The Search for Single Top at the Tevatron

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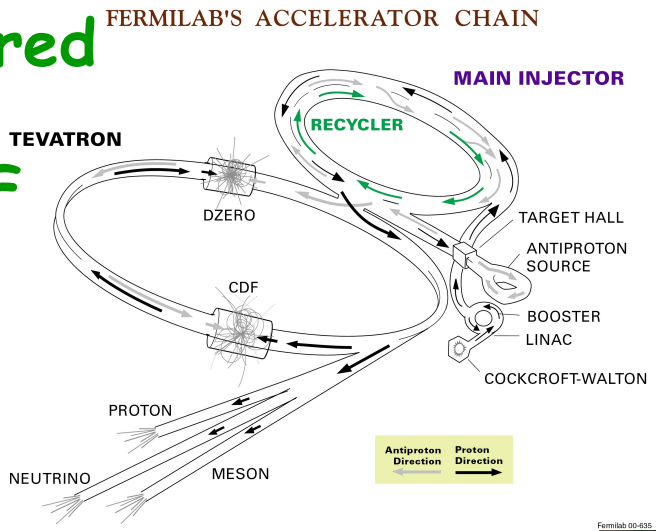
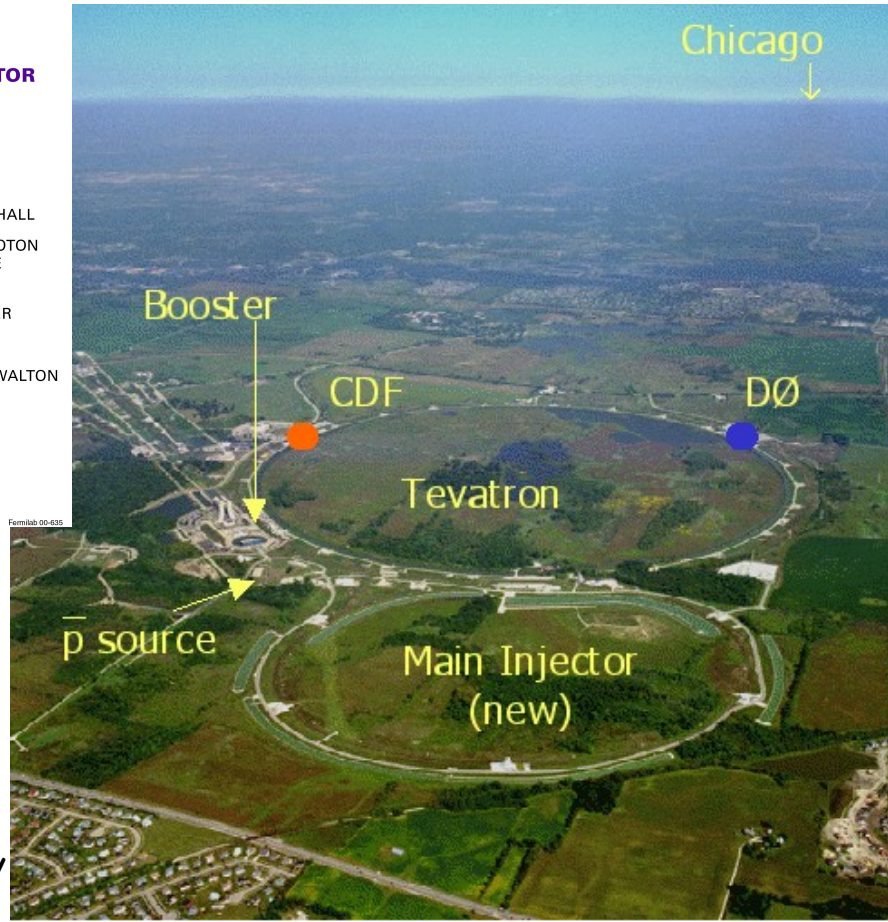
Top at the Tevatron

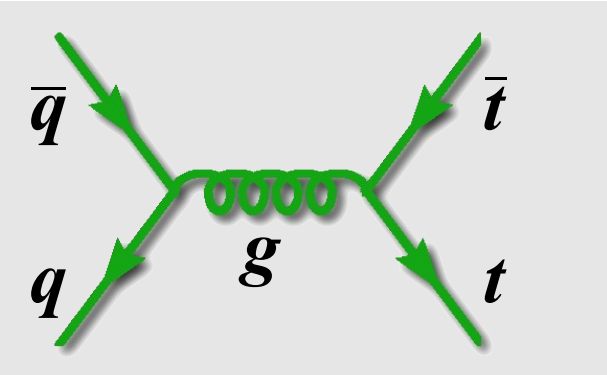
- The top quark is the heaviest fundamental particle discovered so far: 172±2.9 GeV/c^2
  - Mass approximately the same as a gold nucleus!
  - Discovered by DØ and CDF in 1995

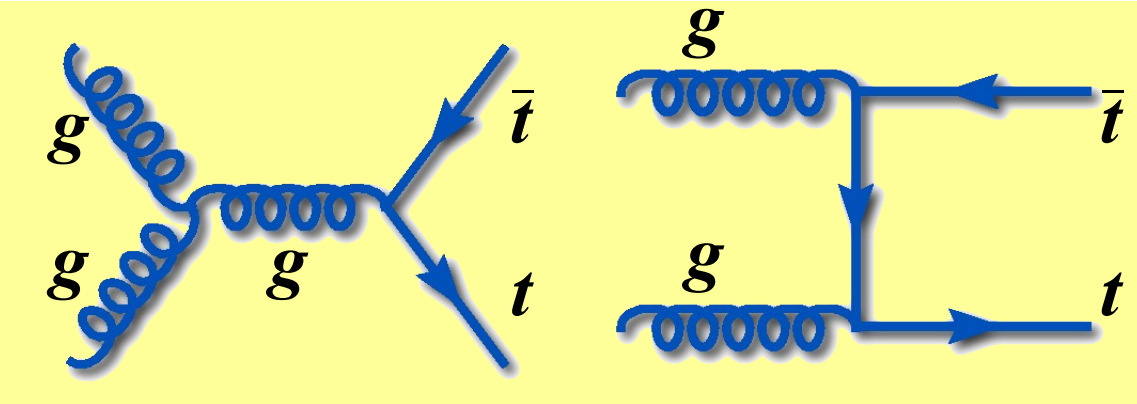




Top Production

- The top was discovered via t-tbar production
  - Strong interaction process (large σ)
  - ...but centre-of-mass energy > 2×m(top)
- Three LO diagrams: qq or gg fusion



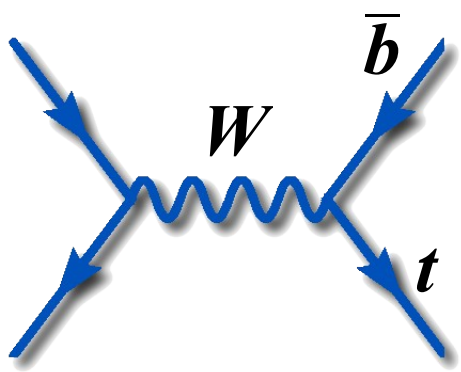


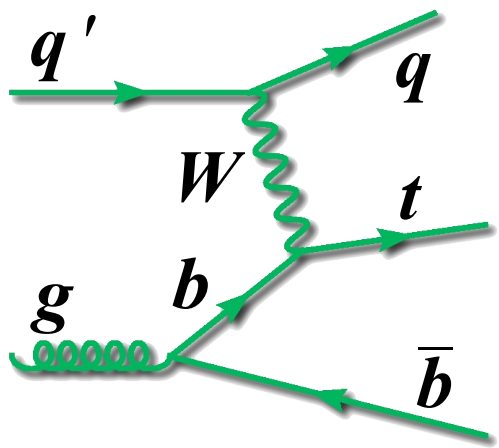
TeV:	qq~85% σ(tt)	gg~15% σ(tt)	7.0pb
LHC:	qq~10% σ(tt)	gg~90% σ(tt)	~800pb

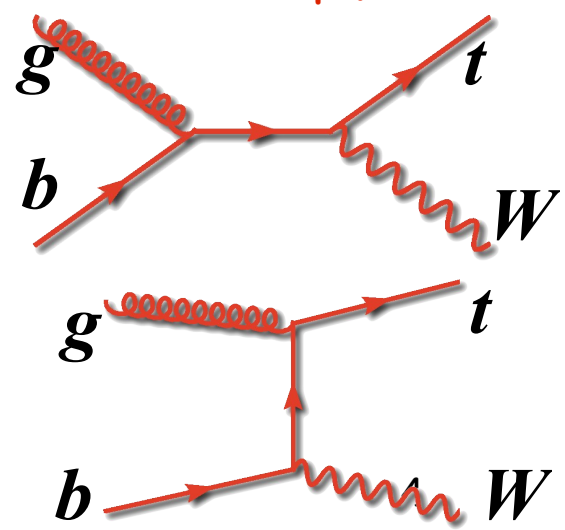
Single Top Production

- Single Top quarks should also be produced by electroweak interactions
  - Weak interaction (low σ)
  - ...but centre-of-mass > m(top) : i.e. ~half ttbar's
- 3 tree-level diagrams: s-channel or t-channel

