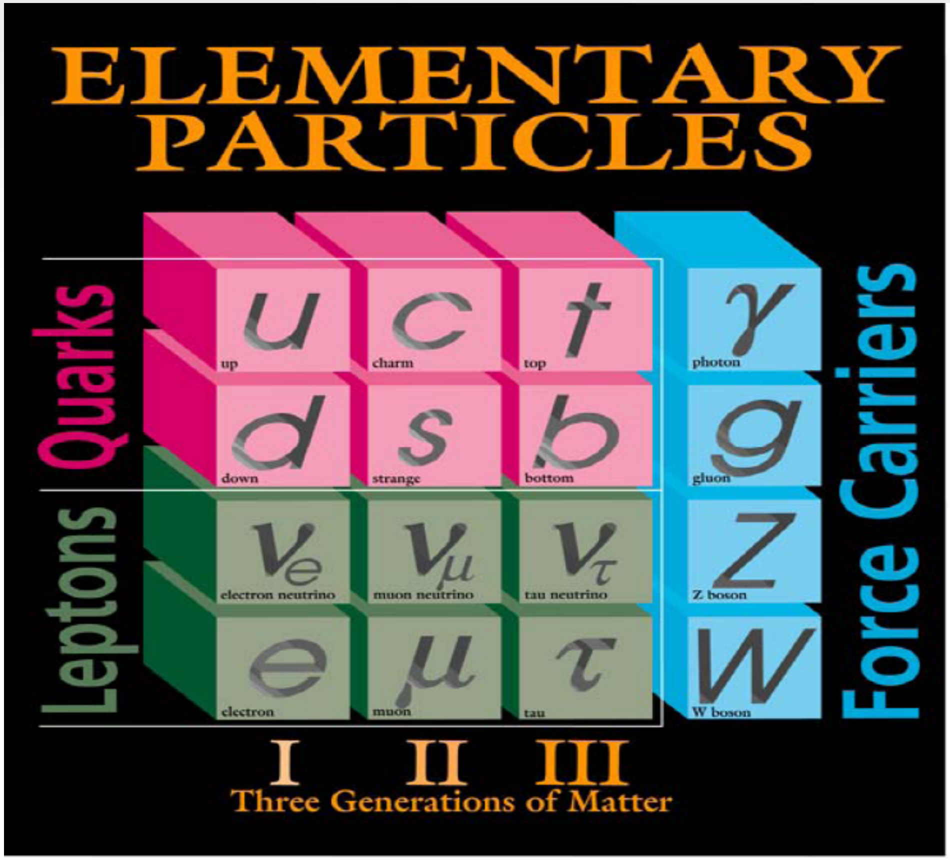
Quark Top Properties

<u>Outline :</u>

- Introduction
- Cross section measurement
- Top Properties Measurements:
  - ✗ Mass
  - ✗ lifetime
  - ✗ charge
- $t\bar{t}$ resonances



Fermilab 95-759

Introduction

Top quark discovered in 1995 by CDF and D0

Missing particle as today it is the Higgs

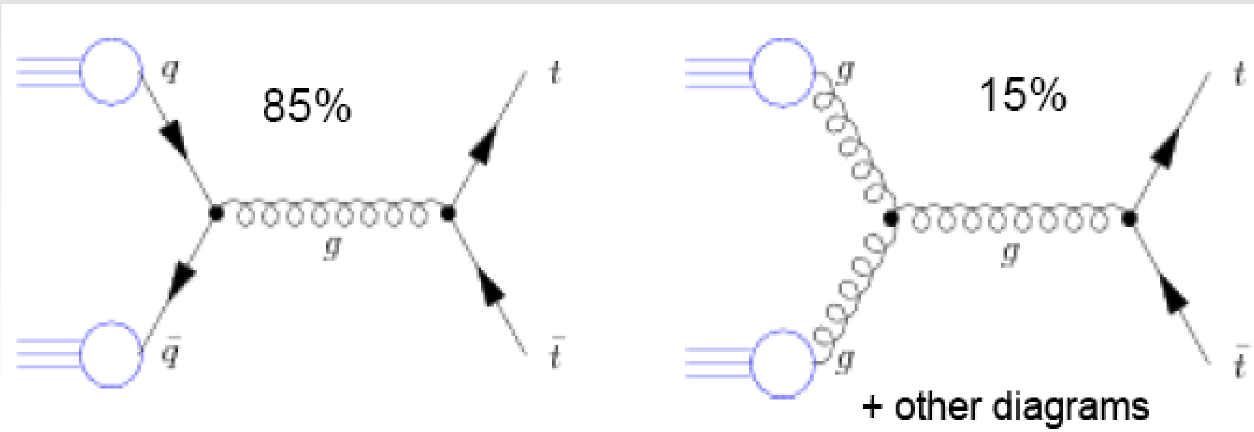
Important to undestand what we missing in the Standard Model

Quark Top Cross Section: Introduction

- Comparison between observed and predicted properties is a test of Standard Model and search for new phenomena
- $\sigma_{t\bar{t}}$ is the most inclusive property and the least sensitive to high order corrections
- Recent s calculations are based on parton-level, $\sigma_{t\bar{t}}$ calculated in pQCD with NLO matrix element
- Top is very heavy and can couple to New Physics at High Energy scale
- An anomalous $t\bar{t}$ rate can be indications of new physics
- Compare $\sigma_{t\bar{t}}$ for different final states
- $\sigma_{t\bar{t}\to l+jet}/\sigma_{t\bar{t}\to ll}$ sensitive to non-W decays
- different channels have different sensitivity

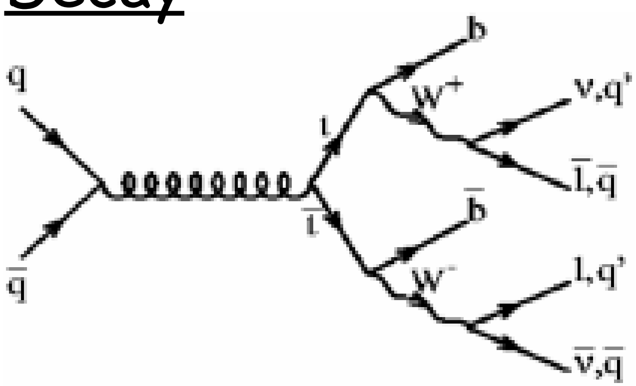
Quark Top Cross Section: Production & Decay

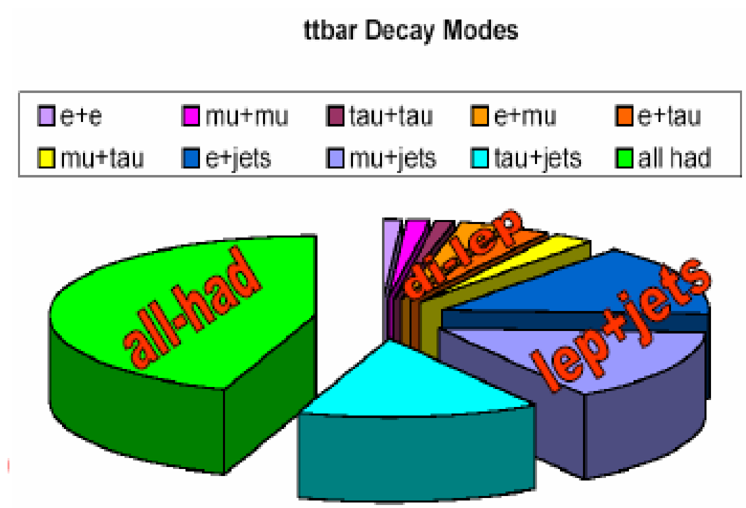
Production



At Tevatron top quark is mainly produced in pairs

Decay





Di-leptons	5%
Leptons+jets	30%
All-hadronic	44%
Others	21%

Quark Top Cross Section: Final States

Each final state has specific characteristics and require a specific approach:

- Di-lepton: low yield, low background, well defined leptonic signature
- Lepton+jets: higher yield, moderate background, lepton signature + MET + jets
- All hadronic: highest yield, huge background, only jets

Quark Top Cross Section: How to measure

Cross section σ measurements are based on counting experiment:

$$\sigma = \frac{N_{observed} - N_{background}}{\varepsilon(m_t)\int L dt}$$

$N_{observed}$ = number of top candidates

$N_{background}$ = number of background events

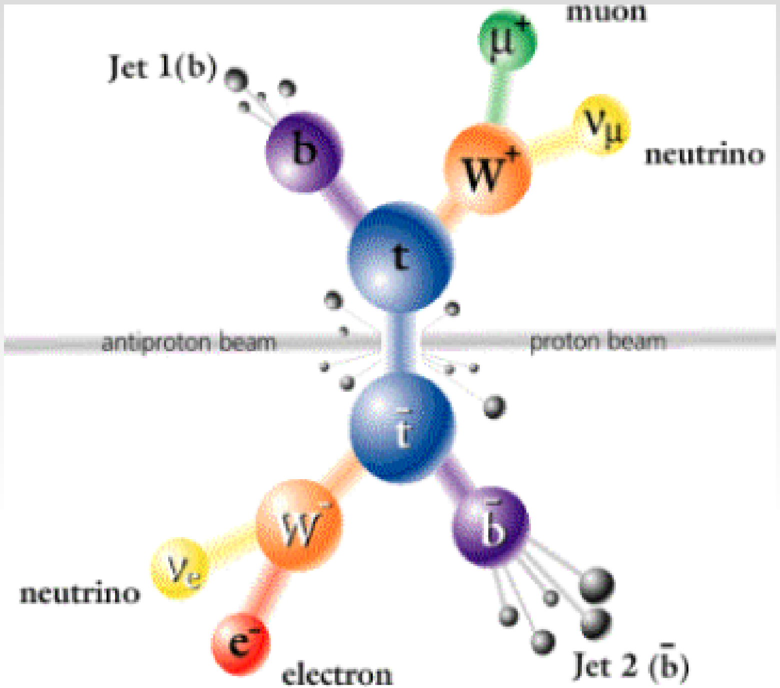
$\varepsilon(m_t)$ = overall efficiency can depends on top mass

