Measurement of the Top Pair Production Cross Section in Proton-Antiproton Collisions at $\sqrt{s} = 1.96$ TeV using Dilepton Events

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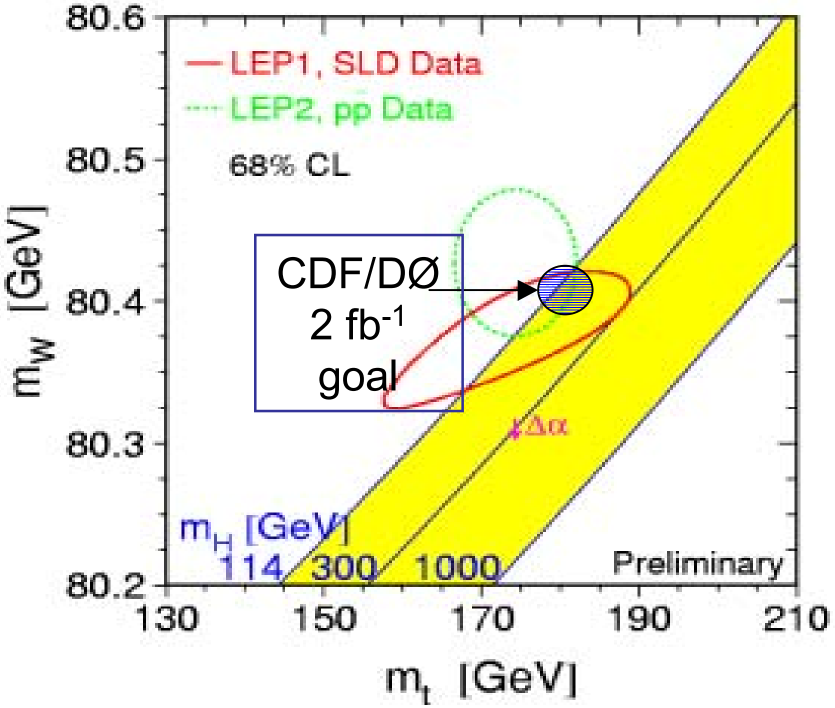
Why study the top quark? (I)

$$y_t = \frac{\sqrt{2}m_t}{v} \approx 1$$

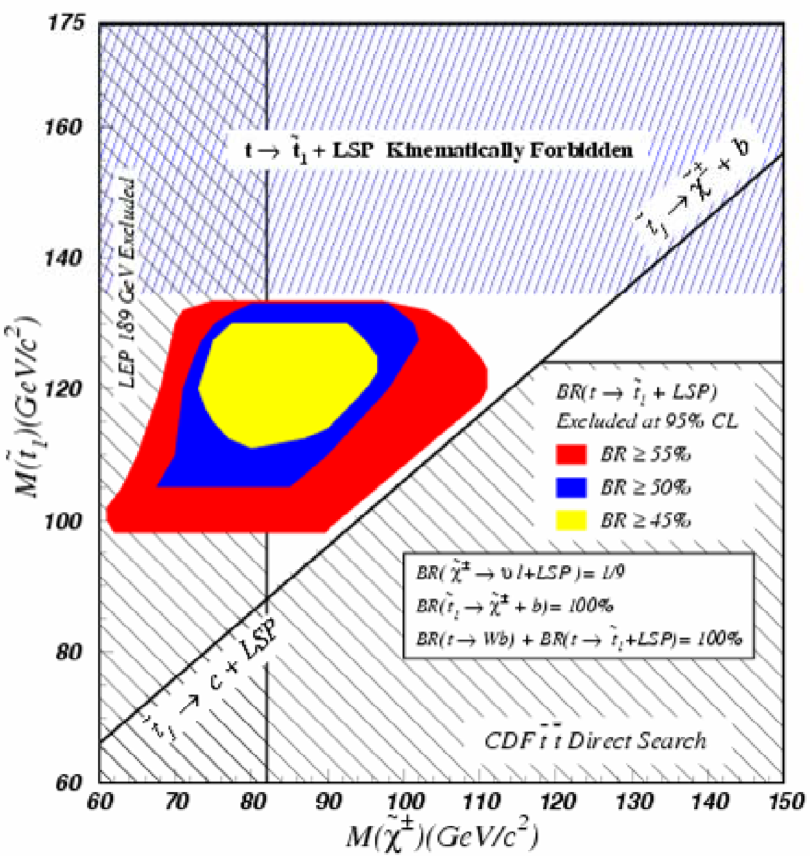
"Yukawa scale"



- *New particle, barely characterized*
  - *CDF & DØ discovery in 1995*
- *Top is extremely heavy (m_{top}≈175 GeV):*
  - *Special relation to Higgs boson*
  - *What is this telling us?*
- **Strategy: look for discrepancies with Standard Model**

Why study the top quark? (II)

- *Open Questions:*
  - *Is top production described by QCD? Resonant production?*
  - *Is BR(t→Wb)≈100%? Non-SM decays?*
  - *Is what we call* top *really top plus X, X possibly exotic?*
- *Today's signal is tomorrow's background*
  - *Understanding of sample of high momentum leptons + missing energy is crucial for exotic searches, e.g., SUSY*



$$t \rightarrow \tilde{t}_1 + LSP$$

CDF: Phys. Rev. **D**63, 091101 (2001)

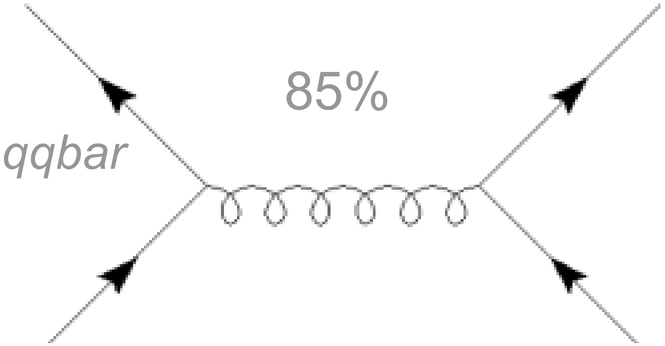
Top production & decay @ Tevatron

- *In p-pbar collisions, top quarks are produced mainly in pairs*
- *At √s=1.96 TeV, qqbar production is dominant process (~85%)*
- *Due to large m_{top}, no toponium states*
- *Standard-model top decays mainly via*

  $t \rightarrow W\, b$

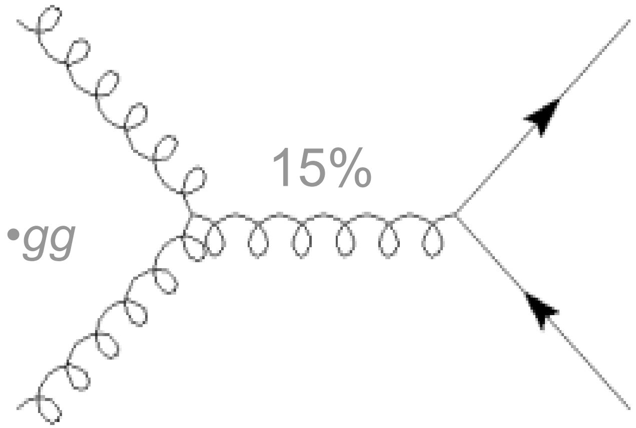
  - W daughters label decay mode

•*qqbar*



(NB: qq, gg fractions reversed at LHC)

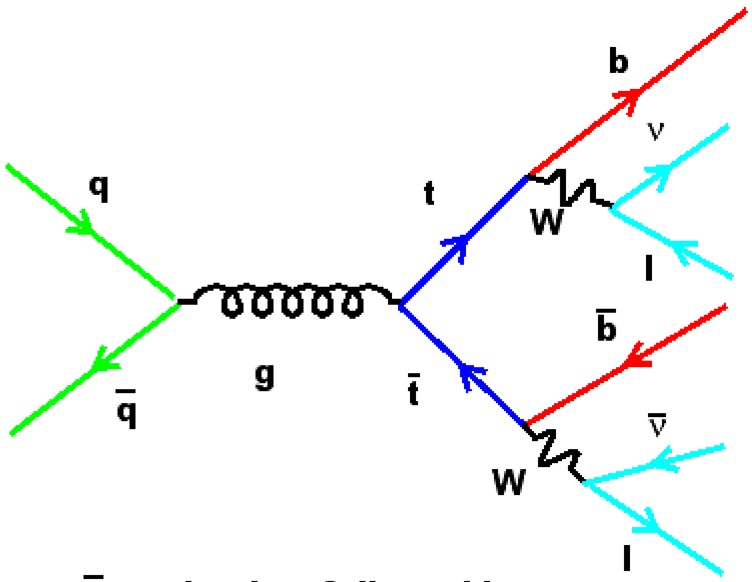
•*gg*



	BR(%)
di-l	10
l+j	44
all-j	46

Why dilepton events?

- *Dilepton channel is*
  - *Clean – small SM backgrounds*
  - *Different experimental requirements from higher-stats channel (l+jets)*
    - *Don't have to identify b quarks*
    - *Different backgrounds*
- *Part of a exp. program*
  - *SM top: dil, l+jet, all-hadronic all agree w/ one-another*
- *Run I dilepton kinematics caused some excitement*
  - *CDF (109/pb)*
  - *7 eμ events out of 9 total*
  - *Small event sample intriguing – check with larger sample (×2 larger)*



p $\bar{p}$ production, followed by $t\bar{t}$ decay into di-lepton mode

$$\sigma(t\bar{t}) = 8.2^{+4.4}_{-3.4}\ pb$$

$$SM : \sigma(t\bar{t}) = 5.2 \pm 0.3 pb @ 1.8 TeV$$

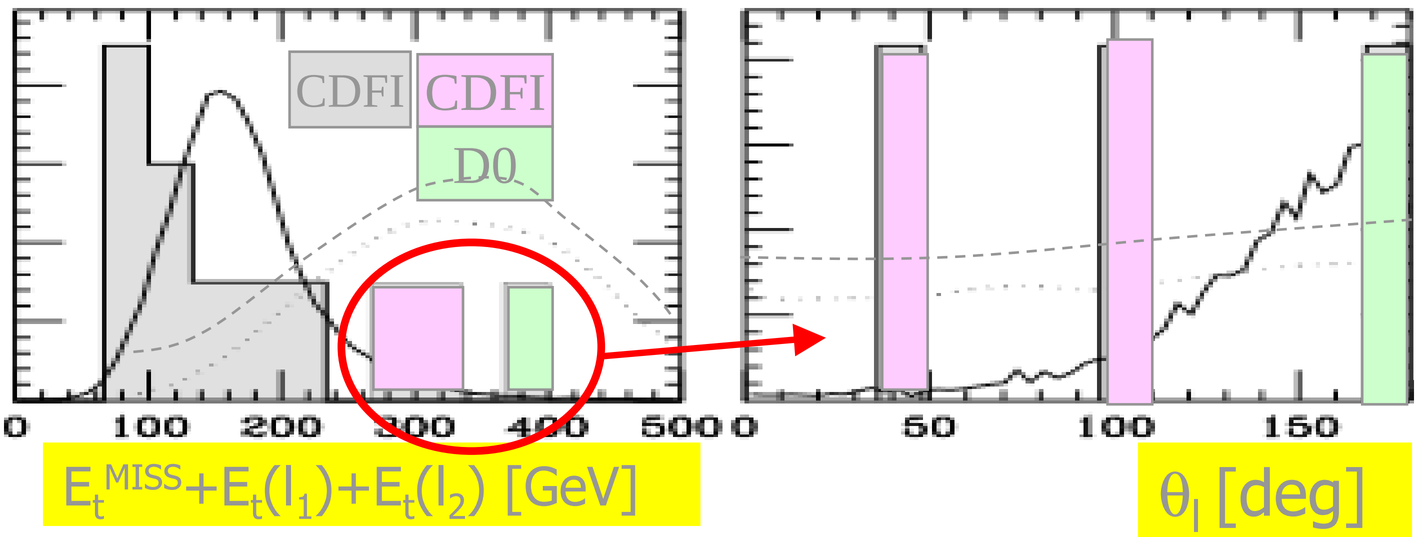
Run I Dileptons: new physics?

