Top Quark Physics at the Tevatron

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For the CDF and DØ Collaborations

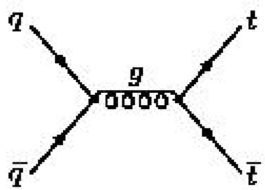
- Introduction
- Latest results from Run 1
- New results from Run 2
- Summary and prospects

Introduction

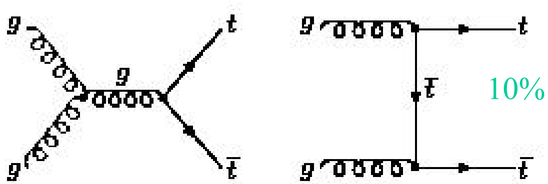
- **Top quark has a special place in the SM** **SM** $\sqrt{2}M_t / v \sim 1$
  - The Yukawa coupling,
  - Special role in EW symmetry breaking?

- **Discovered at Tevatron in 1995**
  - CDF, PRL 74, 2626 (1995)
  - DØ, PRL 74, 2632 (1995)

- **Top quarks have been observed in pair** **pair** **production through strong interaction**: $\sigma(t\bar{t}) \approx 5\text{pb} \quad \text{at} \quad \sqrt{s} = 1.8\text{TeV}$



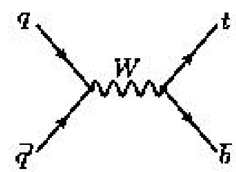
$90\% \text{ of } \sigma(t\bar{t})$



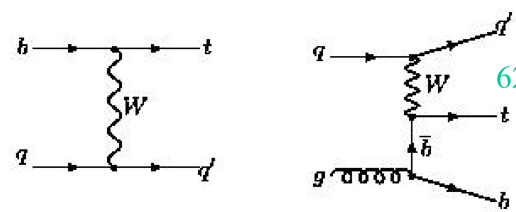
$10\% \text{ of } \sigma(t\bar{t})$

- **3 classes of signal in $t\bar{t}$ production**:
  - Dilepton — 2 high-P_T leptons, 2 b-jets, large E_T^{miss} — BR(ee , $\mu\mu$, eμ) = 5%
  - Lepton+Jets —1 high-P_T lepton, 4jets (2b's), large E_T^{miss} — BR(e,μ+jets) =30% =30%
  - All-hadronic — 6 jets (2b's) — BR=44% BR=44%

- **Another mechanism — single-top production via EW interaction**: $\sigma(\text{single-t}) \approx 2.4\text{pb} \quad \text{at} \quad \sqrt{s} = 1.8\text{TeV}$



$32\% \text{ of } \sigma(\text{single-t})$

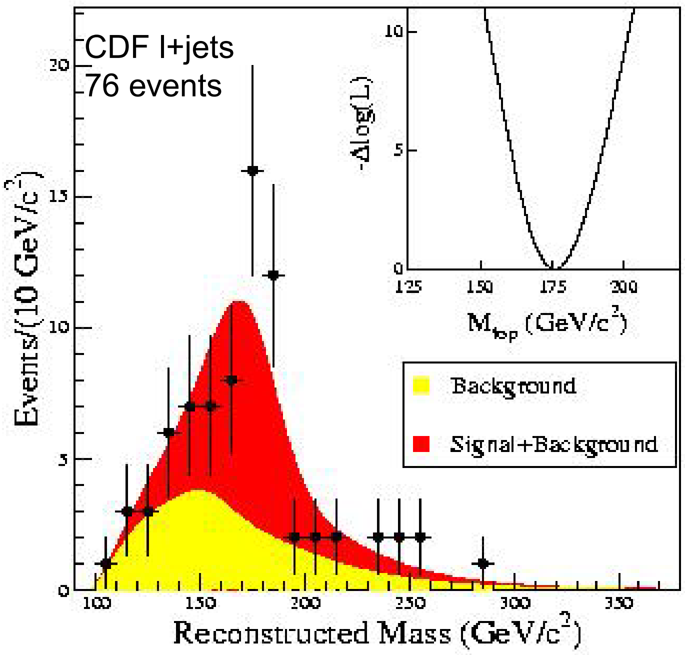


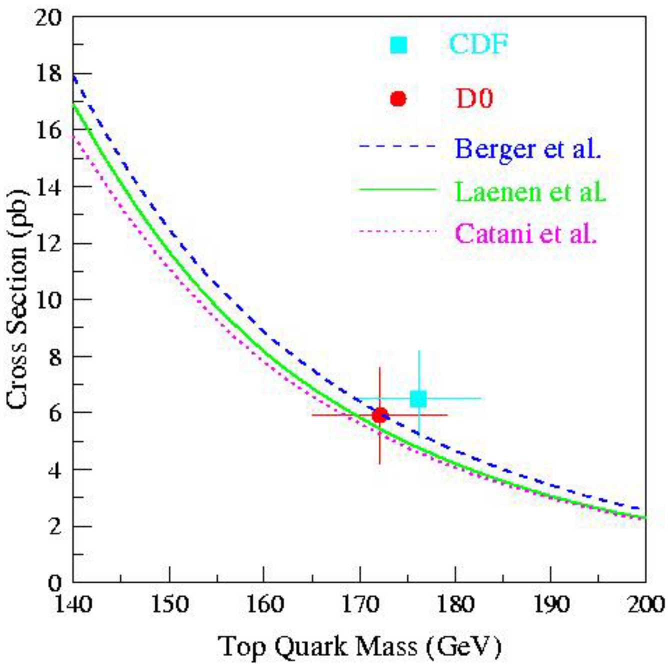
$62\% \text{ of } \sigma(\text{single-t})$

