Production of single top quark - results from the Tevatron and the LHC-

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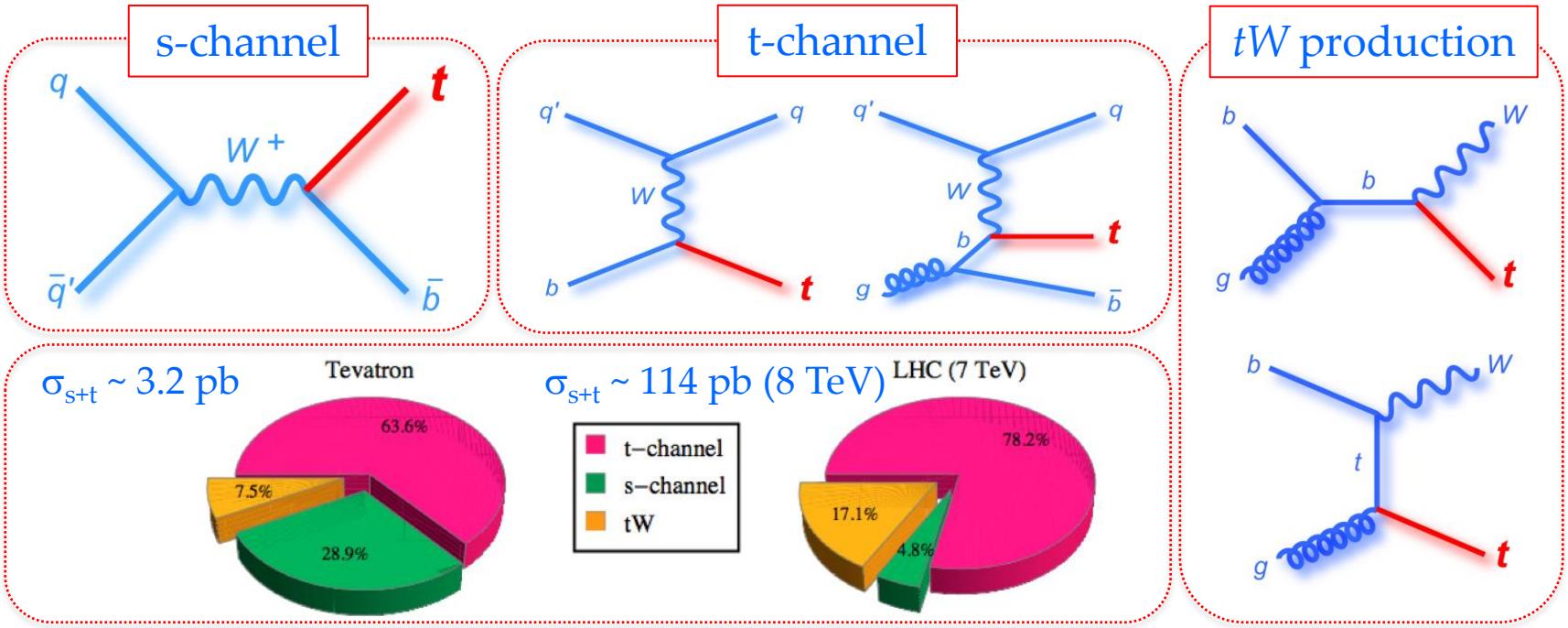
Single Top Production

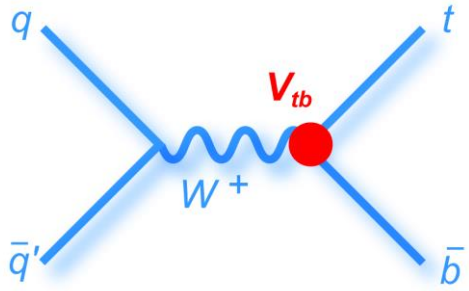
- ✓ Top quarks are produced singly in $p\bar{p}$ or pp collisions via the electroweak interaction.
- ✓ First observed by the CDF and DØ experiments at the Tevatron.
- ✓ Three processes in the SM
  - t-channel, s-channel, and associated production of a top quark and a W boson.

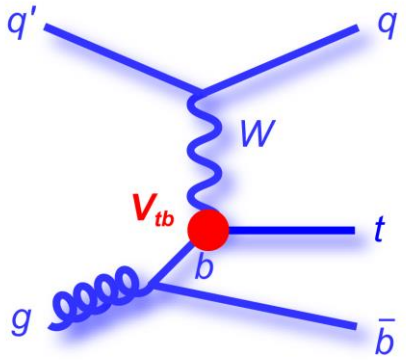


- ✓ Challenging to overcome large background for extraction of the single top signal.
- ✓ Recently many new results have been reported from the Tevatron and LHC.

Physics Motivation

- ✓ Test of the SM prediction
  - Direct measurement of the CKM matrix element $|V_{tb}|$.
  - t-channel single top production cross section provides a test of the b parton distribution function of the proton.



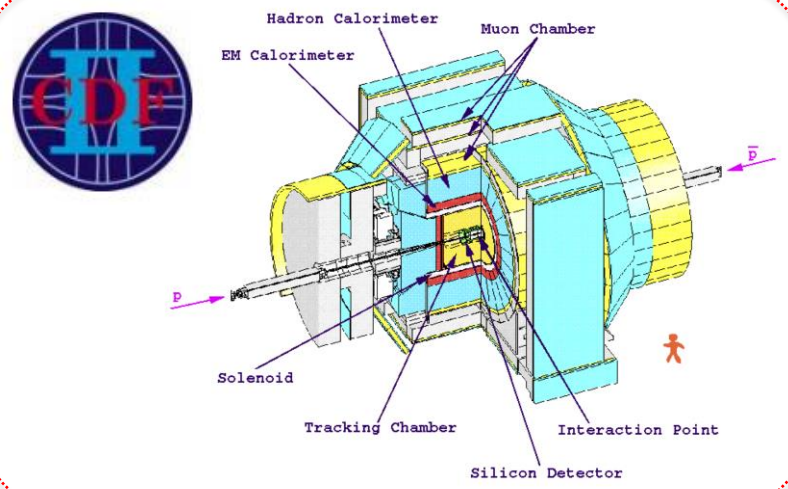


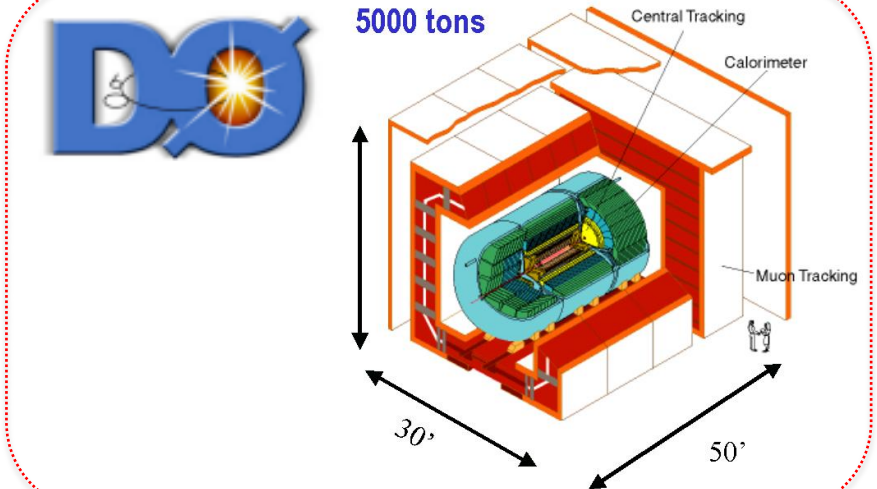
$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- ✓ Sensitive to new physics process.
  - Existence of a fourth generation of fermions remains possible.
  - Flavor-changing *Ztc* coupling, (*e.g.* production of $p\bar{p} \rightarrow t\bar{c}$)
  - Additional charged gauge boson *W'*
  - Charged Higgs production
- ✓ Important background to Higgs production.

