# Top Physics at Tevatron Run II

Boris Tuchming
CEA-Saclay

On behalf of CDF and DØ Collaborations

Many thanks to everyone who helped in the preparation of this talk

# Outline

Introduction

Tevatron performance

Top pair production

Mass

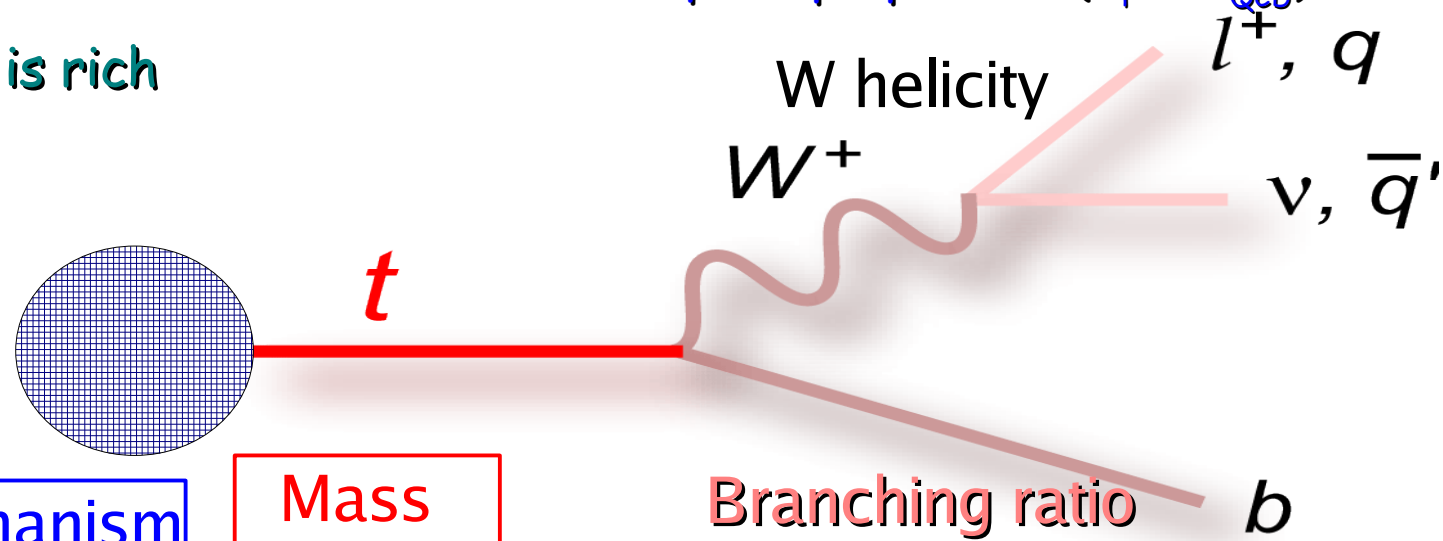
Other Properties

Wtb vertex

Search for new particles with top

# Why is top the golden quark

- Young particle: discovered 11 years ago at Tevatron RunI
  - Still need to be studied in detail
  - Top factory = Tevatron Run II
- Heaviest known fermion (~175 GeV/$c^2$)
  - mass close to Electroweak Symmetry Breaking scale (v=246 GeV/$c^2$)
  - Large yukawa coupling to Higgs ( $Y_t$ ~1)
  - Decays before hadronization. « bare » quark properties. ($\Gamma_t \gg \Lambda_{QCD}$)
- Top physics is rich

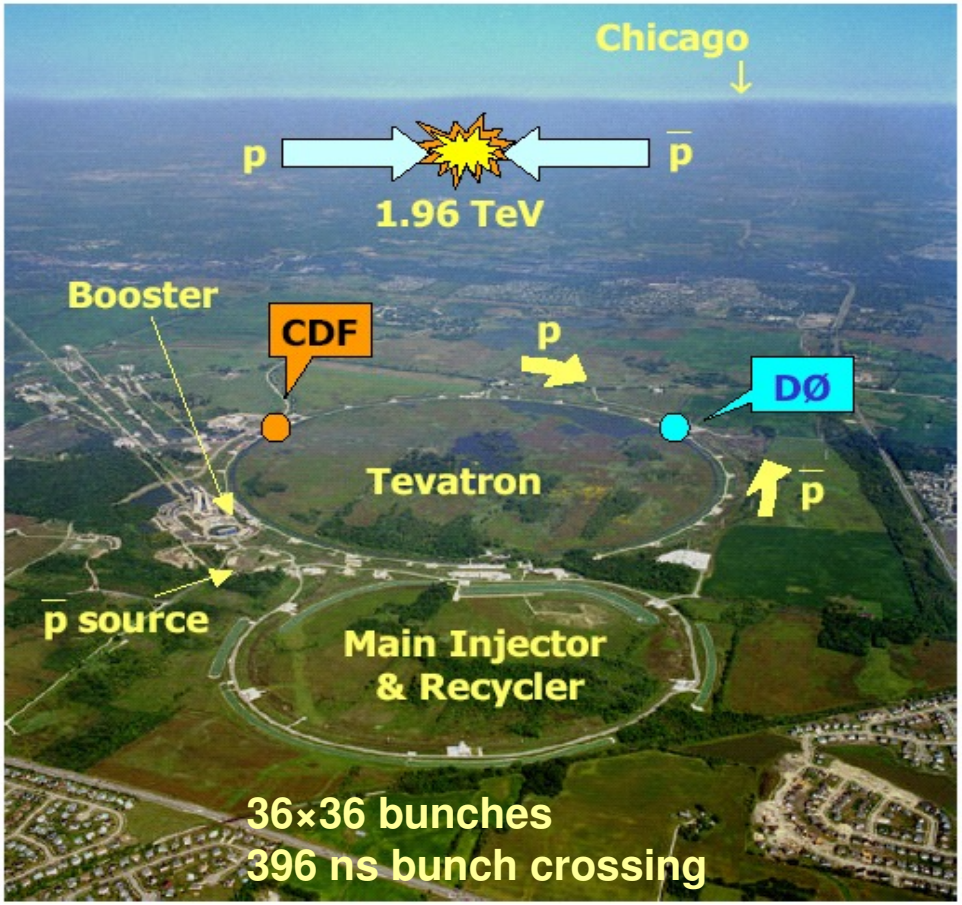



Production mechanism
Resonant production
production kinematics

Mass
width
liftetime
spin
charge

Branching ratio
rare decay
Non SM decay
anomalous coupling
$V_{tb}$

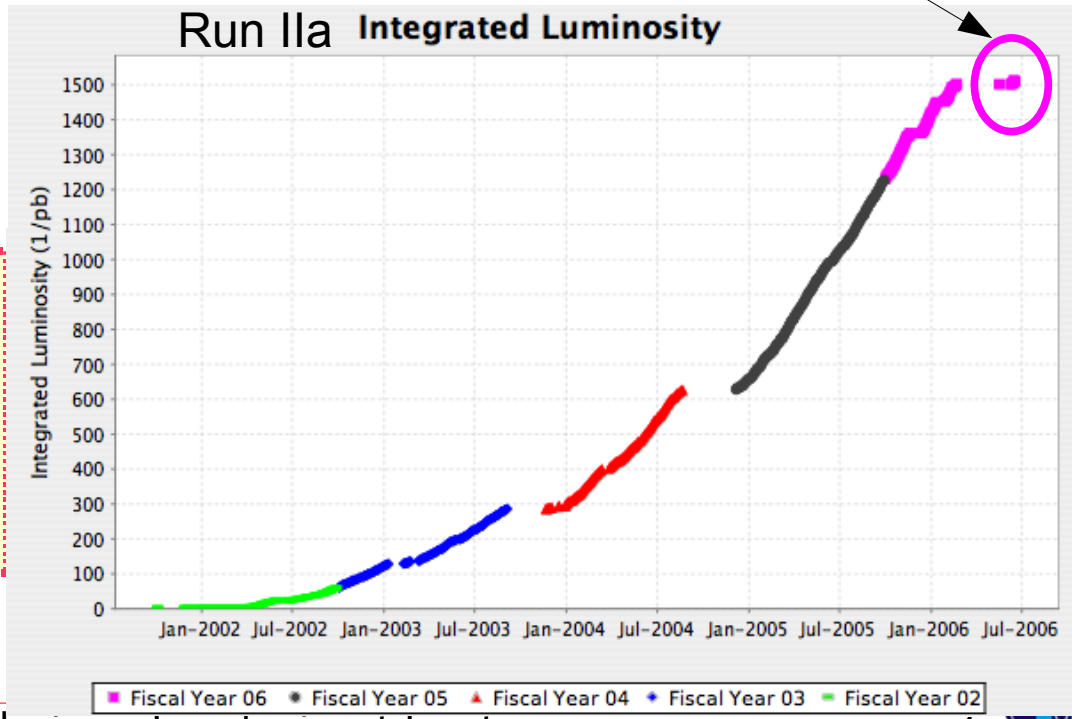
# Tevatron




Run I (1993-1996)
~120 $pb^{-1}$ per experiment

Run IIa: (2002-2006)
~1.5 $fb^{-1}$ per experiment delivered

Run IIb: just started
4 to 8 $fb^{-1}$ in 2009



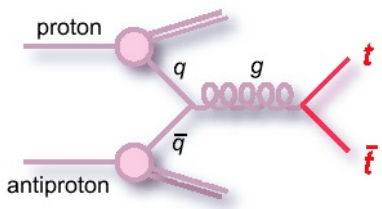

Available for physics in summer 06
more than 1 $fb^{-1}$
Analysis in this talk are based on smaller sample 300 - 750 $pb^{-1}$

# Top production at Tevatron

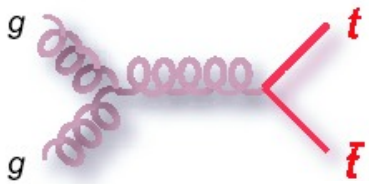
- Pair production: via strong interaction.
  - Only observed process so far

Cacciari etal, JHEP 0404:068,2004 6.7 pb +/- 12%

85%



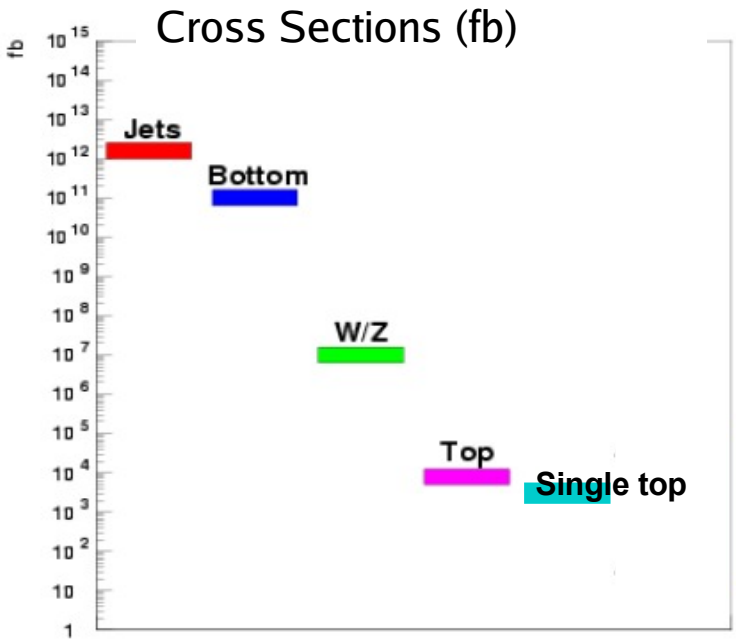

15%




Typically for $1fb^{-1}$: (lepton+jets)

N* Br * A=6700*0.3*0.15

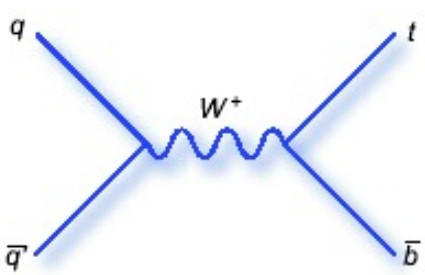
~ 300 events



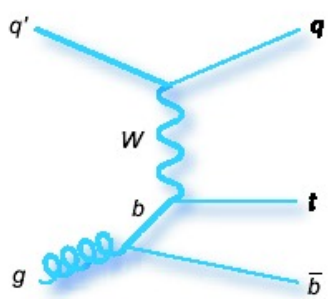

- Single top production (Electroweak)
  - Not observed yet
  - Low yield, high background

Sullivan, Phys.Rev.D70:114012,2004

s-channel 0.88 pb



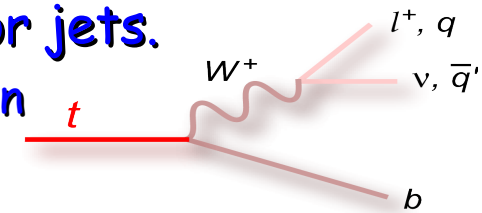

t-channel 1.98pb



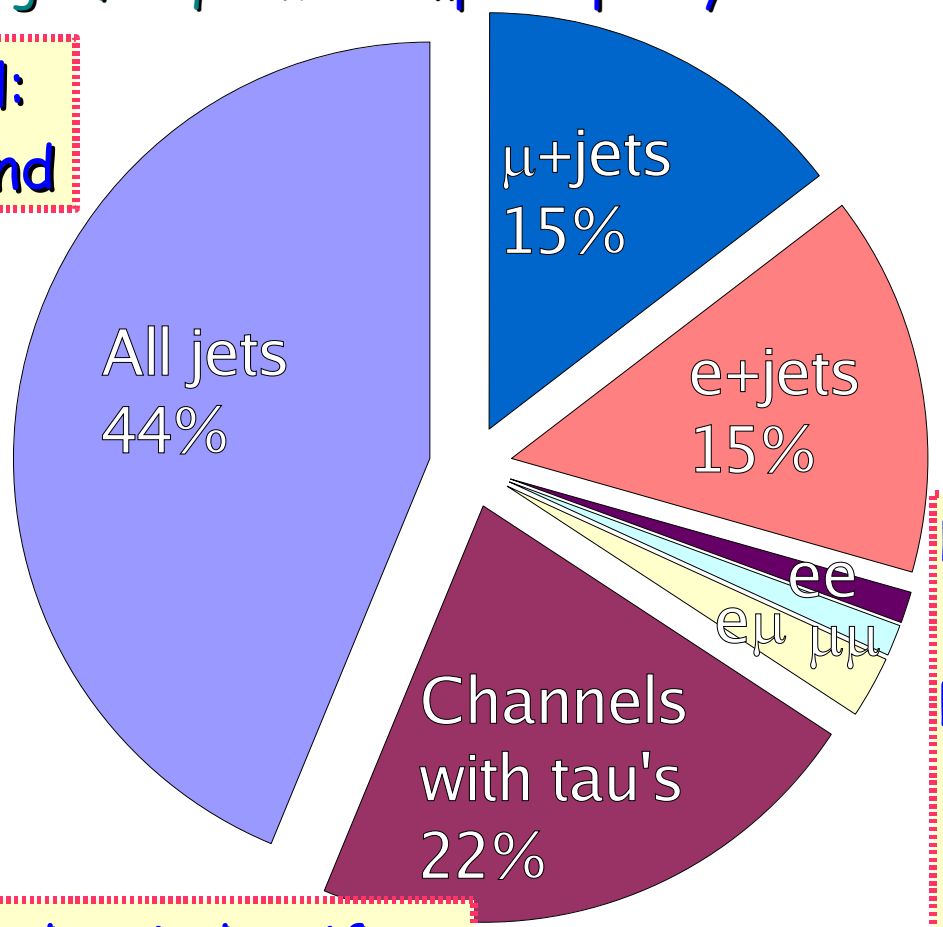
# Pair Production

# Top pair production signature

- Top decays into Wb (~100%). then W-> eν or μν or τν or jets.
  - Decay products with high momenta, large angular separation
  - Need to reconstruct energetic objects: e, μ, jets, $\not{E}_T$
  - tagging of b-quarks to improve purity




all jets channel:
QCD background

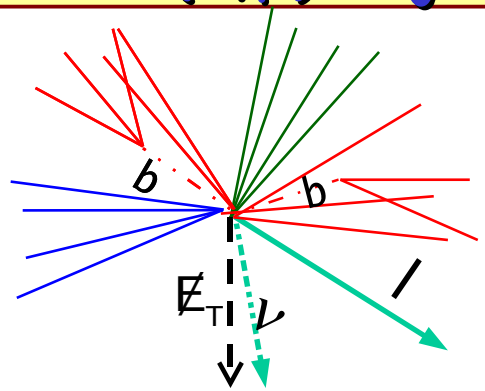



Lepton + jets channels:
background from:
- W+jets
- Z+jets
- QCD

Di-leptons channels: 4.5%
pure but low yield
background from:
- WW+jets
- Z+jets
- Z(ττ)+jets
- QCD

Tau's are hard to indentify.
Many sub-channels

# Leptons (e,μ) + jets channels




**Event signature:**

- Central
- Spherical
- Energetic
- Hight Pt lepton
- large Missing $E_T$
- 4 or more jets ( 2 b-quark jets)

**Selection:**

- High Pt lepton trigger (+jets D0)
- Isolated lepton $p_T$>20 GeV
- $\not{E}_T$ > 20 GeV
- 4 Jets $p_T$>15 GeV
- $H_T=\Sigma_i|p_{Ti}|$ > xx GeV

**B-tagging or topological cuts**

**two complementary approaches**

**Acceptance:**

- typically ~ 10-20% ( $N_{jets} \geq 3$)
- DATA/MC scale factor measured on independent sample

**Backgrounds**

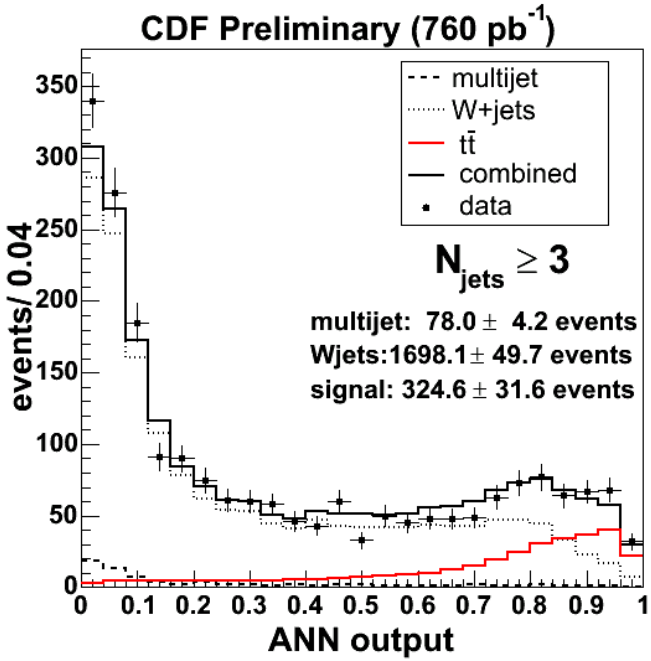
- W+ n jets (Wbbj, Wccj, Wjjj)
  - Determined with MC (ALPGEN)
  - Normalized on the DATA
- Non-W (QCD: fake lepton)
  - Determined on the Data
- WW + jets using MC

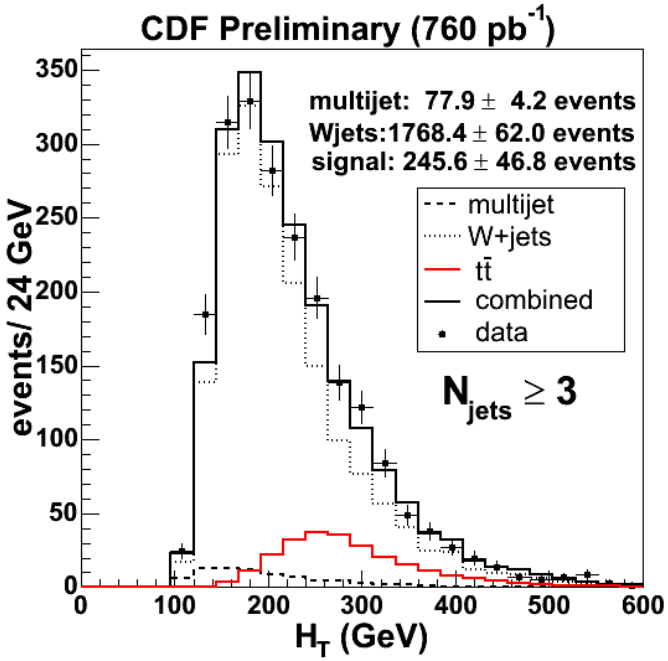
# Lepton + jets with topological analysis at CDF

- Artificial Neural Network combine 7 kinematical variables
  - $H_T$, aplanarity, min di-jet mass, $\Sigma p_z/\Sigma E_T$, $\Sigma_3^5 E^i_T$, min( $\Delta R_{ij}$), max jet $\eta$
  - Discriminate against main backgroud: W+jets. S/B=1/5
- Likelihood fit of the NN output to determine $t\bar{t}$ content
- Main uncertainties: JES (8.3%), W+jets modeling (10.2%)

CDF Preliminary (760 pb$^{-1}$)

| Sample | Events | Fitted $t\bar{t}$ | $\sigma(t\bar{t})$ |
|---|---|---|---|
| $W+\geq 3$ jets | 2102 | $324.6 \pm 31.6$ | $6.0 \pm 0.6 \pm 0.9$ pb |
| $W+\geq$ 4-Jet | 461 | $166.0 \pm 22.1$ | $5.8 \pm 0.8 \pm 1.3$ pb |



# Lepton + jets with b-tagging at CDF

- Secondary vertex tag to increase S/B
- Cross-section from the 3rd and 4th jet bin.

