Precision Measurements of the Top Mass at CDF

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The University of Manchester

Particle Physics Seminar

at University College London

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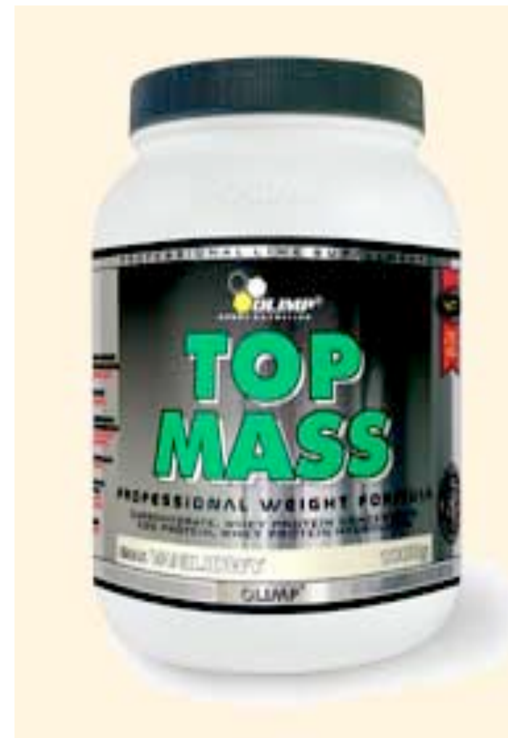
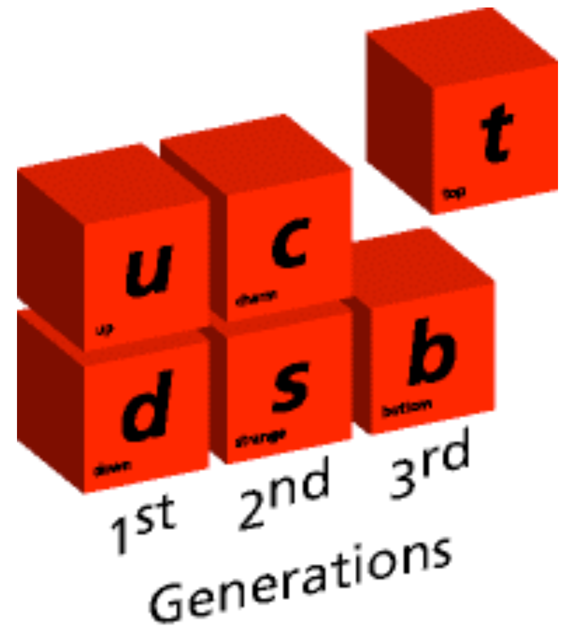


Healthy food to make HEP program very strong!

Top Quark

➢ Discovery of the top quark in 1995;
Heaviest Fermion (about Au nucleus)

- ❑ Opportunity to study a "free" quark
  - Decays before hadronization
- ❑ Insight into generation of mass in the Standard Model
  - where does this structure come from?
  - why so heavy?

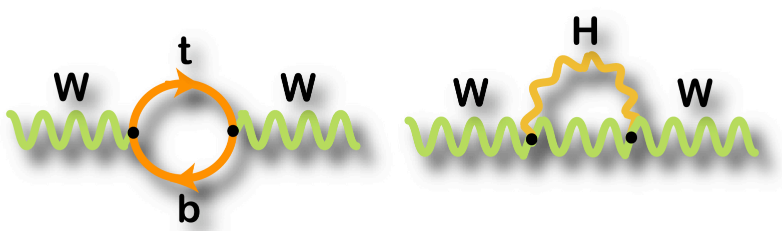


➢ Very statistics limited

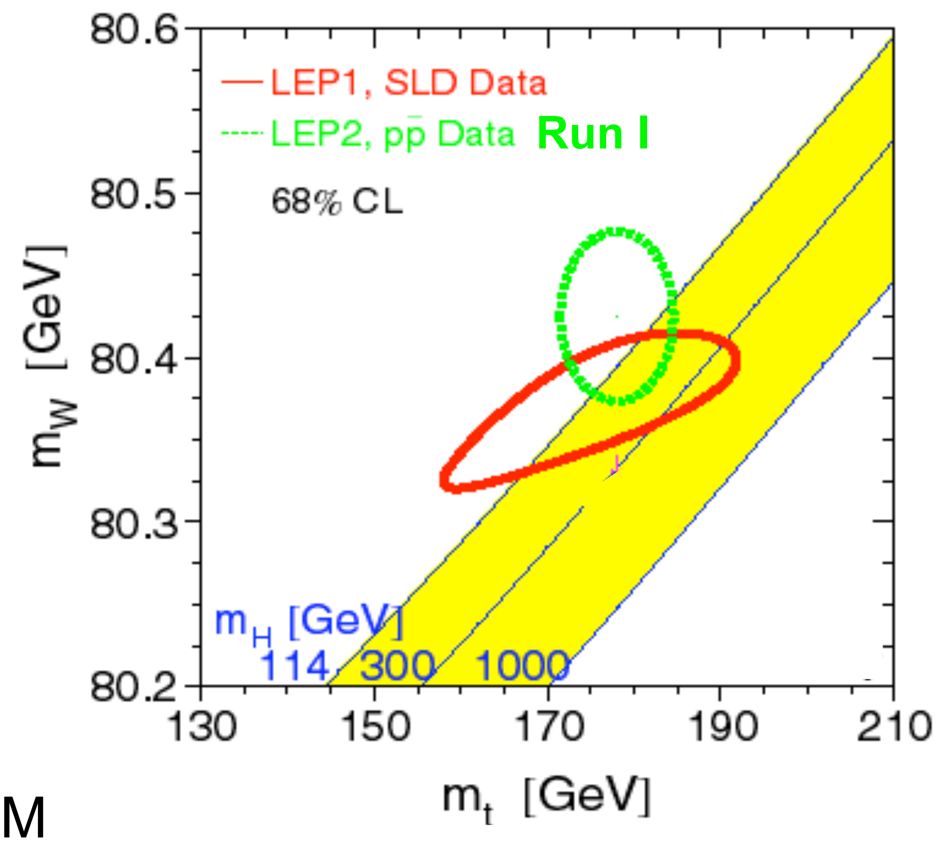
- ❑ D0 and CDF collected approximately 100 pb^{-1} in Run I (1992-1996)

Why Top Mass?

- Top mass is a fundamental SM parameter
  - ❑ Important in loop corrections



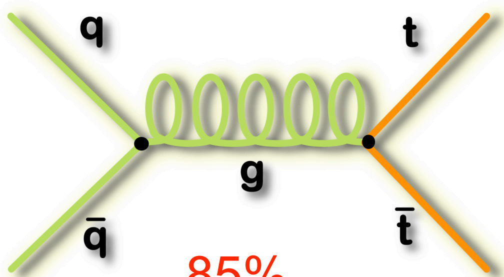
  - ❑ Precise Top & W masses
    - Constraint on SM Higgs
      - It can point to physics BSM
    - Constrain new physics (SUSY) with M_{Higgs}



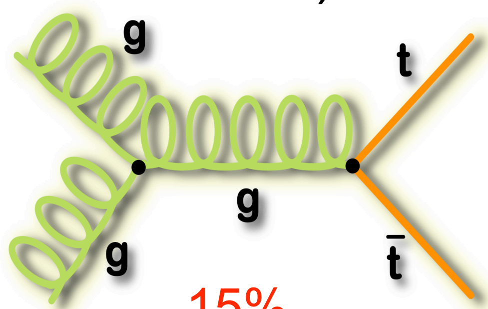
- Is it a SM top?

Top Production and Decay

- At the Tevatron, mainly primarily produced in pairs via strong interaction (σ~7pb: 1 for every 10^{10} collisions)



85%

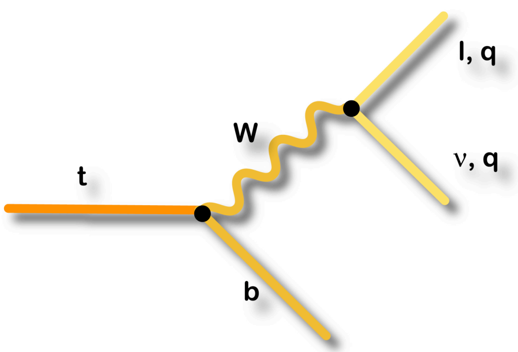


15%

LHC (90%)

~100σ

- Top decays as free quark due to large mass ($\tau_{top} \sim 4 \times 10^{-25}$ 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)

Summary of Run I Measurements

- M_{top} in Run I (~100pb^{-1})

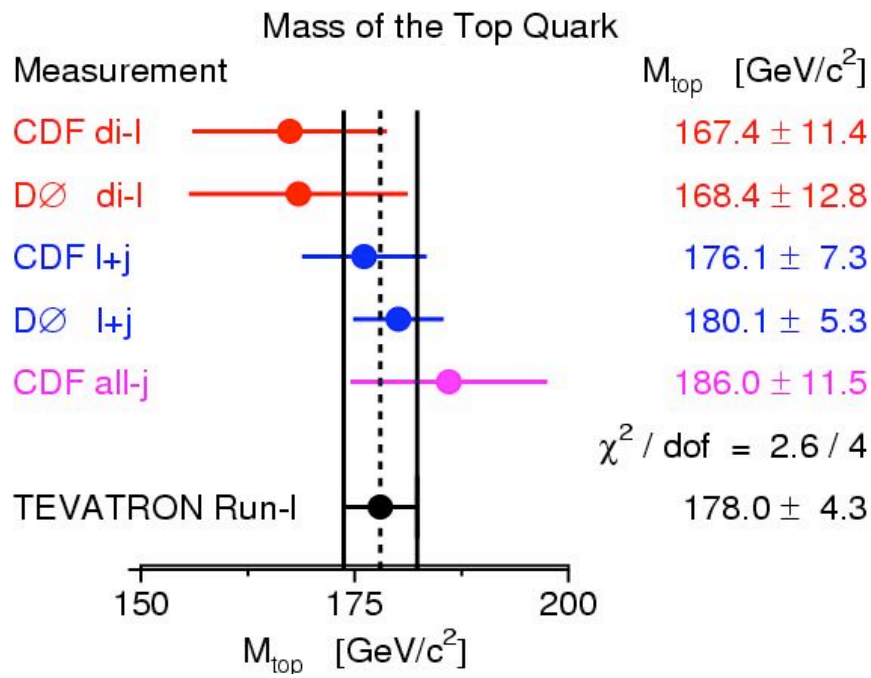
$$M_{top} = 178.0 \pm 4.3 \text{ GeV/c}^2$$

- Higgs mass fit

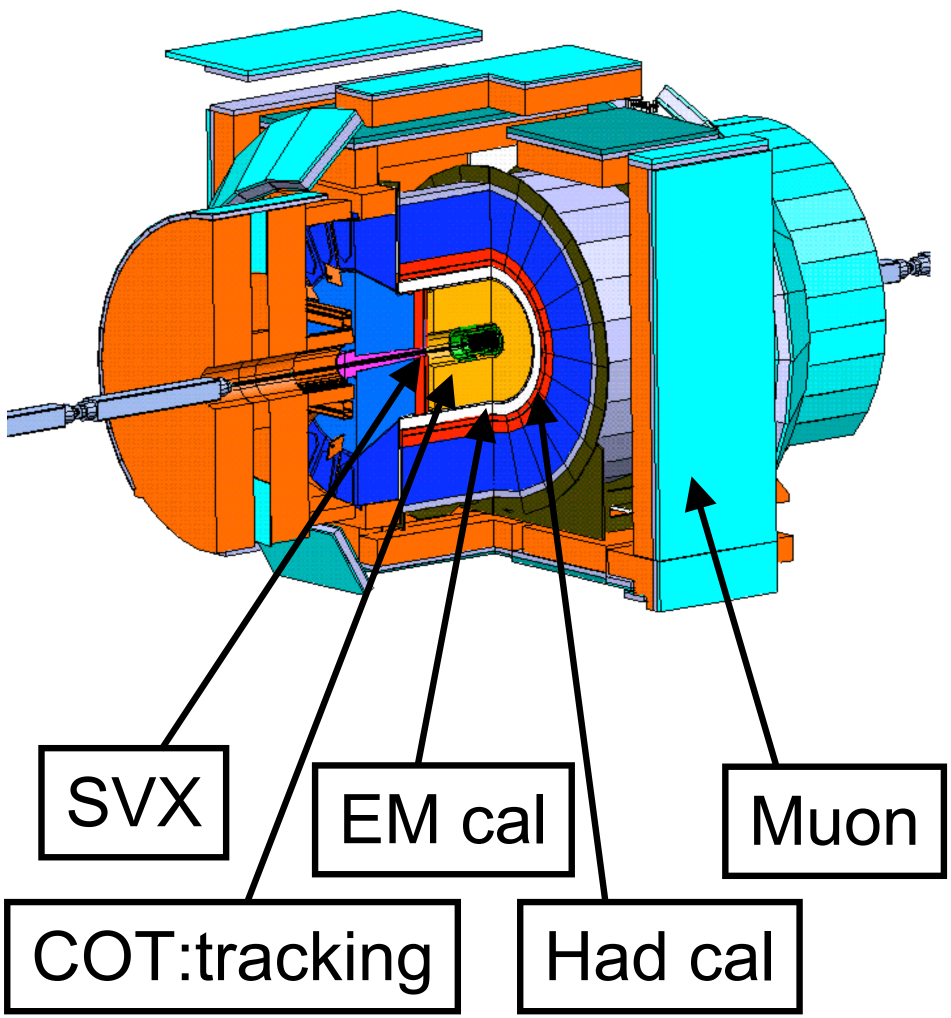
$$M_H = 126^{+73}_{-48} \text{GeV/c}^2$$

$$M_H < 280 \text{ GeV/c}^2 @ 95\% C.L$$

- Run II goals (based on Run I)
  - $\delta M_{top} \approx 3 \text{ GeV/c}^2 @ 2\text{fb}^{-1}$
  - SM M_{top}?
    - Consistency among different channels (non-SM: t->bH**+**)
    - Consistency with Xsection (non-SM X_0, t' contributions)