Single top at the Tevatron

- ✓ $p\bar{p}$ collision at $\sqrt{s}$= 1.96 TeV
- ✓ CDF and DØ experiments
- ✓ Run II (2001–11) : ~12 fb^{-1} delivered (~10 fb^{-1} recorded)
- ✓ The s and t channel processes are dominant. advantage in s-channel studies but negligible *tW* production.
  - σ_s = **1.05 ± 0.06 pb** (NLO+NNLL, m_{top} = 172.5 GeV)
    - N. Kidonakis, PRD 81, 054028 (2010)
  - σ_t = **2.10 ± 0.13 pb** (NLO+NNLL, m_{top} = 172.5 GeV)
    - N. Kidonakis, PRD 83, 091503 (2011)

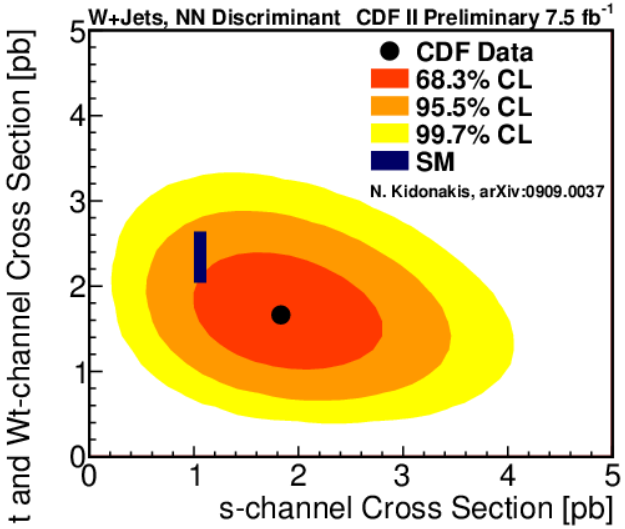


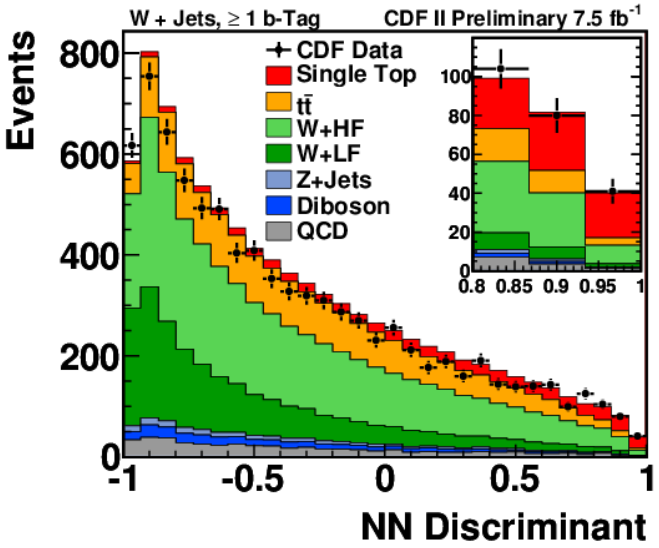


Single top in $l\nu b\bar{b}$ with 7.5 fb^{-1}

- ✓ s + t + *tW* combined cross section measurement
- ✓ Event Selection
  - 1 high p_T electron or muon ($P_T > 20$ GeV/c)
  - Missing Transverse Energy(MET) > 25 GeV/c^2
  - 2 or 3 jets ($E_T > 20$ GeV/c^2)
  - At lease one b-tagging
- ✓ Result
  - **$\sigma = 3.04^{+0.57}_{-0.53}$ pb ($m_{top} = 172.5$ GeV)**
  - 2D fit for s-channel and t-channel
    - **$\sigma_s = 1.81^{+0.63}_{-0.58}$ pb, $\sigma_t = 1.49^{+0.47}_{-0.42}$ pb**
  - **$|V_{tb}| = 0.96 \pm 0.09$(stat. + syst.) ± 0.05(theory)**
  - 95% confidence level lower limit of $|V_{tb}| > 0.78$

Processes	W + 2 jets, 1 tag	W + 3 jets, 1 tag	W + 2 jets, 2 tag	W + 3 jets, 2 tag
$t\bar{t}$	474 ± 49	1067 ± 109	98 ± 14	284 ± 42
WW	148 ± 21	48 ± 7	1.1 ± 0.3	1.2 ± 0.3
WZ	53 ± 6	14 ± 2	8.8 ± 1.3	2.4 ± 0.4
ZZ	1.7 ± 0.2	0.7 ± 0.1	0.3 ± 0.0	0.1 ± 0.0
Z+Jets	118 ± 15	46 ± 6	4.8 ± 0.7	2.7 ± 0.4
Wbb	1452 ± 437	434 ± 131	183 ± 56	65 ± 20
Wcc	766 ± 233	254 ± 77	10 ± 3	7 ± 2
Wcj	583 ± 177	128 ± 39	7.8 ± 2.4	3.5 ± 1.1
W+Mistags	1459 ± 148	433 ± 47	7.4 ± 1.5	5.4 ± 1.1
Non-W	316 ± 126	141 ± 57	6.8 ± 3.5	3.4 ± 3.2
t-channel	193 ± 25	84 ± 11	6 ± 1	15 ± 2.4
s-channel	128 ± 11	43 ± 4	32 ± 4	12 ± 1.6
Wt-channel	16 ± 4	26 ± 7	0.7 ± 0.2	2.3 ± 0.6
Total Prediction	5707 ± 877	2719 ± 293	367 ± 66	403 ± 53
Observed	5533	2432	335	355

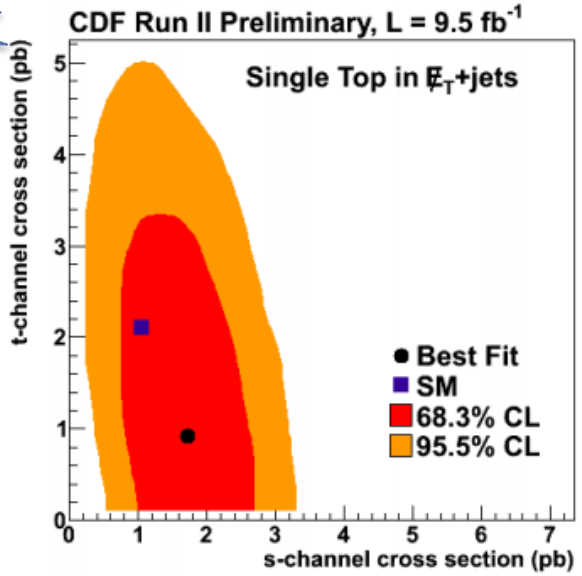


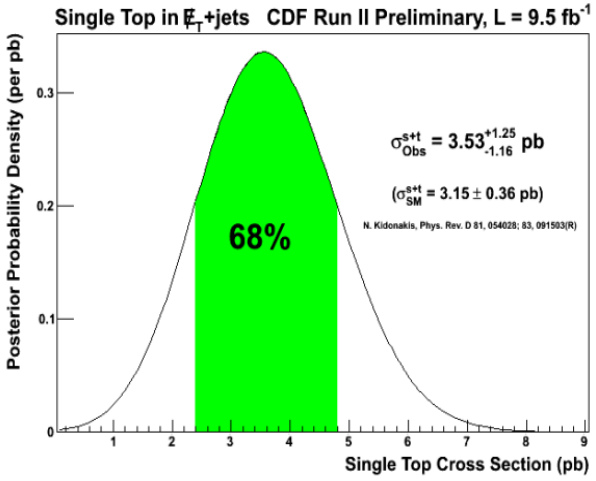


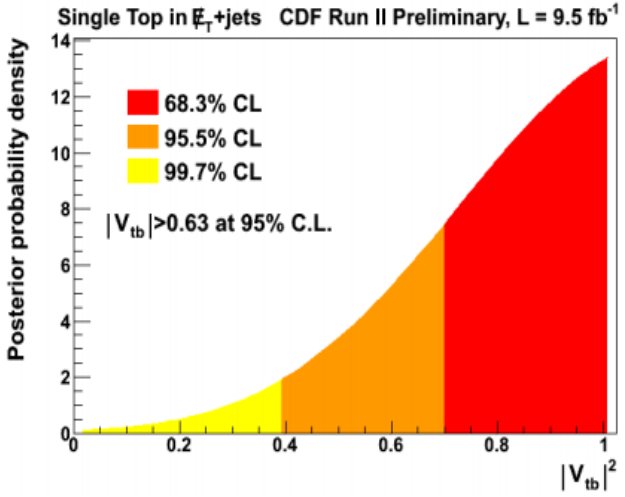
Single top in $E_T^{miss} b\bar{b}$ with 9.5 fb^{-1}

