Top Quark Physics – 10 years later

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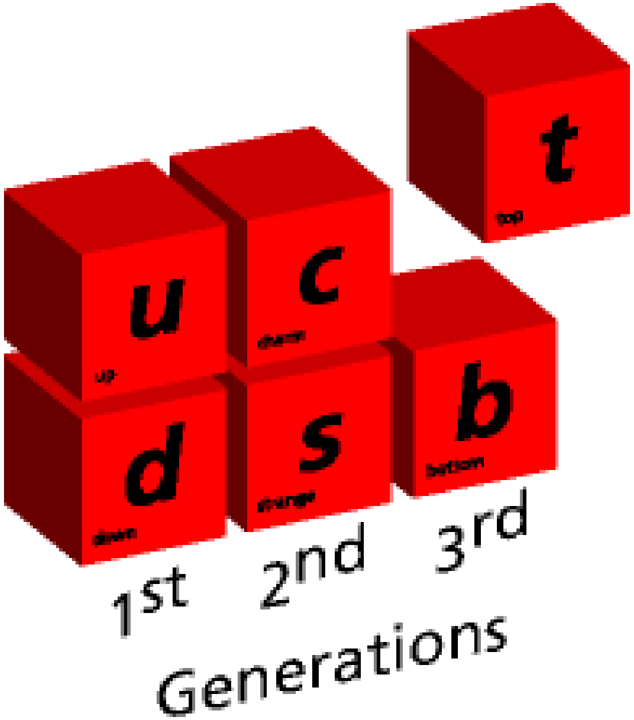
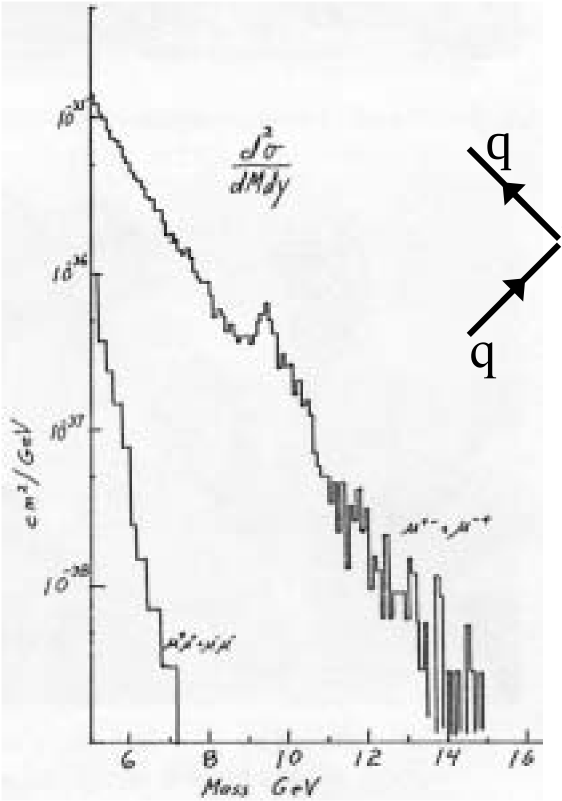
The top quark in the Standard Model

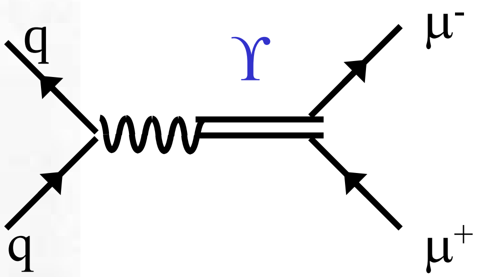
- The 6th quark
  - Last of 6 to be discovered
- The isospin partner of the b-quark
  - Important in loop cancellations
- The heaviest known fundamental particle
  - Mass ~175 GeV
- The last quark?
  - Z decays prove no 4-generation of light neutrinos with SM couplings
- Mass is not a parameter predicted by the SM

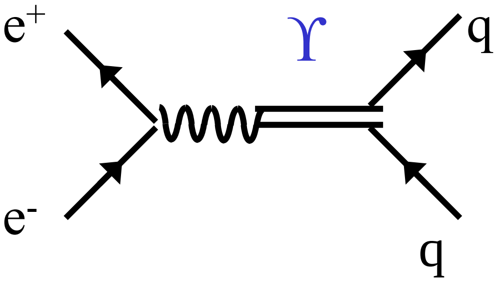


29 Years ago – discovery of the b-quark

- Like the charm quark, the bottom quark was first discovered in is QQ “onium state”
    - bb, J=1 state = Upsilon (ϒ)
- Fermilab experiment E288 (Leon Lederman)
    - $pp \rightarrow \Upsilon + X \rightarrow \mu^+\mu^-$
    - peak in $\mu^+\mu^-$ invariant mass
- Further study at DORIS (DESY) and CESR (Cornell)
    - $e+e- \rightarrow \Upsilon \rightarrow ff$
    - signature #1: resonant peak at Upsilon mass
    - signature #2: step in the ratio R=(had/muon)

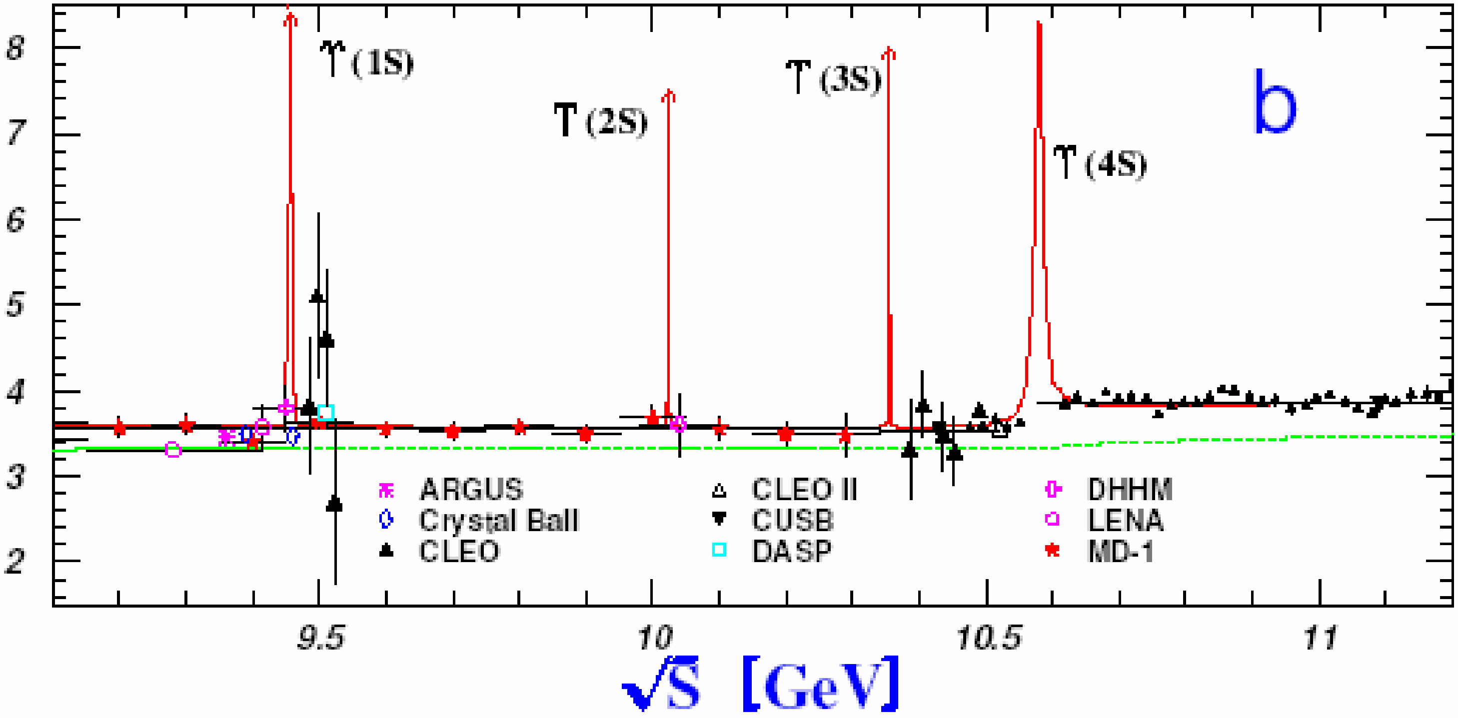






R in the b-threshold region

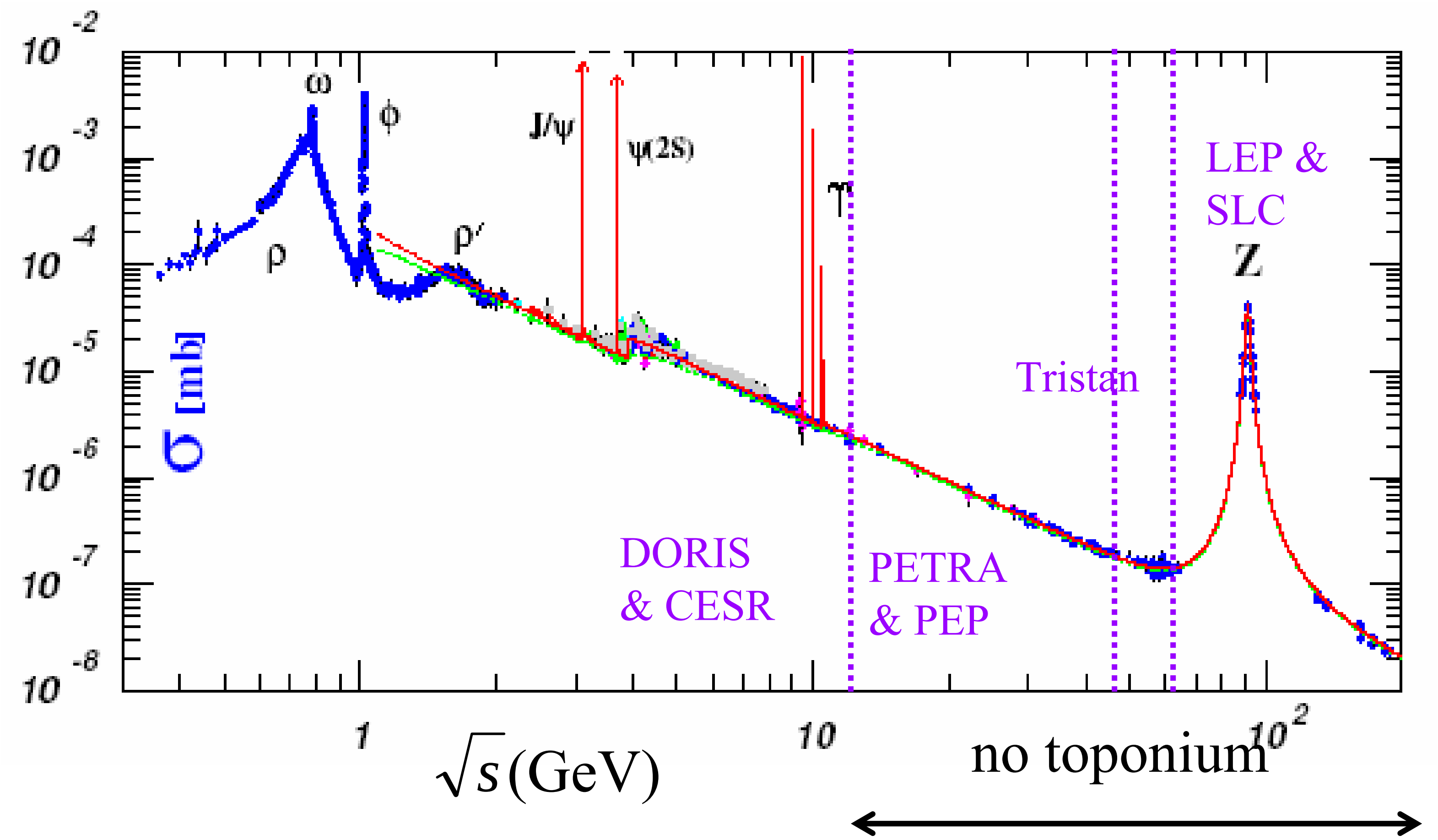
$$R = \sigma(e^{+}e^{-} \to hadrons)/\sigma(e^{+}e^{-} \to \mu^{+}\mu^{-})$$



Search for the top quark begins

- naive predictions (based on quark mass ratios) implied $m_t \approx 10\text{-}20$ GeV
- e+e- →t t searches
  - PETRA (DESY) scanned up to sqrt(s)=46.4 GeV (mt<23 GeV)
  - TRISTAN (KEK) scanned up to sqrt(s)=64 GeV (mt<32 GeV)
  - SLC/LEP at the Z pole, $m_t < 46$ GeV

