Experimental Top Quark Physics
Part I

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Outline

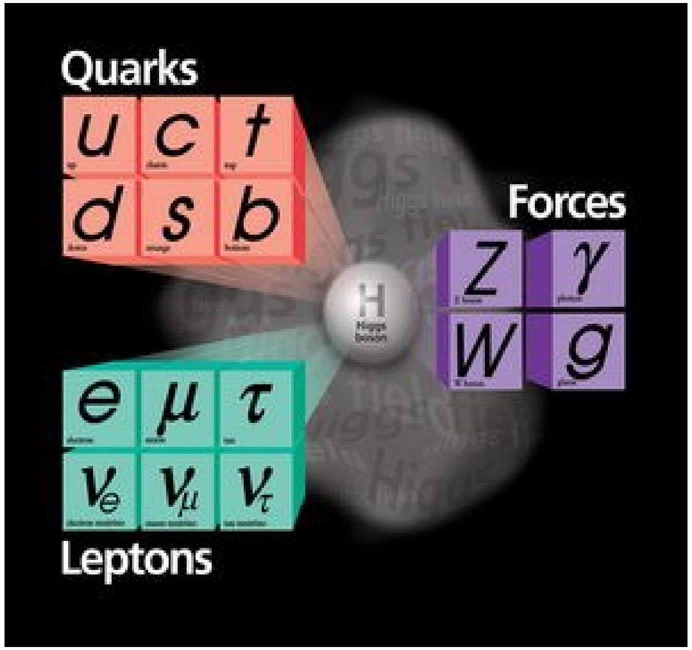
- Part I: top quark production
  - Tt production
  - Single top production
- Part II: Properties
  - Top quark mass
  - Spin correlations
- Part III: Asymmetry and searches
  - $t\bar{t}$ asymmetry
  - Direct searches in the top sector (Overview)

Part I: Production

- $t\bar{t}$ cross section
  - Methods
  - Background determination
- Differential cross sections
- Single top

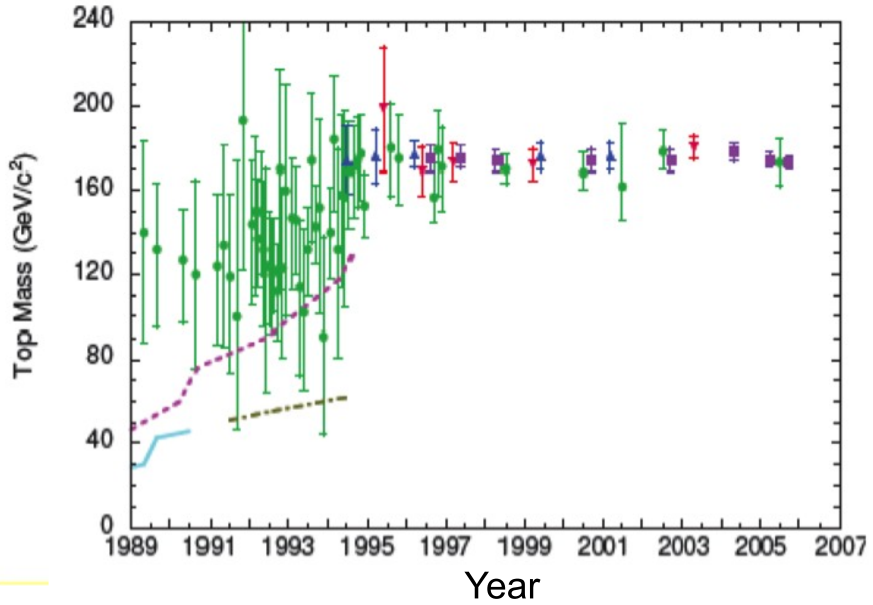
The Standard Model

- Described the fundamental particles and their interactions
  - 6 quarks and leptons + their antiparticles
  - 4 fundamental forces (Gravity not in SM)
- 1960: Electromagnetic and weak interaction unification by S. Glashow
- Weinberg and Salam 1967: incorporated Higgs mechanism into SM
- 1973: discovery of weak currents caused by Z → establishing of SM
- All this happened way before the discovery that a 3rd family existed!



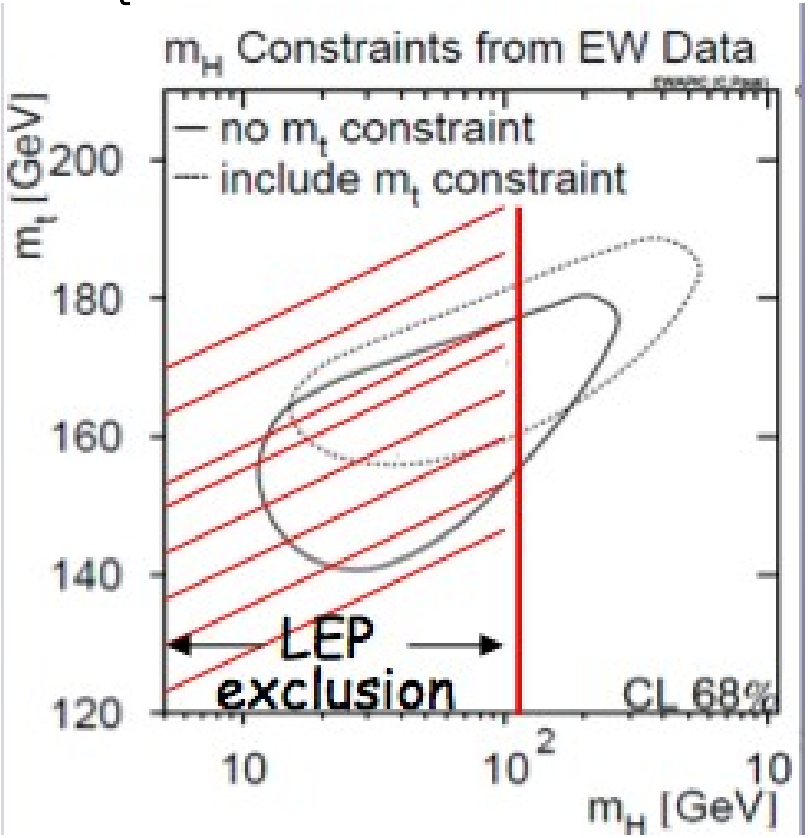
Brief History of the Top Quark

- 1976: Discovery of Upsilon at Fermilab
  - Contains a 5th quark: the b-quark
    → Structure of quark families suggested existence of a 6th quark: the top
- From here on the race to find the top began
  - Petra (e^+e^-): m_t>23.3GeV in 1984
  - Tristan (e^+e^-) in Japan: m_t>30.2GeV in late 80s
  - SPS ($p\bar{p}$): discovery of W and Z in 1983
  - UA1: m_t>44GeV in 1988
    (after having an excess in 1984
    which they thought was evidence for top)
  - LEP: m_t>45.8GeV in 1990
  - UA2: m_t>69GeV
    W → $t\bar{b}$ search channel closed down



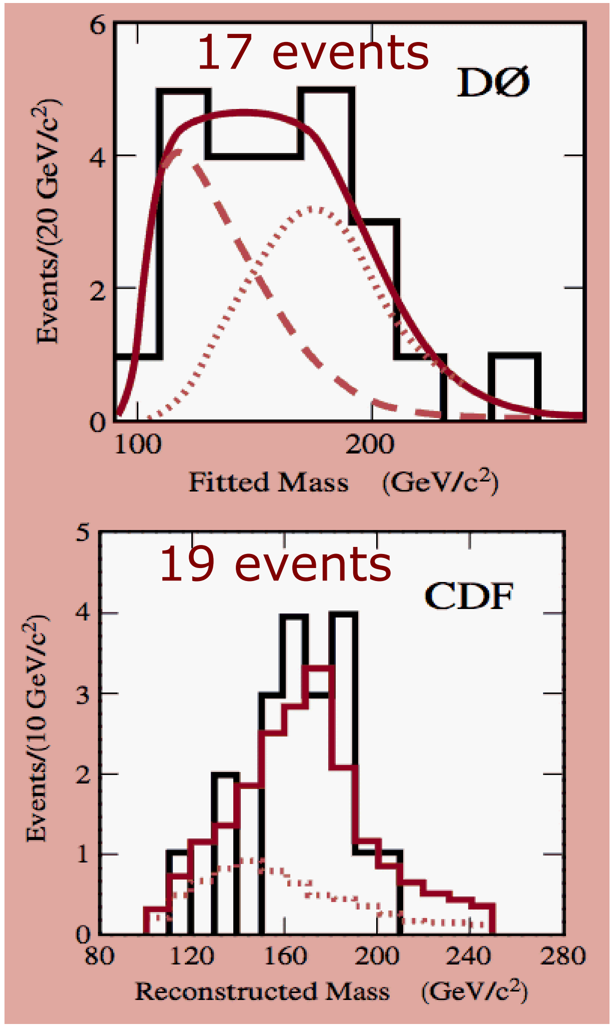
Brief History of the Top Quark

- Searching again for $t\bar{t}$ production with top mass above W mass
- 1992: First lower limits on top from CDF (m_t>91GeV)
- 1994: First lower limits on top from DØ (m_t>131GeV)
- Electroweak fits from LEP/SLC/Tevatron data:
  155GeV<m_t<185GeV
- Early 1994: "Evidence" for top at CDF



Discovery Datasets

- February 24th 1995: Simultaneous submission of Top Discovery papers to PRL, by CDF and DØ
- 50 pb^{-1} at DØ
  - m_t = 199±30 GeV
  - $_{t\bar{t}}$ = 6.4±2.2 pb
  - Background-only hypothesis rejected at 4.6
- 67 pb^{-1} at CDF
  - m_t = 176±13 GeV
  - $_{t\bar{t}} = 6.8^{+3.6}_{-2.4}$ pb
  - Background-only hypothesis rejected at 4.8

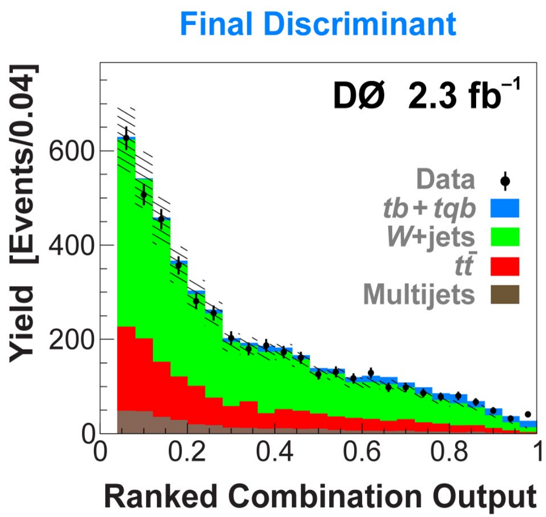


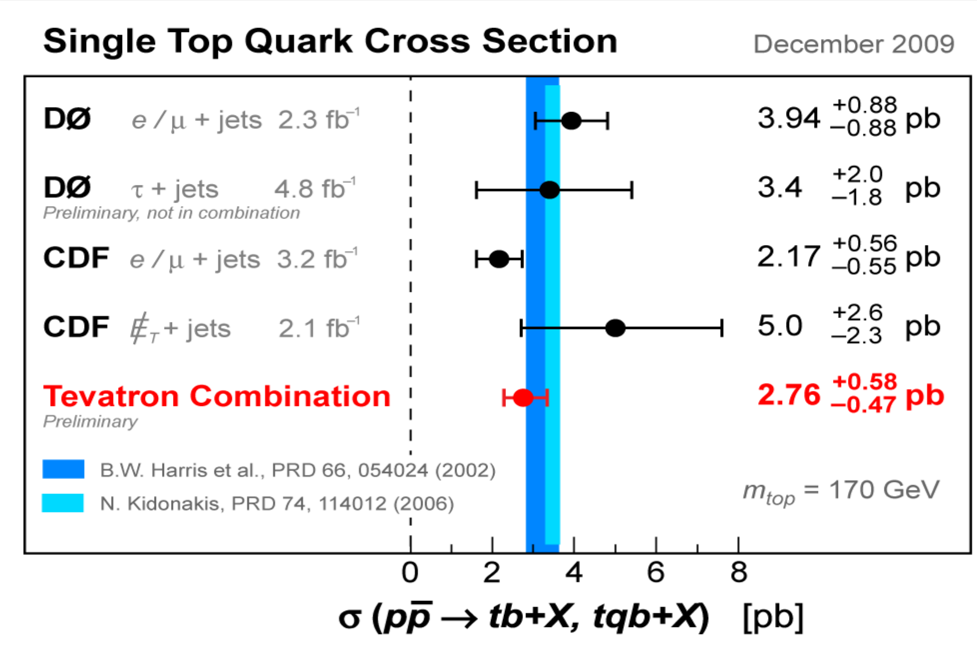
TOP Announcement

- March 2nd, 1995: First announcement of Top Discovery in public seminar at Fermilab

Discovery of lonely Tops

- 2009: Observation of top quarks in single top production
  - 5 by CDF & DØ!
- Single top: very challenging channel
  - Low signal: similar signature like W+jets!
  - Counting only: Uncertainty on background larger than expected signal → use of multivariate techniques



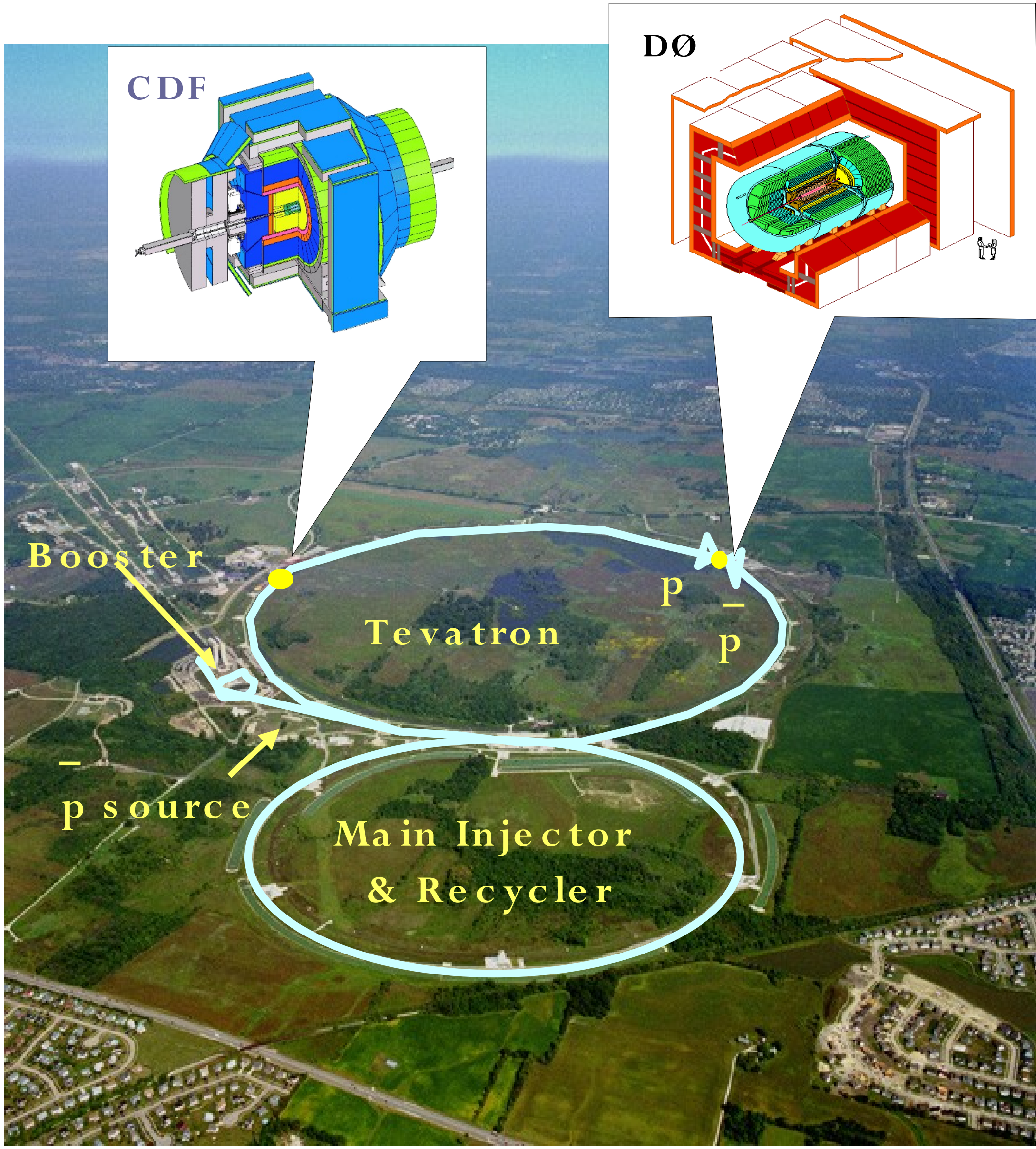


Celebrating Single Top Discovery

- March 10th, 2009: Wine&Cheese seminar at Fermilab to announce single top observation

