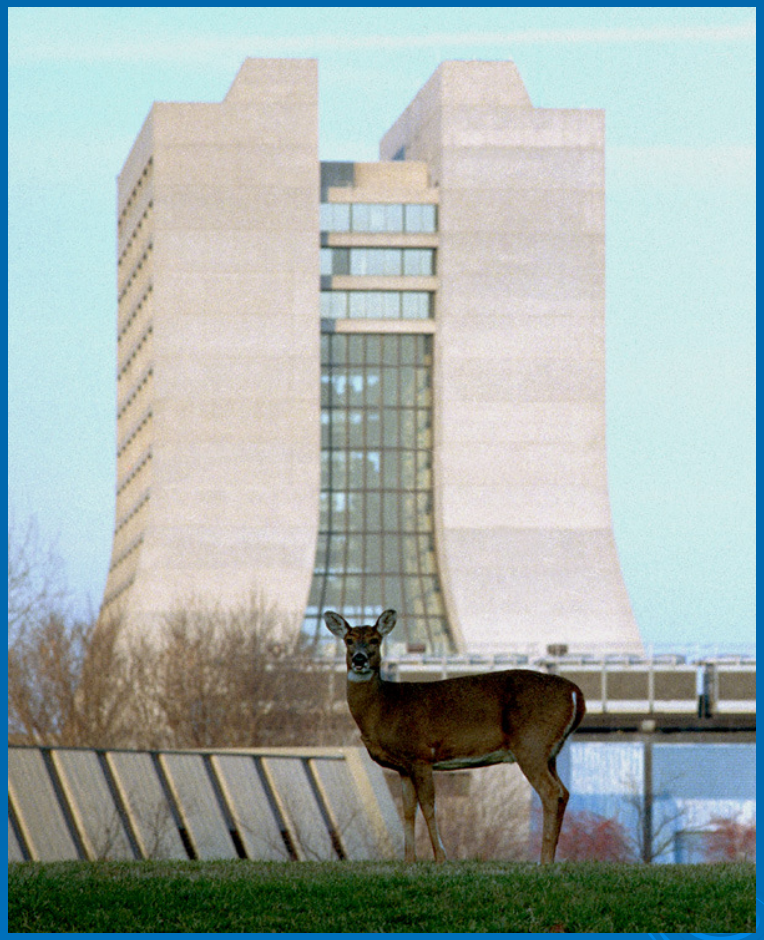
Top production and decay properties at the Tevatron

Michele Weber
Fermilab

For the D0 and CDF collaborations



There's more than buffaloes at Fermilab !

top quark physics

Top Spin

W helicity

Pair production (QCD)

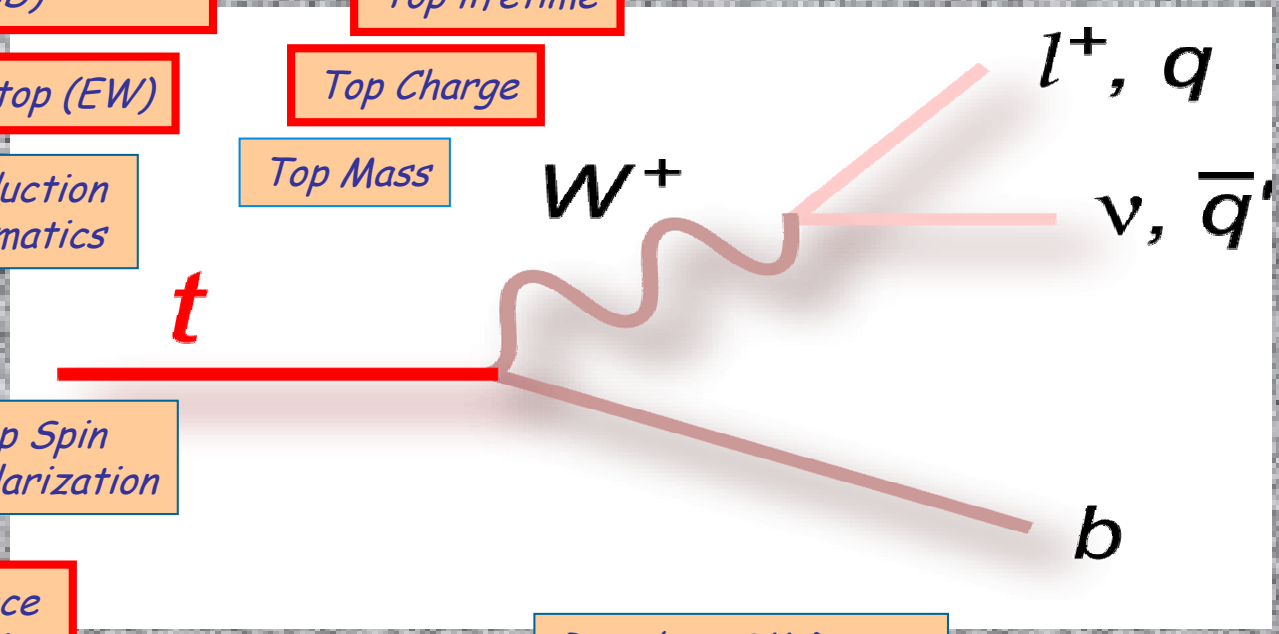
Top lifetime

Single top (EW)

Top Charge

Production kinematics

Top Mass



Top Spin Polarization

Resonance production

Rare/non SM Decays

t prime

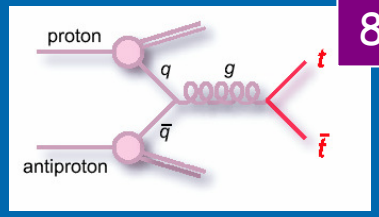
Branching Ratios

Anomalous Couplings

New Physics

Top quark production at 1.96TeV

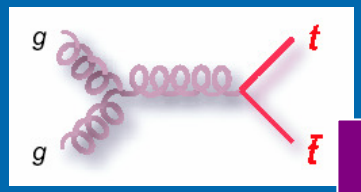
Top quark pair production via strong interaction



85%

Cacciari etal, JHEP 0404:068,2004

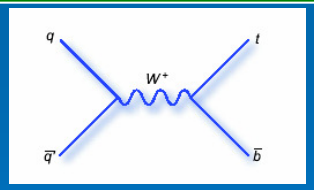
6.7 pb (1.96TeV, m_t=175GeV/c^2)



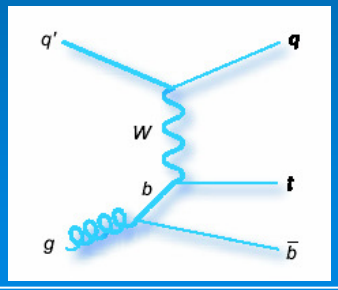
15%

Single top quark production via weak interaction

Not discovered yet

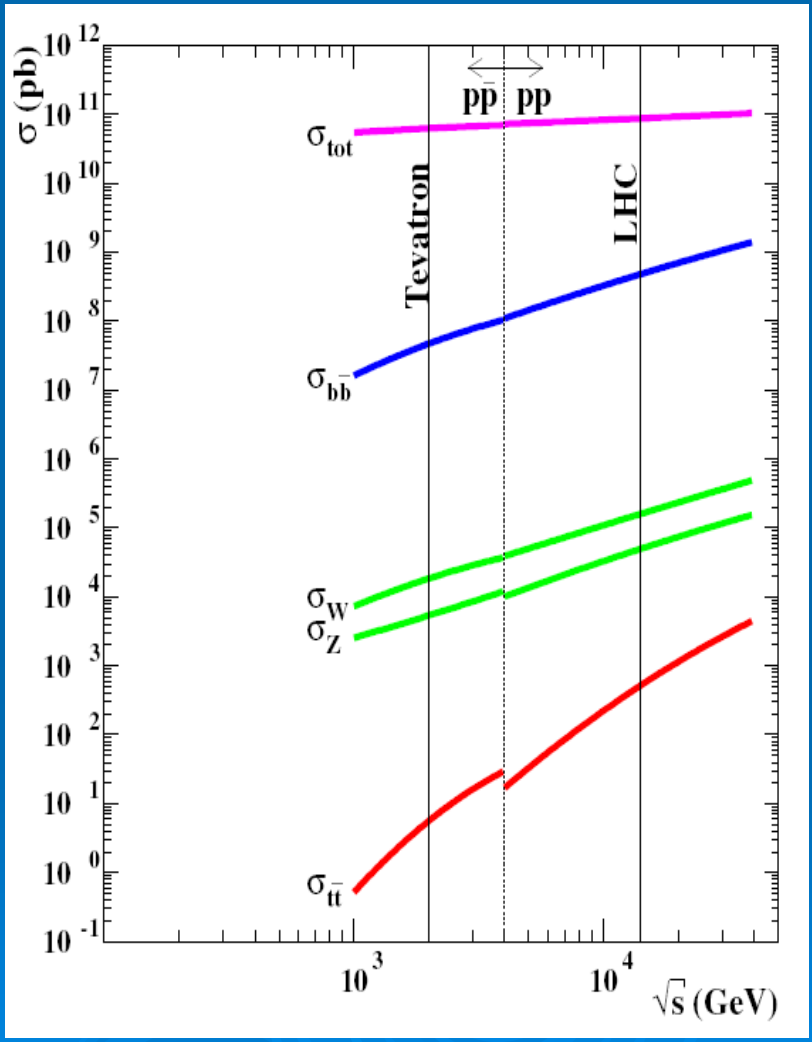


s-channel: 0.88pb



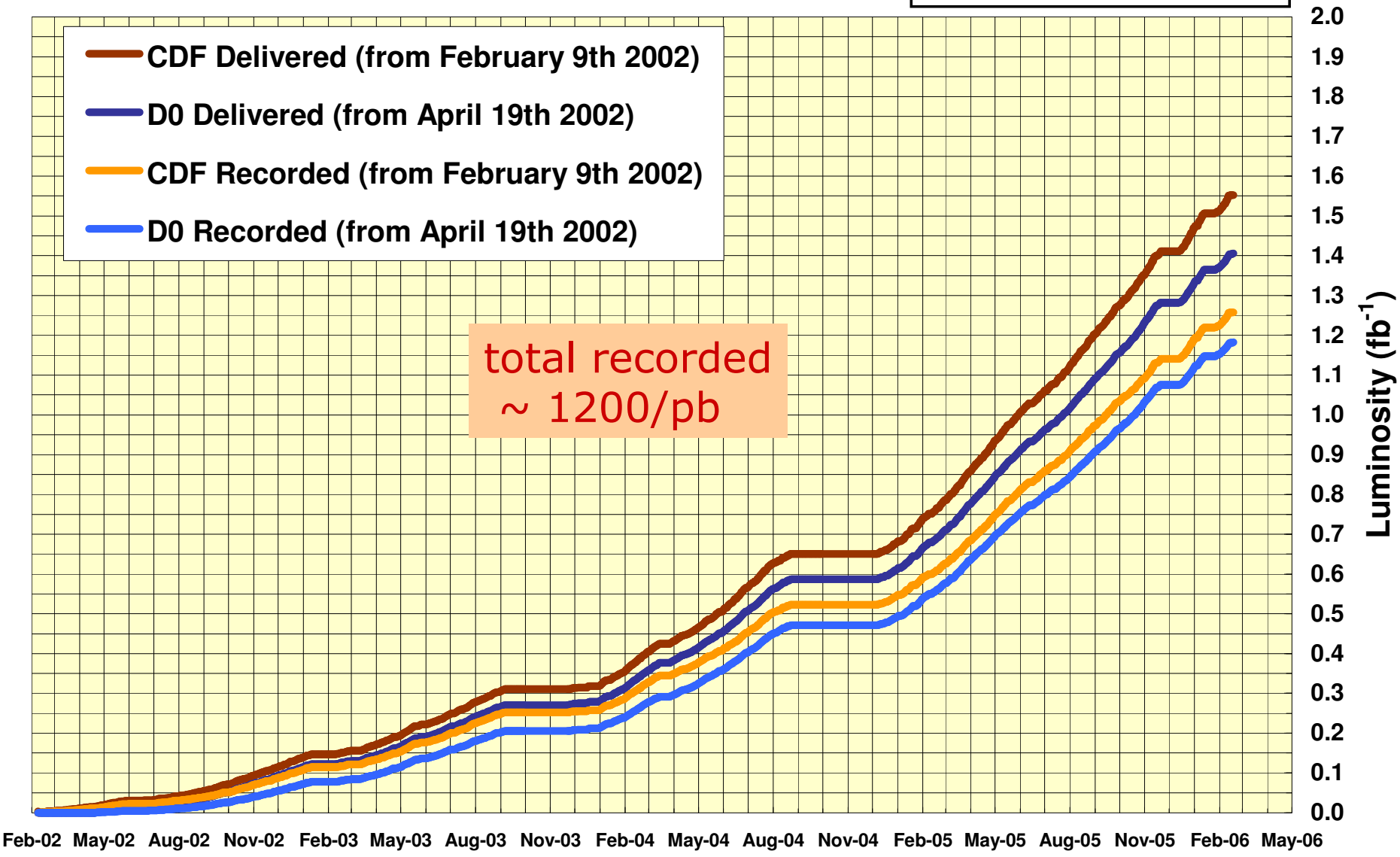
Sullivan, Phys.Rev.D70:114012,2004

t-channel: 1.98pb

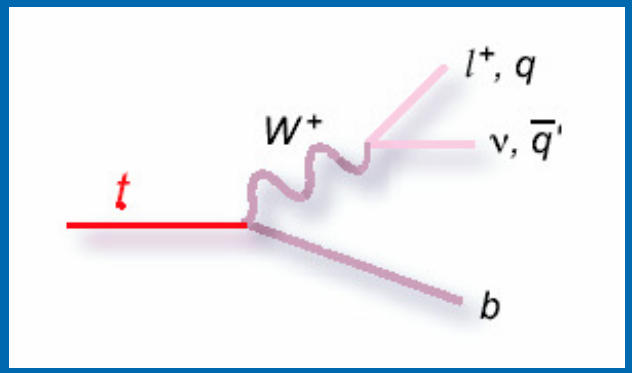


D0 & CDF Run II Integrated Luminosity

through 18 February 2006



Top quark decay & identification

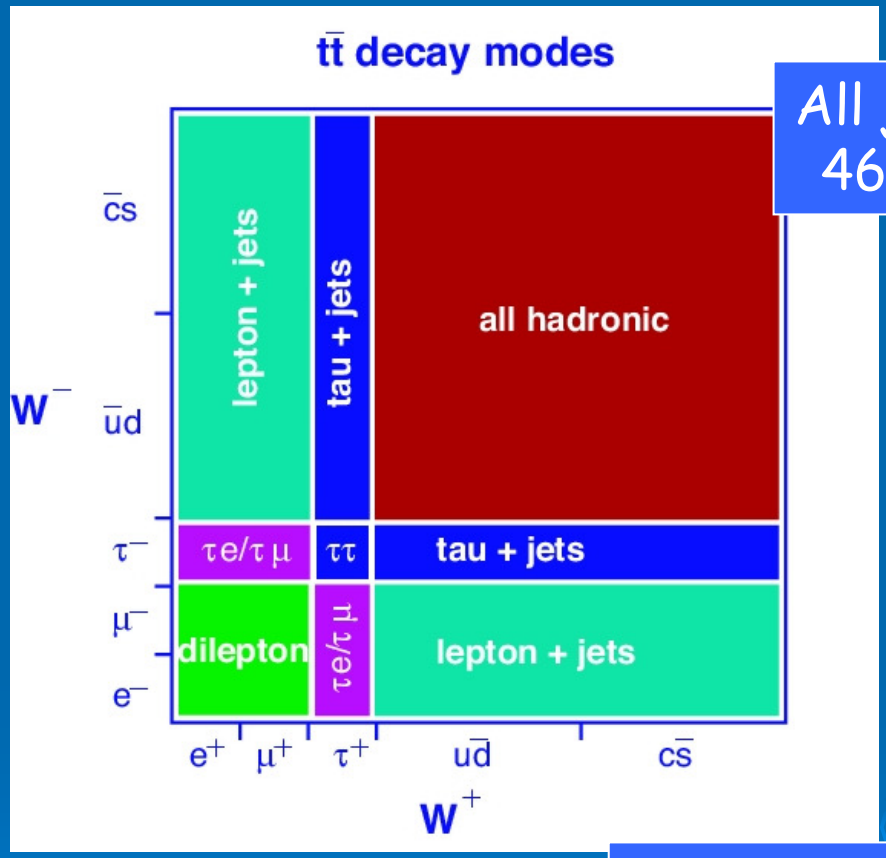


$t \rightarrow Wb \cong 100\%$

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

decay product have:

- good angular separation in the lab frame
- high transverse momentum

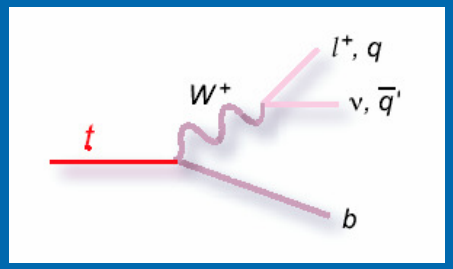


All jet 46%

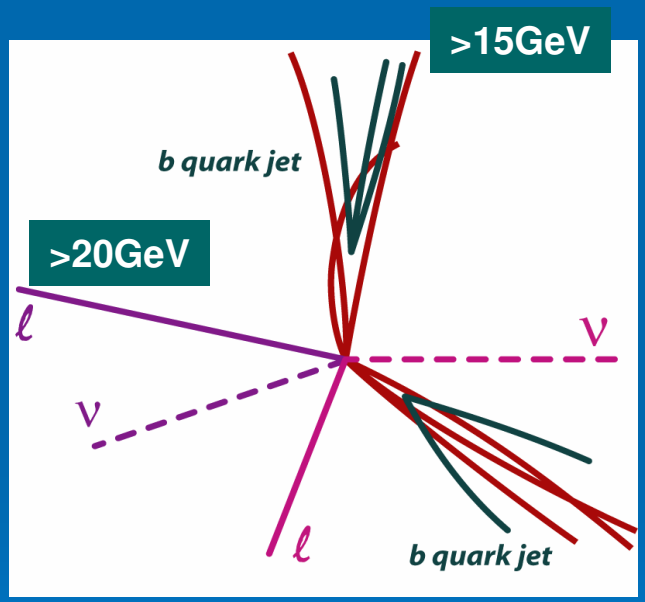
dilepton (e/μ) 4.5%

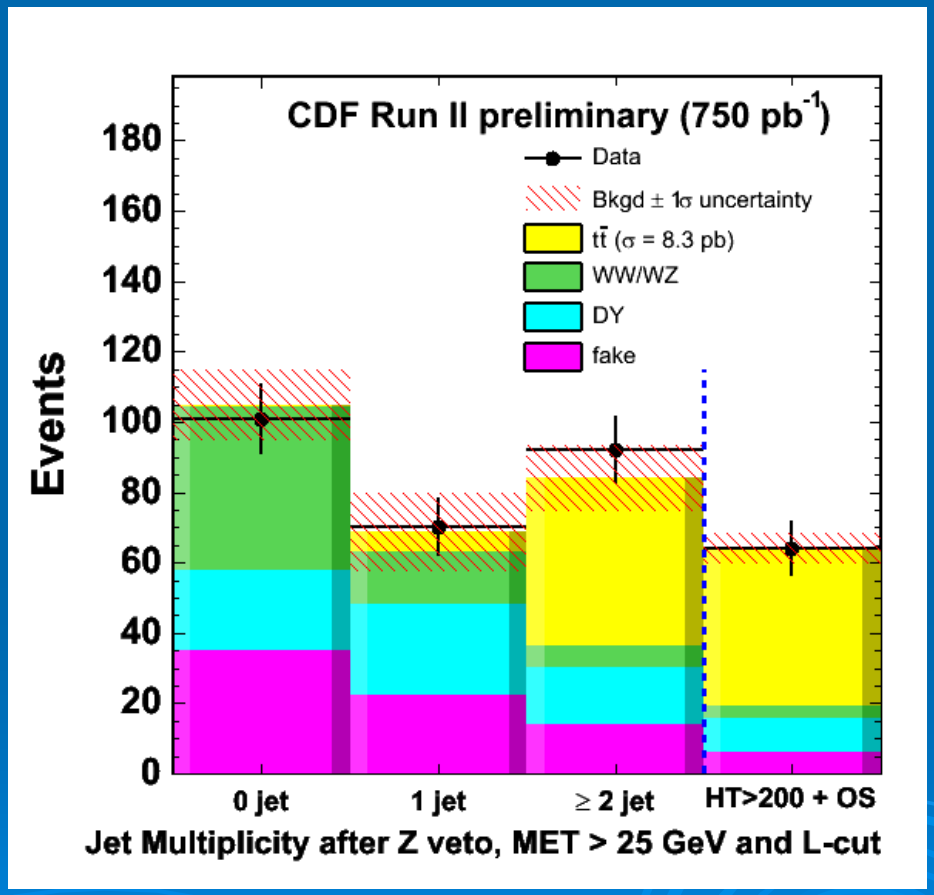
e/mu + jets 29%

Dilepton cross section



low BG but low yield

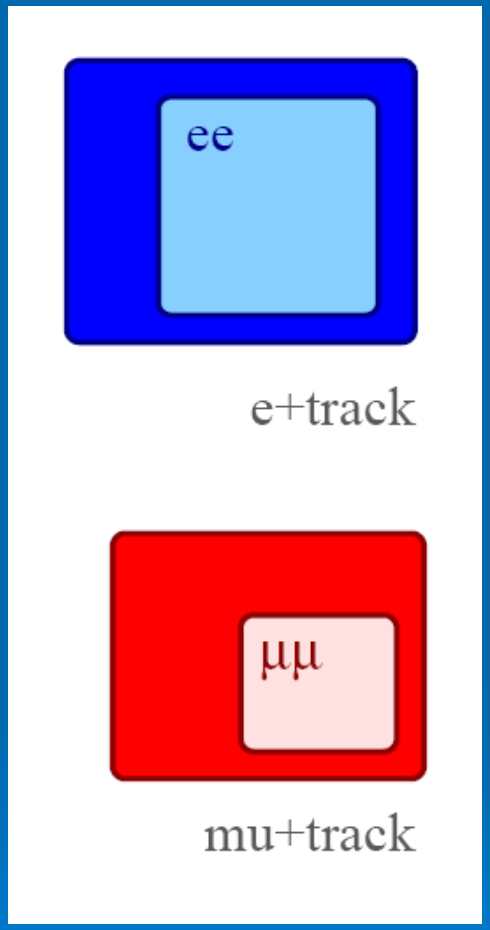




Sample recorded on inclusive lepton triggers with $E_T(l)>18$GeV

$$\sigma_{tt} = 8.3 \pm 1.5(\text{stat}) \pm 1.0(\text{syst}) \pm 0.5(\text{lumi}) \ \text{pb}$$

Add lepton+track events



- Loosen the selection
  (one reconstructed letpton + one track)

- Recover S/B with b-tagging

l+track $\sigma_{tt} = 7.1^{+2.6}_{-2.2}(\text{stat})^{+1.3}_{-1.3}(\text{syst})\text{pb}$

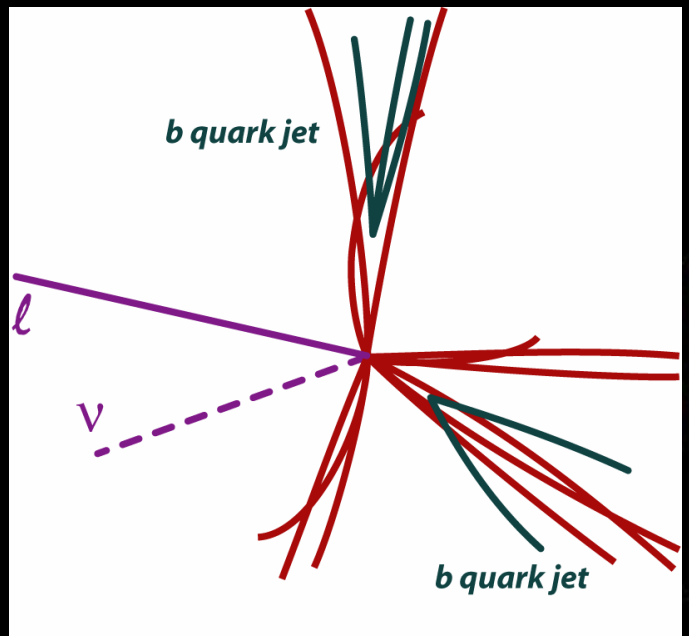
- Veto 2nd other flavour lepton
  (combination with e+μ)

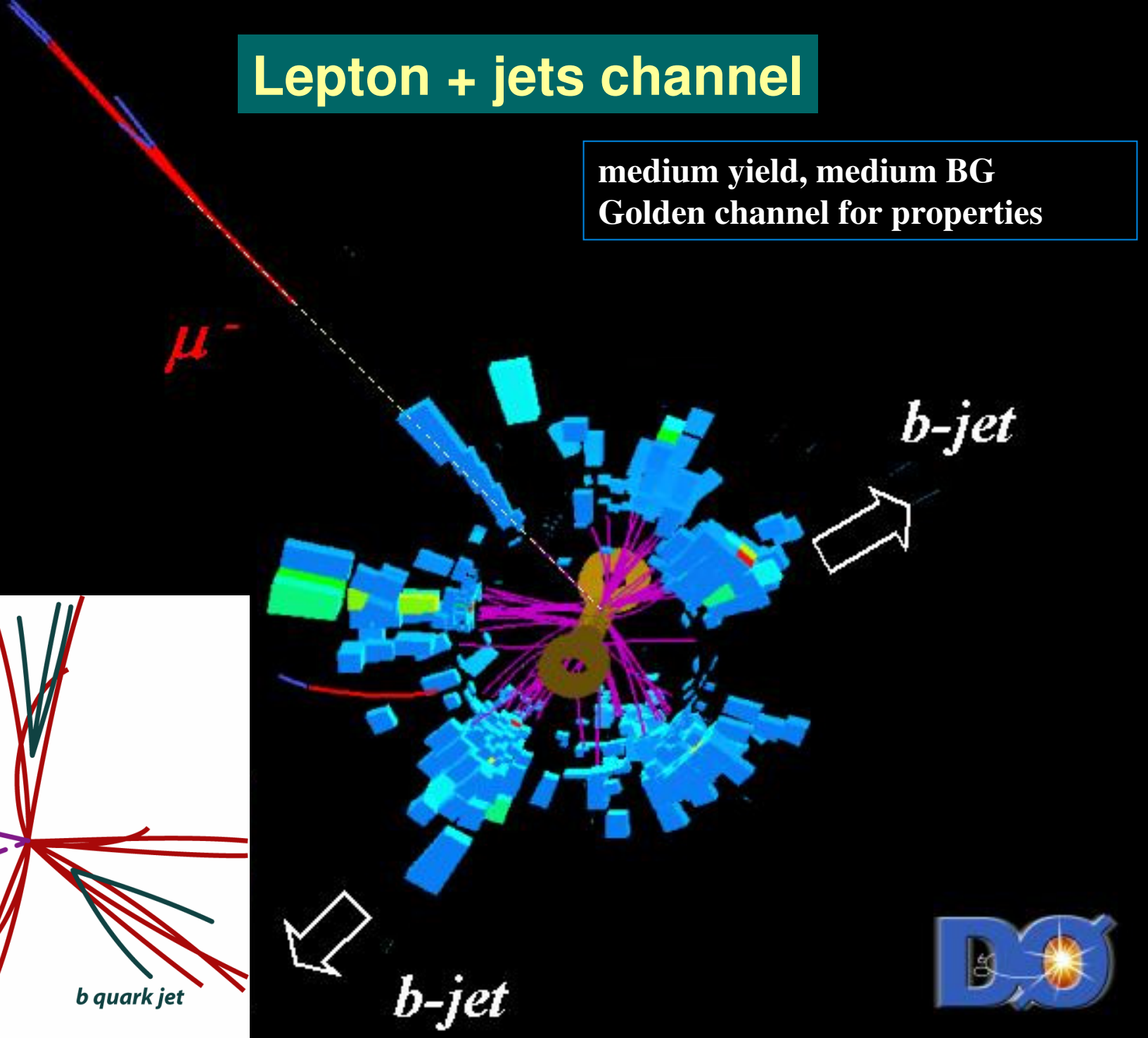
l+track + eμ $\sigma_{tt} = 8.6^{+1.9}_{-1.7}(\text{stat})^{+1.1}_{-1.1}(\text{syst})\text{pb}$

Compare to: ee + μμ + eμ $\sigma_{tt} = 8.6^{+2.3}_{-2.0}(\text{stat})^{+1.2}_{-1.0}(\text{syst})\text{pb}$

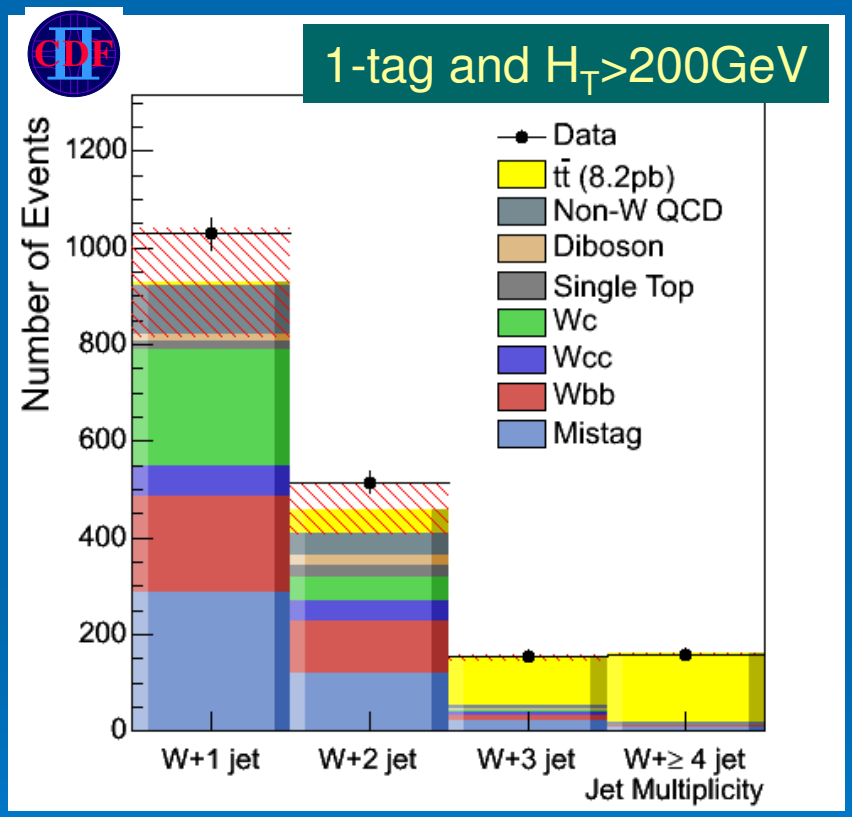
Lepton + jets channel

medium yield, medium BG
Golden channel for properties

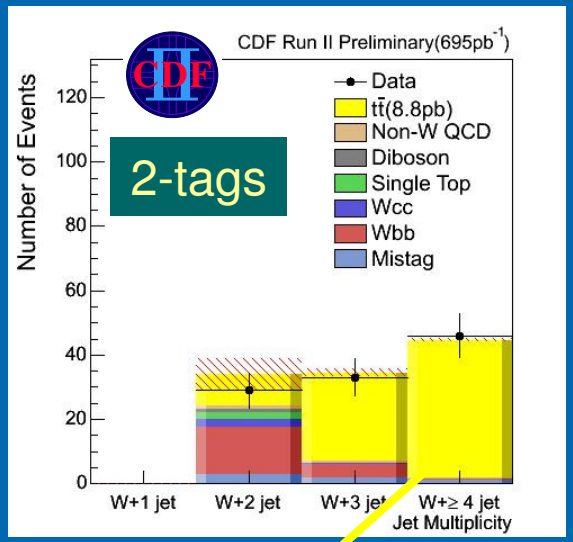




l+jets with b-tagging



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

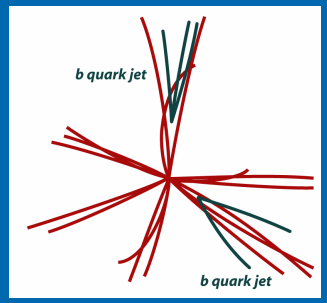


'Ultra-pure' top sample

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

Relative systematic uncertainties:

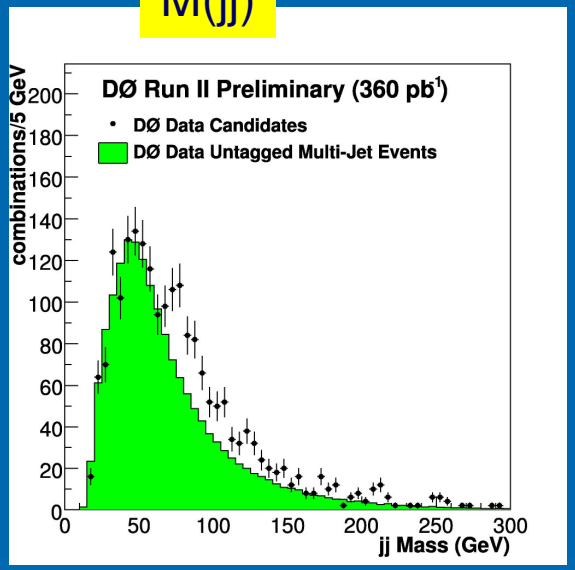
Source	Uncertainty (%)
b-tagging	6.5
luminosity	6.0
parton distribution functions	5.8
jet energy scale	3.0
initial/final state radiation	2.6
lepton identification	2.0
Total	11.5



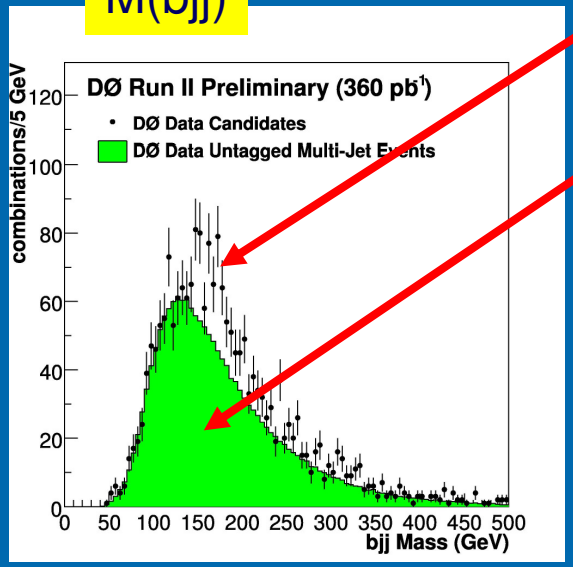
All jet

High yield, high BG

M(jj)

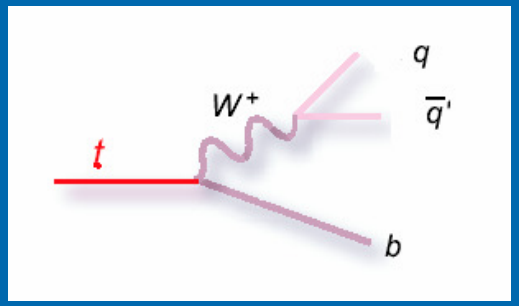


M(bjj)