- **Wealth of information extracted with ~100 $t\bar{t}$ events per experiment based** **based** **on ~110 pb^{-1} Run1 data**

Top Physics in Run 1

- $t\bar{t}$ **Xsection and top mass**
  - CDF: $\sigma(t\bar{t}) = 6.5^{+1.7}_{-1.4}$ pb *(Phys.Rev.D64 03022, 2001)*
  - DØ: $\sigma(t\bar{t}) = 5.7 \pm 1.2(stat) + 1.0(sys)$ pb *(hep-ex/0205019,2002)*
  - CDF+ DØ: $M_t = 174.3 \pm 5.1$ GeV *(Fermilab-TM-2084, 1999)*
  - in good agreement with theory





Top Physics in Run 1

- **Studied top-antitop spin correlation using 6 dilepton events (DØ,** *Phys.Rev.Lett. 85, 256,2000***):**

$$\frac{1}{\sigma}\frac{d^2\sigma}{d(\cos\theta_+)d(\cos\theta_-)} = \frac{1+k\cos\theta_+\cos\theta_-}{4}$$

  - SM: K ~ 0.9
  - DØ : K > -0.25 at 68% C.L.

- **Branching ratio R=BR(t→Wb)/BR(t→Wq) and $|V_{tb}|$ (CDF,** *Phys.Rev.Lett.86, 3233, 2001***):**

$$R = 0.94^{+0.31}_{-0.24}$$

$$|V_{tb}| = 0.97^{+0.16}_{-0.12} \text{ assuming 3 generations}$$

- **W helicity in top decays using dilepton dilepton and lepton+jets sample (CDF, (CDF,** *Phys.Rev.Lett. 84, 216, 2000***):**

$$F_0 \equiv \frac{\Gamma(h_W=0)}{\Gamma(h_W=0)+\Gamma(h_W=-1)} = \frac{m_t^2/(2m_W^2)}{1+m_t^2/(2m_W^2)} \approx 0.7 \text{ in SM}$$

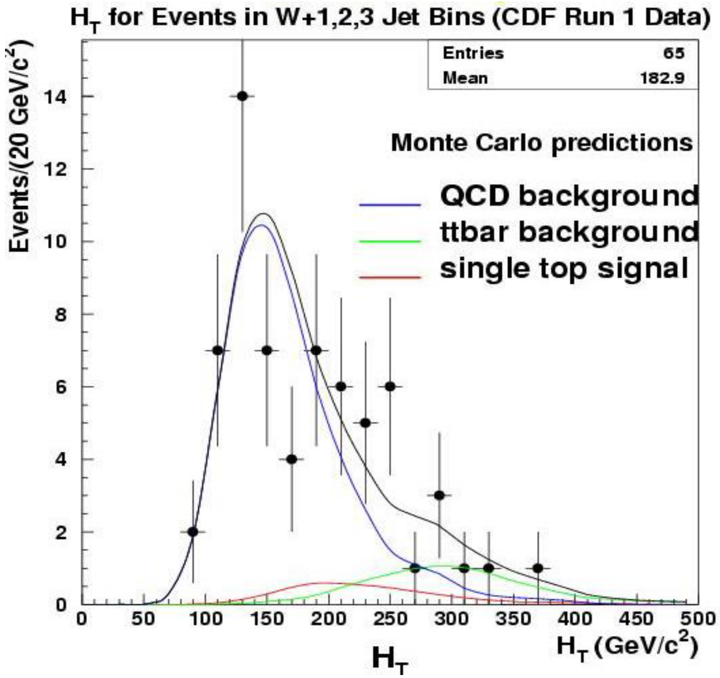
  - SM: $F_0 \approx 0.7,\ F_+ = 0$
  - CDF: $F_0 = 0.91 \pm 0.37 \pm 0.13,$ $F_+ = 0.11 \pm 0.15 \pm 0.06$

- **Top quark P_T distribution (CDF,** *Phys.Rev.Lett. 87, 102001, 2001***; DØ,** *Phys.Rev.D58, 052001,1998***)**

- **All measurements in agreement with the Standard Model**

Search for single top production in Run 1

- **At Tevatron dominant single top production processes are:**
  - $q\bar{q}' \rightarrow t\bar{b}$ (s-channel)
  - $qg \rightarrow t q' \bar{b}$ (t-channel)
- **Final state consists of W decay products plus jet(s) :**
  - Searches are restricted to leptonicaly decaying W → eν, μν
- **Single top processes are harder to observe than $t\bar{t}$ production:**
  - final states containing fewer jets suffer from a larger background
  - A priori no sensitivity expected in Run I data, unless new physics processes enhance production rate rate
- **CDF and DØ have performed searches searches for s-channel and t-channel channel separately**
- **CDF has also performed search for two single-top processes combined. Derived Xsection limit is:**
  - **σ (single-t) < 14 pb at 95% C.L.** (*Phys.Rev.D65, 091102, 2002*)



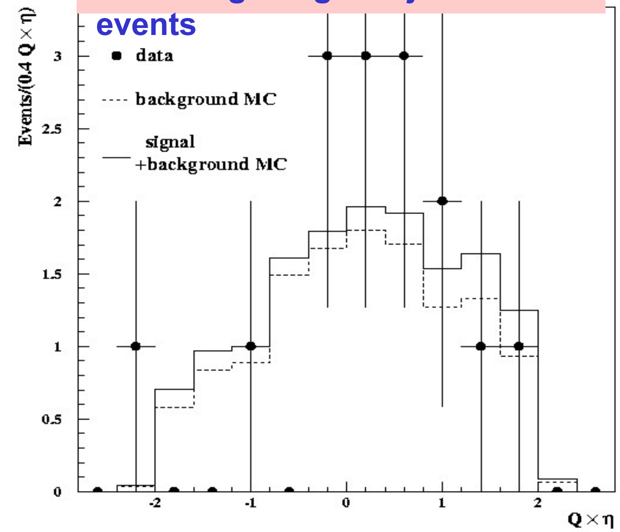
Search for single top production in Run 1

