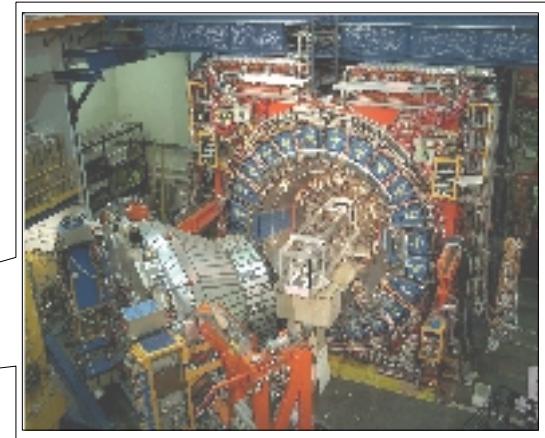
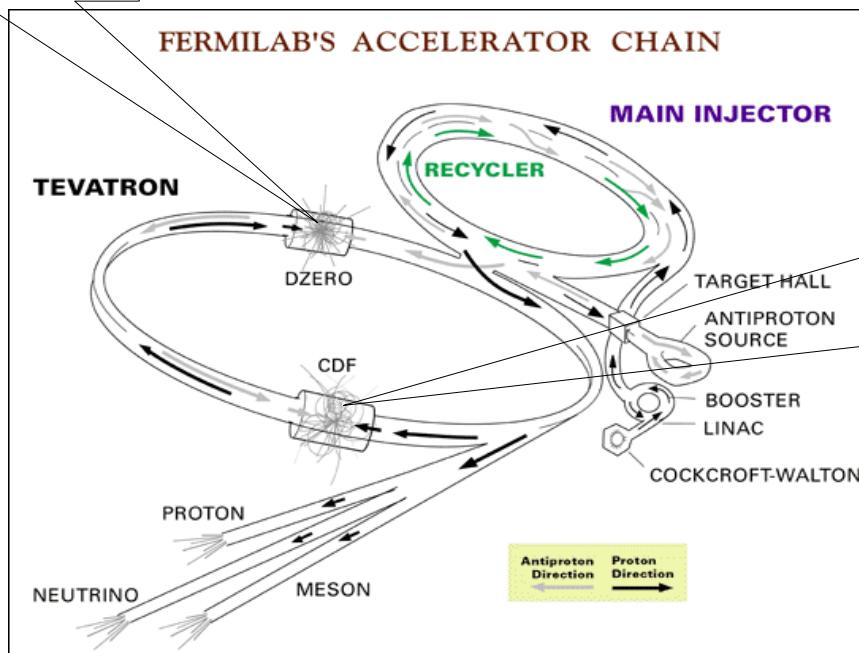


$t\bar{t}$ Production and Single Top Quark Search at the Tevatron



Miroslav Kopál
University of Oklahoma

on behalf of the DØ and CDF collaborations



Top Quark Physics

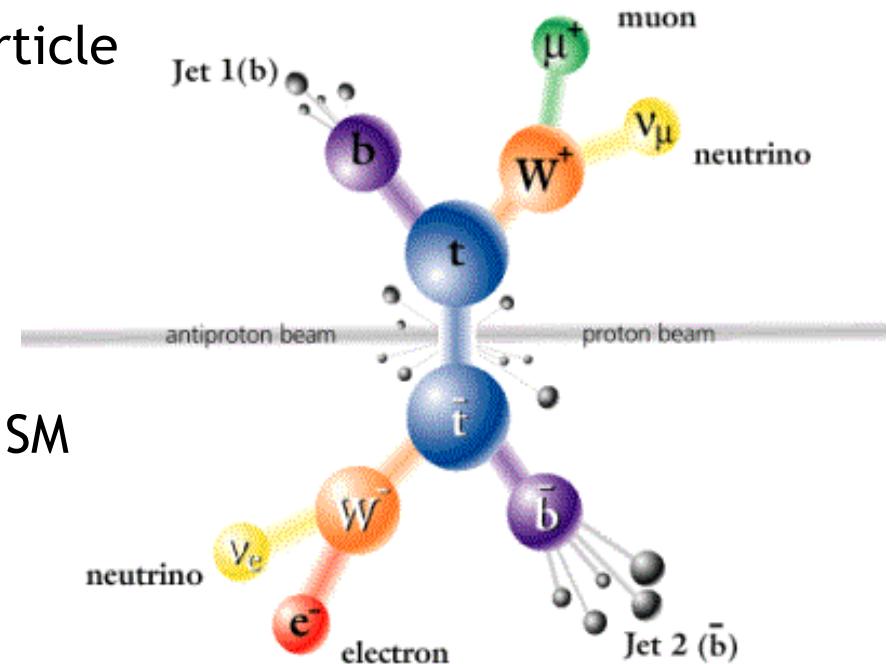
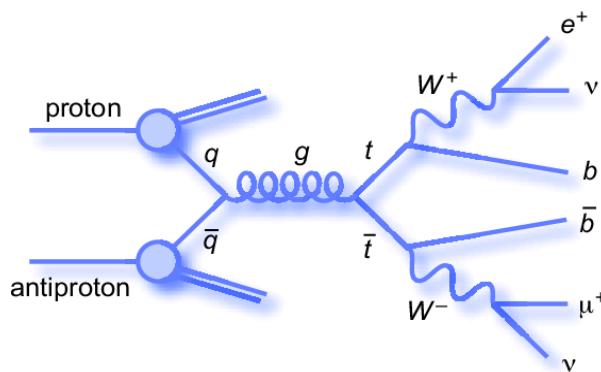
Top quark - the heaviest known particle

- ▷ decays before it hadronizes

Cross section measurement

- ▷ $t\bar{t}$ production
- ▷ search for single top and W' production

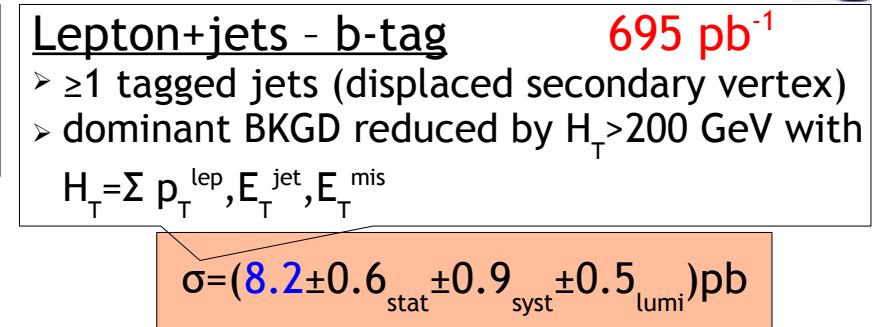
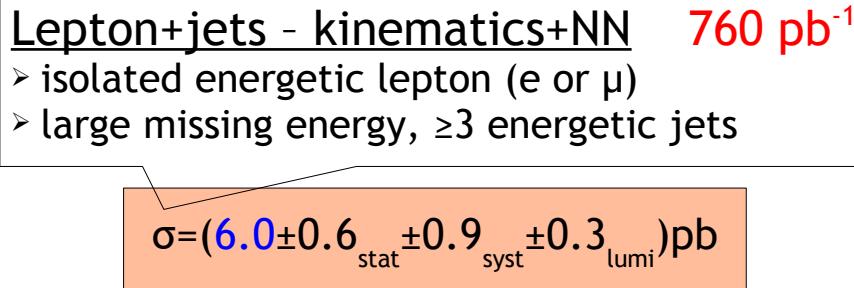
Top properties and physics beyond SM



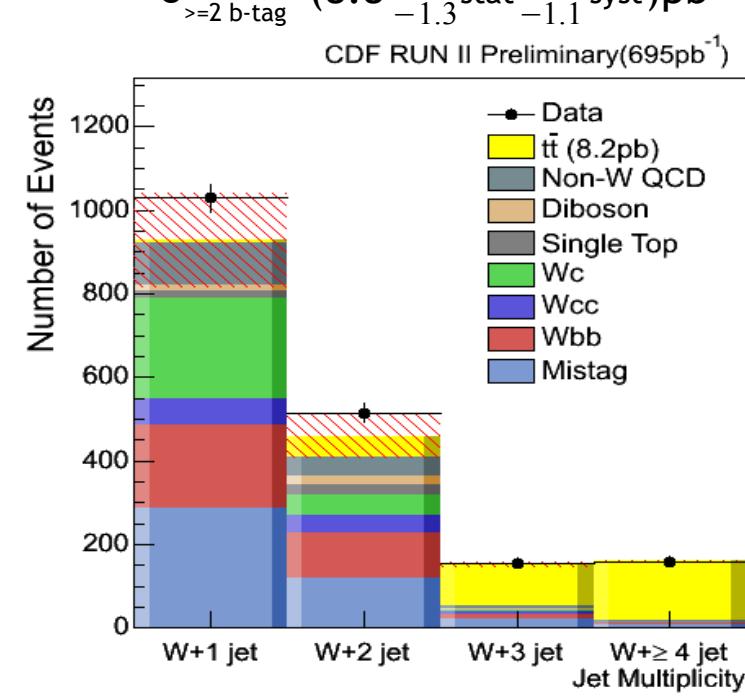
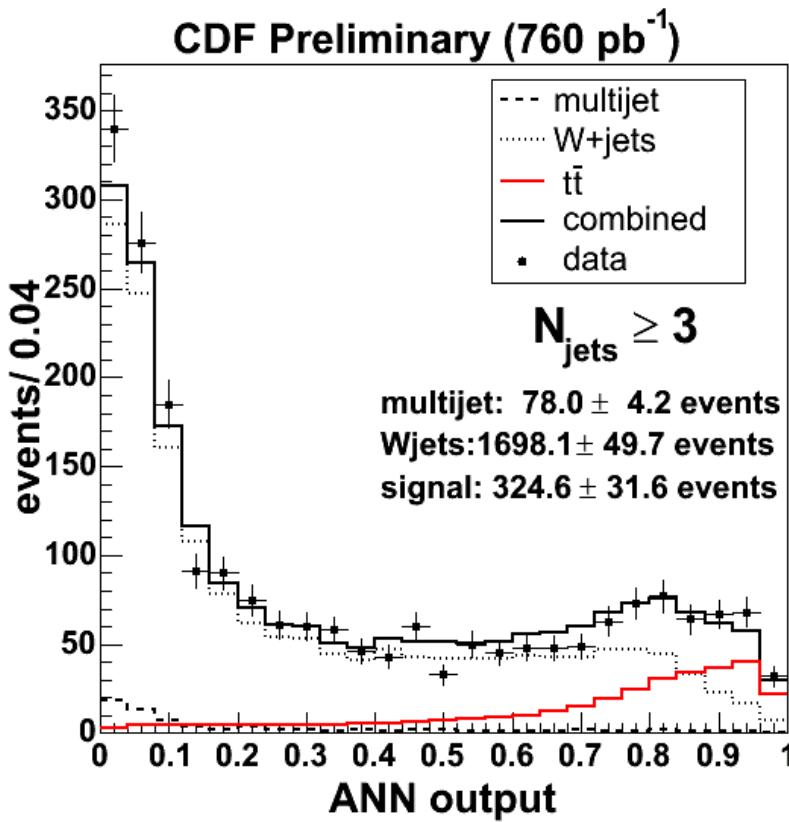
$t\bar{t}$ production: strong interaction
 Dominant mode: $\sigma_{\text{NNLO}} = 6.8 \pm 1.2 \text{ pb}$



