Measurement of $t\bar{t}$ Production Cross Sections at the Tevatron

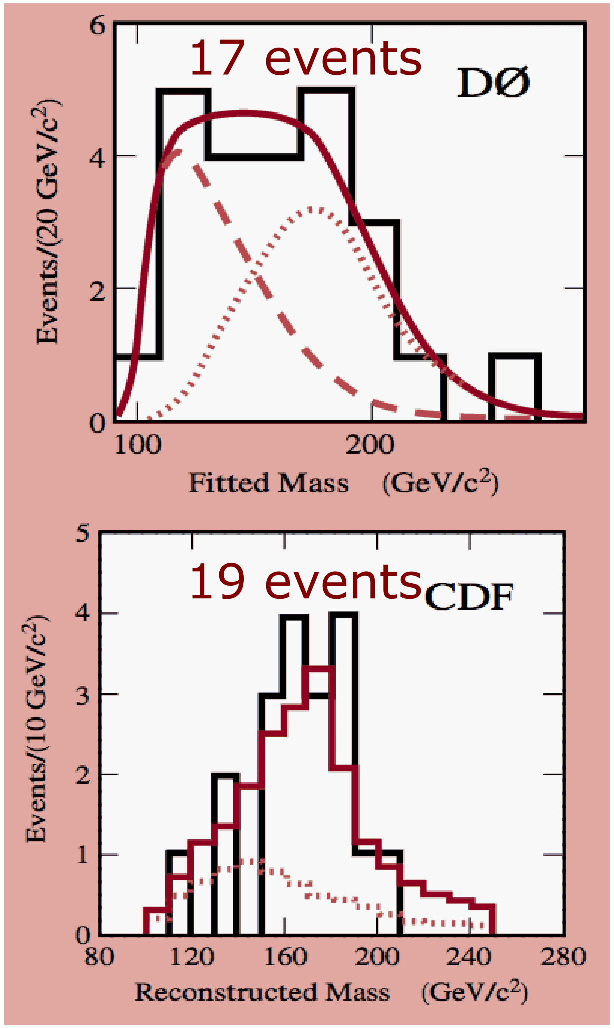
Reinhild Yvonne Peters

The University of Manchester, also at DESY

on behalf of the CDF and DØ Collaboration

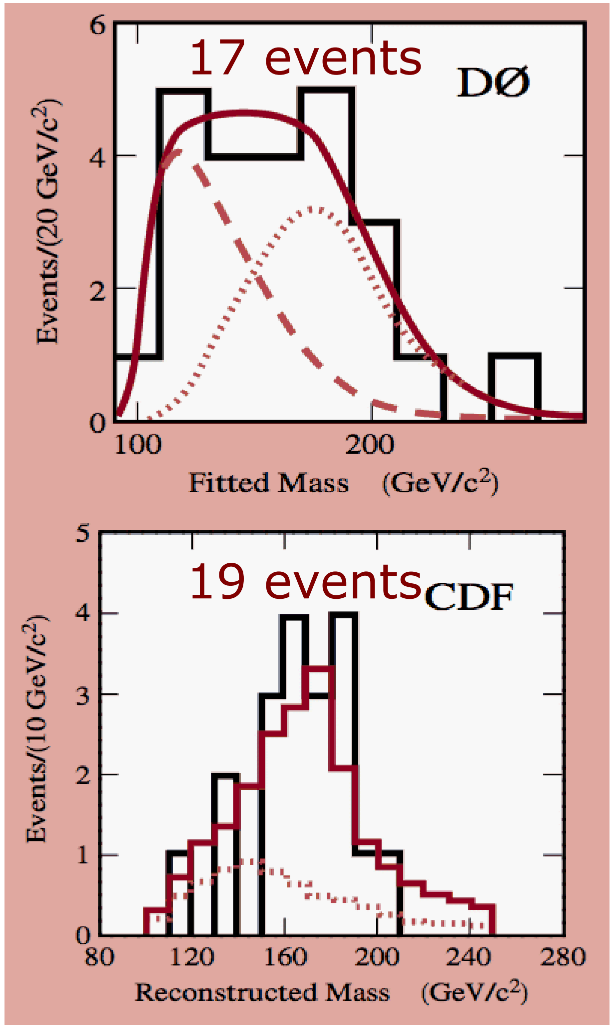
The Top Quark

Discovered in 1995 by CDF and DØ at Fermilab (with few events)



The Top Quark

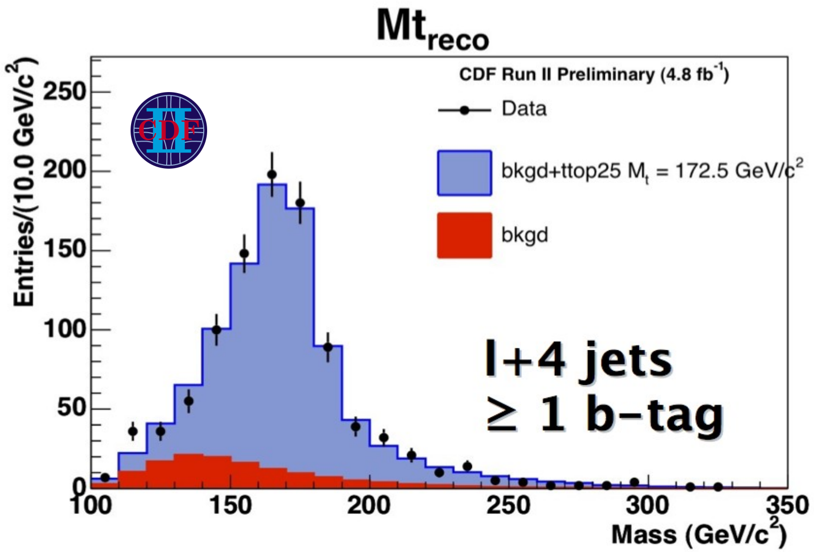
Discovered in 1995 by CDF and DØ at Fermilab (with few events)

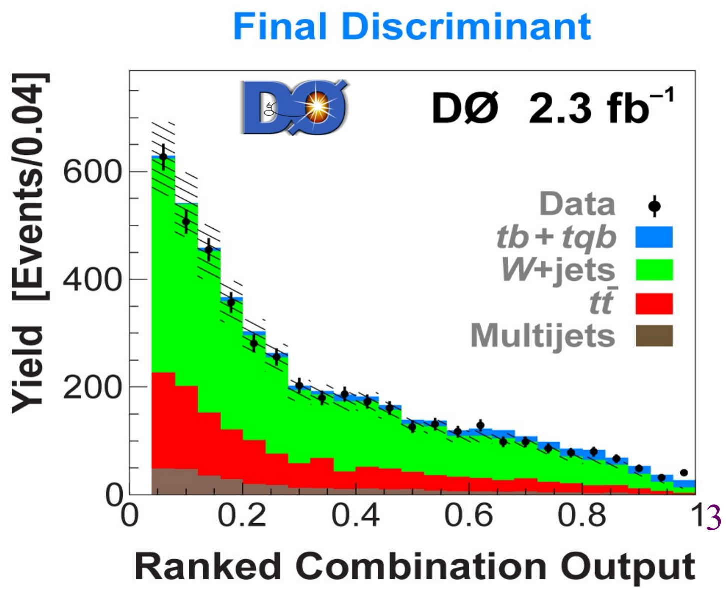


Situation today:

1000s of events!

Rediscovered in 2009 in single top production

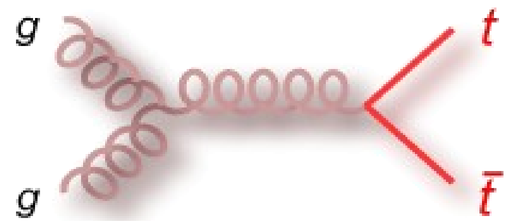




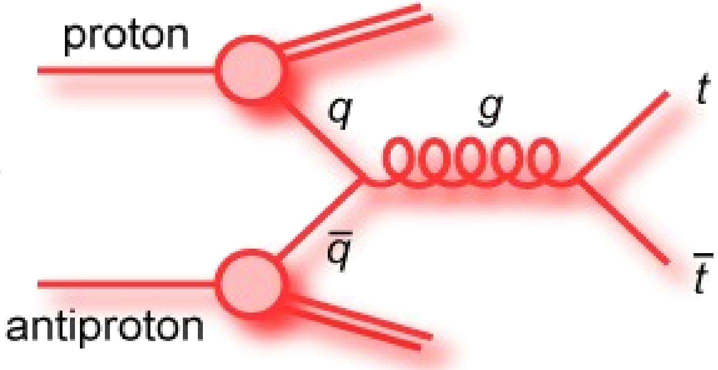
Since 2010 LHC operating → top quark factory

Top Quark Pair Production

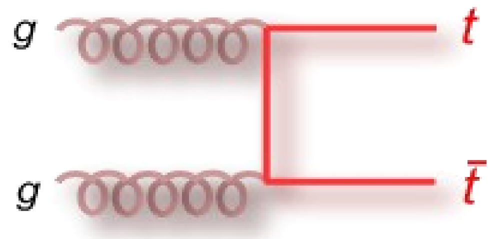
- Via strong interaction
- At the Tevatron:



85%



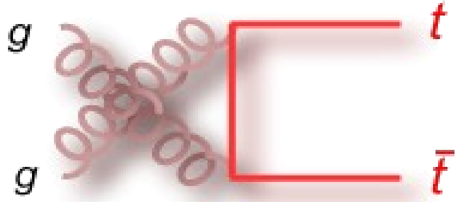
+ 15%



At LHC:

14 TeV: 10% + 90%

7 TeV: 15% + 85%



- Production cross section (@Tevatron):

NNLO+NNLL: $\sigma = 7.16^{+0.20}_{-0.23}\, pb$ @ m_t=173.3GeV

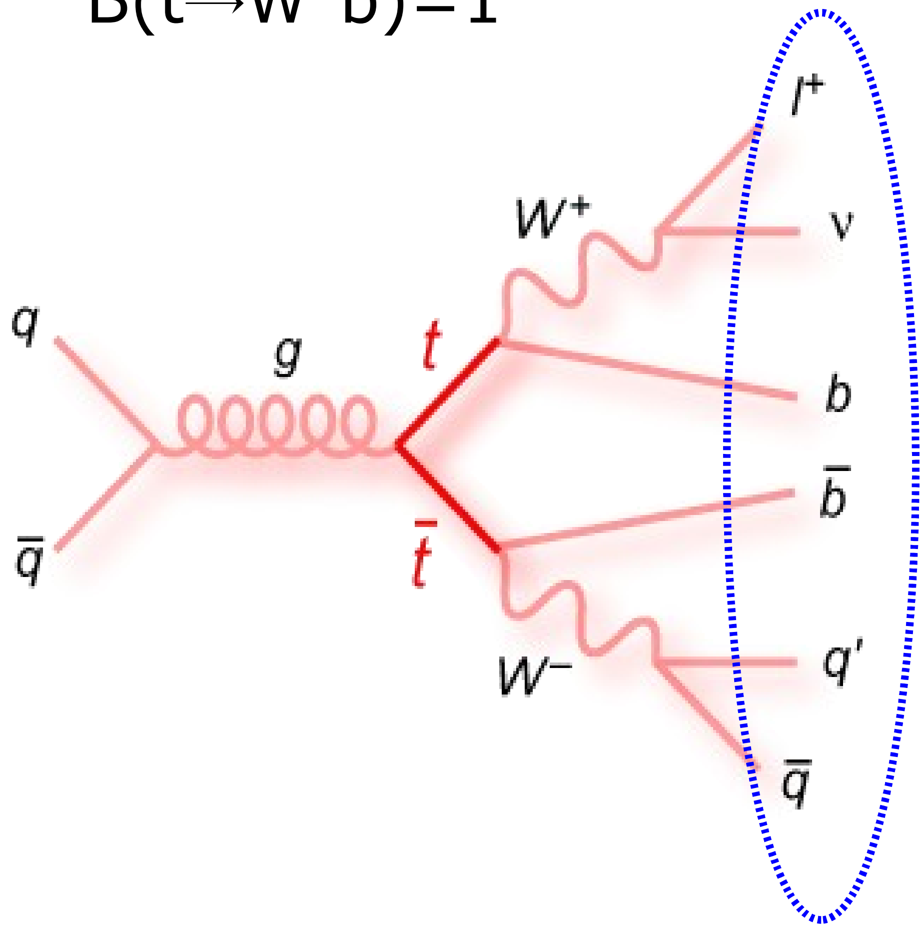
Czakon, Fiedler, Mitov, PRL 110, 252004 (2013)

