CERN EP Seminar

January 29th 2007

Measurement of the Top Quark Mass wit the Matrix Element Method at the Tevatron Run II

Outline:

- The Tevatron and its Detectors in Run II
- Top Quark Pair Production and Decay at Tevatron
- The Top Quark Mass
- The Matrix Element Method
- Applications of the Matrix Element Method to Run II Data
- Summary

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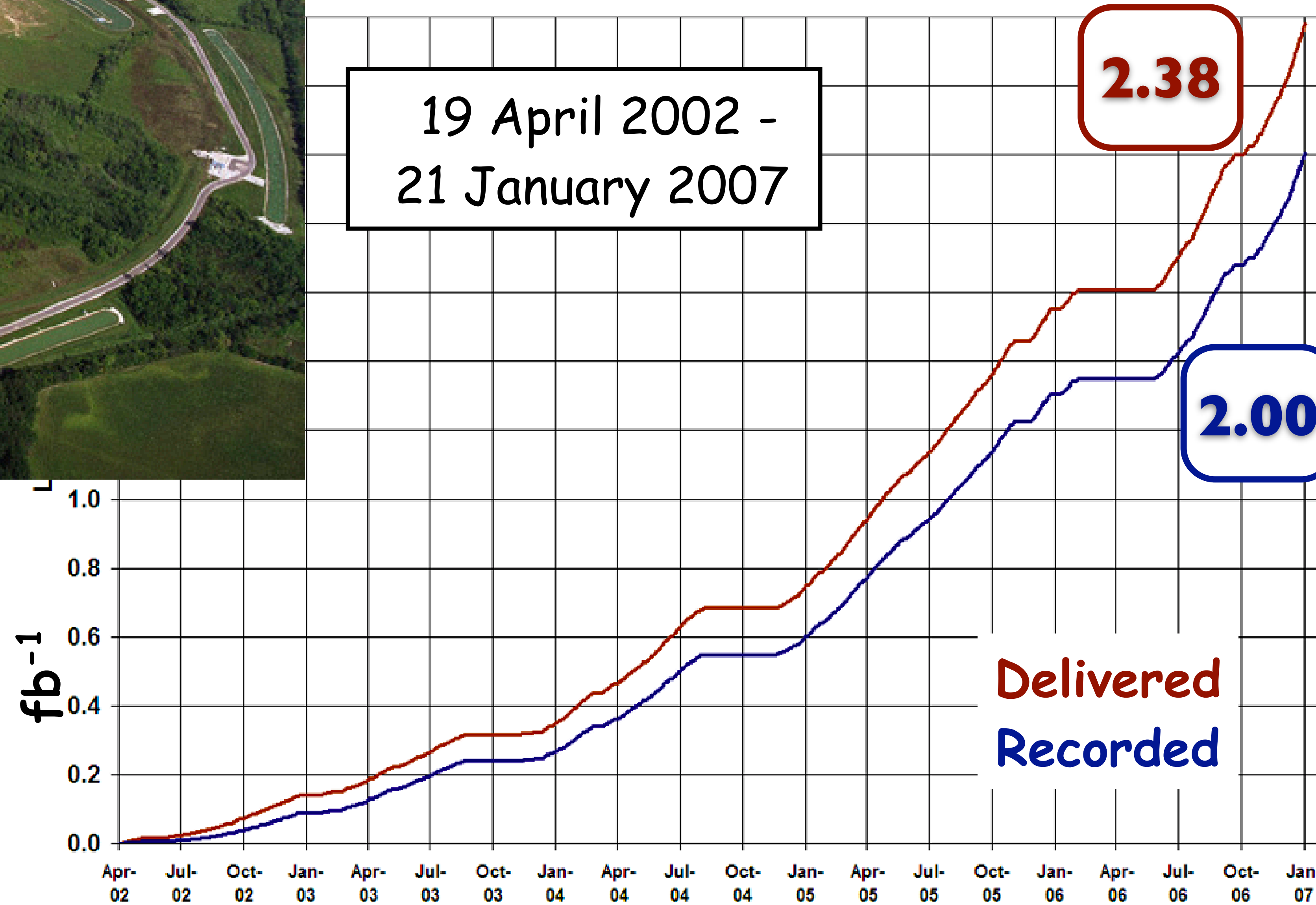
Tevatron Run II

