Single Top @ the Tevatron

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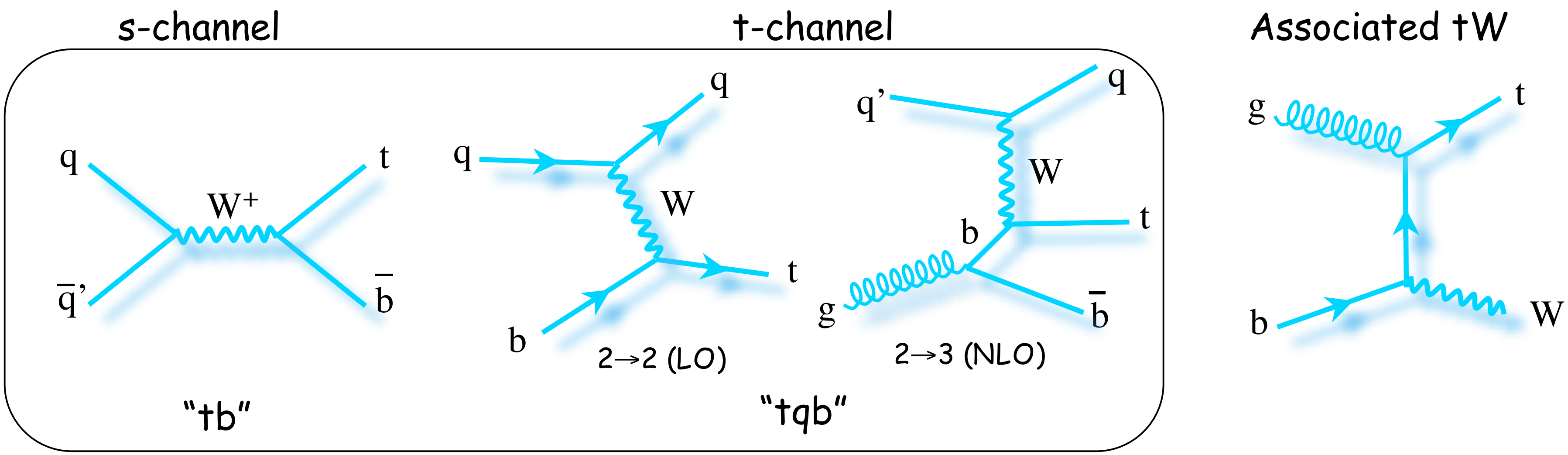
On behalf of the CDF & D0 collaborations

Top Quark Electroweak Production



Single top quark (dominantly) produced @ Tevatron via interactions involving a W boson & b quark

➔ Rate proportional to $|V_{tb}|^2$

		s-channel	t-channel	Associate tW	Combine (s+t)
Tevatron σ_{NLO}		0.88±0.11 pb	1.98±0.25 pb	< 0.1 pb	
LHC σ_{NLO}		10.6±1.1 pb	247±25 pb	$62\ ^{+17}_{-4}$ pb	
Run I 95% CL limits	CDF	< 18 pb	< 13 pb		< 14 pb
	D0	< 17 pb	< 22 pb		

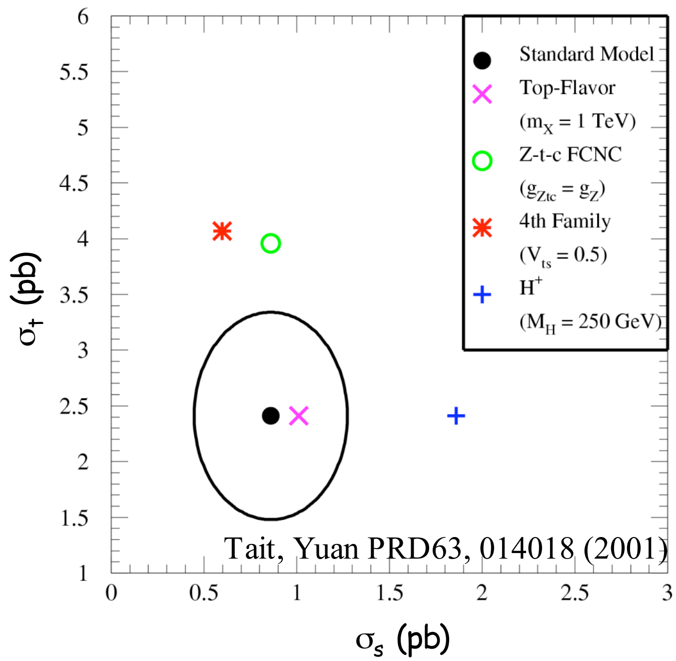
M_{top} =175 GeV/c^2

B. W. Harris et al.: Phys. Rev. D66, 054024 Tait: hep-ph/9909352

Z. Sullivan Phys.Rev.D70:114012 Belyaev, Boos: hep-ph/0003260

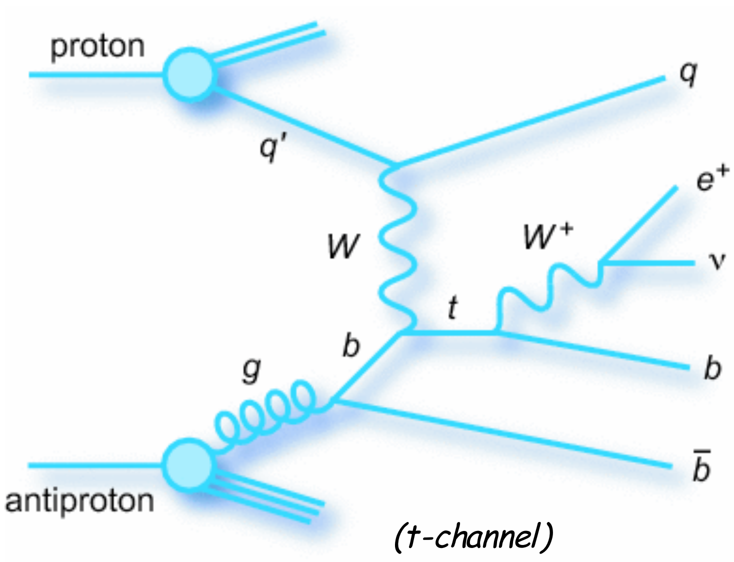
Why Single Top Is So Exciting ?

- Not yet observed… but that's our goal & we are getting close
- Observation of single top allows access to V_{tb} CKM matrix element
- Study top polarisation and V-A structure of EWK top interaction
- Probe b-quark PDF (t-channel)
- Look for physics beyond SM
  - Different sensitivity for s-channel & t-channel
    - 4th generation ($|V_{ub}|^2+|V_{cb}|^2+|V_{tb}|^2+|V_{tx}|^2= 1$)
    - anomalous Wtb couplings
    - FCNC ($t \to Z/\gamma\ c$)
    - new charge gauge boson (W': top flavor)
    - etc …



- Irreducible background to associated Higgs production

Single Top Signature & Backgrounds



If t-channel, extra light quark

High P_T e/μ

High P_T neutrino

High P_T b-quark

b-quark

Signal for s & t channel mostly similar

- Lepton + Missing E_T + Jets
- t-channel extra b tends to be forward
- Similar to top pair production, but with less jets
  - Harder Signal To Find

Backgounds

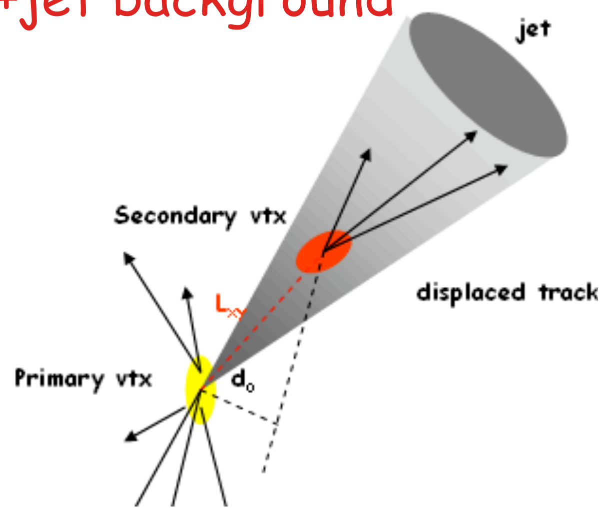
W/Z + jets production
Top pair production
Multijet events (misidentified lepton)
WW, WZ, $Z \rightarrow \tau\tau$

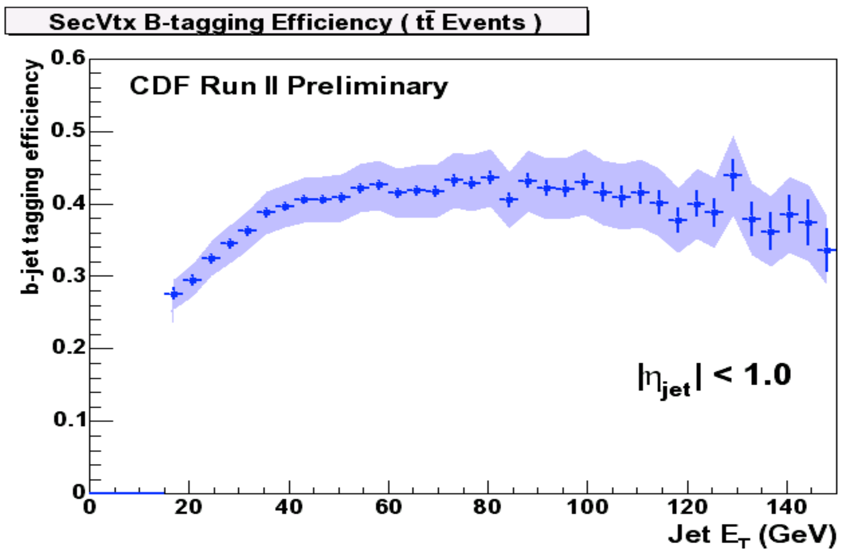
Much worse than pair production because of lower jet multiplicity