(LHC@13TeV: >100 times larger $t\bar{t}$ cross section)

Final States in $t\bar{t}$

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

$B(t \rightarrow W^+ b) = 1$



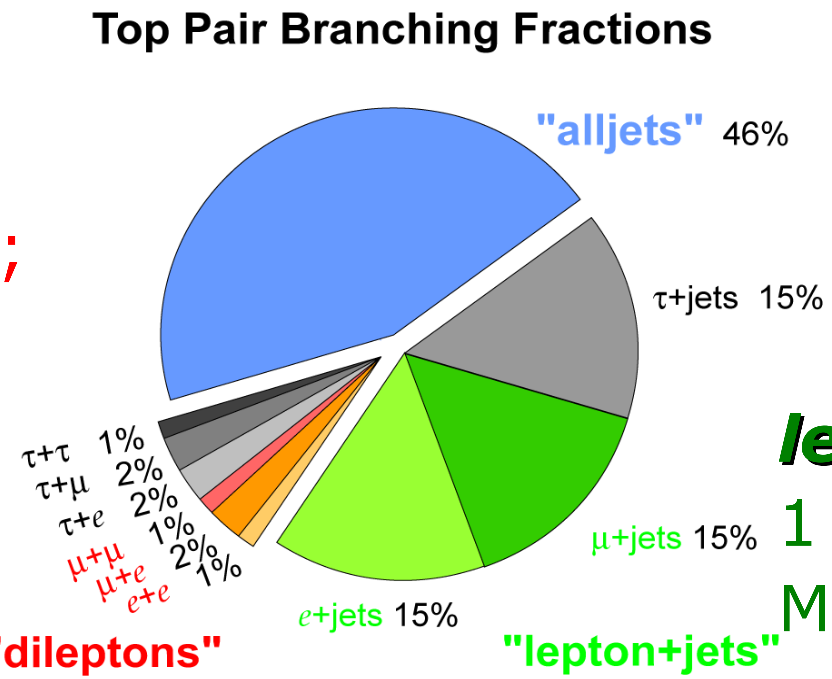
Final States in $t\bar{t}$

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

$B(t \rightarrow W^+ b) = 1$

pure hadronic:
≥6 jets (2 b-jets)

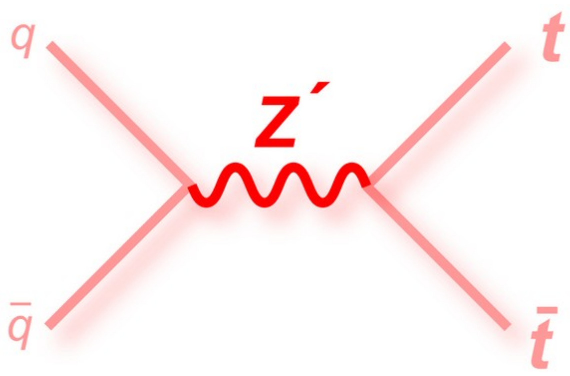
dilepton:
2 isolated leptons;
High missing E_T from neutrinos;
2 b-jets



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

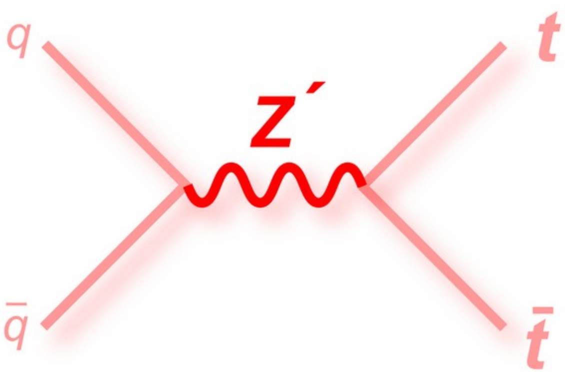
Motivation

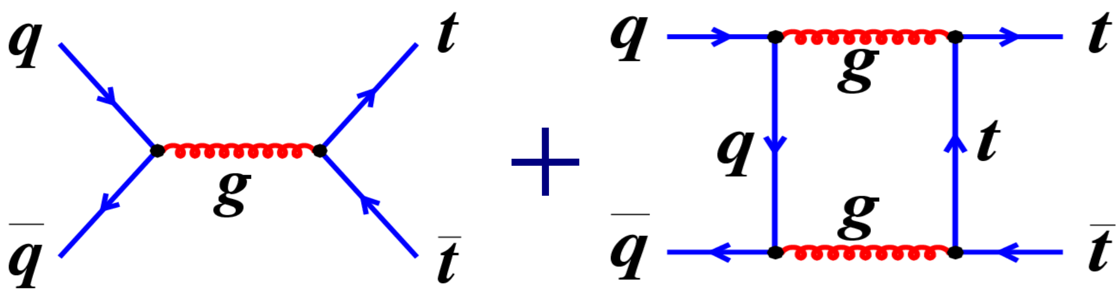
- Measurements of inclusive & differential $t\bar{t}$ cross section
  - Direct test of pQCD
- Deviation of measured $t\bar{t}$ cross section could hint for new physics
  - Due to change in production
    - Inclusive



Motivation

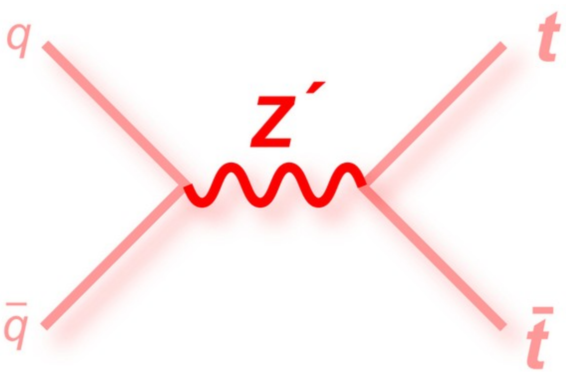
- Measurements of inclusive & differential $t\bar{t}$ cross section
  - Direct test of pQCD
- Deviation of measured $t\bar{t}$ cross section could hint for new physics
  - Due to change in production
    - Inclusive or kinematics

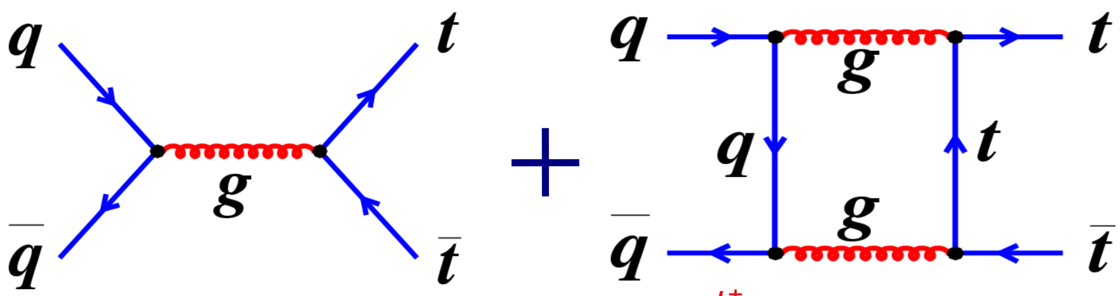




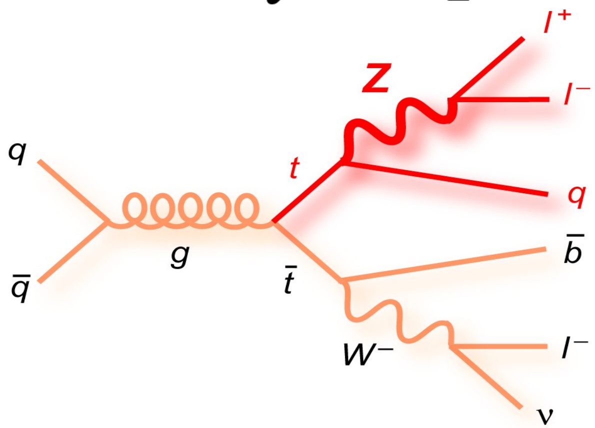
Motivation

- Measurements of inclusive & differential $t\bar{t}$ cross section
  - Direct test of pQCD
- Deviation of measured $t\bar{t}$ cross section could hint for new physics
  - Due to change in production
    - Inclusive or kinematics

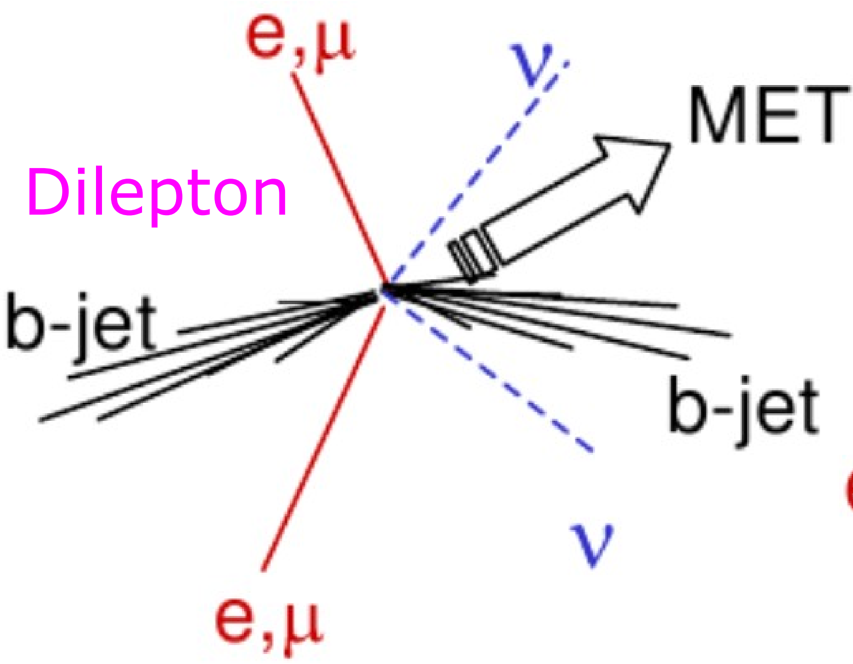




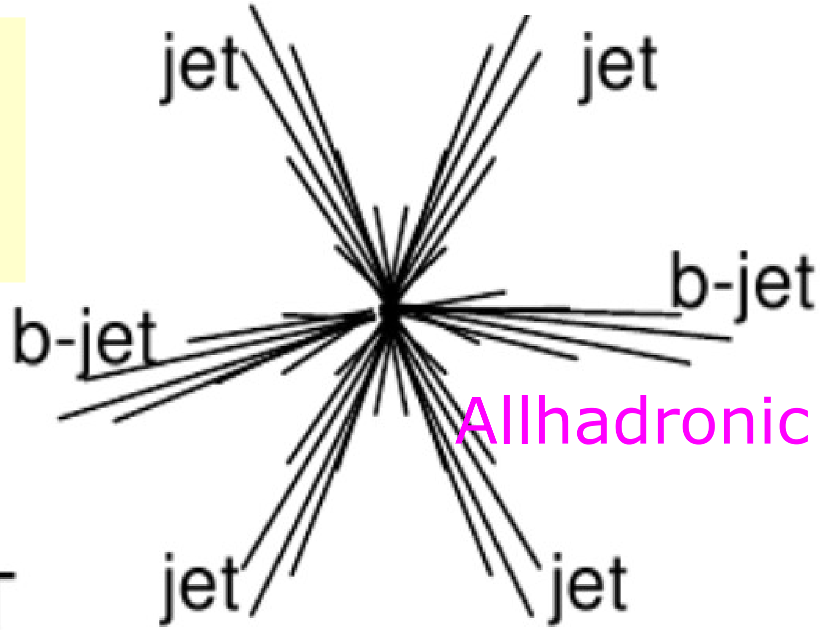
  - Due to change of fractions of different final state

