Search for Single Top Quark Production at DØ in Run II

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Outline

- Introduction
- The Top Quark
- Top Quark Electroweak Interactions
- Single Top Production and Decay at NLO in QCD
- The DØ Experiment at the Tevatron
- Search for Single Top at DØ
- Questions
- Conclusions/Outlook

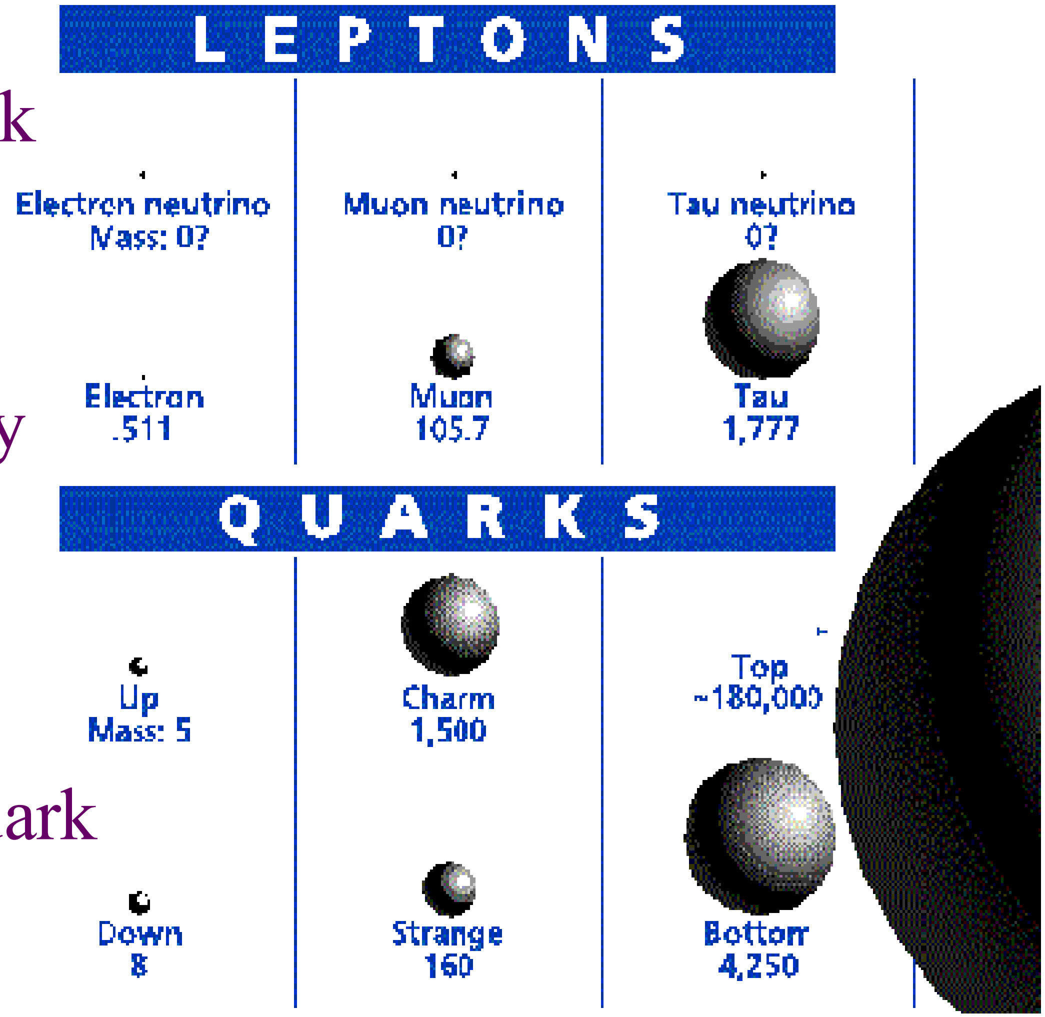
Introduction

- The top quark presents a unique laboratory to study Physics at the edge of the Standard Model
  - Origin of mass: top quark Yukawa coupling ~1
- Run II at the Tevatron is well on its way
  - Physics at the energy frontier
  - Analyzed data samples exceed Run I luminosity
- We are exploring uncharted territory
  - Top Physics as precision measurements
    - Top mass measurements have large impact on Higgs expectation
  - Look for new Physics beyond the Standard Model
    - And within the Standard Model
      - Higgs Boson
      - Single Top Production

The Top Quark

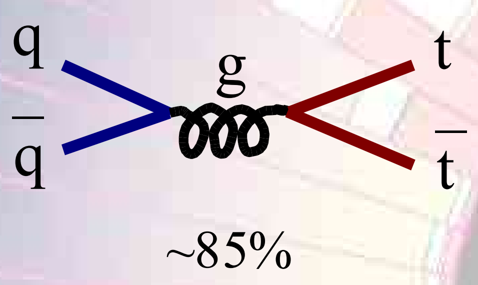
KING OF FERMIONS

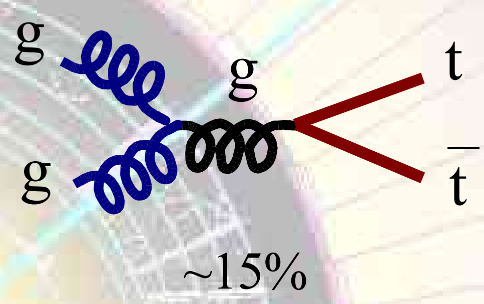
- Discovered in 1995 by CDF and DØ at the Tevatron
- Heaviest of all fermions
  - 40 times heavier than b quark
- Couples strongly to Higgs boson
  - Study electroweak symmetry breaking
- Only quark that decays before it hadronized
  - Clean laboratory to study quark properties



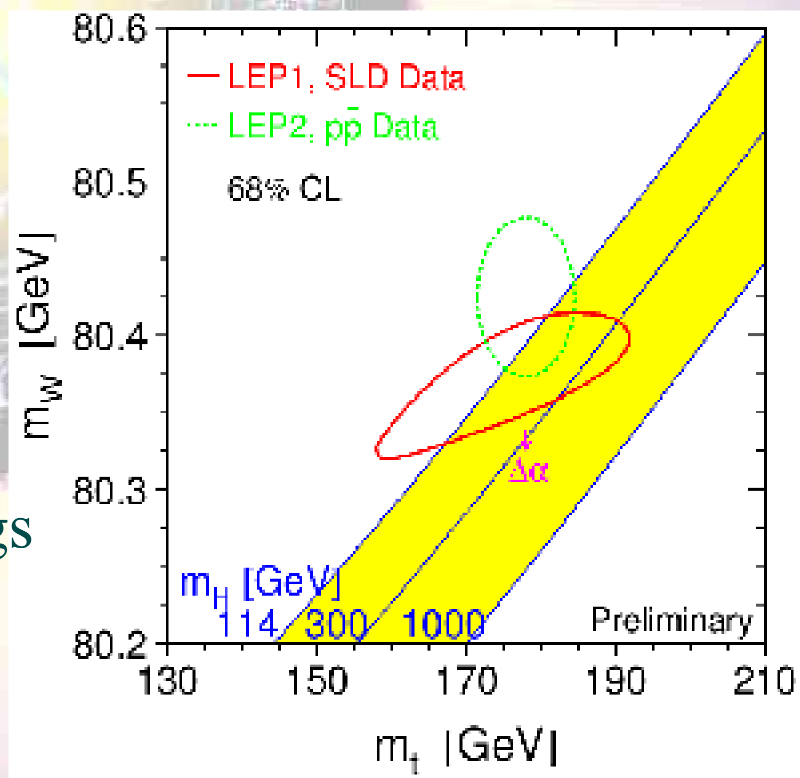
Standard Tevatron Top Physics

- Top Pair Production at a Proton-Antiproton collider

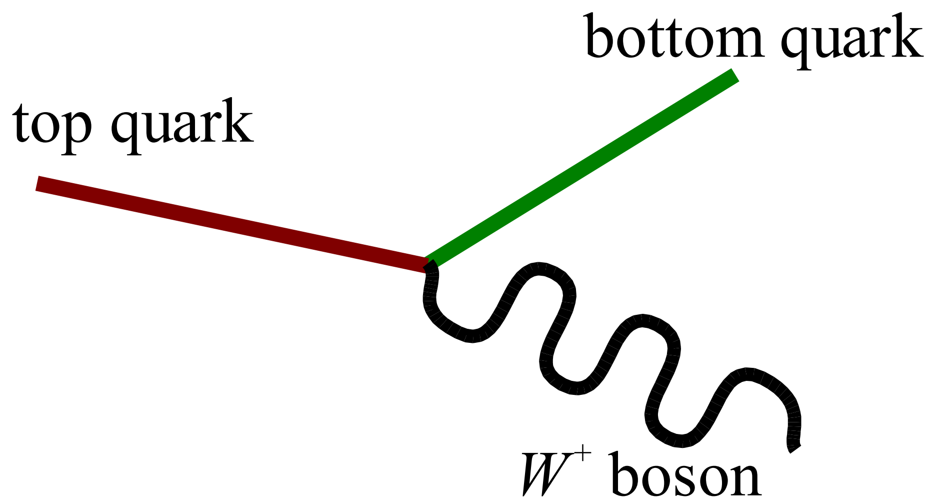




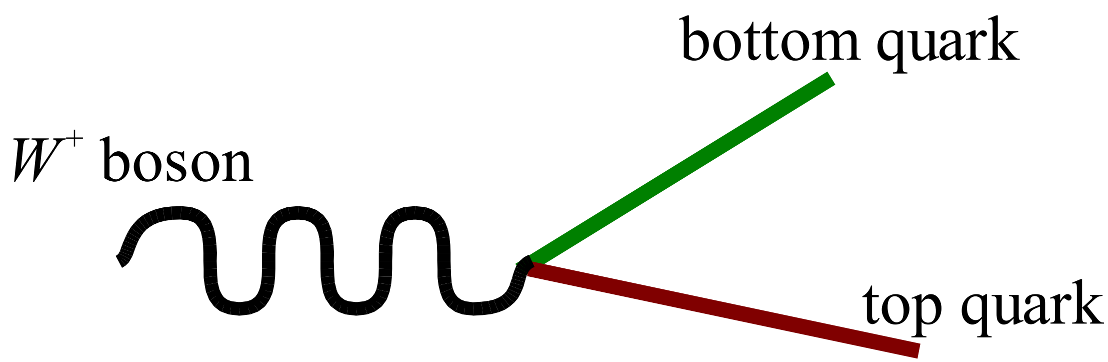
- Top Pair Studies at the Tevatron
  - Production cross section
    - Many different final states
    - Test of QCD
  - Top mass measurements
    - Implications for Standard Model Higgs
  - W helicity measurement



Top Quark Electroweak Interaction



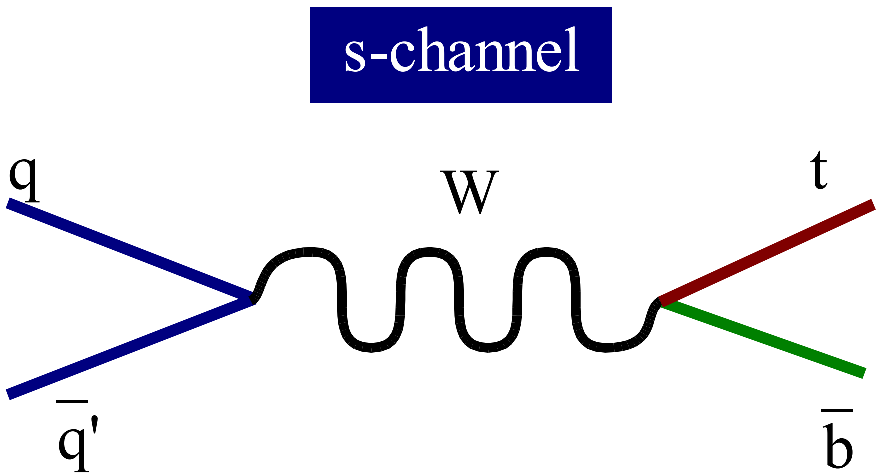
- Dominant mechanism for top quark decay

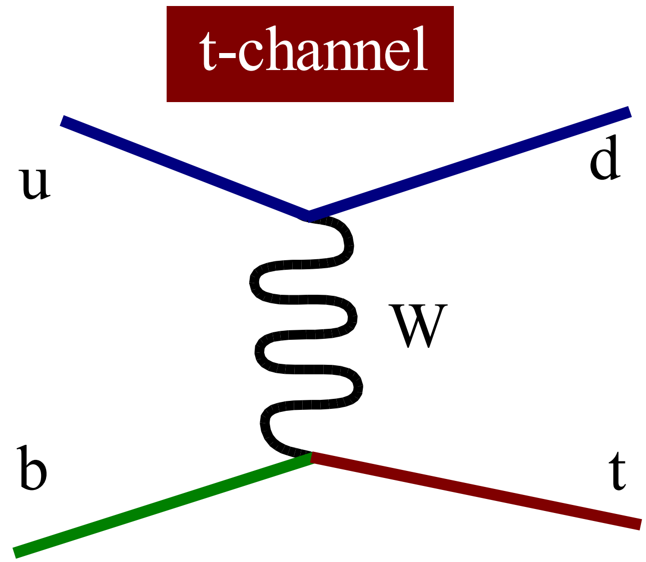


- Possible top quark production mode: “*Single Top*”

Single Top Physics at the Tevatron

- Electroweak Production of Single Top Quarks





Single Top Physics at the Tevatron

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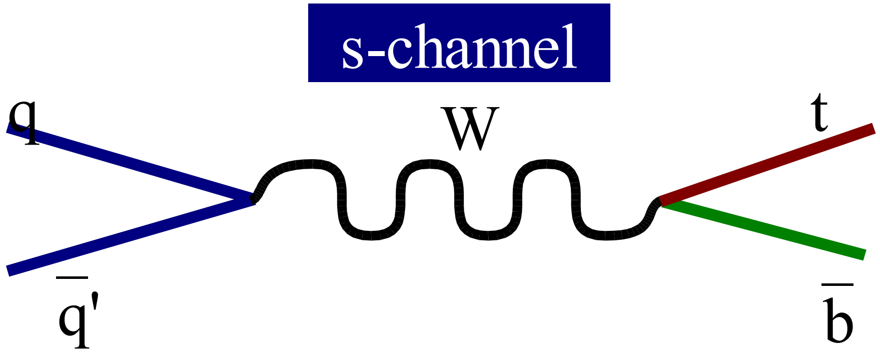
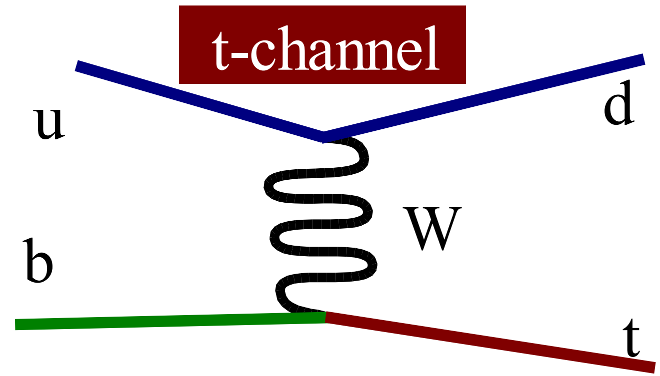


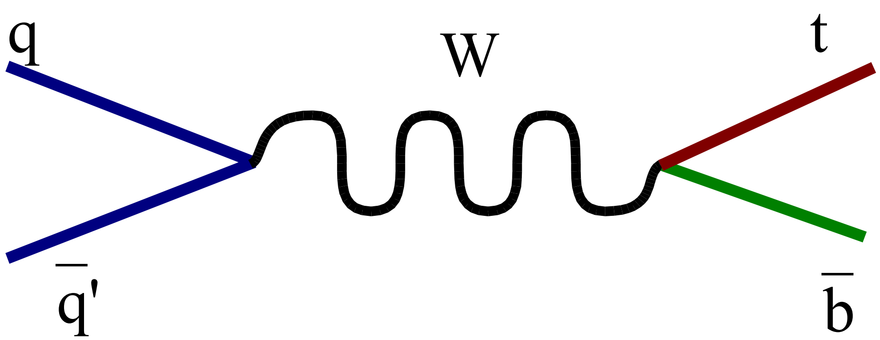


Tevatron Single Top in Run II:

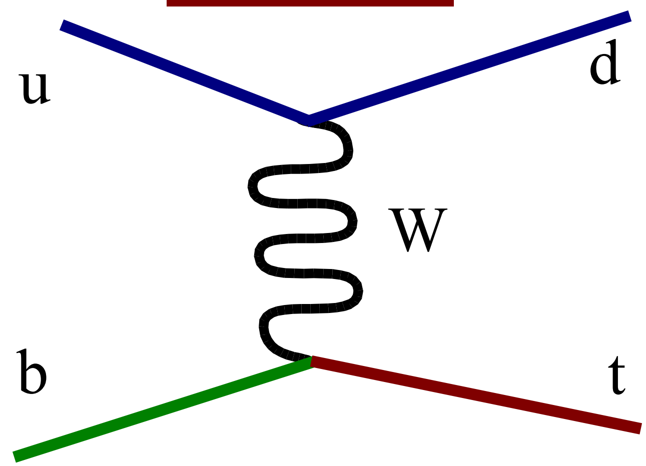
- Observe Single Top Production
- Measure Production cross section

Electroweak Production of Top at the Tevatron

s-channel



t-channel



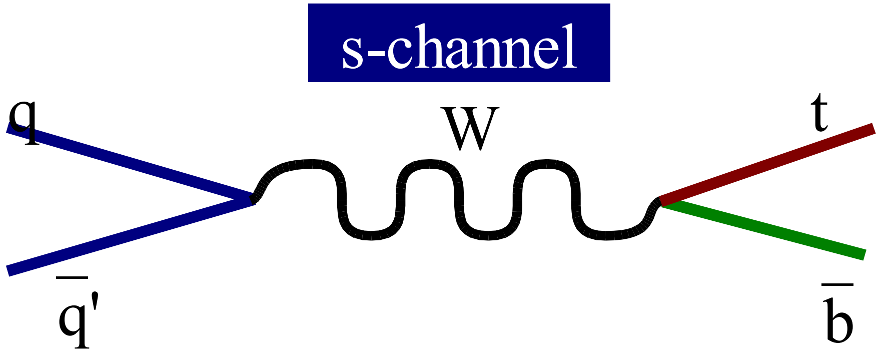
- Production cross section:

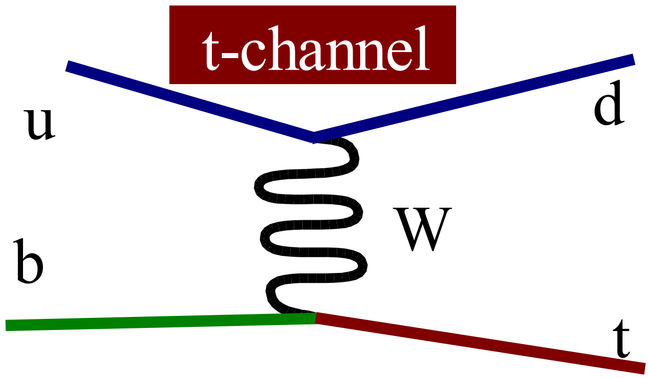
	s-channel	*t-channel*	*s+t channel*
– NLO cross-sections:	0.88pb ± 8%	1.98pb ± 11%	
– Run I 95% CL limits, DØ:	<17pb	<22pb	
CDF:	<18pb	<13pb	<14pb

- Other Standard Model production modes negligible

Single Top Physics at the Tevatron

- Electroweak Production of Single Top Quarks

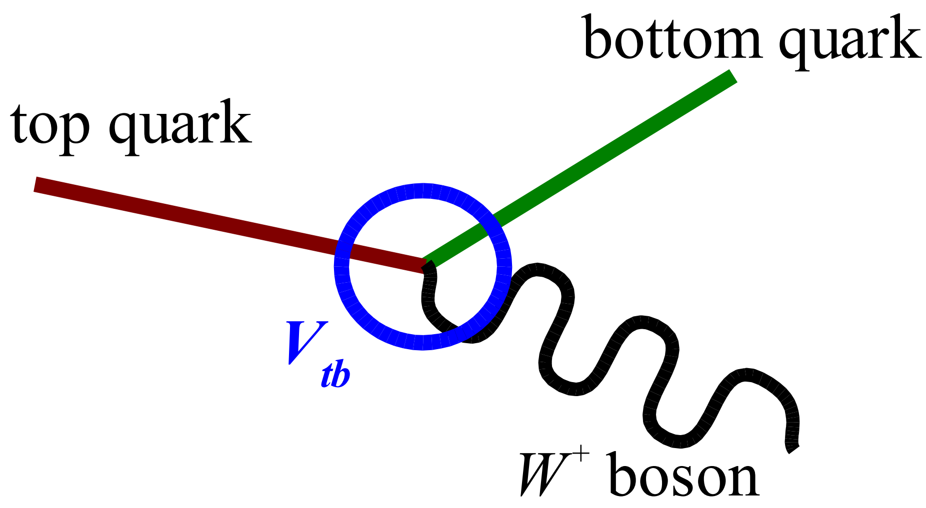




Tevatron Single Top in Run II:

- Observe Single Top Production
- Measure Production cross section
  - Confirm Standard Model Prediction
    - CKM matrix element V_{tb}