≥1 b-tag with HT >200 GeV

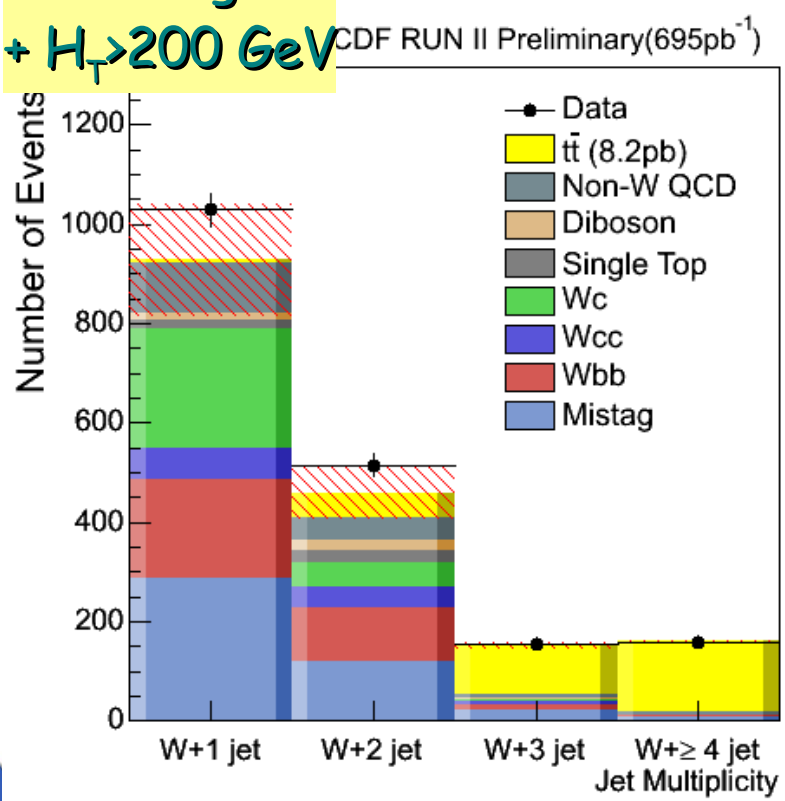
$\sigma_{t\bar{t}}$ =8.2 ± 0.6 (stat.) ± 1.0 (sys.)pb

>=2 b-tag

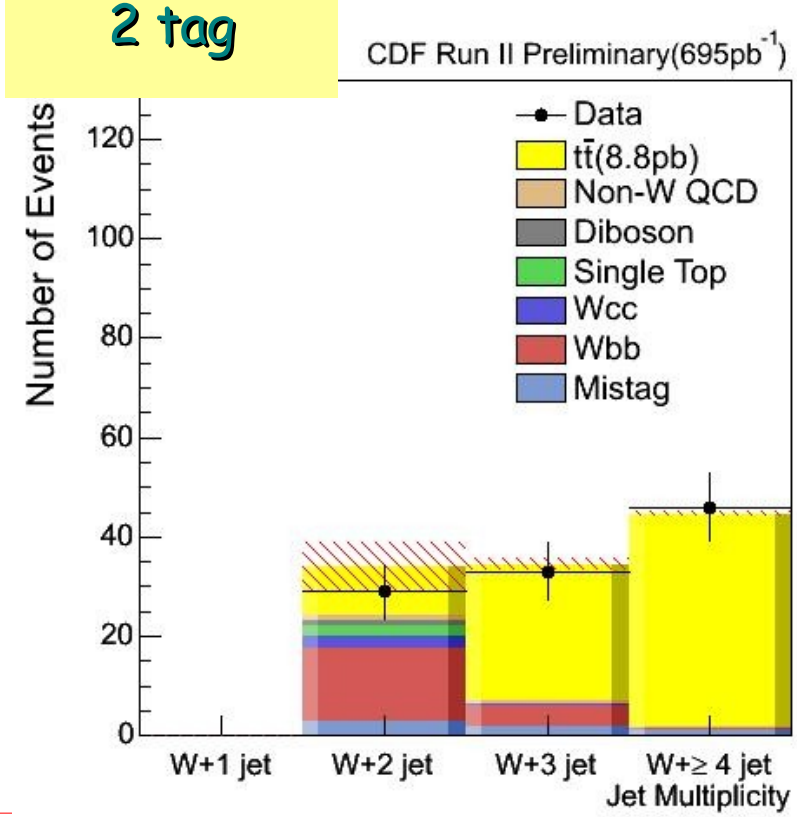
$\sigma_{t\bar{t}} = 8.8^{+1.2}_{-1.1}$ (stat.) $^{+2.0}_{-1.3}$ (sys.) pb

| Source | Systematic (%) |
|---|---|
| b-tagging | 6.5 |
| Luminosity | 6.0 |
| PDF | 5.8 |
| Jet Energy Scale | 3.0 |
| ISR/FSR | 2.6 |
| Lepton Identification | 2.0 |
| Total | 11.5 |

≥1 tag
+ $H_T$>200 GeV



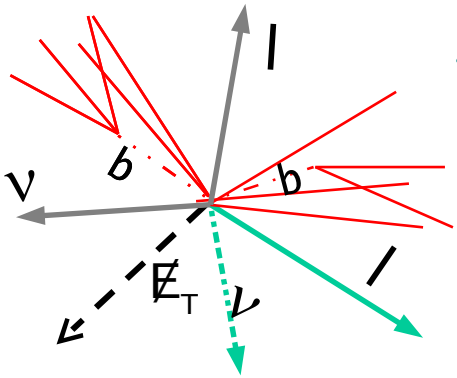

2 tag



# Di-leptons channels

**Event signature:**

- Central
- Spherical
- Energetic
- Hight Pt lepton l
- large Missing $E_T$
- 2 b-quark jets




**Acceptance:**

- 10-15%
- DATA/MC scale factor measured on independent sample

**Selection:**

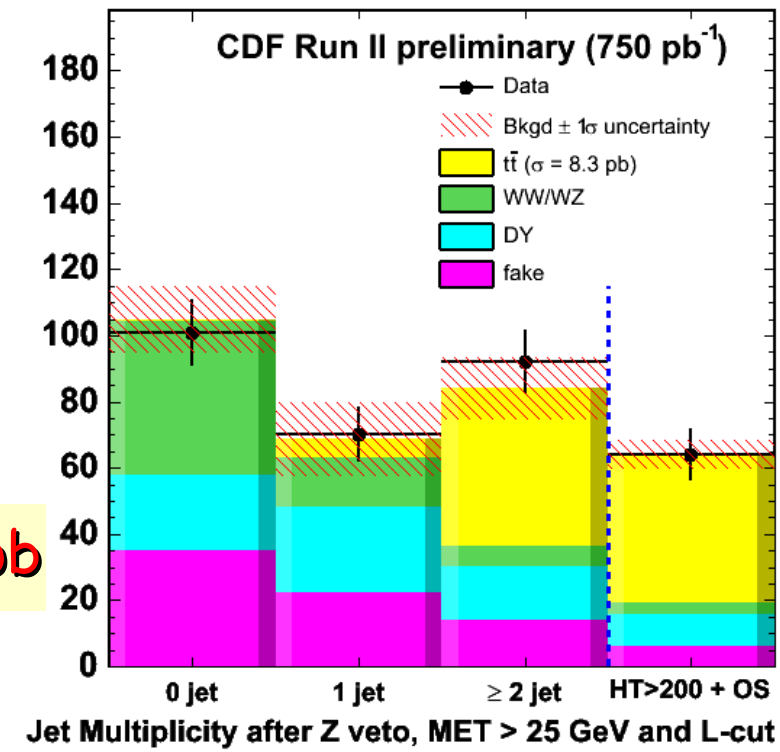
- High $p_T$ (di)-lepton trigger
- Isolated leptons $p_T$>20 GeV
- $\not{E}_T$ > 20 GeV
- 2 Jets $p_T$>15 GeV
- $H_T=\Sigma_i|p_{Ti}|$ > 120-200 GeV

**Backgrounds:**

- Z -> μμ, ee, ττ njets
- WW, (ZW)+ 2 jet
  - Normalized on the DATA
- Non-W (QCD: fake lepton)
  - Determined on the Data

# Di-lepton

| | Events per 750 pb$^{-1}$ after $\geq$2 jet cut | | | |
|---|---|---|---|---|
| Source | ee | $\mu\mu$ | e$\mu$ | $\ell\ell$ |
| WW | 0.79±0.15 | 0.45±0.09 | 1.45±0.25 | 2.70±0.42 |
| WZ | 0.41±0.07 | 0.31±0.06 | 0.20±0.04 | 0.93±0.15 |
| DY→ $\tau\tau$ | 0.38±0.10 | 0.39±0.10 | 0.83±0.21 | 1.60±0.38 |
| DY→ $ee + \mu\mu$ | 3.52±1.57 | 4.31±1.86 | 0.00±0.00 | 7.83±3.15 |
| Fakes | 1.00±0.50 | 2.06±0.63 | 3.23±1.30 | 6.29±1.53 |
| Total background | 6.10±1.87 | 7.52±2.12 | 5.72±1.38 | 19.34±4.26 |
| $t\bar{t}$ ($\sigma = 6.7$ pb) | 8.25±0.38 | 8.57±0.39 | 19.27±0.88 | 36.09±1.24 |
| Total SM expectation | 14.35±2.08 | 16.09±2.30 | 24.99±1.75 | 55.43±5.11 |
| Candidates in 750 pb$^{-1}$ | 12 | 24 | 28 | 64 |

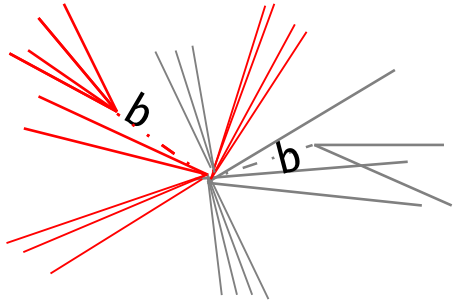


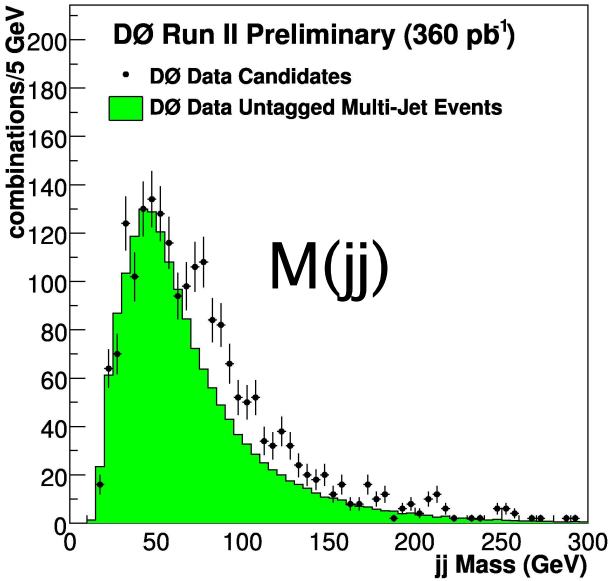

$\sigma_{t\bar{t}}$ =8.3 ± 1.5 (stat.) ± 1.0 (sys.)± 0.5 (lumi) pb

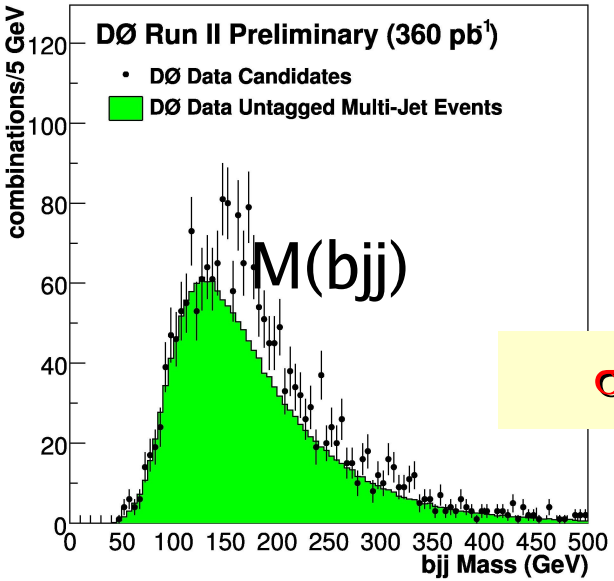
- Statistical uncertainty comparable to systematic
- Main systematics
  - Lepton id 4%
  - JES 3.1%
  - $t\bar{t}$ modeling 5%

# All jets channels at D0 with 360 pb$^{-1}$

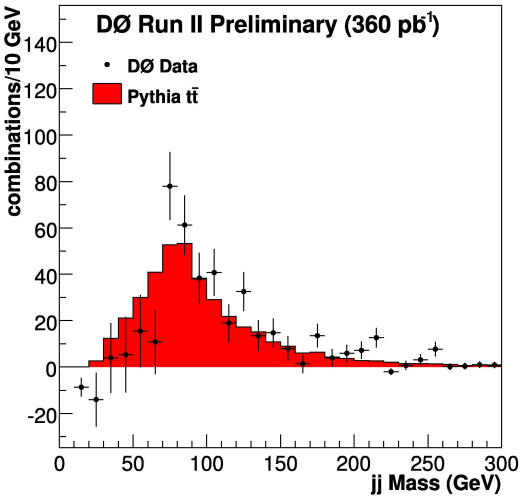
- Large QCD background : use 2 b-tag to remove it
- Large combinatoric

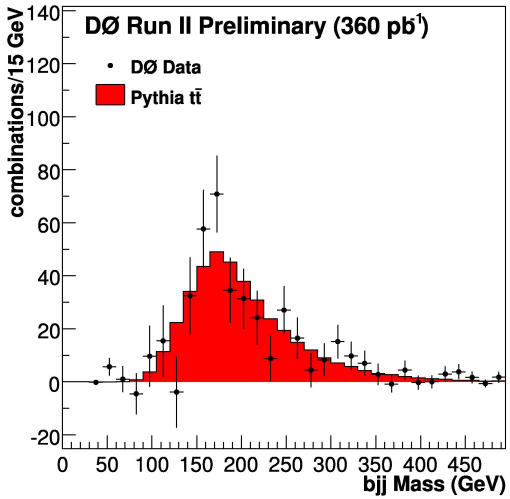



$\sigma_{t\bar{t}}$ =12.1 ± 4.9 (stat.) ± 4.6 (sys.) pb

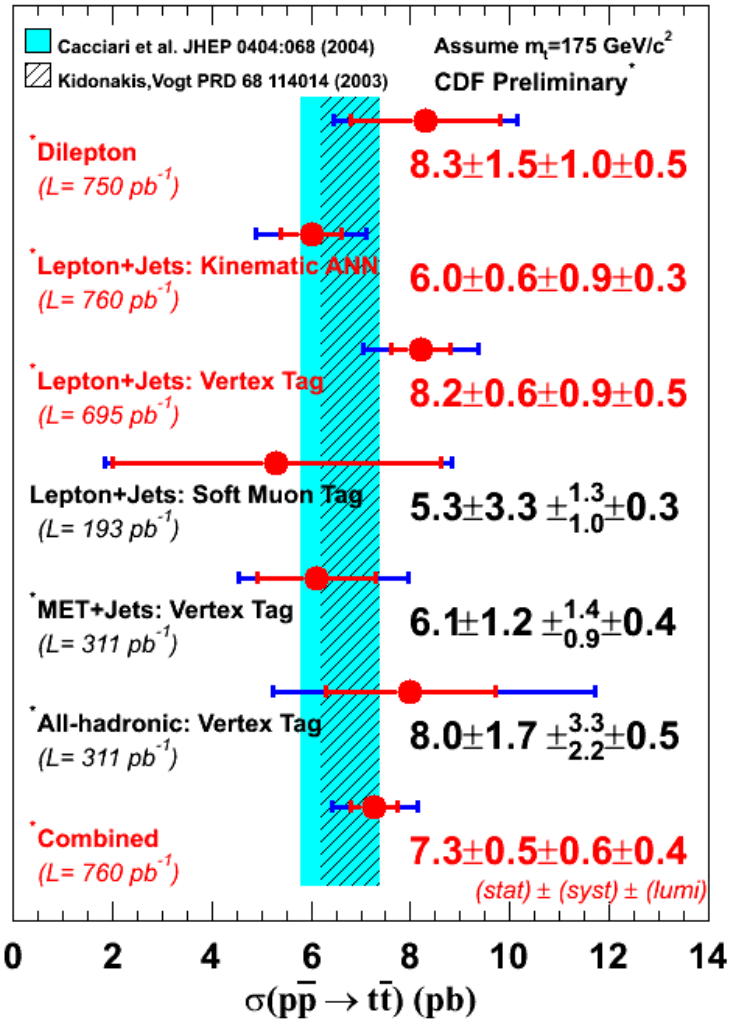


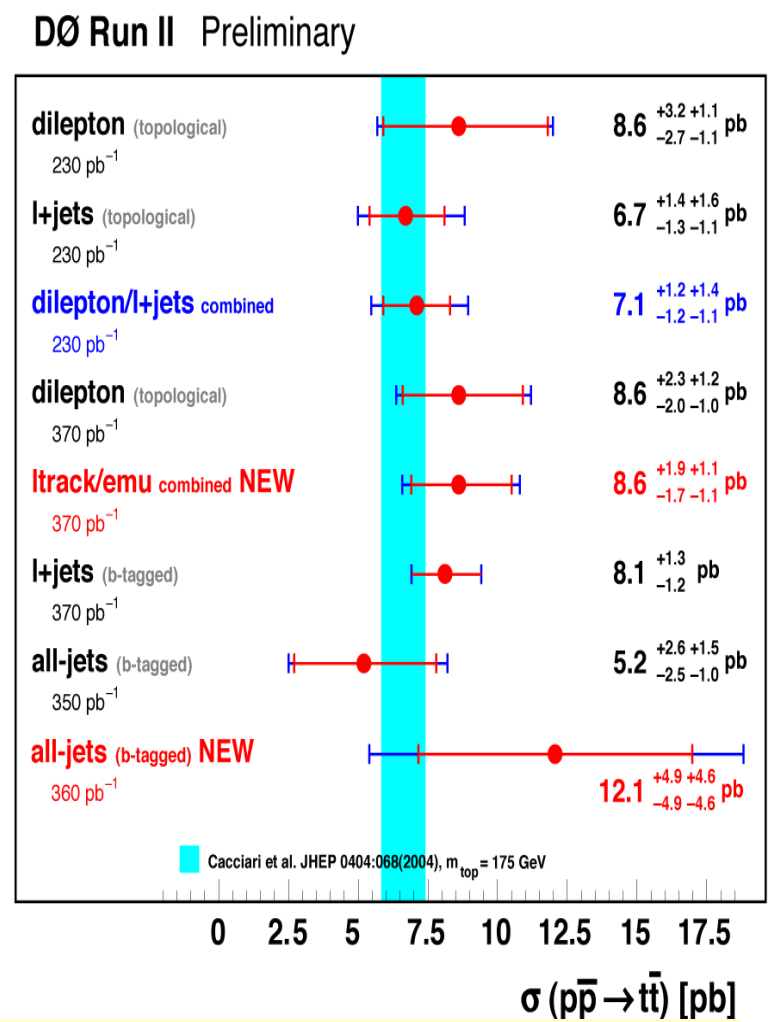




Main sources of systematics:

| | |
|---|---|
| background subtraction | 25% |
| JES | 15% |
| b-tagging efficiency | 18% |

# Top pair cross-section summary, CDF and DØ



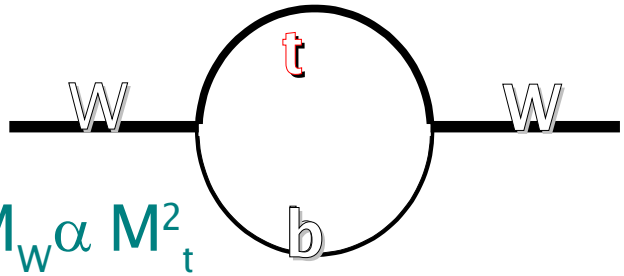

$\sigma_{t\bar{t}}$ =7.3 ± 0.5 (stat.) ± 0.6 (sys.) ± 0.4 (lumi.)pb CDF

- 12% relative uncertainty. (same as theoritical precision)
- No more dominated by statistics.
- Entering a precision era