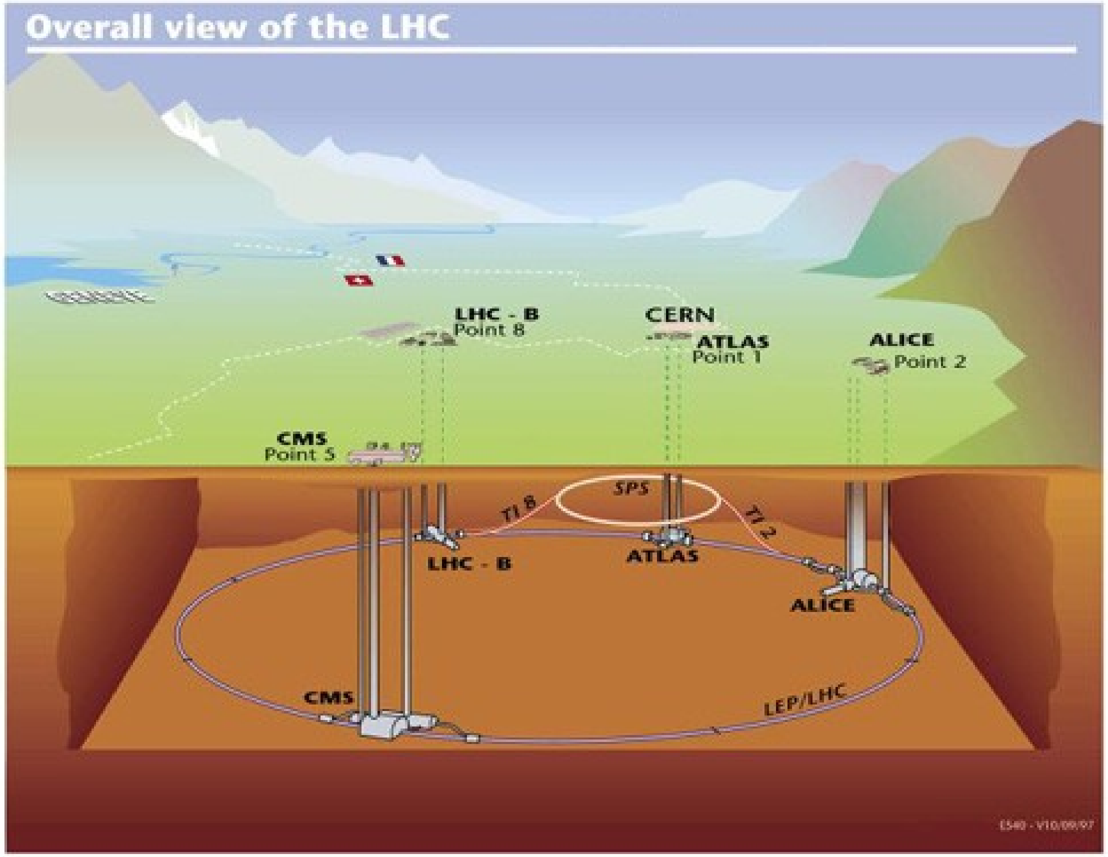
Where Top Quarks can be produced: The Tevatron

- Tevatron: proton antiproton collisions
  - Run I: 1992-1996 with $\sqrt{s}$=1.8 TeV
  - Run II: March 2001 to 30.09.2011, 14:00 with $\sqrt{s}$=1.96 TeV



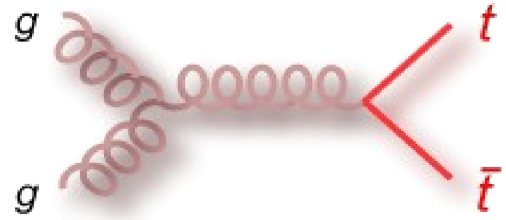
Where Top Quarks can be produced: The LHC

- LHC: 7 (2011) or 8 (2012) TeV proton-proton collisions
  - Started operation in 2010
- Highest energies reached today
- Top Quark Factory

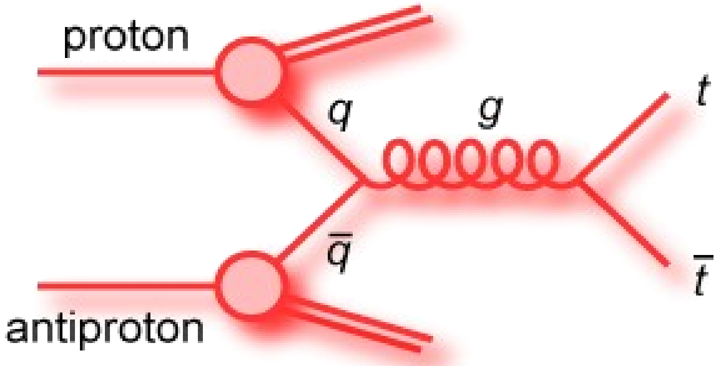


Top Quark Pair Production

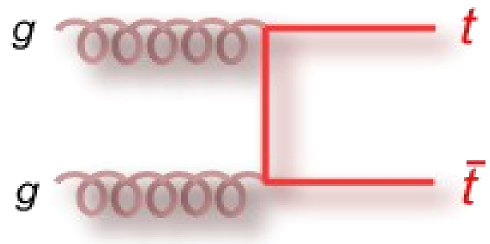
- Via strong interaction
- At the Tevatron:



85%

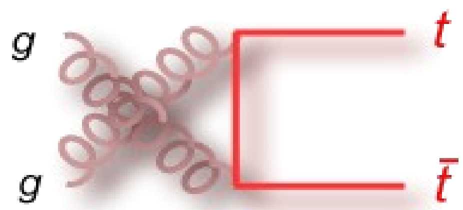


+ 15%



At LHC (7 TeV cms energy):

15% + 85%



- Production cross section (@Tevatron):

NNLO+NNLL: $\sigma = 7.24^{+0.23}_{-0.27}\,pb$ @ m_t=172.5GeV

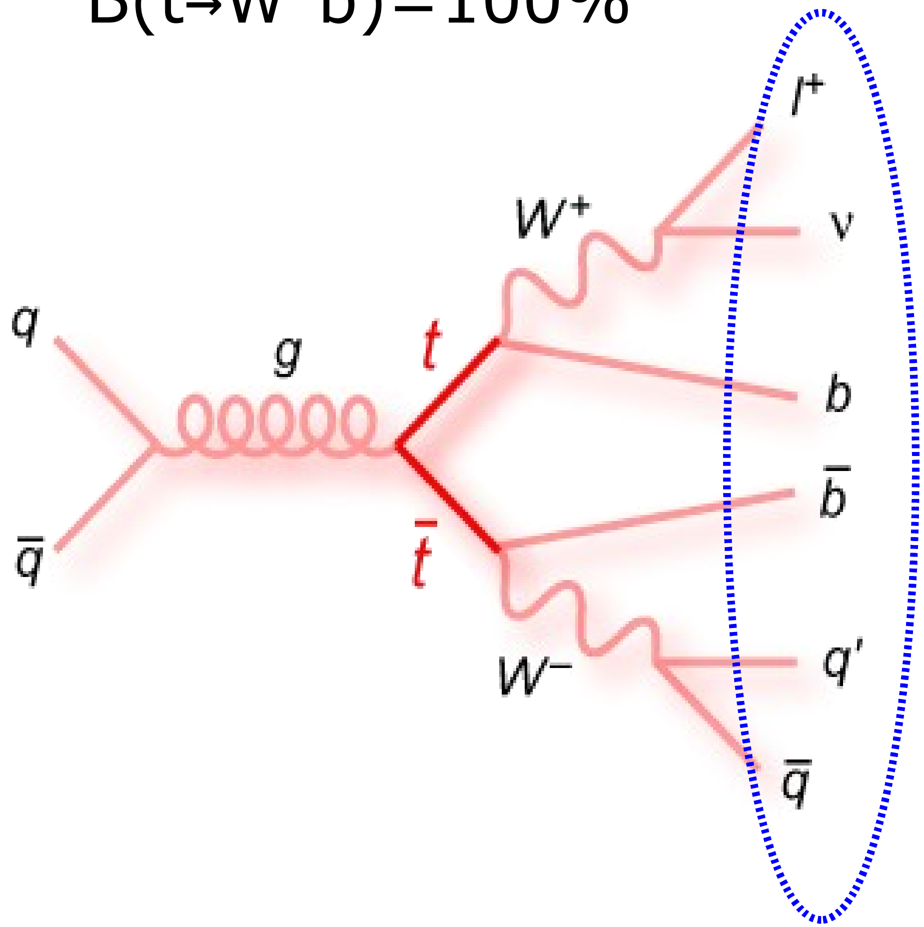
- About 20 times higher at LHC

Baernreuther, Cakon, Mitov, PLB 710, 612 (2012)

Final States in $t\bar{t}$

$t\bar{t} \rightarrow W^+bW^-\bar{b}$: Final states are classified according to W decay

$B(t \rightarrow W^+b) = 100\%$



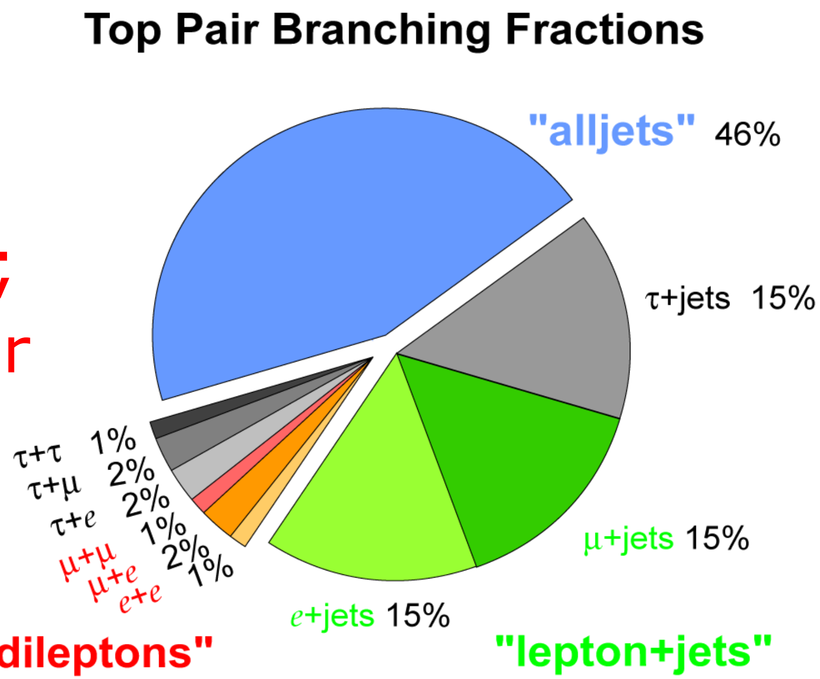
Final States in $t\bar{t}$

$t\bar{t} \rightarrow W^{+}bW^{-}\bar{b}$: Final states are classified according to W decay

$B(t \rightarrow W^{+}b) = 100\%$

pure hadronic:
≥6 jets (2 b-jets)

dilepton:
2 isolated leptons;
High missing E_T for neutrinos;
2 b-jets



lepton+jets:
1 isolated lepton;
Missing E_T for neutrino;
≥4 jets (2 b-jets)

Cross Section: General

- The first thing we want to know: Production cross section

$$N_{production} = \sigma * L$$

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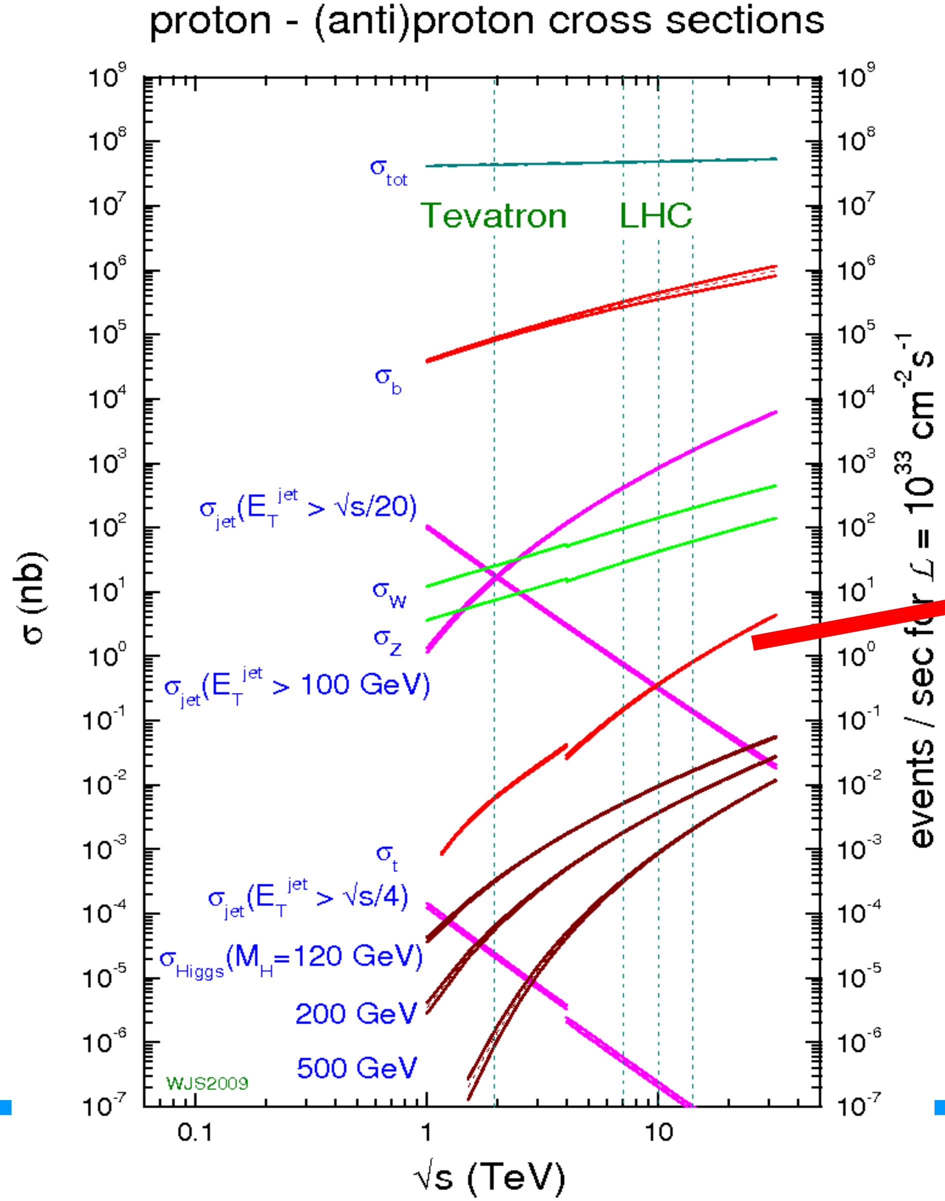
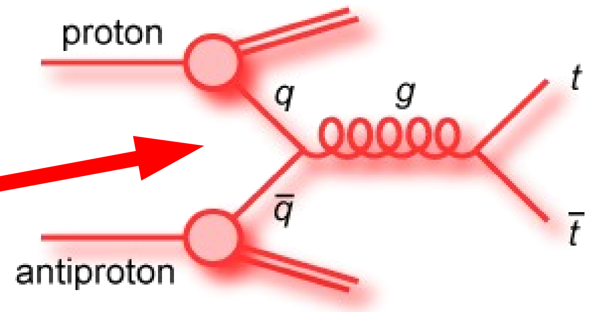




