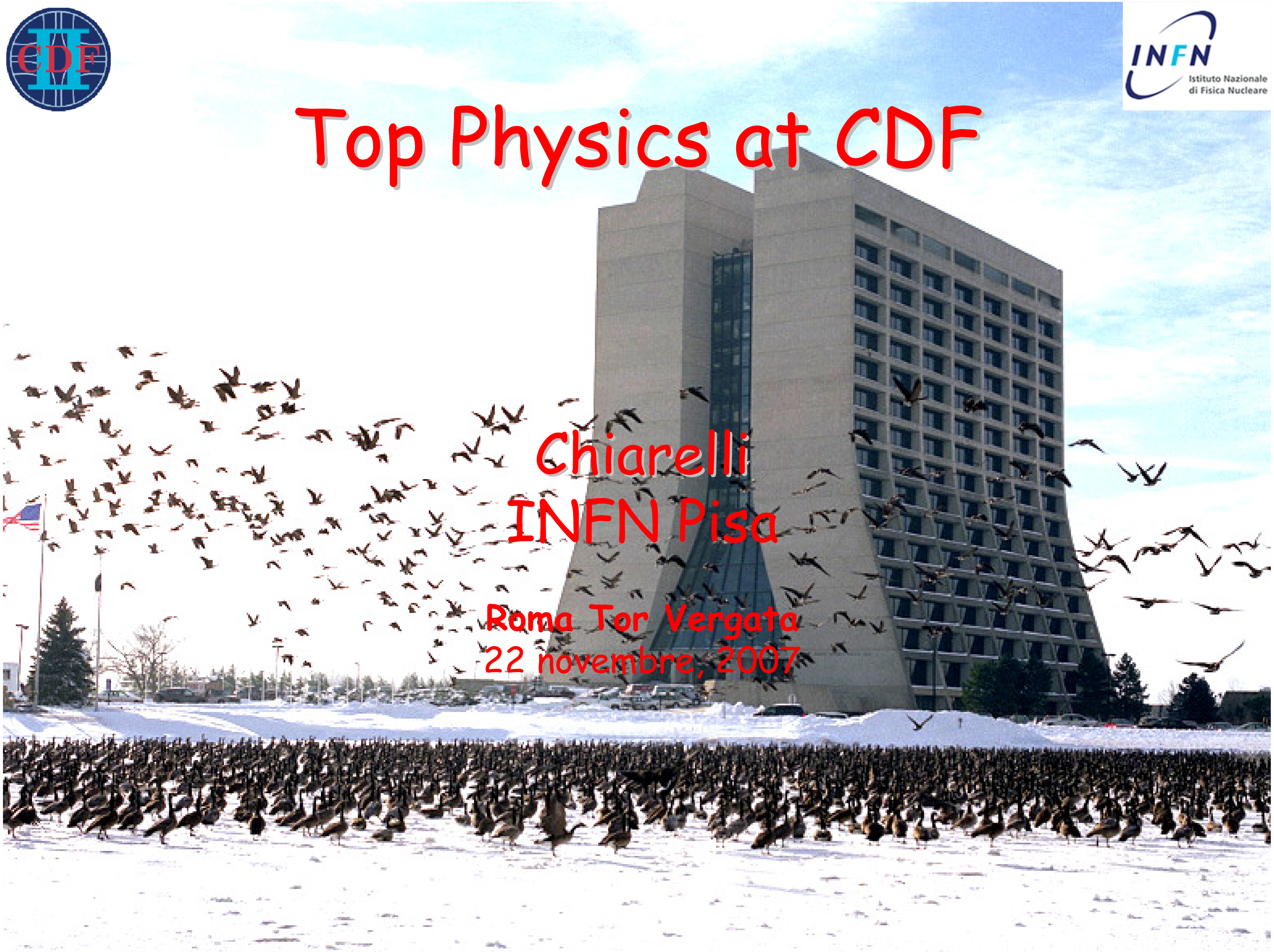
Top Physics at CDF



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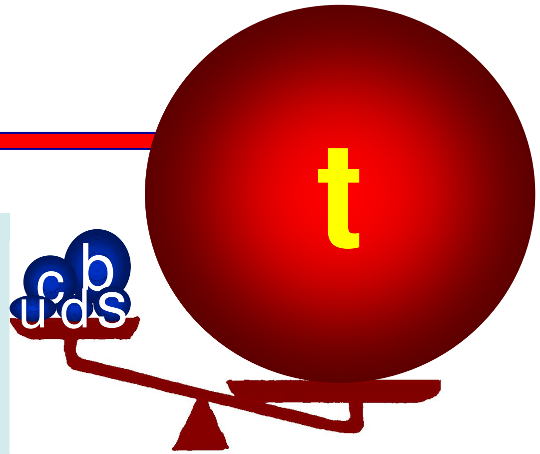
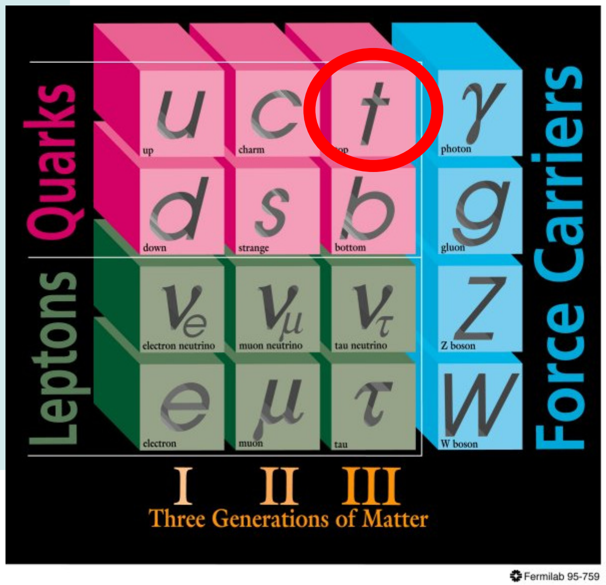
22 novembre, 2007

Outline



- Motivations for studying top
- A brief history
- Top production and decay
- ~~The Tevatron & CDF~~
- Detector issues
- Identification of final states
- Cross section measurement
- ~~Single top production~~
- Mass determination
- Study of top properties
- ~~The lesson for LHC~~



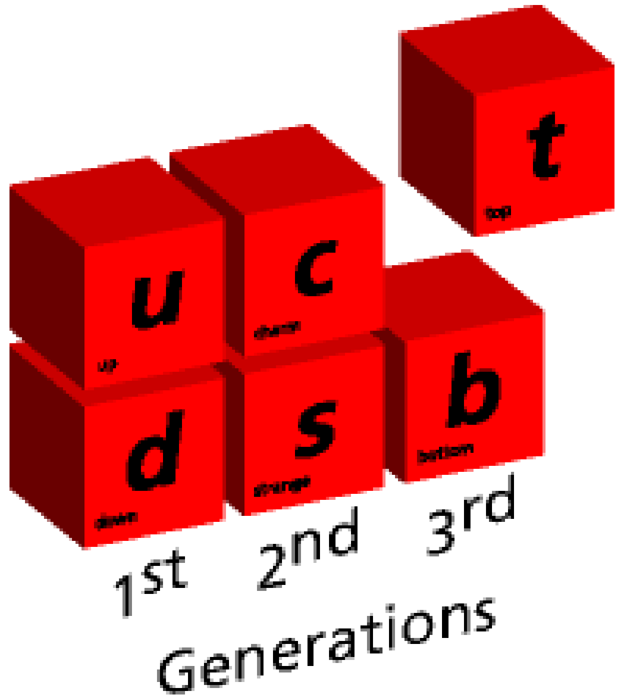
Motivations for Studying Top

- Only known fermion with a mass at the natural electroweak scale.
- Similar mass to tungsten atomic # 74
  35 times heavier than b quark.
  - ⇒Why is Top so heavy?
  - ⇒Is top involved in EWSB?
    - ✓(Does $(2\sqrt{2}\,G_F)^{-1/2} \approx M_{top}$ mean anything?)
  - ⇒Special role in precision electroweak physics?
  - ⇒Is top, or the third generation, special?
- New physics BSM may appear in production (e.g. topcolor) or in decay (e.g. Charged Higgs).

A Brief History of Top

- Top quark was expected in the Standard Model (SM) of electroweak interactions as a partner of b-quark in SU(2) doublet of weak isospin for the third family of quarks

(weak isospin of b can be inferred from the forward-backward asymmetry in $e^+e^- \rightarrow b\bar{b}$)



- Anomaly free SM requires the sum of the family charges to be zero: given the b (and the tau lepton) there should be a 2/3 charge quark

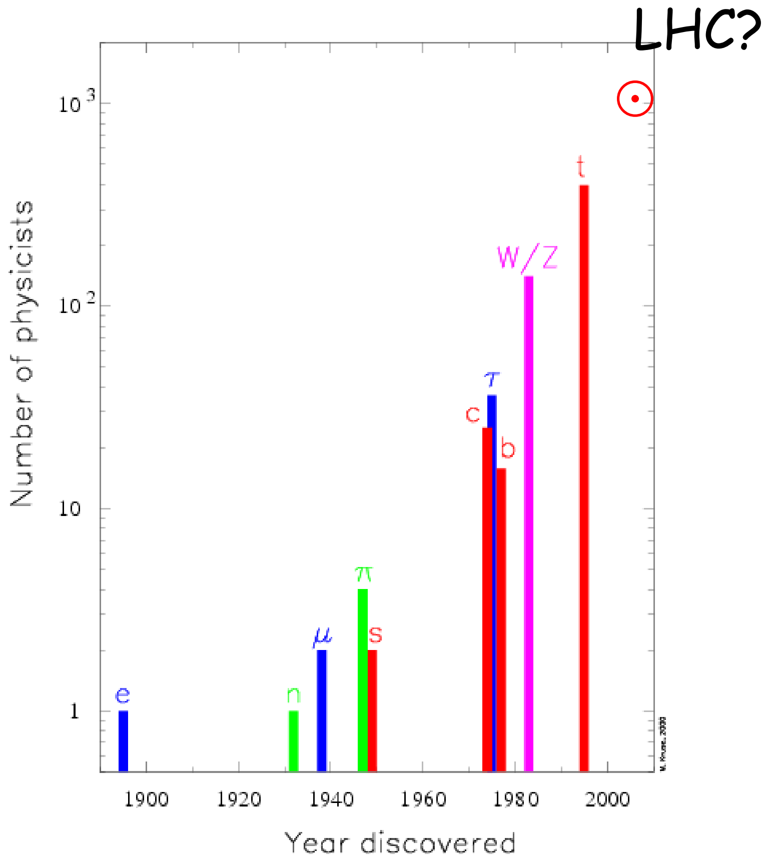
• 1977-1994: increasing lower top mass limits

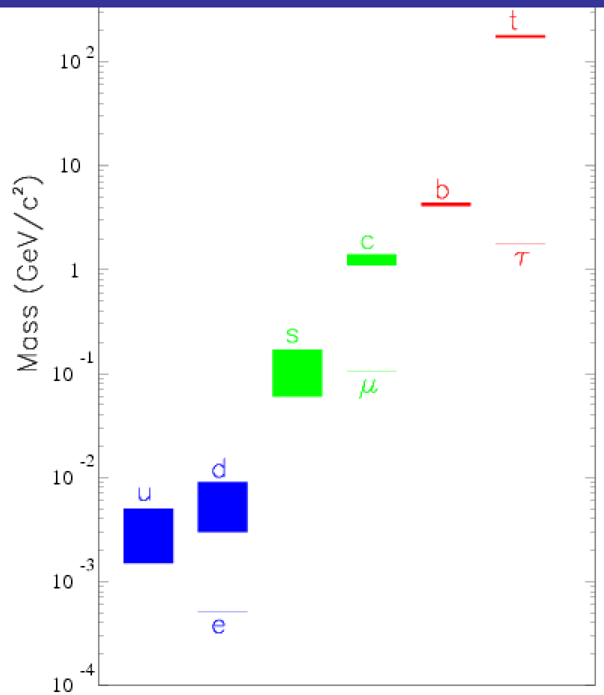
A Brief History of Top

- First top evidence in 1994 in CDF data, 19 pb^{-1}, 15 events on a background of 6,
  - ⇒ 2.8 σ excess, not enough to claim discovery
- Confirmed in 1995 by CDF and D0 in first ~70 pb^{-1} of run 1 data (4.8 σ).
- Final Tevatron Run 1 top analyses based on ~110 pb^{-1}.
  - ⇒ Production σ in many channels.
  - ⇒ Mass: 178.0 ± 4.3 GeV (CDF/DØ)
  - ⇒ Study of several aspects of event kinematics.
  - ⇒ Limits on single top production, rare/non-SM decays.
- Overall consistency with the SM
- But only ~100 analyzable top events
  - ⇒ **analyses statistics-limited.**

A more cultural perspective of Top…

- Top analyses as playground to learn how to optimize the cuts to reduce the bckgnd contamination, optimize the simulation, and realize that you'll have to use <u>real data</u> in order to study all the instrumental effects



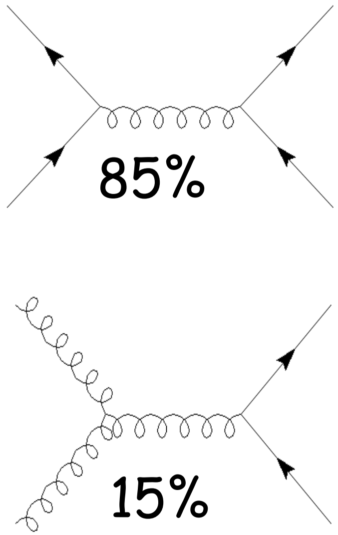


←

About 5 orders of magnitude range in quark masses!

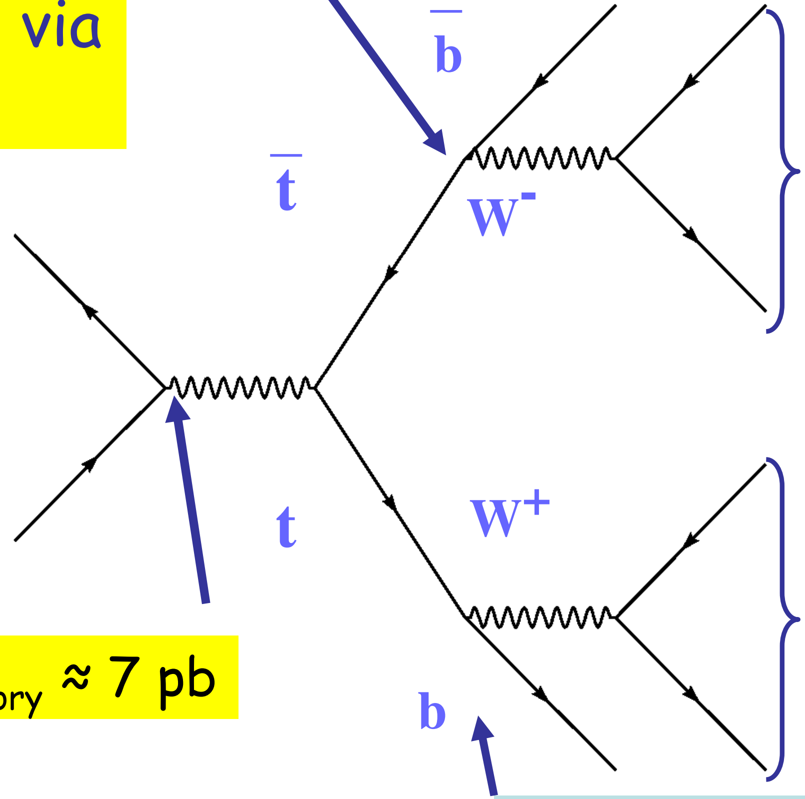
Production and Decay Basics

At the **Tevatron** top quarks are mainly pair produced via strong interaction:



$\sigma_{theory} \approx 7$ pb

SM predicts: BR($t \rightarrow Wb$) ≈ 100%



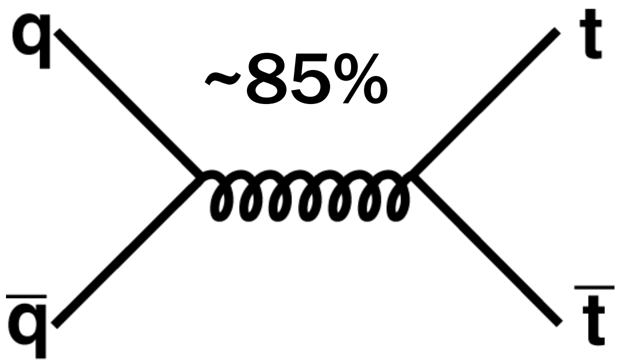
Event topology determined by the decay modes of the 2 W's (W^+W^-) in final state

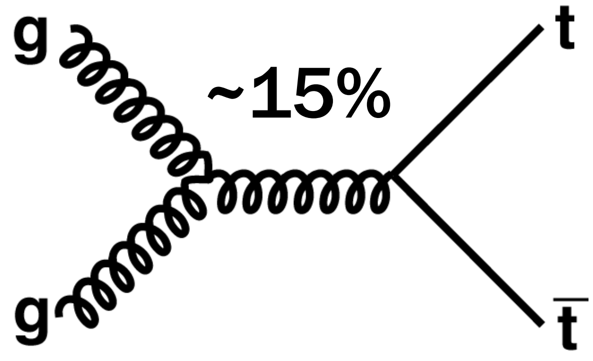
b-jet: identify via secondary vertex or soft lepton tag

NB: qq, gg fractions reversed at LHC

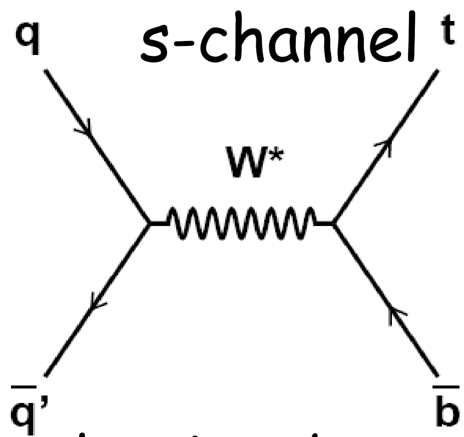
Top Quark Production at Tevatron

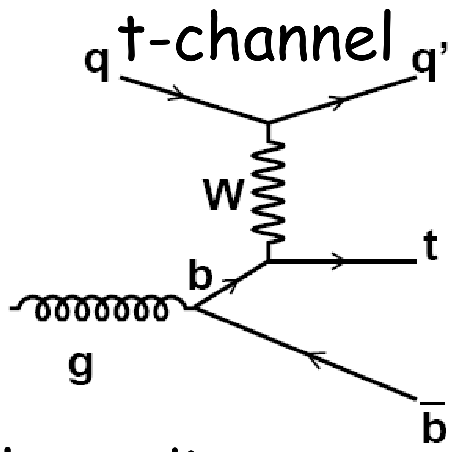
- QCD pair production
  - ⇒ σ_{NLO} = 6.7 pb (for m_{Top}= 175 GeV)
  - ⇒ First observed at Tevatron in 1994





- EWK single-top production
  - s-channel: σ_{NLO} = 0.9 pb
  - t-channel: σ_{NLO} = 2.0 pb (Both for m_{Top}= 175 GeV)
  - First evidence in Dec. 2006





- σ smaller than top pair production, but ➡ allows direct access to Vtb CKM matrix element: cross section $\propto$ |Vtb|
- Single top identification is challenging ➡ huge background

Top Decay : add. Motivation for Studying Top

- **In the SM, assuming V-A coupling with a CKM matrix parameter** $|V_{tb}|$ = 1 for the $t \rightarrow bW$ decay vertex, one gets (LO):

$$\Gamma(t \rightarrow bW) \approx 175 \text{ MeV } (M_T/M_W)^2 \quad (M_T, M_W \gg M_b)$$

$$\Rightarrow \Gamma(t \rightarrow bW) \approx 1.5 \text{ GeV} \quad \Rightarrow \tau(\text{top}) \approx 4 \times 10^{-25} \text{ s}$$

- Non-perturbative QCD hadronization takes place in a time of order: $\Lambda^{-1}_{QCD} \sim (100 \text{ MeV})^{-1} \sim 10^{-23}$ s

  $\Rightarrow$ **top decays before hadronizing, as free quark (no top hadrons, no toponium spectroscopy)**

  $\Rightarrow$ **the top quark provides the first opportunity to study the decay characteristics of a "bare" quark.**

