CDF実験における
トップ・クォーク質量の測定

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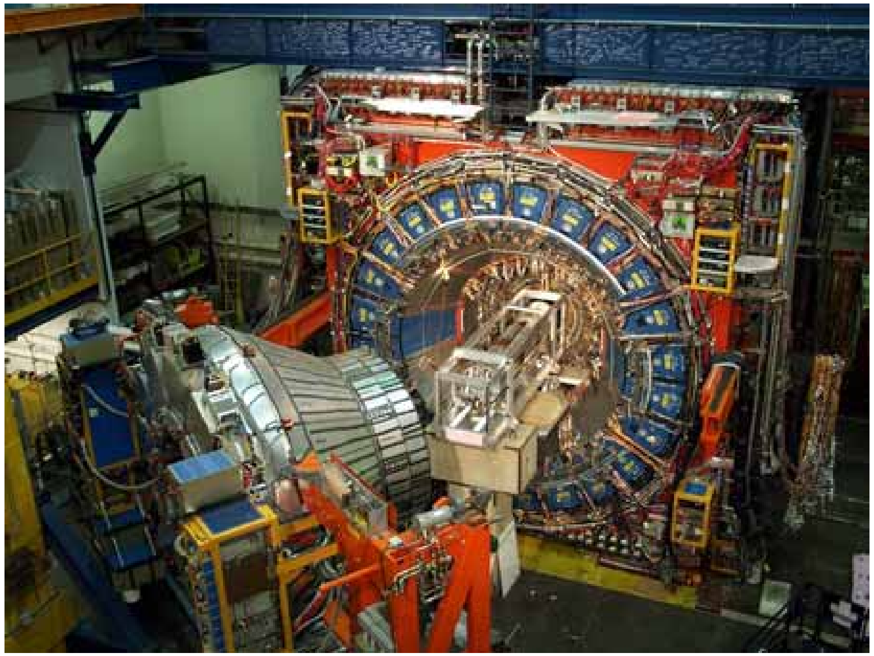

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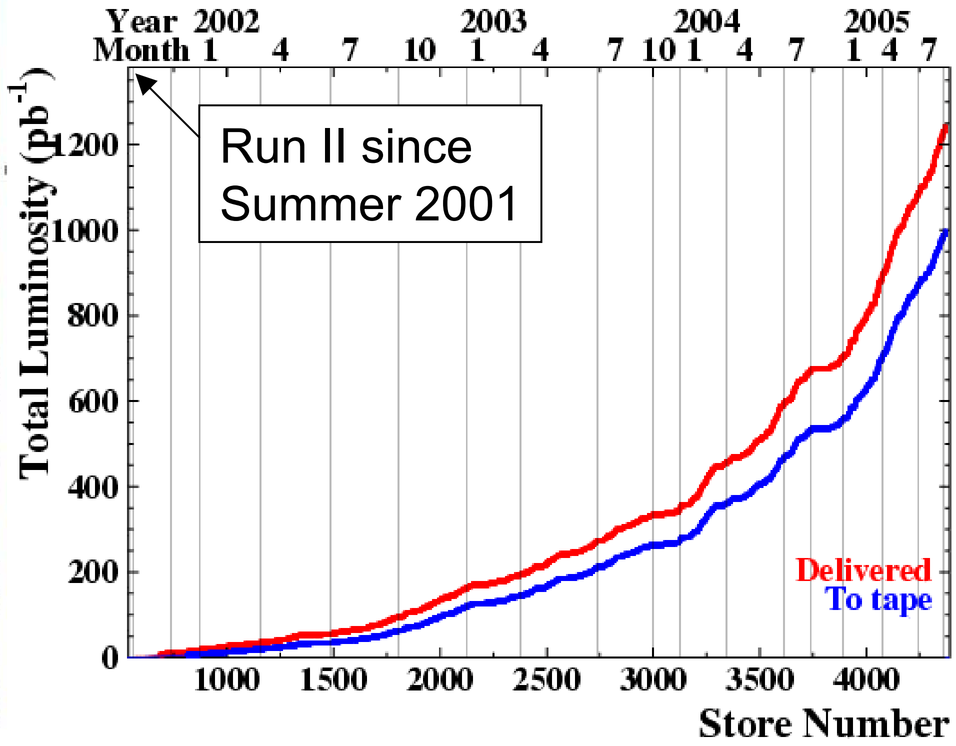
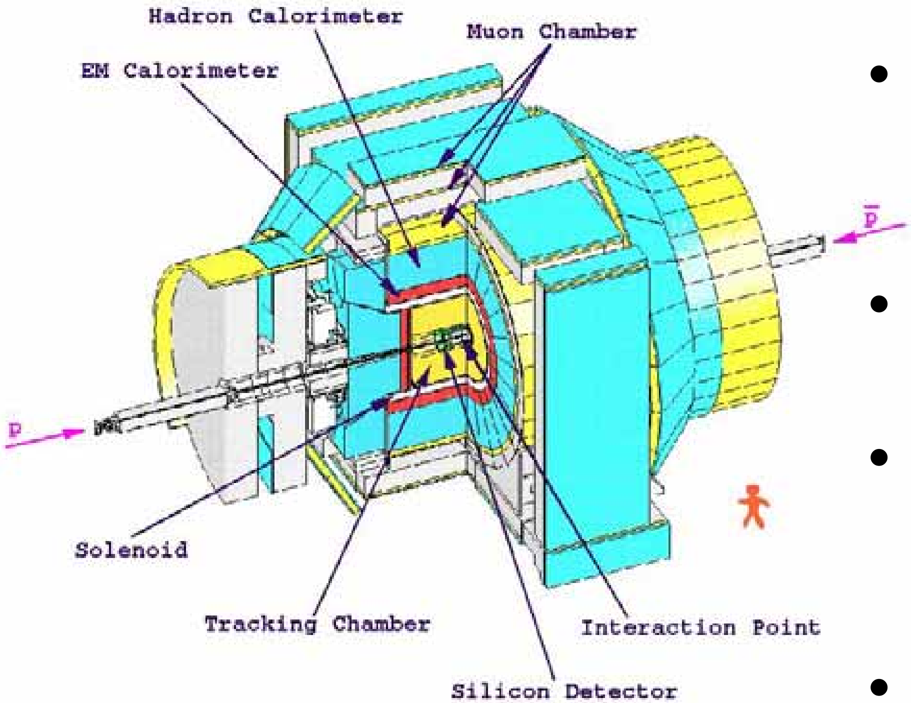
大阪市立大学，2005年9月14日

Tevatron Run II



- $p - \bar{p}$ **collisions at $\sqrt{s}$ = 1.96 TeV** (1.8 TeV in Run I).
- Peak luminosity record : $1.4 \times 10^{32}\ cm^{-2} \cdot s^{-1}$.
- Tevatron has already delivered ~1.2 fb^{-1} of collisions in Run II.
- **CDF has acquired ~1 fb^{-1}** of data.
- Analysis in this presentation uses 318 pb^{-1} of data.
- Direct study on top quark is only possible at Tevatron!

Collider Detector at Fermilab

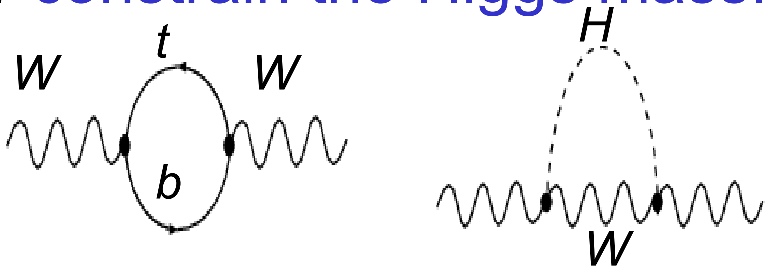


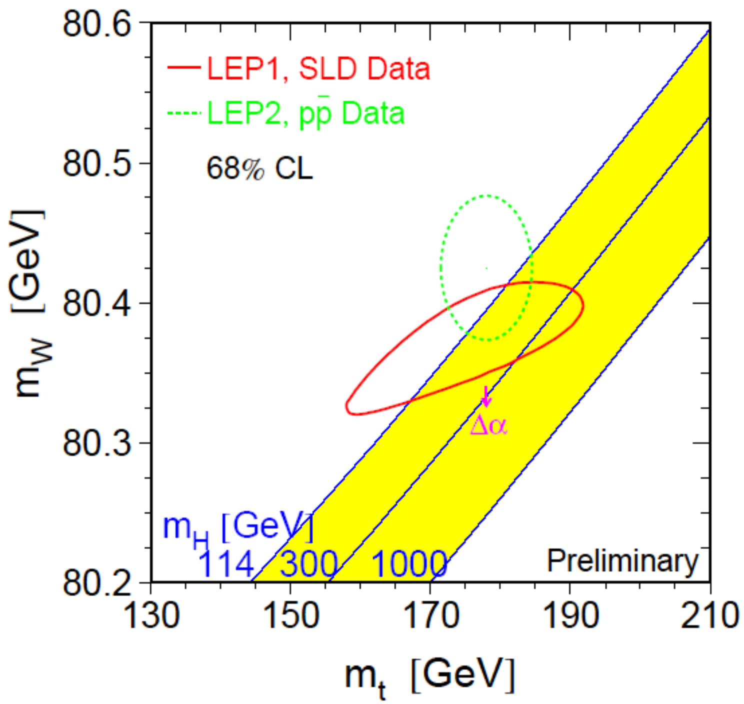
Multi-purpose detector

- **Tracking in magnetic field.**
  - Tracking coverage $|\eta|<\sim 1$.
  - Magnetic field = 1.4 T.
- **Precision tracking with silicon.**
  - 7 layers of silicon detectors.
- **EM and Hadron Calorimeters.**
  - $\sigma_E/E \sim 14\%/\sqrt{E}$ (EM).
  - $\sigma_E/E \sim 84\%/\sqrt{E}$ (HAD).
- **Muon chambers.**

Top Quark Mass - Introduction

- Top is one of the least well studied elementary particles (evidence by CDF in 1994 / discovery by CDF/D0 in 1995).
- Top mass is a fundamental parameter of the Standard Model.
- Mass measurements of top and W constrain the Higgs mass.





- Tevatron Run I average :

  $m_{top} = 178.0 \pm 2.7 \pm 3.0$ GeV/c^2
  $\rightarrow m_{higgs} < 260$ GeV/c^2 (95%)

- CDF Run II goal :
  $\Delta m_{top} \sim 2$ GeV/c^2 $(\int L\,dt = 4-8\ \mathrm{fb}^{-1})$

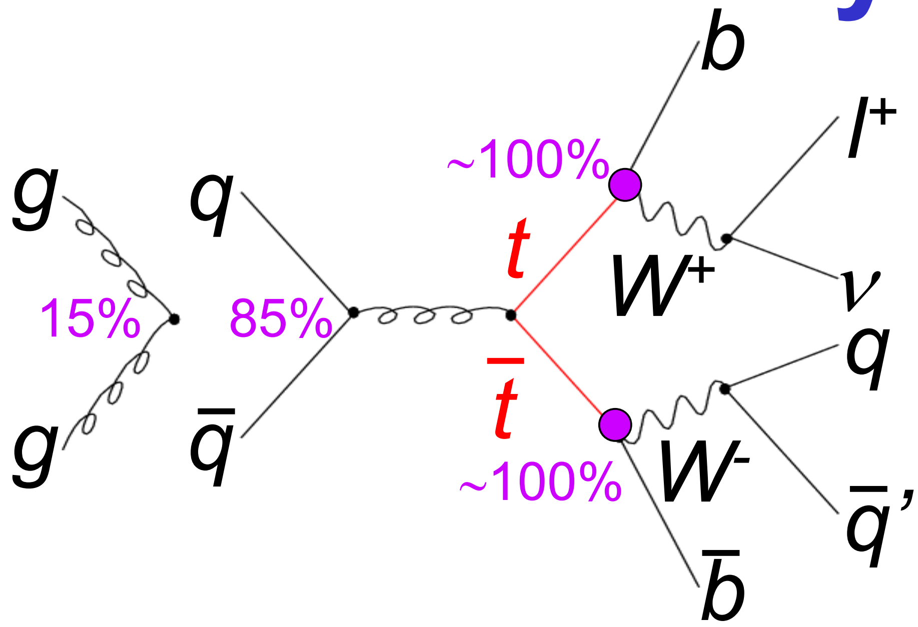
- $m_{top} \sim$ EWSB scale.
  $\rightarrow$Special role of top?

Top Quark Production and Decay

- We use pair creation events (σ~6pb^{-1}) to measure m_{top}.
- Top decays before hadronization.

  τ_{top}=0.4x10^{-24} s < 1/Λ_{QCD}~10^{-23} s.