Top Quark Electroweak Interaction



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Weak Interaction Eigenstates are not Mass Eigenstates
  - Top quark must decay to a W plus a d, s, or b quark

    $$V_{td}^{\ 2} + V_{ts}^{\ 2} + V_{tb}^{\ 2} = 1$$

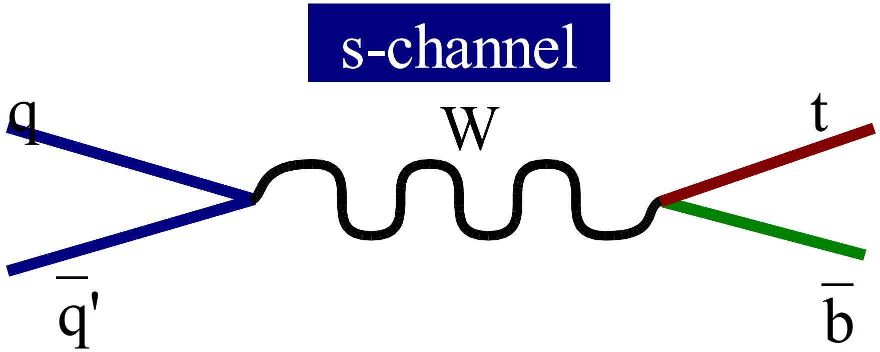
    - In SM, from constraints on V_{td} and V_{ts}: $V_{tb} > 0.999$
  - Or: new Physics that couples to the top quark:

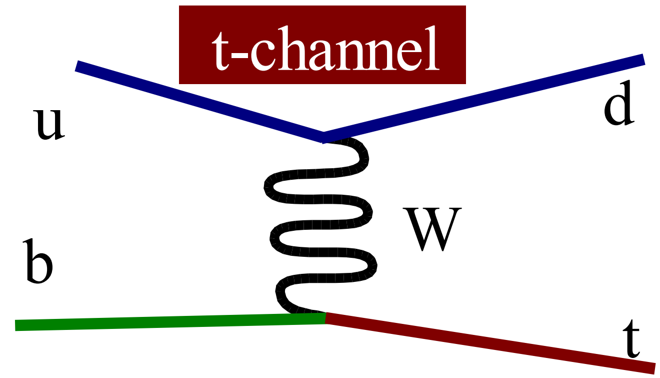
    $$V_{td}^{\ 2} + V_{ts}^{\ 2} + V_{tb}^{\ 2} + V_{tx}^{\ 2} = 1$$

    - No constraint on V_{tb}

Single Top Physics at the Tevatron

- Electroweak Production of Single Top Quarks





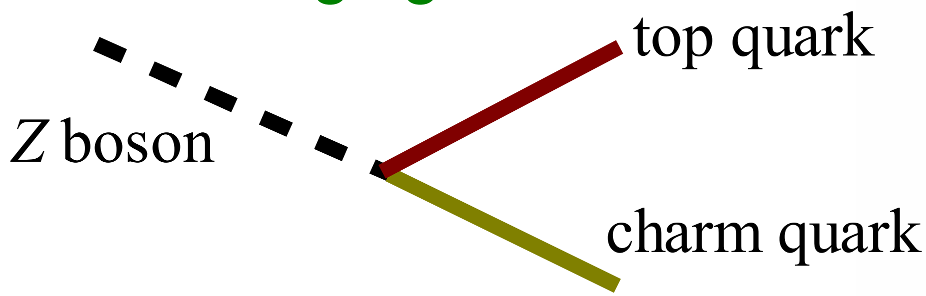
Tevatron Single Top in Run II:

- Observe Single Top Production
- Measure Production cross section
  - Confirm Standard Model Prediction
    - CKM matrix element V_{tb}
- Look for Physics beyond the Standard Model

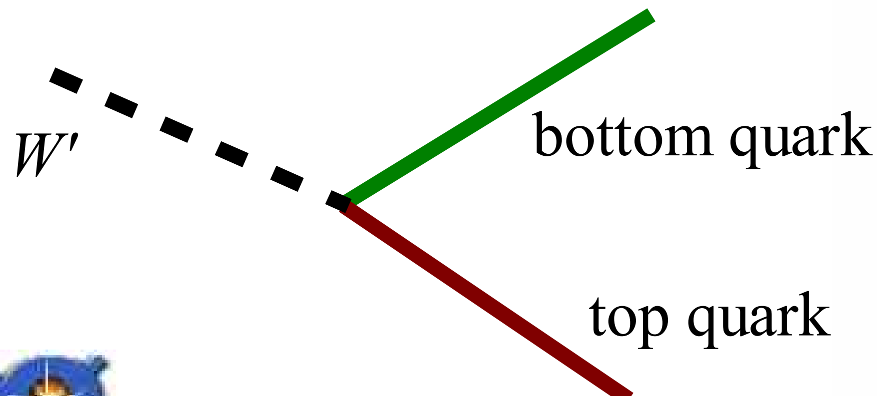
Non-Standard Model Single Top

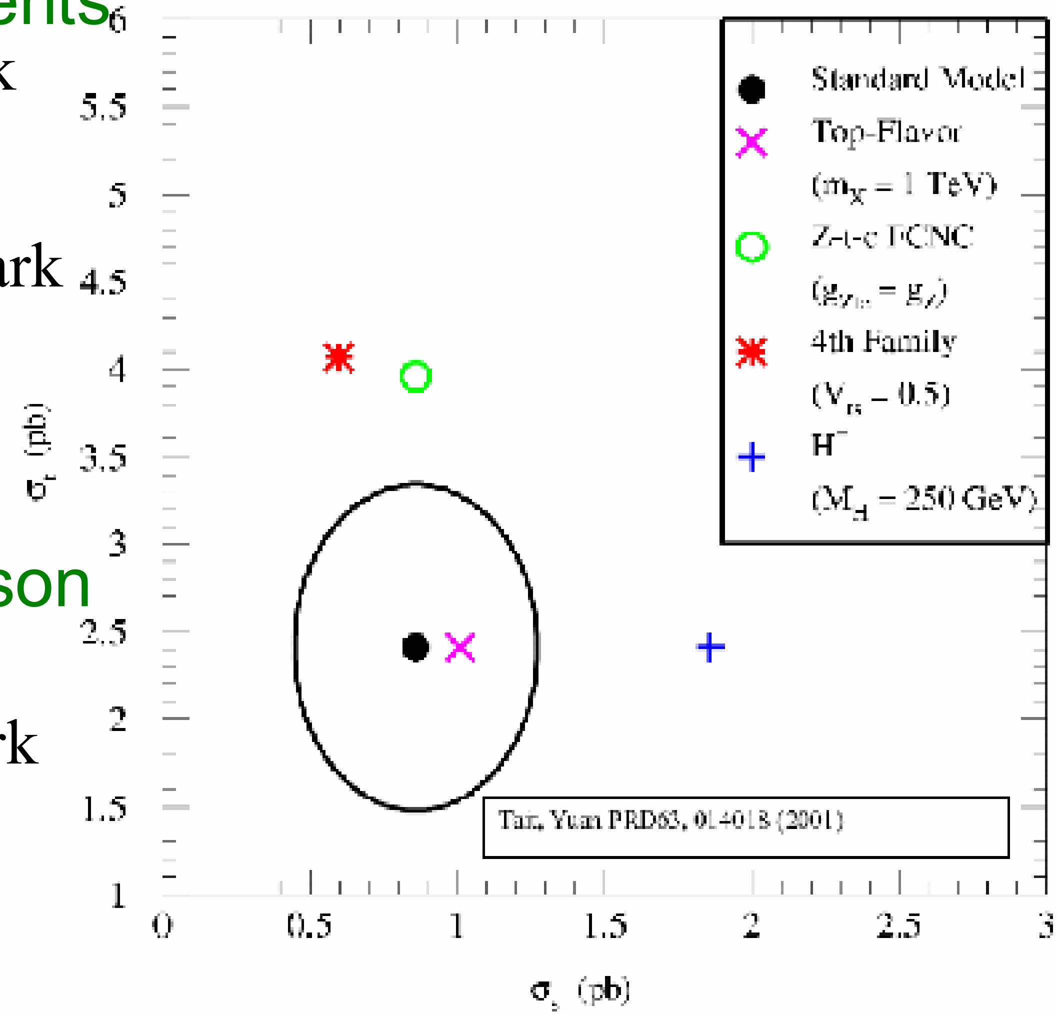
- Single top final state is also produced by many new interactions beyond the Standard Model

Flavor-Changing Neutral Currents



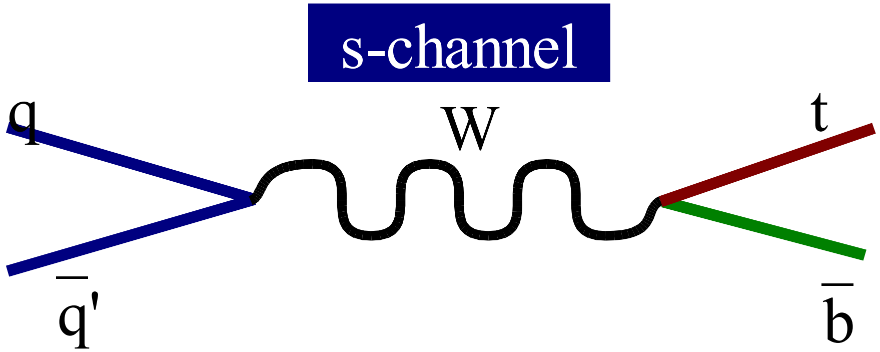
Top-Flavor: another vector boson

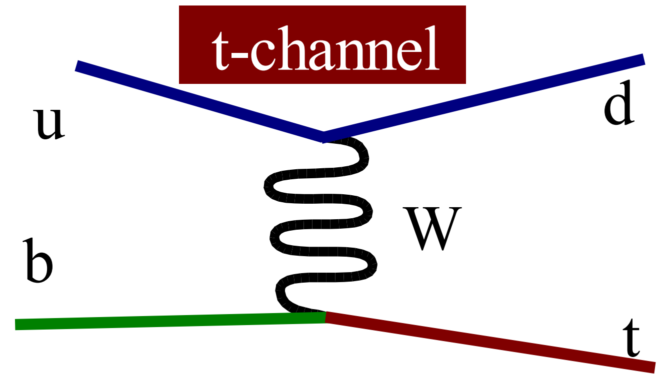




Single Top Physics at the Tevatron

- Electroweak Production of Single Top Quarks



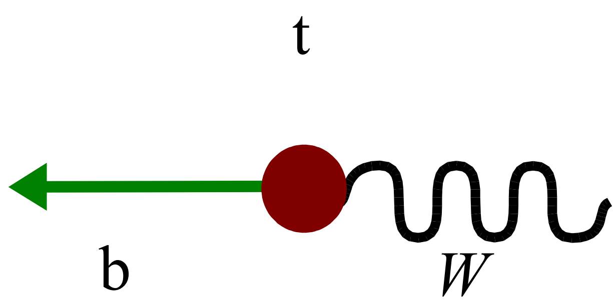


Tevatron Single Top in Run II:

- Observe Single Top Production
- Measure Production cross section
  - Confirm Standard Model Prediction
    - CKM matrix element V_{tb}
- Look for Physics beyond the Standard Model
- Measure top quark spin

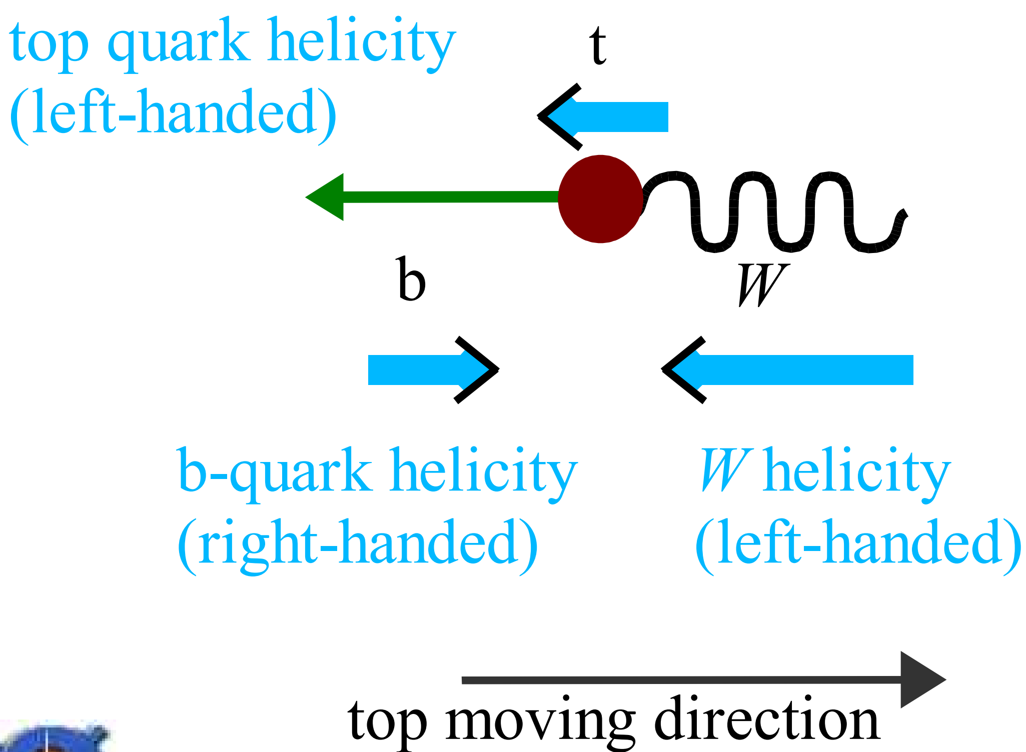
Top Quark Spin

- Top Quark decays before it hadronizes
  - Full spin information is preserved in the decay products
    - b-quark and *W* boson



Top Quark Spin

- Top Quark decays before it hadronizes
  - Full spin information is preserved in the decay products
  - Electroweak charged current interaction is left-handed
- Top polarization in the top rest frame:



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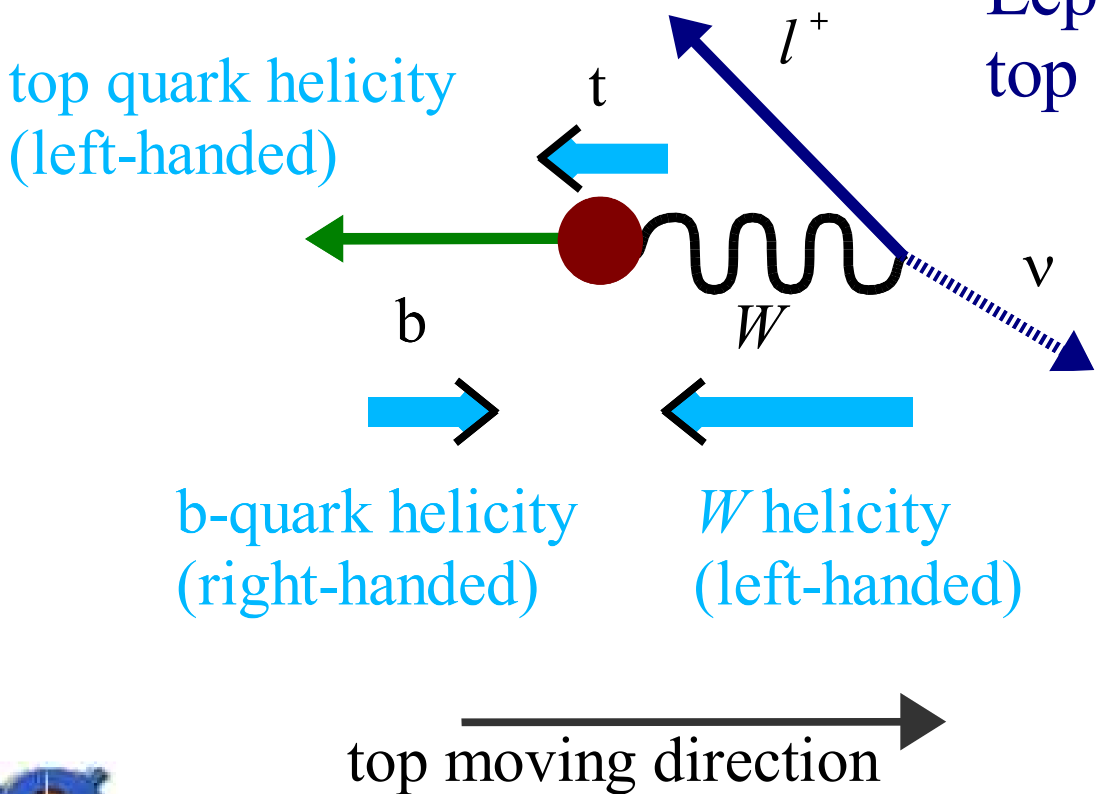

Lepton moves along top spin direction

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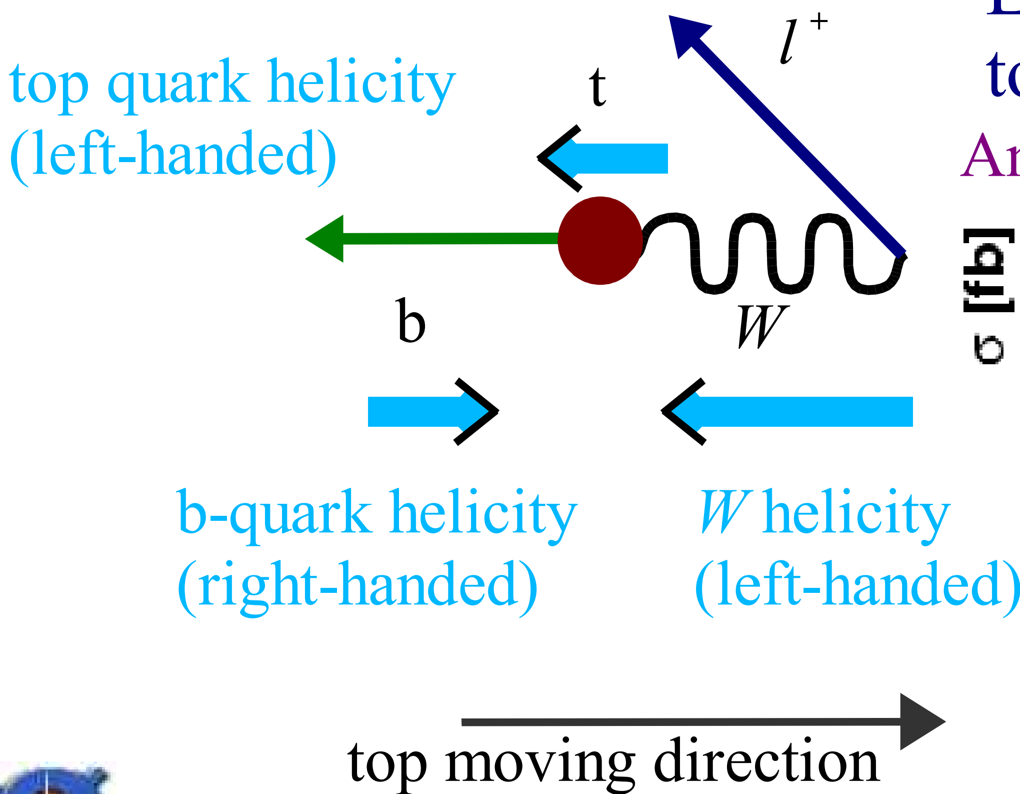
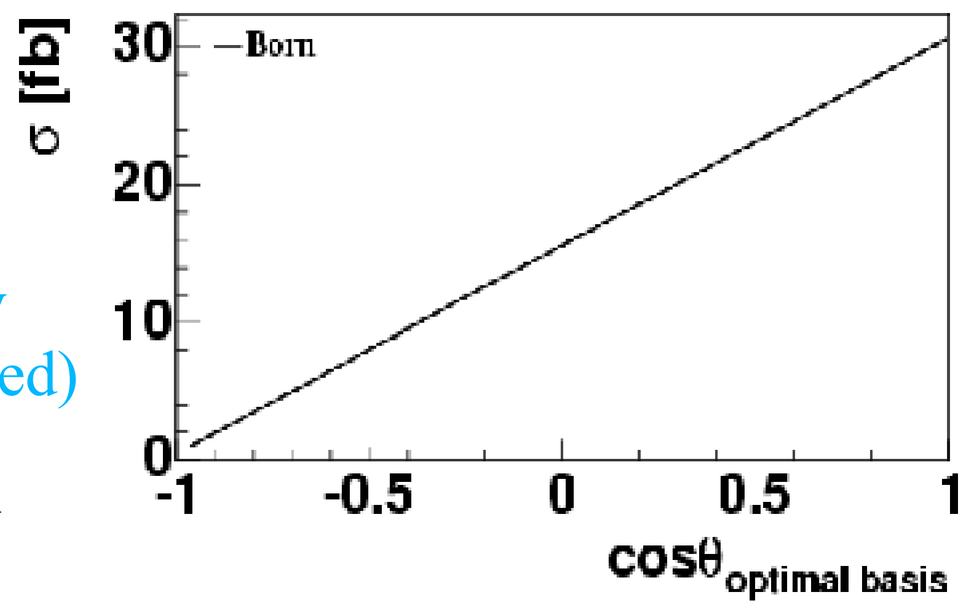


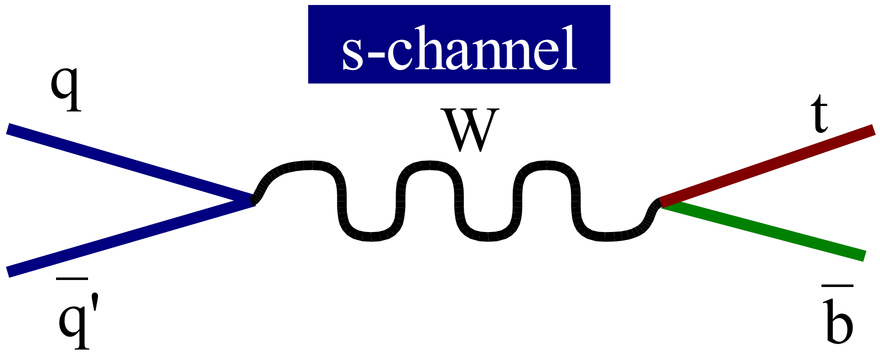
Lepton moves along top spin direction

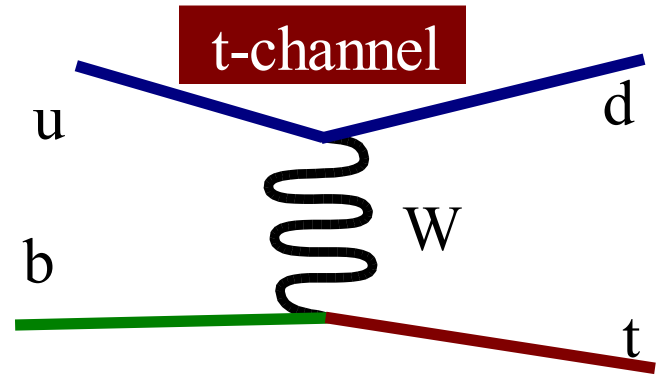
Angle between light quark and lepton:



Single Top Physics at the Tevatron

- Electroweak Production of Single Top Quarks





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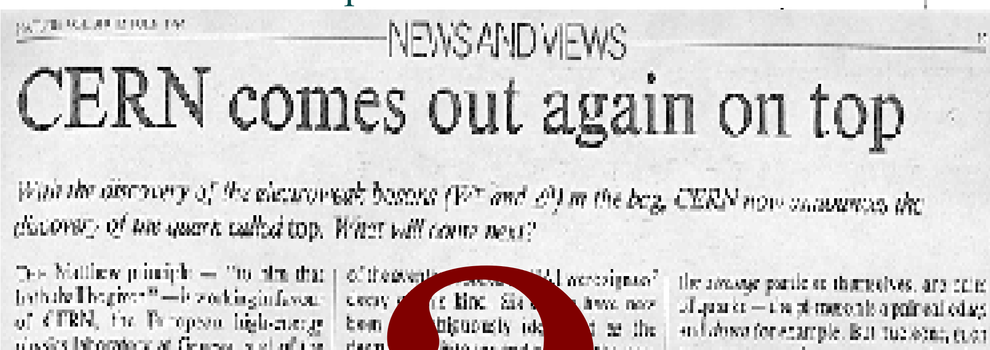
Discovery of Single Top?