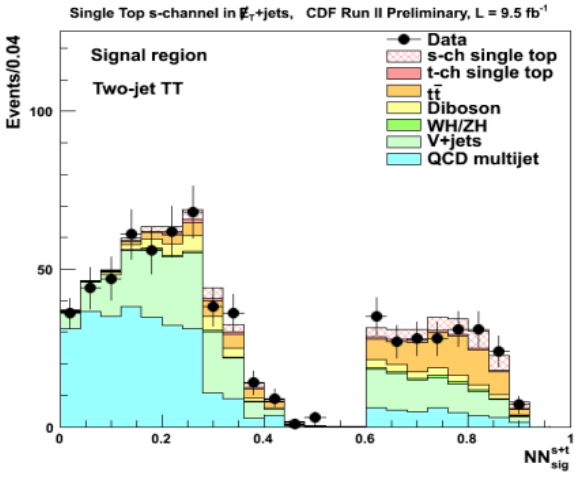
- ✓ s + t combined cross section measurement
- ✓ Event Selection
  - Reject events with isolated leptons
  - MET > 50 GeV/c^2
  - 2 or 3 jets and one of the leading jets central (|eta| < 1).
  - ΔR (leading jets) > 0.8
  - At lease one b-tagging
- ✓ Result
  - **$\sigma_{s+t} = 3.53^{+1.25}_{-1.16}$ pb (m_{top} = 172.5 GeV)**
    - SM prediction: 3.15 ± 0.19 pb N. Kidonakis, PRD 81, 054028 (2010) and PRD 83, 091503 (2011).
    - **$|V_{tb}| > 0.63$ at 95 % C.L.**

New



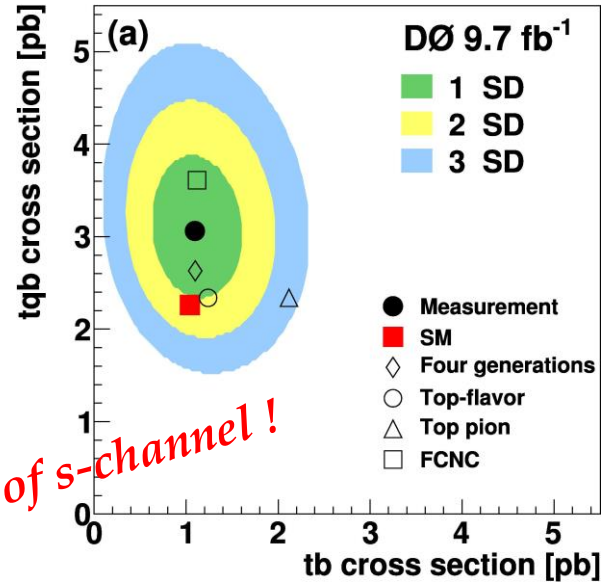




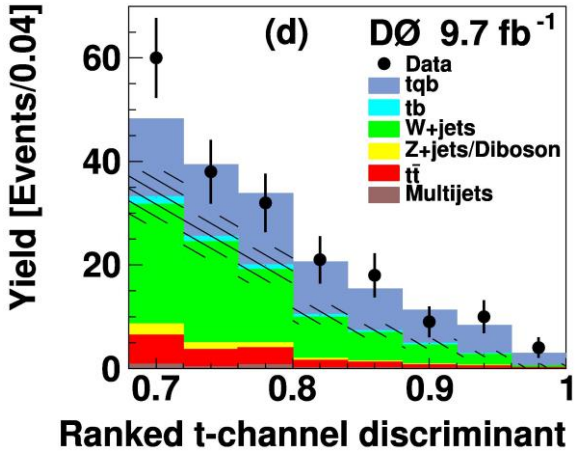


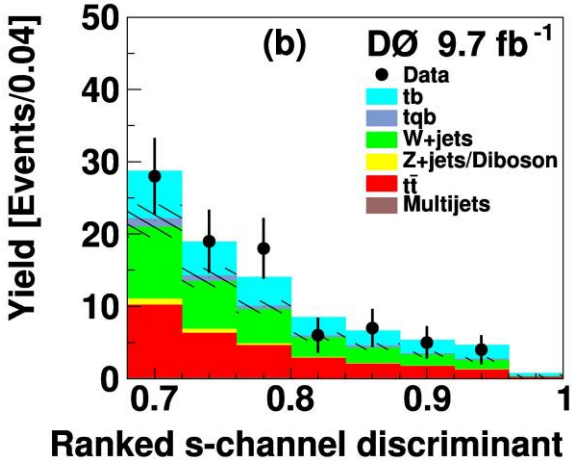
Single top in $l\nu b\bar{b}$ with 9.7 fb^{-1}

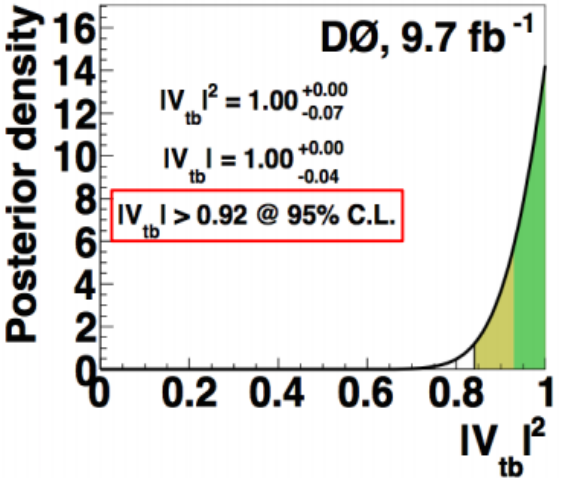
- ✓ Event Selection
  - 1 high p_T electron or muon (P_T> 20 GeV/c)
  - MET > 20(2 jets) or 25(3jets) GeV/c^2
  - 2 or 3 jets (E_T > 20 or 25(leading jet) GeV/c^2)
  - At lease one b-tagging
- ✓ Result
  - $\sigma_{s+t} = 4.11\,^{+0.59}_{-0.55}$ pb (SM prediction : $3.34\,^{+0.53}_{-0.49}$ pb)
  - Simultaneous 2D measurements
    - **$\sigma_s = 1.10\,^{+0.33}_{-0.31}$ pb : 3.7σ (3.7σ expected)**
    - $\sigma_t = 3.07\,^{+0.53}_{-0.49}$ pb : 7.7σ (6.0σ expected)
  - **$|V_{tb}| > 0.92$ at 95% C.L. for $m_{top} = 172.5$ GeV)**



First evidence of s-channel !







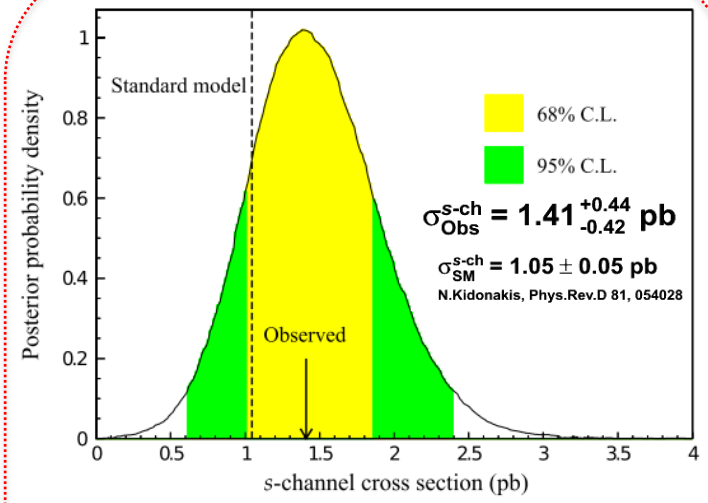
Evidence of s-channel at CDF

New

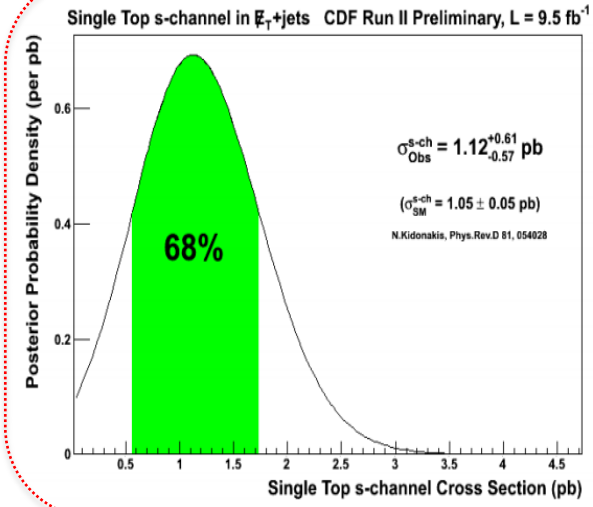
- ✓ $lvb\bar{b}$ analysis
  - $\sigma = 1.41^{+0.44}_{-0.42}$ pb (m_{top} = 172.5 GeV)
  - Observed p-value : 3.8σ (2.9σ expected)
  - Accepted to publish in PRL at Apr. 21, 2014 (arXiv:1402.0484)
- ✓ $E_T^{miss} b\bar{b}$ analysis
  - $\sigma = 1.12^{+0.61}_{-0.57}$ pb (m_{top} = 172.5 GeV)
  - Observed p-value : 1. 9σ (1.8σ expected)
  - Accepted to publish in PRL at May 1, 2014 (arXiv:1402.3756)

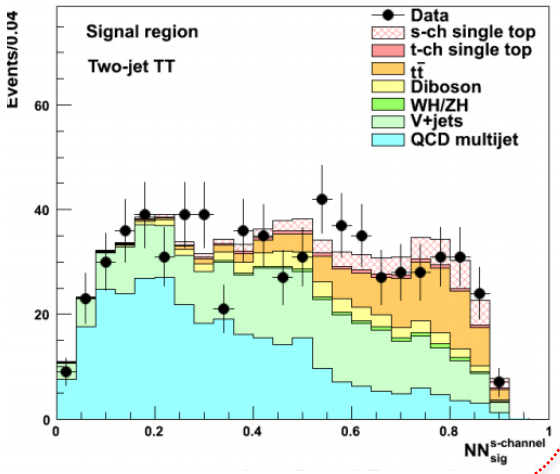
Confirmed the evidence of s-channel !

