# Mass measurements at the Tevatron

## Top2015 conference

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on behalf of the CDF and D0 Collaborations

Ischia, September 16th 2015

# Overview

- Introduction
- Matrix element method
  - ljets channel at D0
- Template method
  - dilepton channel at D0
  - dilepton, ljets and all-hadronic channels at CDF
- Extraction from the cross-section
  - pole mass measurement at D0
- Combinations

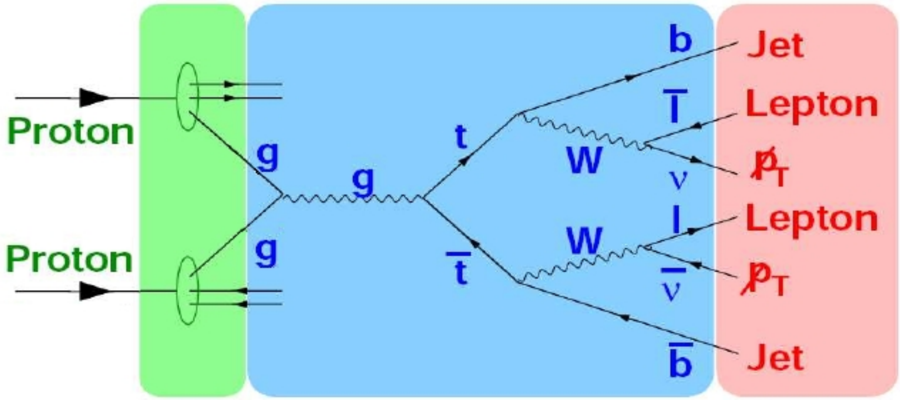
All measurements presented use the **full statistics** collected ($\sim$ 9 $fb^{-1}$)

# Introduction

- What can be **learned from Tevatron measurements**?
  - various **methods** explored
  - results are **competitive**
  - statistics is lower than at the LHC, but measurement limited by signal modelling and JES
- Different methods presented here:
  - **matrix element**: maximum use of the kinematic information in the event
  - **template fits**: use of complementary variables to constrain the main systematics
  - **alternative methods**: mass from the cross-section, clear definition of what is being measured
- **Recent results** of high quality from the experiments

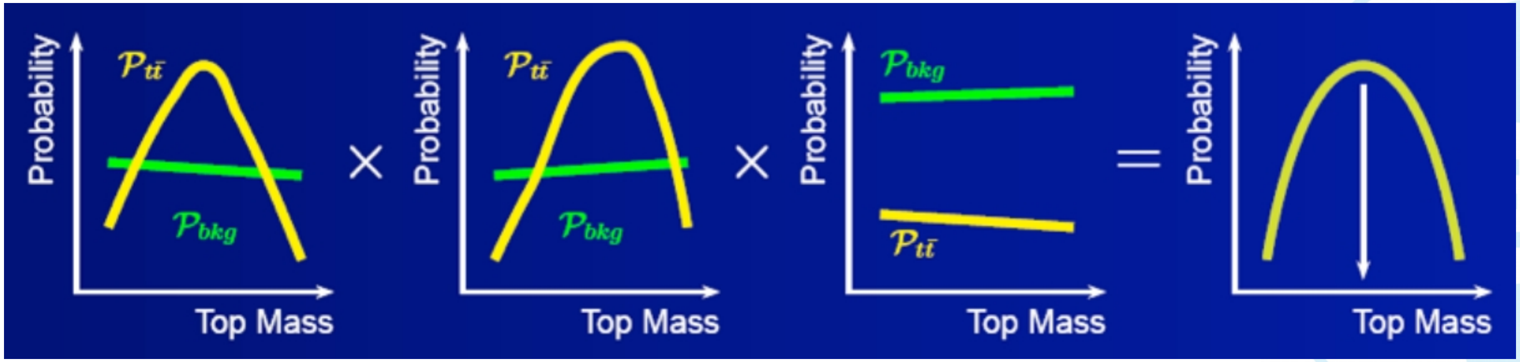
# Matrix element method – intro

- Evaluate an **event-by-event probability** based on the full event kinematics




$$P_{sig} = \frac{1}{\sigma_{obs}(m_t, k_{JES})} \int \sum d\vec{q}_1 d\vec{q}_2 f_{PDF}(d\vec{q}_1) f_{PDF}(d\vec{q}_2) d\sigma(\vec{y}, m_t) W(\vec{x}, \vec{y}; k_{JES})$$

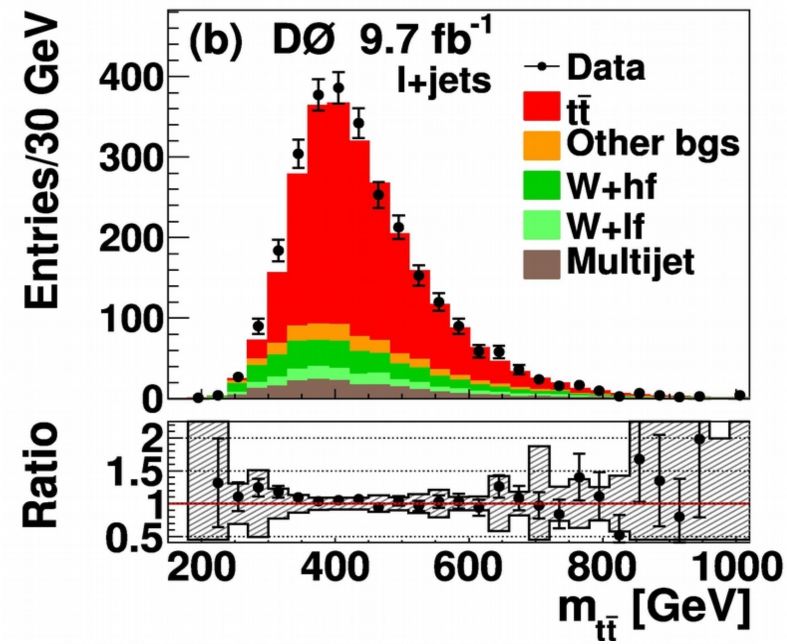
- Get likelihood as a function of the top mass for each event, then global likelihood

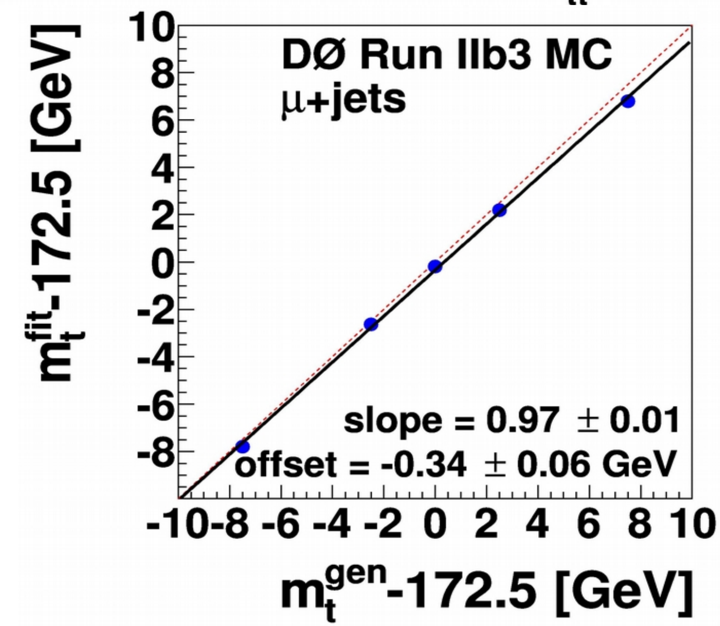


# Matrix element method – ljets at D0

- lepton+jets selection:
  - 4 jets, ≥ 1 b-tag
  - $\sim$ 2600 events, 66% purity
- Huge **improvement of the integration** procedure $\rightarrow$ processing time decreased compare to previous measurements
- 2D measurement of $k_{JES}$ and $m_t$

  + extraction of the signal fraction
- Linearity of the method tested with pseudoexperiments

