Les Rencontres de Physique de la Vallée d' Aoste, La Thuile, March 5, 2009

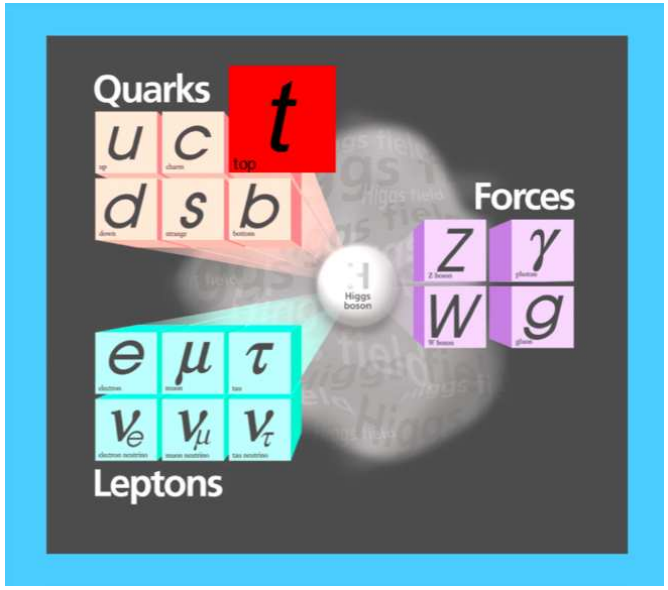
Precision Determination of the Top Mass

L. Brigliadori
University of Bologna & INFN

On behalf of the CDF and DØ Collaborations

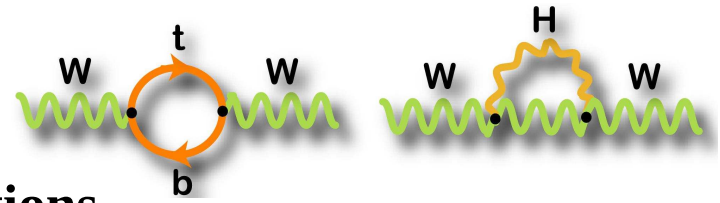
- The Top Quark and its Mass.
- Experimental Environment.
- Measurement Strategies.
- Most Recent Results.
- Summary and Conclusions.

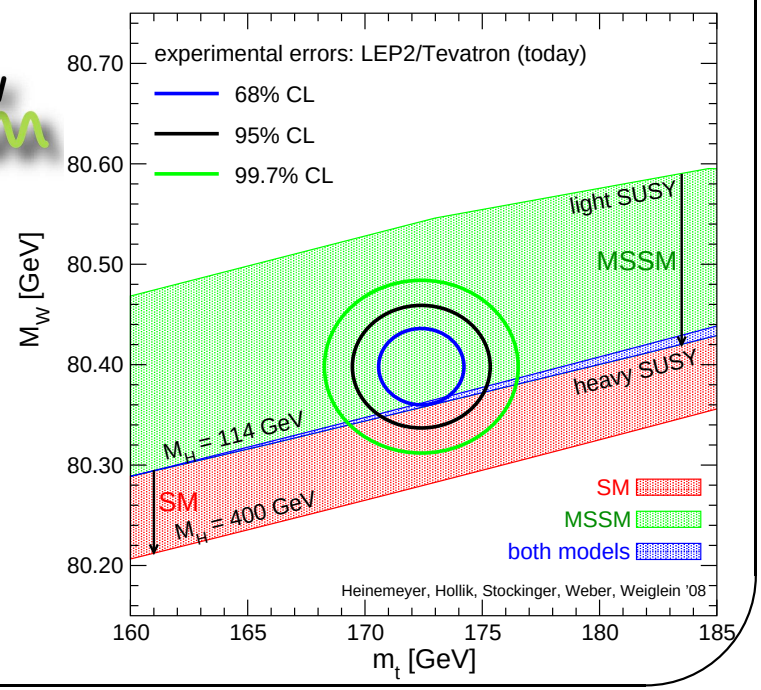
The Top Quark



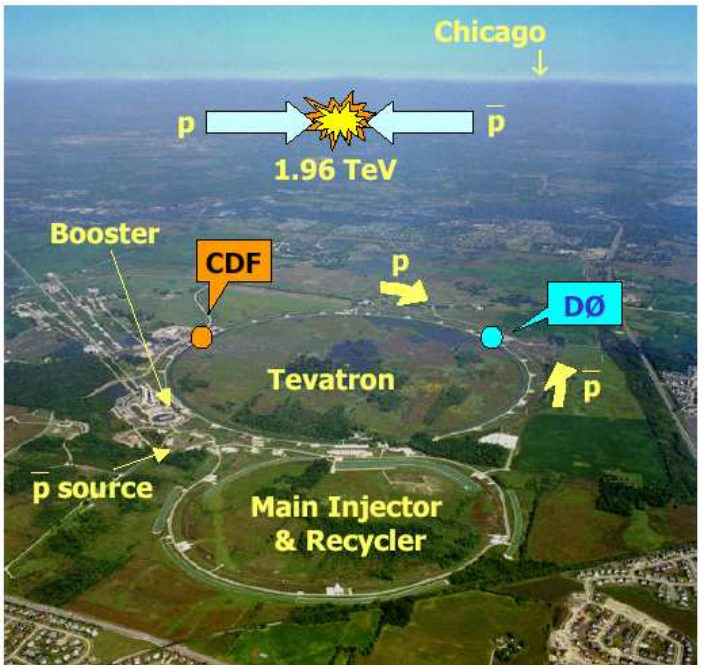
- **Observed in 1995 at Fermilab....**
  ... not a big surprise..
- $M_{top} \approx 175\,\text{GeV} \approx 35 \cdot M_{bottom}$....
  ... STRIKING!...Why so large?

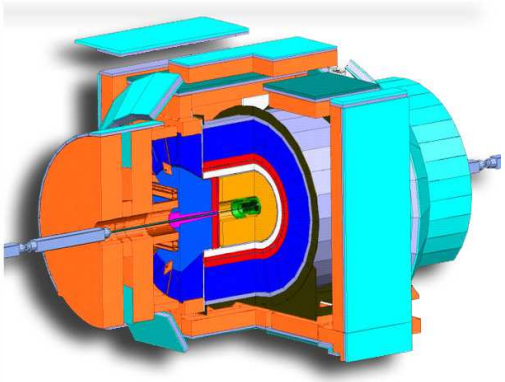
- **Why measuring M_{top} ?**
  - **Inside the SM :**
    - **Test SM predictions**
    - **Test SM consistency**
    - **Hints on unobserved Higgs**
  - **Beyond the SM :**
    - **Constraints on New Physics**
    - **Hints on EWSB?**



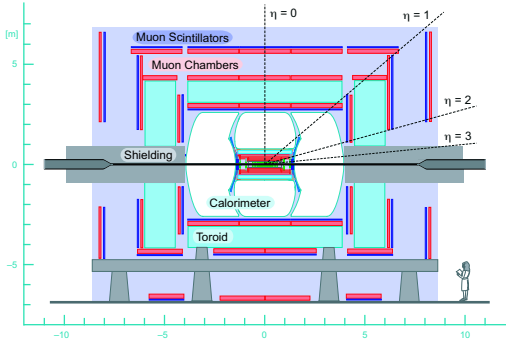


Experimental Environment

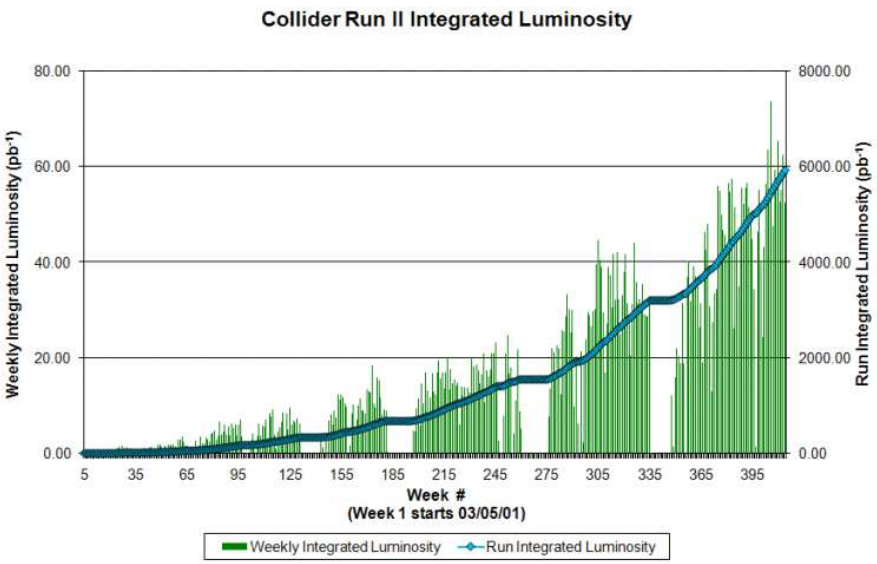




CDF



DØ

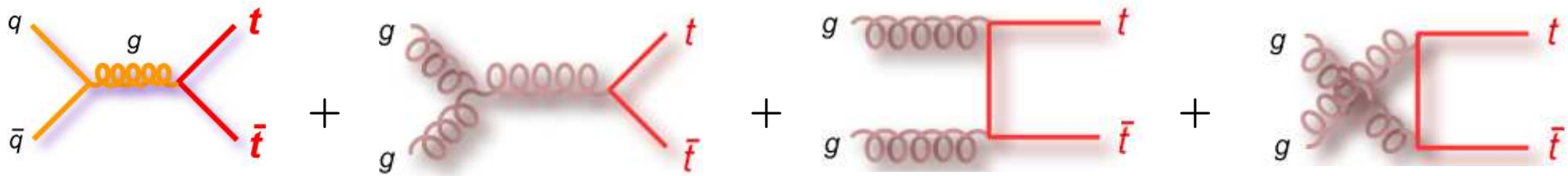


- Top produced only at Fermilab Tevatron
- $p\bar{p}$ collisions at 1.96 TeV (Run II, since 2001).
- The machine is performing well
  Luminosity record (January '09) :
  $3.5 \cdot 10^{32}\ \mathrm{cm}^{-2}\ s^{-1}$
- About $6\,\mathrm{fb}^{-1}$ delivered to experiments.
  Run II goal $4 \div 8\,\mathrm{fb}^{-1}$.
- CDF and DØ have $\sim 5\,\mathrm{fb}^{-1}$ recorded on tape.

