Top Quark Physics

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Outline

- Introduction
- Tevatron
  - Production mechanisms
  - Decay properties
  - Top mass
- LHC
  - What will be different

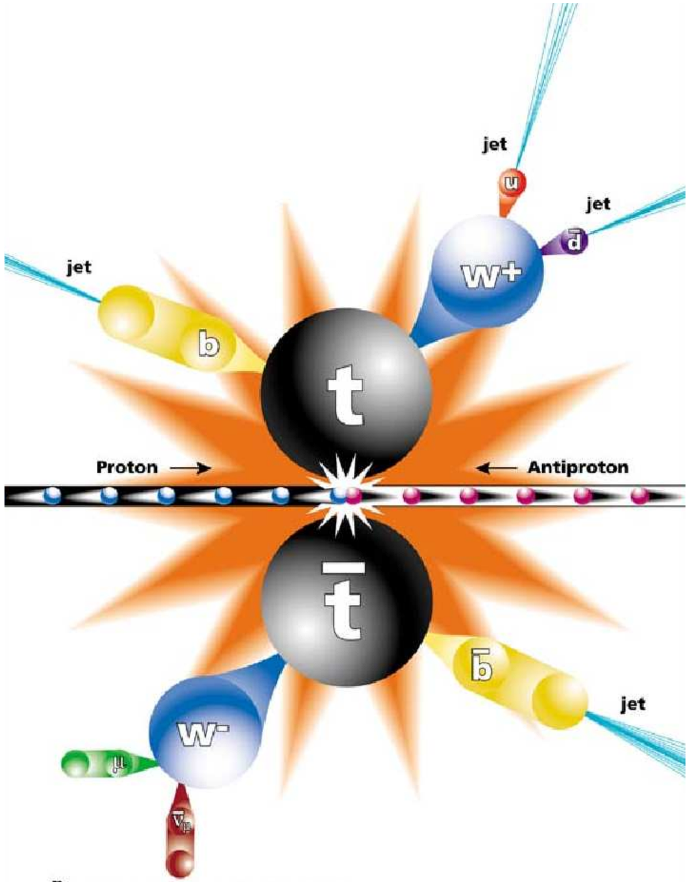
Introduction

The Top Quark

- Discovered by CDF and DØ in 1995.

- Completes set of quarks in SM.
- Quantum numbers as for up-type quarks.

- Production and decay properties
  fully defined in Standard Model.



Only few of its predicted properties verified

Is the Top Quark special?

Yes, it is! It is ...

- more than 30 time heavier than the second heaviest elementary Fermion.
  Its mass is surprisingly close to electro-weak scale.
- the only bare quark (i.e. decays before it hadronises)
- the last of the predicted quarks.

No, it isn't! It has ...

- the same electrical charge as u and c-quarks.
- the same weak couplings as the other quarks.
- the same colour charge as the other quarks. *Really??*

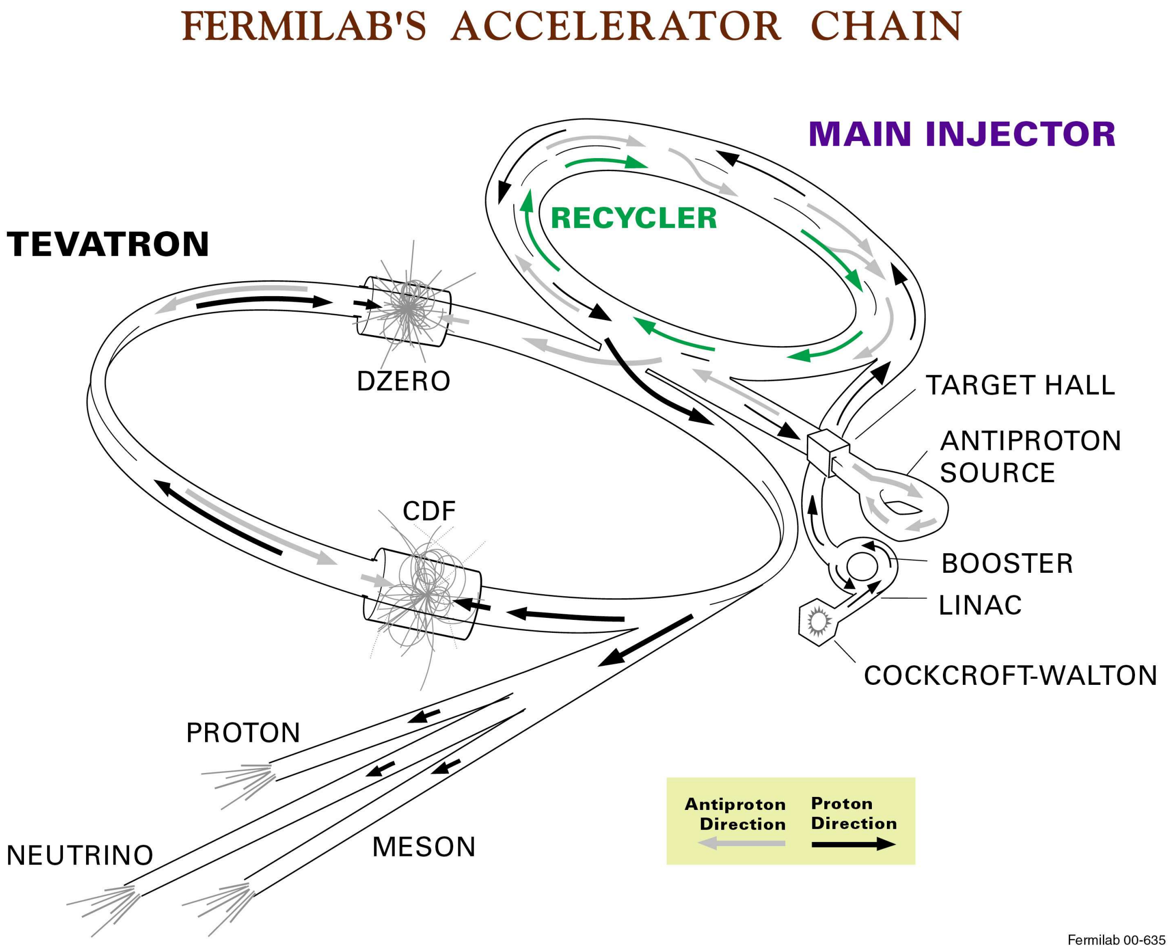
Maybe ...

- it has different couplings ($\Rightarrow$ new physics)
- it isn't last quark ($\Rightarrow$ new physics) *very interesting!*

Tevatron

The $p\bar{p}$ Accelerator Tevatron

- Circumfence 7 km.
- $p\bar{p}$ collisions
- Run I (1987-1995)
- Run II (since 2001)
  Collision energy 2 TeV
- 2 experiments,
  CDF and DØ,
  record events.

