CDF 実験での top quark 質量測定

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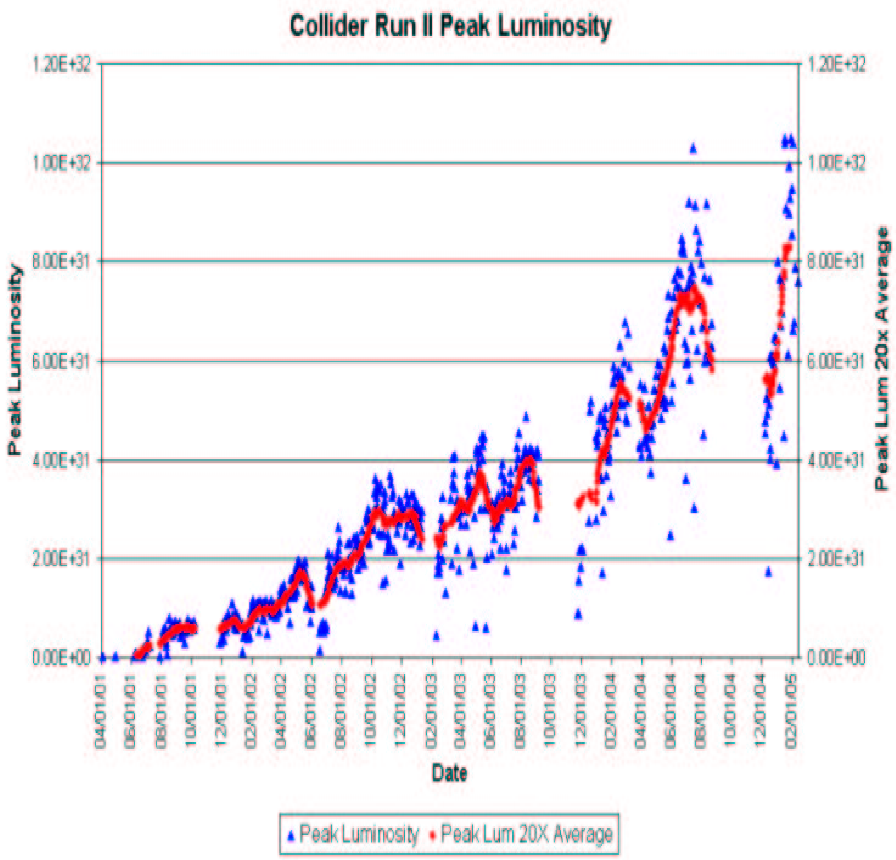
「質量起源と超対称性物理の研究」

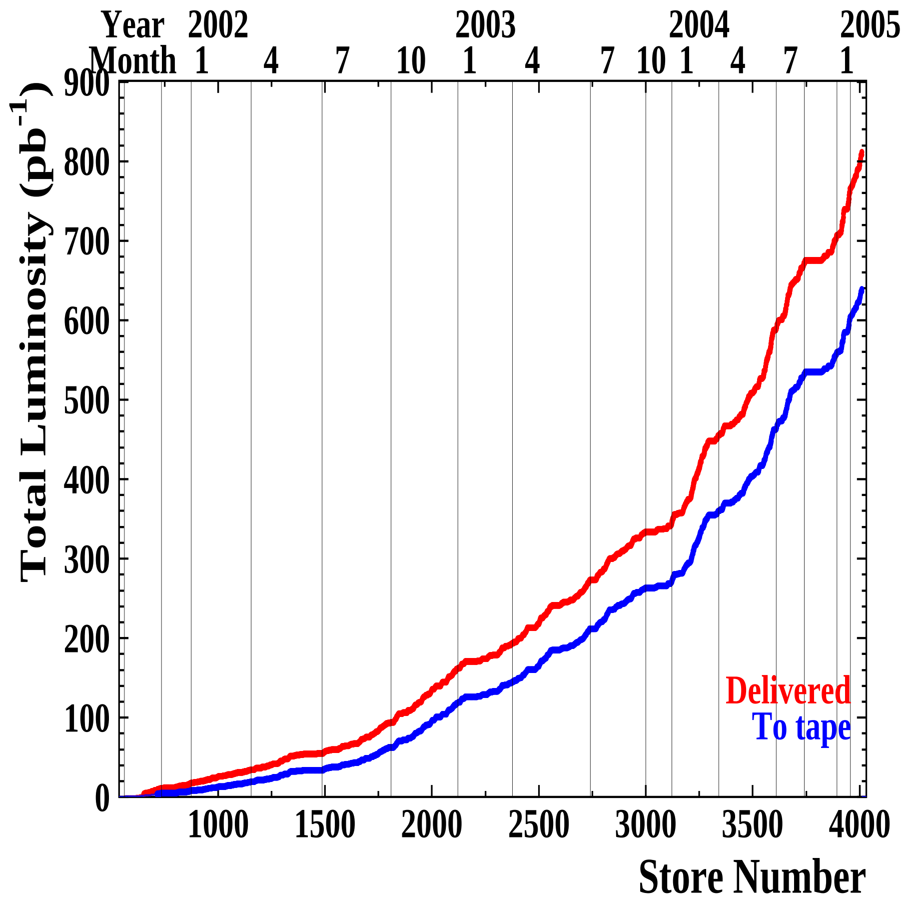
Tevatron Run II

- Started Spring 2001.
- proton-antiproton collider with $\sqrt{s} = 1.96$ TeV (Run I : 1.8 TeV).
- antiproton recycler commissioning
  - electron cooling operational by Summer '05.
  - 40% increase in luminosity.
- 36 bunches × 36 bunches.
  396 ns crossing time.
- Long term luminosity projection :
  - Base goal : 4.4 fb^{-1}
  - Design : 8.5 fb^{-1}

  by end FY2009.

Tevatron Performance





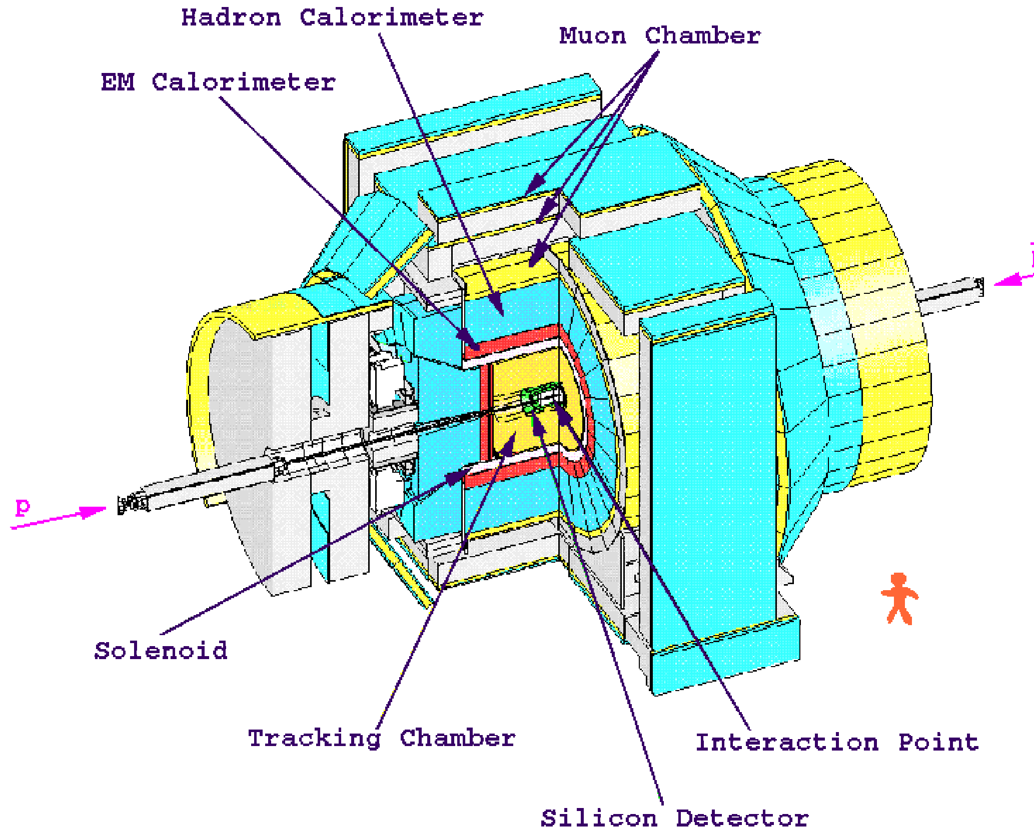
- Record : $1.2 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$.
- $\sim 800\ \mathrm{pb}^{-1}$ of collisions delivered in Run II.
- Tevatron delivered more than $\sim 350\ \mathrm{pb}^{-1}$ in 2004.
- CDF already collected $\sim 600\ \mathrm{pb}^{-1}$ on tape.

CDF Run II Detector

General purpose detectors with :

- tracking in magnetic field
- precision tracking with silicon
- calorimeter
- muon chamber

- Already collected $\sim$ 600 pb^{-1} on tape.
- This analysis uses $\sim 200\ \mathrm{pb}^{-1}$.



Top Quark Physics - motivation -

Most recently discovered quark, and the least well understood.

- Discovered by CDF and D0 in 1995.

Intimate relationship with EWSB.

- Top mass is close to the EWSB scale.
- Strongly coupled to Higgs boson : $g_f \propto m_f$.

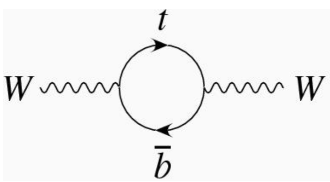
Top may be sensitive to new physics.

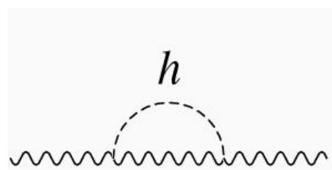
- Studying top tests electroweak theory.
- We can look for non-SM production or decay of top :
  $X \to t\bar{t}$ $\qquad$ $t \to Xb$

Background for new particle searches.
Study on top is only possible at Tevatron until LHC.

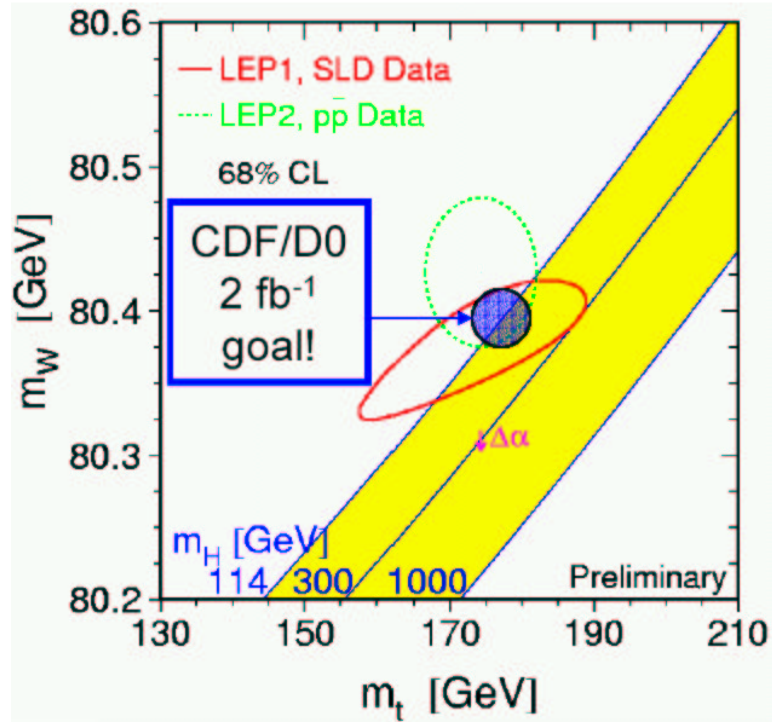
Top Mass Measurement - Motivation

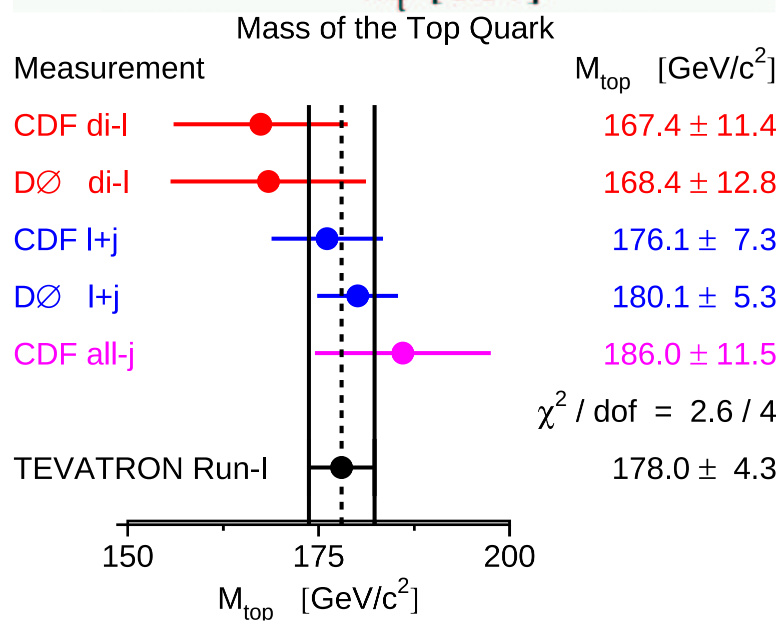
- Top mass is a fundamental parameter of SM.
- Related to Higgs mass through radiative correction.