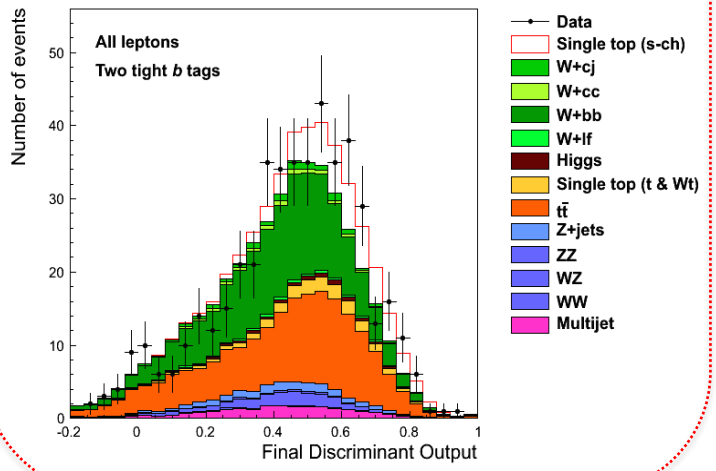
$E_T^{miss} b\bar{b}$



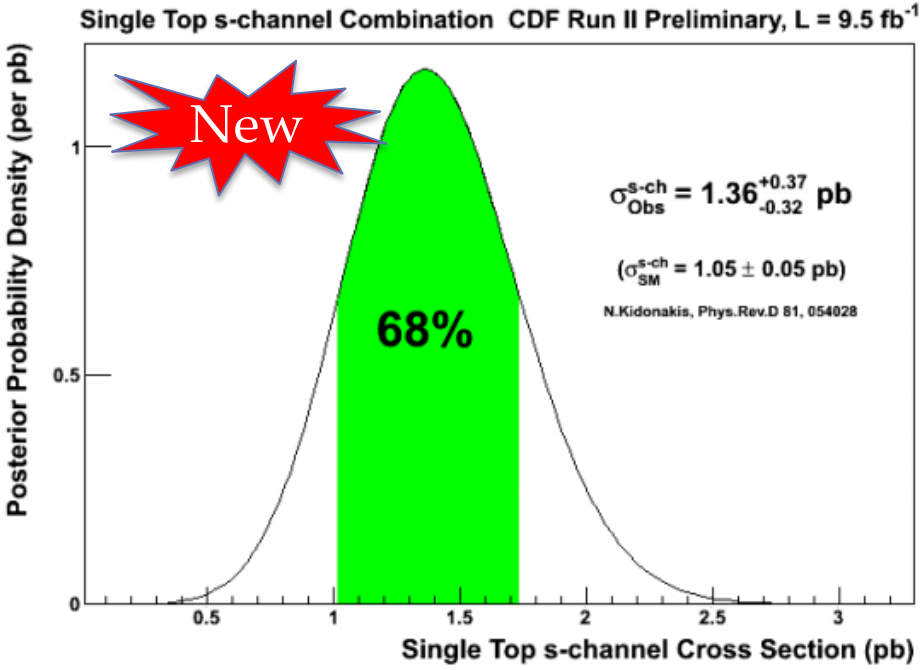
$lvb\bar{b}$

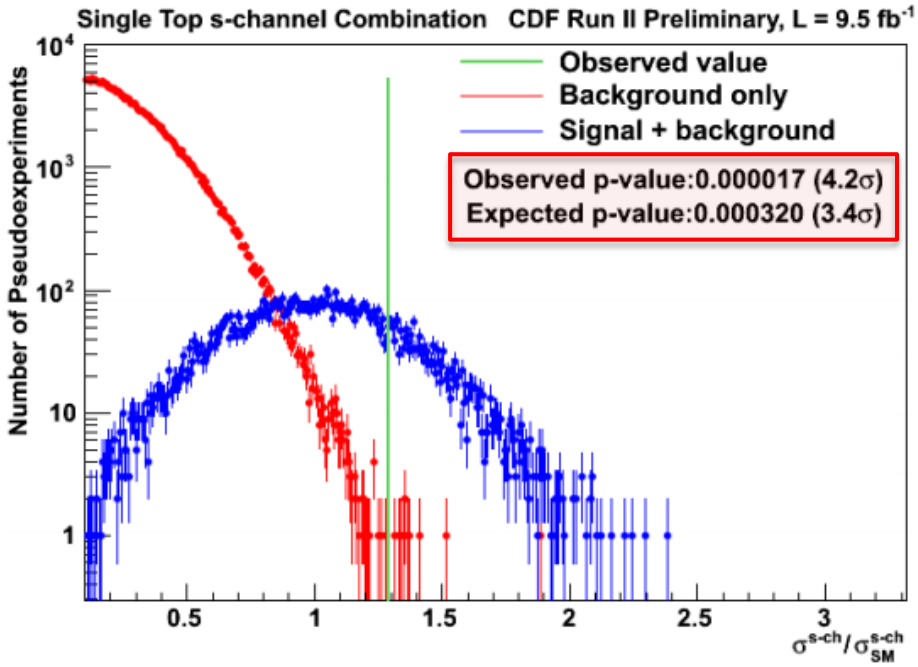






New CDF s-channel combination





$\sigma^{s\text{-}ch}_{Obs} = 1.36^{+0.37}_{-0.32}$ pb

$(\sigma^{s\text{-}ch}_{SM} = 1.05 \pm 0.05$ pb)

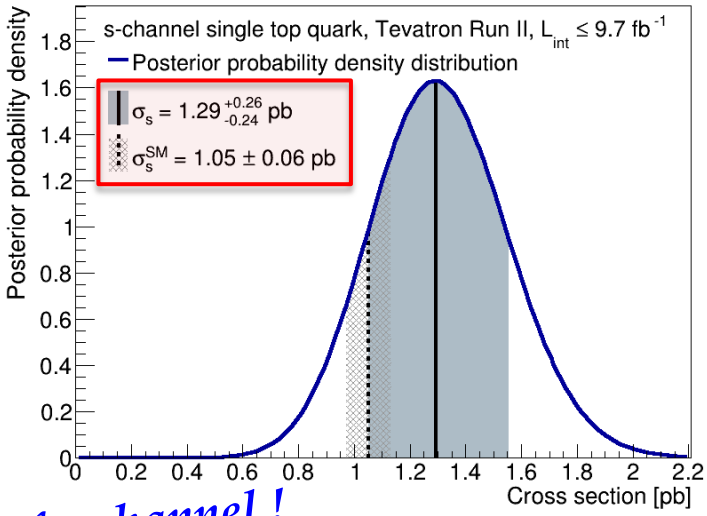
N.Kidonakis, Phys.Rev.D 81, 054028

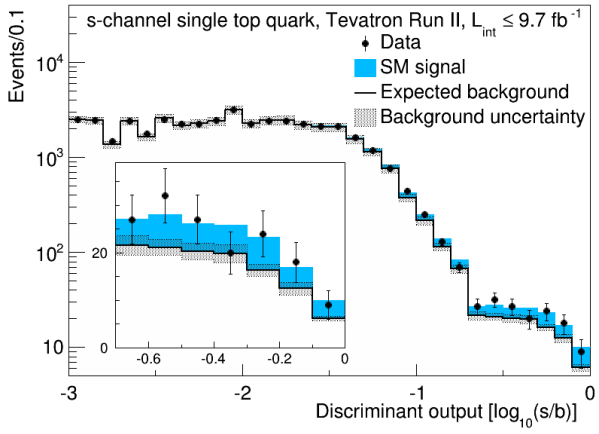
- ✓ Accepted to publish this combination result by PRL with s-channel cross section measurement in $E_T^{miss} b\bar{b}$ events at May 1, 2014 (arXiv:1402.3756)

