Heavy Flavor Physics lecture 1

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CTEQ Physics Summer School

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Outline

- Review Top Discovery
- How far have we come….
- The state of the art

Think Back

- To the early 90’s
- Ok – so you were all probably in grade school…
  - Before iPhones
  - Before laptops were commonplace
  - When physicists ran jobs on DEC VAX’s and lived in their offices day and night
  - We programmed in FORTRAN, used PAW, and had to learn about ZEBRA – a memory management system
  - We thought we knew a lot back then…. BUT
- Silicon detectors had not been tried in a hadron collider environment

Keep Thinking Back

- Our MC did not differentiate b-quarks from light quarks (VECBOS)
- We did not know how to b-tag
- We did not even know if a silicon detector would work in a hadron collider environment?
- How long would it last before the accelerator put a hole in it?
- We did not know how to measure b-tagging efficiency
- It took us a year to collect 20 pb-1
- But we were motivated!!!

A Simplified History of the Quark Model

- 1964 - Gell-Mann, Zweig - idea for 3 quarks - up, down, strange (u, d, s)
- 1970 - Glashow, Iliopoulos and Maiani - 4 quarks - up, down, strange, charm (u, d, s, c)
- 1973 - Kobayashi and Maskawa - add 2 quarks top and bottom (t, b) to explain CP violation
- 1974 - Ting, Richter discover charm
- 1977 - Lederman (Fermilab) discovers bottom
- B weak isospin = -1/2, need +1/2 partner

There must be a Top!

Top Mass Predictions and Discovery

- Several top mass predictions in late 70s
  - Predict $5 < M_{top} < 65$ GeV
  - Rule of 3

s	c	b	t	Quark
0.5	1.5	4.5	**15**	**Mass (GeV)**

- Jan. 1983 UA1 & UA2 discover W boson
- May 1983 UA1 discovers Z boson
- June-July 1984 Rubbia discovers Top!
  - Articles (*Nature*, *NY Times*) and press release
  - Mass peak between 30-50 GeV

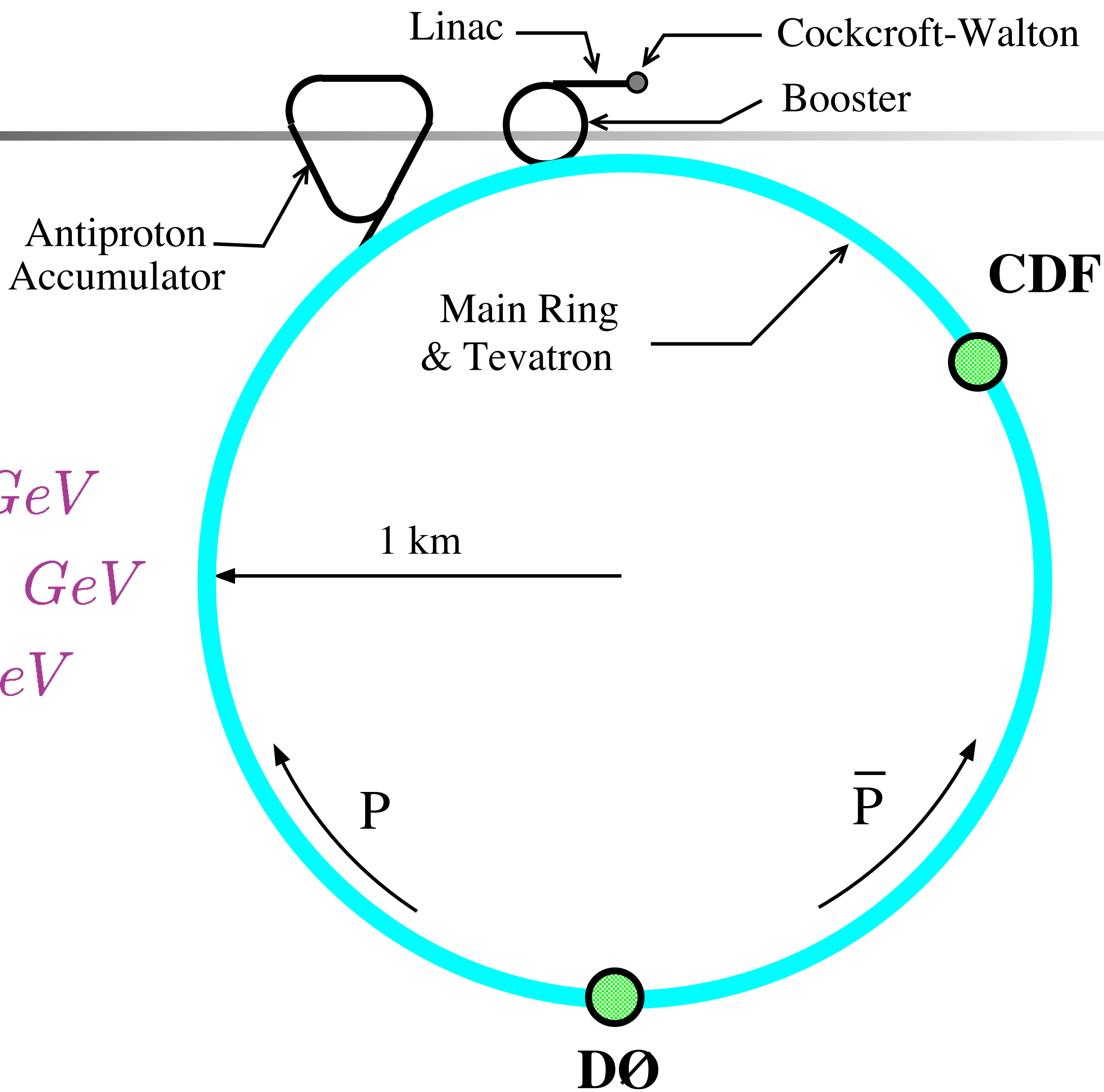
A Fun Aside

- I heard there was a recent “event” at CERN on the 4th of July – something about a boson… ☺
- Last time CERN had a special announcement on that date, it was 1984 and Carlo Rubbia was announcing the discovery of the Top Quark at 40 GeV
- I hope this one goes better!!!

Meanwhile back at Fermilab

- 1977 - First discussions of colliding p-pbar beams at Fermilab and a detector
- 1981 - CDF Design Report - general purpose detector with magnetic field
- Oct. '85 - CDF sees first p-pbar collisions - collect total 23 events
- Run 0 - June '88 - May '89, collect < 5 pb^{-1}
  - Set limits on M_{top} > 91 GeV using Dilepton and L+jets channels (first use of SLT tagging)
  - Mass too high for CERN, Fermilab only game in town

Fermilab Run 1



$$E_{proton} = 900\ GeV$$

$$E_{antiproton} = 900\ GeV$$

$$E_{cm} = 1800\ GeV$$

A Quick Review on Top Production and Decay

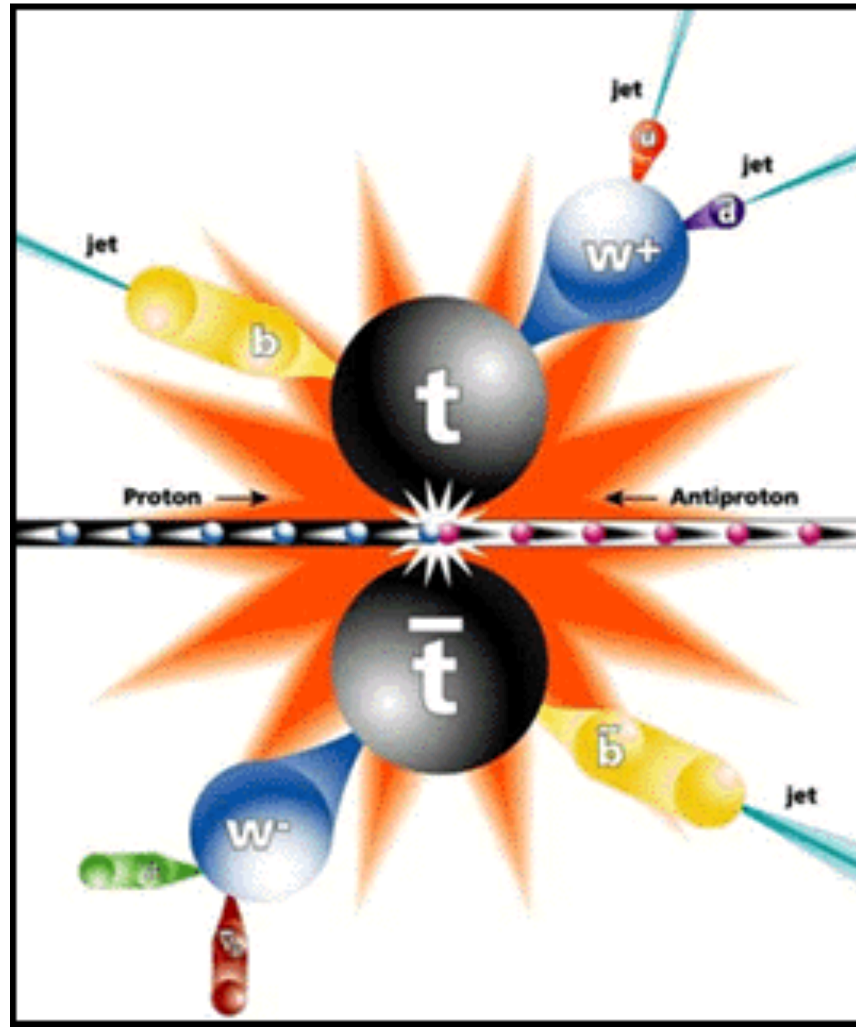
- Top pair production via the strong interaction:

$90\%\ q\bar{q}\ 10\%\ gg\ at\ Tevatron\ \sqrt{s} = 1.8\ TeV$

$85\%\ q\bar{q}\ 15\%\ gg\ at\ Tevatron\ \sqrt{s} = 1.96\ TeV$

$10\%\ q\bar{q}\ 90\%\ gg\ at\ LHC\ \sqrt{s} = 14\ TeV$

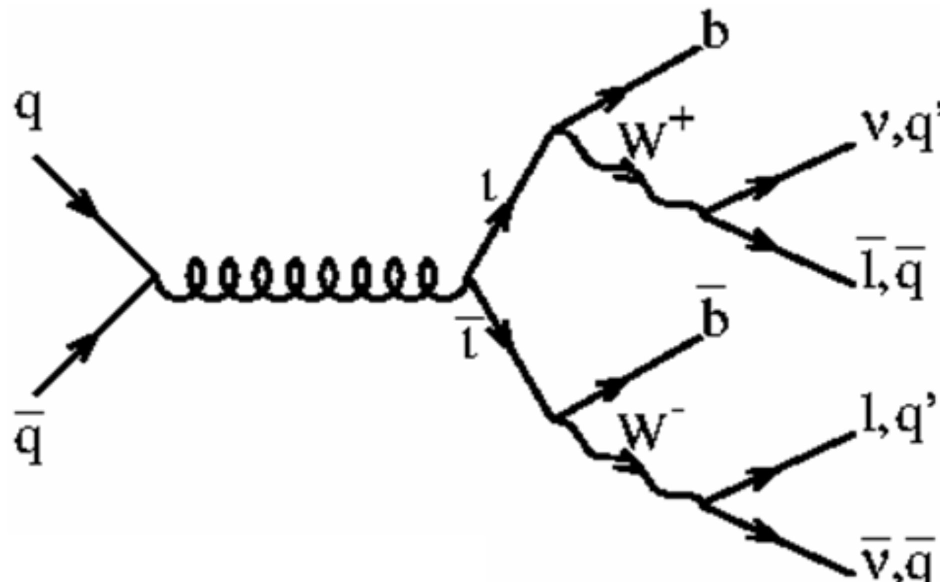
- Top decays t->Wb ~100%
- Top lifetime ~ 4×10^{-25} sec
  - Doesn't hadronize
- Decay of W identifies channel
  - Dilepton, L+jets, All-hadronic
  - Each channel poses its own unique challenges



How to identify the top quark

SM: tt pair production, Br($t \rightarrow bW$)=100% , Br($W \rightarrow l\nu$)=1/9=11%

dilepton	***(4/81)***	**2 leptons + 2 jets + missing E_T**
l+jets	***(24/81)***	**1 lepton + 4 jets + missing E_T**
fully hadronic	***(36/81)***	**6 jets**



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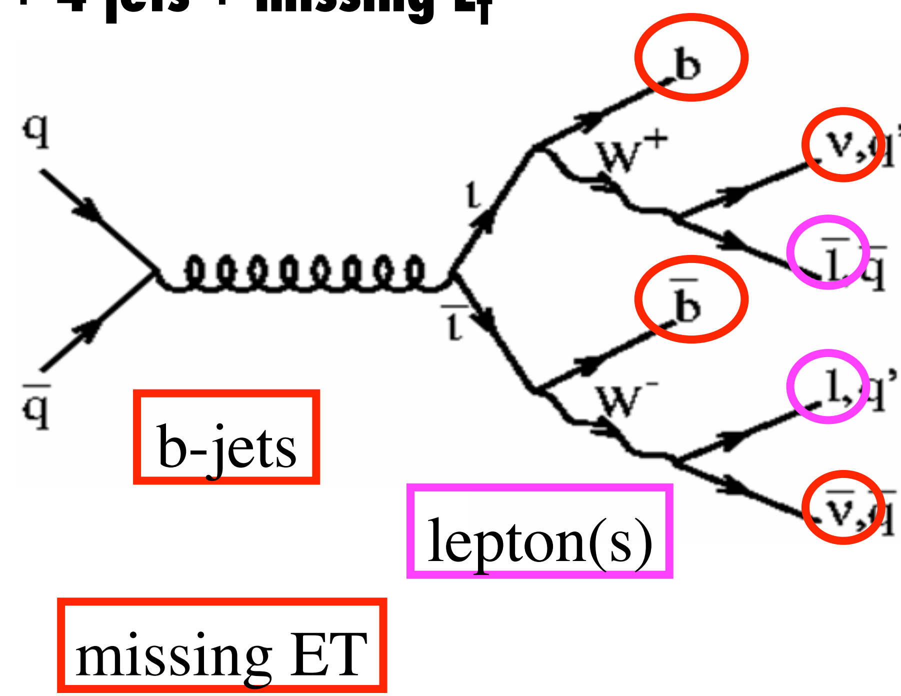

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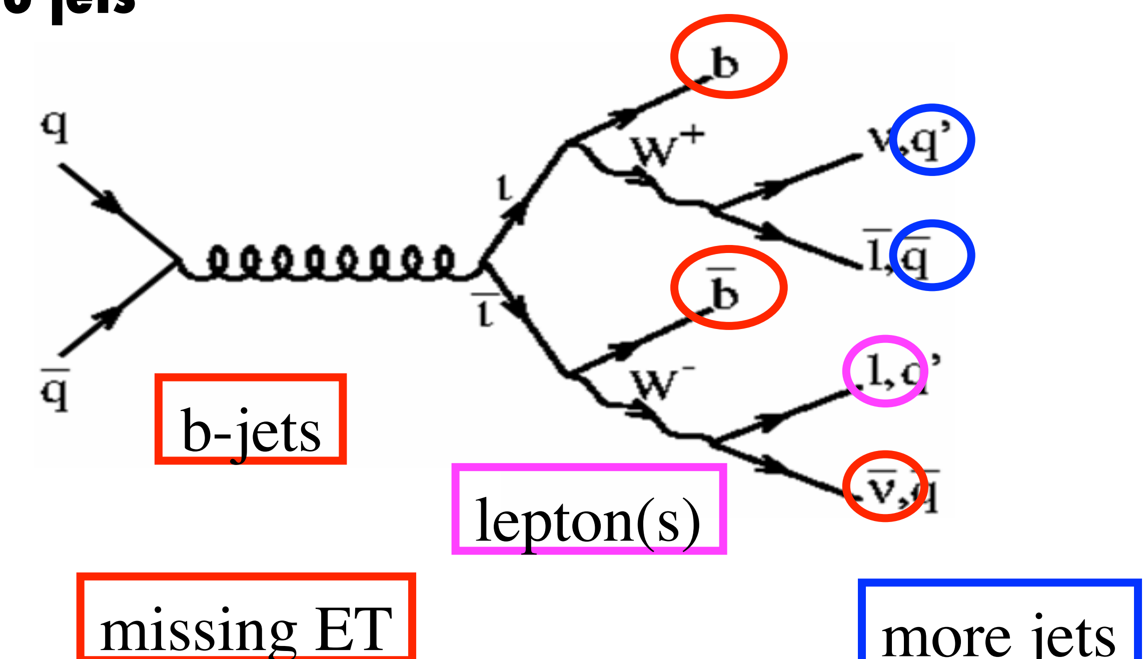

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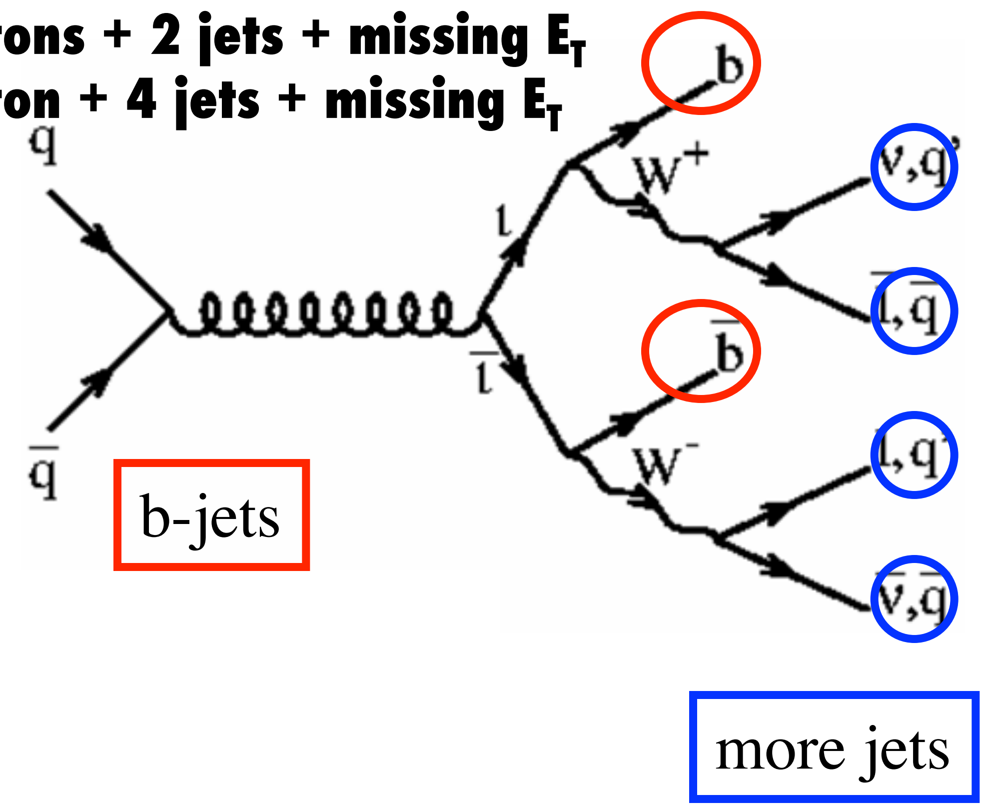
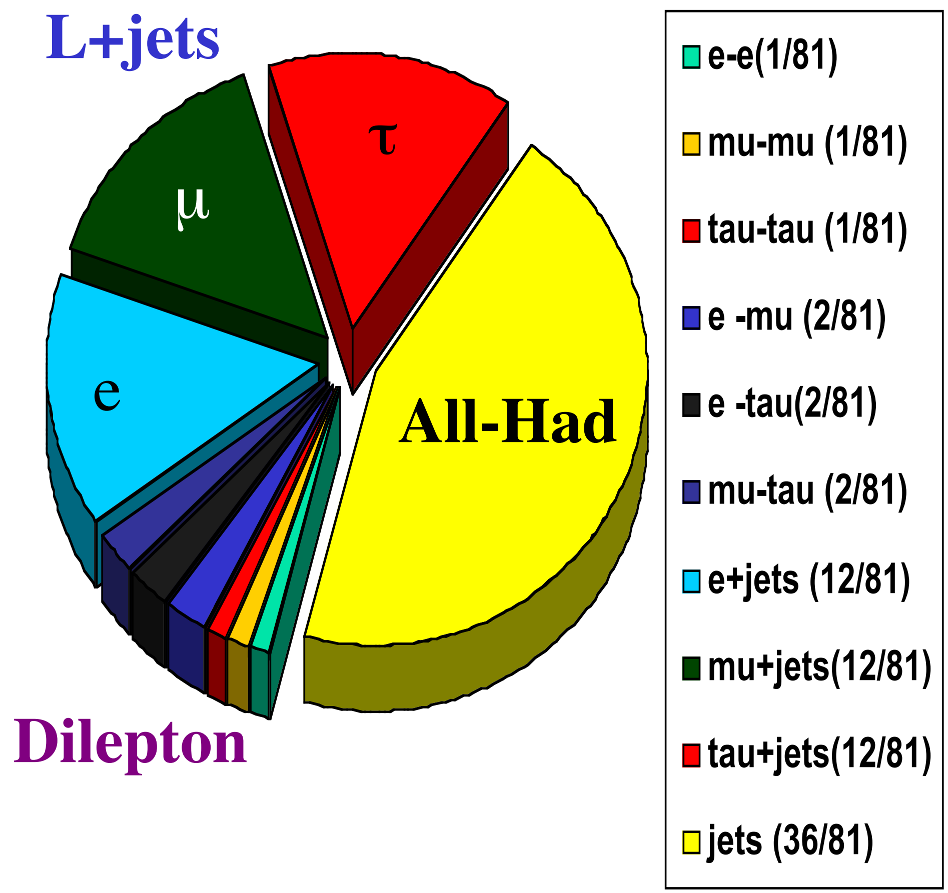
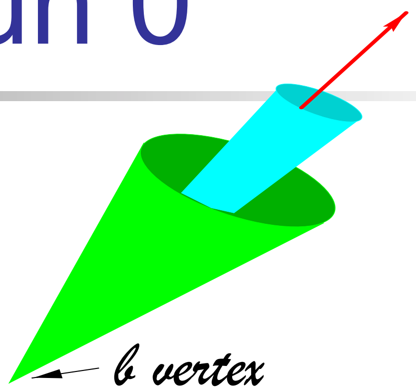


Top Decay Channel Summary

- **Dilepton**
  - Few events but pure
  - final state: lν lν **bb**
- **Lepton + Jets**
  - More events, less pure
    - Add b-tags
  - final state: lν qq **bb**
- All-Hadronic
  - Lots of events, huge QCD bkg
  - final state: qq qq **bb**
  - Not used in discovery



Looking for Top in Run 0



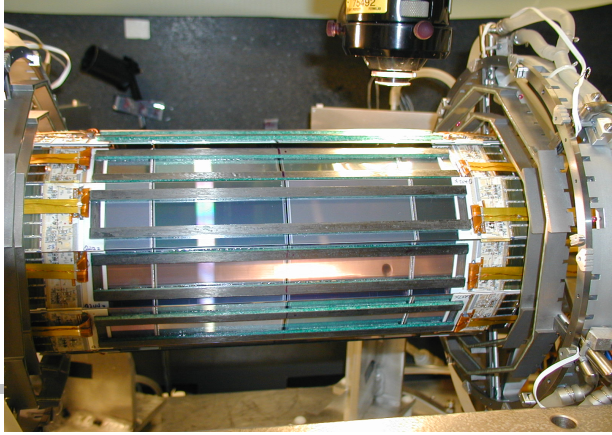
- Believe $M_{Top} < M_W$
  - Decay mode would be W -> tb with t -> blν
- Search strategies
  - Dilepton channel
    - ee, eμ, and μμ
  - L+jets channel
    - Added **SLT** tags
- Set limit M_{Top} > 91 GeV
- **CDF had no silicon yet!**

- Soft Lepton Tagging
- Identify semileptonic B decay

$$b \rightarrow l \;,\; b \rightarrow c \rightarrow l$$

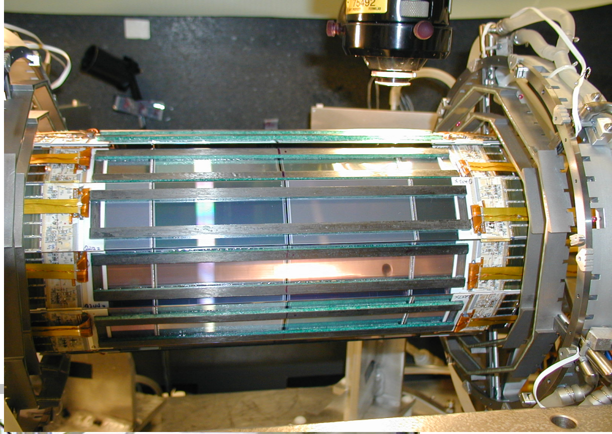
- ε(SLT) ~ 20%

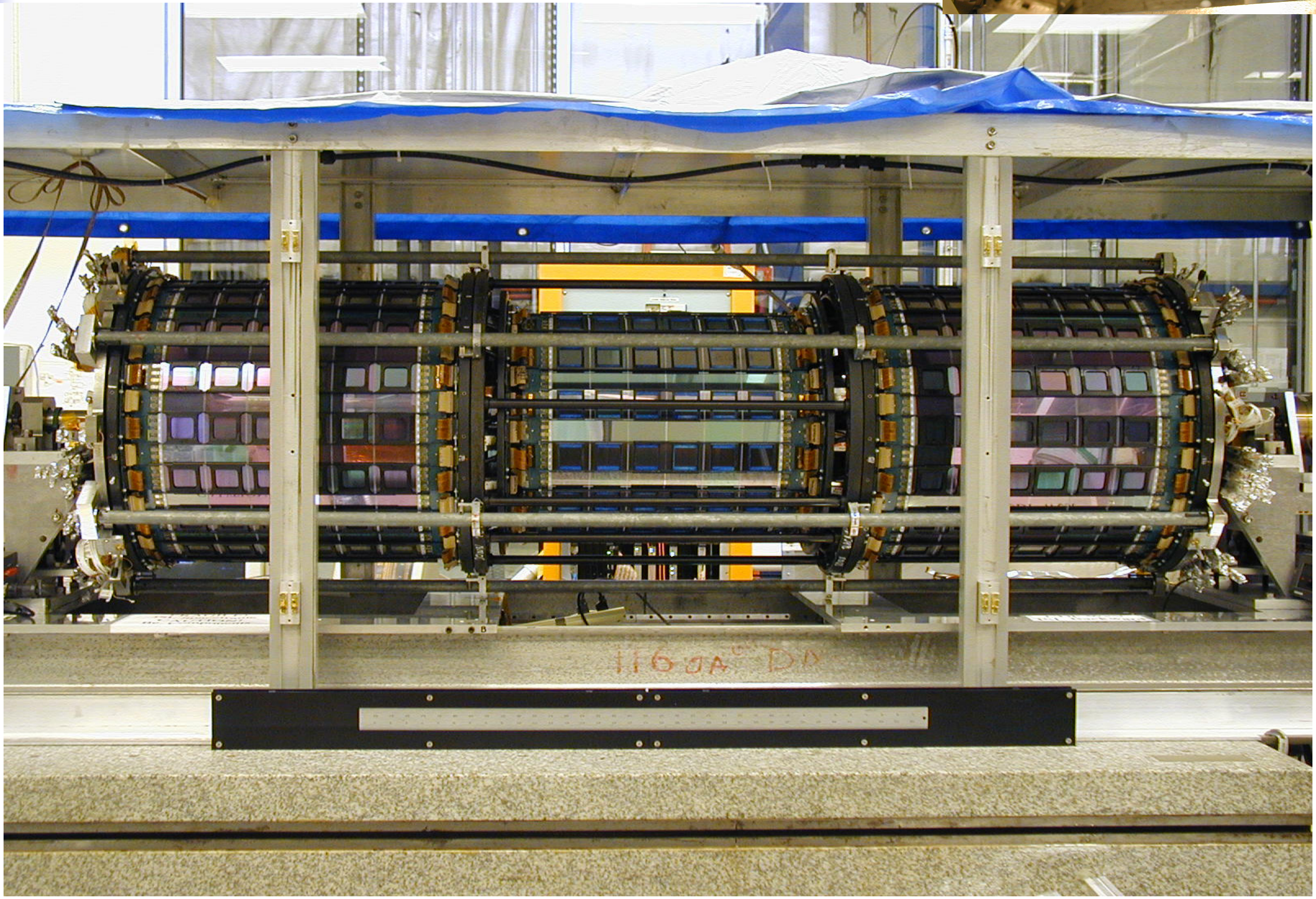
Building the Silicon VerteX Detector



- Silicon used at fixed target to measure particle lifetimes and tag particles
- Not easy to sell idea to CDF
  - Hadron environment too messy to do precision tracking and heavy flavor physics (b and c)
  - No obvious physics case for device
    - Top discovery not a factor, didn't consider b-tagging – people thought all-jets was the way to find it back then!
  - Many technical challenges with construction and readout in collider environment
- Dedication by Pisa (especially Aldo Menzione) and LBL groups got detector built