- Top and W mass measurements constrain Higgs mass.
  - $m_H > 114.4$ GeV$/c^2$ (LEP direct search)
  - $m_H < 260$ GeV$/c^2$ (LEP/Tevatron Run I data)
- Top mass measurement in Run I : 178.0 ± 4.3 GeV$/c^2$

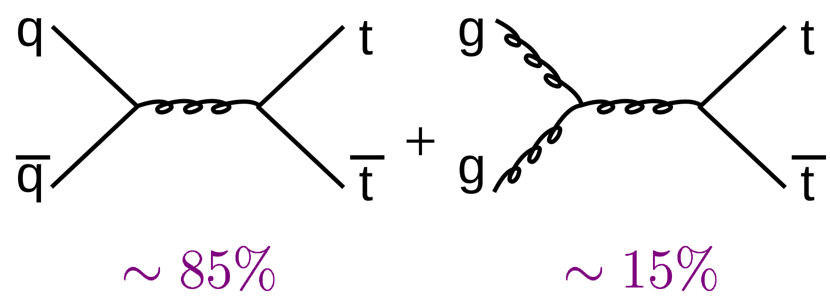




Production and Decay of Top Quark at Tevatron

Production

- Predominantly pair production.
- Theoretical total cross section : $\sigma_{t\bar{t}} \sim 6.7$ pb.
- $\sim$ 2 events in an hour at 10^{32} cm^{-2}s^{-1}.

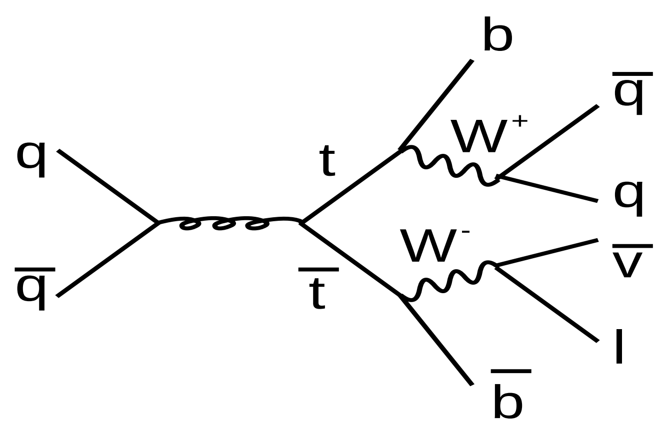


Decay

- Decays before it hadronizes.

  $\tau_{top} \sim 0.4 \times 10^{-24}$ s $<$ $1/\Lambda_{QCD} \sim 10^{-24}$ s

- $Br\,(t \to Wb) \approx 100\%$



Mode	Br. (%)	
dilepton	5	Clean but few signal. Two ν in final state.
lepton+jets	30	One ν in final state.
all jets	44	Challenging background.
τ + X	23	τ ID and backgrounds challenging.

Particle Identification and Event Selection

- One isolated high p_T lepton (e, μ).
  - $e : E_T > 20$ GeV, $|\eta| < 1.1$, shower shape, matching between calorimeter cluster and track.
  - $\mu : p_T > 20$ GeV, $|\eta| < 1.0$, energy deposit in calorimeter, matching between muon detector hit and track.
- Missing $E_T > 20$ GeV to ensure there was a ν in the final state.
- Jets are reconstructed using JETCLU algorithm with cone size 0.4.
  - 1 and 2 tag channels :
    - More than three jets with $E_T > 15$ GeV, $|\eta| < 2.0$.
    - The fourth jet with $E_T > 8$ GeV, $|\eta| < 2.0$.
  - 0 tag channel :
    - Four jets with $E_T > 21$ GeV, $|\eta| < 2.0$.
- When ≥ 5 jets are found in a event, we only consider the leading four jets as the products of $t\bar{t}$ decay.
- We use 2 b-tagging algorithms – SECVTX and Jet Probability.

Top Mass Reconstruction in Each $\mathbf{l + jets}$ Event

χ^2 fit

$$\chi^2 = \Sigma_{l,jets} \frac{(\hat{P}_T - P_T^{meas.})^2}{{\sigma_{P_T}}^2} + \Sigma_{j=x,y} \frac{(\hat{UE}_j - UE_j^{meas.})^2}{{\sigma_{UE_j}}^2} + \frac{(M_{l\nu} - M_W)^2}{{\Gamma_W}^2} + \frac{(M_{q\bar{q}'} - M_W)^2}{{\Gamma_W}^2} + \frac{(M_{l\nu b} - M_t)^2}{{\Gamma_t}^2} + \frac{(M_{q\bar{q}'b} - M_t)^2}{{\Gamma_t}^2}$$

- $p_T^{\vec{\nu}} = -\left(\Sigma_{l,jets} \vec{p_T} + U\vec{E}\right)$
- $M_W = 80.41$ GeV, $\Gamma_W = 2.12$ GeV, $\Gamma_t = 2.5$ GeV

- Fluctuate particle momenta around measured values.
- Constrain reconstructed W masses.
- Assume $m_{top} = m_{anti-top}$.
- Minimization with M_t as a free parameter.

2 jets from W, and 2 b-jets. $\rightarrow$ 12 jet-parton permutations.
2 p_Z^ν solutions.
Wrong reconstruction $\rightarrow$ combinatorial background.

# b-tagged jets	# solutions
0	24
1	12
2	4

Choose solution with smallest χ^2.
M_t $\rightarrow$ reconstructed mass in each event.

Combinatorial Background

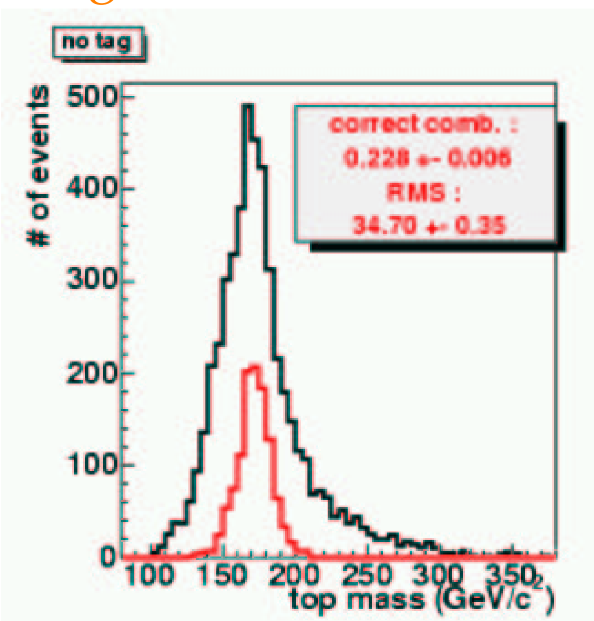
b-taggers :

- SECVTX - displacement of secondary vertex.
- Jet Probability - impact parameter of tracks.

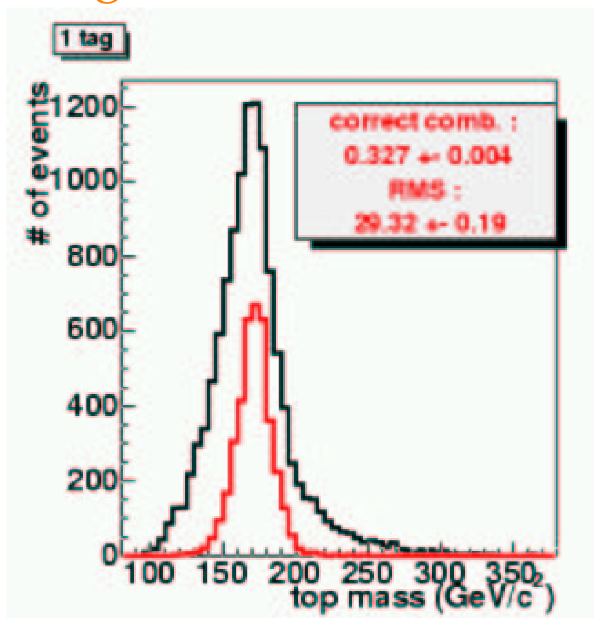
Subdivide the sample into 0, 1, and 2 tag samples.

Combinatorial Background in $t\bar{t}$ Monte Carlo ($m_{top} = 175$ GeV$/c^2$)

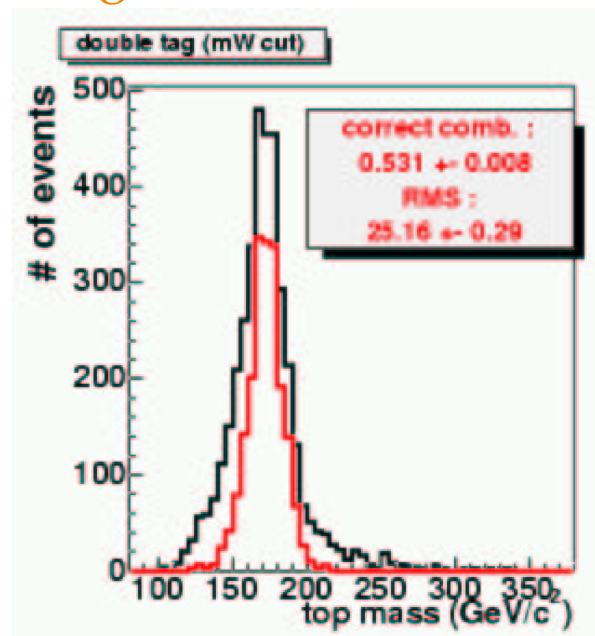
0 tag



1 tag



2 tag



Tightened tagging condition reduces combinatorial background.

