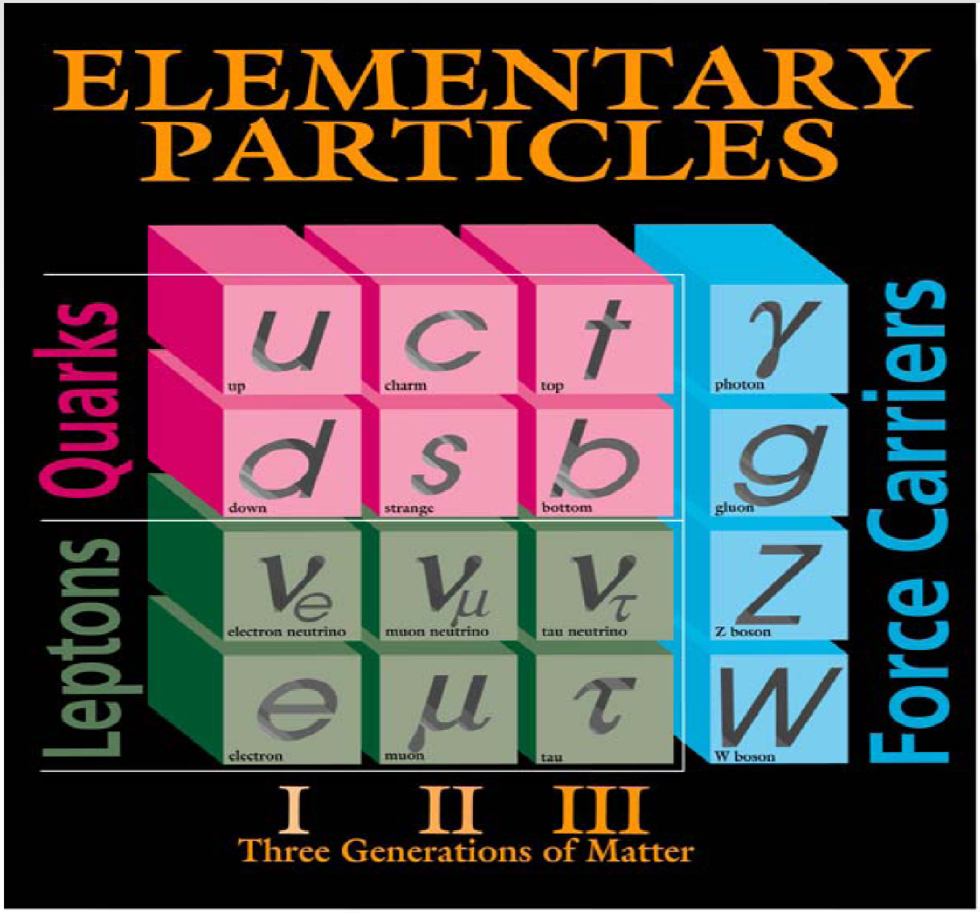
Top quark properties and SM fit

Outline :

- Introduction on the Top quark
- Top mass measurement
- Top Mass and Standard Model Fit
- Top charge
- Top width
- Top-antiTop resonances
- Top branching ratio
- Top spin correlation
- .....

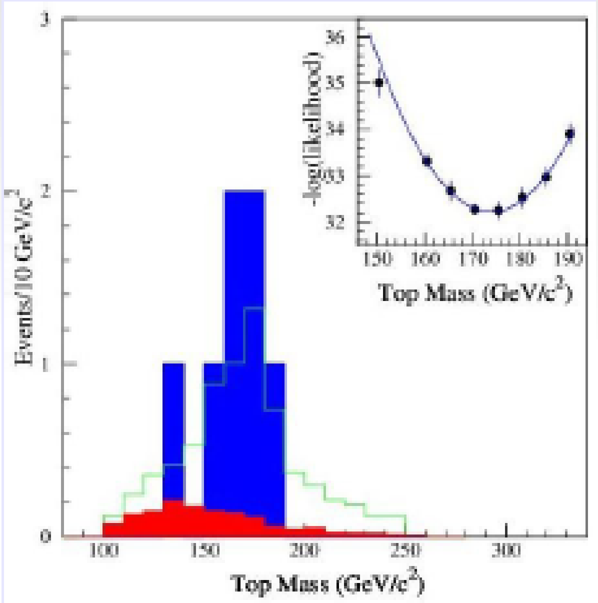
Top on Wikipedia



Fermilab 95-759

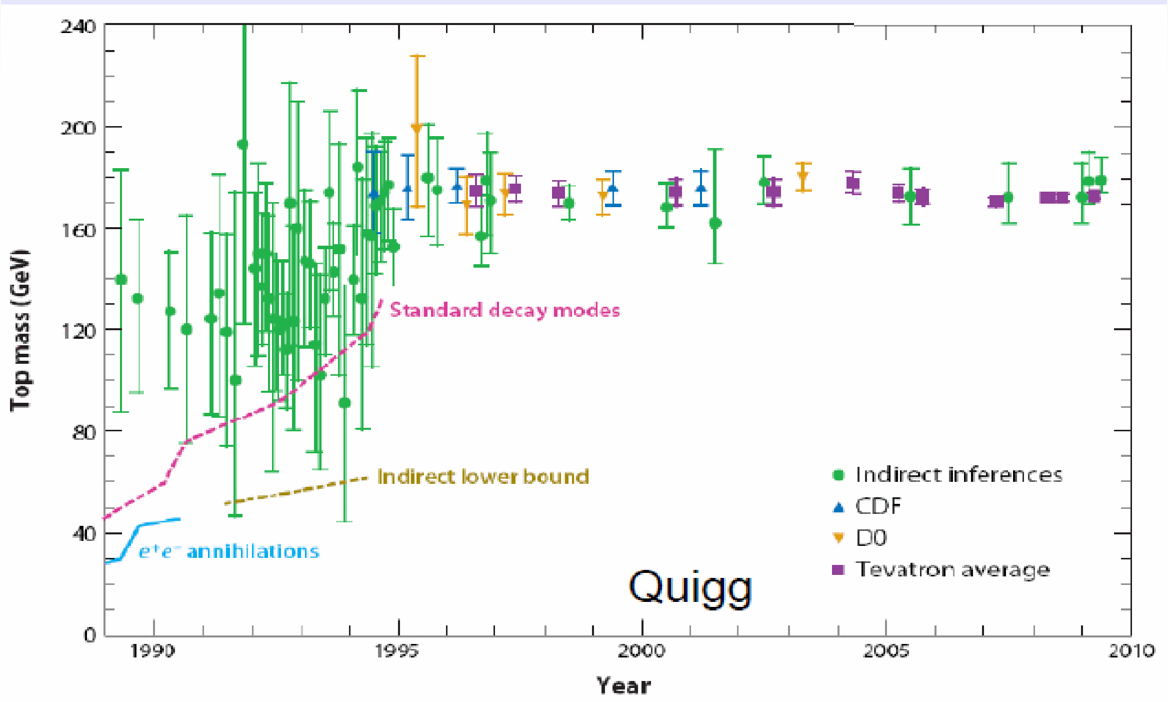
Top Quark Introduction

Top quark discovered in 1995 by CDF and D0: it is the 15th birthday!



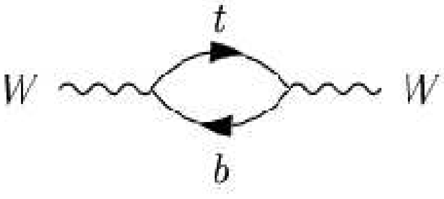
$$M_{top} = 174 \pm 10 \; ^{+13}_{-12} \; \mathrm{GeV}$$

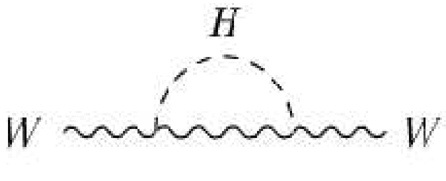
7 events with 1.4 of background



Top Quark Introduction

- Top quark was expected to be very heavy, m_T~170 GeV
- It decays with a very short lifetime $\tau \sim \hbar/\Gamma \sim 10^{-25}$s it has no time to hadronize $\tau^{QCD} \sim 10^{-24}$s
- It is possible to study the bare quark: measure the mass of the quark important SM parameter
- Important ingredient for SM precison tests: $B \to X_s \gamma$ and $K_L \to \pi^0 \nu\nu$
- It helps in understanding the Higgs sector due to the interreletionship with W and H

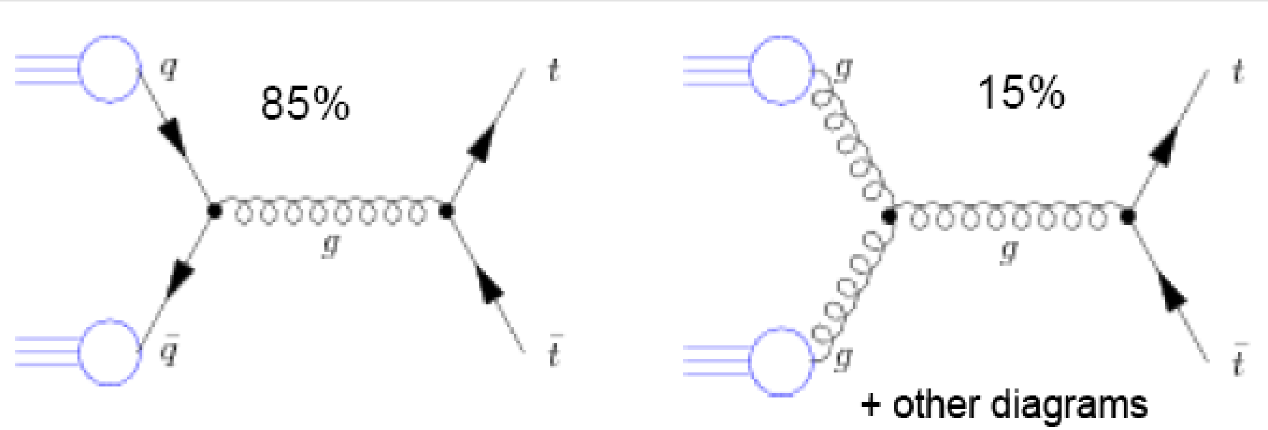




W propagator, and hence its coupling to the H vacuum expectation value (Mw) is affected through internal loops with top quark and H

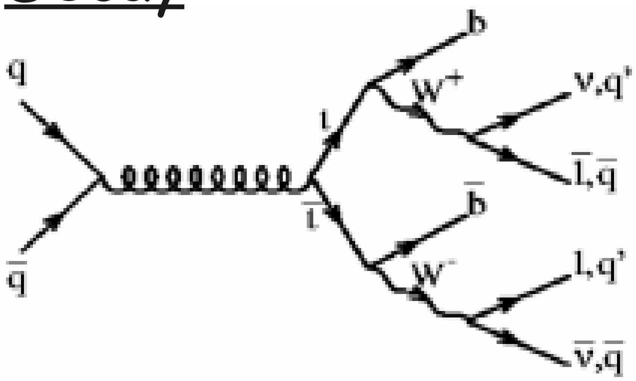
Top Quark Production & Decay at Tevatron