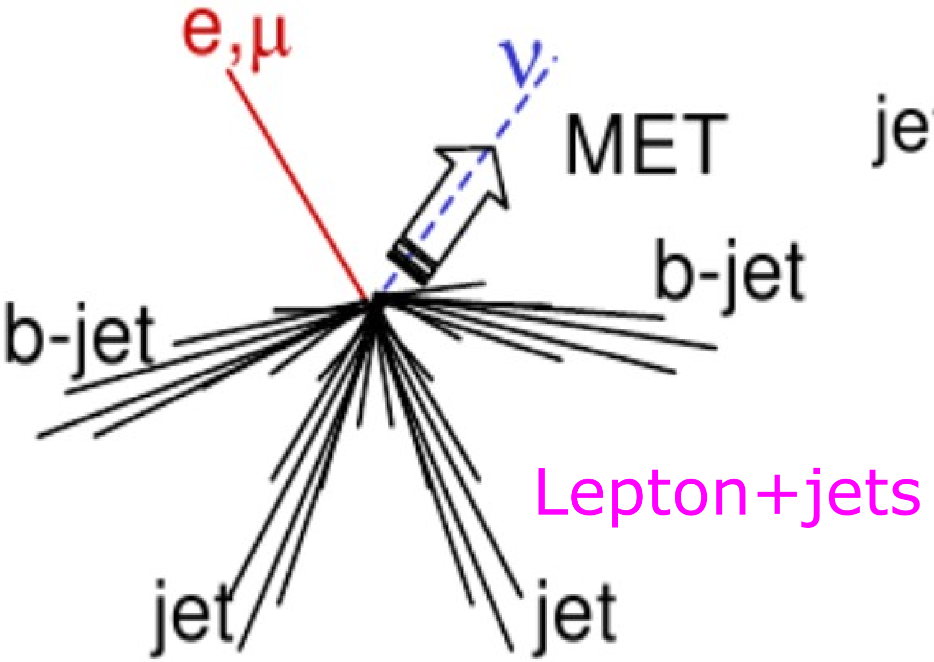


Event selection: Use the signature!



High E̸ for the neutrino



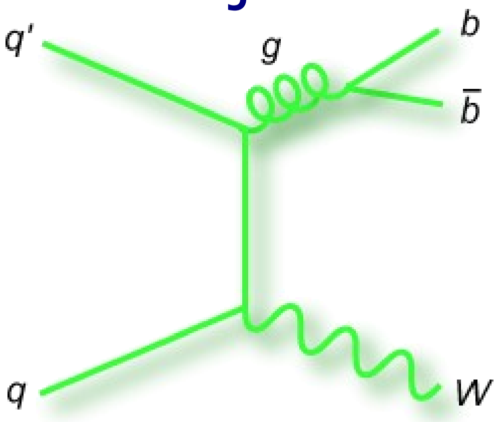


Isolated, high momentum leptons

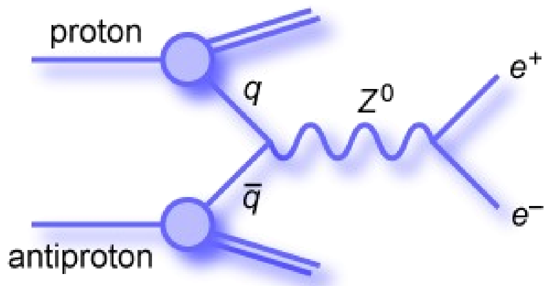
High momentum (b-)jets

Background events

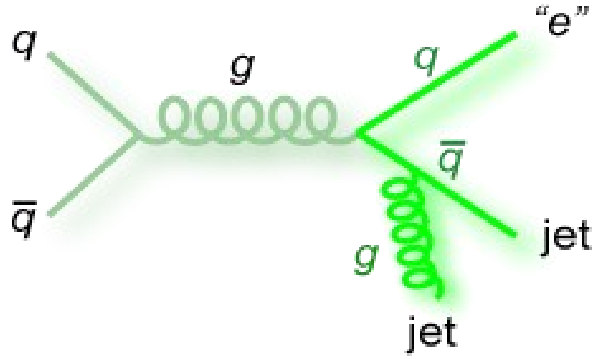
W+jets:
Main background in l+jets



Z+jets:
Main background in dilepton



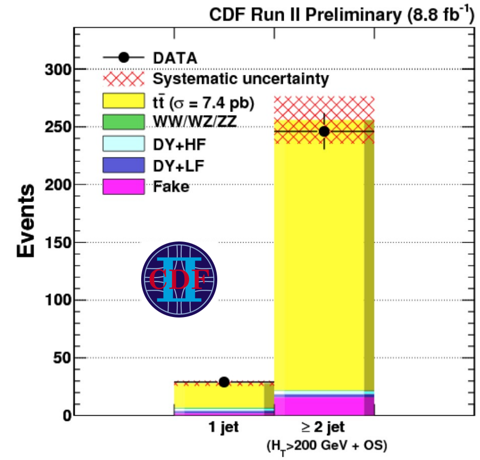
Multijet:
Main background in allhadronic
Modeled from Data



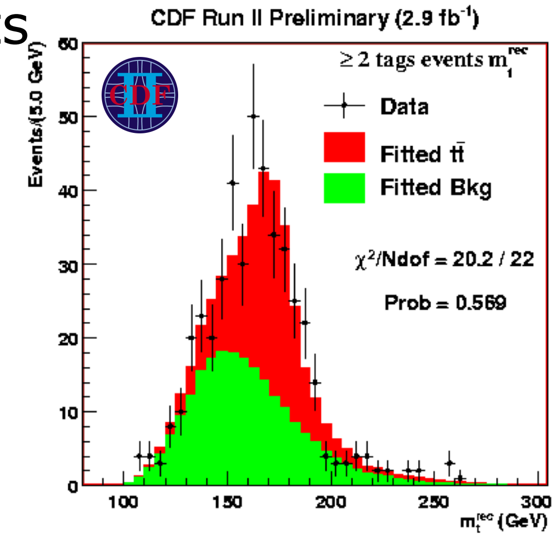
- Smaller background contributions
  - Z+jets in l+jets: one lepton of the Z decay is not identified
  - DiBoson background (WW, WZ and ZZ)
  - single top events (not in single top measurement of course)

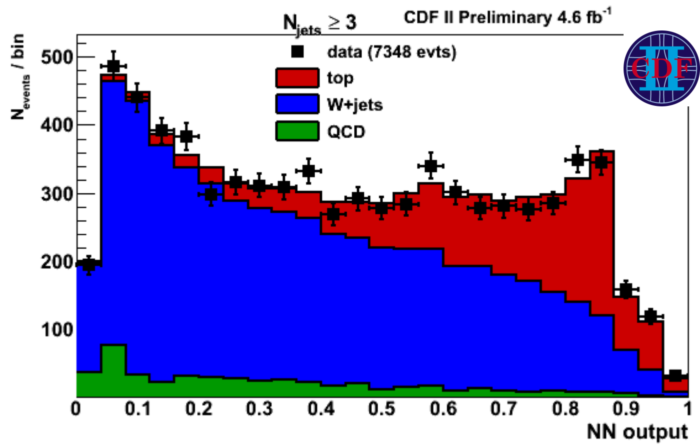
Tevatron $t\bar{t}$ Cross Section Combination

- Combination of $t\bar{t}$ cross section from CDF and D0
  - 4 analyses from CDF, 2 from D0
- CDF: 2 l+jets, 1 dilepton, 1 allhadronic
  - Dilepton: counting events with ≥1 b-tagged jets
  - l+jets:
    - Analysis 1: Construct NN discriminant based on kinematic variables (No b-tagging)
    - Analysis 2: counting events with ≥1 b-tagged jets
  - Allhadronic: fit to reconstructed top quark mass in events with ==1 and >1 b-tagged jets



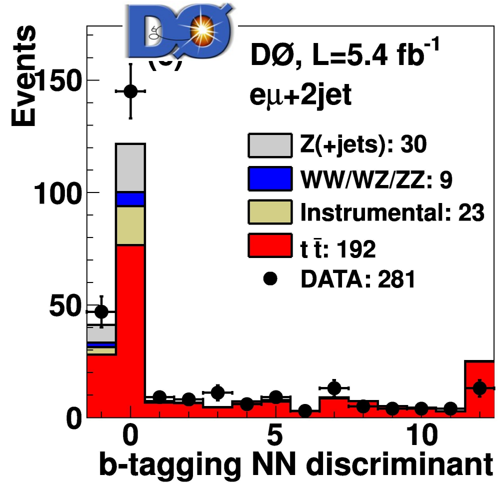
1 jet and signal b-tagged dilepton events