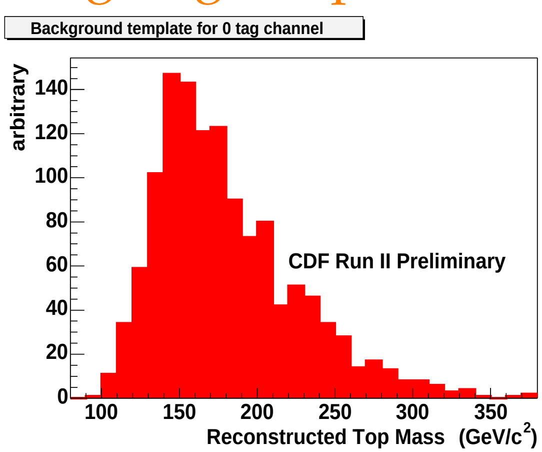
$\sim 30\%$ of events are dilepton or w/ gluon jet.

of Candidates and Background Estimate

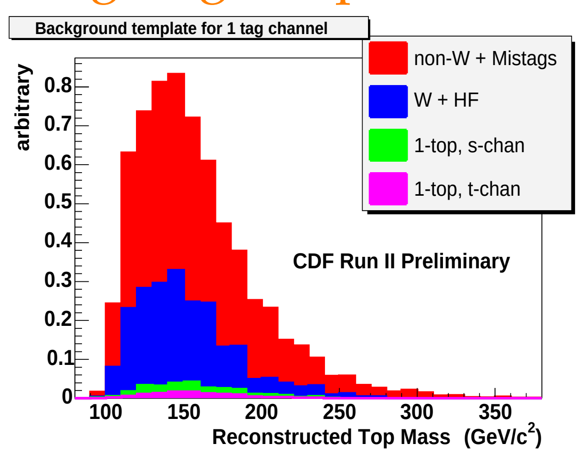
estimated number of background events

process	0tag	1 tag	2 tag
non-W/W+LF	–	4.4 ± 0.8	$0.066^{+0.19}_{-0.008}$
W + HF / VV	–	1.9 ± 0.5	0.17 ± 0.05
single top (s)	–	0.16 ± 0.02	0.037 ± 0.008
single top (t)	–	0.12 ± 0.02	0.011 ± 0.004
total	24.5 ± 7.0	6.5 ± 1.2	$0.28^{+0.20}_{-0.05}$
# Candidates	40	17	11
$\mathcal{L}$ (pb^{-1})	193	162	162

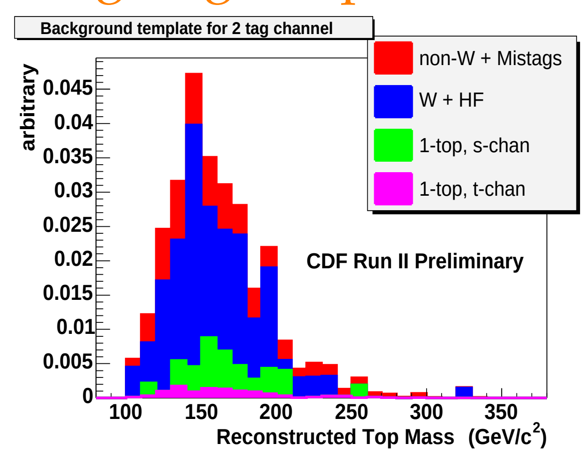
0 tag Bkg template



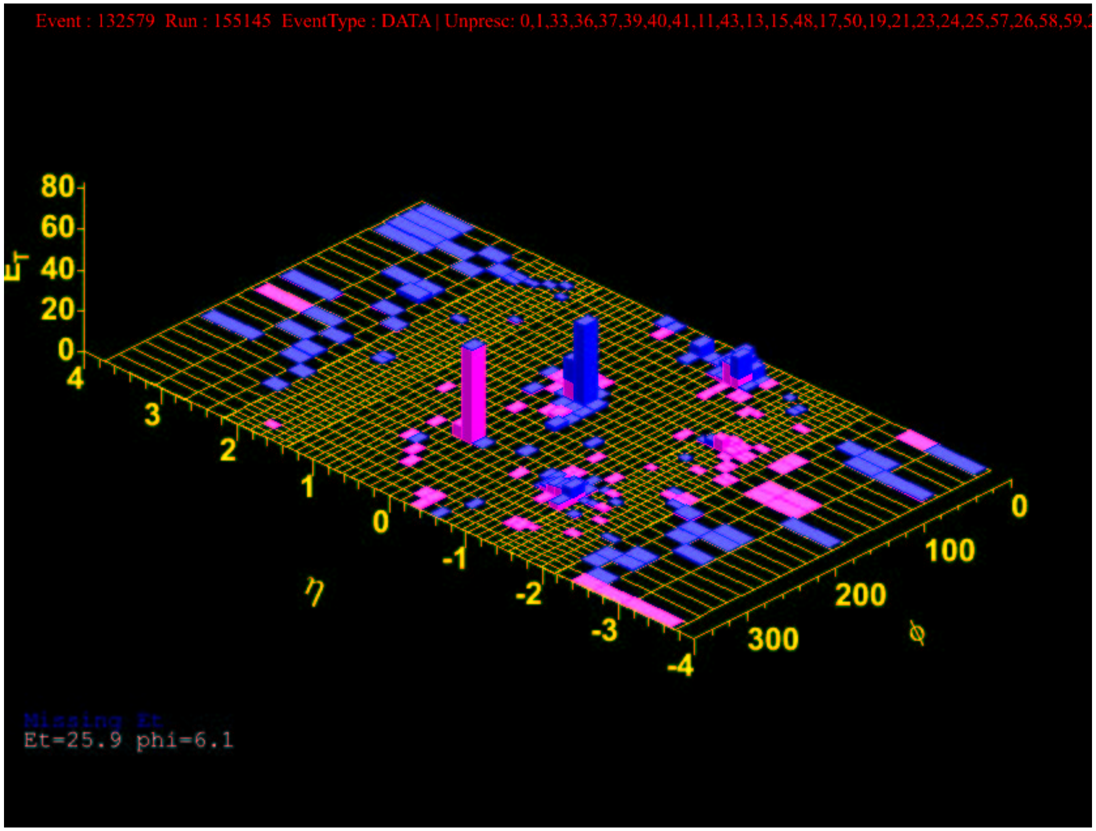
1 tag Bkg template

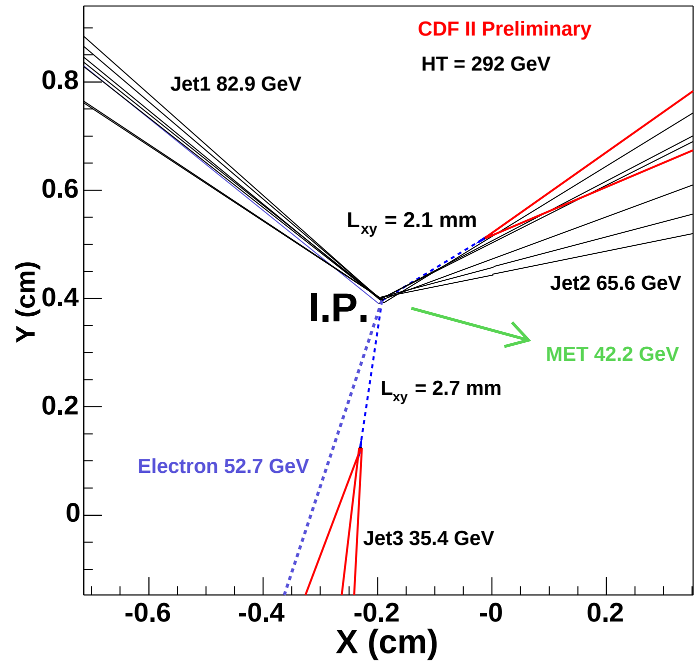


2 tag Bkg template



$t\bar{t} \rightarrow$ lepton + jets Candidate Event with 2 SECVTX Tagged Jets in CDF





$M_t = 169.9\ \mathrm{GeV}/c^2$

Mass Template Fitting Function

We will describe the signal / background distribution shapes with the following functions.

top mass template :

M_t : reconstructed mass in the event
m_{top} : true mass of top quark

$$f_s(M_t|m_{top}) = \quad p_8 \cdot Gauss\,(M_t, \{p_1, p_2, p_3\}) + p_9 \cdot Gamma\,(M_t, \{p_4, p_5\}) + (1 - p_8 - p_9) \cdot Gamma\,(M_t, \{p_6, p_7\})$$

where

$$p_i = \alpha_i + \alpha_{i+9} \cdot m_{top} \quad \text{(to include } m_{top} \text{ dependence).}$$

background template :

$$f_b(M_t) = \beta_7 \cdot Gamma\,(M_t, \{\beta_1, \beta_2, \beta_3\}) + (1 - \beta_7) \cdot Gamma\,(M_t, \{\beta_4, \beta_5, \beta_6\})$$

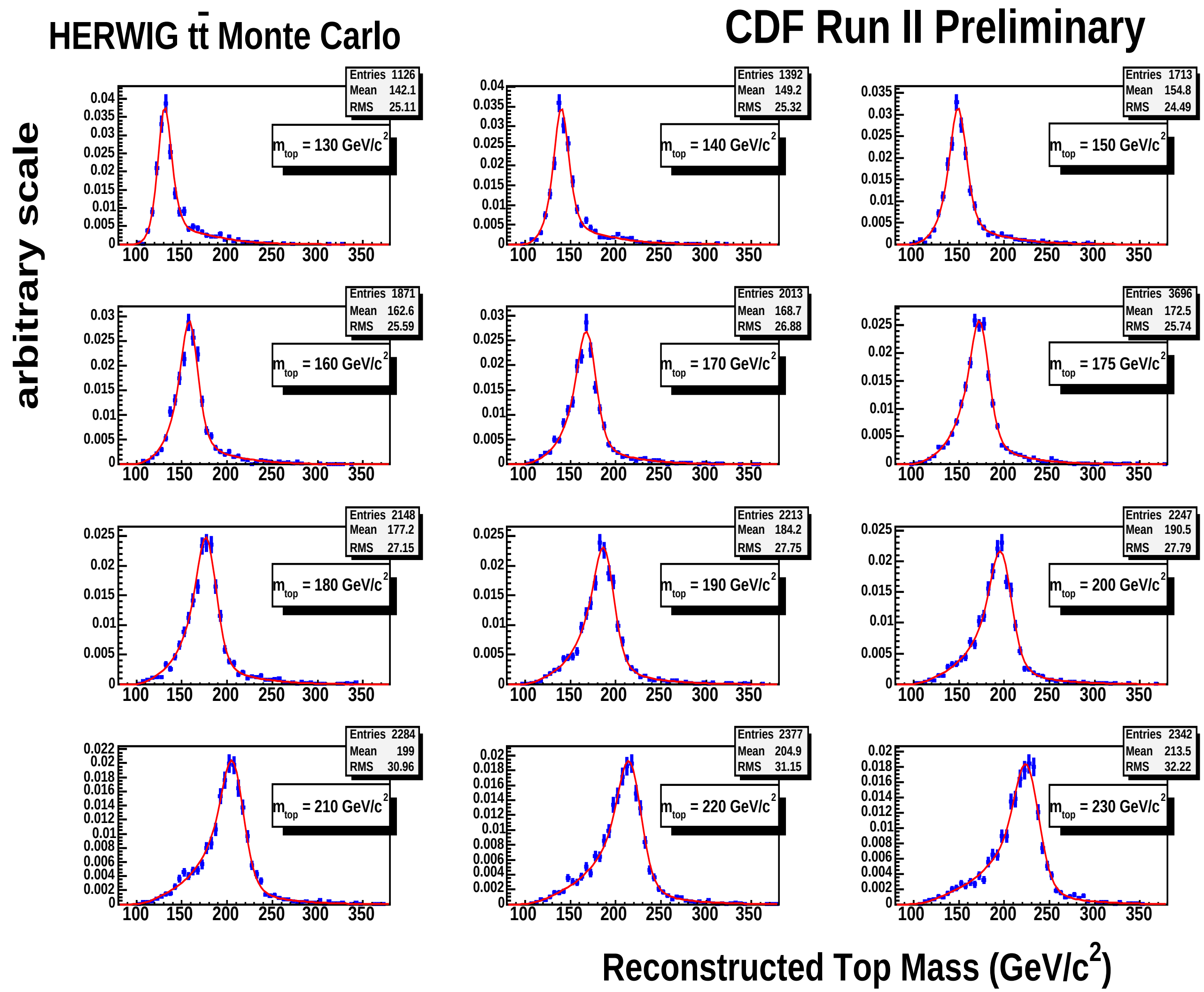
For 1 and 2 tag channel β_7 is fixed to 1.

