Top Mass at the Tevatron

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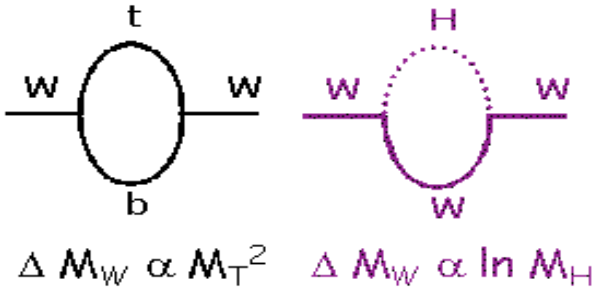
On behalf of the D0 and CDF Collaborations

HCP 2006 at Duke, May 22-26, 2006

Why do we care about Top Mass?

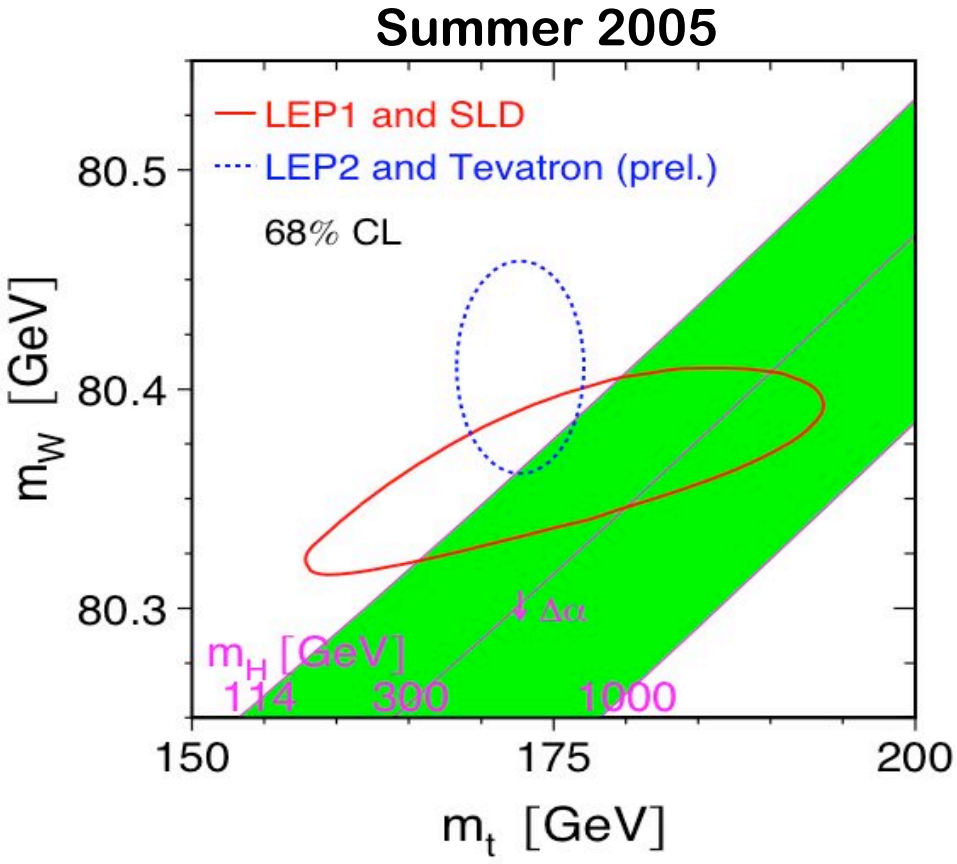
- Top mass is a fundamental SM parameter

  - important in radiative corrections:



$\Delta M_W \propto M_T^2$ $\Delta M_W \propto \ln M_H$

  - Yukawa coupling ~1

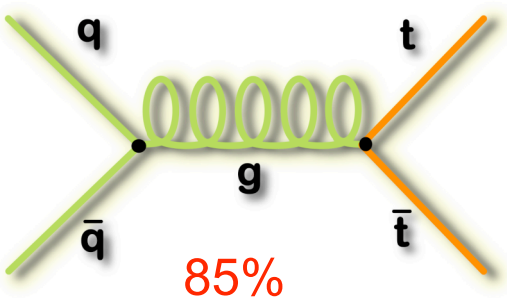


- Consistency check of SM, and it constrains M_{Higgs} with M_w and other electroweak precision measurements

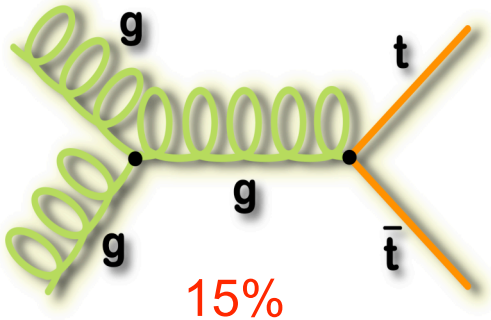
- A key to understand electroweak symmetry breaking?
- Constraint on SUSY models

Top Production and Decay

- At the Tevatron, mainly primarily produced in pairs (σ~7pb) via strong interaction.



85%

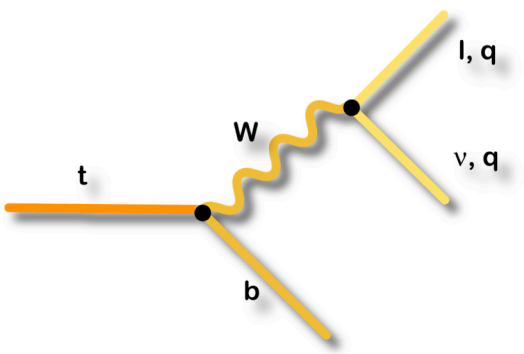


15%

LHC (90%)

~100σ

- Top decays as free quark due to large mass (τ_{top} ~ 4 x 10^{-25} s)



- Dilepton (5%, small bkgds)

  2 leptons(e/μ), 2 b jets, missing E_T (2νs)

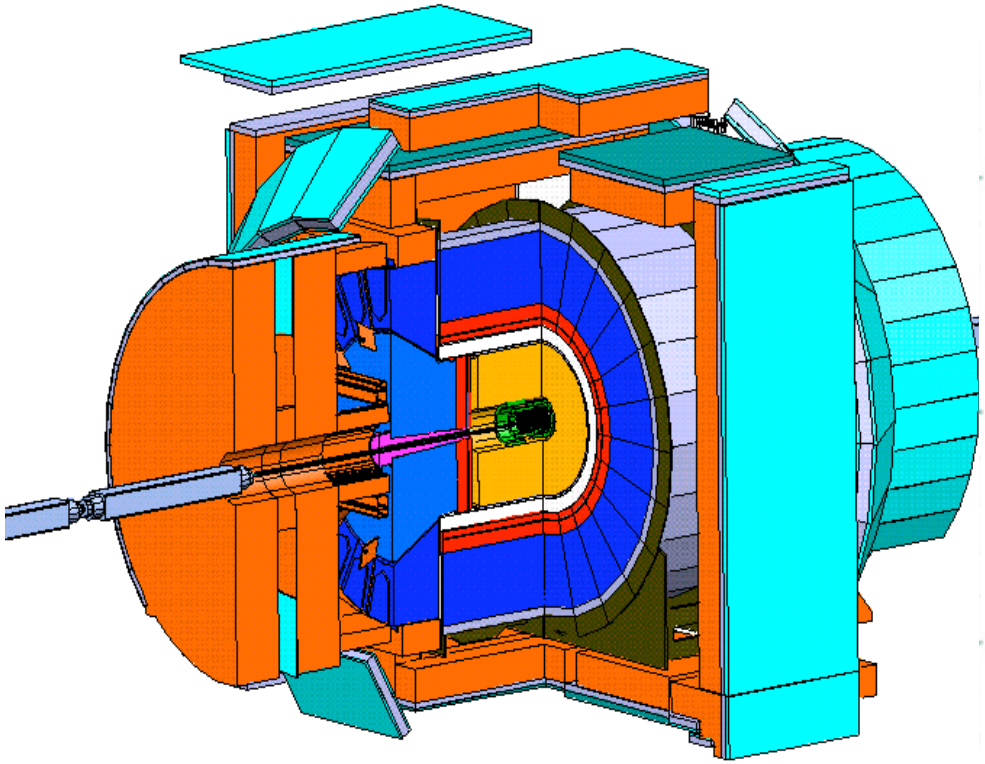
- Lepton+Jet (30%, manageable bkgds)

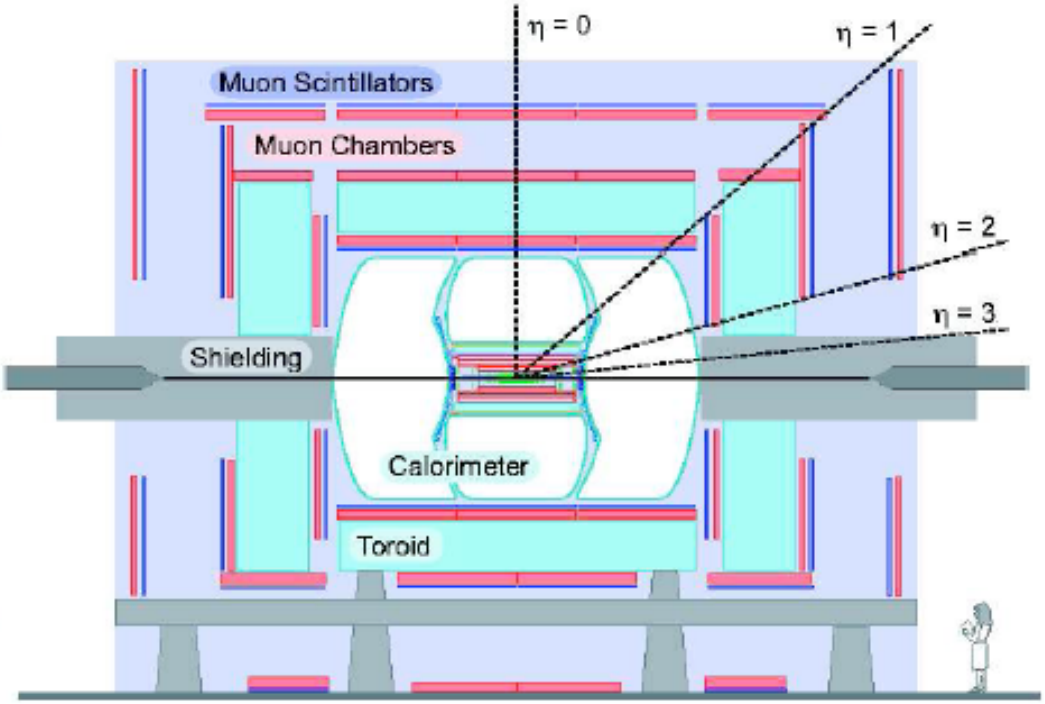
  1 lepton(e/μ), 4 jets (2 b jets), missing E_T (1ν)

