FSP 101 ATLAS

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

Top quark mass: from Tevatron to early LHC

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Standard Model discoveries with early LHC data
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Outline

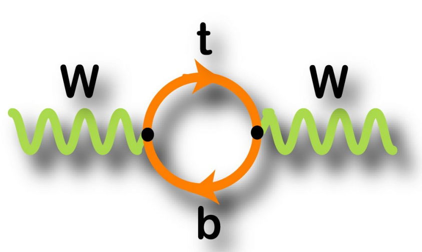
- Motivation
- Analysis strategies at Tevatron
- Jet energy calibration
- Methods and latest results from Tevatron
- Uncertainties on top mass
- Top mass with early LHC data
- Conclusion

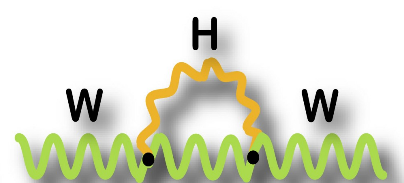
Top quark mass

- Fundamental parameter of the SM
- Heavy: Yukawa coupling to Higgs ~ 1
- Constrains SM Higgs mass together with W mass
  - a guide to Higgs search
- The most precisely known property of the top quark

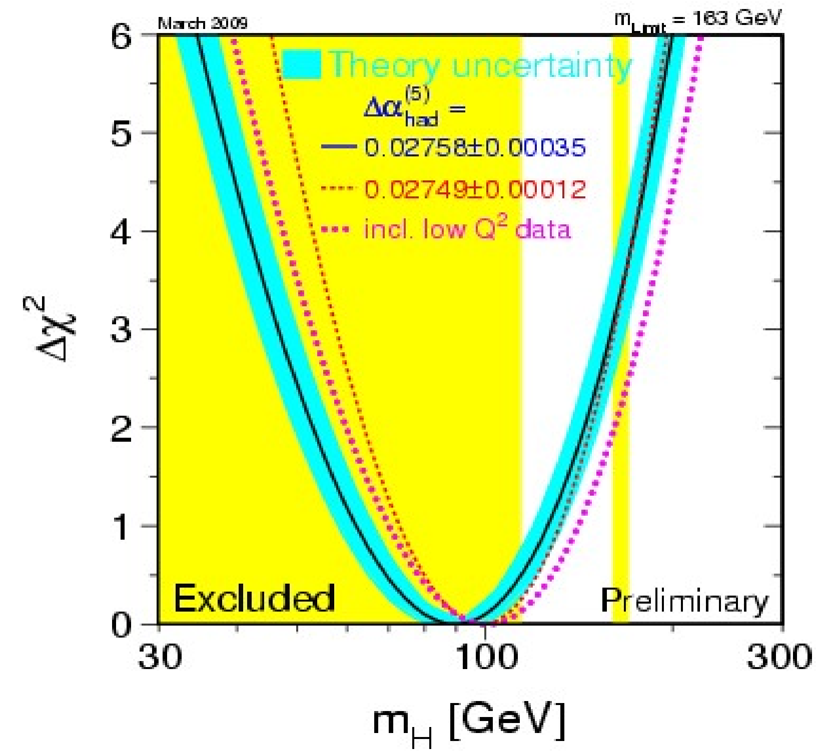
M_H<163 GeV @ 95% CL
New the most precise D0 W mass not included

Radiative corrections to W mass:





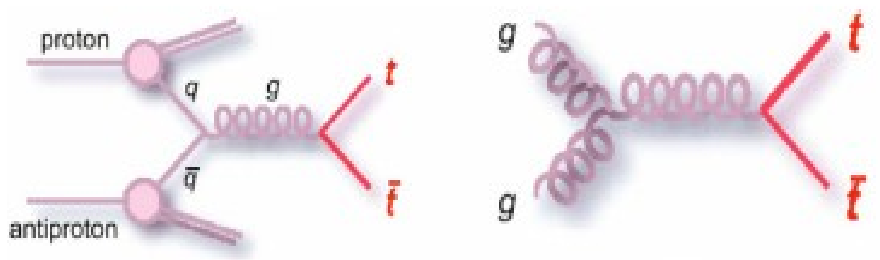
$\Delta r_t \sim m_t^2$ $\Delta r_{Higgs} \sim \ln(m_H^2)$