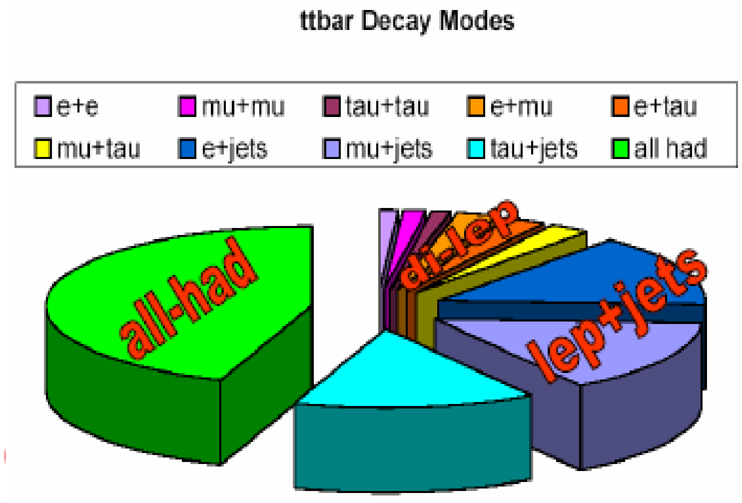
Production



At Tevatron top quark is mainly produced in pairs

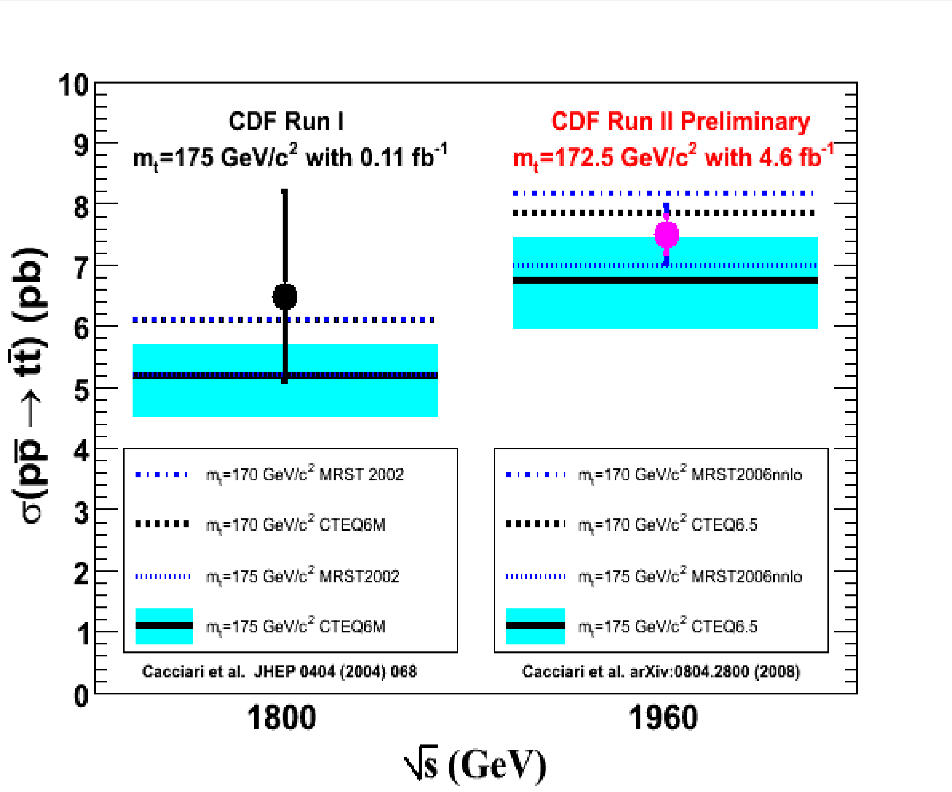
Decay

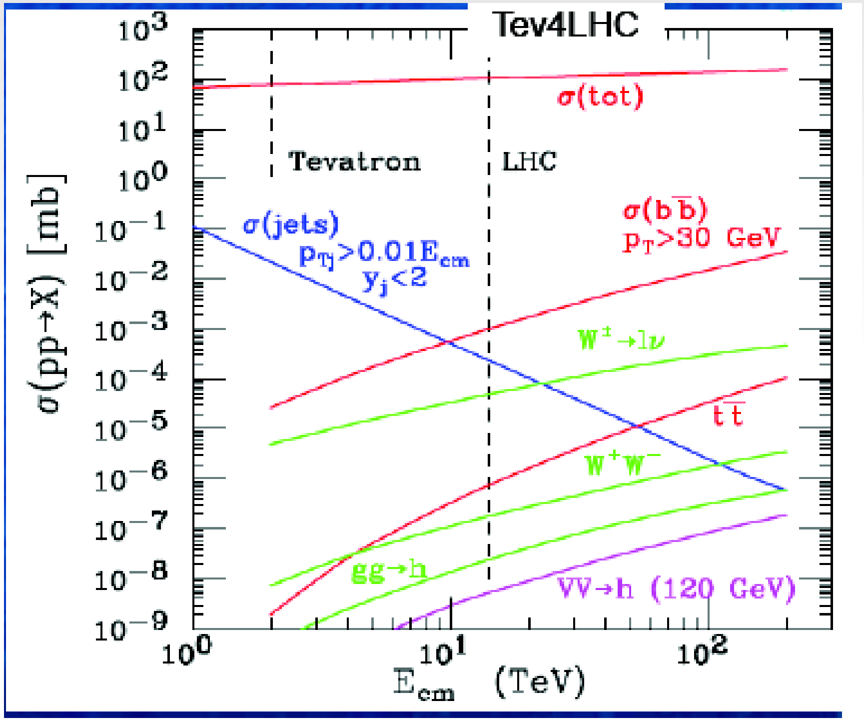




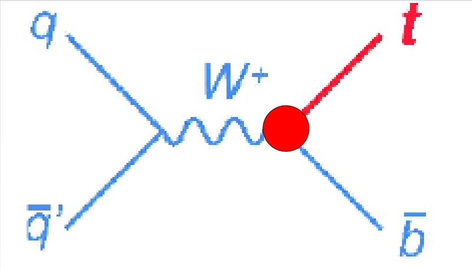
Di-leptons	5%
Leptons+jets	30%
All-hadronic	44%
Others	21%

Top quark cross section

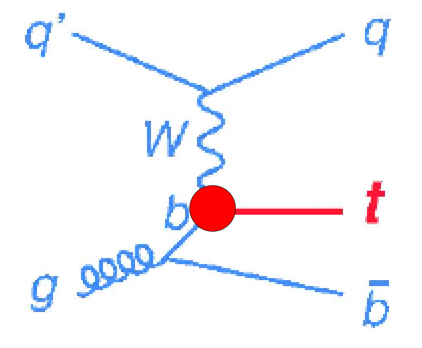




Single-Top quark production

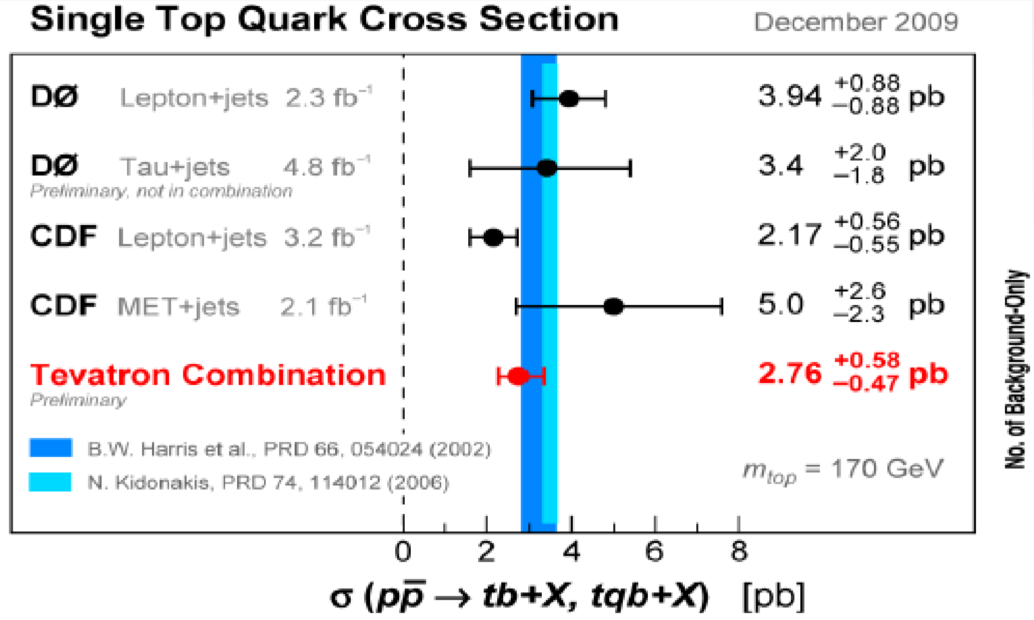


s-channel
$\sigma(tb)=0.88\pm0.05$pb

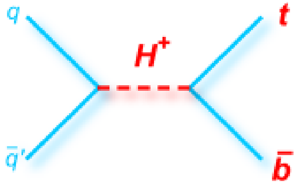


t-channel
$\sigma(tqb)=2.34\pm0.13$pb

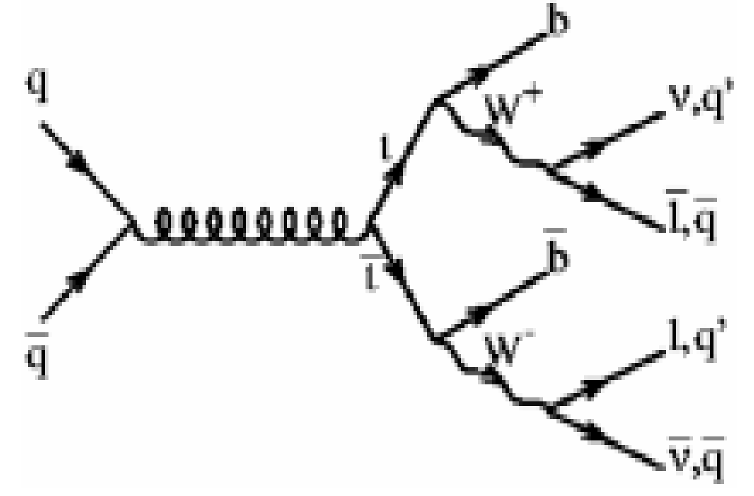
Top identification and reconstruction similar to $t\bar{t}$ analysis, see later.
High background and low signal contribution.

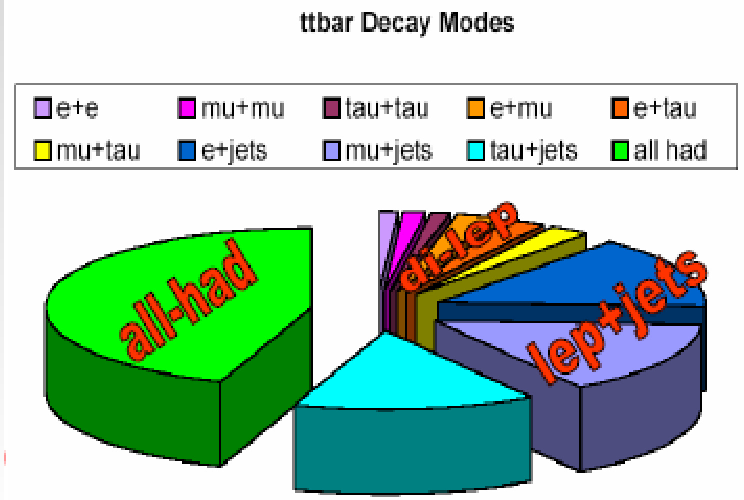


- Measure V_{tb}
- SingleTop polarized non SM contribution can change it
- Sensitive to new physics



Top Quark Final States





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

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

Data Collection: Lepton Triggers

Dilepton and single lepton channels use "high pt muon" and " high pt electron" triggers.

High_PT_muon trigger:

Level 1 : stub in the muon chambers

Level 2: track reconstructed in the central chamber Pt>15 GeV/c point to a stub

Level 3: muon recostructed with offline quality

High_PT_electron trigger:

Level 1: em. calorimetric tower Et>8 GeV & proto-track

Level 2: em. jet Et>18 GeV & Ehad/Eem <0.125 & track point to a jet

Level 3: em jet reconstructed with L0 energy calibration, i.e pedestal subtraction

Data Collection: Hadronic Trigger

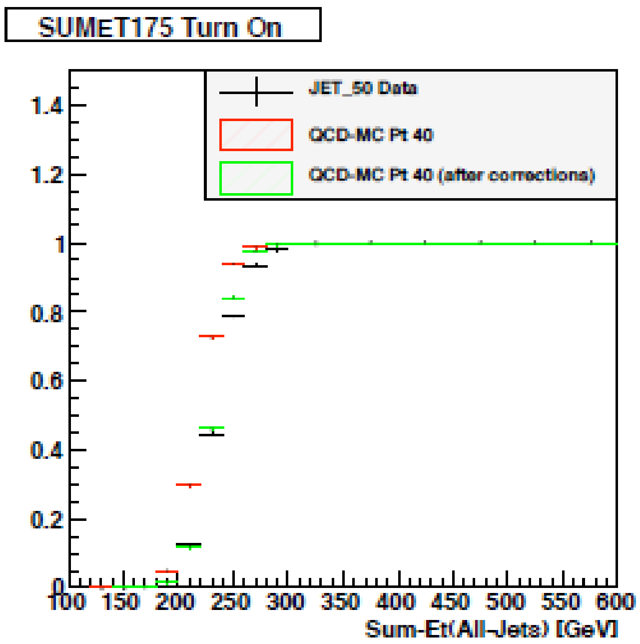
Hadronic channel uses "Multi jets" trigger

