Top Physics with CDF

Run I Results and Run II Prospects

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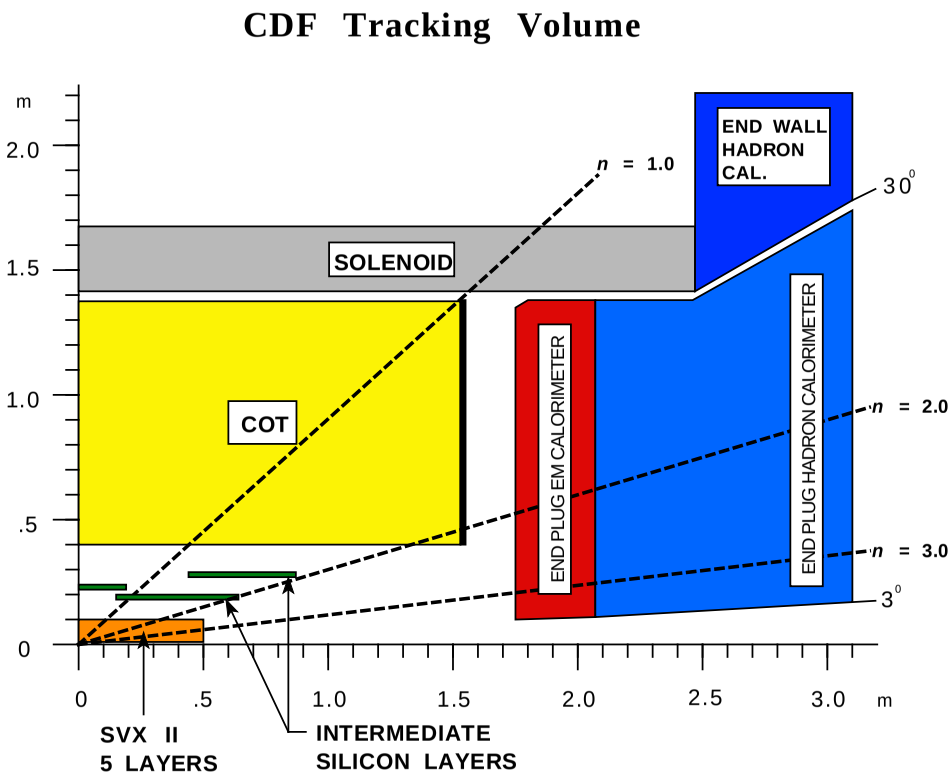
for the CDF collaboration

- **Towards top quark physics in Run 2**
- **Search for single top production**
- **Searches for anomalous top couplings**

CDF upgrade for Run II



- Faster front end electronics (132 ns)
- Trigger/DAQ pipelined, 70 Hz to tape

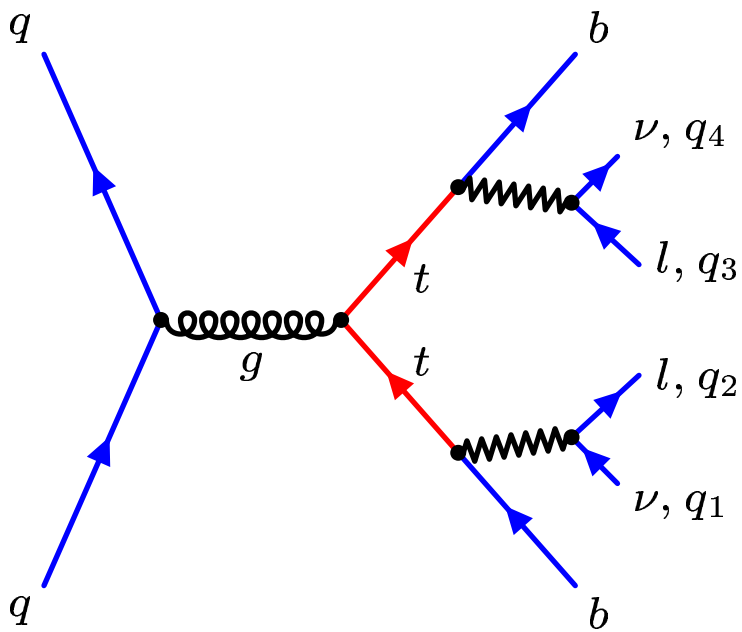
- Completely new tracking system:

  Silicon vertex detector (Layer 00+SVX II)
  Intermediate Silicon Layers (ISL)
  Central Outer Tracker

  Full silicon coverage: $|\eta| < 2$
  13 (15) views: $r\phi$, rz, stereo

- Extended muon systems: $|\eta| < 1.5$
- New calorimeter endplugs
- Time of Flight (K/π Id)

$t\bar{t}$ production at the Tevatron



- top quark does not hadronize

$$\tau_{top} \sim \quad 1/m_{top}^3 \quad \sim 10^{-24}\ \mathrm{s}$$

$$\tau_{QCD} \sim \quad 1/\Lambda_{QCD} \quad \sim 10^{-23}\ \mathrm{s}$$

- in SM: BR($t \to W^+ + b$) $\simeq 100\%$

$t\bar{t}$ event classification:

- **Dilepton channel:** $\ell_1\nu_1 + \ell_2\nu_2 + b\bar{b}$
- **Lepton + Jets:** $\ell\nu + q_1\overline{q_2} + b\bar{b}$
- **All hadronic:** $q_1\overline{q_2} + q_3\overline{q_4} + b\bar{b}$

theoretical cross section predictions:

perturbation theory at NLO + (N)LL resummation

	$\sqrt{s}$ = 1.8 TeV	$\sqrt{s}$ = 2.0 TeV
Laenen 1994	$4.95^{+0.70}_{-0.42}$ pb	—
Berger 1998	$5.52^{+0.07}_{-0.45}$ pb	$7.56^{+0.10}_{-0.55}$ pb
Catani 1998	$5.06^{+0.13}_{-0.35}$ pb	$6.97^{+0.15}_{-0.47}$ pb

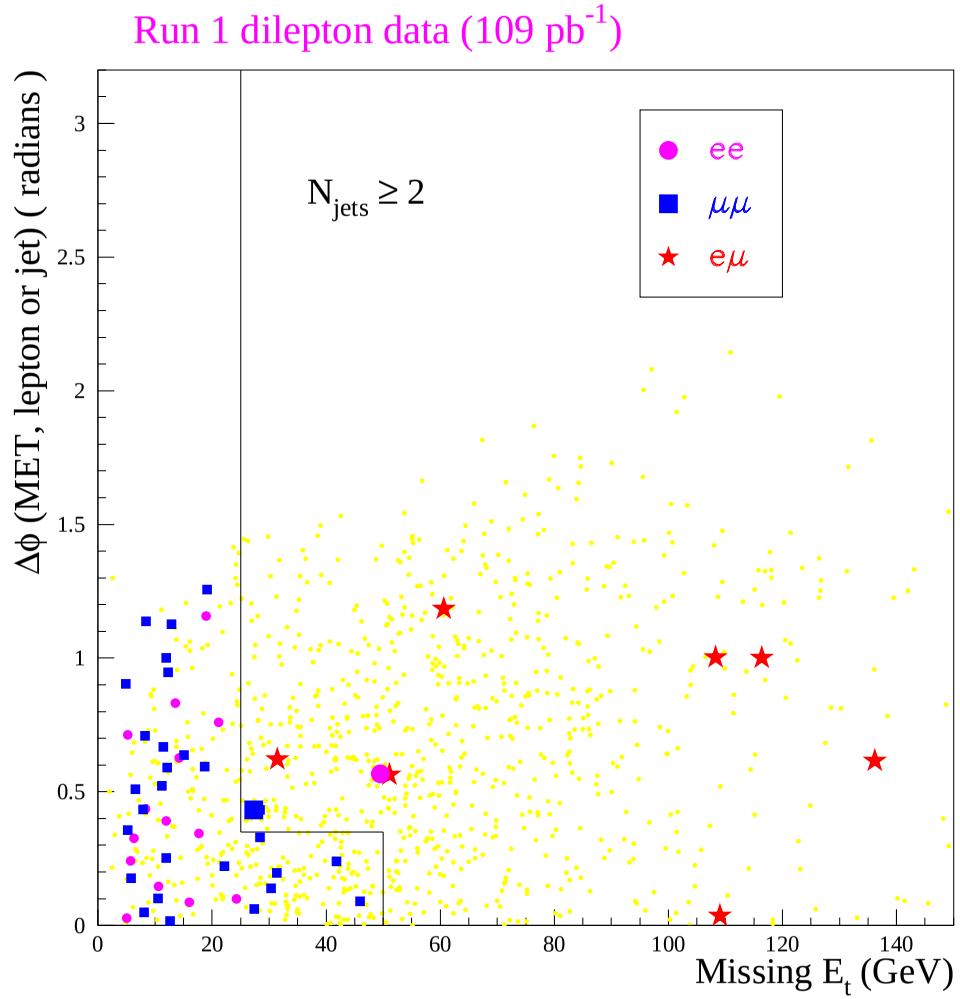
in fact Run 2: $\sqrt{s}$ = 1.96 TeV $\Rightarrow$ $\gtrsim +30\%$
(linear interpolation)