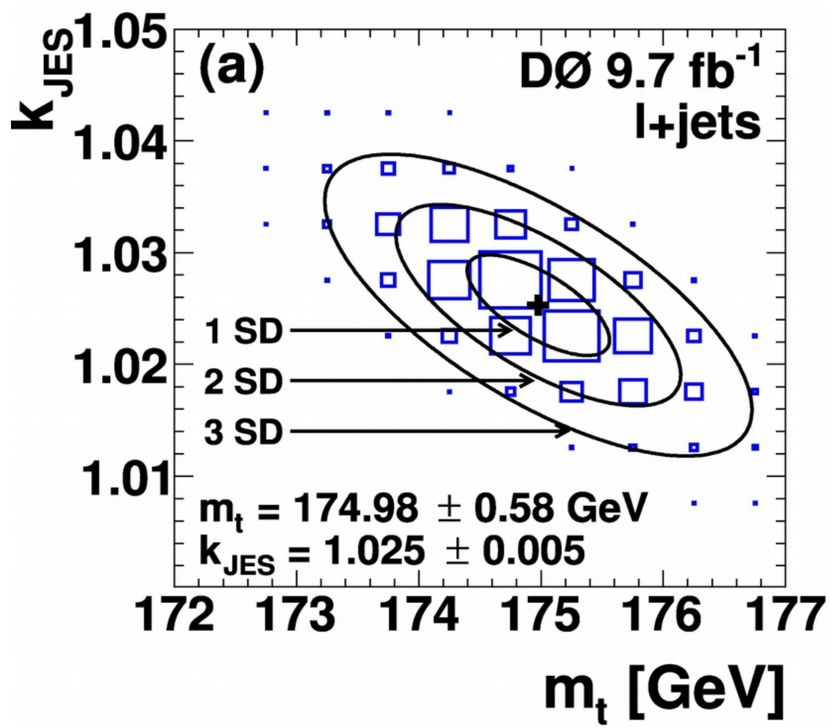


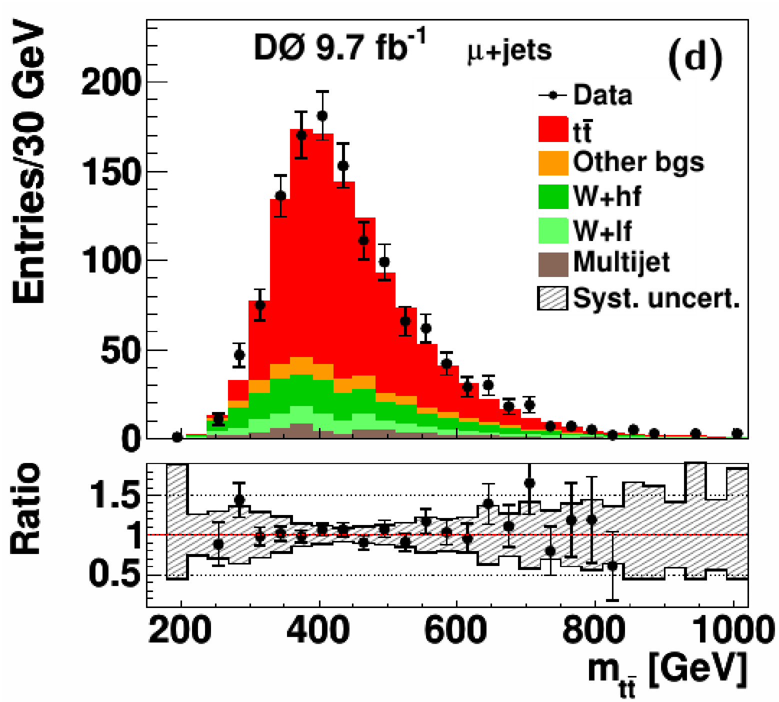




*PRL 113, 032002 (2014)*
*PRD 91, 112003 (2015)*

# Matrix element method – ljets at D0

- **Single most precise Tevatron measurement!**
  - $m_t = 174.98 \pm 0.58$ (stat.) $\pm 0.49$ (syst) GeV **$\delta m_t/m_t = 0.43$ % !**
  - $k_{JES} = 1.025 \pm 0.005$ (stat.)
- Dominant systs:
  hadronization, underlying event and residual JES



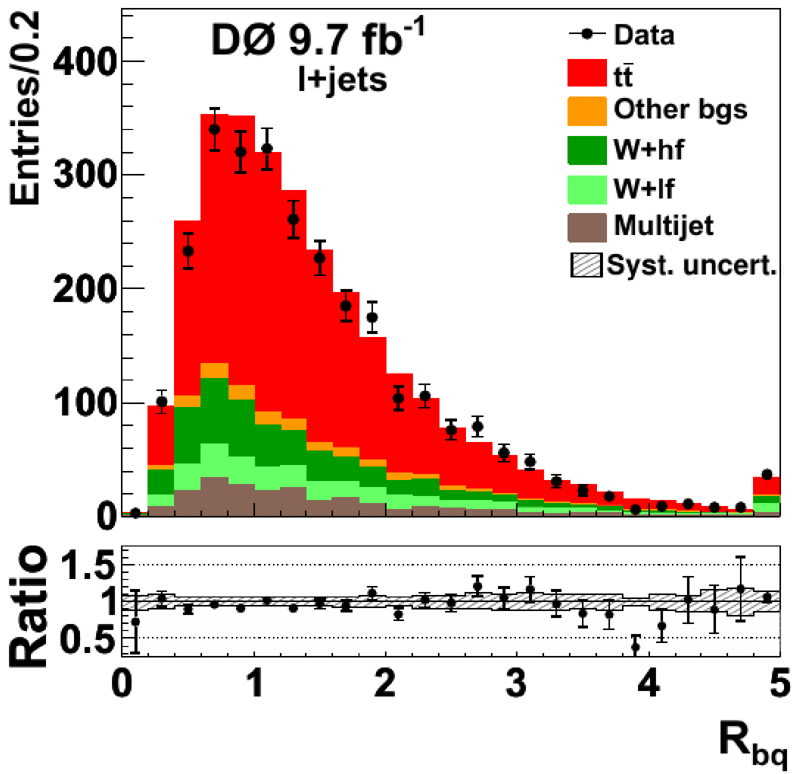




- Check the data/predictions agreement after applying the corrections ($m_t$, $k_{JES}$, $f_{sig}$)

# Matrix element method – ljets at D0

- Check the b-JES after the corrections are applied ($m_t$, $k_{JES}$, $f_{sig}$)

  → use the $R_{bq}$ ratio (same in ATLAS mass measurement): $R_{bq} = \frac{p_T^{b1} + p_T^{b2}}{p_T^{q1} + p_T^{q2}}$

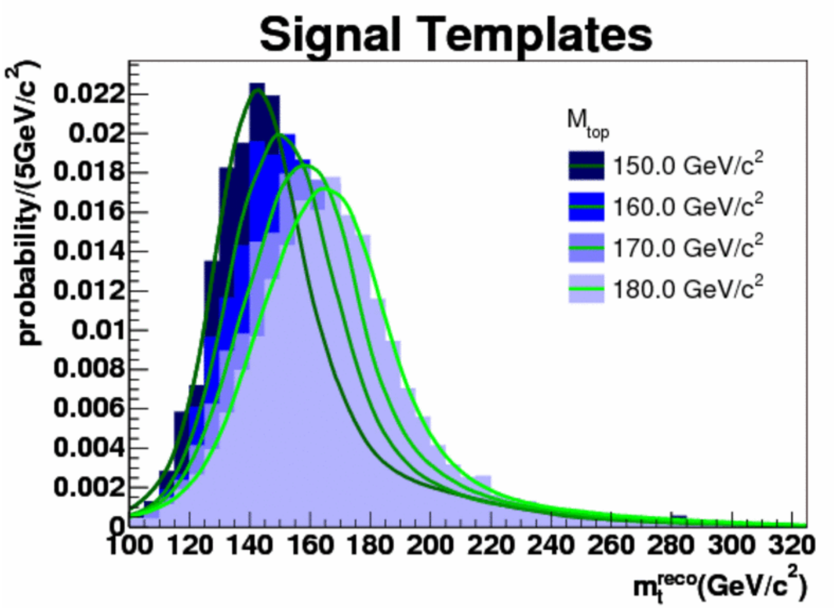



- Extract $R_{bq} = 1.008 \pm 0.0195$ (stat.) $\pm\,^{0.037}_{0.031}$ (syst.)

# Template method

- Ideally, pick observables which are very **correlated with the mass**, not sensitive to the systematics and perform a **likelihood fit** to various templates
- In practice:
  - use the decay products of the top to estimate the mass (contain jets → sensitive to JES)
  - choose an additional observable to constrain the JES
- Need to correctly **associate the decay products of the top**
  - requires some reconstruction or pairing technique (eg $\chi^2$ function minimization)
  - tighten the selection (eg by requiring many b-jets)

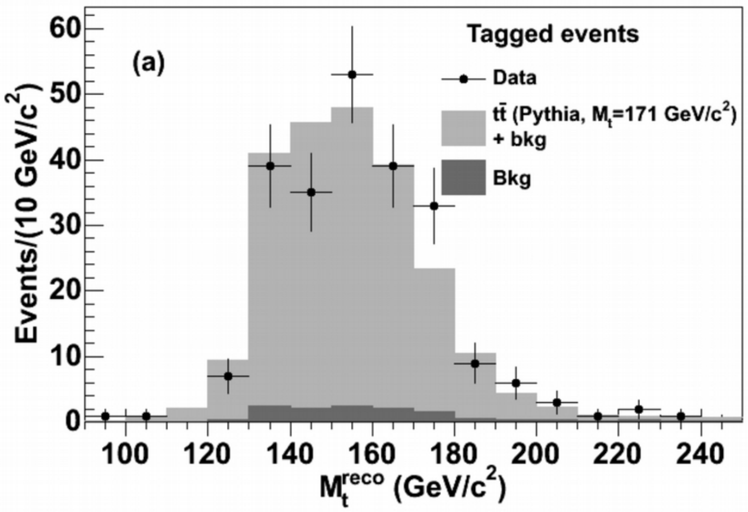
$$\chi_t^2 = \frac{\left(m_{jj}^{(1)} - M_W\right)^2 c^4}{\Gamma_W^2} + \frac{\left(m_{jj}^{(2)} - M_W\right)^2 c^4}{\Gamma_W^2} + \frac{\left(m_{jjb}^{(1)} - m_t^{\rm rec}\right)^2 c^4}{\Gamma_t^2} + \frac{\left(m_{jjb}^{(2)} - m_t^{\rm rec}\right)^2 c^4}{\Gamma_t^2}$$



# Template method – dilepton at CDF

- Select events with 2 leptons, large MET, ≥ 2 jets
  - additional requirements in the $Z$ mass region for ee and μμ
  - split the events having 0 or 1 b-tag