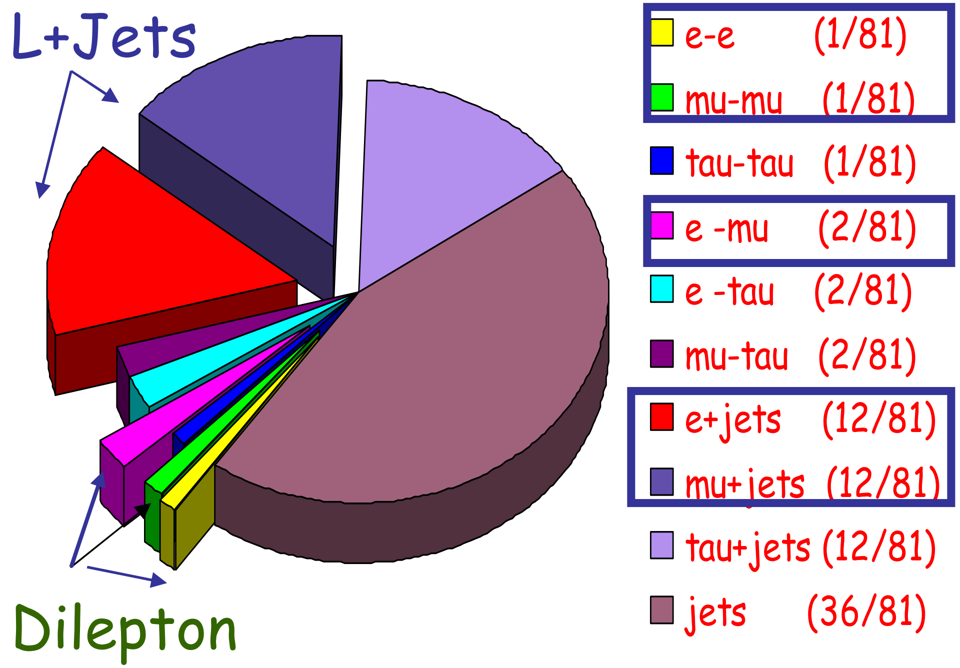
- $t \rightarrow Ws$, $t \rightarrow Wd$ allowed but suppressed by factors of $\sim 10^{-3}$ and $\sim 5 \times 10^{-5}$ respectively

t-tbar Final States

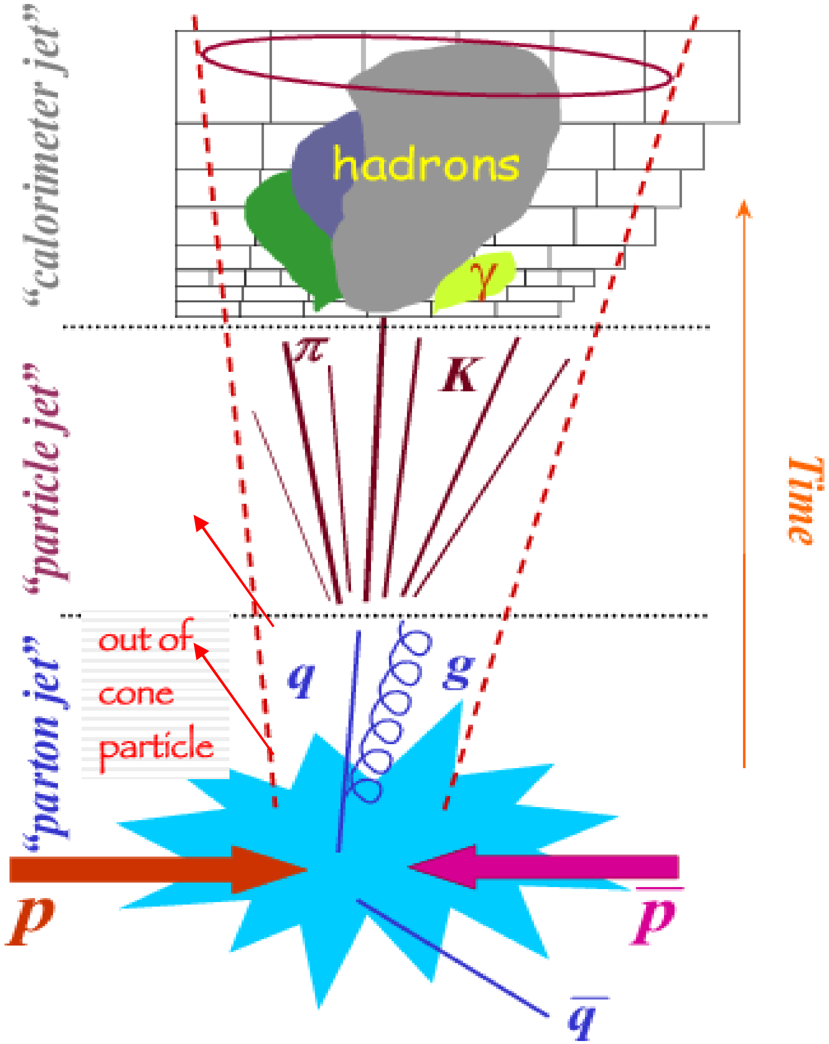
- Dilepton (ee, μμ, eμ)
  - ⇒ BR = 5%
  - ⇒ 2 high-P_T leptons + 2 b-jets + large missing-E_T
- Lepton (e or μ) + jets
  - ⇒ BR = 30%
  - ⇒ single lepton + 4 jets (2 from b's) + missing-E_T
- All-hadronic
  - ⇒ BR = 44%
  - ⇒ six jets, no missing-E_T
- τ_{had} +X
  - ⇒ BR = 21%

Most favorable channels for top physics

More challenging backgrounds, but measurements still possible



More details on Jets



A jet is a complicated object:

- measured by calorimeter towers
- defined by a clustering algorithm

- Doing analysis with jets requires the energy of the measured jet to be converted to the energy of the parent parton or particle jet.

- From measured jet energies to parton energies we need to correct for:
  - Instrumental effects
  - Physics effects
  - Jet Algorithm effects

"Physics at a hadron collider…

…Is all about the trigger!"

High p_T lepton
High E_T jet, photon
High Missing E_T (MET)

Examine each $p\bar{p}$ collision
Select few interesting events (<70 Hz)
Store for further offline analysis

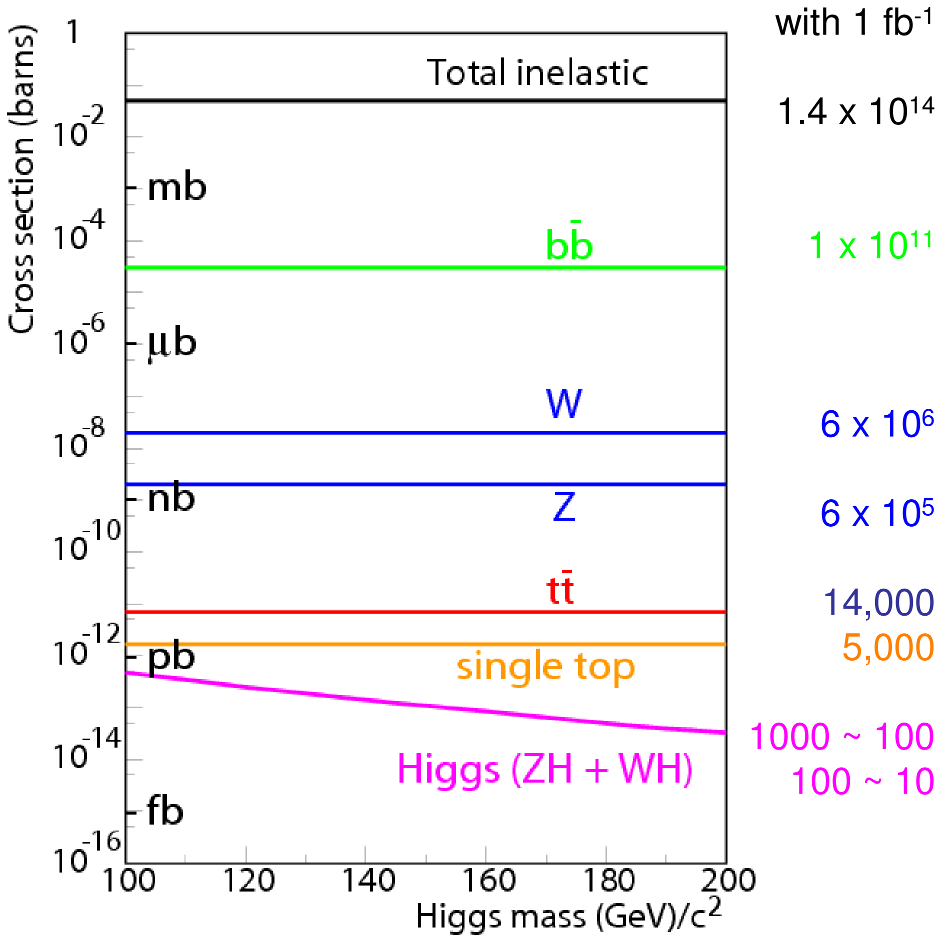
Keep 1 out of 25,000

Process	Cross-section	Event Rate
Inelastic $p\bar{p}$	60 mb	6 MHz
$\bar{p}p \rightarrow bb$ (b p_T>6 GeV, $\lvert\eta\rvert$<1)	10 μb	1 kHz
$\bar{p}p \rightarrow WX \rightarrow \ell\nu X$	5 nb	0.4 Hz
$\bar{p}p \rightarrow ZX \rightarrow \ell\ell X$	0.5 nb	0.04 Hz
$\bar{p}p \rightarrow tt \rightarrow WWbb \rightarrow \ell\nu bbX$	2 pb	0.0002 Hz
$\bar{p}p \rightarrow WH \rightarrow \ell\nu bb$ (if M_H=120GeV)	15 fb	0.0000015 Hz

Assume L =100x10^{30} cm^{-2}s^{-1}, ℓ=electron or muon

Comparison of Cross Sections

- In 1 fb^{-1} of data, ~ 1.4 x 10^{14} total collisions, one in every 10^{10} producing a ttbar event (c.f. one every 2.5 x 10^{6} producing a W event)



Note: LHC will be a top factory, producing ~ 2800 ttbar events per hour at low luminosity (10^{33})

$\sigma_{Tevatron}$ @ NLO: 6.7 ± 1.2 pb

σ_{LHC} @ NLO: ~830 ± 100 pb

Method to identify a top signal

- Start from "counting events" passing cuts in all decay channels
  - ⇒Optimization of signal region with respect to SM background processes (control region)

- Background dominates the production of ttbar pairs by several orders of magnitude
- How to separate signal from background:
  - ⇒Top events have very distinctive signatures
    - ✓Decay products (leptons, neut., jets) have large p_T's
    - ✓Event topology: central and spherical
    - ✓Heavy flavor content: always 2 b jets in the final state!

Why Measure the ttbar Cross Section?

- Basic engineering number, absolute measurement ($\rightarrow$ very difficult!) , prior step to any top property study.
- Requires detailed understanding of backgrounds and selection efficiencies.
- Test of SM

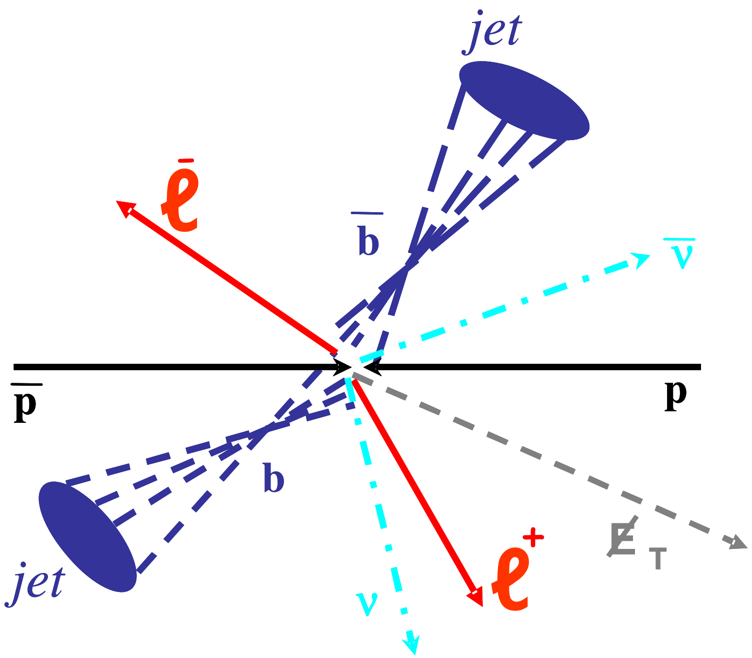
  $\Rightarrow$Departures from QCD prediction could indicate nonstandard production mechanisms, i.e. production through decays of SUSY states.

$$\sigma(t\bar{t}) = \frac{N_{obs} - N_{back}}{\varepsilon \times A \times \int L dt}$$

Dilepton Channel

Relatively clean:

- Top and a small amount of SM bkgds
- Down side is small event samples



Signature:

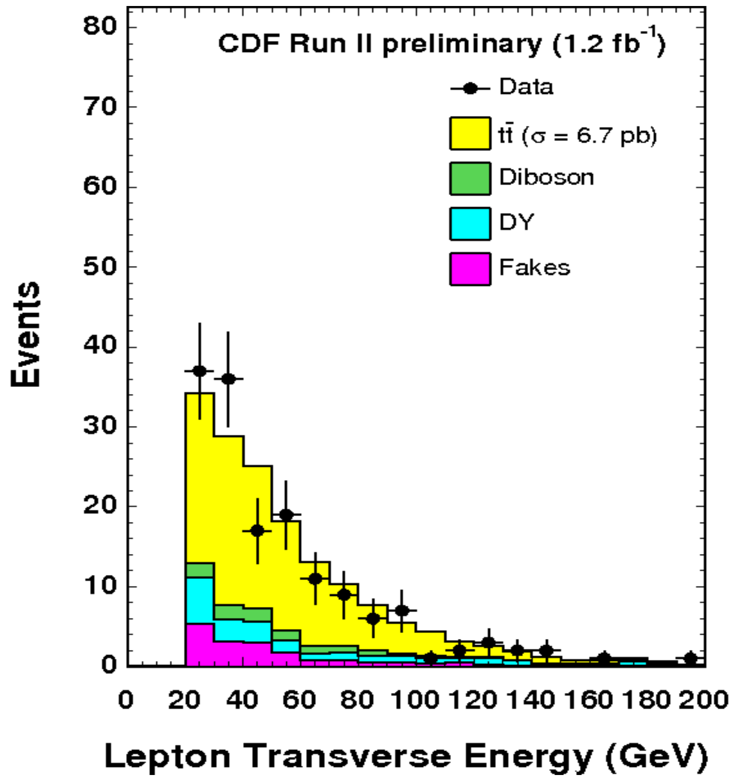
- Two high p_T Isolated leptons opposite sign
- Veto Z, cosmic, conversion
- $\Delta\Phi(\not{E}_T, l/j) > 20^o$, or $\not{E}_T > 50$ GeV
- $\not{E}_T > 25$
- Two jets with $E_T > 10$ GeV
- Total $E_T > 200$ GeV (H_T = Scalar summed E_T of jets, leptons, and $\not{E}_T$)

Expect: S/B ~ 9

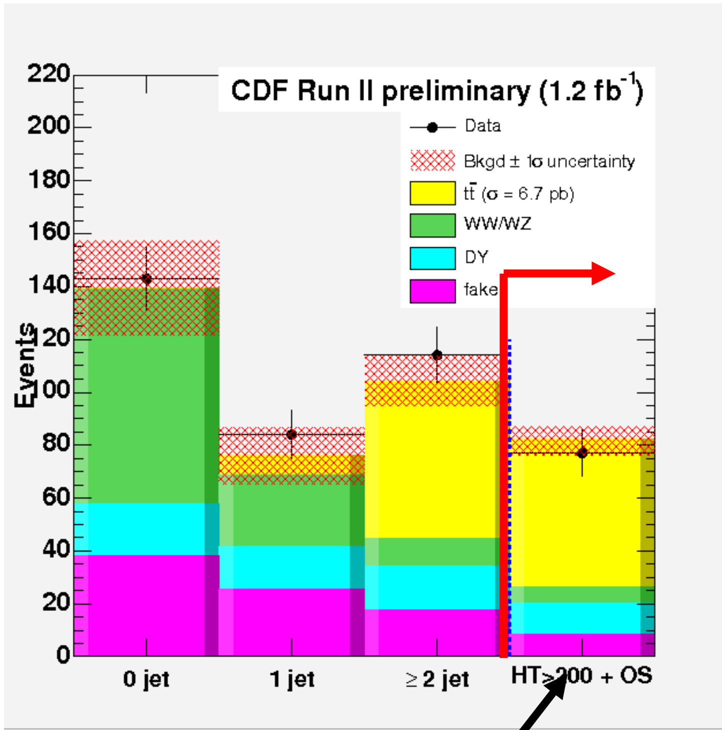
Dominant backgrounds:

Drell-Yan, W+jets ("fakes")

P_T Dilepton Channel: ee, eμ, μμ (1.2 fb^{-1})



Jet Multiplicity



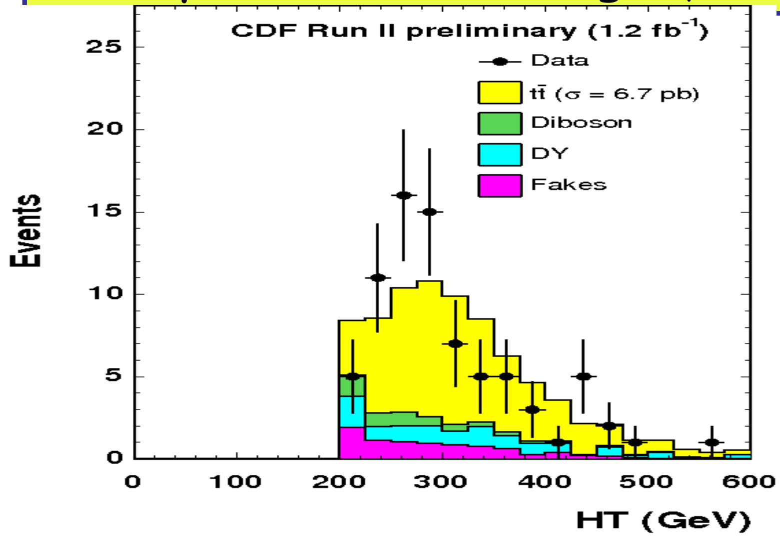
77 events on 25.6 ± 5.5 background
16 ee, 26 μμ, 35 eμ

ttbar signal bin

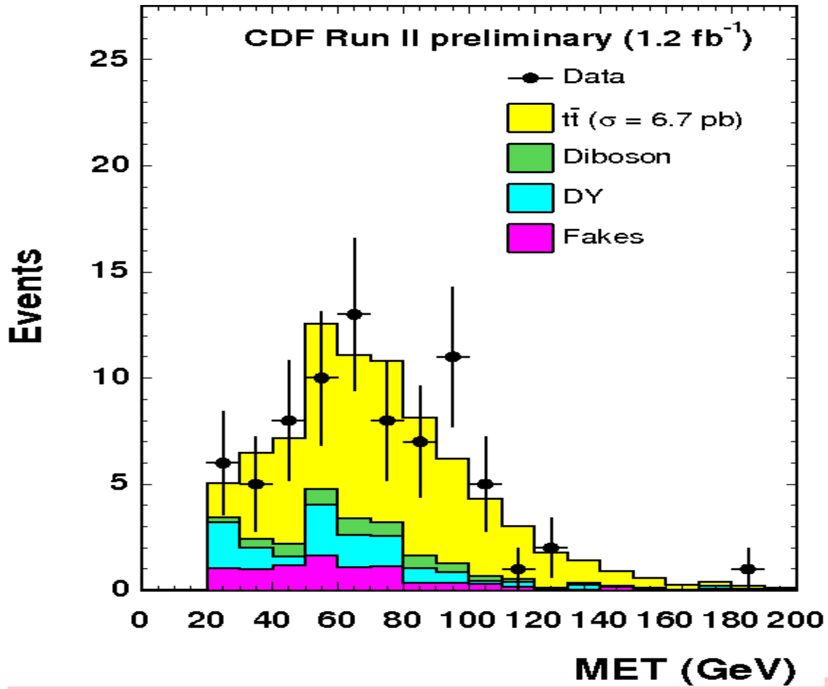
Dilepton Kinematics

RunI: had seen hints of discrepancy in kinematic distributions

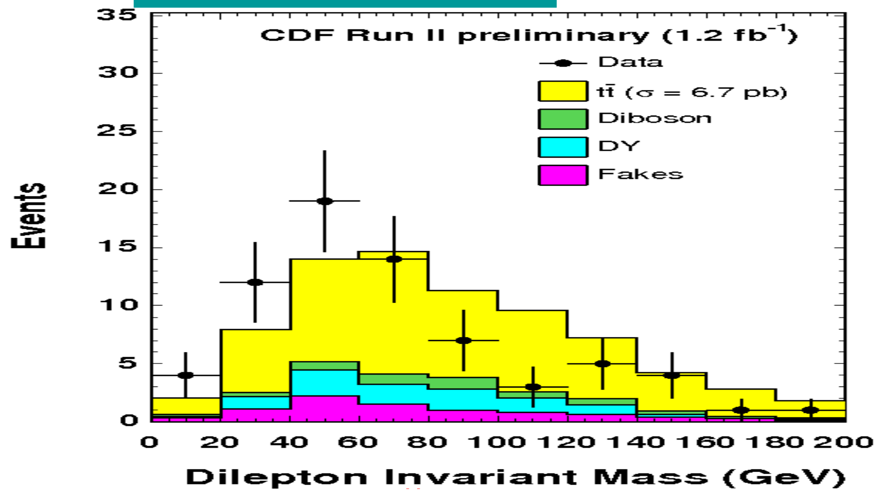
H_t:Scalar summed E_T of jets, leptons, and missing E_T



