Institut de Física d'Altes Energies

Barcelona, January 11, 2005

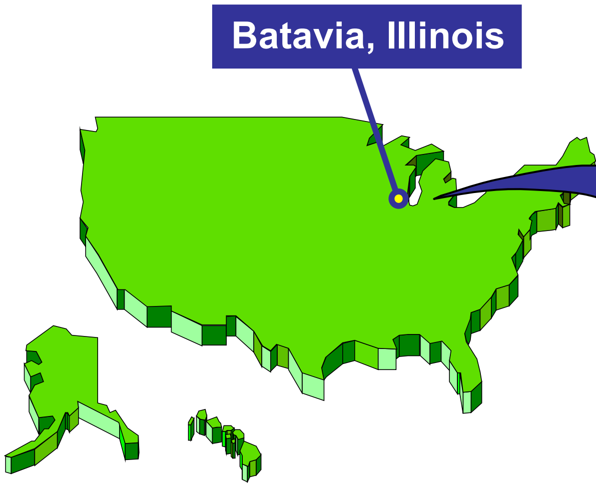
Search for lonely top quarks at DØ

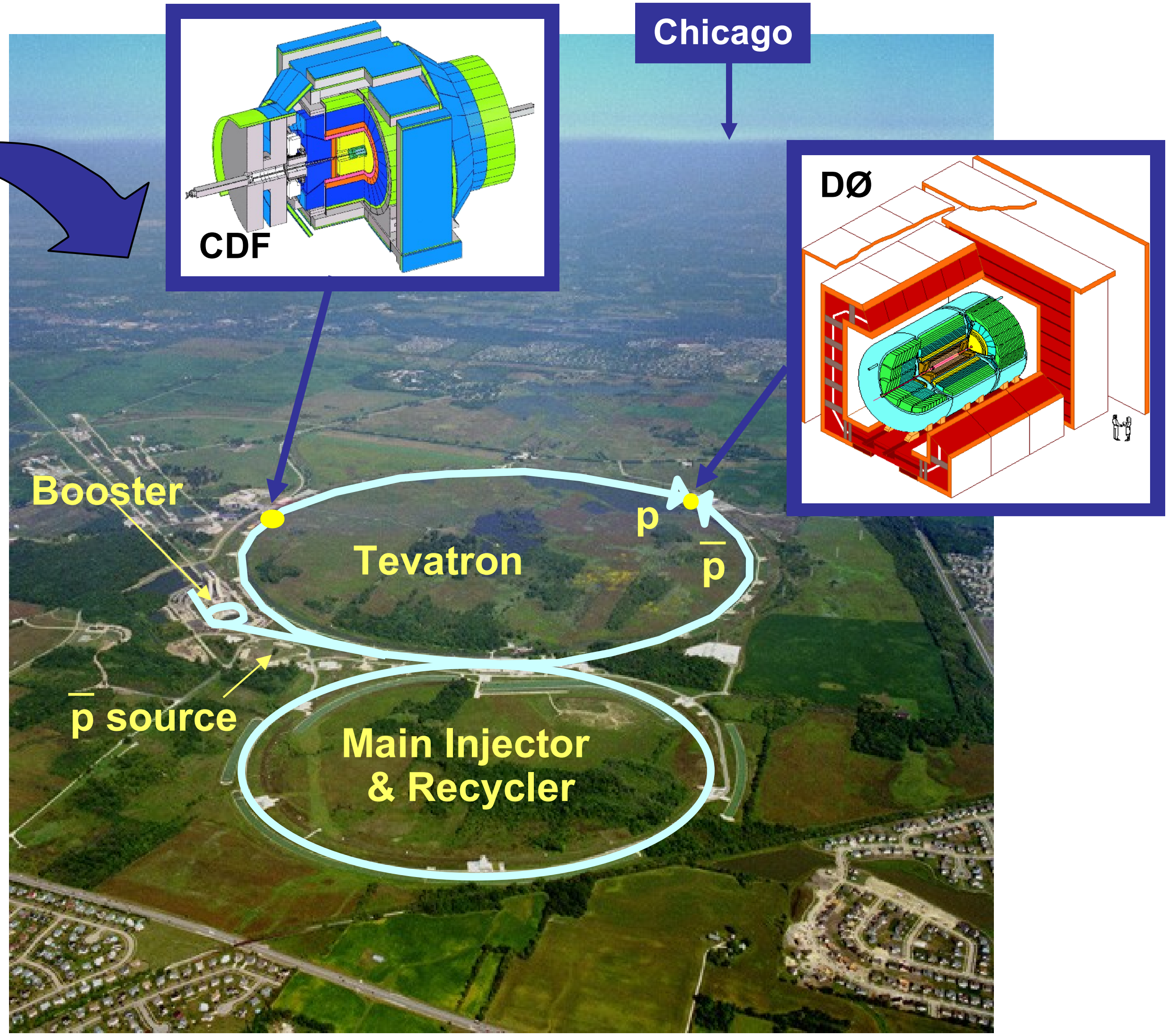
- The DØ RunII detector. Operations. Upgrade
- Top quarks at the Tevatron
- Sigle top quark production and kinematics
- Analysis overview. B-tagging. Background estimation
- Final results. Limits
- Expectation vs reality
- Outlook. Major issues
- TeV4LHC workshop advertising

Arán García-Bellido

UNIVERSITY OF WASHINGTON

Tevatron at Fermilab





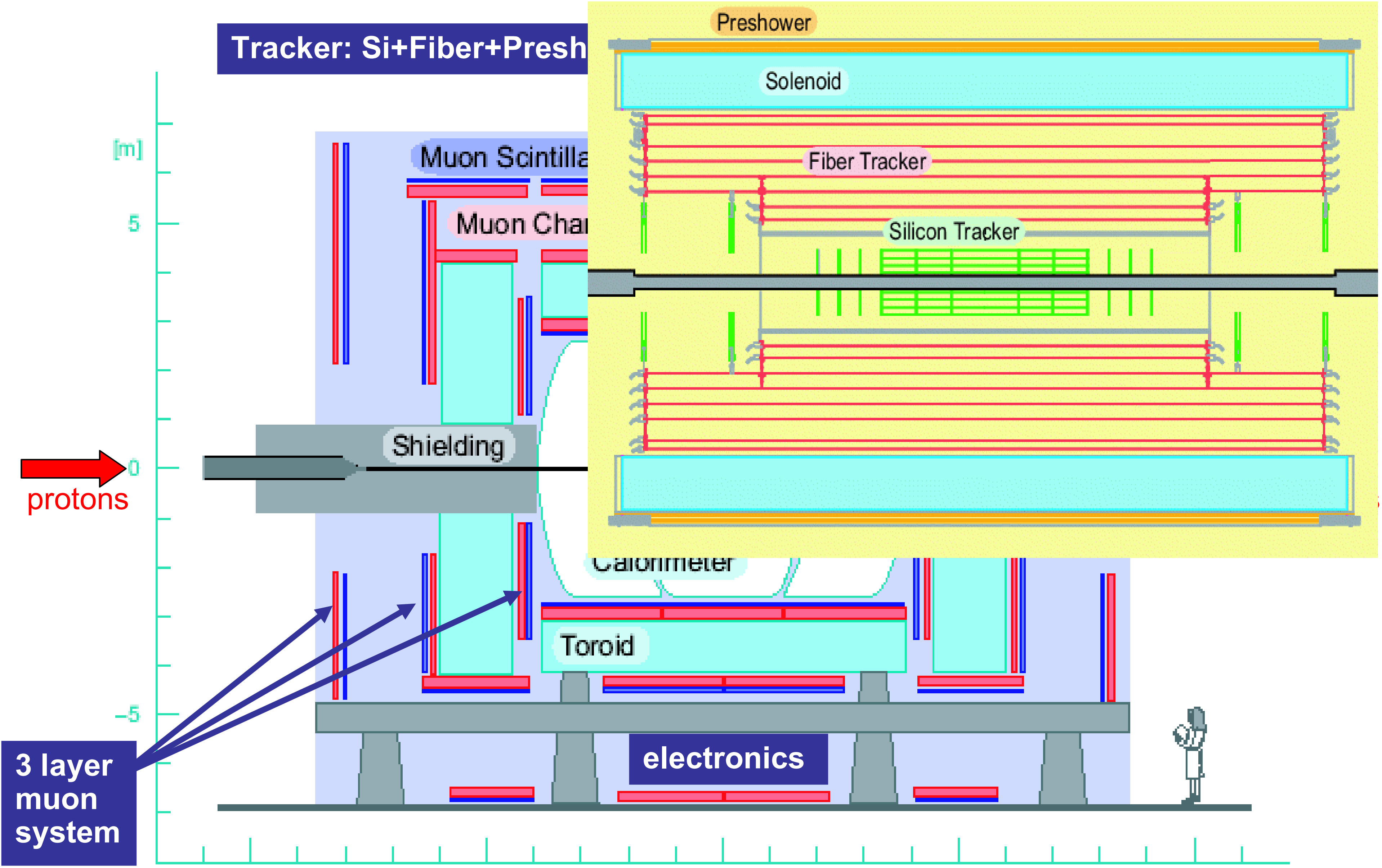
Run I 1992-95

- Top quark discovered!

Run II 2001-09(?)

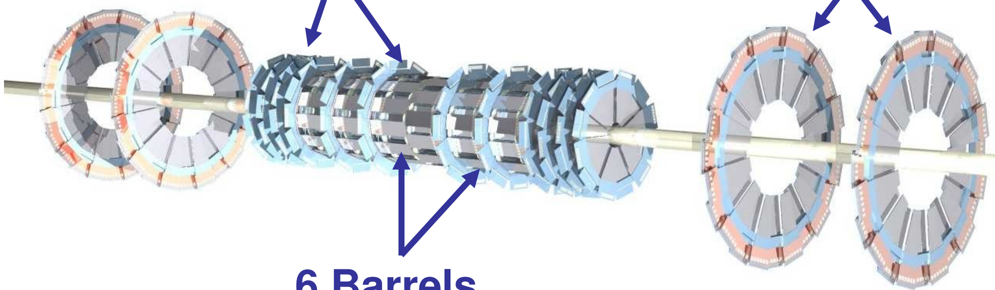
- $\sqrt{s}$ =1.96 TeV
- Δt = 396 ns
- 36x36 bunches
- Peak Lum 10^{32} $cm^{-2}s^{-1}$
- Delivered ~500 pb^{-1}

The Run II DØ detector



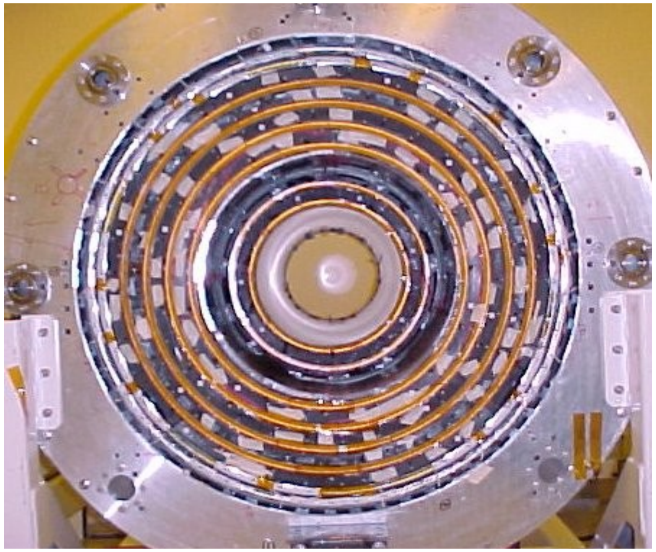
New for Run II: Tracking in 2T

Silicon Vertex Detector



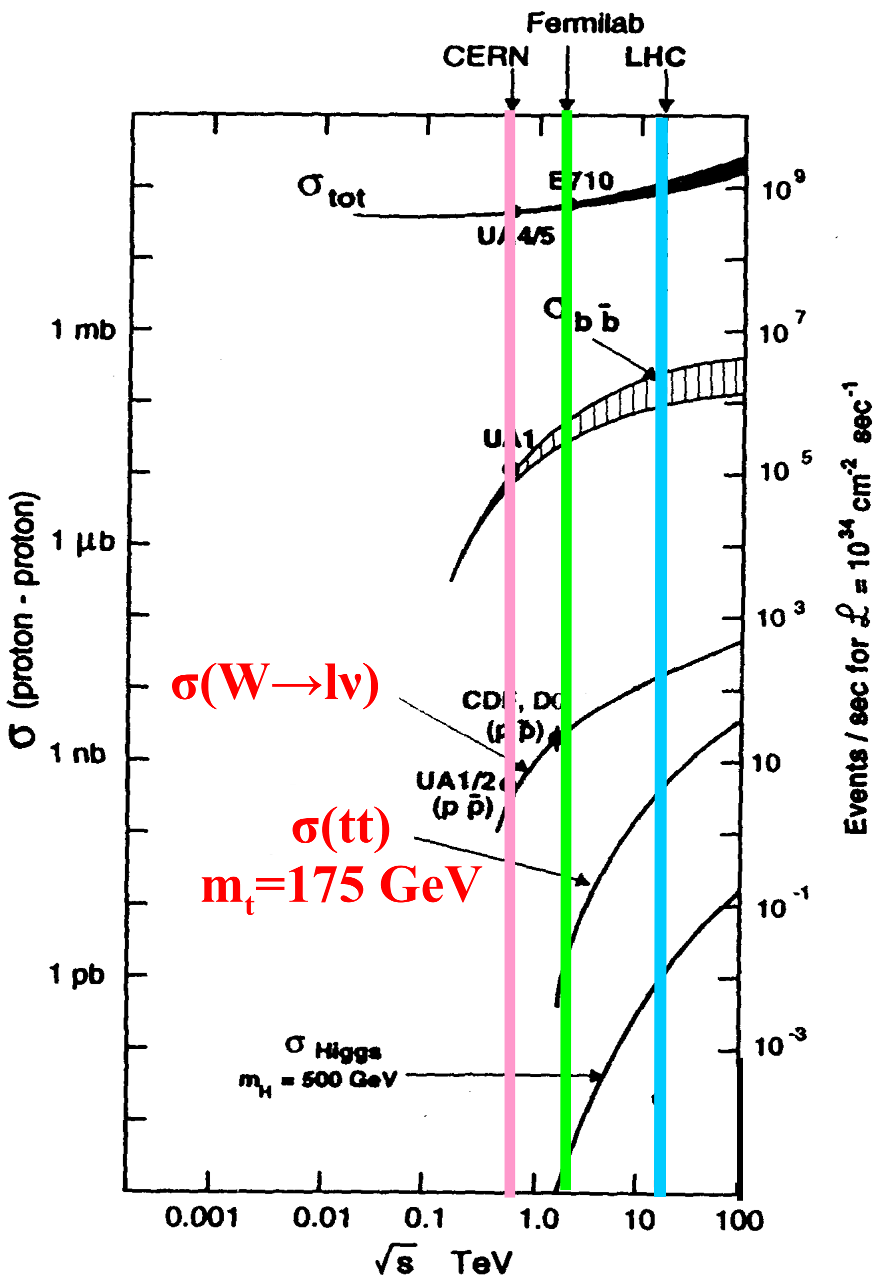
3m² of Si, 1.2m in length

Central Fiber Tracker



8 axial & 8 stereo fiber layers

- Improved momentum resolution and coverage for muons
- New electronics for LAr calorimeter: working on noise and isolation
- Track-based b-quark jet identification
- Will install a Layer 0 for the Si (from RunIIb) in 2005 shutdown



Triggering

Collision rate is huge:

- ►Every 396ns at the Tevatron
- ►Every 25ns at the LHC

Total cross section is also big ~0.1b

- ►2-3 interactions per collision at $L=10^{32}$
- ►20 interactions per collision at $L=10^{34}$

W, Z, top, H are relatively rare

Trigger and Luminosity are crucial

Trigger and DAQ system

Bunch crossing: 396 ns ⇒2.5 MHz

	Level 1	→	Level 2	→	Level 3	→	tape
Spec:		5 kHz		1000 Hz		50 Hz	
Operating:		1.4 kHz		800 Hz		50 Hz	