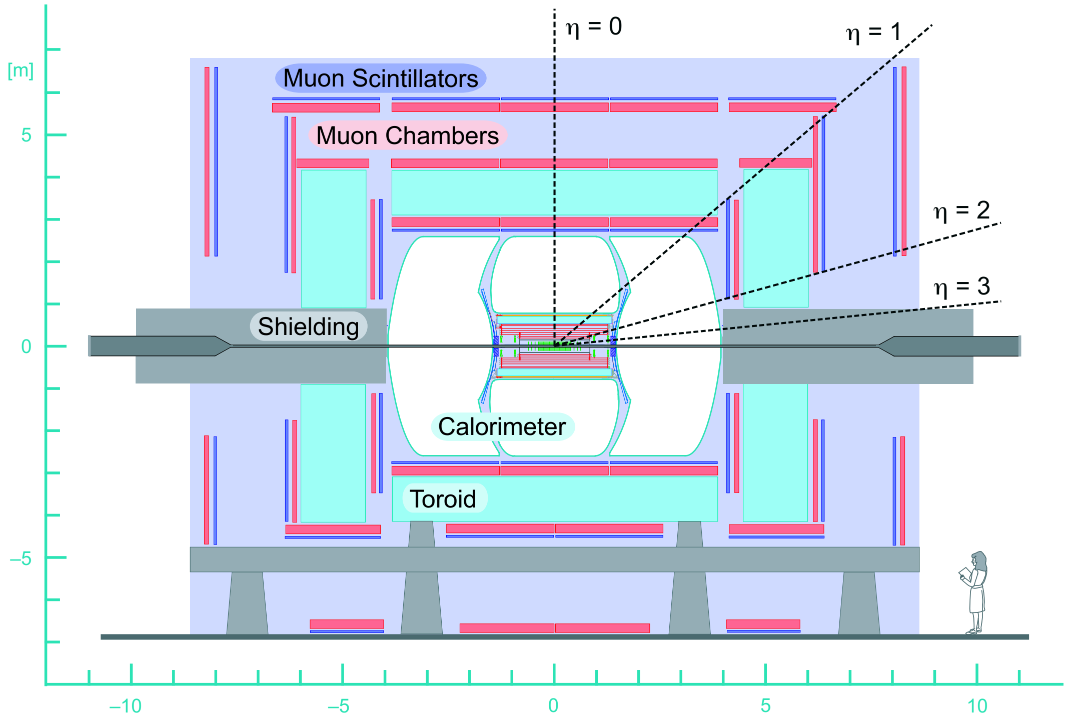


The Tevatron

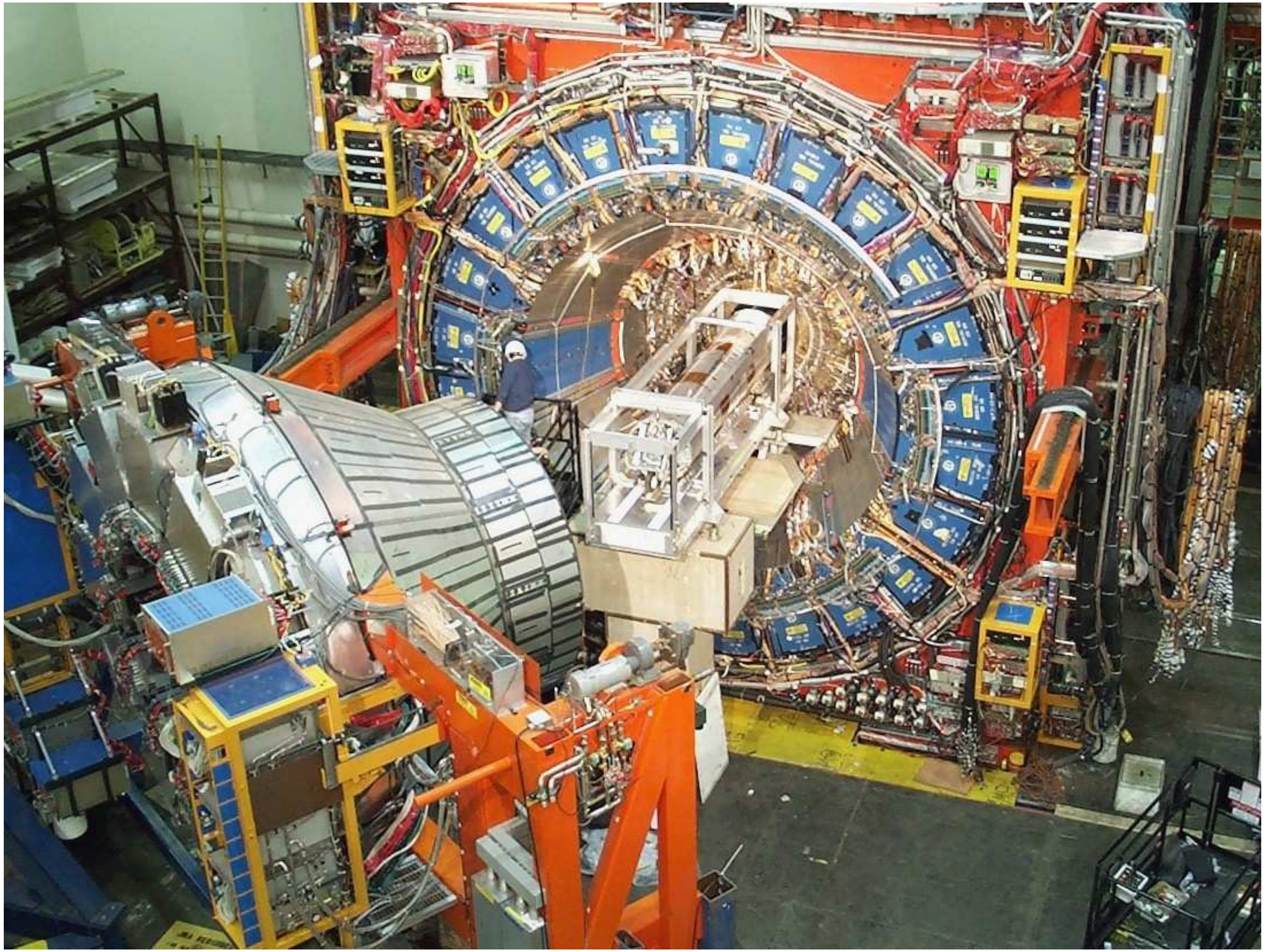
The DØ Detector

A 4π general purpose detector: Dimensions: $12 \times 12 \times 20\text{m}^3$

- Tracking in 2T solenoid
  - Silicon microstrip
  - Scintilating fiber tracker
- Calorimetry
  - Uranium/liquid argon
- Muon spectrometer
  - 3 layers of drift tubes
  - Toroidal magnetic field (1.9T between inner 2 layers)

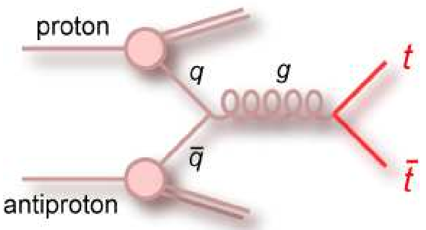


The CDF Detector

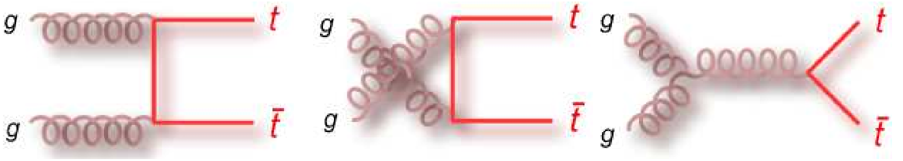


Top Quark Production at the Tevatron

Strong top production

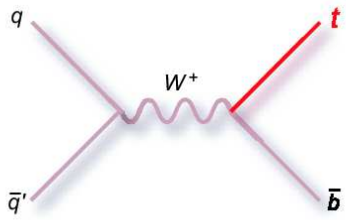


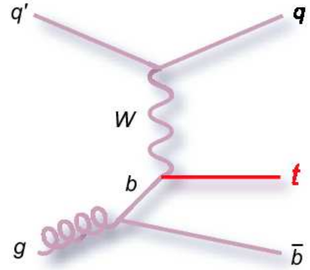
$$\begin{array}{ll} 85\% & q\bar{q} \to t\bar{t} \\ 15\% & gg \to t\bar{t} \end{array}$$



- $\sigma(t\bar{t}) = 6.77 \pm 0.42$pb

Weak top production





Drell-Yan s-channel

W-g fusion t-channel

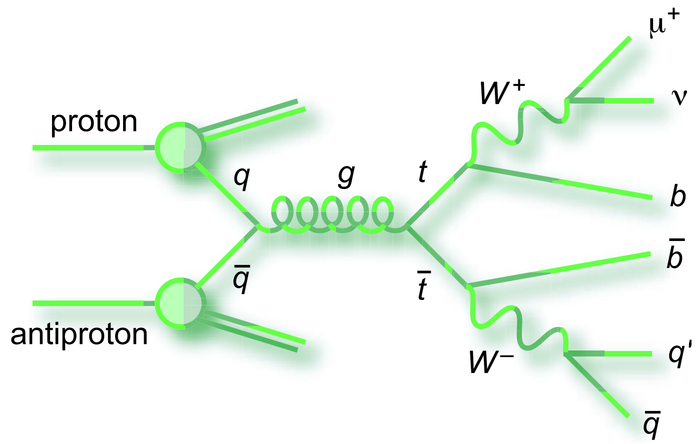
- $\sigma(t\bar{t}) \simeq 2.5$pb

For integrated luminosity of $\sim 1\,\text{fb}^{-1}$ around 7000 top pairs expected.

Available results analyse $1/3$.

Top Quark Decay

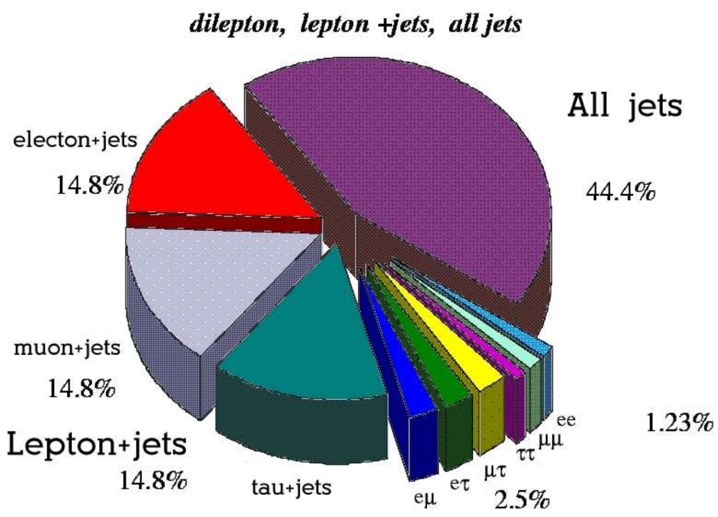
Top quarks decay to bW (nearly) 100%.



Pair Production Signatures

Decay modes are defined by W-decays:

- Dilepton $(2b + 2l + 2\nu)$
- Lepton+jets $(2b + 2q + l\nu)$
- Alljets $(2b + 4q)$



Single Top Signatures

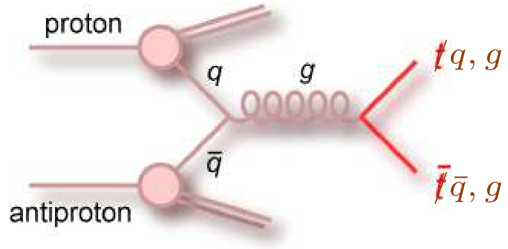
Defined by W-decays and channel;
e.g. leptonic decay:

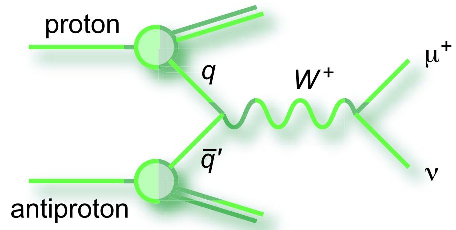
- s-channel $(2b + l + \nu)$
- t-channel $(b + j + l + \nu)$

Pair Production Cross-Section

The strong production mechanism

$$\sigma_{t\bar{t}} = \frac{N - B}{\varepsilon \mathcal{L} \cdot \mathrm{BR}}$$





Backgrounds

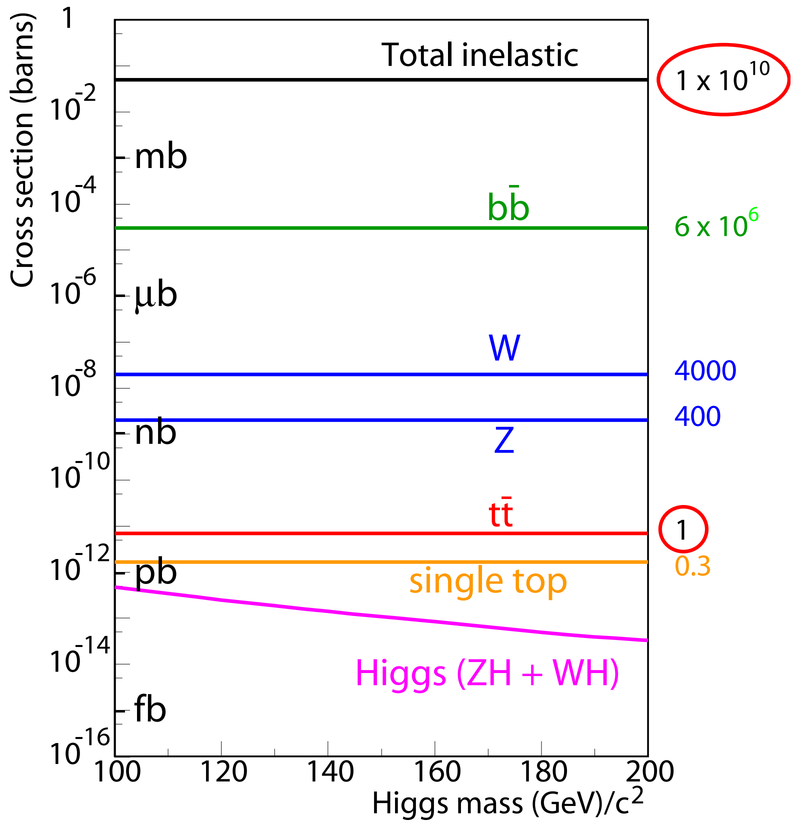
Physics background

- Multijet ($q\bar{q}$ or gg + gluon rad.)
- W+jets
- Z+jets

Instrumental background

- Physics object misidentification
- Mismeasurement of energies

Small, but amplified by cross-section.