- Excess of lepton+MET+2jet events at UA1 in 1984
  - Consistent with production of single top quark and bottom quark
    - $M_{top} \approx 40GeV$

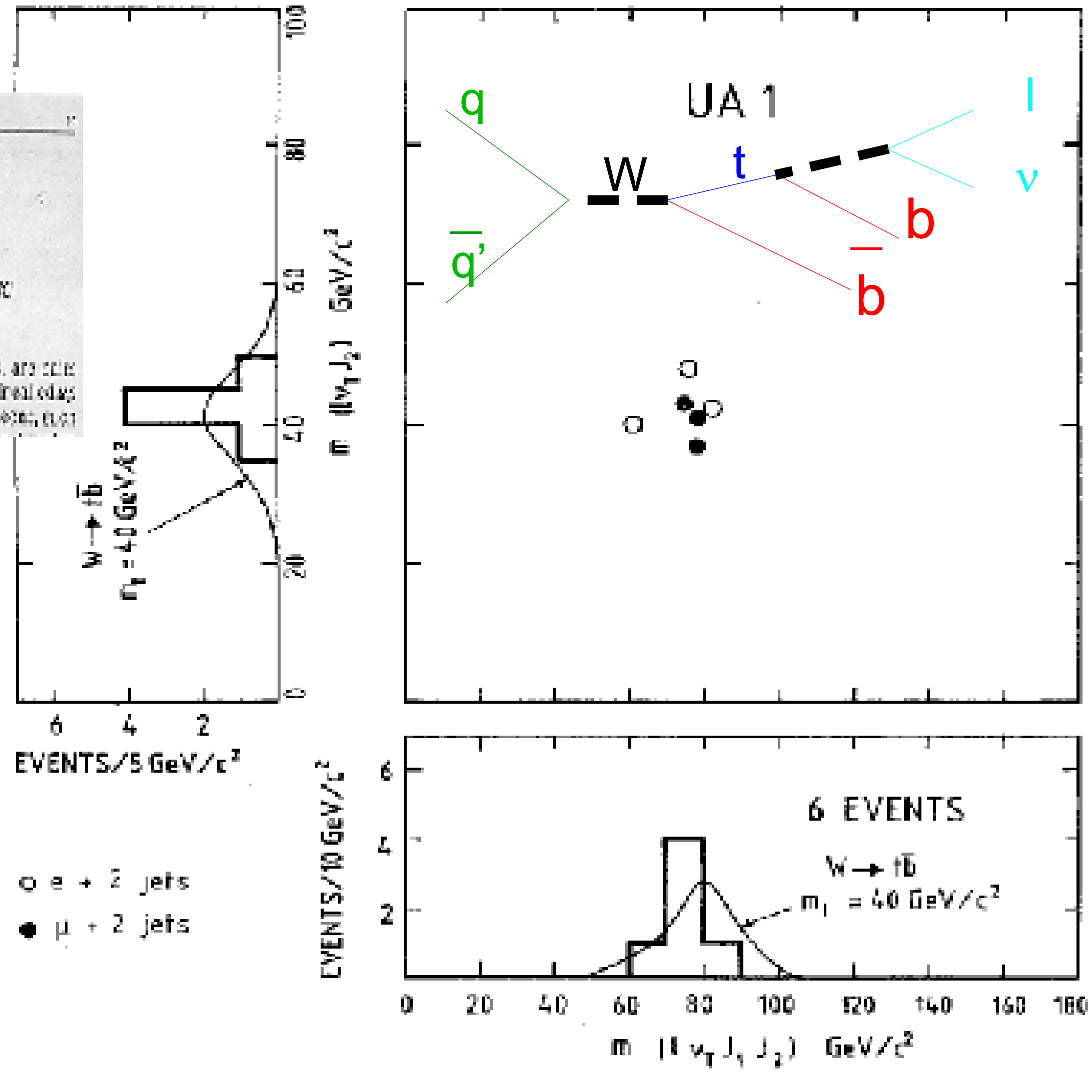


NEWS AND VIEWS

CERN comes out again on top

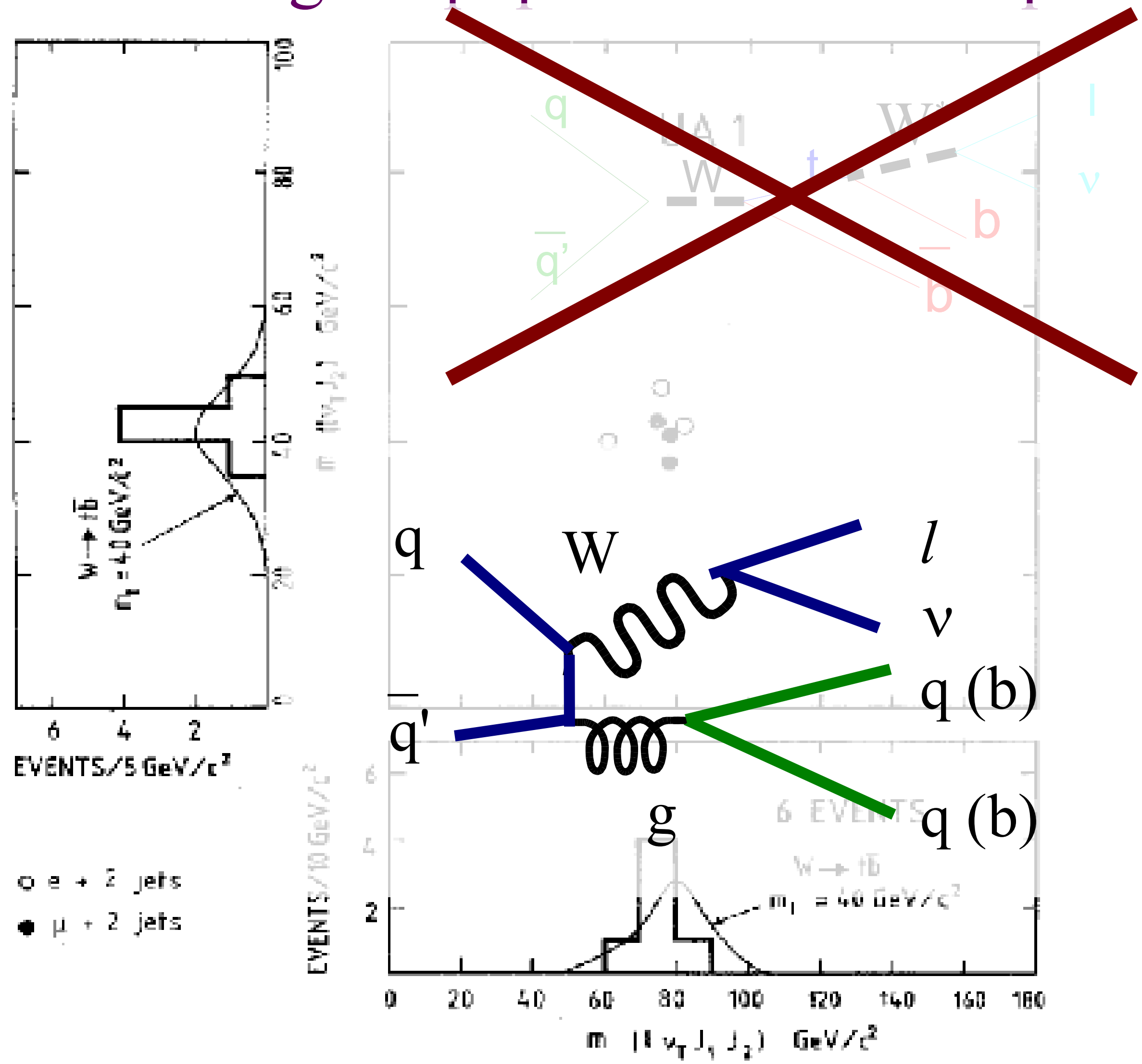
With the discovery of the electroweak bosons (W± and Z0) in the bag, CERN now announces the discovery of the quark called top. What will come next?

?

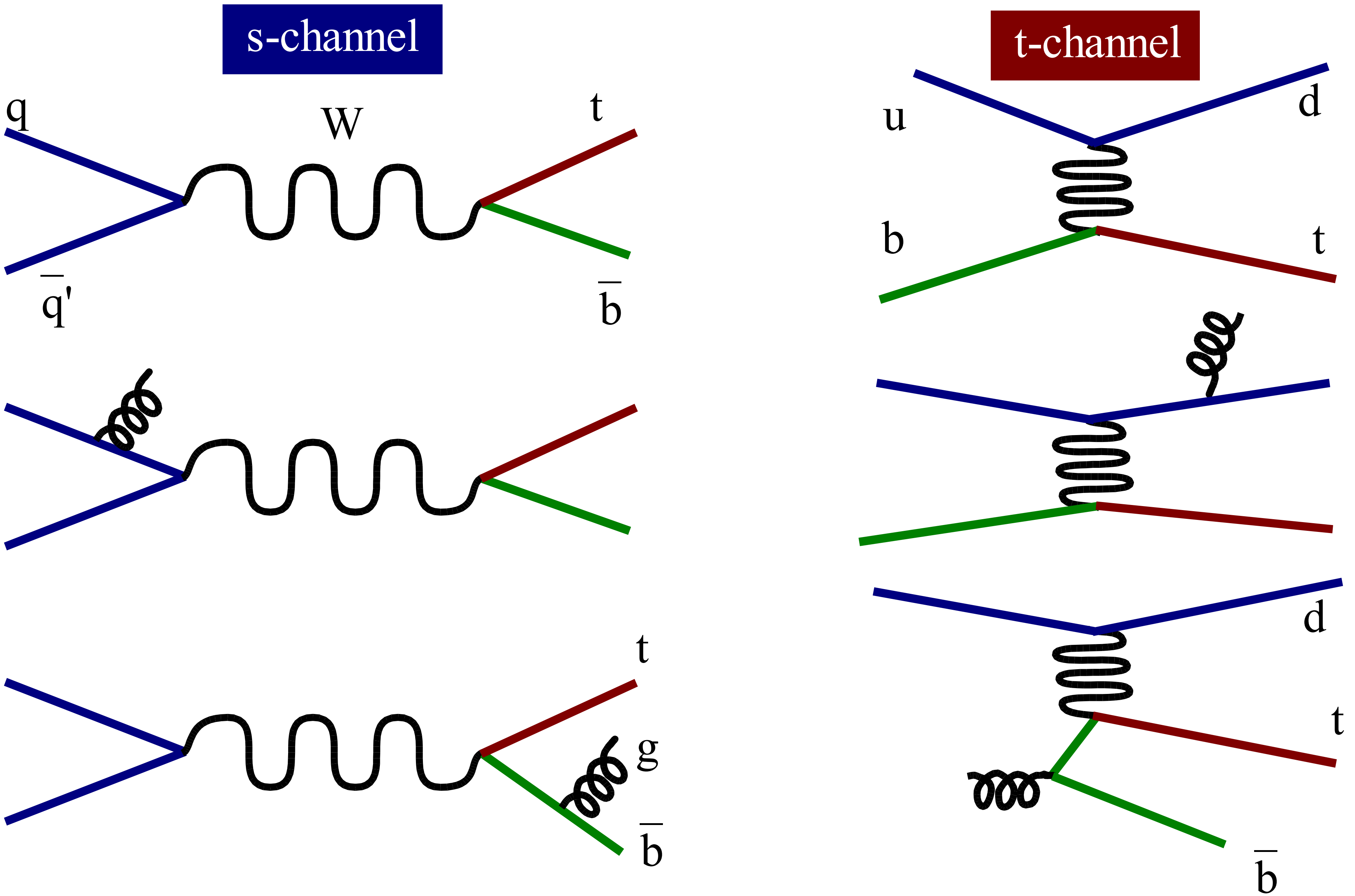


Discovery of Single Top?

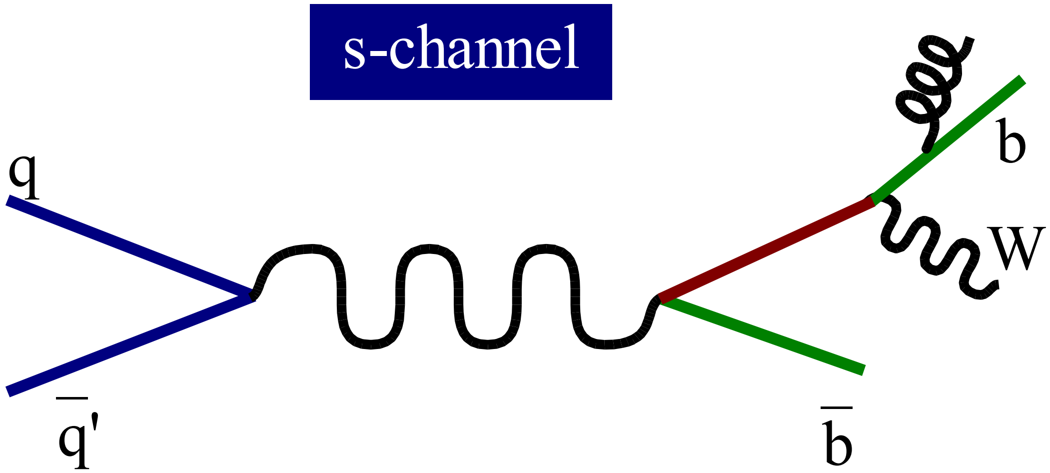
- Excess of lepton+MET+2jet events at UA1 in 1984
  - Consistent with production of single top quark and bottom quark
    - $M_{top} \approx 40$GeV
  - Not confirmed after more data and better background estimation
    - W+jets production

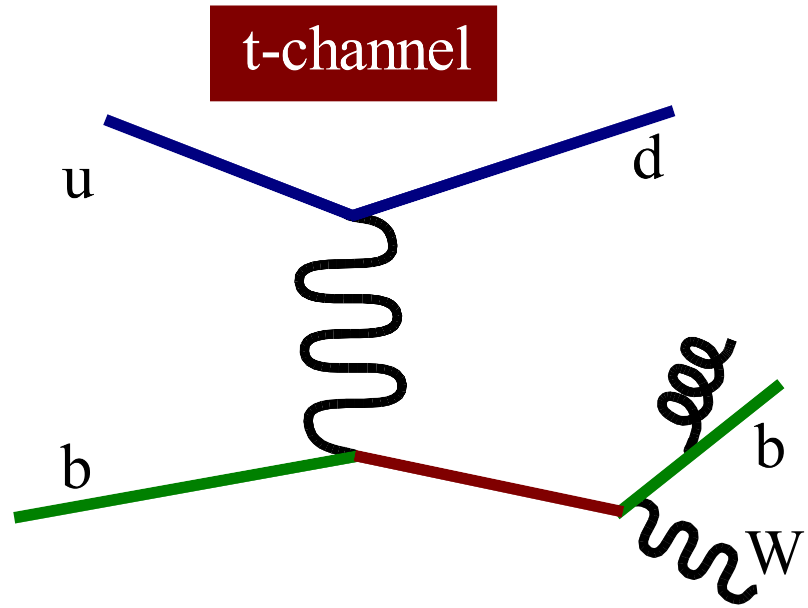


Electroweak Production of Top at the Tevatron at next-to-leading order in QCD



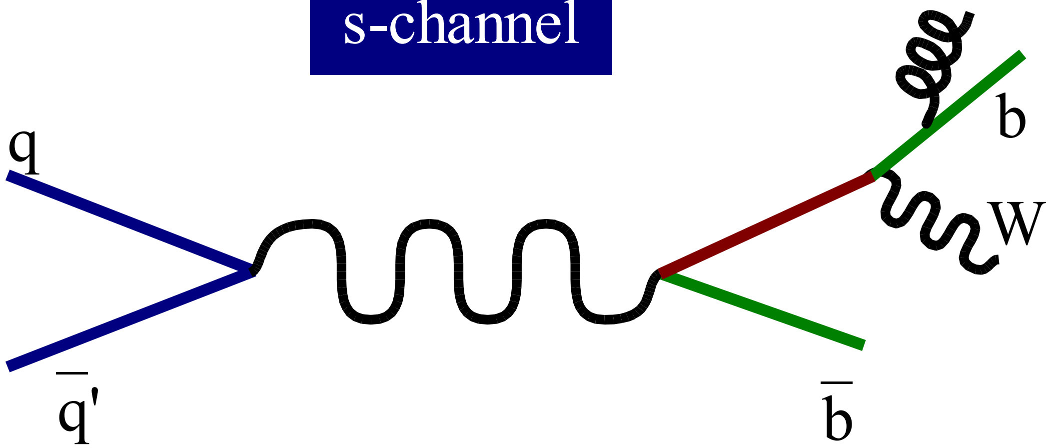
Electroweak Production *and Decay* at next-to-leading order in QCD



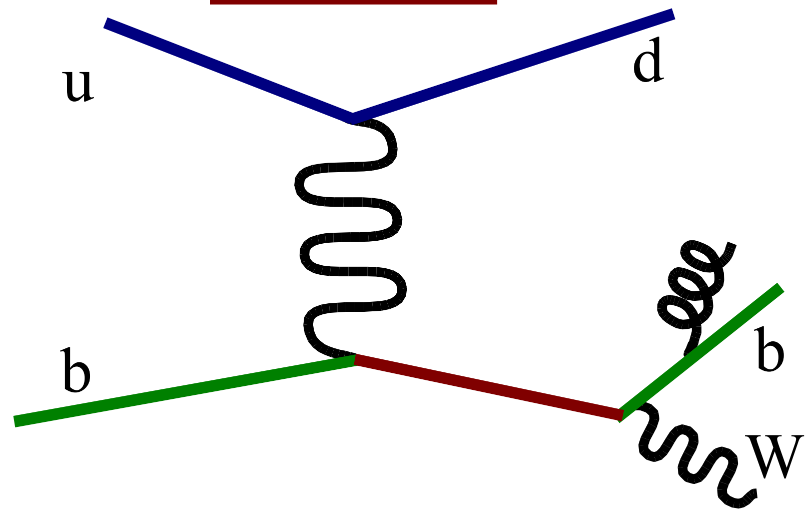


Electroweak Production *and Decay* at next-to-leading order in QCD

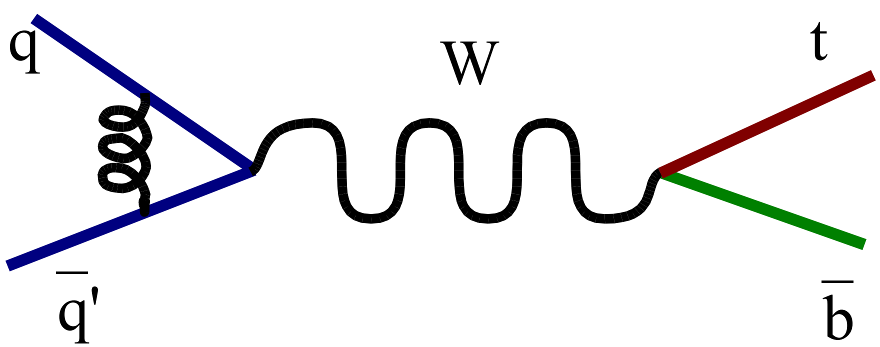
s-channel

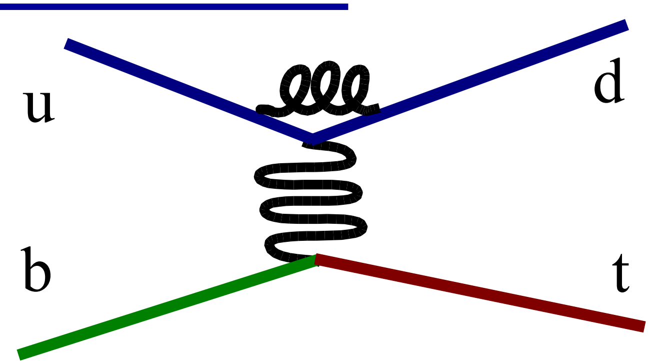


t-channel



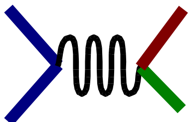
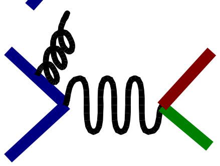
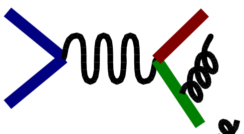
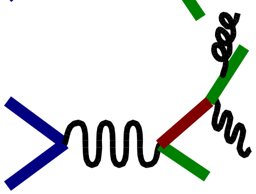
And virtual corrections