- All-hadronic (44%, large bkgds)

  6 jets (2 b jets)

The CDF and DØ Detectors

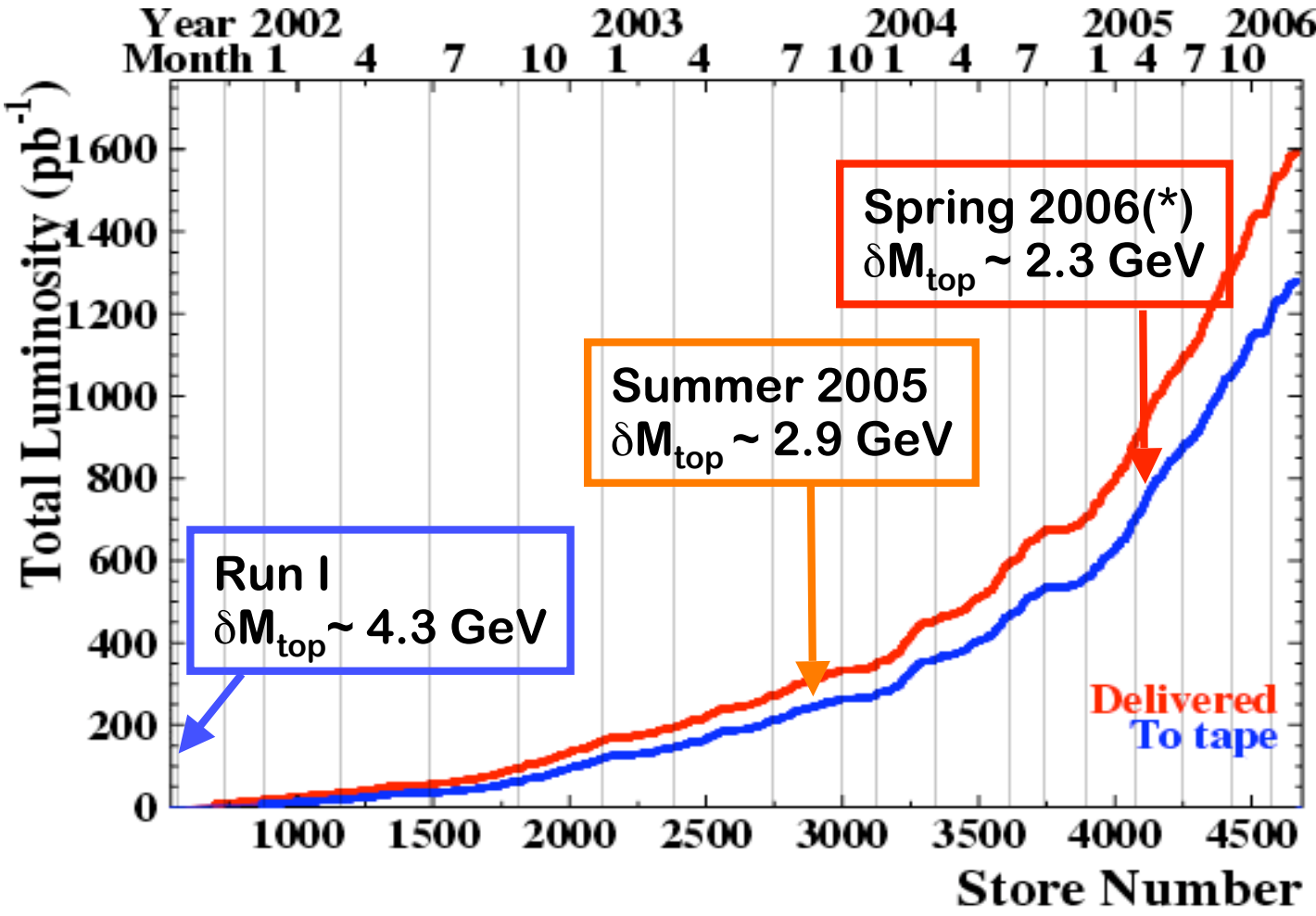




- Calorimeters ($\sigma/E \sim 80\% /\sqrt{E}$)
- Precision tracking with SI:
- Muon chambers
- Excellent muon coverage(D0), excellent tracking (CDF)

→ Multi-purpose detector; precision measurements search for new physics

Great Performance
(Tevatron, D0, and CDF)

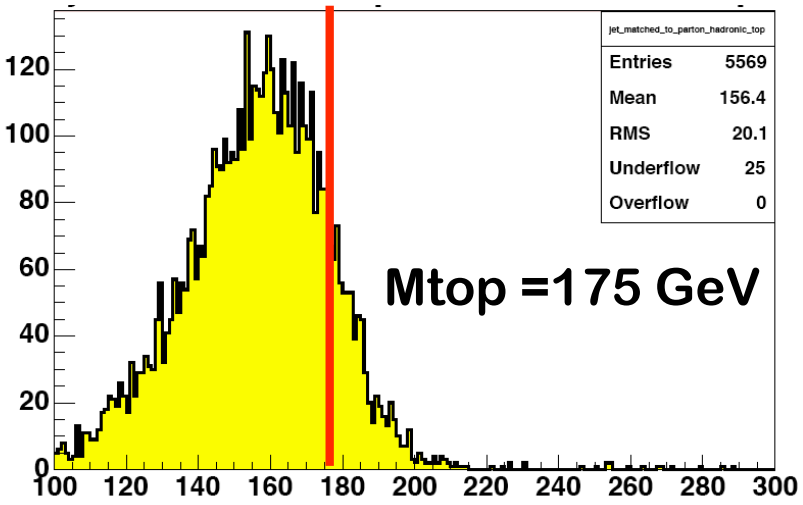


Recorded ~1.3 fb^{-1}
Peak Inst. Lum
~1.7E32 $cm^{-2}s^{-1}$

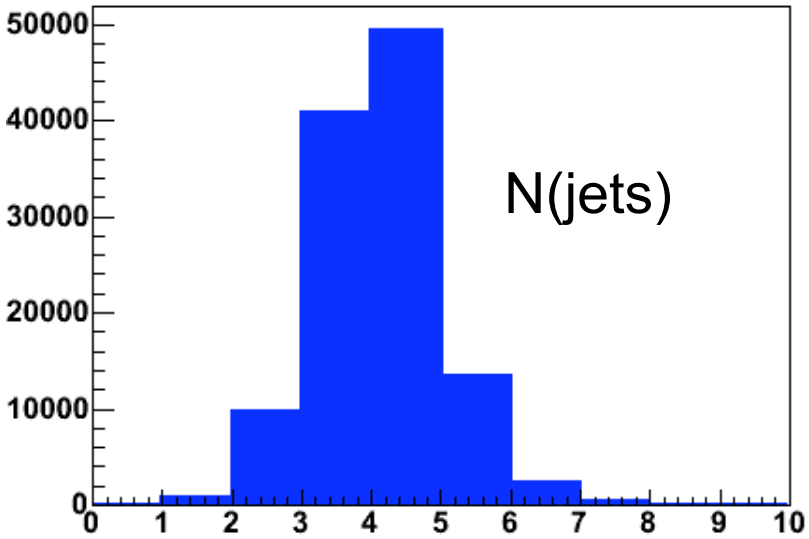
* Not all D0 data included

M_{top} Measurement : Challenge 1

- Not a just calculation of the invariant mass of W(jj) and b!!!



Why M(bjj) ≠ 175 GeV?



- Measured jet energy

  ≠ quark energy from top decay

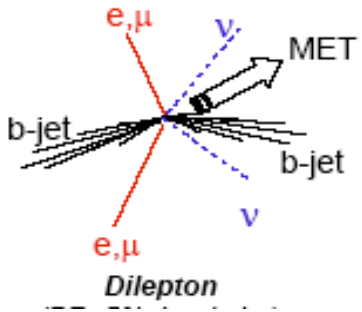
  - Quarks: showering, hadronization, jet clustering
  - Extra radiated jets

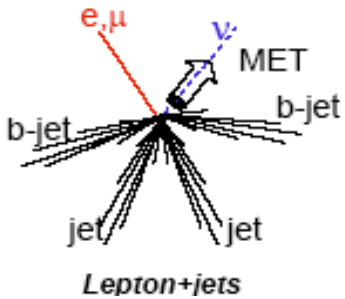
- Excellent jet energy correction and good modeling of extra gluon radiations (40%)

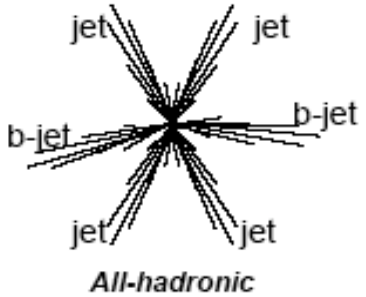
Challenge 2

- There are two top quarks, not all final states available
  - Good to have more than one:but too many possibilities to find a correct combination (all jets: 90), not enough information for dilepton channel

3 constraints: two M(w)=80.4, one M(t)=M(tb)





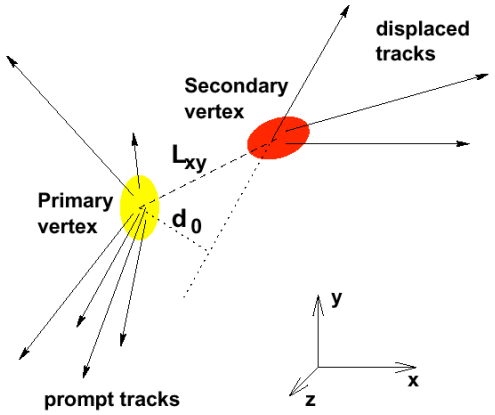


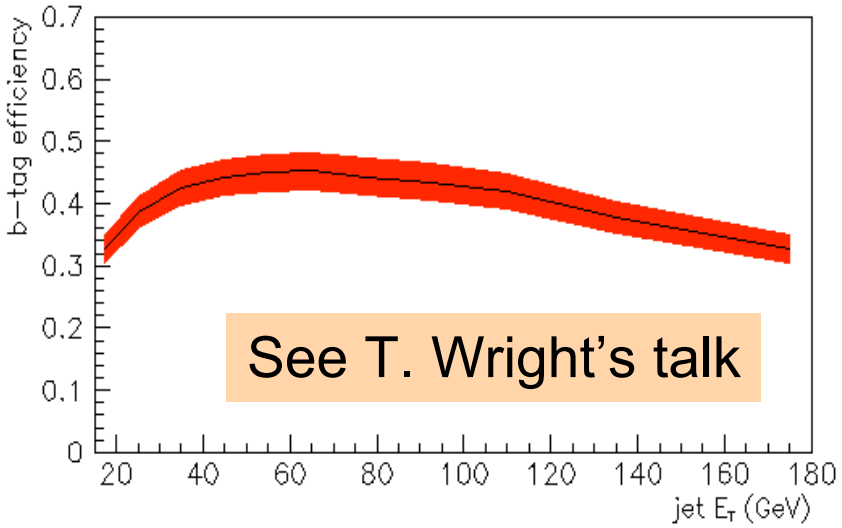
Ncomb(btag)	2(2)	12 (6)	360(90)
	2 missing ν Unconstrained: Small BR	1 missing ν Overconstrained: Golden Channel	No missing Overconstrained: Large bkgds

- B-tagging help!