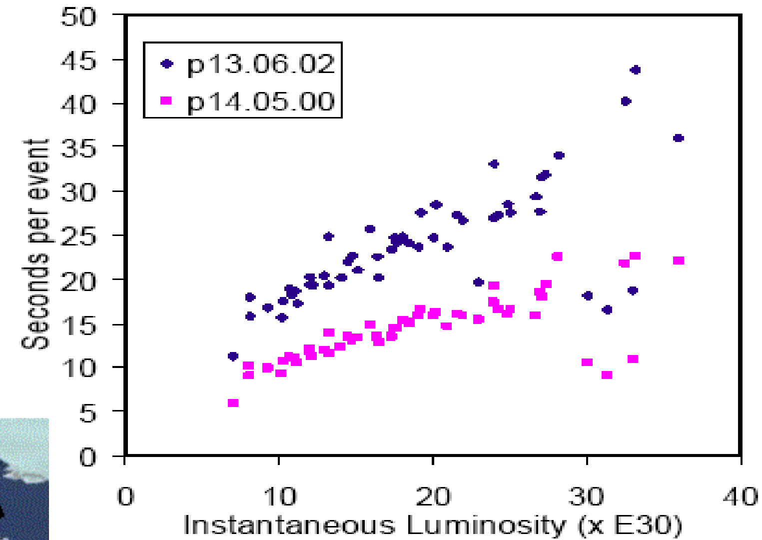
1M channels ~250KB/event

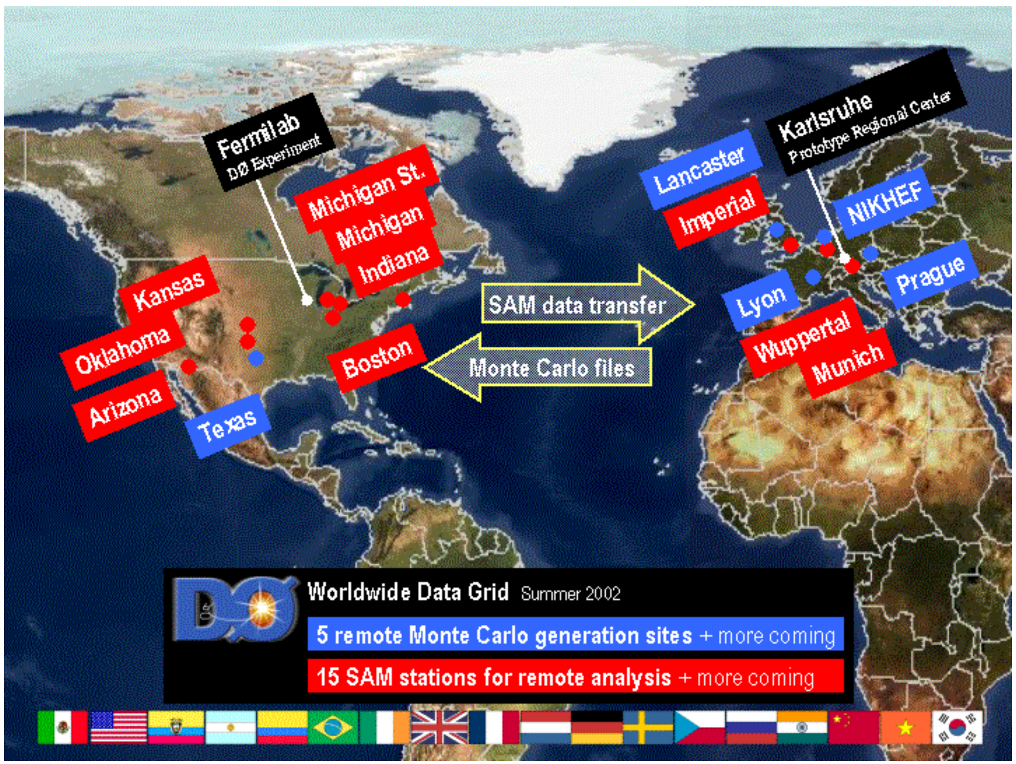
- ► Runs comfortably up to $5x10^{31}$ $cm^{-2}s^{-1}$ and will keep pace with luminosity growth as tracking triggers completed, CPUs added.
- ► L1: >100 independent trigger bits
  - ► Fast trigger pick-offs from all detectors
  - ► Custom hardware/firmware
  - ► Trigger on hit patters in individual detector elements
- ► L2: Combine Level 1 regions and objects
  - ► Input rate expansion w/ processor replacements
- ► L3: Full detector readout
  - ► Extensive suite of filters available
- ► DAQ: VME-based PCs and Ethernet switches
  - ► Working to reduce Front End Busy rate (~4%, mostly tracking)
  - ► Event reconstruction: Linux commodity farm to make L3 decision
  - ► Can monitor from a cell phone!
  - ► Upgrade: Extra 50 Hz to tape
  - ► Possibly: another extra 50 Hz (for a total of 150Hz) of B physics triggers

Offline event reconstruction and analysis

DØ Reconstruction Farm

- 240 1.8 GHz dual CPU machines
- 20M event/week capacity
- events processed within days of collection
- 1G events processed in Run II so far





Globally Distributed Resources

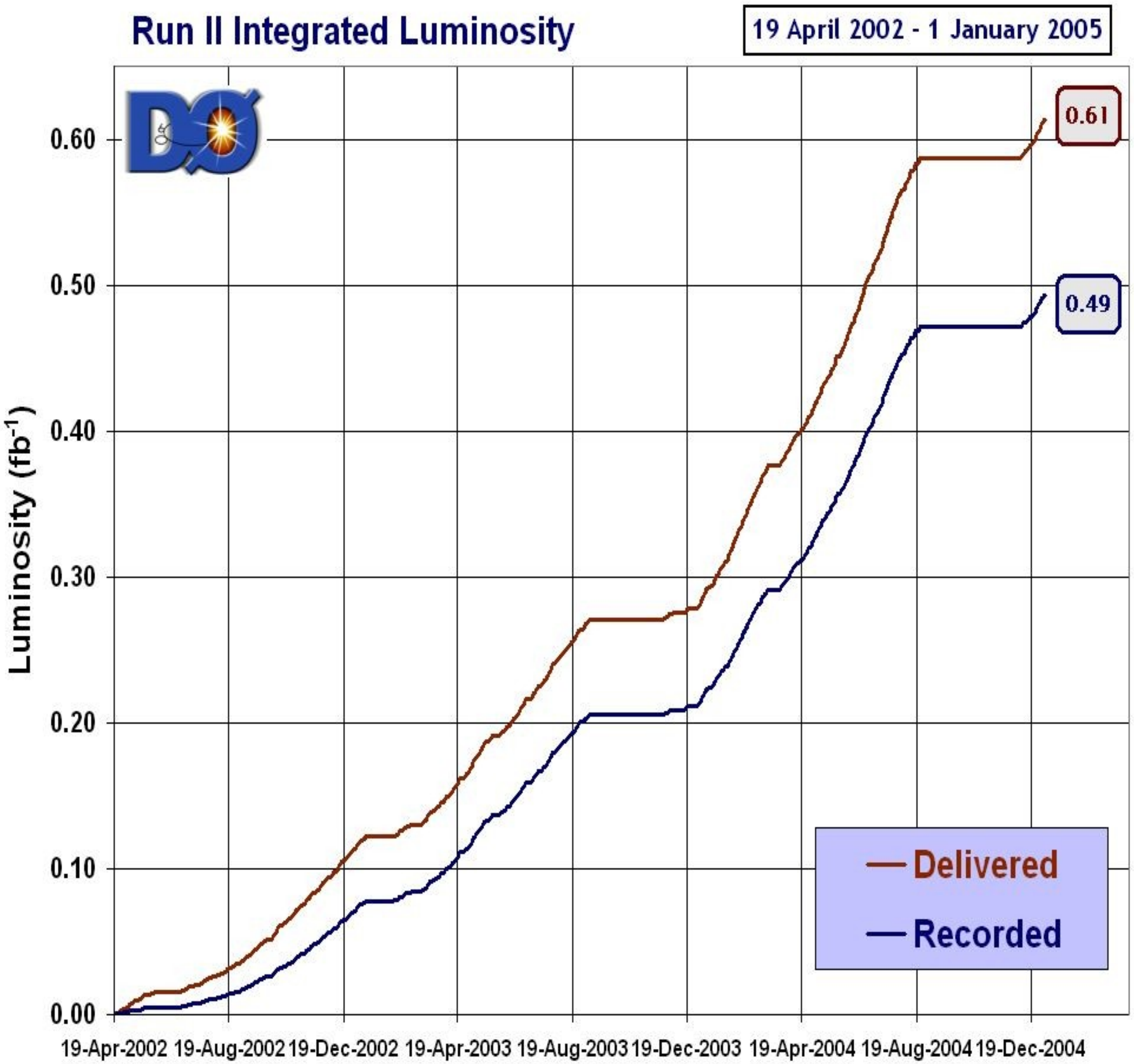
11 remote Monte Carlo Farms

- Running full GEANT, DØ reconstruction and trigger simulation

40 SAM stations for remote analysis

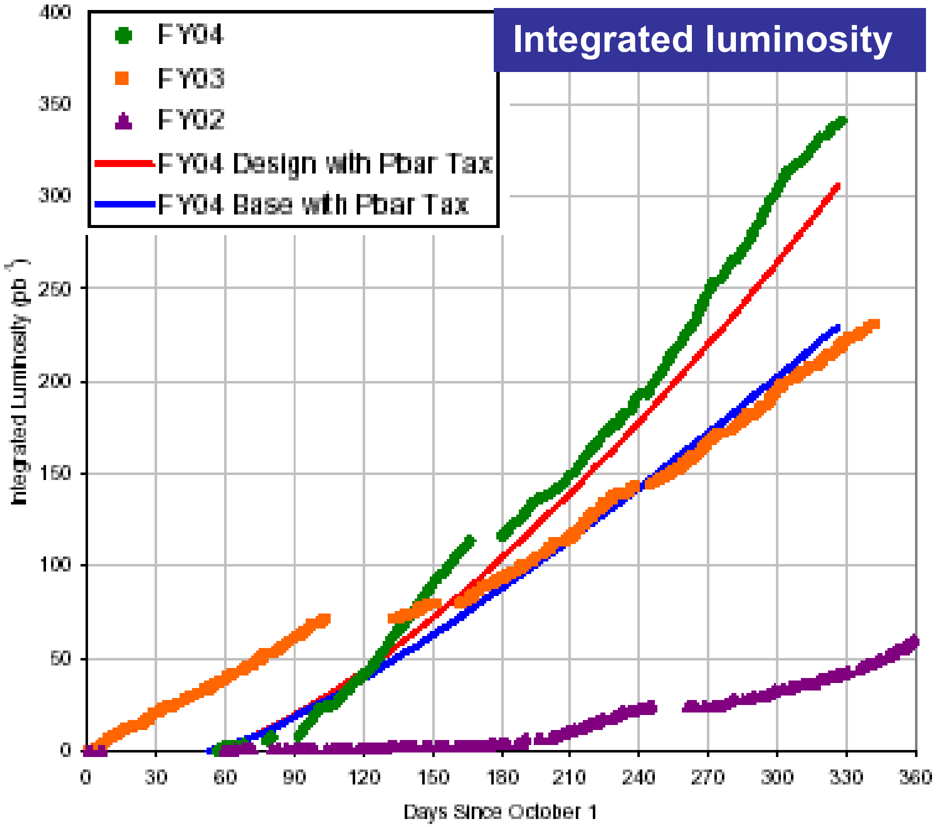
- Over 2Pb moved last year
- Up to 200Tb/month

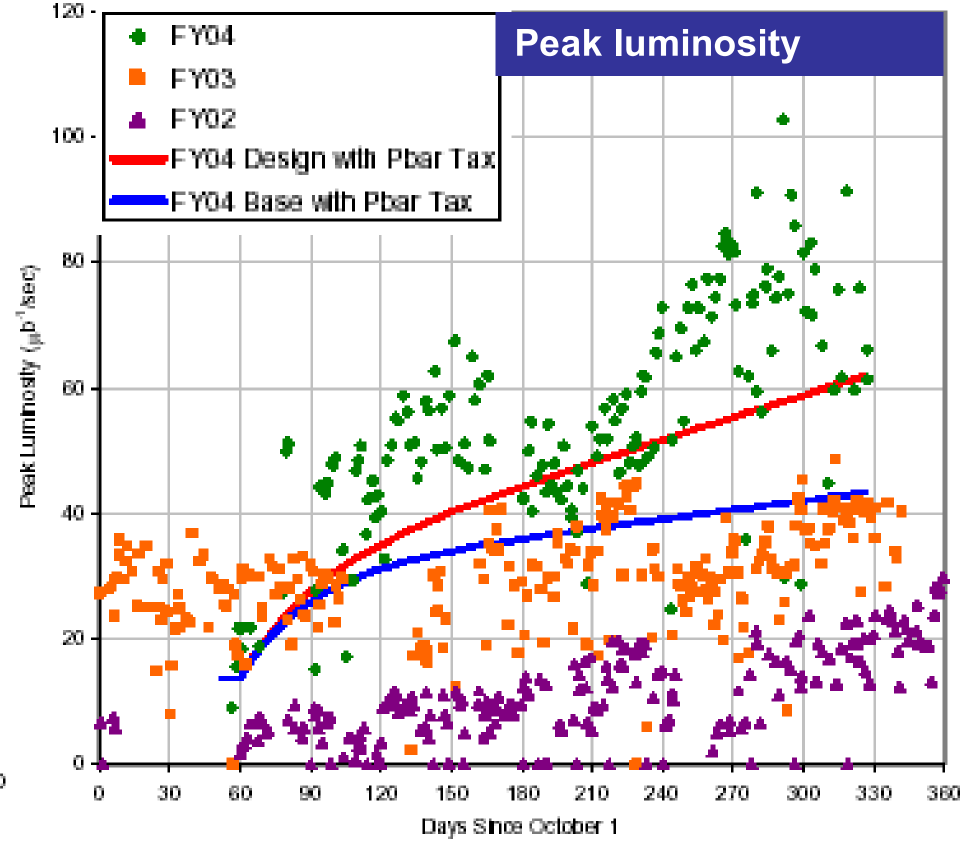
Integrated Luminosity



- ►~490 pb^{-1} on tape: an overall 85% efficiency
- ►Inefficiency due to:
  - ~ 5% FEB
  - ~ 5% losses in store & run transitions
  - ~ 5% “incidentals”
- ►Lately recording data with 90% efficiency
- ►Average 8 pb^{-1}/week

Tevatron progress

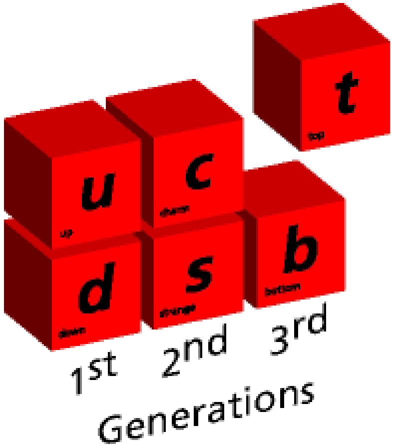




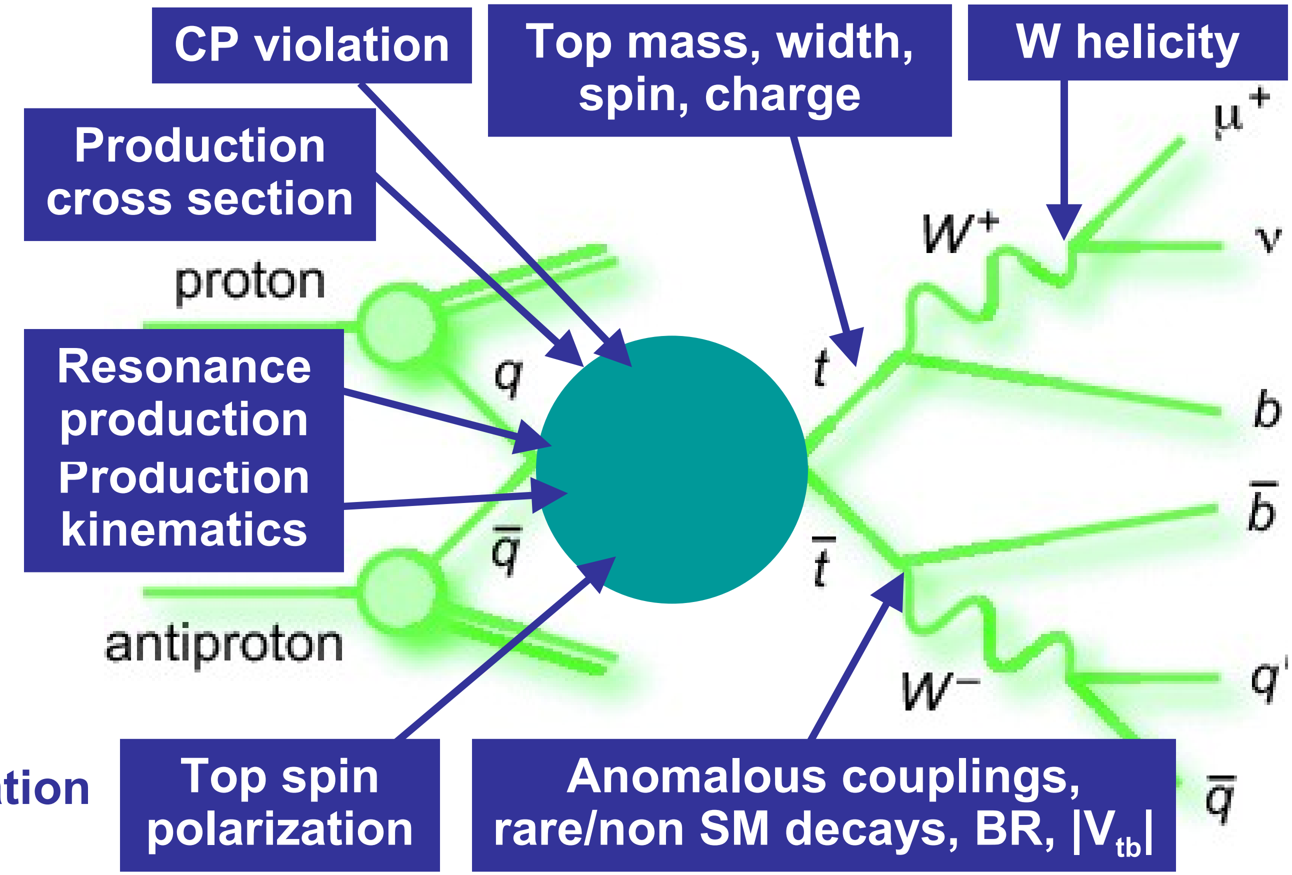
- ▶ Latest record: 1.0×10^{32} $cm^{-2}s^{-1}$
- ▶ Stores last around 20h
- ▶ We just had a major shutdown:
  - Electron cooling installed in the recycler
  - Still improving pbar production
  - Will aim at $14 pb^{-1}$/week for FY05

Great performance! Well above expectation!

DØ was taking data after 3 minutes



Top quark physics in Run II



The Tevatron is the world’s only source of top quarks!

Top quark has a special place in the SM: $M_t \sim v/\sqrt{2}$ Window into EWSB?

