Top-Quark Physics at the Tevatron

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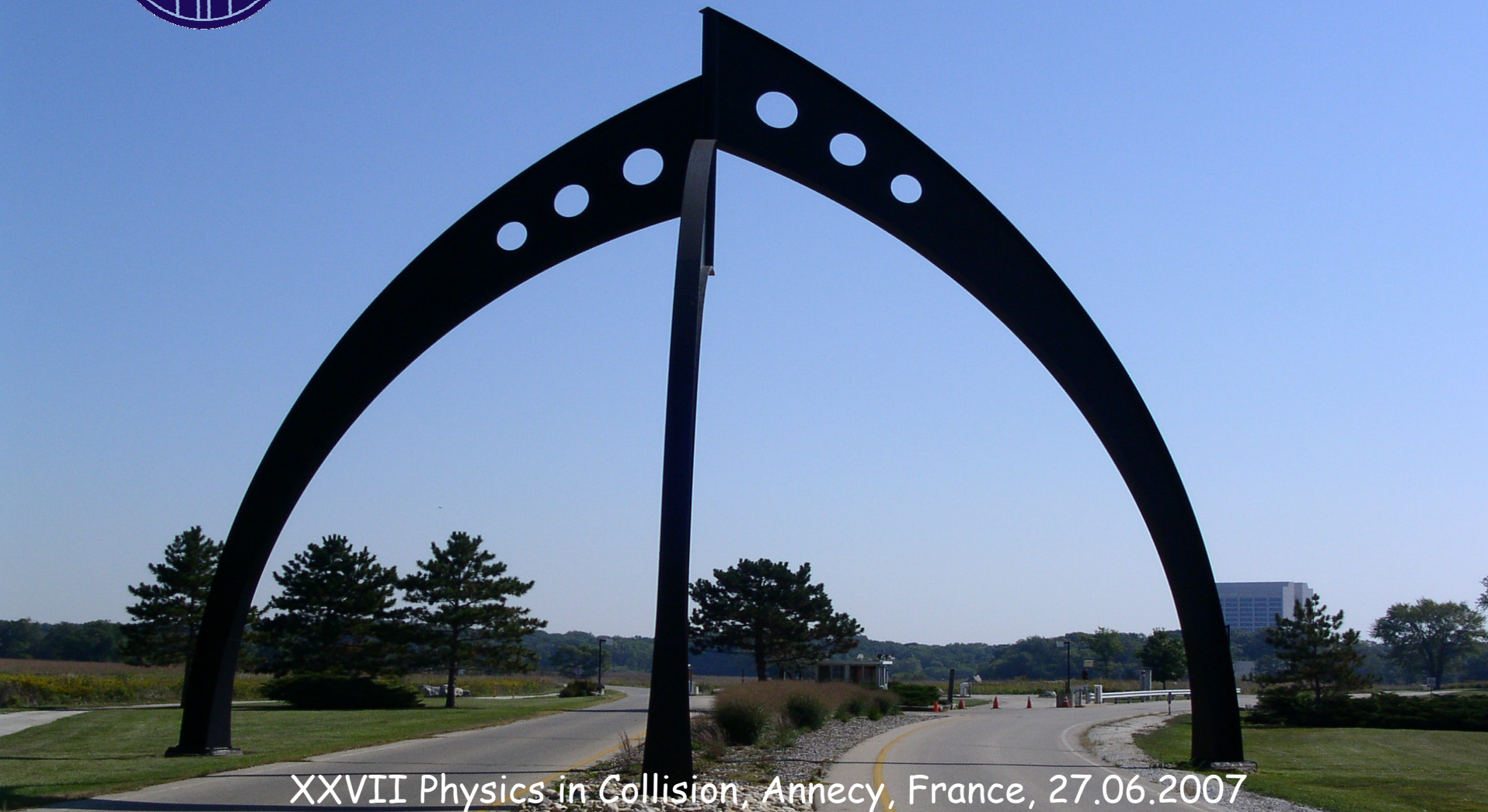
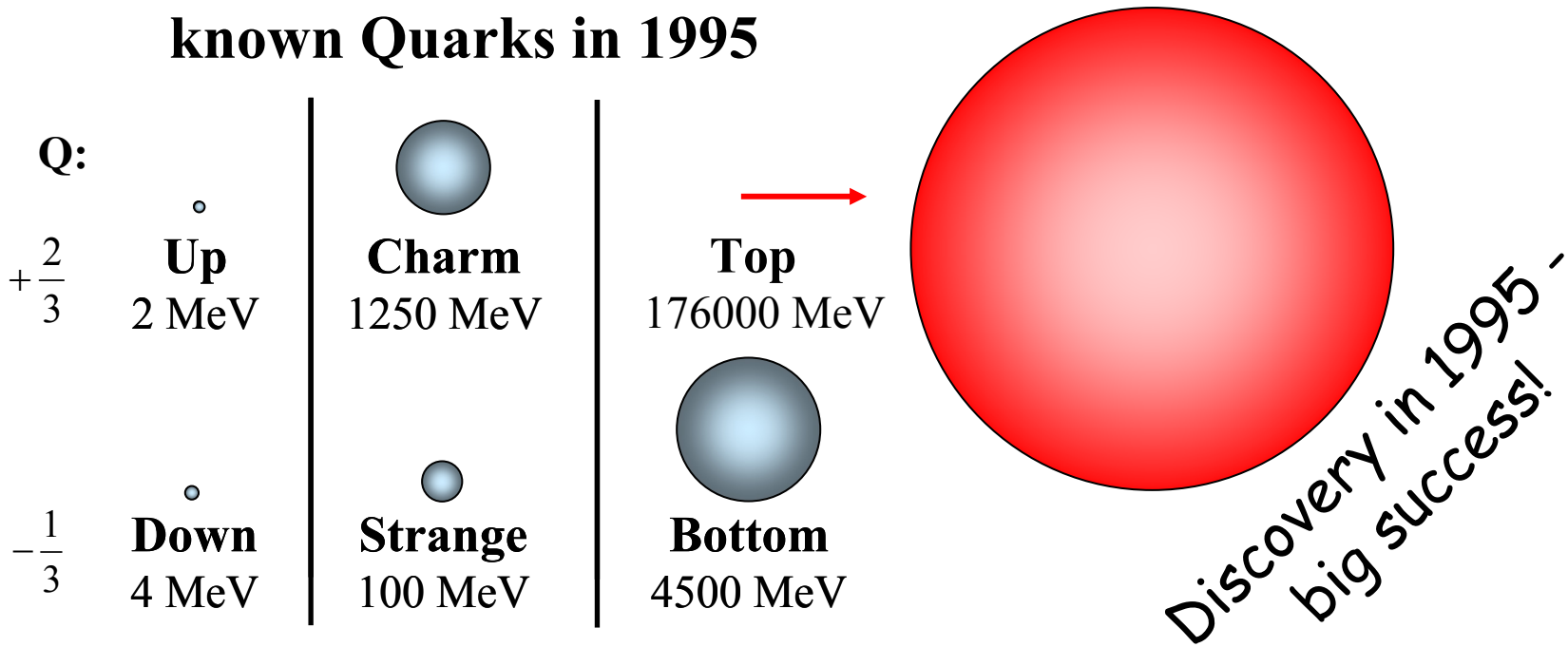


XXVII Physics in Collision, Annecy, France, 27.06.2007

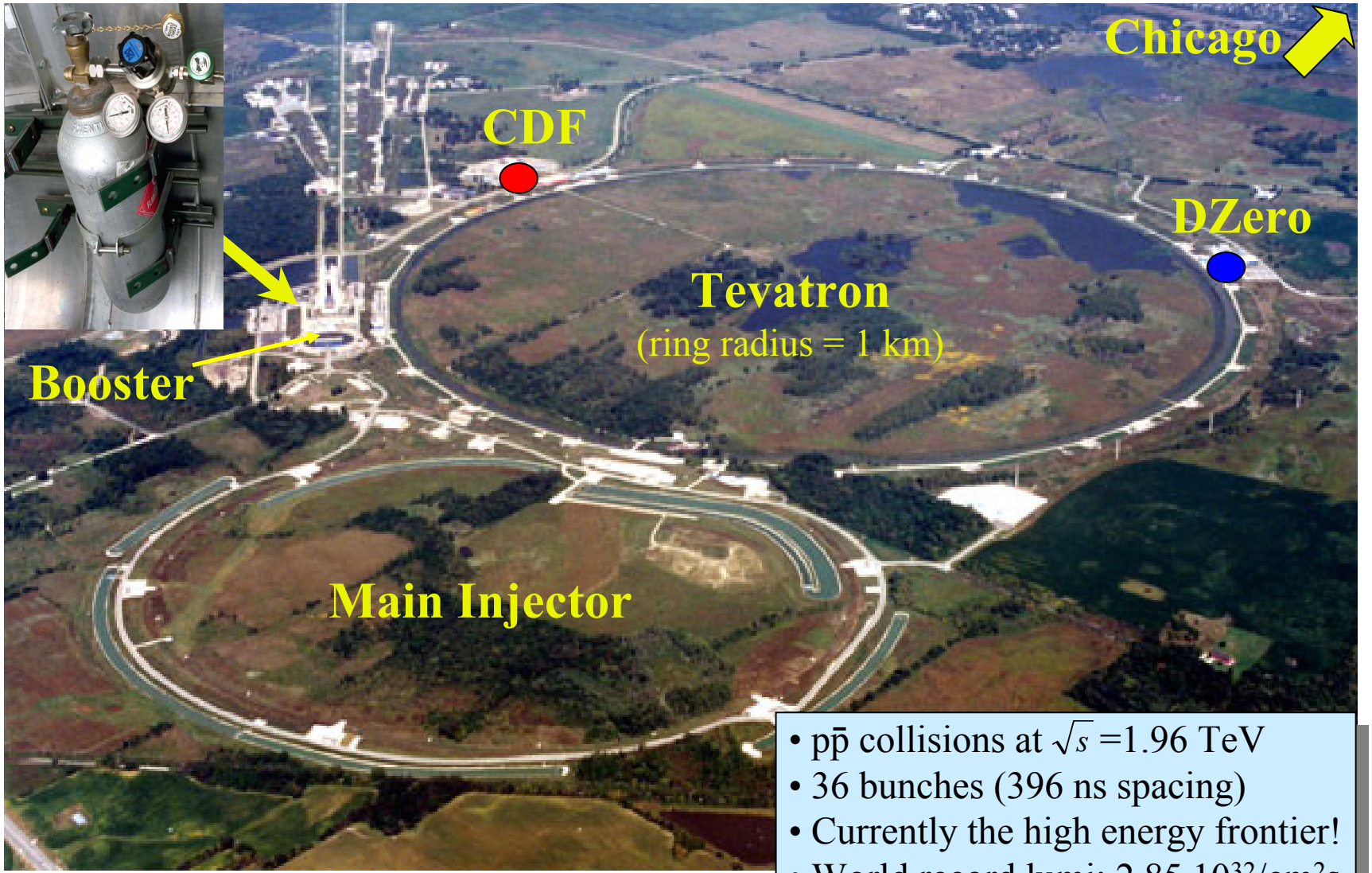
The discovery of the Top Quark



- **Top is massive: $m_t = 176 \pm 13$ GeV (using 12 Top events!)**
- **Short lifetime $\tau \approx 5 \cdot 10^{-25}$s $\Rightarrow$ decay before hadronisation**
- **Very little is known about this particle…**
- **Is this really the Standard-Model Top Quark???**

Where can we study Top Quarks?