Missing E_T



Invariant mass



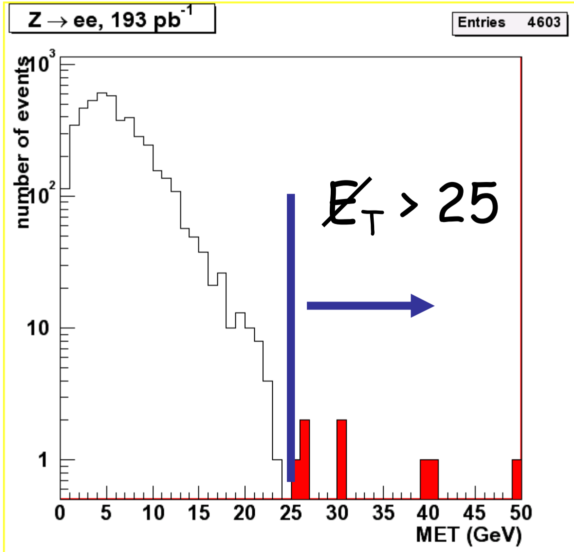
With higher statistics in Run II
Data follow SM expected distribution of top + bkgd

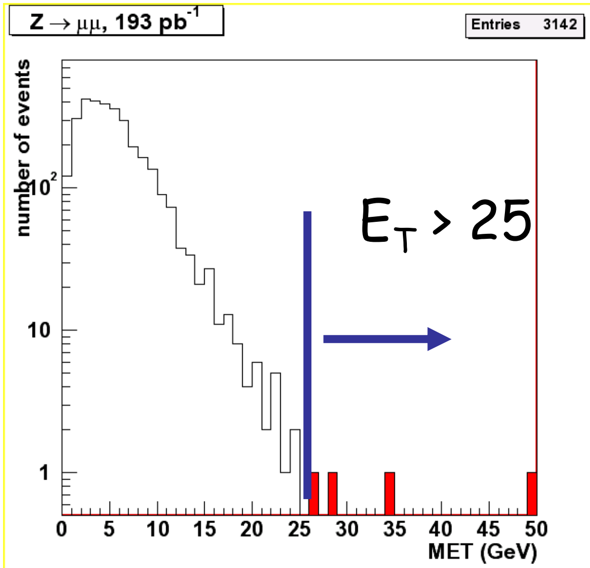
Dilepton background overview

- Instrumental backgrounds
  - Drell-Yan (ee, $\mu\mu$)
    - False $\not{E}_T$ from mismeasured leptons, jets
  - Fake leptons
    - W+jets with jet misidentified as lepton
  - Use data whenever possible
- Physics backgrounds
  - Diboson (WW/WZ/ZZ) and $Z \to \tau\tau$
    - Real leptons, $\not{E}_T$, jets
    - Evaluate using MC
- Determine bkgd in 0j, 1j bins to give confidence in signal bin prediction

Dilepton: DY (ee, μμ) background

- Large cross section but no intrinsic $\not{E}_T$
- False $\not{E}_t$
  - Detector coverage isn't 4π
  - Reconstruction isn't perfect
- Tails of $\not{E}_T$ resolution critical
- Simulation doesn't accurately model this
- Extra cuts in "Z window"
- Estimate residual contamination:
  - Use loose Z data to normalize (subtract expected non-Z's)
  - Use MC to distribute inside - outside Z window, across jet bins



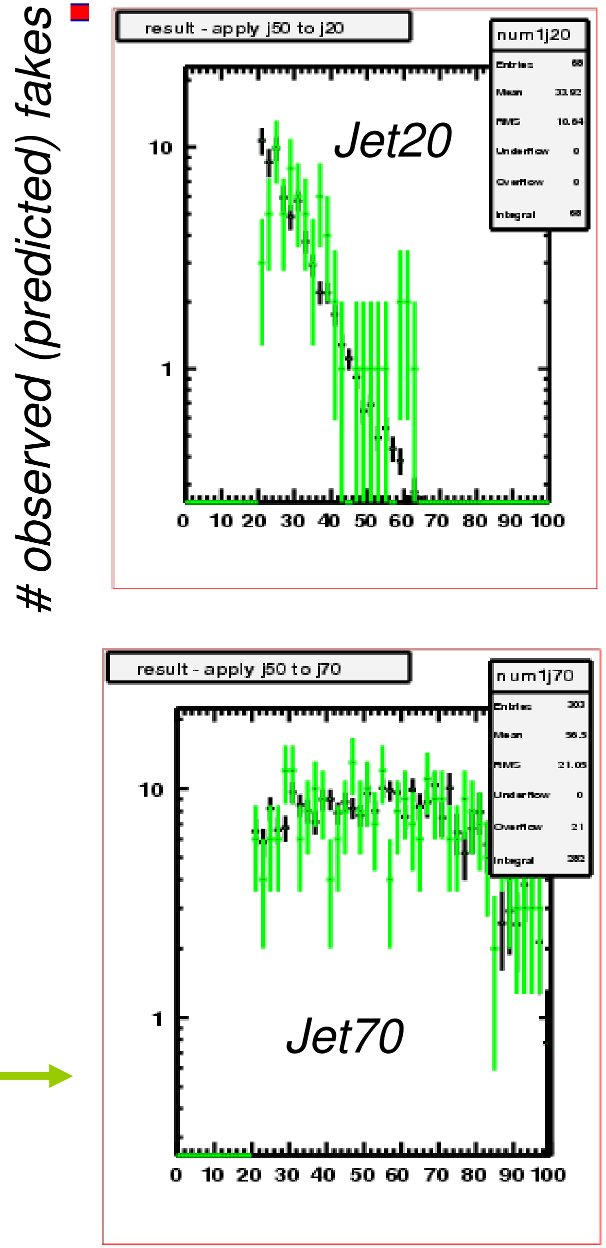


Dilepton: Fake lepton backgrounds

- Determine lepton fake rate from jets in j50 sample
- Cross-check fake rates in other samples with jets
- Apply fake rates to jets in W+jets data sample

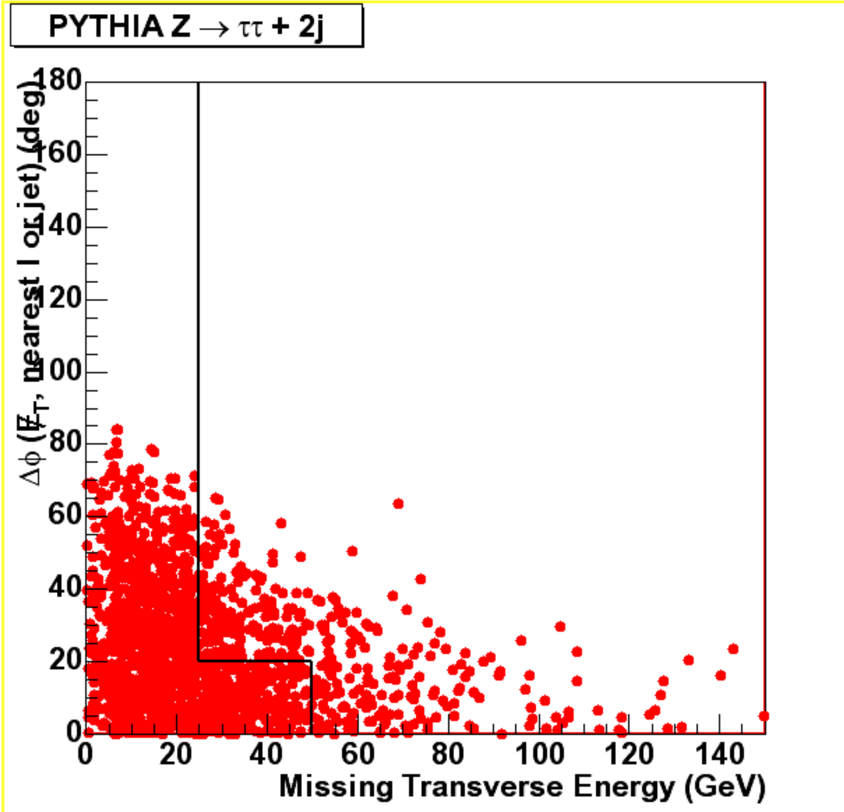
DIL	Obsv	Pred
j20	51	49 +/- 6
j70	75	65 +/- 9
j100	69	114 +/- 31

E_T of observed (predicted) fake tracks in green (black)

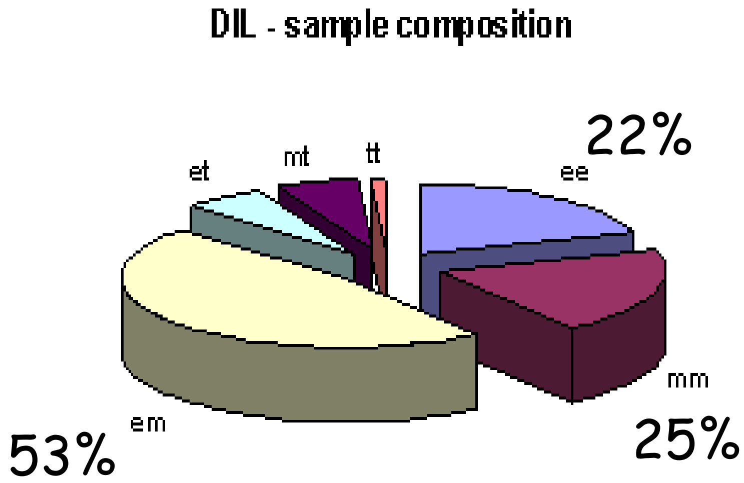


Dilepton:Z -> ττ, diboson bkgds

- In both cases:
  - ⇒Real missing energy
  - ⇒Jets from decays or initial/final state radiation
- Estimates derived using PYTHIA, ALPGEN+HERWIG MC, normalized to theoretical xsecs
- Correct for underestimation of extra jets in MC
  - ⇒Determine jet bin reweighting factors for Z → ττ from Z→ee, μμ data
  - ⇒Reweight WW similarly



Dilepton: $t\bar{t}$ acceptance and efficiencies



Acceptance:

- Determine from PYTHIA MC (m_t=175 GeV)
- Apply trigger efficiencies, lepton ID MC correction factors, luminosity weights for different detector categories

Lepton efficiencies:

- Determined in Z -> ℓ ℓ using second leg of Z's
- Get efficiency for data and MC, estimate difference and derive scale factor (90%, 79%, 83% for ee, μμ, eμ respectively)

Final acceptance x eff = 0.732 %

Dilepton:Signal acceptance systematics

Must take into account many effects potentially contributing to the acceptance uncertainty:

Systematic	DIL(%)
Lepton Identification -variation of data/MC SF with isolation	4
Jet Energy Scale, conversion, Njets in MC (correlated data-mc systematics	3.2
Initial-state radiation - ISR: difference from no-ISR sample	1.7
Final-state radiation - FSR: parton-matching method, different PYTHIA tune	1.1
Monte Carlo Generators - compare acceptance of PYTHIA to HERWIG	1.5
Parton Distribution Functions (PDF's) - default CTEQ5L vs MRST PDF's, different α_s samples	0.8

Dilepton: Systematic Uncertainty on Background Estimate

Systematic	DIL(%)
Lepton efficiency – same as signal	4
Jet Energy Scale – same procedure on bkgnd acc.	5-25
WW, WZ, ZZ estimate - Compare WW+0p+(njet scaling) to WW+2p	6-10
Drell-Yan Estimate - Absolute scale (data driven), Monte Carlo shape	42
Fake Estimate - J20, J50, J70, J100 x-check	30-50

Dilepton: Cross section results

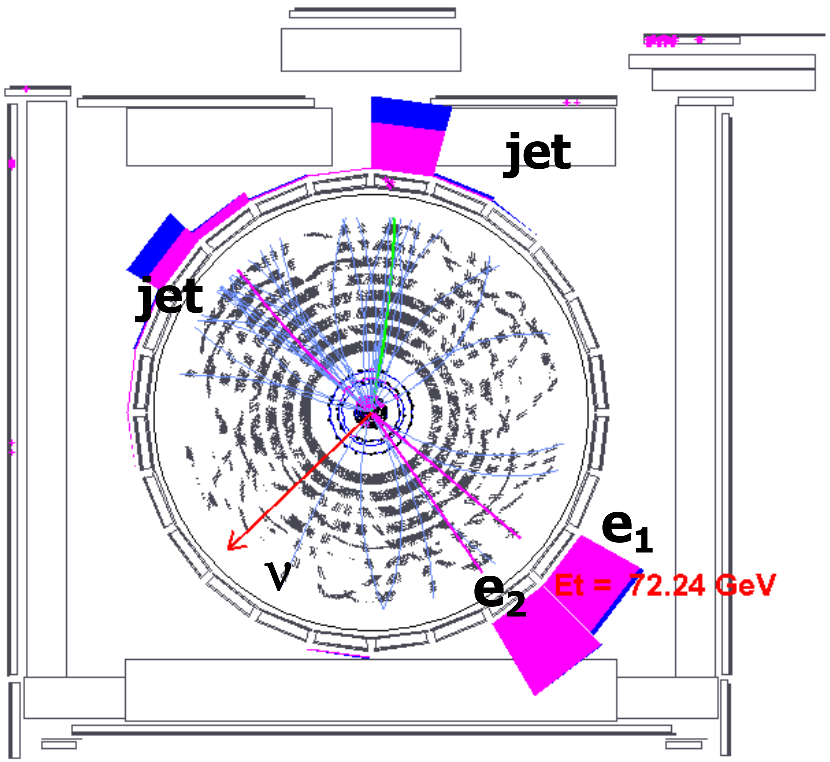
$$\sigma(t\bar{t}) = \frac{N_{obs} - N_{back}}{\varepsilon \times A \times \int L dt}$$

1203 pb^{-1}

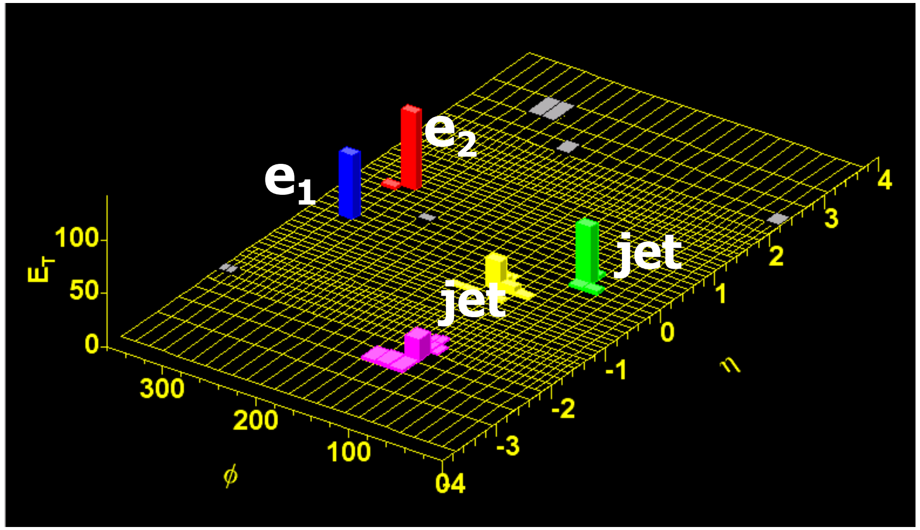
$\sigma(t\bar{t})$ = 6.16 ± 1.05 (stat) ± 0.72 (syst) + 0.37 (lumi) pb

SM: σ = 6.7 pb (m_t = 175 GeV/c^2)

Dilepton event display



•2 electrons (E_{T1}=73 GeV, P_{T2}=63 GeV)
• Missing E_T = 59 GeV
• 2 central jets + 1 forward jet

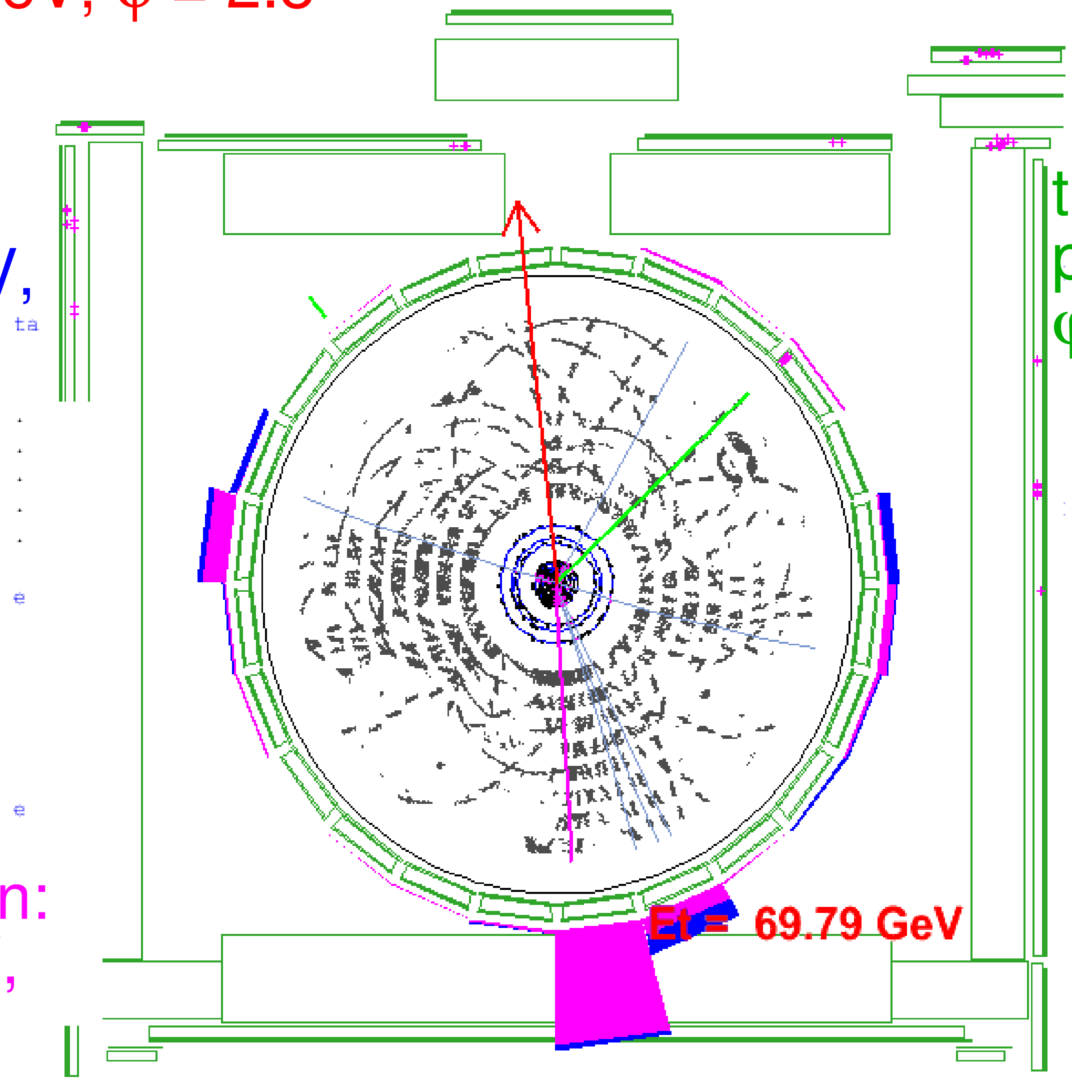


e-μ event

MET: 91 GeV, φ = 2.8

CDF Run II Preliminary (360 pb^{-1})

Jet 2:
E_T = 37 GeV,
tagged



tl (= CMX muon):
p_T = 102 GeV,
φ = 0.8

Jet 1:
E_T = 43 GeV,
tagged

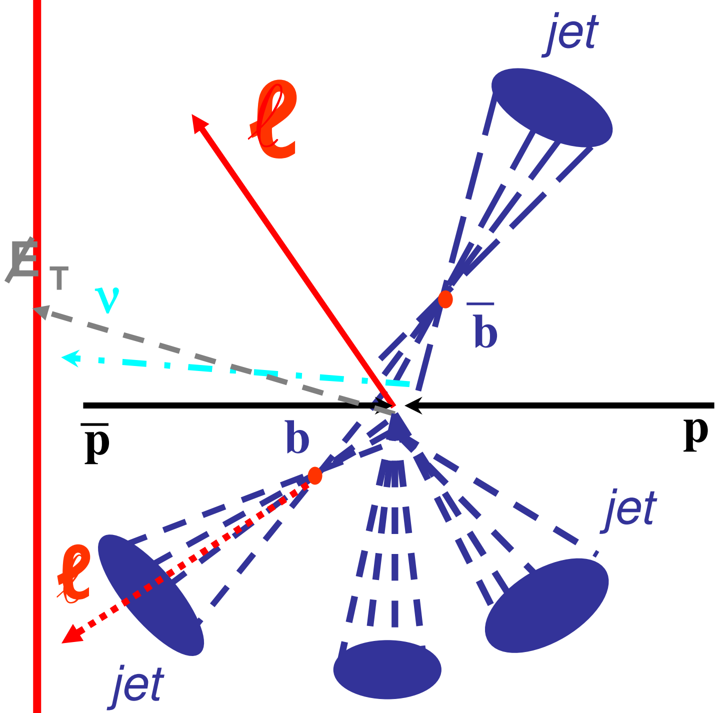
Jet 3:
E_T = 36 GeV

CEM electron:
E_T = 61 GeV,
φ = 4.8

Single lepton channel (Lepton + jets)

Signature:

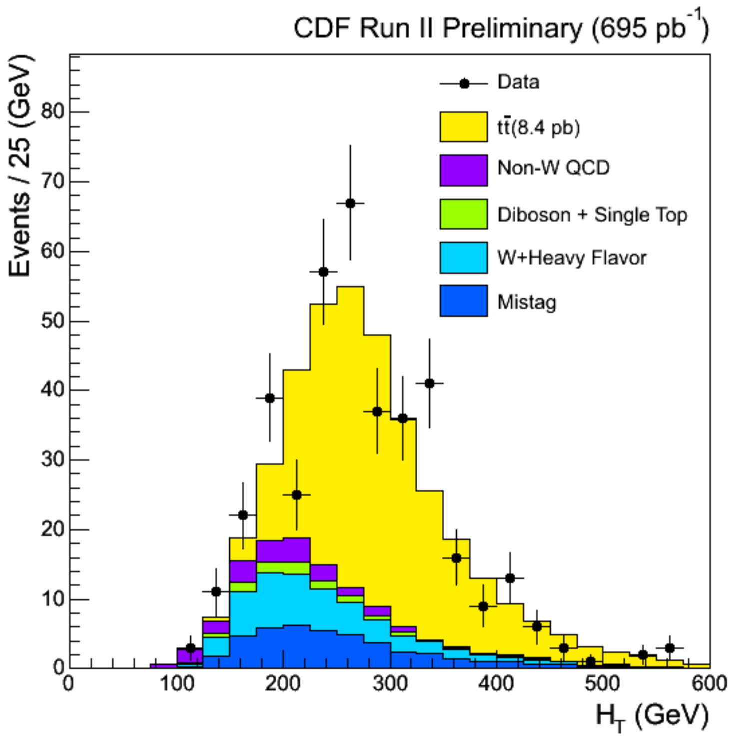
- One high p_T Isolated lepton
- Veto Z, cosmic, conversion, dilepton
- $\not{E}_T > 20$ GeV
- 3 or more jets with $E_T > 15$ GeV $|\eta| < 2.0$
- S/B ~ 1/6
  - Improve by requiring *b-tagging*



	W + 1 jet	W + 2 jets	W + 3 jets	W+>=4 jets
Secondary vertex sample (~1.2fb^{-1})	78903	12873	870	543
Tags	1067	585	185	231

Lepton + jets Channel: H_T cut

- H_T is the scalar sum of E_T of jets, leptons, and $\not{E}_T$
- H_T is a powerful discriminator for Top signal
- H_T > 200 GeV keep 96% of signal and reject 38% of background



An H_T cut increases the systematics due to Top mass dependence, Energy scale and Heavy flavor fraction, but still small compared with other syst (SF, lum)

Lepton +jets channel: counting events

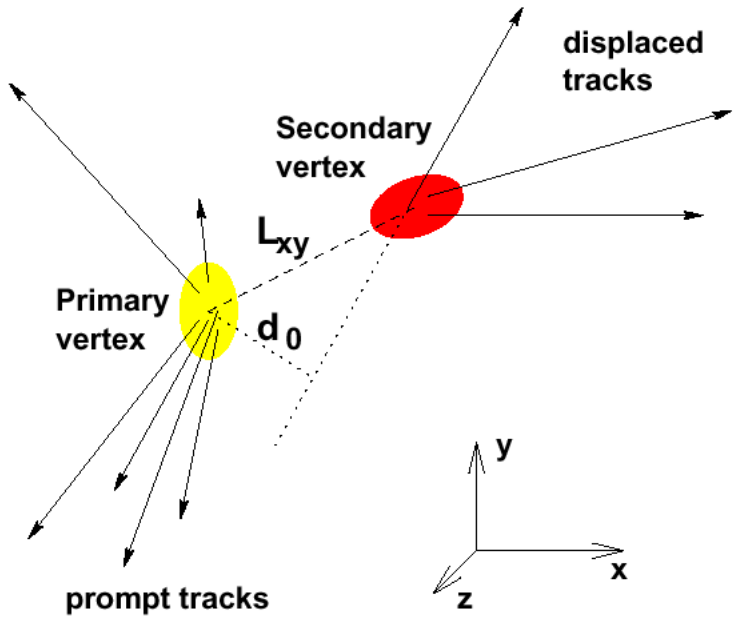
- Require ≥ 1 jet to be identified as a b-jet ("b-tagged")
- Motivation of using b-tags:
  - ⇒Reduce the backgrounds, especially W + light flavor jets events while keeping good efficiency on ttbar signal
  - ⇒B tag improves S/B from 1/6 →3/1
- Count ttbar candidate events
- Predict rates for SM non-top processes in tagged W+jets, excess in ≥3 jets is top
- Use data as much as possible to determine background contamination (non-W QCD, fake tags)
- Use MC when necessary (diboson, W+heavy flavor)

Tagging Tools: Vertexing and Soft Muons

B hadrons in top signal events:

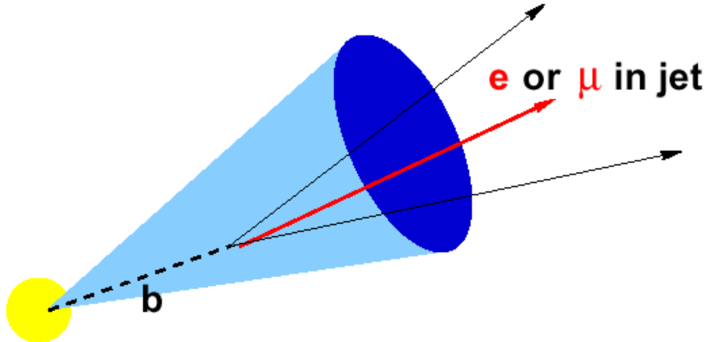
are long-lived and massive

Vertex of displaced tracks



may decay semileptonically

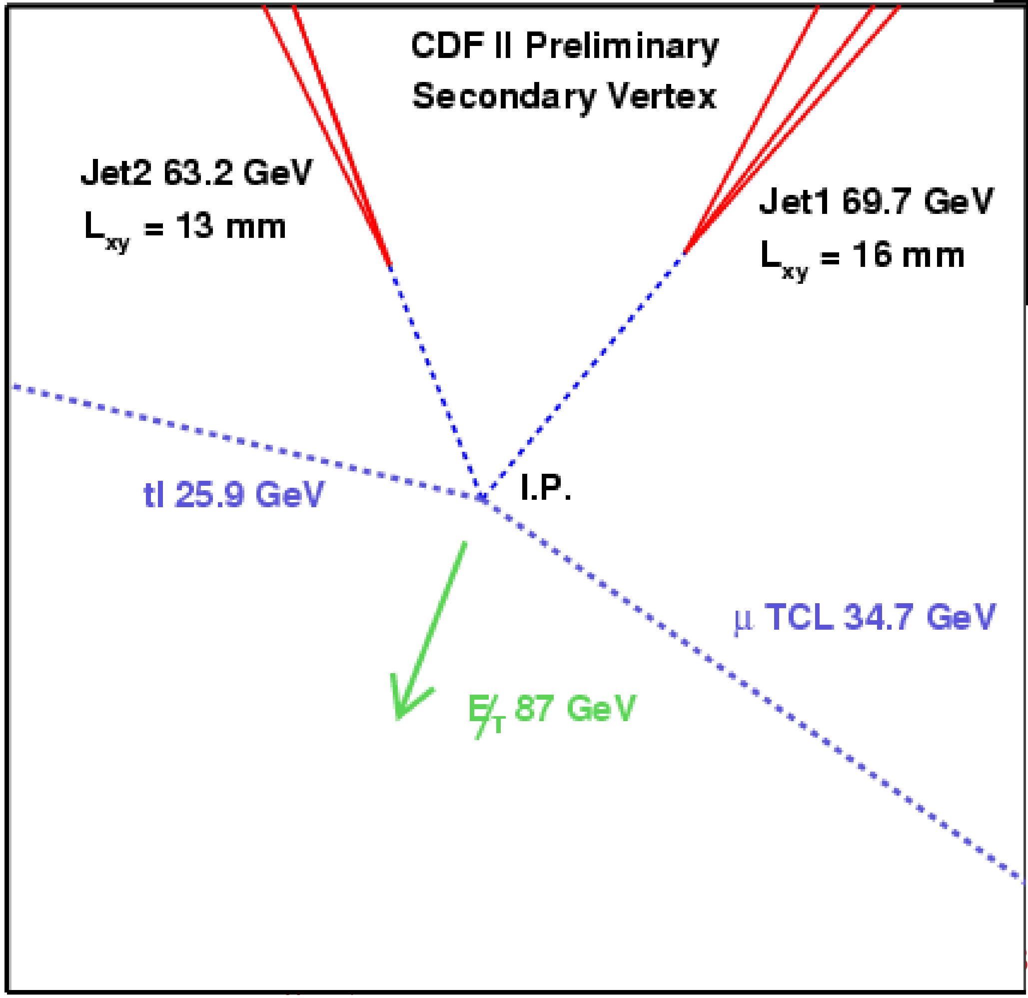
Identify low-pt muon from decay

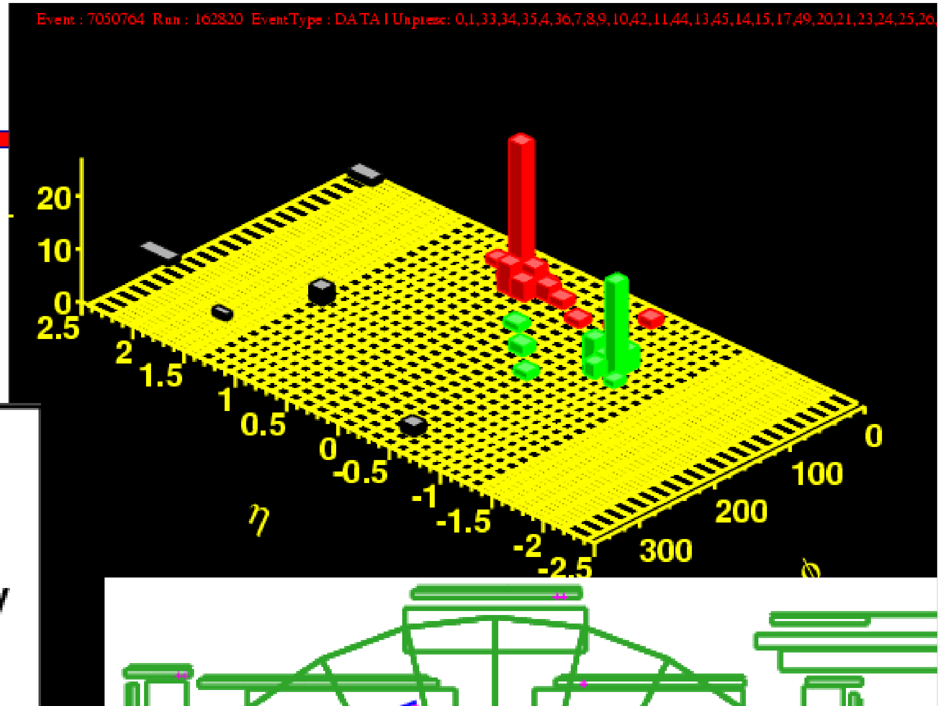


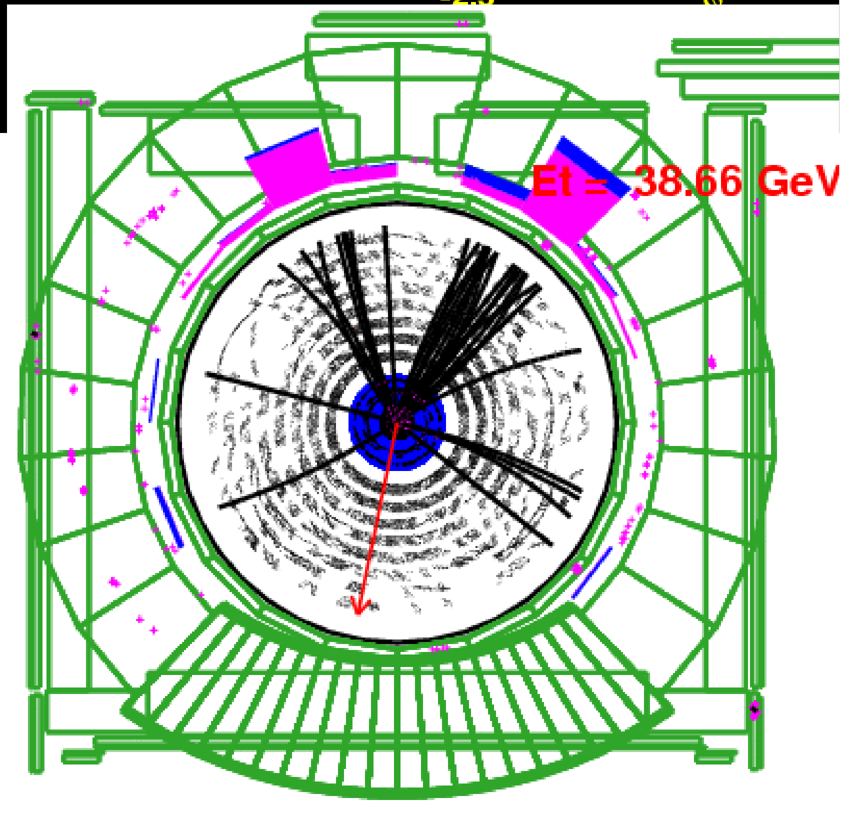
- $b \to \ell\nu c$ (BR ~ 20%)
- $b \to c \to \ell\nu s$ (BR ~ 20%)

60%	Top Event Tag Efficiency	15%
0.5%	False Tag Rate (QCD jets)	~2%

Double b-tagged Lep+Trk event at CDF

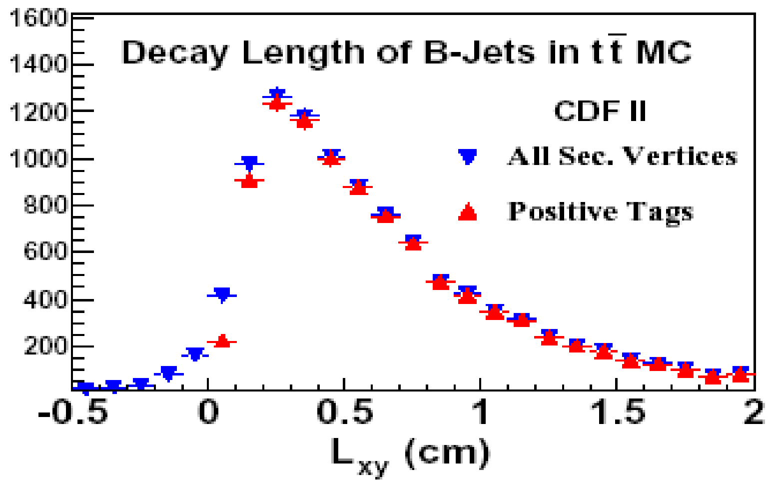


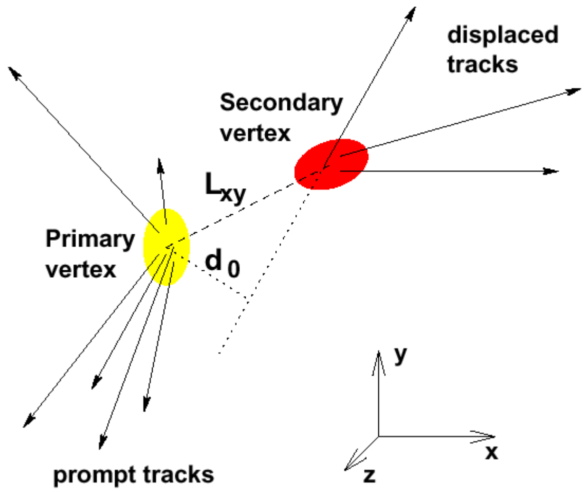




Vertex Tagging Algorithm

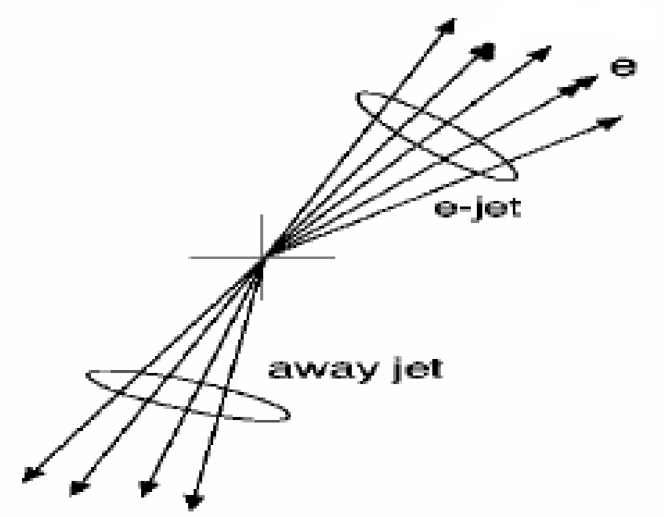
- Take advantage of the long lifetime of B hadrons: $\tau(b) \sim 1$ ps ($c\tau \approx 450\ \mu m$) $\Rightarrow$ B hadrons travel $L_{xy} \sim 3$mm before decay
- Select good quality tracks with large impact parameter.
- Try to reconstruct a vertex with ≥ 2 traks
  - $\Rightarrow$ **first pass** searches for at least 3 tracks with loose kin and Pt >2 GeV/c
  - $\Rightarrow$ **second pass** looks for 2 tracks vertices with tighter cuts on tracks quality and Pt> 3 GeV/c
- A jet containing a vertex is considered b-tagged if has large (positive) decay length significance: $L_{xy}/\sigma_{Lxy} > 7.5$ (typically $\sigma_{Lxy} \sim 150\ \mu m$)





Vertex b-Tagging Efficiency

- Use events with back-to-back jets, non-isolated electron, require away jet to be tagged (enriched in heavy flavor)
- The efficiency of b-tagging determined by the ratio of the number of double tagged to single tagged events, in data and MC
- Define a Scale Factor between data and MC tagging efficiency (usually $\varepsilon_{DATA} < \varepsilon_{MC}$) $SF \approx 0.95 \pm 0.05$
  - $\Rightarrow$ SF < 1 due to # of good vertex tracks higher in MC
- Check in generic jets the E_T dependence of the b-tagging efficiency



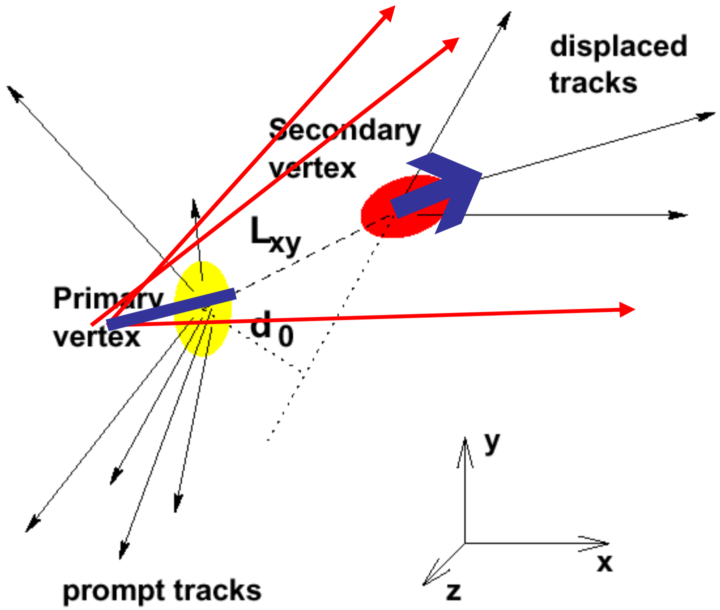
▪Efficiency for tagging at least one jet in a ttbar event (L+>=3 jets, including data-MC scaling):

$$\varepsilon \approx 60 \pm 4\ \%$$

Vertex Tagging Background

- Most from W+heavy flavor and W+mistags
- W+mistags: from generic jet data
- In generic jets heavy flavor pairs are produced by both direct production and gluon splitting. In W+jets by gluon splitting only.
  - ⇒The fraction of Wbb, Wcc events is determined from MC and scaled to the observed number of W events in each jet multiplicity bin
- The (smaller) QCD (non-W) background is evaluated from data: lepton isolation vs Missing E_T method (standard)

W + mistags background



- "Fake tags" background:
  - ⇒The fake background is measured from generic jet data using negative decay-length tags
    - ✓Assume that positive mistag rates are well described by negative (L_{xy} <0) tag rates.
    - ✓Probability to have a negative L_{xy} (~ 0.5% per jet)
      - it is parametrized as a function of the jet E_T, jet silicon track multiplicity, η
      - it is used to estimate the mistag rate:
        - » Negative- non-physical tags = positive mistags
  - ⇒This probability matrix is then applied to W+jets events to obtain the background estimate in our sample

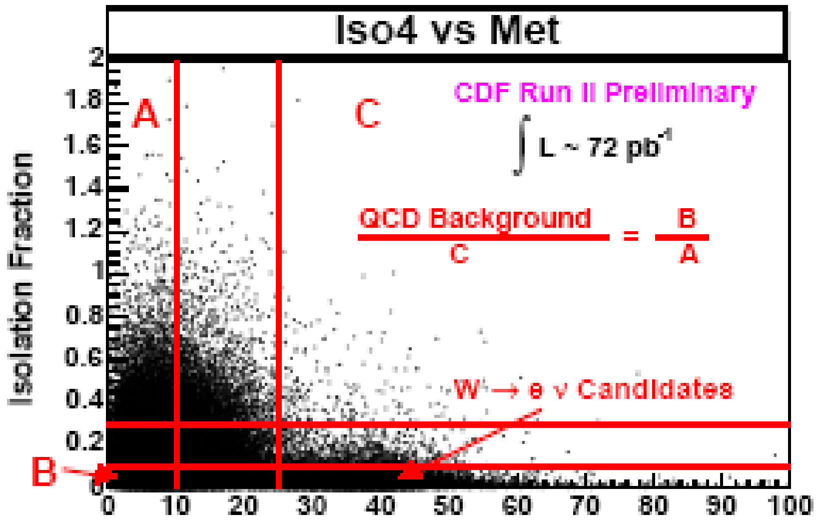
Non-W "QCD" Background: "Iso vs MET"

The simplest and most discriminating difference between an "isolated" electron as the one coming from the W decay and a jet is the Isolation.