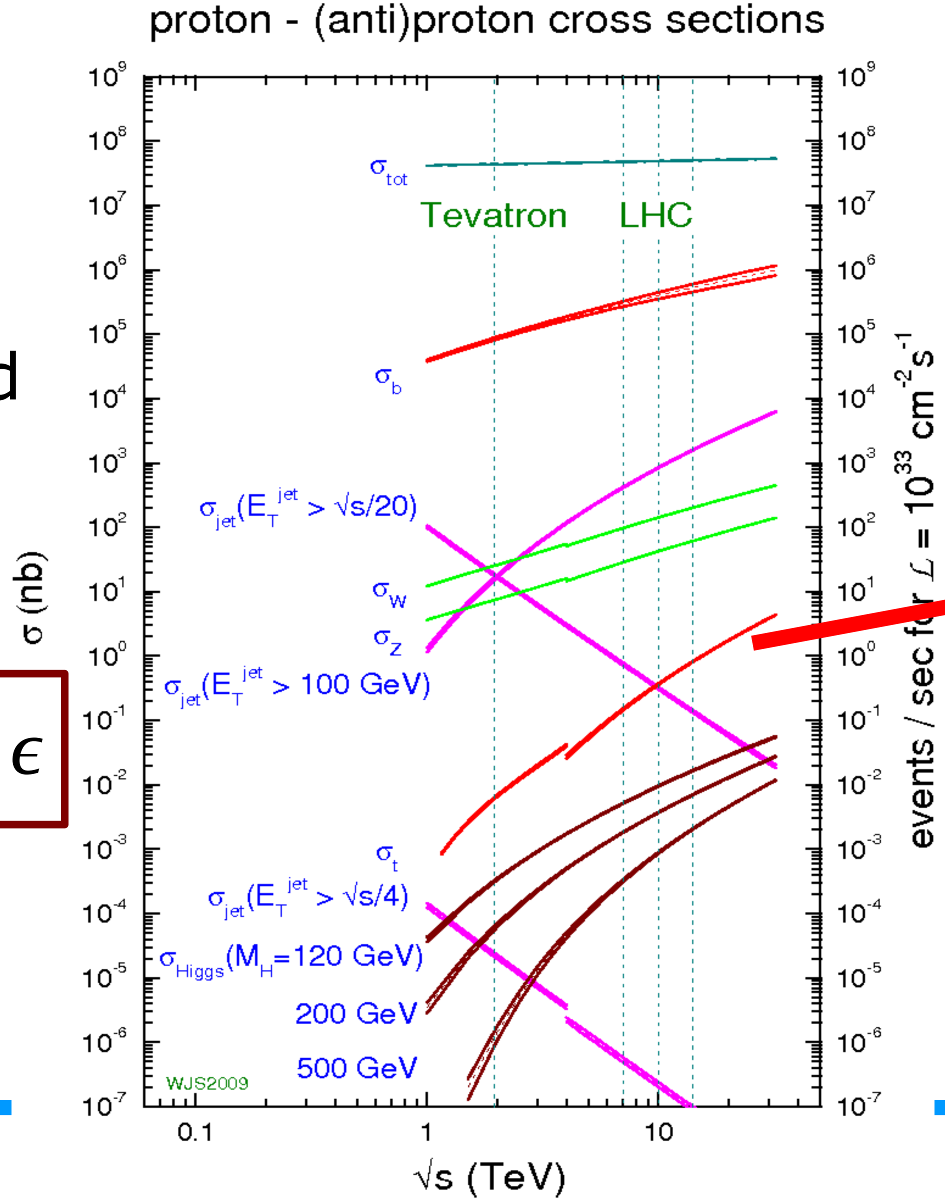
Cross Section: General

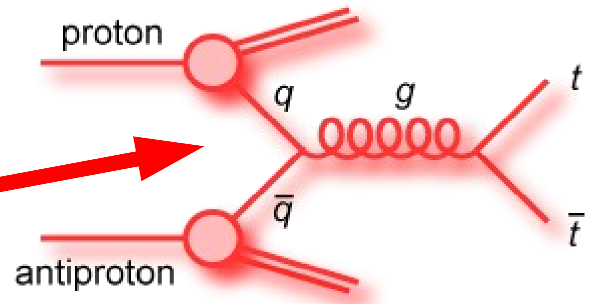
- The first thing we want to know: Production cross section

$$N_{production} = \sigma * L$$

- Selection required
- Background modeling crucial

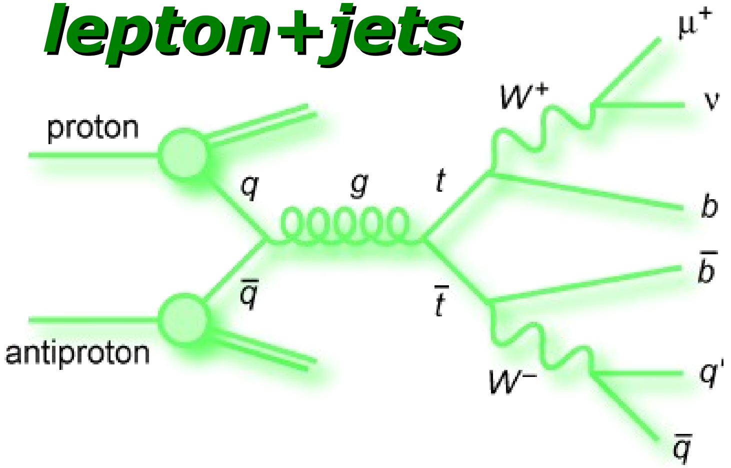
$$N_{post-selection} = \sigma * L * \epsilon$$



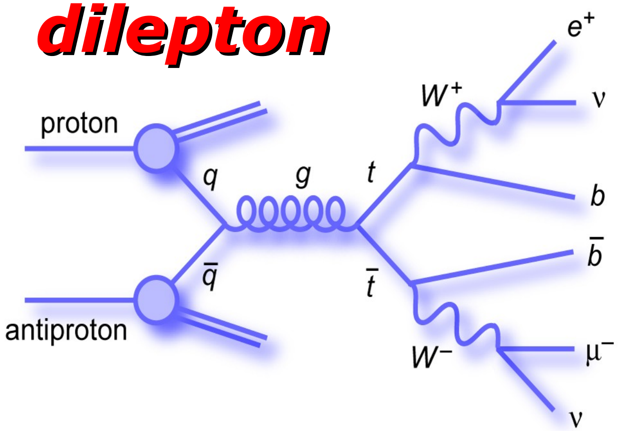


Signal events

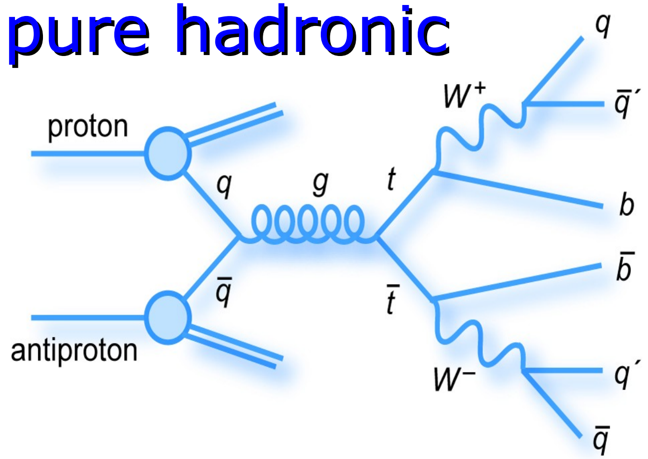
lepton+jets



dilepton

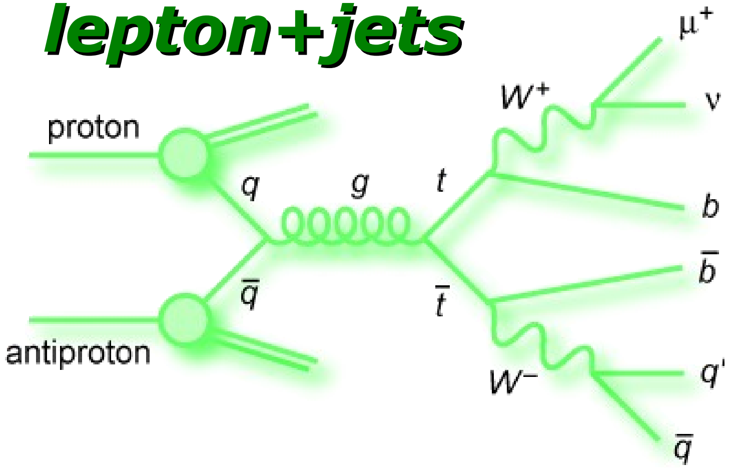


pure hadronic

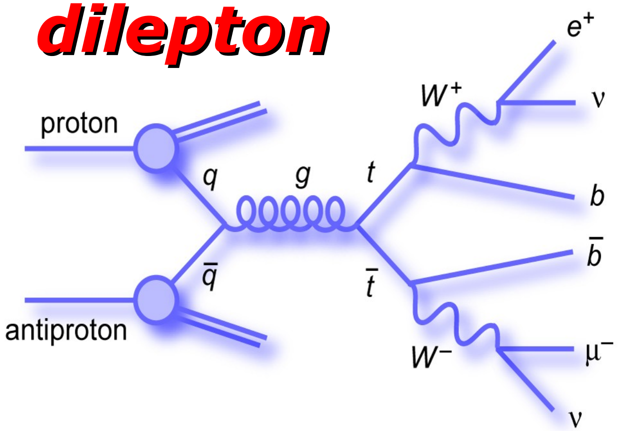


Signal and background events

lepton+jets



dilepton



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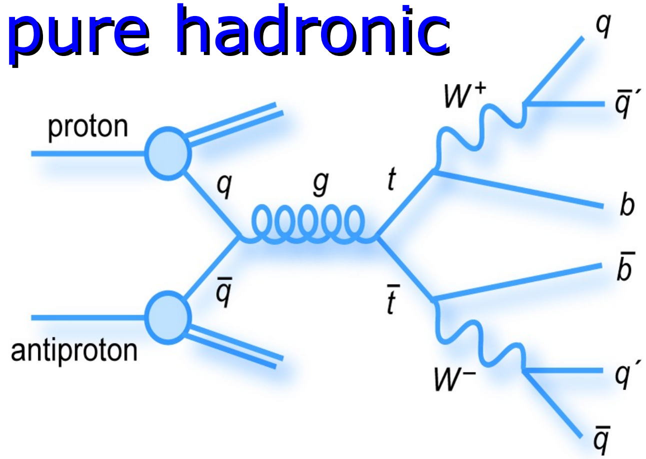
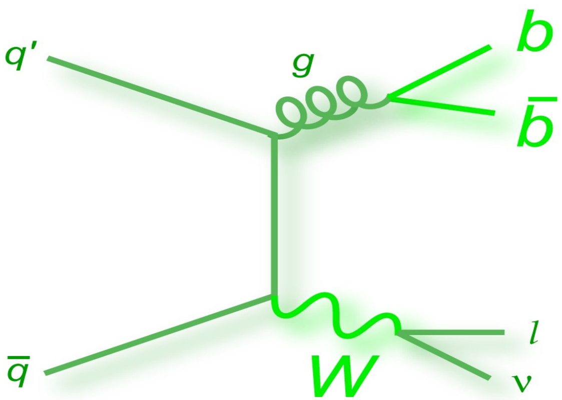
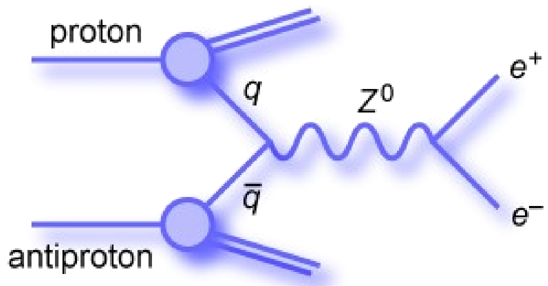


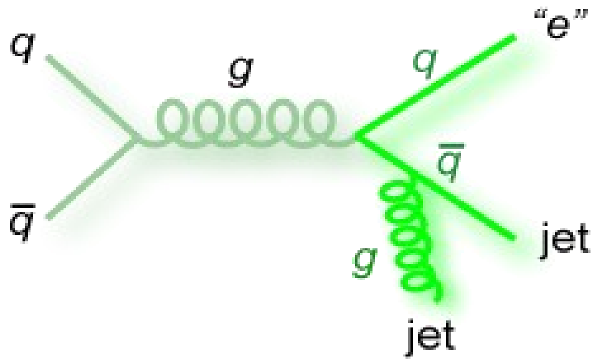
W+jets:
Main background
in l+jets

Z+jets:
Main background
in dilepton

Multijet:
Modeled from Data
Main background in
allhadronic

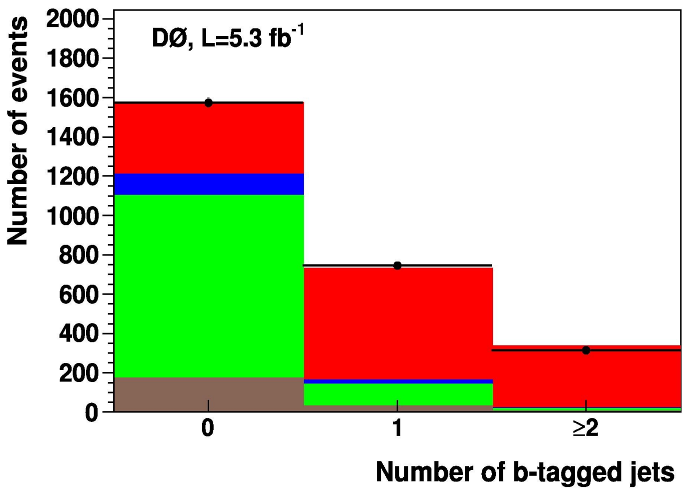


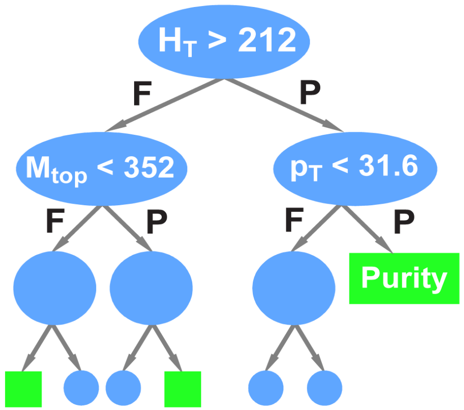




Cross Section: Selection

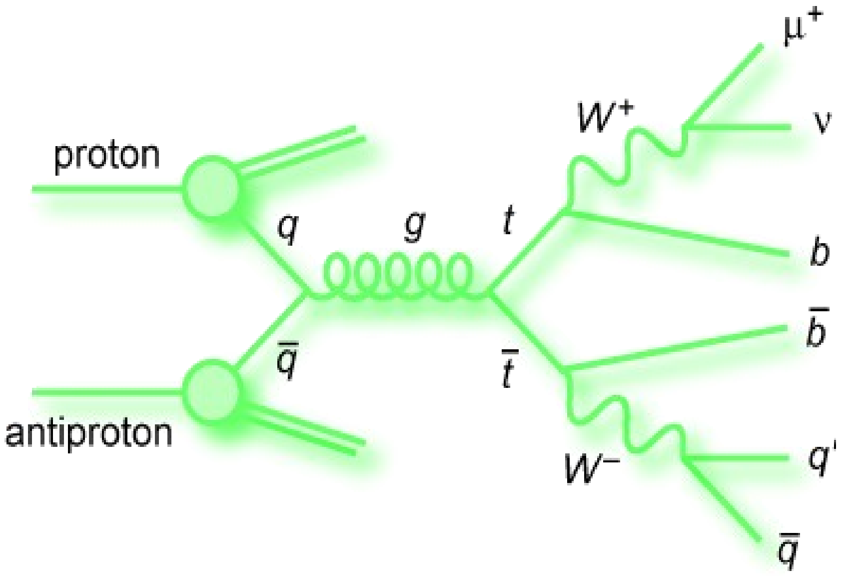
- Knowing signal and background event signatures, we now need to enrich the data sample in signal events
- Important tools:
  - B-tagging
  - Multivariate analysis techniques





Selection: Example l+jets

- Select according to topology and kinematics of the final state



One isolated lepton with high p_T

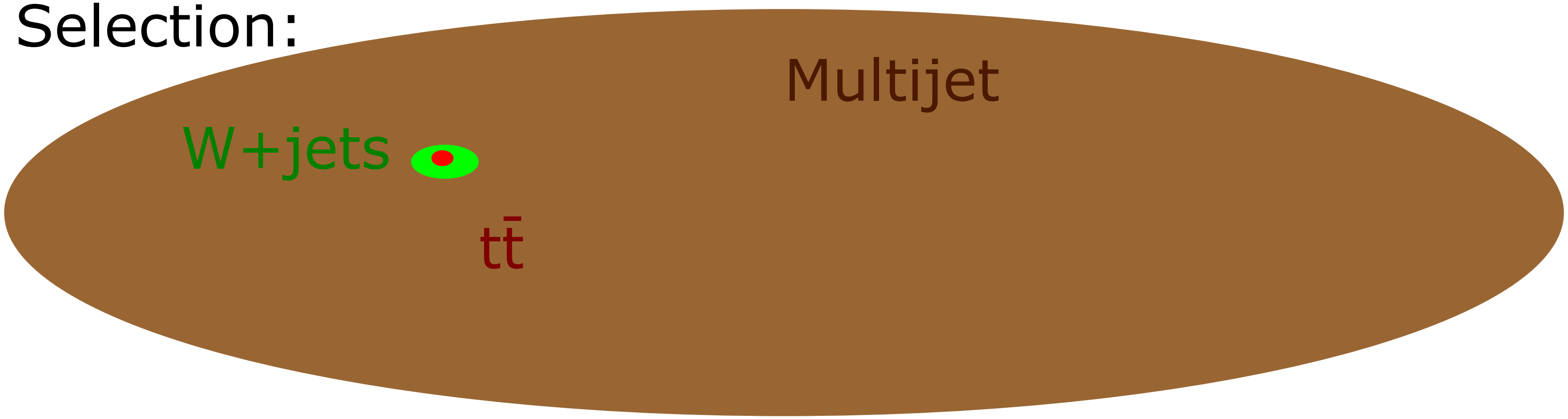
Large missing transverse energy to account of the neutrino

At least 4 jets with high p_T and central; sometimes certain number of tracks pointing to primary vertex required

Additional requirements on angles; e. g. angle between lepton and MET should not be back-to-back to reduce mismeasurements

Background Determinations: Multijet

Before Selection:



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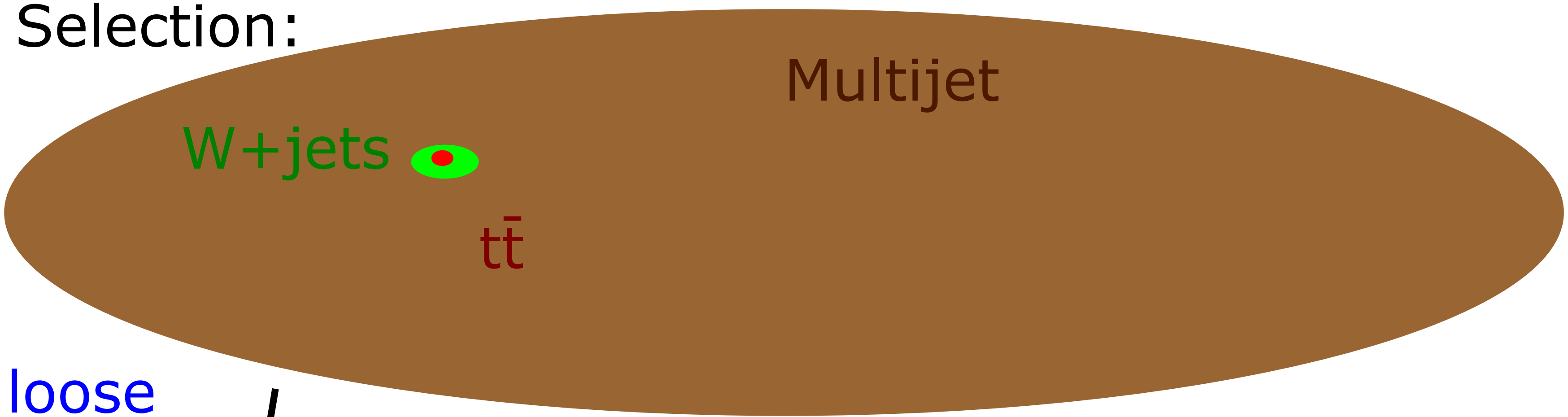
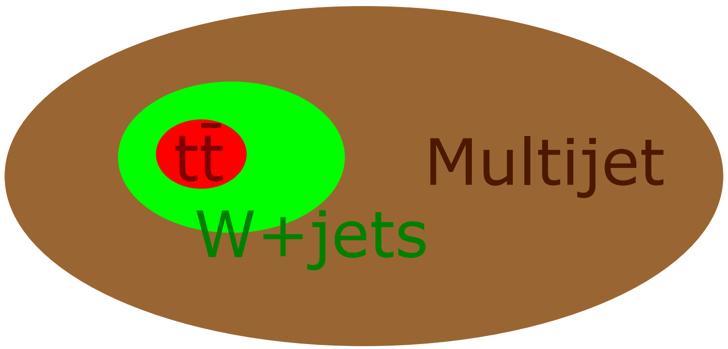


Require loose isolated lepton

$N_{loose} = N_{fake} + N_{W-like}$



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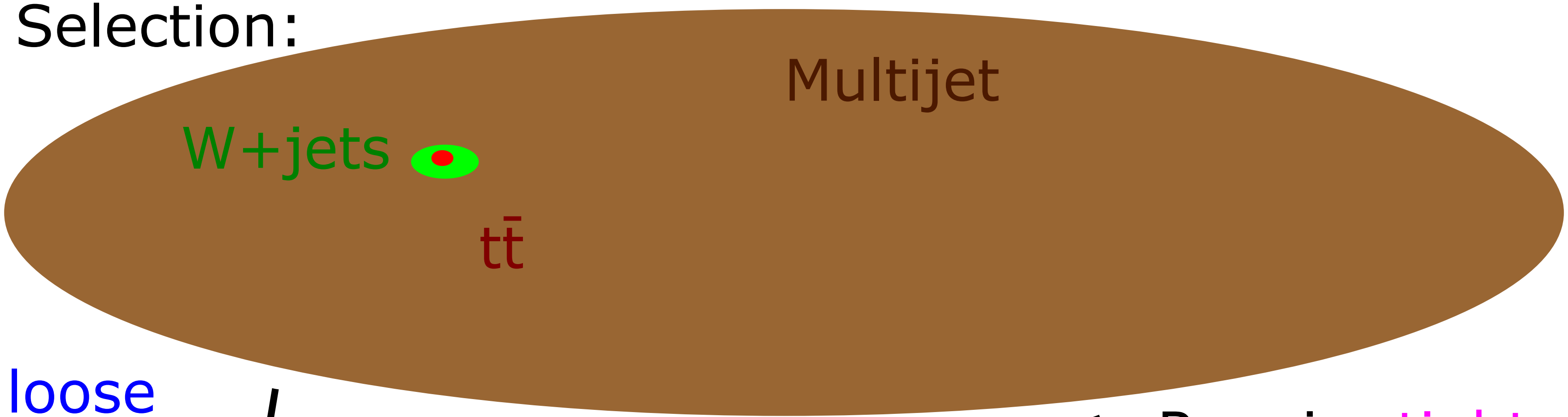
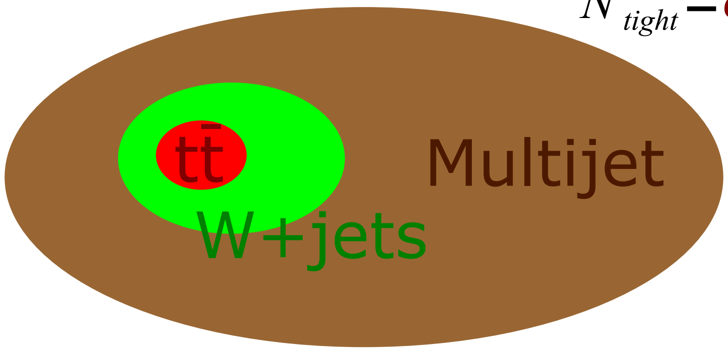


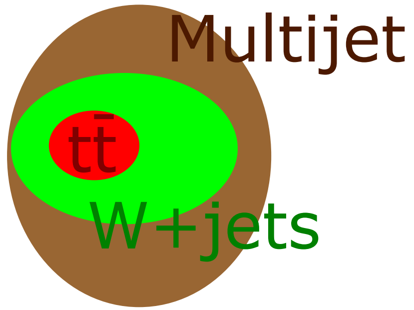
Require loose isolated lepton

Require tight isolated lepton

$$N_{loose} = N_{fake} + N_{W-like}$$

$$N_{tight} = \epsilon_{fake} * N_{fake} + \epsilon_{true} * N_{W-like}$$





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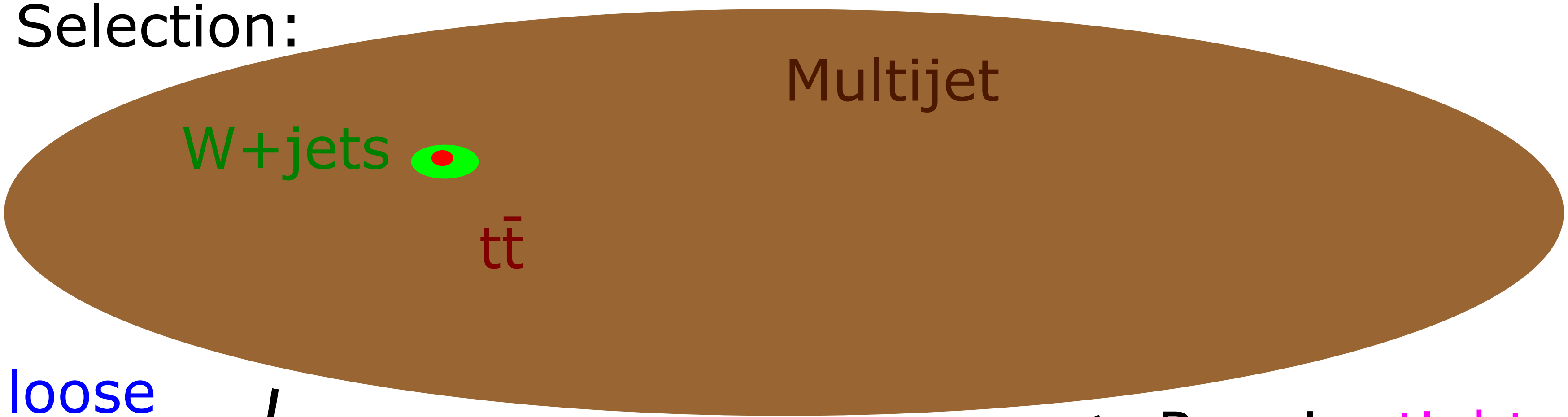

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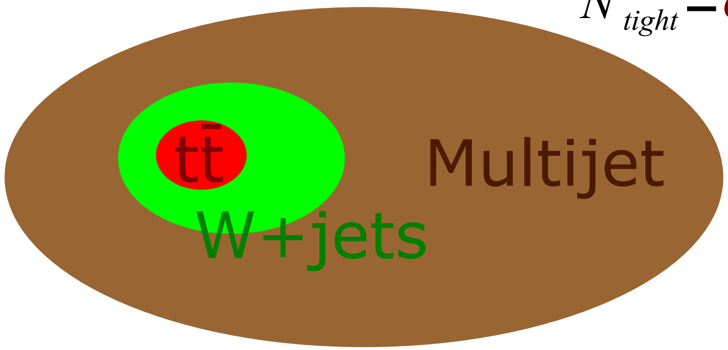
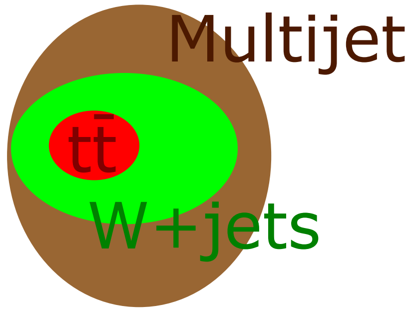




N_{fake} from MM equation

Multijet Background Determination: The Matrix Method

- Matrix Method requires fake rate and true lepton rate

$$N_{loose} = N_{fake} + N_{W-like}$$

$$N_{tight} = \epsilon_{fake} * N_{fake} + \epsilon_{true} * N_{W-like}$$

- ϵ_{fake} : determined from multijet-dominated dataset
  - For example for low missing transverse energy → multijet dominated
- ϵ_{true} : can be either
  - determined from W+jets/$t\bar{t}$ MC sample (DØ), or
  - From tag and probe in Z+jets sample (ATLAS)

Background Determinations: W+jets

- Main background in l+jets final state: W+jets contribution
- Challenge:
  - Theory predictions not accurate enough for background determination (esp. for events with many jets)
  - W+heavy flavor relative to W+light flavor contribution not known precisely enough
- Various methods for determination of total W+jets contribution
  - Fit to Data before b-jet identification
  - W+jets determination example at Atlas: charge asymmetry method
- Heavy Flavor Fraction determination usually by comparing yields in different b-tag bins

W+jets background Determination: Asymmetry Method

- W-boson production at pp collider: charge asymmetric
  - $u\bar{d} \rightarrow W^{+}$ versus $d\bar{u} \rightarrow W^{-}$ (uud valence quarks, $\bar{d}$,$\bar{u}$ sea quarks)
- Well understood quantity:

$$r = \frac{\sigma(pp \rightarrow W^{+})}{\sigma(pp \rightarrow W^{-})}$$

W+jets background Determination: Asymmetry Method

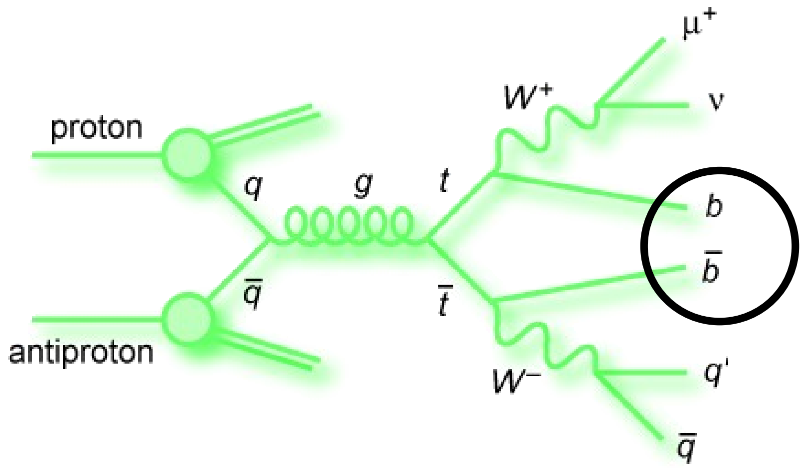
- W-boson production at pp collider: charge asymmetric
  - $u\bar{d} \to W^+$ versus $d\bar{u} \to W^-$ (uud valence quarks, $\bar{d}$,$\bar{u}$ sea quarks)
- Well understood quantity: $$r = \frac{\sigma(pp \to W^+)}{\sigma(pp \to W^-)}$$
- Calculate W+jets using r:

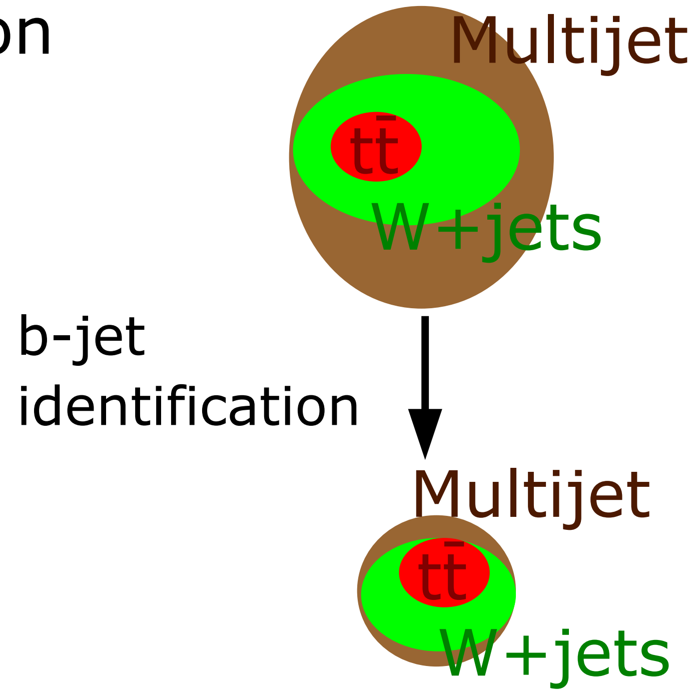
$$N_{W^+} + N_{W^-} = \frac{N_{W^+}^{MC} + N_{W^-}^{MC}}{N_{W^+}^{MC} - N_{W^-}^{MC}} (D^+ - D^-) = \frac{r_{MC} + 1}{r_{MC} - 1} (D^+ - D^-)$$

  - D^+ and D^-: data with positive (negative) charged leptons
    - Using approximation that all other backgrounds are charge symmetric
  - r_{MC}: evaluated using MC, using signal region kinematic cuts

B-Tagging

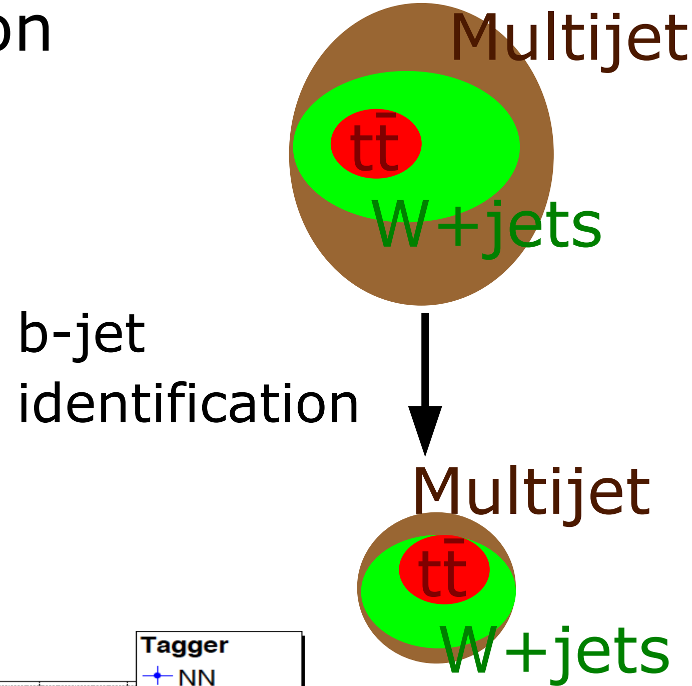
- Further enrichment of $t\bar{t}$: b-jet identification

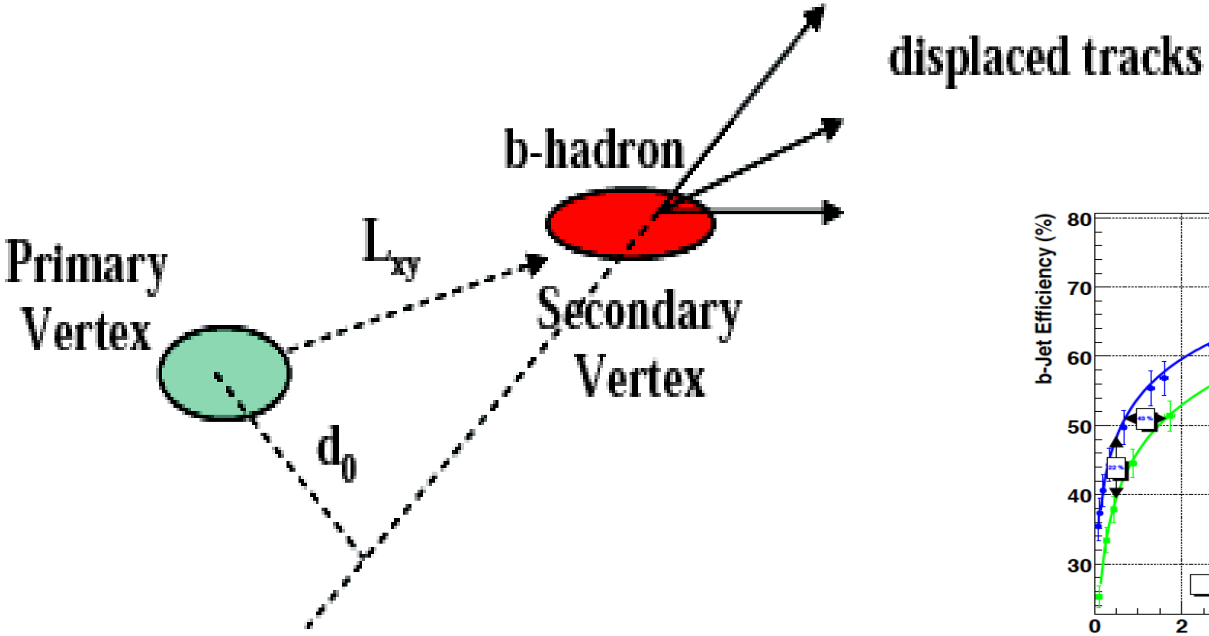


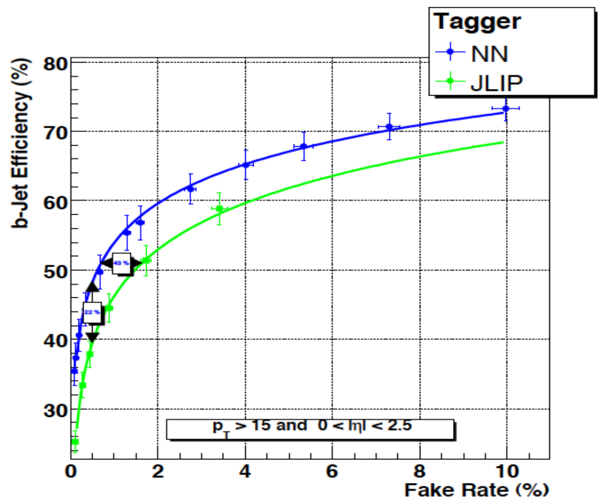


B-Tagging

- Further enrichment of $t\bar{t}$: b-jet identification
- B-Hadron: travels some millimeters before it decays
- Use properties of displaced vertices and/or displaced vertices to