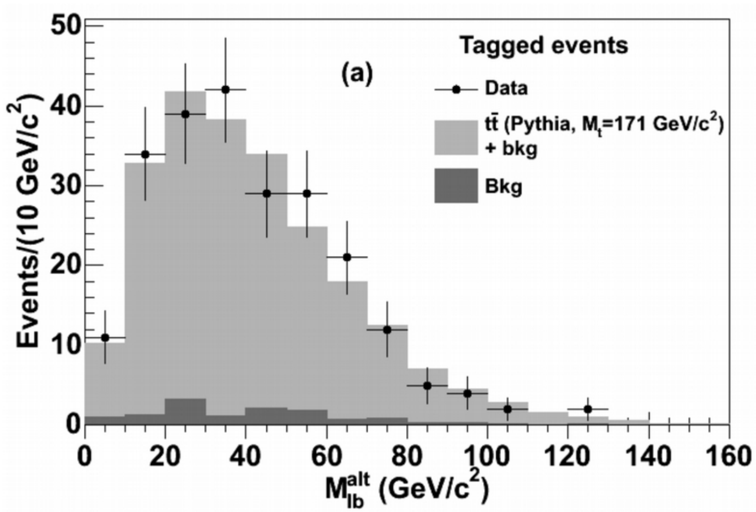
    $\rightarrow$ 520 events, purity of 77%




- Associate two reconstruction methods:
  - **"neutrino phi-weighting"**:
    - scan neutrino phi
    - get mass by minimizing $\chi^2$
    - associate weight to the solution

    $\rightarrow$ uses all the information from the event, good sensitivity but depends on JES
  - **"alternative mass"** defined by: $M_{lb}^{alt} = c^2 \sqrt{\frac{\langle l1, b1 \rangle . \langle l2, b2 \rangle}{E_{b1} . E_{b2}}}$

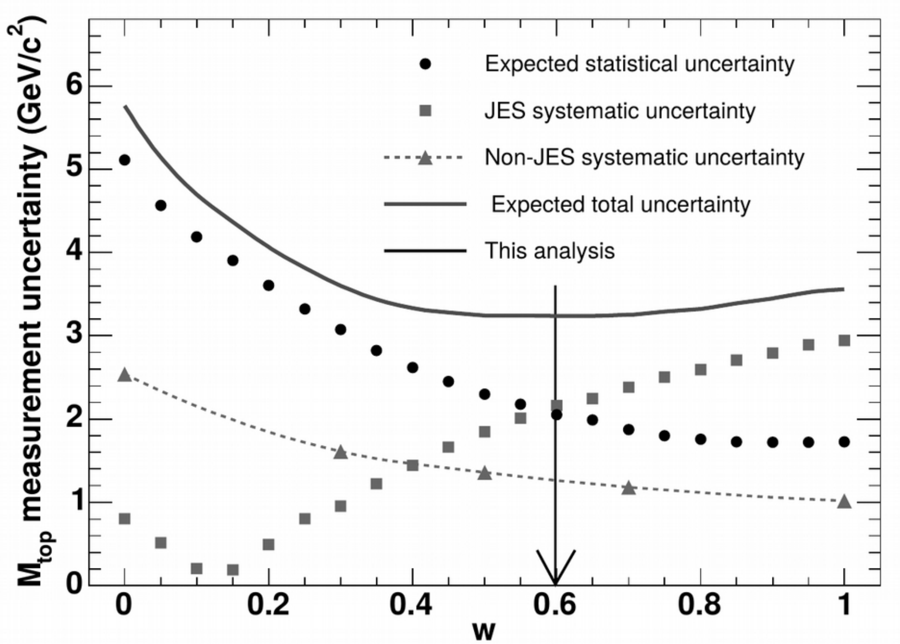
    $\rightarrow$ not as sensitive but JES uncertainty cancels

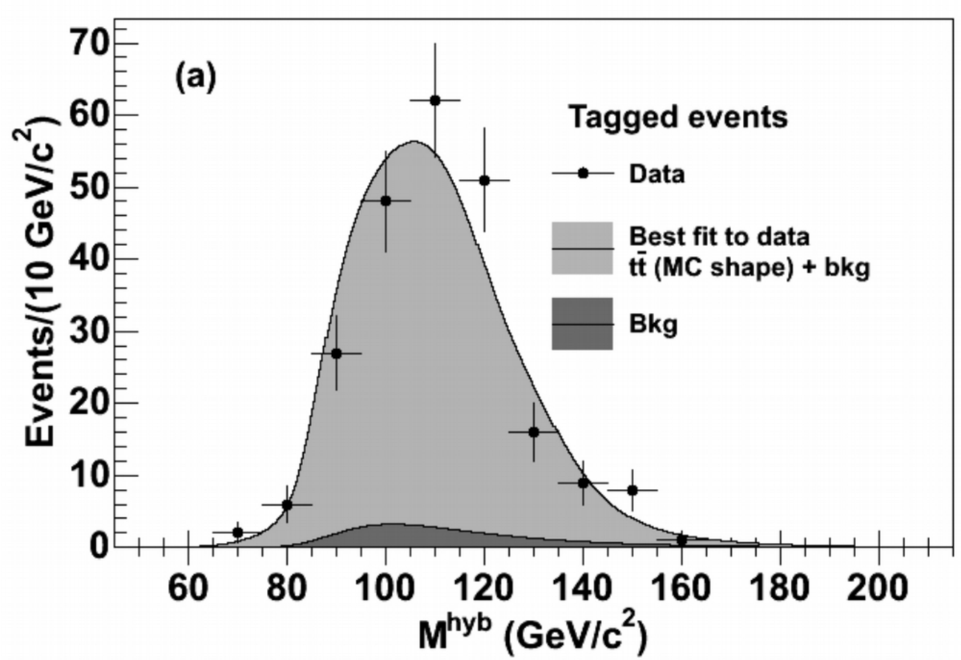



*PRD 92 032003 (2014)*

# Template method – dilepton at CDF

- Templates built with **hybrid mass** defined as: $m^{hyb} = w.m^{reco} + (1\text{-}w).m^{alt}$ , w optimized to minimize expected uncertainty




- Result:
  - $m_t = 171.5 \pm 1.9$ (stat.) $\pm$ 2.5 (syst) GeV
  - main systs: JES and NLO effects
  - uncertainties reduced by 14% compared to previous (similar) measurement

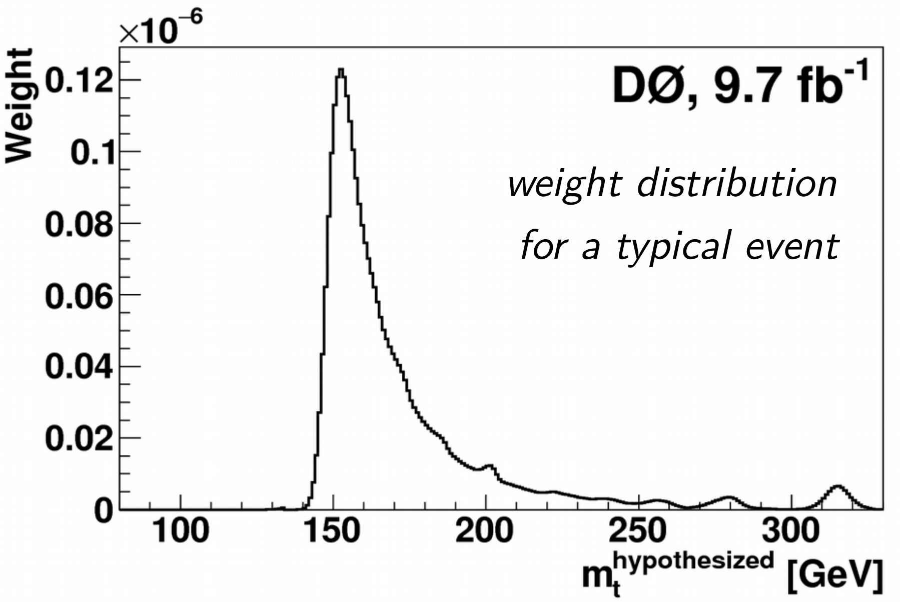
$\delta m_t/m_t = 1.9$ %

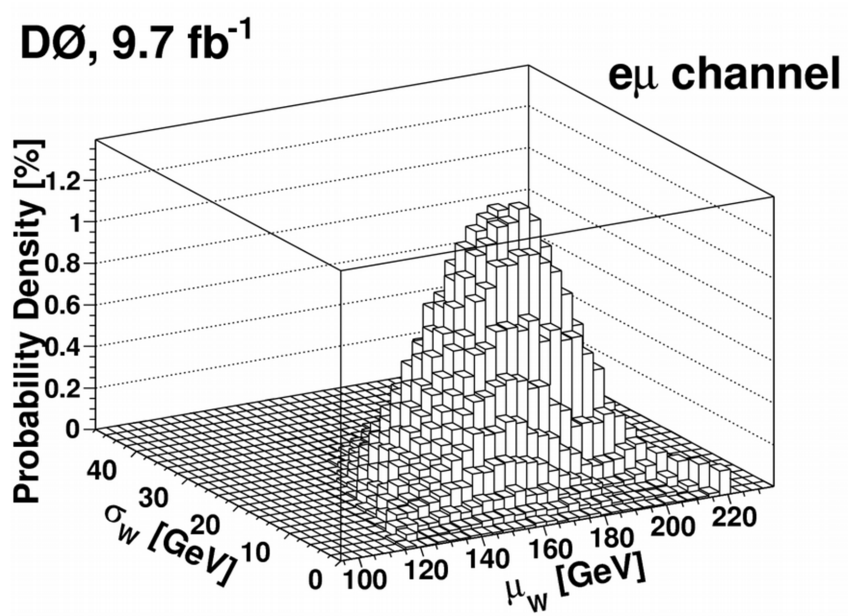
# Template method – dilepton at D0 NEW!