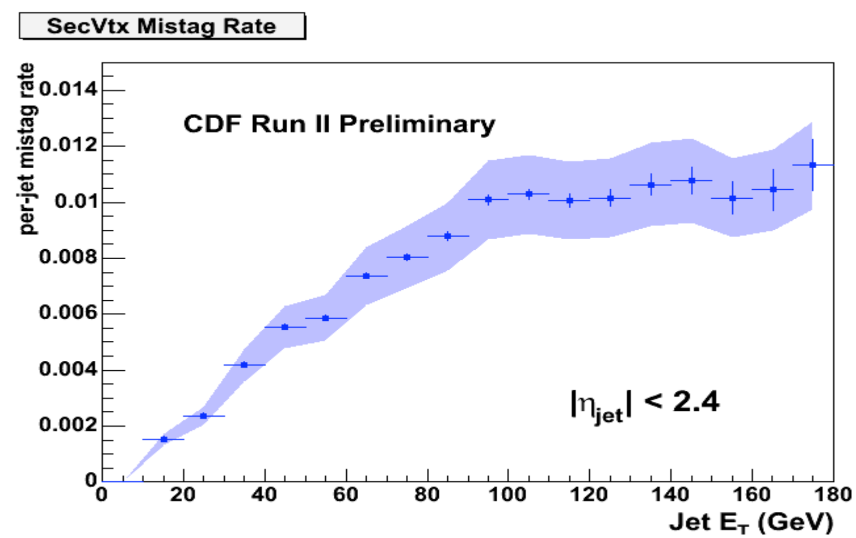
Anything with a lepton + jets + $\not{E}_T$ signature

Tagging b-jets

- Both CDF & D0 use Secondary Vertex b-tagging algorithm to reduce the W+jet background







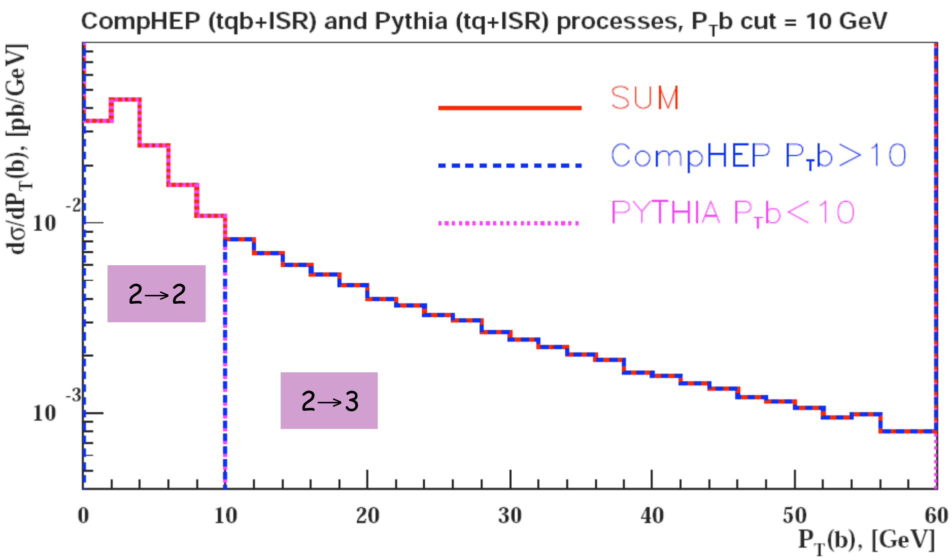
- Efficiency ~40% per b-jet
- Mistag rate (light jets) ~0.5-1%
- Charm tag rate ~25% of b
- CDF has now an improved tagger: 15% better efficiency (not used here)

- D0 tagger performance very similar
  ~40% eff, ~2% mistag rate

Signal Modeling

- Understanding characteristics of the single top signal is crucial for discovery
- For the s-channel MC generator are in very good agreement with NLO calculations. However the t-channel is not well modeled.

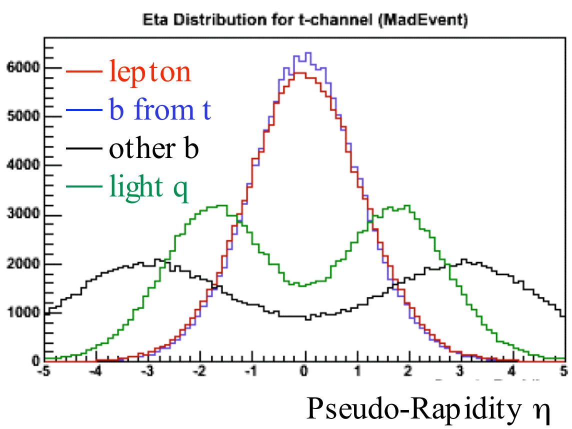
- CDF uses MADEVENT while DØ uses CompHEP
  - Generate 2→2 and 2→3 separately and merge them to reproduce the b P_T spectrum from NLO (ZTOP)

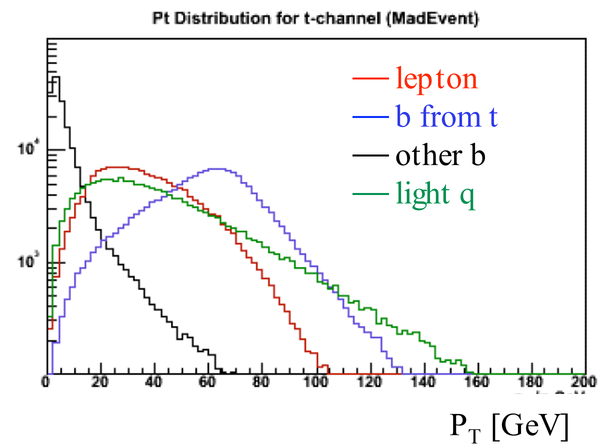


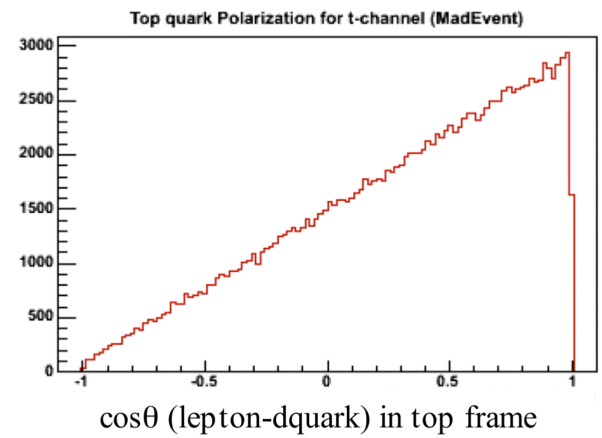
Single Top Kinematics

Pseudo-Rapidity | P_T | Polarisation

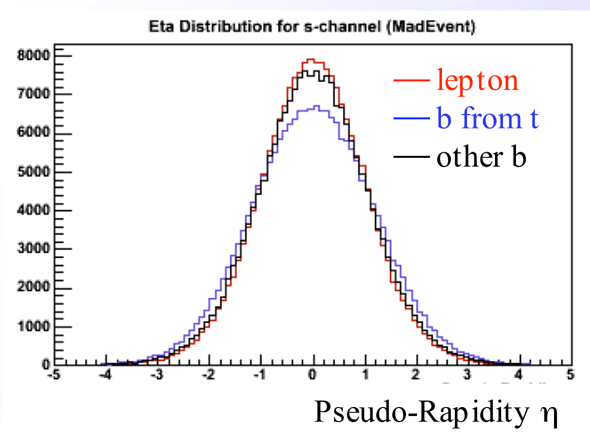
t-channel

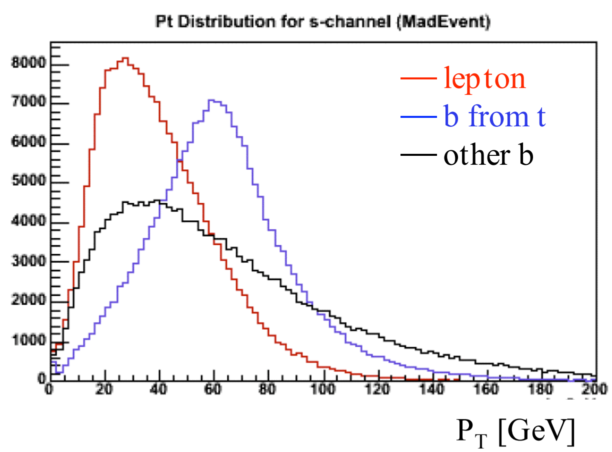


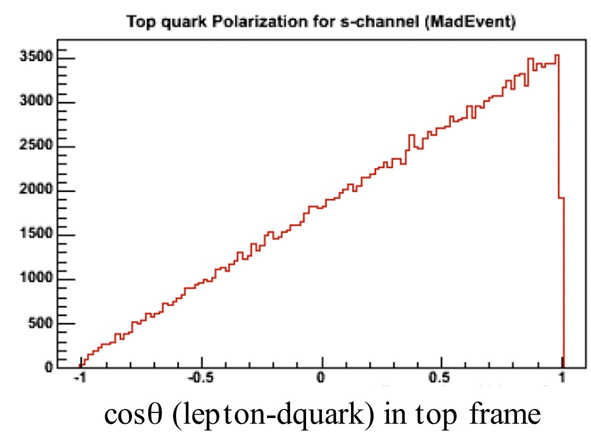




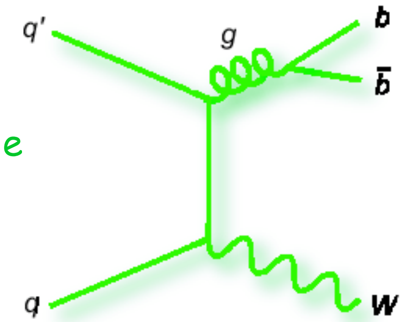
s-channel



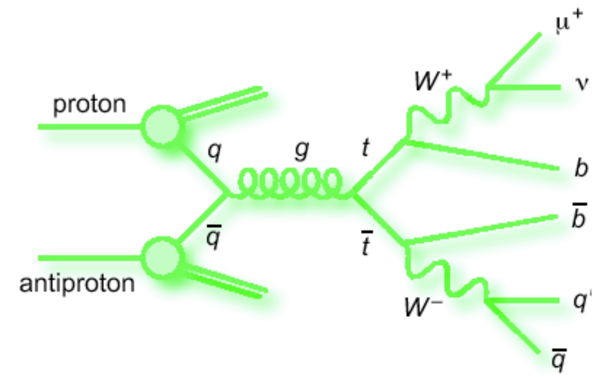




Background Modeling



- W+jets (Wbb, Wcc, Wc…)
    - Challenging background both in term of quantification & shape variable
  - Estimated from data & MC
  - Heavy Flavor fractions (b,c) from ALPGEN
  - Normalization from data before b-tagging