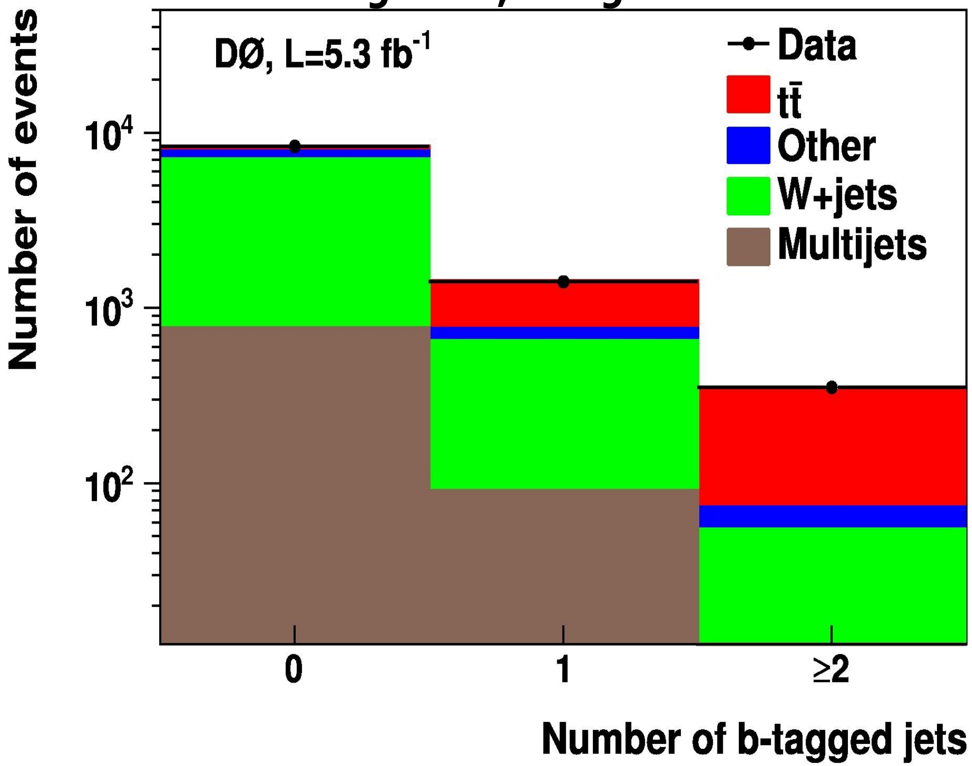




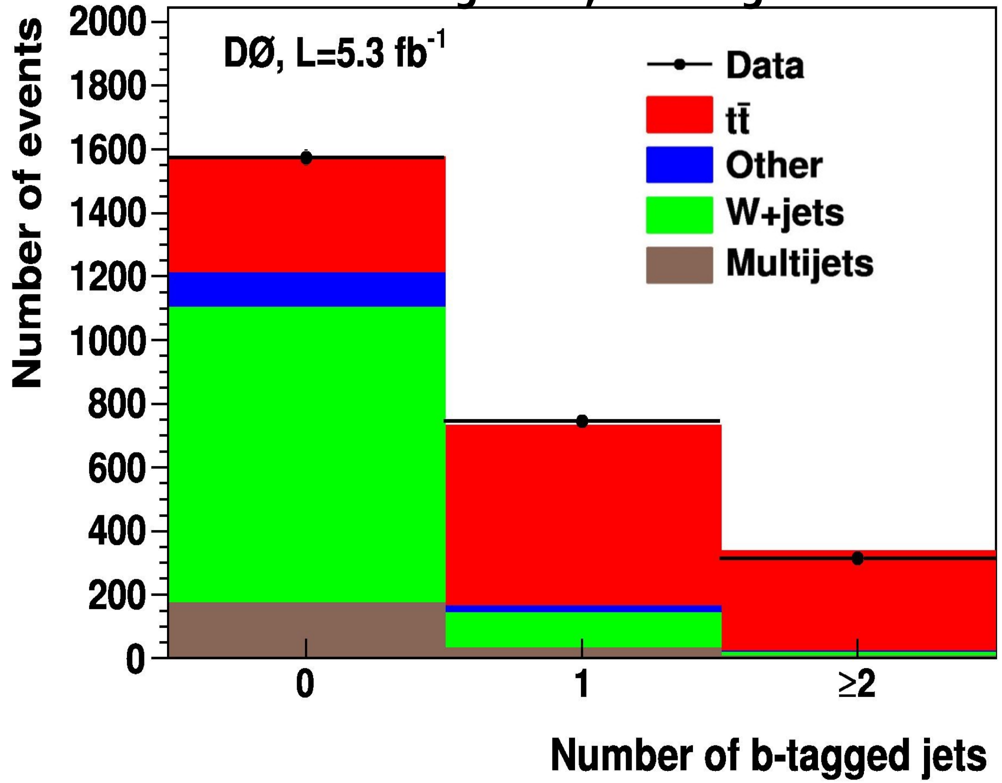
B-Tag Cross Section Example

- Example from DØ: b-tagging
  - Counting only
  - Main systematic uncertainty usually from b-tagging uncertainties

l+jets; 3 jets

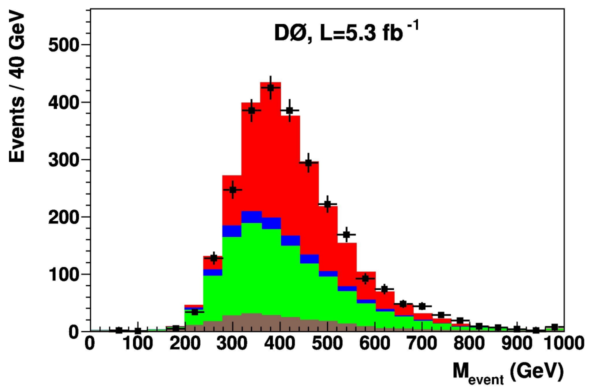


l+jets; ≥4 jets



Cross Section: Other Methods

- Base signal-background separation on kinematic properties
  - Use many variables with small discrimination



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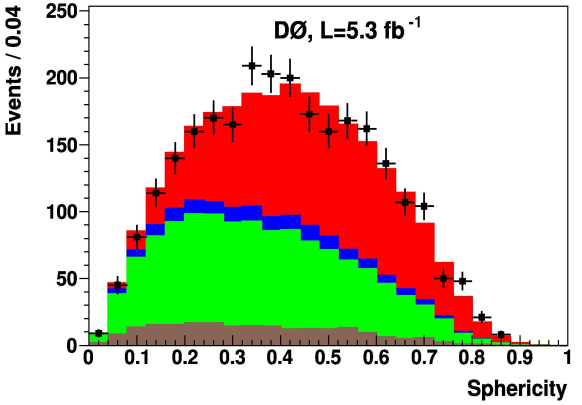
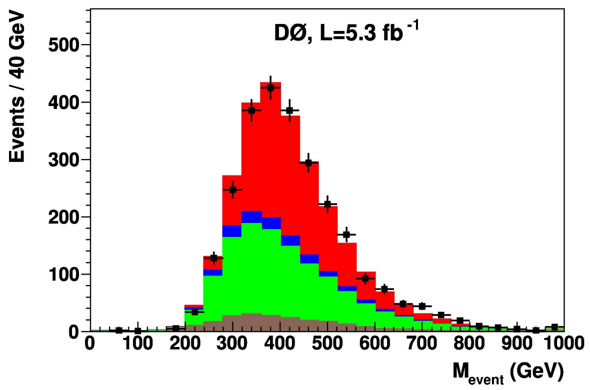
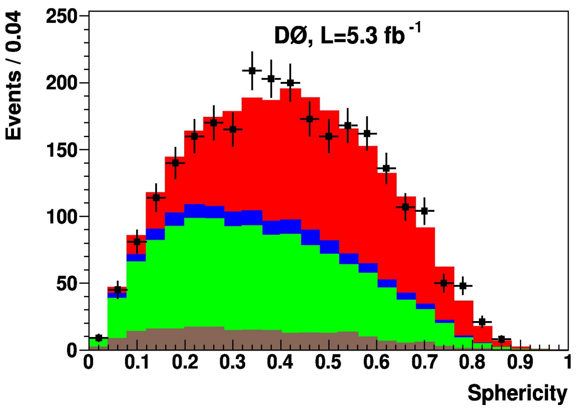
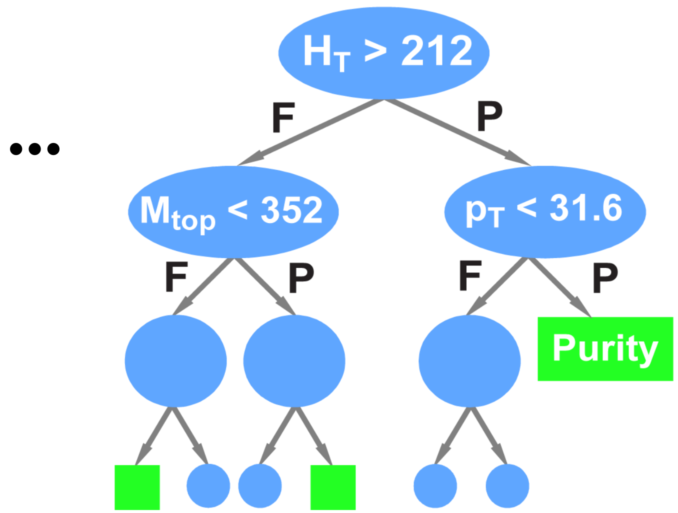


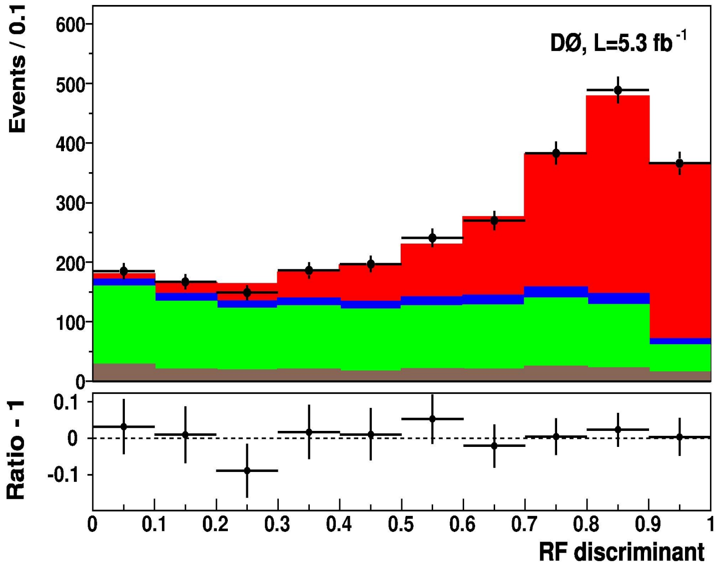
Cross Section: Other Methods

- Base signal-background separation on kinematic properties
  - Use many variables with small discrimination
  - Combine using multivariate analysis technique



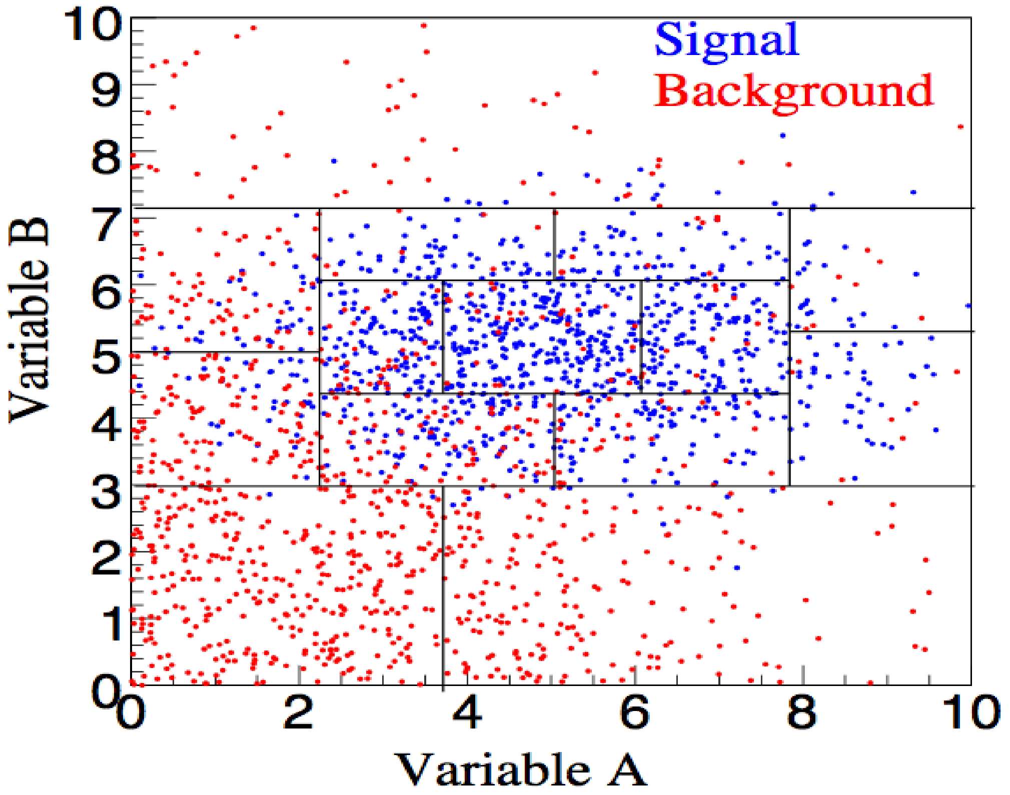






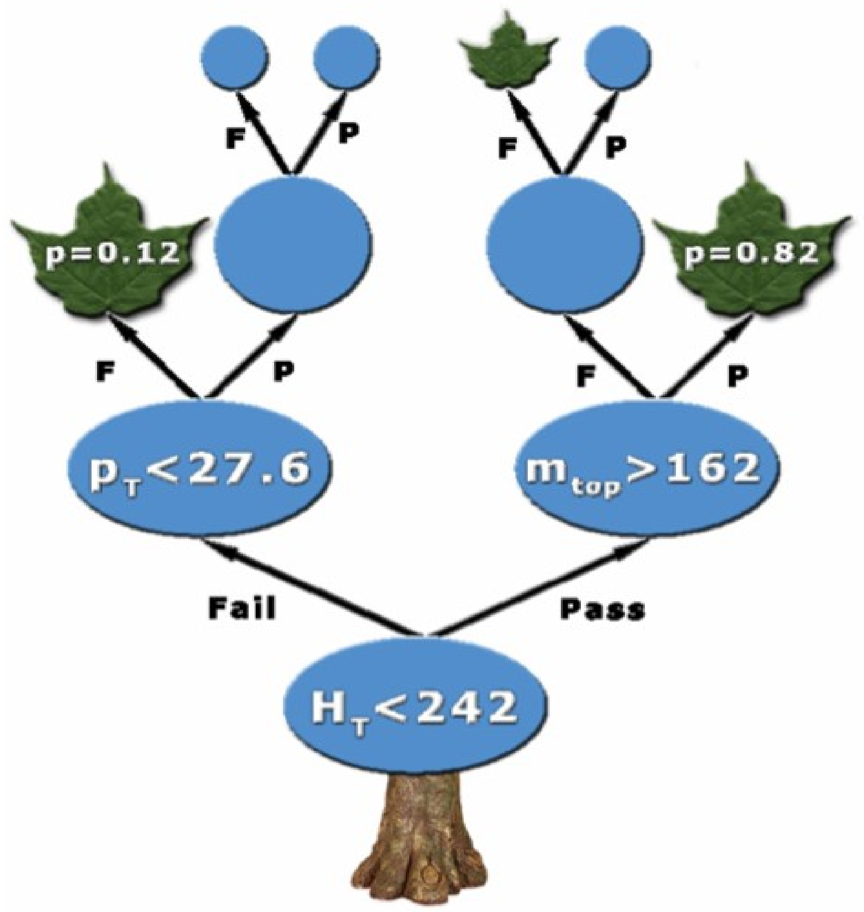
Multivariate Analysis Techniques

- Variety of various techniques on the market
  - Boosted decision trees, random forests, neural networks, etc.
- Example: decision tree
  - Idea: divide multi-dimensional event-space into cells
  - For each cell, estimate the purity
  - Chose cuts to separate high and low purity regions



