Alexander Golossanov
Fermilab
for CDF and $D0$ Collaborations

Combined Measurement of Top Quark Mass from Tevatron

November 01, 2006
DPF+JPS Meeting
Honolulu, Hawaii

1. The outline

1 Imortance of precise m_t value

2 Measuring m_t at the Tevatron

3 Single most precise m_t measurement to date

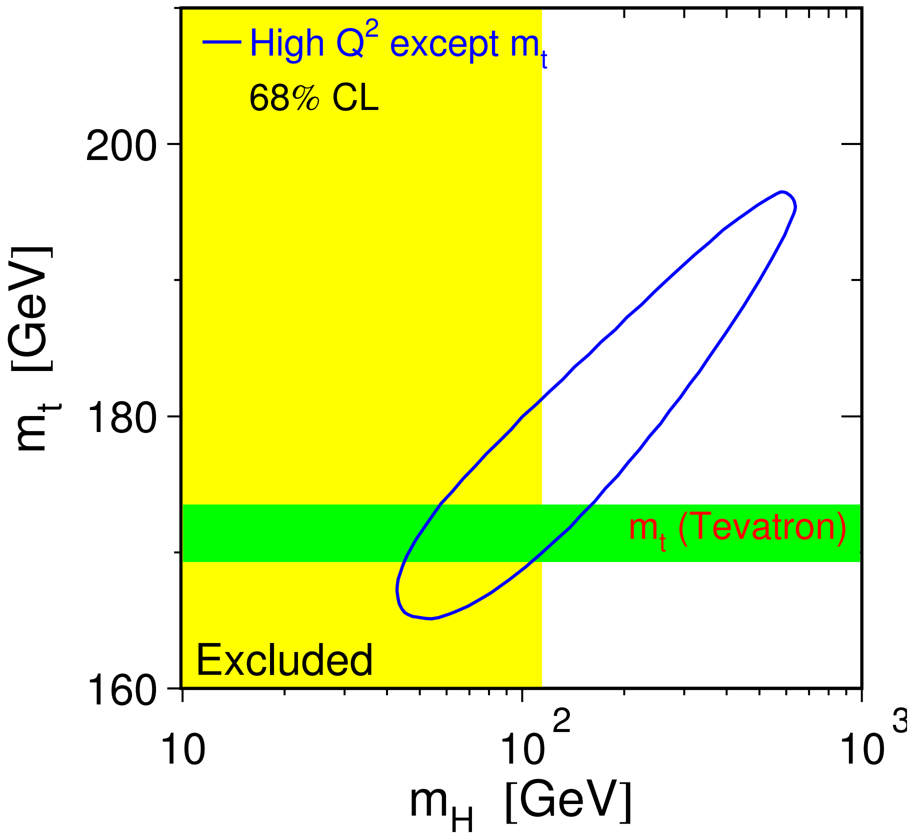
4 Combining 11 best m_t measurements

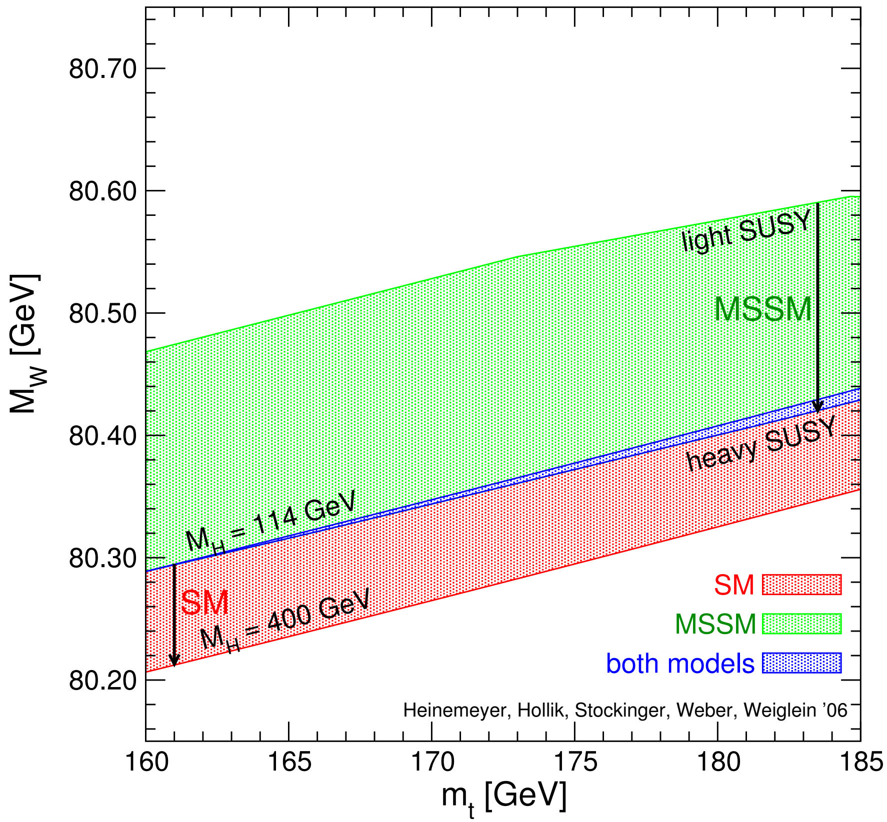
5 Results, conclusions and outlook

2. m_t is important detail of Standard Model and beyond

Higgs mass range is extremely sensitive to the m_t precision

$$m_W \approx a + b \cdot \left[\left(\frac{m_t}{172\,GeV} \right)^2 - 1 \right] - c \cdot ln \left(\frac{m_H}{100\,GeV} \right)$$

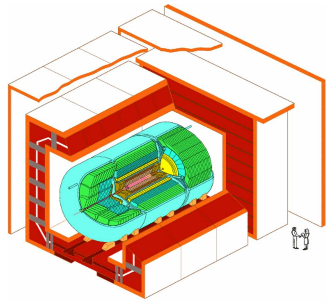


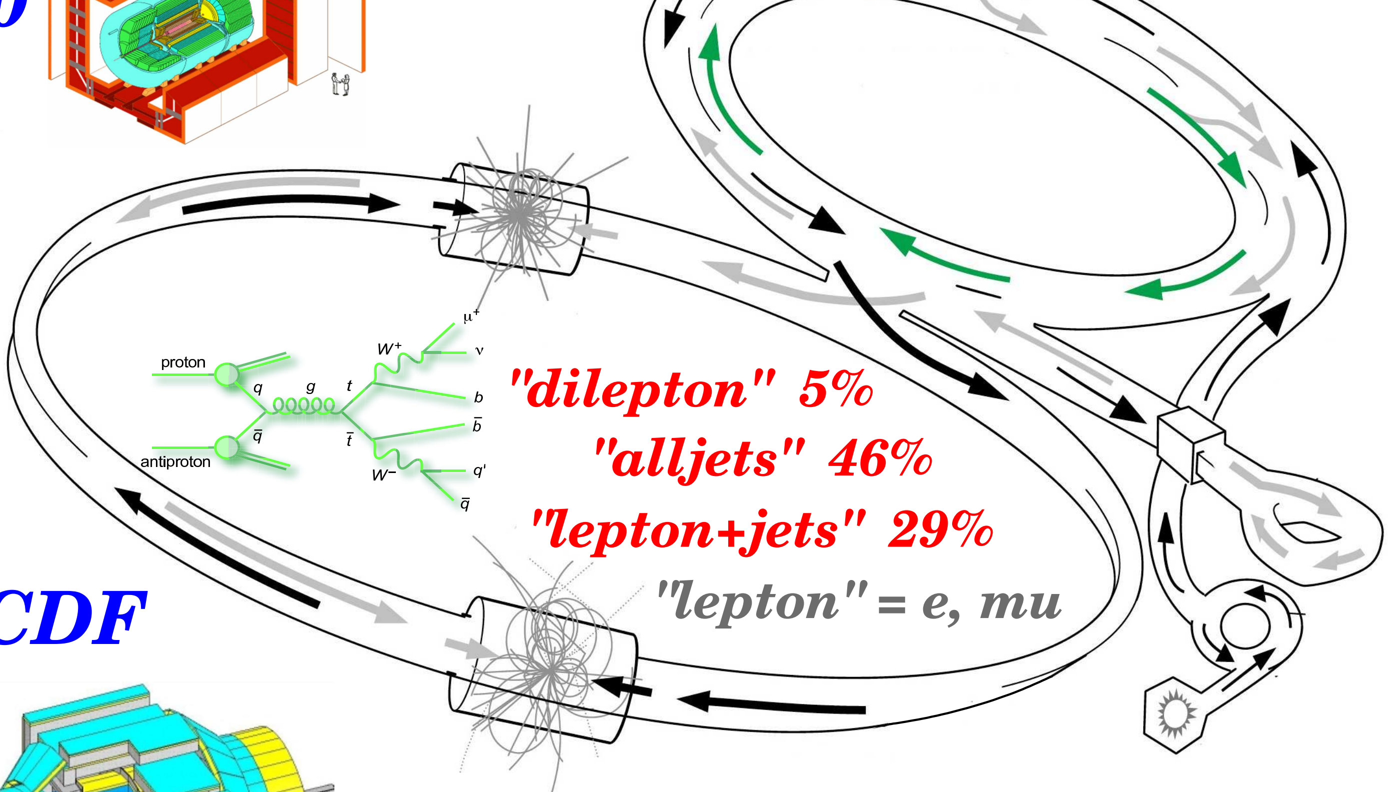


and so are SUSY models

3. Direct m_t measurements come only from Tevatron

D0





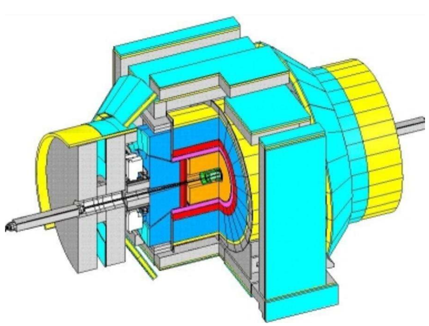
"dilepton" 5%

"alljets" 46%

"lepton+jets" 29%

"lepton" = e, mu

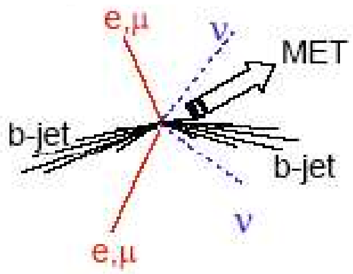
CDF

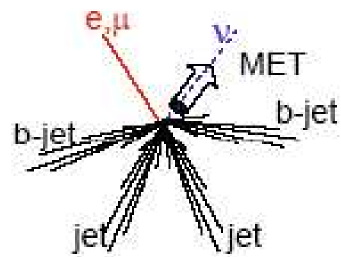


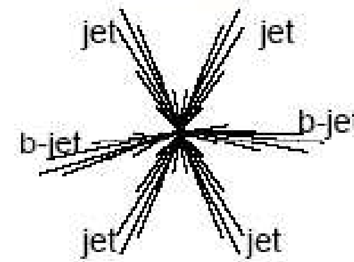
Run I 1992–1996 [100pb^{-1}/exp]