$\sigma(t\bar{t})$ in the Dilepton Channel in Run 1

- Event selection:
  - 2 oppositely charged leptons (e or μ).
  - leptons: $p_t > 20$ GeV$/c$, $|\eta| < 1.1$
  - At least 1 isolated lepton: $I_{CAL} < 0.1$, $I_{track} < 0.1$
  - Z veto: $m_{\ell\ell} < 75$ GeV$/c^2$ or $m_{\ell\ell} > 105$ GeV$/c^2$
  - neutrinos: $|\not{E}_T| > 25$ GeV
  - At least 2 jets with $|E_t| > 10$ GeV
- 9 candidate events; background: 2.4 ± 0.5

$$\sigma(t\bar{t}) = 8.4^{+4.5}_{-3.5} \text{ pb}$$

PRL 80, 2779 (1998)

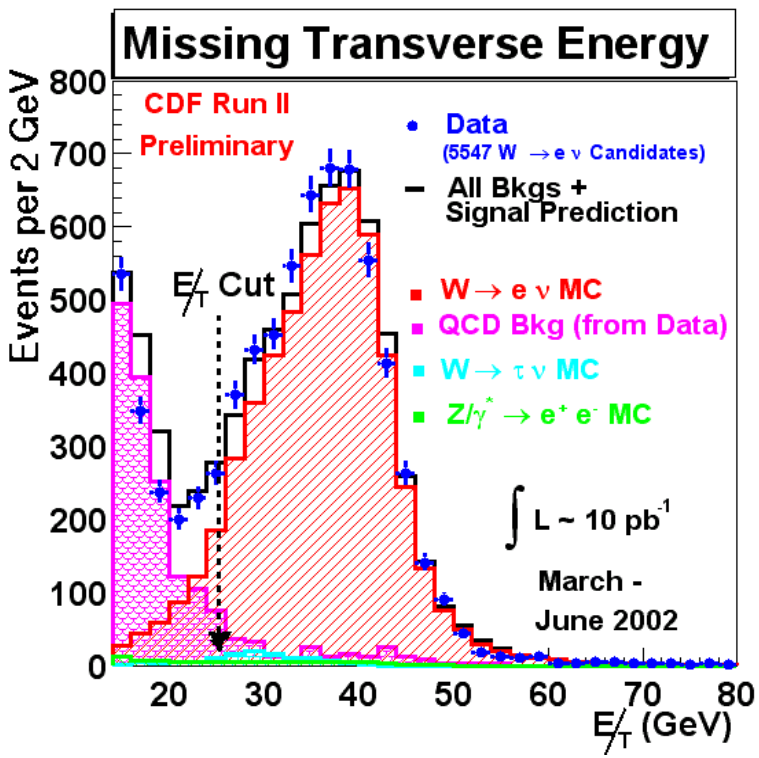


Modelling kinematics of $W \to e\nu$

Pioneer analysis:

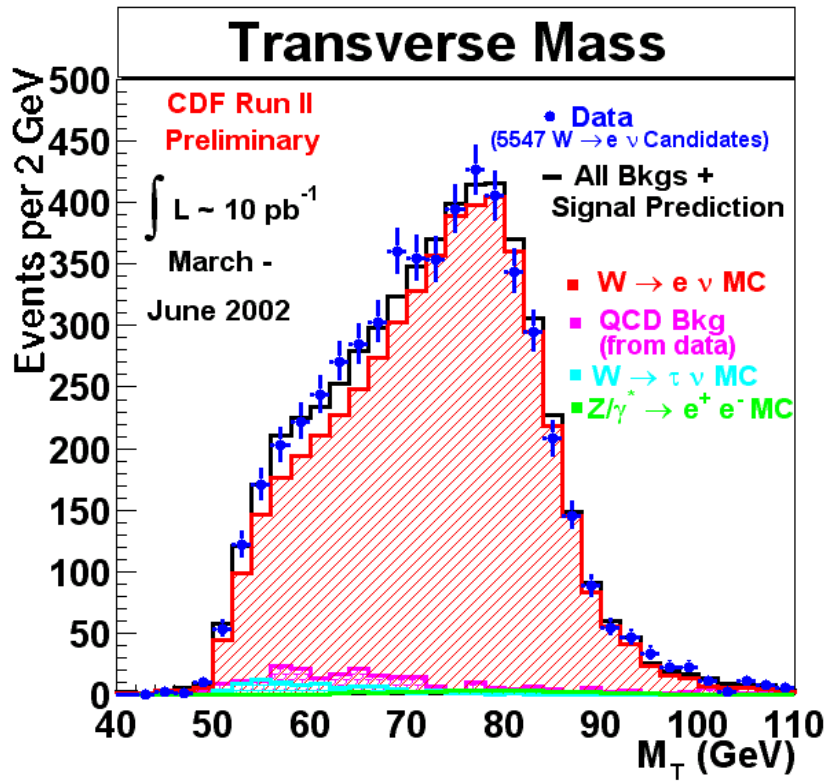
$p\bar{p} \to W + X \to e\nu + X$

cross section measurement



8% background
(QCD, $Z \to e^+e^-$, $W \to \tau\nu_\tau$)

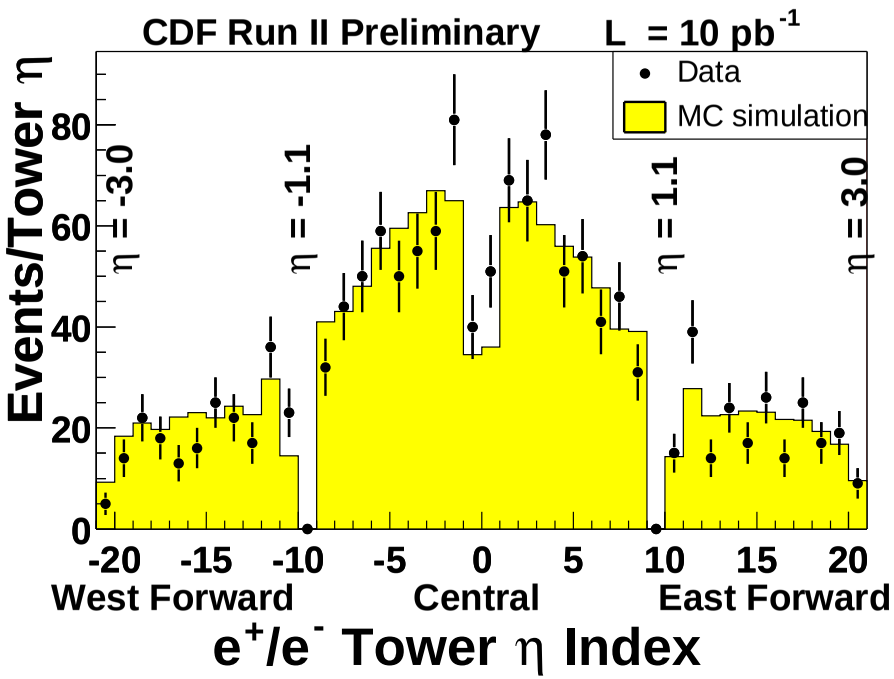
5547 candidates in 10 pb^{-1}



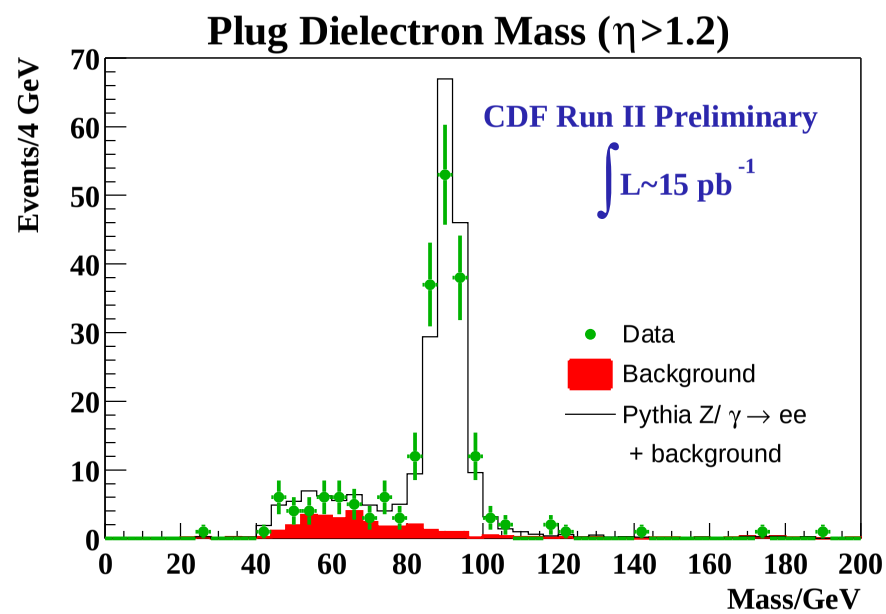
$$\sigma(W + X) \cdot \mathrm{BR}(W \to e\nu) =$$
$$(2.60 \pm 0.07_{\mathrm{stat}} \pm 0.11_{\mathrm{syst}} \pm 0.26_{\mathrm{lum}})\ \mathrm{nb}$$