Relative Contributions to NLO rate including Top Production and Decay

s-channel

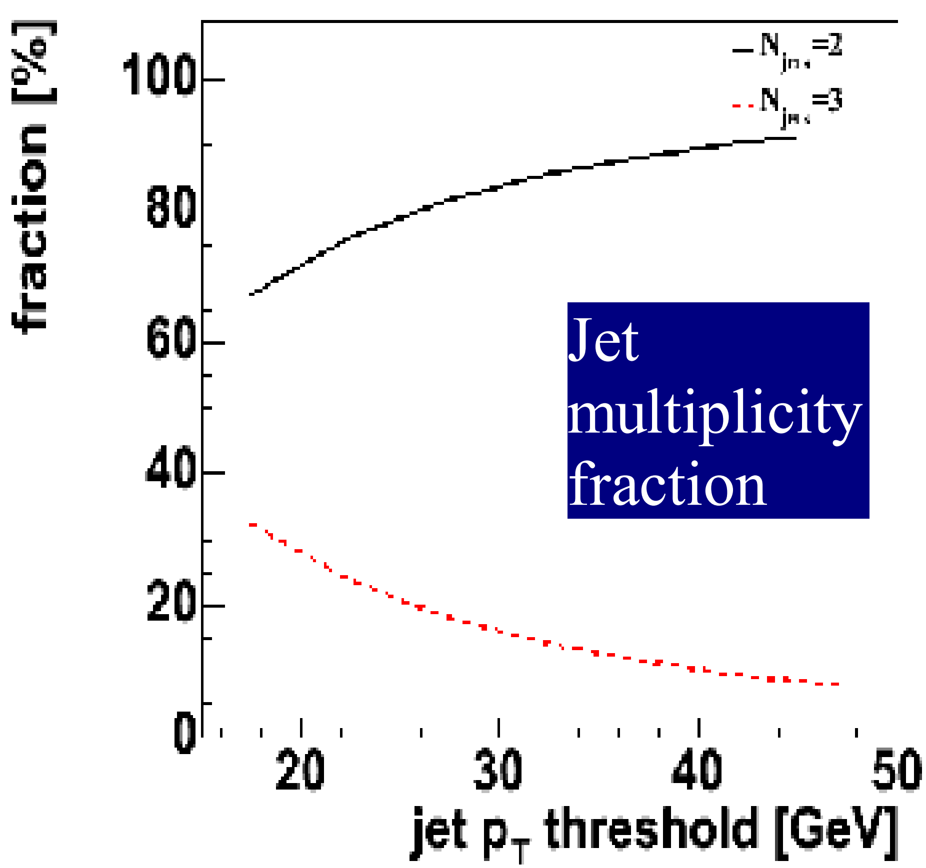
	NLO rate	0.86pb
	Born level	65%
	Initial state	22%
	Final state	11.5%
	Decay	1.2%

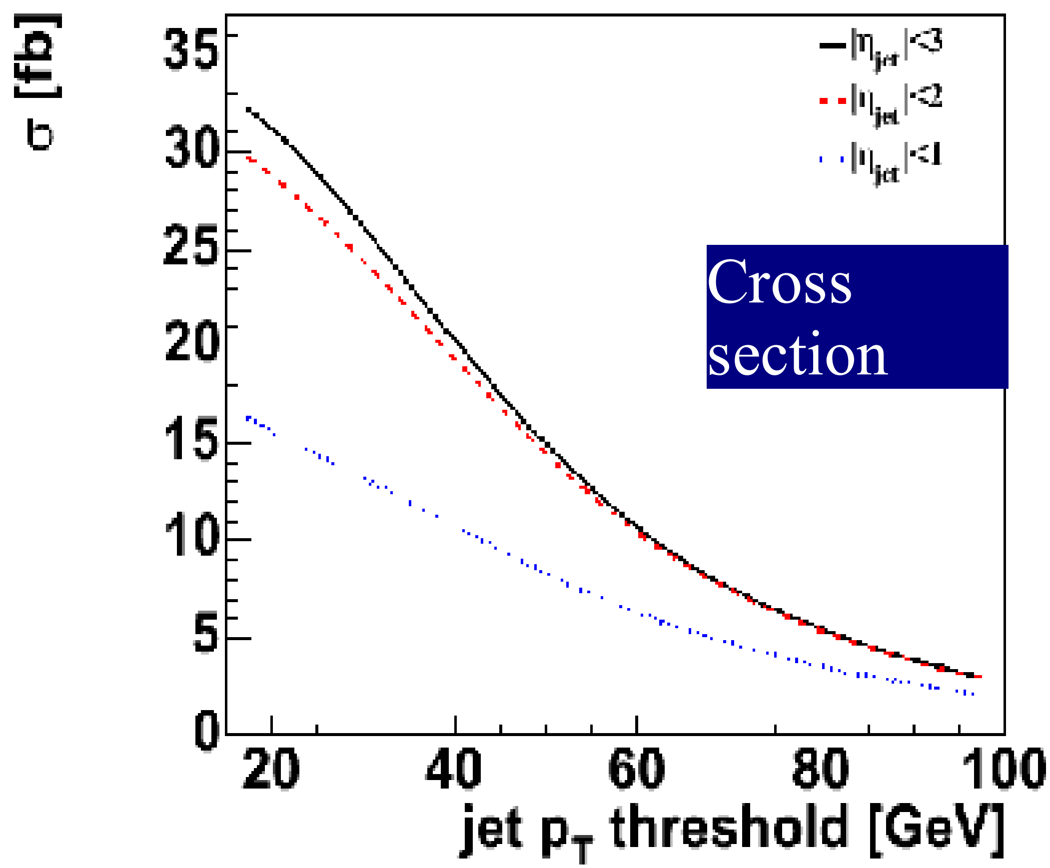
Cao, RS, Yuan hep-ph/0409040

- O(as) corrections large for the s-channel
  - Decay correction is 2nd order effect, top mass and top width

Kinematic effect of NLO Corrections

- After simple parton level selection cuts:
  - 1 lepton, p_T>15GeV, $|\eta|$<2, missing E_T>15GeV
  - ≥2 jets, p_T>15GeV, $|\eta|$<3
- Example: s-channel jet multiplicity

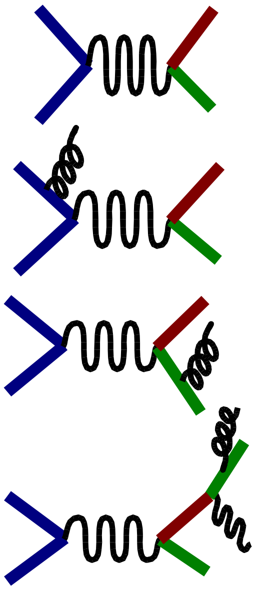


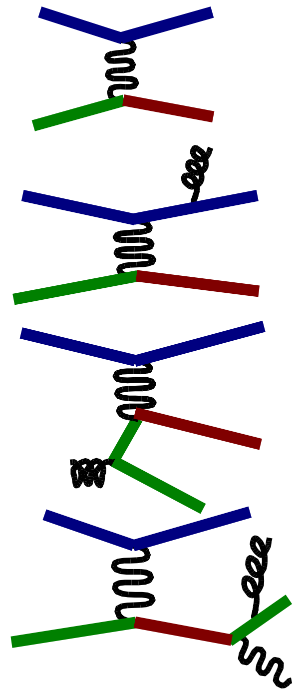


Cao, RS, Yuan hep-ph/0409040

Relative Contributions to NLO rate including Top Production and Decay

s-channel		t-channel	
NLO rate	0.86pb	NLO rate	1.9pb
Born level	65%	Born level	105%
Initial state	22%	Light quark	13%
Final state	11.5%	Heavy quark	-11%
Decay	1.2%	Decay	-7%

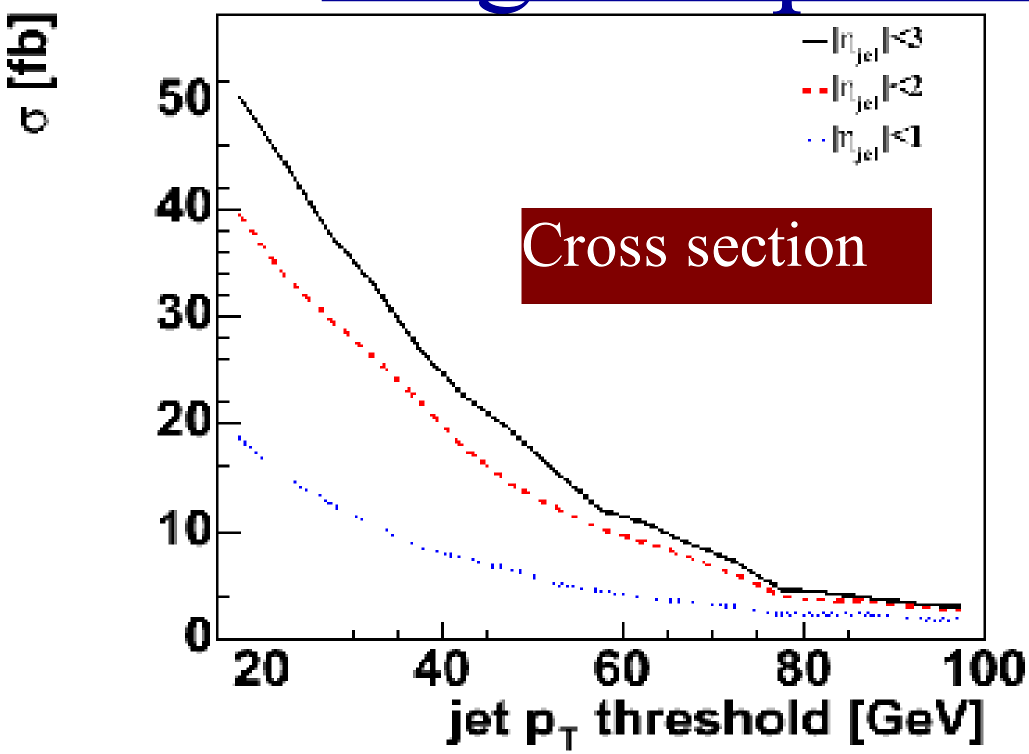


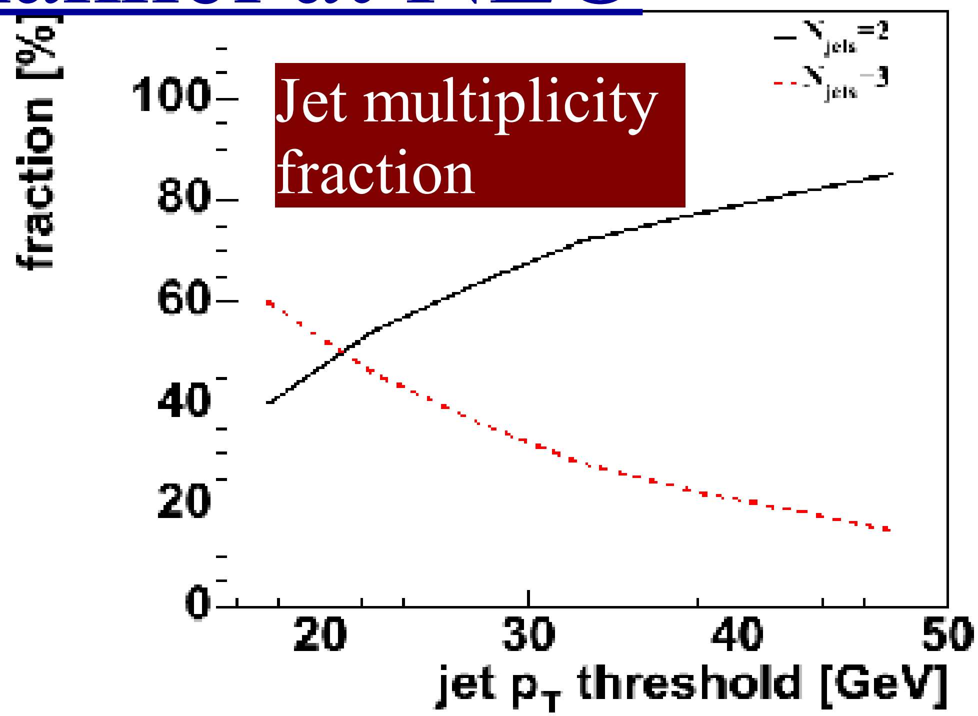


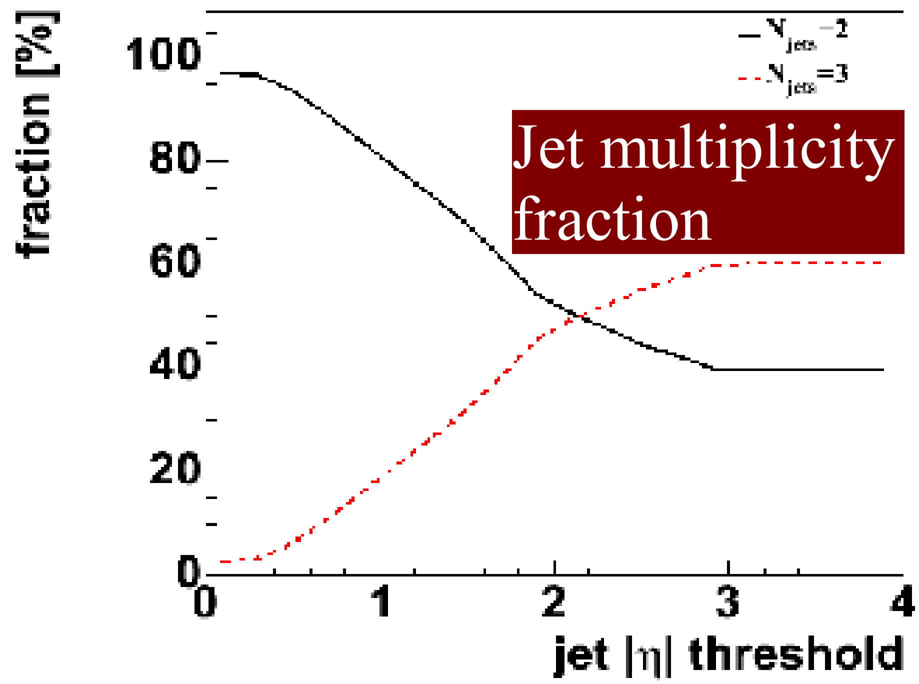
Cao, RS, Yuan hep-ph/0409040

- O(as) corrections large for the s-channel
  - Only small rate correction for the t-channel
    - Decay correction is 2nd order effect, top mass and top width

Single Top t-channel at NLO





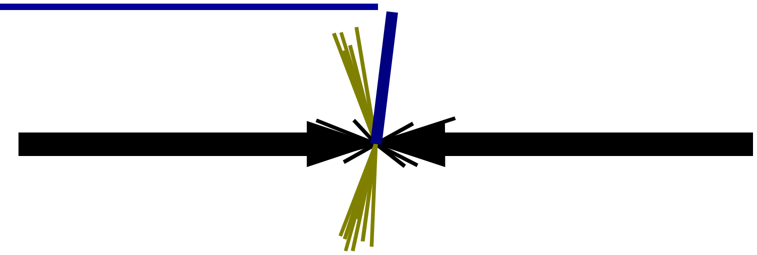
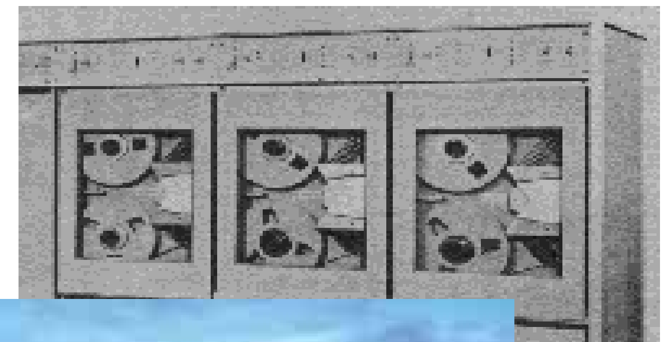


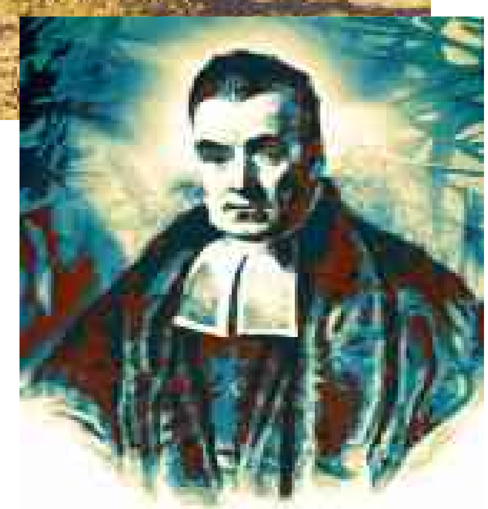
- After simple cuts
  - Large number of 3-jet events
    - Depends strongly on jet p_T and η cuts

Experimental Detection of Single Top Events

Experimental Procedure

- Produce Single Top Events
  - Collide protons with anti-protons
- Record Single Top Events
  - Detector, triggering
- Reconstruct final state objects
  - Leptons, jets
- Select Single Top Events
  - Out of large backgrounds
- Statistical Analysis

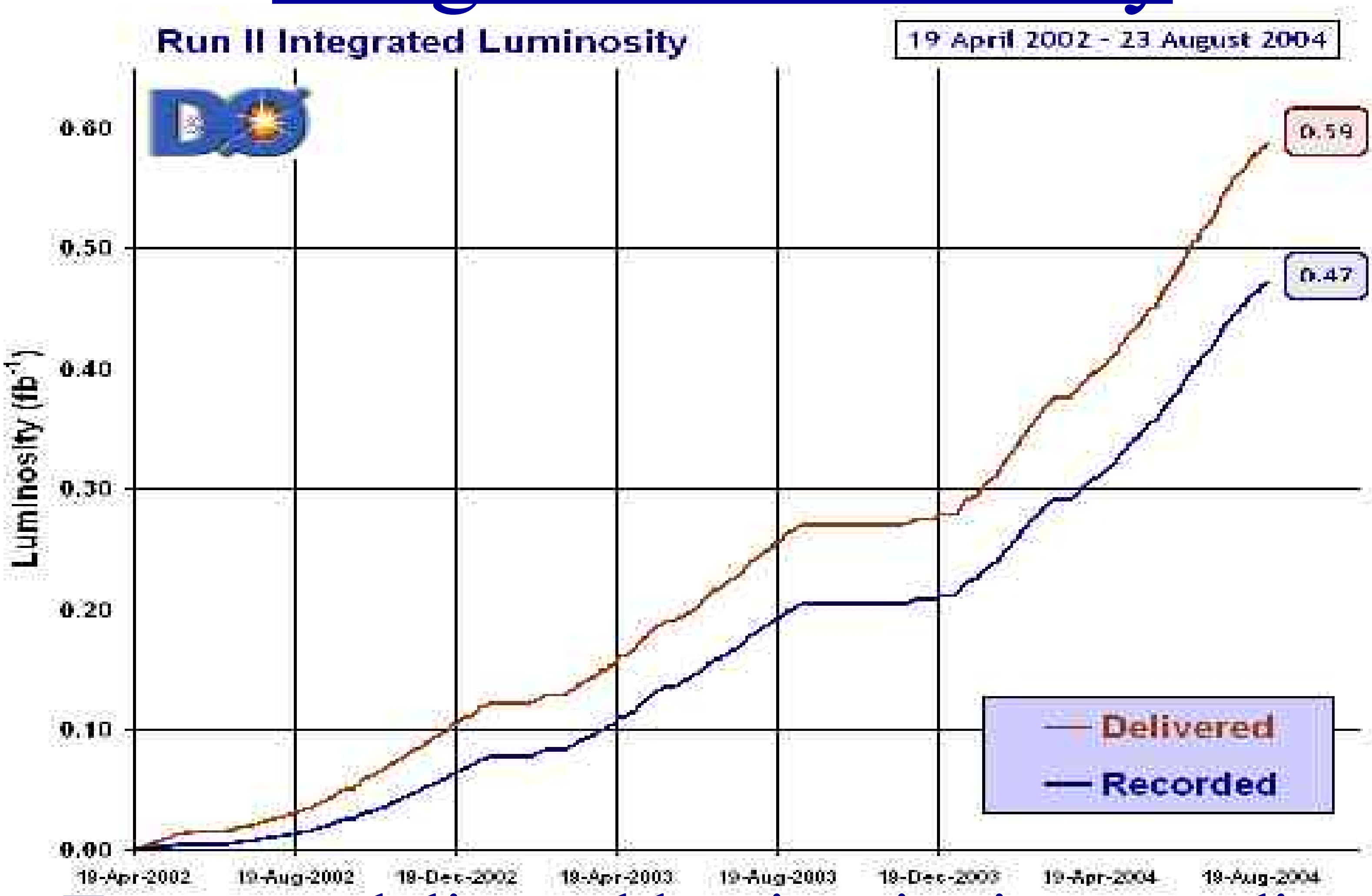





Experimental Setup: Fermilab Tevatron in Run II

- **Proton-Antiproton Collider**
- **CM Energy 1.96TeV**
- **One interaction (bunch crossing) every 396ns**
- **Achieved peak Luminosity > 1×10^{32}**