Decision Trees Example

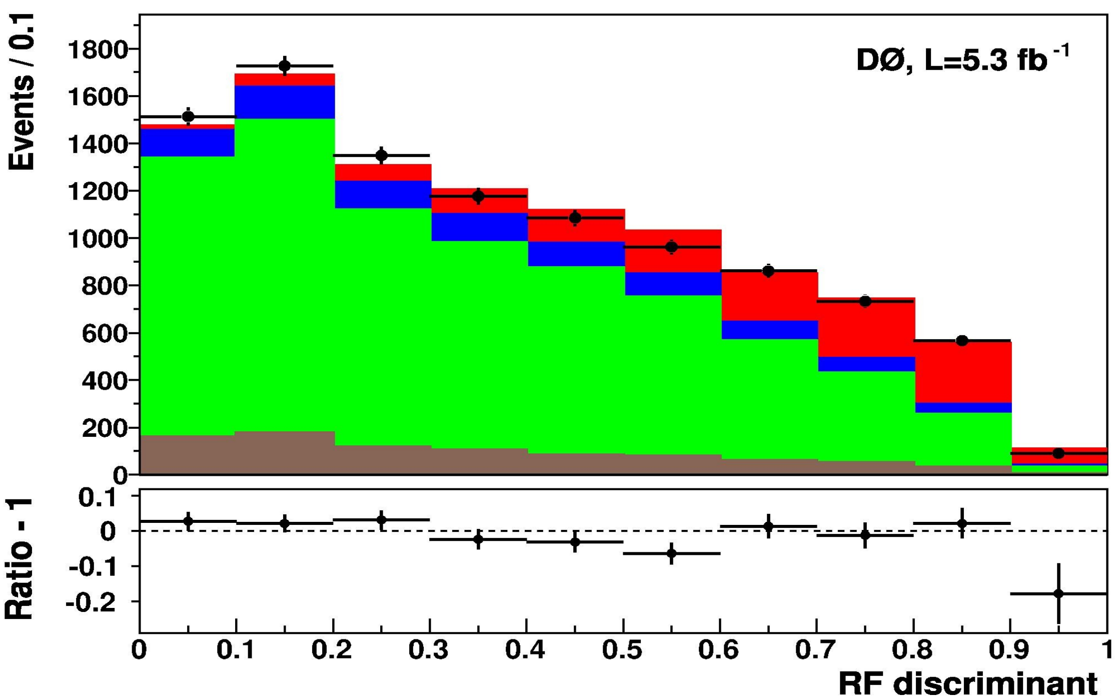
- Start with one node containing the full sample
  - Find the cut that maximizes a splitting criteria (e. g. purity separation)
  - Repeat this step on each new node
  - The final "leaves" are reached one a stopping criteria is reached
  - Purity of leaves used as discriminator
- These trees can be "boosted": misclassified events get increased weight for retraining of next tree

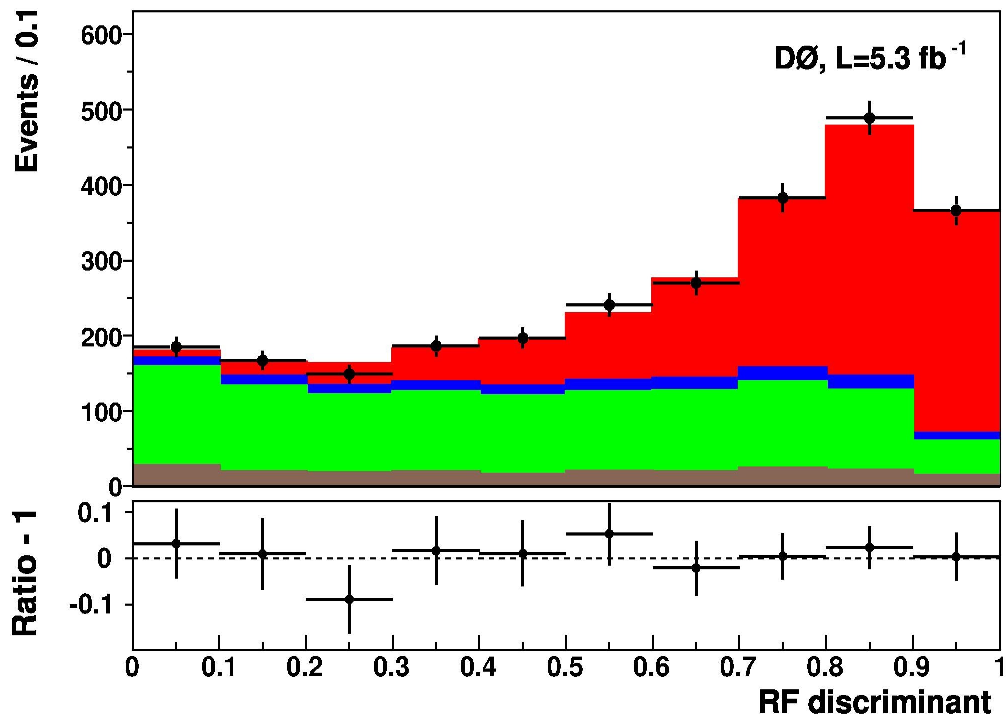


MVA Cross Section Example

- Example from DØ: cross section extraction using topological info
- Various combinations also possible
  - e. g. use MVA for some b-tag bins, counting in others...

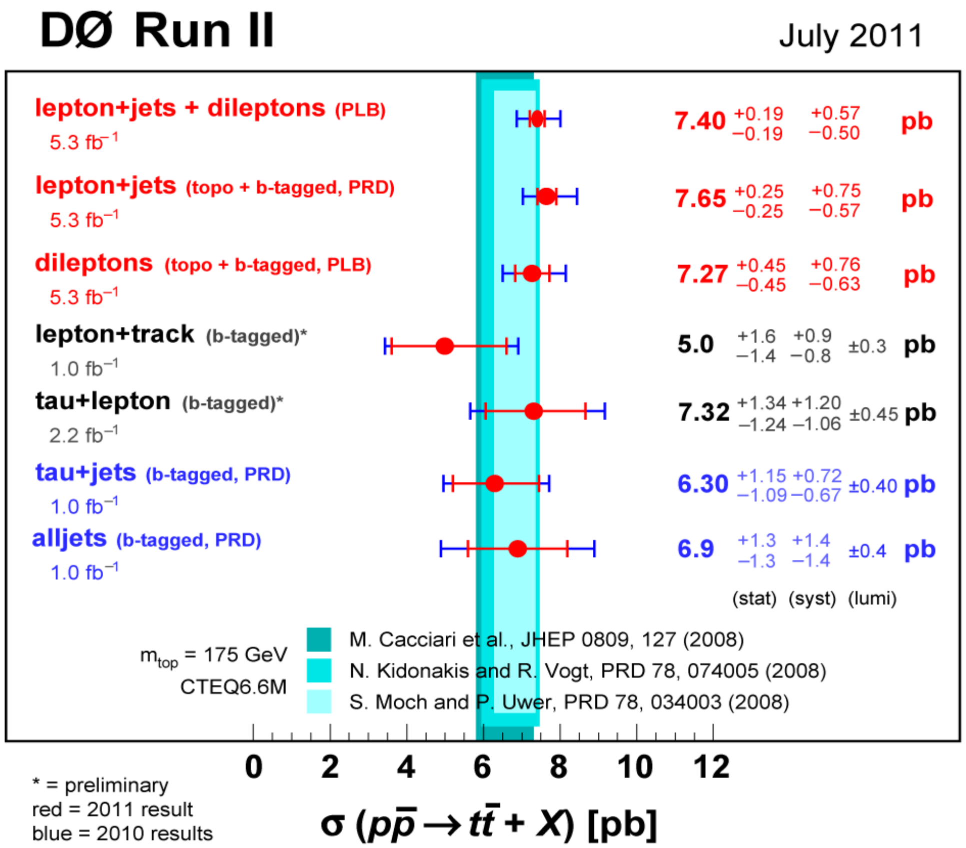
l+jets; ≥4 jets

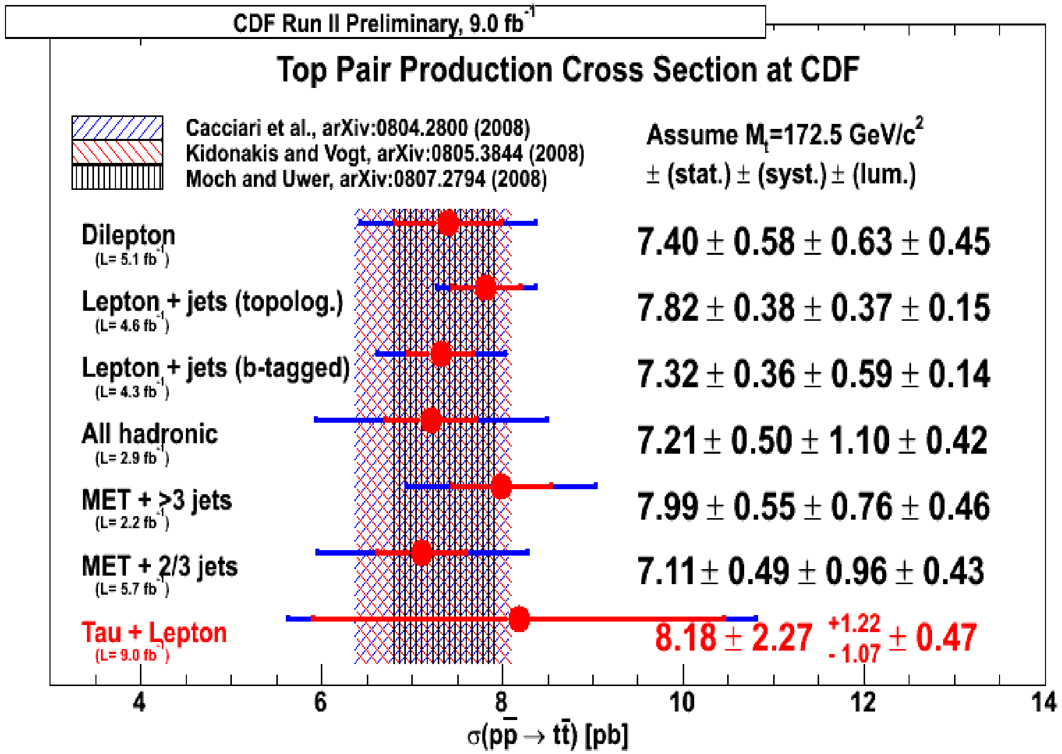




$t\bar{t}$ Cross Section Overview

- $t\bar{t}$ cross sections measured in all different final states
- Deviations between channels or from SM prediction could indicate new physics





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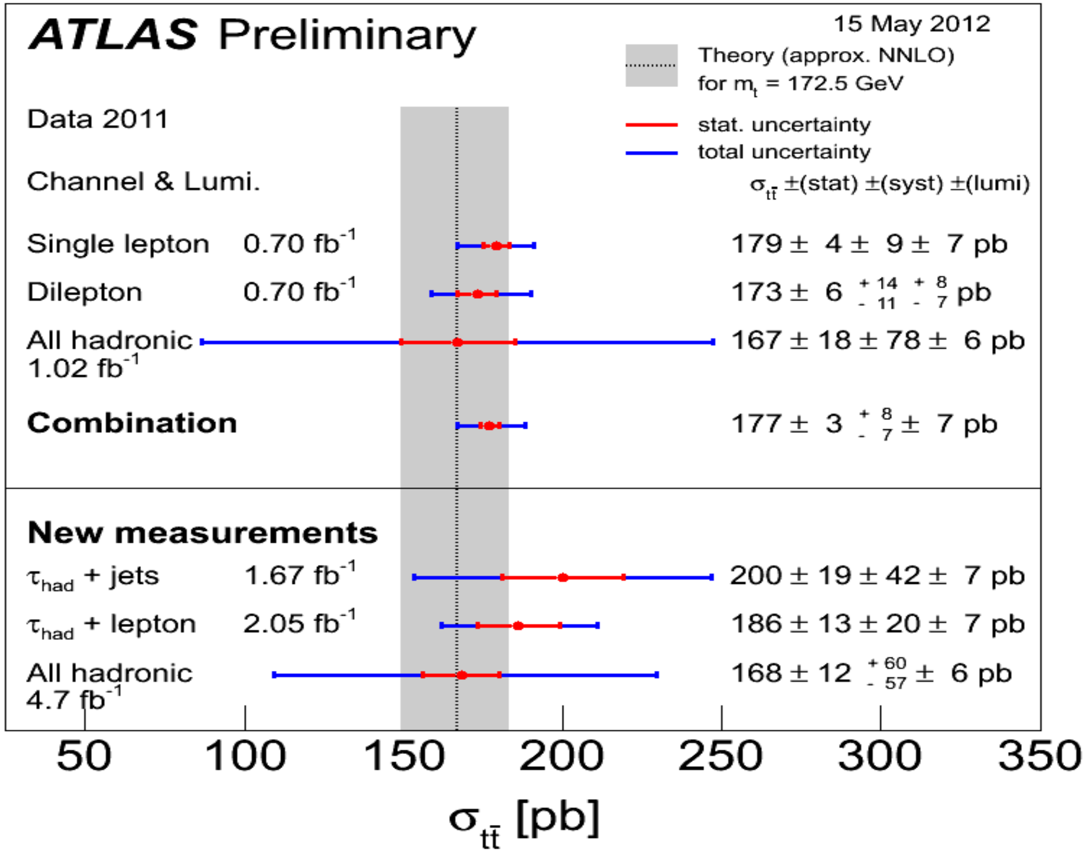