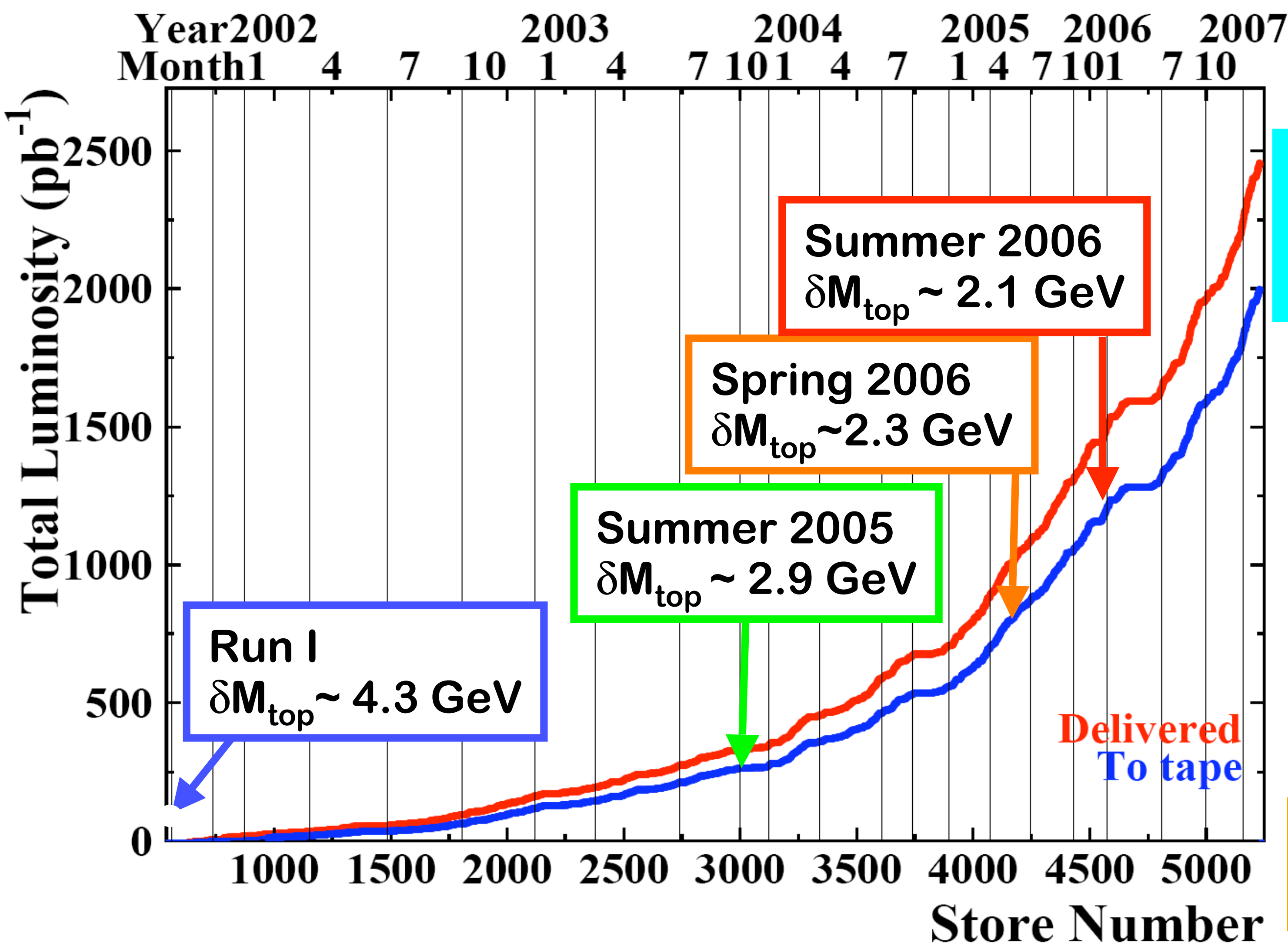
CDF at Tevatron



Multi-purpose detector: precision meas. & search for new physics

- Silicon detector (SVX):
  - top event b-tag: ~ 55%
- COT: drift chamber
  - Coverage: $|\eta|<1$
  - σ_{Pt} / Pt ~ 0.15% P_T
- Calorimeters:
  - Central, wall, plug
  - Coverage: $|\eta|<3.6$
  - EM: σ_E / E ~ 14% /$\sqrt{E}$
  - HAD: σ_E / E ~ 80% /$\sqrt{E}$
- Muon: scintillator+chamber
  - muon ID up-to $|\eta|=1.5$

Great Performance

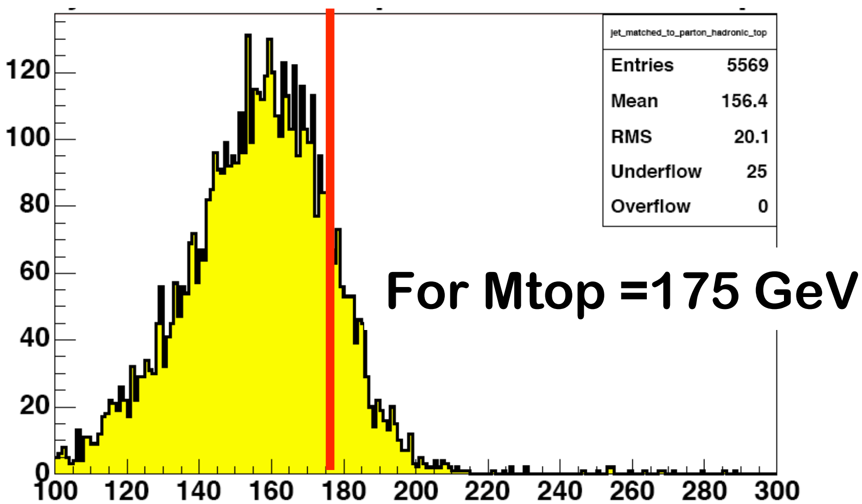


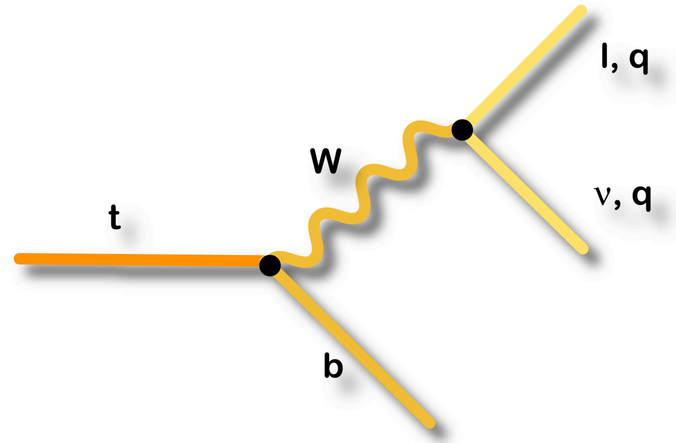
Delivered ~2.4 fb $^{-1}$
Peak Inst. Lum
~2.7E32 cm^{-2}s^{-1}

74% weight by CDF
(D0: only 350pb-1)

M_{top} Measurement : Challenge 1

➢ Not a simple calculation of the invariant mass of W(jj) and b!!!





Why M(bjj) ≠ 175 GeV?

M_{top} Measurement : Challenge 1

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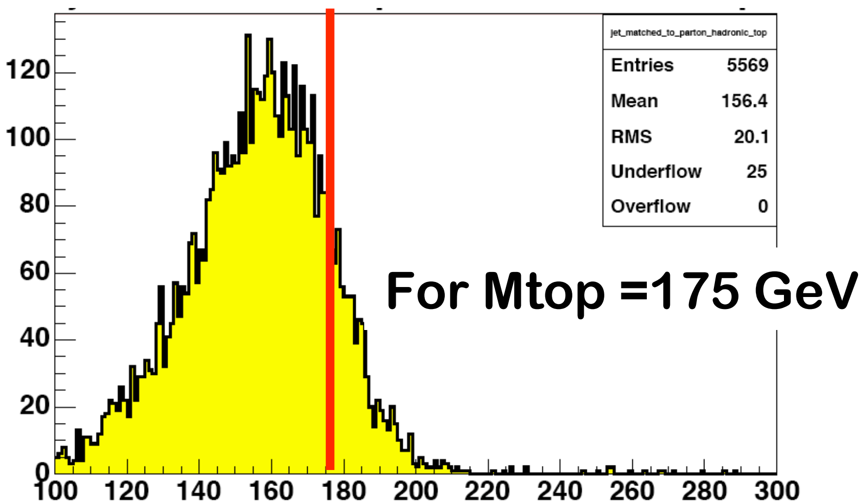

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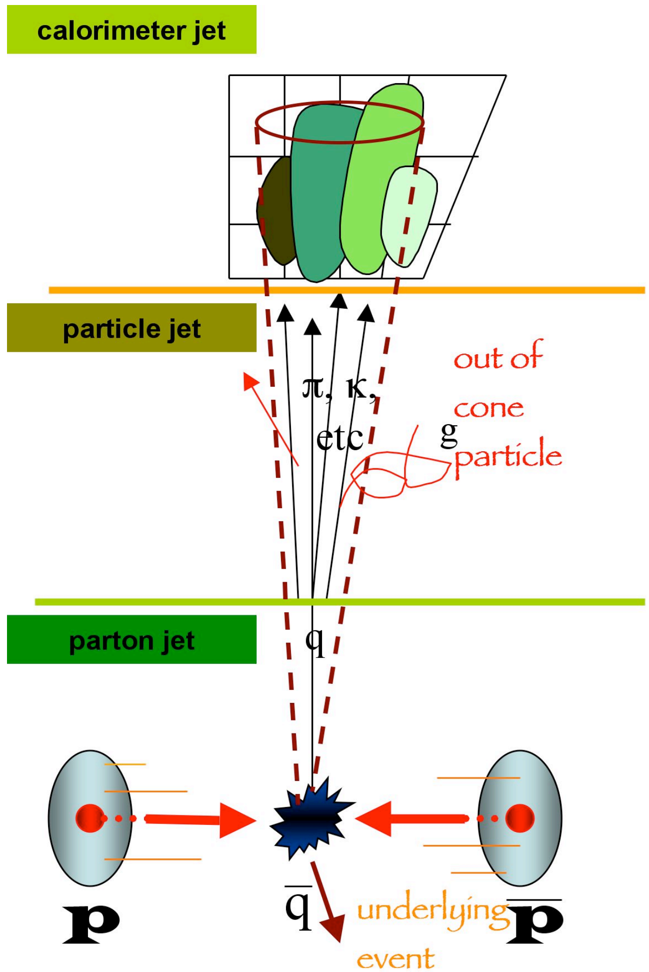