Extending electron ID to the forward region

- New plug calorimeter covering $|\eta| > 1.1$
- Full silicon tracker coverage up to $|\eta| < 2.0$
  partially covered by drift chamber (COT)
- Algorithm seeded by EM cluster picks up silicon hits



- 160 $Z \to e^+e^-$ candidates
- both electrons in the forward region $|\eta| > 1.2$

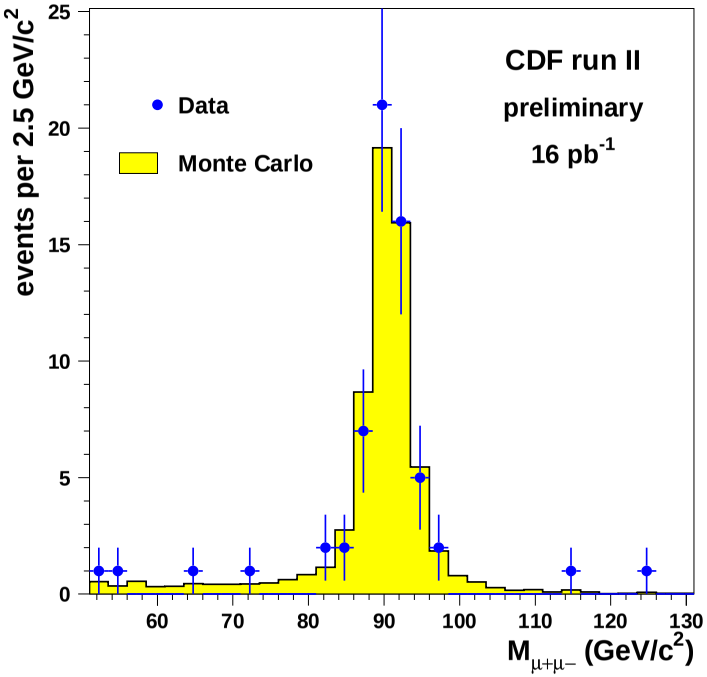


- $+33\%$ for high-p_t electrons from $t\bar{t}$.

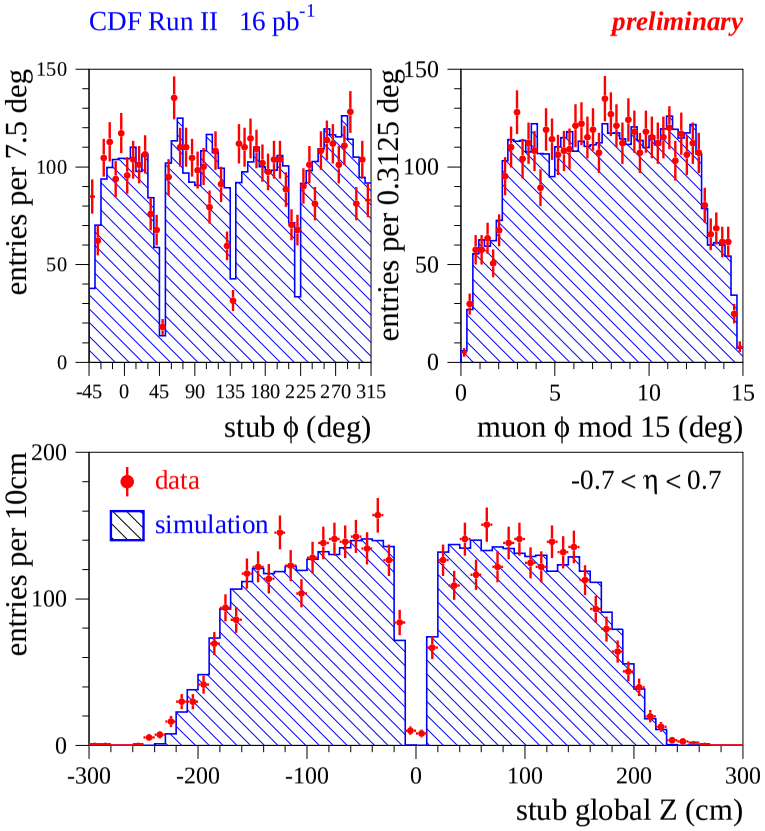
High-p_t Muons in Run 2

Pioneer analyses:

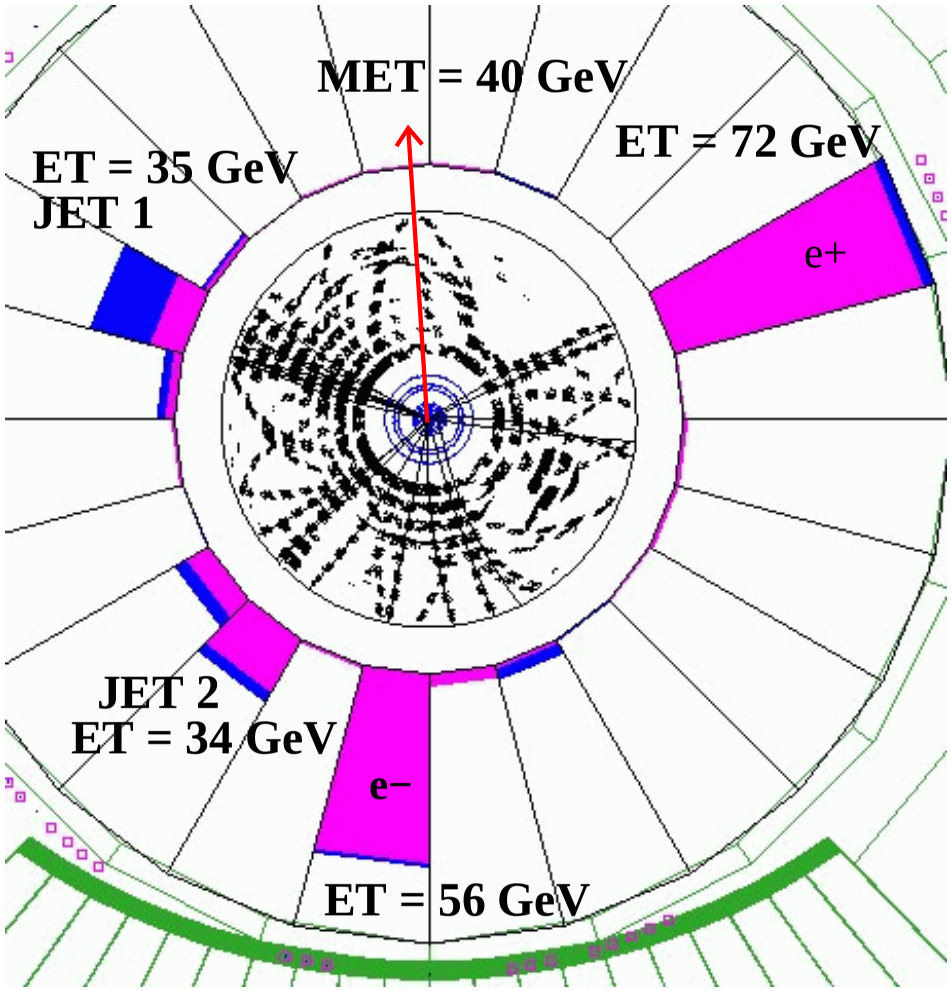
- $\sigma(p\overline{p} \to W + X) \cdot \mathrm{BR}(W \to \mu\nu)$
  $= (2.70 \pm .4_{\mathrm{stat}} \pm .19_{\mathrm{syst}} \pm .27_{\mathrm{lum}})$ nb
- $R = \frac{\sigma(W)\cdot \mathrm{BR}(W\to\mu\nu)}{\sigma(Z)\cdot \mathrm{BR}(Z\to\mu^+\mu^-)} = 13.66 \pm 2.24$



- $+$ 12% in muon acceptance from $t\bar{t}$
- CMU acceptance well understood:



Towards a dilepton $t\bar{t}$ cross section measurement in Run 2



$M_{ee} = 118$ GeV$/c^2$ and $H_t = 255$ GeV

- Two candidate events:

  Run 136286 (Jan. 2002) event 54713

  Run 144424 event 1583234 $H_t = 242$ GeV

  Run 146847 event 551244 $H_t = 238$ GeV

  Run 150090 event 3158836 $H_t = 289$ GeV

- Strong analysis group in place

- Expect first cross section results by March 2003

lepton + jets: the golden sample for m_{top} and $\sigma(t\bar{t})$

- lepton + jets in Run 1:

  $m_{top} = (176.1 \pm 5.1 \pm 5.3)$ GeV

  CDF: $m_{top} = (176.1 \pm 6.6)$ GeV

  Tev.: $m_{top} = (174.3 \pm 5.1)$ GeV

- systematic uncertainties:

Jet energy scale	4.4 GeV
ISR / FSR	2.6 GeV
Background model	1.3 GeV
b-tagging	0.4 GeV
PDFs	0.3 GeV
MC generators	0.1 GeV
Total	5.3 GeV

- Run 1: $\approx$ 20 $t\bar{t}$ b-tagged lep.+jets events

- Run 2 increase: 20 $\times$ 1.3 $\times$ 1.6 ≈ 40

  $\approx$ 800 single-tagged lepton + jets events

  ➜ stat. uncertainty ≈ 1 GeV

- reducing the syst. uncertainty to ≈ 2 GeV

  ➜ control samples:

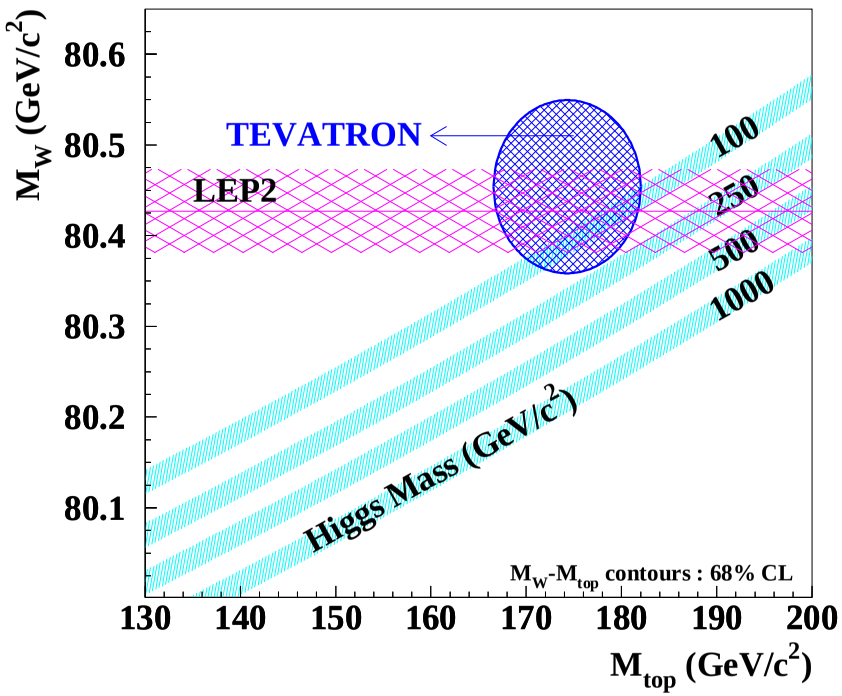
  Z + jets, $Z \to b\bar{b}$, $W \to q\bar{q}$

  ➜ exp. study of soft gluon radiation

- $\delta M_{top} = 2$ to 3 GeV$/c^2$ per experiment

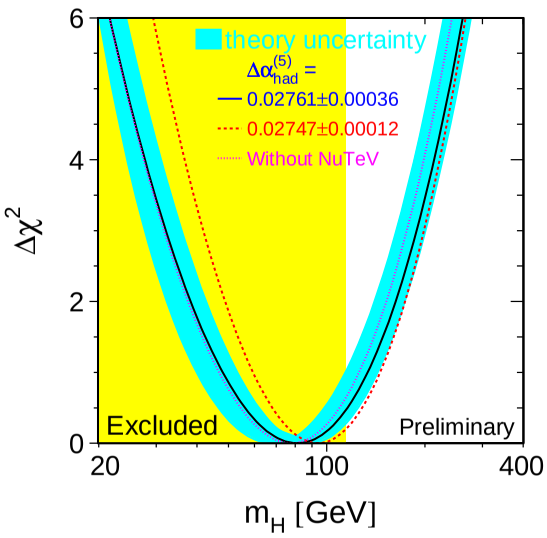
Indirect Higgs mass constraints

- Given M_Z, G_F and α_{QED}:
  ➜ M_W and M_{top} constrain M_{Higgs}.



- Run 2a prospects:
  $\delta M_{top} = 2$ to 3 GeV$/c^2$ per experiment
  $\delta M_W \simeq 40$ MeV$/c^2$ per experiment

- CDF $\oplus$ DØ Run I: $\delta(M_W) = 59\,\mathrm{MeV}/c^2$
- LEP 2 combined (ICHEP 2002):
  $\delta(M_W) = 42\,\mathrm{MeV}/c^2$
- CDF $\oplus$ DØ (Run I): $\delta M_{top} = 5\,\mathrm{GeV}/c^2$
- Current Higgs limits (ICHEP 2002):



LEP EWWG

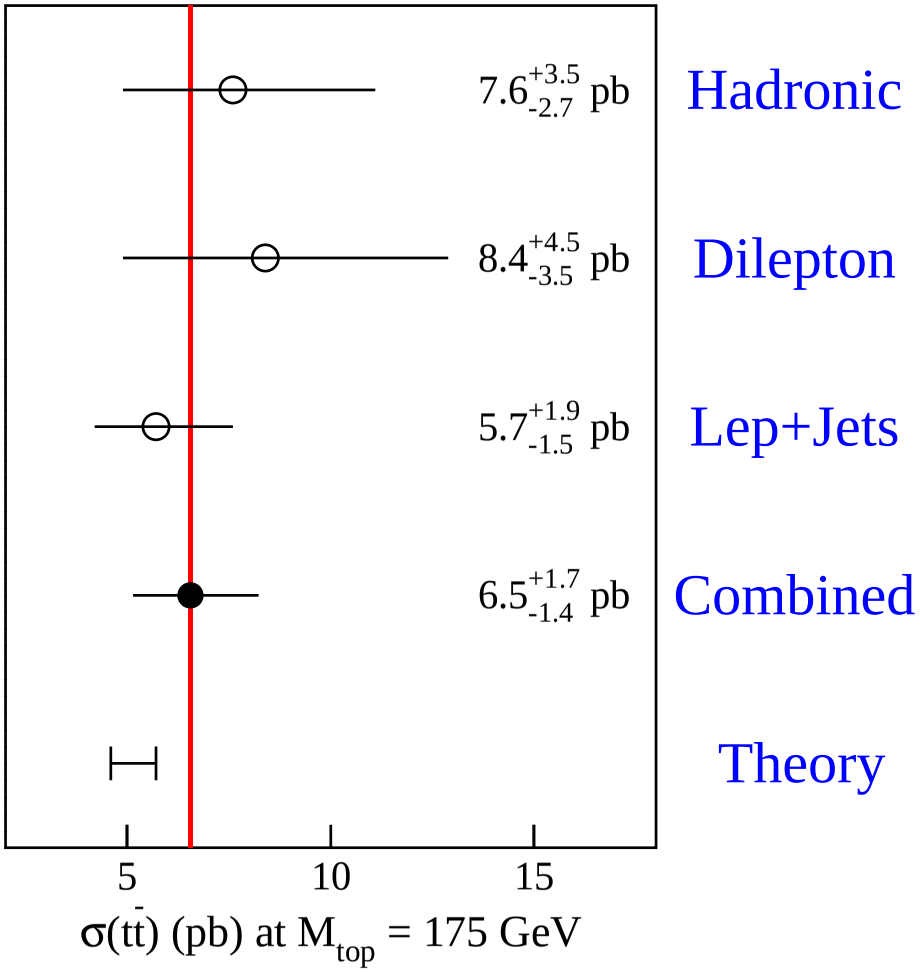
$m_H < 193$ GeV

best fit:

$m_H = 81^{+52}_{-33}$ GeV

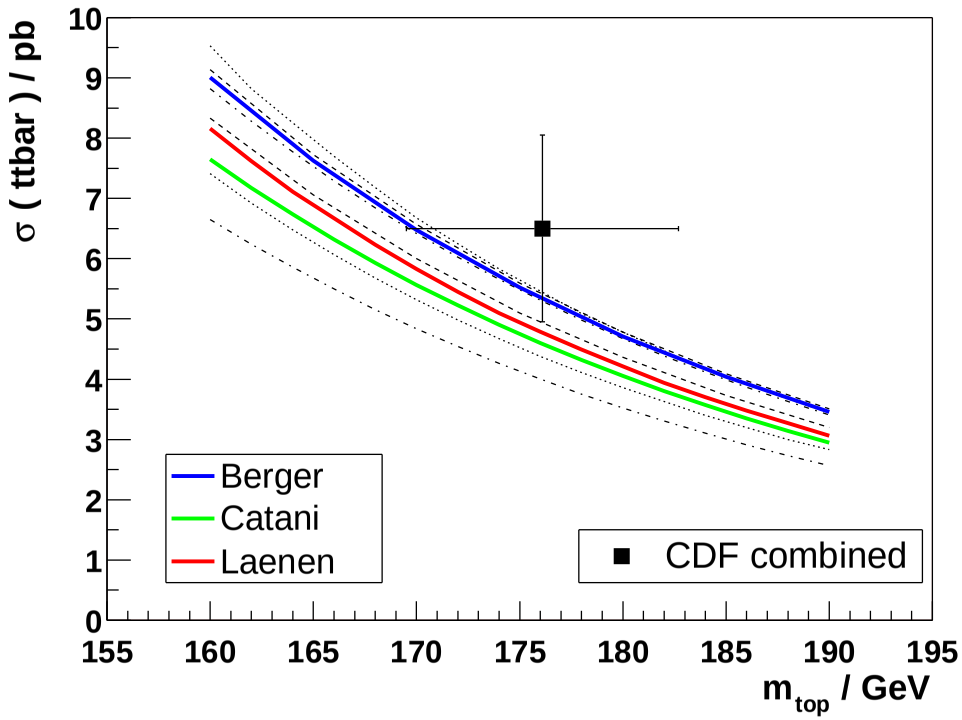
Run 1 $t\bar{t}$ Cross Section Summary

CDF Final Run 1 Results



Comparison w/ pQCD predictions:

$\sigma(\,t\bar{t}\,)$ versus m_{top}



Run 2a prospects: $\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} < 7\%$

(Run I: 26%)

Measurement of R_{tb} with $t\bar{t}$ Events in Run 1

- SM: BR$(t \to W^+ + b) \simeq 100\%$
- experimental test: measure

$$R_{tb} \equiv \frac{\mathrm{BR}\,(t \to W + b)}{\mathrm{BR}\,(t \to W + q)}$$

- use two CDF $t\bar{t}$ data sets:

  di-lepton and lepton+jets

  $\int \mathcal{L}\,\mathbf{dt} = \mathbf{109}\ \mathrm{pb}^{-1}$

- two tagging algorith.: SVX and SLT

- likelihood fit to tagging multiplicity

Sample	00	01	1	2
ℓ + jets	126	14	18	5
di-lepton	6	n/a	3	0

$$|R_{tb}| = 0.94\,^{+0.31}_{-0.24}$$
$$> 0.56 \quad @\ 95\%\mathrm{C.L.}$$

Phys. Rev. Lett. 86 3233 (2001) hep-ex/0012029

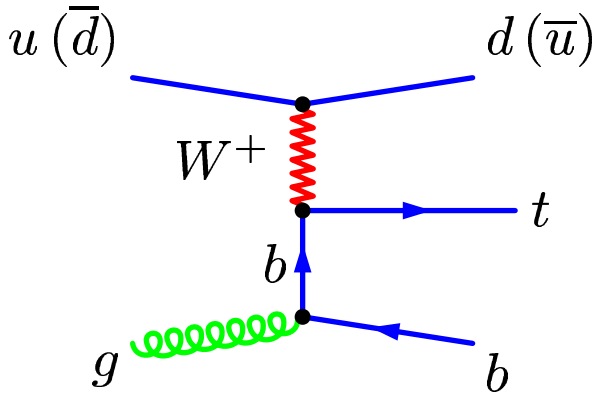
- w/ unitarity: $|V_{tb}| = 0.97\,^{+0.16}_{-0.12}$

- Expectation for Run 2a: $\frac{\delta|\mathbf{R_{tb}}|}{|\mathbf{R_{tb}}|} = \mathbf{3}\%$

Single Top Production

$t\bar{t}$ **production: strong interaction** $\Longleftrightarrow$ **Single top: electroweak Wtb vertex**

t-channel (Wg-Fusion)

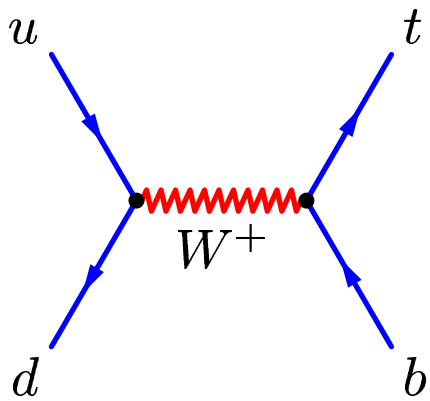


(2.44 ± 0.12) pb

Stelzer et al. 1998

W + b jet + u/d jet

s-channel (W^*)

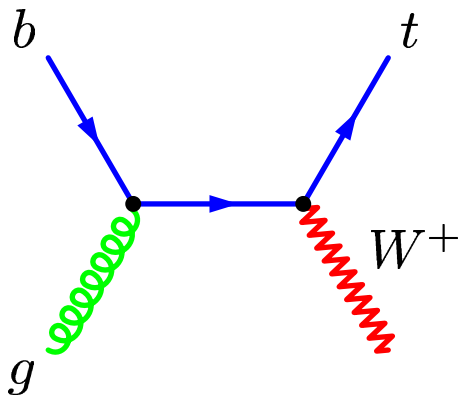


(0.88 ± 0.05) pb

Smith / Willenbrock 1996

W + 2 b jets

associated production



$\sigma \leq 0.1$ pb

Tait 1999

2 W + b jet

relevant at LHC (51 pb)

Run I Single Top Searches at CDF

- cross sections at $\sqrt{s} = 1.8$ TeV

$$\sigma(Wg) = (1.70 \pm 0.09)\ \mathrm{pb}$$
$$\sigma(W^*) = (0.73 \pm 0.04)\ \mathrm{pb}$$

- 3 analyses:
  1. combined search for Wg $\oplus W^*$ maximum likelihood
  2. separate search for Wg and W^* maximum likelihood
  3. combined search for Wg $\oplus W^*$ neural network

- 1) and 2) publish.: PRD D65, 091102 (2002)

Basic event selection common to all 3:

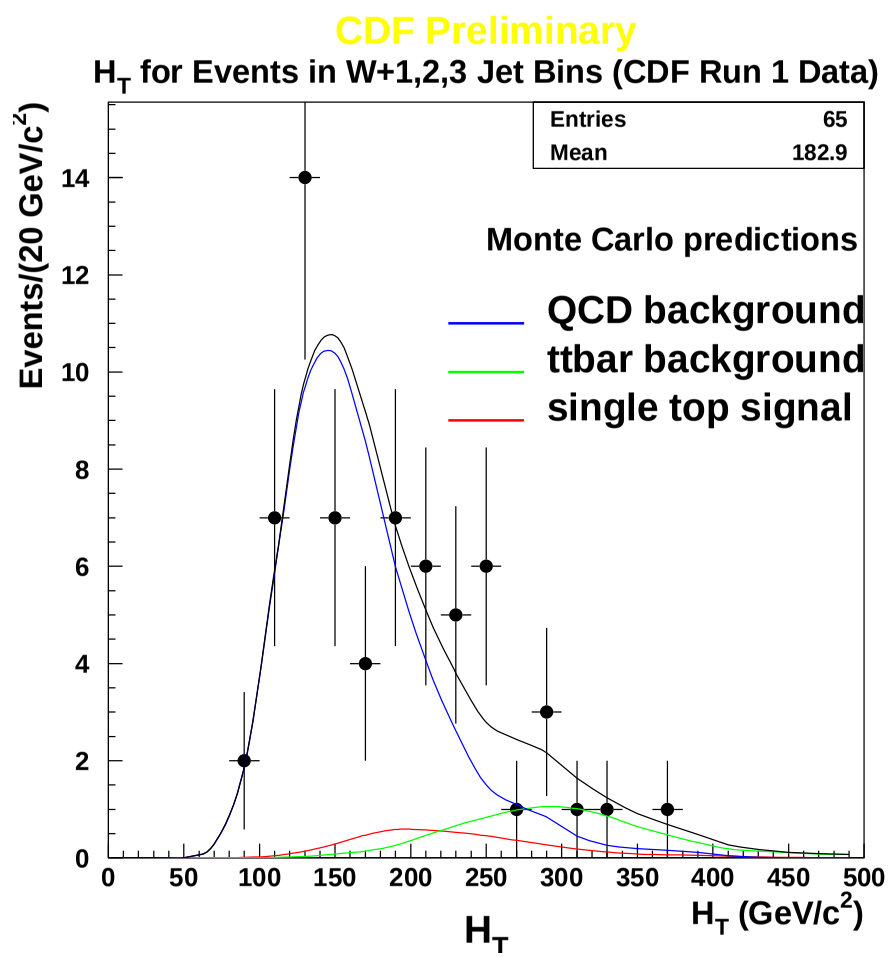
- isolated $e^{+/-}$ or $\mu^{+/-}$, $E_t(\ p_t\ ) > 20$ GeV (GeV/c)
- $\not{E}_T > 20$ GeV
- Z^0 veto, dilepton removal
- 1, 2 or 3 jets with $E_t > 15$ GeV and $|\eta| < 2.0$ (cone $\Delta R = 0.4$)
- ≥ 1 b-tagged (SECVTX) jet