—— $t\bar{t}$

········ $\tilde{l} \rightarrow l\nu\tilde{\chi}_1^0$

} SM top or SUSY?

Theory interest from hep-ph/9609313



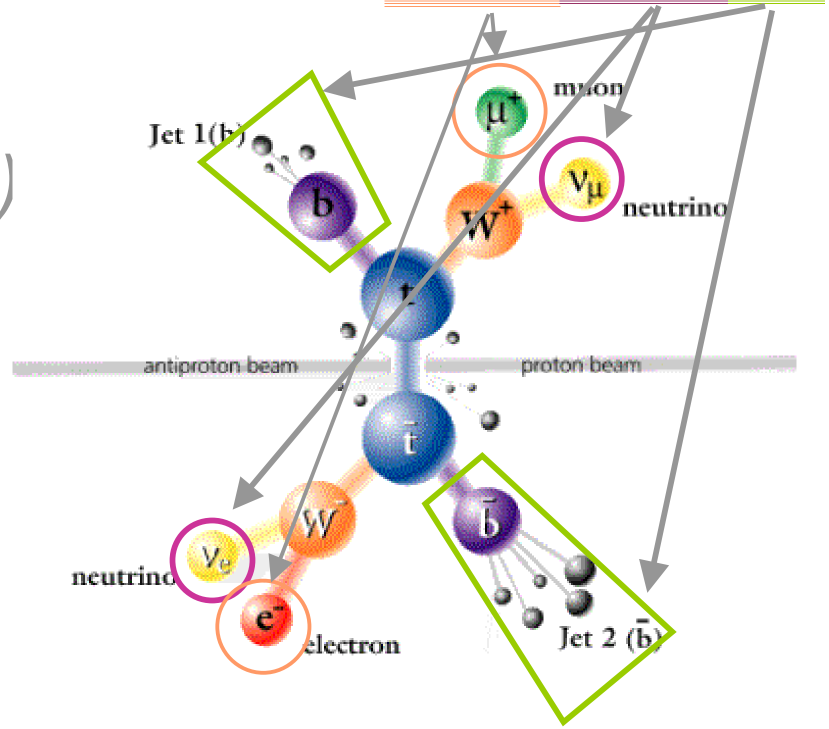
ttbar or cascade decay of squarks with masses around 300 GeV?

Kinematics in Dilepton Events

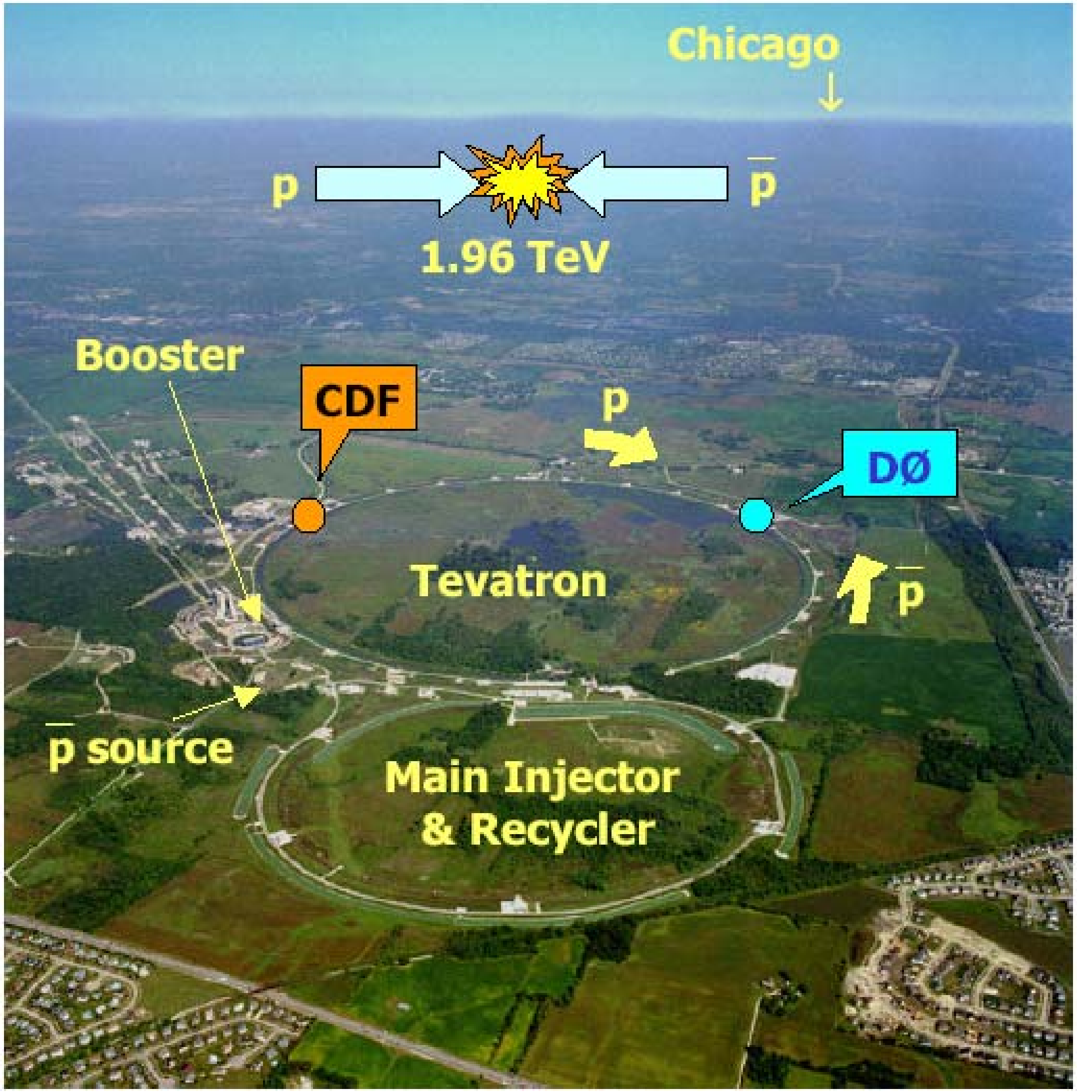
Event topology

- *Two high-momentum, opposite-sign leptons*
  - *(e,μ, some τ) from W decay*
- *2 b jets*
  - *Heavy flavor ID* not used for *this analysis*
- *Large missing energy (E_T^{miss})*
  - *Two escaping neutrinos*

$$
\begin{aligned}
p\bar{p} &\rightarrow t\bar{t} \\
&\rightarrow W^-W^+b\bar{b} \\
&\rightarrow l^-l^+\nu\bar{\nu}b\bar{b} \\
&\rightarrow l^+l^-E_T^{miss}jj
\end{aligned}
$$

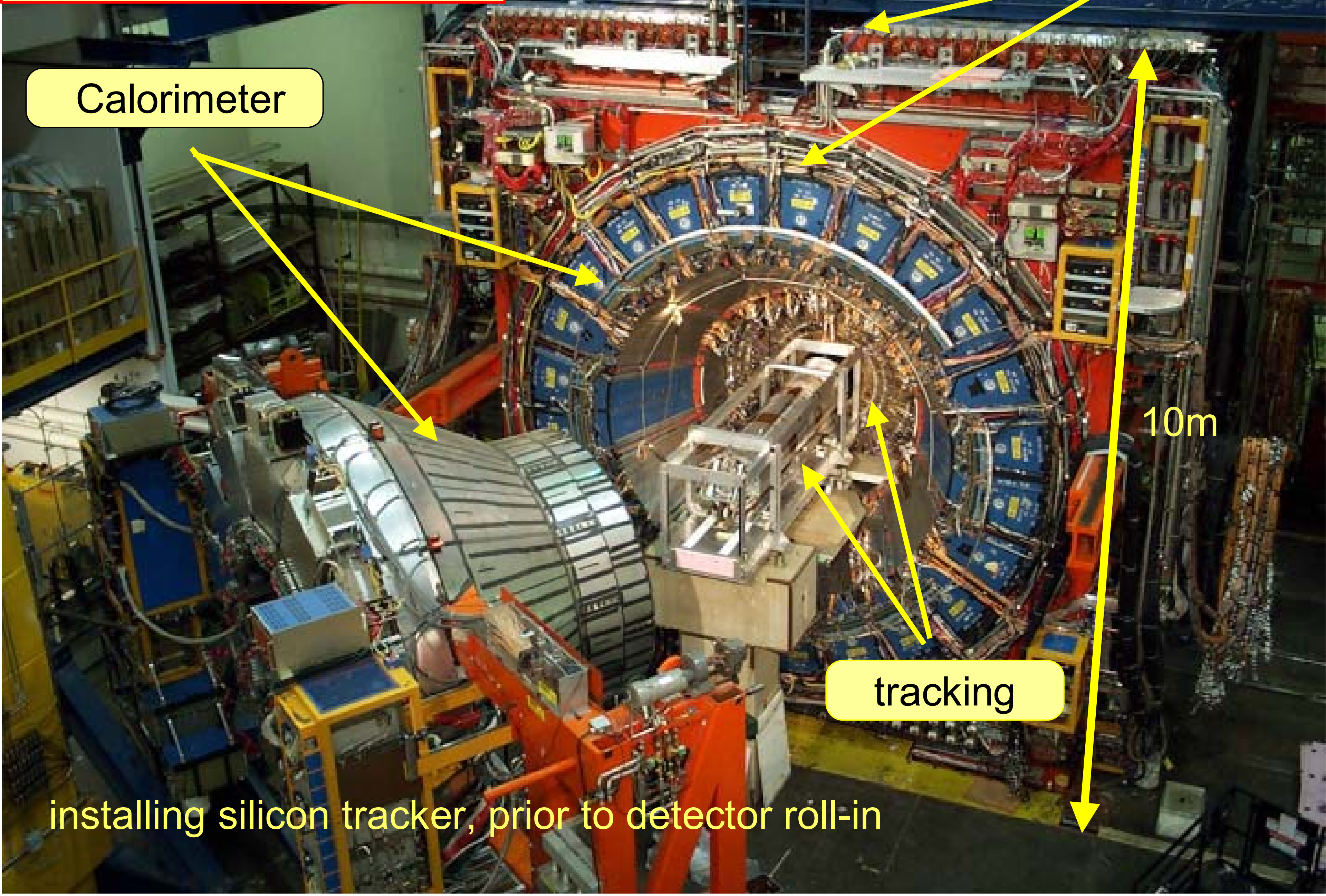


Fermilab's Tevatron Collider



- *Tevatron is world's highest energy p-pbar collider with $\sqrt{s}$ = 1.96 TeV*
- *CDF and D0 upgraded for Run 2*
- *Run 2 data-taking started in 2001*

