Top Quark Measurements by the DØ Collaboration

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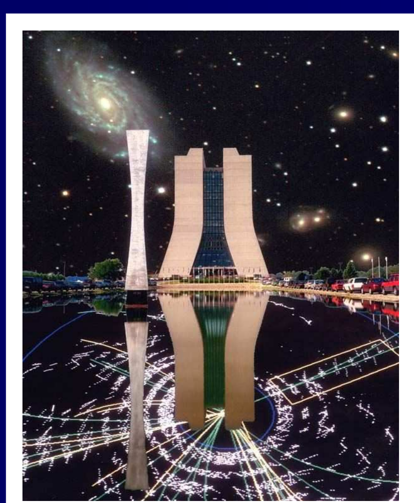
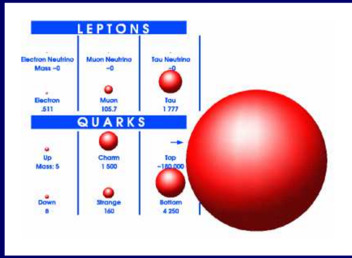


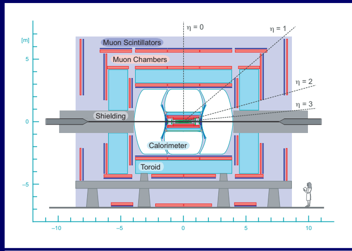
SMU Physics Seminar

March 5, 2007

Outline



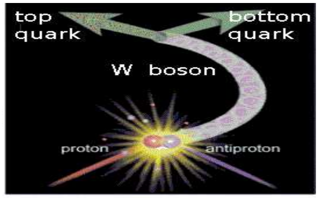
Why is the top quark interesting?



How do we produce and detect top quarks?

Top Quark Pair Production

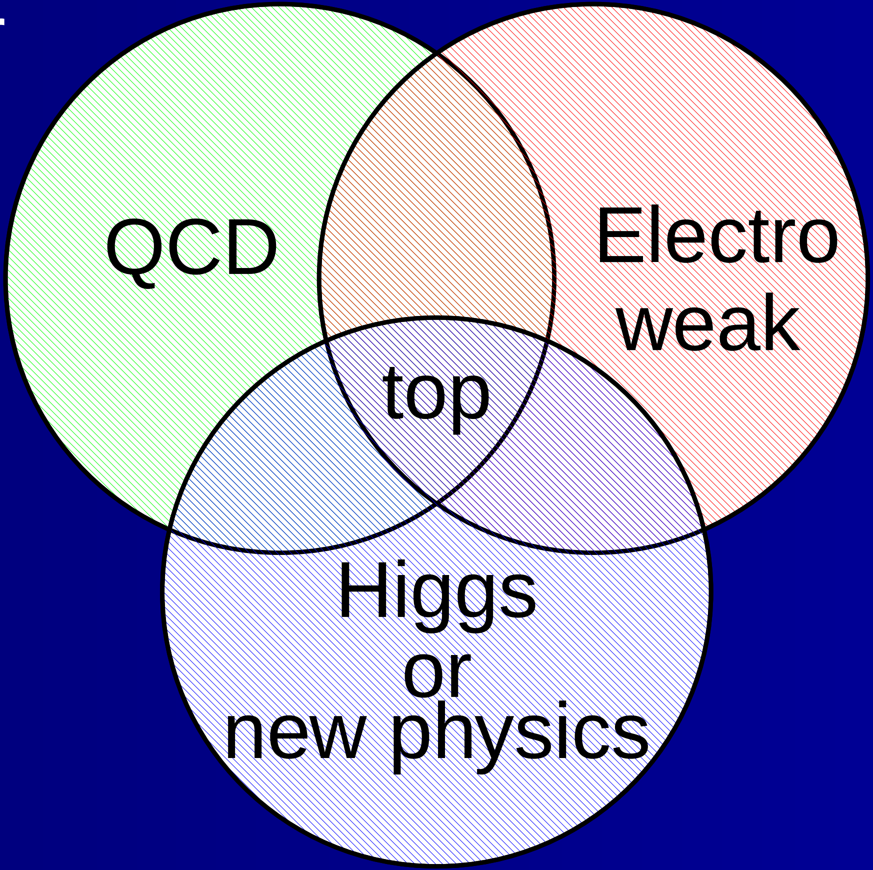
Mass



Single Top Quark Production

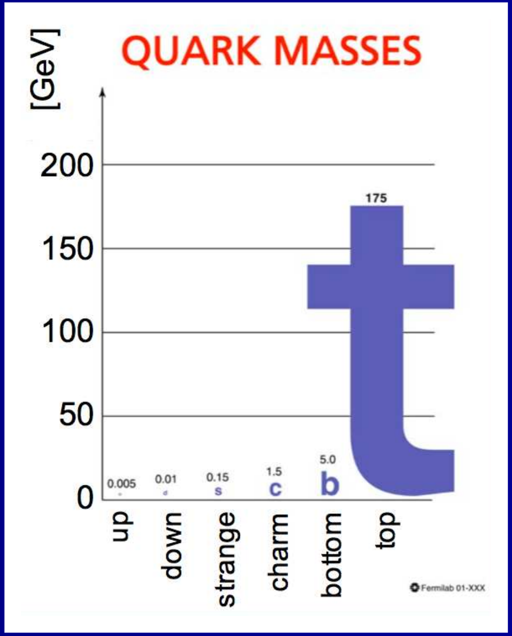
Unique Physics Laboratory

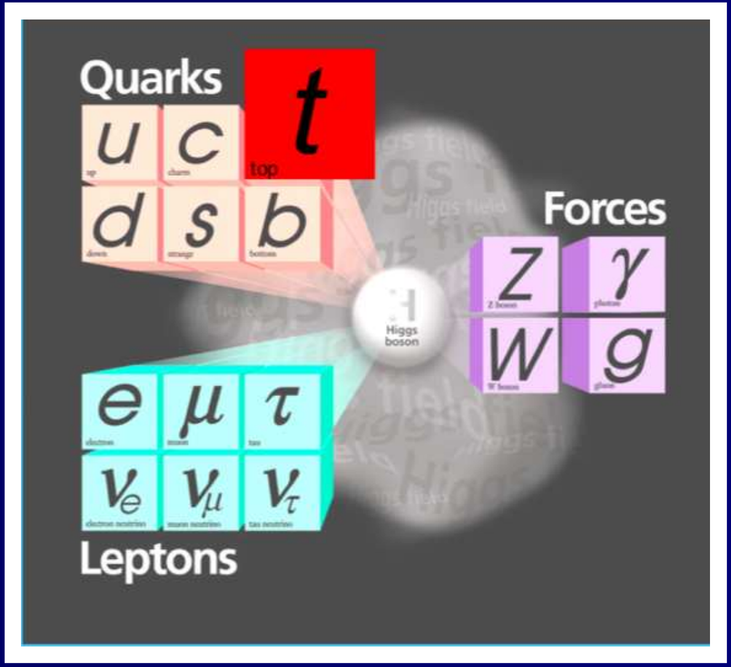
The top quark exists at the interface between Electroweak and QCD physics. Its production and properties are sensitive to the existence of new physical phenomena and offer insights on the Electroweak symmetry breaking mechanism.



What is the Top Quark?

- Discovered in 1995 by CDF and DØ at Fermilab
- $m_t \approx 175$ GeV *vs* $m_b \approx 5$ GeV
  Top-Higgs Yukawa coupling $\lambda_t = \sqrt{2}\frac{m_t}{v} \approx 1$
- We still know very little about the top quark. Is it the particle required by the Standard Model?
- If it is a normal quark, then it is still special:





$m_t > m_W$ so $t \to Wb$

$\Gamma_t \approx 1.4$ GeV

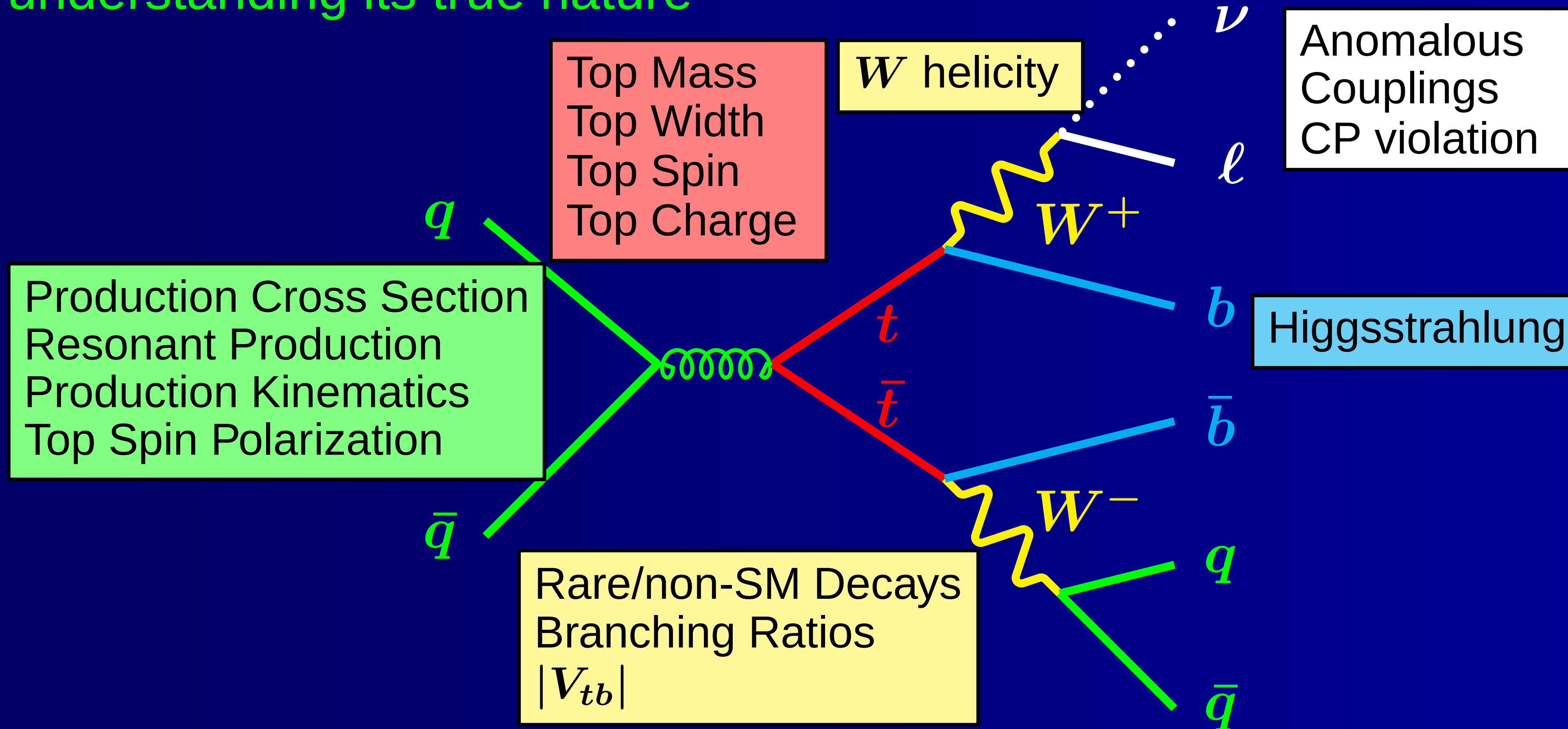
$\tau_t \approx 4 \times 10^{-25}$ sec

$\Rightarrow$ so top quarks decay before they interact via the strong force $\left(\frac{1}{\Lambda_{QCD}} \approx 3 \times 10^{-24}\,\mathrm{sec}\right)$.

Top quarks are effectively bare quarks!

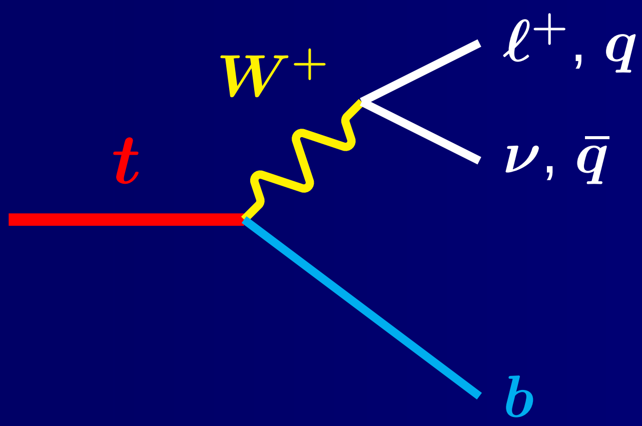
Top Quark Physics

Precision measurements of top quark properties are crucial to understanding its true nature



We are now transitioning between the discovery phase and making precision measurements of top quark properties

Classifying Top Events

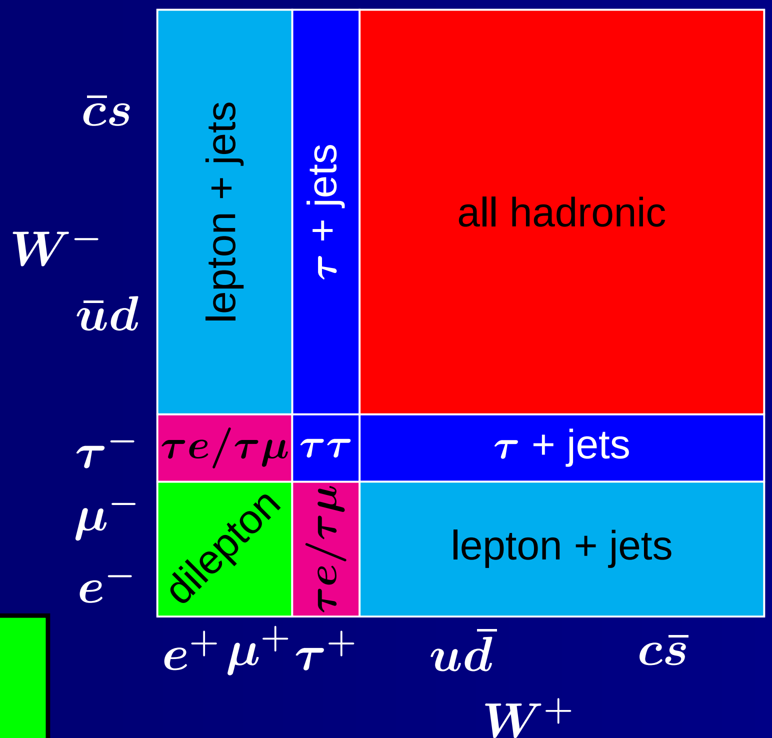


$t \to Wb$ is $\approx 100\%$

It is important to measure all decay channels as they have different sensitivities to new physics

(eg, $H^\pm$ in τ)