Decays before hadronization

Still know very little experimentally about the top quark

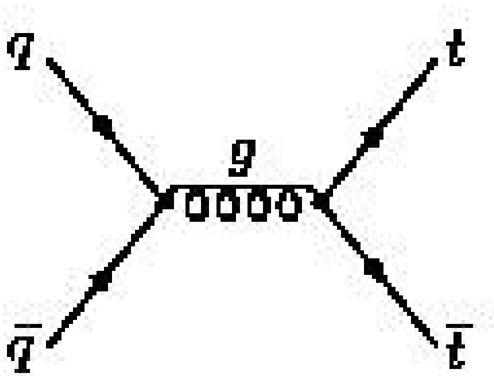
Run I:
Identified ~100 top events

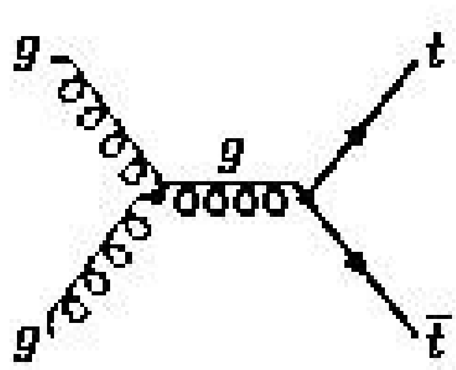
Top quark strong production

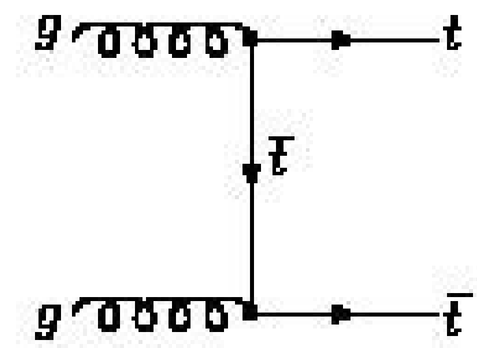
Pair production through strong interaction

σ(tt) ~ 7.5 pb at √s=1.96TeV (NNLO CTEQ5M, Kidonakis et al.)

- ► Main production mode at Tevatron
- ► 30% higher σ(tt) than in Run I
- ► 0.8 events/hour at recent Luminosities







TeV: qq~85% of σ (tt) **gg~15% of σ (tt)**

LHC: qq~10% of σ (tt) **gg~90% of σ (tt)**

σ(tt) ~ 833±100 pb at √s=14TeV (Cacciari et al.)

0.8 events/second at initial (low) luminosities

Top quark Electroweak production

Single top production via EW interaction

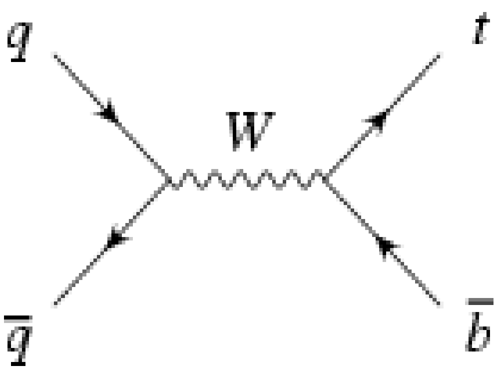
$\sigma(t) \sim 2.86$ pb at $\sqrt{s}$=1.96TeV (NLO Sullivan et al.)

- ► Flagship measurement at Run II
- ► Dominant bkgs: Wjj, tt, QCD
- ► Measure s- and t-channel cross sections separately
- ► First direct probe of $|V_{tb}|$

TeV: 0.88± 0.11 pb

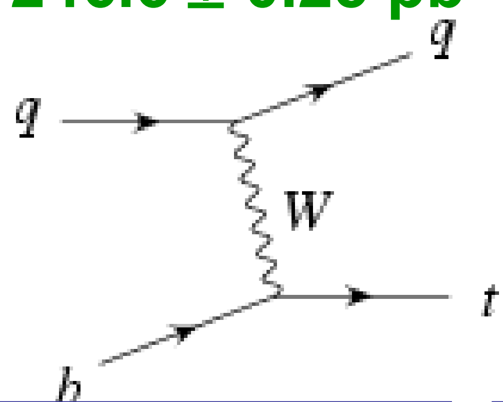
LHC: 10.6 ± 1.1 pb

pb



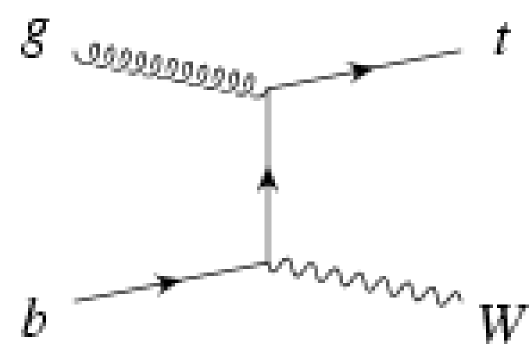
1.98± 0.25 pb

246.6 ± 0.25 pb



<0.1 pb

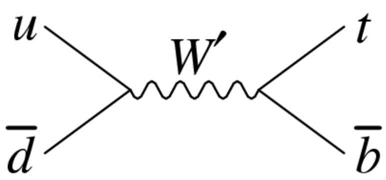
$62.0^{+16.6}_{-3.6}$

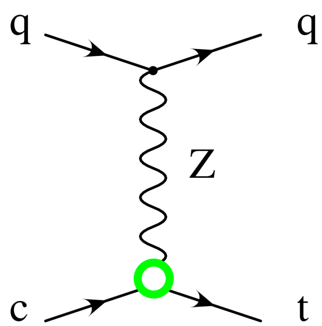


Harris, Laenen, Phaf, Sullivan, Weinzierl, PRD 66 (02) 054024
Sullivan hep-ph/0408049

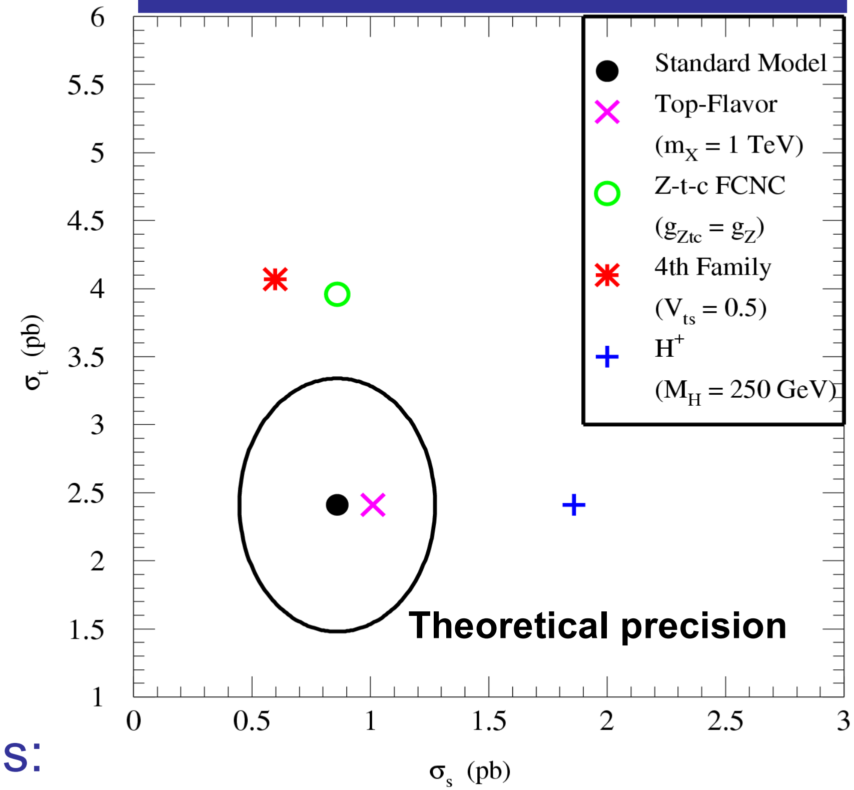
Tait, PRD 61 (00) 034001
Belyaev, Boos, PRD 63 (01)

Why search for single top?

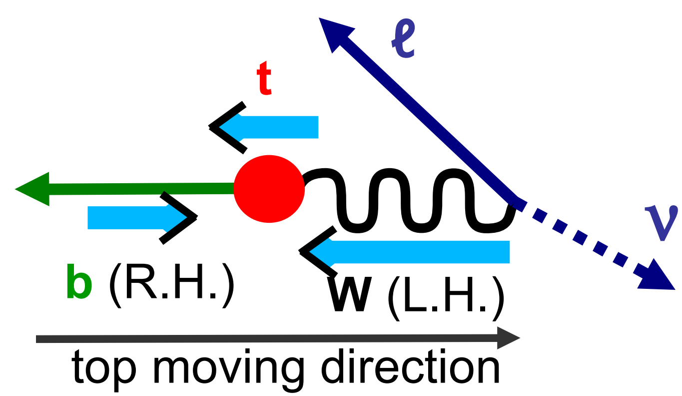


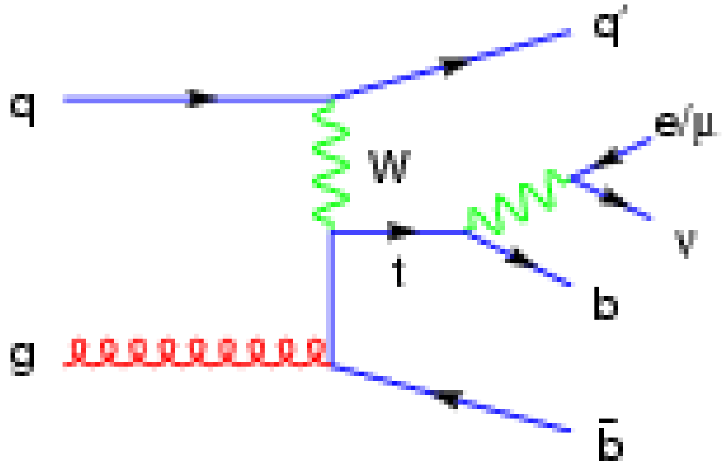


Tait, Yuan PRD63, 014018 (2001)



- ▶Access Wtb
  - ▶measure Vtb directly
  - ▶ test unitarity of CKM
- ▶Test V-A structure of SM
- ▶New physics:
  - ▶s-channel sensitive to resonances: W', top pions, SUSY, etc…
  - ▶t-channel sensitive to FCNCs
- ▶Study top polarization, mass

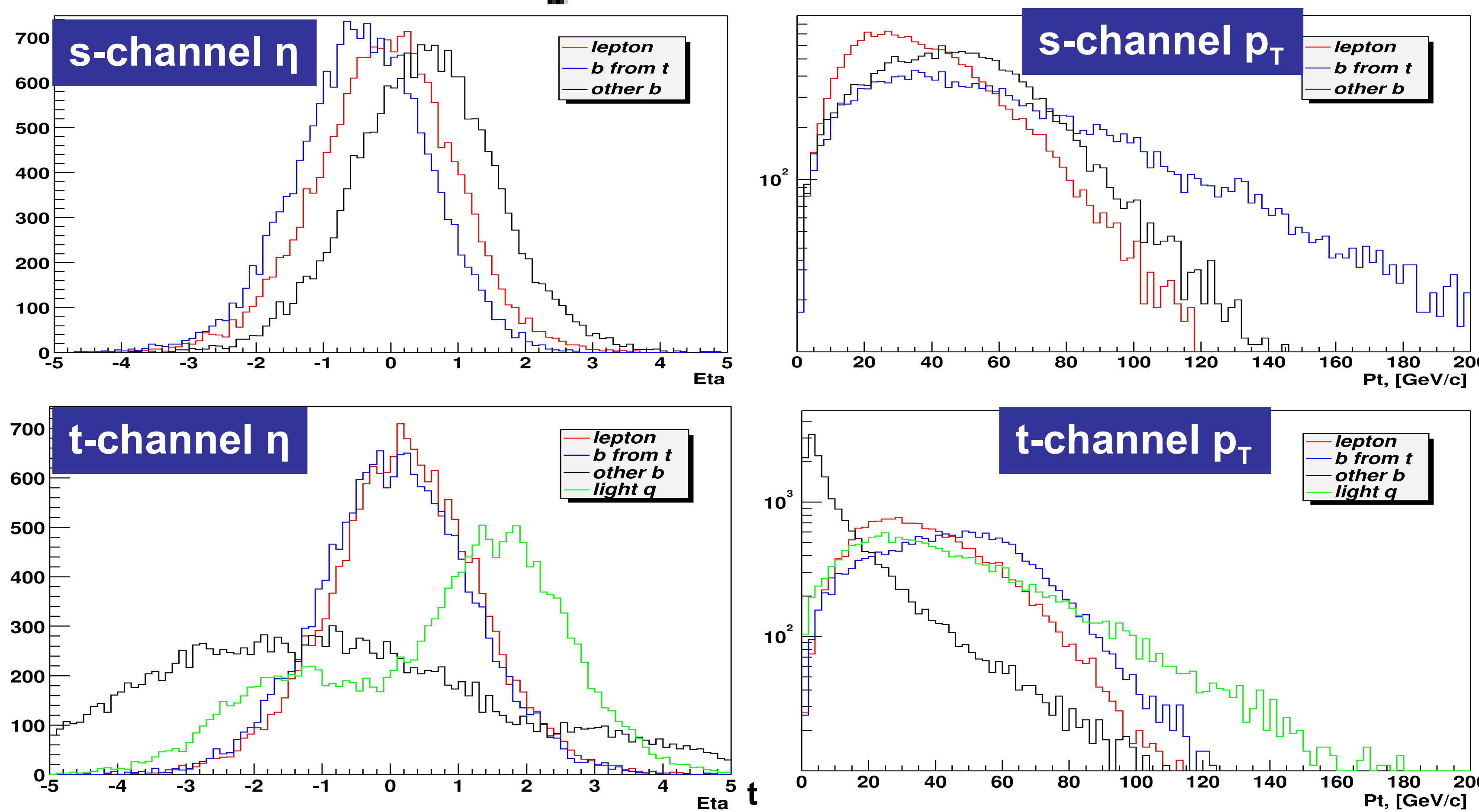




Signal topology

We are looking for:

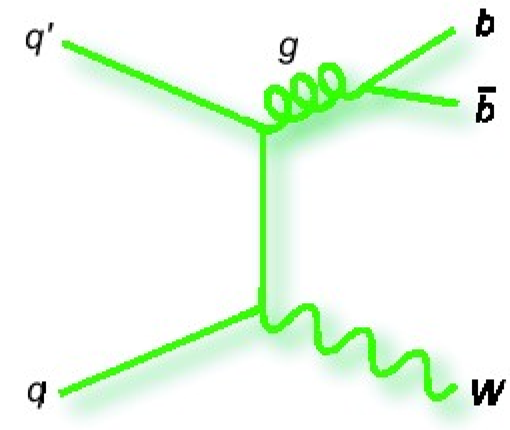
- ▶ One high p_T isolated lepton (from W)
- ▶ MET (ν from W)
- ▶ One b-quark jet (from top)
- ▶ A light flavor jet and/or another b-jet

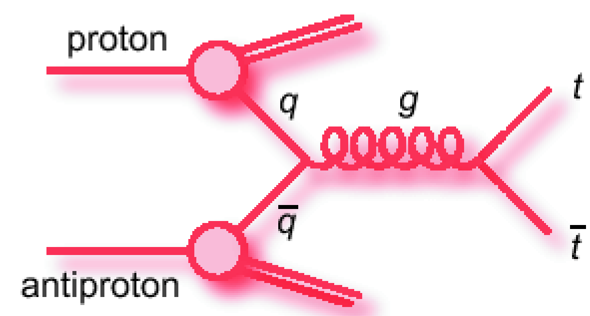


t

Main backgrounds

- For this analysis, use data as much as possible to estimate backgrounds
- W/Z+jets production (real-ℓ)
  - Estimated from data
    - Distributions from untagged sample
    - Normalization from preselected sample
    - Tag probability from QCD sample
- Top-pair production
  - Estimated from Alpgen MC
- Mis-reconstructed multi-jet events (fake-ℓ)
  - Estimated from data
- Other (WZ, WW, Ztt, cosmic rays,...)
  - Included in data W/Z+jets estimate





DØ single top search strategy

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
   - ►Use b-tagging to enhance signal-to-noise ratio
   - ►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, ...