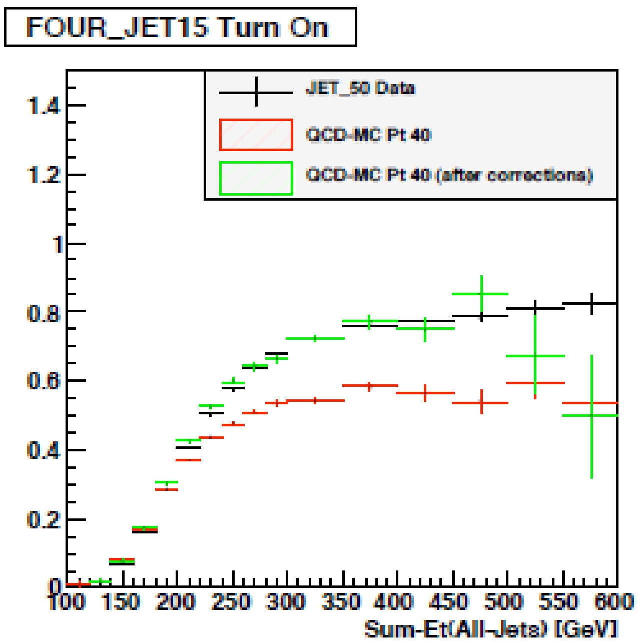
Multi_jets trigger:

Level 1: calorimetric tower Et>20 GeV

Level 2: Four jets Et>15 GeV & Total Et>175 GeV

Level 3: Jets reconstructed with L0 energy calibration

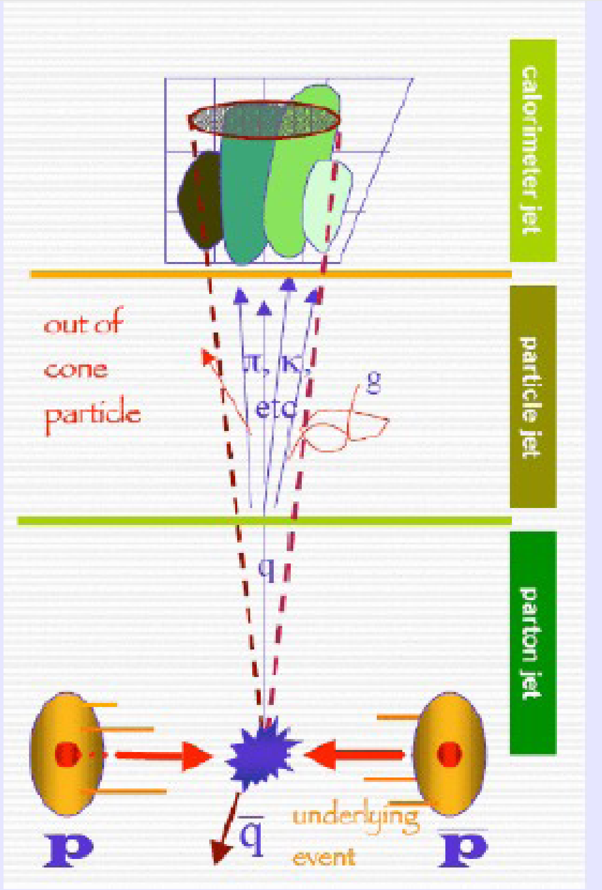




Trigger efficiecies are nedeed then to simulate Monte Carlo.

Challenge 1: Jet Energy determination

- Final states have jets but partons information are needed.



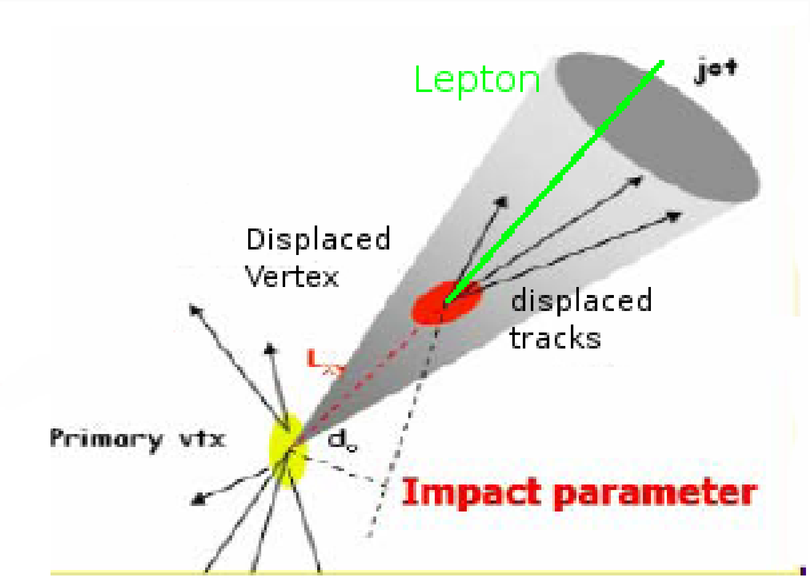
Use cone algorithm

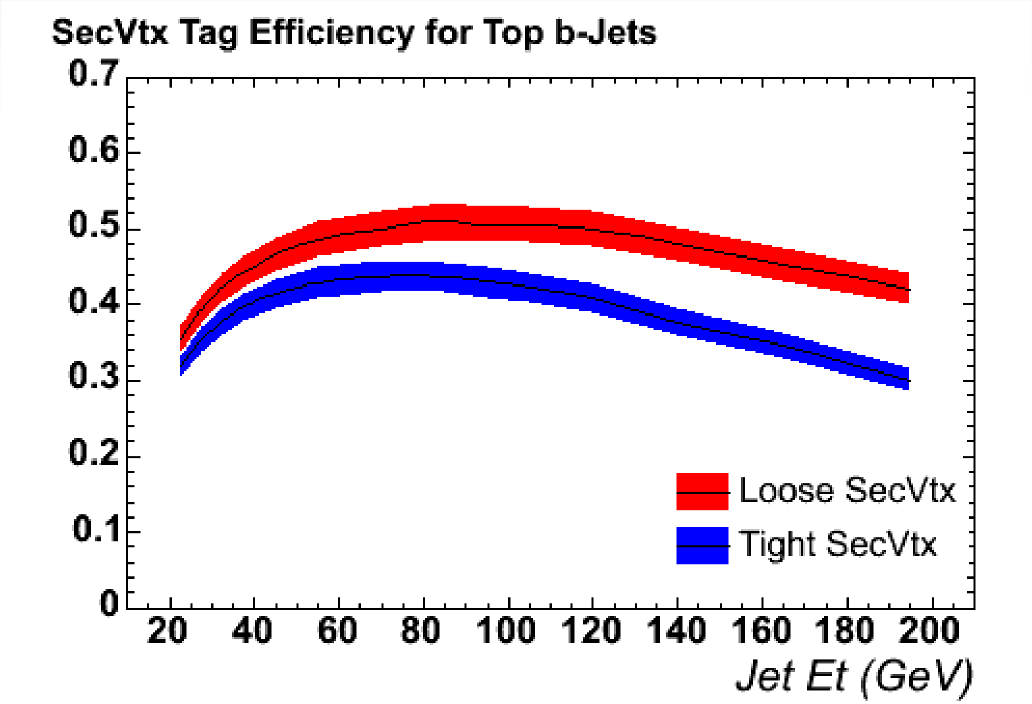
Jet Energy Scale (JES) is one of the major source of uncertainty. Lepton+jets and hadronic decay channel use the "in situ" calibration: constraint W->jet-jet to measured W mass.

Challenge 2: tagging of b-jets

Final states always with b-quark → b-tag algorithm used to find it

- Select tracks with high impact parameter wrt primary vertex
- Fit to identify a secondary vertex
- Cut on decay lenght L_{xy}

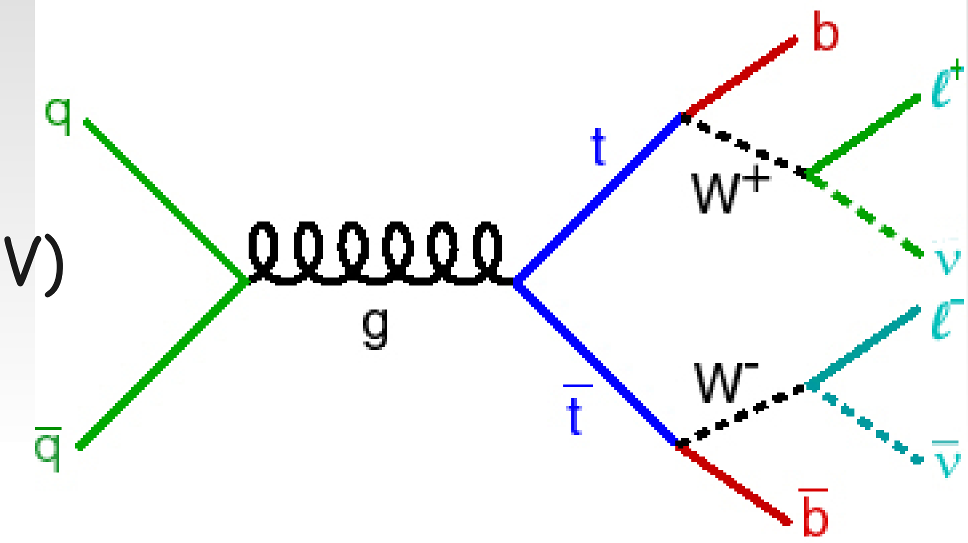




Top Quark Events Selection: Dileptons

Requirements:

- two high P_T opposite charge isolated leptons (Pt>15 GeV)
- at least 2 high E_T jets (E_T>20 GeV)
- at least one vertex b-tag
- MET> 25 GeV



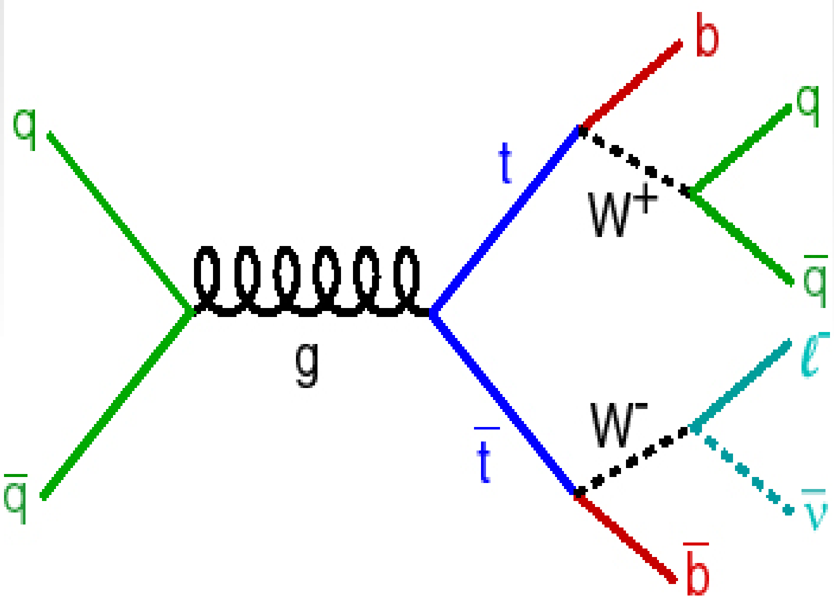
Major Backgrounds

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

Top Quark Events Selection: leptons+jets

Requirements:

- one high P_T isolated leptons (Pt>20 GeV)
- at least 4 high E_T jets (E_T >20 GeV)
- at least one b-tag
- MET>20 GeV



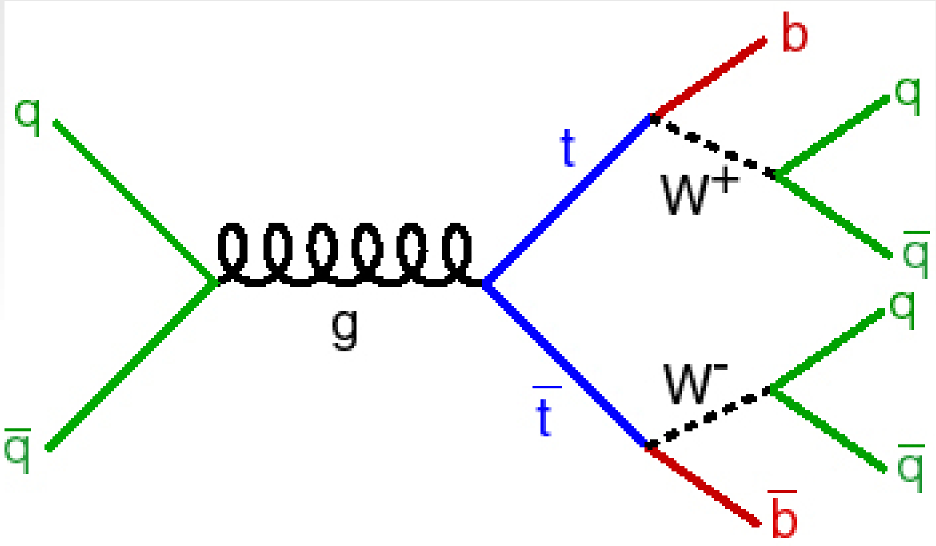
Major Background

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

Top Quark Events Selection: all jets

Requirements:

- at least 6 high E_T jets (E_T >15 GeV)
- at least one b-tag
- Small MET
- No leptons