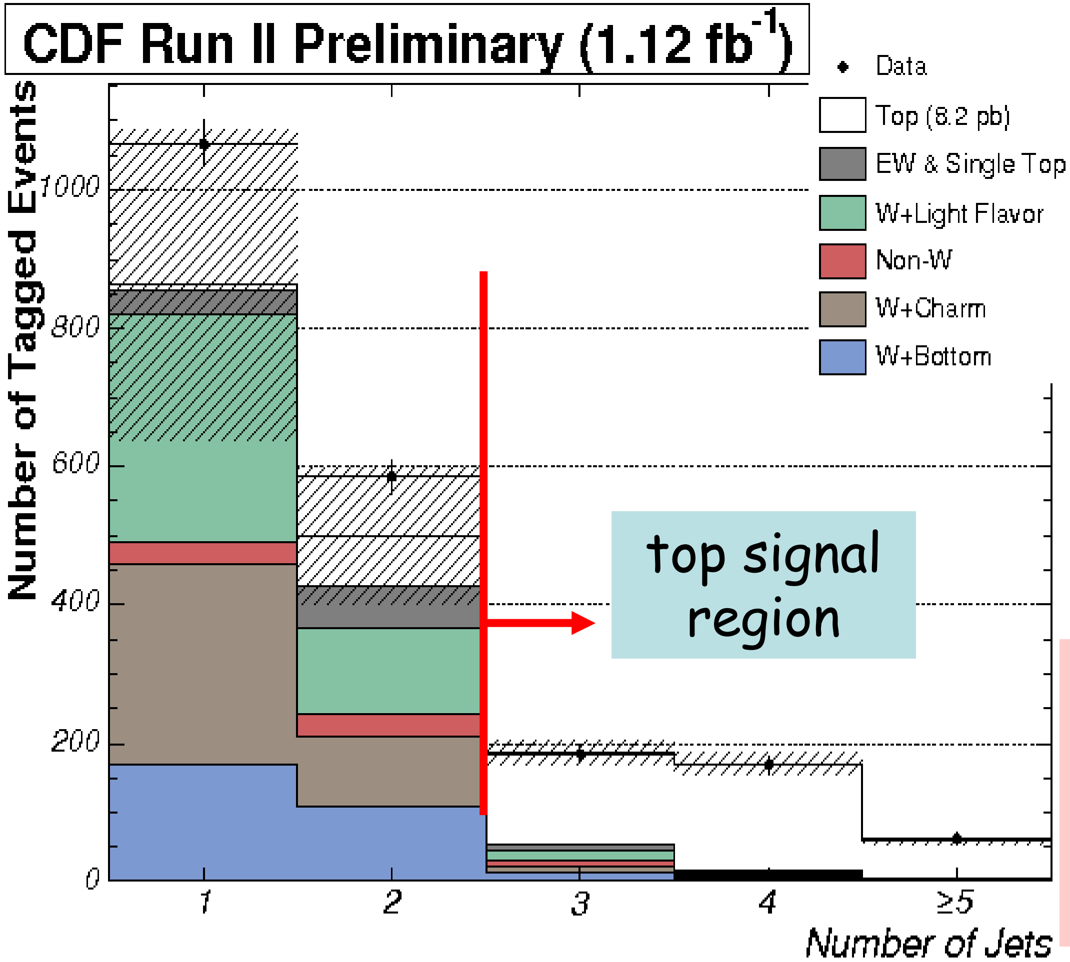
There is NO correlation between Missing Transverse Energy and Isolation for dijet events faking a W->eν candidate.

→"Isorel vs MET" method

Non trivial statement



Lepton + jets with = 1 vertex tag:results



Number of jets per event:

Mis tag from Generic jet data

MET vs Isolation method: data driven

Method II: based on MC

=1 SecVerteX = 416 events on 74 ± 21 bkgnd

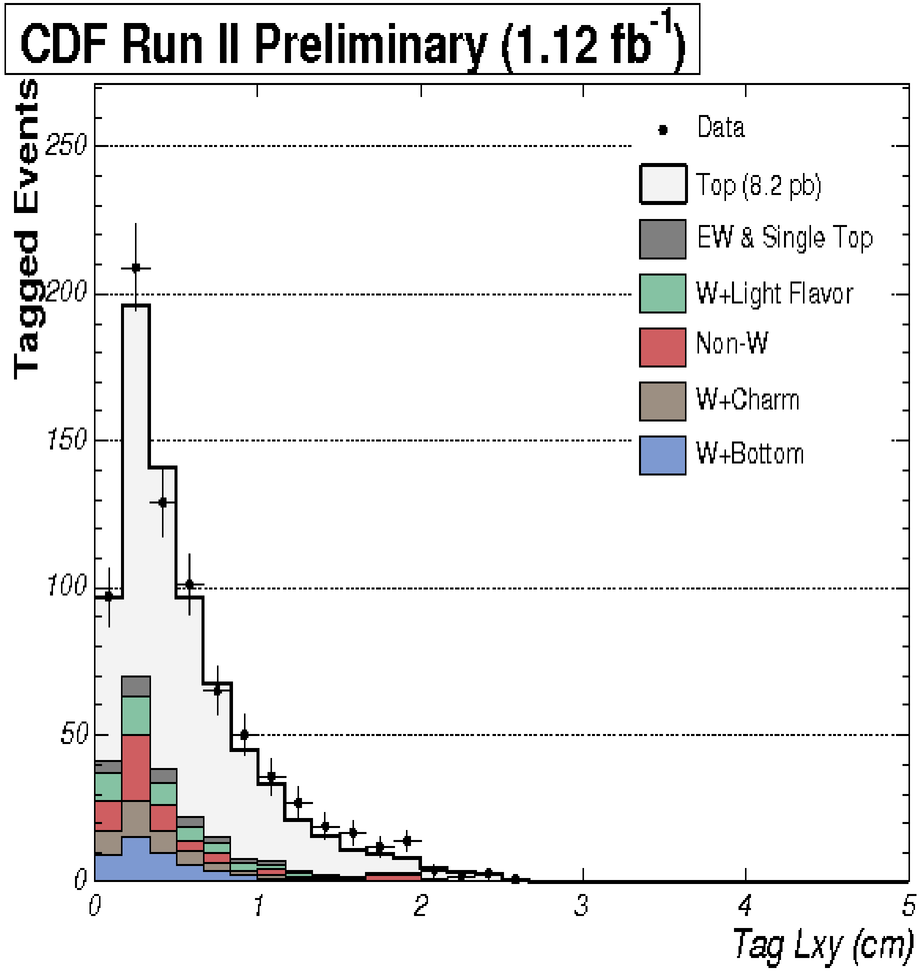
=2 SecVerteX = 165 on 16±8

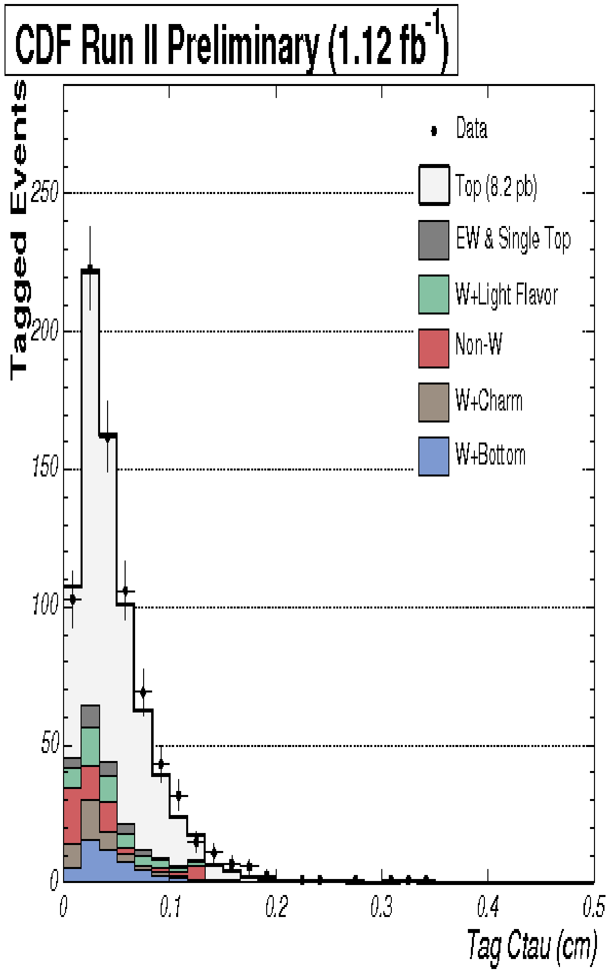
Summary of secondary vertex counting

Require H_T > 200 (250) GeV for 3, ≥ 4 jets bins only,

	W + 1 j	W + 2 j	W + 3 j	W + ≥ 4 j
Single tag sample				
Events before tagging	78903	12873	870	543
Observed positive tags	1067	585	185	231
Back	854±225	427±100	53±14	21±8
Loose double tags sample				
Pretag	78903	12873	1515	639
Double tags	-	63	64	101
Back	-	34±10	12±5	4±3

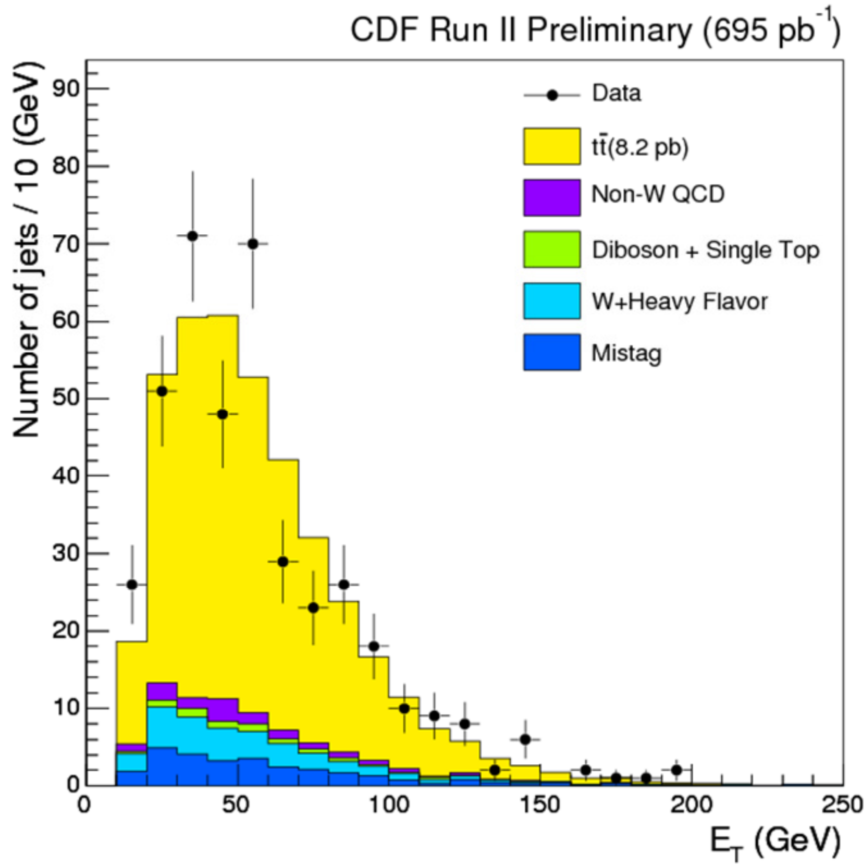
Tagged Jets Properties





The tagged events contain b quarks, as seen by the decay length L_{xy} distribution

Tagged Jets Properties



The tagged jets are kinematically consistent with the expectation from top, as seen by their E_T distribution

Lepton +jets cross section

1.2 fb^{-1}

- High pt lepton plus missing E_T
- N(jet) ≥ 3
- ≥ 1 jet SEC(ondary) VTX
- H_T>200 GeV

$$\sigma(t\bar{t}) = \frac{N(W + \geq 3\ jets) - N(BKG)}{A \cdot \varepsilon \cdot \int Ldt}$$

A: **ttbar acceptance** ε: b-jet eff. for ttbar

$\sigma(t\bar{t}) =$ **8.2±0.5**(stat)±**0.8**(syst) pb

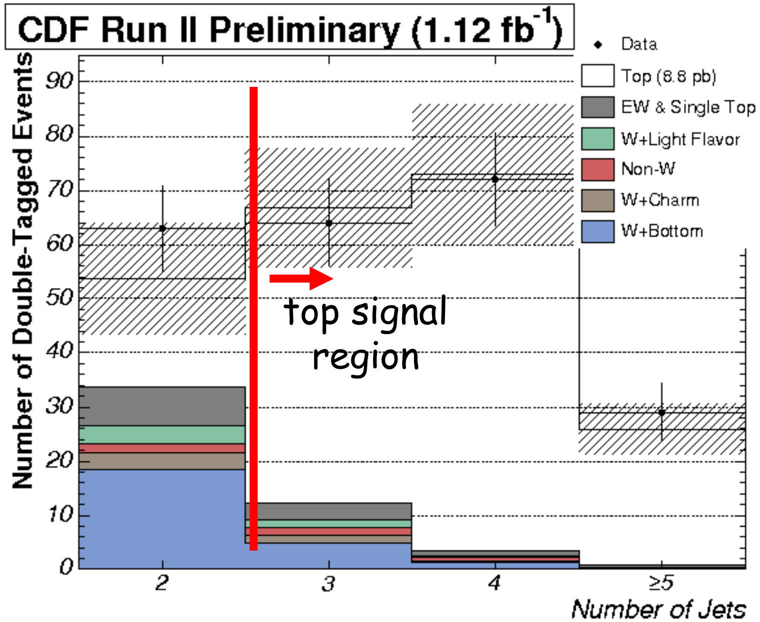
Assuming a top mass of 175 GeV/c^2

Lepton +jets with ≥ 2 vertex tags

Lower statistics but low background:
79 events observed in top region, 9.1 ± 1.8 bkgd expected

b-tagging efficiency and its uncertainty enters twice here

2 jet bin:
63 events observed,
~ 34±10 bkg.
~ 20 ttbar expected



# of jets per event:

$\sigma(tt) =$ 8.8±0.8(stat.)±1.3(sys.) pb

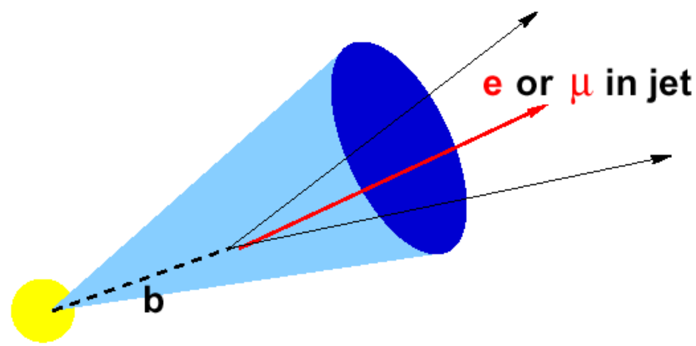
for a top mass of 175 GeV/c^2

Soft Lepton Tagging

- Leptons from semi-leptonic decays of B have a softer p_T spectrum than W/Z leptons and are less isolated

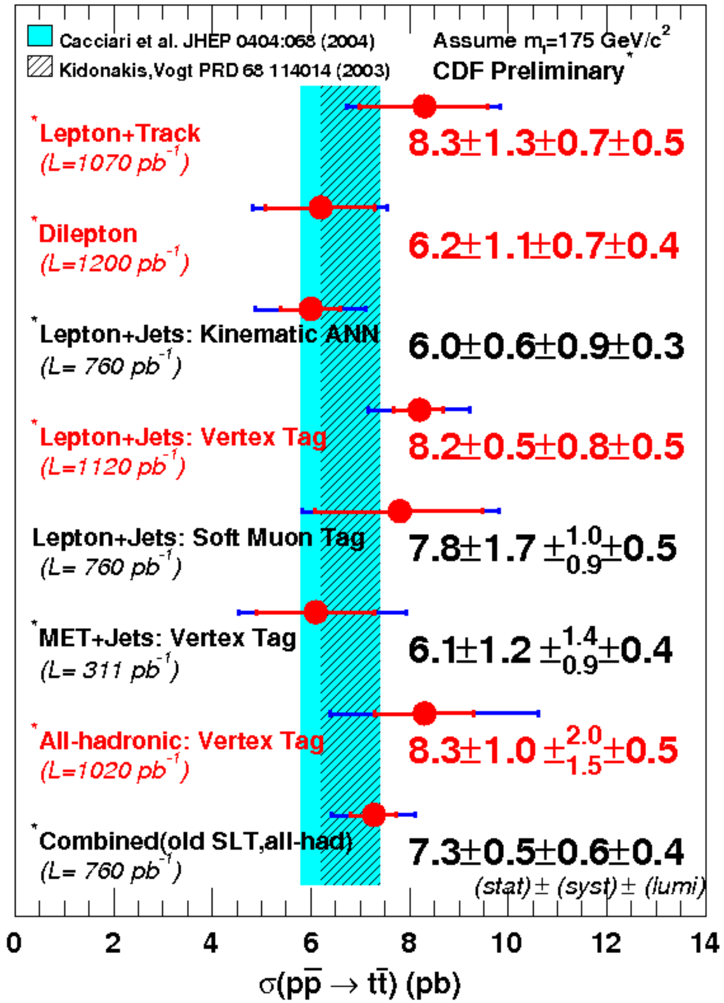
❖ Soft Muon Tagger based on a "Global χ^2" to identify low-p_t muons:
  - "Global χ^2" combines information from muon matching variables
  - There is no calorimetry or isolation requirements

❖ b-tagging with SLTμ:
  - Track with $dR_{slt\text{-}jet}<0.6$, $|dZ_{slt\text{-}Zvtx}|<5$cm & $p_T>3$ GeV/c are considered by the SLTμ tagger
  - An event is tagged if at least one SLTμ tag is found

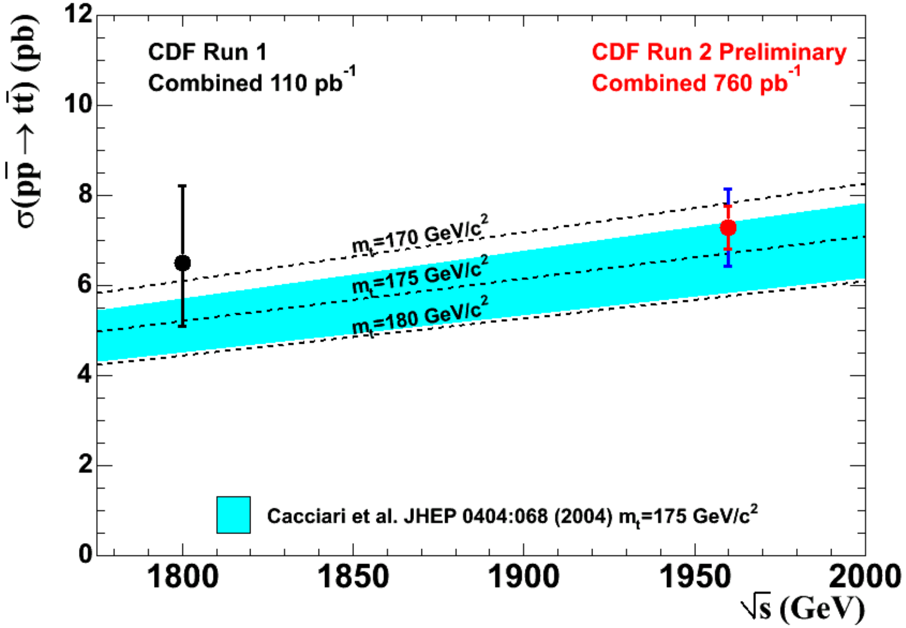


- $b \to \ell\nu c$ (BR $\sim$ 20%)
- $b \to c \to \ell\nu s$ (BR $\sim$ 20%)

