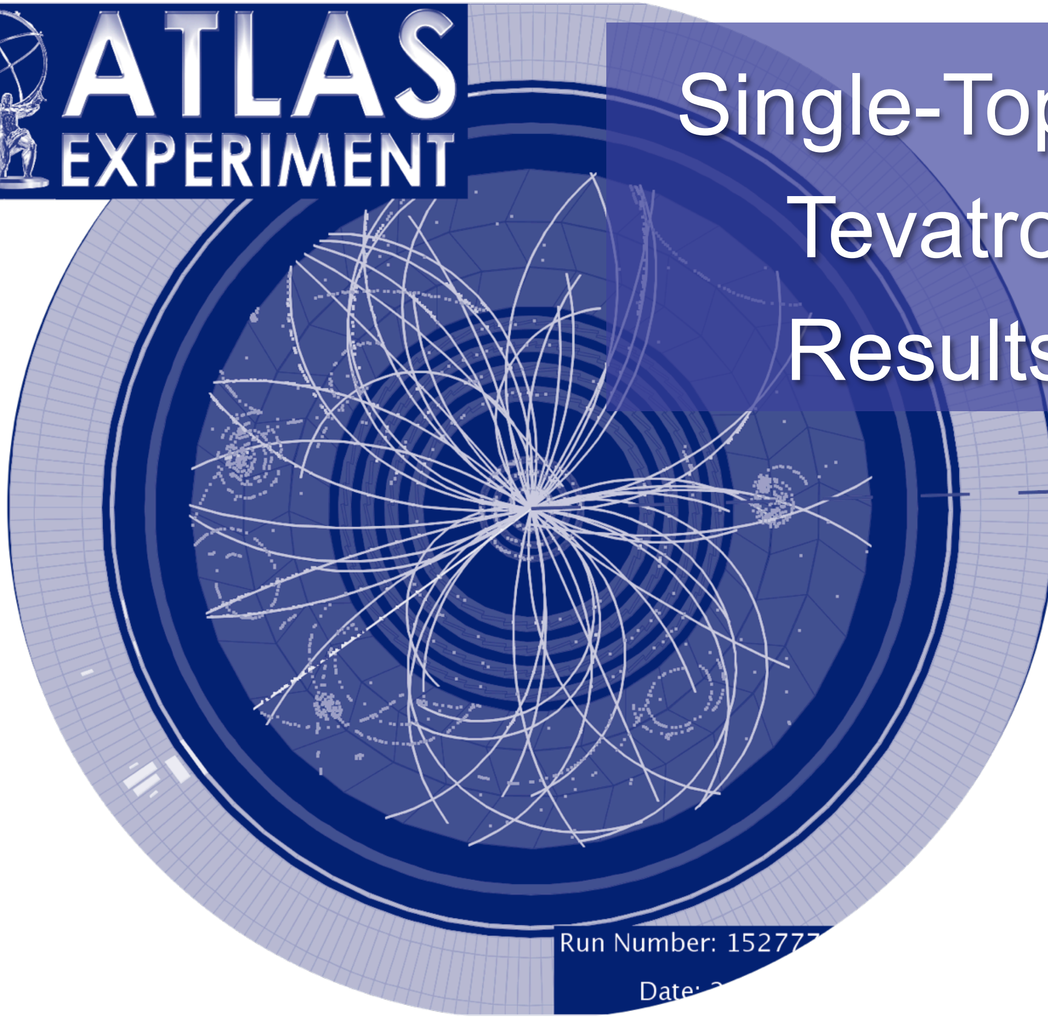
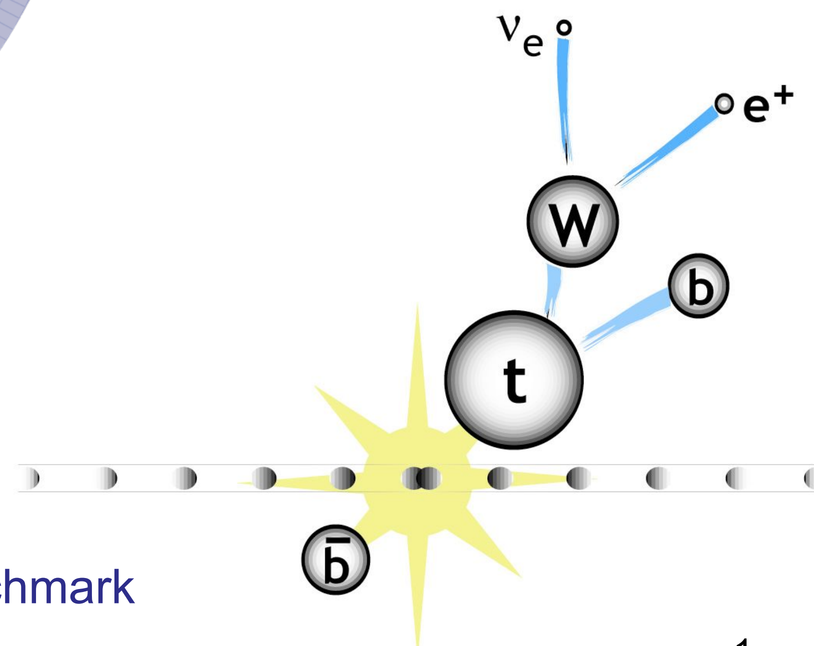
Single-Top Production at the Tevatron and the LHC: Results and Prospects



Wolfgang Wagner
Bergische Universität Wuppertal

DESY Zeuthen, June 16, 2011



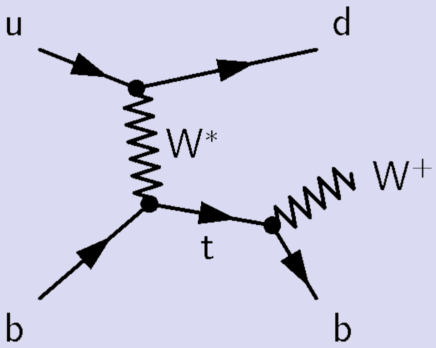
Content:

1) Introduction / History
2) Experimental Status
3) Prospects – Single Top as a Standard Benchmark

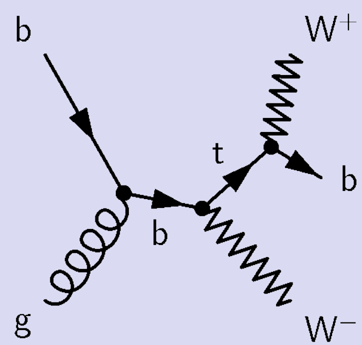
1) Introduction

top-quark production via the weak interaction.

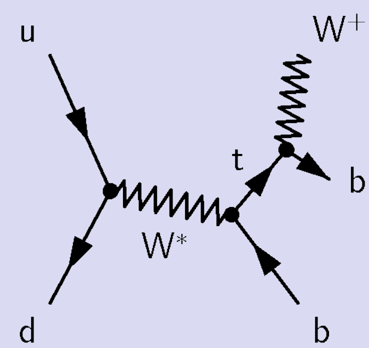
t-channel



associated Wt production



s-channel



cross sections at LHC with $\sqrt{s}$ = 7 TeV (m_t = 173 GeV)

64.2 ± 2.6 pb | 15.6 ± 1.3 pb | 4.6 ± 0.2 pb

cross sections at the Tevatron with $\sqrt{s}$ = 1.96 TeV (m_t = 173 GeV)

2.1 ± 0.1 pb | 0.25 ± 0.03 pb | 1.05 ± 0.05 pb

Calculation by N. Kidonakis: arXiv 1103.2792, 1005.4451, 1001.5034

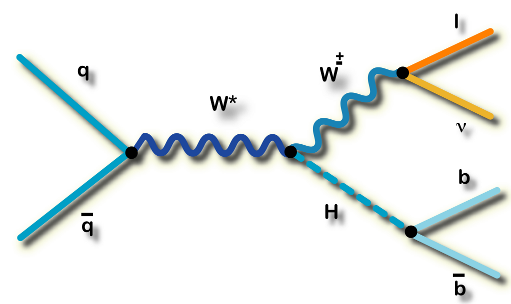
Why look for Single Top-Quarks?

1. Test of the SM prediction.
   - Does it exist? ✔
   - Cross section ∝ $|V_{tb}|^2$
     Test unitarity of the CKM matrix, .e.g.
     Hints for existence of a 4th generation ?