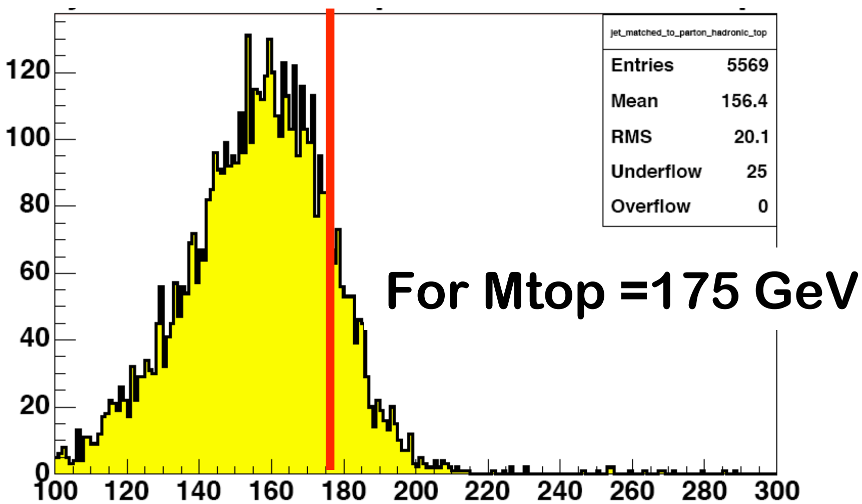
- Measured jet energy

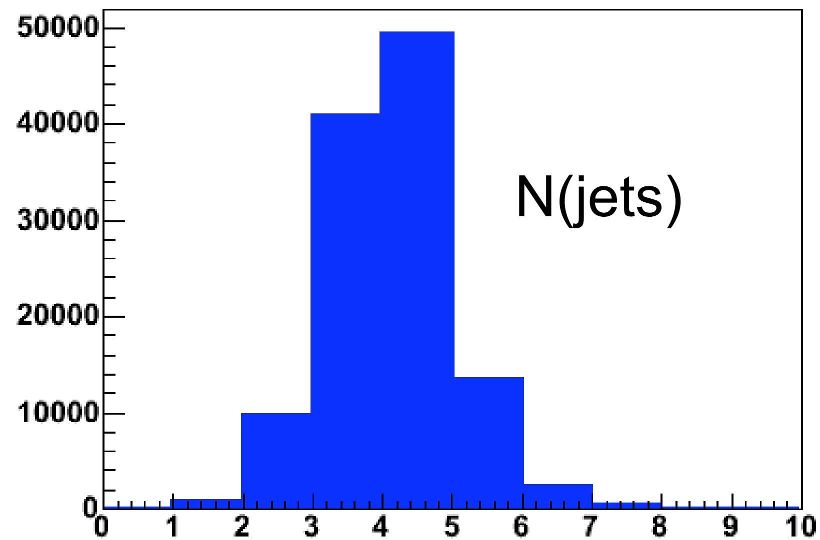
  ≠ quark energy from top decay

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

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

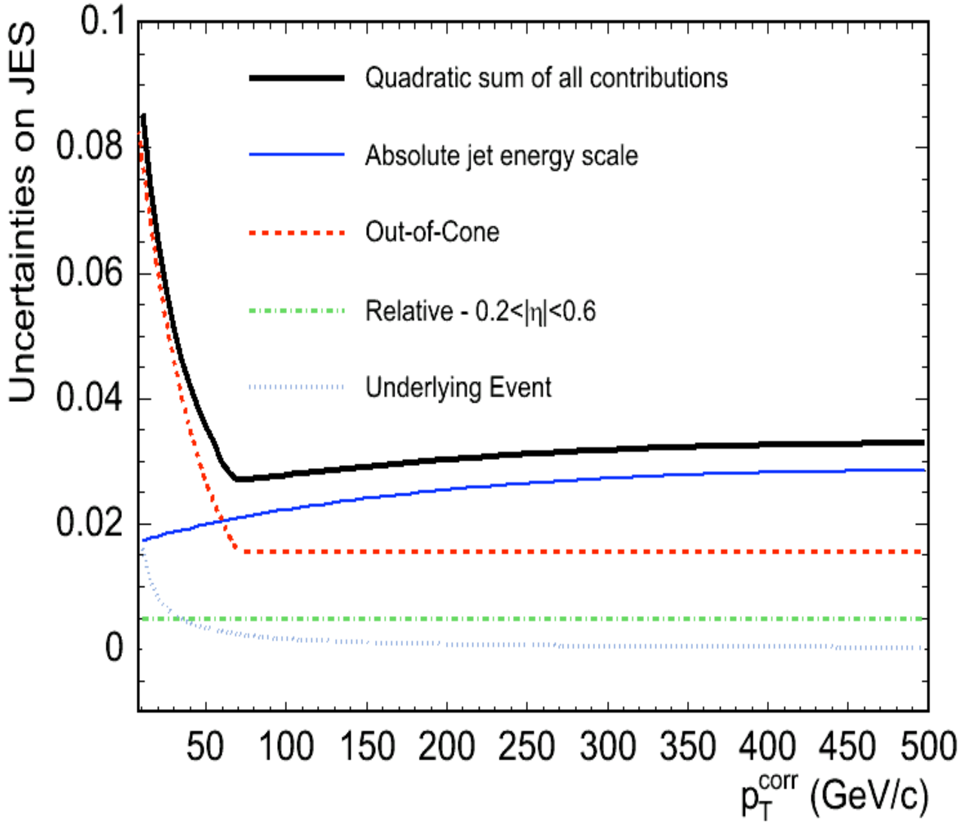
  ≠ quark energy from top decay

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

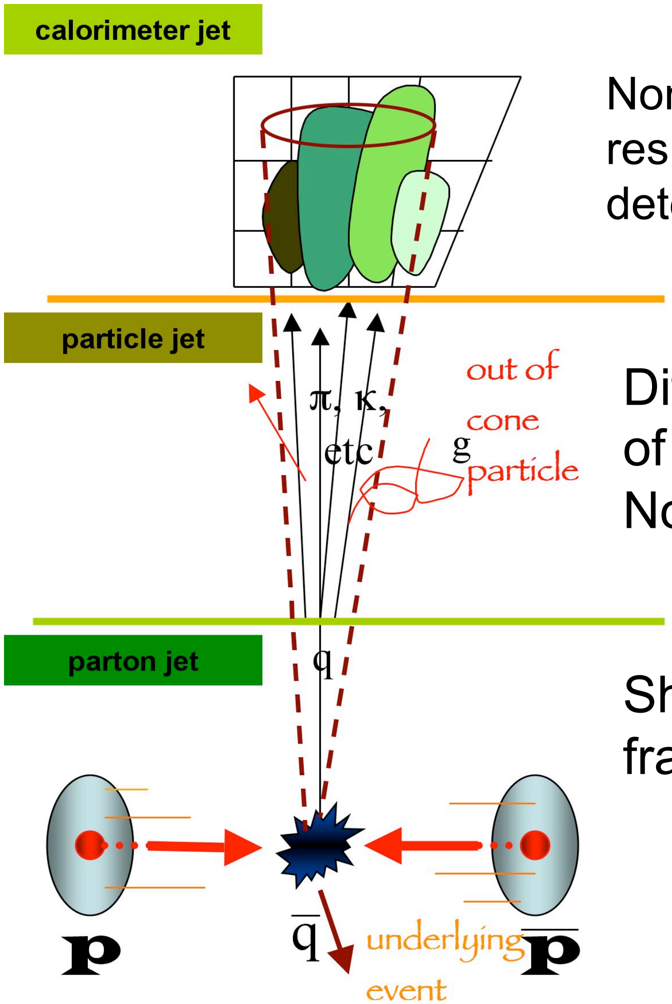
- Require excellent jet energy correction and good modeling of extra gluon radiations (40%)

Jet Energy Scale(JES) Uncertainties

Standard calib. (dijet, γ-jets etc)



About 3 GeV of M_{top}



Non-uniform response over detector

Diff responses of π0/πi+- Non-linearity

Showering, fragmentation

Jet Energy Scale(JES) Uncertainties

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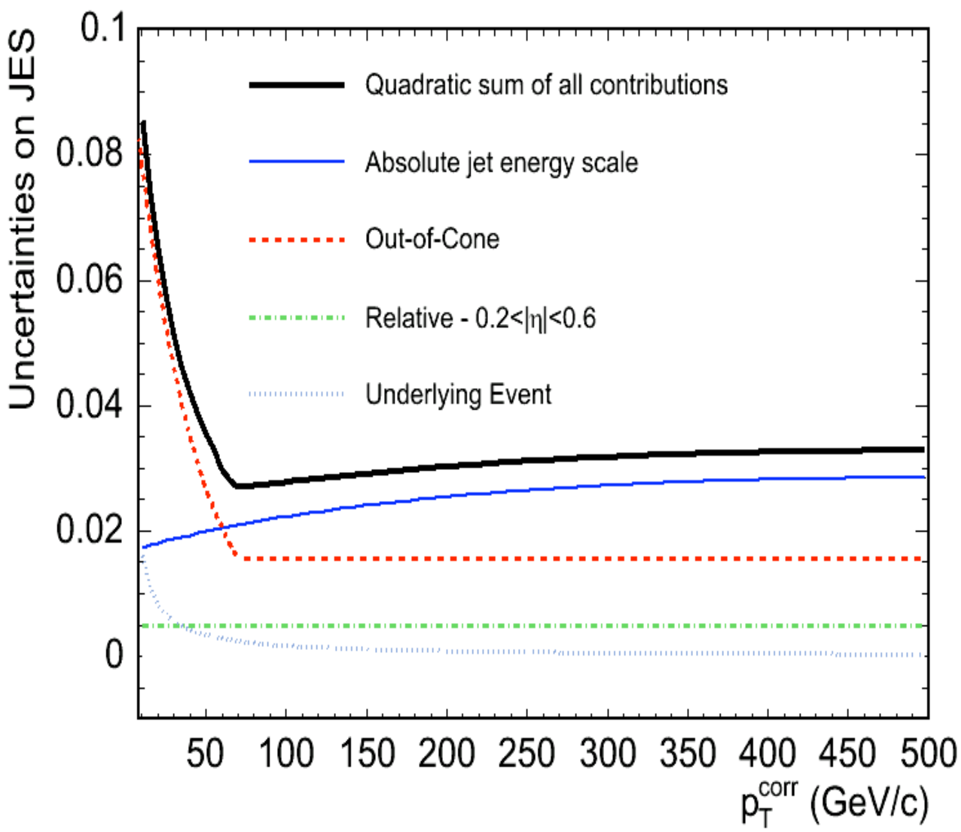
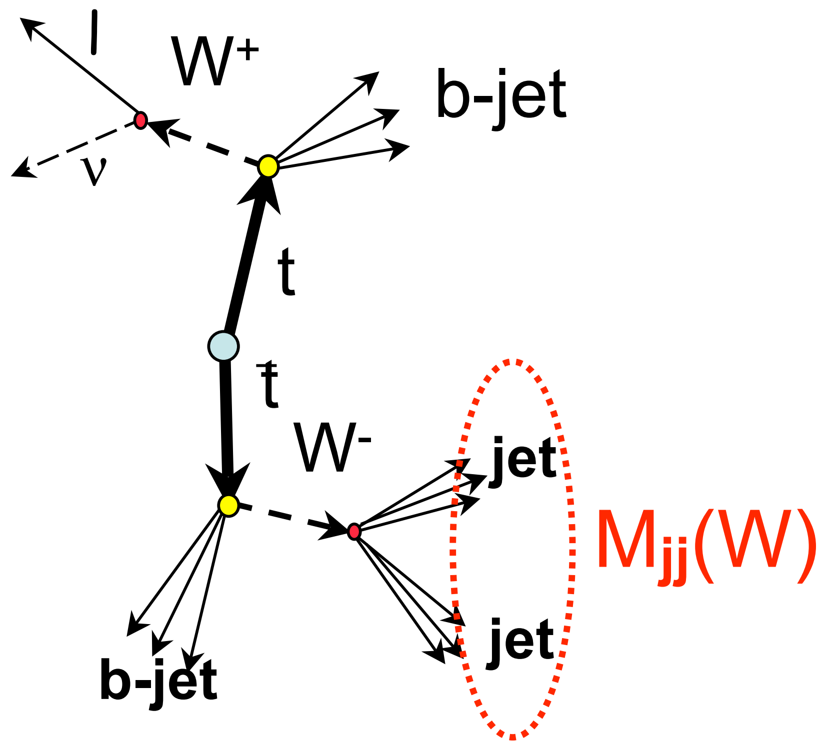


About 3 GeV of M_{top}

In-situ calibration: W->jj resonance

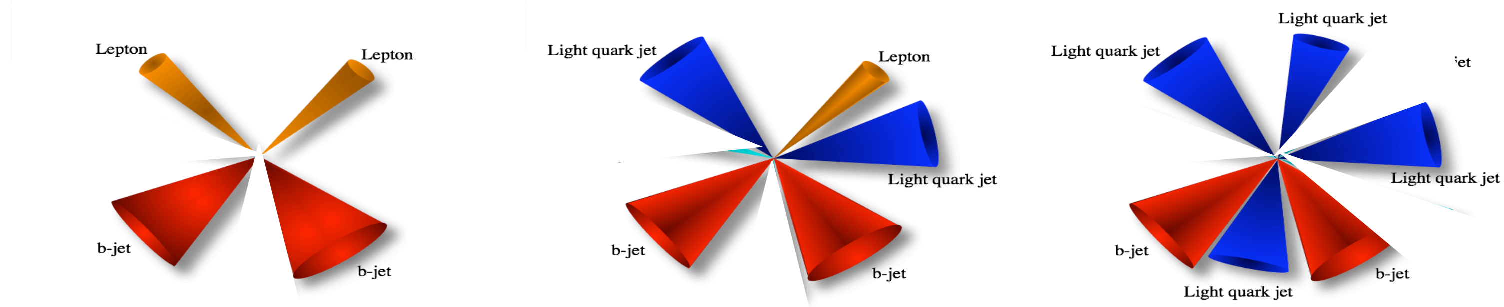


JES uncertainty:
mostly statistical,
scaled with lum

Challenge 2

- There are two top quarks & not all final states available
  - Too many combination to construct two top quarks (all jets: 90), missing information in dilepton channel

