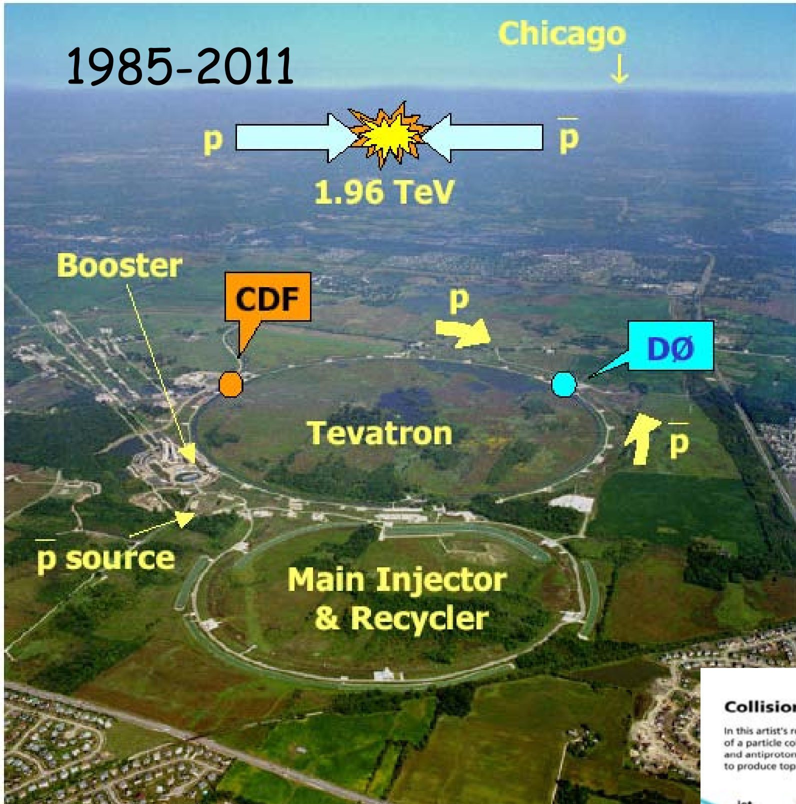
# Methods for Measurement of the Top Quark Mass at the Tevatron


Sandra Leone
(INFN Pisa)


Top mass workshop
Frascati, May 7, 2015

# The Fermilab Tevatron




Run II: $\sqrt{s}$ = 1.96 TeV, 10 $fb^{-1}$ on tape
Tevatron stopped operating on September 2011 after a 26 years career

The birthplace of the top quark, observed in 1995 by CDF and D0

Announcement of top quark discovery:
**March 2nd, 1995 ⇒Top is twenty!!**

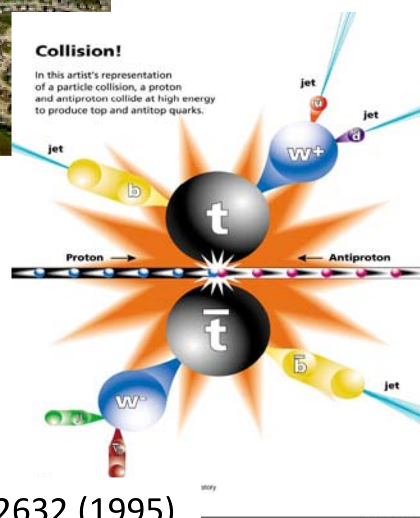

news release
fermi national accelerator laboratory
Operated by Universities Research Association, Inc. for the U.S. Department of Energy
Public Information Office, P.O. Box 500, Batavia, IL 60510 • Telephone: 708-840-3351 • Facsimile: 708-840-8780

NEWS MEDIA CONTACTS:
Judy Jackson, 708/840-4112 (Fermilab)
Gary Pitchford, 708/252-2013 (DOE)
Jeff Sherwood, 202/586-5806 (DOE)

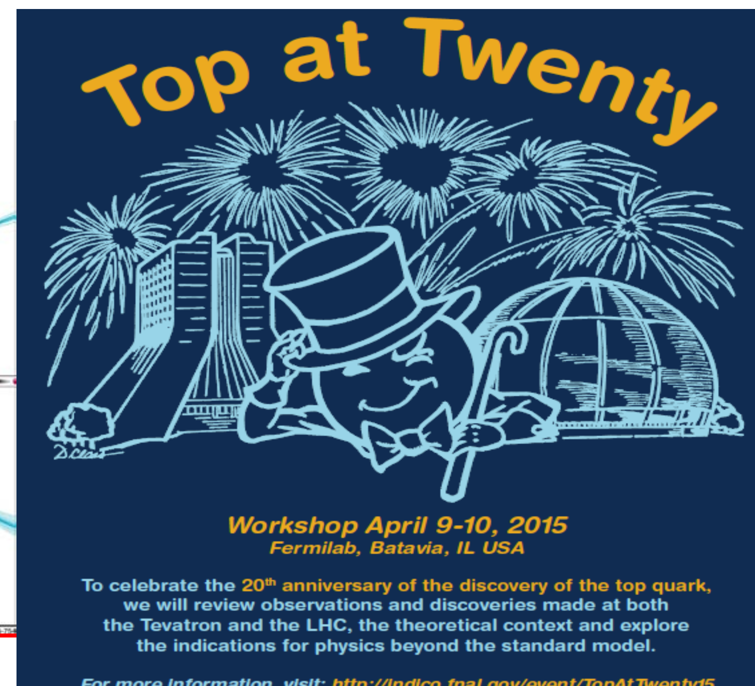
95-2
March 1, 1995

PHYSICISTS DISCOVER TOP QUARK

Batavia, IL—Physicists at the Department of Energy's Fermi National Accelerator Laboratory




PRL 74 2626, PRL 74 2632 (1995)



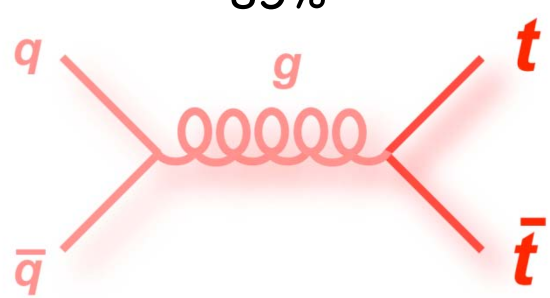
# Top Quark Production at Tevatron

- QCD pair production

$\sigma_{SM} = 7.35^{+0.28}_{\;0.33}$ pb

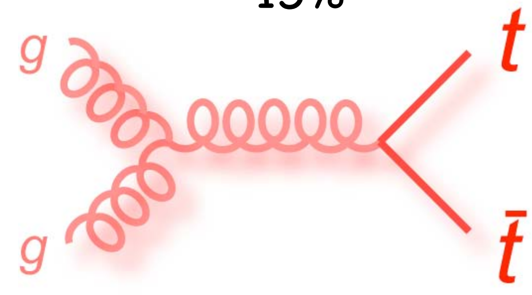
(for $m_{Top}$= 172.5 GeV)
(PRL 110, 252004 (2013))

~85%




Dominant process at Tevatron

~15%




Dominant process at LHC (~90%)

Tevatron is the right place to study the $q\bar{q}$ annihilation in $t\bar{t}$ production

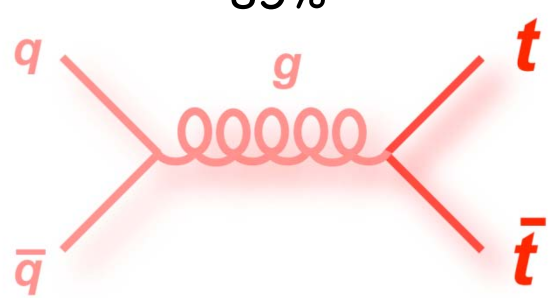
# Top Quark Production at Tevatron

- <u>QCD pair production</u>

$\sigma_{SM} = 7.35^{+0.28}{}_{0.33}$ pb

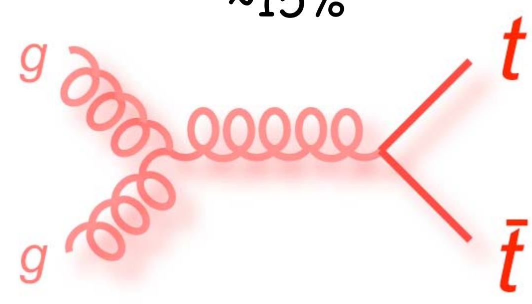
(for $m_{Top}$= 172.5 GeV)
(PRL 110, 252004 (2013))

~85%




Dominant process at Tevatron

~15%




Dominant process at LHC (~90%)

Tevatron is the right place to study the $q\bar{q}$ annihilation in $t\bar{t}$ production

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Small cross section!
$\Rightarrow$ Observation in ~ 67 $pb^{-1}$ $\Rightarrow$ ~ 500 ttbar pairs produced per experiment

$\Rightarrow$ In 10 $fb^{-1}$ $\Rightarrow$ ~ 73500 ttbar pairs produced

# Top Quark Production at Tevatron

- QCD pair production

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(for $m_{Top}$= 172.5 GeV)
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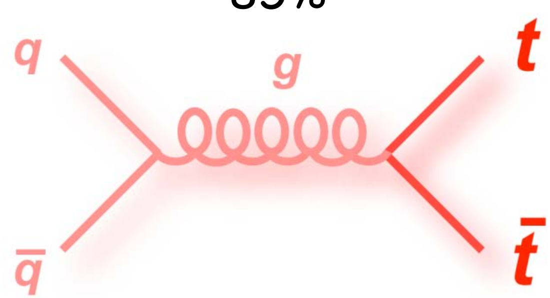
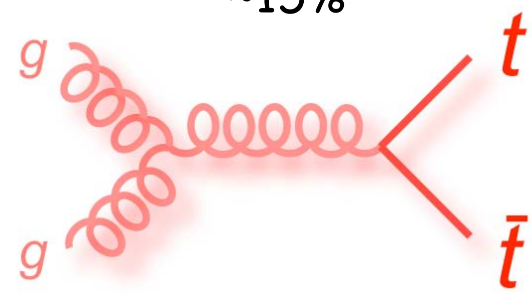



Dominant process at Tevatron

~15%




Dominant process at LHC

Tevatron is the right place to study the $q\bar{q}$ annihilation in $t\bar{t}$ production

- EWK single-top production
- first observed at Tevatron in 2009
- (PRL 103 092001, PRL 103 092002 (2009))

> s-channel: $\sigma_{SM}$ = 1.04 ± 0.06 pb
> t-channel: $\sigma_{SM}$ = 2.1 ± 0.1 pb

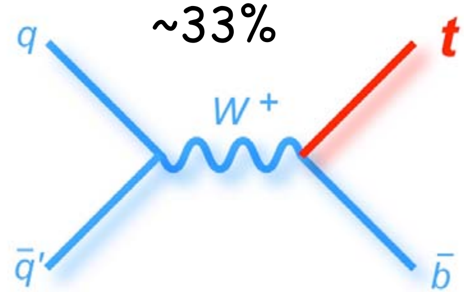
(for $m_{Top}$= 173 GeV)

PRD 83, 091503 (2011),PRD 81, 054028 (2010)
PRD 82, 054018 (2010) arxiv:1210.7813.

Dominant modes at Tevatron:

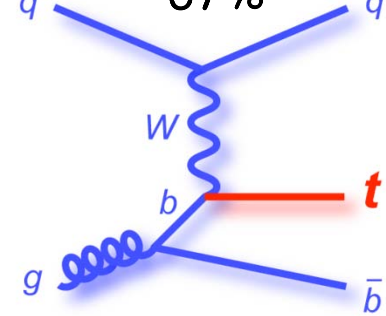
s-channel

~33%



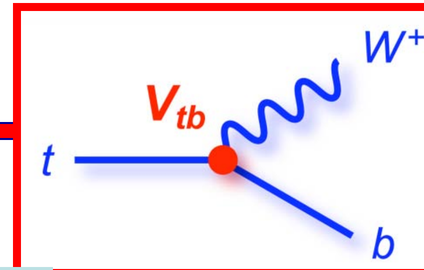

t-channel

~67%




- Single top associated production Wt: σ ~ 0.2 pb, too small at the Tevatron

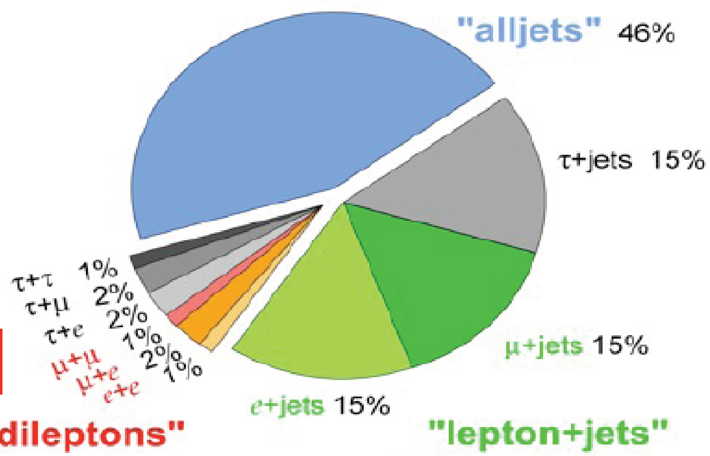
# Top Quark Decay




SM predicts BR( $t \rightarrow Wb$) ≈ 100%

Event topology determined by the W decay mode

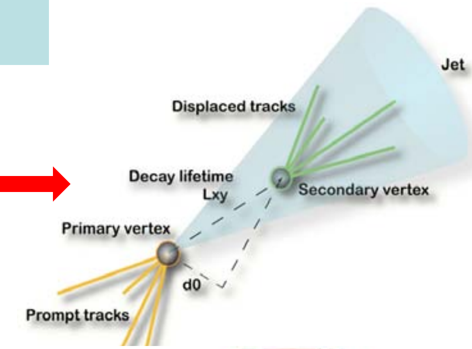
Top Pair Branching Fractions

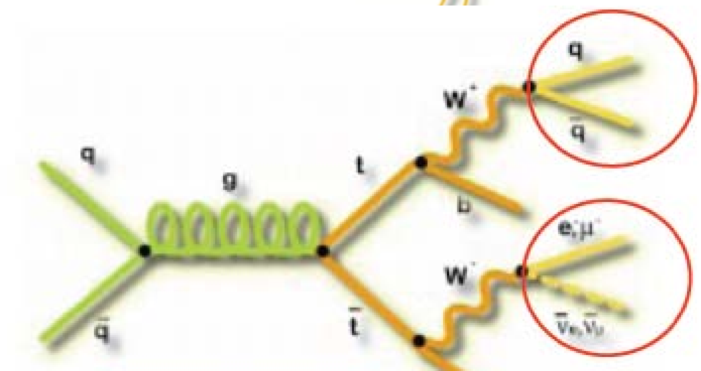



~4.5%

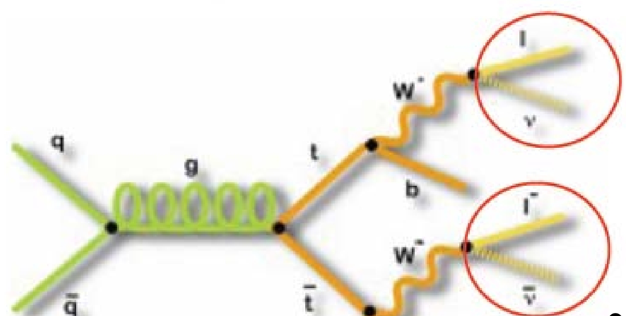
~30%

b quarks are always present



lepton+jets



dileptons

- Small rate
- Small background

- Golden channel:
- Good rate
- Manageable background

# Top mass: what do we measure?

- 20 years ago, CDF & D0 first assembled all the pieces needed to discover the top
  - ⇒ The strategy to study the top quark remains the same today
- Top quark mass is not "directly measured":
  - ⇒ we do kinematic reconstruction of final state objects (leptons, jets, and missing transverse energy)
  - ⇒ fit to invariant mass distribution
- Experimental accuracy of $M_{top}$:
  - ⇒ Measurement ⇔ comparison of data with Monte Carlo
  - ⇒ we measure the mass that is implemented as input in the MC
    - ✓ MC top mass is unique for each MC
    - ✓ measured mass is not strictly model independent
- Situation at the Tevatron:
  - ⇒ $\delta M_{top} = \pm 0.64$ GeV/c$^2$ (< 0.4%)
- Conceptual uncertainty of about 1 GeV/c$^2$ when relating the MC mass to a field theory mass….

