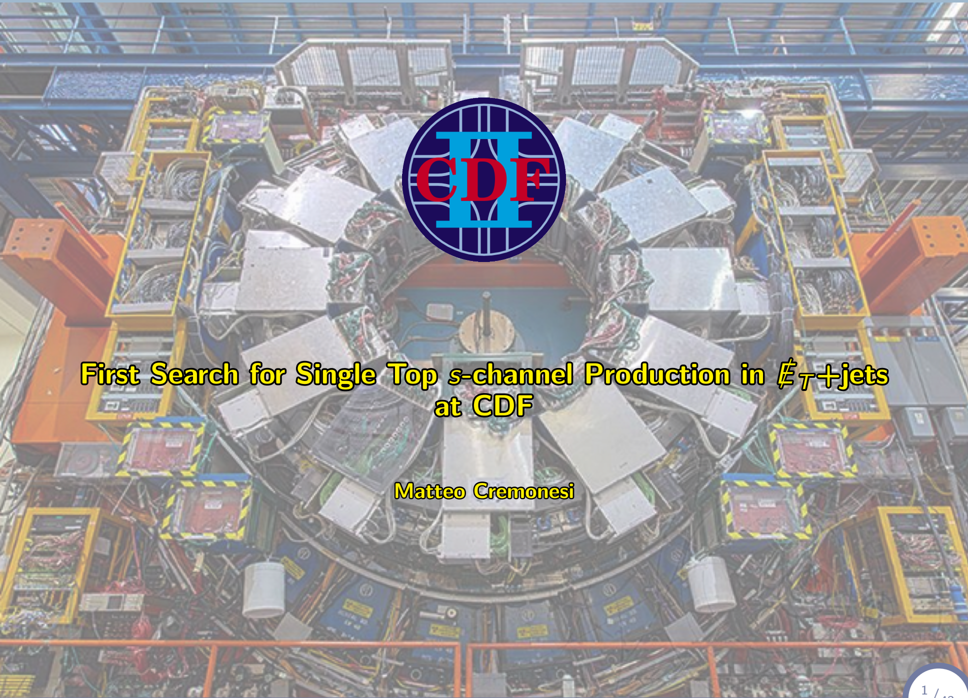


First Search for Single Top s-channel Production in $\not\!\!E_T$+jets at CDF

Matteo Cremonesi

Single Top Quark Production

The top quark can be produced:

- in $t\bar{t}$ pairs through strong interaction;
- as **single top via EW interaction**.

Observed by CDF and DØ in 2009:

- T. Aaltonen, et al. [CDF collaboration], Phys. Rev. Lett. 103, 092002 (2009)
- V.M. Abazov et al. [DØ Collaboration], Phys. Rev. Lett. 103, 092001 (2009)

Two dominant processes:

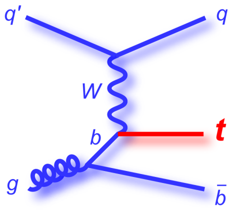
- t-channel;
- s-channel.
  - Wt-channel has a small cross section at the Tevatron.

	σ(pb)
s-ch	1.05 ± 0.05 [a]
t-ch	2.08 ± 0.08 [b]
Wt-ch	0.25 ± 0.03 [c]
$t\bar{t}$	7.08 ± 0.49 [d]

Theoretical cross sections at Tevatron considering $m_t = 173\text{GeV/c}^2$

[a] N. Kidonakis, arXiv:1001.5034
[b] N. Kidonakis, arXiv:1103.2792
[c] N. Kidonakis, arXiv:1005.4451
[d] N. Kidonakis, arXiv:1205.3453

Single Top t-channel

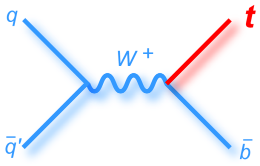


- It has already been established by the LHC experiments[1] [2];
- The light-flavor jet is more forward:
  - For a precise measurement, a good η coverage is required;

[1] ATLAS Collaboration, Measurement of the t-channel Single Top-Quark Production Cross Section in 0.70 fb^{-1} pp Collisions $\sqrt{s} = 7$ TeV with the ATLAS detector, ATLAS-CONF-2011-101(2011)

[2] CMS Collaboration, Measurement of the t-channel single top quark production cross sec tion in pp collisions at $\sqrt{s} = 7$ TeV, CMS-TOP-10-008 (2011)

Single Top s-channel



- It has not been observed yet;
  - DØ recently claimed a 3.7 σ evidence[3].
- Difficult at LHC;
  - $\sigma^{SM}_{s-ch} \cong$ 5 pb, $\sigma^{SM}_{t-ch} \cong$ 65 pb at LHC 7 TeV.
- Deviations from SM prediction may indicate new physics, like the existence of a W' or of a charged Higgs boson[4].