Run II 2001–... [1000pb^{-1}/exp ...so far]

4. Jet combinatorics and missing ν's complicate reco



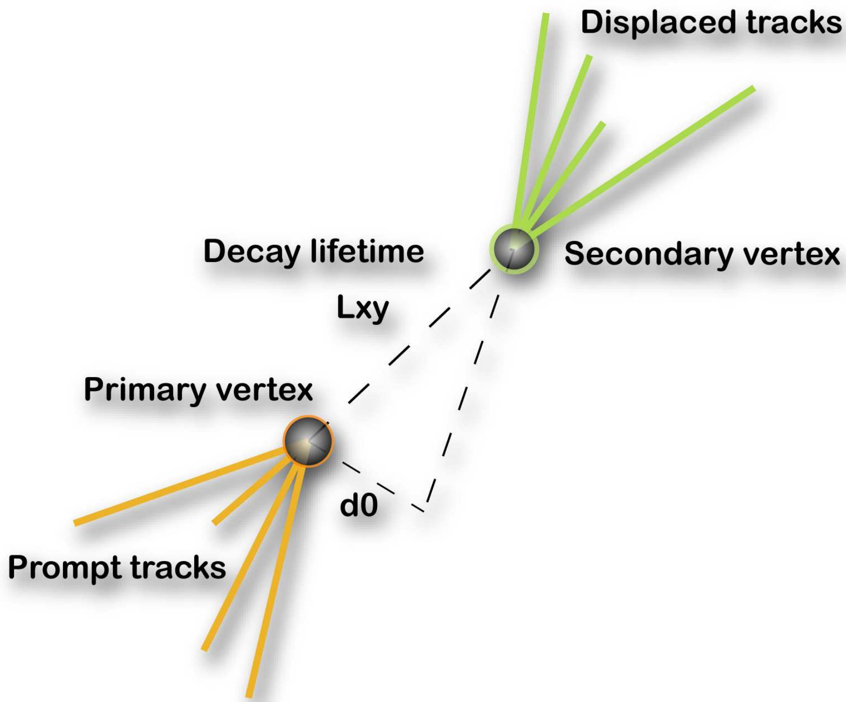


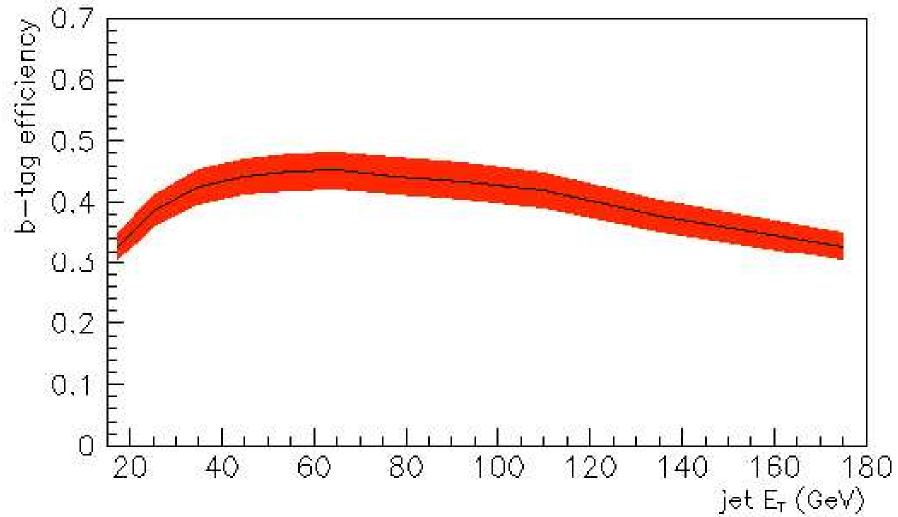


	dilepton	**lepton+jets**	alljets
combinations:	2	**12**	360
after b-jet ID:	2	**6**	90
missing nu's:	2	**1**	*none*

- ★ **many possible combinations when assigning jets to partons, but only one is correct**
- ★ **deduce escaping ν's from missing E_T [MET]**
- ★ **will focus on letpon+jets channel in this talk**
- ★ **b-quark ID helps reduce combinatorics and backgrounds...**

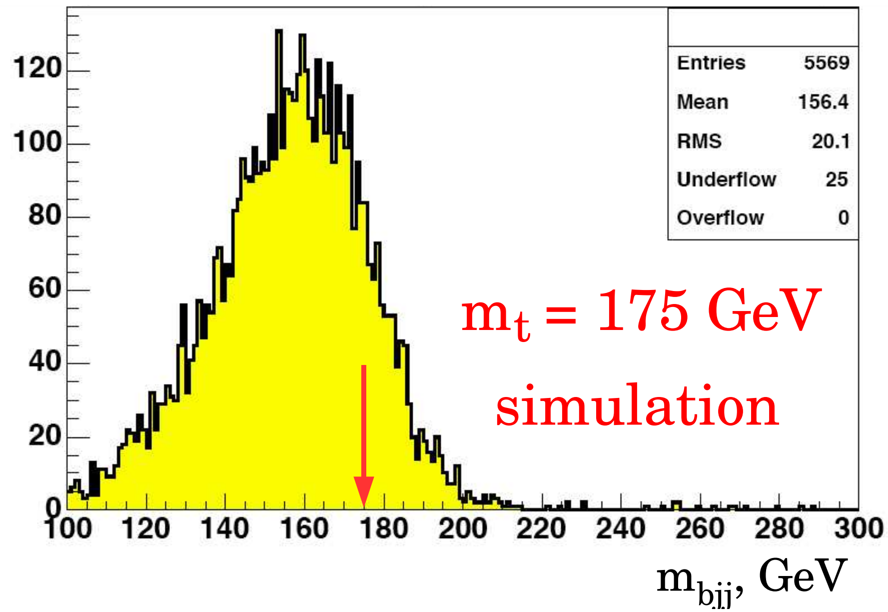
5. Lifetime of b-quark helps its identification

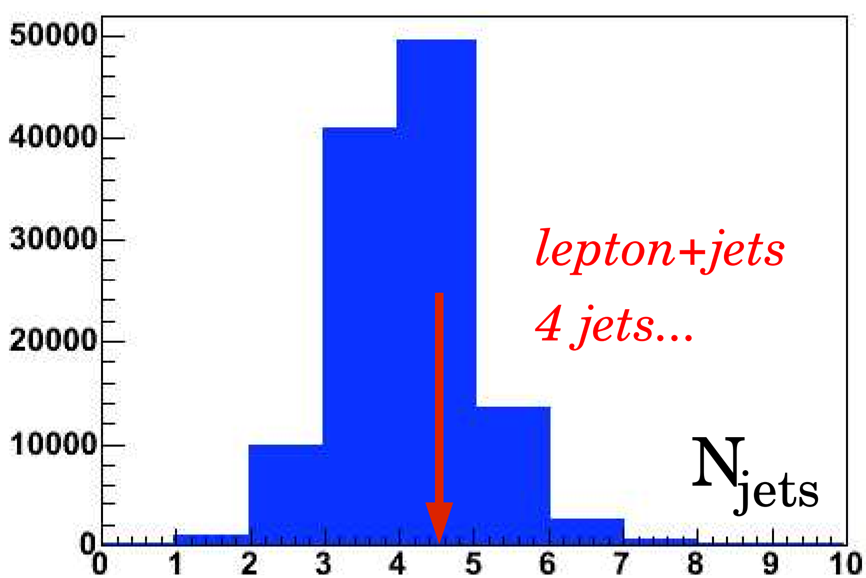




- ★ can reconstract secondary decay vertex from b-quark
- ★ significantly reduces combinatorial and other backgounds
- ★ improves overall m_t sensitivity

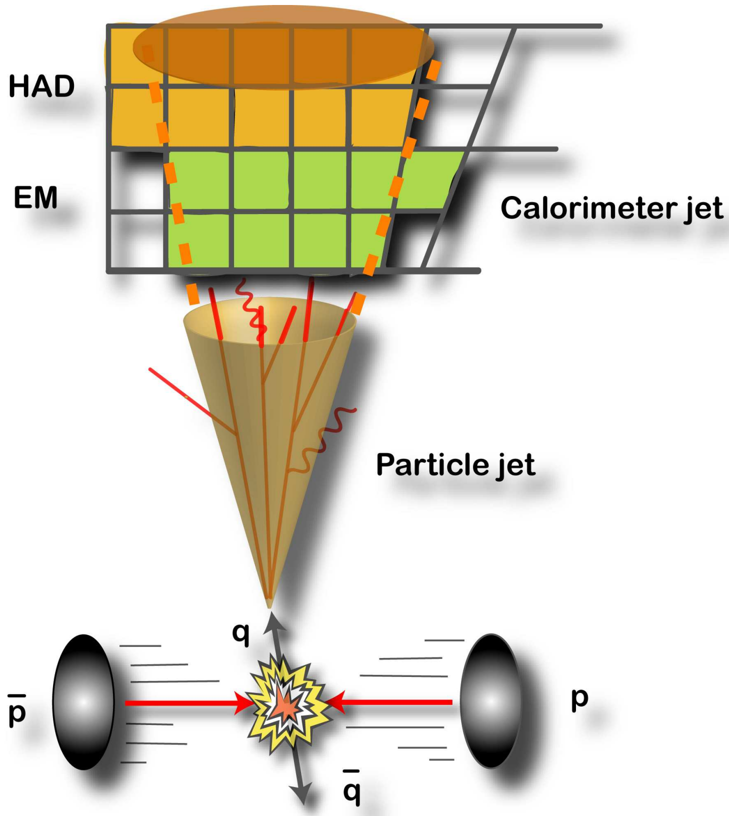
6. Measuring m_t at Tevatron is possible, but not easy