Top cross section summary



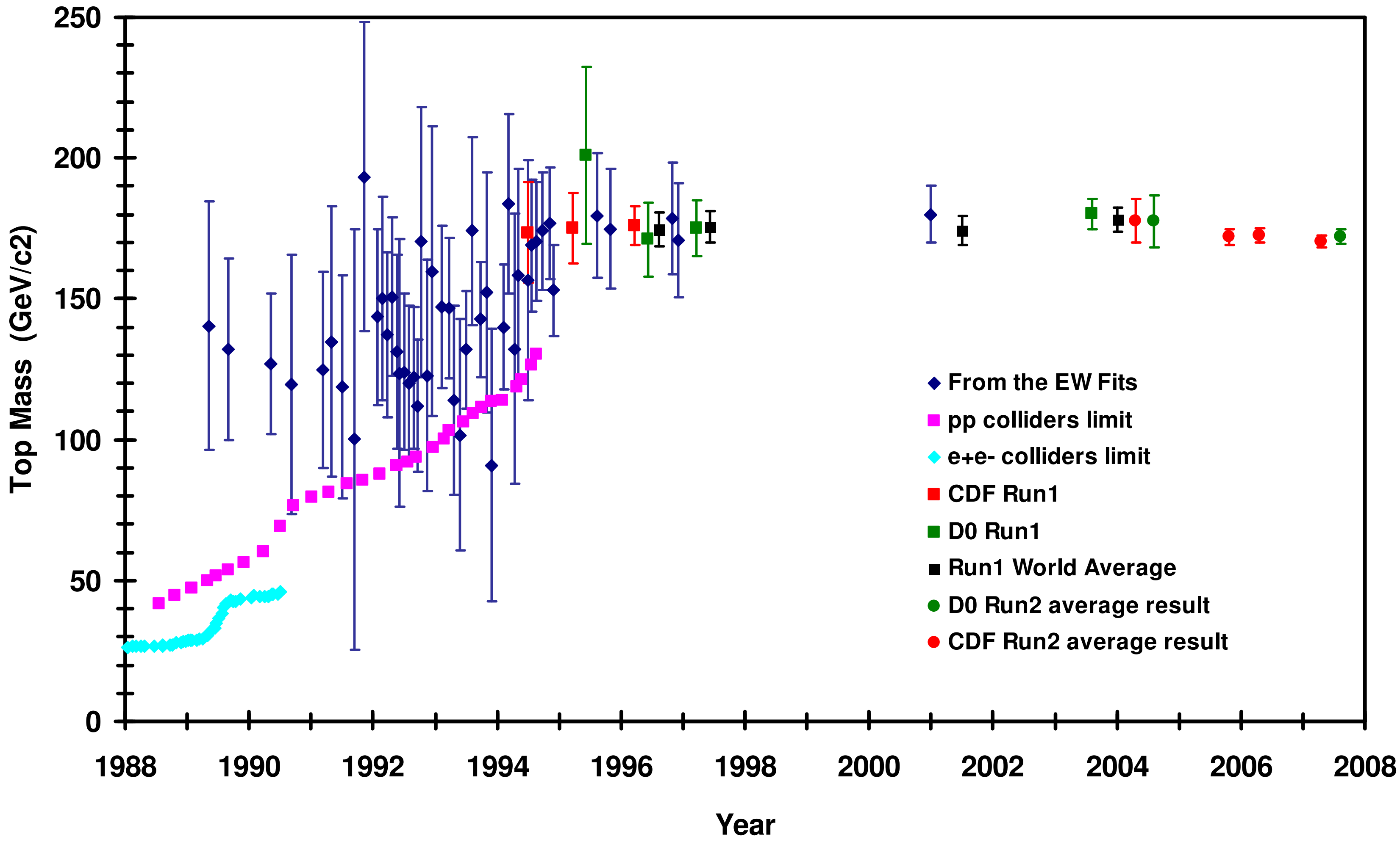
√s-Dependence:



⇒ Main data driven systematics (jet energy scale, ISR, ε_{btag}) scale with $1/\sqrt{N}$:

⇒ RunII(2fb^{-1}) $\delta\sigma_{tt}/\sigma_{tt}$ <10%

Top Mass

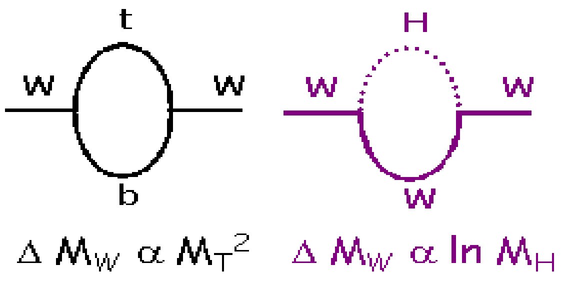


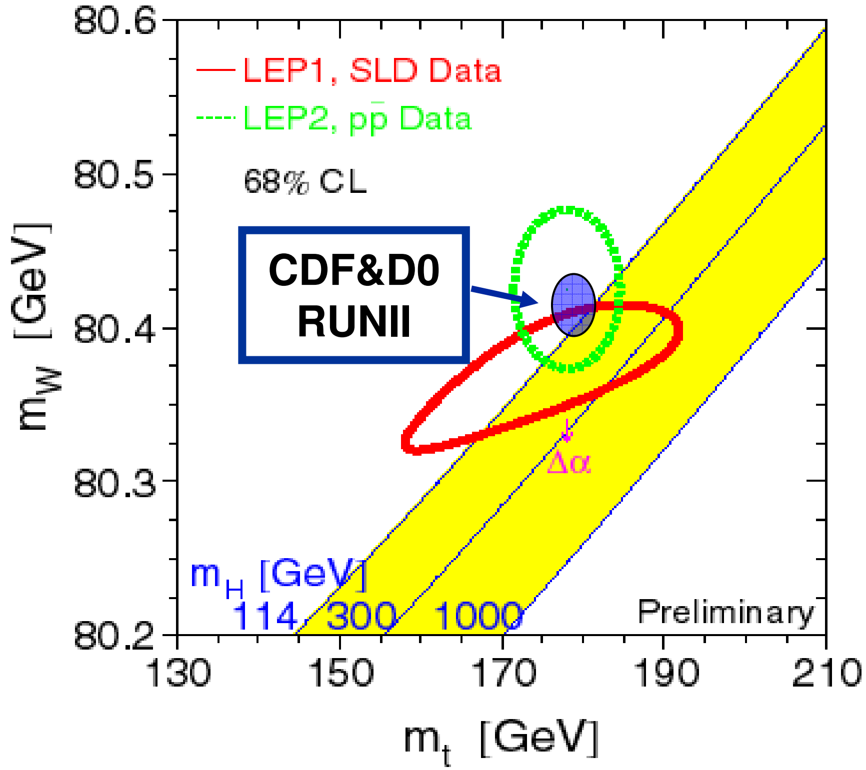
250
200
150
100
50
0
Top Mass (GeV/c2)
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Year
From the EW Fits
pp colliders limit
e+e- colliders limit
CDF Run1
D0 Run1
Run1 World Average
D0 Run2 average result
CDF Run2 average result

Why is Top Mass so special?

Top mass is a fundamental SM parameter

- Related through radiative corrections to other EW observables.





- Very important for precision tests of SM.
- Together with M_w and other electroweak precision measurements, it constrains M_{Higgs}
- By far the largest quark mass, largest mass of all known fundamental particles

What is the top mass?

- Particle masses are not “directly measured”
  - ⇒ one can only measure cross sections, decay rates
- Measurement of M_{top}: at Tevatron, LHC:
  - ⇒ kinematic reconstruction, fit to invariant mass distribution
  - ⇒ Best measurement from lepton +jets
- Experimental accuracy of M_{top} :
  - ⇒ Measurement ⇔ comparison data from Monte Carlo
  - ⇒ you measure the mass that is implemented in your MC
    - ✓ measured mass is not strictly model independent
- Situation at the Tevatron:
  - ⇒ δM_{top} = 1.8 GeV (Tevatron; today, stat+sys.)
- Projections at the LHC:
  - ⇒ δM_{top} < **1 GeV with 10 fb^{-1}**

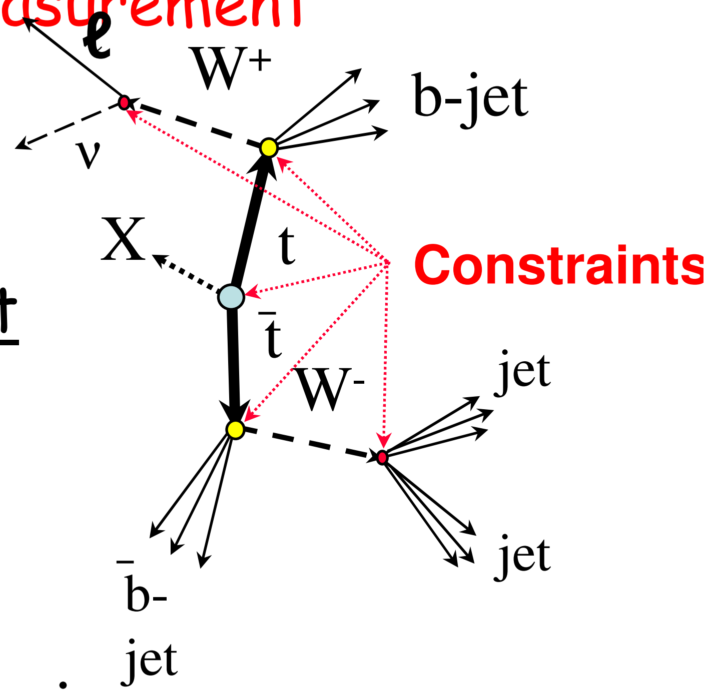
→Will Tevatron get there first?

Top Mass Measurement Challenges

Why so challenging? It is a difficult measurement

Many combinations of leptons and jets:

- Events are complicated!
- Measurements are not perfect!
- Experimental observations are not as *pretty* as Feynman diagrams!



- Missing neutrino
- Confusion in ID assignment (add. Jets from ISR/FSR, b-tag: not 100% correct)

- Link observables to parton-level energies
- Large syst uncert. from jet energy scale
- Need accurate detector simulation

Method: reconstruct M_{top} with 2 constraints:
$M(W^+)=M(W^-)$, $M(t)=M(tbar)$

Lepton + ≥ 4 jets: template method

Datasets

Data

Wbb MC

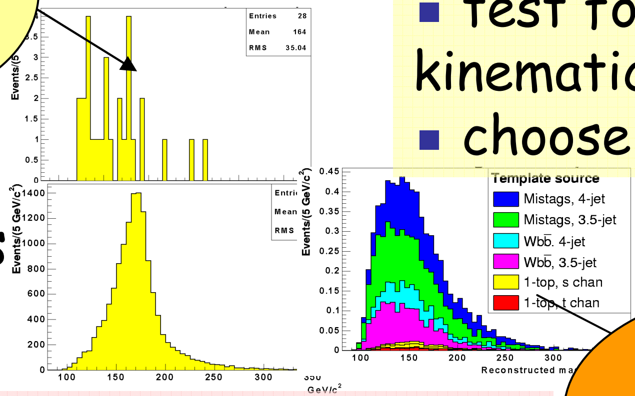
tt MC

Mass fitter

χ^2 mass fitter:

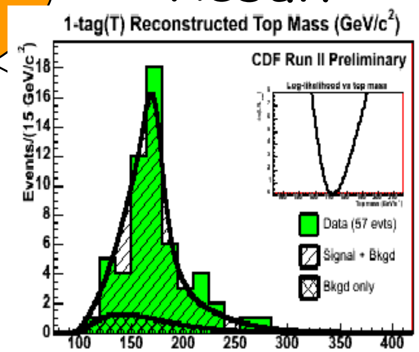
- Finds top mass that fits event best
- *All event info into one number*
- 12 parton/jet matching assignments possible, 2 longit. neutrino possible, use b-tag to reduce permutations
- test for consistency with top using kinematic constraints
- choose combination with lowest χ^2

Templates



Likelihood fit

Result



Likelihood fit:

- fit resulting mass distribution to MC background + top signal templates at different values of M_{top}
- Best template to fit data gives mass
- Constraint on background normalization

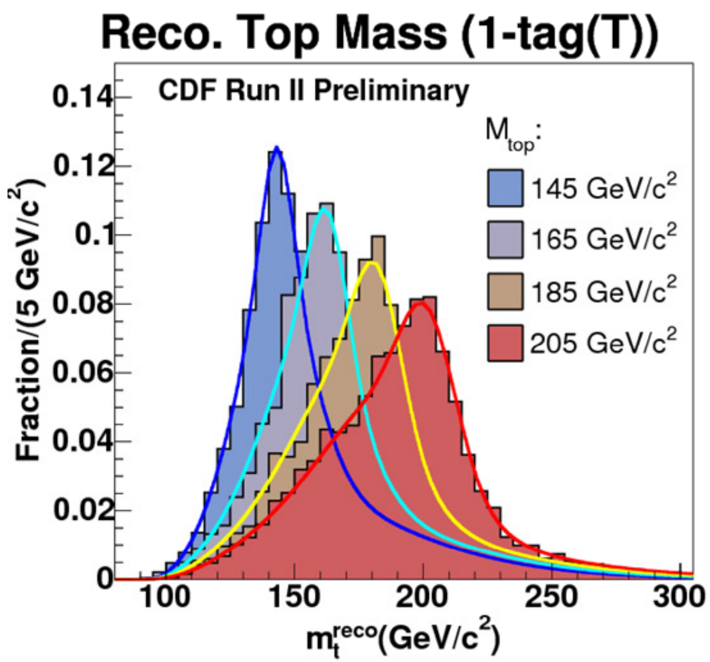
The new CDF top mass measurement in Lepton+Jets channel with 1.7 fb^{-1}

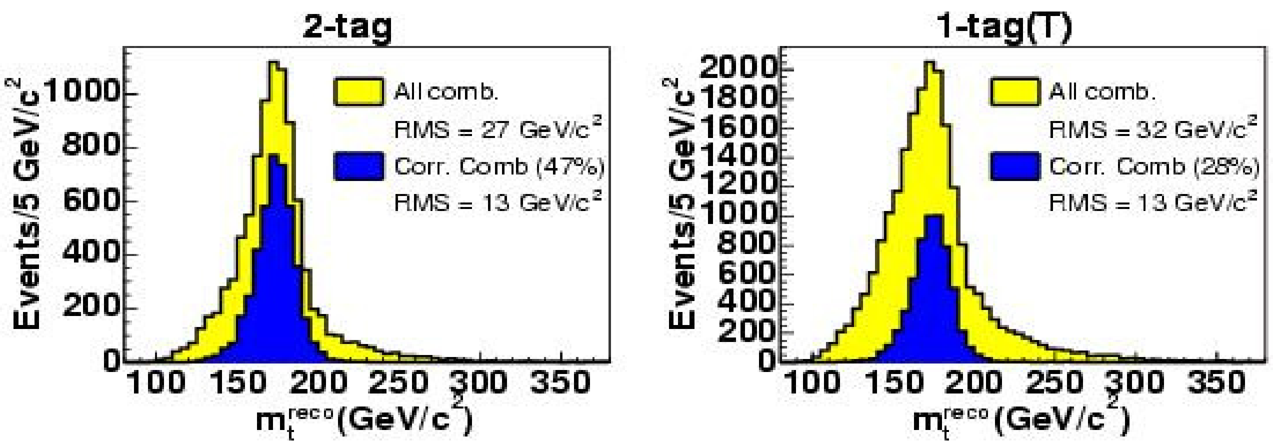
Improve stat. power of the method dividing the sample in 2 categories of events that have different backg. contamination and different sensitivity to the top mass

Categ.	1-tag	2-tag
j1-j3 j4	E_T>20 E_T>20	E_T>20 E_T>12
exp-.back	36.6±7.1	6.4±1.7
Obs.# ev.	218	89

- Subdivision improves statistical uncertainty.
  - ⇒ Pure and well reconstructed events contribute more to result.
  - ⇒ Adds 0-tag events.
- Subdivision does *not* improve systematic uncertainty.
  - ⇒ Most systematics, including jet energy scale, are highly correlated among the samples.

Top Mass reconstruction in Montecarlo events





Mass analysis event selection & Backgrounds

- W+heavy flavor jets(bb,cc,c)
  - ⇒ Heavy flavor fraction from MC
  - ⇒ Normalized to data
- W+jets(mistag)
  - ⇒ Use measured mistag rate, applied to the data
- Multijet:non-W (jet->e, track->μ)
  - ⇒ Estimated from data
- Single top, diboson (WW,WZ)
  - ⇒ Estimated from MC

In 1700 pb^{-1}
307 candidate events used for top mass measurement

Systematic Errors (based on 318pb^{-1})

Systematic	ΔM_{top} (GeV/c^2)
Jet Energy Scale	**3.1**
ISR	0.4
FSR	0.4
PDFs	0.4
Generators	0.3
Background shape	1.0
b-jet energy scale	0.6
b-tagging	0.2
MC statistics	0.4
TOTAL	3.4

Dominated by jet energy scale:

Can we improve jet systematic?

Systematic Errors

Systematic	ΔM_{top} (GeV/c^2)
Jet Energy Scale	**3.1**
ISR	0.4
FSR	0.4
PDFs	0.4
Generators	0.3
Background shape	1.0
***b*-jet energy scale**	**0.6**
b-tagging	0.2
MC statistics	0.4
TOTAL	3.4

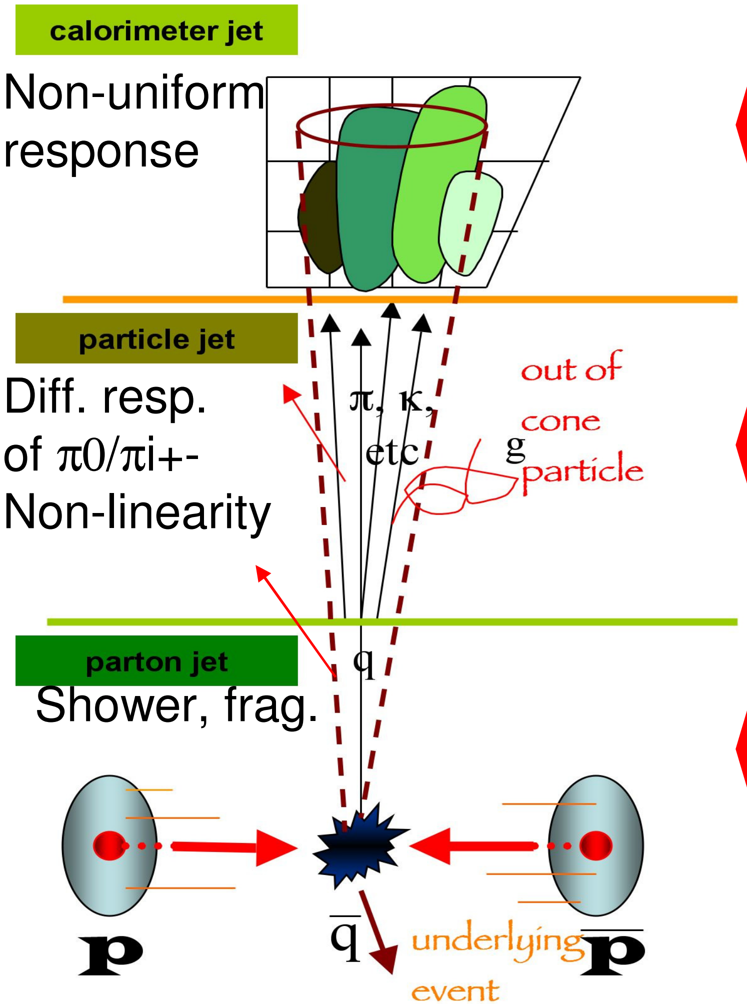
→

B-jet energy scale	ΔM_{top} (GeV/c^2)
Heavy quark fragmentation	0.4
Color flow	0.3
Semi-leptonic decay	0.4
Total	0.6

Though we find that 70% of JES uncertainty comes from b-jet, b-jet uncertainty is mainly due to generic jet corrections: only 0.6 GeV/c^2 additional uncertainty on M_{top} due to b-jet-specific systematics

Jet Energy Mismeasurement

Precision on the determination of jet energies is necessary for M_{top} measurements.
Jets may be mismeasured due to a variety of effects:



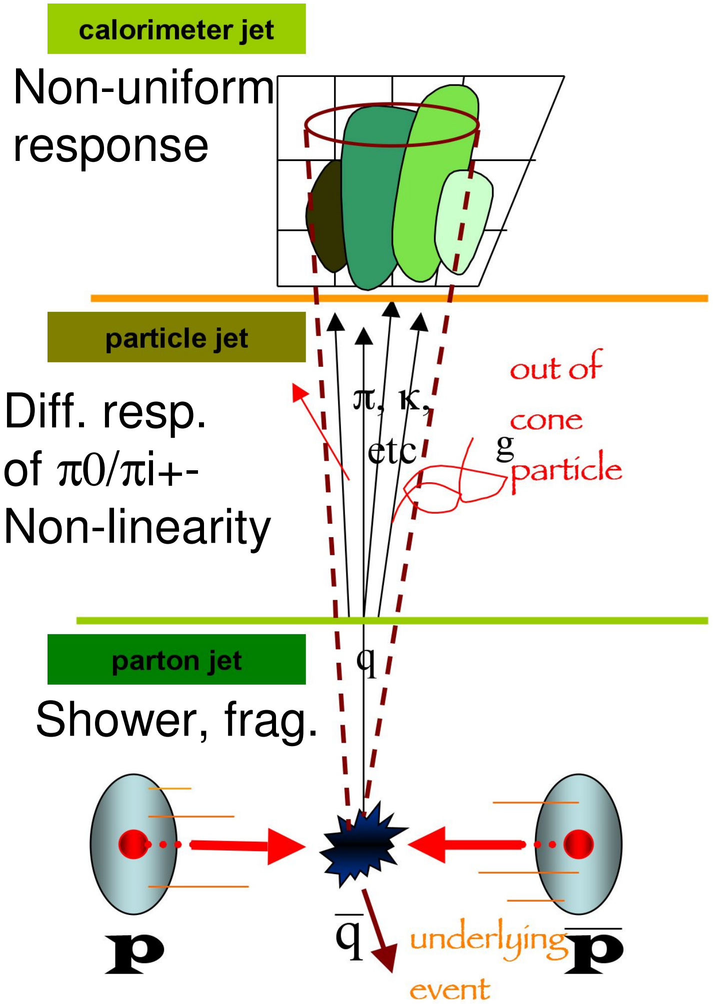
- **Instrumental effects:**
  - calorimeter non-linearities
  - non-instrumented regions
  - non-compensating calorimeter