Event selection

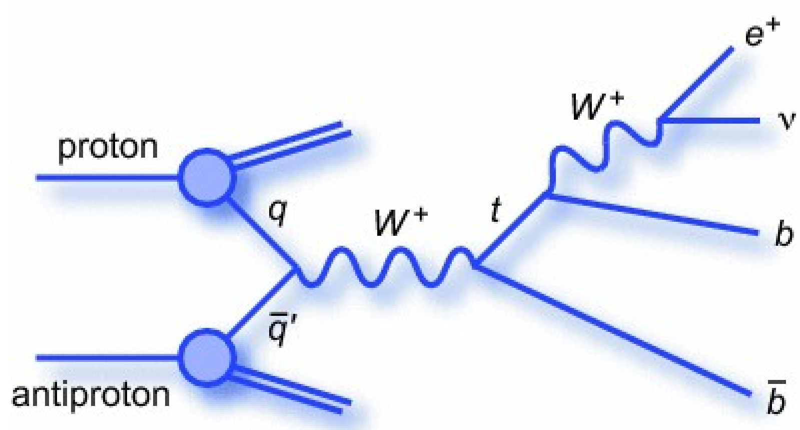
	L1	L2	L3
e	≥1 EM object p_T>11GeV	—	≥1 EM object p_T>15GeV
μ	≥ 1 muon hit	1 muon	—
jet	≥1 jet	≥1 jet	≥1 jet

Trigger efficiency:

- 85% electron channel
- 89% muon channel

Loose preselection to keep data with similar final state objects to signals:

- One good quality isolated e(μ), E_T > 15 GeV, |η| < 1.1 (2.0)
- MET > 15 GeV
- 2 ≤ Njets ≤ 4
  p_T > 15GeV
  |η| < 3.4
  p_T (jet 1) > 25GeV
  Require at least one b-tagged jet
- Reject misreconstructed events
  and regions not well described by backgrounds

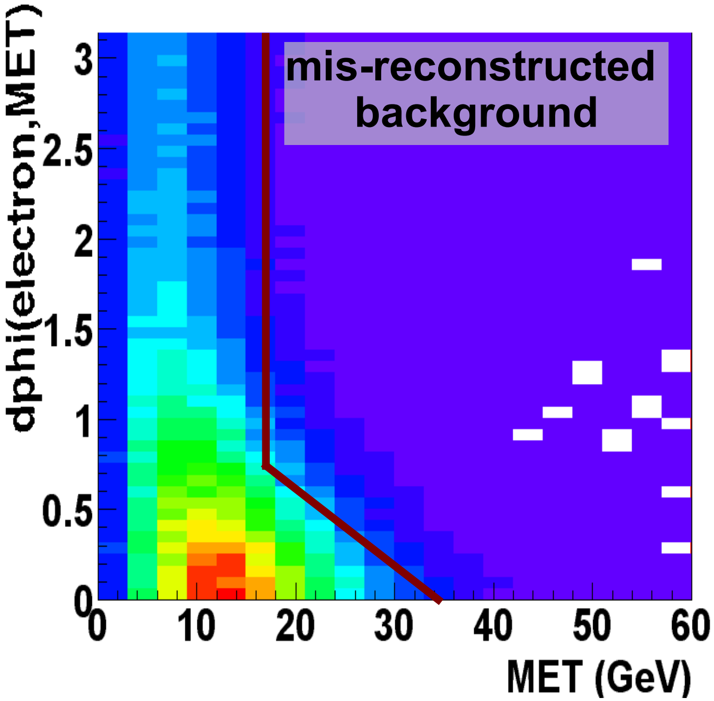


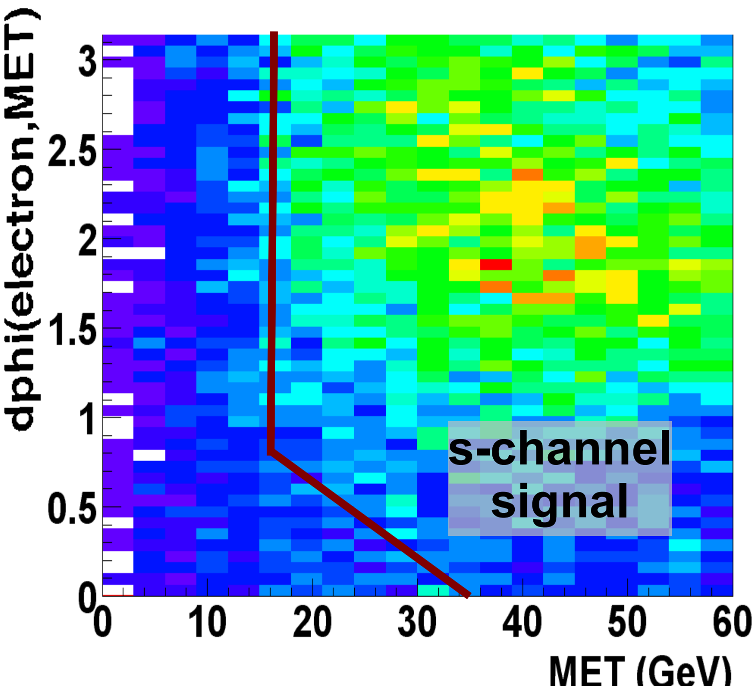
Mis-reconstructed Events?

- Cosmic rays (muons)
- Primary vertex constraints
  - Primary vertex with ≥3 tracks
  - Lepton originates from the PV
- Mis-reconstructed jets and leptons
  - fake electron
  - fake isolated muon
  - mis-measured jet

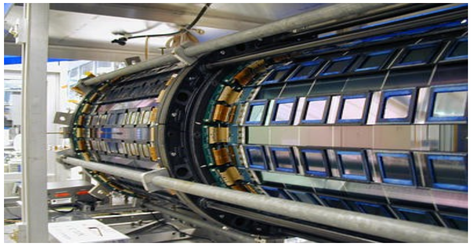
The PV position affects the MET

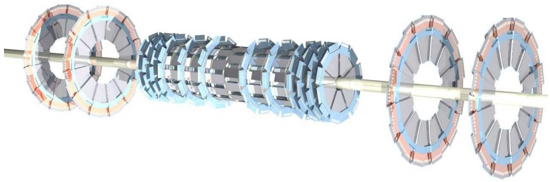
Use triangle cuts to reject mis-reconstructed leptons and jets in ΔΦ(ℓ/jet1/jet2,MET) vs. MET



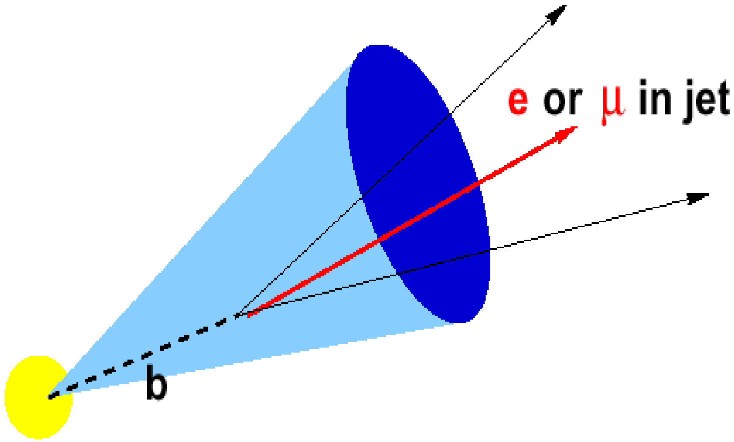


Tagging b-jets



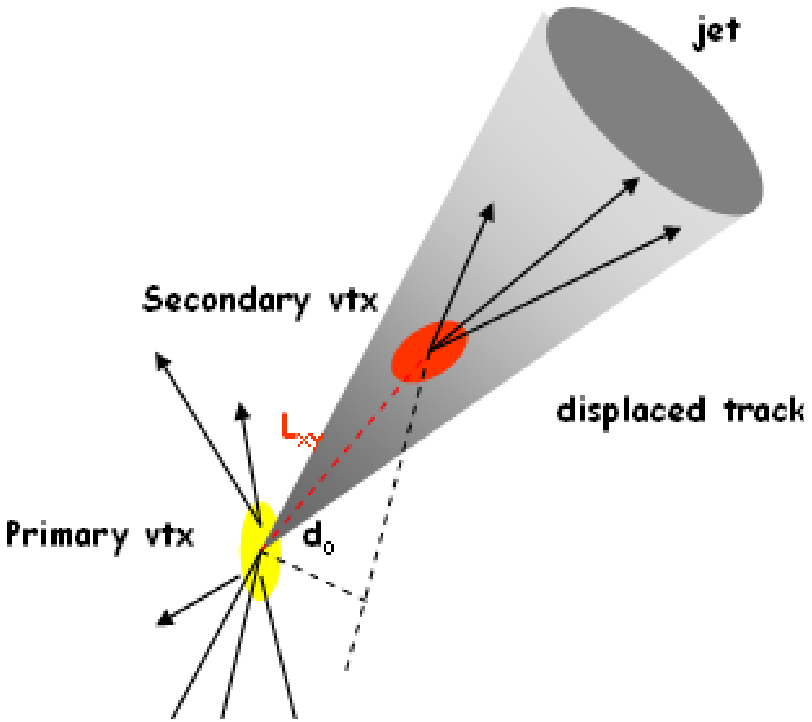


B-mesons can decay semileptonically
▶ Identify low-p_T muon from decay



- $b \to \ell \nu c$ (BR ~ 20%)
- $b \to c \to \ell \nu s$ (BR ~ 20%)

B-mesons are long-lived and massive
▶ Identify vertex of displaced tracks

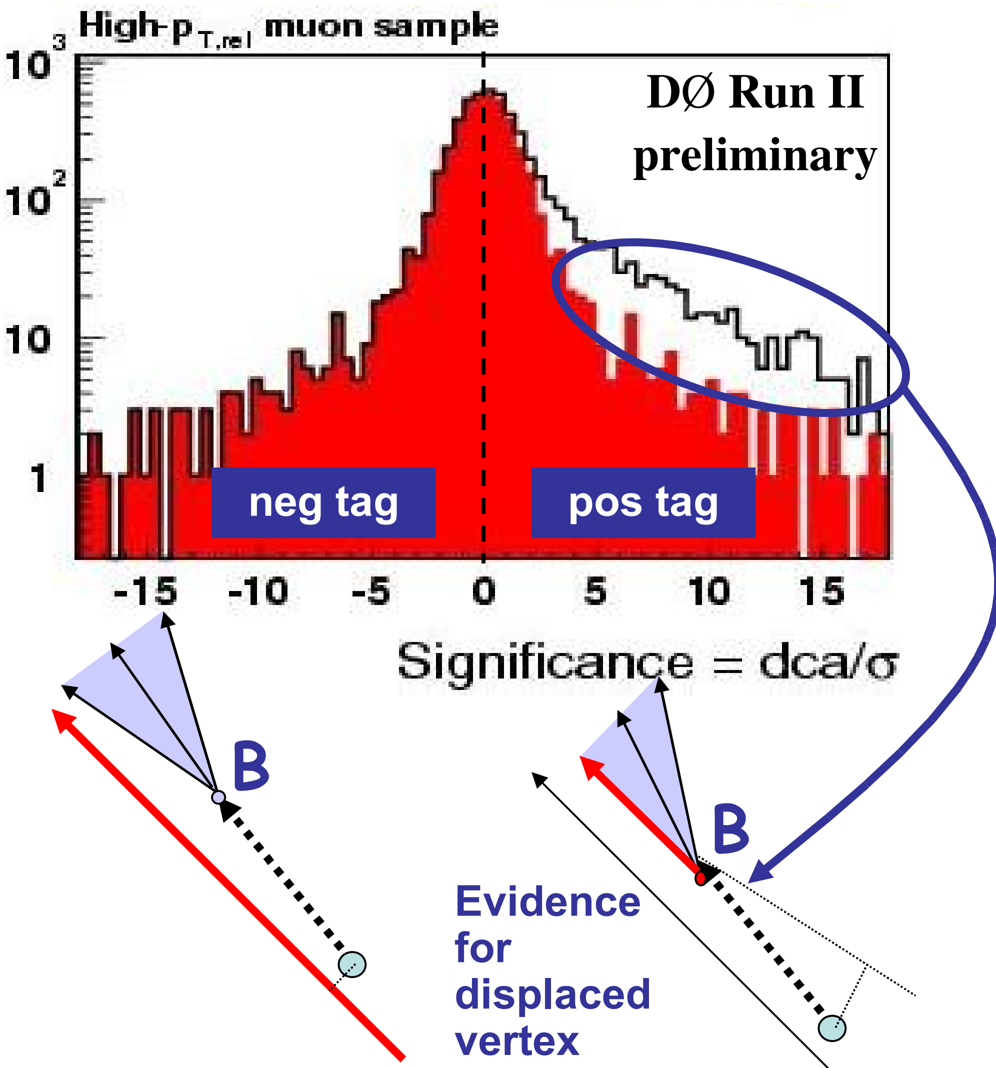


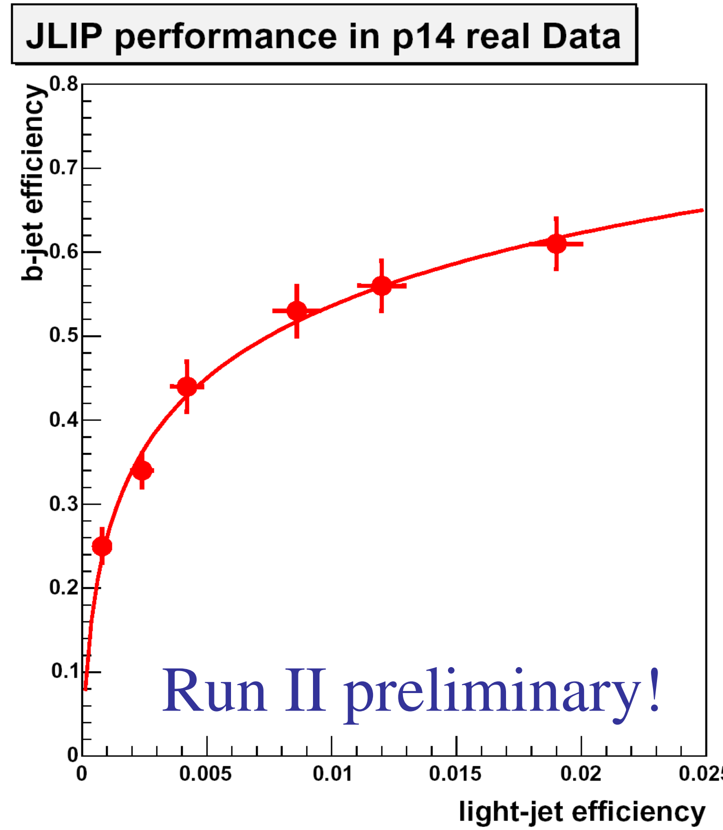
Both experiments can tag b-jets with up to 55% efficiency for 0.5% fake rate tag (SVX)

Lifetime *b*-tagging

Three different algorithms:

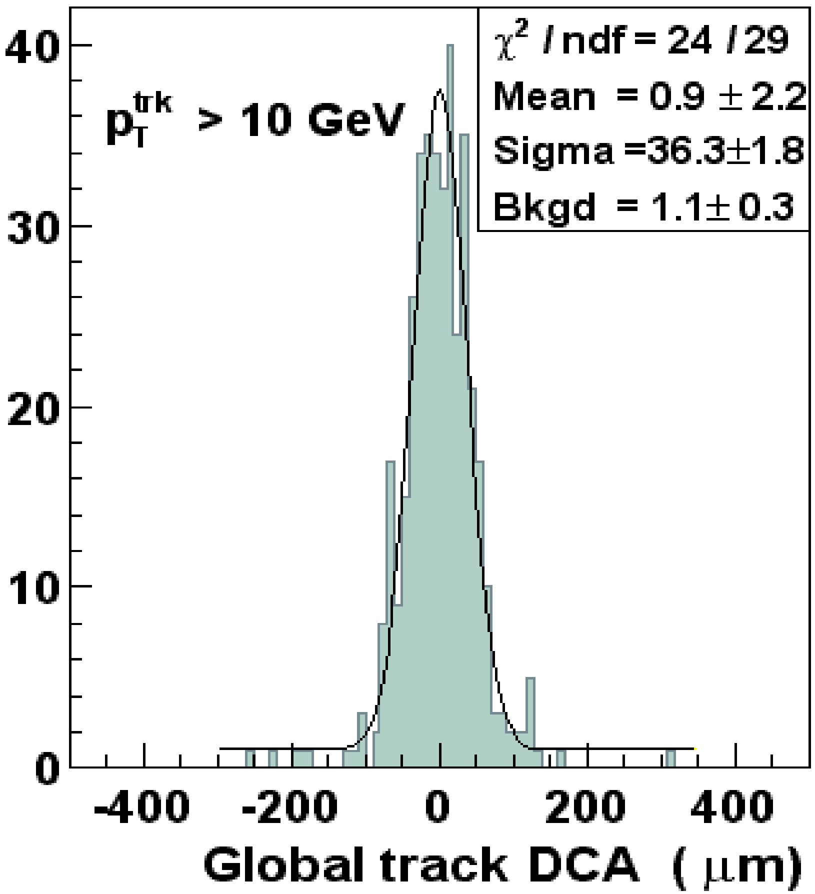
- **Two based on tracks with large IPs**
- **One based on secondary vertices**





~ 50% *b*-tagging eff at a fake rate of 1%, to be compared with ~60% for MC ⇒ Improvements to be made by tuning the algorithms