Top Quark Pair Production



best SIGN/BKGD (BR~30%) with dominant $W+jets$ BKGD



Top Quark Pair Production

clean signature but small BR~4%

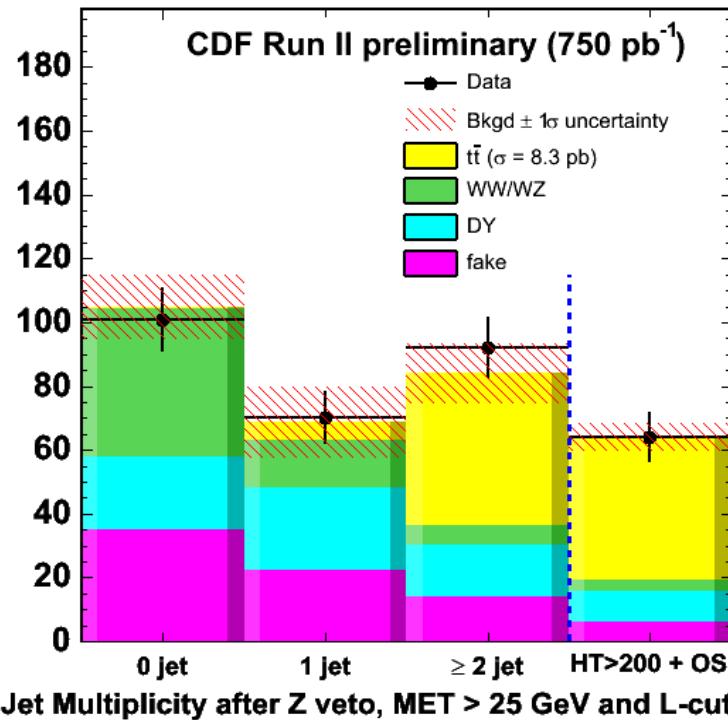
Di-Lepton

750 pb⁻¹



- ee, e μ and $\mu\mu$ final states only
- ≥ 2 energetic jets, $H_T > 200$ GeV
- bins 0 and 1 → control sample for BKGD determination

$$\sigma = (8.3 \pm 1.5_{\text{stat}} \pm 1.0_{\text{syst}} \pm 0.5_{\text{lumi}}) \text{ pb}$$



Di-Lepton

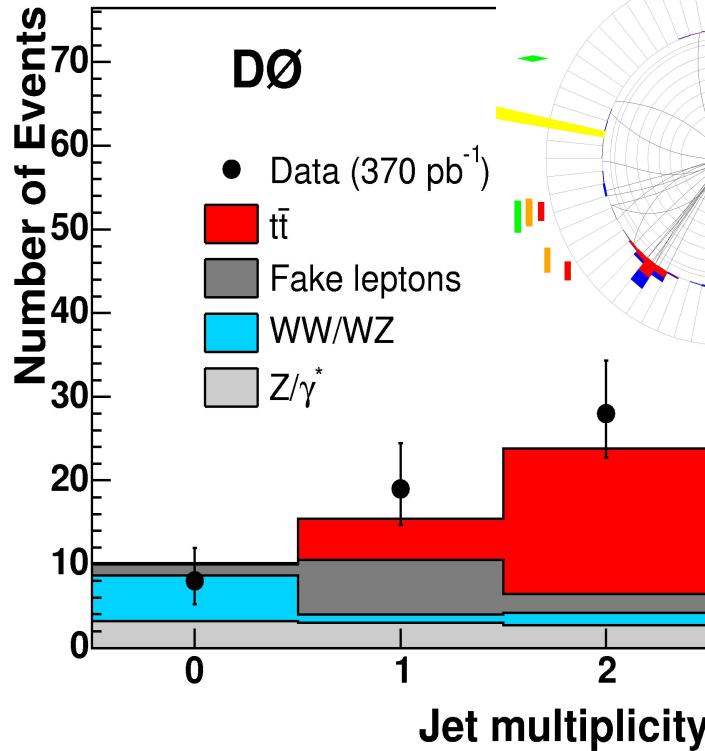
370 pb⁻¹



- topological cuts, no b-tagging

$$\sigma = 8.6^{+2.3}_{-2.0} {}^{+1.2}_{-1.0} \text{ pb}$$

Run 19332 Evt 3472458 Tue Jan 25 15:58:40 2005
ET scale: 54 GeV



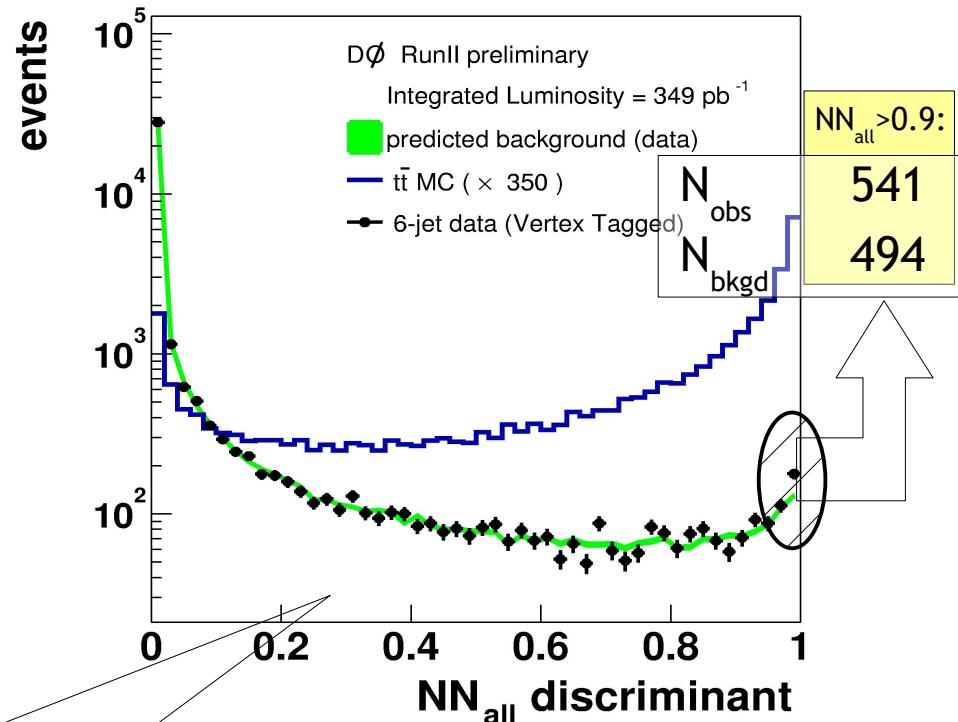
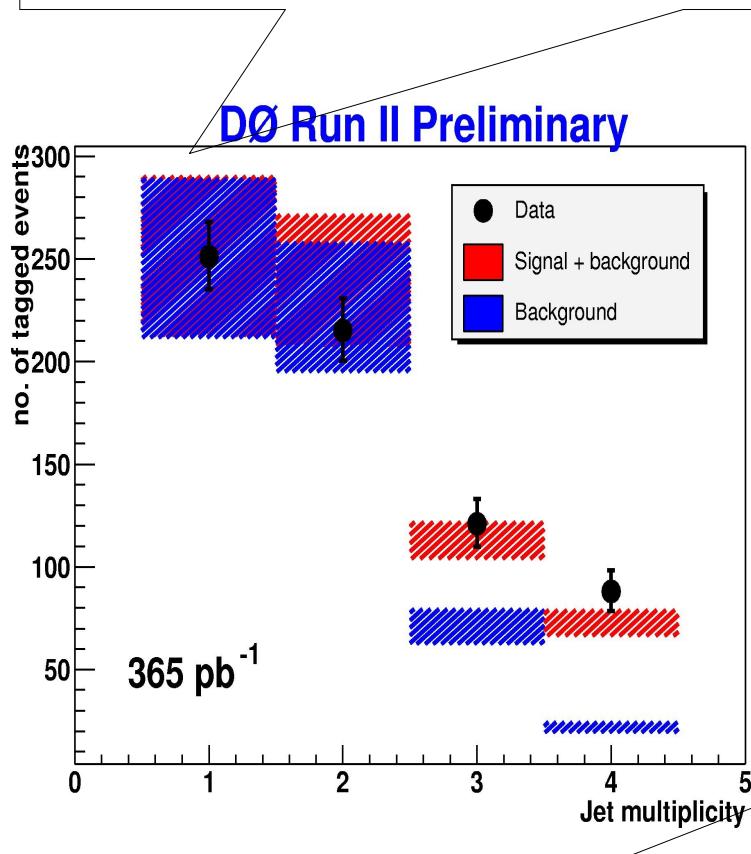
Top Quark Pair Production

Lepton+jets

365 pb⁻¹

- topological selection with b-tagged (Secondary Vertex Tagging) of 1 or 2 jets

$$\sigma = 8.2^{+0.9 \atop -0.9} {}^{+1.1 \atop -1.0} \text{ pb}$$



All jets

$\int \mathcal{L} \cdot dt = 349 \text{ pb}^{-1}$

- large BR (~44%) but with large QCD multi-jet BKGD
- topological variables combined in NN, b-tagging (SVT)

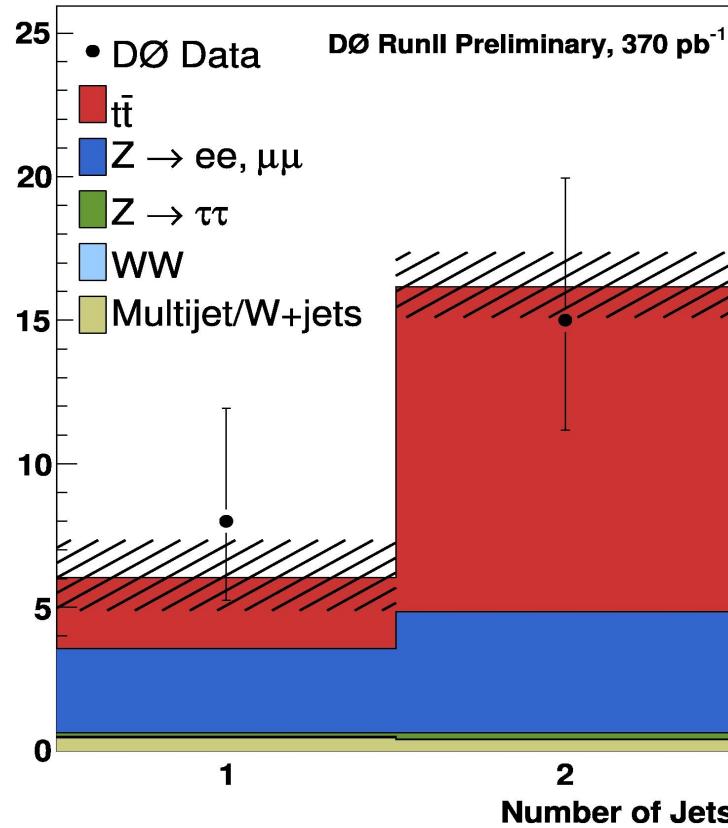
$$\sigma = 5.2^{+2.6 \atop -2.5} {}^{+1.5 \atop -1.0} \text{ pb}$$