Analysis (lepton+jets)

Signal selection

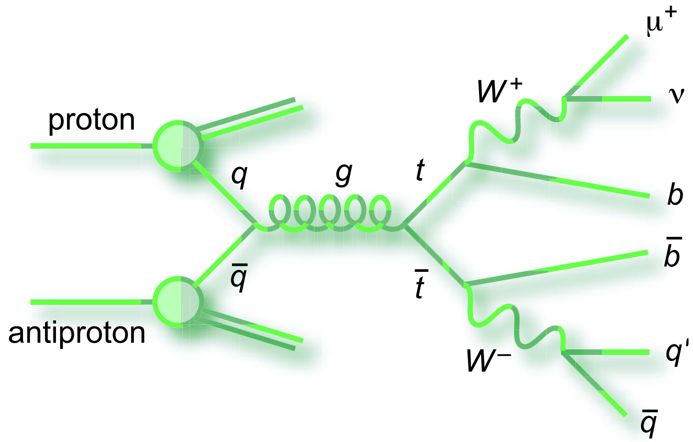
Require

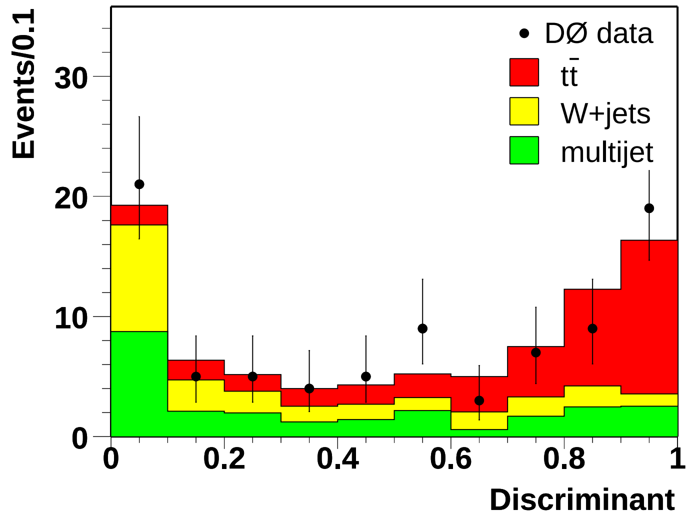
- at least 4 jets
- isolated lepton (not collinear)
- and missing transverse momentum

all with $p_T > 20$ GeV
$230\,\text{pb}^{-1}$ lead to 87 (80) $e(\mu)$+jets events

Background description

- Construct discriminant to distiguish bkg. from signal on statistical basis
- Instrumental bkg. from data
- Fit signal to phys. background ratio

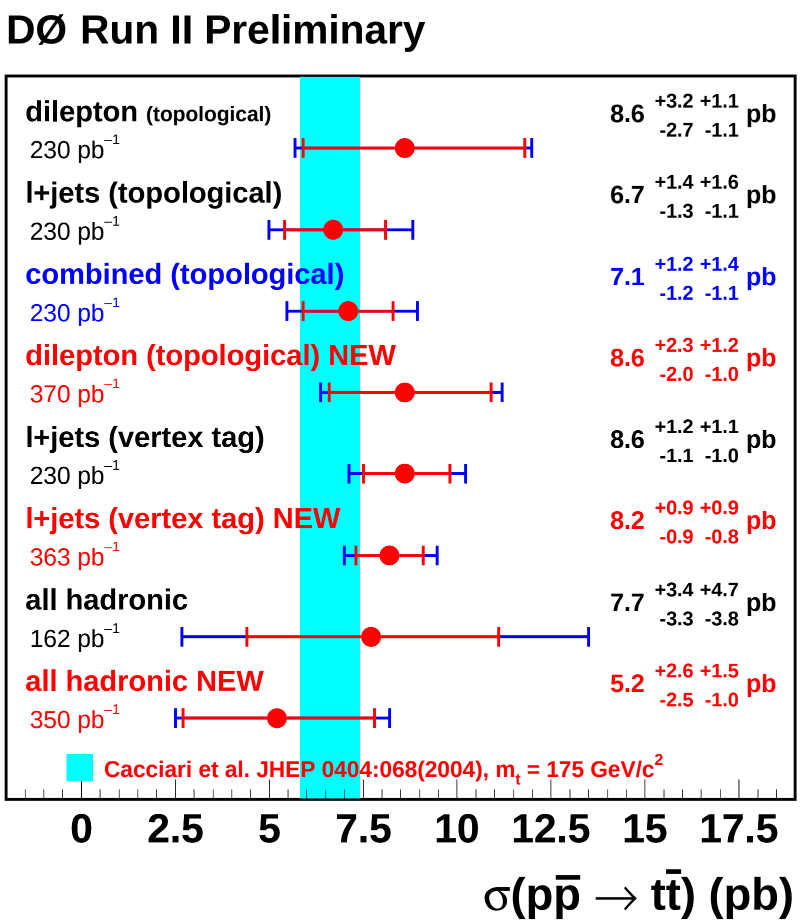


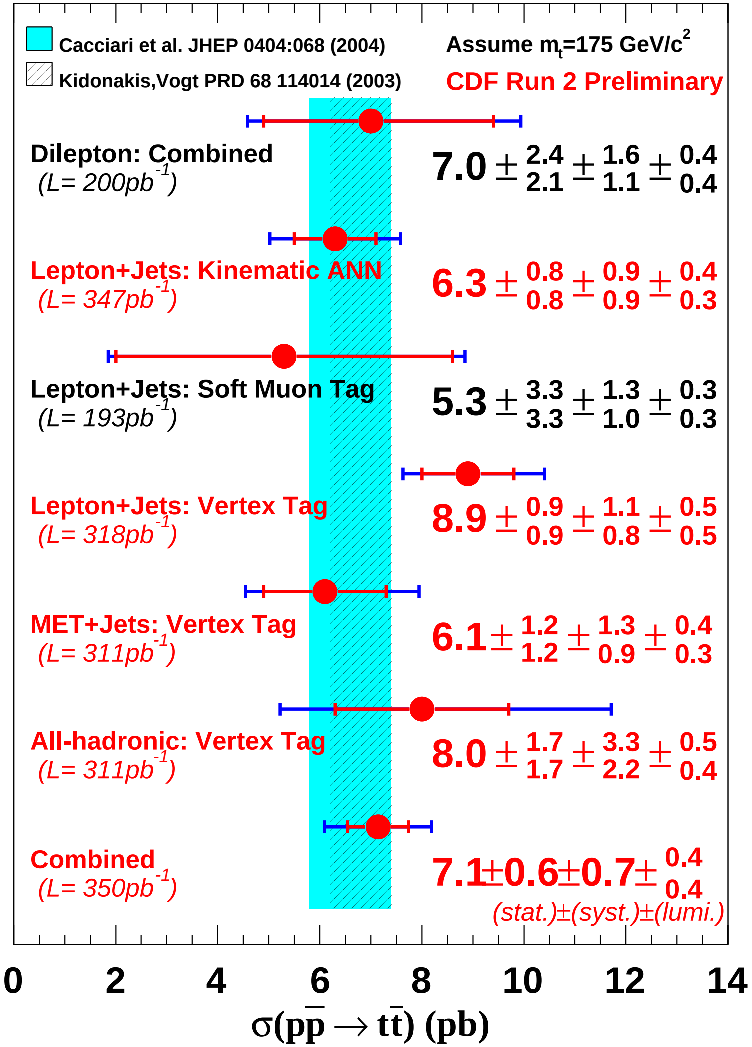


$$\mathcal{D} = S/(S+B)$$

Results on top pair production

Various channels & methods explored
Good consistency and agreement with SM (prediction $\sigma_{t\bar{t}} = 6.77 \pm 0.42$pb)

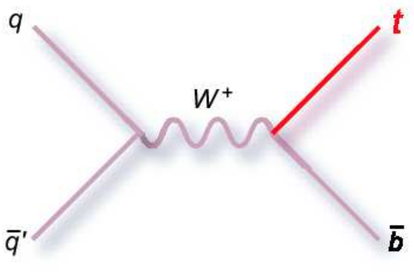




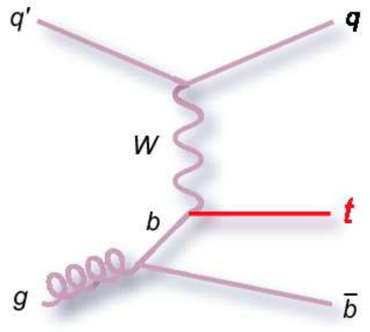
Single Top Production

The electroweak production meachanism

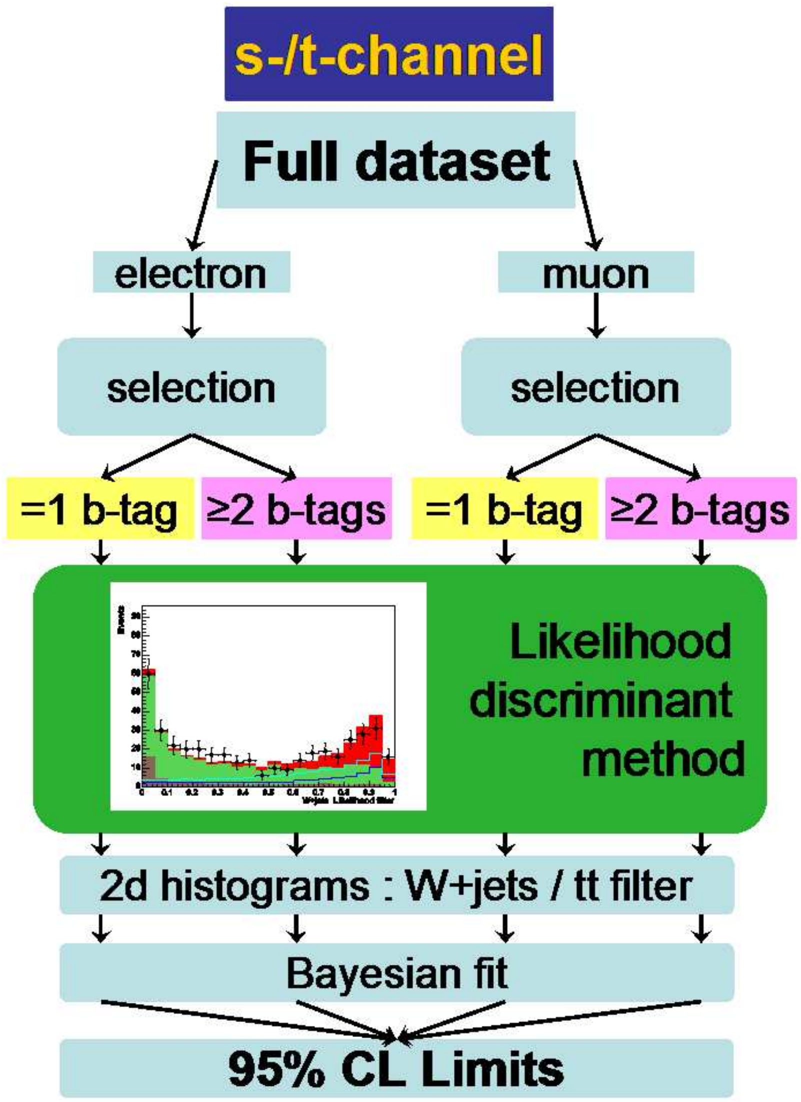
Only $t \to bW \to b + l\nu$ considered.