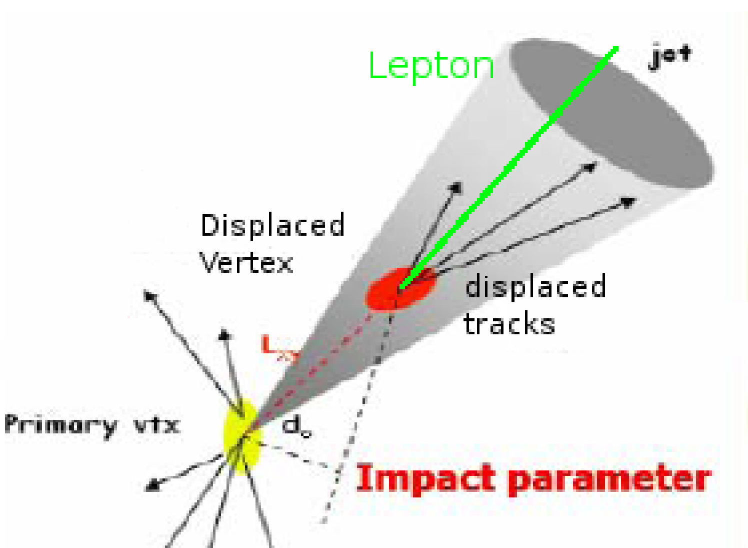
$\int Ldt$ = total Luminosity

Background evaluation is the most critical part, two methods used:

- data driven
- simulated

Quark Top Cross Section:How to measure (2)





Needed:

- Lepton, μ,e, identification
- b-jets identification:
  - soft-lepton
  - vertex tag

<u>Soft-lepton:</u>

Select μ,e from B semileptonic decays

<u>Vertex tag:</u>

Select tracks with high impact parameter wrt primary vertex

Fit to identify a secondary vertex

Cut on decay lenght L_{xy}

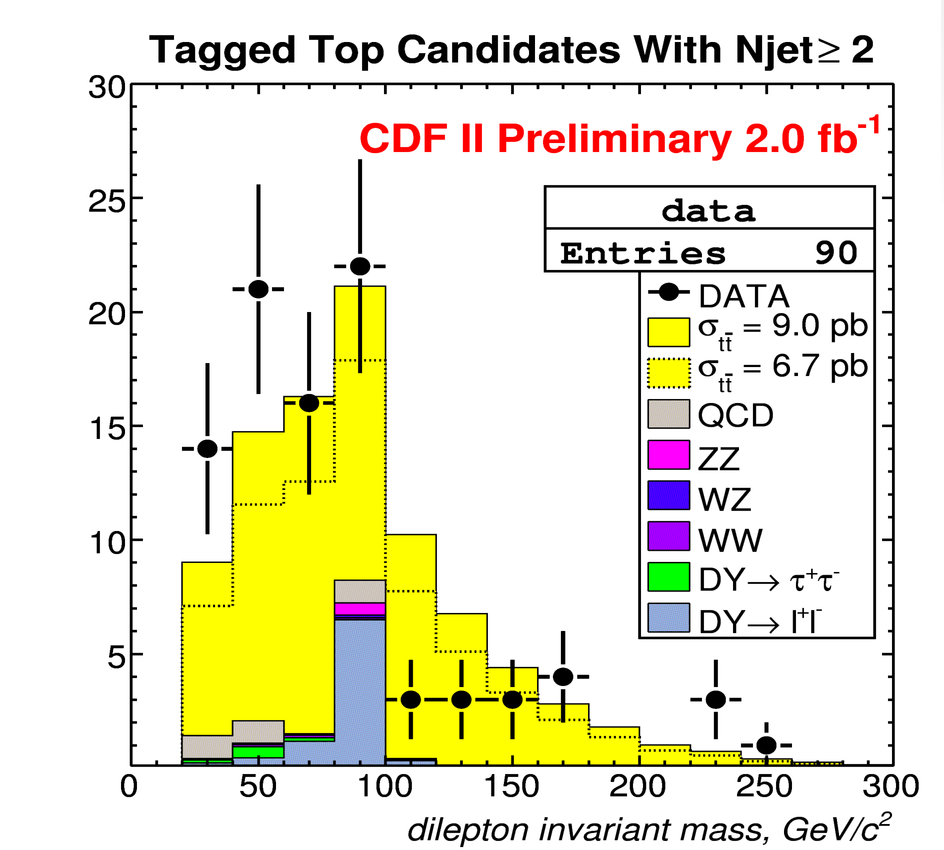
Quark Top Cross Section: Di-lepton decays

Requirements:

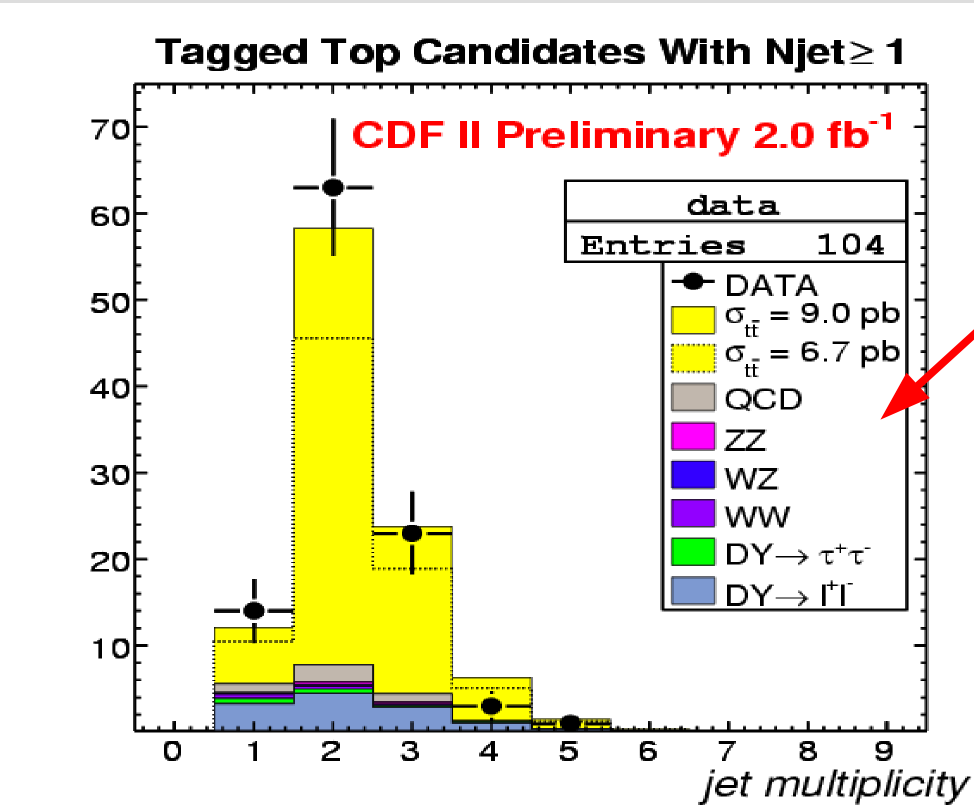
- two high P_T opposite charge isolated leptons (Pt>20)
- at least 2 high ET jets with at least one vertex b-tag
- MET

Major Backgrounds

- Drell-Yan Z/γ*: calculated using control region
- Di-boson: WW,WZ,ZZ
- QCD: fake leptons



Quark Top Cross Section: Di-lepton result



$$\sigma = \frac{N_{observed} - N_{background}}{\varepsilon(m_t)\int L dt}$$

Data & MC

$N_{Observed}=90$

$N_{Background}=13\pm2$

σ(tt) = 9.0 ± 1.1 (stat) ± 0.7 (sys) ± 0.5 (lum) pb

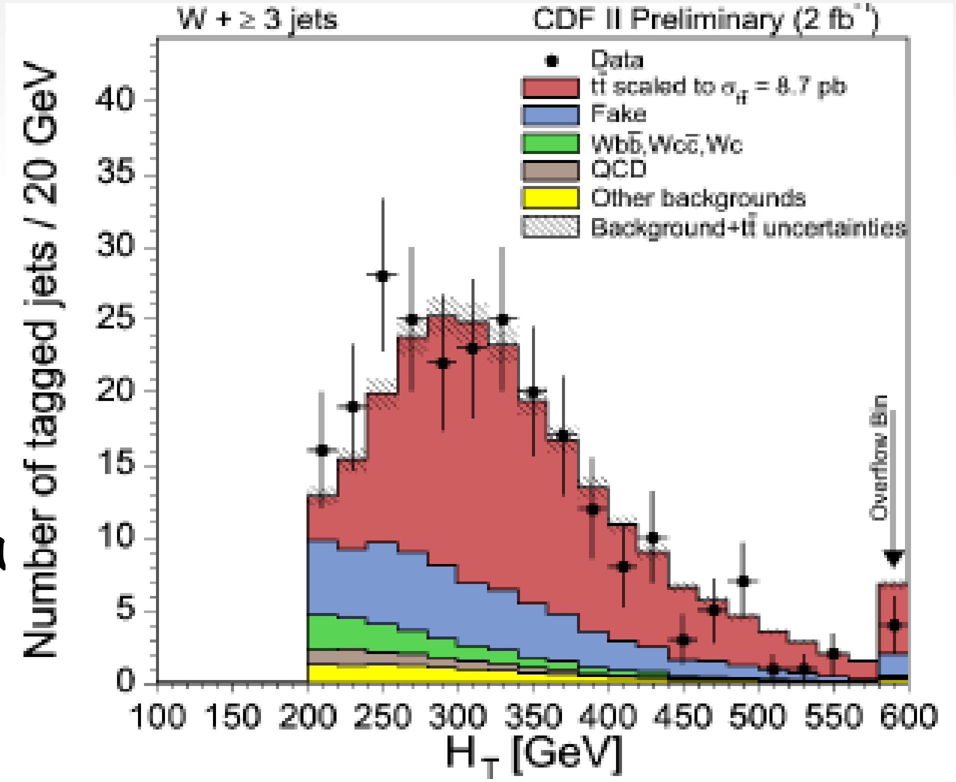
Dominant systematic error:

Jet Energy Scale and background contribution

Quark Top Cross Section:lepton+jets decays

Requirements:

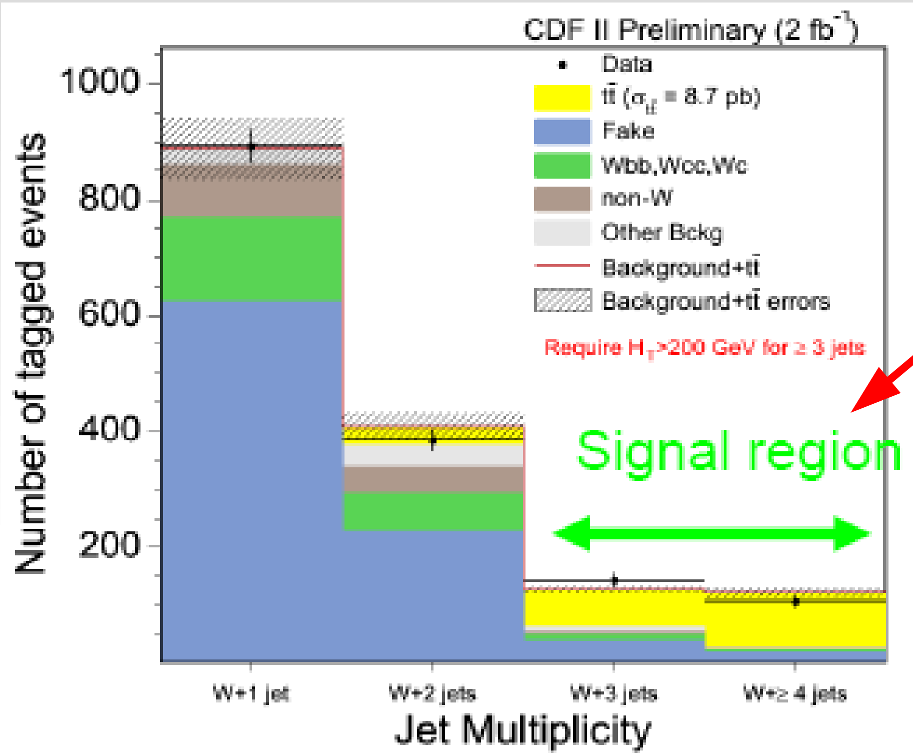
- one high P_T isolated leptons (Pt>20)
- at least 3 high E_T jets with at least one soft lepton b-tag
- MET
- $H_T = \Sigma(E_T + P_T \text{ MET}) > 200$ GeV



Major Background

- W+jets:
  - Heavy Flavour fraction and shape dermined with MC & data
  - light flavour from data
- Other contributions from non-W

Quark Top Cross Section:lepton+jets result



$$\sigma = \frac{N_{observed} - N_{background}}{\varepsilon(m_t)\int L dt}$$

Data & MC

$N_{Observed}$=248

$N_{Background}$=87±6

σ(tt) = 8.7 ± 1.1 (stat) ± 0.9 (sys) ± 0.6 (lum) pb

Dominant systematic error:
soft-lepton tag efficiency and background contribution

Quark Top Cross Section:Final results

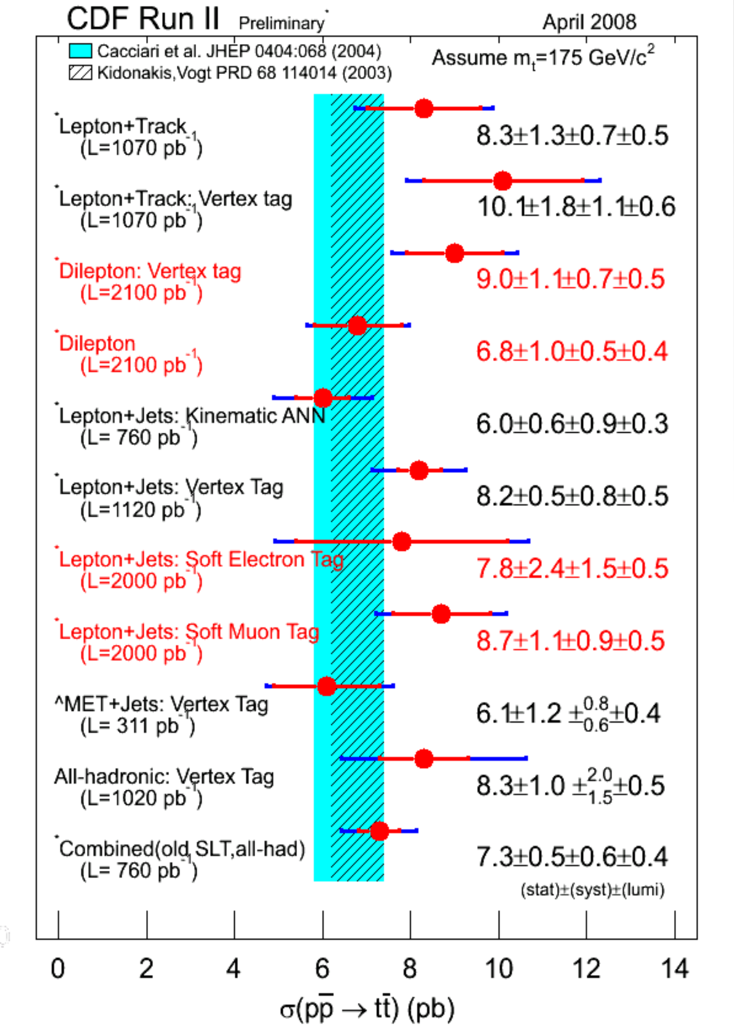
All the measurements are then combined

What we learn:

- ✔ All the decay channels are consistent
- ✔ Lepton+jets is most accurate
- ✔ Close to the theoretical predictions

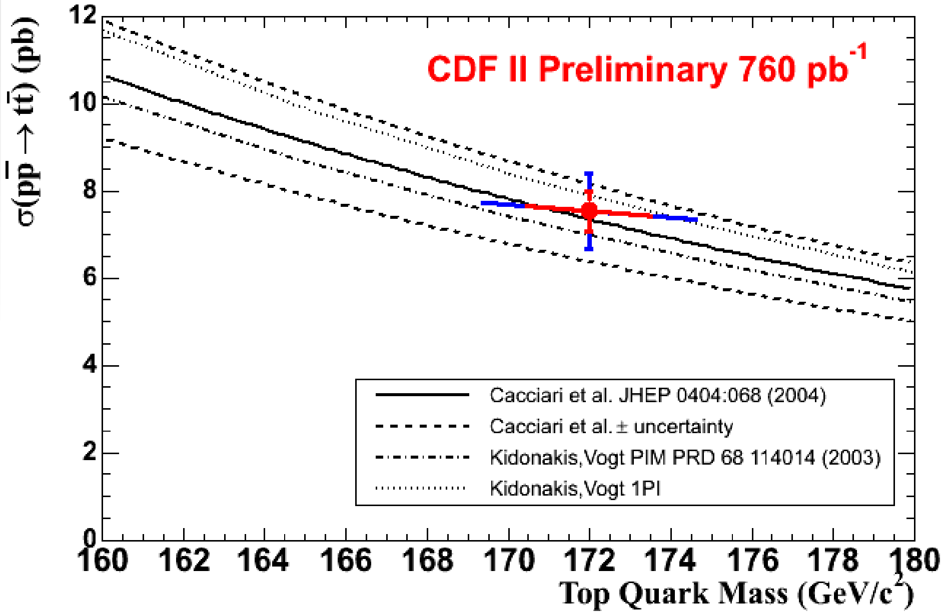
It has the higher number of events with not so large systematic error.

