

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
- Conclusions/Outlook



Introduction

- The Top Quark is the heaviest elementary particle found to date
 - As heavy as a gold atom
 - Discovered in 1995 by CDF and DØ at the Fermilab Tevatron
- 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)

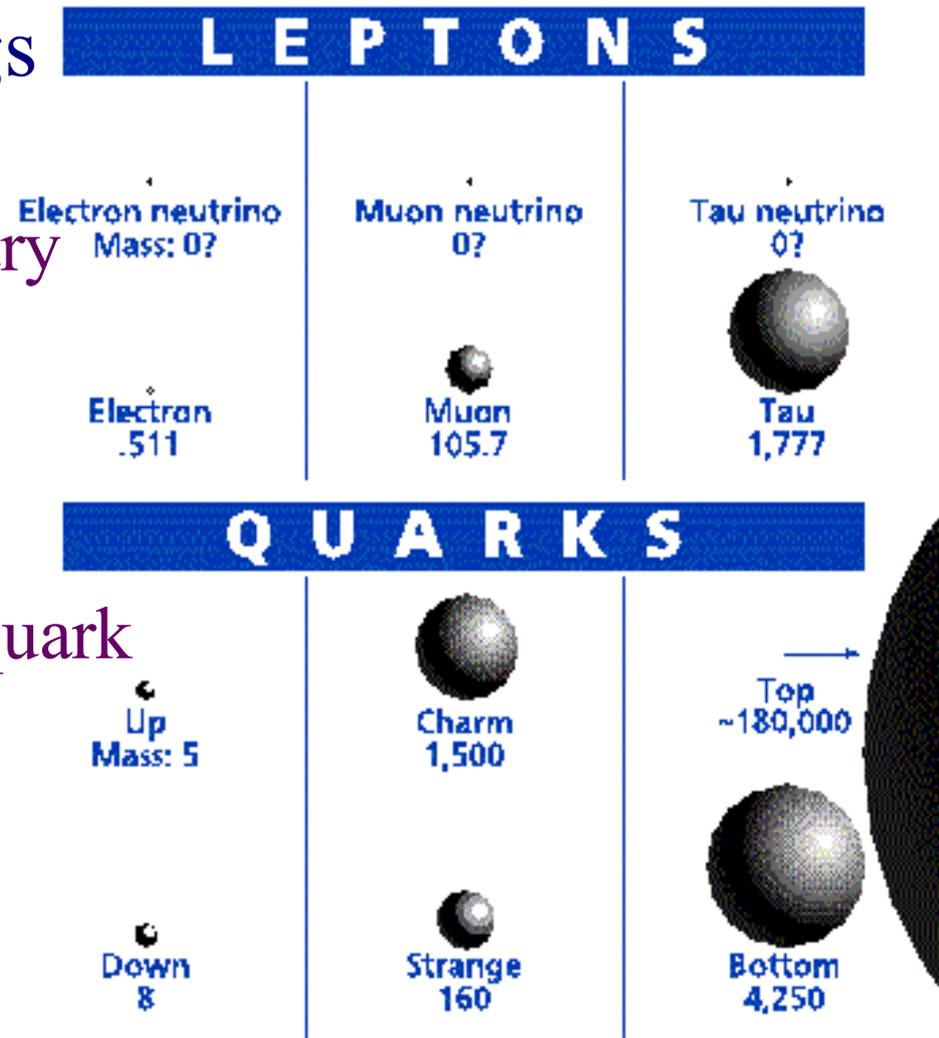


The Top Quark



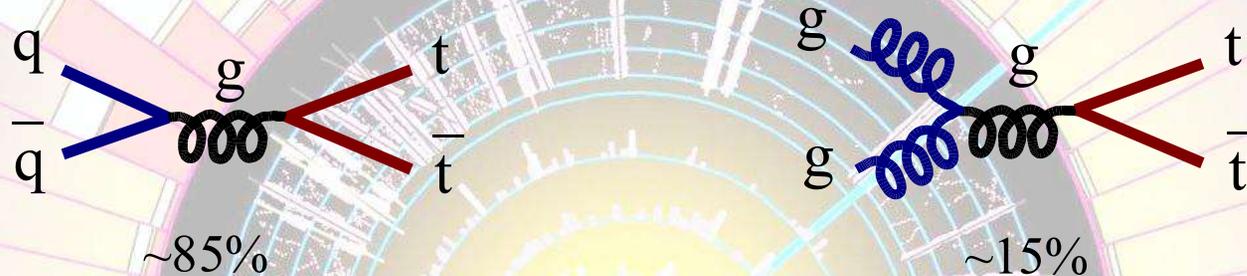
KING OF FERMIONS

- 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

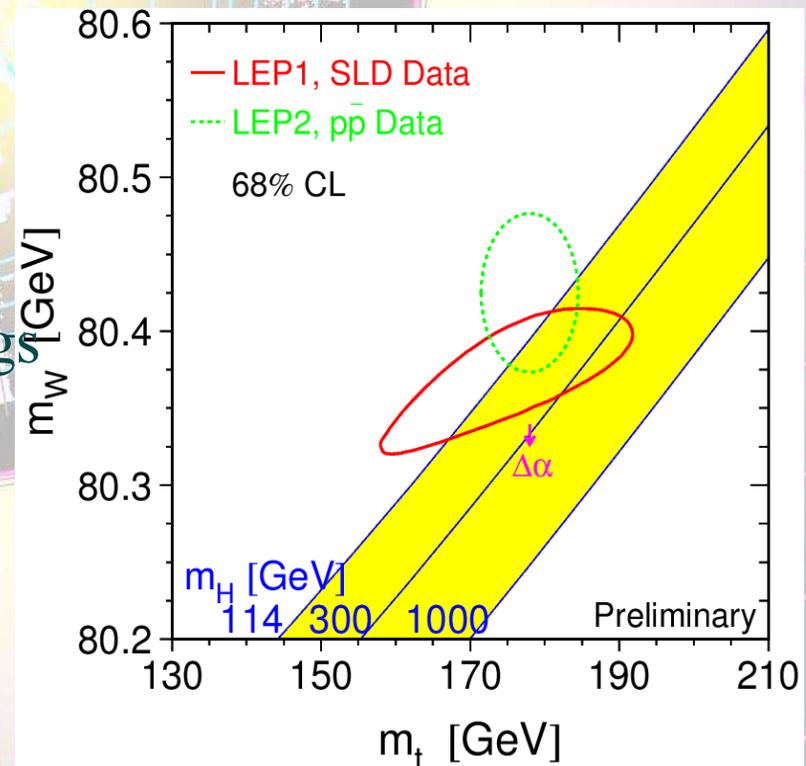
- Production cross section

- Test of QCD

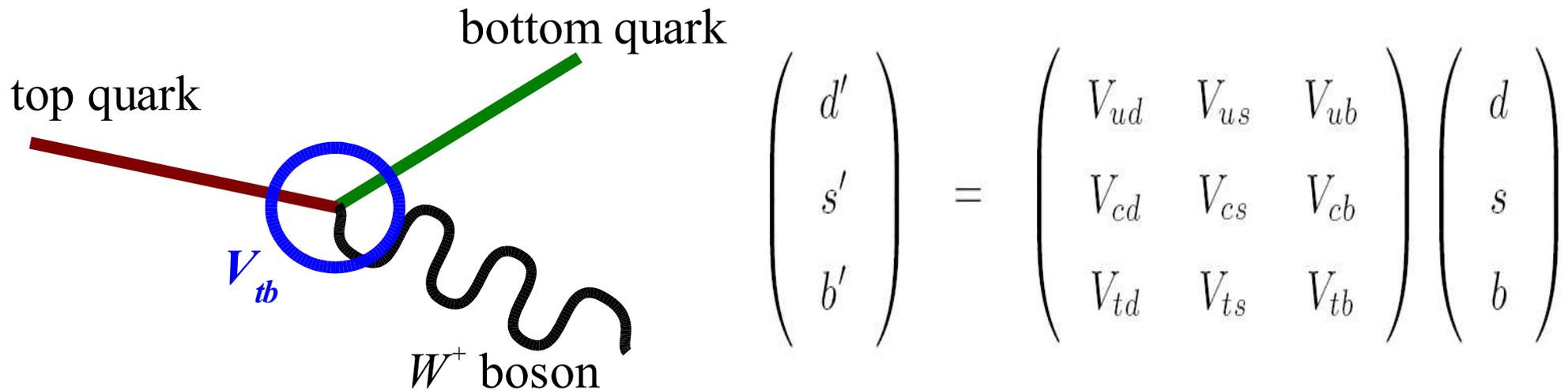
- Top mass measurements

- Implications for Standard Model Higgs

- W helicity measurement



Top Quark Electroweak Interaction



- Weak Interaction Eigenstates are not Mass Eigenstates

- Top quark must decay to a W plus 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:

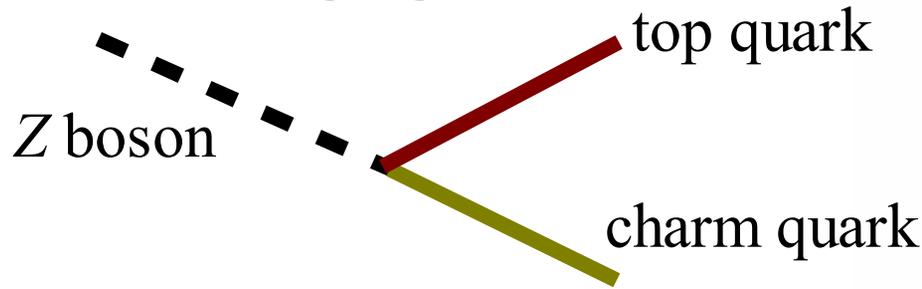
$$V_{td}^2 + V_{ts}^2 + V_{tb}^2 + V_{tx}^2 = 1$$

- No constraint on V_{tb}

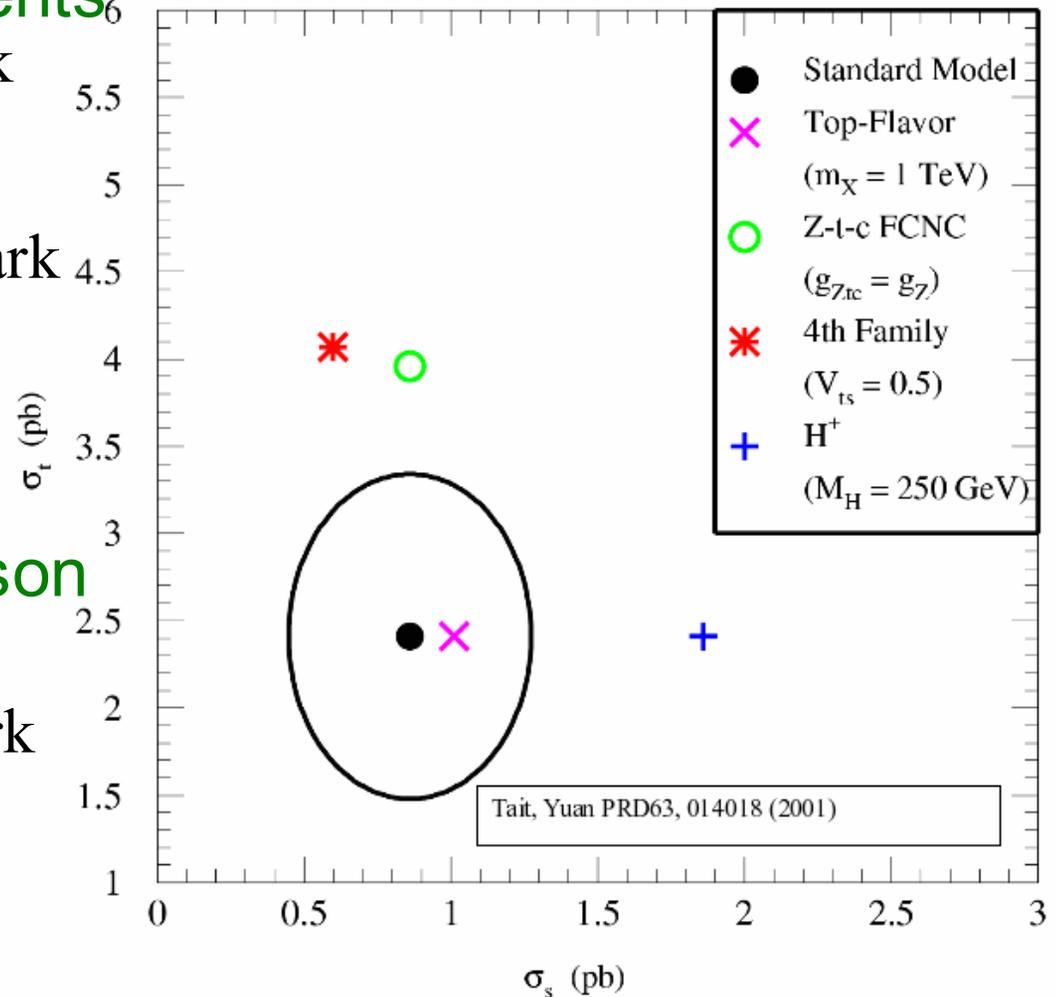
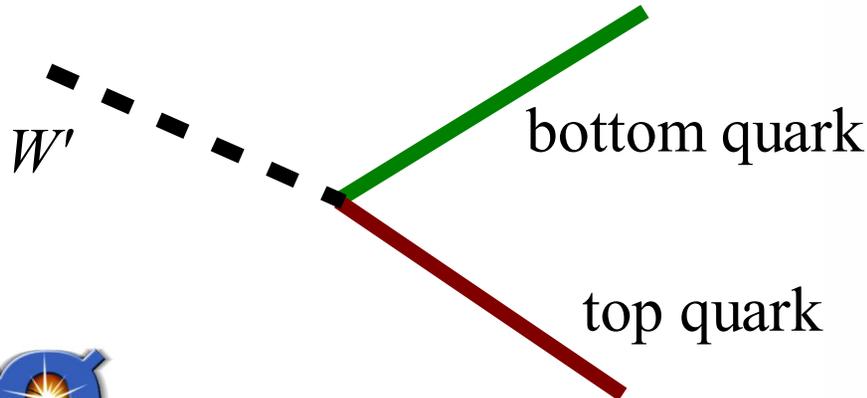
Non-Standard Model Single Top

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

Flavor-Changing Neutral Currents



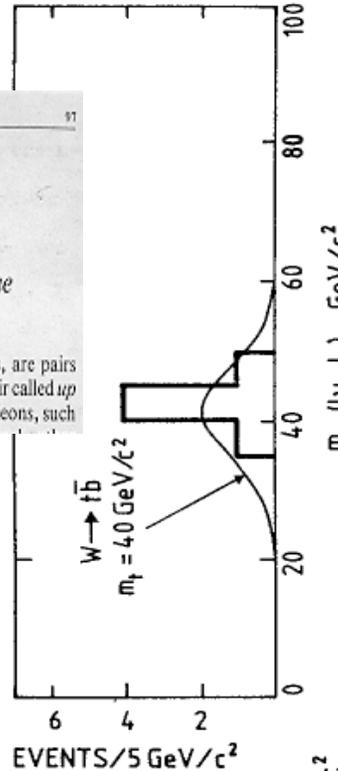
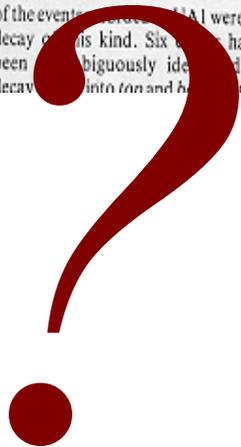
Top-Flavor: another vector boson



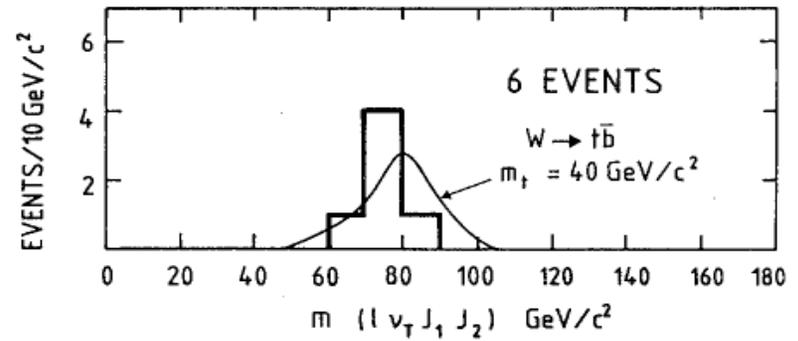
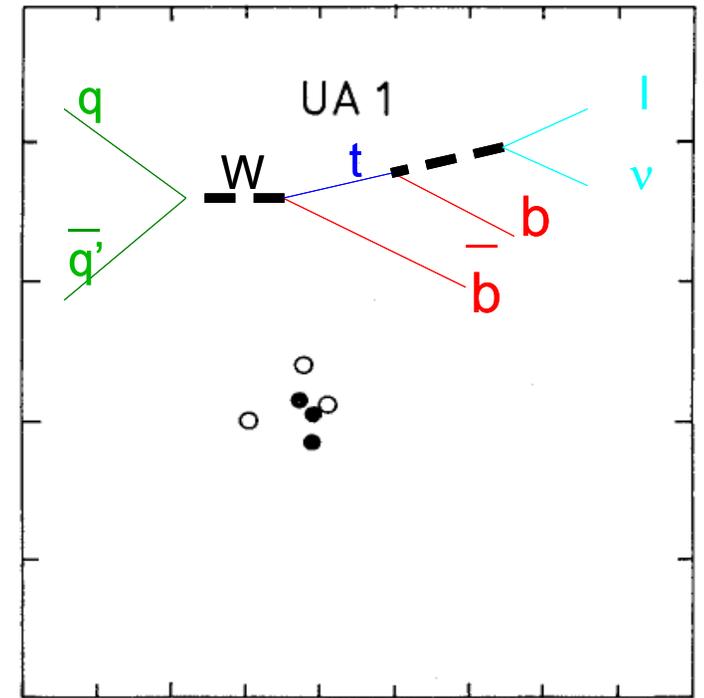
Discovery of Single Top?

- Excess of lepton+MET+2jet events at UA1 in 1984
 - Consistent with production of single top quark and bottom quark

- $M_{\text{top}} \approx 40\text{GeV}$

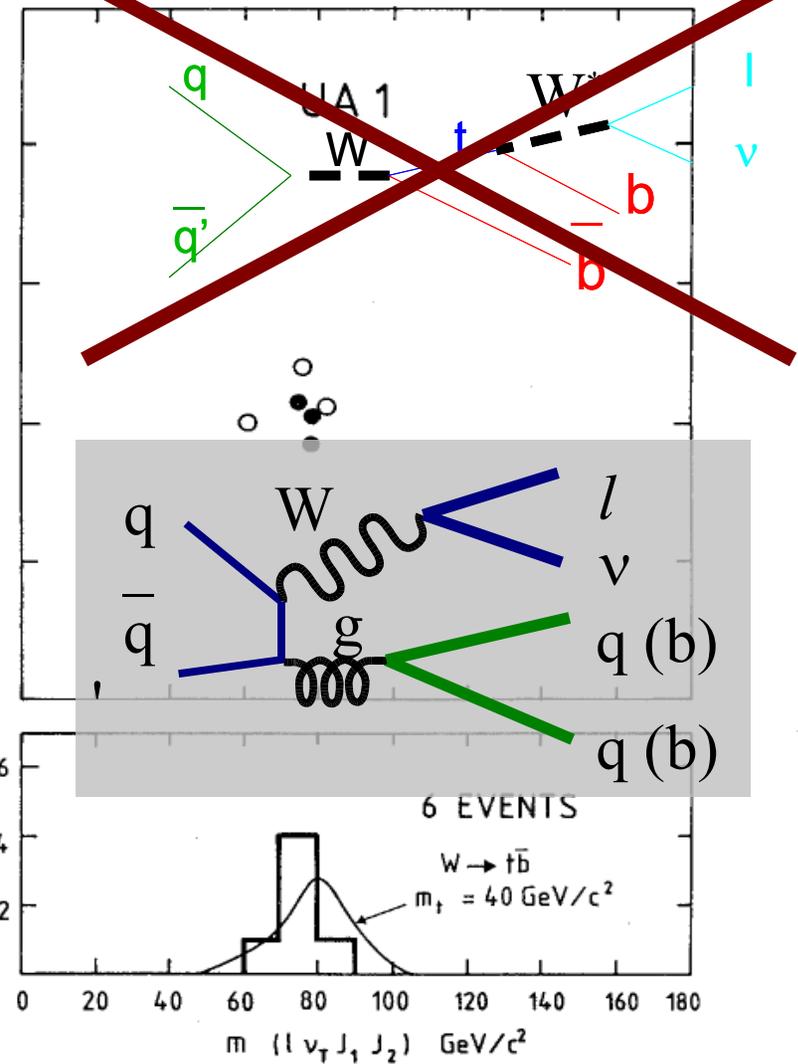
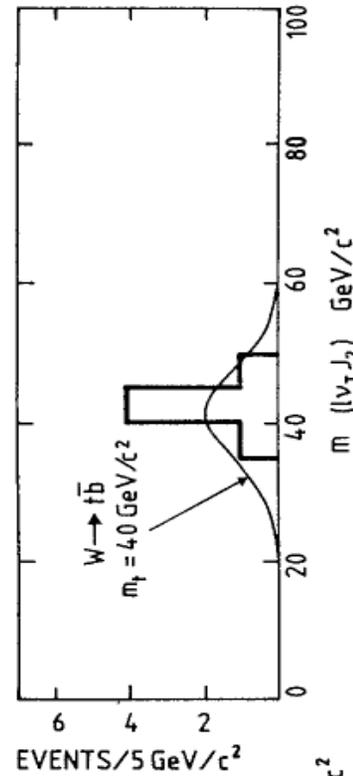


○ e + 2 jets
● μ + 2 jets



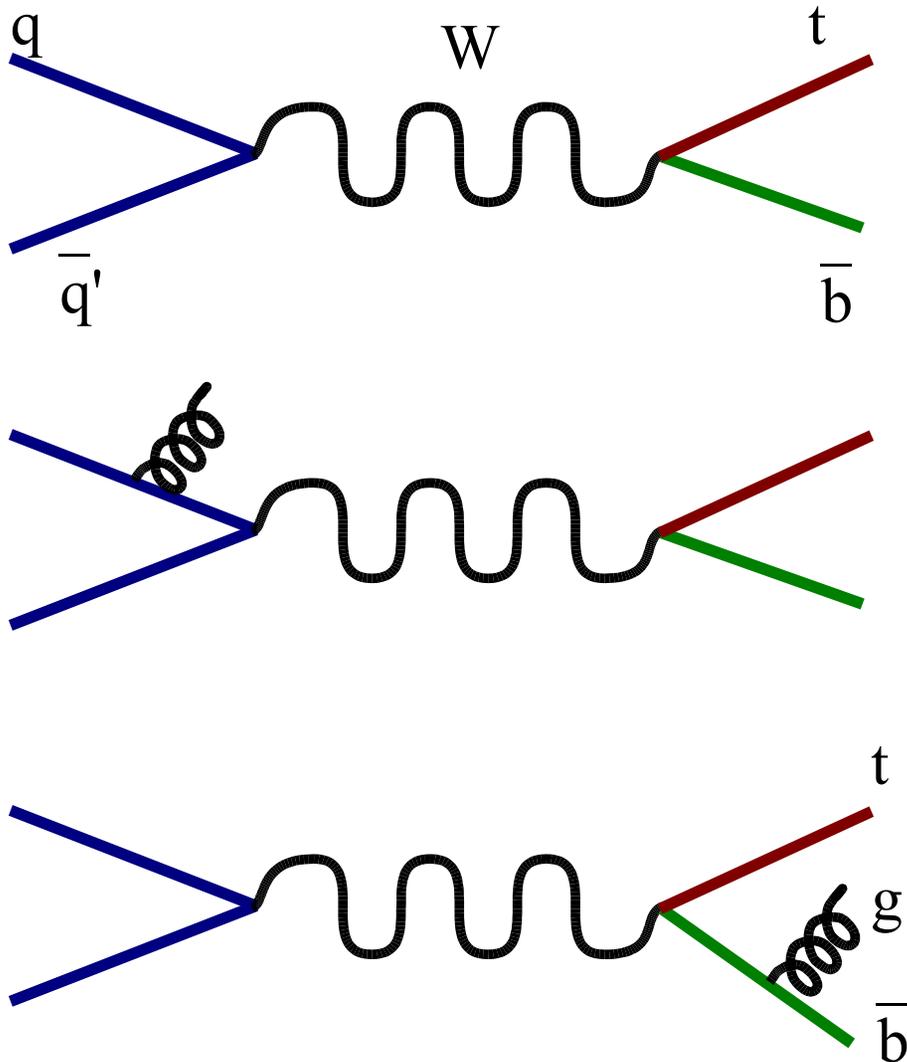
Discovery of Single Top?