Template Fitting (2 tag sample)

2 tag Signal Template (Gamma + 2 Gauss)

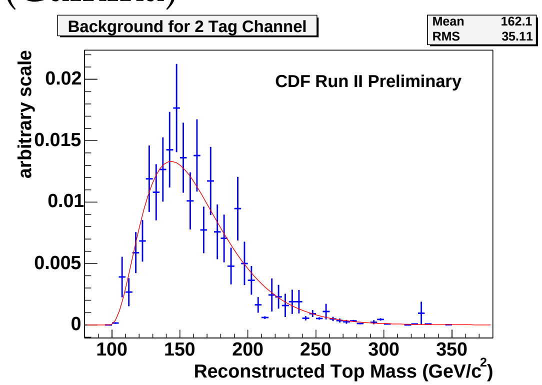
HERWIG $t\bar{t}$ samples with 21 different m_{top}.

$\rightarrow$ Signal function parametrization.



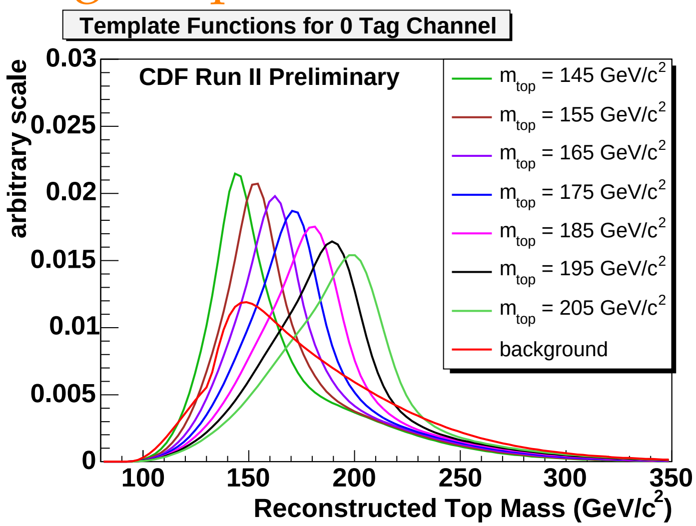
2 tag Bkg Template

(Gamma)



Obtained Template Functions -

0 tag template

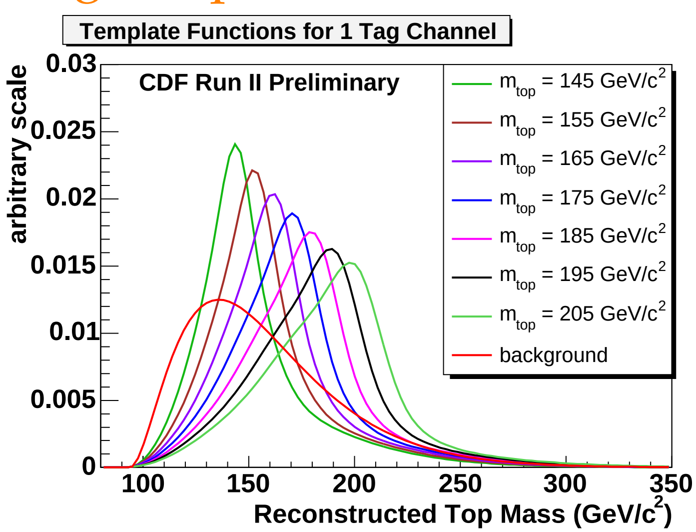


χ^2 in template fitting -

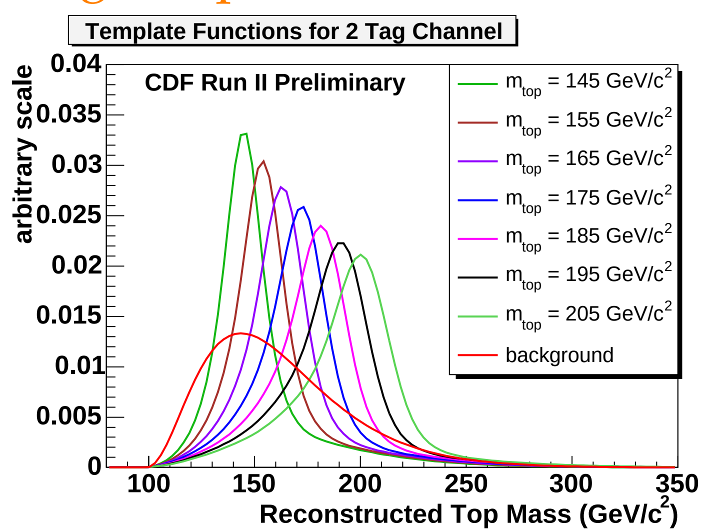
CDF Run II Preliminary

χ^2/N_{dof}	0tag	1tag	2tag
signal	1078.4 / 878	923.7 / 862	774.5 / 697
background	28.9 / 34	36.7 / 32	28.9 / 34

1 tag template



2 tag template



Shape of reconstructed mass distribution is parametrized as a function of m_{top}.

Measurement of the Top Mass - Likelihood Definition

$$L = L_{shape} \times L_{bkg}$$

$$L_{shape} = \frac{e^{-(N_s+N_b)}(N_s+N_b)^N}{N!} \Pi_{i=1}^{N_{events}} \frac{N_s f_s(M_t^i | m_{top}, \vec{\alpha}) + N_b f_b(M_t^i | \vec{\beta})}{N_s + N_b}$$

$$L_{bkg} = exp\left(-\frac{1}{2}\left[\frac{N_b - N_b^{pred.}}{\sigma^2_{N_b^{pred.}}}\right]^2\right)$$

M_t^i	the reconstructed top mass for each event in the sample to be fitted.
m_{top}	true top mass for each event in data sample.
N	number of candidate events in the sample.
N_s	number of signal events.
N_b	number of background events.
$\vec{\alpha}, \vec{\beta}$	Template function parametrization.
m_{top}, N_s and N_b	free parameters in the fit.

- Look for m_{top} and background fraction that best reproduce the data distribution.
- Constrain # of background around the estimated number.

Likelihood Definition for Combined Fitting : $L^{combined} = L^{0tag} \times L^{1tag} \times L^{2tag}$

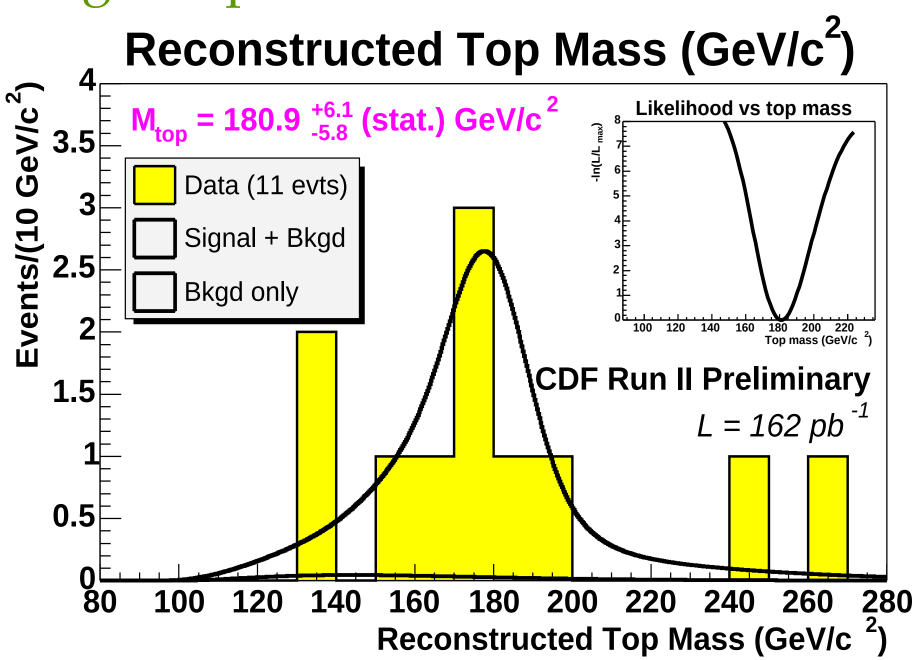
Likelihood Fit

of Candidates:

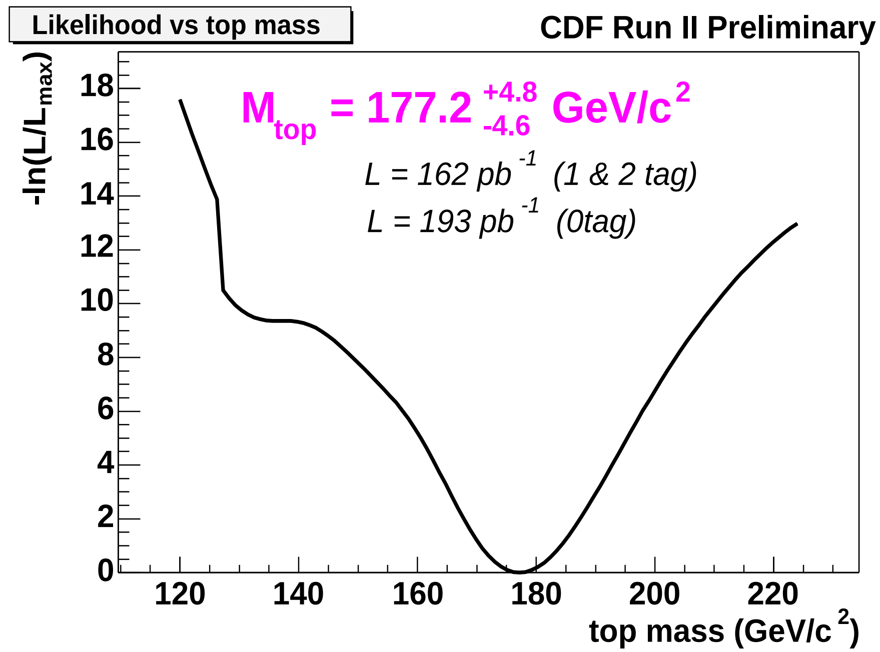
sample	$\mathcal{L}$ (pb^{-1})	# of Candidates
2 tag	162	11
1 tag	162	17
0 tag	193	40

Likelihood fit with m_{top} and background frac as free parameter.

2 tag sample



0, 1 and 2 tag samples combined



Results :

2 tag sample	$180.9\,^{+6.4}_{-5.8}$ (stat) $\pm$ 5.8 (syst) GeV/c^2
combined	$177.2\,^{+4.9}_{-4.7}$ (stat) $\pm$ 6.6 (syst) GeV/c^2

Systematic Uncertainty and Near Future Prospects

We are updating the measurements with $320\ \mathrm{pb}^{-1}$ of data in CDF (double stat.).