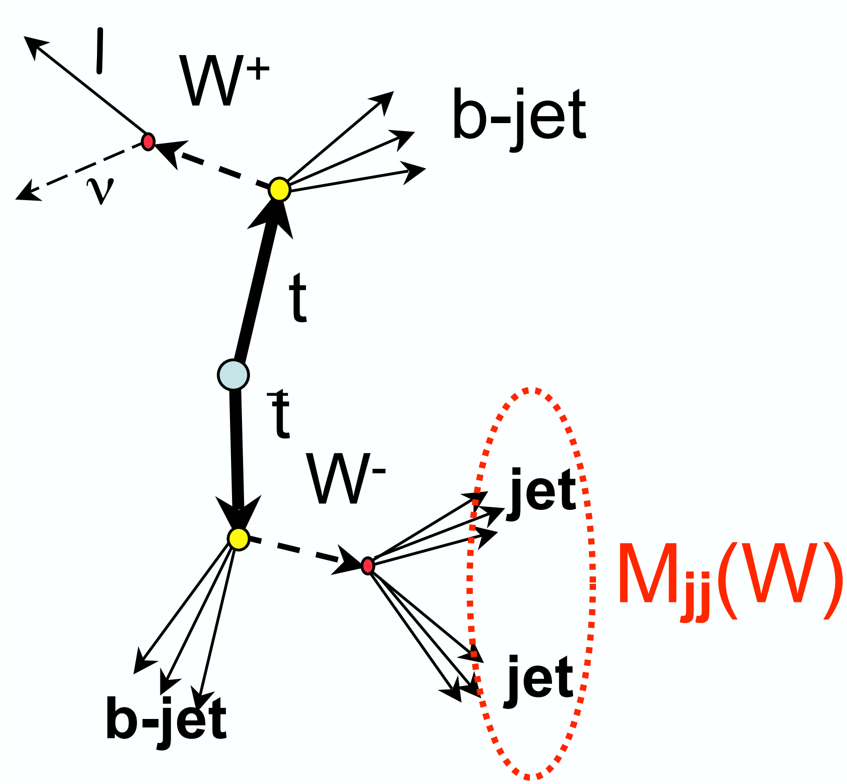




1. not just a calculation of trijet invariant mass
2. quarks turn into hadronic jets through complicated process
3. additional jets from gluon radiation
4. thus must have excellent energy corrections and good modeling of gluon radiation

7. Jet energy scale corrections and calibration





1 In order to obtain parton enrgies, multiple corrections applied to jet energies to account for instrumental, physical and reconstruction effects.

2 In situ $W \rightarrow jj$ calibration adds crucial correction and allows precision measurement of m_t . JES uncertainty now scales with statistics.

8. m_t measured in all channels using many methods

1 **Template.** For each event choose best reconstracted m_t using over-contrained **kinematic fit**. Obtain probability using MC templates for different hypophetical masses. Get m_t using **maximum likelihood fit**

2 **Matrix Element / Dynamic Likelihood**. Similar to a method originally suggested by Kunitaka Kondo *[J.Phys.Soc.Jpn***G62***:1177,1993]* and Dalitz and Goldstein *[PR***D45***:1531,1992, PL***B287***:225,1992]* and first used by Gaston Gutierez et al in $D0$ *[Nature***429***:638,2004]*. Probability for each event is calculated using **LO matrix element** for $t\bar{t}$ production and decay *[talks by P. Lujan and C. Garcia, plus more in this talk...]*

3 **Ideogram**. First used at LEP *[Eur.Phys.J.***C2***:581,1998]* for m_W measurement. Combines features of two methods above. Each event weighted with χ^2 probablity of kinematical fit and event probability

4 L_{xy}. Recently proposed by Chris Hill et al in CDF. **Lorentz boost** given to b-quark in top decay is proportional to m_t . Measuring transverse decay lenngh Ł$_{xy}$ of b-hadrons from top decay gives m_t

★ **Dilepton** assumes $\eta(\nu)$, $\phi(\nu)$, $p_z(\,t\bar{t}\,)$ to deal with 2 missing ν's *[talks by T. Maki, B. Jayatilaka and J. Temple]*. **Alljets** employs **neural network** to reduce huge background *[F. Margaroli's talk]*

9. Recap

1 Imortance of precise m_t value

2 Measuring m_t at the Tevatron

3 **Single most precise m_t measurement to date**

4 Combining 11 best m_t measurements

5 Results, conclusions and outlook

10. Comes from CDF matrix element technique analysis

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

$$P(x;M_{top},JES) = \frac{1}{\sigma}\int dq_1 dq_2 f(q_1) f(q_2) \quad d\sigma(y;M_{top}) \quad W(x,y,JES)$$

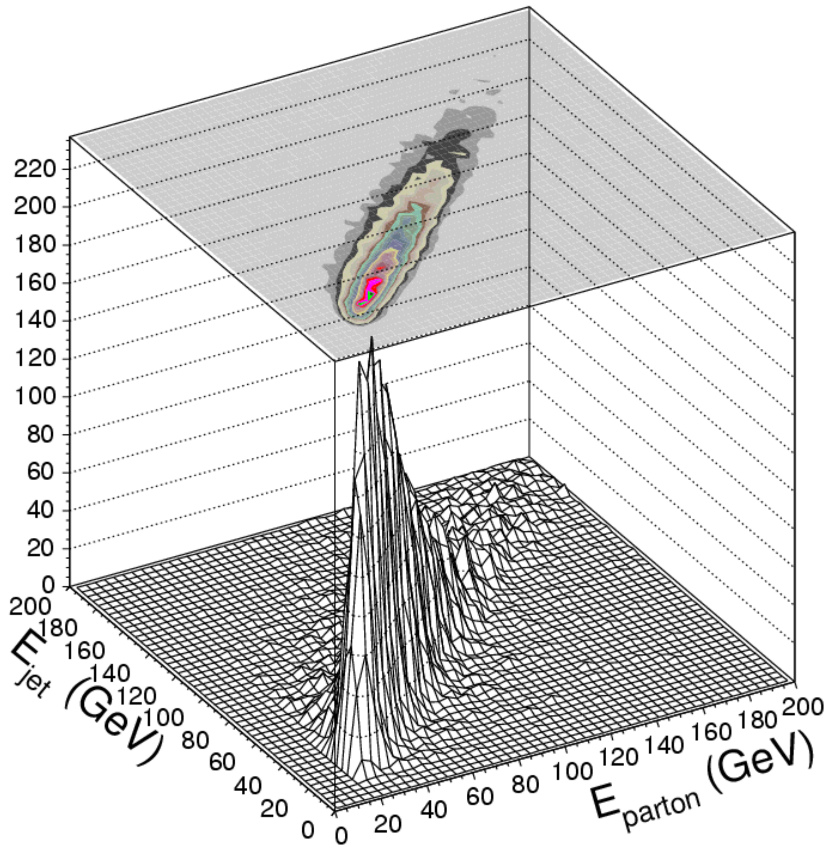
Differential cross section: LO ME (qq->tt) only

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

- JES is a free parameter, constrained in situ by mass of the W
- Background probability is similar, but no dependence on M_{top}

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

11. Transfer function



- Detector resolution modeled with "transfer functions" using Monte Carlo
- HERWIG/PYTHIA generation and parton showering
- GEANT detector simulation
- Probability of jet with energy E^{jet} originating from a parton with energy E^{parton}.

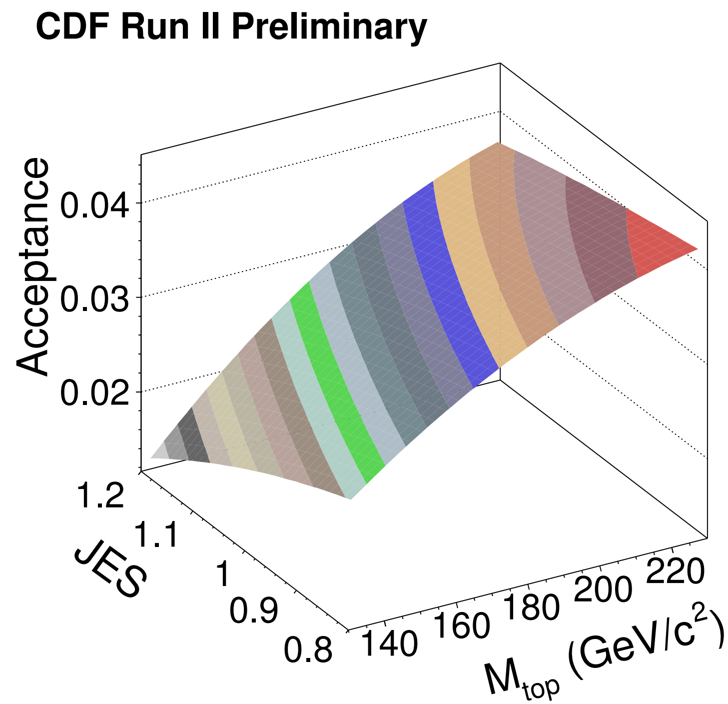
$$W_{jet}(\delta, E^{parton}) = \frac{1}{\sqrt{2\pi}p_2 + p_3 p_5}[\exp[\frac{-(\delta - p_1)^2}{2p_2}] + p_3\exp[\frac{-(\delta - p_4)^2}{2p_5}]]$$

$$\delta \equiv E^{parton} - E^{jet}, p_i = a_i + b_i E^{parton}$$

12. CDF lepton+jets signal selection and acceptance

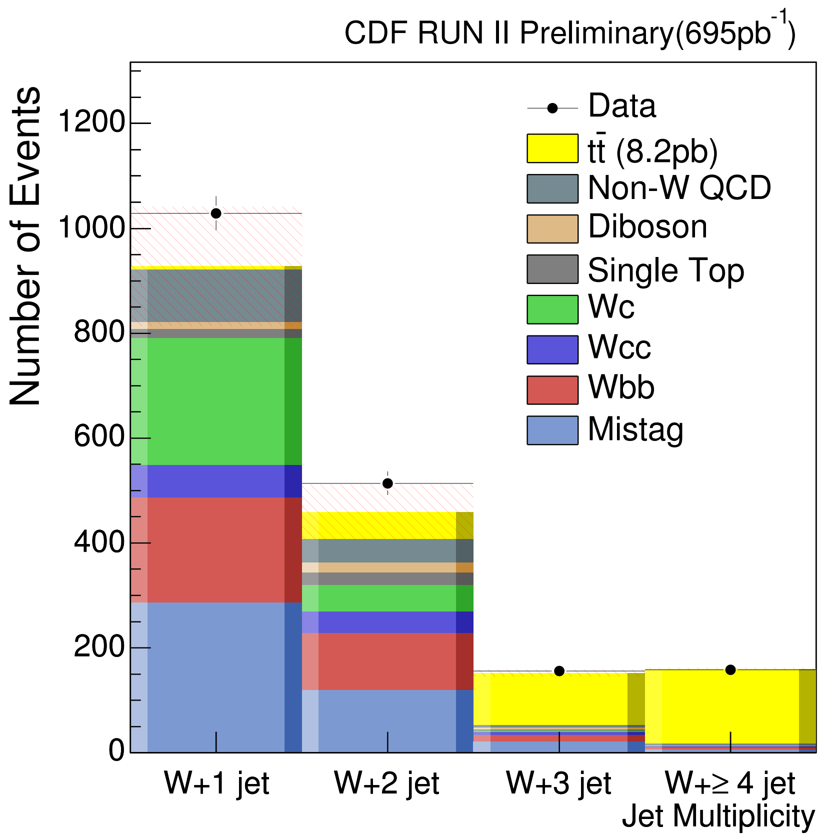
- ★ **lepton**: $E_T >$20 GeV (electron), $p_T >$20 GeV/c (μ)
- ★ **4 jets**: $E_T > 15$ GeV, $|\eta| < 2.0$
- ★ **missing E_T**: $\not{E}_T > 20$ GeV
- ★ **b-tag**: ≥ 1 from secondary vertex
- ★ **non-W veto**: $\Delta\phi < 0.5$ or $\Delta\phi > 2.5$ ($\not{E}_T < 30$ GeV)