Present results use up to $\sim 3\,\mathrm{fb}^{-1}$ of data

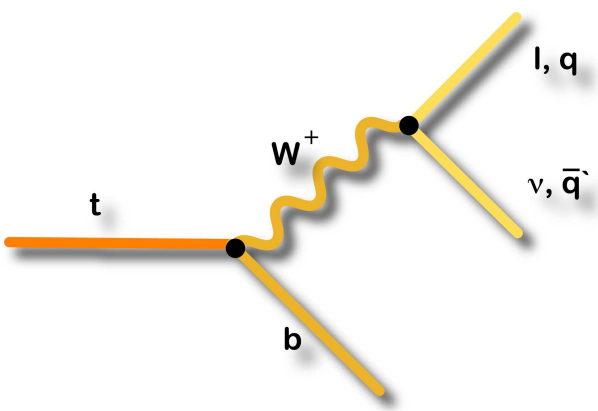
Top Quark Signatures

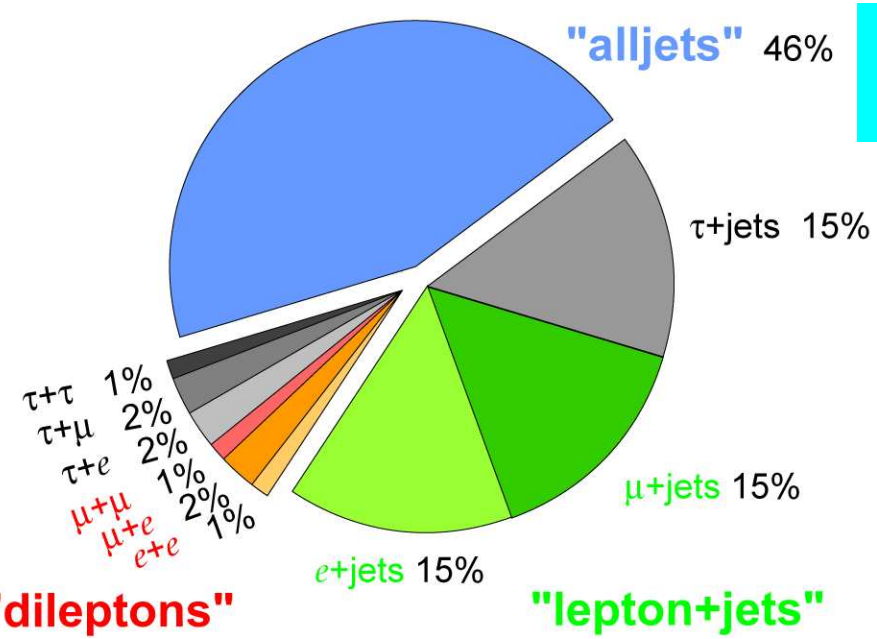
At the Tevatron mainly $t\bar{t}$ production via strong interaction



$\sim 85\%$ $\sim 15\%$

In the SM : $BR(t \to Wb) \simeq 100\%$ $\Longrightarrow$ **$t\bar{t}$ final states defined by Ws' decays**





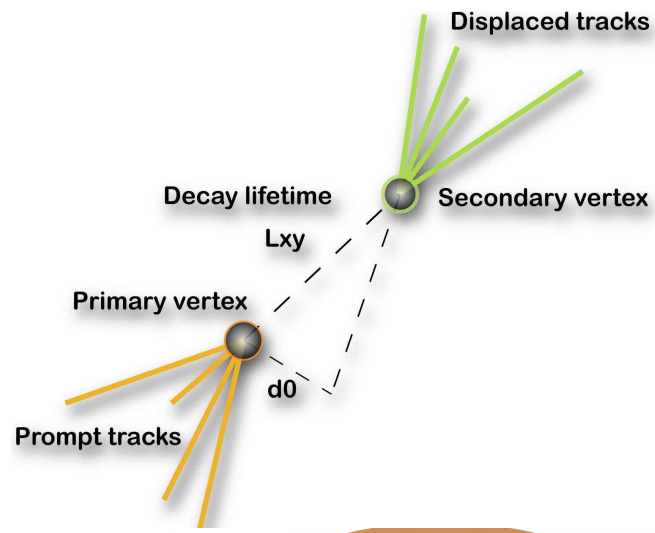
4 q-jets, 2 b-jets

2 high p_T charged leptons, 2 b-jets, $\not{E}_T$

1 high p_T charged lepton, 2 q-jets, 2 b-jets, $\not{E}_T$

Top Mass Challenges

- $\sigma_{t\bar{t}} / \sigma_{inel} \simeq 10^{-10}$!!! ... **Event Selection :**
  - b-tagging algorithms.
  - High E_T and central ($|\eta| \leq 2$) Jets.
  - Lepton Id (Dilepton, Lepton + jets).



- **Reconstruction :**
  - **Measure "Jets" and not partons**

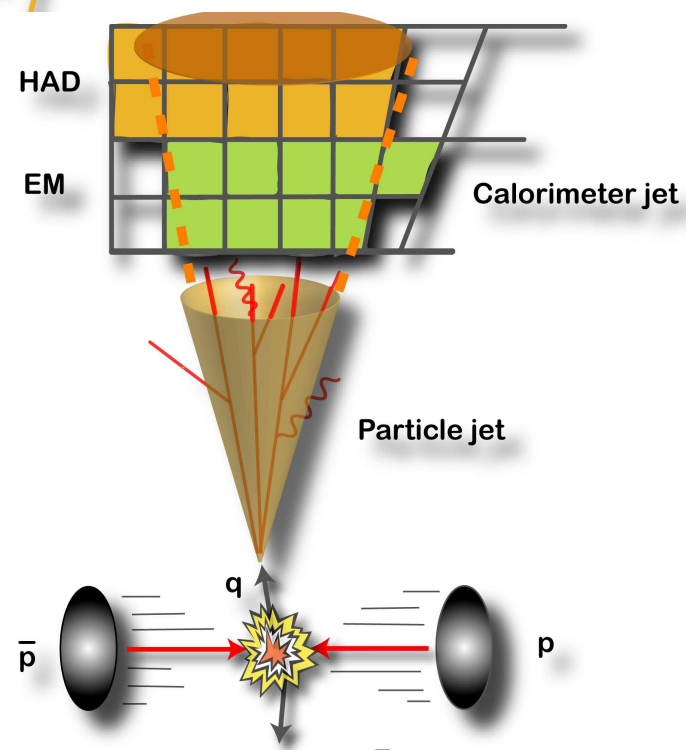
    Need corrections to obtain parton energy
    $\Rightarrow$ Jet Energy Scale. $\sigma_{JES}/JES \approx 3\%$ to 6%
    $\Rightarrow$ dominant contribution to $\delta M_{top}(syst)$

  - **Jets-to-partons assignments**

    Which jet comes from which particle?
    Combinatoric problem!

  - **Undetected ν's** (Dilepton, Lepton + jets).

    Need assumptions. Multiple solutions.



Measurement Strategies

- **Matrix Element (ME)**

  - Define the probability, P_{ev}, that the *observed* kinematics, $\vec{y}$, arise from possible signal or bkg kinematics $\vec{x}$ at parton level :

    * $d\sigma(\vec{x})$ LO differential x-section of a final state $\vec{x}$ at parton level. Depending on M_{top} for $t\bar{t}$ events, but not for bkg.
    * $\mathcal{W}(\vec{y},\ \vec{x})$ "Transfer function", i.e. probability to measure the observed set of variables $\vec{y}$, given $\vec{x}$ at parton level. Depends on JES.
    * $f_{t\bar{t}}$ Fraction of signal events expected in the data.

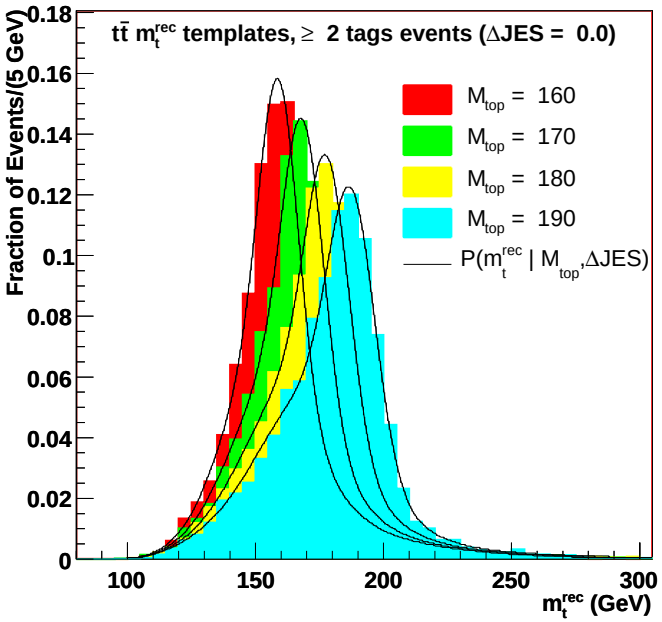
  - Maximize $\mathcal{L}_{sample} \propto \prod_{events} P_{ev}(\vec{y},\ f_{t\bar{t}},\ M_{top})$ evaluated for observed data