- **Algorithm effects:**
  - might not capture all particles (out of cone)
  - low energy jets might not be possible to define

- **Physics effects**
  - Contribution from underlaying event
  - multiple ppbar interactions
  - there are different types of jets

Jet Energy Correction

Determine true "parton" E from measured jet E in a cone 0.4



The correction factor depends on jet E_T and η and is meant to reproduce the average jet E_T correctly, (not to reduce the jet fluctuations around this mean)

A set of corrections was developed for generic jets:

⇒Absolute corrections (photon-jet balancing)

⇒Relative corrections (central-forward calorimeters, dijet balancing)

Out-of-Cone: correction to parton

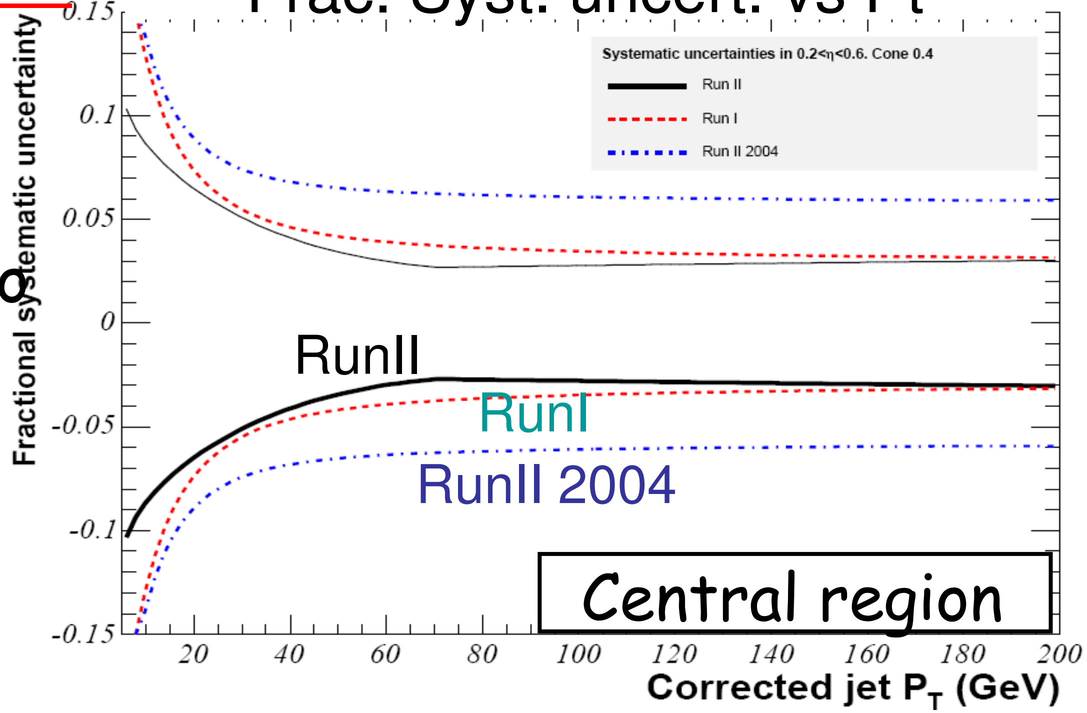
Underlying event

"top-specific correction" to light quark jets and b-jets separately

Jet Energy Systematics

- What is jet energy scale “JES”?
- Measures how incorrect is our nominal jet energy measurement.
- Units of σ: correspond to one s.d. of jet energy uncertainty
  - ⇒ Accounts for E_T, η dependence.

Frac. Syst. uncert. vs Pt



A lot of work has been done to reduce the syst. from jet-energy scale (a factor of two improvement compared to start of RunII). The new Run II systematic uncertainties are now better than Run I.

World's Best Top Quark Mass: M_{top}+ JES simultaneous fit

- Measure JES *in situ.*
- Perform simultaneous fit.

⇒ Extend 1-D template (only on *reconstructed M_{top}*) to maximize sensitivity to Jet Energy Scale:

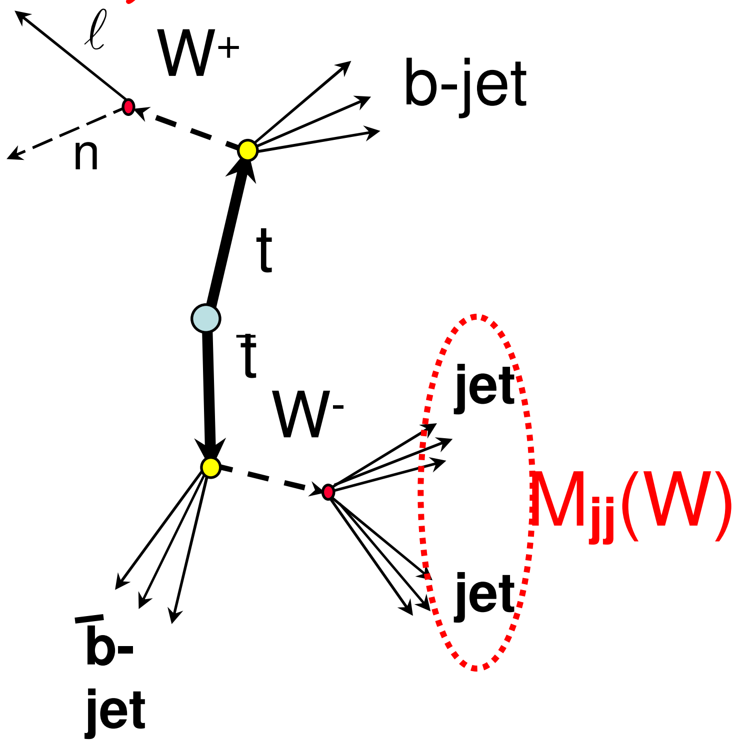
⇒ M_{top} and JES are simultaneously determined in likelihood fit using shape comparisons of *Reconstructed M_{top}* and, *Reconstructed M_{jj}* distributions, taking correlations between them

JES and Mtop measurements
- 2D Template Analysis -

Simultaneous fit to JES and Mtop using top mass and W mass templates:

M_t (true M_{top}, JES), M_{jj} (true M_{top}, JES)

- Identify jets coming from W
  - All non-btagged jets pairs are taken into account equally.
  - 1/3/6 M_{jj} per event with 2/1/0 b-tag
- Reconstruct their invariant mass M_{jj}
- M_{jj} strongly dependent on JES
  - Make Mjj templates by varying JES
  - Fit data with Wjj to measure JES!
- M_W uncertainty is negligible (< 50 MeV)
- M_{jj} mostly independent of M_{top}
- This scale is applied to b-jets and light-quark jets



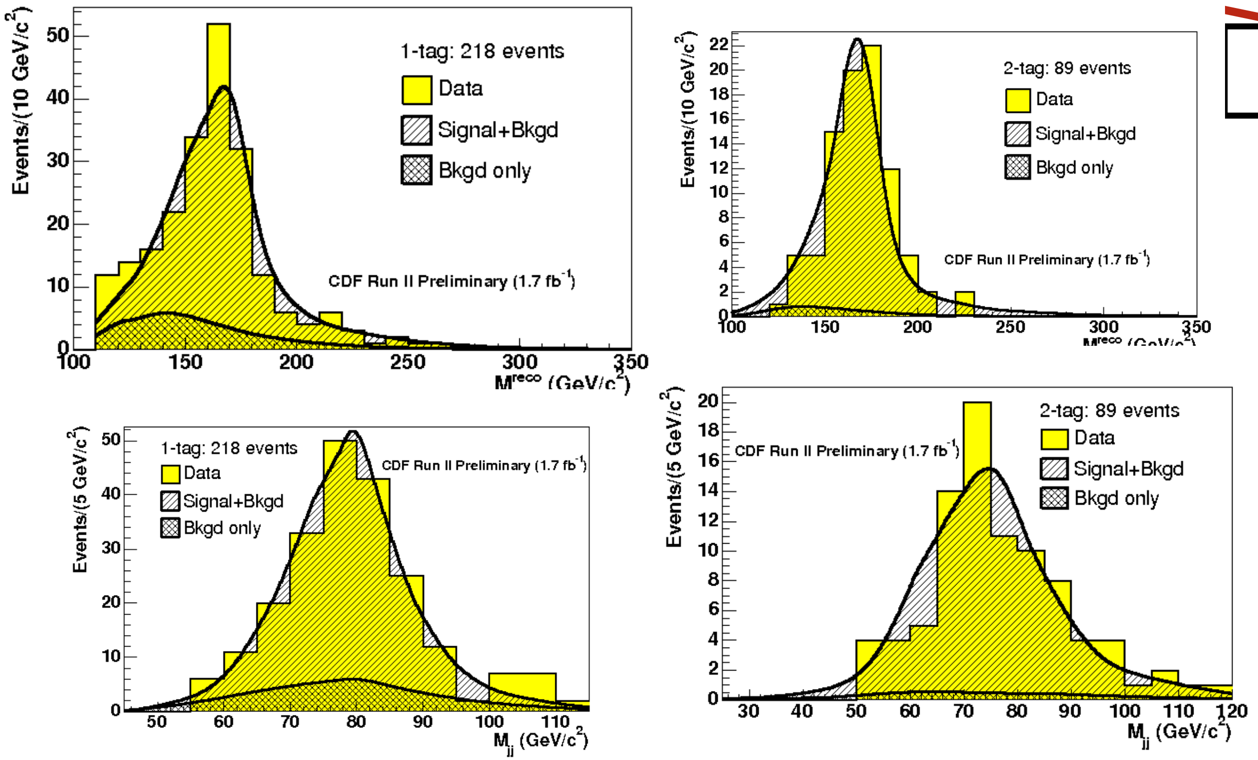
JES from W→jj is mostly statistical → luminosity scale !

2D Top Mass Result with 1.7 fb^{-1}

Using 307 candidates in 1.7 fb^{-1} we measure:

$$M_{top} = 171.6 \pm 2.1\,(\text{stat}) \pm 1.1\,(\text{syst})\ \text{GeV}/c^2$$

$\pm$ 1.5 (stat) $\pm$ 1.5 (JES)



M_{top} = 171.6 $\pm$ 2.4 GeV/c^2

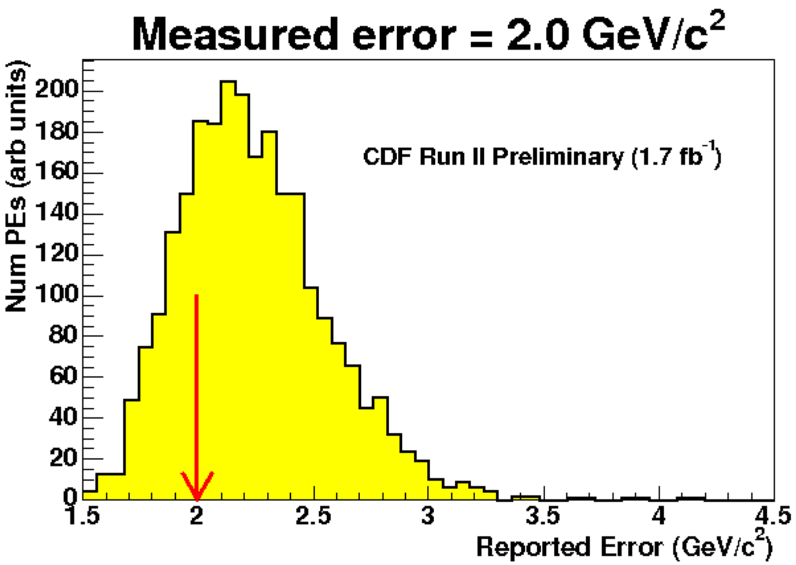
Best single measurement in the world!

m_t^{reco} in data w/ global best fit overlaid

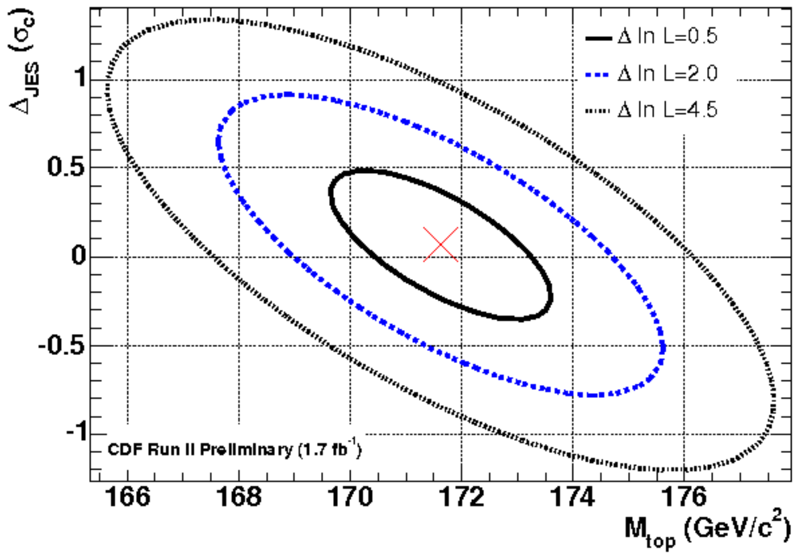
JES Results with 1.7 fb^{-1}

$$\Delta_{JES} = -0.3 \pm 0.6\ (\text{stat.} + M_{top})\ \sigma_c$$

- Check if measured error consistent with expected (using pseudo-experiments)



JES vs Mtop Log likelohood contours



Systematic Uncertainty in 1.7 fb^{-1}

Systematic	ΔM_{top} (GeV/c^2)
Residual JES	0.55
B-jet energy scale	0.6
Bkgd JES	0.38
Bkgd Shape	0.2
ISR	0.37
FSR	0.23
Generators	0.25
PDFs	0.17
MC stats	0.1
QCD modelling	0.11
TOTAL	**1.1**

← From pT and η dependence of modeling uncertainties

} Model constrained by Z+jets data

Systematics are largely due to uncertainties in modeling.

Top mass: matrix element (ME) method

- Optimizes the use of kinematic and dynamic information
- Calculate a probability per event to be signal or background as a function of the top mass
- Signal probability for a set of measured jets and lepton (x)

$$L = \frac{1}{N(m_t)} \frac{1}{A(m_t, \mathrm{JES})} \sum_{i=1}^{24} w_i \int \frac{f(z_1) f(z_2)}{FF} \mathrm{TF}(\vec{y} \cdot \mathrm{JES} \mid \vec{x}) \, |M_{t\bar{t}}(m_t, \vec{x})|^2 \, d\Phi(\vec{x})$$

$$\text{with} \quad L = L(\vec{y} \mid m_t, \mathrm{JES})$$

Transfer function: probability to measure x when parton-level y was produced

Differential cross section: LO ME (qq->tt) only

- Likelihood simultaneously determines M_{top}, Jet Energy Scale, and signal fraction:

$$L(f_{top}, M_{top}, JES) \propto \prod_{i}^{Nevents} \left(f_{top} \, P_{top,i}(M_{top}, JES) + (1 - f_{top}) \, P_{bkgd,i}(JES) \right)$$

- All jet-parton assignments and neutrino solutions are considered, weighted.
- Select events with exactly 4 jets, well described by LO ME.

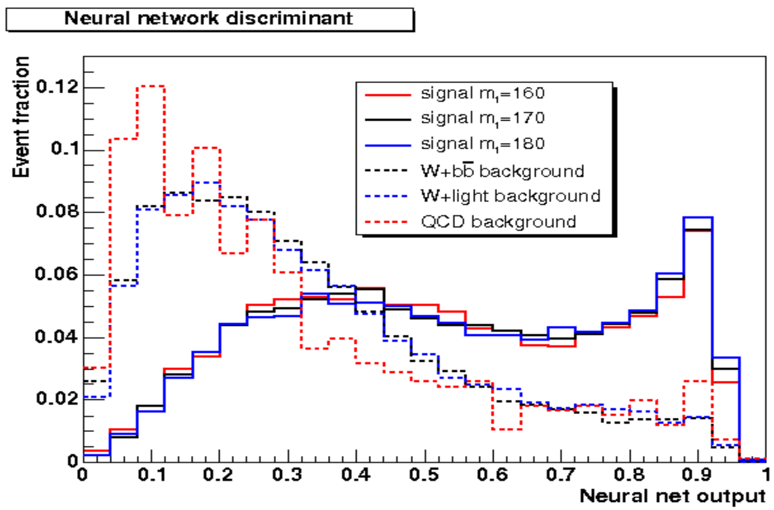
Selection

- After kinematic selection:

Background	1 tag	$\geq$ 2 tags
non-W QCD	12.48 ± 10.76	0.42 ± 1.50
W+light mistag	14.52 ± 3.20	0.28 ± 0.08
diboson (WW, WZ, ZZ)	2.95 ± 0.24	0.24 ± 0.02
$Z \to ee, \mu\mu, \tau\tau$	1.72 ± 0.18	0.06 ± 0.01
Sum of above 3	19.19 ± 3.21	0.58 ± 0.08
W+$b\bar{b}$	12.14 ± 4.90	2.46 ± 1.01
W+$c\bar{c}$, c	11.07 ± 4.50	0.51 ± 0.22
Single top	2.78 ± 0.17	0.83 ± 0.07
Sum of above 3	25.99 ± 9.13	3.80 ± 1.20
Total background	57.66 ± 14.88	4.80 ± 2.37
Events observed	263	80

Measurement

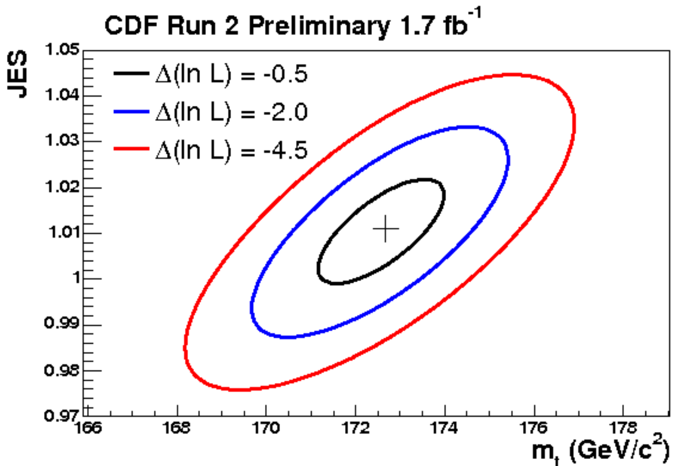
- Each event is treated as top
  - ⇒We know there is background
  - ⇒Create a weight to be top or background
- A kinematic NN is applied. Its output used to weight events :
- Also exploited to reject some background



Matrix Element (L+J) Results—1.7 fb^{-1}

- **Exactly 4 jets with ≥ 1 b tags**
- JES here is a constant multiplicative factor.
  - $\Rightarrow E^{data} = E^{MC}/JES$
- JES = 1.02 ± 0.02.
  - ⇒Consistent with template method
- Virtually identical sensitivity with fewer events!