[See E. Thomson's talk for selection details]



1. Relative to m_t =175 GeV and JES=1, acceptance varies by about $\pm 50\%$ over relevant range
2. Important to account for this when forming likelihood function
3. Used Pythia MC samples at 5 GeV intervals from 130-230 and interpolated between intermediate points

13. Backgounds are well understood and simulated

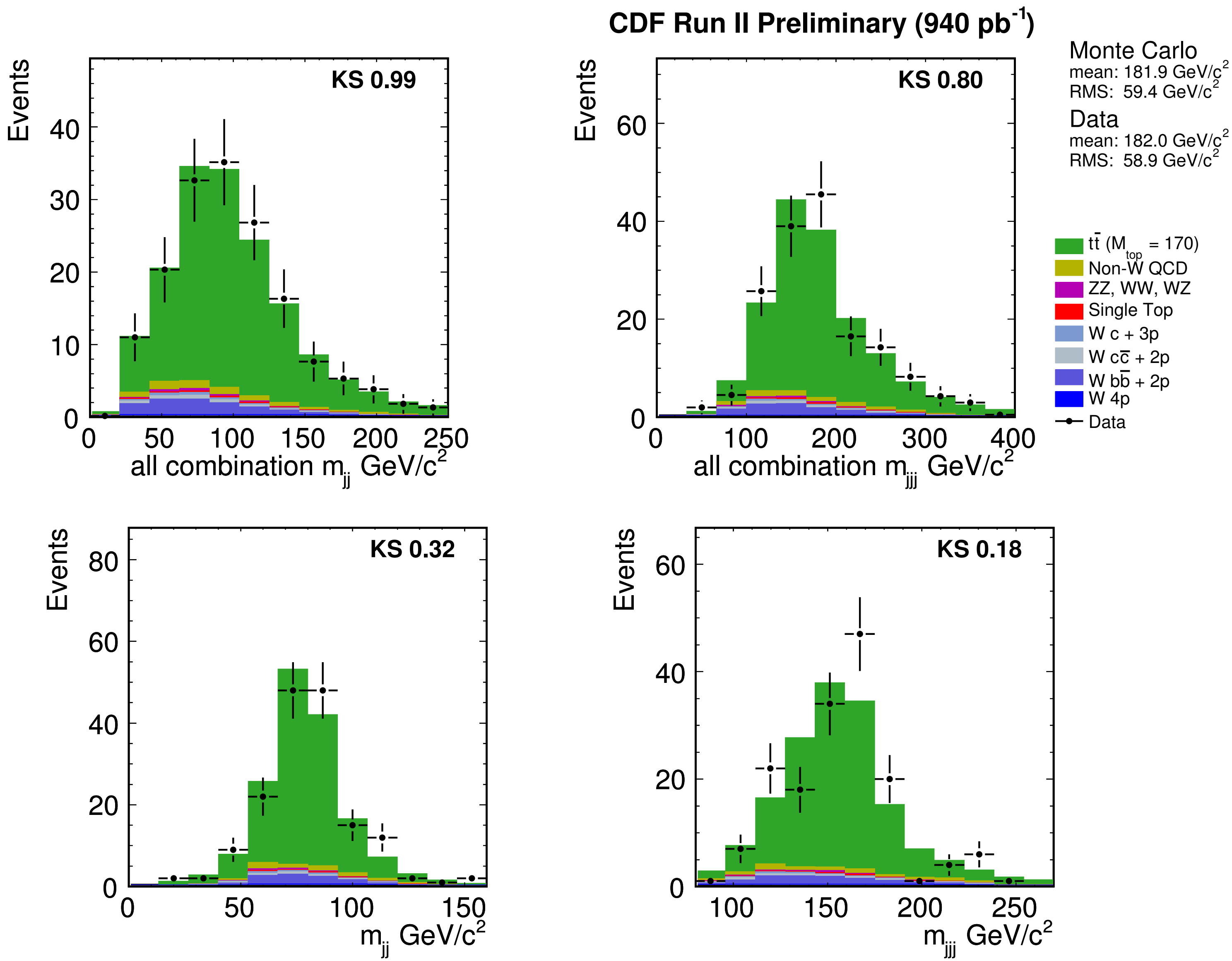


Sample	Expected Events
Background	
$W + 4p$ (Mistags)	6.06 ± 1.26
Non-W (QCD)	5.18 ± 2.57
$Wb\bar{b}$	4.62 ± 2.13
$Wc\bar{c}$	2.21 ± 1.05
Wc	1.38 ± 0.62
single top	1.12 ± 0.26
EW (WW,WZ,ZZ)	1.06 ± 0.23
Total Background	21.63 ± 8.12
Signal	
$t\bar{t}$ (8.0 pb)	142.81 ± 16.24
Observed	
Data	166

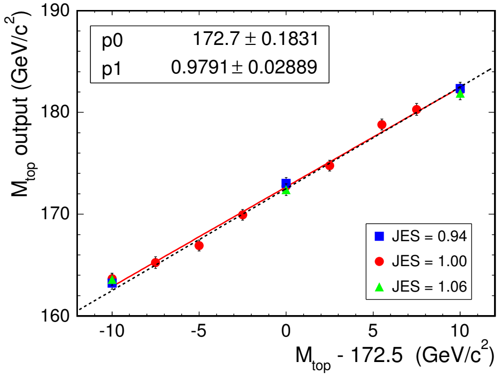
★ **Fractions were scaled from 695 pb^{-1} to 940 pb^{-1}**

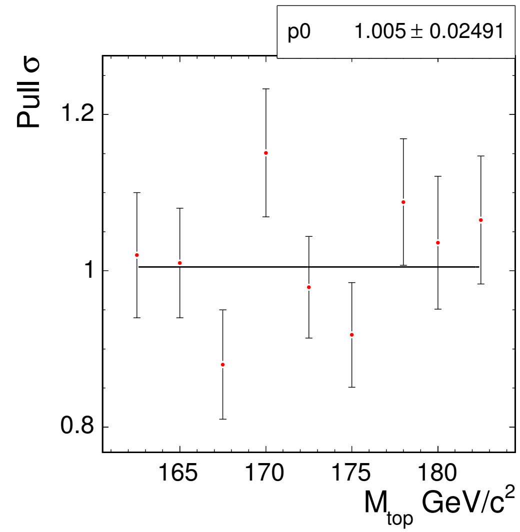
★ **Important for checking the method, but not used in m_t measurement**

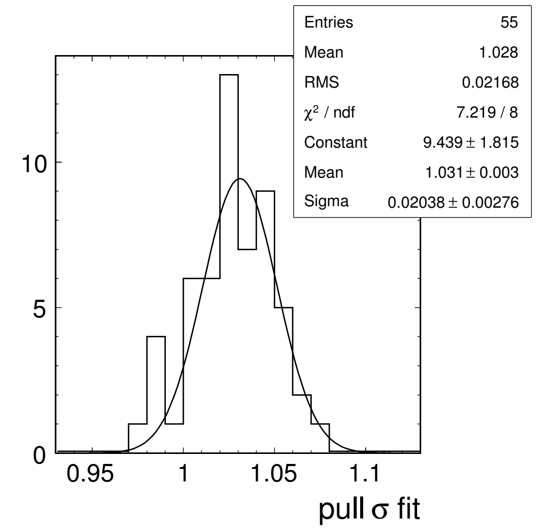
14. Data is well described by signal and background MC



15. Pseudo-experiments prove that ME method works well







★ **Pseudo-experiments were generated using signal and backgrouns MC mixed appropriately. This studies prove that:**

1. **estimator has no bias**
2. **method is consistent and robust**
3. **statistical uncertainty has Gaussian nature**