CDF Run II Preliminary

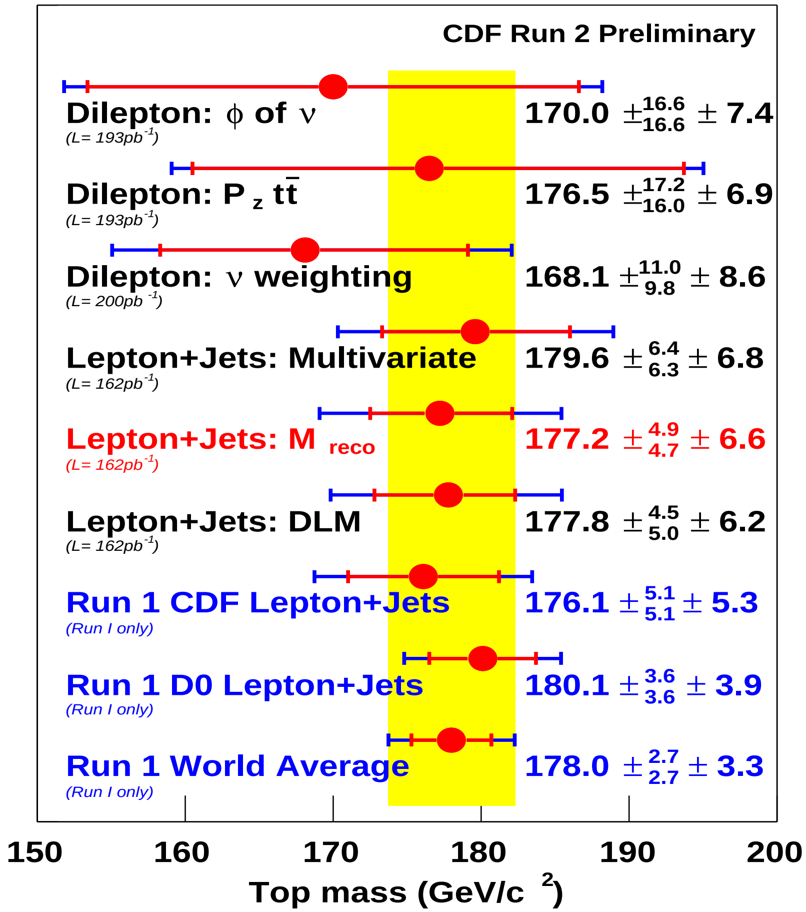
source	combined (GeV/c^2)	2 tag (GeV/c^2)
ISR	0.61	0.69
FSR	1.00	1.20
PDF	0.19	0.15
b-tagging	0.20	0.27
bkgd shape	0.68	0.17
jet resolution	0.71	0.54
jet energy scale	6.37	5.56
generator	0.11	0.03
total	6.56	5.77

Current systematic uncertainty dominated by Jet Energy Scale (JES).

Lots of work done to reduce JES in CDF.
Expect JES to scale down to $\sim 3\ \mathrm{GeV}/c^2$ level this Spring.

Top Mass Measurements in Run II - Summary

CDF Run II results



Dilepton

- Underconstraint system with 2 ν.
- Assumption on distribution of kinematic variables ϕ^{ν}, $P_z^{t\bar{t}}$, η^{ν}.
- Template fit.

Lepton + Jets

M_{reco}	Template Fit. Minimum assumpti
MultiVariate	Template fit w/ kinematic variabl in likelihood.
DLM	Matrix element.

D0 Run II results

L+Jets $(229\ pb^{-1})$: 170.6 ± 4.2 (stat) ± 6.0 (syst)

Dilepton $(260\ pb^{-1})$: $155\ ^{+14}_{-13}$ (stat) ± 7 (syst)

Summary

- Tevatron and CDF are operating well.
- We measured the top mass with the lepton+jets channel.
- Following # of candidates :

sample	$\mathcal{L}$ (pb^{-1})	# of Candidates
2 tag	162	11
1 tag	162	17
0 tag	193	40

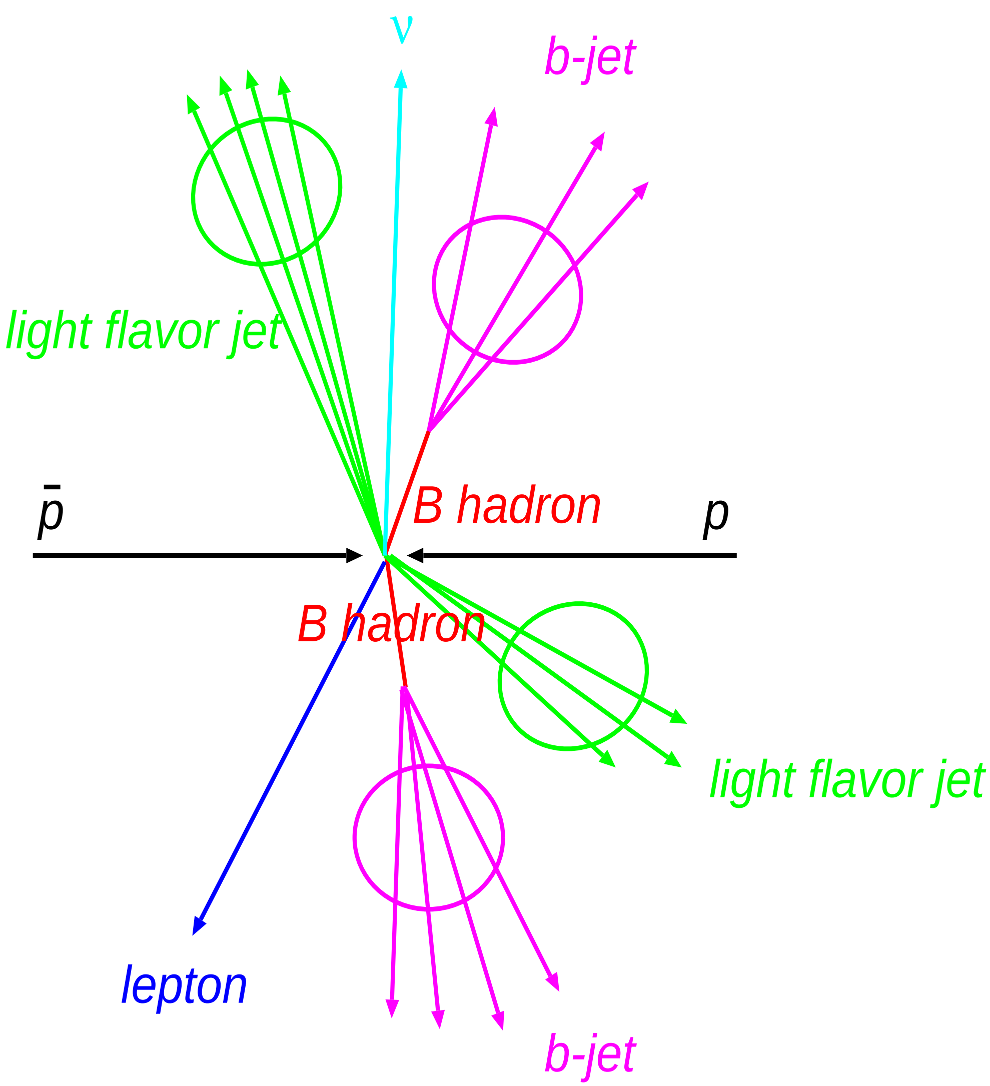
- Results of top mass measurement :

2 tag sample	:	$180.9\ ^{+6.4}_{-5.8}$ (stat) $\pm\ 5.8$ (syst) GeV/c^2
combined	:	$177.2\ ^{+4.9}_{-4.7}$ (stat) $\pm\ 6.6$ (syst) GeV/c^2

- Updating our measurement ($\sim$ few months).
  - Using ~ 320 pb^{-1} $\rightarrow$ $\sim$ double stat..
  - Systematic uncertainty largely scaled down.
  - Current total error in combined measurement $\sim 8\ \mathrm{GeV}/c^2 \rightarrow$ $\sim 5\ \mathrm{GeV}/c^2$

BACKUP

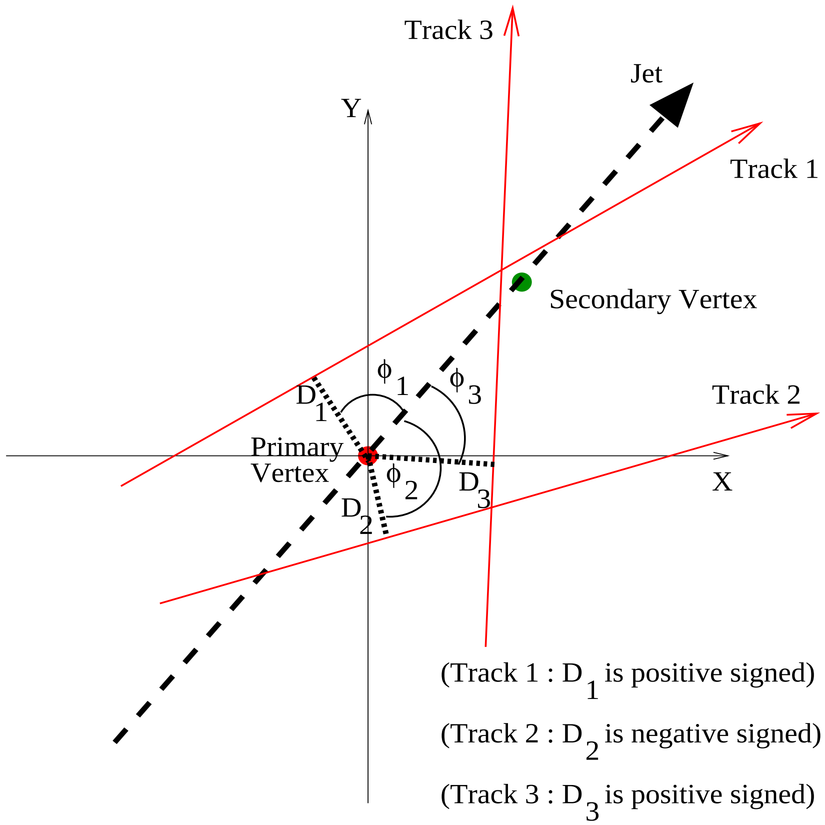
SECVTX Algorithm – main tagging algorithm in CDF –



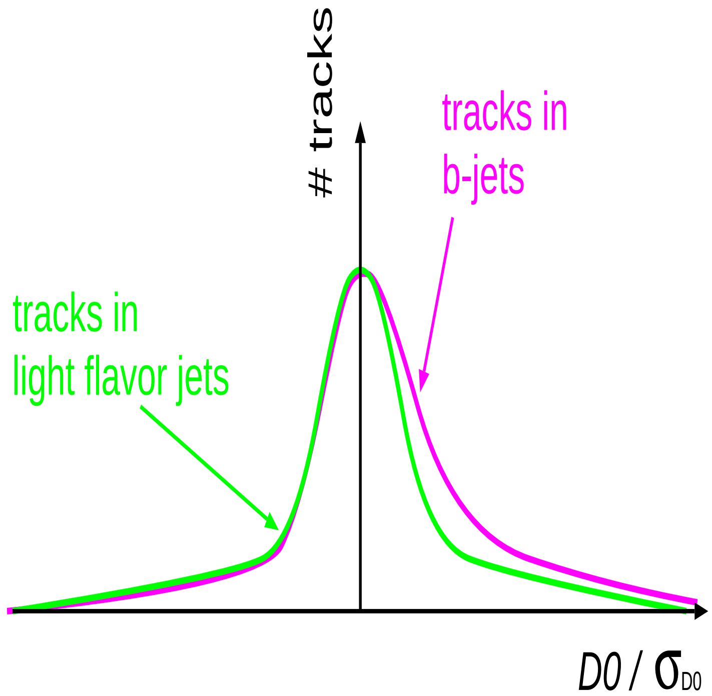
B hadrons decay after running a distance.

- Reconstruct the secondary vertex using tracks in the jet.
- Require cut on the decay length significance : $\frac{L_{xy}}{\sigma L_{xy}} > 3$.