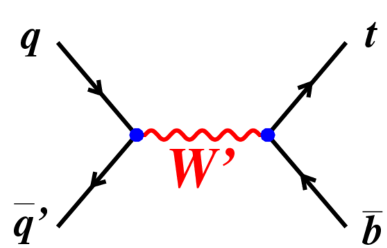
$$V_{ub}^2 + V_{cb}^2 + V_{tb}^2 \stackrel{?}{=} 1$$

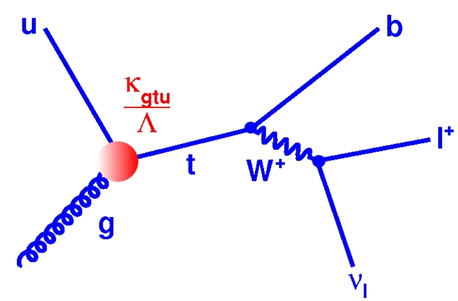
   - Test of *b* quark PDF: DGLAP evolution

2. At the Tevatron:
   - Stepping stone to the Higgs.
   - Same signature as WH.
     ➔ backgrounds are the same

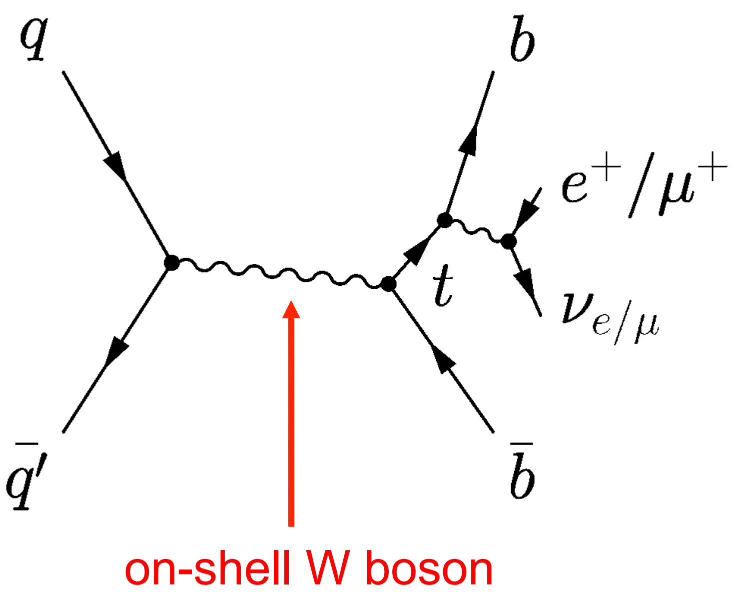


3. Test non-SM phenomena
   – Search W' or H⁺ (s-channel signature)
   – Search for FCNC, e.g. ug → t
   – ...

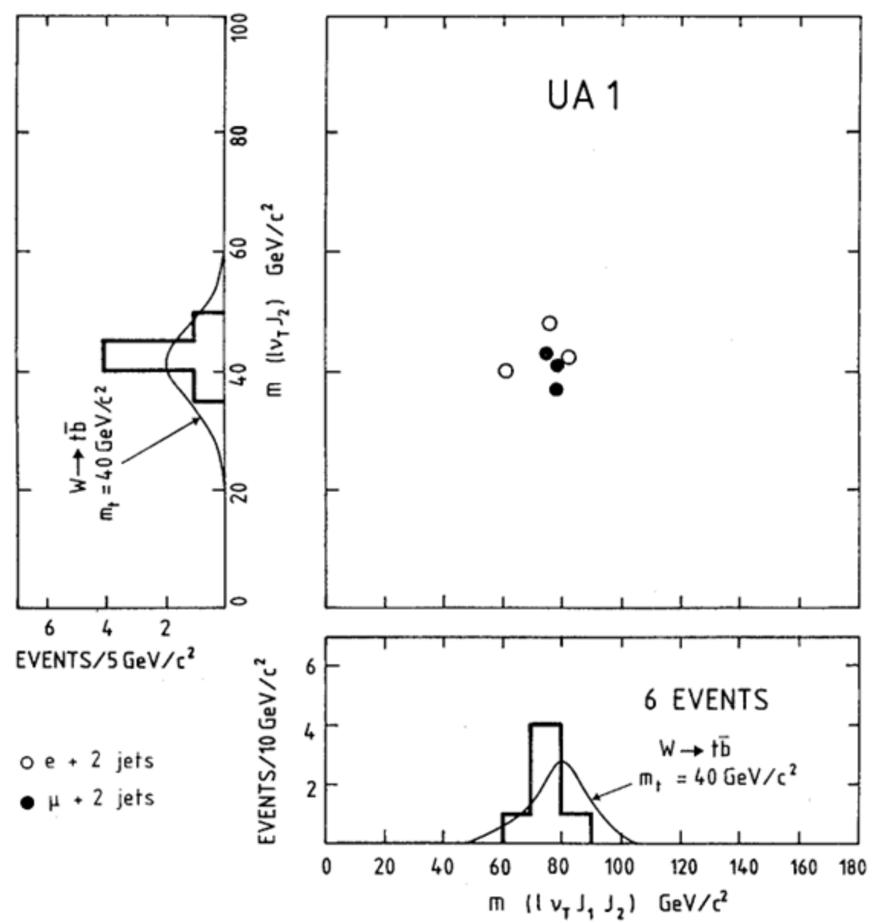




First Attempt to Discover (Single) Top …



… in 1984 by UA1 at CERN SppS



- excess in $M_{l\nu b}$ vs. $M_{l\nu bb}$ scatter plot
- compatible with m_t = 40 ± 10 GeV
- later improved background estimate

→ background very challenging in single top

Phys. Lett. B 147, 493 (1984)

Recognition of the Relevance of the t-Channel

PHYSICAL REVIEW D VOLUME 34, NUMBER 1 1 JULY 1986

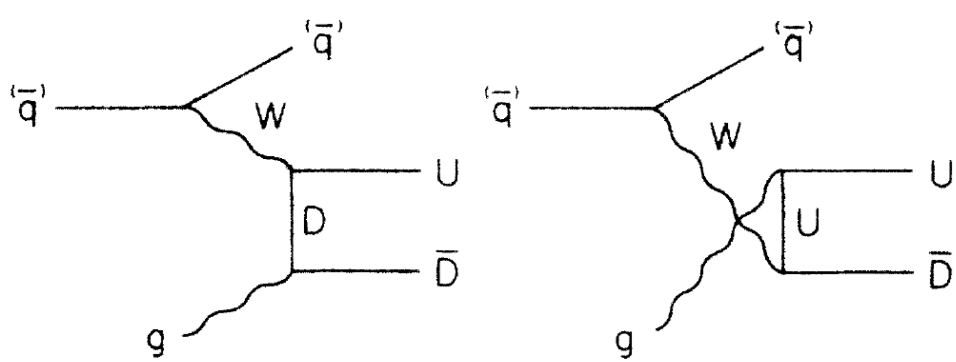
Production of heavy quarks from *W*-gluon fusion

Scott S. D. Willenbrock and Duane A. Dicus

Theory Group and Center for Particle Theory, University of Texas, Austin, Texas 78712

(Received 3 February 1986)

We show that heavy-quark production via *W*-gluon fusion in high-energy pp and $\bar{p}p$ collisions is an important source of the heavier member of an $SU(2)_L$ doublet of quarks if the mass splitting within the doublet is large. *W*-gluon fusion exceeds the strong production of heavy quarks for mass splittings greater than 300–350 GeV at $\sqrt{s}=10$ TeV and 400–450 GeV at $\sqrt{s}=40$ TeV. An alternative way to regard *W*-gluon fusion is as the production of the heavier quark by fusing its light partner with a *W* boson. We use a distribution function for the light partner to show that this process gives results which agree qualitatively with *W*-gluon fusion. We also discuss the Drell-Yan production of an $SU(2)_L$ doublet of heavy quarks via a virtual *W* boson and corrections to this process from initial gluons. We find that at the Fermilab Tevatron energy $\sqrt{s}=2$ TeV, *W*-gluon fusion exceeds the Drell-Yan production of top quarks for masses above 100 GeV.

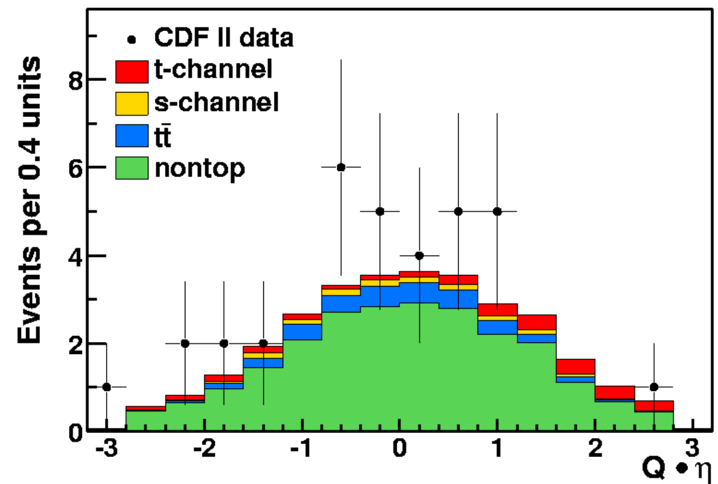


Single-Top Searches in Run I and Early Run II

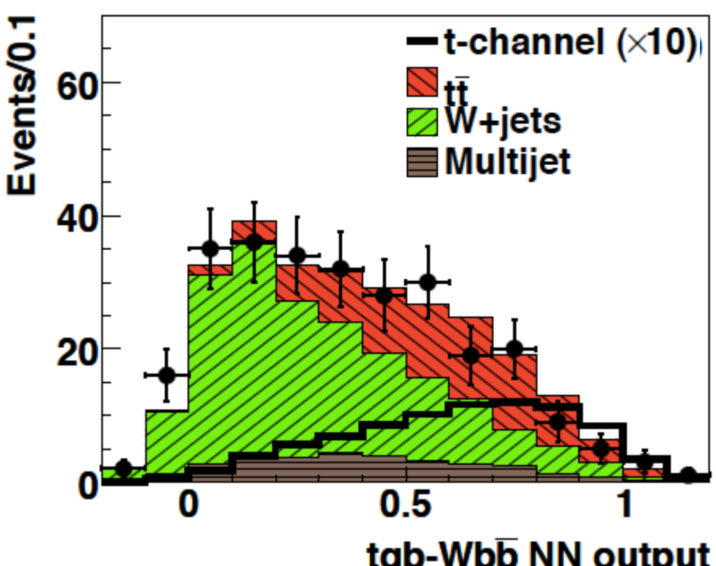
Run I:

- DØ, Phys. Rev. D 63 (2000) 031101
- DØ, Phys. Lett. B 517 (2001) 282 – 294 (neural networks)
- CDF, Phys. Rev. D 65 (2002) 091102 (H_T and $Q\cdot\eta$ fit)
- CDF, Phys. Rev. D 69 (2004) 052003 (neural network)