# Top Mass: Experimental Challenges

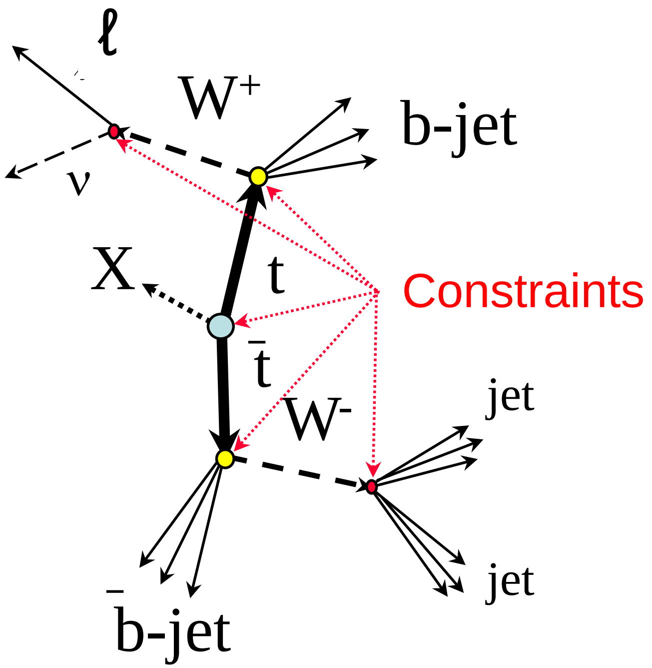
Why so challenging? It is a difficult measurement

Many combinations of leptons and jets:

Events are complicated!

Experimental observations are not as *pretty* as Feynman diagrams!

- Large backgrounds
- Missing neutrino(s)
- Confusion in ID assignment (add. Jets from ISR/FSR, b-tag: not 100% correct)
- Measurements are not perfect!




- Link observables to parton-level energies
- Large syst uncert. from jet energy scale
- Need accurate detector simulation

# Backgrounds

- The Tevatron is a hadron collider:
  - →Very high backgrounds!
- Backgrounds can bias the top mass measurement

**Typical Backgrounds:**

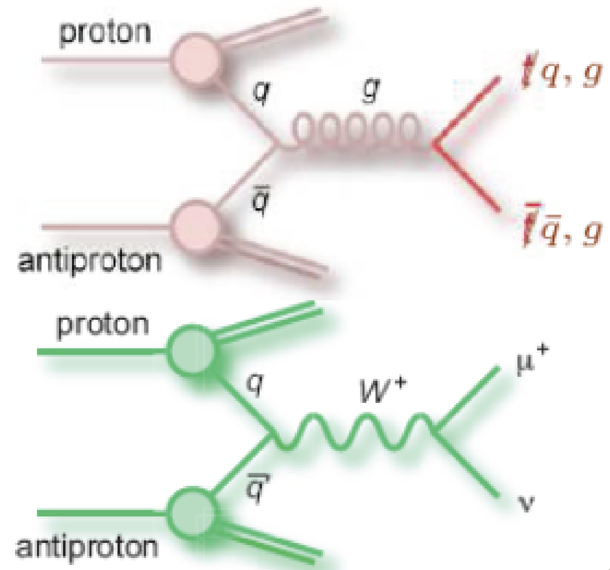
**W+jets**

**Z+jets**

**QCD multijet prod'n**

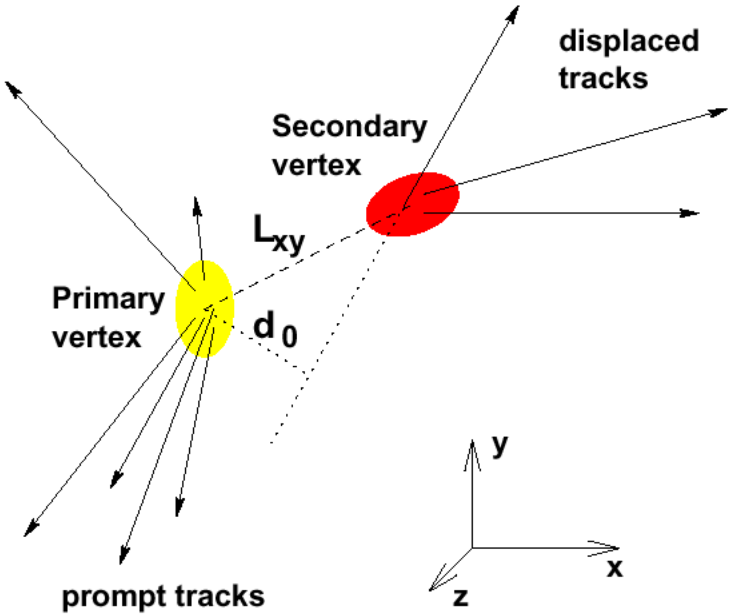
**Diboson prod'n**

**Single top prod'n**



# Backgrounds & B-tagging algorithms

- The Tevatron is a hadron collider:
  - →Very high backgrounds!
- Backgrounds can bias the top mass measurement
- Control backgrounds using b-tagging information




CDF: Secondary Vertex tagger (SVX)

- reconstructs secondary vertex
- significance $L_{2D}/\sigma > 7.5$

D0: Neural Network tagger

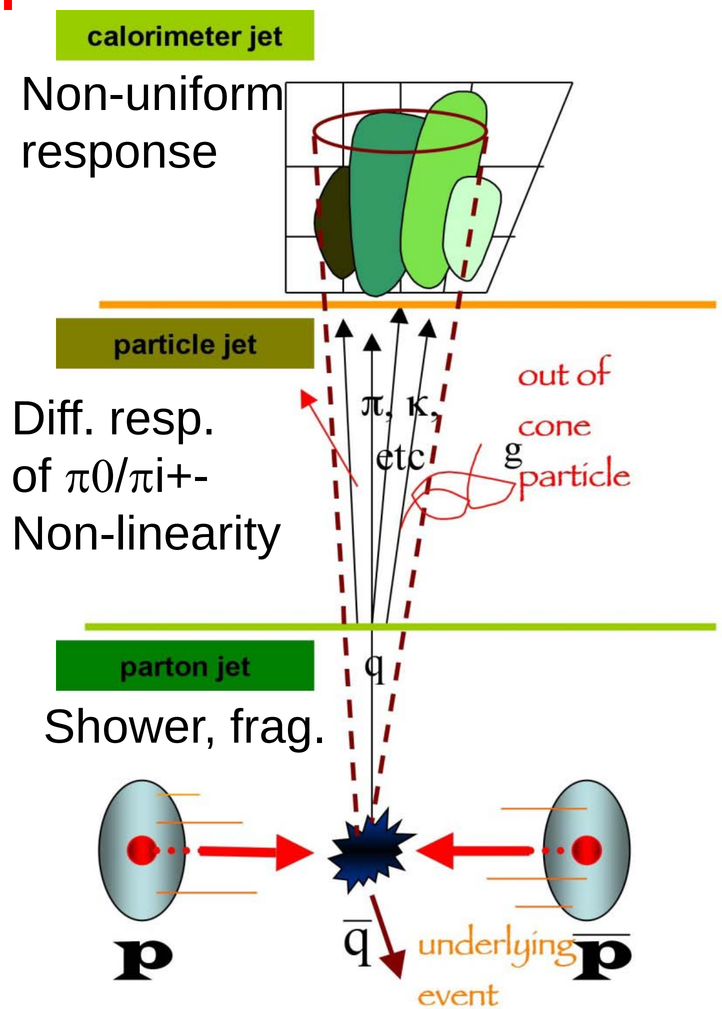
- combines properties of displaced tracks and secondary vertex
- 9 variables total

| Channel | B-tags | S:B | Perm. |
|---|---|---|---|
| Dilepton | ≥ 0 | 1:4 | 2 |
| | ≥ 1 | 4:1 | 2 |
| Lepton+jets | ≥ 0 | < 1:1 | 12 |
| | ≥ 1 | 2.5:1 | 6 |
| | ≥ 2 | 10:1 | 2 |
| All-hadronic | ≥ 1 | 1:4 | 30 |
| | ≥ 2 | 4:1 | 6 |

- At the same time:
  - → help combinatorics!

# Jet Energy Correction

## Determine true "parton" (or "particle") E from measured jet E




The correction factor depends on jet $E_T$ and η and is meant to reproduce the average jet $E_T$ correctly, (not to reduce the jet fluctuations around this mean)

Corrections for generic jets:

⇒ Use Zee for em energy calibration

⇒Absolute corrections (γ-jet balancing)

⇒ Relative corrections (central-forward calorimeters, dijet balancing)

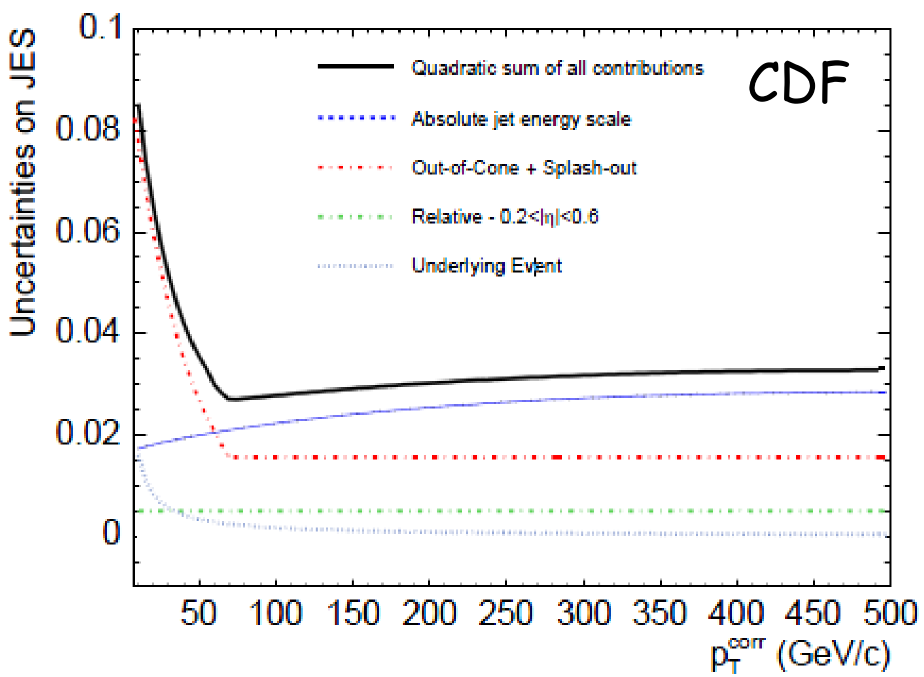
Out-of-Cone: correction to parton

Underlying event

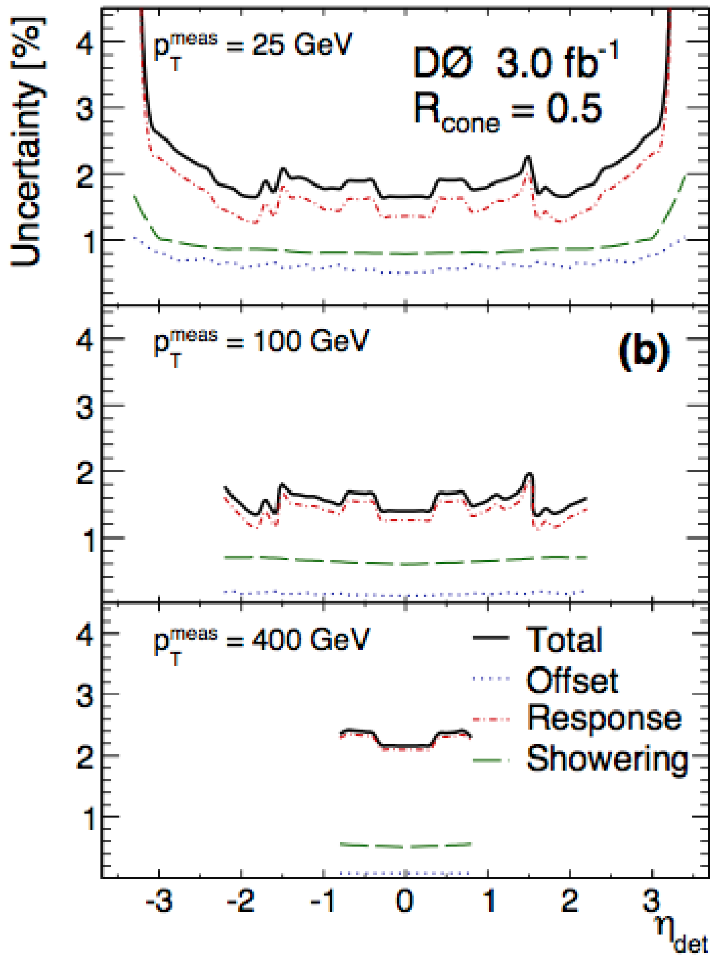
"top-specific correction" to light quark jets and b-jets separately

# JES uncertainty

- What is jet energy scale uncertainty?
  - ⇒ Measures how incorrect is our nominal jet energy measurement
  - ⇒ Accounts for $E_T$, η dependence.