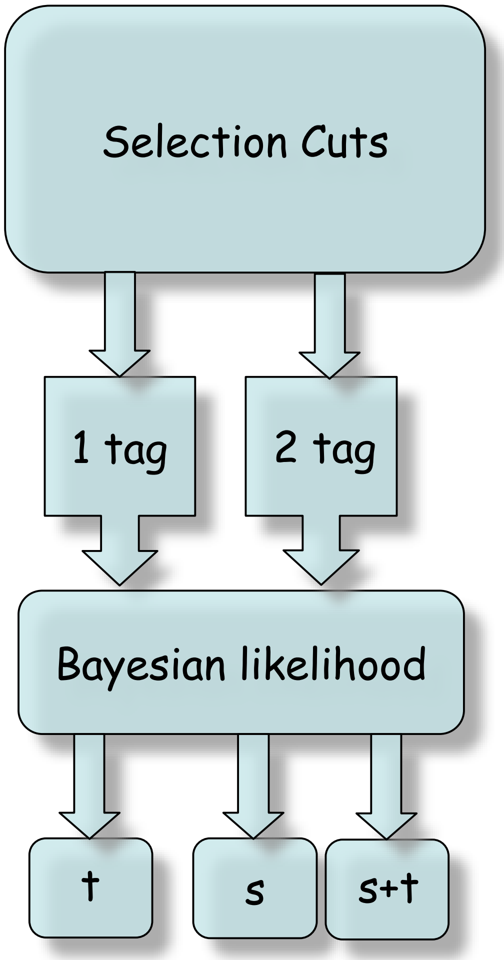


- Top pair production
  - Contribution from lepton+jets
  - Estimated from Pythia (CDF) and Alpgen (D0)

- Multijet events
  - Jet misidentified as lepton & semi-leptonic decay of HF jets (bb)
  - Estimated from data

- WW, WZ, $Z \rightarrow \tau\tau$
  - Estimated from Pythia (CDF) and Alpgen (D0)

CDF Search Strategy



- Lepton (e/μ): P_T>20 GeV, $|\eta|$<1.0
- Jets: Exactly 2, E_T>15 GeV, $|\eta|$<2.8
- Missing E_T: $\not{E}_T$>20 GeV
- Top mass cut: 140<$M_{l\nu b}$<210 GeV/c^2
  - Not applied to s-channel for separate search
- @ least 1-b-tag jet
  - For 1 btag channel, leading jet E_T>30 GeV
- Combine (s+t) use H_T distribution

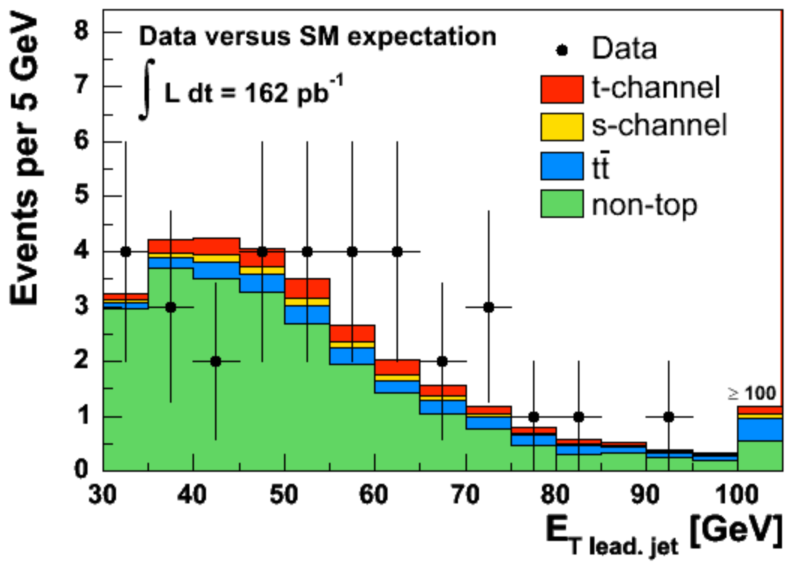
To discover

- Joint likelihood

To see new physics

  - t-channel: use 1 tag $Q_{lepton} \times \eta_{forward\ jet}$ distribution
  - s-channel: counting of 2 tag events

CDF Analysis After Selection



Sample composition

		t-channel	s-channel
Process	Combined	1-tag	2-tag
t-channel	2.8 ± 0.5	2.7 ± 0.4	0.02 ± 0.01
s-channel	1.5 ± 0.2	1.1 ± 0.2	0.32 ± 0.05
$t\bar{t}$	3.8 ± 0.9	3.2 ± 0.7	0.60 ± 0.14
non-top	30.0 ± 5.8	23.3 ± 4.6	2.59 ± 0.71
Total Background	33.8 ± 5.9	26.5 ± 4.7	3.19 ± 0.72
Total Expected	38.1 ± 5.9	30.3 ± 4.7	3.53 ± 0.72
Observed	42	33	6

S/B~10%

Bkg dominated by non-top events (~89%)

Systematic Uncertainties

Fractional change in ε_{evt}

Source	t-channel	s-channel	Combined
JES	$^{+2.4}_{-6.7}$	$^{+0.4}_{-3.1}$	$^{+0.1}_{-4.3}$
ISR	± 1.0	± 0.6	± 1.0
FSR	± 2.2	± 5.3	± 2.6
PDF	± 4.4	± 2.5	± 3.8
Generator	± 5	± 2	± 3
Top quark mass	$^{+0.7}_{-6.9}$	-2.3	-4.4
ϵ_{trig}, ϵ_{ID}, luminosity	± 9.8	± 9.8	± 9.8