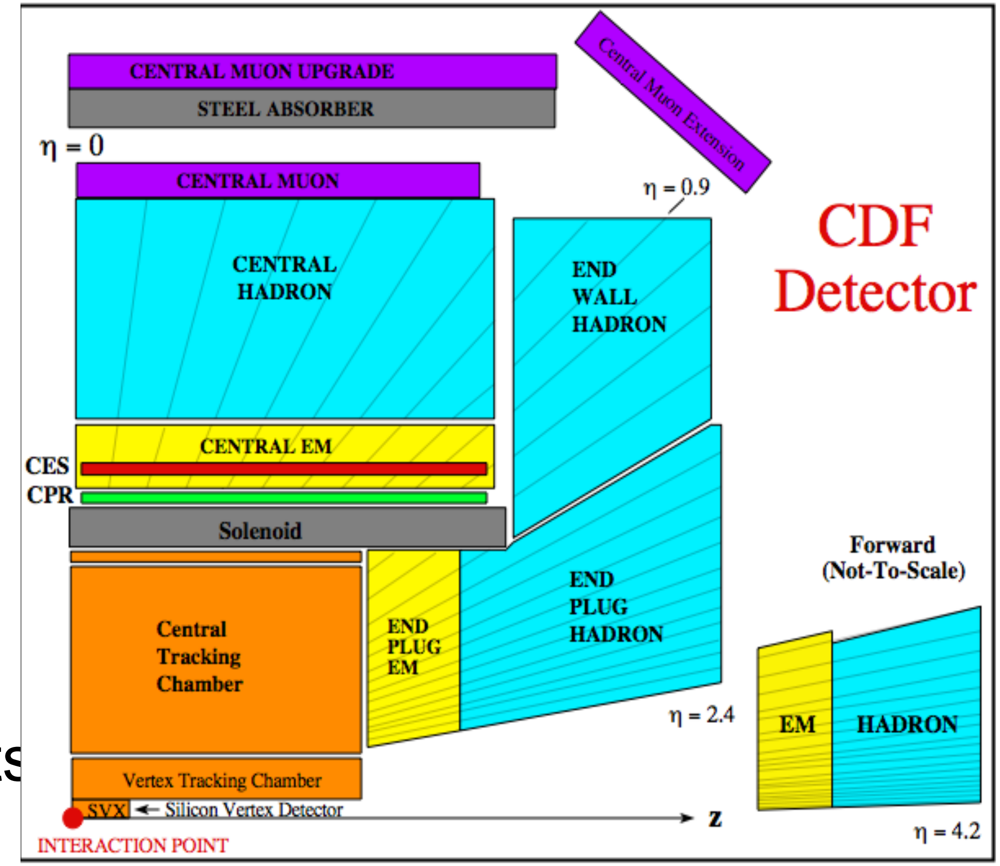
First and Last





Fermilab Gets Serious
Run Ia

- June '92 - May '93
- CDF now has SVX and muon upgrades
- D0 is now taking data too
- Developing strategies for discovering top
  - Counting experiments
  - Kinematic analyses

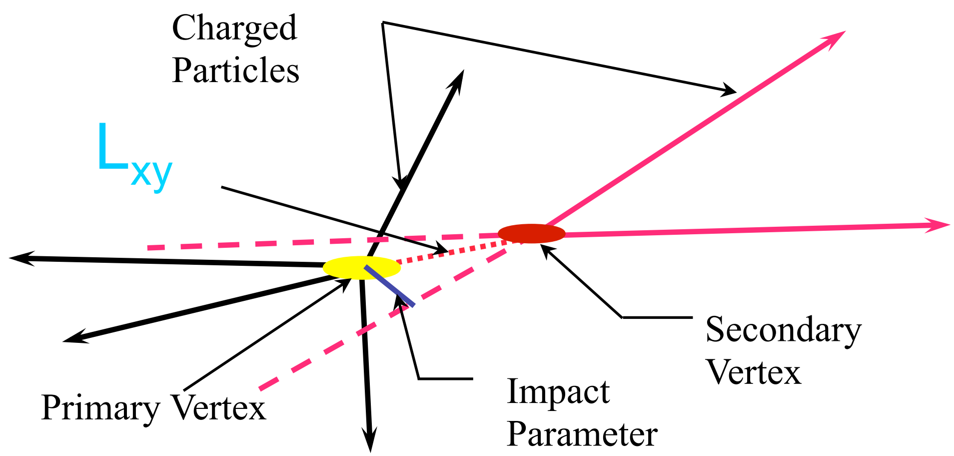


How Hard is it going to be?

- Tevatron was running at 900 GeV and colliding beam at 300,000 times/sec
- A ttbar event is created about once every 10 billion collisions
- So in Run 1A, about 1 trillion collisions
- For a top mass of 175, we made about 100 total!!! (not taking into account acceptance, trigger etc)

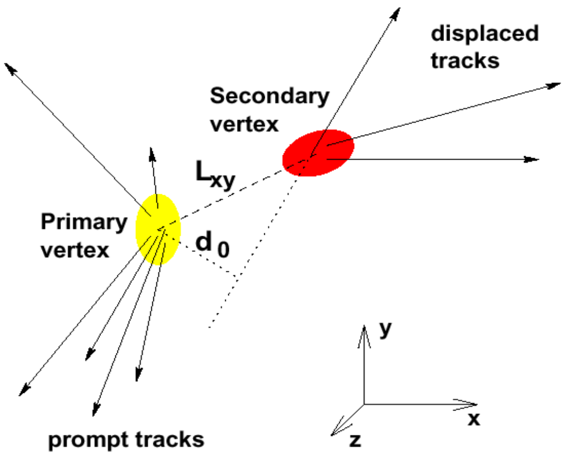
b-tagging using Secondary Vertices

- Use new SVX and b lifetime
  - $c\tau$ ~ 450mm
  - b hadrons travel L_{xy} ~ 3 mm before decay
- Run 1a had 3 SVX taggers
  - **Jetvtx** - ≥2 tracks form secondary vertex with $|Lxy|/\sigma_{Lxy} \geq 3$
  - **Jet Probability** - use track impact parameter, probability of track consistent with primary vertex
  - **d-ϕ** - Uses impact parameter, d, and azimuthal angle, ϕ, of tracks



- Secondary VerteX Tagging
- ε(SVX) ~ 40%

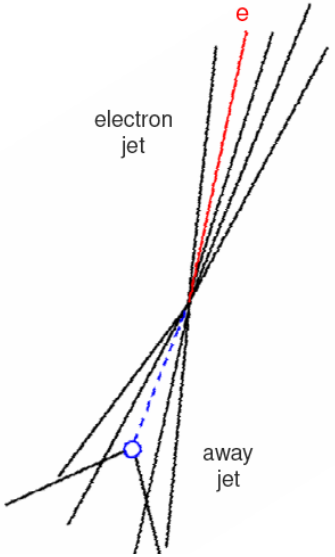
Finding the b-jets

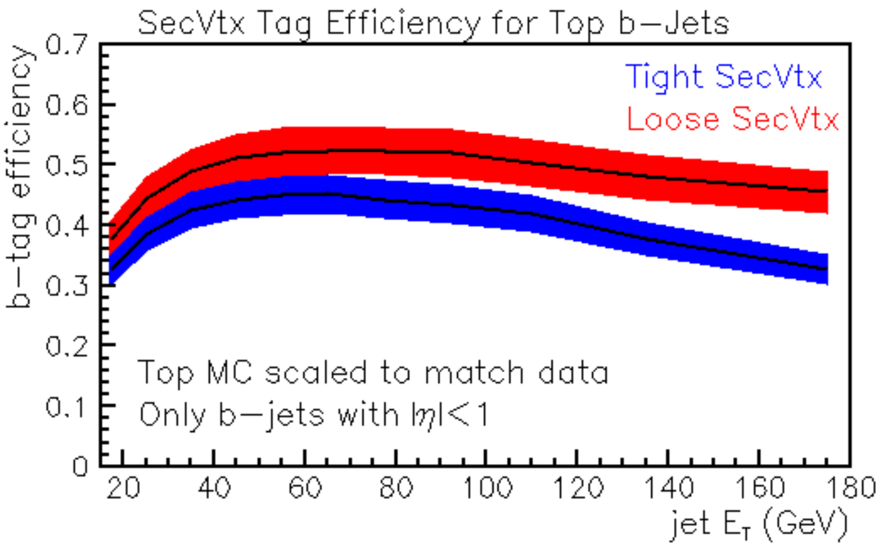


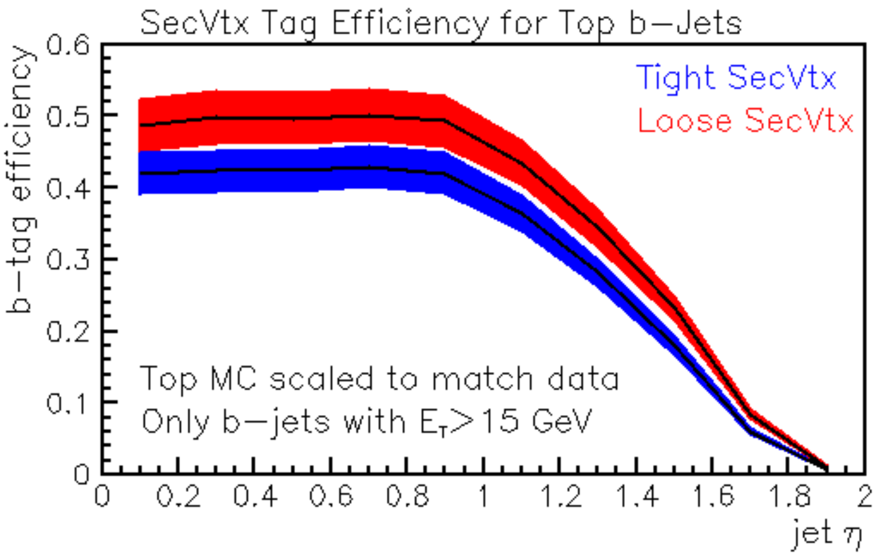
- Procedure "Secondary Vertex":
  - reconstruct primary vertex:
    - resolution ~ 30 μm
  - Search tracks inconsistent with primary vertex:
    - Candidates for secondary vertex
    - See whether three or two of those intersect at one point
  - Require displacement of secondary from primary vertex
    - Form Lxy: transverse decay distance projected onto jet axis:
      - Lxy>0: b-tag along the jet direction => real b-tag or mistag
      - Lxy<0: b-tag opposite to jet direction => mistag!
    - Significance: $L_{xy} > 7\ \delta(L_{xy})$ i.e. 7 sigma

Characterize the B-tagger: Efficiency

- Efficiency of tagging a true b-jet
  - Use Data sample enriched in b-jets
  - Select jets with electron or muons
    - From semileptonic b-decay
  - Measure efficiency in data and MC





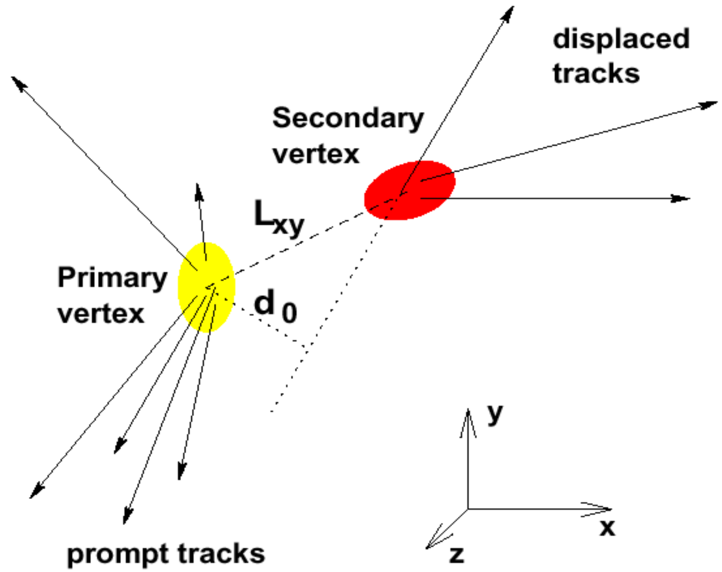


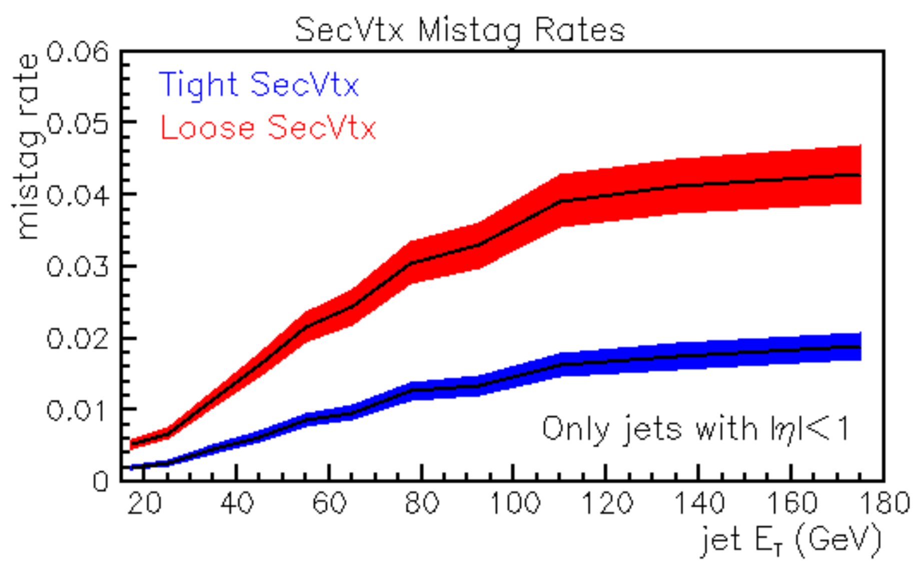
Achieve about 40-50%

(fall-off at high eta due to limited tracking coverage)

Characterize the B-tagger: Mistag rate

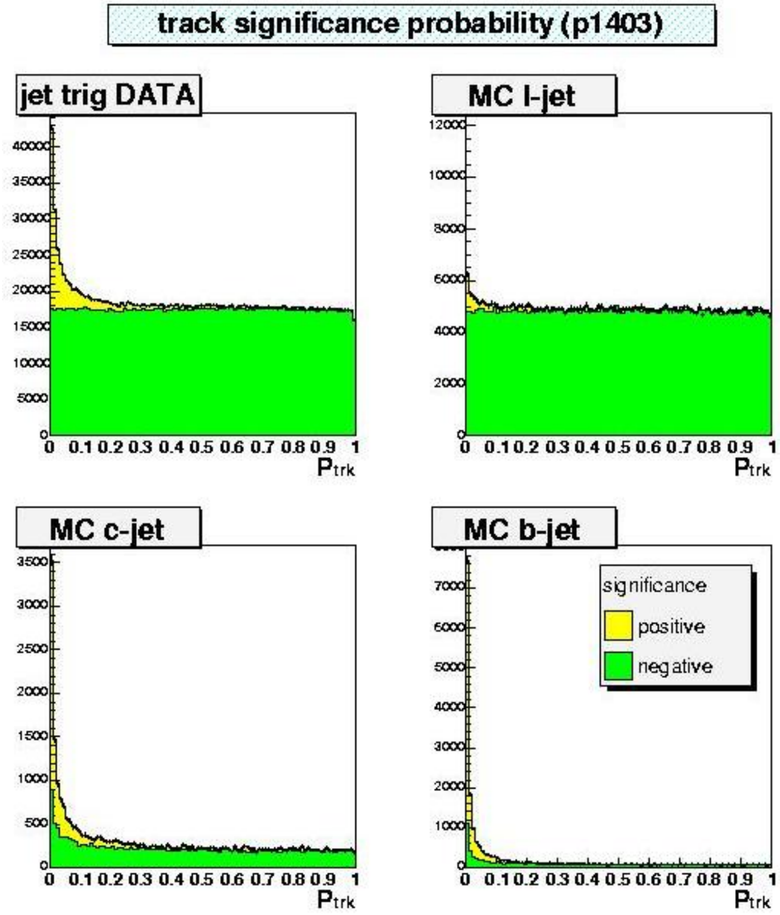
- Mistag Rate measurement:
  - Probability of light quarks to be misidentified
  - Use "negative" tags: $L_{xy}<0$
    - Can only arise due to misreconstruction
  - Result:
    - Tight: 1% (ε=40%)
    - Loose: 3% (ε=50%)
  - Depending on physics analy
    - Choose "tight" or "loose" tagging algorithm





Jet probability

- Complementary to full secondary vertex reconstruction:
  - Evaluate probability of tracks to be prompt
    - Multiply probabilities of individual tracks together
  - "Jet Probability"
- Continuous distribution
  - Can optimize cut valued for each analysis
  - Can also use this well for charm



Silicon Vertex Detectors Work (in a hadron collider)!

e + 4 jet event

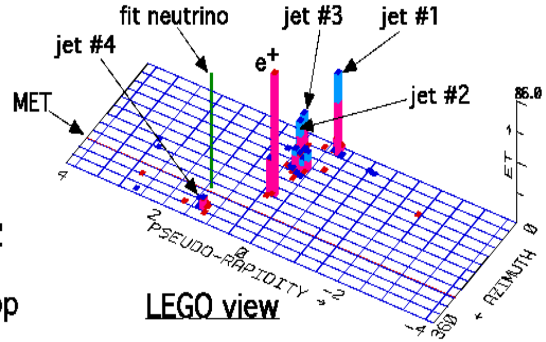
40758_44414
24-September, 1992

TWO jets tagged by SVX

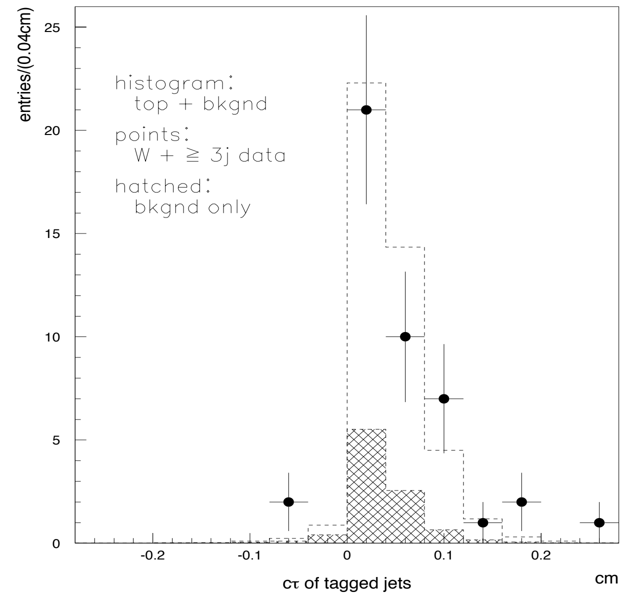
fit top mass is $175 \pm 10\ GeV/c^2$

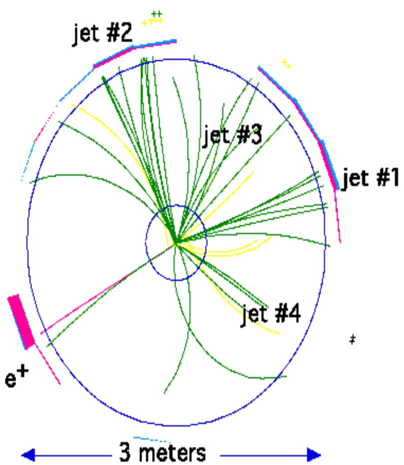
e^+, Missing E_t, jet #4 from top

jets 1,2,3 from top (2&3 from W)

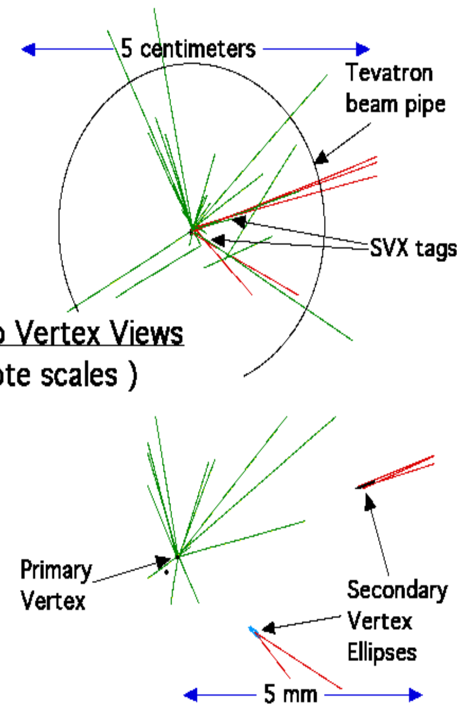


LEGO view

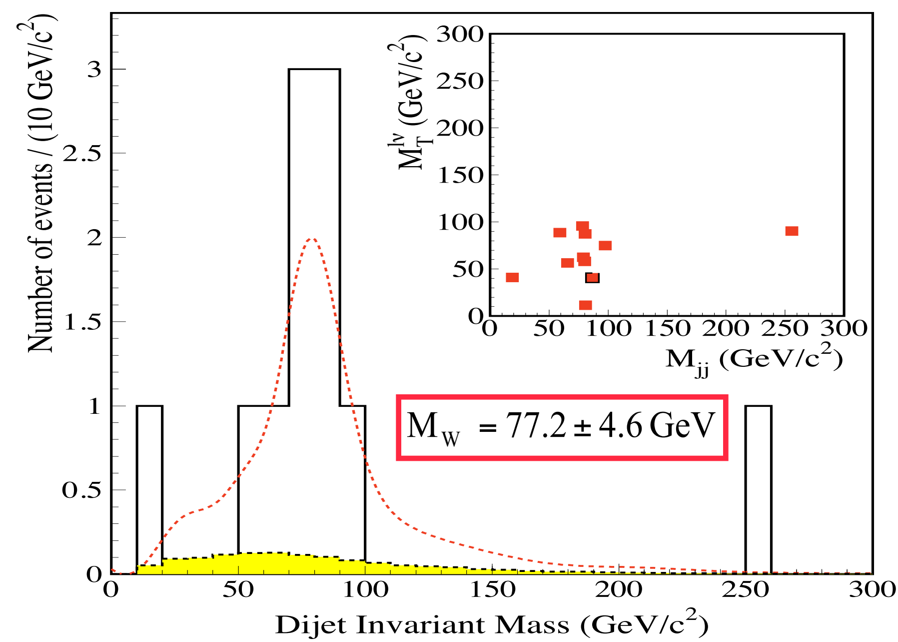




Tracking View

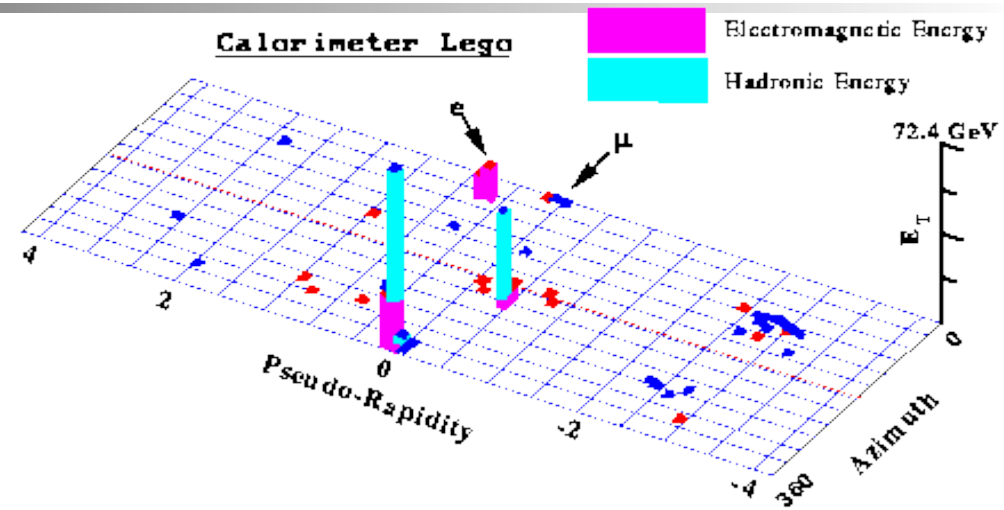


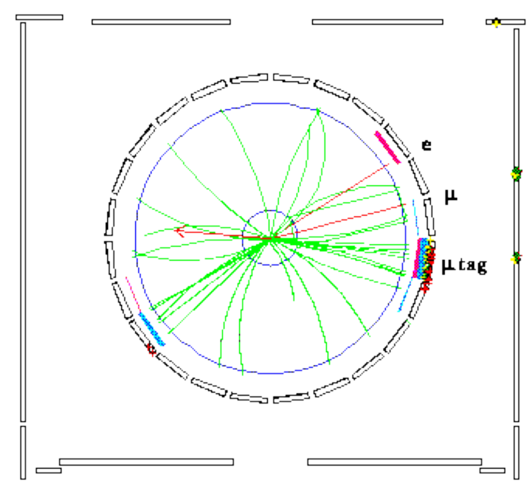
Two Vertex Views
(note scales)

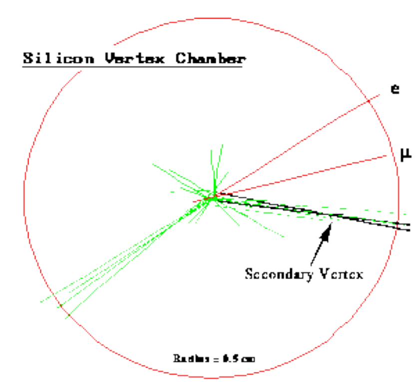


The Golden Event

- "DPF event"
  - Oct. 22, 1992
  - That year ALL candidate events were "named"
  - eμ + 2 jet event
    - 1 jet tagged by both SLT and SVX
  - Decide not to declare discovery on 1 event
    - D0 similar experience
- **Push for top is on!**







Game Plan

- Perform counting experiments
- Deliberate decision to NOT use NN because people did not trust that MC would model shapes with sufficient accuracy
- Base Findings on counting experiment only – use peak in mass plot (hopefully) and kinematic plots as confirmation

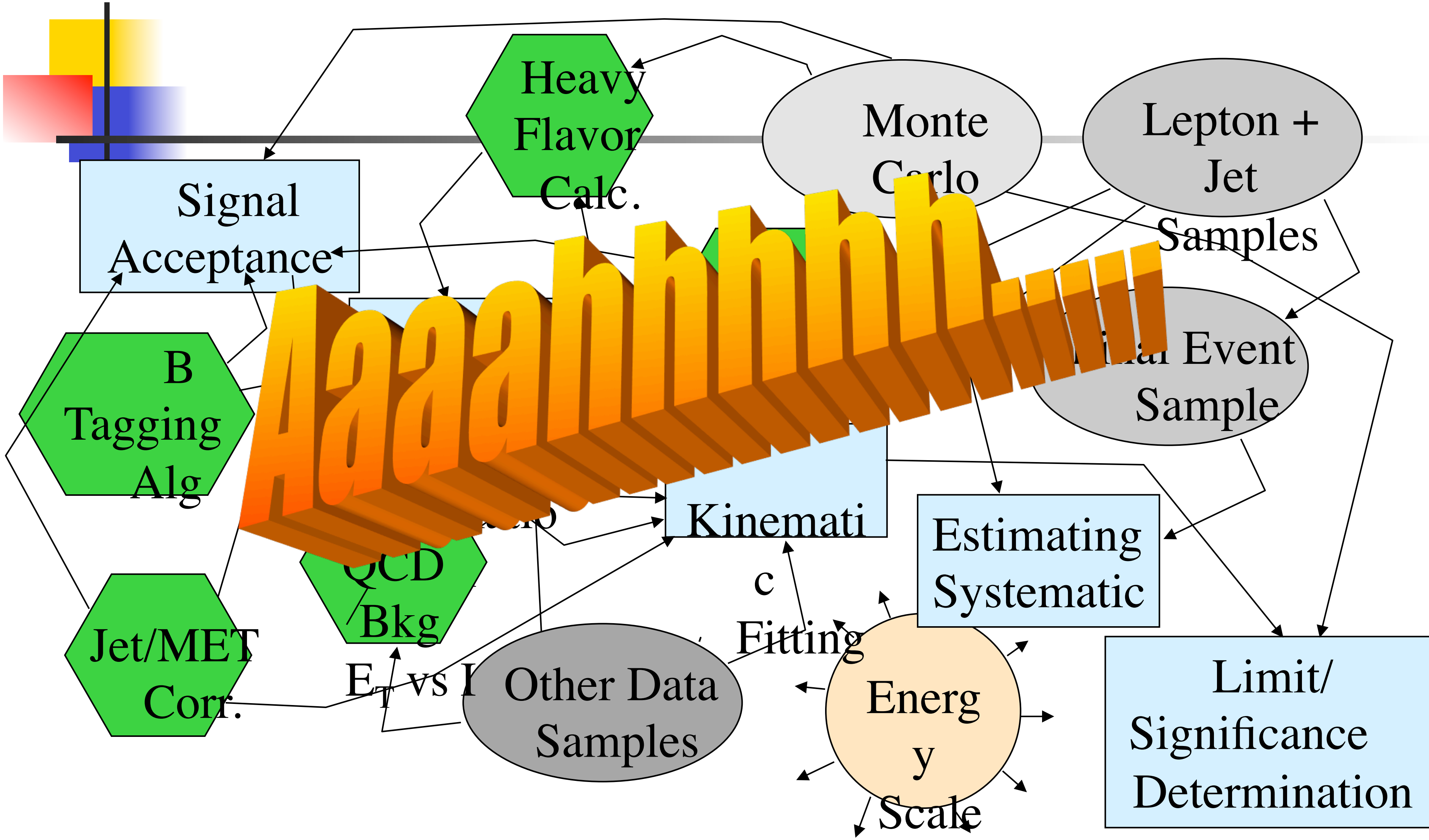
Backgrounds – How to Estimate?