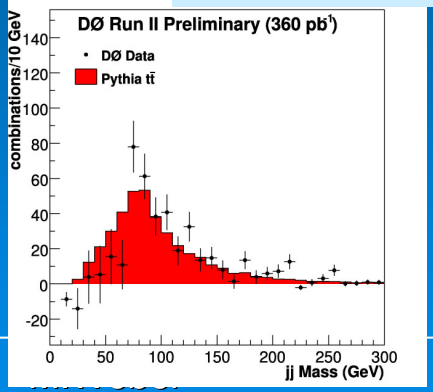


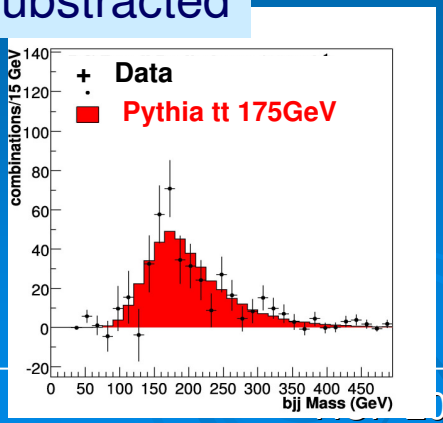
Data with final selection (with btagging)

Background From data



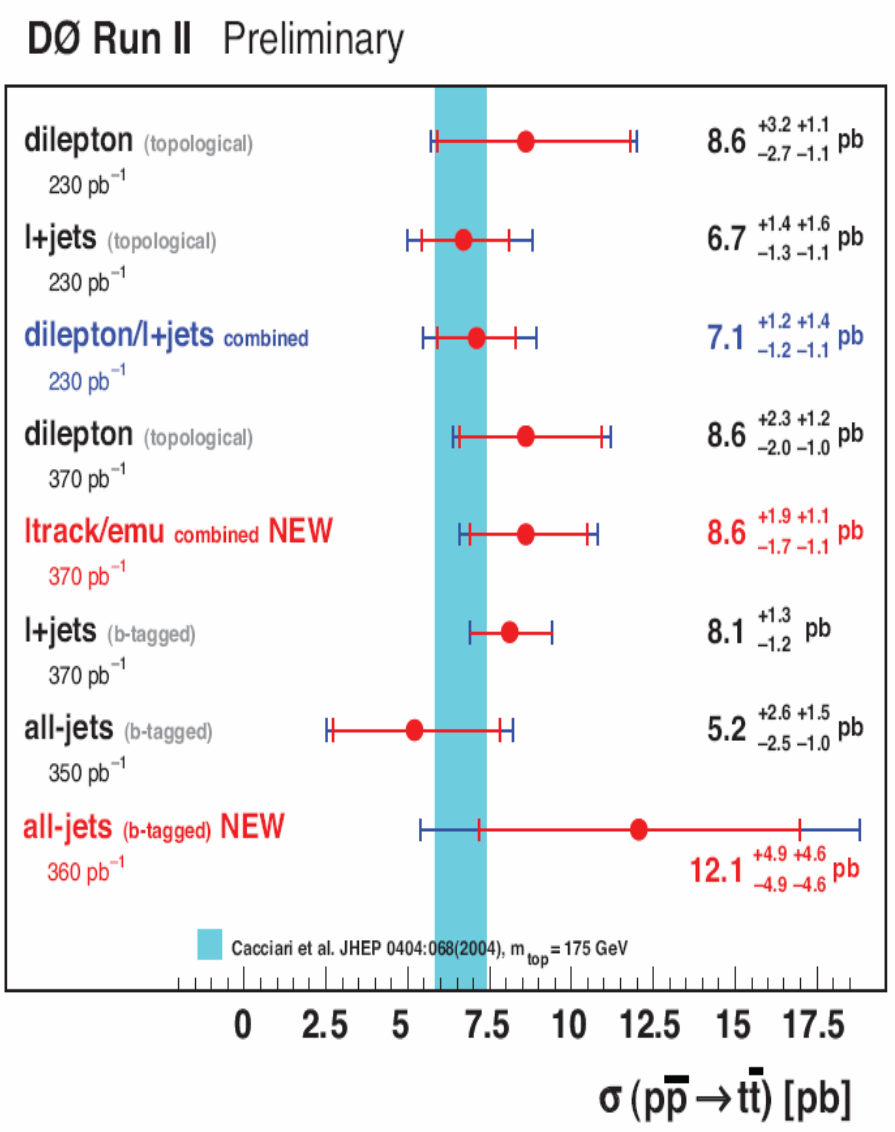
Background substracted

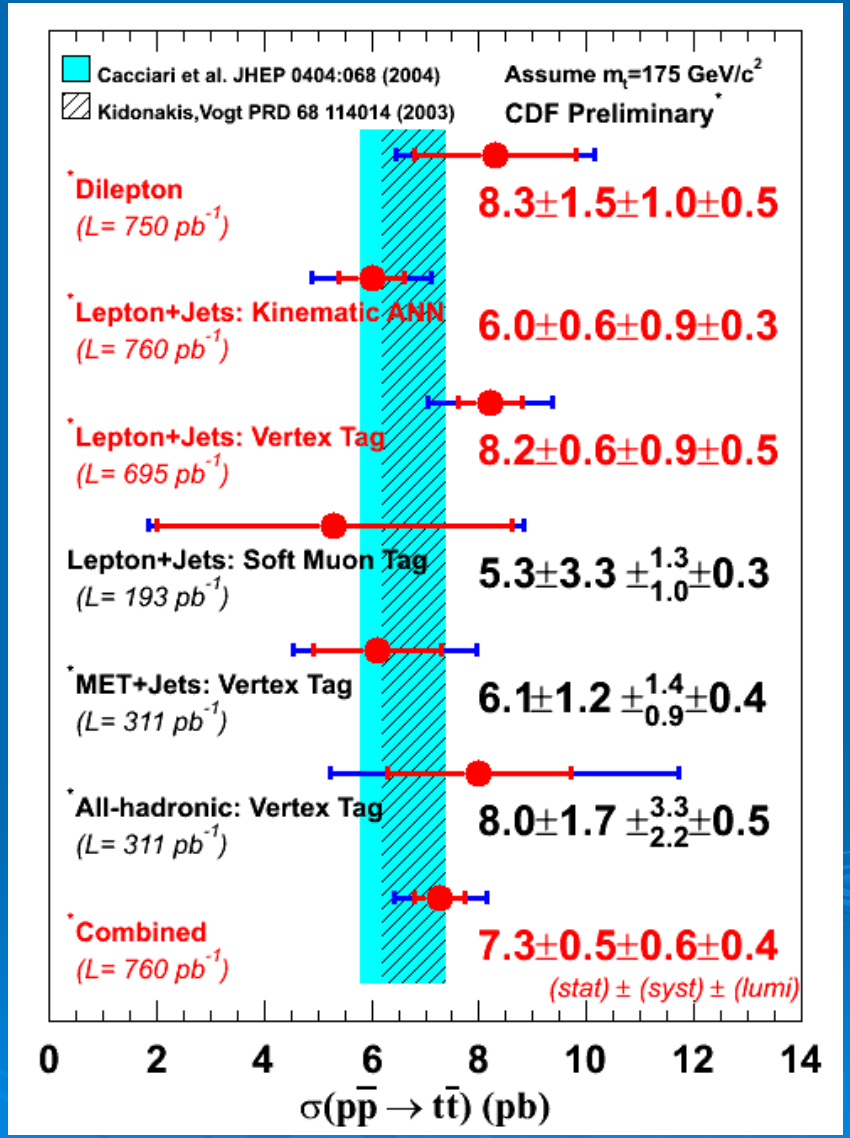




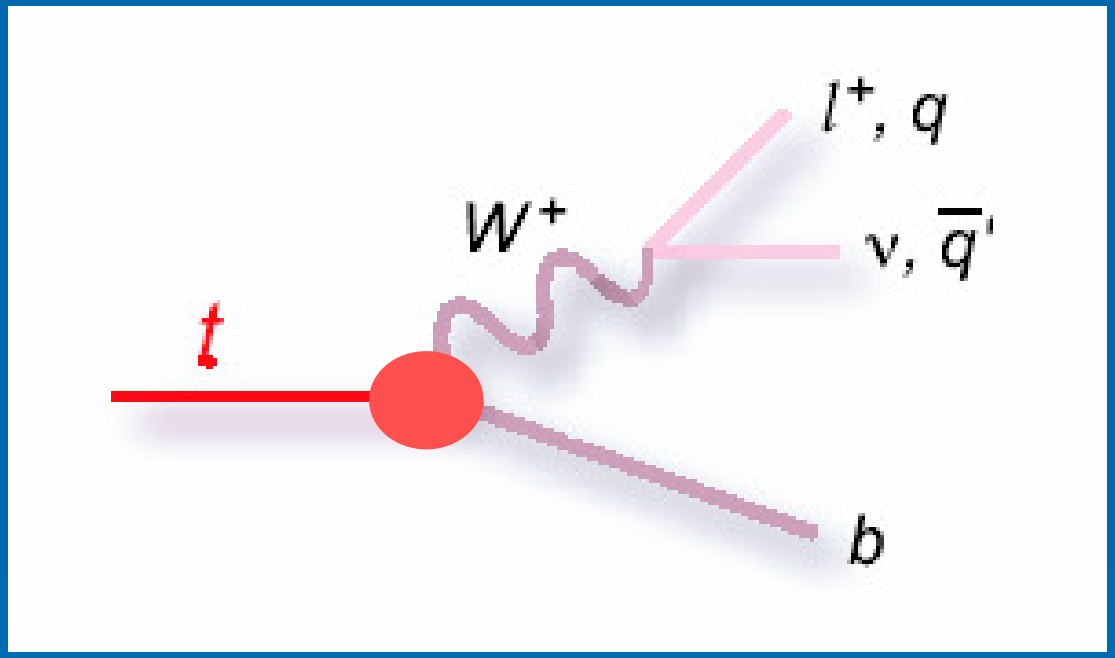
360/pb

$$12.1 \pm 4.9(\text{stat}) \pm 4.6(\text{syst})\text{pb}$$


DØ Run II Preliminary
dilepton (topological)
230 pb^{-1}
8.6 $^{+3.2}_{-2.7}$ $^{+1.1}_{-1.1}$ pb
l+jets (topological)
230 pb^{-1}
6.7 $^{+1.4}_{-1.3}$ $^{+1.6}_{-1.1}$ pb
dilepton/l+jets combined
230 pb^{-1}
7.1 $^{+1.2}_{-1.2}$ $^{+1.4}_{-1.1}$ pb
dilepton (topological)
370 pb^{-1}
8.6 $^{+2.3}_{-2.0}$ $^{+1.2}_{-1.0}$ pb
ltrack/emu combined NEW
370 pb^{-1}
8.6 $^{+1.9}_{-1.7}$ $^{+1.1}_{-1.1}$ pb
l+jets (b-tagged)
370 pb^{-1}
8.1 $^{+1.3}_{-1.2}$ pb
all-jets (b-tagged)
350 pb^{-1}
5.2 $^{+2.6}_{-2.5}$ $^{+1.5}_{-1.0}$ pb
all-jets (b-tagged) NEW
360 pb^{-1}
12.1 $^{+4.9}_{-4.9}$ $^{+4.6}_{-4.6}$ pb
Cacciari et al. JHEP 0404:068(2004), m_{top} = 175 GeV
0 2.5 5 7.5 10 12.5 15 17.5
$\sigma(p\bar{p} \to t\bar{t})$ [pb]


Cacciari et al. JHEP 0404:068 (2004)
Kidonakis,Vogt PRD 68 114014 (2003)
Assume m_t=175 GeV/c^2
CDF Preliminary*
*Dilepton
(L= 750 pb^{-1})
8.3±1.5±1.0±0.5
*Lepton+Jets: Kinematic ANN
(L= 760 pb^{-1})
6.0±0.6±0.9±0.3
*Lepton+Jets: Vertex Tag
(L= 695 pb^{-1})
8.2±0.6±0.9±0.5
Lepton+Jets: Soft Muon Tag
(L= 193 pb^{-1})
5.3±3.3 $\pm^{1.3}_{1.0}$±0.3
*MET+Jets: Vertex Tag
(L= 311 pb^{-1})
6.1±1.2 $\pm^{1.4}_{0.9}$±0.4
*All-hadronic: Vertex Tag
(L= 311 pb^{-1})
8.0±1.7 $\pm^{3.3}_{2.2}$±0.5
*Combined
(L= 760 pb^{-1})
7.3±0.5±0.6±0.4
(stat) ± (syst) ± (lumi)
0 2 4 6 8 10 12 14
$\sigma(p\bar{p} \to t\bar{t})$ (pb)

Probing the Wtb vertex



- t→Wb / t→Wq
- W helicity in top events
- single top

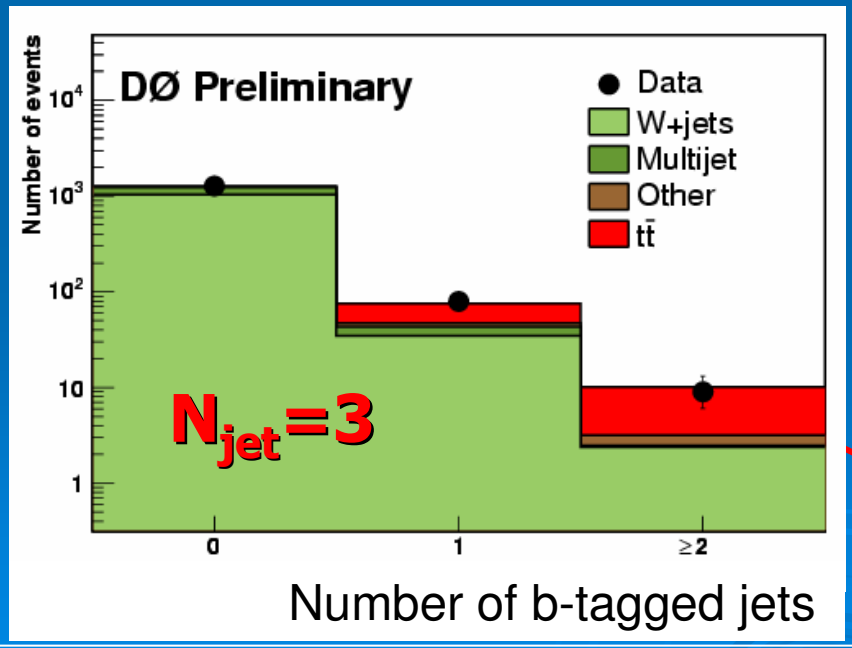
Anomalies = New physics ?

Probing the assumption

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

(True in SM with three quark generations)

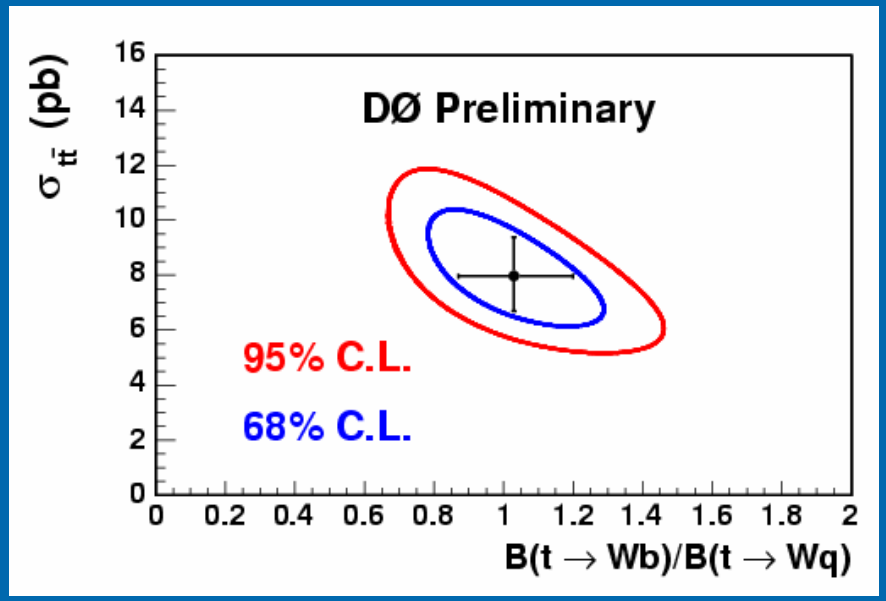
Measurement: count b-jets.
The number of b-jets depends strongly on R and the tagging efficiency.