Jet Probability Algorithm (1)



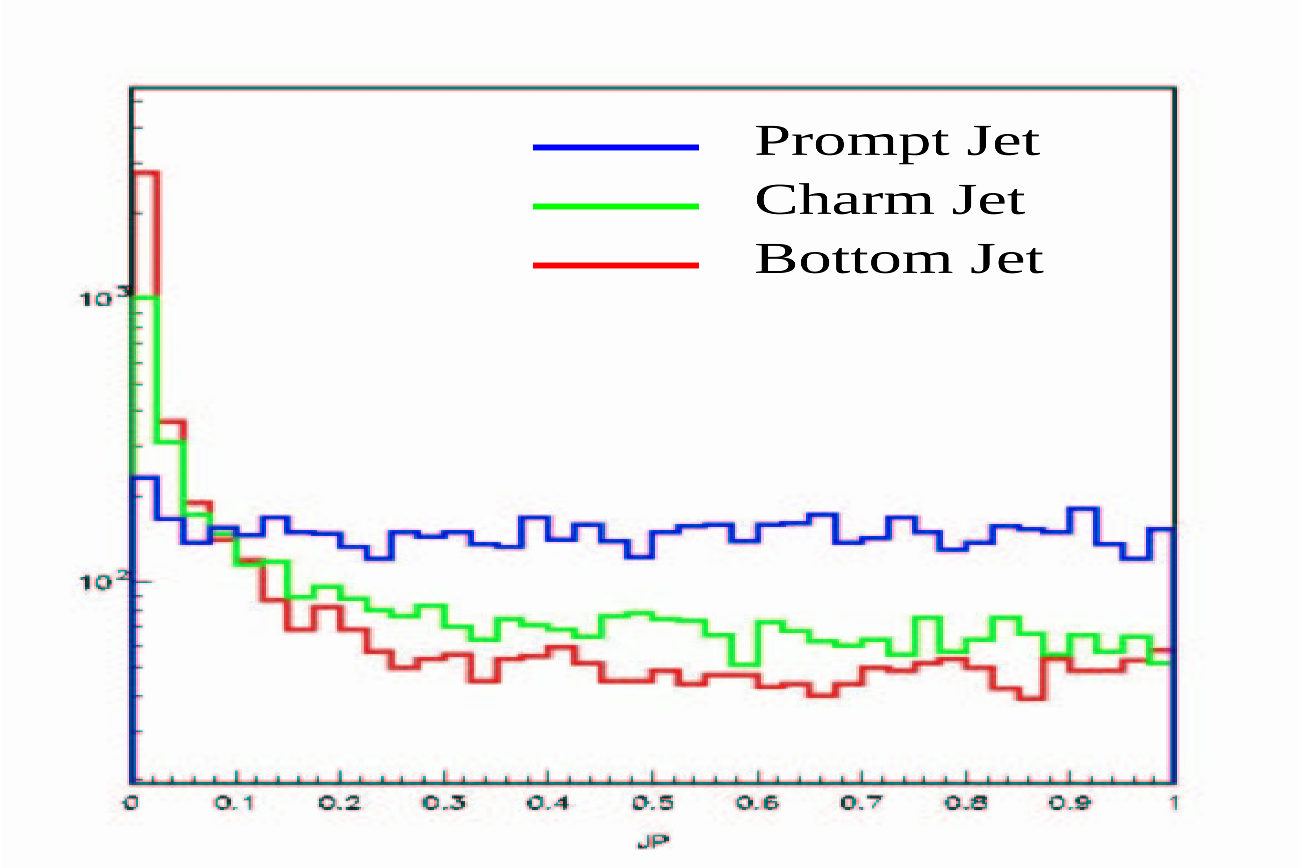
x



Assign sign (±) to the impact parameter $D0$ of each track based on its direction.

Jet Probability Algorithm (2)

Combine $D0$ significance of all the tracks in the jet and calculate "the probability of the jet originating in the primary vertex" (Jet Probability).



(Jet Probability in $t\bar{t}$ MC Events)

We can cut at arbitrary Jet Probability value for the b-tagging.
This enables us to loosen the b-tagging condition easily.

Acceptance for $t\bar{t}$ HERWIG Events ($m_t = 175$) - for JP cut = 0.05 -

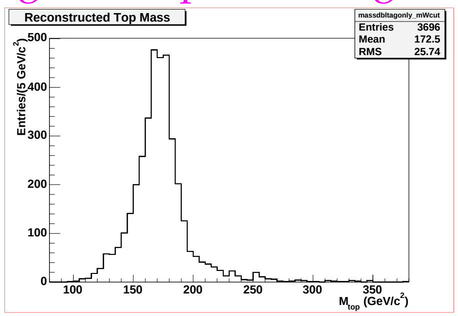
cut	0 tag (%)	1 tag (%)	2 tag (%)	2 SECVTX (%)
kinematic	7.19 ± 0.04	7.19 ± 0.04	7.19 ± 0.04	0.19 ± 0.04
tag	1.41 ± 0.02	2.75 ± 0.03	1.77 ± 0.02	0.79 ± 0.01
chi2	1.29 ± 0.02	2.09 ± 0.02	1.14 ± 0.02	0.53 ± 0.01
mW	–	–	0.97 ± 0.02	–

- errors are from MC statistics.
- If we put $\sigma_{t\bar{t}} \sim 6.7$pb, we can expect ~ 11 events in 2 tag sample at 162pb^{-1}.
- We double the acceptance for 2tag channel by the use of jet probability.

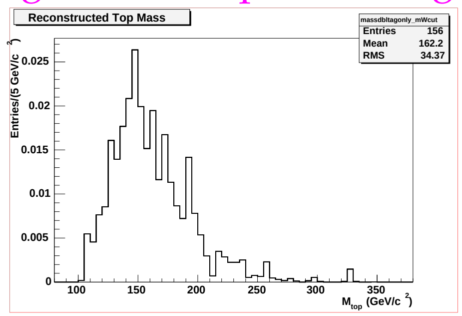
Pseudo Experiment (PE)

2 tag channel, Jet Probability Cut=0.05, 162 pb^{-1}, $m_t = 175\ \text{GeV}/c^2$

signal template histogram



background template histogram



↓ generate pseudo signal masses ↓ generate pseudo background masses

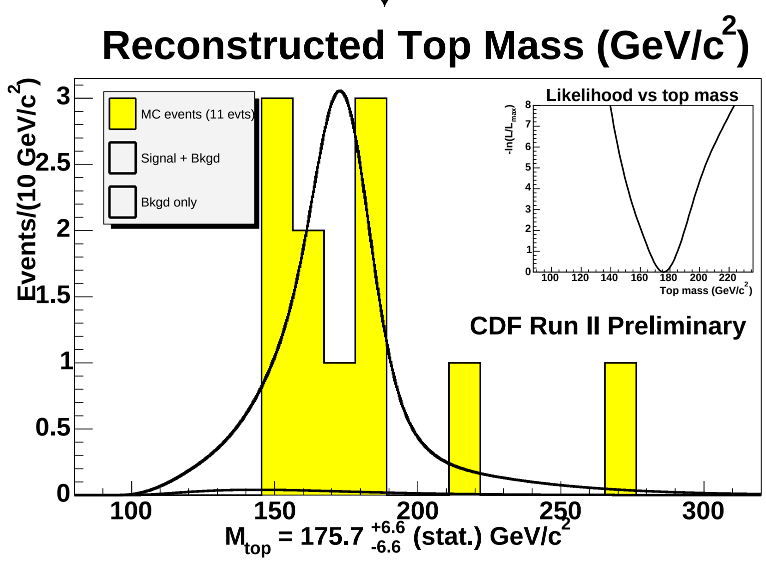
↓ ↓

pseudo data sample

↓

perform likelihood fit

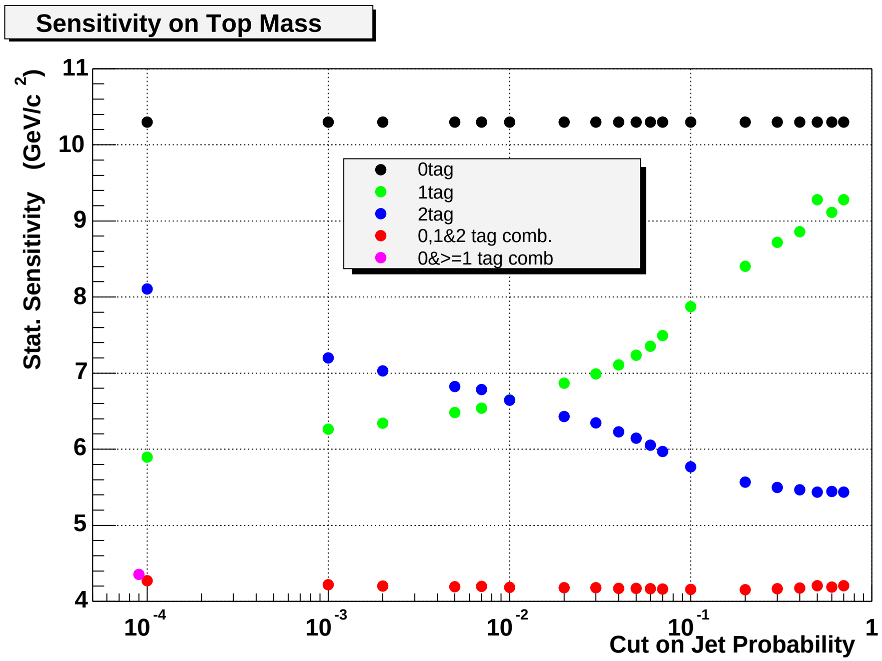
↓

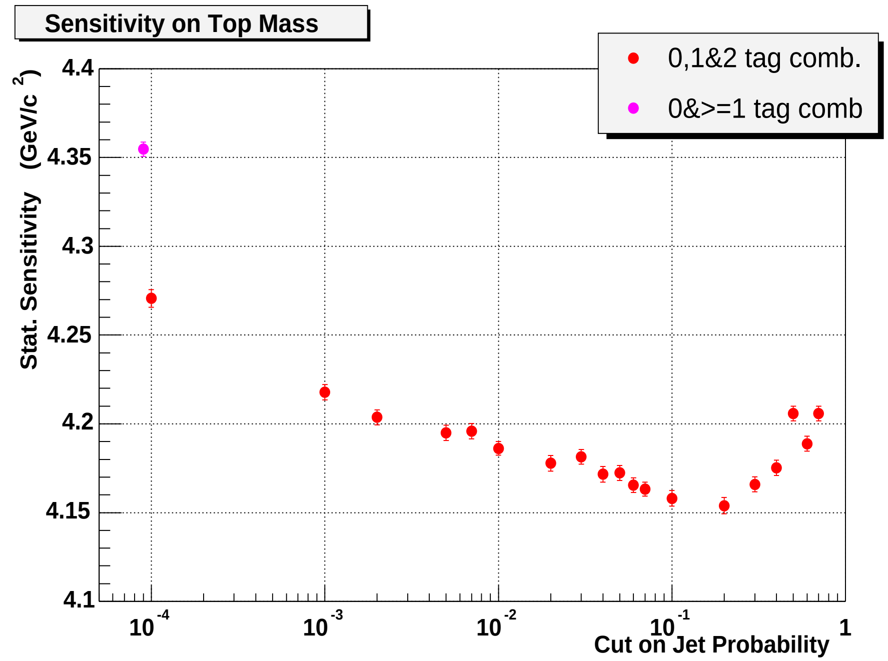


PEs are performed for :

- sensitivity study
- validation of the likelihood fit method
- estimation of the systematic uncertainty

Sensitivity Study - expected statistical errors at - 200pb^{-1} -





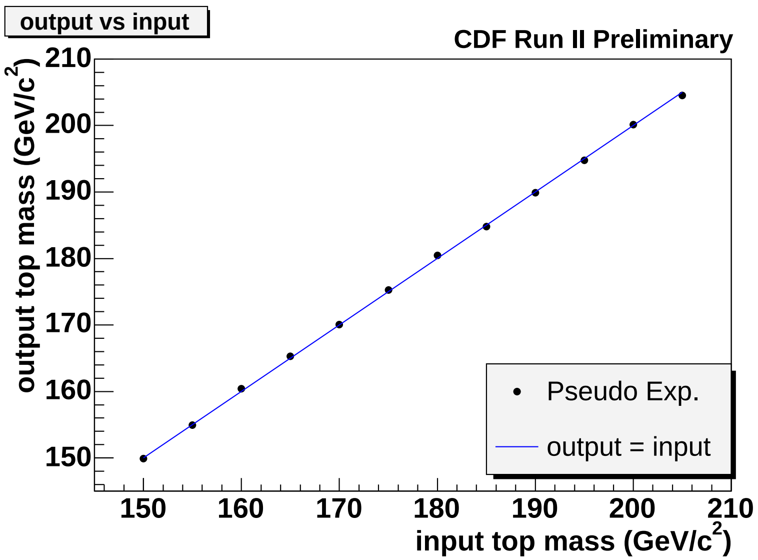
The far left point is for SECVTX-only analysis. We use JP cut = 0.05 for now, because this is the best point among the calibrated. Pink point is for 0 tag and ≥ 1 SECVTX tag channels combined.