- We weren't sure – so we did it 2 ways…
- Method 1
  - fully tied to data. Developed a mistag matrix vs Jet Et and Eta and applied it to all non-tagged jets in sample
  - Felt this was an over-estimate of background
- Method 2
  - Uses MC to determine ratio's
  - Applied to our untagged W+jet data

At some point in 1991…

- Change of attitude – very important
- A realization that one person or one university group was NOT going to discover top by themselves
- Groups became less competitive, started sharing information and working in a coherent fashion

Naïve Schematic of Typical L+J Analysis



The "Evidence" Paper

- July 1993 - CDF collaboration meeting
  - Seeing excess in all channels
  - Decide to write 4 PRLs
- Oct. '93 - CDF collab meeting
  - Reject PRLs and opt for giant PRD
- Jan. '94 - CDF collab meeting
  - Many questions and concerns (next slide)
- April 26, 1994 - Submit "Evidence for Top Quark Production" - PRD 50, p.2966-3026

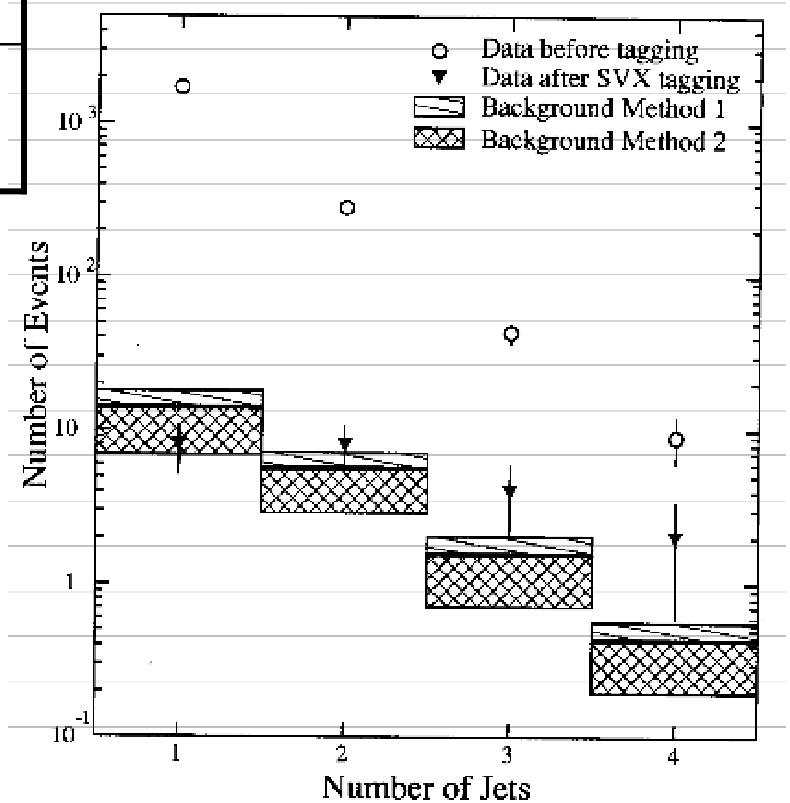
Comments on "Evidence"

- 9 months of endless meetings answering questions while attempting to keep results quiet
- Some of the concerns raised:
  - Choice of official SVX b-tagger
    - Tuning on data
  - Method 1 vs. Method 2 background
    - Overestimate from data or trust MC
  - Role of kinematic analyses
    - Supporting evidence but not in significance
  - Calculate significance
    - Events or tags, weight of double tags

Results for Evidence Paper

Channel:	SVX	SLT	Dilepton
Expected Bkg.	2.3±0.3	3.1±0.3	0.56±0.25
Observed Events	6	7	2

- Combining all channels with 19 pb^{-1}
- Prob bkg fluctuate up to observed = 0.26% (2.8σ)
- Back then – we did not consider a Look Elsewhere Effect



There were reasons for "Pause"

- We had far too many Z+b jet events in our Run 1a data from what we expected
- (in run 1b – did not have ANY)

Run Ib and Observation

- Run Ib Feb. ‘94 - Dec. ‘95
  - New rad-hard silicon - SVX’
  - Optimized SVX b-tagger - Secvtx
- Jan ‘95 - CDF collaboration meeting
  - See significant excess in all channels
  - Slight changes to Evidence analyses
    - One optimized SVX b-tagger - Secvtx
    - Use Method 2 background (smaller # of bkg events)
- March ‘95 - D0 and CDF submit PRL’s

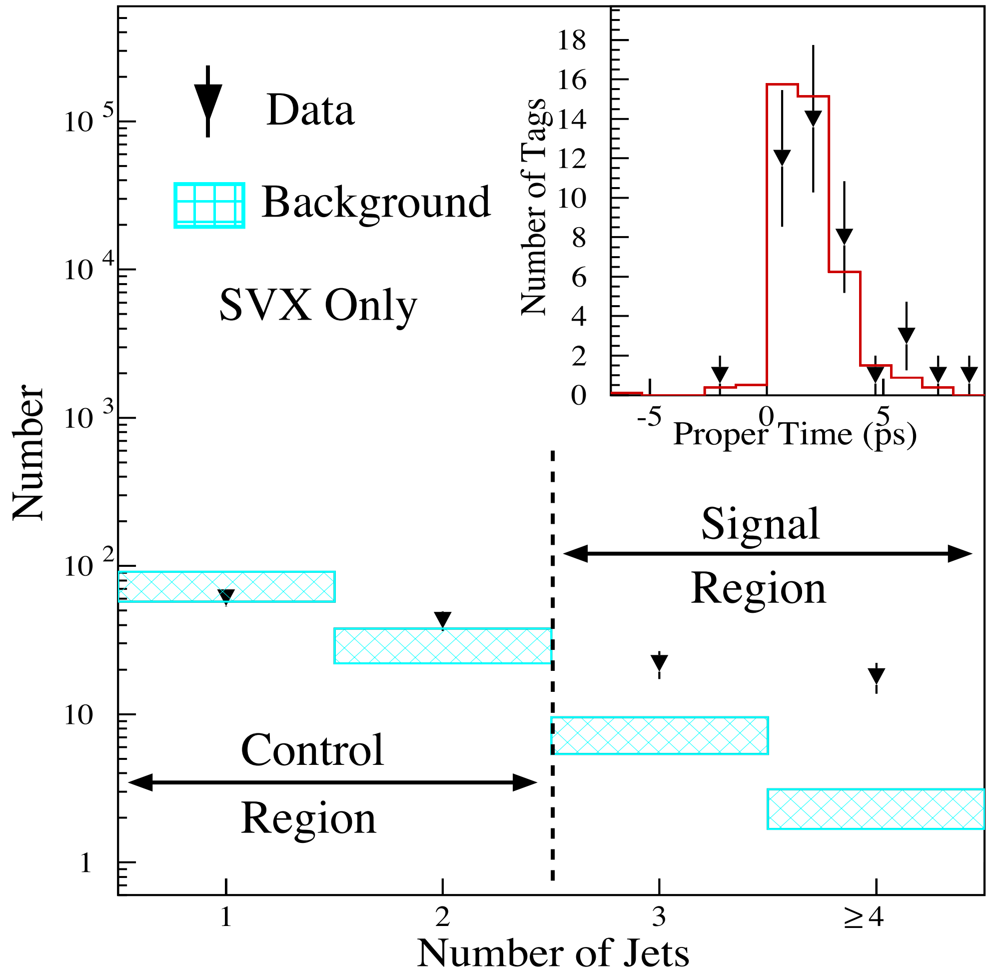
Top Discovery

Channel	SVX	SLT	Dilepton
Observed	27 tags	23 tags	6 events
Exp. bkg	6.7±2.1	15.4±2.0	1.3±0.3
Probability	$2x10^{-5}$	$6x10^{-2}$	$3x10^{-3}$

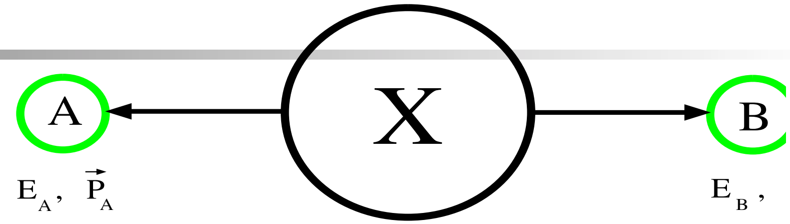
- Using 67 pb-1 (includes Evidence data) combined Prob = $1x10^{-6}$ (4.8σ)
- If include mass distribution Prob = $3.7x10^{-7}$ (5.0σ)

The Discovery!!!

"N" Jets Plot for Discovery

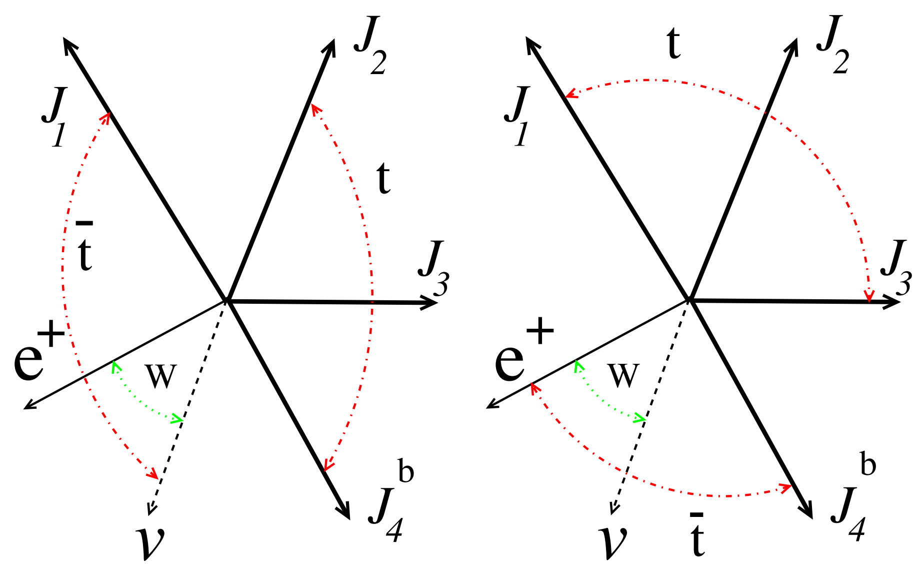


Determining the Mass



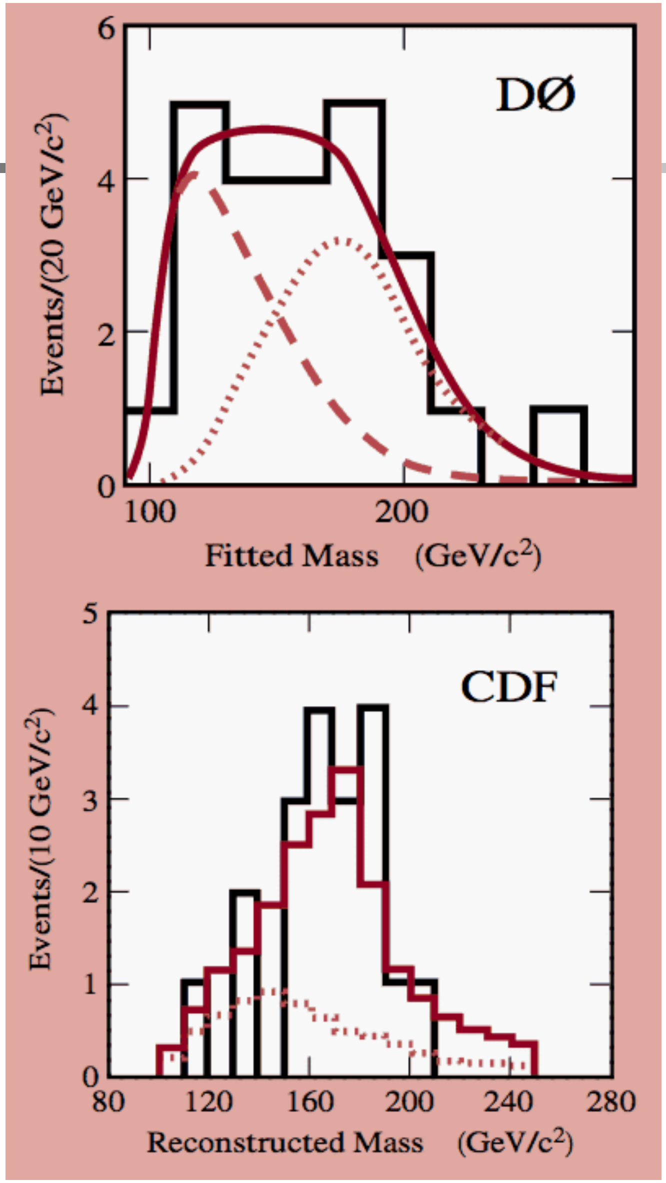
$$M_X = \sqrt{(E_A + E_B) + (\vec{P}_A + \vec{P}_B)}$$

- Each event has two top's so you have two chances in each event
- We don't know which decay products belong to which top
- We try ALL combinations
- Constrain M(w) = 80
- Mtop = M antitop



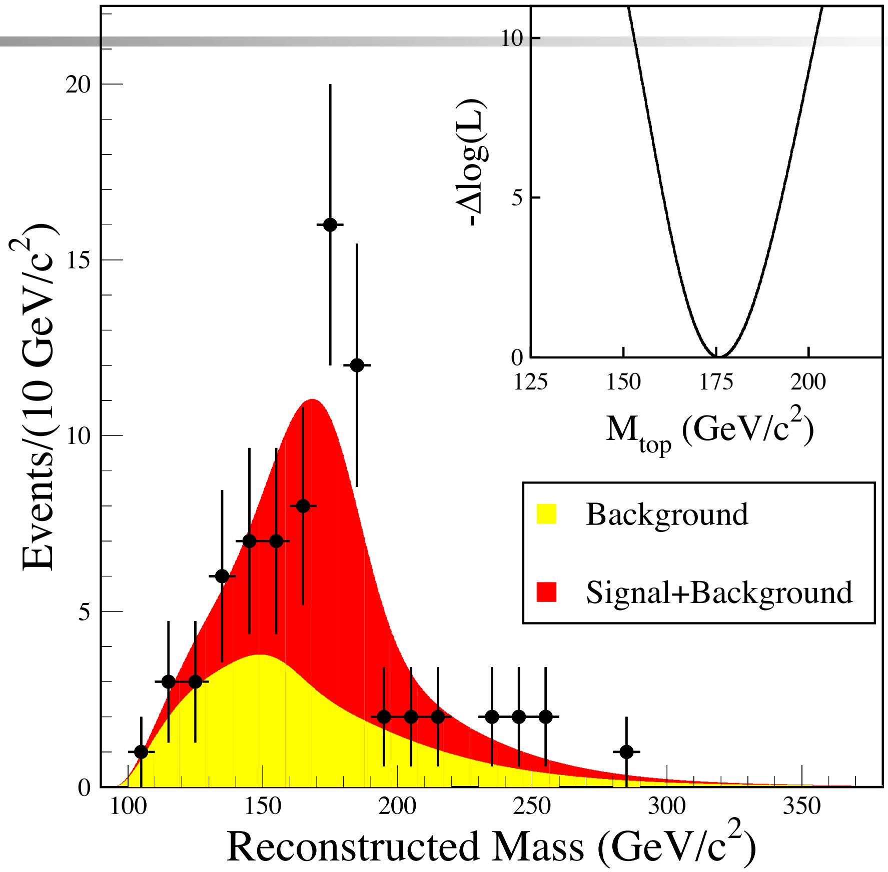
(a) (b)

CDF and D0 Discovery Mass Plots



Final Run I Result

Using 100 pb-1

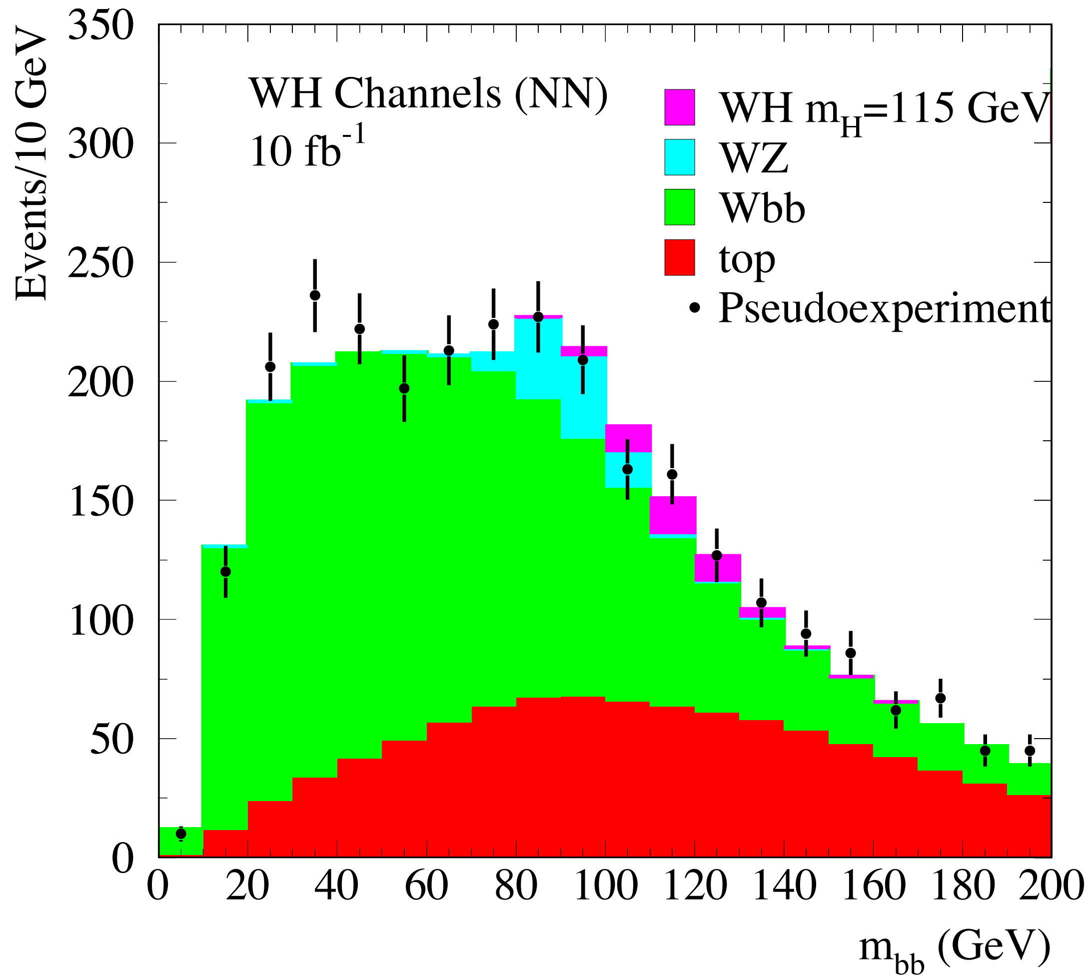


- Top Mass is $175.9 \pm 4.8(\text{stat}) \pm 4.9(\text{sys})$ GeV/c^2

Yesterday's sensation is today's calibration and tomorrow's background.

- Feynman

- Calibration sample
  - Just like we used Ws, Zs
    - Jet Energy Scale
    - B-tagging
- Background
  - Higgs



Our Projections for Run II

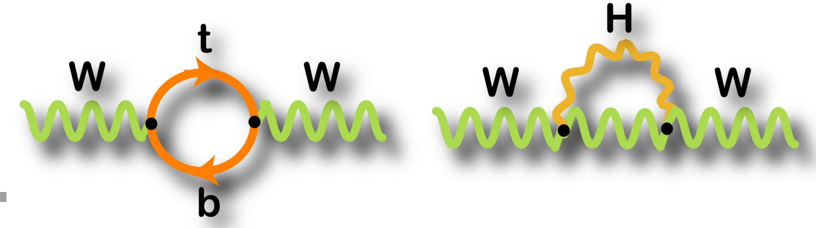
- In our physics plan for Run II, written based on run 1 experience we predicted
  - Top Mass uncertainty of 3 GeV
  - Top Cross Section uncertainty of 10%

  - Why were we so far off?

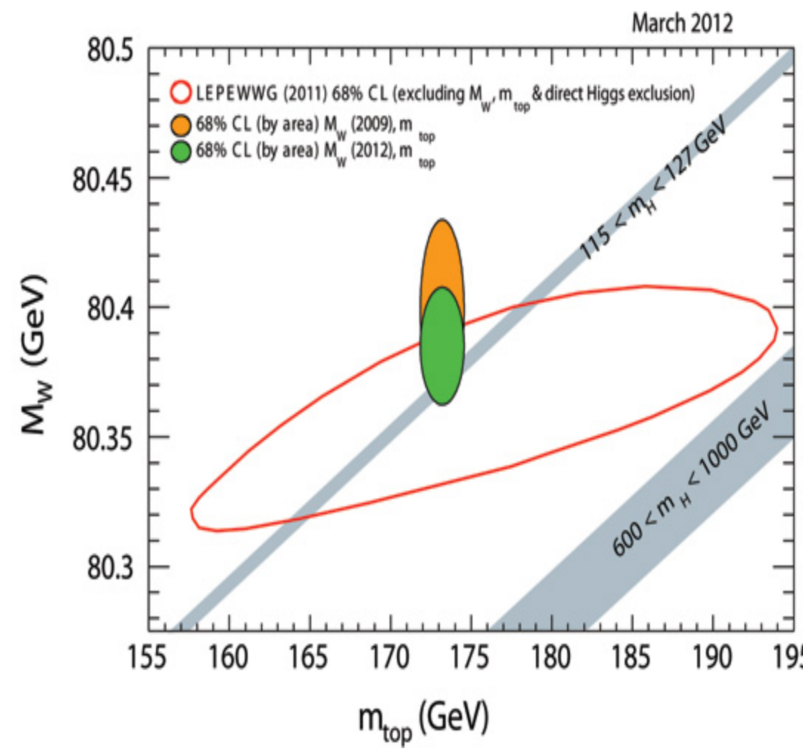
The Reasons….

- An entire new set of tools were developed – ALPGEN, MADGRAPH etc
- Large data sets allowed us to really tune the MC's, underlying event etc so data/mc agreement was excellent
- We got more creative
  - Maximizing information in events with a variety of neural network techniques
  - Separating out the Jet energy scale
  - Better detector performance out of much more pixelated devices

Why Should We Care?