At **CDF**, two statistically independent samples are analyzed, looking for single top s-channel production:

- the $\boldsymbol{l\nu b\bar{b}}$ sample;
  - one isolated lepton, missing transverse energy and jets are required; see previous talk.
- the $\boldsymbol{\not{E}_T b\bar{b}}$ sample.

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[3] http://theory.fnal.gov/jetp/talks/WineAndCheese_20130621_v6.pdf

[4] T. M. P. Tait and C. P. Yuan, Single top quark production as a window to physics beyond the standard model, Phys. Rev. D 63 (2000) 014018.

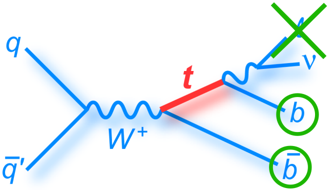
The $\not\!\!E_T b\bar{b}$ sample

We look for single top s-channel events when t→Wb and W decays leptonically, but:

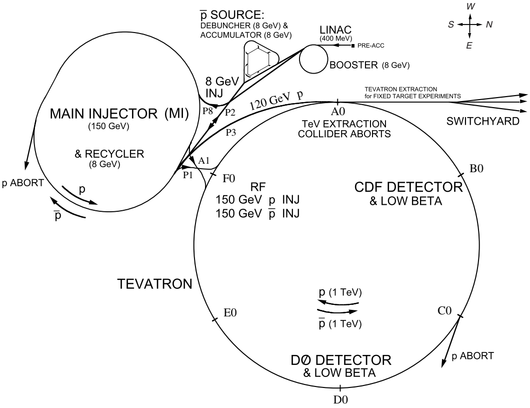
- There are no identified leptons;

  or

- There are τs that decay hadronically.
  - This analysis is sensitive to the $t \to Wb \to \tau\nu b$ channel, where the τ is reconstructed as a jet in the calorimeters, even if we do not apply a τ reconstruction.

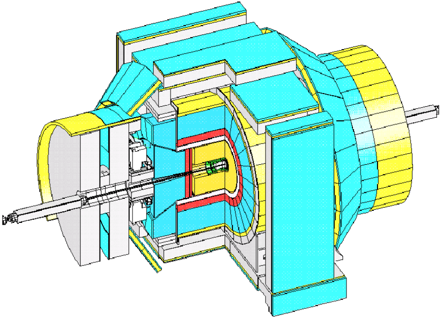


The Tevatron



- Collider $p\bar{p}$ $\sqrt{s} = 1.96$ TeV
- Radius $R = 1$ km
- Two experiments: CDF and DØ
- Run II (2001–2011): ~ 12 fb^{-1} of $p\bar{p}$ collisions, ~ 10 fb^{-1} recorded by CDF.

The CDF Detector



- Multipurpose detector, BØ interaction point at Tevatron
- Tracking system in magnetic field at 1.4 T
- Calorimeters
  - Electromagnetic and hadronic
  - Sampling
  - Projective towers
- Muon chambers
  - 4 layers of drift chambers
- Trigger system
  - three levels of *online* selection

Analysis Strategy

1. Select events with large missing transverse energy and 2/3 jets in the final state;

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   - Reconstruct the top quark;

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Analysis Strategy

1. **Select events with large missing transverse energy and 2/3 jets in the final state**;

Event Pre-selection

Data and triggers:

- The full CDF Run II dataset (9.5 fb^{-1}) is analyzed;
- Events are accepted on line by the trigger if they contain large $\not\!\!E_T$ and at least two jets.