- **To separate two single-top processes consider non-overlapping W+2jets samples:**
  - single-tag events -- dominated by t-channel channel
  - double-tag events -- dominated by s-channel channel
- **In t-channel light-quark often is in the same hemisphere as the (anti)proton when (anti)top is produced**
- **In double-tag events use $M_{l\nu b}$ distribution distribution to extract s-channel contribution**
- **95% C.L. limits are set by CDF at:**
  - **σ(s-channel) < 18 pb**
  - **σ(t-channel) < 13 pb**

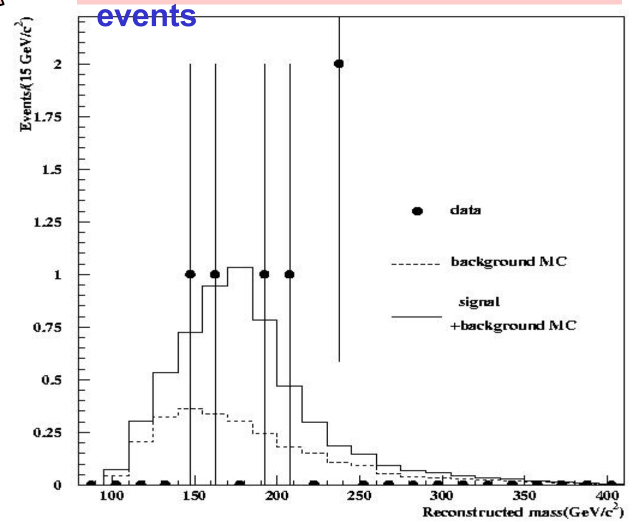
    (*Phys.Rev.D65, 091102, 2002*)
- **95% C.L. limits derived by DØ:**
  - **σ(s-channel) < 17 pb**
  - **σ(t-channel) < 22 pb**

    (*Phys.Lett.B517, 282, 2001*)