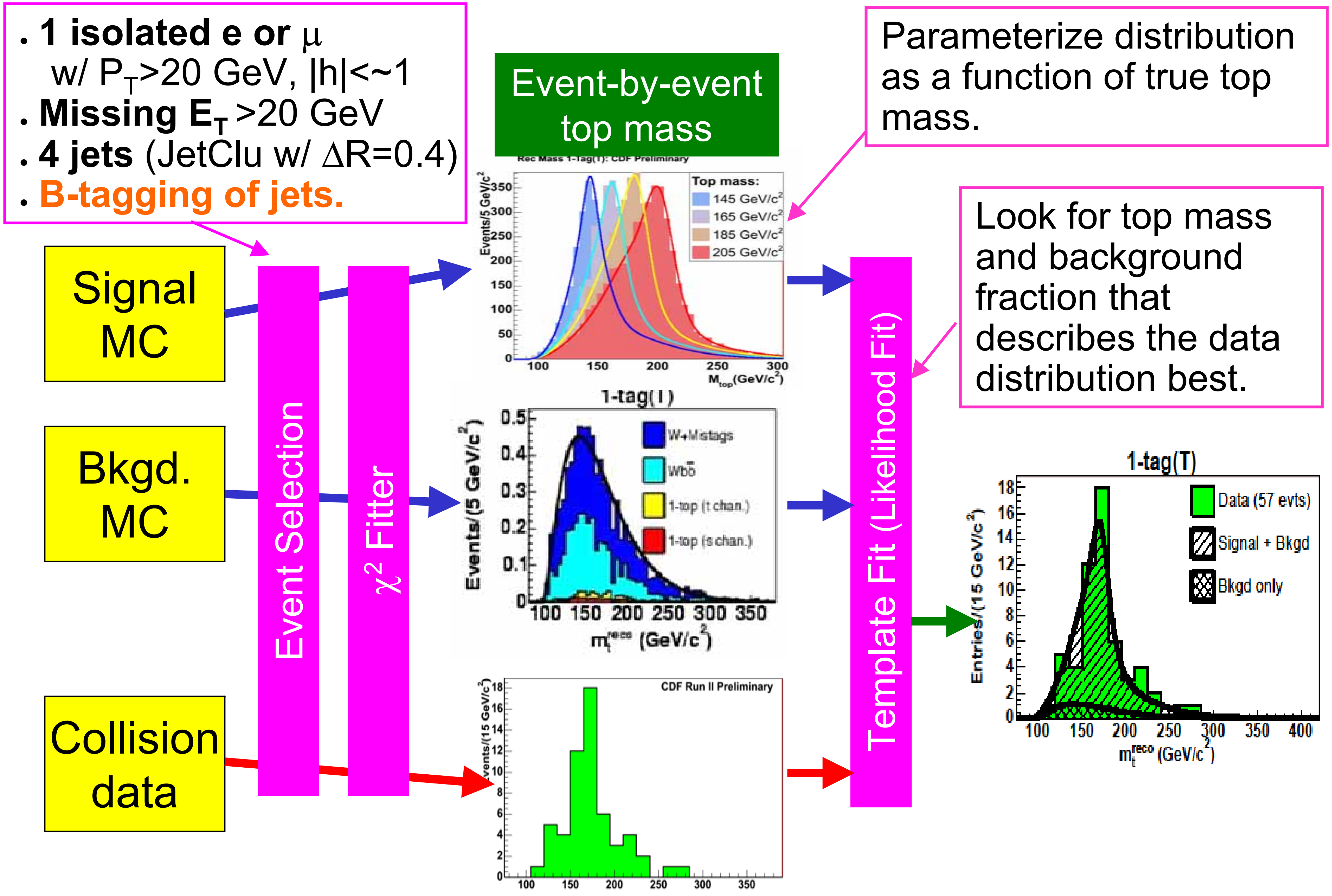
  Br(t→Wb) ~ 100%.



Final states : We measure top mass in l+jets channel.

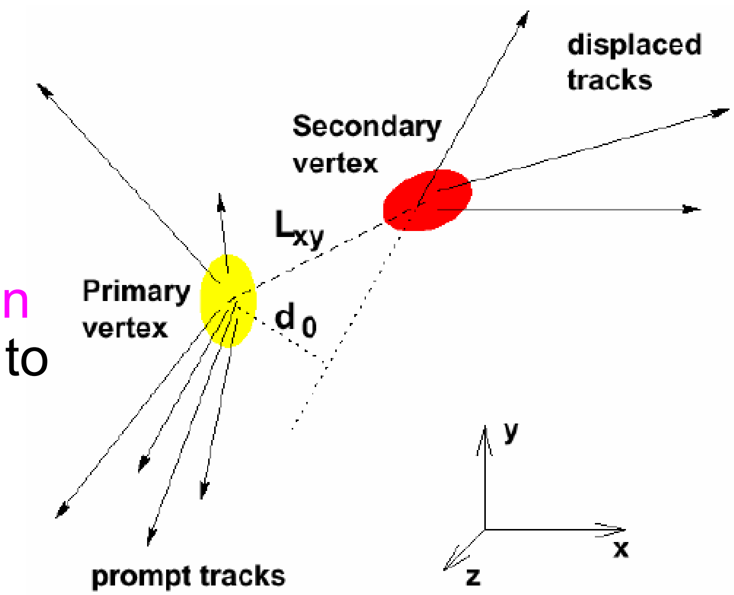
Mode	Br.(%)	
dilepton	5%	Clean but few signal. Two ν's in final state.
lepton+jets	30%	One ν in final state. Manageable bkgd.
all hadronic	44%	Large background.
τ + X	21%	τ-ID is challenging.

Flow of Mass Measurement



B-Tagging Algorithms

- **SECVTX**
  - Reconstructs secondary vertex of B-hadron decay.
  - Tags b-jets by displacement of secondry vertex from primary vertex.
- **Jet Probability (JP)**
  - Looks at the impact parameters of tracks in the jet and calculates probability of the jet to originate from the primary vertex.
  - Tags b-jet according to the calculated probability.
  - We have optimized JP algorithm for the best sensitivity to top mass.

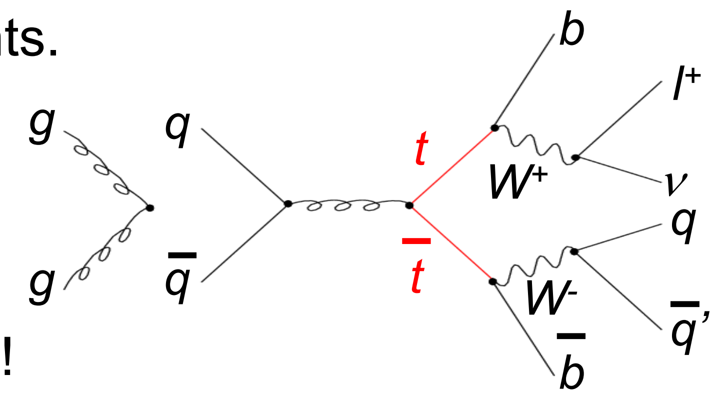


	ε_b	$\varepsilon_{light\ flavor}$
SECVTX	28%	0.34%
JP	33%	4.1%

JP has looser tagging condition with larger b-tagging efficiency.

Subsample Categorization

4 jets in final state →12 parton-to-jet assignments.
B-tagging information helps in correct reconstruction of signal events!
→ Uncertainty minimum in double tagged candidates.
Use of JP doubles the double tagging efficiency!



Category	2-tag (S+S)	2-tag (S+J)	1-tag(T)	1-tag(L)	0-tag
j1-j3 j4	$E_T>15$ $E_T>8$	$E_T>15$ $E_T>8$	$E_T>15$ $E_T>15$	$E_T>15$ $15>E_T>8$	$E_T>21$ $E_T>21$
b-tag condition	2 SECVTX	1 SECVTX + 1 JP	1 SECVTX	1 SECVTX	0 SECVTX
# parton-jet Assignment	2	2	6	6	12
S/N (318 pb^{-1})	17/1	15/1	36/7	11/10	~20/20

2-tag samples are much purer and easier to reconstruct!

Extracting Top Mass for each Candidate Event

Minimize χ^2 to reconstruct event-by-event top mass (2-C fit).

Fluctuate particle momenta according to detector resolution.

$$\chi^2 = \sum_{i=l,jets} \frac{(P_T^{i,fit} - P_T^{i,meas.})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(UE_j^{j,fit} - UE_j^{j,meas.})^2}{\sigma_j^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{l\nu b} - M_{top})^2}{\Gamma_{top}^2} + \frac{(M_{jjb} - M_{top})^2}{\Gamma_{top}^2}$$

M_{top} as free param.

Constrain masses of 2 W's.

t and $\bar{t}$ have the same mass.

- 2jets from W decay + 2*b*-jets. →12 jet-parton assignments.

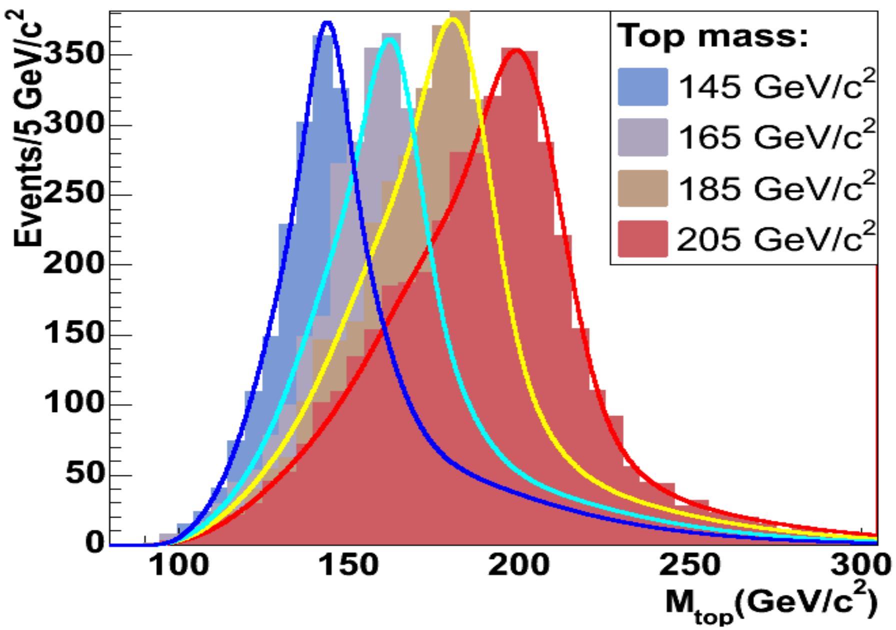
> Assignment inconsistent with b-tagging information is rejected.
> We choose the assignment with smallest χ^2 as seemingly correct event reconstruction.

- We reject events with χ^2>9, as seemingly background.

Top Mass Templates

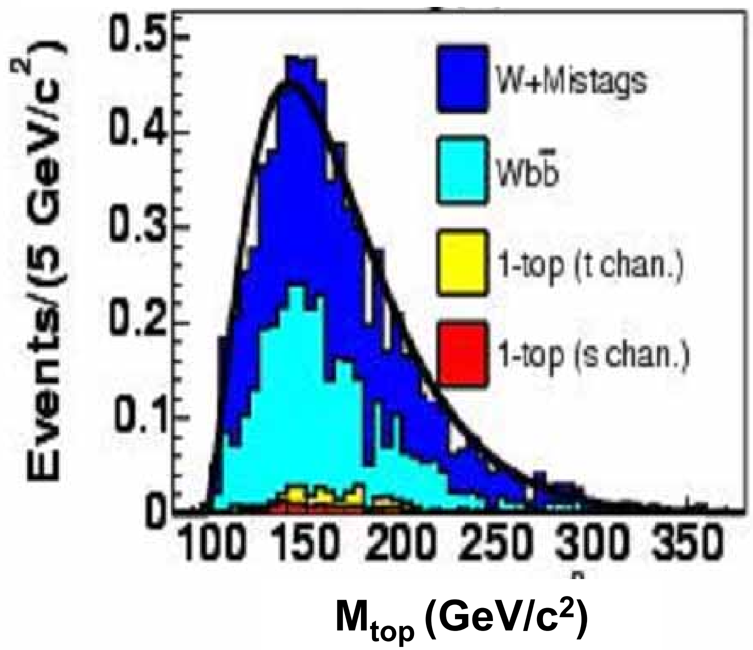
M_{top} distribution shape is parameterized as a function of true top mass using ttbar Monte Carlo samples with different top mass assumptions.

Signal Template (1tagT)



Background distribution is also fit into a function, but NOT dependent of top mass.

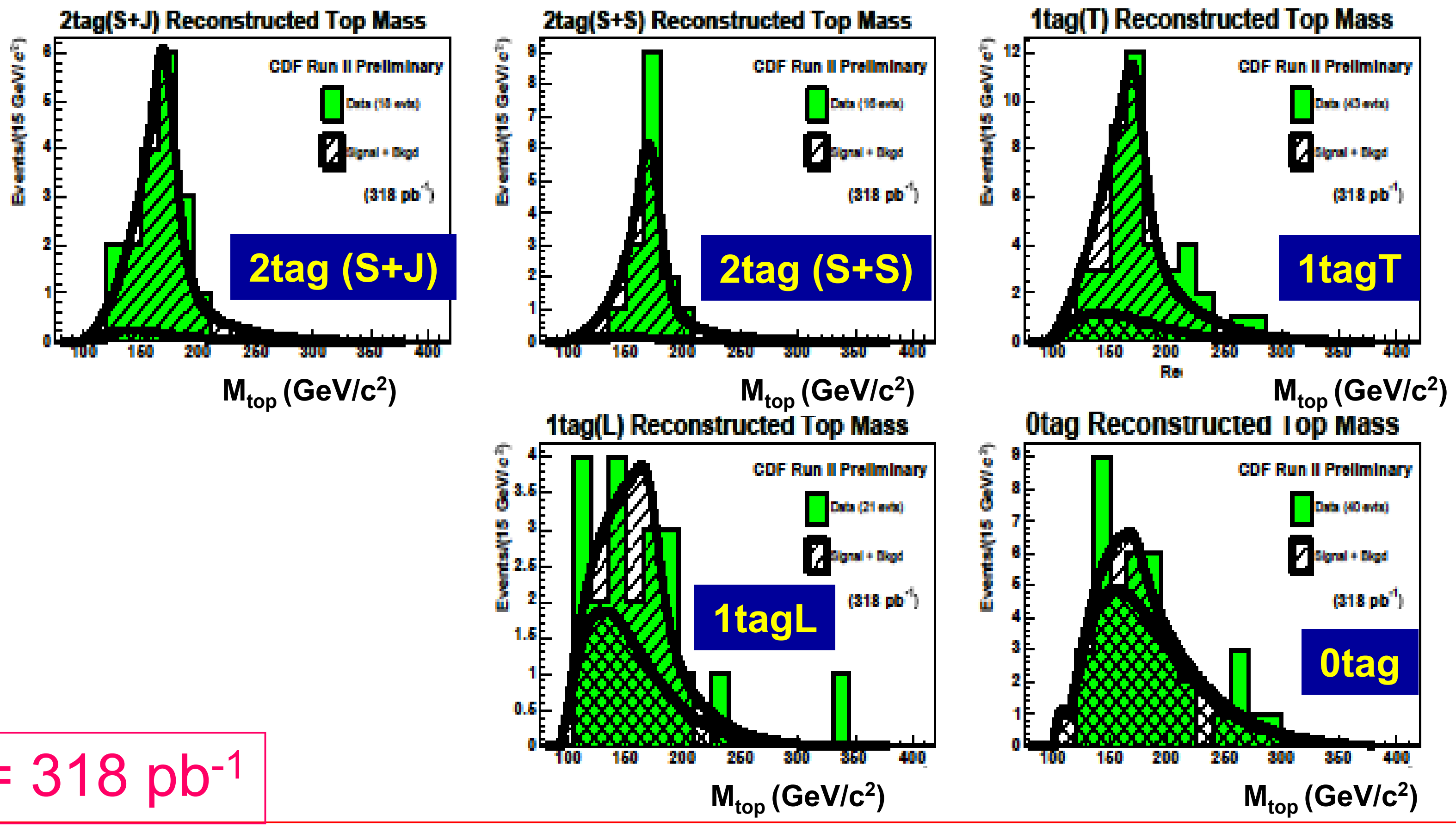
Background Template (1tagT)



Result of Fit to Data

Likelihood fit looks for top mass that describes the data M_{top} distribution best (template fit).