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

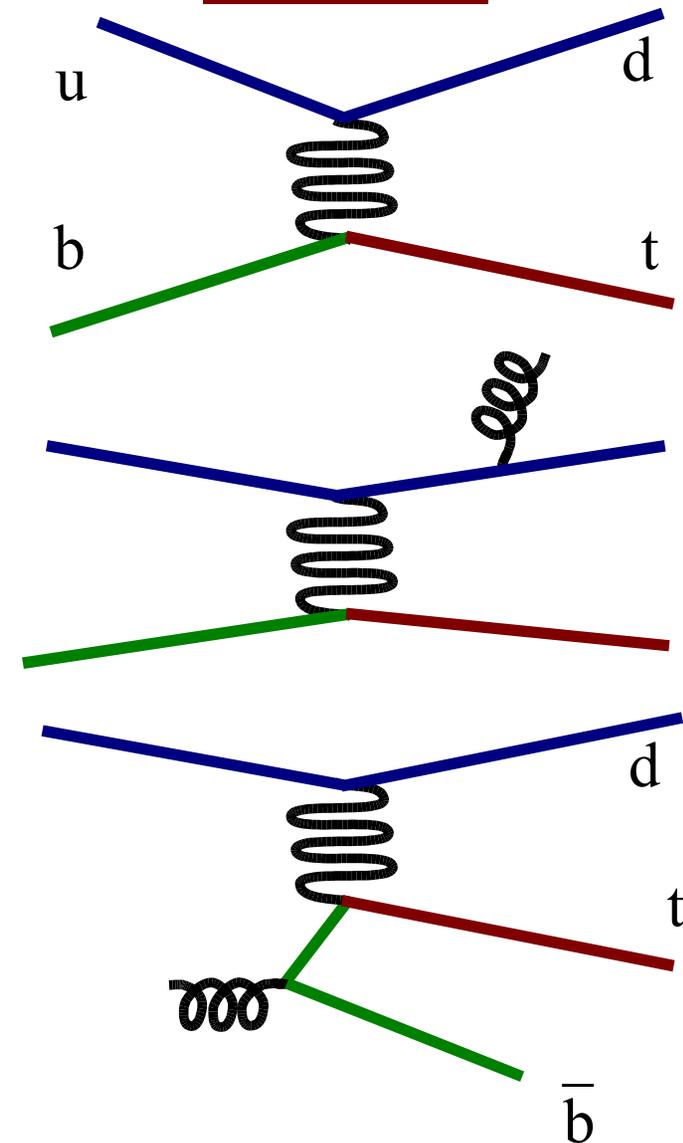


Electroweak Production of Top at the Tevatron at next-to-leading order in QCD

s-channel

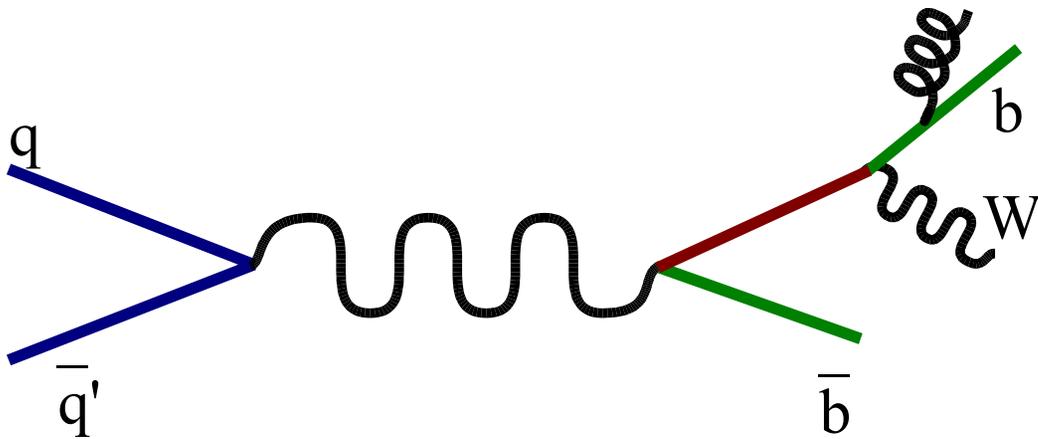


t-channel

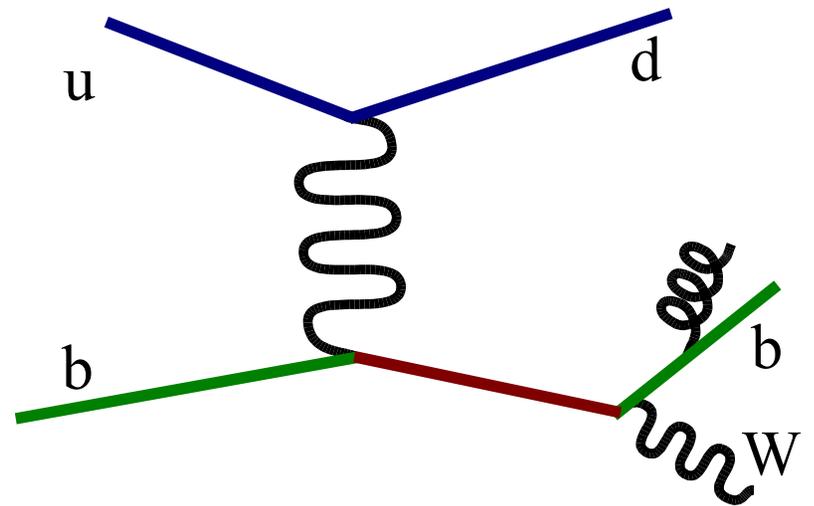


Electroweak Production *and Decay* at next-to-leading order in QCD

s-channel

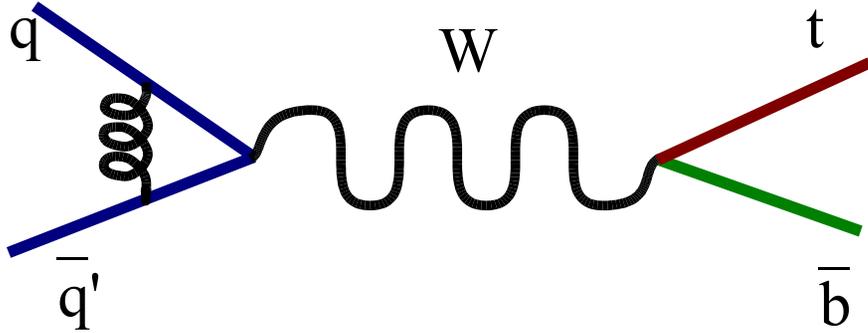


t-channel

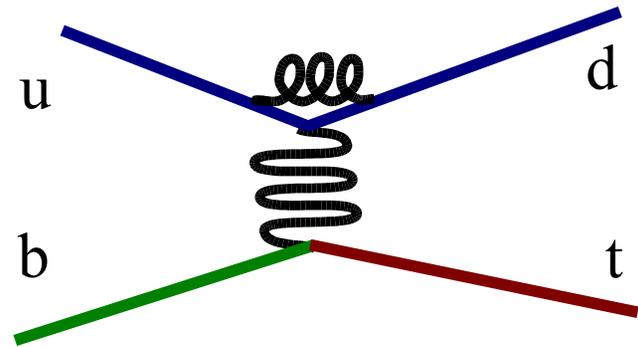


Don't forget virtual corrections

s-channel



t-channel



Relative Contributions to NLO rate including Top Production and Decay

s-channel

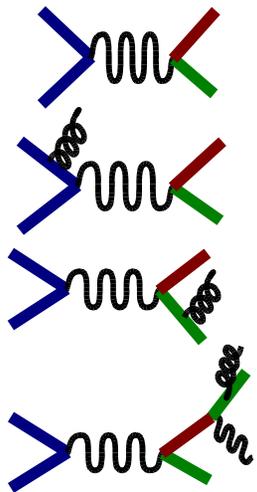
NLO rate 0.86pb

Born level 65%

Initial state 22%

Final state 11.5%

Decay 1.2%



t-channel

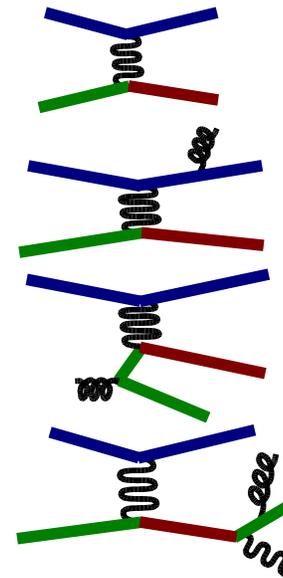
NLO rate 1.7pb

Born level 100%

Light quark 13%

Heavy quark -11%

Decay -7%

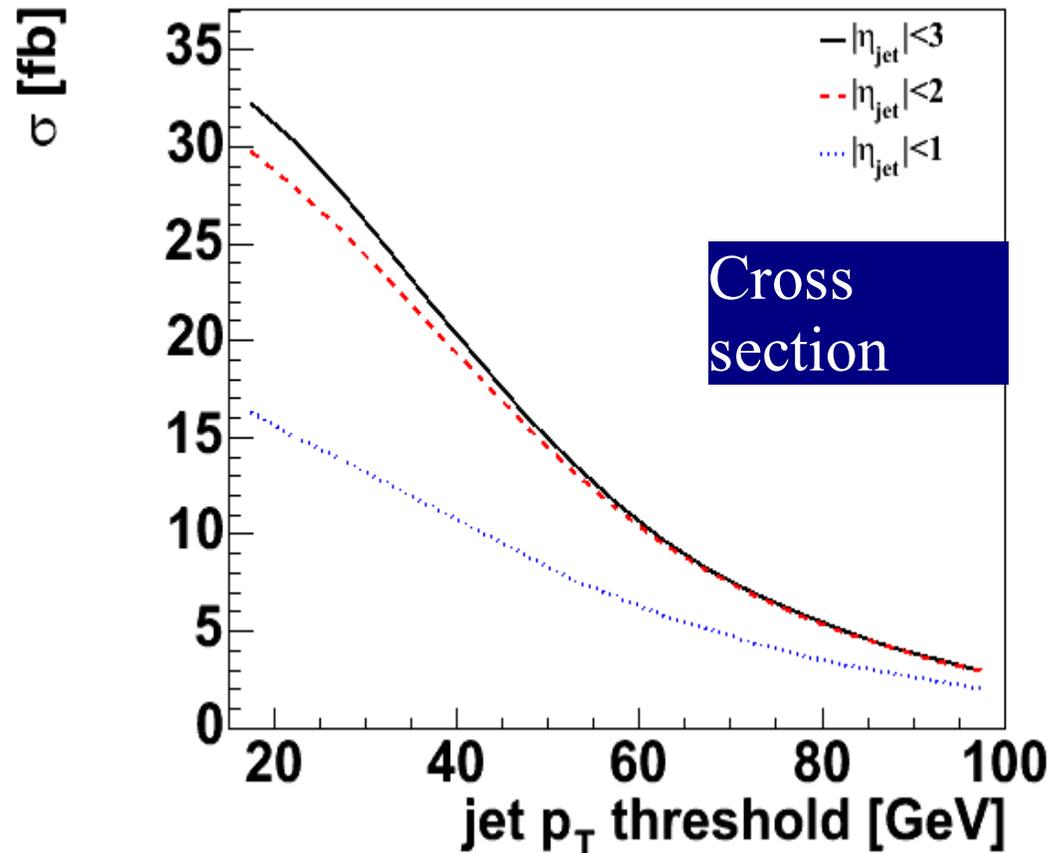
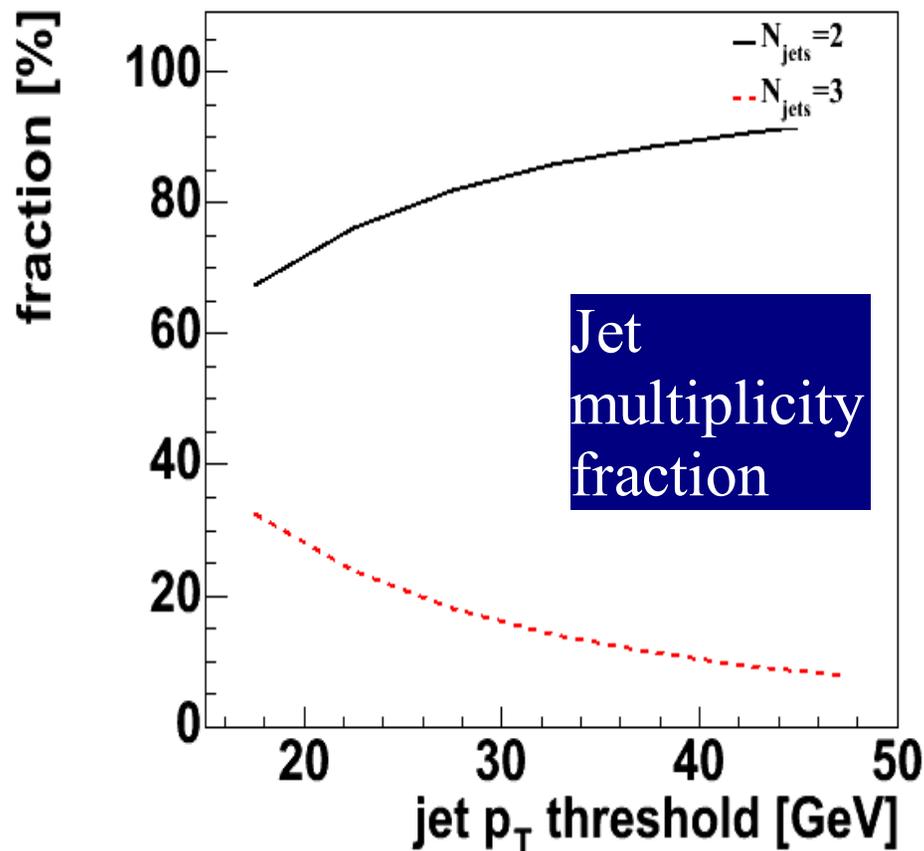


Cao, RS, Yuan hep-ph/0409040

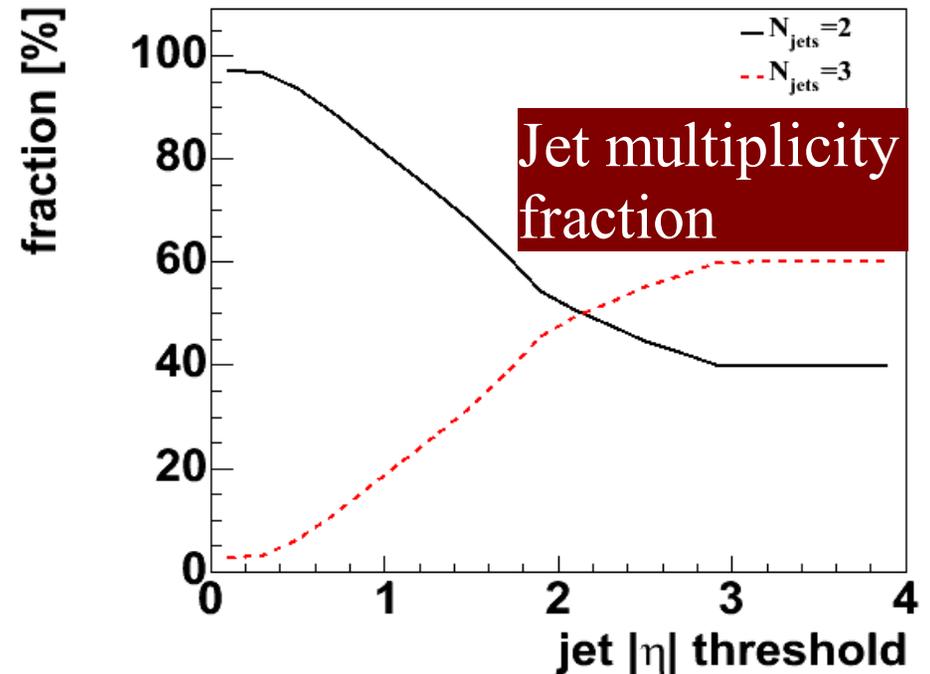
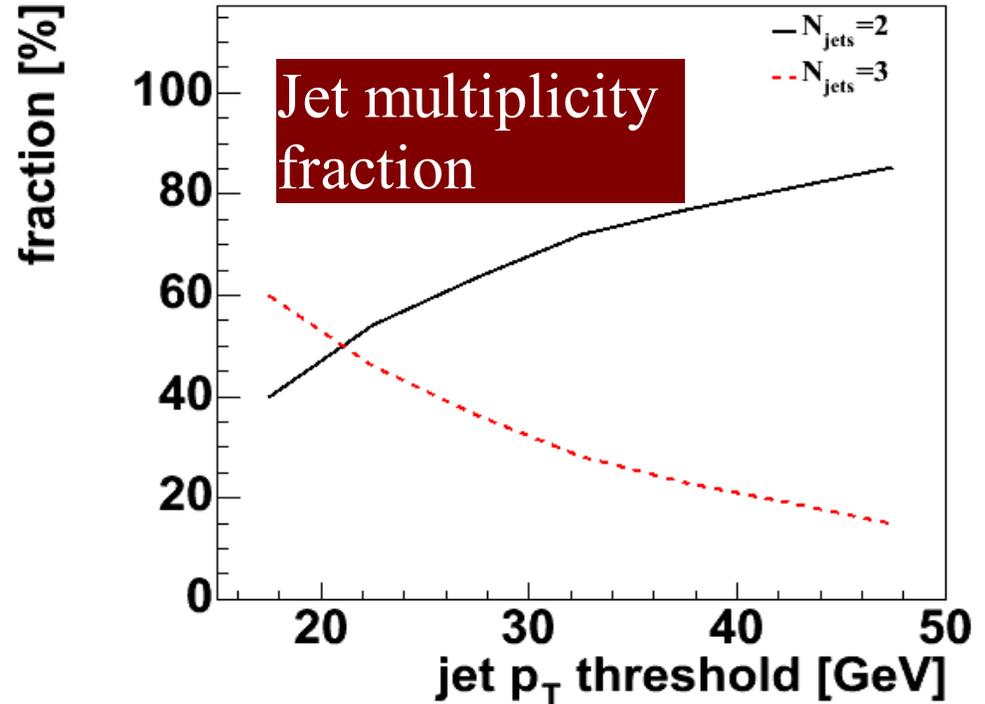
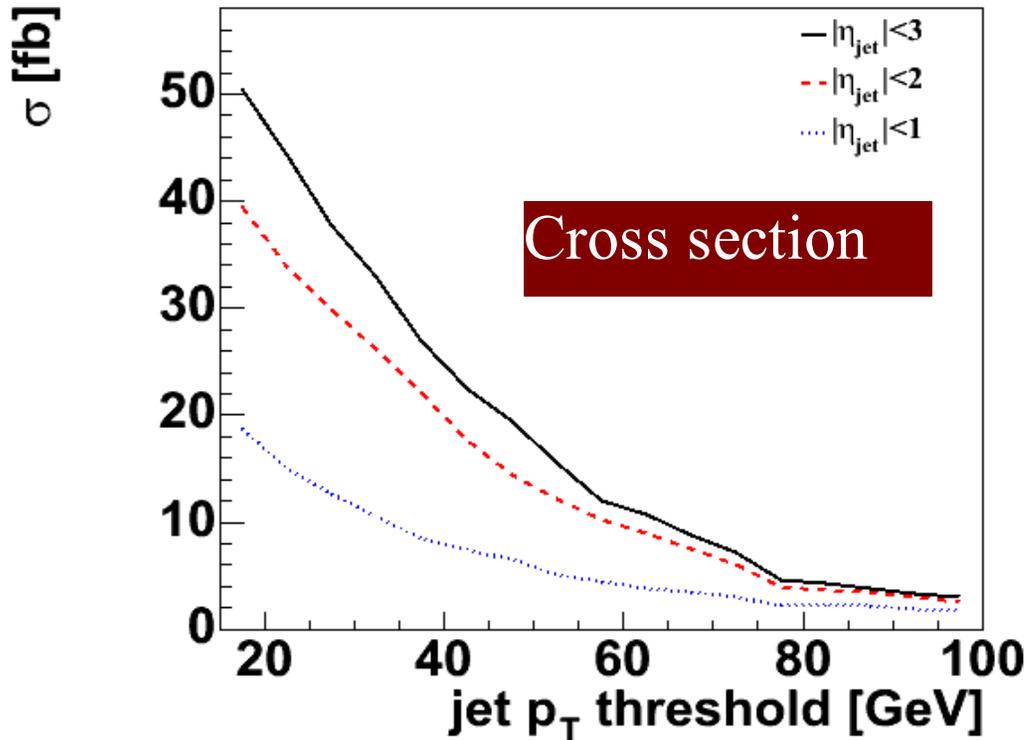
- $O(\alpha_s)$ corrections large for the s-channel
 - Only small rate correction for the t-channel
- Decay correction comparable to other corrections