CDF

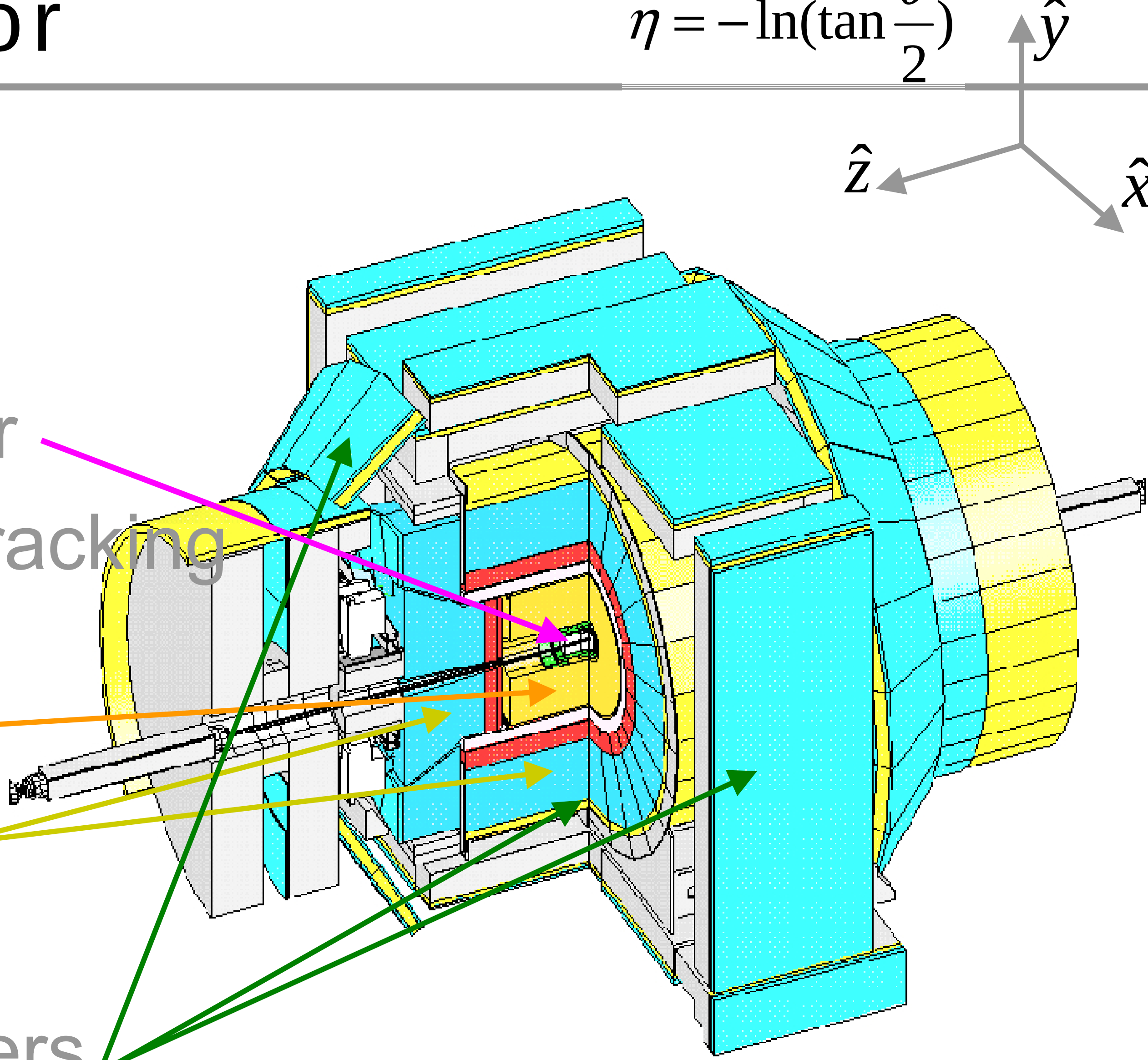

muon
Calorimeter
10m
tracking
installing silicon tracker, prior to detector roll-in

CDF detector

$$\eta = -\ln(\tan\frac{\theta}{2})$$

Features:

- Silicon tracker
- large radius tracking wire chamber (COT)
- Calorimeter
  - (|η| < 3.6)
- muon chambers
  - (|η| < 1)



Measurement strategy

$$\sigma(t\bar{t}) = \frac{N_{obs} - N_{bgnd}}{(\varepsilon \times A)\int L dt}$$

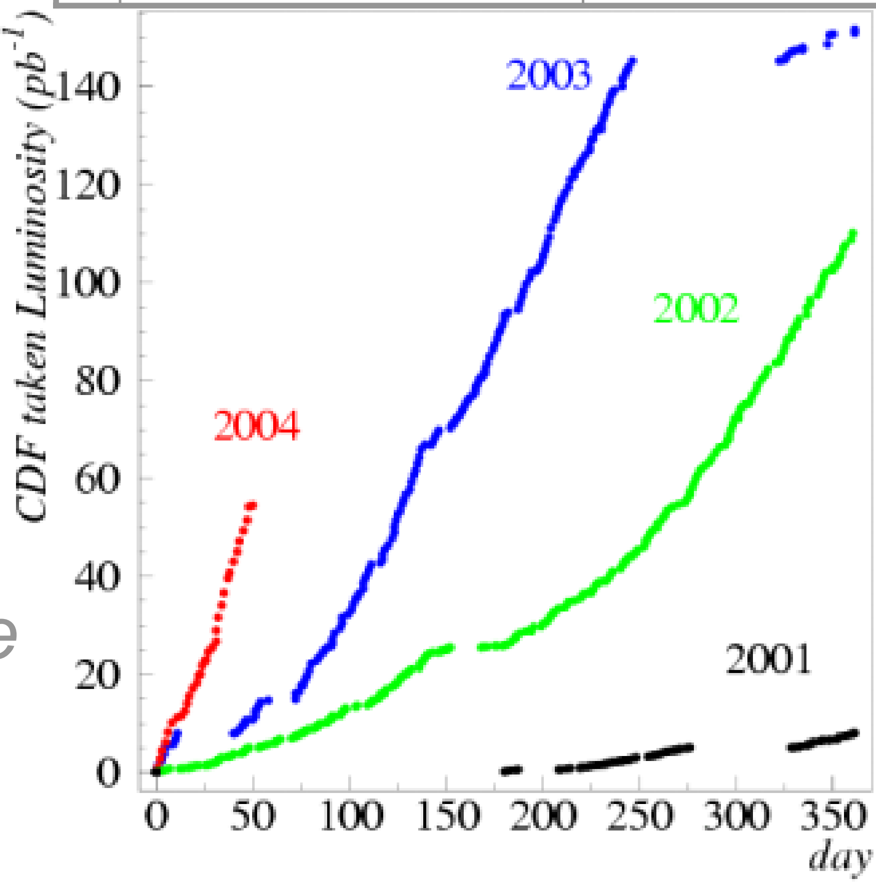
- *For this measurement we need to*
  - *Collect lots of data (L)*
  - *Select signal events (N_{obs})*
  - *Understand our signal acceptance (A)*
  - *Understand corrections to this acceptance (ε)*
  - *Estimate our backgrounds (N_{bgnd})*
- *Consider control region ($n_{jet} < 2$) to test background estimates*
- *We pursue two independent and complementary analysis approaches*

Collecting the data

- *Events are triggered on one high-momentum lepton*
- *We use data collected up to 9/2003, corresponding to 197 pb^{-1}*
  - *(cf ~108 pb^{-1} Run I)*
- *Additionally*
  - *$\sqrt{s}$ 1.8 TeV→ 1.96 TeV*
  - *Electron acceptance*
    - *$\eta < |1| \rightarrow \eta < |2|$*
- *→ expect more than twice Run I yield*

Trigger

e	*Central ($\|\eta\|<1$)*	*$E_T>18$ GeV, $P_T>8$ GeV*
	Forward ($1.0<\|\eta\|<2.6$)	*$E_T>20$ GeV $E_T^{miss}>15$ GeV*
μ	*Central ($\|\eta\|<1$)*	*$P_T>18$ GeV*



Event Selection: Two independent analyses

Each analysis is seeded by a single, isolated high-momentum lepton (e or μ)

- *Electron is track plus matching calorimeter cluster consistent with electron test beam*
- *Muon is track plus matching stub in muon chambers*

Split occurs when we look for the second lepton

"DIL" analysis

- Second lepton uses traditional lepton ID in calorimeter, muon chambers
- Two well-identified leptons
- **Higher purity, lower statistical significance**

"LTRK" analysis

- Second lepton is just track isolated in drift chamber ("**tl**")
- Increase acceptance at expense of purity
  - Get ~hadronic τ & holes in lepton ID coverage
- **Lower purity, higher statistical significance**

→ *Two independent, complementary approaches*

Event selection details (I)

- *Identify lepton leg*
  - *Central muon (|η|<1) or central or forward electron (|η|<2)*
  - *E_T,p_T>20 GeV, isolated in the calorimeter*
- *Re-cluster jets, recalculate missing energy (E_T^{miss}) with respect to lepton*
  - *Defines event vertex in Z*
- *Split when looking for second lepton:*

DIL:

- *Select second lepton with possibly looser selection*
  - *Allow non-isolated leptons and "stubless" muons*

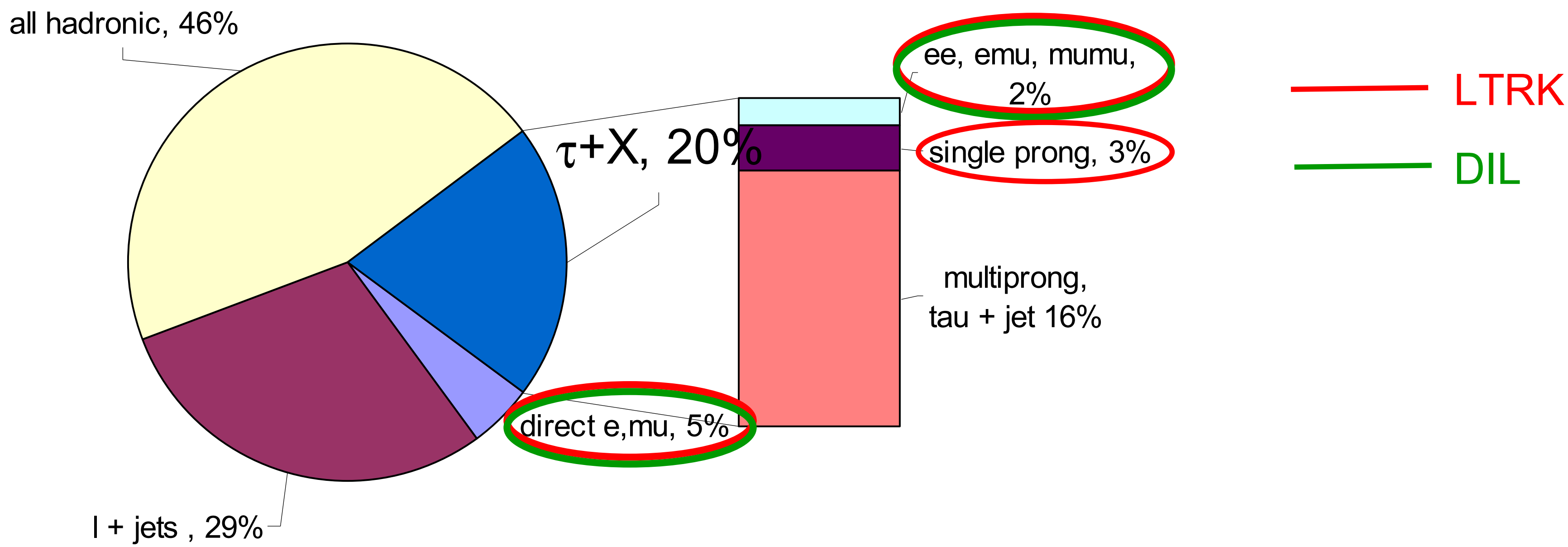
LTRK:

- *Identify isolated track candidates*
- *Correct E_T^{miss} for isolated track candidates*
- *Select highest momentum isolated track*

Event selection details (II)

- *Require E_T^{miss}>25 GeV*
  - *Reject events with E_T^{miss} co-linear with jets or lepton*
  - *LTRK: Reject events with E_T^{miss} parallel or anti-parallel to isolated track*
- *If lepton pair mass is in Z region, apply additional rejection*
- *Require ≥2 jets*
- *Require leptons to have opposite charge*
- *DIL:*
  - *Increase purity by requiring H_T ≡ (scalar sum of event energy) > 200 GeV*

Signal: Top acceptance



- Determine from PYTHIA Monte Carlo (m_T=175 GeV)
- Apply trigger efficiencies, lepton ID Monte Carlo correction factors, luminosity weights for different detector categories
- DIL: (0.62 ± 0.09)%
- LTRK: (0.88 ± 0.14)%

[This acceptance includes the BR(W→lnu)=10.8%]

Estimate efficiencies from data

- *Estimate differences between simulation and data for Lepton ID using Z data*
  - *Select Z candidates with one tight lepton leg and one probe leg*
  - *Measure efficiencies of probe leg, compare to Monte Carlo efficiencies*
- *Estimate "track lepton" (tl) selection efficiencies:*
  - *Use W sample selected w/o tracking requirement*
  - *Compare track efficiency with efficiency for W track in top Monte Carlo simulation*

Backgrounds

Categorize backgrounds as instrumental *or* physics

- *Instrumental backgrounds*
  - *False E_T^{miss} or leptons*
  - *Drell-Yan $Z \rightarrow ee, \mu\mu$*
    - *Mismeasurement gives false E_T^{miss}*
  - *W+jets*
    - *Jet is mis-id'd as lepton*
- *Physics backgrounds:*
  - *Real leptons, E_T^{miss}*
  - *Diboson (WW, WZ)*
  - *Drell Yan $Z \rightarrow \tau\tau$*