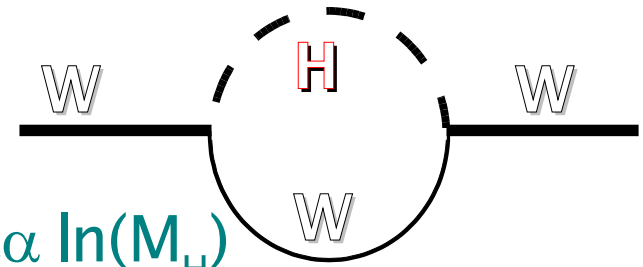
# Top mass

# Mass: sensitivity to Higgs

- Top mass fundamental SM parameter
- Radiative corrections relate all electroweak precision measurements

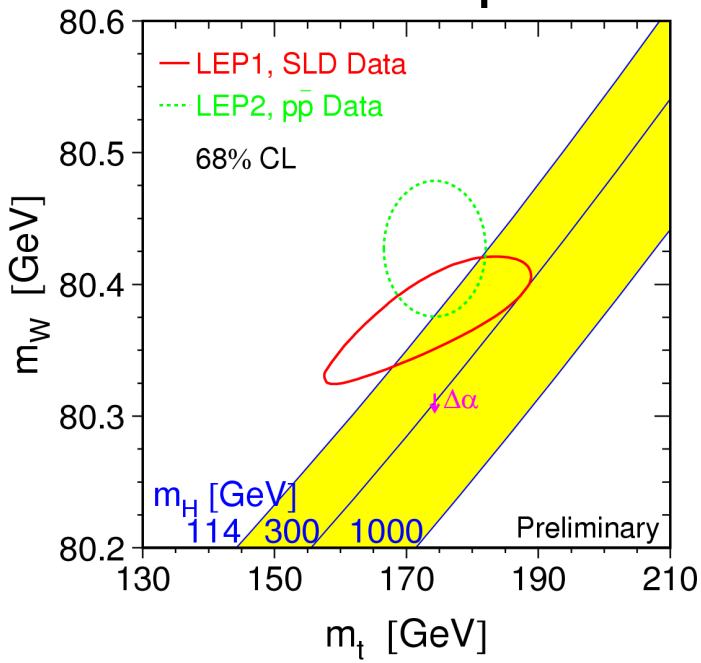



$\Delta M_W \alpha\ M^2_t$




$\Delta M_W \alpha\ \ln(M_H)$

2003 (obsolete)results as an example

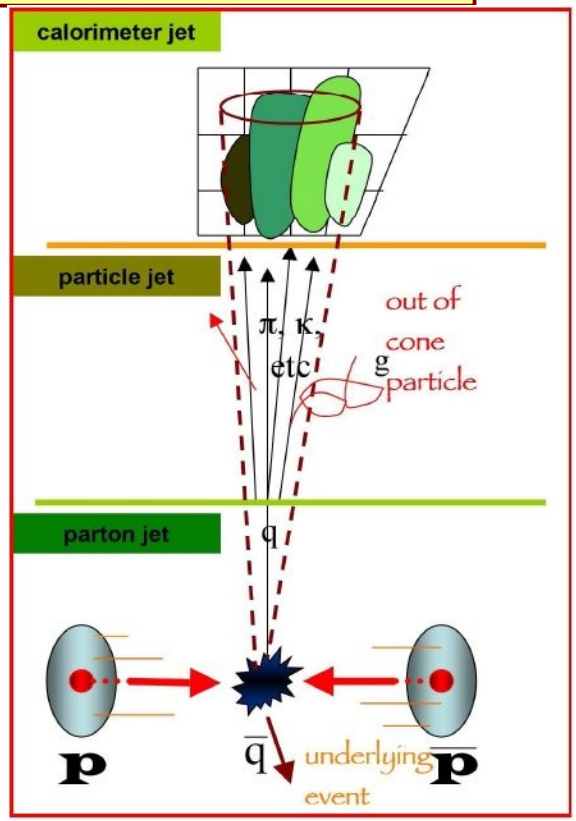


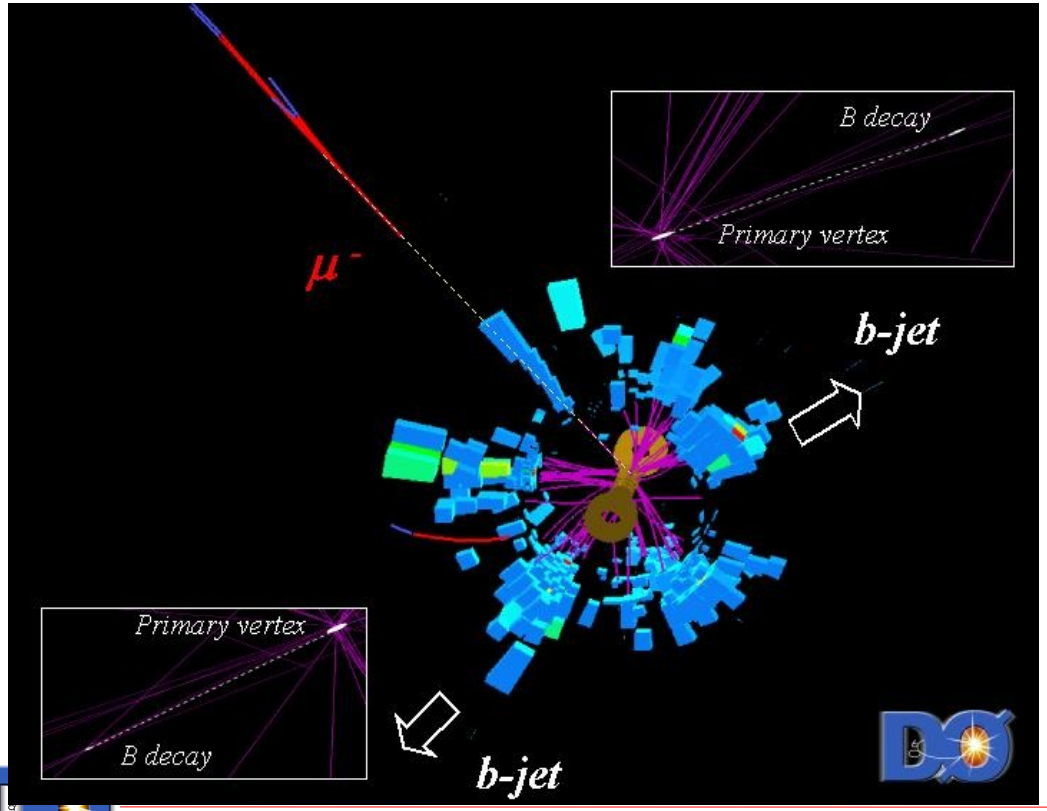

- Measuring top mass:
  - Check consistency of SM
  - Key to EWSB mechanism
  - Constrains SM Higgs Mass
  - Sensitive to new Physics

Run IIa goal 2.5 GeV CDF/D0 combined with 2fb$^{-1}$ exceeded, see following slides

# Why is mass measurement difficult ?

- Complicated events : 6 particles in finale state
- background contamination
  - Should understand background to prevent bias
- Combinatorics when assigning jets to initial quarks
- Missing Energy: in lepton channels. Two neutrinos in di-leptons.




mapping measured jet energy to partons

- Jet resolution
  - Typically $85\%/\sqrt{E_T}$
  - Goes down with statistics.
- Jet Energy Scale
  - Systematics, typically ~2-4%
- Recent method: in-situ calibration

# Various methods, channels

- Many analysis from CDF and D0 depending on
  - Channel : l+jets, di-leptons, all-hadronic
  - Selection of candidates, eg requiring 0, 1, 2 b-tag
  - Matching parton multiplicity to jet multiplicity
  - Methods
- Consistency check
- Not sensitive to same systematics
- Gain precision with combinations

Cover only a few of them in this talk

Templates method

kinematic information

Choose kinematic observable

Create MC templates at different $M_{top}$

Template for background

likelihood fit to best template

Matrix Element method

kinematic +dynamics

Build likelihood from:

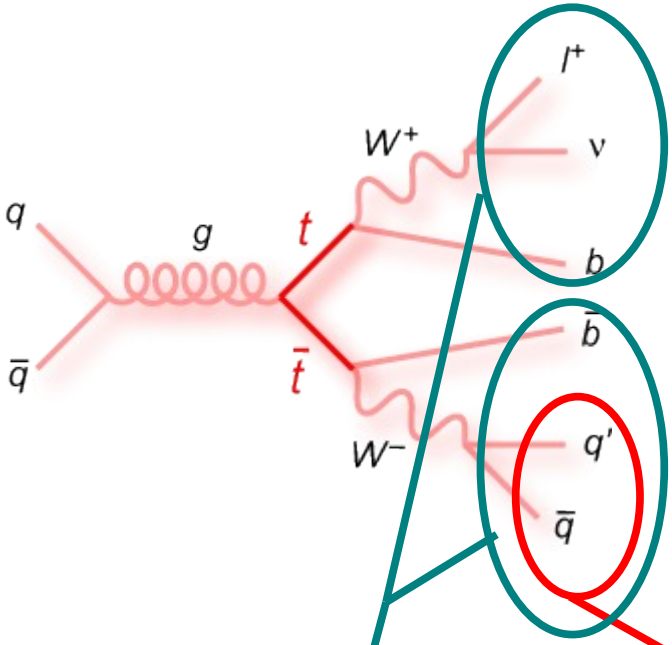
PDF, Matrix elements, Transfer function (quark <-> jets)

Integrate over unmeasured quantities

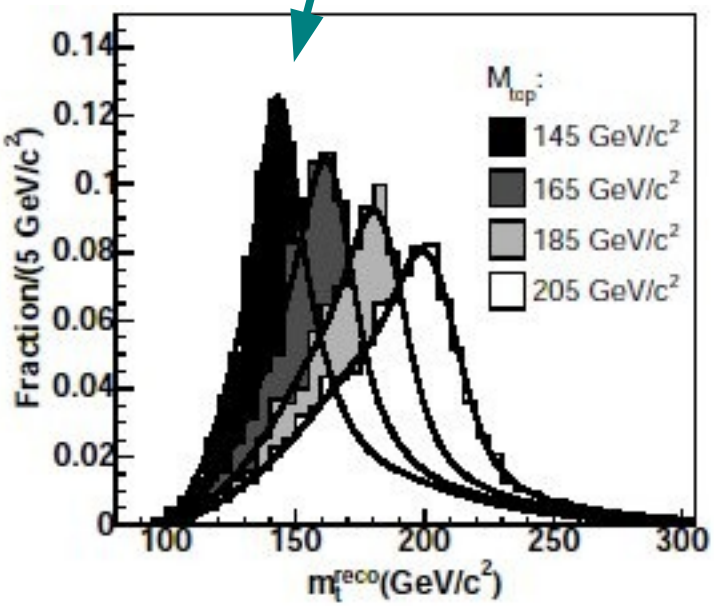
Max Likelihood fit

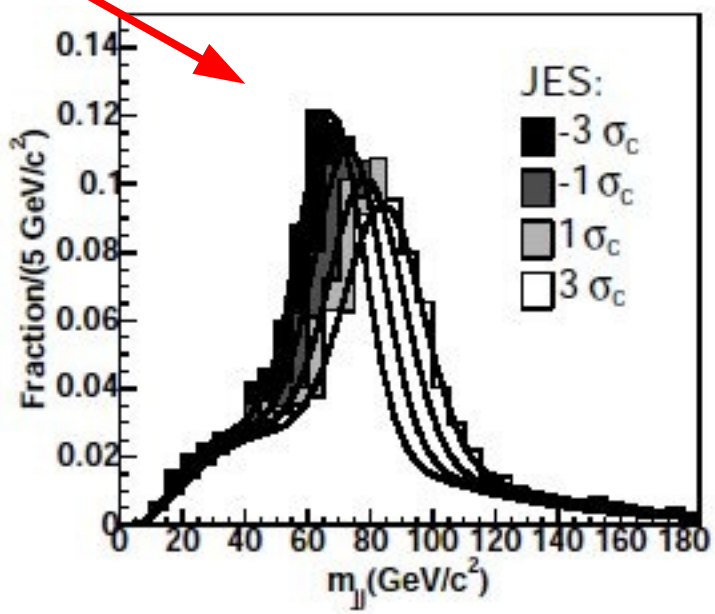
Calibrate measurement with MC

# Lepton+jets template method at CDF

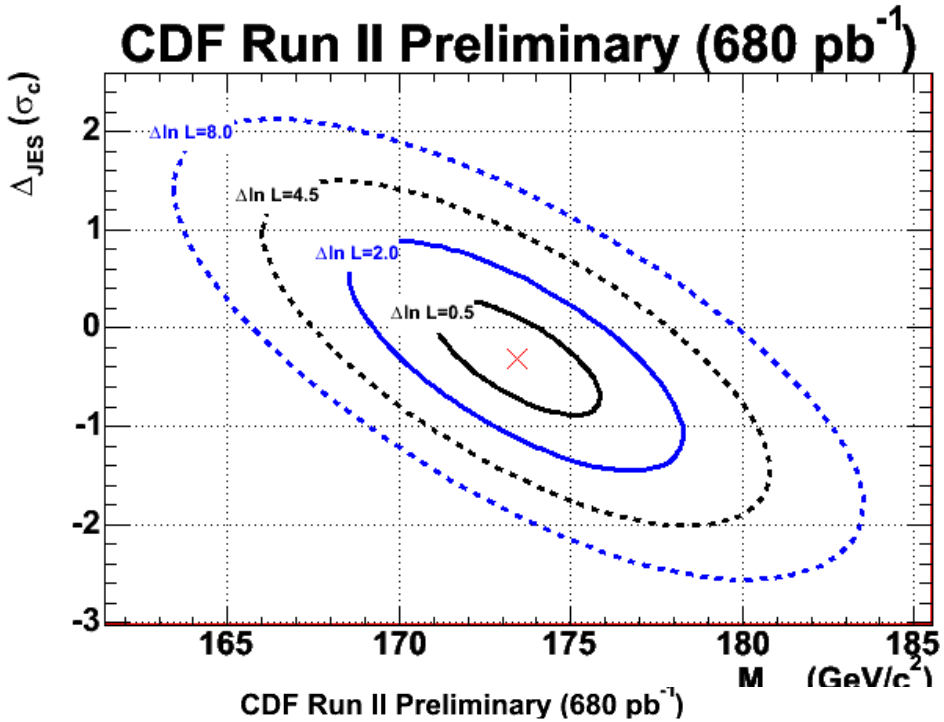


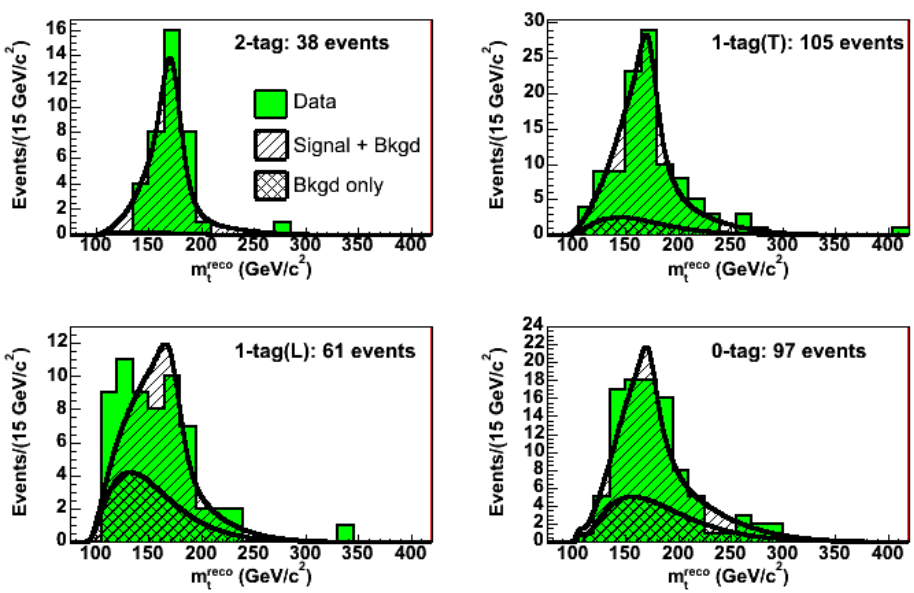

- 4 exclusive event selections with different purities
  - 0 b-tag, 1 b-tag L, 1 b-tag T, 2 b-tag
- Kinematic fit to reconstruct one top mass per
  - chose among combinations
- In situ calibration, allow jet energy scale to vary
  - ΔJES = deviation from external calibration in unit of external calibration
  - non b-quark jets should form a W $M_W$=80.4 GeV
- Simultaneous likelihood fit of ($M_{top}$, ΔJES)



# Lepton+jets results at CDF - 680 pb$^{-1}$




**Best single measurement in the world**

**$M_{top}$=173.4± 2.5 (stat)± 1.3 (syst) GeV**

**ΔJES=-0.3± 0.6 (stat+Mtop)$\sigma_c$**

- JES systematic scaled by 0.6 with in SITU calibration
- Further decrease with more stat

| Systematic Source | $\Delta M_{top}$ |
|---|---|
| b-jet energy scale | 0.6 |
| Residual JES | 0.7 |
| Background JES | 0.4 |
| ISR | 0.5 |
| FSR | 0.2 |
| Parton Distribution Functions | 0.3 |
| Generators | 0.2 |
| Background Shape | 0.5 |
| b-tagging | 0.1 |
| Monte Carlo statistics | 0.3 |
| TOTAL | 1.3 |

# Matrix elements at D0 in l+jets channel

- Maximize kinematic and dynamic information
- Signal probability for a set of measurements (jets, letpons) : x

$$P(\vec{x}, M_t, JES) = \frac{1}{\sigma} \int d\sigma(\vec{y}, M_t) f(\tilde{q}_1) f(\tilde{q}_2) W(\vec{x}, \vec{y}, JES) d\tilde{q}_1 d\tilde{q}_2$$

Differential cross section

Proton PDF

Transfer function
from true y to measured x

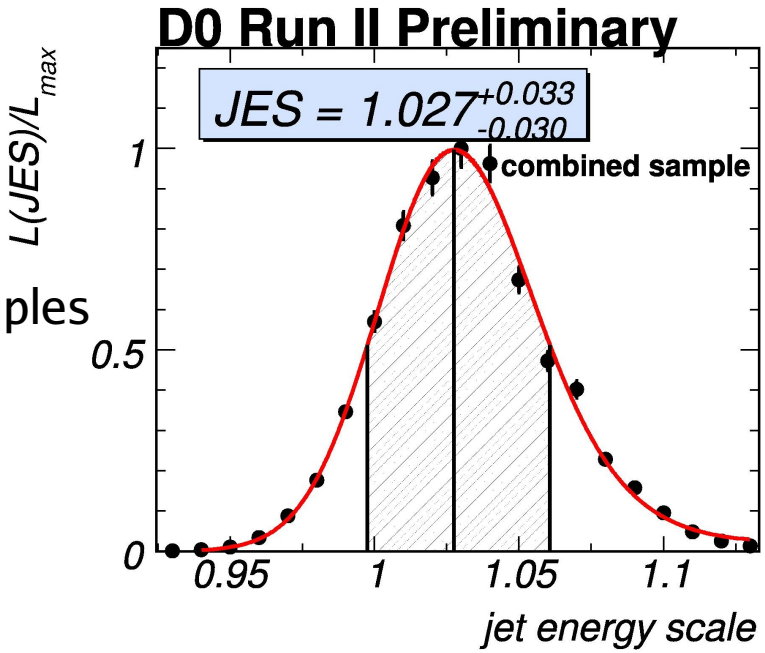
JES is a free parameter: in situ calibration constrained by W mass

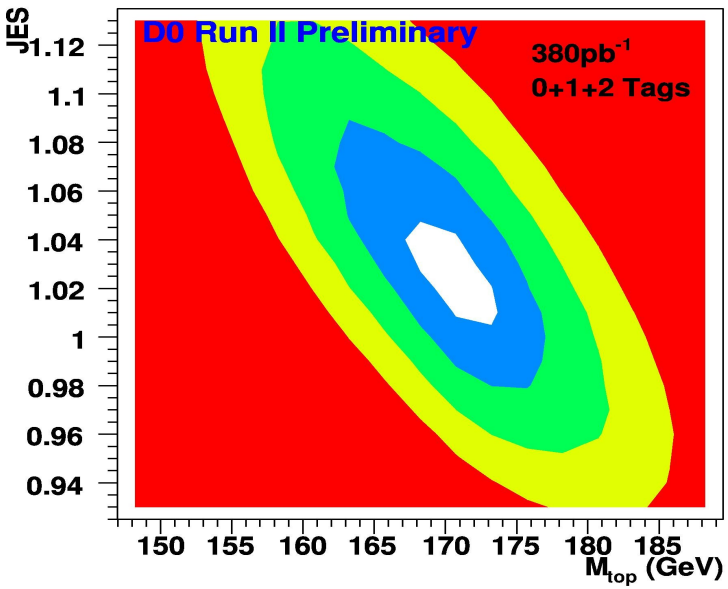
- Build similar probability for background $P_{bkg}$ (no $M_t$ dependence).
- Final Likelihood:

$$\mathcal{L} = \Pi_{evt} f_{\rm top} P(x, M_t, JES) + (1 - f_{\rm top}) P_{\rm bkg}(x, JES)$$