Dominant Background

- 🟩 QCD multi-jets

Mass Measurement Methods

Template method

- Choose and observable,x, sensitive to m_T
- x can be: lepton Pt, reconstructed top mass, decay length
- Predict the x distribution as a function of m_T using Monte Carlo (templates)
- For each event evaluate the likelihood for each m_T value
- Maximize the likelihood for the entire sample

Matrix Element

- Use all information from the event integration over the least known variables

Matrix Element Method Introduction

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

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

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

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

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

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

Normalization depends on m_t

Includes acceptance effects

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

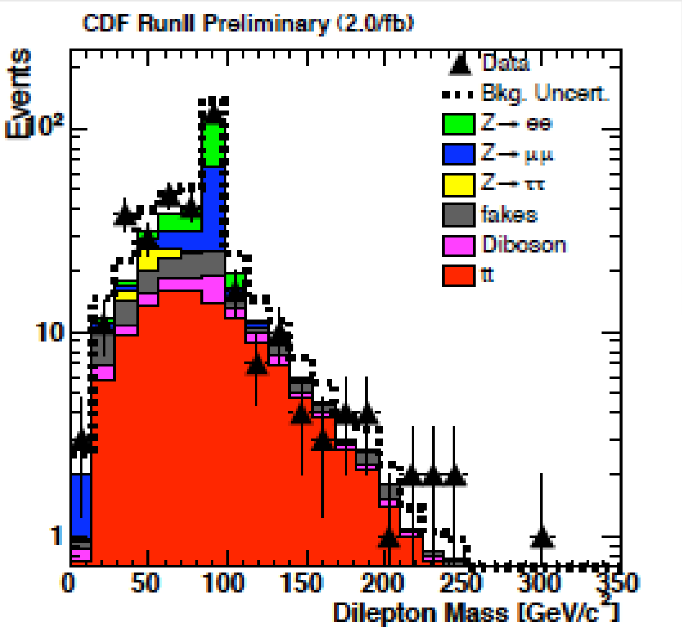
Integrate over unknown:

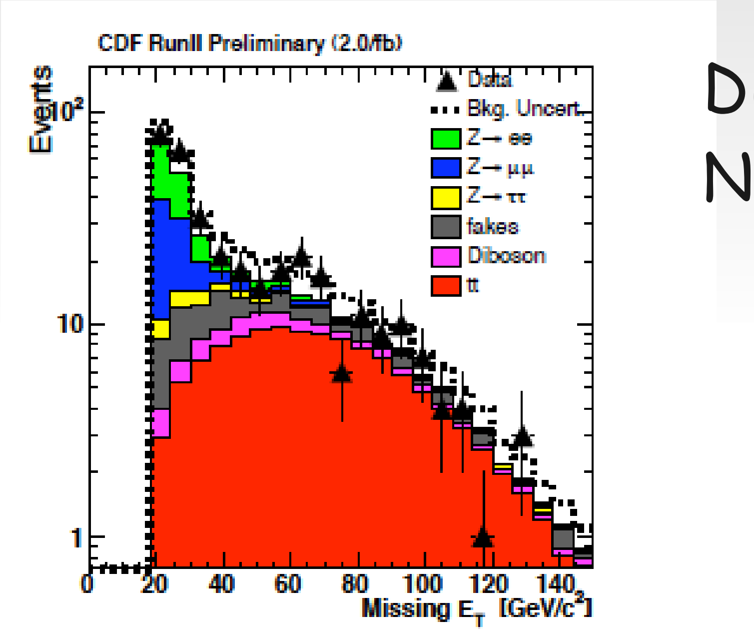
kinematical variable q_1,q_2 of initial states parton and final states parton y

Approximations: LO matrix element and *qq->tt* process only (no gluon fusion – 15%)

Dileptons Events Analysis

Matrix Element and Neural Network are applied to discriminate signal from background





Distributions after NN before ME

The information contained in an event regarding top mass is expressed as conditional probability

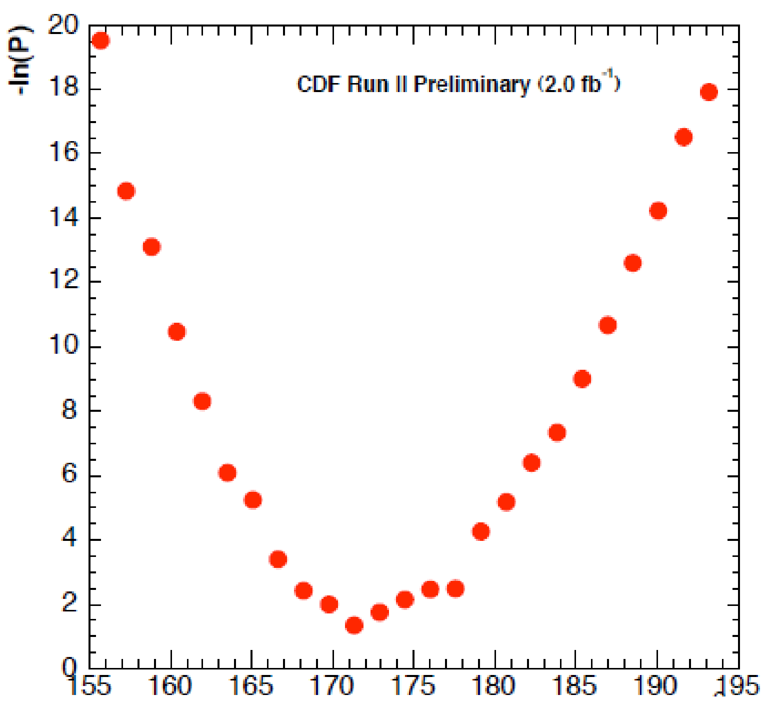
$$P(\mathrm{x}|M_t) = \frac{1}{\sigma(M_t)}\frac{d\sigma(M_t)}{d\mathrm{x}}$$

M_t is the top pole mass, x is the vector of measured quantities

Dileptons Events Result

The simple formula is then modified to include background contributions and then integrated.

Fit posterior probability to extract M_t



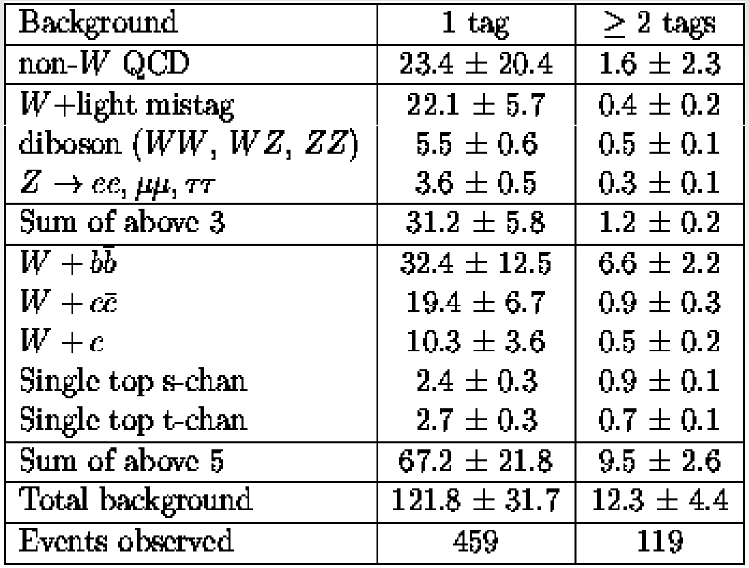
Systematics error are evaluated and included in the fitter

Source	Size (GeV/c^2)
Jet Energy Scale	2.5
Lepton Energy Scale	0.1
Generator	0.7
Method	0.4
Sample composition uncertainty	0.3
Background statistics	0.5
Background modeling	0.2
FSR modeling	0.3
ISR modeling	0.3
PDFs	0.6
Total	2.9

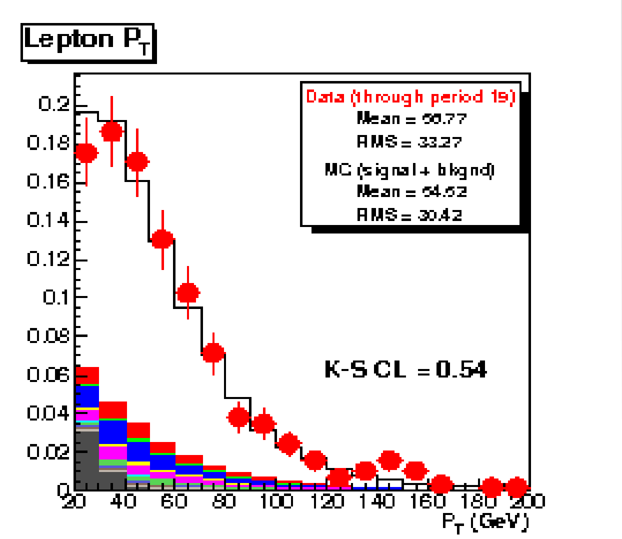
$$M_{top} = 171.2 \pm 2.7(\text{stat.}) \pm 2.9(\text{syst.})\ \text{GeV}/c^2$$

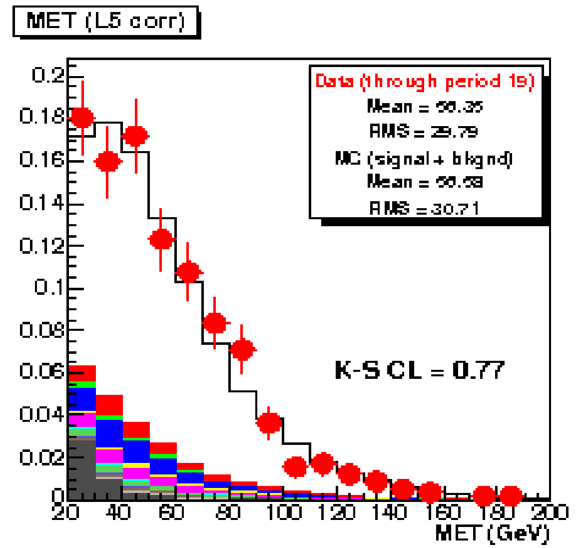
Lepton+jets analisys

Sample composition after event selection



Background	1 tag	≥ 2 tags
non-W QCD	23.4 ± 20.4	1.6 ± 2.3
W+light mistag	22.1 ± 5.7	0.4 ± 0.2
diboson (WW, WZ, ZZ)	5.5 ± 0.6	0.5 ± 0.1
$Z \to ee, \mu\mu, \tau\tau$	3.6 ± 0.5	0.3 ± 0.1
Sum of above 3	31.2 ± 5.8	1.2 ± 0.2
$W + b\bar{b}$	32.4 ± 12.5	6.6 ± 2.2
$W + c\bar{c}$	19.4 ± 6.7	0.9 ± 0.3
$W + c$	10.3 ± 3.6	0.5 ± 0.2
Single top s-chan	2.4 ± 0.3	0.9 ± 0.1
Single top t-chan	2.7 ± 0.3	0.7 ± 0.1
Sum of above 5	67.2 ± 21.8	9.5 ± 2.6
Total background	121.8 ± 31.7	12.3 ± 4.4
Events observed	459	119





Signal likelihood calculation is performed by integrating over the matrix element using the following formula:

$$L(\vec{y} \mid m_t, \Delta_{\mathrm{JES}}) = \frac{1}{N(m_t)} \frac{1}{A(m_t, \Delta_{\mathrm{JES}})} \sum_{i=1}^{24} w_i L_i(\vec{y} \mid m_t, \Delta_{\mathrm{JES}})$$

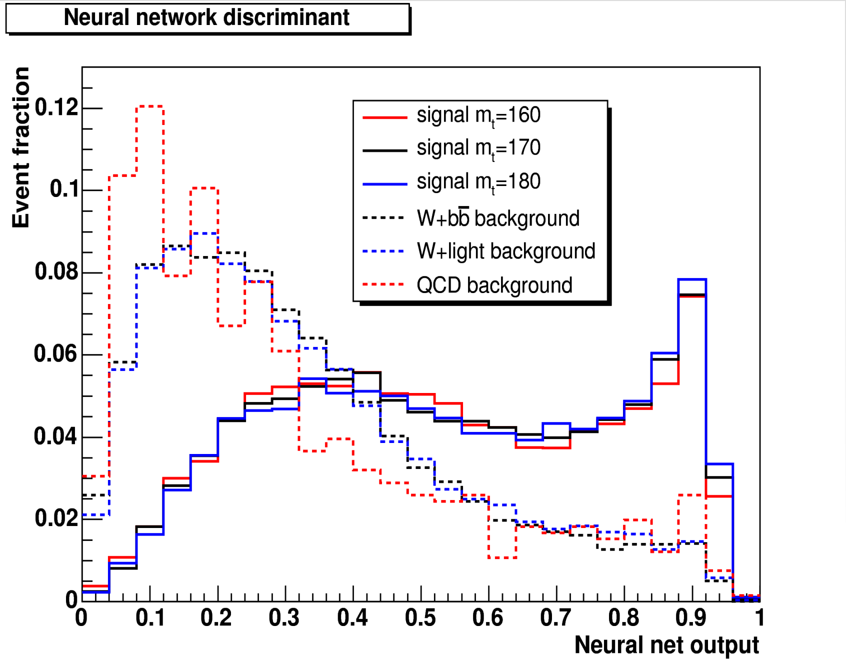
L_i = event likelihood

Lepton+jets Analysis

For each event calculate the background fraction for that event $f_{bg}(q) = B(q)/(S(q)+B(q))$, where q is neural network output for that event.