*arxiv:1508.03322 submitted to PLB*

- Select events with 2 leptons, ≥ 2 jets and ≥ 1 b-jet
  - MET cuts in the ee and μμ channels, $H_T$ cut in the eμ channel

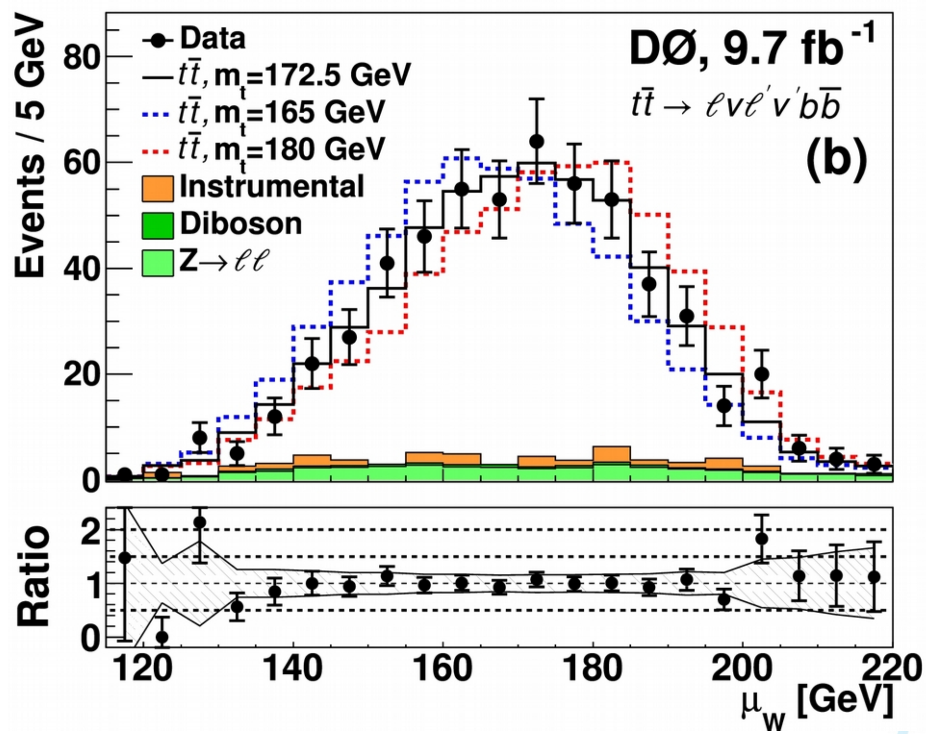
    → 565 events, purity of 85%
- Use **JES constraint from lepton+jets** measurement
- Reconstruction with **"neutrino weighting"** technique for various top mass hypotheses:
  - scan neutrino rapidities, reconstruct the system
  - compute weight w by comparing neutrino momenta with measured MET
  - extract mean and standard deviation from the distribution $w(m_t)$



# Template method – dilepton at D0 NEW!

- Parameters of the reconstruction optimized to minimize the expected statistical uncertainty
- Maximum likelihood fit to the templates



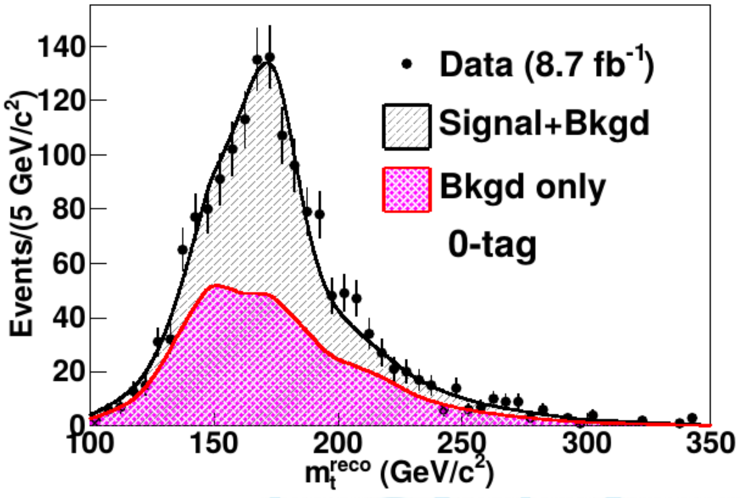

- Result:
  - $m_t = 173.32 \pm 1.36$ (stat.) $\pm$ 0.85 (syst) GeV
  - most precise dilepton measurement at the Tevatron!
  - main systs: JES and higher order effects

$\delta m_t/m_t$ = 0.93 %

# Template method – ljets at CDF

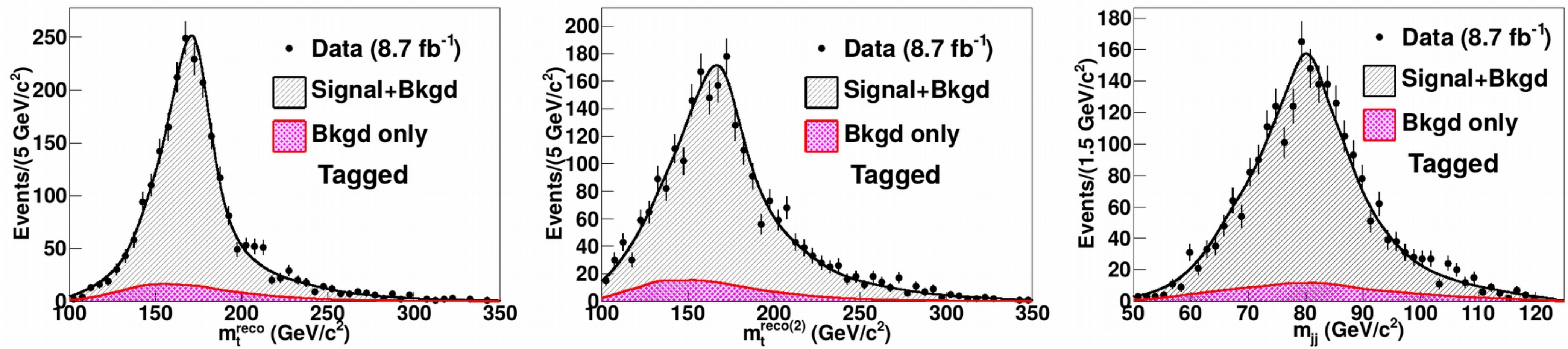
- Select events with one lepton, large MET, ≥ 4 jets
  - define channels using b-tags and number of tight jets (3 in loose selection, ≥ 4 in tight)
  - 5 channels defined: 0 b-tag, 1 b-tag L, 1 b-tag T, 2 b-tag L, 2 b-tag T
  - additional $H_T$ requirements in 0 and 1-tag

    $\rightarrow \sim$ 4000 events with 73% purity
- Reconstruction done using $\chi^2$ **minimization**
- **Variables** used to build the **templates**:
  - $m_t^{reco}$, value that yields the lowest $\chi^2$
  - $m_t^{reco2}$, value that yields the second lowest $\chi^2$
  - $m_{jj}$, invariant mass of the two jets associated to the *W*




*PRL 109 152003 (2012)*

# Template method – ljets at CDF




- Unbinned maximum likelihood fit in the 5 channels
- Result:
  - $m_t = 172.85 \pm 0.71$ (stat.) $\pm$ 0.85 (syst) GeV $\delta m_t/m_t = 0.63\%$
  - main systs: residual JES and signal modelling