CDF, NIM A 566, 375 (2006)



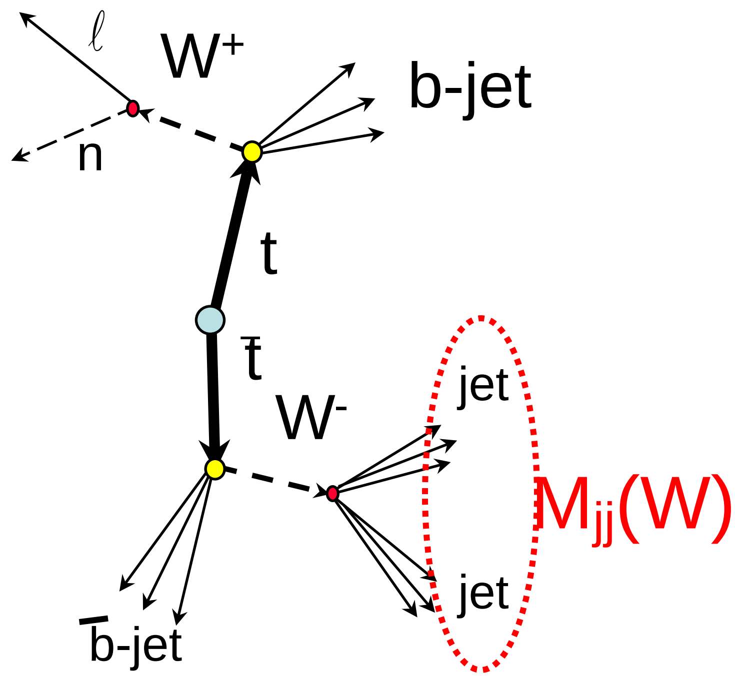

D0: NIM A 763, 290 (2014)
NIM A 763, 442 (2014)

# “In situ” jet energy calibration

Simultaneous fit to Mjj and Mtop using top mass and JES templates for lepton plus jets and all hadronic events:

$M_t$ ( true $M_{top}$, JES), $M_{jj}$ ( true $M_{top}$, JES)

- Identify jets coming from W
  - All non-btagged jets pairs are taken into account equally.
  - 1/3/6 $m_{jj}$ per event with 2/1/0 b-tag
- Reconstruct their invariant mass $m_{jj}$
- $m_{jj}$ strongly dependent on JES
  - Make Mjj templates by varying JES
  - Fit data with Wjj to measure JES!
- $M_W$ uncertainty is negligible (< 50 MeV)
- $m_{jj}$ mostly independent of $M_{top}$
- This scale is applied to b-jets and light-quark jet

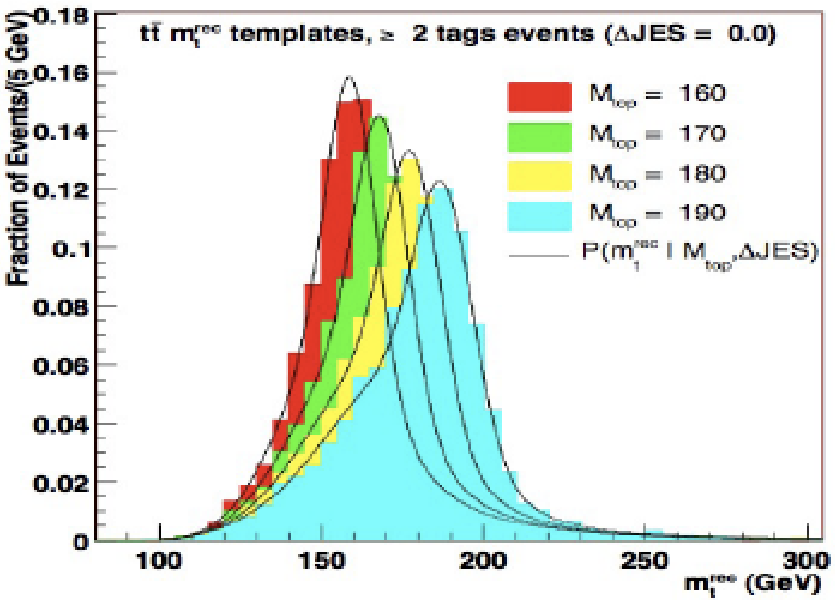



JES from W→jj is mostly statistical

→ luminosity scale !

# Top Mass Measurement: Methods

- The measurements shown today are based on:
  - ⇒ Template method
  - ⇒ Matrix Element method
- Template method:
  - ⇒ Exploit dependence on $m_t$ of kinematic observables xi
  - ⇒ Create "templates" = distributions of xi using MC
    - ✓ For signal: xi=xi(mtop)
    - ✓ For background
  - ⇒ Maximise consistency with the observation, given $m_t$
  - ⇒ Advantages:
    - ✓ Few assumptions
    - ✓ fairly straight forward
  - ⇒ Drawback:
    - ✓ Sub-optimal sensitivity



# Top Mass Measurement: Methods

- The measurements shown today are based on:
  - ⇒ Template method
  - ⇒ Matrix Element method
- Matrix element method:
  - ⇒ Directly calculate the event probability as:

$$P_{\rm evt}(m_{\rm top}) \propto f P_{\rm sig}(m_{\rm top}) + (1-f) P_{\rm bgr}$$

$$P_{\rm sig}(m_{\rm top}) \propto \int ...{\rm d}\sigma_{t\bar{t}}(m_{\rm top}) \qquad {\rm d}\sigma_{t\bar{t}} \propto |\mathcal{M}_{t\bar{t}}|^2(m_{\rm top})$$

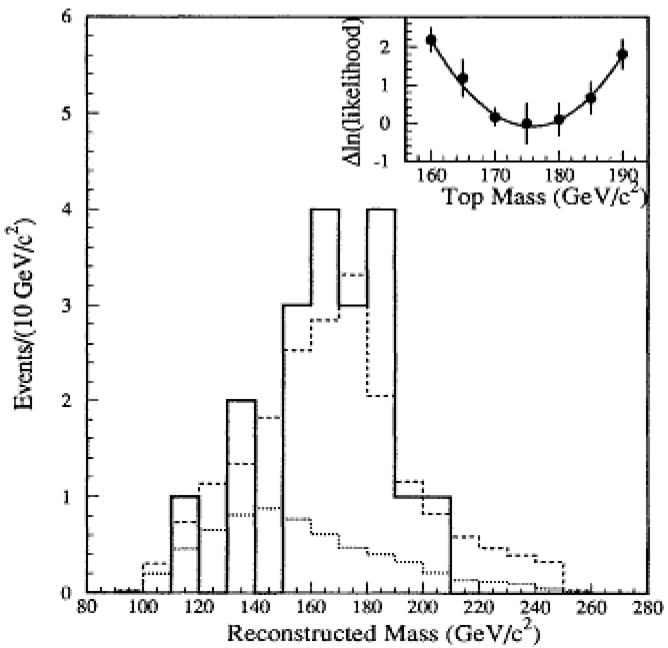
  - ⇒ Advantages:
- Use full 4-vectors with maximal kinematic and topological information
- higher weight is assigned to events that are more likely to be from ttbar
  - ⇒ Drawbacks:
- High computational demand
- Theory assumptions: incorrect modeling due to missing theory corrections

# First measurement of top quark mass

- First measurement of top quark mass performed in the lepton plus jets channel, using a sample of 19 events with an expected background of ~ 7 at CDF and 17 events with ~ 4 backg at D0 .

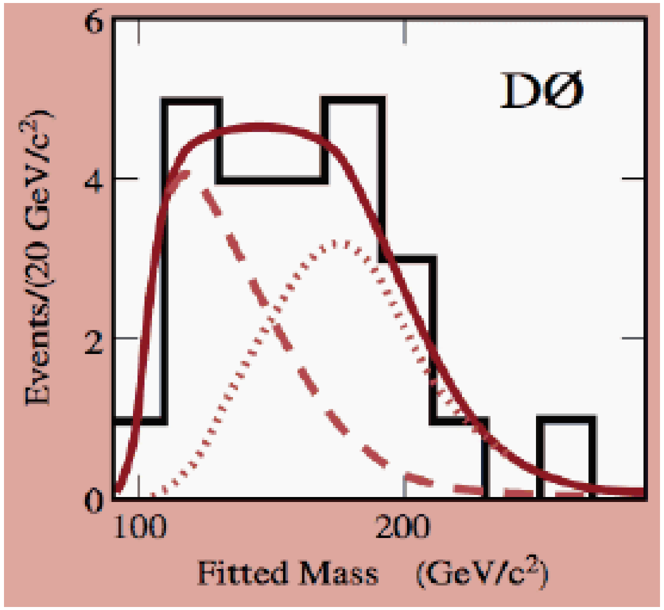
Reconstruct $M_{top}$ with 2 constraints: $M(W^+)=M(W^-)$, $M(t)=M(tbar)$

- $M_{top}$ **= 176 ± 13 GeV /c²**




PRL 74 2626 (1995)

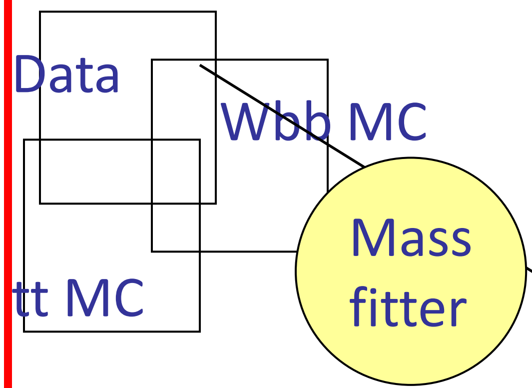
$M_{top}$ **= 199 ± 30 GeV /c²**




PRL 74 2632 (1995)

# Lepton + 4 jets: template method

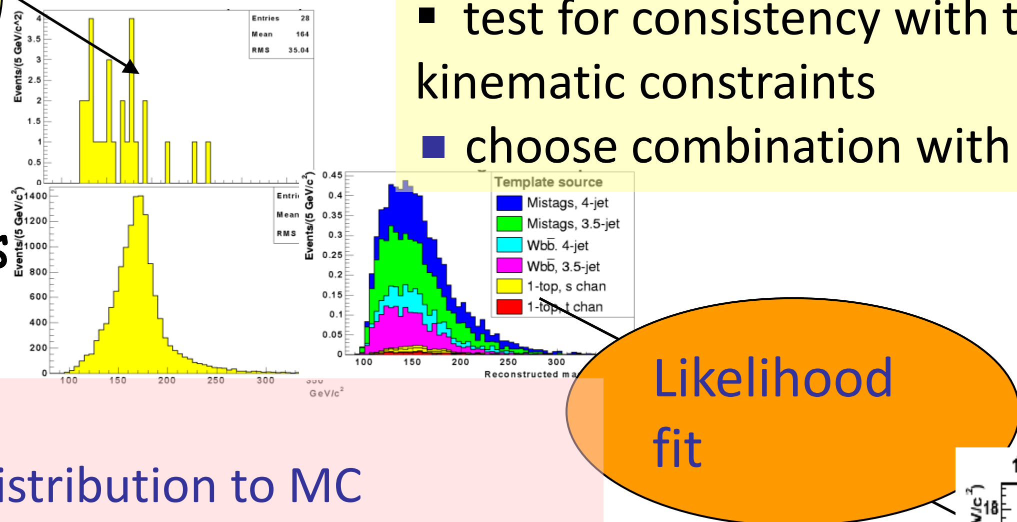
Datasets




## $\chi^2$ mass fitter:

- Finds top mass that fits event best
- All event info into one number
- 12 parton/jet matching assignments possible, 2 longit. neutrino possible, use b-tag to reduce permutations
- test for consistency with top using kinematic constraints
- choose combination with lowest $\chi^2$

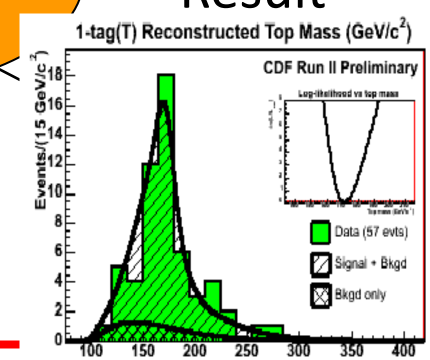
Templates




## Likelihood fit:

- fit resulting mass distribution to MC background + top signal templates at different values of $M_{top}$
- Best signal + bkgd templates to fit data
- Constraint on background normalization

Result



# CDF Lepton plus jets mode

- Full RunII dataset, 8.7 $fb^{-1}$
- Golden mode:
  - $\Rightarrow t \rightarrow W(\rightarrow \ell\nu)\ j_b,\ t \rightarrow W(\rightarrow jj)\ j_b$
  - $\Rightarrow$ Separate event samples into subsamples with 0,1, or 2 b tags
    - ✓ Loosen cuts with added tag(s)
- Reconstruction with kinematic fit
  - $\Rightarrow$Constraints: $M(t)=M(tbar)$, $M(jj)=M_W$, $M(\ell\nu)=M_W$
  - $\Rightarrow$b tags reduce combinatorics
  - $\Rightarrow$Jet Energy scale derived from M(jj)
- 3D template fit
  - $\Rightarrow$Use $M_t^{reco}$, M(jj) and 2nd best $M_t^{reco}$
  - $\Rightarrow$Free parameters $M_t$ and $\Delta_{JES}$

# CDF Lepton plus jets mode

- Determined mostly from Monte Carlo

  ⇒ data give normalization

CDF II Preliminary 8.7 $fb^{-1}$

| | 0-tag | 1-tagL | 1-tagT | 2-tagL | 2-tagT |
|---|---|---|---|---|---|
| $Wb\bar{b}$ | 37.6±15.9 | 54.4±22.6 | 34.0±14.3 | 8.5±3.6 | 6.1±2.6 |
| $Wc\bar{c}$ | 117.8±46.2 | 35.7±13.6 | 22.3±9.0 | 1.4±0.7 | 1.2±0.5 |
| $Wc$ | 54.2±25.1 | 19.1±10.0 | 10.4±5.1 | 0.8±0.3 | 0.5±0.2 |
| W+light jets | 493.6±111.5 | 60.5±13.5 | 35.4±9.0 | 0.9±0.3 | 0.6±0.2 |
| Z+jets | 52.3±4.4 | 8.9±1.1 | 5.9±0.7 | 0.8±0.1 | 0.5±0.1 |
| single top | 4.9±0.5 | 10.5±0.9 | 6.8±0.6 | 2.2±0.3 | 1.7±0.2 |
| Diboson | 60.3±5.6 | 11.1±1.4 | 8.5±1.1 | 1.0±0.2 | 0.8±0.1 |
| QCD | 143.0±114.4 | 34.5±12.6 | 20.7±16.6 | 4.4±2.5 | 2.5±2.4 |
| Total | 963.5±229.3 | 234.7±61.1 | 144.0±40.9 | 19.9±5.5 | 13.8±4.2 |
| $t\bar{t}$ | 644.8±86.3 | 695.0±86.7 | 867.3±107.6 | 192.3±29.7 | 303.7±46.6 |
| Expected Events | 1608.4±245.0 | 929.8±106.1 | 1011.3±115.1 | 212.2±30.2 | 317.6±46.8 |
| Observed Events | 1627 | 882 | 997 | 208 | 275 |

ttbar : Pythia

W+jets : Alpgen+Pythia

W+cc, W+bb: Alpgen+Pythia

Multijets events : from data

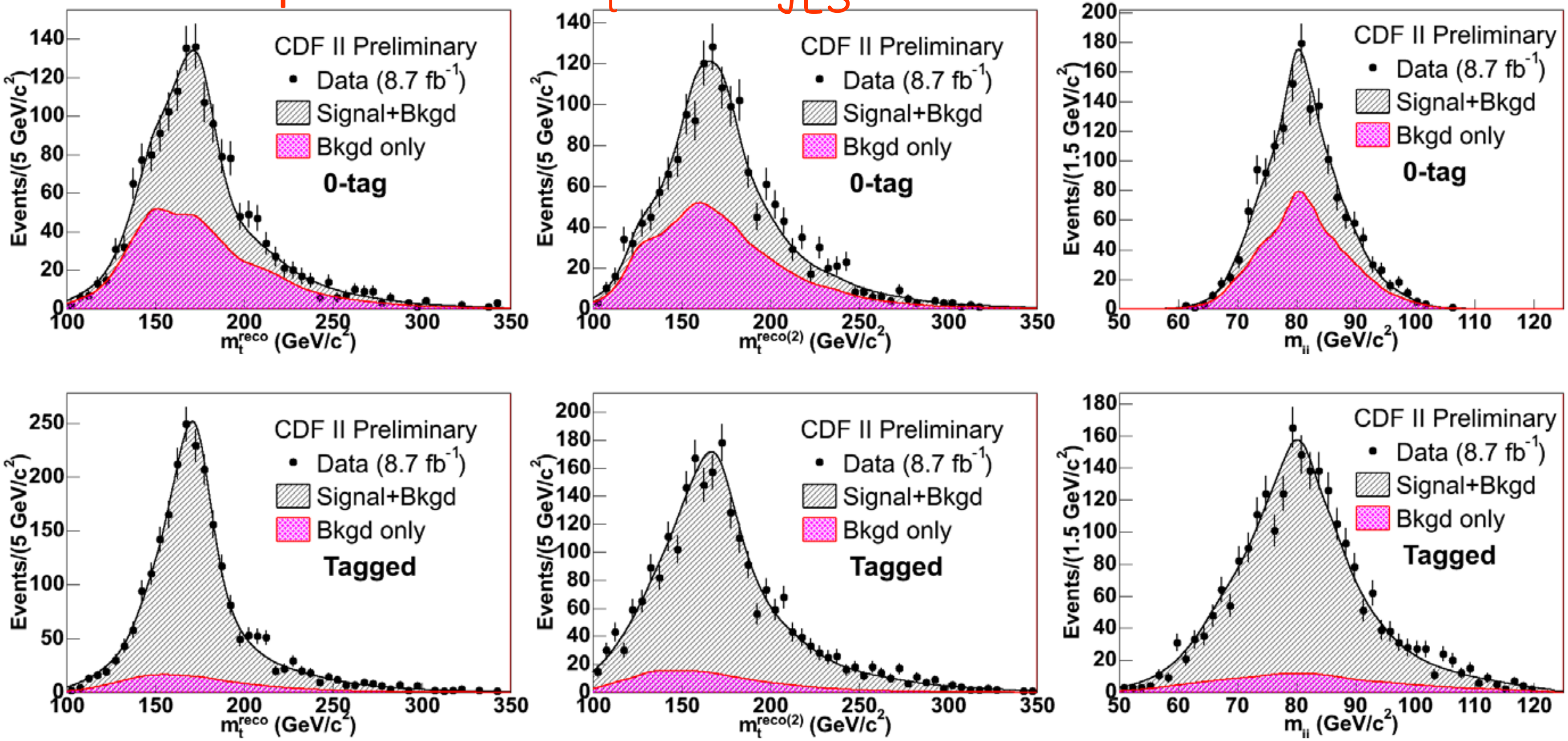
⇒ about 4000 observed events in total , ~2700 ttbar expected