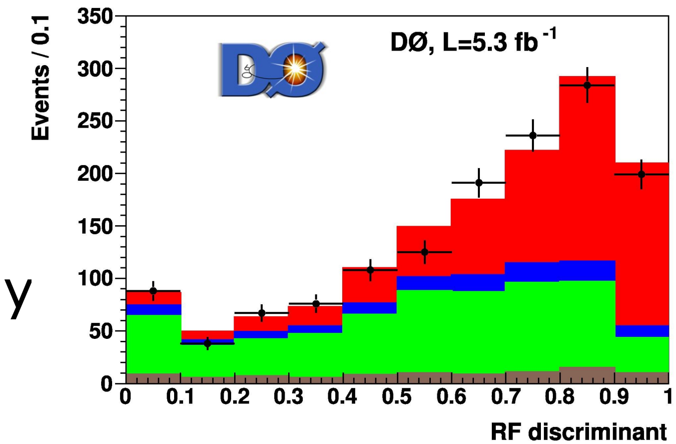


Tevatron $t\bar{t}$ Cross Section Combination

- D0: 1 dilepton, 1 l+jets



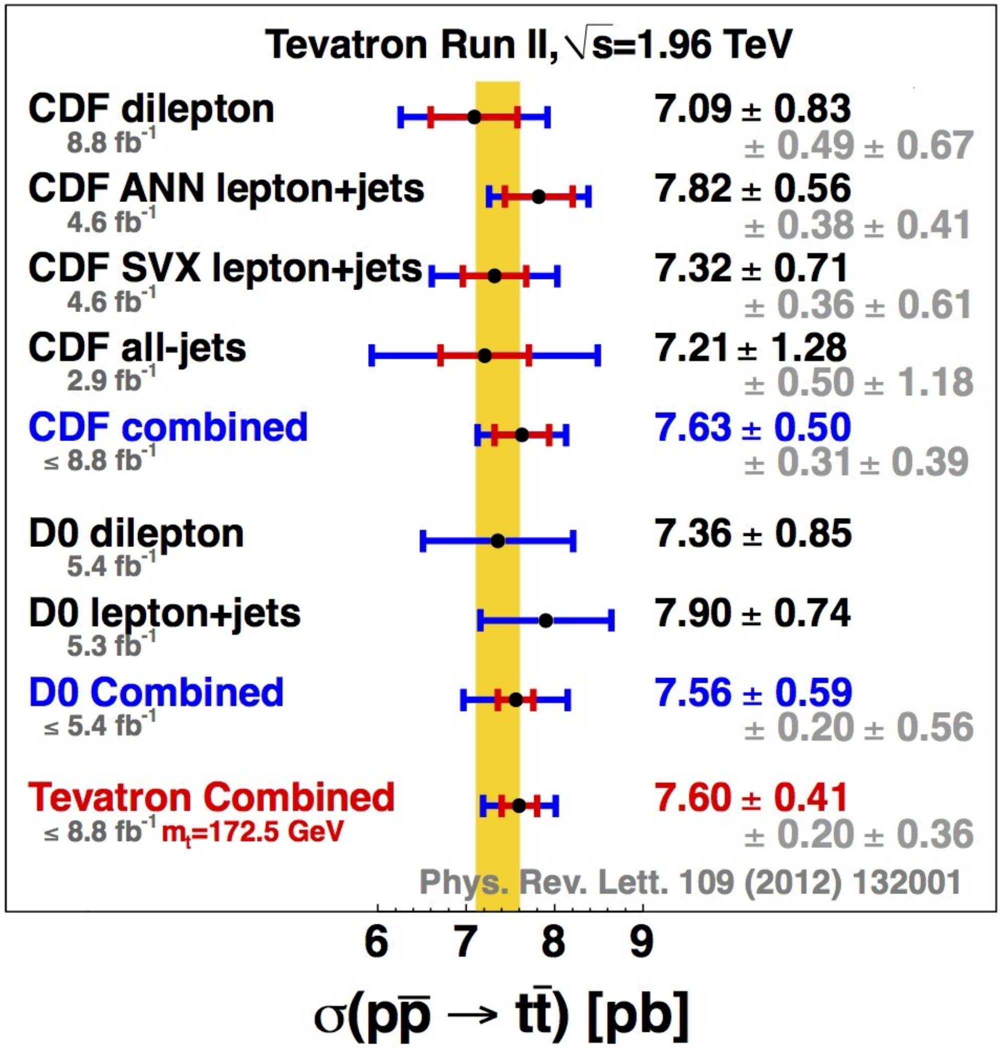
  - Dilepton: likelihood fit to discriminant based on NN b-jet identification algorithm
  - l+jets: events with 3 & >3 jets, split into 0, 1 or >1 b-tagged jets
    - In background dominated samples: use random forest discriminant
    - Likelihood fit to all subsamples simultaneously



  - Combination with likelihood fit, systematics treated as nuisance parameters
- BLUE combination of CDF and D0 input combinations

$t\bar{t}$ Cross Section: Tevatron Combination

- Correlation between measurements from CDF and D0: 17%
- CDF measurement: weight 60%; D0: 40%

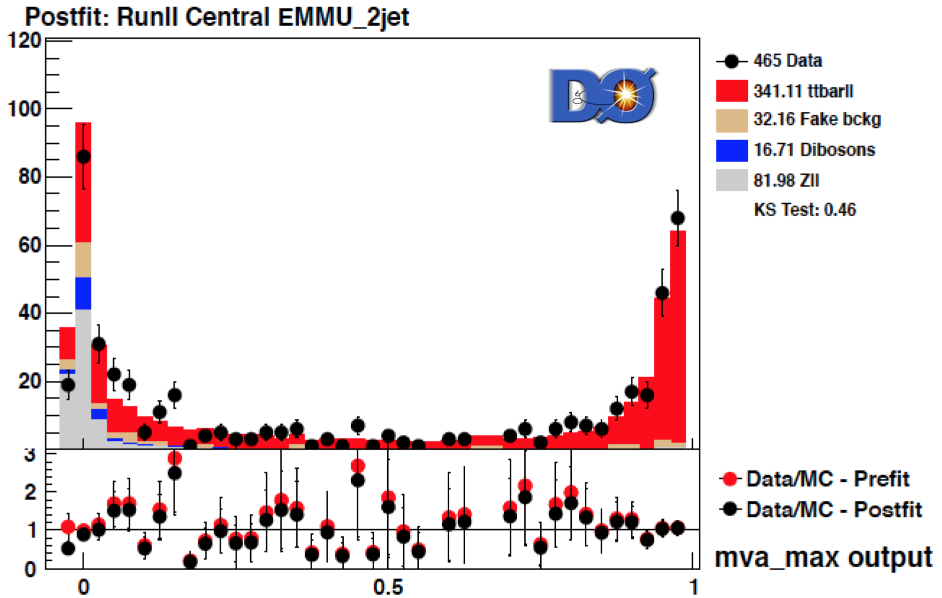


- All channels compatible with each other and SM value

Phys.Rev. D 89, 072001 (2014)

Inclusive $t\bar{t}$ Cross Section

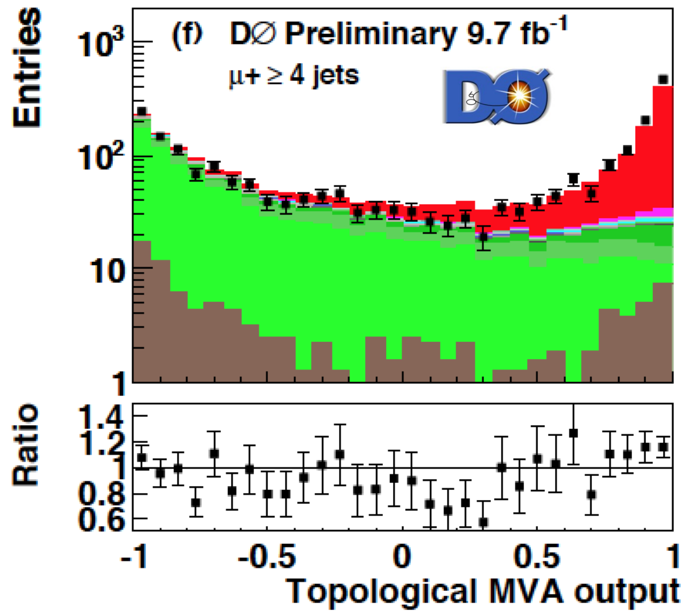
- New inclusive $t\bar{t}$ cross section measurement using full D0 dataset
  - l+jets and dilepton
    - Dilepton: use b-tag MVA output as discriminant
    - l+jets: toplogical discriminant
      - based on BDTs
      - Split into 2, 3, ≥4 jets



- Result:

$$\sigma_{t\bar{t}} = 7.73 \pm 0.13\,(stat) \pm 0.55\,(syst)\;pb$$

  - Relative uncertainty: 7.3%
  - Largest contribution to systematics from hadronization

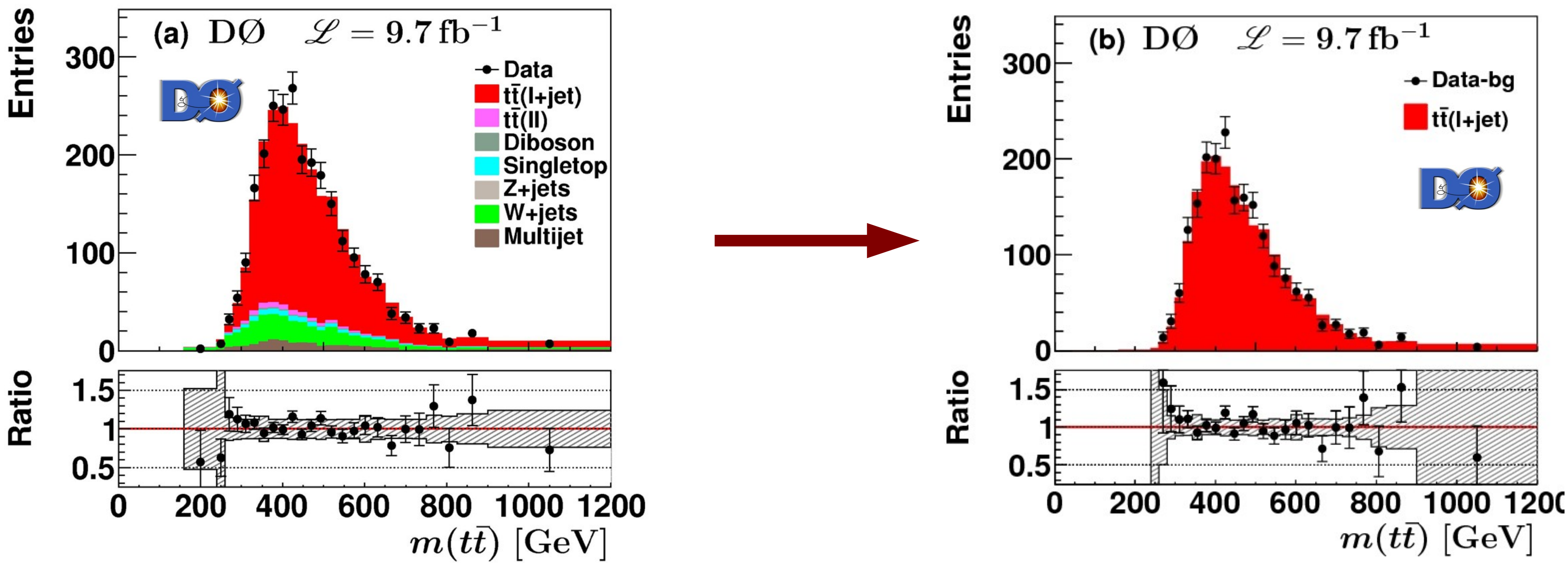


- Consistent with SM

conference note out tomorrow

Differential Cross Section

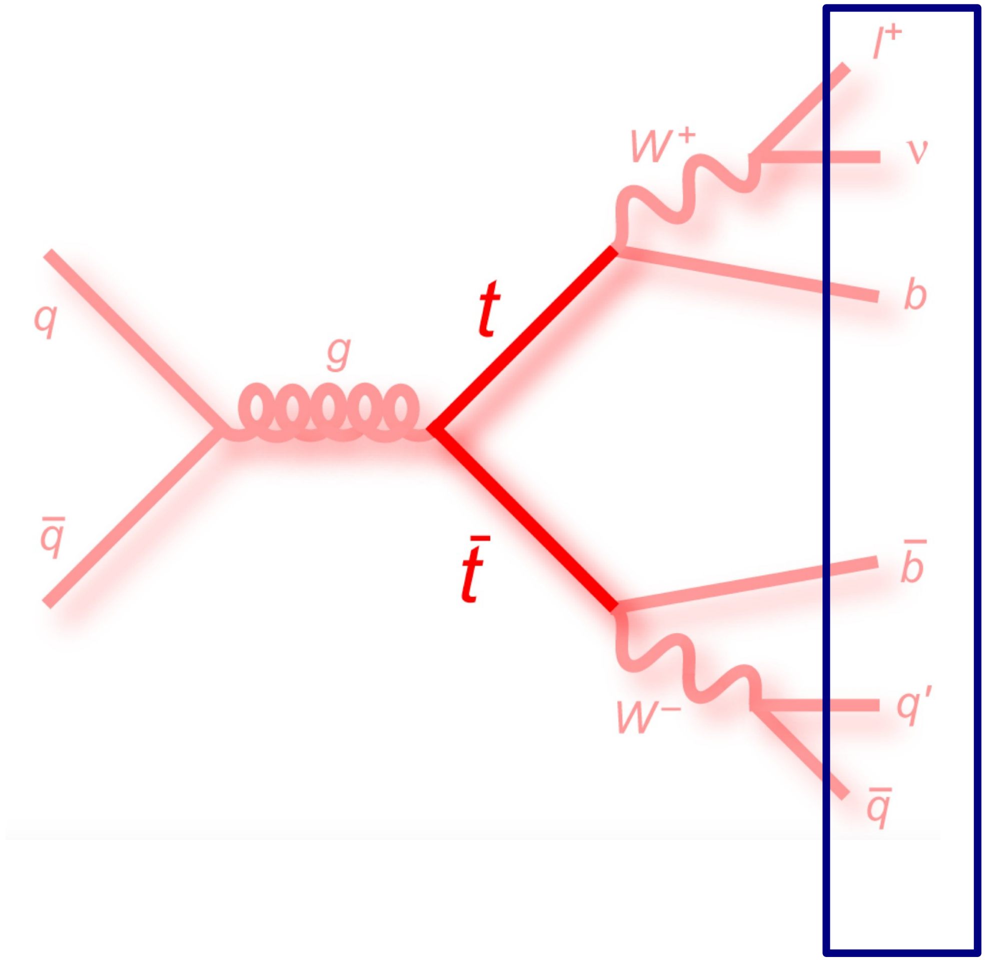
- Differential measurements as function of $m_{t\bar{t}}$, $|y^{top}|$, & p_T^{top}
- In l+jets topology, using full Run II data sample
  - Subtract background prediction from data