$t\bar{t}$ Decay Modes



all hadronic
high BF
high BG

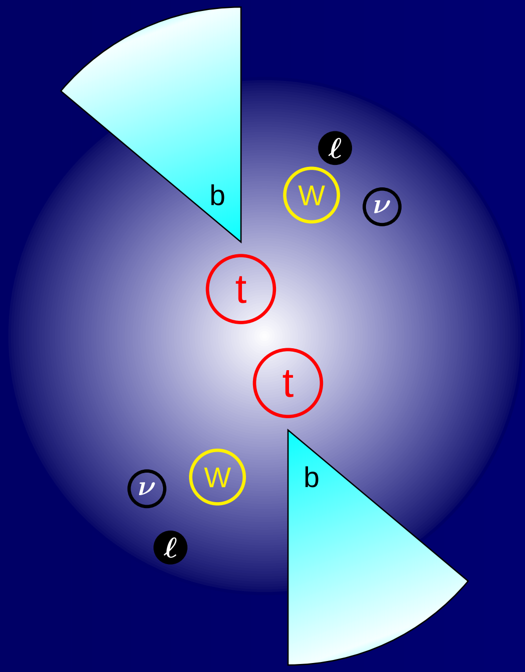
dilepton
low BF
low BG

lepton + jet
(includes $\tau \to e/\mu$)
high BF
managable BG

Classifying Top Events

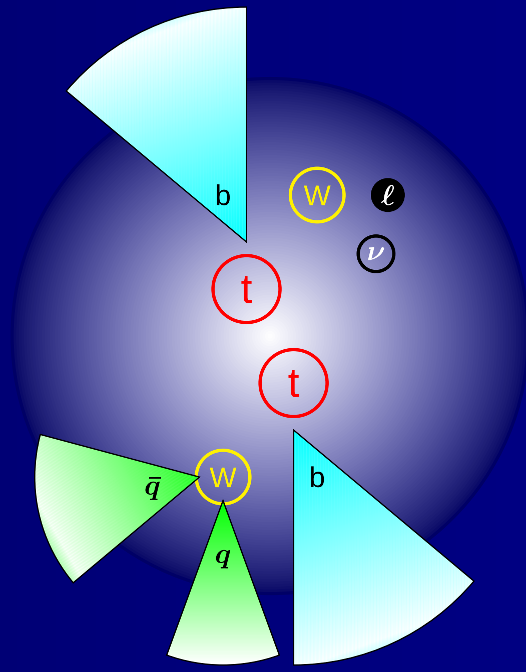
Dilepton

Two high-p_T leptons
Missing $\not{E}_T$
Two high-p_T jets



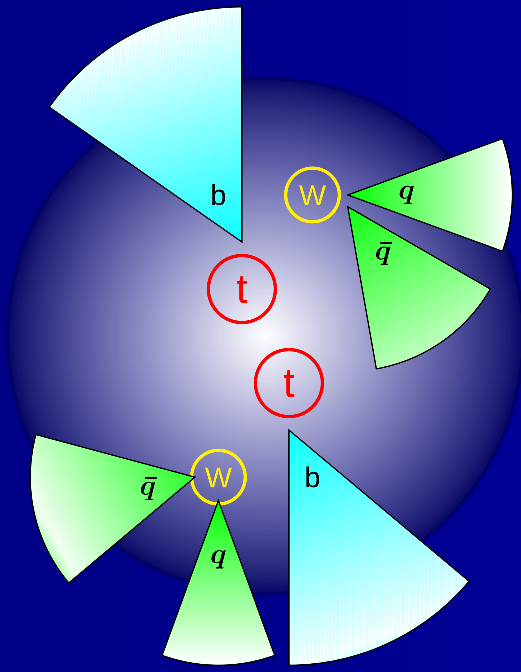
Lepton + Jets

One high-p_T lepton
Missing $\not{E}_T$
Four high-p_T jets



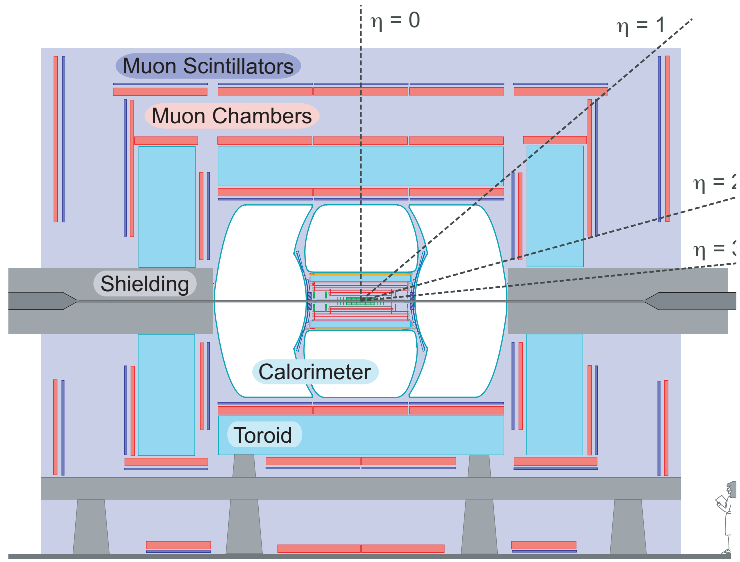
All Hadronic

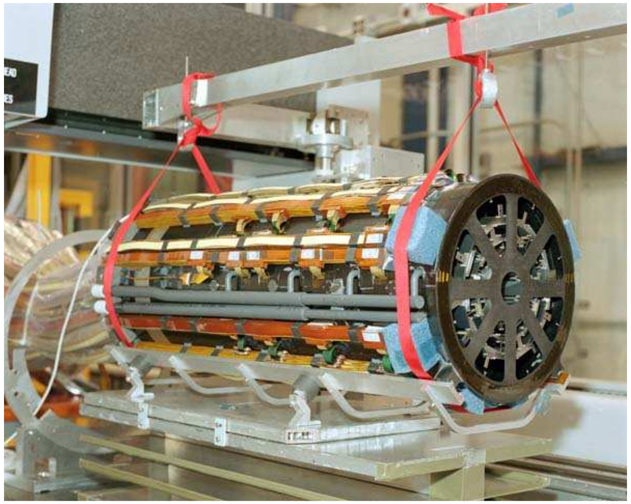
Six high-p_T jets

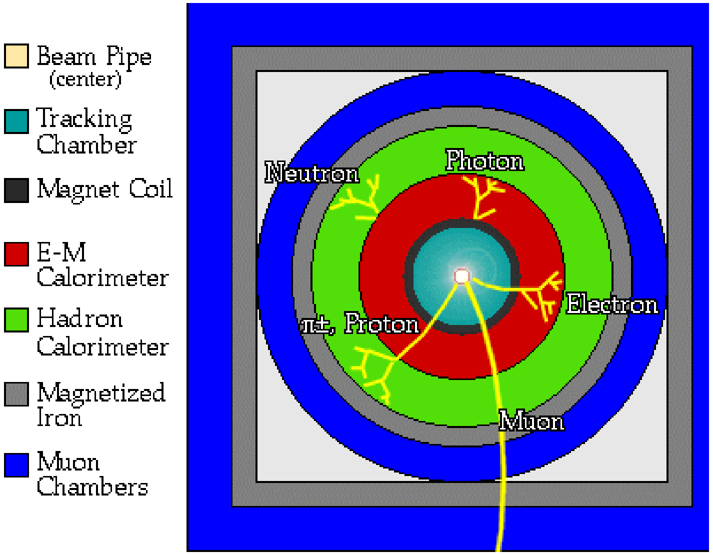


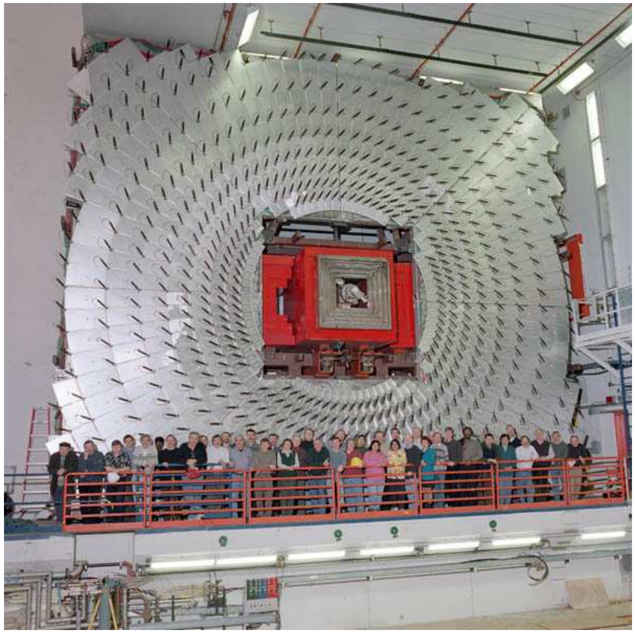
Need to reconstruct electrons, muons, jets, b-jets, and missing transverse energy

DØ Detector


η = 0
η = 1
Muon Scintillators
Muon Chambers
Shielding
Calorimeter
Toroid



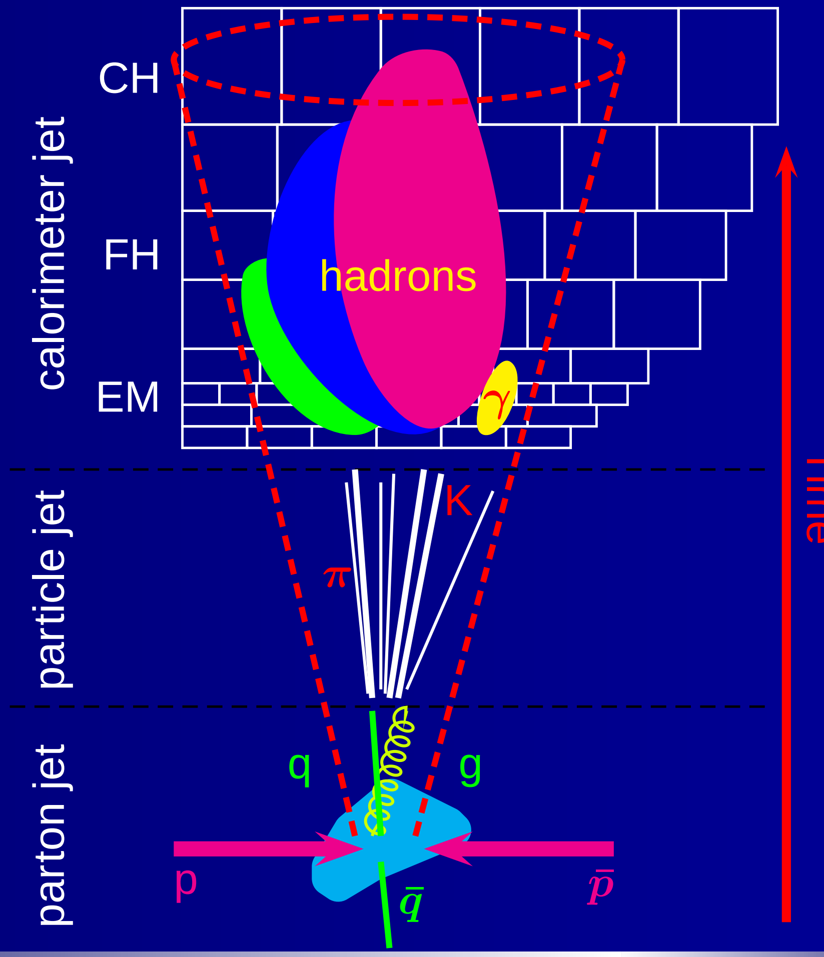

Beam Pipe (center)
Tracking Chamber
Magnet Coil
E-M Calorimeter
Hadron Calorimeter
Magnetized Iron
Muon Chambers
Neutron
Photon
Electron
π±, Proton
Muon



Jet Energy Scale

Top quark measurements require a clean mapping between reconstructed objects and partons

- Reconstruct jets using iterative cone algorithm with midpoints ($\mathcal{R}_{cone} = 0.5$)
- Calibrate jet energies to particle level
- Map jets to partons
- Correct jet energies to parton level

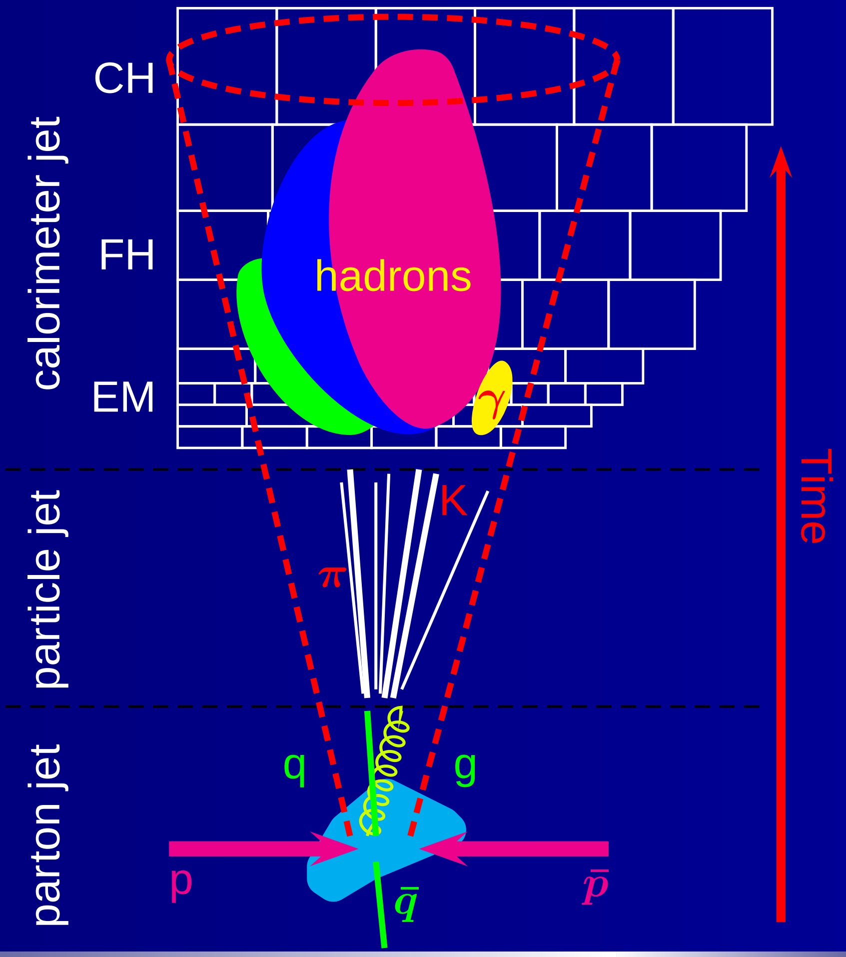


Jet Energy Scale

Top quark measurements require a clean mapping between reconstructed objects and partons

- Response of calorimeter to jets is a dominant systematic uncertainty
- Jet energy scale derived from samples of
  - zero and minimum bias events
  - photon + jet events
  - Z + jet events
  - dijet events

  in data and simulation



Jet Energy Scale

Top quark measurements require a clean mapping between reconstructed objects and partons

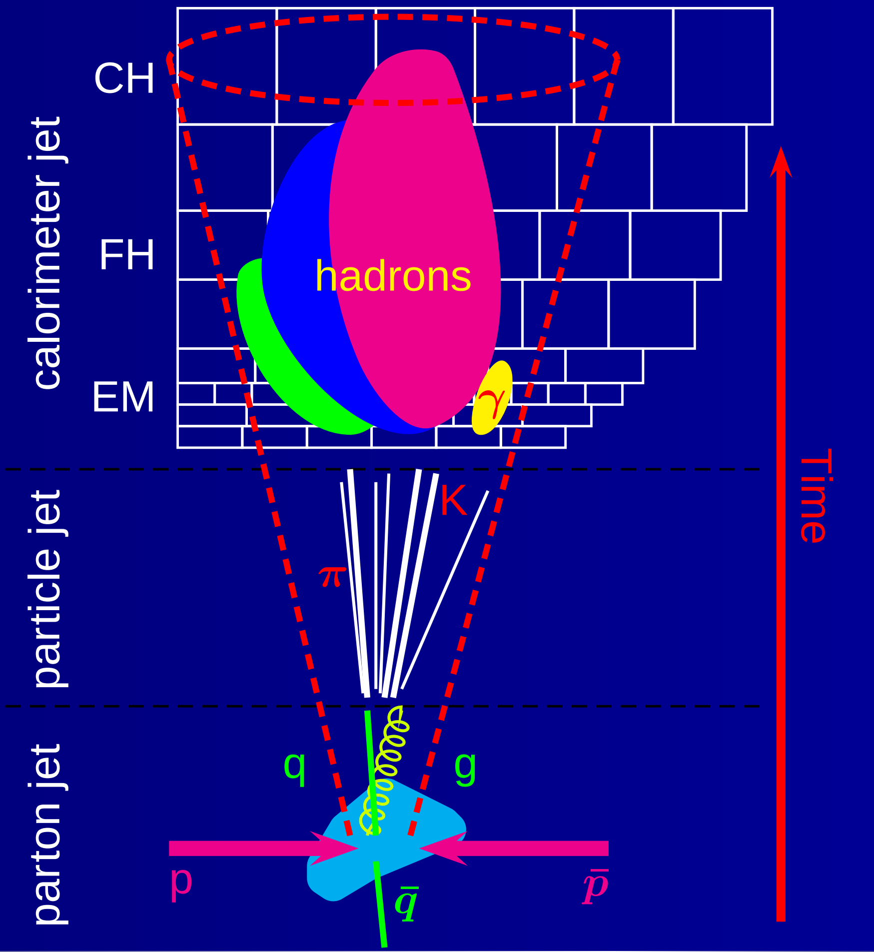
- Response of calorimeter to jets is a dominant systematic uncertainty

Offset Correction
multiple interactions
underlying event

$$E_{corr} = \frac{E_{meas} - O}{R \times S}$$

Response Correction
hadronic response
uninstrumented regions

Showering Correction
particles in-&-out of cone



Jet Energy Scale

Top quark measurements require a clean mapping between reconstructed objects and partons