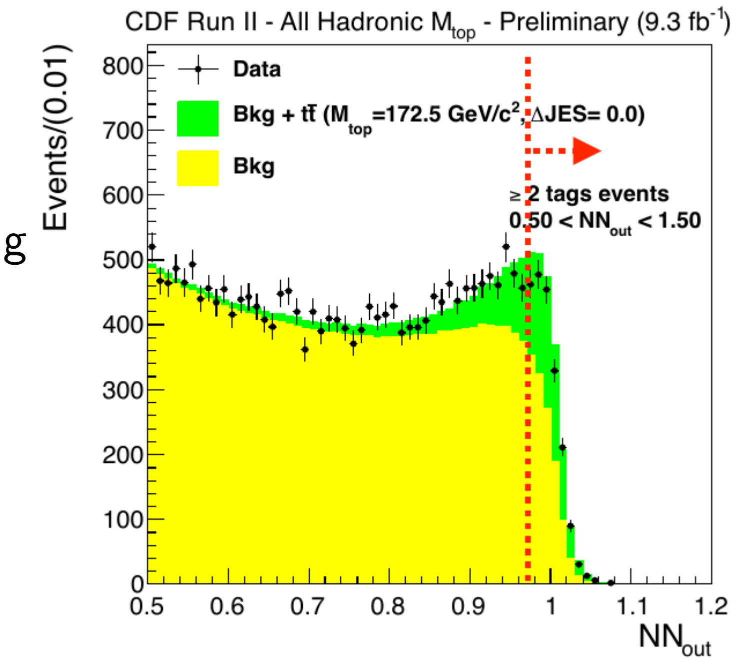
# Template method – all-hadronic at CDF

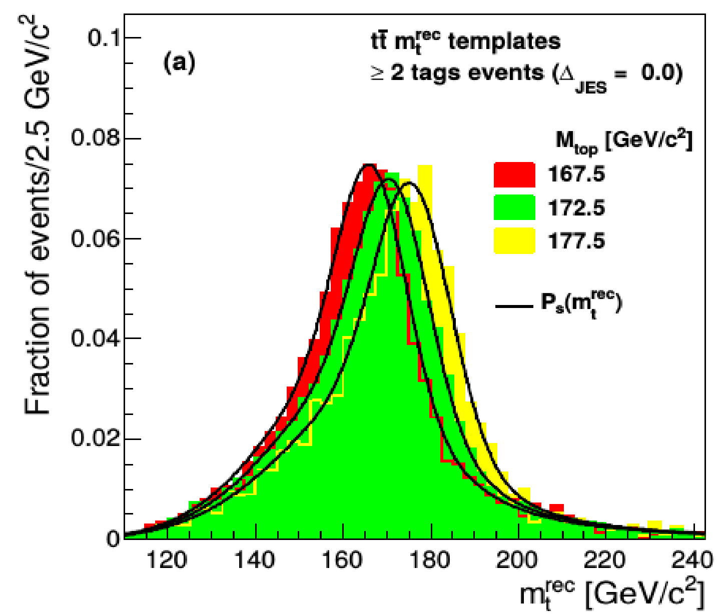
- **Preselect** events with no isolated lepton, **at least 6 jets**, small MET
  - purity of 1/700, increased by using NN and b-tagging
  - events with 1, 2 and 3 b-tags considered

- **Multijet** bkg estimated in events with 5 jets, using **tag-rate** in each channel

- **Reconstruction**:
  - all permutations of jets considered (30, 6 and 18 in the 1, 2 and 3 b-tags)
  - $\chi^2$ minimization on the invariant masses of the $W$ and tops
  - $\chi^2$ function with free $W$ mass

  $\rightarrow$ signal and background templates



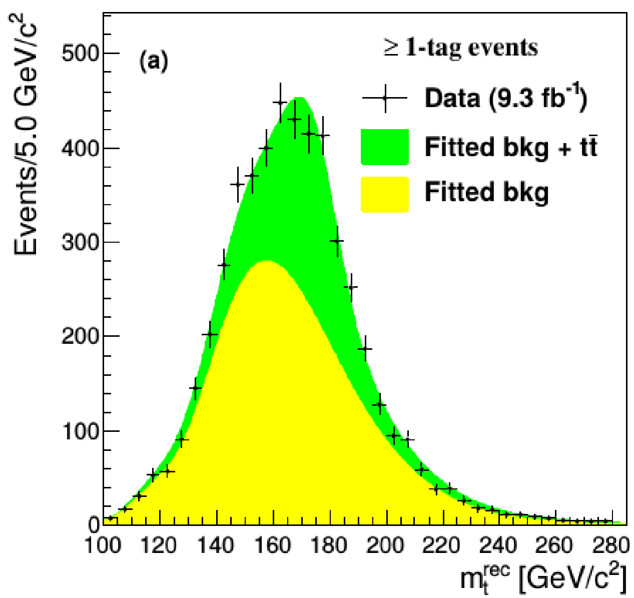


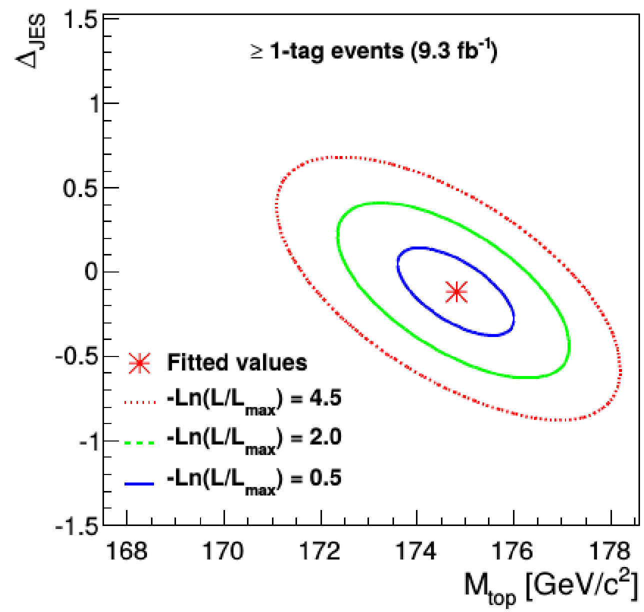

*PRD 90, 091101(R) (2014)*

# Template method – all-hadronic at CDF

- **Final selection** on the NN and $\chi^2$
  - one sample to constrain the JES
  - one sample to measure $m_t$

| | Sample | $N_{\text{obs}}$ | Expected $t\bar{t}$ |
|---|---|---|---|
| 1-tag | $S_{\text{JES}}$ | 7890 | $1886 \pm 150$ |
| | $S_{M_{\text{top}}}$ | 4130 | $1270 \pm 101$ |
| $\geq$ 2-tags | $S_{\text{JES}}$ | 1758 | $782 \pm 64$ |
| | $S_{M_{\text{top}}}$ | 901 | $514 \pm 42$ |



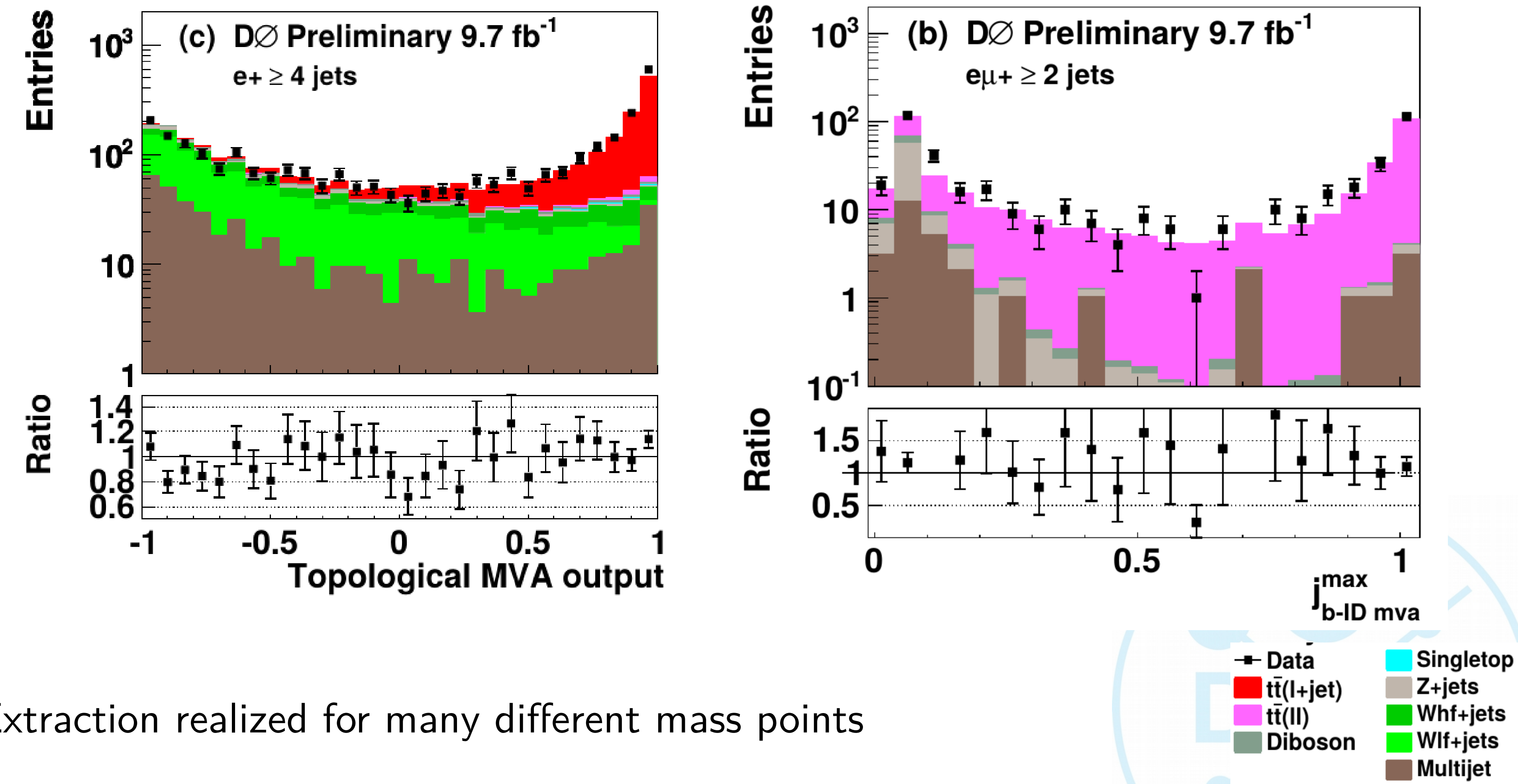




- Result:
  - $m_t = 175.07 \pm 1.19\ (\text{stat.}) \pm {}^{1.55}_{1.58}\ (\text{syst})\ \text{GeV}$ $\delta m_t/m_t = 1.1\ \%$
  - main systs: JES and trigger

# Pole mass extraction – ljets/dilepton at D0

NEW!