This method does not include an explicit background likelihood.

All events are treated as signal.

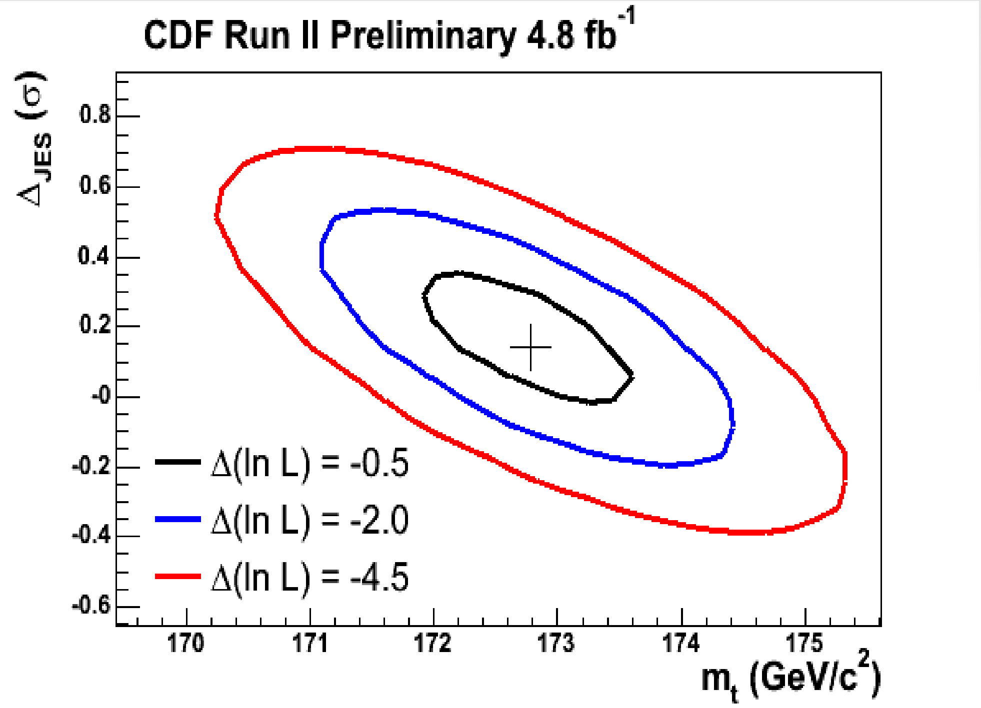


Data are a mixture of signal and background and to recover the likelihood for the signal events, the background contribution is subtracted>

$$\log L_{sig}(mt,JES) = \Sigma_i[\log L_i(mt,JES)] - n_{bg} \log L_{avg}(mt, JES \mid bck)$$

Lepton+jets Result

The W->jj is constrained to the measured W mass to improve JES



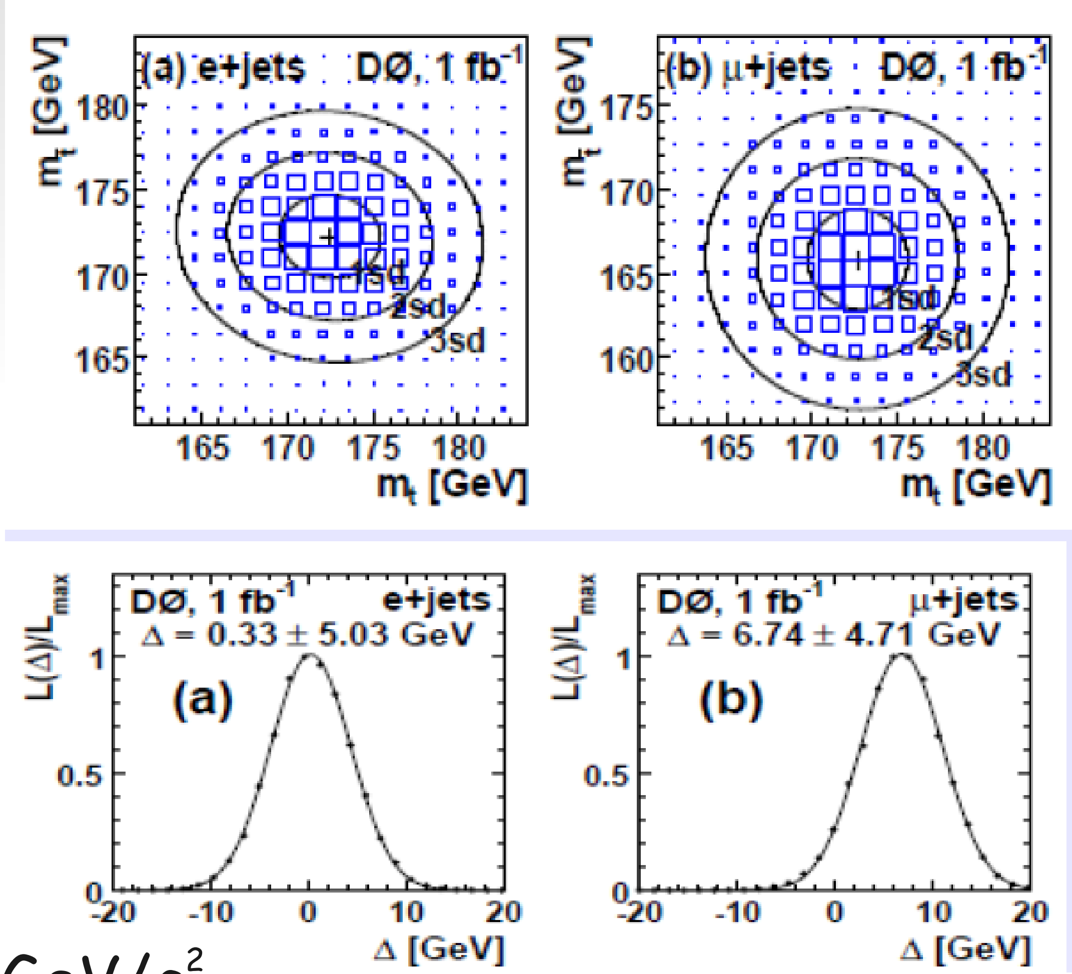
The results of the fit are

m_t=172.8 ±0.7(stat) ±0.6(JES) ± 0.8(Sys)GeV/c^2

Top-antiTop mass difference

Test of CPT in the top sector. First test done with quarks!

- Same analysis of mass measurement.
- Use Matrix Element with m_T different from $m_{\overline{T}}$
- Likelihood written as function of $\Delta m = m_T - m_{\overline{T}}$



$\Delta m_t = 3.8 \pm 3.4(\mathrm{stat}) \pm 1.2(\mathrm{Sys})\mathrm{GeV}/c^2$

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

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

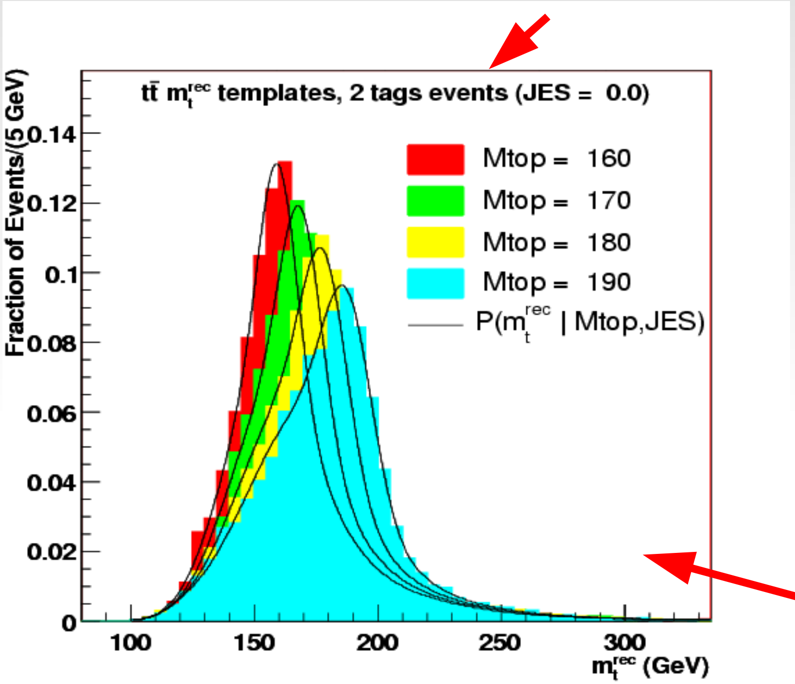
P_T^{fit} =top transv. momentum

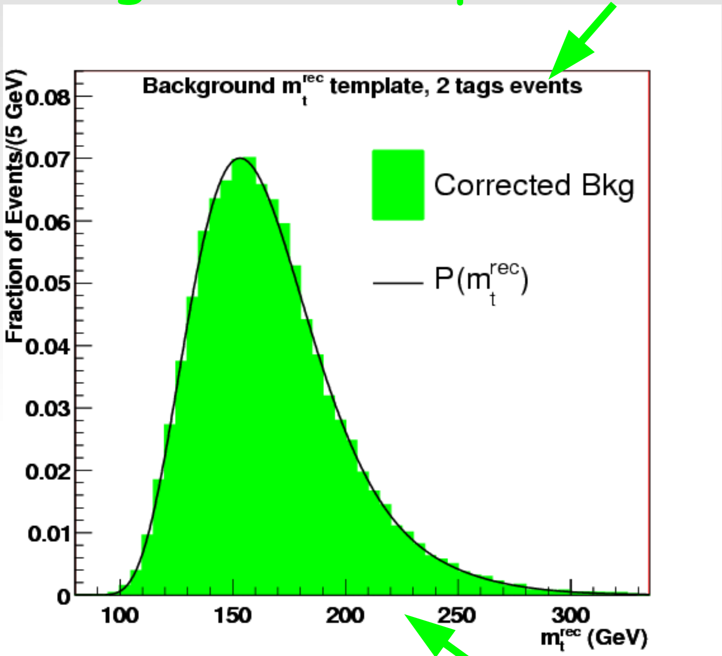
For each permutation we obtain m_t^{rec} this forms the template for signal (MC) and background (data)