Integrated Luminosity

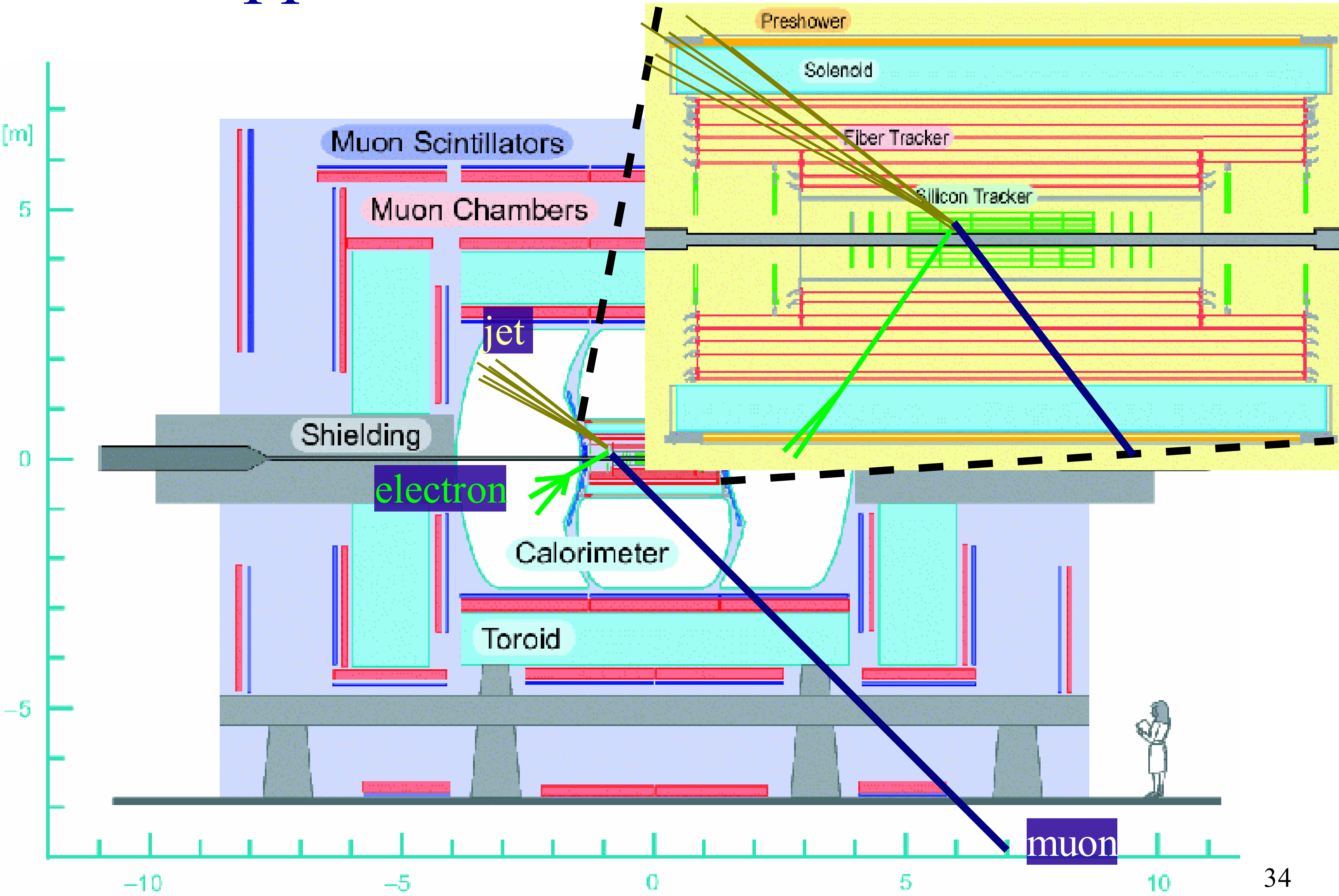


- Tevatron delivered luminosity is exceeding "baseline" and "design" projections
- DØ is now recording data with >90% efficiency

Experimenters: The DØ Collaboration

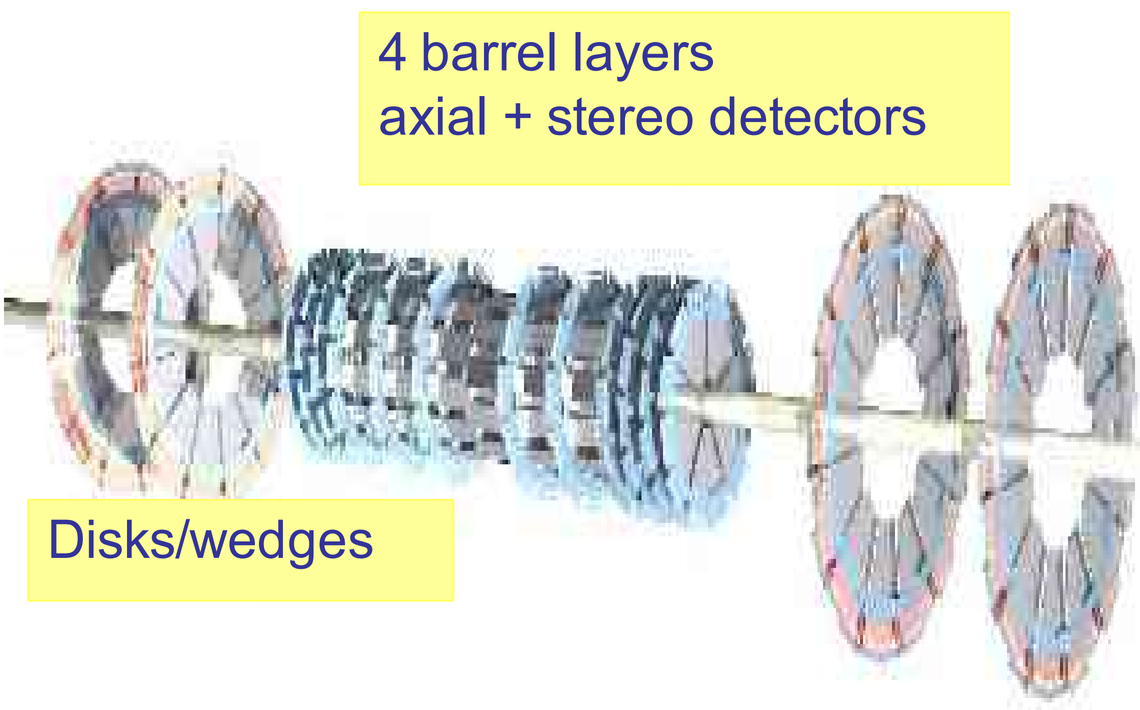
- **19 countries**
- **80 institutions**
- **670 physicists**

Apparatus: Run II DØ Detector

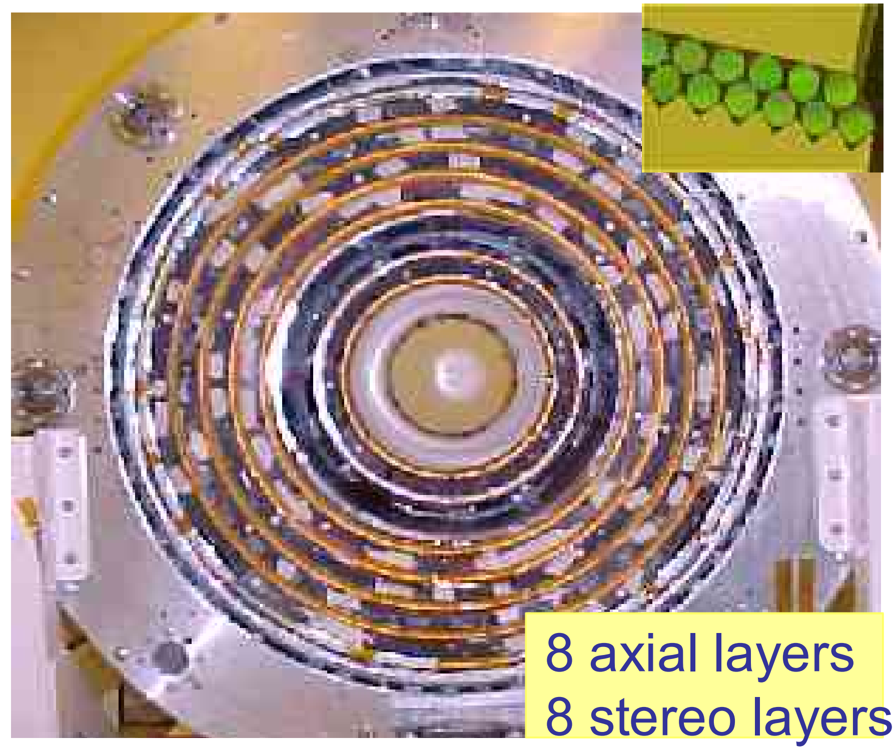


New for Run II DØ: Tracking Systems in a 2T magnetic field

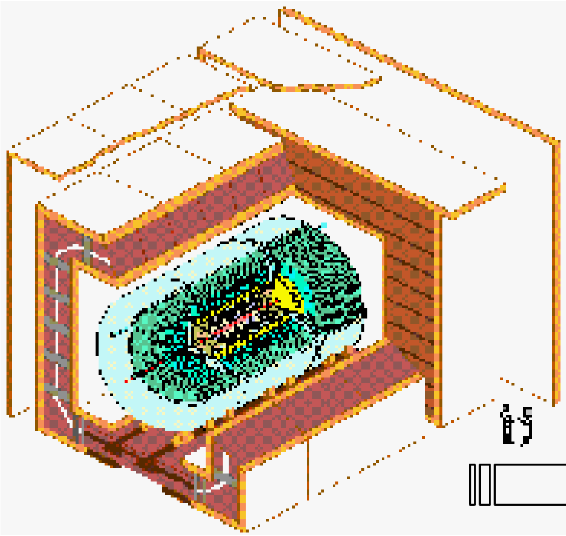
Silicon Vertex Detectors



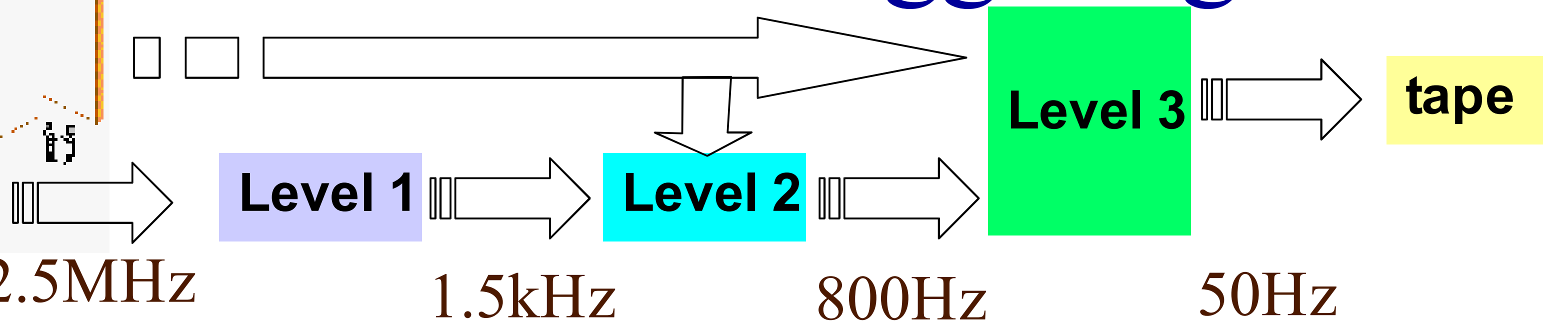
Central Fiber Tracker



- Improved momentum resolution for muons (and electrons)
- Track-based b-quark jet identification



Significantly Upgraded for Run II: Triggering



- Multi-level, pipelined, buffered Trigger Strategy
  - Level 1: one interaction every 396ns
    - Fast trigger pick-offs from all detectors
    - Custom hardware/firmware
    - Trigger on hit patters in individual detector elements
  - Level 2: Combine Level 1 regions and objects
  - Level 3: Full detector readout
    - Commodity based readout system
      - VME-based PCs and Ethernet switches
    - Complete event reconstruction
      - Linux processor farm to make trigger decision

Level 2 Trigger

- Design: reduce 6kHz L1 accept rate to 1kHz
- Both custom hardware/firmware and commodity-based components
  - Dataflow from L1 and detector systems in custom systems
  - Algorithms in software running on commodity-based system
- Build Physics objects
  - Jets and EM objects are built from L1 calorimeter towers
  - Central tracks are built from L1 track trigger tracks
    - Now also Secondary Vertex Tagging
  - Muons are reconstructed from raw muon chamber hits
- Combine objects from different detector systems
  - Track matching to muons, electrons, or jets
- Allow for 128 different combinations
  - 1-1 matching of bits between L1 and L2

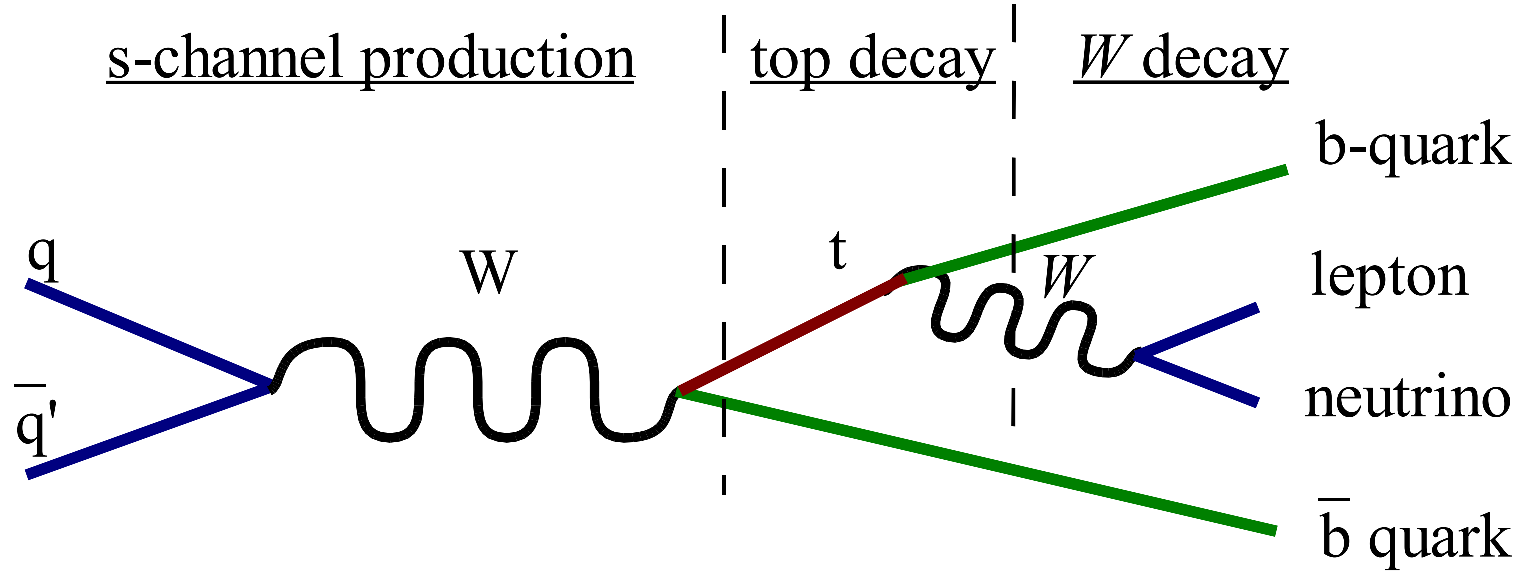
Analysis Outline

Goal:

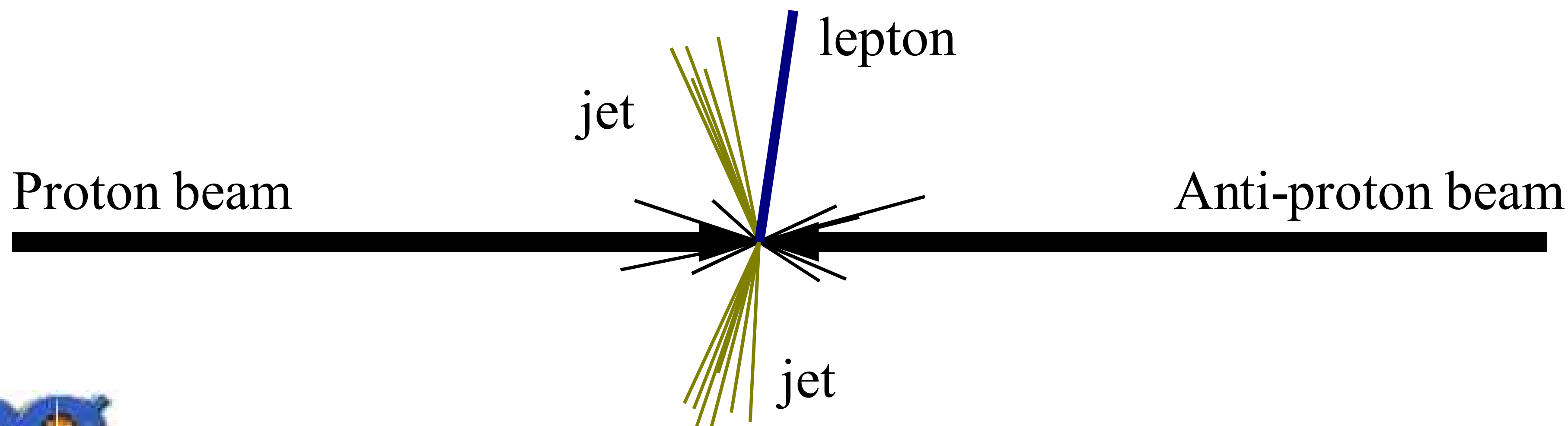
Observe electroweak production of single top quarks

1. Select single top events out of large background
   - Loose "Pre-Selection", reject QCD multi-jet events
   - Maximize acceptance
   - Check modeling of remaining backgrounds
2. Tight selection of single top events
   - Find (or form) sensitive variable for s-channel and t-channel
   - Separate s-channel from backgrounds
   - Separate t-channel from backgrounds
3. Determine cross section
   - Event counting, likelihood fitting, ...