expected stat. error

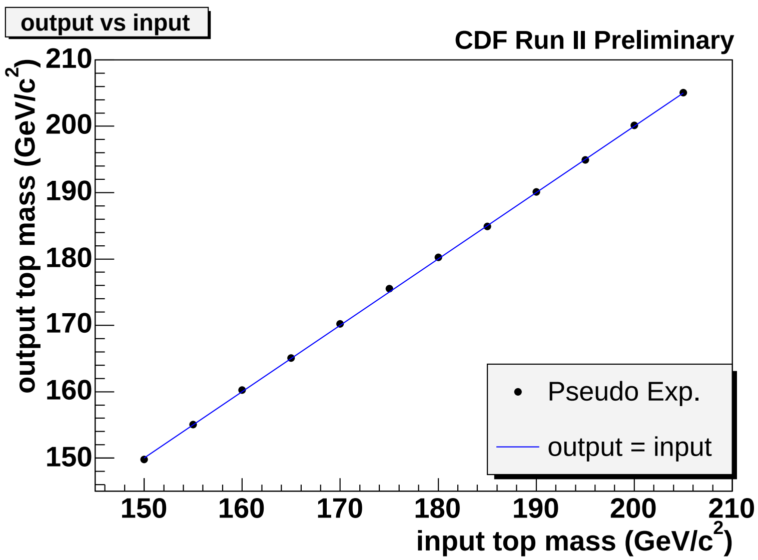
Cut	$\sigma^{comb.}_{0,1\&2tag}$ (GeV)			(%)
≥ 1 tag	4.355	$\pm$	0.004	-
SECV	4.271	$\pm$	0.005	2.0
0.01	4.186	$\pm$	0.004	3.9
0.05	4.172	$\pm$	0.004	4.2
0.2	4.154	$\pm$	0.005	4.6