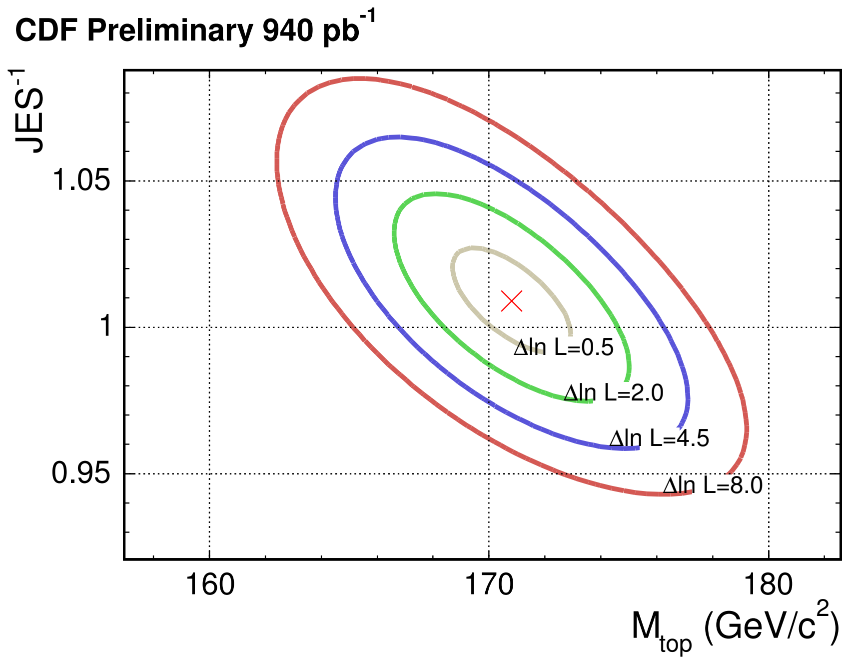
⇒ **can apply to data**

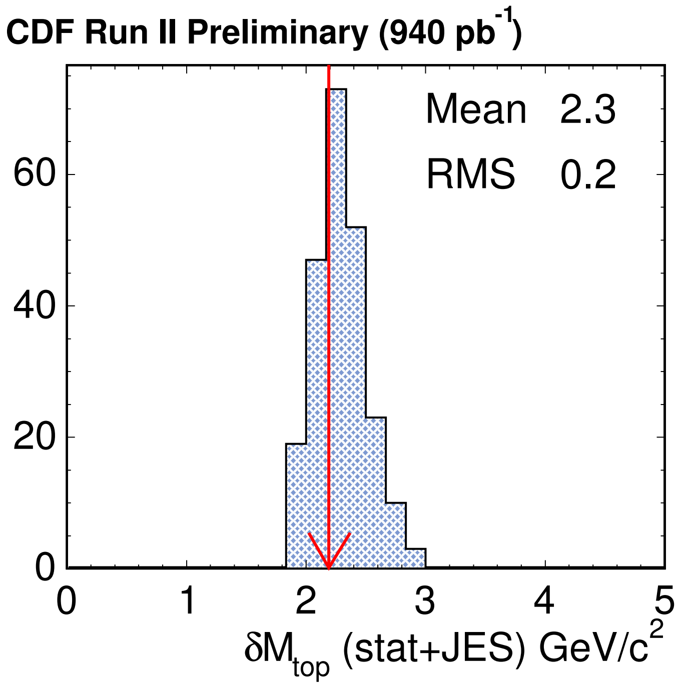
16. Maximum likelihood fit result

1 $m_t = 170.9 \pm 2.1(stat + \ JES\ )\ GeV^2/c^2$

$m_t = 170.9 \pm 1.6(stat)\ GeV^2/c^2$

2 $JES = 0.99 \pm 0.02(stat)$





17. Comlete m_t result and its systematic uncertainties

$$[170.9 \pm 2.1(stat + JES) \pm 1.4(syst)]\ GeV/c^2$$

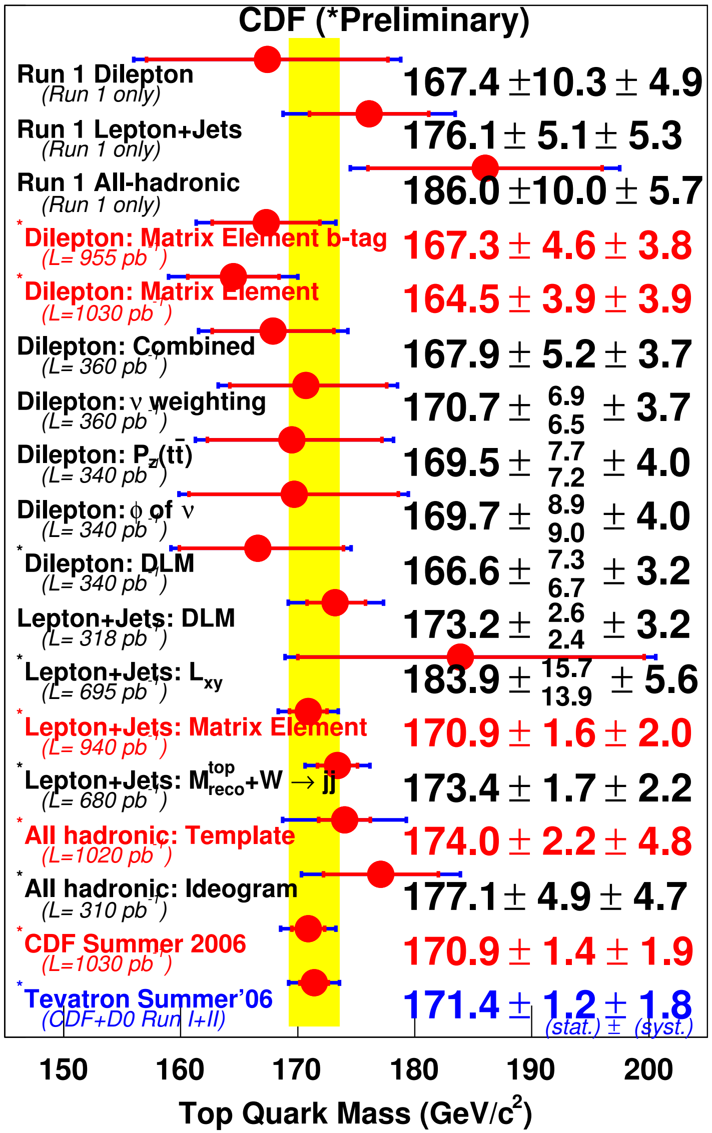
$$[170.9 \pm 1.6(stat) \pm 1.9(JES + syst)]\ GeV/c^2$$

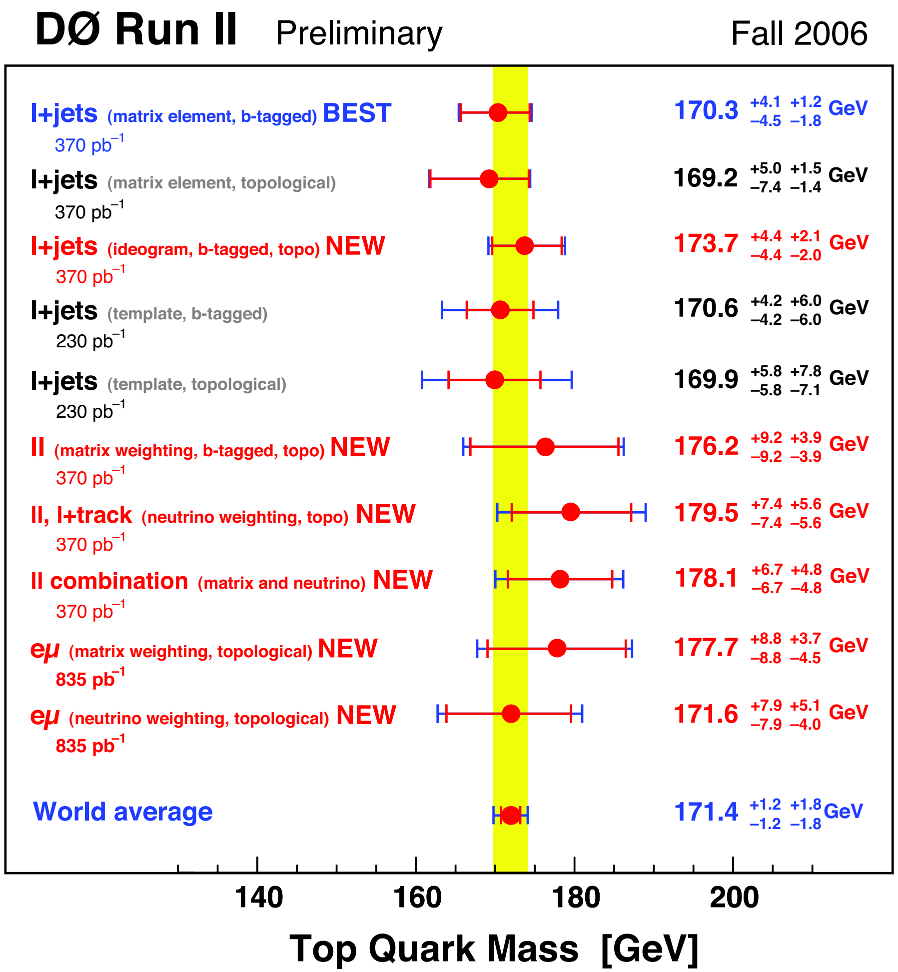
$$[170.9 \pm 2.5\ GeV/c^2]\ GeV/c^2$$

⇒ **Best single measurement in the world!**

Source of uncertainty	CDF Magnitude (GeV/c²)
b-JES	0.6
Signal (Initial and final state radiation, parton distribution functions)	1.1
Background (composition and shape)	0.2
Fit (Method, Monte Carlo statistics)	0.4
Monte Carlo (Modeling of ttbar)	0.2
Total	**1.4**

18. I showed the best, but one of many...

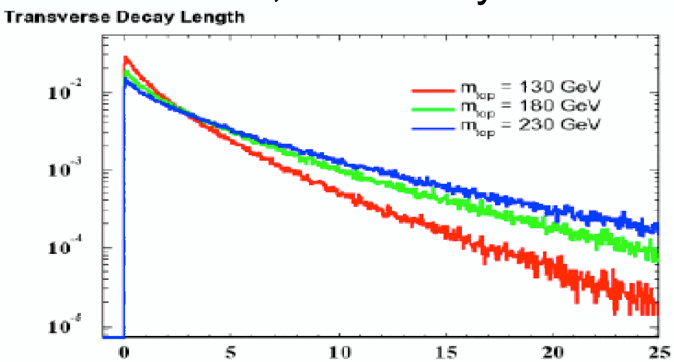


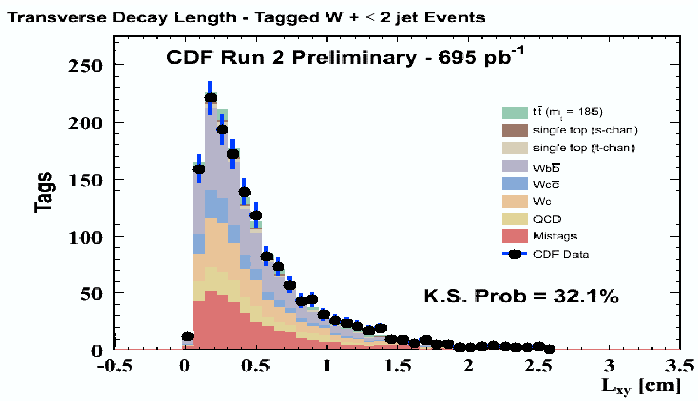


19. Example of original new method: L_{xy}

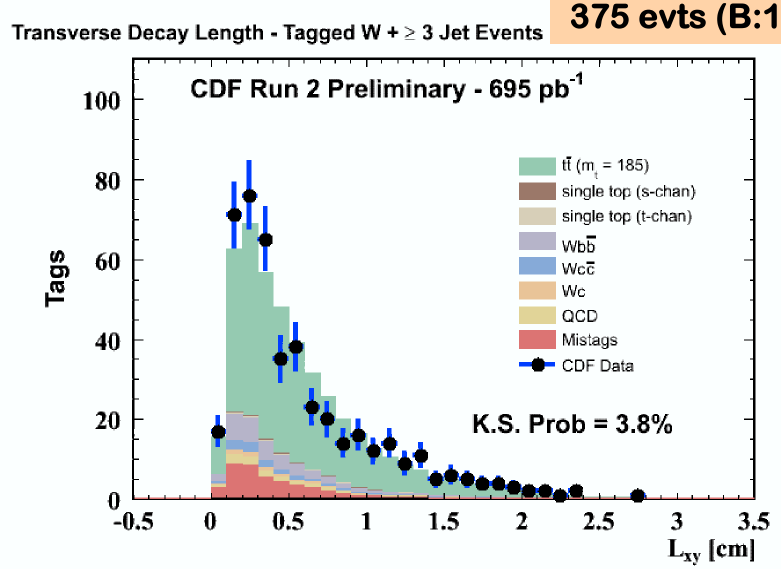
- Uses the average transverse decay length, Lxy of the b-hadrons
- B hadron decay length ∝ b-jet boost ∝ M_{top} (>=3jets)