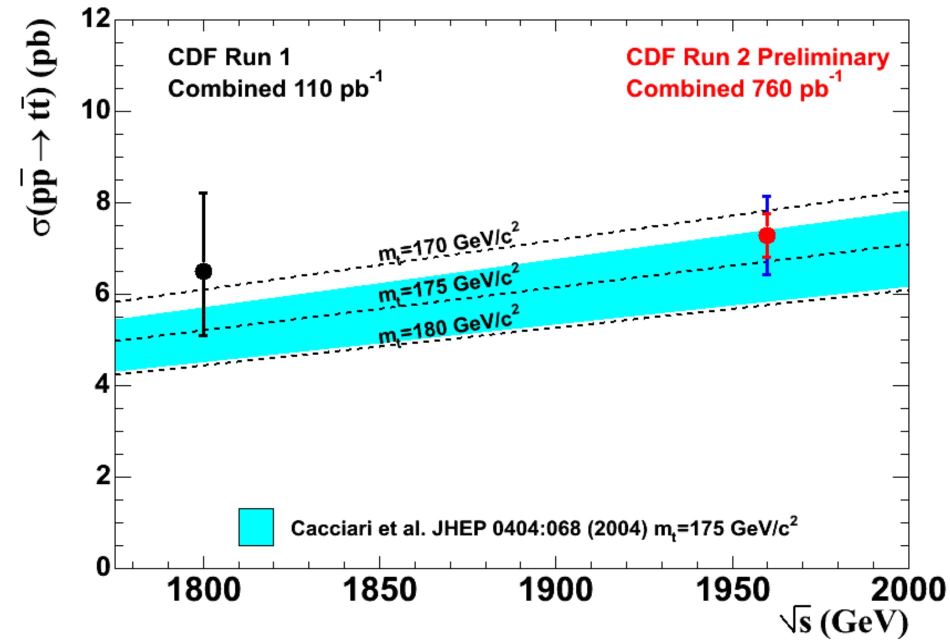
All hadronic suffers for large backgroud



Quark Top Cross Section:Final results(2)

The result is compared to the theory





It is consistent with the theory:

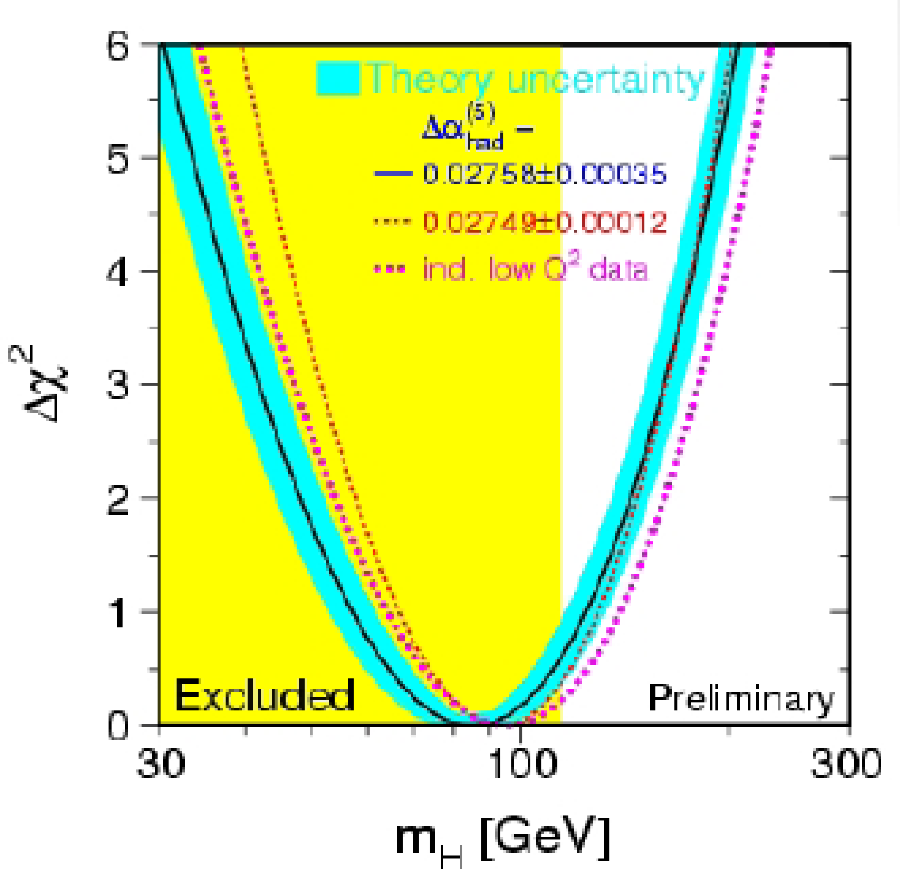
- ✔ as function of Top Mass
- ✔ as function of the center of mass energy

Quark Top Mass: Introduction

- Fundamental parameter of Standard Model
- Important ingredient for Electro-Weak precison test
- Precise determination of top mass helps to infer Higgs mass.
- If Higgs is found -> test of Standard Model

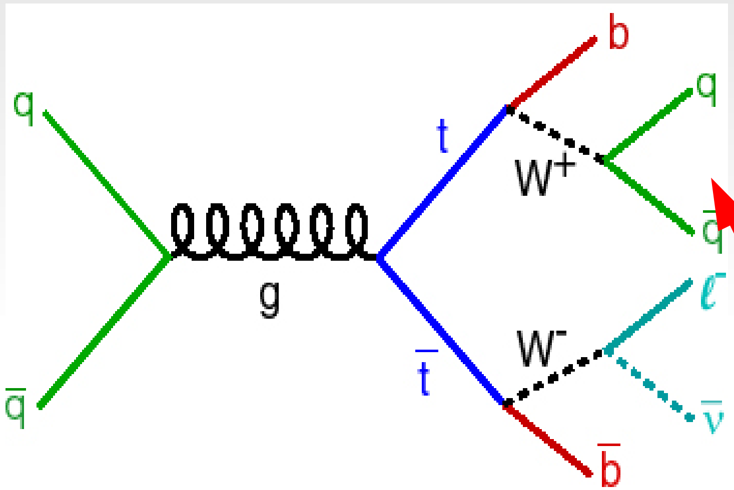
$$m_H = 76^{+33}_{-24}\ \text{GeV}$$

$$m_H < 182\ \text{GeV}\ \text{(95\%CL)}$$



Quark Top Mass: Introduction

Decay Channels: Same used for cross section



Main issues:

- ✗ missing ν momentum
- ✗ combinatorics
- ✗ Jet Energy Scale (JES)

To redure the error W->jj calibration

Analysis with at least one hadronic W

measure simultaneously M_T and JES:

scale Jet energy to match M_W spectrum

Method used to extract the mass:

template

Matrix Element

Quark Top Mass: Template Method

Method: build top mass and JES template for signal and background
Use the templates as pdf in the Likelihood.
Extract top mass and JES

All hadronic decay channel

Reconstruct the event kinematic by minimizing:

$$\chi^2 = \frac{(m_{jj}^{(1)} - M_W)^2}{\Gamma_W^2} + \frac{(m_{jj}^{(2)} - M_W)^2}{\Gamma_W^2} + \frac{(m_{jjb}^{(1)} - m_t^{rec})^2}{\Gamma_t^2} + + \frac{(m_{jjb}^{(2)} - m_t^{rec})^2}{\Gamma_t^2} + \sum_{i=1}^{6} \frac{(p_{T,i}^{fit} - p_{T,i}^{meas})^2}{\sigma_i^2}$$

mjj = invariant mass of two light jets

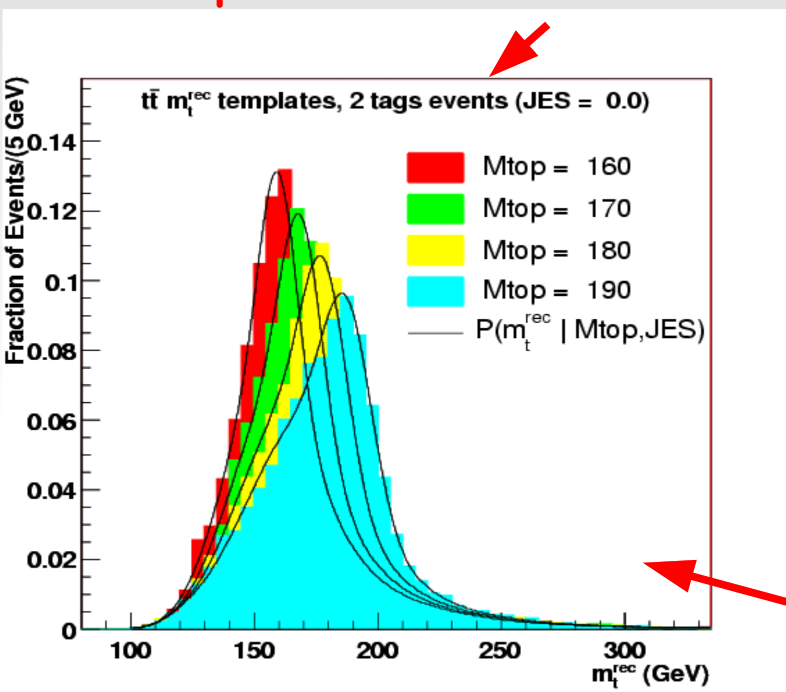
mjjb = invariant mass of three jets

P_T^{fit} =top transv. momentum

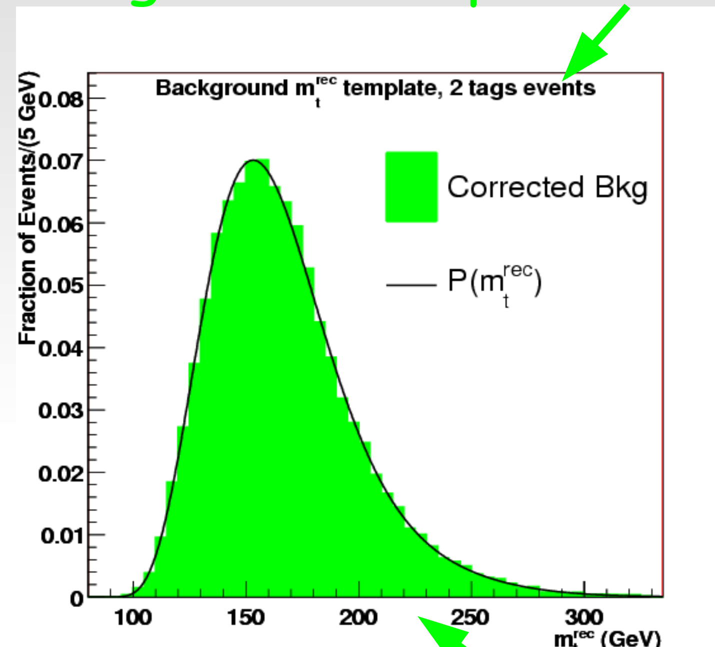
For each permutation we obtain m_t^{rec} this forms the template for signal (MC) and background (data)