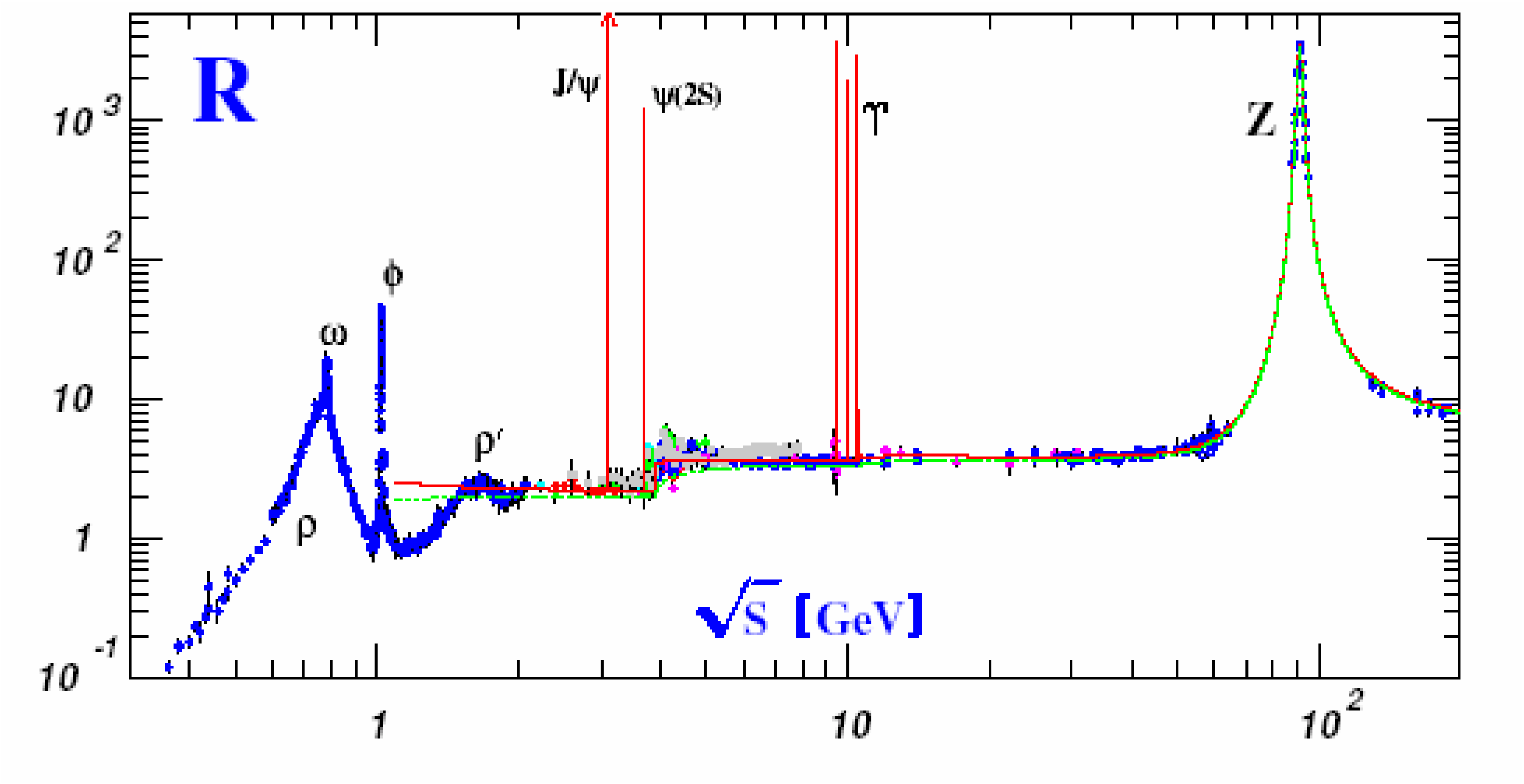
e+e- collider energy scans



no toponium

R

$$R = \sigma(e^+e^- \to hadrons) / \sigma(e^+e^- \to \mu^+\mu^-)$$

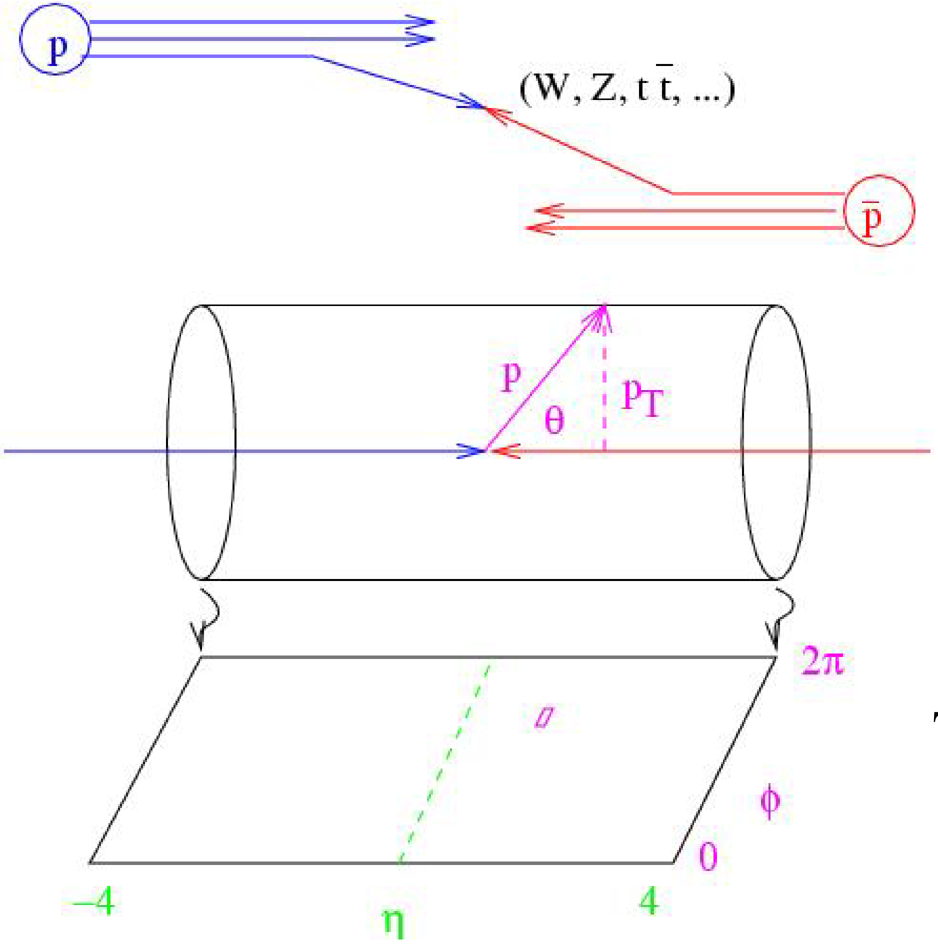


Searches for top at hadron colliders

- We know now that $m_t \approx 175$ GeV
  - Question: Why wasn't top discovered at the SppS collider, where sqrt(s)=630 GeV?
- We know that top was eventually discovered in 1995 at the Tevatron with sqrt(s)=1800 GeV. The Tevatron began running at this energy in 1987.
  - Question: Why did it take so long to find top at the Tevatron?

- The answers have to do with
  - parton distributions
  - backgrounds
  - statistics

Coordinate system



Beam axis : z

Azimuth: φ

Rapidity:

$$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$$

pseudorapidity:

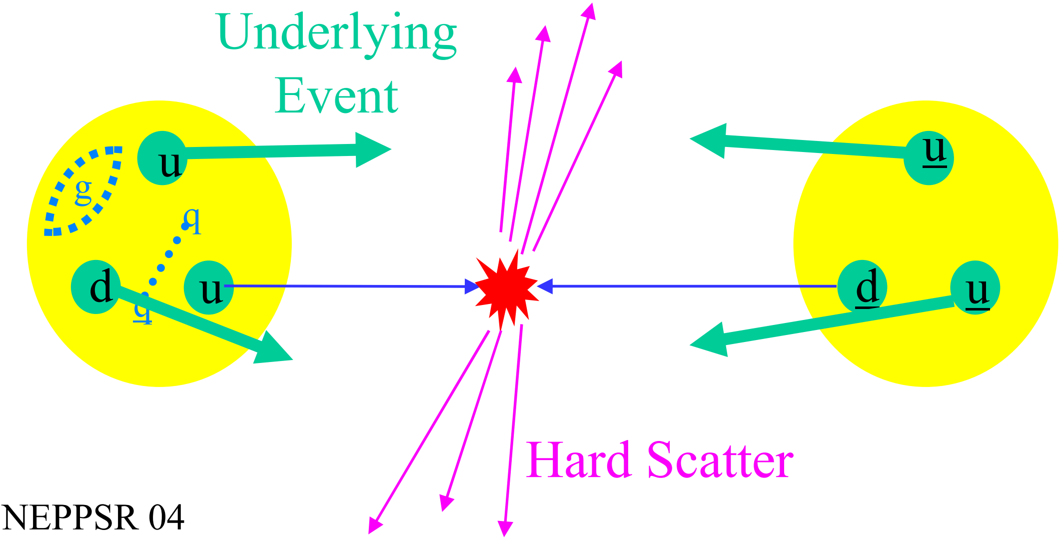
$$\eta = -\ln(\tan(\theta/2)) \approx y$$

Transverse momentum:

$$p_T = p\sin\theta = \sqrt{p_x^2 + p_y^2}$$

Hadron collisions: experimental consequences

- Energy involved in "hard scatter" is less (typically <10%) than the full proton-antiproton center-of-mass energy
- "hard scatter" system is generally
  - Not at rest along the beam direction $\sum p_z \neq 0$
  - Nearly at rest transverse to the beam direction $\sum \vec{p}_T \approx 0$
- Additional particles & energy are present from the "underlying event"

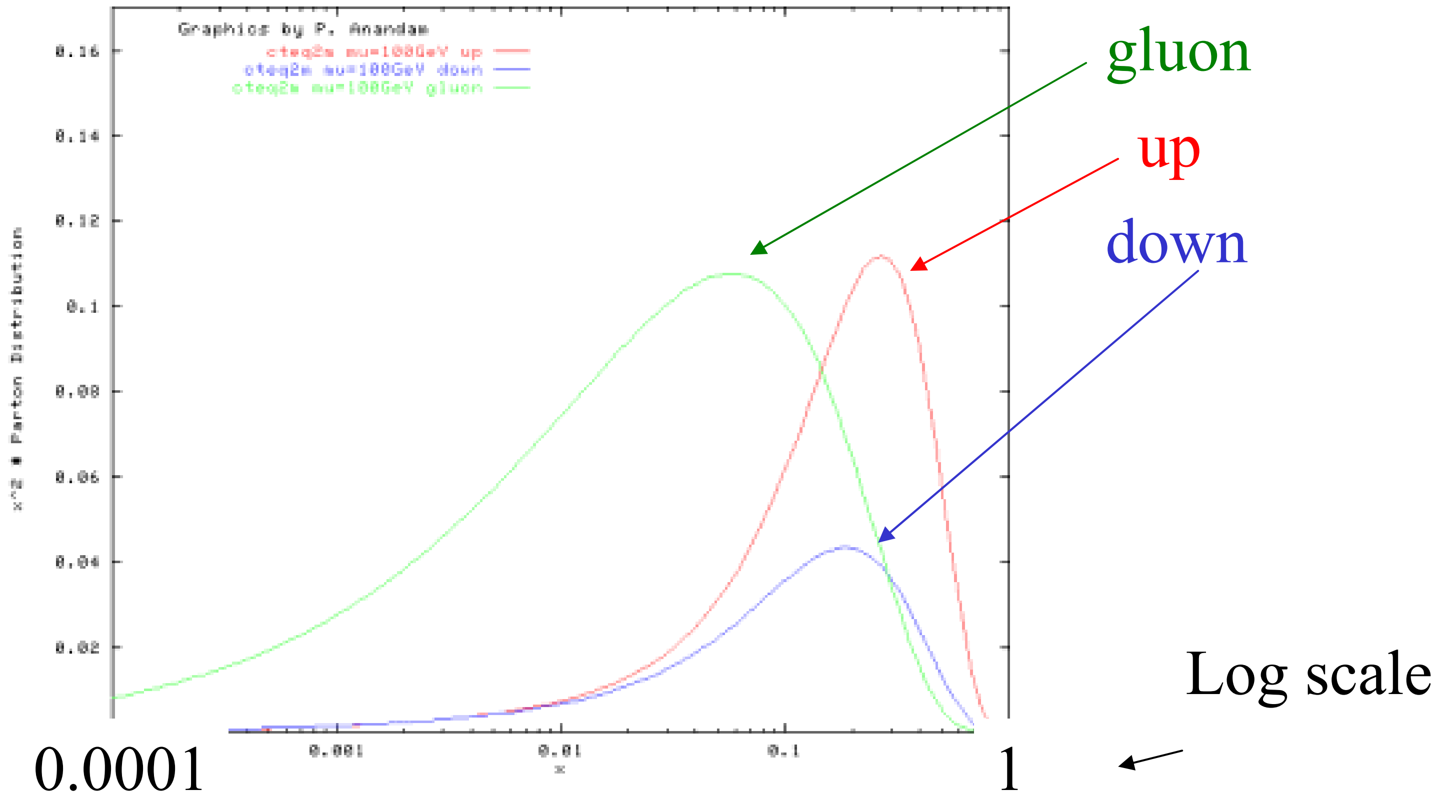


Parton distribution functions

- Probability of finding a parton (quark or gluon) with a fraction *x* of the (anti)proton's momentum is given by the pdf, $f(x,Q^2)$ for a momentum scale Q

x^2*pdf

(on a log scale area under x^2*pdf shows momentum fraction)