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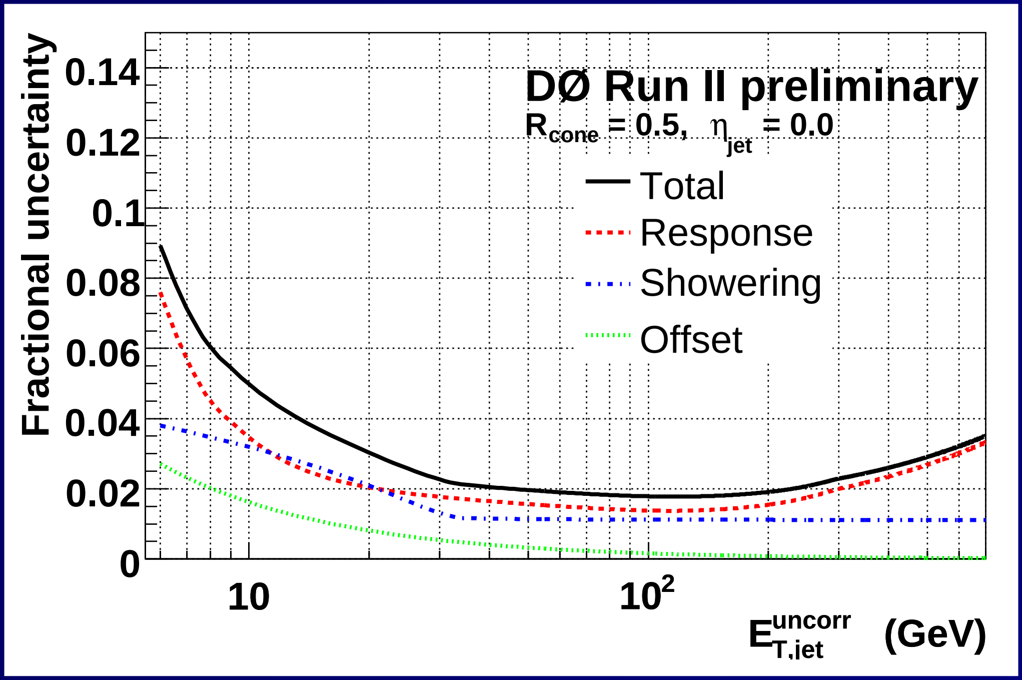
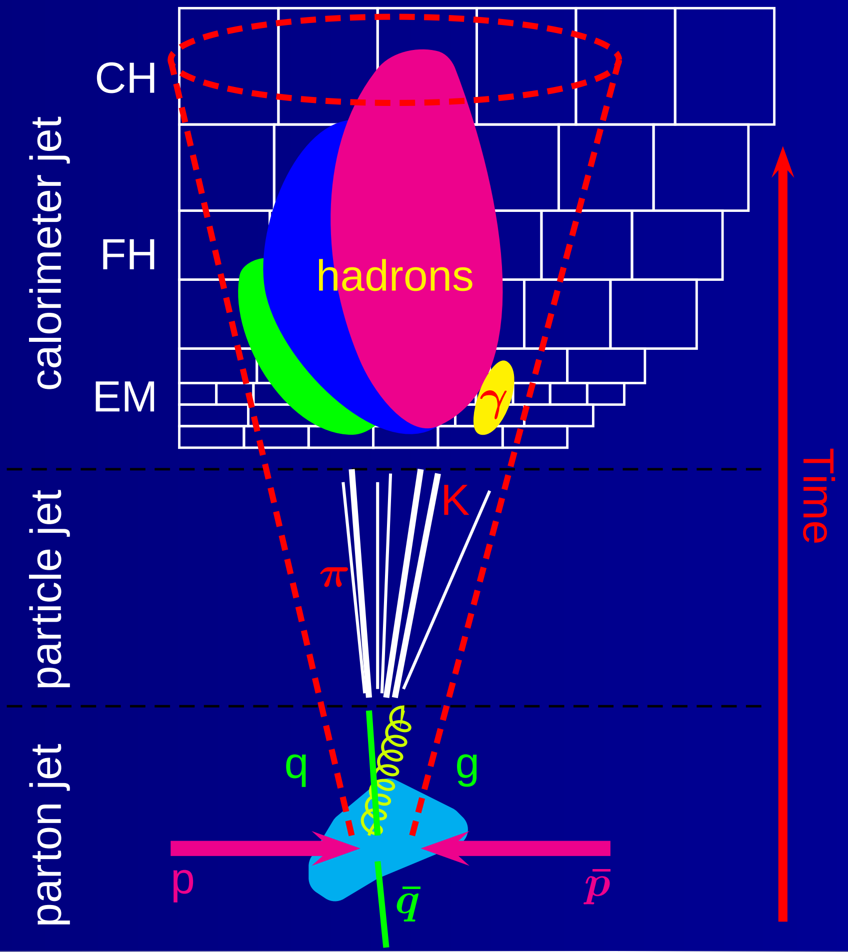
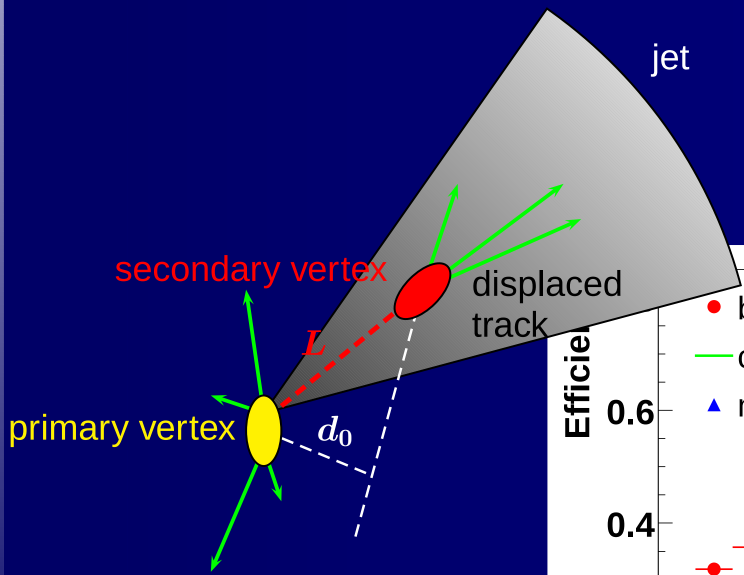


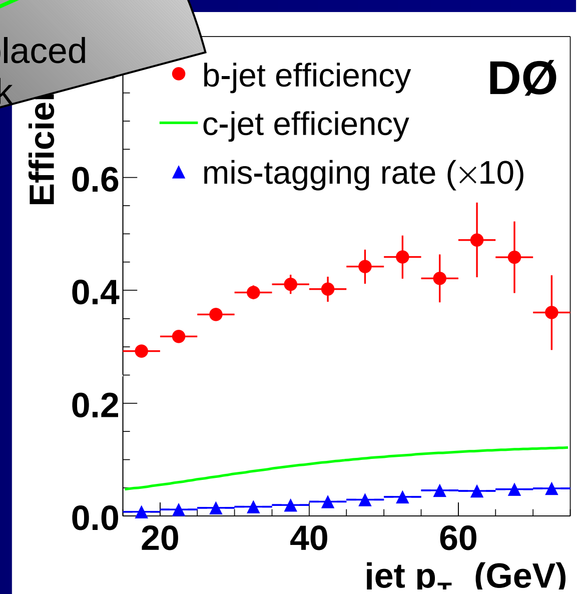


b Jet Identification

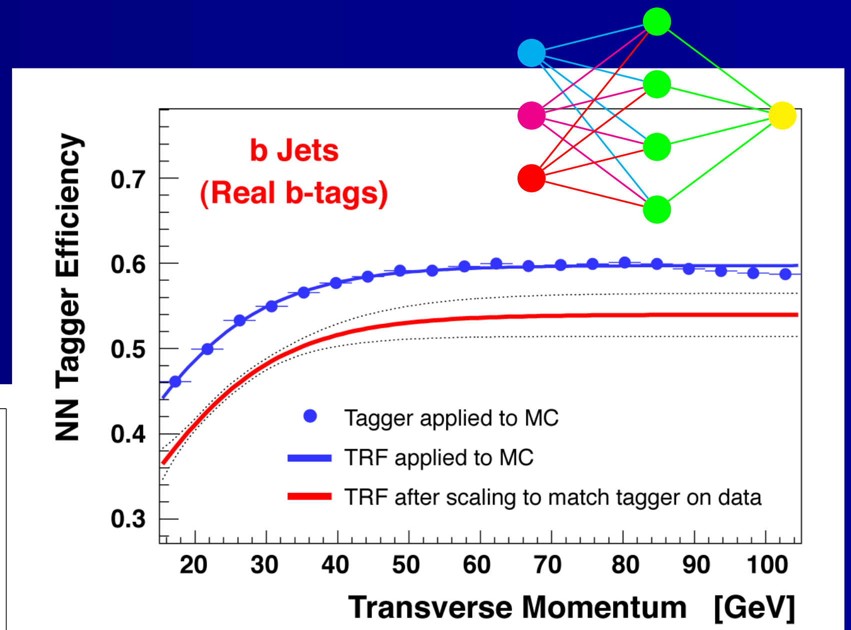
b-jet identification is an important discriminant between top signal and background

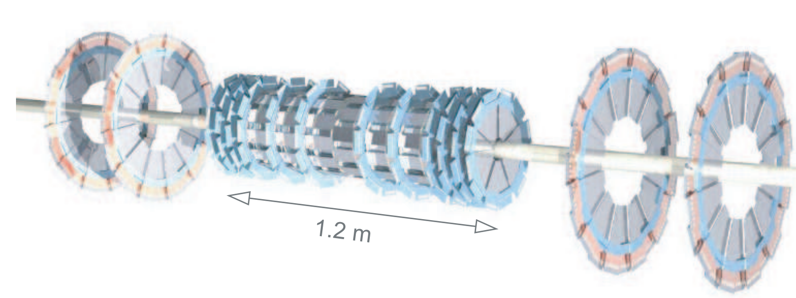
Secondary Vertex Tagger



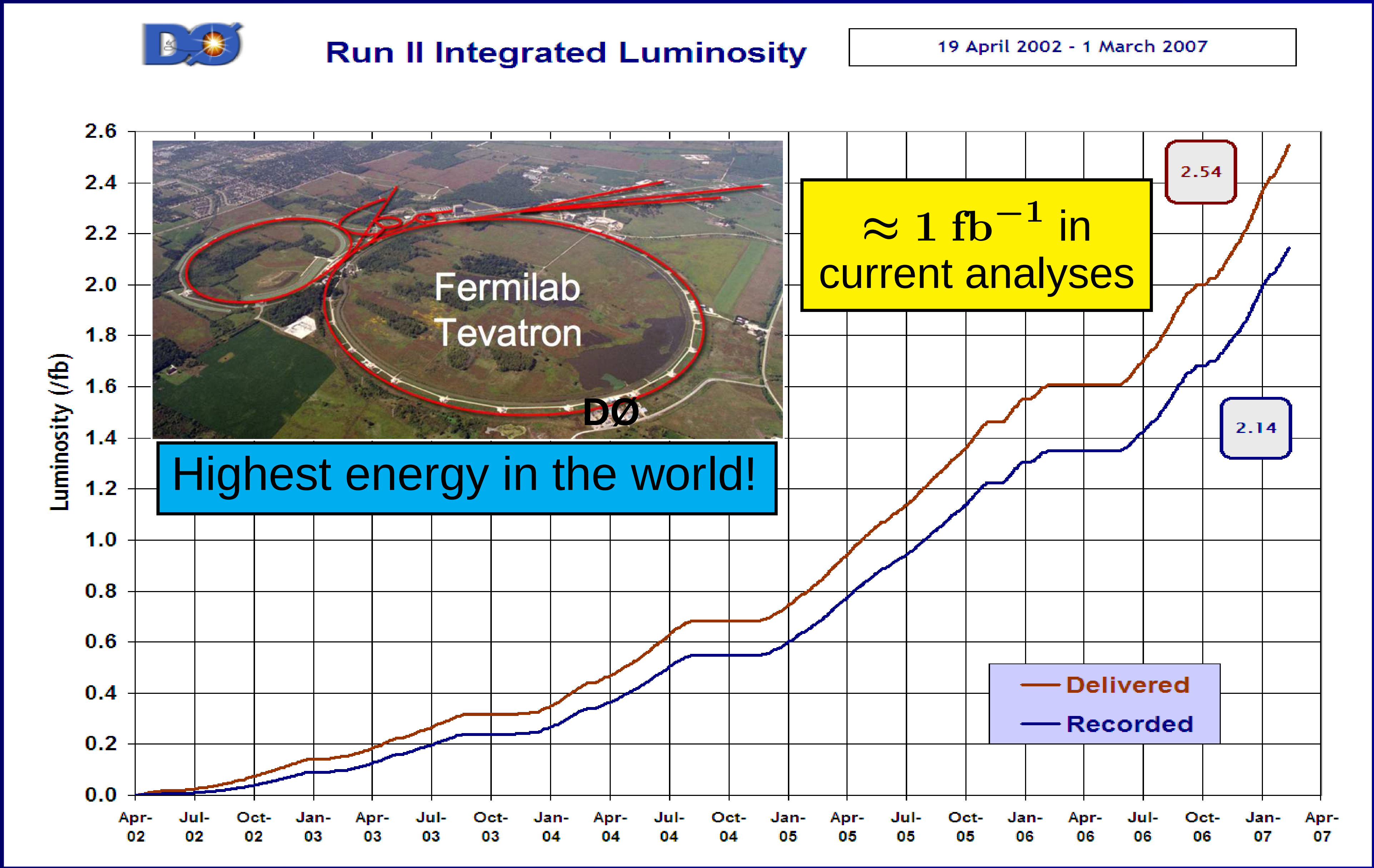


Neural Network Tagger





Fermilab Tevatron $p\bar{p}$ Collider



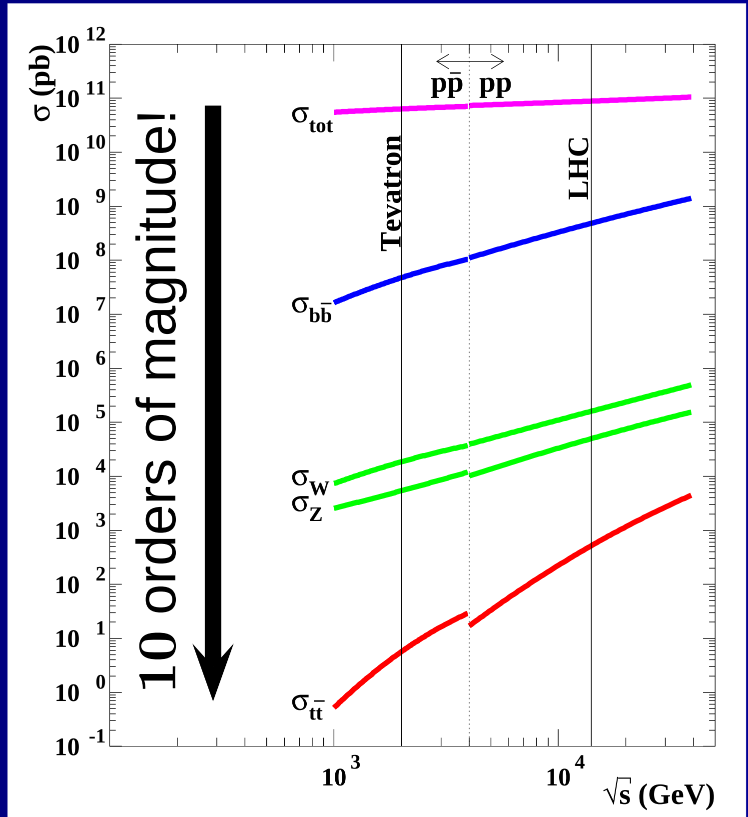
Top Quark Pair Production

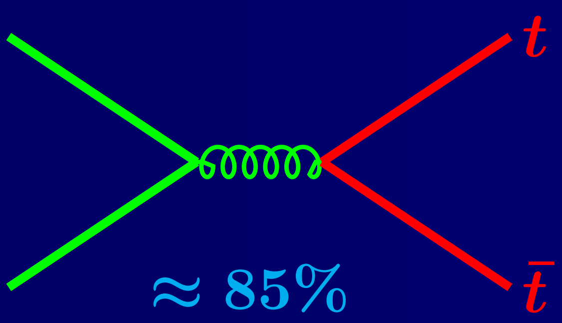
$t\bar{t}$ Cross Section

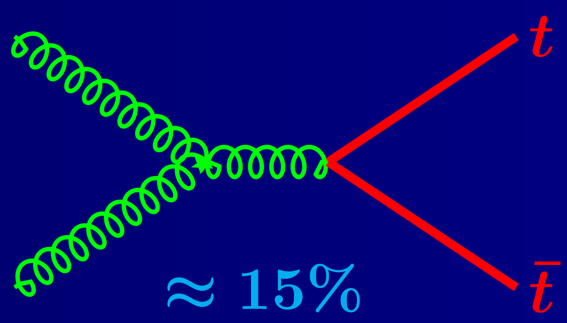
Top quarks are mainly produced in pairs via strong interactions

Measurement of the $t\bar{t}$ production rate provides precision tests of (N)NLO pQCD and is sensitive to the presence of new phenomena

- resonant states
- additional decay modes
- anomalous couplings
- compositeness







$$\sigma_{\text{NLL}} = 6.7^{+0.7}_{-0.9}\ \text{pb}$$
at $m_t = 175$ GeV

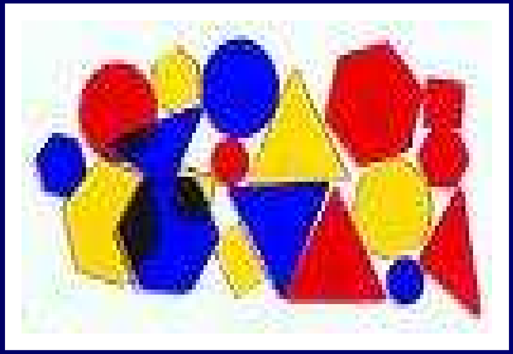
Methodology

$$\sigma = \frac{1}{\mathcal{L}} \frac{N_{\mathrm{cand}} - N_{\mathrm{bkg}}}{\epsilon}$$

Counting Experiment

- select signal-like events
- measure number of background events
- best when signal easily distinguished from background
- optimize signal acceptance