Tevatron s-channel combination

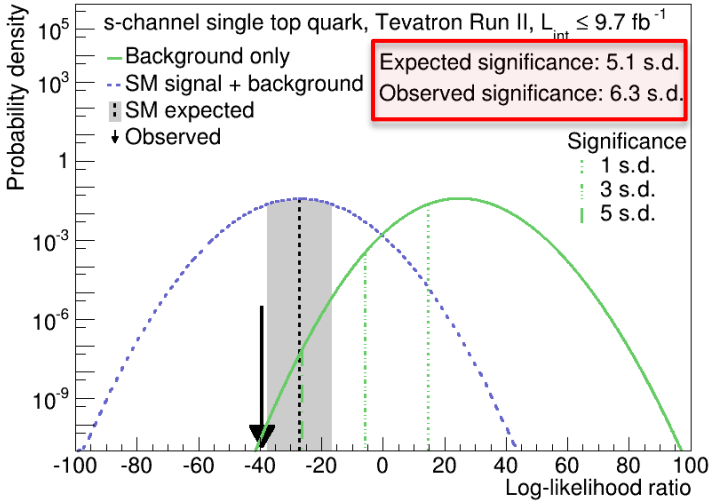
New

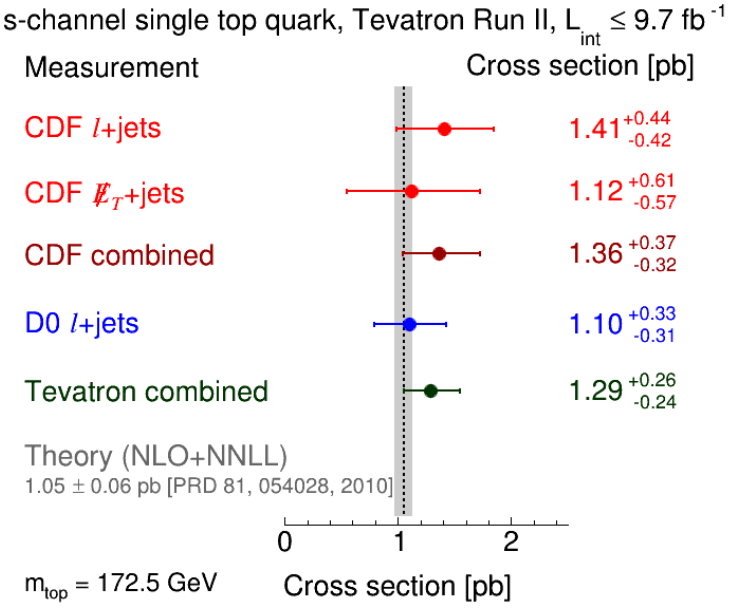
Accepted to publish in PRL at Apr. 24, 2014 (arXiv:1402.5126)





First observation of s-channel !





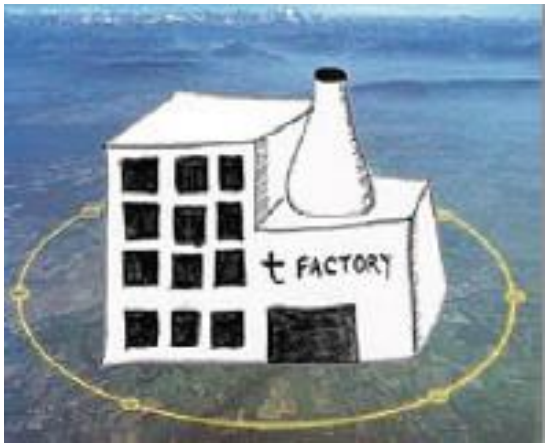
Single top at the LHC

- ✓ pp collision at $\sqrt{s} = 7$ and 8 TeV
- ✓ CMS and ATLAS experiments
- ✓ Run I (2010–12) : ~5 fb^{-1} (7 TeV), ~20 fb^{-1} (8 TeV)
- ✓ The t and tW channel processes are dominant. s–channel not reachable yet.

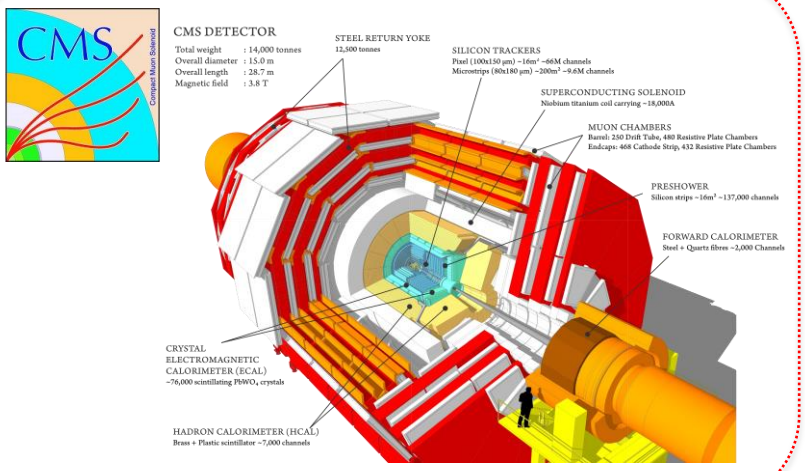
LHC 7 TeV	$\sigma(t) + \sigma(\bar{t})$ (pb)
t-channel	$65.9^{+2.1+1.5}_{-0.7-1.7}$
s-channel	$4.56 \pm 0.07^{+0.18}_{-0.17}$
tW	$15.6 \pm 0.4 \pm 1.1$

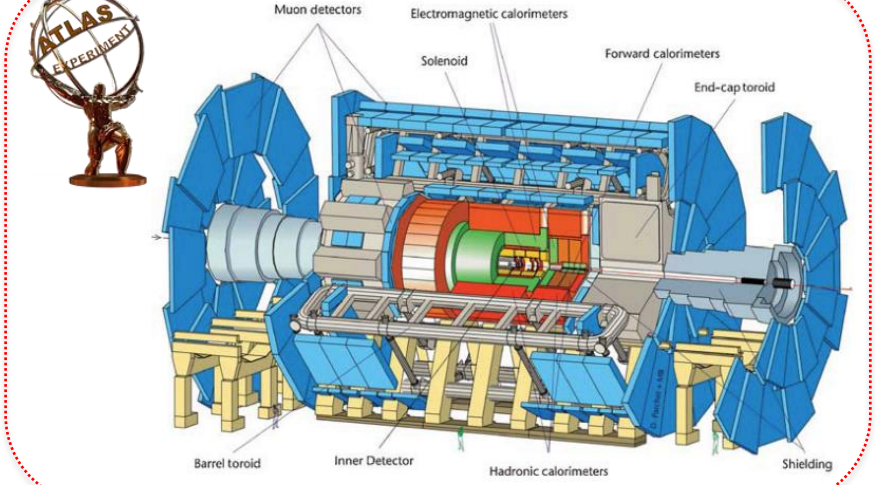
LHC 8 TeV	$\sigma(t) + \sigma(\bar{t})$ (pb)
t-channel	$87.2^{+2.8+2.0}_{-1.0-2.2}$
s-channel	$5.55 \pm 0.08 \pm 0.21$
tW	$22.2 \pm 0.6 \pm 1.4$

m_{top} = 173 GeV, Kidonakis, arXiv:1210.7813 (2012)



LHC : top quark factory!