- Result is obtained from a binned maximum likelihood fit to data for $N_{jet}=3$ and $N_{jet}=4$
- Simultaneous fit to R and cross section

$Br(t \to Wb)=1$ and $\sigma_{tt}=7$ pb

Result



230 pb^{-1}

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

The most precise measurement to date hep-ex/0603002

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

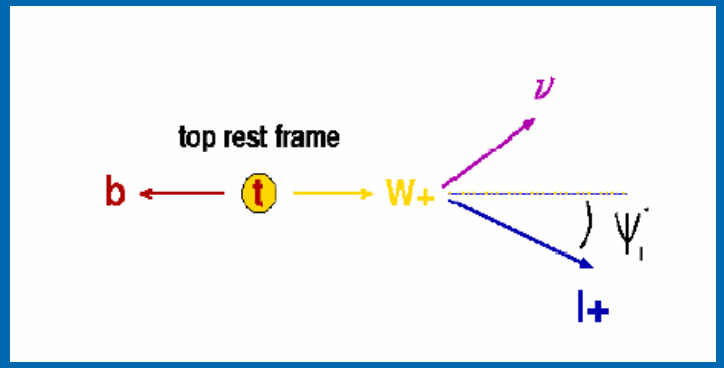
Model independent cross section measurement

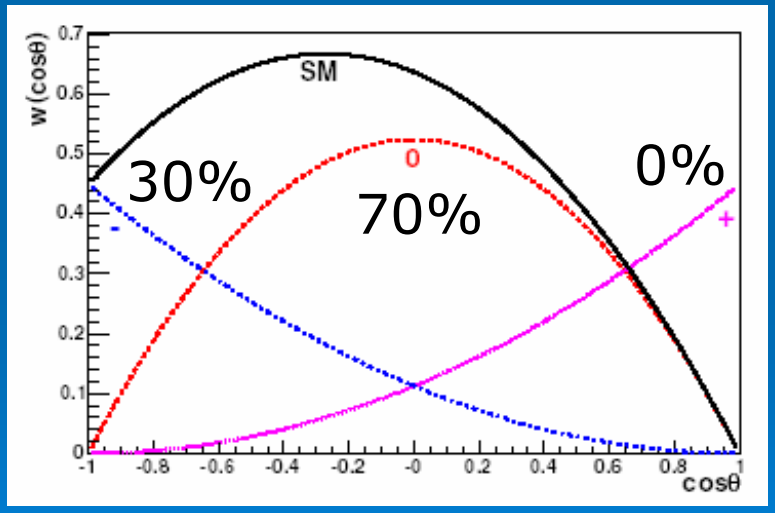
$$\frac{Br(t \to Wb)}{Br(t \to Wq)} = 1.12^{+0.21}_{-0.19}(\text{stat})\ ^{+0.17}_{-0.13}(\text{syst})$$

PRL 95, 102002

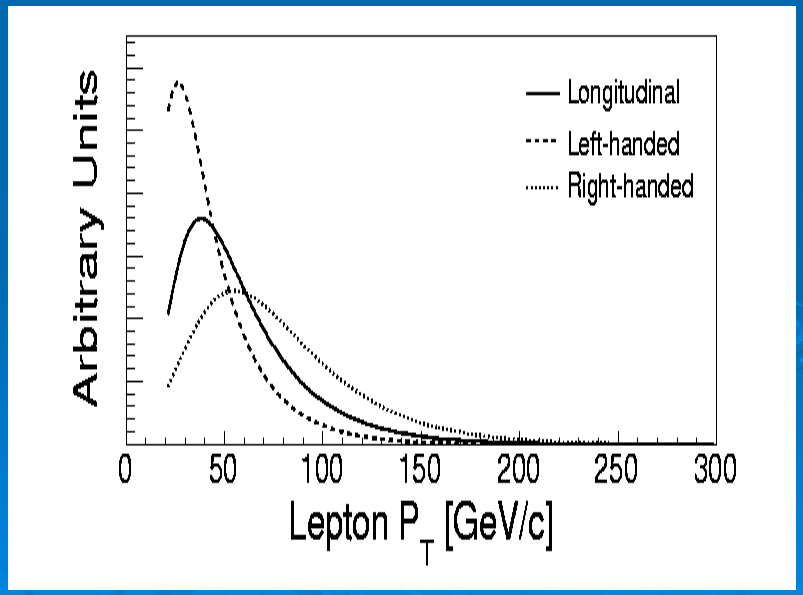
W Helicity from t→Wb Decays

- Examines the nature of the tWb vertex, probing the structure of weak interactions at energy scales near EWSB
- Stringent test of SM and its V-A type of interaction.
- Uses boosted W from top decays

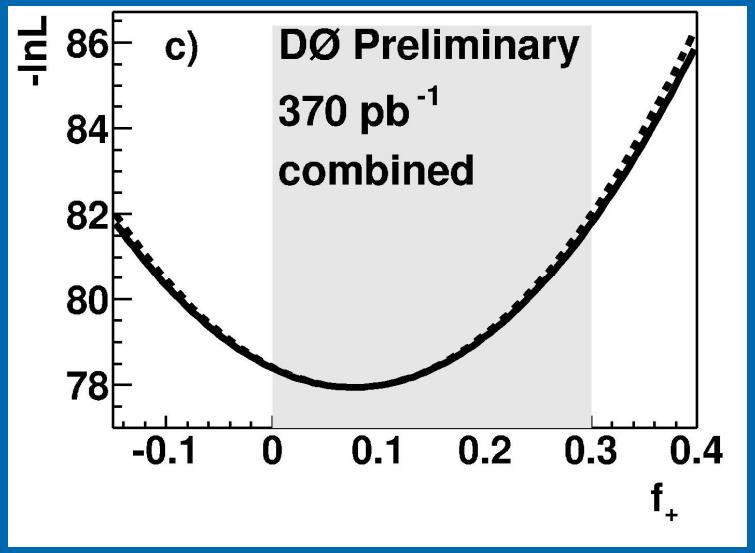


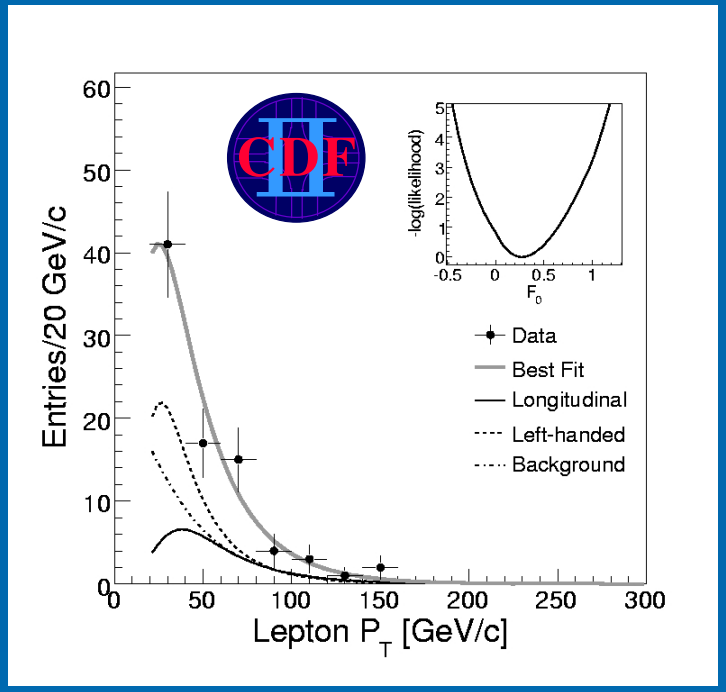


$$M^2_{l+b} = 1/2 \cdot (M^2_T - M^2_W)(1 + cos\psi^\star_l)$$



Results





M_{lb}
(l+jets + dilepton)

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

Update with respect to:
PRD 72, 011104 (2005)

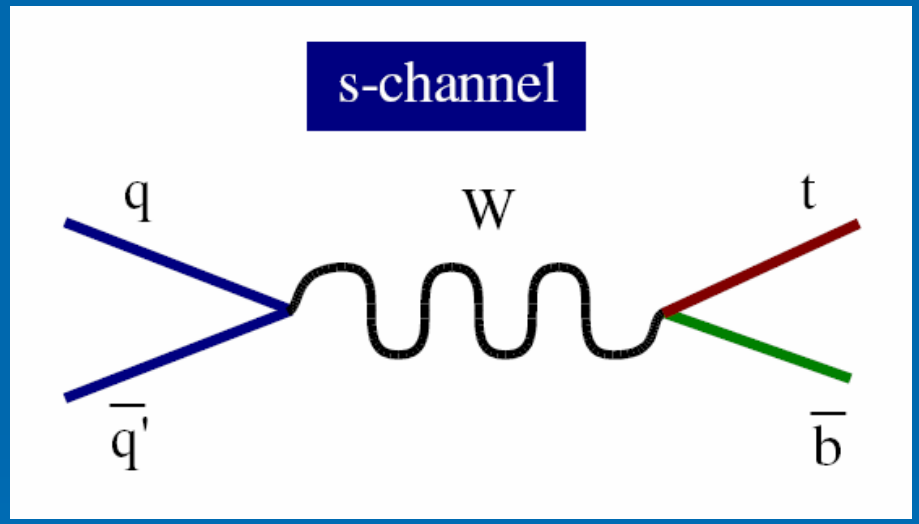
$$F^0 = 0.74^{+0.22}_{-0.34}(\text{stat} + \text{syst})$$

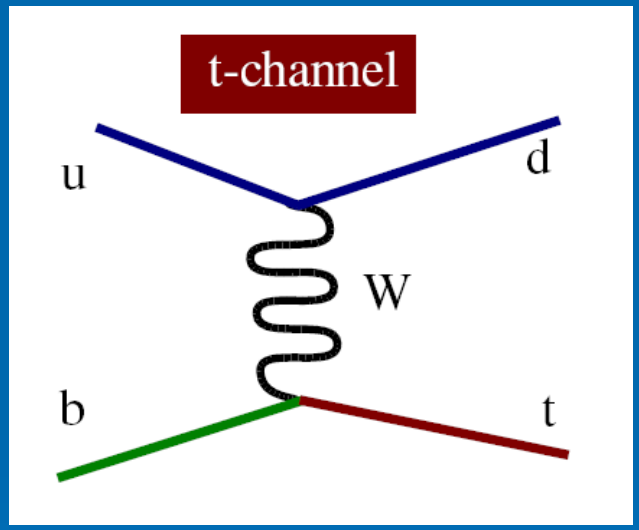
$$F^+ < 0.27 \ @ \ 95\% \text{ CL } (162/\text{pb})$$

M_{lb} + lepton pt
hep-ex/0511023

EW top quark production ("single top")

Not discovered yet





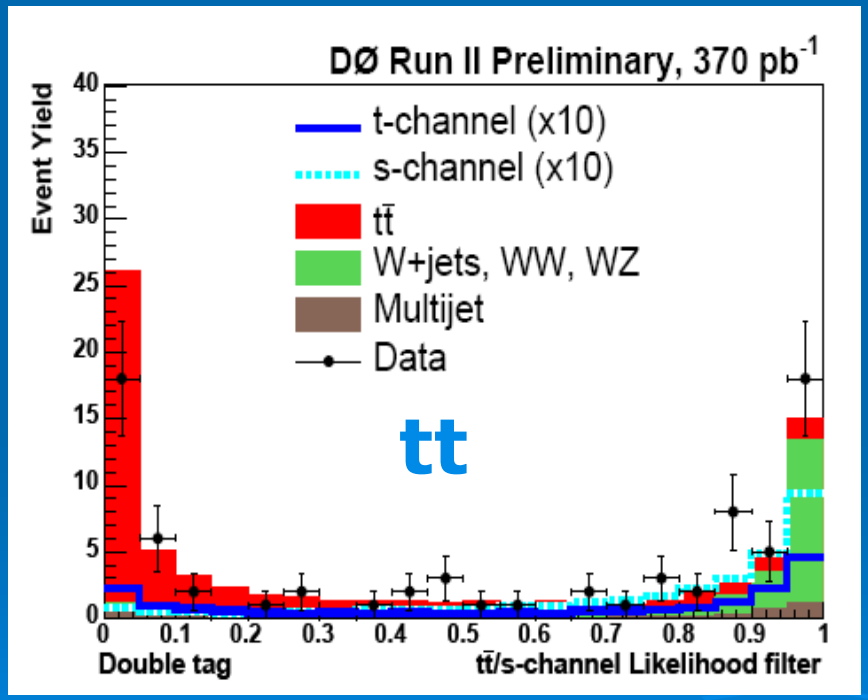
	s-channel	*t-channel*
NLO calculation:	**0.88pb (±8%)**	**1.98pb (±11%)**

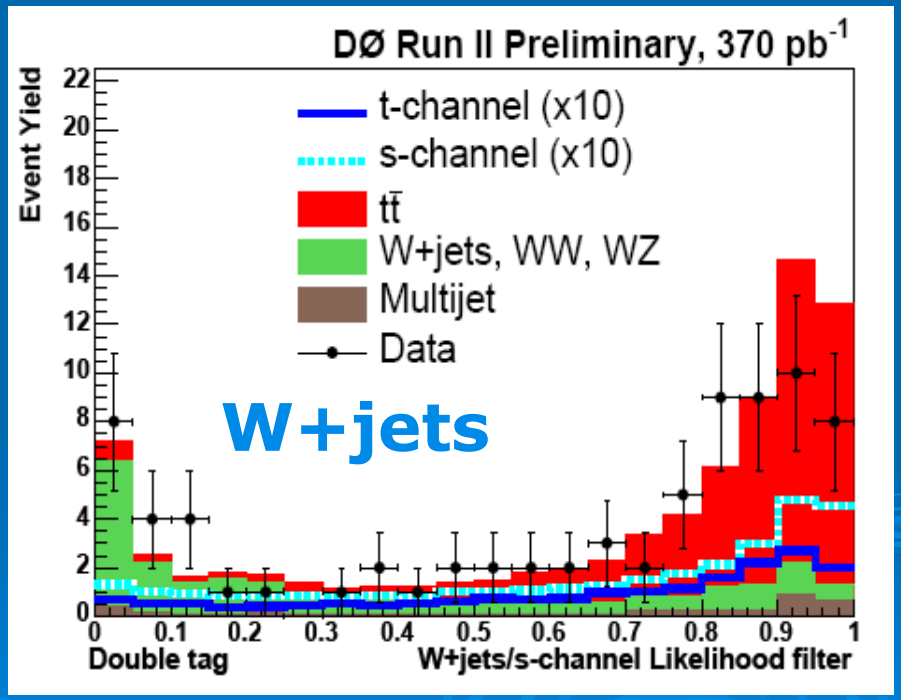
See also poster

Analyses

use of kinematical distributions to separate single-top from t-tbar and W+jets

Different approaches: discriminant / NN / decision trees





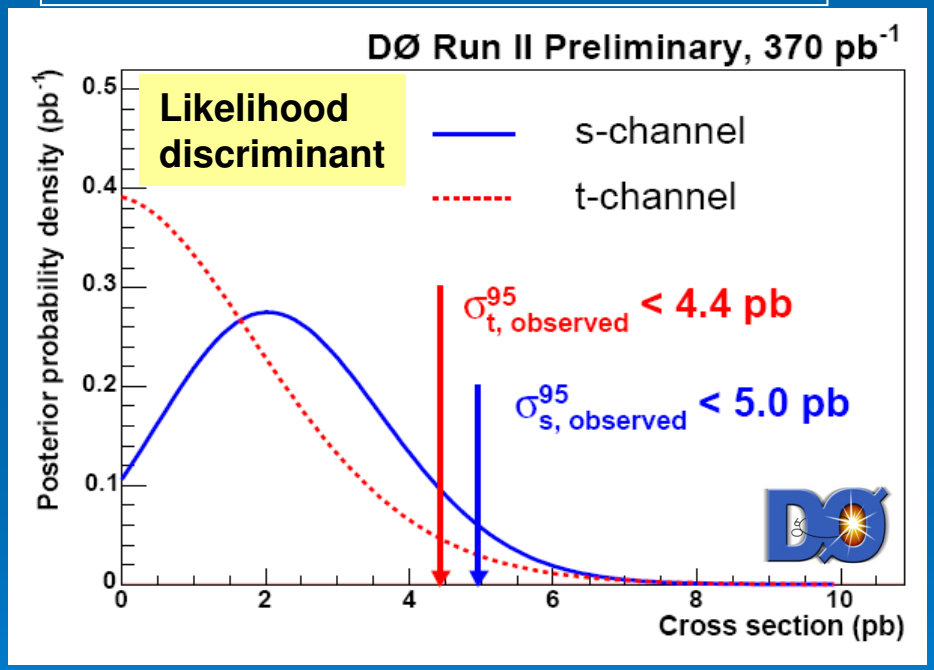
Results

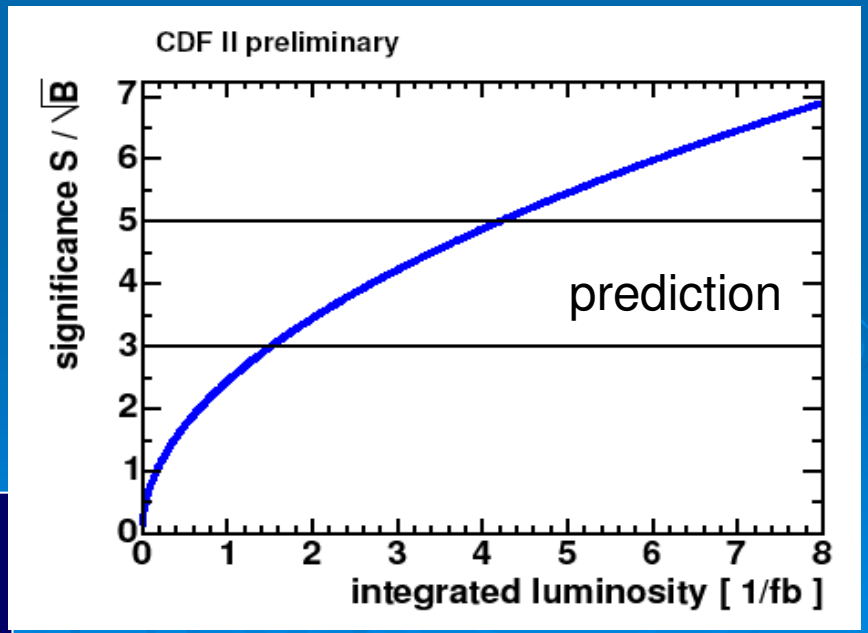
Latest results (370/pb) likelihood
s: < 5.0 pb @ 95% C.L.
t: < 4.4 pb @ 95% C.L.

Earlier limits published in PLB 622, 265 (2005)

Latest CDF results (695/pb) NN
s: <3.2 pb @ 95% C.L.
t: <3.1 pb @ 95% C.L.
s+t: <3.4 pb @ 95% C.L.