- **Template Method**

  - Consider a set of observables, $\vec{x}$, sensitive to M_{top}. Evaluate and plot the set for each event
    $\Rightarrow$ "Templates"

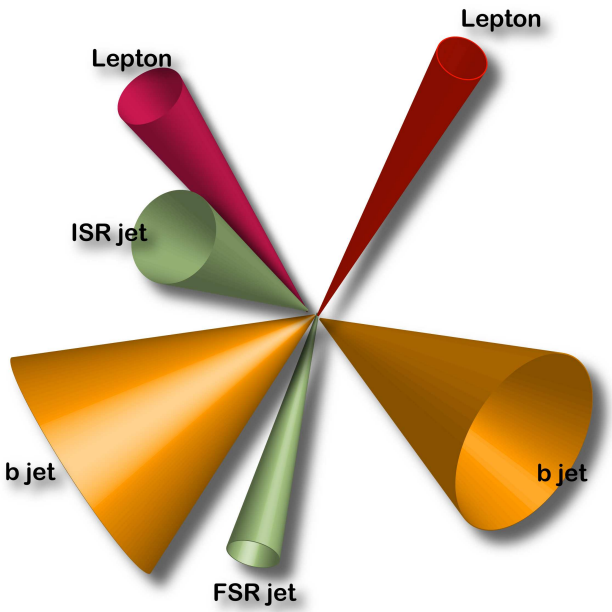
  - Maximize a likelihood where *observed* distributions are compared to expectations for different M_{top} and signal fractions, $f_{t\bar{t}}$.

$$\mathcal{L}_{\text{sample}} \propto \prod_{events} \prod_{\vec{x}} \mathcal{L}_{\text{shape}}(x_i | f_{t\bar{t}},\ M_{top})$$



Dilepton Channel

The cleanest sample.... The smallest statistics...



Typical Event Selection

- 2 oppositely charged leptons (e, μ), $E_T \geq 15$ GeV.
- 2 energetic jets, $E_T \geq 20$ GeV.
- ≥ 0 or ≥ 1 b-tag
- Large $\not{E}_T$ (≥ 25 GeV)
- Large H_T (Total transverse energy)

Main backgrounds

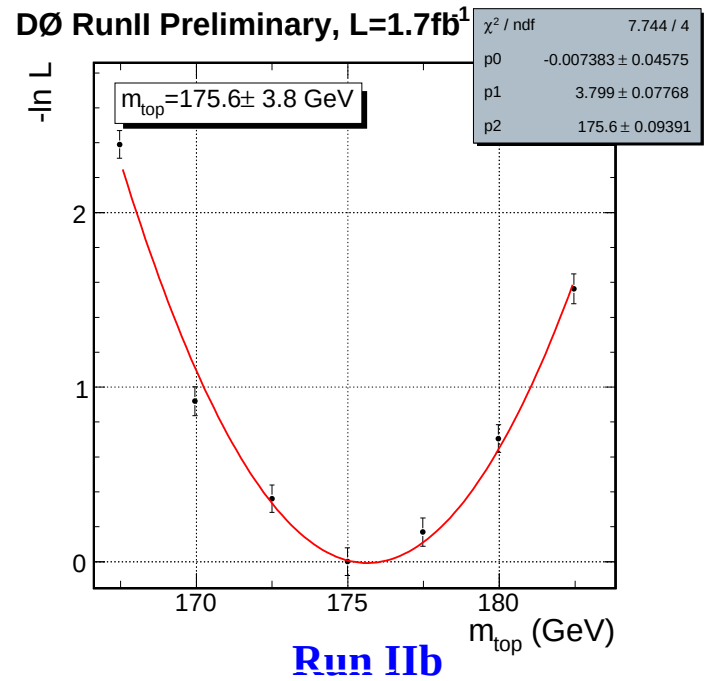
- Diboson : ZZ, WW, WW
- Drell-Yan
- W + jets (fake leptons)

- S/B between 2 and 4 (≈ 10 with b-tag)
- Small combinatoric problem (only 2 parton-jet assignments)
- Underconstrained kinematics (2 undetected ν)

Dilepton Channel

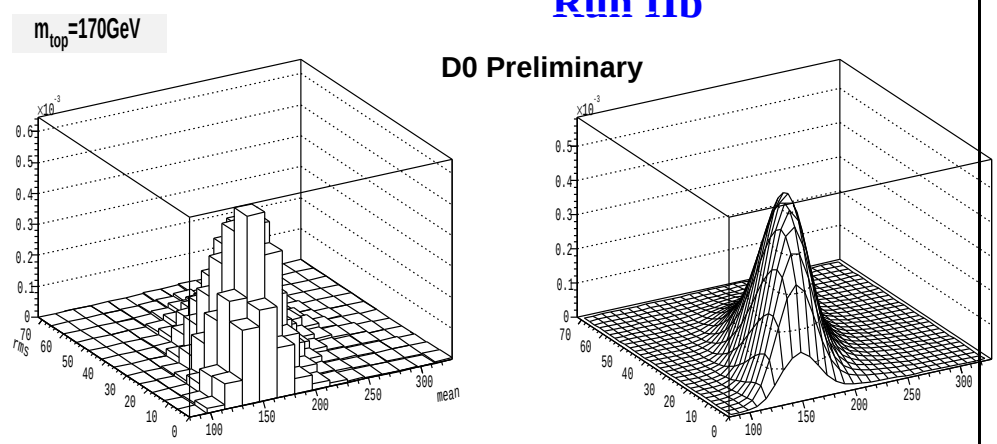
- **DØ, Matrix Element, $2.8\,\mathrm{fb}^{-1}$**
  - $e + \mu$ channel only ($BR \approx 2.5\%$).
  - Main bkg $Z \to \tau\tau$, $\not{E}_T$ cut not effective
  - 30 events selected from Run IIa ($1.1\,\mathrm{fb}^{-1}$), 68 from Run IIb ($1.7\,\mathrm{fb}^{-1}$) .
  - Combine Run IIa and Run IIb measurements to obtain :

$$M_{top} = [172.9 \pm 3.6\,(stat) \pm 2.3\,(syst)]\,\mathrm{GeV}$$
$$\delta M_{top}/M_{top} \simeq 2.5\%$$



Run IIb

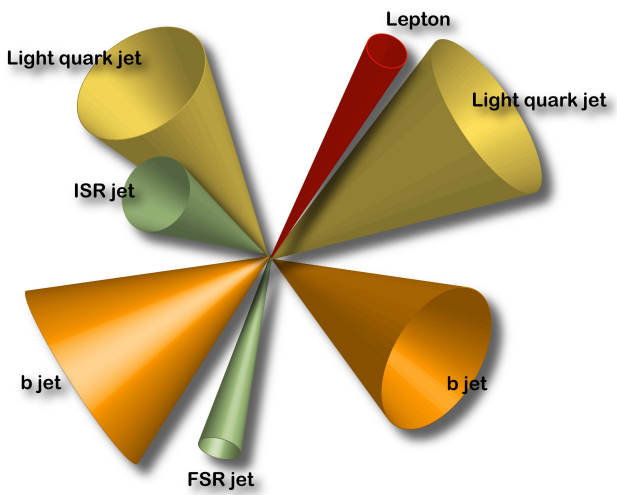
- Combine with result from Template Method by "Neutrino Weighting Algorithm" ($1\,\mathrm{fb}^{-1}$)
  - NWA uses templates built by an event weight obtained by integration over assumptions done to solve underconstrained kinematics.



$$M_{top} = [174.4 \pm 3.2\,(stat) \pm 2.1\,(syst)]\,\mathrm{GeV}$$
$$\delta M_{top}/M_{top} \simeq 2.2\%$$

Lepton + Jets Channel

Reasonable Bkg, Good Statistics.... The Golden Channel!



Typical Event Selection

- $\equiv$ 1 charged lepton (e, μ), $E_T \geq 20$ GeV.
- $\geq$ 4 energetic jets, $E_T \geq 20$ GeV.
- ≥ 1 b-tag
- Large $\not{E}_T$ ($\geq$ 20 GeV)

Main backgrounds

- W + HF ($W + b\bar{b}$, $W + c\bar{c}$, $W + c$)
- W + jets (fake b-tags)
- Multi-Jets (fake leptons)

- S/B between 3 and 10 (with 1 or ≥ 2 b-tags)
- Jets - partons assignment ambiguity (24 possibilities, eventually reduced by b-tags)
- Well reconstructed kinematic (but $\vec{p}_z^{\,\nu}$ ambiguity)

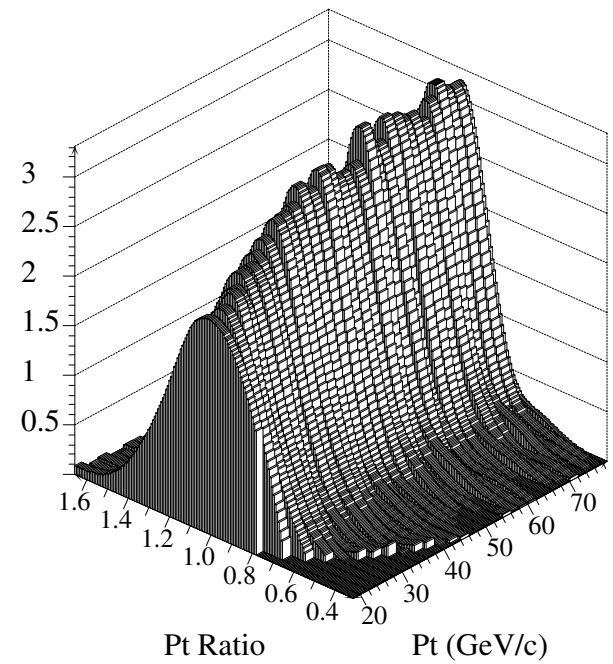
Lepton + Jets Channel

- **CDF, Matrix Element, $3.2\,\mathrm{fb}^{-1}$**
  - 578 events selected (1 e or μ, $\equiv$ 4 Jets, large $\not{E}_T$, $\geq$ 1 b-tag)
  - For each event evaluate ME-based probability as a sum over parton-jet combinations