PRD 71, 054029 by C. Hill *et al.*





375 evts (B:111)



$$M_{top} = 183.9^{+15.7}_{-13.9}\,(\text{stat}) \pm 0.3\,(JES) \pm 5.6\,(\text{syst})\ \text{GeV}/c^2$$

Insensitive to JES, but need Lxy simulation

Statistics limited, but can make big contributions at Run IIb, LHC

Recap

1 **Imortance of precise m_t value**

2 **Measuring m_t at the Tevatron**

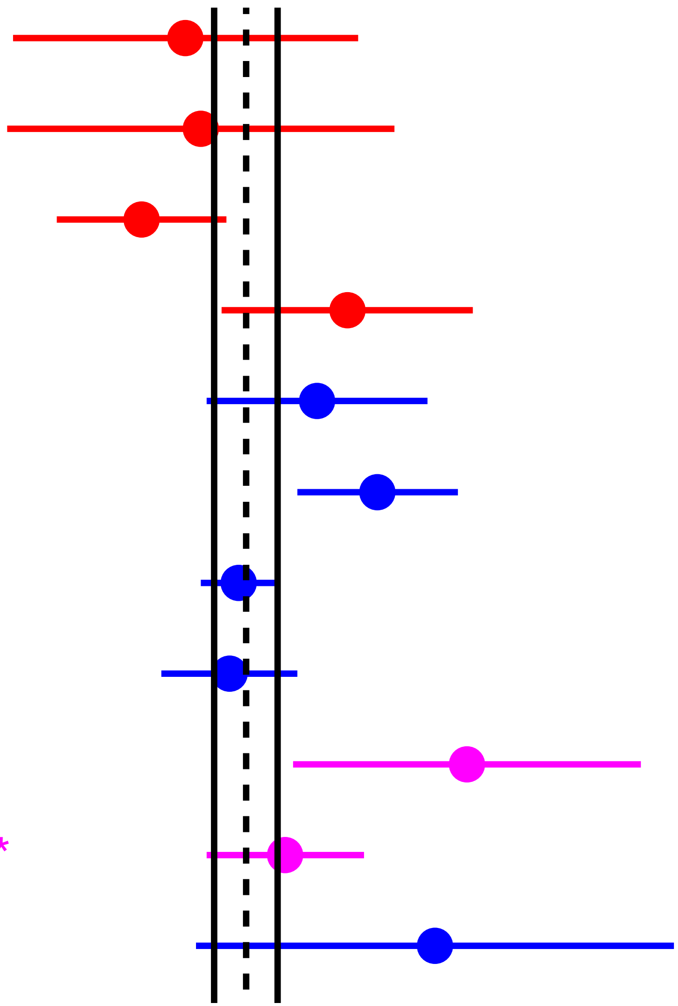
3 **Single most precise m_t measurement to date**

4 **Combining 11 best m_t measurements**

5 **Results, conclusions and outlook**

21. Combine measurements to reduce σ_{m_t}

Measurement	M_{top} [GeV/c^2]	
CDF-I di-l	167.4 ± 11.4	
DØ-I di-l	168.4 ± 12.8	
CDF-II di-l*	164.5 ± 5.6	★ **Bo Jayatilaka's talk**
DØ-II di-l*	178.1 ± 8.3	★ **Jeffrey Temple's talk**
CDF-I l+j	176.1 ± 7.3	
DØ-I l+j	180.1 ± 5.3	
CDF-II l+j*	170.9 ± 2.5	★ **this talk**
DØ-II l+j*	170.3 ± 4.5	★ **Carlos Garcia's talk**
CDF-I all-j	186.0 ± 11.5	
CDF-II all-j*	174.0 ± 5.2	★ **Fabrizio Margaroli's talk**
CDF-II lxy*	183.9 ± 15.8	



[see arXiv:hep-ex/0608032 for details]

22. Combination method

- Best Linear Unbiased Estimator (BLUE)
  - L.Lyons, *et al*., NIM A270 (1988) 110.
  - A.Valassi, *et al*., NIM A500 (2003) 391.
- Returns a weighted average, including breakdown of uncertainties by input category
- Results cross-checked with a MINUIT χ^2 – minimization
- Was used for final (CDF+D0) Run-I average and all world averages since then

23. Must decide on error categories

★ **Jet energy scale:**

- **aJES**: $D0$ Run II e/h calibration
- **bJES**: JES uncertainties specific to b-jets
- **cJES**: fragmentation and OOC showering
- **dJES**: correlated within experiment but not between RunI&II
- **iJES**: in-situ calibration from Wjj
- **rJES**: remaining JES

★ **Signal**: signal modeling (ISR, FSR, PDF)

★ **Bgd**: background normalizatin and shape

★ **UN/MI**: $D0$ Run I uranium noise and MI

★ **Fit**: fit method, finite MC sample size

★ **MC**: Pythia vs Herwig (vs ISAJET)

★ **Statistical**: limited data size

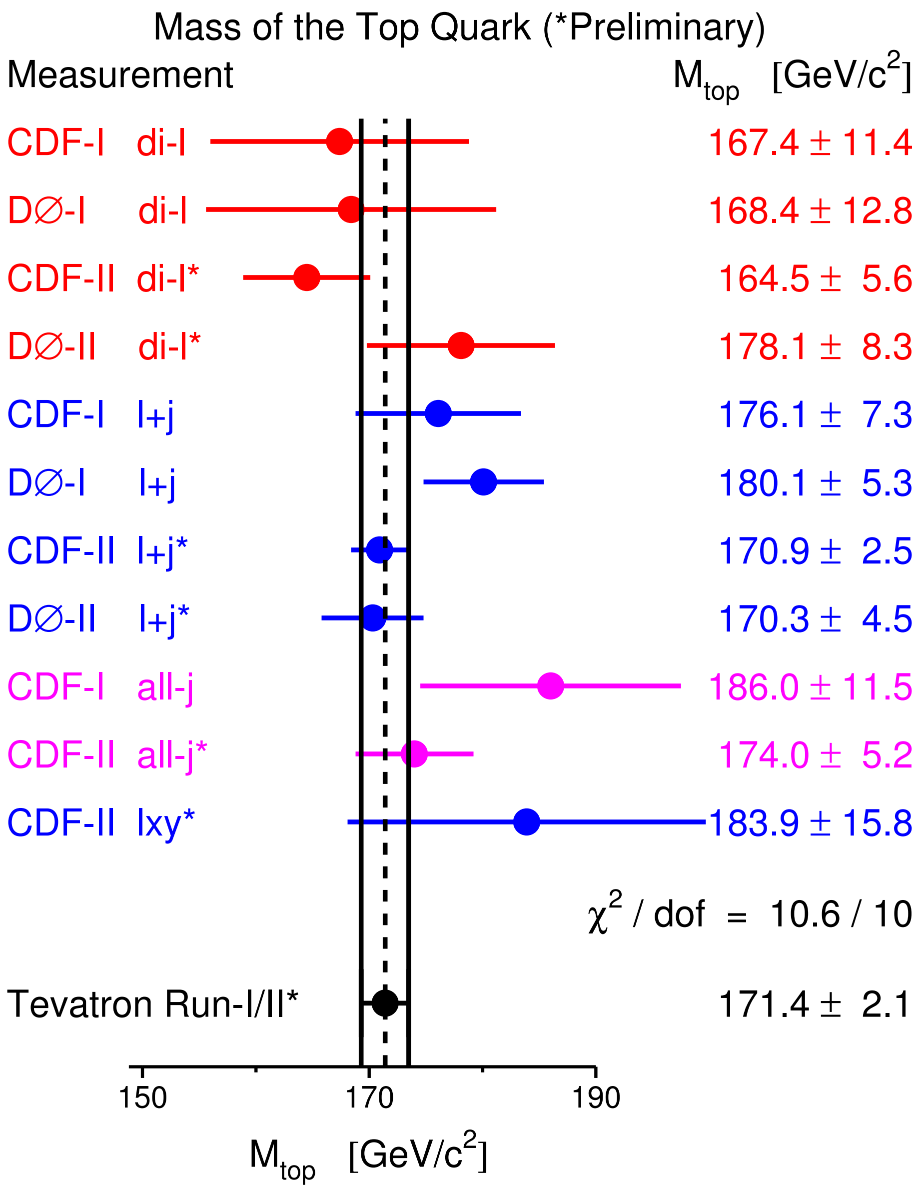
24. All uncertainties were carefully categorized

	Run-I published					Run-II preliminary					
	CDF			DØ		CDF				DØ	
	all-j	l+j	di-l	l+j	di-l	l+j	di-l	all-j	lxy	l+j	di-l
Lumi (pb^{-1})	110	105	110	125	125	955	1030	1020	695	370	370
Result	186.0	176.1	167.4	180.1	168.4	170.9	164.5	174.0	183.9	170.3	178.1
iJES	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	0.0
aJES	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.5
bJES	0.6	0.6	0.8	0.7	0.7	0.6	0.6	0.5	0.0	0.6	1.4
cJES	3.0	2.7	2.6	2.0	2.0	0.0	2.8	3.1	0.0	0.0	0.0
dJES	0.3	0.7	0.6	0.0	0.0	0.2	1.6	0.8	0.0	3.5	3.8
rJES	4.0	3.4	2.7	2.5	1.1	0.0	1.3	3.0	0.3	0.0	0.0
Signal	1.8	2.6	2.8	1.1	1.8	1.1	0.9	0.9	1.4	0.5	1.7
BG	1.7	1.3	0.3	1.0	1.1	0.2	0.7	0.7	2.3	0.5	1.0
Fit	0.6	0.0	0.7	0.6	1.1	0.4	0.9	0.0	4.8	0.5	0.9
MC	0.8	0.1	0.6	0.0	0.0	0.2	0.9	1.0	0.7	0.0	0.0
UN/MI	0.0	0.0	0.0	1.3	1.3	0.0	0.0	0.0	0.0	0.0	0.0
Syst.	5.7	5.3	4.9	3.9	3.6	1.9	3.9	4.7	5.6	3.8	4.8
Stat.	10.0	5.1	10.3	3.6	12.3	1.6	3.9	2.2	14.8	2.5	6.7
Total	11.5	7.3	11.4	5.3	12.8	2.5	5.6	5.2	15.8	4.5	8.3