M_H<154 GeV @ 95% CL summer 2008
Δm(top) = 0.7 GeV

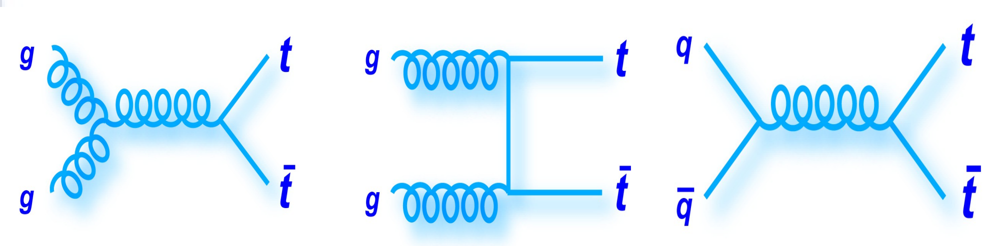
Top quark production and decay

- Produced mainly in pairs
  - σ ≈ 7 pb @ 2 TeV



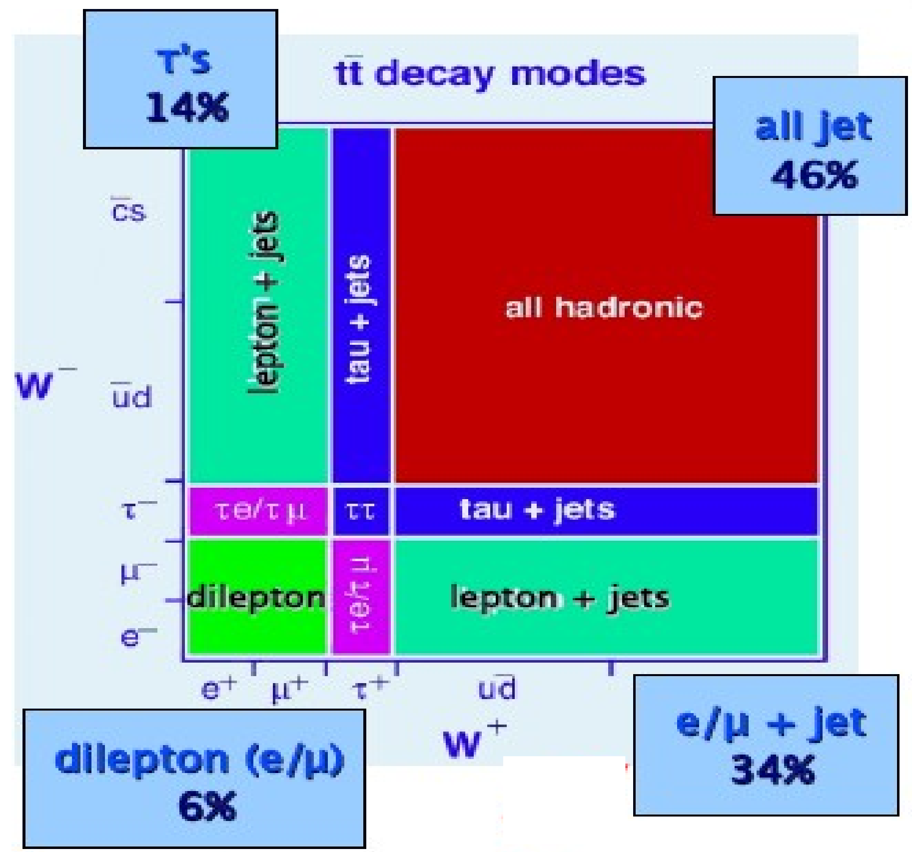
85% 15%

  - σ ≈ 400 pb @ 10 TeV



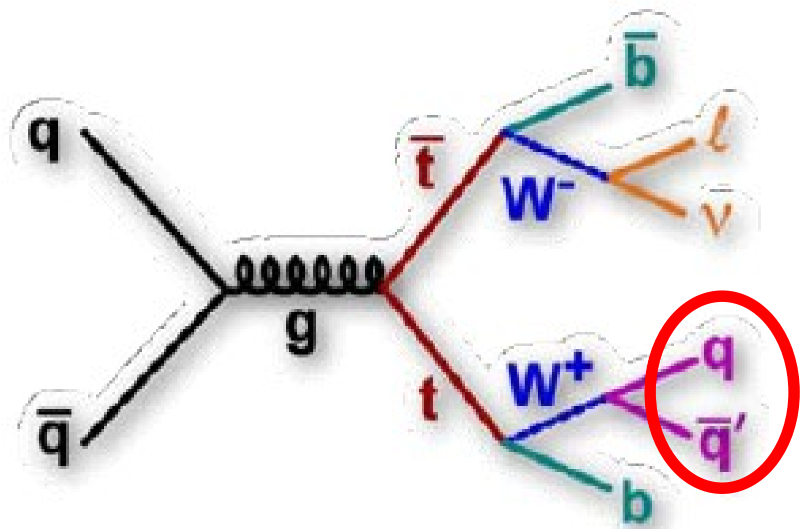
90% **10%**

- SM decay: t→Wb ~100%
- W decays define final state



Mass: challenges and new ideas

- Combinatorics
- Jet energy calibration



- Hadronic decay W → qq: in-situ calibration of jet energies
- Routinely used at Tevatron

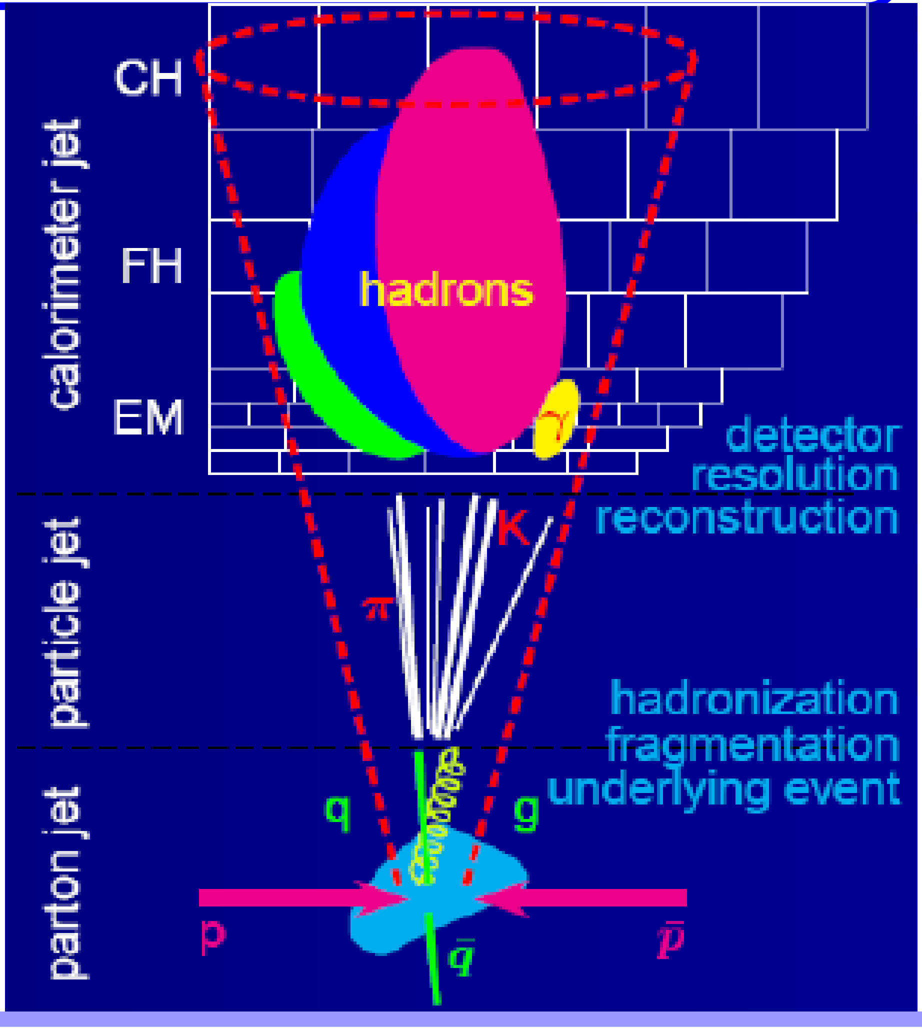
Recent developments

- Include cross section information or extract mass from cross section
- Combine several final states into one analysis
  - Simultaneous measurement in dilepton and l+jets channels calibrates in-situ JES in dilepton channel
- Use observables less sensitive to dominant systematic uncertainties
  - Lepton pT spectrum
  - Decay length of B-hadrons

General concept

Top quark mass measurements require a clean mapping between reconstructed objects and partons

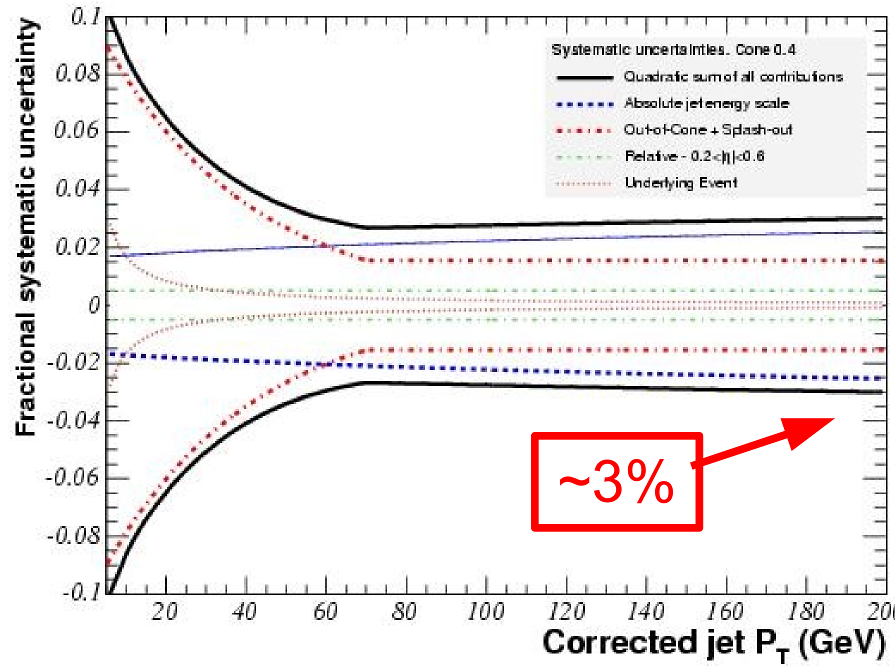
- Reconstruct jets using cone algorithm
- Calibrate jet energies to particle level
- Map jets to partons
- Correct jet energies to parton level



JES: CDF

- Corrects to parton level
- Divided into different levels to accommodate different effects
  - response of the calorimeter
  - non-linearity of response
  - non-instrumented regions
  - spectator interactions
  - energy radiated outside the jet clustering algorithm cone
- Single particle response tuned to
  - Collision data at pT<20 GeV
  - Test beam data for pT>20 GeV
- Depending on the physics analyses, a subset of these corrections can be applied

- Smaller uncertainties due to better tuning of MC to data (factor of ~5)