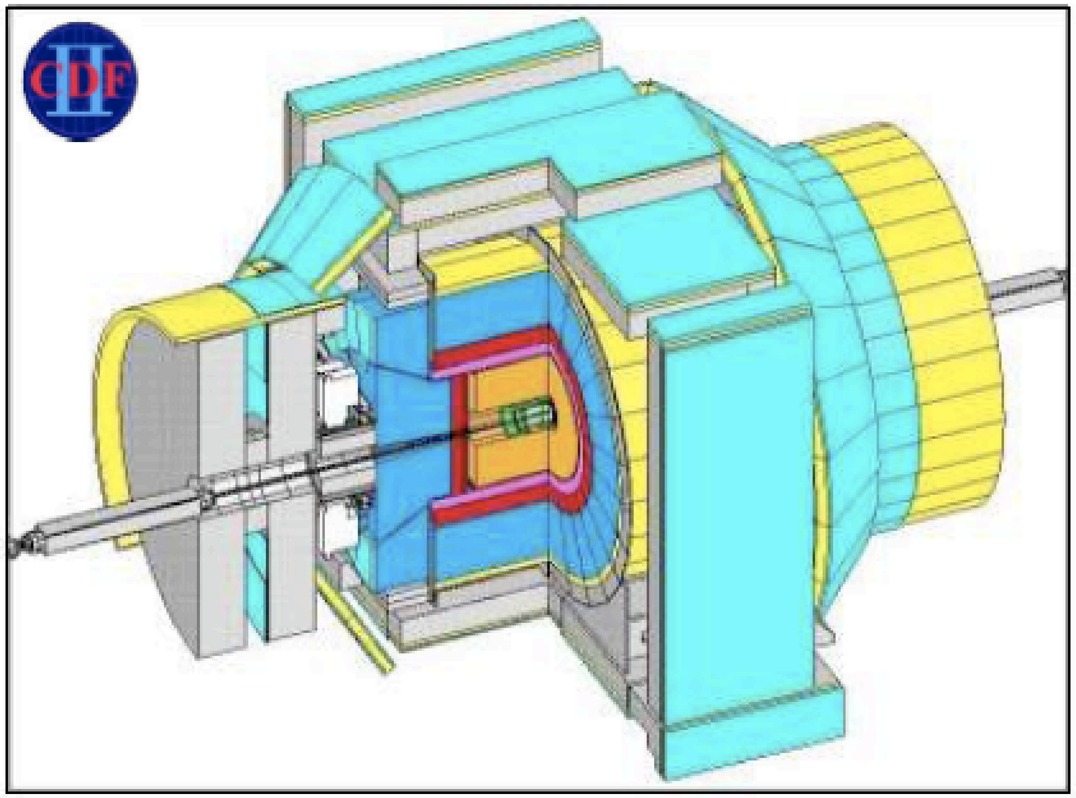
The World's only top quark factory to date!

Run II Integrated Luminosity (DØ)