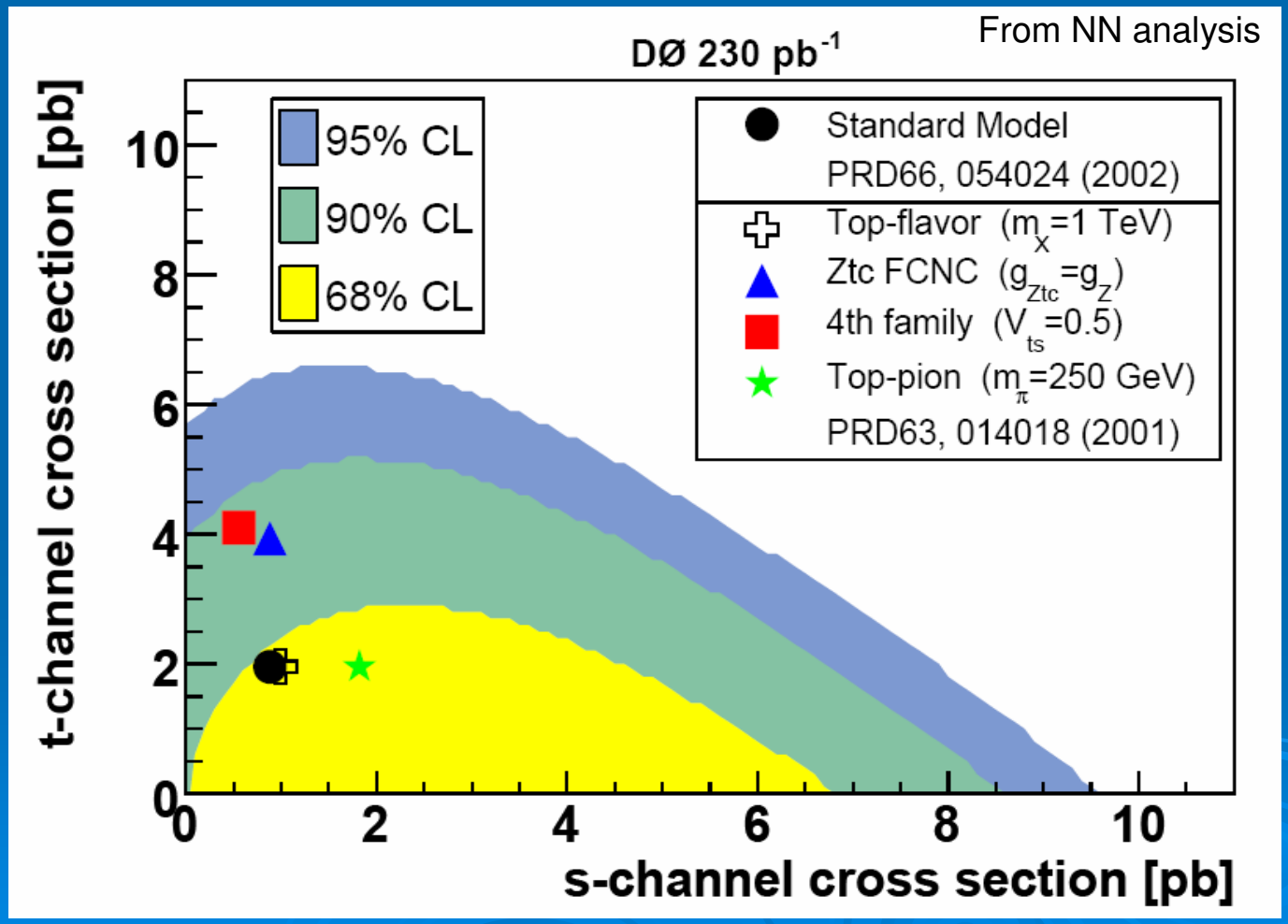
Earlier limits published in PRD 71 012005



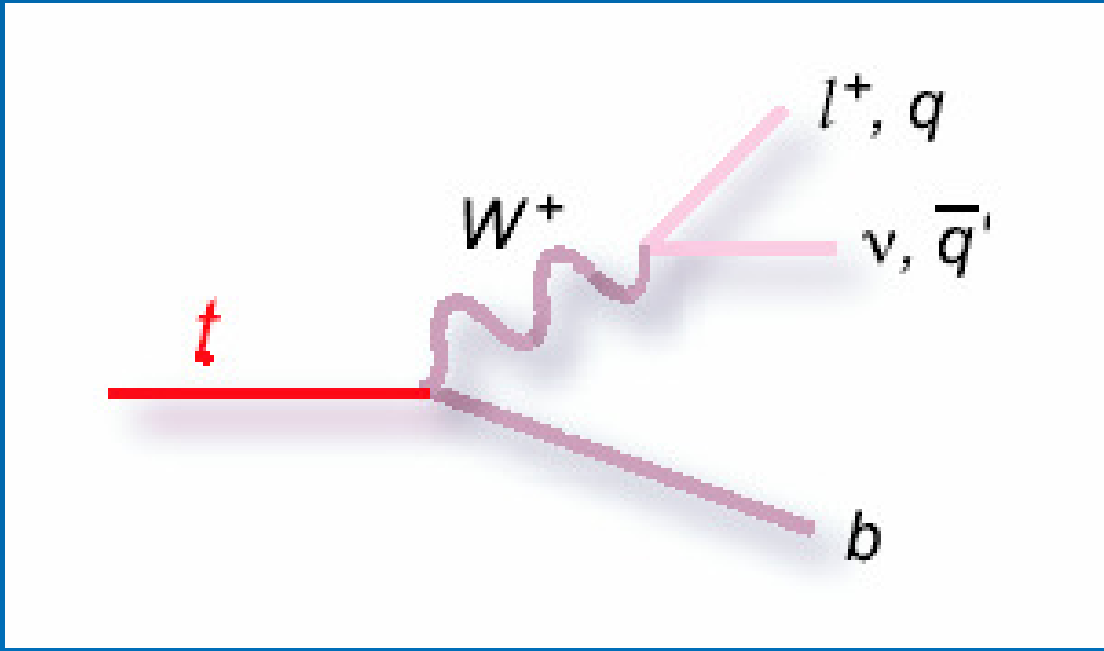


Limits will hopefully **not** decrease, but the signal significance increase

Single top searches probing new physics



Is the ‘top’ the SM top ?

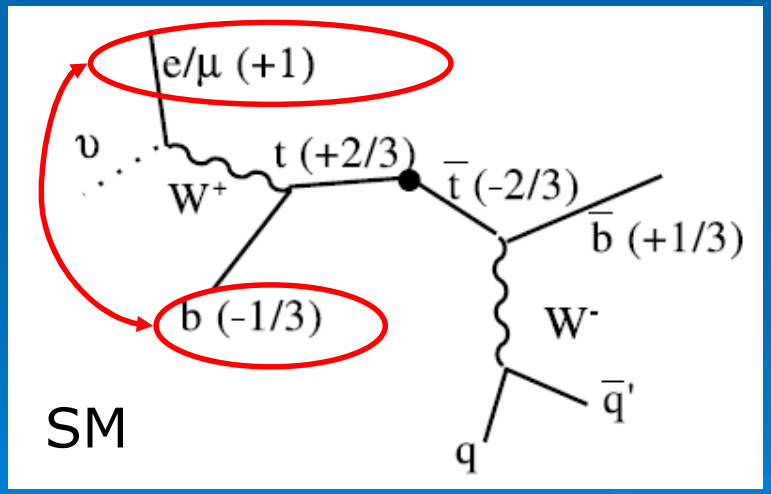


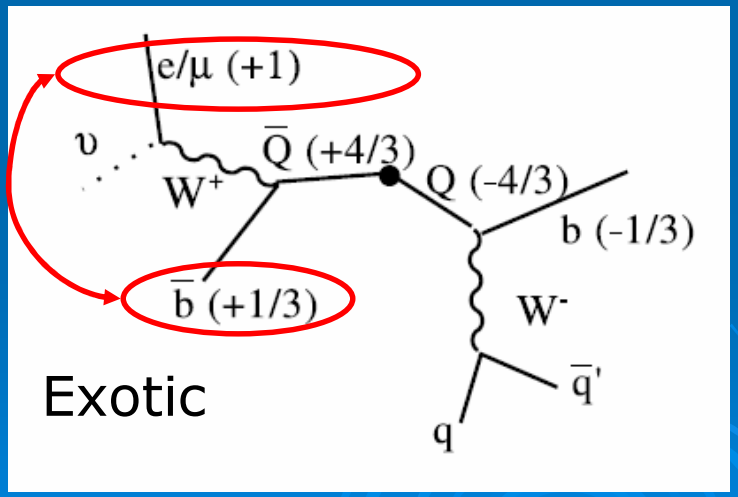
- charge
- lifetime

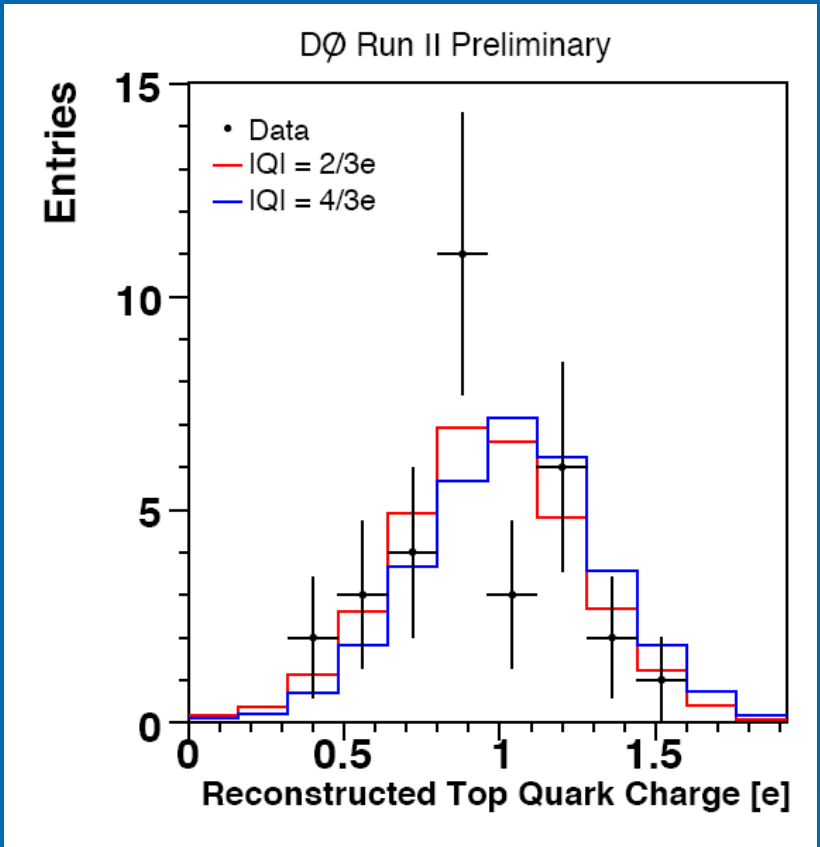
Top charge

See also poster

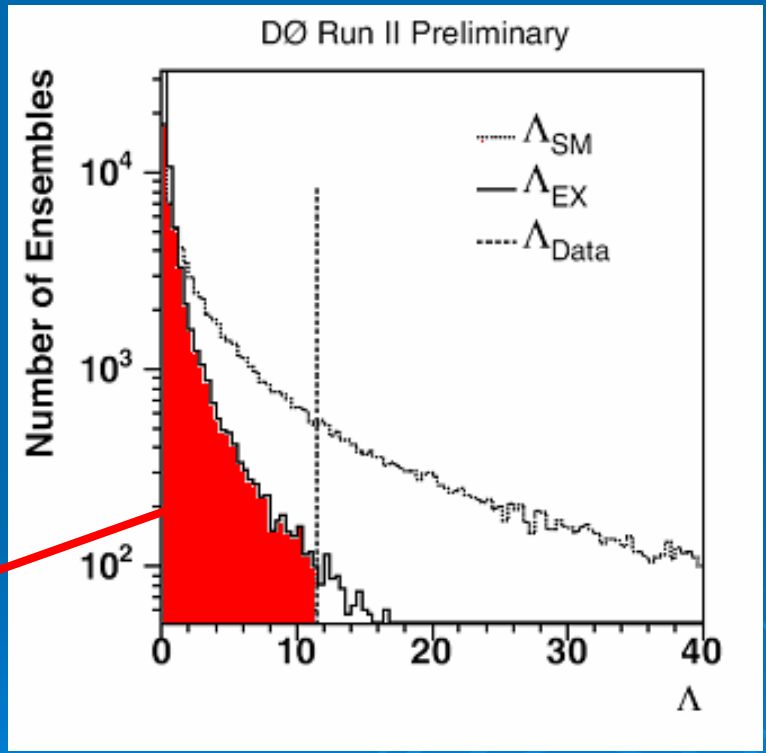
- A most fundamental quantity characterizing a particle
- Possible alternative to +2/3e (D.Chang etal PRD59, 09153(99))
  - Introduce an exotic 4th family $(Q_1,Q_4)_R$, with charge (-1/3,-4/3)
  - Q_4 is the "discovered top quark"
  - True top quark has a mass of ~270 GeV and escaped detection







$$\Lambda = \frac{\prod_i p^{\mathrm{sm}}(q_i)}{\prod_i p^{\mathrm{ex}}(q_i)}$$



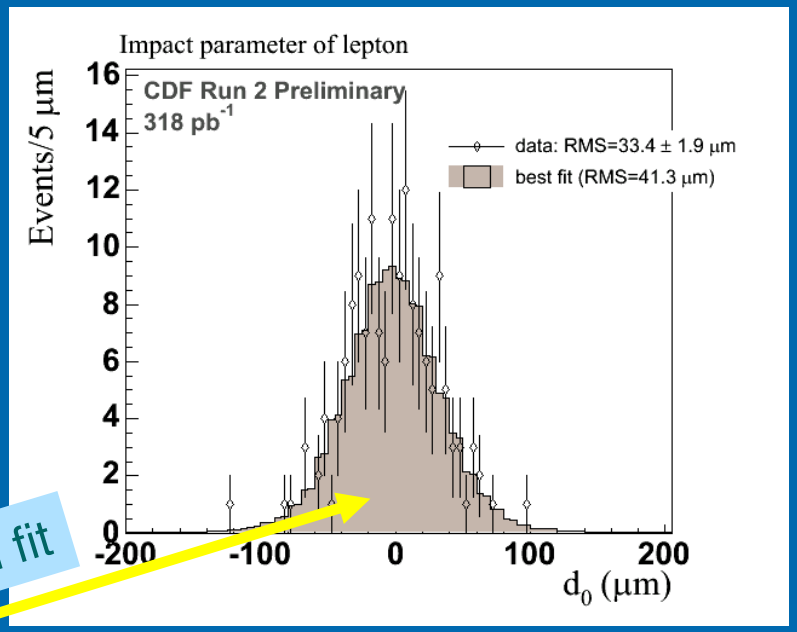
93.7% $\Lambda_{EX} < \Lambda_{data}$

top lifetime

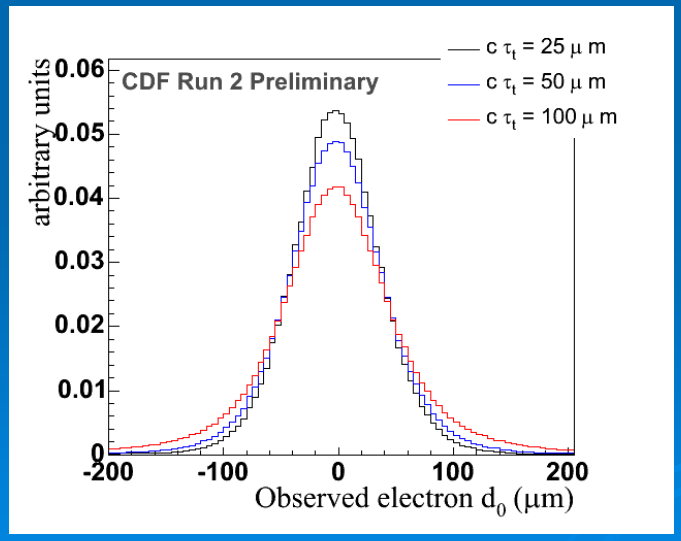
Lepton + jets channel with 1 tagged jet

Primary Vertex constrained by jets

Measure the lepton impact parameter



Likelihood fit

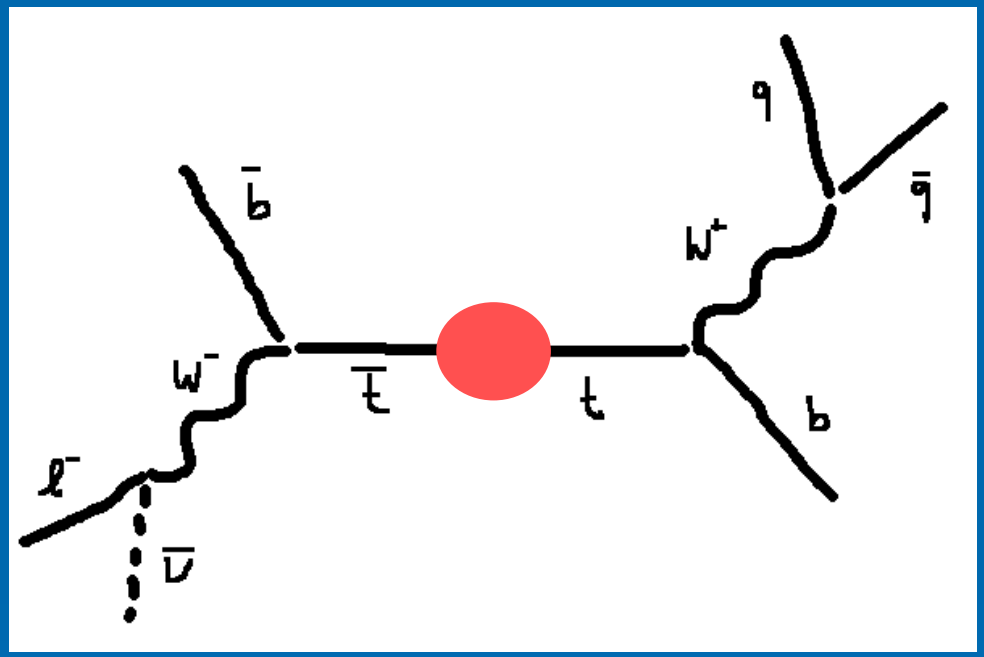


Maximum likelihood for $c\tau_{top}$=0 μm

$$c\tau_{top} < 52.5\mu m \quad \text{at } 95\% \text{ CL}$$

SM: 3×10^{-10}μm

Is there more than the top ?