Kinematic effect of NLO Corrections

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



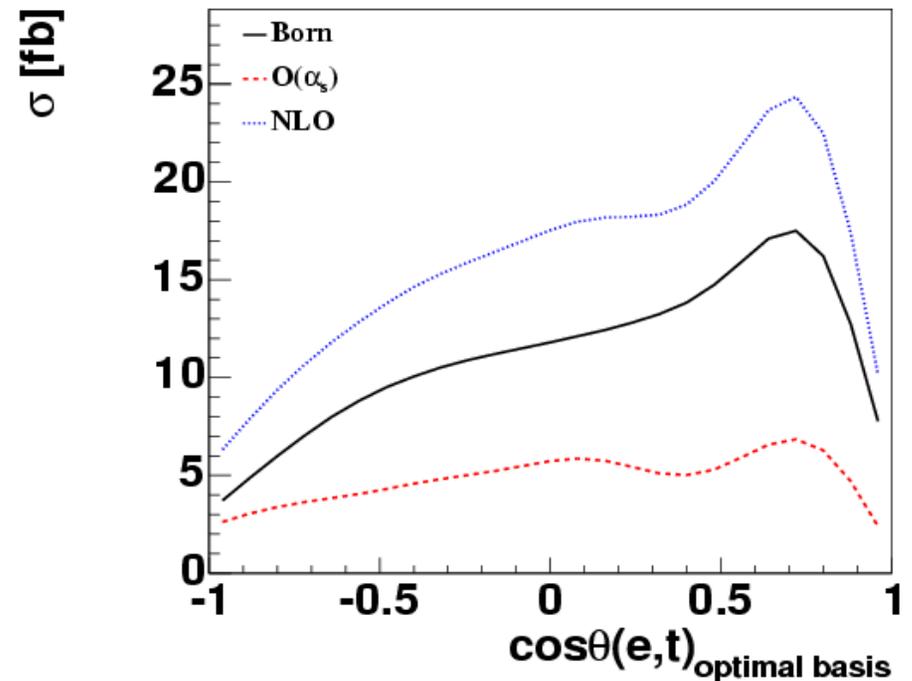
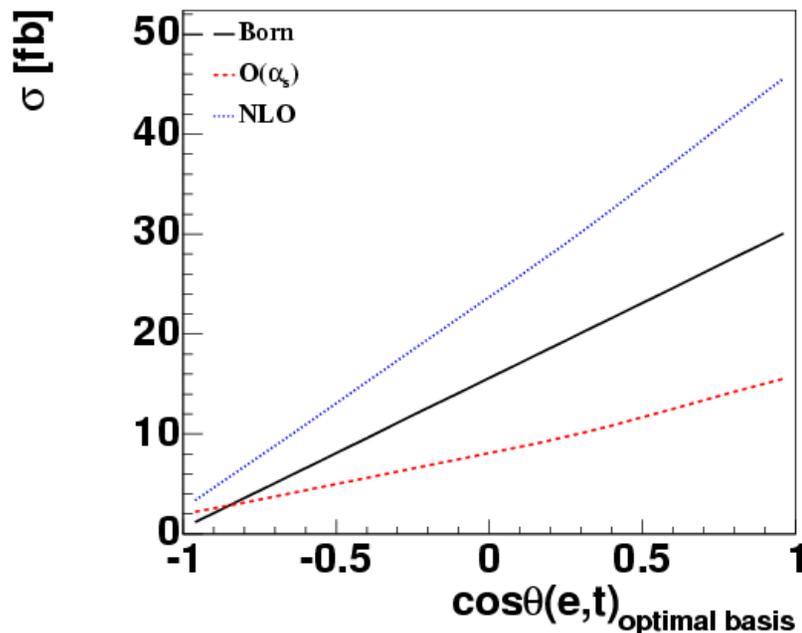
Single Top t-channel at NLO



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

Single Top s-channel spin at NLO

- Top quark decays before it hadronizes
 - Study top spin
- Observe maximum polarization in the “optimal basis”
 - Angle between lepton and incoming quark in top quark rest frame



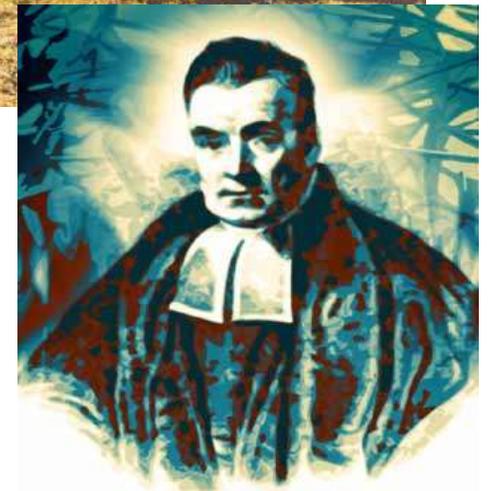
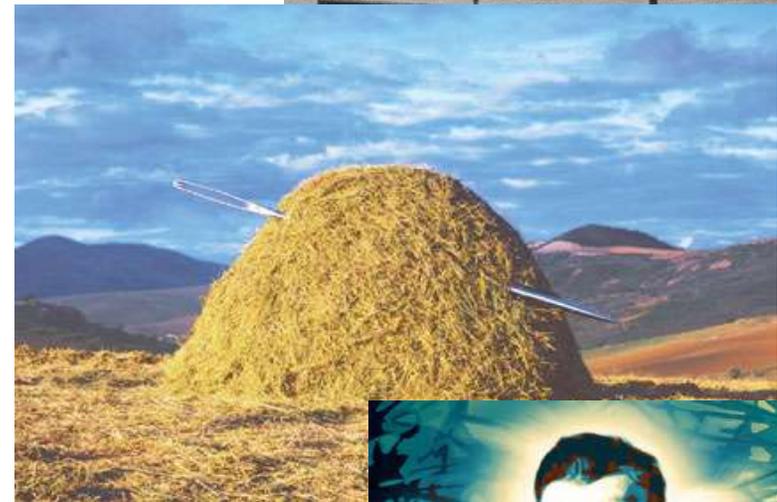
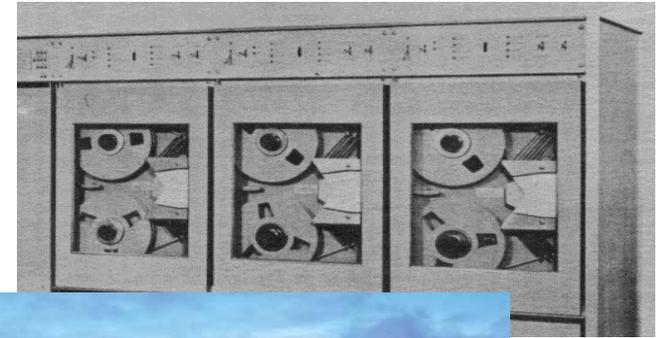
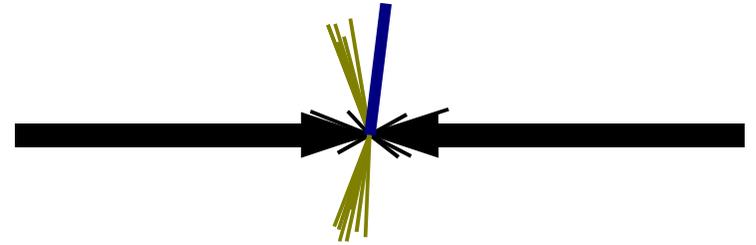
- Parton level:
 - Degree of polarization: -0.92
- Event reconstruction (from partons):
 - Degree of polarization: -0.42

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



Analysis Outline

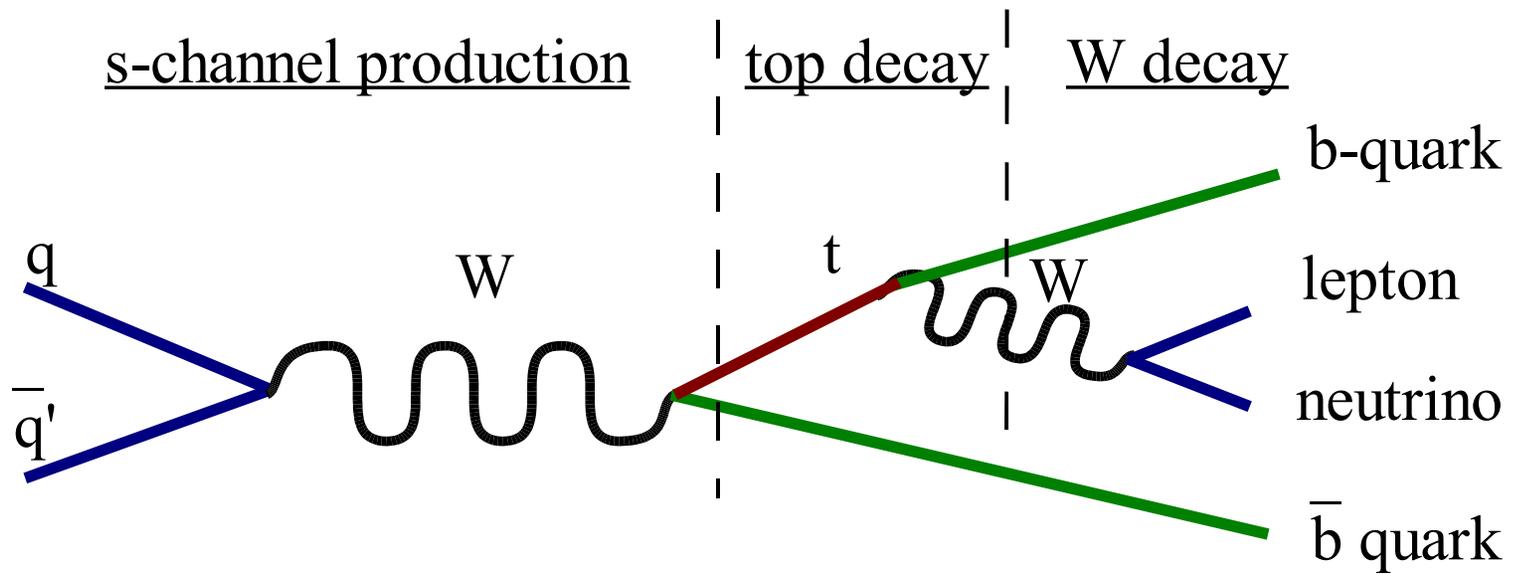
Goal:

Observe electroweak production of single top quarks

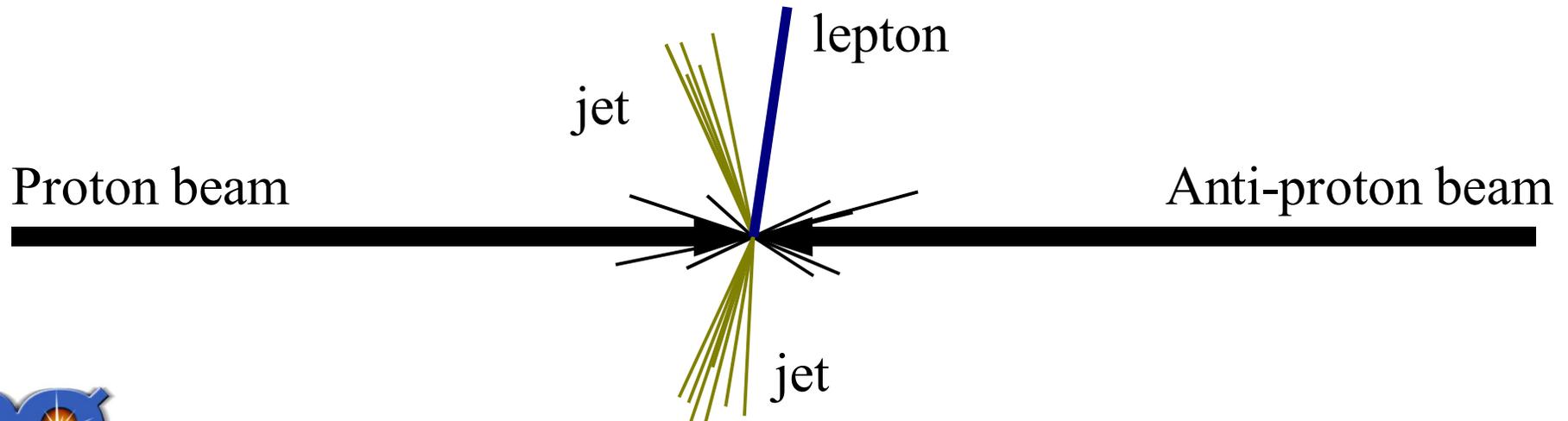
1. Select single top events out of large background
 - Loose “Pre-Selection”, reject QCD multi-jet events
 - Maximize acceptance
 - Check modeling of remaining backgrounds
2. Tight selection of single top events
 - Find (or form) sensitive variable for s-channel and t-channel
 - Separate s-channel from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



Single Top Event Signature



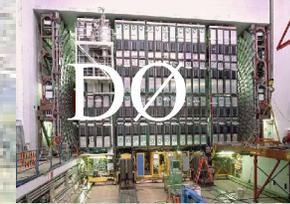
Final State Objects



Experimental Setup: Fermilab Tevatron in

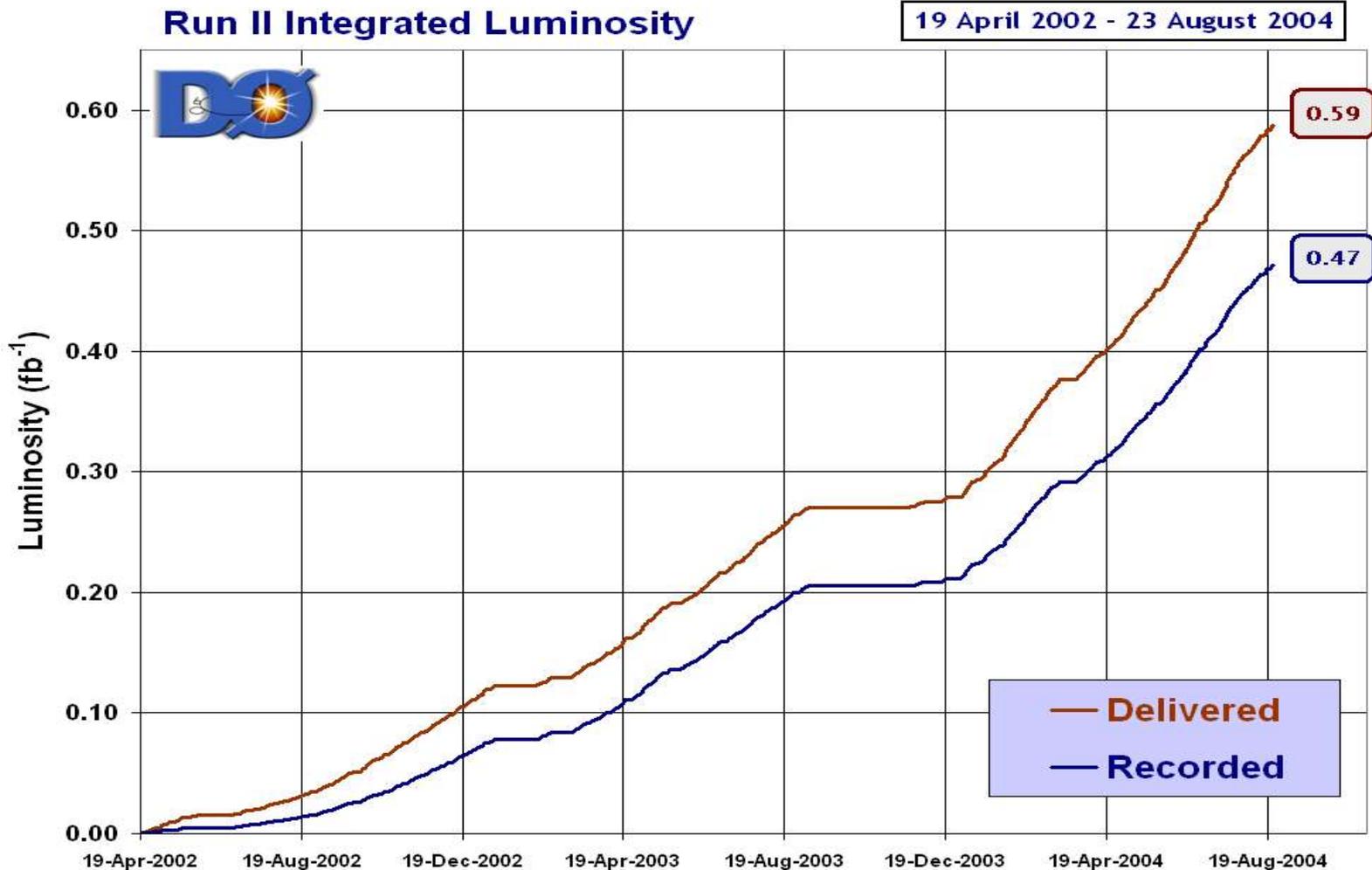


Run II



- **Proton-Antiproton Collider**
- **CM Energy 1.96TeV**
- **Bunch crossing every 396ns**
- **Peak Luminosity $>80 \times 10^{30}$**
 - **Decays to $\sim 20 \times 10^{30}$ during store**
- **Store duration up to 20 hours**

Integrated Luminosity



- Tevatron delivered luminosity is exceeding “baseline” and “design” projections
- DØ is now recording data with $>90\%$ efficiency



Experimenters: The DØ Collaboration

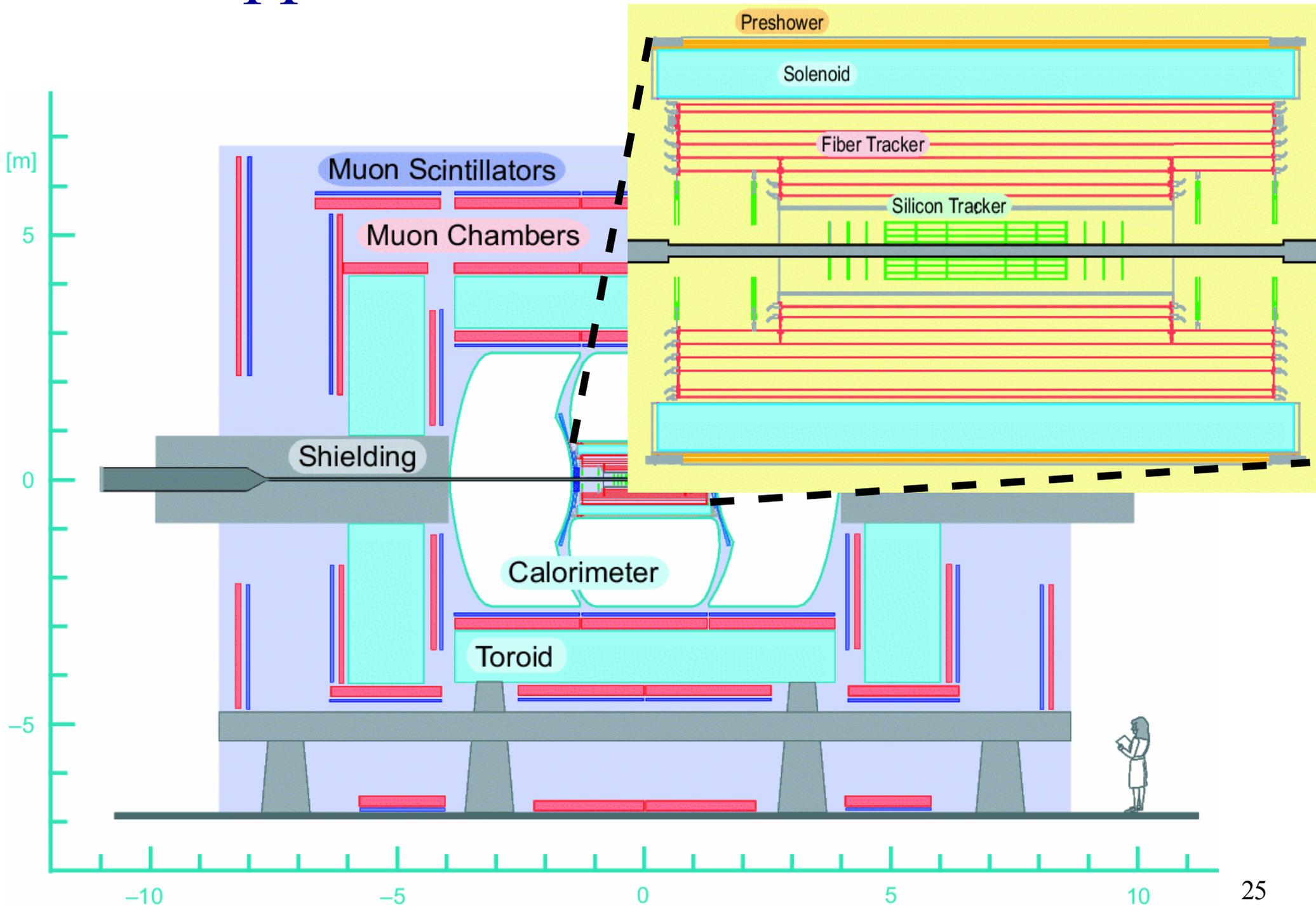


- **19 countries**
- **80 institutions**
- **670 physicists**

More than 50% non-US



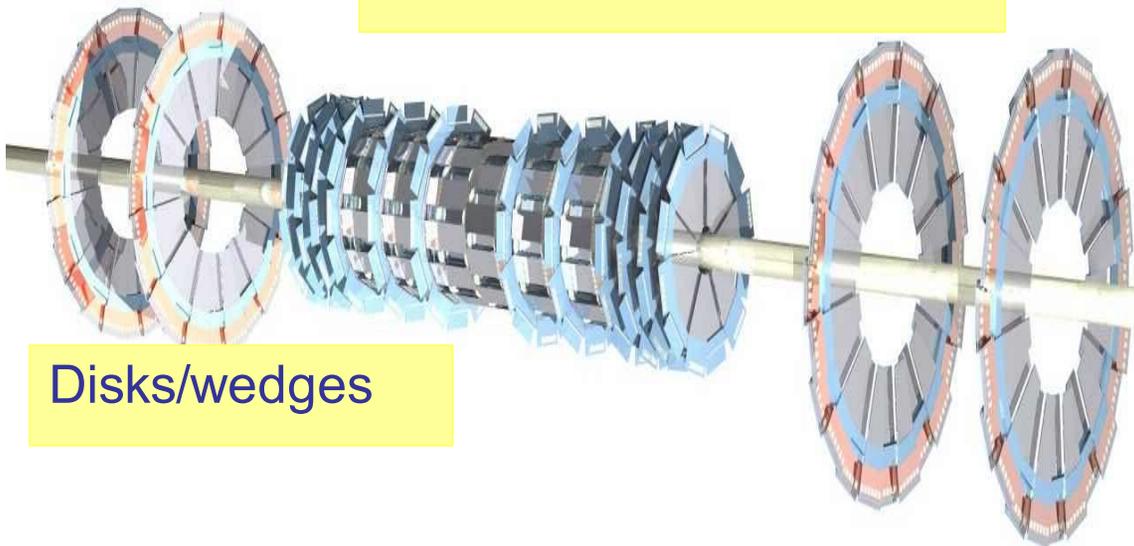
Apparatus: Run II DØ Detector



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

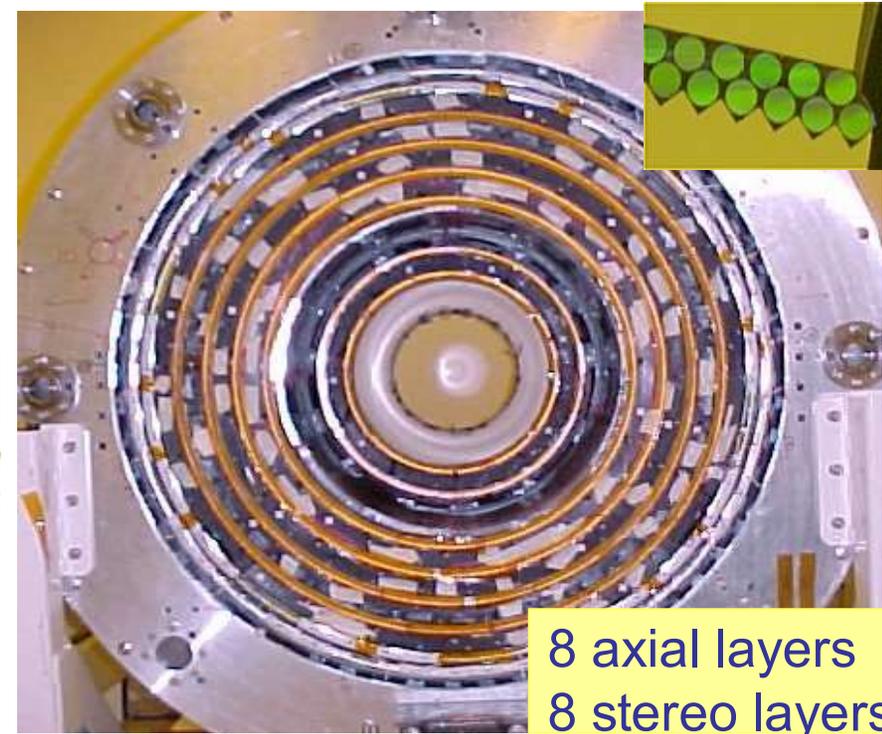
Silicon Vertex Detectors

4 barrel layers
axial + stereo detectors



Disks/wedges

Central Fiber Tracker

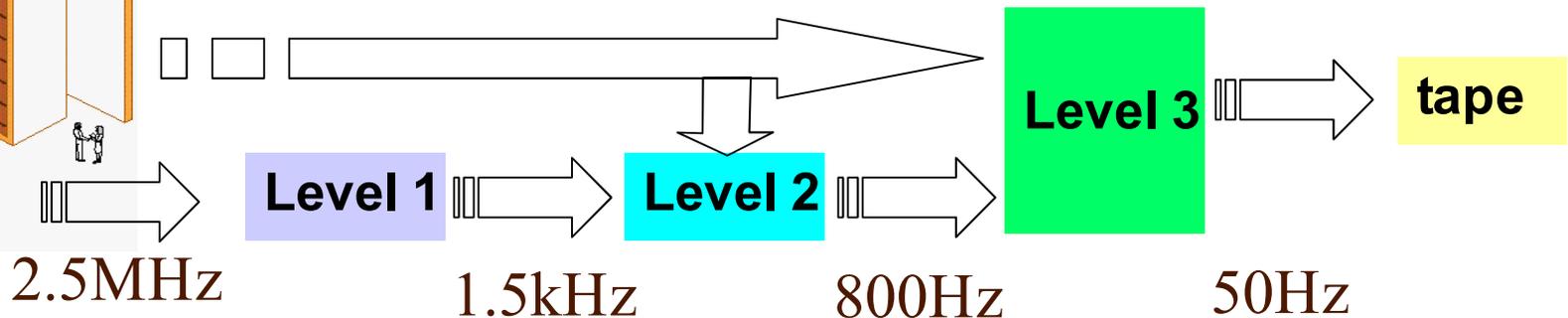
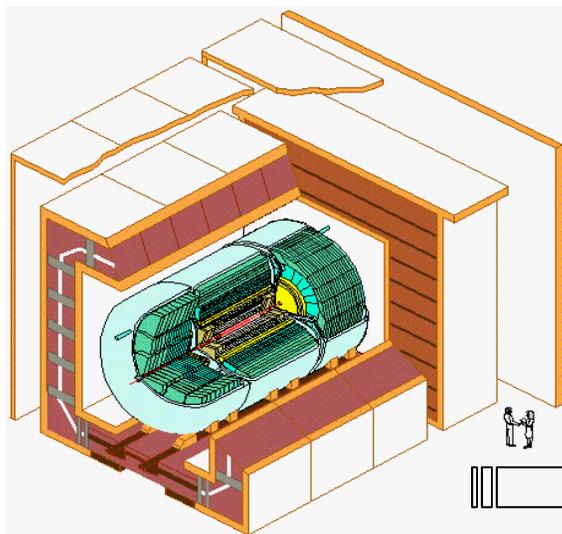