Run I Single Top (1): Combined Search

- reconstruct $M_{\ell\nu b}$, apply W mass constraint
- cut: $140 < M_{\ell\nu b} < 210\ \mathrm{GeV}/c^2$
- event numbers:

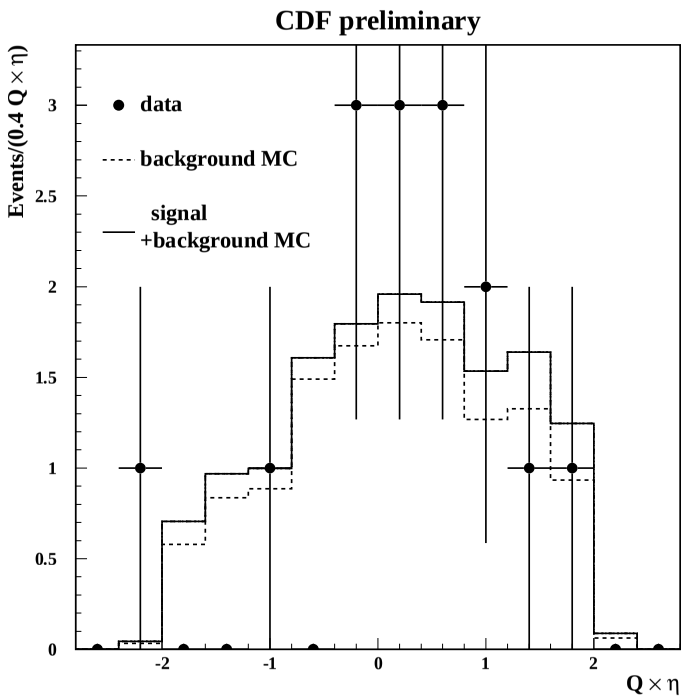
Wg	W^*	$t\bar{t}$	non-top	total	observ.
3.0	1.3	8.4	54	67	65

- $H_t \equiv |\not{E}_T| + |E_t(\ell)| + \sum |E_t(\text{ all jets })|$
- unbinned maximum likelihood fit to H_t distribution
- upper limit: $\sigma(Wg + W^*) < 14$ pb

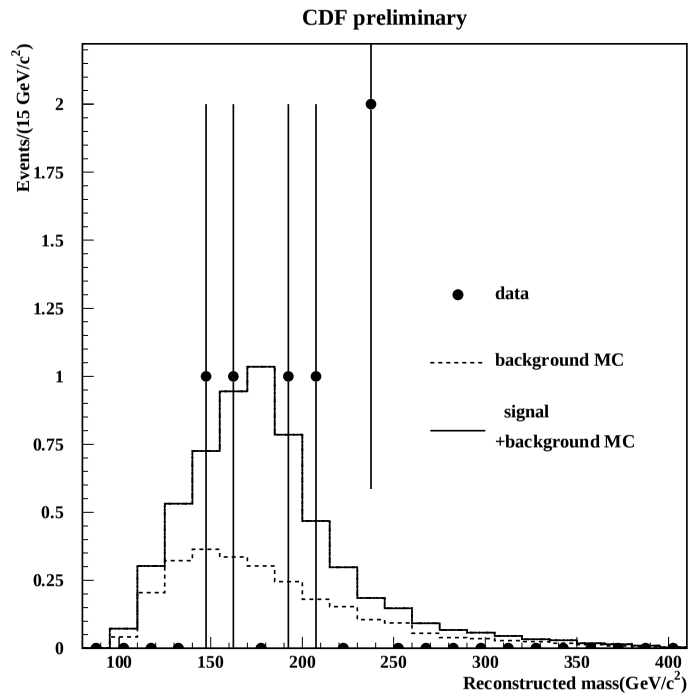


Run I Single Top (2): Separate Search

- use only W+2-jets sample
- sample 1: exactly 1 b-tagged jet
- binned ML fit to $Q \times \eta$ distribution
  ➜ extract Wg content
- $\sigma(Wg) < 13$ pb



- sample 2: exactly 2 b-tagged jets
- binned ML fit to reconstructed top mass $M_{\ell\nu b}$ ➜ $7.6^{+5.9}_{-4.8}$ W^* events
- $\sigma(W^*) < 18$ pb



Run I Single Top (3): NN Search

- **Results are preliminary !**
- Additional selection criteria:
  - if $N_{jets} = 1$ ($E_t > 15$ GeV): ≥ 1 jet with $E_t > 8$ GeV
  - if $N_{jets} = 3$ ($E_t > 15$ GeV): no additional jet with $E_t > 8$ GeV
- 3-layer network
- 7 input variables: $E_t(\mathrm{jet1})$, $E_t(\mathrm{jet2})$, $E_t(\ell)$, H_t, $p_t(\mathrm{jet1}+\mathrm{jet2})$ and $Q \times \eta$

Event numbers:

Wg + W^*	$t\bar{t}$	QCD	expec.	obs.
4.2	7.4	43.3	54.9	64

NN output:

Wg + W^*	$t\bar{t}$	QCD
22.9 ± 7.6	7.6 ± 2.0	36.1 ± 6.2

- 2.5 σ effect
- Further checks are ongoing.
- Resolve issue in Run 2a: more data $\oplus$ better background simulation.

Run I Single Top Summary and Run 2a Outlook

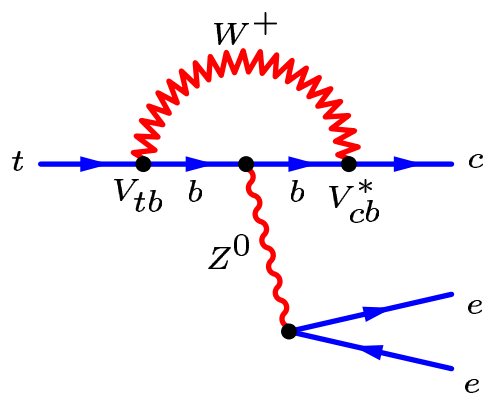
	t-channel	s-channel
σ predicted NLO ($\sqrt{s} = 1.8$ TeV)	(1.70 ± 0.09) pb Stelzer et al. 1998	(0.73 ± 0.04) pb Smith/Willenbrock 1996

	accep. $\times$ BR	$\sigma(Wg)$	W^*	accep. $\times$ BR
CDF separate Max. Lik.	1.0 %	$\sigma_t < 13$ pb	$\sigma_s < 18$ pb	1.5 %
DØ NN analysis PLB 517:282 (2001)	0.16 %	$\sigma_t < 22$ pb	$\sigma_s < 17$ pb	0.24 %
CDF combined Max. Lik.	1.7 %	$\sigma < 14$ pb		1.7 %

- Run 2a will allow discovery of single top if the SM is correct.
- We expect about 100 – 150 signal events in 2 fb^{-1}.
- Directly measure $|V_{tb}|$ with 10 – 15% precision.

Top decays via FCNC

Top quark decays **via FCNC** are **strongly GIM suppressed** in the SM, e.g.:



Theoretical SM predictions:

$t \to c + Z/\gamma$: BR $\approx 10^{-12}$ to 10^{-13}

$t \to c + g$: BR $\approx 10^{-10}$

Eilam, Hewett, Soni: Phys. Rev. D 44, 1473 (1991)

$\mathbf{t \to u/c + \gamma \ / \ Z \ / \ g}$

could be enhanced due to non SM physics, e.g.:

Fritzsch: Phys. Lett. B 224, 423 (1989)

Malkawi, Tait: hep-ph/9511337

Han et al.: Phys. Lett. B 385, 311 (1996)

general ansatz:
add anomalous effective coupling $\frac{\kappa}{\Lambda}$
to Lagrangian

partial decay width:

$$\Gamma(t \to c + g) = \frac{8\alpha_s m_t^3 \kappa^2}{3\Lambda^2}$$

Search for FCNC top quark decays at CDF in Run I

$p\overline{p} \to t\overline{t} + X$ with $t \to W + b$
$\overline{t} \to \overline{u}/\overline{c} + \gamma$

- $W \to e/\mu + \nu$: $E_t(\gamma) > 20$ GeV
  2 jets: $E_t > 15$ GeV
- $W \to$ jets : $E_t(\gamma) > 50$ GeV
  3 jets: $E_t > 15$ GeV
- additional topological cuts:
  acceptance $\times$ BR $= 5\%$
- Result: 1 event seen, 1 event background expected

$$\mathrm{BR}\,(\mathbf{t} \to \mathbf{u/c} + \gamma) < \mathbf{3.2\%}$$

Phys. Rev. Lett. **80** (1998) 2525

$p\overline{p} \to t\overline{t} + X$ with $t \to W + b$
$\overline{t} \to \overline{u}/\overline{c} + Z^0$