# M.E Results in lepton+jets at D0 with 370 pb$^{-1}$

3 Exclusive samples
- 0 tag
- 1 tag
- 2tag

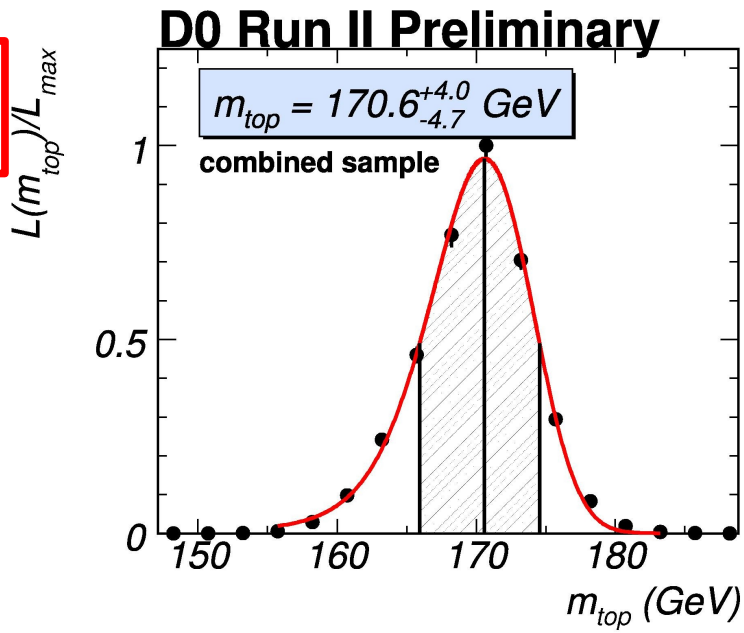



JES error reduced with in-situ calibration

Expect further improvments with more stat

$$M_{\rm top} = 170.6^{+4.0}_{-4.7}\ ({\rm stat + JES}) \pm 1.4\ (syst)\ {\rm GeV}$$




systematics:

| | |
|---|---|
| b-fragmentation | 0.7 GeV |
| b response | 0.8 GeV |
| MC calibration | 0.5 GeV |
| W bkg | 0.3 GeV |
| QCD bkg | 0.3 GeV |

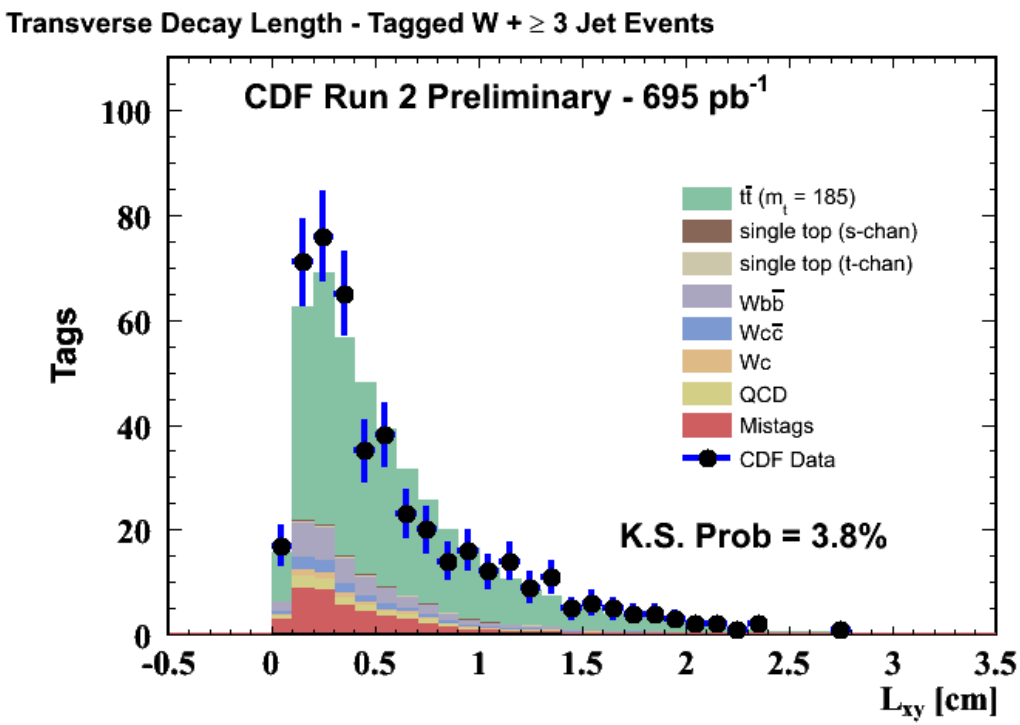
# New method: template using decay length at CDF

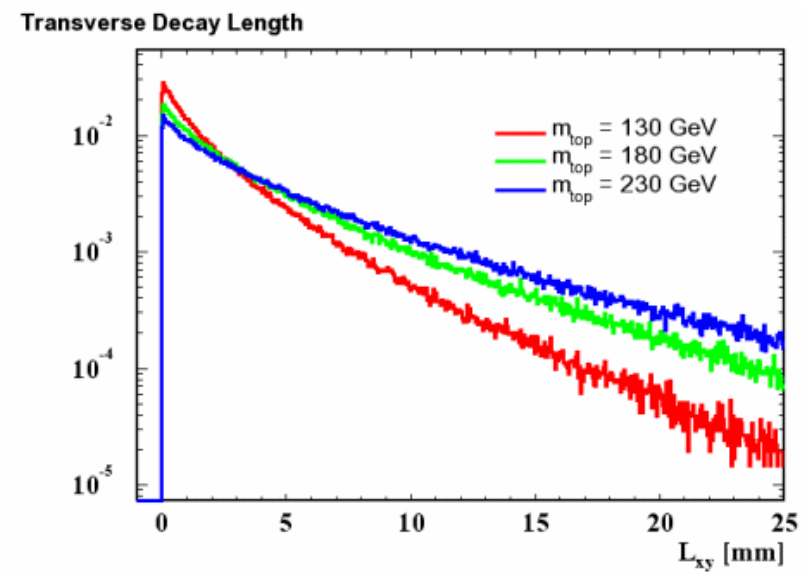
t->Wb $$\gamma_b = \frac{m_t^2 + m_b^2 - m_W^2}{2 m_t m_b} \approx 0.4 \frac{m_t}{m_b}$$

use B hadron decay length <-> b-quark boost <-> $M_{top}$

Important cross-check with reduced JES impact

Need good understanding of tracking resolution



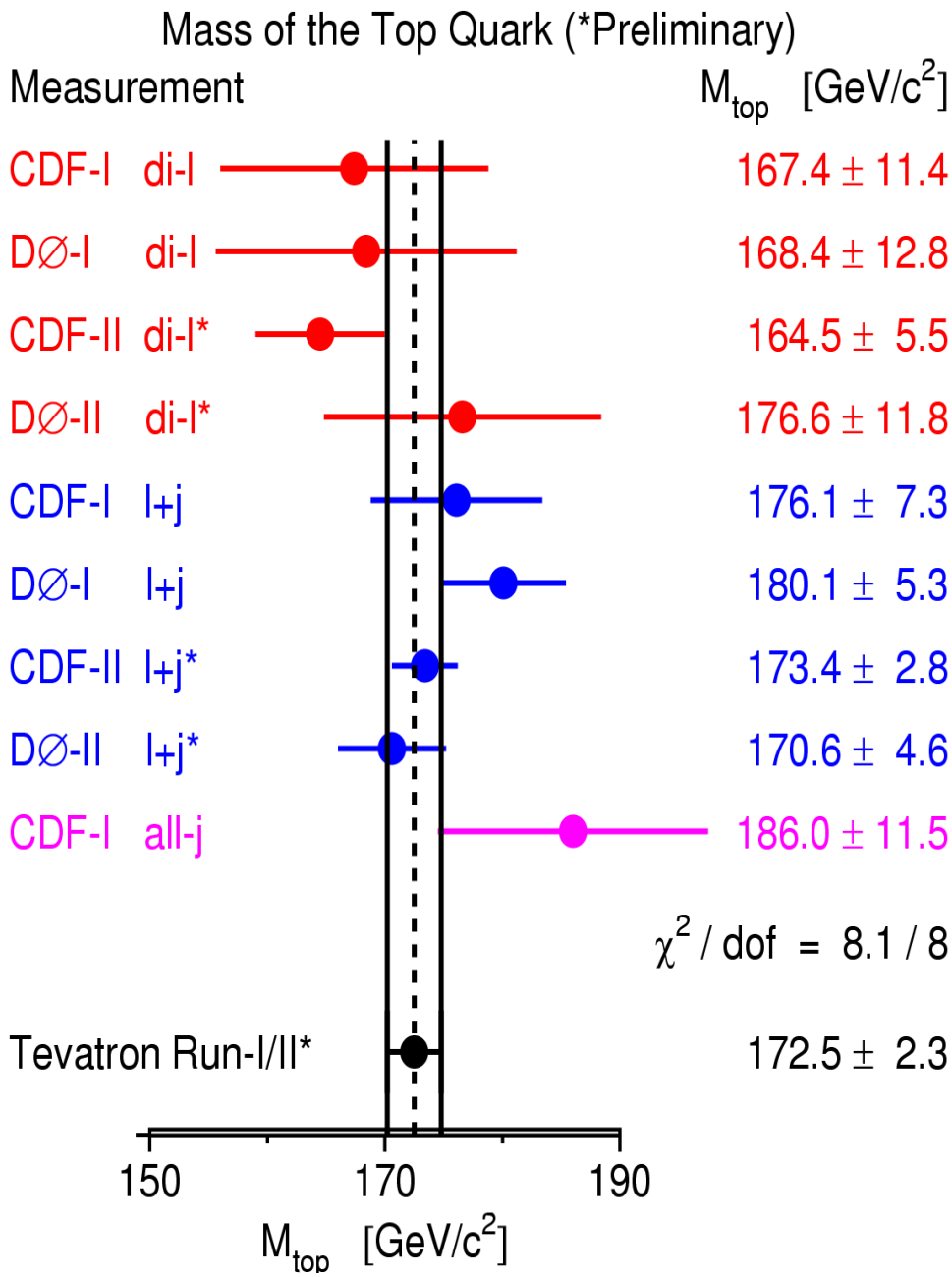




$$M_{top} = 183.9^{+15.7}_{-13.9}(\text{stat}) \pm 0.3(\text{JES}) \pm 5.6(\text{syst})\ \text{GeV}$$

statistically

limited with present sample

# Combination of all direct measurements

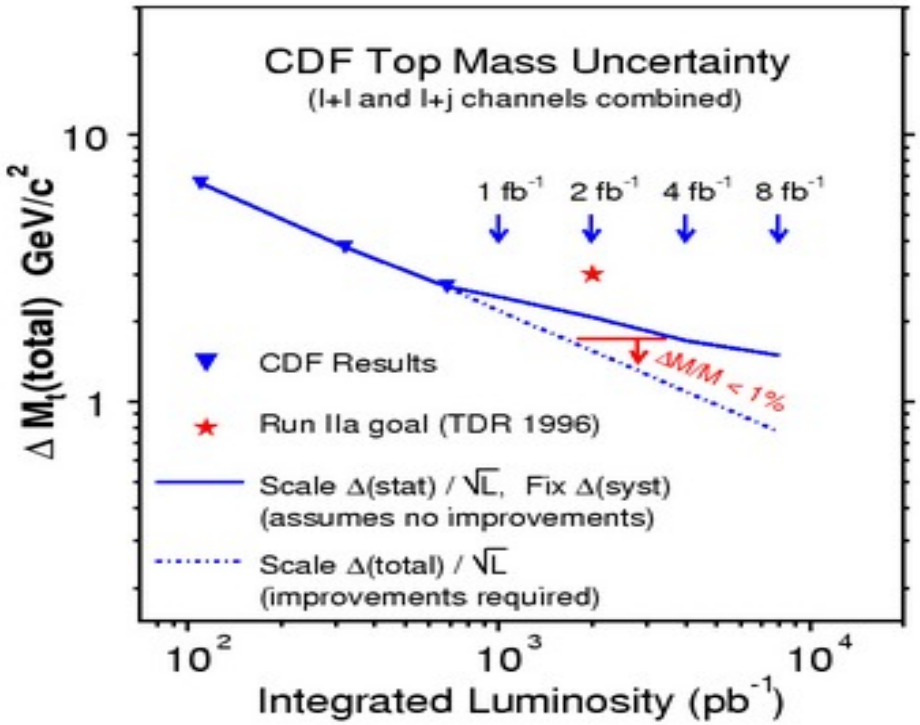



**Present world average (March 06)**

**$M_{top}$=172.5±1.3 (stat) ±1.9 (syst) GeV**

achieve 1.3% accuracy

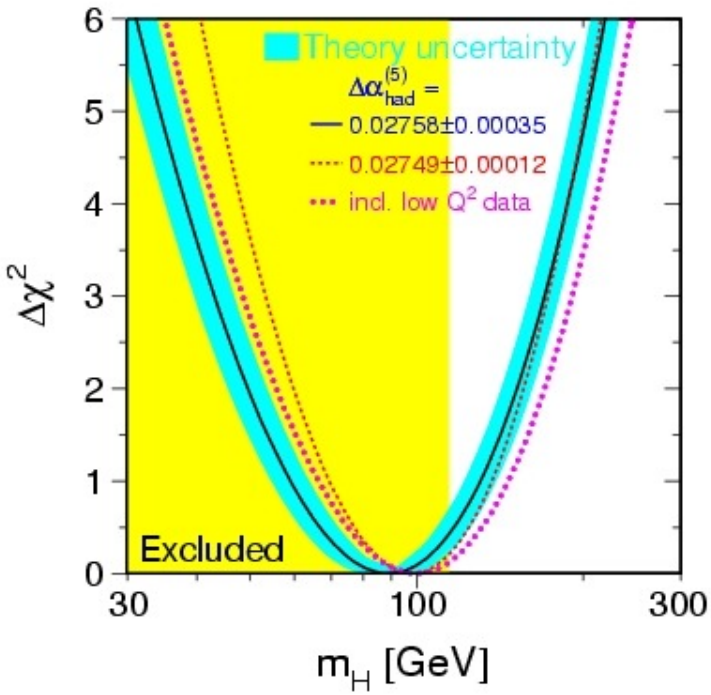
consistency check: $\chi^2$/dof= 8.1/8




**below 1% uncertainty in sight**

# Impact on Higgs Mass

## Precision EWK Fit

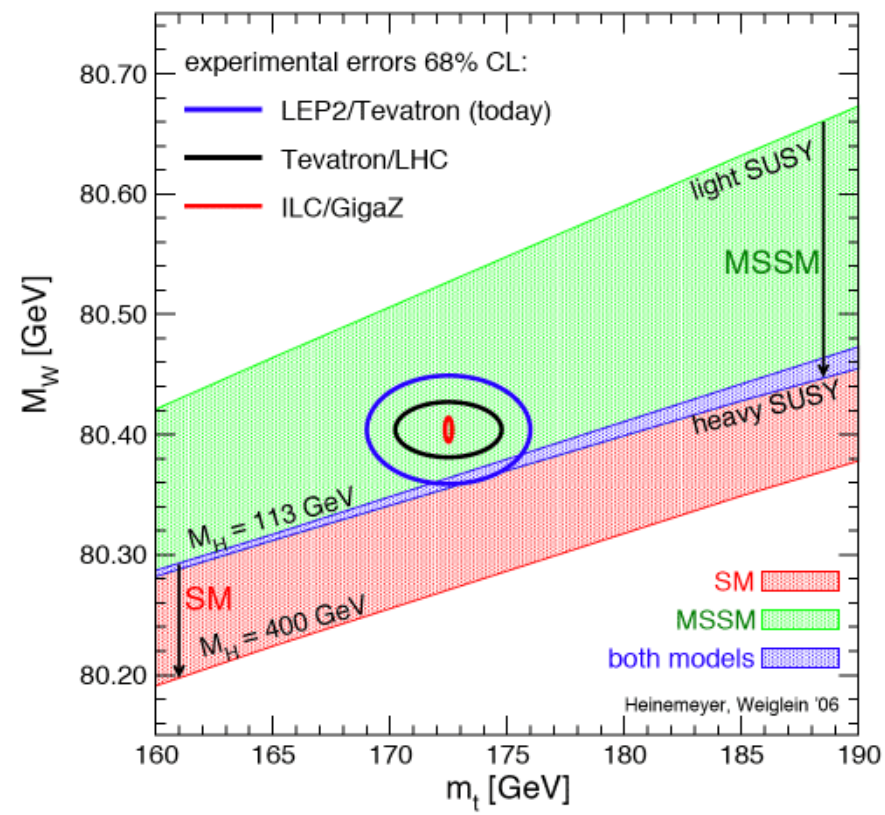



$$M_H = 89^{+42}_{-30}\ \mathrm{GeV}/c^2$$

$$M_H < 175\ \mathrm{GeV}/c^2\ @\ 95\%\ C.L.$$

$M_H$ > 114 GeV (direct search at LEP)

New results favor Supersymmetry over SM.



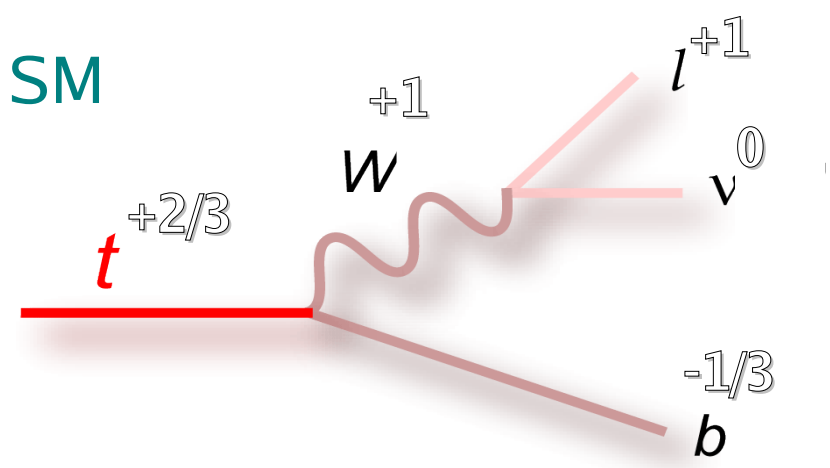
# Other Top Properties

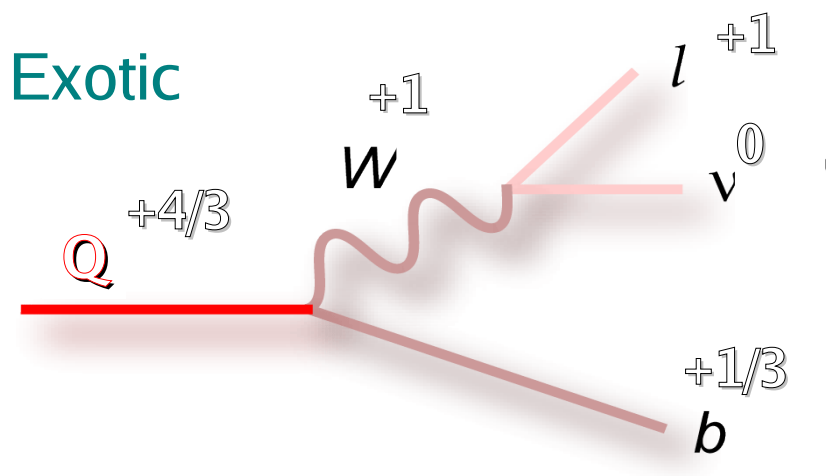
# Top charge

Is the top quark at Tevatron the Standard Model top with Q=+2/3 ?

Eg : D. Chang et al PRD59, 09153 (99)

- $4^{th}$ generation + Higgs triplet
- $4^{th}$ family $(Q_1, Q_4)_R$ with charge (-1/3,-4/3)
- $Q_4$ is the discoverted top quark.