- The background fraction is constrained by estimation for tagged samples.
- The background fraction is free in 0 tag sample.

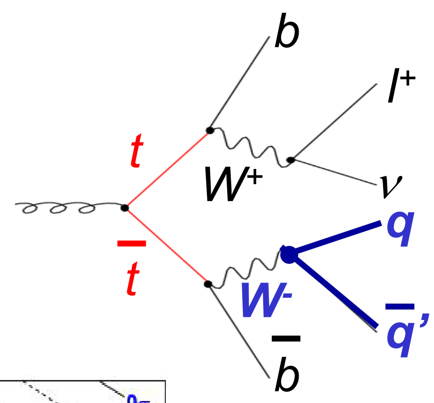


$\mathcal{L} = 318\ pb^{-1}$

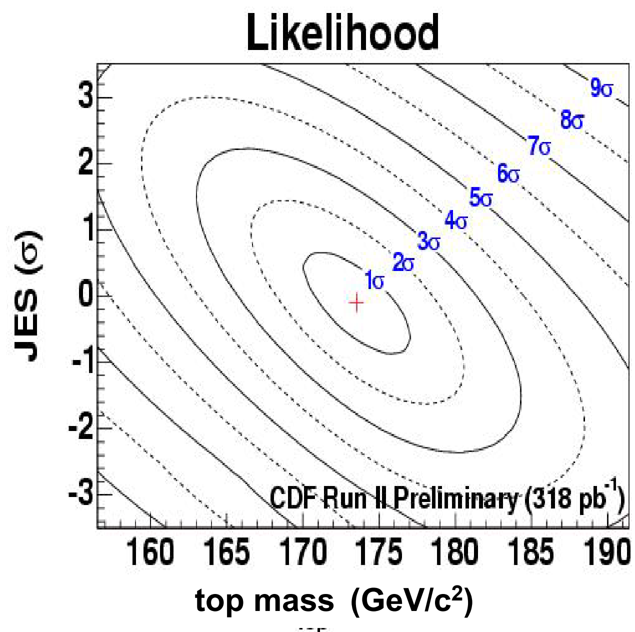
$$m_{top} = 173.0 \,{+2.9/-2.8}\ (stat) \pm 3.3\ (syst)\ GeV/c^2$$

Jet Energy Scale (JES) Uncertainty = ±3.0 GeV/*c*²

Improved Fitting



- In-situ JES calibration w/ W→jj invariant mass in candidate events.
- (M_{top}, W invariant mass) are parametrized as functions of (true top mass, JES).
- Likelihood fit is performed in (true top mass, JES) plane (2-D fit).
- Currently only using SECVTX tagger.
- Further improvement can be achieved by optimizing b-tagging conditions.



World's Best Single Measurement!!

Even better than Run I World Ave!

$\mathcal{L}$ = 318 pb^{-1}

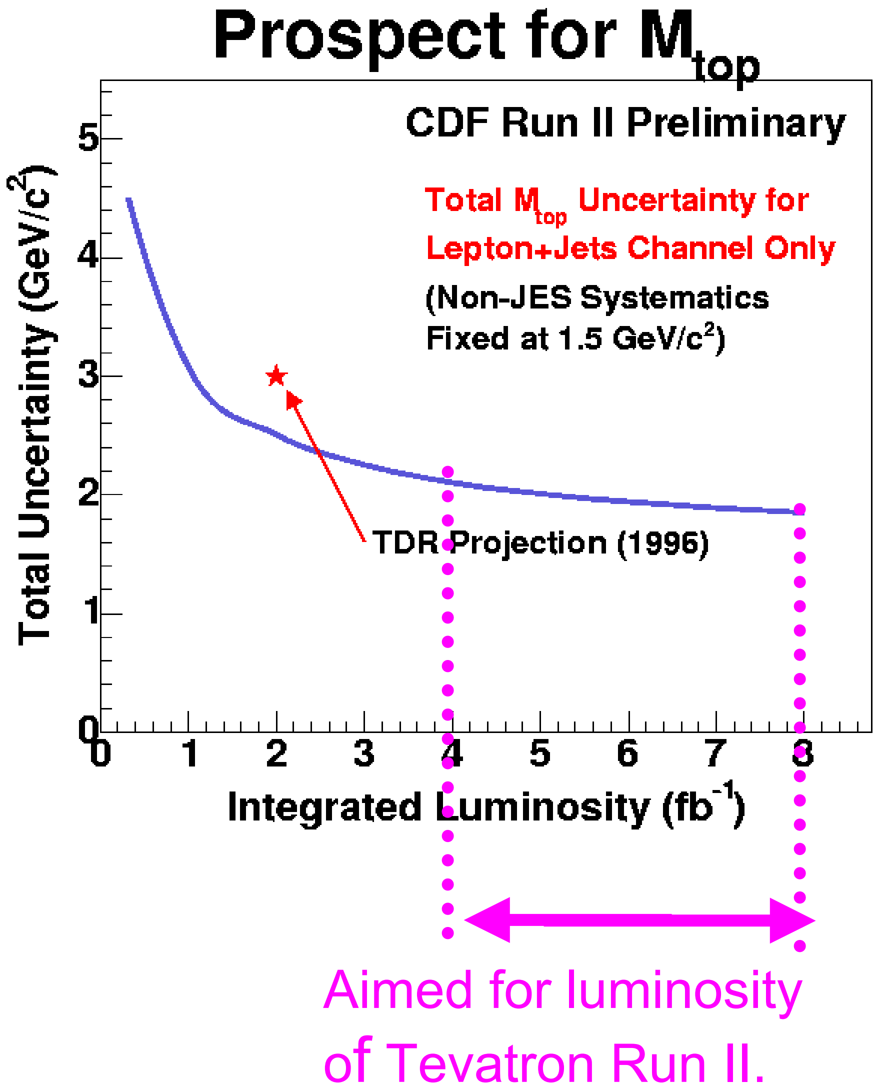
m_{top} = 173.5 +2.7/-2.6 (stat) ± 3.0 (syst) GeV/c^2

JES syst = ±2.5 compared to ±3.0 wo/ in situ calibration

Future Projection

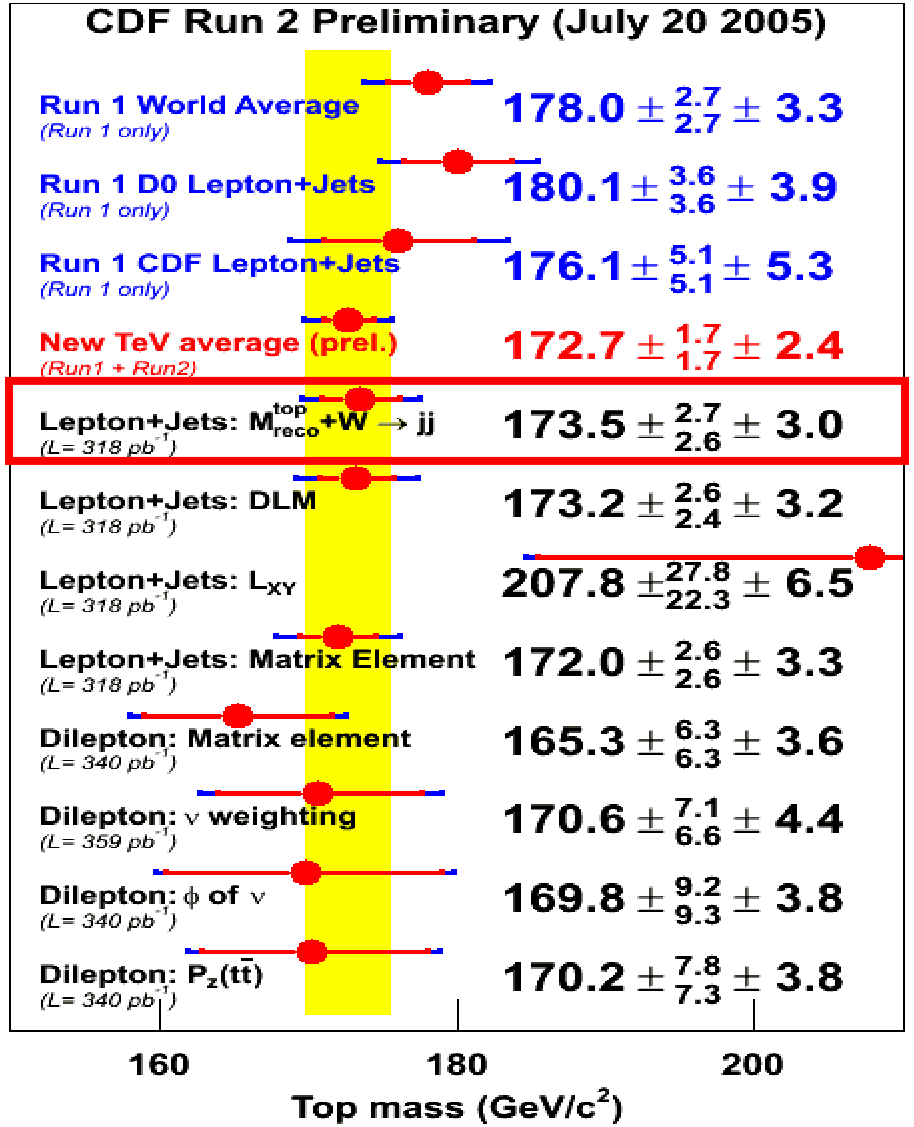
- Total uncertainty of 2-D fit measurement will achieve
  $\Delta m_{top} \sim 2$ **GeV/c²**
  in the end of CDF Run II.
- Conservative projection assuming only stat. and JES will improve.
  - We can improve other syst. uncertainties.
  - We will optimize b-tagging condition for 2-D fit in the next round. Currently it only uses SECVTX.

→ We will do better!



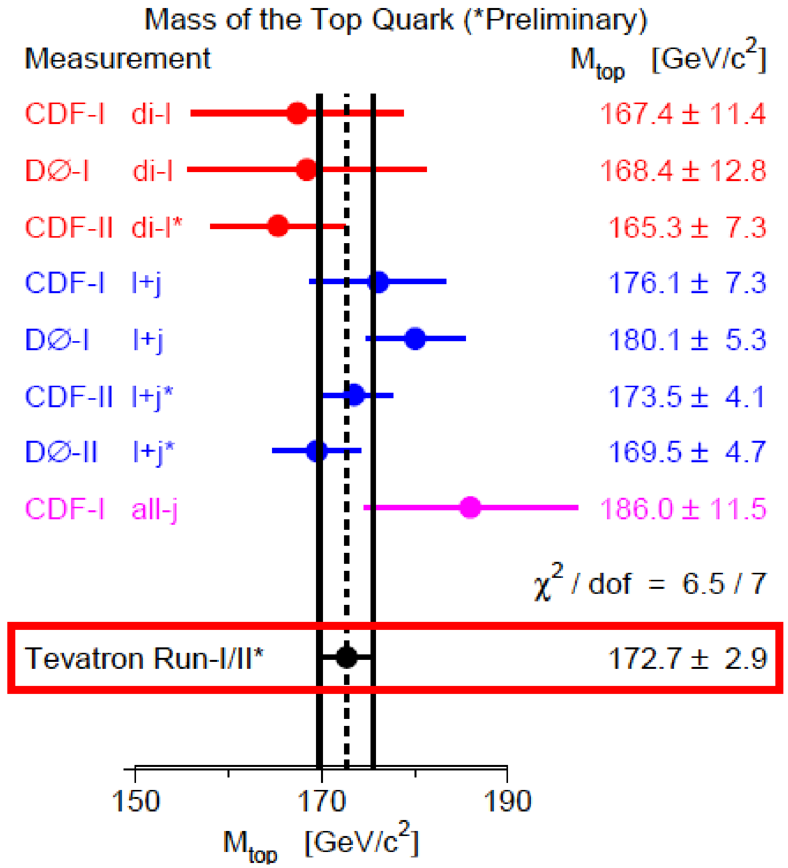
Summary of Run II Measurements

CDF Run II Top Mass Measurements



Preliminary World Average with CDF/D0, Run I/Run II Measurements

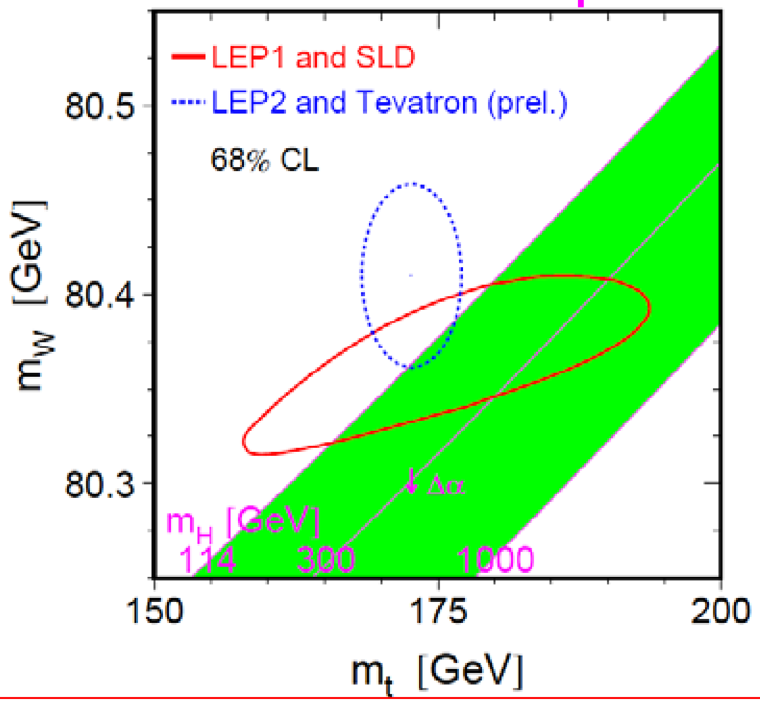
Only best analysis from each decay mode, each experiment.