From website zebu.oregon.edu/~parton/partongraph.html

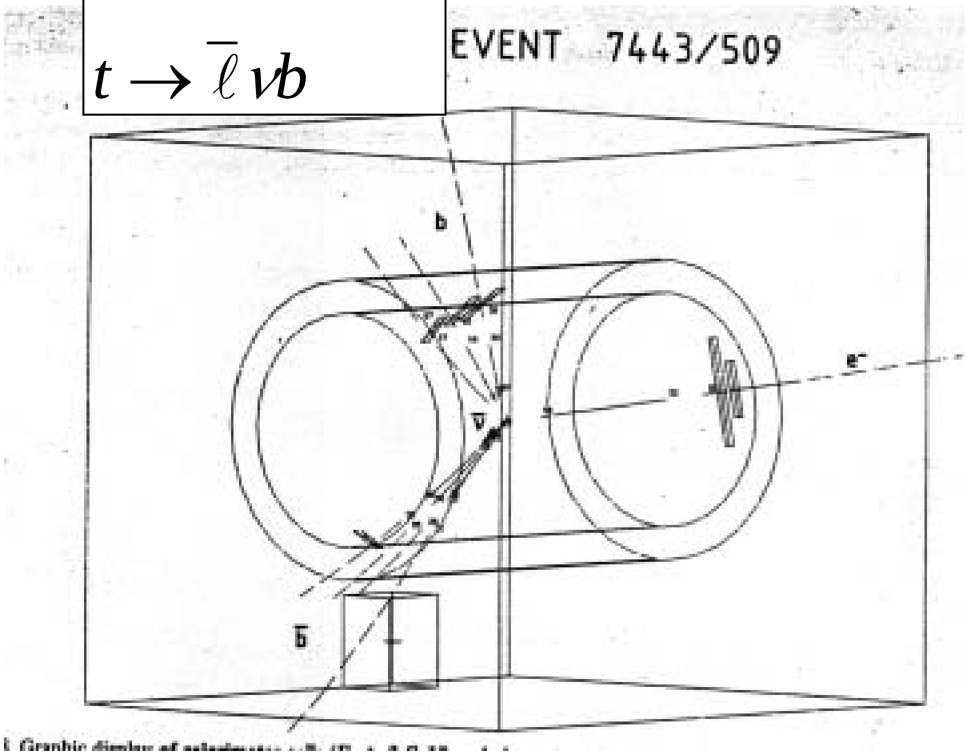
UA1 & UA2 top searches

- SppS, proton-antiproton collider, sqrt(s)=630 GeV
- Searches concentrated on top lighter than $M_w - M_b$:
- Final state signature
  - one isolated lepton of moderately-high transverse momentum
  - missing transverse energy (from the neutrino)
  - two jets (from b and b)

$$p\bar{p} \rightarrow W + X$$

$$W \rightarrow t\bar{b}$$

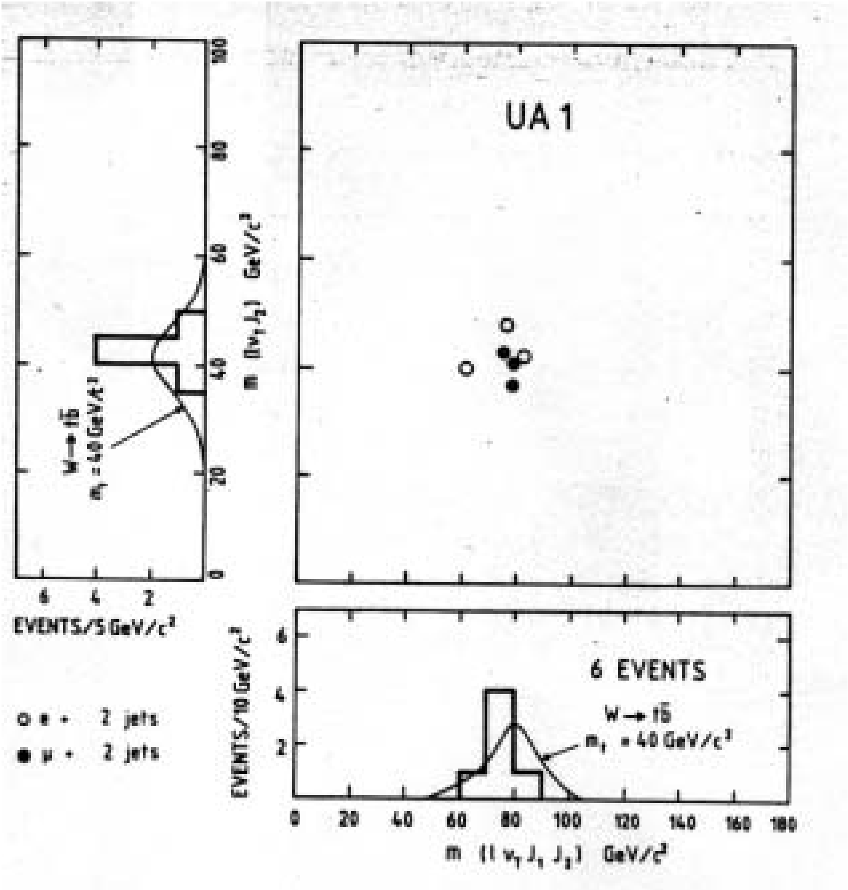
$$t \rightarrow \bar{\ell}\nu b$$



UA1 & UA2 top searches (cont.)

- 1984: Publication by UA1 of excess of events attributable to a top quark with a mass in the range 30-50 GeV (PL 147B, 493)

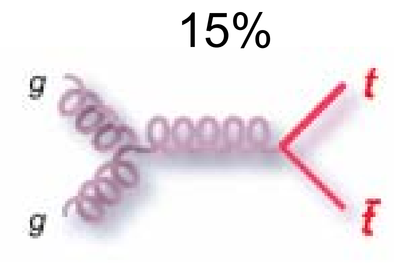
- UA1 claim later retracted with analysis of more data and better understanding of backgrounds (J/ψ,Y,bb and cc)
- Final limits from the SppS:
  - UA1: m_t>60 GeV
  - UA2: m_t>69 GeV



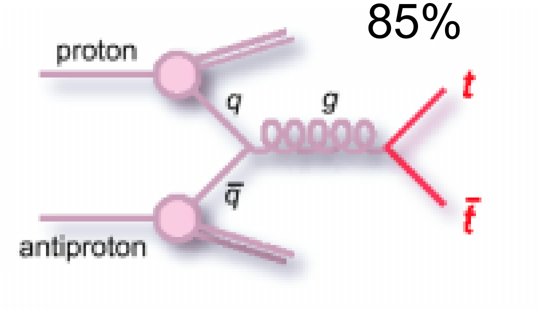
top production at the Tevatron

- In proton anti-proton collisions at Tevatron energies, top quarks are primarily produced in pairs via strong interactions

15%

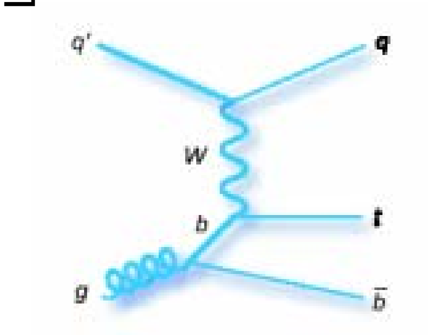


85%

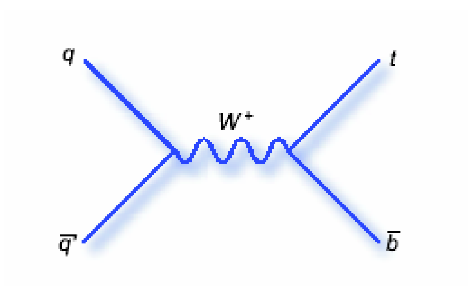


LO diagrams

- EW single top production: not yet observed

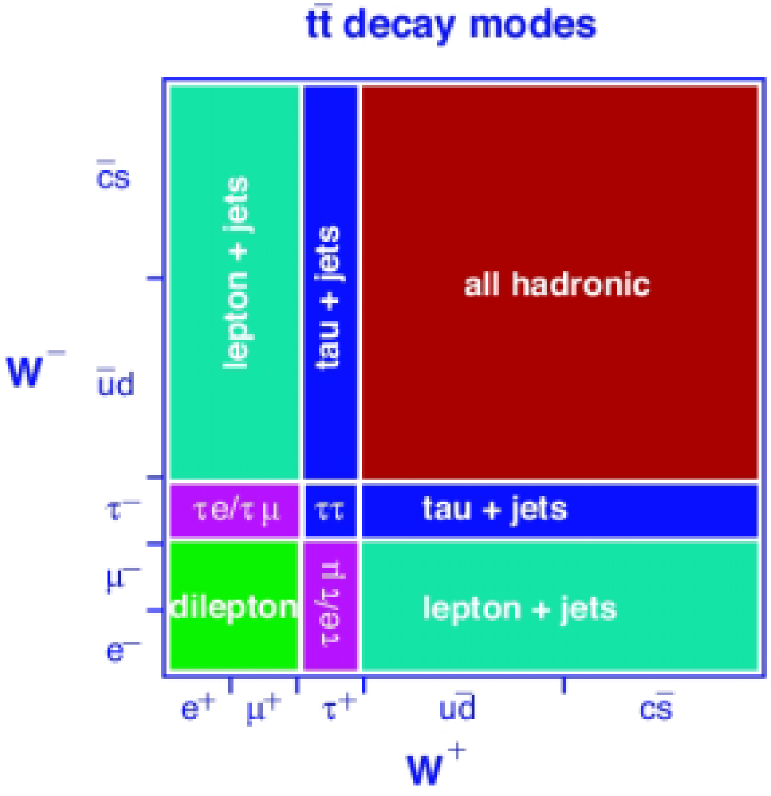


t-channel



s-channel

- Br(t→Wb)=100%

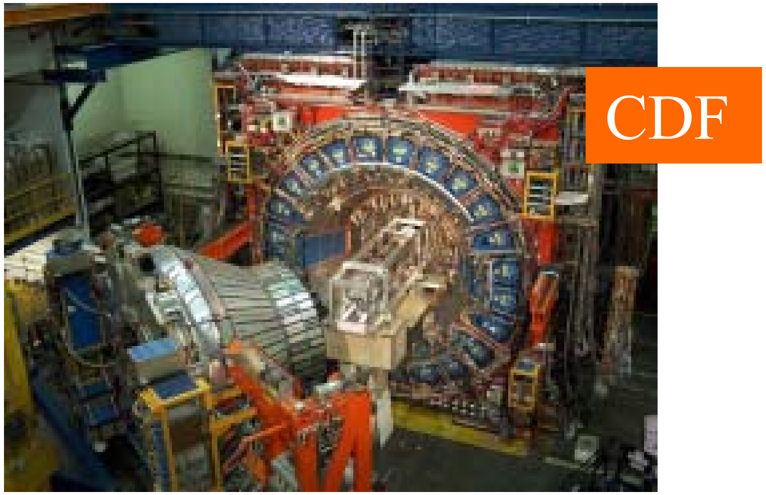


Typical production rates for p-p at 2 TeV

Final state	Cross section (pb)	Rate at L=10^{32} $cm^{-2}s^{-1}$
"minimum bias"	$4x10^{10}$	4 MHz
2 jets	$4x10^{6}$	400 Hz
4 jets	$1.6x10^{5}$	16 Hz
6 jets	6000	0.6 Hz
W	30000	3 Hz
Z	9000	0.9 Hz
WZ	3.5	$3.5x10^{-4}$ Hz (1.3/hour)
t tbar	**7.5**	**$7.5x10^{-4}$ Hz (3/hour)**

Hadron Collider Detectors

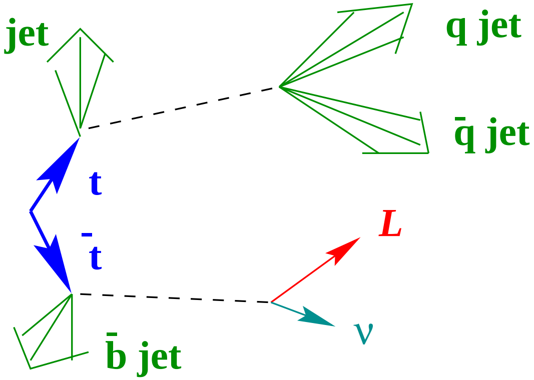
- Important features to keep in mind
  - Collisions take place at the (approximate) center of the detectors
  - Detectors must have apertures in the forward and backward directions for the beams to enter and exit
  - Detectors try to measure momentum and or energy of particles produced in collison



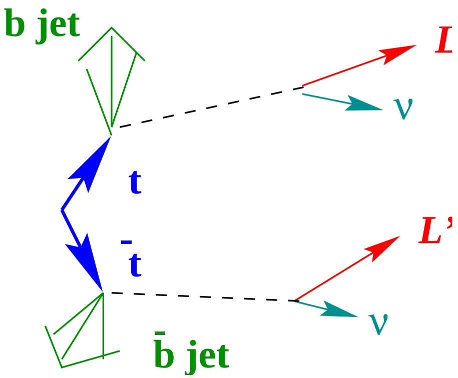
Top quark event signatures

Two most used channels:

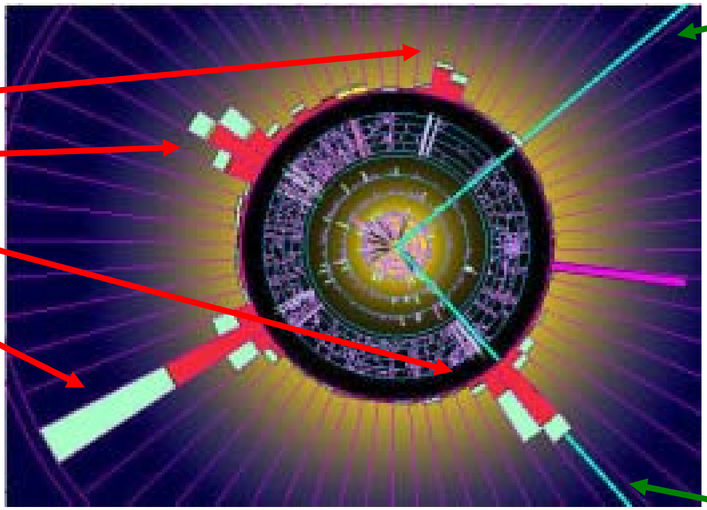
lepton+jets



dilepton



Example lepton+jets event:



jets

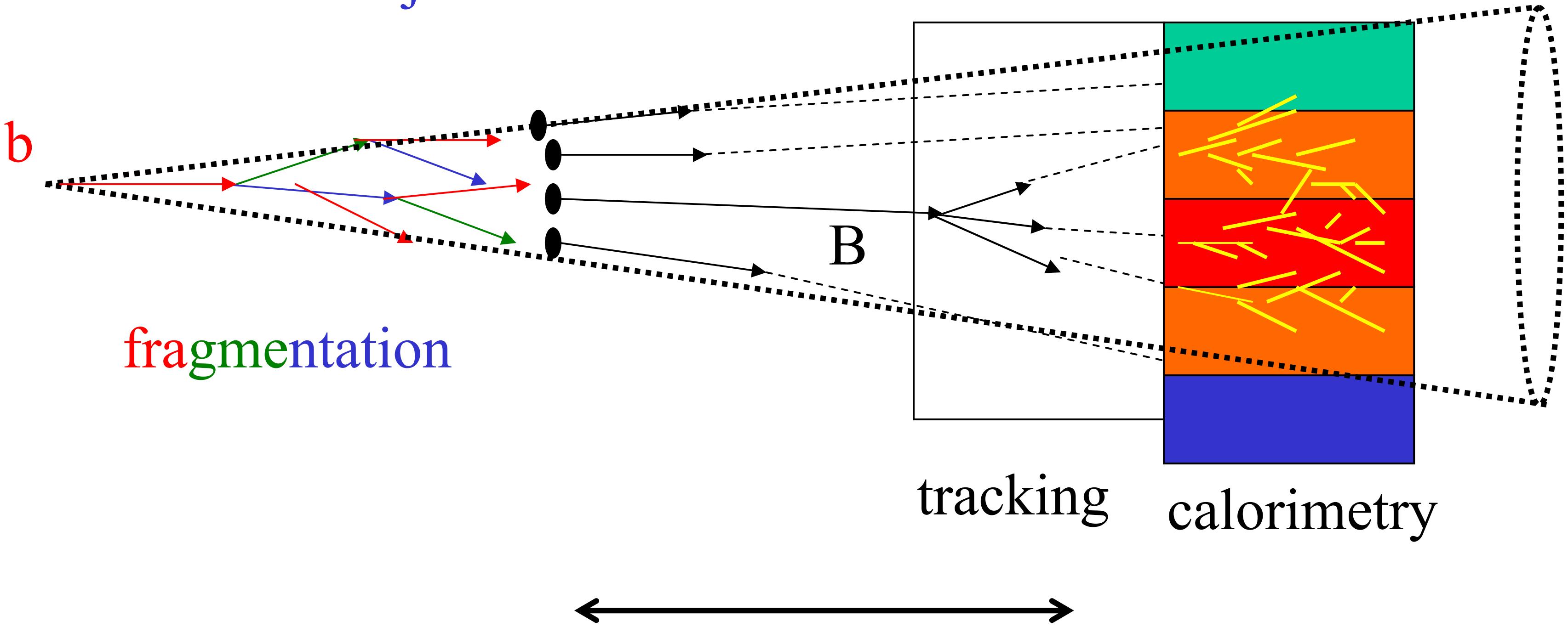
Muon from W decay

Missing momentum from neutrinos

Muon from b-quark decay

b-quark jets

- Recall the steps between production of a quark and detection of a jet:



b

fragmentation

B

tracking

calorimetry

parton production

decays

jet finding

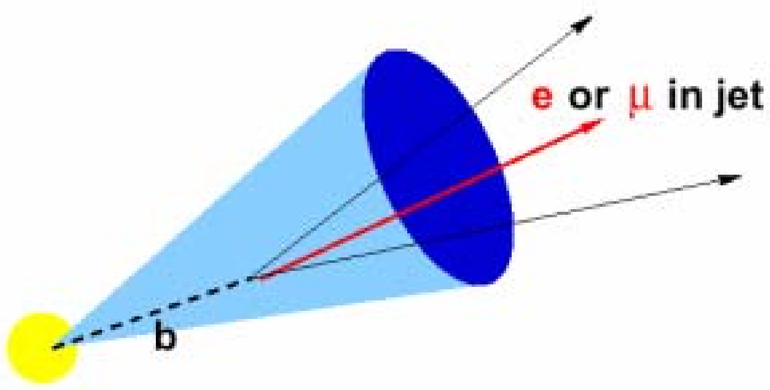
Identifying b-jets ("tagging")

Tagged analyses: higher purity, loss in efficiency

Soft Lepton tagging

Exploits the *b*-quarks semi-leptonic decays:

- These leptons have a softer p_T spectrum than leptons from W/Z
- are not isolated

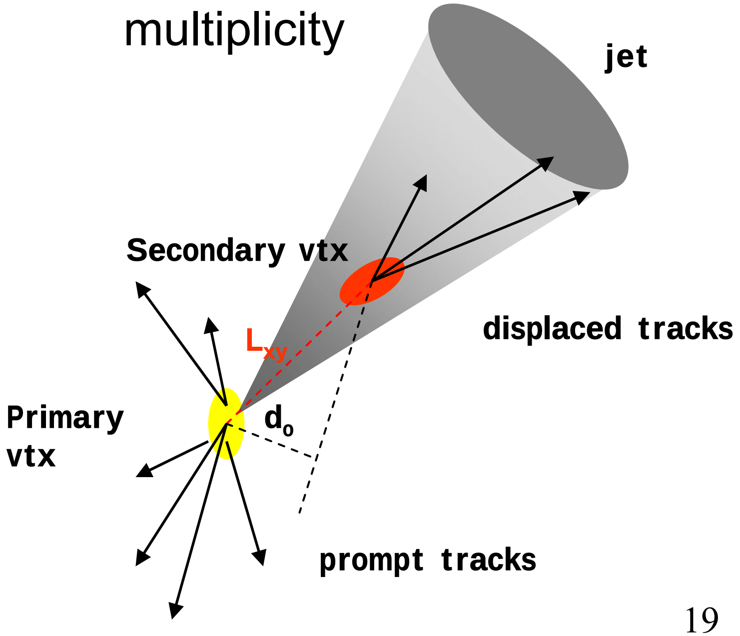


- $b \to \ell \nu c$ (BR ~ 20%)
- $b \to c \to \ell \nu s$ (BR ~ 20%)

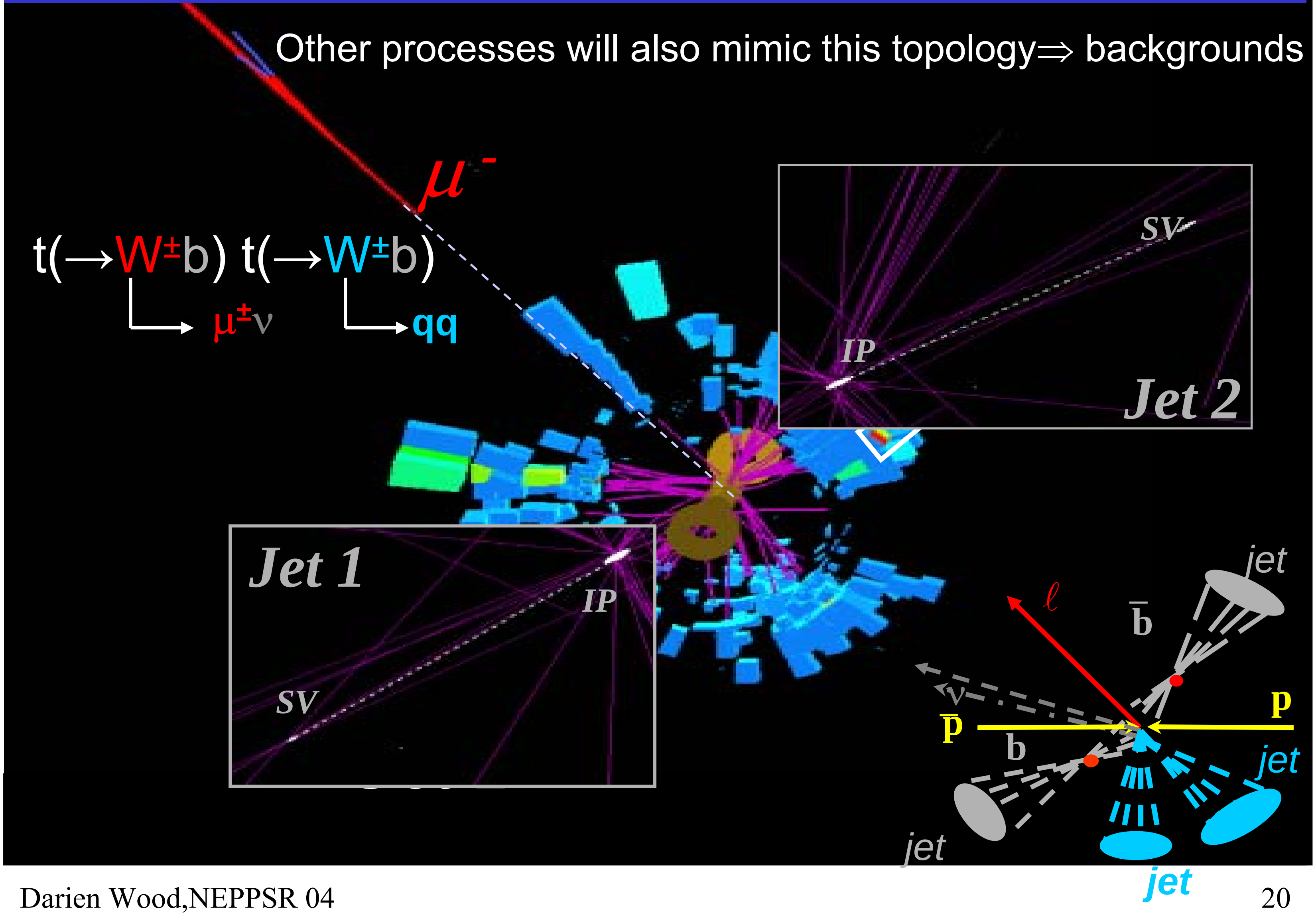
Lifetime tagging

Signature of a *b*-decay is a displaced vertex:

- Long lifetime of b-hadrons ($c\tau$~450μm)+boost
  - B hadrons travel L_{xy} ~ 3mm before decay with large charge track multiplicity



t-tbar candidate event with b-tags



Other processes will also mimic this topology⇒ backgrounds

t(→W±b) t(→W±b)

↳ μ±ν ↳ qq

Decaying particles: examples

Particles	Lifetime	$c\tau$	Lifetime signature
W,Z,top	$<10^{-23}$ s	~0	Decay immediately
$\pi^0(\rightarrow\gamma\gamma)$	$8\text{x}10^{-16}$ s	25 nm	Decay length undetectable
τ	$2.9\text{x}10^{-13}$ s	87 μm	Inside beam pipe; hard even with SMT
$D^0/D^\pm/D_s$	$0.4\text{-}1.0\text{x}10^{-12}$ s	150-350 μm	Inside beam pipe; possible w/ SMT
$B^0/B^\pm/B_s$/b-baryon	$\sim 1.5\text{x}10^{-12}$ s	450 μm	Inside beam pipe; possible w/ SMT
$K^0_s(\rightarrow\pi\pi)$	$0.8\text{x}10^{-10}$ s	2.7 cm	decays in outer tracking chamber
$K^\pm$, $\pi^\pm$, $\mu^\pm$	$>10^{-8}$ s	>3 m	reach cal without decaying

Tevatron top physics: pre-discovery

- Mass limits from Tevatron:

Year	Experiment	limit on m_t
1990	CDF	77 GeV
1992	CDF	91 GeV
1994	CDF	118 GeV
1995	DØ	131 GeV

- 1994 statistical excesses (CDF evidence publication)

Experiment	Observed events	expected (non-top) background	stat. significance
CDF	12	6.0	2.8σ
DØ	9	3.8	1.9σ

1995 – Observation of the top quark

- March 2, 2005 – presentations at Fermilab
- Articles from DØ and CDF published in same issue of Physical Review Letters:
  - PRL 74, 2632 (1995).
  - PRL 75, 2662 (1995).
- Headlines around the world
- Social hour activity: ask faculty when and how they were first convinced that the top quark had been found
  - many people here at NEPPSR who were in the middle of it all in 1995

March '95: top counting

- Statistical excess over non-top background:
  - CDF:

prob of bkg fluctuation: 1×10^{-6}

channel	SVX-tagged	SLT-tagged	Dilepton
observed	27 tags	23 tags	6 events
expected bkg	6.7±2.1	15.4±2.0	1.3±0.3

  - DØ

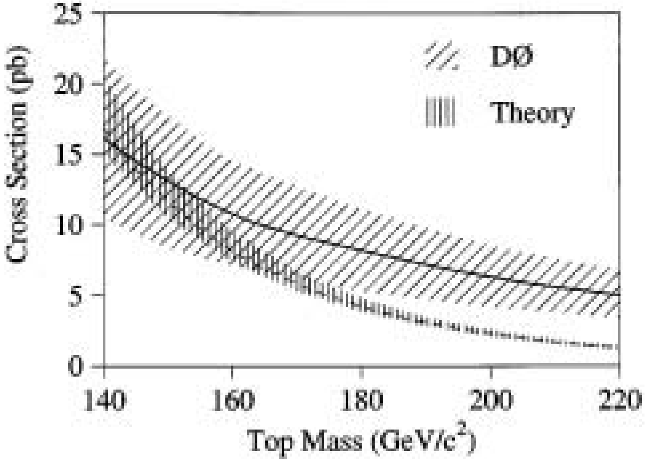
prob of bkg fluctuation: 2×10^{-6}

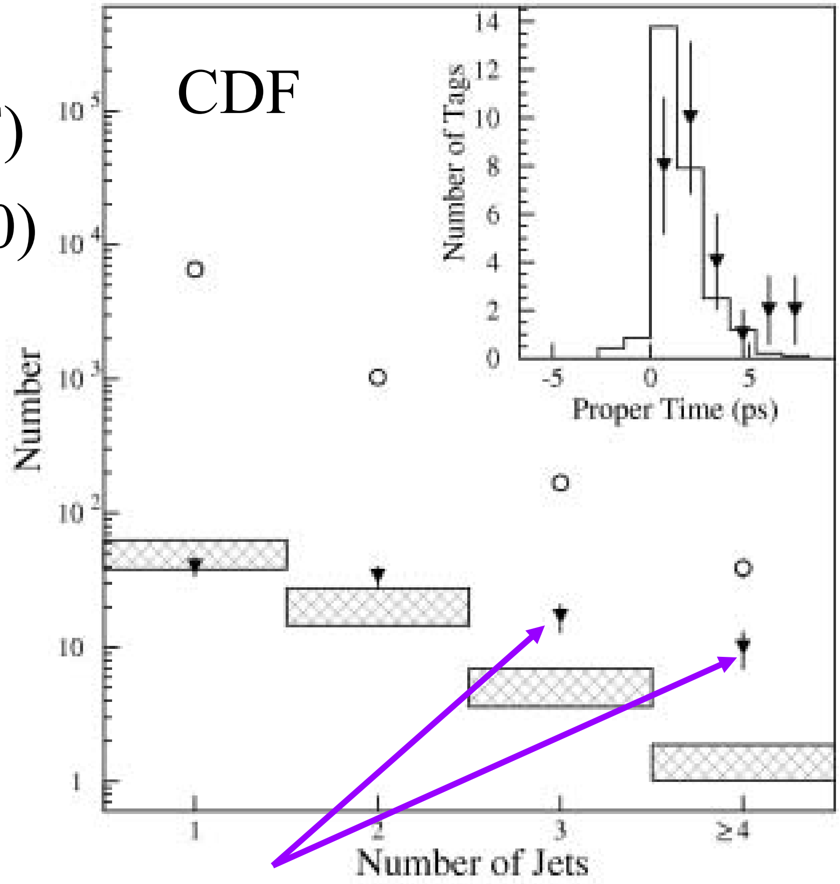
channel (exclus.)	untagged l+jets	SLT-tagged	Dilepton	Total
observed	8 events	6 events	3 events	17 events
expected bkg	0.65	1.2	1.9	3.8±0.6