Single Top Event Signature

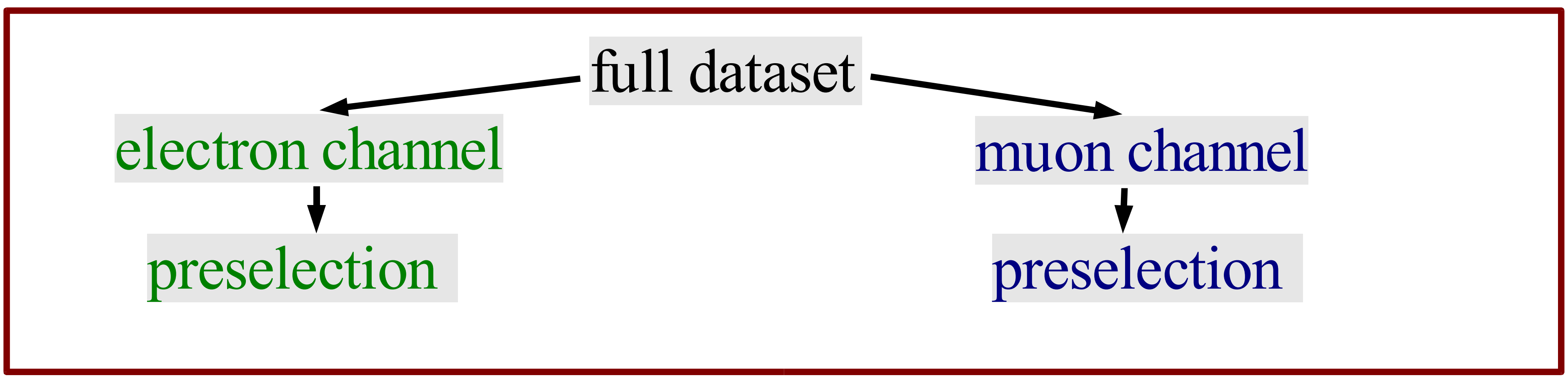


Final State Objects



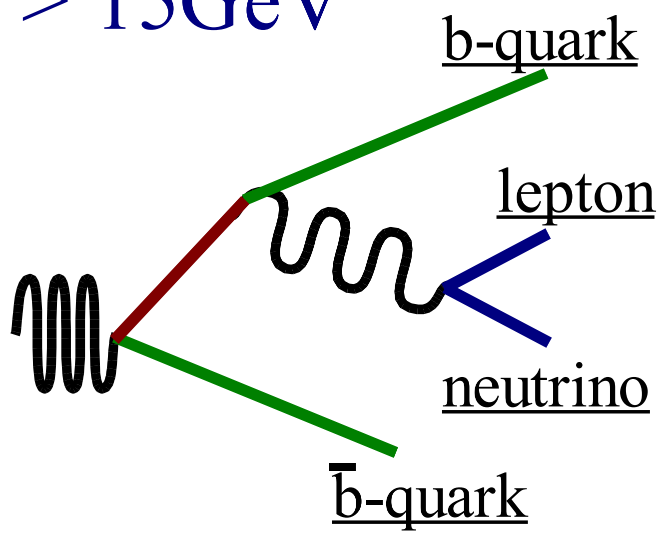
DØ Single Top Search Strategy

- Split data into orthogonal channels
  - Optimize each channel, then combine
  - Separate by lepton:
    electron channel ⇔ muon channel
      - Veto on events containing the other lepton
    - Electron channel: better energy resolution
    - Muon channel: wider η coverage
- Simple preselection cuts



Single Top Event Selection

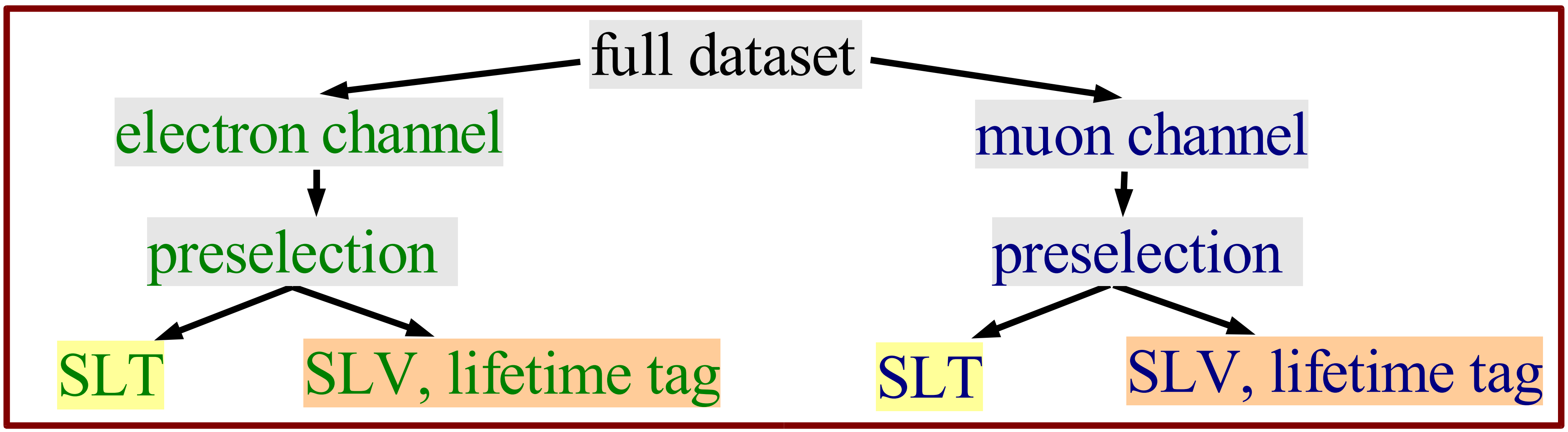
- Lepton: 1 electron or muon, $p_T > 15$GeV
- Neutrino: missing transverse energy > 15GeV
- Jets:
  - $p_T > 15$GeV, $|\eta|<3.4$, p_T (jet 1)> 25GeV
  - $2 \leq n_{jets} \leq 4$
  - At least one b-tag



- Trigger:
  - L1: Lepton: ≥1 EM object, pT>10GeV or ≥1 muon hit   Jets: ≥1 jet
  - L2: Lepton: ≥1 EM object, pT>12GeV or ≥1 muon   Jets: ≥ 1 jet
  - L3: Lepton: ≥1 EM object, pT>15GeV   Jets: ≥ 1 jet
  - Efficiency: ~85% (electron channel), ~89% (muon channel)
- Reject mis-reconstructed events

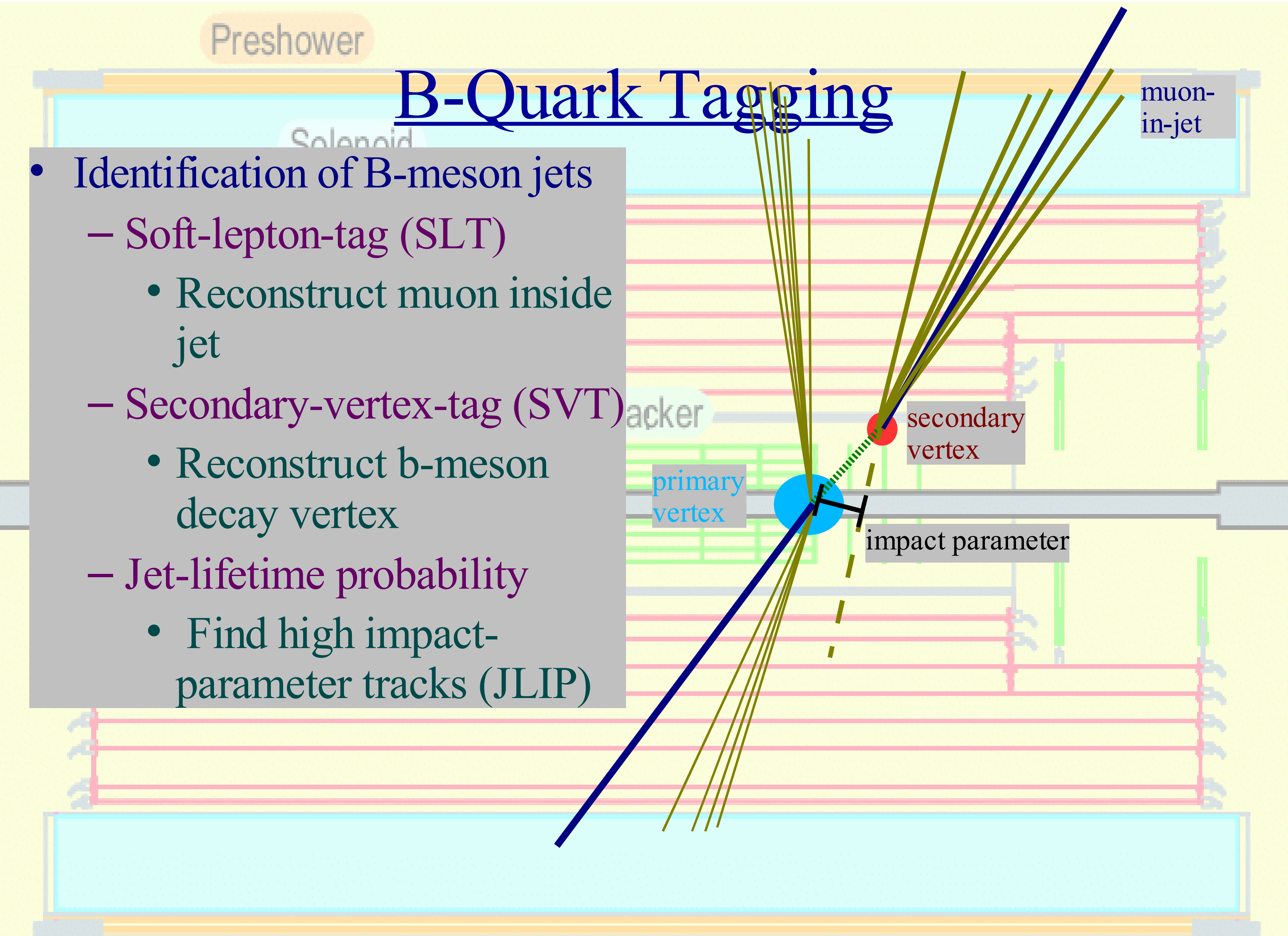
DØ Single Top Search Strategy

- Split data into orthogonal channels
  - Separate by lepton
  - Separate by b-tagging:
    Soft-lepton-tagging (SLT) ⇔ lifetime tagging
    - Lifetime tagging analyses apply SLT Veto
    - Use several lifetime tagging methods for cross-check
      - Not orthogonal, cannot combine
- Background estimation and model check



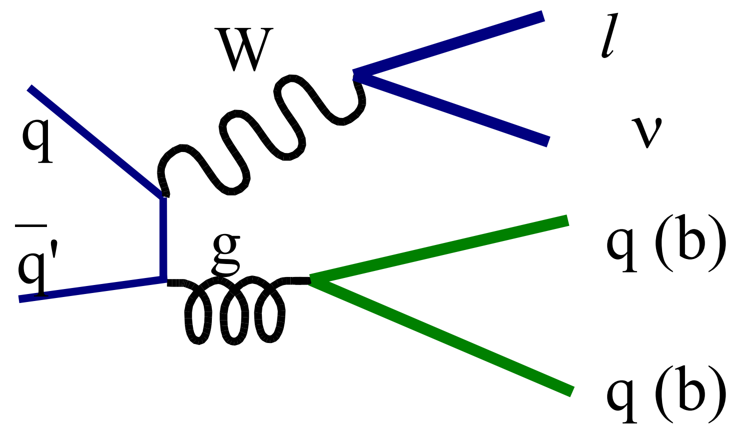
B-Quark Tagging

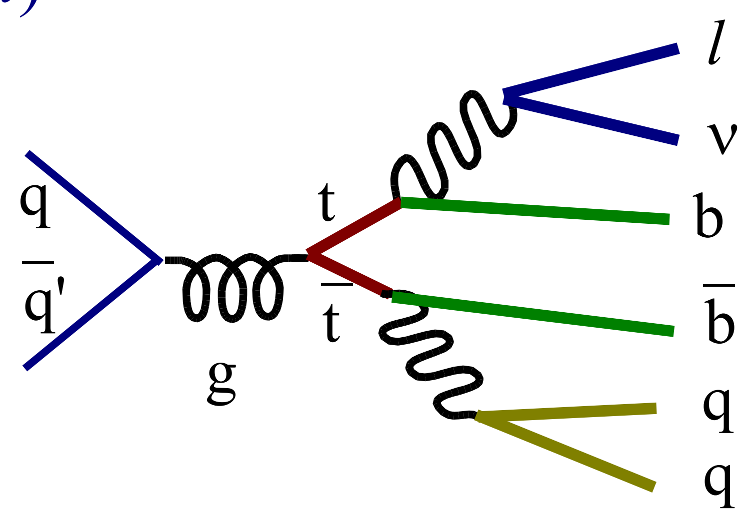
- Identification of B-meson jets
  - Soft-lepton-tag (SLT)
    - Reconstruct muon inside jet
  - Secondary-vertex-tag (SVT)
    - Reconstruct b-meson decay vertex
  - Jet-lifetime probability
    - Find high impact-parameter tracks (JLIP)



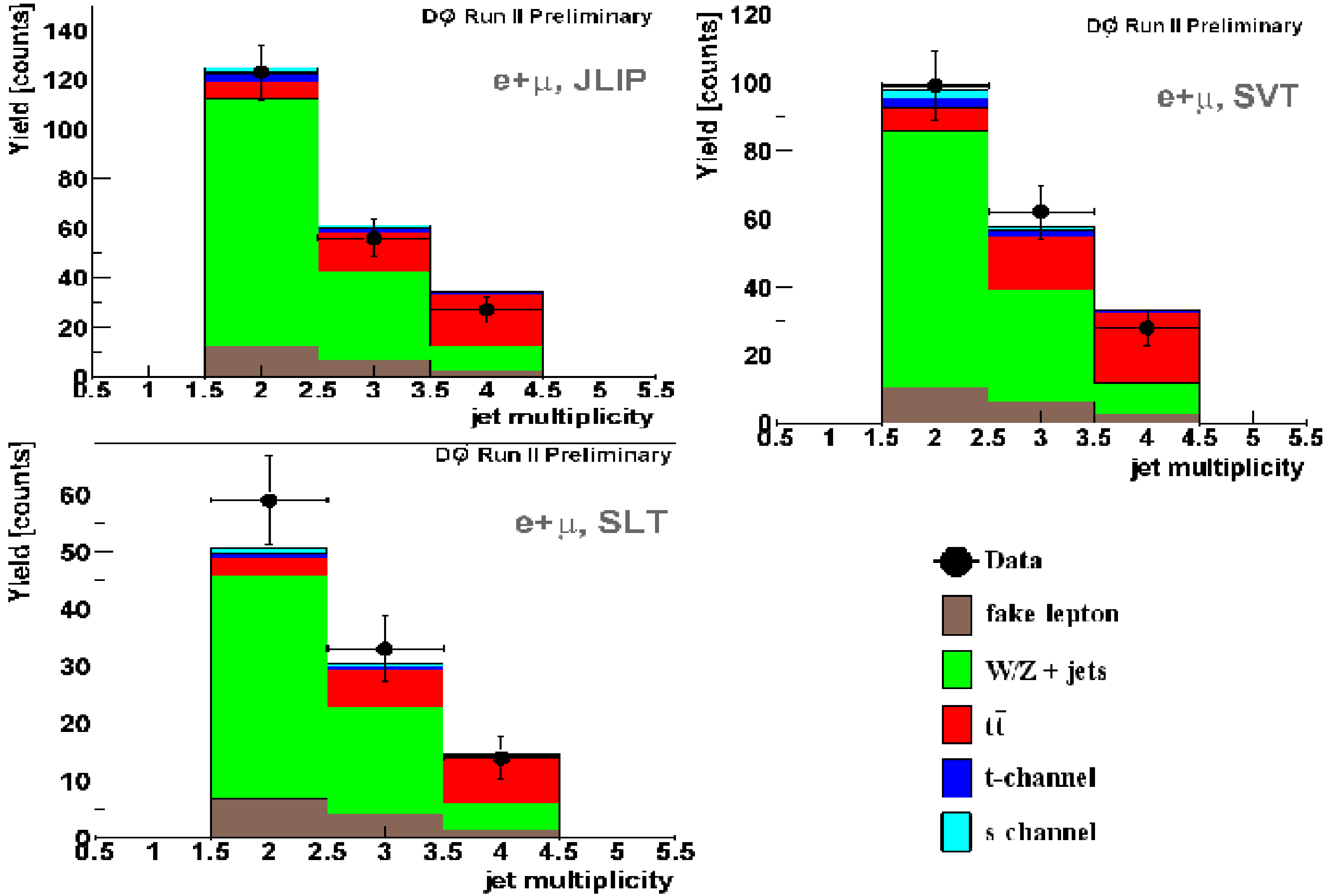
Standard Model Background Estimation

- Based on data as much as possible
- W/Z+jets production (real-*l*)
  - Estimated from data (DØ)
    - Distributions from untagged sample
    - Normalization from preselected sample
    - Tag probability from QCD sample
- Mis-reconstructed multi-jet events (fake-*l*)
  - Estimated from data
- Top-pair production
  - Estimated from MC
- Other (WZ, WW, Zττ, cosmic rays,...)
  - Included in data W/Z+jets estimate (DØ)