Sanity Check

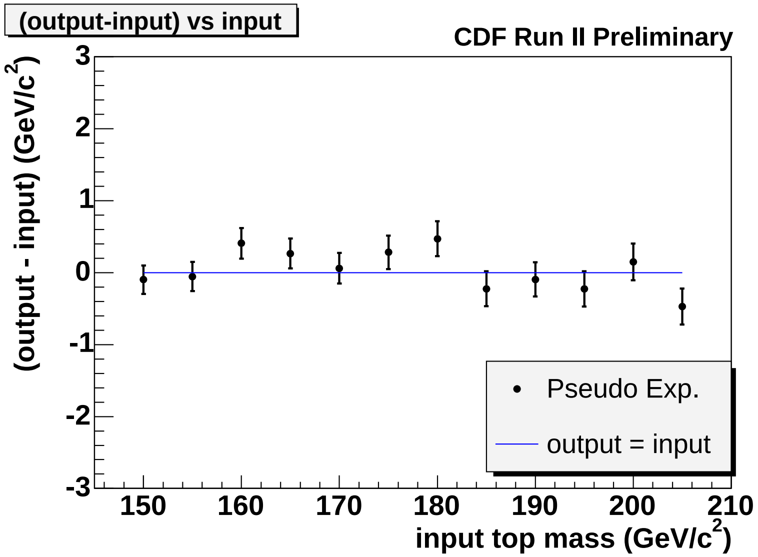
2tag: output vs input



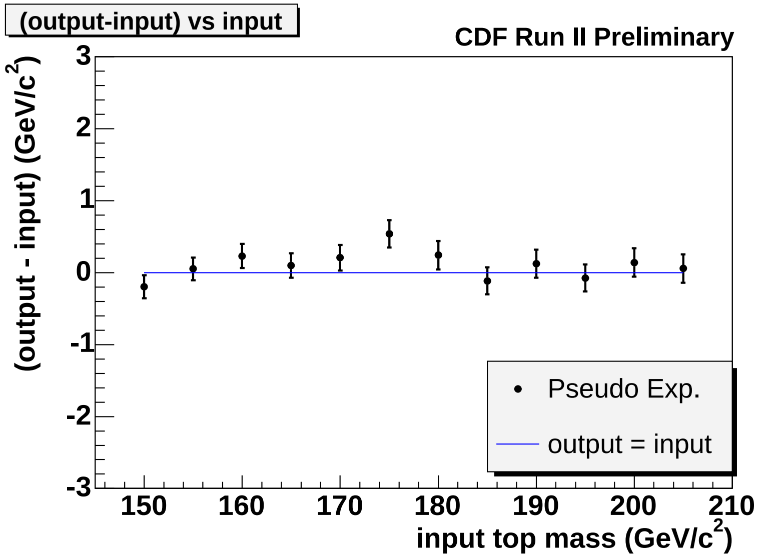
combined: output vs input



2tag: (output-input) vs input

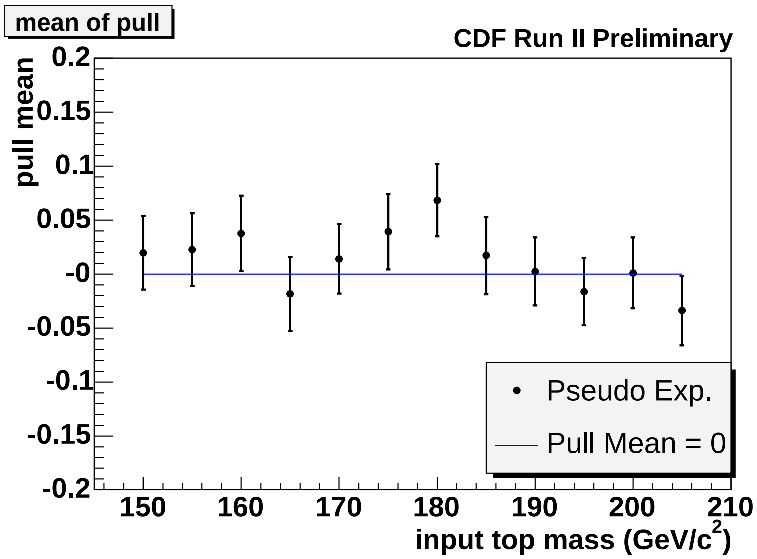


combined: (output-input) vs input

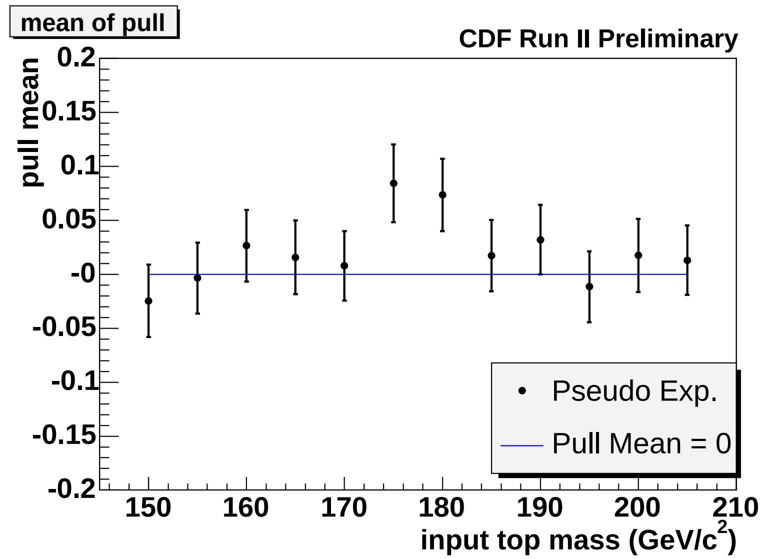


Pull Study

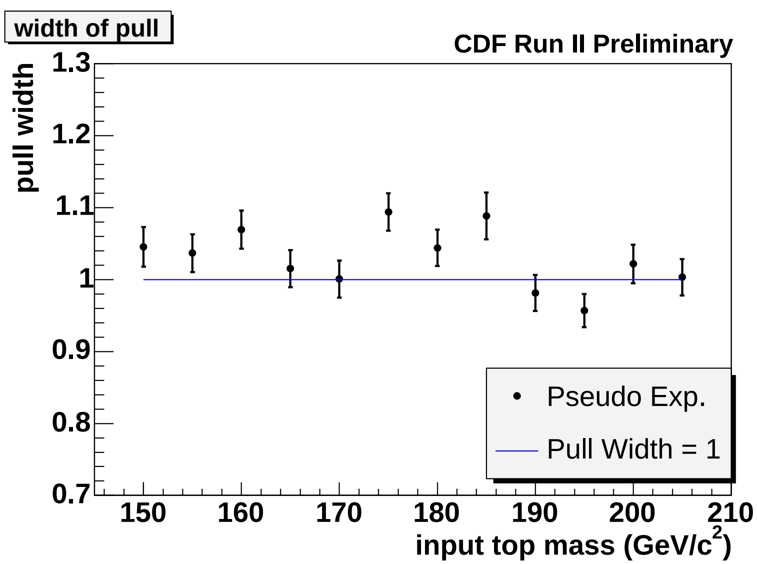
2tag: pull mean vs input



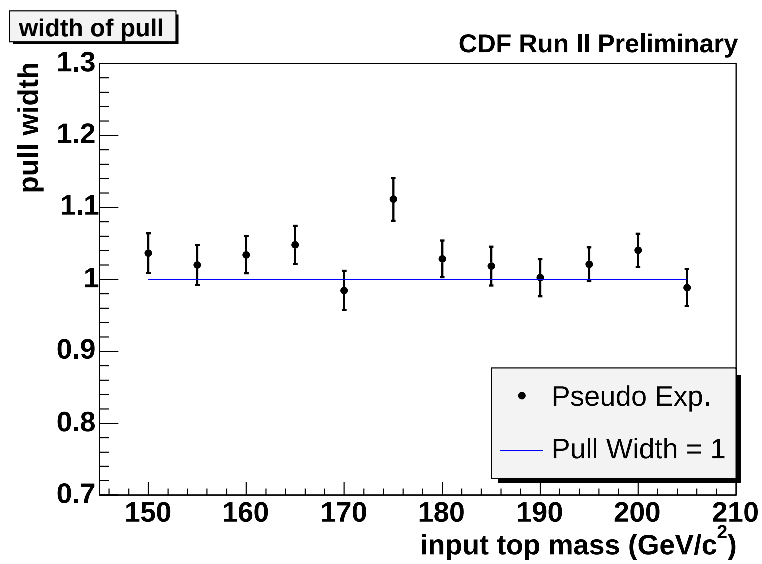
combined: pull mean vs input



2tag: pull width vs input



combined: pull width vs input

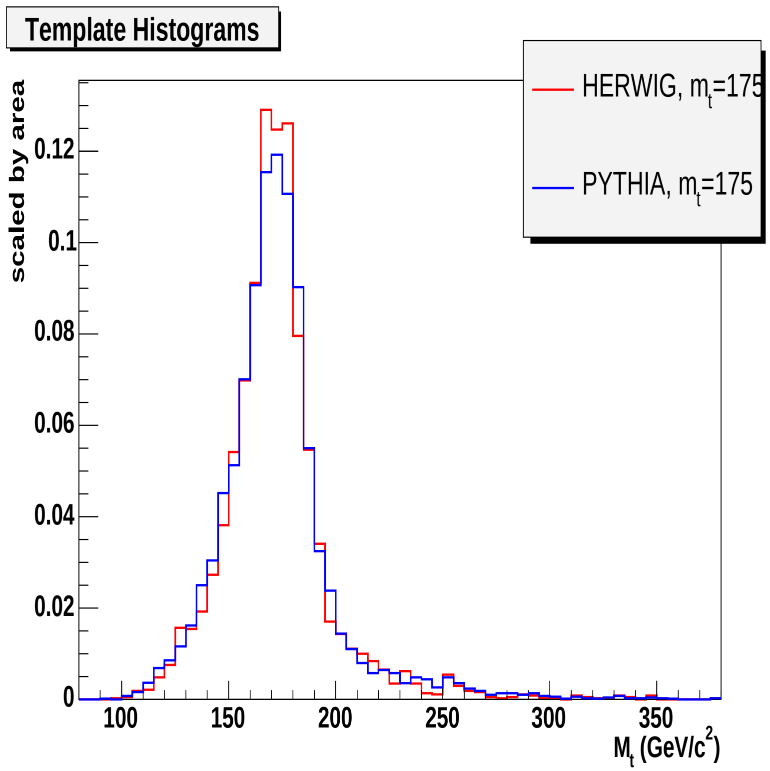


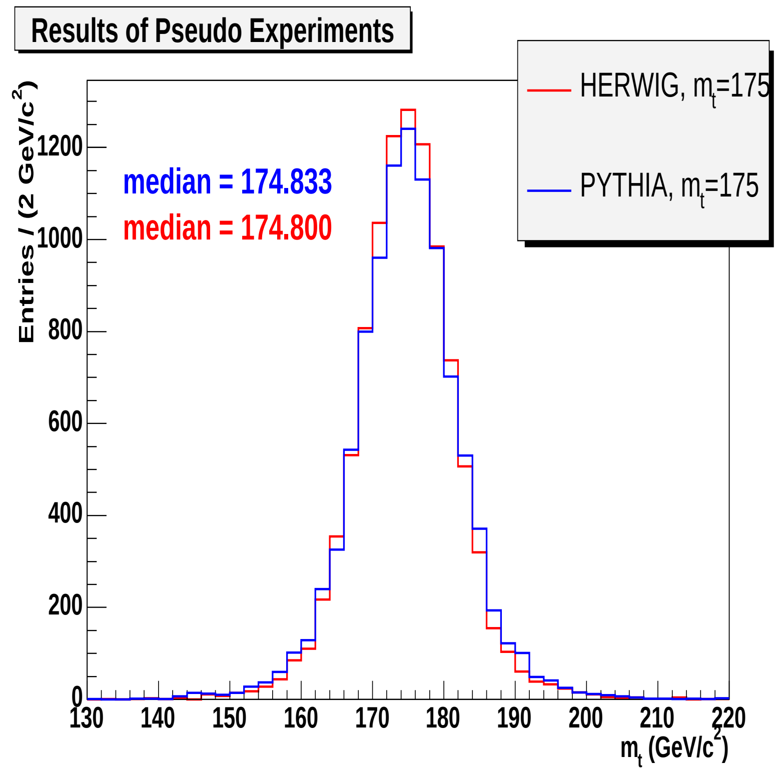
Pull width tends to be larger than 1. We will revisit this later.

Estimation of Systematic Uncertainties

– example of Monte Carlo generator dependence of 2 tag channel –

signal templates | results of pseudo experiments





We assign

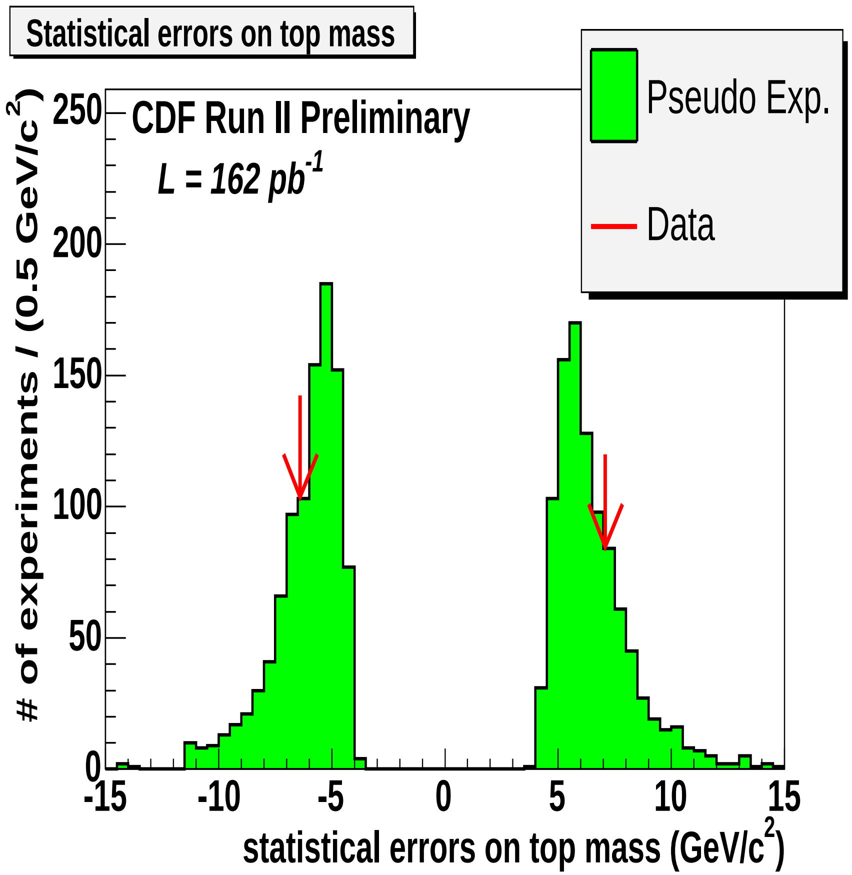
$$174.833 - 174.800 = 0.033 \mathrm{GeV}/c^2$$

as the systematic uncertainty coming from this source.

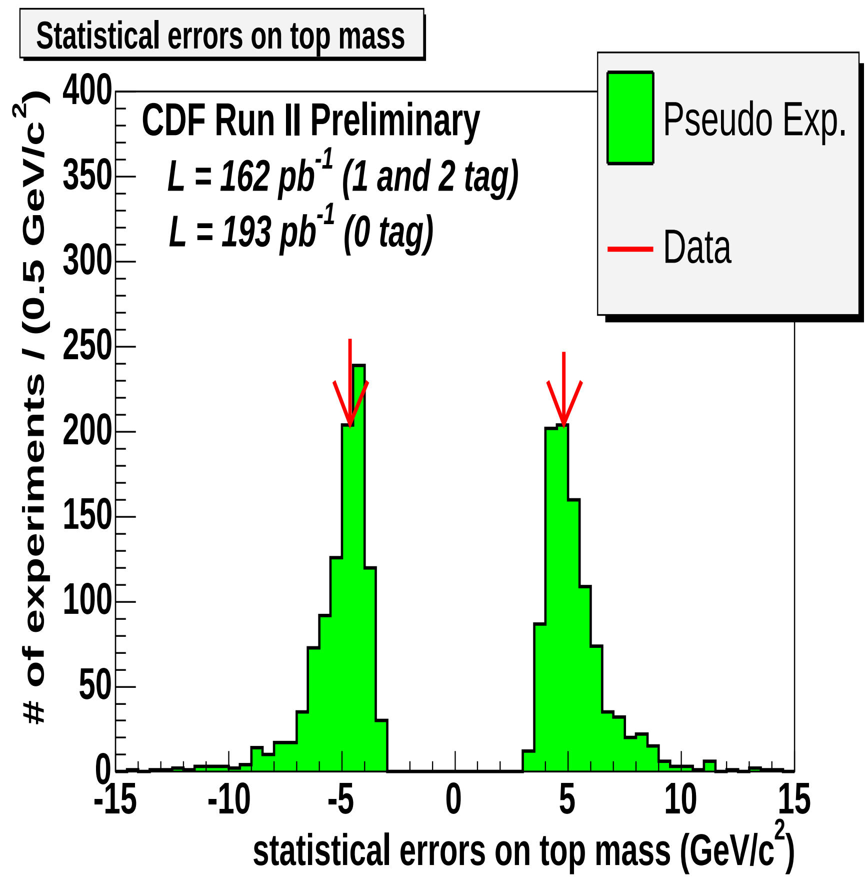
Checking of Result with Pseudo Experiments

- Pseudo experiments assume $m_t = 175 \text{ GeV}/c^2$
- Red arrows indicate results from fit to data.

2 tag channel



combined fit

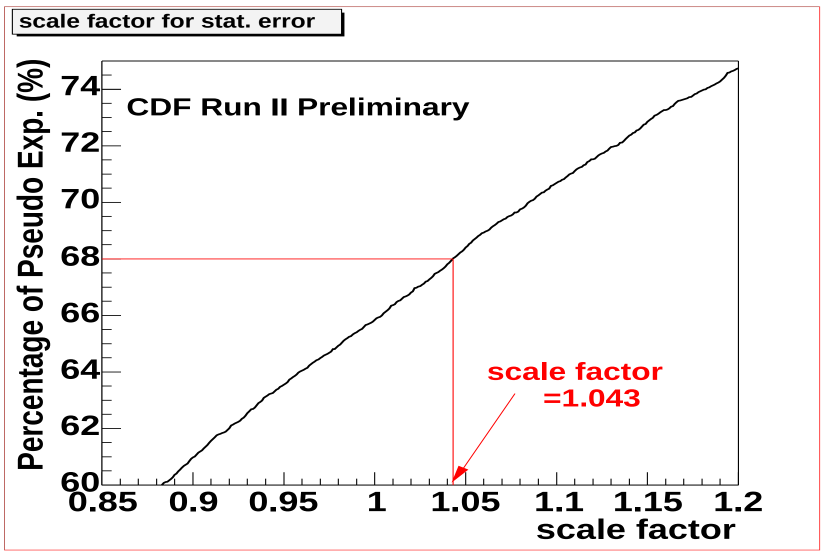


Scale factor for the statistical error

Our pull width is a few % larger than 1. We have to apply a scale factor to correct the statistical error.

- Suppose an arbitrary scale factor for the statistical error.
- Measure the percentage of the PEs which has the input m_{top} within the stat. error of the center value from the fit (Using $m_{top} = 175\text{GeV}$ sample).
- Decide the scale factor so that the above percentage comes to 68%.

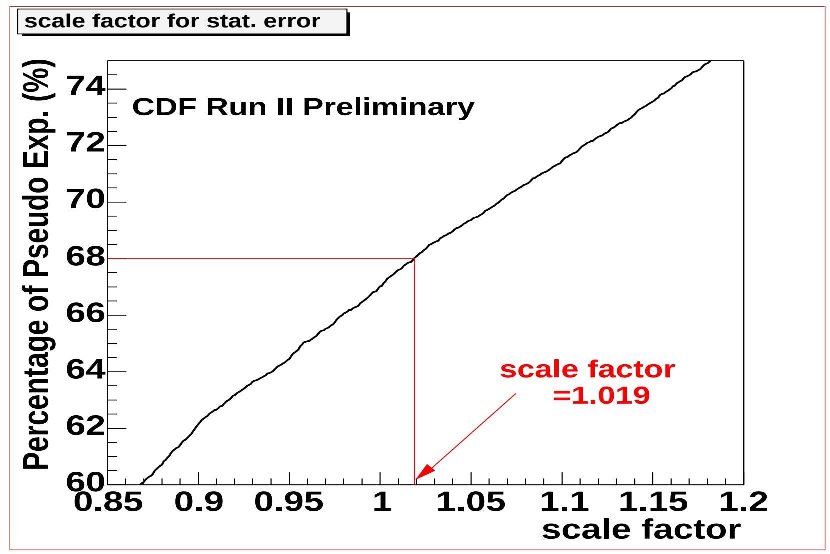
2tag: scale factor scan



scale factor = 1.043

$180.9^{+6.4}_{-6.0} \pm 5.8(\text{GeV}/c^2)$

combined: scale factor scan



scale factor = 1.019

$177.2^{+4.9}_{-4.7} \pm 6.6(\text{GeV}/c^2)$