Examples: $e\mu$, ℓ+jet with b tagging



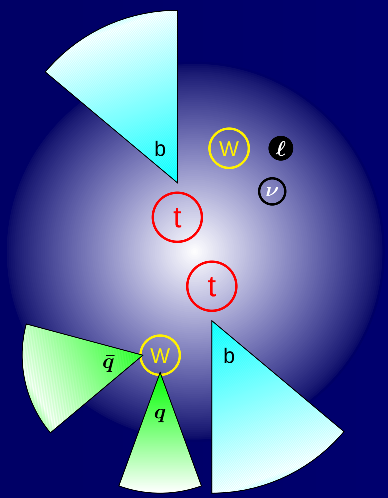
Shape-based Measurements

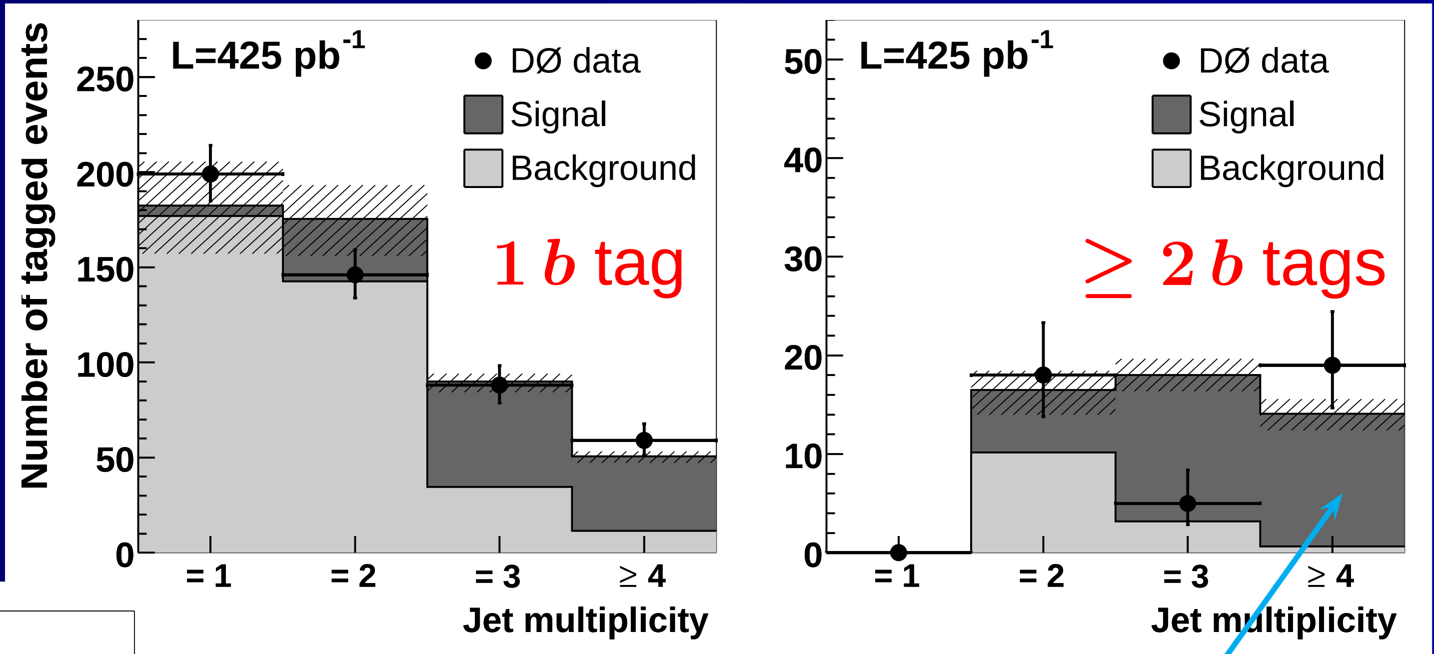
- select signal-like events
- identify variables that distinguish signal from background
- optimize separation between signal and background

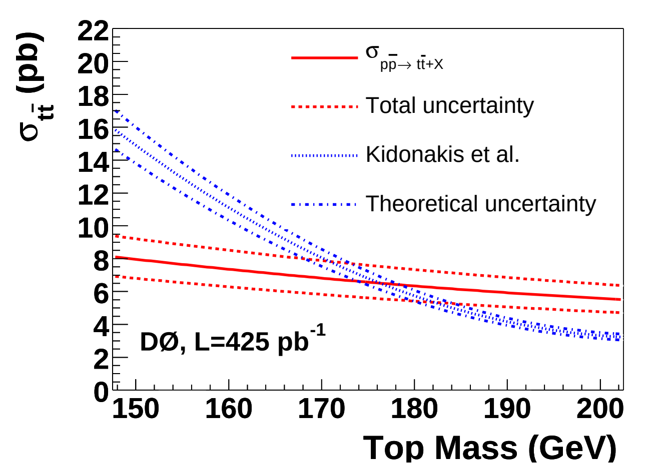
Examples: ℓ+jet without b tagging, all hadronic

$t\bar{t}$ in Lepton + Jets Channel

Counting experiment using b-tagged jets to separate signal from background







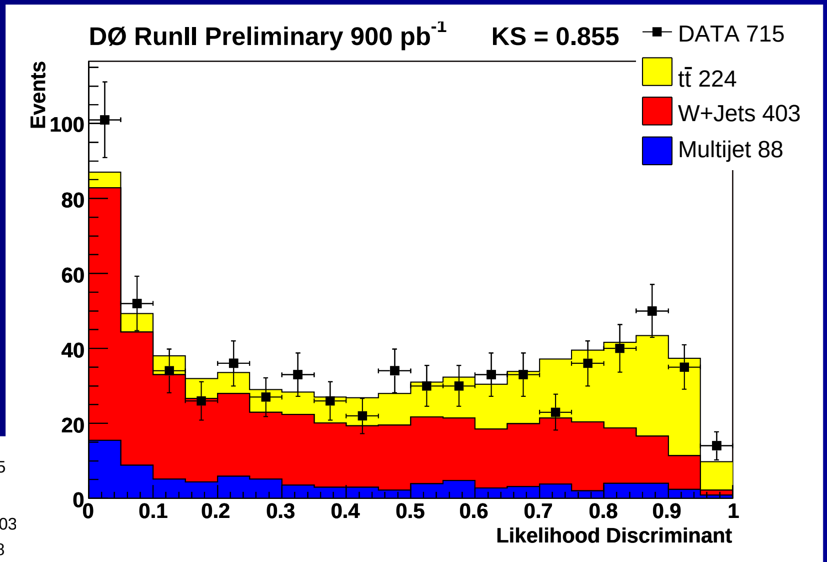
Almost pure $t\bar{t}$
19 observed events
$0.6 \pm 0.4 \pm 0.1$ BG events

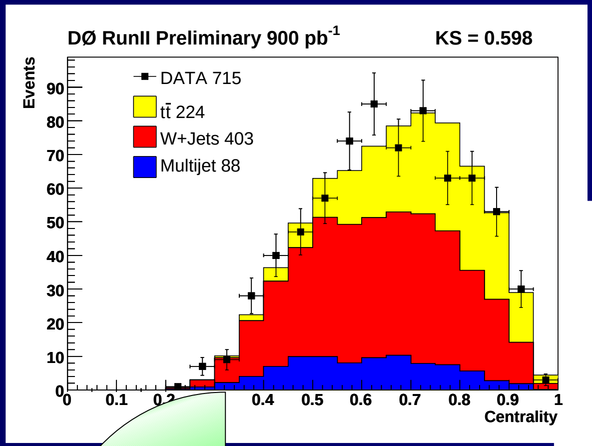
$$\sigma_{t\bar{t}} = 6.6 \pm 0.9\ (\text{stat.} + \text{sys.})\ \pm 0.4\ (\text{lum.})\ \text{pb}$$

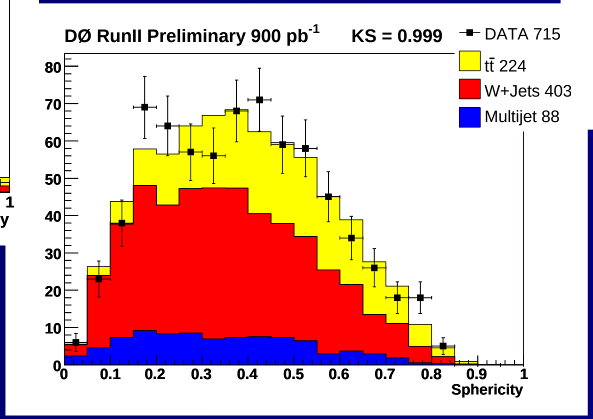
$t\bar{t}$ in Lepton + Jets Channel

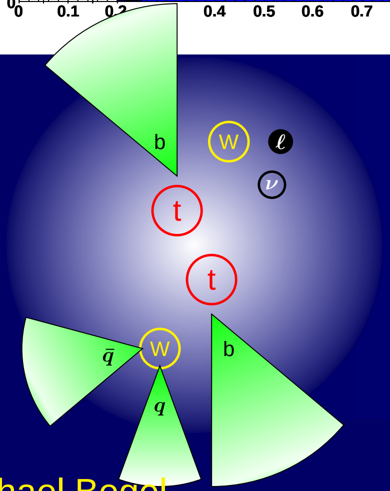
Avoid b ID to improve efficiency. Use kinematic distributions in a likelihood function to separate signal from background.

$$\mathcal{L} = \frac{\mathcal{P}_{t\bar{t}}(x_1, x_2, \ldots)}{\mathcal{P}_{t\bar{t}}(x_1, x_2, \ldots) + \mathcal{P}_{W}(x_1, x_2, \ldots)}$$





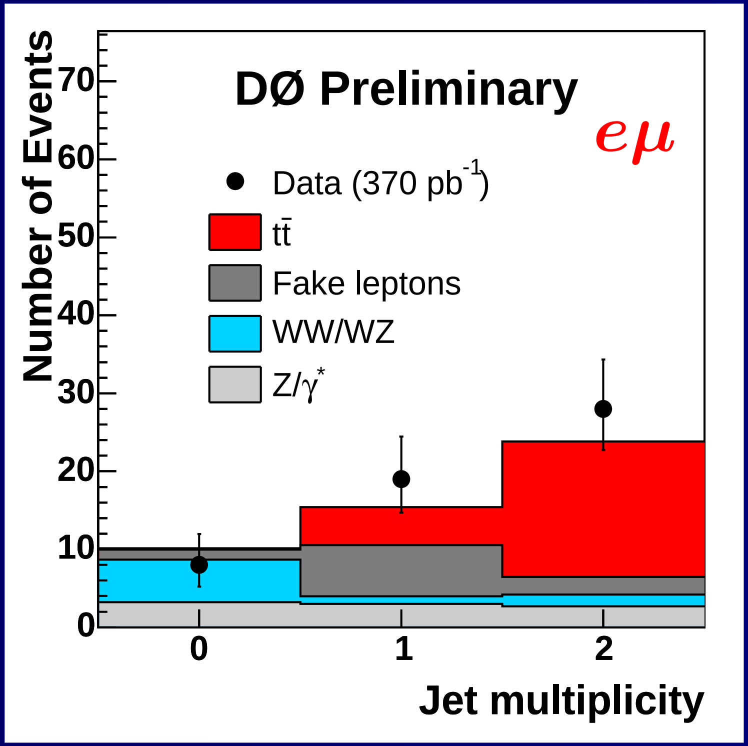


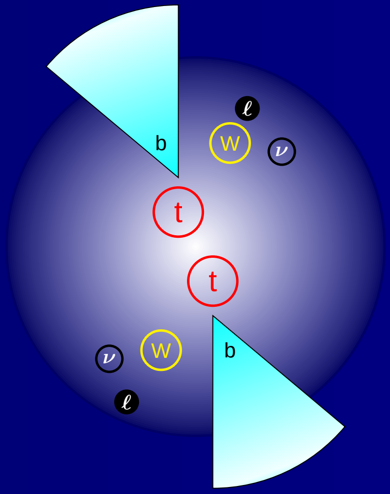


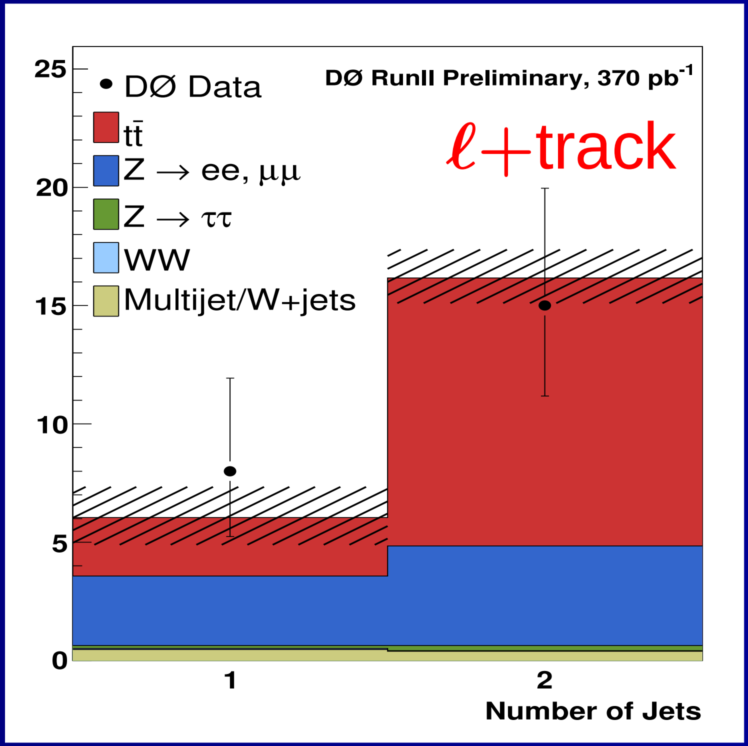
$$\sigma_{t\bar{t}} = 6.3^{+0.9}_{-0.8}\ (\text{stat.}) \pm 0.7\ (\text{sys.}) \pm 0.4\ (\text{lum.})\ \text{pb}$$

$t\bar{t}$ in Dilepton Channel

Includes contributions from $e\mu$ (very pure), ee, and $\mu\mu$ channels. Also includes ℓ+track events where the track is a lepton that failed to be included in the other dilepton analyses.





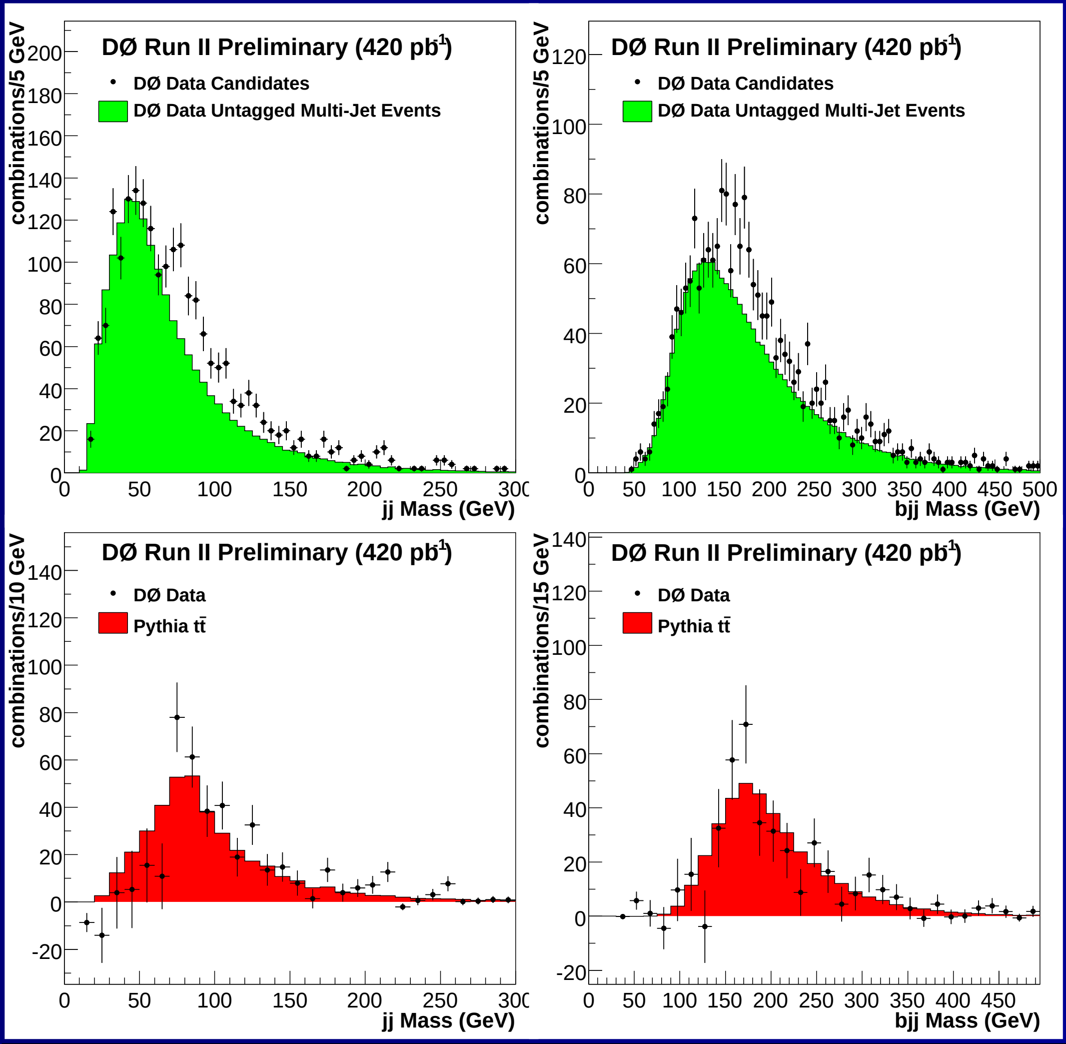


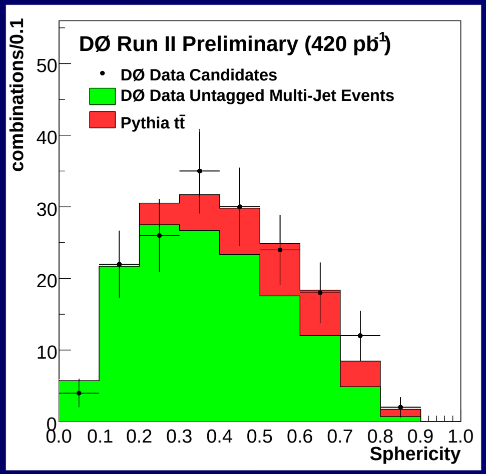
$$\sigma_{t\bar{t}} = 8.6^{+1.9}_{-1.7}\ \text{(stat.)} \pm 1.1\ \text{(sys.)}\ \pm 0.6\ \text{(lum.) pb}$$