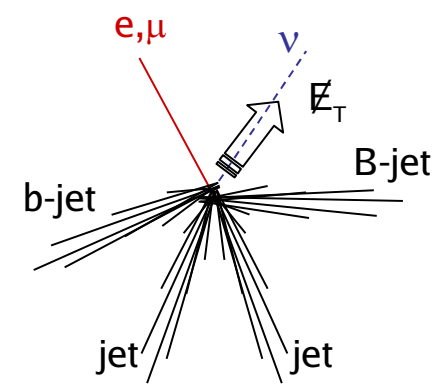
# Top charge at D0

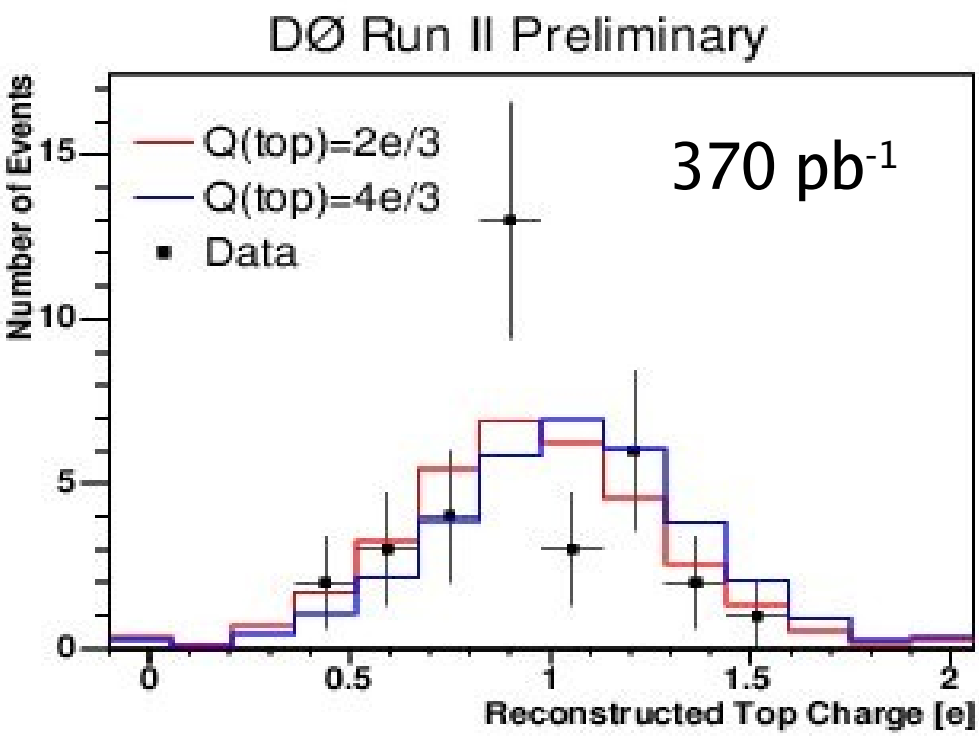
**Sample:**

- lepton +jets +2 b-tag

**Strategy:**

- Reconstruct charge of b-jets $Q_{jet} = \frac{\sum_i q_i \cdot p_{T_i}^{\kappa}}{\sum_i q_i \cdot p_{T_i}}$ with $\kappa = 0.6$
- b-tagging to find b-jets
- Accociate right b-jet to lepton with a fit to top mass.
- 2 observables: $Q_1 = |q_b + q_l|$, $Q_2 = |-q_B + q_l|$




**Q= 4/3 excluded @ 93.7% CL**

# Top lifetime

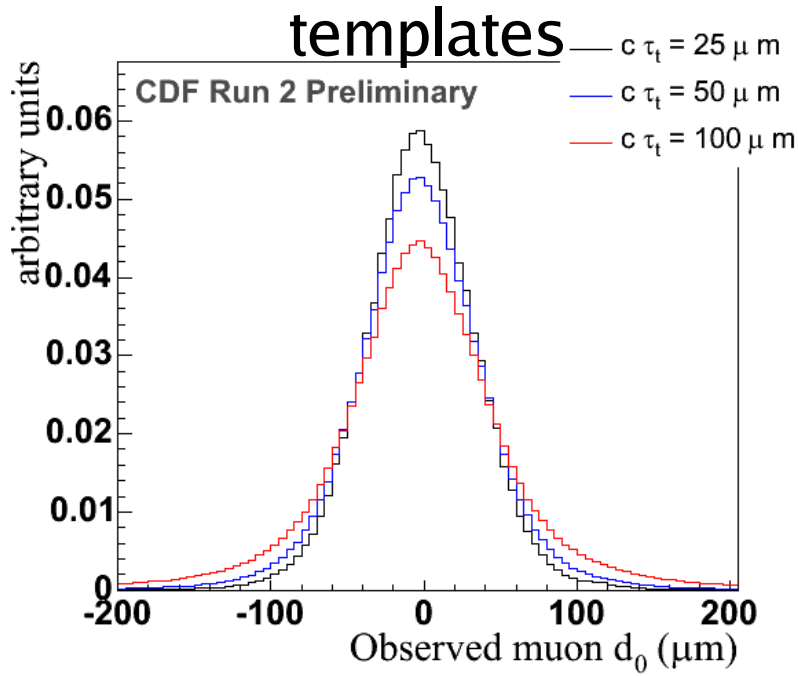
**Sample**

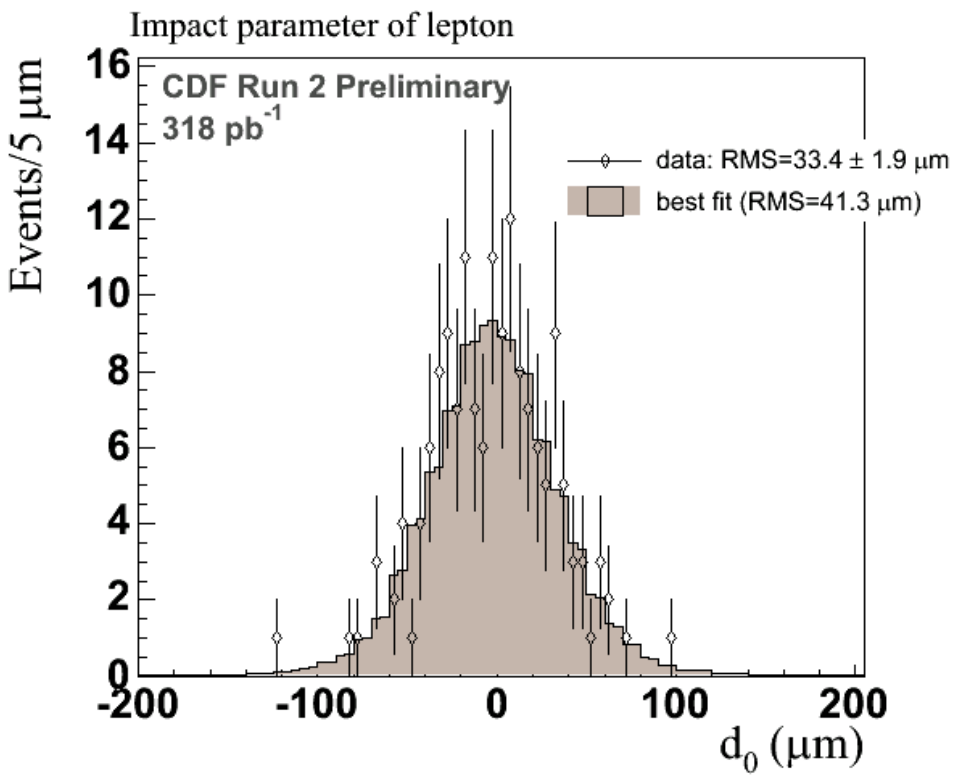
- Lepton+jets channel + 1 b-tag

**Strategy:**

- Primary vertex reconstructed with jets
- Measure Lepton impact parameter
- Background
  - Short lifetime :W+jets
  - Long lifetime: QCD (b), $\tau$'s, $\gamma$ conversion

templates




**Maximum Likelihood fit**

$c\tau < 52.5\ \mu m$ @ 95% CL

SM value: $c\tau = 3.\ 10^{-10}\ \mu m$

# Wtb vertex and $V_{tb}$ couplings

# $V_{tb}$ measurement from branching ratios

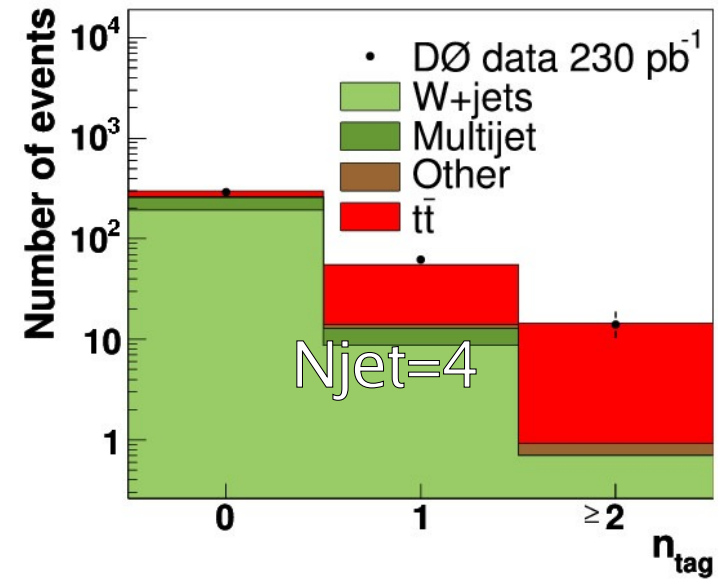
**In Standard Model** $R = \frac{Br(t \to Wb)}{Br(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} = 0.9980 \text{ to } 0.9984$

**Sample:**

Lepton+jets

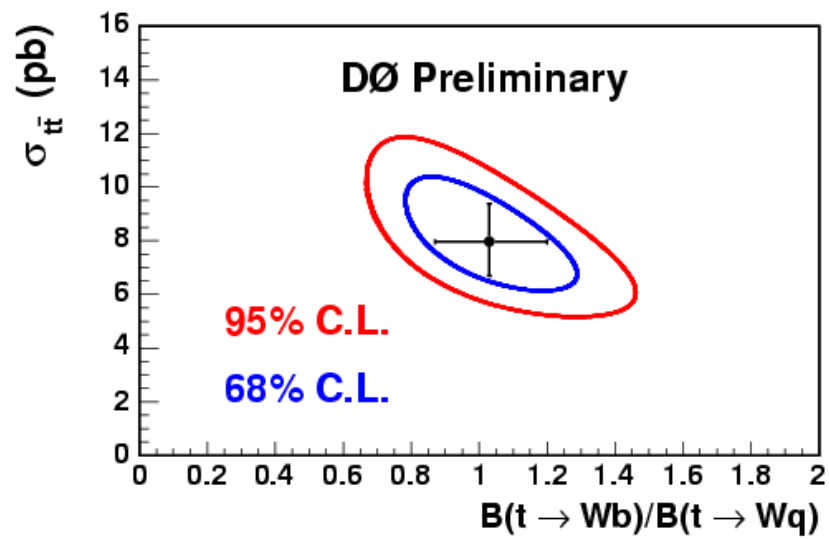
**Strategy:**

- Count b-tag jets in $t\bar{t}$ events
- Simultaneous fit of R and cross-section
  model independent cross-section




**DØ** $\sigma_{t\bar{t}} = 7.9^{+1.7}_{-1.5}$ (stat+syst) pb

$$\frac{Br(t \to Wb)}{Br(t \to Wq)} = 1.03^{+0.19}_{-0.17} \text{ (stat + syst)}$$




**CDF PRL 95, 102002**

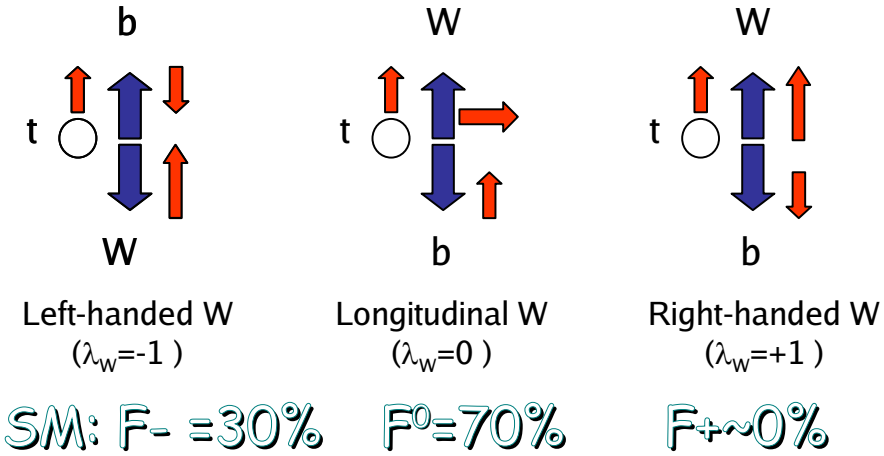
$$\frac{Br(t \to Wb)}{Br(t \to Wq)} = 1.12^{+0.21}_{-0.19} \text{ (stat)}^{+0.17}_{-0.13} \text{ (syst)}$$

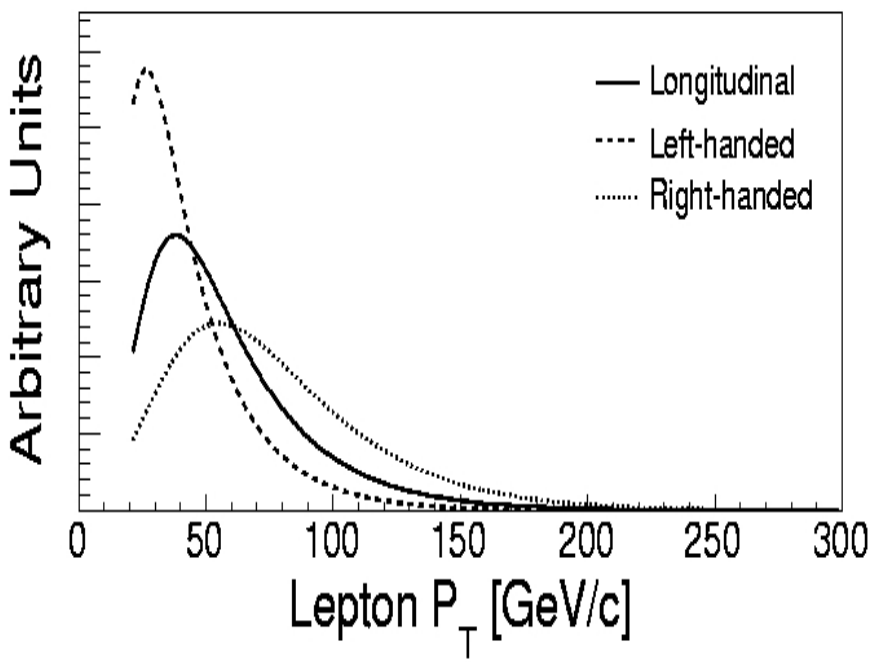
# W helicity

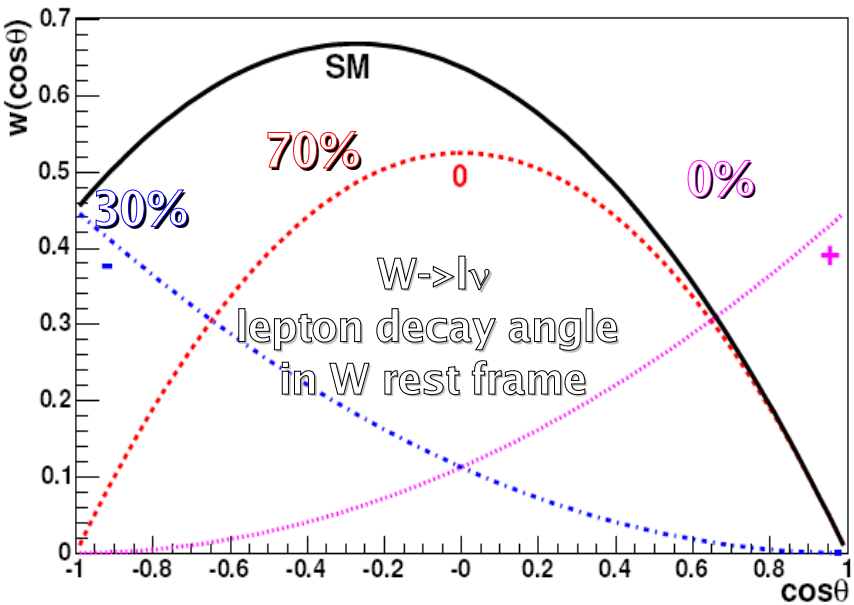
in Standard Model:

- Wtb vertex: (V-A) coupling
- ~0% W with helicity=+1 in top decay

- Study kinematics of W decay product to probe V-A structure of EW interaction close to EWSB scale
  - Pt of leptons
  - Decay angle = cos θ*
  - $M^2_{lb}=1/2\,(M^2_T-M^2_W)(1+\cos\theta^*)$



# W helicity

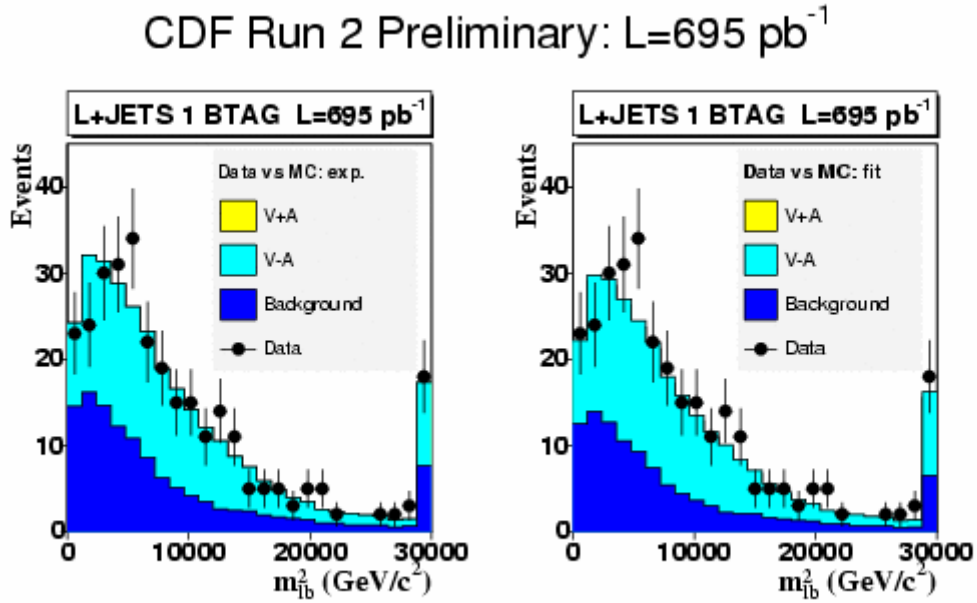
CDF

$M^2_{lb}$ (l+jets and dilepton samples)

$$F^+ = 0.02 \pm 0.07$$

$$F^+ < 0.09 \text{ @ } 95\% \text{ CL}$$

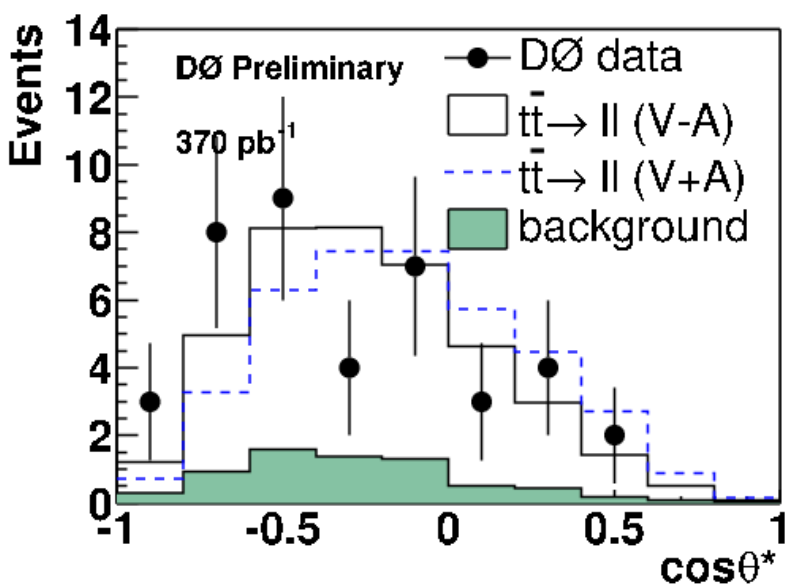
update of PRD 71,031101 (2005)

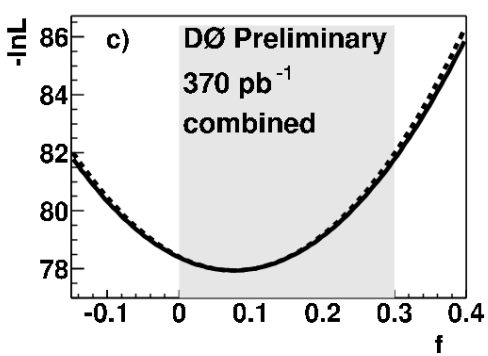



DO cos θ* lepton+jet and dilepton samples

$$F^+ = 0.08 \pm 0.08(\text{stat}) \pm 0.06(\text{syst})$$

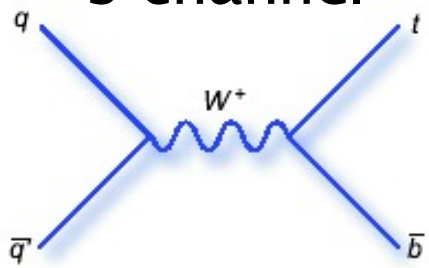
update of PRD 72, 011104 (2005)