b-tagging performance

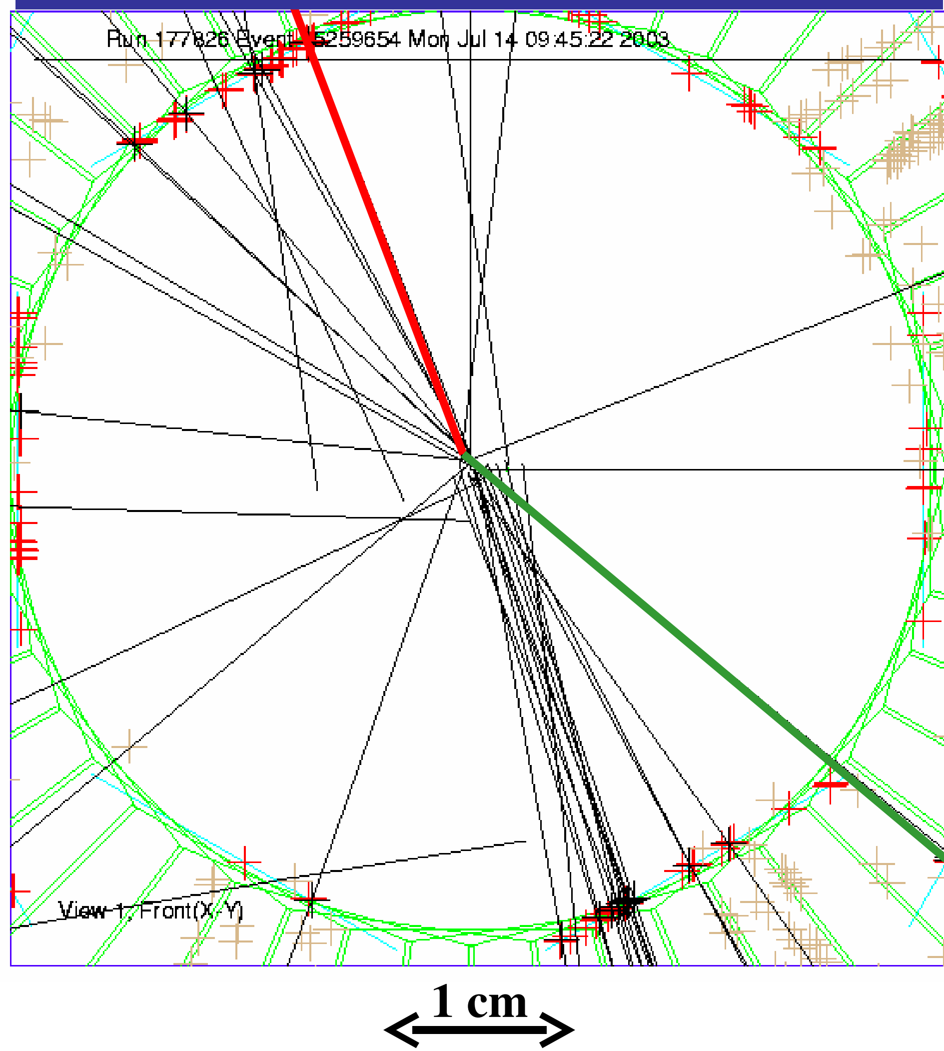


Width = 36.3 ± 1.8 μm

Beam ~ 30 μm

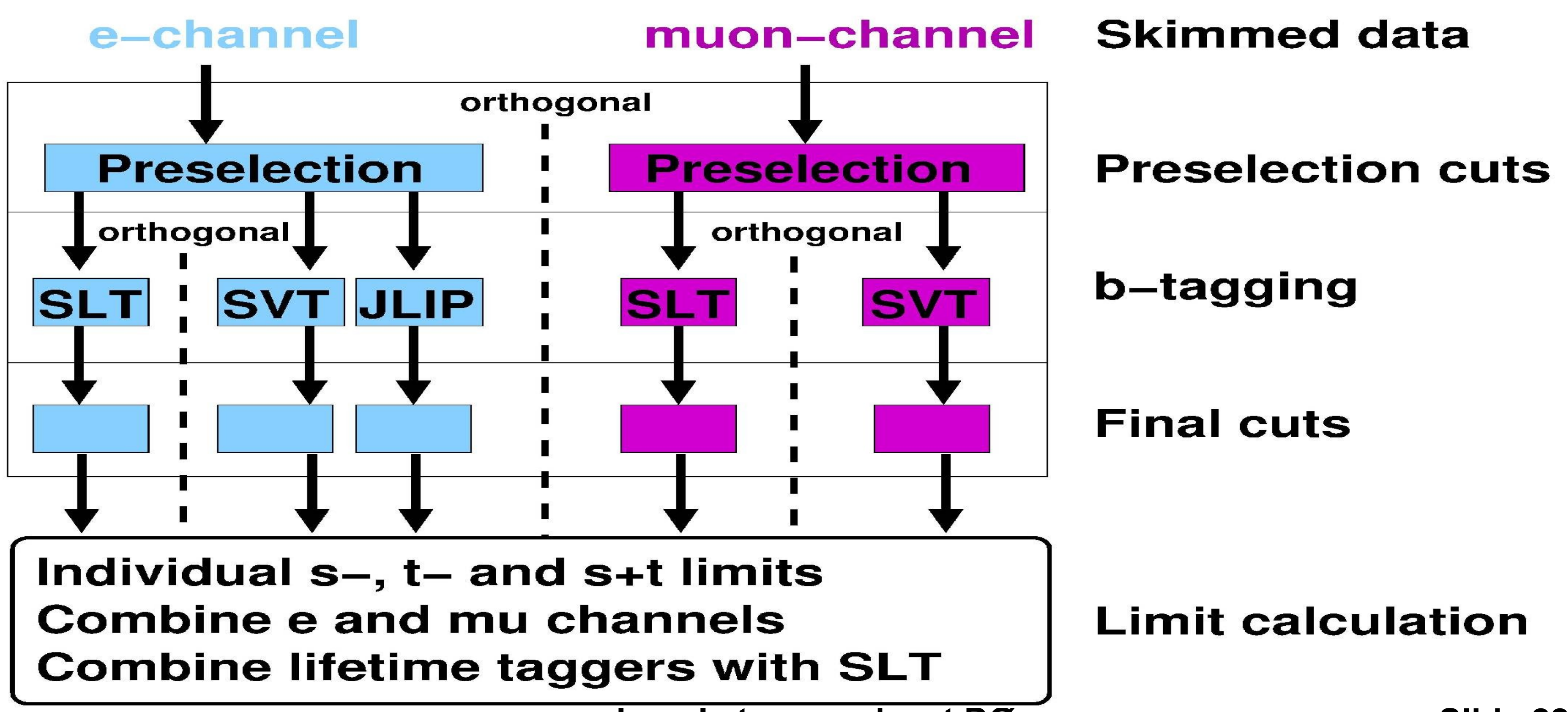
⇒ IP resolution ~ 10 μm

CSIP tagged eμ top candidate



Analysis outline

- ► Make e and mu channels orthogonal (veto the other lepton)
- ► Make lifetime taggers orthogonal from SLT (apply soft lepton veto)
- ► Use several lifetime taggers for cross-check
  but they are not orthogonal: cannot combine
- ► For this first pass of the analysis with $160pb^{-1}$:
  We do NOT have a separate analysis for s- and t-channel:
  just count each one in the other's SM background
  We apply a simple final cut, more refined statistical methods on the pipeline



Data based background estimation

Normalization and shape from data from preselected sample

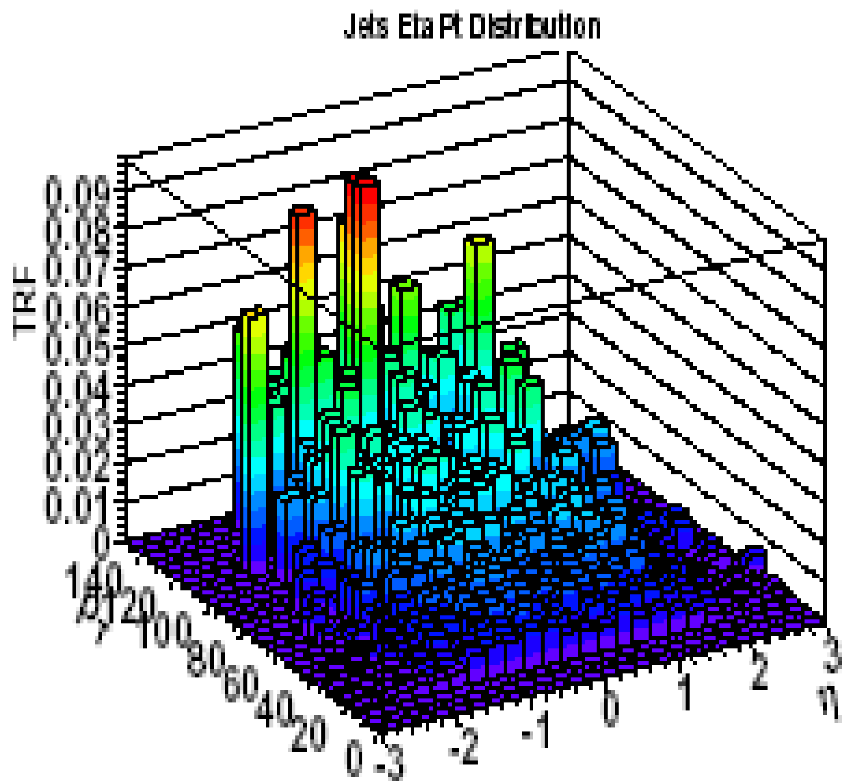
The fake-lepton background sample is obtained by:

2. Reversing the lepton isolation cut
3. Scaling it to the size of the pretagged sample
4. Applying the tagger

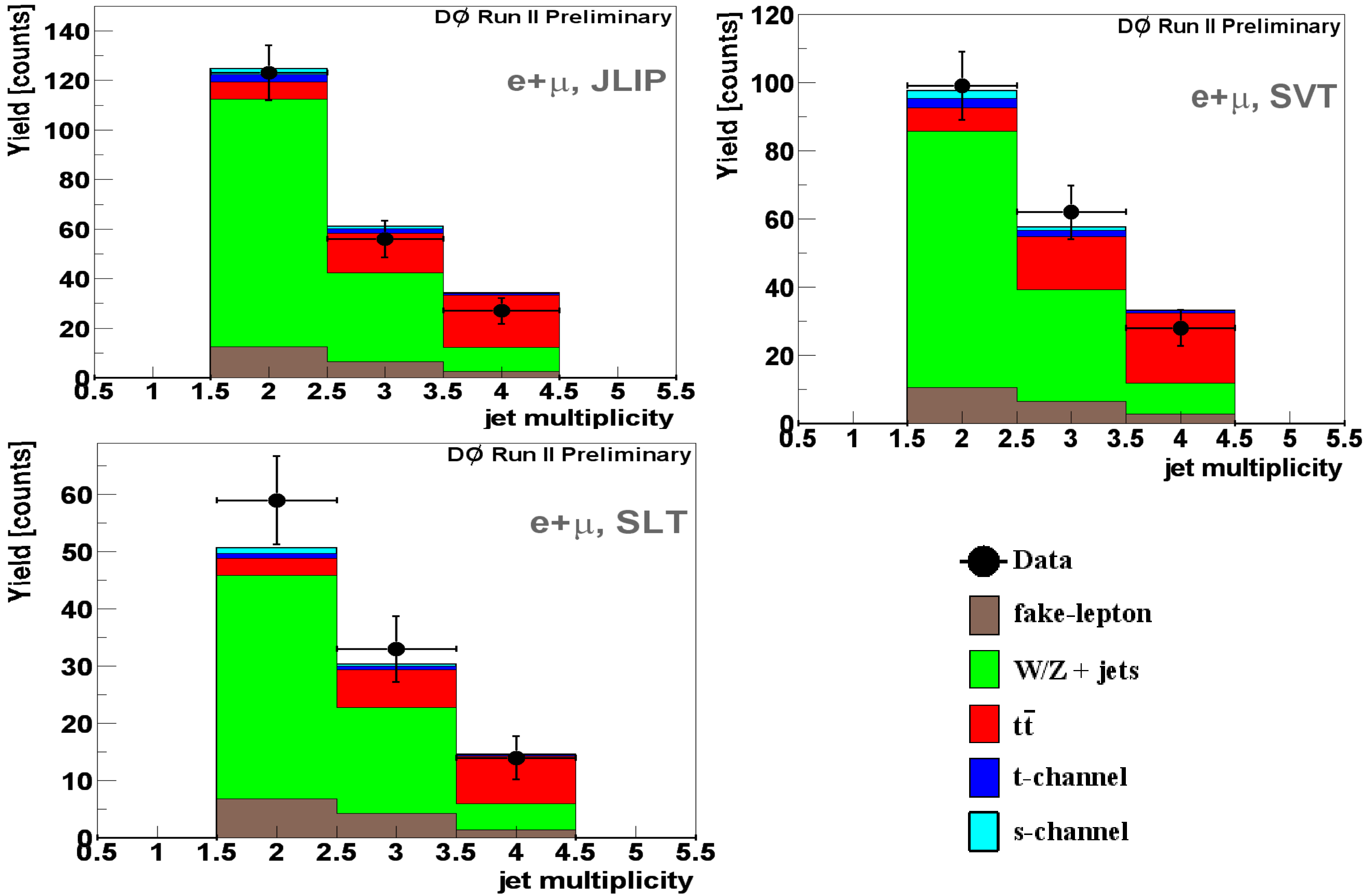
		Tight lepton ID	
		Pass	Fail
B-tagging	Pass	signal data	fake-lepton
	Fail	W+jets	not used

The W+jets sample is obtained by applying an inclusive Tag Rate Function over the preselected sample with 0 tags:

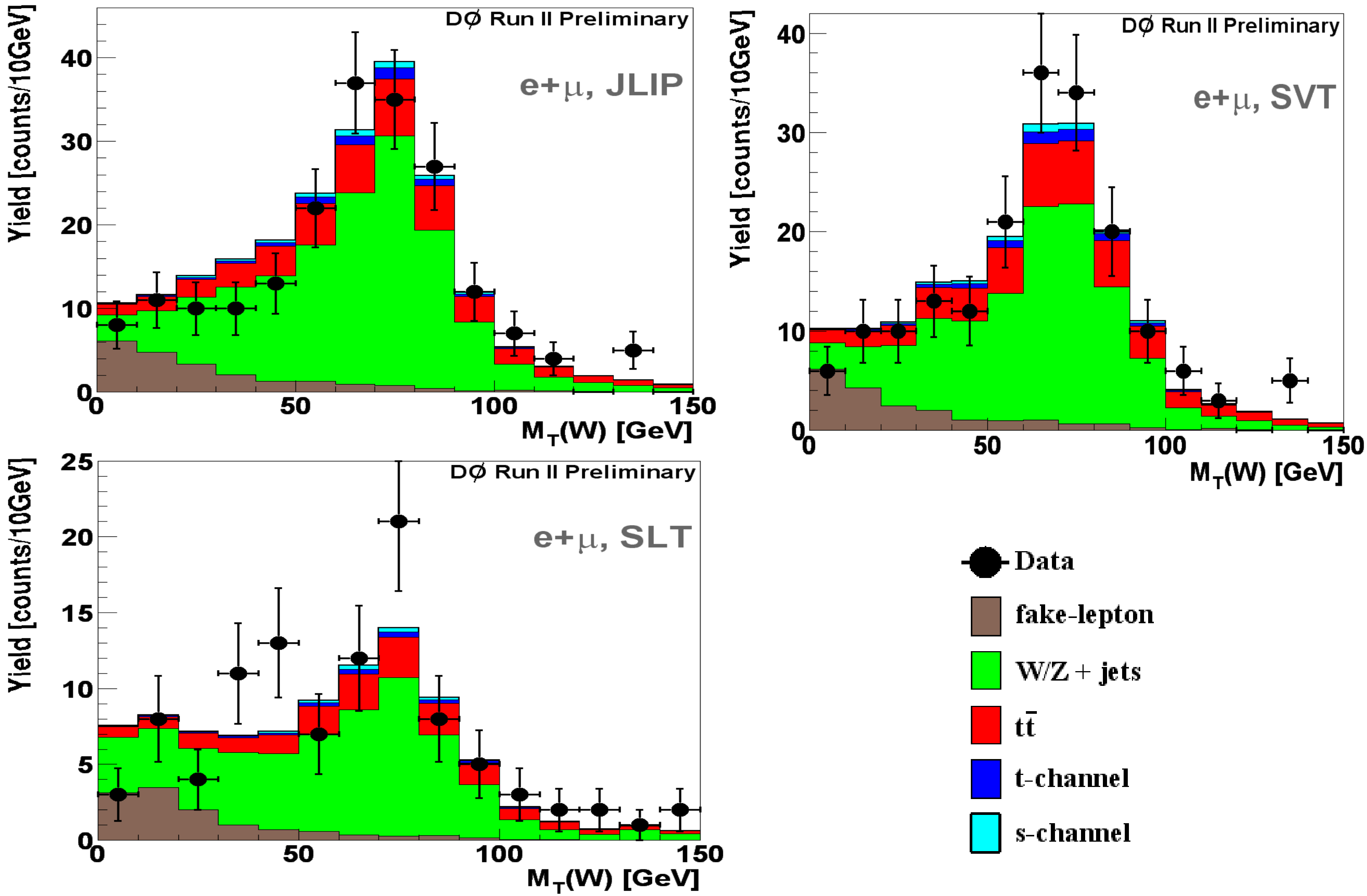
- ► Derive inclusive TRF from multijet sample→ assume that heavy flavor content is the same in the W+jets and multijets samples for events with the same jet multiplicity: ~20% uncertainty
- ► Check assumption with clean W+jets samples and Z+jets (free of top quarks)
- ► The tagger applied directly and the TRF agree within errors