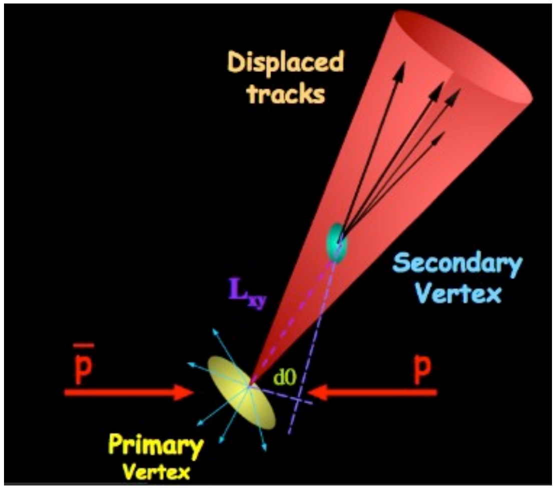
3 constraints: two M(w)=80.4, one M(t)=M(tb)

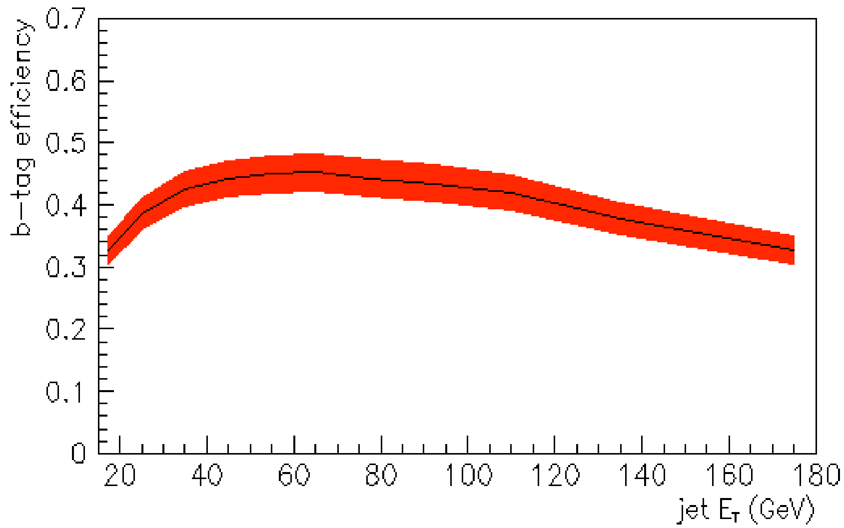


Ncomb(btag)	2(2)	12 (6)	360(90)
	2 missing ν Unconstrained: Small BR	1 missing ν Overconstrained: Golden Channel	No missing Overconstrained: Large bkgds

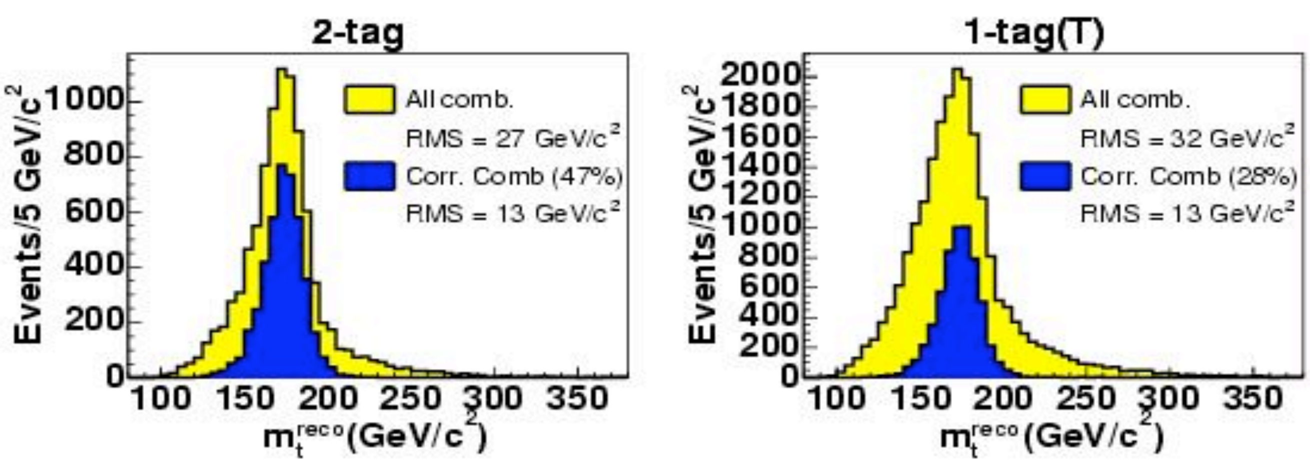
B-tagging

- B-tag: SecVtx tagger





- B-tagging helps!: reduces wrong comb. and improves resolution



Top Mass Measurements

Template

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

Matrix Element

- Calculate probability as top mass for all combinations in each event by Matrix Element calculation
  - maximize dynamic information
- Build Likelihood directly from the probabilities
- Calibrate measured mass and it's error using simulated events

Strategy

- Precision & consistency
  - Different channels
  - Different methods (using different information)
- New Physics (bias)

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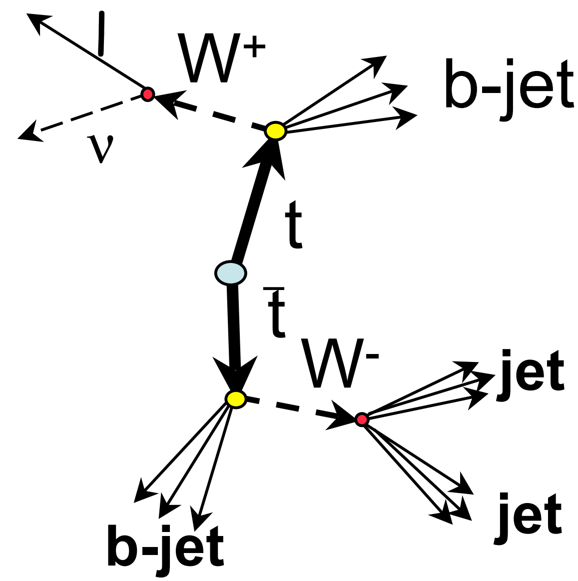
	Method	Njets		B-tag		JES			Rec. variables
		Exact	+extra	Yes	No	Wjj+std	Wjj	No	
LJ	TMP	4	>4						mt, m_{jj}, Lxy
	ME	4							P(Mt,JES)
DIL	TMP	2	>2						mt, Pt(lep)
	ME	2							P(Mt)
All-J	TMP+ME	6	>6						Mt, m_{jj}

Completed(~15 analyses groups)

Template Method in lepton+jets

- Event selection
  - High-pt central leptons (e,mu): Pt>20 GeV
  - 4 jets: Et>15 GeV, |η|<2.0
  - Large missing Et > 20 GeV



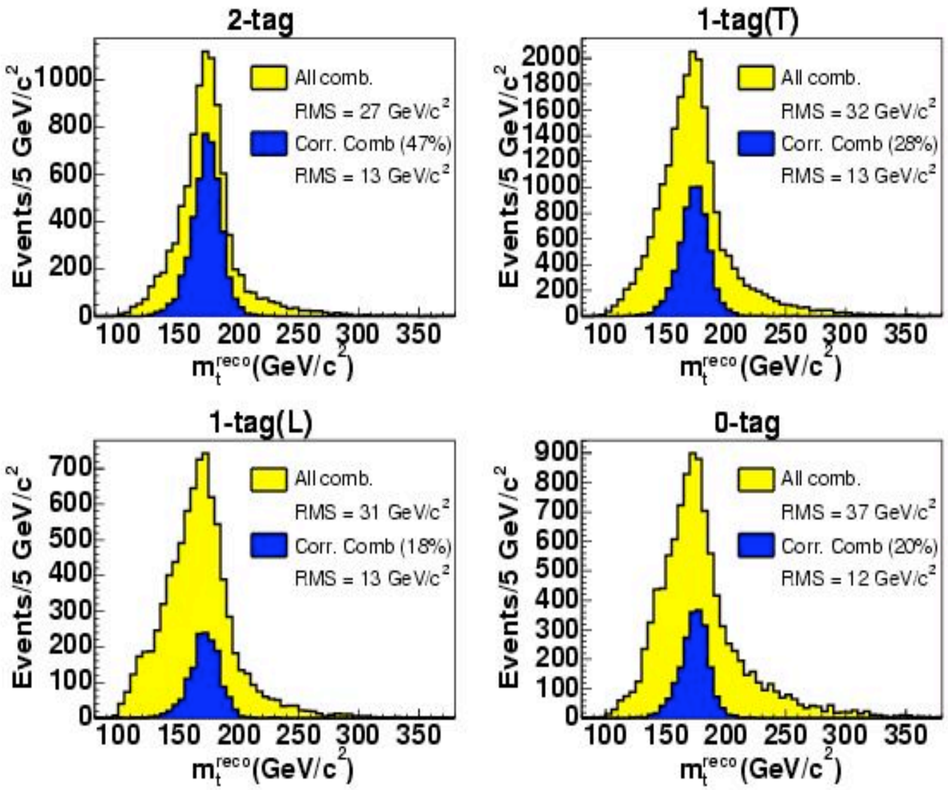
- χ^2 kinematic fitter: fully reco. ttbar system

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

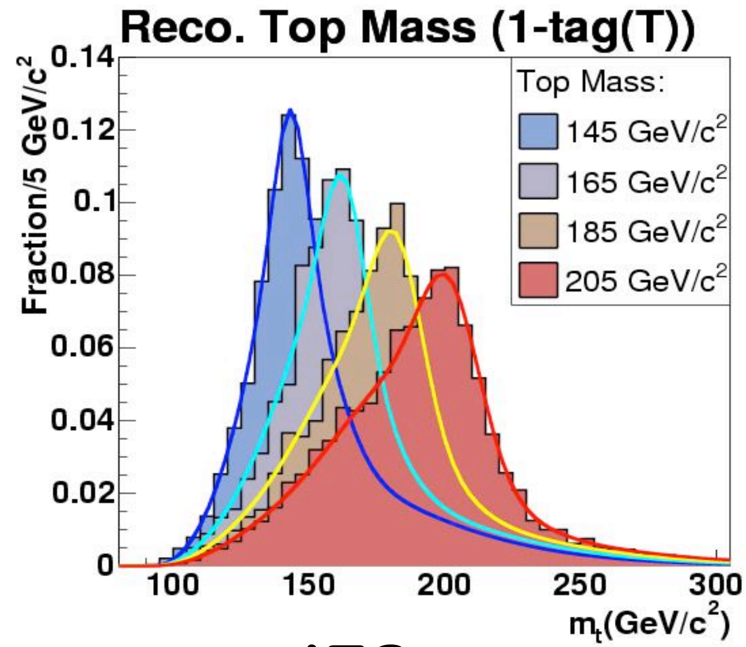
$$+ \frac{(m_{jj} - m_W)^2}{\Gamma_W^2} + \frac{(m_{l\nu} - m_W)^2}{\Gamma_W^2} + \frac{(m_{bjj} - m_t)^2}{\Gamma_t^2} + \frac{(m_{bl\nu} - m_t)^2}{\Gamma_t^2}$$

- ❑ Find m_t that fits event best over all combinations (m_W=80.4 GeV, $m_t = m_{\bar{t}}$)
- ❑ Reject badly reconstructed event

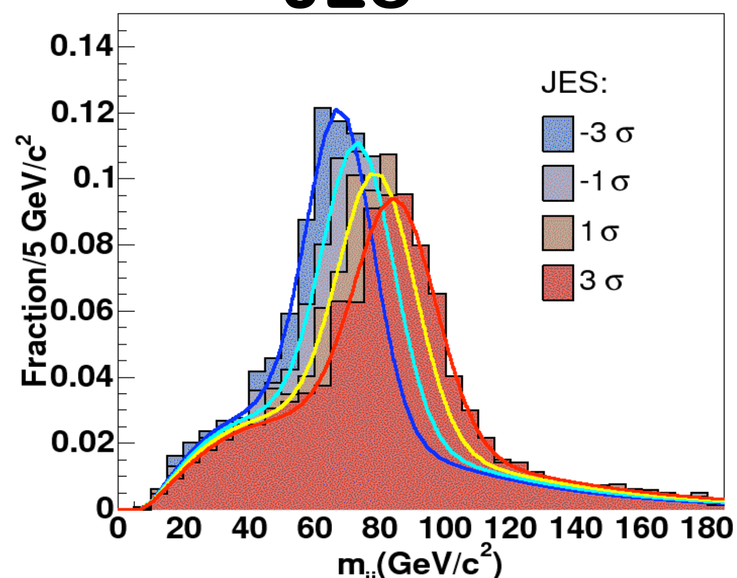
Signal Templates (m_t, JES)