Top Quark Pair Production

Lepton+track/electron-muon (combined)

370 pb⁻¹

- two leptons, second one identified only as isolated track
- topological, b-tagging
- eμ events are explicitly vetoed in lepton+track → eμ purely topological
- straightforward combination of lepton+track cross section

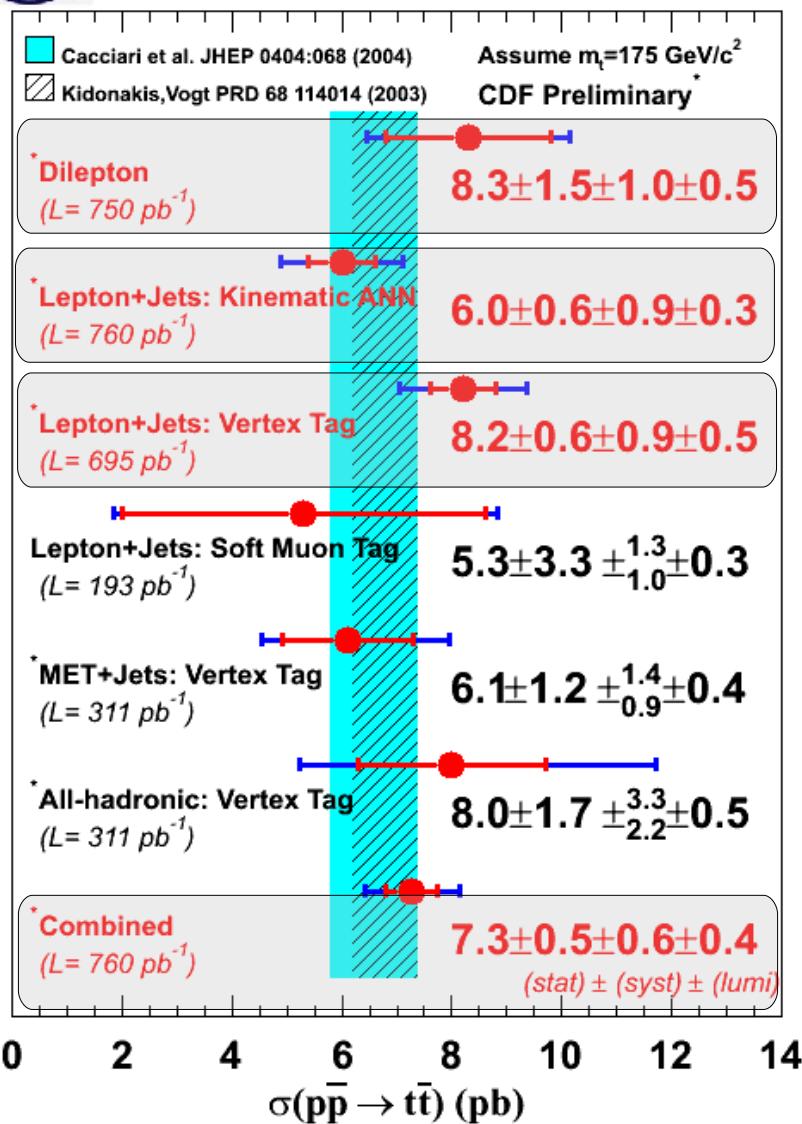


$$\sigma = 8.6^{+1.9}_{-1.7} {}^{+1.1}_{-1.1} \text{ pb}$$

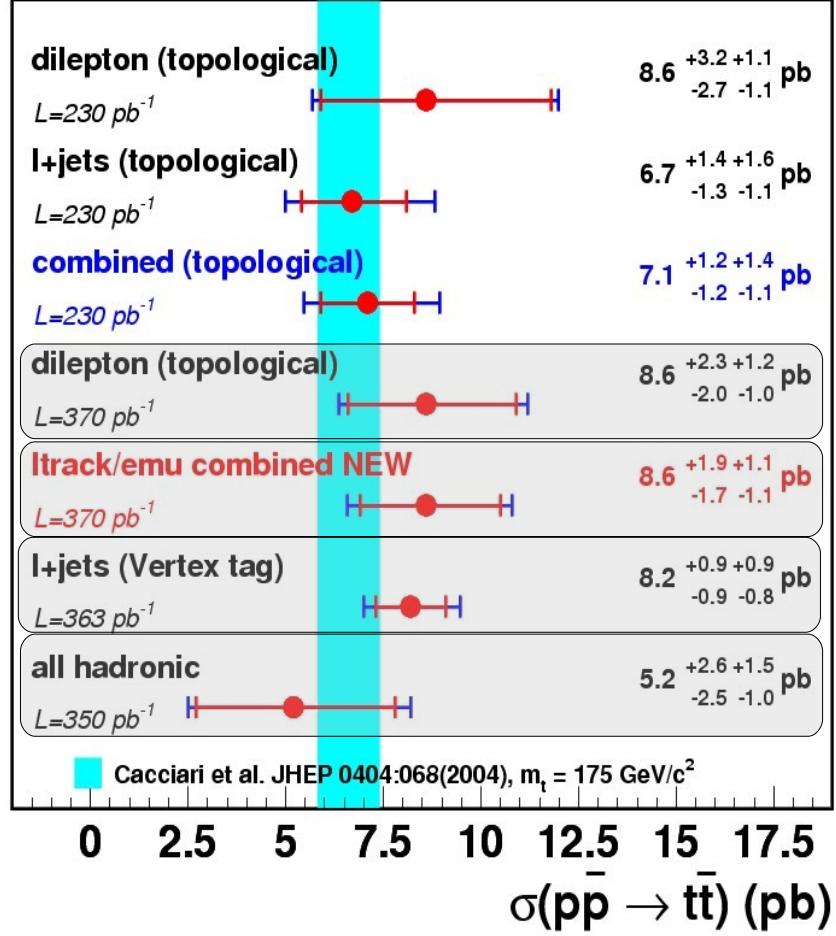
$$\text{lepton+track: } \sigma = 7.1^{+2.6}_{-2.2} {}^{+1.3}_{-1.3} \text{ pb}$$



Top Quark Pair Production



DØ Run II Preliminary



Single Top Quark search

Single top: electroweak interaction

s-channel mode: $\sigma_{\text{NLO}} = 0.88 \pm 0.14 \text{ pb}$

t-channel mode: $\sigma_{\text{NLO}} = 1.98 \pm 0.30 \text{ pb}$

→ direct measurement of CKM's $|V_{tb}|$

→ test unitarity of CKM, test SM's V-A structure

→ top polarization+mass

→ new physics - s-channel is sensitive to heavy resonances (W'), SUSY, etc., t-channel is sensitive to FCNCs

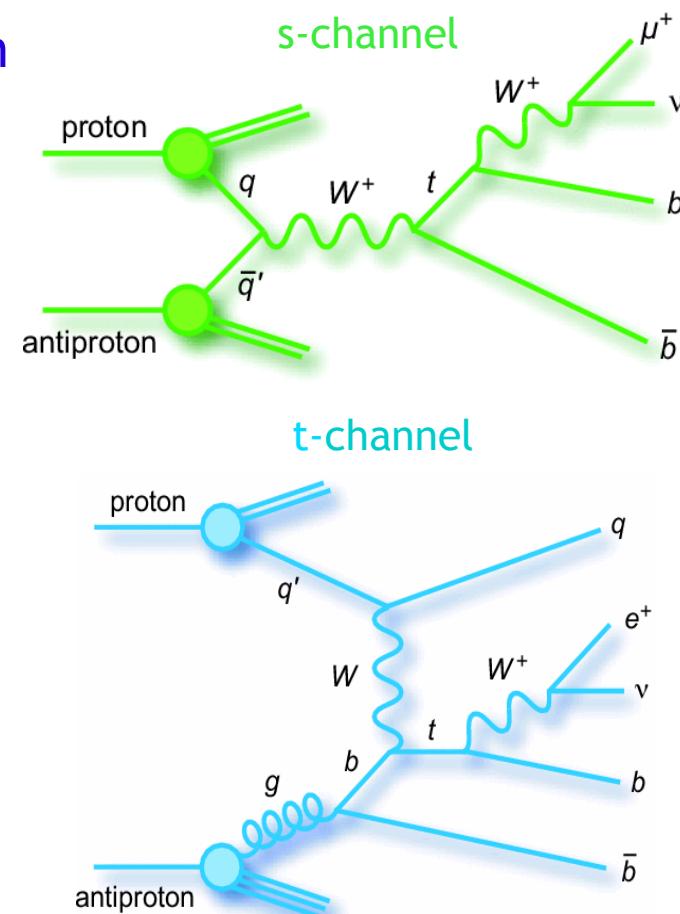
Topology:

→ energetic isolated lepton

→ missing energy

→ one b-quark (from top)

→ light flavor jet + another b-jet

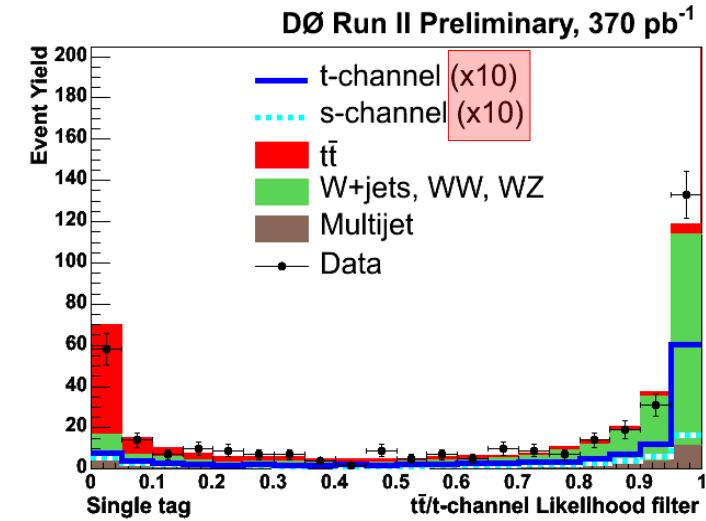
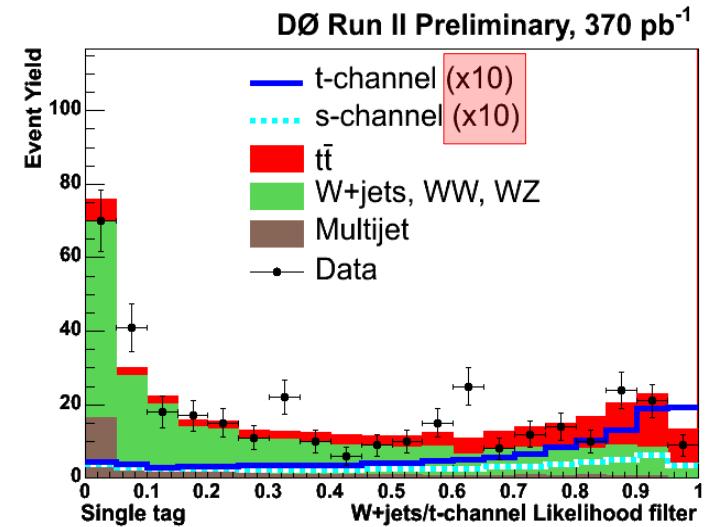
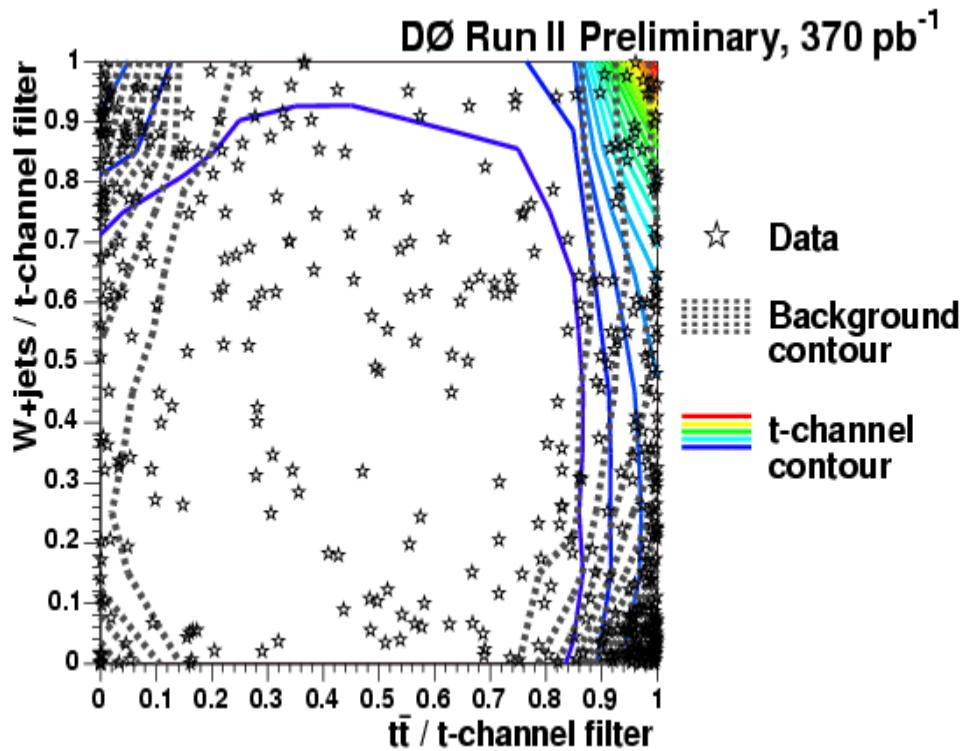