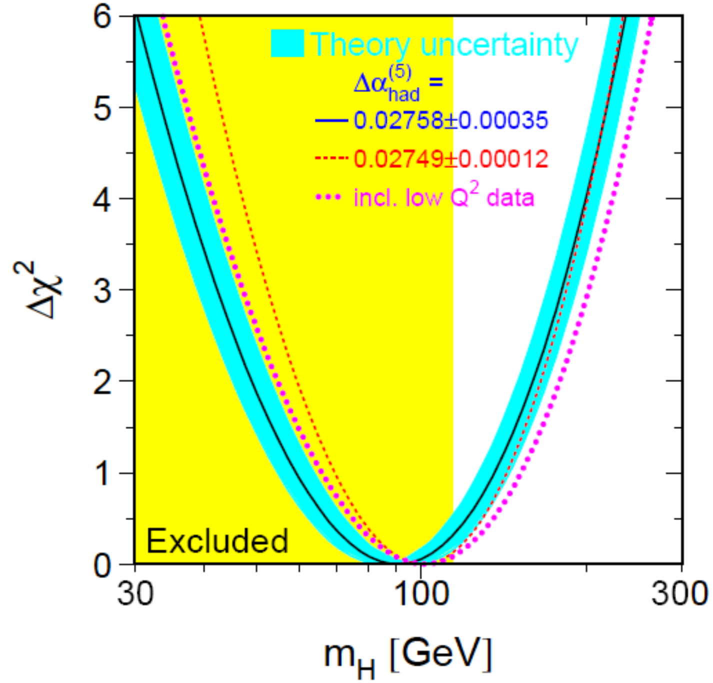


Updated Electroweak Fit

w/ Preliminary CDF + D0, Run I + Run II Combined :

m_{top}=172.7 ±2.9 GeV/c^2





m_{higgs}=91 +45/-32 GeV/c^2

m_{higgs}<186 GeV/c^2 (95% CL)

w/ Tevatron Run I average : 178.0 ± 4.3 GeV/c^2 :

m_{higgs}=114 +69/-45 GeV/c^2, m_{higgs}<260 GeV/c^2 (95% CL)

Summary

- **CDF L+Jets Template w/ JP :**

  m_{top}=173.0 +4.4/-4.3 GeV/c^2 (318 pb^{-1}).

- **Template fit with in-situ JES calibration** is the best single measurement and better than Run I World Average :

  m_{top}=173.5 +4.1/-4.0 GeV/c^2 (318 pb^{-1}).

  This analysis will achieve Δm_{top} ~ 2 GeV/c^2 in the end of Run II.

- **Preliminary combination** of CDF and D0 (RunI + Run II):

  m_{top}=172.7 $\pm$ 2.9 GeV/c^2.

  (Run I World Average : 178.0 $\pm$ 4.3 GeV/c^2)

  $\rightarrow$ m_{higgs}=91 +45/-32 GeV/c^2, m_{higgs}<186 GeV/c^2 (95% CL).

  (m_{higgs}<260 GeV/c^2 using Run I World Average)

- **Next Winter with ~1fb^{-1} dataset** ($\times$3 statistics).

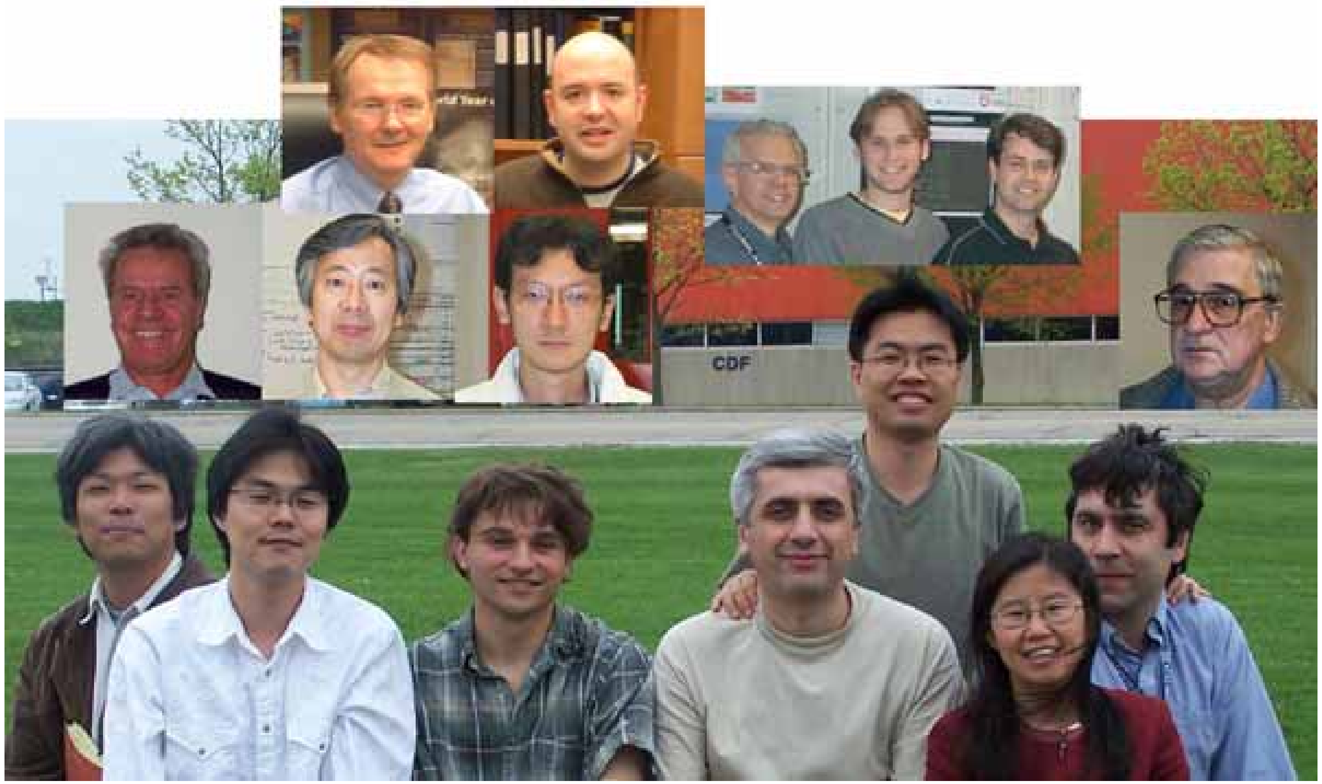
  - Improvement of dominant uncertainties by ~1/$\sqrt{L}$.
  - D0 Run II Dilepton and All Hadronic channel from CDF/D0 Run II will be newly included in combined measurement.
  - We expect a good improvement in precision of measurement again!

Backup

Results of Template Measurements

	Template	Template + JP	Template + JES
Summer 2004	$176.7^{+6.0}_{-5.4} \pm 7.1$	$177.2^{+4.9}_{-4.7} \pm 6.6$	–
Summer 2005	$173.2^{+2.9}_{-2.8} \pm 3.4$	$173.0^{+2.9}_{-2.8} \pm 3.3$	$173.5^{+2.7}_{-2.6} \pm 3.0$

CDF L+jets Template Group



Intstitutes :
Tronto 3
UC Berkeley 2
Chicago 4
JINR 2
Fermilab 1
Pisa 1
Tsukuba 4
Rockefeller 1

- Template Method measurement was reported by
  - Fermilab Today "CDF Tops the Top World Average“ (April 21, 2005)
  - KEK News "質量起源の解明をめざして" (May 19, 2005)

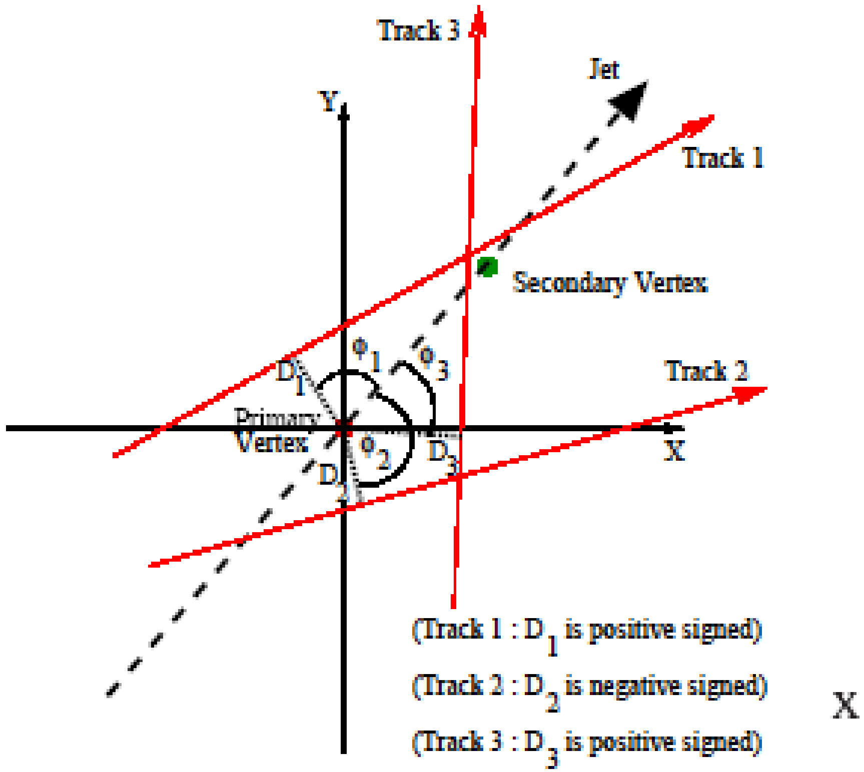
Event Selection

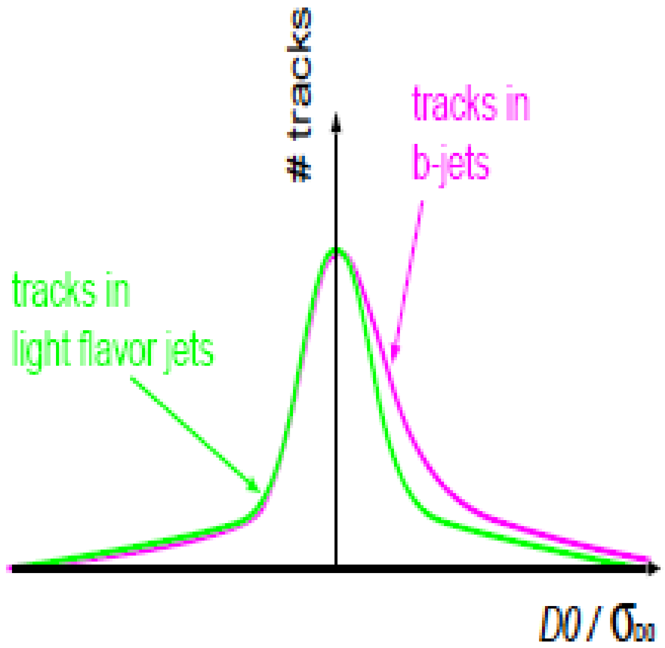
- One isolated high P_T lepton (e/μ).
  - e : E_T > 20 GeV, $|\eta|$<1.1, shower shape, matching between calorimeter cluster and track.
  - μ : P_T > 20 GeV, $|\eta|$<1.0, matching between muon chamber hits and track, energy deposit in calorimeter.
- Missing E_T > 20 GeV, to ensure there was a ν in the final state.
- 4 Jets reconstructed using JETCLU algorithm with cone size 0.4.

  Sample subdivision by b-tagging conditions.
  - 1 and 2 tag channels :
    - More than 3 jets with E_T >15 GeV, $|\eta|$<2.0.
    - The 4th jet with E_T >8 GeV, $|\eta|$<2.0.
  - 0 tag channel :
    - 4 jets with E_T >21 GeV, $|\eta|$<2.0.

- We only consider the leading 4 jets as products of ttbar decay, when $\geq$5 jets are found in a event.
- Two b-tagging algorithms – SECVTX and Jet Probability.

Jet Probability Algorithm (1)

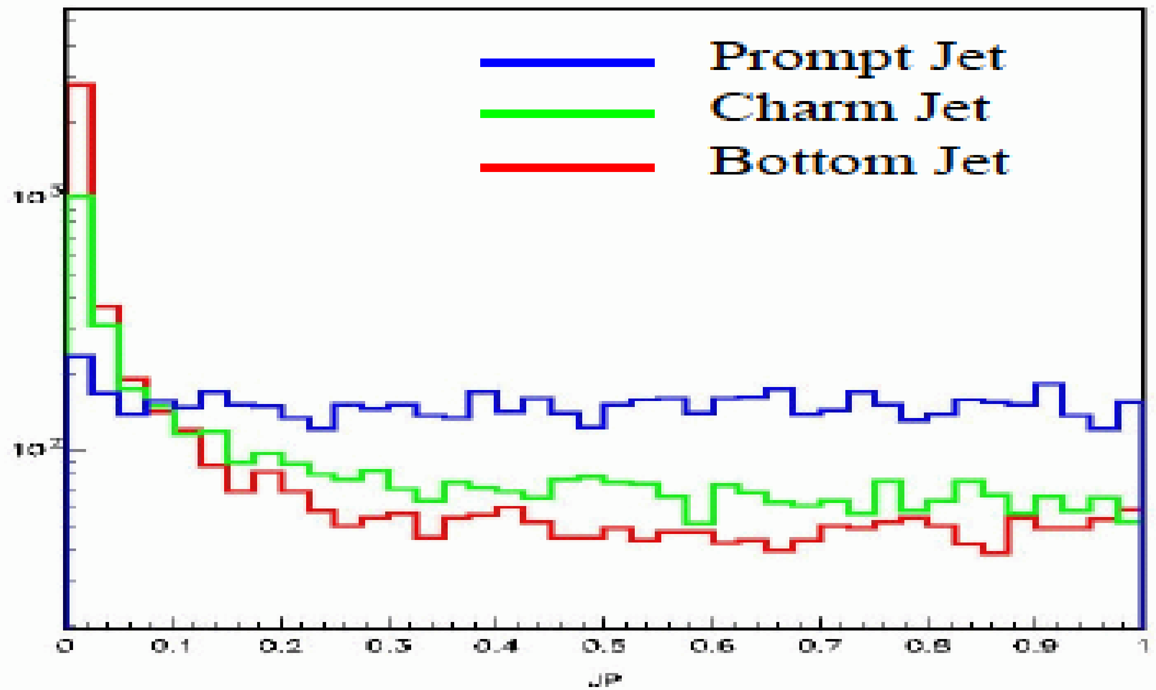




Assign sign (±) to the impact parameter $D0$ of each track based on its direction.