CDF Run II (2005): $Q\cdot\eta$ fit



DØ Run II (2007): neural networks



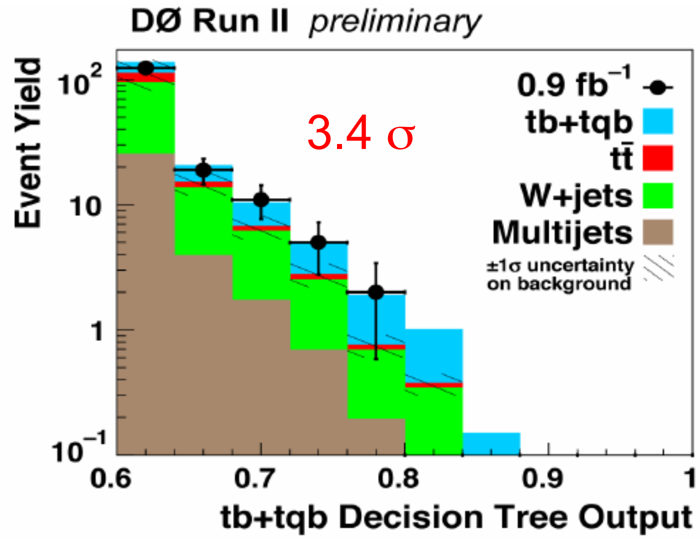
Run II:

- CDF, Phys. Rev. D 71 (2005) 012005 (H_T and $Q\cdot\eta$ fit)
- DØ, Phys. Lett. B 622 (2005) 265 – 276 (neural networks)
- DØ, Phys. Rev. D 75 (2007) 092007 (cut based and neural networks)

➔ cross section limits: 5 to 6 pb

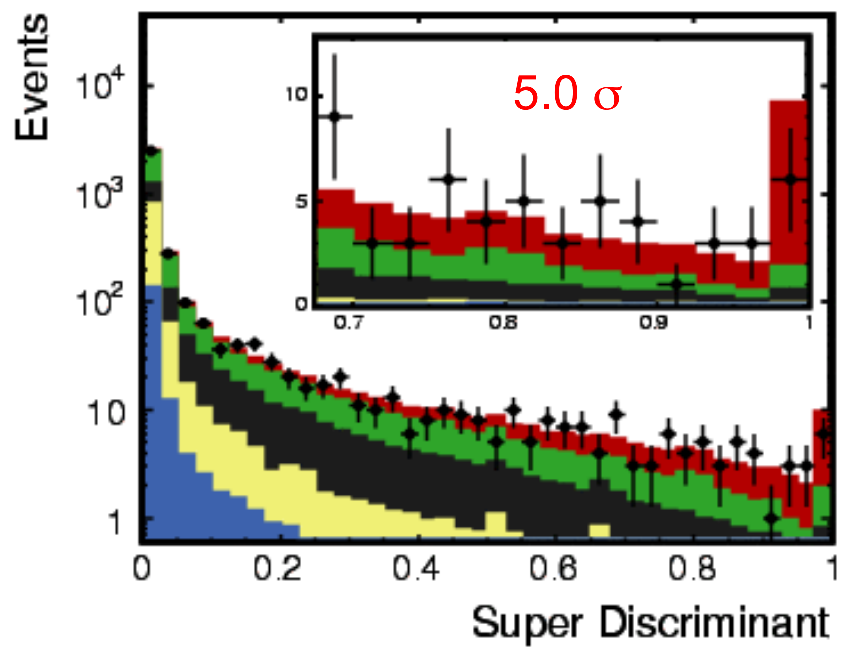
Evidence and Observation for Single-Top Production

Boosted decision tree analysis
(evidence at DØ, 2006)



- Combined t-channel + s-channel analysis
- Several multivariate analysis techniques.
- Combination of analyses (not results).
- Very intense checks on kinematic modeling.
- Mainly relying on ALPGEN W+jets MC.
- Signal models: CompHep (DØ) and MadEvent (CDF)

Combination of all multivariate analyses
(observation at CDF 2009)



Evidence Papers

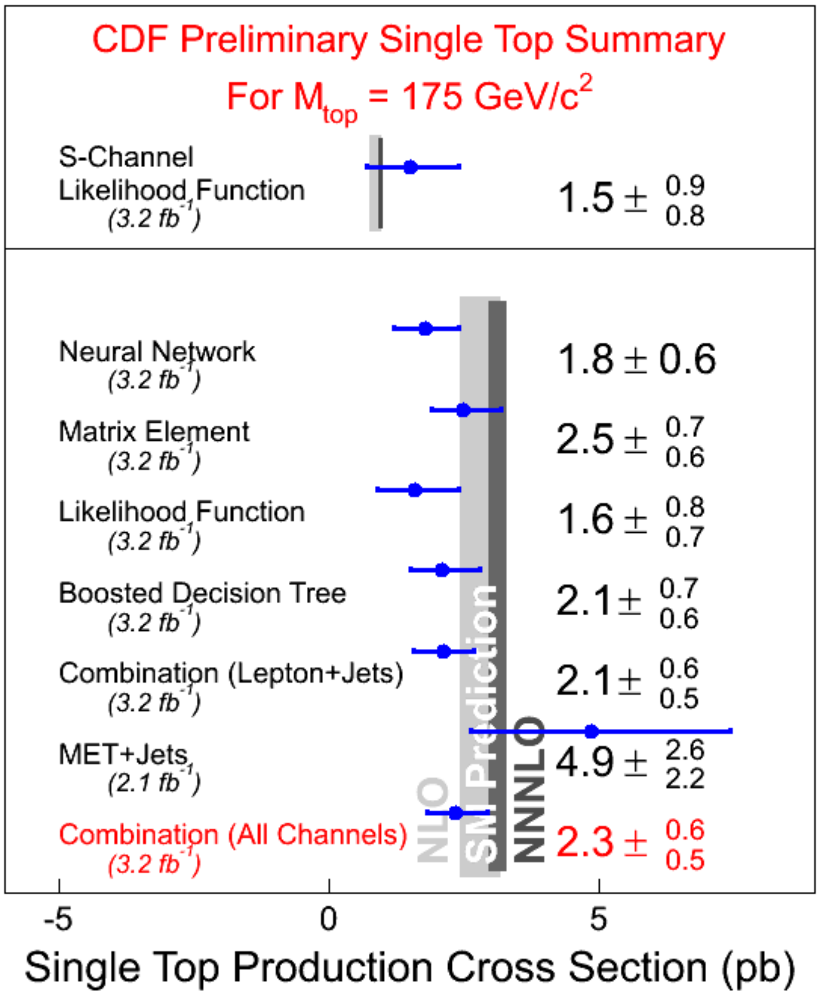
- DØ, Phys. Rev. Lett. 98 (2007) 181802, Phys. Rev. D 78 (2008) 012005
- CDF, Phys. Rev. Lett. 101 (2008) 252001

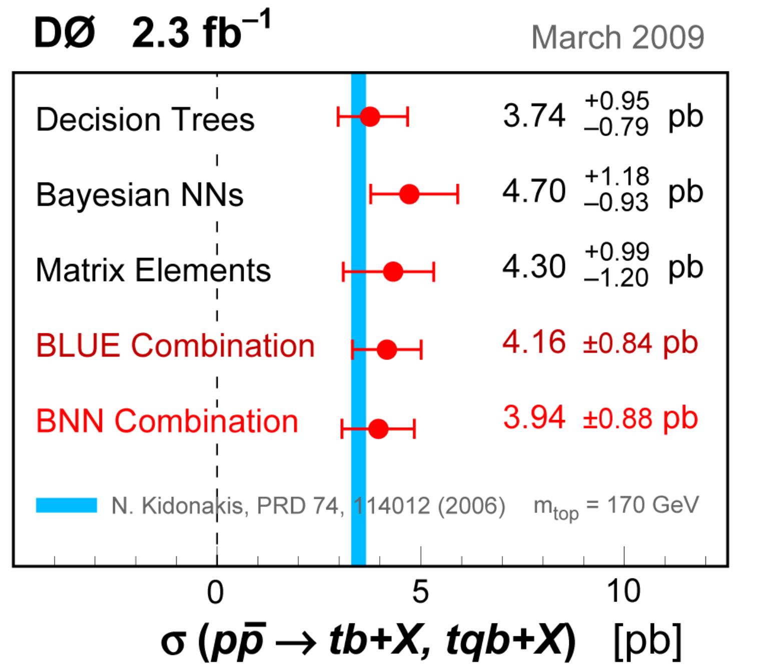
Observation Papers

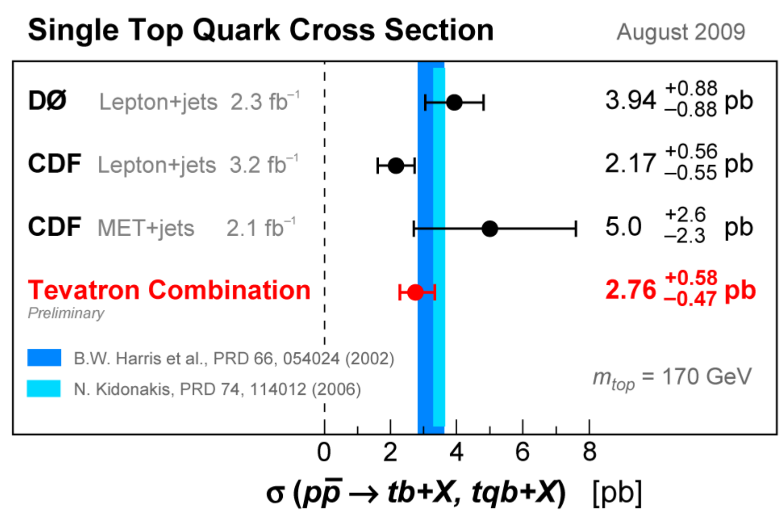
- DØ, Phys. Rev. Lett.103 (2009) 092001.
- CDF, Phys. Rev. Lett. 103 (2009) 092002, Phys. Rev. D 81 (2010) 072003, Phys. Rev. D 82 (2010) 112005.