Event detection efficiency

s-channel 1.06±0.08 %

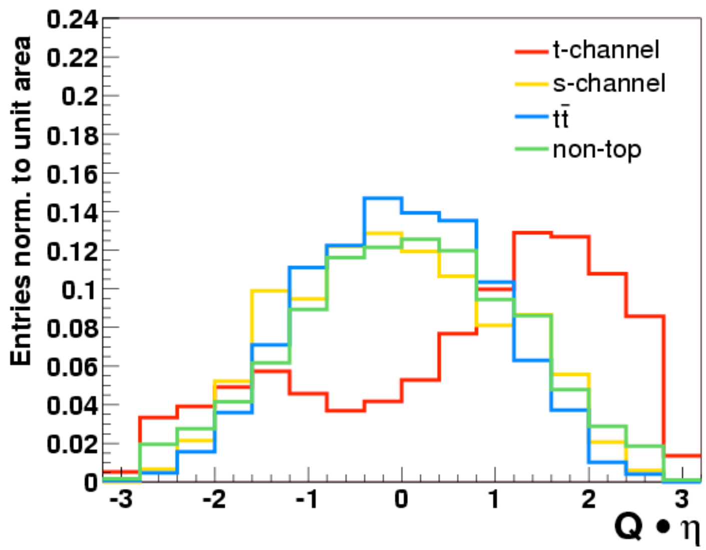
t-channel 0.89±0.07 %

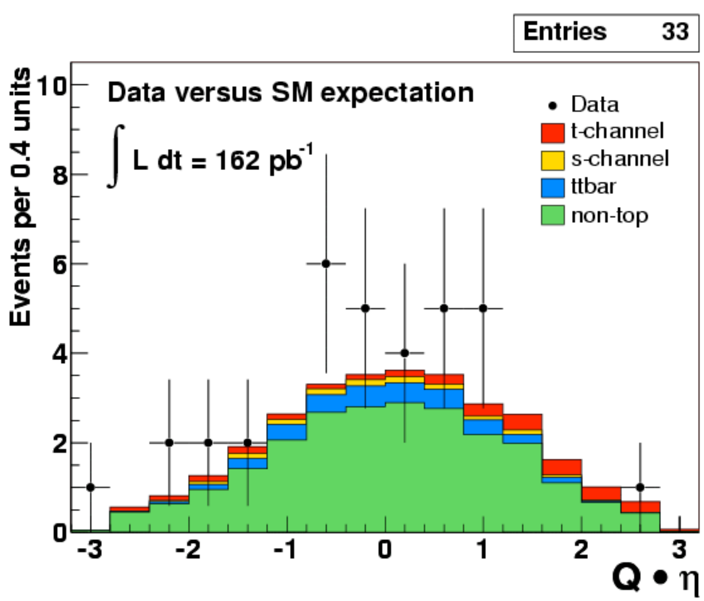
Main systematics

b-tag ε	7%
Luminosity	6%
M_{top}	4%
JES	4%

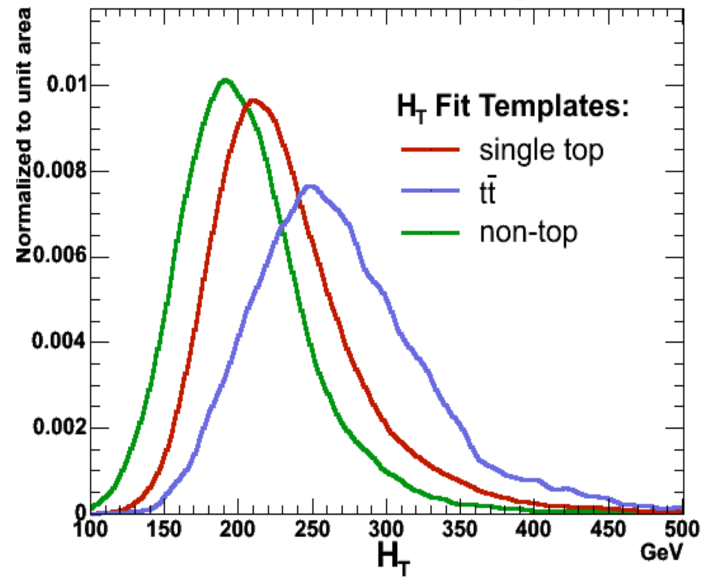
CDF distributions

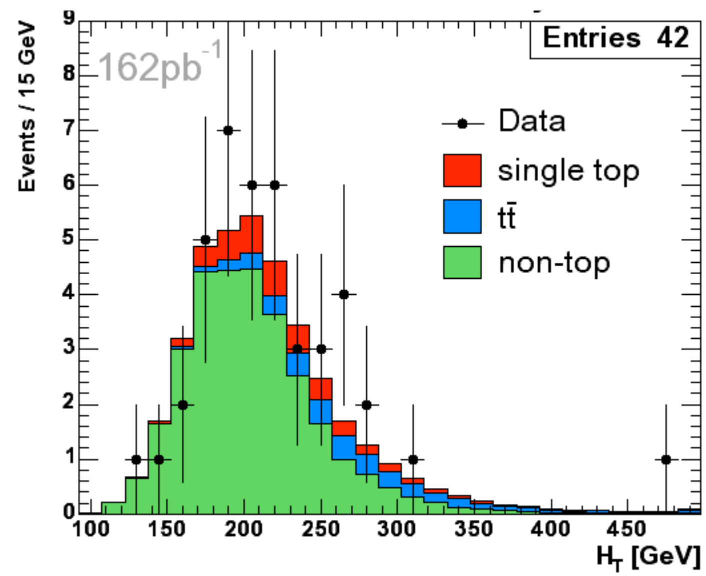
t-channel





Combined search



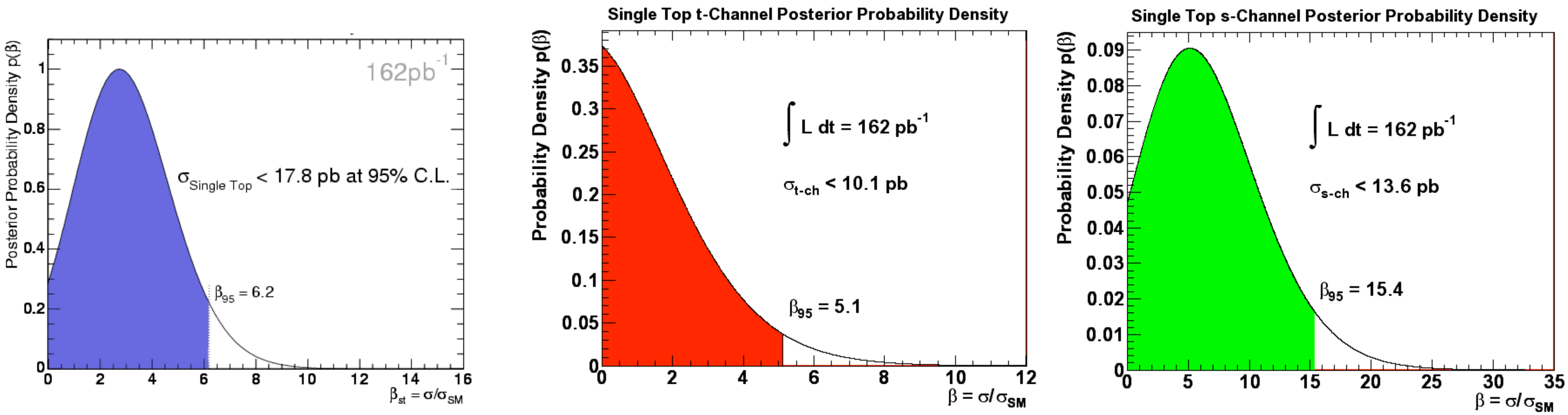


CDF Limits

Phys. Rev. D71,012005

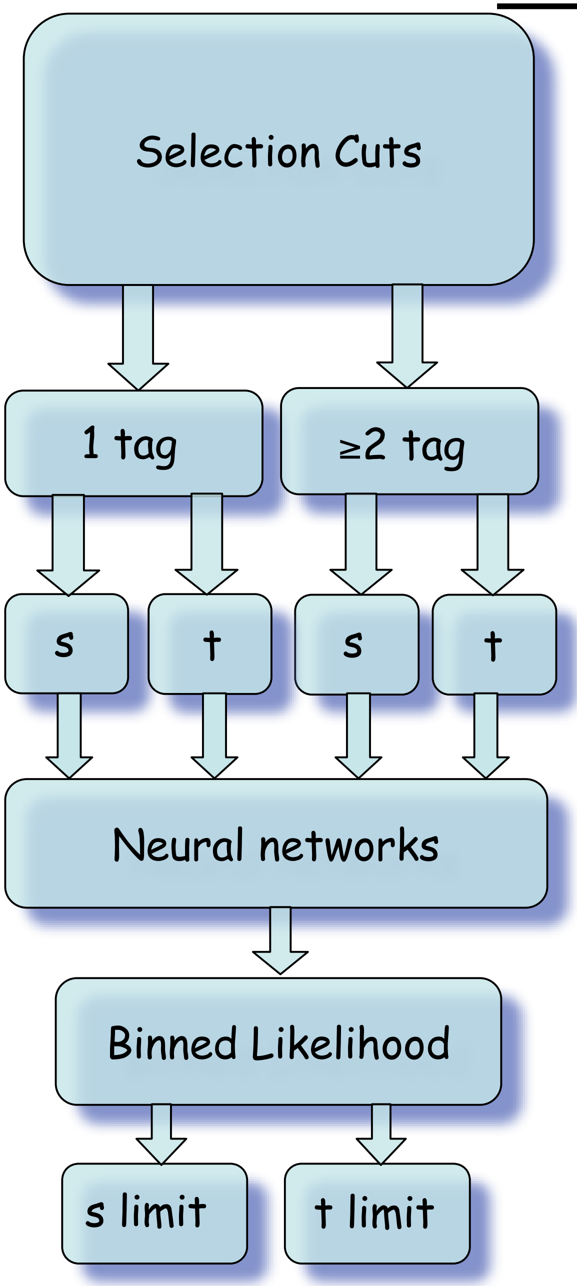
- Maximum likelihood fit to data
  - Background allowed to float but constraint to expectation
  - Shape of systematic uncertainties included in likelihood

Cross section upper limits (pb) @ 95% CL: $\mathcal{L}$=162 pb^{-1}



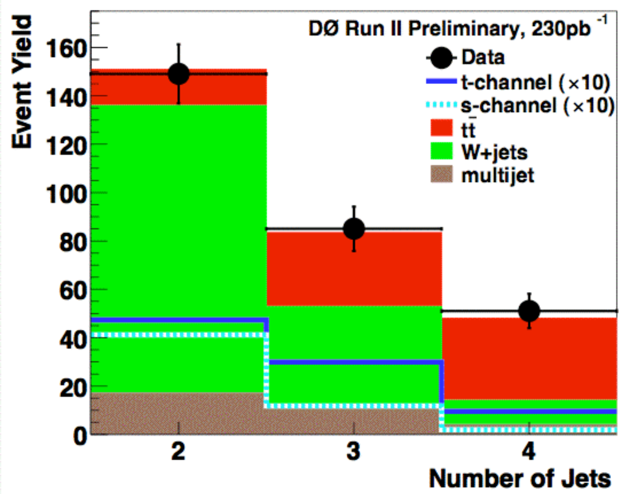
Combined		t-channel		s-channel	
Observed	Expected	Observed	Expected	Observed	Expected
17.8 pb	13.6 pb	10.1 pb	11.2 pb	13.6 pb	12.1 pb

DO Search Strategy



- Lepton (e/μ): P_T>15 GeV, $|\eta_{e(\mu)}|$<1.1 (2.0)
- Jets: $2 \le N_{jets} \le 4$, E_T>15 GeV, $|\eta|$<3.4, E_T^{J1}> 25 GeV
- Missing E_T: $\not{E}_T$>15 GeV
- Require 1 or ≥2 b-tags
- t-channel: @ least 1 non b-tagged jet
- Combined several discriminating kinematic variables in 2 neural networks (Wbb & $t\bar{t} \rightarrow$ l+jets)
- Use 2D output in a likelihood

D0 analysis after selection



Sample composition

Source	s-channel search	t-channel search
tb	5.5 ± 1.2	4.7 ± 1.0
tqb	8.6 ± 1.9	8.5 ± 1.9
W+jets	169.1 ± 19.2	163.9 ± 17.8
$t\bar{t}$	78.3 ± 17.6	75.9 ± 17.0
Multijet	31.4 ± 3.3	31.3 ± 3.2
Total background	287.4 ± 31.4	275.8 ± 31.5
Observed events	283	271

S/B~2-3%

Bkg domninated by non-top events (~70%)

MC Systematic Uncertainties

Components affecting normalization	
$\sigma_{t\bar{t}}$ theory and mass	18 %
$\sigma_{s(t)}$ theory	15 %(16 %)
Jet Fragmentation	6.0 %
ℓ ID	4.1 %
Branching Fraction	2.0 %
Components affecting shape and normalization	
SVT modeling, single (double) tag	10 %(20 %)
Jet Energy Scale	10 %
Trigger Modeling	6 %
Jet ID	5 %
Jet Energy Resolution	4 %

Event detection efficiency

s-channel 2.7±0.2 %

t-channel 1.9±0.2 %

Total systematics

	=1 tag	≥2 tags
Signal acceptance	15%	25%
Background Sum	10%	26%

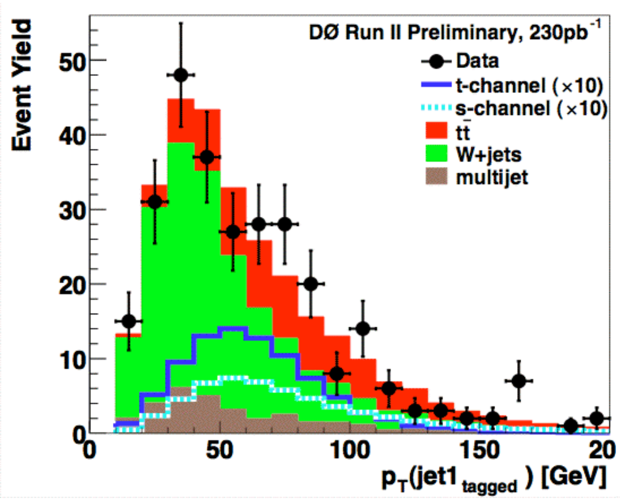
Some will improve with increased luminosity