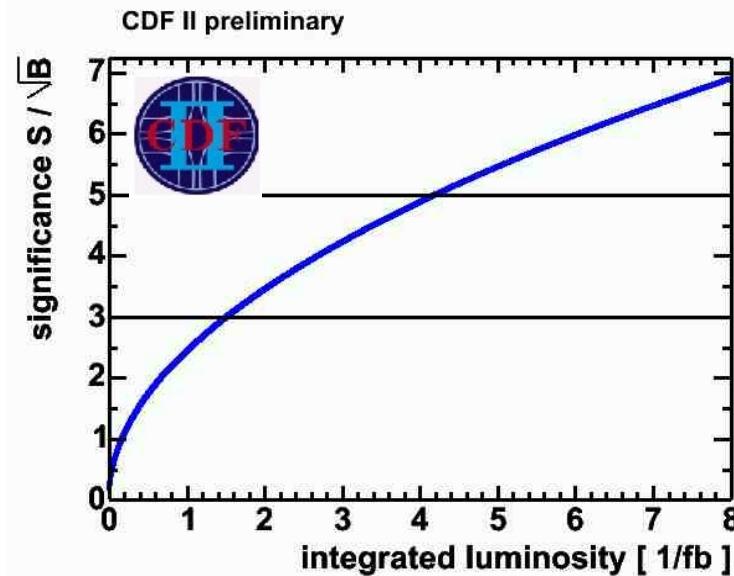
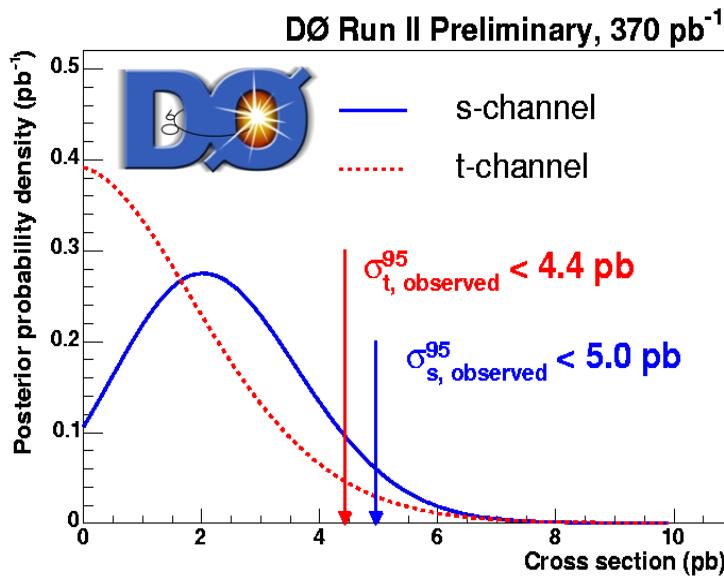
Single Top Quark search

Analysis flow:

- separate s- and t-channel in electron and muon, and 1 or 2 b-tags
- apply discrimination method (likelihood, cuts based)
- 2dim histograms of $Wb\bar{b}$ and $t\bar{t}$ NN outputs, construct binned likelihood and evaluate signal hypothesis



Single Top Quark search



3 σ evidence expected with 1.5 fb⁻¹ (27.3 signal events).
At 1 fb⁻¹ - expected 2.4 σ excess. (No systematic uncertainties taken into account.)

Limits @ 95% CL

162 pb⁻¹

370 pb⁻¹

σ_{combined}

< 17.8 pb

$\sigma_{\text{t-channel}}$

< 10.1 pb

$\sigma_{\text{s-channel}}$

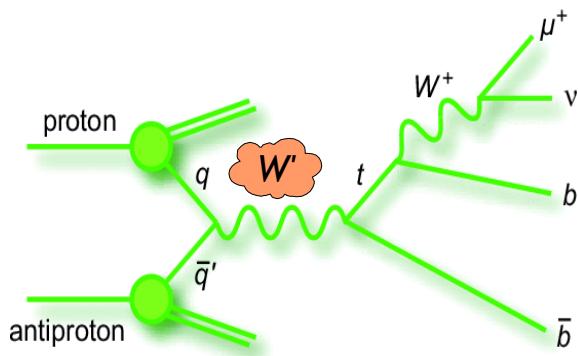
< 13.6 pb

< 4.4 pb

< 5.0 pb

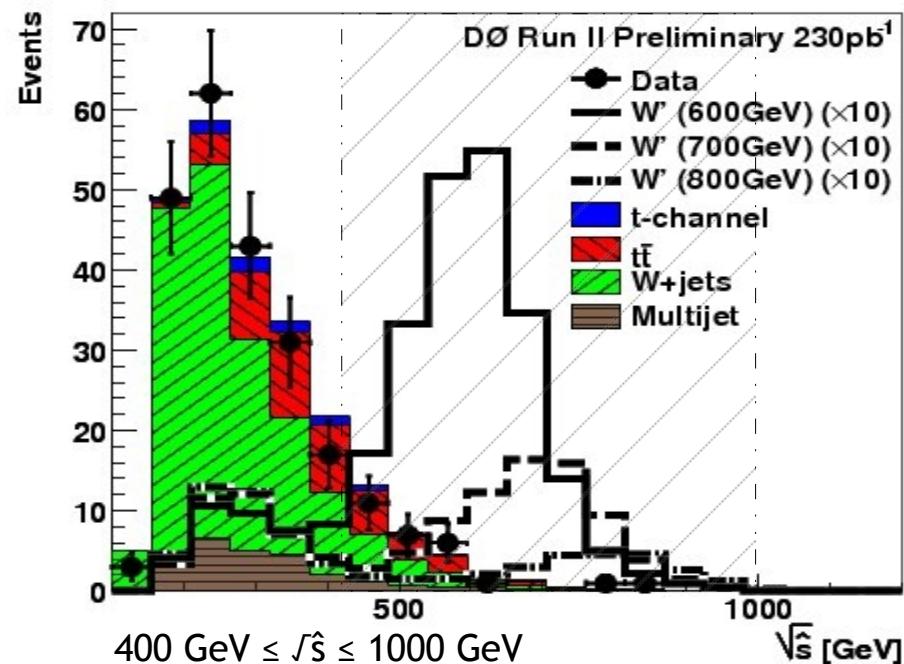
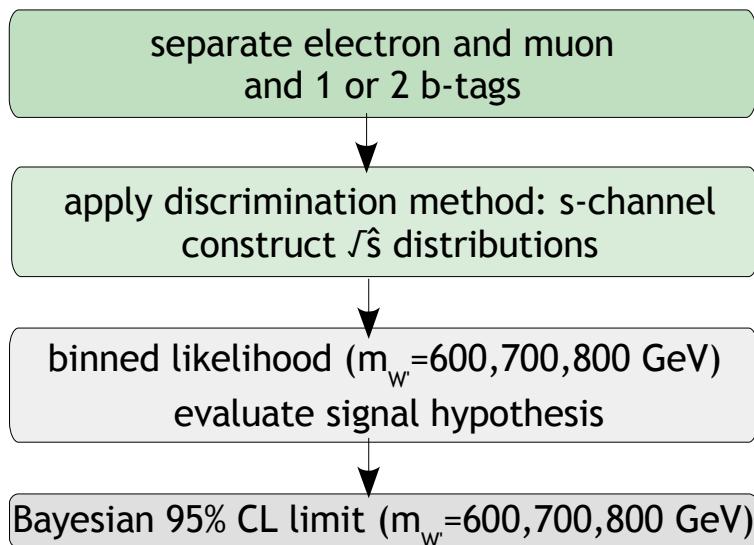
The 1st presentation of this new result!