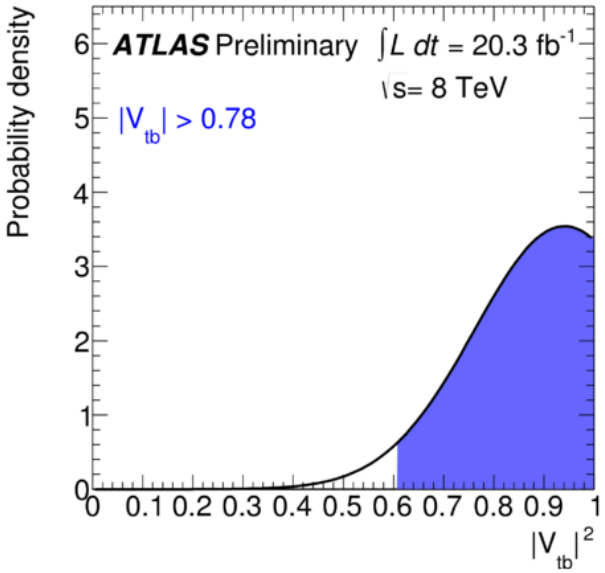


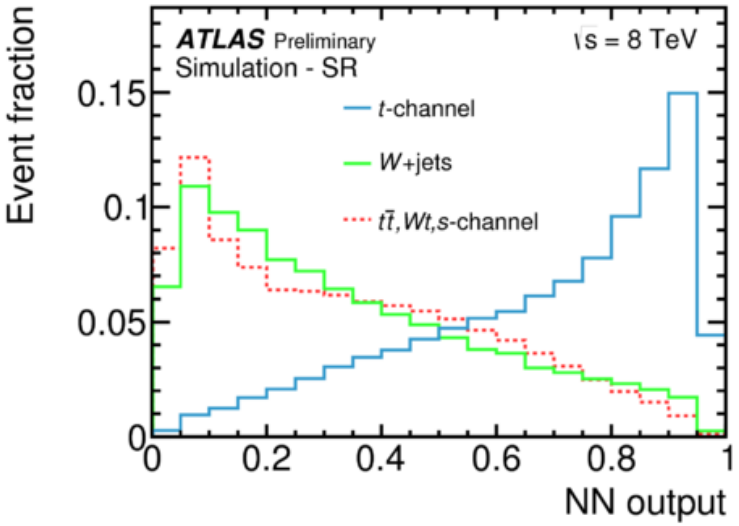


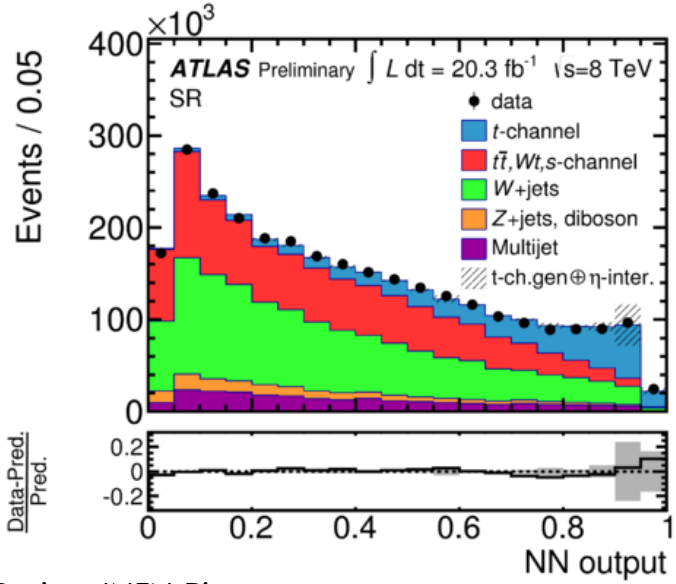
t-channel measurement at ATLAS

New

- ✓ Event Selection
  - 1 isolated electron or muon (p_T> 25 GeV/c)
  - 2 jets (at lease one b-tagging, (E_T> 30 GeV/c^2)
  - MET > 30 GeV/c^2, Transverse W-boson mass, m_T (W) > 50 GeV
  - ΔR (lepton, jet) > 0.4
- ✓ Result
  - $\sigma_t = 82.6 \pm 1.2\,(\text{stat.}) \pm 11.4\,(\text{syst.}) \pm 3.1\,(\text{PDF}) \pm 2.3\,(\text{lumi.})$ pb
    - SM prediction : $87.2^{+2.8}_{-1.0}{}^{+2.0}_{-2.2}$ pb
  - **$|V_{tb}| = 0.97\ ^{+0.09}_{-0.10}$ ($|V_{tb}| > 0.78$ at 95 % C.L.)**





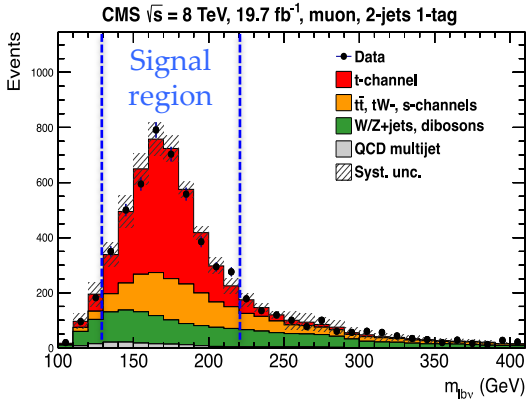


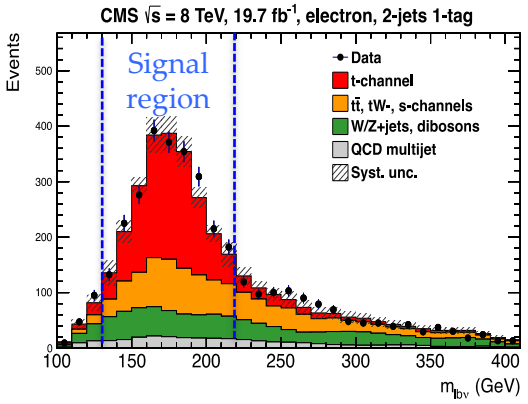
t-channel measurement at CMS

New

✓ Event Selection

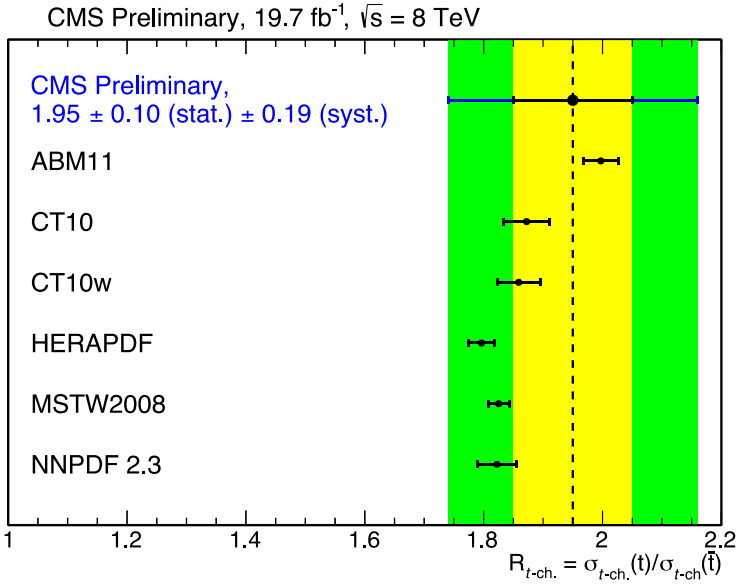
- 1 isolated lepton
  - electron (p_T> 30 GeV/c)
  - muon (p_T> 26 GeV/c)
- 2 High E_T jets
  - At lease one b-tagging, E_T > 40 GeV/c^2
- Kinematic cuts (anti QCD):
  - m_T (W) > 50 GeV for muon
  - MET > 45GeV/c^2 for electron
- Signal region : 130 < m_{lvb} < 220 GeV





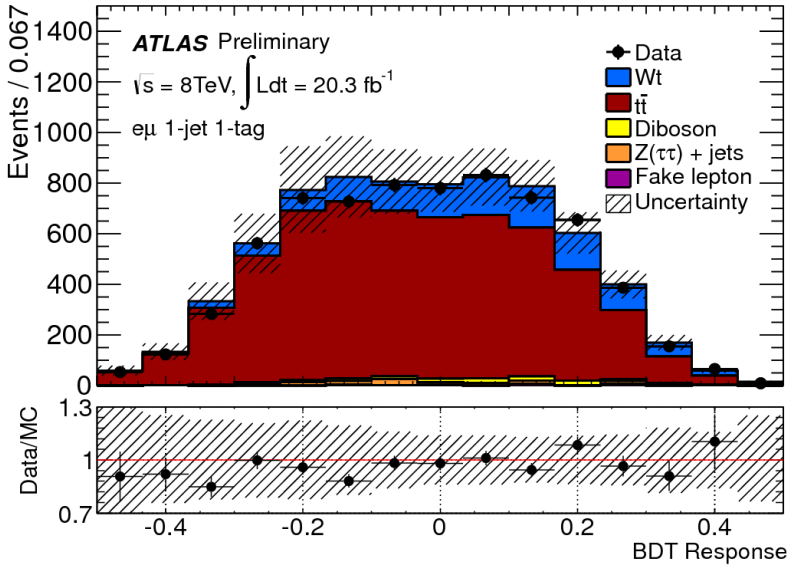
✓ Result

- **σ = 83.6 ± 2.3(stat.) ± 7.4(syst) pb** (SM: $87.2^{+2.8}_{-1.0}{}^{+2.0}_{-2.2}$)
- $|V_{tb}|$ = 0.98±0.05(exp.)±0.02(th.)
  - **$|V_{tb}|$ > 0.92 (95% C.L.)**
- Accepted to publish in JHEP
- Charge ratio
  - **σ_{top} = 53.8 ± 1.5(stat.) ± 4.4(syst) pb**
    - SM : σ_{top}= 56.4 (+2.1-0.3) ±1.1 pb
  - **$\sigma_{anti\text{-}top}$= 27.6 ± 1.3(stat.) ± 4.4(syst) pb**
    - SM : $\sigma_{anti\text{-}top}$= 30.7 ± 0.7 (+0.9-1.1) pb
  - **R (top/anti-top) = 1.95 ± 0.10(stat) ± 0.19(syst)**