CDF: single-tag W+2jets events events



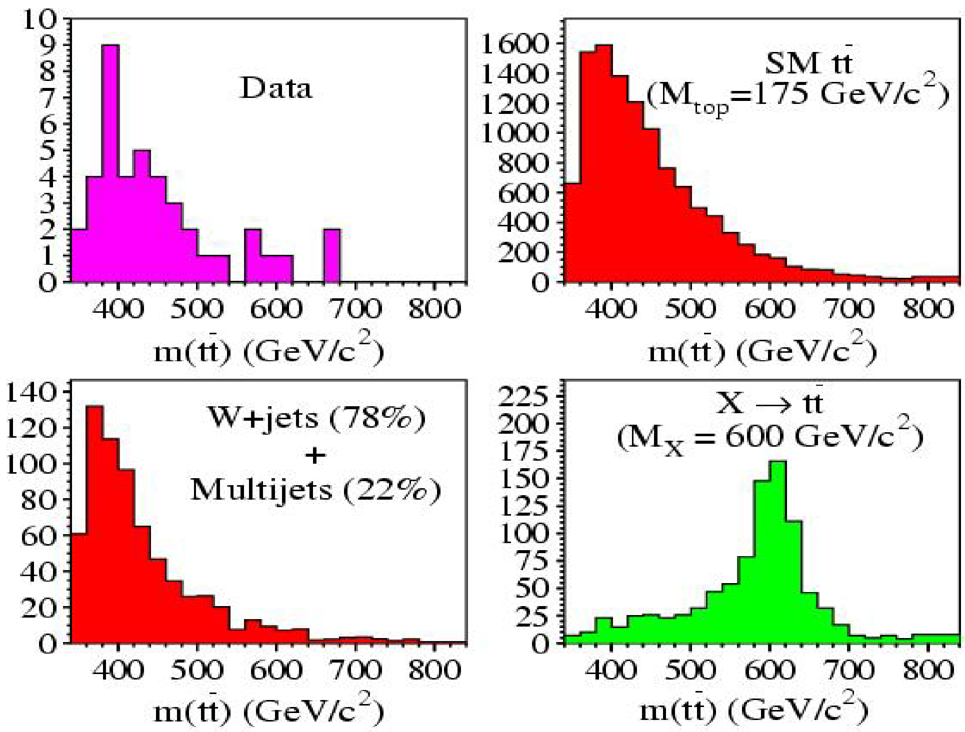
CDF: double-tag W+2jets events events



Search for $t\bar{t}$ resonances in Run 1

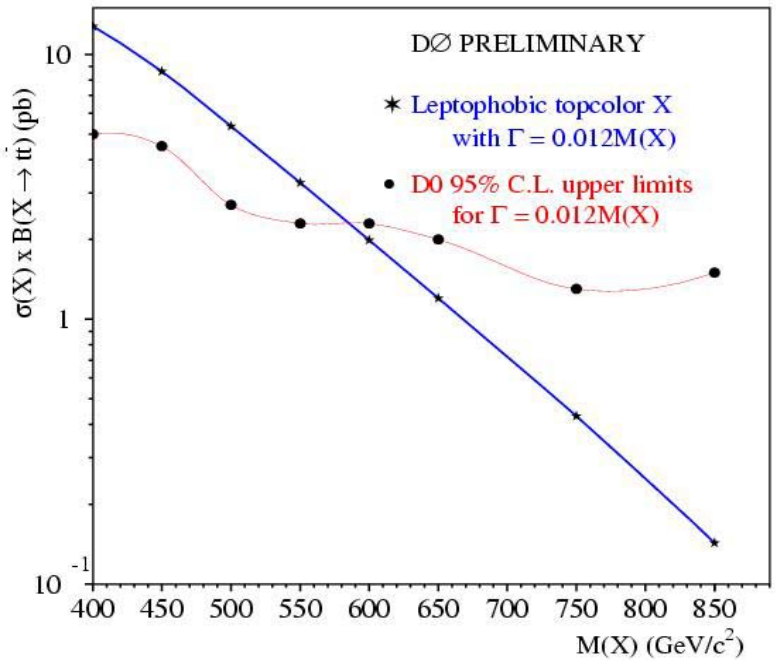
- **Models with dynamically broken EW symmetry ("Technicolor") predict existence of top quark condensate X that can decay to $t\bar{t}$ pair,** $X \to t\bar{t}$
- **Search for narrow** $X \to t\bar{t}$ **resonance resonance** — reduce sensitivity to the model details
- **Use lepton + jets events.** Fit observed distribution of $M(t\bar{t})$ to derive probability distributions of N_{events} for signal, top pair, and other SM background processes.

DØ PRELIMINARY



Search for $t\bar{t}$ resonances in Run I

- **No statistically significant excess has been observed and therefore 95% C.L. limit has been derived on production Xsection assuming Γ_x=0.012M_x and M_t=175GeV**



- **For particular model of leptophobic topcolor** (*C.T.Hill and S.Parke, hep-hep-ph/9911288*) **DØ excludes M_x< 560 GeV at 95% C.L.**

- **Under the same assumption CDF has set lower limit of 480 GeV at 95% C.L.** (*Phys.Rev.Lett.85,2062,2000*)

Tevatron Upgrade

- **New Main Injector and Recycler Ring**
- **Improved Antiproton source and Booster**
  - Increase pbar yield
  - Increase luminosity
- **Increase number of bunches**
  - Reduce number of interactions per crossing
  - Reduce bunch spacing

- **Increase beam energy 900→980GeV**
  - Increase Xsections for interesting physics processes, e.g. by 30-40% for top production:

    - from ~5 to ~7 pb for top pair,

    - from ~2.4 to ~3 pb for single top top

Run 1 → Run 2a → Run 2b
$0.1\ fb^{-1}$ → $2\ fb^{-1}$ → $15\ fb^{-1}$

	Run 1b	Run 2a	Run 2b
#bunches	6x6	36x36	140x103
√s (TeV)	1.8	1.96	1.96
typ L ($cm^{-2}s^{-1}$)	1.6×10^{30}	8.6×10^{31}	5.2×10^{32}
∫ Ldt (pb^{-1}/week)	3.2	17.3	105
bunch xing (ns)	3500	396	132 or 396
interaction/xing	2.5	2.3	4.8

Run2 data taking started in spring 2001

Run 2 detectors

- **CDF upgrades**
  - New Silicon Vertex Detector (SVX) and faster tracking drift chamber (COT)
  - New scintillating tile end-plug calorimeters
  - Increased $\eta\phi$ coverage for muon detectors
  - New scintillator time of flight system
- **DØ upgrades**
  - New Silicon (SMT) and Fiber (CFT) trackers, placed in 2 T magnetic field
  - Calorimeter supplemented with the preshower detectors
  - Significantly improved muon system

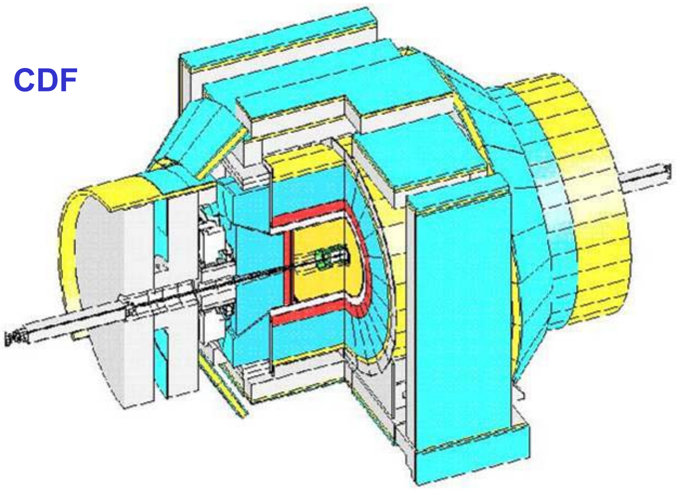
Both detectors:

- b-tagging capability through displaced vertices

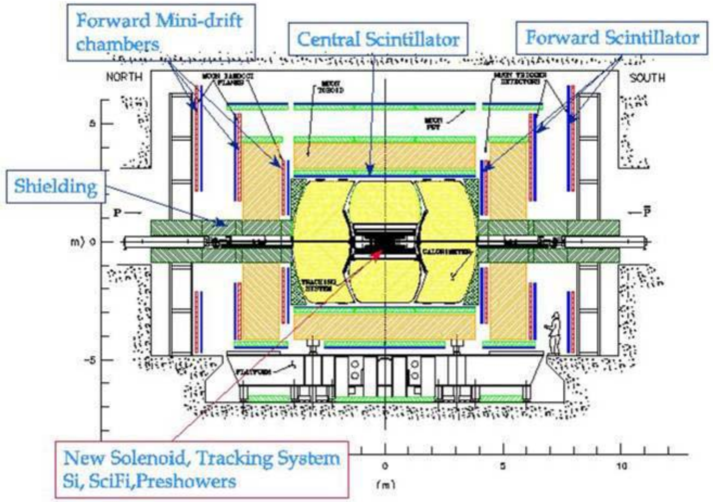
- Improved lepton identification systems