Heavy boson (W') search



- $W' \rightarrow tb$ with SM-like coupling to fermions
- single top s-channel with new heavy boson, $m_{W'} > m_t + m_b$ (below 200 GeV = SM W)
- t-channel - BKGD, $\sigma_{W'} \ll \sigma_{\text{single top}}$
- interference between s-channel and W' is included (smaller for larger $m_{W'}$)
- only lepton final states - better BKGD rejection

Analysis flow (single top search)



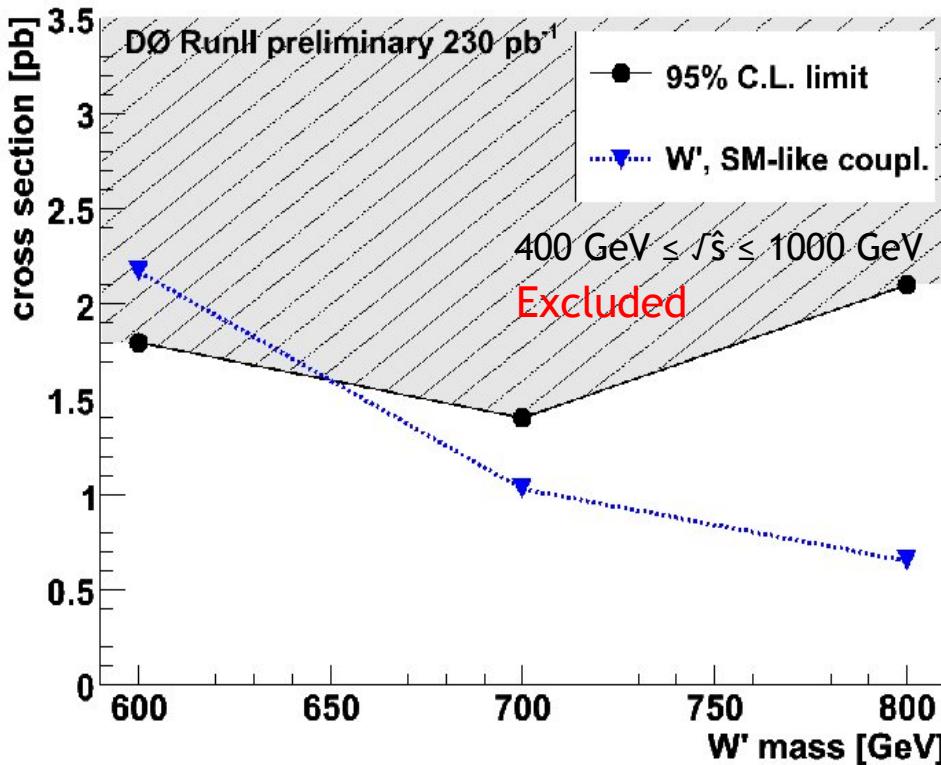
M. Kopál - RENCONTRES DE MORIOND
EW Interactions and Unified Theories
La Thuile (Italy), March 11-18 2006





The 1st presentation of this new result!

Heavy boson (W') search



	$\sigma_{600 \text{ GeV}}$	$\sigma_{700 \text{ GeV}}$	$\sigma_{800 \text{ GeV}}$
Expected limit	< 1.8 pb	< 1.6 pb	< 2.1 pb
Measured limit	< 1.7 pb	< 1.4 pb	< 2.1 pb

Current limits:
 $m_{W' \rightarrow \text{any}} > 786 \text{ GeV}$

RunI DØ:
 $m_{W' \rightarrow (\text{only})\text{qq}} > 800 \text{ GeV}$

Systematic uncertainties included:

	sign	bkgd
b-tag modeling	4-16%	5-20%
Jet energy calib.	1-2%	15-30%
Other (trigger, ID)	1-5%	1-5%

The 1st time in top decay!
 $m_{W'} > 650 \text{ GeV}$
 (SM-like coupling to fermions)



Conclusions

$t\bar{t}$ production

updated results - large analyzed samples

- CDF with $\sim 760 \text{ pb}^{-1}$ for di-lepton, lepton+jets (kinem.+NN and b-tag)
- DØ with $\sim 360 \text{ pb}^{-1}$ for di-lepton, lepton+jets, all jets and lepton+track/e μ (**new result!**)

Single Top Quark search

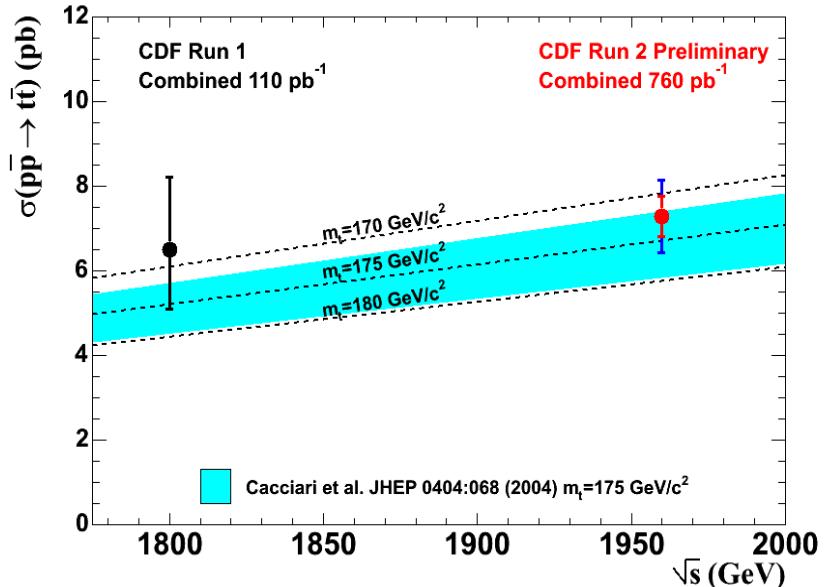
moving towards the observation

- CDF: $\sigma_t < 10.1 \text{ pb}$, $\sigma_s < 13.6 \text{ pb}$
- DØ: $\sigma_t < 4.4 \text{ pb}$, $\sigma_s < 5.0 \text{ pb}$

Heavy bosons (W') search - new physics

- DØ: $m_{W'} > 650 \text{ GeV}$ (SM-like coupling to fermions)

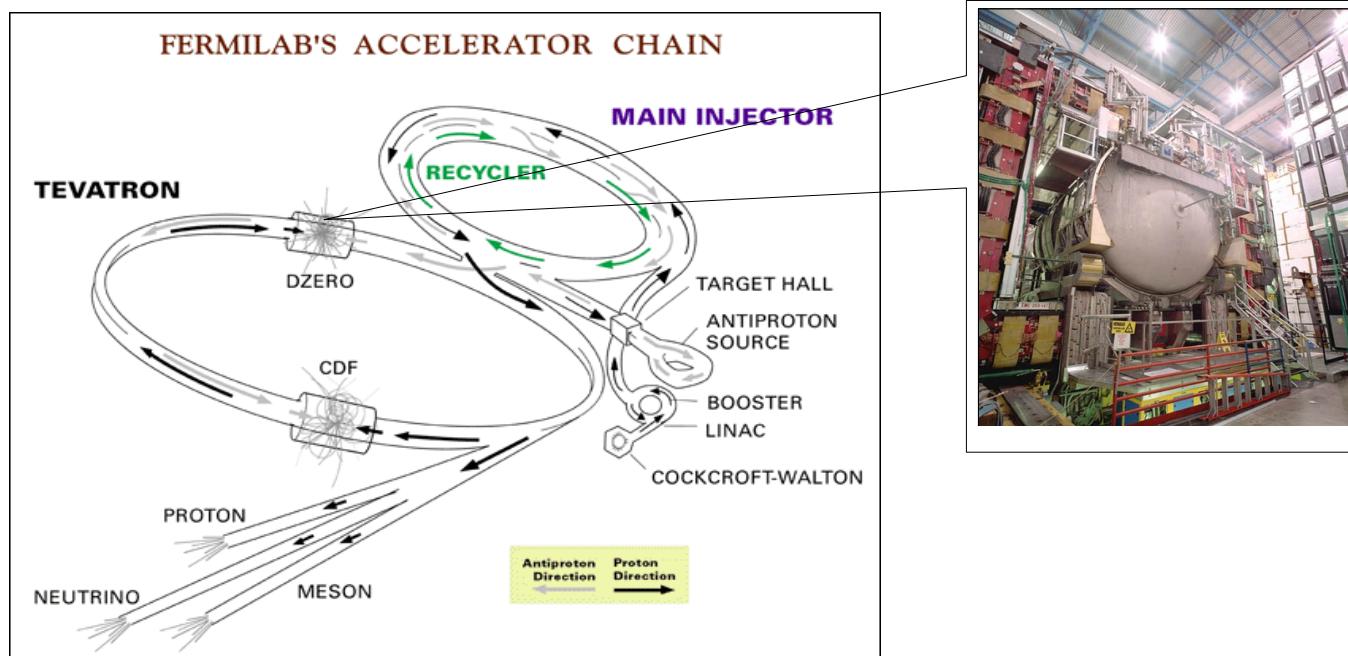
With $\sim 1 \text{ fb}^{-1}$ of data on tape, good performance of the post-shutdown detectors and the Tevatron, an exciting future is ahead!



Top Quark Mass from D \emptyset

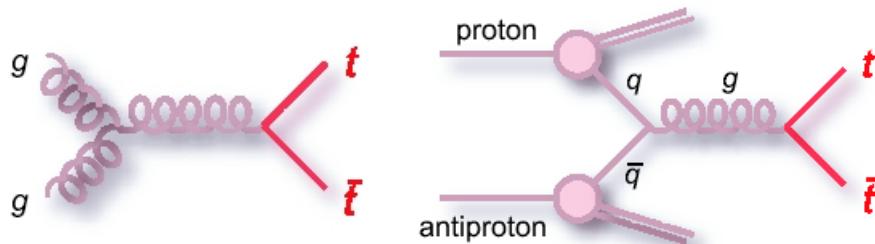
on behalf of the D \emptyset collaboration

Miroslav Kopál
University of Oklahoma



Top Quark Mass

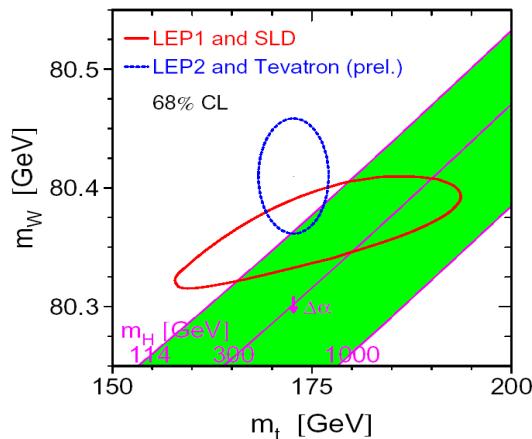
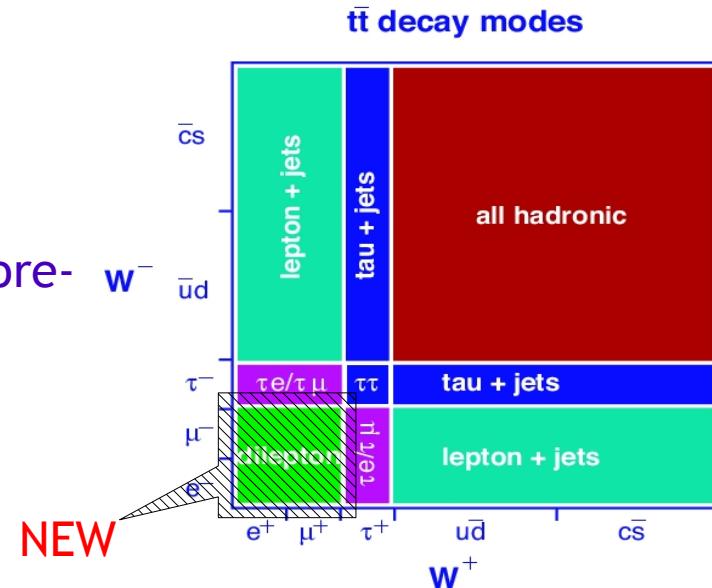
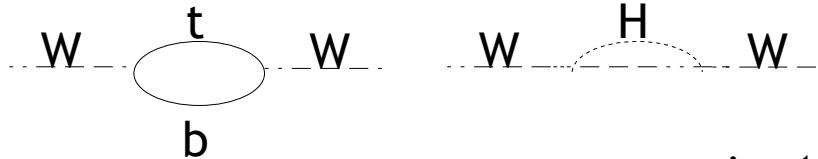
- Primary top quark production via strong interactions (top in pairs)