- Cross-section measurement in the ll and ljets channels using MVA and template fits



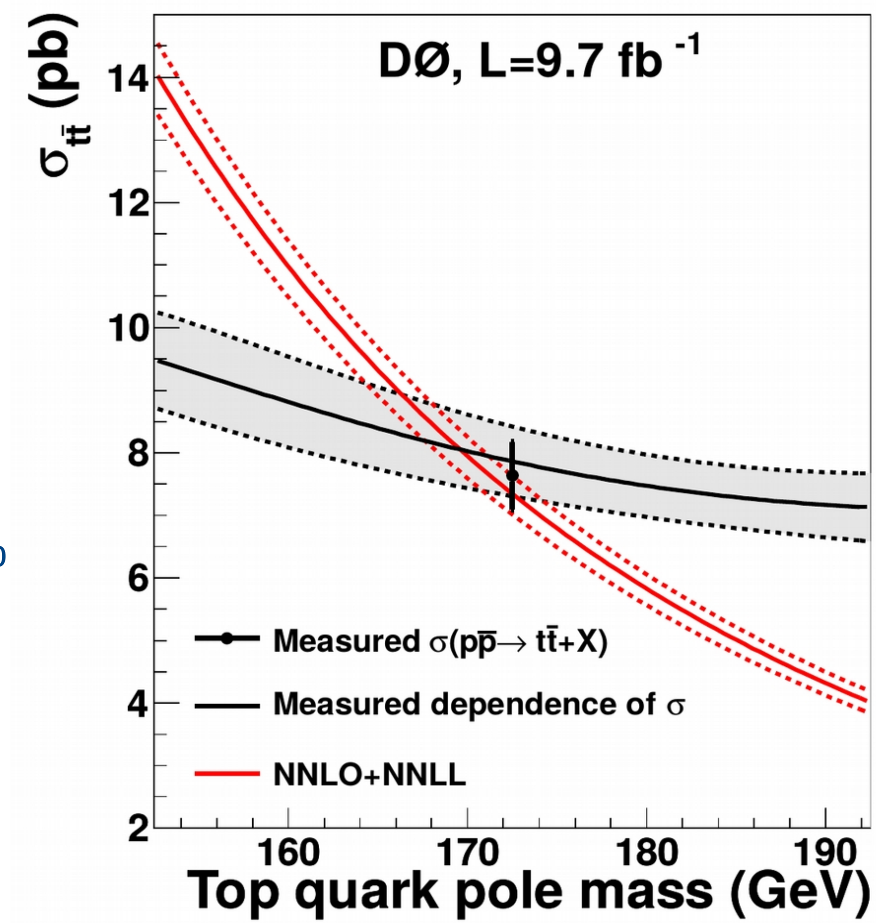

- Extraction realized for many different mass points

*D0 Conf note 6453 (2015)*

# Pole mass extraction – ljets/dilepton at D0

NEW!

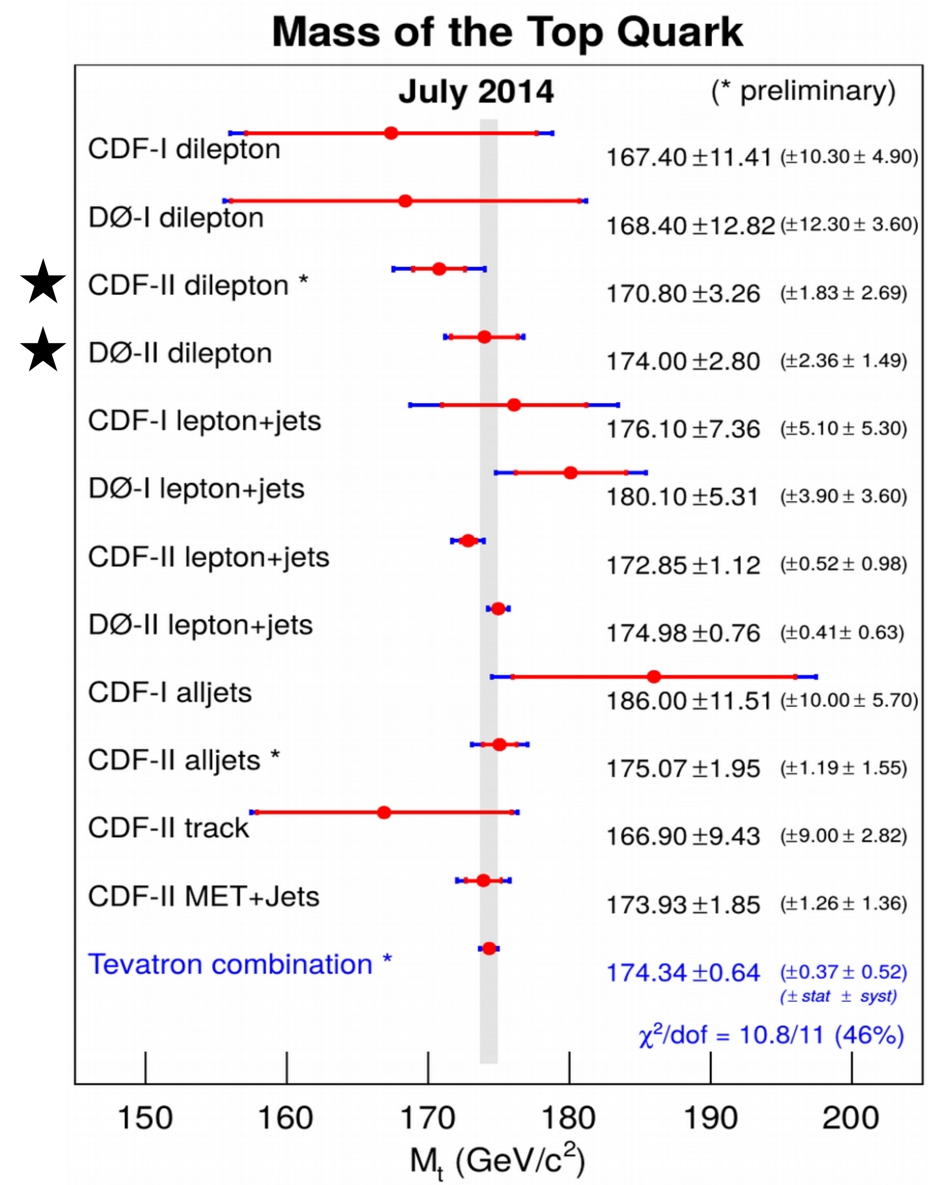
- Mass extraction:
  - cubic fit to the individual measurements
  - normalized joint likelihood function
- Result:
  - $m_t = 169.5 \pm^{3.3}_{3.4}$ (total) GeV    $\delta m_t/m_t = 2.0\ \%$
  - most precise pole mass measurement at the Tevatron



# Tevatron combination

- Run I and II measurements combined with BLUE
- Careful study of all correlations between systematics of the various channels, measurements and experiments

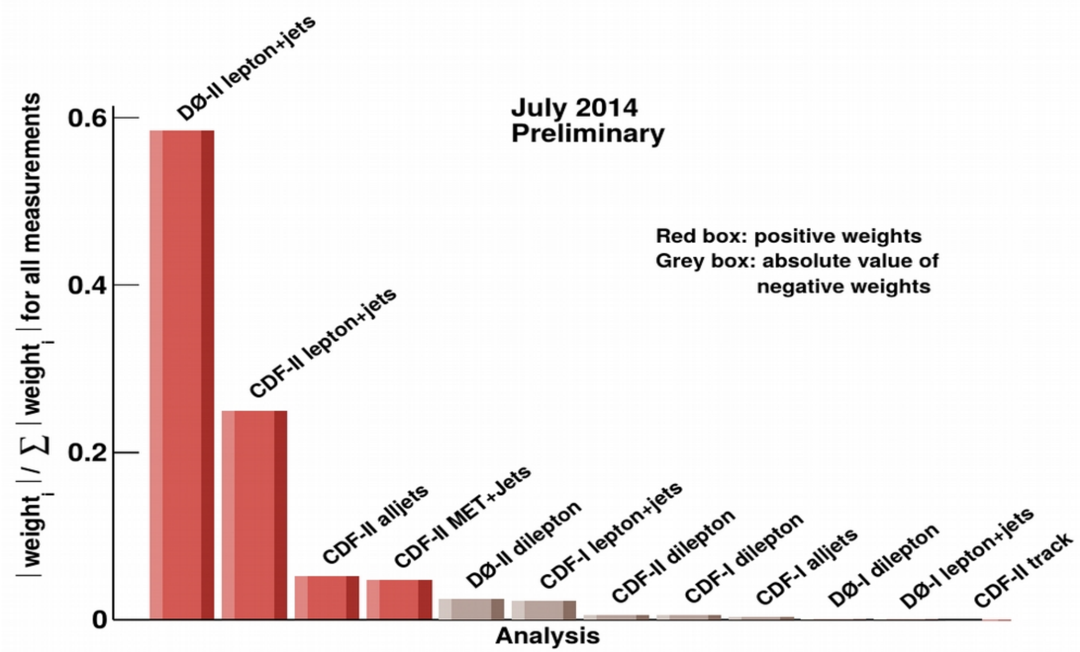
| | Tevatron combined values (GeV/$c^2$) |
|---|---|
| $M_t$ | 174.34 |
| *In situ* light-jet calibration (iJES) | 0.31 |
| Response to $b/q/g$ jets (aJES) | 0.10 |
| Model for $b$ jets (bJES) | 0.10 |
| Out-of-cone correction (cJES) | 0.02 |
| Light-jet response (1) (rJES) | 0.05 |
| Light-jet response (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 |