TeV:	0.88±0.11pb	1.98±0.25pb	<0.1 pb
LHC: $t/\bar{t}$	6.6/4.1 pb	156/91 pb	62^{+17}_{-4} pb

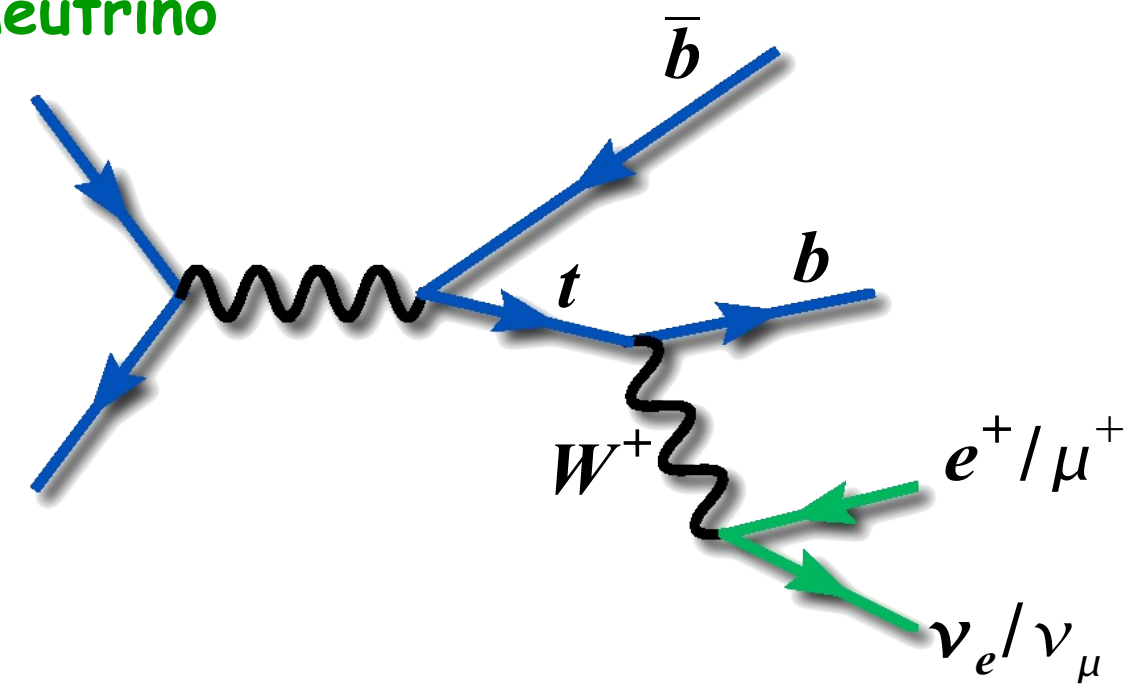






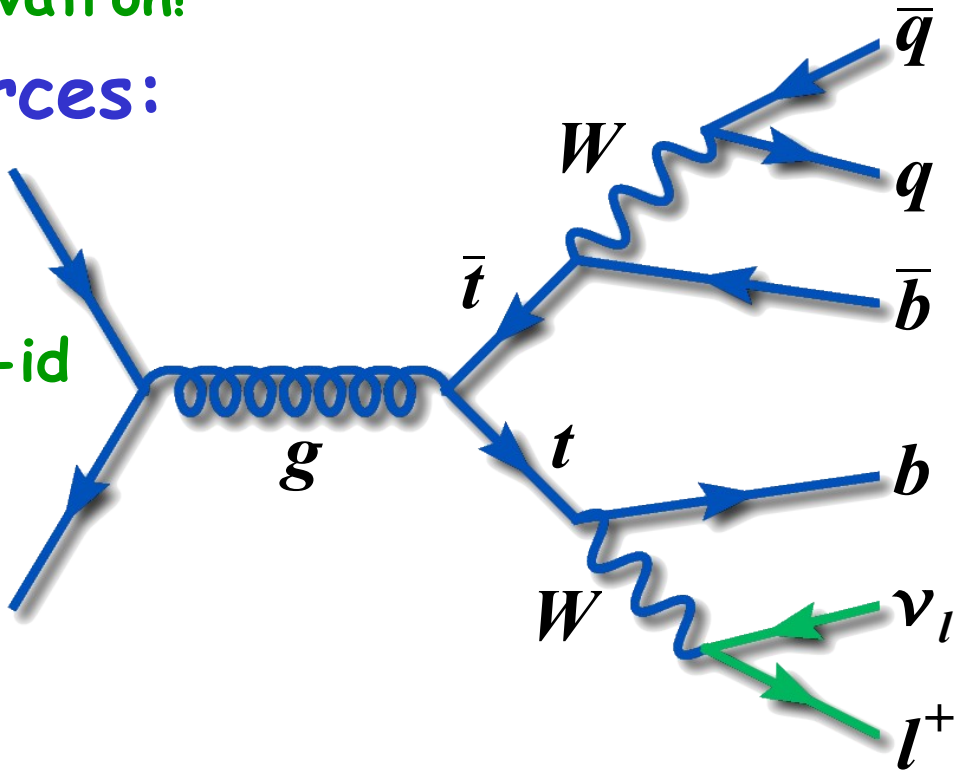
Signal

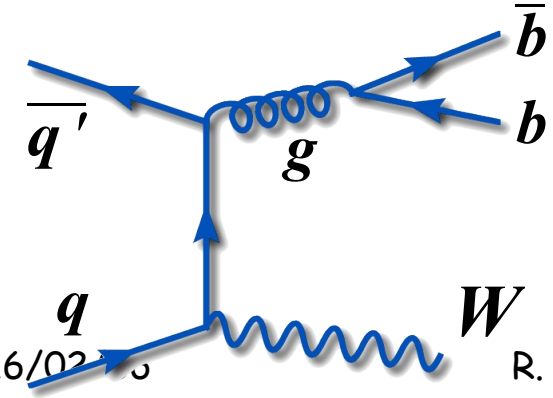
- Top quark decays to Wb with ~100% BR
  - Require leptonic W decay to $e^{\pm}$ or $\mu^{\pm}$ + neutrino
- Signature looked for is therefore
  - High p_T isolated lepton (electron/muon)
  - Missing E_T from neutrino
  - b-quark jet
    - Displaced vertex/ impact parameter
  - (t-channel only) additional jet which is untagged



Single Top Backgrounds

- Reason single top production has not yet been seen is because of large backgrounds
  - Ironically single-top itself is one of the backgrounds for Higgs discovery at the Tevatron!
- Major background sources:
  - W+jets (Wbb) [1,000pb]
  - t-tbar [~7pb]
  - QCD multi-jet+lepton mis-id
  - Diboson WZ, WW [small]



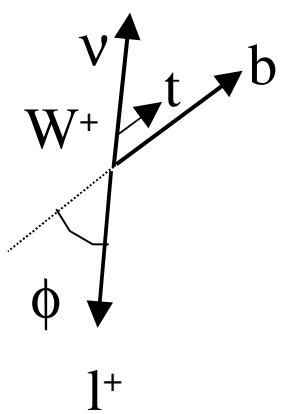


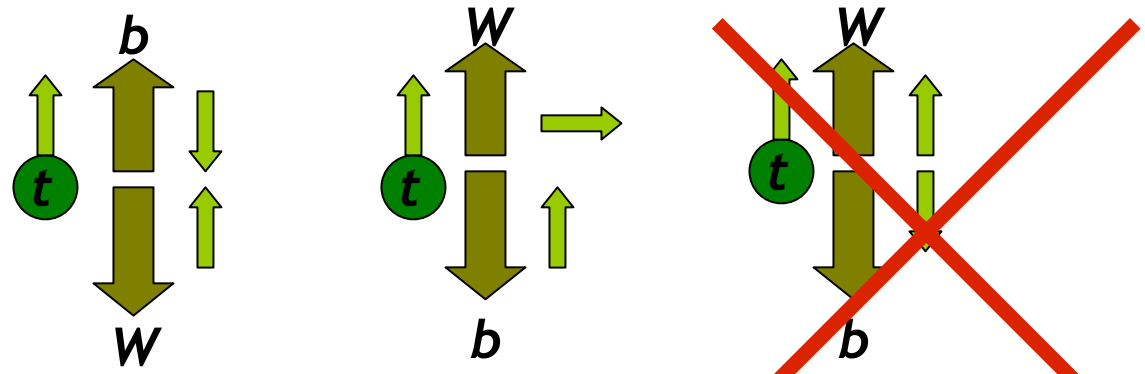
Single Top Physics

- Few characteristics of the top quark have been measured
  - Know mass, production cross-section [σ(tt)] charge, and BR(t->Wb)~1 (if we assume SM)
- Decay width, lifetime, spin, BRs (w/o assuming SM) are all experimentally undetermined
  - Plenty of room to surprise theorists!
- One property of top, which is unique amongst quarks, is that it decays as a free particle
  - Its lifetime is so short that it decays before it can hadronize: $\tau(top) \sim 5\times10^{-25}s < \Lambda_{QCD}^{-1}$
  - Spin information not lost: passed to decay products