Jet Probability Algorithm (2)

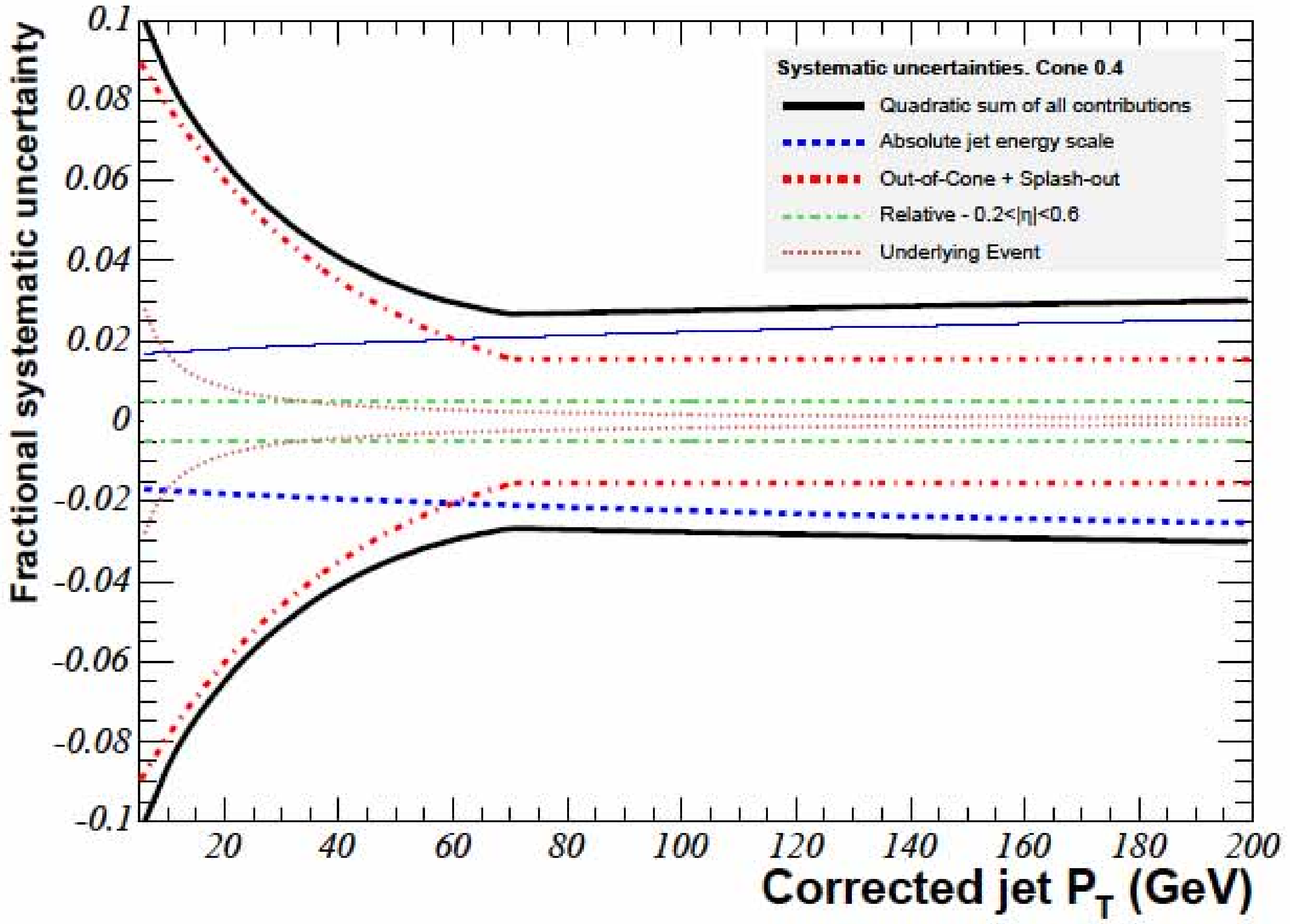
Combine $D0$ significance of all the tracks in the jet and calculate "the probability of the jet originating in the primary vertex" (Jet Probability).



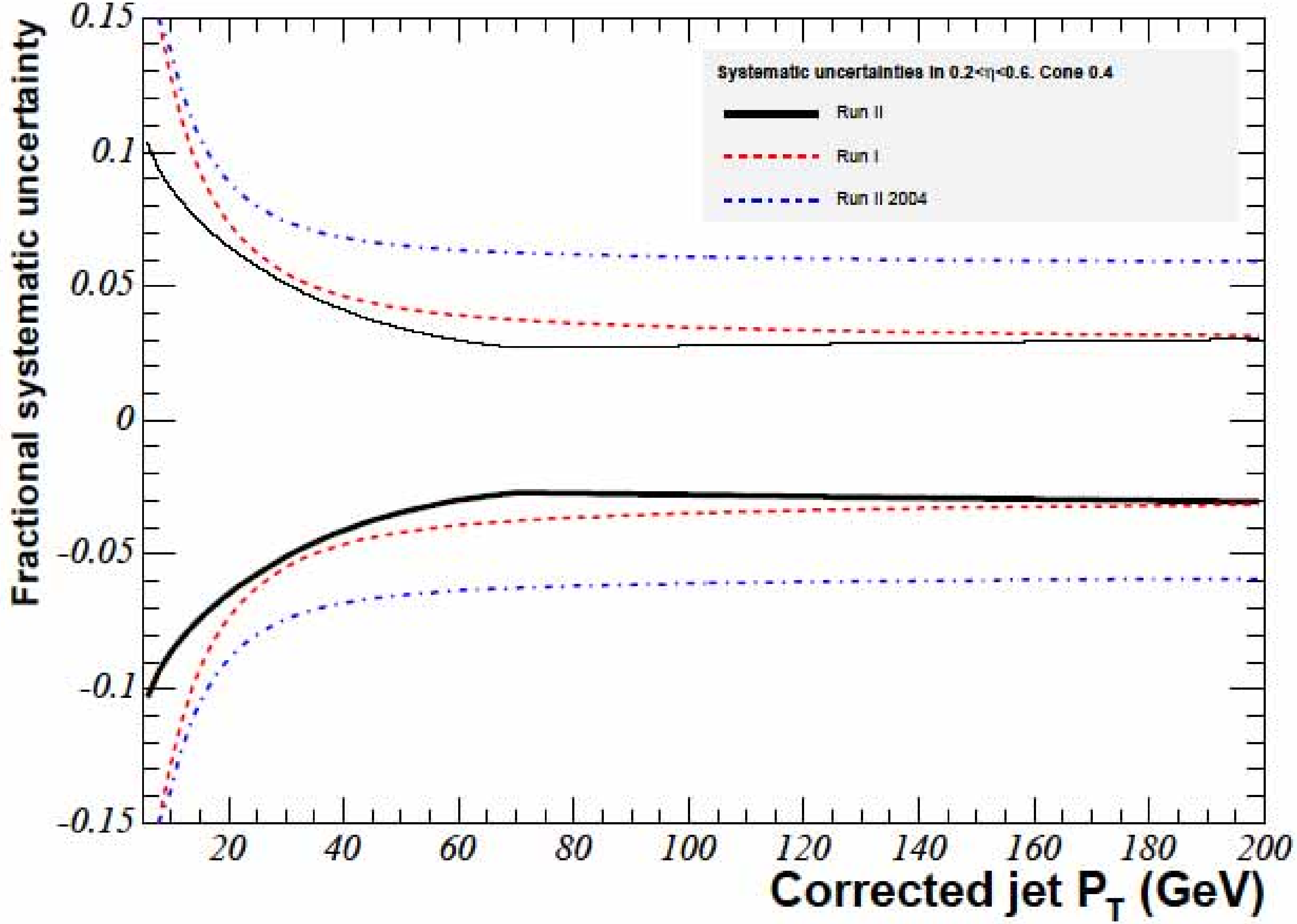
(Jet Probability in $t\bar{t}$ MC Events)

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

Uncertainty on Jet Energy Measurement

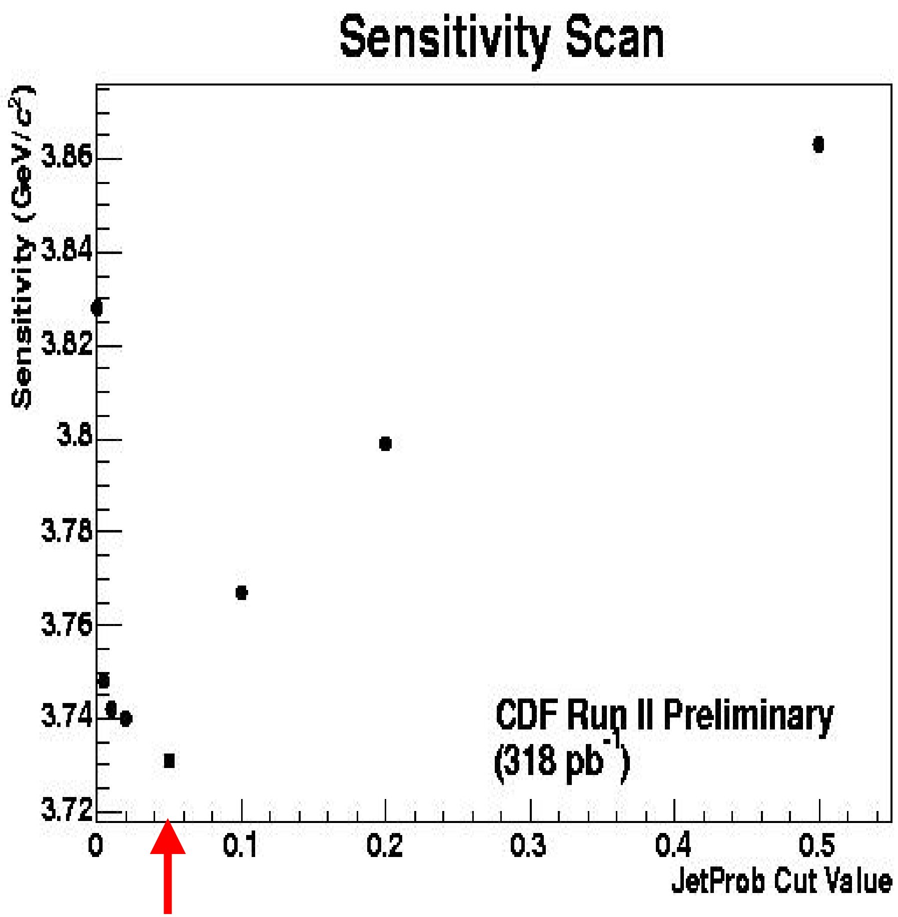


Jet Energy Uncertainty Compared with Run I



Optimization of Jet Probability

- Jet Probability algorithm calculates probability of the jet to originate from the primary vertex.
- We apply a cut on the calculated probability for b-tagging.
- We optimized the cut value for the best statistical sensitivity to top quark mass in a Monte Carlo study.



Statistical error minimum for top mass measurement!

Expected Number of Events

Comparison of number of events between data and expectation :

CDF Run II Preliminary (318 pb^{-1})

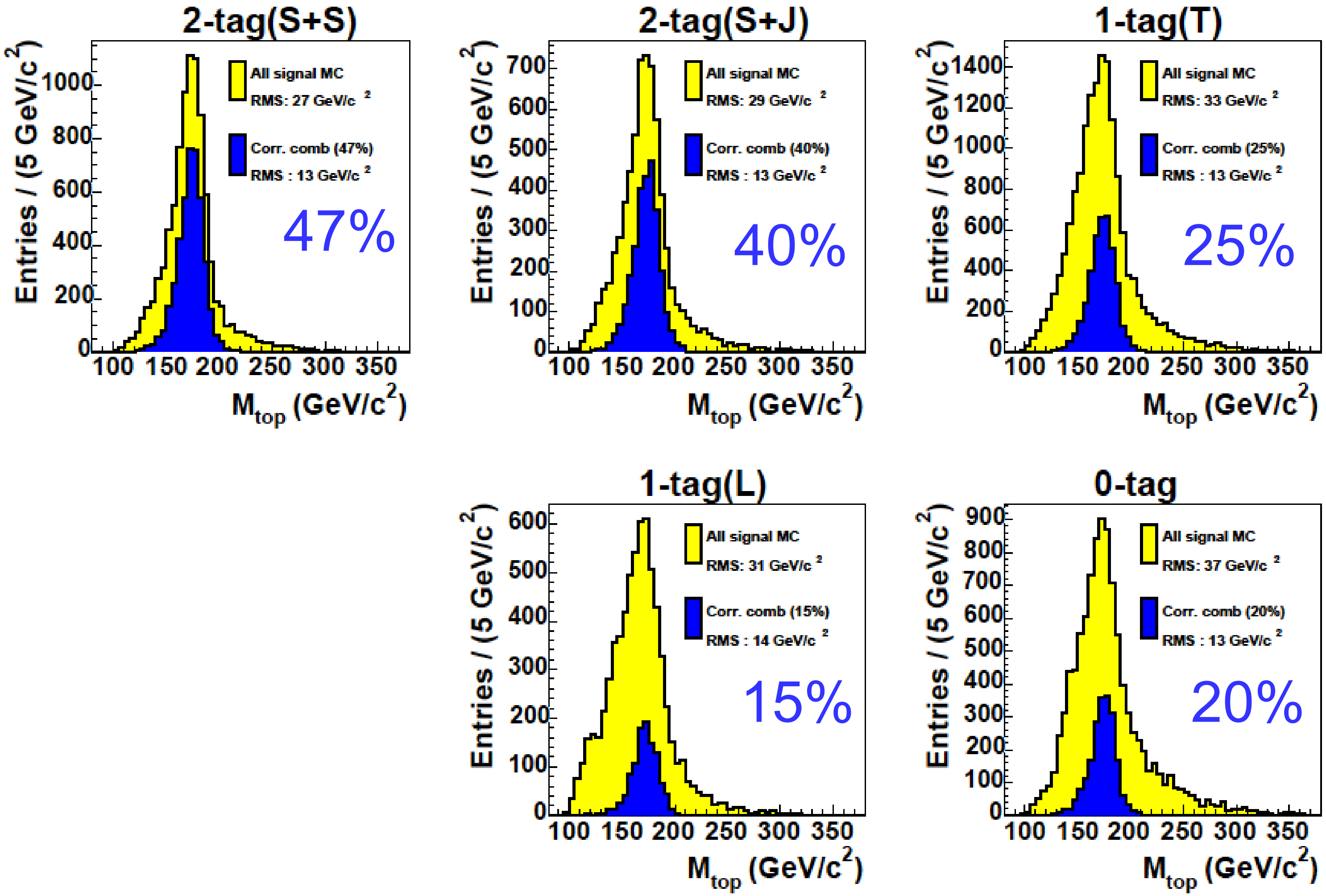
	2tag(S+J)	2tag(S+S)	1tag(T)	1tag(L)	0tag
Background	1.18 ± 0.59	0.71 ± 0.18	7.11 ± 1.24	9.55 ± 1.71	—
$t\bar{t}$ (6.1 pb)	8.6	14.0	25.7	11.1	19.4
$t\bar{t}$ (8.0 pb)	11.3	18.4	33.7	14.6	25.4
Total (6.1 pb)	9.8	14.7	32.8	20.6	—
Total (8.0 pb)	12.5	19.1	40.8	24.1	—
Observed	18	16	43	21	40