LTRK dominant

DIL: equal

Instrumental: Drell-Yan background (I)

$$p\bar{p} \to Z/\gamma^* \to l^+ l^-$$

$$BR \times \sigma = 252\, pb$$

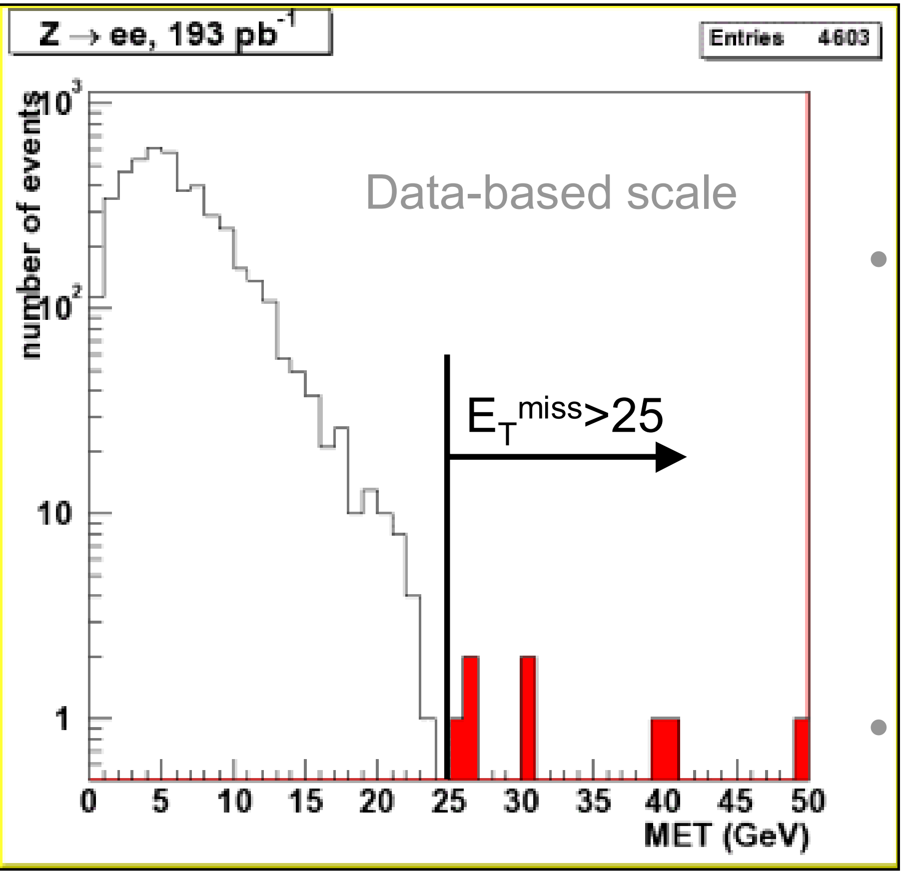
- *Large cross section but no intrinsic E_T^{miss}*
- *False E_T^{miss}*
  - *Detector coverage isn't 4π*
  - *Reconstruction isn't perfect*
- *Tails of E_T^{miss} resolution critical*
  - *Simulation doesn't accurately model this*

- *For optimal E_T^{miss} resolution:*
  - *Correct jets for uniform calorimeter behavior*
  - *Correct E_T^{miss} with these jets*
  - *LTRK: for "tl", correct E_T^{miss} if tl is min ionizing*
    - *mu's*
    - *Undermeasured e's*

Drell Yan background (II)

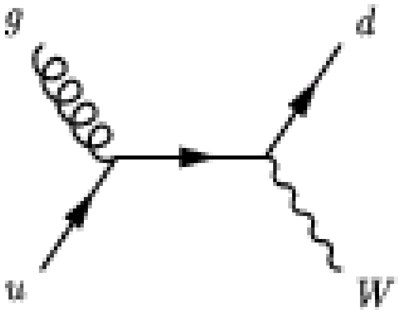
$$j = \frac{E_T^{Miss}}{\sum \vec{E}_T \cdot \vec{E}_T^{Miss}} > 8$$

Jet significance



- *DIL and LTRK use special cuts to suppress DY background*
  - *Require min $\delta\Phi$(j or l, E_T^{Miss})*
- *Additionally in "Z window"* *($76<m_{ll}<106$ GeV)*
  - *DIL: "Jet significance"*
  - *LTRK: Boost E_T^{Miss} requirement: >40 GeV*
- *Estimate residual contamination*
  - *Overall normalization: Z-like data set: Two leptons, high E_T^{Miss}, in Z window*
  - *Remove signal contribution*
  - *Use simulation to estimate background outside of Z window*
- *Low data counts dominant uncertainty*

Instrumental: fake lepton background

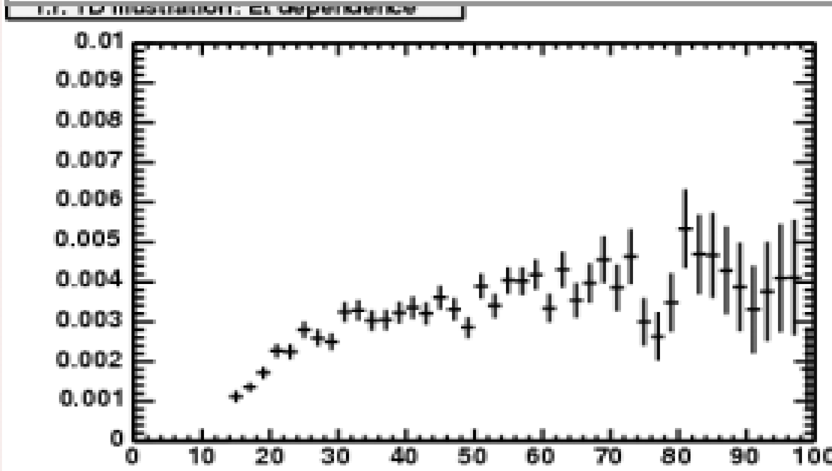


•Fakes from W+1p

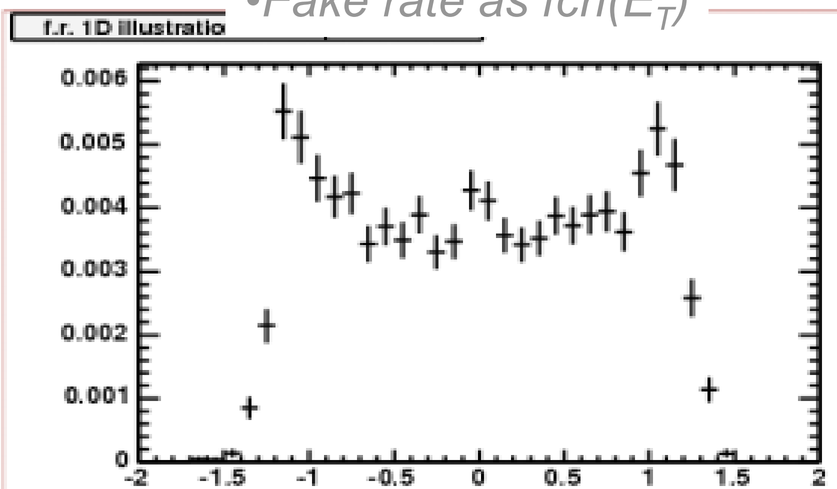
One or both leptons are not real

- *LTRK*
  - *Single pions from jets*
- *DIL:*
  - *Jet that passes electron requirements*
  - *π punch-through to muon chambers*
- *Measure probability from jet sample*
  - *Sample with triggered on one jet with more than 50 GeV of energy (a.k.a. 'Jet50')*
- *Apply to our data sample*

Illustrative fake rate example for LTRK



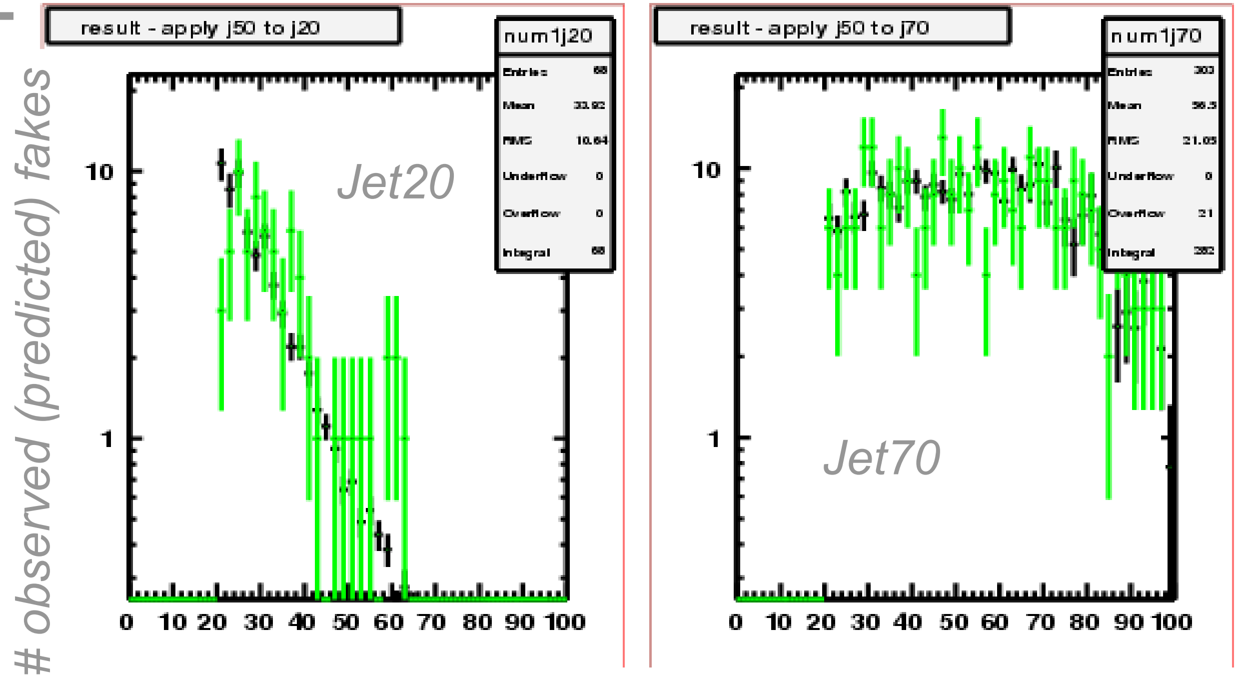
•Fake rate as fcn(E_T)



•Fake rate as fcn(eta)

Instrumental: fake lepton background

- *Cross-check technique on different samples*
- *Check scalar prediction and shapes*
  - *Scalar prediction of rates*



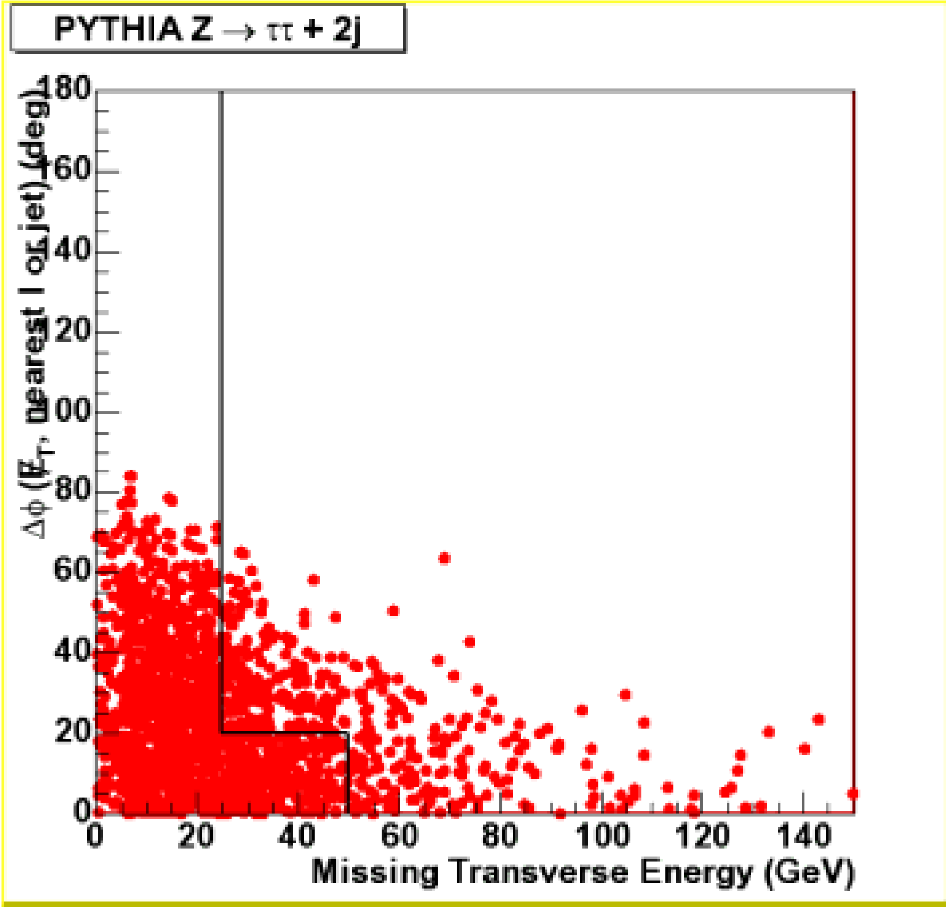
E_T of observed (predicted) fake tracks in green (black)