25. Must decide on correlations

- Uncorrelated: Stat, Fit, iJES
- Correlated across all inputs
  - in same run: dJES
  - in same channel: Bgd
  - everywhere: Signal, bJES, cJES, rJES, MC
- Correlation taken to be 0 or 100%
  - Variations considered as part of cross-checks

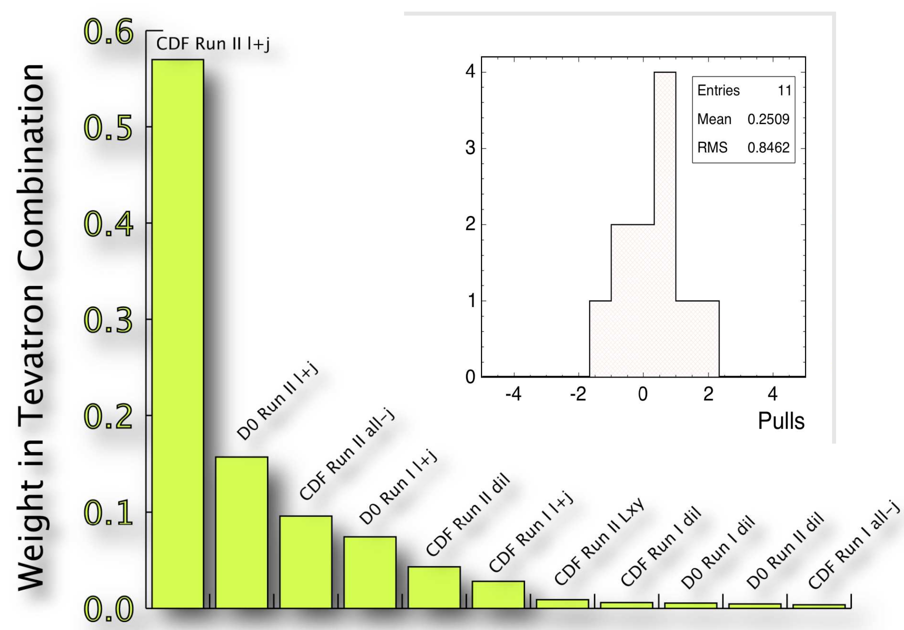
26. Combination result



1 **Measurements are consistant**
$\chi^2/\text{dof} = 10.6/10 \Rightarrow (39\%)$

2 **CDF RunII uses** $700 - 1000\ pb^{-1}$

3 **D0 Run II uses** $380\ pb^{-1}$



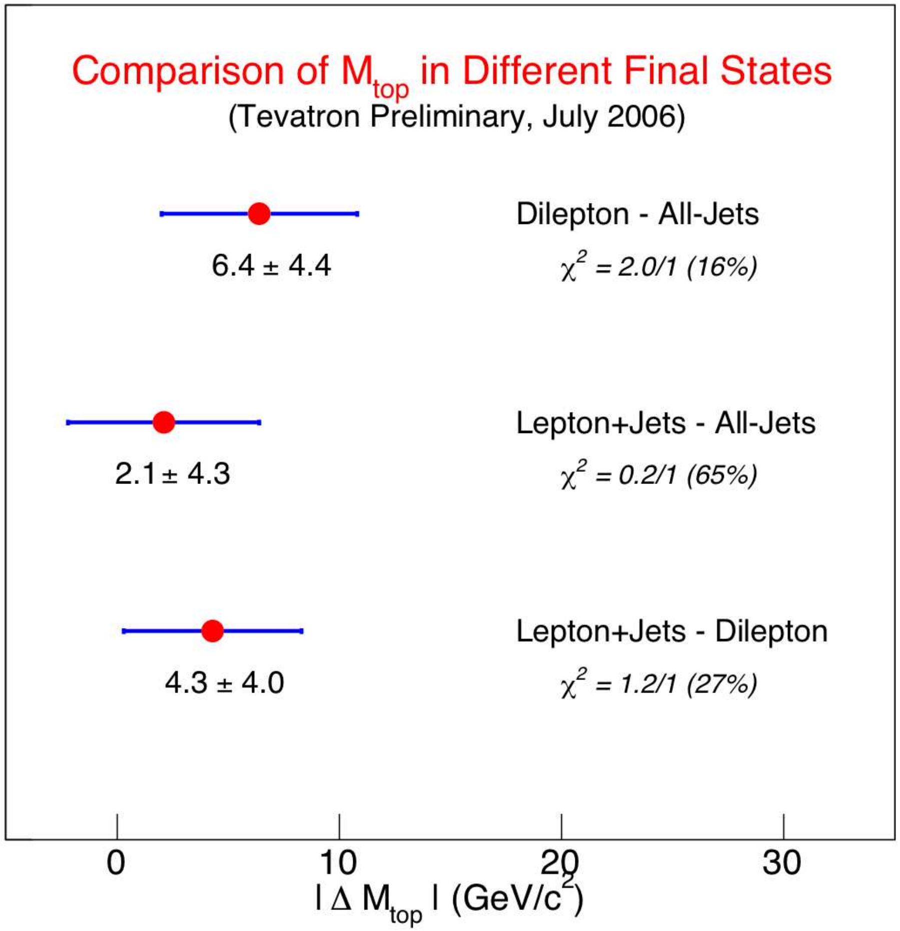
27. Cross Checks

- Repeated combination with these variations
  - Used each extreme of asymmetric stat uncertainty
  - Varied ρ(LJT-Lxy) by +/- 5% for their stat errors
  - Varied correlations among all inputs by 10% for bJES, cJES, rJES, Signal, MC, and Bgd simultaneously
  - Varied treatment of Run I uncertainties

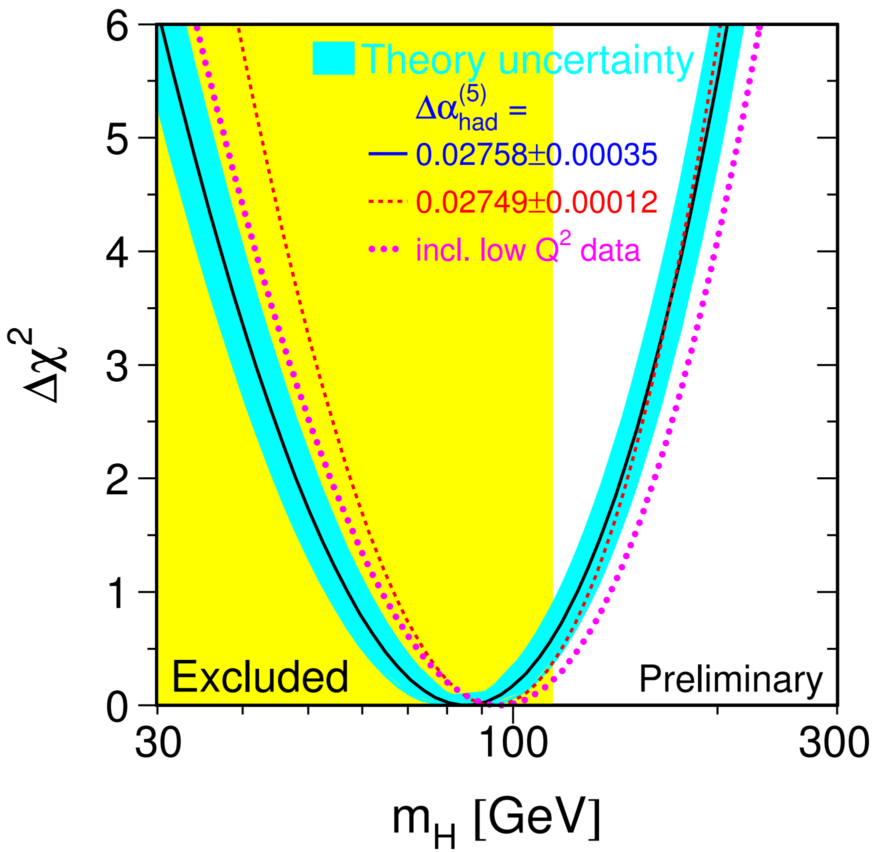
- Central value and total uncertainty both affected by <100 MeV/c^2 level in all cases

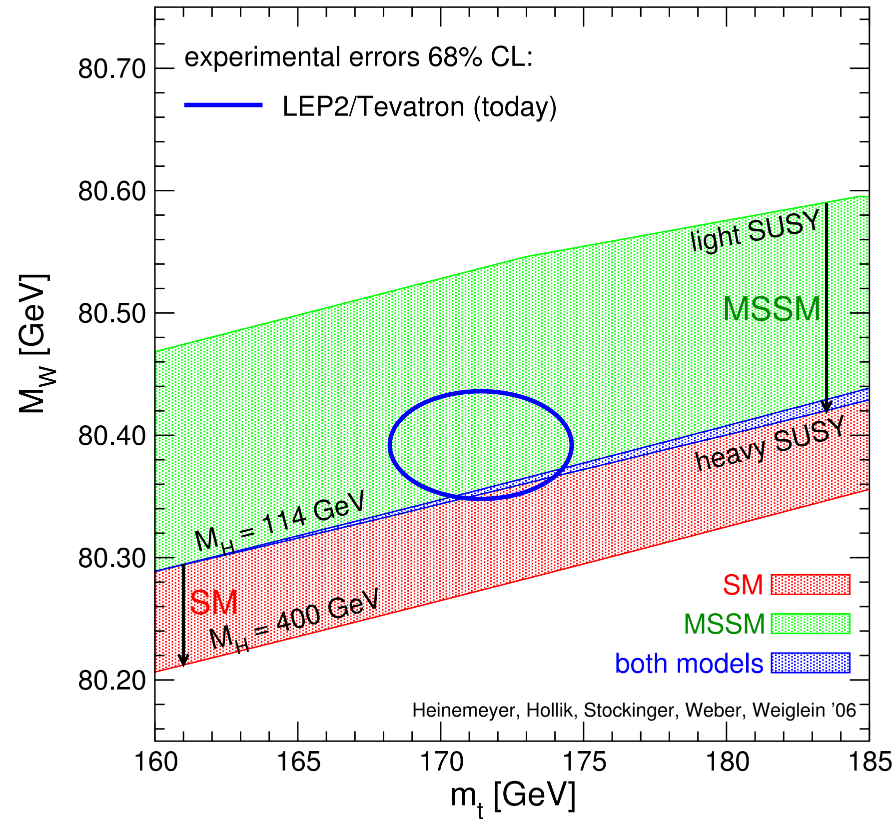
28. Results are consistant among the channels