2 Experimental Status

status of Tevatron measurements



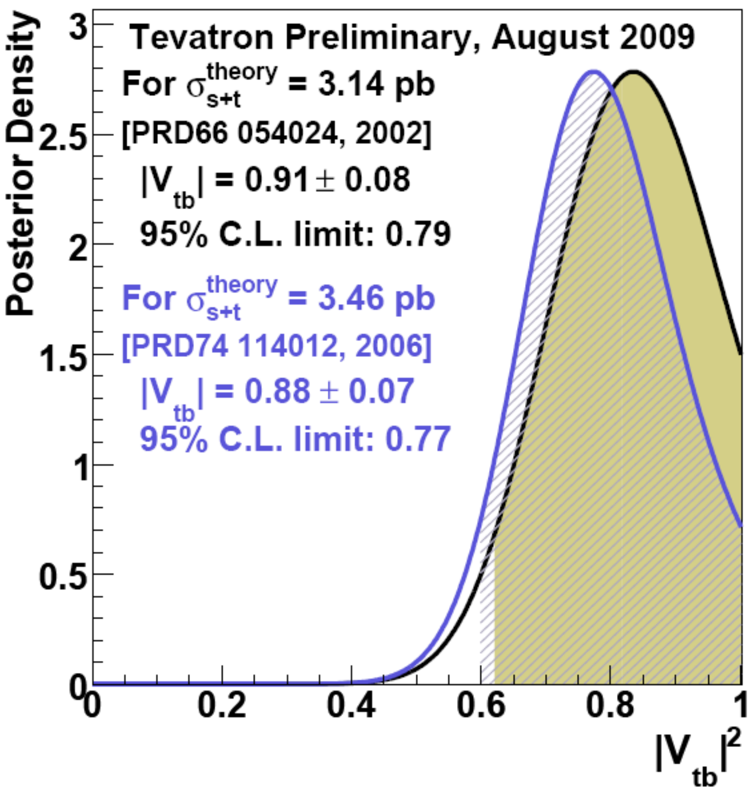


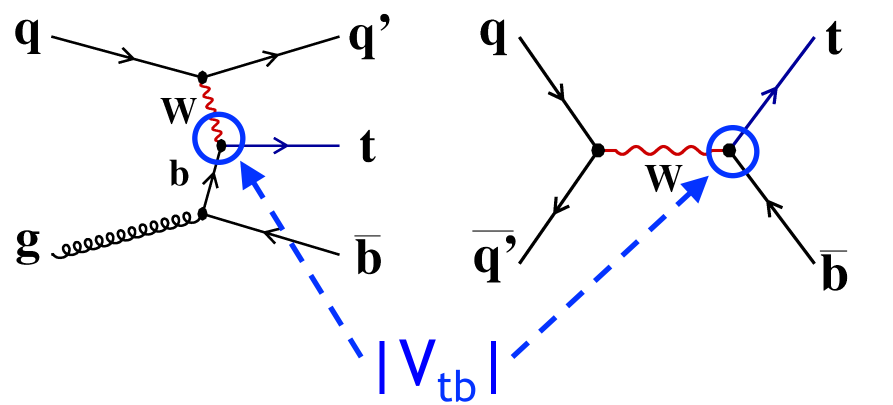


$|V_{tb}|$ Determination

- Using cross section result measure $|V_{tb}|$
- Assume Standard Model (V-A) coupling and $|V_{tb}| >> |V_{ts}|, |V_{td}|$ (from BR($t \rightarrow Wb$) measurements)

$$|V_{tb,meas}|^2 = \frac{\sigma_{meas}}{\sigma_{SM}} \cdot |V_{tb,SM}|^2$$



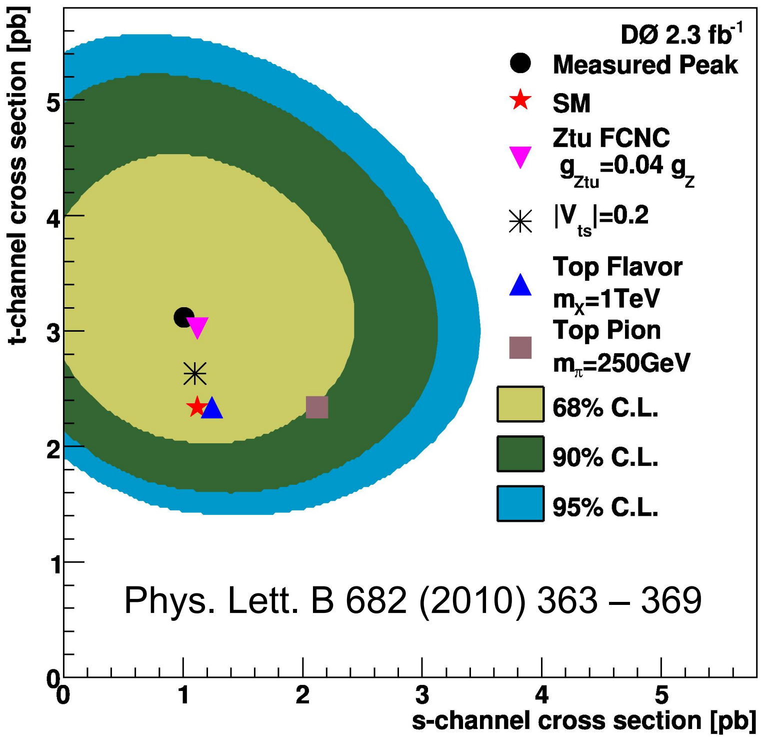


$|V_{tb}|$= 0.88 ± 0.07 (stat+syst) ± 0.07 (theory)

CDF and DØ Collaborations:
arXiv: 0908.2171 [hep-ex]

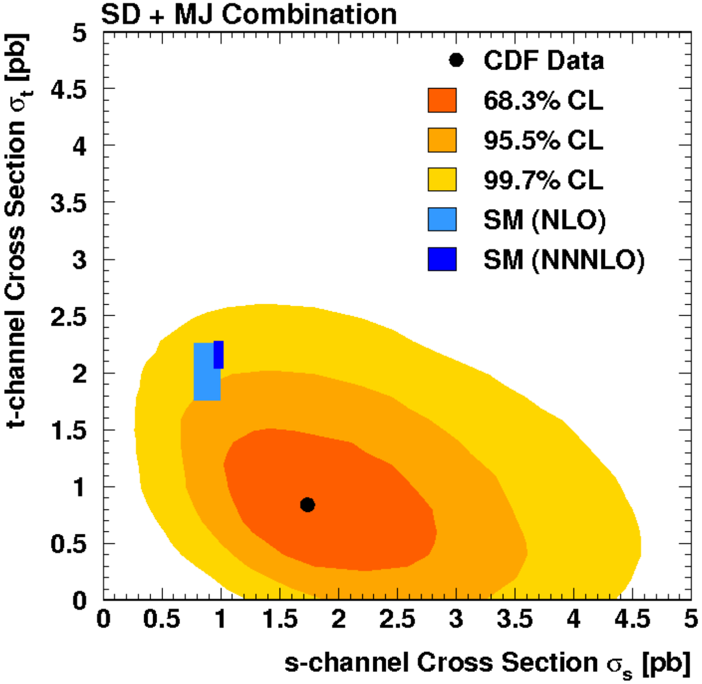
Separation of t-channel and s-channel

- Measure σ_s and σ_t separately
- Interesting because s- and t-channels have different sensitivity to BSM models
- Train dedicated s-channel and t-channel discriminants and fit 2D