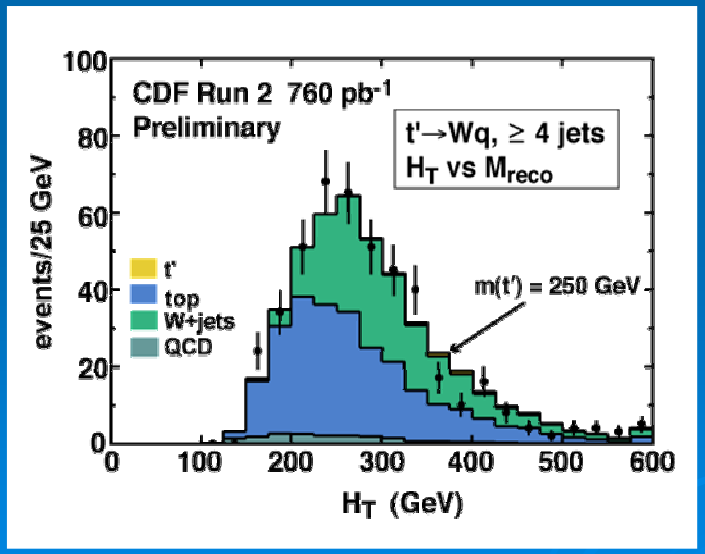


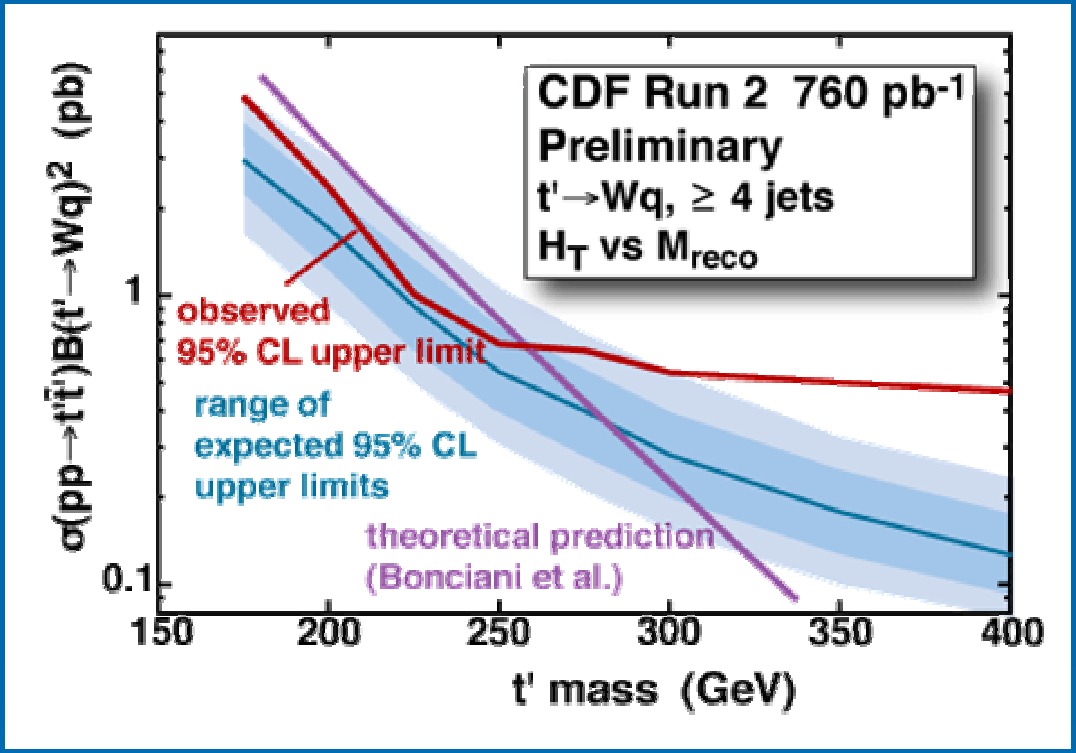
- t-prime
- resonamces

Search for a t' - > Wb

Search for a heavy
4th generation quark
(He etal. Hep-ph/0102144)

Template fit in (H_T, M_T)



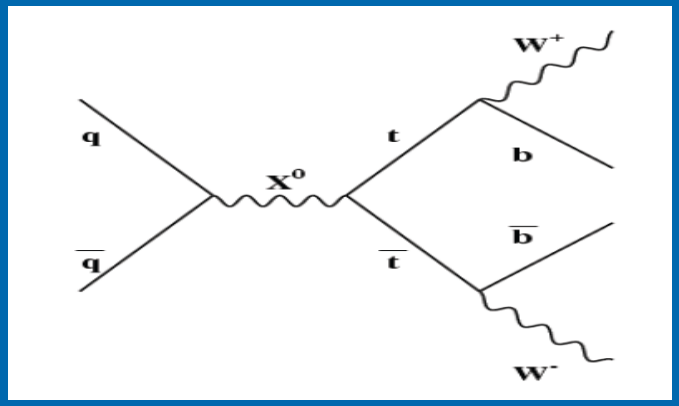


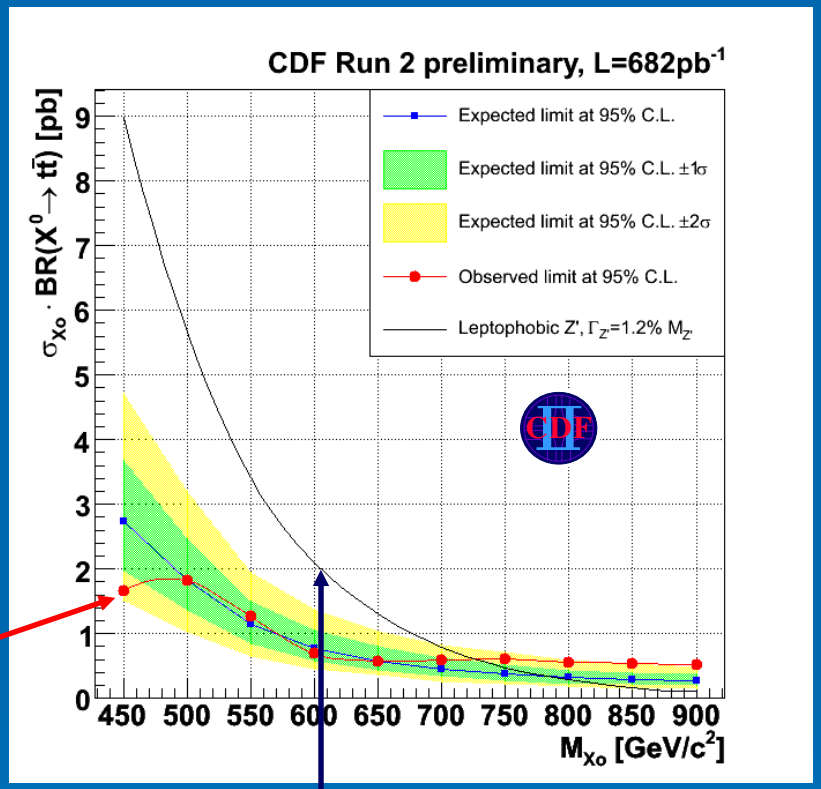
Lower limit on the t' mass of 258GeV/c^2 at 95% C.L.

Expect m(t')>300 GeV/c^2 with 2/fb, unless…

t-tbar resonances in *l+jets*

Search for a resonance in the t-tbar invariant mass spectrum





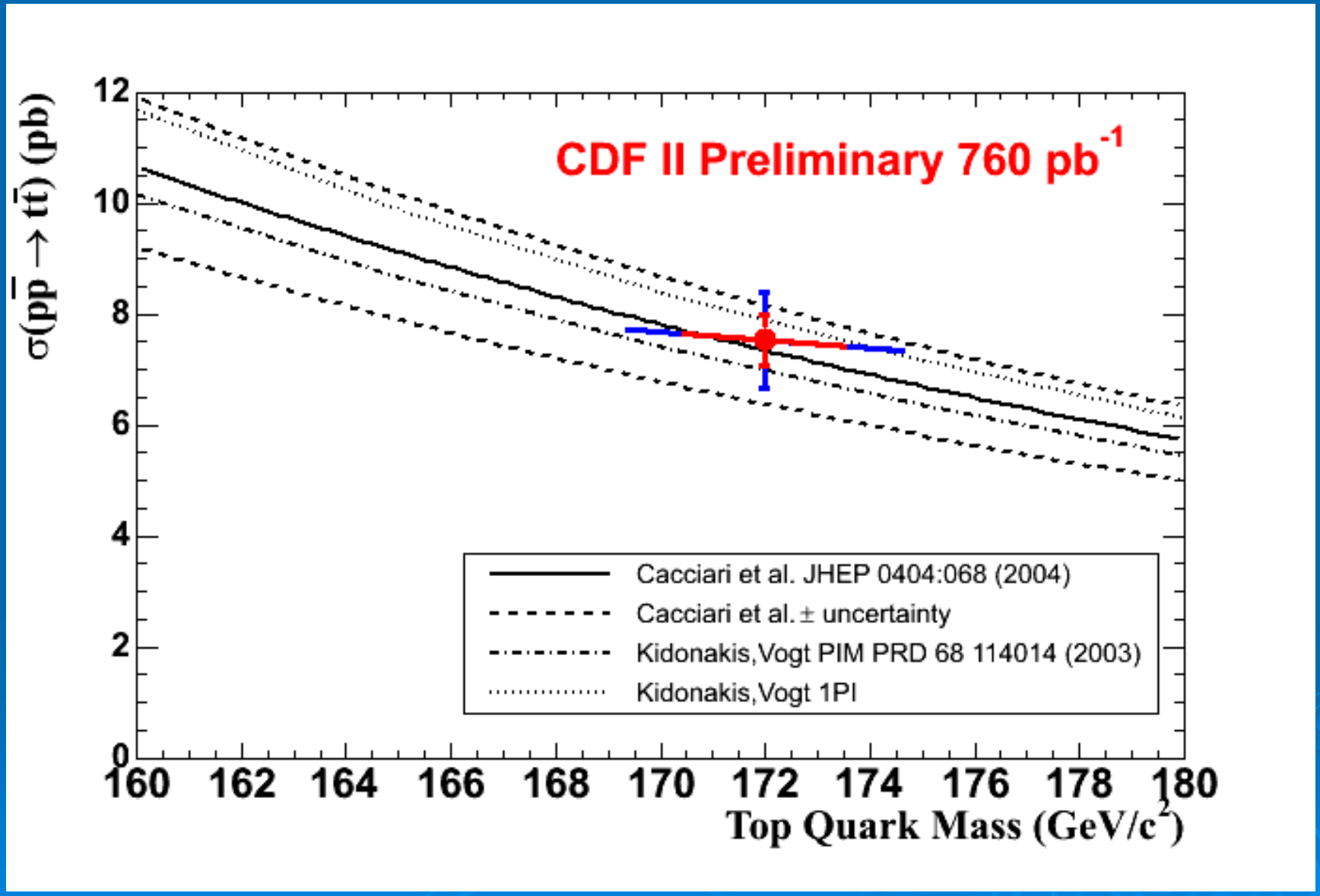
Result: upper limits

- Model exclusion: narrow leptophobic Z' with Γ=1.2%$M_{Z'}$
  - CDF: exclude M(Z')<725GeV/c^2
  - D0: exclude M(Z')<680 GeV/c^2

Conclusions

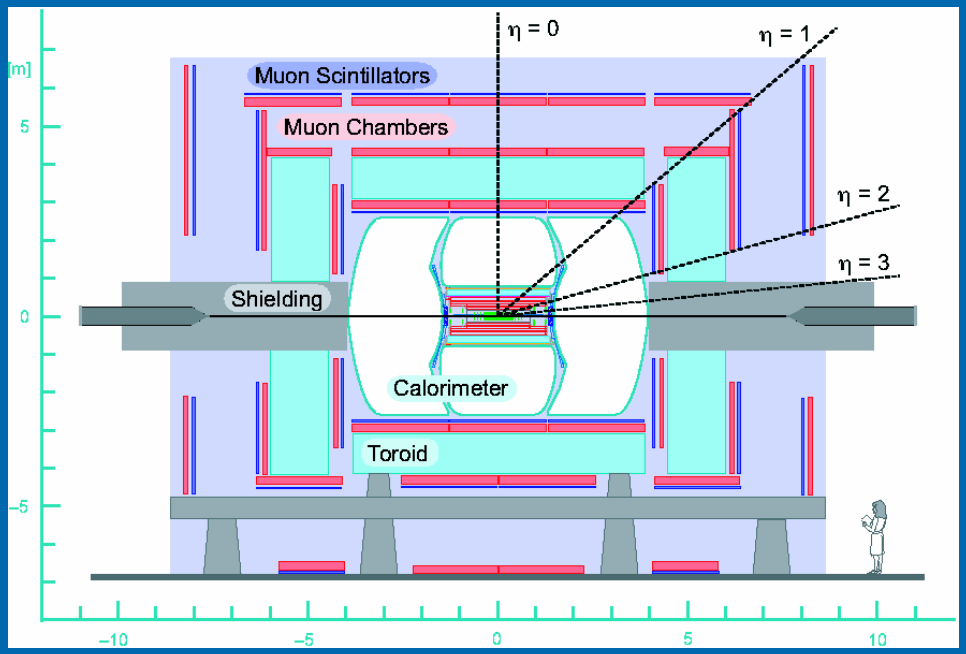
- Top turns eleven, we are now in the precision era of top physics
- Top production is consistent with the standard model expectation. There is still space for anomalies.
- Detailed studies of EW from the tWb vertex
- Single top (EW production) to be discovered
- Searches for exotics

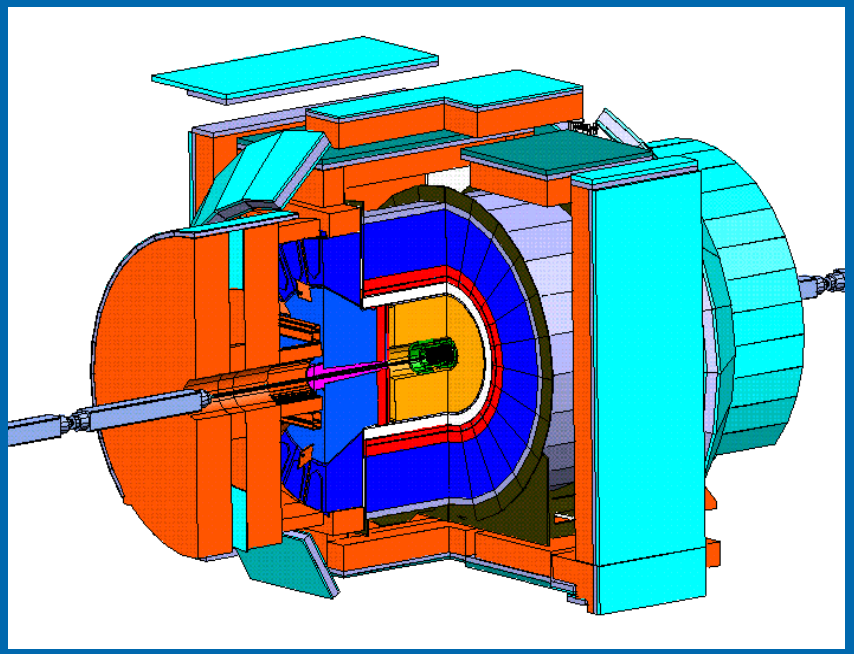
Understanding top quark production and properties will be crucial for success at LHC. What we learn at the Tevatron, both physics and analysis tools, extends directly to LHC!


CDF II Preliminary 760 pb^{-1}
$\sigma(p\bar{p} \to t\bar{t})$ (pb)
Top Quark Mass (GeV/c^2)
Cacciari et al. JHEP 0404:068 (2004)
Cacciari et al. ± uncertainty
Kidonakis,Vogt PIM PRD 68 114014 (2003)
Kidonakis,Vogt 1PI
0
2
4
6
8
10
12
160
162
164
166
168
170
172
174
176
178
180

20 nations
92 institutions
~700 physicists

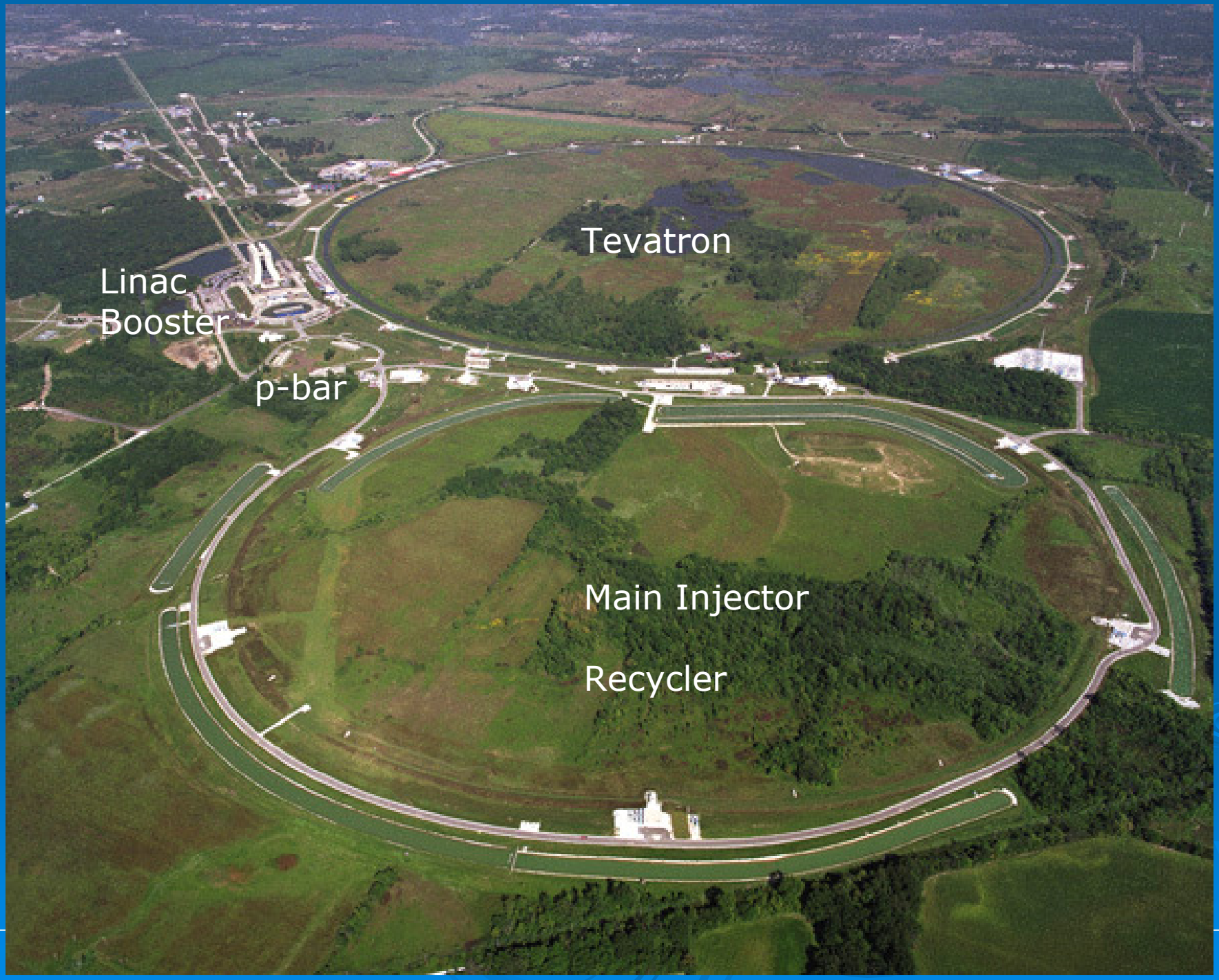
12 nations
60 institutions
~800 physicists