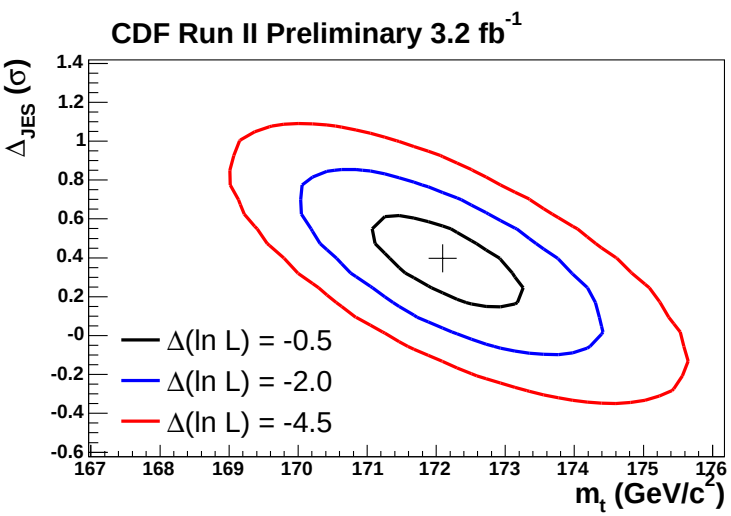
$$P_{ev} = \frac{1}{N}\sum_{i=1}^{24} w_i \cdot P_i(\vec{y}\,|\,M_{top},\,JES)$$

  - Average bkg contribution subtracted.
  - w_i : b-tag probability of the assumed parton-jet association.
  - Dependence on JES given by Transfer Functions $\mathcal{W}(\vec{y},\,\vec{x})$
  - Possible simultaneous JES calibration by jets assigned to W boson.

Transfer Function



Transfer Functions



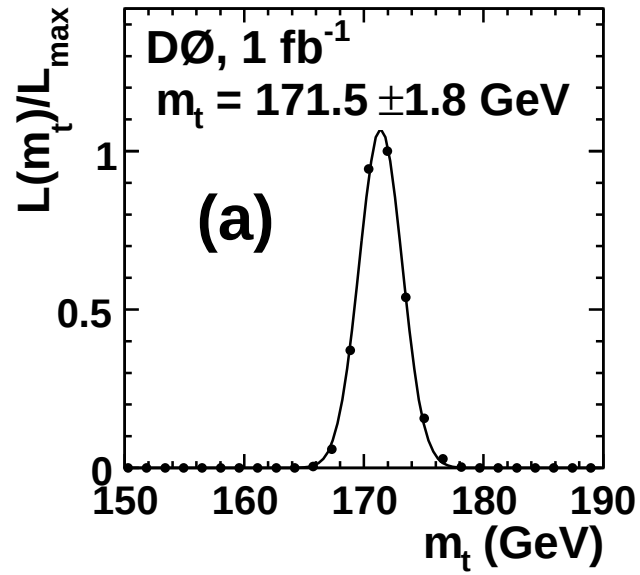
$$M_{top} = [172.1 \pm 0.9\,(stat) \pm 1.3\,(syst)]\,\mathrm{GeV}$$
$$\delta M_{top}/M_{top} \simeq 0.9\%$$

Best individual measurement from CDF

Lepton + Jets Channel

- **DØ Matrix Element, $2.2\,\mathrm{fb}^{-1}$**
  - Event selection totally analogous to CDF's.
    220 events from Run IIa ($1.0\,\mathrm{fb}^{-1}$),
    271 from Run IIb ($1.2\,\mathrm{fb}^{-1}$)
  - Use NN-based b-tagger.
  - Similar event probability, but Bkg ME explicitly calculated

$$P_{ev} = f_{t\bar{t}} \cdot P_{ev}^{t\bar{t}}(M_{top}) + (1 - f_{t\bar{t}}) \cdot P_{ev}^{bkg}$$



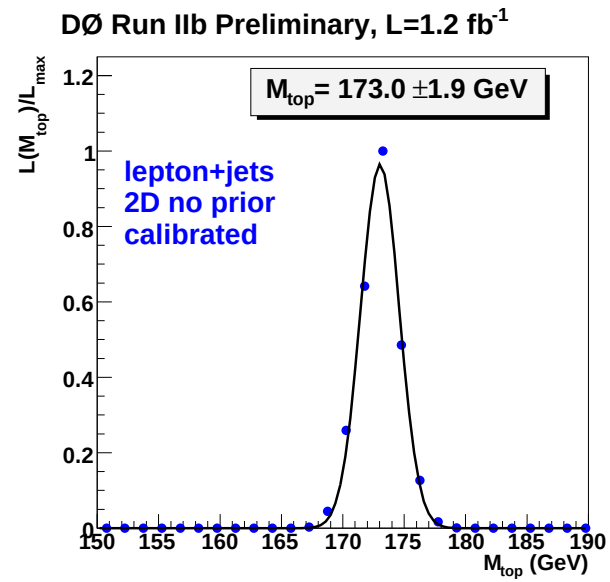
Run IIa

Run IIa

$$M_{top} = [171.5 \pm 1.5\,(stat) \pm 1.5\,(syst)]\,\mathrm{GeV}$$

Run IIb

$$M_{top} = [173.0 \pm 1.3\,(stat) \pm 1.7\,(syst)]\,\mathrm{GeV}$$



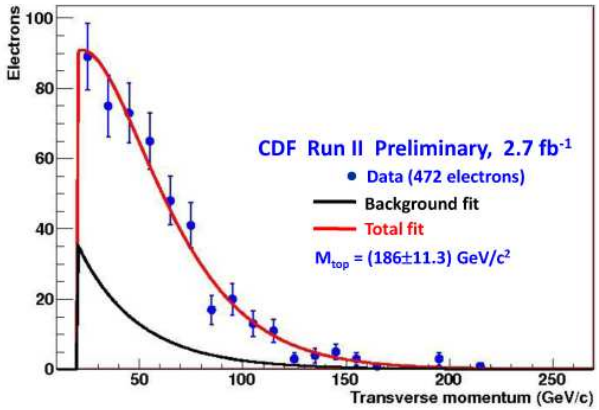
Run IIb

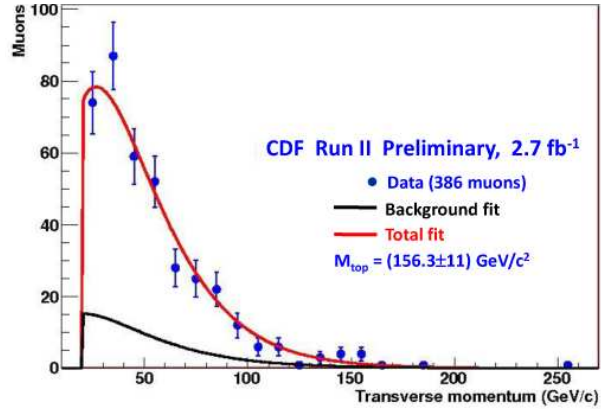
Combined $\Rightarrow$ Best DØ measurement

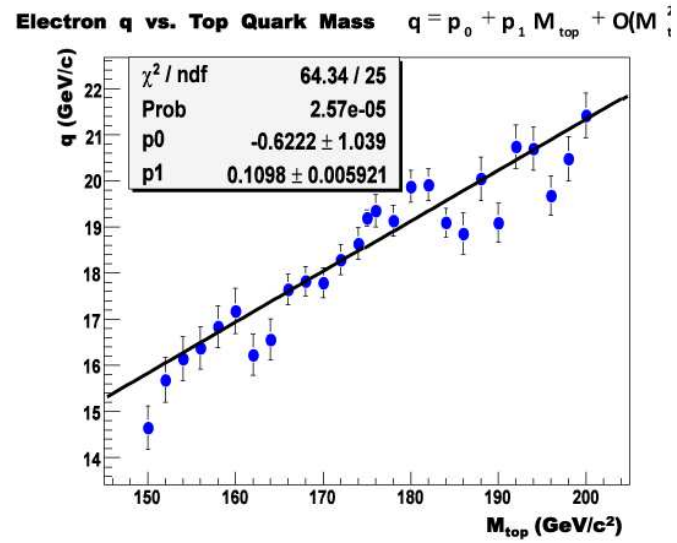
$$M_{top} = [172.2 \pm 1.0\,(stat) \pm 1.4\,(syst)]\,\mathrm{GeV}$$
$$\delta M_{top}/M_{top} \simeq 1.0\%$$

Lepton + Jets Channel

- **CDF, Lepton P_T Template, 2.7 fb^{-1}**
  - **Lepton P_T distribution is sensitive to M_{top} $\Rightarrow$ Template!**
  - **Fit M_{top}-dependent templates to observed distributions (separately for e + jets and μ + jets)**







$$f(P_T) = \underbrace{\frac{1/q}{\Gamma(1+p)}\left(\frac{P_T}{q}\right)^p \exp\left(-\frac{P_T}{q}\right)}_{\Gamma\ \text{distribution}}$$

Source	Top mass error (GeV/c^2)
MC statistics	±0.4
Global P_T scale	±0.1
Local P_T scale	±1.1
Generator	±1.4
IFSR	±1.4
PDF	±0.6
Q^2	±0.7
JES	±0.0
Mult. Had. Interactions	±0.1
Fakes	±1.8
Total	±3.0