The Tevatron @ Fermilab



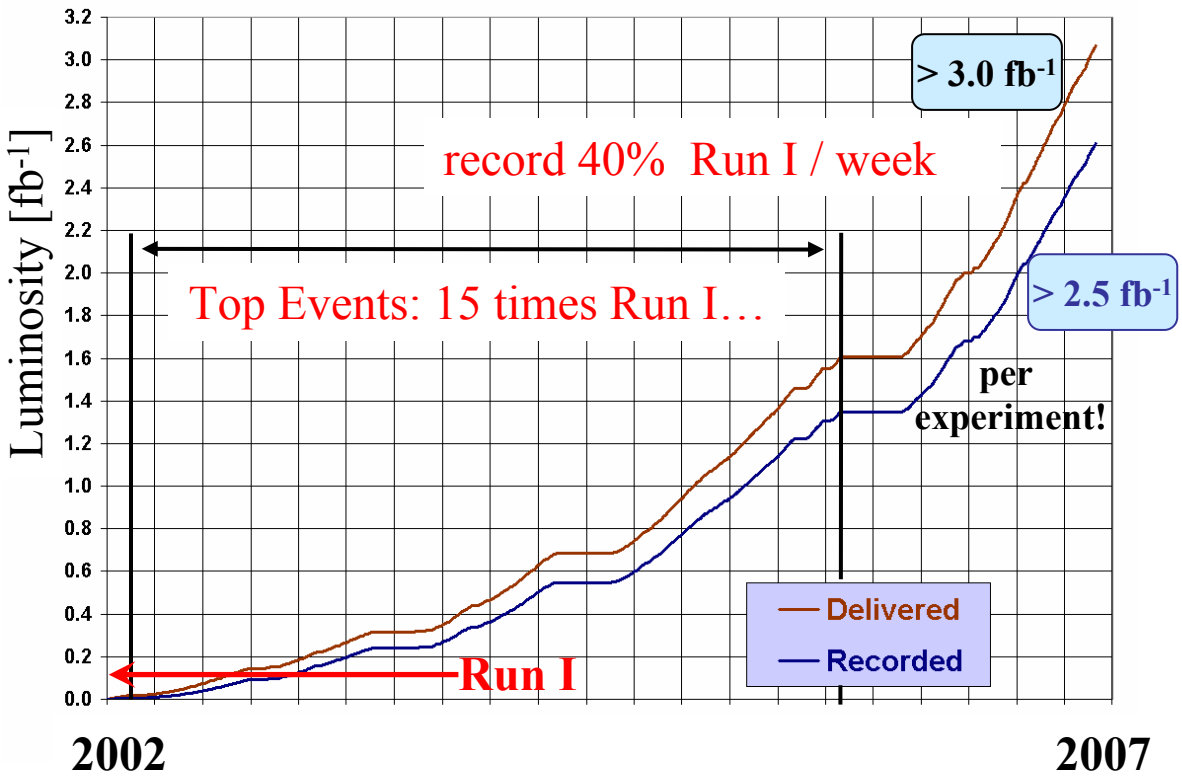
- $p\bar{p}$ collisions at $\sqrt{s}$ =1.96 TeV
- 36 bunches (396 ns spacing)
- Currently the high energy frontier!
- World record lumi: $2.85 \cdot 10^{32}/cm^2s$

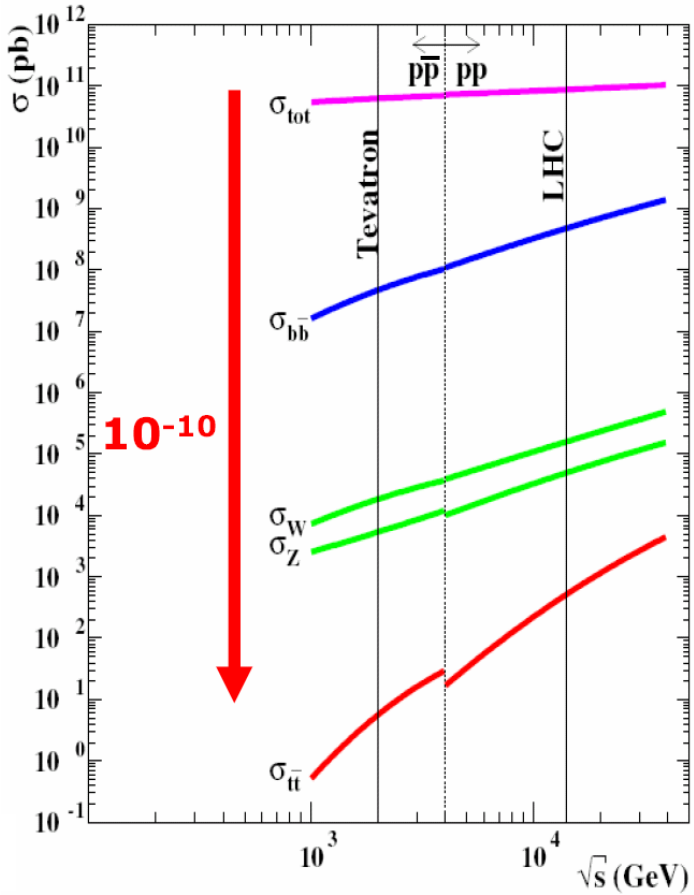
Top Quark Production @ Tevatron: The precision era

Top Discovery: Tevatron "Run I" ('92-'96): ~125pb^{-1}, $\sqrt{s}$ = 1.8 TeV.

Now "RunII":
- Increased luminosity
- Increased $\sqrt{s}$: 1.96 TeV $\Rightarrow$ +30% σ_{Top}

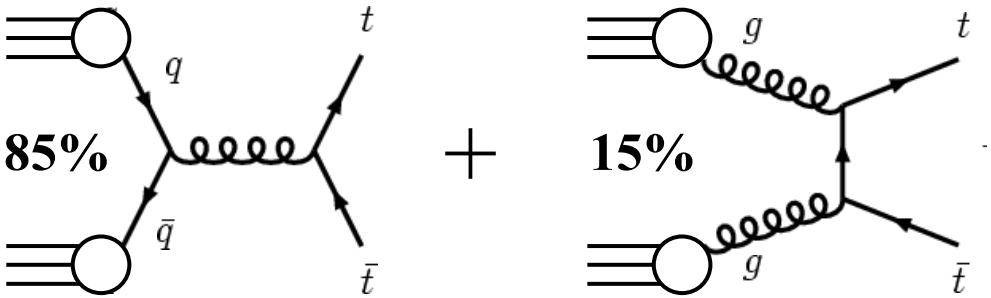
Run II Integrated Luminosity 19.4.2002 – 17.6.2007





Top Quark Production & Decay

- Main **production** of Top Quarks – via strong interaction in *pairs*:

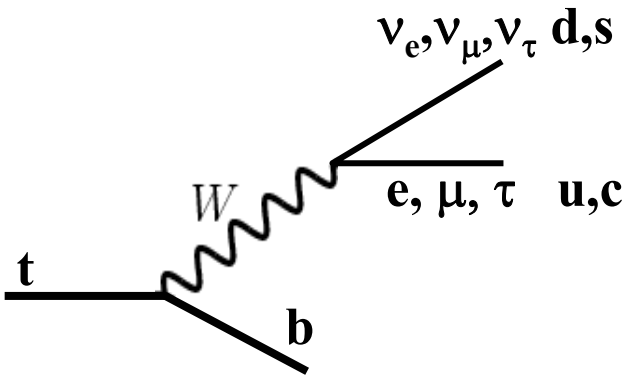


Theoretical expectation:

$$\sigma_{t\bar{t}} = (6.77 \pm 0.65)\ \text{pb}$$

N. Kidonakis, priv. comm., m_t=175 GeV/c^2

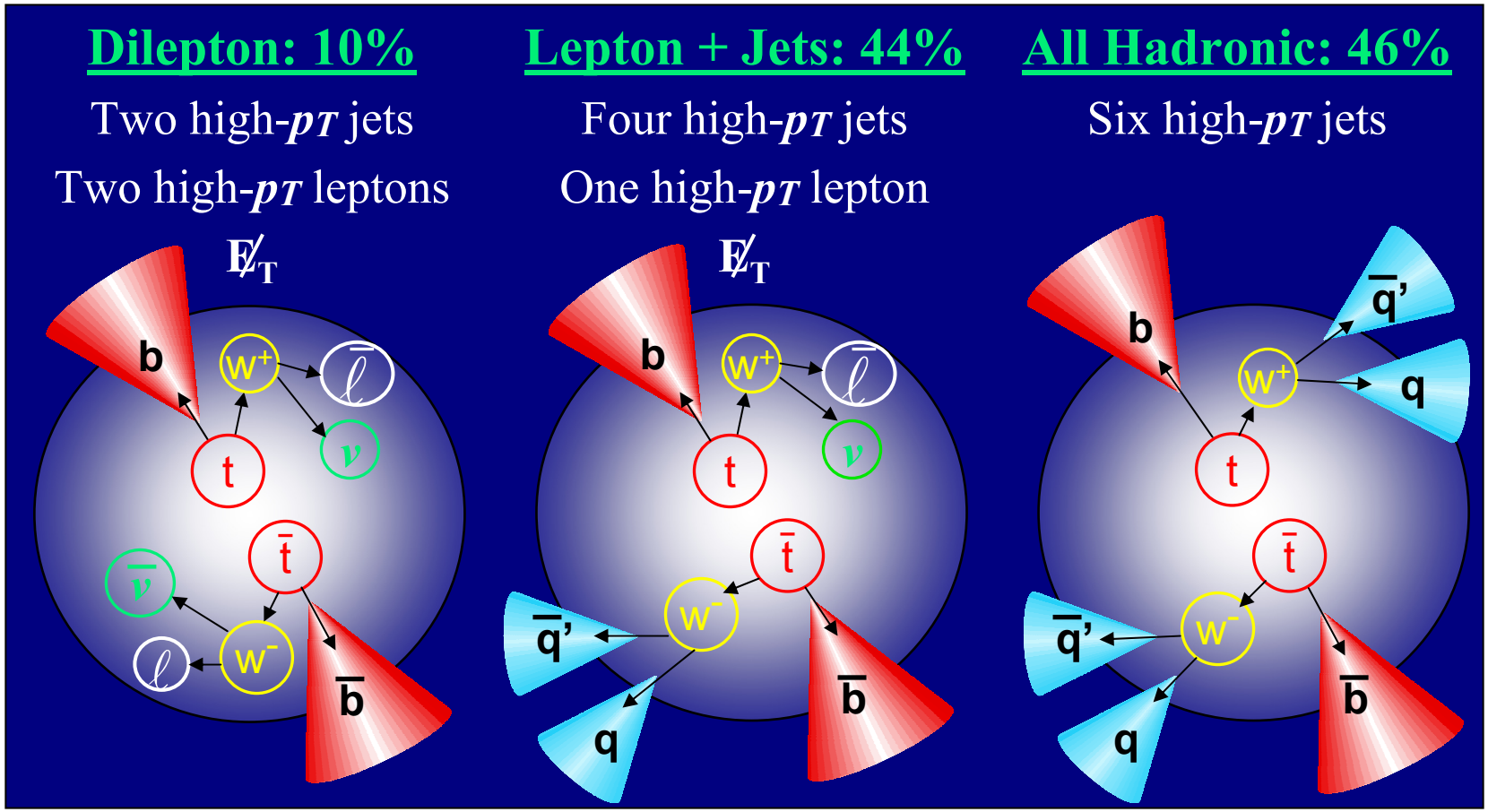
- EW *Single Top* production: first evidence by DØ, *see next presentation*!
- SM Top **decay** ≈100% Wb ⇒ Final states determined by W decay mode
  - ⇒ 2 b-jets,
  - ⇒ Up to two charged leptons/neutrinos
  - ⇒ Up to four additional jets



Need to reconstruct/identify:

- **Electrons, muons, taus,**
- **Missing transverse energy**
- **Jets/b-jets**

Classification of Top Quark pair events



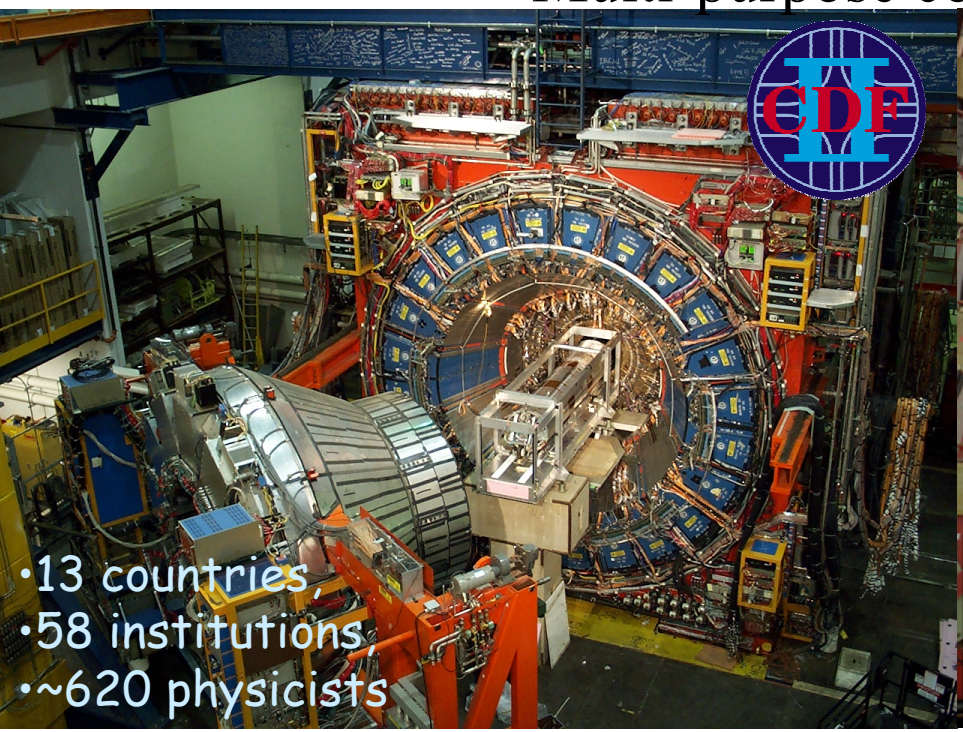
- low branching fraction
- low background
  (WW+jets, Z+jets, W+jets)