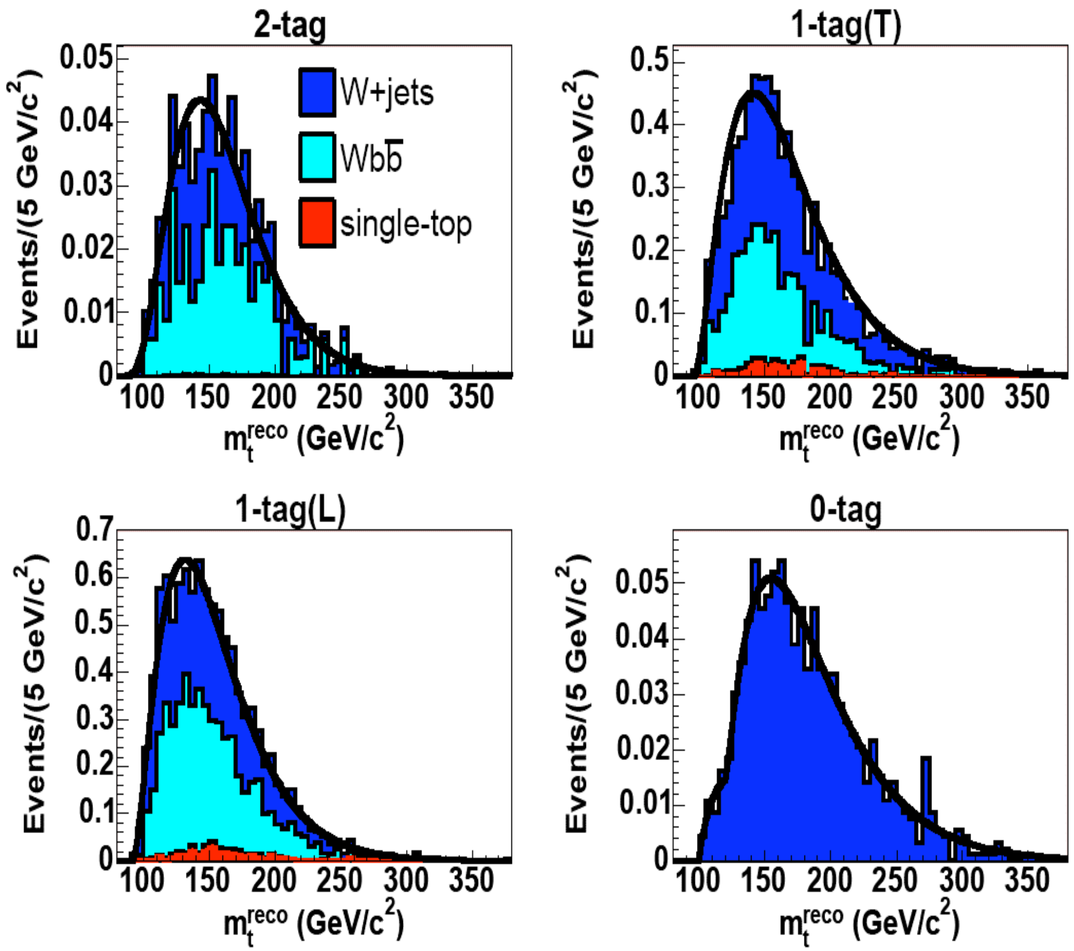
Reconstructed top mass (m_t) dist.
For Mtop = 178 GeV



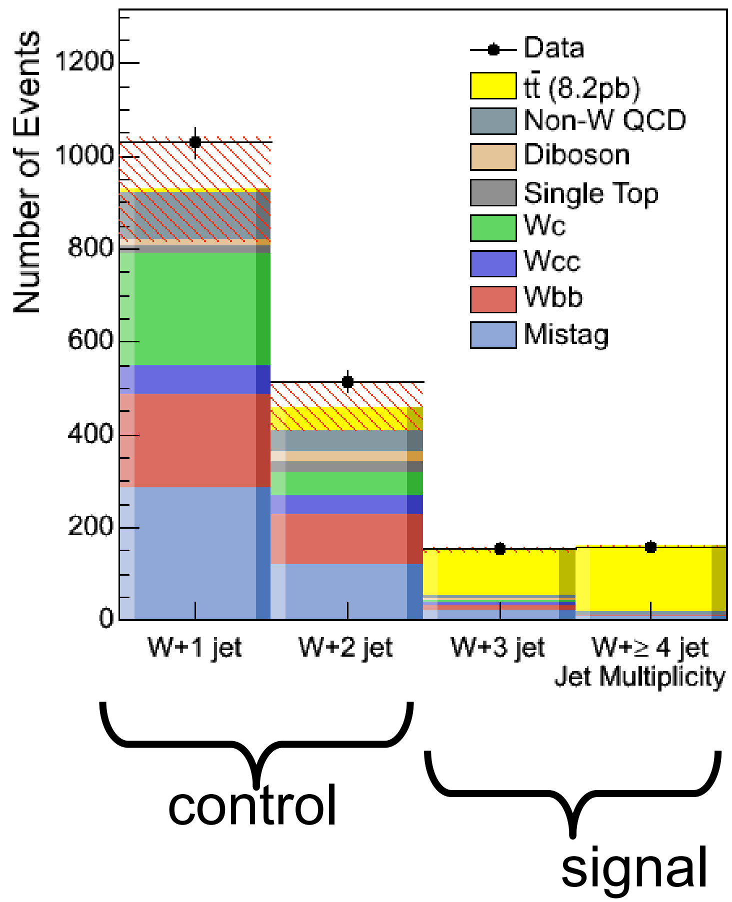
JES



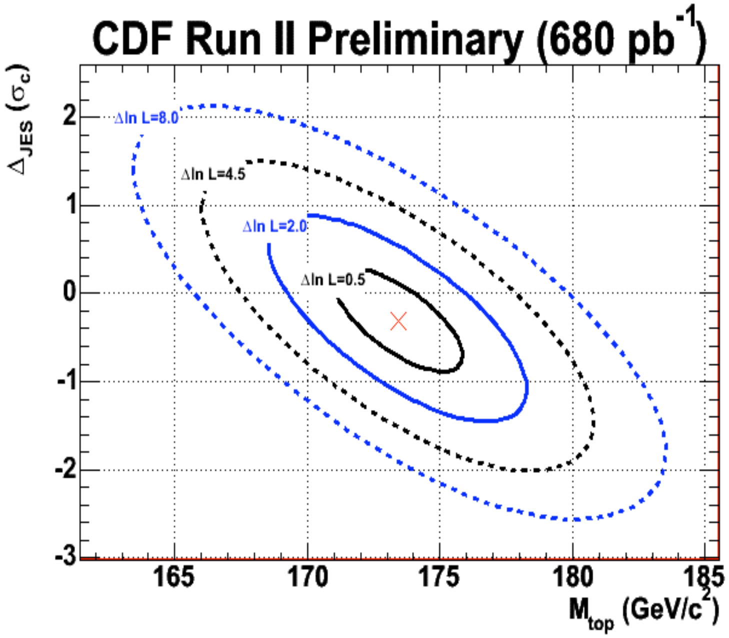
Backgrounds Templates



Backgrounds:with b-tag



Template Results in lepton+jets

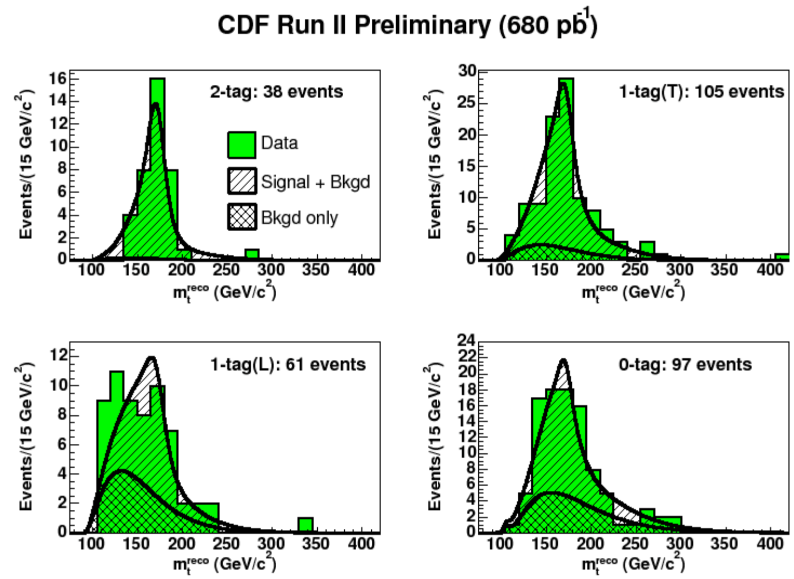


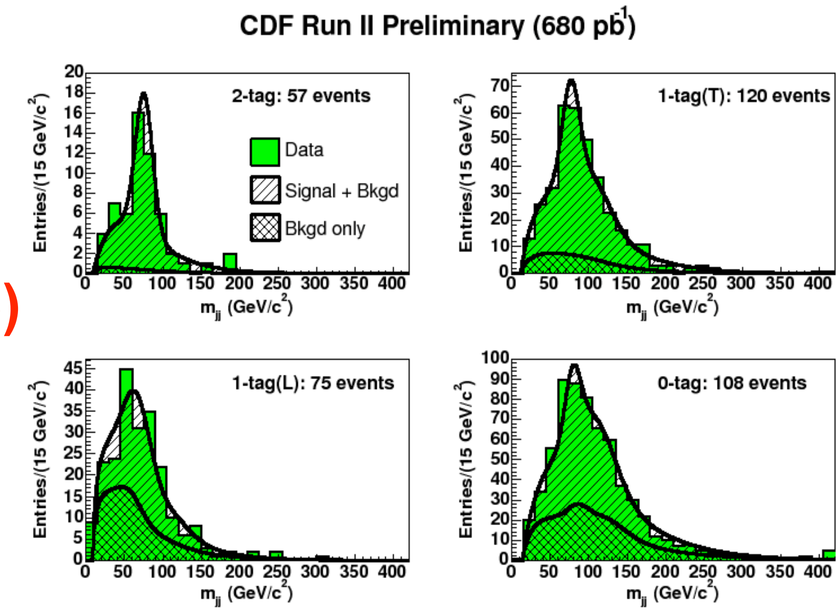
$$M_{top} = 173.4 \pm 2.5(\text{stat.} + \text{JES})$$
$$\pm 1.3\,(\text{syst.})\ \text{GeV}/c^2$$

- **World best measurement (Spring06)**

  40% improvement on JES using Wjj

- PRD/PRL with 320pb-1
- Toward 2nd publication with 1fb-1





Matrix Element Method in lepton+jets

- Maximize kinematic and dynamic information
- Calculate a probability for a signal and background as a function of the top mass
- Integrate over all the unmeasured quantities convoluting the differential cross-section with the experimental resolutions

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

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

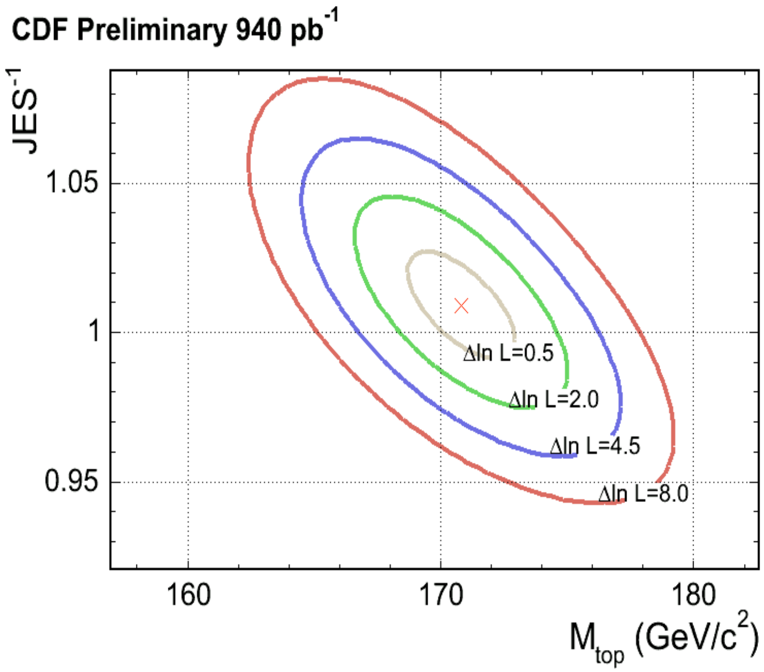
Transfer function: probability to measure jet x for parton y