8 axial layers
8 stereo layers

- Improved momentum resolution for muons
- Track-based b-quark jet identification



Significantly Upgraded for Run II: Triggering



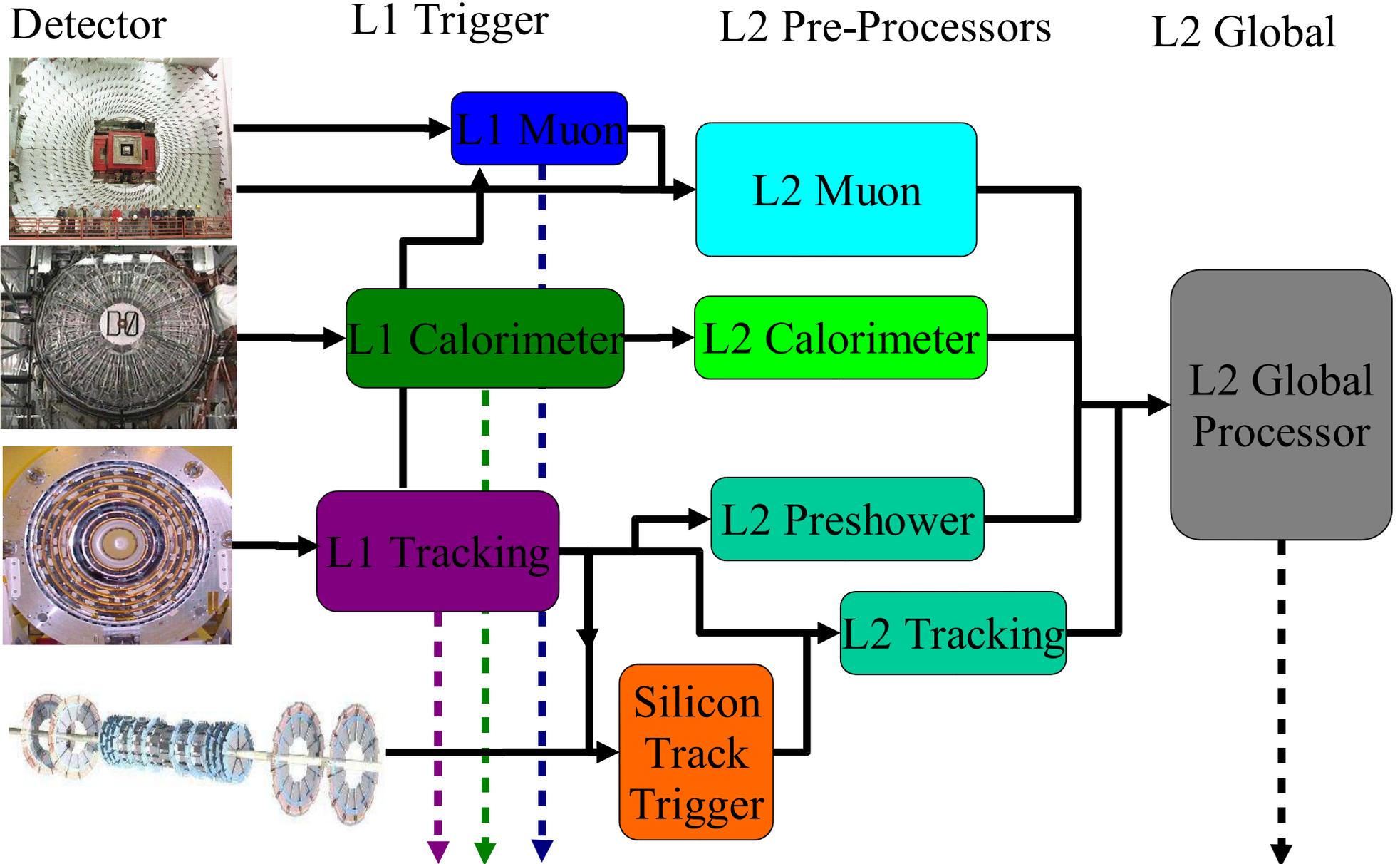
- Multi-level, pipelined, buffered Trigger Strategy
 - Level 1: one interaction every 396ns
 - Fast trigger pick-offs from all detectors
 - Custom hardware/firmware
 - Trigger on hit patterns in individual detector elements
 - Level 2: Combine Level 1 regions and objects
 - Level 3: Full detector readout
 - 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



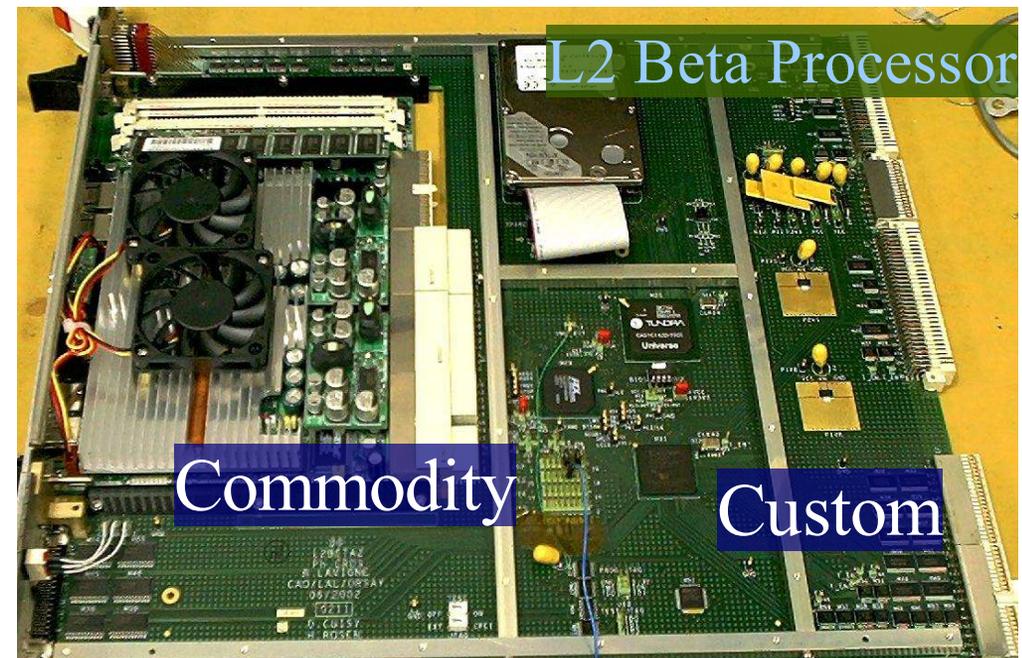
Trigger Level 1/Level 2 Dataflow



Trigger Framework, coordinates L1 trigger and L2 trigger and detector readout

Trigger Hardware: Custom-built vs Commodity

- Trigger Level 1/Level 2 relies heavily on custom-built hardware/firmware
 - Cards designed/built mostly by Engineers – feedback from Physicists
 - Systems commissioned mostly by Physicists – help from Engineers
 - Firmware written by Engineers/Physicists
 - Most Firmware tasks too complex to be written by Physicists alone
- Trigger Level 2/Level 3 relies heavily on commodity systems
 - Off-the-shelf products (computers, interfaces/cables)
 - Interfaced to custom-built cards
 - Software written by Physicists



DØ Single Top Search Strategy

Goal:

Observe electroweak production of single top quarks

- Aim for observation
 - Right from the start
 - Even though we do not yet have sufficient luminosity
 - This analysis uses 160pb^{-1}
- Maximize signal acceptance
 - Event reconstruction
 - Selection cuts
- Study background model in detail
- Apply advanced final selection methods
 - Simple cut in this analysis



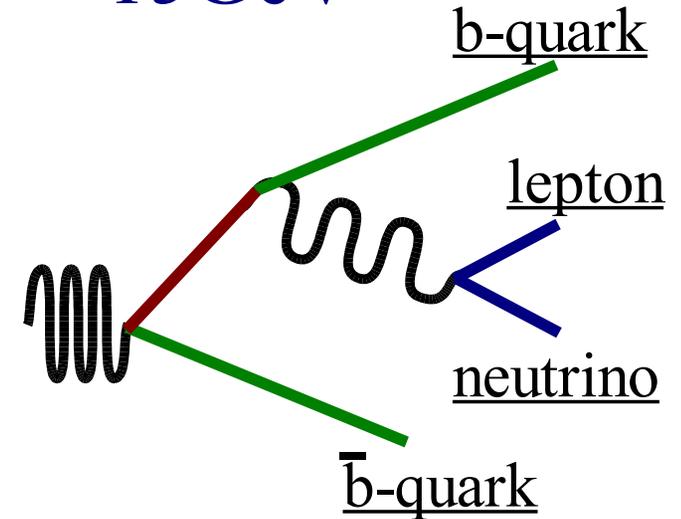
DØ Single Top Search Strategy

- Split data into orthogonal channels
 - Optimize each channel, then combine
 - Separate by lepton:
electron channel \leftrightarrow 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 Preselection

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



- Trigger:
 - L1: Lepton: ≥ 1 EM object, $p_T > 10\text{GeV}$ or ≥ 1 muon hit Jets: ≥ 1 jet
 - L2: Lepton: ≥ 1 EM object, $p_T > 12\text{GeV}$ or ≥ 1 muon Jets: ≥ 1 jet
 - L3: Lepton: ≥ 1 EM object, $p_T > 15\text{GeV}$ Jets: ≥ 1 jet
 - Efficiency: $\sim 85\%$ (electron channel), $\sim 89\%$ (muon channel)
- Reject mis-reconstructed events



Mis-reconstructed Events?

- Cosmic rays (muons)
- Mis-reconstructed vertex
 - Affects missing transverse energy

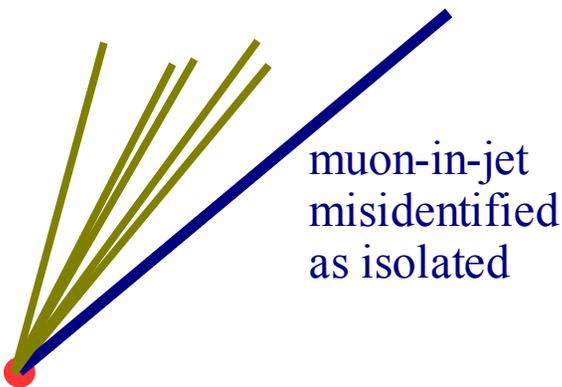
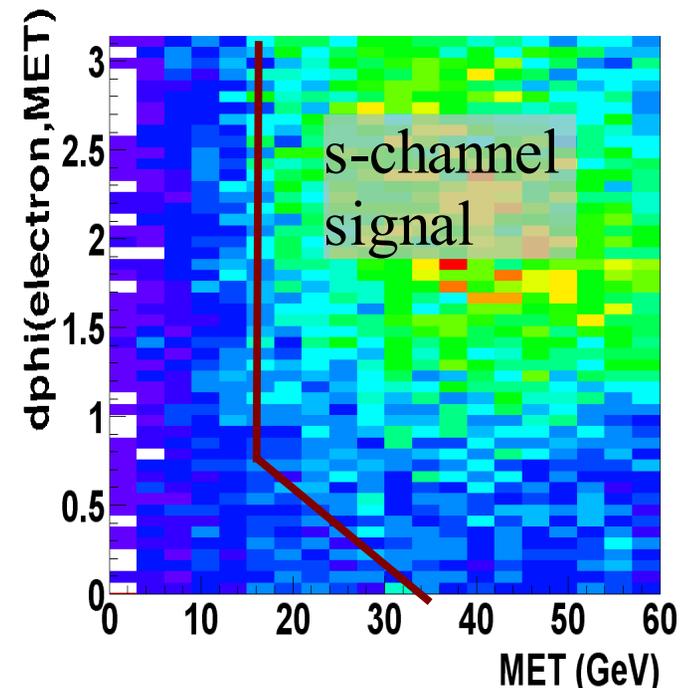
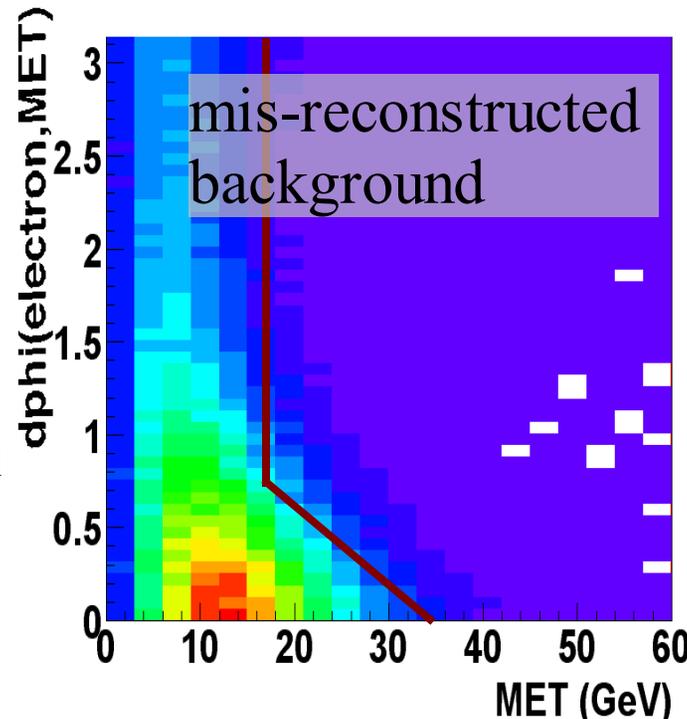
→ Primary vertex constraints

- Primary vertex with ≥ 3 tracks
- Lepton is required to originate from primary vertex

- Mis-reconstructed jets

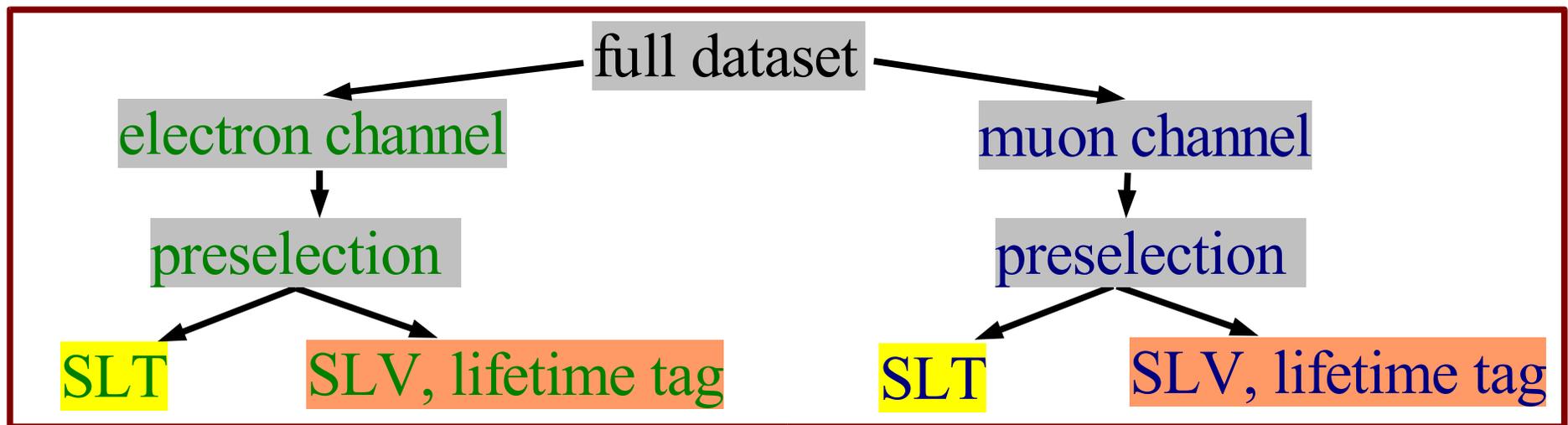
→ Triangle Cuts

- fake electron
- fake isolated muon



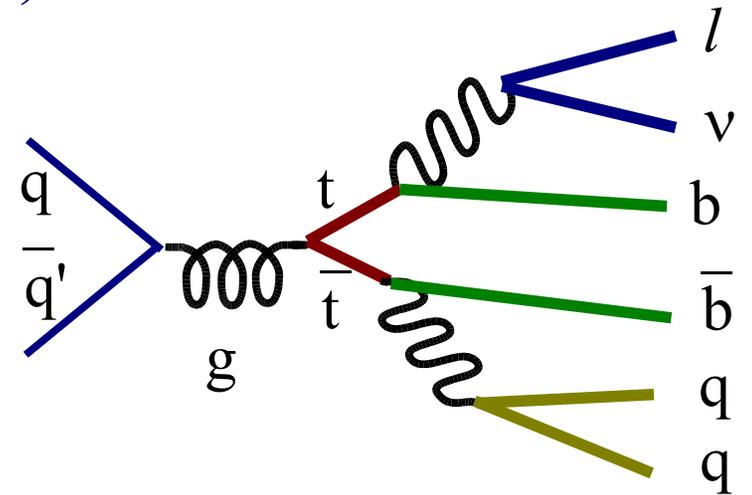
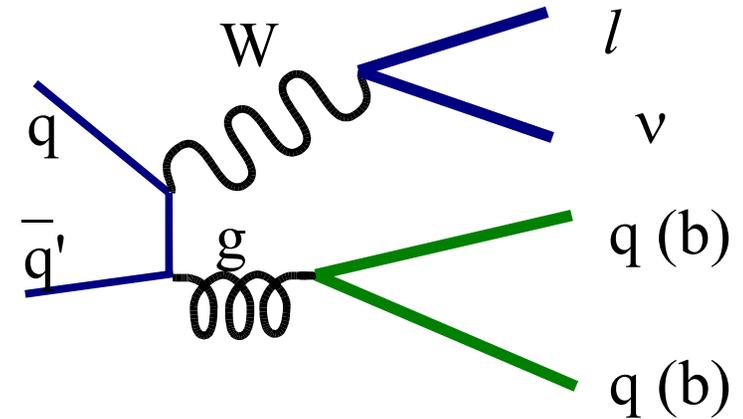
DØ Single Top Search Strategy

- Split data into orthogonal channels
 - Separate by lepton
 - Separate by b-tagging:
 - Soft-muon-tagging (SLT) \Leftrightarrow 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



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, $Z\tau\tau$, cosmic rays,...)
 - Included in data W/Z+jets estimate (DØ)



Data-Based Background Estimation

- Normalization and shape from data

- From preselected sample

		Tight lepton ID	
		<i>pass</i>	<i>fail</i>
b-tagging	<i>pass</i>	<i>signal data</i>	<i>fake-lepton background sample</i>
	<i>fail</i>	<i>W+jets background sample</i>	<i>not used</i>

- Flavor composition

- Assumption:

- similar flavor composition in QCD multi-jet and W+jets sample

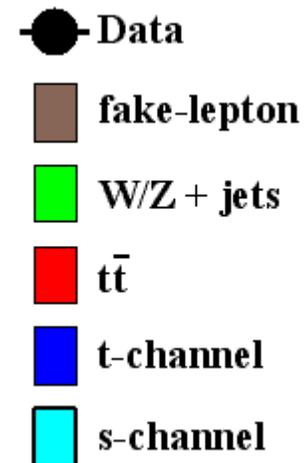
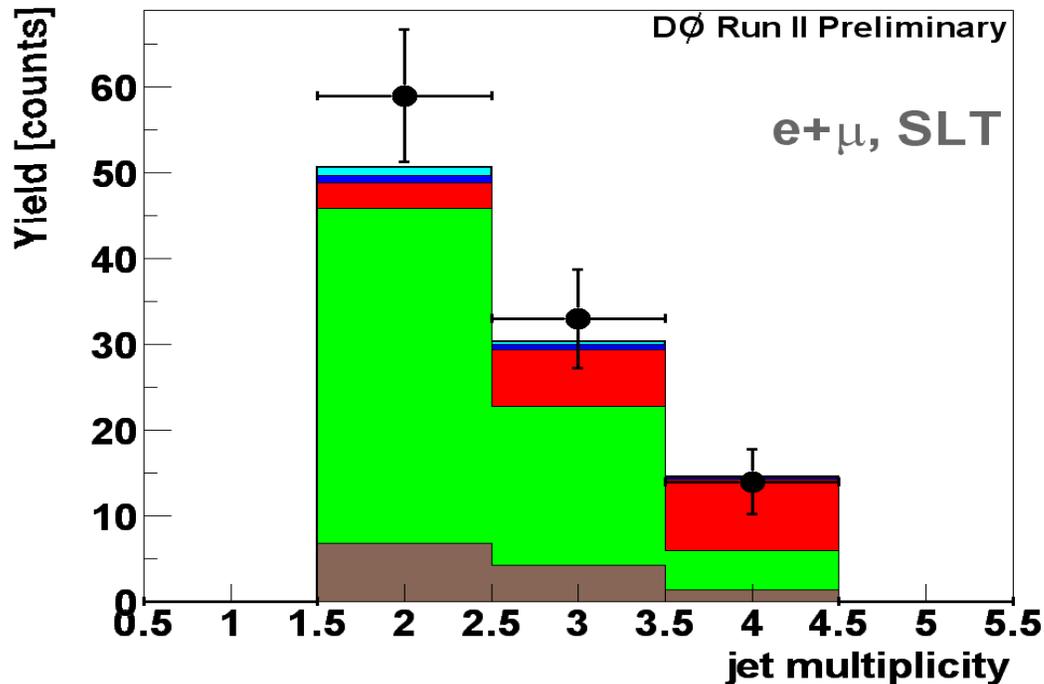
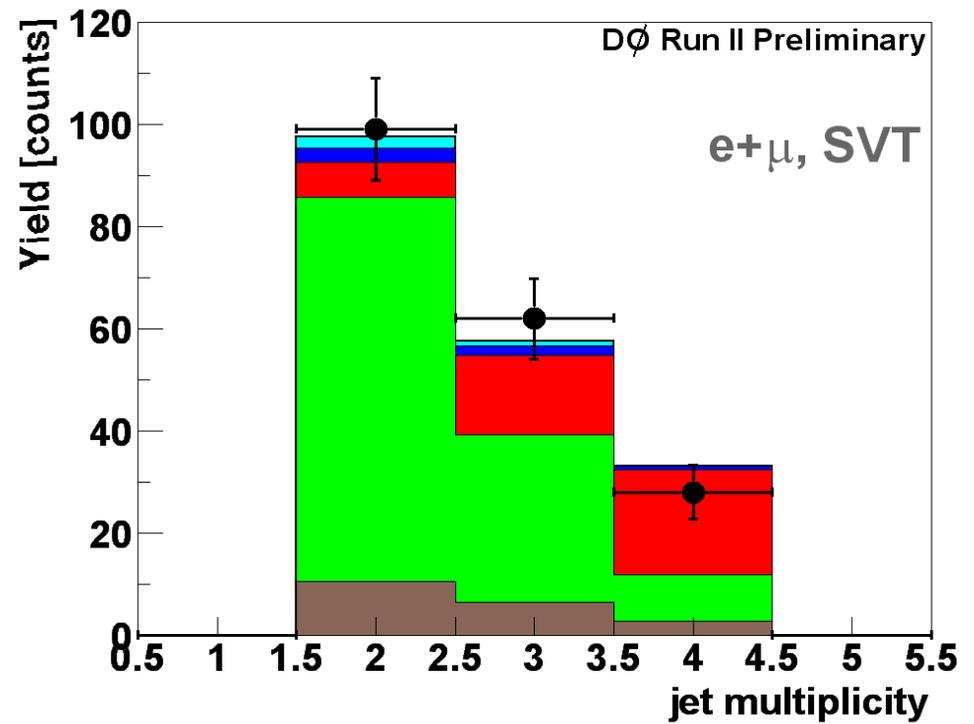
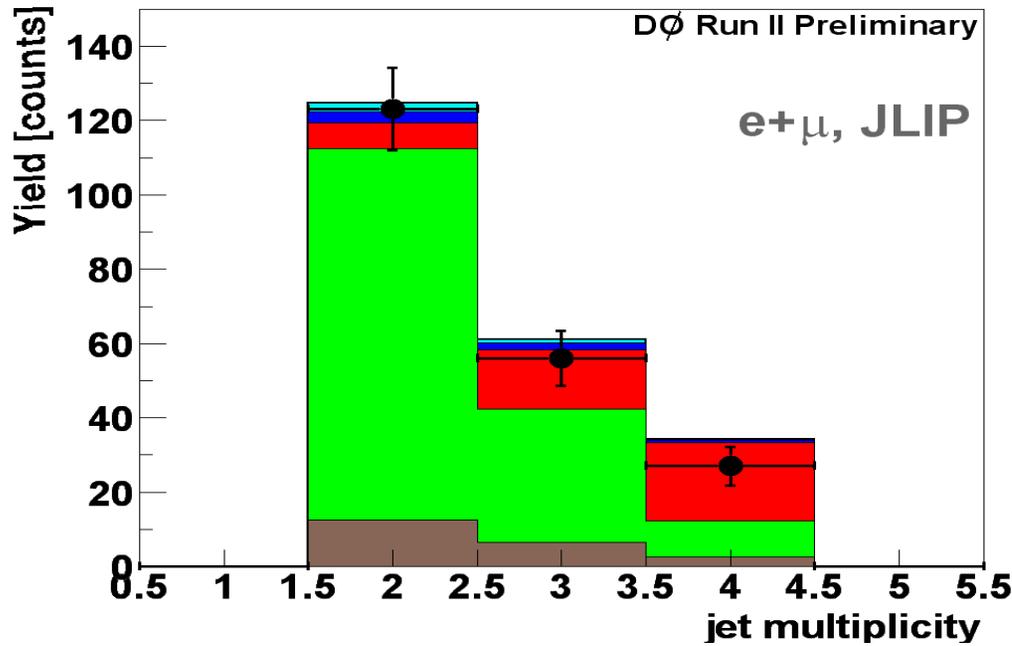
- Within ~20% uncertainty

- Check in Z+jets and in W+jets low-HT sample

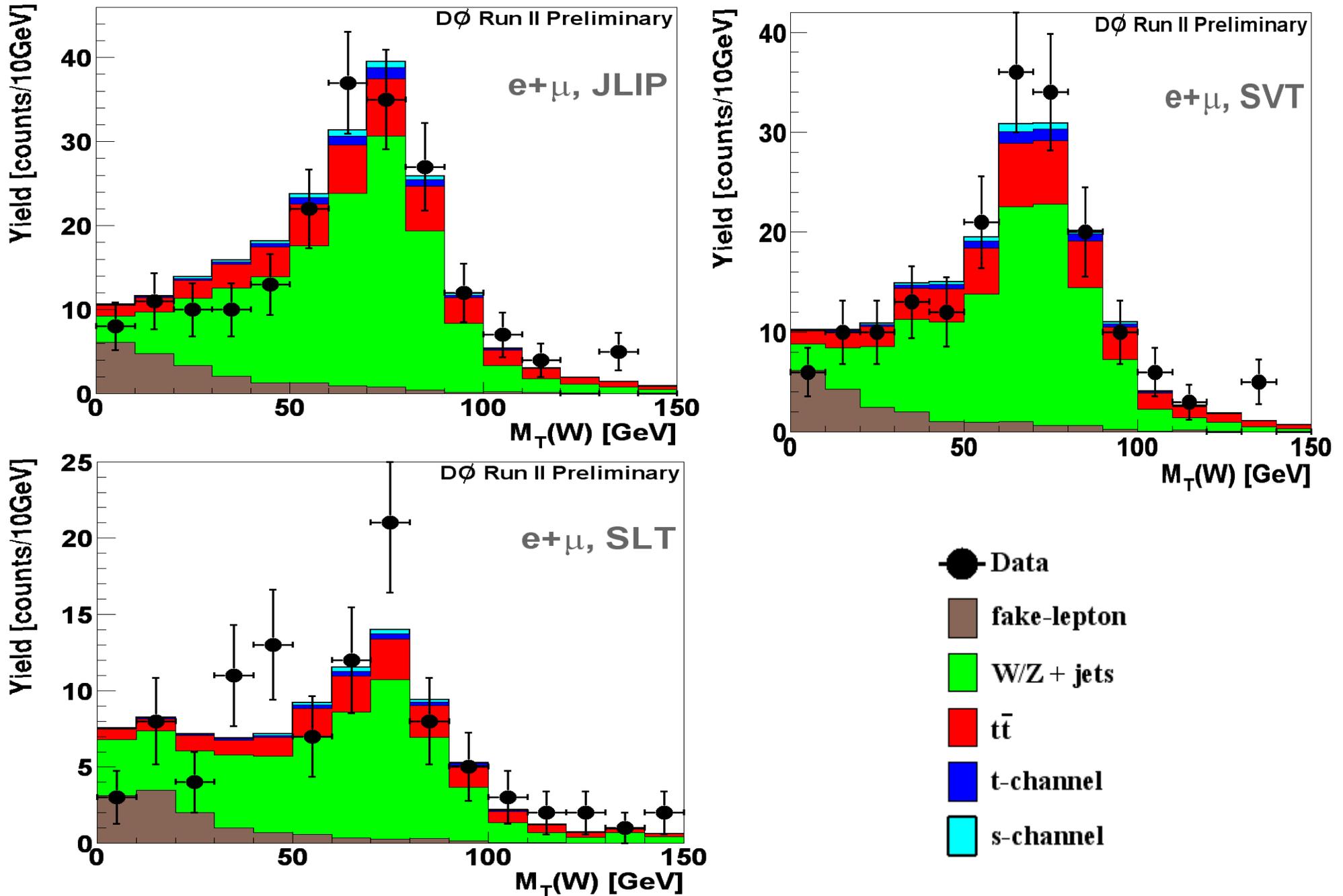
- Free of top pair and single top

- Measure flavor composition as per jet tag probability in QCD multi-jet sample

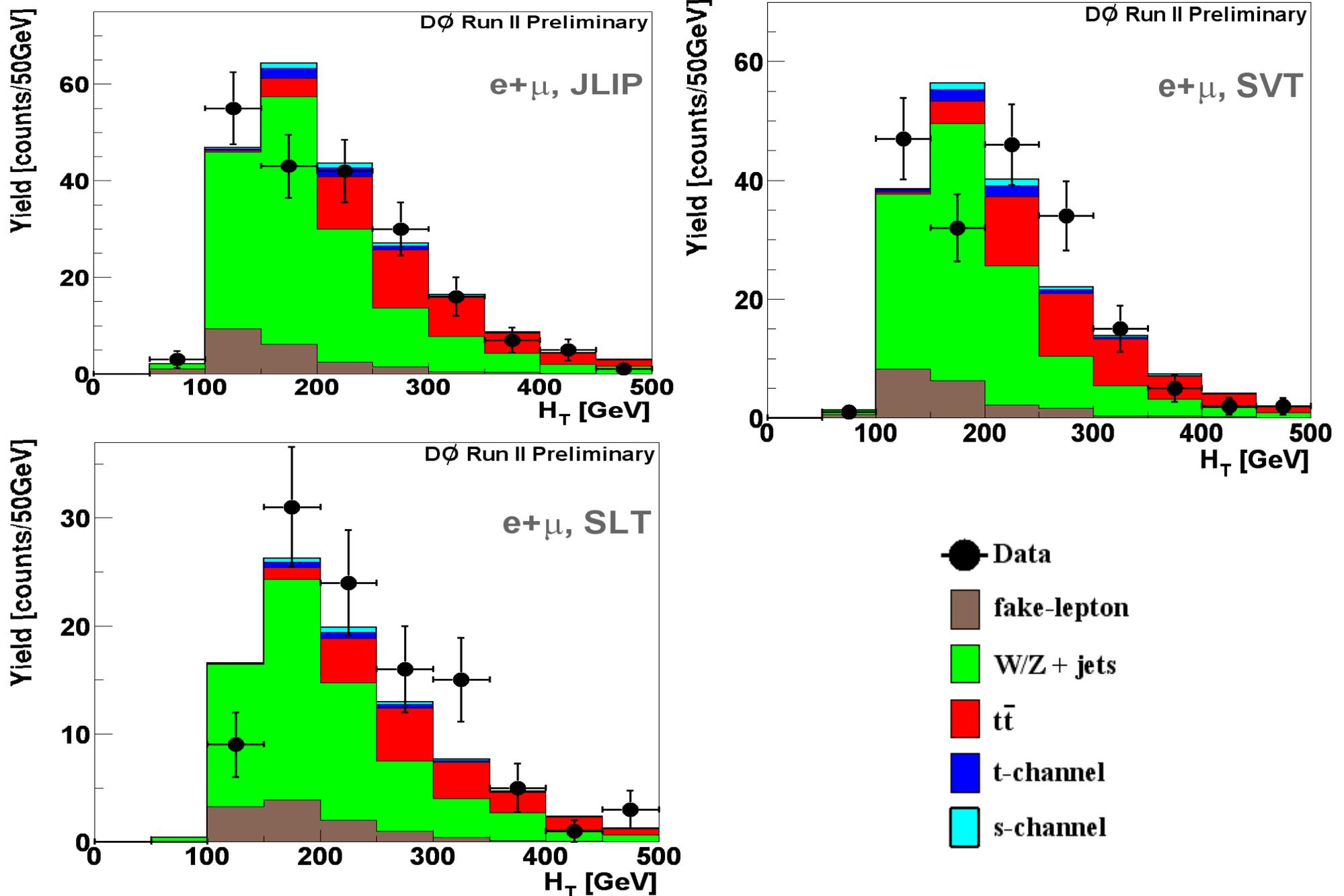
Event Yields after Preselection



W Reconstruction after Preselection

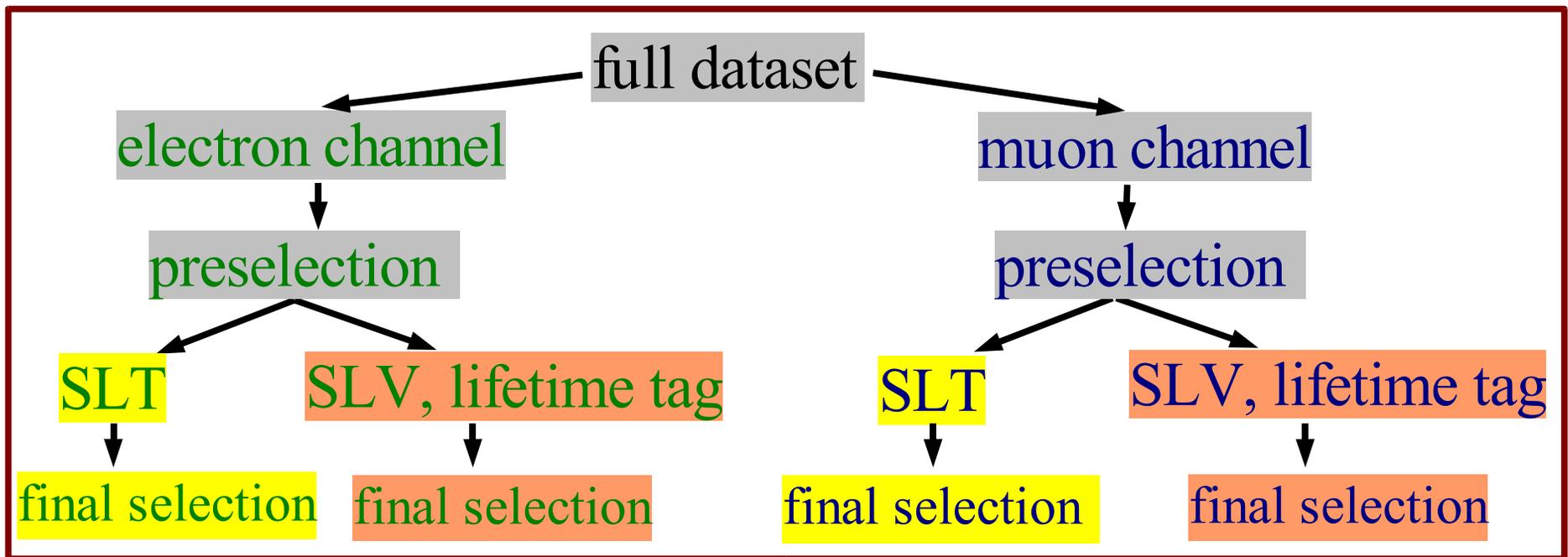


Transverse Energy after Preselection



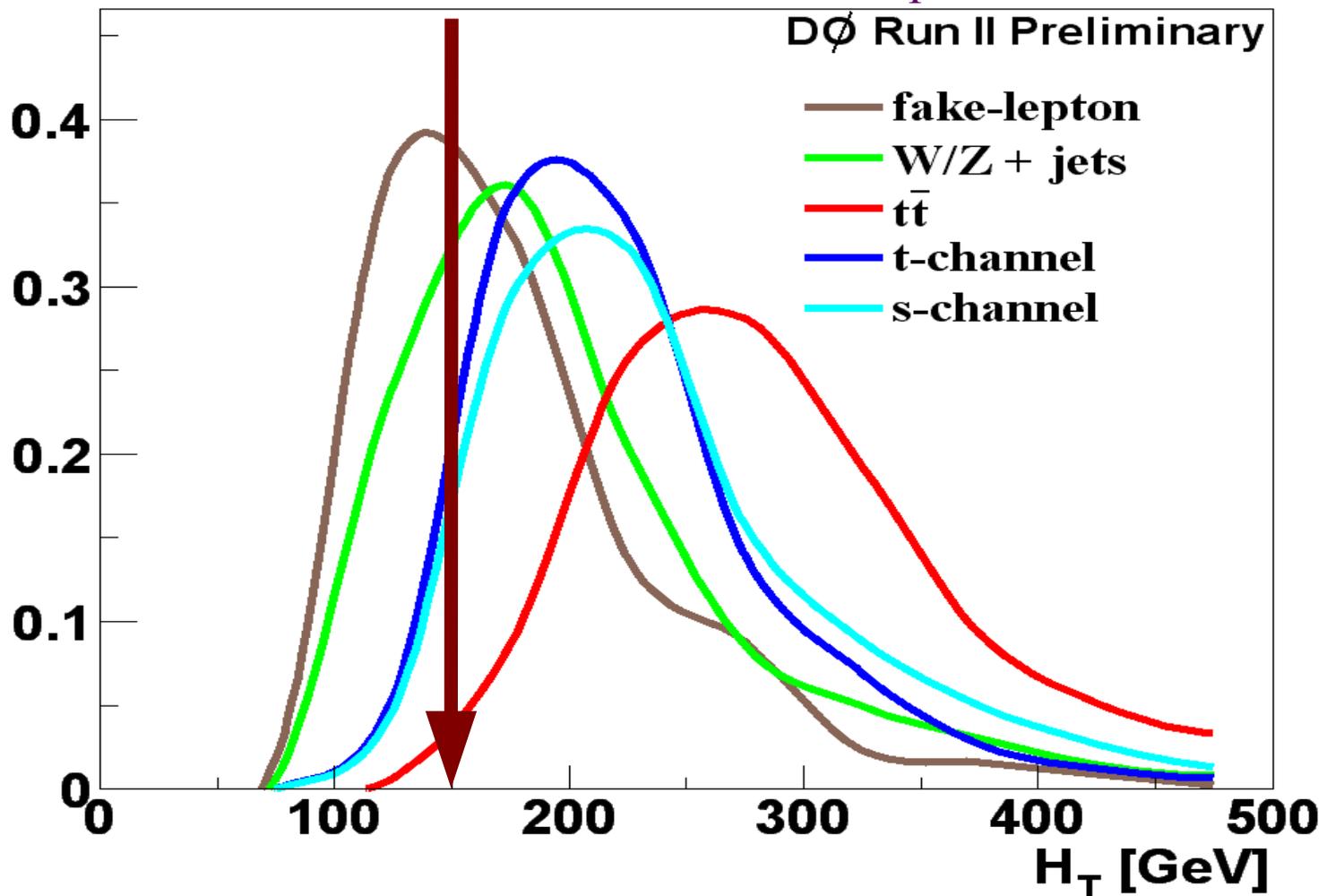
DØ Single Top Search Strategy

- 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 $W+\text{jets}$: $H_T > 150 \text{ GeV}$



Final Event Yields

Muon Channel Event Yields

	SLT	SVT	JLIP
Signal			
s-channel	0.6 ± 0.1	1.3 ± 0.3	1.3 ± 0.3
t-channel	0.8 ± 0.2	2.1 ± 0.6	2.2 ± 0.6
s+t combined	1.4 ± 0.3	3.4 ± 0.9	3.5 ± 0.9
Backgrounds			
W/Z+jets+fake-l	33 ± 7	48 ± 9	60 ± 11
top pairs	8 ± 2	19 ± 4	19 ± 4
Sum of Backgrounds	41 ± 6	68 ± 10	80 ± 13
Observed event yield	43	75	70



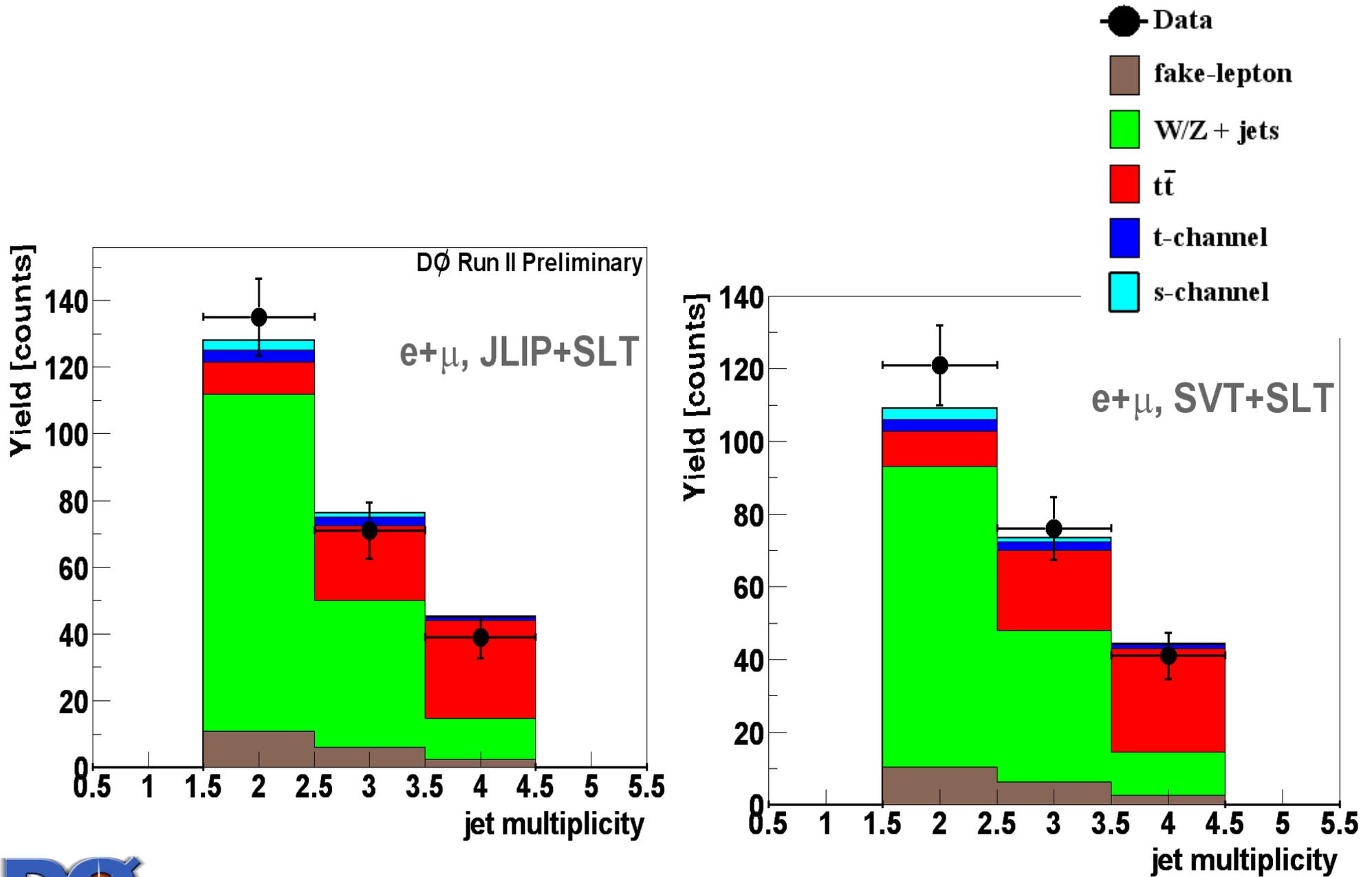
Final Event Yields

Electron Channel Event Yields

	SLT	SVT	JLIP
Signal			
s-channel	0.65 ± 0.1	1.8 ± 0.4	1.8 ± 0.4
t-channel	0.91 ± 0.2	3.0 ± 0.7	3.0 ± 0.7
s+t combined	1.6 ± 0.3	4.8 ± 1.1	4.8 ± 1.0
Backgrounds			
W/Z+jets+fake-l	26 ± 4	46 ± 9	62 ± 13
top pairs	10 ± 2	24 ± 5	24 ± 5
Sum of Backgrounds	36 ± 5	70 ± 10	86 ± 14
Observed event yield	54	63	78