# CDF Lepton plus jets

- 3D template fit

  ⇒Use $M_t^{reco}$, M(jj) and 2nd best $M_t^{reco}$

  ⇒Free parameters $M_t$ and $\Delta_{JES}$




Input $m_{top}^{MC}$ = 173 GeV/c²

# CDF Lepton plus jets: syst uncertainties

- Dominant systematic uncertainty are residual JES and signal modeling

TABLE II. Estimated systematic uncertainties (units in GeV/$c^2$).

| Source | Systematic uncertainty |
|---|---|
| Residual jet energy scale | 0.52 |
| Signal modeling | 0.56 |
| Higher-order corrections | 0.09 |
| $b$ jet energy scale | 0.18 |
| $b$-tagging efficiency | 0.03 |
| Initial and final state radiation | 0.06 |
| Parton distribution functions | 0.08 |
| Gluon fusion fraction | 0.03 |
| Lepton energy scale | 0.03 |
| Background shape | 0.20 |
| Multiple hadron interaction | 0.07 |
| Color reconnection | 0.21 |
| MC statistics | 0.05 |
| Total systematic uncertainty | 0.85 |

Vary JES parameters within their uncertainties

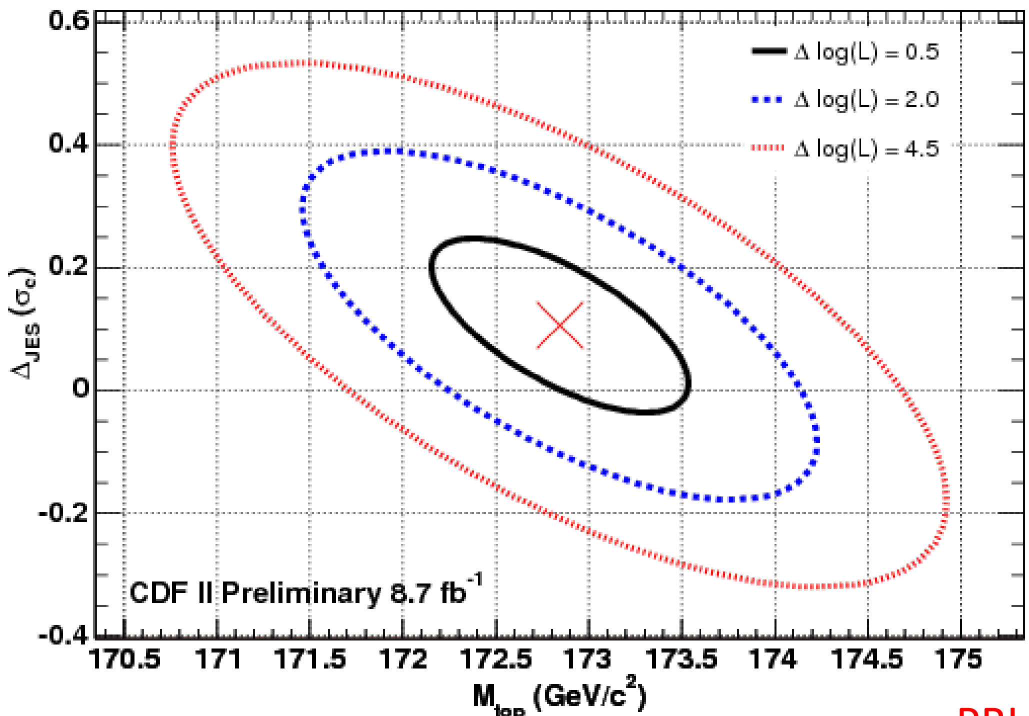
Pythia-Herwig PE

MC@NLO

# CDF Lepton plus jets: results

- Unbinned maximum likelihood fit to the observable in data
- Independent likelihood used for each subsample
- $M_{top}$ = 172.85 ± 0.71 (stat.+JES) ± 0.84 (syst) GeV/$c^2$

Precision: 0.6%




PRL **109**, 152003 (2012)

# D0 Lepton plus jets

- Full D0 data set 9.7 $fb^{-1}$
- Selection:
  - ⇒ Exactly one electron or muon with pT> 20 GeV, |ηe| < 1.1, |ημ| < 2.0
  - ⇒ Exactly four jets pT leading > 40 GeV, pT> 20 GeV
  - ⇒ One or more b-tagged jets (efficiency ~ 65%, mistag rate ~5%)
  - ⇒ MET > 20 GeV + topological cuts
- Simulation
  - ⇒ ttbar : Alpgen +Pythia modified tune A),
  - ⇒ W+jets : Alpgen+Pythia
  - ⇒ W+cc, W+bb: Alpgen+Pythia
  - ⇒ Multijets events : from data

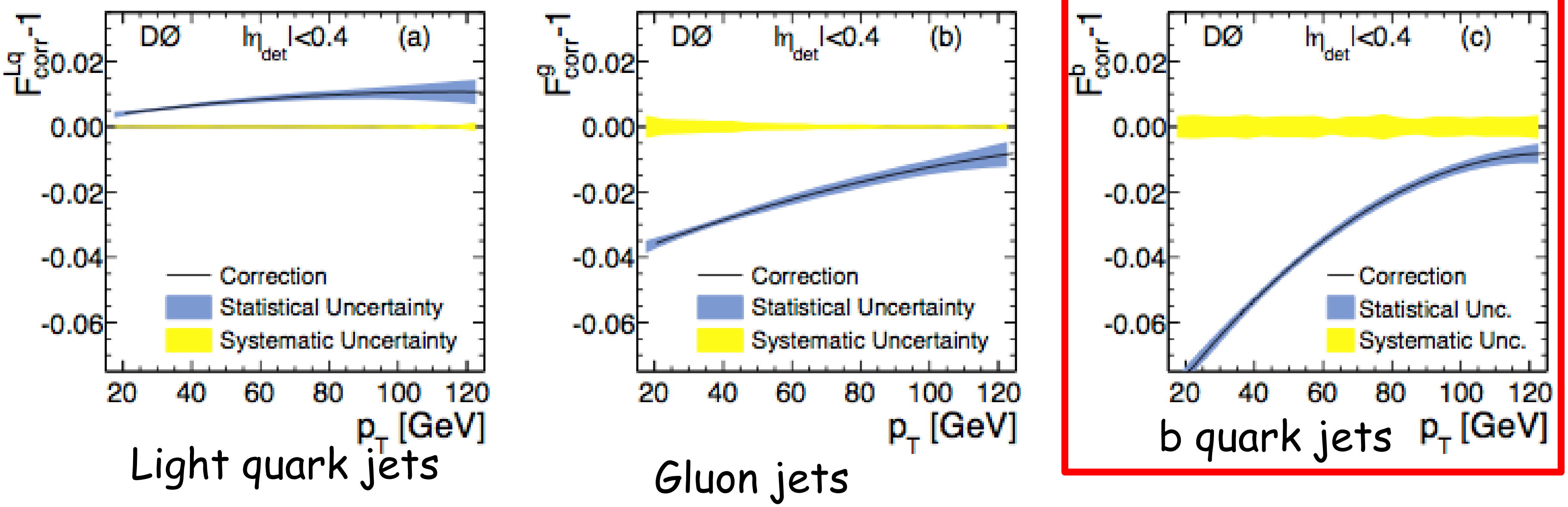
| Contribution | $e$+jets | | | $\mu$+jets | | |
|---|---|---|---|---|---|---|
| $t\bar{t}$ | 918.11 | ± | 3.63 | 824.88 | ± | 3.48 |
| $W$ + jets | 77.85 | ± | 2.13 | 101.03 | ± | 2.93 |
| $W$ + HF | 125.98 | ± | 2.12 | 162.21 | ± | 2.81 |
| Multijet | 144.41 | ± | 24.19 | 48.17 | ± | 16.11 |
| Other backgrounds | 97.75 | ± | 0.51 | 79.24 | ± | 0.94 |
| Expected | 1364.10 | ± | 24.65 | 1215.53 | ± | 17.00 |
| Observed | **1502** | | | **1286** | | |

about 2800 observed events in total ,
~1750 ttbar expected

Expected signal fraction:
61% e+jets 64% μ+jets

# D0: refined JES calibration

- The final flavour-dependent correction:




- The correction accounts for the difference in JES for b quark jets and light quark jets:

  ⇒Substantial reduction of one of the dominant systematic uncertainties

# D0: Matrix element (ME) method

- 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**

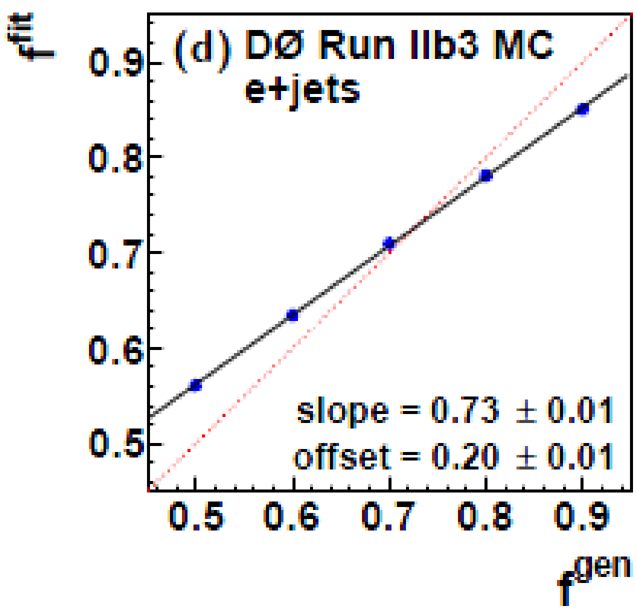
**Transfer function: probability to measure x when parton-level y was produced (detector resp.)**

- Select events with exactly 4 jets, well described by LO ME.
- Sum over 24 possible jet-parton assignments with b-tag dependent weights
- Integrate over 10 variables using MC integration
- Use W-boson mass as an additional constraint for the JES correction factor
- Multiply probabilities for all events -> likelihood simultaneously determines top quark mass and JES correction.

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

# D0: calibration of the ME method

- We need to calibrate the method:
  - ⇒ we use $P_{sig}$ and $P_{bck}$ from first principles with a LO ME and parametrized detector response → calibration is imperative
- Study this using pseudo-experiments:
  - ⇒ Draw ensembles of pseudo-experiments from MC
  - ⇒PEs include:
    - ✓ W+jets background
    - ✓ Multijets backg.
- Step1: determine the fraction of signal $f_{top}$ in data sample



# D0: calibration of the ME method

- We need to calibrate the method:

  ⇒ we use $P_{sig}$ and $P_{bck}$ from first principles with a LO ME and parametrized detector response → calibration is imperative

- Study this using pseudo-experiments:

  ⇒ Draw ensembles of pseudo-experiments from MC

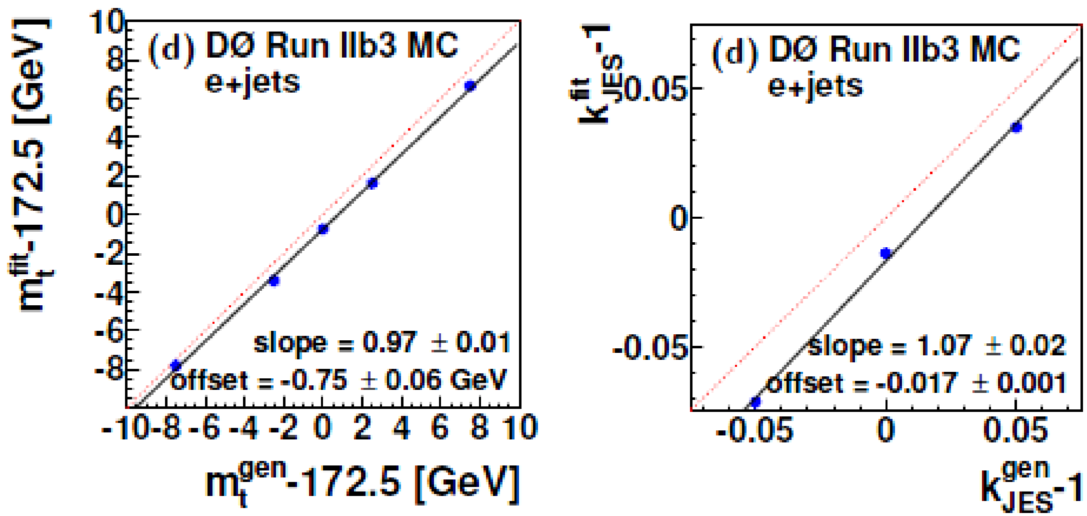
  ⇒PEs include:

  ✓ W+jets background

  ✓ Multijets backg.