B-tagging

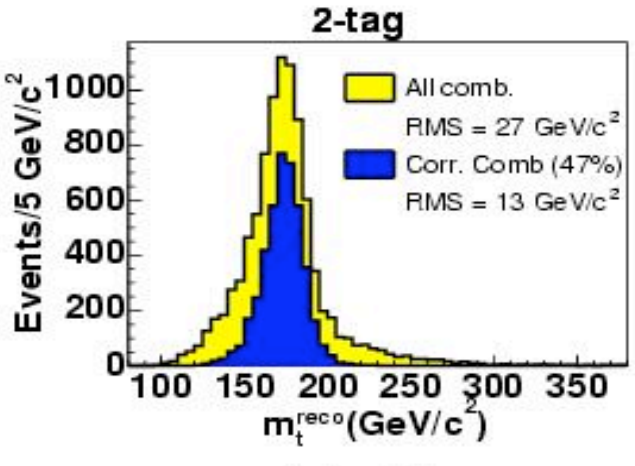
- B-tag: SecVtx tagger

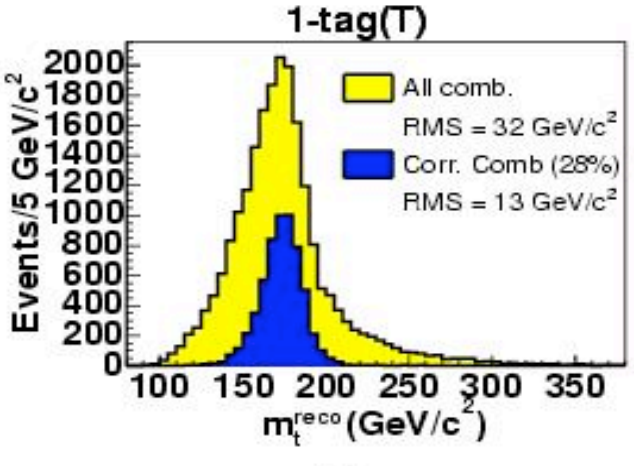




See T. Wright's talk

- B-tagging helps: reduced wrong comb., and improves resolution.





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Top Mass Measurements

Template

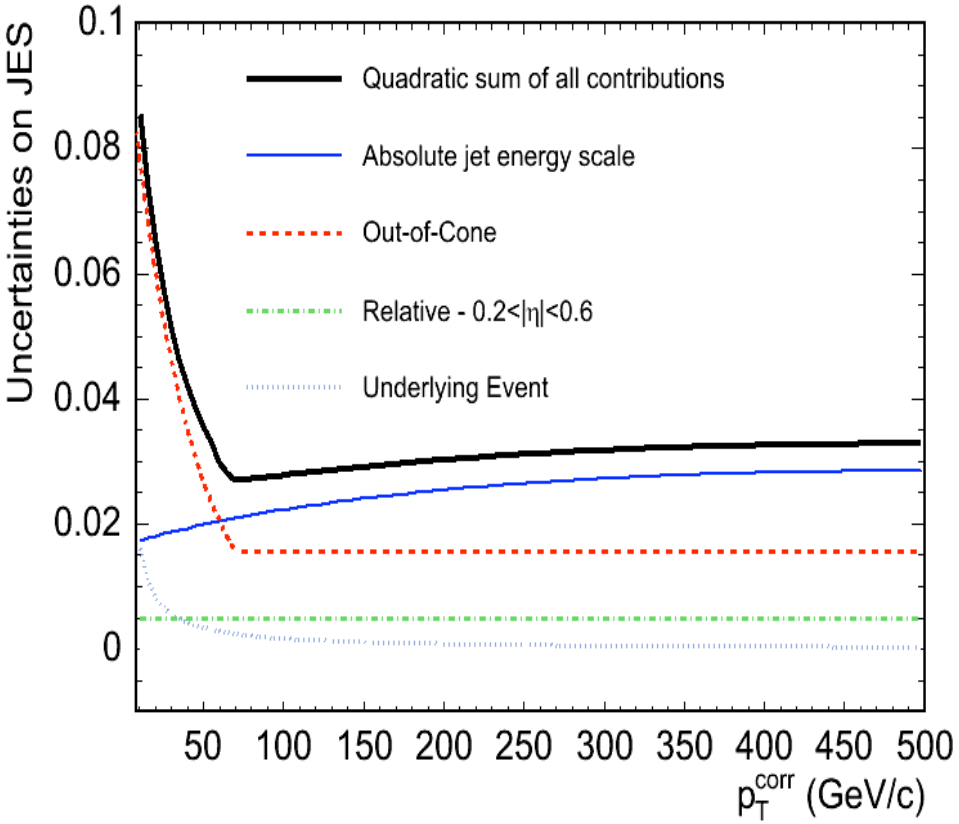
- Reconstruct m_t event-by-event - the best value per each event
- Create "templates" using simulated events with different top mass values, and backgrounds.
- Maximum Likelihood fit using signal+backgrounds templates

Matrix Element

- Calculate probability as top massfor all combinations in each event by Matrix Element calculation - maximize dynamic info.
- Build likelihood directly from the probabilities.
- Calibrate measured mass and error using simulated events

Jet Energy Scale(JES) Uncertainties

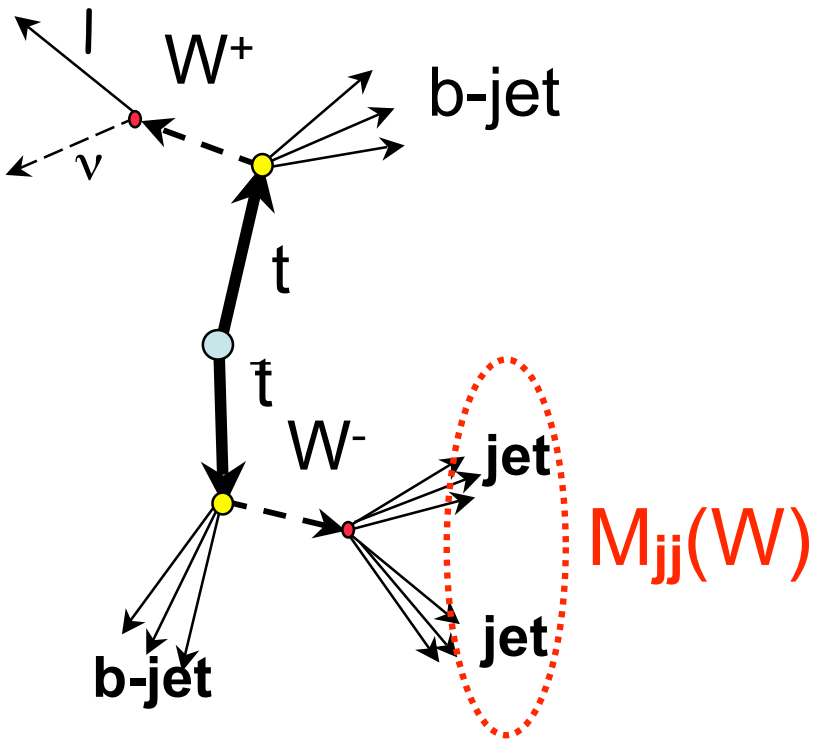
Standard Calib. (dijet, γ-jets etc)



About 3% of M_{top}

See R. Hirosky's talk

In-situ Calibration



JES uncertainty:
mostly statistical,
scaled with lum

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Strategy

- Precision
- Consistency (different channels, methods)
- New Physics (bias)