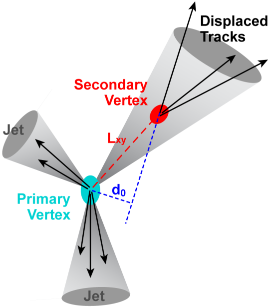
Basic selection:

- Large missing transverse energy ($\not\!\!E_T$);
- No isolated leptons;
  - We use loose identification cuts to reject events with isolated leptons.
- 2 or 3 jets;
- At least one of the jets has to be central ($|\eta| < 1$)
- $\Delta\phi(\not\!\!E_T, j_2) > 0.4$.

Analysis Strategy

1. Select events with large missing transverse energy and 2/3 jets in the final state;
2. **Require at least one *b*-tag to reduce the large backgrounds from light-flavor jet production**;

Tagging categories



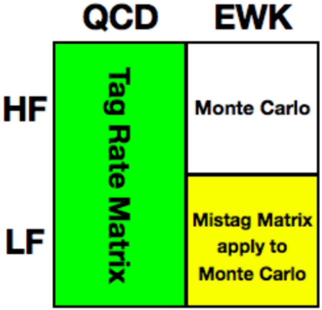
- At least one of the jets has to be b-tagged;
- We employ a new b-jet identification algorithm optimized for $H \to b\bar{b}$ searches: HOBIT[5];
- Two different HOBIT cuts are used: tight b-tag (T), loose b-tag (L);
- The selected sample is subdivided in three different tagging categories, according to the number of tight/loose tagged jets:
  - 1T: single tight b-tag;
  - TL: one tight b-tag and one loose b-tag
  - TT: double tight b-tag.

[5] J. Freeman, T. Junk, M. Kirby, Y. Oksuzian, T. J. Phillips, F. D. Snider, M. Trovato, J. Vizan, and W. M. Yao, Nucl. Instrum. Methods Phys. Res., Sect. A **697**, 64 (2013).

Analysis Strategy

1. Select events with large missing transverse energy and 2/3 jets in the final state;
2. Require at least one *b*-tag to reduce the large backgrounds from light-flavor jet production;
3. **Model signal and backgrounds**:

Signal and Background Model



Electroweak/Top: W+ Heavy Flavor (W+HF), Z+ Heavy Flavor (Z+HF), single top and diboson are modeled by Monte Carlo, as well as $t\bar{t}$:

- Signal: POWHEG
- t-channel: POWHEG
- W/Z+jets: ALPGEN, normalization left unconstrained in the final fit
- $t\bar{t}$, WW/WZ/ZZ, WH/ZH: PYTHIA
  - $t\bar{t}$ is normalized to the measured cross section.

The parton showering is performed by PYTHIA.

Mistags from Electroweak light flavor:

- Mistag rate matrix model to estimate mis-tagged light flavor Electroweak production (diboson, W/Z+ Light Flavor (W/Z+LF)).

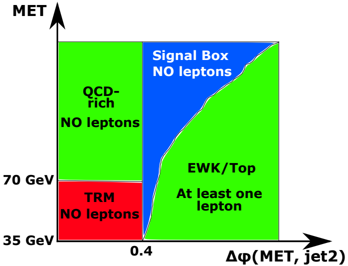
QCD multijet:

- Data-derived model to predict the tagged heavy flavor QCD and mis-tagged light flavor QCD;
- Validated in several control regions.

Analysis Strategy

1. Select events with large missing transverse energy and 2/3 jets in the final state;
2. Require at least one *b*-tag to reduce the large backgrounds from light-flavor jet production;
3. Model signal and backgrounds:
   - **QCD multijet modeled with a data-derived method (tag-rate matrix)**;

Regions Definition



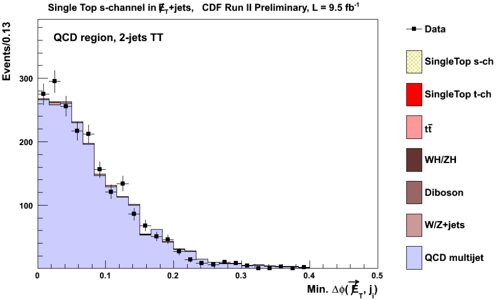
QCD Mulitjet events generally do not have intrinsic $\not{E}_T$:

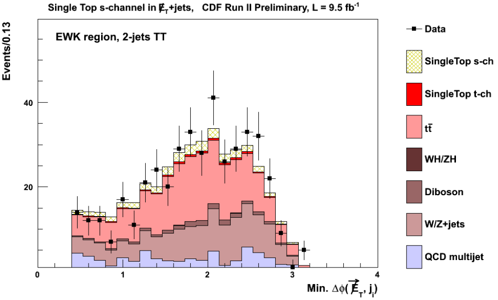
- Mismeasured jets do cause imbalance in the total transverse energy;
- In QCD *b*-quark pair production, if one *b* undergoes a semi-leptonic decay, large $\not{E}_T$ arises.

In both cases, the $\not{E}_T$ tends to be aligned parallel or anti-parallel to the first or second most energetic jet. We divide the sample in 4 regions:

- **TRM** (**T**ag **R**ate **M**atrix): $\Delta\phi(\not{E}_T, j_2) < 0.4$, 35 Gev $< \not{E}_T <$ 70 GeV, veto lepton;
- **QCD**: $\Delta\phi(\not{E}_T, j_2) < 0.4$, $\not{E}_T >$ 70 GeV, veto lepton;
- **EWK**: $\Delta\phi(\not{E}_T, j_2) > 0.4$, lepton events;
- **Preselection**: $\Delta\phi(\not{E}_T, j_2) > 0.4$, veto lepton;

QCD Multijet Model





The QCD contribution is estimated by a data-derived model:

- **Tag Rate Matrix**;
- A tagging rate function is built in the **TRM** background populated region;
- We use this function to predict the QCD multijet contributions (both HF and LF mistags) in the signal and other control regions.
- We check the predicted shape in the QCD and EWK control regions; the modeling is satisfying;

Tag Rate Matrix

An **event based** model is used. The tag rate probabilities are parameterized as a function of 6 variables. A separate 6D matrix is derived for each tag catetory: 1T, TL, and TT.

- The tagging rate in each bin of a tagging category:

$$rate = \frac{No.\ of\ \ Tagged\ Events}{No.\ of\ \ Taggable\ Events}$$

  - The definition of a taggable event depends on the underlying jets

- To estimate the multijet shape:

$$multijet = pretag\ data \times rate - \Sigma pretag\ electroweak\ process \times rate$$

  where, the electroweak processes include top, diboson, W+jets and Z+jets productions.

Analysis Strategy

1. Select events with large missing transverse energy and 2/3 jets in the final state;
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3. Model signal and backgrounds:
   - QCD multijet modeled with a data-derived method (tag-rate matrix);
   - **Mistag light-flavor events modeled with a mistag matrix**;

Mistag Model

The mistag rate is estimated for each tagging category (1T, TT, TL). The mistag rate for each jet by two different HOBIT cuts are denoted by M_T and M_L, respectively:

- 1T: $M_{Tj1} \times (1 - M_{Tj2}) + M_{Tj2} \times (1 - M_{Tj1})$
- TT: $M_{Tj1} \times M_{Tj2}$
- TL: $M_{Tj1} \times (1 - M_{Tj2}) \times M_{Lj2} + M_{Tj2} \times (1 - M_{Tj1}) \times M_{Lj1}$

The mistag rate is applied to light flavor Monte Carlo samples: W+LF, Z+LF and diboson. We also veto jets matched with a HEPG b/c quark.

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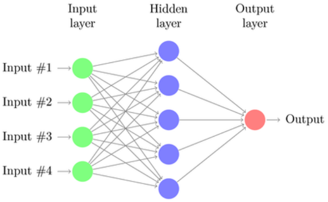
4. **Use multivariate techniques**:

Multivariate Analysis



Since we are looking for a small signal in a very large background, we need to use **Multivariate Techniques**. Several Neural Networks (NN) with different purpose are employed in this analysis:

- a NN to reconstruct the **top quark** finding the *b*-jet that comes from top decay;
- a NN **QCD veto**, to reject the QCD multijet production as much as possible. It reduces this background by an order of magnitude;
- two other dedicated NNs:
  - to distinguish signal from $W/Z{+}jets$ production;
  - to distinguish signal from $t\bar{t}$ background.

  combined together in a **Final Discriminant** used to fit for signal.