Parameter	Value (GeV/c^2)	Correlations		
M_t^{all-j}	173.4 ± 4.3	1.00		
M_t^{l+j}	171.3 ± 2.2	0.29	1.00	
M_t^{di-l}	167.0 ± 4.3	0.46	0.37	1.00



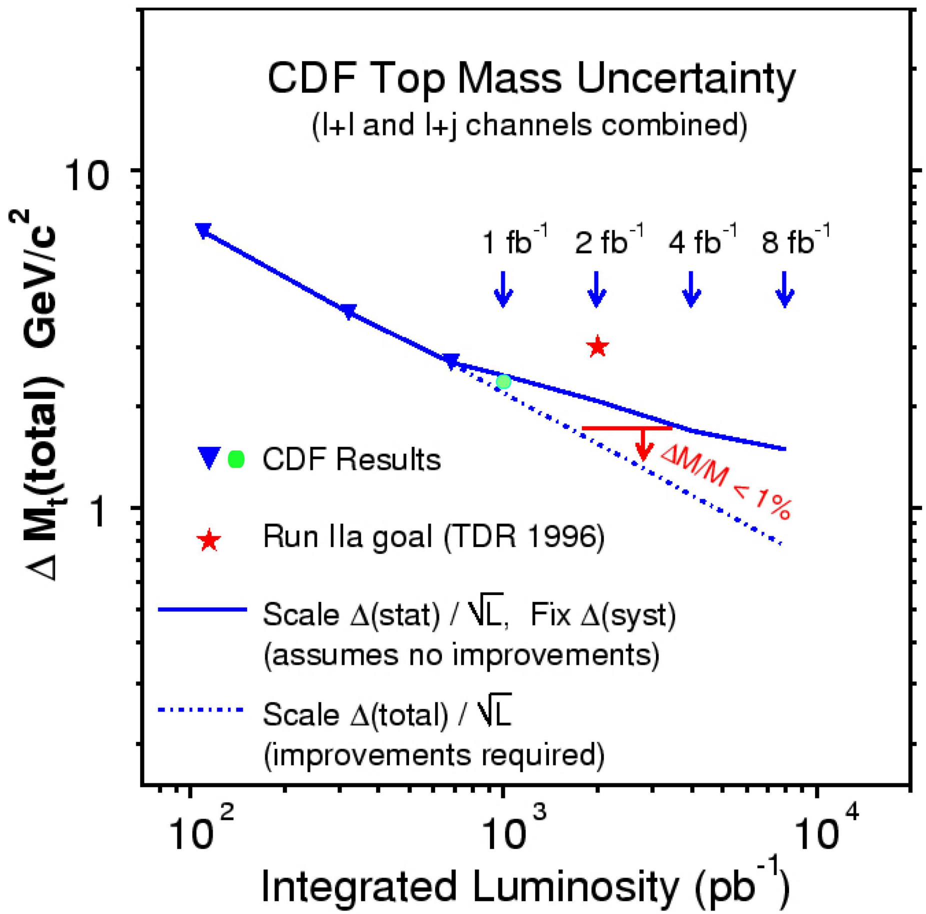
29. $m_t = 171.4 \pm 2.1\ GeV^2/c^2$: lighter Higgs and SUSY





$$
\begin{aligned}
m_H &= 85^{+39}_{-28}\ GeV/c^2\ (68\%\ CL) \\
&< 166\ GeV/c^2\ (\text{one sided } 95\%\ CL) \\
&< 199\ GeV/c^2\ (95\%\ CL,\ \text{if LEP2 limit of } 114\ GeV \text{ included}) \qquad (1)
\end{aligned}
$$

30. Bright prospects for m_t ...



1 New combined result exceeds Run II TDR goal already!

2 Adding JES to alljets may result in sensetivity comparable to leptop+jets

3 Tevatron perfomance and combination of results from CDF and $D0$ will reduce uncertainty even further

4 Tevatron Run II result is expected to achieve unceraínty of about 1 GeV

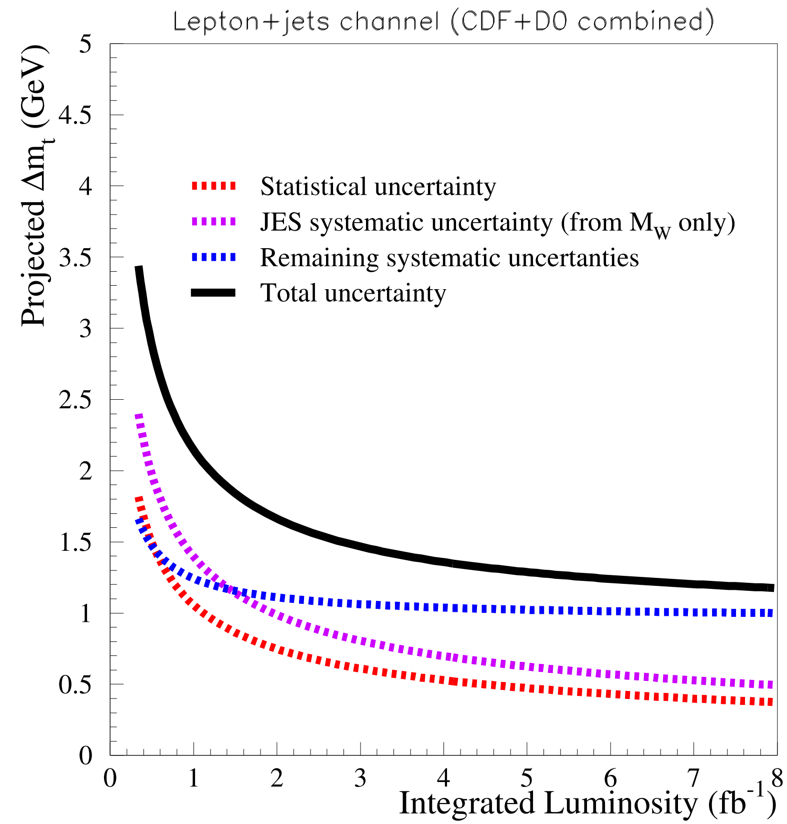
31. ... but improvements are required

The Fit (all quantities in GeV/c^2)

- JES: 1.4
  - iJES: 0.9
  - aJES: 0.2
  - bJES: 0.6
  - cJES: 0.5
  - dJES: 0.7
  - rJES: 0.3
- Signal : 0.9
- Bgd: 0.3
- Fit: 0.3
- MC: 0.3
- UN/MI: 0.1

- Total Systematic: 1.7
- Statistical: 1.2

- Total: 2.1



1 **Will have to improve understanding of systematic uncertainties**

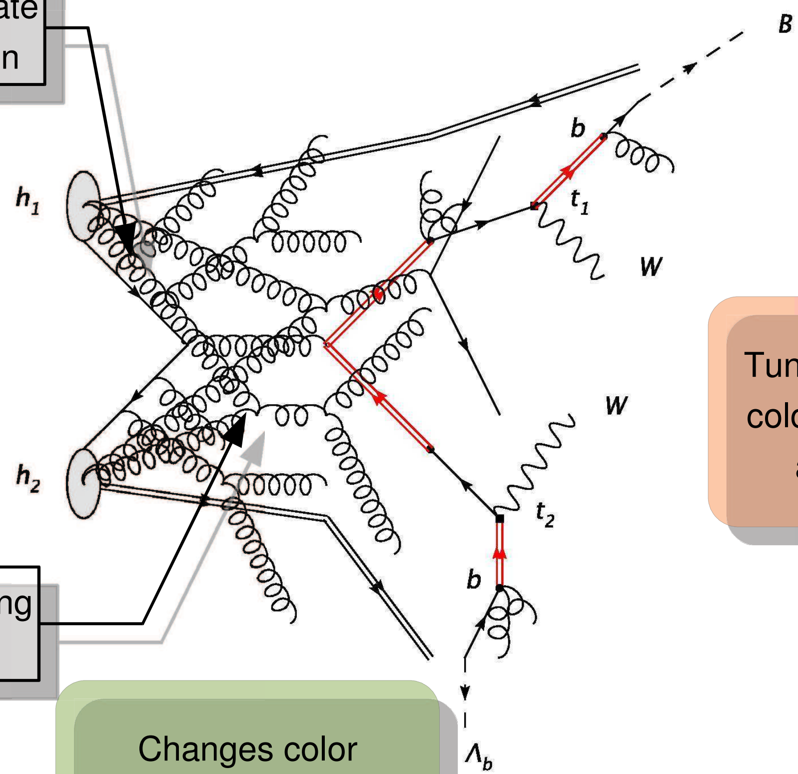
2 **Similar to m_W measurement at LEP 2**

3 **Real precision measurement at hadron collider!**

32. How large are these QCD effects?

Initial State radiation

Causes confusion in top mass reconstruction



Tune A showed that color re-connections are important

Underlying Event

Changes color connections, hence fragmentation

33. Summary and outlook:

1 New world average combines Tevatron Run I and best recent Run II measurements with up to 1 fb^{-1} of data [σ_{m_t} / m_t $\approx 1.2\%$!]

$$m_t = 171.4 \pm 2.1 \; GeV^2/c^2$$

2 New single most accurate measurement from CDF dominates the world average

$$m_t = 170.9 \pm 2.5 \; GeV^2/c^2$$

3 Expect to approach $\sigma_{m_t} \sim 1 \; GeV$ in combined precision if Tevatron provides more data and physicists improve their understanding of systematics: *challenging even at LHC!*

4 New m_t and m_W values hint lighter Standard Model Higgs...
and lighter Higgs is easier to find at Tevatron!

$$\Rightarrow \; m_H^{SM} = 85^{+39}_{-28} \; GeV/c^2$$