Quark Top Mass: All Hadronic

Signal template: Monte Carlo data



Background template: data



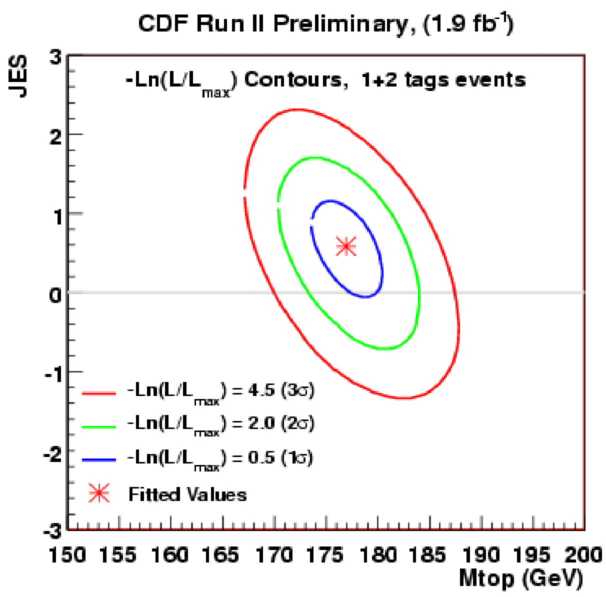
$$L_{tot} = L_{M_{top}} + L_{JES}$$

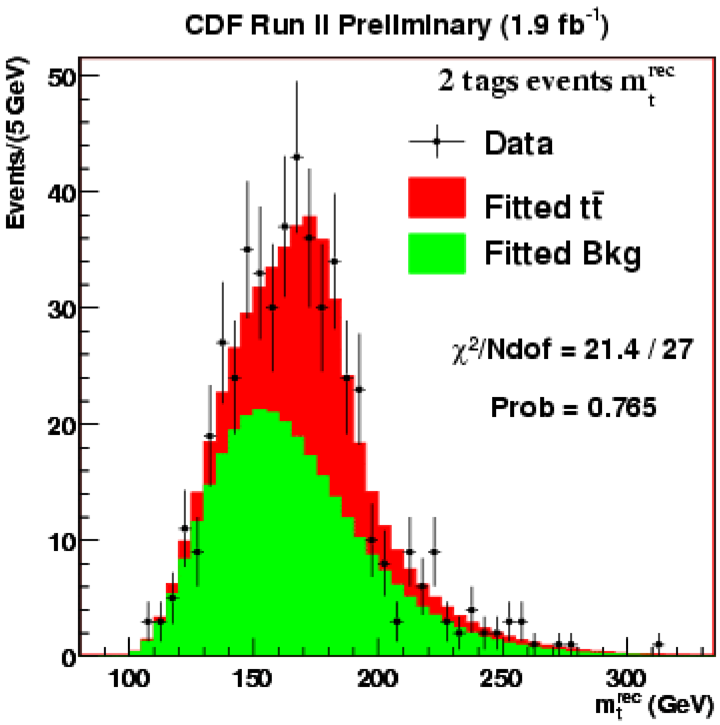
$$\mathcal{L}_{M_{top}} = \prod_{i=1}^{N_{obs}} \frac{n_s \cdot P_{sig}^{m_t^{rec}}(m_{t,i} \mid M_{top}, \mathrm{JES}) + n_b \cdot P_{bkd}^{m_t^{rec}}(m_{t,i})}{n_s + n_b}$$

$$\mathcal{L}_{\mathrm{JES}} = \prod_{i=1}^{N_{obs}} \frac{n_s \cdot P_{sig}^{m_W^{rec}}(m_{W,i} \mid M_{top}, \mathrm{JES}) + n_b \cdot P_{bkd}^{m_W^{rec}}(m_{W,i})}{n_s + n_b}$$

The Likelihood has two terms: one for the mass and one for JES

Quark Top Mass: All Hadronic result





$$M_{top} = 177.0 \pm 3.7\ (stat+JES) \pm 1.6\ (syst)\ GeV/c^2$$

Quark Top Mass: Matrix Element Method

Observables: measured momenta of jets and leptons

Question: for an observed set of kinematic variables x what is the most probable top mass

Method: start with an observed set of events of given kinematics and find maximum of the likelihood, which provides the best measurement of top quark mass

Our sample is a mixture of signal and background

$$P_{evt}(x, m_t) = f_{top} \cdot P_{\text{sgn}}(x, m_t) + (1 - f_{top}) \cdot P_{bkg}(x)$$

$P_{bkg}(X)$ depends on the decay channel

Quark Top Mass: Matrix Element Method

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

$d^n\sigma$ is the differential cross section
Contains **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***.
Parton Energy ↔ Jet Energy

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

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

Normalization depends on m_t
Includes acceptance effects

Integrate over unknown:
kinematical variable q_1,q_2 of initial states parton and final states parton y
Approximations: LO matrix element and *qq->tt* process only (no gluon fusion – 15%)

Quark Top Mass: ME in Lepton+jets

Select events as in the cross section measurement

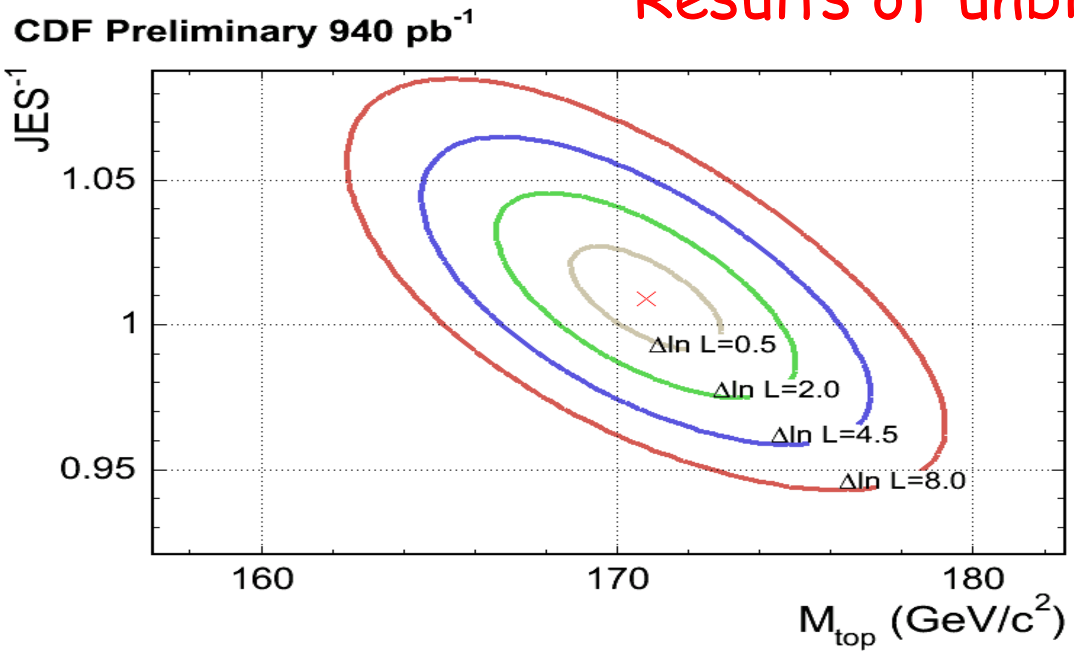
Recall: Major background is W+jets

Likelihood minimized for: M_{top}, JES, C_S=signal fraction of events

$$\mathcal{L}(M_{top}, JES, C_s; \vec{x}) \propto \prod_{i=1}^{N} [C_s P_{t\bar{t}}(\vec{x}; M_{top}, JES) + (1 - C_s) P_{W+\text{jets}}(\vec{x}; JES)]$$