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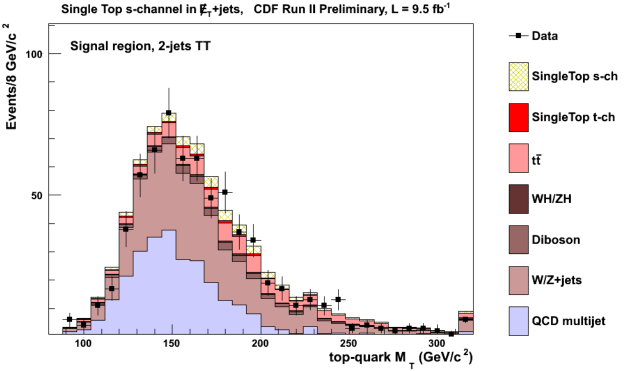
4. Use multivariate techniques:
   - **Reconstruct the top quark;**;

Top Quark Reconstruction

A NN is trained to choose which one of the jets in the final state is the one that comes from the top quark decay:

- This tool allow us to recostruct some kinematic variables such as the top quark transverse mass.



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4. Use multivariate techniques:
   - Reconstruct the top quark;
   - **Reduce the QCD Multijet background**;

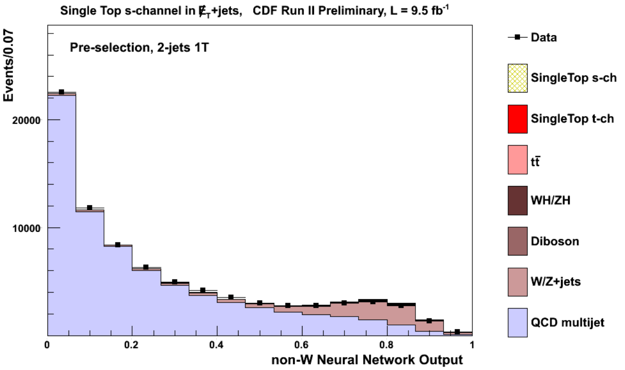
QCD veto

A NN is trained to distinguish between QCD Multijet events and other processes:

- Signal sample: W+jets Monte Carlo;
- Background sample: pretag data reweightened by the tag rate probability.

A cut on the output of this NN is choosen in order to reject as much QCD Multijet events as possible:

- After appying the QCD veto, we derive the QCD multijet normalization in the rejected region.



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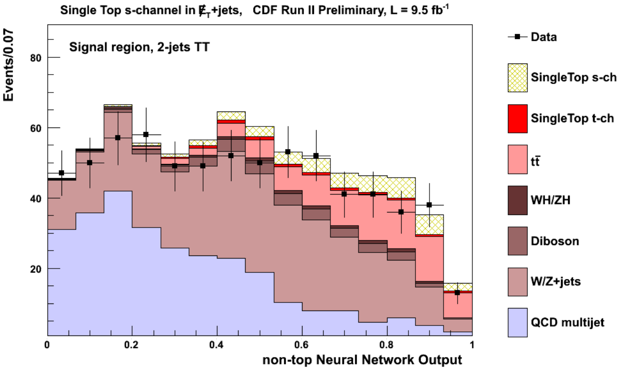
   - **Develop a final discriminant as a combination of a W/Z+jets and $t\bar{t}$ Neural Networks**;

W/Z+jets NN

The W/Z+jets NN is trained to distinguish between W/Z+jets-like events and signal events:

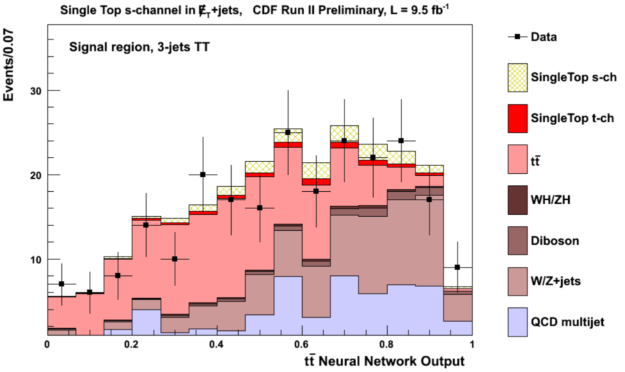
- Signal sample: single top *s*-channel Monte Carlo;
- Background sample: pretag data reweightened by the tag rate probability after the application of the QCD veto.