- **Entirely new DAQ and trigger systems to handle high event rate**
- **Both CDF and DØ will replace Silicon detectors during 2004 shutdown — dictated by radiation damage.**

CDF



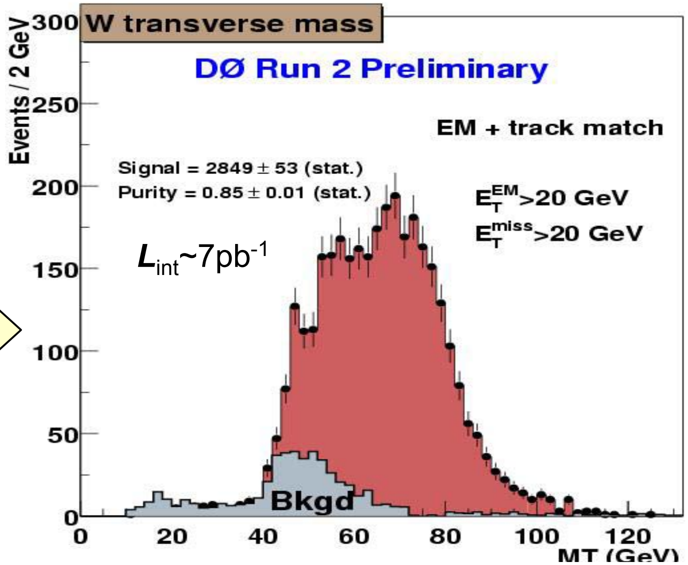
DØ



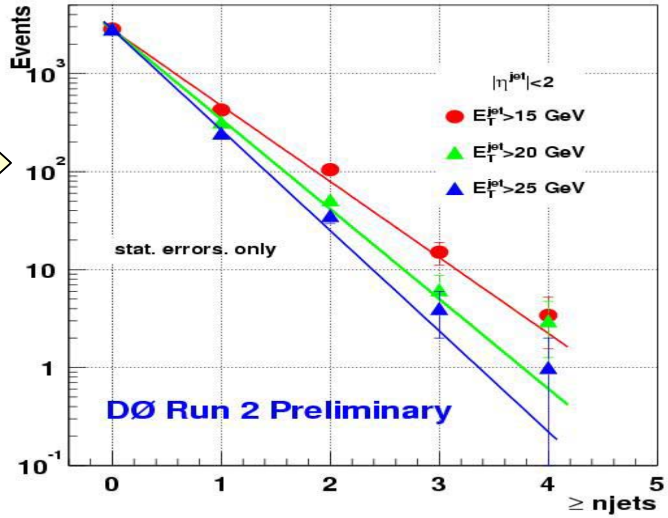
W → e ν candidates in Run 2 DØ data

- W+jets and Z+jets are primary backgrounds to top → Study these processes to asses detector performance before enough top events are detected

- W transverse mass spectrum in e + missing E_T inclusive sample. QCD background derived from the data



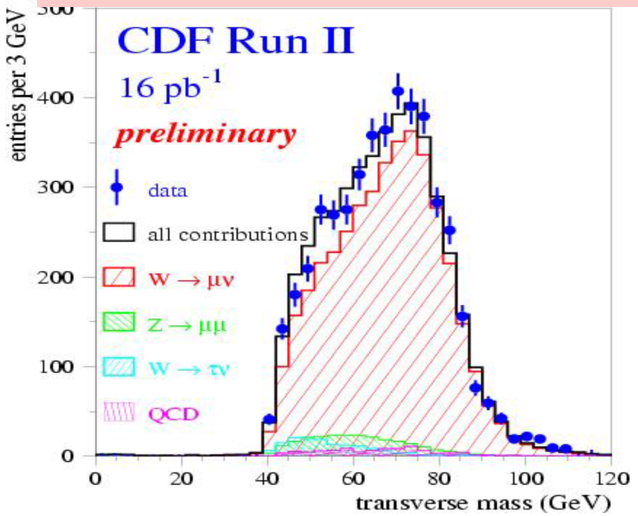
- Inclusive jet multiplicity in background subtructed W→eν sample — follows to linear in log law (Berends scaling)



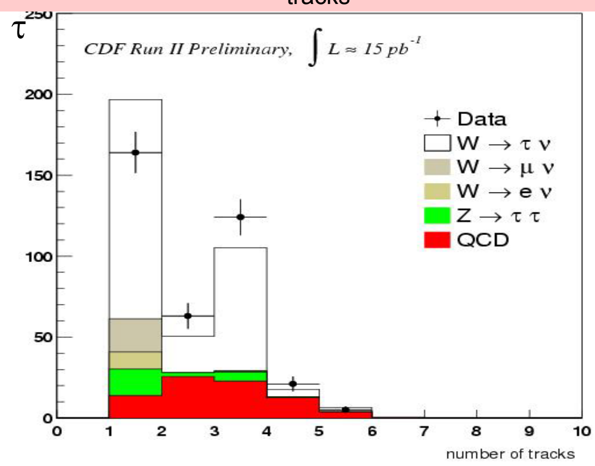
- With higher statistics and b-tagging requirement, enhancement at W+4jets will indicate ttbar→eνj+jjj contribution