s-channel

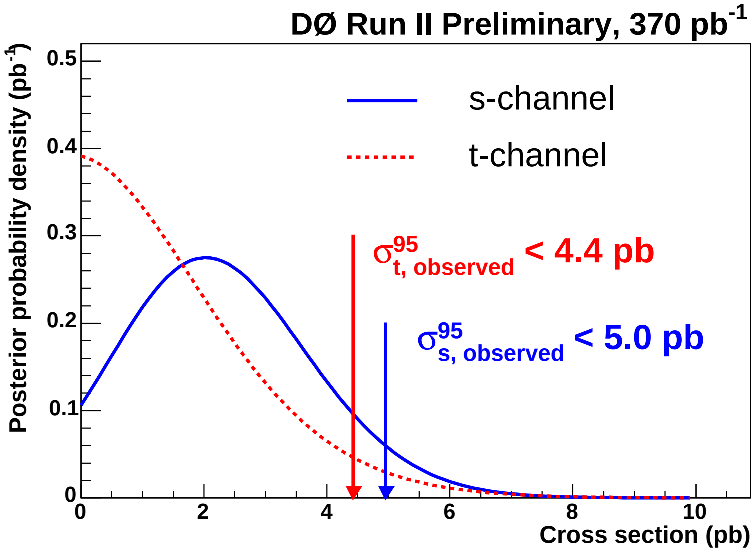


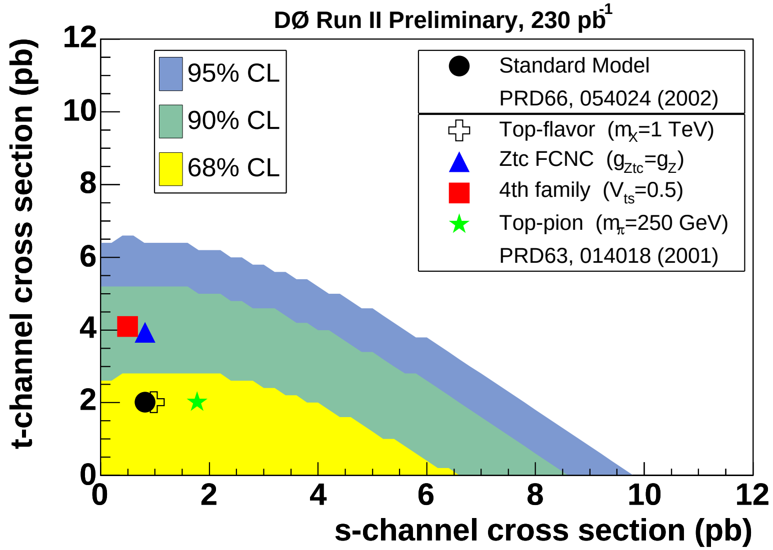
t-channel



Results on single top quark production

Using $370\,\text{pb}^{-1}$ DØ set upper limits





s-channel: $\sigma < 5.0$pb 95%CL
t-channel: $\sigma < 4.4$pb 95%CL

Current worlds best limit

CDF

s-channel: $\sigma < 13.6$pb 95%CL
t-channel: $\sigma < 10.1$pb 95%CL

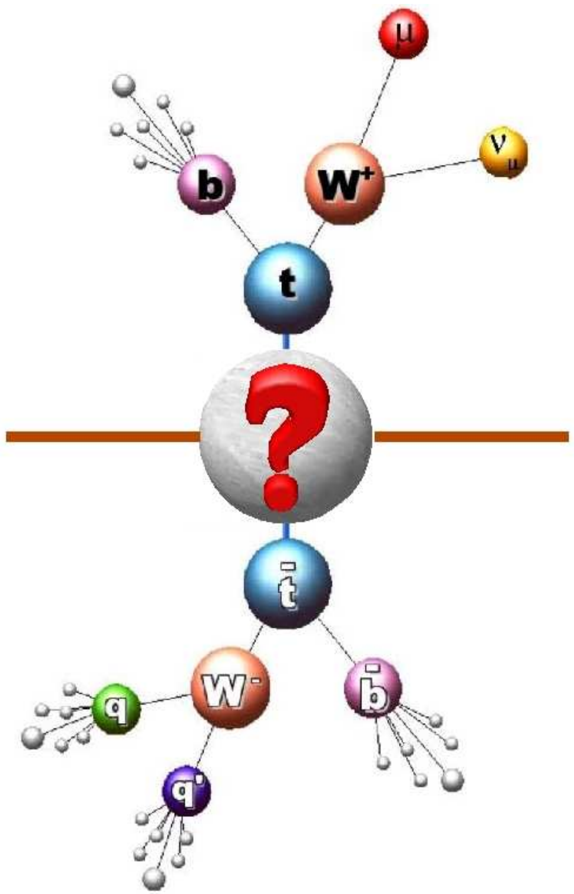
(using $162\,\text{pb}^{-1}$ only)

Resonant $t\bar{t}$ production

No resonance production in $t\bar{t}$ expected in SM,

but some models predict bound $t\bar{t}$-states

- new strong gauge force coupling to 3rd generation
- top assisted technicolour: Z'



Such a resonance should create a bump in differential cross-section $\dfrac{\mathrm{d}\sigma}{\mathrm{d}m_{t\bar{t}}}$

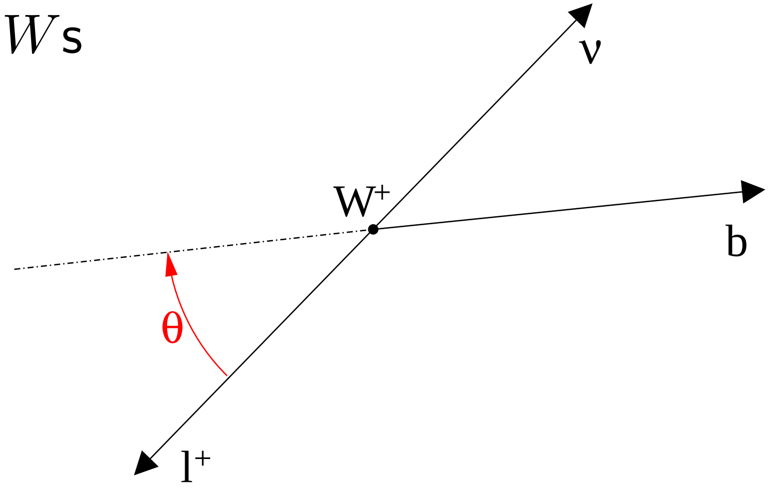
→ *See Maren Vaupel's talk.*

W-Helicity in Top Decays

- SM predicts only lefthanded tops couple to Ws ($V - A$ coupling)

- Visible in angular distributions:
  Best: angle θ between lepton and direction from where the top came in W restframe.

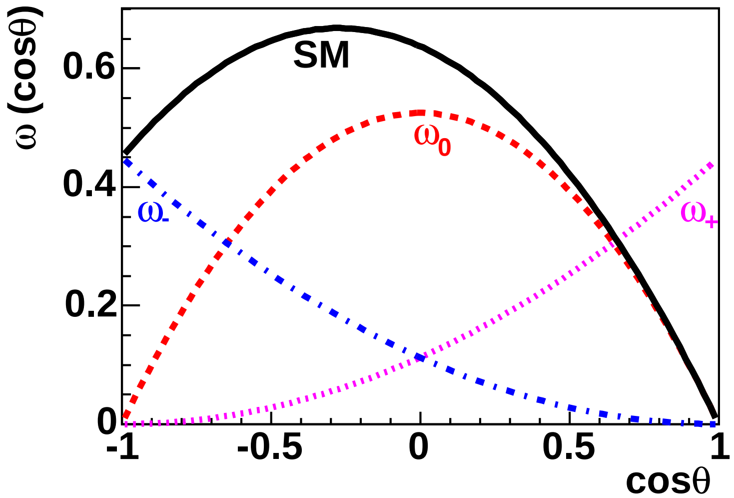
- SM suppresses leptons against top direction



DØ Analysis

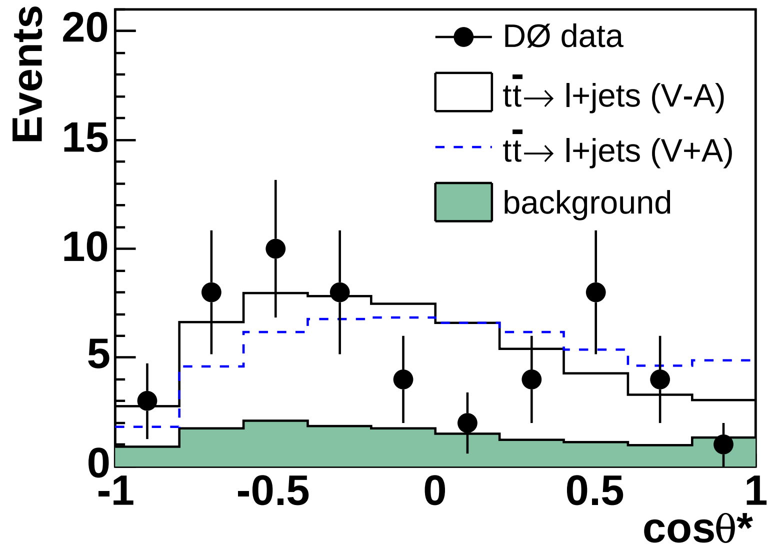
- $230\,\text{pb}^{-1}$ lepton + jets events
  - Electron and muon separately

- 2 analyses methods
  - selection with b-tag
  - kinematic selection



Measured $V + A$ contribution

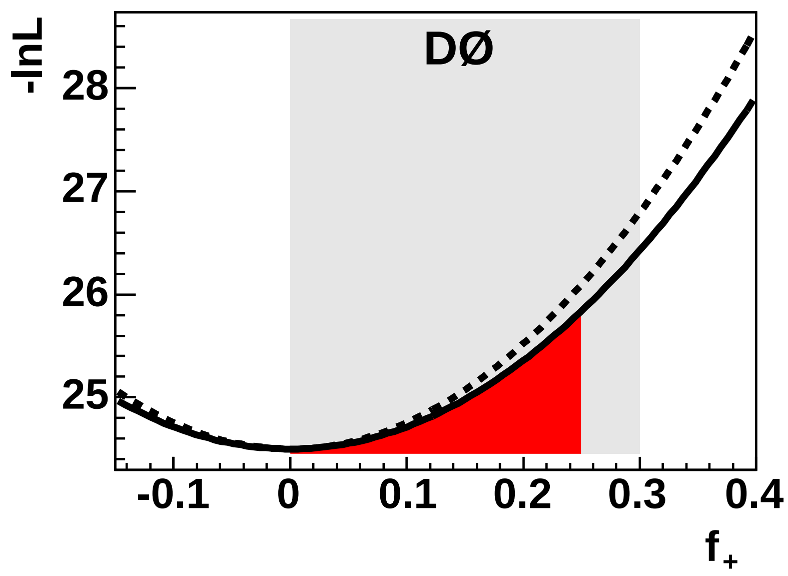
- Compare $V \pm A$ templates to data.
- Determine likelihood of various $V + A$ admixtures.
- Combine likelihoods for result



DØ Combined results:

$$f_+ = 0.00 \pm 0.13(\mathrm{stat}) \pm 0.07(\mathrm{syst})$$

Bayesian limit: $f_+ < 0.25 \quad 95\%\mathrm{CL}$



CDF result (Run I):

Frequentist limit: $f_+ < 0.18 \quad 95\%\mathrm{CL}$

Flavour of Top Decay: V_{tb}

$R = B(t \to Wb)/B(t \to Wq)$ from ratio of 0, 1 and double b-tagged top events.