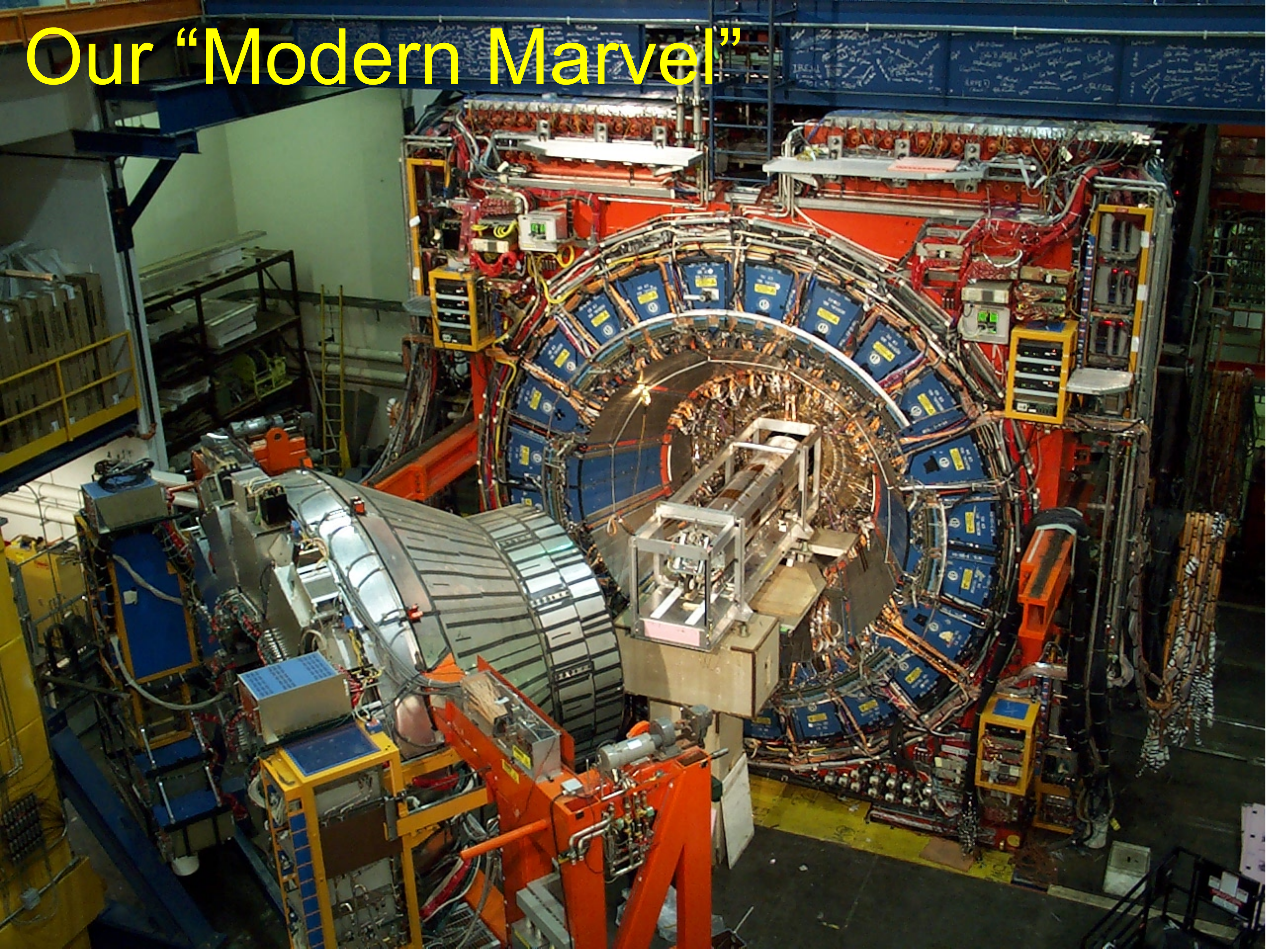


- Heaviest known fundamental particle
  - M_{top}=172.7+-1.1 GeV
- Is this large mass telling us something about electroweak symmetry breaking?
- Related to m_W and m_H:
  - $m_W \sim M_{top}^2$
  - $m_W \sim \ln(m_H)$
- If there are new particles the relation might change:
  - Precision measurement of top quark and W boson mass can reveal new physics

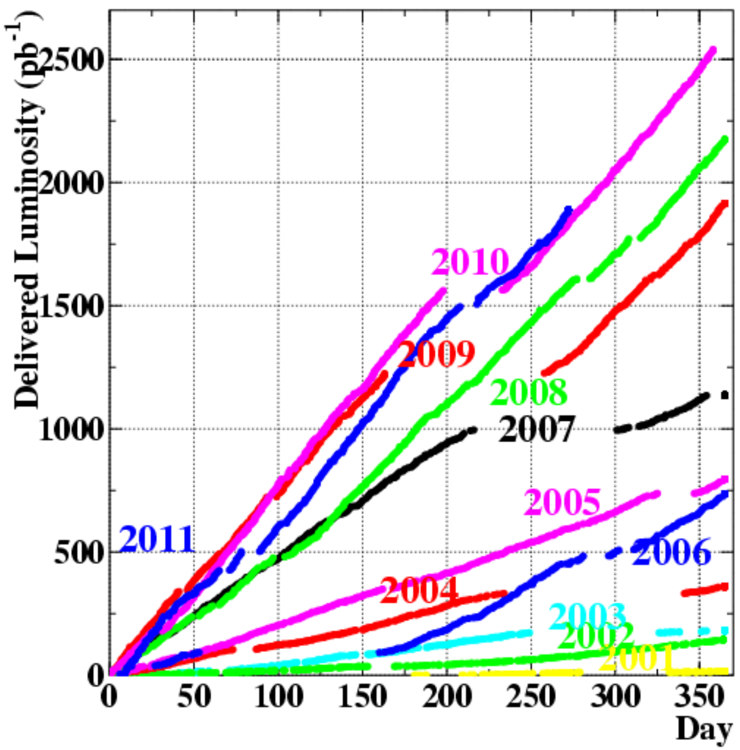


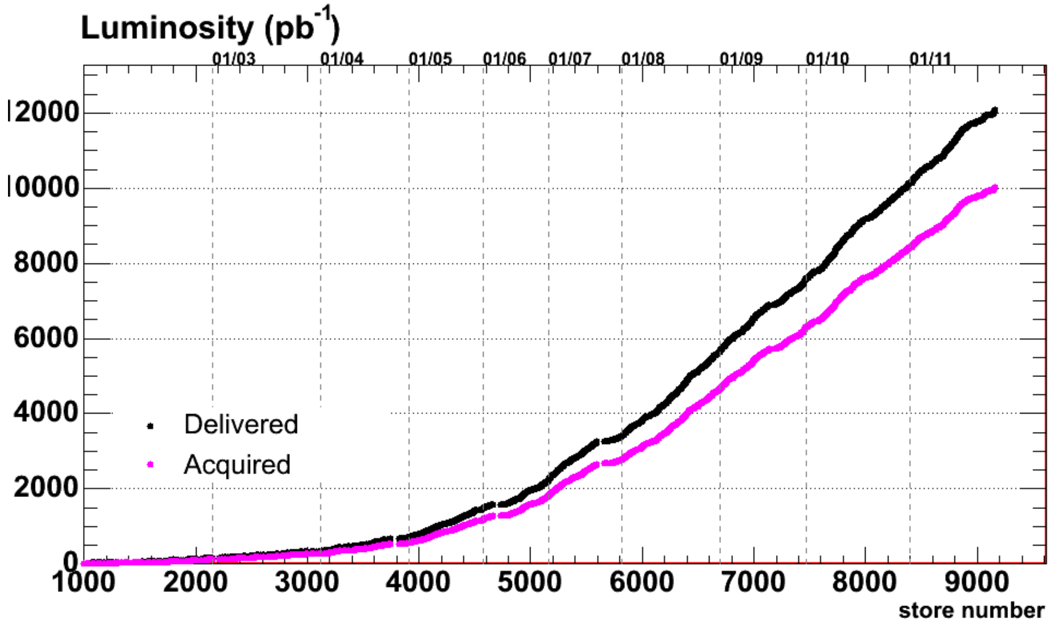
America's Once Most Powerful Accelerator: Fermilab's Tevatron

Our “Modern Marvel”

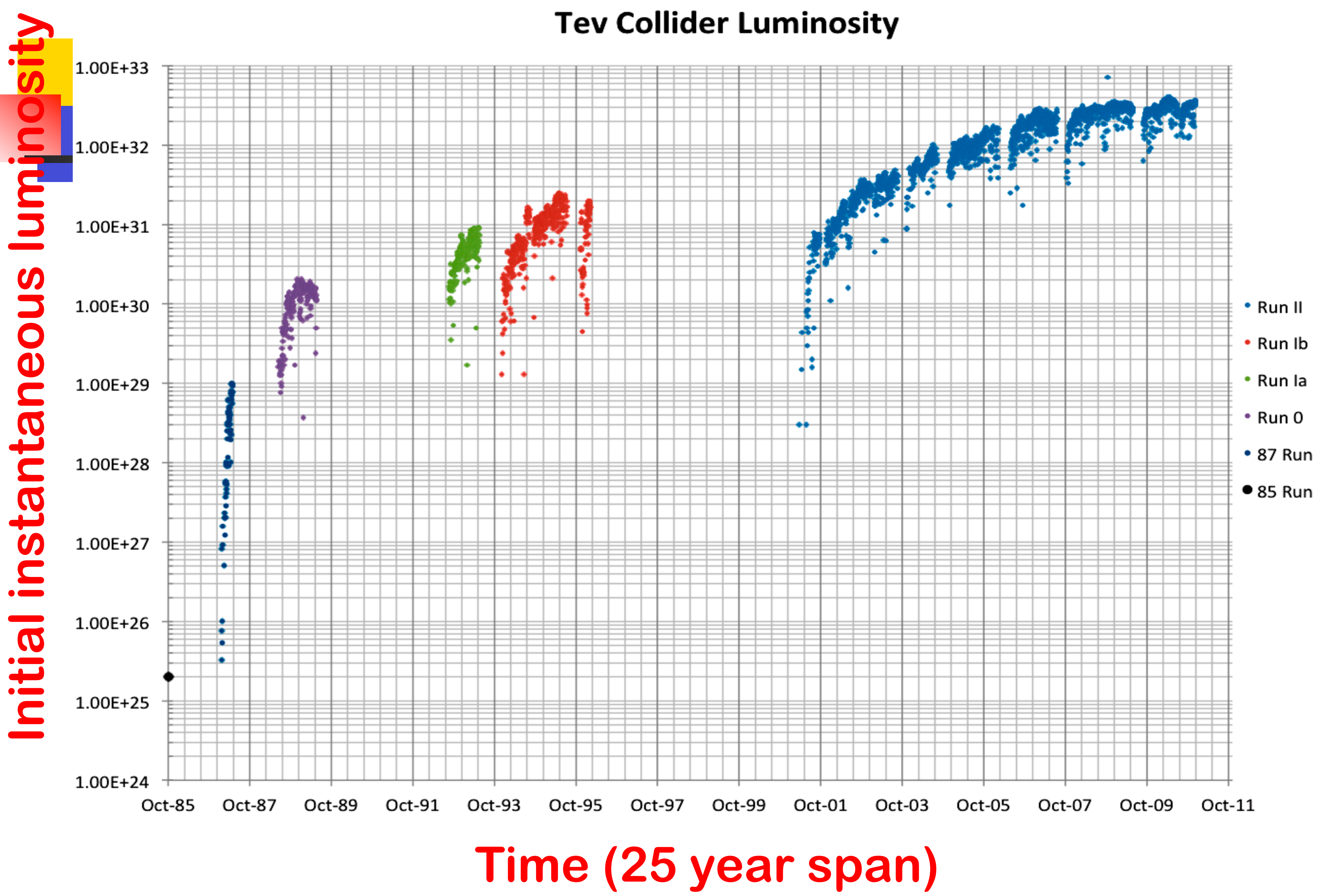


Run II accelerator performance

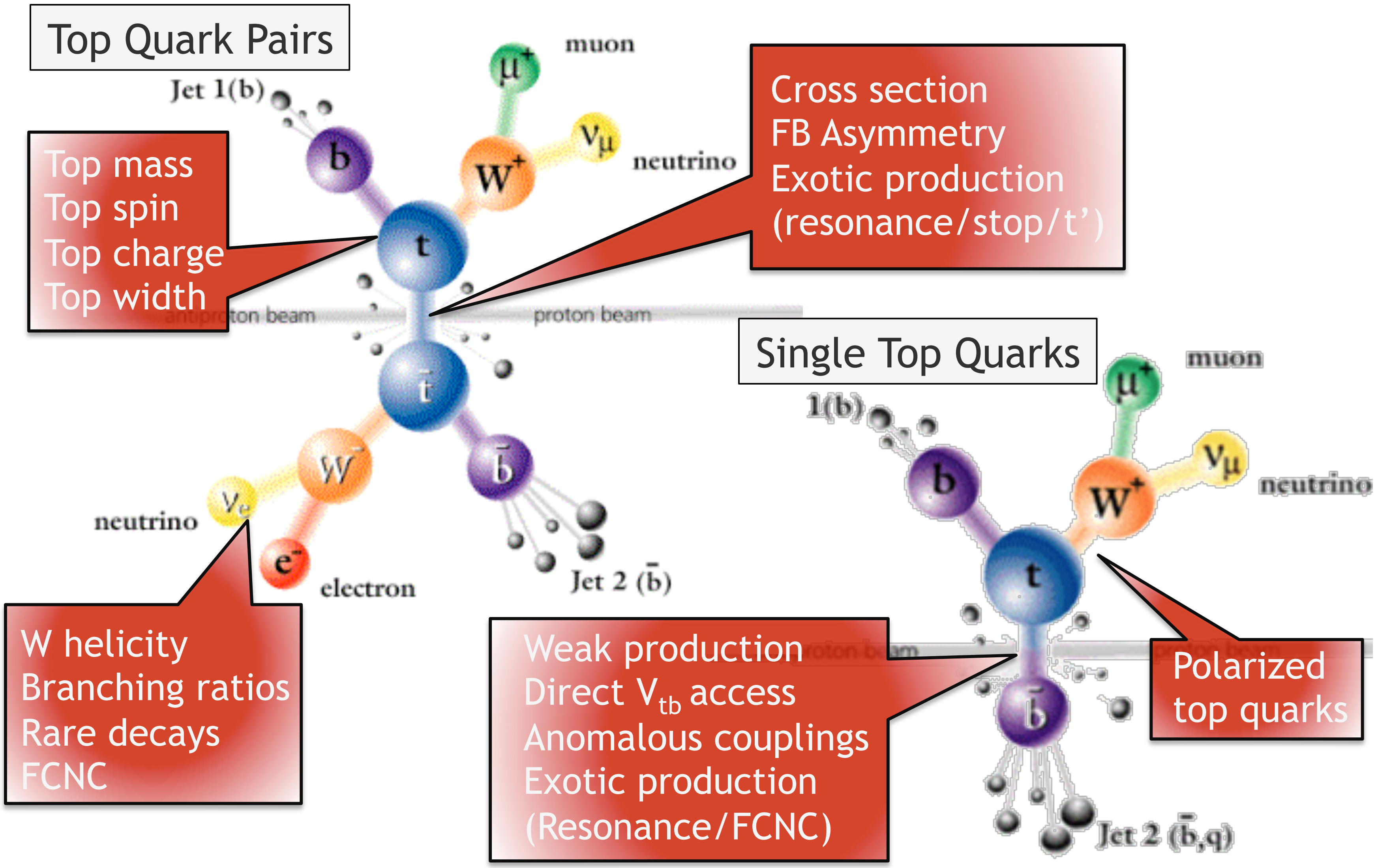




25 years of Luminosity



CDF Top Quark Physics Program

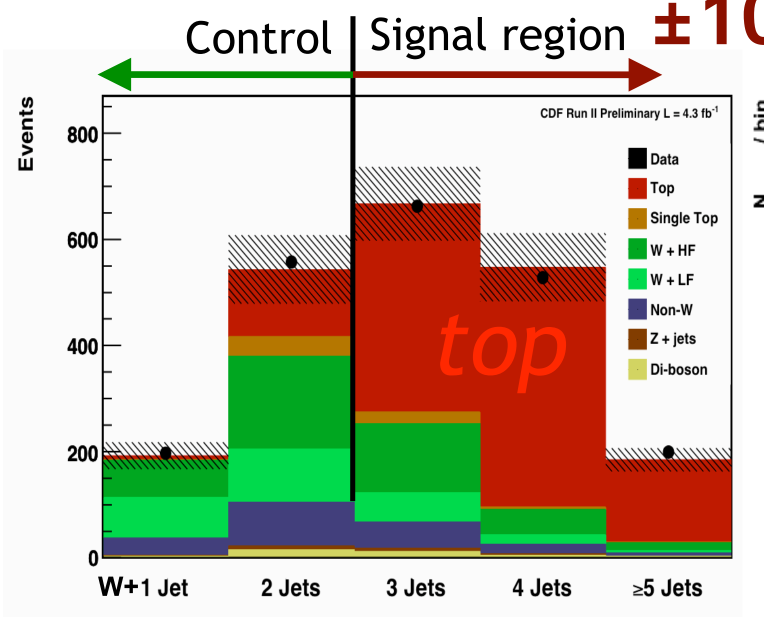


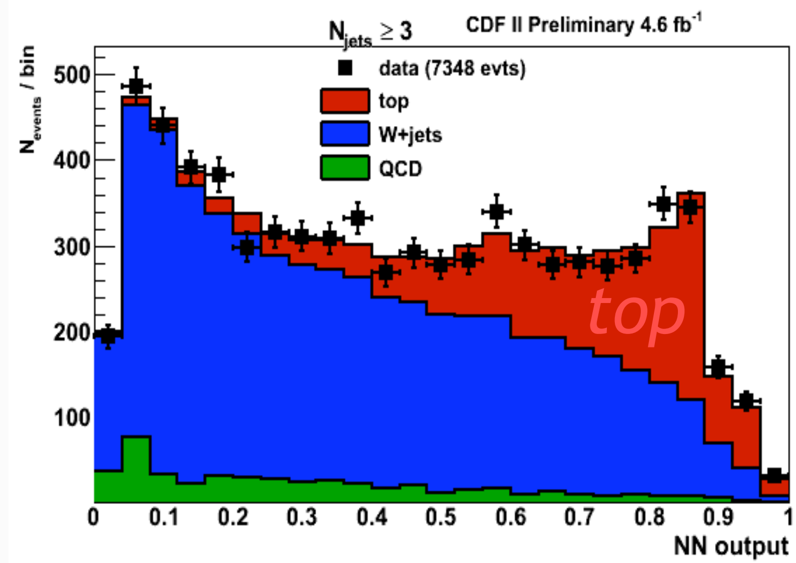
CDF program is systematically studying the physics of top quarks…

Top Cross Section

(Golden) Lepton + Jets Channel

±10% **±7%**





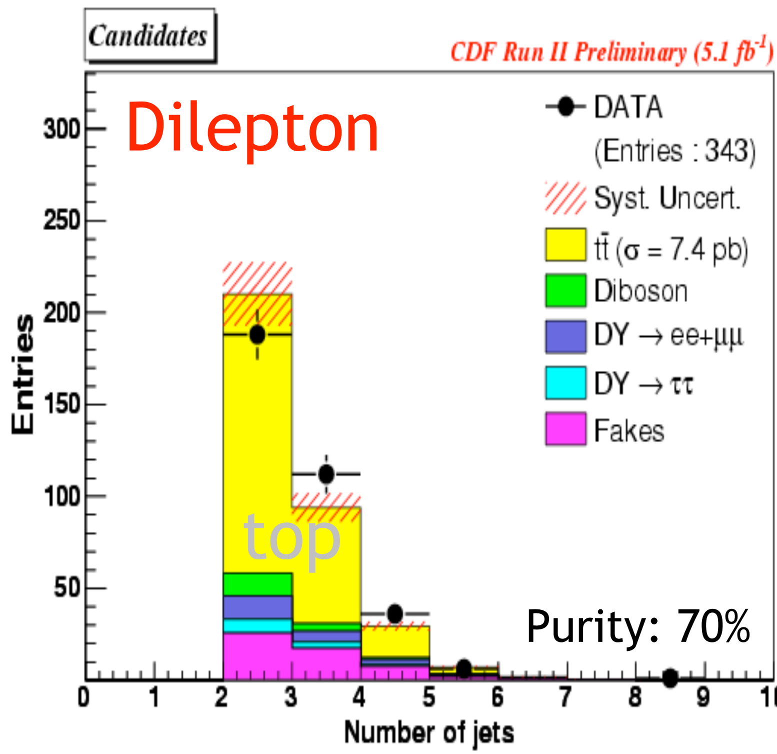
- Measure top using b-tagging *or* using topological Neural Network
- Luminosity is the largest uncertainty in both measurements
  - Reduced by normalizing to *Z cross section* $\sigma_{t\bar{t}} = R \bullet \sigma_Z^{theory}$

CDF (4.3 fb^{-1}, m_t= 172.5 GeV), b-tagged:	CDF (4.6 fb^{-1}, m_t= 172.5 GeV), topo NN:
σ_{tt}=7.32±0.35(stat)±0.59(syst)±0.14(Z_{theo}) pb	**σ_{tt}=7.8±0.4(stat)±0.4(syst)±0.15(Z_{theo}) pb**

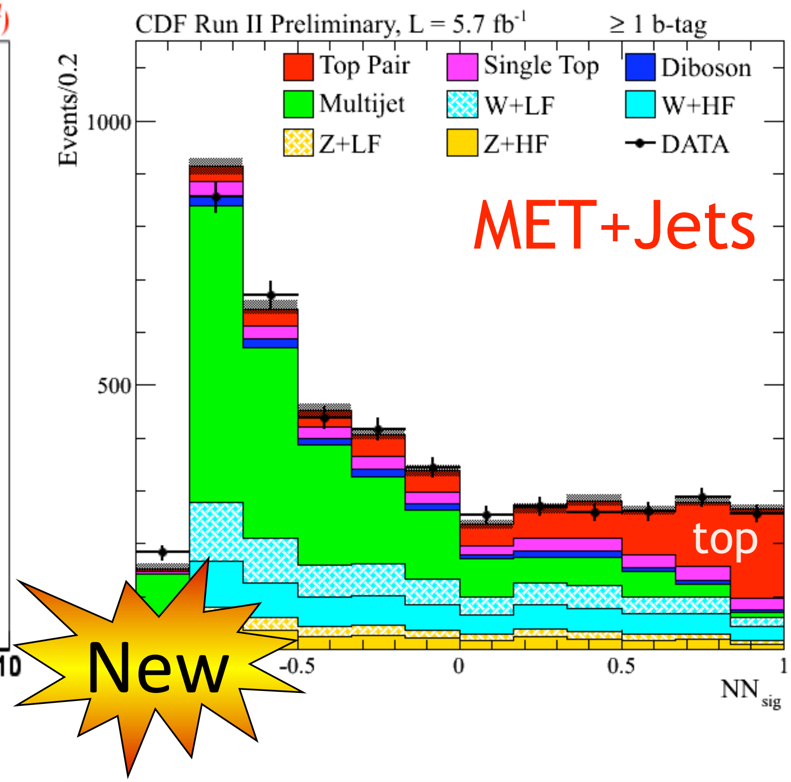
Top Cross Section

Dilepton Channel and MET+Jet Channel

±13%



±17%



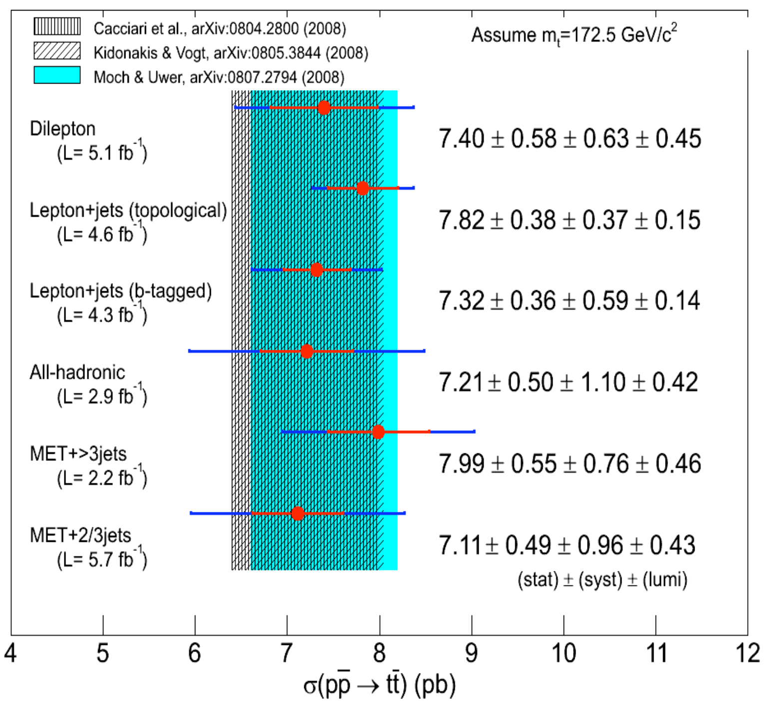
CDF (4.5 fb^{-1}, m_t= 172.5 GeV)
σ_{tt} = 7.4±0.6(stat)±0.6(syst)±0.5(lumi) pb

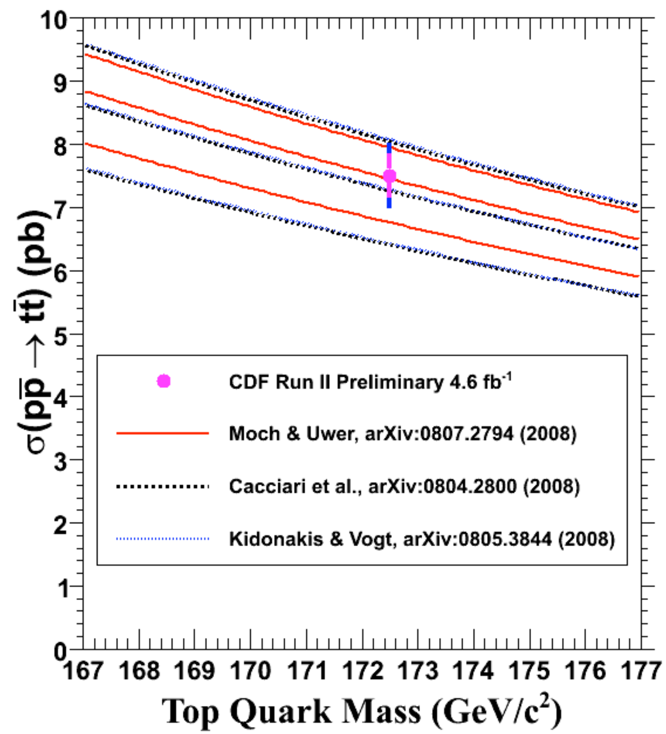
CDF (5.7 fb^{-1}, m_t= 172.5 GeV)
$\sigma_{tt} = 7.12^{+1.20}_{-1.12}$(stat+syst) pb

Top Cross Section

CDF Combination

±6%



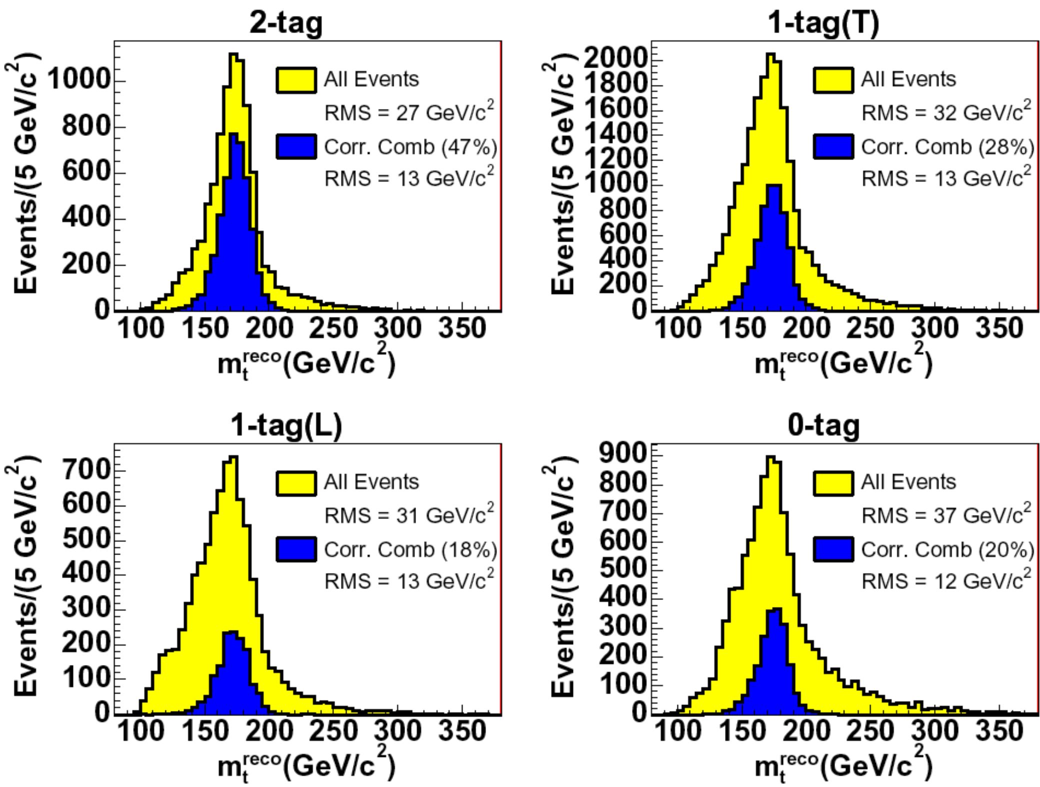


CDF Combined (4.6 fb^{-1}, m_t= 172.5 GeV)
σ_{tt} = 7.5±0.3(stat)±0.3(syst)±0.15(Z_{theo}) pb

Good agreement with Standard Model in all channels

Top Mass – state of the art!