Phys. Lett. B 682 (2010) 363 – 369

Phys. Rev. D 82 (2010) 112005

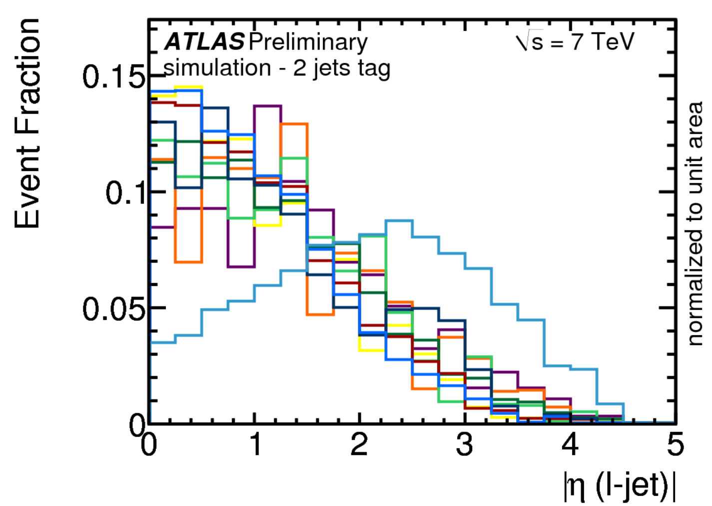


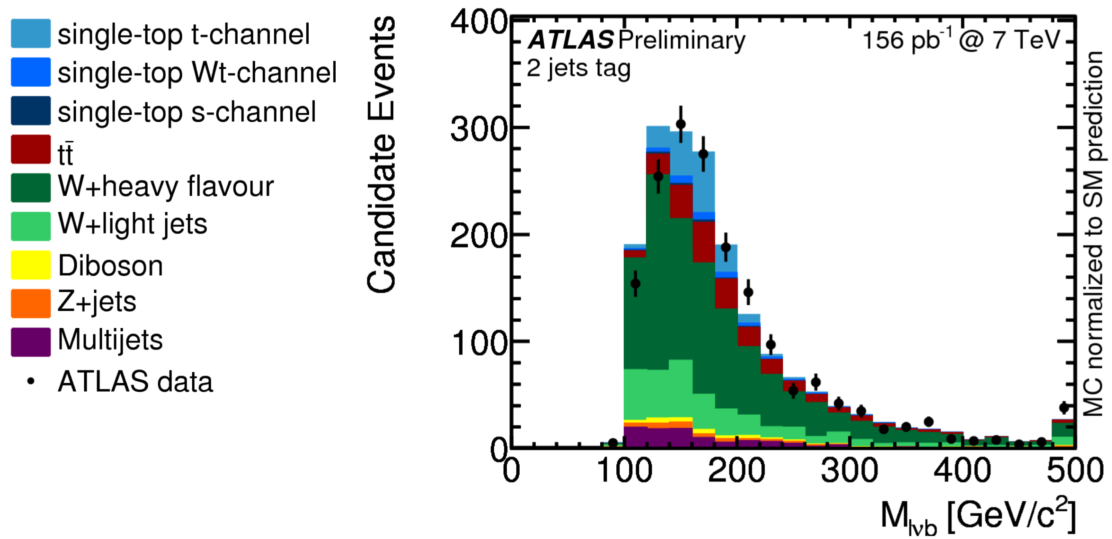
$$\sigma_{t\text{-channel}} = 3.14\,^{+0.94}_{-0.80}\ \text{pb}$$
$$\sigma_{s\text{-channel}} = 1.05 \pm 0.81\ \text{pb}$$

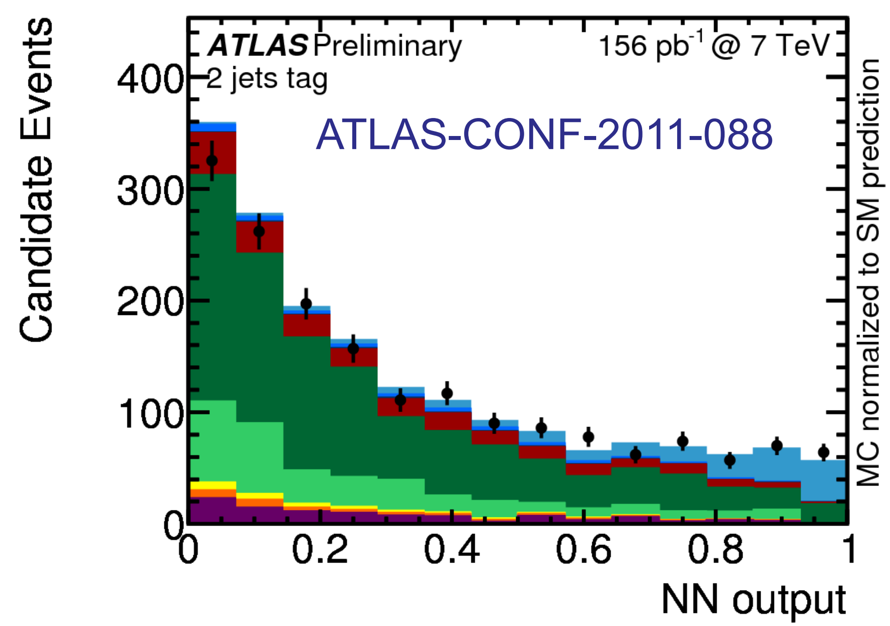
$$\sigma_{t\text{-channel}} = 0.8 \pm 0.4\ \text{pb}$$
$$\sigma_{s\text{-channel}} = 1.8\,^{+0.7}_{-0.5}\ \text{pb}$$

t-Channel Cross Section at ATLAS

- Better S/B (= 10.1%) after event selection than at Tevatron (6.9%).
- Very good acceptance for forward jets: $|\eta_{det}| < 4.5$.
- Neural network analysis + cut based as cross check.







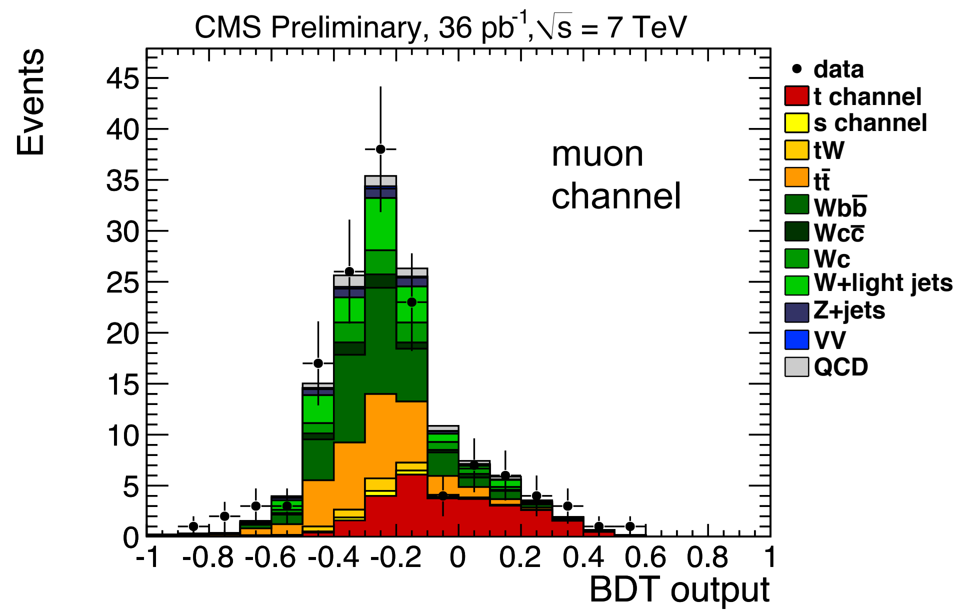
- Observed significance: 6.2 s.d.
  Expected: 5.7 s.d.

σ (t-ch.) = 76^{+41}_{-21} pb

t-Channel Cross Section at CMS

- Boosted decision tree analysis
- 2D-analysis: η(light jet), polarisation angle cos θ (light jet, lepton)$_{\text{top r.f.}}$
- χ^2 combination of results
- CMS PAS TOP-10-008

σ (t-ch.) = 84 ± 30 pb

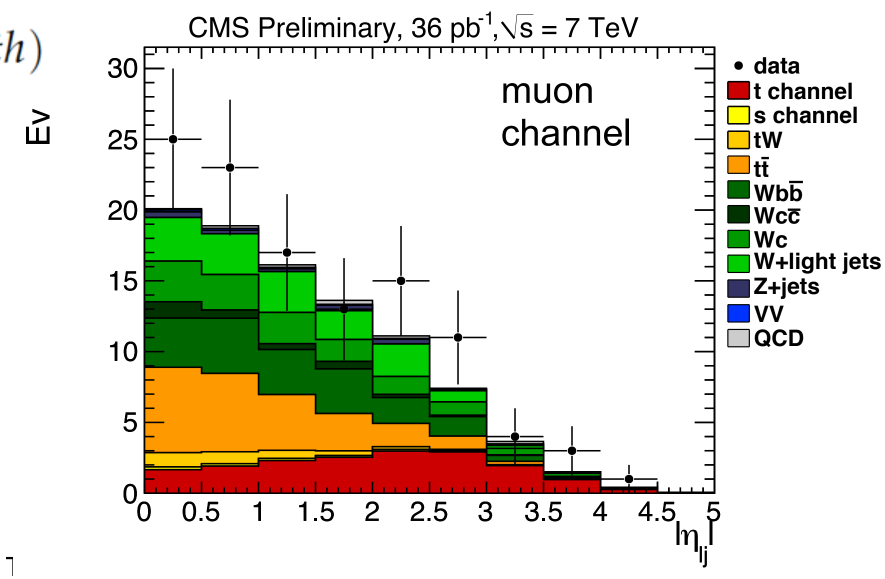


- Extraction of $|V_{tb}|$:

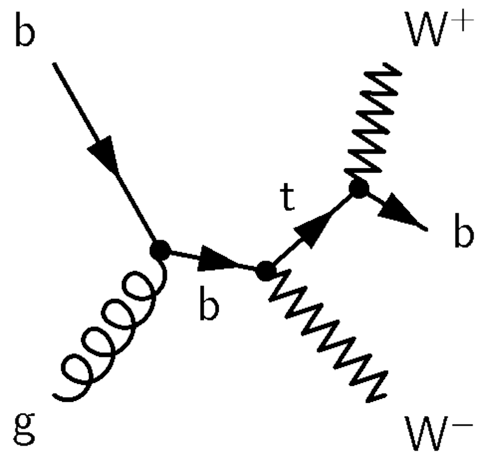
$$|V_{tb}| = \sqrt{\frac{\sigma^{exp}}{\sigma^{th}}} = 1.16 \pm 0.22(exp) \pm 0.02(th)$$