CDF

$R = 1.11^{+0.21}_{-0.19}$

$R > 0.62$ 95% CL

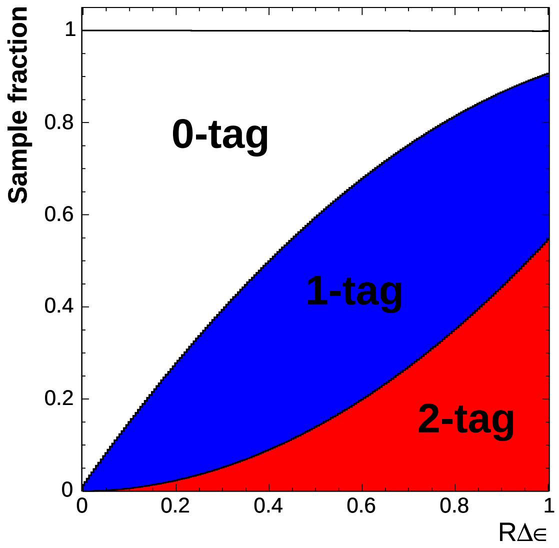
$|V_{tb}| > 0.78$ 95% CL

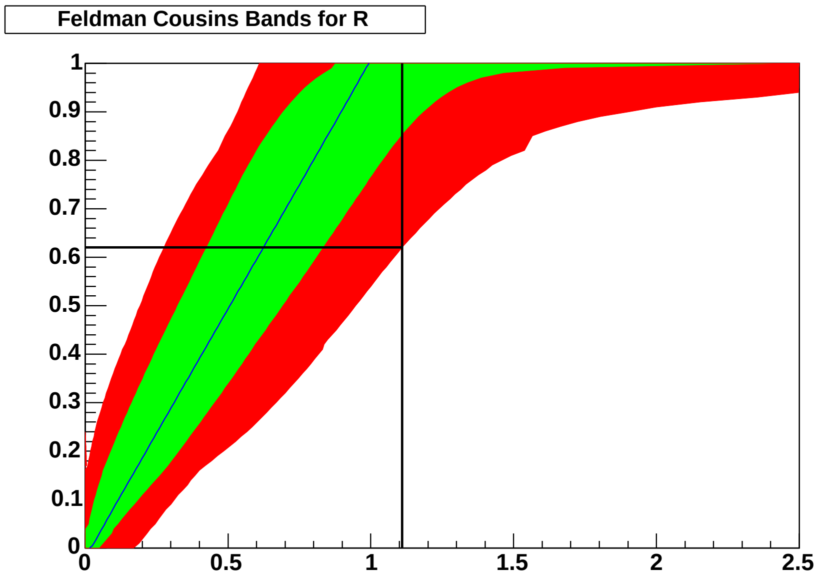
DØ

$R = 1.03^{+0.19}_{-0.17}$

$R > 0.64$ 95% CL

$|V_{tb}| > 0.80$ 95% CL



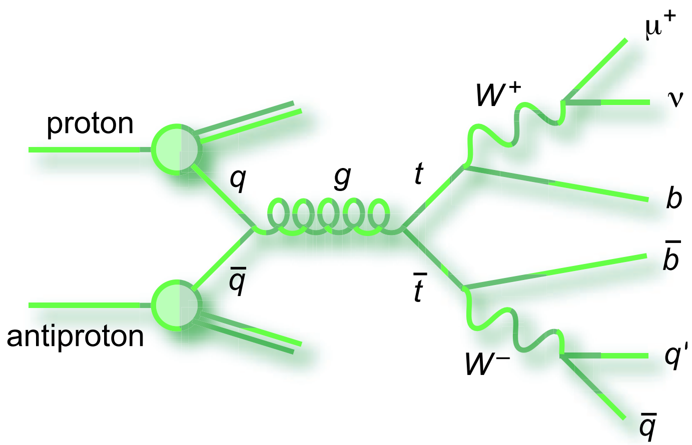


A long way to SM $|V_{tb}| \simeq 0.999$

Top Mass: Template Method (CDF)

Signal Sample

- Semileptonic decay mode (lepton+jets)
- Selection similar to cross-section.
- Performed on 4 samples:
  $0\,b$-tag, $1\,b$-tag loose, $1\,b$-tag tight, $2\,b$-tag



Determination of m_t

Find 4-momenta of t-quarks event by event

CDF Run II Preliminary (318pb^{-1})

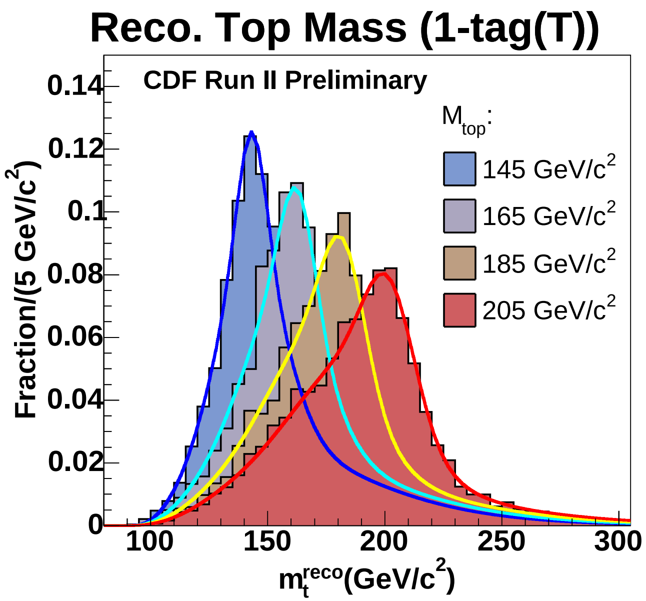
Subsample	Number of events m_t	Number of events m_{jj}
2-tag	16	25
1-tag(T)	57	63
1-tag(L)	25	33
0-tag	40	44

- Recover ν momentum
- Assign (correctly) $l\nu$ and 4 jets to 2 tops
- Sum measured 4-momenta for particles assigned to each top; $m^2 = E^2 - \vec{p}^2$

Actually done with fitter: assumes 2 top-masses be equal and m_W nominal
Correct assignment and precise momenta crucial: lowest χ^2 taken.

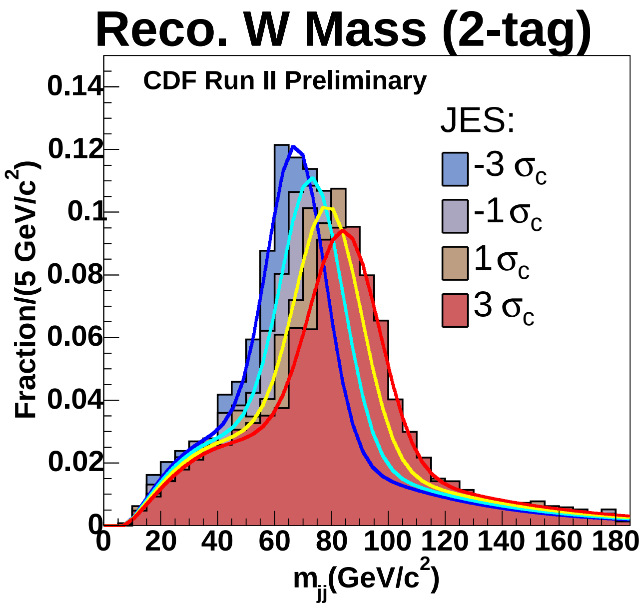
Determination of m_t (2)

- Build histogramms of observed masses
- Compare data to simulation
  - made for various values of m_t and JES.
  - including the expected amount of background
- Choose m_t that yields best agreement.



Constraining JES

- Templates for m_W reconstructed from m_{jj}.
- Constraint fit not employed.
- All pairs of not b-tagged jets considered



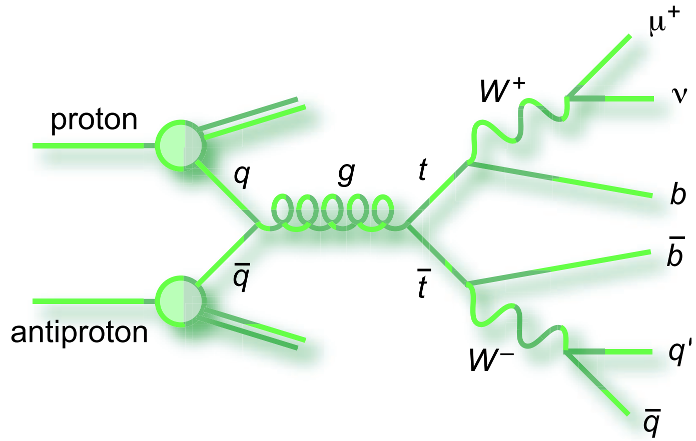
Top mass and JES determined by 2d fit:

$$m_t = 173.5^{+3.7}_{+3.6}(\mathrm{stat}+\mathrm{JES}) \pm 1.3(\mathrm{syst})\ \mathrm{GeV}$$

Top Mass: Matrix Element Method (DØ)

Signal Sample

- Semileptonic decay mode (lepton+jets)
- Selection similar to cross-section meas.



Determination of m_t

Probability to observe event with kinematic configuration x as function of m_t:

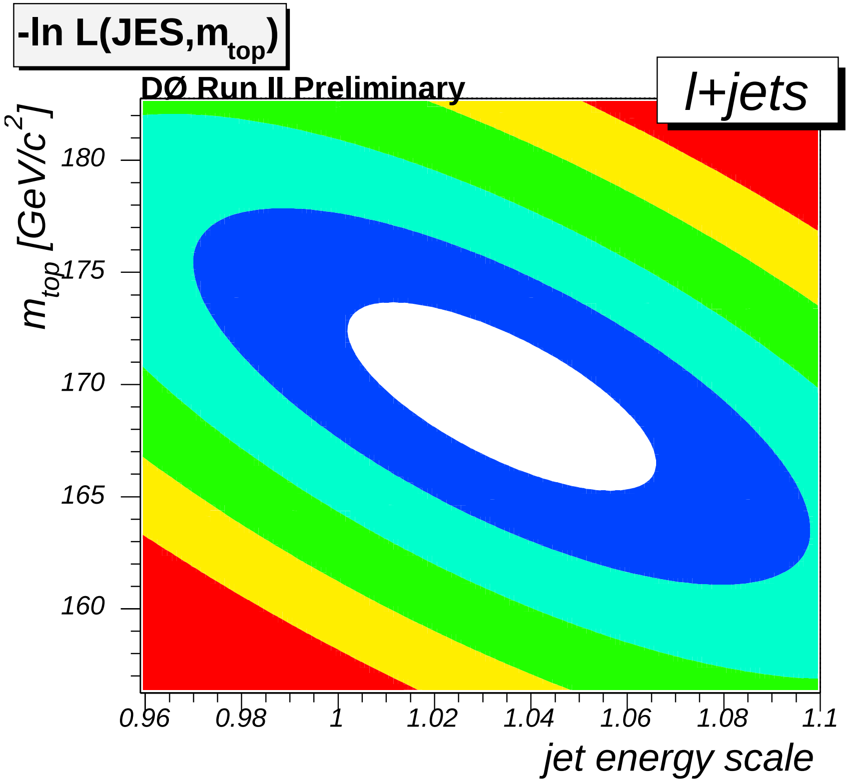
$$P_{\text{evt}}(x; m_t) = f_{\text{top}} P_{\text{sgn}}(x; m_t) + (1 - f_{\text{top}}) P_{\text{bkg}}(x)$$