March ’95: top cross section

$$\sigma(p\bar{p} \to t\bar{t} + X) = 6.8^{+3.6}_{-2.4}\,\mathrm{pb(CDF)}$$

$$\sigma(p\bar{p} \to t\bar{t} + X) = 6.4 \pm 2.2\,\mathrm{pb(D0)}$$





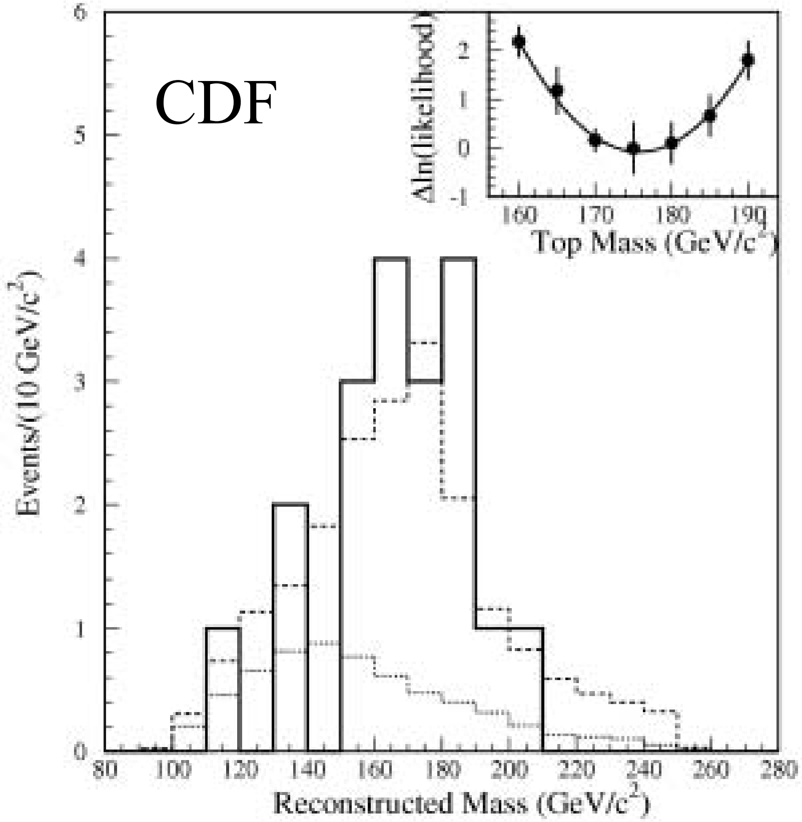
excess

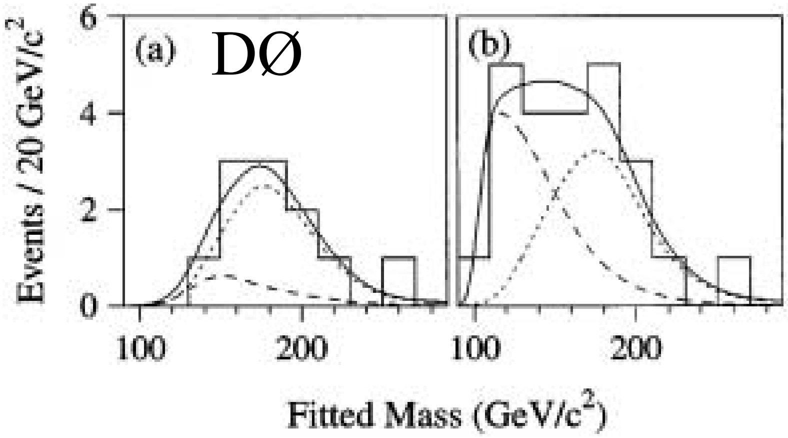
March ’95: top mass

Lepton+jets channel only used in mass

$$m_t = 176 \pm 8(\text{stat.}) \pm 10(\text{sys.})\text{GeV[CDF]}$$

$$m_t = 199^{+19}_{-21}(\text{stat.}) \pm 22(\text{sys.})\text{GeV[D0]}$$





Top Quark Physics: beyond discovery

Discovery: ~50 pb^{-1}

-cross section

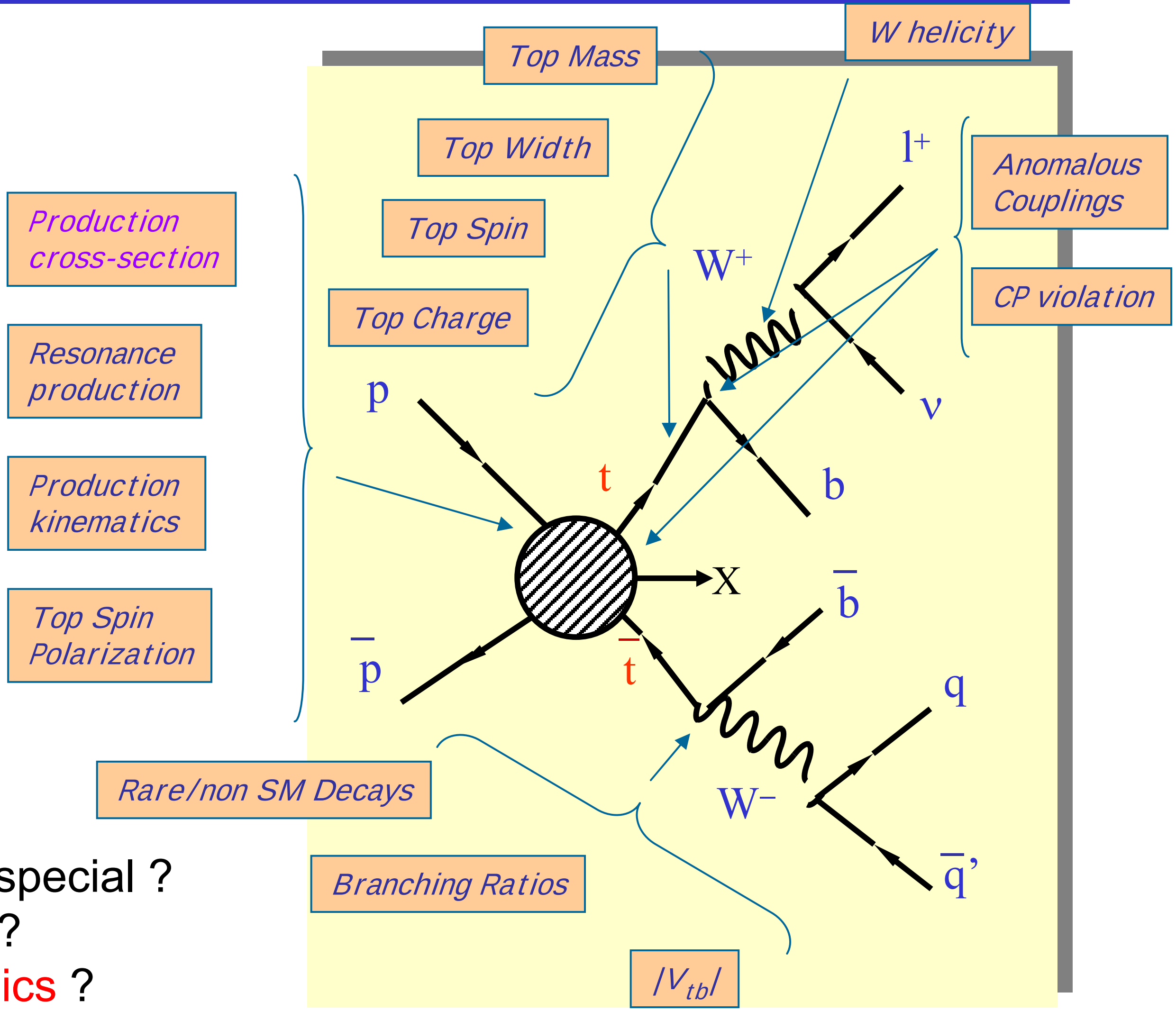
-mass

Run I + Run II: ~1 fb^{-1} so far

-higher precision

-greater sensitivity to rare processes

- Why is top so heavy ?
- Is it or the third generation special ?
- Is top involved with EWSB ?
- Is it connected to new physics ?