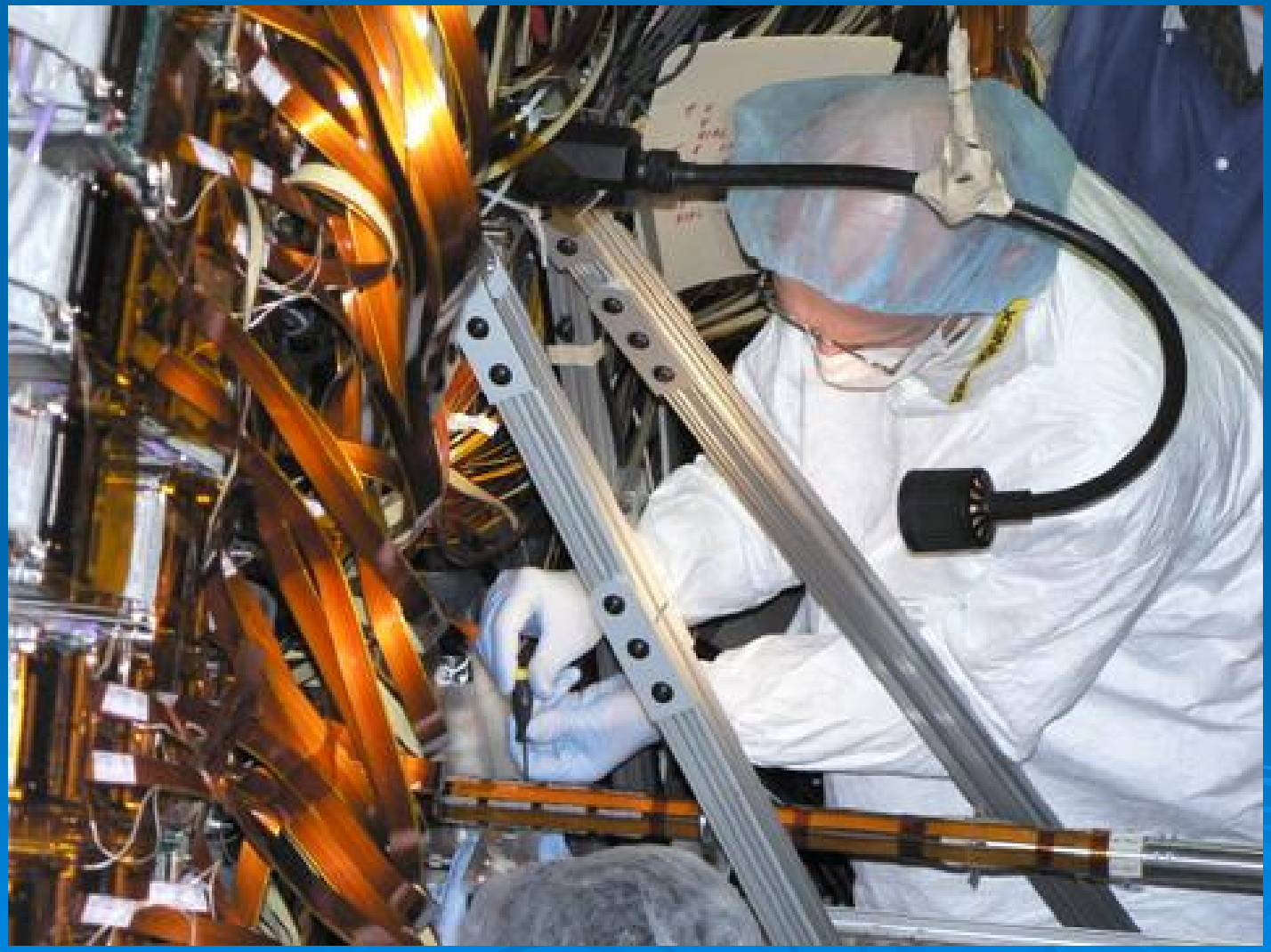


- 8 layer silicon
- 16 layers scintillating fibers
- 2T Solenoid
- Calorimeter:
  Cental + EndCap
- 1.8T Toroid
- 3 layers muon scintillator + drift tubes

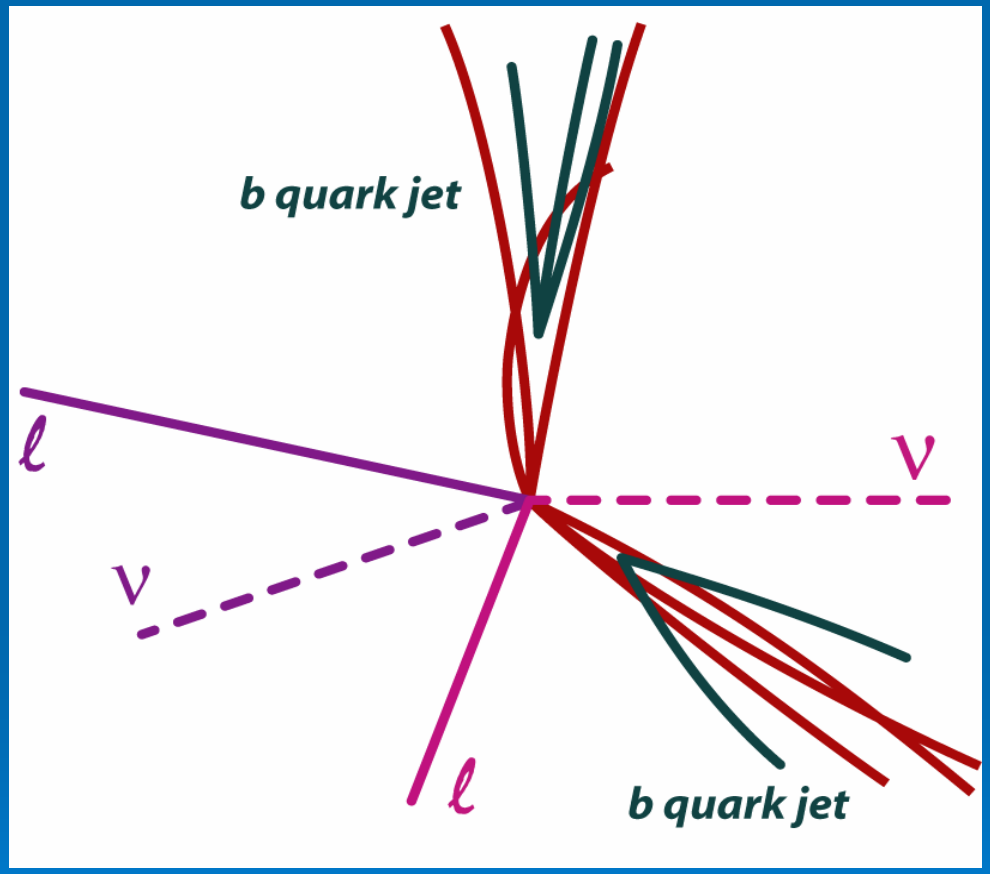
- Silicon detector
- COT: drift chamber
- Solenoid
- Calorimeters:
  Central, wall, plug
- Muon:
  scintillator + chamber

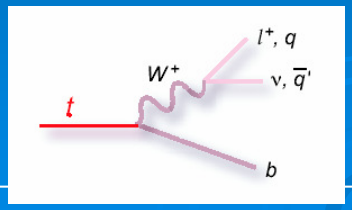

Tevatron
Linac
Booster
p-bar
Main Injector
Recycler

Layer 0 installed at DZero!



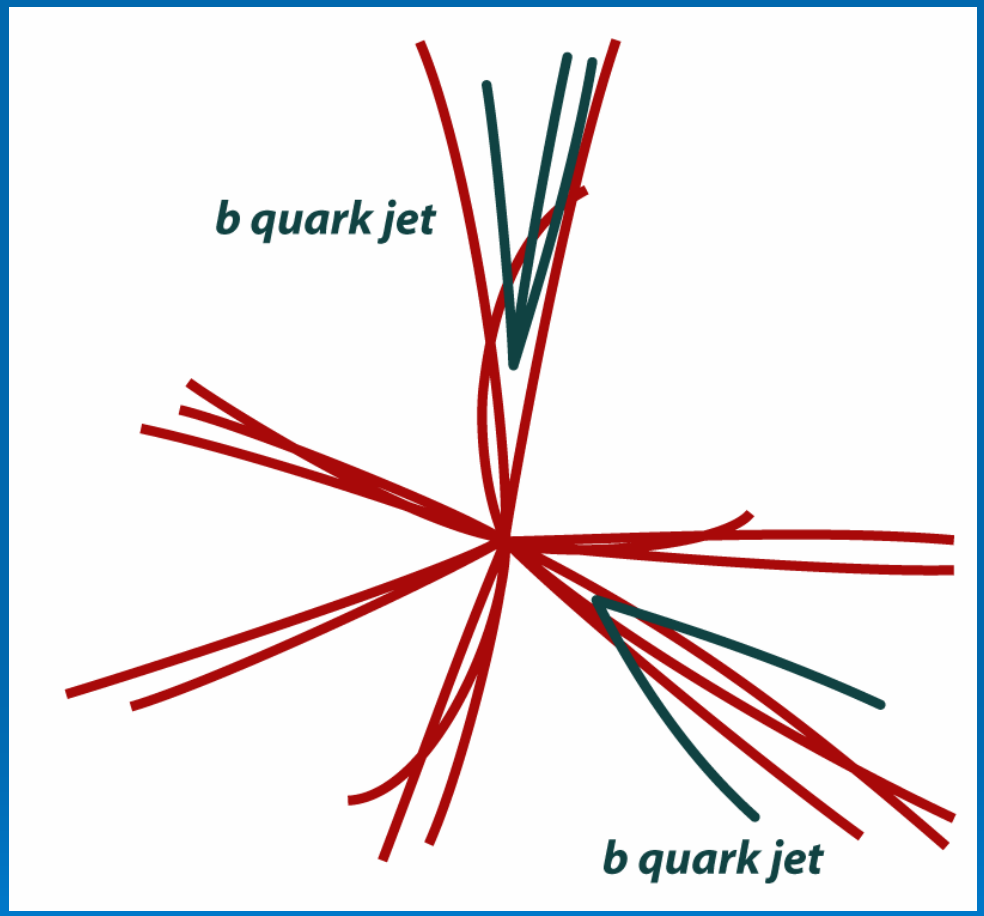
Dilepton channel(s)



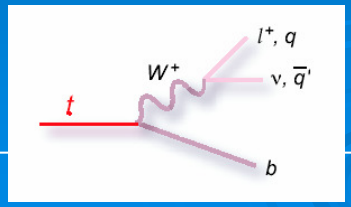


- Features:
  - Small *Br*
  - Small background
- Selection
  - Jets with E_T > 15GeV
  - Two charged opposite sign leptons pT>15 GeV
  - Or 1 lepton and one track
  - E_{tmiss} and additional selection optimized by channel
- Backgrounds
  - WW/WZ, $Z/\gamma^* \rightarrow \tau\tau \rightarrow ll$
  - fake E_{tmiss} in DY or fake leptons in multijet

All hadronic channel

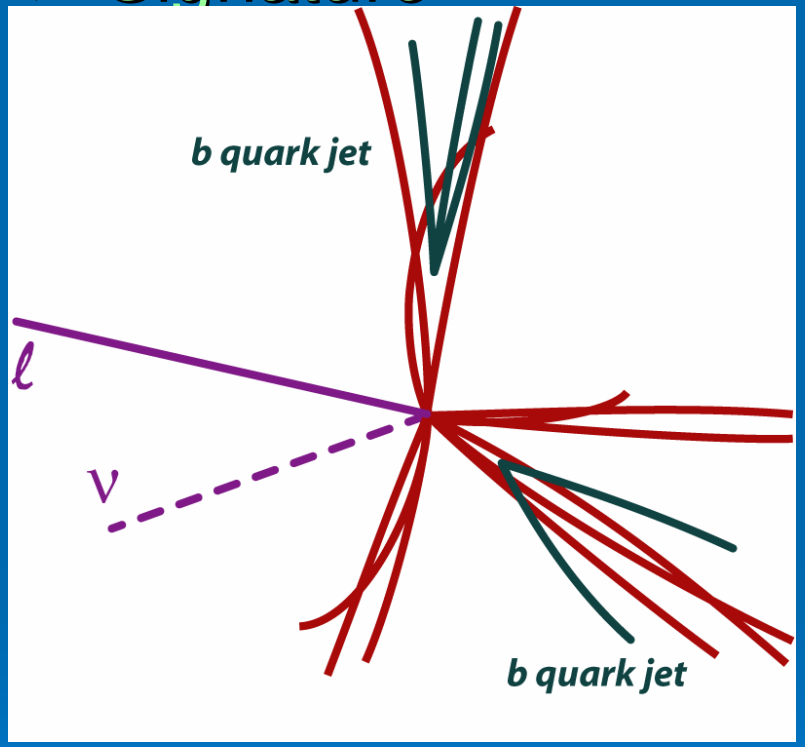


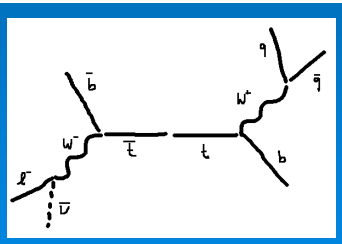
- Features:
  - Large *Br*
  - Large background (S/B~1/300)
  - Need b-jet tagging
- Selection
  - At least six jets pT>15 GeV
  - 1 hard primary vertex
  - >3 jets assigned to it
  - ΔR(tagged jets)>1.5
- Backgrounds
  - multijet production



Lepton+jets channel

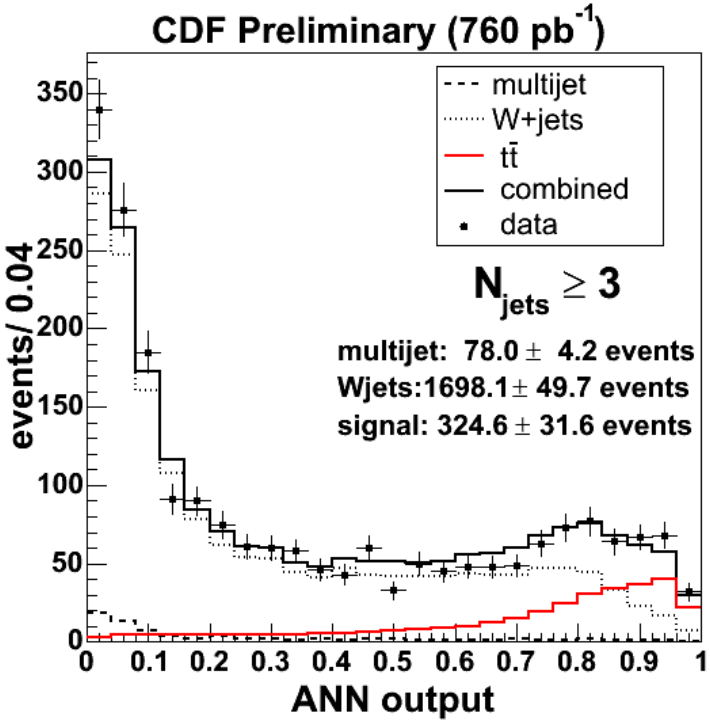
- Signature





- Features:
  - Relatively high *Br (29%)*
  - Manageable background
  - Perfect for studies of top properties
- Selection
  - One isolated pT>20 GeV
  - ≥ 3 jets with pT>15 GeV
  - ≥ 1 jet with b-tag
  - E_{Tmiss}>20 GeV
- Backgrounds
  - W + jets
  - Multijet

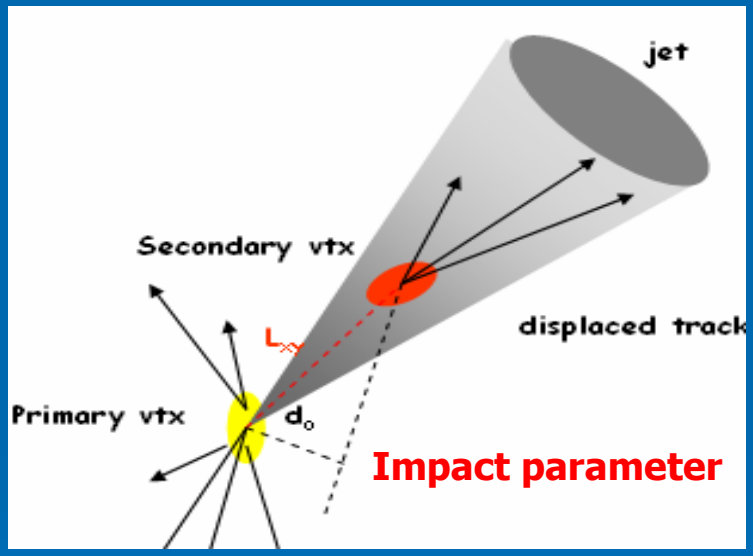
topological X-section



CDF Preliminary (760 pb^{-1})