Result is statistically limited

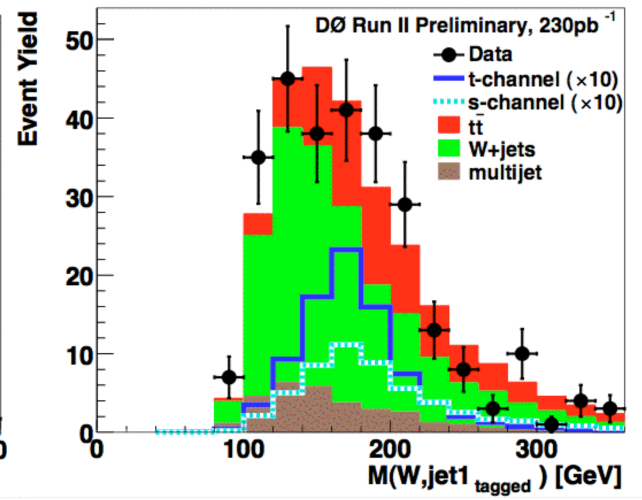
Discriminating variables

3 broad categories; 25 distributions

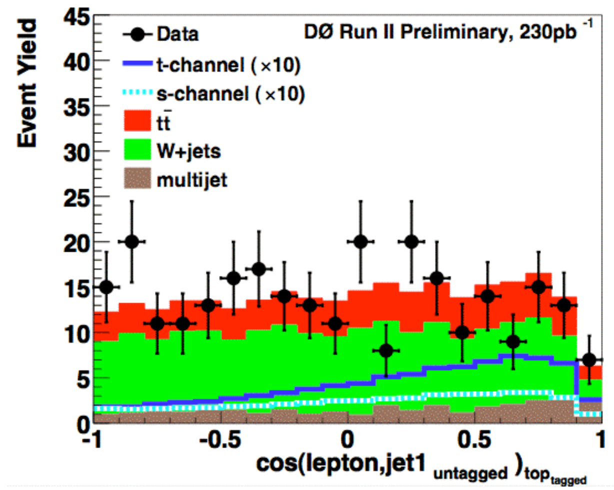
Object kinematics



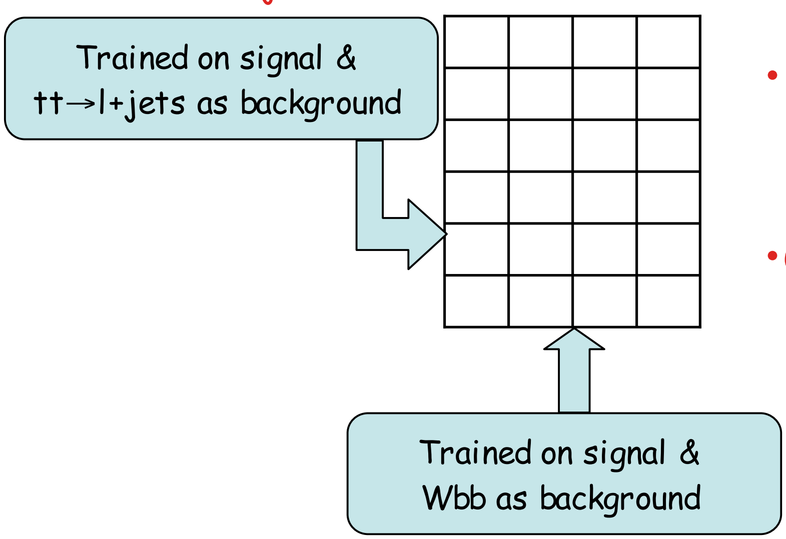
Global event kinematics



Angular correlations



NN tt→l+jets



NN Wbb

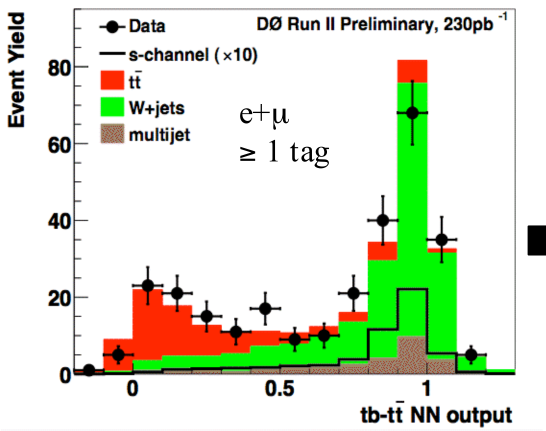
- Focus on dominating backgrounds:
  - Wbb & tt→l+jets
- Optimized separately for s-channel & t-channel
  - Separately for e/μ due to different resolution & η range (same variables)

➔ 8 differents NN

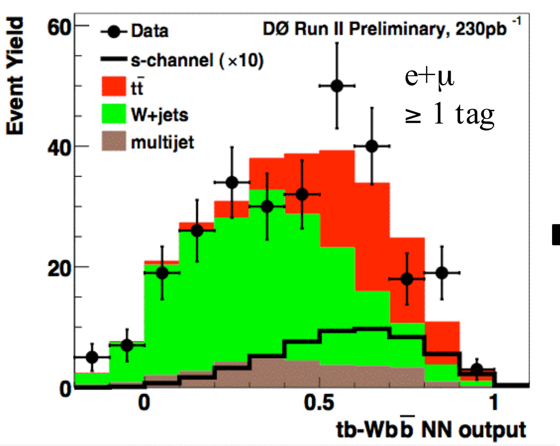
(11 variables each)

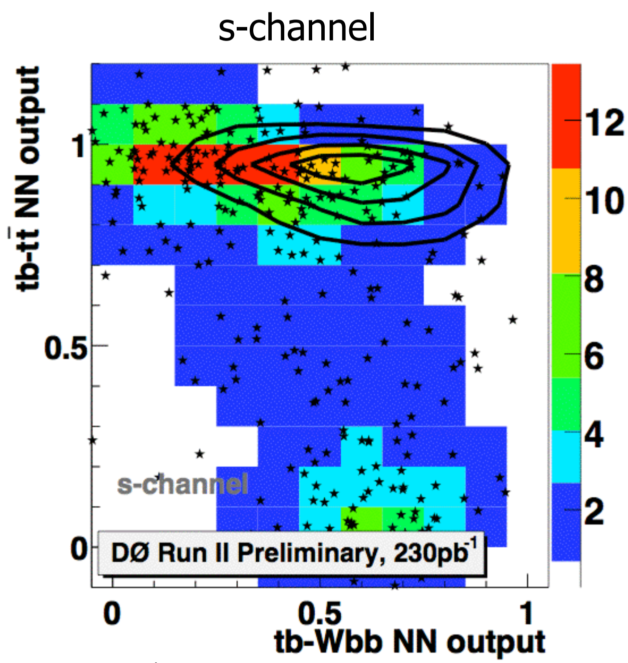
D0 NN output

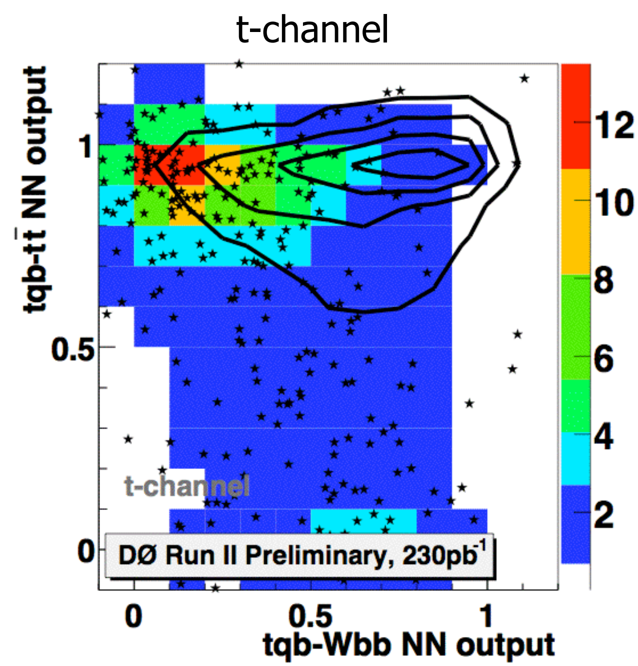
* Data
Sum bkgd
Single top



Good separation for tt
less Wbb







- No evidence for single top signal
- Set 95 % CL upper cross section limit
  - Extract limit from 2D binned likelihood
  - Bayesian approach including bin by bin systematic & correlations