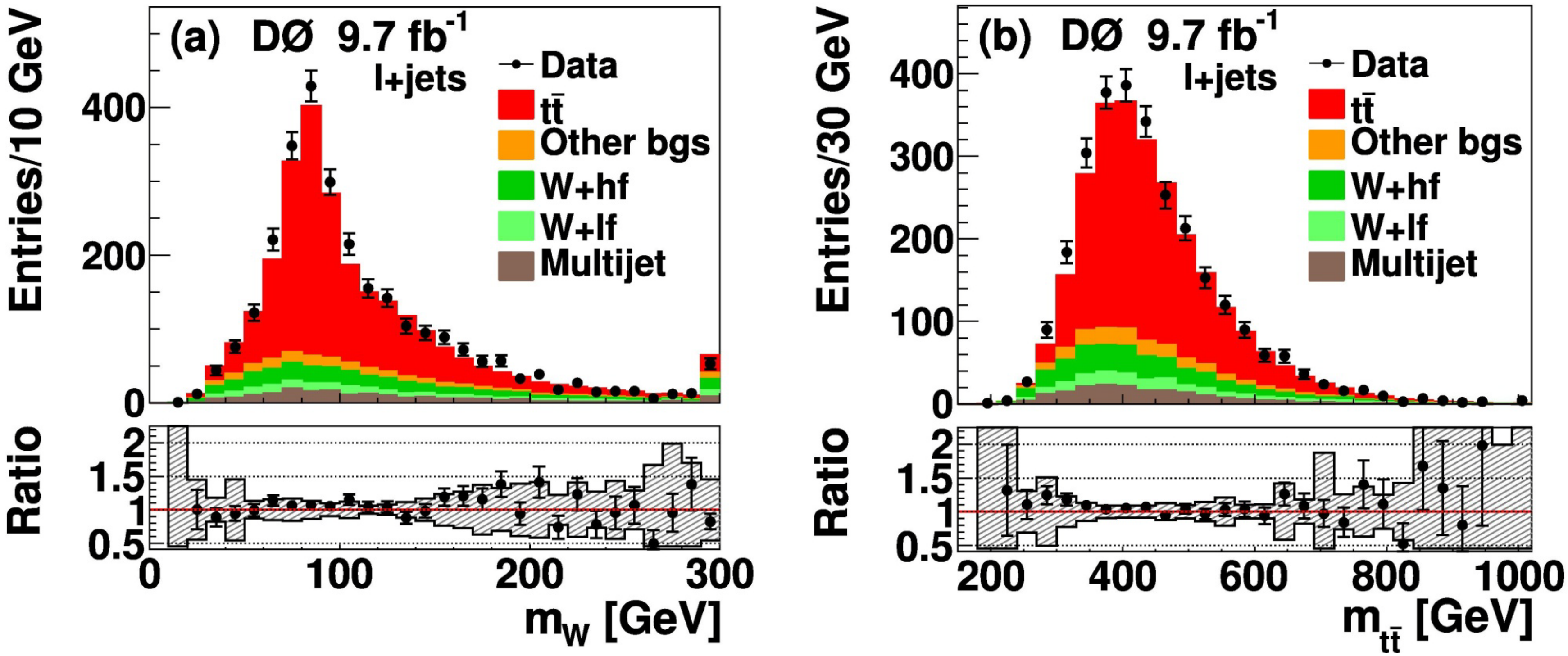
- Step2: determine $m_{top}$ and JES calibration + pull width

  (for $f_{top}$ from Step 1)



# D0 Lepton plus jets

Comparison of SM predictions to data




Input $m_{top}^{MC}$ = 172.5 GeV/$c^2$

# D0: Systematic Uncertainties Estimate

| Source of uncertainty | Effect on $m_t$ (GeV) |
|---|---|
| *Signal and background modeling:* | |
| Higher order corrections | $+0.15$ |
| Initial/final state radiation | $\pm 0.09$ |
| Hadronization and underlying event | $+0.26$ |
| Color reconnection | $+0.10$ |
| Multiple $p\bar{p}$ interactions | $-0.06$ |
| Heavy flavor scale factor | $\pm 0.06$ |
| $b$ quark jet modeling | $+0.09$ |
| Parton distribution functions | $\pm 0.11$ |
| *Detector modeling:* | |
| Residual jet energy scale | $\pm 0.21$ |
| Flavor-dependent response to jets | $\pm 0.16$ |
| $b$ tagging | $\pm 0.10$ |
| Trigger | $\pm 0.01$ |
| Lepton momentum scale | $\pm 0.01$ |
| Jet energy resolution | $\pm 0.07$ |
| Jet identification efficiency | $-0.01$ |
| *Method:* | |
| Modeling of multijet events | $+0.04$ |
| Signal fraction | $\pm 0.08$ |
| MC calibration | $\pm 0.07$ |
| *Total systematic uncertainty* | $\pm 0.49$ |
| *Total statistical uncertainty* | $\pm 0.58$ |
| *Total uncertainty* | $\pm 0.76$ |

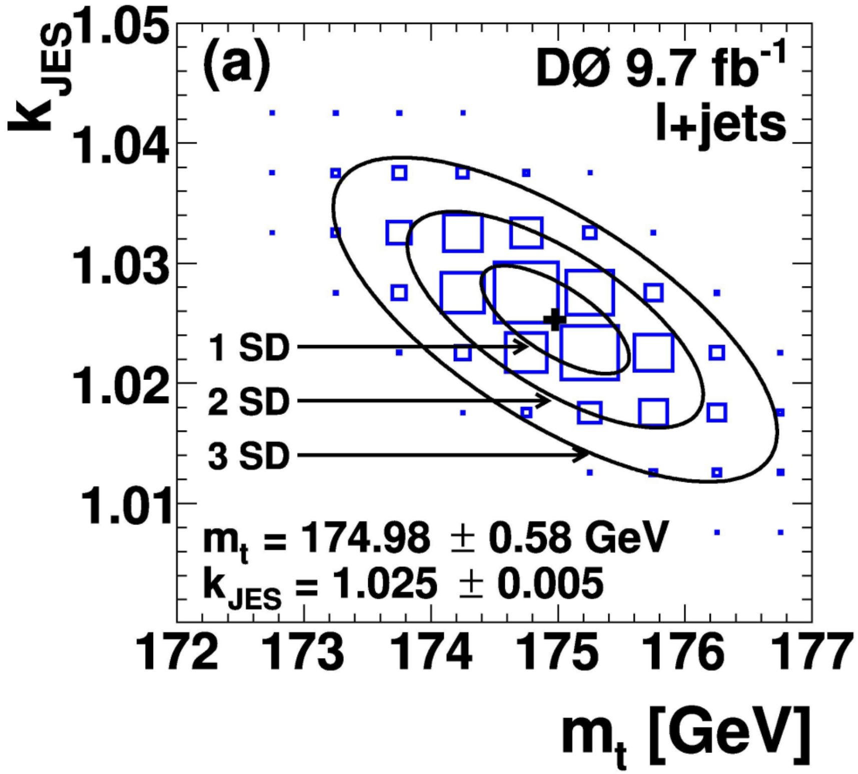
Higher order corrections → MC@NLO +Herwig – Alpgen + Herwig

Initial/final state radiation → Vary renormalisation scale in Alpgen by 1.5 + reweight pT of ttbar system

Hadronization and underlying event → Alpgen +Herwig – Alpgen + Pythia for particle-level jets

Color reconnection → Pythia, Perugia 2011 – Perugia 2001NOCR

# D0 lepton plus jets Results




Precision: 0.44%

$M_{top}$ = 174.98 ± 0.76 (stat+syst) GeV/$c^2$

± 0.58(stat+JES) ± 0.49 (syst) GeV/$c^2$

PRL 113, 032002 (2014)
arXiv:1501.07912v1 submitted to PRD

# D0: Lepton plus jets top quark mass

## Systematic uncertainties comparison with previous D0 analysis

| Source of uncertainty | Effect on $m_t$ (GeV) |
|---|---|
| *Signal and background modeling:* | |
| Higher order corrections* | 0.15 |
| Initial/final state radiation* | 0.09 |
| Hadronization & UE* | 0.26 |
| Color reconnection* | 0.10 |
| Multiple $p\bar{p}$ interactions | 0.06 |
| Heavy flavor scale factor | 0.06 |
| $b$-jet modeling | 0.09 |
| PDF uncertainty | 0.11 |
| *Detector modeling:* | |
| Residual jet energy scale | 0.21 |
| Data-MC jet response difference | 0.16 |
| $b$-tagging | 0.10 |
| Trigger | 0.01 |
| Lepton momentum scale | 0.01 |
| Jet energy resolution | 0.07 |
| Jet ID efficiency | 0.01 |
| *Method:* | |
| Modeling of multijet events | 0.04 |
| Signal fraction | 0.08 |
| MC calibration | 0.07 |
| *Total systematic uncertainty* | 0.49 |
| *Total statistical uncertainty* | 0.58 |
| *Total uncertainty* | 0.76 |

PRL113 032002 (2014) 9.7 fb$^{-1}$

**0.49 GeV**

**1.02 GeV**

| Source | Uncertainty (GeV) |
|---|---|
| *Modeling of production:* | |
| *Modeling of signal:* | |
| Higher-order effects | ±0.25 |
| ISR/FSR | ±0.26 |
| Hadronization and UE | ±0.58 |
| Color reconnection | ±0.28 |
| Multiple $p\bar{p}$ interactions | ±0.07 |
| Modeling of background | ±0.16 |
| $W$+jets heavy-flavor scale factor | ±0.07 |
| Modeling of $b$ jets | ±0.09 |
| Choice of PDF | ±0.24 |
| *Modeling of detector:* | |
| Residual jet energy scale | ±0.21 |
| Data-MC jet response difference | ±0.28 |
| $b$-tagging efficiency | ±0.08 |
| Trigger efficiency | ±0.01 |
| Lepton momentum scale | ±0.17 |
| Jet energy resolution | ±0.32 |
| Jet ID efficiency | ±0.26 |
| *Method:* | |
| Multijet contamination | ±0.14 |
| Signal fraction | ±0.10 |
| MC calibration | ±0.20 |
| Total | ±1.02 |

PRD84 032004 (2011) 3.6 fb$^{-1}$

# CDF dilepton top-quark mass

- Small branching ratio (5% for ee, eμ, μμ final states)
- Measurement with the full RunII dataset 9.1 $fb^{-1}$

  → statistics is no longer the limiting uncertainty, this analysis optimized the influence of jet energy scale
- Sample: two charged leptons, missing transverse energy and two jets
- Top-quark mass reconstruction difficult due to 2 undetectable neutrinos

CDF Run II Preliminary (8.8 $fb^{-1}$)

| $t\bar{t}$ **dilepton sample, tagged events** | |
|---|---|
| Source | $ll$ |
| $WW$ | 0.57 ± 0.15 |
| $WZ$ | 0.12 ± 0.03 |
| $ZZ$ | 0.20 ± 0.06 |
| DY+LF | 2.35 ± 0.31 |
| DY+HF | 2.09 ± 0.20 |
| Fakes | 8.59 ± 2.74 |
| Total background | 13.92 ± 2.83 |
| $t\bar{t}$ ($\sigma = 7.4$ pb) | 227.19 ± 16.17 |
| Total SM expectation | 241.11 ± 16.42 |
| Observed | 230 |

CDF Run II Preliminary (9.1 $fb^{-1}$)

| $t\bar{t}$ **dilepton sample, 0 tags** | |
|---|---|
| Source | $ll$ |
| $WW$ | 16.39 ± 3.60 |
| $WZ$ | 5.21 ± 1.00 |
| $ZZ$ | 3.01 ± 0.50 |
| $Z/\gamma^* \to ee + \mu\mu + \tau\tau$ | 51.15 ± 8.00 |
| Fakes | 21.41 ± 6.16 |
| Total background | 97.16 ± 14.45 |
| $t\bar{t}$ ($\sigma = 7.4$ pb) | 173.16 ± 19.70 |
| Total SM expectation | 270.33 ± 33.34 |
| Observed | 290 |

# CDF dilepton top-quark mass

- Template analysis using an hybrid variable formed by:
  - → $M_t^{reco}$: reconstructed top mass (neutrino Φ weighting)
    - ⇒ account for unconstrained event kinematics with scan over the space of possibilities for the azimuthal angles of neutrinos
    - ⇒ reconstruct top quark mass by minimizing a $\chi^2$ function in the assumption of ttbar -> dilepton final state
    - ⇒ assign weights to the solutions and build a single mass for each event
    - ⇒ requires external JES
  - → $M_{lb}^{alt}$: based only on lepton 4-momenta and jet directions:

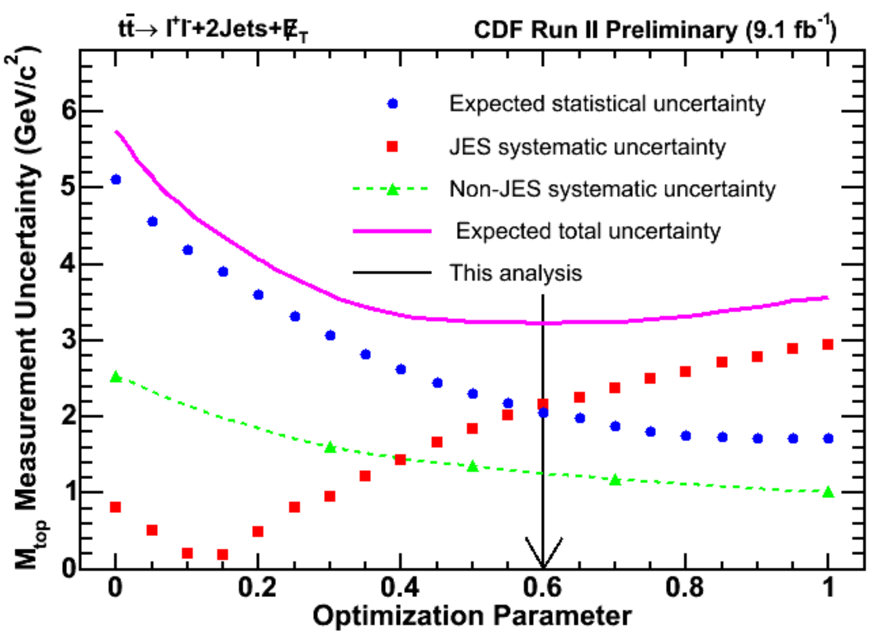
$$M_{lb}^{\mathrm{alt}} = c^2 \sqrt{\frac{\langle l_1, b_1 \rangle \cdot \langle l_2, b_2 \rangle}{E_{b_1} \cdot E_{b_2}}}$$

    - ⇒ insensitive to jet energies, less sensistive to $m_{top}$
- → Definition of the "hybrid variable": $M^{\mathrm{hyb}} = w \cdot M_t^{\mathrm{reco}} + (1 - w) \cdot M_{lb}^{\mathrm{alt}}$
- → we can choose *w* with requirement of minimal expected stat+JES error
  - ⇒ optimization of the uncertainty obtained with *w* = 0.6

# CDF dilepton top-quark mass

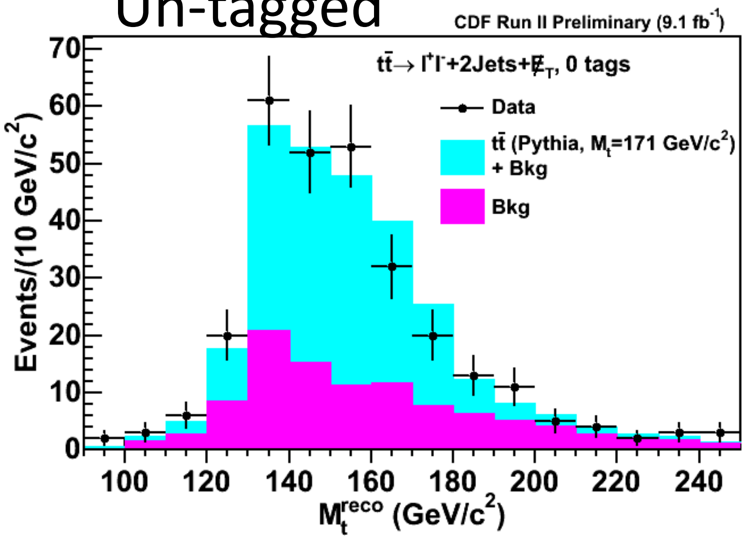
- General procedure:
- Scan interval of [0,1] for parameter *w* to find optimal value for our measurement
- Define expected stat. error as mean of error distribution from PE's for $M_{top}$=172.5GeV/$c^2$
- Define JES systematic error by applying shifts in JES
- Choose optimal *w* with requirement of minimal expected stat+JES error