Using 293 candidates in 1.7 fb^{-1}

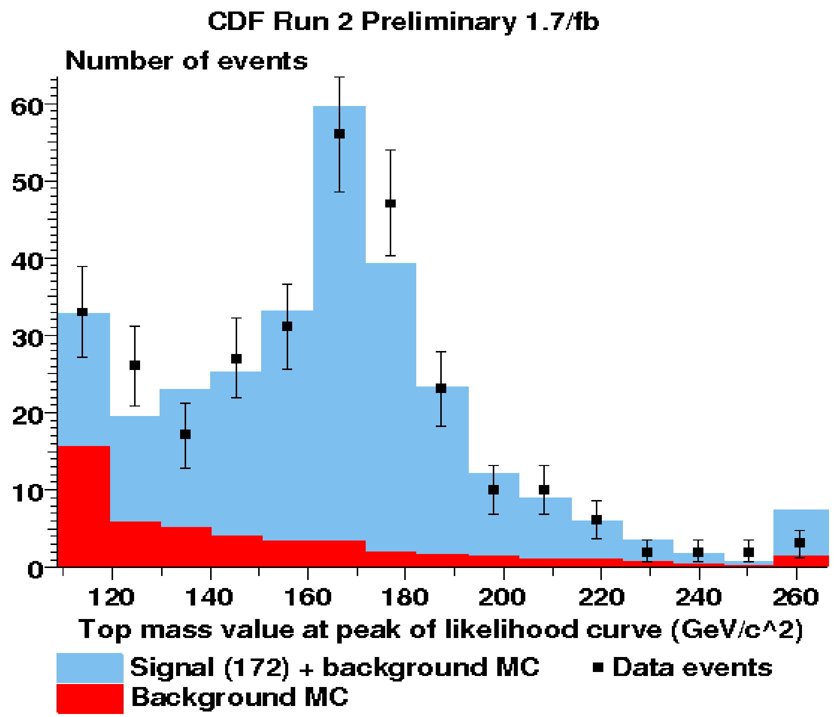


Systematic source	Systematic uncertainty (GeV/c^2)
Calibration	0.09
MC generator	0.19 ± 0.36
ISR	0.26 ± 0.37
FSR	0.13 ± 0.38
Residual JES	0.53
b-JES	0.36
Lepton P_T	0.11
Permutation weighting	0.03
Multiple interactions	0.05
PDFs	0.25
Background fraction	0.33
Background composition	0.39
Background average shape	0.31
Background Q^2	0.07 ± 0.20
Gluon fraction	0.14
b-tag E_T dependence	0.16
Total	1.16

$$M_{top}(\mathrm{ME/LJ}) = 172.7 \pm 1.8\,(\mathrm{stat+JES}) \pm 1.2\,(\mathrm{syst})\,\mathrm{GeV}/c^2$$

One dimensional projection

- If one looks at the 1d projection:



Top mass summary

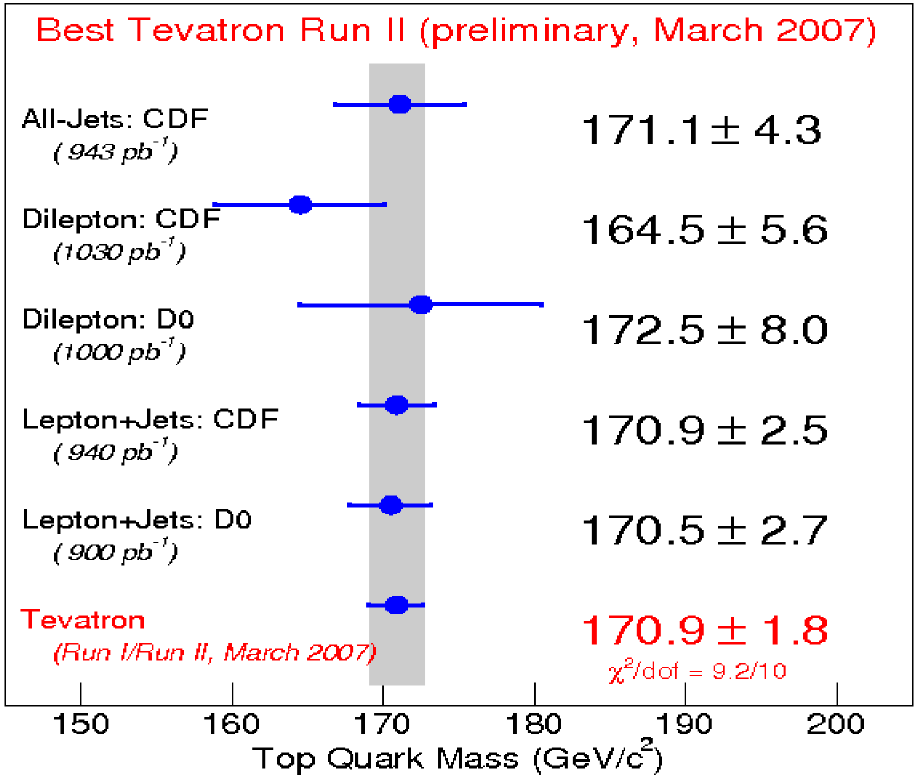
Tevatron March 07: 170.9± 1.1±1.5

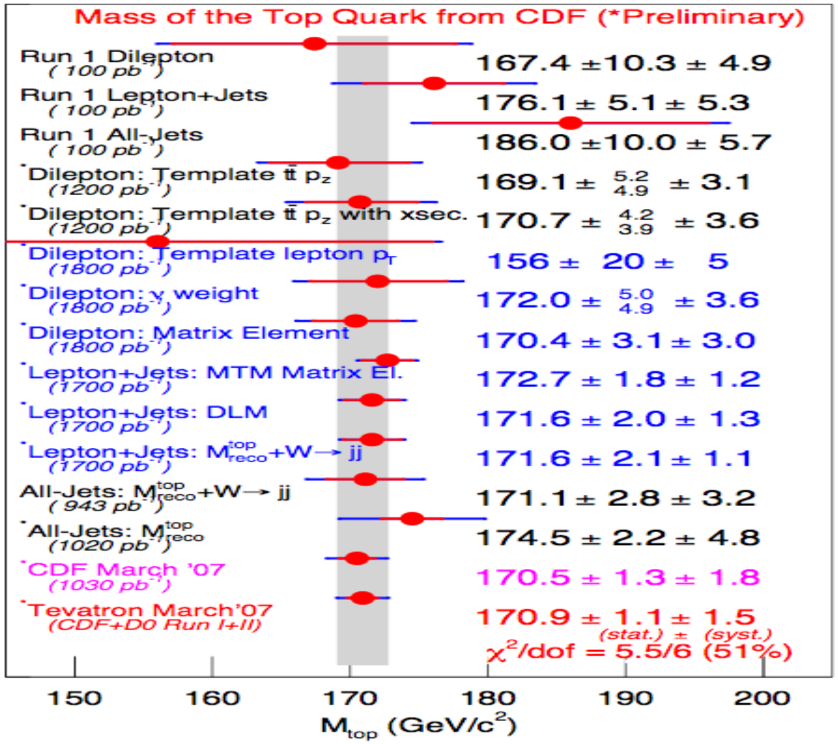
CDF (single measurement) Fall 07 : 172.7± 1.8 ± 1.2

More measurements performed

⇒using other samples (dilepton, all-hadron)

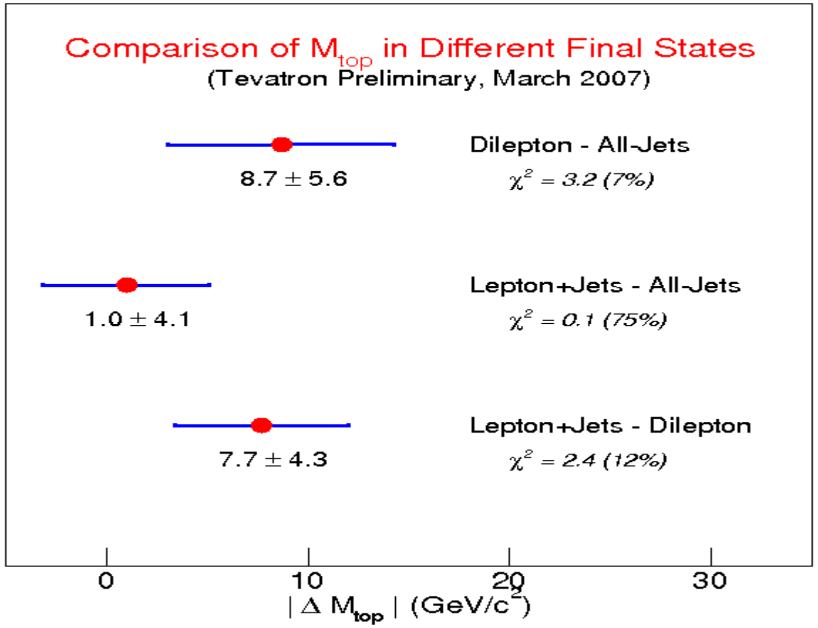
⇒different techniques





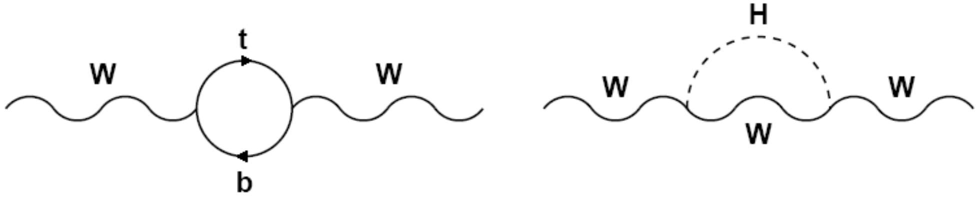
Keep an eye on…

- Discrepancy btw L+jets, Dilepton ch. measurements…?
- Is it statistical?
- Is there a missing systematic?
- Is our assumption of SM ttbar incorrect??



Stay tuned…

Consequences on the Higgs Mass

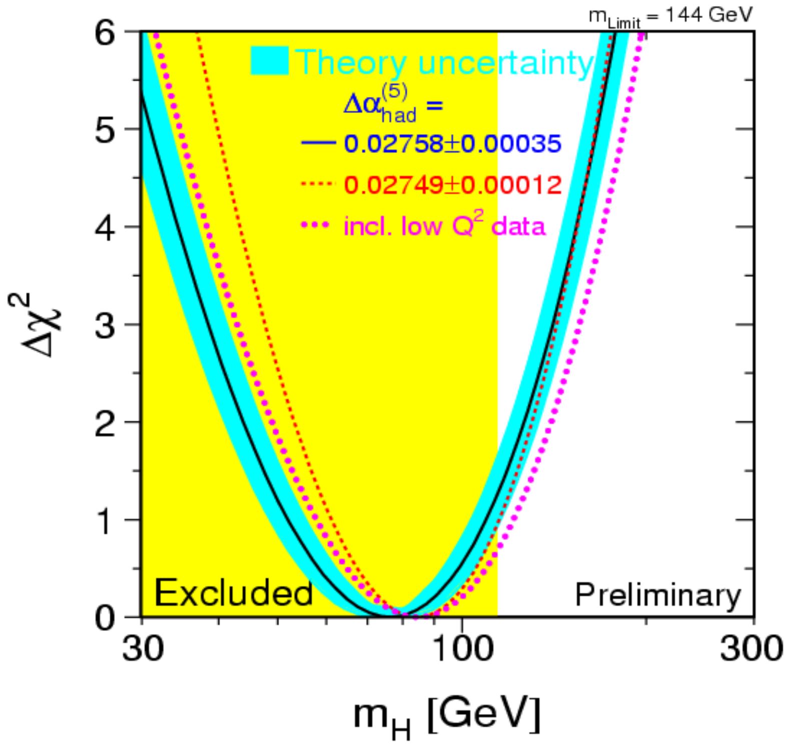


Preferred M_{Higgs}

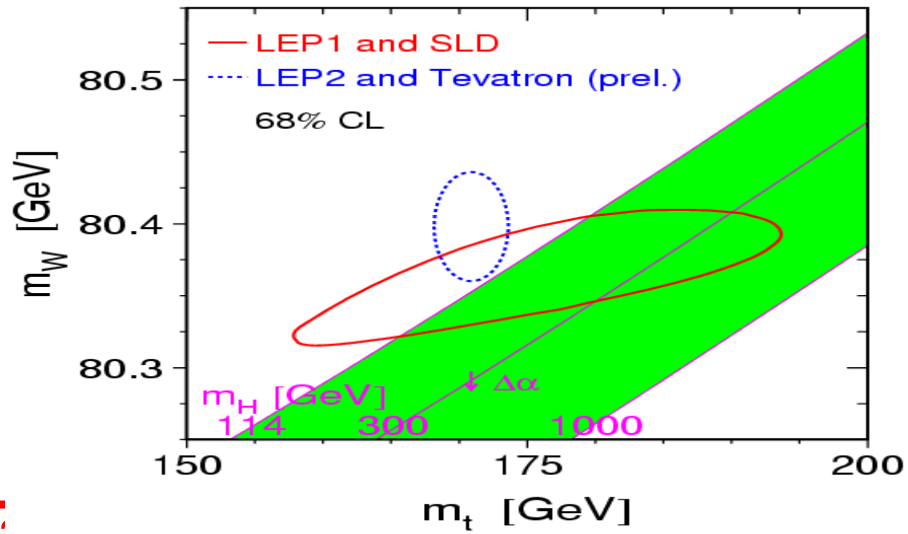
$M_{Higgs} = 76^{+33}_{-24}$ GeV

$M_{Higgs} < 182$ GeV @ 95% CL

Winter 2007



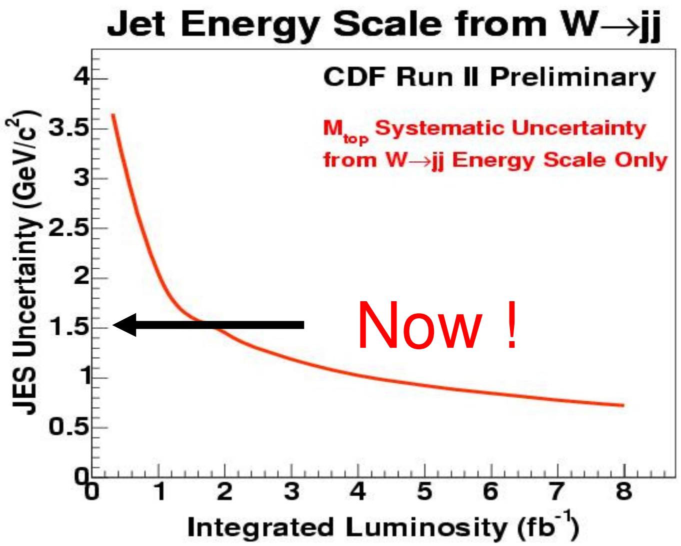
Winter 2007

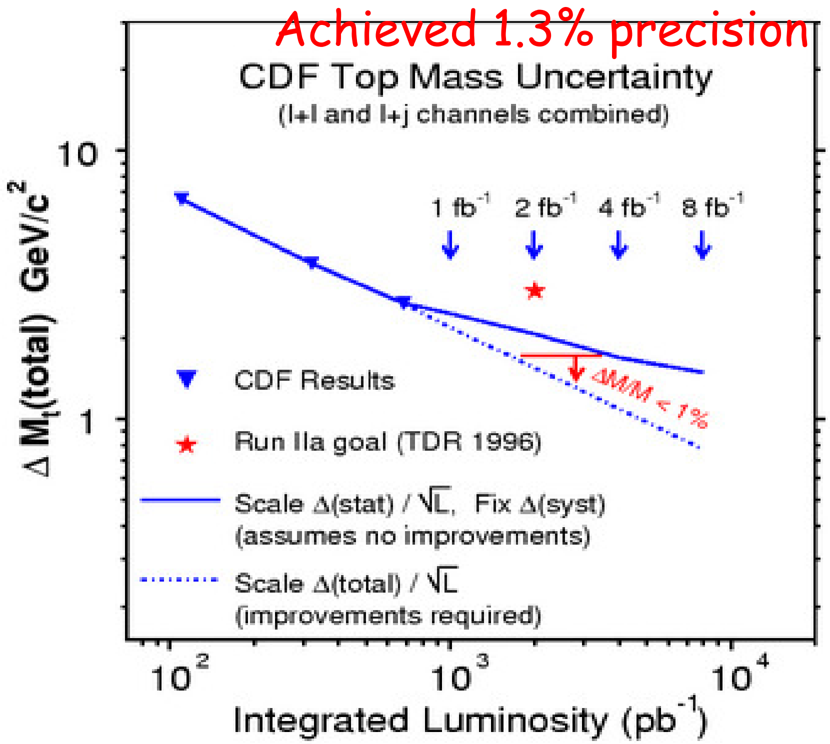


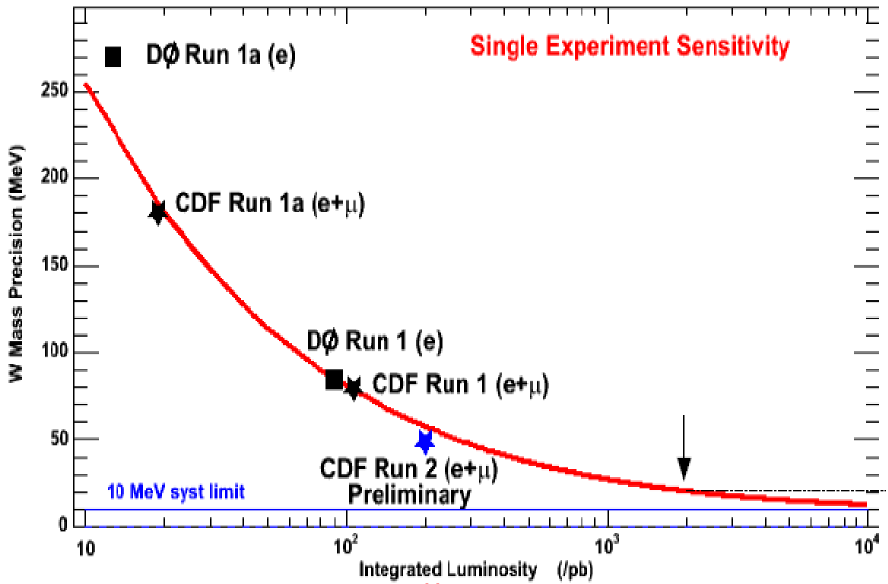
The Future Prospects for top mass

- Using $W \to jj$: JES uncertainty becomes mostly statistical

  So we can reach JES uncert. < 1 GeV/c^2 in Run II
- Reaching total δM_{top} < 1.5 GeV/c^2 can be possible with full Run II dataset

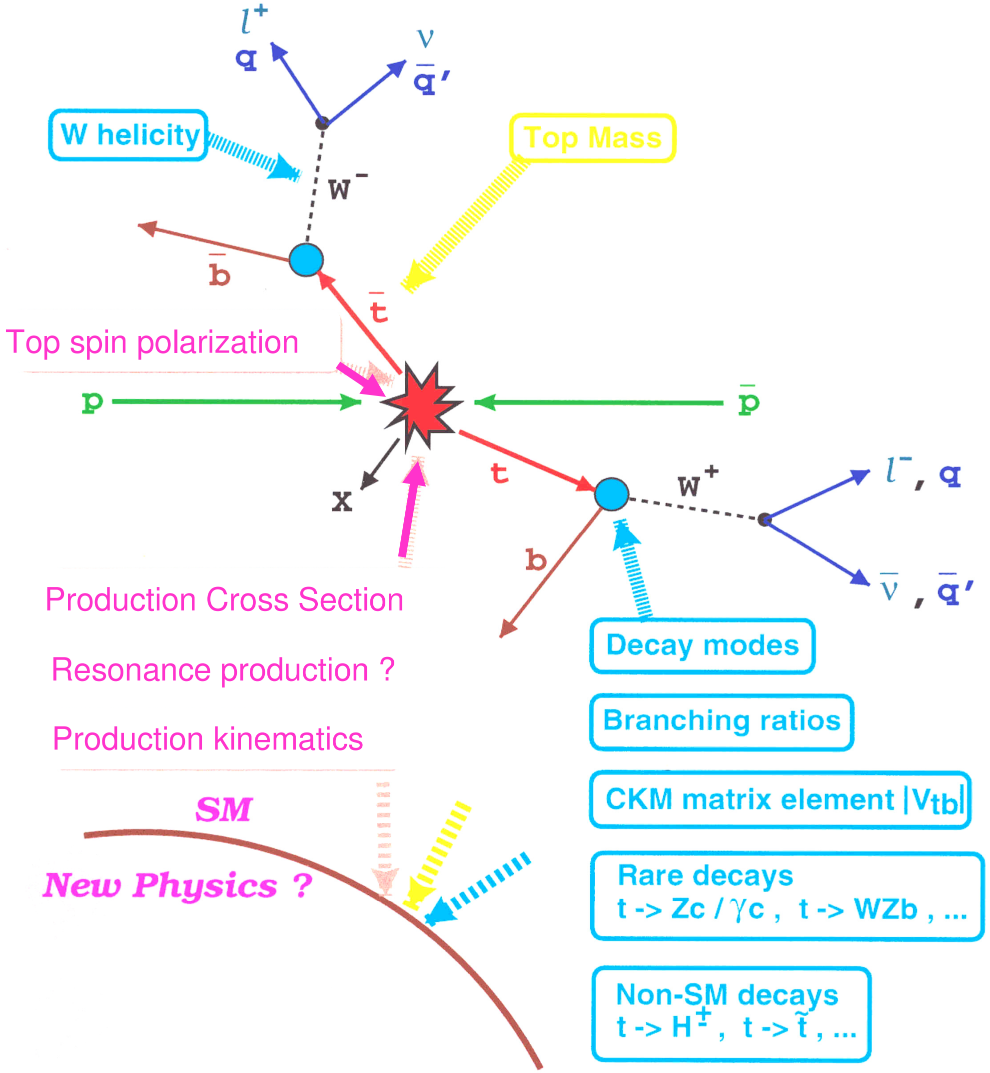






Measurement of Top Quark Production and Decay Properties

- Let's continue on the natural path of measuring top quark properties in order to confirm SM or find deviations from it
  - ⇒ Is top quark adequately described by the Standard Model?



Conclusion

- I just touched two of the basic top physics measurements
  - ⇒Production cross section
  - ⇒Measurement of the top mass
- Until the Tevatron will run, it will be the source of knowledge on top physics
  - ⇒Interesting check of production and decay
    - ✓QCD, structure of EWSB
  - ⇒Possible place to look for new physics…

More readings

⇒1994 "Evidence": PRD **50:2966-3026**

- ✓A "classic" scientific paper

⇒Several recent "conference papers" available from http://www-cdf.fnal.gov/physics/new/top/top.html

- ✓Measurement of ttbar x-sect in 1.1 fb^{-1} in l+jets channel CDF note 8795
- ✓Measurement of ttbar-xsect in 1.2 fb^{-1} in dilepton channel CDF note 8802
- ✓Template based Top quark mass in 1.7 fb^{-1} CDF note 8949
- ✓Top mass in l+jets with ME in 1.7 fb^{-1} CDF note 9025
- ✓Combined cdf top mass results (winter 07) CDF note 8743
- ✓Tevatron top mass combined (winter 07) CDF note 8735 (anche arXiv:hep-ex/0703034v1 19/03/2007)

⇒Queste lezioni: www.pi.infn.it/~giorgio/