	Method	Njets		B-tag		JES			Rec. variables
		Exact	+extra	Yes	No	Wjj+std	Wjj	No	
LJ	TMP	4							mt, mjj, Lxy
LJ	ME								P(Mt,JES)
DIL	TMP	2							mt
DIL	ME								P(Mt)
All-J	TMP+ME	6							mt, mtb

both Only D0 Only CDF

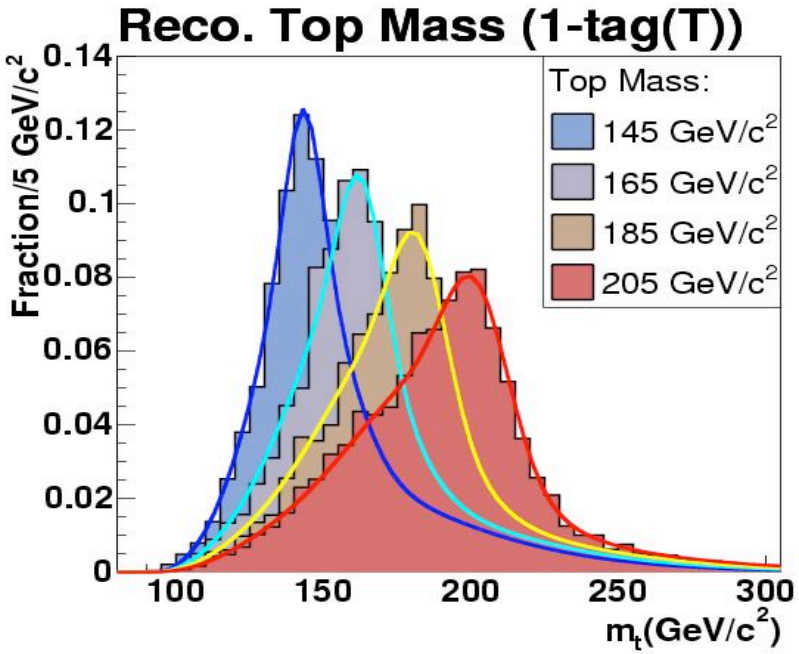
Template Method in lepton+jet

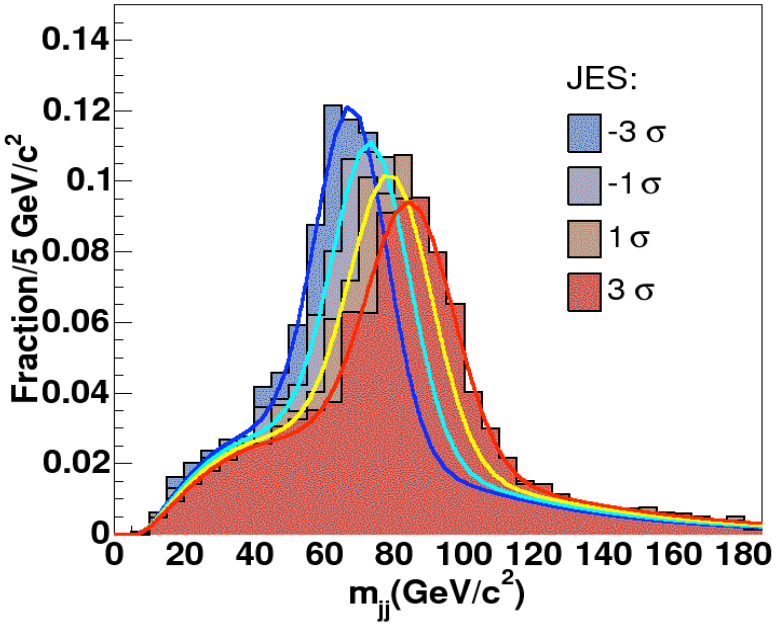
- χ^2 kinematic fitter

$$\chi^2 = \sum_{i=l,4\ jets} \frac{(\hat{p}_T^i - p_T^i)^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(\hat{p}_T^{UE} - p_T^{UE})^2}{\sigma_j^2}$$

$$+ \frac{(m_{jj} - m_W)^2}{\Gamma_W^2} + \frac{(m_{lv} - m_W)^2}{\Gamma_W^2} + \frac{(m_{bjj} - m_t)^2}{\Gamma_t^2} + \frac{(m_{blv} - m_t)^2}{\Gamma_t^2}$$

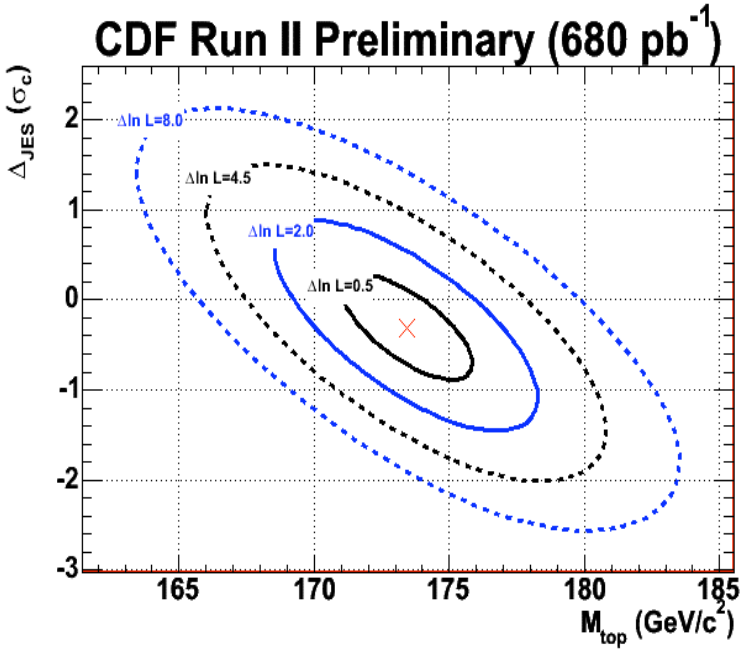
- Select reco. m_t from assignment yielding lowest χ^2

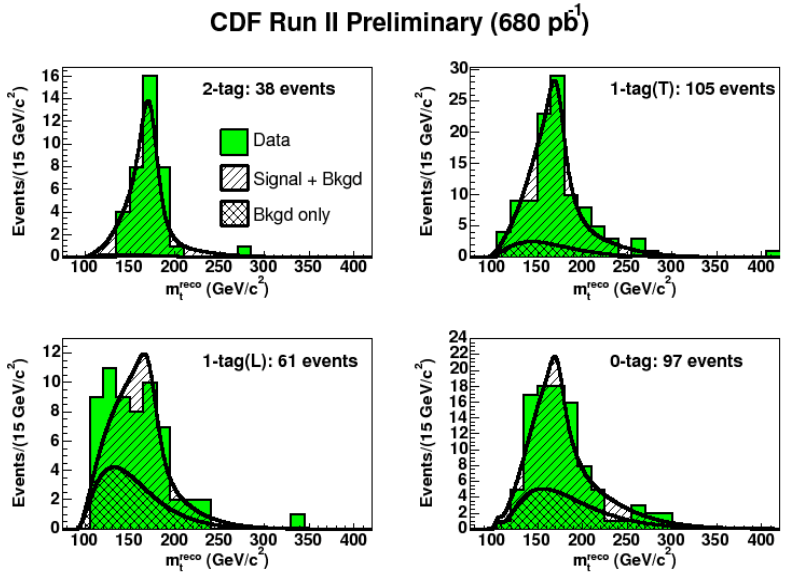


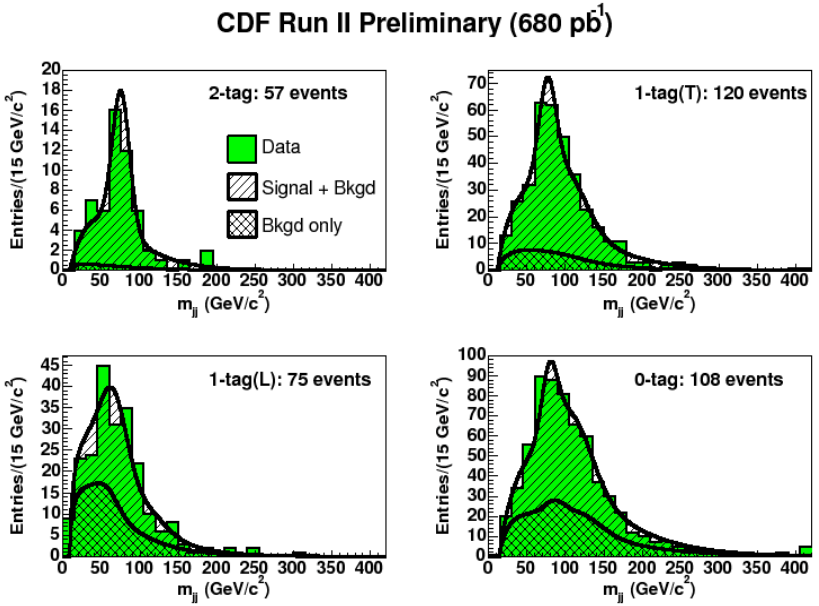


Mtop and JES : by likelihood fit using shape comparisons of m_t & m_{jj} dist.

Template Results in lepton+jets







$$M_{top} = 173.4 \pm 3.5(\text{stat.} + \text{JES}) \pm 1.3\ (\text{syst.})\ \text{GeV}/c^2$$

World best single measurement!

40% improvement on JES using in-situ JES calibration

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Matrix Element Method in lepton+jets

- 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}

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

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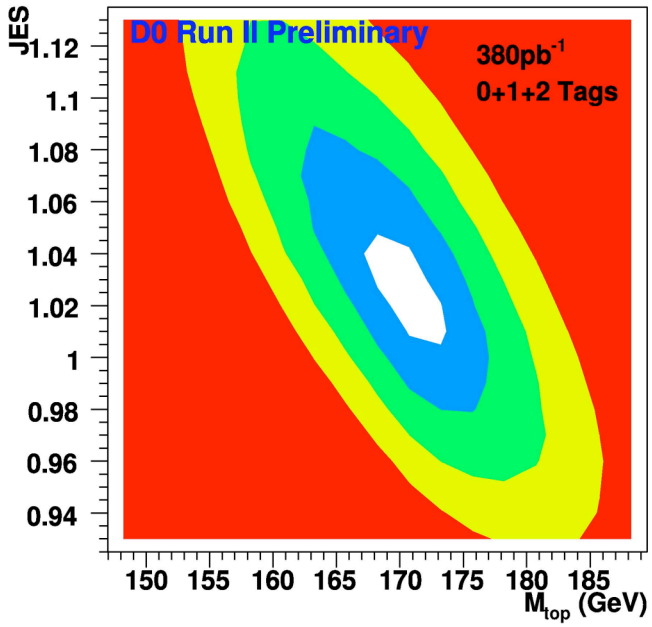
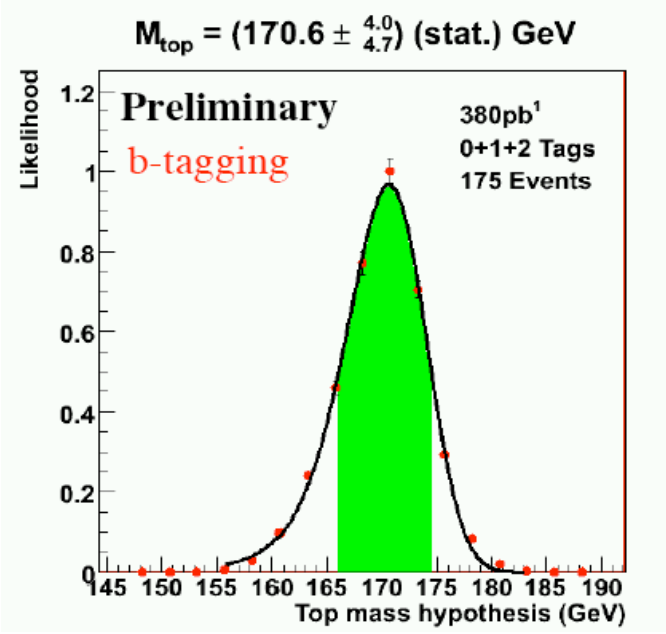
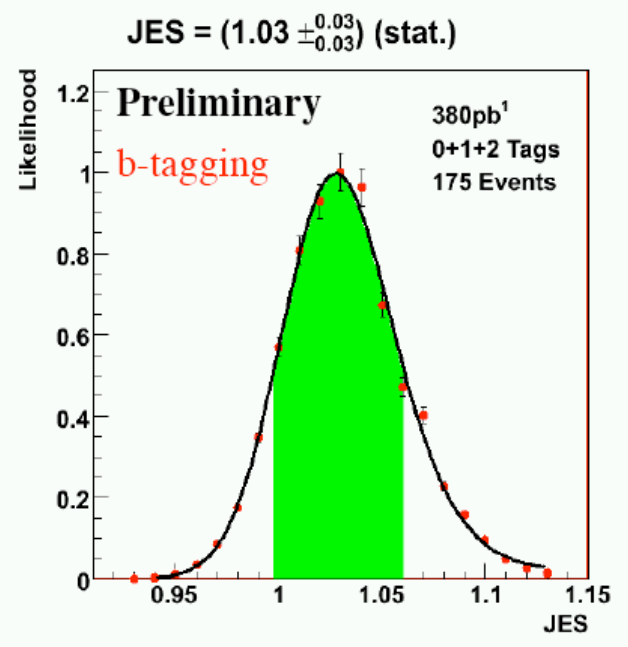
M.E. Results in lepton+jets