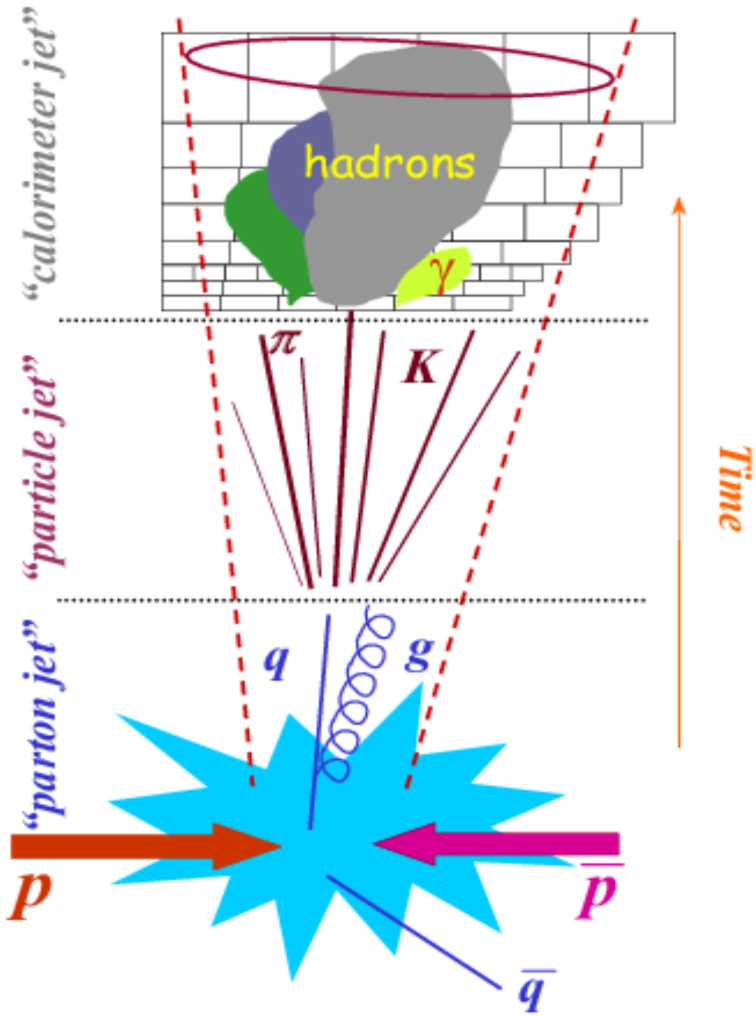
- 4 jets, 1 lepton and missing E_T
  - Which jet belongs to what?
  - Combinatorics!
- B-tagging helps:
  - 2 b-tags =>2 combinations
  - 1 b-tag => 6 combinations
  - 0 b-tags =>12 combinations
- Two Strategies:
  - Template method:
    - Uses "best" combination
    - Chi2 fit requires m(t)=m(t)
  - Matrix Element method:
    - Uses all combinations
    - Assign probability depending on kinematic consistency with top



Selecting correct combination 20-50% of the time

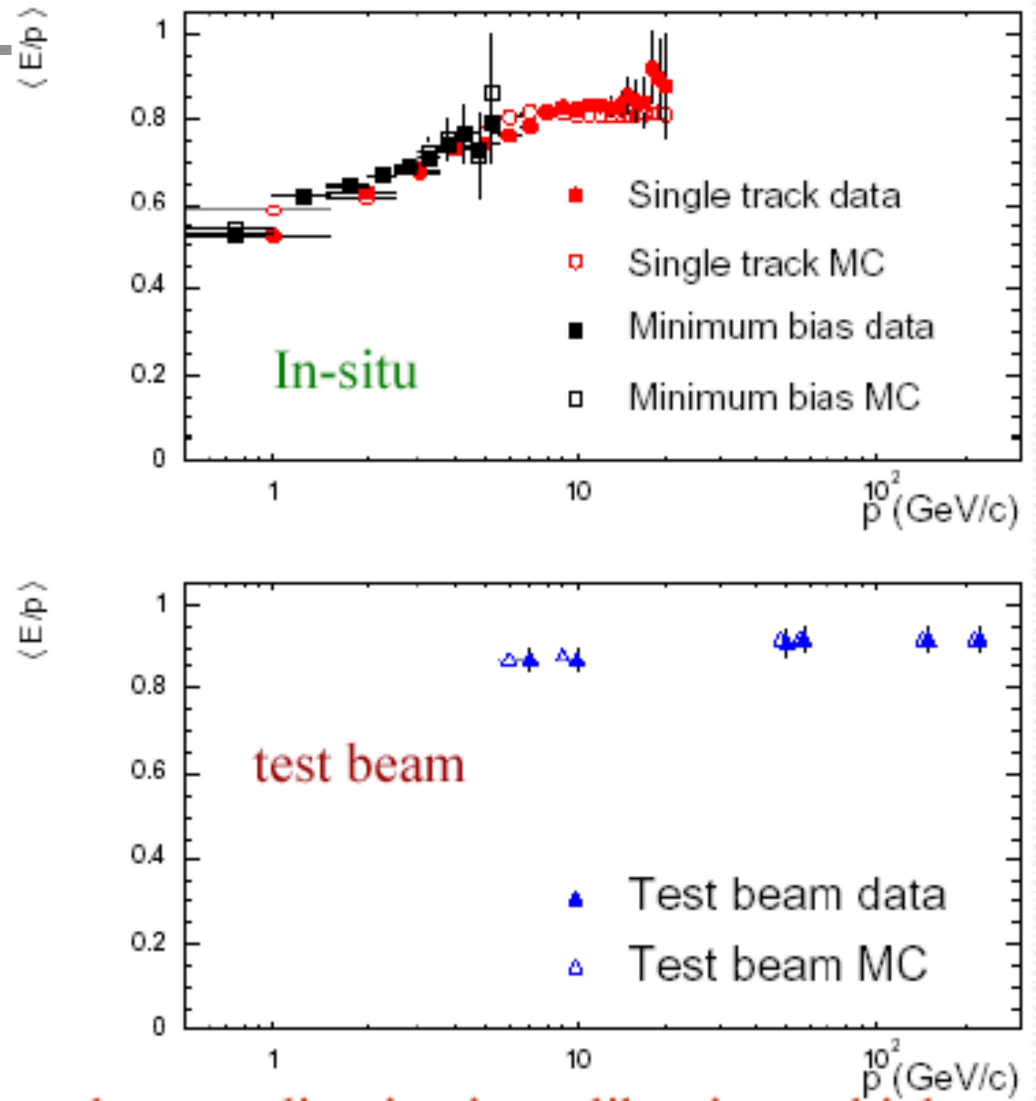
Jet Energy Scale Composition

- Jet energy scale
  - Determine the energy of the partons produced in the hard scattering process
  - Instrumental effects:
    - Non-linearity of calorimeter
    - Response to hadrons
    - Poorly instrumented regions
  - Physics effects:
    - Initial and final state radiation
    - Underlying event
    - Hadronization
    - Flavor of parton
- Test each in data and MC

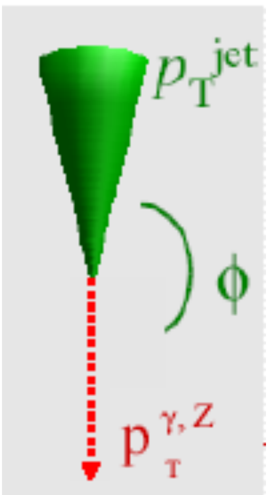


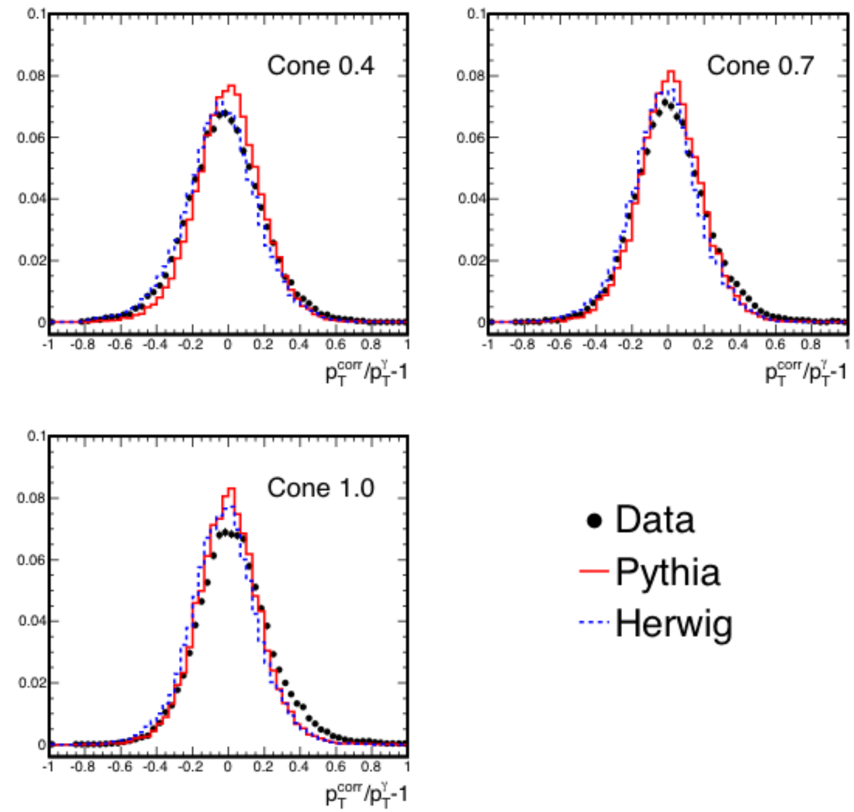
JES Studies

- Measure energy response to charged particles
  - Test beam and in situ
  - CDF: Response rather non-linear
  - DØ: compensating =>has better response
    - Some compensation "lost" due to shorter gate in run 2
- CDF uses fast parameterized showers:
  - Tuned to data
- DØ uses full GEANT



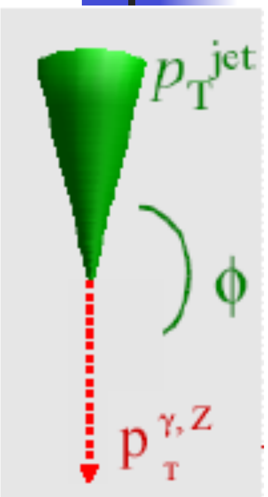
Testing Jets in Photon-Jet Data

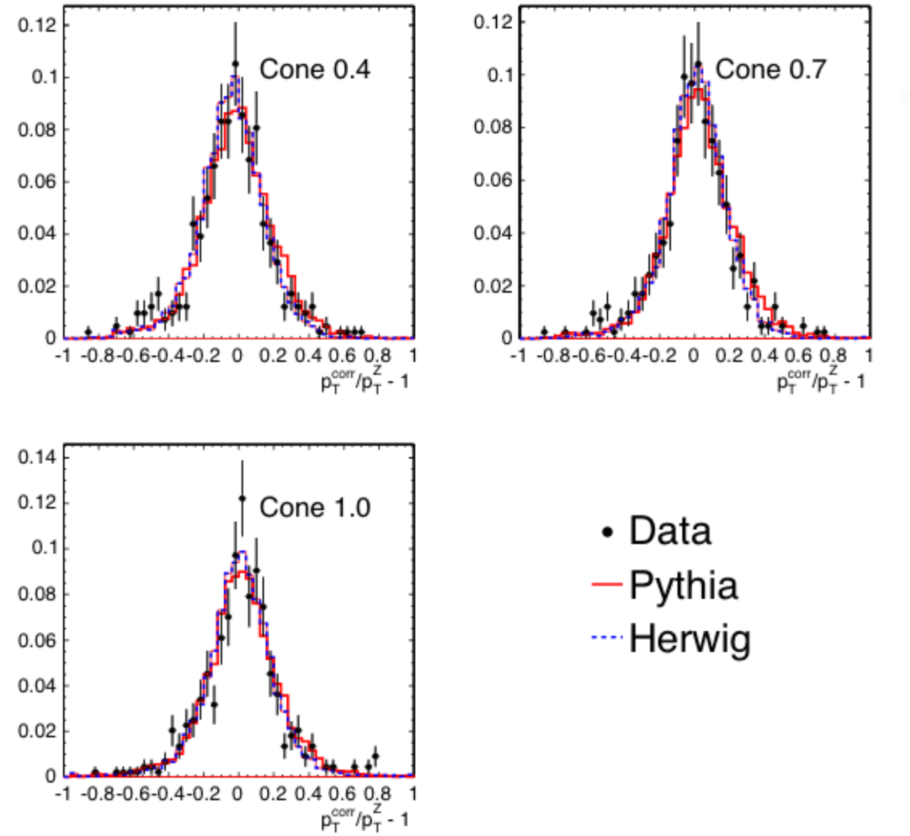




- Agreement within 3% but differences in distributions!
  - Data, Pythia and Herwig all a little different
- These are difficult physics effects to get right!

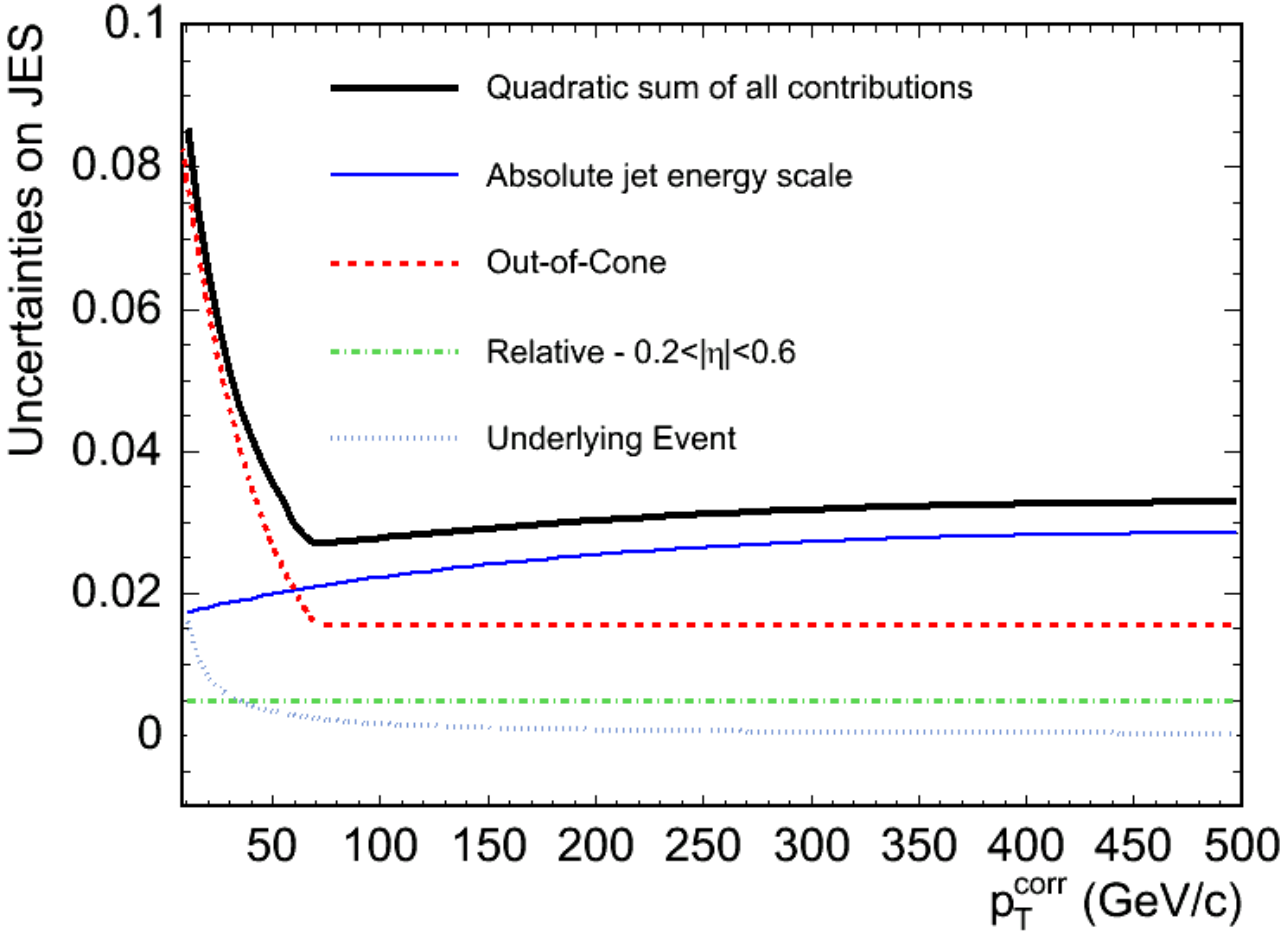
Testing Z+jet data





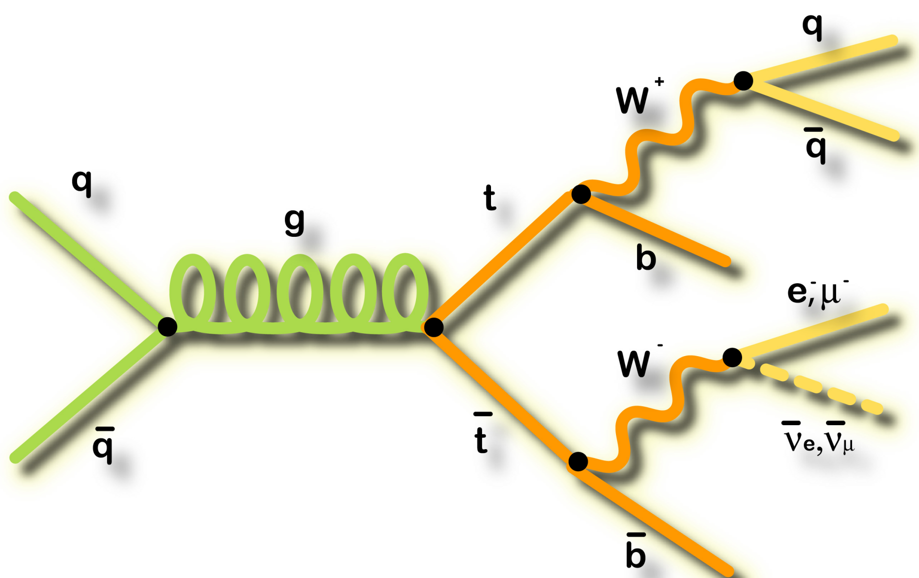
- Better agreement of data and MC than in photon-jet data
  - This is an older plot – worked with Herwig and Pythia authors and improved this further

JES Uncertainties



In-situ Measurement of JES

- Additionally, use W→jj mass resonance (M_{jj}) to measure the jet energy scale (JES) uncertainty

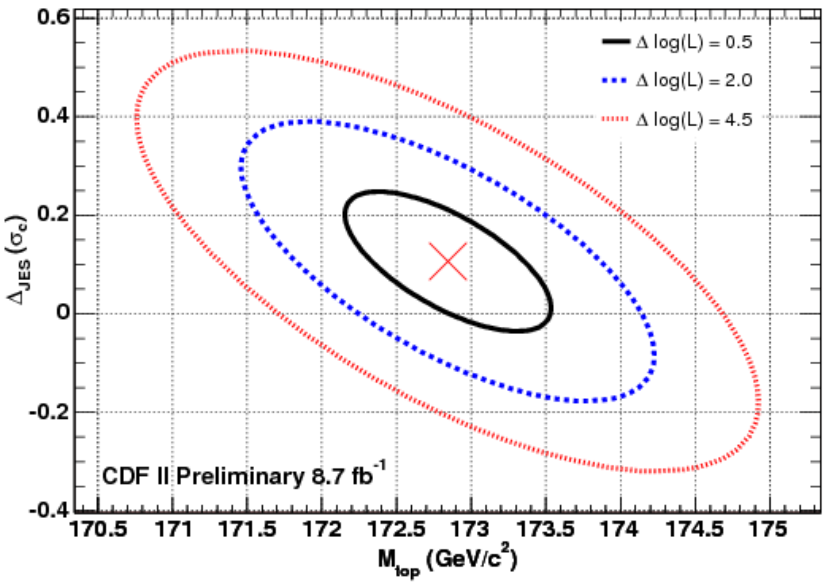


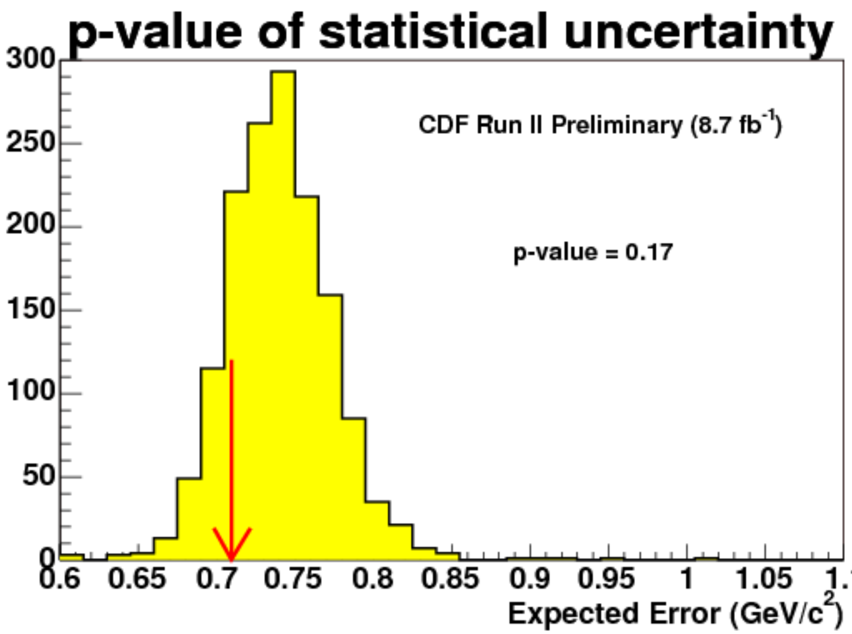
2D fit of the invariant mass of the non-b-jets and the top mass:

JES $\propto$ M(jj)- 80.4 GeV/c^2

Measurement of JES scales directly with data statistics

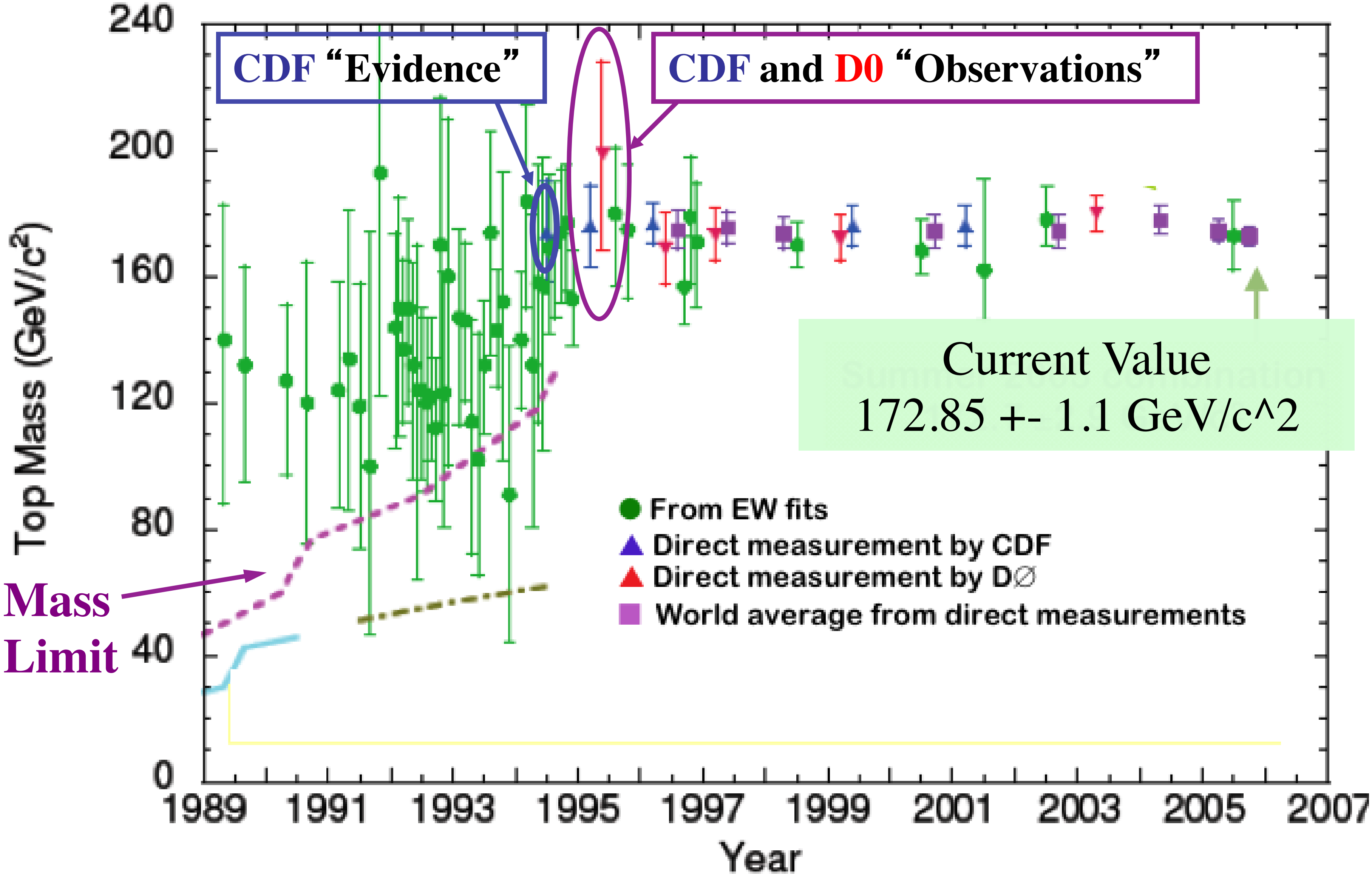
CDF Lepton+Jets Mass





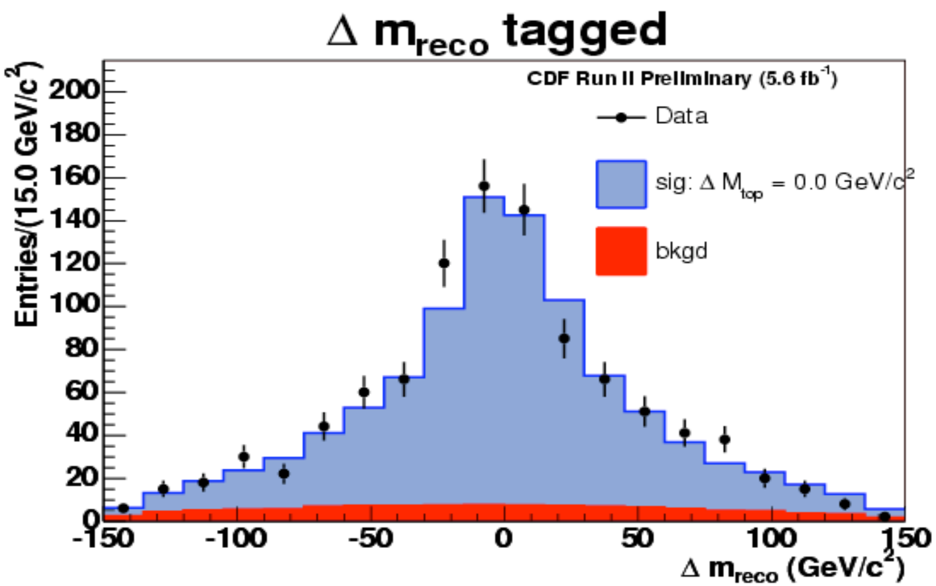
- M_{top} = 172.85 +/- 0.71 (stat.+JES) +/- 0.84 GeV/c^2 (syst)
- 172.85 +/- 1.10 GeV/c

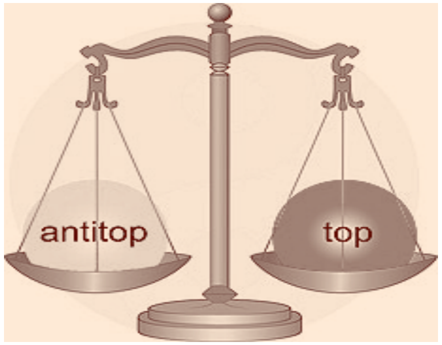
Top Mass vs. Year



Top Anti-Top Mass Difference

- If *CPT is a good symmetry of nature:* $\Delta M_t = M_{top} - M_{anti\text{-}top} = 0$





Only measurement for a "bare quark"

Consistent with SM expectations

CDF (5.6 fb^{-1}):
ΔM_t=-3.3 ±1.4(stat)±1.0(sys)GeV

statistics limited

Start of Lecture 2…

- A few thoughts from yesterday
  - While progress seems slow – the field of HEP has made tremendous progress in the last 15 years
  - Think about how the world has changed -- top, higgs, neutrino's have mass, dark energy and dark matter, ….
  - Tools and approaches continue to improve as we advance our field
  - What you are doing now will look to you as very rudimentary a decade from now
  - We will surpass your expectations in time!!!