LTRK	Obsv	Pred
j20	74	70 ± 14
j70	316	314 ± 73
inc lep	231	189 ± 37

DIL	Obsv	Pred
j20	51	49 ± 6
j70	75	65 ± 9
j100	69	114 ± 31

Physics backgrounds

- *Diboson:*
  - *WW, WZ, ZZ*
- *Drell Yan $Z/\gamma^* \rightarrow \tau\tau$*
- *In both cases:*
  - *Real missing energy*
  - *Jets from decays or initial/final state radiation*
- *Estimates derived from Monte Carlo samples*
  - *ALPGEN, PYTHIA, HERWIG*
  - *Cross sections normalized to theoretical calculations*
- *Correct for underestimation of extra jets in MC*
  - *Determine jet bin reweighting factors for $Z \rightarrow \tau\tau$ from $Z \rightarrow ee$, $\mu\mu$ data*
  - *Reweight WW similarly*



Signal acceptance systematics (I)

Systematic	*LTRK(%)*	*DIL(%)*
Lepton ID efficiency *- Variation of data/MC correction factor with isolation*	*5*	*5*
tl efficiency *- iso efficiency difference btw W+2j data and ttbar MC*	*6*	*-*
Jet Energy Scale *- vary jet corrections by $\pm 1\sigma$, δ(acc) for evts w/$\geq$2 jets*	*6*	*5*

Signal acceptance systematics (II)

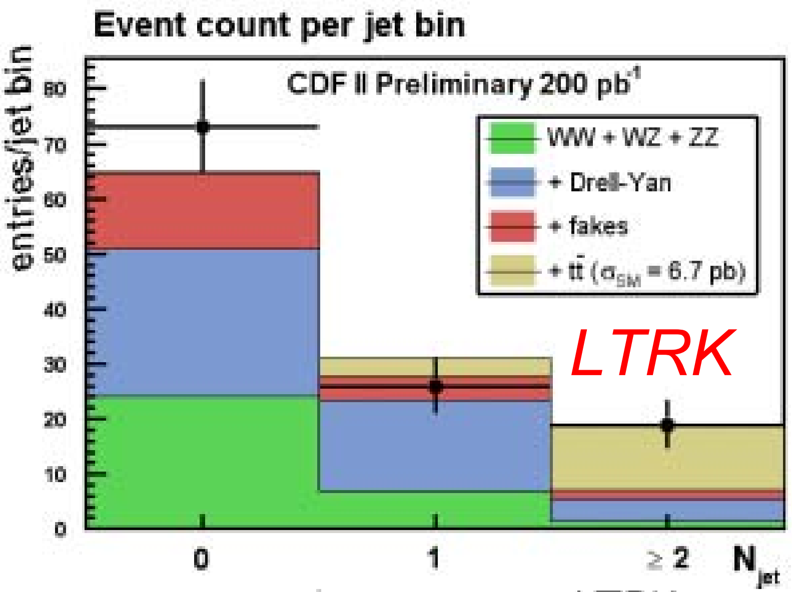
Signal Systematics Continued	*LTRK(%)*	*DIL(%)*
Initial- and Final-state radiation *- ISR: difference from no-ISR sample* *- FSR: parton-matching method, different PYTHIA tune*	*7*	*2*
Parton Distribution Functions (PDF's) *- default CTEQ5L vs MRST PDF's, different α_s samples*	*6*	*6*
Monte Carlo Generators *- compare acceptance of PYTHIA to HERWIG*	*5*	*6*

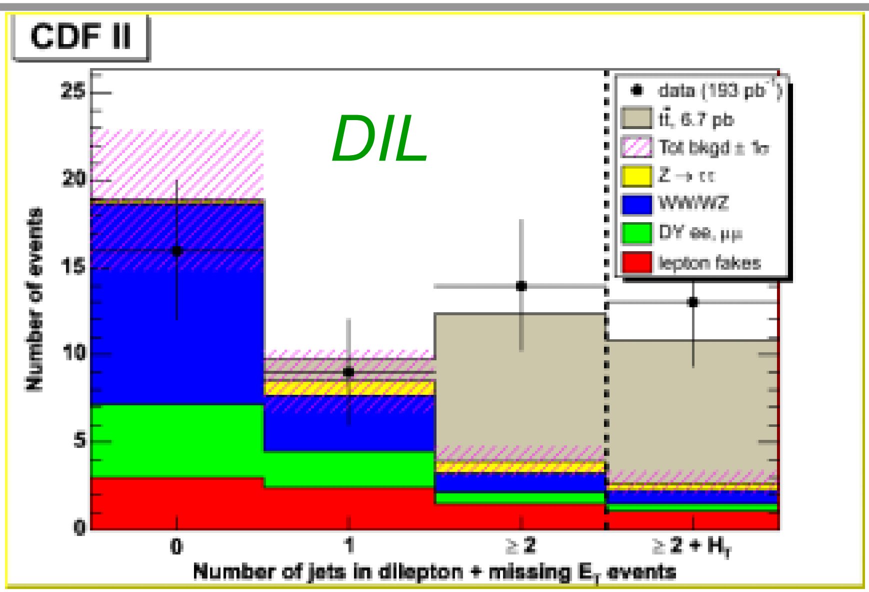
Systematic Uncertainty on Background Estimate

Systematic	*LTRK(%)*	*DIL(%)*
Lepton (track) efficiency – same as signal	*5 (6)*	*5(-)*
Jet Energy Scale – same procedure on bkgnd acc.	*10*	*18-29*
WW, WZ, ZZ estimate *- Compare scaled MC jet estimate to straight calculation*	*20*	*20*
Drell-Yan Estimate *- Absolute scale (data driven), Monte Carlo shape*	*30*	*51*
Fake Estimate *- J20, J50, J70, J100 x-check* *- DIL: statistical uncertainty*	*12*	*41*

- *Total syst uncertainty due to background is ±0.6 pb for DIL, ±1.0 pb for LTRK*

Signal and background vs data





	LTRK		DIL	
	$N_{jet} = 0$	$N_{jet} = 1$	$N_{jet} = 0$	$N_{jet} = 1$
WW, WZ, ZZ	21.8 ± 5.5	6.3 ± 1.6	11.4 ± 3.3	3.2 ± 0.9
Drell-Yan	26.5 ± 9.8	16.4 ± 6.0	4.4 ± 1.9	2.9 ± 1.1
Fakes	16.5 ± 2.4	5.0 ± 1.0	3.0 ± 1.2	2.4 ± 1.0
Total Bkgd	64.8 ± 11.5	27.7 ± 6.3	18.8 ± 4.0	8.5 ± 1.8
Expected $t\bar{t}$	0.3 ± 0.2	3.4 ± 0.6	0.1 ± 0.0	1.3 ± 0.2
Total	65.1 ± 11.5	31.1 ± 6.3	18.9 ± 4.0	9.8 ± 1.9
Observed	73	26	16	9

Good agreement in background region

σ(tt) signal region

Cross section results

$$\sigma(t\bar{t}) = \frac{N_{obs} - N_{bgnd}}{(\varepsilon \times A)\int L dt}$$

$$SM : \sigma(t\bar{t}) = 6.7^{+0.7}_{-0.9}\, pb$$

At NLO @ √s=1.96 TeV for m_{top} = 175 GeV:
hep-ph/0303085 (Mangano et al)

DIL:

$$\sigma(t\bar{t}) = 8.4^{+3.2}_{-2.7}(stat)^{+1.5}_{-1.1}(syst) \pm 0.5(lum)\ \mathrm{pb}$$

LTRK:

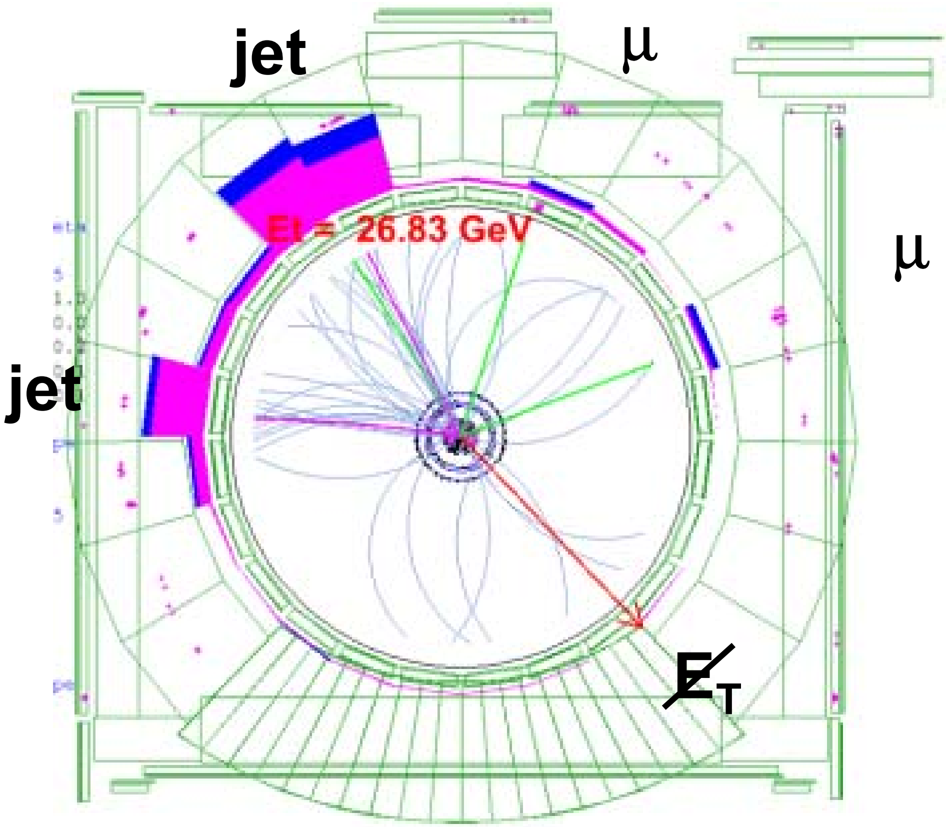
$$\sigma(t\bar{t}) = 7.0^{+2.7}_{-2.3}(stat)^{+1.5}_{-1.3}(syst) \pm 0.4(lum)\ \mathrm{pb}$$