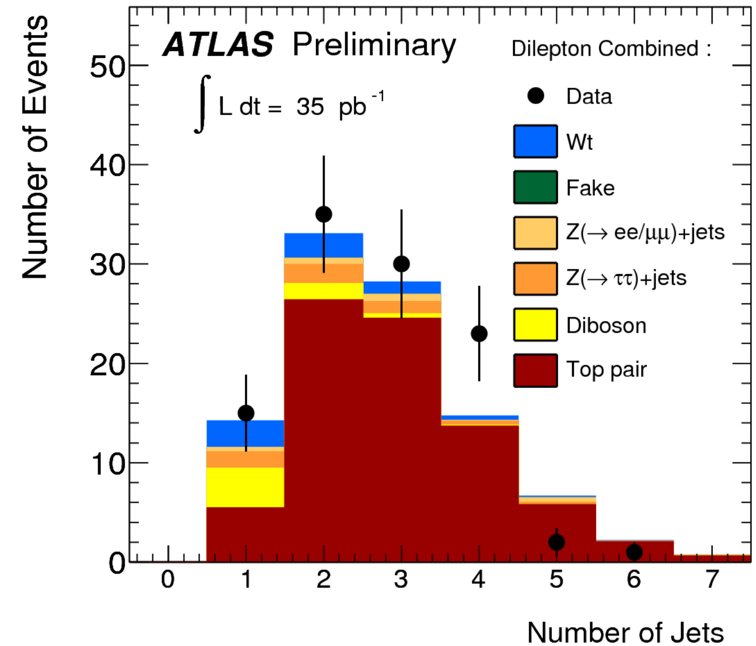
using $\sigma^{th} = 62.3^{+2.3}_{-2.4}$ pb

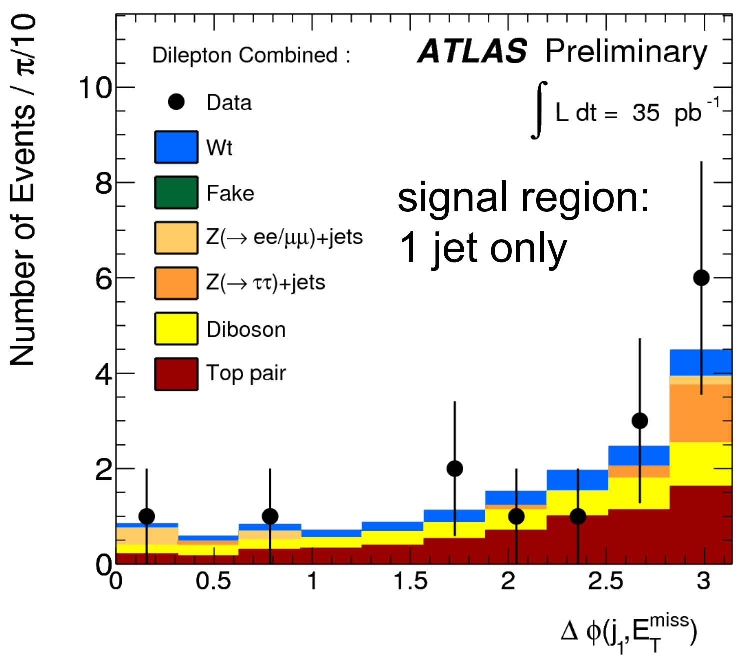
NLO prediction in the 5-flavour scheme, Campbell, Frederix, Maltoni, JHEP 10 (2009) 042.



Search for Wt Production







- ATLAS-CONF-2011-027
- Dilepton channel more sensitive than lepton+jets channel.
- σ (Wt) < 158 pb at the 95% C.L.

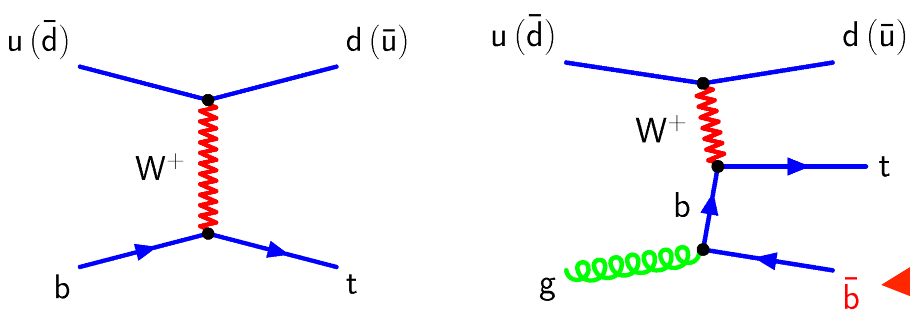
3 Prospects – Single Top as a Benchmark

Theory:

1) To extract V_{tb} we need the theory cross section as input.
2) Assume unitarity in 3 generations ➔V_{tb} known, test other theory aspects

Two issues of recent discussion:

a) 5 flavour vs. 4 flavour scheme



- Small effect on total cross section
- Relevant for differential cross sections, particularly 2nd b-quark ➔modeling

See calculations: Campbell, Frederix, Maltoni, JHEP 10 (2009) 042.

b) Influence of soft gluon effects: resummation at NNLL level

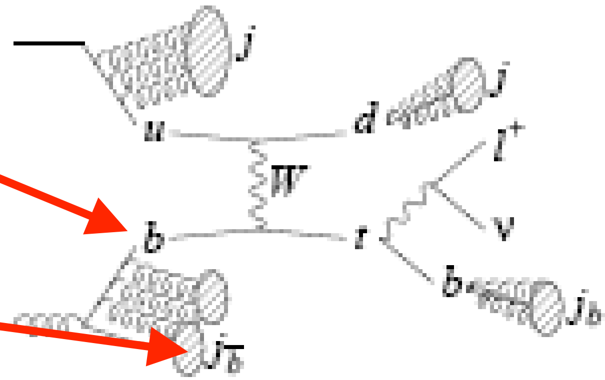
- N. Kidonakis, Phys. Rev. D 83 (2011) 091503 (arXiv 1103.2792), Phys. Rev. D 82 (2010) 054018 (arXiv 1005.4451), Phys. Rev. D 81 (2010) 054028 (arXiv 1001.5034).
- H.X. Zhu, C.S. Li, J. Wang, J.J. Zhang, JHEP 1102 (2011) 099 (arXiv:1006.0681), arXiv:1010.4509.

m_t(GeV)	171	172	173	174	175
σ_{LO}(pb)	$44.9^{-3.1}_{+2.2}$	$44.4^{-3.1}_{+2.1}$	$43.9^{-3.0}_{+2.1}$	$43.5^{-3.0}_{+2.1}$	$43.0^{-2.9}_{+2.0}$
σ_{NLO}(pb)	$42.6^{-0.8}_{+1.0}$	$42.2^{-0.7}_{+1.2}$	$41.9^{-0.6}_{+0.9}$	$41.6^{-0.8}_{+0.8}$	$41.1^{-0.7}_{+0.9}$
σ_{RES}(pb)	$41.7^{-0.1}_{+0.2}$	$41.3^{-0.1}_{+0.3}$	$40.9^{-0.1}_{+0.1}$	$40.7^{-0.1}_{+0.1}$	$40.2^{-0.1}_{+0.1}$

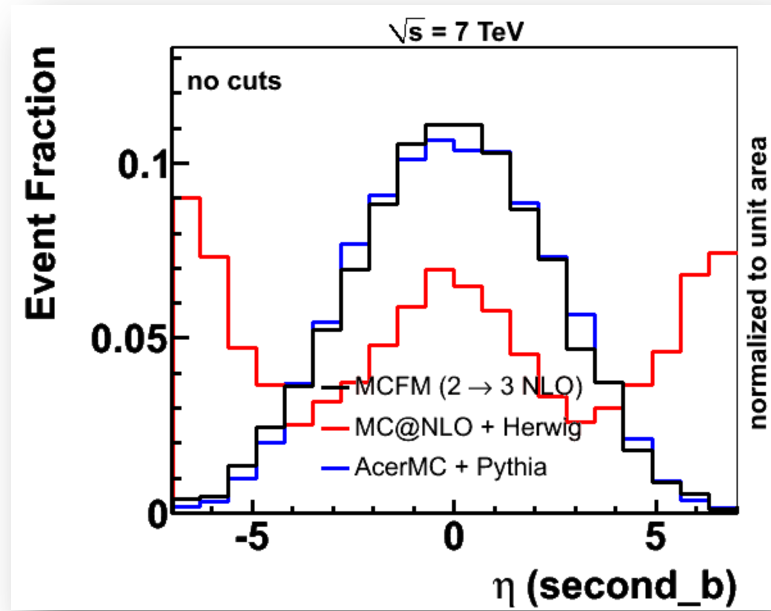
Modeling of Single-Top Events: Example 2^{nd} b Quark

from b-quark structure function

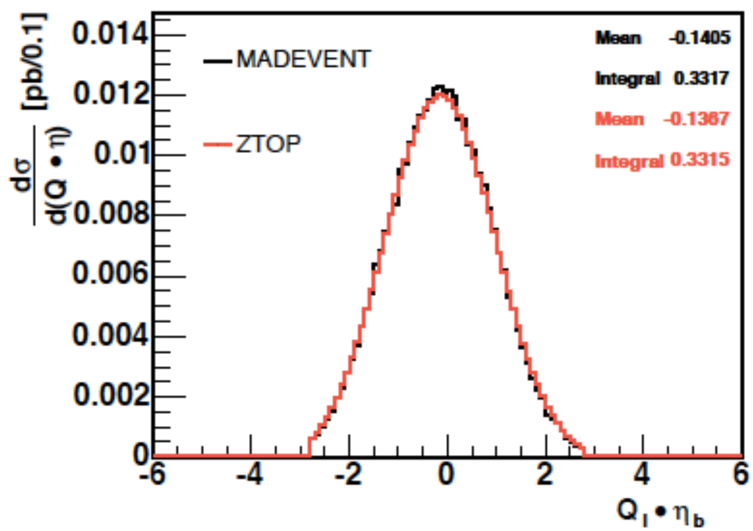
flavour conservation (in strong interaction):
2^{nd} b from shower MC (DGLAP evolution)