- **No event reconstruction.**

$\Rightarrow$ ***JES* systematic negligible!!**

- **Combine e/μ results by BLUE (Best Linear Unbiased Estimator)**

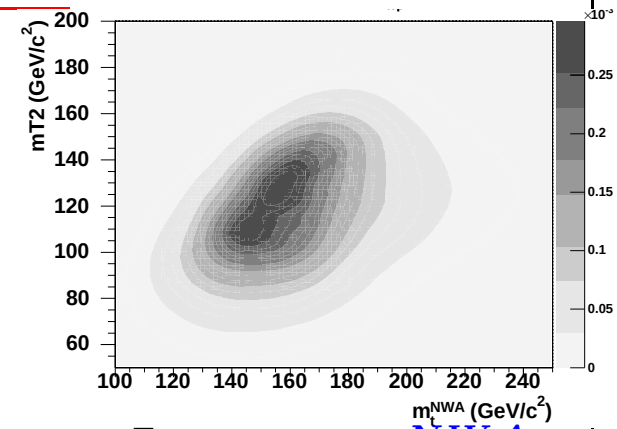
$$M_{top} = [172.1 \pm 7.9\,(stat) \pm 3.0\,(syst)]\ \text{GeV}$$
$$\delta M_{top}/M_{top} \simeq 4.9\%$$

Dilepton | **Lepton + Jets**

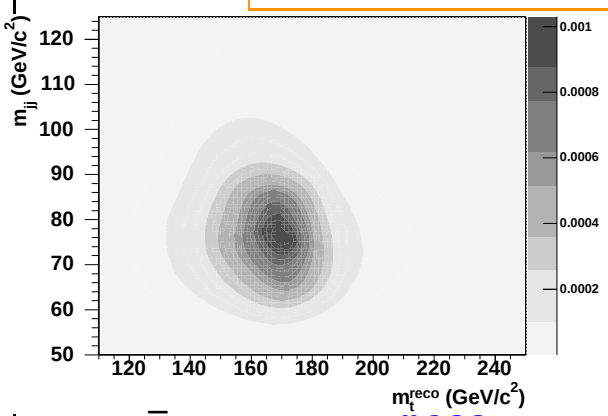
CDF, Templates, $3.0\,\mathrm{fb}^{-1}$

- **Simultaneous, template-based, measurement in L+J and Dilepton channels**

- **Dilepton 2D Template** : $mT2$ vs m_t^{NWA}
  - $mT2$: evaluated from top-quark transverse mass calculated by assumptions on m_t, $\vec{p}^{\nu}_{T,1}$, $\vec{p}^{\nu}_{T,2}$
  - m_t^{NWA} : from distribution by Neutrino Weighting Algorithm. Need assumptions on m_t, $|\eta_1^{\nu}|$, $|\eta_2^{\nu}|$.
  - $M_{top} = [169.0 \pm 2.6\,(stat) \pm 3.2\,(syst)]$ GeV



$t\bar{t}$ $mT2$ vs m_t^{NWA}



$t\bar{t}$ m_{jj} vs m_t^{reco}

- **Lepton + Jets 2D Template** : m_{jj} vs m_t^{reco}
  - m_t^{reco} : top mass reconstructed in the event by χ^2 fit.
  - m_{jj} : invariant mass of untagged di-jet systems. Related to M_W $\Rightarrow$ *in situ* JES calibration.
  - $M_{top} = [172.5 \pm 1.6\,(stat + JES) \pm 1.1\,(syst)]$ GeV

Dilepton / Lepton + Jets (unique likelihood)

$$M_{top} = [171.8 \pm 1.5\,(stat + JES) \pm 1.1\,(syst)]\ \mathrm{GeV}$$
$$\delta M_{top}/M_{top} \simeq 1.1\%$$

Dilepton | **Lepton + Jets**

DØ, M_{top} from $\sigma_{t\bar{t}}$, $1.0\,\mathrm{fb}^{-1}$

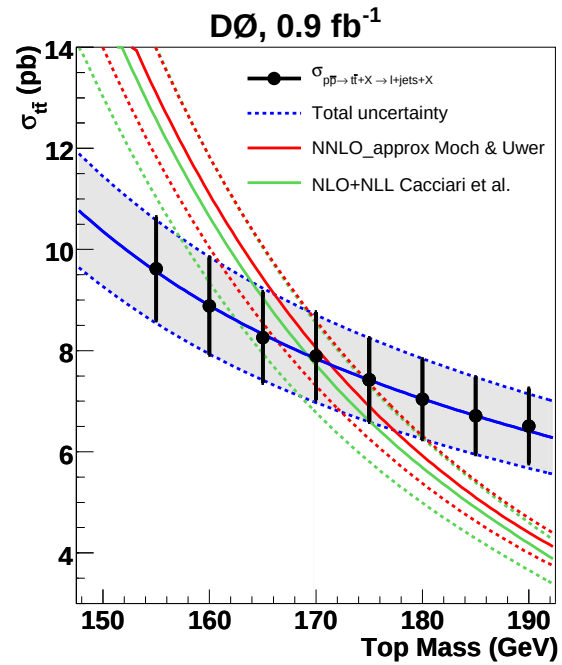
- **Combination of experimental measurements and SM theoretical predictions for $\sigma_{t\bar{t}}(M_{top})$.**
- **Measurements from two selected samples of (L+J) + Dilepton events**
  $\Rightarrow \sigma_{t\bar{t}}^{\mathrm{obs}}(M_{top}) \pm \delta\sigma_{t\bar{t}}^{\mathrm{obs}}(M_{top})$
- **Theoretical calculations :**
  - **NLO+NLL** (M. Cacciari *et al*, arXiv:0804.2800 [hep-ph])
  - **NNLO$_{\mathrm{approx}}$ (NNLL)** (S. Moch, P. Uwer, arXiv:0804.1476 [hep-ph])

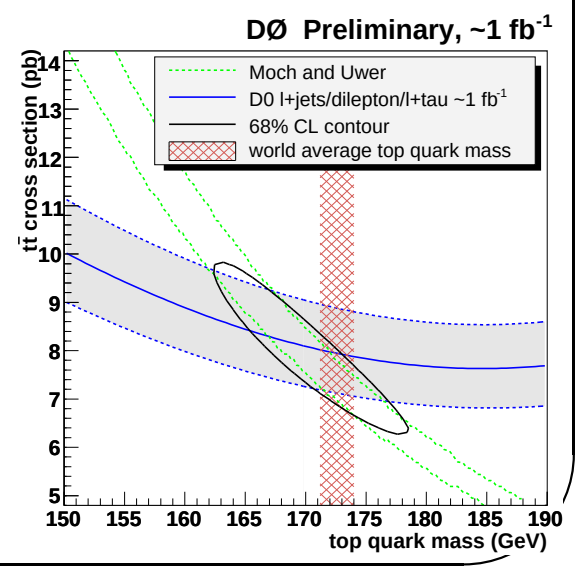
  $\Rightarrow \sigma_{t\bar{t}}^{\mathrm{theo}}(M_{top}) \pm \delta\sigma_{t\bar{t}}^{\mathrm{theo}}(M_{top})$
- **Maximize**

$$\mathcal{L}(\sigma_{t\bar{t}}, M_{top}) = \mathcal{L}^{obs}\left(\sigma_{t\bar{t}}, \sigma_{t\bar{t}}^{obs}, \delta\sigma_{t\bar{t}}^{obs}\right) \times \mathcal{L}^{theo}\left(\sigma_{t\bar{t}}, \sigma_{t\bar{t}}^{theo}, \delta\sigma_{t\bar{t}}^{theo}\right)$$

x-section sample	NLO+NLL	NNLO$_{\mathrm{approx}}$
sample 1 ($0.9\,\mathrm{fb}^{-1}$)	$169.1^{+6.6}_{-6.5}$	$171.2^{+6.5}_{-6.2}$
sample 2 ($1.0\,\mathrm{fb}^{-1}$)	$167.8^{+5.7}_{-5.7}$	$169.6^{+5.4}_{-5.5}$

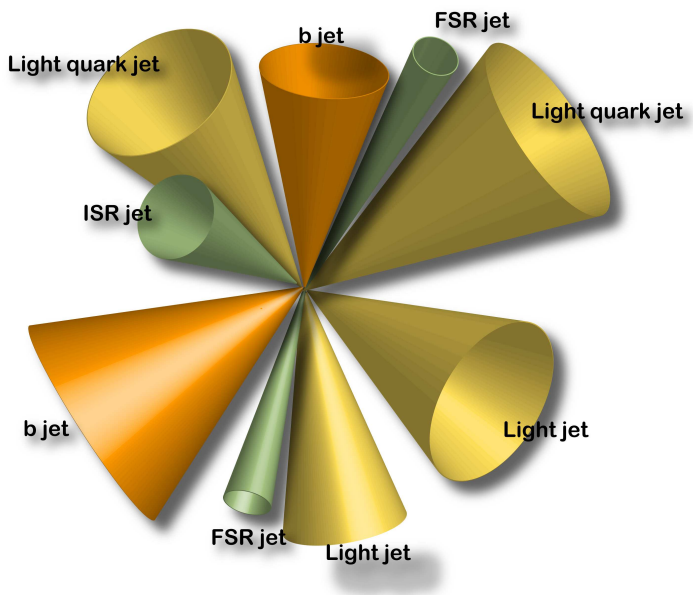
$\delta M_{top}/M_{top} \simeq 3.2\%$





All-Hadronic Channel

Huge Bkg, Large Statistics.... Challenging!