$P_{W+jets}(x; JES)$ obtained from Monte Carlo

Results of unbinned Likelihood fit



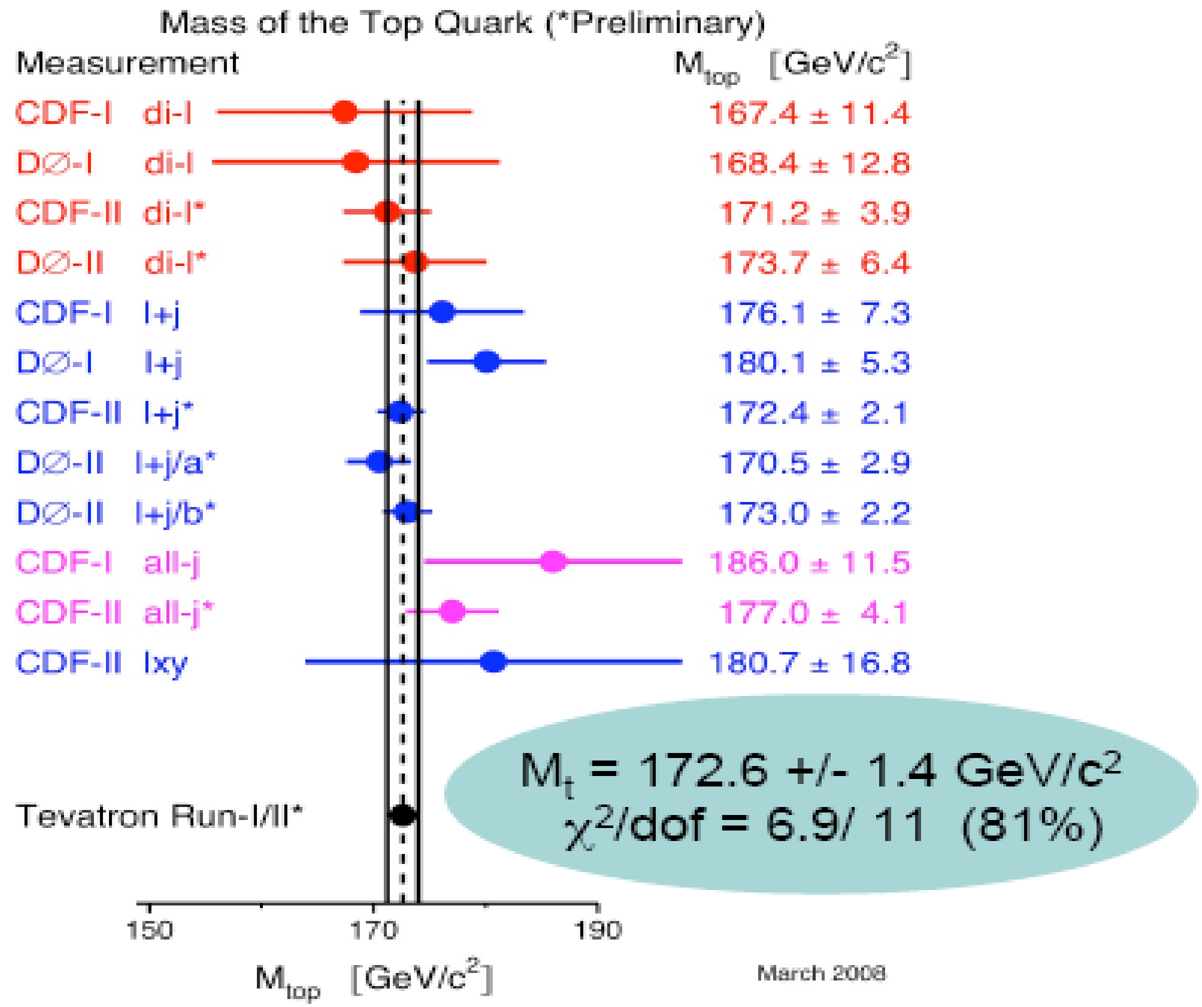
M_{top} = 170.9 ± 2.2 (stat+JES) ± 1.4 (syst) GeV/c^2

JES = 0.99 ± 0.02 (stat)

Cs = 0.68 ± 0.05 (stat)

(S/(S+B) = 0.84)

Quark Top Mass: CDF+D0



- Relative uncertainty: 0.8%

Quark Top Mass: What are we measuring?

- All M_t measurements are calibrated to MC
  - MC calibration not unique to top mass
- In the MC, the parameter we calibrate to is the top-quark pole mass
  - Numerous discussions with numerous authors
  - All say: “It’s pole mass w/i $\sim\Lambda_{qcd}\sim 200$ MeV/c^2”

Quark Top Mass: What are we measuring?

- There's a *theoretical* issue since t-quark is not a color singlet
  - What we need is an experimental observable that's
    - A color singlet
    - Sensitive to M_t
    - Well defined at a hadron collider
    - Can be modeled theoretically in a well defined manner
  - What we have are experimental observables that are affected by numerous non-perturbative (QCD) effects
    - Makes theoretical interpretation difficult, since mapping from the perturbative to observables requires non-perturbative model
    - This is what the modeling systematic uncertainties are meant to address… how sensitive are we to varying these effects in MC? A: moderately, ~500 MeV/c^2

Top Quark Width

Direct measurement of top lifetime very difficult: $\tau \approx 4 \times 10^{-25}$ s

$\tau = h / \Gamma$ -> Γ_t~1.5 GeV

$$\Gamma_{top} = \frac{G_F m_t^3}{8\pi\sqrt{2}},$$

Width of reconstruct the Top mass sensitive to Γ_t

Lepton+jets decay channel with the template method:

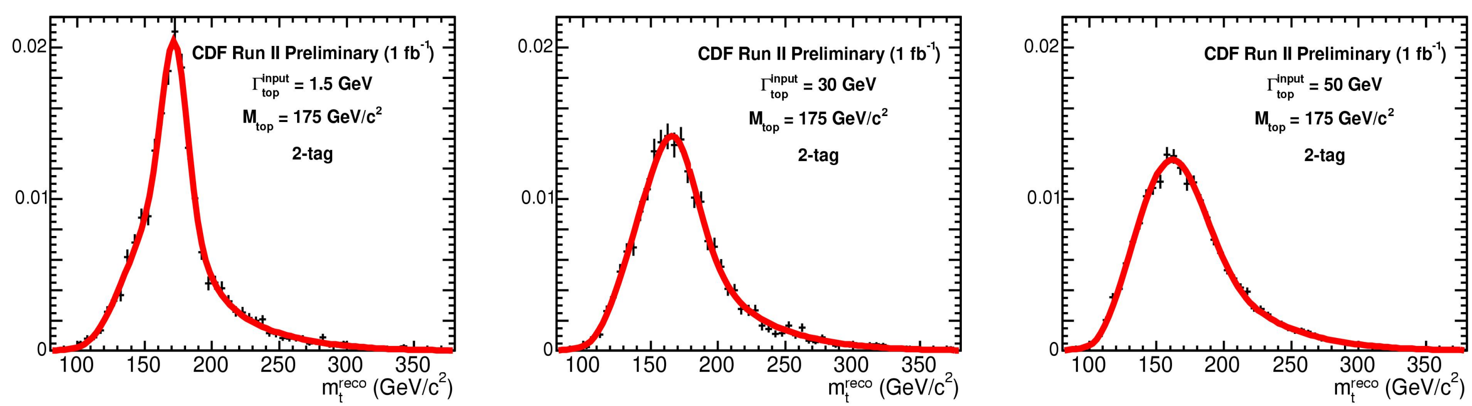
- construct template fitting event kinematic

$$\chi^2 = \Sigma_{i=l,4jets} \frac{(p_T^{i,\,fit} - p_T^{i,\,meas})^2}{\sigma_i^2} + \Sigma_{j=x,y} \frac{(p_j^{UE,\,fit} - p_j^{UE,\,meas})^2}{\sigma_j^2}$$
$$+ \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2}$$
$$+ \frac{(M_{bl\nu} - m_t^{reco})^2}{\Gamma_t^2} + \frac{(M_{bjj} - m_t^{reco})^2}{\Gamma_t^2}.$$

Templates:

Signal: MC, M_t for different Γ_t

Background: MC + data

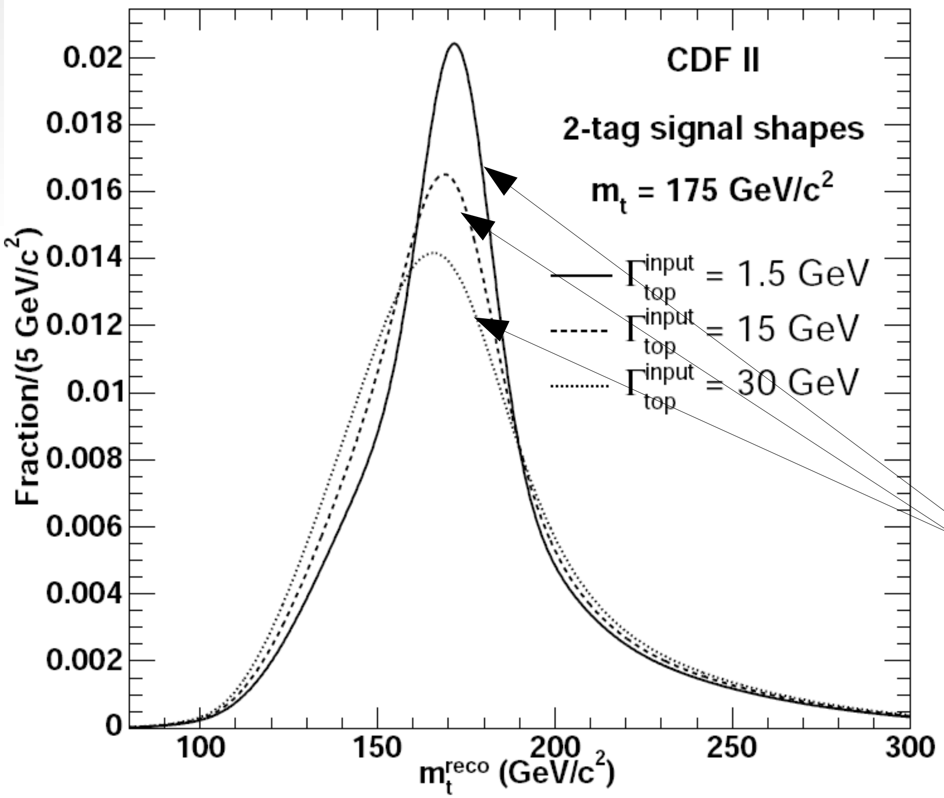


Top Quark Width Fit

The likelihood is $\mathcal{L} = \mathcal{L}_{\rm shape} \times \mathcal{L}_{\rm bg}$

$$\mathcal{L}_{\rm shape} = \frac{e^{-(n_s+n_b)}(n_s+n_b)^N}{N!} \Pi_{i=1}^{N} \frac{n_s P_{sig}(m_i;\Gamma_{top}) + n_b P_b(m_i)}{n_s+n_b}$$