Quark Top Mass: All Hadronic

Signal template: Monte Carlo data

Background template: data





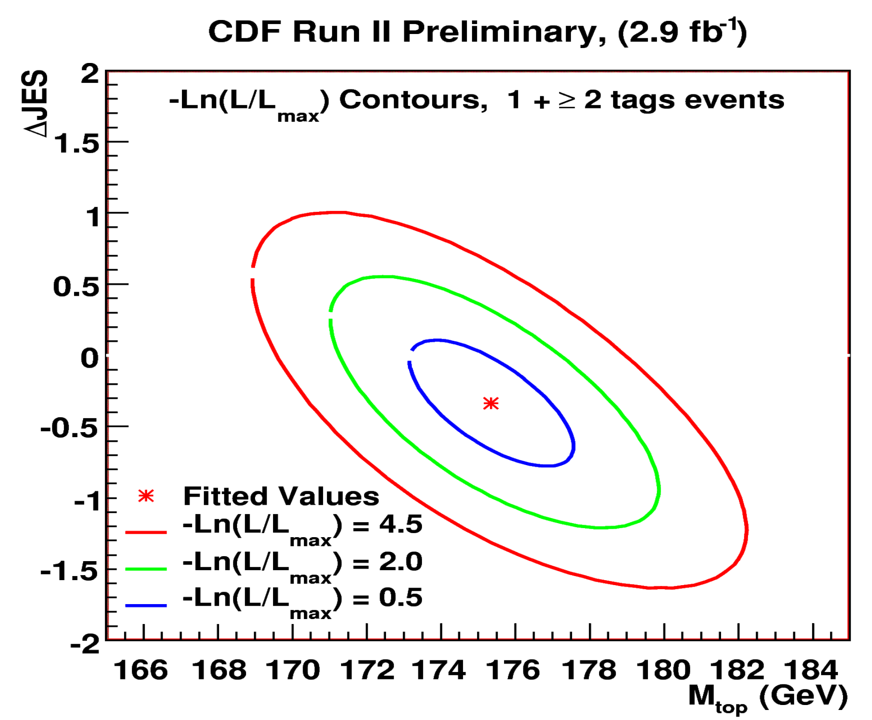
$$L_{tot} = L_{M_{top}} + L_{JES}$$

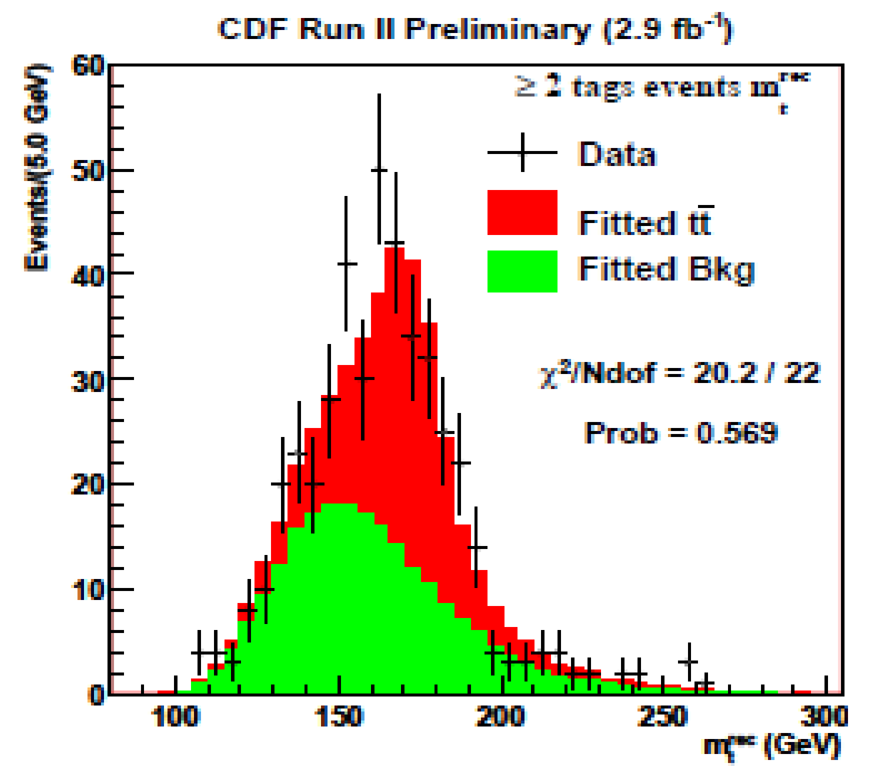
$$\mathcal{L}_{M_{top}} = \prod_{i=1}^{N_{obs}} \frac{n_s \cdot P_{sig}^{m_t^{rec}}(m_{t,i} \,|\, M_{top}, \mathrm{JES}) + n_b \cdot P_{bkd}^{m_t^{rec}}(m_{t,i})}{n_s + n_b}$$

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

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

All Hadronic result

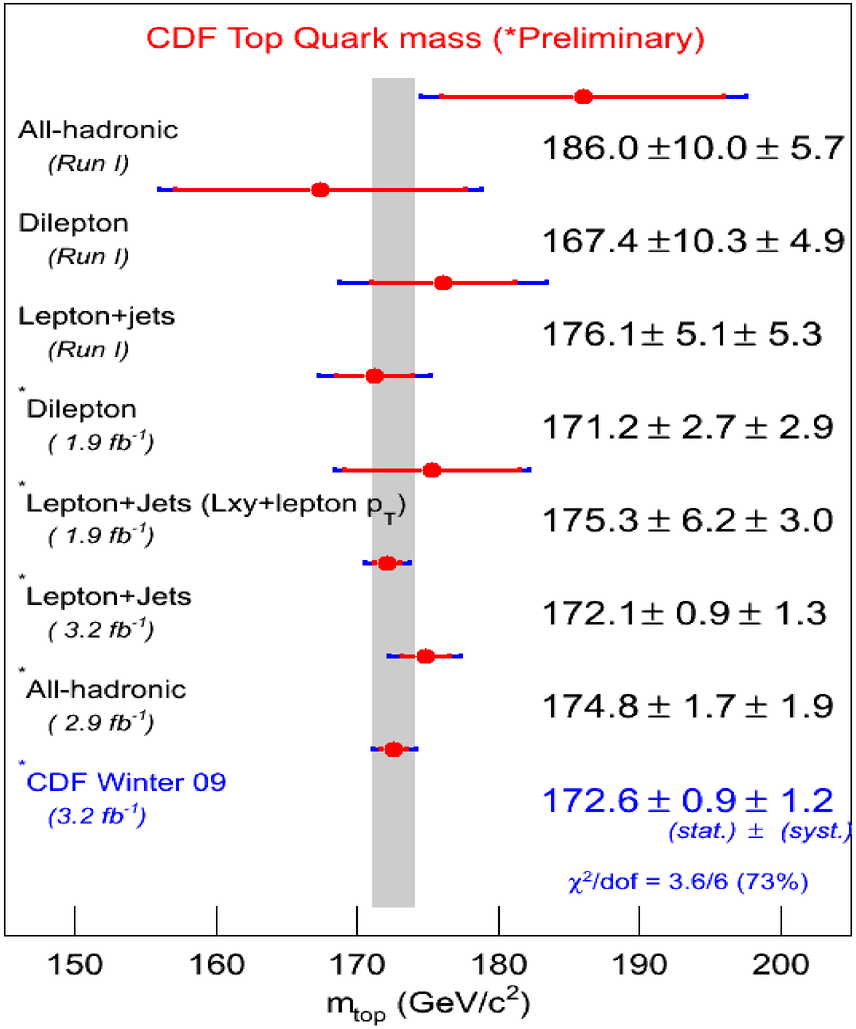


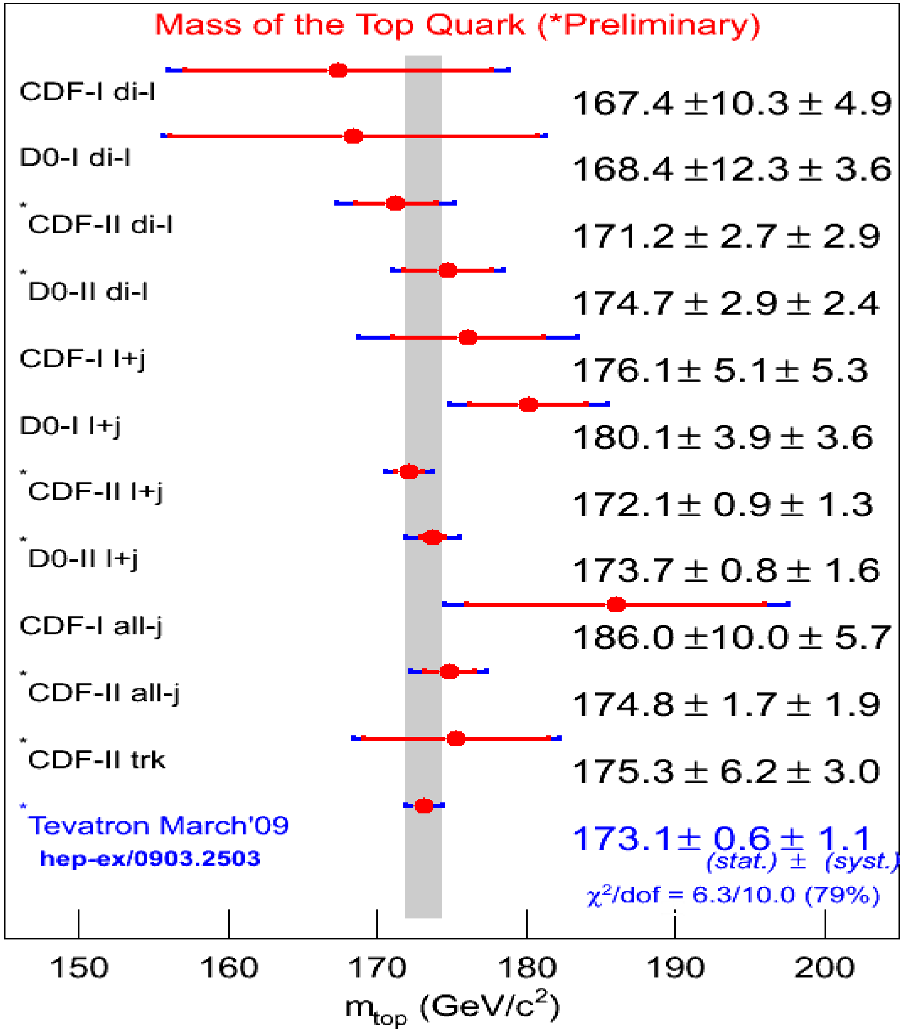


$$M_{top} = 174.8 \pm 1.7\ (\text{stat}) \pm 1.9\ (\text{syst})\ \text{GeV}/c^2$$

$$\delta M_{top}/M_{top} \simeq 1.5\%$$

Top Quark mass combination





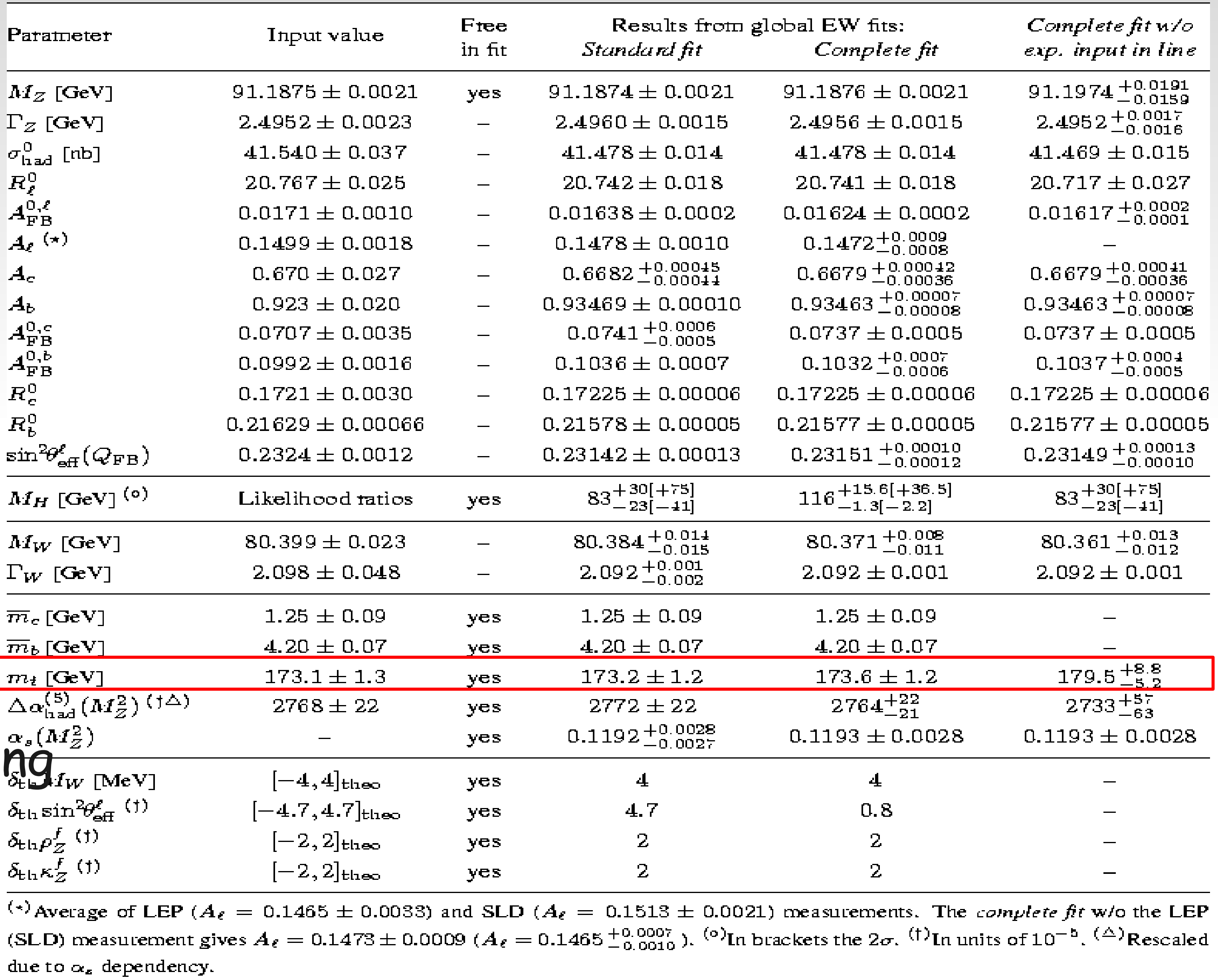
172.6±0.9(stat)±1.2(syst) GeV/c^2 173.1±0.6(stat)±1.1(syst) GeV/c^2

Top Quark Mass: What are we measuring?