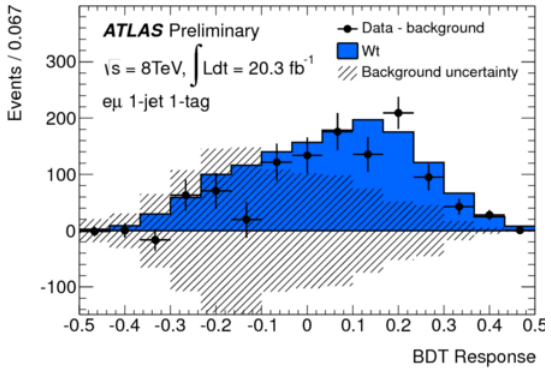
First evidence of *tW*-channel at ATLAS

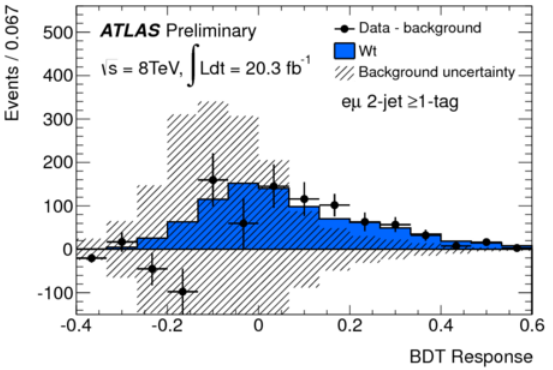
- ✓ Event Selection
  - 2 High p_T opposite-charge isolated leptons (ee, μμ and eμ)
    - Electron, Muon $p_T > 25$ GeV/c
  - 1 or 2 jets (at lease one b-tagging, $E_T > 30$ GeV/c^2)
  - BDT classifier discriminates the signal from background
    - 19 variables (1 jet), 20 variables (2 jet)
- ✓ Result
  - **$\sigma_{tW} = 27.2 \pm 2.8(\text{stat.}) \pm 5.4(\text{syst.})$ pb**
    - SM prediction: 22.2 ± 0.6 ± 1.4 pb
  - Significance: **4.2σ (4.0σ expected)**
  - $|V_{tb}| = 1.10 \pm 0.12(\text{exp.}) \pm 0.03(\text{th.})$
    - **$|V_{tb}| > 0.72$ at 95%CL**



First evidence of of tW-channel !

Process	1-jet	2-jet
Wt	1140 ± 190	710 ± 100
$t\bar{t}$	5700 ± 800	12700 ± 1400
Diboson	120 ± 30	79 ± 28
$Z(\tau\tau)$ + jets	110 ± 40	90 ± 40
Fake lepton	27 ± 14	22 ± 11
Total Expected	7100 ± 1100	13600 ± 1600
Data Observed	6906	13159

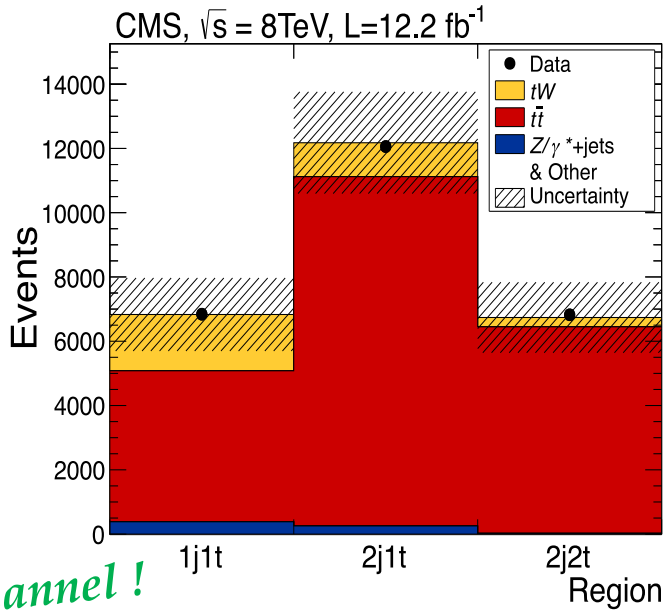




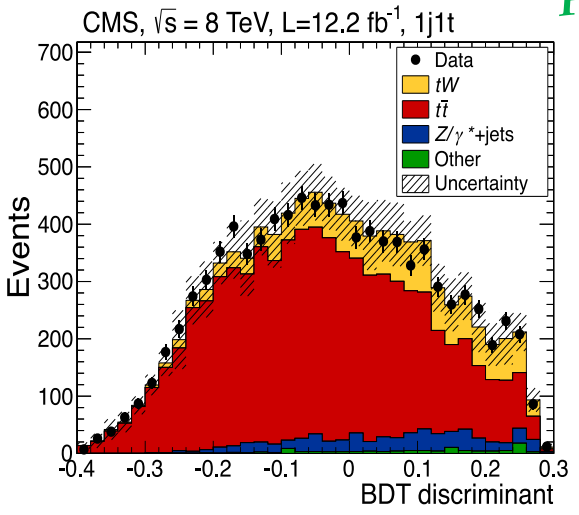
First observation of *tW*-channel at CMS

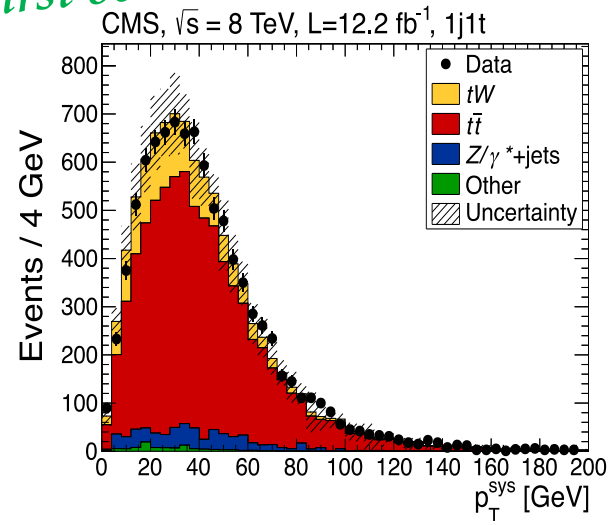
New

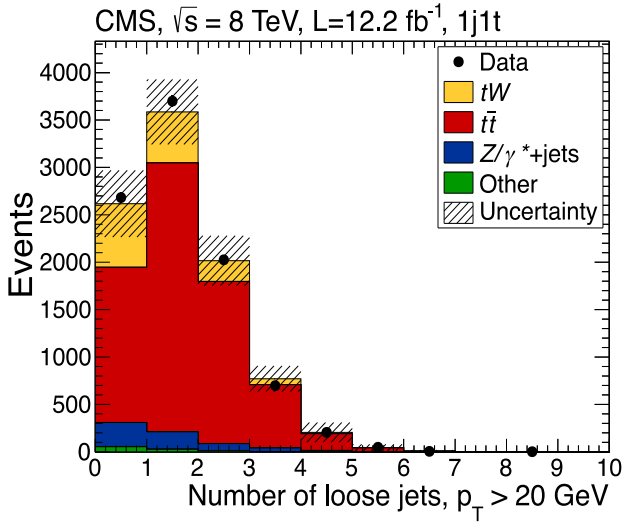
- ✓ Event Selection
  - 2 isolated leptons, opposite charge (e,μ)
  - Only 1 jet, b-tagging required **(1j1t)**
  - MET > 30 GeV/c^2
  - Veto of Z mass window (m_{ll}),
  - BDT build with 13 variables (variables related to loose jets most powerful to discriminate)
- ✓ Result
  - σ_{tW} = 23.4 ± 5.4 pb (SM : 22.2±0.6±1.4 pb)
  - *tW* signal observed with a significance of **6.1σ (5.4σ expected)**
  - **$|V_{tb}|$ = 1.03±0.12(exp.)±0.04(th.) →$|V_{tb}|$ > 0.78 (95% C.L.)**
  - Accepted by PRL (arXiv:1401.2942)



First observation of tW-channel !