Single Top Physics

- All this makes single top great test of SM and probe for new physics beyond
  - Study W-t-b vertex: measure Vtb directly
    - Test CKM unitarity at higher C-of-M than b system
  - Test V-A nature of weak interactions
    - Top produced from W: polarized state
    - Study decay product distribution





W_- Left-Handed fraction F_-

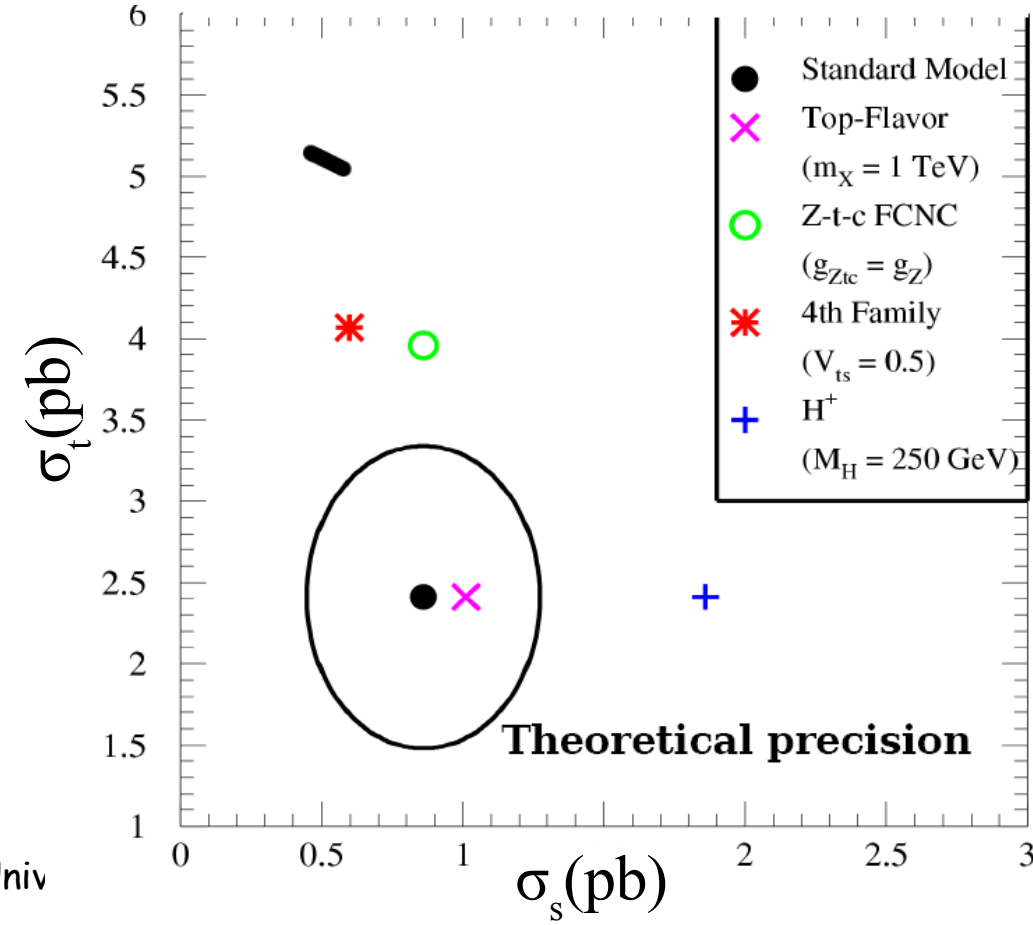
W_0 Longitudinal fraction F_0

W_+ Right-Handed fraction F_+

Single Top Physics

- The s and t production channels are sensitive to different kinds of new physics
  - t-channel sensitive to FCNCs
  - s-channel sensitive to new resonances
    - e.g. SUSY, W', charged Higgs...
- In principle the two production channels can be distinguished experimentally

Tait, Yuan PRD 63, 014018 (2001)



Simulation

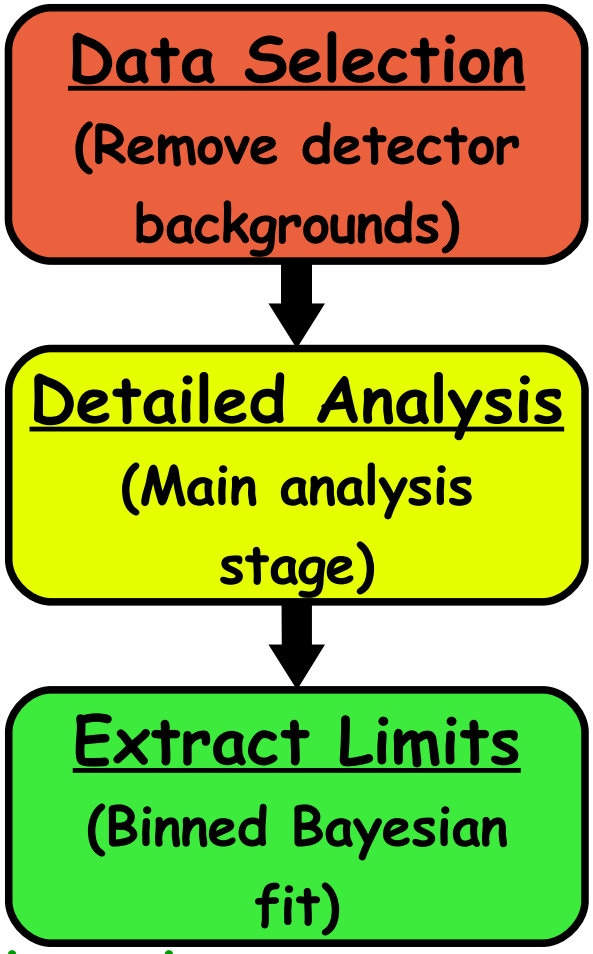
- Good signal simulation essential due to high background rates
  - Use LO generator tuned to NLO predictions
  - DØ: SingleTop + COMPHEP + PYTHIA
  - CDF: MADEVENT + PYTHIA
    - PYTHIA handles ISR, FSR, hadronization etc.
- Background simulation
  - W+jets: data/ALPGEN
  - Top pair production
  - WW, WZ, ZZ etc.
  - QCD multi-jet: data

DØ: ALPGEN+PYTHIA

CDF: PYTHIA

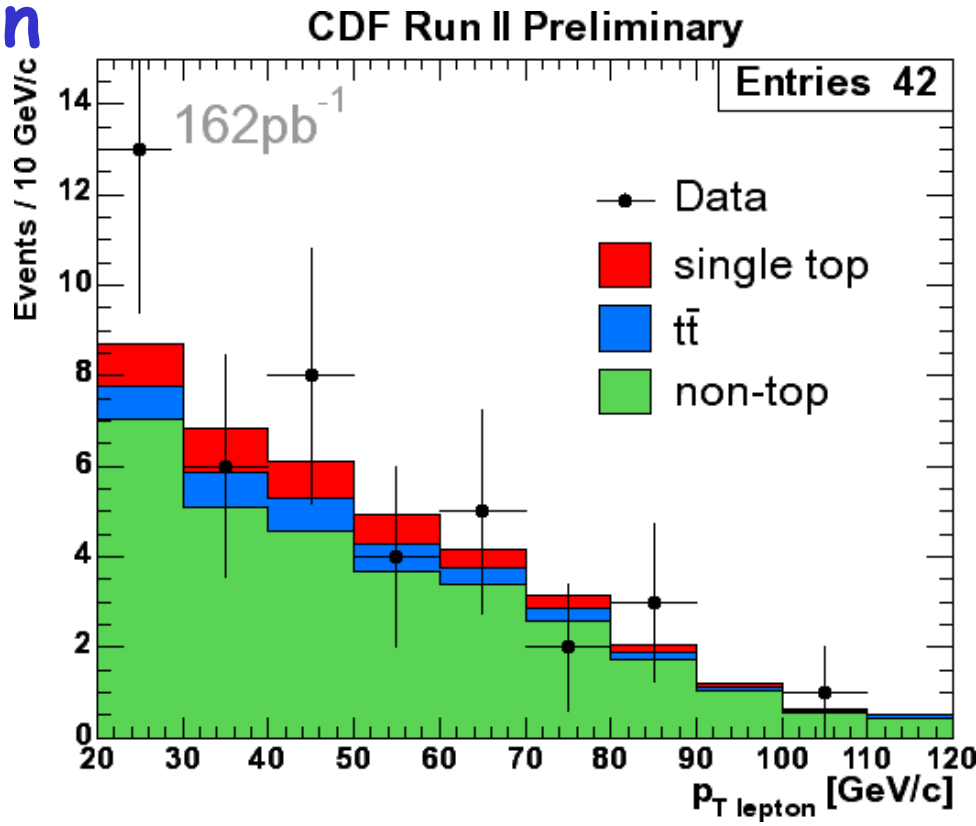
Three Stage Analysis

- DØ and CDF analyses both use a three stage process
- Clean up data
  - DØ loose, CDF tight cuts
  - Create event sample which is reproducible by MC
- Detailed Criteria
  - b-tagging, optimize S/B
  - CDF: counting, DØ likelihoods
- Extraction of limits
  - Bayesian fit of signal and background expectation compared to data