Typical Event Selection

- No energetic lepton.
- ≥ 6 energetic and central jets : $E_T \geq 15$ GeV, $|\eta| < 2$.
- Small $\not{E}_T$
- ≥ 1 b-tag

Main background

– QCD Multi-Jets

– Need Neural Net and "fine tuned" selection to increase S/B up to $\approx 1/1$ (with ≥ 2 b-tags)

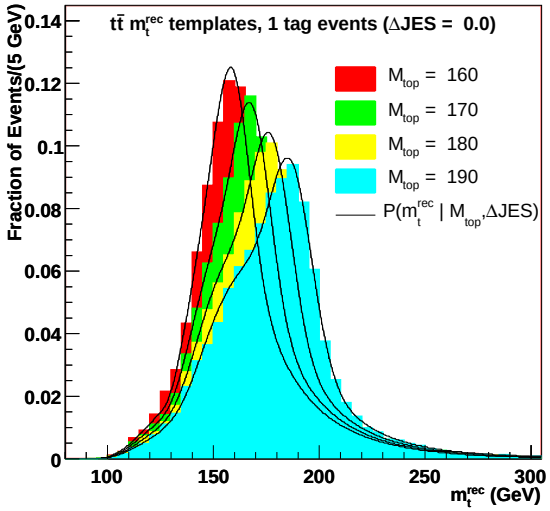
– Large Jets - partons assignment ambiguity

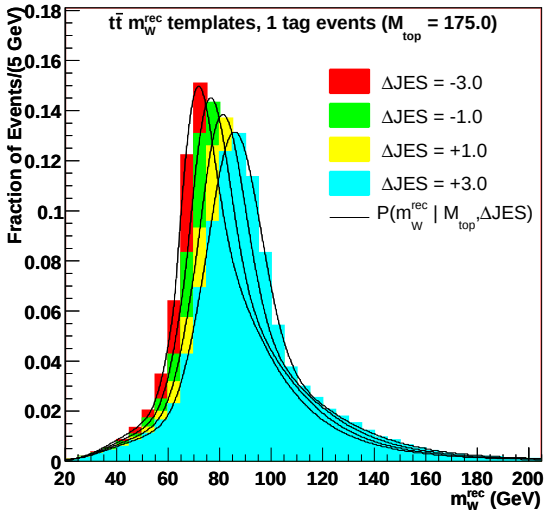
– Fully reconstructed kinematics

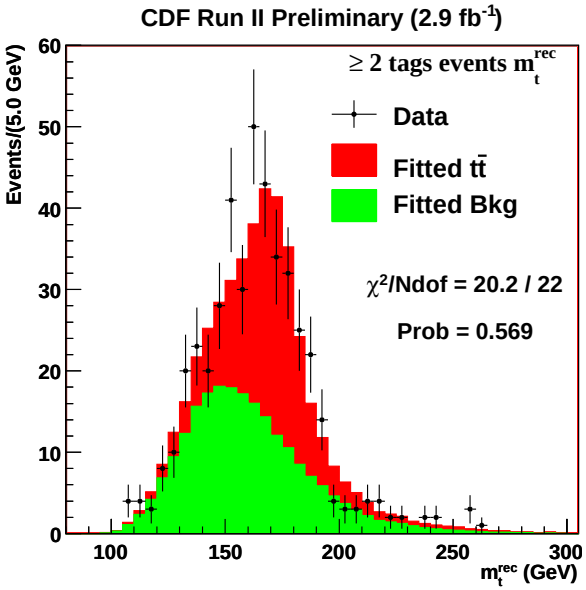
All-Hadronic Channel

CDF, Template Method, $2.9\ fb^{-1}$

- Recent inclusion of Jet-shape variables in the NN exploits differences between gluon jets (Bkg) and light quark jets ($t\bar{t}$)
- NN and careful tuning of event selection pushed S/B up to $1/1$.
- In each event reconstruct :
  - a "top mass", m_t^{rec}
  - a "W mass", m_W^{rec} $\Rightarrow$ JES calibration
- Maximize $\mathcal{L}(M_{top}, JES)$ evaluated by 3452 events with 1 tag and 441 with ≥ 2 tags.





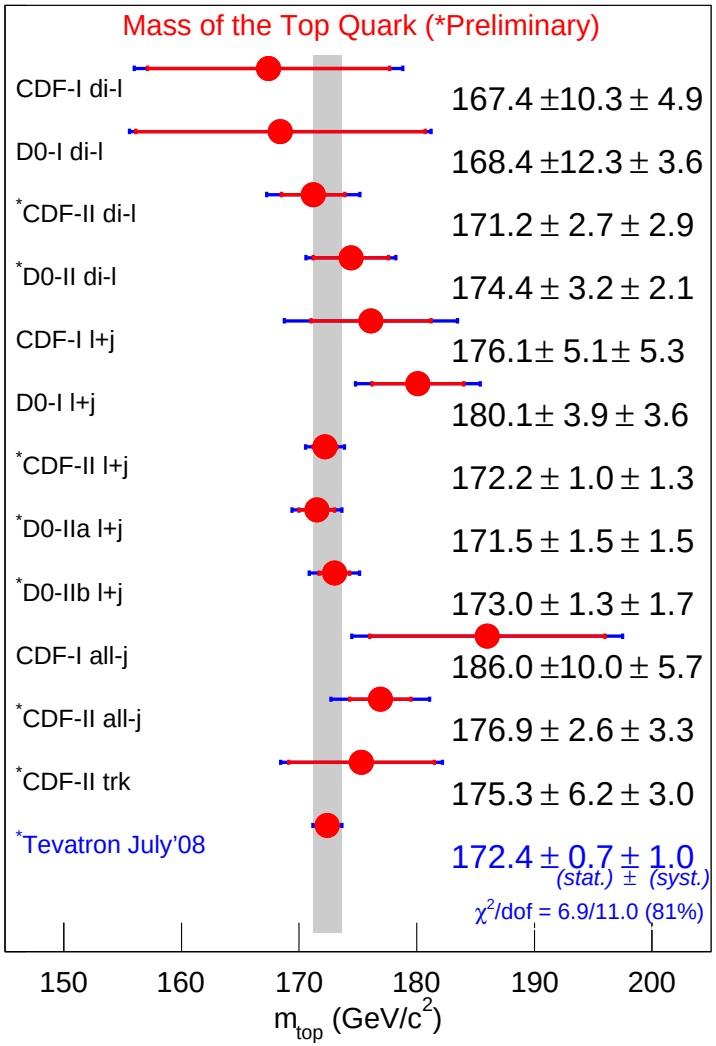


$$M_{top} = [174.8 \pm 1.7\,(stat) \pm 1.9\,(syst)]\ \text{GeV}$$

$$\delta M_{top}/M_{top} \simeq 1.5\%$$

Top Mass at the Tevatron

CDF + DØ, July 2008



Individual channels

Dilepton	$M_{top} = [171.5 \pm 2.6]$ GeV
Lepton + Jets	$M_{top} = [172.1 \pm 1.2]$ GeV
All-Hadronic	$M_{top} = [177.5 \pm 4.0]$ GeV

- **Best results of each experiment in each channel from Run I and Run II combined.**
- **All correlations taken into account.**
- **Single contributions are consistent.**
- **M_{top} known at 0.7% (July '08).**
- **Precision now limited by systematic uncertainties.**

Systematic Uncertainties on the Top Mass

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

- **Precision on the Top Mass measurement now limited by systematic uncertainties.**
- **JES uncertainty greatly reduced by *in situ* calibration techniques**
  $\Rightarrow$ **it becomes statistical!!**
- **....Anyway still the dominant contribution ($\sim 40\%$ of $\delta M_{top}(syst)$)**

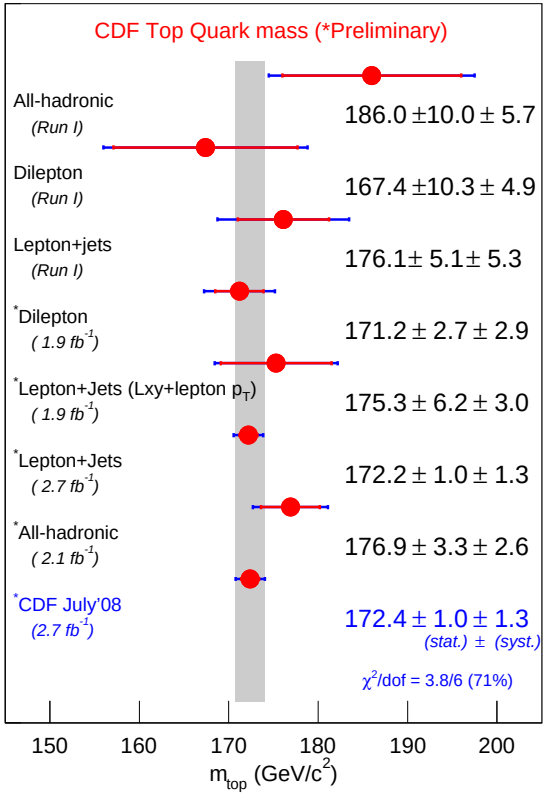
Example of Systematic Uncertainties on M_{top} (from CDF L+J ME)

- **CDF and DØ Collaborations are performing a joint effort in order :**
  - $*$ **to define a common way to evaluate systematics**
  - $*$ **to avoid possible "double counting" of some effect**
  - $*$ **to study possible still neglected sources of uncertainties (e.g. Color Reconnections Models)**

Top Mass at the Tevatron

BRAND NEW RESULT

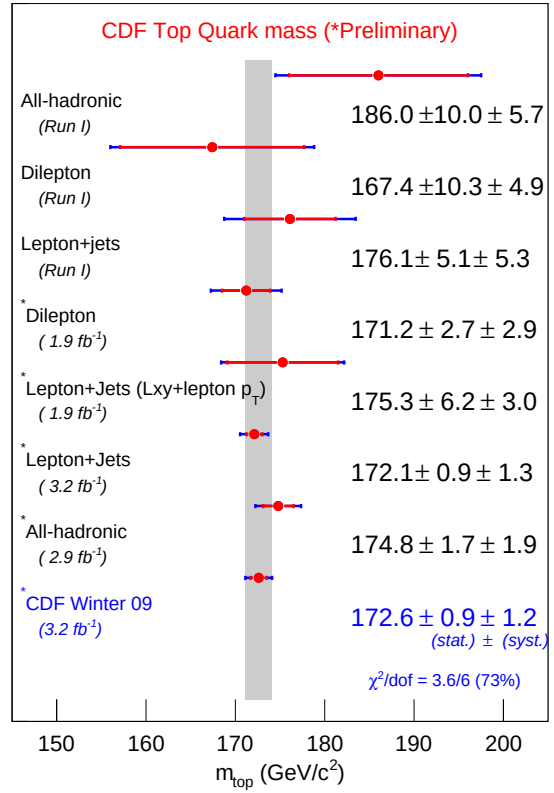
- **The CDF collaboration just approved (..a few hours ago...) an updated combination of measurements, including new results obtained by up to $3.2\,\mathrm{fb}^{-1}$ of data and showed in this talk.**



