012)

CMS detector and data sample





- Data taking at 7 TeV (2011): 5.2 fb^{-1}
- Analyses presented today based on a fraction of the data:
  - t-channel: 1.2fb^{-1}(μ)/1.6 fb^{-1}(e)
  - tW-channel: 2.1 fb^{-1}

t-channel systematics

Uncertainty source	in pb	in %
Statistical	±5.2	±7.4%
W+heavy flavours extraction	±5.0	±7.1%
Jet energy scale	−4.4/+6.5	−6.2/+9.2%
Jet energy res.	−0.48/+0.87	−0.69/+1.2%
Unclustered $\not{E}_T$	±0.37	±0.53%
$t\bar{t}$ rate	−2.4/+2.8	−3.5/+4.0%
Q^2, $t\bar{t}$	−2.8/+1.5	−4.0/+2.1%
Q^2, t-channel	±4.9	±7.0%
t-channel generator	±3.5	±5.0%
Muon trigger + reco.	−1.1/+1.2	−1.5/+1.7%
Electron trigger + reco.	−0.53/+0.66	−0.76/+0.94%
Pile up	−0.23/+0.13	−0.33/+0.18%
QCD, muon	−0.67/+0.63	−0.95/+0.89%
QCD, electron	−0.26/+0.21	−0.37/+0.29%
s-, tW-channel, dibosons	±0.38	±0.54%
b-tagging	±2.2	±3.1%
Hadronic trigger	±0.95	±1.4%
PDF	±1.8	±2.5%
Total syst.	±10	±15%
Total	±12	±17%

tW Z+jets estimate

- Using MC and data event counts in the Z mass veto region and MC event counts in the signal region:

$$N^{estimated}_{\ell\ell,out} = \frac{N^{MC}_{\ell\ell,out}}{N^{MC}_{\ell\ell,in}} \cdot (N^{observed}_{\ell\ell,in} - \frac{1}{2}k \cdot N^{observed}_{e\mu,in})$$

- Result and cross-check using MC instead of observed data counts:

	ee channel	$\mu\mu$ channel
Data-driven estimate	20.7 ± 3.9	45.7 ± 6.1
Estimated from simulation	12 ± 2	26 ± 3

tW systematics

Systematic uncertainty ($ee/e\mu/\mu\mu$) [%]	signal tW	$t\bar{t}$	$Z/\gamma^{\star}$	other
Luminosity	4.5	4.5	-	4.5
Pile-up multiplicity	0.48/0.55/0.73	$\star$	-	$\star$
Trigger Efficiency	1.5	1.5	-	1.5
Muon reconstruction and identification	- /1/1	- /1/1	-	- /1/1
Electron reconstruction and identification	2/2/ -	2/2/ -	-	2/2/ -
JES	$^{-2.5}_{+1.6}$ / $^{-2.4}_{+0.1}$ / $^{-0.6}_{+1.0}$	$^{-5.6}_{+4.4}$ / $^{-6.0}_{+4.7}$ / $^{-5.9}_{+2.3}$	-	$\star$
JER	1.1/0.5/0.4	3.1/3.9/4.4	-	$\star$
B-tagging	$^{-9.5}_{+10}$ / $^{-9.8}_{+9.8}$ / $^{-9.5}_{+10}$	$^{-8.5}_{+10}$ / $^{-11}_{+10}$ / $^{-9.1}_{+11}$	-	$\star$
Factorization/Normalization Scale (Q^2)	7.7/6/10	7.7/11/12	-	$\star$
ME/PS matching thresholds	-	5.7/0.7/2.3	-	$\star$
ISR/FSR	-	8.9/7.3/7.3	-	$\star$
DR/DS scheme	8.2/9.1/6.6	-	-	$\star$
$E_{\mathrm{T}}^{\mathrm{miss}}$ modeling	2.3/0.9/0.9	$\star$	-	$\star$
PDF uncertainties	4.5/4.5/4.5	$\star$	-	$\star$
Background Normalization	-	15/15/15	50/ 50/ 50	$\star$
Simulation statistics	3.5/1.9/2.7	-	-	17/21/11

Cross-section vs. sqrt(s)