PRD 90, 092006 (2014)

Reconstruction

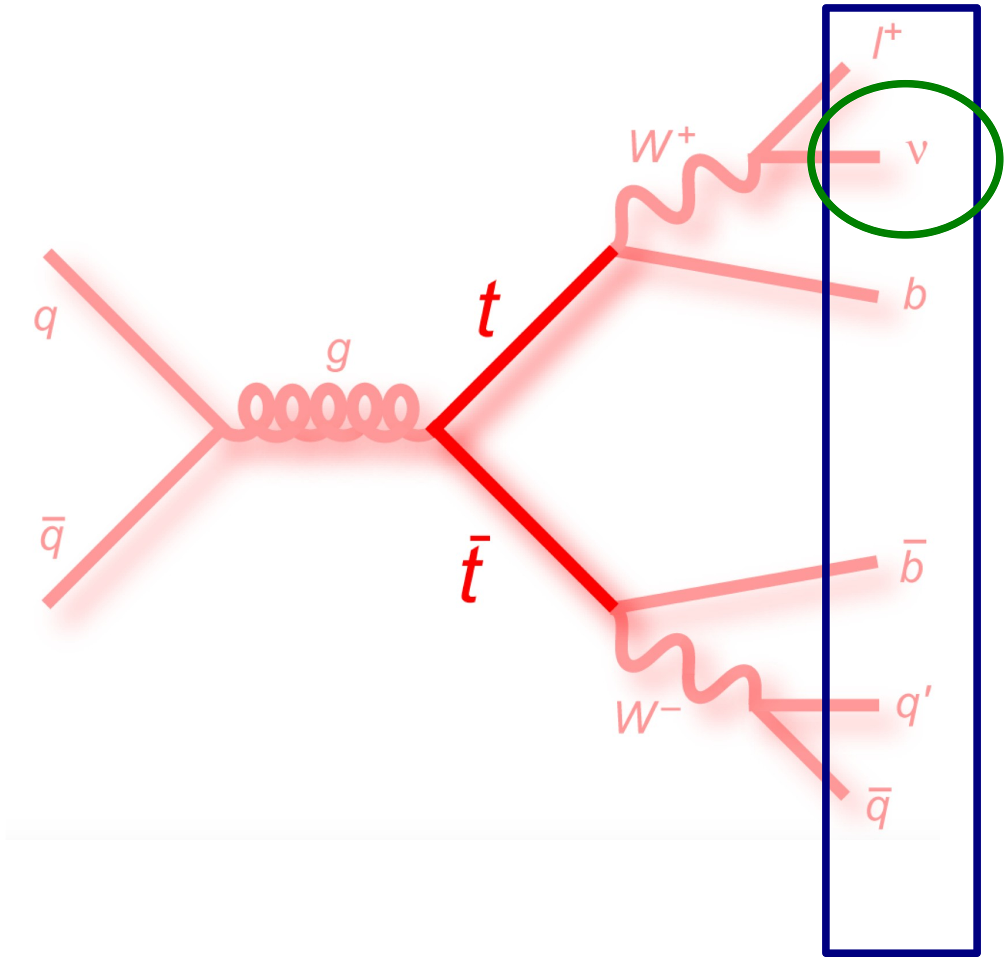
- $t\bar{t}$ event reconstruction using constrained kinematic fitter



- Input: 18 parameters based on jet, lepton and $\not{E}_T$ measurements

Reconstruction

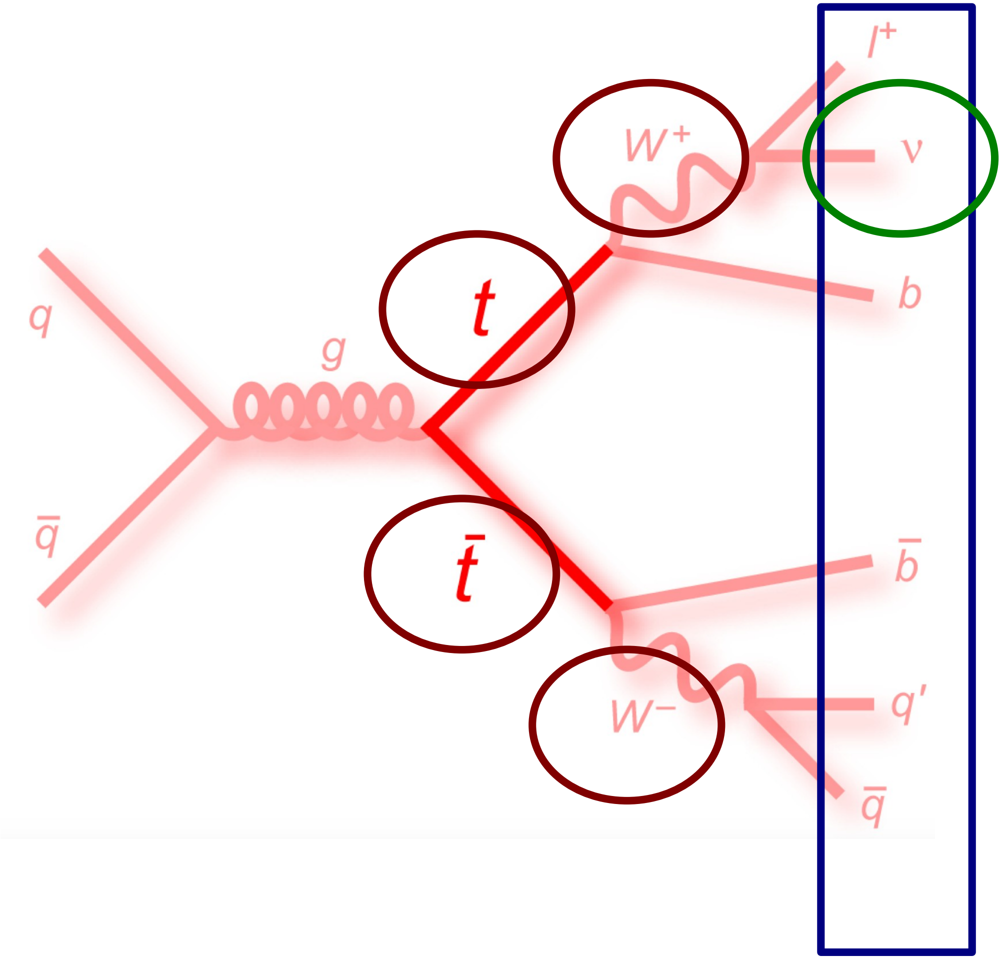
- $t\bar{t}$ event reconstruction using constrained kinematic fitter



- Input: 18 parameters based on jet, lepton and $\not{E}_T$ measurements
  - $\not{E}_T$: estimate for neutrino

Reconstruction

- $t\bar{t}$ event reconstruction using constrained kinematic fitter

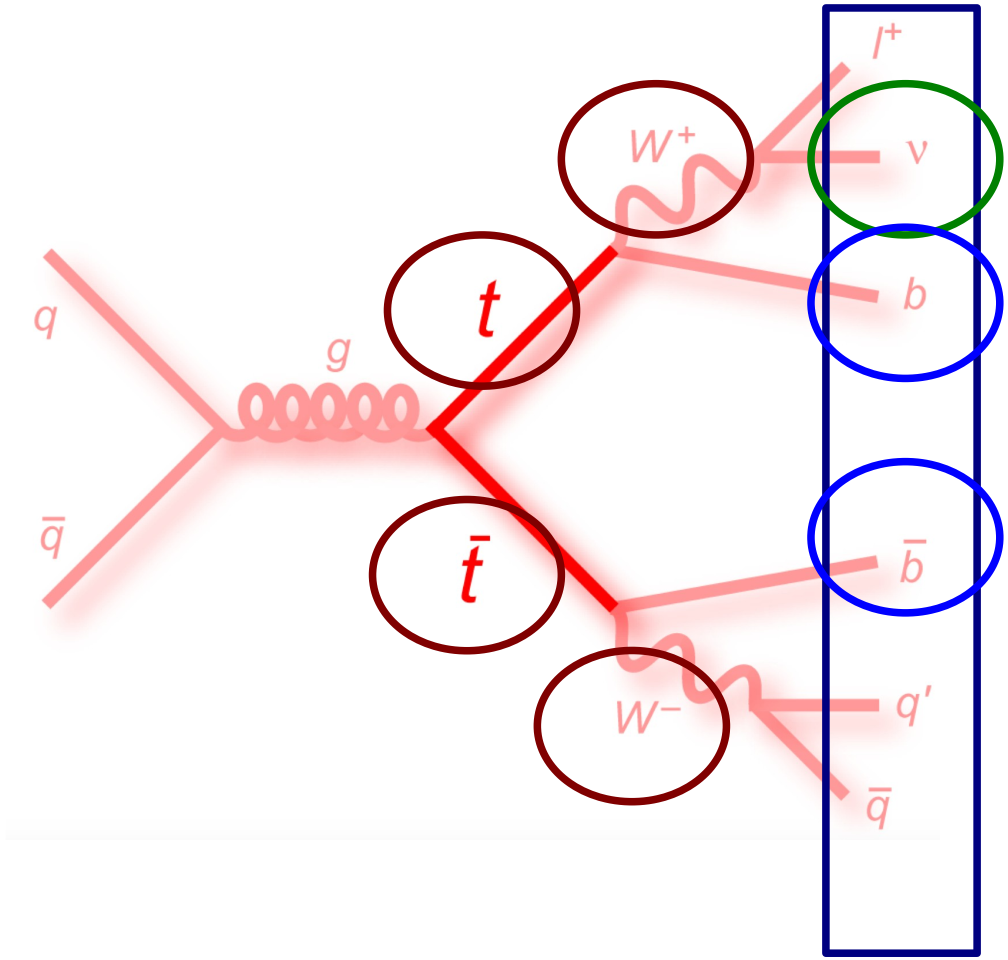


- Input: 18 parameters based on jet, lepton and $\not{E}_T$ measurements
  - $\not{E}_T$: estimate for neutrino
- Fix top and W mass to known values
  - p_z of neutrino: from W mass constraint