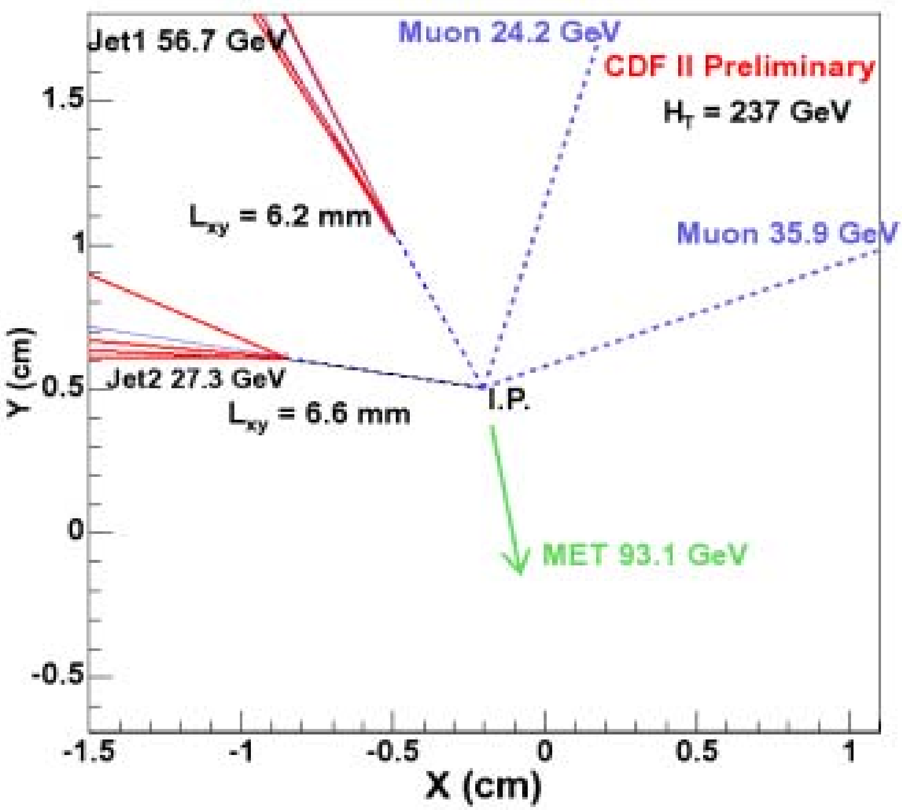
(Assume BR(W→lν)=10.8%)

- *Both measurements consistent with SM calc*
- *Error is statistics-dominated*
  - *Combining results makes for better measurement*

Double-tagged top dilepton candidate

- *An event with 2 jets and 2 muons*





- *Both jets show displaced secondary vertices from the interaction point: b jet candidates*

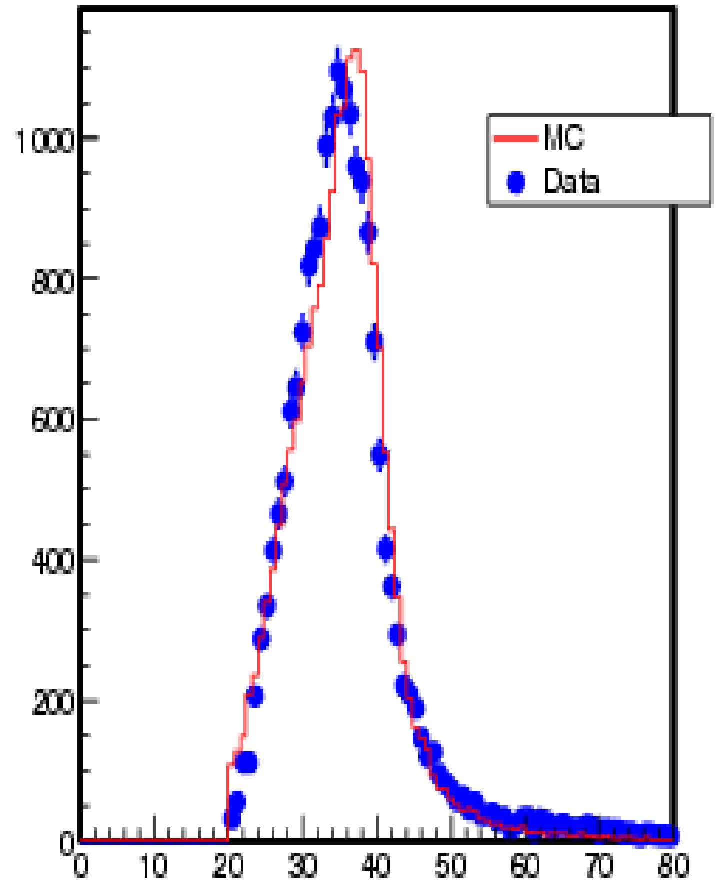
Cross-checks:

- *Measure W, Z cross sections*
  - *Use analysis tools, selections and samples*
- *Validates Monte Carlo, scale factors, luminosity estimate*
- *Good agreement with other measurements in all cases*

$$BR(Z/\gamma^* \rightarrow ll) \times \sigma(p\bar{p} \rightarrow Z/\gamma^*) = 252\ pb$$

$$BR(W \rightarrow l\nu) \times \sigma(p\bar{p} \rightarrow W) = 2.69\ nb$$

Forward W electron candidates

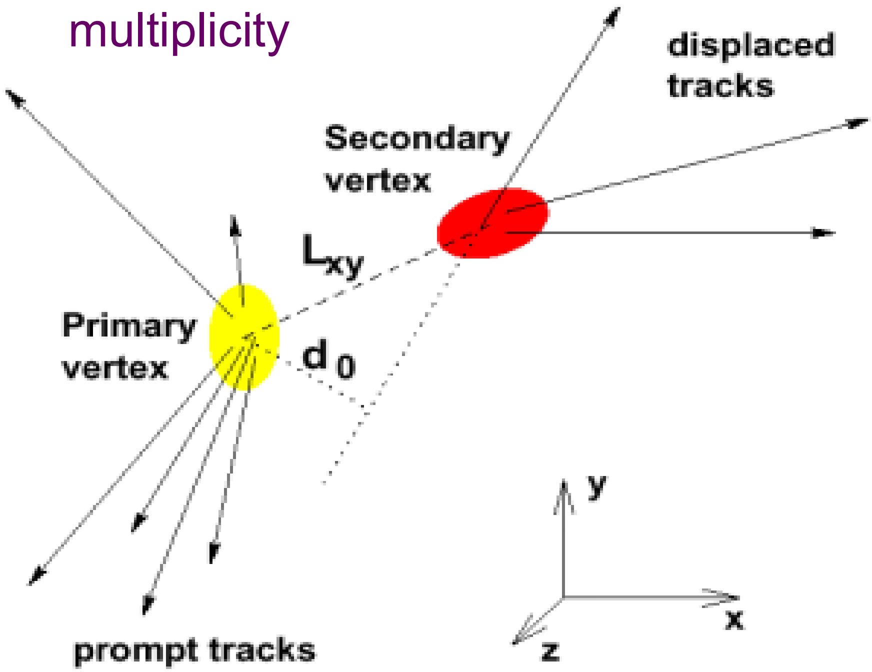


E_T(GeV)

Cross-checks: b content

•Signature of a B decay is a displaced vertex:

- •Long lifetime of B hadrons (cτ ~ 450 μm)+ boost
- •B hadrons travel Lxy~3mm before decay with large charged track multiplicity



Top Event Tag Efficiency 55%
False Tag Rate (QCD jets) 0.5%

- *Top decays should have two b quarks per event*
  - *We don't use this info here*
- *Check **b** quark content as check*
  - *Look for jets consistent with long-lived particles detected in Silicon Vertex tracker*
- *→ Number of events with detected b-like quark jets consistent w/expectation*
  - *DIL: 7, LTRK: 10*

Cross-check: Tighten 2nd lepton ID

	0 jets		1 jet		≥2 jets	
	#	uncert	#	uncert	#	uncert
Top dilepton	**0.11**	**0.03**	**1.40**	**0.24**	**4.52**	**0.74**
Diboson	8.44	2.15	2.54	0.67	0.48	0.15
Drell-Yan	3.21	2.31	2.59	1.51	0.75	0.50
Fakes	**1.24**	**0.26**	**0.37**	**0.08**	**0.11**	**0.02**
Total bkgnd	**12.88**	**3.17**	**5.50**	**1.65**	**1.33**	**0.52**
Total pred.	**12.99**	**3.17**	**6.89**	**1.67**	**5.85**	**0.90**
Observed	**14**		**4**		**7**	

Signal

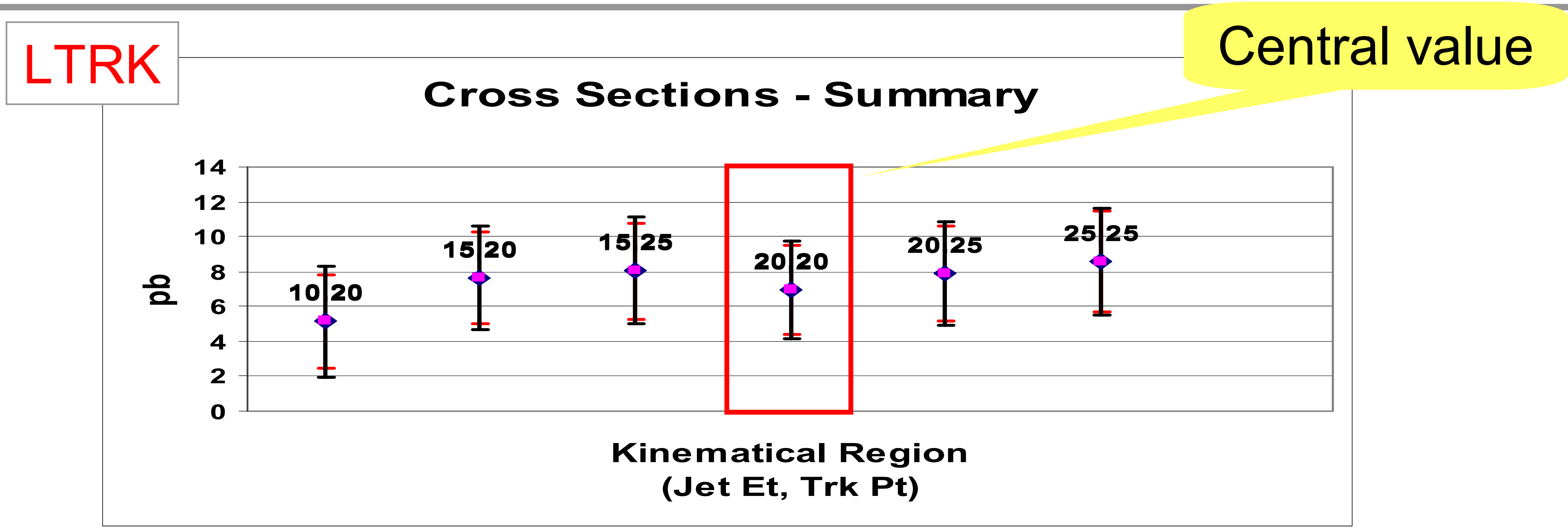
background

- *LTRK sample: apply traditional lepton ID on tl*
- *Very few fake leptons, no hadronic τ's*

$$\sigma(t\bar{t}) = 8.5^{+4.5}_{-3.5}(stat)^{+1.8}_{-1.4}(syst) \pm 0.5(lum)\ \text{pb}$$

- *Good agreement with DIL, LTRK*

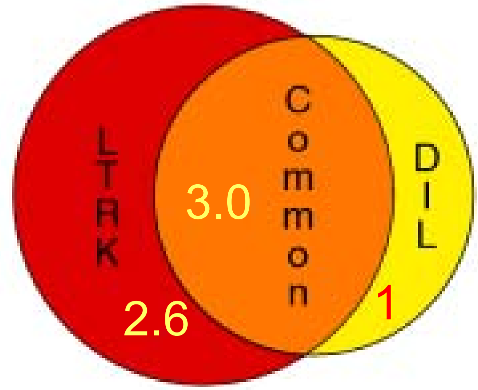
Cross-check: vary Jet, 2nd lepton thresholds



- *Vary jet threshold, 2nd lepton momentum threshold*
- *Changes background composition*
  - *Fake dominated→ physics dominated*
- *→ See consistent results (NB Uncerts very correlated)*
- *Choose value with best* a-priori *S/σ as central value*

Combining the cross sections

- *Combining two measurement reduces the largest uncertainty (**statistics**)*
- *Strategy: divide signal, background expectation and data into **three** disjoint regions*
- *Use extra information about events (high purity, low purity) and higher stats to get better measurement*



Acceptance ratio:

*DIL:LTRK:Common **1:2.6:3.0***

Signal Event Candidates

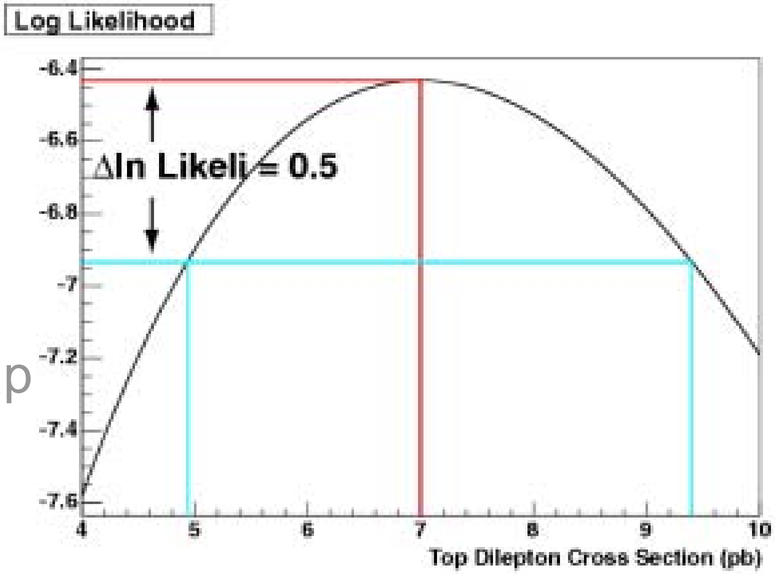
	Events
Common	11
DIL-Only	2
LTRK-Only	8
Total	21

	Background Events
Common	1.8
DIL-Only	0.9
LTRK-Only	5.1
Total	7.8

Combination technique

$$L = \prod_{\alpha}^{subgroup} P(n_{obs}^{\alpha} \mid n_{pred}^{\alpha}(\sigma_{t\bar{t}}))$$

α=product over DIL only, LTRK only, overlap



- For three regions, maximize combined Poisson likelihood
- Be conservative w/ systematics between regions
    - Treat as 100% correlated, distribute to give largest total systematic

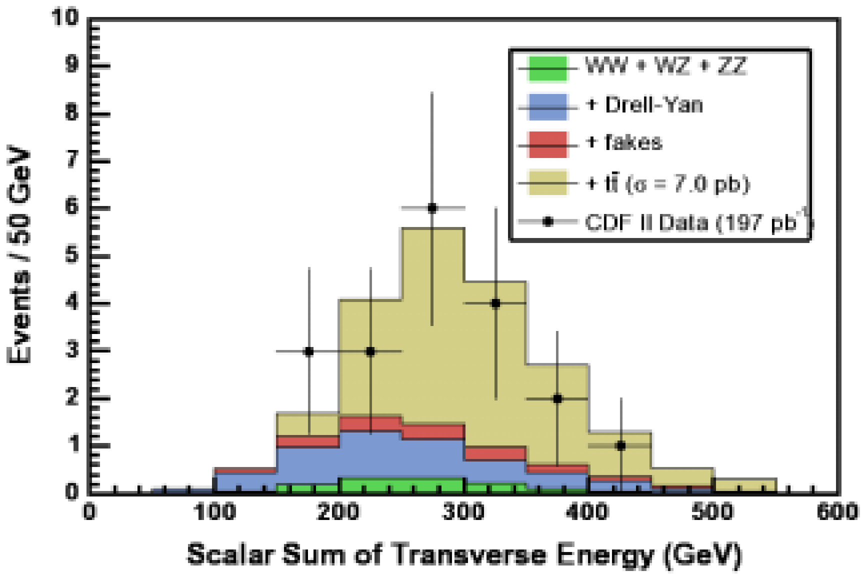
$$\sigma(t\bar{t}) = 7.0^{+2.4}_{-2.1}(stat)^{+1.6}_{-1.1}(syst) \pm 0.4(lum)\ \mathrm{pb}$$

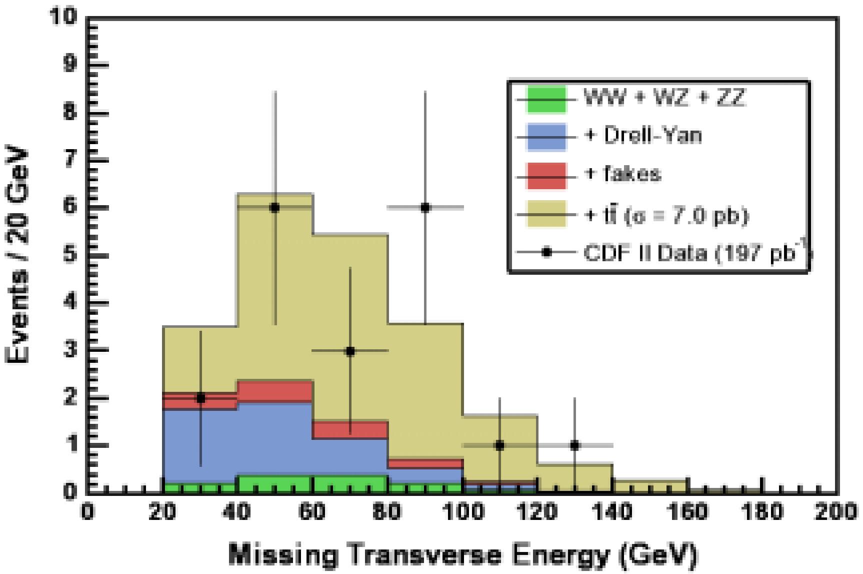
→ 12% reduction in statistical error

Kinematical distributions

With larger statistics, we can start going beyond counting experiments to do shape tests on our selected sample.

Use larger statistics of LTRK to examine sample kinematics





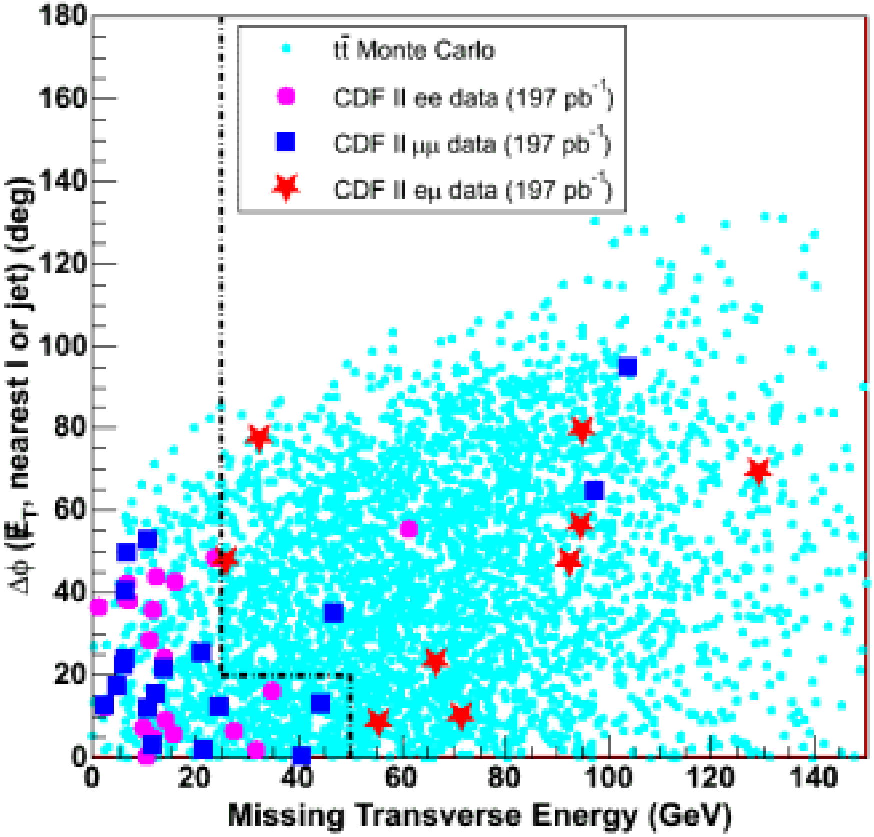
KS = 75%

KS = 66%

Data follow expected distribution of top + background

Flavor distribution

Use sample with two identified lepton (DIL) to look at flavor distribution

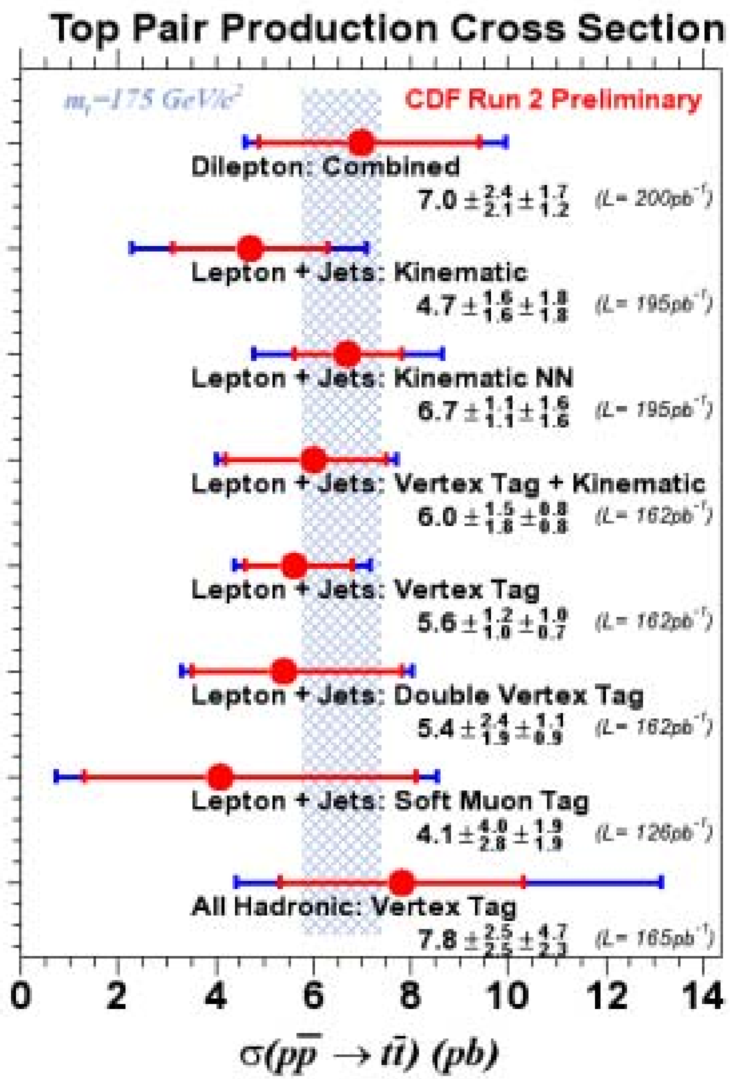


channel	Expected (scaled to 13 total obsv'd)	Observed
ee	*3.3 ± 0.5*	*1*
μμ	*2.8 ± 0.5*	*3*
eμ	*6.8 ± 0.8*	*9*

→ Flavor distribution is consistent with expectation.

What's next for top?