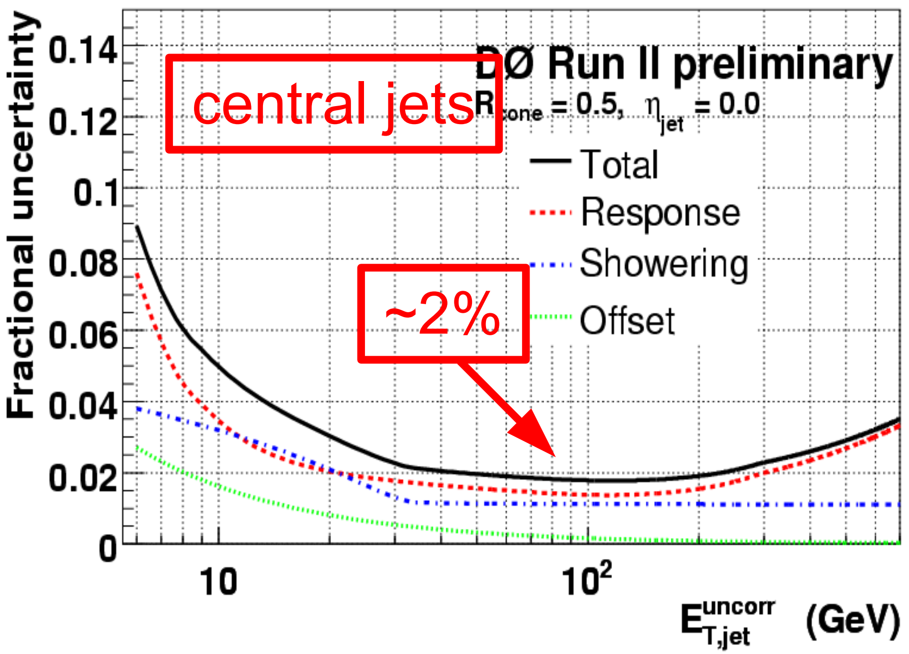
- Main contributions:
  - Out-of -cone at low pT
  - Absolute JES at high pT

JES: D0

- Corrects to particle level

$$E_{corr} = \frac{E_{meas} - O}{R \times S}$$

- Offset – energy not associated with hard scatter: noise, pile-up, multiple interactions
- Response – fraction of particle jet energy deposited in calorimeter by particles; R (F_{η}) – absolute (relative) correction
- Showering – energy flow in/out of calorimeter jet due to detector effects (finite calorimeter tower and hadron shower size, magnetic field)

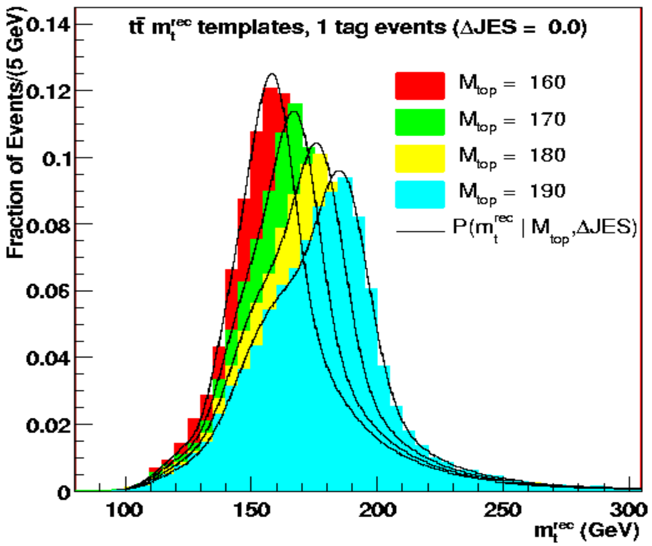


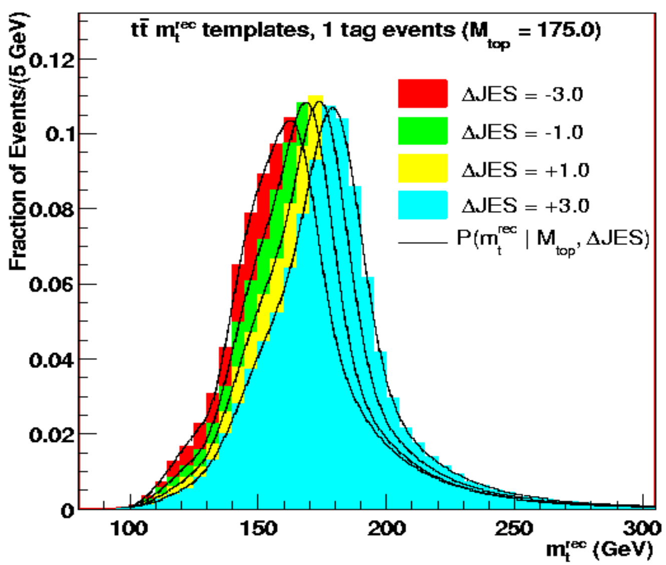
- Two separate JES: for data, MC
- Derived mainly from γ + jets data and MC events, verified with multijet and Z+ jets
- Largest uncertainty – absolute response correction

Methods and results

Template method

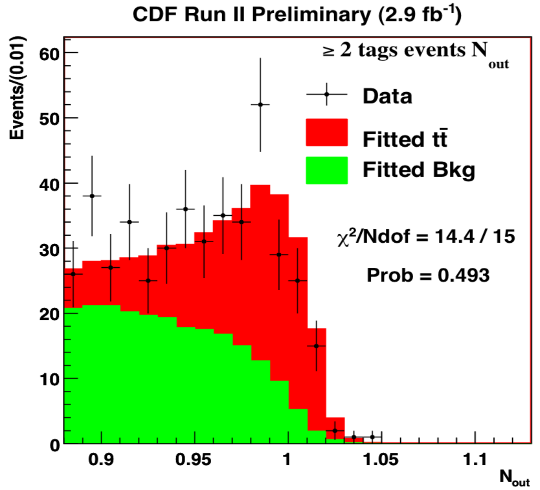
- Choose and calculate per event one or more observables sensitive to true m_t
- Build templates for signal and background distributions in this observable at different m_t (and JES) values
- Determine most likely top mass from templates fit to data



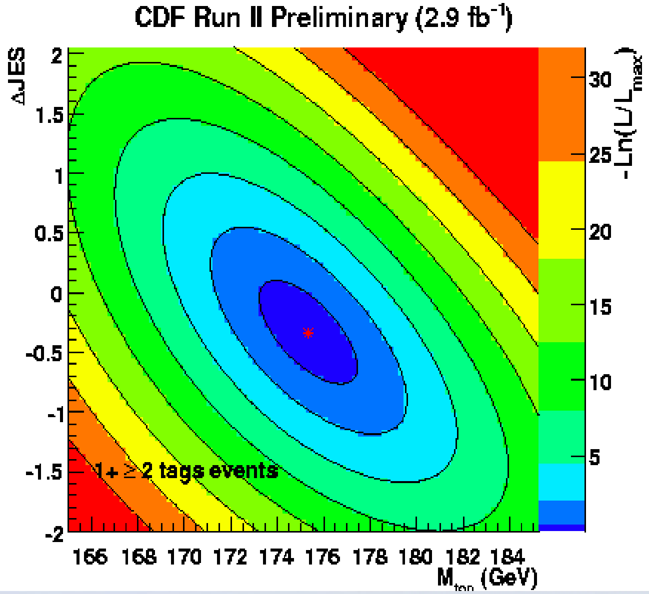


Mass in all-hadronic channel

- Selection: 6-8 good jets, ≥ 1 b-tags, cut on 13 variable NN output
- Data-based background model
- Kinematic fitter:
  - compare reconstructed top and W masses with MC expectation
  - for templates keep combination with best χ^2



$$\chi^2 = \frac{\left(m_{jj}^{(1)} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(m_{jj}^{(2)} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(m_{jjb}^{(1)} - m_t^{rec}\right)^2}{\Gamma_t^2} + \frac{\left(m_{jjb}^{(2)} - m_t^{rec}\right)^2}{\Gamma_t^2} + \sum_{i=1}^{6} \frac{\left(p_{T,i}^{fit} - p_{T,i}^{meas}\right)^2}{\sigma_i^2}$$