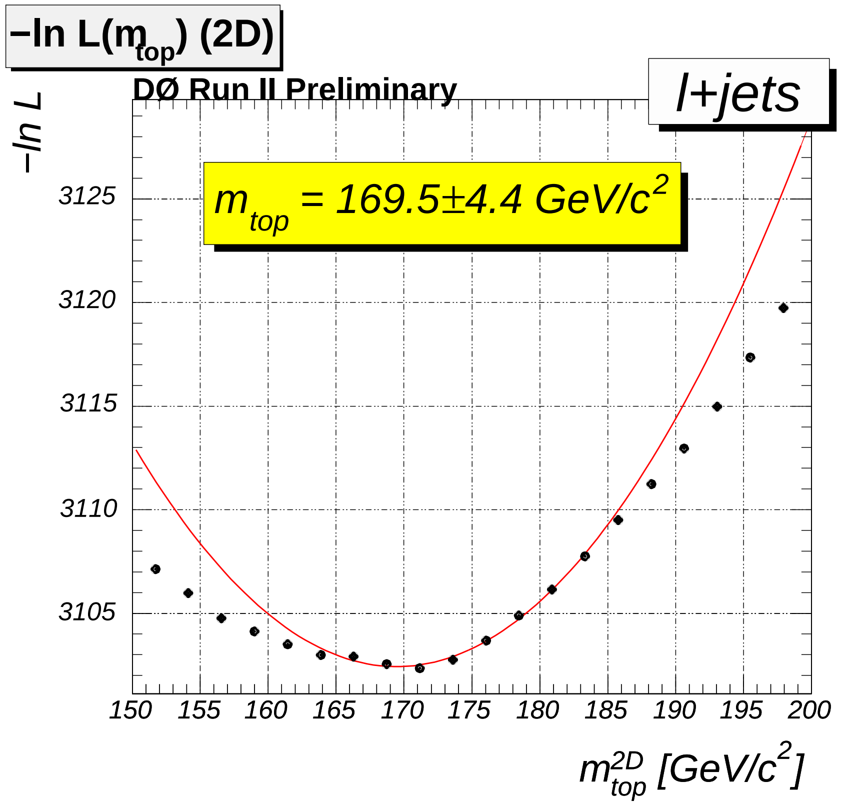
$$P_{\text{sgn}}(x; m_t) = \frac{1}{\sigma_{t\bar{t}}(m_t)} \int \mathrm{d}q_1 \, \mathrm{d}q_2 \, \underbrace{\mathrm{d}^n\sigma(q\bar{q} \to t\bar{t} \to y; m_t)}_{\text{Matrix Element}} \, \underbrace{f(q_1) f(q_2)}_{\text{PDFs}} \underbrace{W(y, x; \text{JES})}_{\text{Resolution}}$$

- ME used are $q\bar{q} \to t\bar{t}$ and $q\bar{q} \to W + \text{jets}$. Multijet treated as syst. uncertainty.
- Extended to fit Jet Energy Scale simultaneously (prev. dominating systematics)

Determination of m_t (2)

m_t (and JES) those that are most likely to produce observed sample





$$m_t = 169.5 \pm 4.4(\mathrm{stat} + \mathrm{JES})^{+1.7}_{-1.6}(\mathrm{syst})\ \text{GeV}$$

Top Mass: Results

Different channels and method investigated yield consitent results.

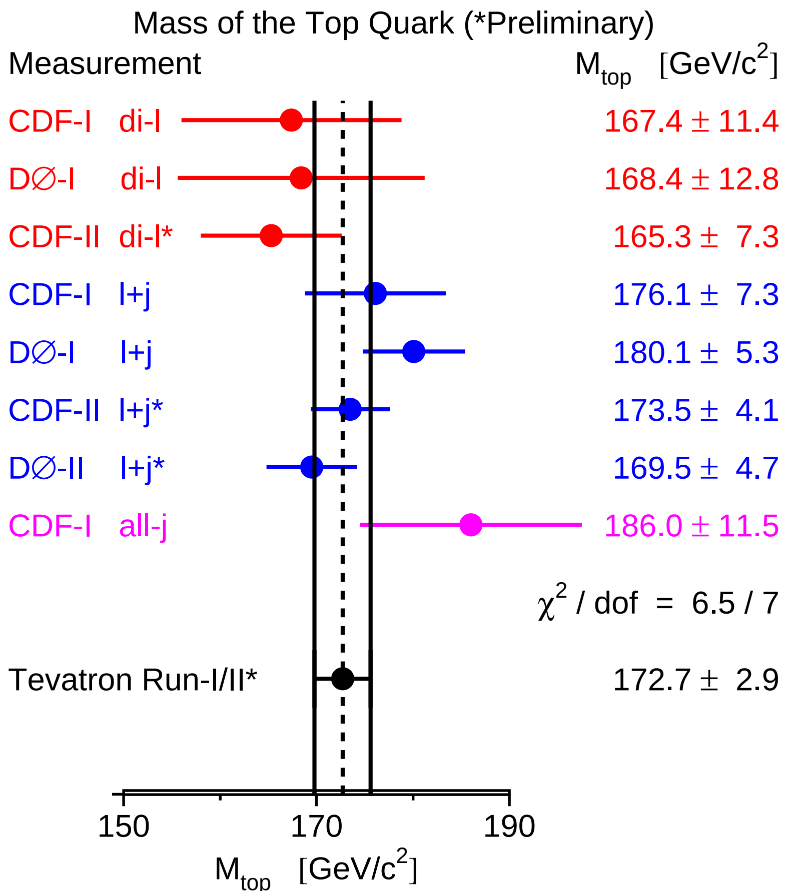
Presented l+jets results most precise.

Systematic uncertainties

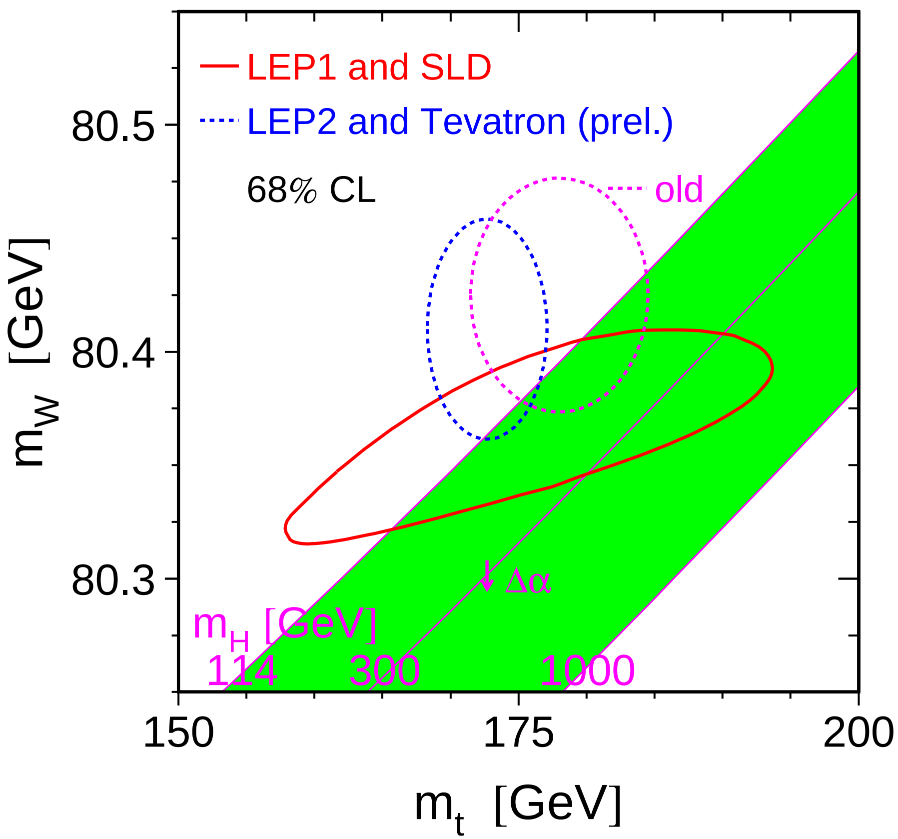
- Still dominated by jet energy scale.
- but now coupled to statistics.
- b-jet energy scale and
  heavy quark bkg. will take over.

Current World Average:

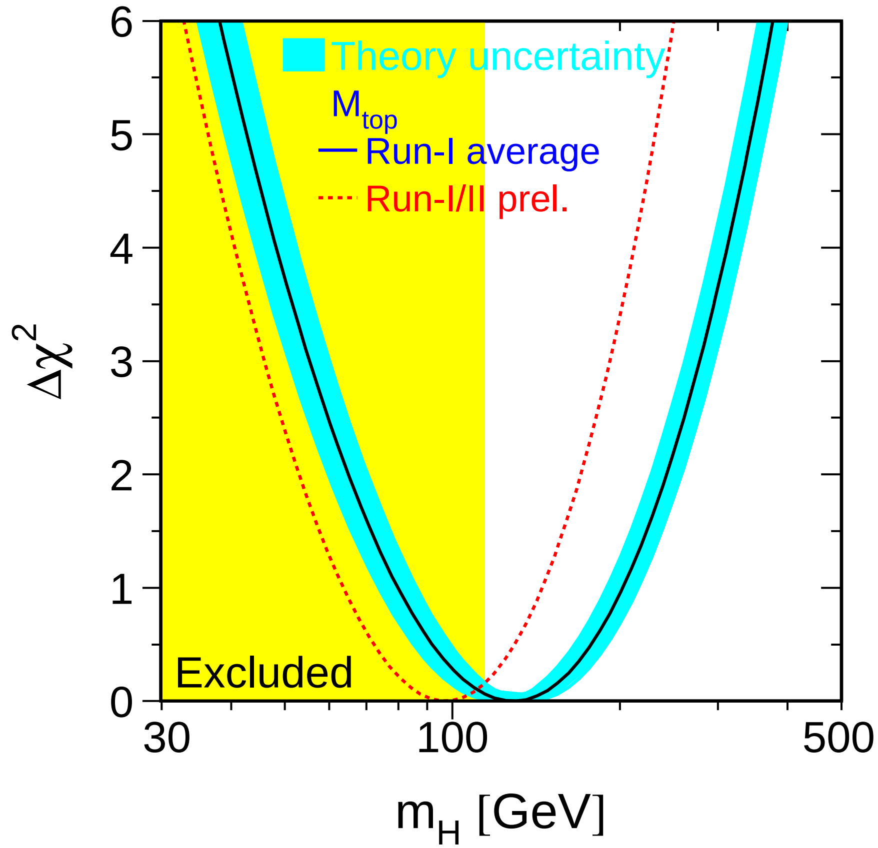
172.7 ± 2.9 GeV



Consequences



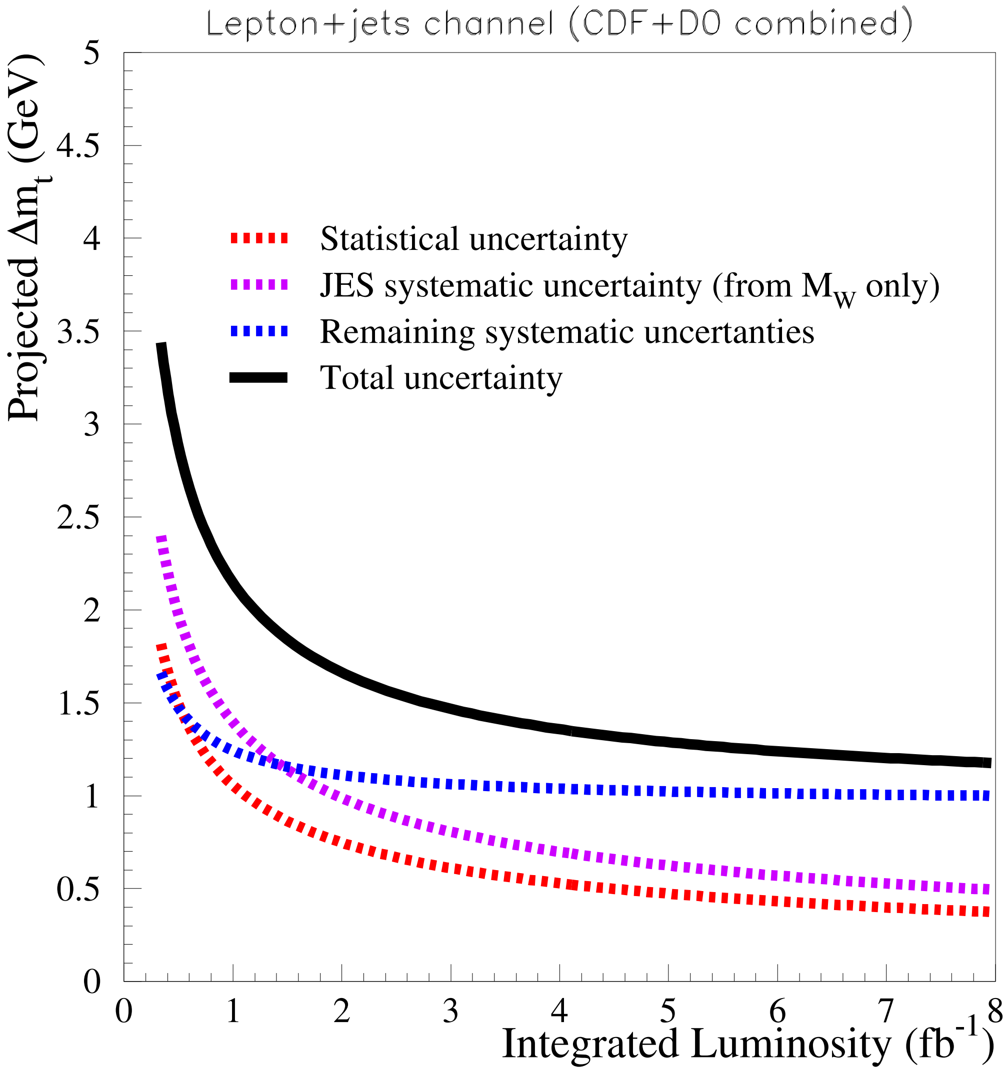
Combined m_W and m_t results



Higgs mass projection

$m_H = 91^{+45}_{-32}$ GeV

Top Mass Prospects



- Tevatron RunII (–2009) expected integrated luminosity $4 - 8\,\text{fb}^{-1}$.

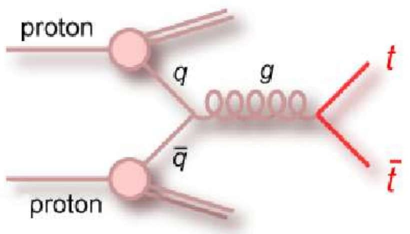
- $\delta m_t \simeq 1.3\,\text{GeV} \simeq \Gamma_t$ (DØ+ CDF combined)

- JES no longer limiting syst.

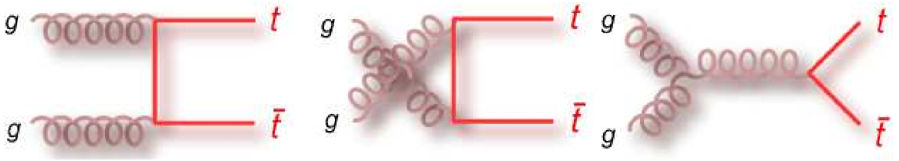
LHC

Top Quark Production at LHC

Strong top production

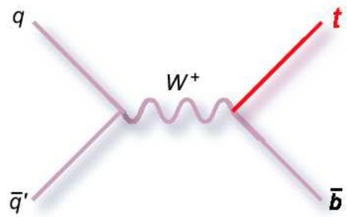


$$\begin{array}{ll} 13\% & q\bar{q} \rightarrow t\bar{t} \\ 87\% & gg \rightarrow t\bar{t} \end{array}$$

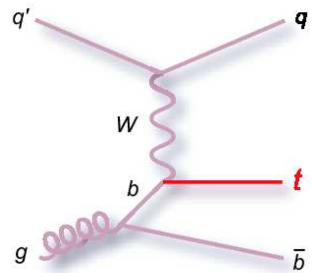


- $\sigma(t\bar{t}) = 825 \pm 150$pb
  NNLO-NNNLL: PRD 68 (03) 114014.
- Relative weight of graphs inverted (wrt. Tevatron)

Weak top production



Drell-Yan
s-channel



W-g fusion
t-channel

- $\sigma(t\bar{t}) \simeq 300$pb

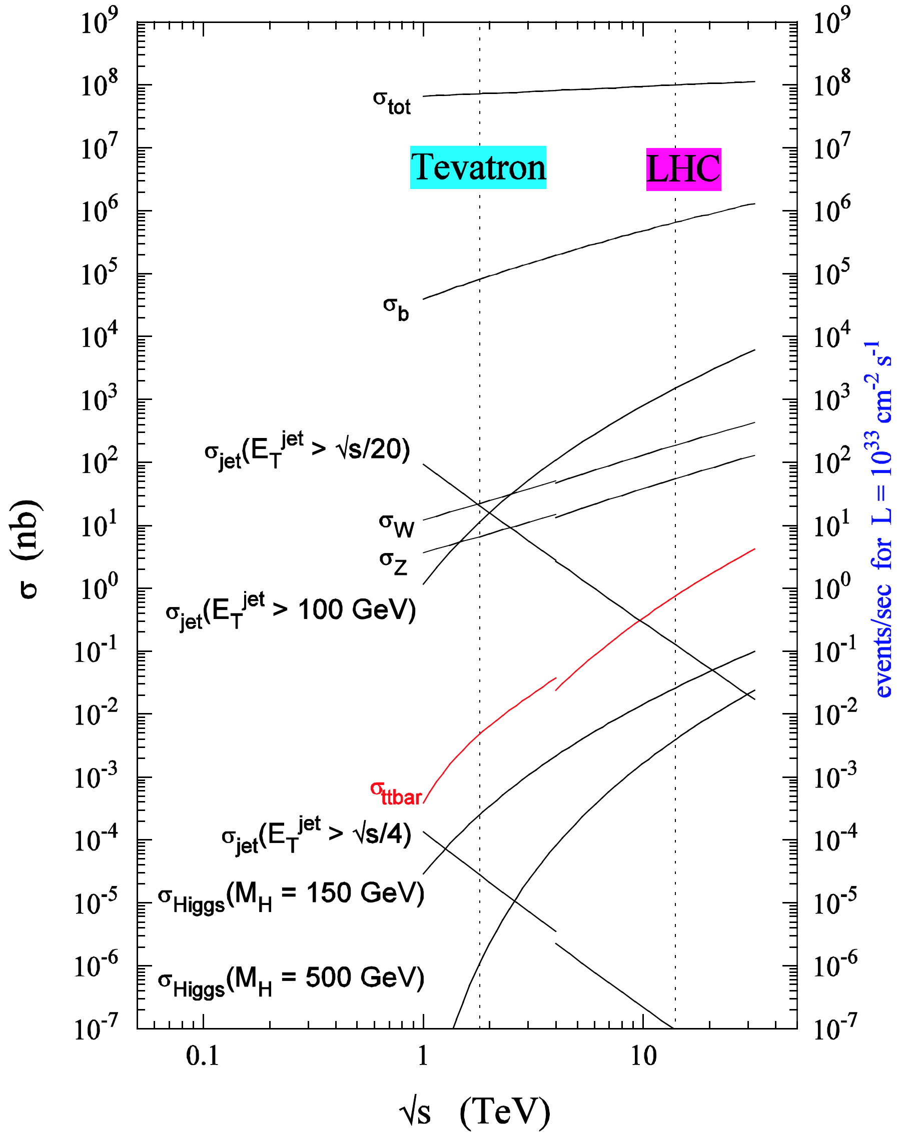
Cross-sections 100fold increased. Luminosity 10fold increased (“low luminosity”)

$\Rightarrow$ 10 million $t\bar{t}$ pairs per year (i.e. 1 per second) at low luminosity.

Cross sections at LHC and Tevatron

Process	N/s	N/year	
$t\bar{t}$	1	10^7	10^4 Tevatron
$Z \rightarrow ee$	1.5	10^7	10^6 LEP
$W \rightarrow e\nu$	15	10^8	10^7 Tevatron
$b\bar{b}$	10^6	10^{12-13}	10^9 Belle/ BaBar

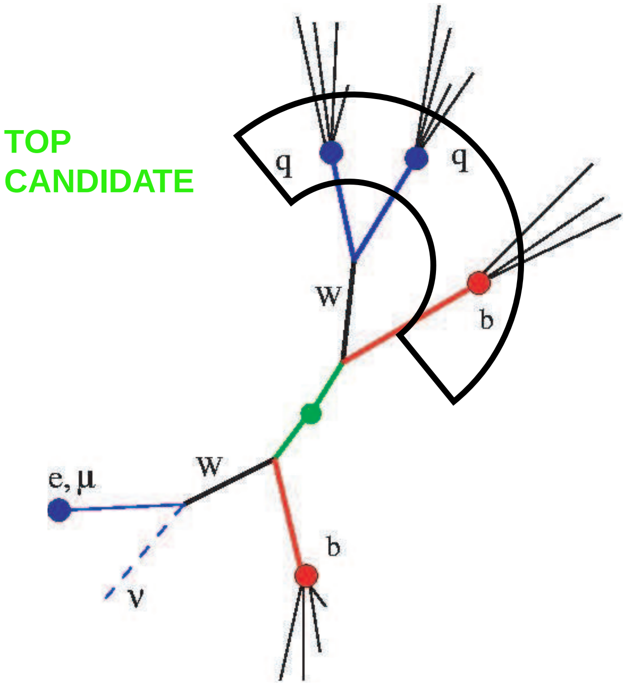
- $\sigma_{t\bar{t}}$ at LHC 100 times bigger.
- background processes less increased
- LHC is a top fabric



Top Physics during Commissioning

Can we do top physics during the commissioning phase? $\Rightarrow$ Without b-tag