D0 limits

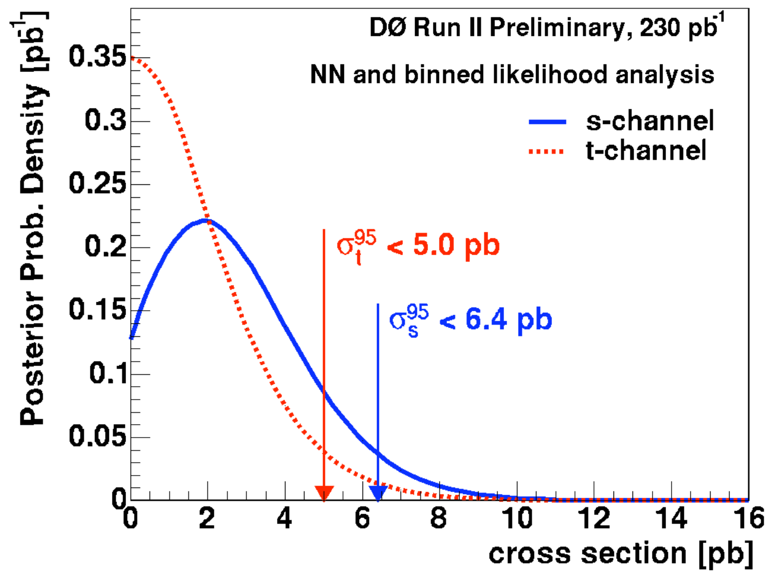
hep-ex 0505031
Submitted to PLB

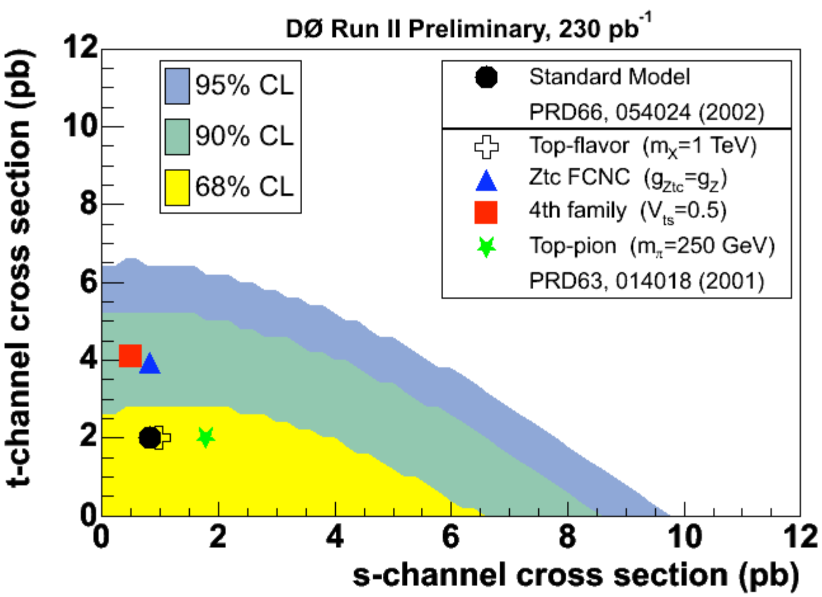
Cross section upper limits (pb) @ 95% CL: $\mathcal{L}$=230 pb^{-1}

Expected/Observed limit

σ_s < 4.5 / 6.4 pb

σ_t < 5.8 / 5.0 pb





μ data only

e data only

Reaching sensitivity to new Physics:
FCNC or 4th quark family

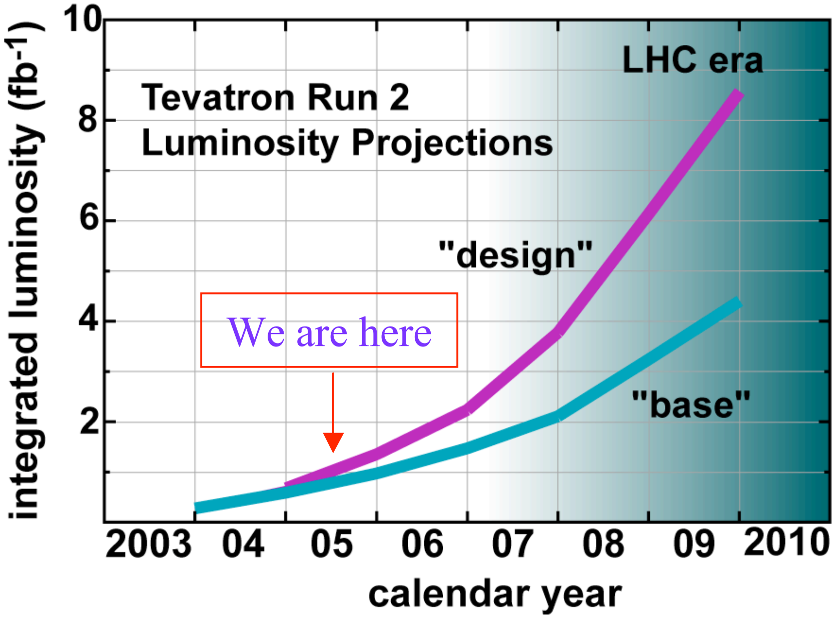
From limits to discovery

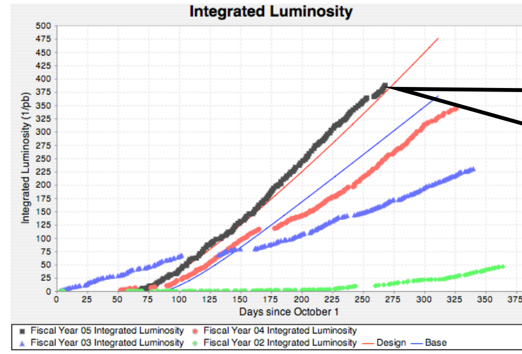
- Advanced analysis technique required to make observation soon !
  (Neural network, Kinematic fitter/Matrix element, optimize likelihood etc…)
  - Identify variables that give good S/B separation
    - Need accurate modeling of signal & backgrounds
- Optimized analysis:
  - Increase acceptance, better lepton ID.
  - Improve b-tagger
    - To reduce W+jets background
    - Increase purity (reduce charm tagging)
      - Combine different b-tagger into NN (secondary vertex, jet Probability, Soft Muon tagging)
- Improve systematic uncertainties
  - JES
  - Accurate models for backgrounds (shape & normalization)
    - Drive HF fraction estimate & understanding of systematic uncertainties

Challenging… (hence fun)
But not impossible

Lots of room for improvement…
Both collaborations taking an aggressive approach

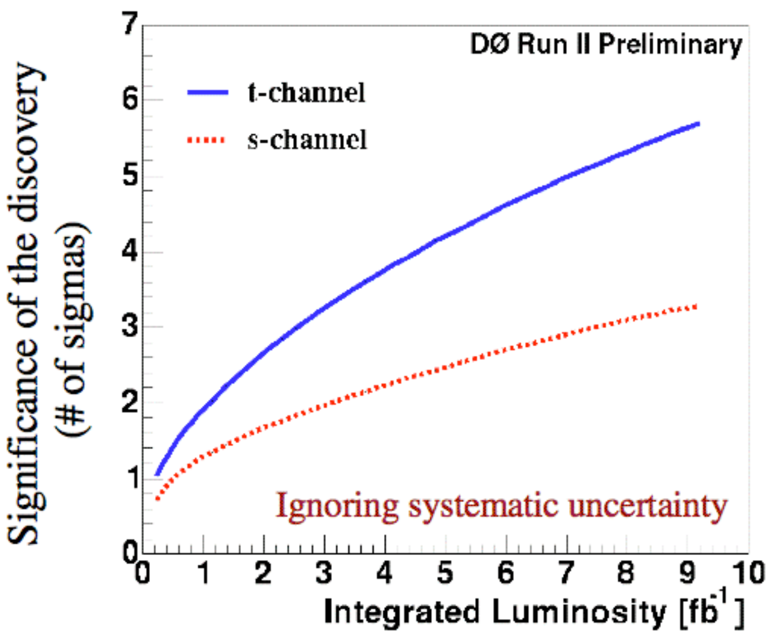
Projections





Tevatron performing on design

- So far, >800 pb-1 to tape for both CDF & D0
- Total Luminosity till 2009: ~8 fb^{-1} (Design)



With current D0 analysis as is:

- 3σ evidence:
  - t-channel ~2.5 fb^{-1}
  - s-channel <8 fb^{-1}
- 5σ discovery: t-channel ~7 fb^{-1}

However, with advance analysis techniques & combining s+t channel could need as little as 1.5† fb^{-1} for 3σ evidence

† Only statistical uncertainty consider

Summary

- Current results set promising single top limits… starting reaching sensitivity to new physics.
  - Phys. Rev D71, 012005
  - Hep-ex 0505031
    - Submitted to PLB

95% C.L. limits Observed (Expected)

Channel	CDF [pb] (162 pb^{-1})	D0 [pb] (230 pb^{-1})
s+t	<17.8 (13.6)	
s	<13.6 (12.1)	<6.4 (4.5)
t	<10.1 (11.2)	<5.0 (5.8)

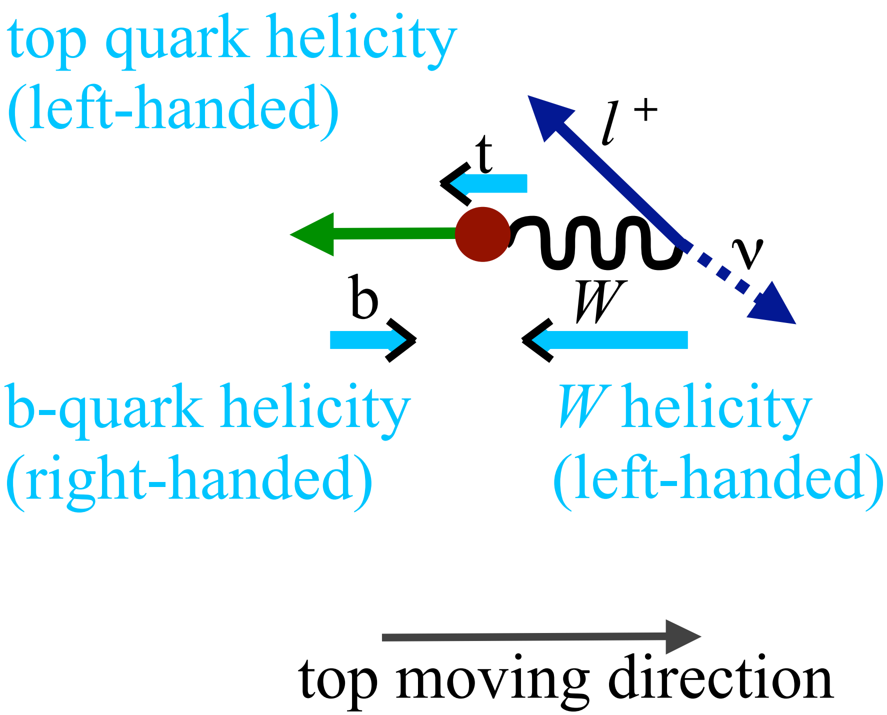
- Challenging analysis
  - Need advance analysis technique to observe single top in the next 1-2 years
  - Plenty of room for improvement