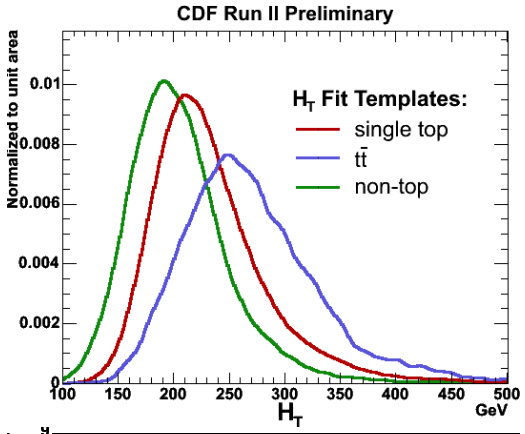
CDF Event Selection

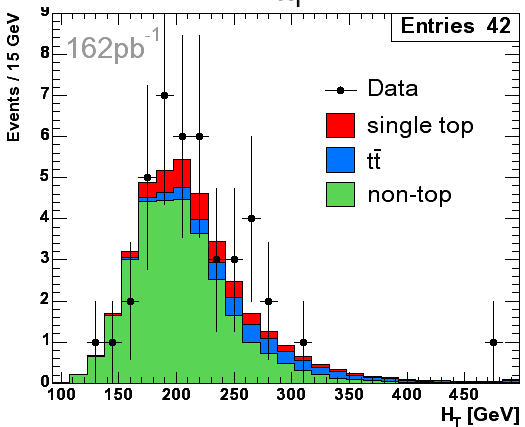
- Use 162pb^{-1} of data (analysis ~2 years old)
- W: One isolated lepton
  - p_T>20 GeV/c, |η|<1.0
  - Missing E_T>20 GeV
- Jets: exactly 2 jets in event
  - Each with E_T>15 GeV, |η|<2.8
  - 1+ jets are b-tagged
    - If only one tag then leading jet E_T>30 GeV
  - 140 ≤ M_{lvb} ≤ 200 GeV/c^2 (=m_{top} for t-tbar events)



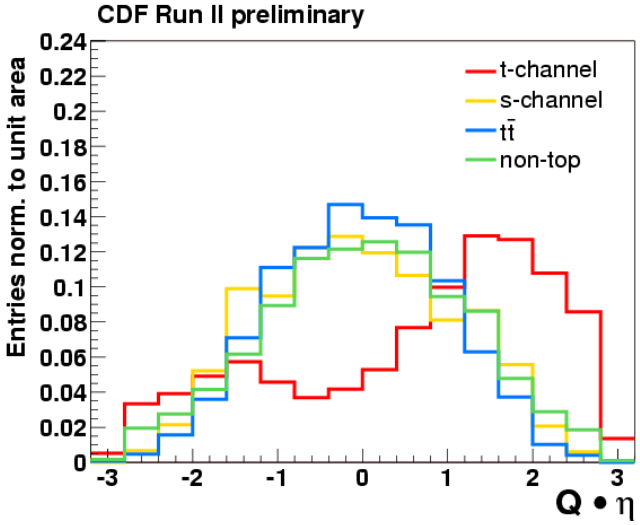
CDF Analysis

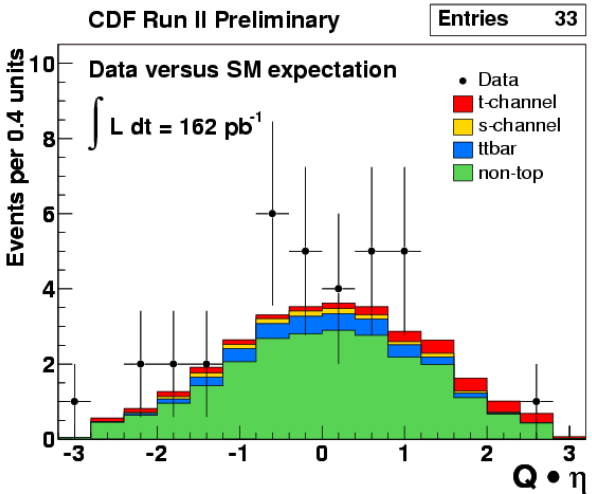
- Two analyses: separate s/t-channel & combined
- Combined approach: use H_T max likelihood
  - $H_T = MET + E_T(l) + \Sigma E_T(jet)$





- Separate channels
  - $Q \cdot \eta$ for t-channel (1 tag)
    - Q Lepton charge, η untagged jet
  - Counting experiment for s-channel (2 tags)





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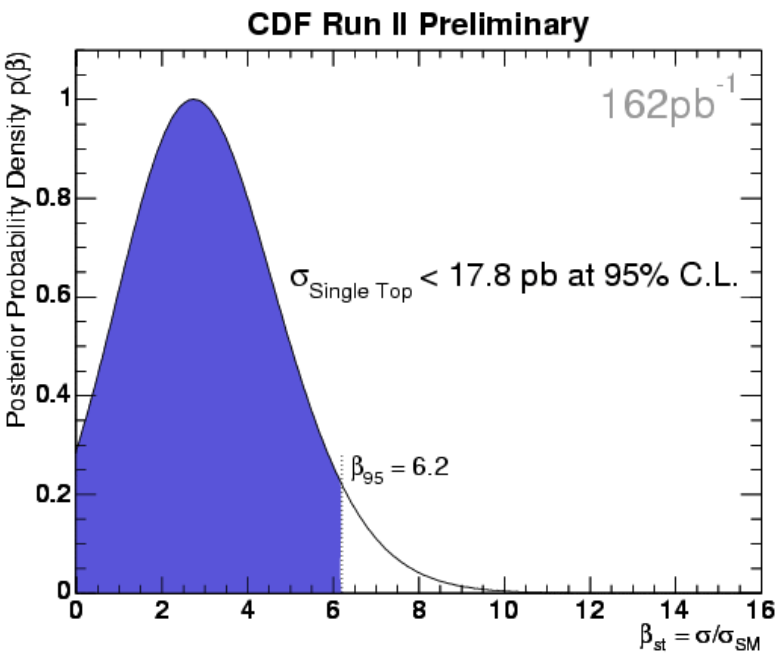
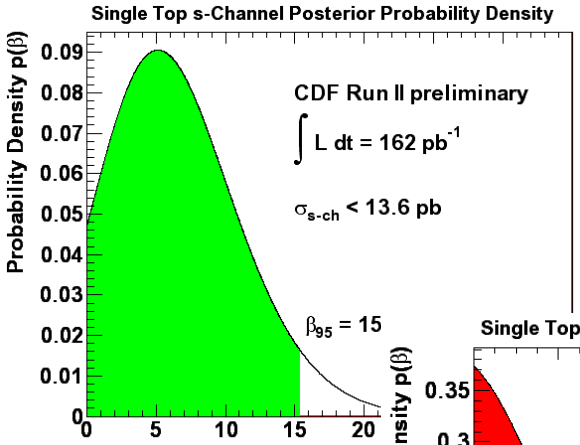
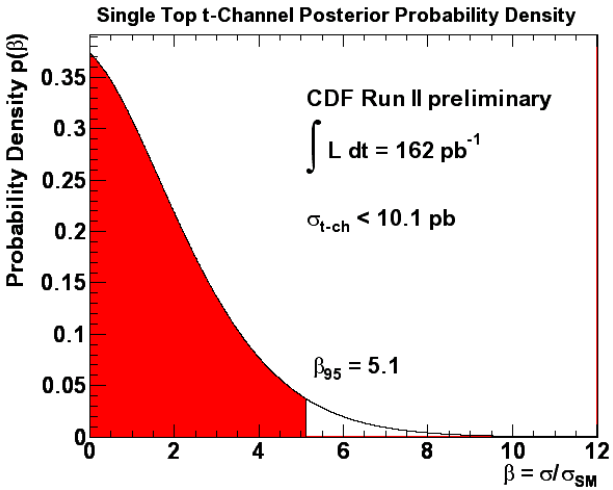
CDF Results

Phys. Rev. D 71, 012005 (2005)