Production cross-section

Resonance production

Production kinematics

Top Spin Polarization

Top Mass

Top Width

Top Spin

Top Charge

W helicity

Anomalous Couplings

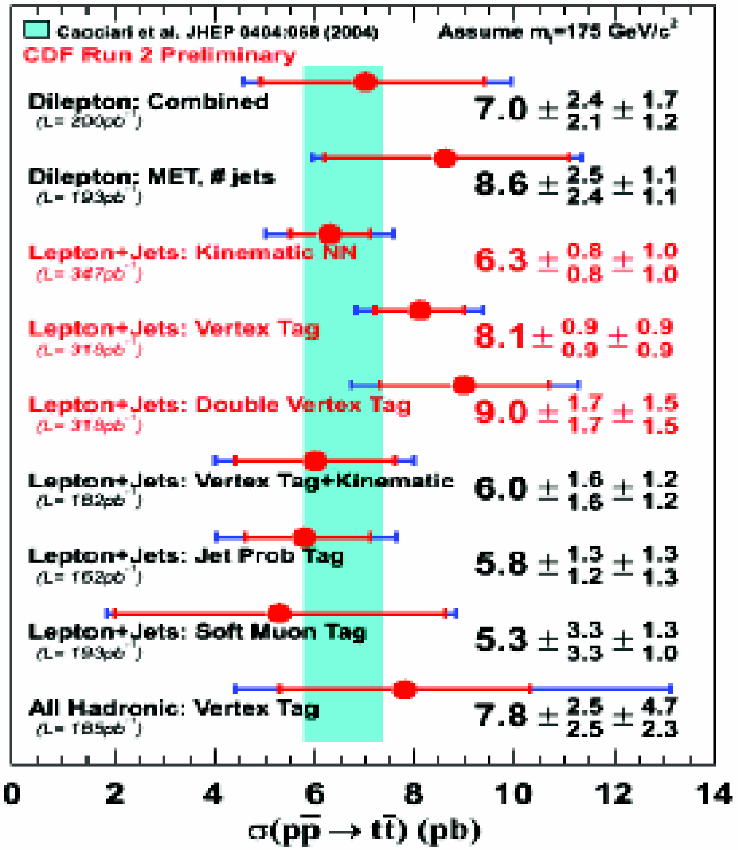
CP violation

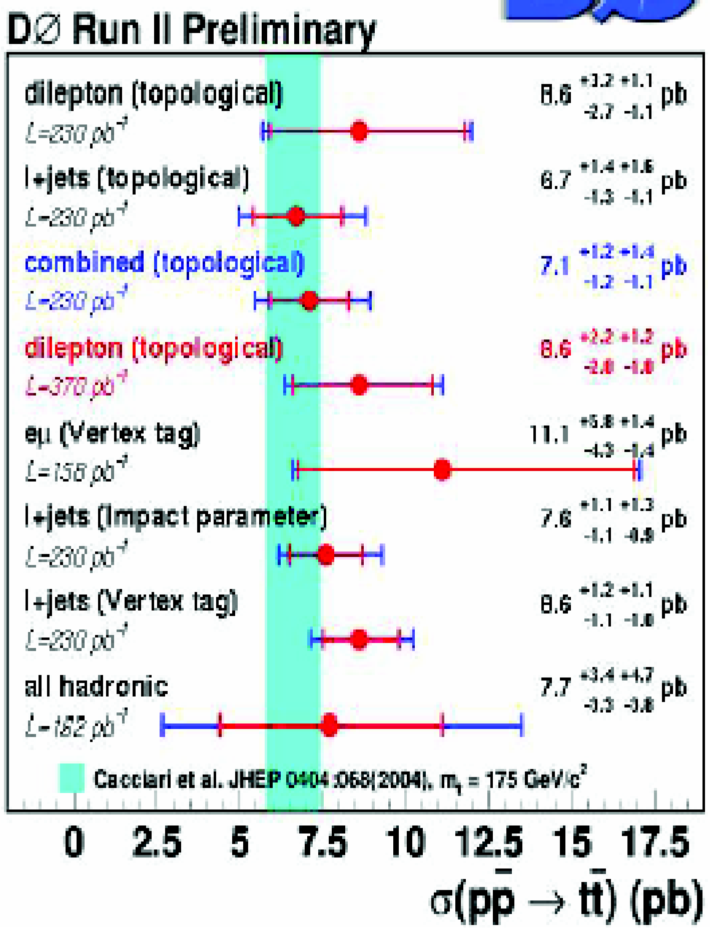
Rare/non SM Decays

Branching Ratios

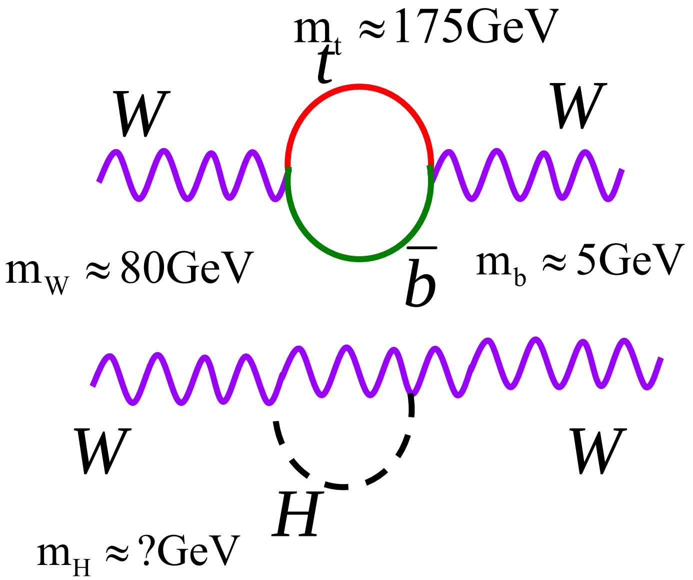
$|V_{tb}|$

Cross section

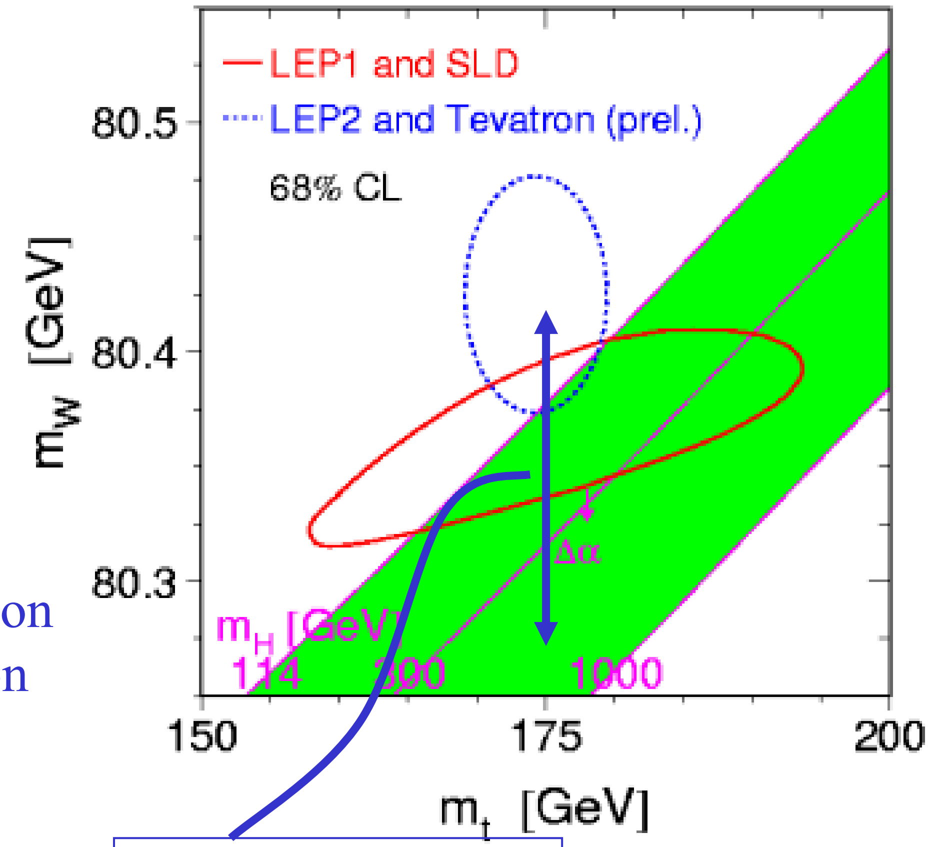




Virtual effects: one reason why m_t is so interesting



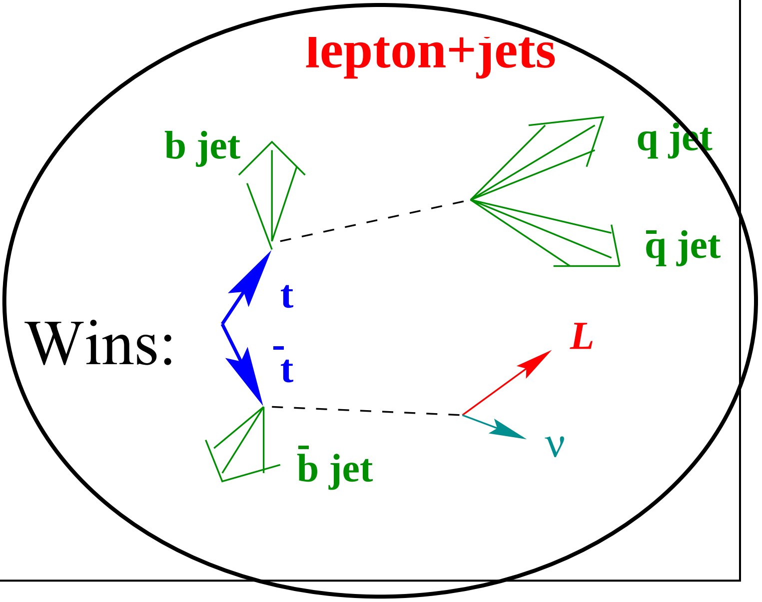
- W mass has quadratic dependence on top mass, logarithmic dependence on Higgs mass
- top mass is essential in
  - predicting Higgs mass
  - tests SM if Higgs is found



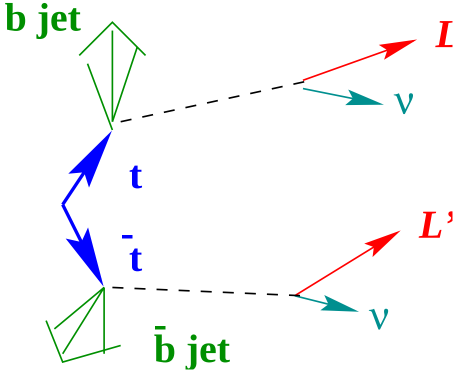
Mass shift from virtual Higgs effects (?)

Top quark mass measurement

- advantages
  - 2nd largest branching ratio
  - only one neutrino


lepton+jets

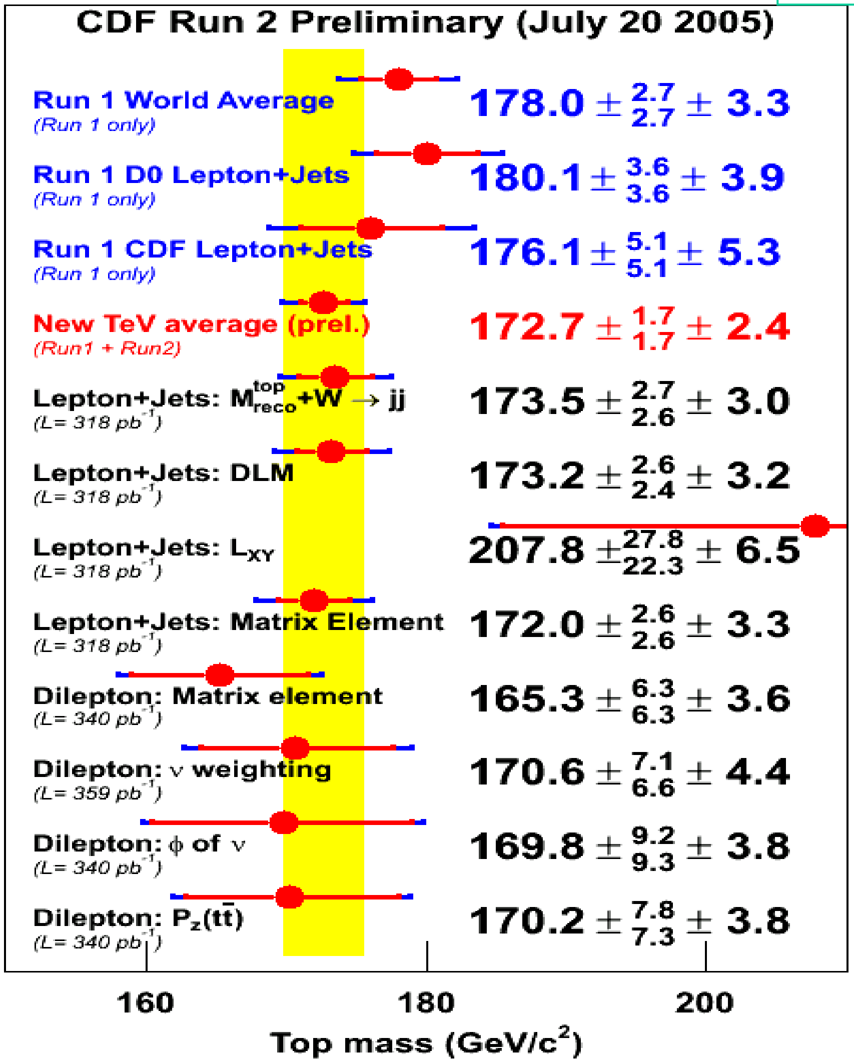
- advantages
  - low background
  - better energy resolution for leptons than for jets

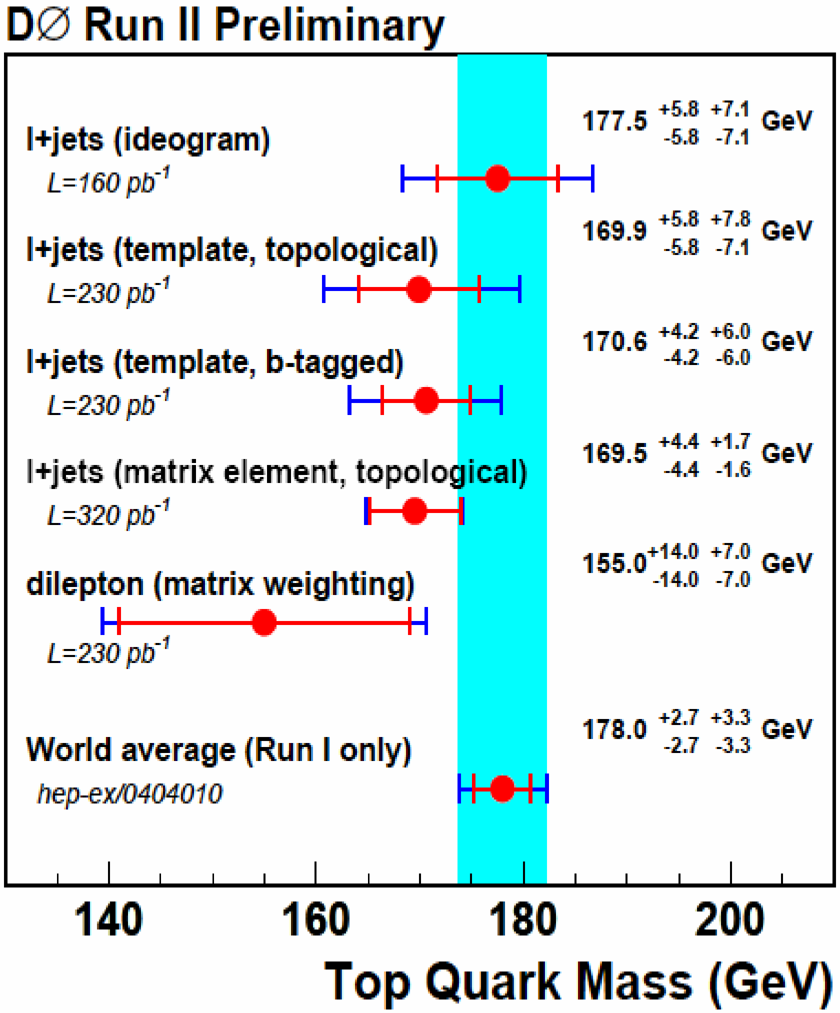

dilepton

Summary of m_t Measurements

1995 world ave.

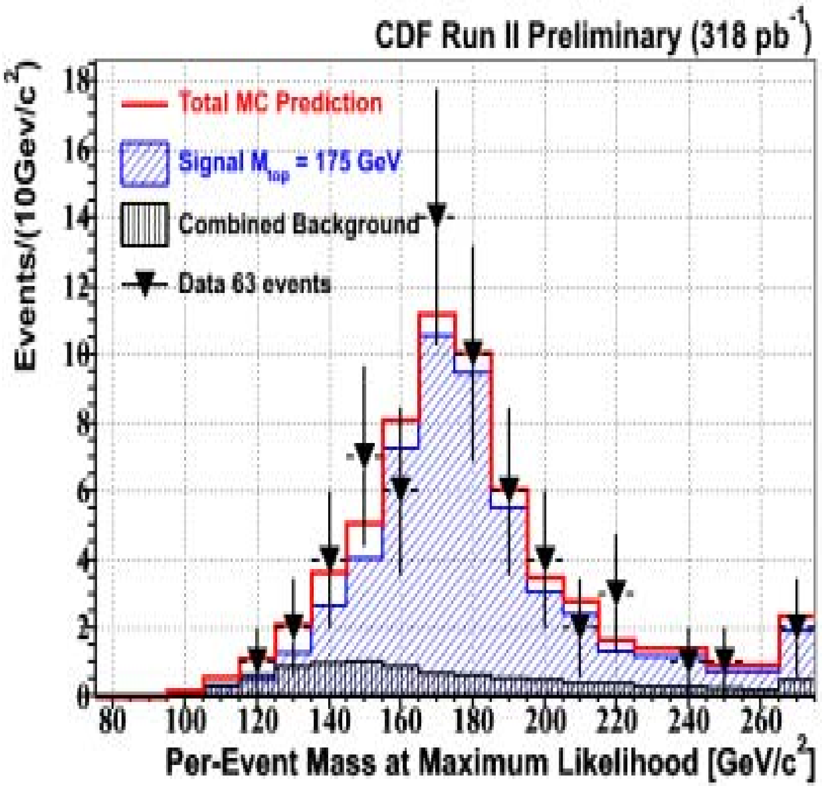
180±12





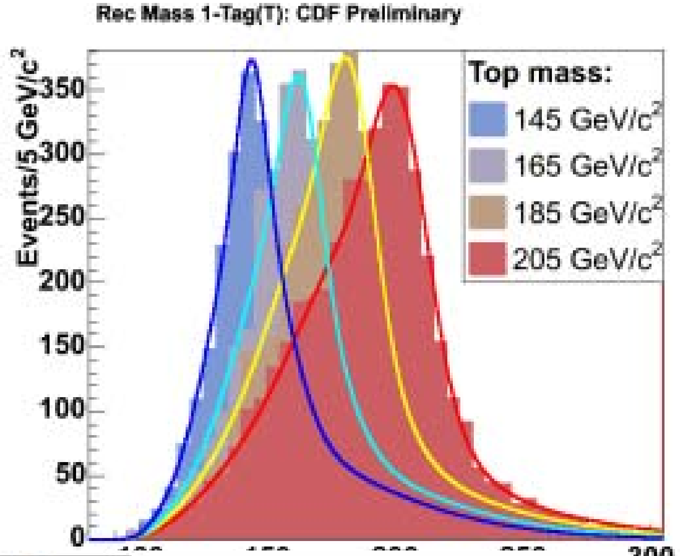
Improvements in top mass since discovery