- Effect from including/removing events after shift in JES $\Rightarrow$ non-zero JES systematics if *w* nearly 0
- If *w*=0.1 JES error is zero because effect of changing alternative variable after shift is compensated by effect from including/removing events

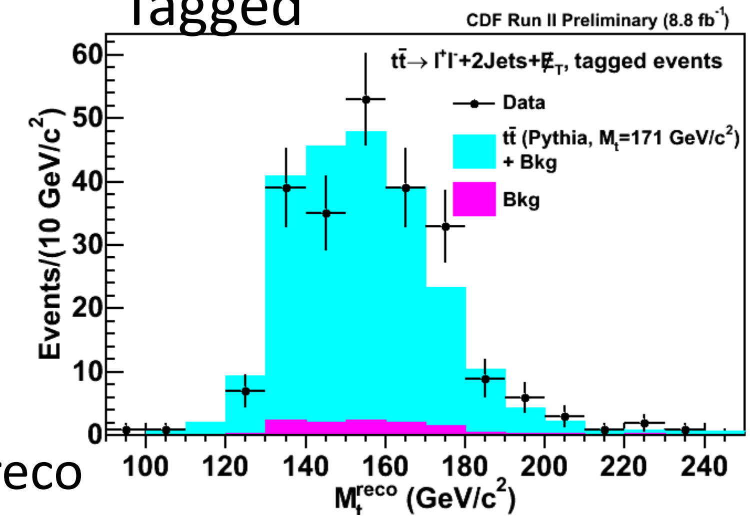


# CDF dilepton top-quark mass

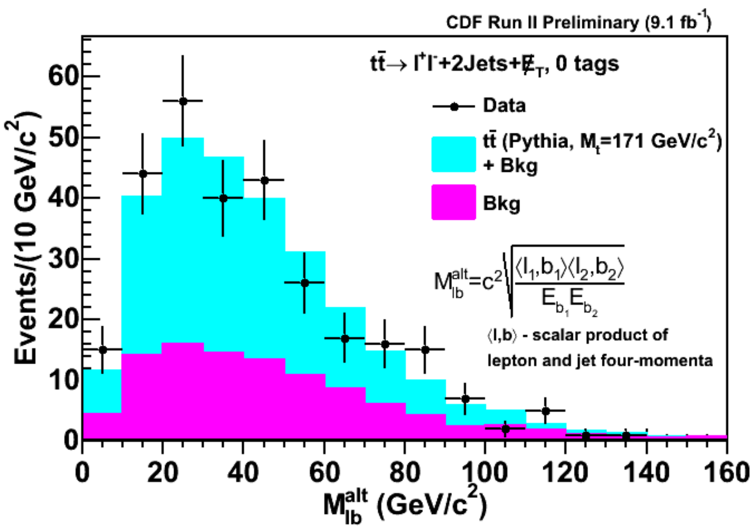
Un-tagged

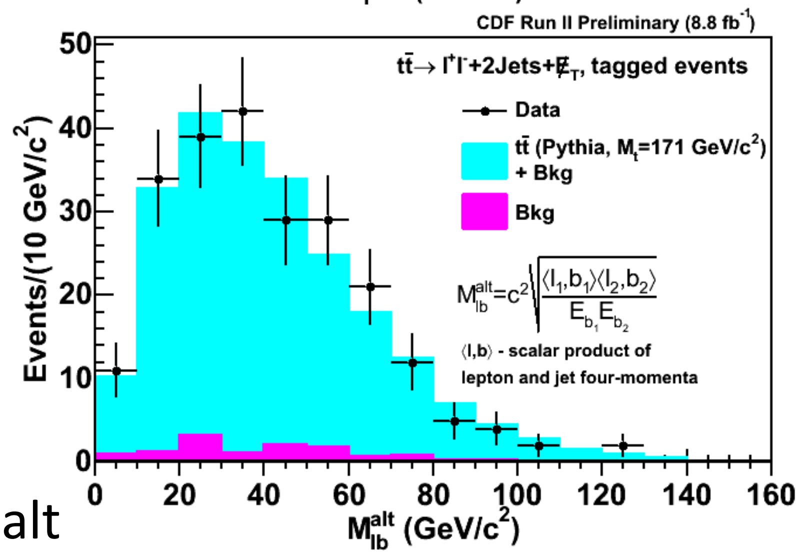



Tagged




$M_t^{reco}$




$M_{lb}^{alt}$

# CDF dilepton top-quark mass syst.

## Summary of uncertainties

- Parameters used for generation are modified by ±1 standard deviation in their uncertainties and new templates are built.
- PE's from modified templates are performed
- Difference between median of top quark mass from PE's and nominal top mass is used as estimate of the systematic uncertainty.

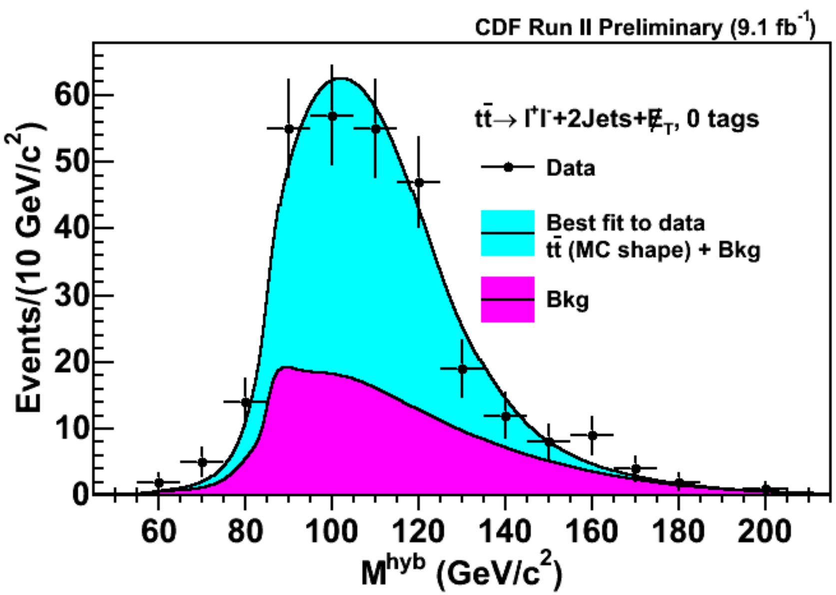
| Source | Uncertainty (GeV/$c^2$) |
|---|---|
| Jet-energy scale | 2.2 |
| NLO effects | 0.7 |
| Monte Carlo generators | 0.5 |
| Lepton-energy scale | 0.4 |
| Background modeling | 0.4 |
| Initial- and final-state radiation | 0.4 |
| $gg$ fraction | 0.3 |
| $b$-jet-energy scale | 0.3 |
| Luminosity profile | 0.3 |
| Color reconnection | 0.2 |
| MC sample size | 0.2 |
| Parton distribution functions | 0.2 |
| $b$-tagging | 0.1 |
| Total systematic uncertainty | 2.5 |
| Statistical uncertainty | 1.9 |
| Total | 3.2 |

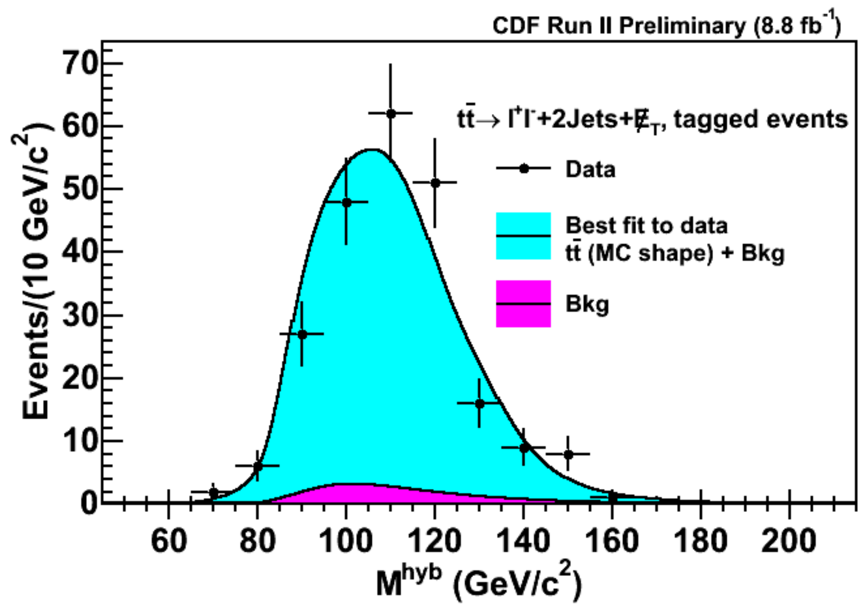
# CDF dilepton: template fits

We define $M_{top}$ as maximum of likelihood function

$M_{top}$ and its positive and negative statistical uncertainties are returned by MINUIT

$$L^{tot} = L^{tagged} \cdot L^{non-tagged}$$




$M_{top}$ = 171.5 ± 1.9 (stat) ± 2.5(syst) GeV/$c^2$

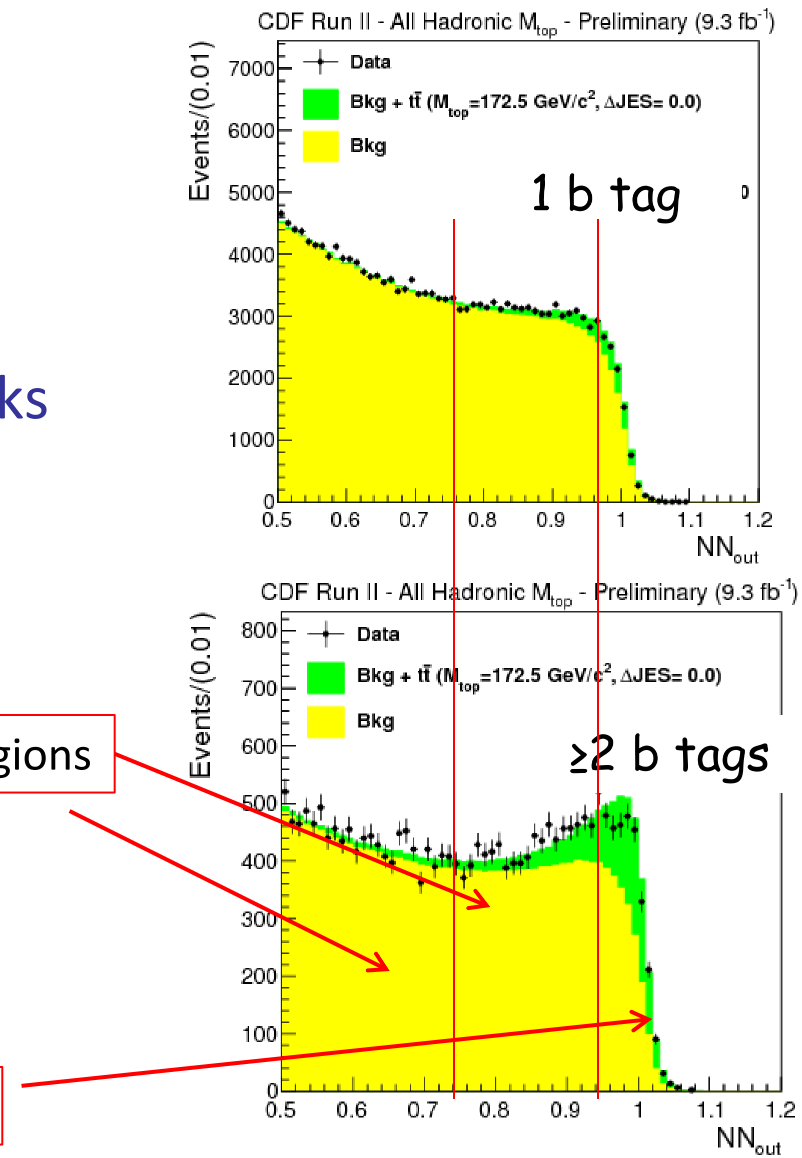
arXiv:1505.00500v1

Precision: 1.9%

14% reduced uncertainty compared to the previous CDF result in this channel

# CDF: All Hadronic

- Full Run II dataset   9.3 fb-1
- Largest branching ratio (46%), but also large backgrounds
  - ⇒ Highly challenging
- 2 bottom quarks and 4 lighter quarks in the final state
- Template Method
- Sample: require at least 6 jets
  - ⇒ Dedicated trigger
- Neural net classifier
  - ⇒ Signal from POWHEG+Pythia
  - ⇒ Background from MC with jet mistag rate from data
- 



# CDF All hadronic: reconstruction

- Kinematic fit to find best candidate jet assignments

$$\chi^2 = \frac{\left(m_{jj}^{(1)} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(m_{jj}^{(2)} - M_W\right)^2}{\Gamma_W^2} +$$

Double $m_W$ constraint for JES

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

Constraint on $m_{top}$

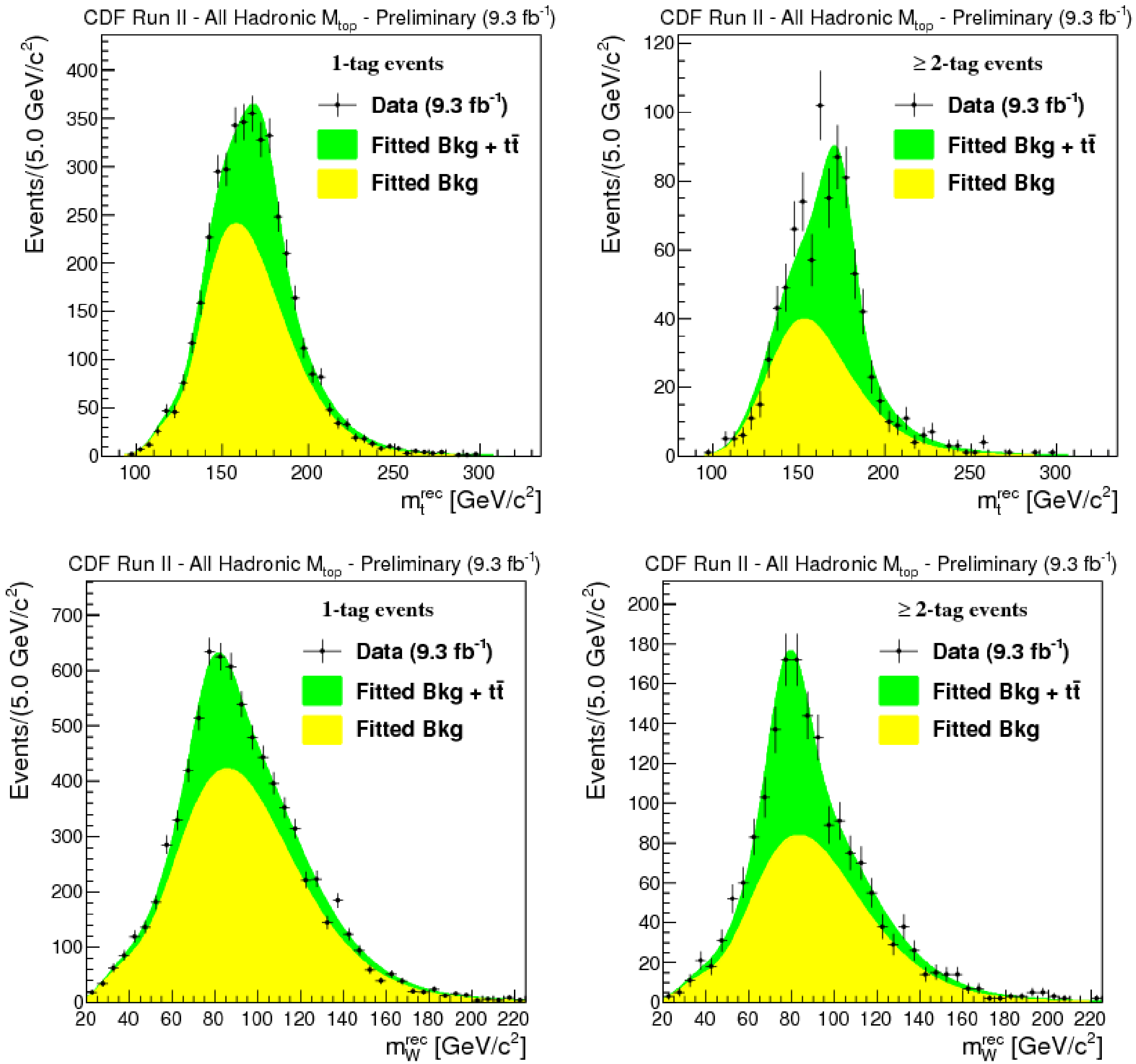
Consistence of fitted 4-momenta with measured ones