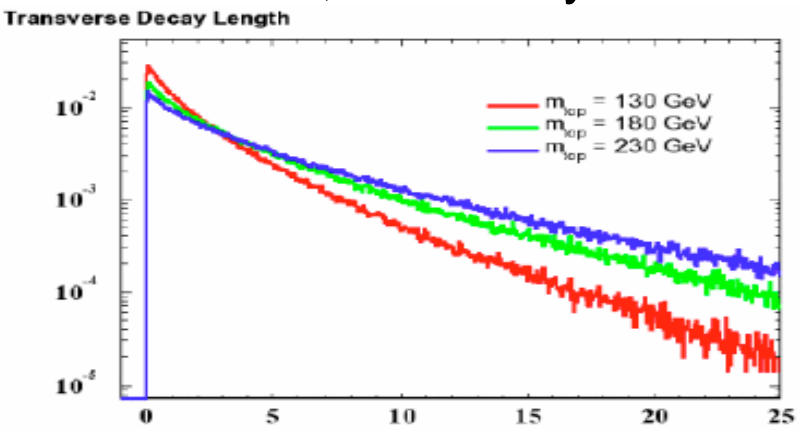
$$M_{top} = 170.6^{+4.0}_{-4.7}(\text{stat.} + \text{JES}) \pm 1.4\,(\text{syst.})\,\text{GeV}/c^2$$

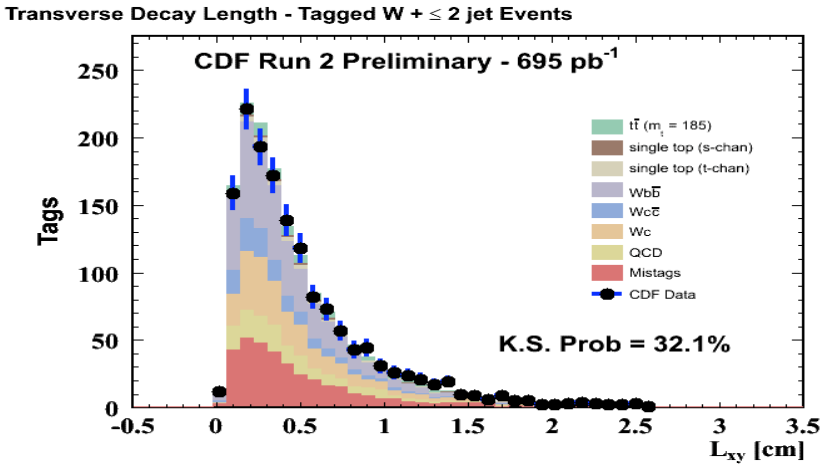
- Reduced the JES error with in-situ calibration, consistent with external calibration (JES=1)
- The b-tagging information improves δMtop(stat) by 35% (17% expected)

Template using Decay Length (Lxy)

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

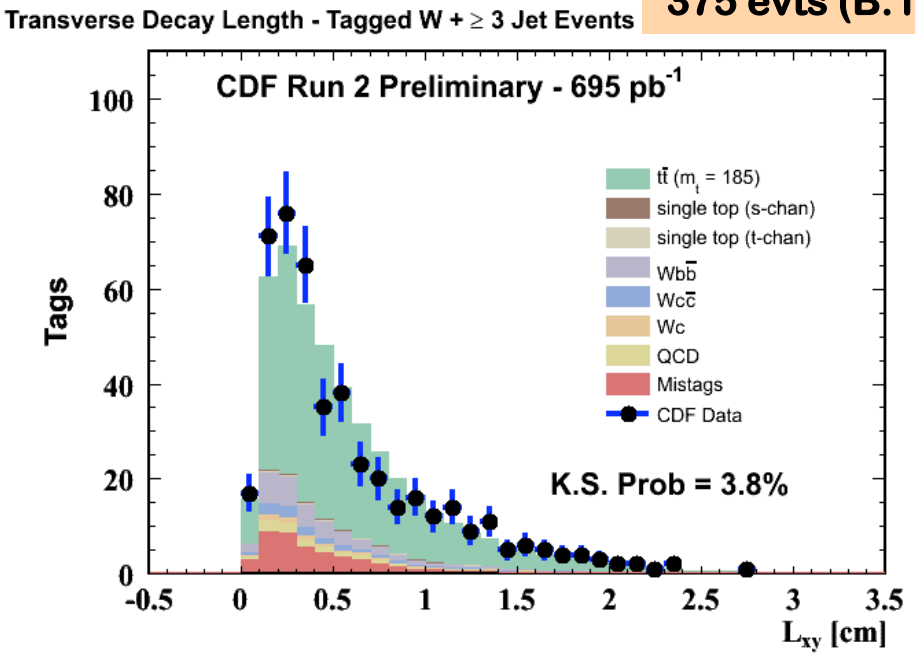
PRD 71, 054029 by C. Hill *et al.*





Insensitive to JES, but need Lxy simulation

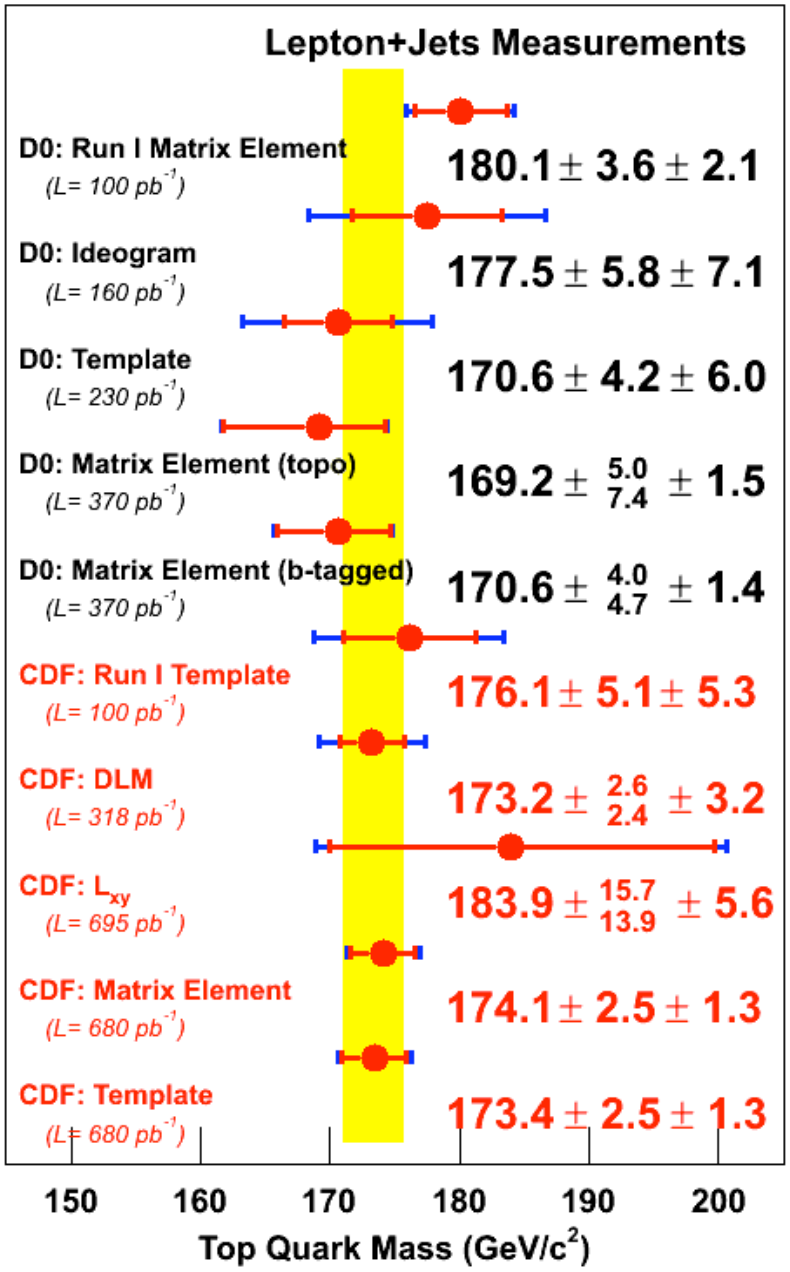
375 evts (B:111)