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

b-jet tagging



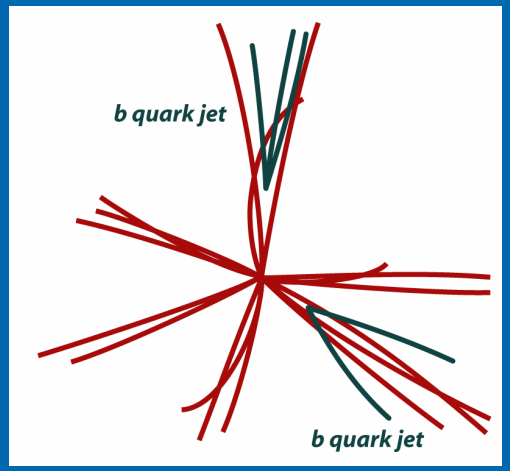
Both CDF & D0 use Secondary Vertex b-tagging algorithm to reduce the W+jet background for top events (require tagged jets)

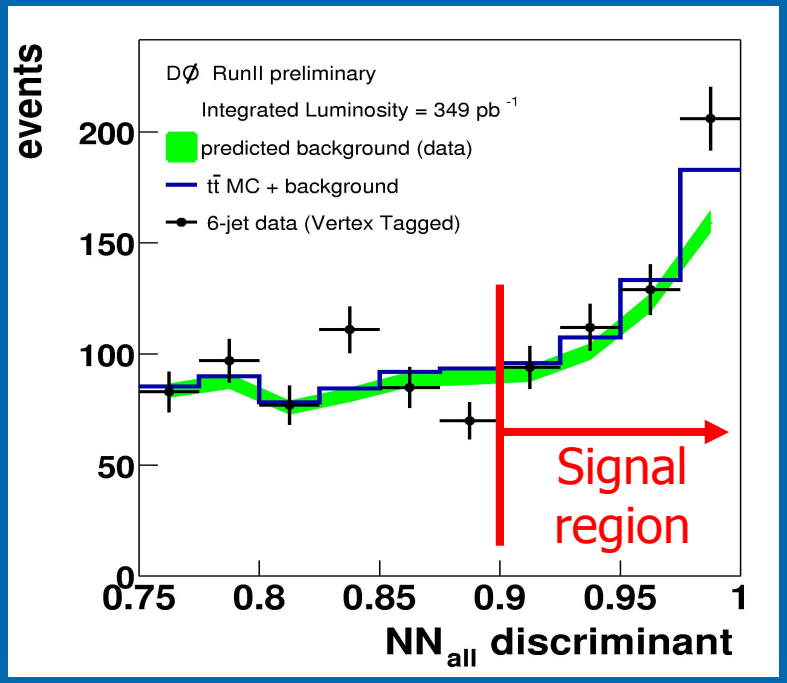
b-quark lifetime
$c\tau \sim 450\mu m$

$\rightarrow$ B hadrons travel ~3 mm before decay

All jet

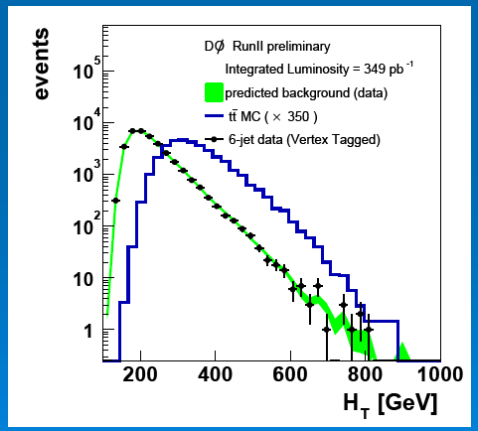
High yield, high BG





350/pb

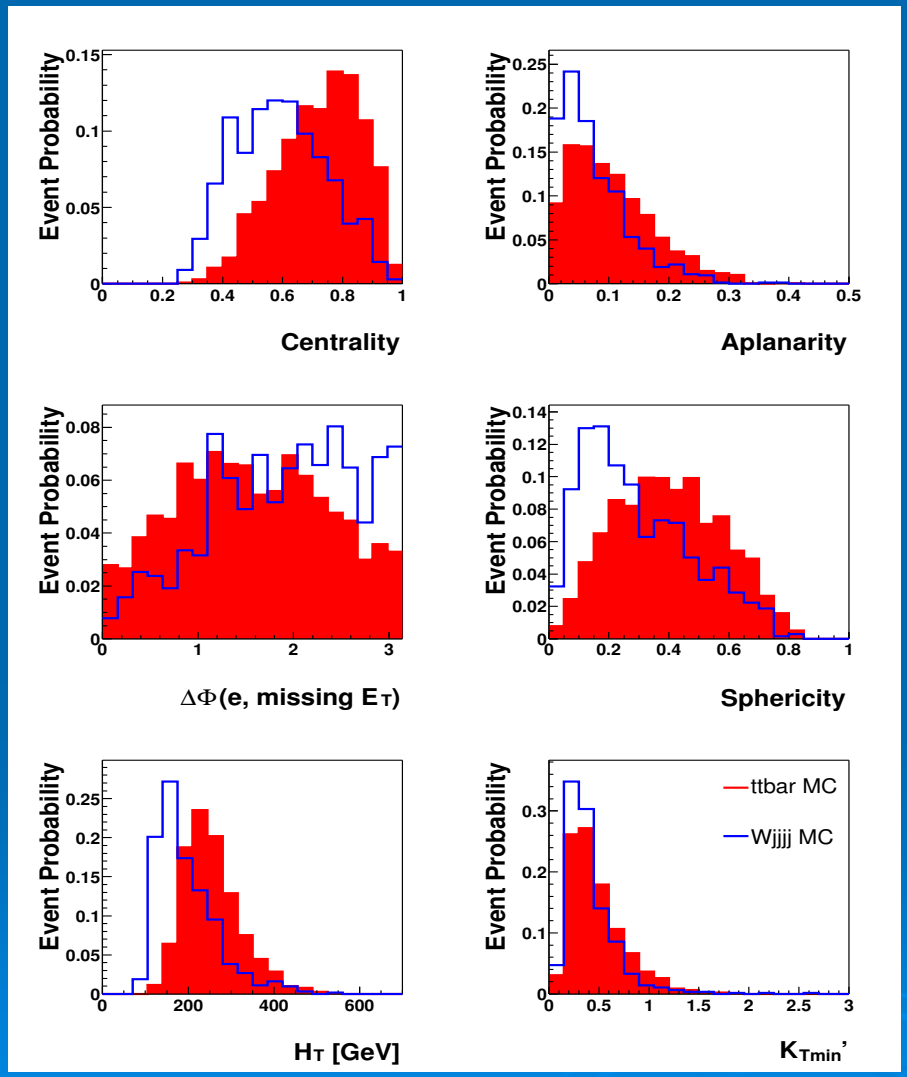
NN
H_T plus 5 more variables



NN>0.9 $N_{obs} = 541$
$N_{Predict} = 494 \pm 8$

$$\sigma_{t\bar{t}} = 5.2^{+2.6}_{-2.5}\,(\text{stat})^{+1.5}_{-1.0}\,(\text{syst})\text{pb}$$

Discriminating variables



Top events are

- Energetic
  - H_T
- Central
  - Centrality: H_T/H
- Spherical
  - Aplanarity (large $A \Rightarrow$ spherical events)
  - Sphericity (large $S \Rightarrow$ isotropic events)
- $\Delta\varphi(l, E_{TMiss})$
- k_{Tmin}
  - measure of minimum jet p_T relative to another

Discriminant function

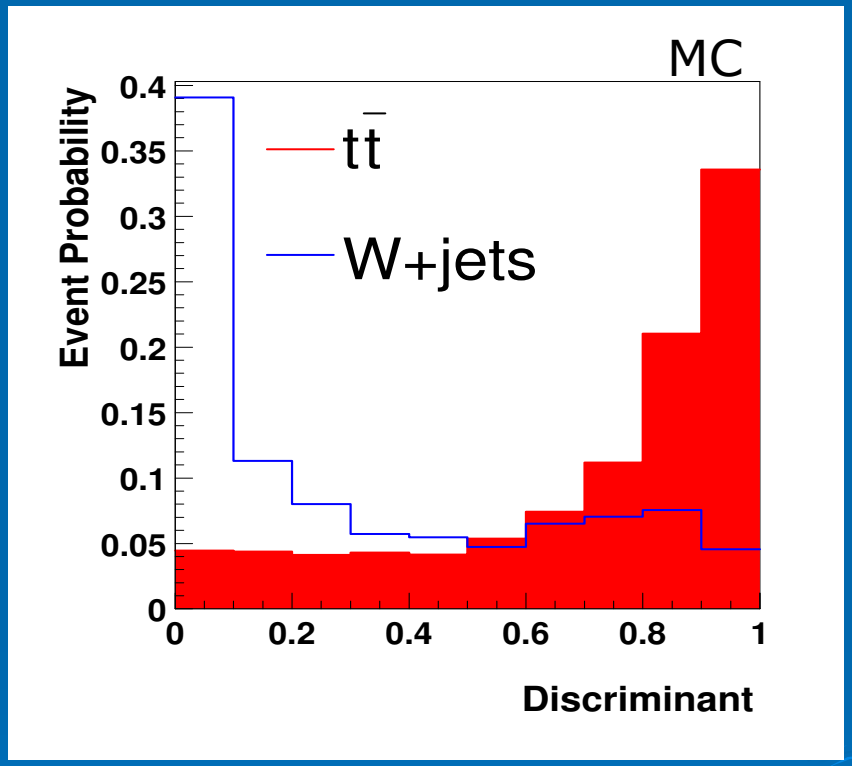
$$D = \frac{S(x_1, x_2, \ldots)}{S(x_1, x_2, \ldots) + B(x_1, x_2, \ldots)}$$

S , B – probability density functions for signal and background

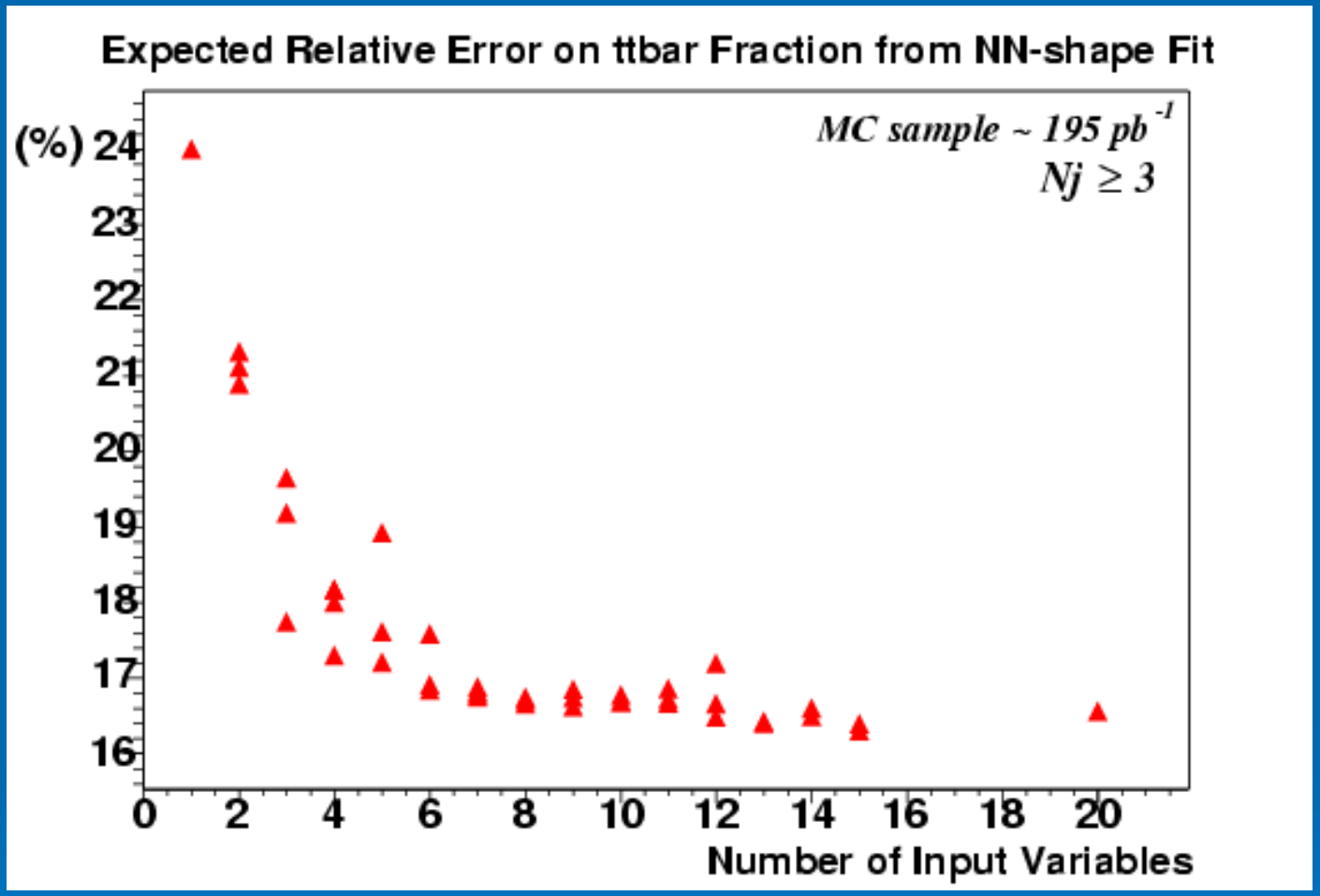
x_1 , x_2 ,… – a set of input variables

For uncorrelated variables

$$\approx \frac{\exp(\sum_i (\ln \frac{s_i}{b_i}))}{\exp(\sum_i (\ln \frac{s_i}{b_i})) + 1}$$

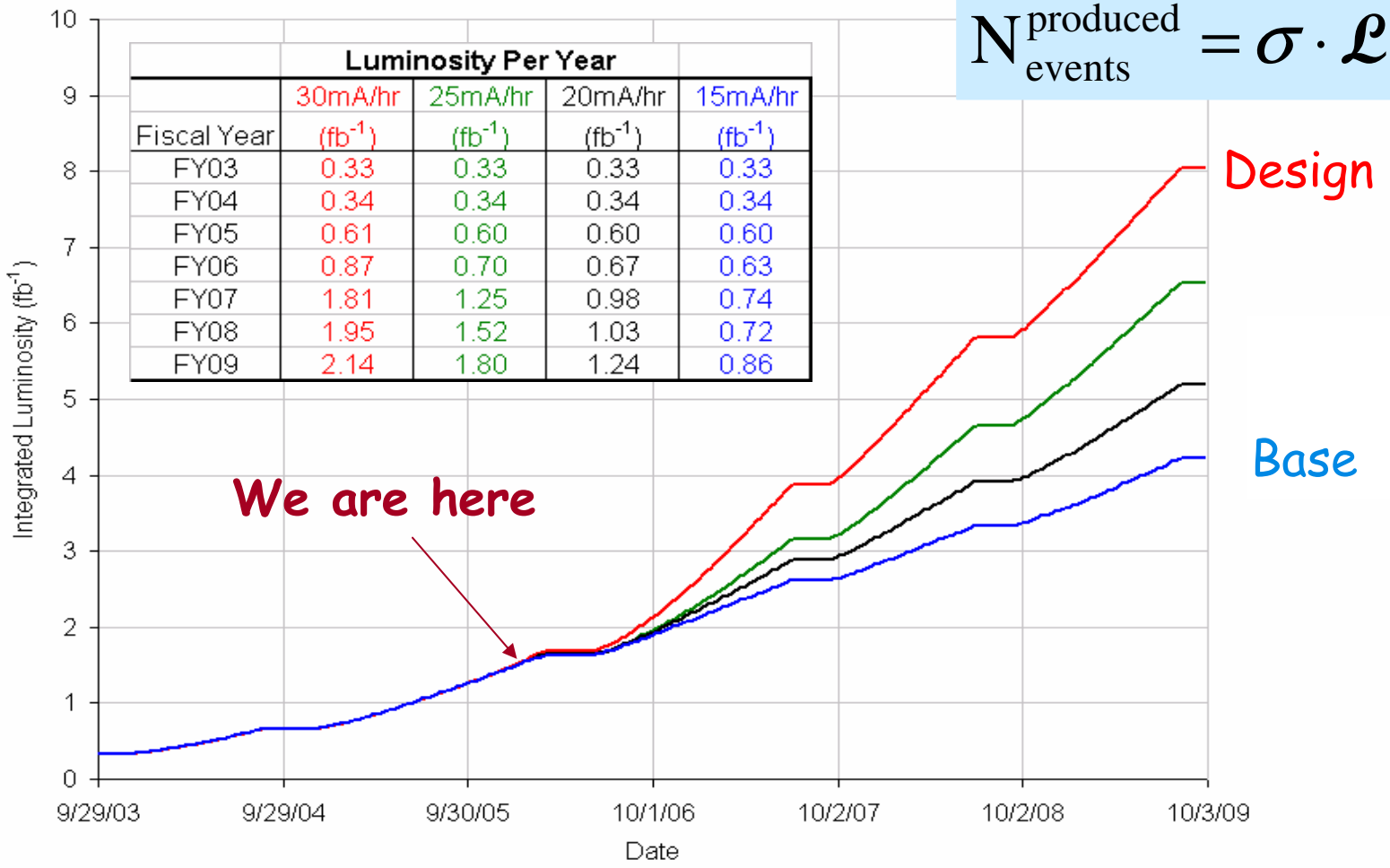


(Only W+jets used in the discriminant as the kinematic properties of multijet are similar)



Adding more event information allows better discrimination of top events.

Integrated Luminosity

$$N_{\text{events}}^{\text{produced}} = \sigma \cdot \mathcal{L}$$

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