- Likelihood plots of single top cross-sections







- 95% CL Limits

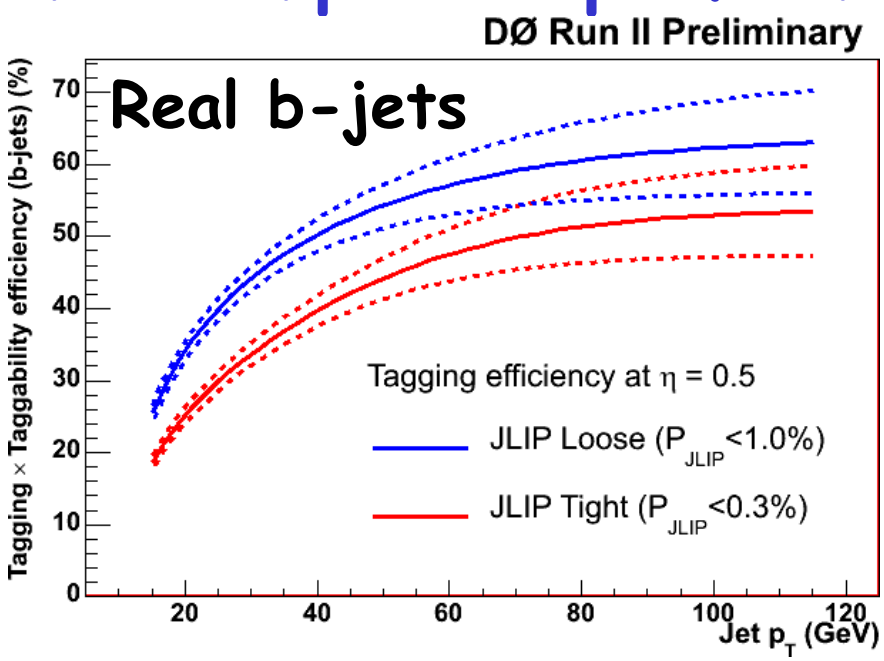
	Combined	s-channel	t-channel
Observed	17.8 pb	10.1 pb	13.6 pb
Expected	13.6 pb	11.2 pb	12.1 pb

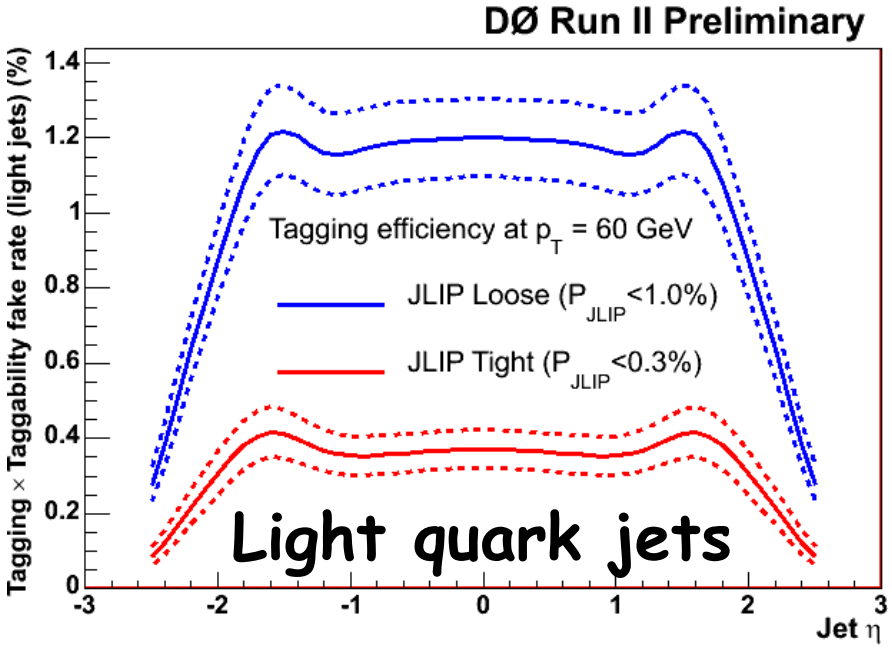
DØ Event Selection

- Start with 370pb^{-1} of data
- W: One isolated lepton
  - Reject 2+ isolated leptons
    - Reduces WW, WZ, tt events
  - p_T>15 GeV/c, $|\eta_{e/\mu}|$<2.0/1.1
  - Missing E_T>15 GeV
  - $\Delta\varphi$(X,MET) cuts to remove mis-measured lepton/jet bground
- Jets: 2-4 jets in event
  - Each with E_T>15 GeV, $|\eta|$<3.4
  - Leading jet E_T>25 GeV, $|\eta|$<2.5
  - At least one jet is b-tagged

DØ b-tag

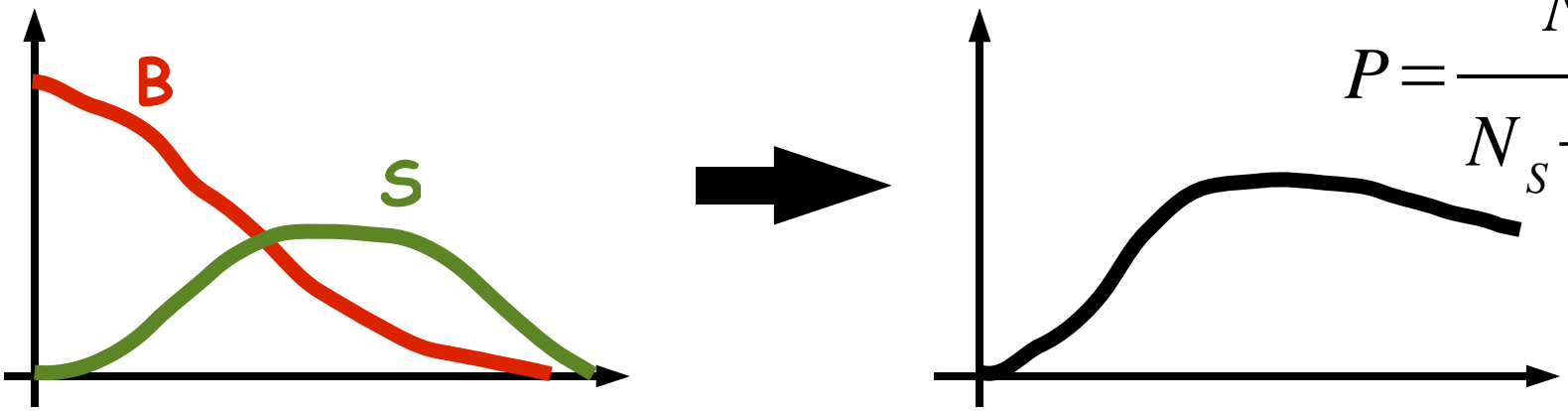
- Search for tracks with large impact parameters with the primary vertex
  - Tagging efficiency ~50%, mistag rate ~0.5%
- NN algorithm in development which will have a much improved performance





Likelihood Analysis

- Reduce each event to a "vector" of values
- Convert each variable in vector into a probability distribution function (pdf)

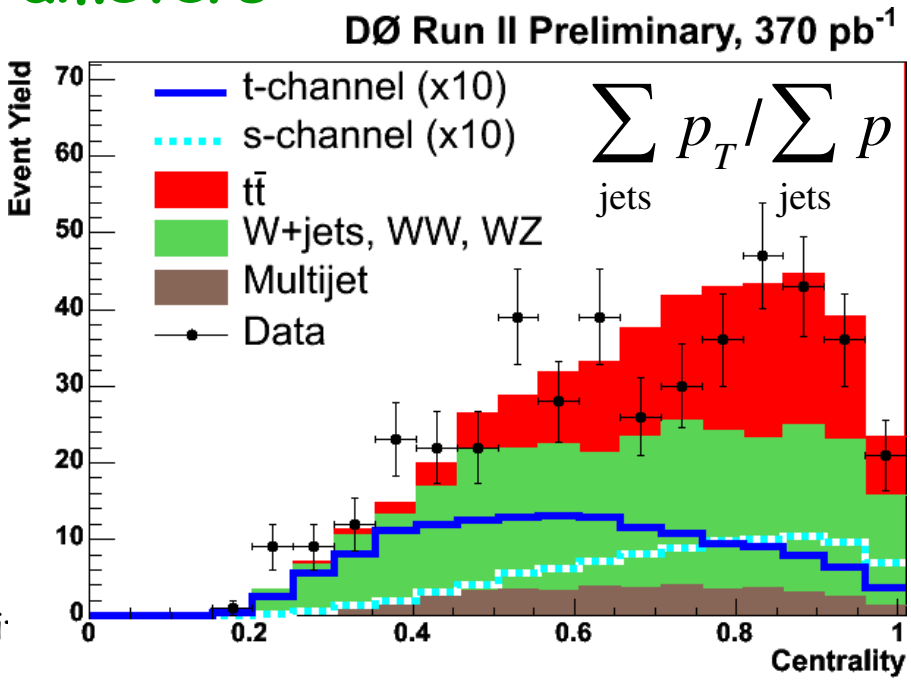


$$P = \frac{N_S}{N_S + N_B}$$

  - Determine pdf from signal and background MC
- Likelihood: product of pdf values for each discriminating variable $L = P_1 \times P_2 \times P_3 \times \ldots$
  - Variables must be uncorrelated

Likelihood Variables

- Select 16 groups of likelihood discriminants
  - 2 signals (s,t channel) × 2 backgrounds (Wjj,tt) ×2 b-tag schemes (1,2 tags)×2 lepton flavours (e,μ)
- Set of 12 discriminants used
  - Best subset chosen for S/B separation given the choice of the above 4 parameters
- Examples of variables used include…
  - p_T of each of the 3 leading jets
  - Scalar sum of MET+lepton p_T