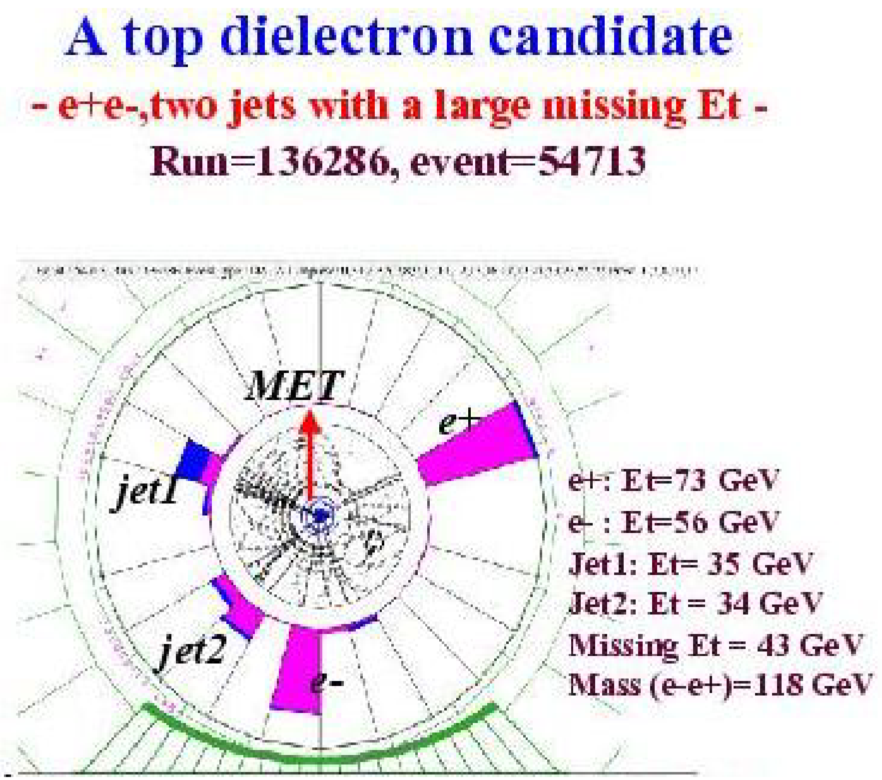
W and Top candidates in Run 2 CDF data

W→μν events



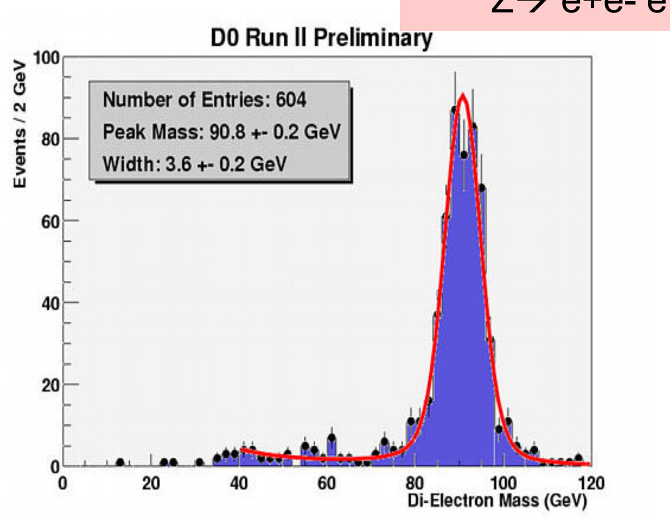
W→τν events: N_{tracks} associated to τ

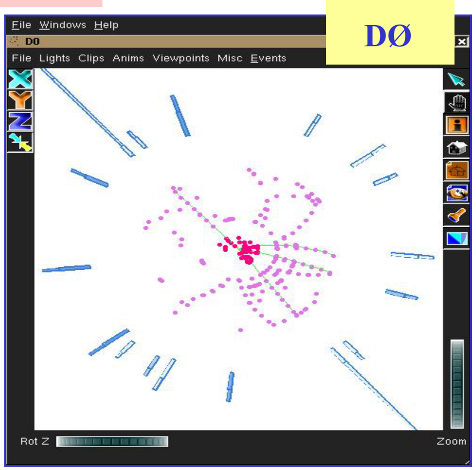




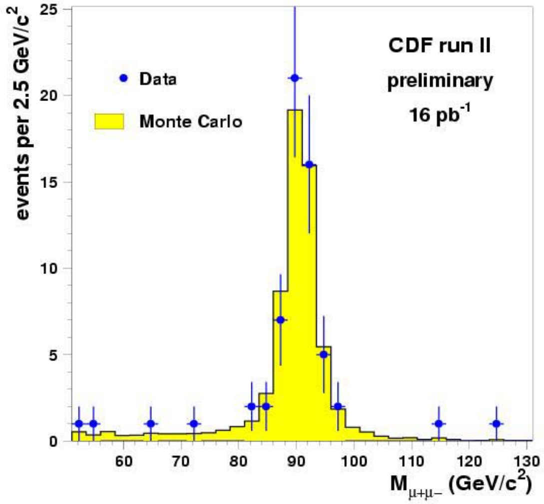
Z candidates in Run 2 data

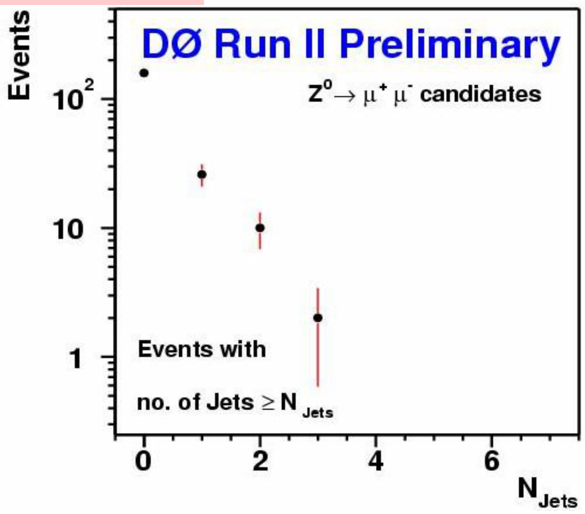
Z→ e+e- events





μ+μ- events



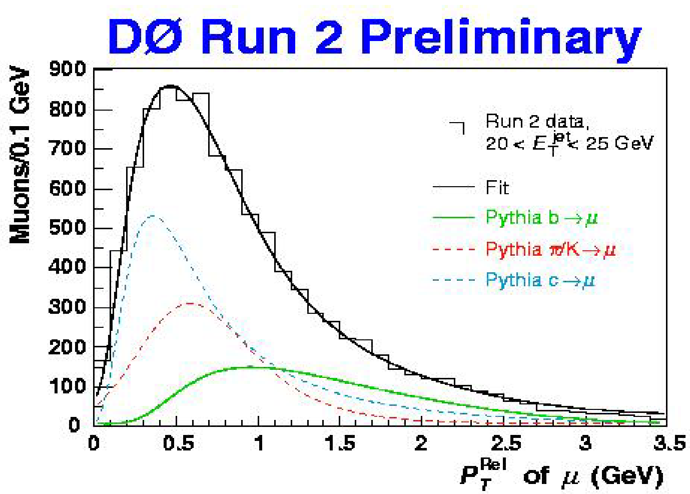


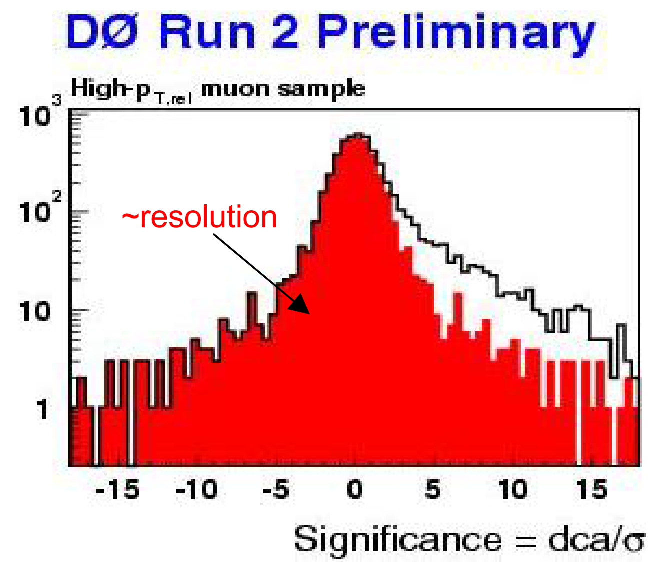
b-tagging in Run 2

- **b-tagging capability important to suppress background to top (W/Z+jets, QCD jets) jets)**