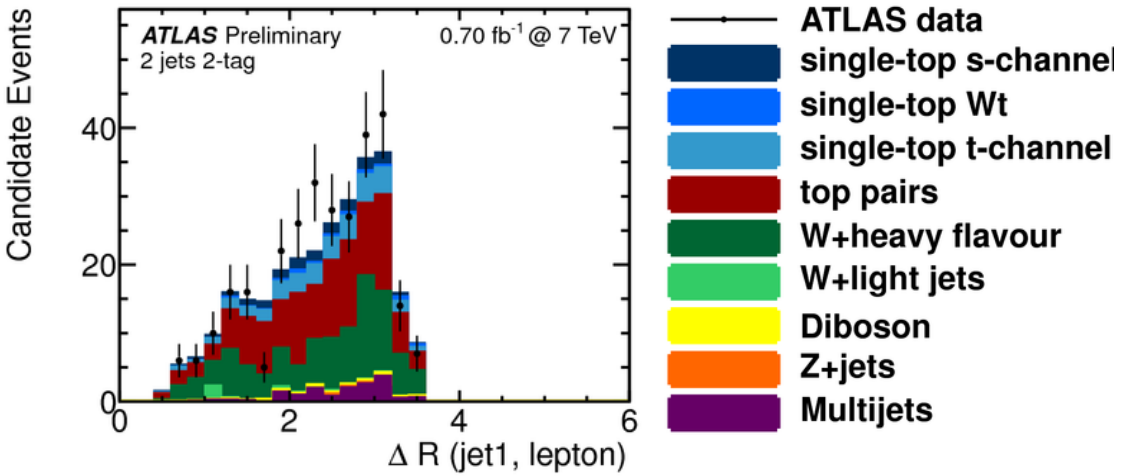


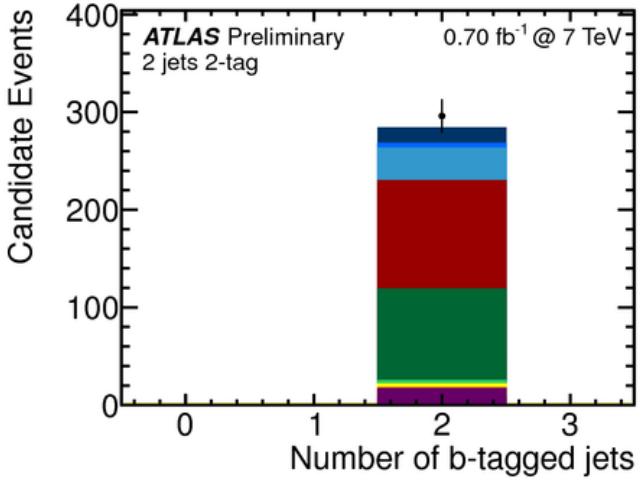


Search for s-channel at ATLAS

- ✓ First search s-channel single top at 7 TeV
- ✓ Event Selection
  - 1 high p_T electron or muon (P_T> 25 GeV/c)
  - MET > 25 GeV/c^2
  - m_T(W) > 60 GeV - MET
  - 2 jets (p_T > 25 GeV/c, at least 1 b-tagging
  - NN discriminate : 15 variables 2j1t, 19 variables 3j1t
  - training done in 4 channels (2 regions, l^+ or l^-)
- ✓ Results
  - **$\sigma_{s\text{-channel}}$ < 26.5 pb at 95%CL (< 20.5 pb expected)**
  - This corresponds to about 5 times the signal SM cross-section ($4.56 \pm 0.07^{+0.18}_{-0.17}$ pb)

	Final Selection
s-channel	16 ± 6
t-channel	33 ± 13
Wt	5 ± 3
$t\bar{t}$	111 ± 47
W+jets	4 ± 5
Wc+jets	10 ± 8
$Wc\bar{c}$+jets	14 ± 12
$Wb\bar{b}$+jets	70 ± 51
Z+jets	1 ± 1
Diboson	4 ± 1
Multijets	17 ± 10
TOTAL Exp	285 ± 17
$S/\sqrt{B}$	0.98
DATA	296



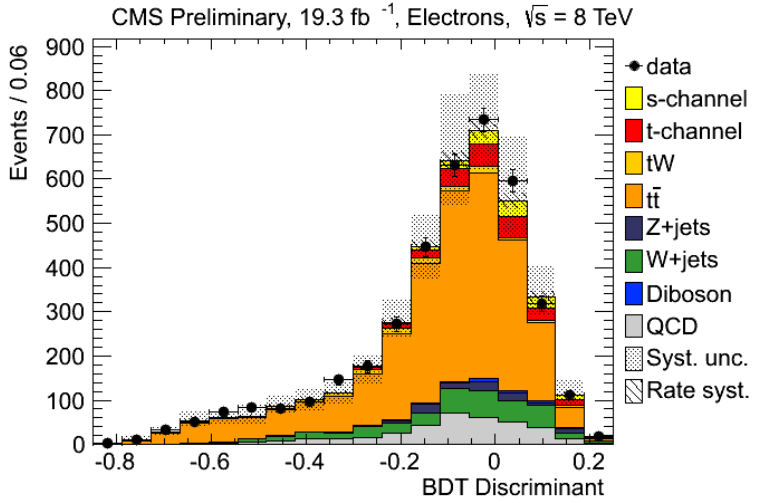


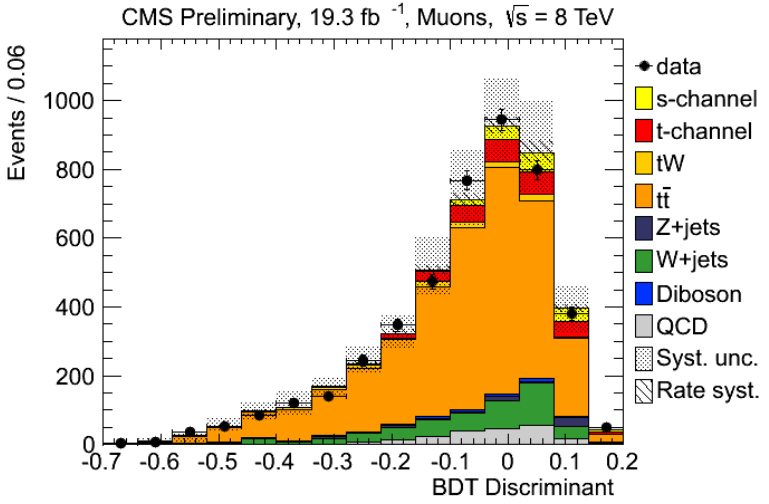
Search for s-channel at CMS

New

- ✓ Event Selection
  - 1 isolated electron or muon (P_T> 30 GeV/c)
  - Missing Transverse Energy
  - 2 b-tagged jets (E_T = 40/30 GeV/c^2)
  - Multivariate analysis based on a BDT :
    - 11 variables for electron, 10 for muon
- ✓ Result
  - $\sigma_{s\text{-ch.}} = 5.9^{+8.6}_{-5.1}$ pb muon channel
  - $\sigma_{s\text{-ch.}} = 6.9^{+8.7}_{-5.7}$ pb electron channel
  - $\sigma_{s\text{-ch.}} = 6.2^{+8.0}_{-5.1}$ pb combined
  - SM prediction: 5.55 ± 0.08 ± 0.21 pb
  - s-channel signal observed significance **0.7σ (0.9σ expected)**
  - **Upper limit on the cross section times branching ratio of 11.5 pb at 95% C.L.**

Process	μ 3-jets 2-tags	μ 2-jets 2-tags	e 3-jets 2-tags	e 2-jets 2-tags
$t\bar{t}$	10043 ± 604	3144 ± 189	8010 ± 494	2483 ± 154
W + *jets*	446 ± 92	449 ± 93	370 ± 76	361 ± 77
Z + *jets*	112 ± 32	65 ± 20	97 ± 29	89 ± 27
Diboson	36 ± 8	45 ± 10	33 ± 7	37 ± 8
QCD	353 ± 74	209 ± 52	222 ± 19	363 ± 69
tW-channel	336 ± 28	102 ±11	259 ± 22	105 ± 11
t-channel	949 ± 61	271 ± 18	750 ± 49	217 ± 15
s-channel	87 ± 5	168 ± 10	70 ± 4	131 ± 8
Total MC	12361 ± 750	4455 ± 286	9811 ± 606	3786 ± 253
Data	11979	4450	10149	3884





Summary

- ✓ Presented the most latest single top results at the Tevatron and LHC.

σ [pb]		t-channel	tW	s-channel
Tevatron (1.96 TeV)	CDF	$1.49^{+0.47}_{-0.42}$ pb	-	$1.36^{+0.37}_{-0.32}$ pb
	DØ	$3.07^{+0.53}_{-0.49}$ pb	-	$1.10^{+0.33}_{-0.31}$ pb
LHC (8 TeV)	CMS	83.6 ± 7.7 pb	23.4 ± 5.4 pb	< 11.5 pb
	ATLAS	82.6 ± 11.9 pb	27.2 ± 6.1 pb	< 26.5 pb

: Observed or Evidence **: Not yet observed** **: Not accessible**

- ✓ All single top production processes are observed with the recent results from the Tevatron and the LHC.
  - Observation of s-channel production from the CDF+D0.
  - Observation of *tW* associated production from CMS.
  - The all measurements are agreed well with the Standard Model.
- ✓ More precise measurements for top quark properties will be performed with the single top events at LHC.