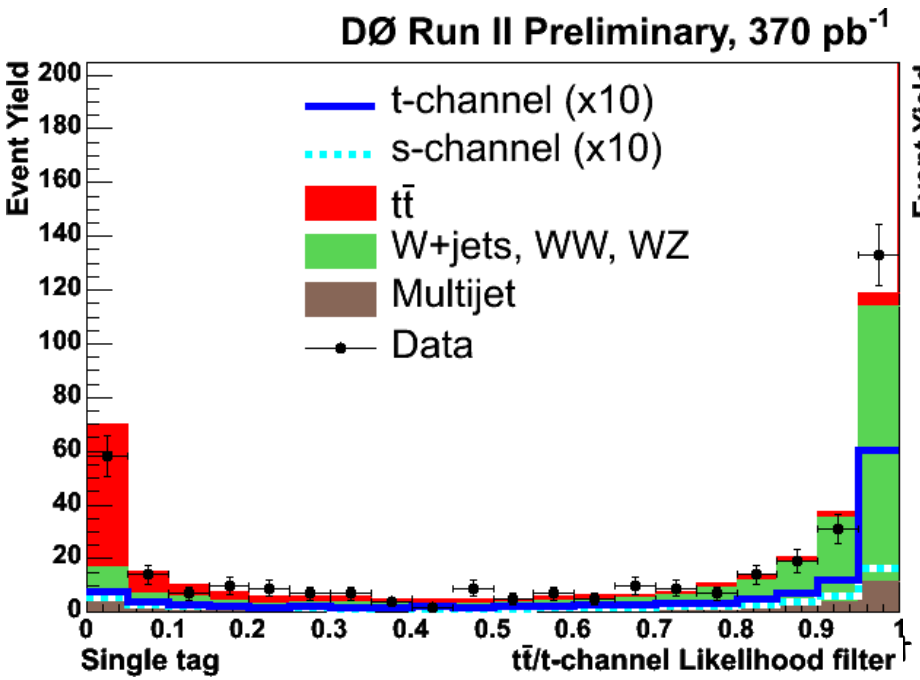


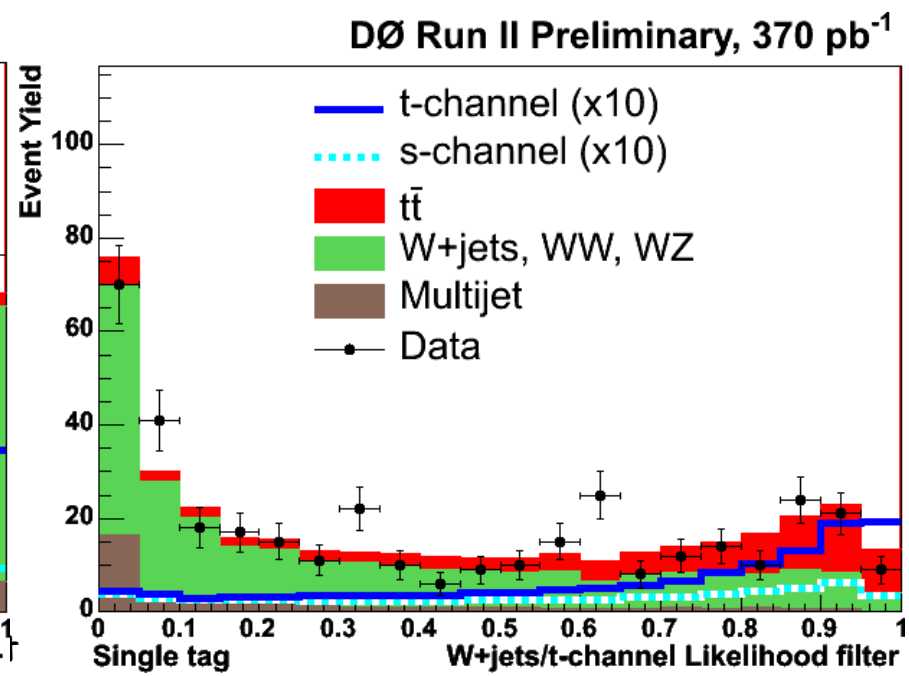
Likelihood Distributions

- Combine probabilities and normalize to calculate likelihood

$$\mathscr{L}(\vec{x}) = \frac{\wp_{\text{signal}}(\vec{x})}{\wp_{\text{signal}}(\vec{x}) + \wp_{\text{background}}(\vec{x})}$$

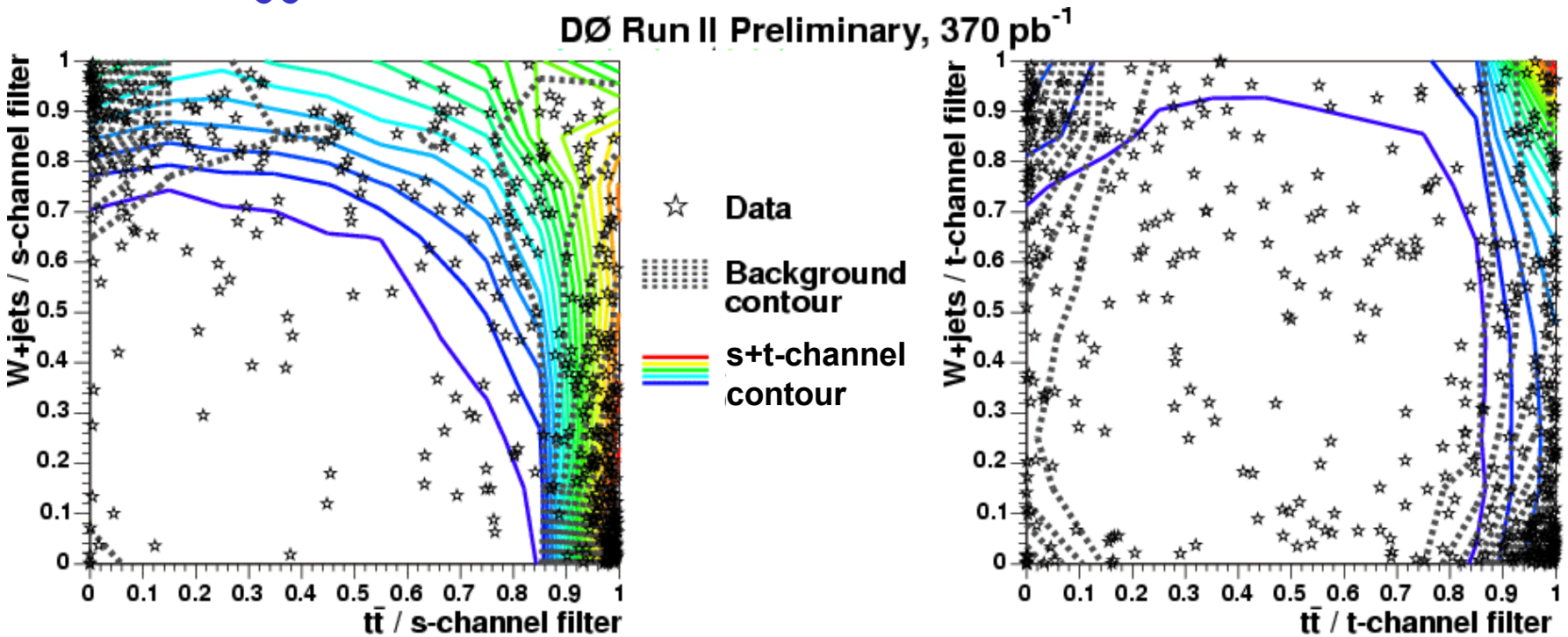
- Combine electron and muon channels…
  - Single tag tt and Wjj discriminants for t-channel





DØ Results

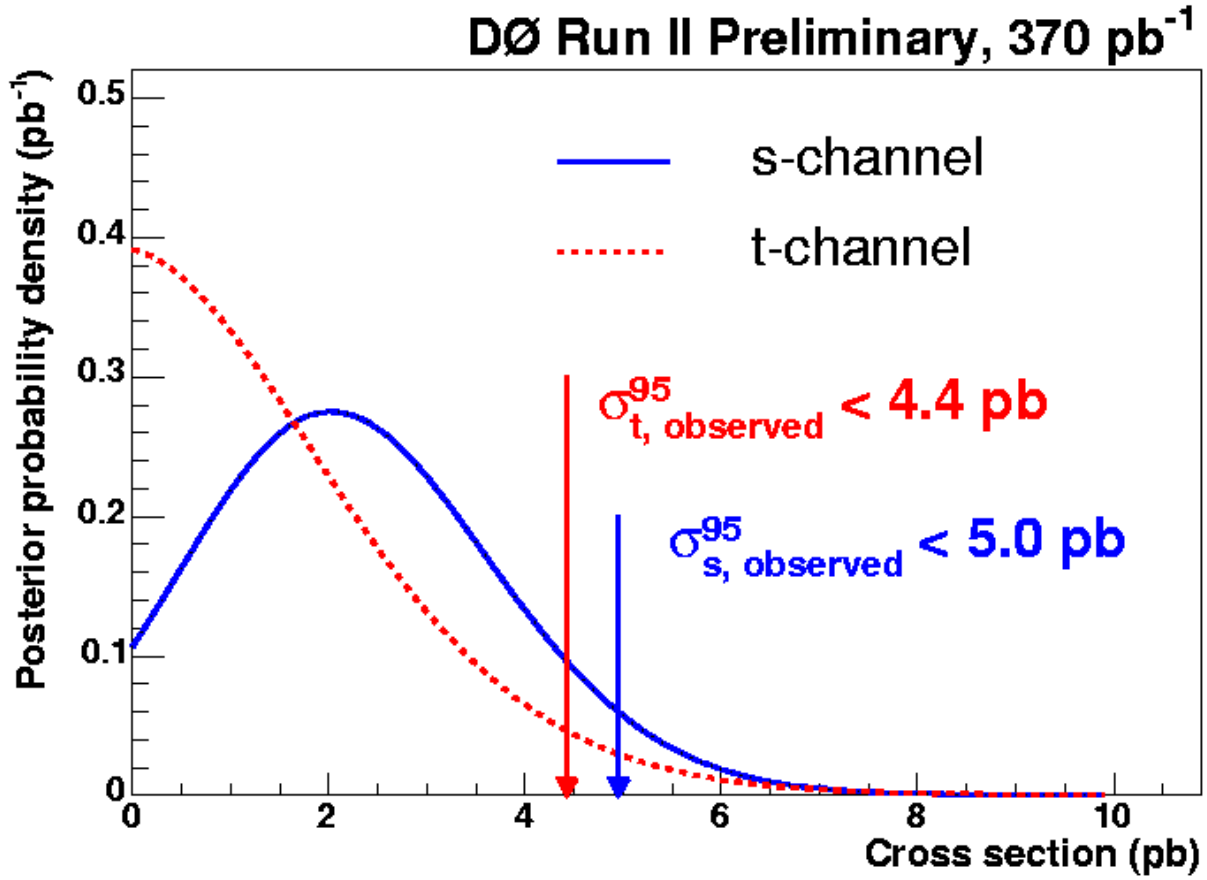
- Need to look at 2D likelihood plot to exclude both Wjj and tt events