- Fundamental SM parameter, affecting predictions of SM via radiative corrections

$$\delta m_W \propto m_{top}^2, \ln(m_H)$$

- m_{top} can be related to m_H via m_W

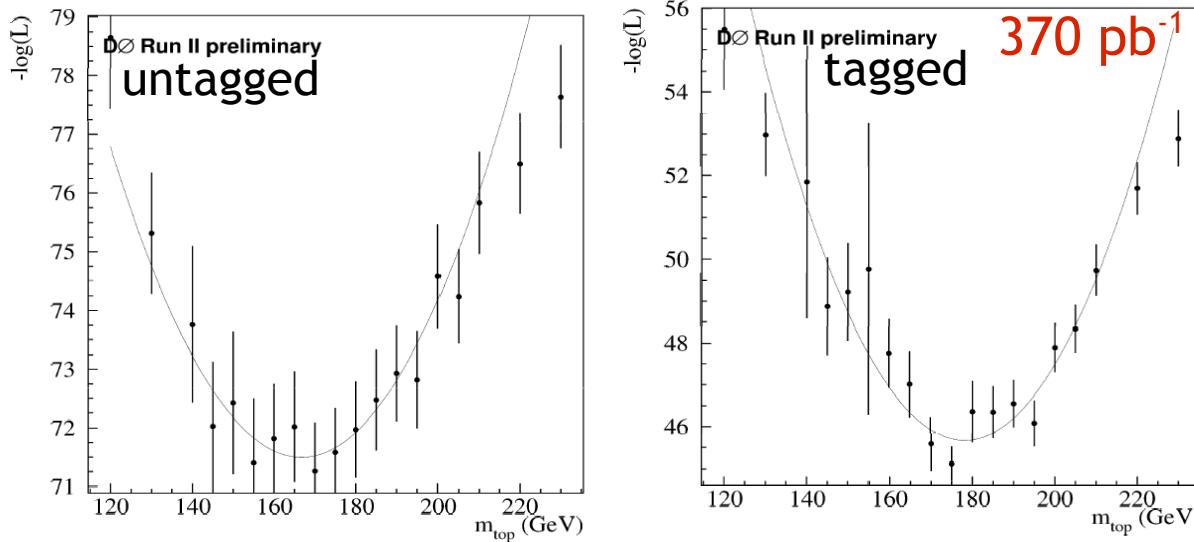


- m_{top} is $\sim 1/2$ the vacuum expectation value of the Higgs field - probing EWSB mechanism (new physics?)
- Precision measurement $\Rightarrow 2 \text{ fb}^{-1}$ projection: $\delta m_t \sim 1.5 \text{ GeV}$ ($\delta m_H / m_H = 30\%$)

Top Quark Mass - di-leptons

General: di-lepton channel is under-constrained. Template methods assume values for certain variables in order to extract a solution, and assign weights to the different solutions. The **Matrix Weighting** method scans over top masses and assigns a weight to the solution, based on the predictions for the lepton p_T 's

$$W_o(m_{\text{top}}) = \sum_{\text{solutions}} \sum_{\text{jets}} f_{\text{PDF}}(x) f_{\text{PDF}}(\bar{x}) p(E_l^* | m_{\text{top}}) p(\bar{E}_l^* | m_{\text{top}})$$



	Systematic uncertainties:	untagged	tagged
JES	3.5	3.5	3.5
PDF	0.9	0.9	0.9
Gluon radiation	0.8	0.8	0.8
background	0.7	0.2	0.2
calibration	0.6	0.6	0.6
template stat.	0.3	0.3	0.3
Total	3.8 GeV	3.8 GeV	3.8 GeV

Topological analysis: 21 candidates with S:B = 4:1
 b-tagged (≥ 1 b-tag): 14 candidates with S:B = 48:1

untagged: $m_{\text{top}} = 165.0 \pm 13.5(\text{stat}) \pm 3.8(\text{syst}) \text{ GeV}$
 tagged: $m_{\text{top}} = 176.6 \pm 11.2(\text{stat}) \pm 3.8(\text{syst}) \text{ GeV}$

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Top Quark Mass - di-leptons

The **Neutrino Weighting** method scans over top masses and the rapidity of the two neutrinos and assigns a weight (as a function of m_{top}) to the solution, based on the agreement of the calculated neutrino p_T and the observed missing E_T

(having 18 quantities total and 12 measured, 6 are still unknown: having two constraints from m_W and one constraint from $m_t = m_{t\bar{b}}$, left unknowns are m_t , n_v and $n_{v\bar{b}}$, we calculate weights for fixed values of unknowns)

$$w = \frac{1}{N_{iter}} \sum_{i=1}^{N_{iter}} \exp \left(\frac{-(E_{x,i}^{calc} - E_x^{obs})^2}{2\sigma_{E_x}^2} \right) \exp \left(\frac{-(E_{y,i}^{calc} - E_y^{obs})^2}{2\sigma_{E_y}^2} \right)$$

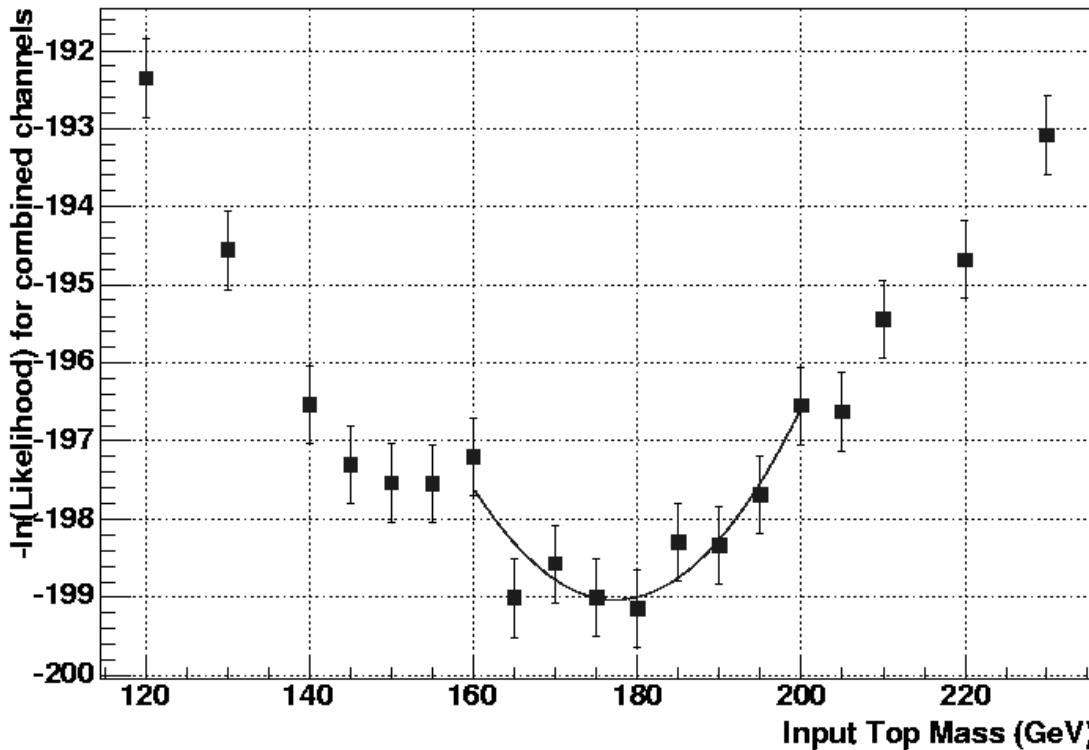
Maximum likelihood fit to sign and bkgd templates (no b-tagging analysis)





Top Quark Mass - di-leptons

D0 RunII Preliminary



370 pb⁻¹

21 candidates with S:B = 4:1

Systematic uncertainties:

JES	5.3
Jet resolution	0.5
Muon resolution	0.4
PDF	0.7
Gluon radiation	2.0
background	1.3
template stat.	0.9
Total	6.0 GeV

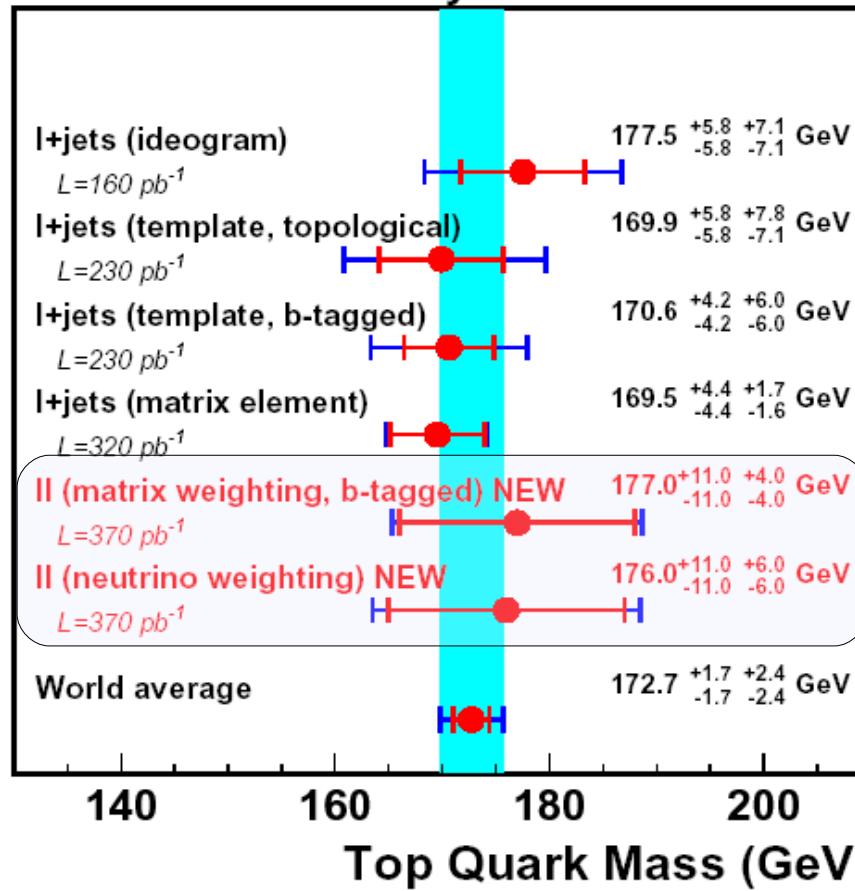
$$m_{\text{top}} = 175.6 \pm 10.7(\text{stat}) \pm 6.0(\text{syst}) \text{ GeV}$$





Top Quark Mass

DØ Run II Preliminary



PS 2005 Run I+ Run II world average: $m_{\text{top}} = (172.7 \pm 2.9) \text{ GeV}$

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Supporting slides



Tevatron collider, CDF and D \emptyset detectors

Canada
McGill Univ.
Univ. of Toronto

Russia
JINR, Dubna
ITEP, Moscow

USA
Argonne National Laboratory, IL
Brandeis Univ., MS
Univ. of Chicago, IL
Davis UC, CA
FNAL, IL
Univ. of Florida, FL
Harvard Univ., MA
Univ. of Illinois, IL
The Johns Hopkins Univ., MD
LBNL, CA
MIT, MA
Michigan State Univ., MI
Univ. of Michigan, MI
Univ. of New Mexico, NM
The Ohio State Univ., OH
Univ. of Pennsylvania, PA
Univ. of Pittsburgh, PA
Purdue Univ., IN
Univ. of Rochester, NY
Rockefeller Univ., NY
Rutgers Univ., NJ
Texas A&M Univ., TX
Texas Tech Univ., TX
Tufts Univ., MA
UCLA, CA
Univ. of Wisconsin, WI
Yale Univ., CT