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

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

Summary in lepton+jets

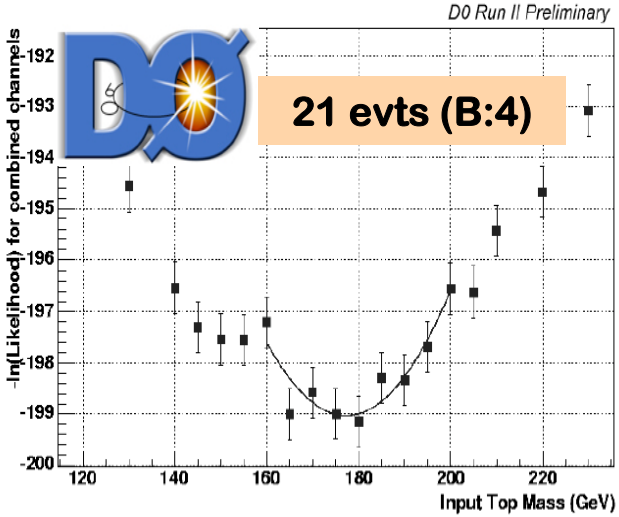


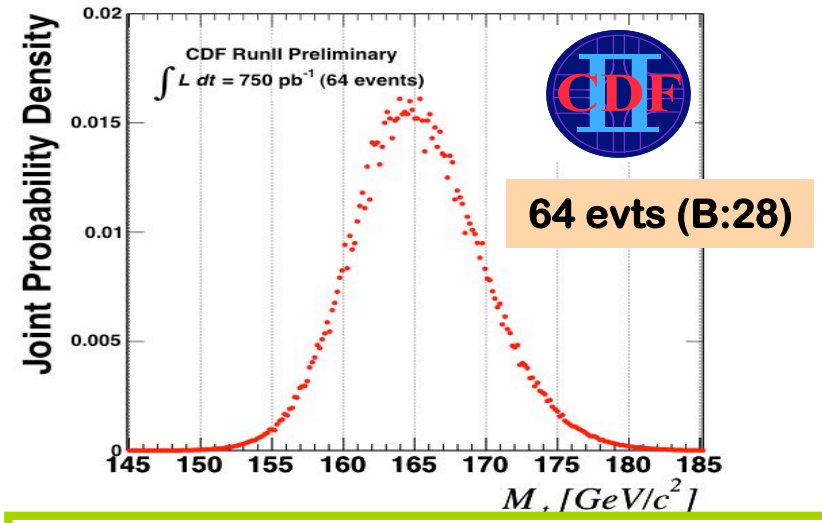
Systematic ΔM_{top}(GeV/c²)	TMT (CDF)	ME (D0)
JES	(1.8)	(3.4)
Residual JES	0.7	0.8
B-jet JES	0.6	0.7
ISR/FSR	0.5	0.5
Bkgd Shape	0.5	0.3
Generators	0.3	
PDFs	0.3	0.1
Method	0.3	0.5
B-tagging	0.1	0.2
TOTAL	1.3	1.4

All consistent!!

Methods in dilepton

- Unconstrained system: 2 neutrinos, but 1 missing E_T observable
  - Template:
    - Assume $\eta(\nu)$ (or $\phi(\nu)$, $P_Z(tt)$)
    - Sum over all kinematic solutions, and (l,b) pairs, select the most probable value as a reco. m_t
  - Matrix Element:
    - Integrated over unknown variables using the LO M.E., assuming jet angles, lepton are perfect, and jets are b's
    - Obtain P(Mtop) for signal and backgrounds
    - Calibrate off-set in pull and pull width using fully simulated MC

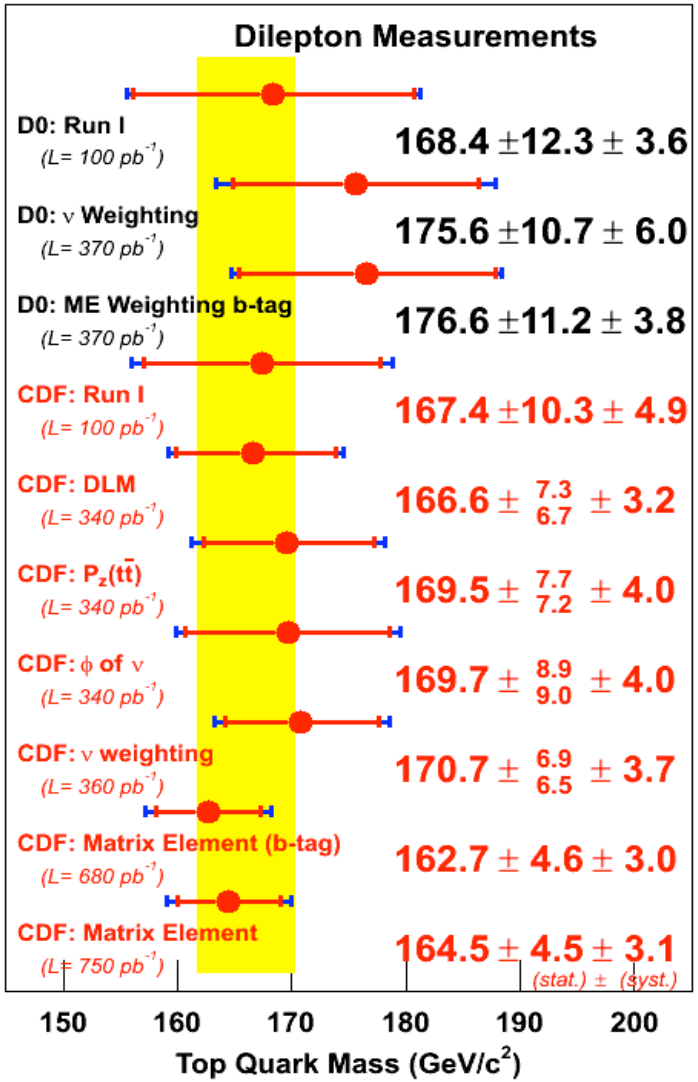




$$M_{top} = 175.6 \pm 10.6\,(stat) \pm 6.0(syst)\ \mathrm{GeV}/c^2$$

$$M_{top} = 164.5 \pm 4.5\ (\mathrm{stat}) \pm 3.1(\mathrm{syst})\ \mathrm{GeV}/c^2$$

Summary in dileptons



Systematic ΔM_{top}(GeV/c^2)	ME (CDF)	TMT (D0)
JES	2.6	3.5
Bkgd Shape	0.8	0.2
Sample composition	0.7	
ISR/FSR	0.7	0.8
Generators	0.5	
PDFs	0.6	0.9
MC stats	0.8	0.3
Method	0.3	0.6
TOTAL	3.1	3.8

All consistent!!

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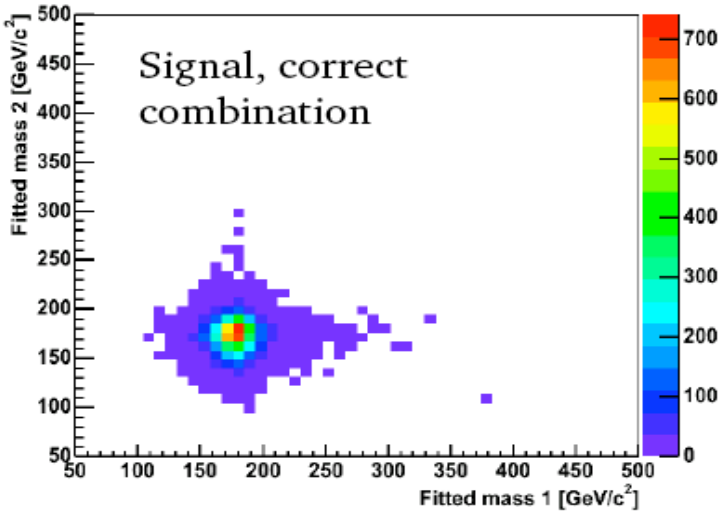
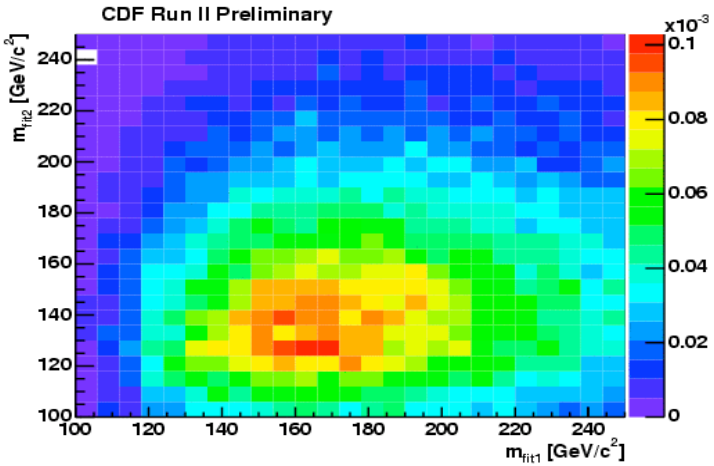
All-Jets

- Largest BR, and no missing information, but large backgrounds, S/B = 1: 8 even after 1 b-tag
- Event Selection
  - $E_T / \sqrt{(\Sigma E_T)} < 3\ (GeV)^{1/2}$
  - $\Sigma E_T \geq 280$ GeV
  - $n_{b\text{-}tag} \geq 1$ (b-tag)
  - Exactly 6 jets



- χ^2 kinematic Fitter with W mass contraint: fit two top quark masses (m1, m2), then use χ^2 value to weight each permutation



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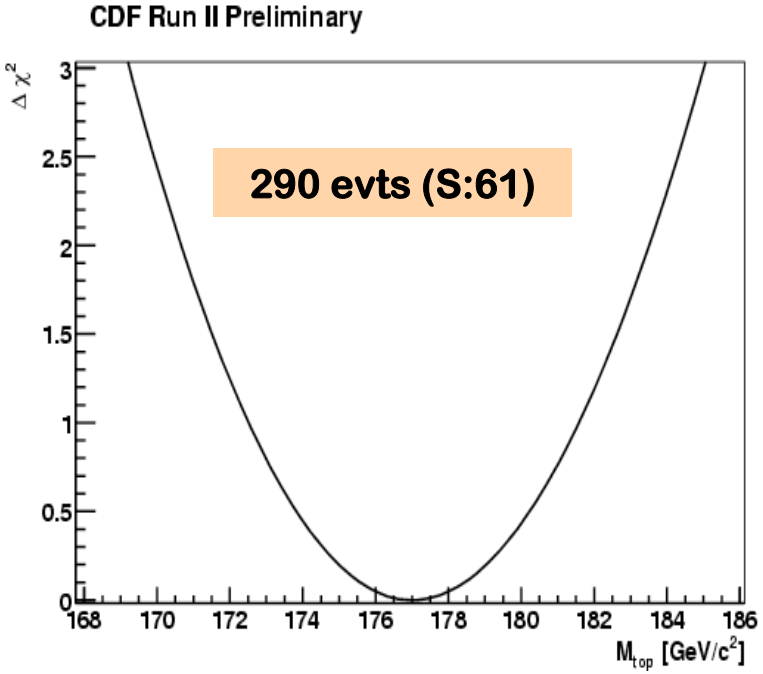
Ideogram in All-jets