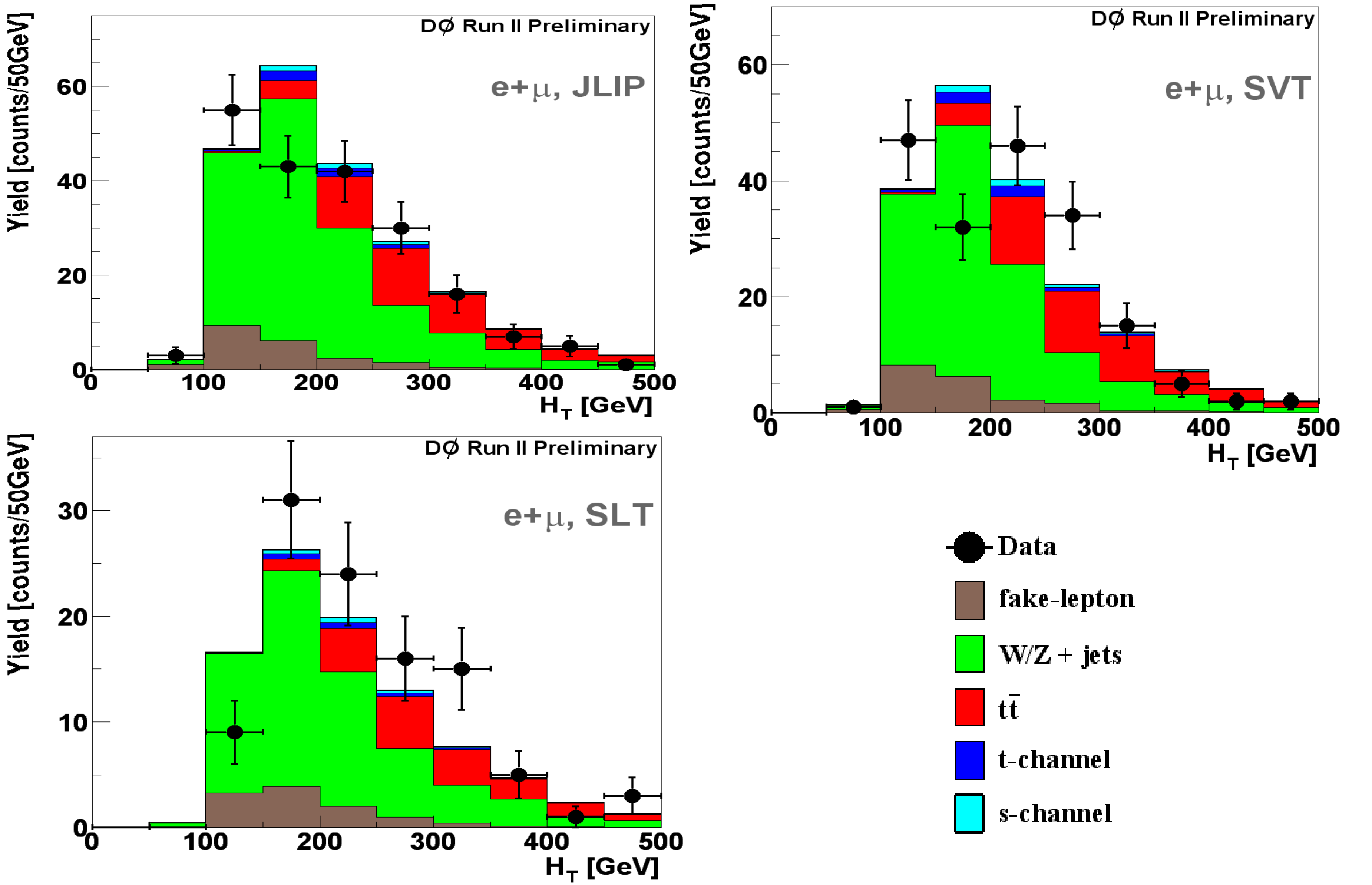
Event Yields after Preselection



W Reconstruction after Preselection

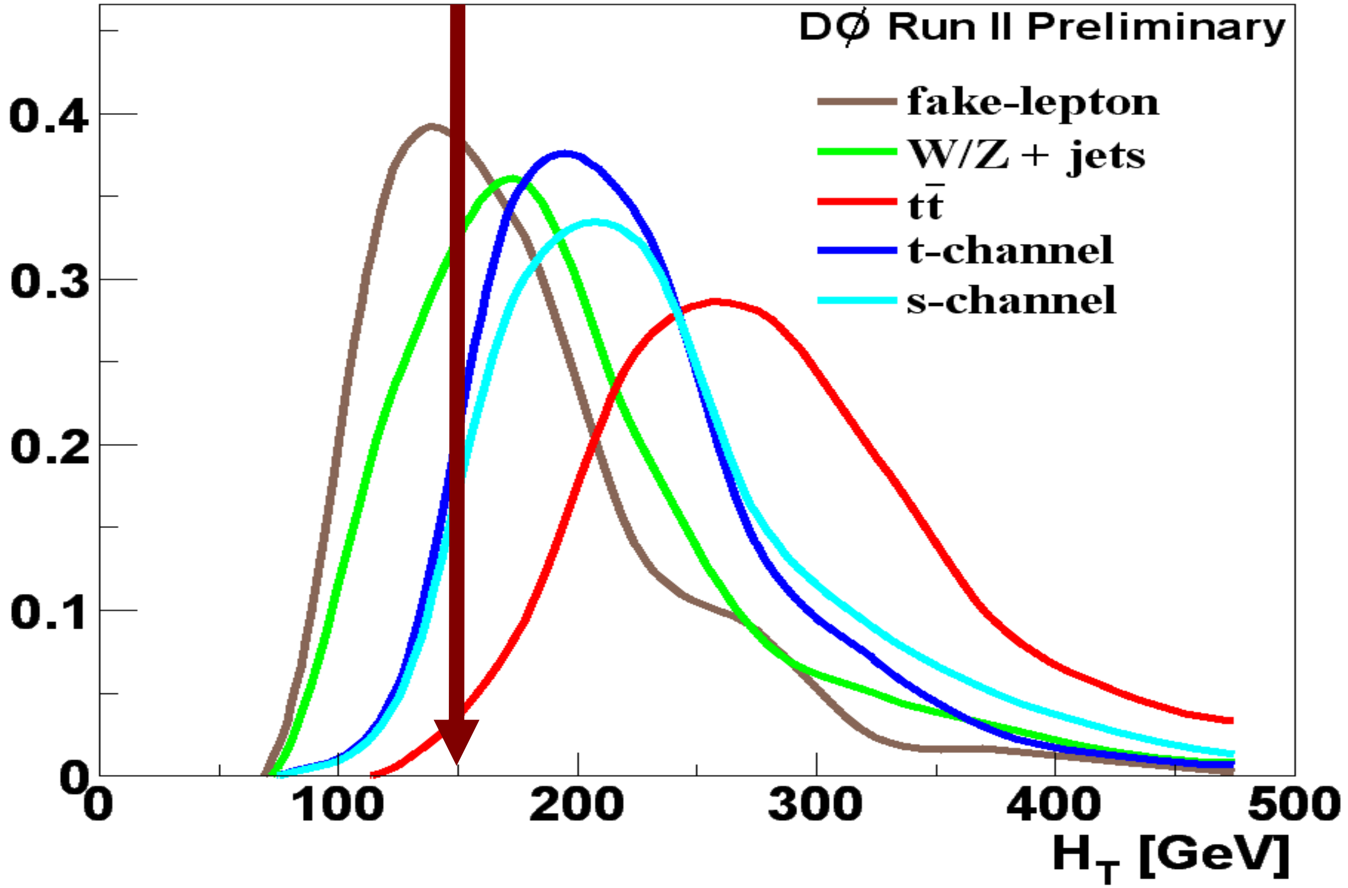


Transverse Energy after Preselection



Sensitive Variable: Transverse Energy

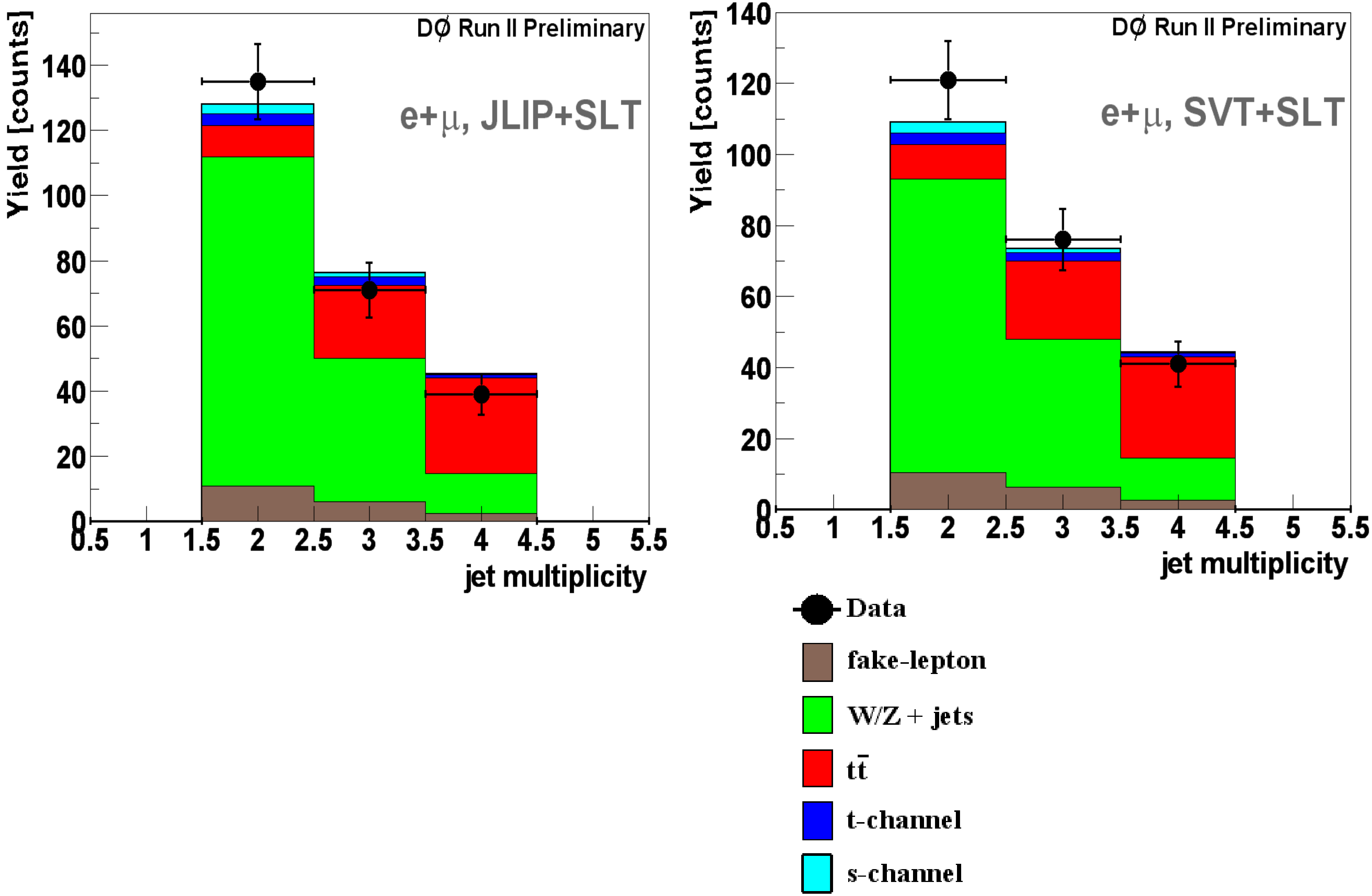
- Select simple final variable that shows good signal-background separation
- Reject main background from W+jets: H_T>150GeV



Final event yields

$e + \mu$ Event Yields			
	SLT	SVT	JLIP
Signal			
$s + t$ combined	3.0 ± 0.4	8.3 ± 1.4	8.4 ± 1.3
Backgrounds			
$t\bar{t} \rightarrow \ell$+jets	13.2 ± 2.2	33.6 ± 5.8	34.1 ± 6.0
$t\bar{t} \rightarrow \ell\ell$	4.7 ± 0.7	9.5 ± 1.7	9.6 ± 1.6
$Z \rightarrow \mu\mu$+jets	10.3 ± 3.5	—	—
W+jets & fake$-\ell$	48.1 ± 5.7	94.2 ± 12.5	122.2 ± 16.9
Sum of backgrounds	76.2 ± 7.6	137.4 ± 14.5	165.9 ± 18.6
Observed events	97	138	148

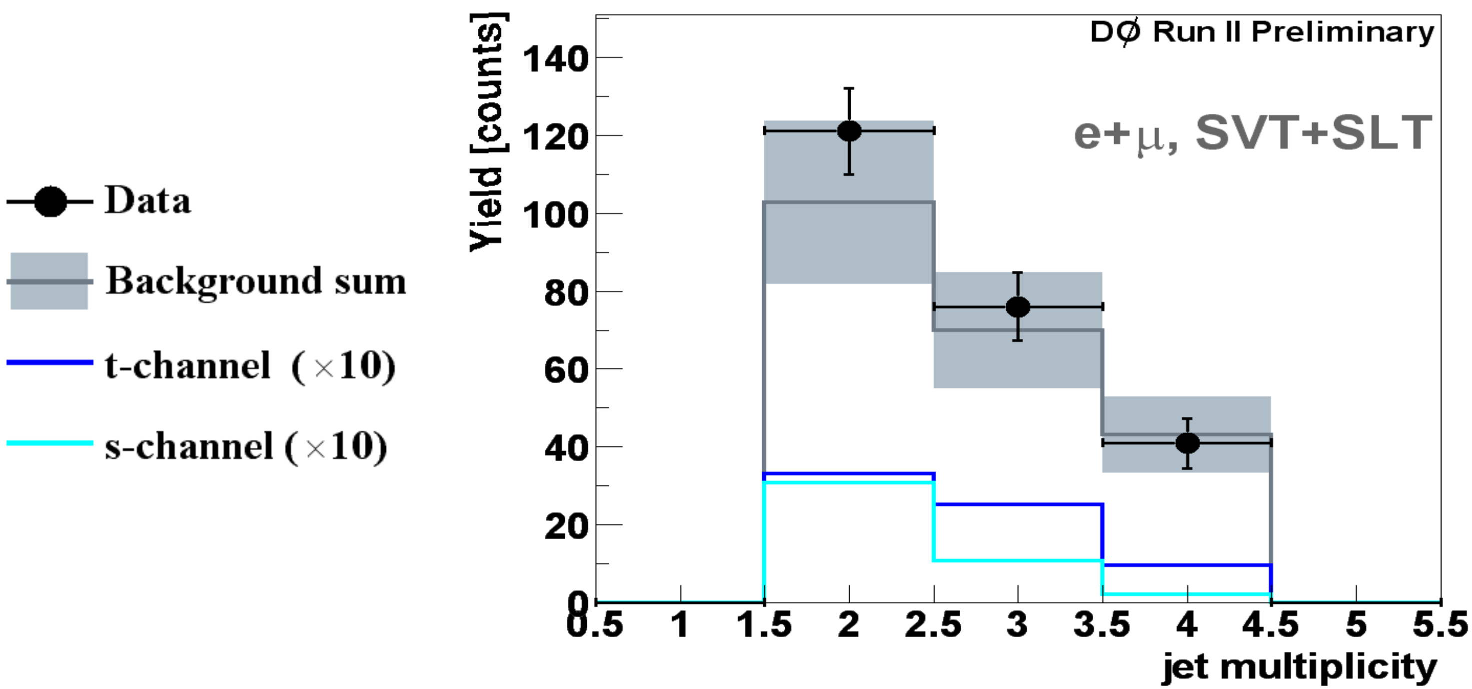
Event Yield after Final Selection



Systematic Uncertainties

Signal acceptance and Monte Carlo Backgrounds

- Jet Energy Scale ~10%
- Trigger Modeling ~10%
- Tagger Modeling ~10%
- Object ID ~ 5%
- Background normalization ~20%

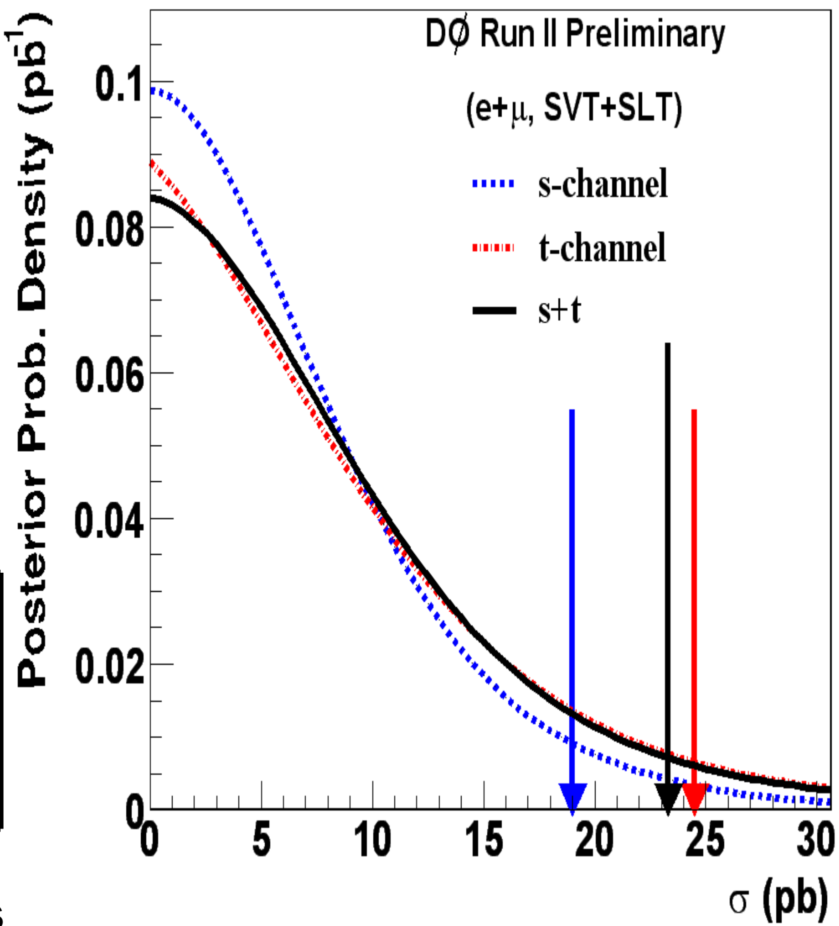


Final result

- With 160 pb^{-1} of Run II data
- No evidence for single top production
- By simple event counting, set a 95% CL on the production cross section
- Using a Bayesian approach and properly including all uncertainties and their correlations

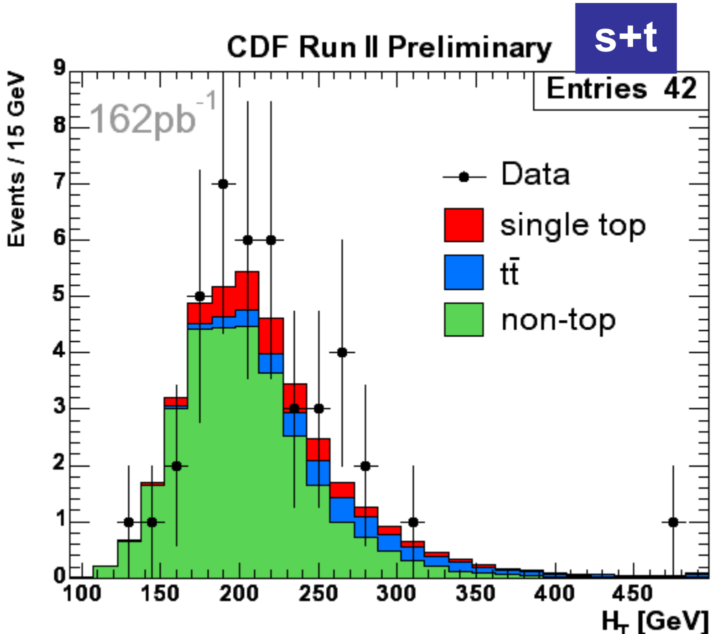
95% C.L.	σ_s	σ_t	σ_{s+}
Observed limit (pb)	19	25	23
Expected limit (pb)	16	23	20

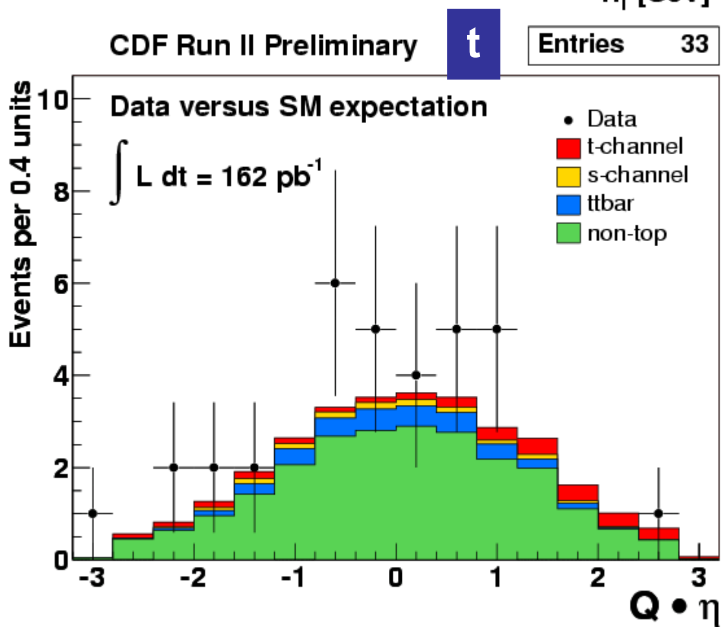
Reached sensitivity of full Run I analysis