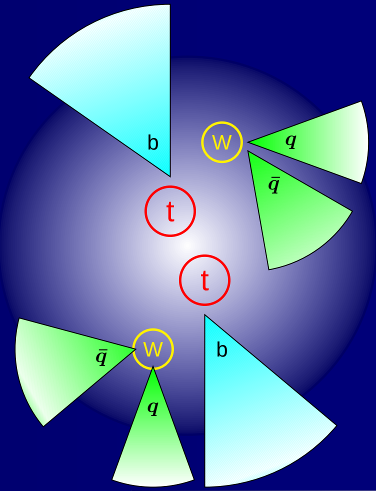
$t\bar{t}$ in the All Hadronic Channel

Use b tagging to improve signal to background

- signal requires two b-tagged jets
- background derived from untagged data and normalized to the kinematic peak
- reconstruct all jj and bjj combinations
- subtract background



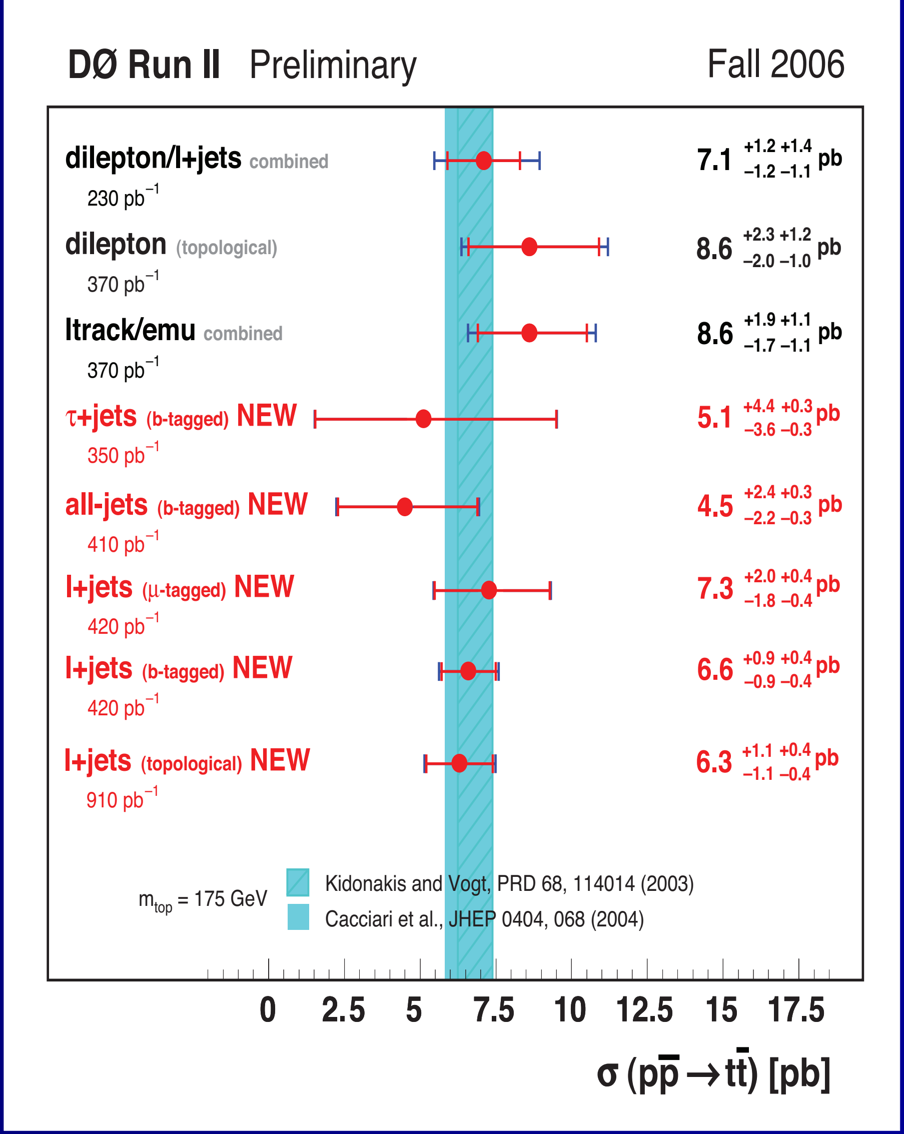




$$\sigma_{t\bar{t}} = 10.4 \pm 4.2\ (\text{stat}) \pm 4.0\ (\text{sys})\ \text{pb}$$

$t\bar{t}$ Production Cross Section

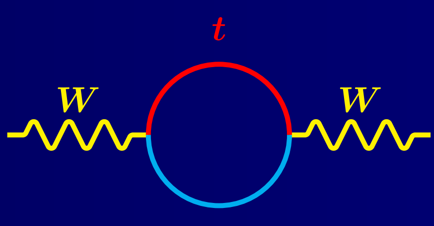
DØ is in the process of extending these measurements to the 1 fb^{-1} data set. A new combined cross section will be available soon.

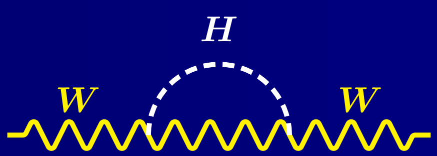


Top Quark Mass

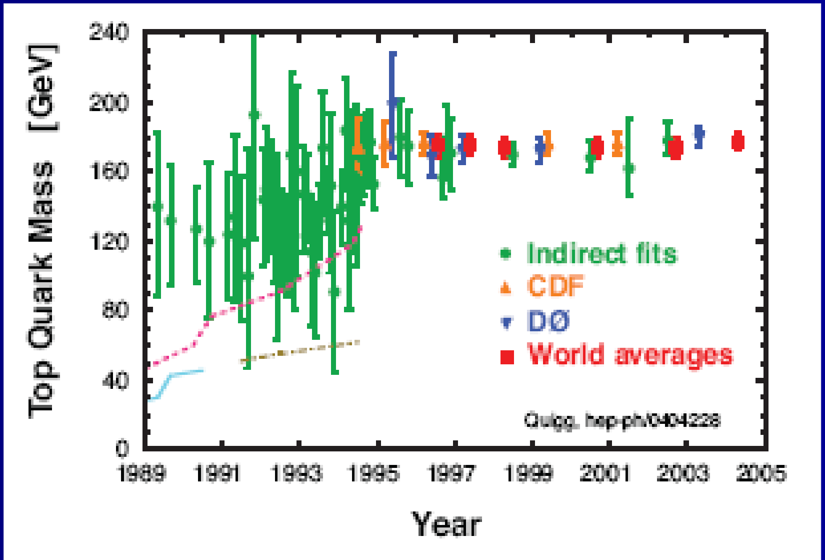
Top Quark Mass

- Fundamental parameter of the Standard Model
- Important ingredient for Electroweak precision analyses initially used to indirectly measure m_t



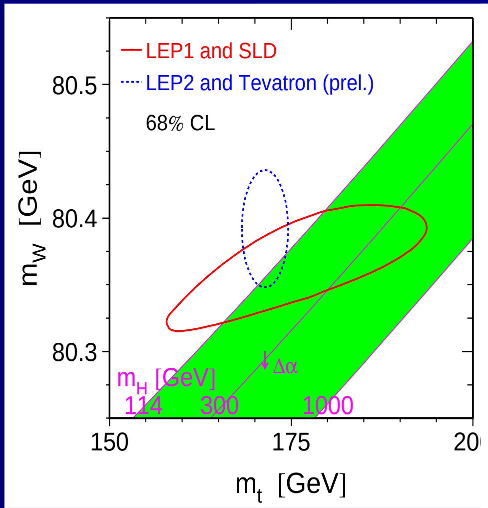


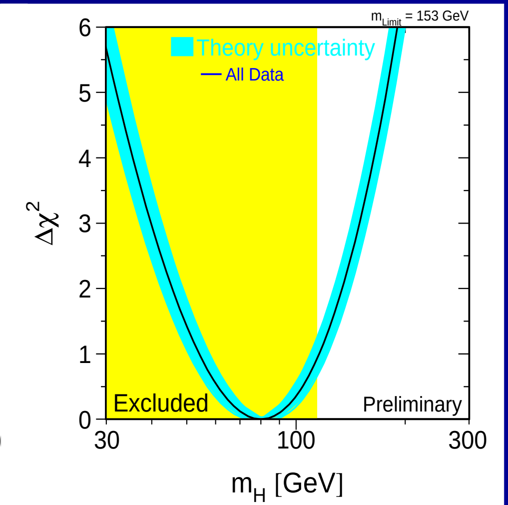
$\delta m_W \propto m_t^2$ $\qquad$ $\delta m_W \propto \ln m_H$



- Use precision measurements of m_W and m_t to constrain the Higgs mass

$$m_H = 85^{+39}_{-28} \text{ GeV}$$





Matrix Element

Calculate the probability that an event is either signal or background as a function of the top mass

Normalization
acceptance & efficiency

Differential Cross Section
based on LO Matrix Element
($q\bar{q} \longrightarrow t\bar{t}$ only)

Transfer Function
probability to measure x when parton-level y was produced

$$\mathcal{P}_{t\bar{t}}(x; m_t, \mathrm{JES}) = \frac{1}{\sigma(m_t)} \int dq_1 dq_2 f(q) f(\bar{q}) \; d\sigma(y; m_t) \; T(x, y, \mathrm{JES})$$

JES is a free parameter in the fit, constrained in situ by the mass of hadronically decaying W boson

Initial State

measurements taken from jets and leptons

Weight each jet–parton assignment with b-tagging event probabilities

24 possible weighted assignments between jets and partons in a ℓ+jets event

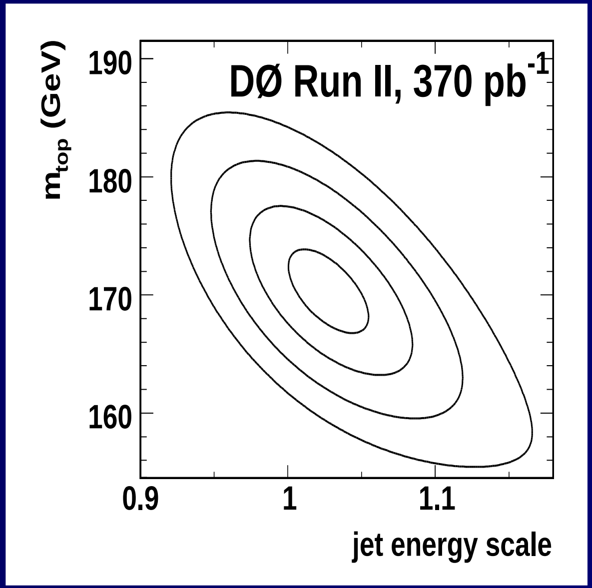
$$\mathcal{P}_{t\bar{t}}^{\mathrm{N\ tag}}(x; m_t, \mathrm{JES}) = \sum_j W_{t\bar{t}}^j \, \mathcal{P}_{t\bar{t}}^j(x; m_t, \mathrm{JES})$$

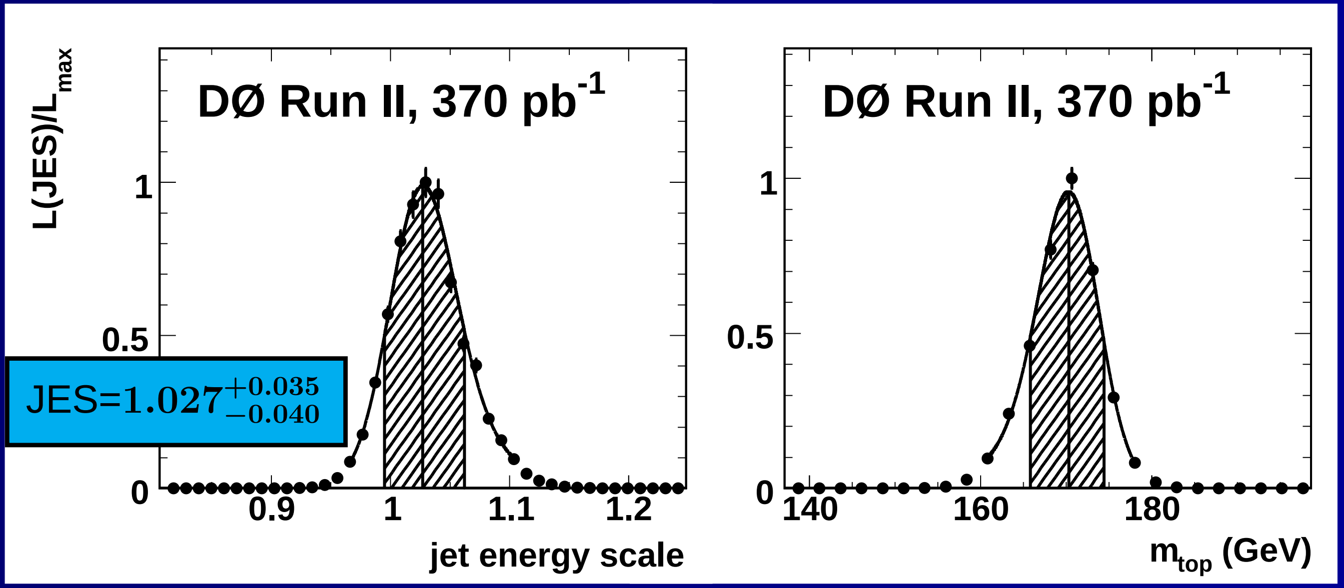
Matrix Element: ℓ+jets

The total event probability is

$$\mathcal{P}^{\text{N tag}}_{\text{event}}(x; m_t, \text{JES}) = f_t\, \mathcal{P}^{\text{N tag}}_{t\bar{t}}(x; m_t, \text{JES}) + (1 - f_t)\mathcal{P}_{bkg}(x, \text{JES})$$

Minimize $\mathcal{L}(x; m_t, \text{JES}) = \prod_n \prod_i \mathcal{P}^{\text{n tag}}_{event}(x_i; m_t, \text{JES}, f_t^{\text{n tag}})$





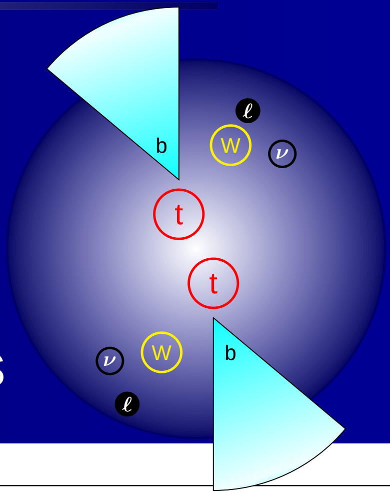
Dominant Systematics

Relative b/light JES	$^{+0.63}_{-1.43}$ GeV
b fragmentation	± 0.56 GeV
MC Calibration	± 0.48 GeV
Signal Modeling	± 0.46 GeV

$$m_t = 170.3^{+4.1}_{-4.5}\ (\text{stat.} + \text{JES})\ ^{+1.2}_{-1.8}\ (\text{sys.})\ \text{GeV}$$