- **To tag b-jets exploit both techniques:**
  - a) soft lepton tagging (SLT); b) tagging with displaced vertices

- **Soft Lepton Tagging:**
  - B(b→lνc)~20%, B(b→c → lνs)~ 20% with l=e and μ
  - use both muons and electrons looking at P_T relative to jet axis
  - Muon tagging has been checked in data for bbbar decay studies

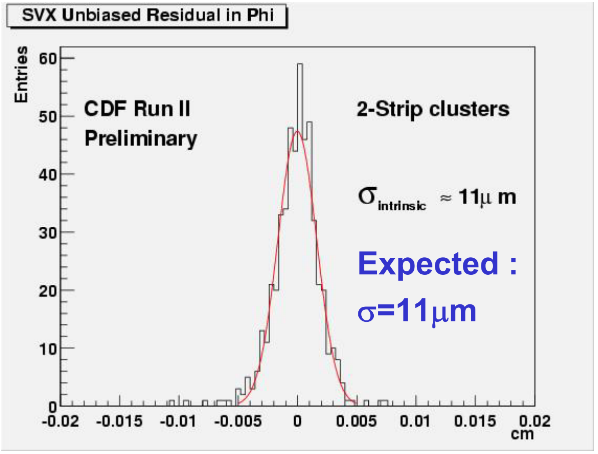
- **Impact Parameter Tagging:**
  - study di-jet events with and without muon
  - di-jet event containing muon within dR <0.7 and P_T^{rel}>1.5 GeV are enhanced in heavy flavour