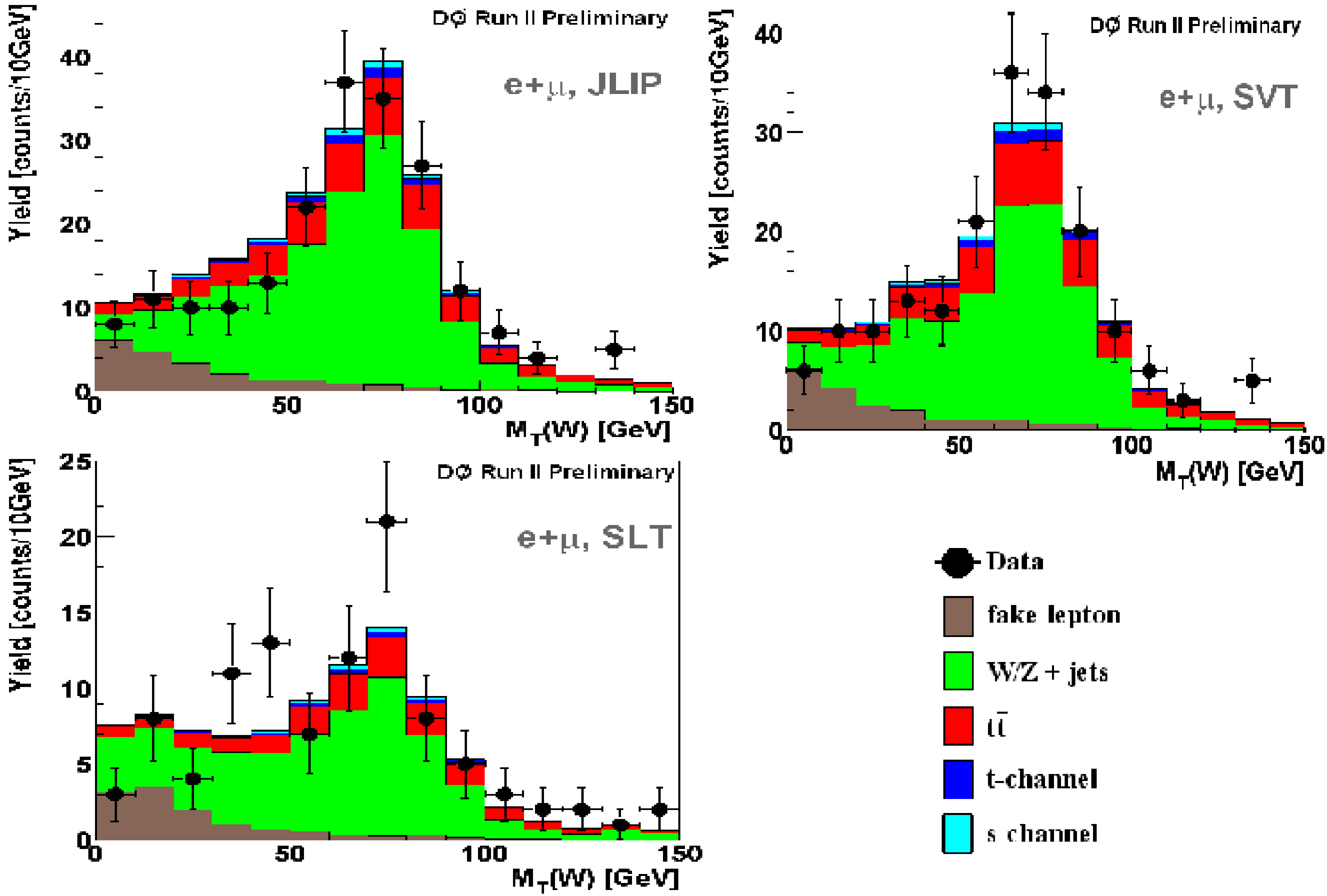




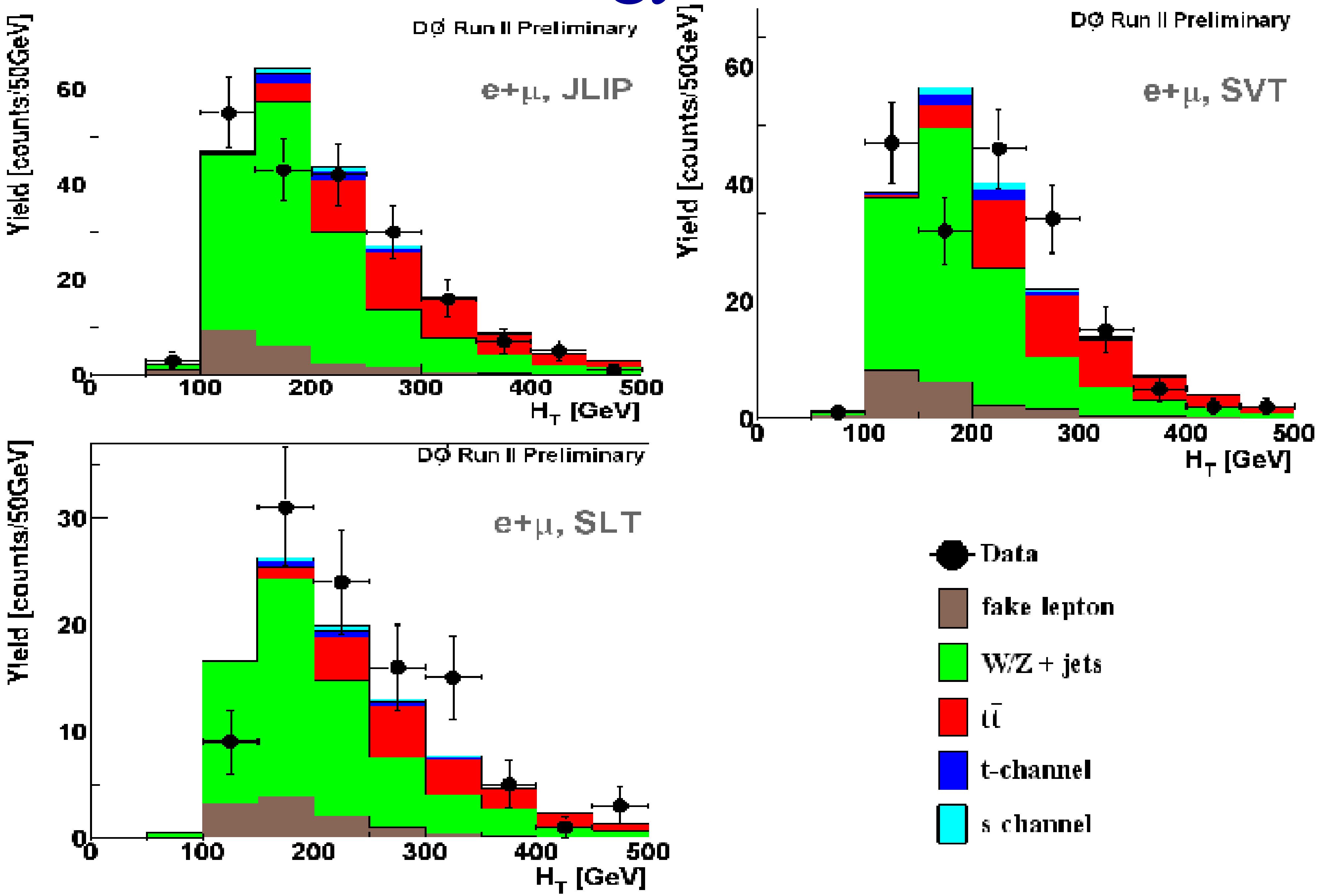
Event Yields after Preselection



W Reconstruction after Preselection

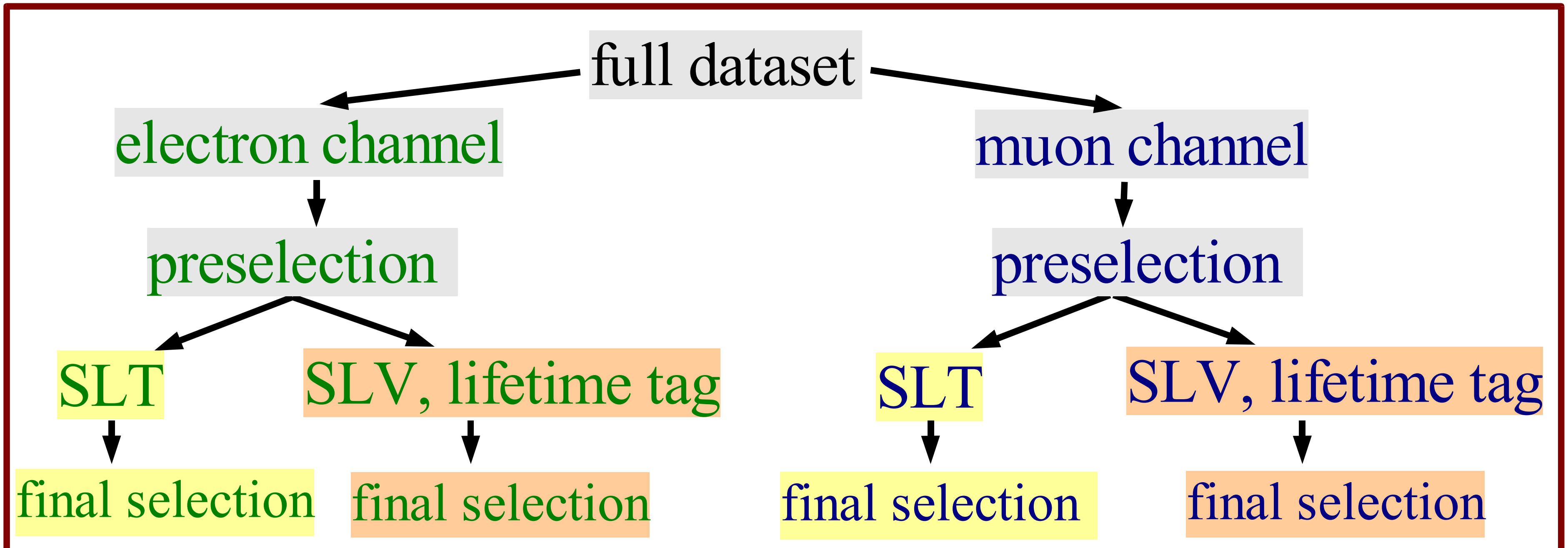


Transverse Energy after Preselection



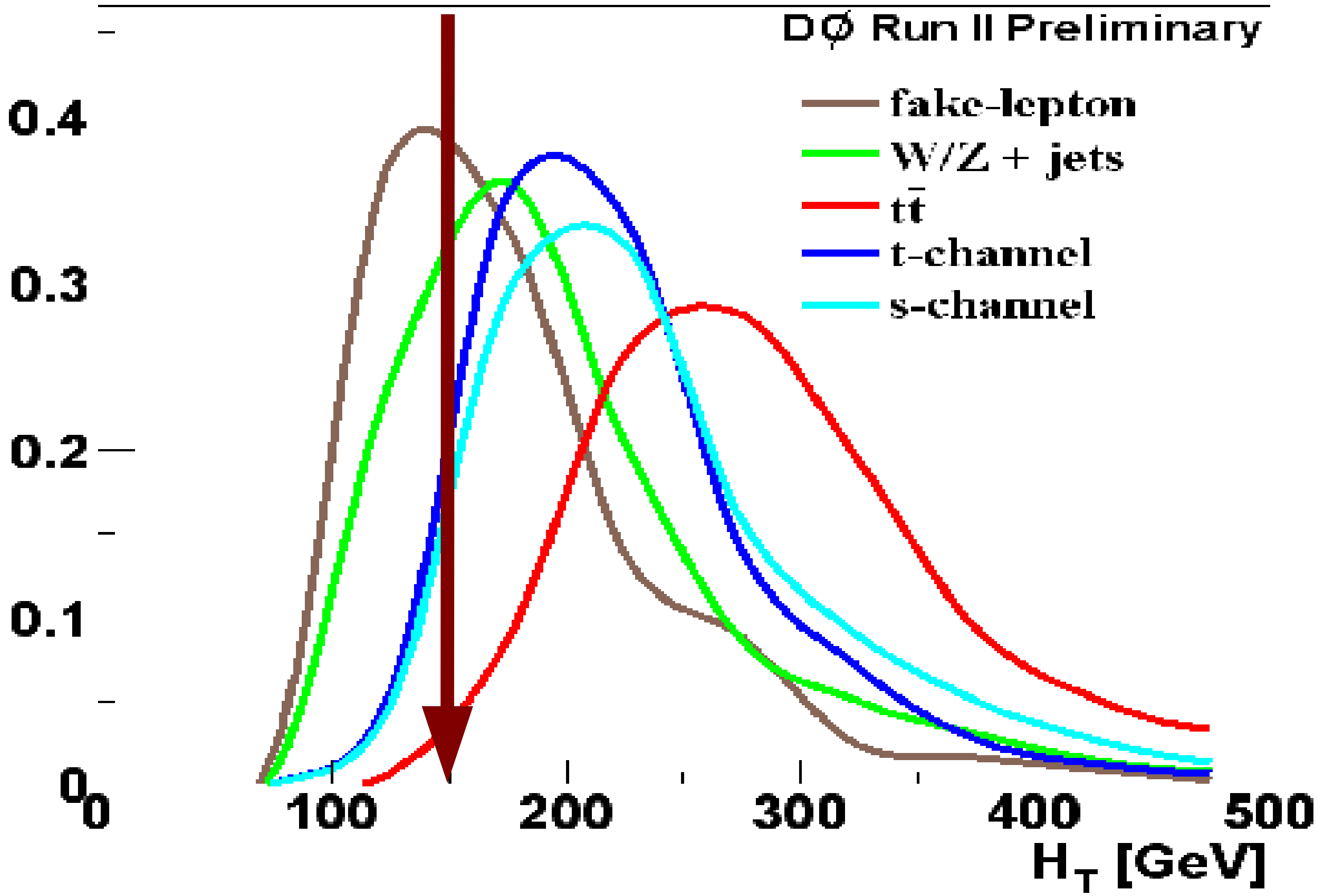
DØ Single Top Search Strategy

- Split data into orthogonal channels
  - Separate by lepton
  - Separate by b-tagging
- Background estimation
- Final event selection



Sensitive Variable: Transverse Energy

- Select simple final variable that shows good signal-background separation
  - Reject main background from W+jets: H_T>150GeV

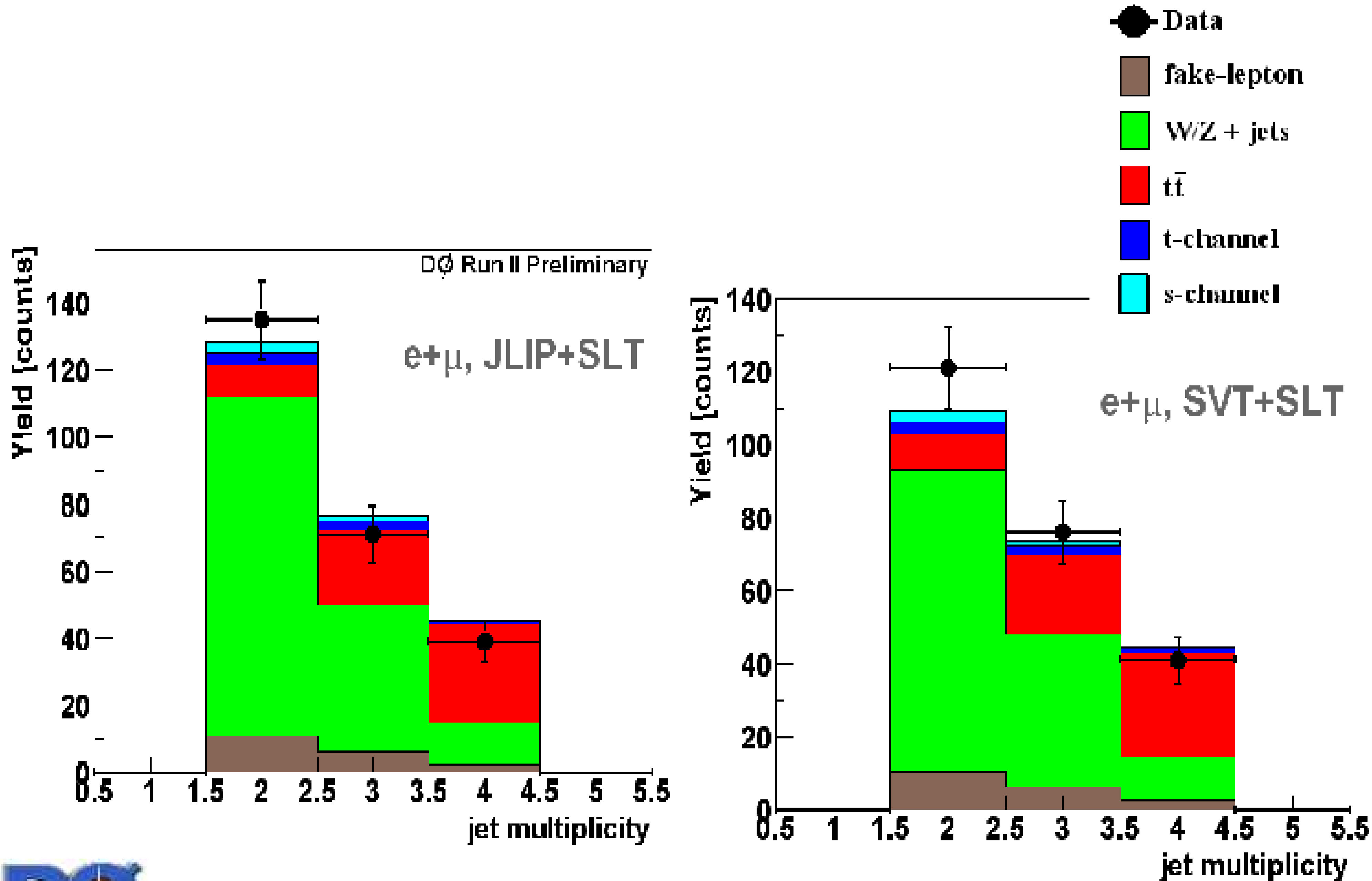


Final Event Yields

combined Electron and Muon Event Yields

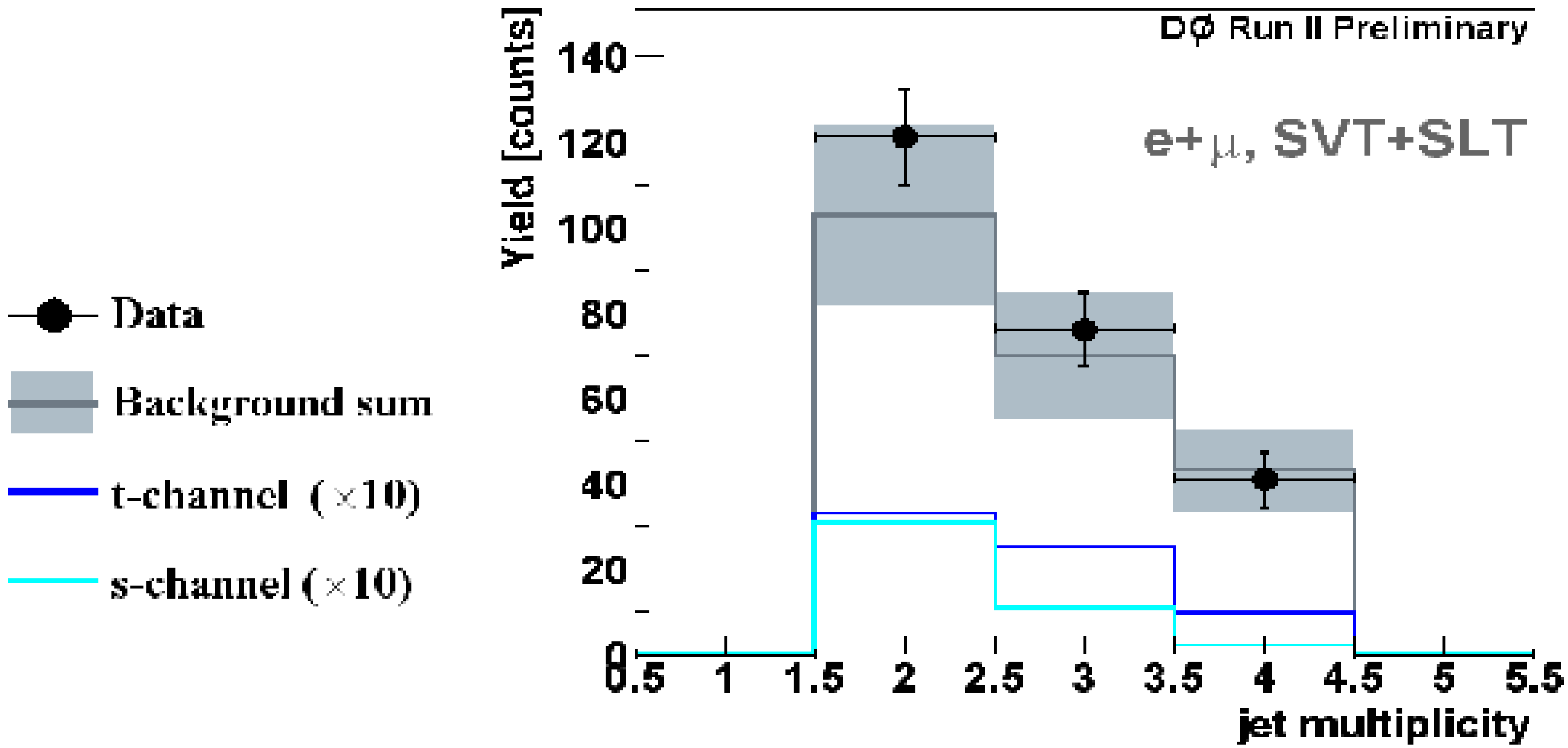
	SLT	SVT	JLIP
Signal			
s-channel	1.3±0.2	3.1±0.5	3.1±0.5
t-channel	1.7±0.3	5.2±0.9	5.3±0.7
s+t combined	3.0±0.4	8.3±1.4	8.4±1.3
Backgrounds			
W/Z+jets+fake-l	59±7	94±13	122±17
top pairs	18±3	43±6	44±7
Sum of Backgrounds	76±8	137±15	166±19
Observed event yield	97	138	148

Event Yield after Final Selection



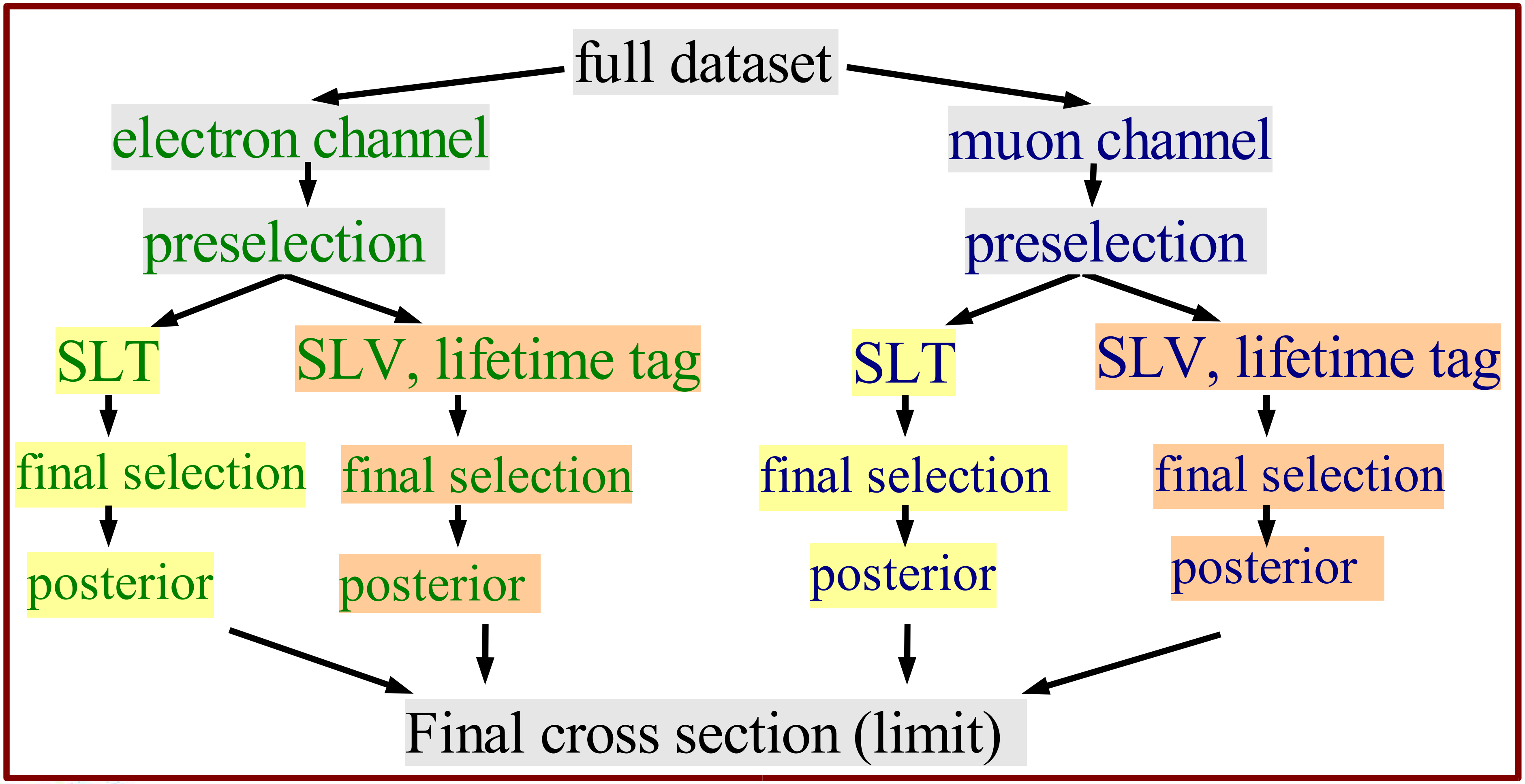
Systematic Uncertainties

- Signal acceptance and Monte Carlo Backgrounds
  - Jet Energy Scale ~10%
  - Trigger Modeling ~10%
  - Tagger Modeling ~10%
  - Object ID ~ 5%
  - Background normalization ~20%



DØ Single Top Search Strategy

- Split data into orthogonal channels
- Final event selection
- Derive likelihood in each channel, then combine for result



Final Result

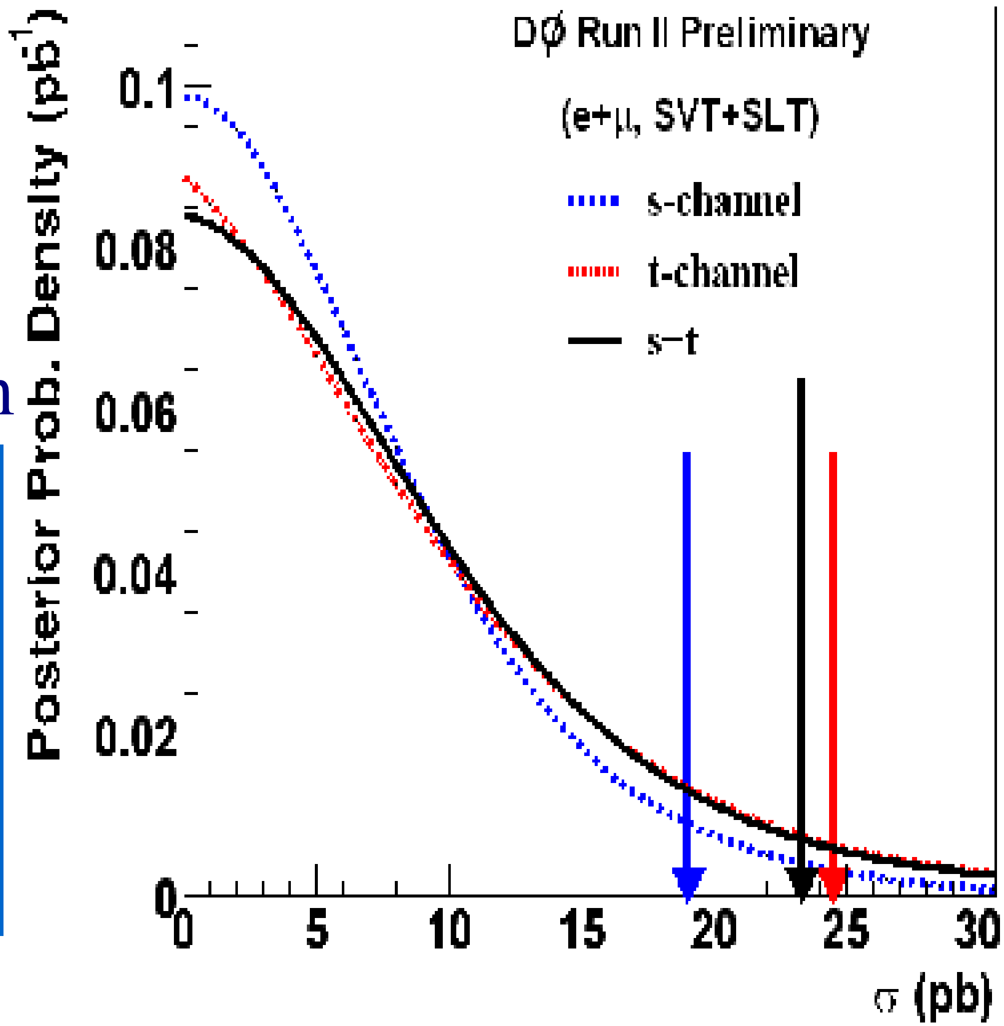
- No evidence for single top production
- Set 95% CL limit on production cross section
  - Using event counting
- Include systematic uncertainties
  - And all correlations
- Bayesian limit setting approach

observed/expected limit:

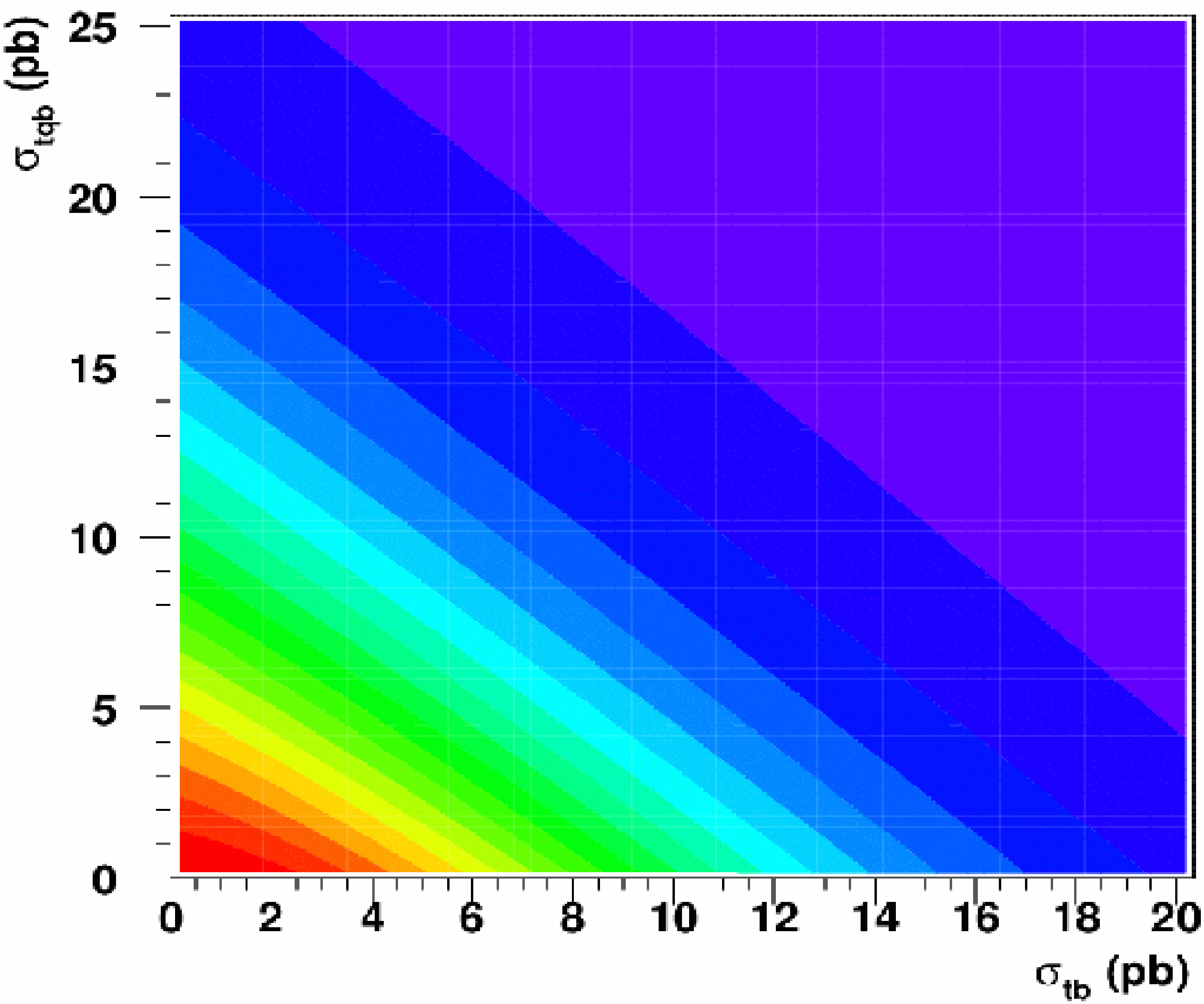
$\sigma_s < 19 / 16$ pb

$\sigma_t < 25 / 23$ pb

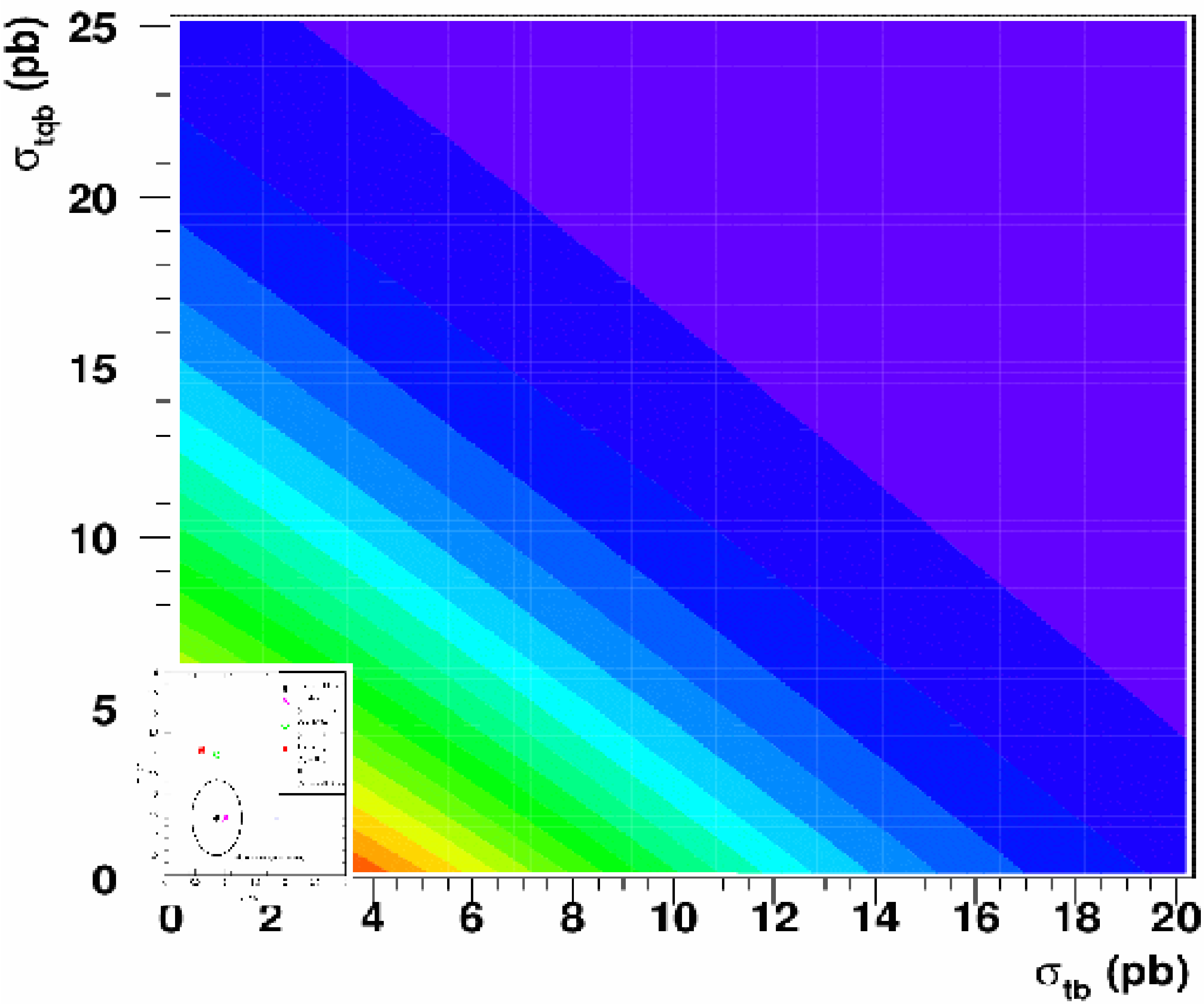
$\sigma_{s+t} < 23/20$ pb



s-channel vs t-channel



s-channel vs t-channel



Questions

- Do we understand our backgrounds?
  - Especially *W*+jets
    - Normalization and flavor composition
    - Flavor composition assumption in data: W+jets vs QCD multi-jet
      - Uncertainty?

Questions

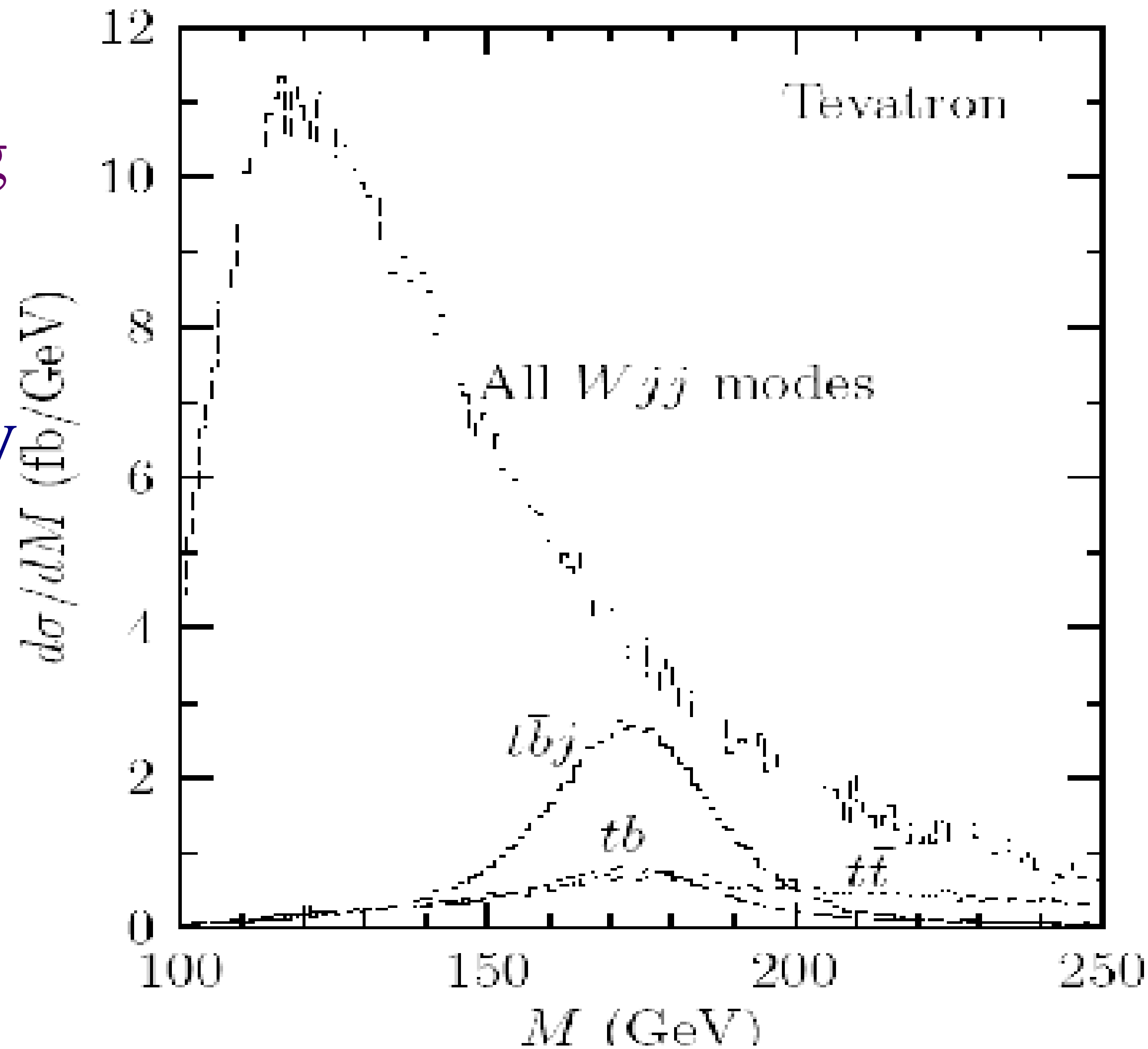
- Do we understand our backgrounds?
  - Especially *W*+jets
- Do we understand our signal?
  - LO MC generators vs NLO shapes

Questions

- Do we understand our backgrounds?
  - Especially *W*+jets
- Do we understand our signal?
  - LO MC generators vs NLO shapes
- When are we going to observe Single Top?

Single Top – Expectation

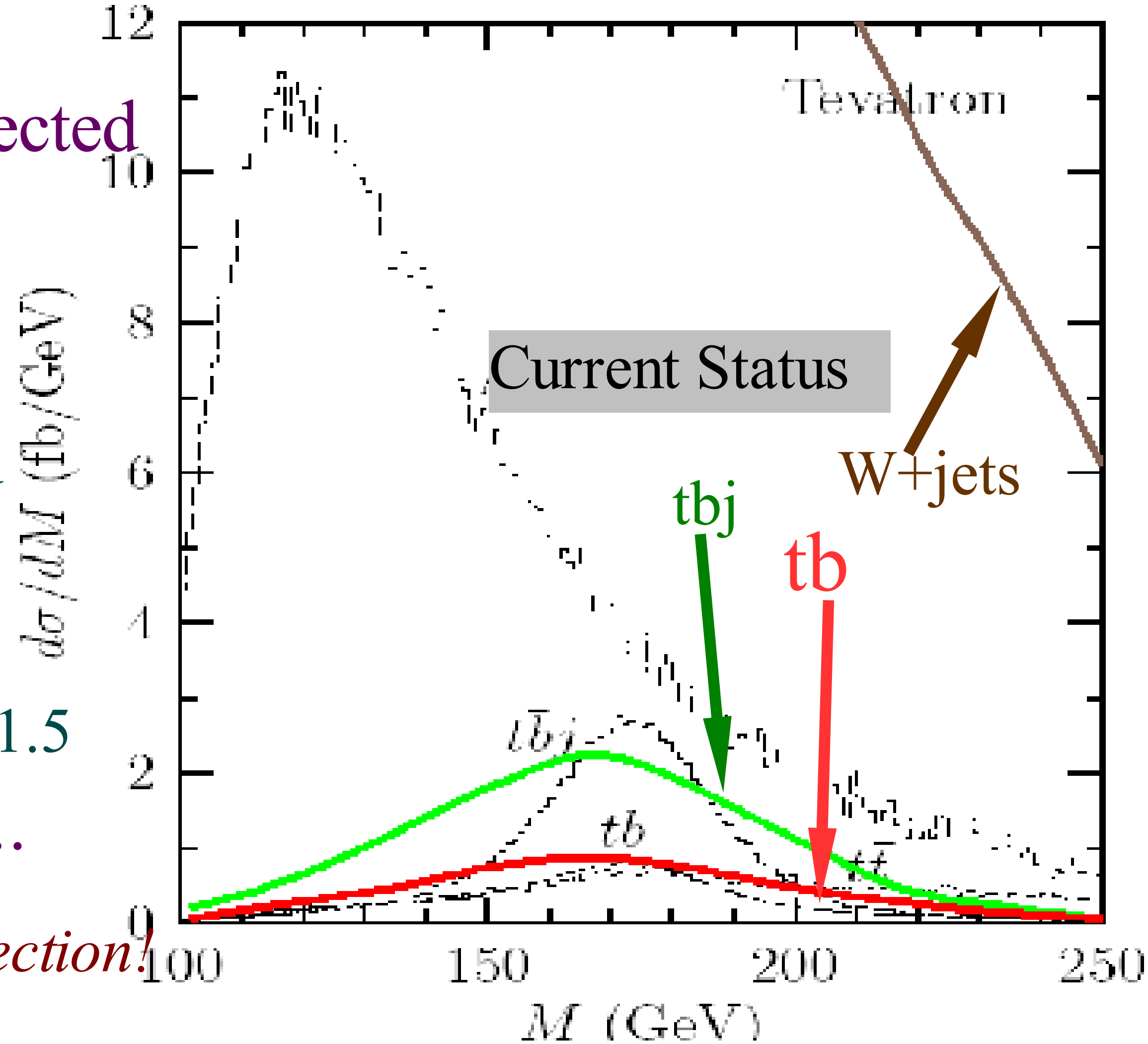
- Predictions for Run II were to be sensitive to single top production with ~500pb^{-1} – *Where is it?*
  - Observation with 2fb^{-1}
  - Starting to be interesting much sooner
- We have recorded >400pb at DØ already
  - Observation soon?



Stelzer, Sullivan, Willenbrock, PRD58 (98)

Single Top – Expectation vs Reality

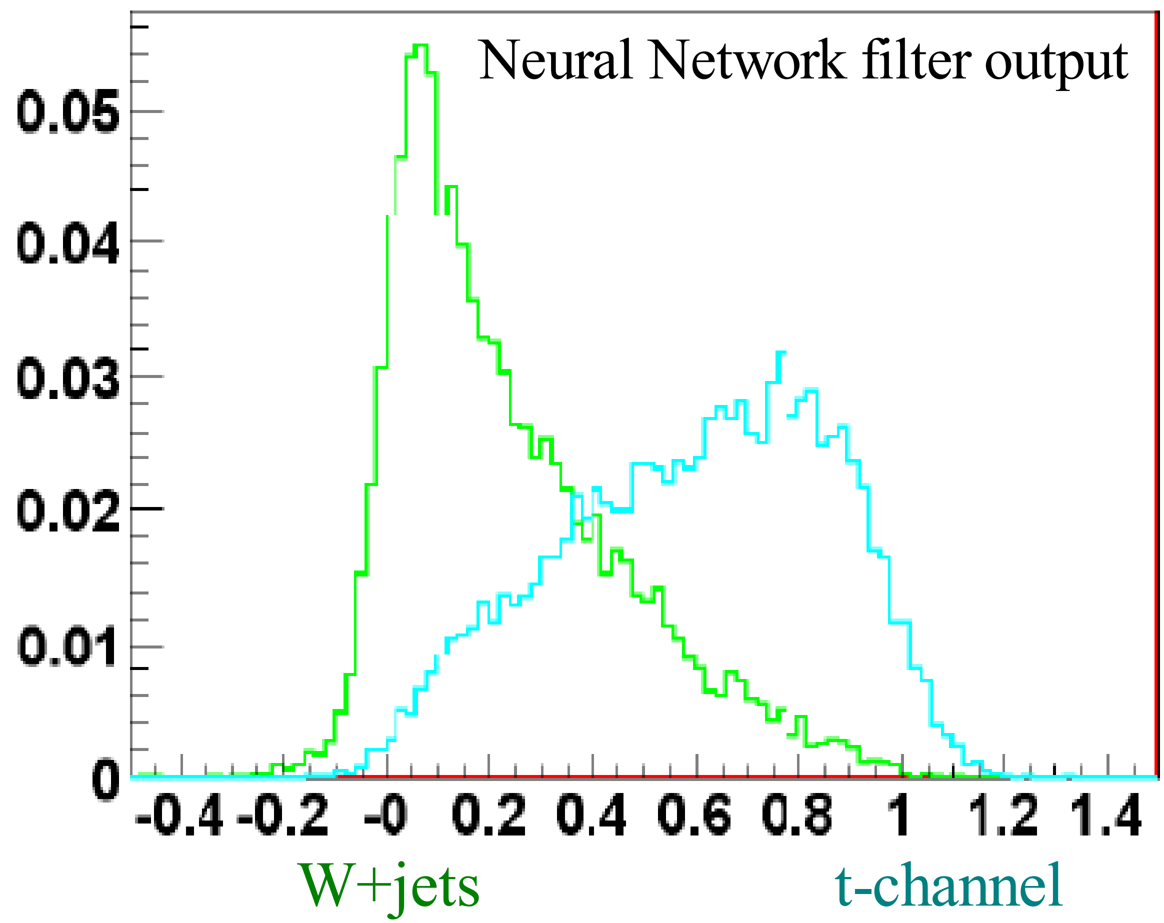
- Predictions for Run II were to be sensitive to single top production with ~500pb^{-1} – *Where is it?*
  - Detector performance not (yet) as good as expected
    - b-tagging ~45% per jet
    - Trigger, ID <100%
    - Jet resolution not (yet) as good as expected
  - W+jets background larger than expected
    - NLO calculations: LO×1.5
  - Top mass, gluon PDF, …



Many effects, all in the wrong direction!

Single Top – Advanced Final Analysis

- DØ currently working on significantly improving the final analysis
  - Current focus on multivariate techniques: Neural Networks
  - Reduce background by factor ~20 and keep ~30% of signal
- Other improvements in the future
  - Acceptance, efficiency
  - Resolution
  - Other multivariate techiques



Questions

- Do we understand our backgrounds?
  - Especially *W*+jets
- Do we understand our signal?
  - LO MC generators vs NLO shapes
- When are we going to observe Single Top?
  - Expect visible excess at about 1fb^{-1}
    - In ~1.5 years
  - Luminosity required for observation >2fb^{-1}
  - We are continuing to work on further improvements

Conclusions/Outlook

- Single Top is an exciting opportunity for Run II
  - A lot of interest, both theoretical and experimental
- The DØ Run II Single Top Search is under way
  - Detector and trigger working, understood
  - First pass analysis with 160pb^{-1} completed
    - Not yet sensitive to single top production
- Currently working on analysis improvements
  - Improved final selection methods
  - Increased dataset and acceptance