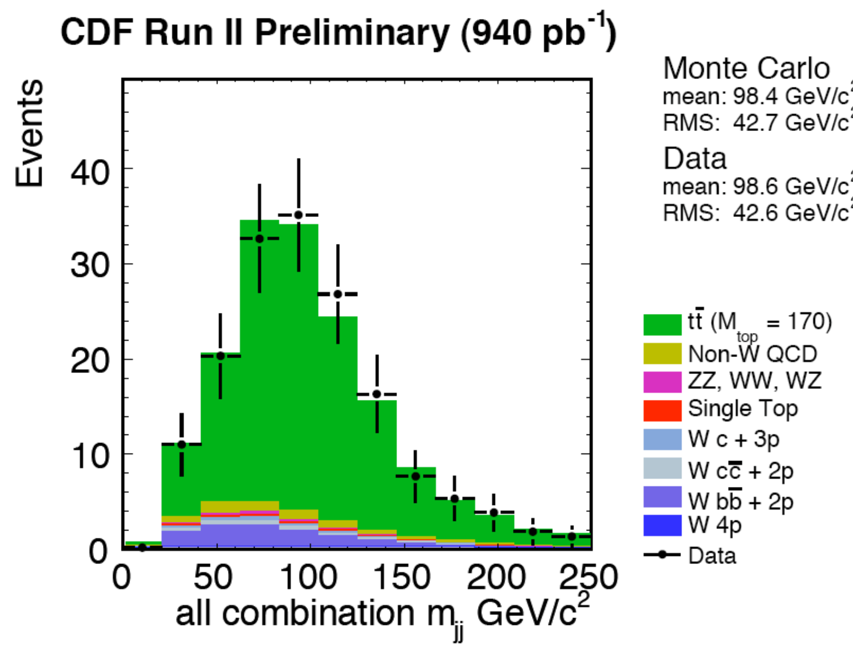
- JES is a free parameter, constrained in situ by the W(->jj) mass
- Likelihood used to fit simultaneously M_{top} and JES

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

M.E. results in lepton+jets

- Event Selection: b-tag but with exact 4jets (166 events)





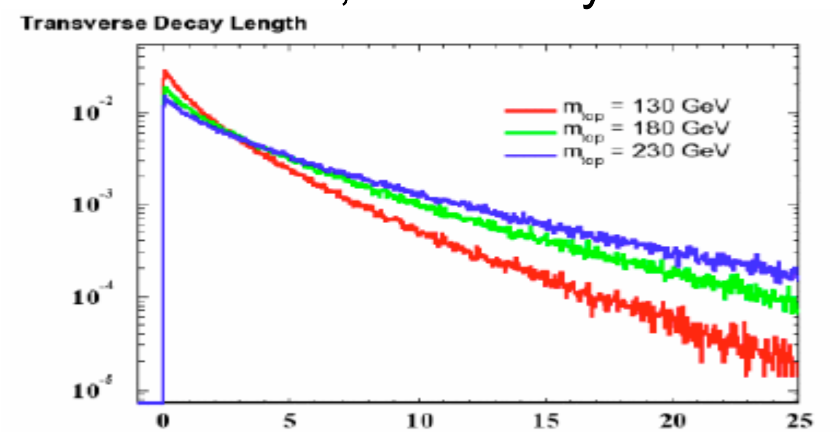
$$M_{top} = 170.9 \pm 1.6\,(\text{stat.}) \pm 1.4\,(\text{JES}) \pm 1.4\,(\text{syst.})\,\text{GeV}/c^2$$

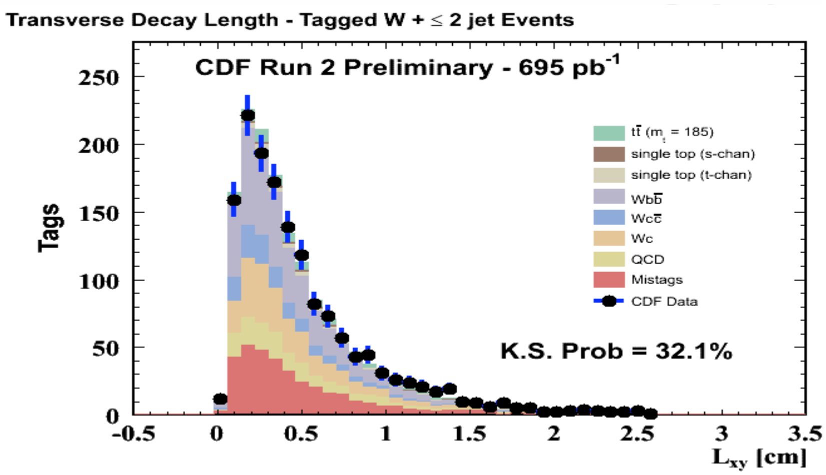
- Most precise world measurement (Summer 06): $1fb^{-1}$
- Toward 2nd publication using $1fb^{-1}$

Template using Decay Length (Lxy)

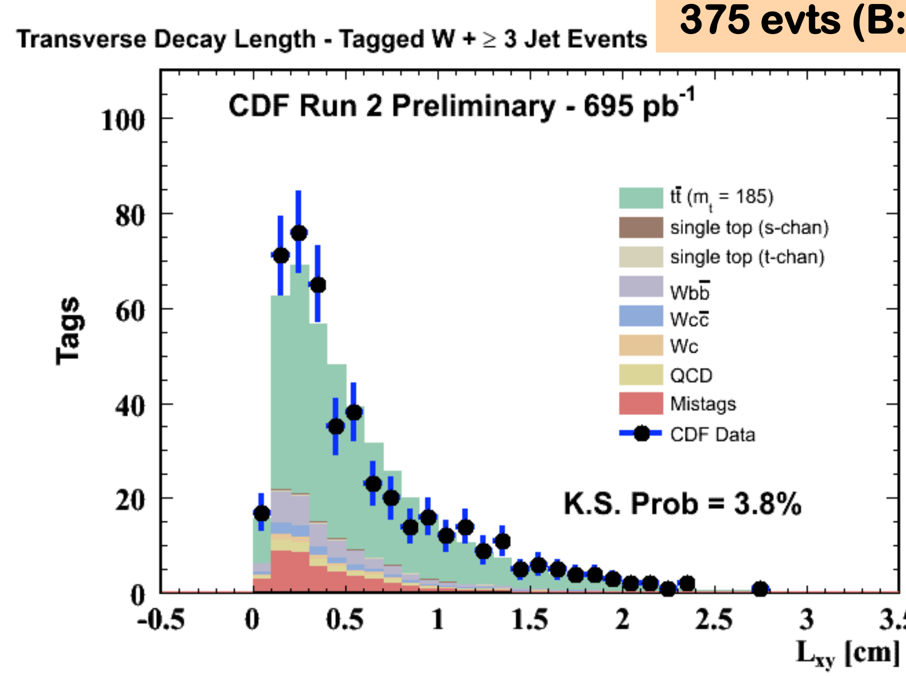
- Uses the average transverse decay length, Lxy of the b-hadrons
- B hadron decay length $\propto$ b-jet boost $\propto$ M_{top} (>=3jets)

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





375 evts (B:111)



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

Insensitive to JES, but need Lxy simulation

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

Comparisons in Lepton+Jets (0.7fb-1)

Measurement	Template	ME	Lxy
JES	(1.8)	(1.7)	0.3
Residual	0.7	0.4	
B-jet JES	0.6	0.6	
ISR/FSR	0.5	1.0	1.3
Bkgd shapes/ normalization	0.5	0.2	3.3
Generators	0.3	0.2	0.7
PDFs	0.3	0.1	Data/MC <Lxy> SF 4.2
Methods	0.3	0.1	
B-tagging	0.1	0.3	
Total	1.3	1.4	5.6

Methods in dilepton

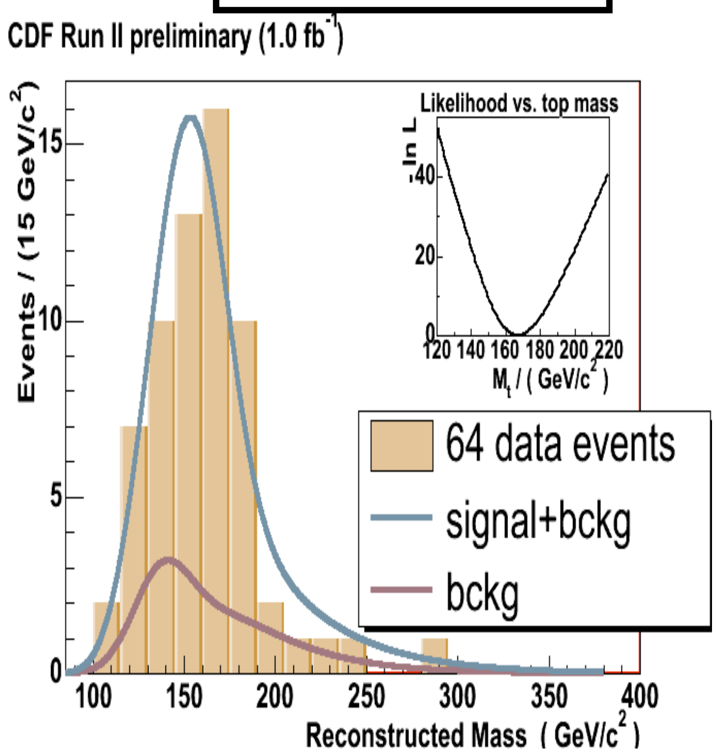
- Unconstrained system;
  2 neutrinos, but 1 missing E_T observable

❑ 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

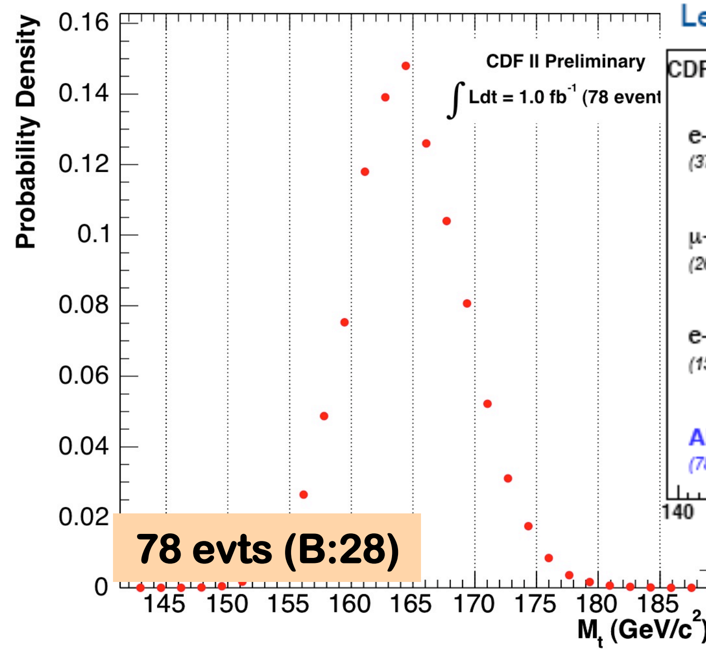
❑ Matrix Element:
- Integrated over unknown variables using the LO Matrix Element assuming jet angles, lepton are perfect, and all jets are b's
- Obtain P(Mtop) for signal and backgrounds
- Calibrate off-set in pull and pull width using fully simulated MC

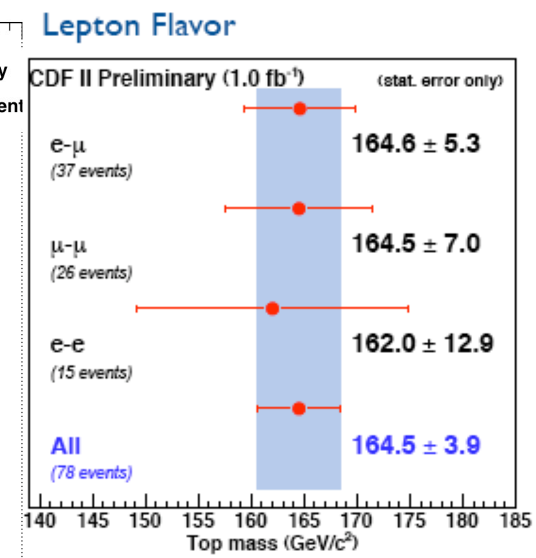
Results in dilepton

Template



Matrix Element





$$M_{top} = 168.1 \pm 5.6\,(\text{stat}) \pm 4.0(\text{syst})\ \text{GeV}/c^2$$

$$M_{top} = 164.5 \pm 3.9\,(\text{stat}) \pm 3.9(\text{syst})\ \text{GeV}/c^2$$

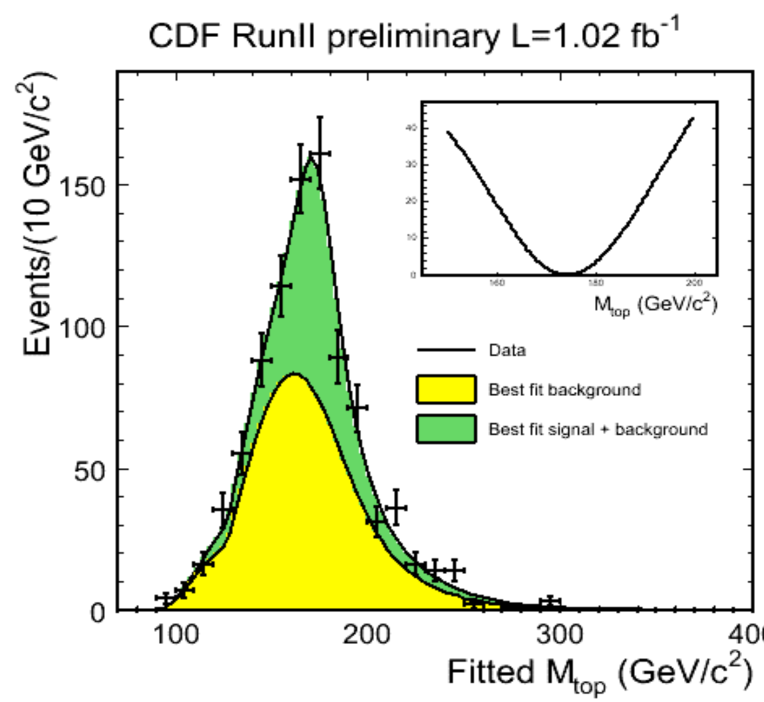
- Event selections: 2 leptons (Pt>20), 2jets (Et>15), MET> 25 GeV
- Syst. error is comparable to the stat. error
- Toward 2nd publications with 1fb^{-1}