- 2D likelihood:

Convolution of Briet-Wigners and Gaussian resolution functions

$$\mathbf{L}(M_{top}, C_s) = \sum_{i=1}^{90} w_i \left[C_s Signal + (1 - C_s) Bkgd \right]$$

$$\text{where } Signal(m_i^1, m_i^2, \sigma_1^2, \sigma_2^2, M_{top}) = p_{mat} S_{mat} + (1 - p_{mat}) S_{comb}$$



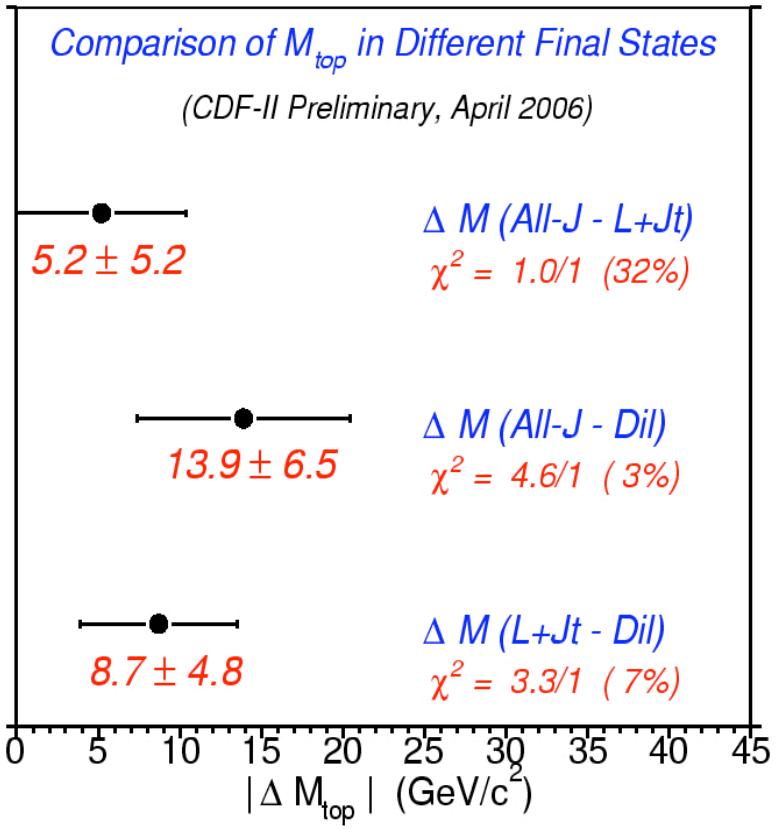
$$M_{top} = 177.1 \pm 4.9\,(stat) \pm 4.3\,(JES) \pm 1.9\,(syst)\ GeV/c^2$$

- First Tevatron Run II all jets M_{top} measurement
- Systematically limited M_{top} Results
- JES is correlated with S/B ratio

Combining M_{top} Results

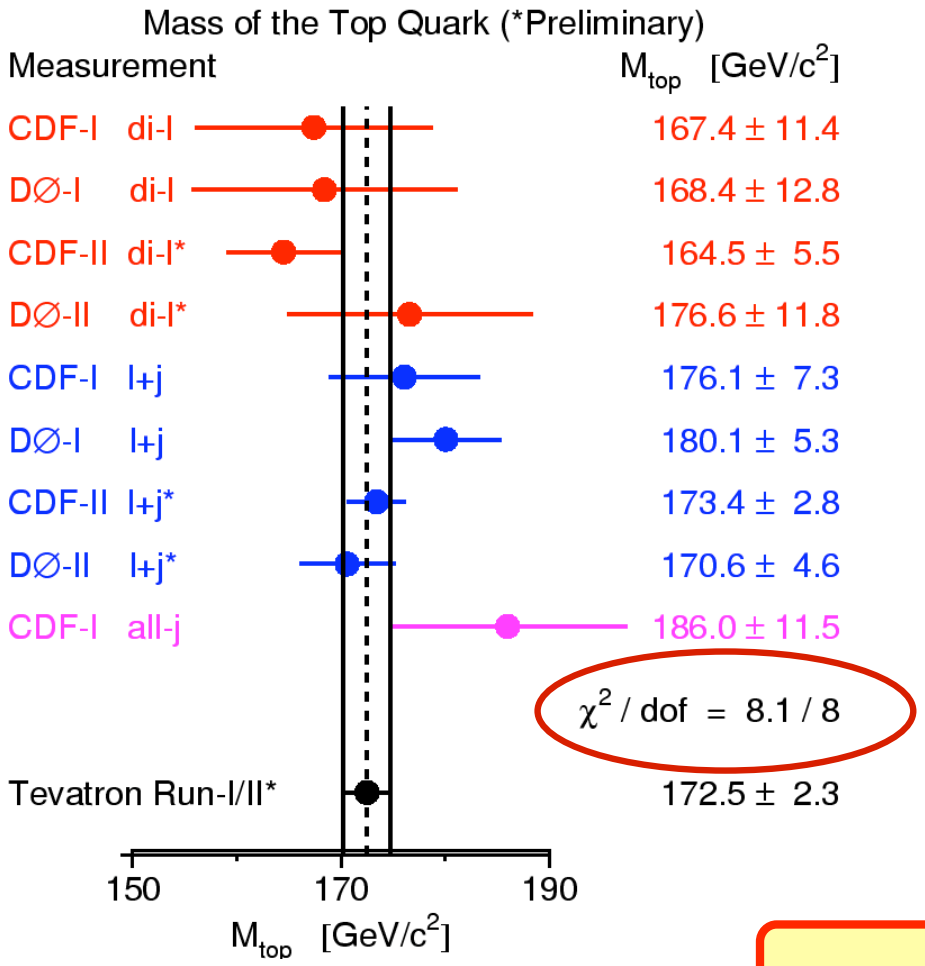
- Are the channels consistent ? (check by CDF)

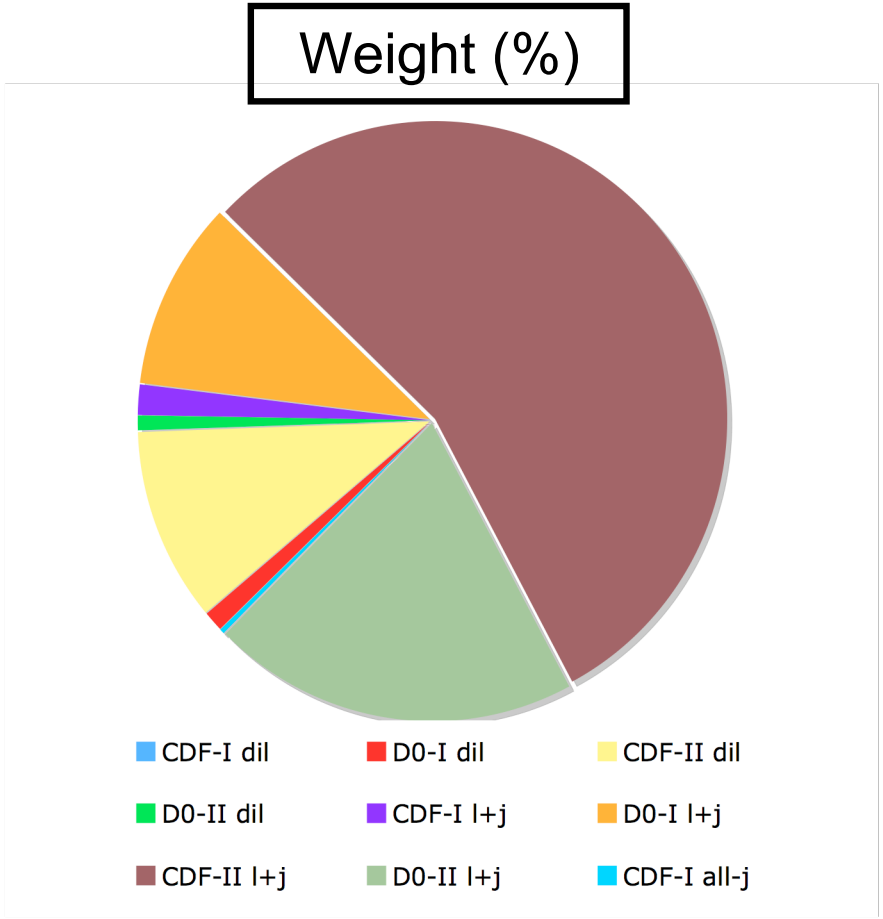
Mtop(All Jets) = 178.7 ± 5.5 GeV/c^2
Mtop(Dilepton) = 164.8 ± 4.8 GeV/c^2
Mtop(Lep+Jets) = 173.5 ± 2.8 GeV/c^2



- Any systematic shift?
  - Missing systematic?
  - Bias due to new physics signal?