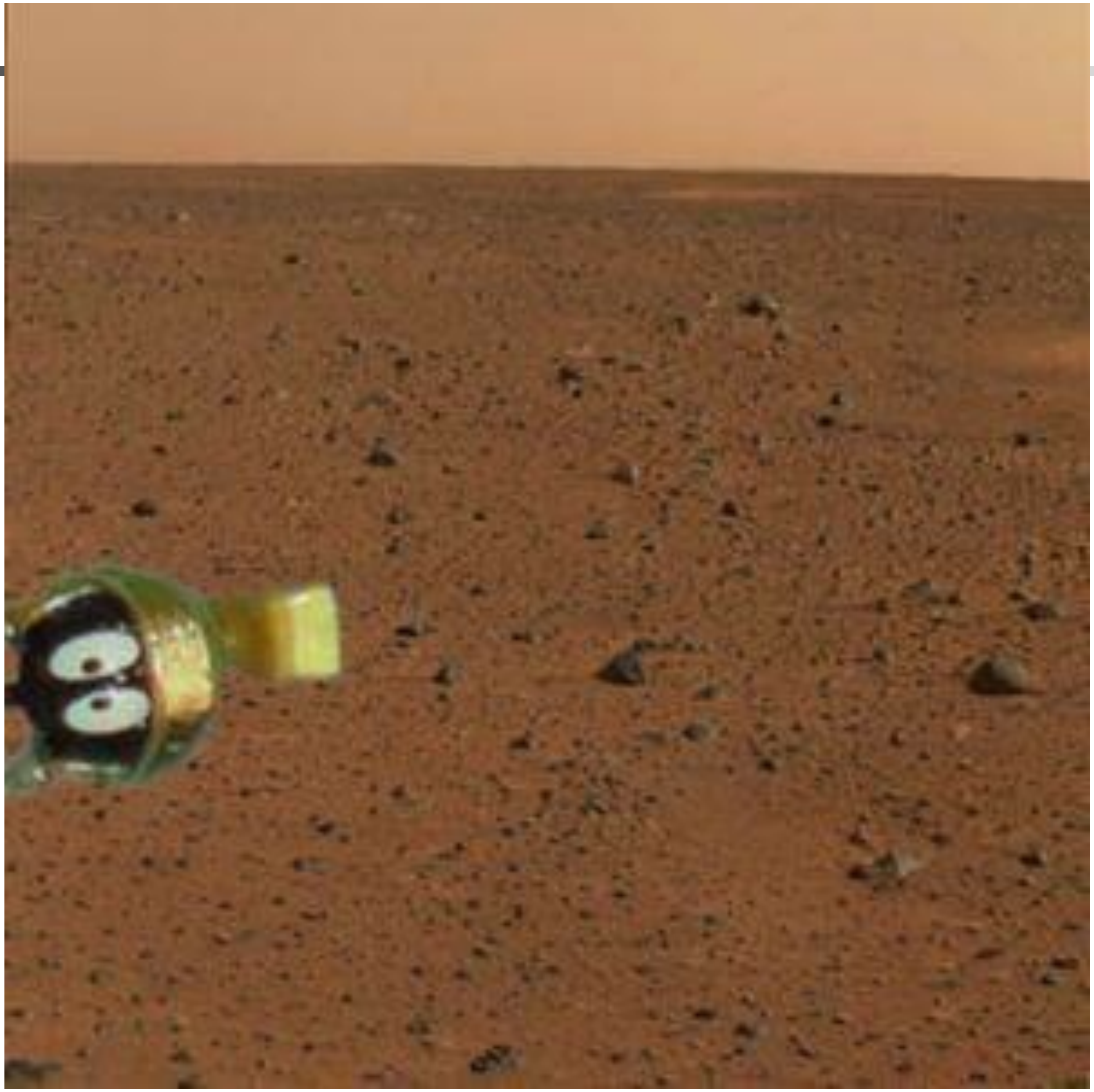
Books on HEP Discoveries

- **Nobel Dreams** by Gary Taubes
  - Discovery of the W,Z bosons and Carlo Rubbia's group
- **The Evidence for the Top Quark** by Kent Staley
  - Philosophy discussion of discovery in science but most of the book looks at CDF's process for the Evidence and Observation papers

Breaking News

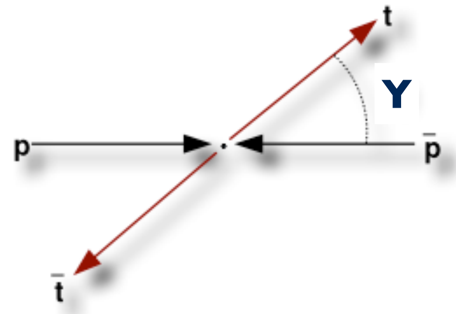
- “Curiosity” -- NASA launched Mars Rover successfully landed on Mars today
- Its about the size of a small car
- On board lab is very sophisticated

First photo



Top Forward/Backward Asymmetry

Why Measure it?



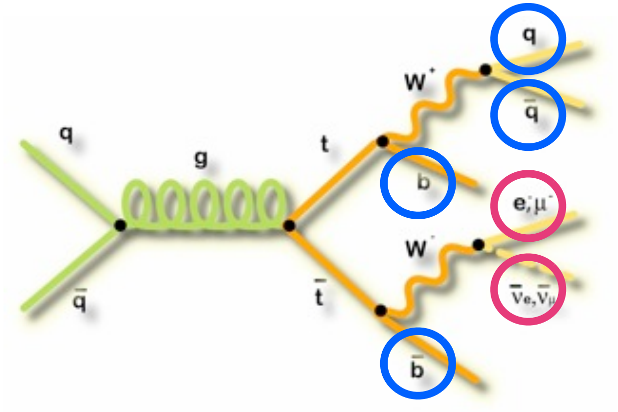
- **Test of discrete symmetries of the strong interaction**
- **NLO QCD predicts small (~6%) asymmetry from $q\bar{q} \rightarrow t\bar{t}$**
- **New physics can show up: Big Gluons with axial vector coupling**

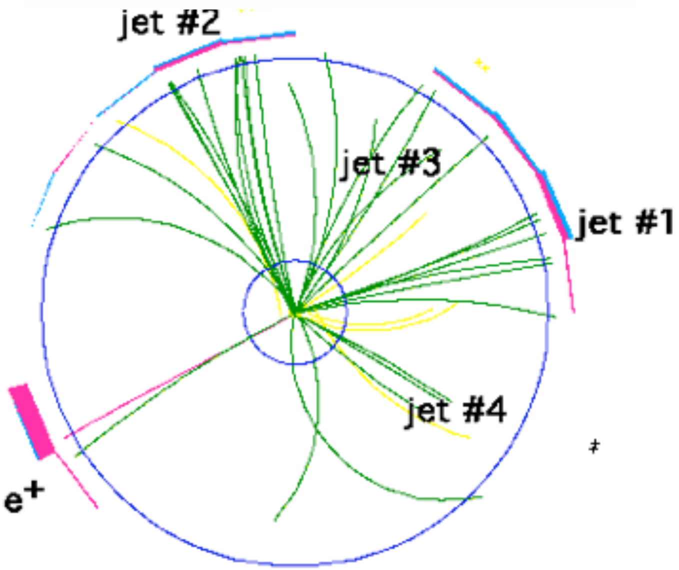
$$A_{FB} = \frac{\mathbf{F} - \mathbf{B}}{\mathbf{F} + \mathbf{B}}$$

Methodology

- **Extract $t\bar{t}$ events from data collected at CDF**
- **Reconstruct the production angle of top in these events**
- **Correct for any distortion from the detector, background processes, and the method of reconstructing the angle**
- **Measure A_{FB}**

Reconstructing the Top Direction

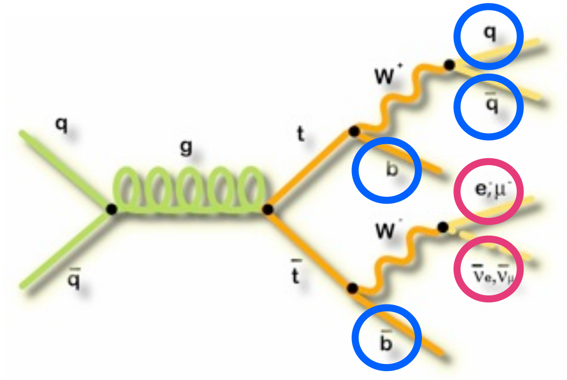


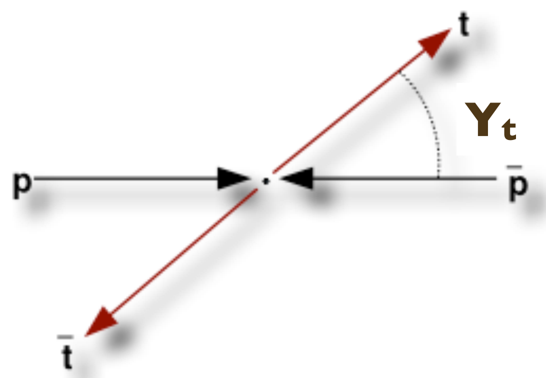


- Reconstruct the top direction from the observables in the detector
- Algorithm used to match jets to partons ➔ just add 4-vectors to get top direction
- We use the rapidity difference (ΔY) of $t \to l\nu b$ and $t \to jjb$, which is proportional to Y_t in $t\bar{t}$ frame

$$Y_t \propto q_{lepton} \cdot \Delta Y$$

Reconstructing the Top Direction





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$$Y_t \propto q_{lepton} \cdot \Delta Y$$

$$\Delta Y = q_{lep} \cdot (Y_{lep} - Y_{had})$$

Measurement

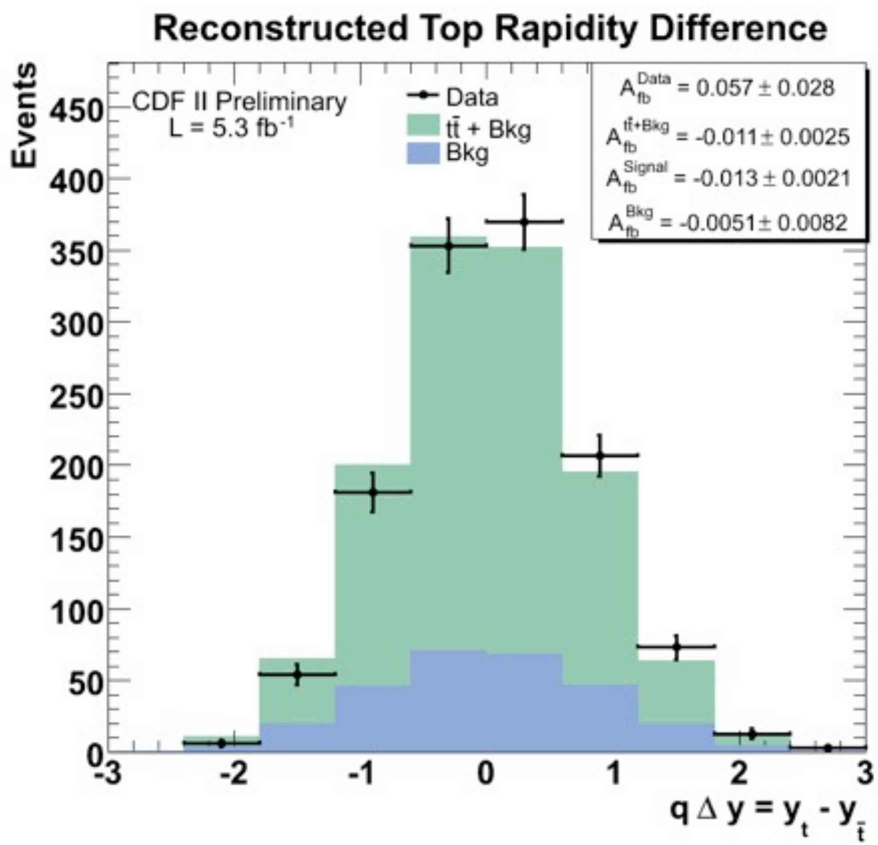
$A_{FB} = 16 \pm 7_{stat} \pm 2_{syst}$ %

5.3 fb^{-1}

Directly comparable to SM

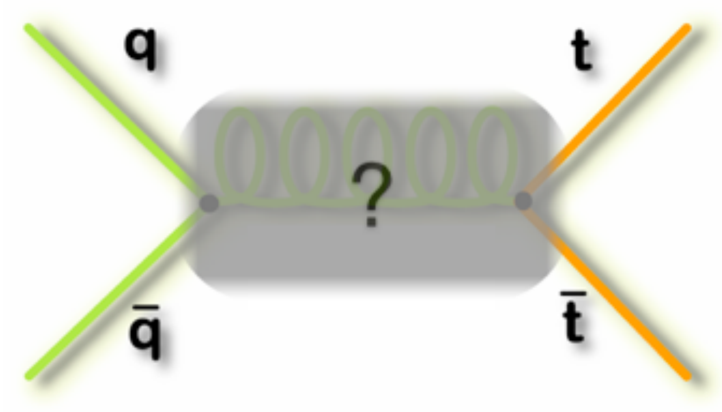
$A_{FB}^{Theory} = 6 \pm 1$ %

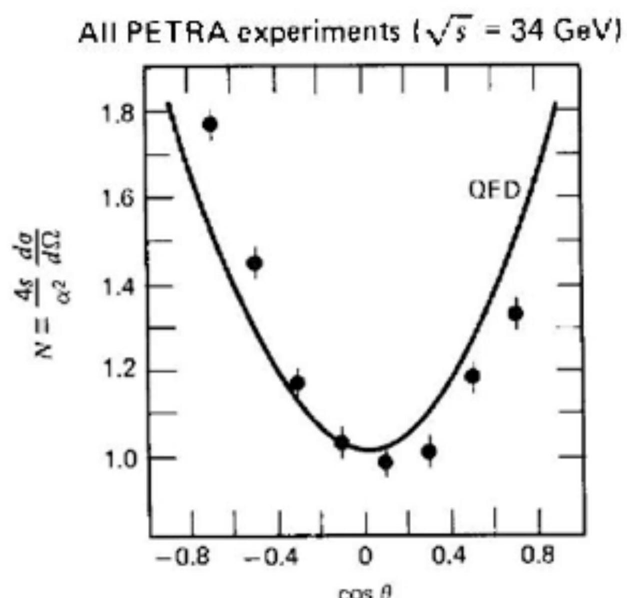
Kuhn, Rodrigo PRL 81,89 (1998)



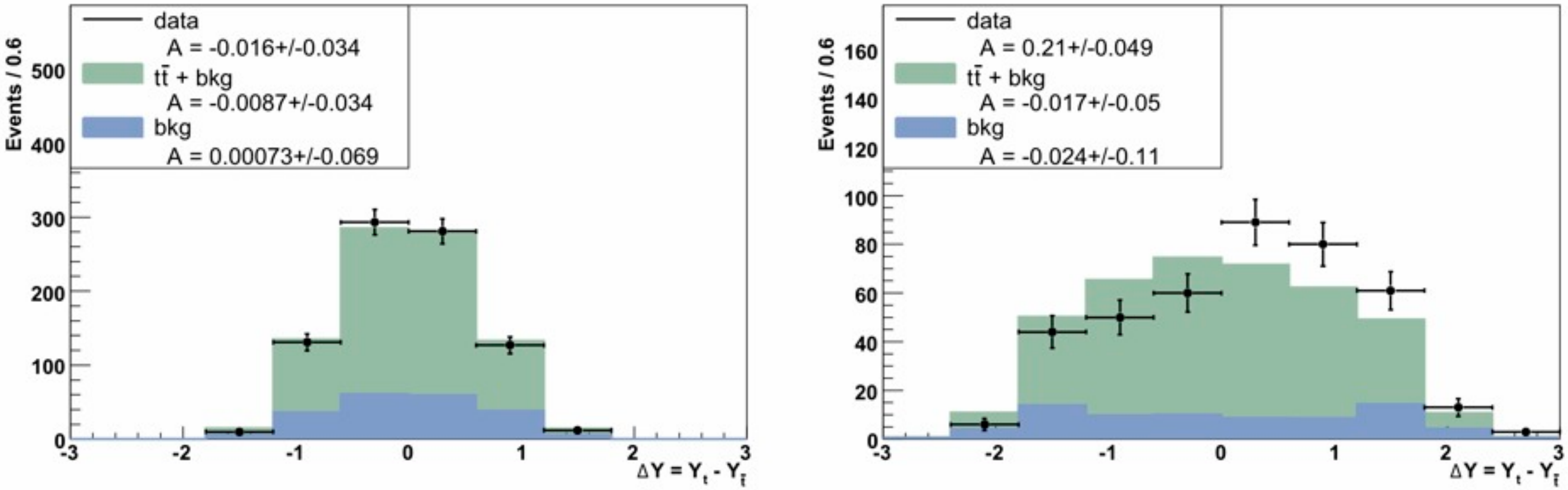
Mtt Dependence

- A_{FB} could increase at higher energy due to new production mechanisms
- Study the asymmetry vs. the mass of the $t\bar{t}$ system ($M_{t\bar{t}}$)
- Simply divide sample into high/low $M_{t\bar{t}}$
- Use 450 GeV → based on MC studies





Mtt Dependence



	Inclusive	M < 450 GeV	M > 450 GeV
Data	5.7 ± 2.8 %	-1 ± 3 %	21 ± 5 %
SM MC	2 ± 0.4 %	1 ± 0.6 %	3 ± 0.7 %

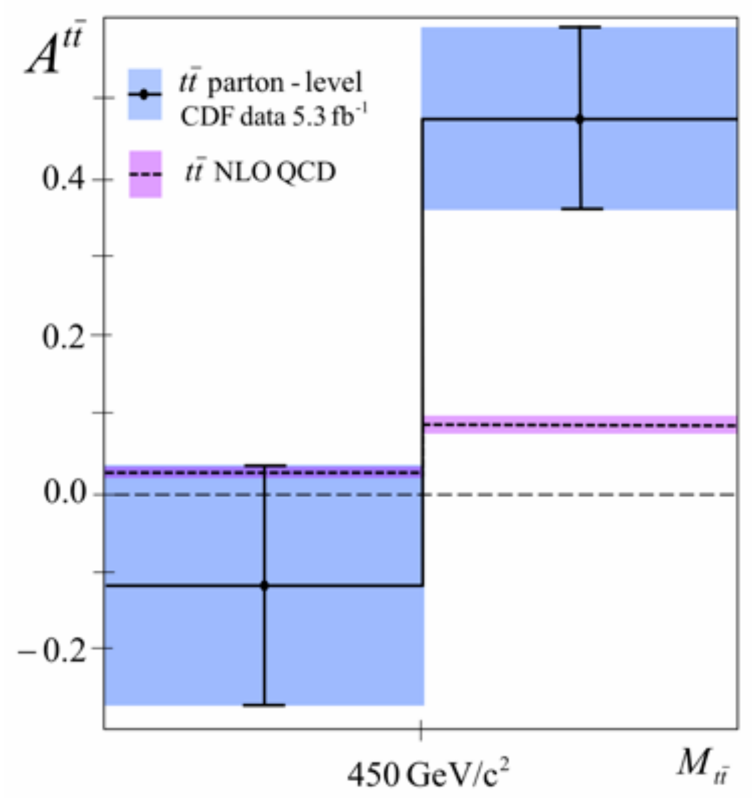
Mtt Dependence

- **Unfold M_{tt} dependence back to parton level**

$A_{FB} = 48 \pm 11_{stat+syst}$ %

5.3 fb^{-1}

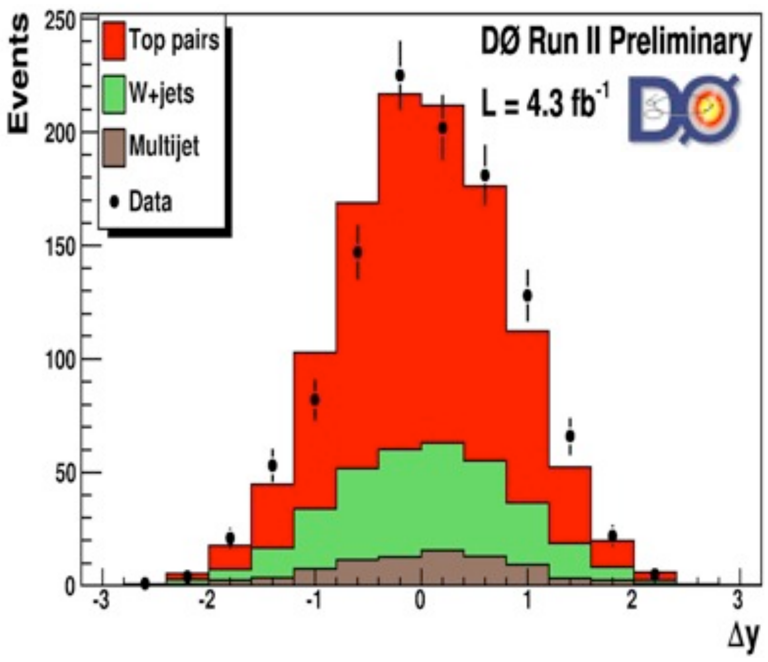
$A_{FB}^{Theory} = 9 \pm 1$ %



Anyone Else?

- DØ collaboration has also performed this measurement
- DØ compares the result to the SM as seen by the detector (only corrects for backgrounds)

$A_{FB}^{data-bkg} = 8 \pm 4_{stat+sys}$ %

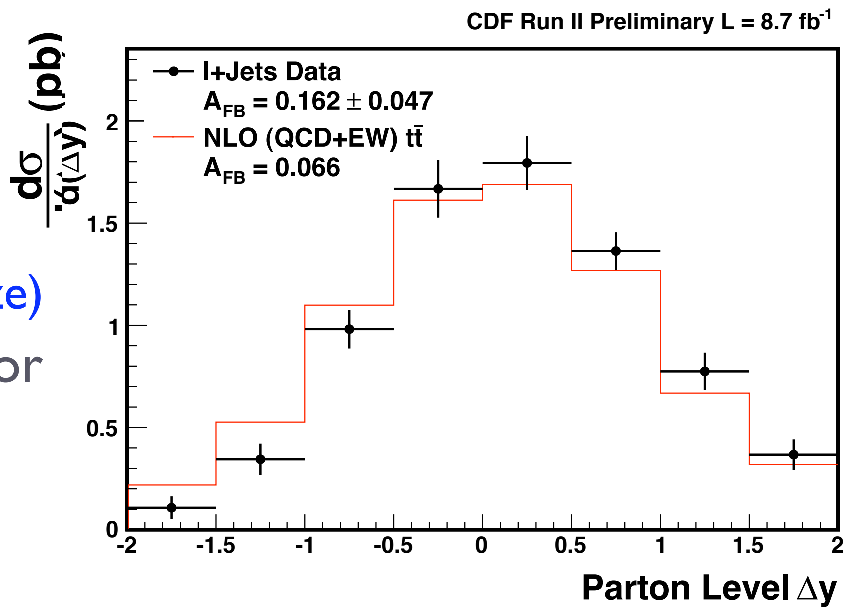


$A_{FB}^{mc@nlo} = 1^{+2.0}_{-1.0}$ %

$A_{FB}^{CDF} = 7.5 \pm 3.7$ %

Now with the full data set

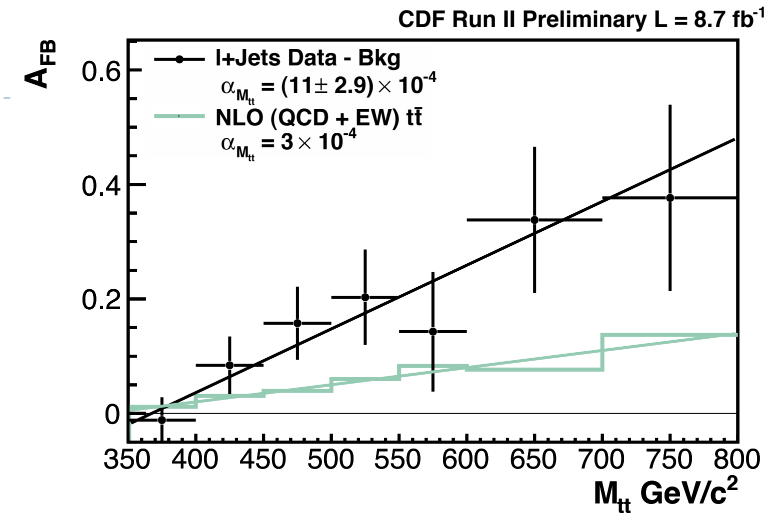
- Updates from CDF's 5.3 fb^{-1} lepton+jets analysis:
  - Add new data stream and increase luminosity to 8.7 fb^{-1}
    - 2498 events (double sample size)
  - Use NLO generator Powheg for signal modeling
  - Parton level shape corrections use regularized unfolding algorithm
    - Proper multi-binned measurement of rapidity and mass dependence
- Parton Level A_{FB}: 16.2 ± 4.7 %

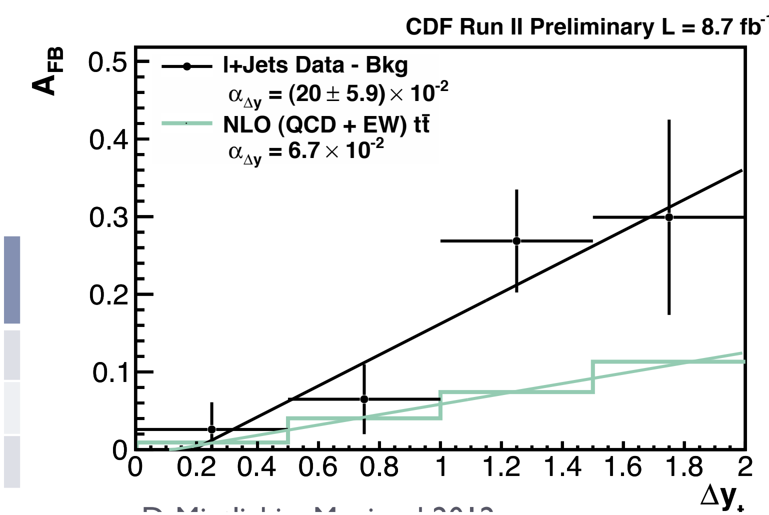


Mtt and Δy dependence (bckg subtracted)

- Predicted background contribution has been removed
  - Measure asymmetry in only top events
- No correction to parton level yet
  - No assumptions about the underlying physics
- Data well-described by linear ansatz – determine best-fit slope
  - χ^2/d.o.f ≤ ~1 for both Δy and M_{tt} dependence
- Determine p-value by comparing observed slope to NLO prediction
  - How often will NLO slope fluctuate to be at least as large as in the data?