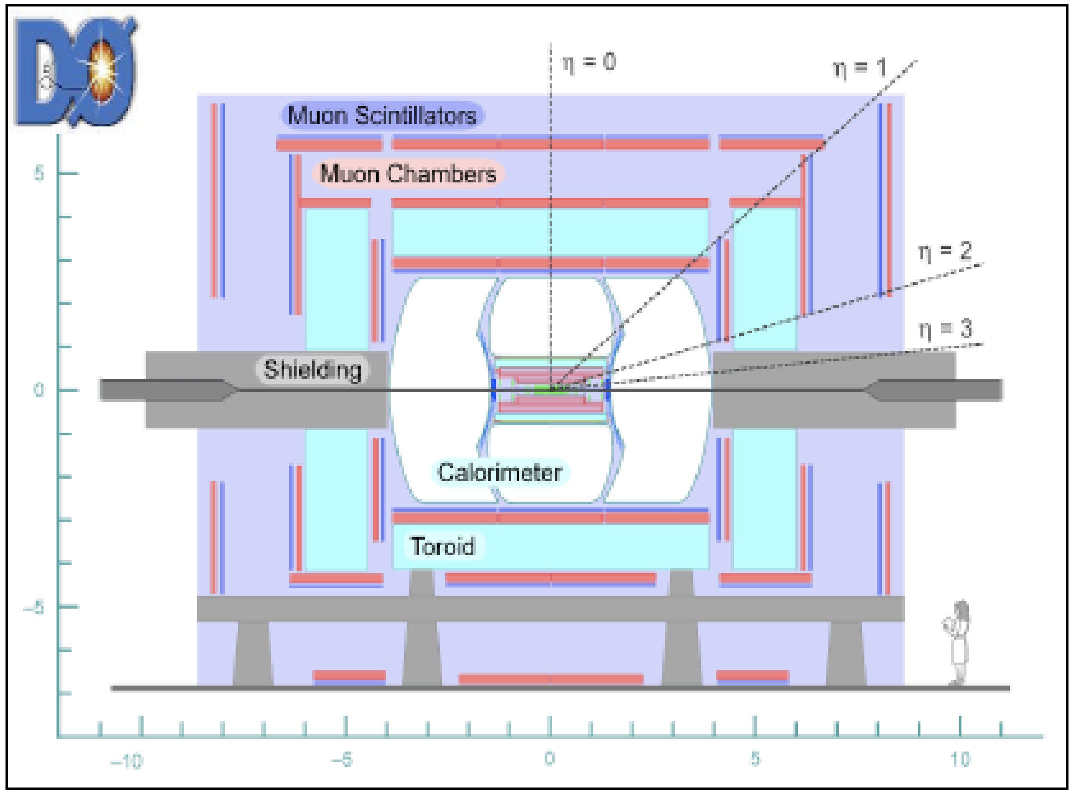
p-pbar collisions
at $\sqrt{s}$ = 1.96 TeV
bunch-crossing: 396ns

CDF & DØ



CDF Run II Upgrades:

- New Silicon Vertex Detector (SVX) and faster tracking drift chamber (COT)
- New scinitllating-tile end-plug calorimeters
- Increased $\eta\varphi$ coverage for muon detectors
- New Scintillator Time-Of-Flight system