Problem in MC@NLO:



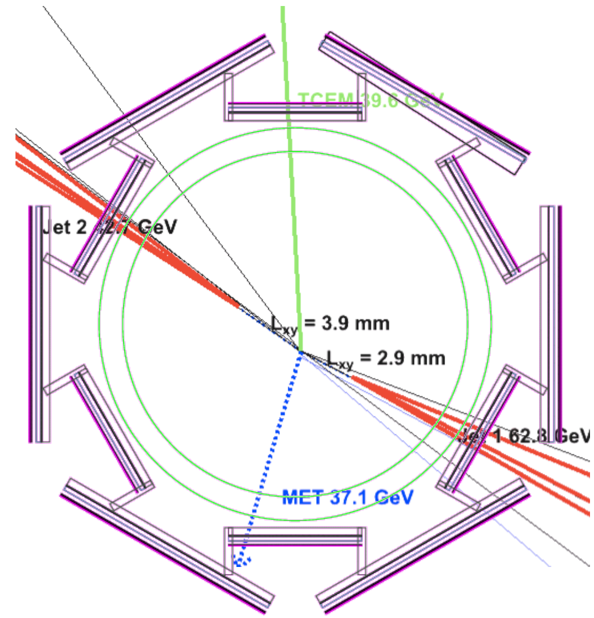
Solution:
matching of bu → td and gu → tdb_{bar} processes



→ excessive uncertainty on signal acceptance in ATLAS analysis

Single-Top: Test Bench for Object ID

- Single-top events feature all important objects of high-p_T physics:
  - electrons
  - muons
  - missing ET
  - jets, especially forward jets
  - b-tagging

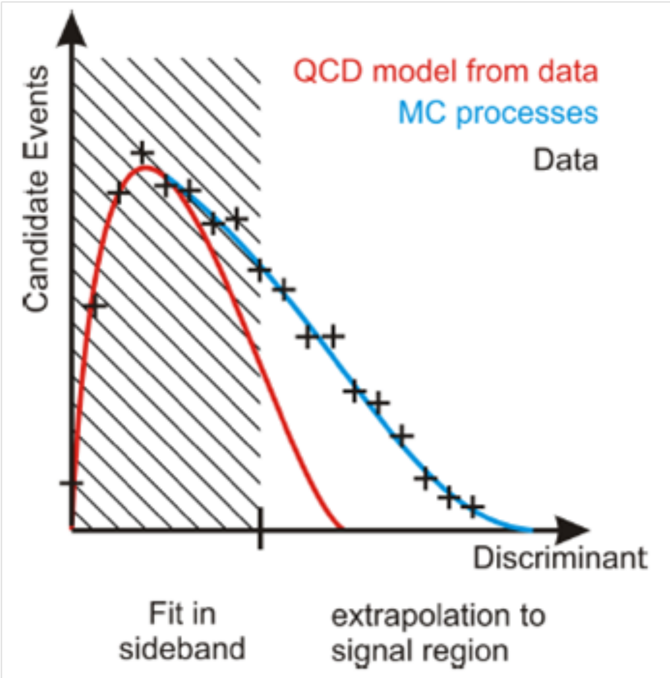


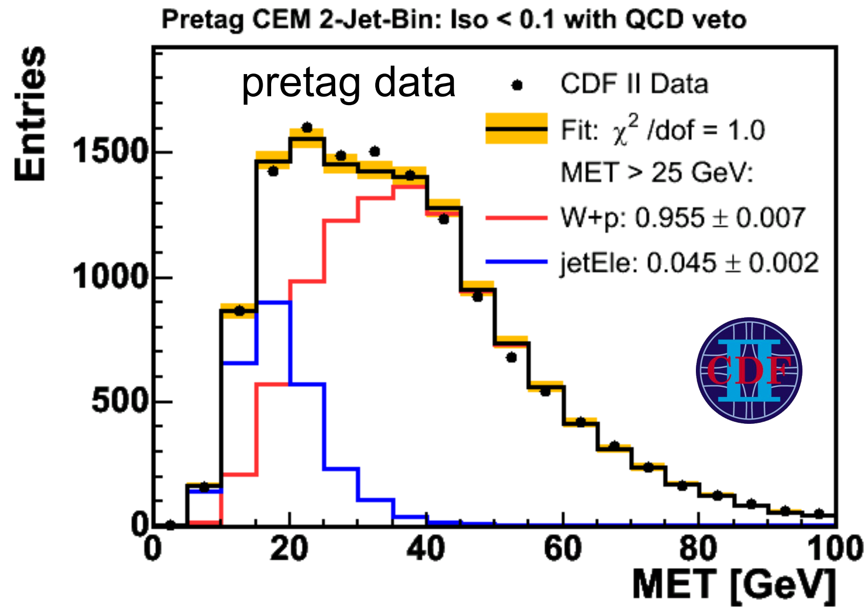
- Backgrounds much more severe for single top than top-pairs
  ➔ a much better understanding is needed
  ➔ driving force for new developments, for example: multijet veto, electron fake event model (CDF, ATLAS), neural network b-tagger (CDF and DØ), forward electron id (CDF), MET+jet trigger for untriggered muons (CDF), forward jet calibrations (ATLAS), …

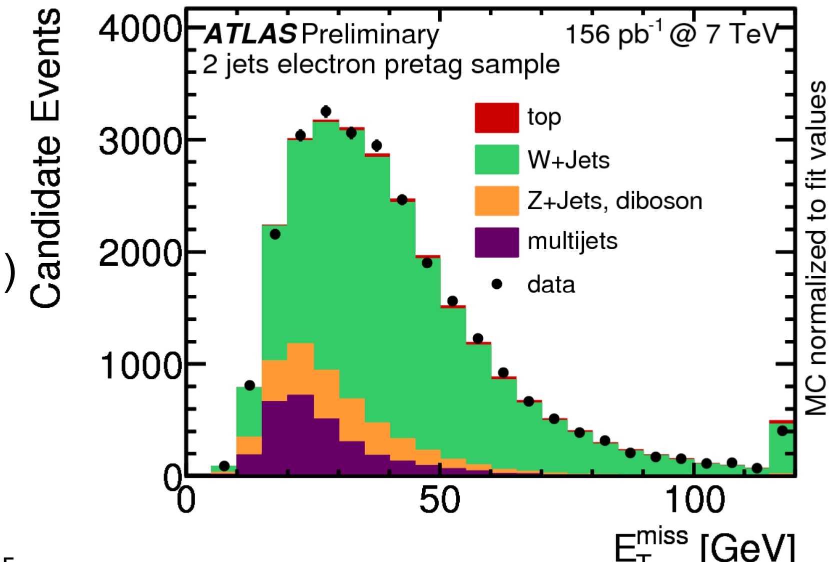
Uncertainties due to instrumental sources of ATLAS (PLHC) analysis (ATLAS-CONF-2011-088):

Source of Uncertainty	$\Delta\sigma/\sigma$
statistical only	+17% / -16%
JES	+18% / -3%
JER	+4% / -3%
jet reconstruction	3%
lepton SF	1%
b-taggging SF	+12% / -9%
light-jet mistagging SF	2%

Estimation and Modeling of Multijet Background







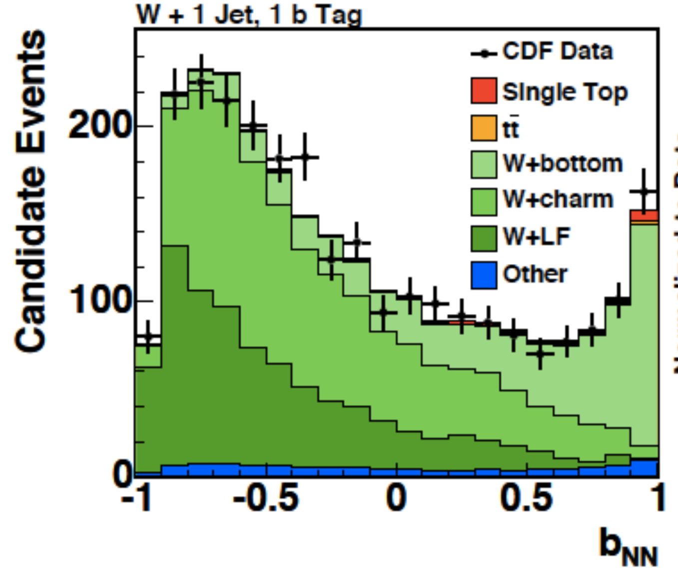
- fit discriminant distribution (e.g. MET) to estimate rate of multijets background
- model misidentified multijet background with jet-triggered events (jet-electron model)
- full event model to facilitate multivariate analyses

W + Heavy Flavour Jets

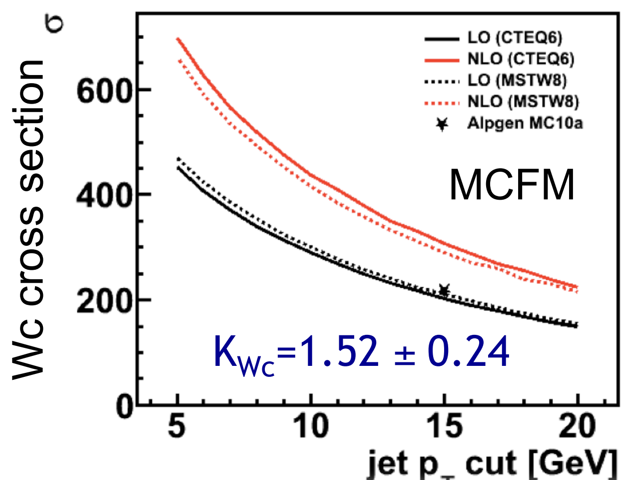
- Observe more W + heavy flavour events after b-tagging than expected from ALPGEN + tagging efficiency.
- True even after normalizing jet-bin-by-jet-bin in the pretag data set.
- Unknown higher orders.
- Pragmatic resolution:
  measure HF scale factors in data
- Problem: extrapolation from sideband
- Better: simultaneous fit in signal region.
- Recently a lot of activity in theory, for example new version of MCFM.
  ➔get k factor from theory