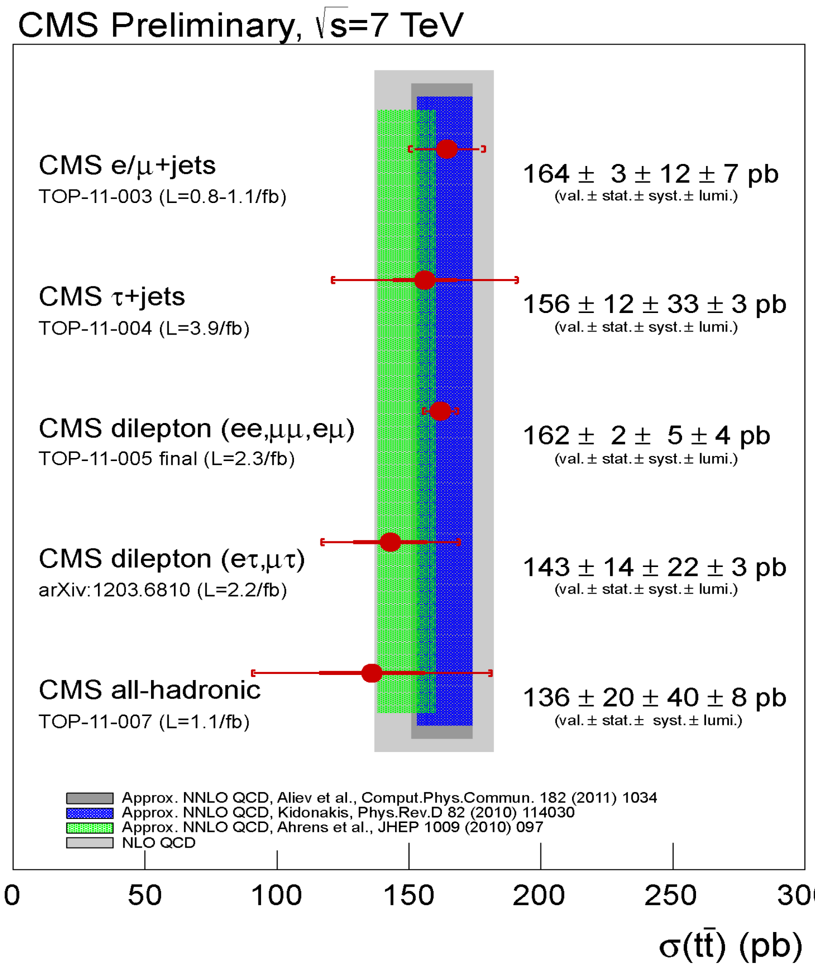

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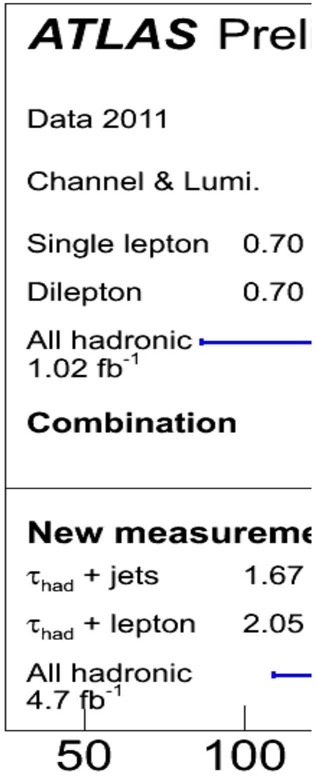
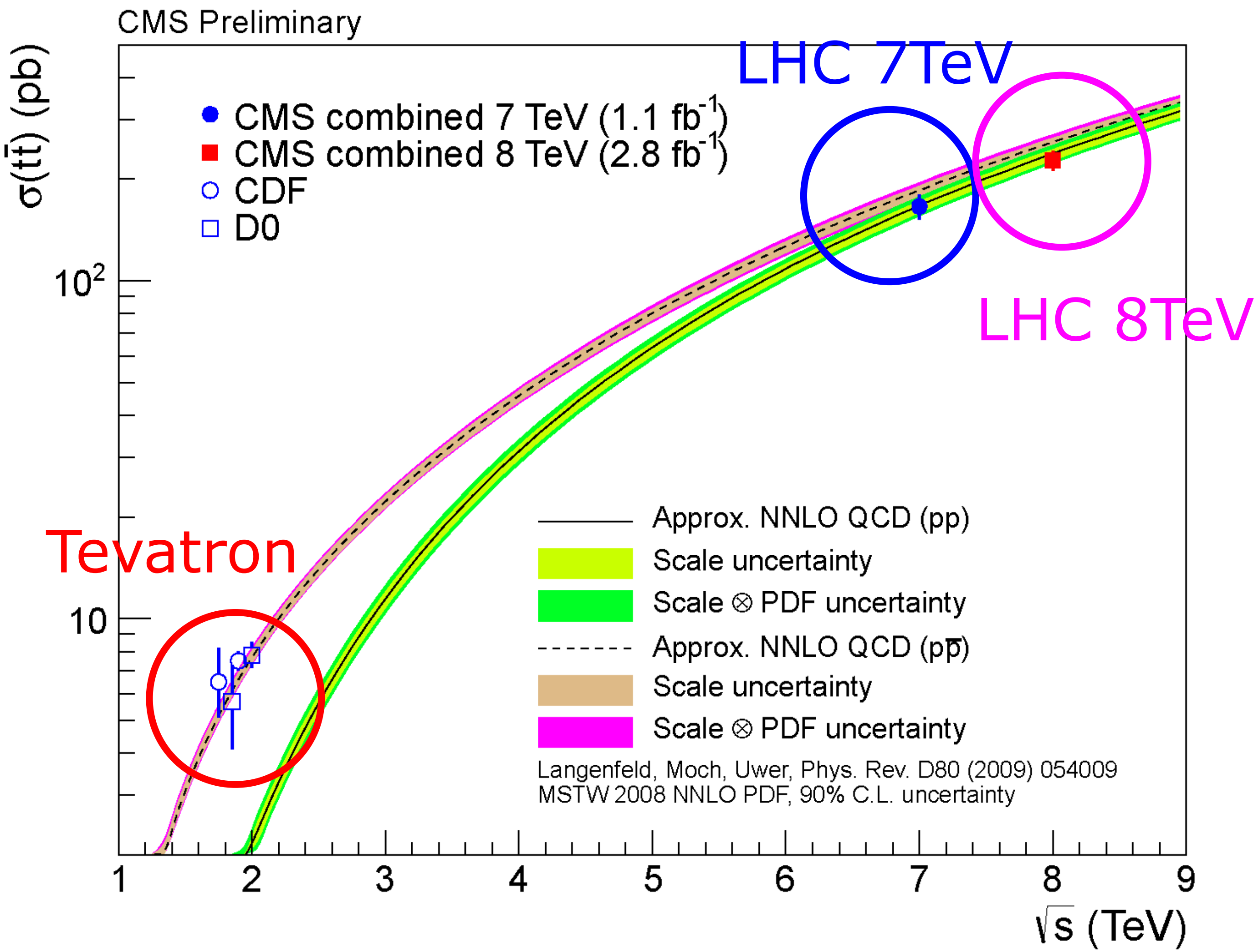
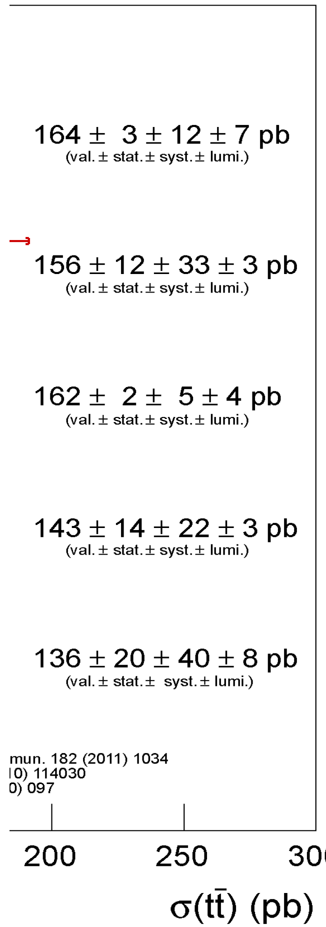
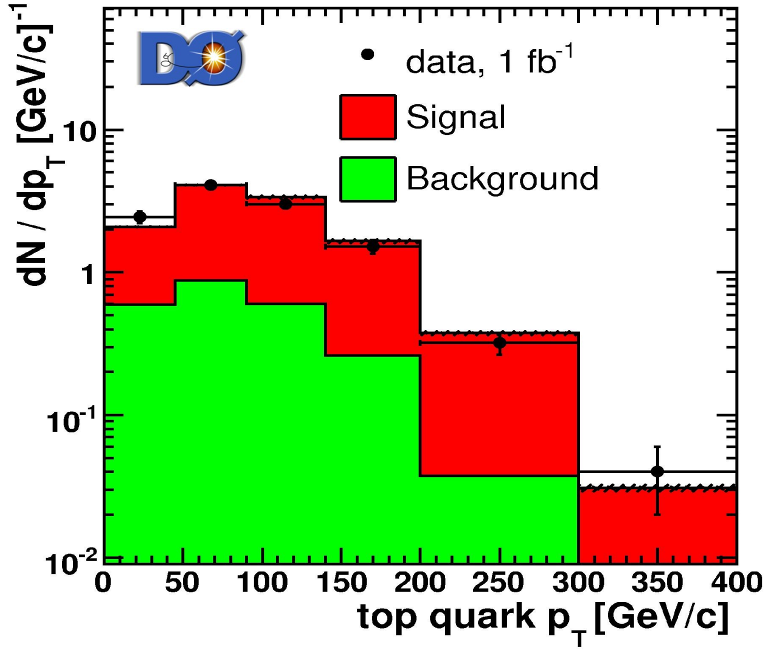






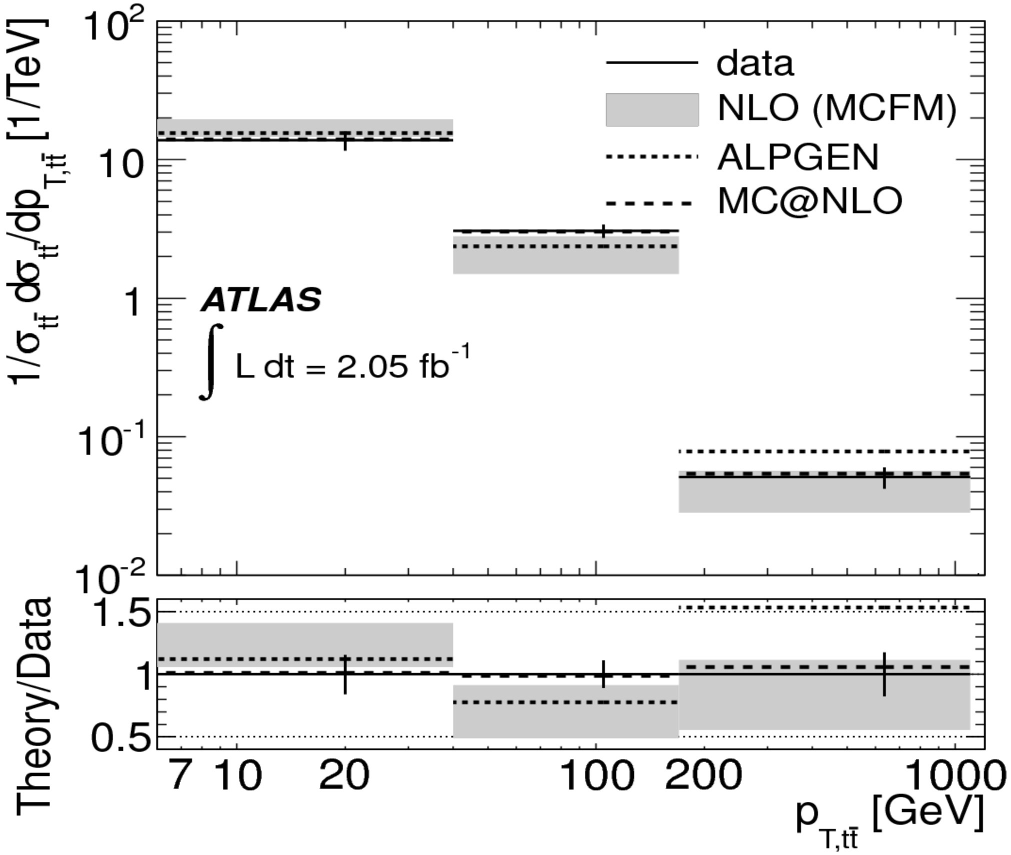
$t\bar{t}$ Differential Cross Section

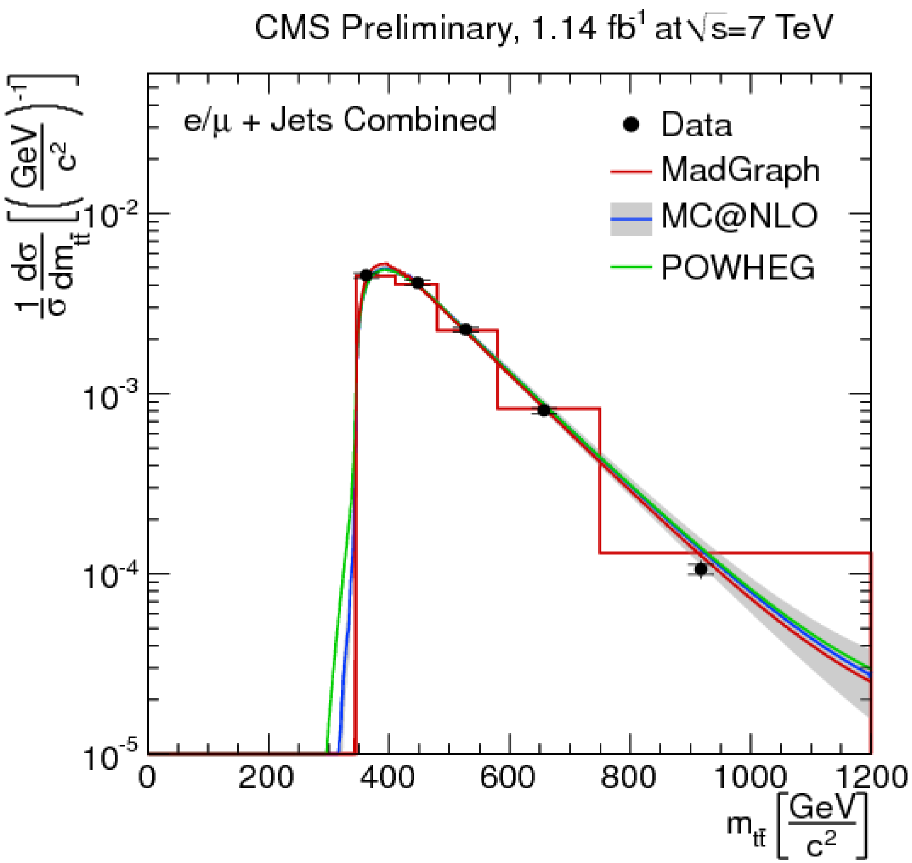
- Test of perturbative QCD calculations
- Generic probe of non-SM physics
- Mostly l+jets events used
  - Allows reconstruction of final state with good resolution
  - Use kinematic fit to reconstruct invariant $t\bar{t}$ mass
- Correct for experimental resolution, e. g. with regularized unfolding
  - After subtracting background from data
- Correction for acceptance on unfolded distributions



$t\bar{t}$ Differential Cross Section

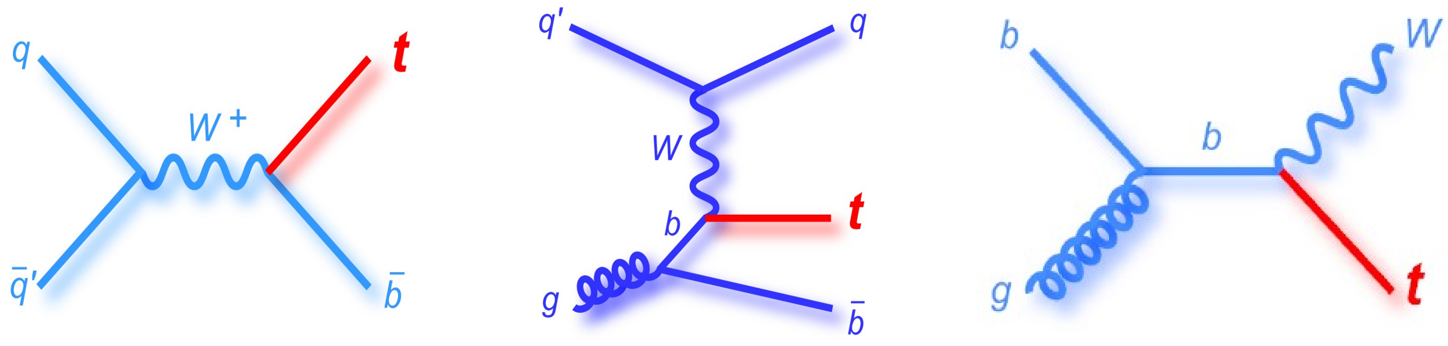
- Test of higher-order QCD calculations
- Generic test of SM; e. g. narrow resonances in $m_{t\bar{t}}$





Single Top Cross Sections

- Single top quark production via electroweak interaction

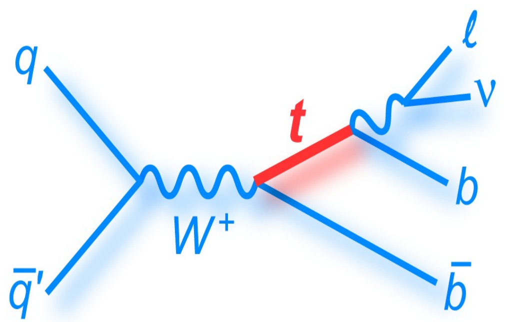


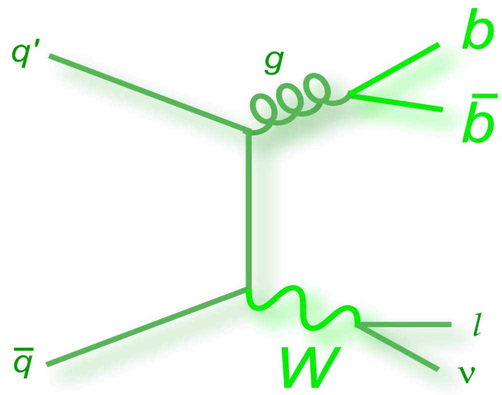
Collider	s-channel: σ_{tb}	t-channel: σ_{tqb}	Wt-channel: σ_{tW}
Tevatron: $p\bar{p}$ (1.96 TeV)	1.04 pb	2.26 pb	0.28 pb
LHC: pp (7 TeV)	4.6 pb	64.6 pb	15.7 pb

- Wt-channel: negligible at the Tevatron
- s-channel: challenging at the LHC

The Challenge

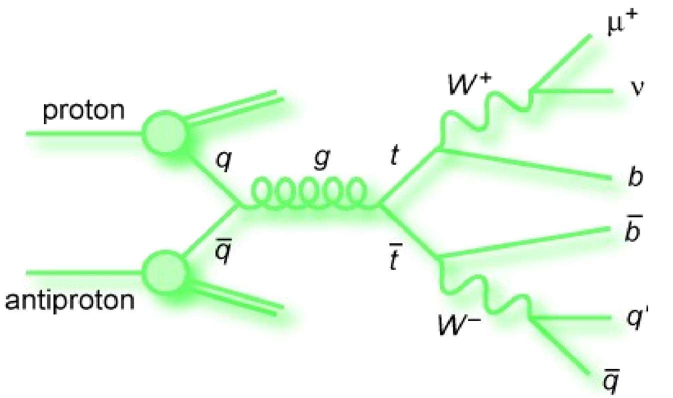
- Production cross section about ½ of $t\bar{t}$
- Single top signature similar to W+jets background



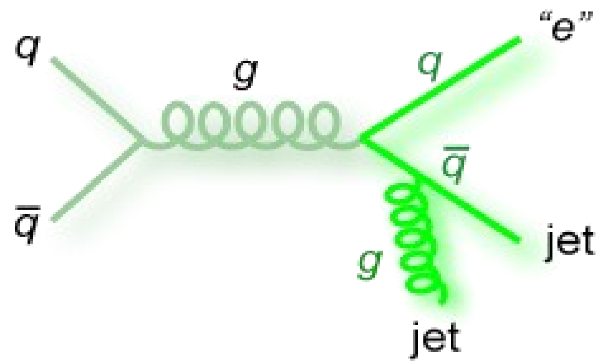


- Other important backgrounds:

$t\bar{t}$

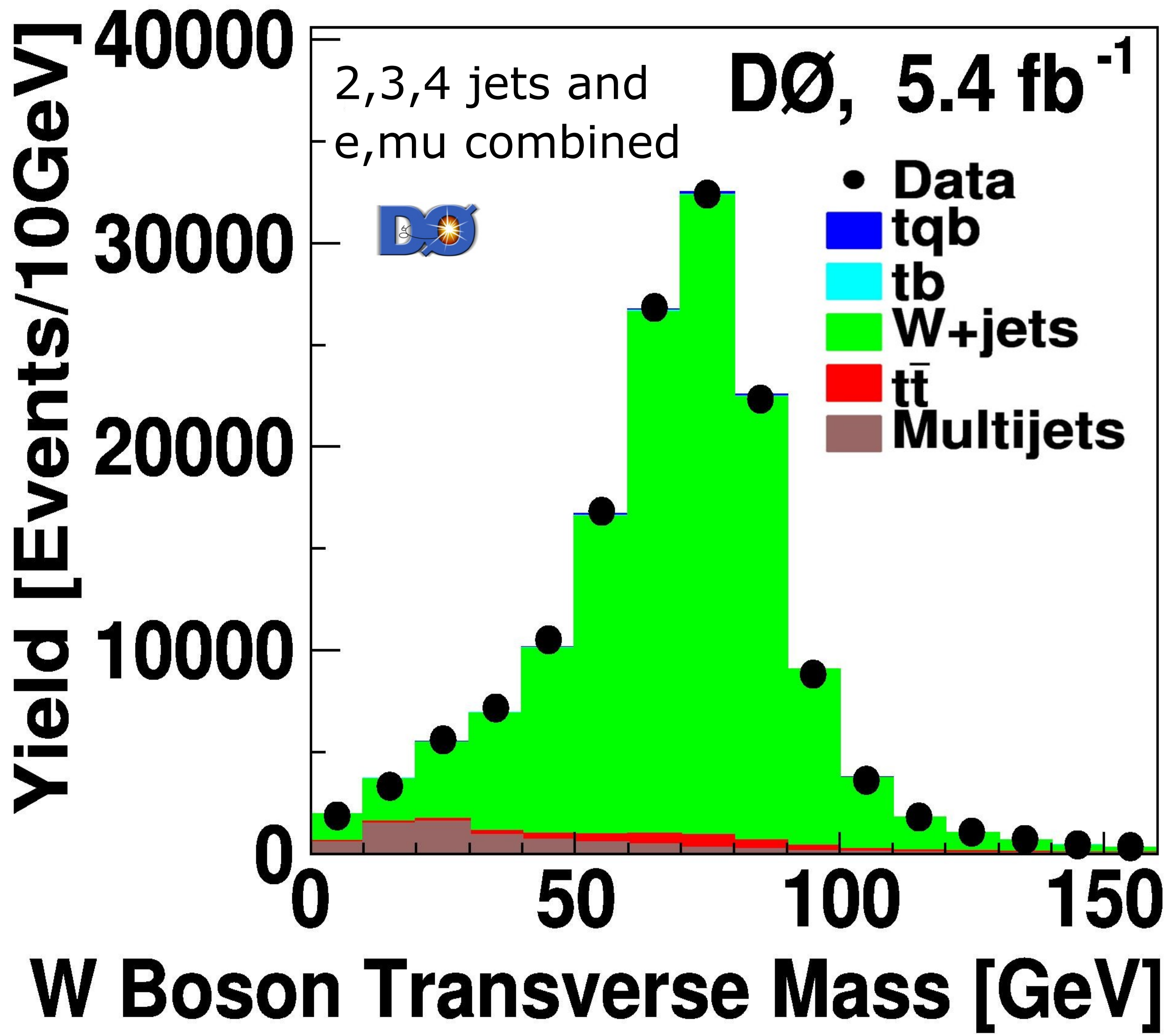


and multijet



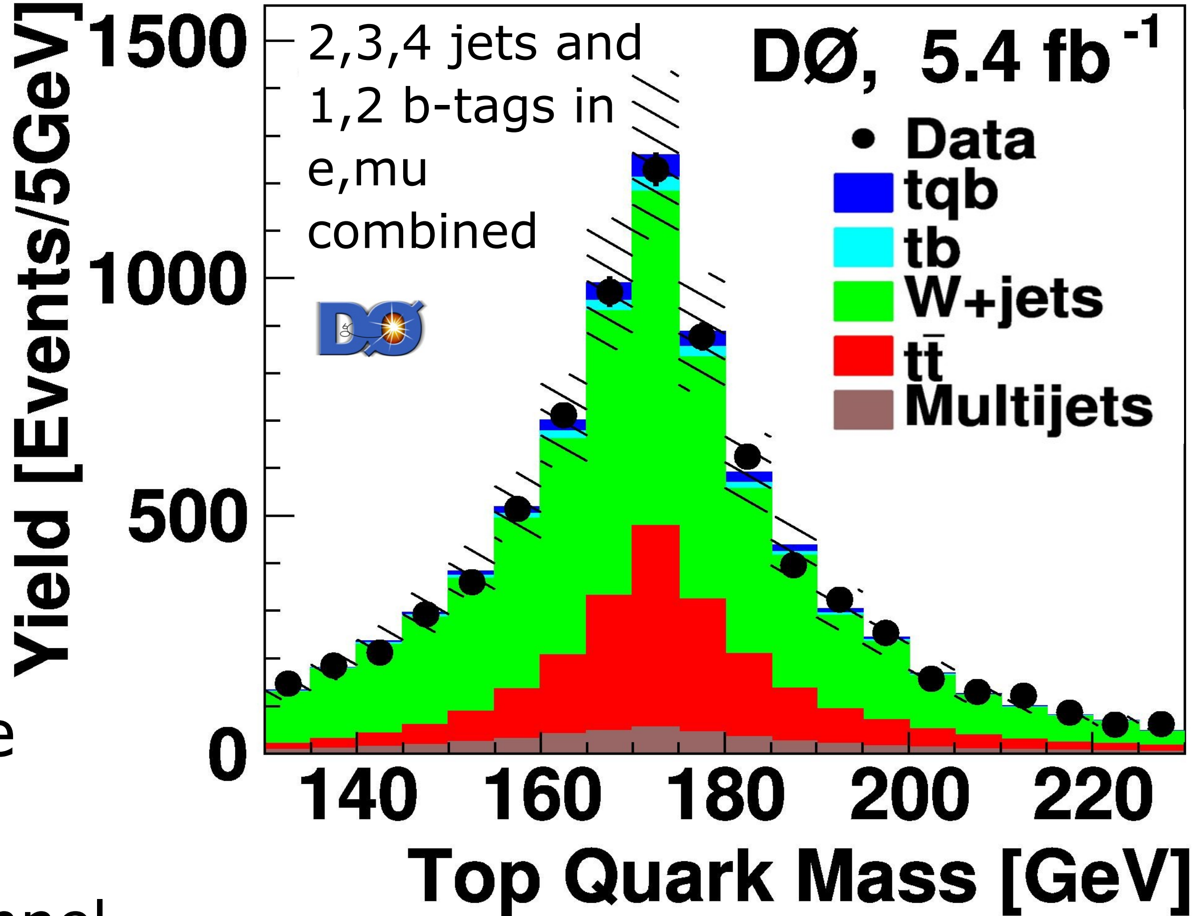
After Event Selection and before b-jet Identification

- Before b-jet identification: single top signal hardly visible!



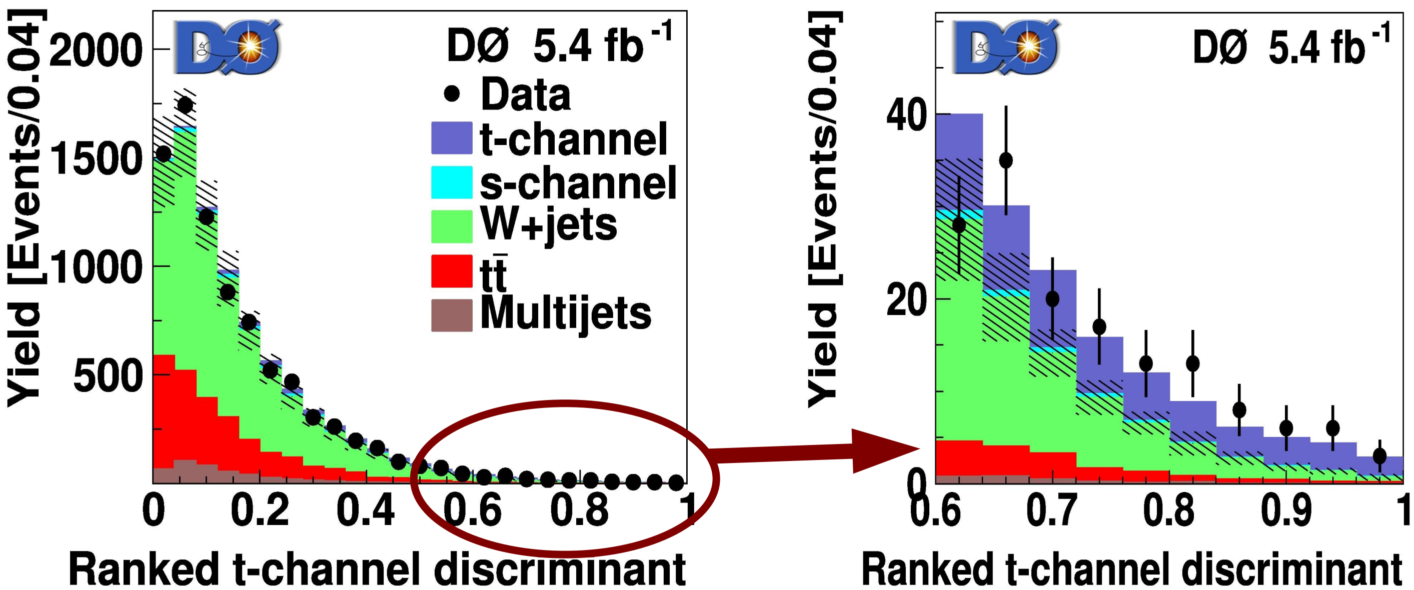
After Event Selection and after b-jet Identification

- Before b-jet identification: single top signal hardly visible!
- After b-jet identification: single top visible – but uncertainty on background model larger than signal
- Extensive use of multivariate analysis techniques!
  - Less extreme at LHC: t-channel extraction via cut-based analysis possible



Training and cross section extraction

- Train MVA on
  - s+t channel using SM ratio between s- and t-channel
  - t-channel with s-channel as background in training (not in fit)
  - s-channel with t-channel as background in training (not in fit)
- Bayesian method to extract cross section results
  - Integration over systematic uncertainties (modeled as Gaussian priors)
- Example: t-channel trained discriminant



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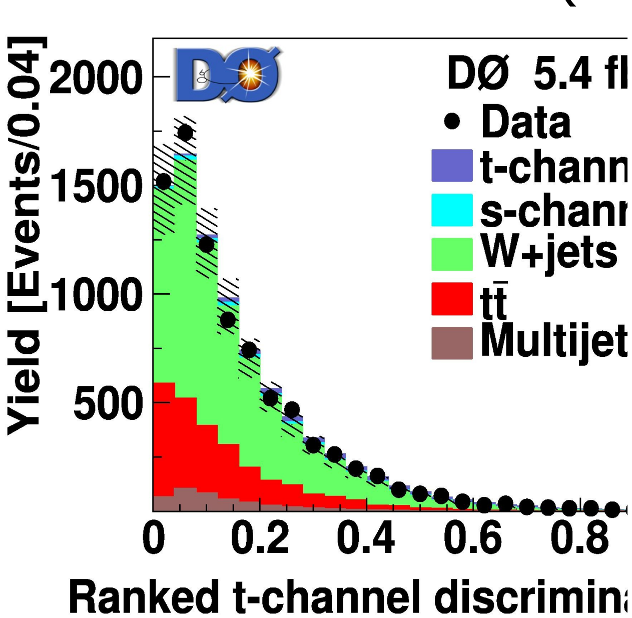
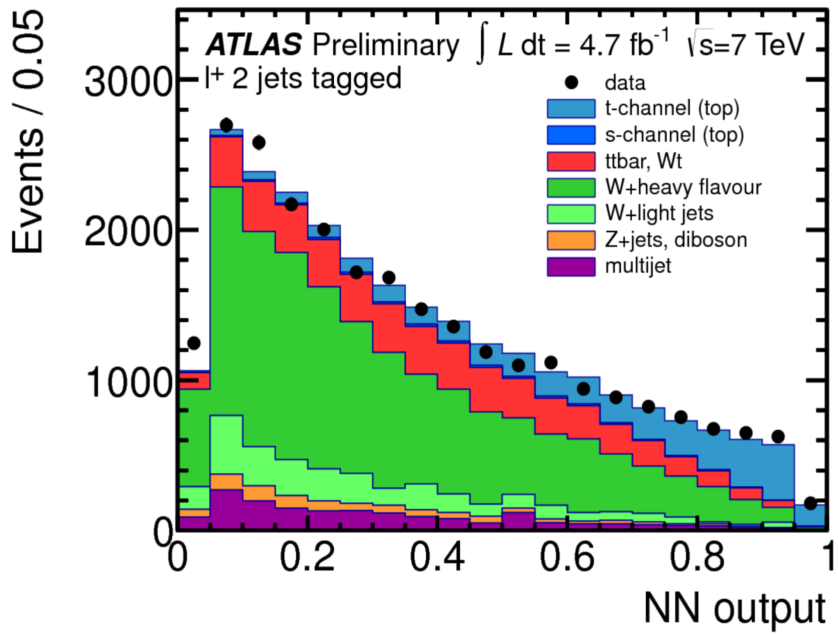
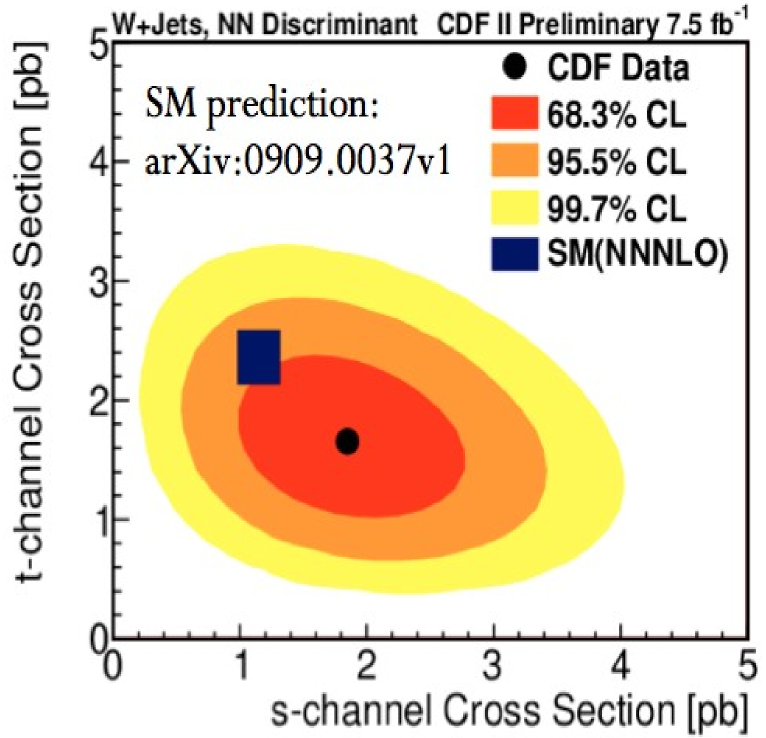
- Bayesian method to extract cross section results
  - Integration over systematic uncertainties (m
- Example: t-channel trained discriminant
- LHC: t-channel much easier visible





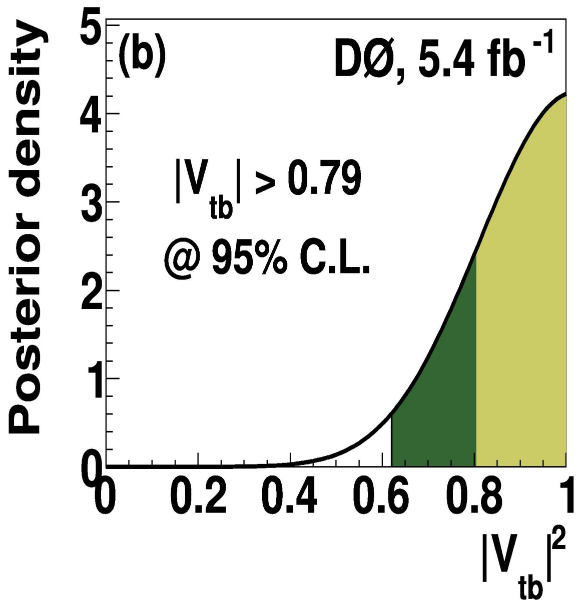
Single Top: Other Measurements

- s- and t-channel are differently sensitive to new physics
  - Measure both channels simultaneously



- Direct extraction of V_{tb} from single top cross section $|V_{tb}|^2 \propto \sigma(s+t)$
  - No assumption about number of generations
  - Assumption: $|V_{ts}|^2+|V_{td}|^2 << |V_{tb}|^2$

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



Summary Production

- Top production mechanisms:
  First thing to understand about top quarks
- Modeling of signal and background events crucial
- Various methods available to enrich data in signal events
  - b-tagging
  - Multivariate analysis techniques
- Single top: more challenging to measure
  → most properties measurements performed in $t\bar{t}$

BACKUP