m_{top} = 175 GeV/c^2 → Total (8.0 pb)

m_{top} = 178 GeV/c^2 → Observed

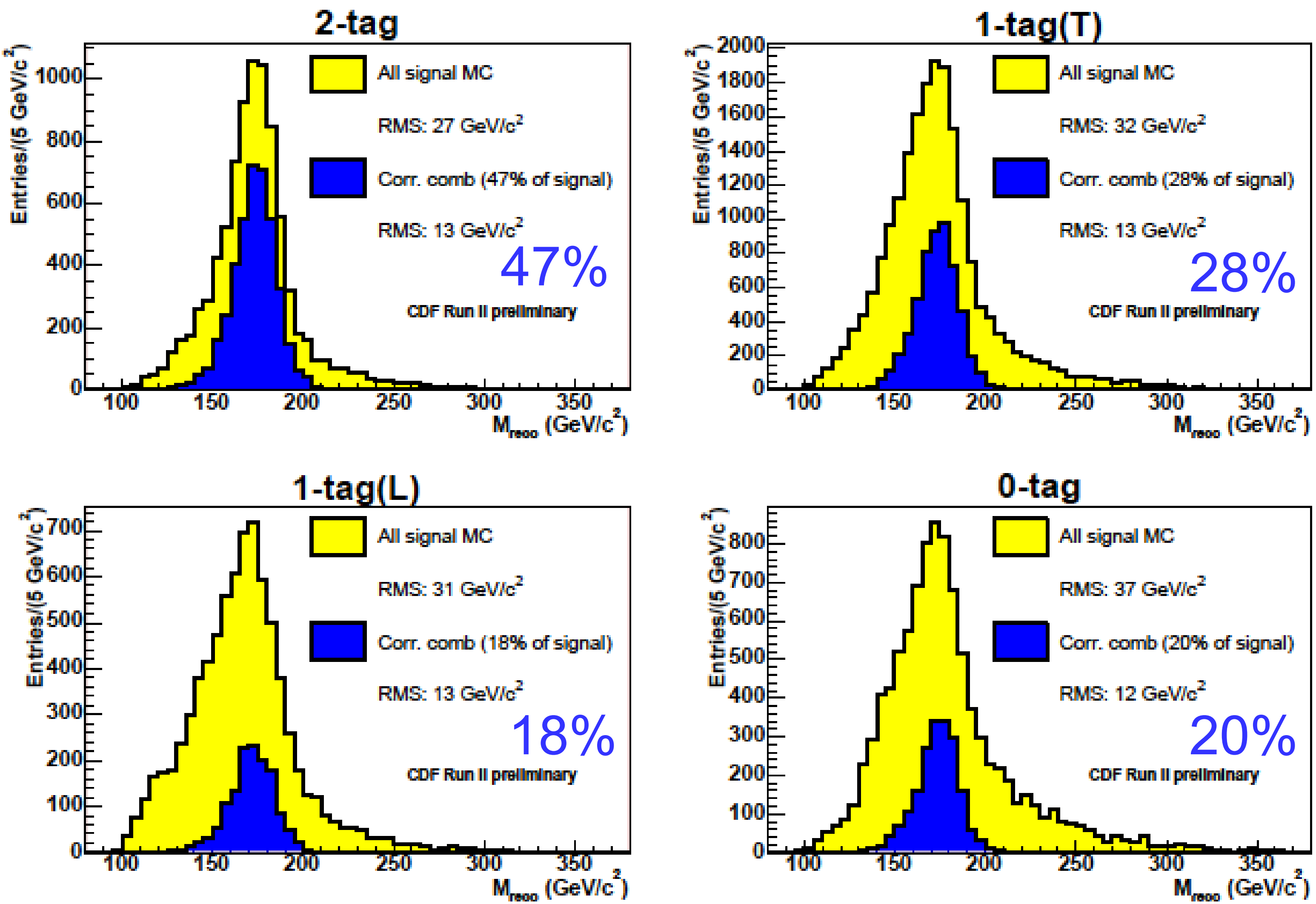
Fraction of Correctly Reconstructed Events

In ttbar MC events with m_{top}=178 GeV/c^2.



Fraction of Correctly Reconstructed Events

In ttbar MC events with m_{top}=178 GeV/c^2. Categorization with SECVTX only.



Definition of Likelihood

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

$$L_{shape} = \frac{e^{-(N_s+N_b)}(N_s+N_b)^N}{N!} \Pi_{i=1}^{Nevents} \frac{N_s P_{sig}(M^i_{recon}, m_t) + N_b f_b(M^i_{recon})}{N_s + N_b}$$

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

- M^i_t the reconstructed top mass for each event in the sample to be fitted.
- m_t 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.

m_t, N_s and N_b are the free parameters in the fit.

No background constraint on 0tag sample.

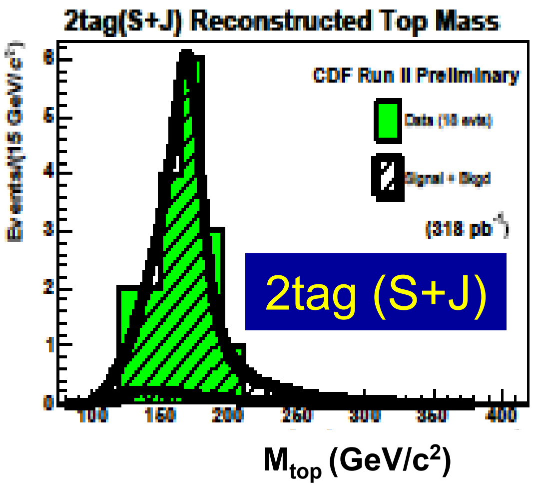
combined likelihood - Each channel is statistically independent.

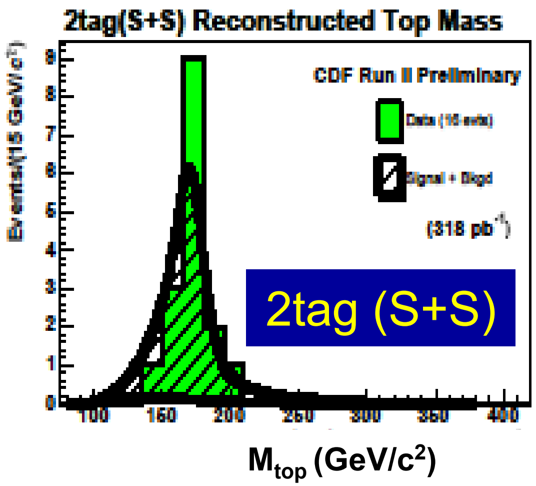
$$L_{comb} = L_{0tag} \times L_{1tagL} \times L_{1tagT} \times L_{2tag(S+S)} \times L_{2tag(S+J)}$$

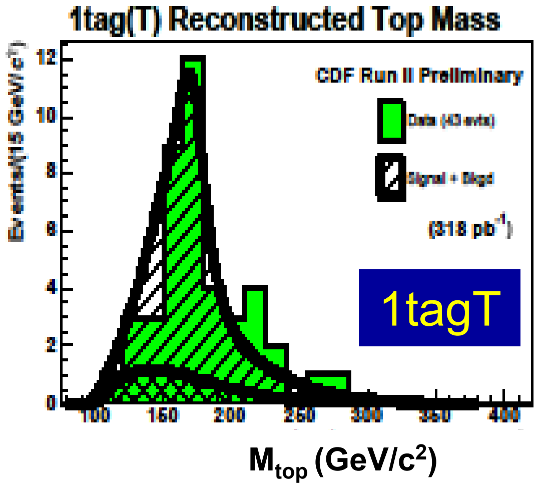
Result of Fit to Data

Likelihood fit looks for top mass that describes the data M_{top} distribution best (template fit).

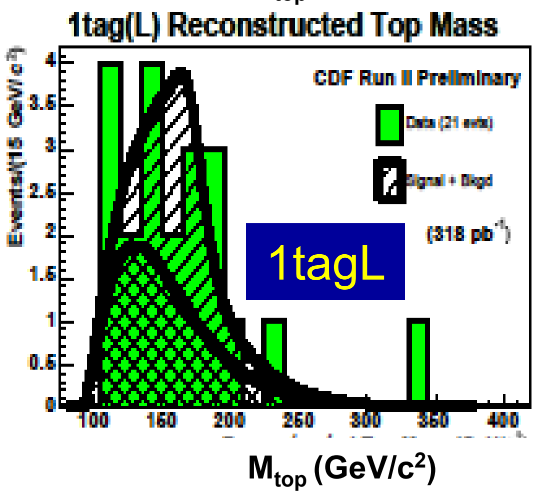
- The background fraction is constrained by estimation for tagged samples.
- The background fraction is free in 0 tag sample.

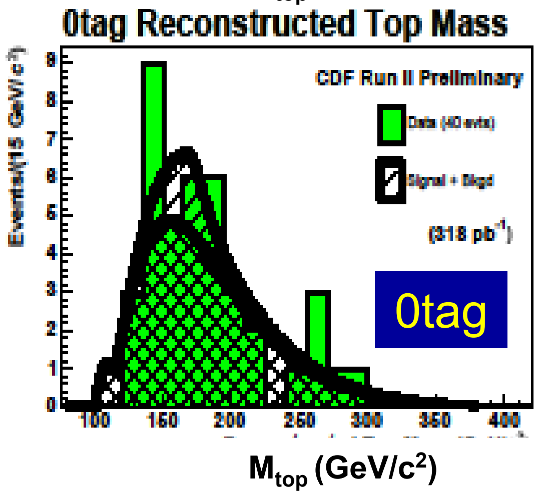






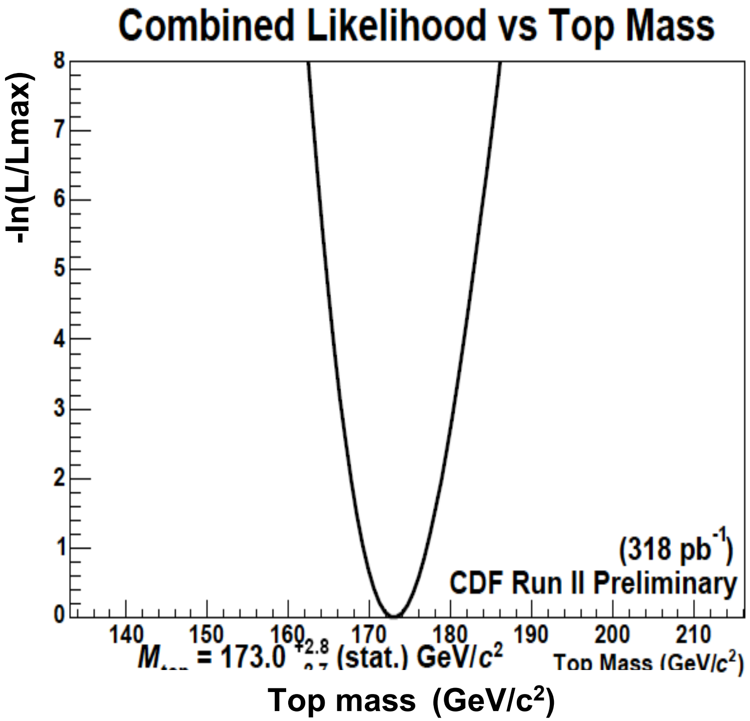
$\mathcal{L}$ = 318 pb^{-1}





Measured Top Mass

Likelihood vs m_{top}



Breakdown of Systematic Errors

CDF Run II Preliminary ($318\ pb^{-1}$)