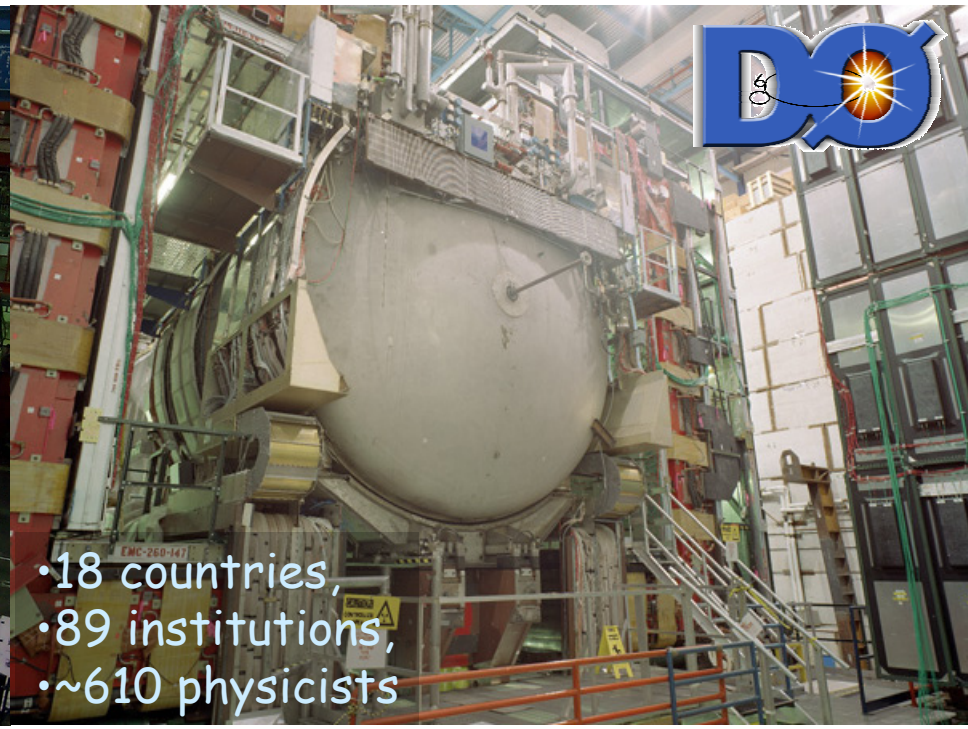
- high branching fraction
- manageable background
  (W+jets, "QCD" multijet prod.)

- high branching fraction
- high background
  ("QCD" multijet production)

The Tevatron Collider Experiments

Multi-purpose collider detectors:



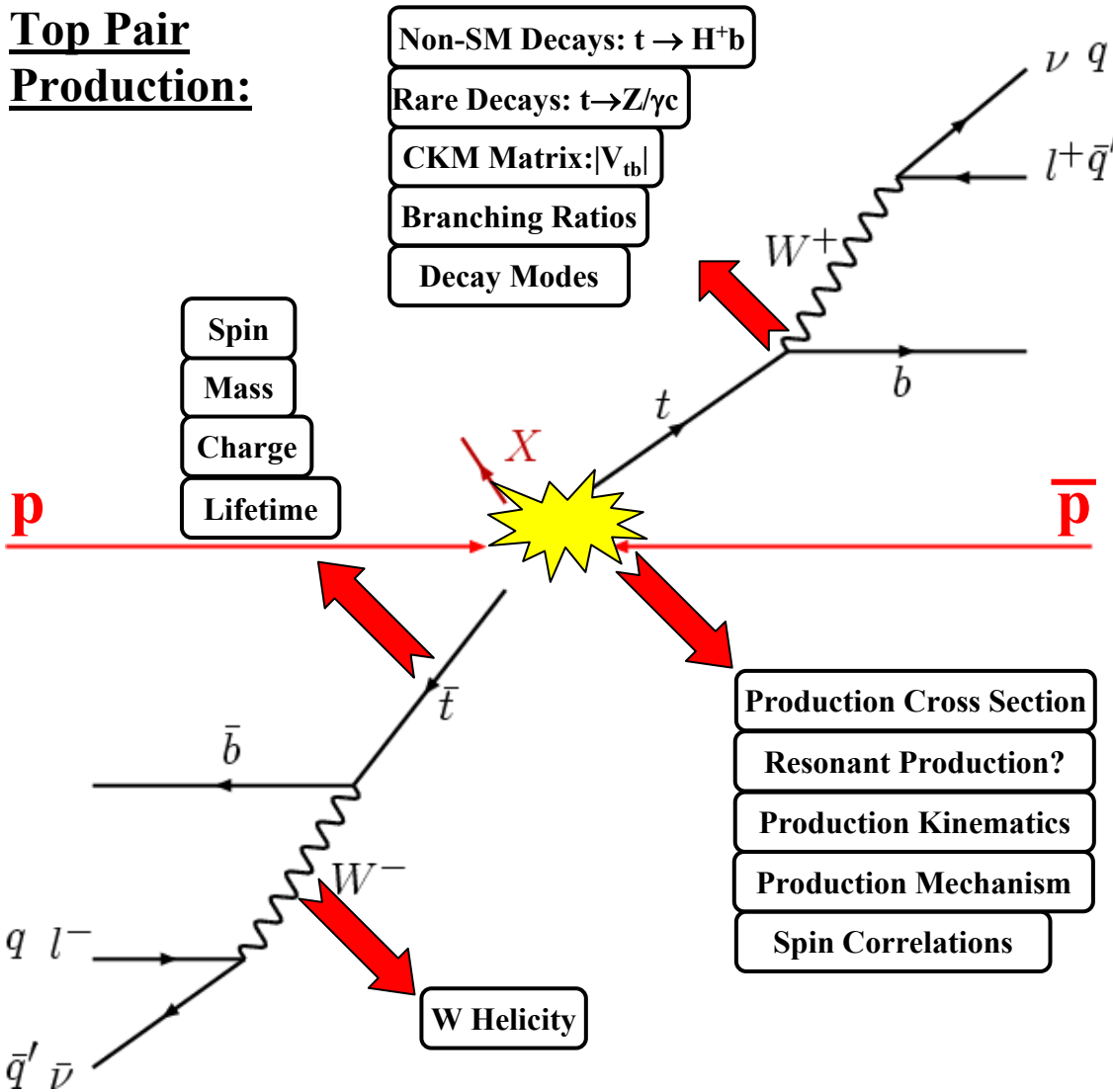


Top Quark physics needs everything:

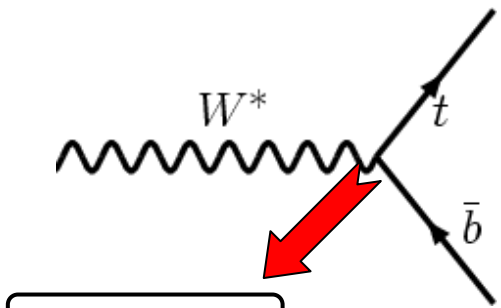
- Central tracking and vertexing (momentum measurement, b-jet ID)
- Excellent calorimetry (jets, electrons, missing transverse energy)
- Good muon detection in large acceptance

What do we want to measure?

Top Pair Production:



Single Top Production:

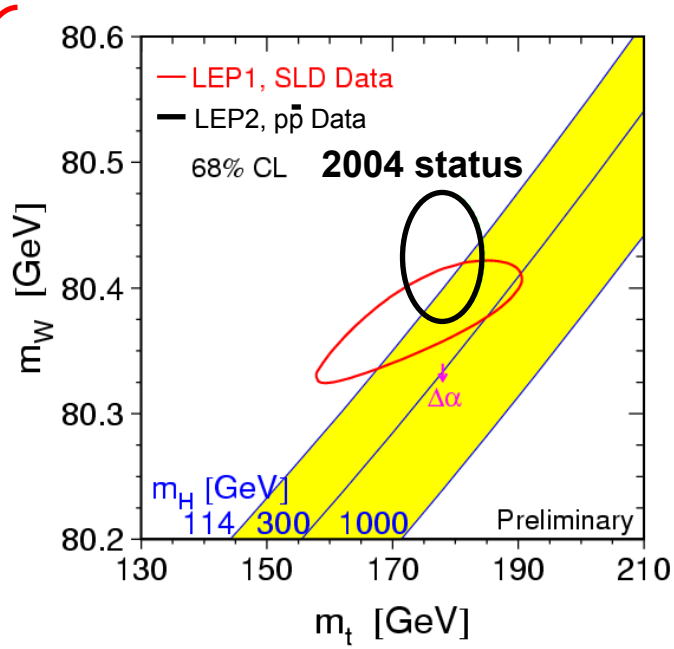


…everything!

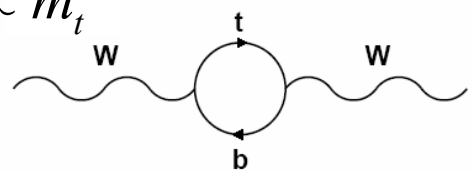
Selected Measurements for today

- **Production rate:**
  Test Standard Model (QCD) predictions
- **Charge:**
  Is the charge of the Top Q = 2/3 ?
- **W-helicity:**
  Test V-A interaction
- **Mass:**
  Radiative corrections on the W mass allow constraints on **Higgs mass** from m_W, m_t

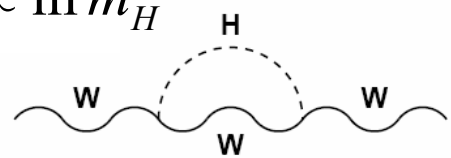
Is this the Standard Model Top Quark?