Template in all-jets

- Template method with fitted M_{top} as observable
- Choose among all possible comb ination of 6 jets

  using a kinematic fitter
- Event seletion:
  - $E_T / \sqrt{(\Sigma E_T)} < 3\ (\mathrm{GeV})^{1/2}$
  - $\Sigma E_T \geq 280$ GeV
  - $n_{b\text{-}tag} \geq 1$ (b-tag)
  - $6 \leq N_{jet} \leq 8$
  - Neural Network selection

    to improve S/B = 1/2 (vs 1/8)
- And data-driven background template



$$M_{top} = 174.0 \pm 2.2\,(stat.) \pm 4.5\,(JES) \pm 1.7\,(syst.)\ GeV/c^2$$

$$\text{New } M_{top} = 171.1 \pm 3.7\,(\text{stat.} + \text{JES}) \pm 2.1\,(\text{syst.})\ \text{GeV}/c^2$$

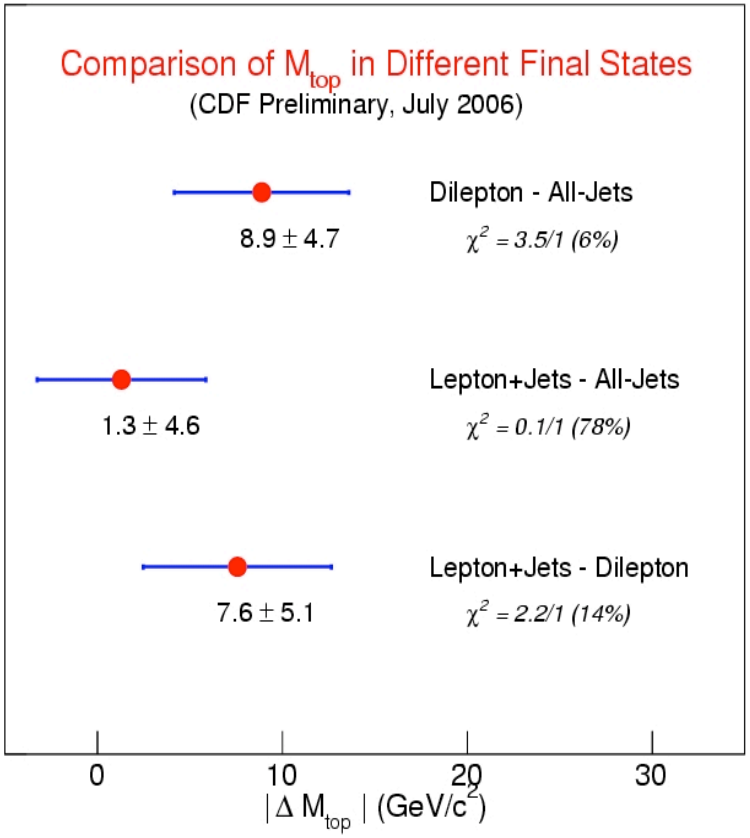
Comparisons of all channels

Measurement	Letpton+Jets (ME)	All-jets (ME+TMT)	Dileptons (ME)
Mtop	**170.9**	**171.1**	**164.5**
JES	(1.6)	(2.4)	3.4
Signal	1.1	1.7	0.7
Backgrounds	0.2	1.0	0.9
Others	0.5	0.8	1.3
Total Syst.	**1.9**	**2.1**	**3.9**
Statistical	**1.6**	**2.8**	**3.9**
Total	**2.5**	**4.3**	**5.5**

Combining M_{top} Results

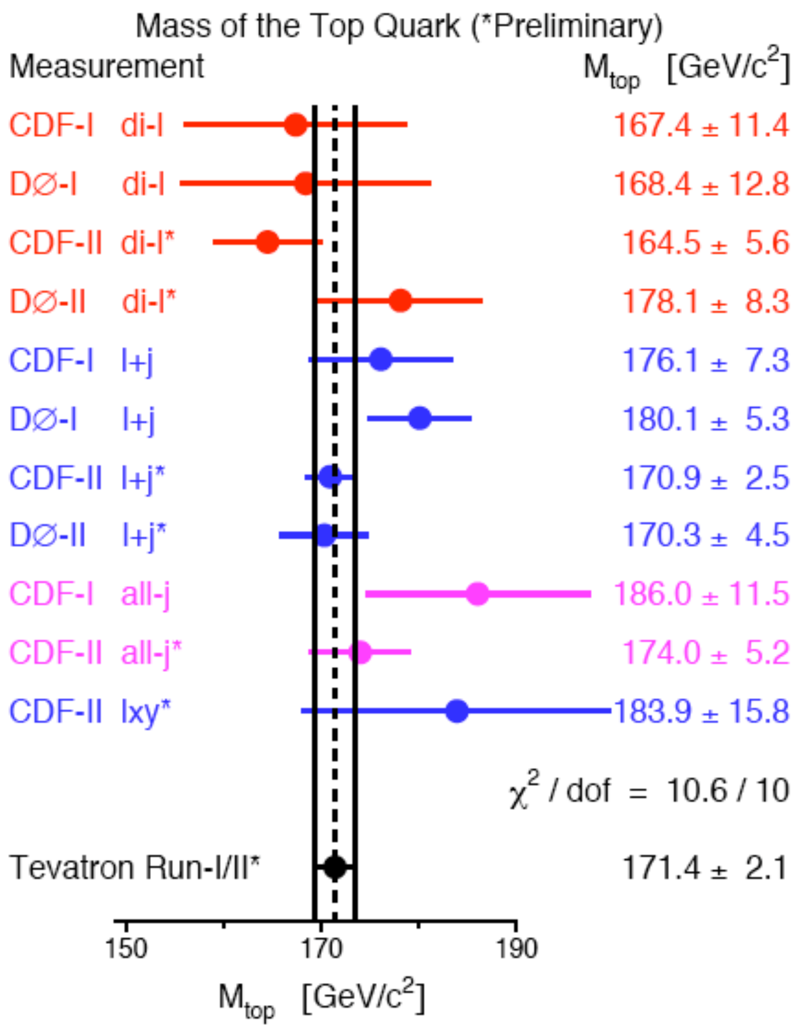
- Are the channels consistent ?

Summer 2006
Mtop(All Jets) = 172.5 ± 4.4 GeV/c^2
Mtop(Dilepton) = 163.6± 5.1 GeV/c^2
Mtop(Lep+Jets) = 171.2 ± 2.5 GeV/c^2

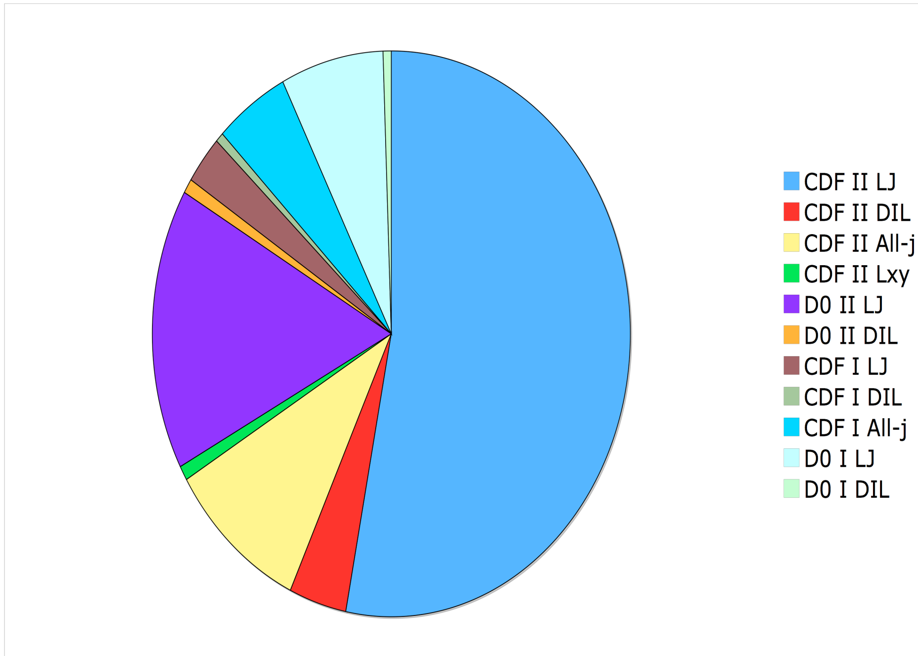


- Any systematic shift?
  - Missing systematic?
  - Bias due to new physics signal?

Tevaron Average



Weight (%)



$$M_{top} = 171.4 \pm 2.1\ \mathrm{GeV}/c^2\ \ (1.2\%)$$

hep-ex/0608032

Constraint on Higgs

- A Precision EWK Fit

$$M_H = 85^{+39}_{-28}\,\mathrm{GeV/c^2}$$

$$M_H < 166\ \mathrm{GeV/c^2}\ @95\%C.L$$

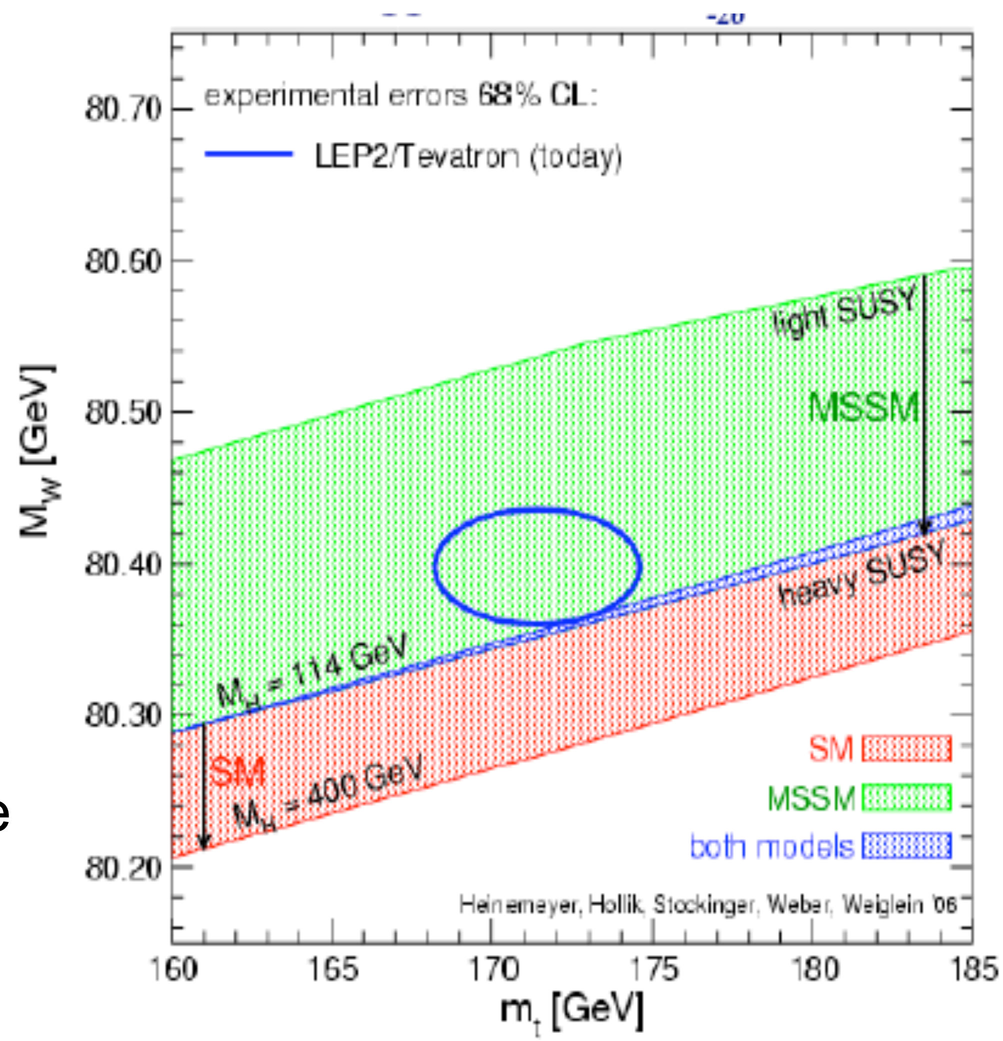
$$M_H = 80^{+36}_{-26}\,\mathrm{GeV/c^2}$$

$$M_H < 153\ \mathrm{GeV/c^2}\ @95\%C.L$$

- Direct search(LEP):

  $M_H > 114$ GeV

- Indicates Higgs is light where Tevatron sensitivity best!