CDF analysis

(hep-ex/0410058)





1 Lepton p_T>20 GeV
MET>20 GeV
Exactly 2 jets E_T>15 GeV |η|<2.8
≥ 1 b-tag
M_{lvb} [140,210] GeV

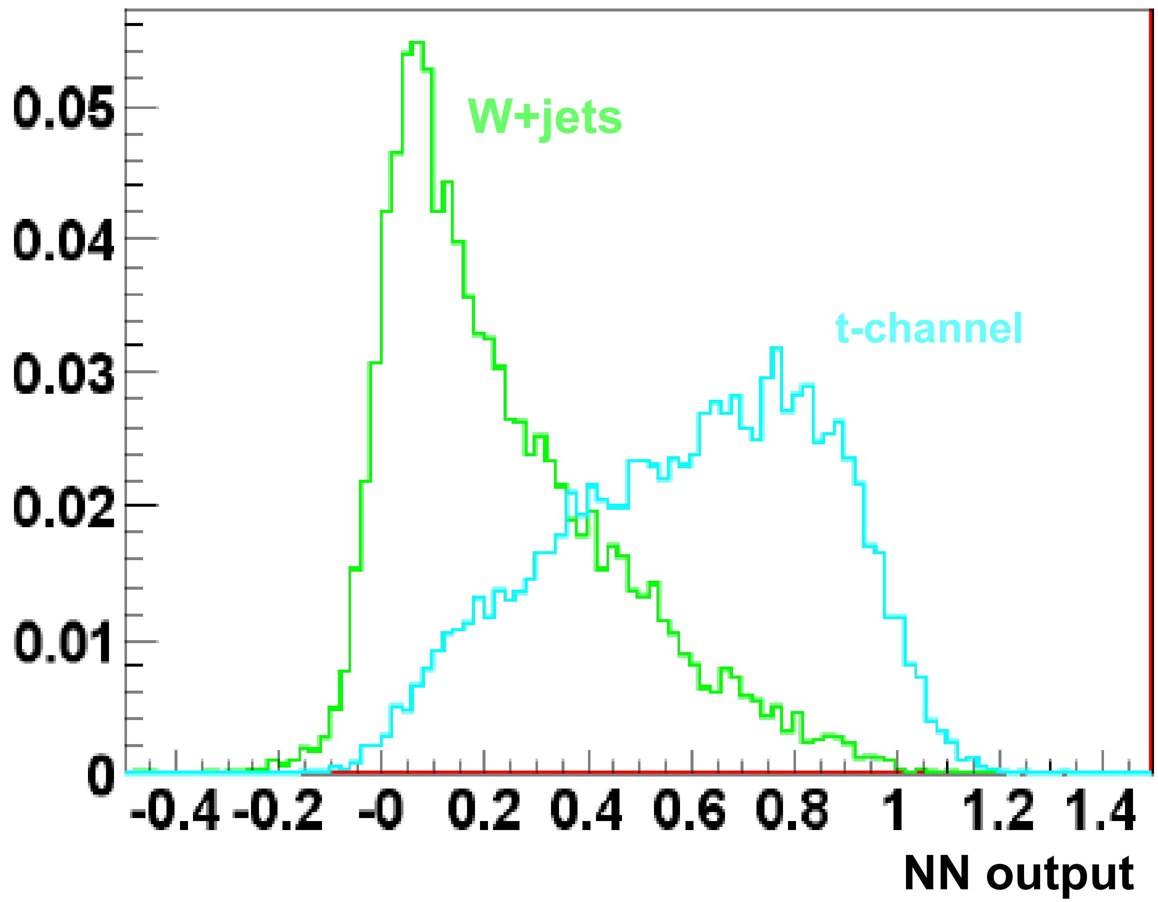
- Maximum likelihood fit to data H_T or Q•η distributions using a sum of templates determined from MC: single top (MadEvent), tt (PYTHIA), non-top: Wbb (ALPGEN)
- Background allowed to float but constrained to expectation.

95% C.L. limits Observed (Expected)

Channel	CDF (pb)	DØ (pb)
s+t	<17.8 (13.6)	<23 (20)
t	<10.1 (11.2)	<25 (23)
s	<13.6 (12.1)	<19 (16)

What's next?

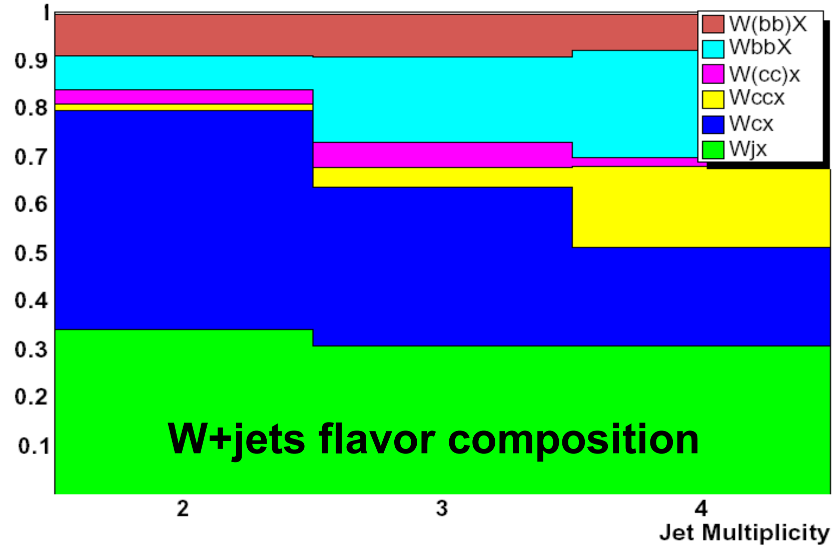
- DØ currently working on significantly improving the final analysis
  - **Current focus on multivariate techniques: Neural Networks**
  - **Reduce background by factor ~20 and keep ~30% of signal**
  - **Expected limits below 10pb for 230pb^{-1} dataset→ publish soon!**
- Other improvements in the future
  - **Acceptance, efficiency**
  - **Resolution**
  - **Other multivariate techiques**



Do we understand our backgrounds?

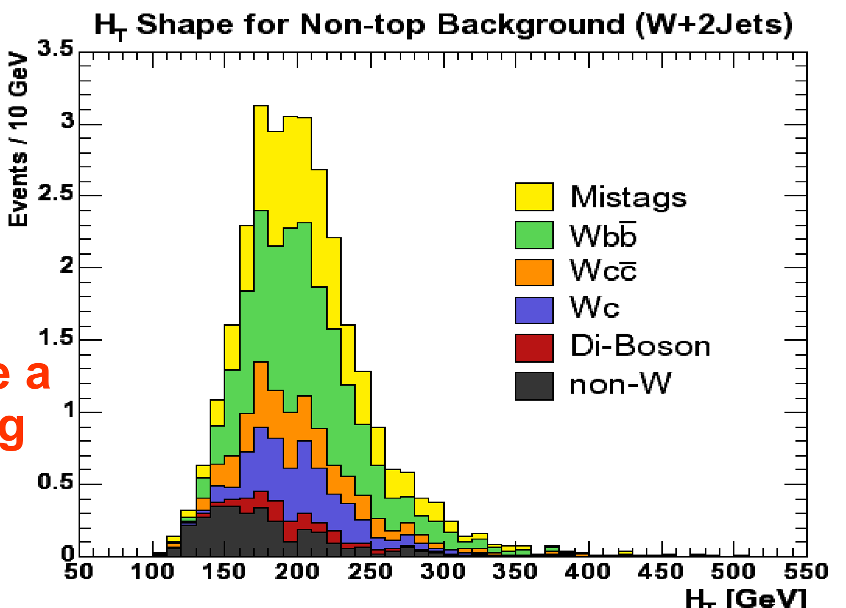
Especially *W*+jets:

- ►Normalization and flavor composition
- ►Flavor composition assumption in data: multijets ~ W+jets
- ►Assign large uncertainty



Single top is kinematically between W+jets and top pair production
NLO calculations for rate and shape very important, especially at LHC

R.K. Ellis, J. Campbell hep-ph/0408158



►W+njets with at least one b-tag is the biggest problem facing us today.
►Wqg→Wqbb is predicted by PYTHIA to be a factor 2 larger than Wbb or Wjj with a mistag
►W+jets syst errors dominate the measurement

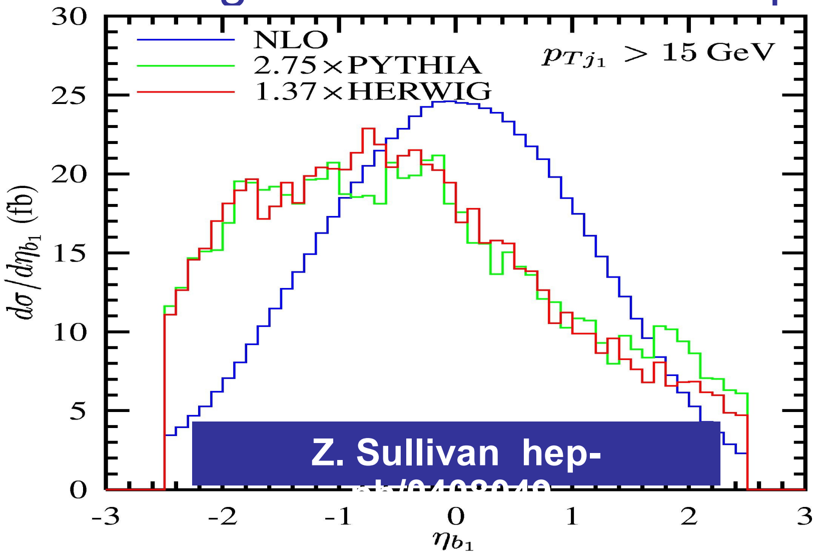
Z. Sullivan hep-ph/0408049
M.Bowen, S.Ellis, M.Strassler, hep-ph/0412223

C.P. Yuan et al hep-ph/0409040
R. Schwienhorst et al. hep-ph/0408180

Do we understand our signal?

Event generators vs. LO t-channel tb:
Pythia and Herwig predict wrong distributions (too soft and too forward) for the non-top b-jet

LO MC generators vs NLO shapes

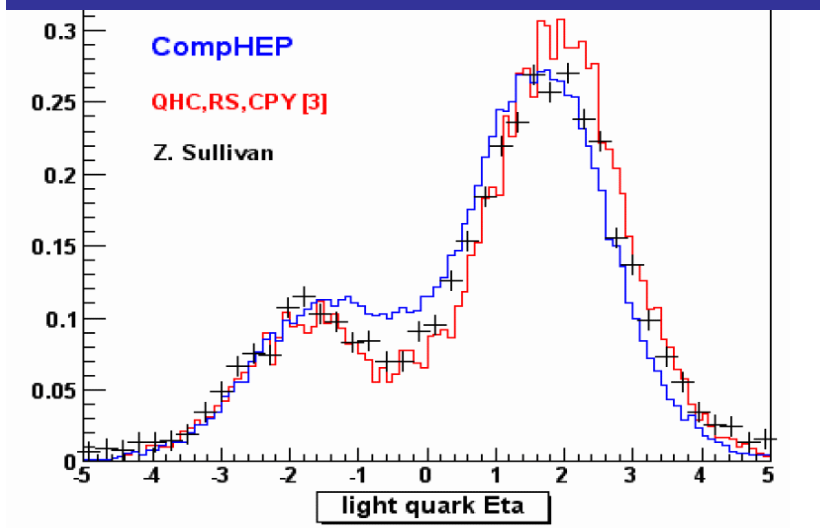


Corrected LO generators with K factors give reasonable results

Event generators vs. NLO s-channel: NLO~1.54xLO

- ►**Pythia and Herwig have the right shape**
- ►**Even after K factor normalization they underestimate the Wbb by a factor of 1.4**
- ►**Both produce too much additional hard radiation**

R. Schwienhorst et al. hep-ph/0408180



Several good solutions on the market with spin correlations:
ZTOP, Singletop (CompHEP), MadEvent, MCFM, new ones being developed

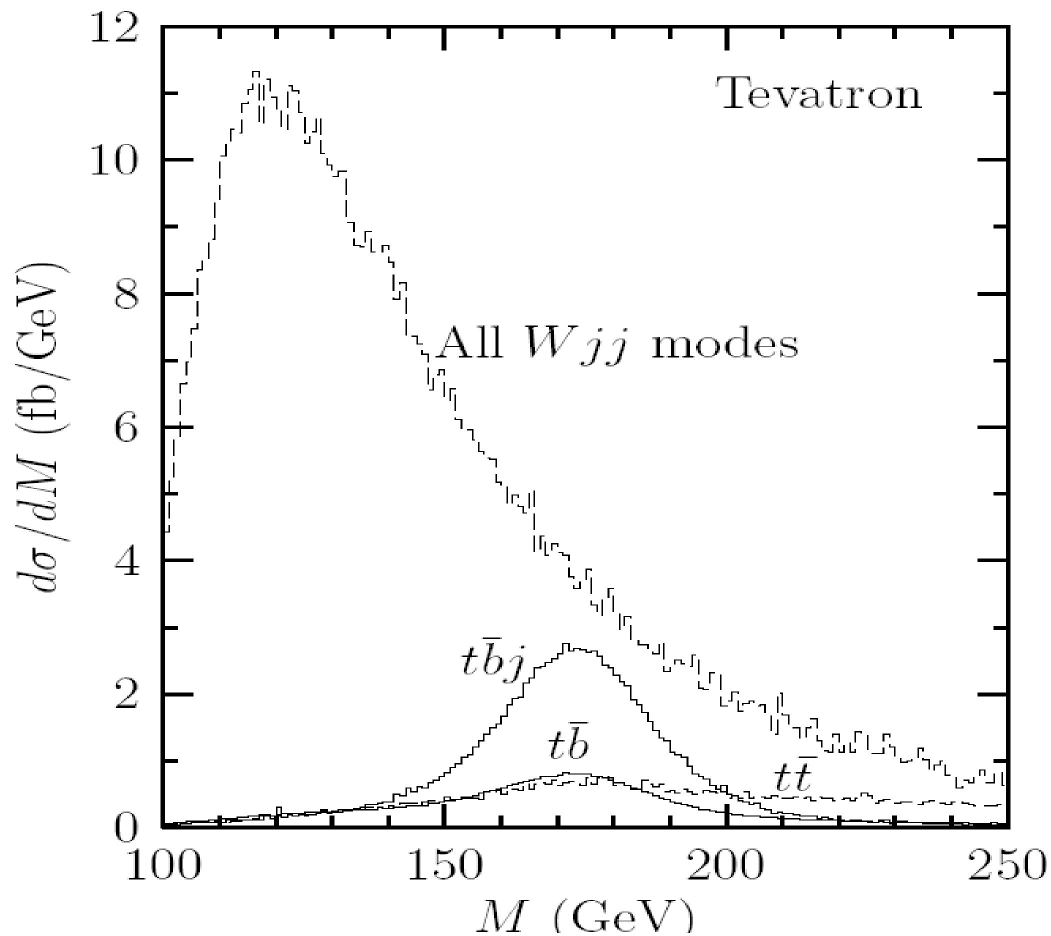
Single Top – Expectation

Predictions for Run II were to be sensitive to single top production with ~500pb^{-1} – *Where is it?*

We have recorded

>470pb at DØ already

Observation soon?