$$\Delta m_W \propto m_t^2$$



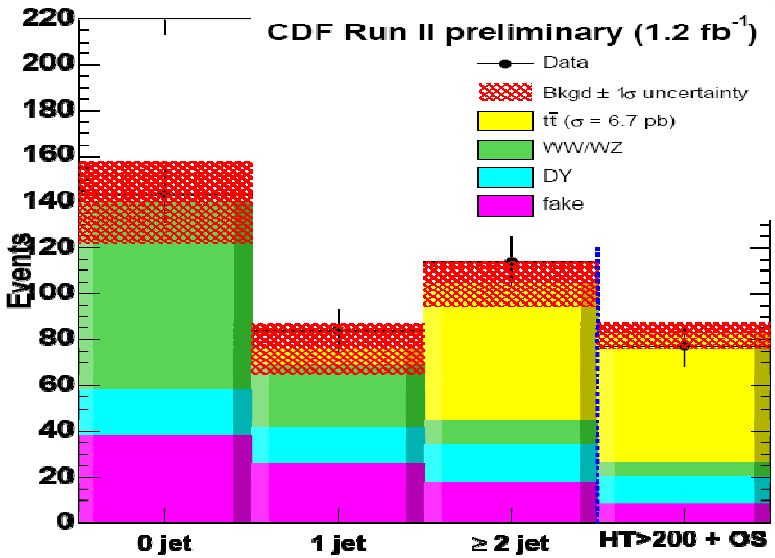
$$\Delta m_W \propto \ln m_H^2$$

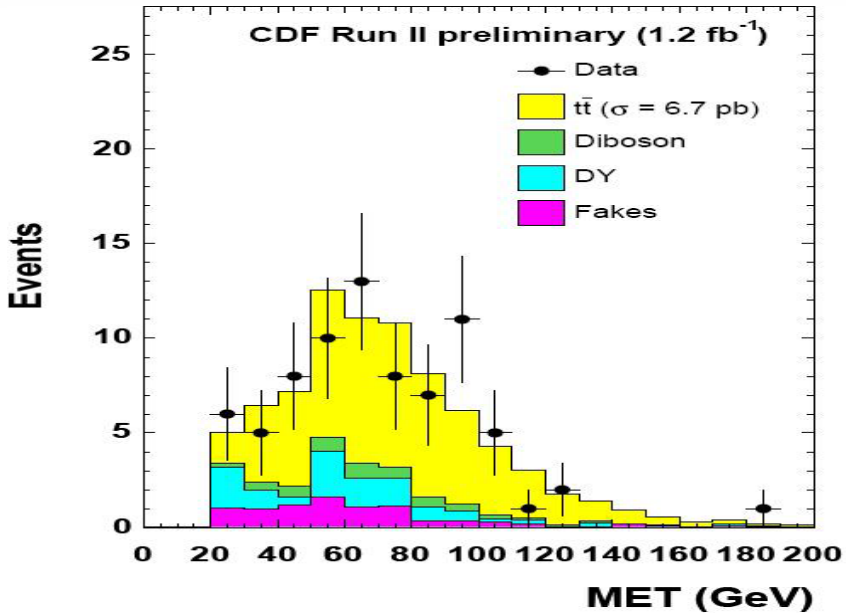


Top Quark Pair Production: Dilepton channels

- **Signature:** isolated high p_T ee, μμ, eμ, ≥ 2 jets, $\not\!\!E_T$
- **Main Backgrounds:**
  - WW(→ ee,μμ,eμ) + jets
  - Z/γ* (→ ττ→ eμ) + jets
  - Z/γ* (→ ee,μμ) + jets
  - W + jets (jet fakes isolated e,μ)

Source	ee	μμ	eμ	ℓℓ
Total background	6.86±1.70	10.47±2.06	8.23±2.30	25.56±5.54
$t\bar{t}$ (σ = 6.7 pb)	12.18±0.94	13.60±1.04	30.17±2.30	55.95±4.26
Total SM expectation	19.04±2.26	24.08±2.68	38.40±3.90	81.52±8.92
DATA	16	26	35	77





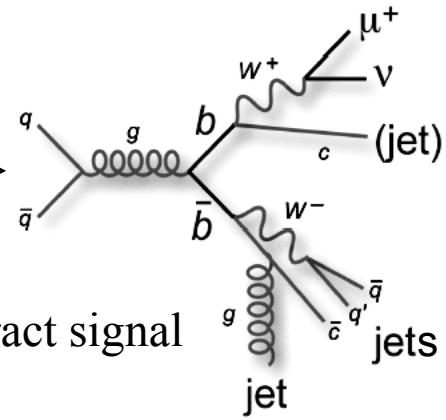
$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bkg}}{\int L\,dt \cdot Br \cdot \varepsilon \cdot A}$$

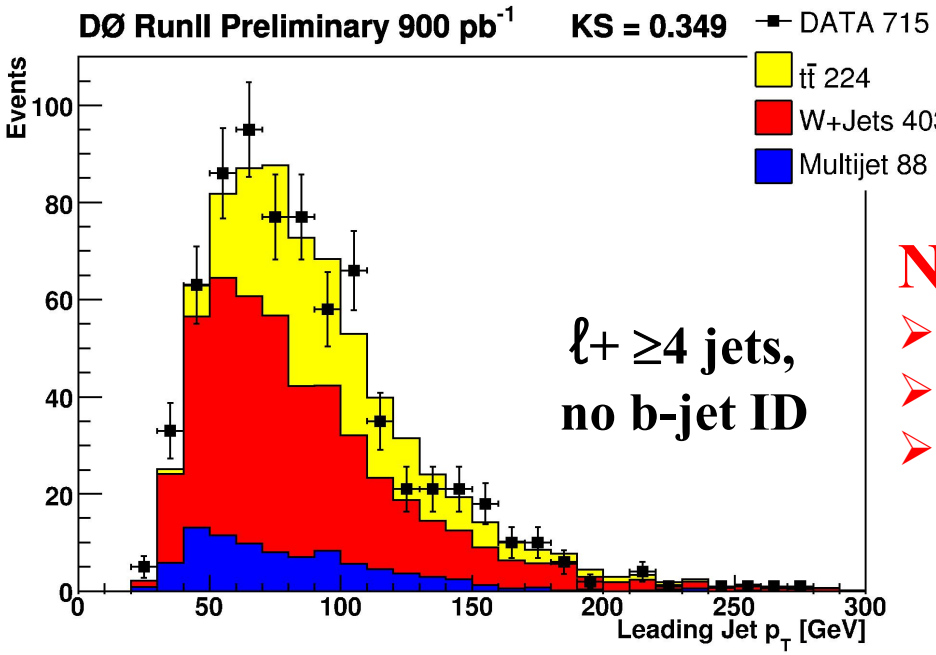
$\sigma_{tt} = 6.2 \pm 1.1$ (stat.) ± 0.7 (syst.) ± 0.4 (lumi) pb

(Standard Model expectation: 6.7 pb)

Top Quark Pair Production: Lepton+Jets channels

- **Signature:** isolated high p_T lepton, $\not\!\!E_T$, ≥4 jets
- **Main Backgrounds:**
  - Multijet production with fake lepton, $\not\!\!E_T$
  - W production, $W \rightarrow \ell+\nu_\ell + \geq 4$ jets from gluon radiation
- Before b-jet identification: high background levels
- Use multivariate discriminant (event topology/kinematics based) to extract signal



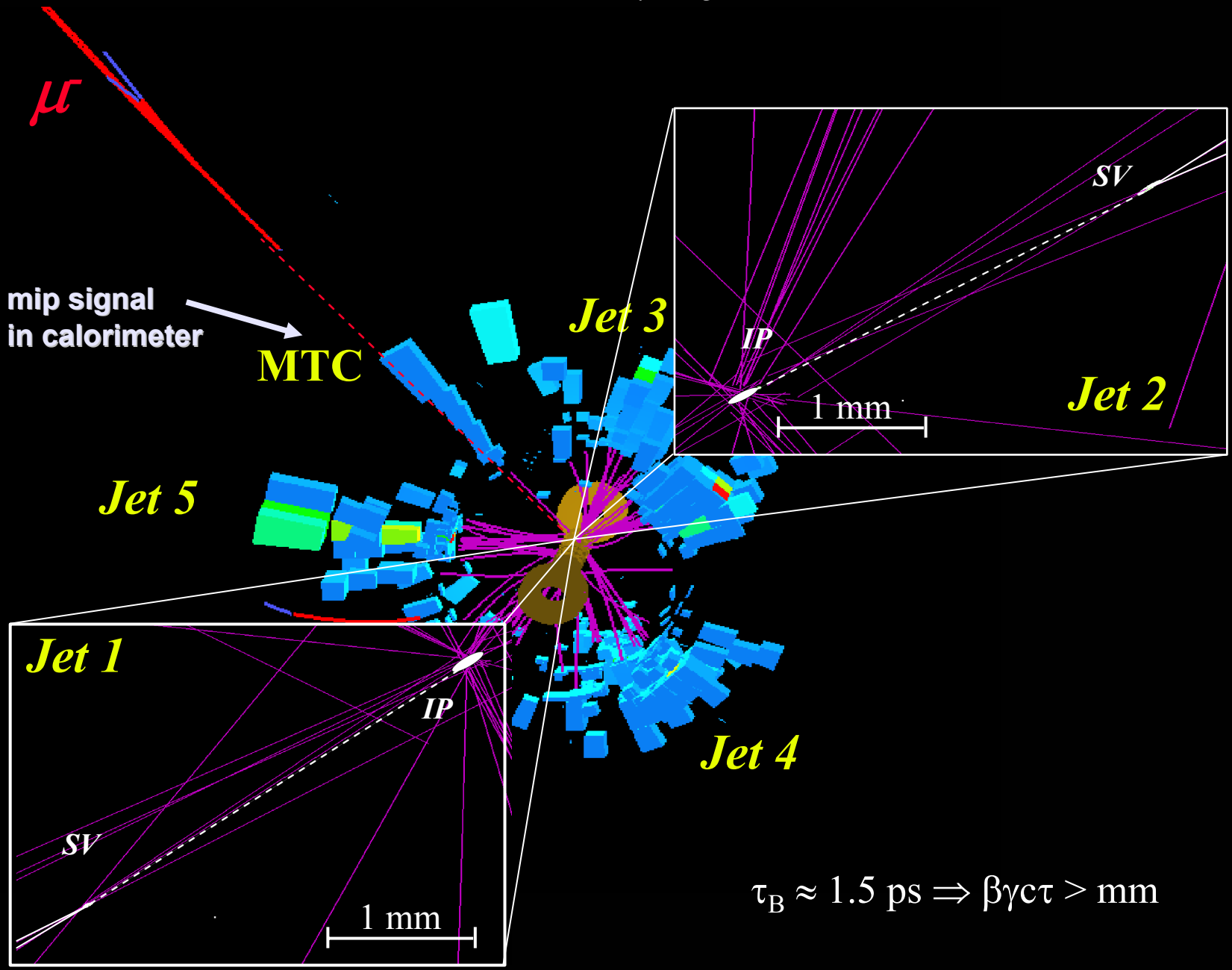


No b-jet identification required:

- ➢less model-dependent measurement
- ➢test understanding of sample composition
- ➢not full information used ⇒ reduced precision

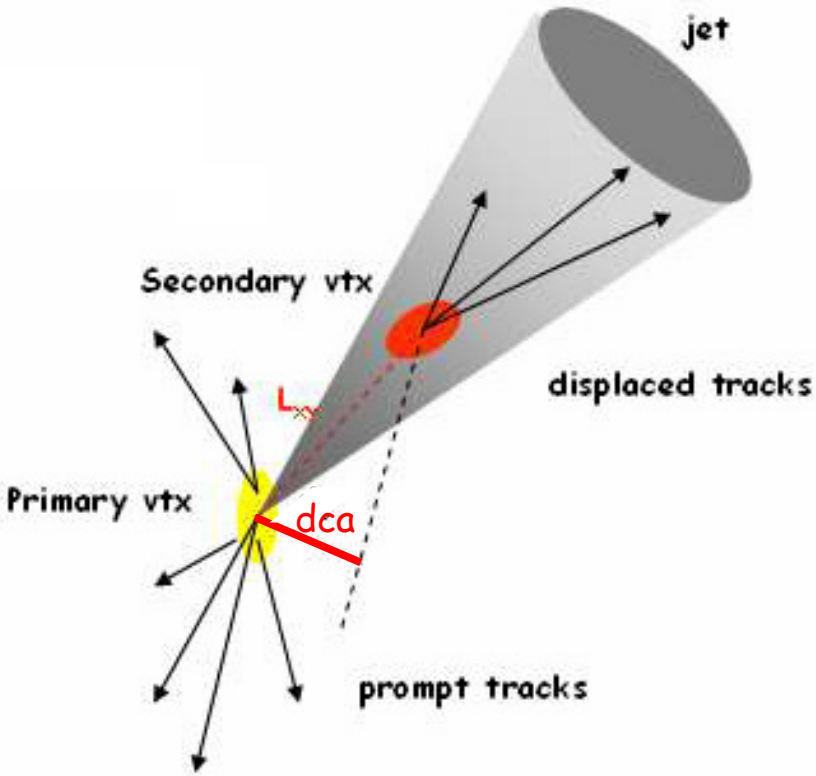
$$\sigma_{tt} = 6.3^{+0.9}_{-0.8}\,(\text{stat}) \pm 0.7\,(\text{syst}) \pm 0.4\,(\text{lumi})\,\text{pb}$$

$t\bar{t} \rightarrow \mu$+jets candidate event



$\tau_B \approx 1.5$ ps $\Rightarrow \beta\gamma c\tau >$ mm

Lifetime b-tagging



(dca = distance of closest approach)