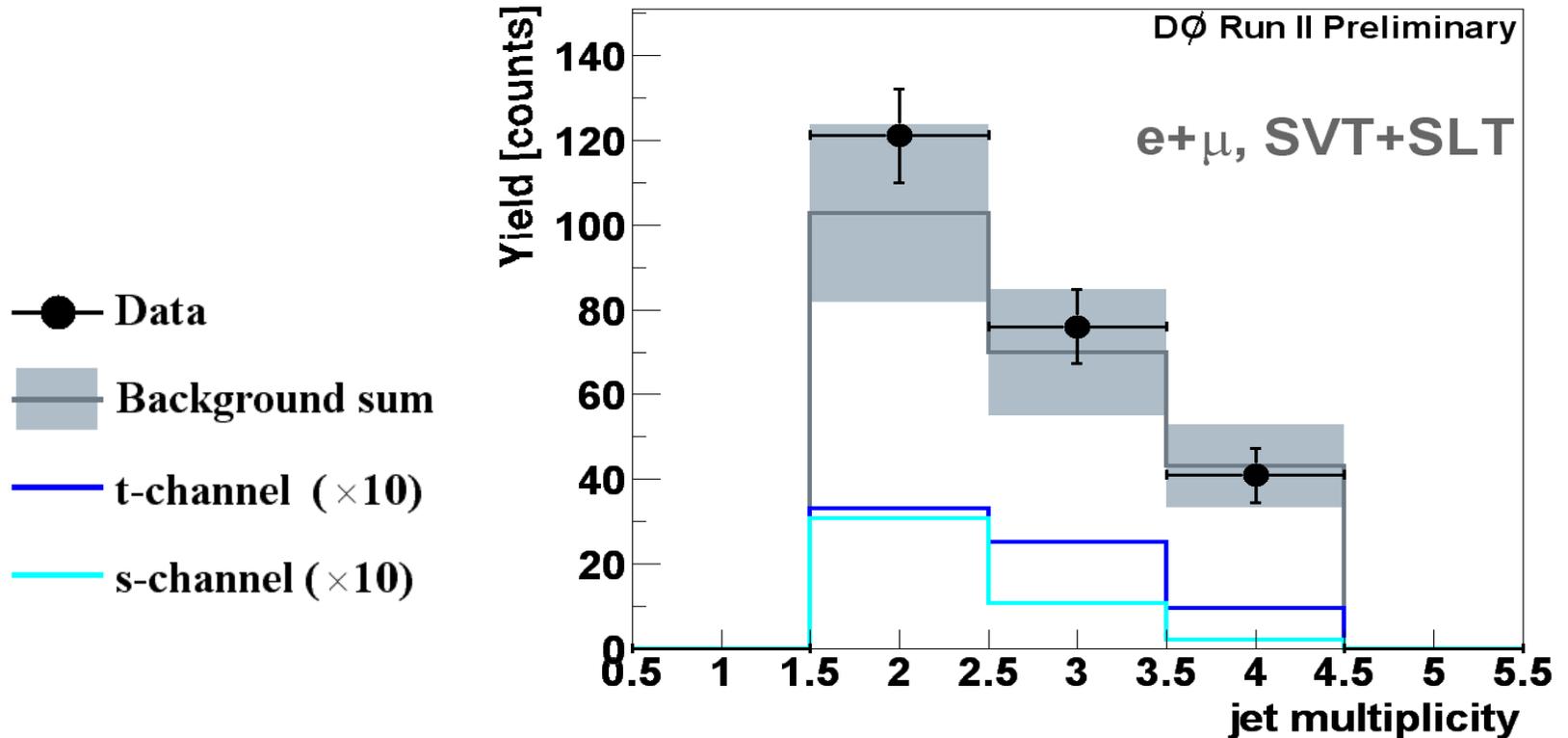


Event Yield after Final Selection



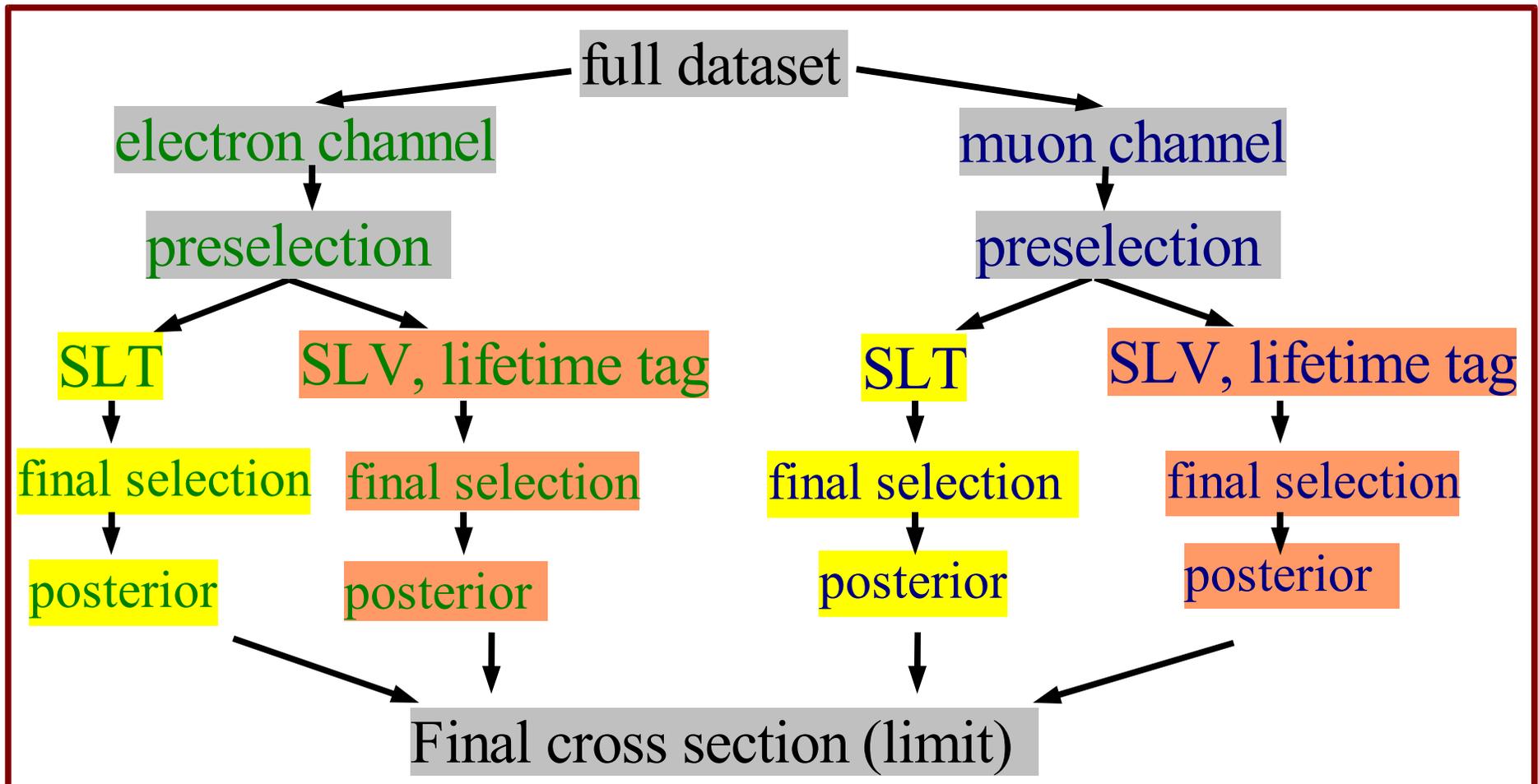
Systematic Uncertainties

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



DØ Single Top Search Strategy

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



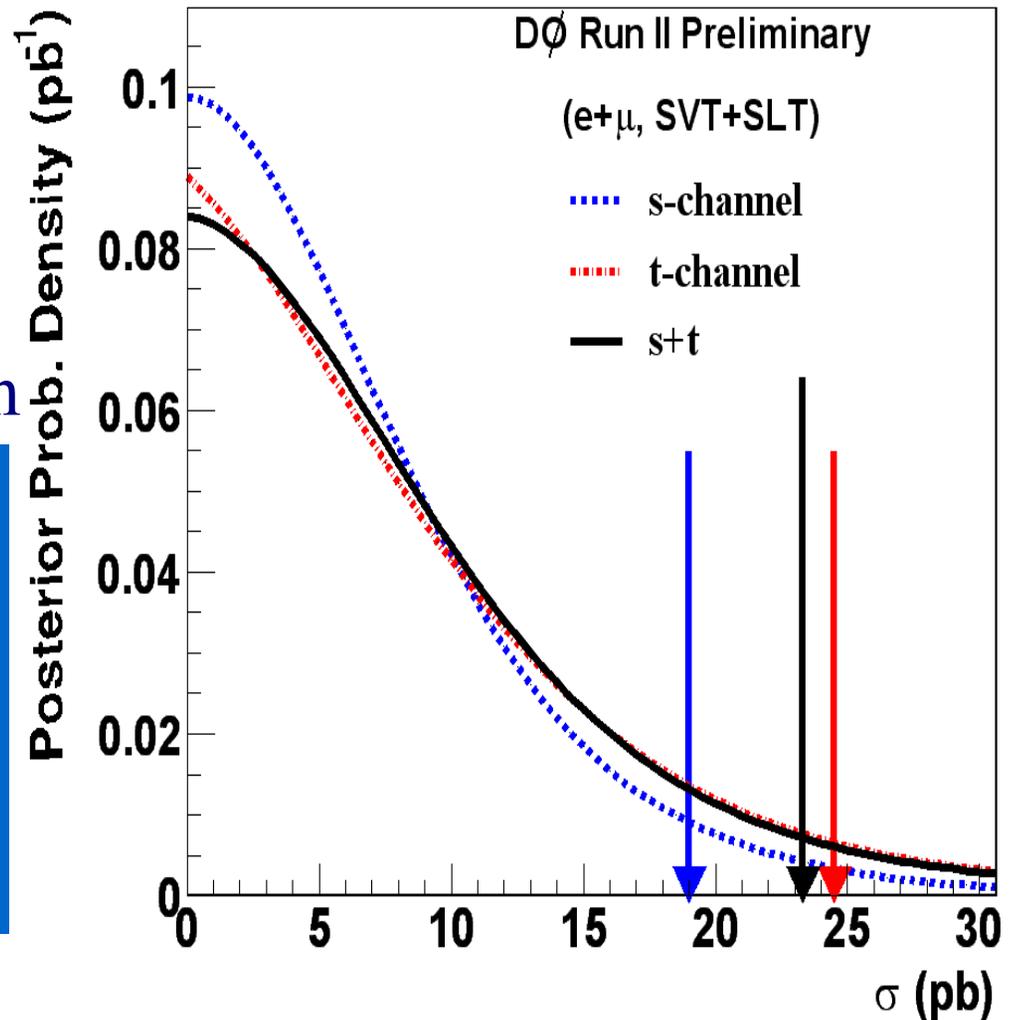
Final Result

- 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

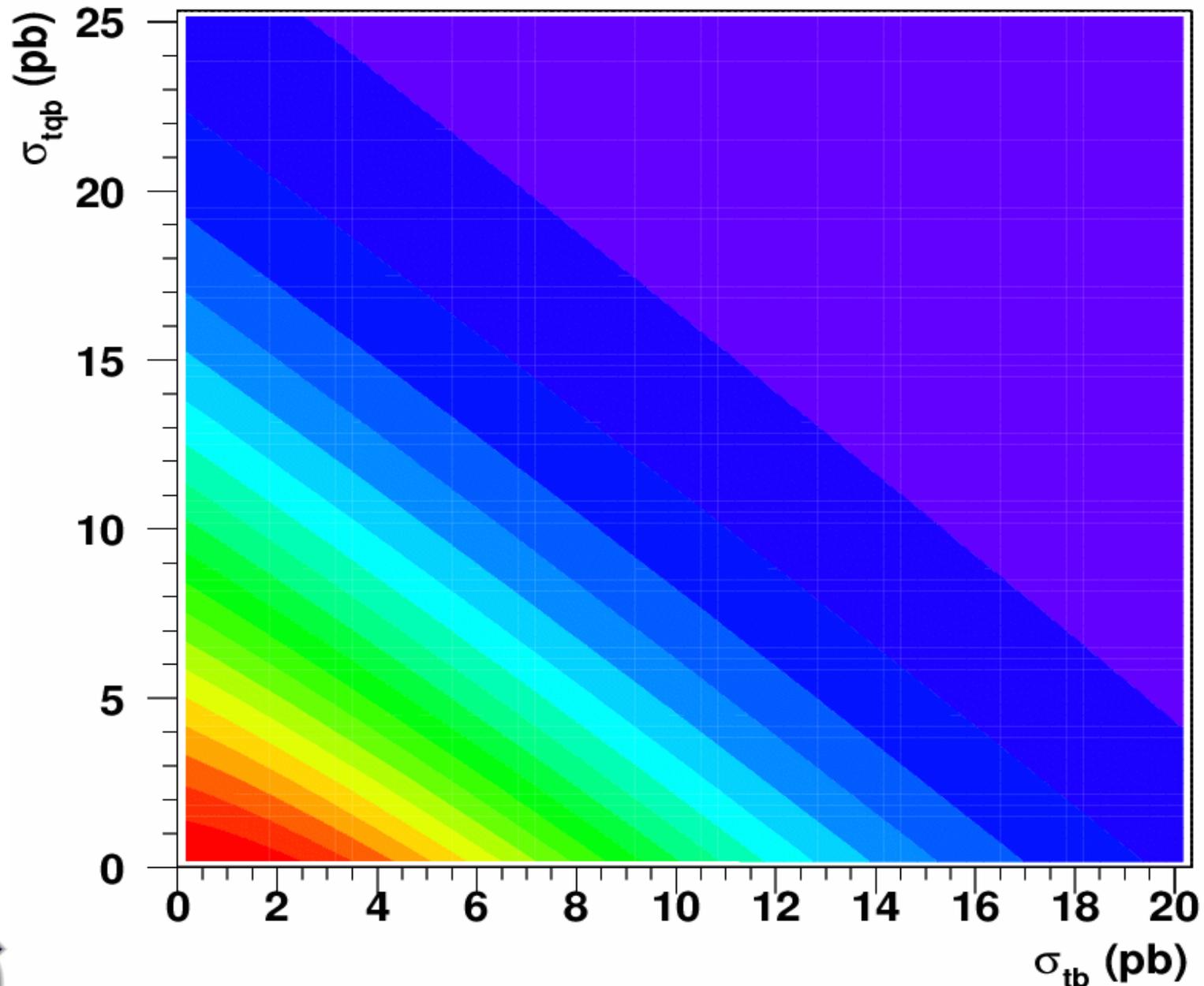
observed/expected limit:

$$\sigma_s < 19 / 16 \text{ pb} \quad \sigma_t < 25 / 23 \text{ pb}$$

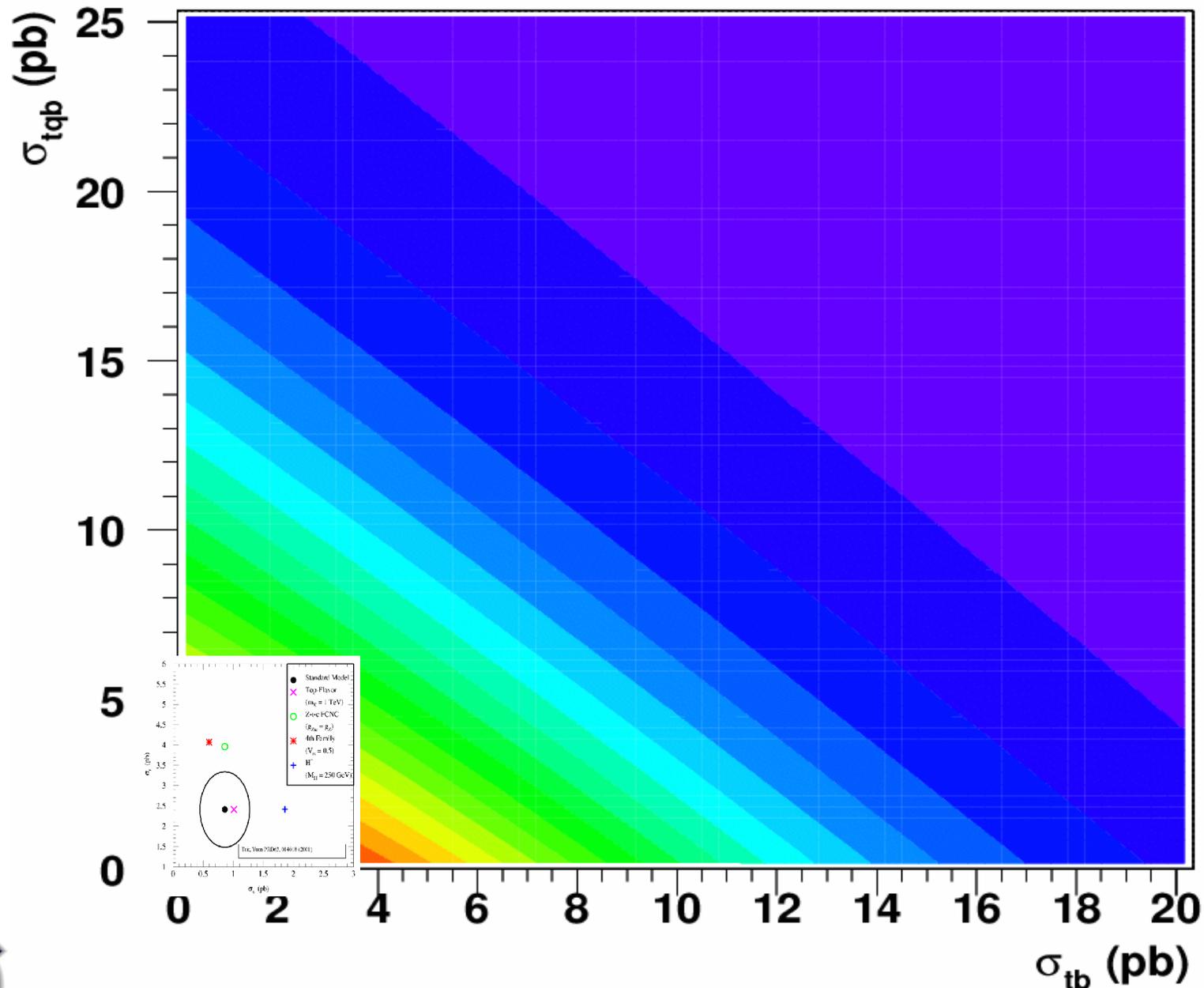
$$\sigma_{s+t} < 23/20 \text{ pb}$$



s-channel vs t-channel



s-channel vs t-channel



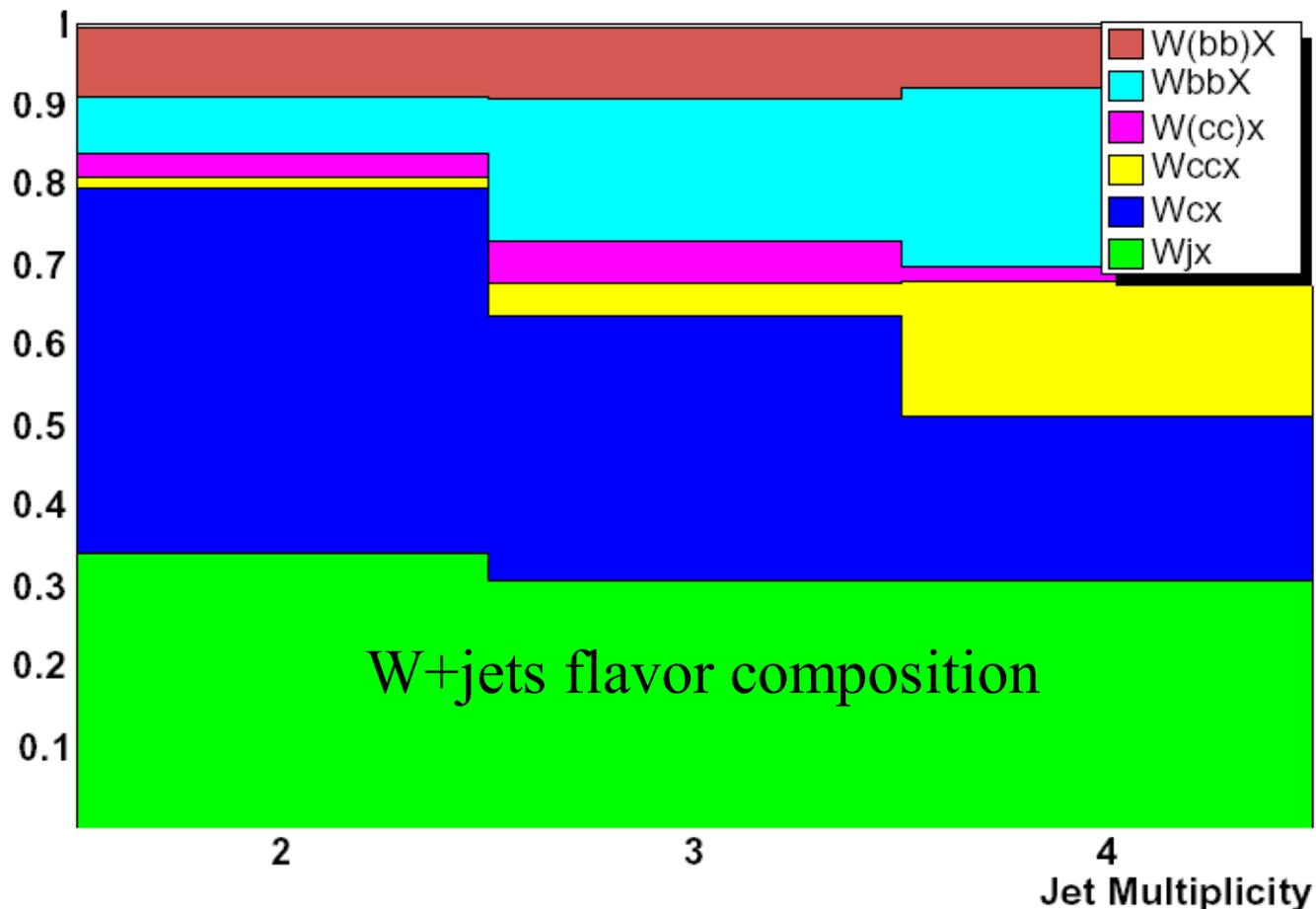
Questions

- 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
 - Flavor composition from data – uncertainty?
 - Flavor composition in MC: W_{bb} vs W_{cc} , W_{bb} vs $W_{gluon \rightarrow bb}$