→ 24 possible solutions

Reconstruction

- $t\bar{t}$ event reconstruction using constrained kinematic fitter



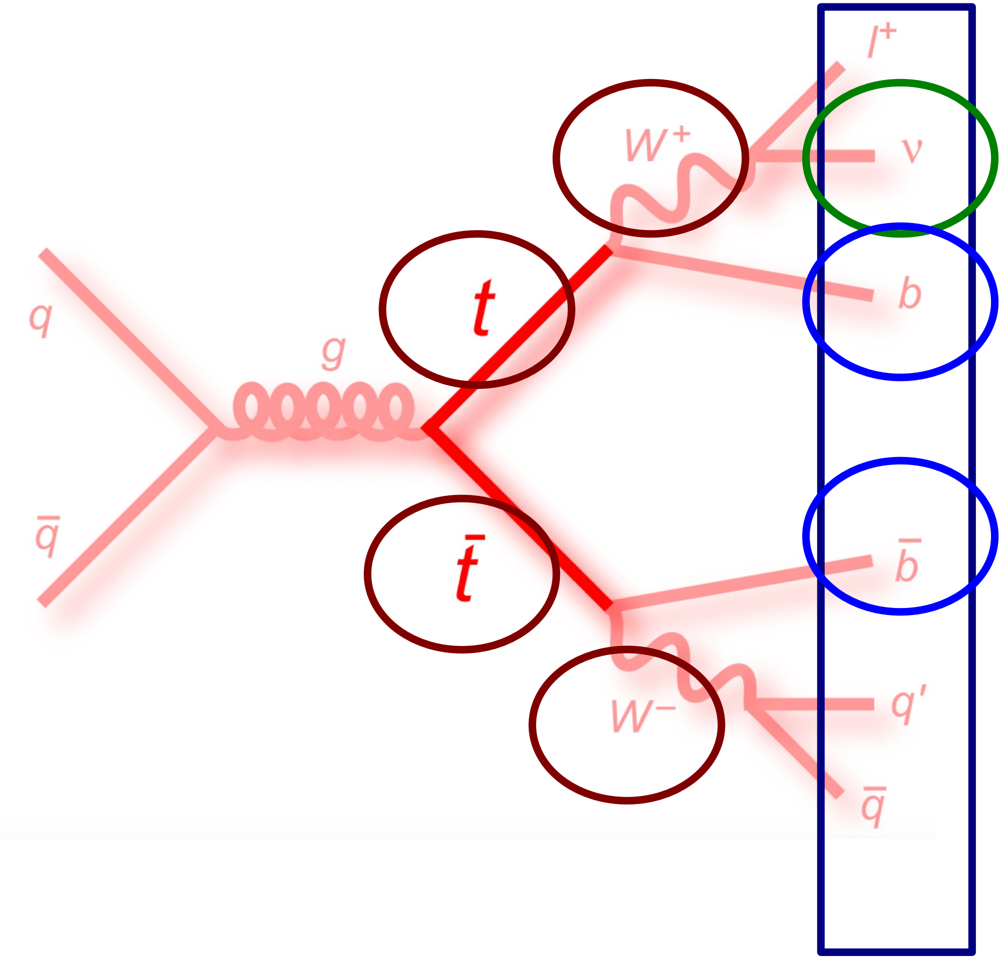
- Input: 18 parameters based on jet, lepton and $\not{E}_T$ measurements
  - $\not{E}_T$: estimate for neutrino
- Fix top and W mass to known values
  - p_z of neutrino: from W mass constraint

→ 24 possible solutions

  - Reduced by using b-tag info

Reconstruction

- $t\bar{t}$ event reconstruction using constrained kinematic fitter

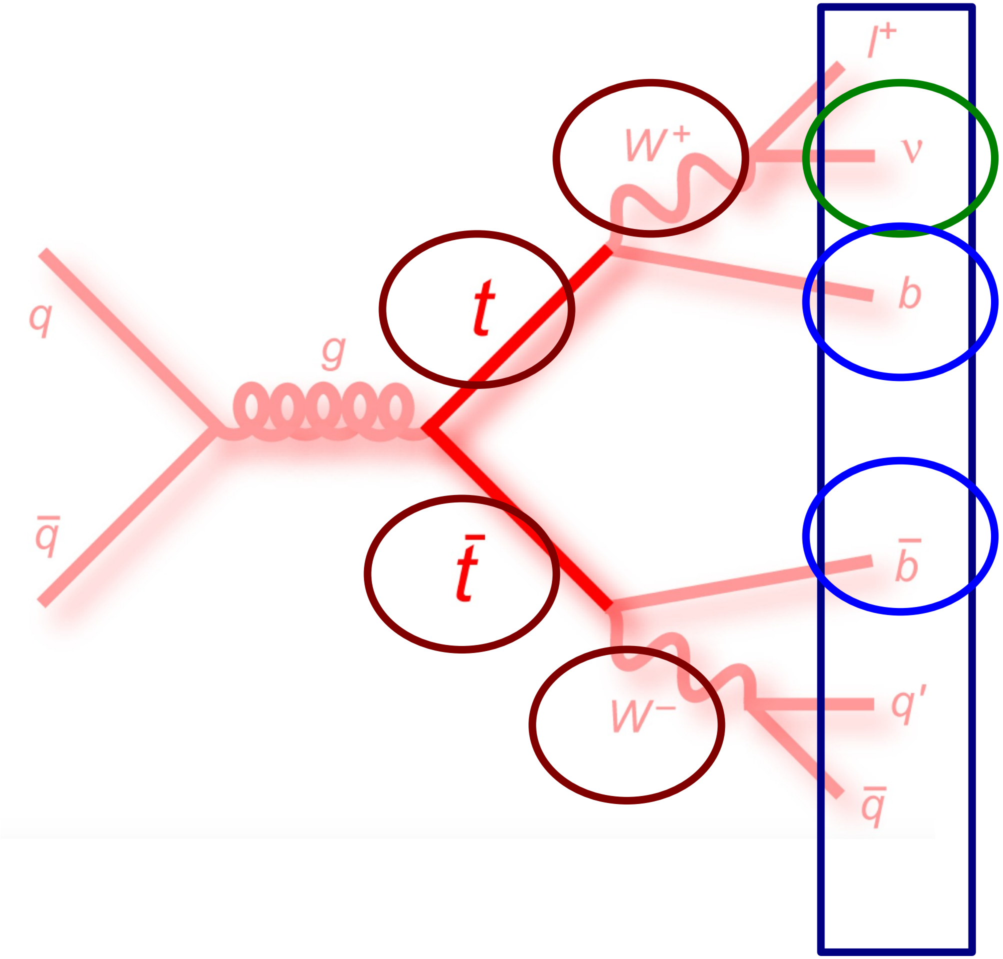


- Input: 18 parameters based on jet, lepton and $\not{E}_T$ measurements
  - $\not{E}_T$: estimate for neutrino
- Fix top and W mass to known values
  - p_z of neutrino: from W mass constraint

  → 24 possible solutions
  - Reduced by using b-tag info
- Solution with best χ^2 taken

Reconstruction

- $t\bar{t}$ event reconstruction using constrained kinematic fitter



- Input: 18 parameters based on jet, lepton and $\not{E}_T$ measurements
  - $\not{E}_T$: estimate for neutrino
- Fix top and W mass to known values
  - p_z of neutrino: from W mass constraint

  → 24 possible solutions
  - Reduced by using b-tag info
- Solution with best χ^2 taken

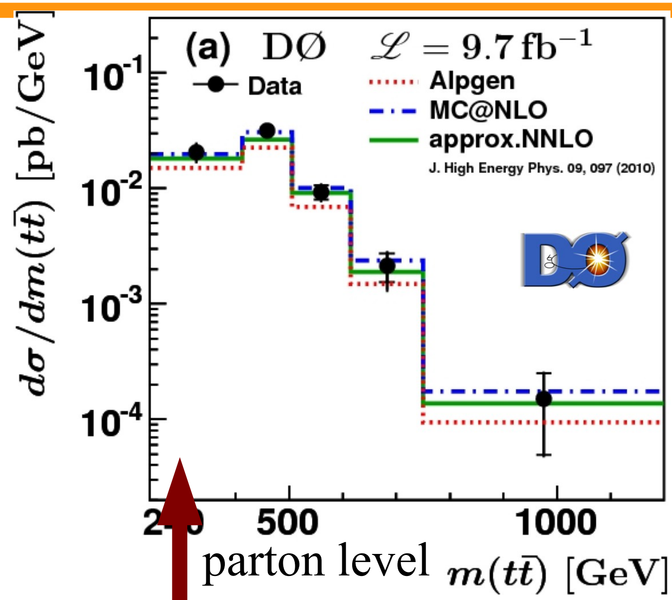
Correct assignment of quarks to jets in 80% of cases

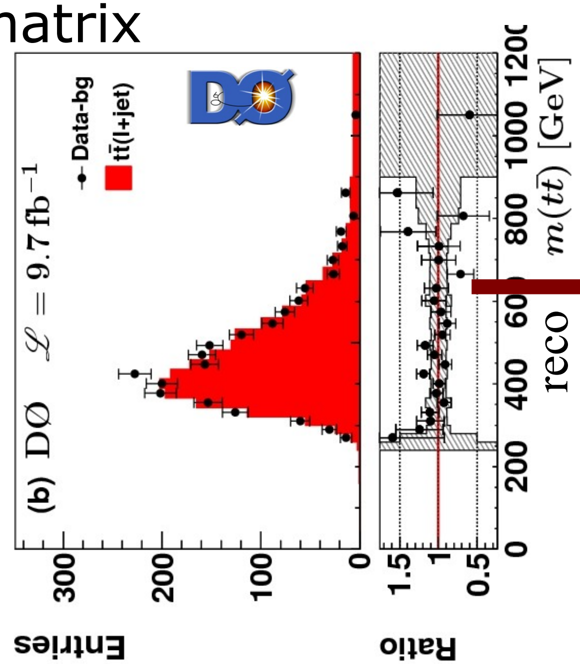
Unfolding

- Measurement: Defined for parton-level top quarks including off-shell effects
  - Correction for detector and acceptance effects using regularized unfolding
    - Regularization based on derivative
    - Use reco-bins twice as narrow as generator level bins in migration matrix
- Full correlation matrix provided
- Cross section:

$$\frac{d\sigma_i}{dX} = \frac{N^{unfold}}{L \cdot B \cdot \Delta X_i}$$

B: branching fraction
L: lumi
i: bin





~~magic~~

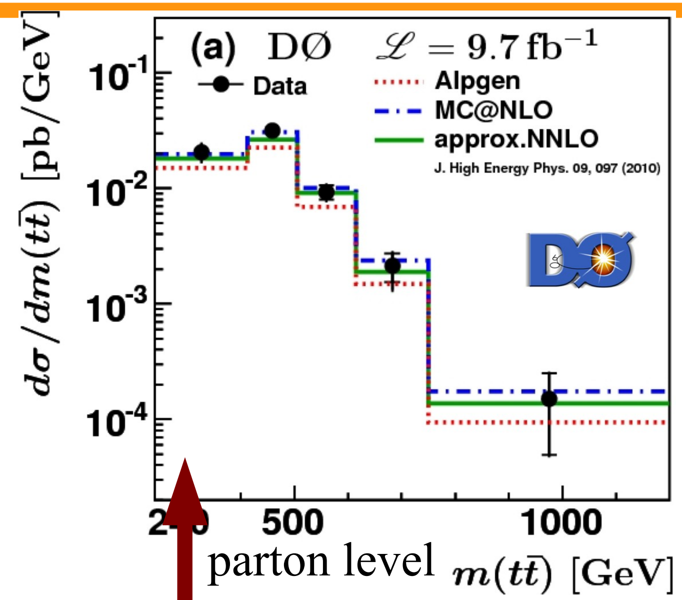
unfolding

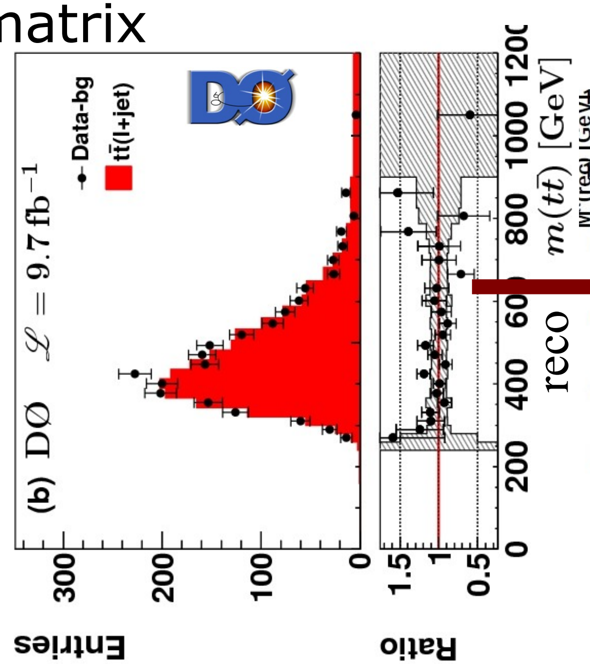
Unfolding

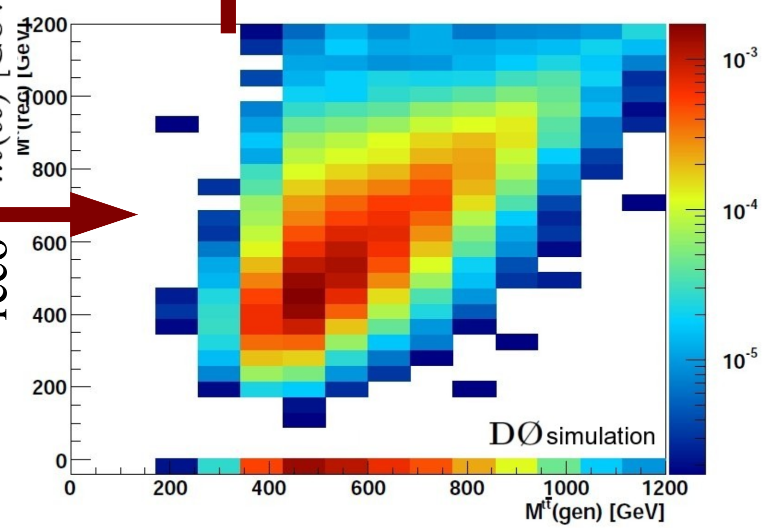
- Measurement: Defined for parton-level top quarks including off-shell effects
  - Correction for detector and acceptance effects using regularized unfolding
    - Regularization based on derivative
    - Use reco-bins twice as narrow as generator level bins in migration matrix
- Full correlation matrix provided
- Cross section:

$$\frac{d\sigma_i}{dX} = \frac{N^{unfold}}{L \cdot B \cdot \Delta X_i}$$

B: branching fraction
L: lumi
i: bin







Systematic Uncertainties

- Several systematic uncertainties affecting measurement
  - Modeling of signal
  - PDFs
  - Detector modeling
  - Sample composition
  - Regularization strength

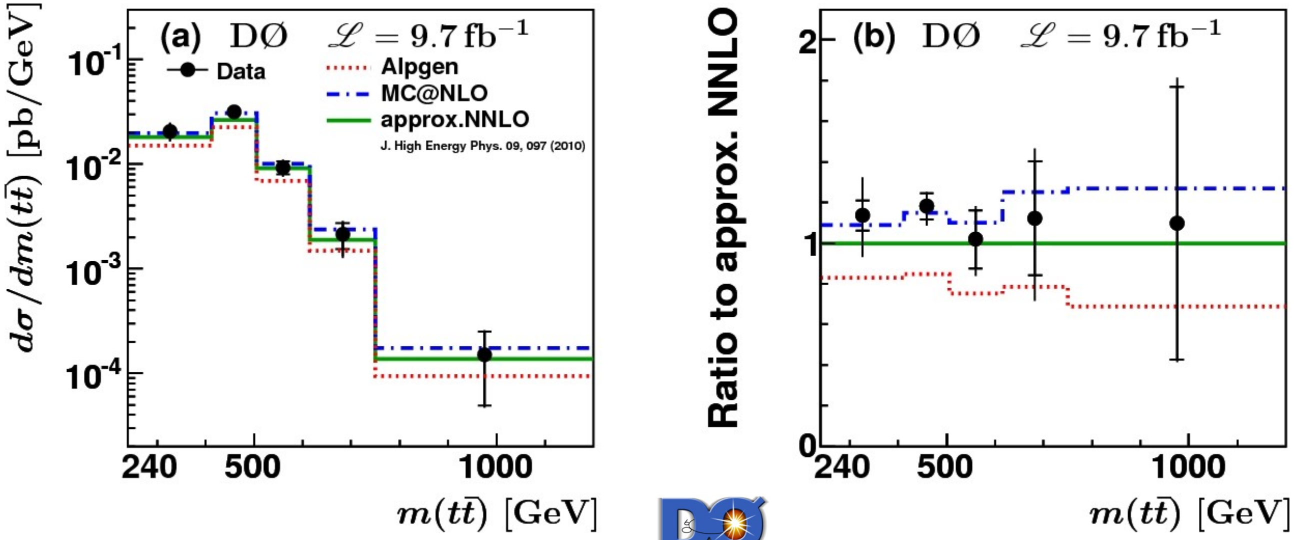
Source of uncertainty	Uncertainties, %	
	δ_{incl}	$\lvert\delta_{\text{diff}}\rvert$
Signal modeling	$^{+5.2}_{-4.4}$	4.0 – 14.2
PDF	$^{+3.0}_{-3.4}$	0.9 – 4.4
Detector Modeling	$^{+4.0}_{-4.1}$	3.1 – 13.7
Sample composition	± 1.8	2.8 – 9.2
Regularization strength	± 0.2	0.8 – 2.1
Integrated luminosity	± 6.1	6.1 – 6.1
Total systematic uncertainty	$^{+9.6}_{-9.3}$	8.5 – 23.1

- Estimated by changing migration matrix and background contribution
  - Largest uncertainties usually at large values of $m_{t\bar{t}}$, $|y^{top}|$, & p_T^{top}

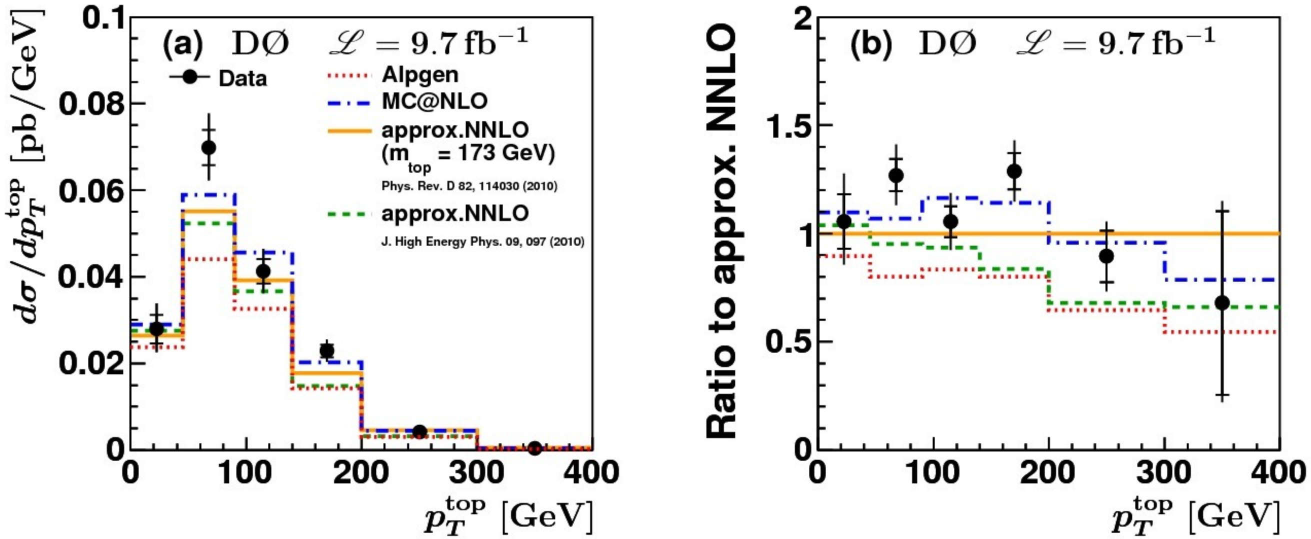
Results

- Differential distributions: (events with ≥4 jets, ≥1 b-tagged)

- $m_{t\bar{t}}$:

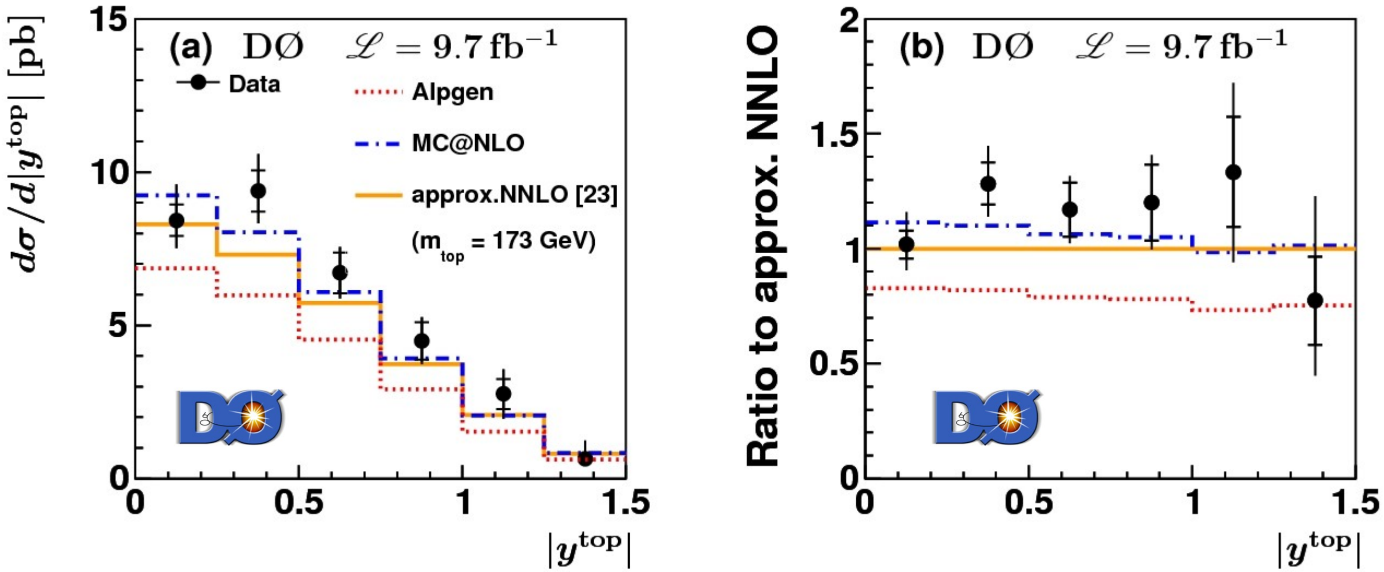


- p_T^{top}



More Results

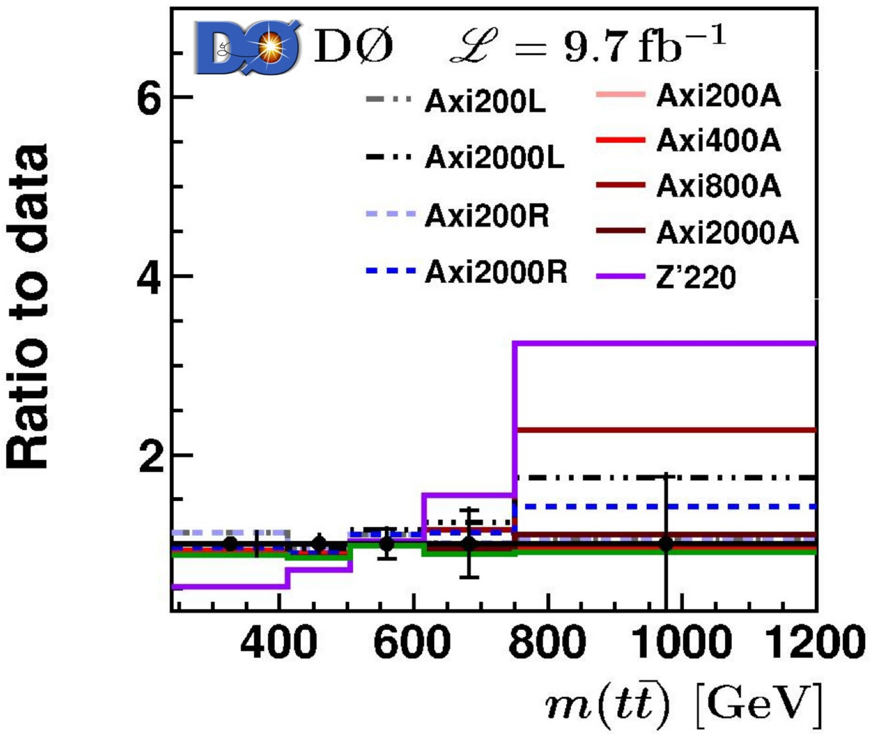
- $|y_{top}|$:

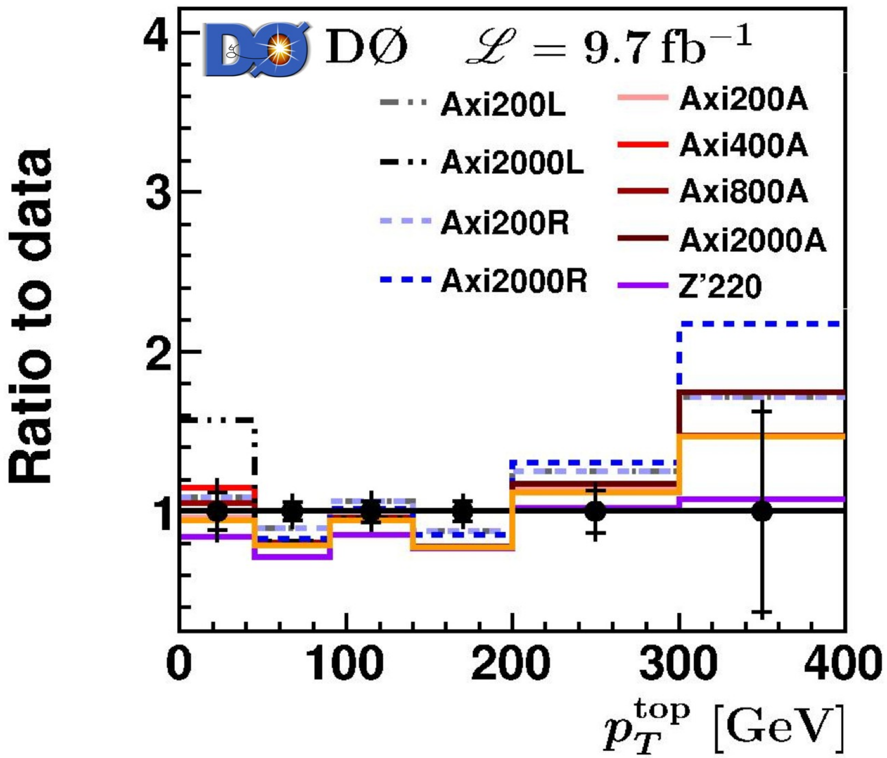


- In general agreement with approx. NNLO & QCD generator predictions
  - ALPGEN low in absolute normalization
  - $|y_{top}|$: MC@NLO describes data better than approximate NNLO prediction

Axigluon Models

- Asymmetry at the Tevatron: slightly larger than predicted
  - Possible new physics model: axigluons
- Differential distributions sensitive to different models





Summary

- Inclusive and differential $t\bar{t}$ cross section measurements
  - Test of QCD
  - Tuning of MC
  - Complementary to LHC

- More information here:

DØ: http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.htm

CDF: http://www-cdf.fnal.gov/physics/new/top/top.html

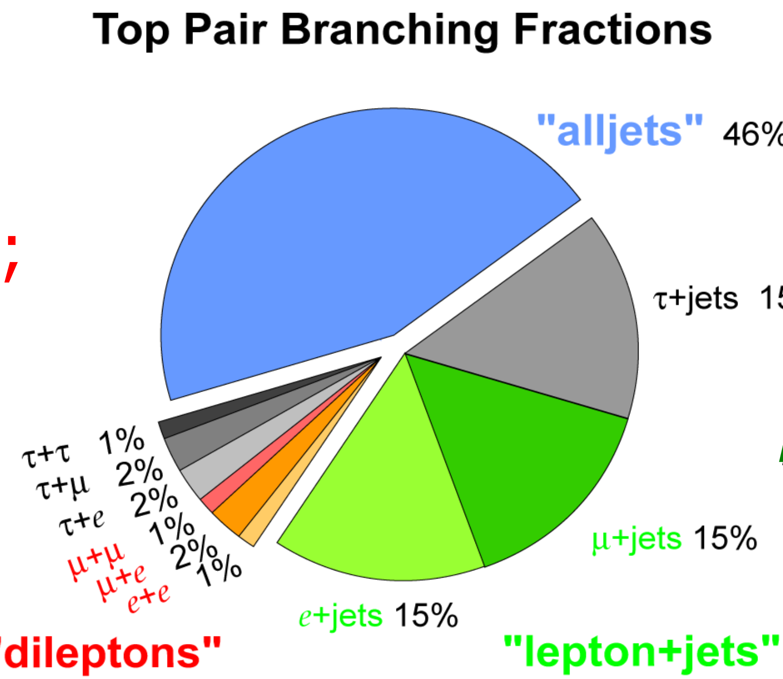
BACKUP

$t\bar{t}$ Final States

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

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

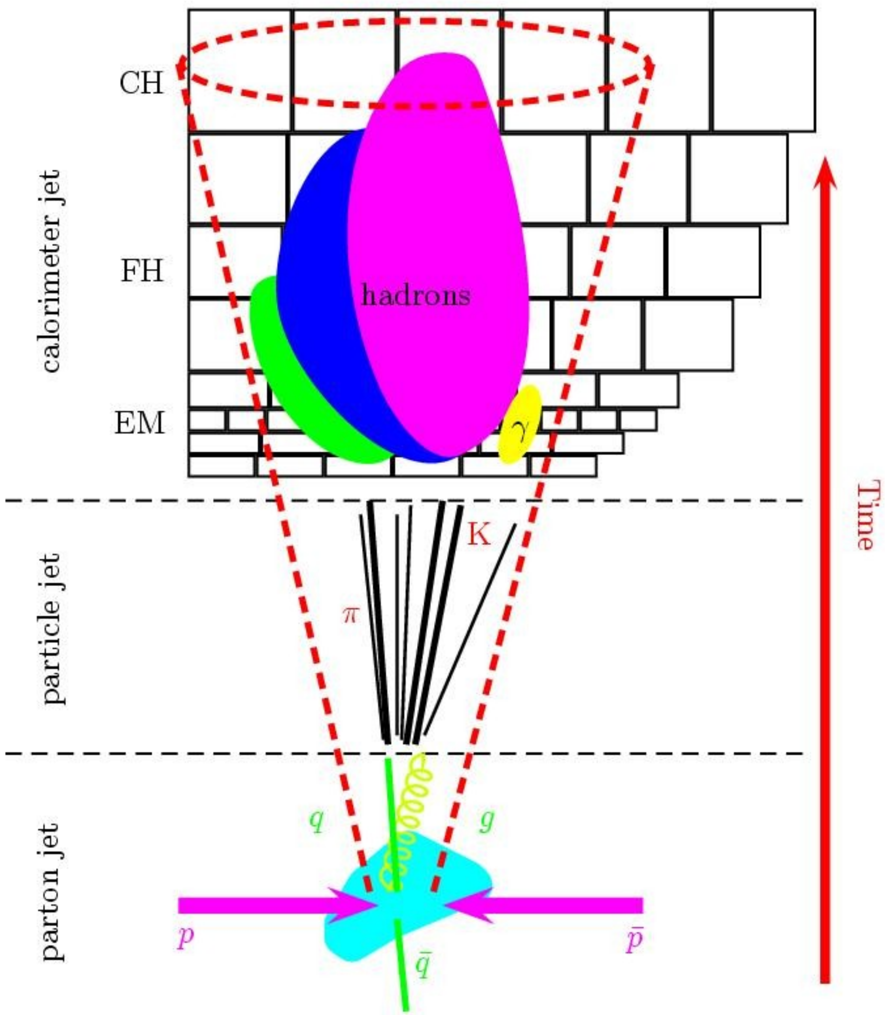
pure hadronic:
≥6 jets (2 b-jets)



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

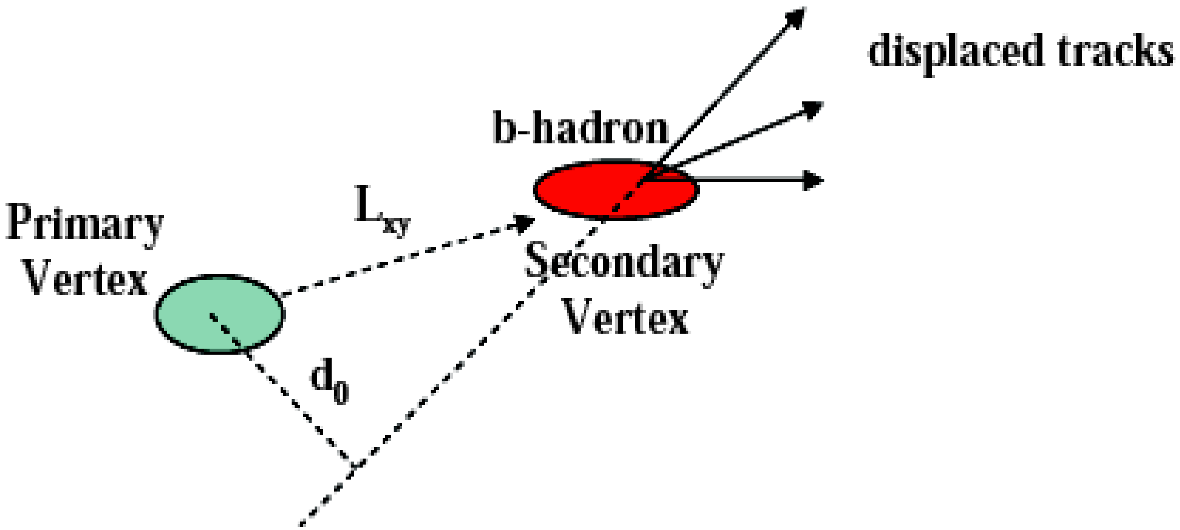
lepton+jets:
1 isolated lepton;
Missing E_T from neutrino;
≥4 jets (2 b-jets)

Jet Energy Scale



Identification of b-jets

- Important to increase $t\bar{t}$ content
- B-Hadron: travels some millimeters before it decays



- Use
  - Information, that the decay vertex of the b-Quarks are displaced from the primary vertex (SVT: used by CDF)
  - Information about displaced tracks
- Neural Network (D0)
  combines properties of displaced tracks and displaced vertices

$t\bar{t}$ Cross Section: Tevatron Combination

- BLUE combination of CDF and D0 input combinations
  - Split systematics into classes according to correlation

	CDF	D0		Tevatron
Central value of $\sigma_{\bar{t}t}$	7.63	7.56		7.60
Sources of systematic uncertainty			Correlation	
Modeling of the detector	0.17	0.22	NO	0.13
Modeling of signal	0.21	0.13	YES	0.18
Modeling of jets	0.21	0.11	NO	0.13
Method of extracting $\sigma_{t\bar{t}}$	0.01	0.07	NO	0.03
Background modeled from theory	0.10	0.08	YES	0.10
Background based on data	0.08	0.06	NO	0.05
Normalization of Z/γ^* prediction	0.13	–	NO	0.08
Luminosity: inelastic $p\bar{p}$ cross section	0.05	0.30	YES	0.15
Luminosity: detector	0.06	0.35	NO	0.14
Total systematic uncertainty	0.39	0.56		0.36
Statistical uncertainty	0.31	0.20		0.20
Total uncertainty	0.50	0.59		0.41