Germany
Univ. Karlsruhe

Switzerland
Univ. of Geneva

UK
Glasgow Univ.
Univ. of Liverpool
Univ. of Oxford
Univ. College London

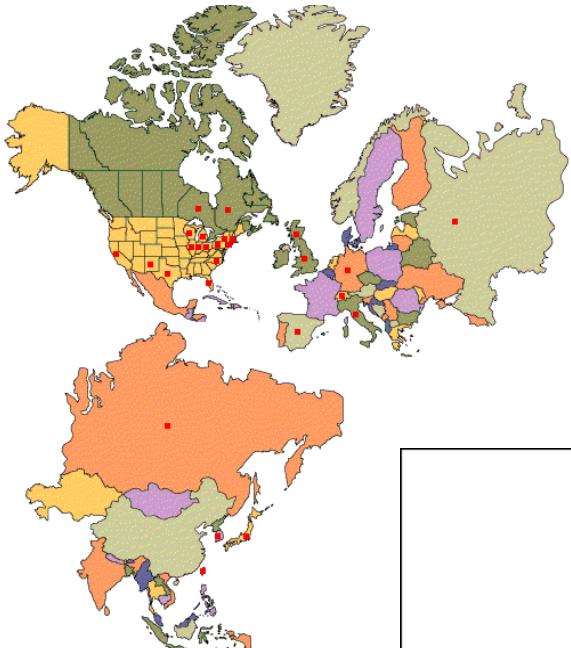
Italy
Univ. of Bologna, INFN
Frascati, INFN
Univ. di Padova, INFN
Pisa, INFN
Univ. di Roma I, INFN
INFN-Trieste
Univ. di Udine

Spain
Univ. of Cantabria

Japan
Hiroshima Univ.
KEK
Osaka City Univ.
Univ. of Tsukuba
Waseda Univ., Tokyo

China
Academia Sinica,
Taiwan

Korea
KHCL

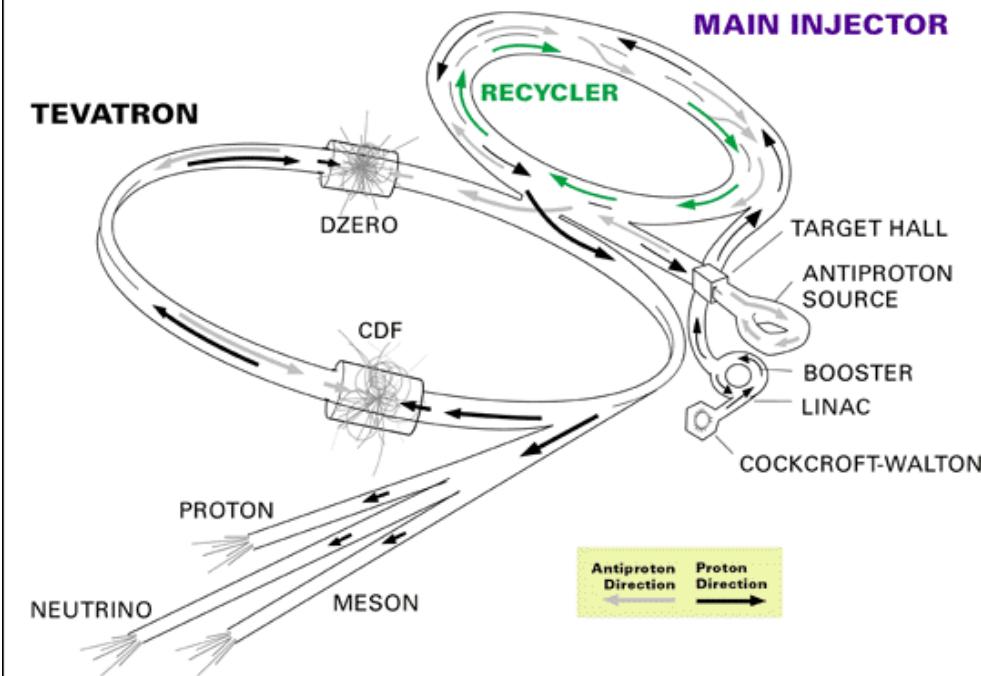


Run IIa(b): '01-'06 ('06-...)	
bunch/turn	36x36
\sqrt{s} [TeV]	1.96
$\int \mathcal{L} dt$ [pb-1/week]	17 (50)
\mathcal{L}_{inst}	1E32 (3E32)
interactions/crossing	2.3 (8)

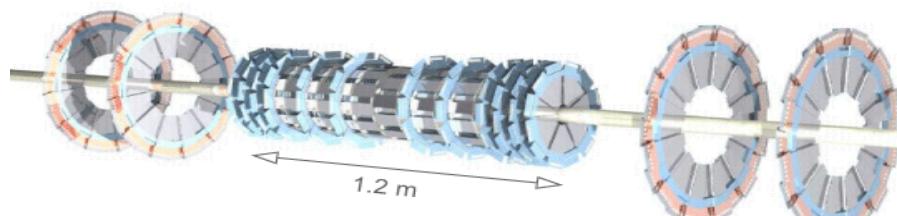
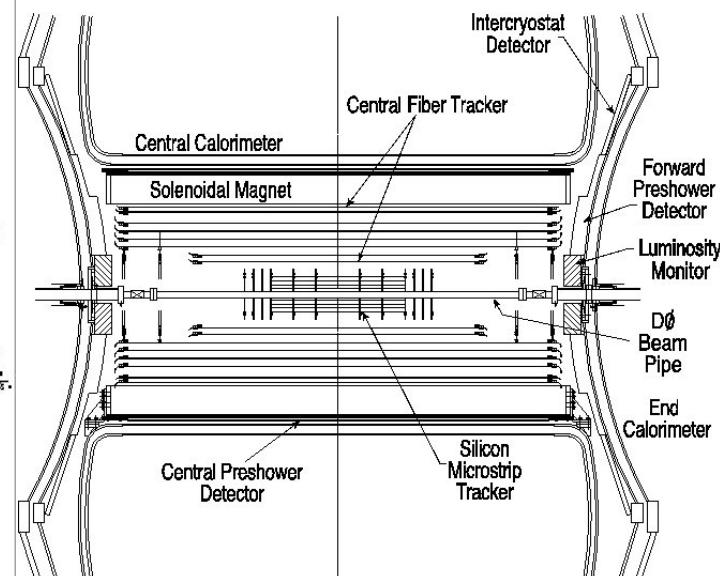
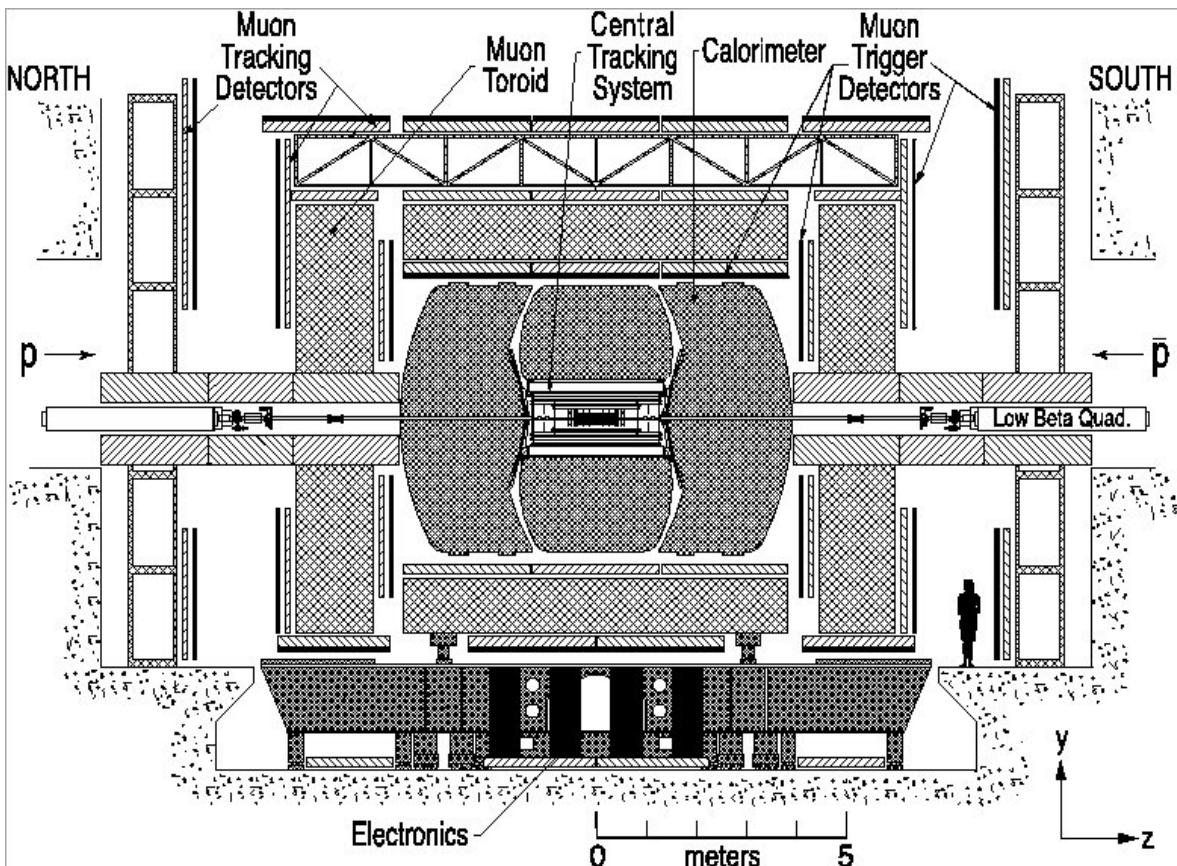
Increase of \bar{p} production:
 \bar{p} recycler (Fall '04)
e-cooling (Summer '05)



FERMILAB'S ACCELERATOR CHAIN



RunIa DØ detector



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Top Quark Pair Production

Main sources of systematics uncertainties

Di-lepton channel

Source	Systematic Error (%)
MC Generator	2.4
ISR/FSR	4.4
PDF's	0.8
JES corrections	3.1
Multiple Interactions	1.7
Lepton Identification	4.0
Total	7.4

Lepton+jets channel

kinematics+NN

Source	ANN (%)
Jet Energy Scale	8.3
W+jets Background	10.2
QCD Background	1.3
t̄t generator	2.6
t̄t PDF	4.4
t̄t ISR/FSR	2.2
Lepton ID	2.4
Luminosity	5.8
Total	15.7

Lepton+jets channel b-tag

Source	Systematic (%)
b-tagging	6.5
Luminosity	6.0
PDF	5.8
Jet Energy Scale	3.0
ISR/FSR	2.6
Lepton Identification	2.0
Total	11.5

Variable	Definition
H_T	Scalar sum of transverse energies of jets, lepton and \cancel{E}_T .
Aplanarity	$3/2Q_1$
$\Sigma p_z / \Sigma E_T$	Ratio of total jet longitudinal momenta to total jet transverse energy.
$\min(M_{jj})$	Minimum di-jet invariant mass
η_{max}	Maximum η of jet.
$\sum_{i=3}^5 E_{T,i}$	Sum E_T of third, fourth and fifth jets.
$\min(\Delta R_{jj})$	Minimum di-jet separation in η and ϕ .
$\sum_{i=1}^n E_{T,i}$	Sum E_T of all jets.
\cancel{E}_T	Missing transverse energy.
Sphericity	$3/2(Q_1 + Q_2)$
M_{event}	Invariant mass of jets, lepton and \cancel{E}_T .
$\sum_{i=1}^3 M_{jj}$	Sum of di-jet invariant masses.
E_T^{j1}	E_T of jet with highest E_T .
$E_T^{j2} + E_T^{j3}$	Sum of E_T of jets with second and third highest E_T .
M_W^{rec}	Reconstructed hadronic W mass
$\Sigma \eta^2$	Sum of η^2 of jets with highest E_T .
$\Delta\Phi_{lm}$	Azimuthal angle between lepton and \cancel{E}_T .
E_T^{j2}	E_T of jet with second highest E_T .
E_T^{j3}	E_T of jet with third highest E_T .
$E_T^{j1} + E_T^{j2}$	Sum of E_T of jets with first and second highest E_T .