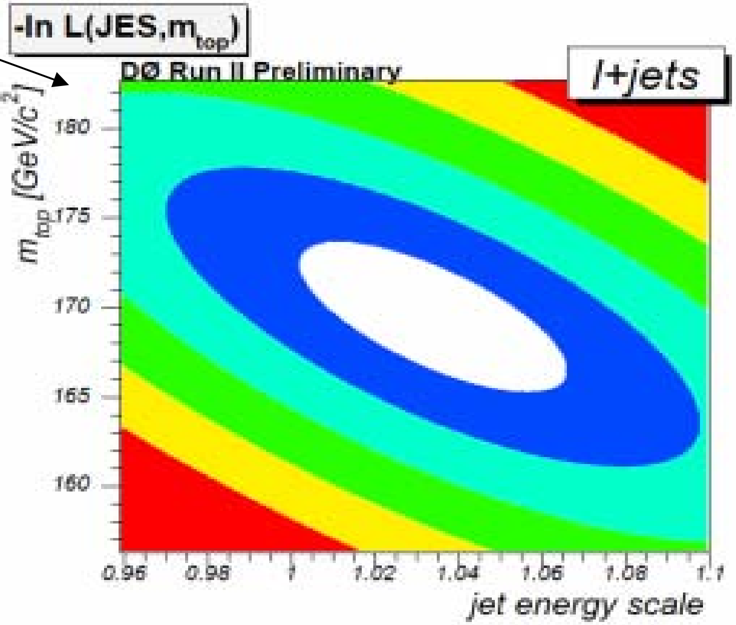
- statistics:
  - ~50-70 pb at discovery, ~300 pb^{-1} used in latest results
  - samples up to ~200 events used in mass fits
- reduced backgrounds (in some cases)
- more channels
  - dilepton (need special treatment because of two neutrinos)
  - all jets
- more advanced methods to extract mass



top mass extraction methods (partial list)

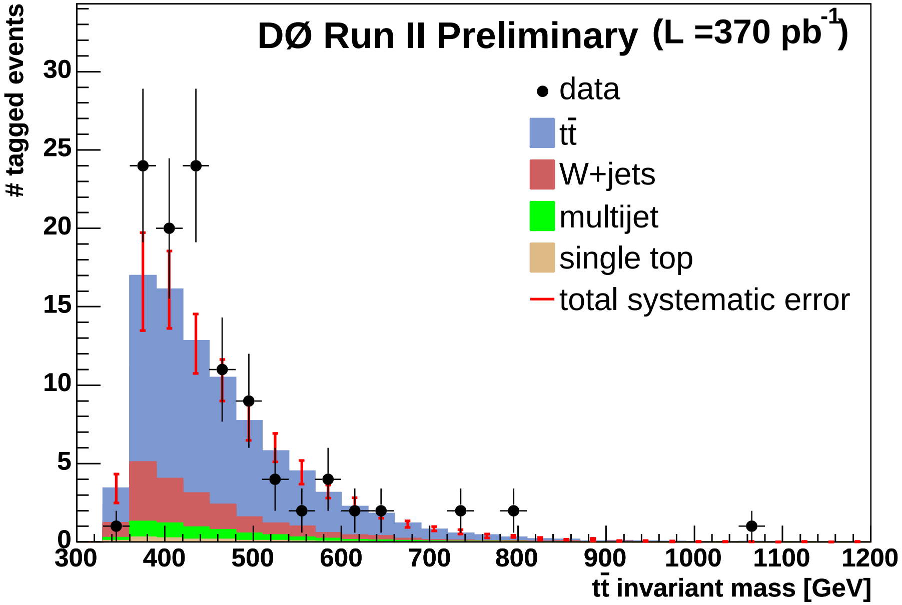
- “template” fits (used in 1995)
  - one mass per event determined by kinematic fit
- “neutrino weighting” in dileptons
- matrix element, dynamical likelihood
  - events get different weights at different top masses according to quality of agreement with SM top production/decay matrix element
  - concurrent fit to jet energy scale calibration from W→qq
- ideogram
  - each event gives a distribution of top masses
- Lxy
  - lifetime measurement of b is used to infer boost which

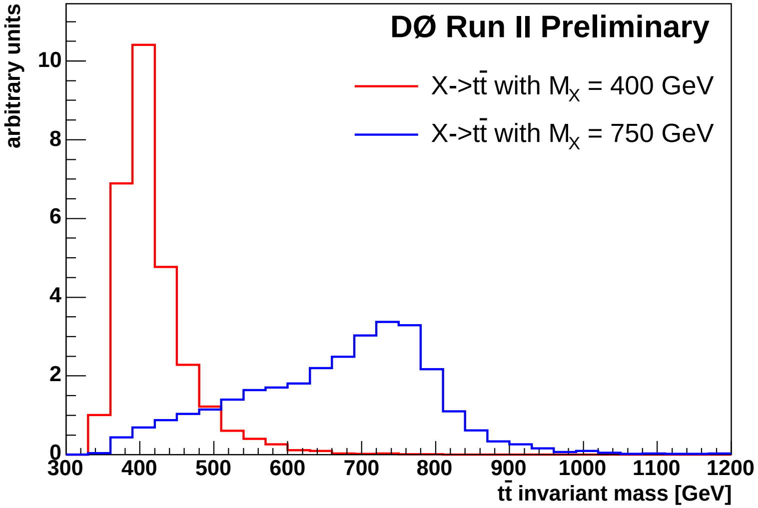




Invariant mass of tt system

- calculate after constraining both t and t systems to 175 GeV each
- test of QCD prediction of tt production
- search for new physics: X→tt would produce at peak at m_X



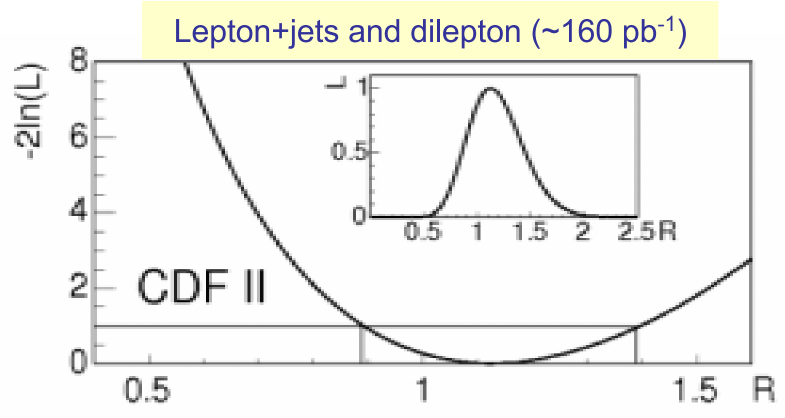


m_x>680 GeV for Z-like couplings

Measurement of $B(t\to Wb)/B(t\to Wq)$

$$R=\frac{B(t\to Wb)}{B(t\to Wq)}=\frac{|V_{tb}|^2}{|V_{ts}|^2+|V_{td}|^2+|V_{tb}|^2}=|V_{tb}|^2 \sim 0.998 \longleftarrow \text{In the SM}$$

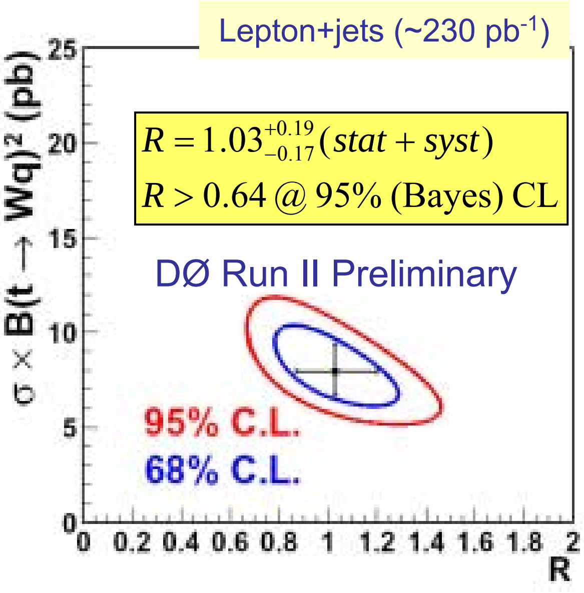
Basic method: compare the number of tt events with 0, 1, and 2 b-tags to extract R


Lepton+jets and dilepton (~160 pb^{-1})

$R=1.12^{+0.27}_{-0.23}(stat+syst)$

$R>0.61 @ 95\% (F\&C) CL$

hep-ex/0505091

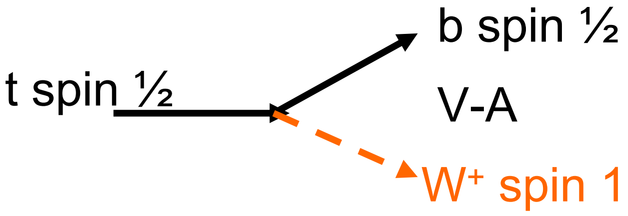

Lepton+jets (~230 pb^{-1})

$R=1.03^{+0.19}_{-0.17}(stat+syst)$

$R>0.64 @ 95\% (Bayes) CL$

Electroweak interactions of top (1): W helicity

- Within the SM, Top has a V-A charge current weak decay:



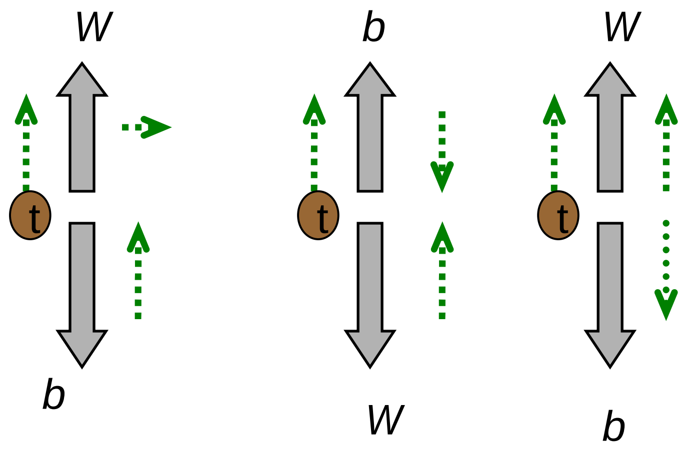
$$F_0 = \frac{1}{1+2\omega} \approx 0.7$$

$$F_- = \frac{2\omega}{1+2\omega} \approx 0.3$$

$$F_+ = 0$$

where $\omega = M_W^2/M_{top}^2$

W helicity



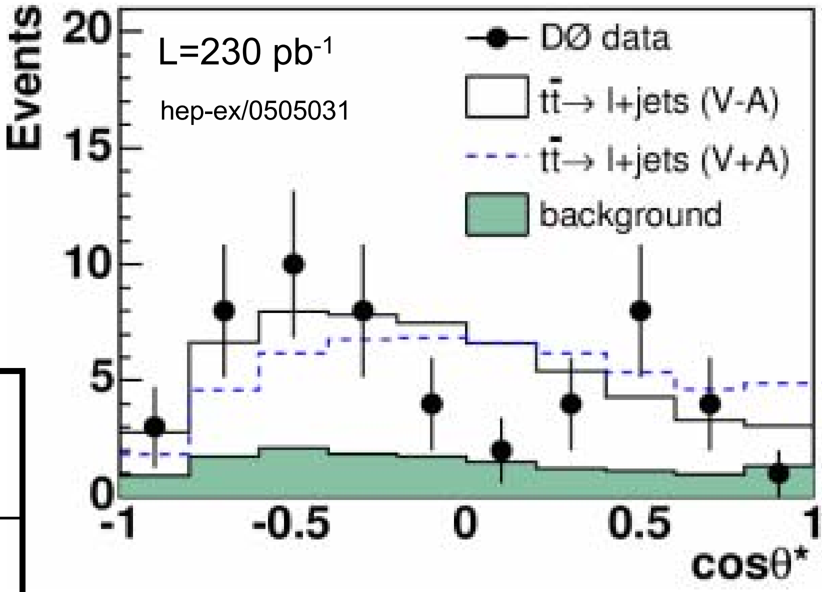
W_0	**W_-**	**W_+**
Longitudinal fraction	Left handed fraction	Right handed fraction
F_0 ~70%	**F_- ~ 30%**	**F_+ ~ 0%**

Spin ⇢ Momentum ⇨

W helicity extraction

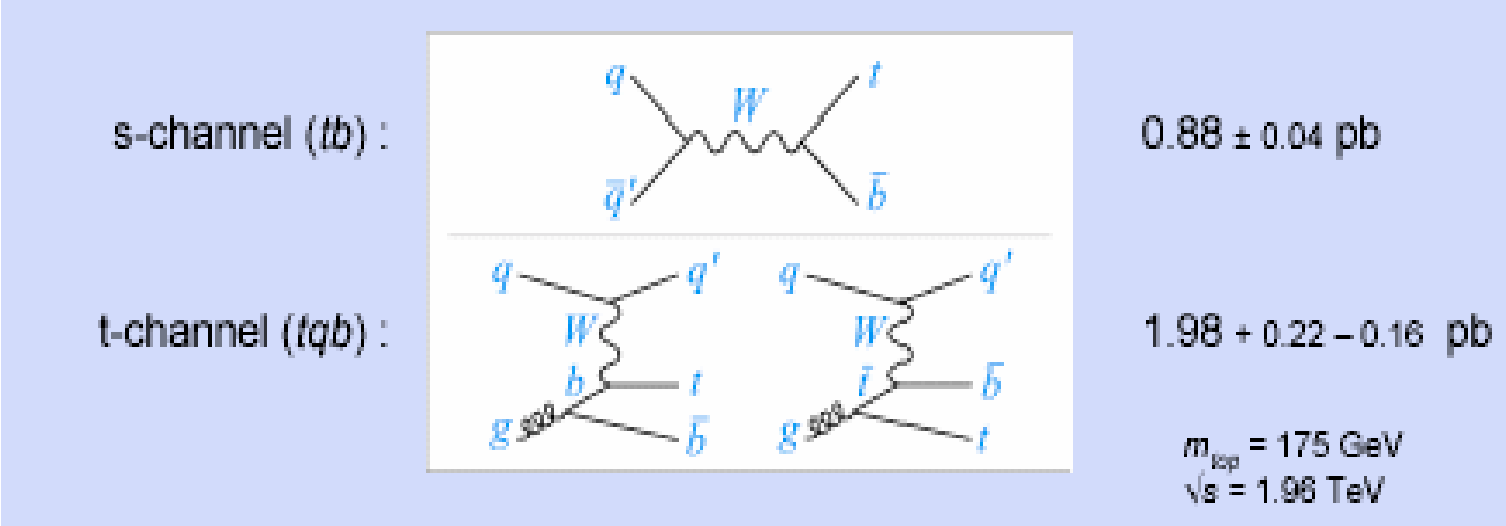
- Fit to distributions of
  - lepton p_T (softer for left-handed W's)
  - angle between lepton and top directions in W rest frame
- Samples
  - lepton + jets
  - dileptons