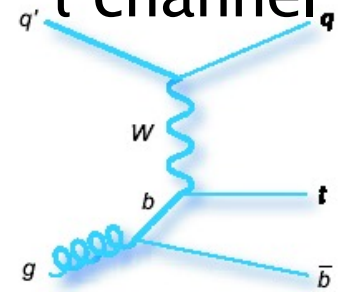
# Search for EW production of top: « single top »

s-channel




$l\nu b\bar{b}$ final states

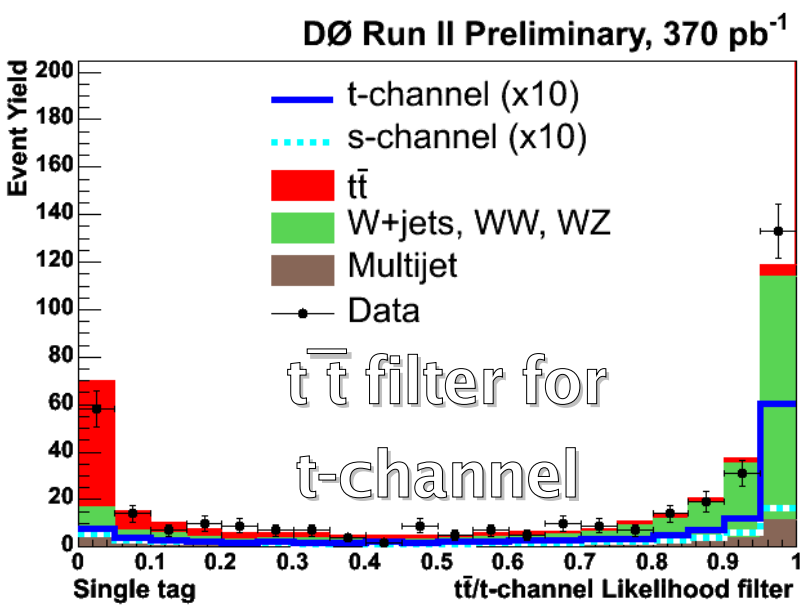
t-channel

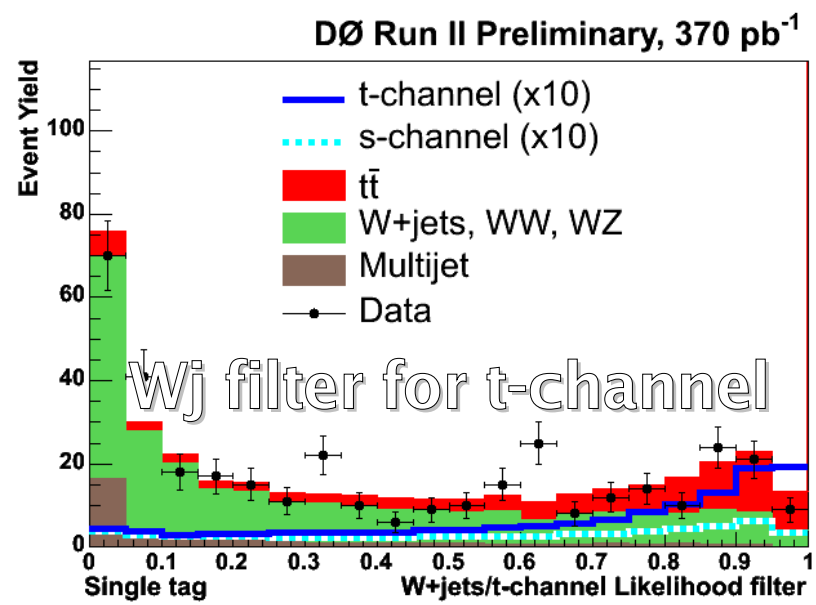



$l\nu qb$ final states

High background: W+ (b) jets, $t\bar{t}$ production:

- Multivariate technics: ANN, Likelihood, decision trees
- Eg D0: 4 Likelihood discriminant (t-channel vs $t\bar{t}$ ) (t-channel vs Wj ) (s-channel vs $t\bar{t}$ ) (s-channel vs Wj)



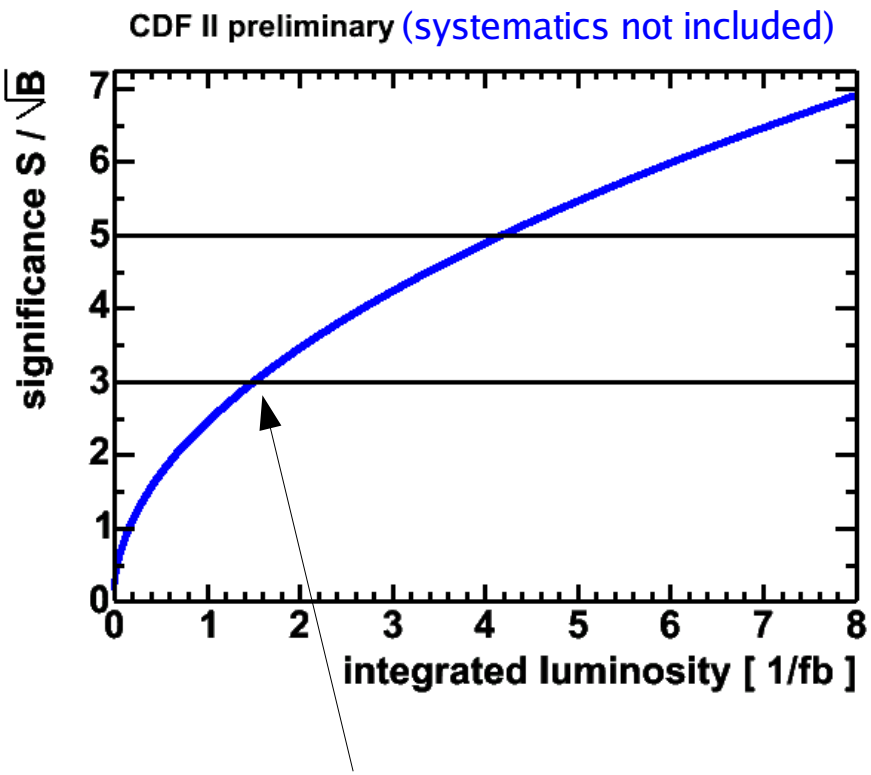



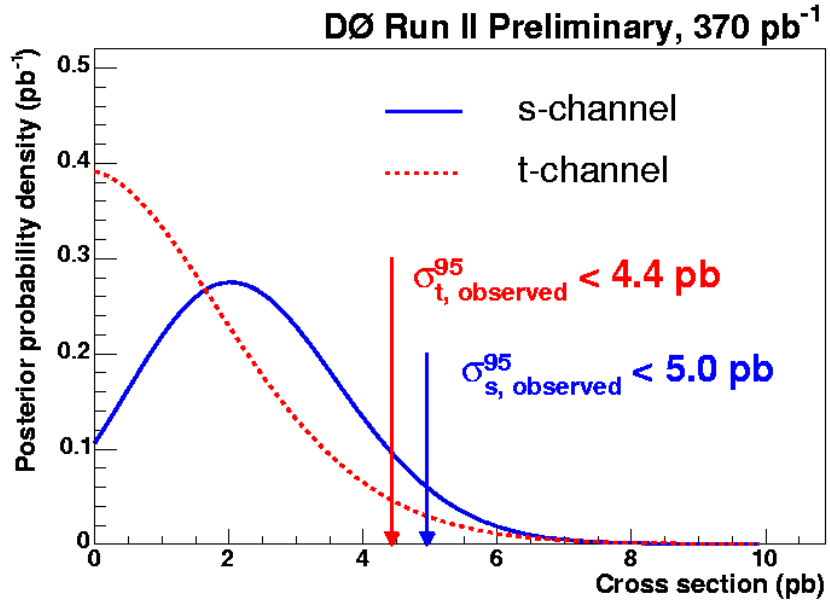
# Limits on single top production

## D0 Likelihood analysis 370 $pb^{-1}$

s: $\sigma$<5.0 pb @95% CL

t: $\sigma$<4.4 pb @95% CL




## CDF NN analysis 695 $pb^{-1}$

s: $\sigma$<3.2 pb @95% CL

t: $\sigma$<3.1 pb @95% CL

s+t: $\sigma$<3.4 pb @95% CL

should see 3$\sigma$ deviation (27.3 signal events) with 1.5$fb^{-1}$ quite soon !

SM cross-sections:

s-channel: 0.88 pb t-channel: 1.98pb

# Search for new Particles with tops

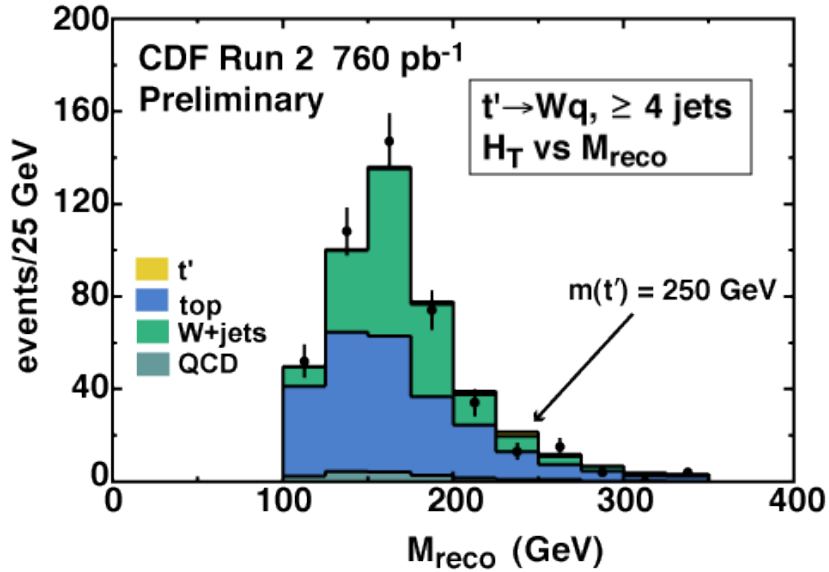
# Heavy top: t'

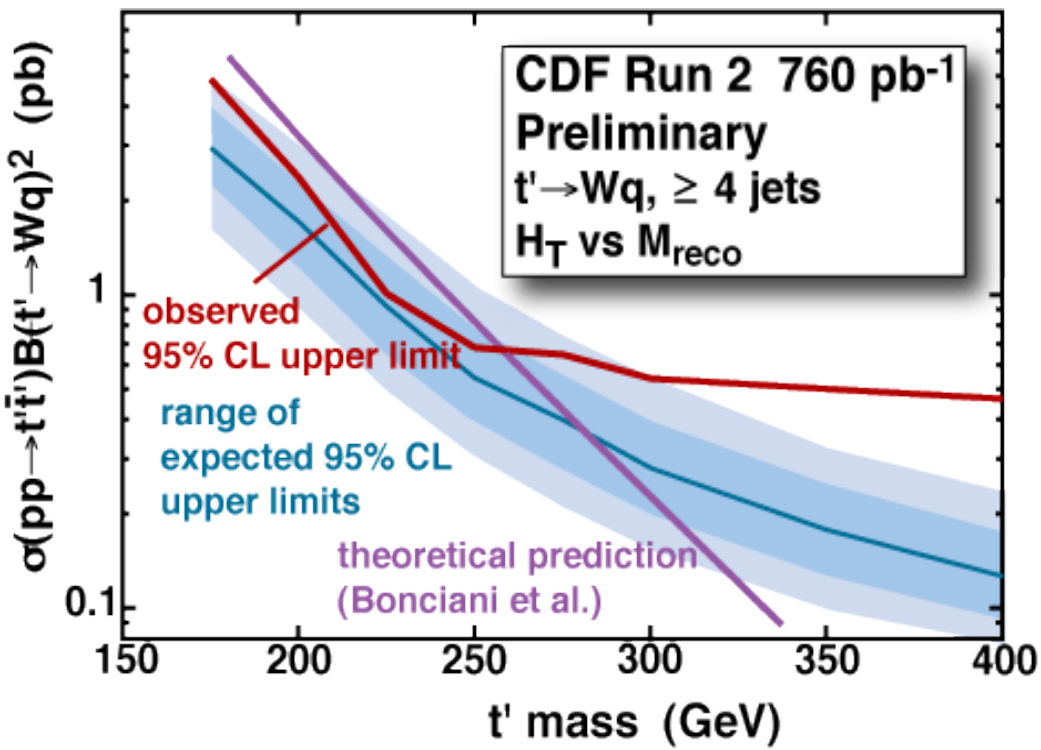
Search for 4th generation heavy quark: t'->Wq

Sample: lepton + jets. (no b-tag)

Strategy:

- reconstruct $M_Q$ $H_T$.
- Large uncertainties from JES, PDF, $Q^2$



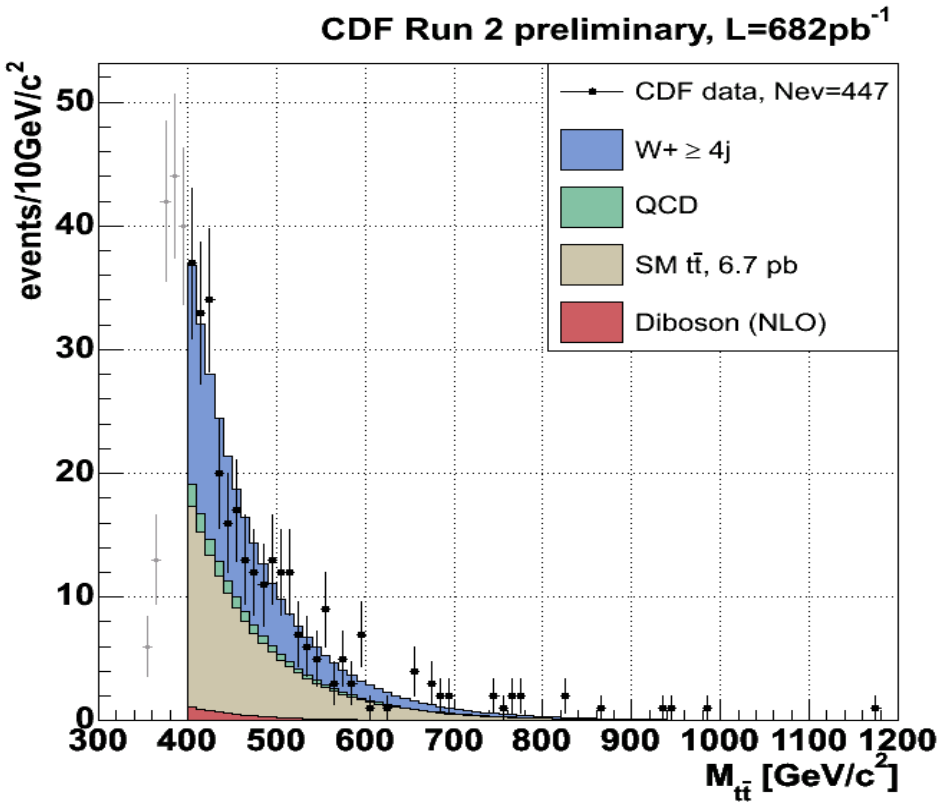

Exclusion of

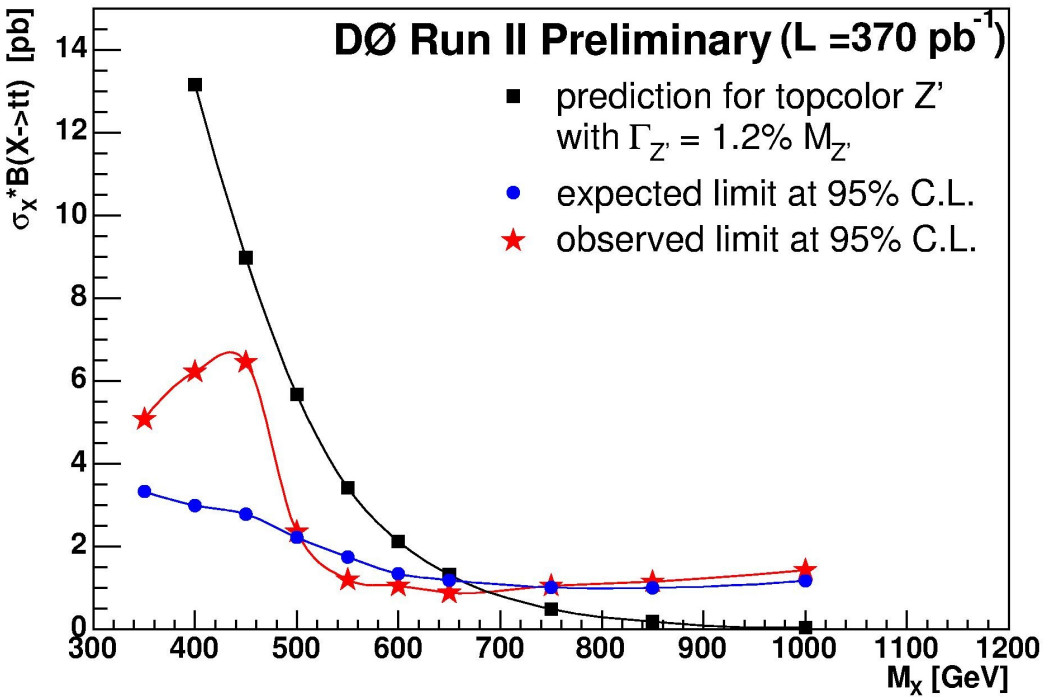
$M_{t'}$ < 258 GeV @ 95% CL

# Resonance in top production

Lepton + jets channel

Reconstruct $M_{t\bar{t}}$ to look for $X \to t\bar{t}$




Leptophobic topcolor model

$\Gamma_{Z'}$=1.2% $M_{Z'}$

Exclusion of

$M_{Z'}$ <725GeV @ 95% CL CDF

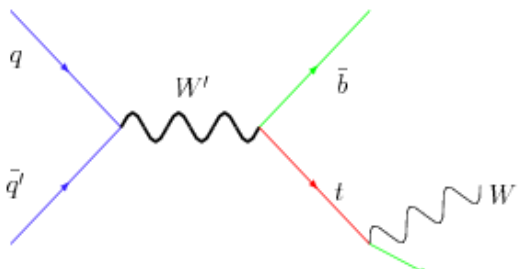
$M_{Z'}$ <680 GeV @ 95% CL D0

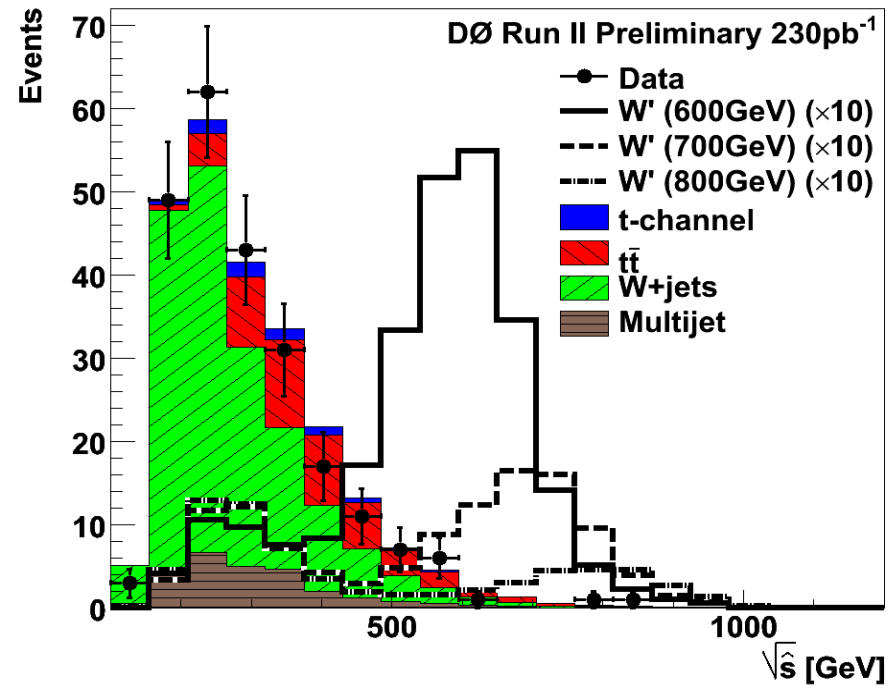
# Search for W' in single top production