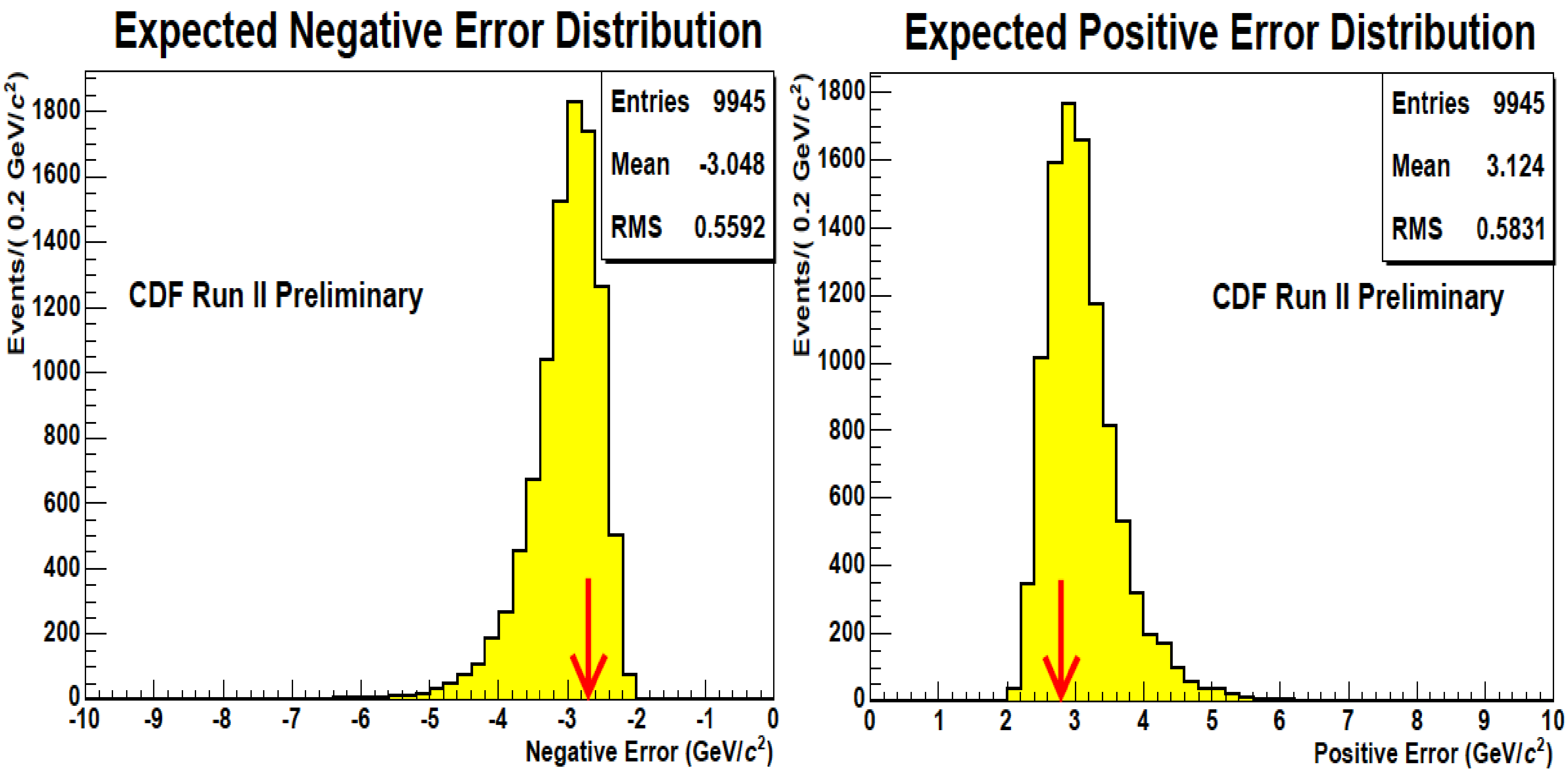
Source	Δm_{top} (GeV/c^2)
Jet Energy	3.0
b-jet Energy	0.6
ISR	0.3
FSR	0.6
PDFs	0.4
Generators	0.2
Background Shape	0.7
b-tagging	0.3
MC Statistics	0.4
Total	3.3

Jet Energy Scale (JES) is dominant!

$\mathcal{L} = 318\ pb^{-1}$

$$m_{top} = 173.0\ +2.9/-2.8\ (stat) \pm 3.3\ (syst)\ GeV/c^2$$

Cross Check

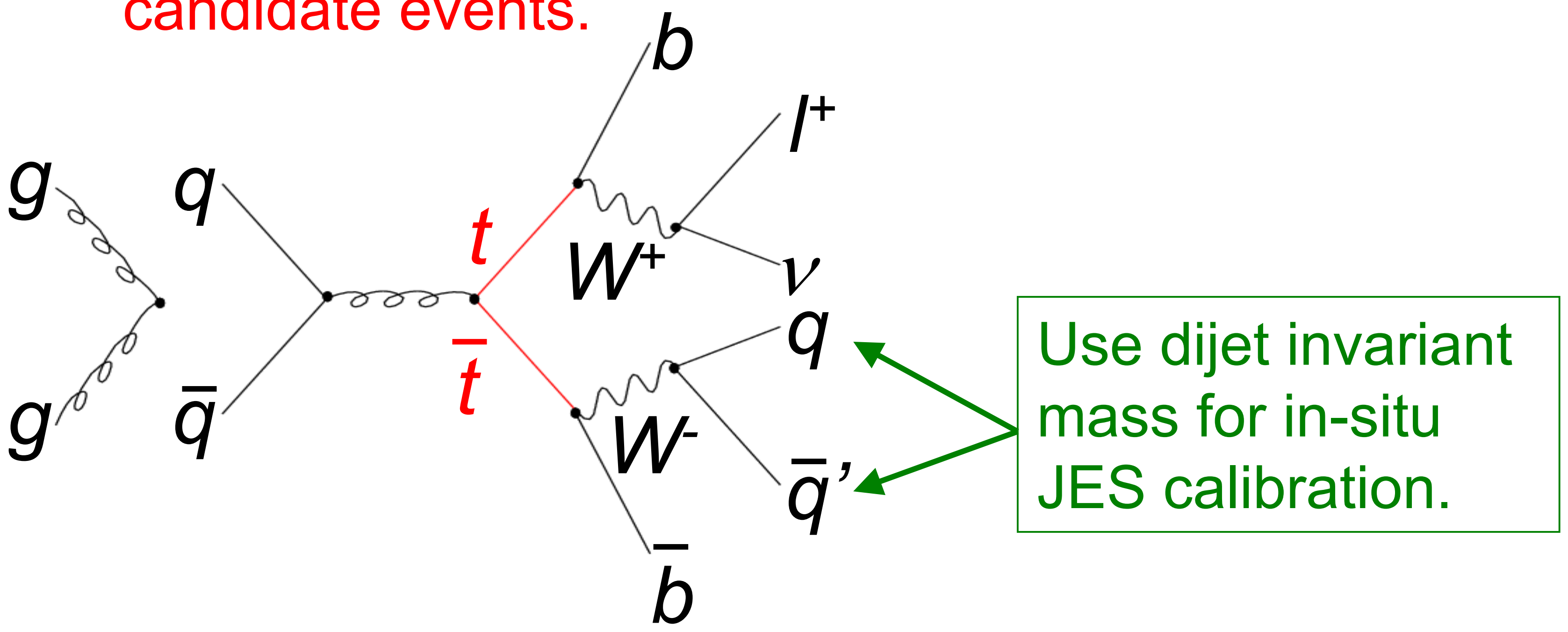


- The obtained statistical uncertainty is consistent with expectation from Monte Carlo study.

Improved Fitting Method

- Syst. Uncertainty = $\pm$3.3 GeV/c^2 is dominated by JES uncertainty ($\pm$3.0 GeV/c^2).
- Most JES uncertainties are shared between light flavor and b-jets. Only 0.6 GeV/c2 additional uncertainty on m_{top} due to b-jet specific systematics.

  $\rightarrow$Likelihood fit with constraint on the dijet mass in candidate events.



Templates with JES

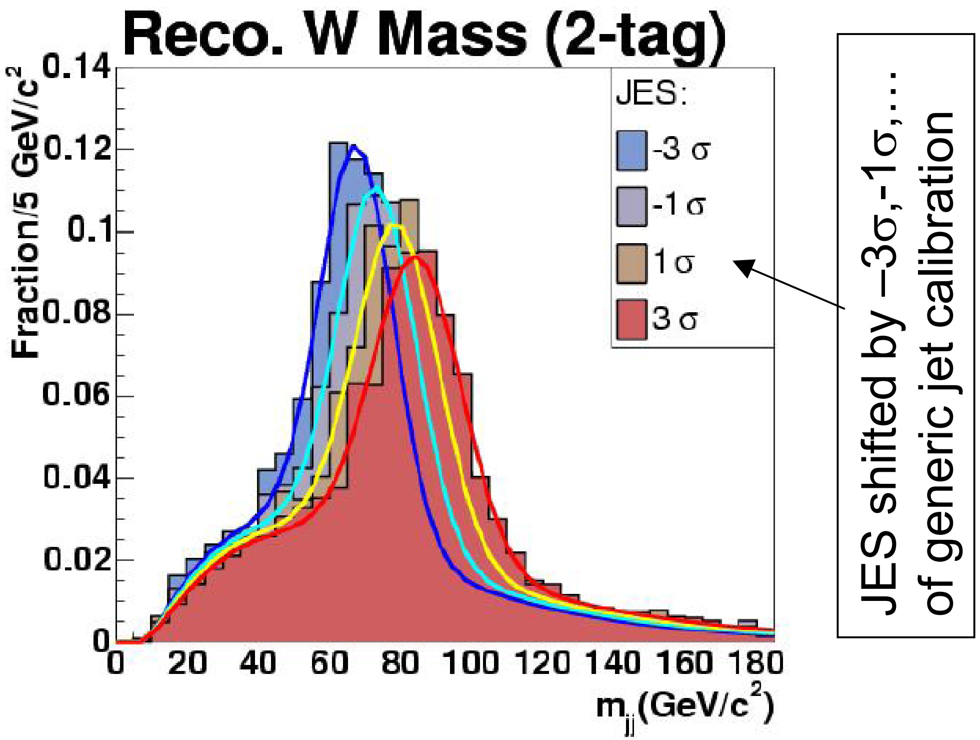
(M$_{top}$, hadronic W invariant mass) are parametrized as functions of (true top mass, JES).

- m_{jj} varies significantly as a function of JES.

- Event-by-event M_{top} is also largely dependent on JES.

  → M_{top} distribution is now parameterized as a function of true top mass m_{top} and JES.

Hadronic W mass Template

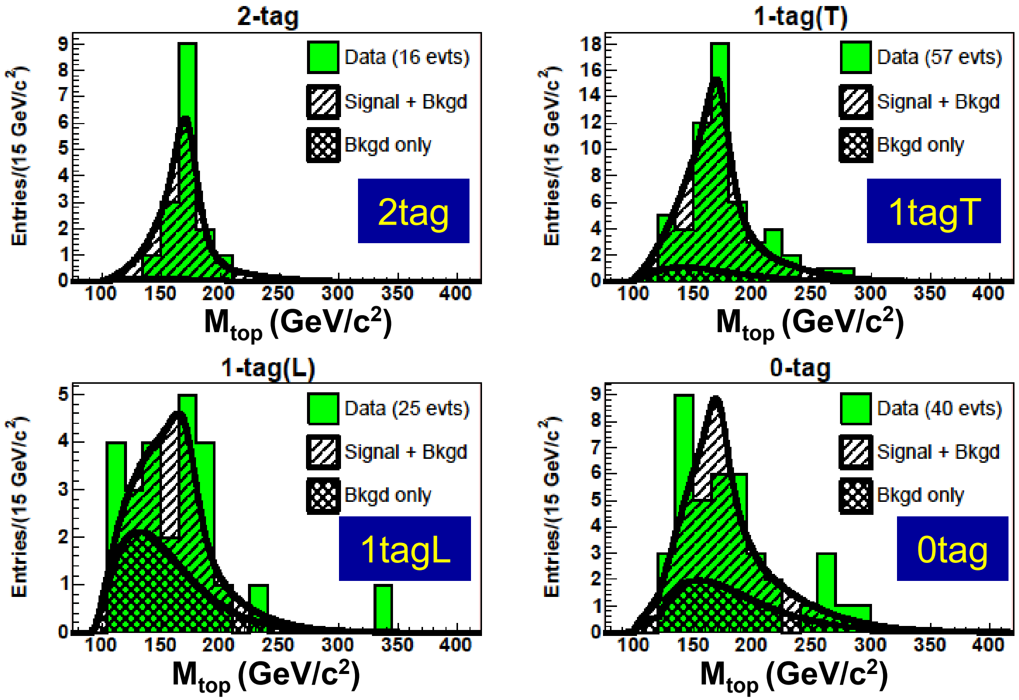


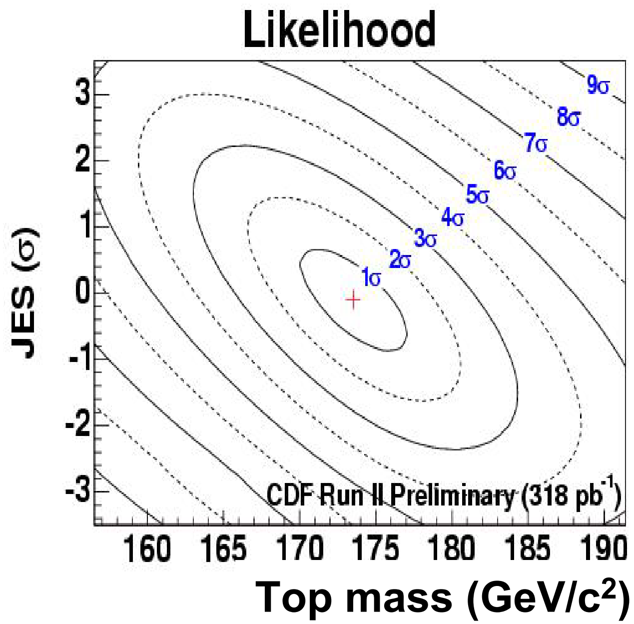
Result of 2-D Fit (with only SECVTX)

Likelihood fit looks for top mass, JES and background fraction that describes the data M_{top} and m_{jj} distributions best.

M_{top} distributions : CDF Run II Preliminary

$\mathcal{L}$ = 318 pb^{-1}





m_{top} = 173.5 +3.7/-3.6 (stat+JES) ± 1.7 (syst) GeV/c^2

m_{top} = 173.5 +2.7/-2.6 (stat) ± 3.0 (syst) GeV/c^2

World's Best Single Measurement!!