- Data completely consistent with zero single top events...although SM expects it contains some

DØ Results

- Use a Bayesian approach to extract limits



Expected limits:

σ_s^{95} < 4.3 pb

σ_t^{95} < 3.3 pb

- Analysis is statistics limited....need more data!

Results Summary

- Summary of all Run II Tevatron searches...

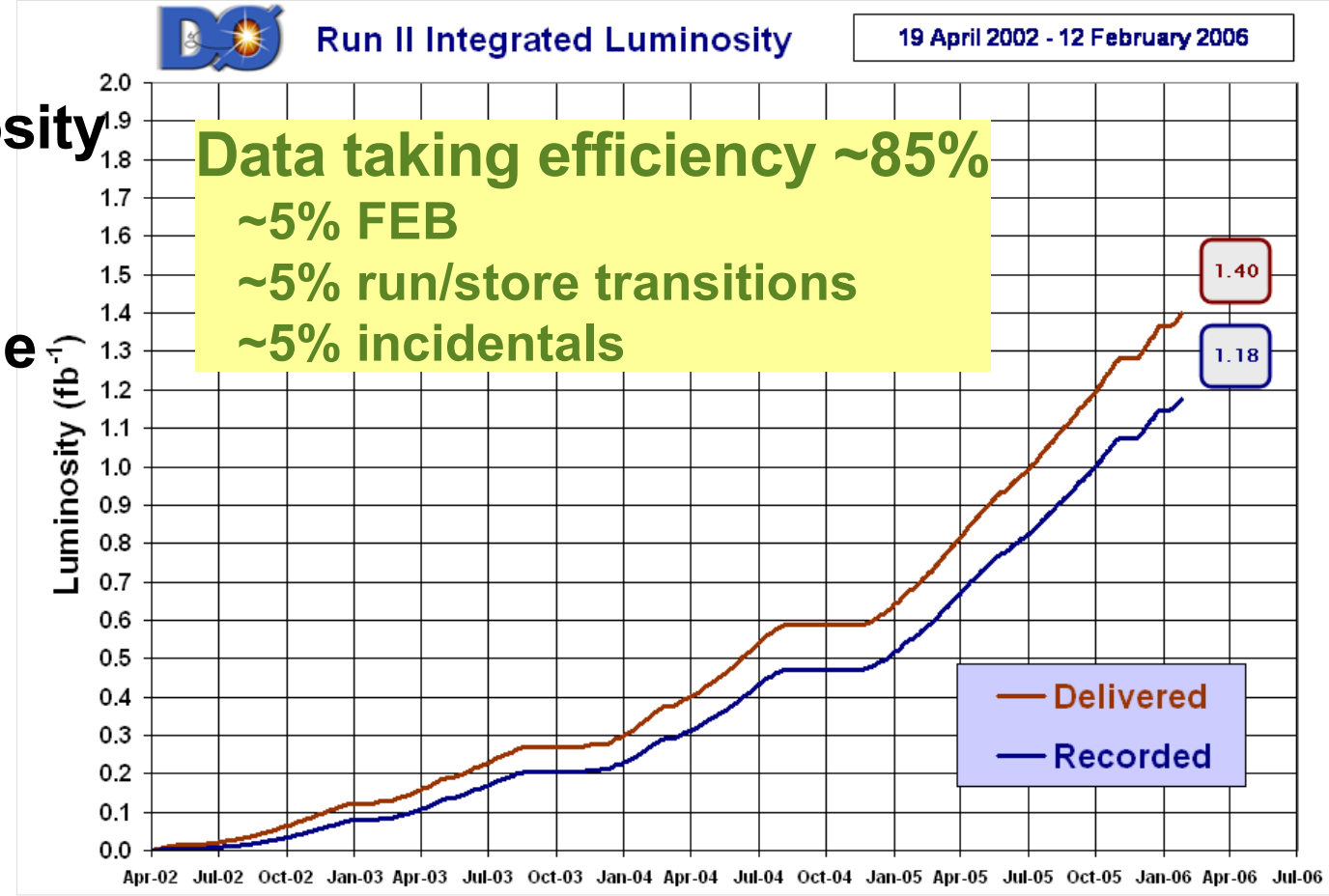
95 % CL Expected/Observed Upper Limits in pb	s-channel, tb	t-channel, tqb	
CDF Run II, 162 pb^{-1}	12.1/13.6	11.2/10.1	PRD 71, 012005
DØ Run II, 230 pb^{-1}			
Cuts	9.8/10.6	12.4/11.3	
DTs & binned likelihood	4.5/8.3	6.4/8.1	PLB 622, 265 (2005); PRD in progress
NNs & binned likelihood	4.5/6.4	5.8/5.0	
DØ Run II, 370 pb^{-1}			
LHs & binned likelihood	**3.3/5.0**	**4.3/4.4**	
NLO theory	$= 0.88$	$= 1.98$	

- New analyses in progress on larger dataset, expect results for summer conferences