Slope Parameter α	A_{FB} vs. M_{tt}	A_{FB} vs. Δy
Data	$(11.1 \pm 2.9)\times10^{-4}$	$(20.0 \pm 5.9)\times10^{-2}$
SM	3.0×10^{-4}	6.7×10^{-2}
p-value	0.00646	0.00892

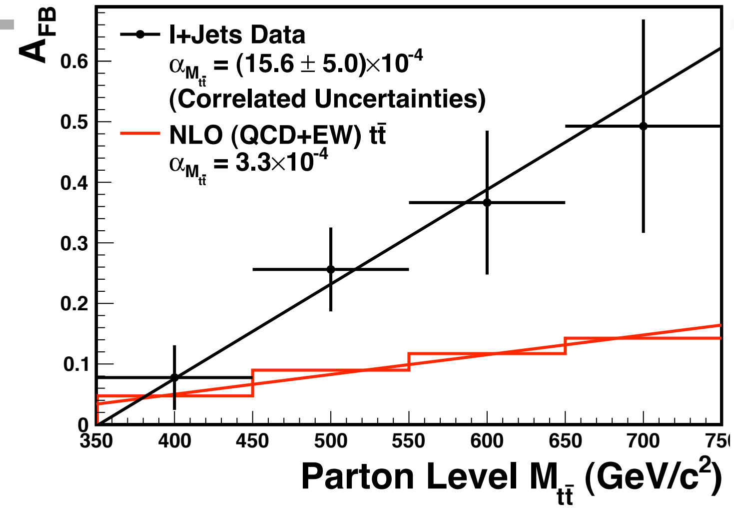


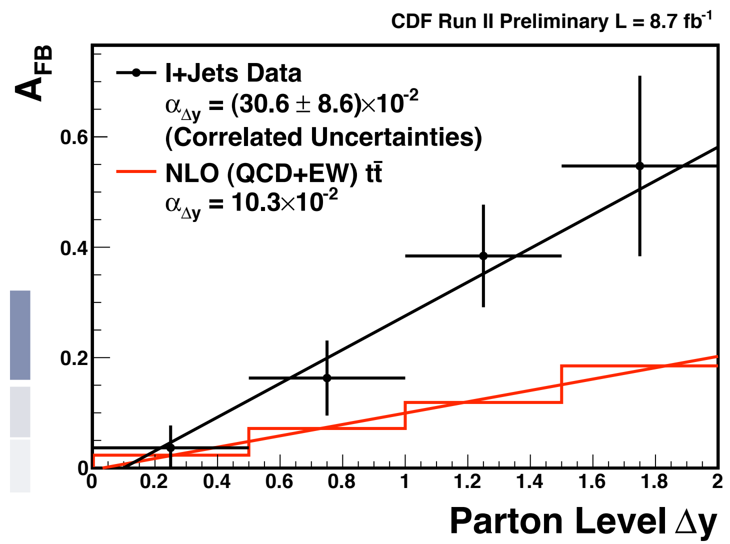


Correcting to the Parton Level

- Correct for acceptance and detector resolution
  - Regularized unfolding algorithm addresses resolution effects
  - Multiplicative acceptance correction factor applied to each bin
  - Both corrections use the NLO generator Powheg as the top model
- Parton level results can be compared directly to theory
- Determine best-fit slope for observed data and compare to NLO prediction

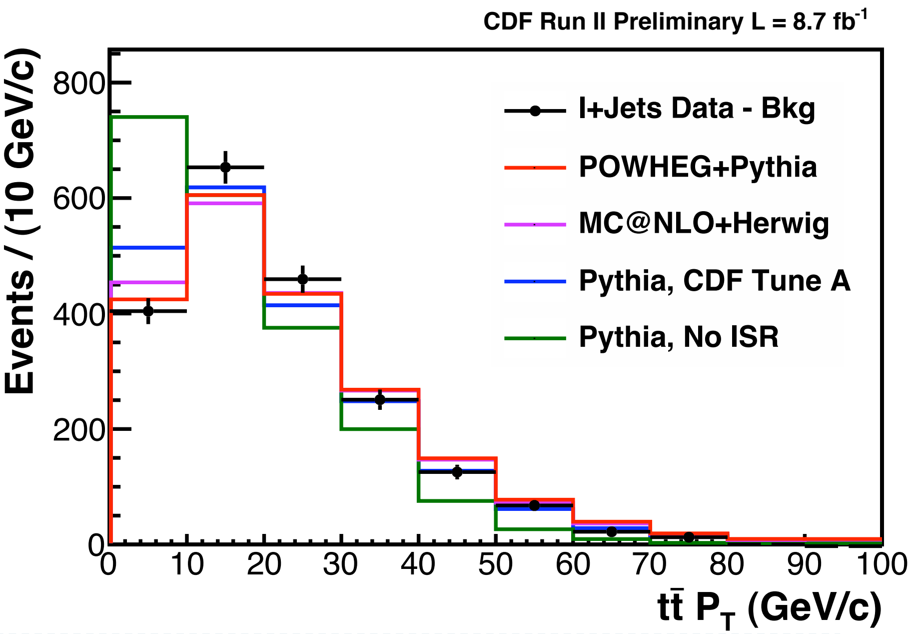
Slope Parameter α	A_{FB} vs. M_{tt}	A_{FB} vs. Δy
Data	$(15.6 \pm 5.0)\times10^{-4}$	$(30.6 \pm 8.6)\times10^{-2}$
SM	3.3×10^{-4}	10.3×10^{-2}





Obvious Culprits?

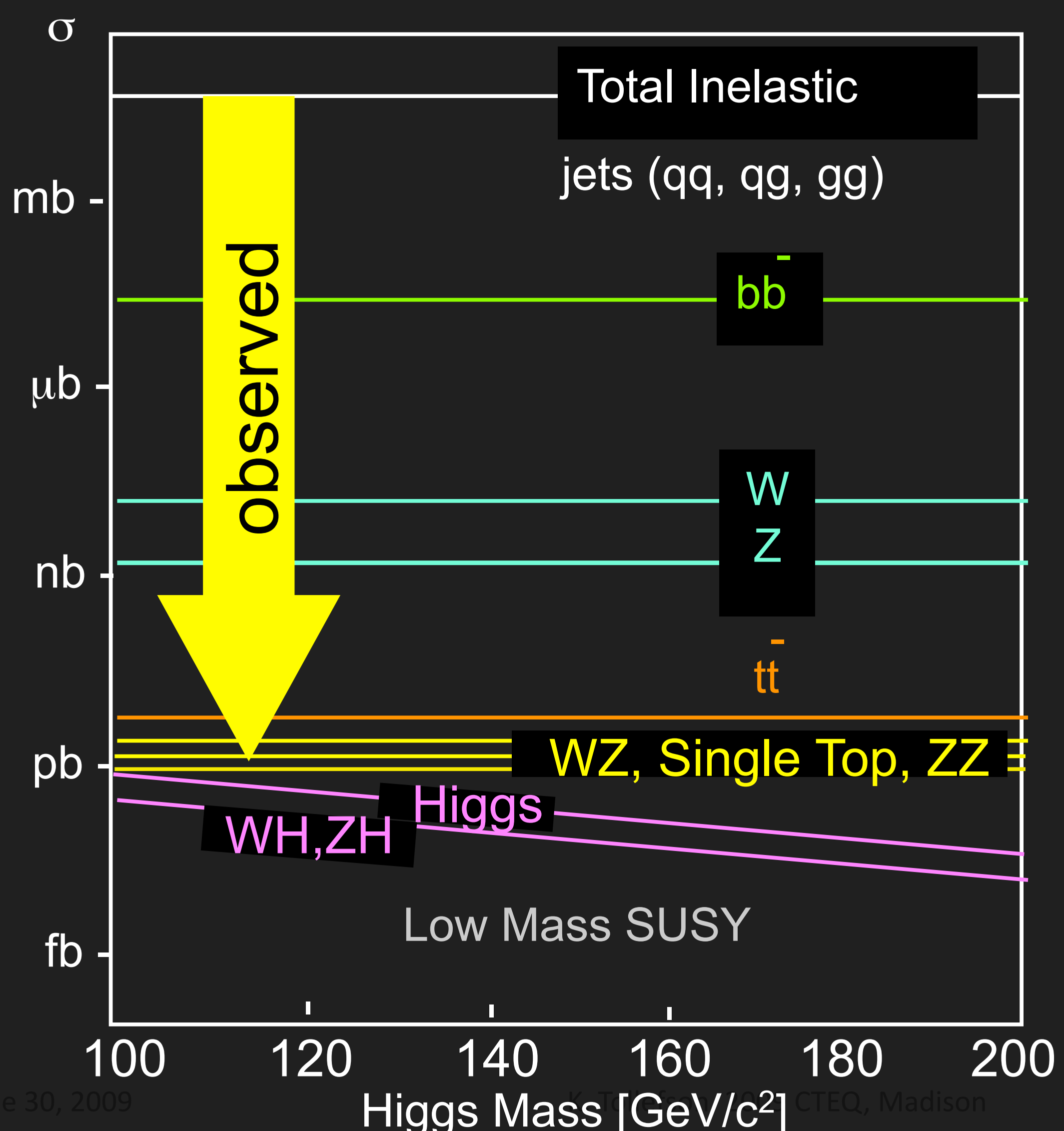
- Is it a problem with the current understanding of the SM?
  - Mis-modeled top pair P_T spectrum?
  - Higher order corrections?
- Is it new physics?
  - Many new models have been proposed
    - Axigluon, Z-prime, W-prime, …
  - Other top properties measurements can help differentiate between the possibilities
    - Differential cross-section in M_{tt}
    - Top spin or polarization



What you Shouldn't worry about!

- Backgrounds
  - Too small, and the predicted asymmetry in backgrounds goes in the opposite direction
- Reconstruction
  - If it's broken, it's broken for MANY precision measurements that agree with the SM and other well-vetted techniques
- Unfolding
  - The significance of the result is present before the acceptance/reconstruction corrections - they only scale the result

On the Road to Higgs



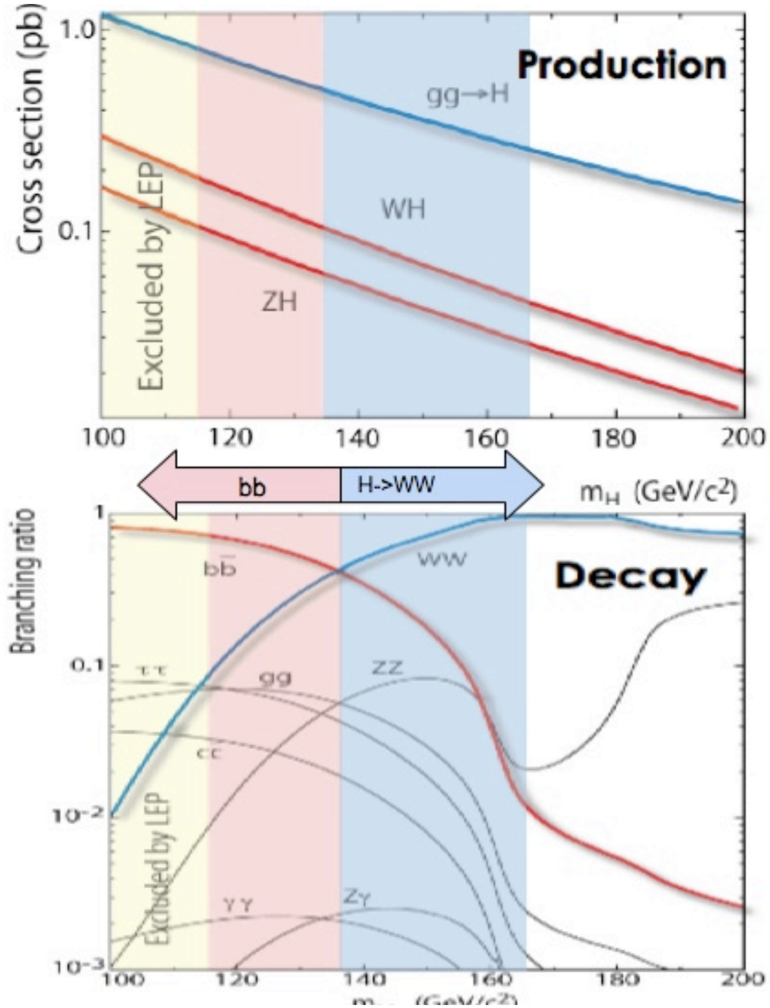
M_W ~ 0.05%

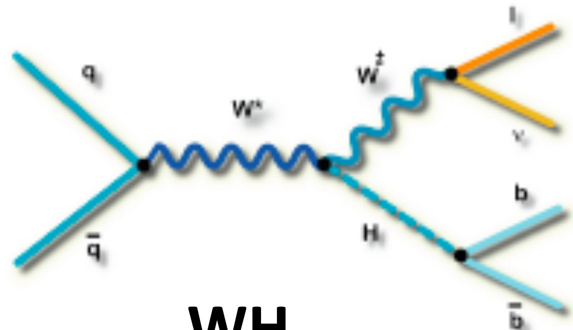
M_{top} ~ 0.7%

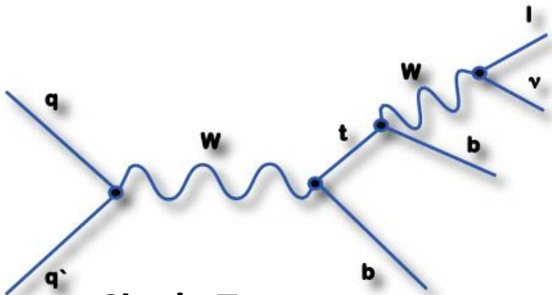
Observed WZ, ZZ and Single Top

Excluded $160 < M_{Higgs} < 170$ GeV at 95% CL

SM Higgs and Single Top





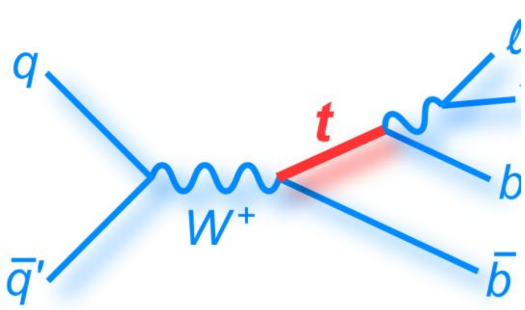


Single Top

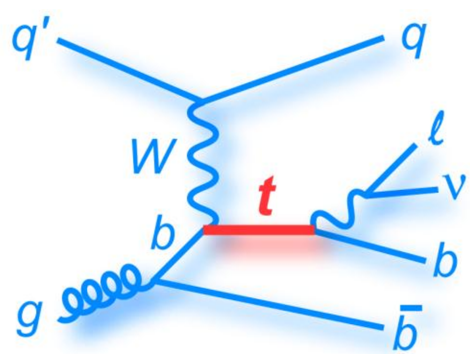
Single top is large background to low mass Higgs searches.

Single Top Production

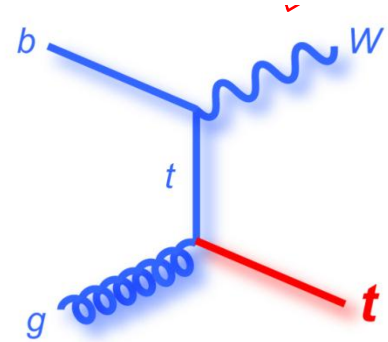
Small at Tevatron



s-channel production



t-channel production

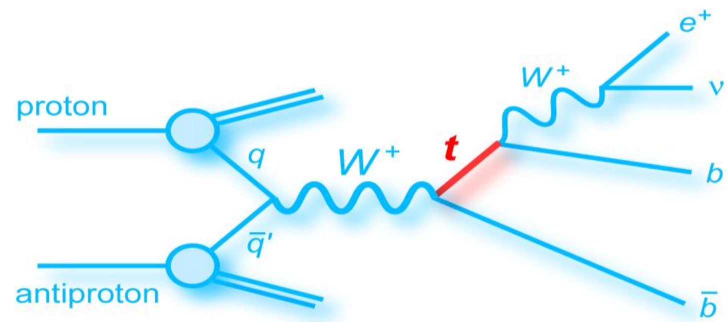


Associated Wt production

- Motivation:
  - Direct measurement of CKM matrix element $|V_{tb}|$ ($\sigma_{s+t} \sim |V_{tb}|^2$)
  - Sensitive to New Physics (FCNC, W'…) and CP violation
  - Additional channel for top quark properties study
- Experimental challenge:
  - Extract small signal out of a large background with large uncertainty

Event Signature

- Main analysis channel: Lepton+Jets
  - Only one isolated lepton
  - Large missing Et from neutrino
  - At least 2 jets
  - At least one of the jets is b-tagged

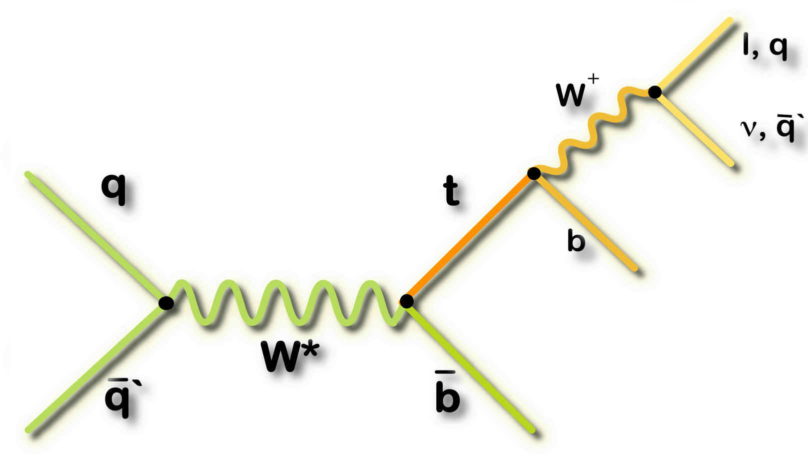


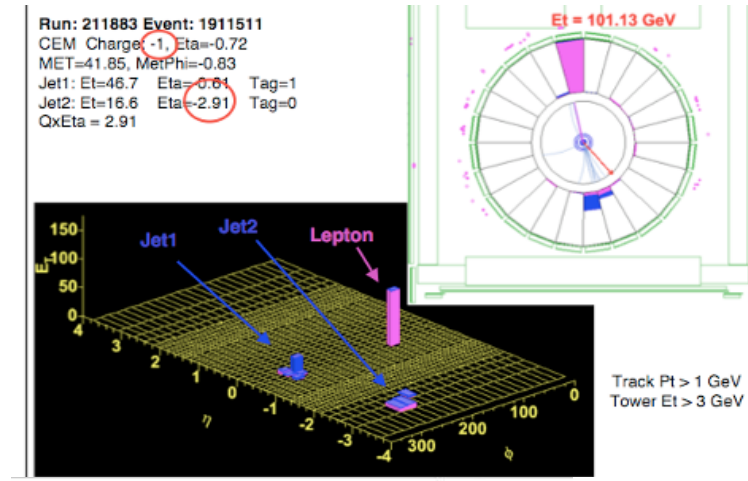
- Background rejection:
  - CDF: Veto QCD, Dilepton, Z and Cosmic
  - D0: Cut on scalar sum (H_T and H_T(alljets)) to suppress QCD and soft-scattering processes
- Still large backgrounds share similar final state after the background rejection.

t-channel
s-channel
W+jets
Z+jet, dibosons
tt
Multijets

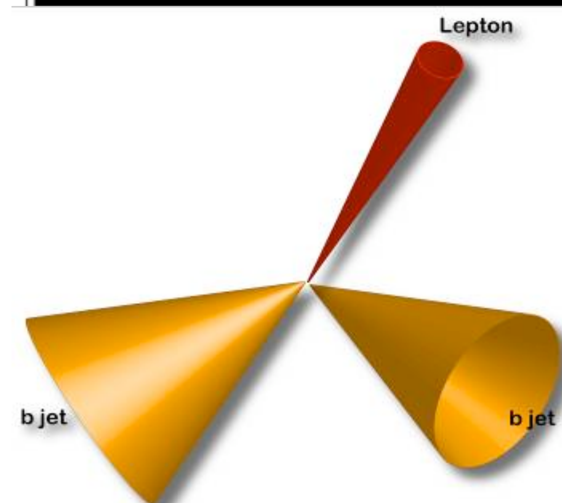
Single Top Event Signature

Top Pair Production with decay into Lepton + 4 Jets final state are very striking signatures!



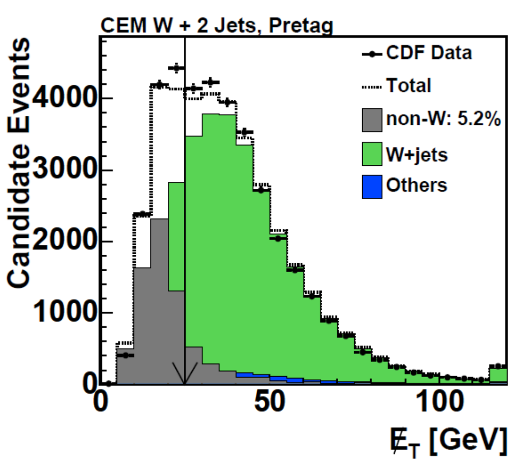


Single top Production with decay Into Lepton + 2 Jets final state is less distinct!

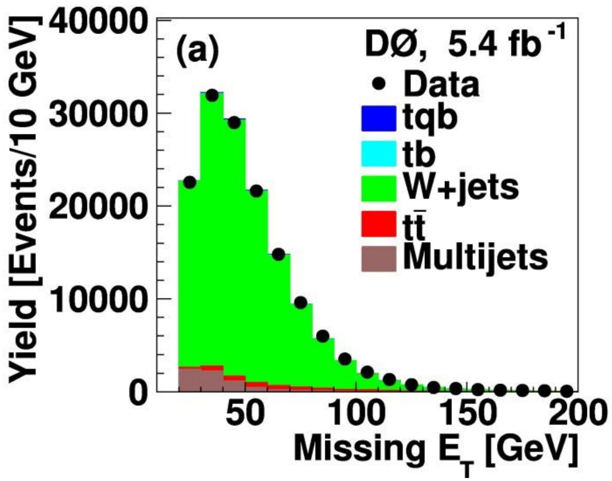


Background Model

- ttbar, diboson and Z+jets are normalized to SM cross section
- QCD models derived from data with non-isolated lepton (D0) or anti-lepton (CDF)
- W+jets are modeled by Alpgen (Wjj, Wbb, Wcc, Wcj)
- W+jets and QCD are normalized to data before b-tagging in missing E_T (CDF) or several variables (D0)



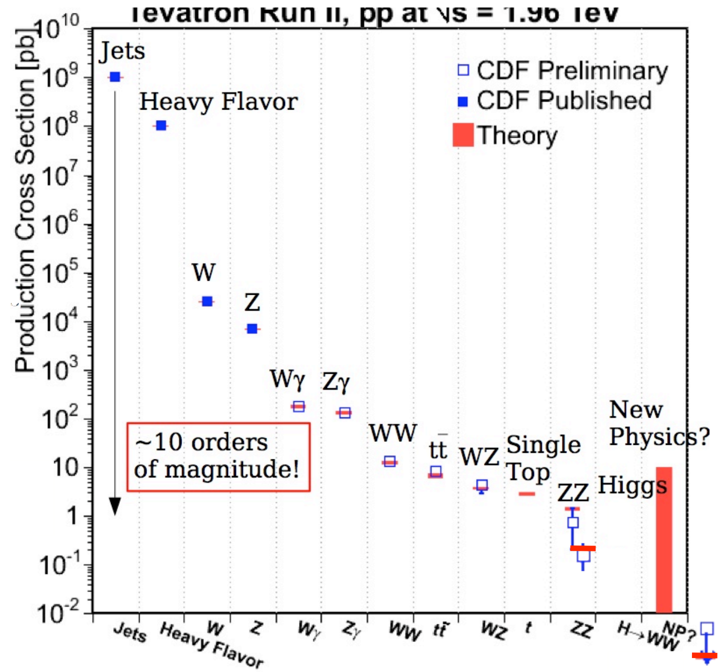
T. Aaltonen, et al. [CDF collaboration], PRD82 112005 (2009)

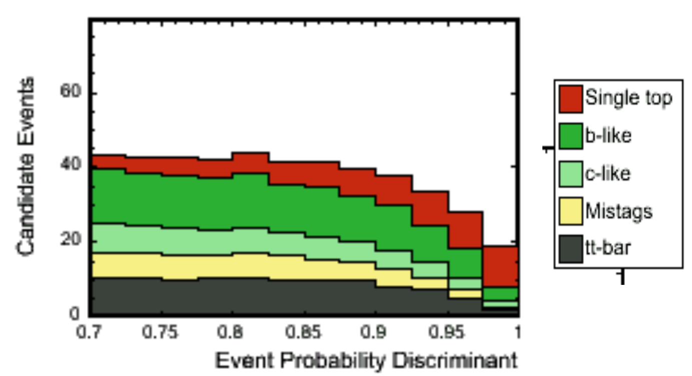


V.M. Abazov et al. [D0 Collaboration], PRD 84, 112001 (2011)