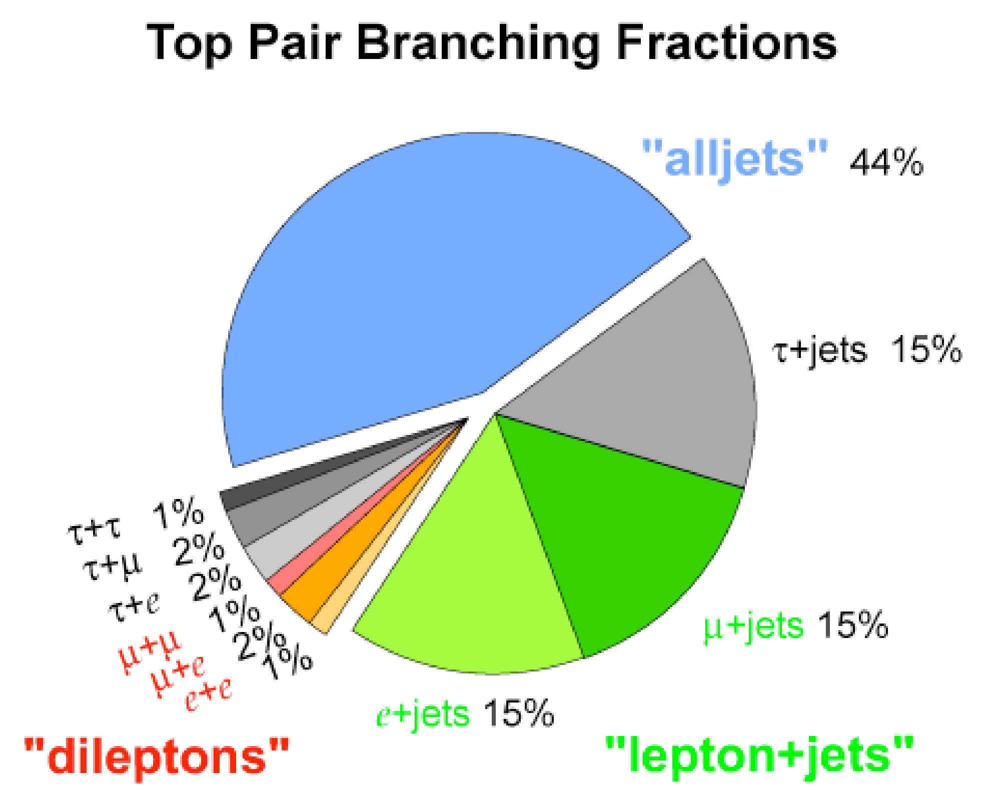
D0 Run II Upgrades:

- New silicon (SMT) and Fiber (CFT) trackers, placed in new 2T Solenoid
- Calorimeters supplemented with Preshower detectors
- Significantly improved Muon System

Both detectors underwent major DAQ/Trigger upgrades w.r.t to Run I to cope with the reduced bunch-crossing rate of 396 ns (Run I: 2.4 μs, LHC: 25 ns)

Top Production and Decay

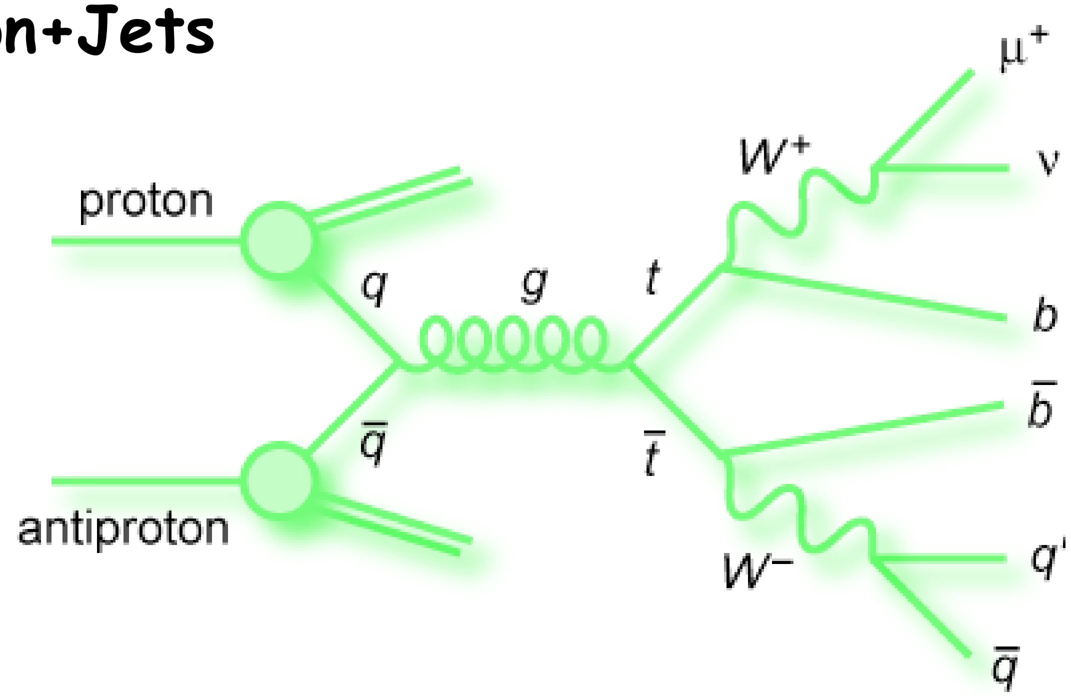
- In p-pbar collisions at $\sqrt{s}$ = 1.96 TeV, top quarks are primarily produced in pairs
  - ★ Standard Model cross-section ~7pb
  - ★ ~85% via quark annihilation
  - ★ ~15% via gluon fusion
- top decays almost exclusively to Wb (SM)
- "Leptons" here refers to Electrons or Muons