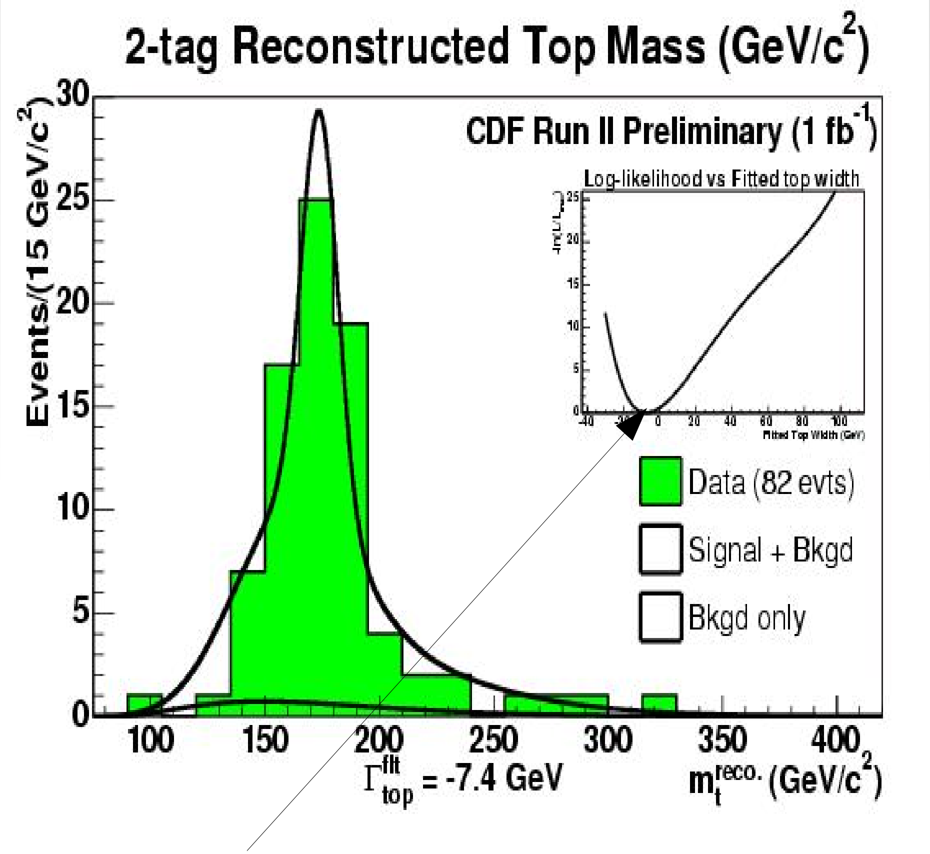
$$-ln(\mathcal{L}_{\rm bg}) = \frac{(n_b - n_b^{exp})^2}{2\sigma_{n_b}^2}.$$



Low sensitivity.

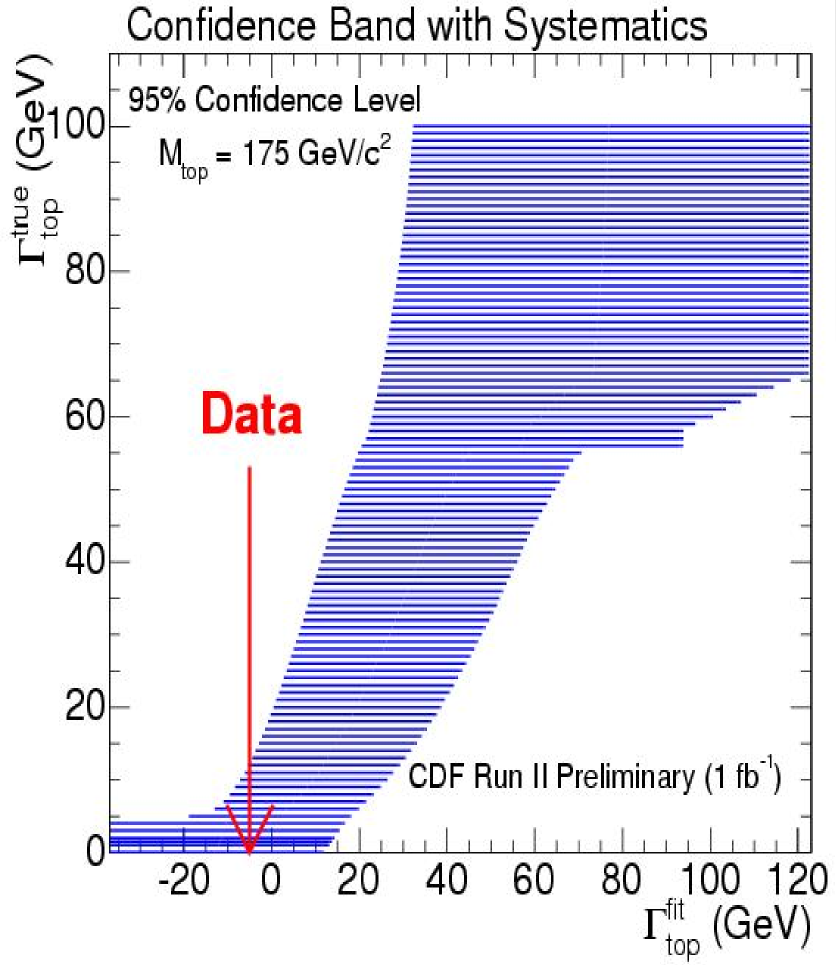
We must distinguish among different curves

Top Quark Width Results

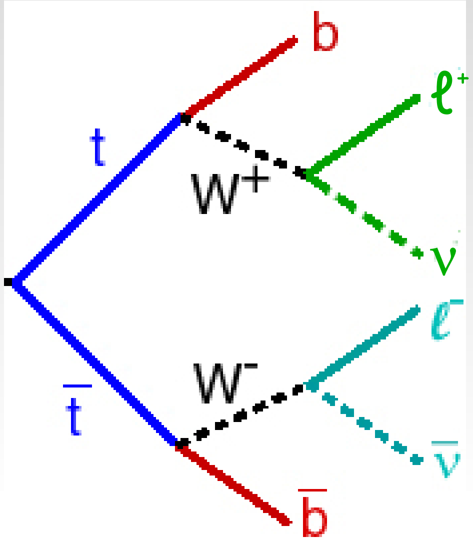


Γ^{fit}_{T} = -4.86 GeV

Γ_{top} <12.7 GeV at 95% CL



Top Quark Charge Introduction



does top->W^{+}+b ?

1. Standard Model top charge=2/3
2. Exotic Model top charge =4/3

Method:

- determine the charge of the W (lepton charge)
- get the flavor of the b-jet
- pair the W with the b jet

  ensure W and b jet come from the same top
- Separate events SM and XM

Use di-lepton and lepton+jet dataset decay channel

Top Quark Charge Analysis

Get the b-jet charge: jet-charge algorithm

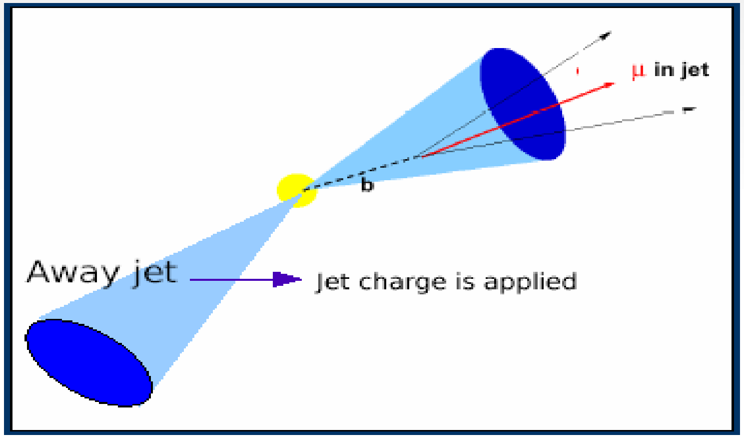
$$Q_{b-jet} = \frac{\sum_i q_i \cdot (\vec{p}_i \cdot \hat{a})^x}{\sum_i (\vec{p}_i \cdot \hat{a})^x}$$

x = weighting factor

$\hat{a}$ = jet axis

$\vec{p}_i$ = track momentum

It is optimized on $b\bar{b}$ sample: one b->μ charge is known



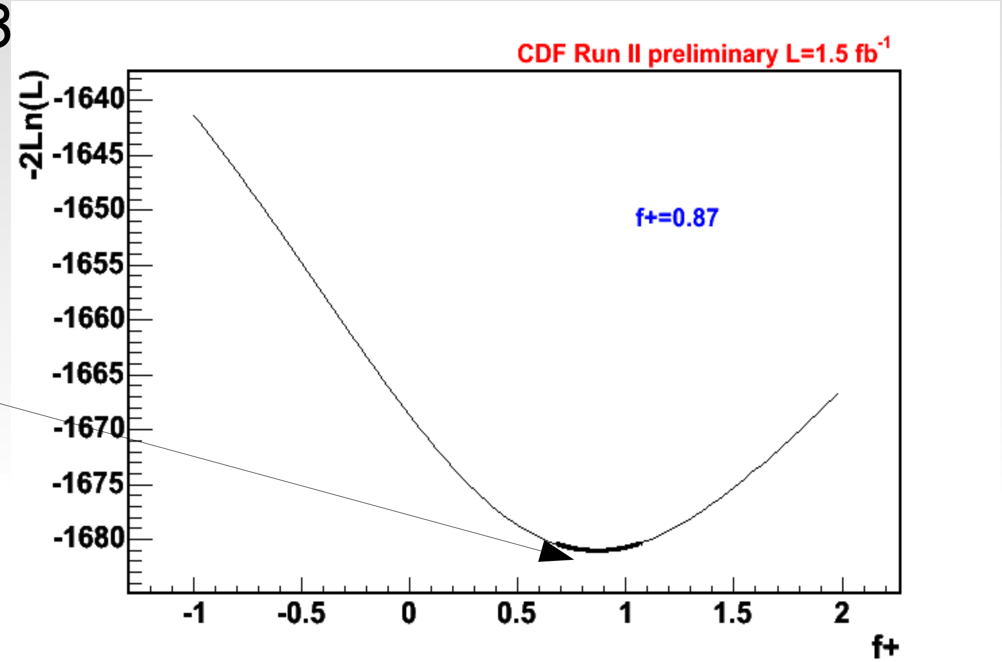
Pair ℓ with b-jet using the best $M_{\ell b\text{-}jet}$ to identify the top.