- *CDF has many other analyses with the dilepton channel in the works*
  - *Dedicated hadronic tau measurement*
  - *Detailed kinematic studies*
  - *W helicity (dil + l + jets)*
  - *Top mass in dilepton channel*
  - *Combined cross section dilepton and l + jets channels*
- *Other cross-sections en route to publication*
- *Mass results*
  - *Dilepton & lepton + jets*
- *See CDF public top results page for full details*



http://www-cdf.fnal.gov/physics/new/top/top.html

Conclusions

- *We have measured the $t\bar{t}$ production cross section in the dilepton decay channel using 197 pb^{-1} of Run II data*
- *Our result is* *(m_t = 175 GeV/c^2, BR($W \to l\nu$)=10.8%)*:

$$\sigma(t\bar{t}) = 7.0^{+2.4}_{-2.1}(stat)^{+1.6}_{-1.1}(syst) \pm 0.4(lum)\ \mathrm{pb}$$

consistent with SM prediction of $\sigma = 6.7^{+0.7}_{-0.9}$ pb

- *Kinematics, flavor distribution of data also consistent with Standard Model expectation*
- *Paper submitted to PRL (arXiv:hep-ex/0404036)*

Backup/storage/dustbin

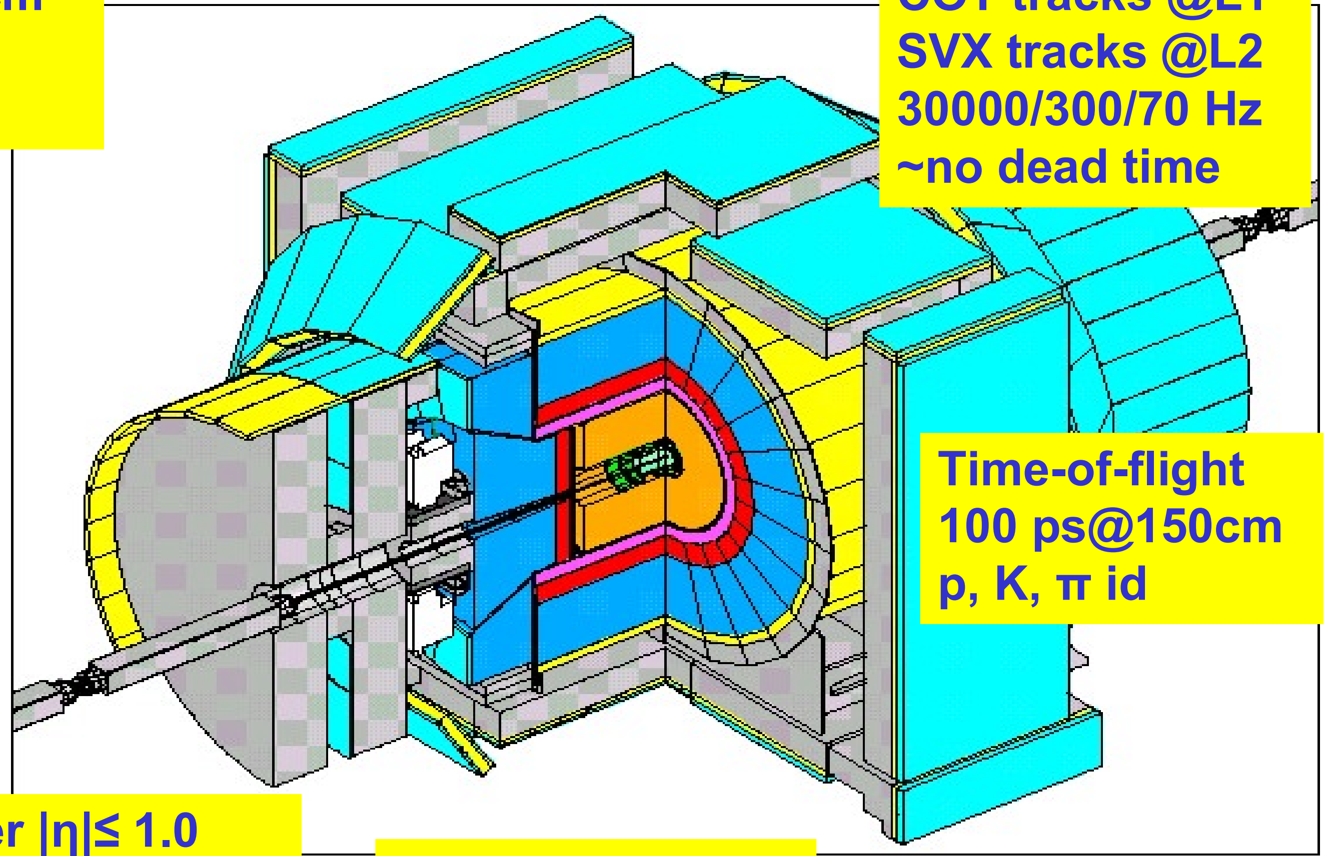
CDF II Detector

From 1995 – 2001, CDF upgrade: better *l* id, b tag, muon coverage, forward cal, DAQ....

7-8 silicon layers
1.6<r<28 cm, |z|<45 cm
$|\eta| \leq 2.0$, cosθ=0.964
σ(hit) ~ 14 μm

1.4 T magnetic field
Lever arm 132 cm

132 ns front end
COT tracks @L1
SVX tracks @L2
30000/300/70 Hz
~no dead time



Some resolutions:
$p_T \sim (0.7 \oplus 0.1\ p_T)\%$
J/Ψ mass ~15 MeV
EM E ~ 16%/√E
Had E ~ 100%/√E
$d_0 \sim 6+22/p_T$ μm
Primary vtx ~10 μm
Secondary vtx
r-Φ ~ 14 μm
r-z ~ 50 μm

Time-of-flight
100 ps@150cm
p, K, π id

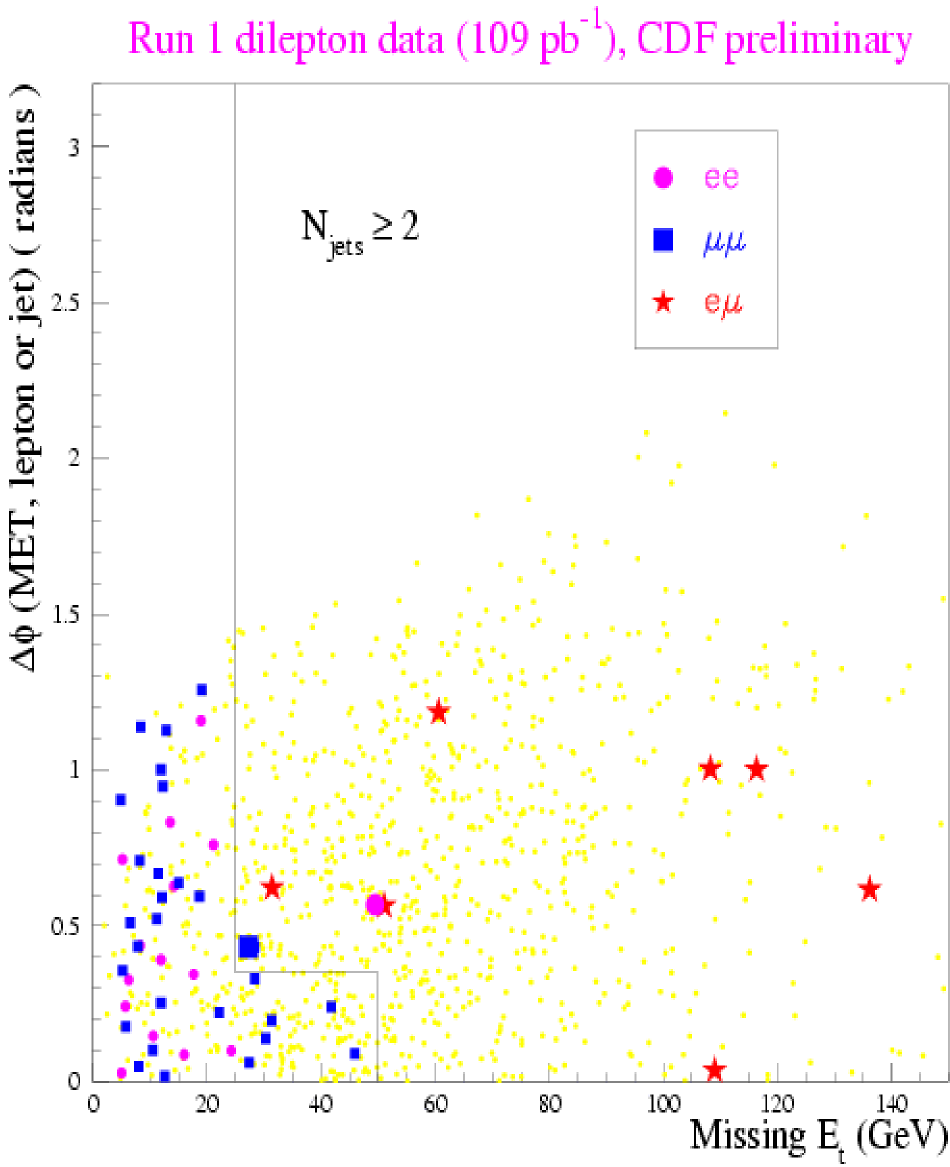
96 layer drift chamber $|\eta| \leq 1.0$
44<r<132 cm, 30k channels
σ(hit) ~ 180 μm
dE/dx for p, K, π id

Tile/fiber endcap calorimeter
$1.1<|\eta|<3.5$

μ coverage to
- **$|\eta| \leq 1.5$**
- **80% in phi**

Dileptons in Run I

- *Run I dilepton sample had some interesting features*
  - *7 eμ events out of 9 total*
  - *Several events with large E_T^{Miss}.*
  - *Measured σ=8.2$^{+4.4}_{-3.4}$ pb (to be compared with 5.2 pb theoretical)*
- *Something to watch in Run II!*



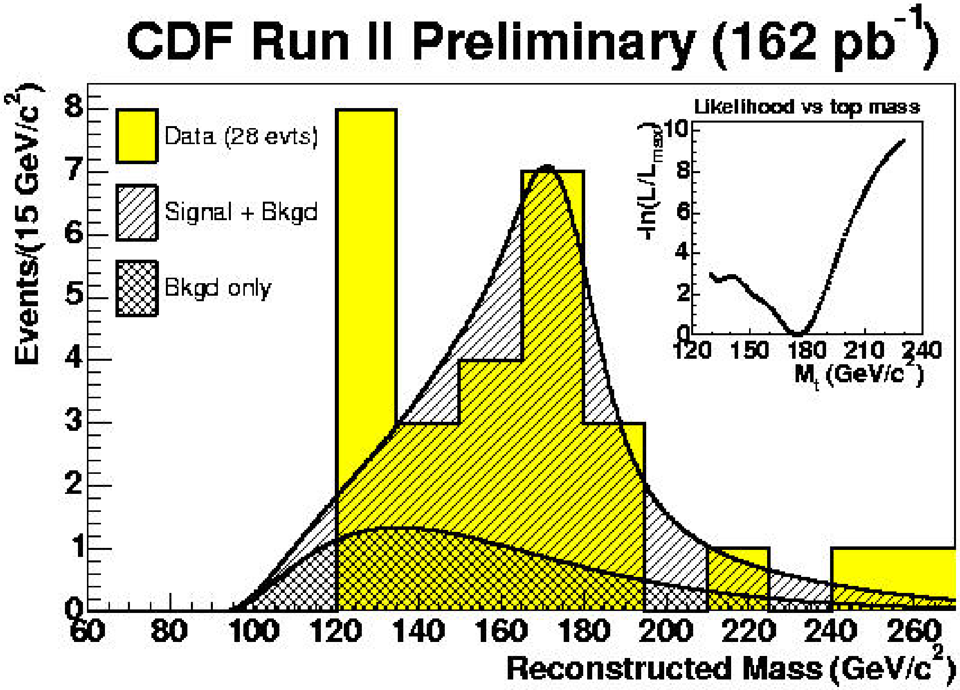
What about m_{top} = 178 GeV?

- *CDF & D0 released a new Run 1 combined top mass result*
- *arXiv:hep-ex/0404010*

$$m_{top} = 178 \pm 2.7(stat) \pm 3.3(syst)\mathrm{GeV}/c^2$$

- *Top acceptances changes ~0.5%/GeV/c^2.*
- *Top cross section would go from 7.0→7.1 pb*

Current CDF top mass results



Top quark mass			
l+j	Vertex b-tag, Dynamic Likelihood	177.8 + 4.5 -5.0 (stat) +- 6.2 (syst) GeV/c^2	162/pb
l+j	Vertex b-tag, template	174.9 +7.1-7.7 (stat) +- 6.5 (syst) GeV/c^2	162/pb
dil	e-e, e-mu, mu-mu	175 + 17.4- 16.9 (stat) +- 8.4 (syst) GeV/c^2	126/pb

COT Gas Recirculation System

- *Change gas direction/speed through COT*
  - *20 schf Historical standard*
    - *One volume change every 30 hours*
  - *40 scfh started Feb. '04. Also, flow reversal Mar. '04*
    - *No obvious aging improvement (or worsening).*
    - *Some aged wires start to recover on new input side.*
  - *200 scfh Imminent*
  - *1000 scfh Perhaps during Summer shutdown, if needed*
- *200 scfh system specifications*
  - *Recycle 80%, exhaust 20% and make-up with new gas*
  - *No specific purification - no alcohol replacement*
  - *Leave room and install hooks for future enhancements*
  - *Meet lab and RR safety requirements*