Fit to NN flavor separator in sideband

$K_{HF}=1.4 \pm 0.4$



Phys. Rev. D 82 (2010) 112005

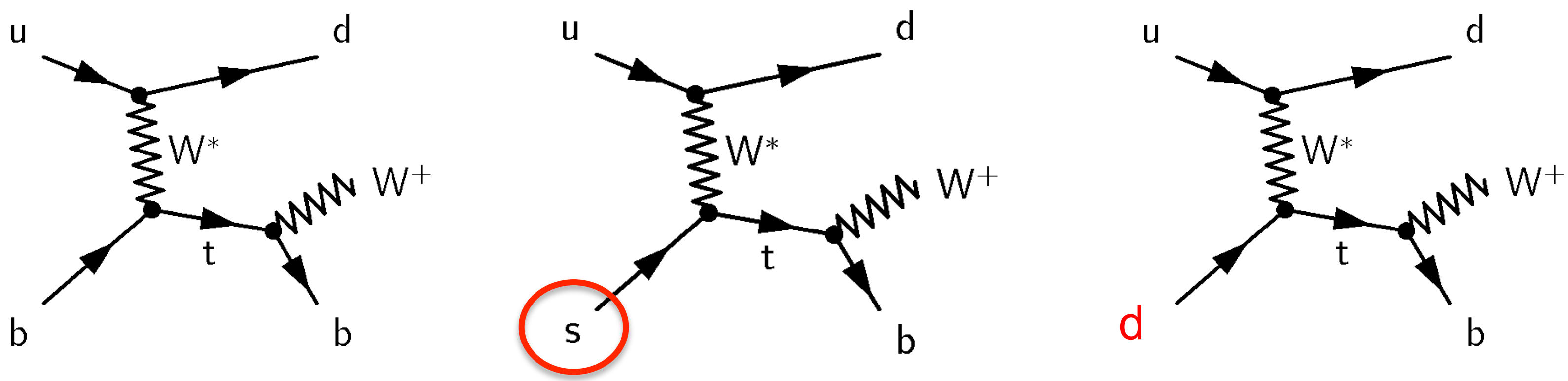


$K_{Wc}=1.52 \pm 0.24$

Work by Dominic Hirschbühl

Can we learn about V_{ts} and V_{td} ?

- So far consider only production via V_{tb}.
- How about production via V_{ts} and V_{td}?



in SM: $\sigma_s = 0.4\% \cdot \sigma_b$

in SM: $\sigma_d = 0.1\% \cdot \sigma_b$

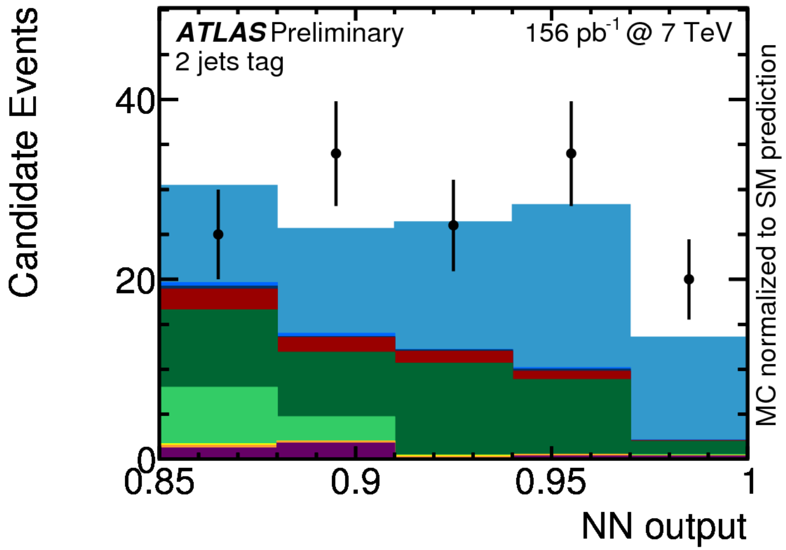
- Need samples of simulated events to compute efficiencies.
- Need also to consider different top decay modes ($t \rightarrow sW$, $t \rightarrow dW$), but low sensitivity due to missing option to flavour-tag.
- Limits on $|V_{ts}|$ and $|V_{td}|$ at the 10% level may be possible in the long run.

Summary

- Tevatron measurements of V_{tb} are still world´s best.

$$|V_{tb}| = 0.88 \pm 0.07\ (\text{stat+syst}) \pm 0.07\ (\text{theory})$$

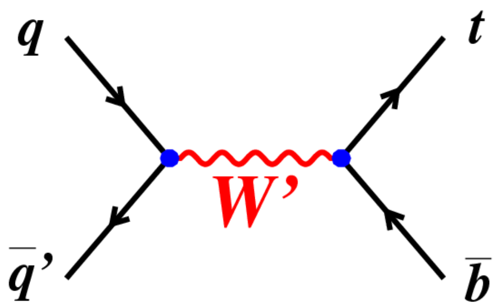
- At LHC, ATLAS (6.2σ) and CMS (3.7σ) have observed t-channel production.



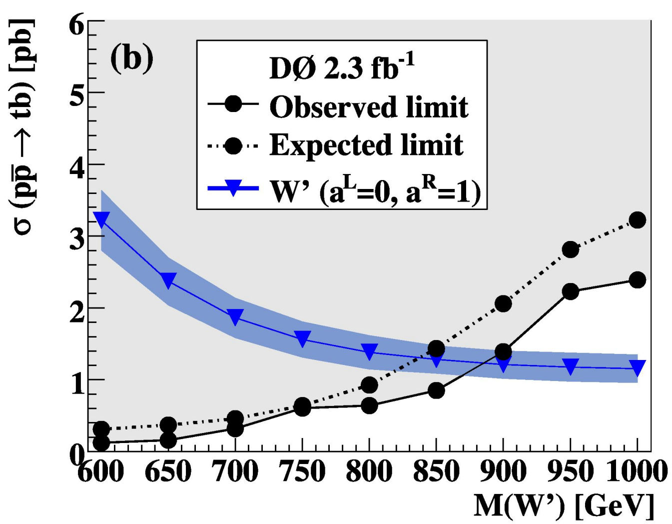
- Single top is an important SM benchmark.
  - Theory: 4 flavour / 5 flavour scheme
  - b-quark PDF
  - MC generators: 2nd b quark
  - Experimentally: Object ID lepton fakes, forward jets, b-tagging
  - W+jets: heavy flavour fractions

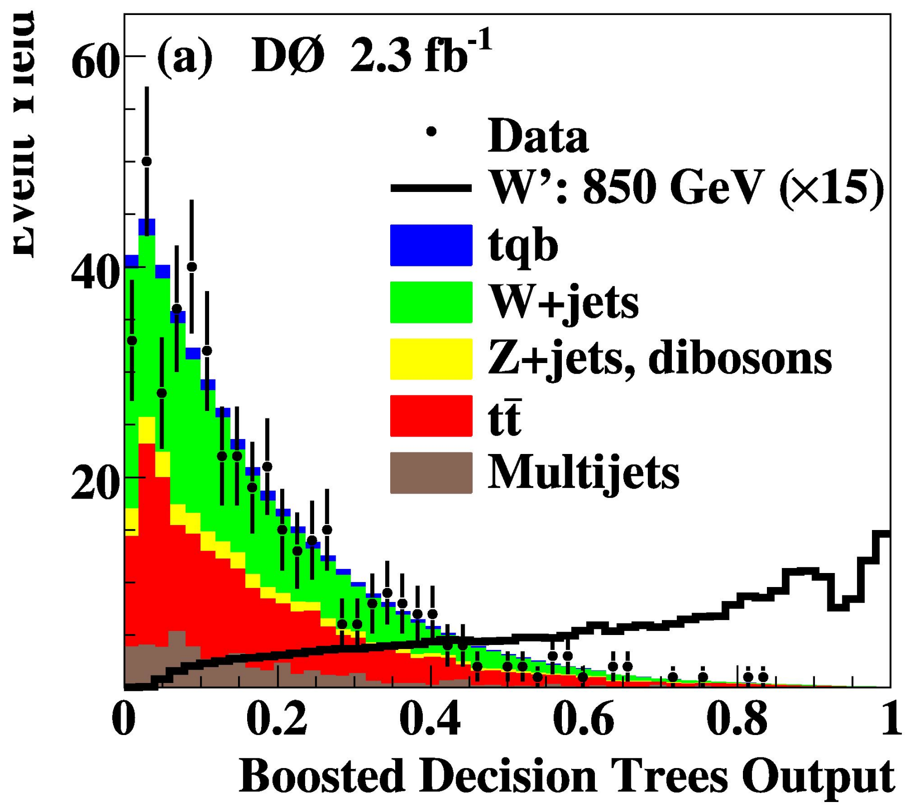
Important for credible discoveries of "new" physics!

Search for W′ → tb Events



- Investigate different left- and right-handed couplings to fermions.
- Limits vary based on assumptions of couplings:
  m(W′) > 863 .. 916 GeV





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