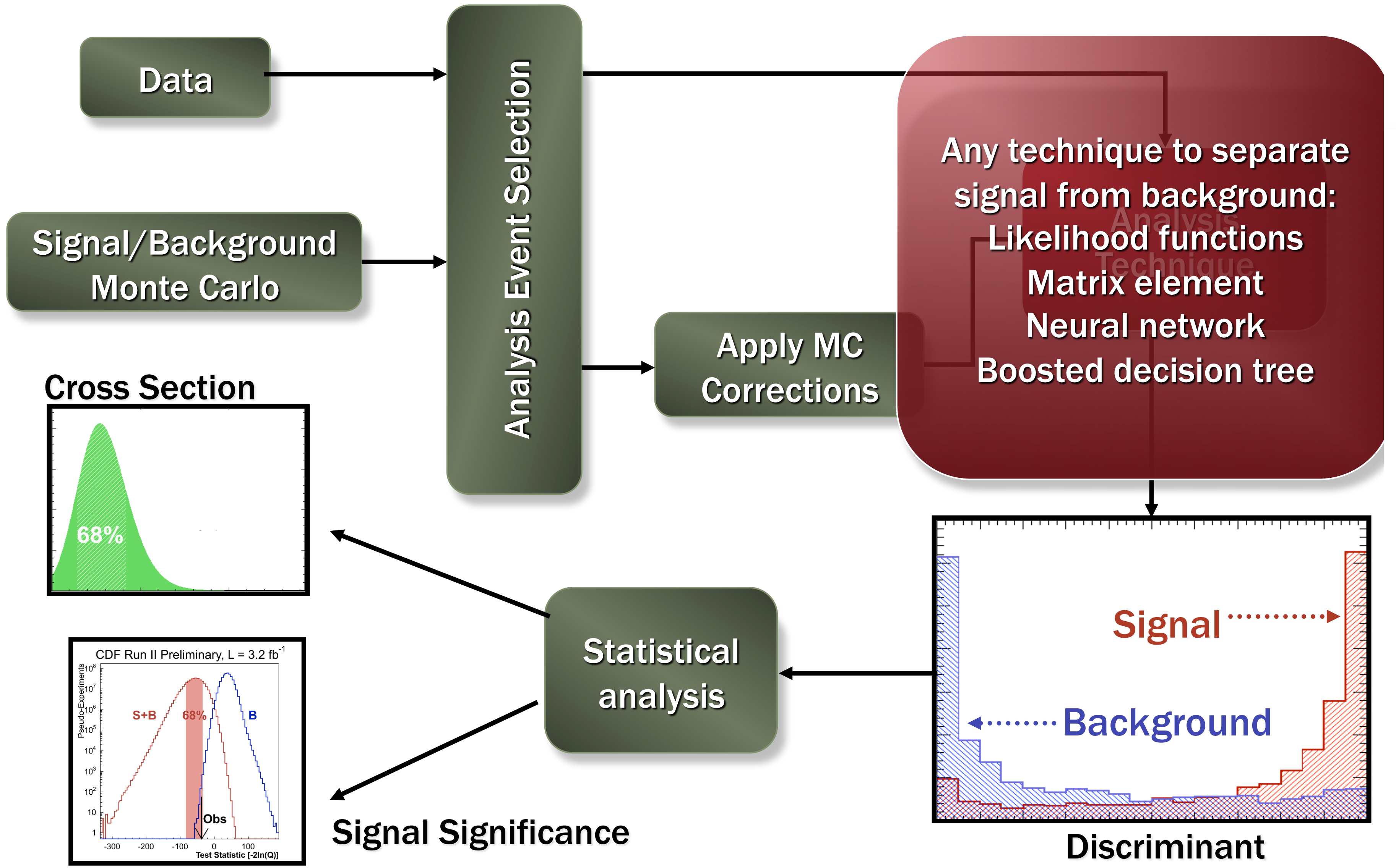
Analysis Strategy

- Single Top production is rare (~3 pb)
  - Signal:Background (S:B) ~ 1:10^9
- First step:
  - Trigger and ID clean leptons/MET improves S:B by a factor ~10^6
  - High p_T lepton triggers (e,μ)
  - MET + jets triggers (recover non-fiducial leptons + hadronic τ decays)
- Second step:
  - Topological event selection
  - Efficient *b*-tagging
  - Careful background estimates
- Third step:
  - Advanced analysis techniques
  - S:B > 1:1 in most significant bins



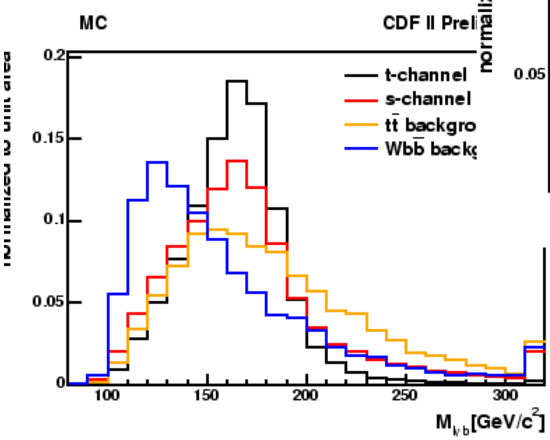


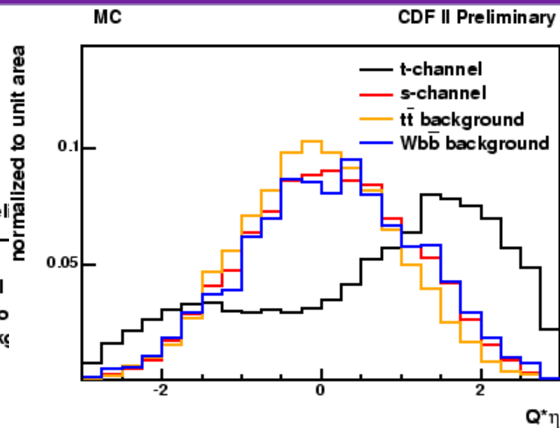
General Analysis Method

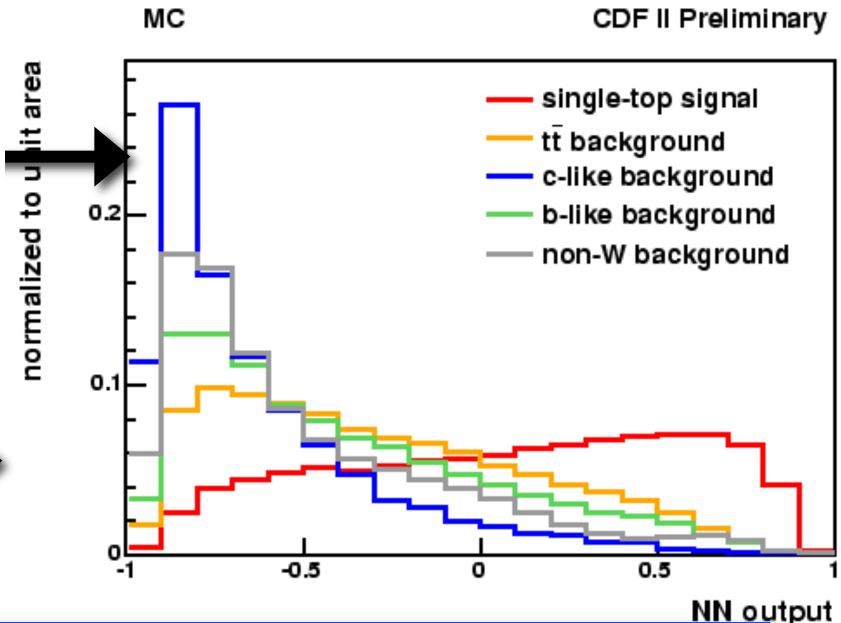


Advanced Techniques

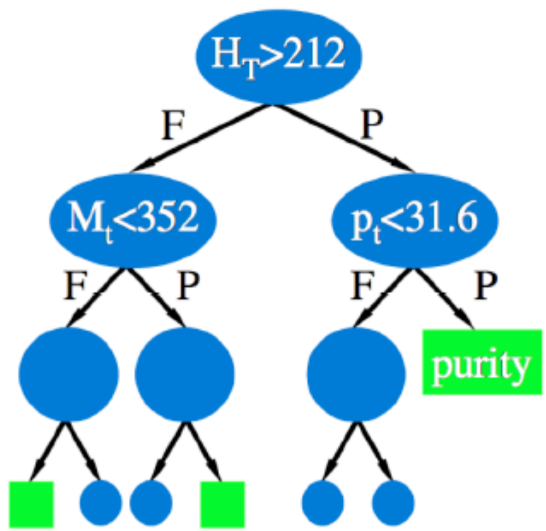
Neural Networks







Boosted Decision Trees

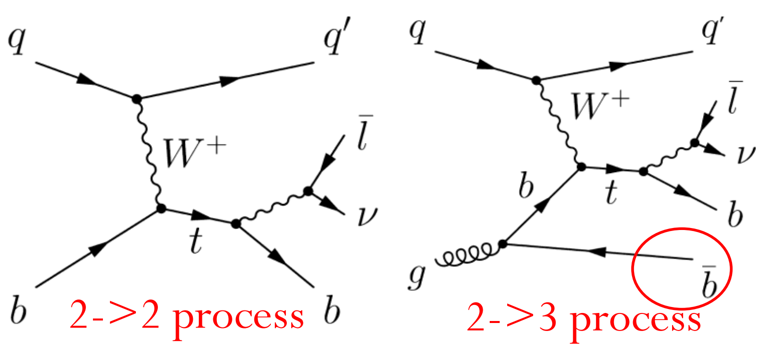


multivariate techniques
can coax signal out
from large backgrounds

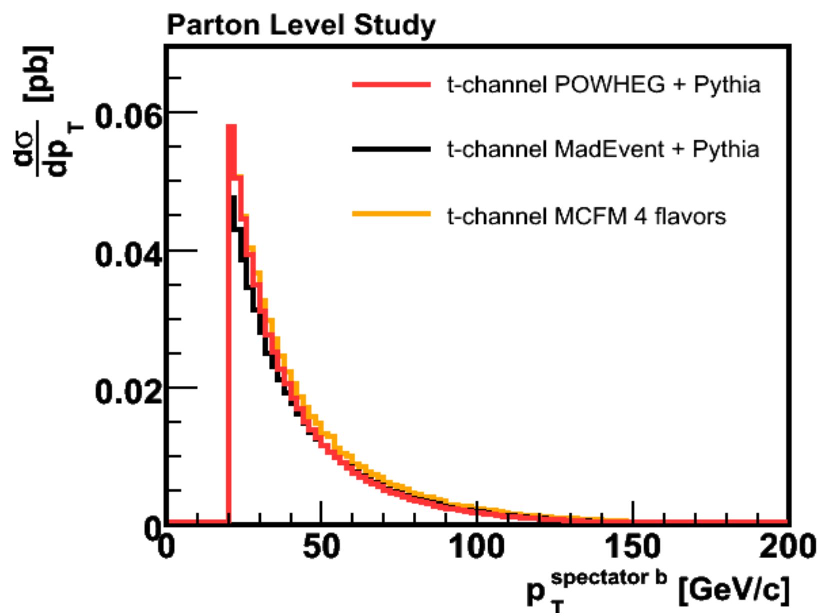
boosted decision trees, matrix element reconstruction, bayesian neural networks, likelihood discriminants

Signal Modeling

- Previously used MadEvent for single top modeling
  - Manually mix two processes of t-channel according to ZTOP prediction
- Using POWHEG for single top modeling with NLO accuracy



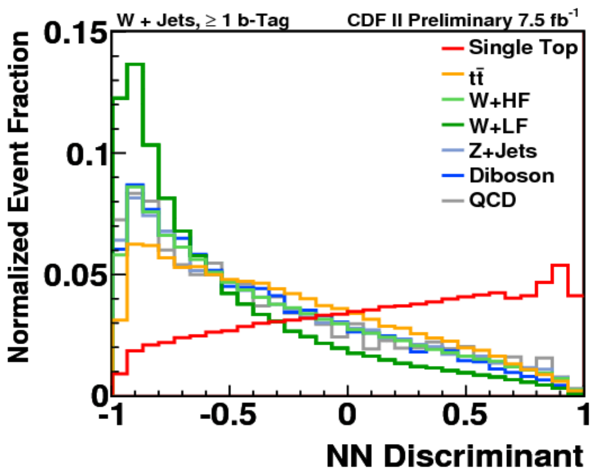
t-channel production

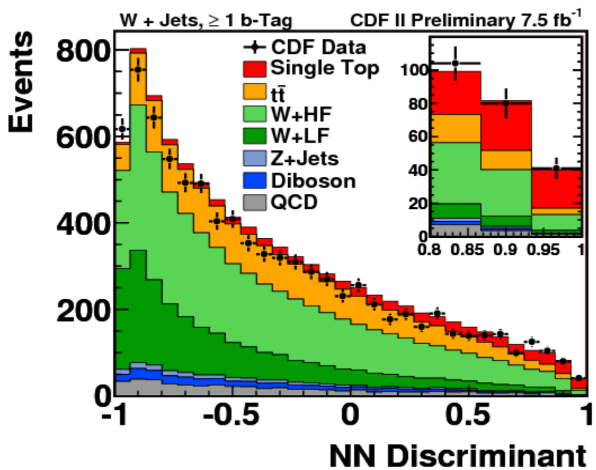


- t-channel shows good agreement with MCFM 4 flavor prediction for both POWHEG and MadEvent
- Add Wt-channel as signal through POWHEG

Neural Network

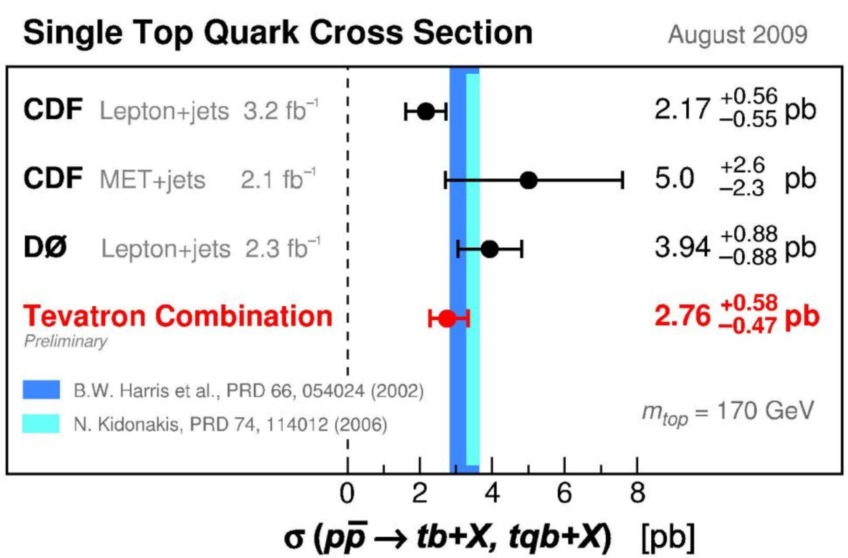
- Train the NN with 11~14 variables in four channels (2, 3 jets with 1, 2 b-tags)
- Train for s-channel in 2 jet 2 b-tags, train for t-channel in the rest channels
- Train the NN with systematic mixed samples for better uncertainty constraint (~3% improvement expected)

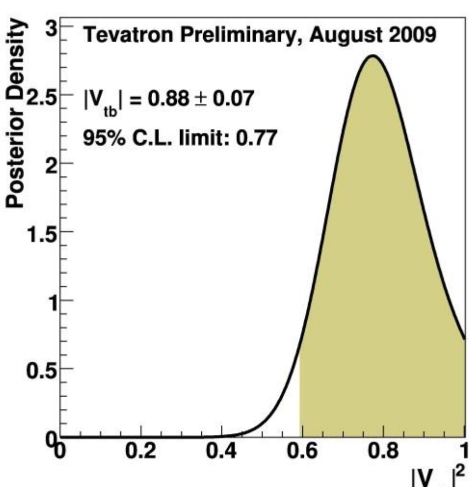




Tevatron Observation

- Observed by CDF and D0 simultaneously in 2009
- Over 100 citations for both observation PRLs
  - T. Aaltonen, et al. [CDF collaboration], Phys. Rev. Lett. 103, 092002 (2009)
  - V.M. Abazov et al. [D0 Collaboration], Phys. Rev. Lett. 103, 092001 (2009)

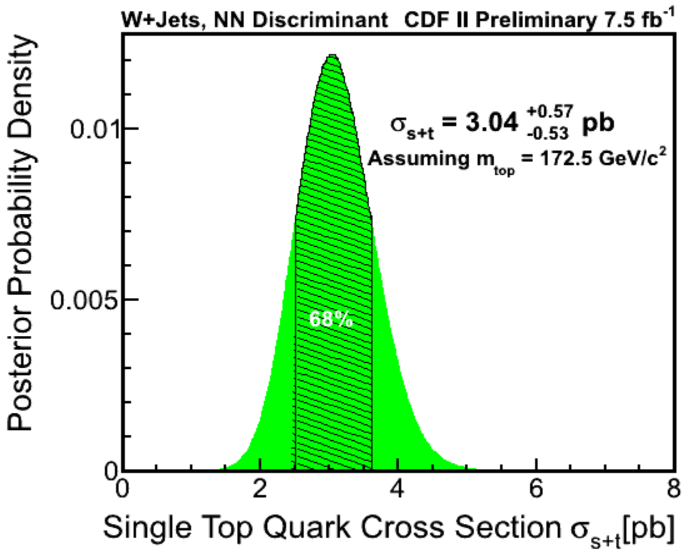




- Combination of CDF and D0:
  - CDF: Four multivariate analysis in Lepton+jets channel with $3.2fb^{-1}$ data.
  - CDF: MET+Jets channel with $2.1fb^{-1}$ data
  - D0: Three multivariate analysis in Lepton+jets channel with $2.3fb^{-1}$ data.

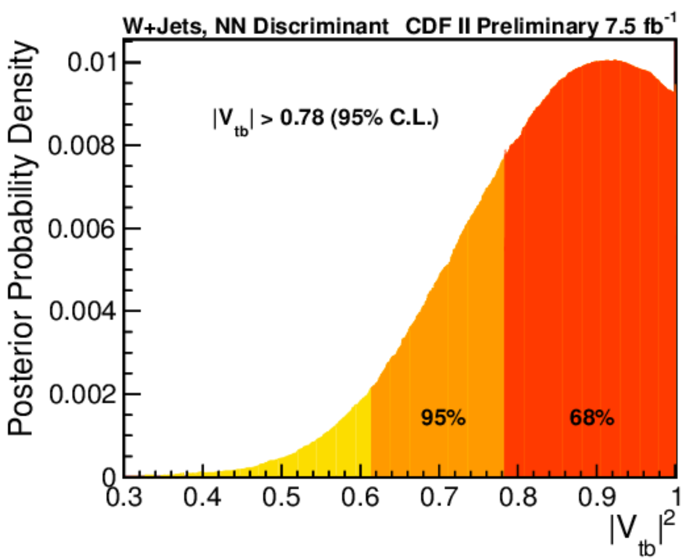
Cross Section and V_{tb}

new



- Assuming $m_{top} = 172.5$ Gev/c^2
- Measured cross section:

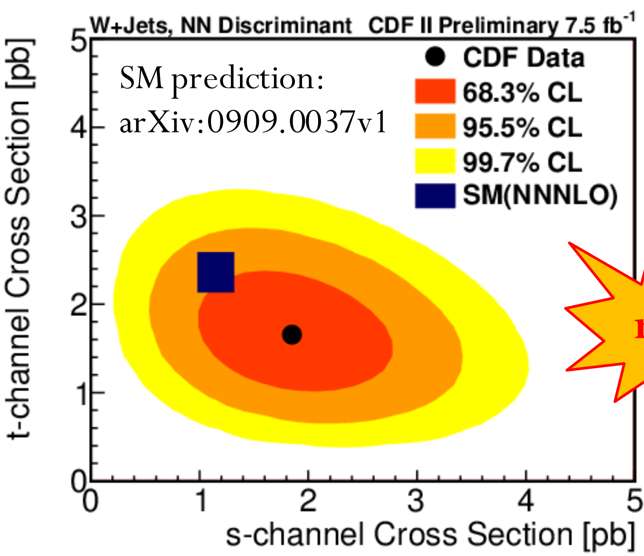
$$\sigma_{s+t} = 3.04^{+0.57}_{-0.53}\ \text{pb}$$

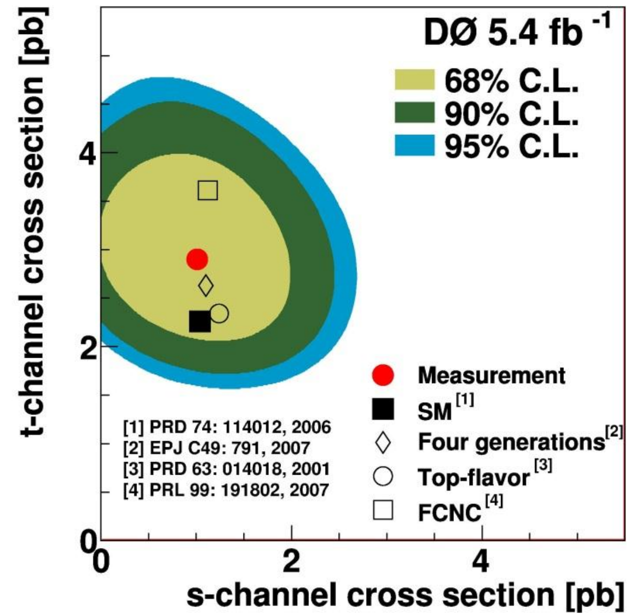


- From the cross section posterior
- Set limit: $|V_{tb}| > 0.78$ at 95% CL

Extracted $|V_{tb}| = 0.92\ ^{+0.10}_{-0.08}$ (stat.+sys.) $\pm$ 0.05(theory)

Simultaneous 2D measurement



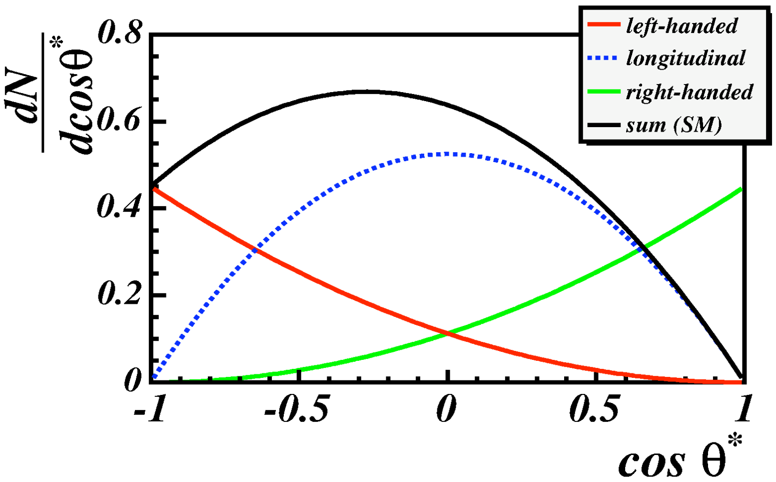


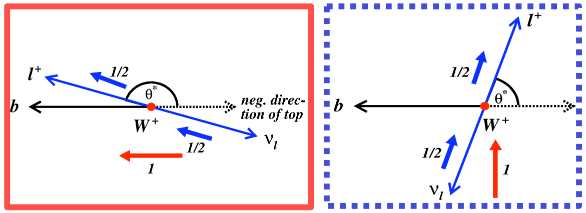
- Measured cross section:
  - $\sigma_s = 1.81^{+0.63}_{-0.58}$ pb **(± ~33%)**
  - $\sigma_t = 1.49^{+0.47}_{-0.42}$ pb
- SM Prediction:
  - $\sigma_s^{SM} = 1.05 \pm 0.07$ pb
  - $\sigma_t^{SM} = 2.10 \pm 0.19$ pb
  - $\sigma_{wt}^{SM} = 0.22 \pm 0.08$ pb (Effect negligible)

- Measured cross section:
  - $\sigma_s = 0.98 \pm 0.63$ pb
  - $\sigma_t = 2.90 \pm 0.59$ pb **(± 20%)**
- SM Prediction:
  - $\sigma_s^{SM} = 1.04 \pm 0.04$ pb
  - $\sigma_t^{SM} = 2.26 \pm 0.12$ pb

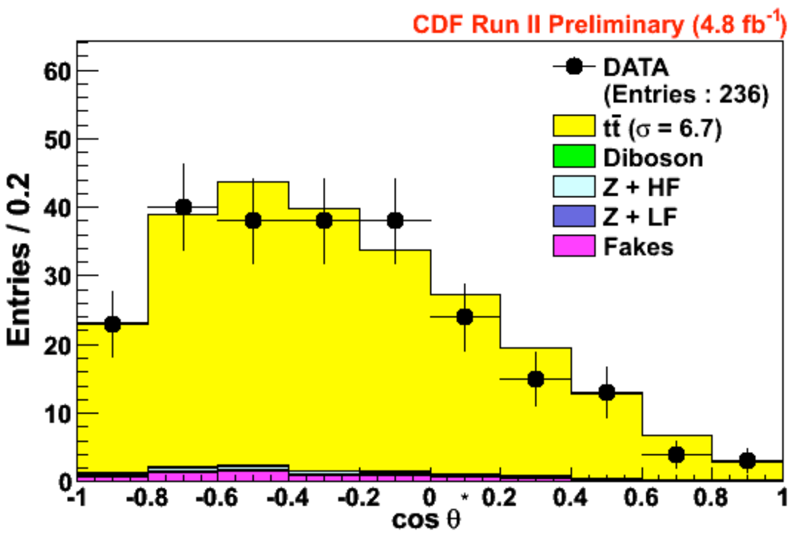
W-boson Helicity Fraction in Top Quark Decays

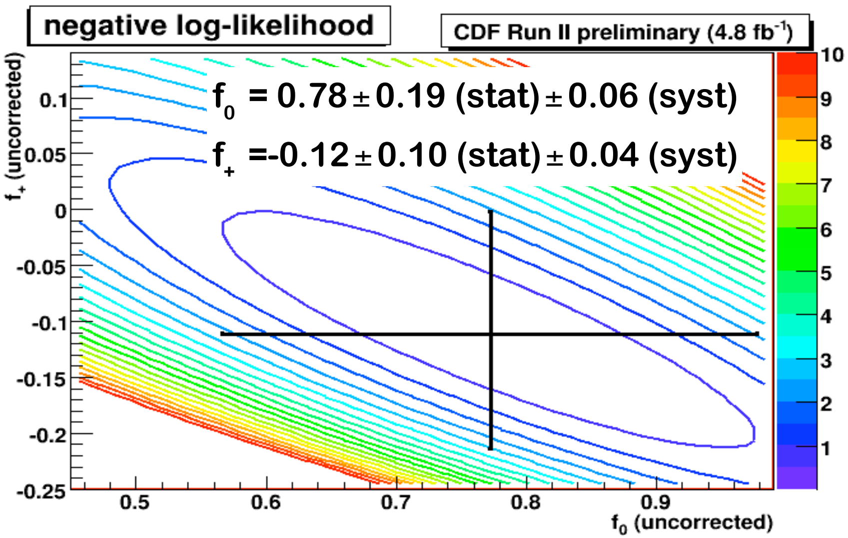
- SM top decays with (V-A) *t-W-b* coupling
- The helicity of *W* boson is predicted as:
  - Longitudinal fraction f_0 ~70%
  - Left-handed fraction f_- ~30%
  - Right-handed fraction f_+ ~0%
- Can use cosθ* to measure f_0, f_+, f_-





$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = f_- \cdot \frac{3}{8}(1-\cos\theta^*)^2 + f_0 \cdot \frac{3}{4}(1-\cos^2\theta^*) + f_+ \cdot \frac{3}{8}(1+\cos\theta^*)^2$$





First model independent result in dilepton channel!

Final Thought on Top

Why physicists really want to study Top…

When Trish discovers Ned works exclusively with top quarks, she will be putty in his hands.

Generic Matrix Element Method

Probability to observe a set of kinematic variables *x* for a given top mass

d^n σ is the differential cross section
Contains (LO) matrix element squared

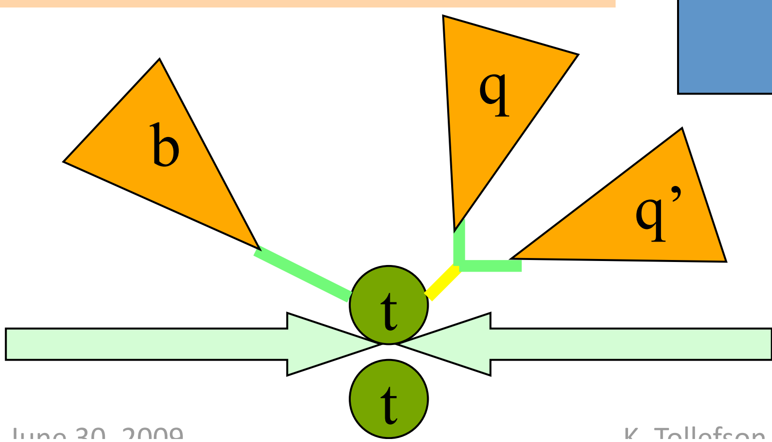
W(x,y) is the probability that a parton level set of variables ***y*** will be measured as a set of variables ***x***

$$P_{\mathrm{sgn}}(x;m_t) = \frac{1}{\sigma(m_t)} \int d^n\sigma(y;m_t)\, dq_1\, dq_2\, f(q_1)\, f(q_2)\, W(x,y)$$

f(q) is the probability distribution that a parton will have momentum ***q***

Normalization depends on m_t
includes acceptance effects

Integrate over unknown q_1, q_2, y



- Maximal extraction of information, but phase space integration is very CPU intensive
- Additional background probability term with varying levels of sophistication