example:



result / prediction	F_0	F_+
SM	0.7	0
DØ	0.56±0.31	<0.25
CDF	0.27+.31-.21	<0.18

Electroweak interactions (2): single top production



s-channel (tb) : 0.88 ± 0.04 pb

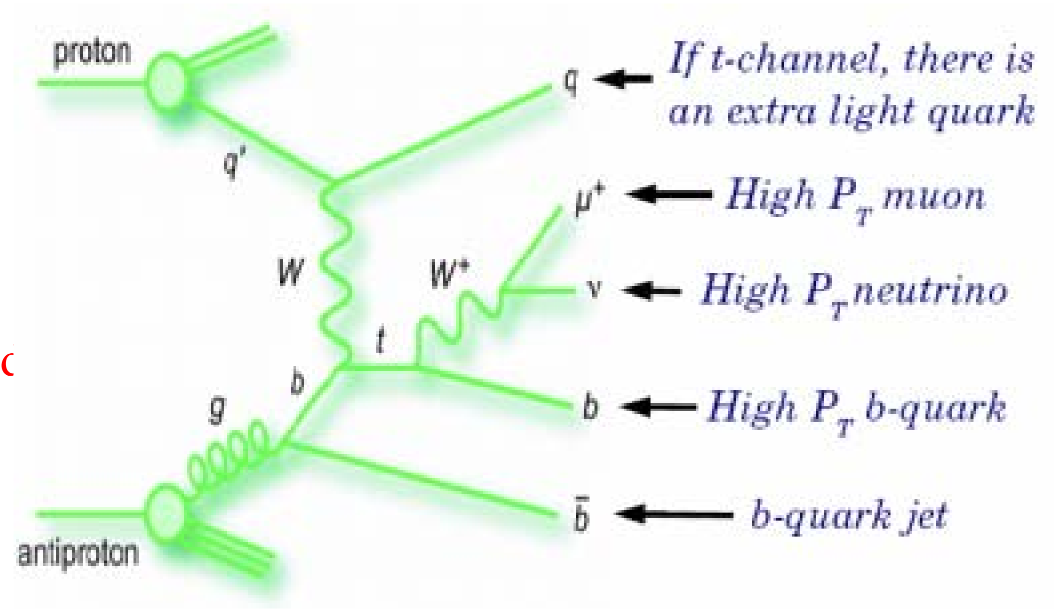
t-channel (tqb) : $1.98 + 0.22 - 0.16$ pb

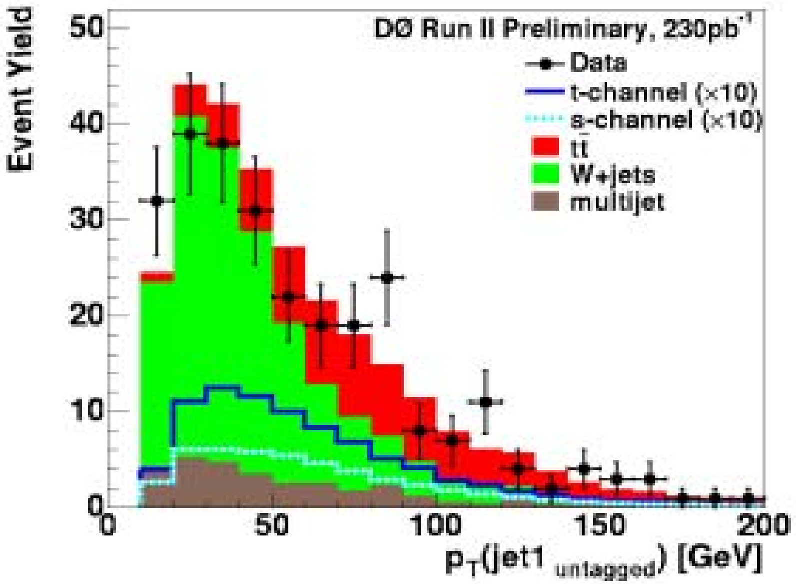
m_{top} = 175 GeV
$\sqrt{s}$ = 1.96 TeV

- rate measurement gives direct measurement of $|V_{tb}|$ CKM element
  - $\sigma \propto |V_{tb}|^2$
- cross sections a few times smaller than for tt
- signals much harder to distinguish from backgrounds
  - W+≥2jets
  - tt
  - bb

extracting single top

- signature
  - lepton
  - neutrino (missing E_T)
  - 2 b-jets (tagged)
  - characteristic kinematic anc angular distributions





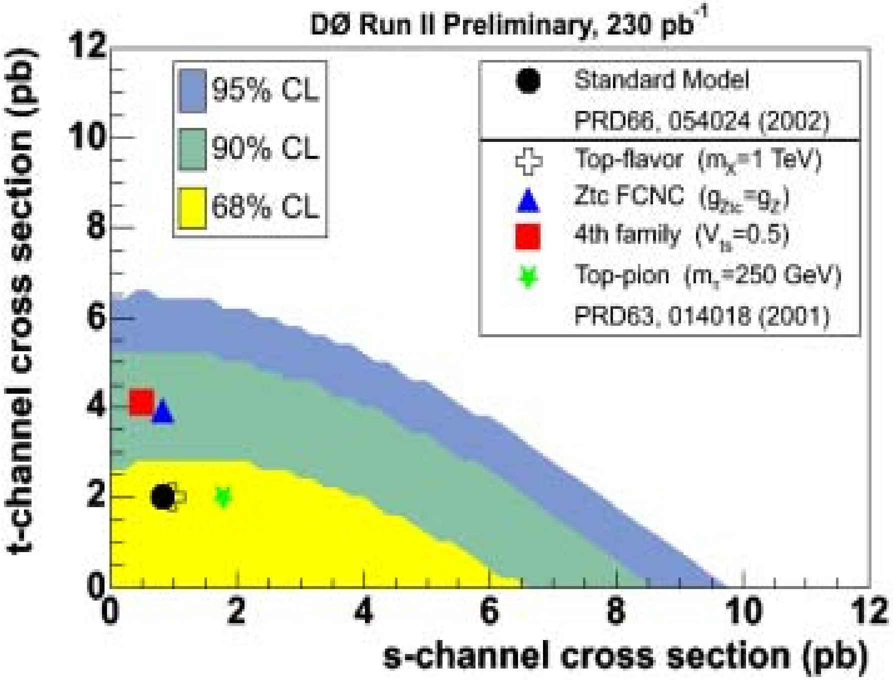
typically get weak separation for each variable⇒ need to combine many variables

- cuts
- likelihoods
- neural nets
- decision trees

single top limits

- no significant signal found yet for single top – limits set

analysis / prediction	s-channel xsec (pb)	t-channel xsec (pb)
CDF (RunII)	<14	<10 pb
DØ cuts	<11	<11
DØ decision tree	<8.3	<8.1
DØ Neural Net	<6.4	<5.0
DØ Likelihood	<5.0	<4.4
Standard Model	0.88	1.98



SM within reach in RunII

top: the next 10 years

- Tevatron:
  - 4-8 fb^{-1} expected in final data sample
    - more than 10 times the statistics of the analyses completed so far (~thousand events per sample)
  - expected top mass prescison: ~2 GeV
  - expect to observe single top
  - look for surprises in top properties
- LHC
  - enormous rate of top production – top factory
  - assuming Higgs is discovered, look at top Yukawa coupling from ttH events
  - …

beyond 10 years

- International Linear Collider
  - for sqrt(s)≈350 GeV e^+e^- collider, could scan over top production threshold
    - just like the 70's
    - no toponium (why not?)
    - precise mass measurement from threshold scan
      - avoids theoretical uncertainties that limit the top mass precision at hadron colliders
    - …

A few review articles

- B. Carithers and P. Grannis, "Discovery of the Top Quark," SLAC *Beam Line* **25**, No. 3, p. 4 (Fall 1995).
- C. Campagnari and M. Franklin, "The discovery of the top quark," hep-ex/9608003 and *Rev. Mod. Phys*. **69**, 137-212 (1997).
- S.J.Wimpenny and B.L.Winer, "The Top Quark," *Ann. Rev. Nucl. Part. Sci.* **46**, 149-195 (1996).
- P. Bhat, H. Prosper and S. Snyder, "Top Quark Physics at the Tevatron," hep-ex/9809011 and *Int. J. Mod. Phys* **13**, 5113 (1998).
- M. Mangano and T. Trippe, "The Top Quark," Particle Data book

backups

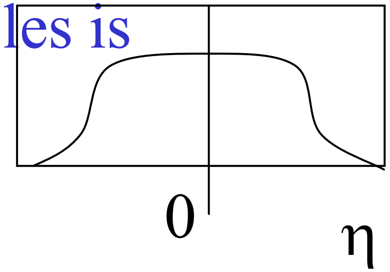
Phase space variables: eta, phi, and p_T

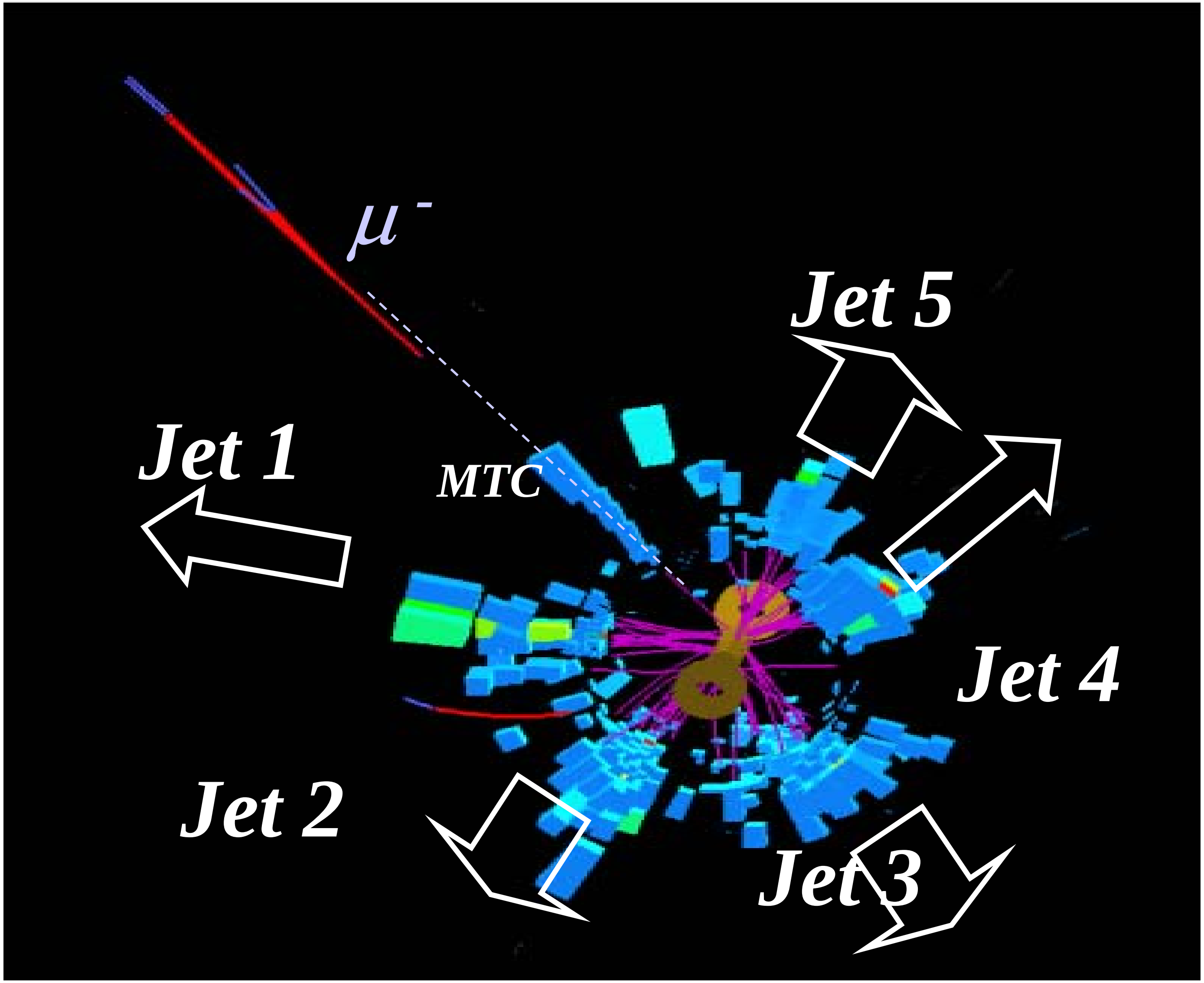
- Recall that the hard scatter system is generally in motion in the z-direction with respect to the laboratory frame
- Under a boost in the z-direction:
  - p_T is invariant
  - ϕ is invariant
  - Rapidity itself is not invariant, but all differences in rapidity are invariant

$$y \to y - \tanh^{-1} \beta$$

$$y_1 - y_2 \to y_1 - y_2$$

- At a given p_T, the expected density of particles is (approximately) uniform in eta and phi.
  - In contrast to e+e$^-$, where cosθ is flat





DØ top to μ+jets Candidate Event

Technique #2: optimized matrix element weighting

Likelihood method using most available information

Measured

to be estimated

resolutions, reconstruction effects

$$P(x;\alpha)=\frac{1}{\sigma}\int d^{n}\sigma(y;\alpha)\,dq_1\,dq_2\;f(q_1)\,f(q_2)\,W(x,y)$$

Matrix Element

PDF’s

LO ME used, 4 jets required exclusively, additional cut on background probability (to improve purity) → 22 events

$$-\ln L(\alpha)=-\sum_{i=1}^{N}\left\{\ln\left[c_1P_{t\bar{t}}(x_i;\alpha)+c_2P_{bkg}(x_i)\right]\right\}$$
$$+N\int A(x)\left[c_1P_{t\bar{t}}(x;\alpha)+c_2P_{bkg}(x)\right]dx$$

Acceptance

Likelihood definition: estimate signal and background fractions and m_{top}