- To derive JES, modify $\chi^2$ to have $m_{jj}^{(1)} = m_{jj}^{(2)} = m_W^{rec}$
- Pick assignment with minimal $\chi^2$
- Now we are able to reconstruct $m_{top}$ and $m_W$

# All Hadronic: Template Fit

$m_t^{rec}$
1 tag

$m_t^{rec}$
≥2 tags




$m_W^{rec}$
1 tag

$m_W^{rec}$
≥2 tags

# All Hadronic: syst uncertainties

| Source | $\sigma_{M_{\rm top}}$ (GeV/$c^2$) | $\sigma_{\Delta_{\rm JES}}$ |
|---|---|---|
| Generator (hadronization) | 0.29 | 0.273 |
| Parton distribution functions | $^{+0.18}_{-0.36}$ | $^{+0.096}_{-0.052}$ |
| Initial / Final state radiation | 0.13 | 0.232 |
| Color reconnection | 0.32 | 0.101 |
| $\Delta_{\rm JES}$ fit | 0.97 | −− |
| $M_{\rm top}$ fit | −− | 0.207 |
| Other free parameters of the fit | 0.41 | 0.040 |
| Templates sample size | 0.34 | 0.071 |
| $t\bar{t}$ cross section | 0.15 | 0.034 |
| Integrated luminosity | 0.15 | 0.032 |
| Trigger | 0.61 | 0.188 |
| Background shape | 0.15 | 0.014 |
| $b$-tagging | 0.04 | 0.018 |
| $b$-jets energy scale | 0.20 | 0.035 |
| Pileup | 0.22 | 0 |
| Residual JES | 0.57 | −− |
| Residual bias / Calibration | $^{+0.27}_{-0.24}$ | $^{+0.077}_{-0.096}$ |
| Total | $^{+1.55}_{-1.58}$ | $^{+0.492}_{-0.488}$ |

Modeling of signal events (Generator through Color reconnection)

Measurement method ($\Delta_{\rm JES}$ fit through Templates sample size)

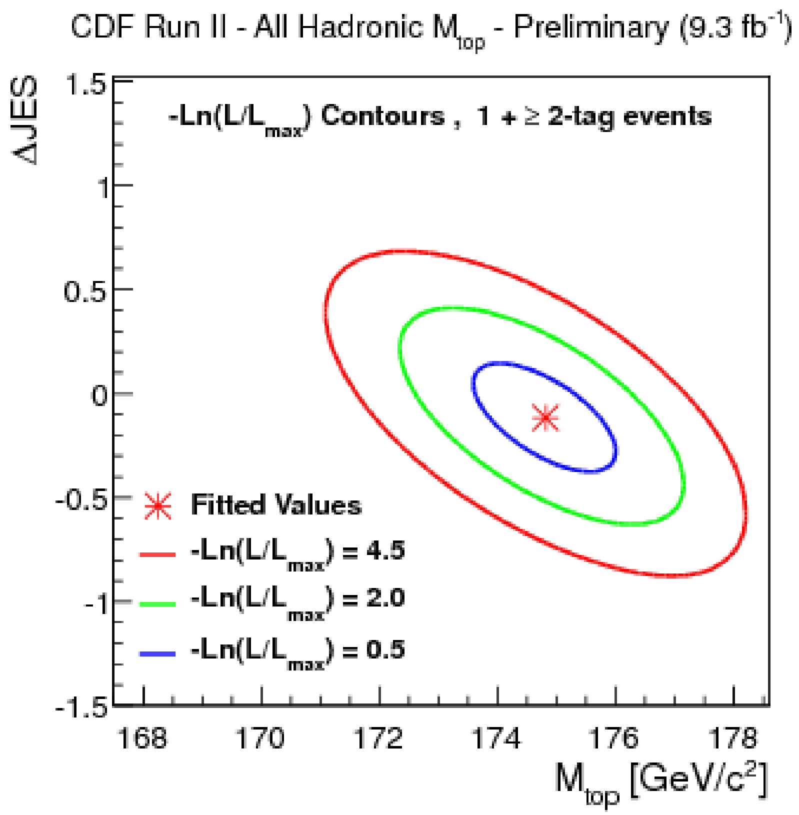
Trigger

Residual JES (Residual JES, Residual bias / Calibration)

# All Hadronic: Results

- $m_t = 175.07 \pm 1.19(\text{stat})^{+1.55}_{-1.58}(\text{syst})\ \text{GeV}/c^2$

Precision: 1.1%

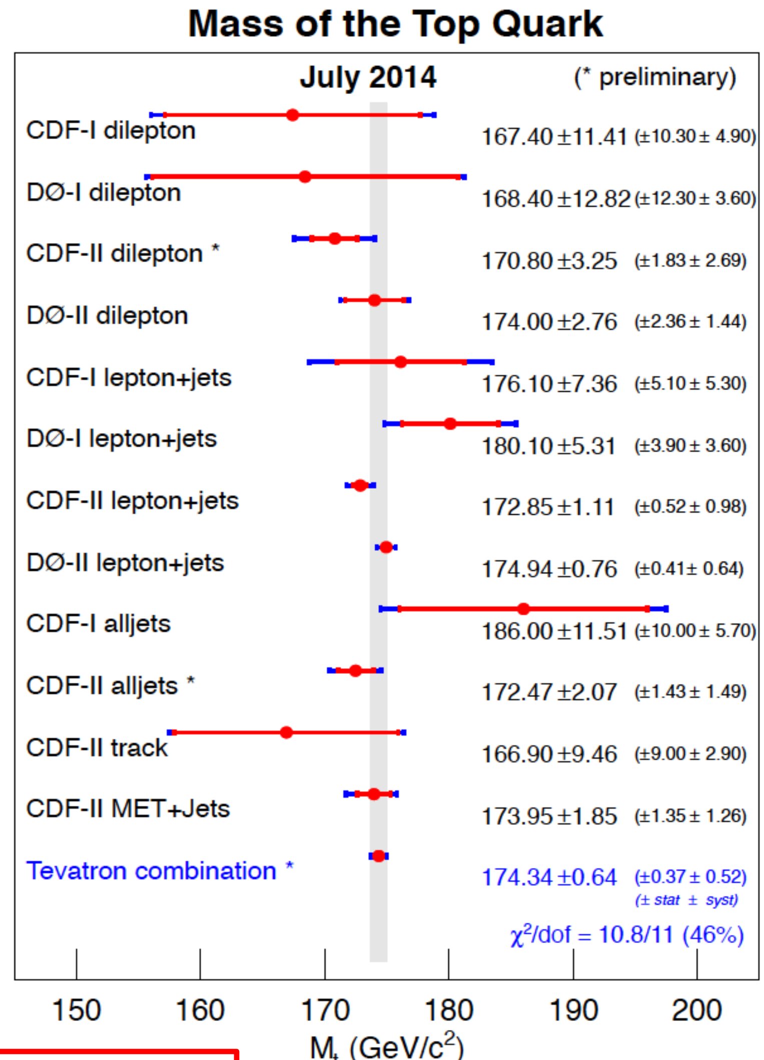



PRD 90, 091101(R) (2014)

# Tevatron top mass combination

- 5 Run I and 7 Run II results
- Combination performed using BLUE
- Update since march 2013:
  - ⇒ CDF analyses in dilepton and alljets
  - ⇒ D0 l+jets measurement using matrix elements
- Limited by systematic uncertainties
  - ⇒ Dominant: signal modeling and jet energy scale uncertainties
- Total uncertainty ± 0.64 GeV/$c^2$ (< 0.4%)

(better than world comb. March 2014: ± 0.76 GeV/$c^2$)

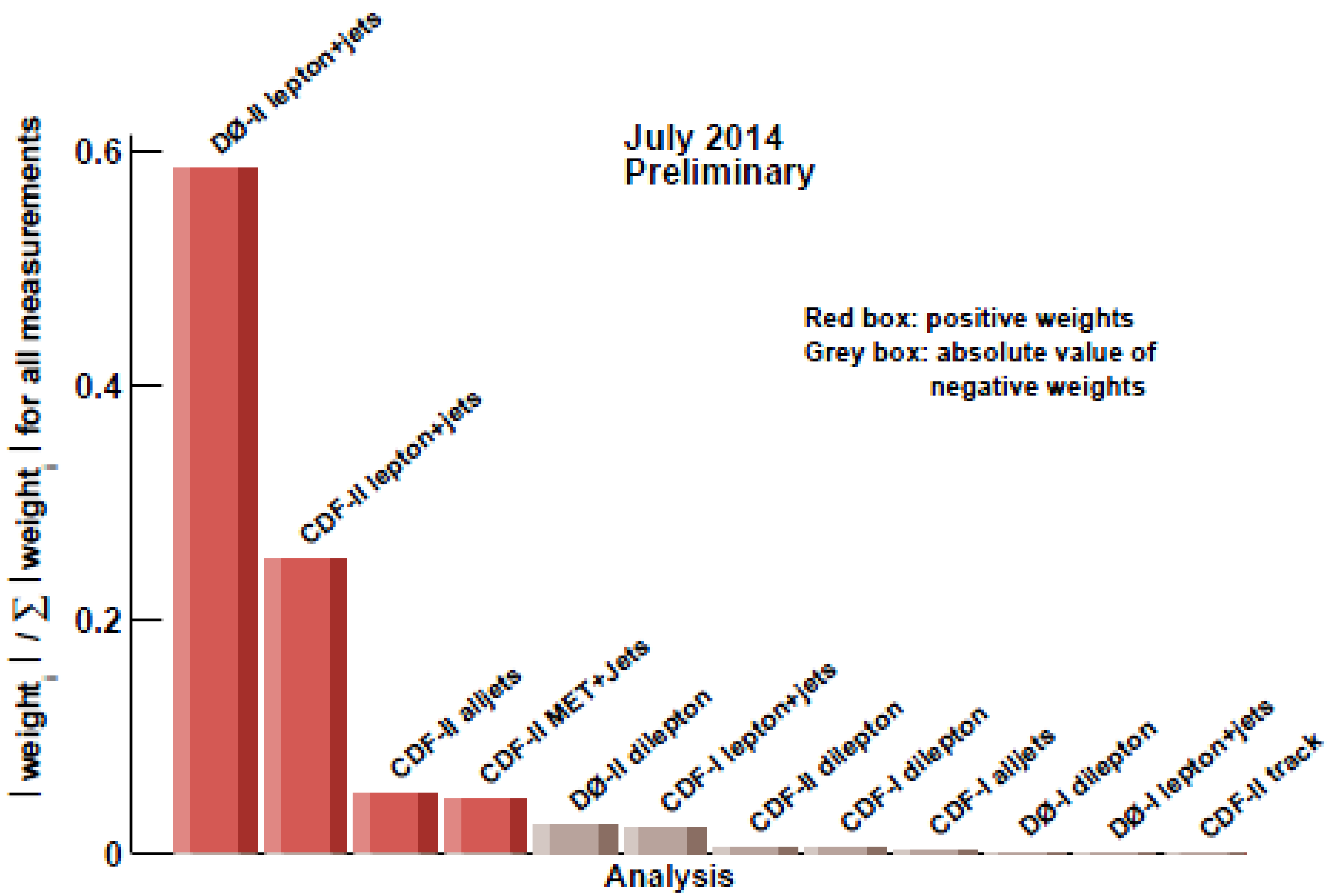



$M_{top}$ = 174.34 ± 0.37 (stat) ± 0.52 (syst) GeV/$c^2$

arXiv:1407.2682

# Tevatron top mass combination

- Weights per measurement:



# Conclusions

- Experimental top quark physics started 20 years ago at the Tevatron, with the observation of top
- Tevatron experiments paved the way to LHC experiments, defining tools and procedures
- Our top mass measurements are systematically limited since years
  - ⇒ Lots of work went into the understanding of the systematic uncertainties and refining the precision
  - ⇒ And unifying their treatment across experiments!
    - ✓ Most precise measurements with the Matrix Element method in the l+jets channel
    - ✓ Followed by the all-hadronic channel + the Template Method
    - ✓ Significant contribution from the dilepton channel
- Several results are coming in dilepton and all-hadronic channels from D0
- 20 years after the discovery of the top quark:
  - ⇒ It's time for the LHC exp. to accomplish precision measurements in the top sector

# Conclusions

- Experimental top quark physics started 20 years ago at the Tevatron, with the observation of top
- Tevatron experim… …ts, defining tools and procedures
- Our measureme…
  - ⇒ Lots of work went into … of the systematics and refining the

Thank you!