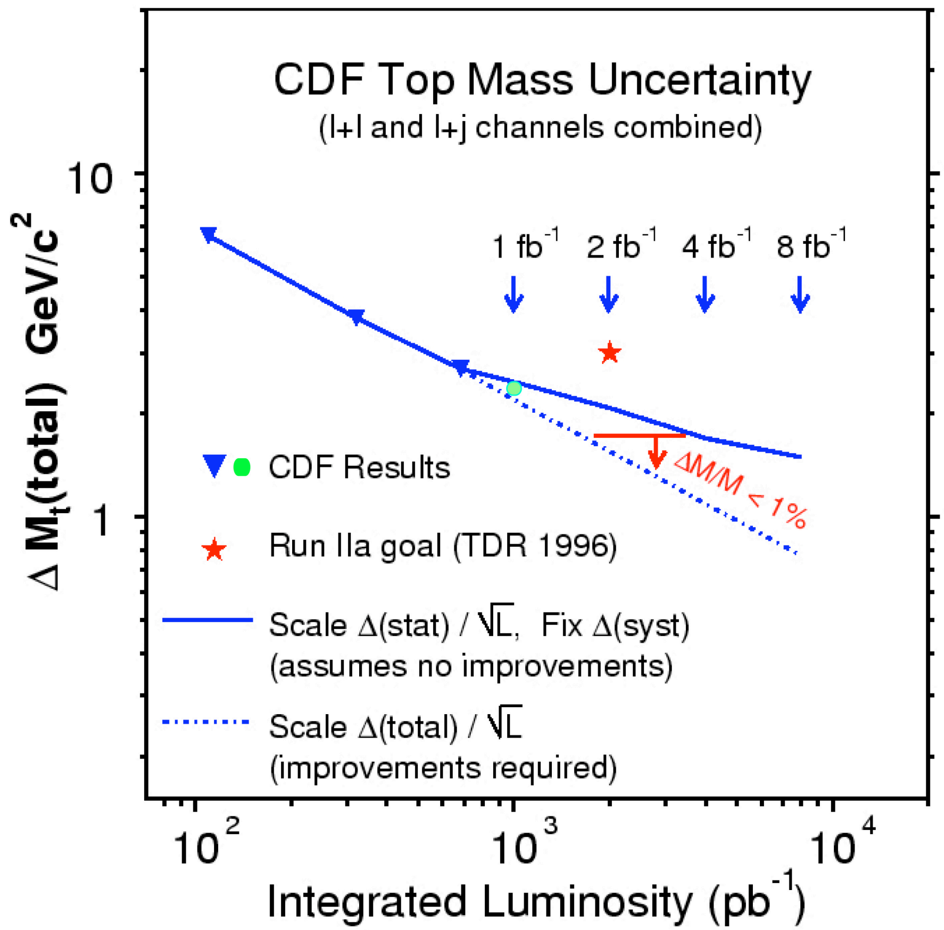


$$M_W = 80413 \pm 34_{stat} \pm 34_{syst}\ \mathrm{MeV}$$

Most precise world measurement

Summary and Future

- Achieved 1.2% precision (surpassed Run IIa goal using only 30% data): strong constraint on the Higgs
- With full Run-II dataset, able to achieve δMtop to < 1 GeV/c^2
- Will be one of the lasting legacies of the Tevatron
- Many developed tools for LHC

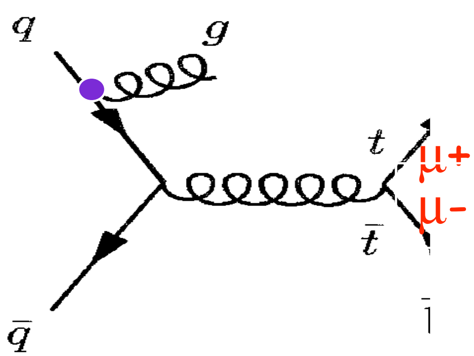


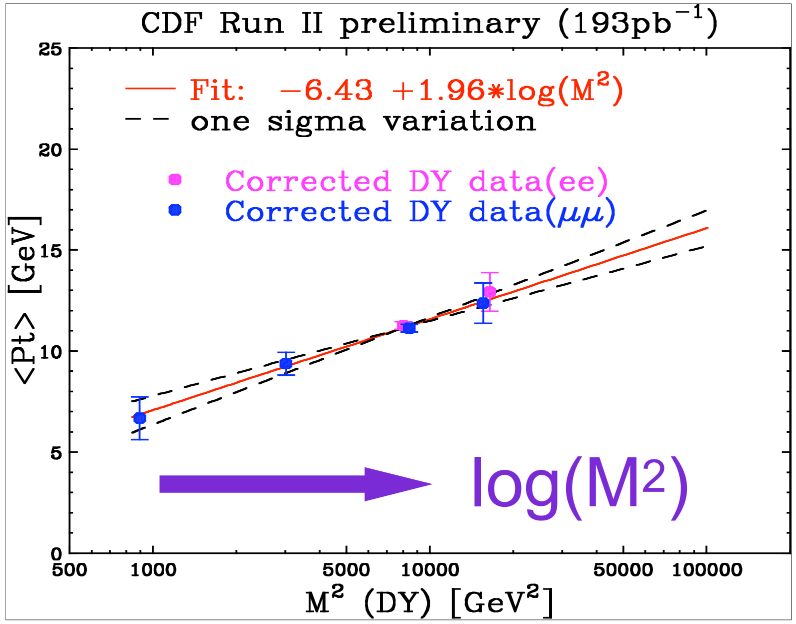
Few Lessons from Tevatron

- A major JES uncertainty is greatly reduced by the Wjj in-situ calibration (50% improvement with 1fb-1 data)
- B-jet specific uncertainty is small (<0.7 GeV)
  - Heavy-quark fragmentation
  - Color-interference (under reinvestigation)
  - 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 GeV difference in top mass: CDF, but only gg 15% events)
- Effect of the multiple interaction is small
- Effect of the backgrounds is small (except all-jets channel)

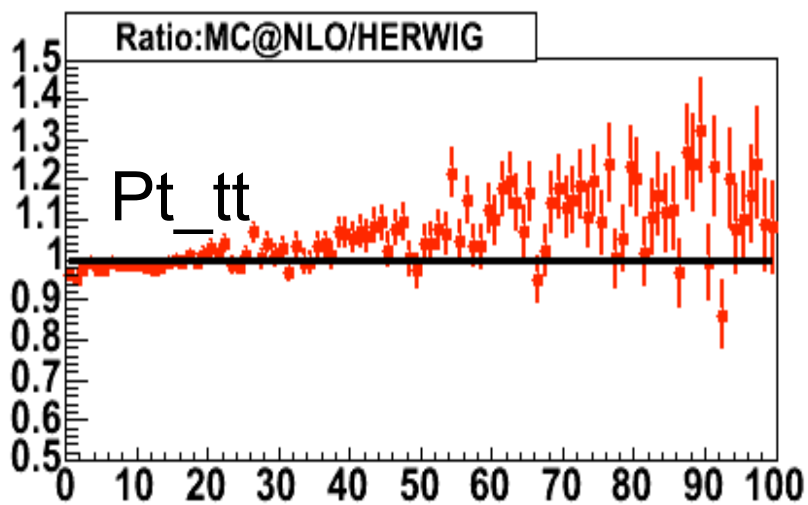
Syst. : ISR/FSR/NLO

- Method in hand to use Drell-Yan events to understand and constrain extra jets from ISR
  - Constraint scales with luminosity
  - Easily extendible to FSR.

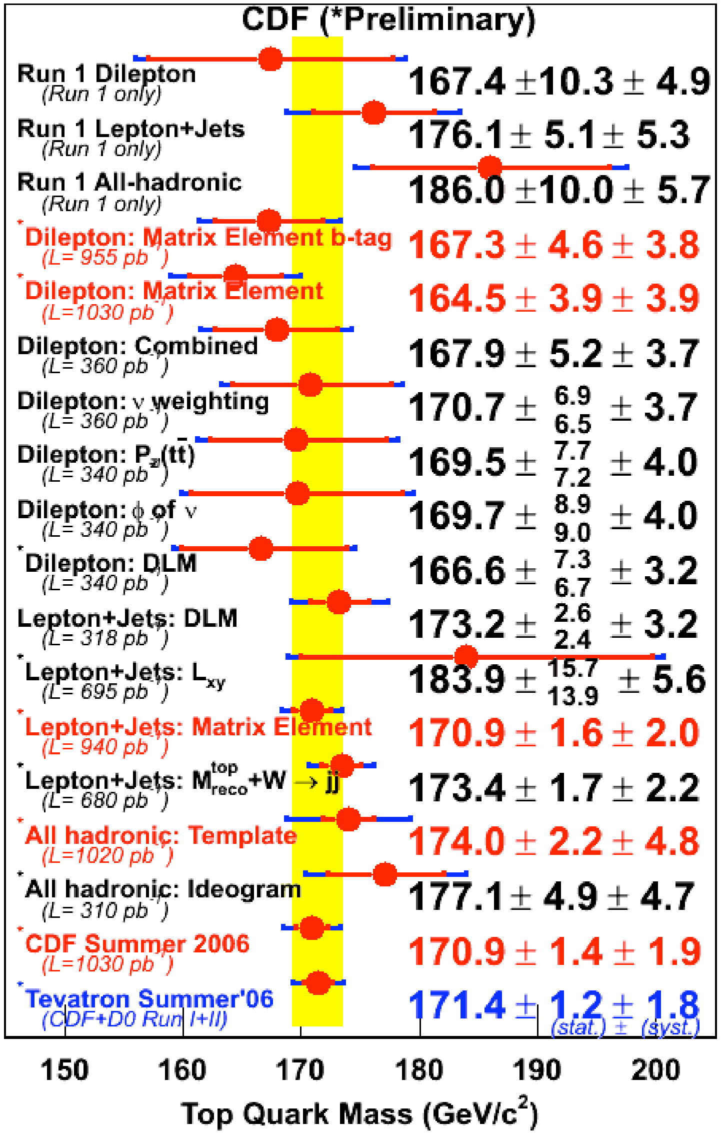


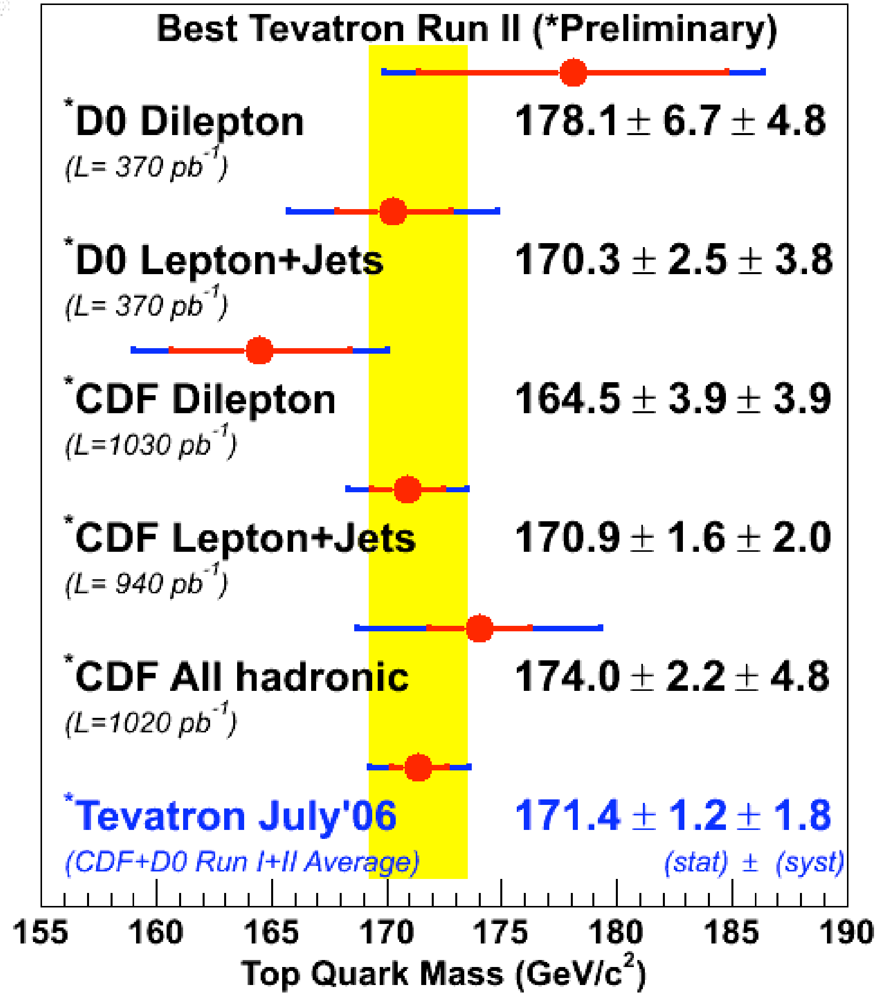


- MC@NLO sample shows no add'l NLO uncertainty is needed.



CDF and Tevatron Summary





Mass vs Cross Section