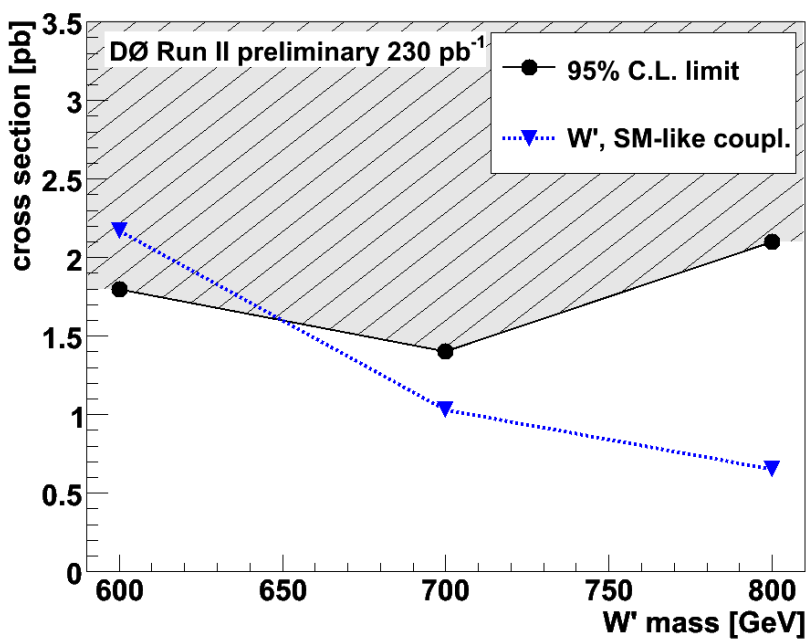
Resonant production of leptophobic W'

Use same technics as for SM single top

- Lepton + jet channels
- Multivariate ANN against $t\bar{t}$ and W+jets



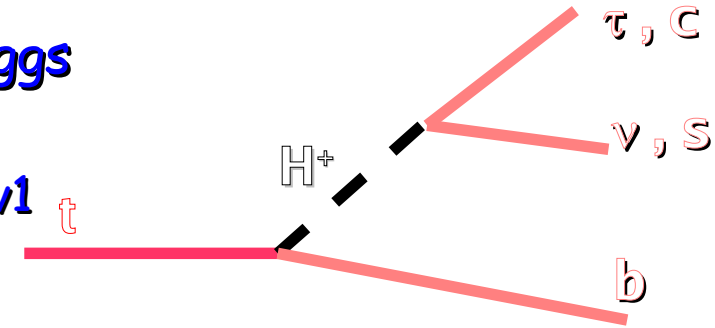




Exclusion of

$200 < M_{W'} < 650$ GeV @ 95% CL

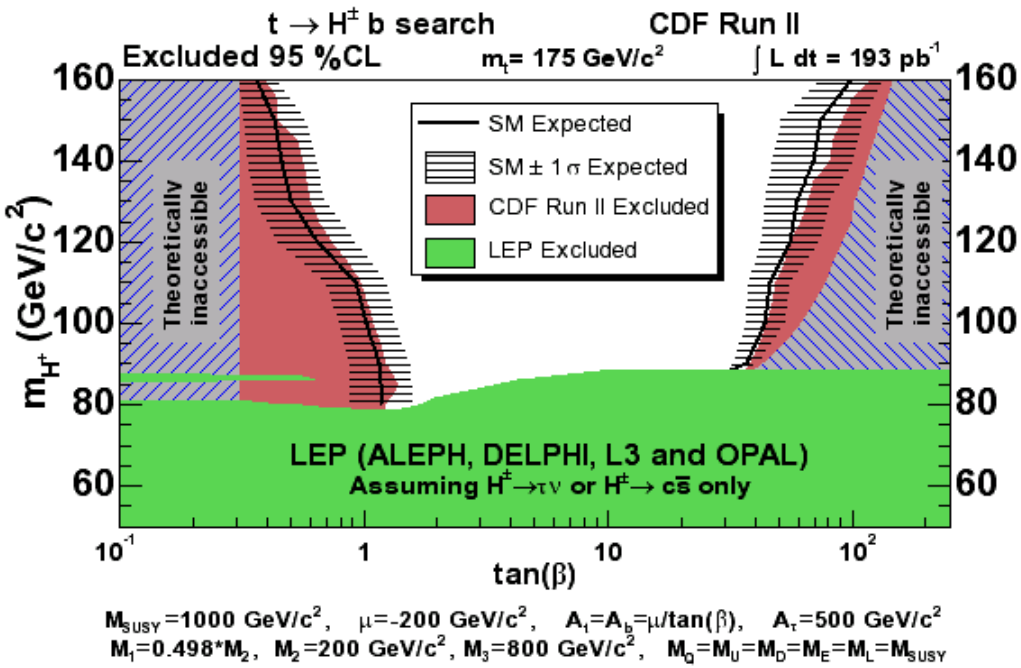
# Charged Higgs in top decay

- Two Higgs doublet model predict charged Higgs
  - eg MSSM
  - Couplings to fermions: function of tanβ= v2/v1

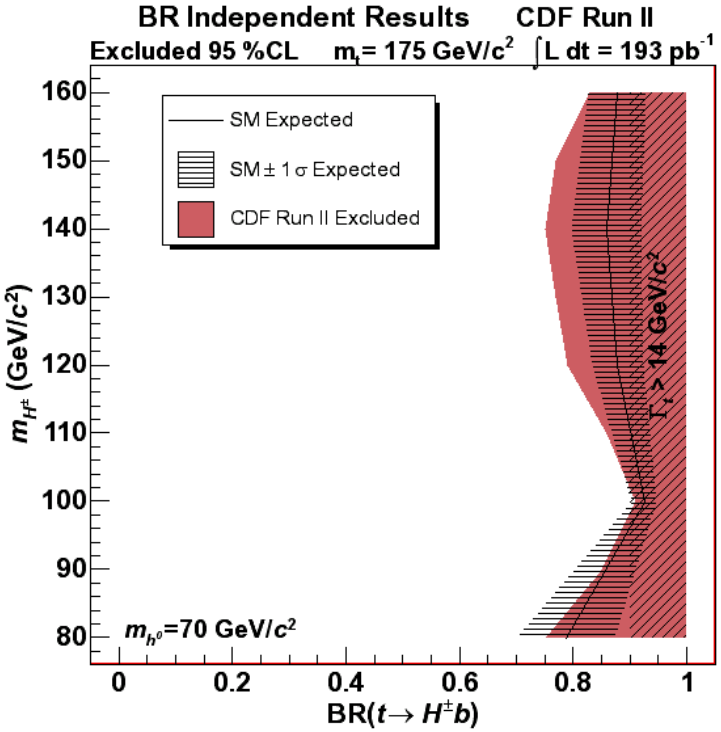



- Possible decays in MSSM:
  - $H^+ \to \tau\nu$, cs, $t^*W^+$, $W^+ h^0 \to W^+bb$ Br depend upon tanβ
  - excess/deficit wrt to expectations in lepton+jets, di-lepton, τ+jets, single/double b-tag channels

CDF: PRL 96,042003




example of MSSM benchmark scenario




model independent limit

# Conclusion

- Tevatron has been running well to produce hundreds of top events
- Entered precision era, in which statistics is no more dominating
  - For mass measurements
  - For cross-section measurements
- Can probe deeply the Standard Moded
  - Top Mass vs EW precision measurements
  - Top quark properties and couplings
  - Physics beyond Standard Model

Run II b just started

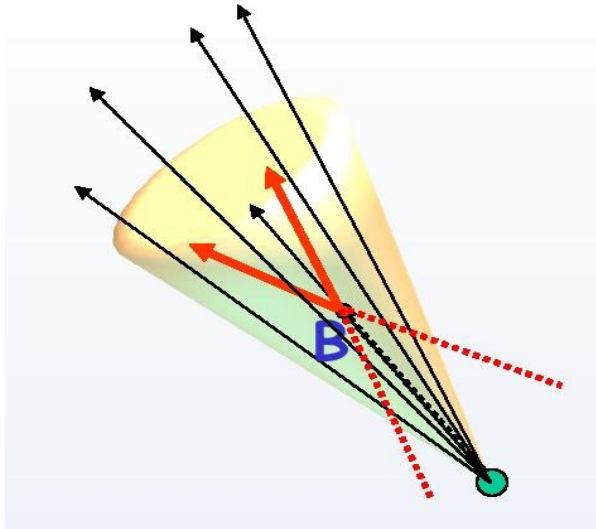
- By the end of 2009 should have > 10 times more statistics than what I have presented.
- More data makes smarter to understand systematics and detector
- Bunch of accurate results expected, and may be surprises.
- Join Tevatron collobarations. Others: don't leave for LHC

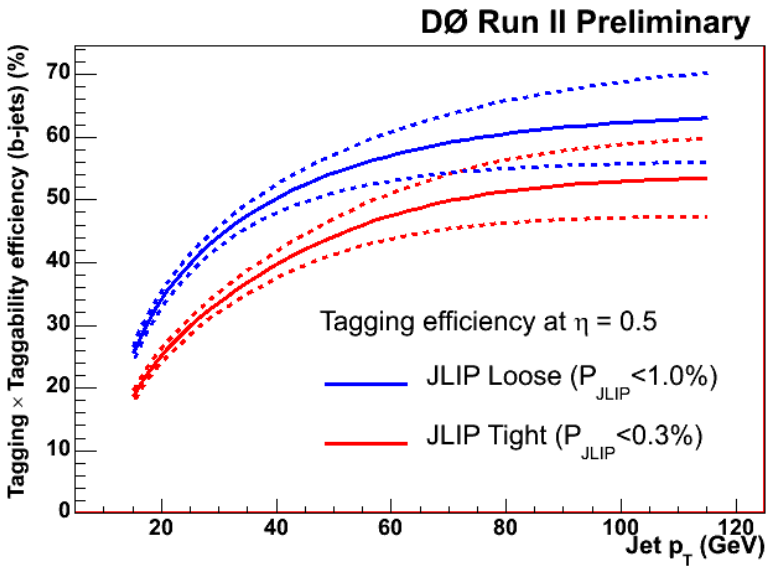
# Support slides

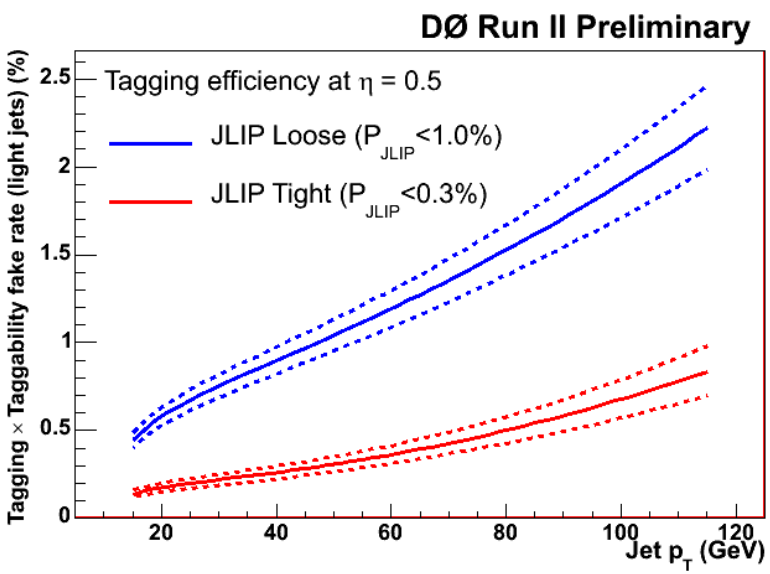
# b-tagging

B-hadron are long lived particles $c\tau$~0.5 mm.

Semi-leptonic decay b->$\mu\nu$c



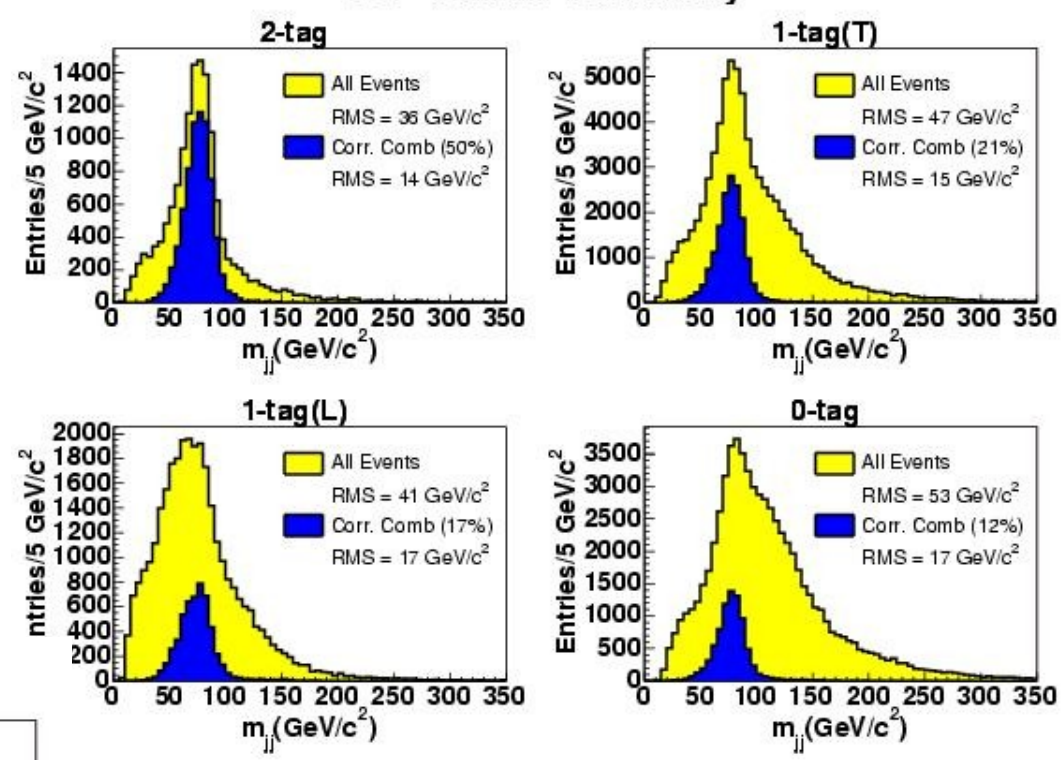



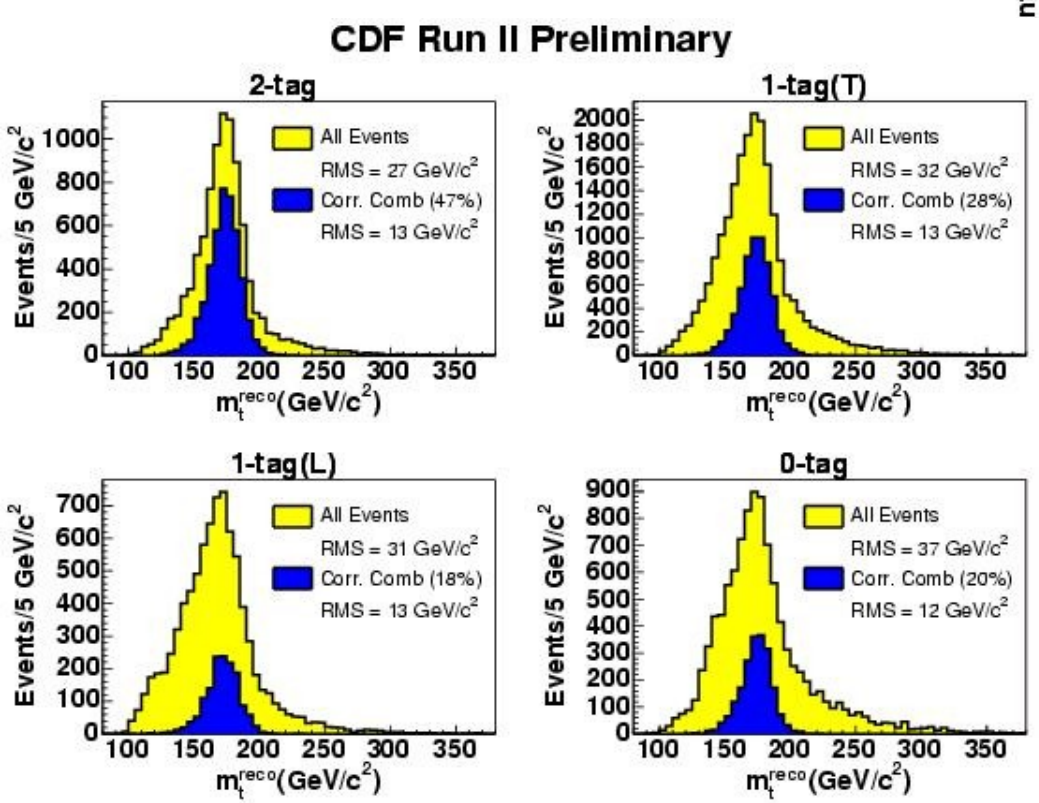




- Can make use of:
  - High impact parameter of tracks
  - Secondary vertex reconstruction
  - Lepton tag
  - b-jet kinematics
  - combination of above with multivariate technics (eg ANN)
- Eg CDF 2nd vertex tag:
  - $\varepsilon$=50% for 0.6% mis-tag at $\eta$<1
- Eg: D0 IP tag:
  - $\varepsilon$=50% for 1% mis-tag at $\eta$=0.5

# B-tagging and combinatoric

- CDF l+jets template analysis



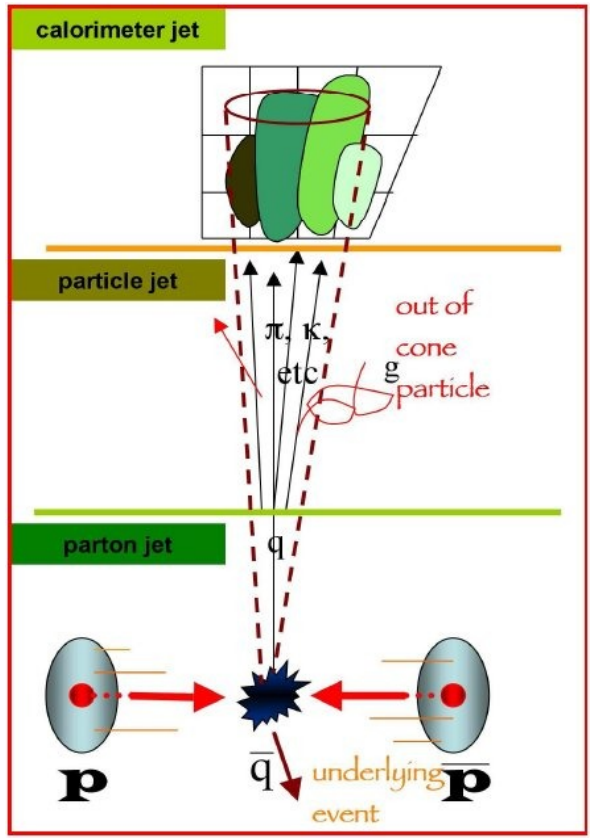



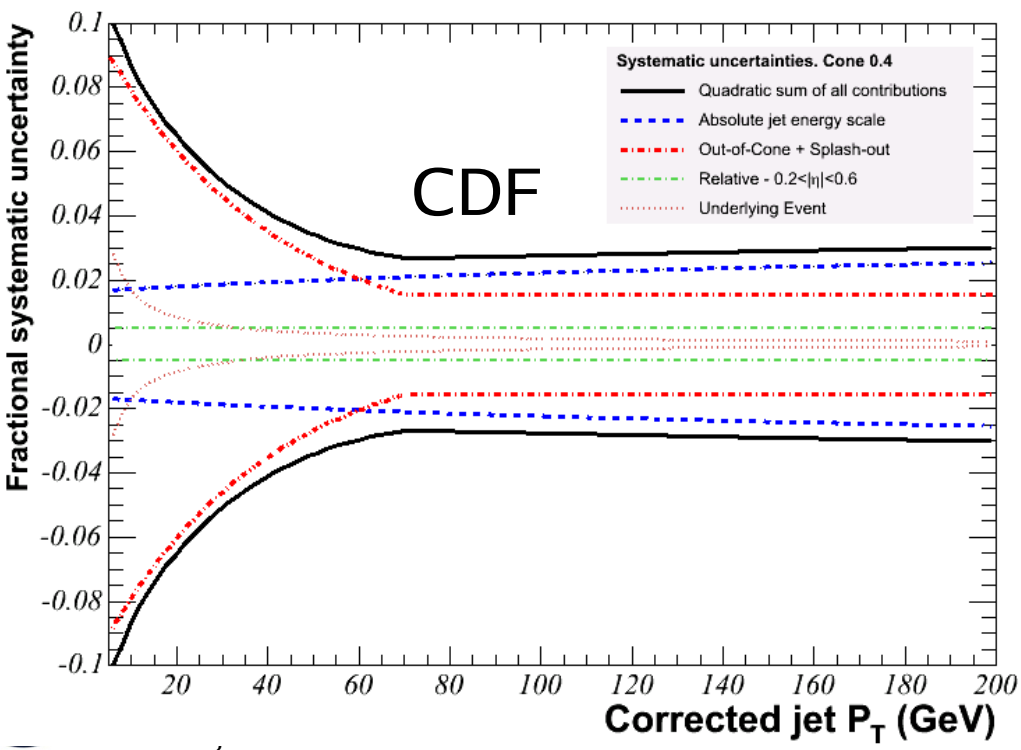
# Jet Energy Scale

Energy measured in calorimeter is not parton energy:

- Limited cone size -> out of cone particles showering
- Different response for hadron/photon
- Uninstrumented regions
- Detector occupancy from
  - Noise
  - Pile-up from previous events
  - Extra interaction in same bunch crossing (typically ~2)

Calibrated using: γ+jet events, Z+jet events, single particles response, MC..