Matrix Weighting: $\ell\ell$+jets

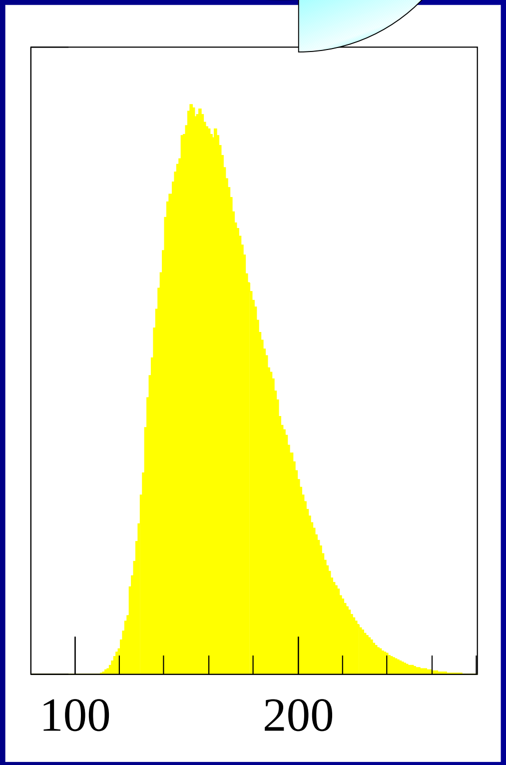
- Underconstrained kinematics given two neutrinos
- Scan potential top masses
- Solve for top momentum
  - assume two leading jets correspond to the b jets
  - $\Rightarrow$ 4 solutions per $t\bar{t}$
  - include detector resolution effects
- Calculate weight as a function of m_t for each event using Dalitz-Goldstein-Kondo method



$$w = f(x)f(x) \times \mathcal{P}(E^\star_\ell|m_t)\mathcal{P}(E^\star_\ell|m_t)$$

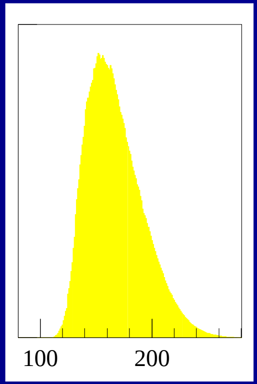
PDF

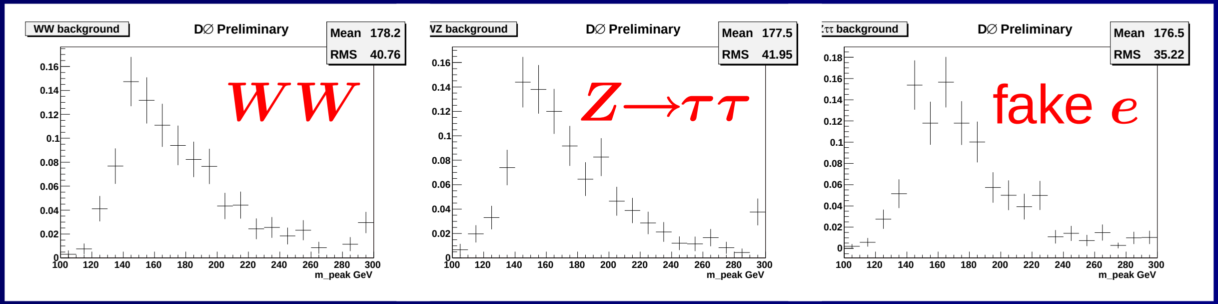
probability that observed lepton energy comes from top quark with mass m_t

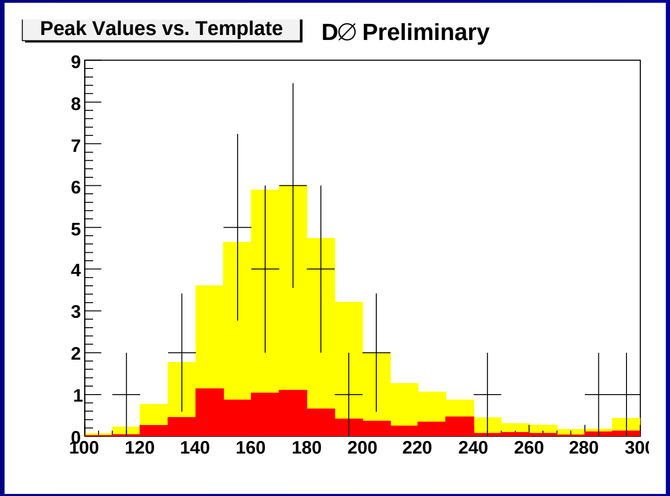


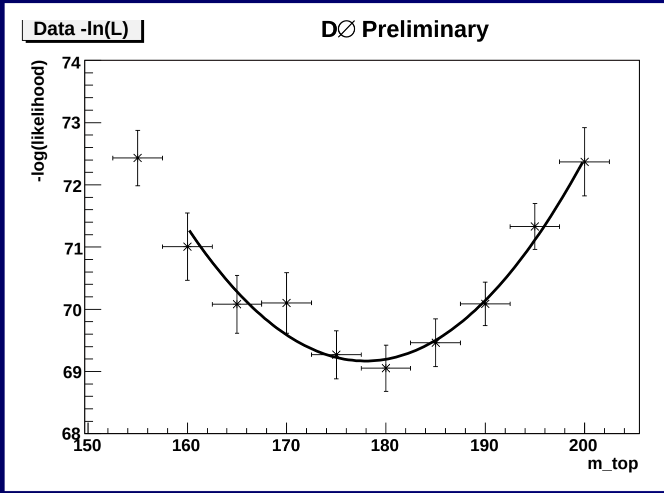
Matrix Weighting: $e\mu$+jets

- Choose value of m_t with maximum likelihood
- Form binned likelihood with signal and background templates









$$m_t = 177.7 \pm 8.8\ \mathbf{(stat.)}\ ^{+3.7}_{-4.5}\ \mathbf{(sys.)\ GeV}$$

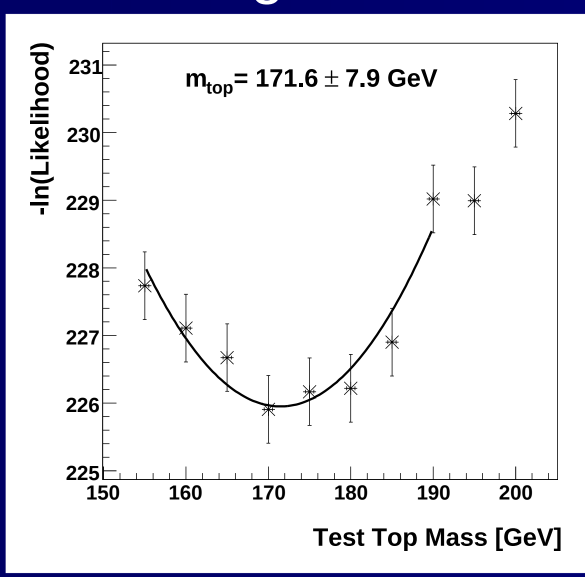
$$\mathcal{L} = 0.8\ \text{fb}^{-1}$$

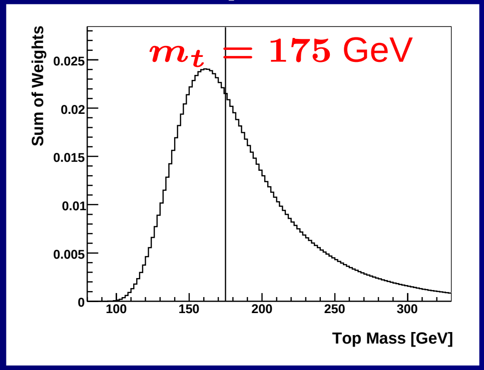
Neutrino Weighting: $e\mu$+jets

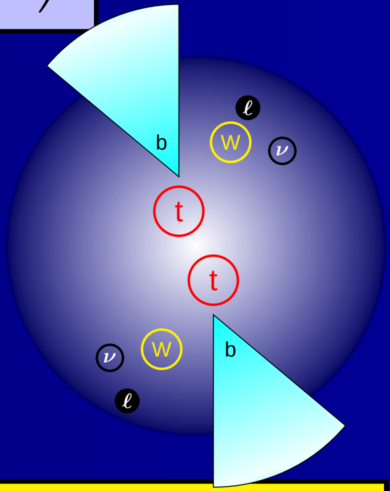
- Underconstrained kinematics given two neutrinos
- Scan potential top masses and neutrino rapidities
- Solve for neutrino 4-vectors
- Sum over weights for neutrino solutions and detector resolution

$$\omega = \frac{1}{N_{\mathrm{iter}}} \sum_{i=1}^{N_{\mathrm{iter}}} \exp\left(\frac{-\left(\not{E}_{x,i}^{\mathrm{calc}} - \not{E}_{x}^{\mathrm{obs}}\right)^2}{2\sigma_{\not{E}_x}^2} \right) \exp\left(\frac{-\left(\not{E}_{y,i}^{\mathrm{calc}} - \not{E}_{y}^{\mathrm{obs}}\right)^2}{2\sigma_{\not{E}_y}^2} \right)$$

- Fit signal and background templates to data



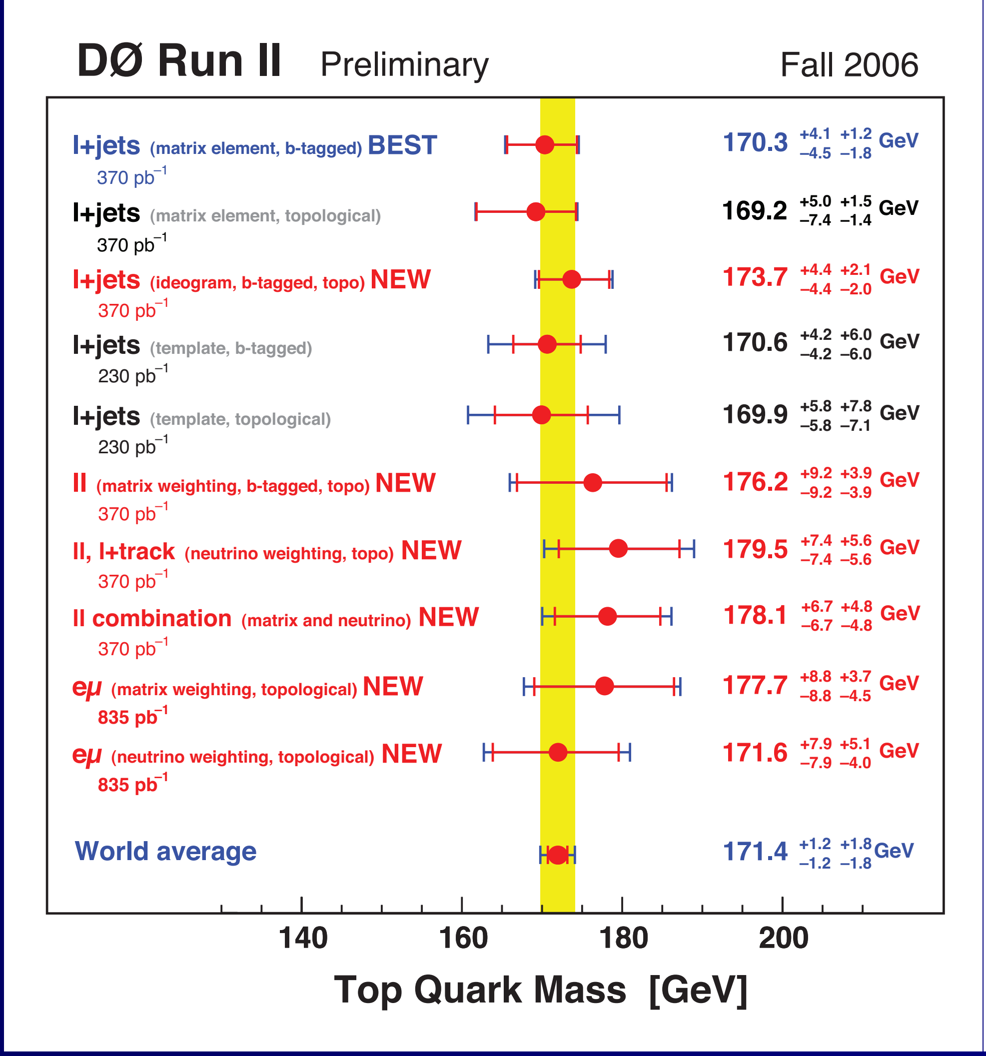


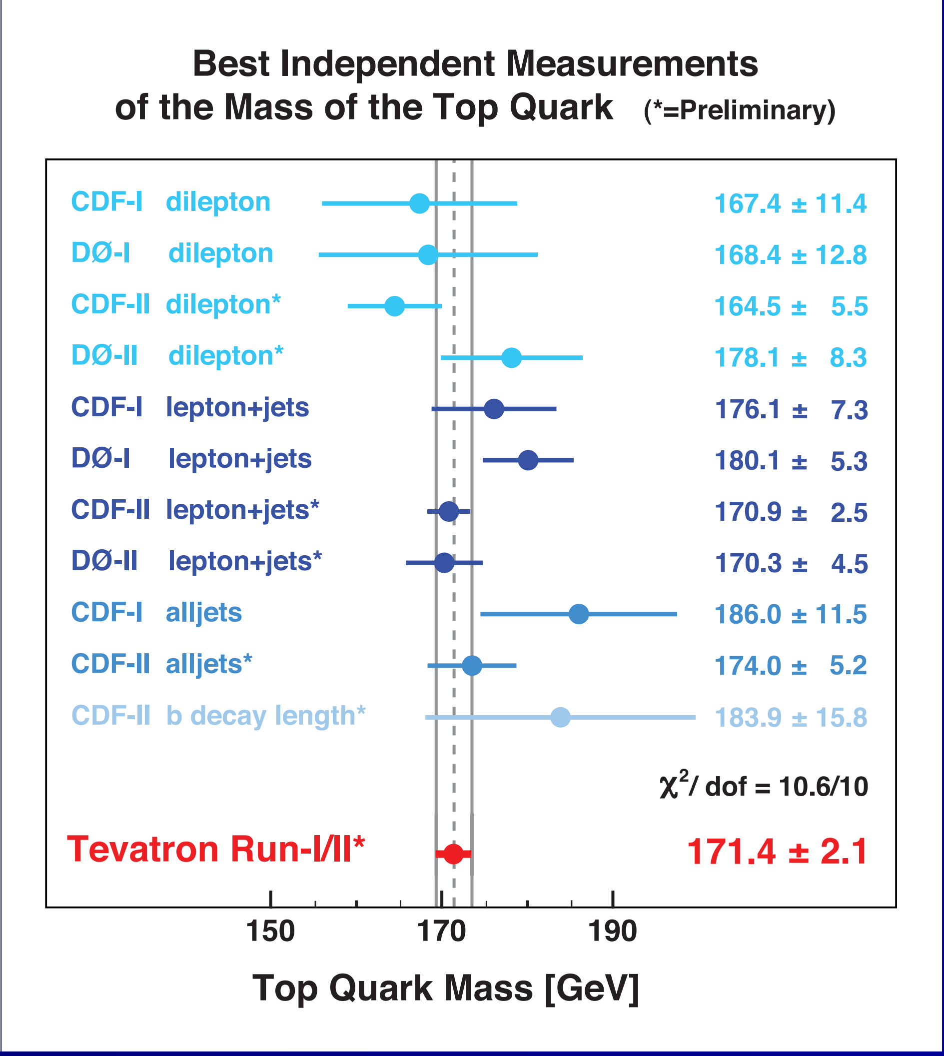


$$m_t = 171.6 \pm 7.9\ (\mathrm{stat.})\ ^{+5.1}_{-4.0}\ (\mathrm{sys.})\ \mathrm{GeV}$$

$$\mathcal{L} = 0.8\ \mathrm{fb}^{-1}$$

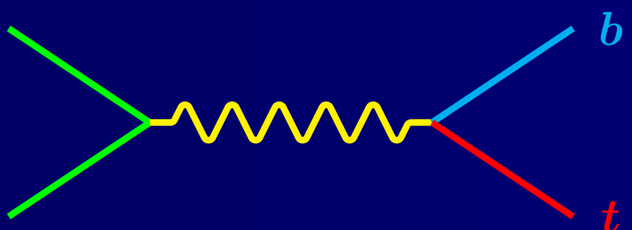
Top Quark Mass Summary





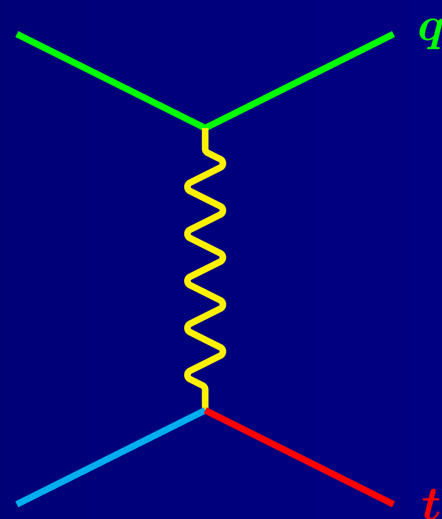
Single Top Quark Production

Single Top Quark Production



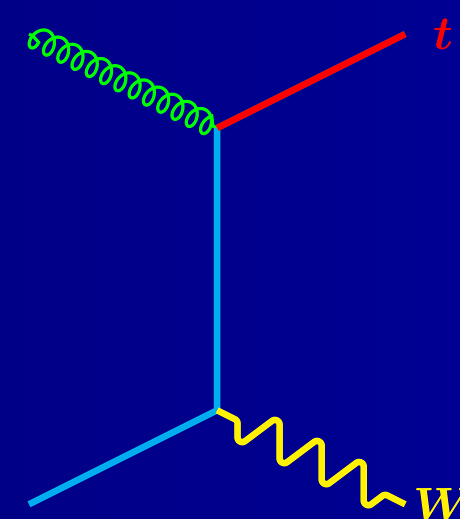
s channel (tb)