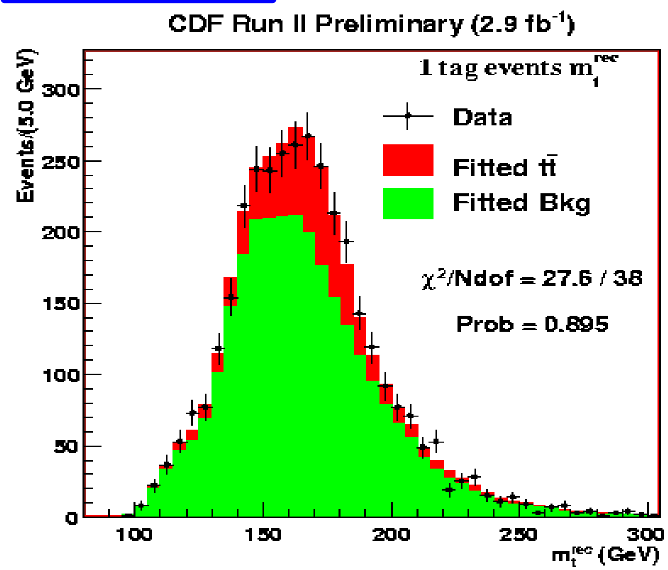
- Define likelihood $L = L(N_{sig}, N_{bkg}, pdf)$
- Find m_t and JES from L_{max}

$$m_t = 174.8 \pm 1.7(stat) \pm 1.6(JES)^{+1.2}_{-1.0}(sys)\ GeV$$

$$\Delta JES = -0.30 \pm 0.47(stat + m_t)^{+0.34}_{-0.37}(sys)$$

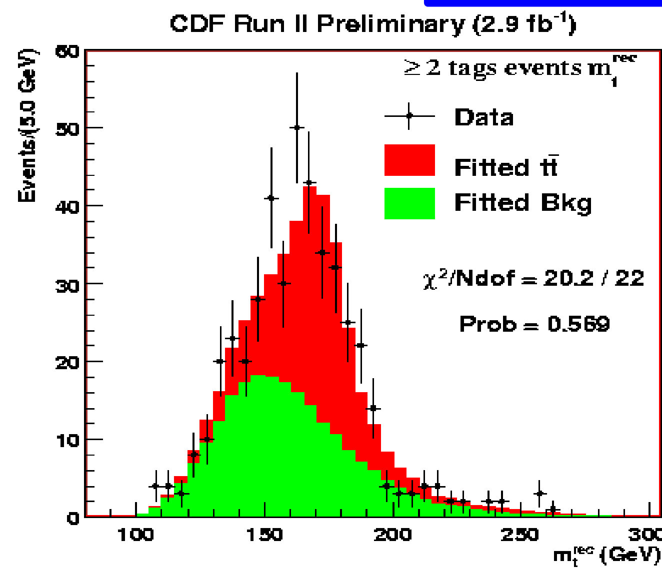
Reconstructed masses

1 b-tag



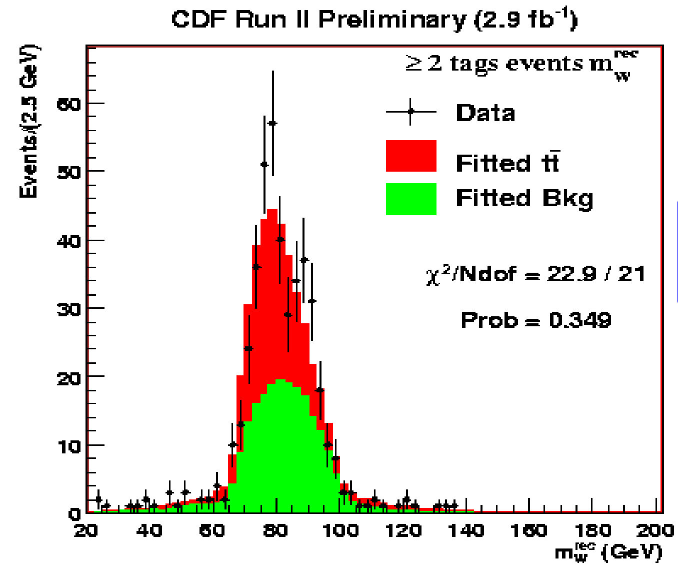
top

2 b-tags



2.9 fb^{-1}

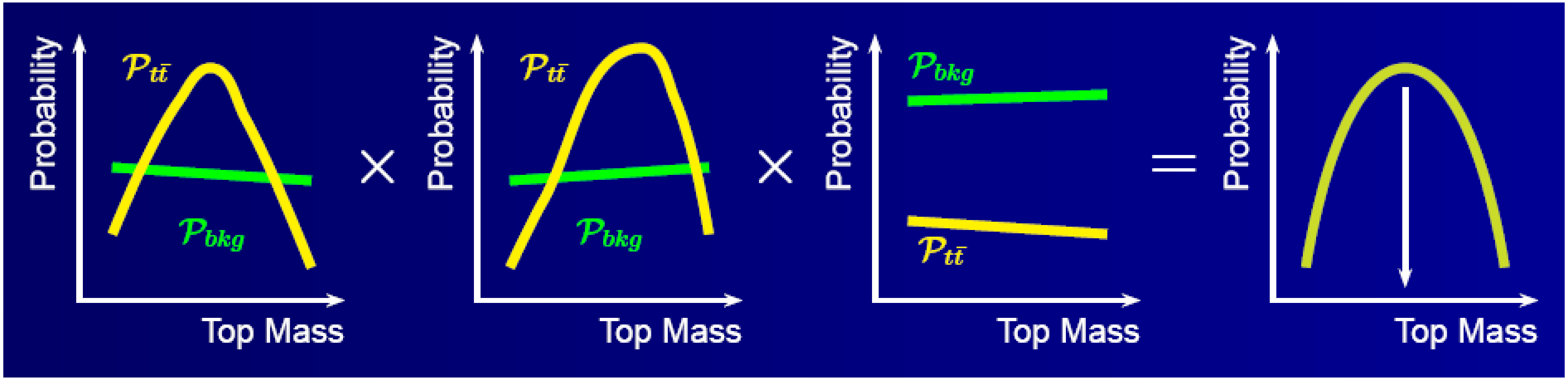
	1 b-tag	2-btags
observed	3452	441
Exp bckg	2785 ± 83	201± 29
Fitted bckg	2802 ± 70	220 ± 21
Fitted tt	643 ± 80	216± 25



W

Matrix element method

- The most accurate measurement of the top quark mass
- Provides advantage in statistically limited regime
  - Calculate per-event probability density for signal and background as a function of the top quark mass using 4-vectors of reconstructed objects
  - Multiply the event probabilities to extract the most likely mass



  - Maximizes statistical power by using all event information
  - Extremely CPU intensive

ME method details

Normalization acceptance & efficiency

Differential cross section based on LO ME

$$P_{t\bar{t}}(x;m_t,JES)=\frac{1}{\sigma(m_t)}\int d^n\sigma(y,m_t)\,dq_1 dq_2 f(q_1) f(q_2)\,W(x,y,JES)$$

Probability to observe a set of kinematic variables x for a given mass and JES

Initial state Probability distribution that a parton will have a momentum q

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

- Integrate over unknown q_1, q_2, y
- The jet energy calibration (JES) is a free parameter in the fit, constrained in-situ by the mass of hadronically decaying W

$$\mathcal{P}_{\rm event}(x;m_t,{\rm JES}) = f_t\,\mathcal{P}_{t\bar{t}}(x;m_t,{\rm JES}) + (1-f_t)\mathcal{P}_{bkg}(x,{\rm JES})$$

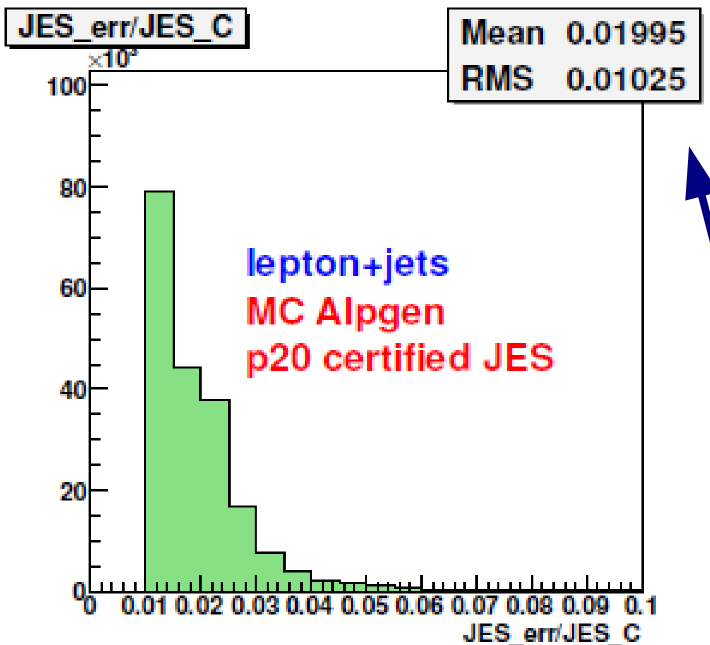
D0: ME in l+jets

- Selection: exactly 4 good jets, ≥ 1 b-tag
- Signal fraction – from ME method itself before b-tagging
  - Event probability depends on f(top)
- Take 24 permutations weighted according to b-tagging information