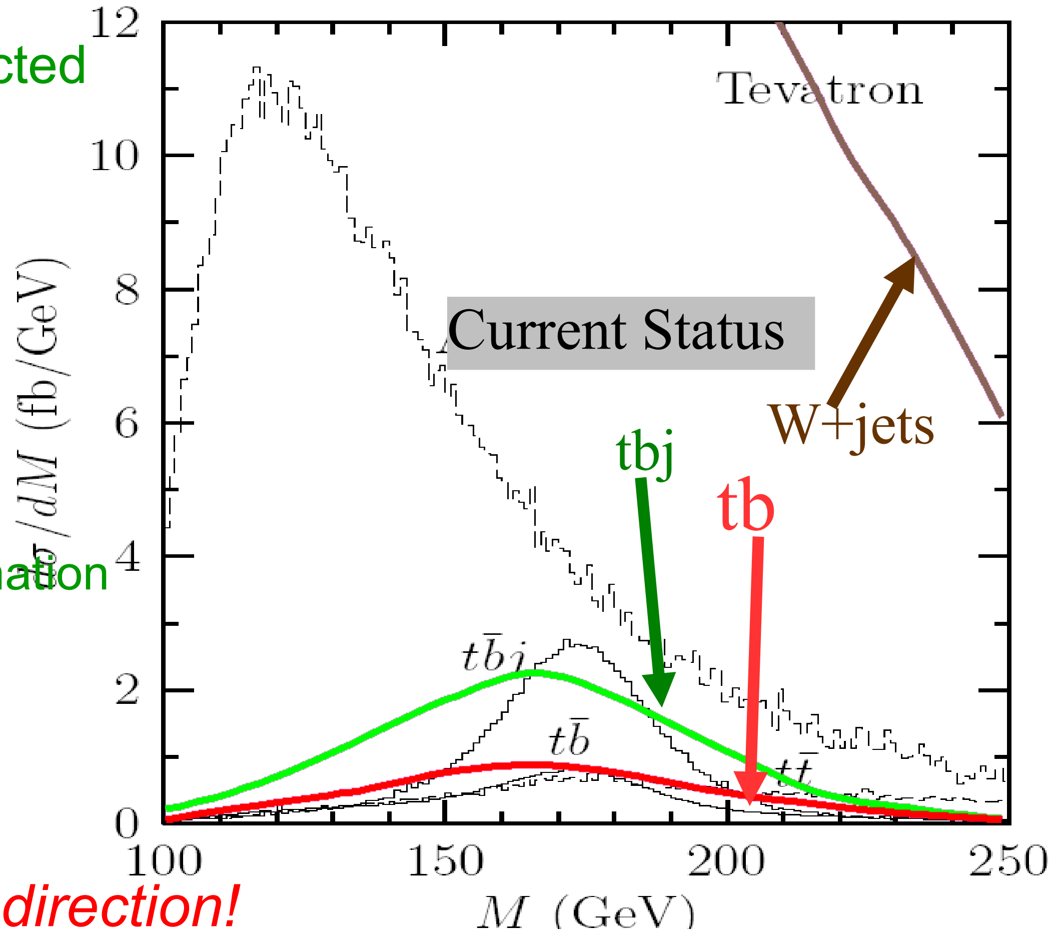


Stelzer, Sullivan, Willenbrock, PRD58 (98)

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
  - Gluon splitting, c-contamination
- 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 ~500pb^{-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, Decision Trees…)

Observation with ~2fb^{-1}

Starting to be interesting much sooner


First Meeting 16 - 18 Sept. '04 Fermilab • Midterm meetings at Brookhaven & CERN • Final meeting at Fermilab, Fall '05
TeV4LHC
WORKSHOP
Using the data & experience
from the Tevatron
to prepare for the LHC
TeV4LHC Organizing Committee:
Georges Azuelos (U. Montreal)
Ulrich Baur (SUNY at Buffalo)
Marcela Carena, Chair (FNAL)
Sally Dawson (BNL)
Dan Green (FNAL)
Ian Hinchliffe (LBL)
Young-Kee Kim (U. Chicago)
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Heidi Schellman (Northwestern)
John Womersley (FNAL)
Working Groups
QCD, Top & Electroweak Physics,
Higgs, and Physics Landscape.
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Information & Registration: http://conferences.fnal.gov/tev4lhc/

TeV4LHC Workshop

The purpose: Use Tevatron data and experience to prepare for the LHC
Identify areas where further theoretical work is needed

Tevatron → LHC

- ►*improved event modelling and theoretical understanding of cross sections for signals and backgrounds*
- ►*experience with real experience*

LHC → Tevatron

- ►*Determine where current LHC prospects are strongly dependent on simulations/extrapolations*
- ►*Identify difficult analyses at LHC to investigate them at the Tevatron*

The Workshop will combine Talks and Working Sessions, with the idea of initiating specific projects in these areas . Connect TeVatron and LHC people to work on these projects.

- ►**The 1st meeting was held at Fermilab, 16-18 September, 2004.**
- ►**The NEXT MEETING will be held at Brookhaven National Lab., 3-5 February, 2005: www.bnl.gov/tev4lhc**
- ►**A follow-up meeting will be held at CERN, in late April, 2005**
- ►**The final meeting will be held at FNAL, in the Fall, 2005**
- ►**Would have liked to have more participation from LHC people**

TeV4LHC Workshop

- From Regina Demina (Rochester) in “Challenges of hadron colliders”:
- Why did it take the TeV almost three years (March 2001-December 2003) to publish the first paper?
- She asked some Run II physics conveners from CDF and DØ:
  What were the limiting factors?
- There was no clear leading limitation but rather several limiting factors:

1. Detector (and accelerator) performance:
   - Calorimeter calibration (in both experiments)
   - Alignment (tracker and calorimeter)
   - Luminosity delivered by the Tevatron (was too low,… now too high?)
   - Tracking and muons: no major complains both worked fine
2. Maturity of reconstruction algorithms
3. Complexity of the software and reliability of the MC (availability of samples)
4. CPU, speed and ease of data access, data format
5. Social issues and politics

TeV4LHC Workshop: Conclusions

- Lessons of commissioning from Run II:

  4 months of CDF Si cabling WHILE taking physics data

  Premature emphasis on physics was counterproductive: it's hard to commission the detector while taking physics data.
- Common final states should share ID's and background calculations!
- Build common tools for the physicist (Luminosity calculation, trigger turn on curves, etc.)
- Big complaint: Lack of involvement from senior people
- Too high standards, perfectionism! (Run I, LEP)

- LHC has probably avoided many mistakes made at the Tevatron
- But many others are general and will be worse at the LHC
- This will affect LHC's ability to do physics
- Tevatron people can give valuable input!
- We all need the LHC to be a success!!

Conclusions

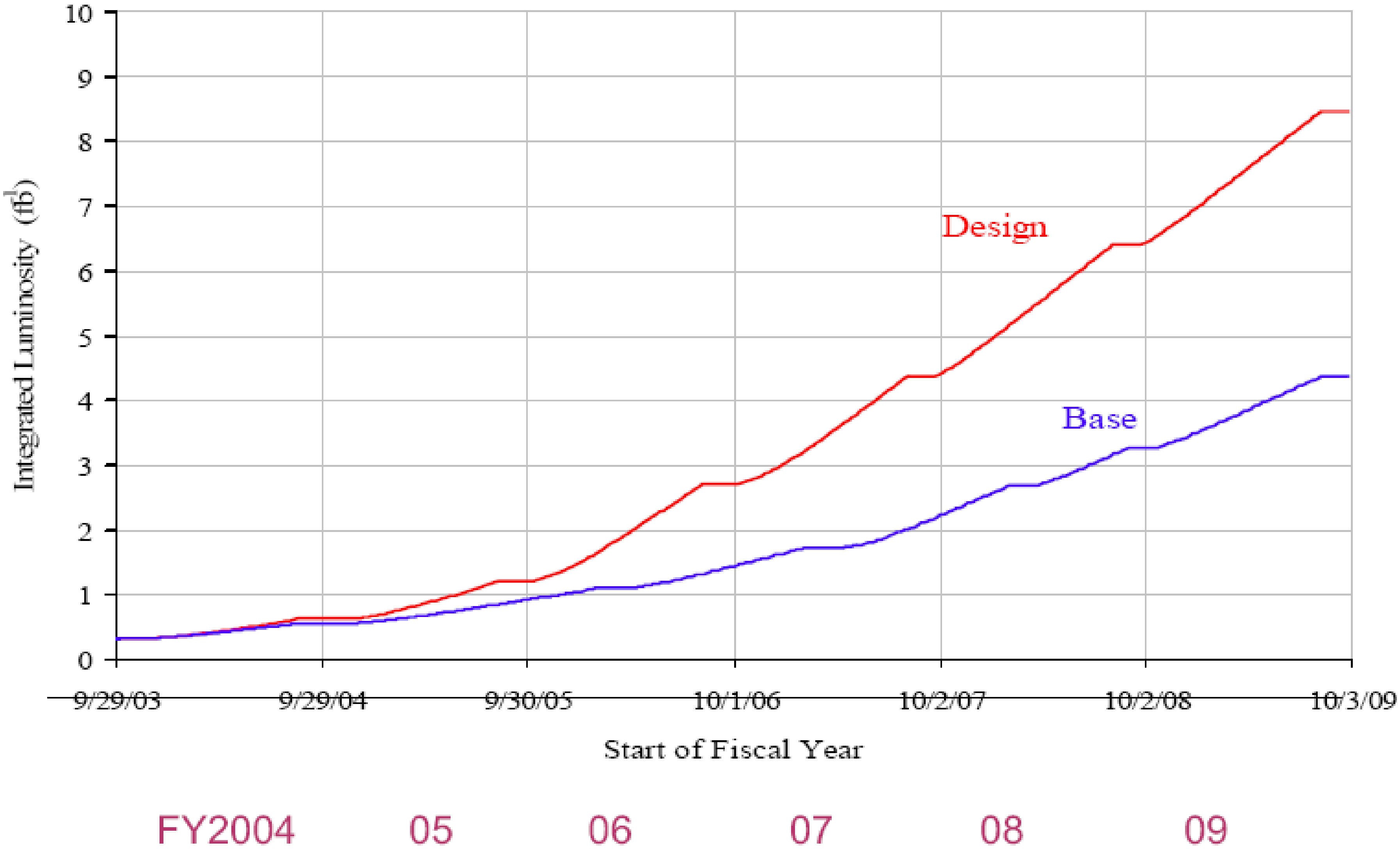
- Single Top is a very exciting opportunity for Run II
  - A lot of activity, both theoretical and experimental
- The DØ Run II Single Top Search is under way
  - Detector and trigger working, understood
  - First pass analysis with $160pb^{-1}$ completed
  - Not yet sensitive to single top production
- 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
- Expect new results with $230pb^{-1}$ and $370pb^{-1}$ soon

Conclusions

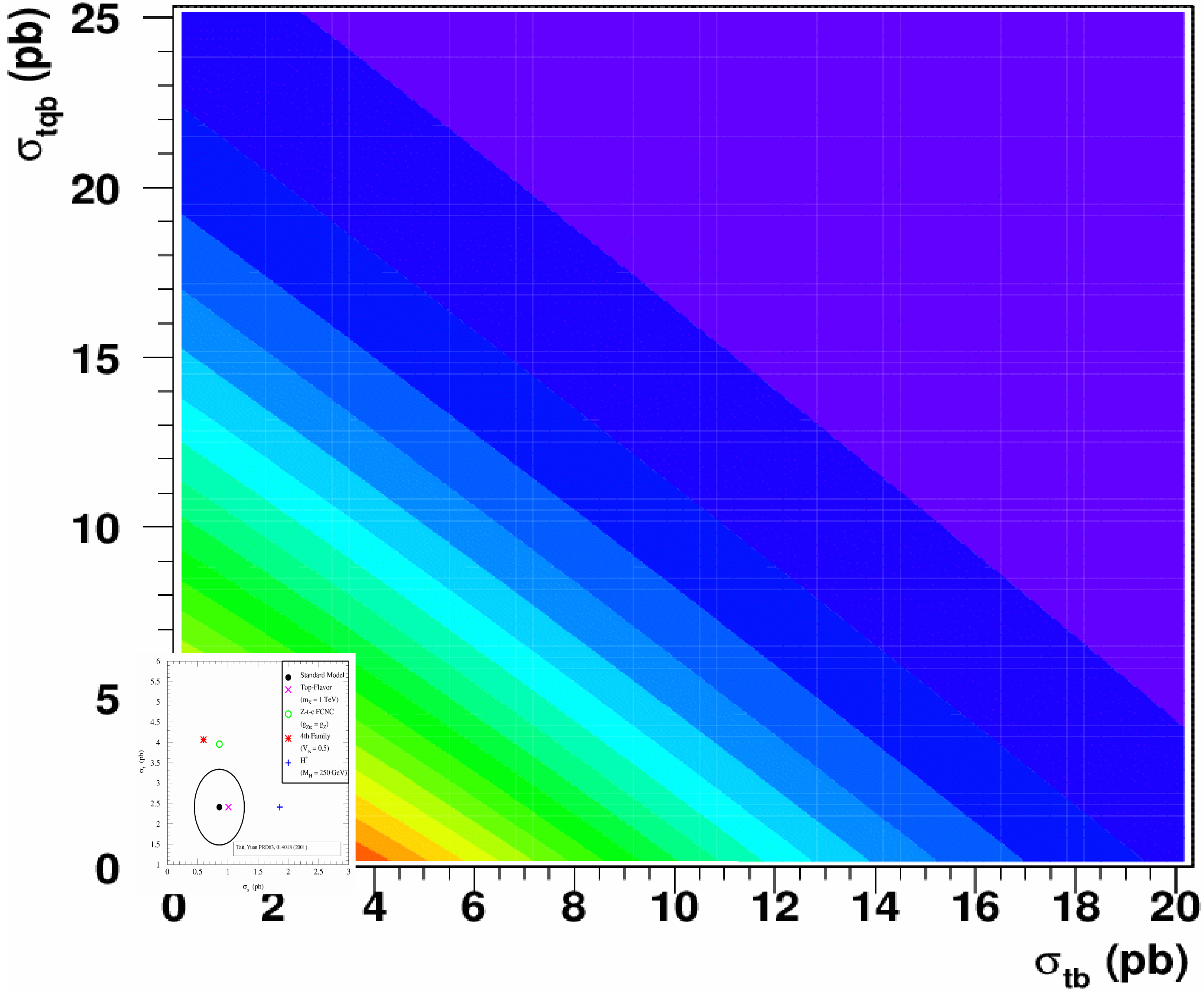
- There is a lot of physics at the Tevatron
  - Will go strong with 2-4 fb^{-1} of data before LHC turn on.
  - Understand now what to measure at TeV to make LHC simpler
- Lots of potential lessons
  - Tevatron also messy environment
  - Large collaboration with significant European contributions
  - Object ID, Algorithms, Data formats, Remote Computing…
- Lots of experience in a hadron - hadron environment
  - We should have even more at a high luminosity by the time the LHC turns on!

Tevatron luminosity prospects

Integrated luminosity will about double every year for next 4 years

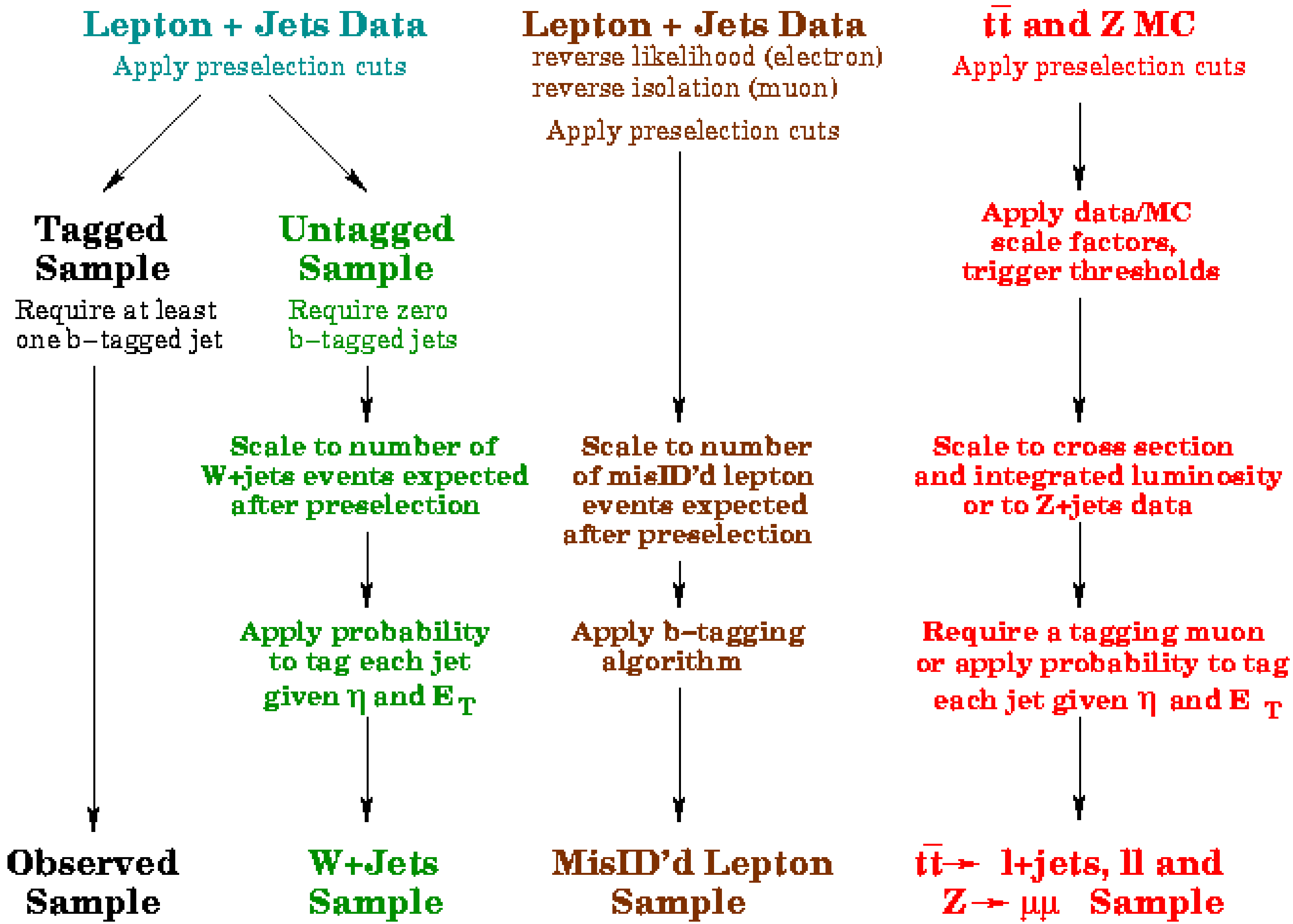


Extra 1



σtqb (pb)
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
18
20
σtb (pb)
Standard Model
Top-Flavor
(mX = 1 TeV)
Z-t-c FCNC
(gZtc = gZ)
4th Family
(Vts = 0.5)
H+
(MH = 250 GeV)
Tait, Yuan PRD63, 014018 (2001)
σt (pb)
σs (pb)

Tagged background estimation methods



Tagged MC estimation methods

For signal, $t\bar{t}$ and $Z \rightarrow \mu\mu$ MC samples:

* Correct from ID efficiencies (measured in $Z \rightarrow \mu^+\mu^-$ data and MC):
  ID, tracking, matching, isolation scale factor $= \varepsilon(data)/\varepsilon(MC) = 0.86 \pm 0.05$

* Apply trigger response and scale to $\sigma\mathcal{L}$

* SVT applies a flavor dependent tag-rate functions after parton matching
  - b-flavor TRF: $f(E_T, \eta)$ from μ+jets sample with $p_T(\mu) > 8\,\mathrm{GeV}/c$
    Count number of muon-jets with vertex, correct with p_T^{rel} templates
  - c-flavor TRF: scale b-TRF by c/b-tagging ratio from MC
  - light-quark TRF: Use negative side of IP significance

↓

$$\mathbf{Probability(tag\ event) = 1 - Probability(no\ jet\ tag)}$$

* SLT applies directly the tagger (find soft muon close to jet) on the MC