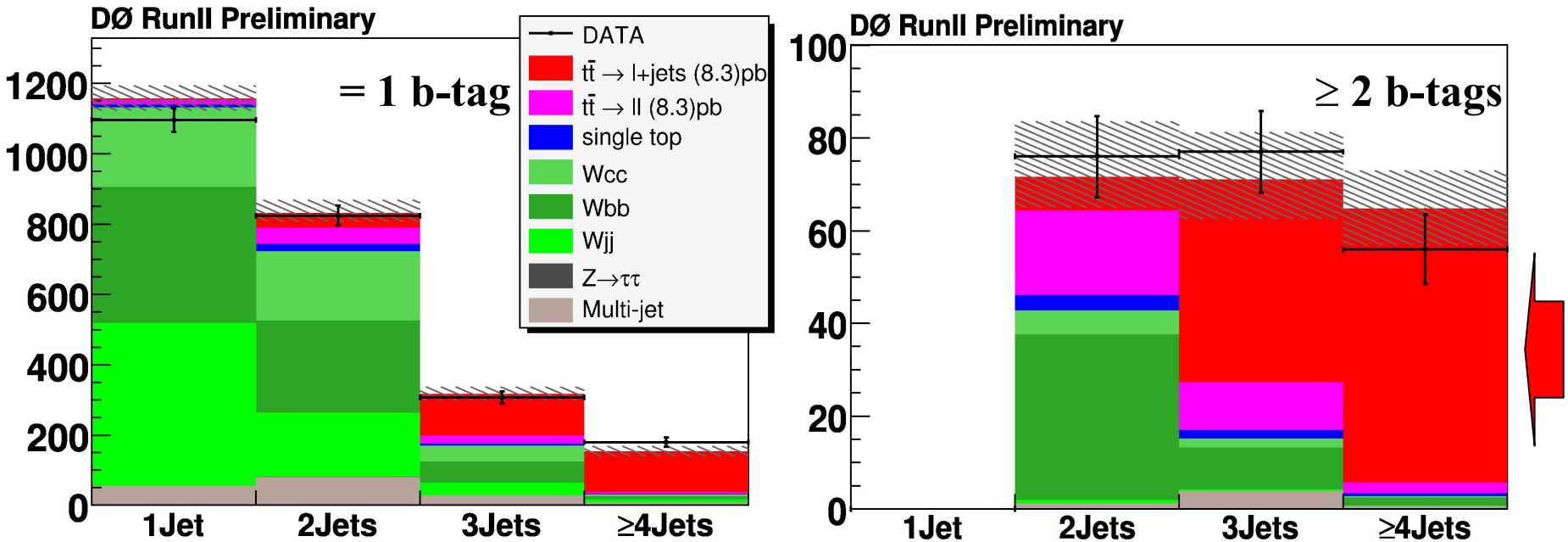
- Separate *b*-jets from light-quark and gluon jets ⇒ reject most multijet & *W*+jets background processes
- $\tau_B \approx 1.5$ ps ⇒ $\beta\gamma c\tau >$ mm
- Use impact parameter / reconstructed secondary vertex information
- "Tagging" efficiencies:
  - *b*-jet ≈ 50%
  - *c*-jet ≈ 10%
  - light-jet ≈ 0.5%

Top Quark Pair Production: Lepton + Jets channels

Strategy:

- **Require b-tagged jets** in the event to further suppress background
- Analyse eight channels separately: e/μ, 1/≥2 tags, 3/≥4 jets
- Perform maximum likelihood fit to observed number of events in the different channels

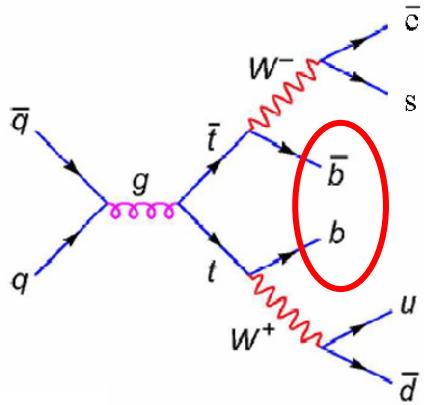
~900 pb^{-1} lepton+jets data

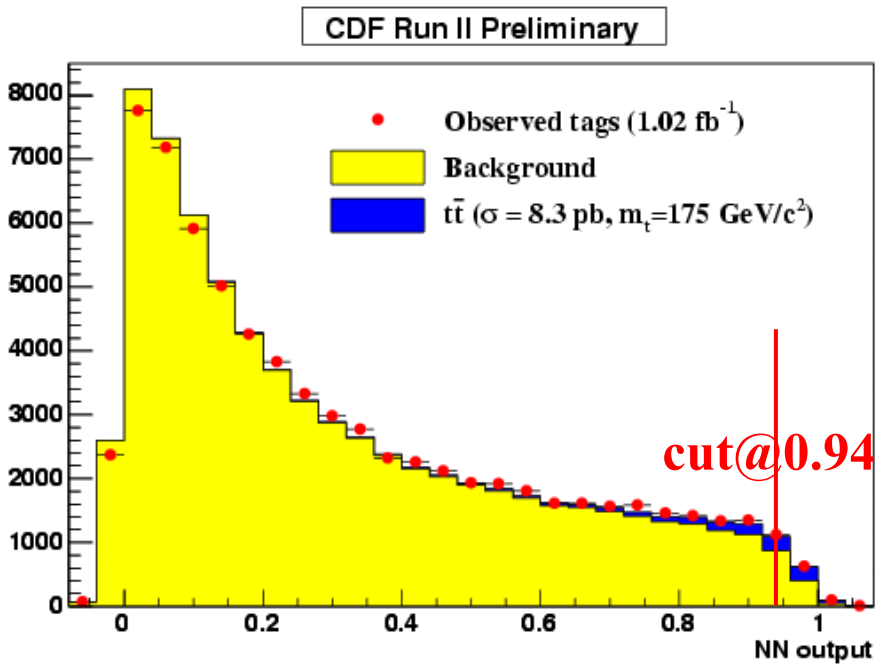


$$\ell + \text{jets} \;:\quad \sigma_{p\bar{p}\to t\bar{t}+X} = 8.3^{+0.6}_{-0.5}(\text{stat})\,^{+0.9}_{-1.0}(\text{syst}) \pm 0.5(\text{lumi})\ \text{pb}$$

Top Quark Pair Production: All hadronic channel

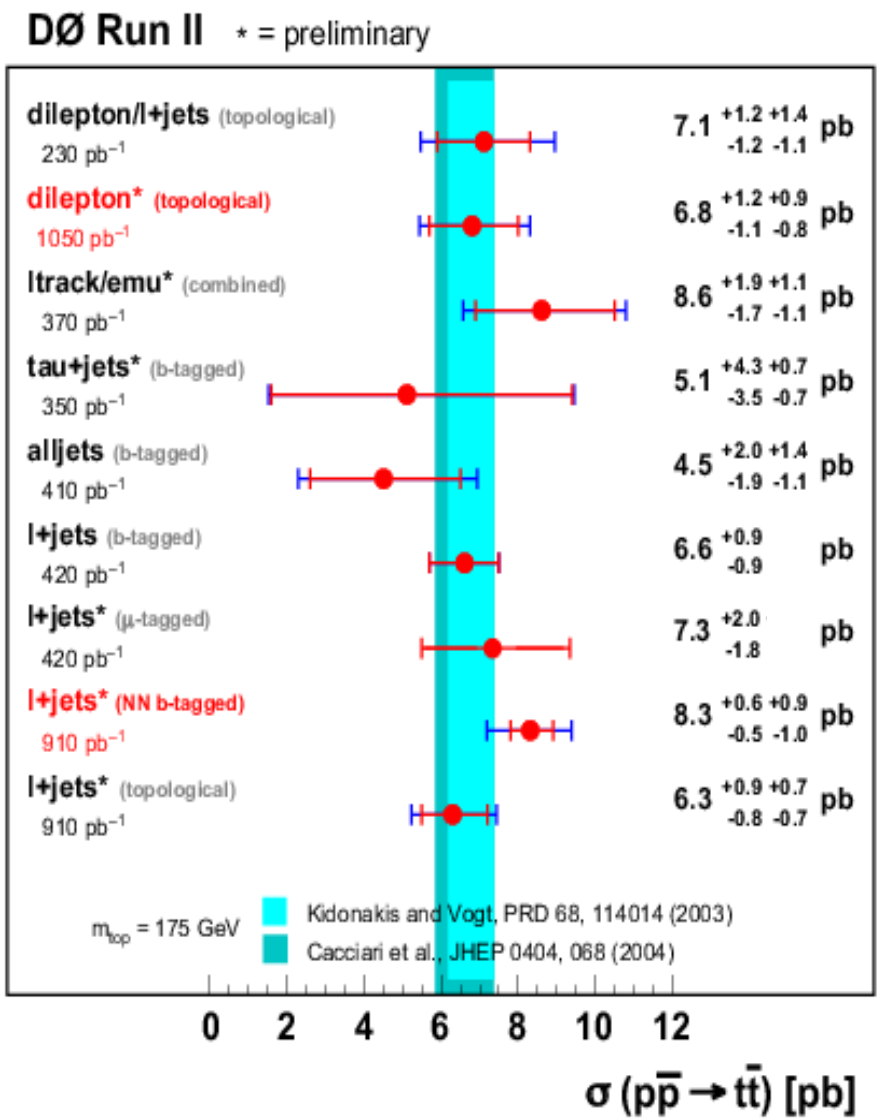
- **Signature:** ≥6 jets, **no** isolated high p_T lepton, **no** $\not\!\!E_T$
- **Main Backgrounds:**
  - Overwhelming "QCD" Multijet production
  - Jets from multiple interactions
- Require ≥ 1 b-jets, use multivariate kinematical selection (based on total transverse energy, masses of jet combinations,…)

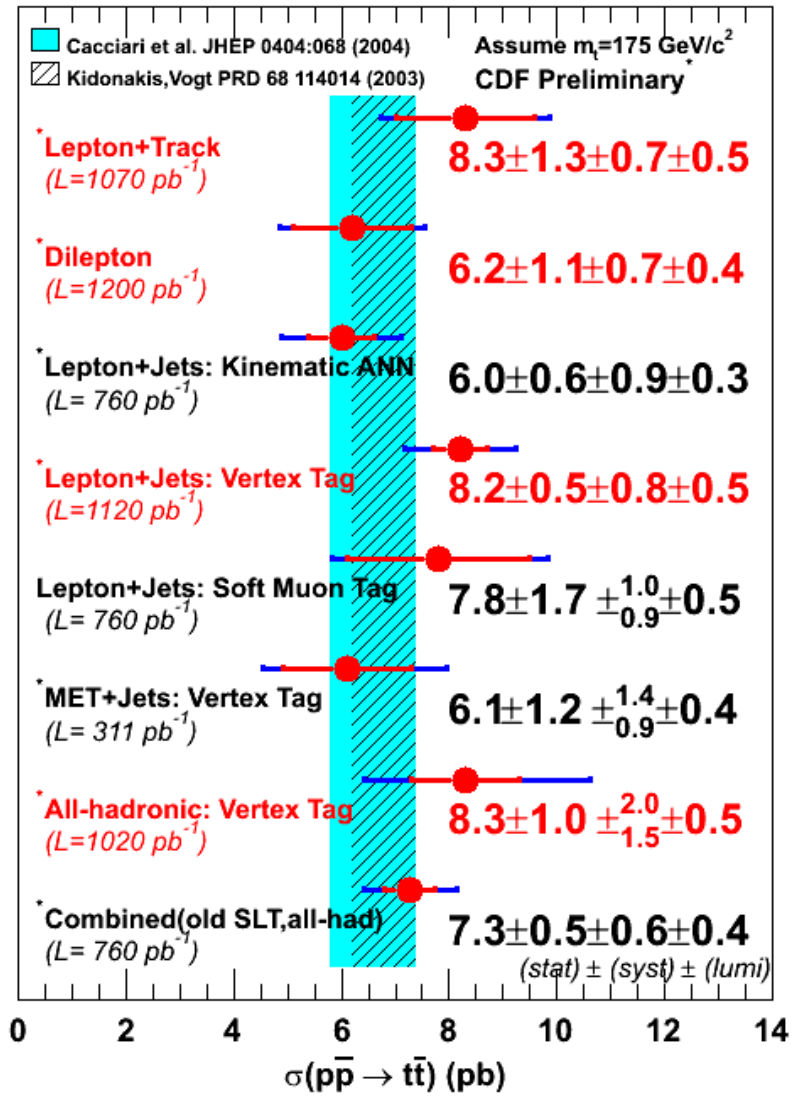




$$\sigma_{tt} = 8.3 \pm 1.0\,(\text{stat})^{+2.0}_{-1.5}\,(\text{syst}) \pm 0.5\,(\text{lumi})\,\text{pb}$$