	1 b-tag	2 b-tags
bckg	152	24
signal	258	172
data	414	201

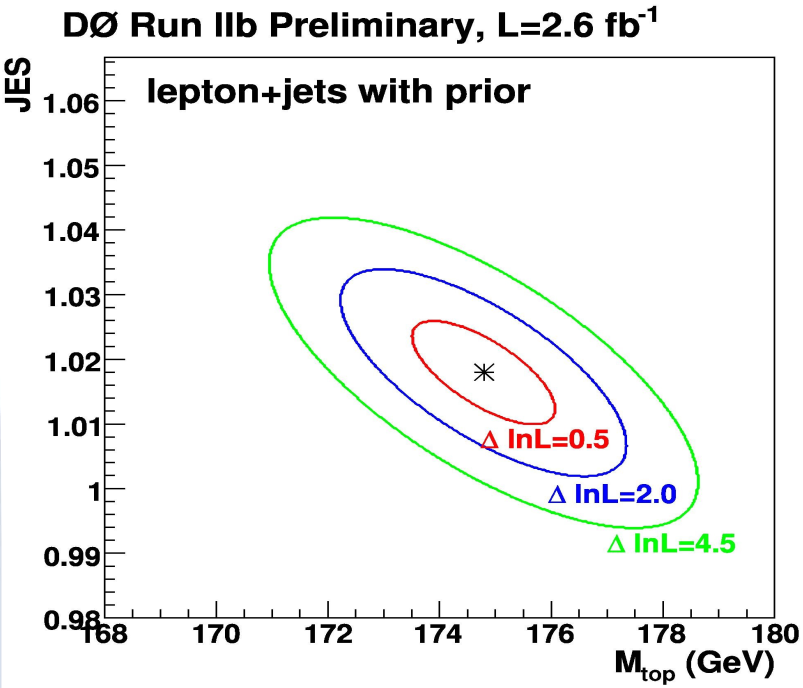
Transfer functions

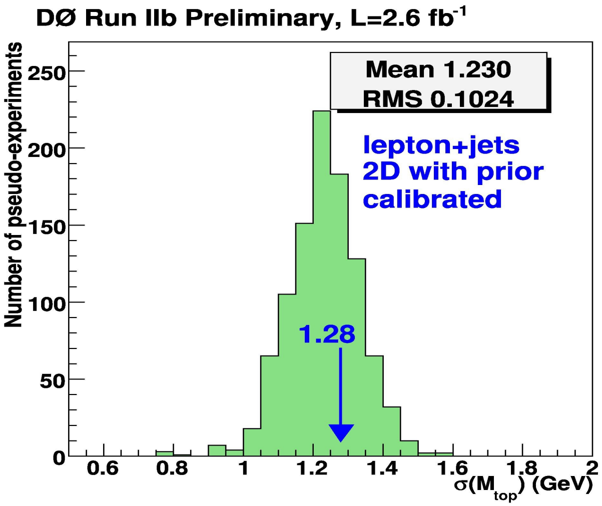
- Angles are well measured
- TFs for muons and electrons
- Momentum TFs for jets in 4 bins
  - for light and b-quarks with and w/o muon tag

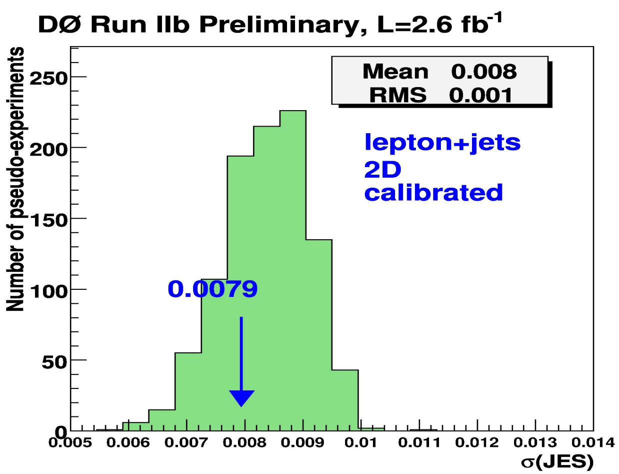


- Calibrate JES in-situ from W mass
- Use information from external JES from γ+jets: Gaussian mean 1 and σ=0.02

D0: ME l+jets result







With prior (8% better stat+JES)

$$m_t = 174.8 \pm 1.3\,(stat + JES) \pm 1.4\,(sys)\,GeV$$

Without prior 2.6 fb^{-1}

$$m_t = 174.5 \pm 1.4\,(stat + JES) \pm 1.4\,(sys)\,GeV$$

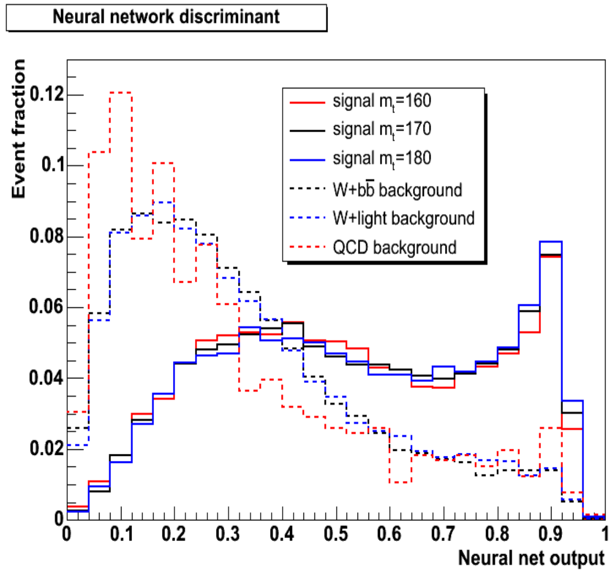
$$JES = 1.018 \pm 0.008\,(stat + m_t)$$ 1%

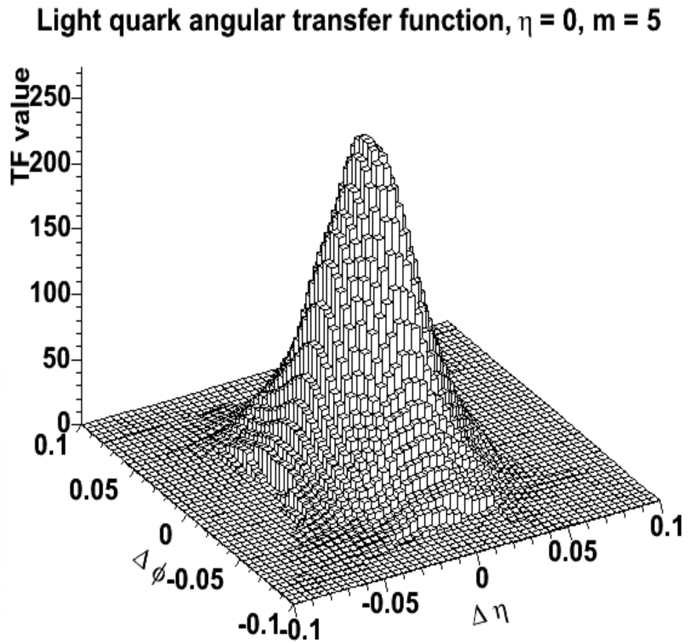
Combine with 1 fb^{-1} result with new uncertainties back propagated 3.6 fb^{-1} 1%

$$m_t = 173.7 \pm 0.8\,(stat) \pm 1.6\,(sys)\,GeV$$

CDF: ME in l+jets

- Selection: exactly 4 good jets, ≥ 1 b-tag
- 7-variable NN for S-B discrimination, not sensitive to top mass
- $f_{bkg}(q) = B(q)/(S(q)+B(q))$
  - S(q), B(q) – NN distributions for S and B normalized to expected signal and backgroun