$\sigma_{\text{NLO}} = 0.88 \pm 0.11$ pb



t channel (tqb)

$\sigma_{\text{NLO}} = 1.98 \pm 0.25$ pb



Wt production

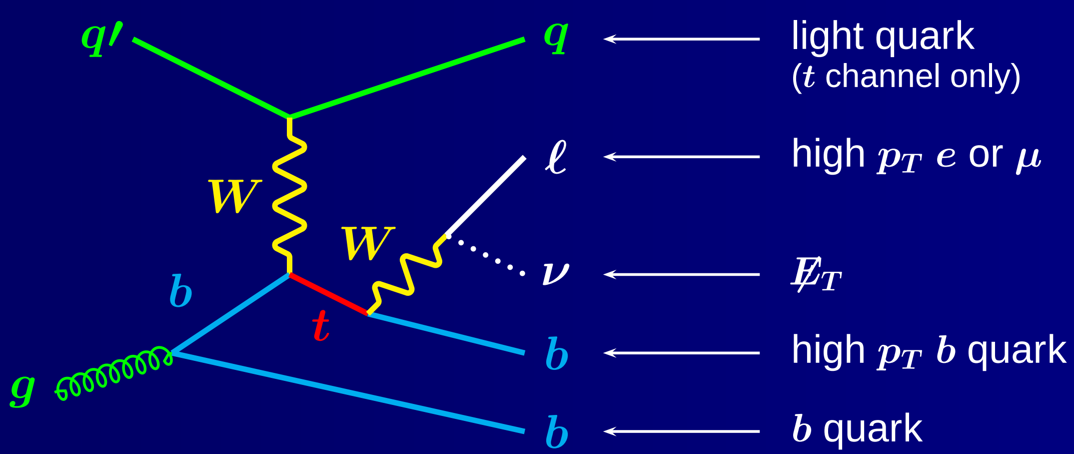
$\sigma_{\text{NLO}} = 0.093 \pm 0.024$ pb

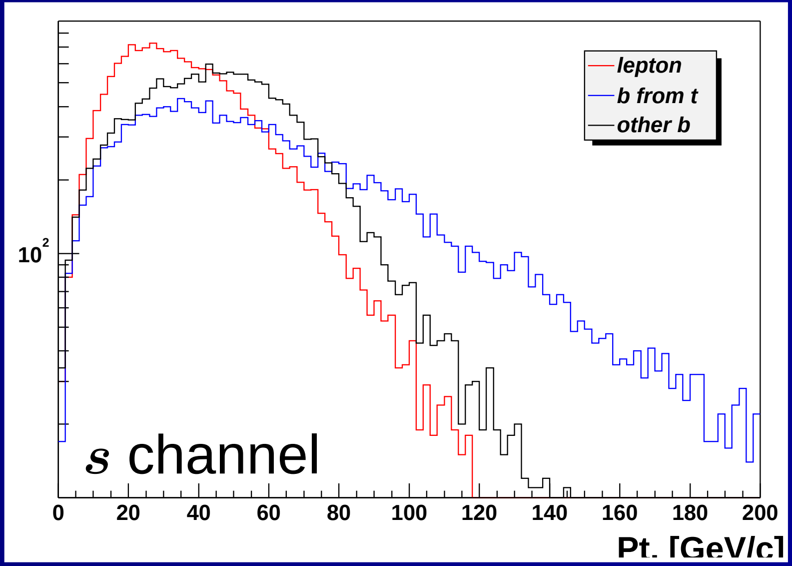
Why search for single top quarks?

- Access $t - b - W$ coupling
- Sensitive to new physics
- Source of polarized top quarks

Need to extract a very small signal out of very large background

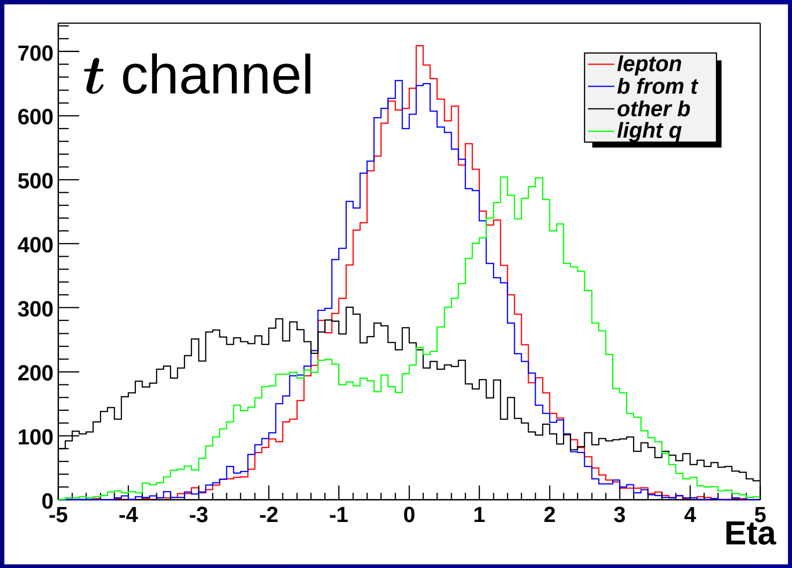
Event Signatures





s- and t-channels are similar

- lepton + $\not\!\!E_T$ + jets
- t channel b jet tends to be forward

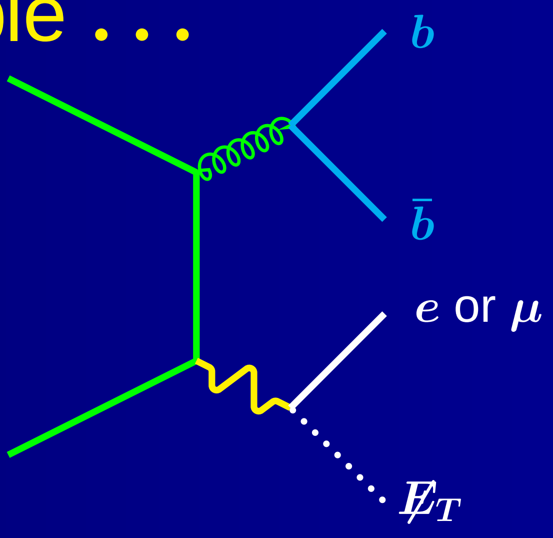


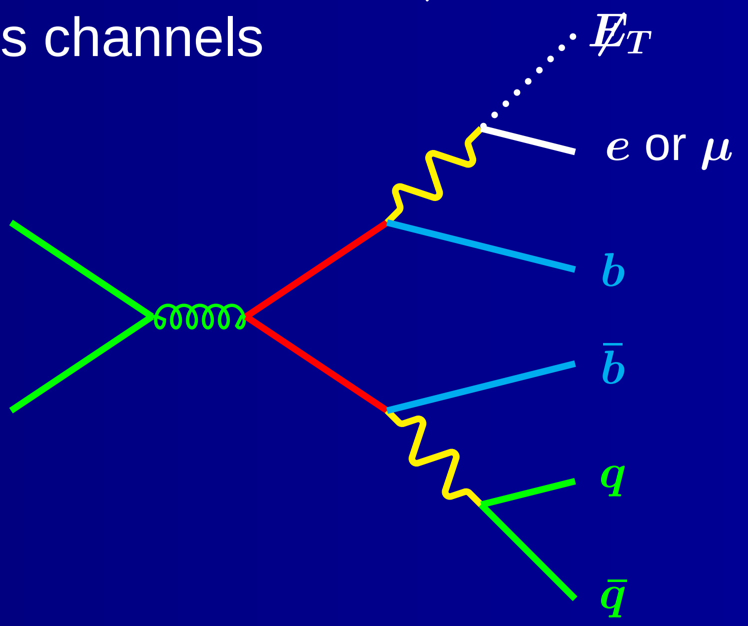
Modeled with CompHEP (matched to NLO)

Background Modeling

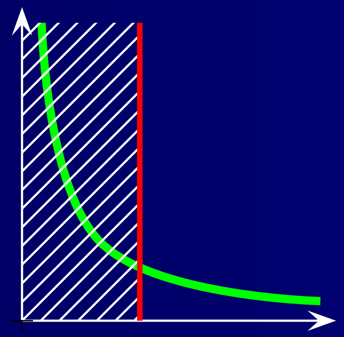
Based on data as much as possible . . .

- W + jets production
  - distributions from matched ALPGEN
  - normalization from pre-tagged sample
  - heavy-flavor fraction from data
- top pair production
  - contribution from the $\ell\ell$+jets and ℓ + jets channels
  - estimated from matched ALPGEN
  - normalized to NNLO pQCD
- multi-jet events
  - jet misidentified as lepton
  - semi-leptonic decay of HF jets ($b\bar{b}$)
  - estimated from data



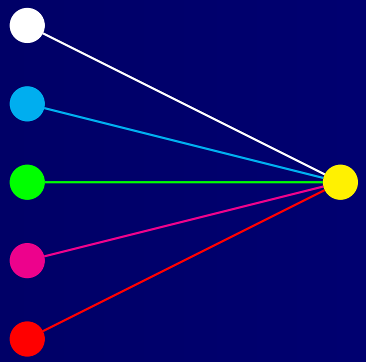


Measurement Strategy



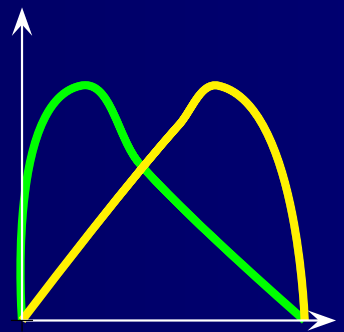
Event Selection

- select W-like events
- maximize signal acceptance
- optimize sensitivity



Separate Signal from Background

- find discriminating variables
- multi-variate techniques



Determine Cross Section

- likelihood
- pseudo-experiments

Event Yields

Percentage of single top *tb+tqb* selected events and S:B ratio (white squares = no plans to analyze)

Electron + Muon	1 jet	2 jets	3 jets	4 jets	≥ 5 jets
0 tags	10% 1 : 3,200	25% 1 : 390	12% 1 : 300	3% 1 : 270	1% 1 : 230
1 tag	6% 1 : 100	21% 1 : 20	11% 1 : 25	3% 1 : 40	1% 1 : 53
2 tags		3% 1 : 11	2% 1 : 15	1% 1 : 38	0% 1 : 43

Source	Event Yields in 0.9 fb^{-1} Data (Electron+muon, 1tag+2tags combined) 2 jets	3 jets	4 jets
tb	16 ± 3	8 ± 2	2 ± 1
tqb	20 ± 4	12 ± 3	4 ± 1
$t\bar{t} \to ll$	39 ± 9	32 ± 7	11 ± 3
$t\bar{t} \to l$+jets	20 ± 5	103 ± 25	143 ± 33
$W+b\bar{b}$	261 ± 55	120 ± 24	35 ± 7
$W+c\bar{c}$	151 ± 31	85 ± 17	23 ± 5
$W+jj$	119 ± 25	43 ± 9	12 ± 2
Multijets	95 ± 19	77 ± 15	29 ± 6
Total background	686 ± 41	460 ± 39	253 ± 38
Data	697	455	246

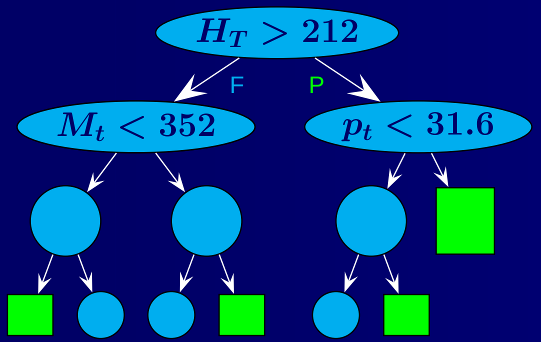
- Selection optimized to maximize acceptance: tb = $(3.2 \pm 0.4)\%$, tqb = $(2.1 \pm 0.3)\%$
- Use multi-variate techniques to separate signal from background

Dominant Systematic Uncertainties

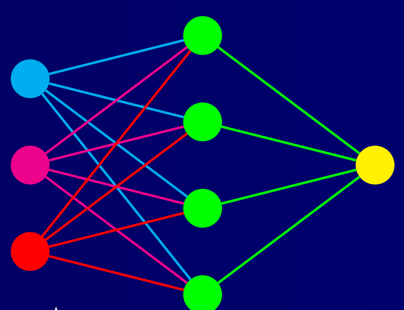
- $t\bar{t}$ cross section: 18%
- W+jets & multi-jet: $18 - 28\%$
- jet energy scale: $1 - 20\%$
- b ID: $2 - 16\%$

Multi-variate Analyses

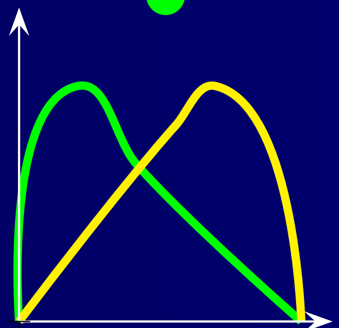
Use multi-variate analysis techniques to separate signal from background



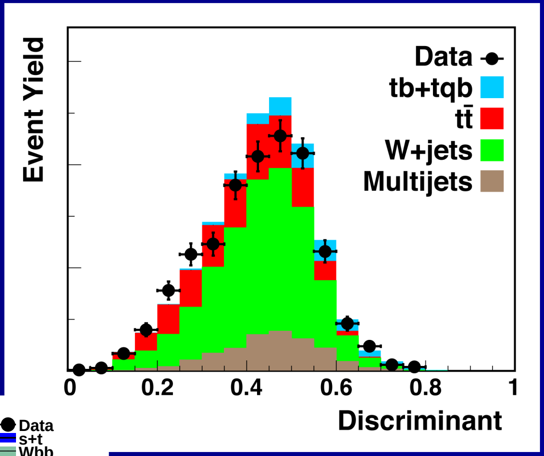
Decision Trees

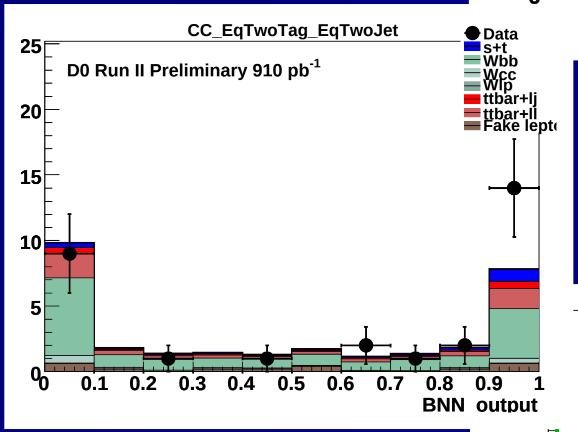


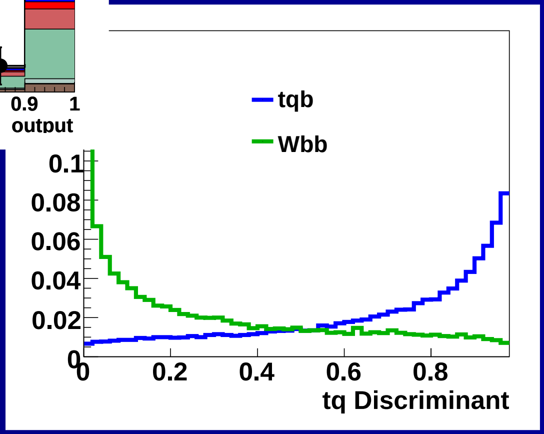
Neural Networks



Matrix Element



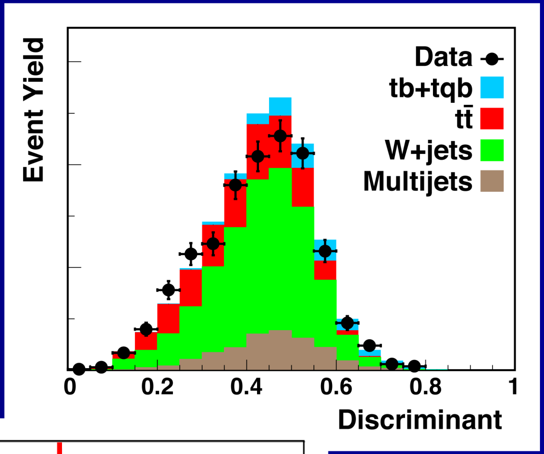




Measuring the Cross Section

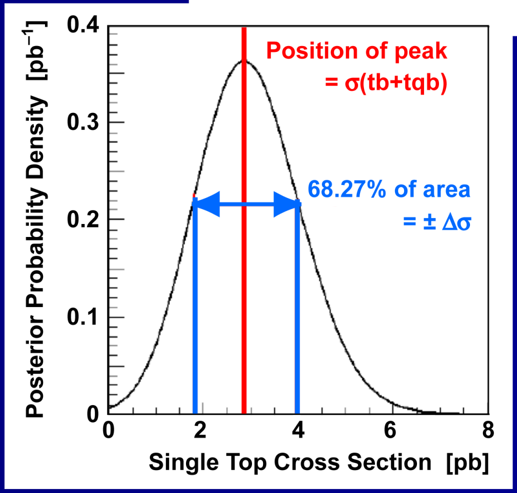
$$d = S + B = \sigma \mathcal{A}\mathcal{L} + B = \sigma a + \sum_{i=1}^{N_{bkg}} b_i$$

d = predicted number of data events
S = predicted number of signal events
B = predicted number of background events
σ = cross section
$\mathcal{A}$ = signal acceptance
$\mathcal{L}$ = integrated luminosity
a = effective luminosity
b_i = number of events in each background component



$$\mathcal{P}(D|d) \equiv \mathcal{P}(D|\sigma, a, b) = \prod_{i=1}^{N_{\text{bins}}} \mathcal{P}(D_i|d_i)$$