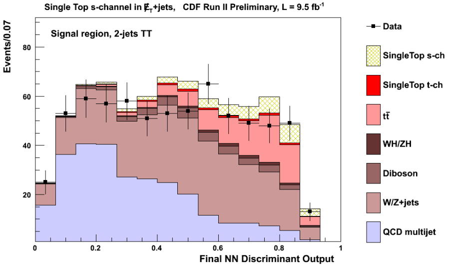
$t\bar{t}$ NN

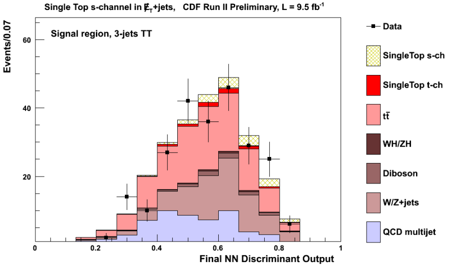
The $t\bar{t}$ NN is trained to distinguish between $t\bar{t}$ events and signal events:

- Signal sample: single top s-channel Monte Carlo;
- Background sample: $t\bar{t}$ Monte Carlo.



Final Discriminant





- Different background composition:
  - 2-jets sample: more W/Z+jets
  - 3-jets sample: more $t\bar{t}$
- We use an optimized combination of the W/Z+jets and $t\bar{t}$ NNs as final discriminant;
- We fit the data distribution of the final discriminant to extract the single top *s*-channel cross section.

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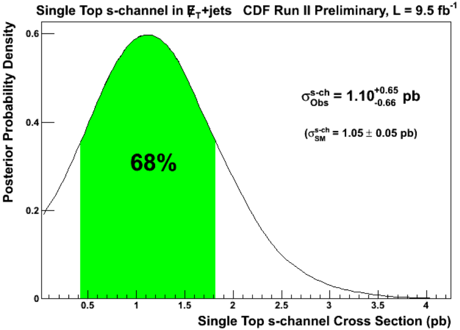
5. **Use the final discriminant to extract cross section**.

Cross Section Measurement

- Bayesian approach: binned likelihood;
- Uniform, non-negative prior for signal cross section;
- All the uncertainties and their correlations taken into account
- Expected result:
  $\sigma^{s-ch}_{exp} = 1.00^{+0.58}_{-0.60} \times SM$ (stat+syst).
- Measured single top s-channel cross section:
  $\sigma^{s-ch}_{obs} = 1.10^{+0.65}_{-0.66}$ (stat+syst) pb.

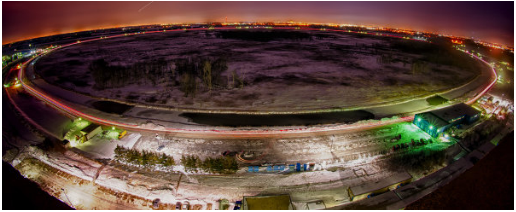


This result is consistent with the standard model cross section $\sigma^{s-ch}_{\mathrm{SM}} = 1.05 \pm 0.05$ pb.

Future Plan

- Both the CDF single top s-channel measurements are approved:
  - For the $l\nu b\bar{b}$ see previous talk
- The CDF combination framework is set up:
  - A very-preliminary result has already been shown at the collaboration;
  - It is still a work-in-progress.
- The discussion with DØ for the Tevatron combination is on-going:
  - There is the possibility to come up with a result by September.

Summary



- Measured the single top s-channel cross section in $\not\!\!E_T$+jets with the full CDF dataset, 9.5 fb^{-1};
- First time that a single top s-channel measurement is performed in the $\not\!\!E_T$+jets final state;
  - Public web page: http://www-cdf.fnal.gov/~matteoc/internal/schannelMETbb.html
- A legacy measurement from CDF/Tevatron;
- The CDF the $l\nu b\bar{b}$ s-channel measurement has just been approved, will combine the results soon;
- Combination with DØ measurement is planned.