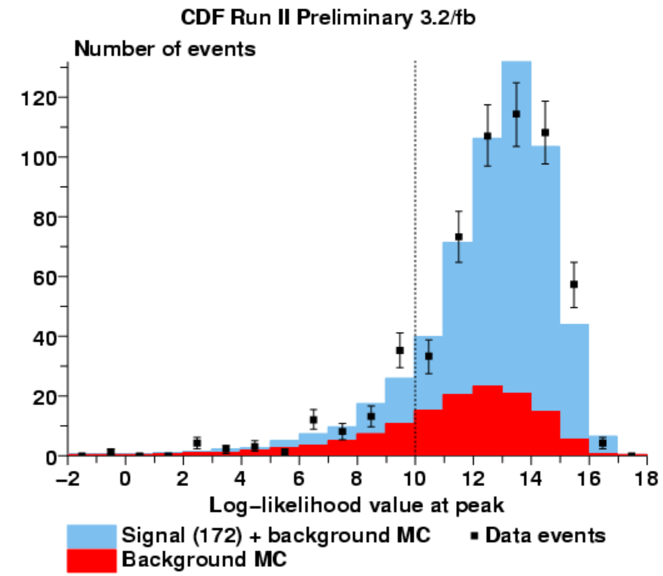


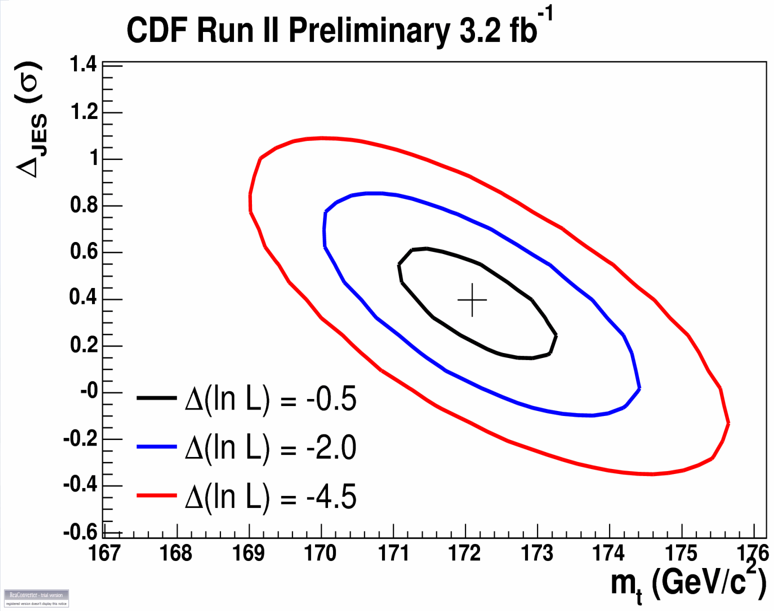


- Integration over 24 permutations weighted according to b-tagging information
- Leptons assumed well measured
- Integration over 19 dimensions of phase space using Quasi-Monte Carlo method
- Momentum and angular transfer functions
  - for light and b-quarks in 4 η bins

CDF: ME l+jets result

- Background treatment
  - No explicit background likelihood
  - All events treated as signal
- Signal LH extraction
  - Add all LHs and subtract expected background contribution using average LH for background events from MC





	1 b-tag	2 b-tags
bckg	121.8 ± 31.7	12.3 ± 4.4
data	459	119
S/B	3:1	10:1

$3.2\ fb^{-1}$

0.9%

$$m_t = 172.1 \pm 1.2(stat+JES) \pm 1.1(sys)\, GeV$$
$$\Delta JES = 0.4 \pm 0.26\sigma$$

Systematic uncertainties

- Measurement became dominated by systematics
- Revision of uncertainties – combined effort by CDF & D0
  - To study new effects that can be important
  - To avoid possible double counting
  - To gain confidence in the quoted numbers
- Monthly CDF/D0 meetings to discuss details and agree on common procedures where possible

Current list

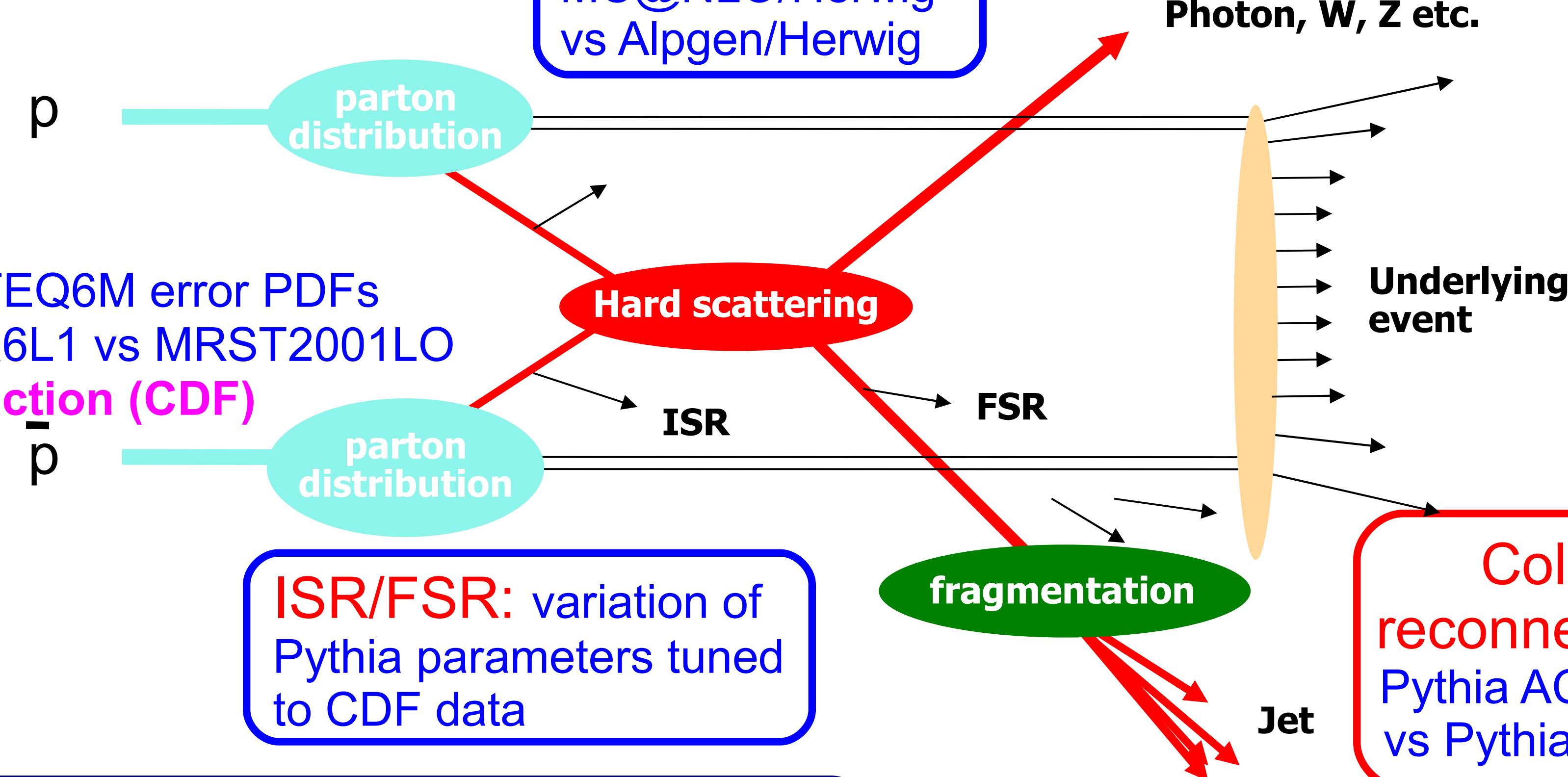
- Jet calibration
  - **In-situ calibration or JES**
  - **Residual JES**
  - **b-JES and b/light response**
  - **Sample-dependent JES**
- Method
- Background fraction and shape
- Multiple proton interactions
- Lepton energy scale
- Signal modeling

Signal modeling

(D0) → **LO vs NLO ME:**
MC@NLO/Herwig
vs Alpgen/Herwig

Hadronization and UE:
Pythia vs Herwig

PDF:
- 20 CTEQ6M error PDFs
- CTEQ6L1 vs MRST2001LO
- **gg fraction (CDF)**



new

Color reconnection:
Pythia ACR(pro)
vs Pythia A(pro)