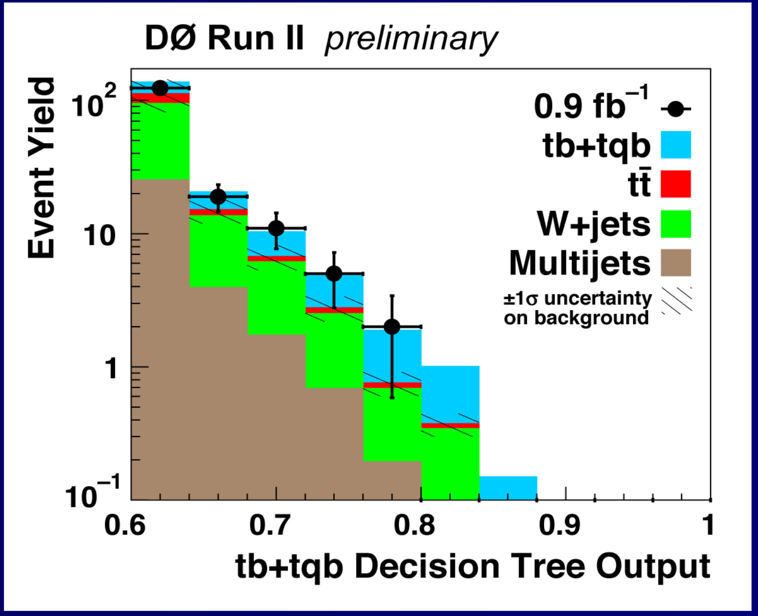
D = observed number of data events
b = vector of background components



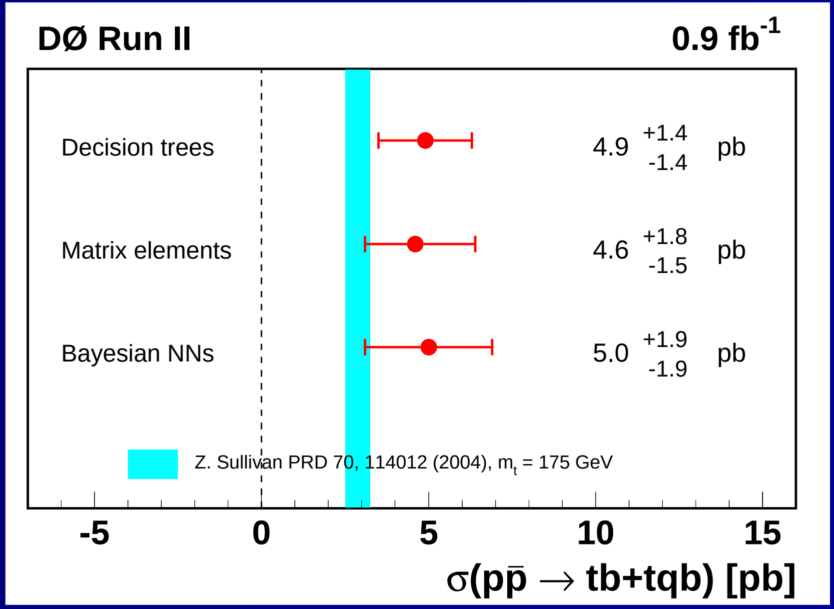
Posterior Probability Density $(\sigma|D) \propto$
$\int_a \int_b \mathcal{P}(D|\sigma, a, b)\text{Prior}(a, b)\text{Prior}(\sigma)\text{d}a\text{d}b$

- $N_{bkg} = 6$ ($tt\ell\ell$, $tt\ell j$, Wbb, Wcc, Wjj, multi-jet), $N_{\text{bins}} = 12$ chann. $\times 100$ bins
- Shape and normalization systematic uncertainties treated as nuisance parameters
- Correlations between uncertainties properly treated
- Signal cross section prior is non-negative and flat

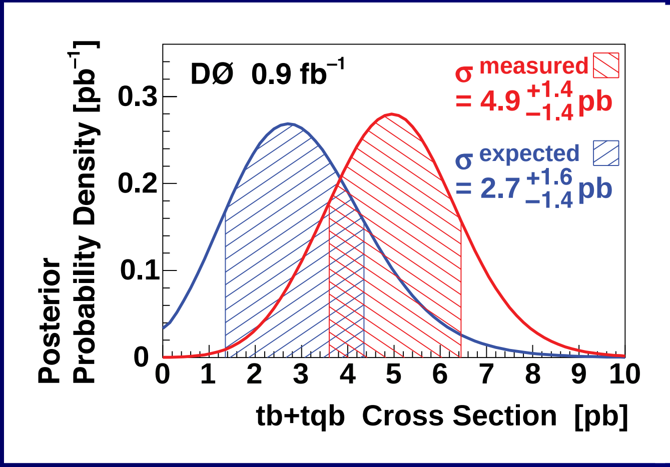
Measuring the Cross Section



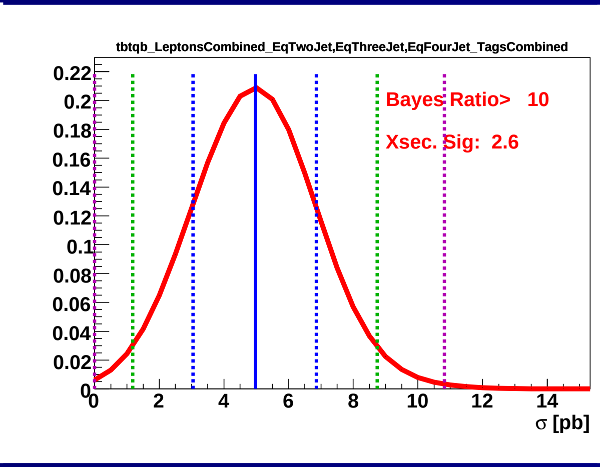
measurements are
≈ 50% correlated;
combination in progress



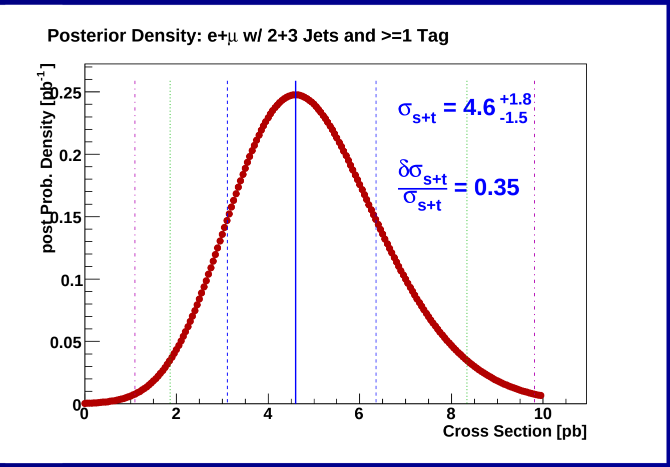
Boosted Decision Tree



Bayesian Neural Network



Matrix Element

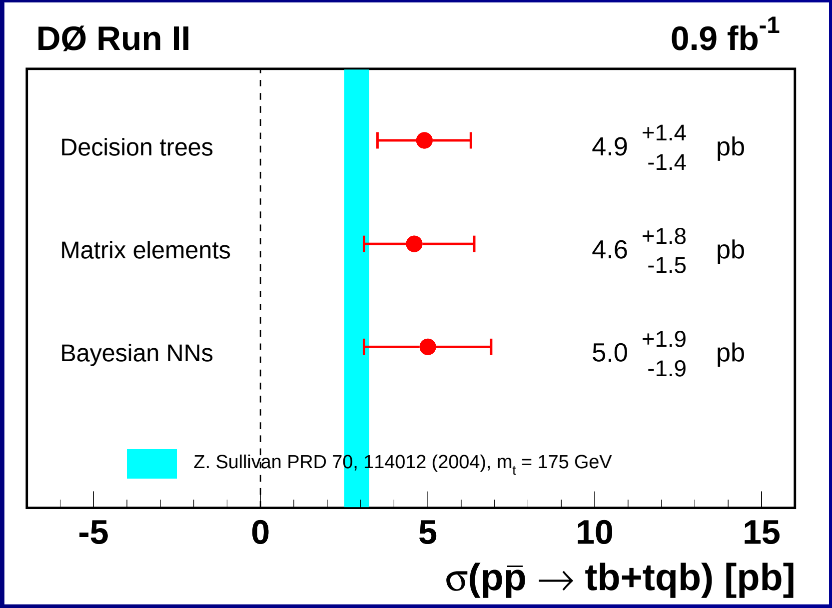


Have we seen it?

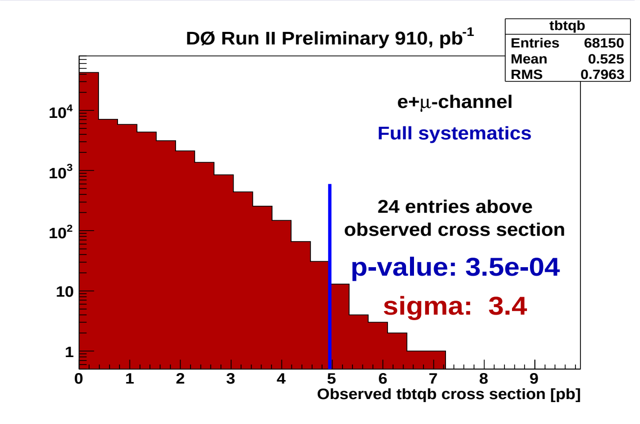
Use ensembles with no signal to determine signficance of each measurement

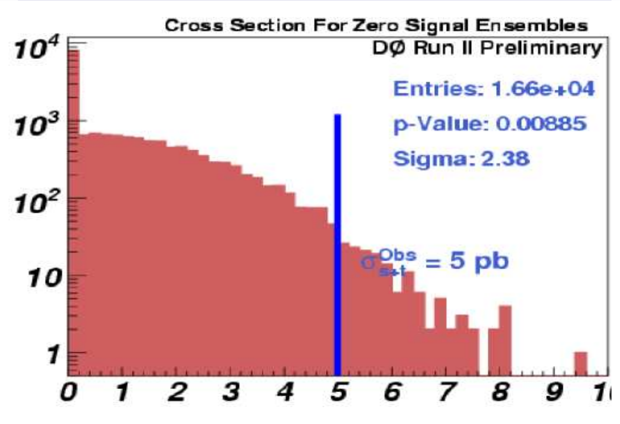
	Observed
Decision Tree	0.035%
Neural Network	0.885%
Matrix Element	0.21%

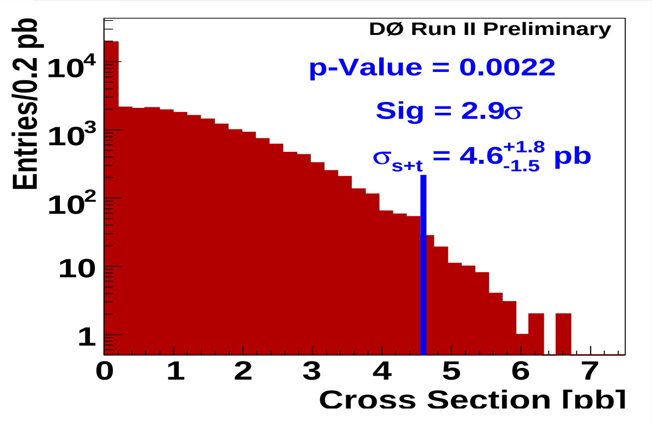
Decision tree has 3.4σ excess (11% compatable with SM)



Boosted Decision Tree | **Bayesian Neural Network** | **Matrix Element**

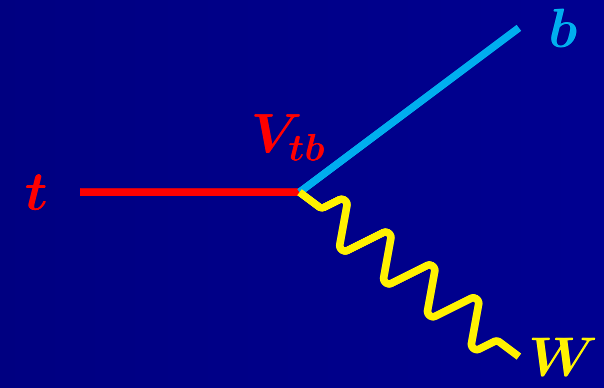






CKM Matrix Element V_{tb}

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

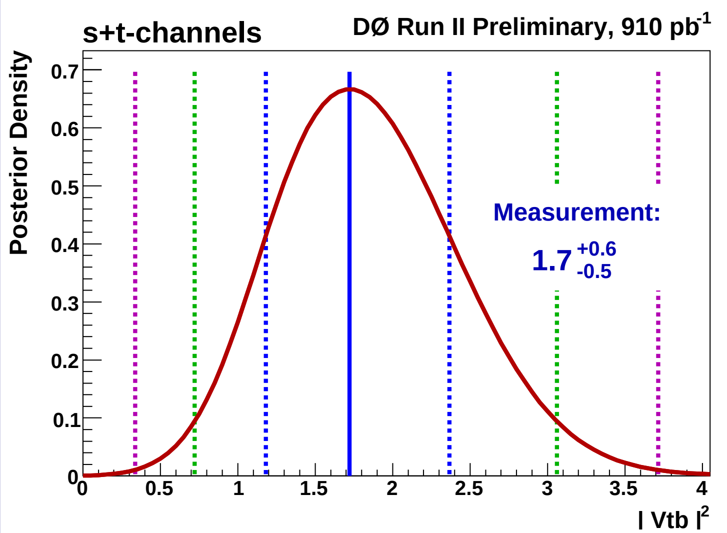


- Weak interaction eigenstates and mass eigenstates are not the same; there is mixing between quarks described by the CKM matrix
- In the SM, top must decay to a W and d, s, or b quark
  - $V_{td}^2 + V_{ts}^2 + V_{tb}^2 = 1$
  - constraints on V_{td} and V_{ts} yield $V_{tb} = 0.999100^{+0.000034}_{-0.000004}$
- If there is new physics then,
  - $V_{td}^2 + V_{ts}^2 + V_{tb}^2 < 1$
  - no constraint on V_{tb}

Measuring $|V_{tb}|$

Use measurement of single top cross section to make first direct measurement of $|V_{tb}|$

- Assume
  - SM top quark decay: $V_{td}^2 + V_{ts}^2 << V_{tb}^2$
  - Pure $V - A$: $f_1^R = 0$
  - CP conservation: $f_2^L = f_2^R = 0$
- No need to assume three quark families or CKM unitarity



$$V_{tb} f_1^L = 1.3 \pm 0.2$$

$$0.68 < |V_{tb}| < 1$$
at 95% C.L.
(assuming $f_1^L = 1$)

Additional theoretical uncertainties

	tb	tqb
Top Mass	13%	8.5%
Scale	5.4%	4.0%
PDF	4.3%	10%
α_s	1.4%	0.01%

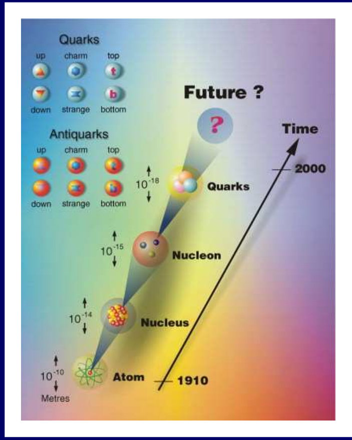
$$\Gamma^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} V_{tb} \left(\gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} \left[f_2^L P_L + f_2^R P_R \right] \right)$$

Summary

DØ is pursuing a rich program of top quark study

Tevatron is the only game in town. . .for now!

- Studies of $t\bar{t}$ production
- Precision measurements of top quark properties
- Observation of single top quark production and first direct measurement of $|V_{tb}|$
- Searches for new physics (Higgs, Z', W', etc)



The LHC will be a top factory and discovery machine — the lessons learned and techniques developed at the Tevatron will enhance our discovery opportunities