CDF, July 2008

$$M_{top} = 172.4 \pm 1.0\,(stat) \pm 1.3\,(syst)$$

$$\delta M_{top}/M_{top} \simeq 0.95\%$$



CDF, March 2009

$$M_{top} = 172.6 \pm 0.9\,(stat) \pm 1.2\,(syst)$$

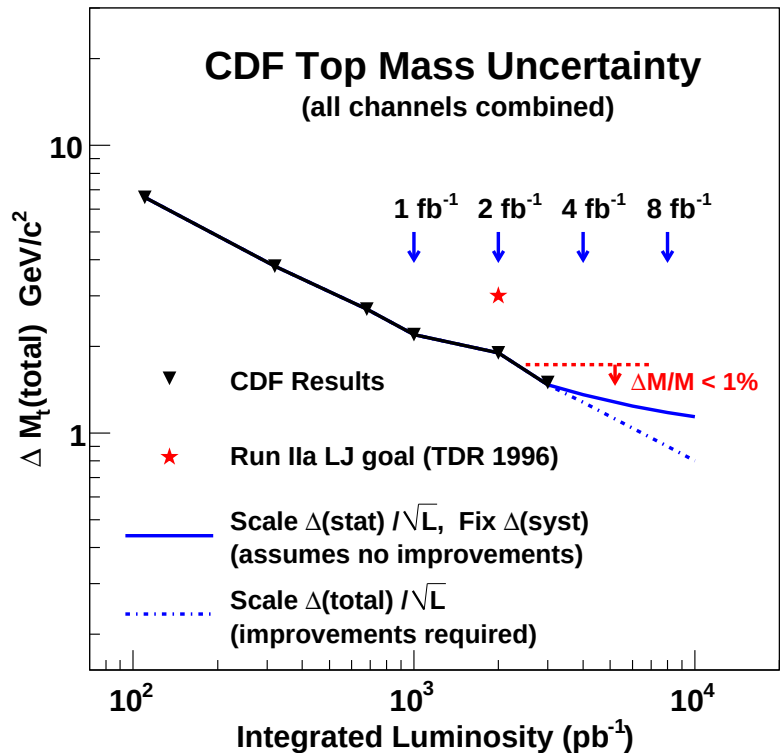
$$\delta M_{top}/M_{top} \simeq 0.87\%$$

Summary

- CDF and DØ experiments at the Fermilab Tevatron keep on performing better and better measurements of the Top Quark mass.
- Only a selection of more recent ones have been presented in this talk. Full details from

  www-cdf.fnal.gov www-d0.fnal.gov

- Excellent and consistent results from all decay channels.
- Combinations of results of individual experiments have precisions already beyond Run IIa goal (and still more data to come..)
- It's now the "systematic era". JES reduced by simultaneous calibration, but efforts are needed (and already exist) to understand precisely all possible contributions and mismodelings.



- CDF + DØ are at the 0.7% level (...July '08, improvements already expected..)...

$$M_{top} = [172.4 \pm 0.7(stat) \pm 1.0(syst)]\,\text{GeV}$$

...but we can even think of $\delta M_{top} \sim 1$ GeV !!!!

Backup

Matrix Element Method

- **Matrix Element (ME)**
  - Define *per-event* probability by Leading Order ME of signal ($t\bar{t}$) and Bkg events as a function of M_{top}, JES and the expected fraction of signal $f_{t\bar{t}}$:

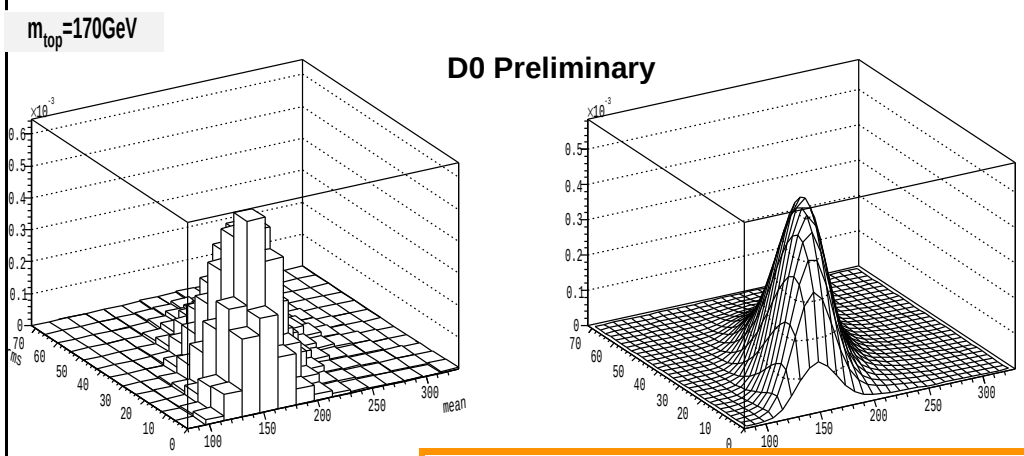
$$P_{ev}\,(\vec{y},\ f_{t\bar{t}},\ M_{top},\ JES) = f_{t\bar{t}} \cdot P_{t\bar{t}}\,(\vec{y},\ M_{top},\ JES) + (1 - f_{t\bar{t}}) \cdot P_{bkg}\,(\vec{y},\ JES)$$

$$P_{t\bar{t}} \propto \frac{1}{N} \int \underbrace{f(z_1)\, f(z_2)\, dz_1\, dz_2}_{\text{p.d.f.}}\ \underbrace{\mathcal{W}(\vec{y},\ \vec{x},\ JES)}_{\text{Transfer function}}\ \underbrace{d\sigma_{t\bar{t}}(\vec{x},\ M_{top})}_{\substack{\text{differential}\\ \text{x-section}}}$$

  - P_{bkg} totally analogous, but $d\sigma_{bkg}\,(\vec{x})$.
  - P_{ev} gives the probability for the *observed* event kinematics, $\vec{y}$, to arise from a signal or a bkg event.
  - N : Normalization factor
  - $f(z)$: Parton density functions
  - $\mathcal{W}\,(\vec{y},\ \vec{x},\ JES)$: Connect observed jets to partons. Give the probability for the *measured* jet momenta $\vec{y}$ given corresponding parton momenta $\vec{x}$. Depend on the Jet Energy Scale.
  - $d\sigma(\vec{x})$: Include ME calculation and phase space. Depend on M_{top} for $t\bar{t}$ events.
- **Maximize sample likelihood** $\mathcal{L}\,(\vec{y},\ f_{t\bar{t}},\ M_{top},\ JES) = \prod_{events} P_{ev}$

Dilepton Channel

- **DØ, Template by Neutrino Weighting Algorithm, $1.0\ fb^{-1}$**
- **Two channels :**
  - 2 leptons (e, μ) + 2 jets
  - 1 lepton + 1 isolated track + 2 jets (≥ 1 b-tag)
- **Underconstrained kinematics :**
  - Solve constraints by assuming values of m_t, $\eta_{\nu 1}$, $\eta_{\nu 2}$. Possible multiple solutions.
  - Weight each solution by its compatibility with *observed* $\not{E}_T$ (Neutrino Weighting Algorithm)
  - Sum weights over $\eta_{\nu 1}$ / $\eta_{\nu 2}$ / jets-assignments / solutions to obtain an event weight for given m_t
  - Set $\vec{x}$ of properties of weights distribution (e.g. peak value, mean, RMS) sensitive to true M_{top} $\Rightarrow$ Templates $f_s(\vec{x}|M_{top})$, $f_b(\vec{x})$.



- Maximize $\mathcal{L}$ w.r.t. M_{top}, n_s, n_b

$$\mathcal{L} \propto \prod_{i=1}^{N_{evt}} \frac{n_s f_s(\vec{x}_i|M_{top}) + n_b f_b(\vec{x}_i)}{n_s + n_b}$$

$$M_{top} = [176.0 \pm 5.3\,(stat) \pm 2.0\,(syst)]\ \text{GeV}$$
$$\delta M_{top}/M_{top} \simeq 3.2\%$$

Dilepton | **Lepton + Jets**

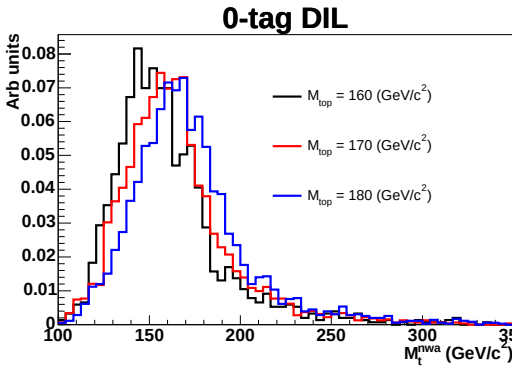
CDF, Templates, $3.0\ fb^{-1}$

- **Simoultaneous, template-based, measurement in L+J and Dilepton channels**

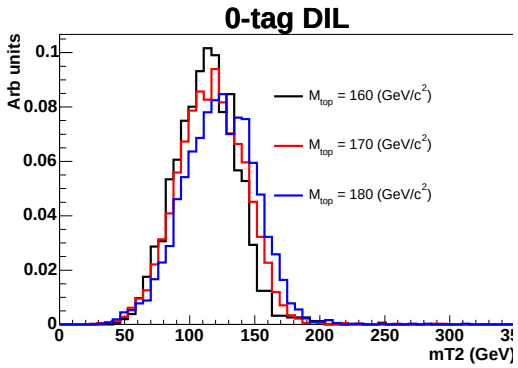
- **Dilepton 2D Template :** $mT2$ **vs** m_t^{NWA}
  - $mT2$ **: evaluated from top-quark transverse mass :**
    - **Assume** $\vec{p}_T$ **of neutrinos (with** $\vec{p}^{\nu}_{T,1} + \vec{p}^{\nu}_{T,2} = \vec{p}_{T\ miss}$**) and a neutrinos / jets assignment to** t **and** $\bar{t}$**.**
    - **Calculate the corresponding transverse masses for** t **and** $\bar{t}$ **(**$m_{T,1}$ **and** $m_{T,2}$**).**

$$m_T^2 = m_{bl}^2 + m_\nu^2 + 2\left(E_T^{bl}\,E_T^{v} - \vec{p}_T^{\,bl}\cdot\vec{p}_T^{\,v}\right)$$