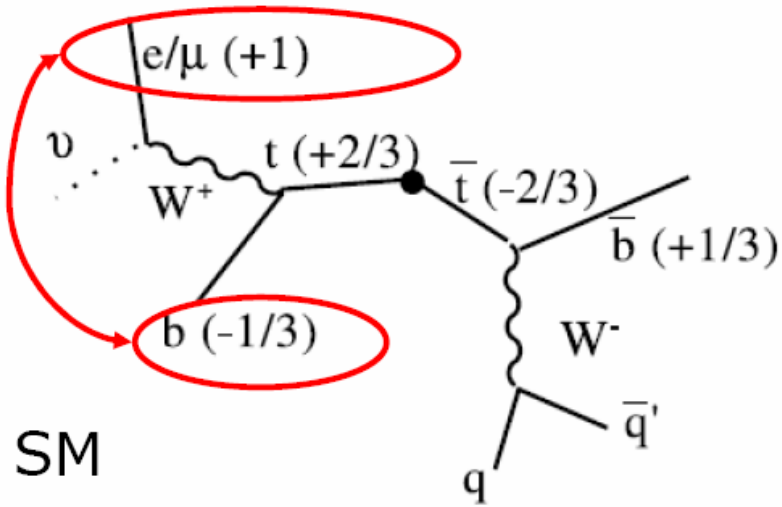
Top Quark Pair Production: cross sections



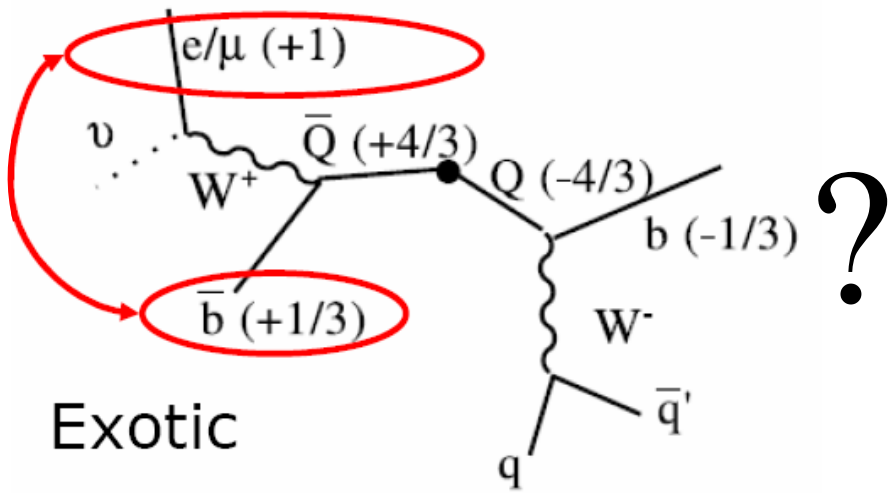


Measurement of the Top Charge

- Standard Model Top Quark has charge Q = +2/3
- Pairing the W boson to the b quark jet in Top pair events is ambiguous
- Discovered particle could have charge |Q| = 2/3 or |Q| = 4/3
- Use pure top samples to investigate: double-tagged l+jets, tagged dilepton
- Exotic model*:
  - Predicts quark doublet with charges Q = -1/3 and Q = - 4/3
  - Particle discovered at Fermilab would be Q = -4/3 particle
  - The Standard Model Top Quark would have m ≈ 270 GeV.



OR



* D. Chang *et. al.*, PRD **59**, 091503 (1999)

Measurement of the Top Charge

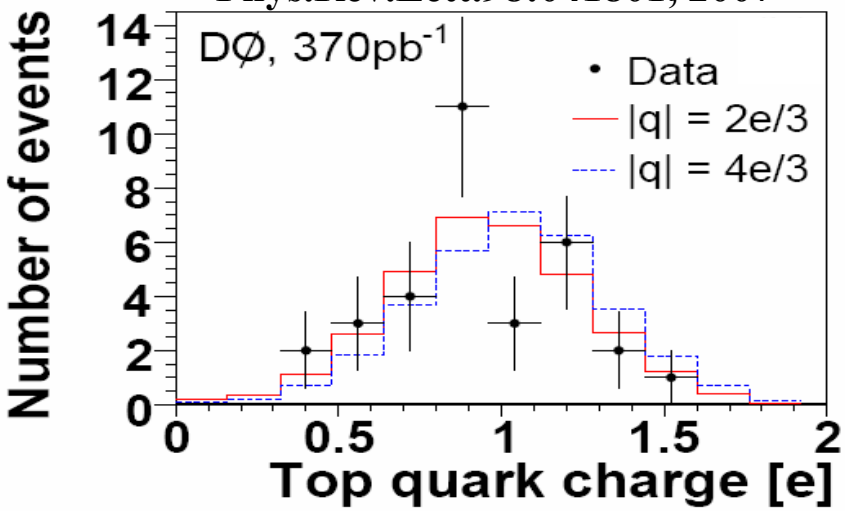
- **Pairing of W and b-jet:**
  Lepton+jets: kinematic fit
  Dilepton: select on $M^2(l,b)$
- **W-charge:** from lepton charge
- **b-jet charge:** use momentum-weighted sum of charged tracks associated to b-jet
- **Calibration:** $b\bar{b}$ data using semi-leptonic b-jet decays to determine the charge (corrected for c-jets and B mixing)
- 2 measurements per event

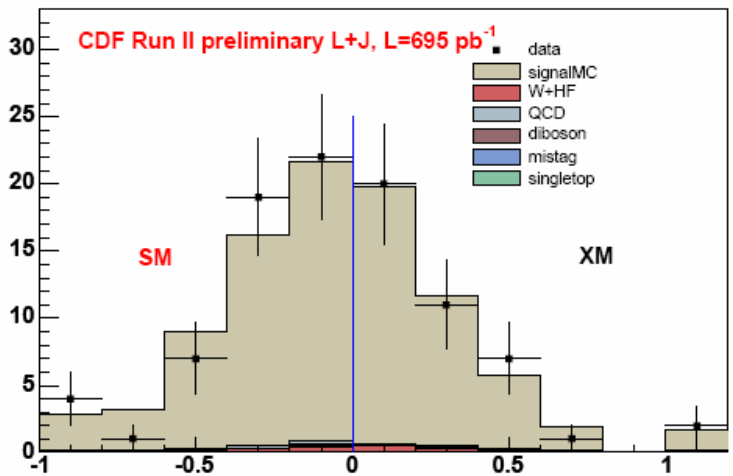
Bayes factor (odds of SM vs. exotic model):

- DZero: 4.3 (L+jets, 370 pb^{-1})
- CDF: 8.5 (Dilepton, L+jets, 695 pb^{-1})

DZero&CDF data strongly favour SM!

Phys.Rev.Lett.98:041801, 2007



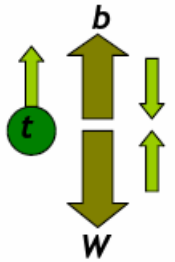


W charge · b-jet charge

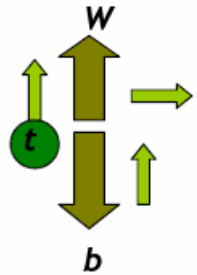
W Helicity

Standard Model top decay: V-A interaction (like for all fermions)

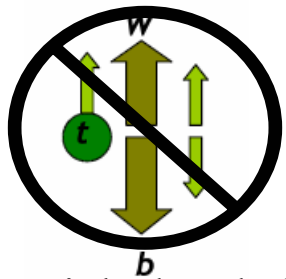
W helicity states:



left-handed fraction: f_-



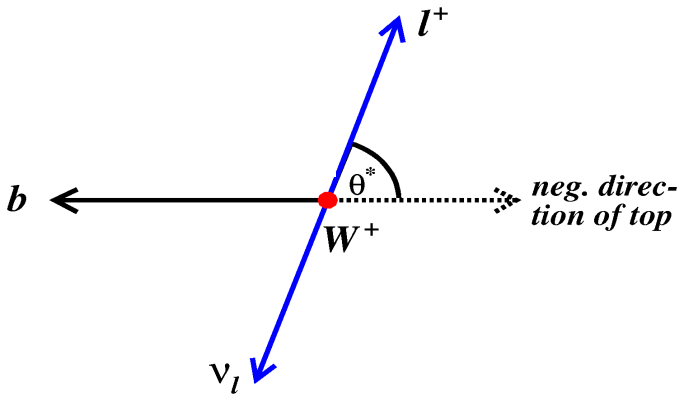
longitudinal fraction: f_0

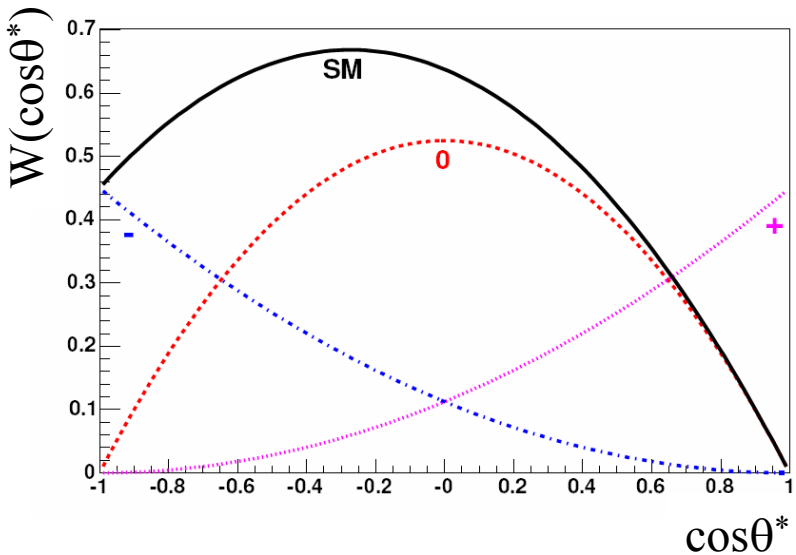


right-handed fraction: f_+

In Standard Model: **~30%** **~70%** **~0.036%**

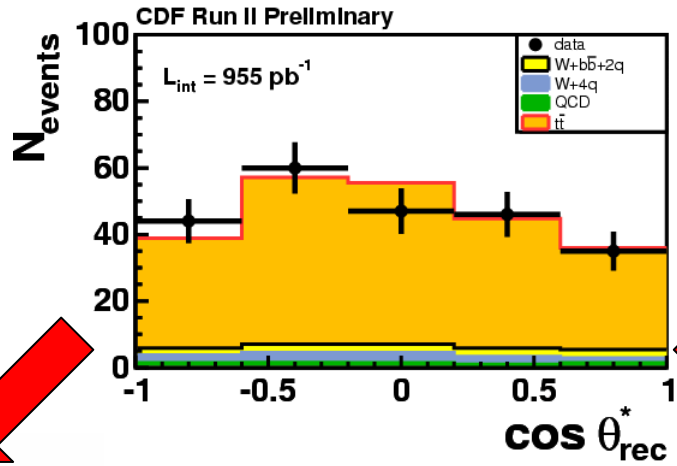
⇒ Measure angular distribution of charged lepton wrt. top in W rest frame: cosθ*