The Future

- Significantly larger dataset now available

DØ luminosity only: CDF comparable

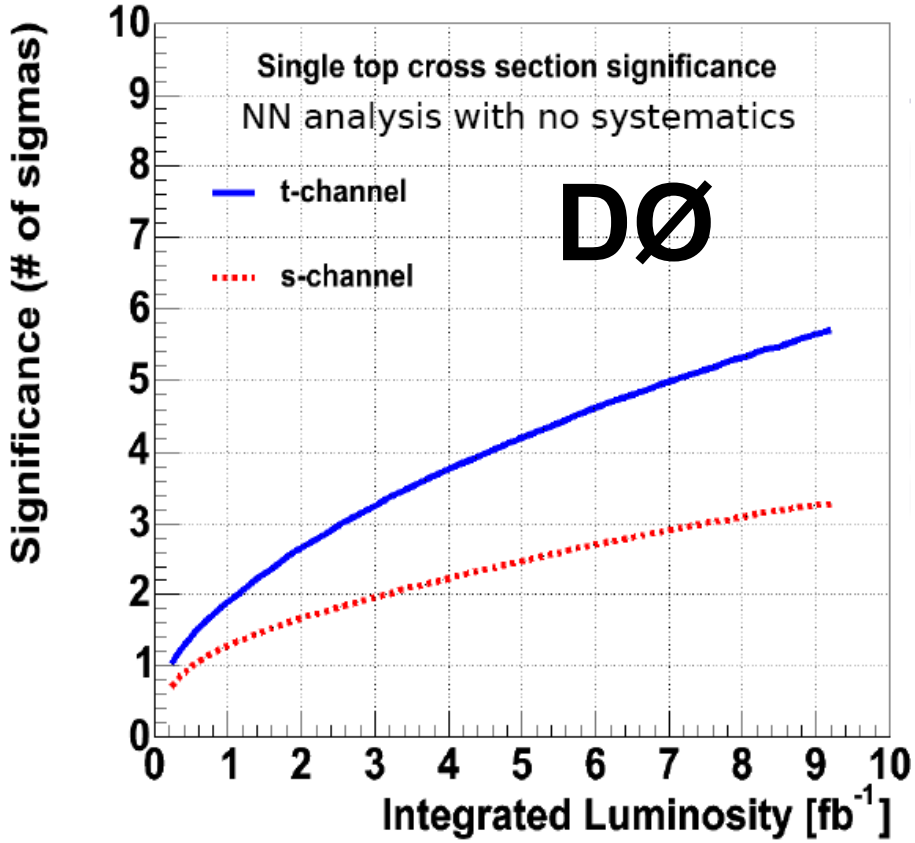


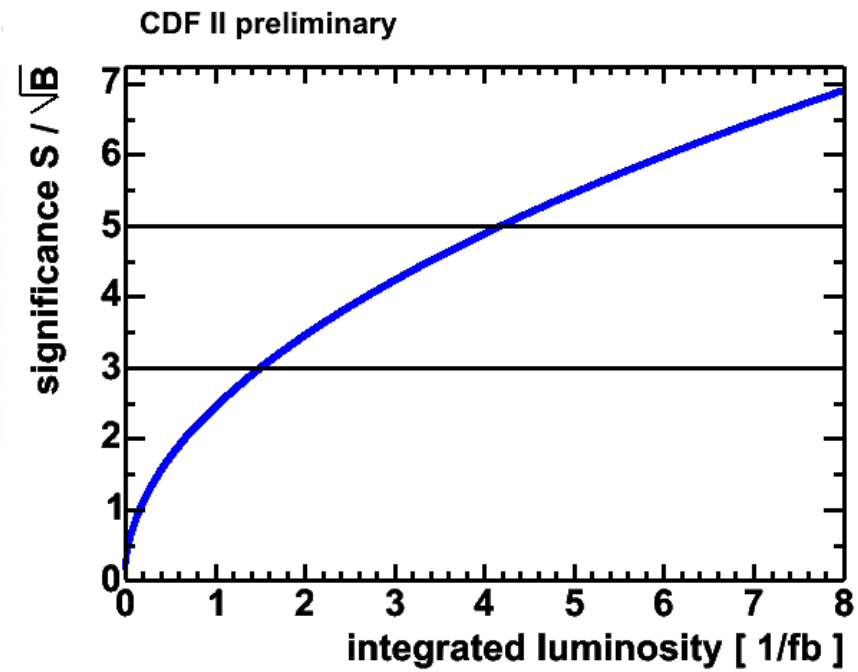
Data taking efficiency ~85%
- ~5% FEB
- ~5% run/store transitions
- ~5% incidentals

- Will this be enough to see single top?

The Future

- New results for this summer! (March for CDF!)

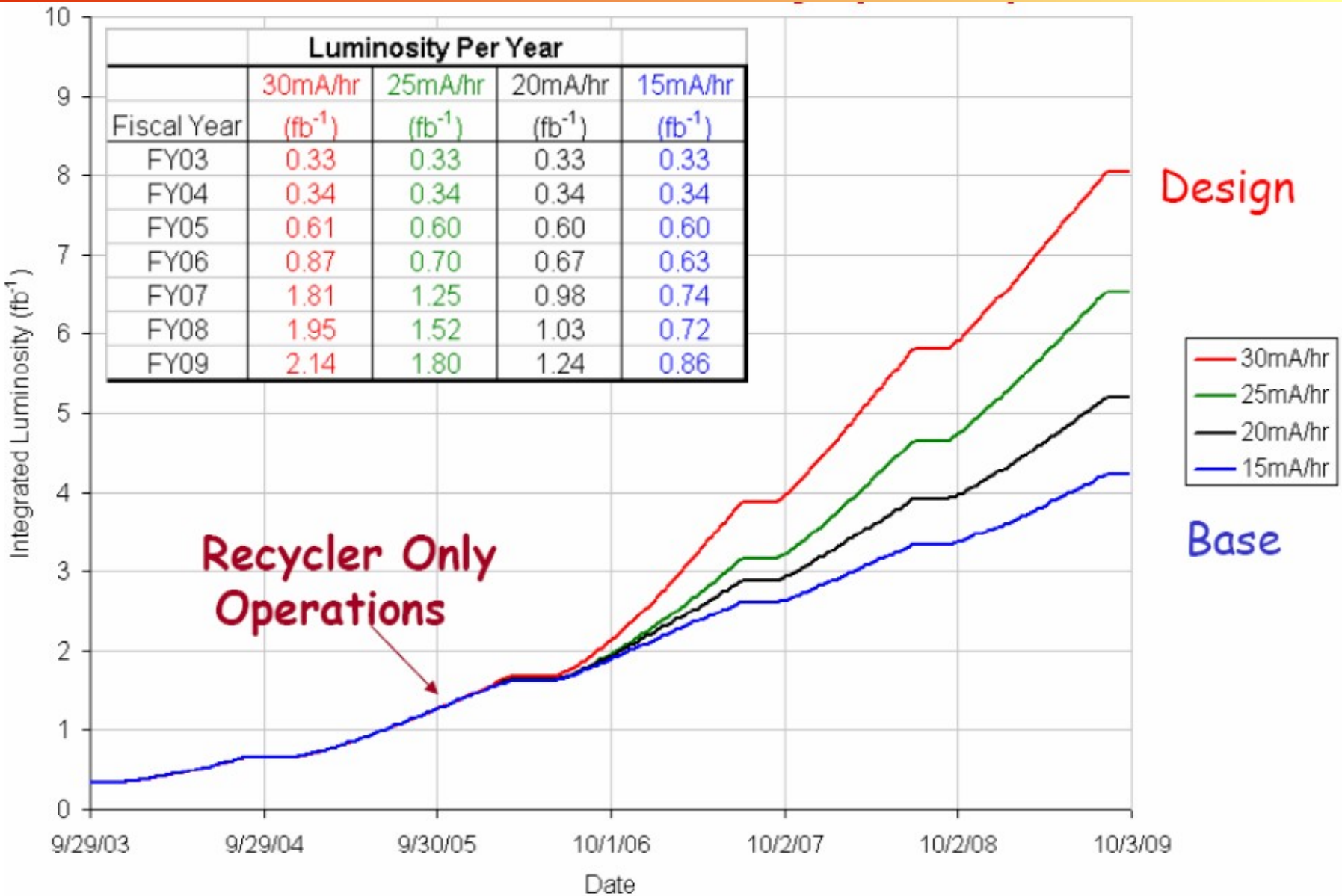




- Improvements to many aspects of the analysis may give better than extrapolated results...

Tevatron Luminosity

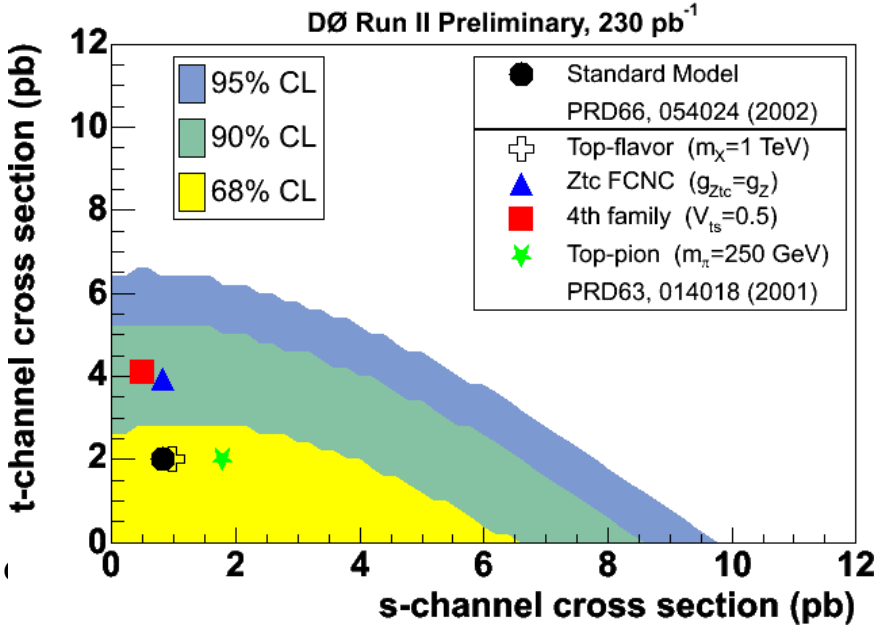
Luminosity Per Year				
Fiscal Year	30mA/hr (fb^{-1})	25mA/hr (fb^{-1})	20mA/hr (fb^{-1})	15mA/hr (fb^{-1})
FY03	0.33	0.33	0.33	0.33
FY04	0.34	0.34	0.34	0.34
FY05	0.61	0.60	0.60	0.60
FY06	0.87	0.70	0.67	0.63
FY07	1.81	1.25	0.98	0.74
FY08	1.95	1.52	1.03	0.72
FY09	2.14	1.80	1.24	0.86



Conclusions

- Limits almost within a factor 2 of the SM cross-section predictions
  - Close to discovery…excitement mounting!
- Limits starting to constrain new physics
- Evidence for single top possible in current dataset …but analysis complex
- Expect to discover single top before LHC turn-on in 2007
  - Watch this space!

Relax SM relation for σ_s and σ_t



DØ Yields

- Signal and background yields for DØ

	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				
$t\bar{t} \to$ lepton + jets	40.4 ± 8.9	20.3 ± 5.4	37.6 ± 8.4	20.6 ± 5.7
$t\bar{t} \to$ 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
Data yield with stat. uncertainties	229 ± 15.1	43 ± 6.6	138 ± 11.7	33 ± 5.7