Tevaron Average





$$M_{top} = 172.5 \pm 2.3\ \mathrm{GeV}/c^2\ (1.3\%)$$

Un-ki Yang, HCP 2006

Implication for Higgs and SUSY

- A Precision EWK Fit

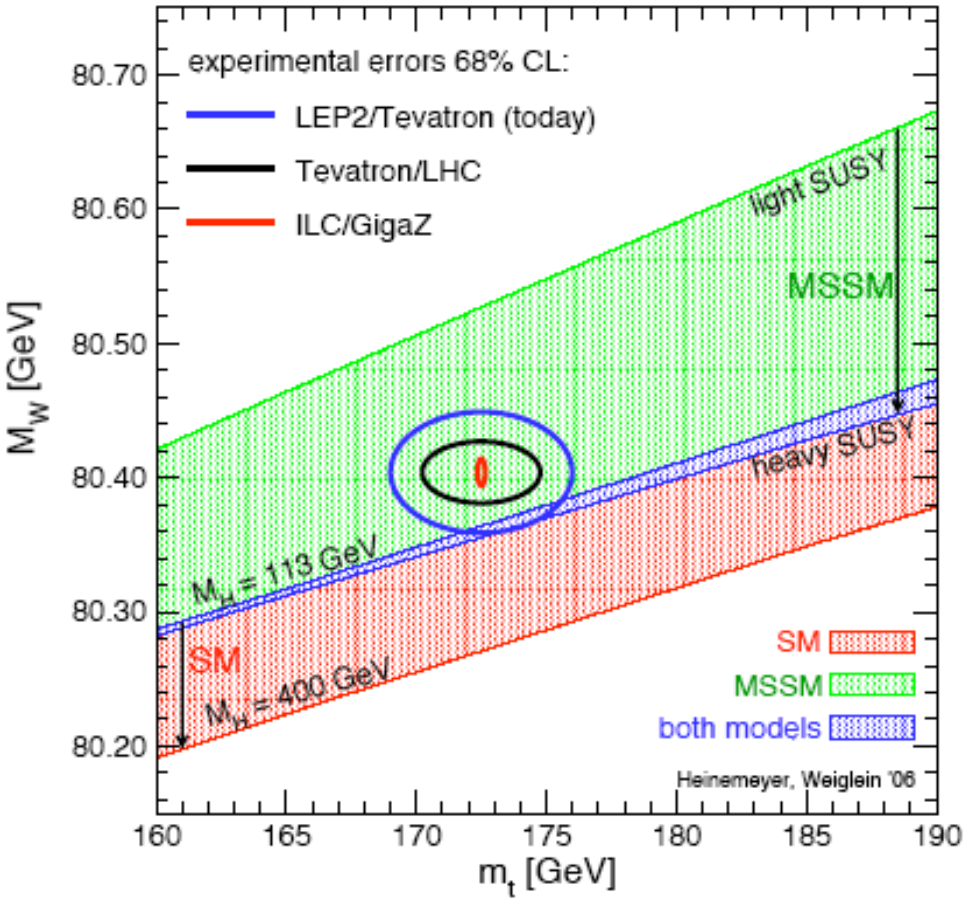
$$M_H = 89^{+42}_{-30}\,\mathrm{GeV/c^2}$$

$$M_H < 175\,\mathrm{GeV/c^2}\ @\ 95\%\,C.L.$$

- Direct search(LEP):

  $M_H > 114$ GeV

- New result favors SUSY over SM, light SUSY



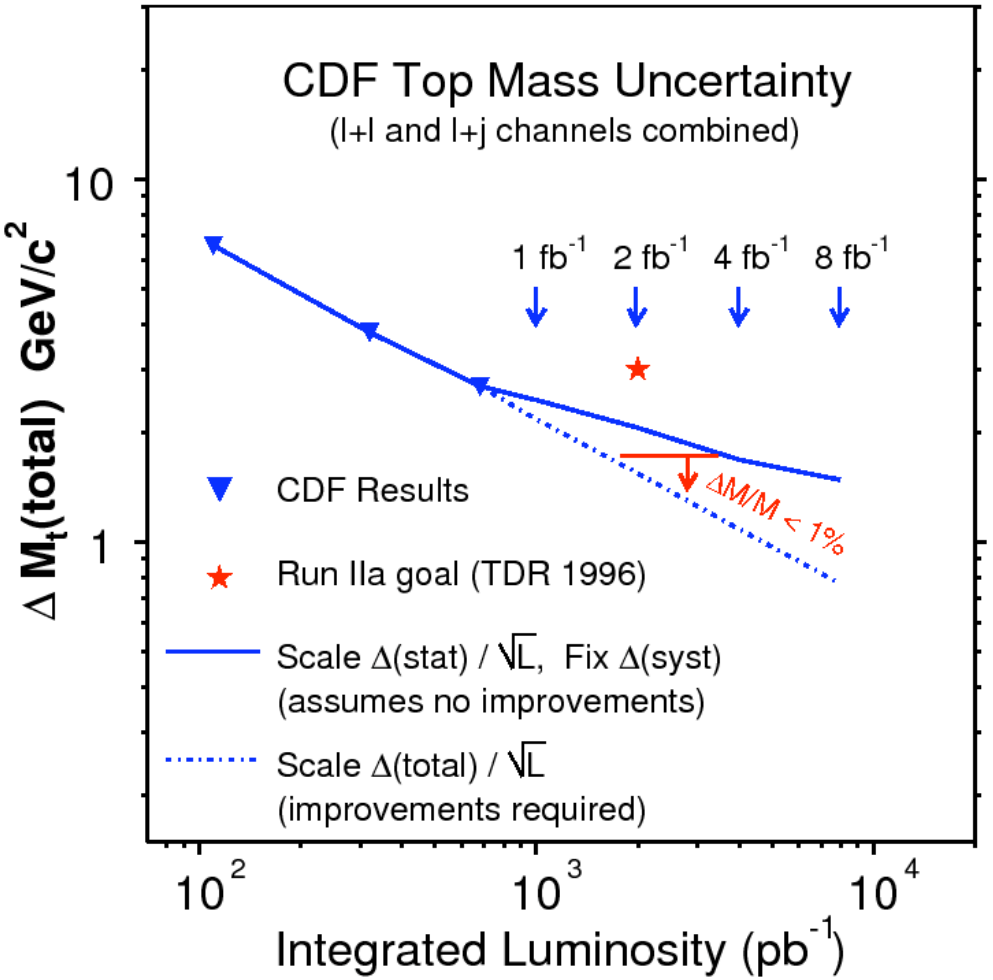
By Heinemeyer et al. (MSSM: m_H<140 GeV)

Few Lessons from Tevatron

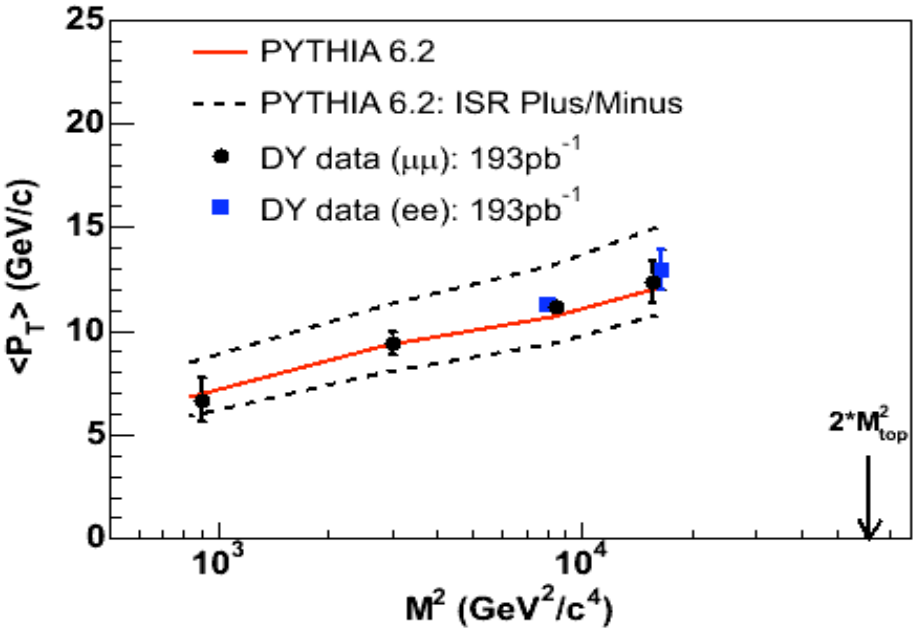
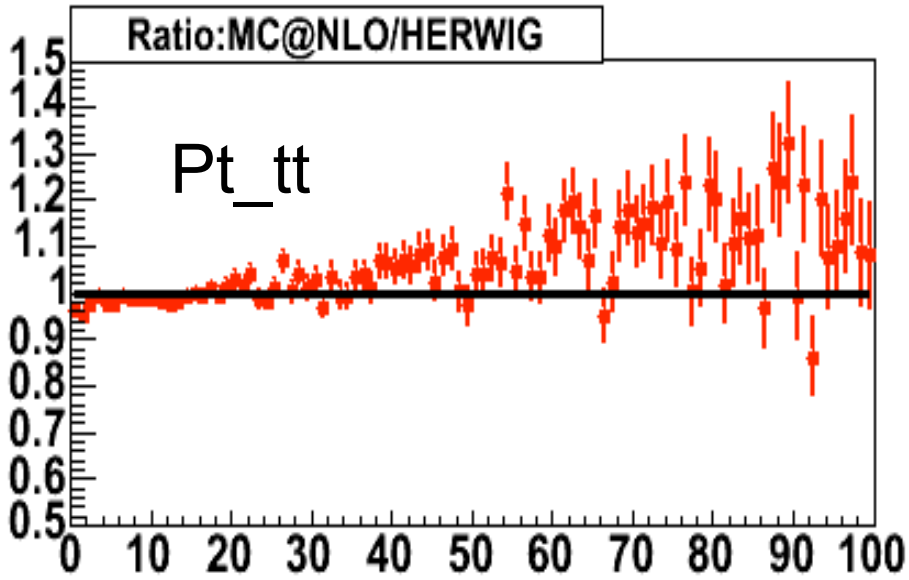
- A major JES uncertainty is greatly reduced by the Wjj in-situ calibration (40% improvement with 700pb-1 data)
- B-jet specific uncertainty is small (<0.7 GeV)
  - Heavy-quark fragmentation
  - Color-interference
  - Semi-leptonic decay
- Good b-tagger is important
- Effect of the higher order (NLO) is small at the Tevatron (<0.5 GeV)
- qq vs gg events have different kinematics
  (2-2.5 GeV difference in top mass: CDF)
- Effect of the multiple interaction is small
- Effect of the backgrounds is small (except all-jets channel)

Summary and Future

- Achieved 1.3% precision of the Mtop measurement (Run IIa goal, δMtop to ~ 3 GeV/c^2 using only 30% data)
- Developed many tools (useful for LHC)
- With full Run-II dataset, able to achieve δMtop to < 1.5 GeV/c^2
- More precision and consistency!!!



Un-ki Yang, HCP 2006

Syst. : ISR/FSR/NLO (backup)

- Method in hand to use Drell-Yan events to understand and constrain extra jets from ISR
  - Constraint scales with luminosity
  - Easily extendible to FSR.
- MC@NLO sample shows no add'l N LO uncertainty is needed.