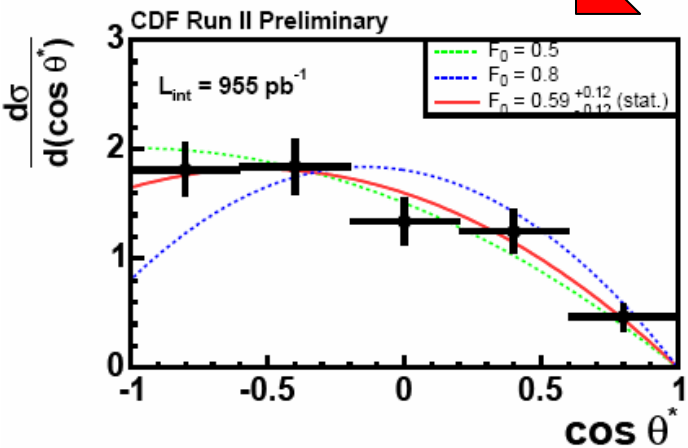


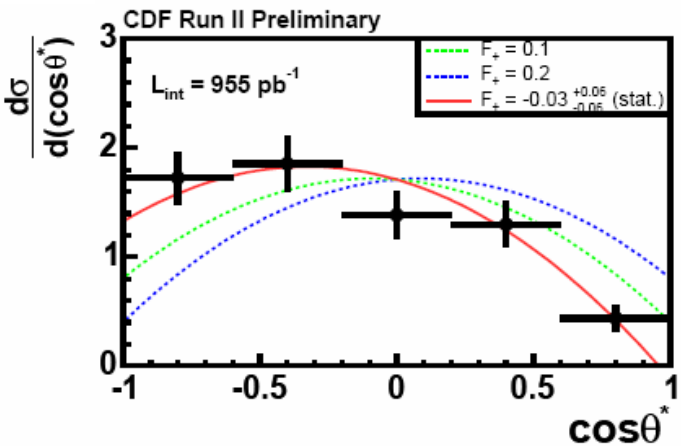
W Helicity

Use Lepton+Jets dataset
≥4 jets, ≥ 1b-jet identified:



subtract background,
correct for detector acceptance





Fit f_0, fixed f_+=0 (SM value):

$$f_0 = 0.59 \pm 0.12(\text{stat})^{+0.07}_{-0.06}(\text{syst})$$

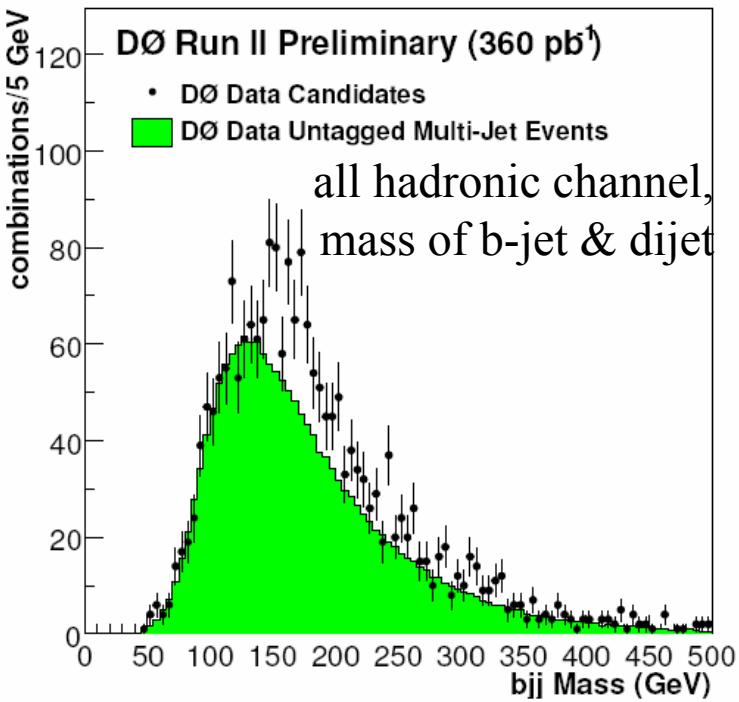
Fit f_+, fixed f_0=0.7 (SM value):

$$f_+ \leq 0.10 \text{ @ } 95\% \text{ C.L.}$$

Top Quark Mass Measurements

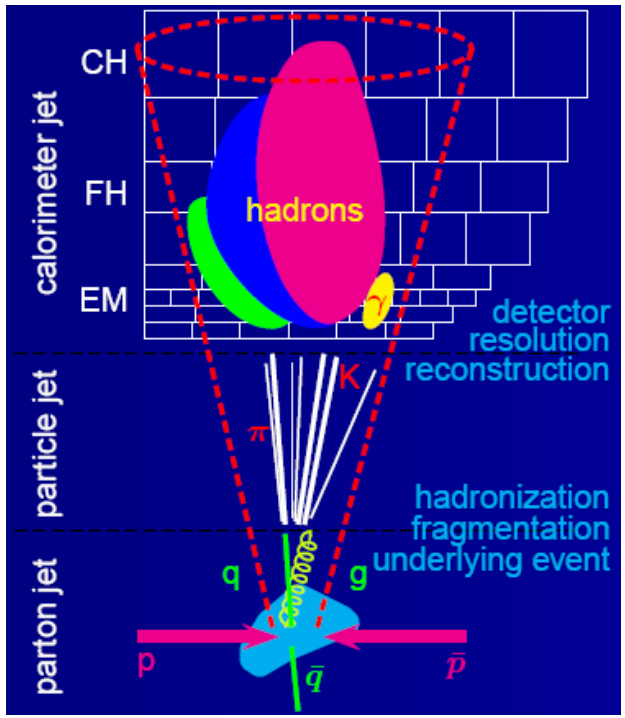
Many Methods exist - general features:

- Measure observable sensitive to Top mass
- Map partons to reconstructed objects (combinatorics!)
- Calibrate with pseudo-experiments
- Obtain mass via maximum likelihood



Need to relate the reconstructed calorimeter jets back to parton level:

Jet Energy Scale is crucial!



Top events: W boson decay products allow for additional **in-situ jet energy calibration**

Top Quark Mass Measurements: Matrix Element Method

- Matrix Element Method: yields so far most precise measurements
- Use four-vectors of reconstructed objects to calculate per event probability density for being signal/background as function of m_t
- Maximises use of information on the event, but CPU intense calculations
- Product of event probabilities allows to extract the most likely mass value:

Normalisation

Partonic differential Cross Section, based on LO Matrix Element

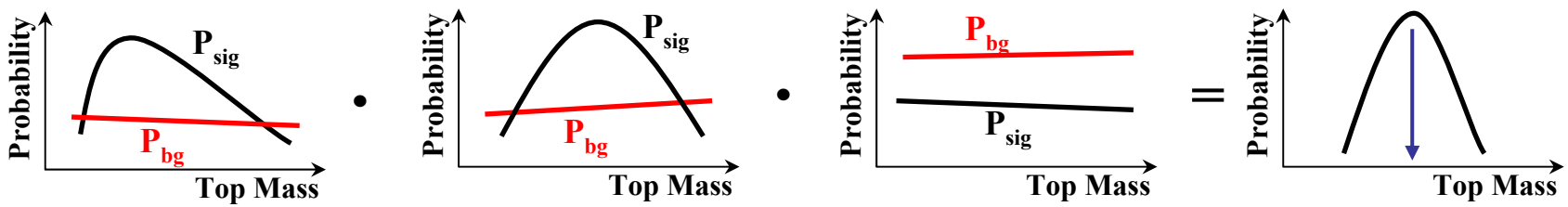
$$P_{t\bar{t}}(x, m_t, JES) = Acc(x)\frac{1}{\sigma_{t\bar{t}}(m_t)}\int dq_1 dq_2 f(q_1) f(q_2)\, d\sigma(y, m_t)\, T(x, y, JES)$$

use hadronic W decay

Acceptance

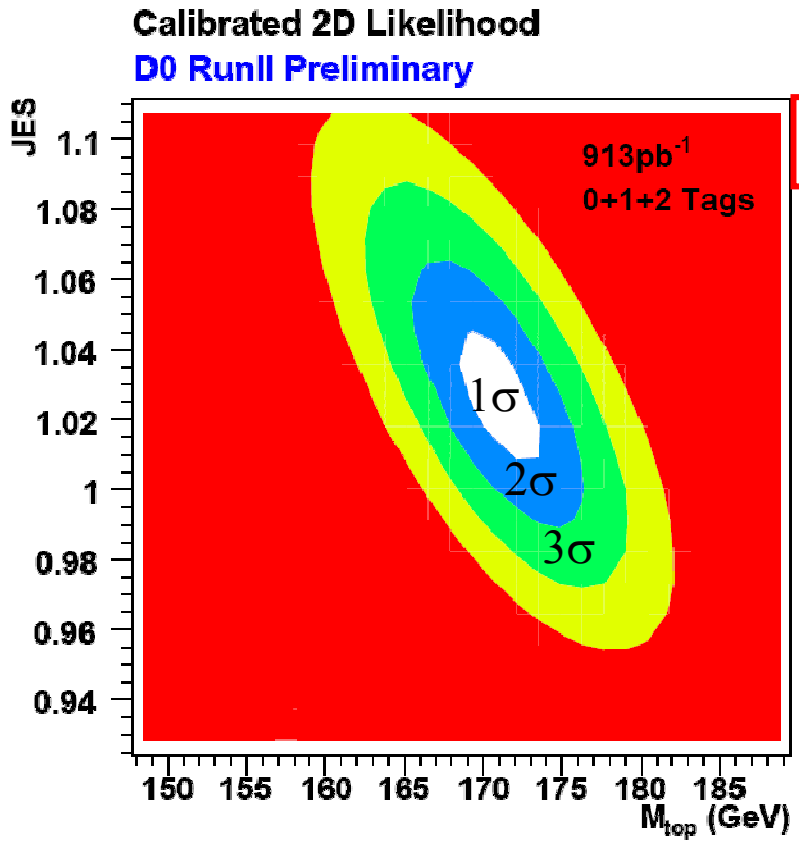
initial state

Transfer Function: Prob. to measure x from parton-level y



Top Quark Mass Measurements: Matrix Element Method

- P_{sig} = sum over all 24 possible object-parton assignments in l+jets events, weighted with b-tagging event probabilities
- Event probability $P = f_{sig}\, P_{sig}(x, m_t, JES) + (1-f_{sig})\, P_{bg}(x)$
- Calibrate method against simulation

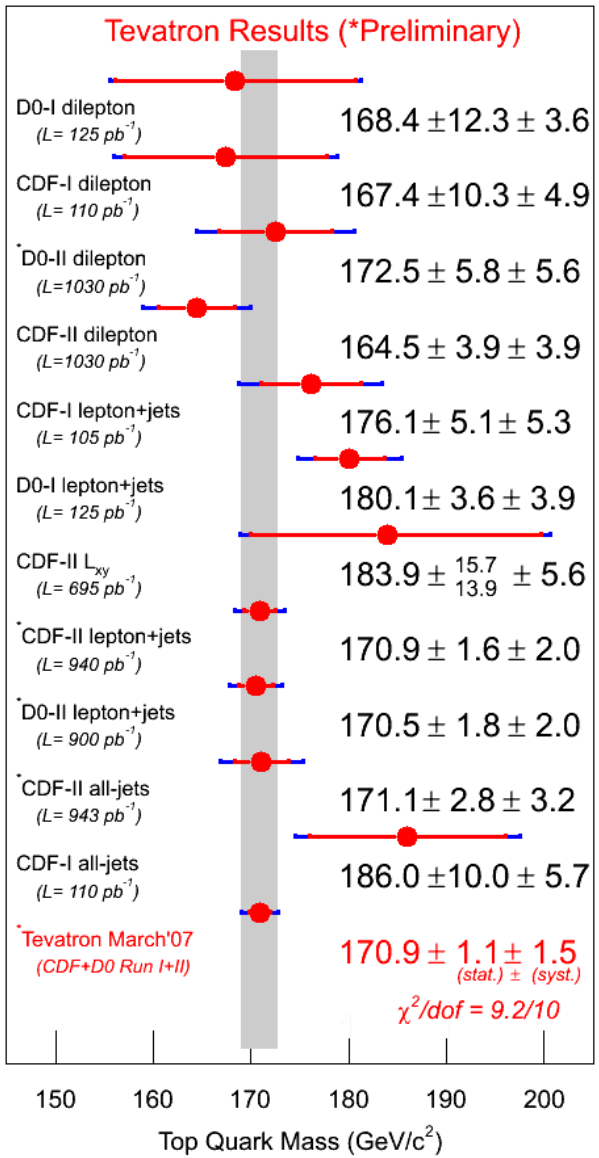


m_{Top} =170.5 ± 2.4(stat. + JES) ± 1.2(syst.) GeV

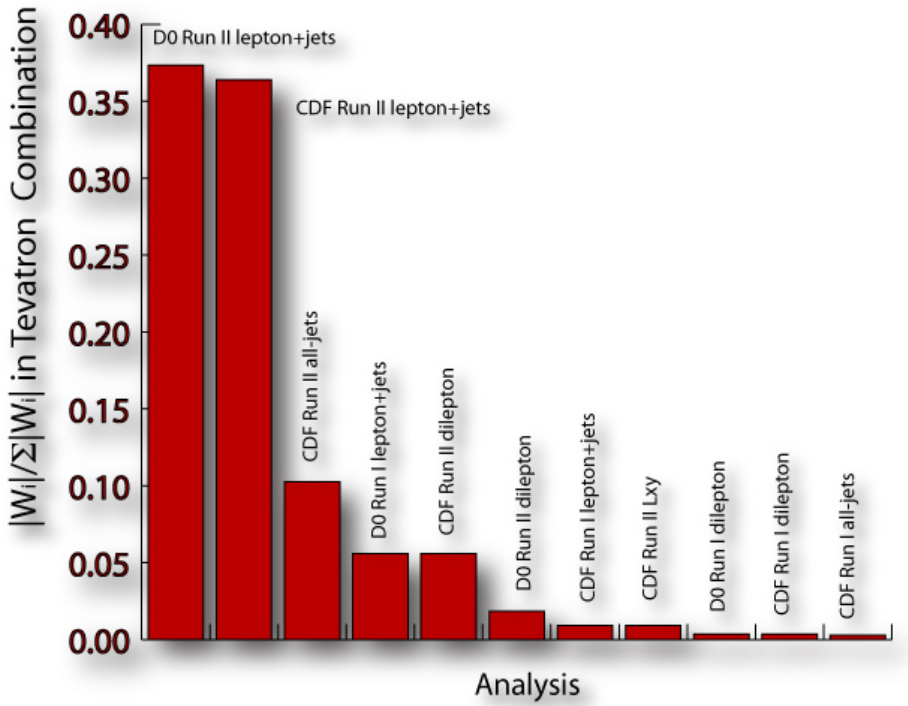
dominant systematic errors:

- relative light/b JES: ±0.57 GeV
- b fragmentation: ±0.54 GeV
- signal fraction: +0.53 -0.24 GeV
- signal modelling: ±0.45 GeV

Tevatron Top Quark Mass



weights in world average:

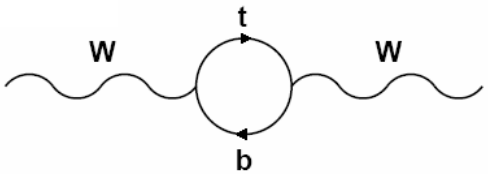


1.1 % precision!

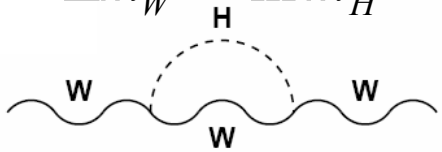
Aim for Δm_t = 1-1.5 GeV in Run II

Top Quark Mass and SM Higgs

$\Delta m_W \propto m_t^2$

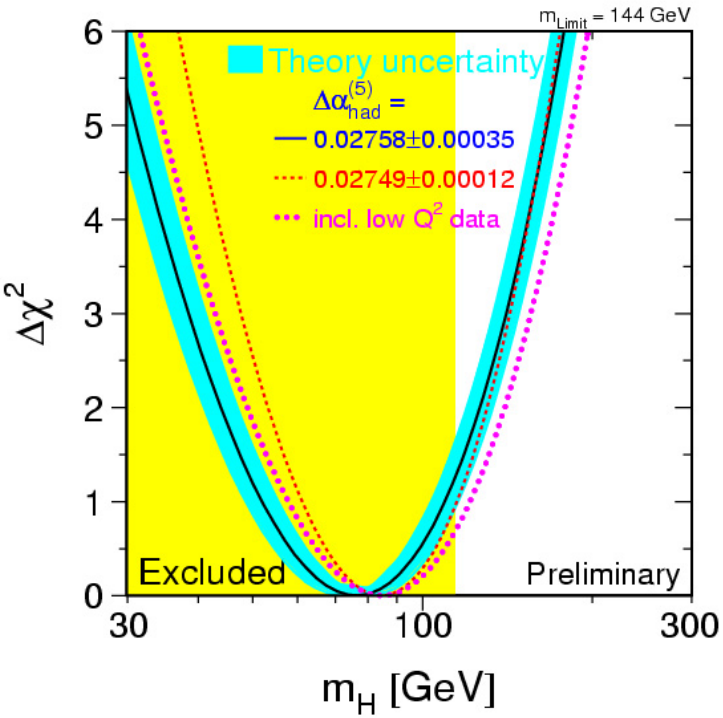


$\Delta m_W \propto \ln m_H^2$

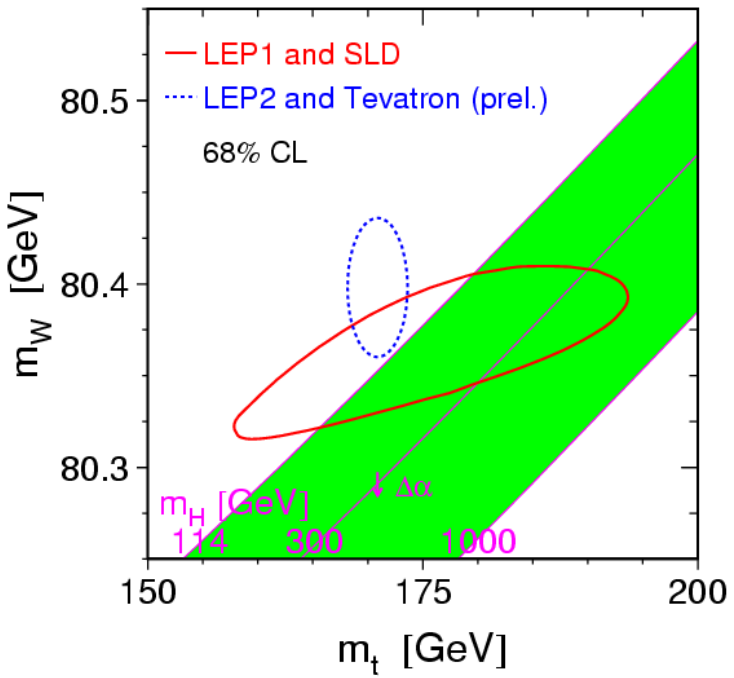


•radiative corrections on the W mass allow constraints on Higgs mass from m_W, m_t

Winter 2007



Winter 2007



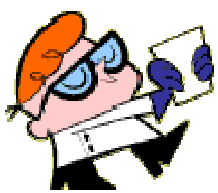
preferred m_H : 76^{+33}_{-24} GeV 114 GeV < **m_H** < 182 GeV @ 95% C.L.

Summary

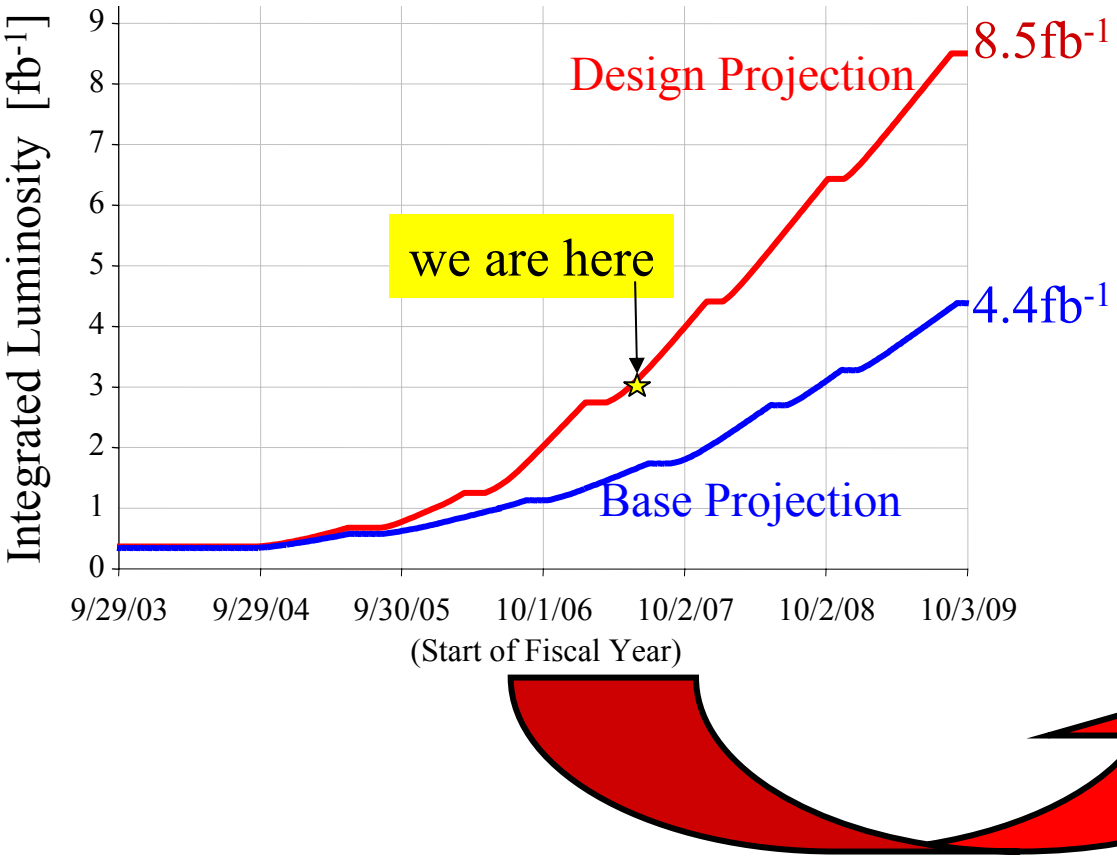
- Important Top Quark properties have been measured:
  - Top pair production cross section: precision $\rightarrow$10%
  - Top charge: consistent with Standard Model
  - W helicity determined: consistent with Standard Model
  - Top mass: 170.9 GeV ± 1.1% – Most precise quark mass!
- Mass and cross section measurements become systematics limited
- Other properties can be measured for the first time w/ large datasets
- There's still plenty room for surprises…

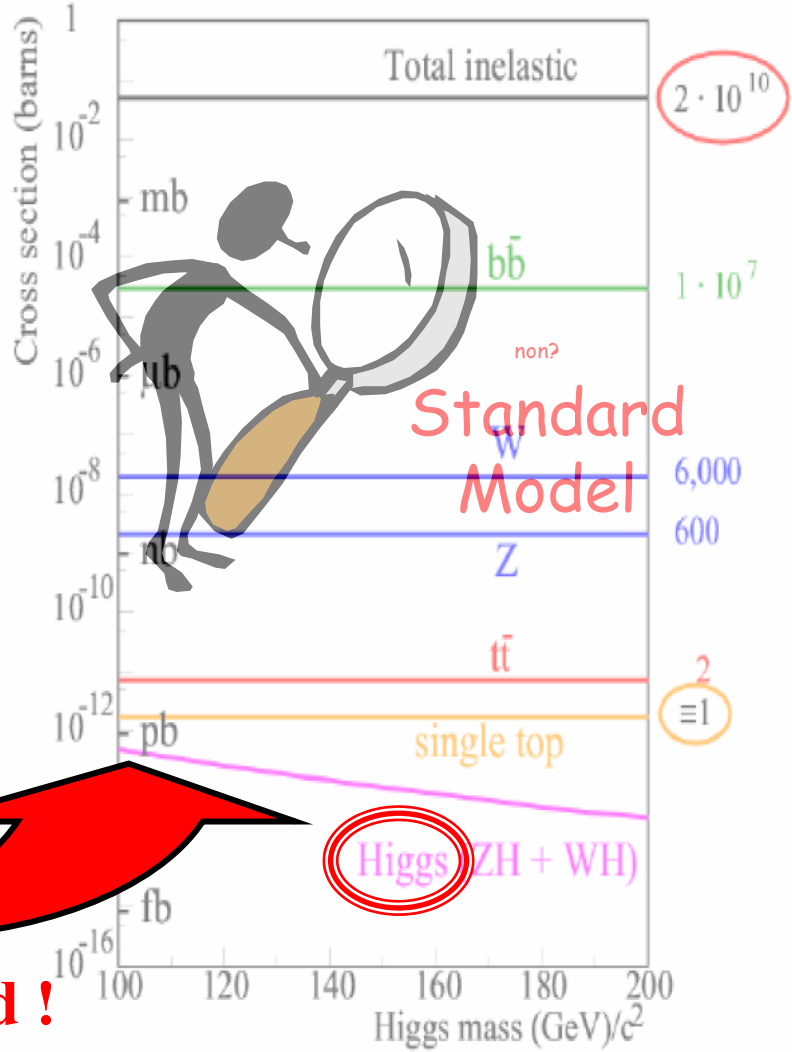
More measurements / information available online:

- http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html
- http://www-cdf.fnal.gov/physics/new/top/top.html



Outlook





More exciting results ahead !