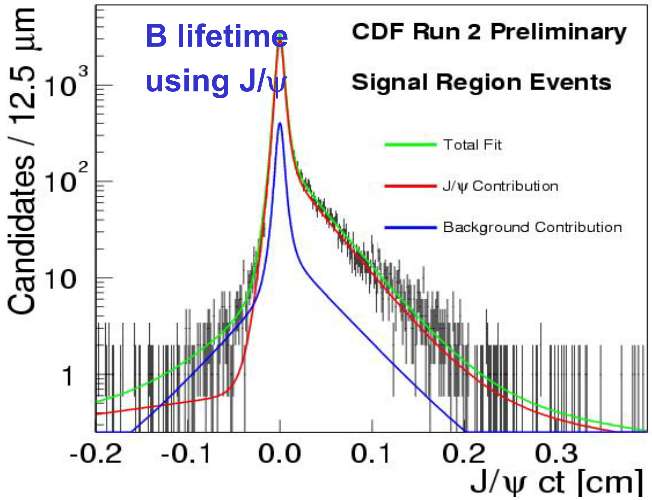




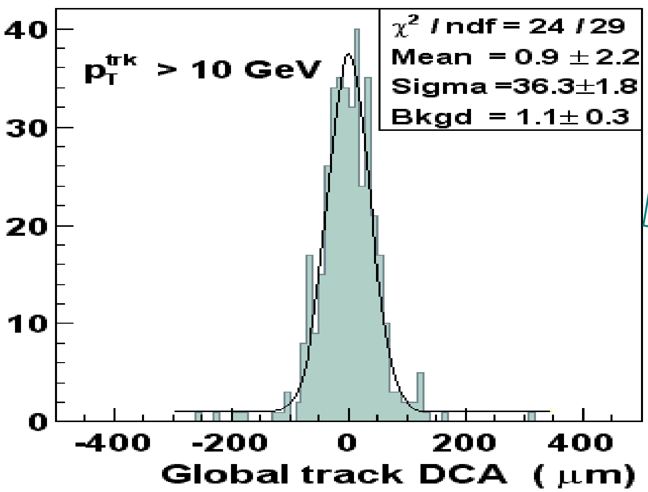
b-tagging in Run 2

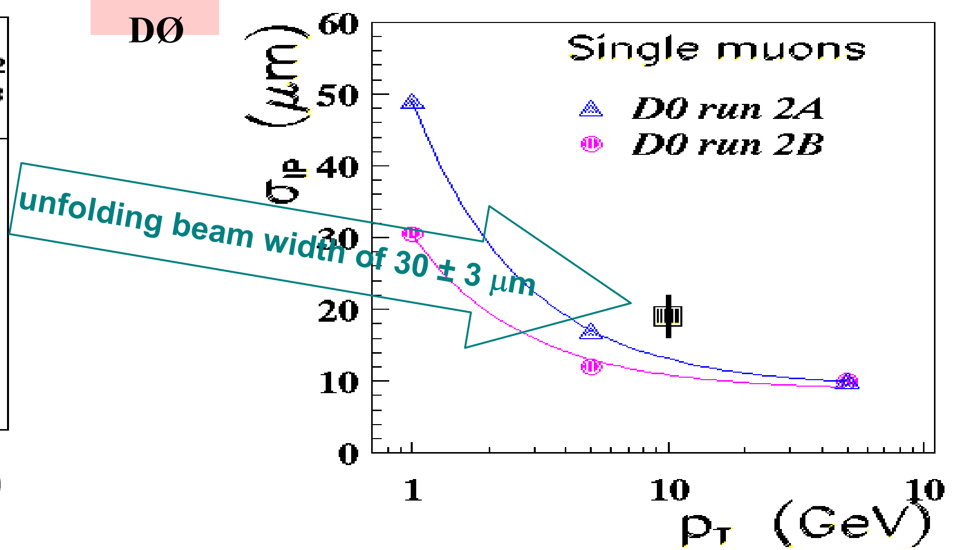
CDF





DØ

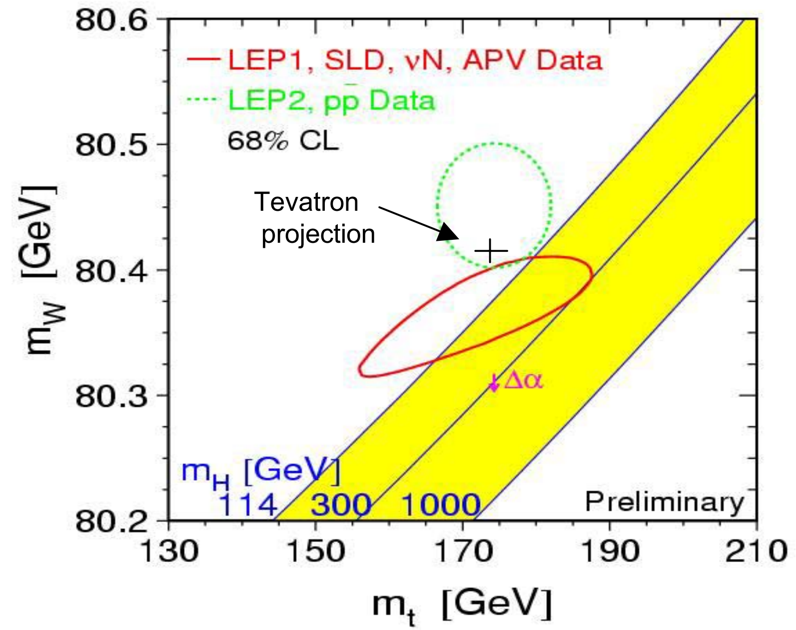




Current performance is approaching Run 2a design figure for both CDF and DØ

Projection on measurement precisions

- **Two largest systematic errors in M_t are due to Jet Energy Scale (JES) and gluon radiation**
- **In Run2, Z→ bb decays will be used to limit JES — relies on L2 Silicon Track Trigger**
- **Gluon radiation correction will be constrained by comparing double-tag events with MC simulation**
- **Expected accuracies by the end of Run2b : Top mass ~ 1.4 GeV, W mass ~ 16 MeV. Gives indirect constraint on higgs mass $\delta M_h/M_h$ ~25%**
(hep-ph/0202001, Snowmass Working Group on Precision EW measurements)



	Run1 prec.	$2fb^{-1}$	$15fb^{-1}$
M_t	2.9%	1.5%	0.8%
σ(ttbar)	25%	10%	5%
W helicity, F_0, F_+	0.4, 0.15	0.09, 0.03	0.04, 0.01
R=BR(t→Wb)/BR(t→Wq) $\|V_{tb}\|$, limit at 90% C.L.	30% >0.05	4.5% >0.25	0.8% >0.50
σ(single-top) Γ(t→Wb) $\|V_{tb}\|$	- - -	20% 25% 12%	8% 10% 5%
BR(t→γq) BR(t→Zq)	0.03 0.30	2×10^{-3} 0.02	2×10^{-4} 2×10^{-3}

Summary

- Successful top quark physics program at Run 1
  - All measurements consistent with the Standard Model Model
  - But limited in statistics
- We are entering exciting era of Run 2. Performance Performance of upgraded CDF and DØ detectors are are already close to expectations — many improvements relevant to top physics
- Tevatron Run 2 will allow to precisely measure top quark properties. Signs of new physics could well show up first in these measurements.