- But, observation of single-top is feasible in Run II

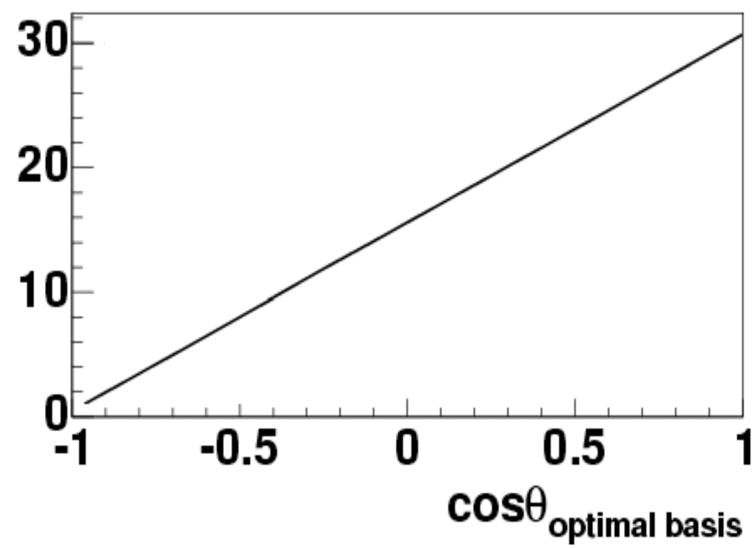

Backup Slides

Polarisation

- Study top quark spin correlations
  - Physics with ~100% polarized top quarks



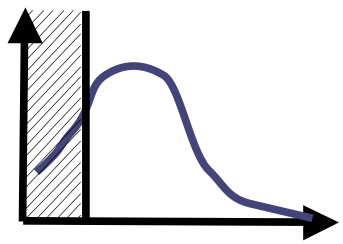
Angle between light quark and lepton



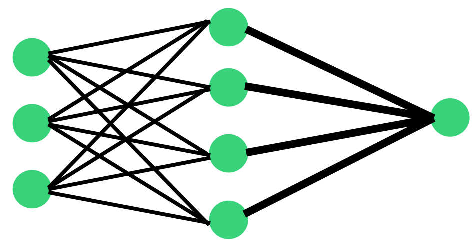
Analysis approches

- Three analysis methods

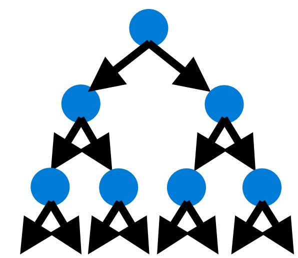
Cut-Based



Neural Networks



Decision Trees



- Each using the same structure:
  - Optimize separately for s-channel and t-channel
    - Optimize separately for electron and muon channel (same variables)
  - Focus on dominant backgrounds: W+jets, tt
    - W+jets – train on tb-Wbb and tqb-Wbb
    - tt – train on tb – tt → / + jets and tqb – tt → / + jets
  - Based on same set of discriminating variables
  - → 8 separate sets of cuts/networks/trees

Cut based analysis

- Cuts on sensitive variables to isolate single top
  - Optimize s-channel and t-channel searches separately
  - Loose cuts on energy-related variables:

$p_T(jet1_{tagged})$
$H(alljets - jet1_{tagged})$
$H(alljets - jet1_{best})$
$H_T(alljets)$
$M(top_{tagged})$
$M(alljets)$
$M(alljets - jet1_{tagged})$
$\sqrt{\hat{s}}$

Expected/Observed limit:

$\sigma_s <$ 9.8 / 10.6 pb

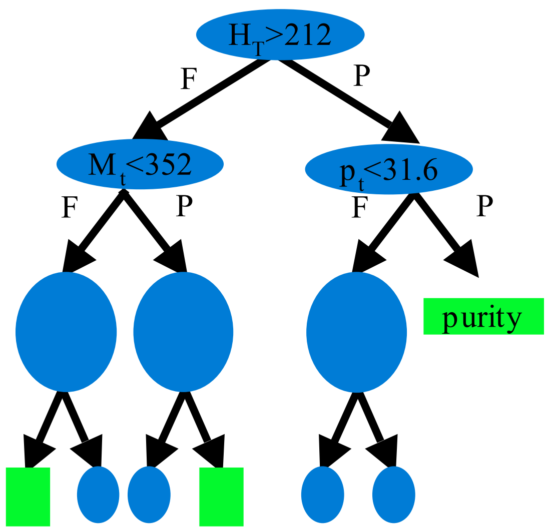
$\sigma_t <$ 12.4 / 11.3 pb

Event Yields

	s-channel search	t-channel search
s-channel signal	$\boxed{4.5}$	3.2
t-channel signal	5.5	$\boxed{7}$
W + jets	103	73
top pairs	28	56
multijet	17	17
Background sum	153±25	149±25
Observed	152	148
Signal/Bkgnd	1:34	1:21

Decision Tree analysis

- For each event, gives probability for an event to be signal
- Widely used in social sciences, recently also in HEP
  - GLAST, Miniboone object ID (see Byron Roe W&C)

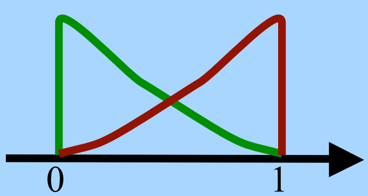


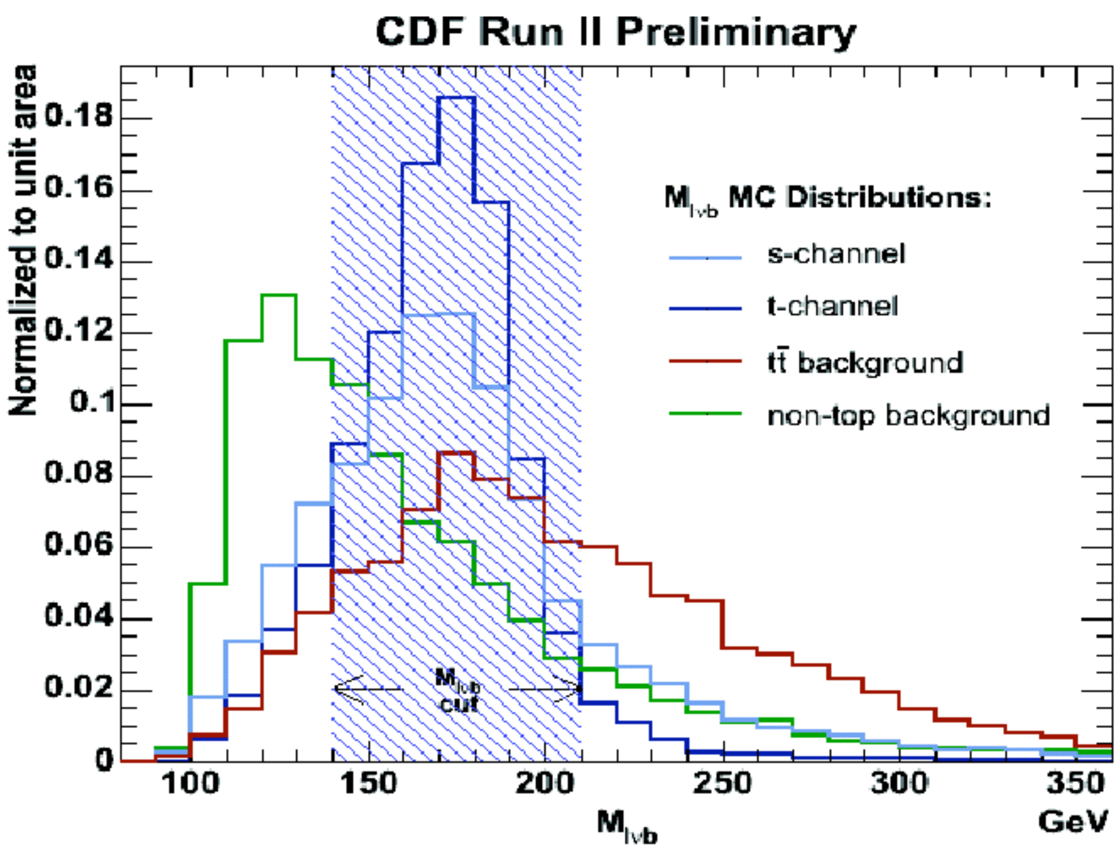
Expected/Observed limit:

σ_s < 4.5 / 8.3 pb

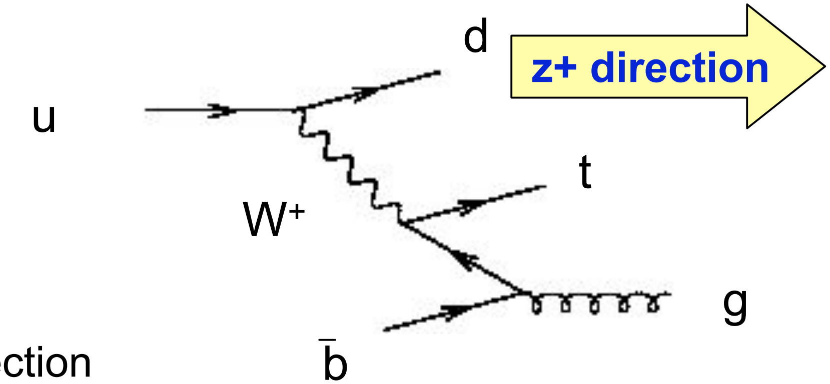
σ_t < 6.4 / 8.1 pb

- Send each event down the tree
- Each node corresponds to a cut
  - Pass cut (P): right
  - Fail cut (F): left
- A leaf corresponds to a node without branches
  - Defines purity = $N_S/(N_S+N_B)$
- Training: optimize Gini improvement
  - Gini = $2\, N_S N_B /(N_S + N_B)$
- Output: purity for each event




CDF Run II Preliminary
Normalized to unit area
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
100
150
200
250
300
350
$M_{l\nu b}$
GeV
$M_{l\nu b}$ MC Distributions:
s-channel
t-channel
$t\bar{t}$ background
non-top background
$M_{l\nu b}$
cut