ISR/FSR: variation of Pythia parameters tuned to CDF data

Important to factorize different effects and avoid double counting – not a trivial task at all

b-fragmentation
vary parameter of Bowler fragmentation function to match LEP or SLD data

Tevatron combination

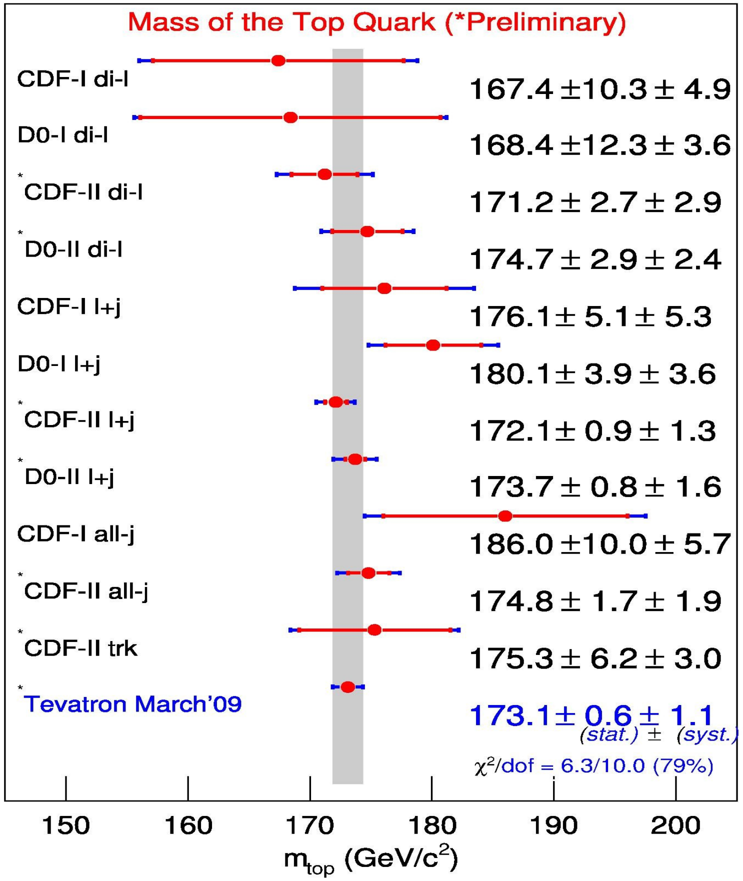
- Performed by Tevatron EW working group using BLUE
- 5 Run I and 6 preliminary Run II
- Very small improvement in precision: 0.75% (0.8% in summer 2008)
  - increase of luminosity from <3.6 fb^{-1} to 2.8 fb^{-1}

	total	stat	sys
JES	0.73	0.48	0.55
signal	0.57		0.57
CR	0.41		0.41
bckg	0.26	0.26	
stat	0.65	0.65	

0.7 (signal + CR)

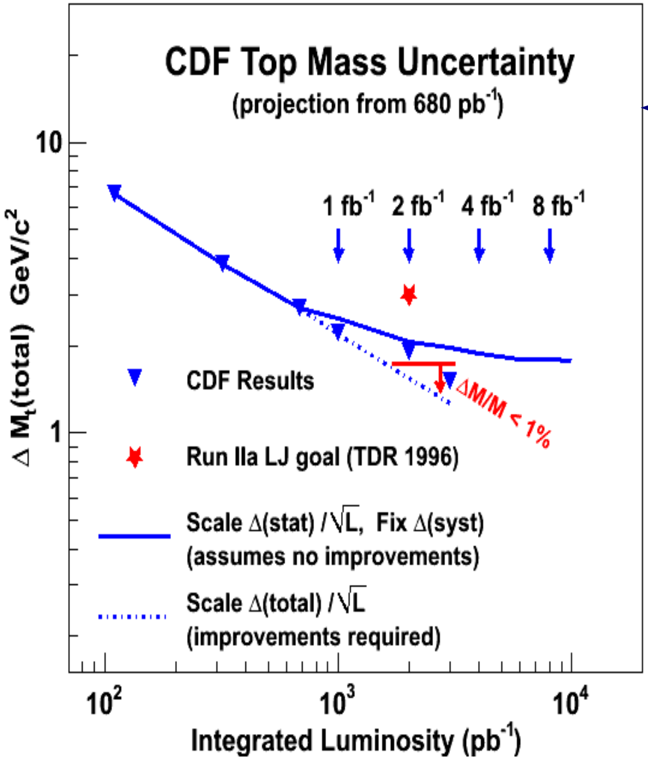
Close in size to JES, hard to decrease

TEVEWWG arXiv:0903.2503v1



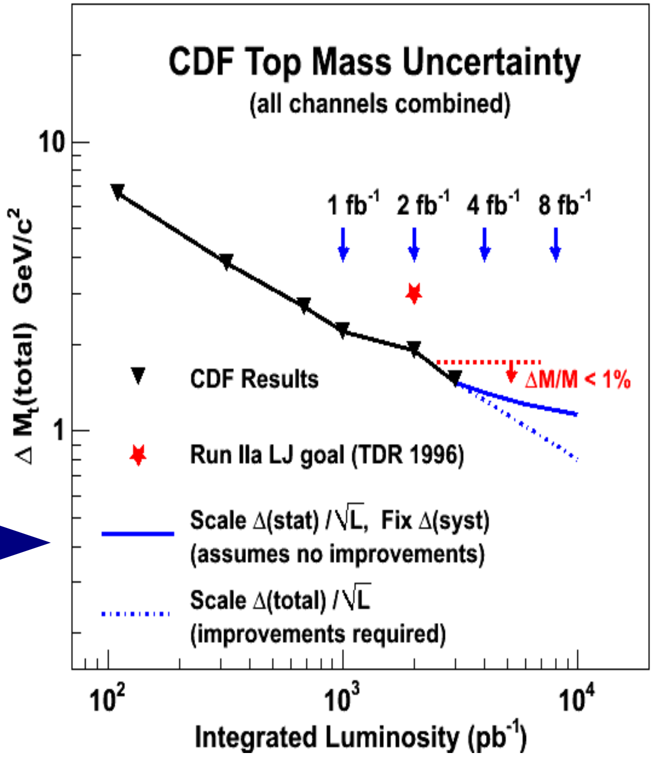
$m_t = 173.1 \pm 1.3$ GeV

Future precision



From 680 pb^{-1}

From 3 fb^{-1}



(1) All systematics is fixed, scale stat+JES from in-situ uncertainties

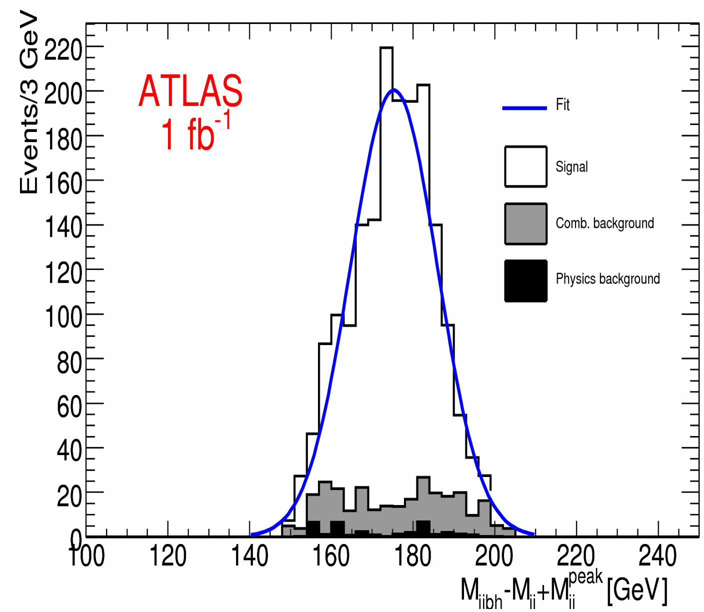
(2) Scale total uncertainty with luminosity