- For more details:
- http://www-cdf.fnal.gov/physics/new/top/top.html
- http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/
- http://tevewwg.fnal.gov

  - ✓ Followed by the all-hadronic channel + the Template Method
  - ✓ Significant co… …nel
- Several results a… …om D0
- 20 years after the…
  - ⇒ It's time for the LHC exp. … …ecision measurements in the top sector

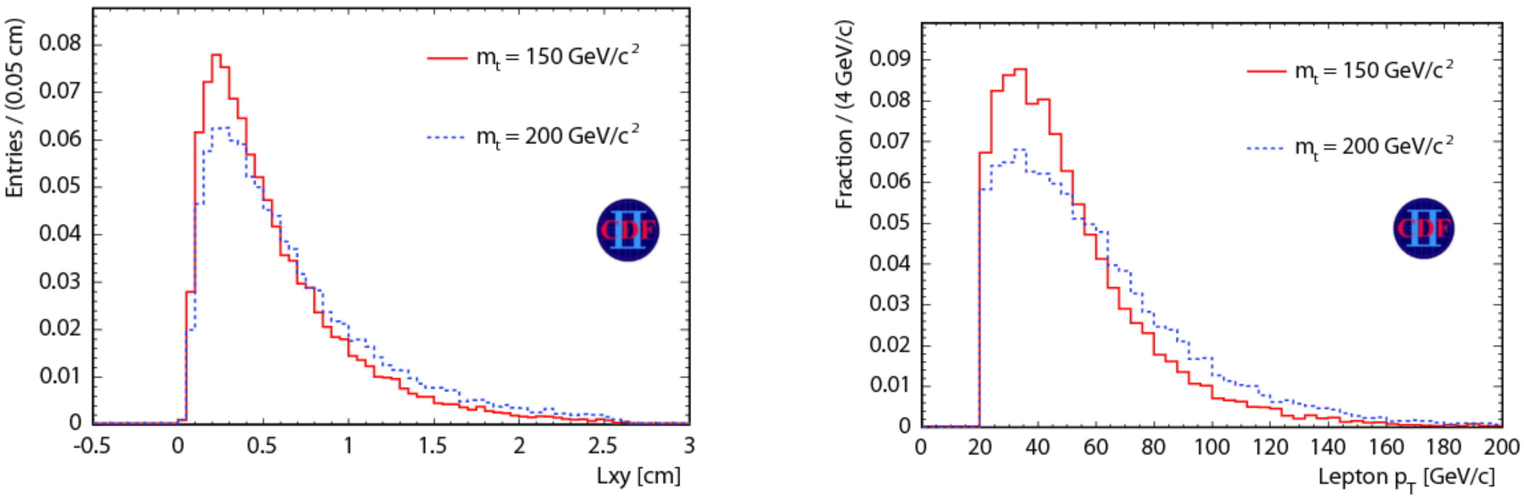
Thanks to all the CDF and D0 collaborators and the Fermilab staff

# Backup

# Alternative Techniques

- B-hadron Lifetime / Lepton pT
  - ⇒ lifetime and (transverse) decay length (Lxy ) of B-hadrons from the top decay depend linearly on mt
  - ⇒ similarly, pT of the charged leptons from the W boson decay can be used
  - ⇒ Lxy and lepton-pT reconstruction based on the tracking (muon) system(s) and EM calo (for e), largely reduced sensitivity to JES unc., however typically larger statistical uncertainties

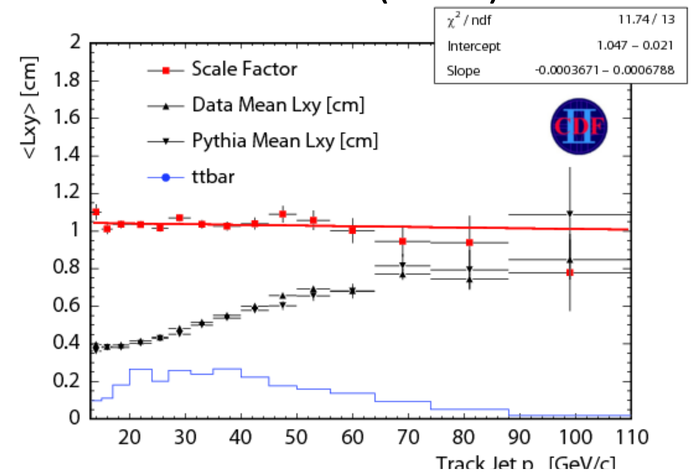
Phys.Rev.D81 032002 (2010)

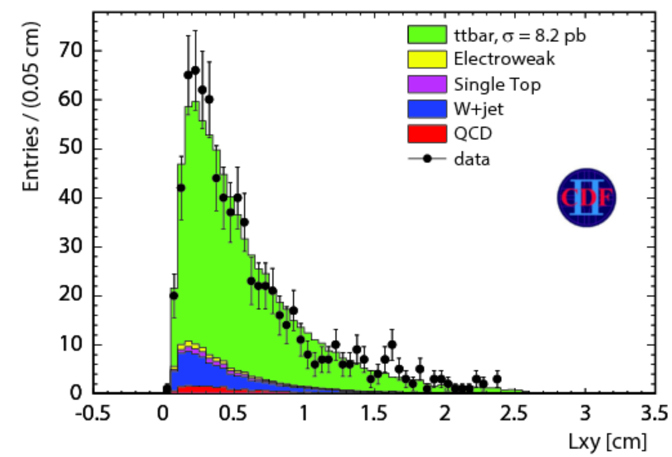


# B-hadron Lifetime / Lepton pT

- L = 1.9 fb$^{-1}$, l+jets channel
- sensitive to:
  - ⇒ modelling of top-pT (PDFs)
  - ⇒ Lxy calibration (b-fragmentation, tracking modelling)
    - ✓ dedicated Lxy calibration using bb events
- Simultaneous fit to Lxy / lepton pT :
- mt = 170.7 ± 6.3 (stat.) ± 2.6 (syst) GeV
- systematic uncertainties dominated by:
  - ⇒ background shape (1.7 GeV)
  - ⇒ lepton pT scale (1.2 GeV)
  - ⇒ Lxy calibration (1.1 GeV)
  - ⇒ calorimeter JES uncertainty: 0.3 GeV
- Phys.Lett.B698:371-379,2011: mt = 176.9 ± 8.0(stat) ± 2.7(syst) GeV (lepton pT only)

PRD81 032002 (2010)



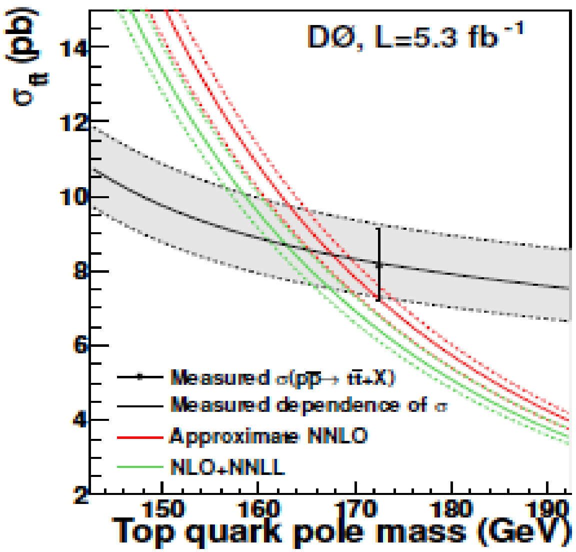
# Top-Quark Mass from tt x-Section

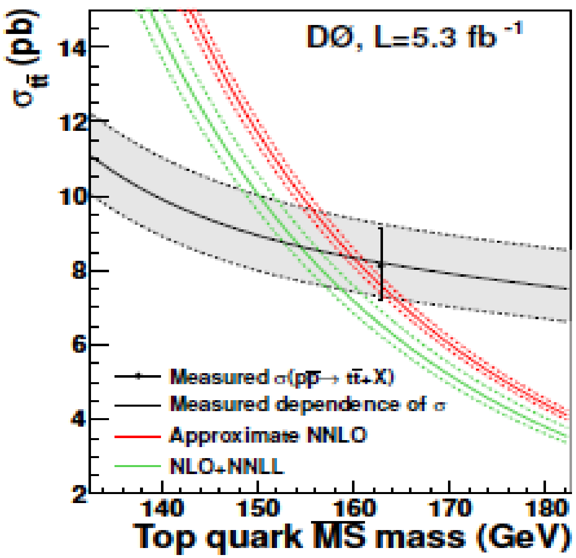
- compare experimental $\sigma_{tt}$ with theory computation PLB 703 , 422 (2011)
  - ⇒ measure $m_t$ in well defined renormalisation scheme ($m_t^{pole}$, $m_t^{MS}$)
  - ⇒ $m_t^{MC}$ only enters via top mass dependence of measured $\sigma_{tt}$ due to event selection criteria
- compare measured and predicted cross-section to find most probable $m_t$ (likelihood maximisation)
- L = 5.3 $fb^{-1}$: l+ jets channel
- theory calculation at approximate NNLO

(JHEP 0307 (2003) 001, Comput. Phys. Commun. 135 (2001) 238)

- theory uncertainties:
  - ⇒ renormalisation/factorisation scales (up/down variation by factor 2)
  - ⇒ PDF uncertainty

# Top-Quark Mass from tt x-Section




- assuming $m_t^{MC} = m_t^{\overline{MS}}$ results in shift of
  - $\Delta m_t^{pole} = -2.7\,\mathrm{GeV}$
  - $\Delta m_t^{\overline{MS}} = -2.6\,\mathrm{GeV}$

→ half of shift included in systematic uncertainties

PLB 703 , 422 (2011)

$m_t^{pole} = 167.5^{+5.2}_{-4.7}$ GeV $\quad m_t^{\overline{MS}} = 160.0^{+4.8}_{-4.2}$ GeV

PRD 80 , 071102 (2009):

$m_t^{pole} = 169.1^{+5.9}_{-5.2}$ ($\ell$+jets + dilepton channel)

# CDF MET +jet channel

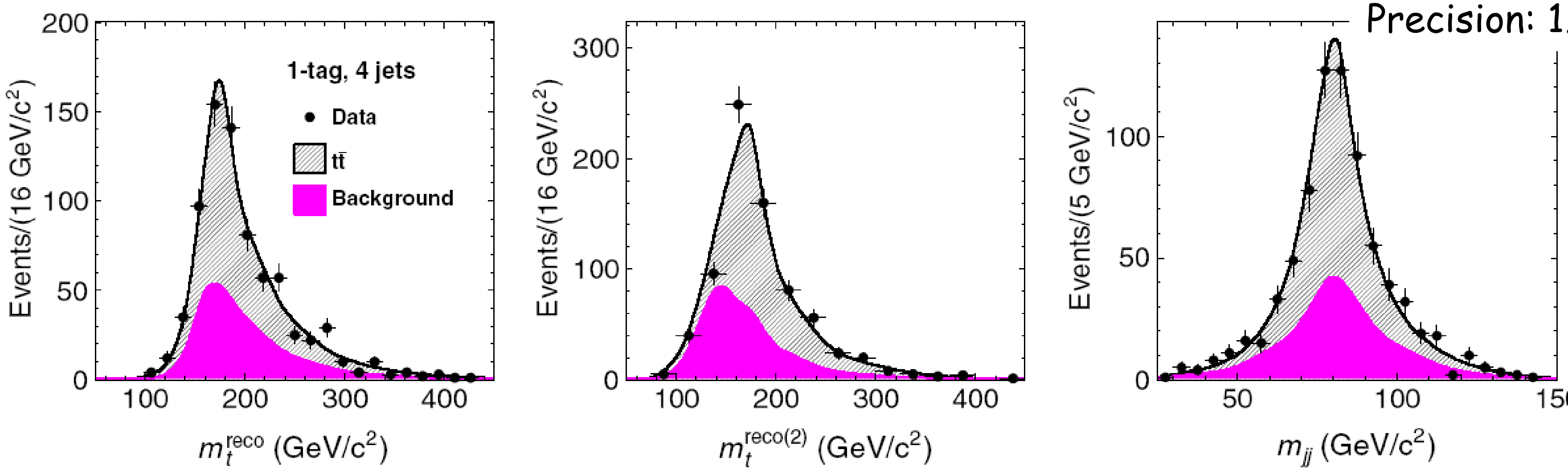
PRD (R) 88 011101 (2013)

- Full Run II dataset 8.7 fb-1
- ttbar simulation: Pythia
- Selection similar to l+jets:
  - ⇒ NO identified leptons, MET significance > 3 $GeV^{1/2}$
  - ⇒ 4 – 6 jets with pT > 15 GeV, |η| < 2.0
  - ⇒ topological cuts + NN discriminant cut
  - ⇒ Use b-tagging to classify events
- Reconstruction procedure similar to l+jets

| Source | Uncertainty (GeV/$c^2$) |
|---|---|
| Residual jet-energy scale | 0.44 |
| MC generator | 0.36 |
| Color reconnection | 0.28 |
| $gg$ fraction | 0.27 |
| Radiation | 0.28 |
| PDFs | 0.16 |
| $b$-jet energy scale | 0.19 |
| Background | 0.15 |
| Calibration | 0.21 |
| Multiple hadron interaction | 0.18 |
| Trigger modeling | 0.13 |

$M_{top}$ = 173.93 ± 1.64 (stat+JES) ± 0.87 (syst) GeV

Precision: 1.1%



# Tevatron top mass combination:

- Matrix of total correlation coefficients:

| | Run I published | | | | | Run II published | | | | | Run II prel. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CDF | | | DØ | | CDF | | | DØ | | CDF | |
| | $\ell$+jets | $\ell\ell$ | all-jets | $\ell$+jets | $\ell\ell$ | $\ell$+jets | $L_{XY}$ | MEt | $\ell$+jets | $\ell\ell$ | $\ell\ell$ | all-jets |
| CDF-I $\ell$+jets | 1.00 | 0.29 | 0.32 | 0.26 | 0.11 | 0.49 | 0.07 | 0.26 | 0.19 | 0.12 | 0.54 | 0.27 |
| CDF-I $\ell\ell$ | 0.29 | 1.00 | 0.19 | 0.15 | 0.08 | 0.29 | 0.04 | 0.16 | 0.12 | 0.08 | 0.32 | 0.17 |
| CDF-I all-jets | 0.32 | 0.19 | 1.00 | 0.14 | 0.07 | 0.30 | 0.04 | 0.16 | 0.08 | 0.06 | 0.37 | 0.18 |
| DØ-I $\ell$+jets | 0.26 | 0.15 | 0.14 | 1.00 | 0.16 | 0.22 | 0.05 | 0.12 | 0.13 | 0.07 | 0.26 | 0.14 |
| DØ-I $\ell\ell$ | 0.11 | 0.08 | 0.07 | 0.16 | 1.00 | 0.11 | 0.02 | 0.07 | 0.07 | 0.05 | 0.13 | 0.07 |
| CDF-II $\ell$+jets | 0.49 | 0.29 | 0.30 | 0.22 | 0.11 | 1.00 | 0.08 | 0.32 | 0.28 | 0.18 | 0.52 | 0.30 |
| CDF-II $L_{XY}$ | 0.07 | 0.04 | 0.04 | 0.05 | 0.02 | 0.08 | 1.00 | 0.04 | 0.05 | 0.03 | 0.06 | 0.04 |
| CDF-II MEt | 0.26 | 0.16 | 0.16 | 0.12 | 0.07 | 0.32 | 0.04 | 1.00 | 0.17 | 0.11 | 0.29 | 0.18 |
| DØ-II $\ell$+jets | 0.19 | 0.12 | 0.08 | 0.13 | 0.07 | 0.28 | 0.05 | 0.17 | 1.00 | 0.36 | 0.15 | 0.14 |
| DØ-II $\ell\ell$ | 0.12 | 0.08 | 0.06 | 0.07 | 0.05 | 0.18 | 0.03 | 0.11 | 0.36 | 1.00 | 0.10 | 0.09 |
| CDF-II $\ell\ell$ | 0.54 | 0.32 | 0.37 | 0.26 | 0.13 | 0.52 | 0.06 | 0.29 | 0.15 | 0.10 | 1.00 | 0.32 |
| CDF-II all-jets | 0.27 | 0.17 | 0.18 | 0.14 | 0.07 | 0.30 | 0.04 | 0.18 | 0.14 | 0.09 | 0.32 | 1.00 |

# Tevatron top mass combination

- Uncertainties on combined top quark mass:

| | Tevatron combined values (GeV/$c^2$) |
|---|---|
| $M_t$ | 174.34 |
| *In situ* light-jet calibration (iJES) | 0.31 |
| Response to $b/q/g$ jets (aJES) | 0.10 |
| Model for $b$ jets (bJES) | 0.10 |
| Out-of-cone correction (cJES) | 0.02 |
| Light-jet response (1) (rJES) | 0.05 |
| Light-jet response (2) (dJES) | 0.13 |
| Lepton modeling (LepPt) | 0.07 |
| Signal modeling (Signal) | 0.34 |
| Jet modeling (DetMod) | 0.03 |
| $b$-tag modeling ($b$-tag) | 0.07 |
| Background from theory (BGMC) | 0.04 |
| Background based on data (BGData) | 0.08 |
| Calibration method (Method) | 0.07 |
| Offset (UN/MI) | 0.00 |
| Multiple interactions model (MHI) | 0.06 |
| Systematic uncertainty (syst) | 0.52 |
| Statistical uncertainty (stat) | 0.37 |
| Total uncertainty | 0.64 |