Standard top analysis



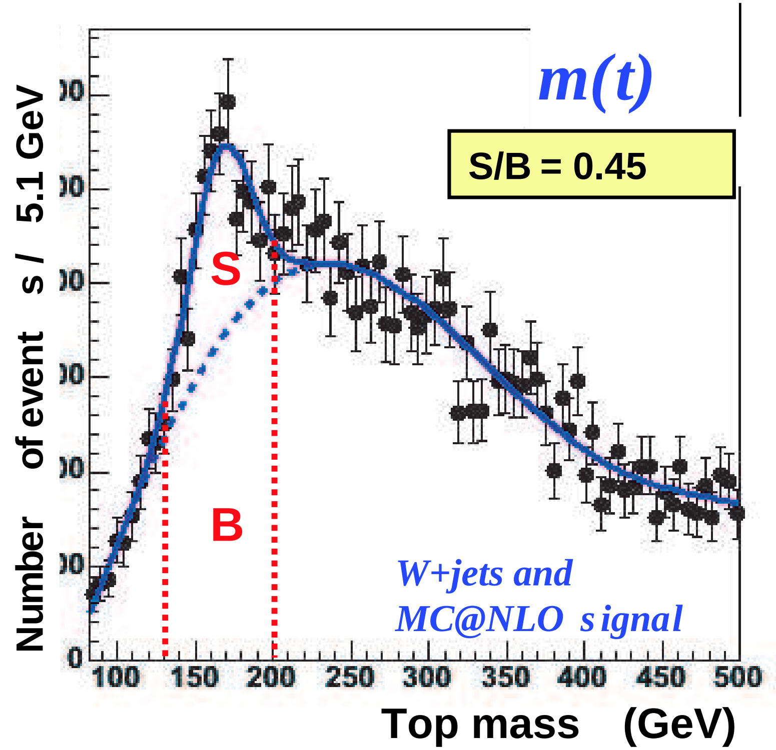
Hadronic top:

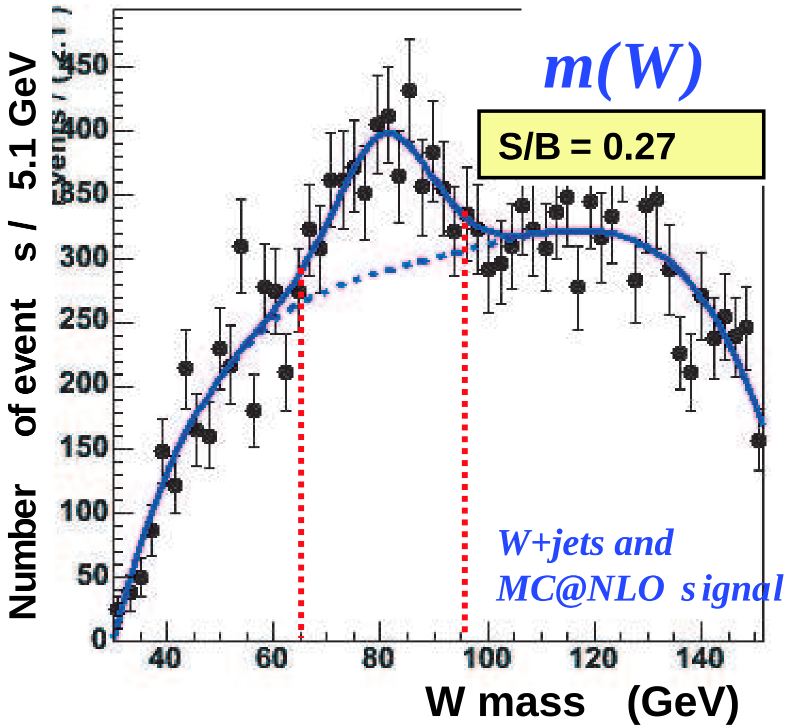
Three jets with highest vector sum p_T.
W-boson: 2 jets with highest momentum in jjj centre-of-mass frame

Selection: (Efficiency $= 5.3\%$)

	$\not{E}_T$	$>$	20 GeV
1 lepton	p_T	$>$	20 GeV
4 jets	p_T	$>$	20 GeV

Top and W Peaks in presence of background



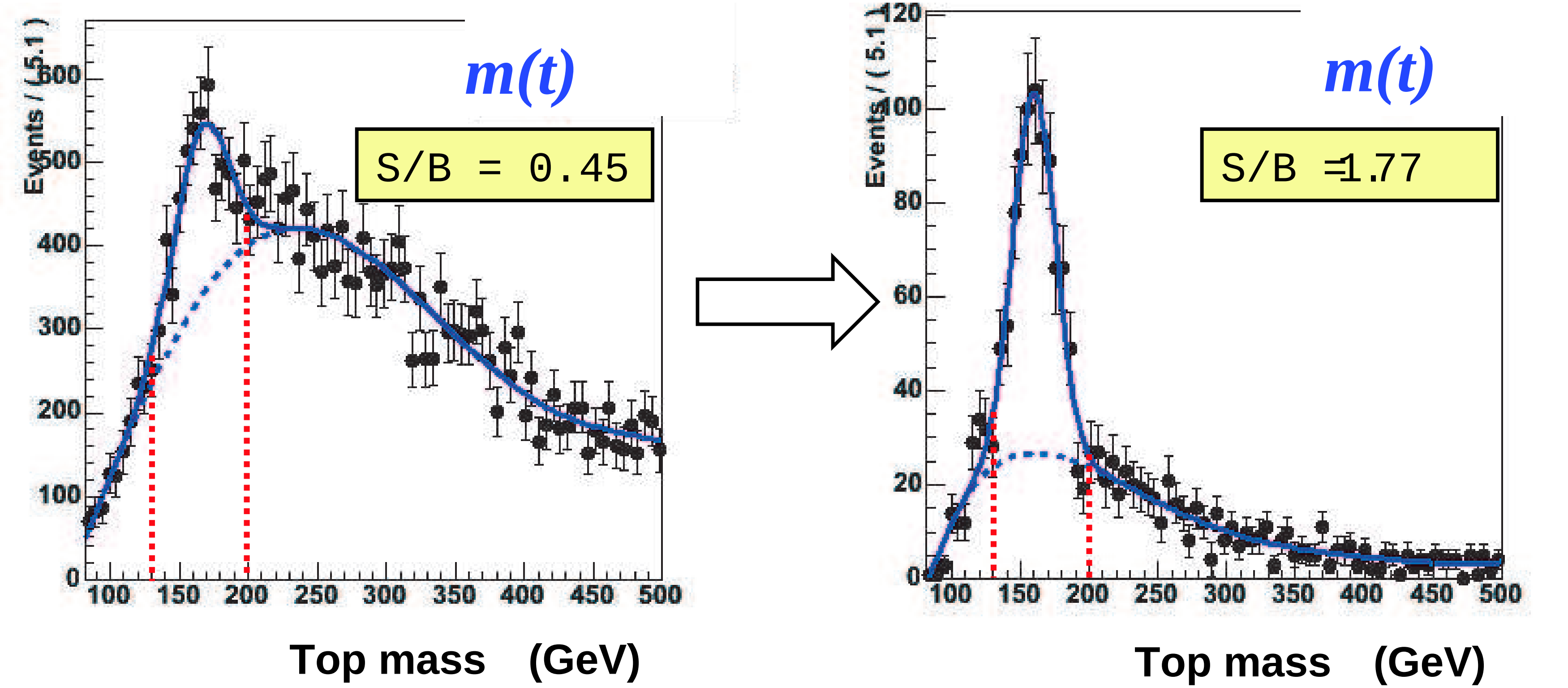


1 week of low luminosity running.

top peak visible as mass spectrum without b-tagging

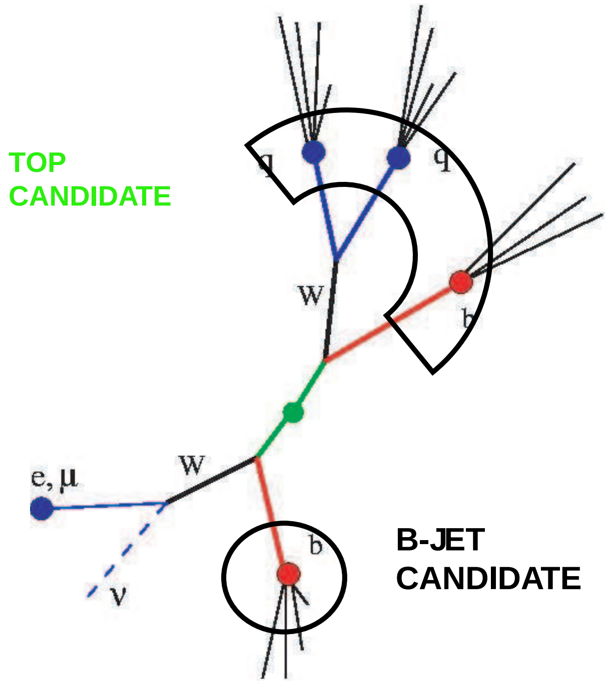
Improving sensitivity

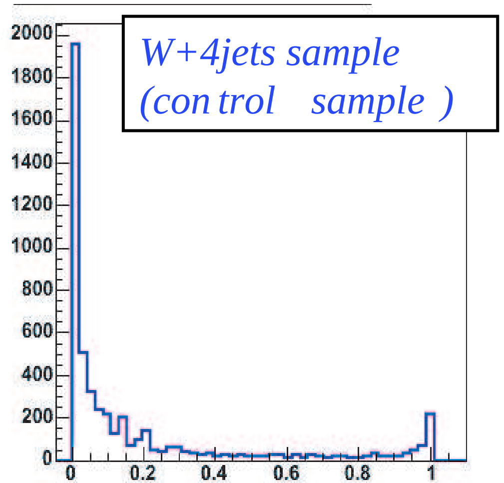
Standard Analysis $\qquad$ M_W within $10\,\mathrm{GeV}$ of nominal value

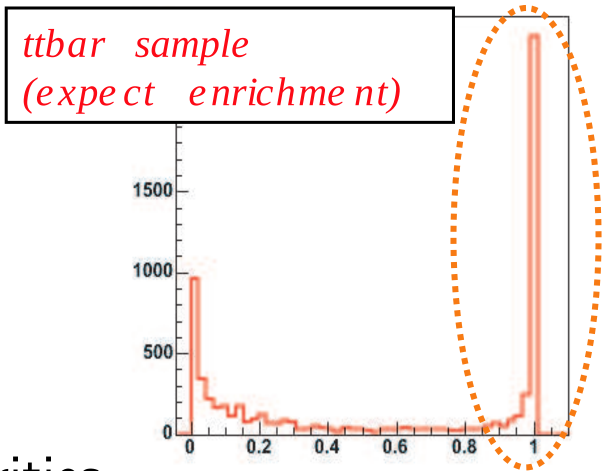


Top peak clearly visible after 1 week of LHC data

Commissioning of b-tagging with top events



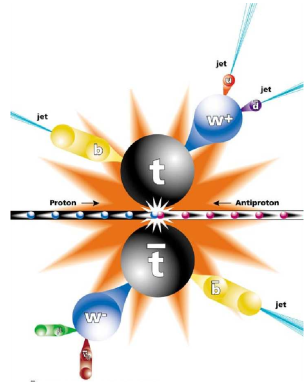




Determine b-tagging probabilities and purities

Hadronic side can be used by applying W-mass constraint.

Summary



- The top quark is very interesting. Only few properties verified.
- Tevatron currently our only top laboratory
  - Pair production cross-sections agree at 20% precision.
  - Single top (weak) production within reach.
  - Additional (resonance) production . . .
  - Decay properties show no deviation from SM.
  - Top mass at 1.7% precision. DØ and CDF challenging LHC aims.
- LHC will be a top factory
  - Measurements will by systematics dominated.
  - Top can and will be used for calibration.
  - Top presents major background for searches.