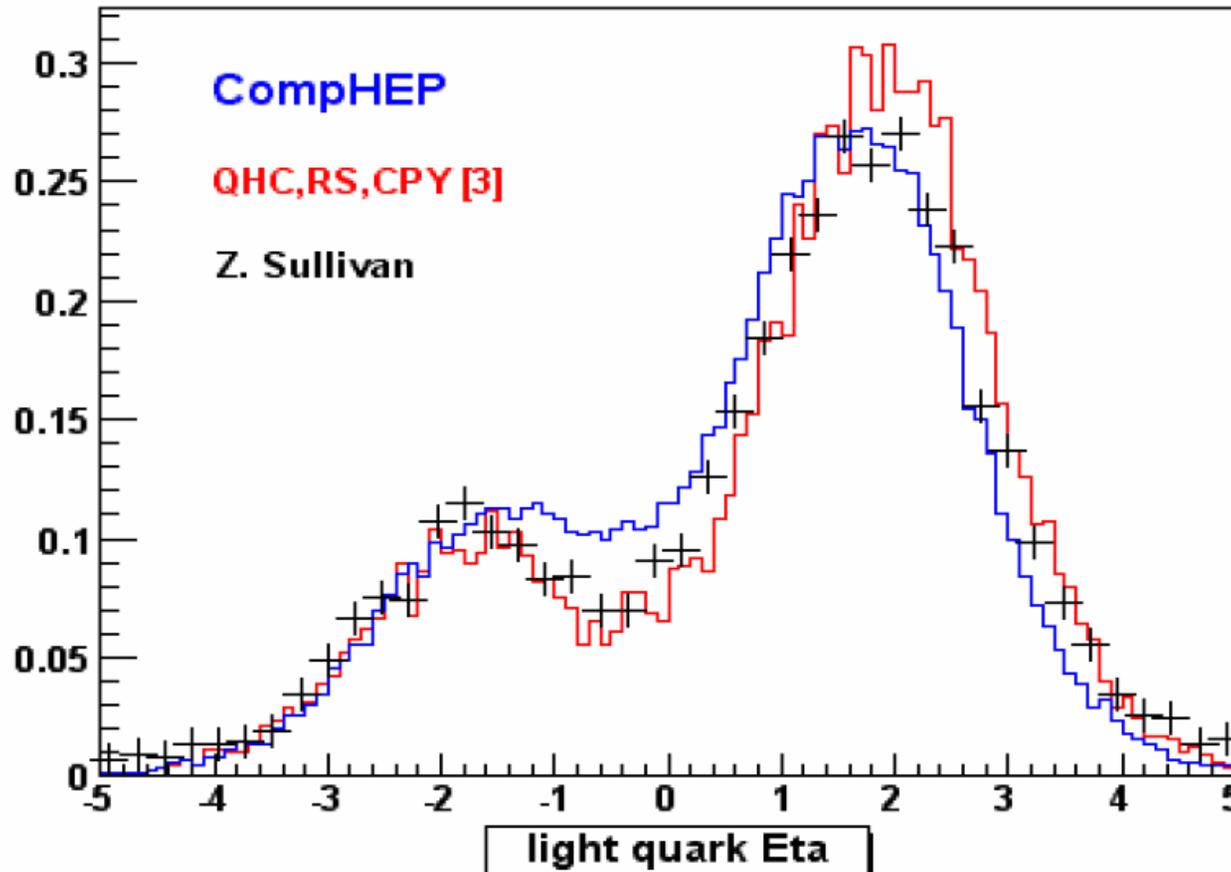
Questions

- 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



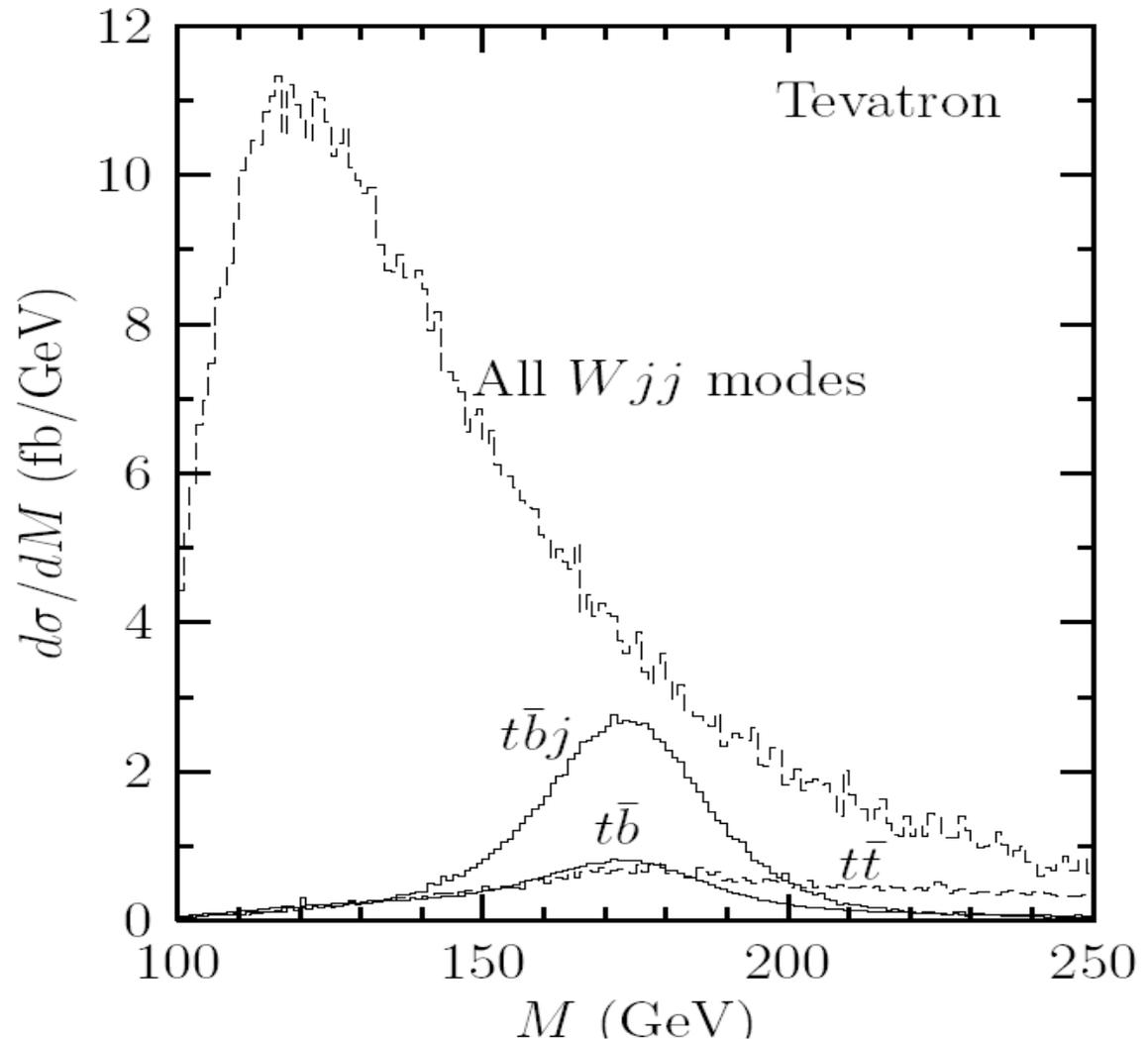
Questions

- 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 $\sim 500\text{pb}^{-1}$ – *Where is it?*
 - Observation with 2fb^{-1}
 - Starting to be interesting much sooner
- We have recorded $>400\text{pb}$ 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 $\sim 500\text{pb}^{-1}$ – *Where is it?*

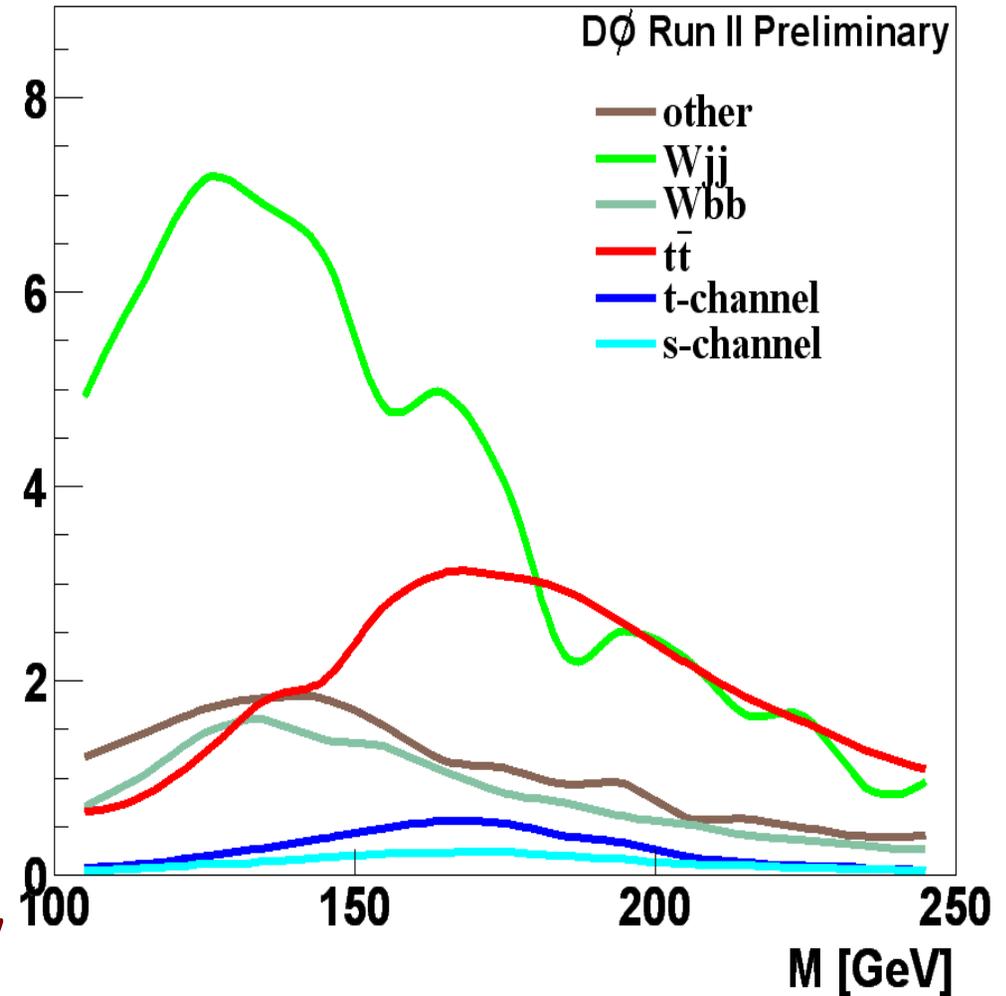
– Detector performance not (yet) as good as expected

- b-tagging $\sim 45\%$ per jet
- Trigger, ID $< 100\%$
- Jet resolution not (yet) as good as expected

– W+jets background larger than expected

- NLO calculations: $\text{LO} \times 1.5$

– Top mass, gluon PDF, ...



Many effects, all in the wrong direction!



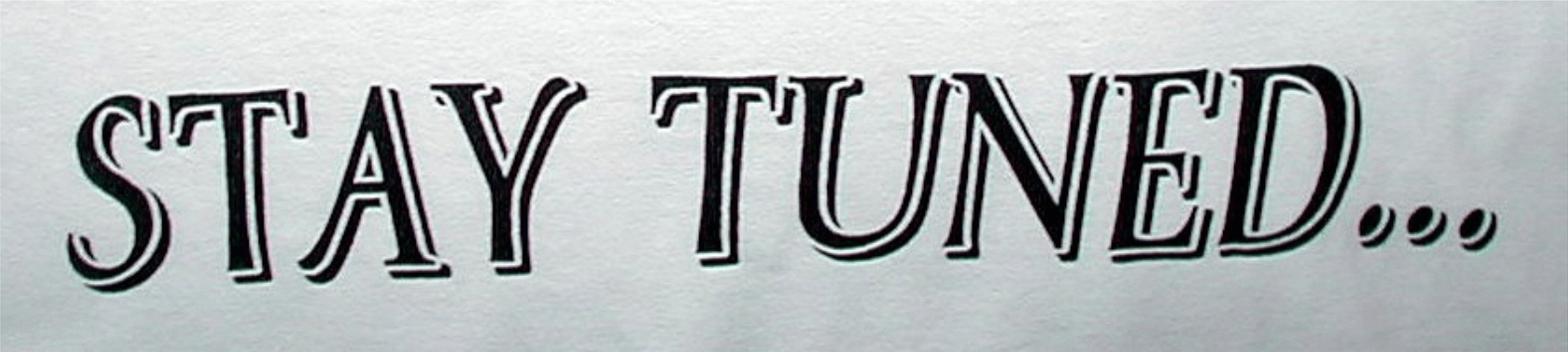
Single Top – Expectation vs Reality

- Predictions for Run II were to be sensitive to single top production with $\sim 500\text{pb}^{-1}$ – *Where is it?*
 - Detector performance not (yet) as good as expected
 - W+jets background larger than expected
 - Top mass, gluon PDF, ...
- Need to significantly improve all aspects of the analysis
 - Acceptance, resolution
 - Object ID, trigger
 - Final analysis
 - Multi-variate analysis techniques (Neural Networks, etc.)



Conclusions/Outlook

- Single Top is an exciting opportunity for Run II
 - A lot of interest, both from theoretical and experimental side
- 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



STAY TUNED...

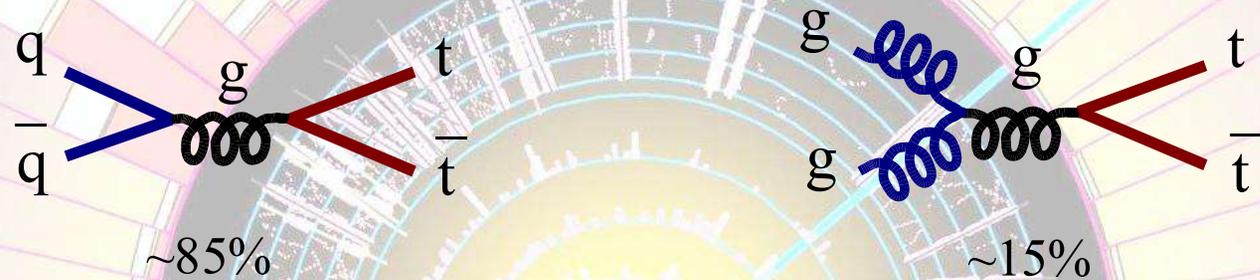


Backup Slides



Standard Tevatron Top Physics

- Top Pair Production at a Proton-Antiproton collider



- Top Pair Event Final State Signatures

– Classify by W boson decay products

- Electron or muon + jets (*lepton+jets*)

– Main channel for many top analyses

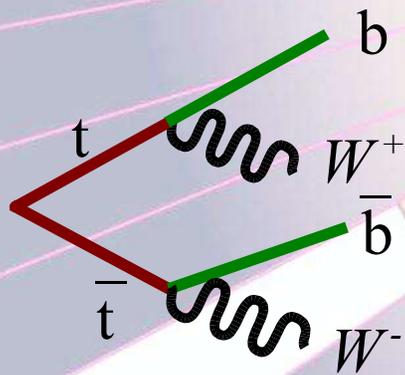
– Top pair production cross section measurement

– Top mass and other properties

- Electron or muon + electron or muon (*dilepton*)

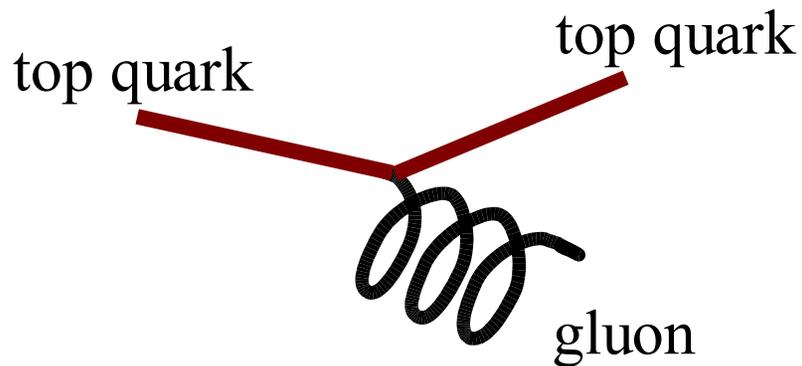
- All-hadronic mode

- Tau lepton modes ($\tau+l+jets$, $\tau+jets$)

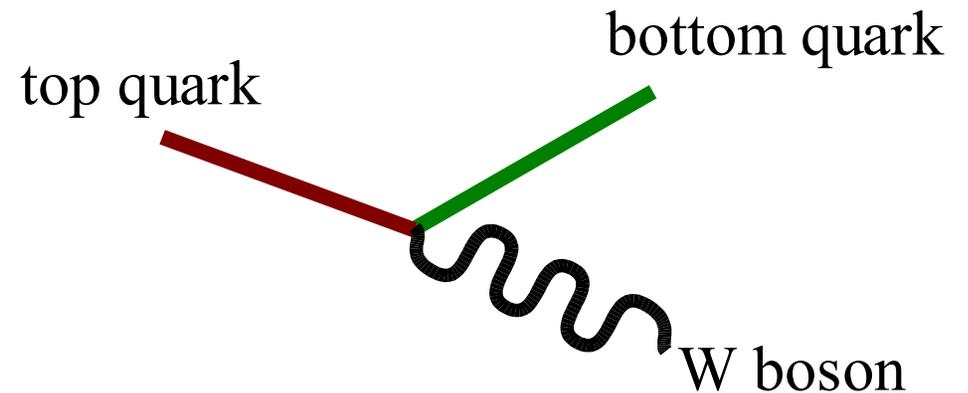


Top Quark Interactions

Strong Interaction



Electroweak Interaction: charged current

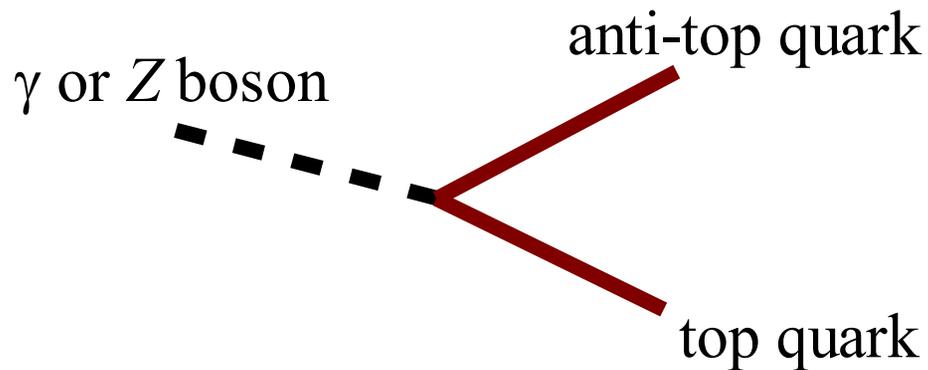


Dominant top quark
production mechanism at
hadron colliders

Dominant top quark
decay mechanism

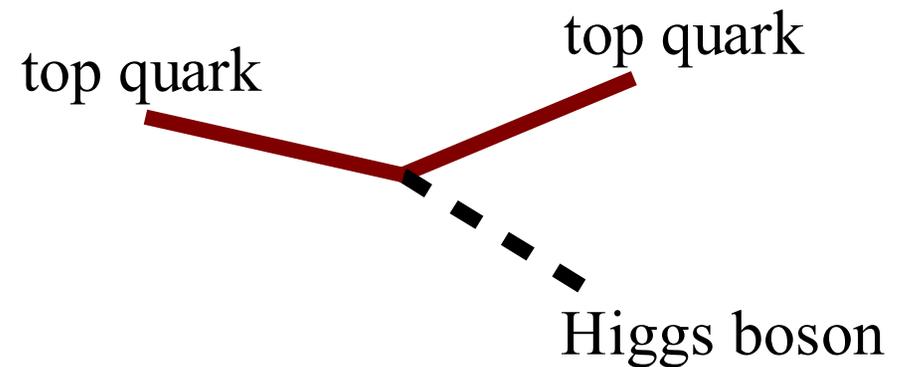
Other Top Quark Interactions

QED, Electroweak Interaction
neutral current



Top quark production mode
at e^+e^- colliders

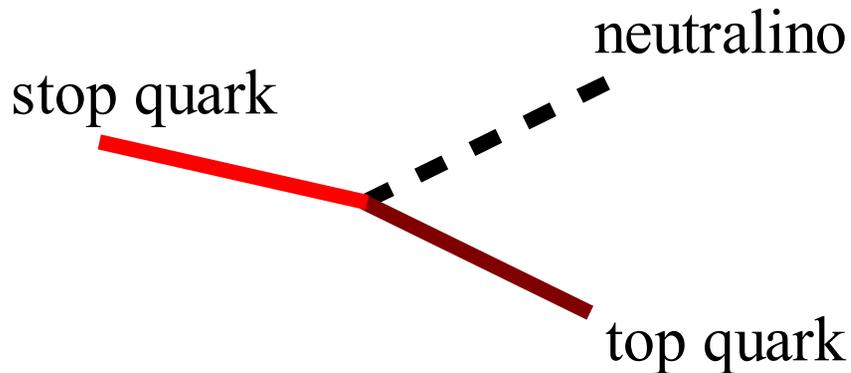
Top-Higgs Coupling



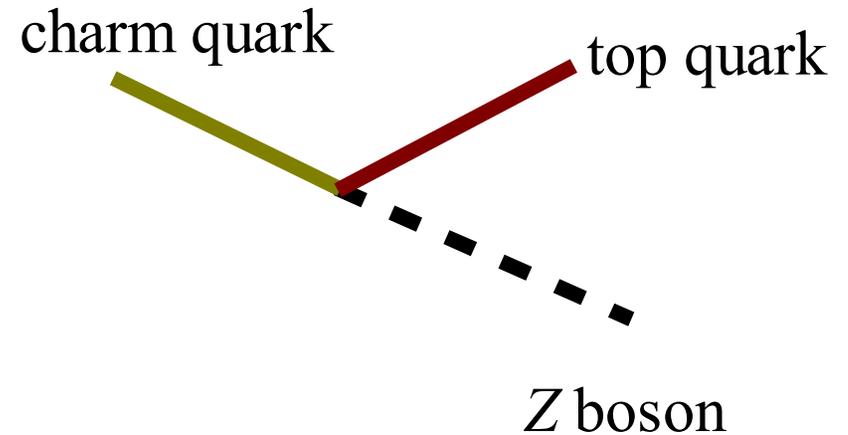
Strongest coupling to Higgs
of all quarks