- $Z^0 \to e^+e^-$ or $\mu^+\mu^-$
  4 jets: $E_t > 20$ GeV
- Result: 1 event seen, $\leq$ 1 event background expected

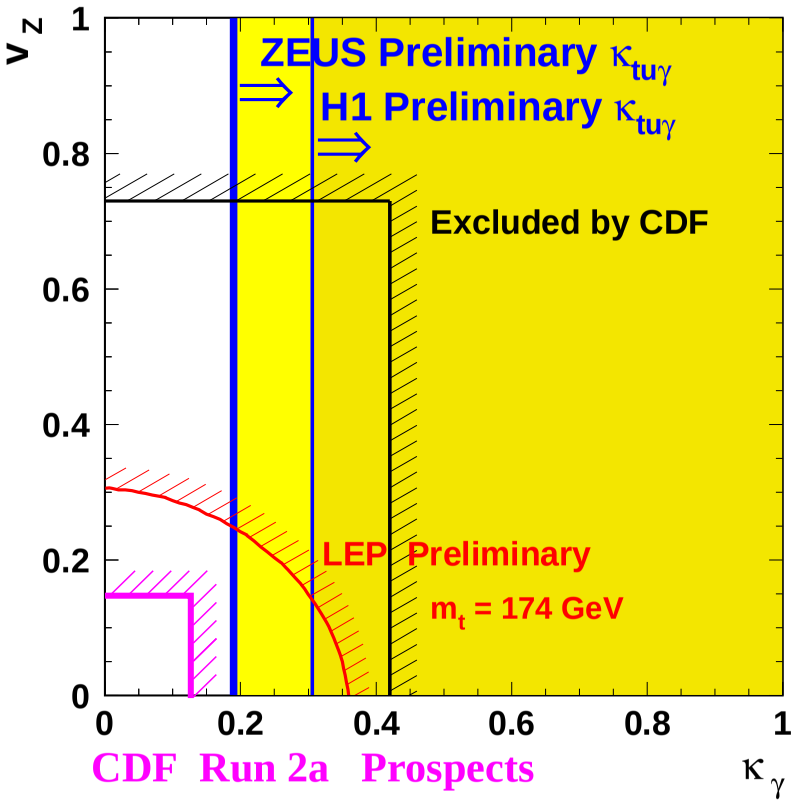
$$\mathrm{BR}\left(\mathbf{t} \to \mathbf{u/c} + \mathbf{Z^0}\right) < \mathbf{33\%}$$

Phys. Rev. Lett. **80** (1998) 2525

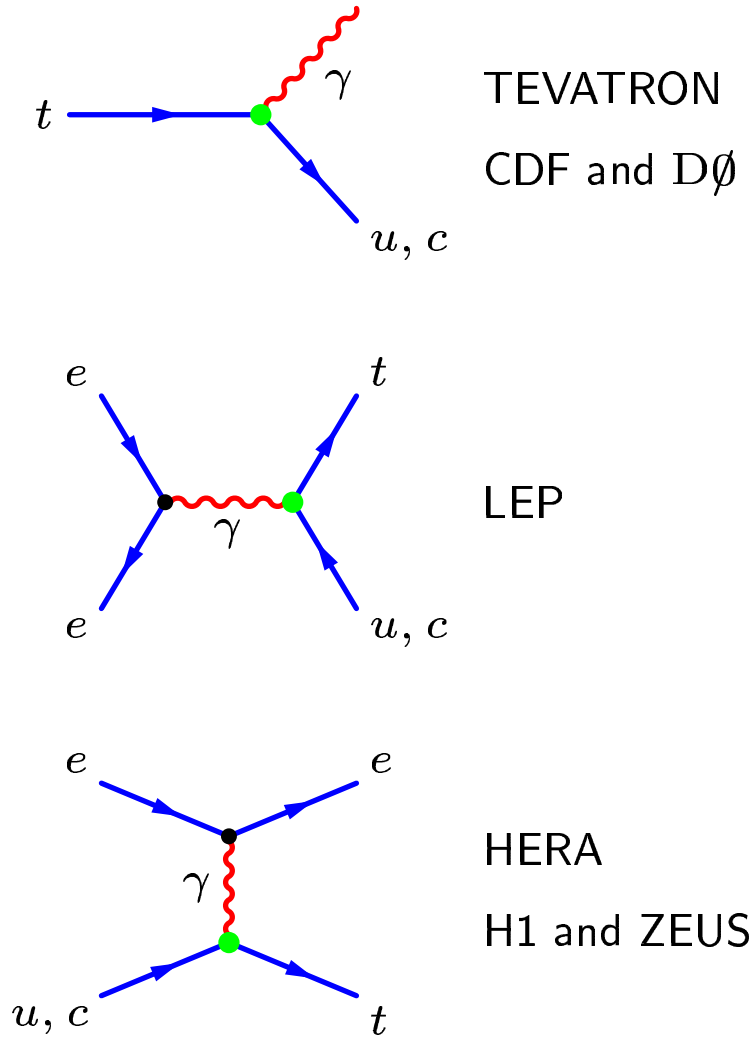
Prospects for Run II:

- data + acceptance + $Z \to b\overline{b}$: data $\times 30$
- $\mathrm{BR}(u/c + \gamma) < 0.3\%$
  $\mathrm{BR}(u/c + Z^0) < 1.5\%$

Status of limits on anomalous couplings



$\kappa_\gamma < 0.13$ and $\kappa_Z < 0.15$



Top Quark Physics at CDF: Summary and Outlook

Run 1 Top Quark Results

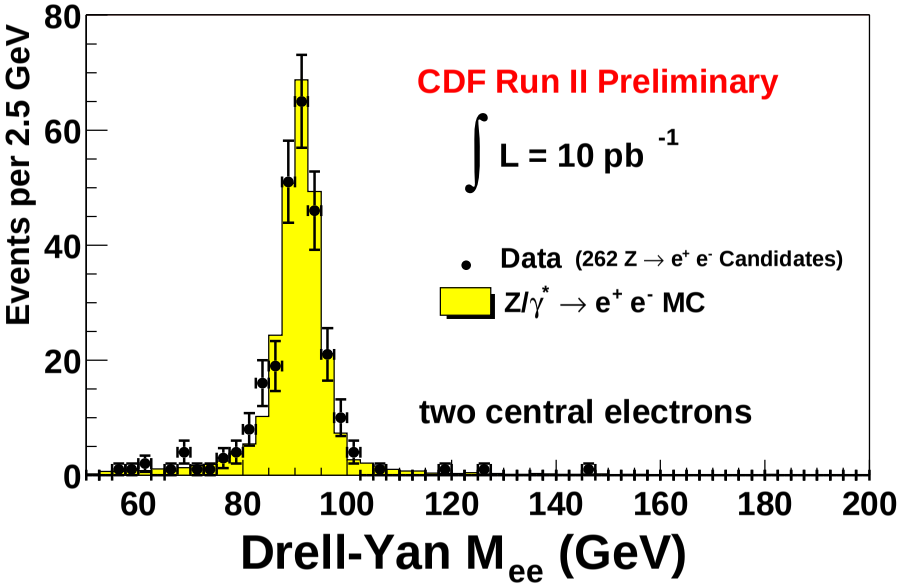
- 20 b-tagged $t\bar{t}$ lepton+jets events
- $\sigma(t\bar{t}) = 6.5^{+1.7}_{-1.4}$ pb
- $m_{top} = (176.1 \pm 6.6)$ GeV$/c^2$
- $\sigma(p\bar{p} \to t\bar{b} + X) < 14$ pb
- $\mathrm{BR}(\mathrm{t} \to \gamma(\mathbf{Z^0})\mathrm{q}) < \mathbf{3.2\%(33\%)}$
- W helicity in top decays (2000)
- Top quark p_t distribution (2001)

Run 2a Top Quark Prospects

- $\approx$ 800 b-tagged $t\bar{t}$ lepton+jets events
- $\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} < 7\%$
- $\Delta m_{top} = 2 - 3$ GeV$/c^2$
- observe single-top production ➜ $|V_{tb}|$
- $\mathrm{BR}(t \to \gamma(Z^0)q) < 0.3\%(1.5\%)$
- $t\bar{t}$ spin correlation
- soft gluon radiation in $t\bar{t}$ events