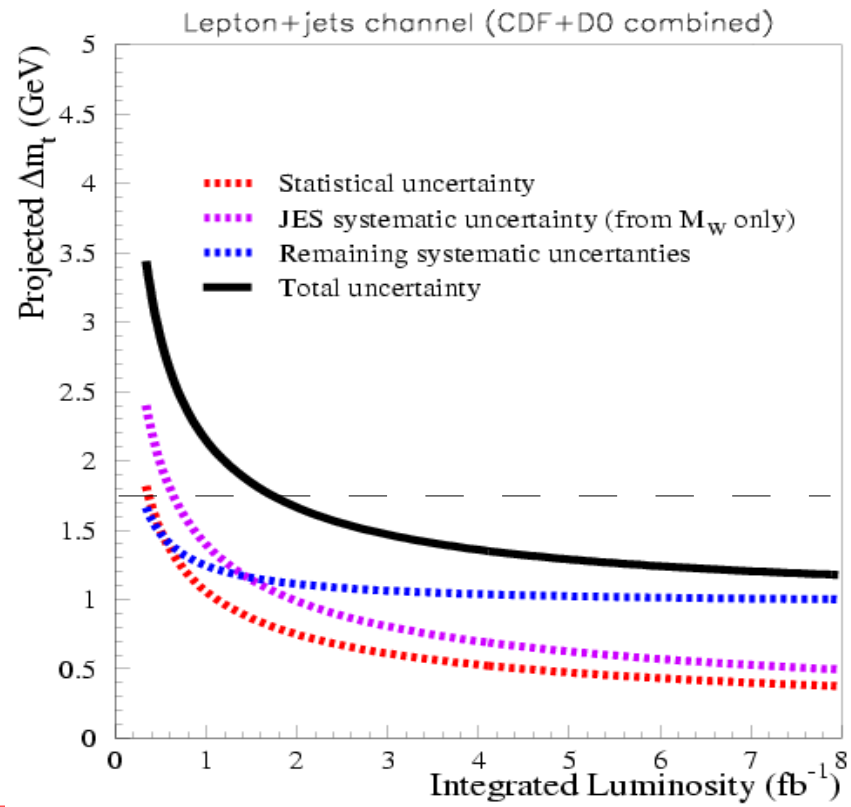


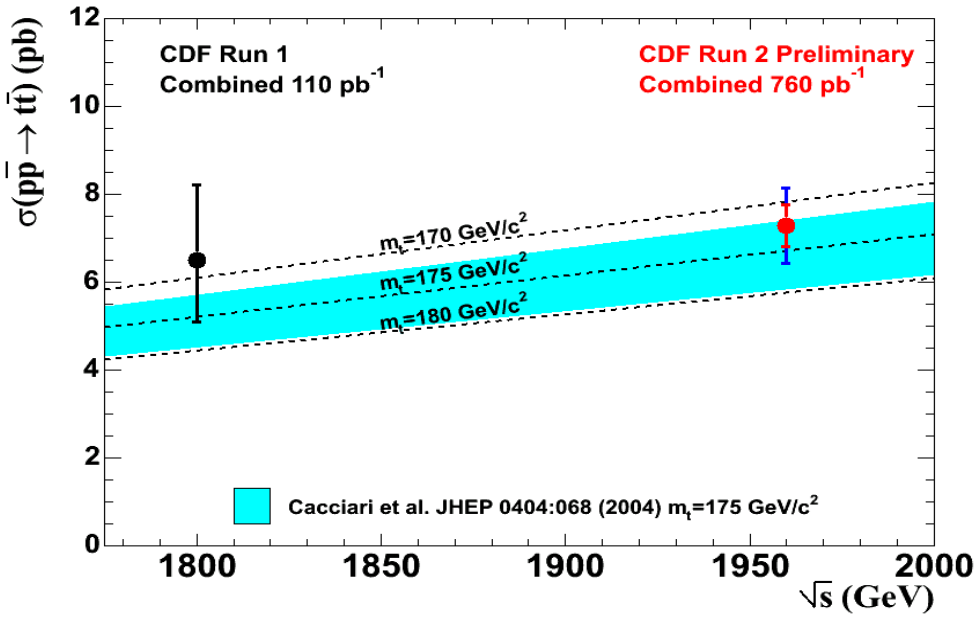

JES systematics, typically ~2-4%

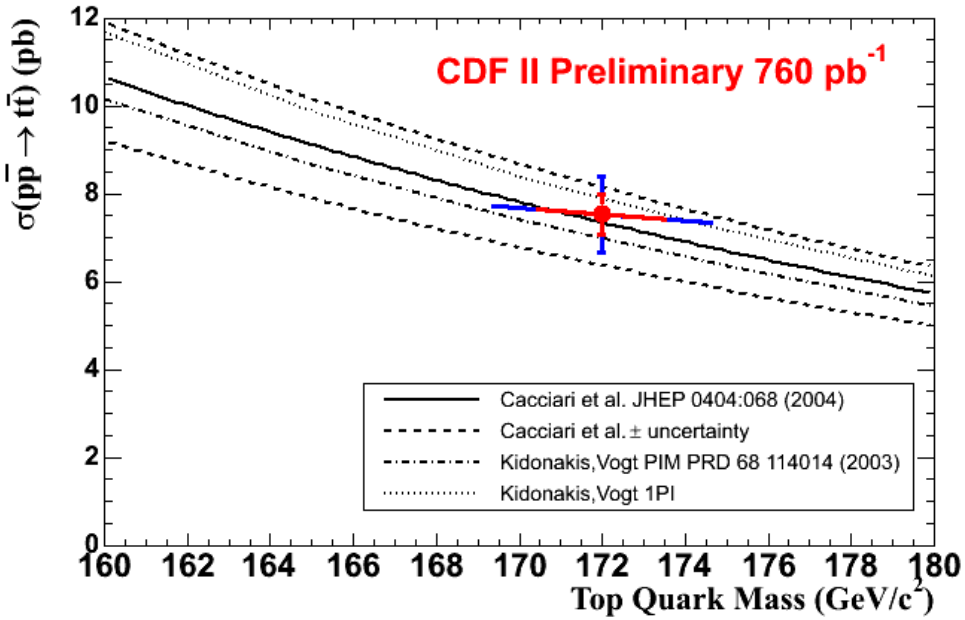
# Top mass systematics

- Jet Energy Scale
  - Light jets response: in-situ calibration using W mass helps reducing uncertainty
  - b-jet response is different : ( b fragmentation, semi-leptonic decay, jet mass)
- Initial State Radiation/ Final state Radiation
  - ISR increase combinatoric background and bias mass.
  - FSR: increase combinatoric background
  - FSR: understimation of jet energies in final states
  - Estimated with MC and Data
- Uncertainties arising from background
  - QCD background contamination
  - Background paremeterization

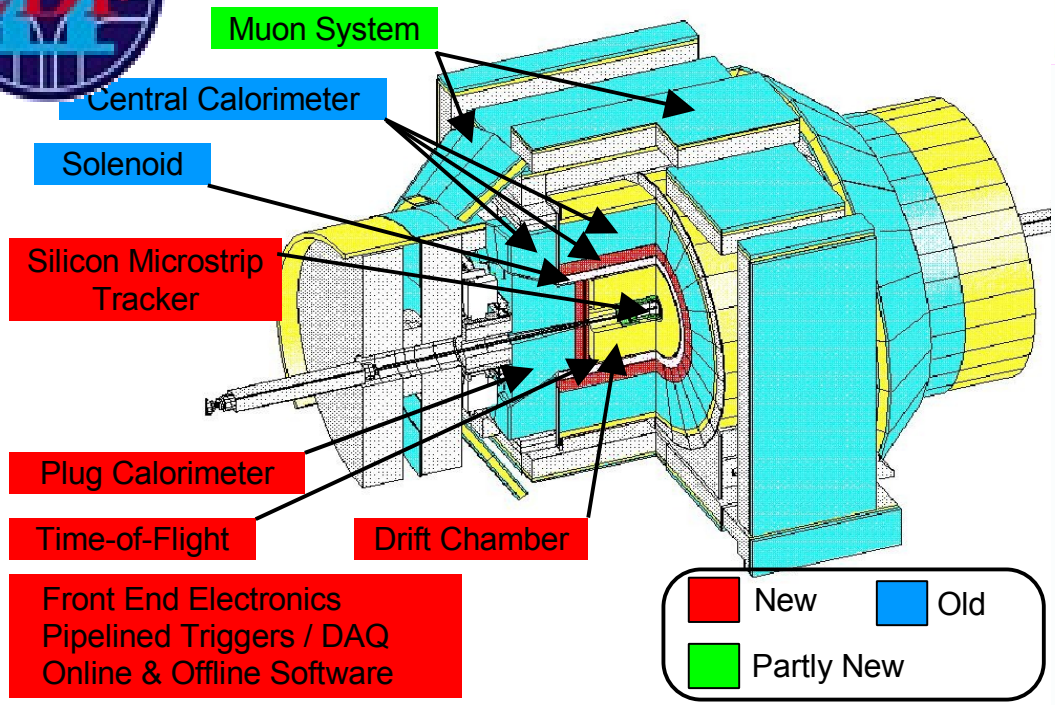


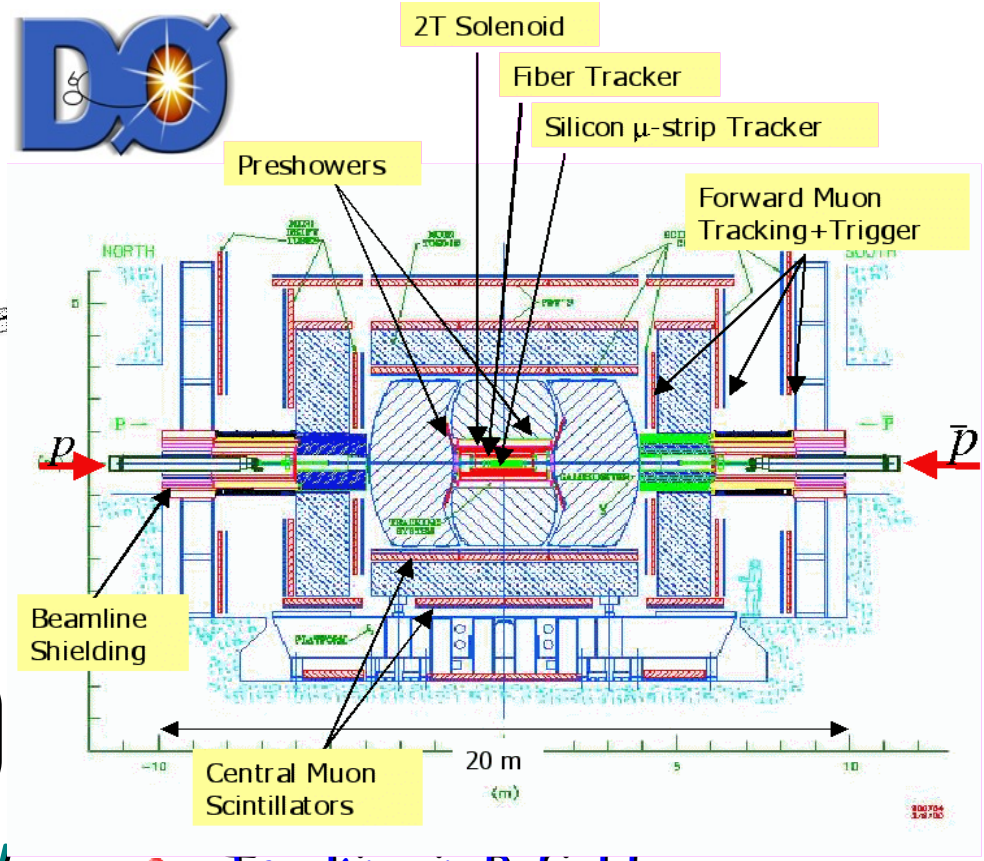
# Cross-section vs sqrt(s)
# Cross-section vs top mass



# Tevatron Experiments at RunIIa




**New**

- silicon detector
- Drift chamber
- TOF PID system

**Upgraded**

- Calorimeter
- DAQ/trigger
- displaced-vertex trigger

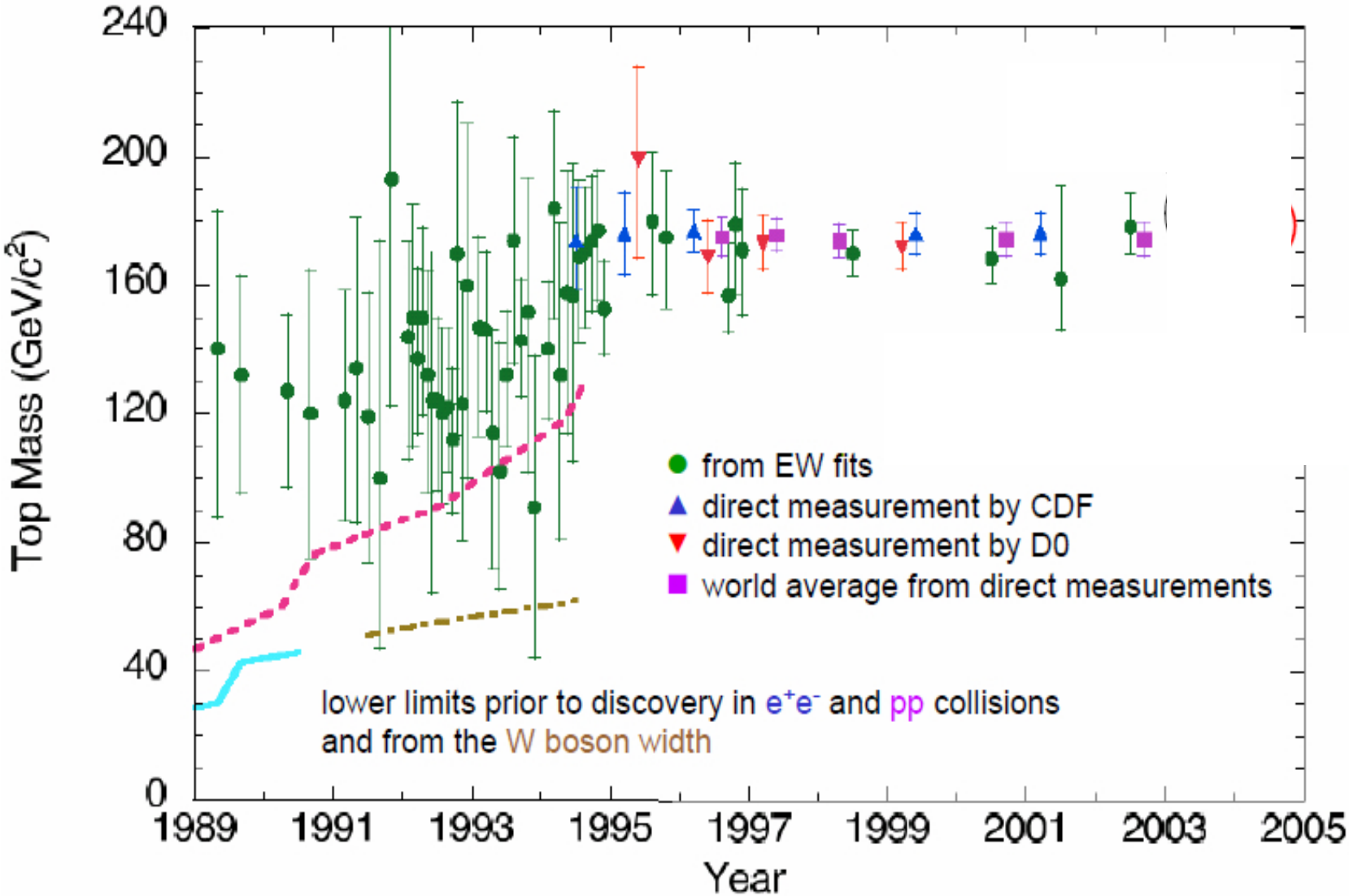
**New**

- Tracking in B-field
- Silicon detector
- fiber tracker

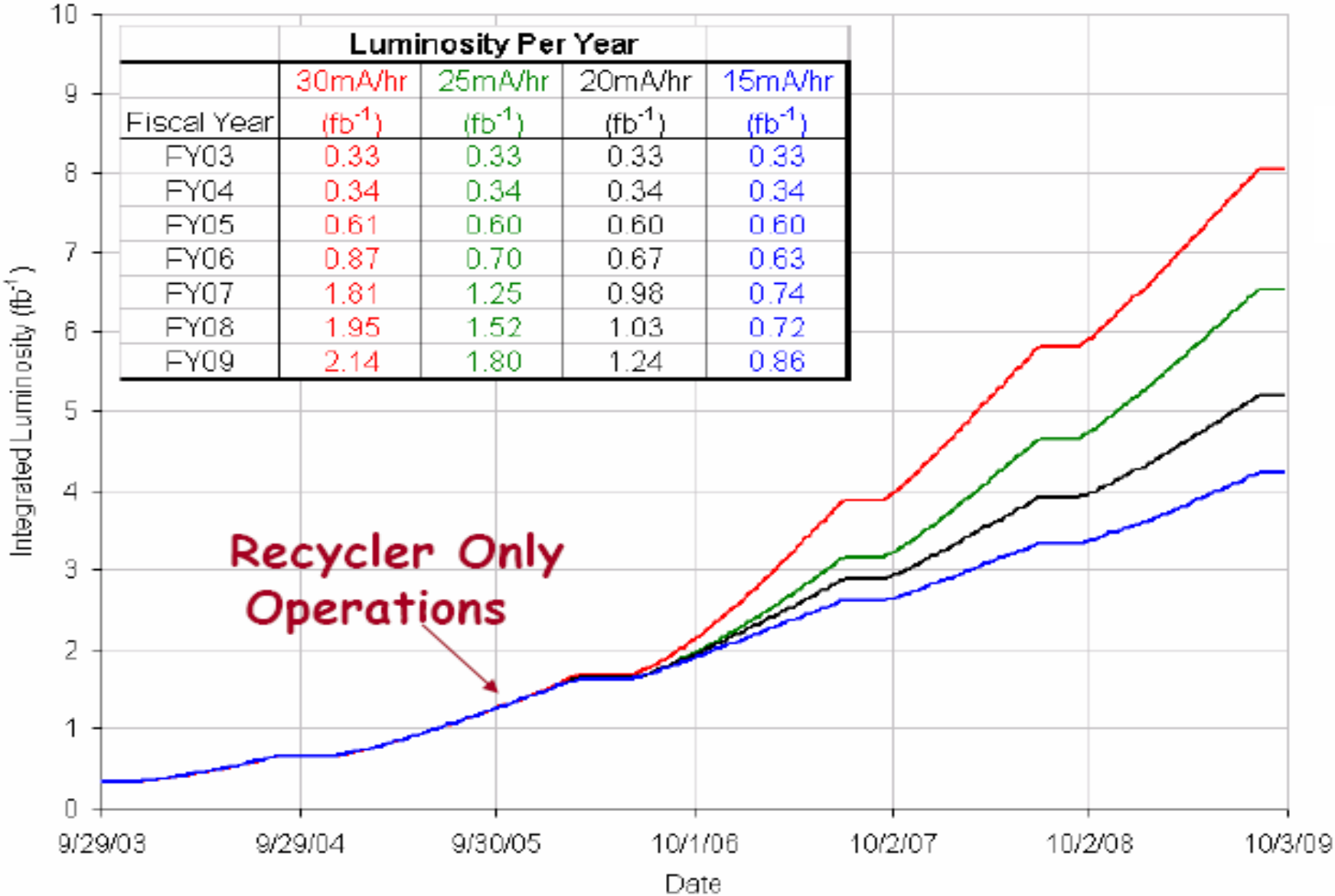
**Upgraded**

- Calorimeter, muon system
- DAQ/trigger

# History


Top Mass (GeV/c²)
240
200
160
120
80
40
0
1989
1991
1993
1995
1997
1999
2001
2003
2005
Year
from EW fits
direct measurement by CDF
direct measurement by D0
world average from direct measurements
lower limits prior to discovery in e⁺e⁻ and pp collisions
and from the W boson width

# Tevatron Luminosity




| Luminosity Per Year | | | | |
|---|---|---|---|---|
| | 30mA/hr | 25mA/hr | 20mA/hr | 15mA/hr |
| Fiscal Year | (fb$^{-1}$) | (fb$^{-1}$) | (fb$^{-1}$) | (fb$^{-1}$) |
| FY03 | 0.33 | 0.33 | 0.33 | 0.33 |
| FY04 | 0.34 | 0.34 | 0.34 | 0.34 |
| FY05 | 0.61 | 0.60 | 0.60 | 0.60 |
| FY06 | 0.87 | 0.70 | 0.67 | 0.63 |
| FY07 | 1.81 | 1.25 | 0.98 | 0.74 |
| FY08 | 1.95 | 1.52 | 1.03 | 0.72 |
| FY09 | 2.14 | 1.80 | 1.24 | 0.86 |