- All Mtop measurements make heavy usage of Monte Carlo
- So we measure the MC top mass!
- Usually in the MC the parameter we calibrate to is the top-quark pole mass.
- All say It's pole mass with Λ_{QCD}~200 MeV/c^2
- If not, the measured top mass should be corrected but the correction factors are small less than 10%.

Top Quark Mass and the Standard Model Fit

List of parameters that enter the Standard Model fit. Last column gives the fit results for each parameter without using the corresponding experimental constraint in the fit



Parameter	Input value	Free in fit	Results from global EW fits: *Standard fit*	*Complete fit*	*Complete fit w/o exp. input in line*
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1874 ± 0.0021	91.1876 ± 0.0021	$91.1974^{+0.0191}_{-0.0159}$
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4960 ± 0.0015	2.4956 ± 0.0015	$2.4952^{+0.0017}_{-0.0016}$
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.478 ± 0.014	41.478 ± 0.014	41.469 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.742 ± 0.018	20.741 ± 0.018	20.717 ± 0.027
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01638 ± 0.0002	0.01624 ± 0.0002	$0.01617^{+0.0002}_{-0.0001}$
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1478 ± 0.0010	$0.1472^{+0.0009}_{-0.0008}$	–
A_c	0.670 ± 0.027	–	$0.6682^{+0.00045}_{-0.00044}$	$0.6679^{+0.00042}_{-0.00036}$	$0.6679^{+0.00041}_{-0.00036}$
A_b	0.923 ± 0.020	–	0.93469 ± 0.00010	$0.93463^{+0.00007}_{-0.00008}$	$0.93463^{+0.00007}_{-0.00008}$
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	$0.0741^{+0.0006}_{-0.0005}$	0.0737 ± 0.0005	0.0737 ± 0.0005
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1036 ± 0.0007	$0.1032^{+0.0007}_{-0.0006}$	$0.1037^{+0.0004}_{-0.0005}$
R^0_c	0.1721 ± 0.0030	–	0.17225 ± 0.00006	0.17225 ± 0.00006	0.17225 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21578 ± 0.00005	0.21577 ± 0.00005	0.21577 ± 0.00005
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	0.23142 ± 0.00013	$0.23151^{+0.00010}_{-0.00012}$	$0.23149^{+0.00013}_{-0.00010}$
M_H [GeV] $^{(\circ)}$	Likelihood ratios	yes	$83^{+30[+75]}_{-23[-41]}$	$116^{+15.6[+36.5]}_{-1.3[-2.2]}$	$83^{+30[+75]}_{-23[-41]}$
M_W [GeV]	80.399 ± 0.023	–	$80.384^{+0.014}_{-0.015}$	$80.371^{+0.008}_{-0.011}$	$80.361^{+0.013}_{-0.012}$
Γ_W [GeV]	2.098 ± 0.048	–	$2.092^{+0.001}_{-0.002}$	2.092 ± 0.001	2.092 ± 0.001
$\overline{m}_c$ [GeV]	1.25 ± 0.09	yes	1.25 ± 0.09	1.25 ± 0.09	–
$\overline{m}_b$ [GeV]	4.20 ± 0.07	yes	4.20 ± 0.07	4.20 ± 0.07	–
m_t [GeV]	173.1 ± 1.3	yes	173.2 ± 1.2	173.6 ± 1.2	$179.5^{+8.8}_{-5.2}$
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	2768 ± 22	yes	2772 ± 22	2764^{+22}_{-21}	2733^{+57}_{-63}
$\alpha_s(M_Z^2)$	–	yes	$0.1192^{+0.0028}_{-0.0027}$	0.1193 ± 0.0028	0.1193 ± 0.0028
$\delta_{\rm th} M_W$ [MeV]	$[-4,4]_{\rm theo}$	yes	4	4	–
$\delta_{\rm th}\sin^2\theta^\ell_{\rm eff}$ $^{(\dagger)}$	$[-4.7,4.7]_{\rm theo}$	yes	4.7	0.8	–
$\delta_{\rm th}\rho^f_Z$ $^{(\dagger)}$	$[-2,2]_{\rm theo}$	yes	2	2	–
$\delta_{\rm th}\kappa^f_Z$ $^{(\dagger)}$	$[-2,2]_{\rm theo}$	yes	2	2	–

$^{(\star)}$Average of LEP ($A_\ell = 0.1465 \pm 0.0033$) and SLD ($A_\ell = 0.1513 \pm 0.0021$) measurements. The *complete fit* w/o the LEP (SLD) measurement gives $A_\ell = 0.1473 \pm 0.0009$ ($A_\ell = 0.1465^{+0.0007}_{-0.0010}$). $^{(\circ)}$In brackets the 2σ. $^{(\dagger)}$In units of 10^{-5}. $^{(\triangle)}$Rescaled due to α_s dependency.

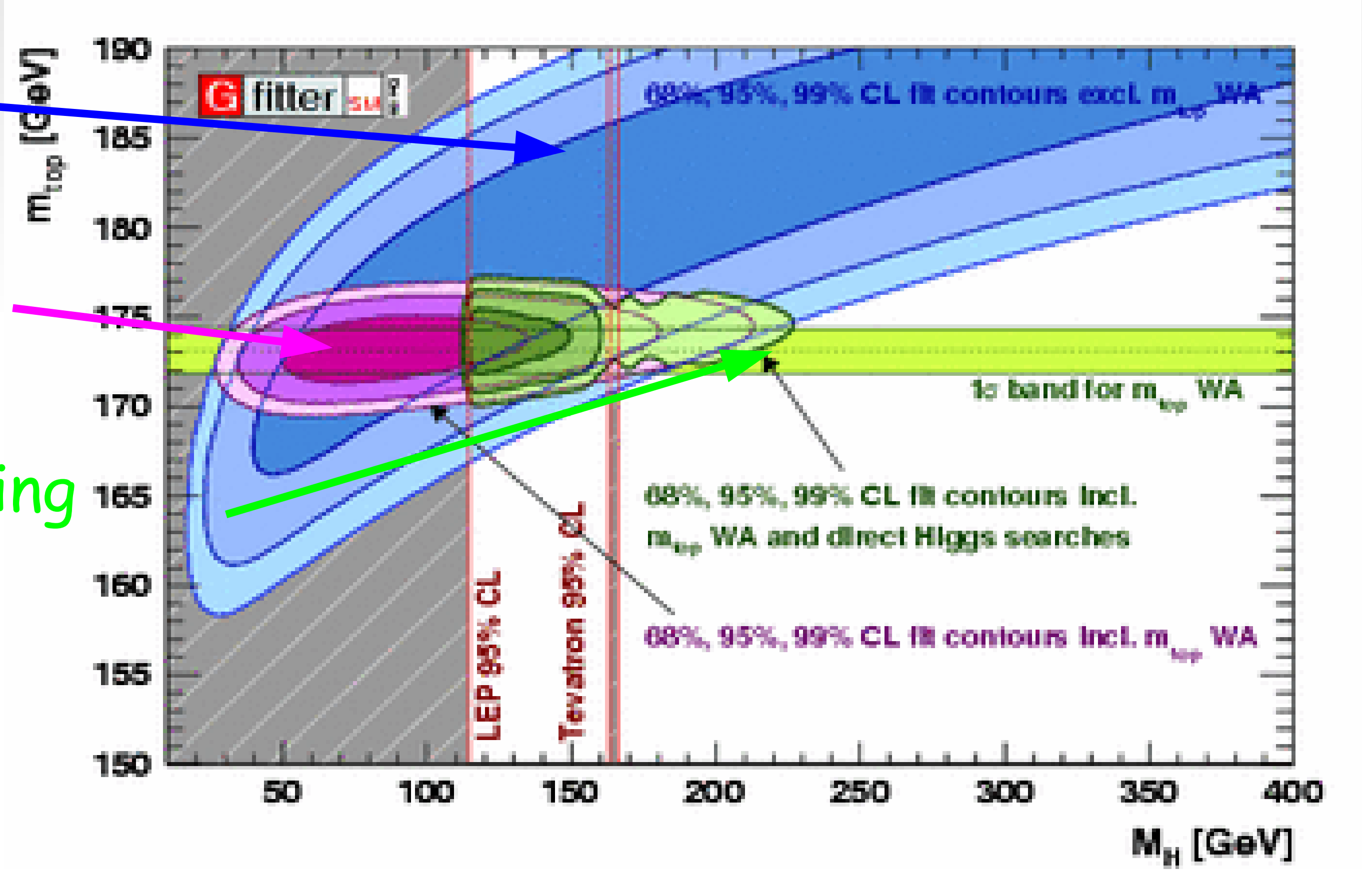
Top Quark Mass and the H

Contours of 68%, 95% and 99% CL obtained from scans of fits with fixed variable pairs m_T vs. MH .

No mt in the fit

m_T in the fit

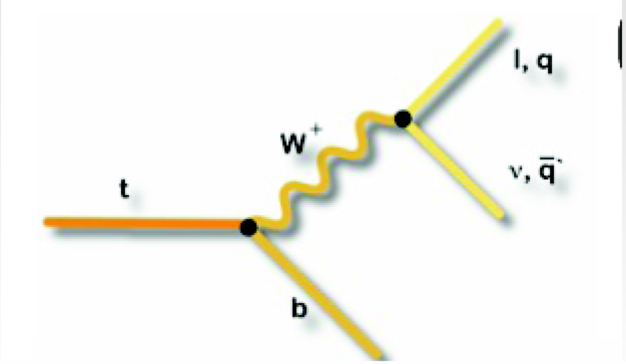
Complete fit including all data



Top Quark Charge

In Standard Model Top is expected q=2/3, exotic quark q=-4/3

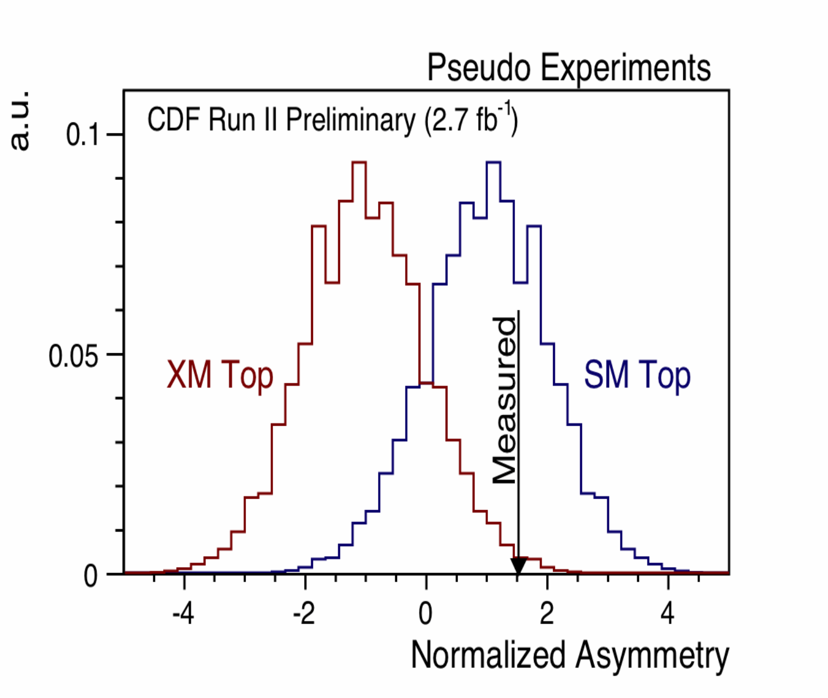
SM: t->W^+b q=2/3 XM: t->W^-b q=-4/3



✗Use a sample of lepton+jets

✗b-jets is required using btag

- Lepton charge gives the W charge
- Charge of the b: require an additional soft lepton b->l^- $\bar{b}$->l^+
- Kinematic fitter determines the b-jet of the final state lvbjjb