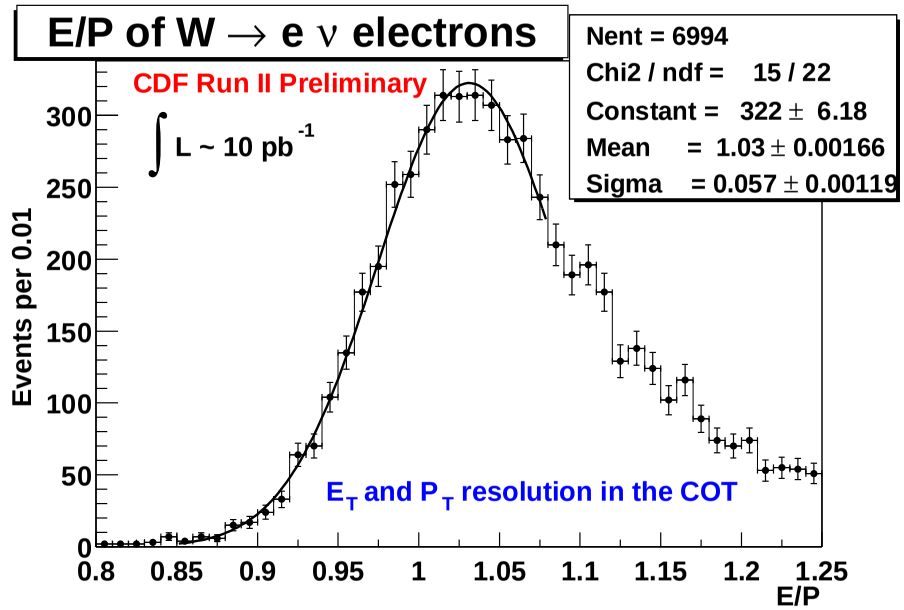
Calibrating the ECAL energy scale

- Calibration with $Z \to e^+e^-$:
  2% correction needed



- 262 $Z \to e^+e^-$ central-central candidates
- mass resolution: $\sigma(M) \simeq 3.5$ GeV

- apply tower to tower corrections the get flat E/P distribution



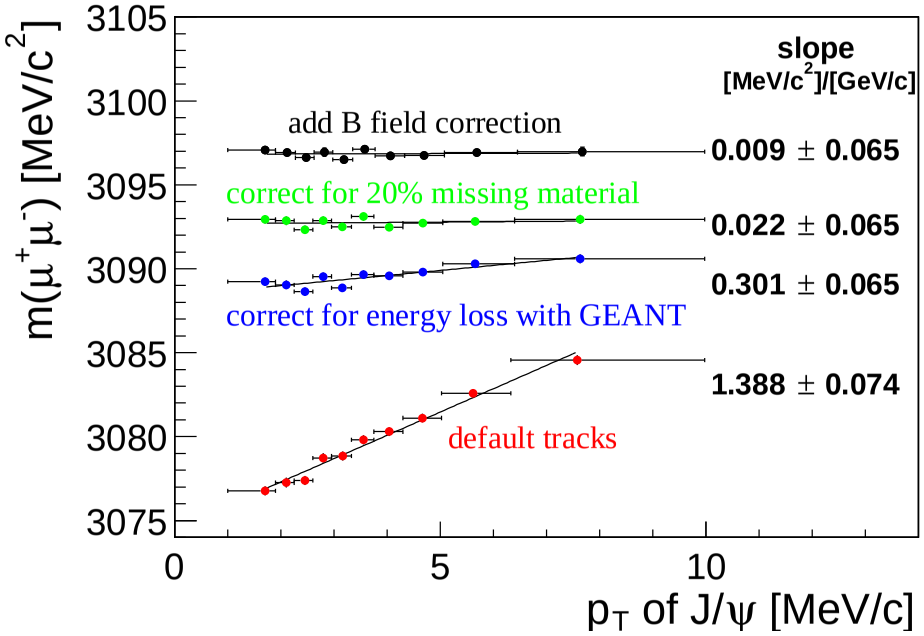
- $\sigma(E/P) \simeq 5.7\%$ (ECAL $\oplus$ tracking)
- gives energy resolution if momentum scale and resultion is determined with other methods

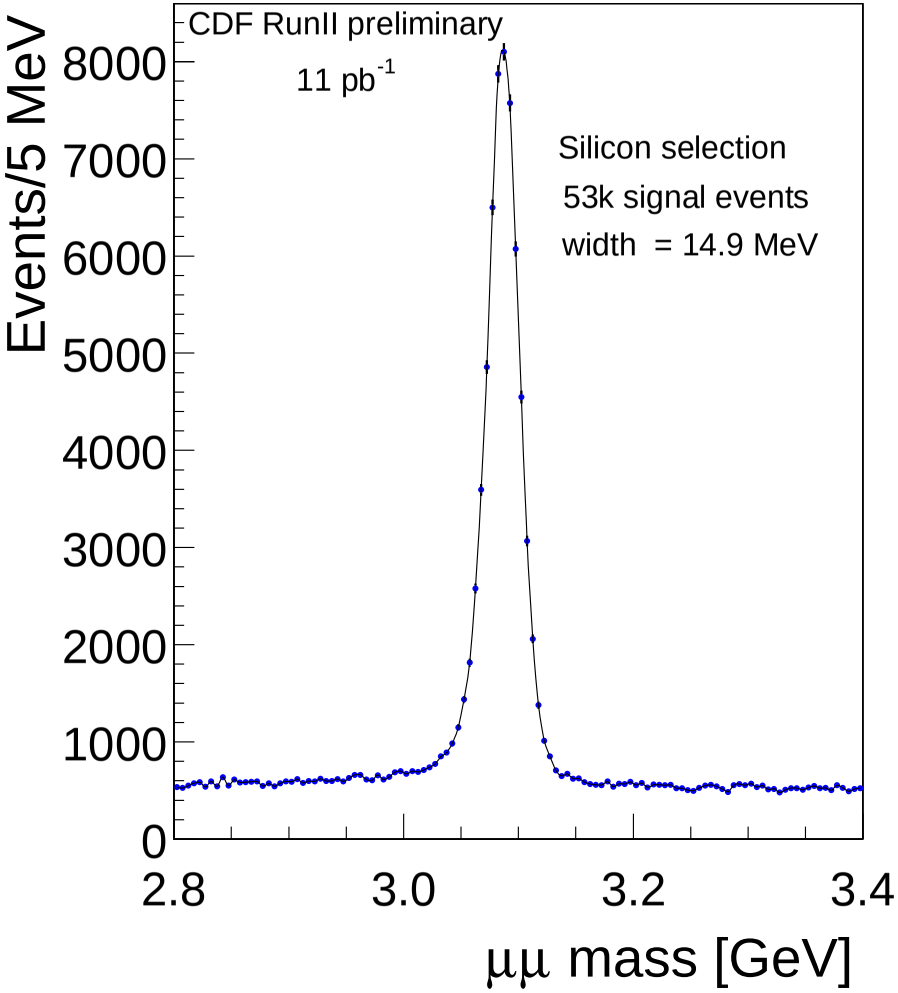
Momentum calibration with $J/\Psi \to \mu^+\mu^-$ decays

- current COT resolution:

  $\sigma(p_t)/p_t^2 < 0.13\%/\text{GeV}$ (Run 1: 0.1%)

- $\sigma(m_{J/\Psi}) = 15$ MeV

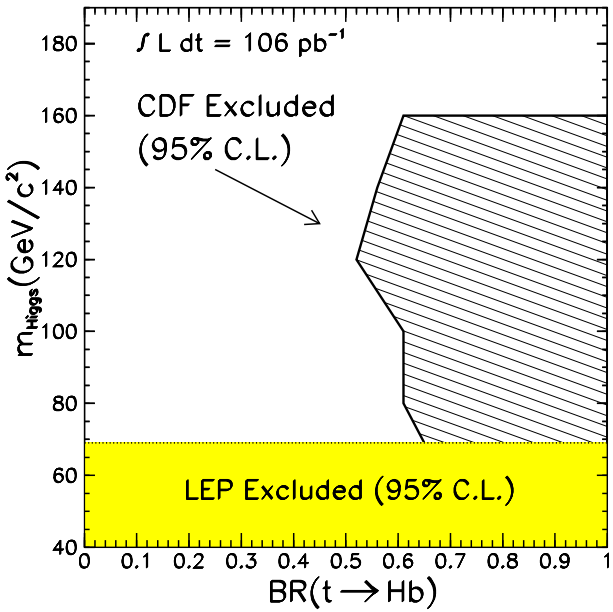




CDF searches for $t \to b + H^+$ in Run I

$$t\bar{t} \quad \to \quad H^+ \, H^- \; / \; W^\pm \, H^\mp + b\bar{b}$$
$$\to \quad e/\mu + \tau + \not{E}_T \; + \text{jets}$$

Phys. Rev. D 62, 012004 (2000); hep-ex/9912013



- $\int \mathcal{L} \, dt = 106 \text{ pb}^{-1}$
- observe 4 events
- (3.1 ± 0.5) background events expected

Other Run I searches:

- search for dilepton final states
  Run Ia, $19.3 \text{ pb}-1$
  $H^+H^- + b\bar{b} \to ll + \not{E}_T \; + X$ with
  Phys. Rev. Lett. 73, 2667 (1994)
- $\not{E}_T \; + \tau + \text{jets}$
  Run Ia, $(18.7 \pm 0.7) \text{ pb}-1$
  Phys. Rev. D 54 , 735 (1996)