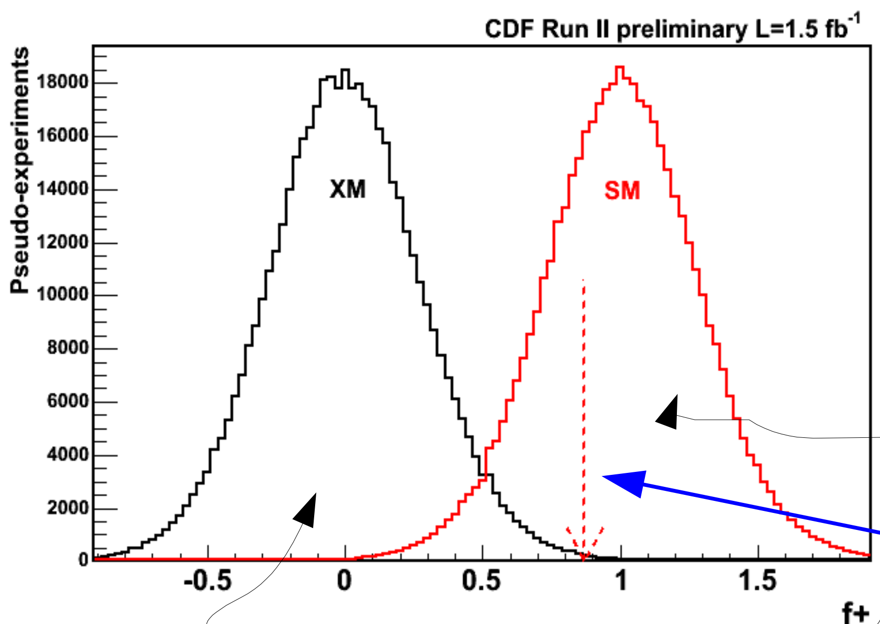
We get

- N^+ = number of SM like events with top charge +2/3
- N^- = number of XM like events with top charge -4/3

Top Quark Charge Results

f+=fraction of top pairs charge +2/3
Profile Likelihood for the Log Likelihood curve for the observed N+ and N- .
Minimum the curve at f+= 0.87.

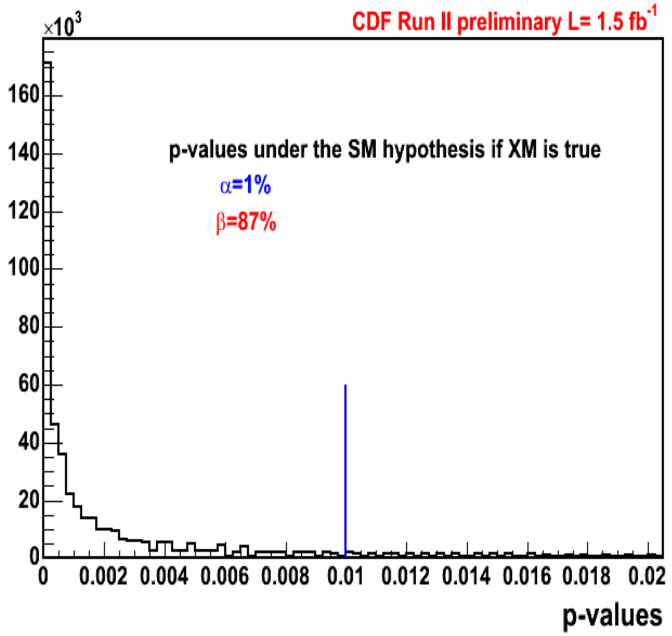




Distribution of the fraction of SM like pairs (f+) assuming either the Exotic or the Standard Model.

measured f+=0.87 corresponds to a p-value of 0.31 .

Top Quark Charge:Results



Generate PE according to XM distribution for each one find the area under SM distribution, this is p-value. Choose α= 1% probability of incorrectly rejecting the SM -> β=area under curve When we have f+ we calculate its p-value. If p-value>α we can say we can exclude XM at β

Since the p-value under the SM hypothesis is 0.31, this is greater than the a priori chosen value of α 0.01, so we exclude the exotic quark model with 87%. confidence.

Search for $t\bar{t}$ resonances: method

Compare Standard Model predictions with data possible hint of New Physics

<u>Method</u>

$$\frac{d\sigma^i}{dM_{t\bar{t}}} = \frac{N_i - N_i^{bkg}}{\mathcal{A}_i \int \mathcal{L}\, \Delta^i_{M_{t\bar{t}}}}$$

N_i = number of events in bin i

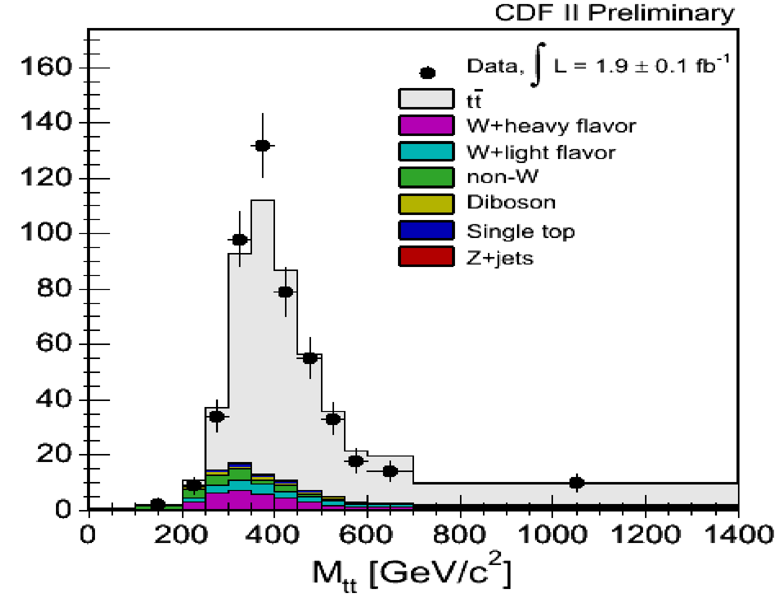
N_i^{bkg} = number of predicted background events in bin i

A_i = acceptance in bin i

Δ^i_{Mttbar} = the width of bin i

$\int L$ = integrated luminosity

- Use lepton+jets decay channel:
  - high Pt lepton + at least 4 jets
- Use four vectors of the 4 jets + lepton+neutrino to measure Mtt
- Evaluate Ai with Monte Carlo



Search for $t\bar{t}$ resonances:unfolding

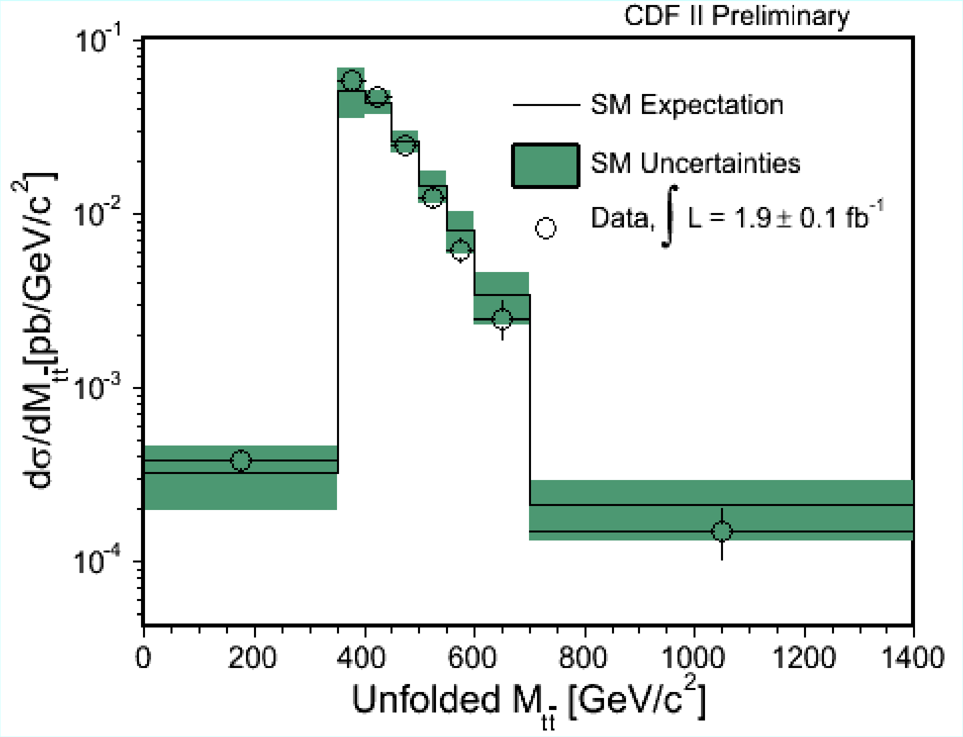
To extract the true Mtt distribution from the measured we model the effect which distort Mtt with Monte Carlo and produce the probability response matrix: Âx=b where x is the true distribution and b the measured.

This is equivalent to:

$$\Sigma_{i=1}^{n_b}\left(\frac{\Sigma_{j=1}^{n_x}\hat{A}_{ij}x_j - b_i}{\Delta b_i}\right)^2 = min$$

A new thecnique is used to avoid singularaties due to not populated bins.

Result consistent with SM



Summary

We studied:

- Cross section measurement
- Top Properties Measurements:
  - Mass
  - lifetime
  - charge
- tt resonances

Missing:

- Top helicity
- BR(t->Wb)/BR(t->Wq)
- Charge Asymmetry AFB