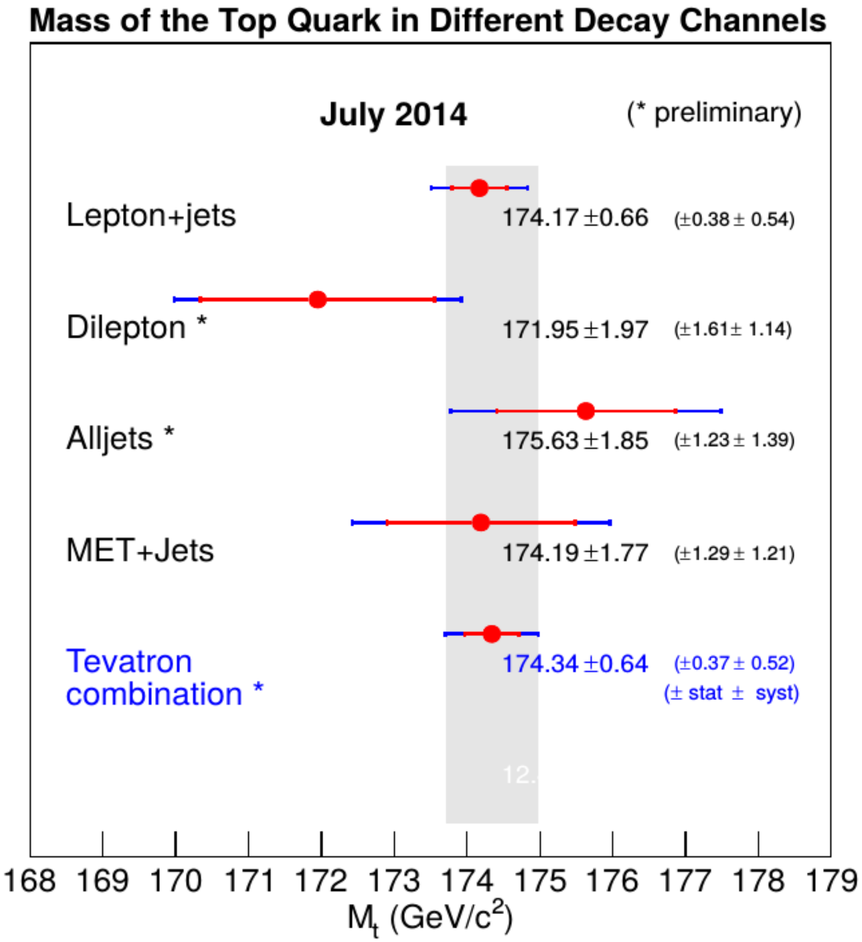



★ *not the latest results*

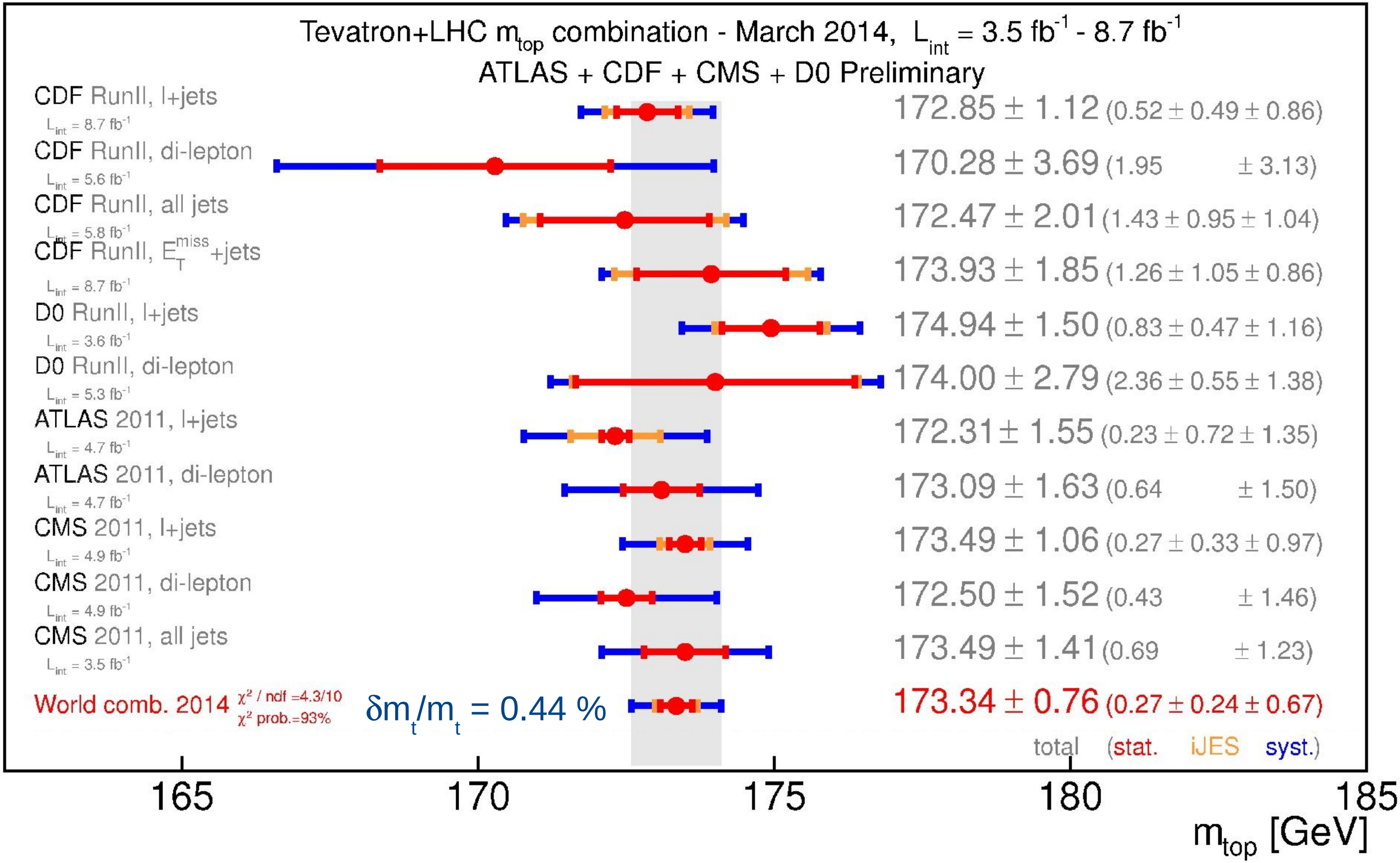
# Tevatron combination

- Result:
  - $m_t = 174.34 \pm 0.37$ (stat.) $\pm 0.52$ (syst) GeV   **$\delta m_t/m_t$ = 0.37% !**
  - $\chi^2$ of combination: $\chi^2/\mathrm{dof} = 10.8/11$ (46 %)



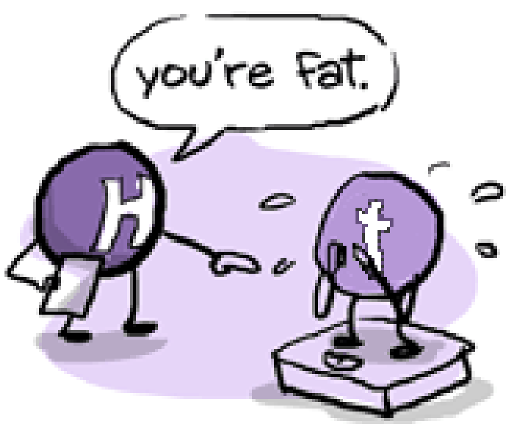
# World combination




*arxiv:1403.4427*

# Conclusion

- Precision measurement of the top quark mass is part of the Tevatron legacy
- Most sensitive channels now updated with the **full statistics**
- **Tevatron combination** (most precise until yesterday!):
  - $m_t = 174.34 \pm 0.37$ (stat.) $\pm 0.52$ (syst) GeV
  - relative uncertainty of 0.37%



# Backup slides

# Systematics – ljets channel at D0

- **Higher order corrections:** MC@NLO+Herwig compared to Alpgen+Herwig
- **ISR/FSR:** variation of the ktfac parameter within Alpgen+Pythia
- **$p_T^{ttbar}$ modelling**: reweighting
- **Hadronization and UE:** Alpgen+Pythia compared to Alpgen+Herwig (at particle level and after reweighting the $p_T^{ttbar}$ spectrum)
- **Color reconnection:** Pythia tunes Perugia 2011 vs Perugia 2011NOCR

| Source of uncertainty | Effect on $m_t$ (GeV) |
|---|---|
| *Signal and background modeling:* | |
| Higher-order corrections | $+0.15$ |
| Initial/final state radiation | $\mp 0.06$ |
| Transverse momentum of the $t\bar{t}$ system | $-0.07$ |
| Hadronization and underlying event | $+0.26$ |
| Color reconnection | $+0.10$ |
| Multiple $p\bar{p}$ interactions | $-0.06$ |
| Heavy-flavor scale factor | $\mp 0.06$ |
| Modeling of $b$-quark jet | $+0.09$ |
| Parton distribution functions | $\pm 0.11$ |
| *Detector modeling:* | |
| Residual jet energy scale | $\pm 0.21$ |
| Flavor-dependent response to jets | $\mp 0.16$ |
| Tagging of $b$ jets | $\mp 0.10$ |
| 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* | $\pm 0.49$ |
| *Statistical uncertainty* | $\pm 0.58$ |
| *Total uncertainty* | $\pm 0.76$ |