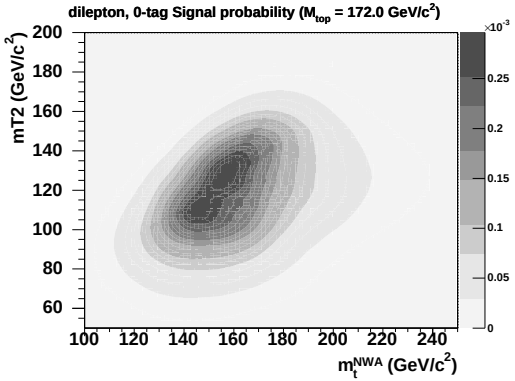
    - **Take** $mT2 = \min\{\max[m_{T,1},\ m_{T,2}]\}$ **where minimization is considered over all neutrinos** $\vec{p}_T$ **and parton assignments.**
  - m_t^{NWA} **... see previous slides**



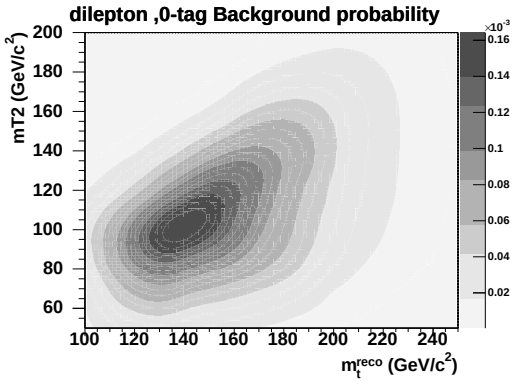
m_t^{NWA}



$mT2$



$t\bar{t}$ $mT2$ **vs** m_t^{NWA}

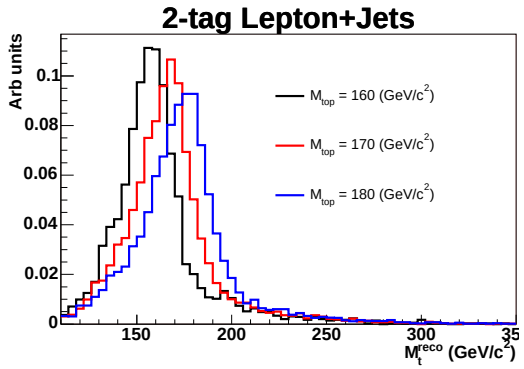


Bkg $mT2$ **vs** m_t^{NWA}

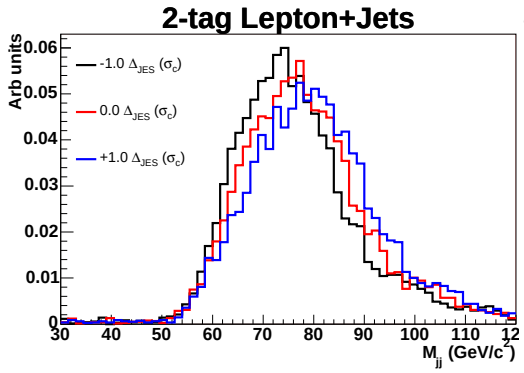
Dilepton | **Lepton + Jets**

CDF, Templates, 3.0 fb^{-1} ....continued

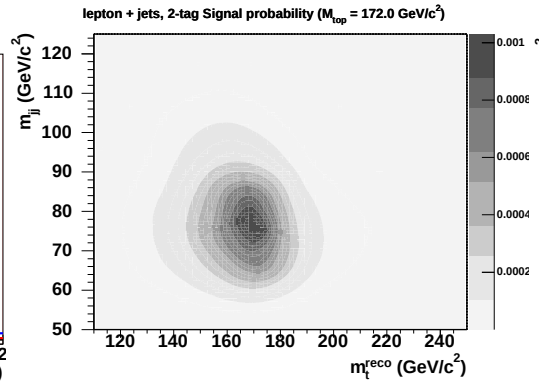
- **Lepton + Jets 2D Template :** m_{jj} **vs** m_t^{reco}
  - m_t^{reco} **is the top mass reconstructed in the event by a** χ^2 **fit. Strongly correlated to "true"** M_{top}**, but also** JES**-dependent.**
  - **All parton-jet assignments and** $\vec{p}_z^{\nu}$ **solutions are considered.** m_t^{reco} **from best** χ^2 **is chosen for the event.**
  - m_{jj} **is the invariant mass of untagged di-jet systems, related to** M_W**. As being sensitive to** JES**, it allows *in situ* calibration.**



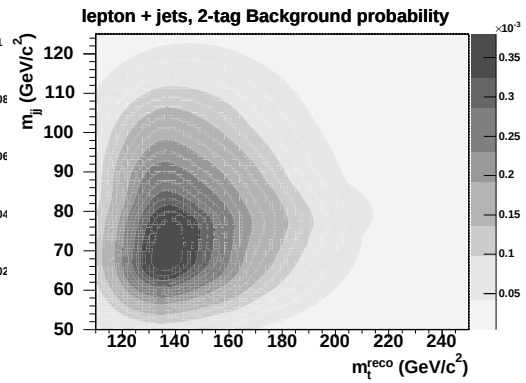
m_t^{reco}



m_{jj}



$t\bar{t}$ m_{jj} vs m_t^{reco}



Bkg m_{jj} vs m_t^{reco}

- **Maximization of** $\mathcal{L} \propto \mathcal{L}^{Dil}_{0\,tags} \times \mathcal{L}^{Dil}_{\geq 1\,tags} \times \mathcal{L}^{LJ}_{1\,tag} \times \mathcal{L}^{LJ}_{\geq 2\,tags}$ **gives**

$$M_{top} = [171.8 \pm 1.5\,(stat + JES) \pm 1.1\,(syst)]\ \text{GeV}$$

Template Method

- **CDF, Lepton + Jets** : χ^2 expression for m_t^{reco} (free parameters m_t^{reco}, $p_{T,i}^{fit}$ and U_j^{fit})

$$\chi^2 = \frac{\left(m_{jj} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(m_{l\nu} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(m_{jjb} - m_t^{reco}\right)^2}{\Gamma_t^2} + \frac{\left(m_{l\nu b} - m_t^{reco}\right)^2}{\Gamma_t^2} + \sum_{i=l,jets} \frac{\left(p_{T,i}^{fit} - p_{T,i}^{meas}\right)^2}{\sigma_i^2} + \sum_{j=x,y} \frac{\left(U_j^{fit} - U_j^{meas}\right)^2}{\sigma_j^2}$$

- **CDF, All-Hadronic** : χ^2 expression for m_t^{rec} (free parameters m_t^{rec} and $p_{T,i}^{fit}$)

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

* $m_{jj}, m_{l\nu}$: Invariant masses of dijet and lepton-neutrino systems
* $m_{jjb}, m_{l\nu b}$: Invariant masses of three-particle systems including b-jets
* $p_{T,i}^{meas}, \sigma_i$: Measured transverse momenta of lepton, jets and uncertainties
* U_j^{meas}, σ_j : components of unclustered energy and uncertainties.
* M_W, Γ_W, Γ_t : Mass of W boson and widths of W and top quark

Color Reconnection Systematics / 1

- New models of Color Reconnection (CR) have been introduced in recent versions of PYTHIA starting with V6.3.
  In our analysis we have been using PYTHIA V6.2 (tune A).

- The latest version (PYTHIA V6.4) includes, in addition to a new model for CR, new models for the parton shower, the Multiple Parton Interaction (MPI), ISR and FSR and the Underlying Event (UE).

- The CDF and DØ Collaborations work together on understanding the effects of these changes and on defining a common procedure to include them in the systematic uncertainties.

- Tuning of PYTHIA V6.4 to data is in progress. Tunes which include LEP data (called "pro") are now available.
  (see Perugia MC meeting, October 2008).

- So far we have looked at two recent tunes : ACR(pro) and S0(pro)

Color Reconnection Systematics / 2

- Tune ACR(pro) : includes only the new CR model.

  Tune S0(pro) : uses new modeling for ISR/FSR, parton shower, MPI, UE and CR.
  For this tune, we have to investigate possible overlaps
  with the systematic uncertainties we are now using.

- At this stage of our studies we evaluate the CR systematics using the ACR(pro) tune, that inlcudes only changes in the CR model. We compare ACR(pro) to A(pro) (tune A in PYTHIA V6.4) tunes.

- This has been done in the Dilepton, the Lepton + Jets and All-Hadronic channels. The three mass shifts agree within statistics.

$$\Delta M_{top} = M_{top}(\mathrm{A(pro)}) - M_{top}(\mathrm{ACR(pro)}) = (0.4 - 0.5) \pm 0.3\,\mathrm{GeV}$$

- Work is in progress to compare jet shapes in PYTHIA V6.4 with data from various samples to isolate the effects of the new parton shower from the CR contribution.