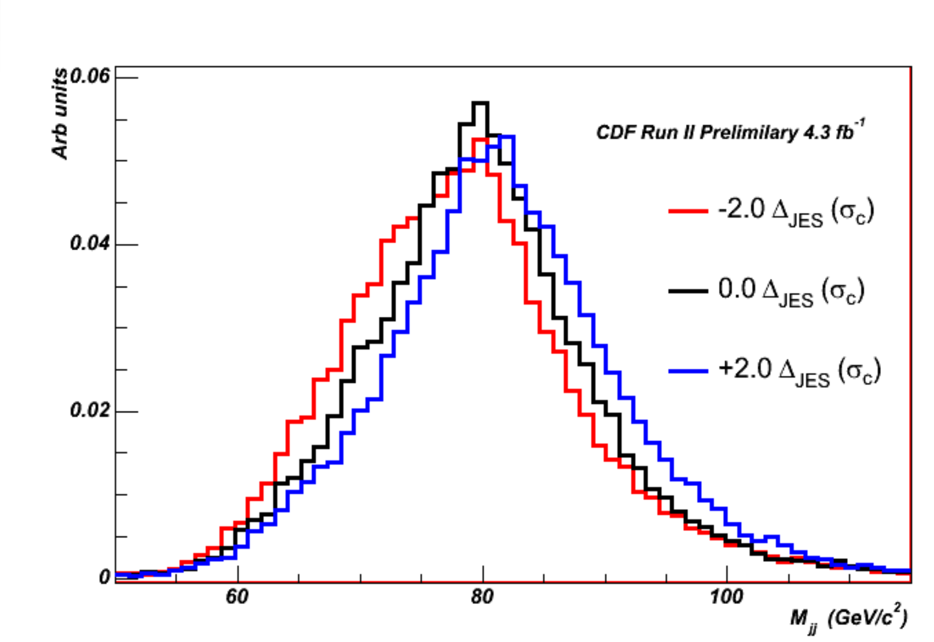
$$A_t = \frac{1}{D}\frac{N_{SM} - N_{XM} - Bkg \times D_{Bkg}}{N_{SM} + N_{XM} - Bkg} \qquad (3)$$

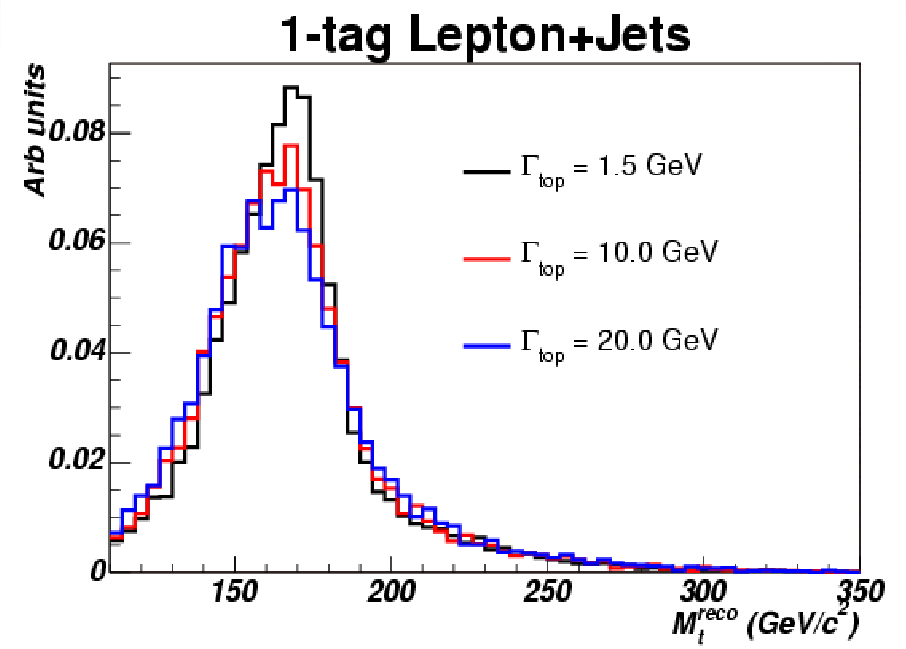
XM excluded at 95% CL

Top Quark Width

Standard Model predicts a Top width~1.5 GeV if m_T=175 GeV/c^2

- Start from a sample of lepton+jets events
- Reconstruct the mass m_T^{reco} minimizing χ^2
- mjj constrained to W mass





Top Quark Width

In order to extract the width the likelihood is minimized

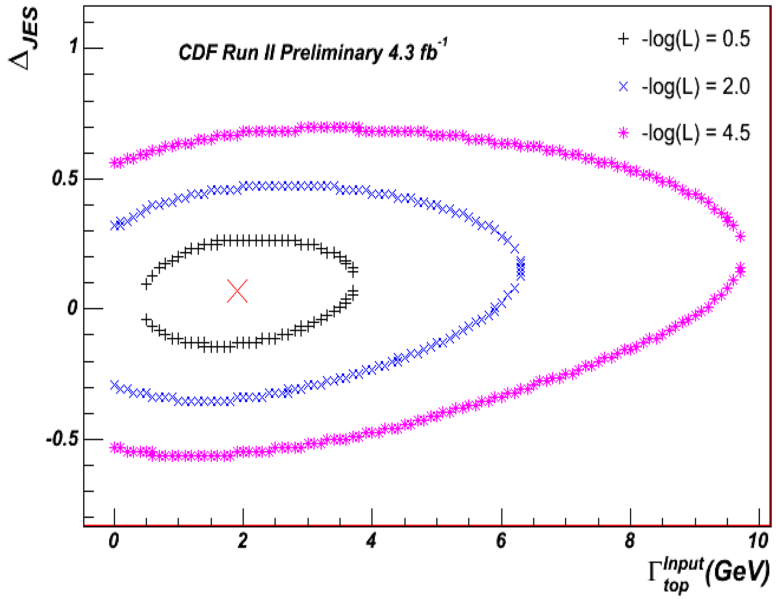
signal

backgroud

$$\mathcal{L}_{shape} = \frac{(n_s + n_b)^N e^{-(n_s+n_b)}}{N!} \times e^{-\frac{(n_{b0}-n_b)^2}{2\sigma^2_{n_{b0}}}} \times \prod_{i=1}^{N} \frac{n_s P_s(M_t^{\mathrm{reco}}, W_{jj}; \Gamma_{top}, \Delta_{\mathrm{JES}}) + n_b P_b(M_t^{\mathrm{reco}}, W_{jj}; \Delta_{\mathrm{JES}})}{n_s + n_b}$$

Reconstructed mass

to be determined



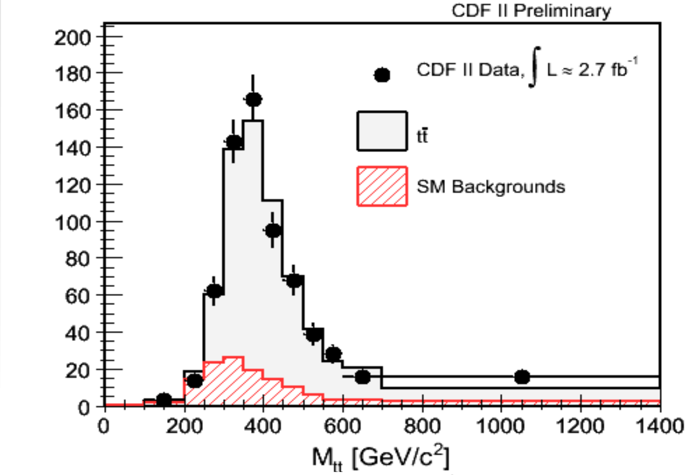
0.4 GeV < Γ_{top}< 4.4 GeV @ 68% CL

Γ_{top}< 7.5 GeV @ 95% CL

Top anti-Top resonances

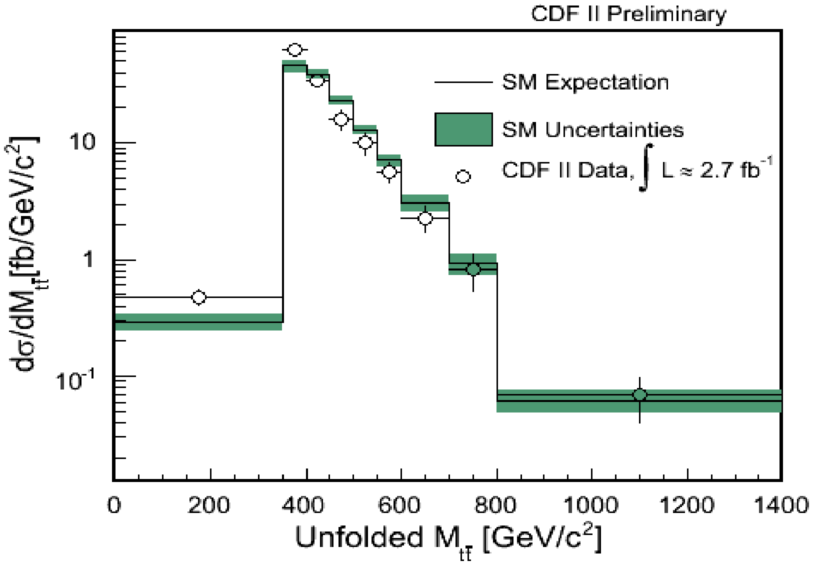
Determine the Top-antiTop cross section in bin of Mtt:

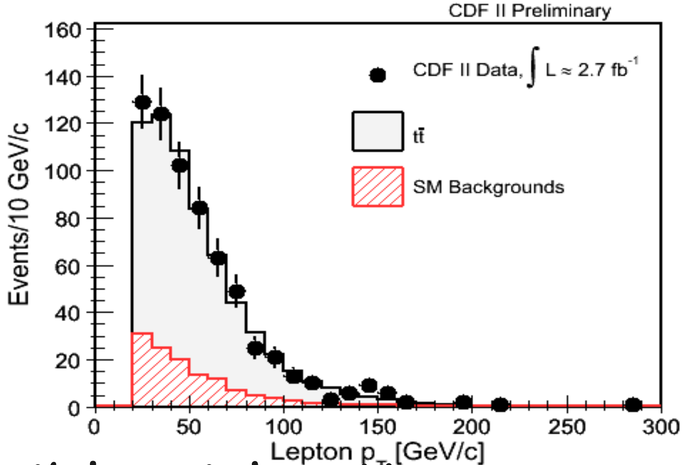
$$\frac{d\sigma^i}{dM_{t\bar{t}}} = \frac{N_i - N_i^{bkg}}{\mathscr{A}_i \int \mathscr{L} \Delta^i_{M_{t\bar{t}}}}$$



- Start from a lepton+jets sample.
- Apply "in situ" JES calibration (mjj)
- Use the unfolding technique to obtain Mtt from the reconstructed tt mass

Result:





Compatible with SM.

Set limit on Randal-Sundrum

Summary

M_t = 172.8 ± 1.3 GeV/c^2

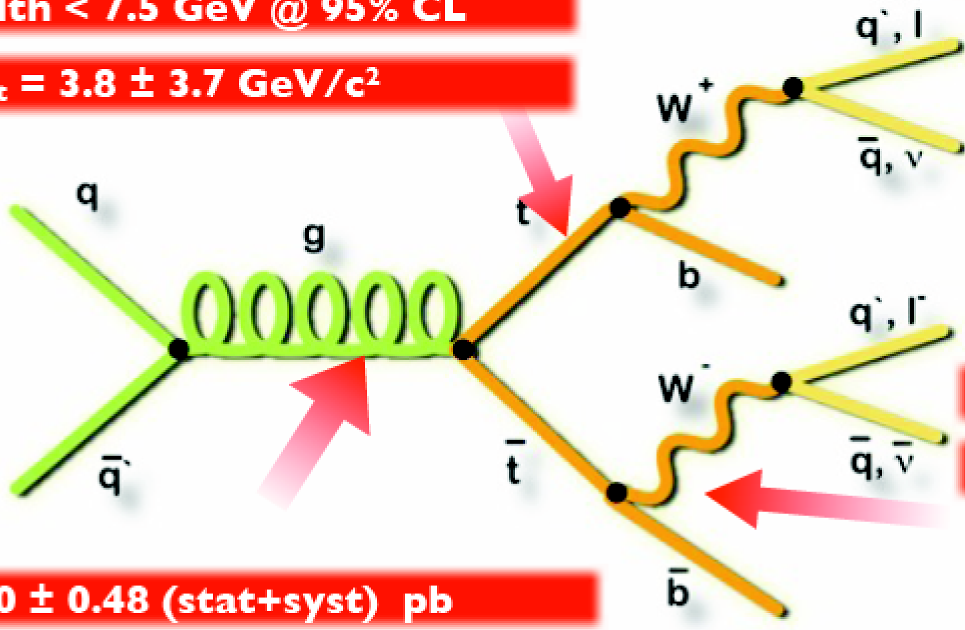
Top charge : not 4/3 @ 95% CL

Top width < 7.5 GeV @ 95% CL

ΔM_t = 3.8 ± 3.7 GeV/c^2

anom coupl : no evidence found

f_+ = 0.110 ± 0.059 (stat) ± 0.052 (syst)



B(t→Wb)/B(t→Wq)=0.97 ± 0.09

BR(t → Zq) < 3.7% at 95% C.L.

σ = 7.50 ± 0.48 (stat+syst) pb

Afb= 19.3 ± 6.5 (stat) ± 2.4 (syst) %

$d\sigma/dM_{tt}$ no discrepancy with SM

$d\sigma/dp_t$ no discrepancy with SM

fraction via gg fusion : $0.07^{+0.15}_{-0.07}$

Single Top Observation !!

Many Searches

V. Sorin