# Systematics – ljets channel at D0

- **b fragmentation:** reweighting of events to a Bowler scheme tuned to LEP data
- **PDF**: intra-PDF unc. using CTEQ6M
- **Residual JES:** various parameterisations studied ((eta, E), linear in E, or none, ie direct application of JES shift on the jets)

| Source of uncertainty | Effect on $m_t$ (GeV) |
|---|---|
| *Signal and background modeling:* | |
| Higher-order corrections | $+0.15$ |
| Initial/final state radiation | $\mp 0.06$ |
| Transverse momentum of the $t\bar{t}$ system | $-0.07$ |
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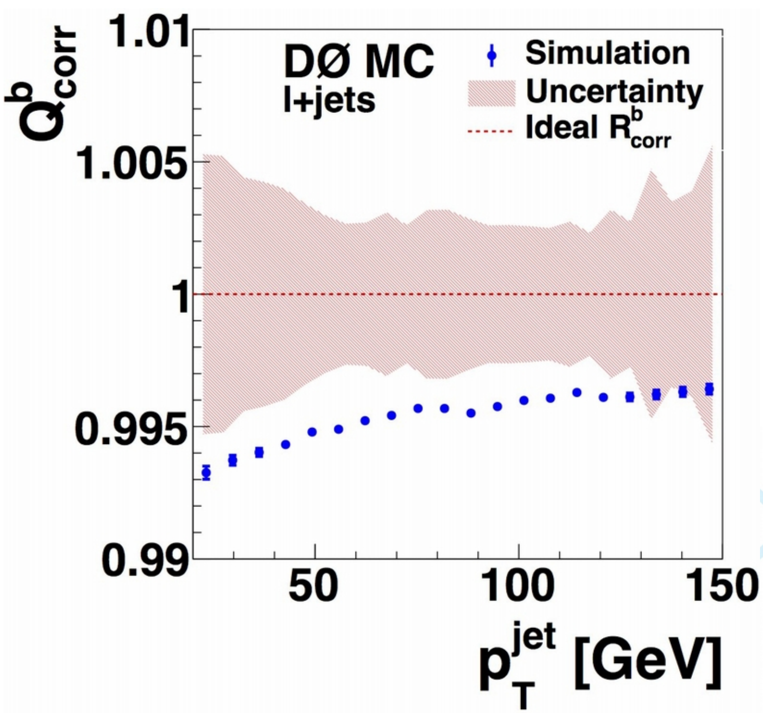
| MC calibration | $\pm 0.07$ |
| *Total systematic uncertainty* | $\pm 0.49$ |
| *Statistical uncertainty* | $\pm 0.58$ |
| *Total uncertainty* | $\pm 0.76$ |

# Systematics – ljets channel at D0

- **Flavor dependent response:** change of the flavor dependent correction by 1 SD
- Additional checks to make sure that the correction is well estimated
  - correction derived using gamma+jet samples
  - ratio $Q^b_{corr}$ between the corrections from Alpgen+Herwig and Alpgen+Pythia studied
  - extraction of $R_{bq}$ (see slide 7)



# Systematics – dilepton channel at CDF

- **JES**: vary the JES parameters by 1 SD
- **NLO effects:** Pythia vs Powheg
- **MC generators**: Pythia vs Herwig
- **ISR/FSR**: Pythia with varied amount of radiation
- **gg fraction**: gluon fraction reweighted from 5 to 20%

| 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 |

# Systematics – ljets channel at CDF

- **Residual JES**: JES parameters varied by 1 SD
- **Signal modelling**: Pythia vs Herwig + NLO effects evaluated using MC@NLO

| Source | Systematic uncertainty |
|---|---|
| Residual jet energy scale | 0.52 |
| Signal modeling | 0.57 |
| $b$ 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 |

# Systematics – dilepton channel at D0

- **JES**: apply uncertainty from the ljets extracted JES
- **b-JES**: parameterise the changes of the standard JES vs ljets JES in (eta, E)
- **higher order effects**: Alpgen+Herwig vs MC@NLO+Herwig

| Source | $\sigma_{m_t}$ [GeV] |
|---|---|
| Jet energy calibration | |
| Absolute scale | $\mp 0.47$ |
| Flavor dependence | $\mp 0.27$ |
| Residual scale | $^{+0.36}_{-0.35}$ |
| $b$ quark fragmentation | $+0.10$ |
| Object reconstruction | |
| Trigger | $-0.06$ |
| Electron $p_T$ resolution | $\pm 0.01$ |
| Muon $p_T$ resolution | $\mp 0.03$ |
| Electron energy scale | $\pm 0.01$ |
| Muon $p_T$ scale | $\pm 0.01$ |
| Jet resolution | $\mp 0.12$ |
| Jet identification | $+0.03$ |
| $b$ tagging | $\mp 0.19$ |
| Signal modeling | |
| Higher-order effects | $-0.33$ |
| ISR/FSR | $\pm 0.15$ |
| $p_T(t\bar{t})$ | $-0.07$ |
| Hadronization | $-0.11$ |
| Color reconnection | $-0.22$ |
| Multiple $p\bar{p}$ interactions | $-0.06$ |
| PDF uncertainty | $\pm 0.08$ |
| Background modeling | |
| Signal fraction | $\pm 0.01$ |
| Heavy-flavor scale factor | $\pm 0.04$ |
| Method | |
| Template statistics | $\pm 0.18$ |
| Calibration | $\pm 0.07$ |
| Total systematic uncertainty | $\pm 0.85$ |

# Matrix element method – ljets channel at D0

- Matrix elements used: LO for qqbar $\rightarrow$ ttbar and W+4 jets
- Integration performed over: the masses of the top and antitop (assumed to be equal), the *W* masses, the energies of the electrons and muons, $E_q/(E_q+E_{q'})$ for the quarks from the *W* decay
- All possible 24 permutations of jets are considered in the transfer function, with weights accounting for the b-tagging information

# Pole mass extraction – ljets/ll at D0

| Top quark mass [GeV] | Cross section $\sigma(t\bar{t})$ [pb] |
|---|---|
| 150 | $10.53 \pm 0.17\,(\text{stat.})\,^{+0.78}_{-0.78}\,(\text{syst.})$ |
| 160 | $9.24 \pm 0.16\,(\text{stat.})\,^{+0.74}_{-0.74}\,(\text{syst.})$ |
| 165 | $8.07 \pm 0.14\,(\text{stat.})\,^{+0.65}_{-0.65}\,(\text{syst.})$ |
| 170 | $8.28 \pm 0.14\,(\text{stat.})\,^{+0.57}_{-0.57}\,(\text{syst.})$ |
| 172.5 | $7.73 \pm 0.13\,(\text{stat.})\,^{+0.55}_{-0.55}\,(\text{syst.})$ |
| 175 | $7.80 \pm 0.13\,(\text{stat.})\,^{+0.51}_{-0.51}\,(\text{syst.})$ |
| 180 | $7.42 \pm 0.13\,(\text{stat.})\,^{+0.50}_{-0.50}\,(\text{syst.})$ |
| 185 | $6.92 \pm 0.12\,(\text{stat.})\,^{+0.45}_{-0.45}\,(\text{syst.})$ |
| 190 | $6.85 \pm 0.12\,(\text{stat.})\,^{+0.43}_{-0.43}\,(\text{syst.})$ |

| Source of uncertainty | Uncertainties $\delta_{\text{combined}}$, pb |
|---|---|
| *Modeling of signal* | |
| Alternative signal model | $\pm 0.09$ |
| Hadronization | $\pm 0.25$ |
| Color reconnection | $\pm 0.11$ |
| ISR/FSR variation | $\pm 0.06$ |
| PDF | $\pm 0.08$ |
| *Modeling of detector* | |
| Jet modeling & identification | $\pm 0.06$ |
| $b$-jet modeling & identification | $\pm 0.16$ |
| Lepton modeling & identification | $\pm 0.02$ |
| Trigger efficiency | $\pm 0.01$ |
| Luminosity | $\pm 0.20$ |
| *Sample Composition* | |
| MC cross sections & branching ratios | $\pm 0.03$ |
| $Z/W$ $p_T$ reweighting | $\pm 0.16$ |
| Multijet contribution | $\pm 0.09$ |
| $W$+jets heavy flavor scale factor | $\pm 0.15$ |
| $W$+jets light parton scale factor | $\pm 0.05$ |
| MC statistics | $\pm 0.01$ |
| Total systematic uncertainty | $\pm 0.55$ |

# Tevatron combination – weights and pulls

| | 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 |
| Pull | 0.24 | −0.61 | +1.01 | +1.09 | −0.46 | −1.64 | −0.791 | −0.24 | +1.60 | −0.13 | −1.11 | 0.39 |
| Weight [%] | −2.6 | −0.7 | −0.4 | −0.1 | −0.14 | +28.8 | +0.1 | +5.5 | +67.2 | −2.9 | −0.66 | +6.0 |