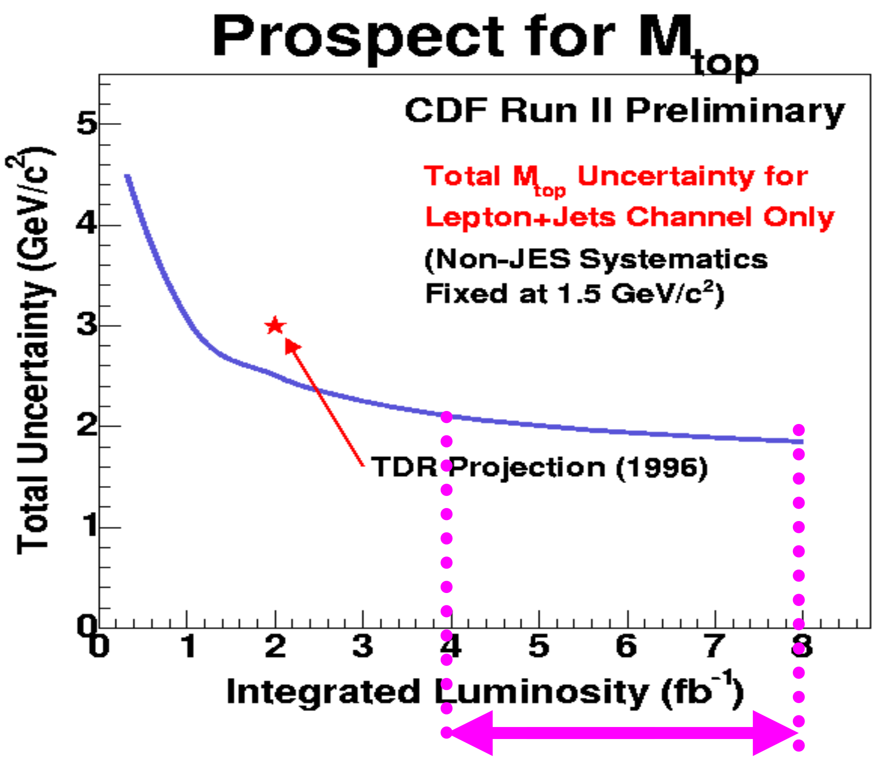
Even better than Run I World Ave!

JES syst 2.5 compared to 3.1 wo/ in situ calibration

Future Projection

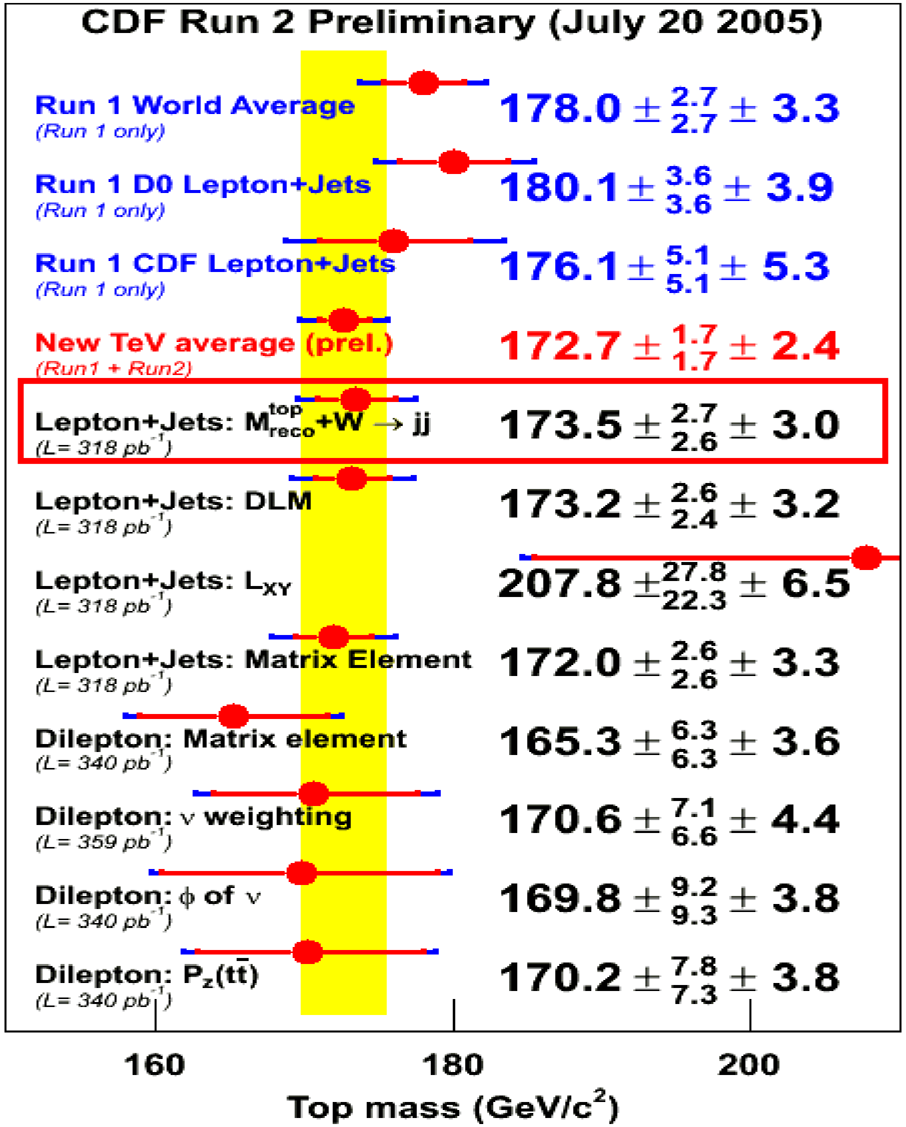
- Total uncertainty of 2-D fit measurement will be
  $\Delta m_{top} \sim 2$ GeV/c^2
  in the end of CDF Run II.
- Conservative projection assuming only stat. and JES will improve.
  - We can improve other syst. uncertainties.
  - We will optimize b-tagging condition for 2-D fit. Currently it only uses SECVTX.

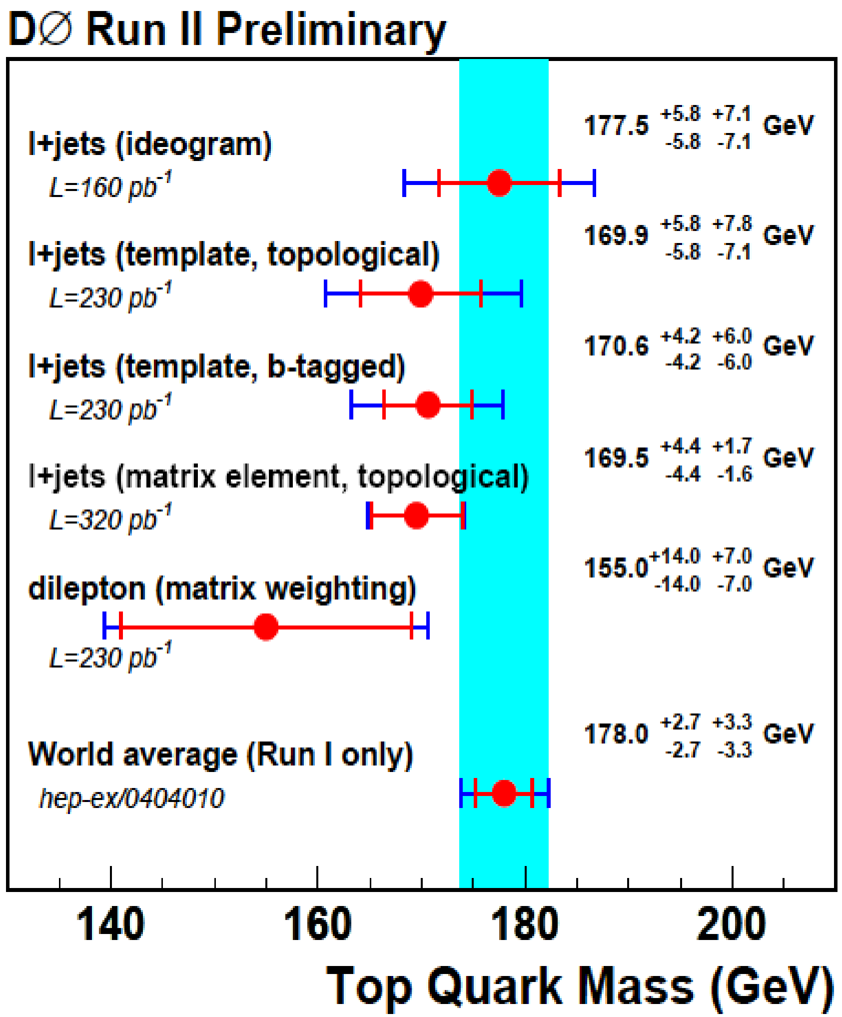
→ We will do better!



Aimed for luminosity of Tevatron Run II.

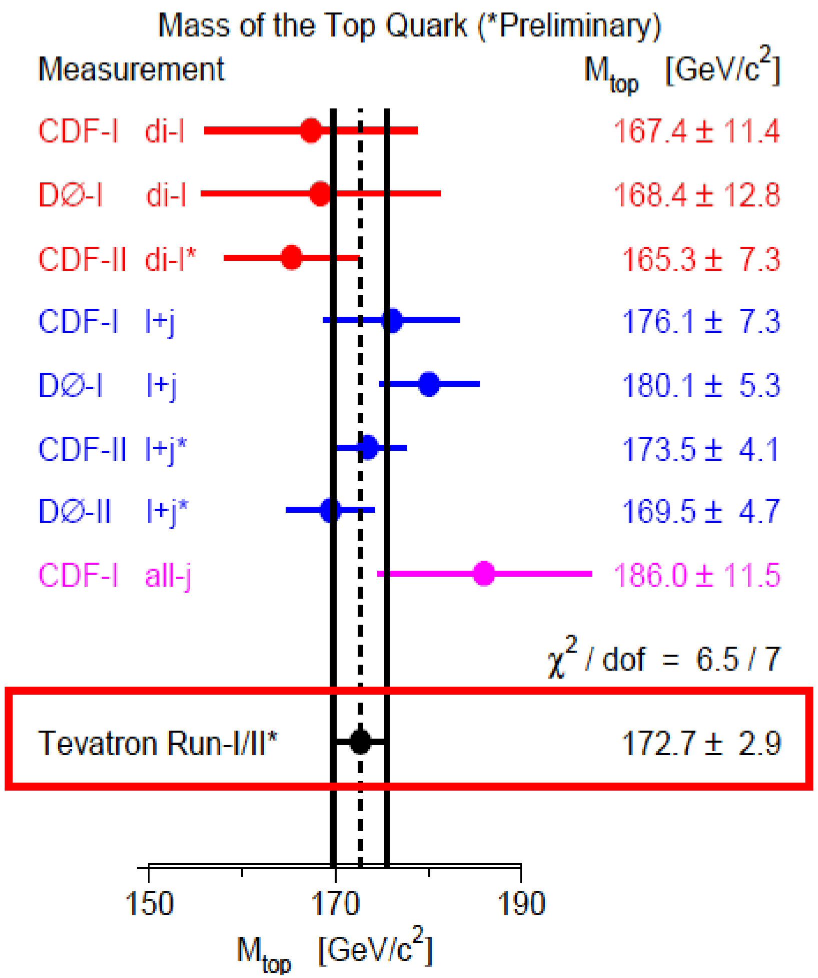
Summary of Run II Measurements





Run II Combined Top Mass

Only best analysis from each decay mode, each experiment.



Correlation :

- uncorrelated
  - stat.
  - fit method
  - in situ JES
- 100% w/i exp (same period)
  - JES due to calorimeter
- 100% w/i channel
  - bkgd. model
- 100% w/i all
  - JES due to fragmentation,
  - signal model
  - MC generator

New Preliminary World Average

Combination of the best analysis from each decay mode, each experiment.

Correlation :

Split into 2 to isolate "in situ" JES systematics from other JES

		Run-I published					Run-II preliminary			
		CDF			DØ		CDF			DØ
		all-j	l+j	di-l	l+j	di-l	$(l+j)_i$	$(l+j)_e$	di-l	l+j
CDF-I	all-j	1.00								
CDF-I	l+j	0.32	1.00							
CDF-I	di-l	0.19	0.29	1.00						
DØ-I	l+j	0.14	0.26	0.15	1.00					
DØ-I	di-l	0.07	0.11	0.08	0.16	1.00				
CDF-II	$(l+j)_i$	0.04	0.12	0.06	0.10	0.03	1.00			
CDF-II	$(l+j)_e$	0.35	0.54	0.29	0.29	0.11	0.45	1.00		
CDF-II	di-l	0.19	0.28	0.18	0.17	0.10	0.06	0.30	1.00	
DØ-II	l+j	0.02	0.07	0.03	0.07	0.02	0.07	0.08	0.03	1.00

$$m_{top} = 172.7 \pm 1.7\ (\text{stat}) \pm 2.4\ (\text{syst})\ \text{GeV}/c^2$$

Future Improvements

Combined Result:

	GeV/c^2
Result	172.7
Stat.	1.7
JES	2.0
Sig. Model	0.9
Bkgd. Model	0.9
Multi-Interaction	0.3
Fit Method	0.3
MC Generator	0.2
Total Syst.	2.4
Total Error	2.9

- Syst. already dominates the uncertainty!
- Basic improvement by $\sim 1/\sqrt{\mathcal{L}}$
  - $\mathcal{L} \sim 1\text{fb}^{-1}$ in next Winter.
  - In-situ JES calibration is a powerful tool. It can be introduced to other L+jets analyses.
- Sig./Bkgd. Modeling (ISR/FSR/Q^2 dependence etc.) can be improved by using our own data.
- D0 Run II Dilepton measurement is coming soon.
- Measurements in All Hadronic mode (CDF/D0) are under development.

$Zb\bar{b}$

Trigger :

- 2 SVT track + 2 10GeV clusters.

Offline Cuts :

- N==2 jets w/ E_T>20GeV, $|\eta|$<1.5 (JetClu cone 0.7).
- Both jets are required to have secondary vertex tag.
- $\Delta\phi(j1,j2)$>3.0.
- $E_T^{3rd\text{-}jet}$<10GeV.