Non-Standard Model Top Interactions

Supersymmetry

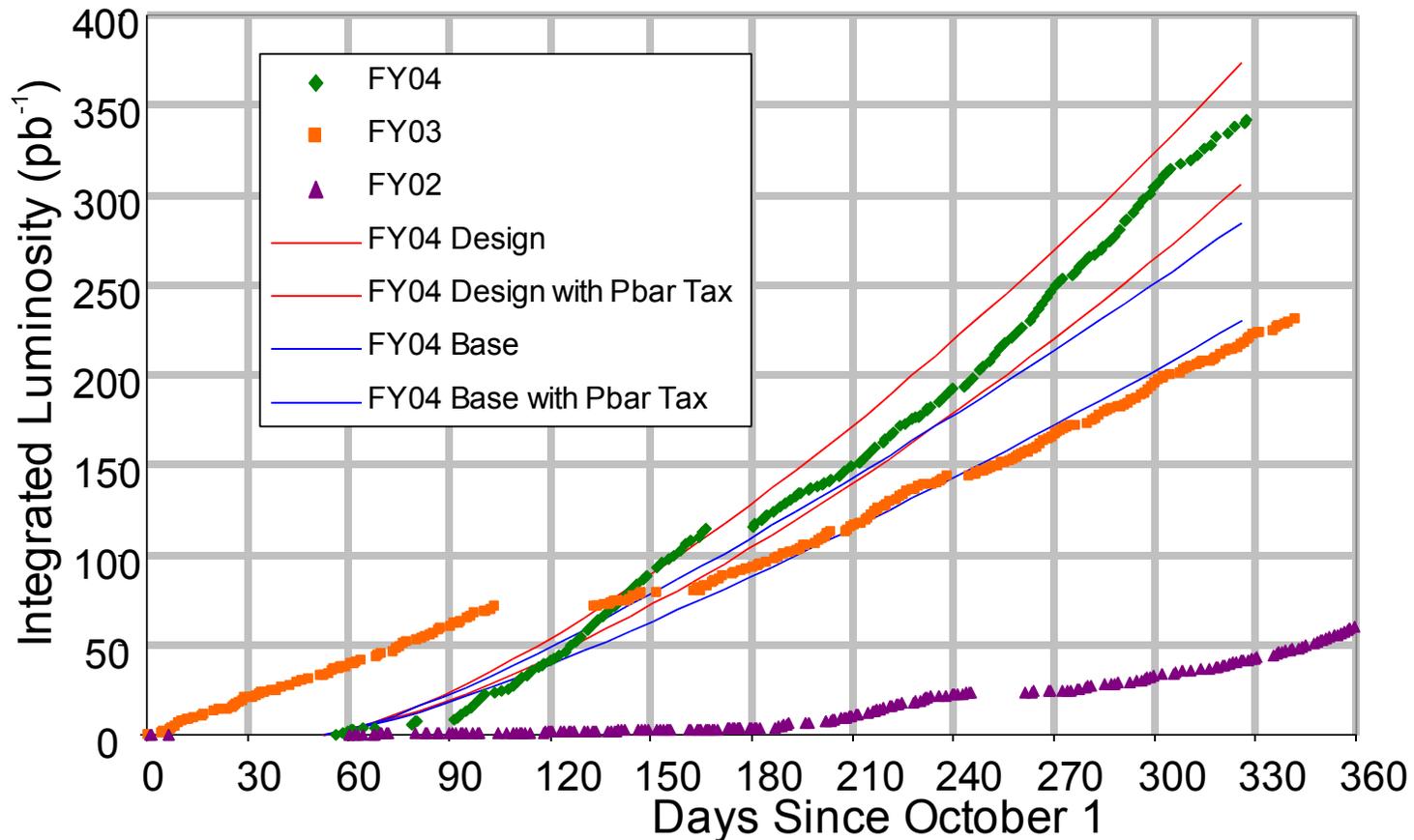


FCNC



- Plus many other possibilities
 - Interactions with W' , charged Higgs, bound top states
 - Technicolor, SUSY, FCNC, ...

Tevatron Integrated Luminosity per year

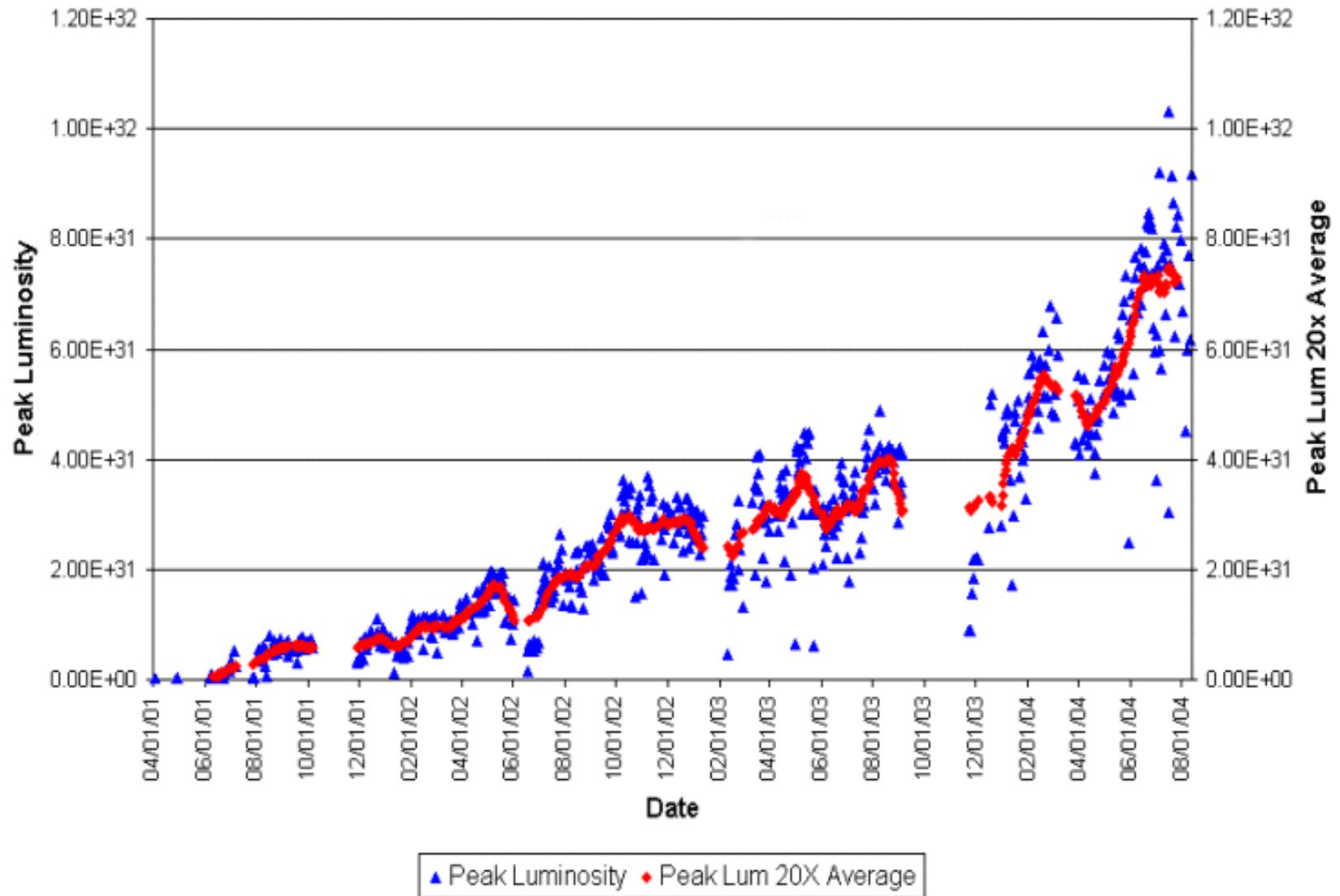


- Tevatron delivered luminosity is exceeding “baseline” and “design” projections



Instantaneous Luminosity

Collider Run II Peak Luminosity



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?
 - We have almost 500pb^{-1} collected, where is it?



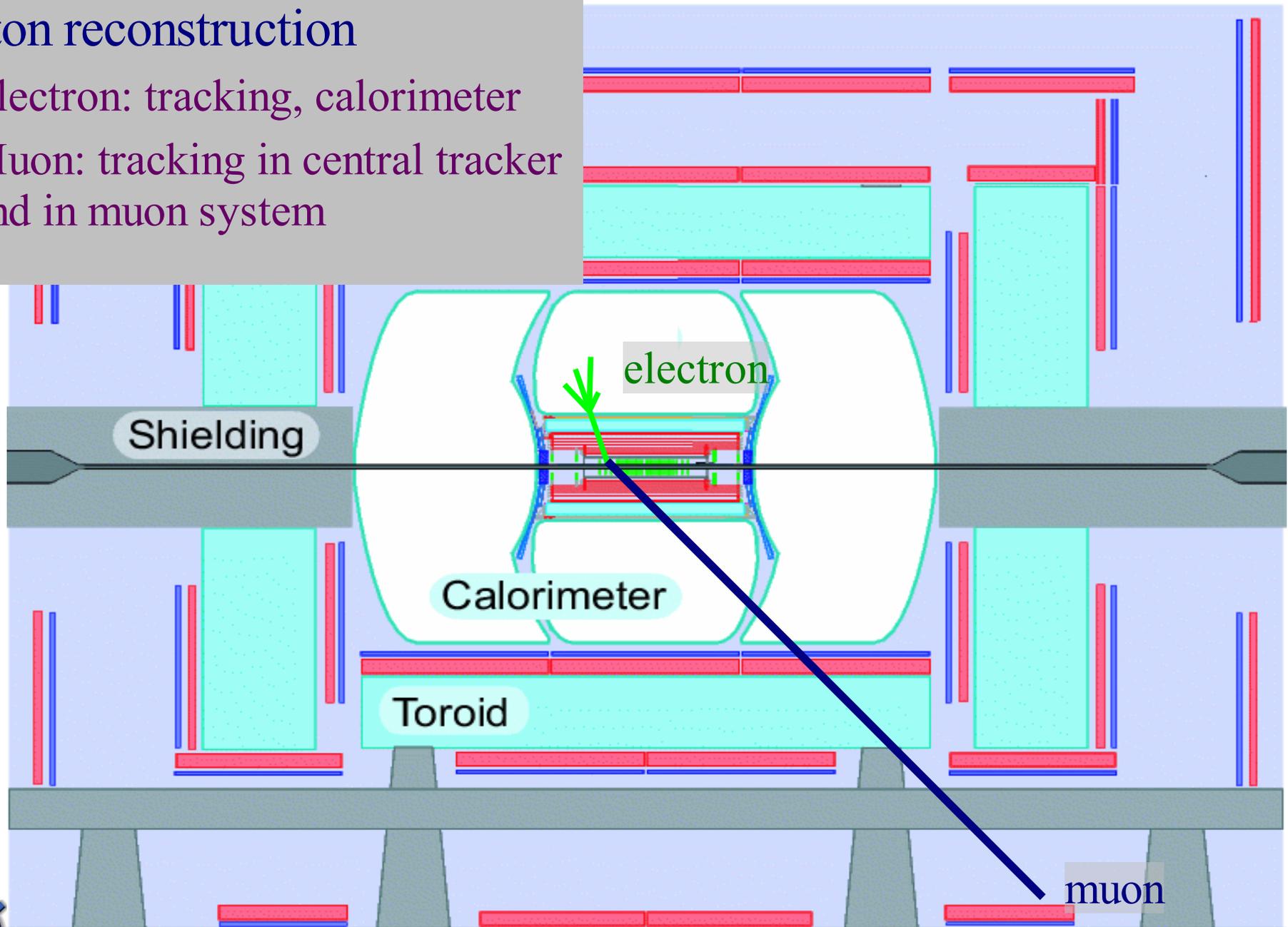
Event Reconstruction



Event Reconstruction

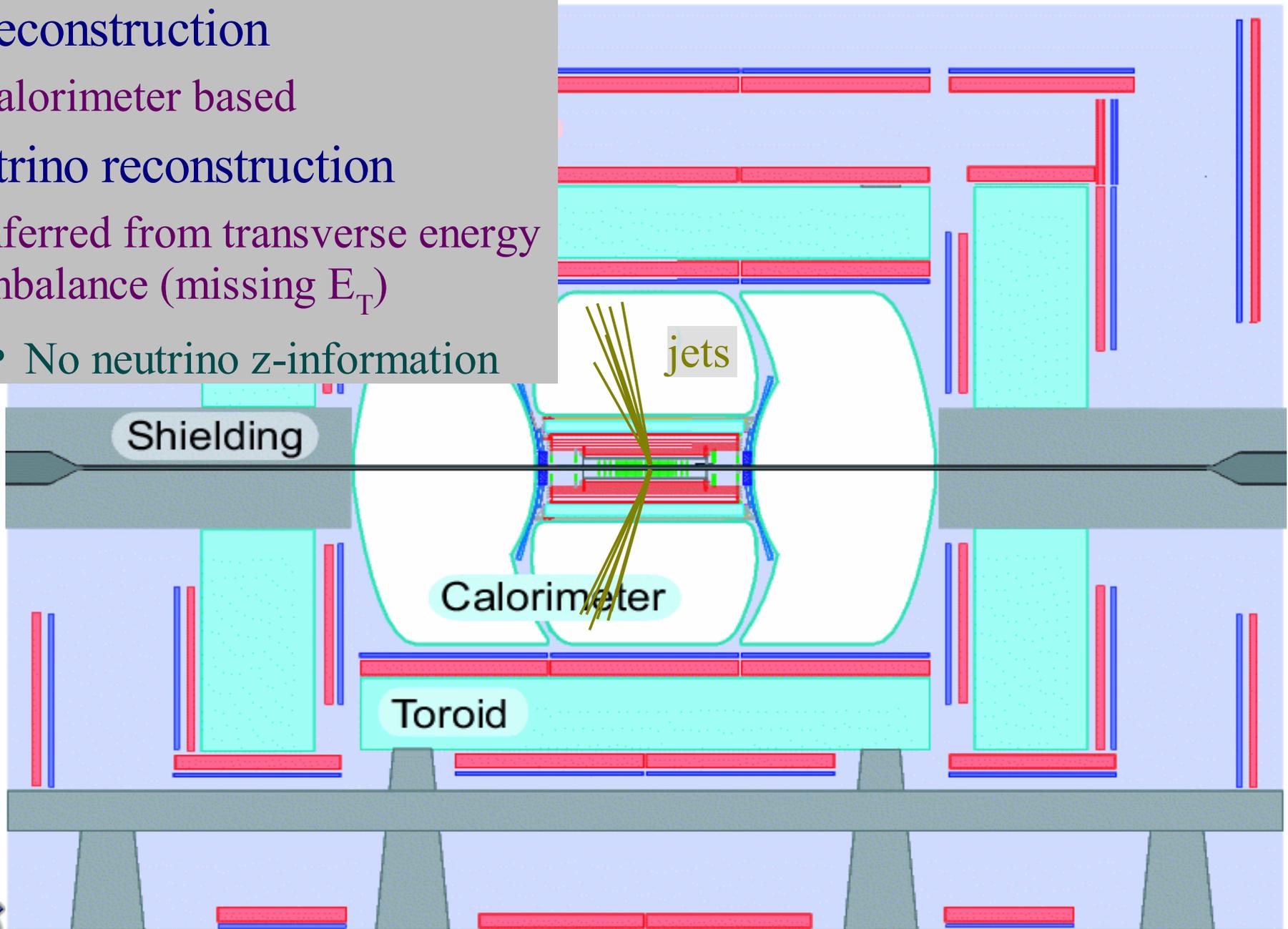
- Lepton reconstruction

- Electron: tracking, calorimeter
- Muon: tracking in central tracker and in muon system



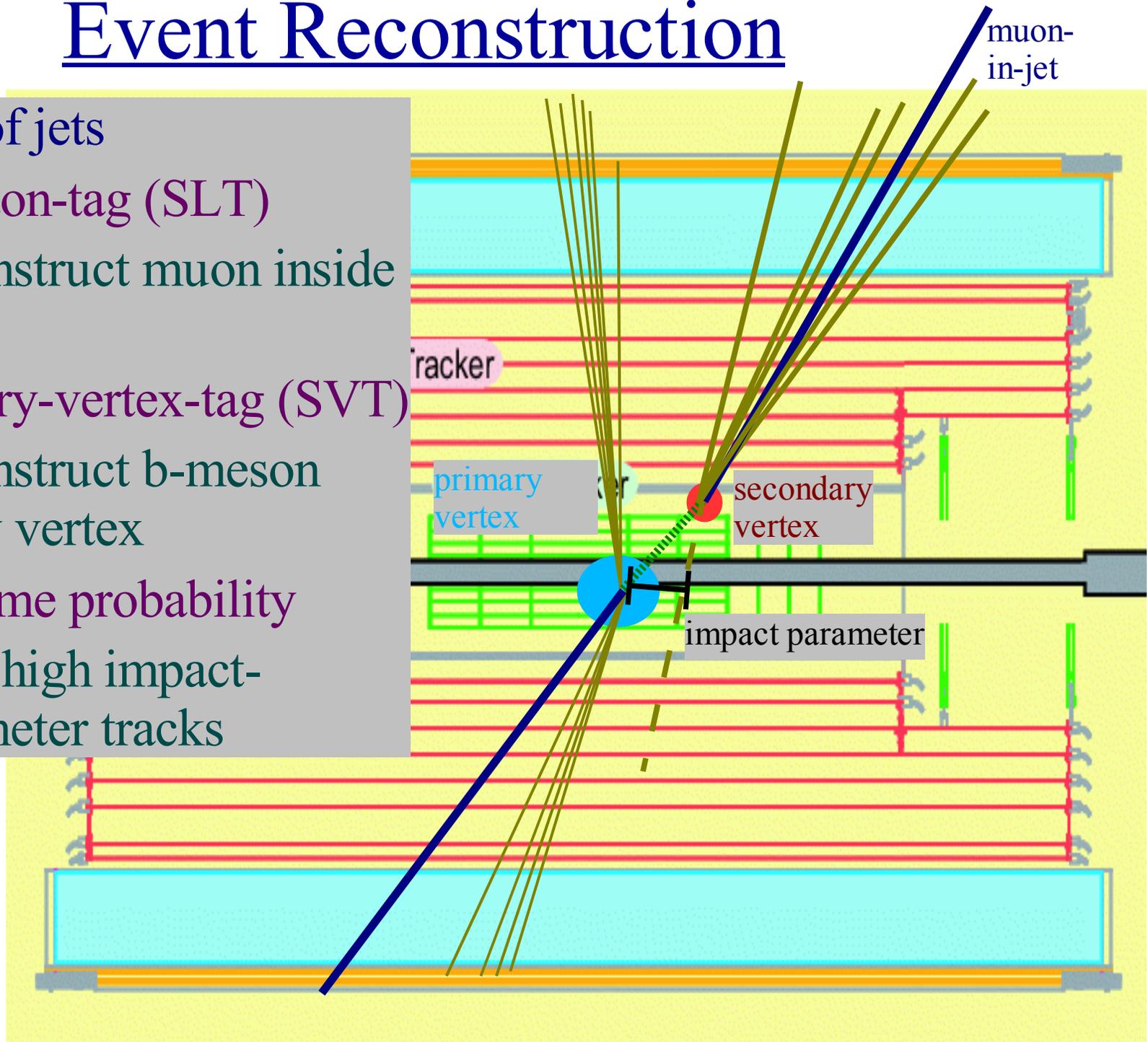
Event Reconstruction

- Jet reconstruction
 - Calorimeter based
- Neutrino reconstruction
 - Inferred from transverse energy imbalance (missing E_T)
 - No neutrino z-information



Event Reconstruction

- B-tagging of 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



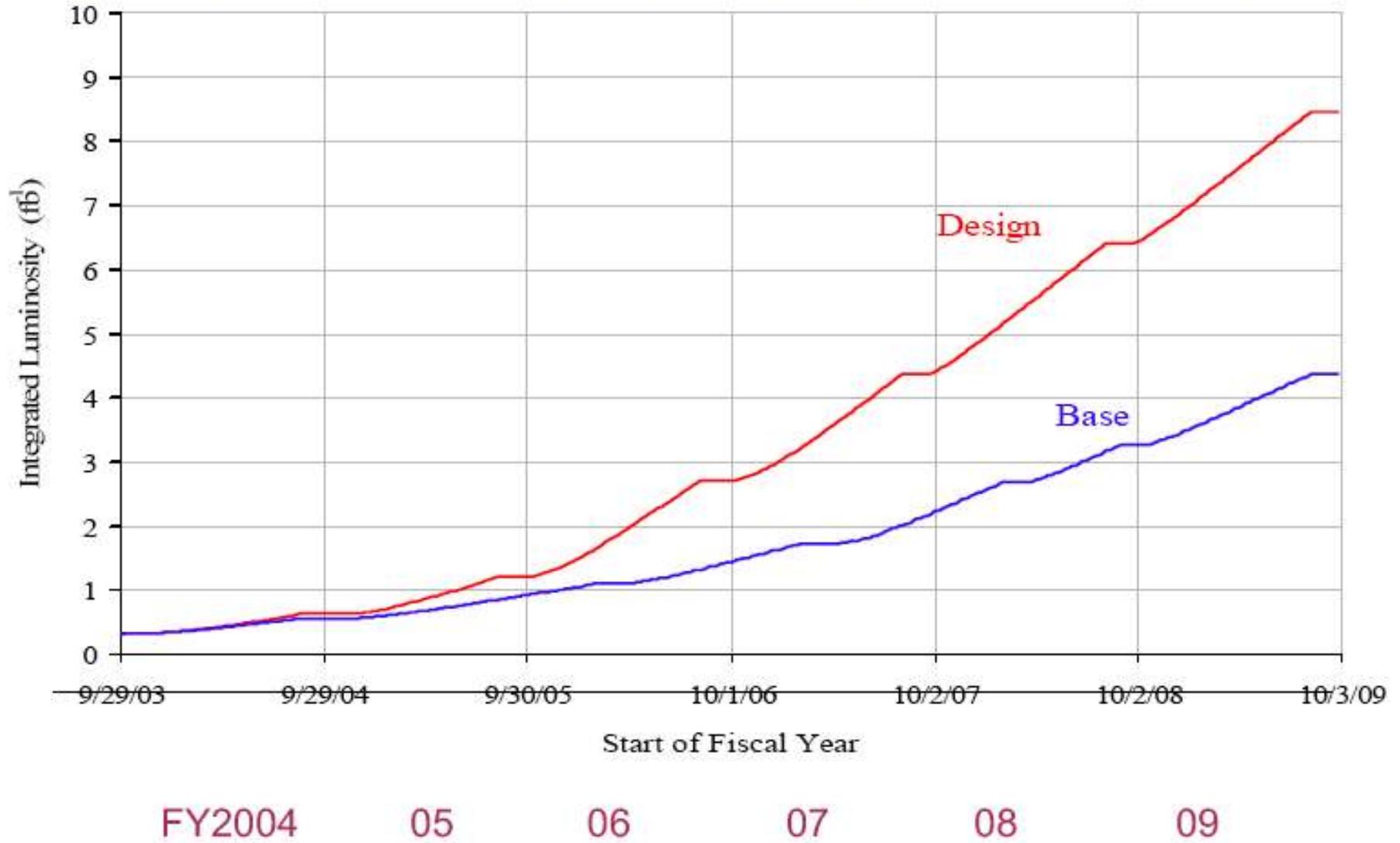
Questions

- 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?
 - What improvements to the analysis are needed?
 - How much luminosity is needed?
 - When will the luminosity be delivered?



Tevatron Luminosity Future

Integrated luminosity will about double every year for next 4 years



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?
 - What improvements to the analysis are needed?
 - How much luminosity is needed?
 - When will the luminosity be delivered?
- How accurately are we going to measure V_{tb} ?
 - Are we going to be sensitive to new Physics?