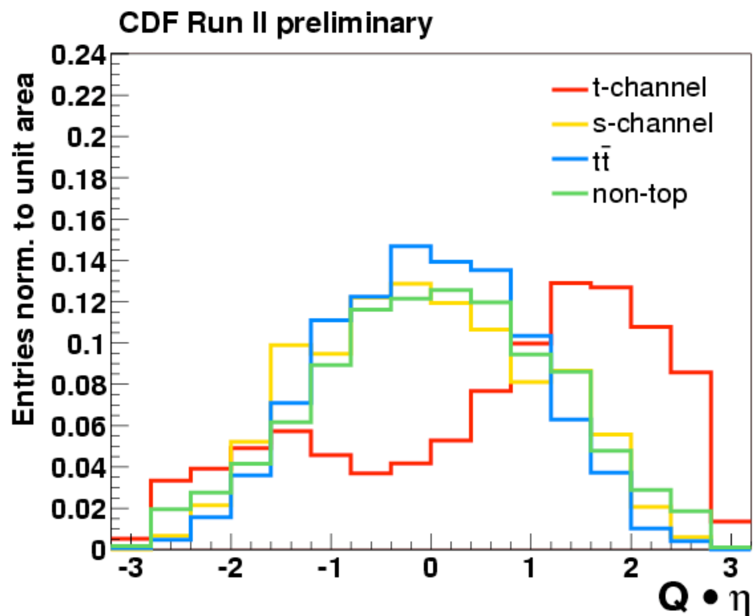
$Q_{lepton} \cdot \eta_{untagged\ jet}$



For t-channel use kinematical boost

- **In proton-antiproton collisions:**
  - top production: light quark jet goes in *p* direction
  - anti-top: light quark jet goes in *p-bar* direction
- **Correlation between**
  - pseudorapidity of untagged jet η
  - lepton charge Q

⇒ **Q. η distribution asymmetric for t-channel**



Likelihood Function

Joint likelihood function for Q.η distribution in the 1-tag sample and number of events in 2-tag samples:

$$\mathcal{L}_{\text{sig}}(\sigma_1, \ldots, \sigma_4; \delta_1, \ldots, \delta_7) = \underbrace{\frac{e^{-\mu_d} \cdot \mu_d^{n_d}}{n_d!} \cdot \prod_{k=1}^{N_{\text{bin}}} \frac{e^{-\mu_k} \cdot \mu_k^{n_k}}{n_k!}}_{\text{Poisson}}$$

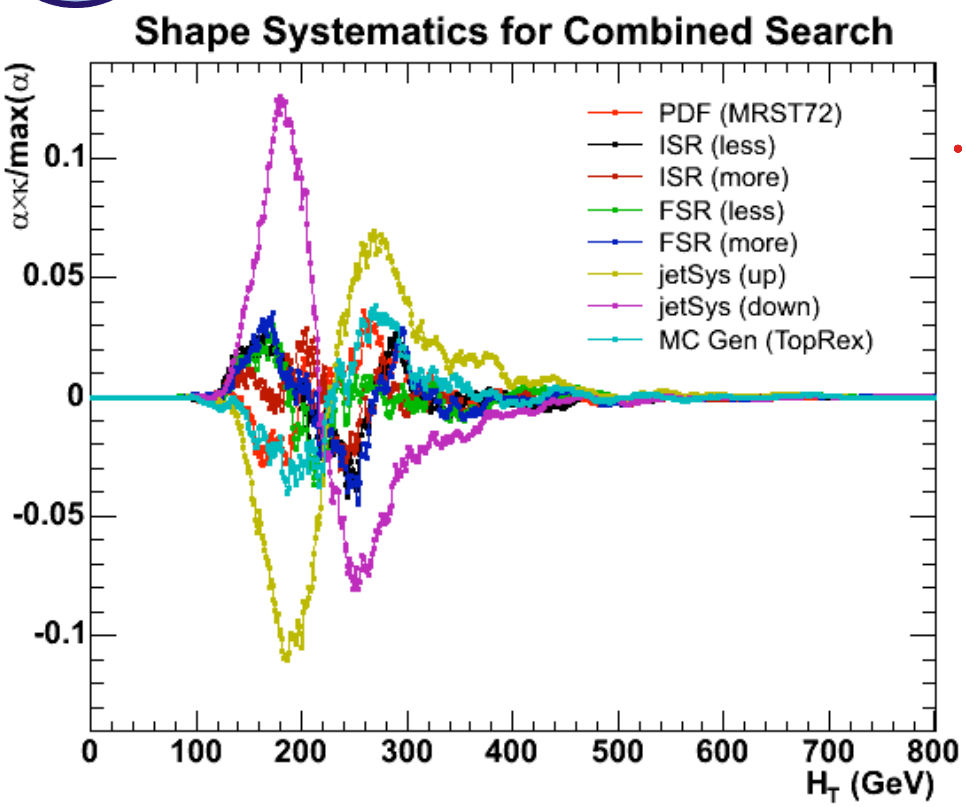
t or s-channel

k: bin index
j: process index

$$\cdot \underbrace{\prod_{\substack{j=1 \\ j \neq sig}}^{4} G(\sigma_j; \sigma_{\text{SM,j}}, \Delta_j)}_{\text{bg gauss. constraints}} \cdot \underbrace{\prod_{i=1}^{7} G(\delta_i; 0, 1)}_{\text{Syst. Uncert.}}$$

- **4 processes**: t-channel (j=1), s-channel (j=2), ttpair and non top (j=3, 4)
- μ_k: mean number of events in bin k of Q.η distribution
- μ_d: mean number of events in the 2-tags sample
- n_k, n_d: observed number in data
- the background is allowed to float but is **constrained to SM predictions**
- 7 sources of **systematic uncertainties**

Shape Uncertainties κ's



- For a given systematic effect *m*, κ_{jmk}'s are obtained from the difference between the shifted H_T template and the default H_T template, divided by the default bin contents α_{jk}

Expected mean in bin k:

$$\mu_k = \sum_{j=1}^{3} \sigma_j \cdot \left\{ \prod_{i=1}^{7} \left[1 + |\delta_i| \cdot \left(\varepsilon_{ji+} H(\delta_i) + \varepsilon_{ji-} H(-\delta_i) \right) \right] \right\}$$

$$\cdot \alpha_{jk} \cdot \left\{ \prod_{m=1}^{7} \left[1 + |\delta_m| \cdot \left(\kappa_{jmk+} H(\delta_m) + \kappa_{jmk-} H(-\delta_m) \right) \right] \right\}$$

k = bin index

j = process index

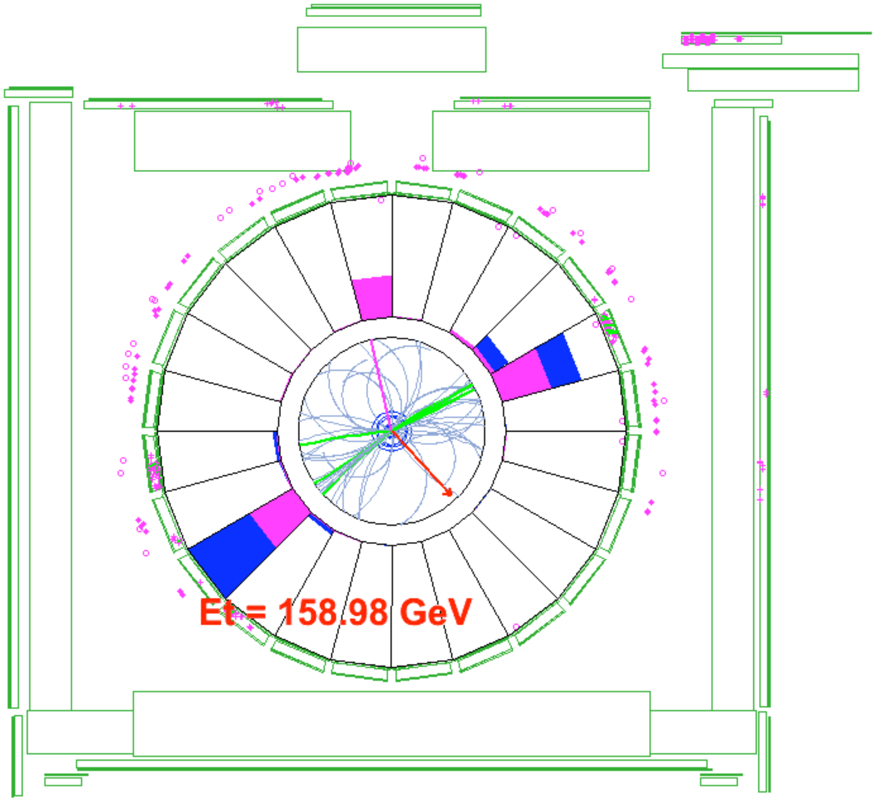
i,m = syst. effect index

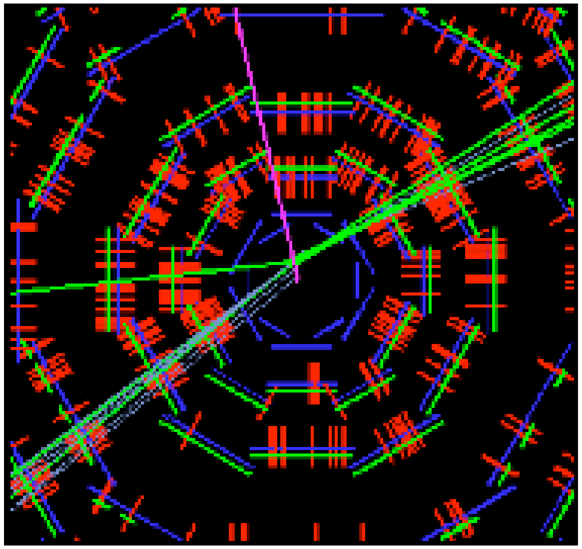
$\varepsilon_{ji+/-}$ = acc. shifts

$\kappa_{jmk+/-}$ = shift, bin k

Event Display

The least "non-top-like" event (H_T = 475 GeV, $M_{l\nu b}$=173 GeV/c^2):





Svx L1,L2/L3 L00

Run: 153389 · Event: 361345

- CEM Electron E_T=50.9 GeV, η =0.24
- MET=25.7 GeV, Phi=5.6
- Jet1 E_T=173.8 GeV, η =0.45
- Jet2 E_T=149.8 GeV, η =-0.13