Top Quark Pair Production

Main sources of systematics uncertainties

All jets channel

Source	Effect on cross section [pb]	
Jet energy calibration	+1.12	-0.73
Jet Identification	+0.68	-0.42
Trigger	+0.27	-0.05
Background prediction	+0.52	-0.50
$t\bar{t}$ tagging probability	+0.34	-0.29
total	+1.48	-1.02

Di-lepton channel

	$\Delta\sigma_{t\bar{t}}$ (pb)	
Jet energy calibration	+ 0.5	- 0.5
Jet identification	+ 0.5	- 0.4
Muon identification	+ 0.5	- 0.4
Electron identification	+ 0.4	- 0.3
Trigger	+ 0.7	- 0.4
Other	+ 0.4	- 0.4
Total	+ 1.2	- 1.0

Lepton+track/e μ channel

Source	$e\mu$		l+track		l+track+ $e\mu$	
Primary Vertex	-0.5	+0.5	-0.6	+0.7	-0.6	+0.6
Electron identification	-3.0	+4.0	-2.8	+4.2	-2.9	+3.7
Electron trigger	-4.9	+5.5	-1.3	+1.7	-0.7	+3.6
Muon identification	-5.9	+6.3	-3.2	+3.4	-4.4	+4.5
Muon trigger	-5.7	+8.4	-1.8	+2.2	-3.6	+5.0
Track identification	0	0	-3.8	+4.2	-1.9	+2.0
Jet energy scale	-5.5	+5.2	-13.7	+8.9	-8.5	+6.6
Jet identification	-3.5	+4.7	-2.5	+0.1	-3.2	+2.2
Jet resolution	-2.4	+4.7	-2.3	+0.6	-2.4	+1.7
Jet trigger	0	0	-0.6	+0.7	-0.2	+0.3
e_{lh} fit and opposite sign req.	-3.7	+4.2	0	0	-1.7	+1.9
$t\bar{t}$ tagging probability	0	0	-3.9	+4.1	-2.1	+2.2
Multijet/ $W+W$ background	0	0	-1.3	+0.8	-0.6	+0.3
WW background	-2.4	+2.4	-0.6	+0.6	-1.6	+1.6
Z background	-0.7	+0.7	-9.9	+13.0	-4.0	+5.2
Other	-2.2	+2.2	-2.0	+2.3	-2.0	+2.2
Total	-12.4	+16.1	-18.9	+18.5	-12.8	+13.3

Lepton+jets channel

Source	Offset	σ^+	σ^-
Muon preselections	+0.02	+0.18	-0.15
Electron preselections	-0.02	+0.18	-0.15
Muon triggers	+0.07	+0.34	-0.28
Jet energy scale	-0.07	+0.24	-0.21
Jet reco and jet ID	-0.09	+0.23	-0.18
SML b-tag eff in MC	+0.03	+0.15	-0.14
Semileptonic b-tagging efficiency in data	+0.18	+0.40	-0.35
Heavy quark mass on W fractions	-0.00	+0.18	-0.19
W fractions matching + higher order effects	+0.01	+0.44	-0.44
Event statistics for matrix method	-0.02	+0.15	-0.15





Single Top Quark search

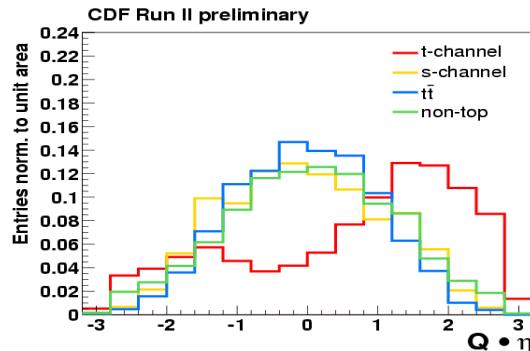
Likelihood Discriminants	Input Variables				Likelihood Discriminant	t-channel	s-channel
	$tb/W + \text{jets}$	$tb/t\bar{t}$	$tqb/W + \text{jets}$	$tqb/t\bar{t}$			
1. $p_T(\text{jet}1)$	✓	✓	✓	✓			
2. $p_T(\text{jet}2)$	✓	✓	✓	✓			
3. $p_T(\text{jet}3)$	—	✓	—	✓			
4. METLep	✓	✓	✓	✓			
5. $M_{\text{all jets}}$	✓	✓	✓	✓			
6. $M_T(W)$	✓	✓	✓	✓			
7. $M(W, \text{tagjet}1)$	✓	—	✓	—			
8. $\Delta R_{\min}(\text{all jets})$	—	✓	—	✓			
9. $\cos(\text{jet}2, \text{lepton})_{\text{top}}$	✓	—	✓	—			
10. Sphericity	—	✓	—	✓			
11. Centrality	—	✓	—	✓			
12. $Q \times \eta$	—	—	✓	✓			
Signals and backgrounds yields with uncertainties							
	Electron channel		Muon channel				
	Single tag	Double tag	Single tag	Double tag			
Signals yields							
tb	3.3 ± 0.5	1.6 ± 0.4	3.0 ± 0.5	1.6 ± 0.4			
tqb	6.9 ± 1.3	1.0 ± 0.2	6.2 ± 1.3	0.9 ± 0.2			
Backgrounds yields							
$t\bar{t} \rightarrow \text{lepton} + \text{jets}$	40.4 ± 8.9	20.3 ± 5.4	37.6 ± 8.4	20.6 ± 5.7			
$t\bar{t} \rightarrow \text{dilepton}$	11.3 ± 2.5	5.5 ± 1.5	10.2 ± 2.3	5.2 ± 1.5			
Wbb	24.2 ± 1.6	8.1 ± 1.6	14.7 ± 1.0	5.4 ± 1.2			
Wjj	111.6 ± 11.0	4.9 ± 1.1	74.7 ± 7.8	3.4 ± 0.8			
WW	2.3 ± 0.5	< 0.1	2.4 ± 0.6	< 0.1			
WZ	2.0 ± 0.5	0.7 ± 0.2	1.8 ± 0.4	0.7 ± 0.7			
Multijet	21.8 ± 3.7	1.4 ± 0.3	17.9 ± 4.5	2.7 ± 0.4			
Total backgrounds	213.6 ± 20.7	40.9 ± 8.5	159.3 ± 17.6	38.0 ± 8.4	M. Kopál - RENCONTRES DE MORIOND EW Interactions and Unified Theories La Thuile (Italy), March 11-18 2006		
Data yield with stat. uncertainties	229 ± 15.1	43 ± 6.6	138 ± 11.7	33 ± 5.7			



Single Top Quark search

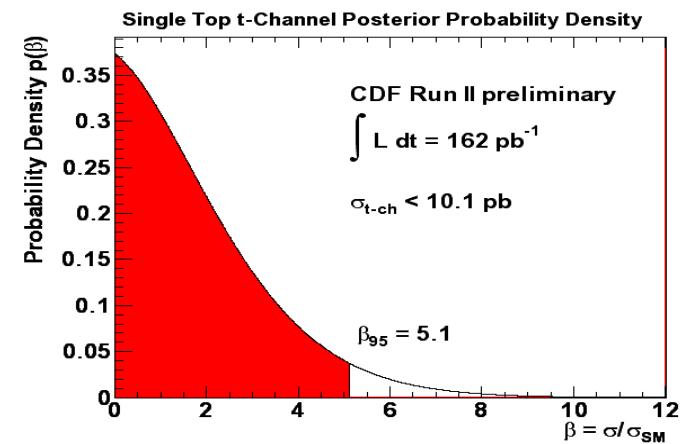
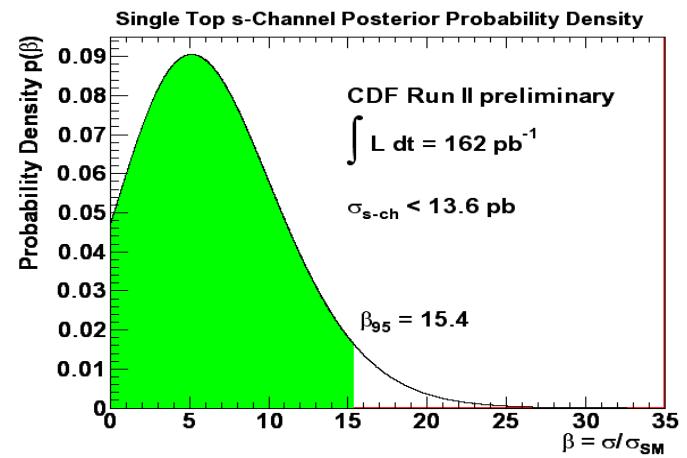
Extracting signal

- > binned likelihood technique (depending only on signal cross sections)
- > $Q \cdot \eta$ - separate t-channel (Q=lepton charge, η =pseudo-rapidity of non b-tagged jet)



Systematic acceptance uncertainties for t- and s- single top channel (combined signal and background)

No.	Source	Separate Search		Combined Search
		t-channel	s-channel	t- and s-channel
1	Jet energy scale	$\pm 2.4\%$ -6.7%	$\pm 0.4\%$ -3.1%	$\pm 0.1\%$ -4.3%
2	ISR	$\pm 1.0\%$	$\pm 0.6\%$	$\pm 1.0\%$
3	FSR	$\pm 2.2\%$	$\pm 5.3\%$	$\pm 2.6\%$
4	PDF	$\pm 4.4\%$	$\pm 2.5\%$	$\pm 3.8\%$
5	Generator	$\pm 5\%$	$\pm 2\%$	$\pm 3\%$
6	Top quark mass	$\pm 0.7\%$ -6.9%	-2.3%	-4.4%
7	$\epsilon_{\text{trig}}, \epsilon_{\text{ID}}$, luminosity	$\pm 9.8\%$	$\pm 9.8\%$	$\pm 9.8\%$



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