We are doing much better than predicted from Run I experience

Prospects for LHC: Atlas

CERN-OPEN-2008-020

- Expect ~200 pb^{-1} delivered lumi at $\sqrt{s}$=10 TeV in 2009-2010
- For analysis ~50 pb^{-1}?
- Studies of potential: 14 TeV & 1fb^{-1}
- Regime of “top factory”
  - No need to worry about acceptance
- Invariant mass of top decay products



M_t = 175.3 ± 0.3 GeV (stat)

- Require ≥1 or ≥2 b-tags
- Reconstruct W boson using 2 jets that were not tagged
  - W mass window cut
  - JES corrections using W_{PDG} mass
- Choose b-W assignments

- Improve purity by combinatorial background with additional cuts
- Reconstruct top mass as bjj mass and fit with Gaussian + polinomial
- Several implementations with small differences in details

Prospects for LHC: CMS

- Study from 2006 in μ+jets channel
- ≥ 4 jets, ≥2 b-tags, 588 events after severe cuts to kill
  - contributions from other tt final states
  - combinatorial background
- Unique mass value per event
- Calibration using W mass
- Simple Gaussian fit of the bjj peak

CMS-NOTE2006-066

- Ideogram method
- Per event likelihood approach
  - Construct probability of the measured event kinematics to agree with the reconstructed top mass given fitted mass and its uncertainty
- Significantly improves statistical uncertainty
- Much less sensitive to many systematics uncertainties

Calibrated results

	Gaussian Fit	Gaussian Ideogram	Full Scan Ideogram
Bias (GeV/c^2)	-0.84±0.59	-4.35±0.54	-2.58±0.31
Pull	0.82	1.01	1.01
Expected uncertainty for $1fb^{-1}$ (GeV/c^2)	1.01	1.14	0.66

3% light quarks JES shift ($1fb^{-1}$)	3.6±0.6	0.32±0.23	0.10±0.20

Back to reality: early data

- @ 10 TeV and ~50 pb^{-1}
- 40 times less signal
  - ~1000 signal events before b-tagging
- Similar to current statistics at Tevatron but smaller background
- Methods based on per event information (ME-type) are expected to have a better performance
- Allow 2D fits and will help to perform JES calibration
  - constrain top mass to Tevatron average and fit JES

CERN-OPEN-2008-020

Process	>= 4 jets $p_T > 40$ GeV	2 b-jets $p_T > 40$ GeV
Signal	43370	15780
W boson backgrounds	9450	200
all-jets (top pairs)	560	160
di-lepton (top pairs)	2050	720
single top, t channel	1230	330
single top, *W* t channel	770	170
single top, s channel	11	5

- ~2% for light <JES> with 50 pb^{-1} (Atlas)
- ~1% for light <JES> and b<JES> with 100 pb^{-1} (CMS)
- perform ME analysis in 3D ?

Conclusions and outlook

- "Scientists working on the XXX accelerator are struggling to overcome serious technical problems. If the setbacks aren't resolved soon ... the XXX may even fail to meet some of its scientific goals"

Science 8 February 2002:
Vol. 295. no. 5557, pp. 942 - 943

- Startup is never easy. Tevatron is measuring top mass with outstanding precision... but
- Top quark mass is a benchmark SM measurement which will demonstrate that we understand our detectors
- If ME method routinely used at the Tevatron can be ever useful for LHC – early data is the time!
  - Provides maximum sensitivity with limited statistics
  - Less sensitive to many systematic uncertainties (signal modeling, for example) than "peak fit" methods

Backup

ME l+jets uncertaintries: CDF

Systematic source	Systematic uncertainty (GeV/c^2)
Calibration	0.2
MC generator	0.5
ISR and FSR	0.3
Residual JES	0.5
b-JES	0.4
Lepton P_T	0.2
Multiple hadron interactions	0.1
PDFs	0.2
Background	0.5
Color reconnection	0.4
Total	1.1

ME uncertainties: D0

Source	Uncertainty on top mass in Run IIb (GeV)	Uncertainty on top mass in Run IIa (GeV)
Higher Order Effects	±0.25	±0.25
ISR/FSR	±0.26	±0.40
Hadronization and UE	±0.58	±0.58
Color Reconnection	±0.40	±0.40
Multiple Hadron Interactions	±0.07	±0.01
Background Modeling	±0.03	±0.04
W HF factor	±0.07	±0.09
b-Modeling	±0.09	±0.03
PDF Uncertainty	±0.24	±0.14
Residual JES Uncertainty	±0.21	±0.10
Relative b/Light Response	±0.81	±0.83
Sample-Dependent JES	±0.56	±0.56
b-Tagging Efficiency	±0.08	±0.15
Trigger Efficiency	±0.01	±0.19
Lepton Momentum Scale	±0.17	±0.17
Jet Identification Efficiency	±0.26	±0.26
Jet Energy Resolution	±0.32	±0.03
QCD Background	±0.14	±0.14
Signal Fraction	±0.10	±0.09
Muon Resolution	-	±0.10
Signal Contamination	-	±0.13
MC Calibration	±0.20	±0.26
Total	±1.41	±1.43

Dilepton and l+jets

	1-tag	2-tag
W$b\bar{b}$	21.40 ± 8.95	5.48 ± 2.77
W$c\bar{c}$/Wc	19.95 ± 8.37	1.52 ± 0.74
W LF	14.11 ± 5.14	0.34 ± 0.16
single top	3.34 ± 0.36	1.27 ± 0.23
Diboson	4.13 ± 0.59	0.41 ± 0.12
QCD	18.32 ± 16.64	1.90 ± 2.64
Total	81.25 ± 27.96	10.91 ± 4.53
$t\bar{t}$ (σ=6.7pb M_{top}=175 GeV/c^2)	264.35 ± 37.09	131.02 ± 14.05

	0-tag	tagged
WW	10.76 ± 1.85	0.39 ± 0.07
WZ	2.58 ± 0.41	0.05 ± 0.01
ZZ	1.62 ± 1.28	0.11 ± 0.09
Wγ	0.26 ± 0.28	0.0 ± 0.0
DY$\tau\tau$	8.09 ± 1.56	0.43 ± 0.08
DYee$\mu\mu$	23.00 ± 3.15	1.26 ±0.17
Fakes	31.19 ± 8.86	4.53 ±1.29
Total	77.50 ± 9.80	6.77 ± 1.31
$t\bar{t}$ (σ=6.7pb M_{top}=175 GeV/c^2)	68.73 ± 6.75	88.39 ± 8.18

$$\mathcal{L}_k = \exp\left(-\frac{(n_b - n_b^0)^2}{2\sigma_{n_b}^2}\right) \times \prod_{i=1}^{N} \frac{n_s P_{sig}(m_i, y_i; M_{top}, \Delta_{JES}) + n_b P_{bg}(m_i, y_i)}{n_s + n_b}$$

Systematics: Atlas vs CMS

Systematic uncertainty	χ^2 minimization method	geometric method
Light jet energy scale	0.2 GeV/%	0.2 GeV/%
b jet energy scale	0.7 GeV/%	0.7 GeV/%
ISR/FSR	$\simeq$ 0.3 GeV	$\simeq$ 0.4 GeV
b quark fragmentation	$\leq$ 0.1 GeV	$\leq$ 0.1 GeV
Background	negligible	negligible
Method	0.1 to 0.2 GeV	0.1 to 0.2 GeV

	Standard Selection			Alternative Selection
	Gaussian Fit Δm_t (GeV/c^2)	Gaussian Ideogram Δm_t (GeV/c^2)	Full Scan Ideogram Δm_t (GeV/c^2)	Full Scan Ideogram Δm_t (GeV/c^2)
Pile-Up	1.9	1.4	1.2	1.2
Underlying Event	1.0	0.7	0.5	0.5
Jet Energy Scale (light)	2.4	0.1	0.1	0.1
Jet Energy Scale (heavy)	1.4	1.3	1.2	1.2
Radiation (pQCD)	0.8	0.3	0.2	0.2
Fragmentation	0.4	0.4	0.3	0.3
b-tagging	2.0	0.5	0.3	0.3
Background (*)	0.4	0.4	0.4	0.4
Parton Density Functions	0.1	0.1	0.1	0.1
Total Systematical uncertainty	4.9	2.3	1.9	1.9
Statistical Uncertainty (10fb^{-1})	0.32	0.36	0.21	0.31
Total Uncertainty	4.9	2.3	1.9	1.9