	All-Jets	Lepton+Jets	Dilepton
BR	~44%	~30%	~5%
S/B	1:1000 to 1:4	1:4 to 11:1 varies w/ #b-tags	~2:1
Backgrounds	Jet Production	W+jets fake leptons	Z+jets WW,WZ

Lepton+Jets and Dilepton Final-States

Lepton+Jets



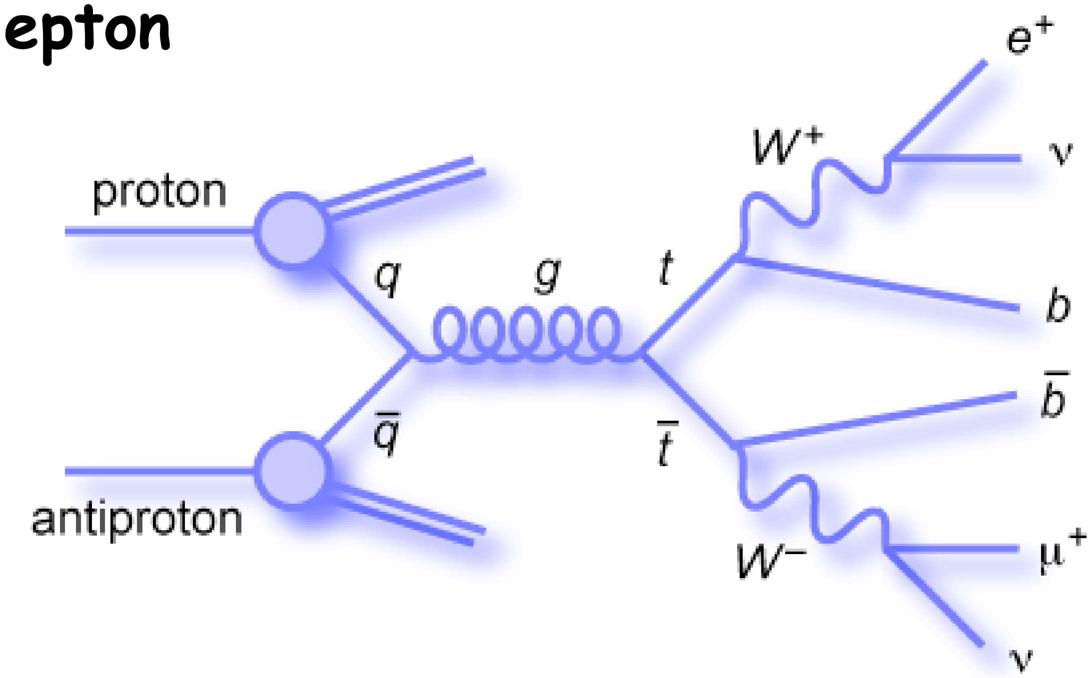
Signature:

- Four [or more] Calorimeter Jets
- Exactly one Isolated Energetic Lepton (e or μ)
- Significant Missing Transverse Energy > 20GeV
- pT>20GeV required for jets/lepton
- 24 possible jet/parton assignments -> use life-time tagging information

Backgrounds:

- W+jets production
- Instrumental background due to fake leptons (Jet Production, "QCD")

Dilepton



Signature:

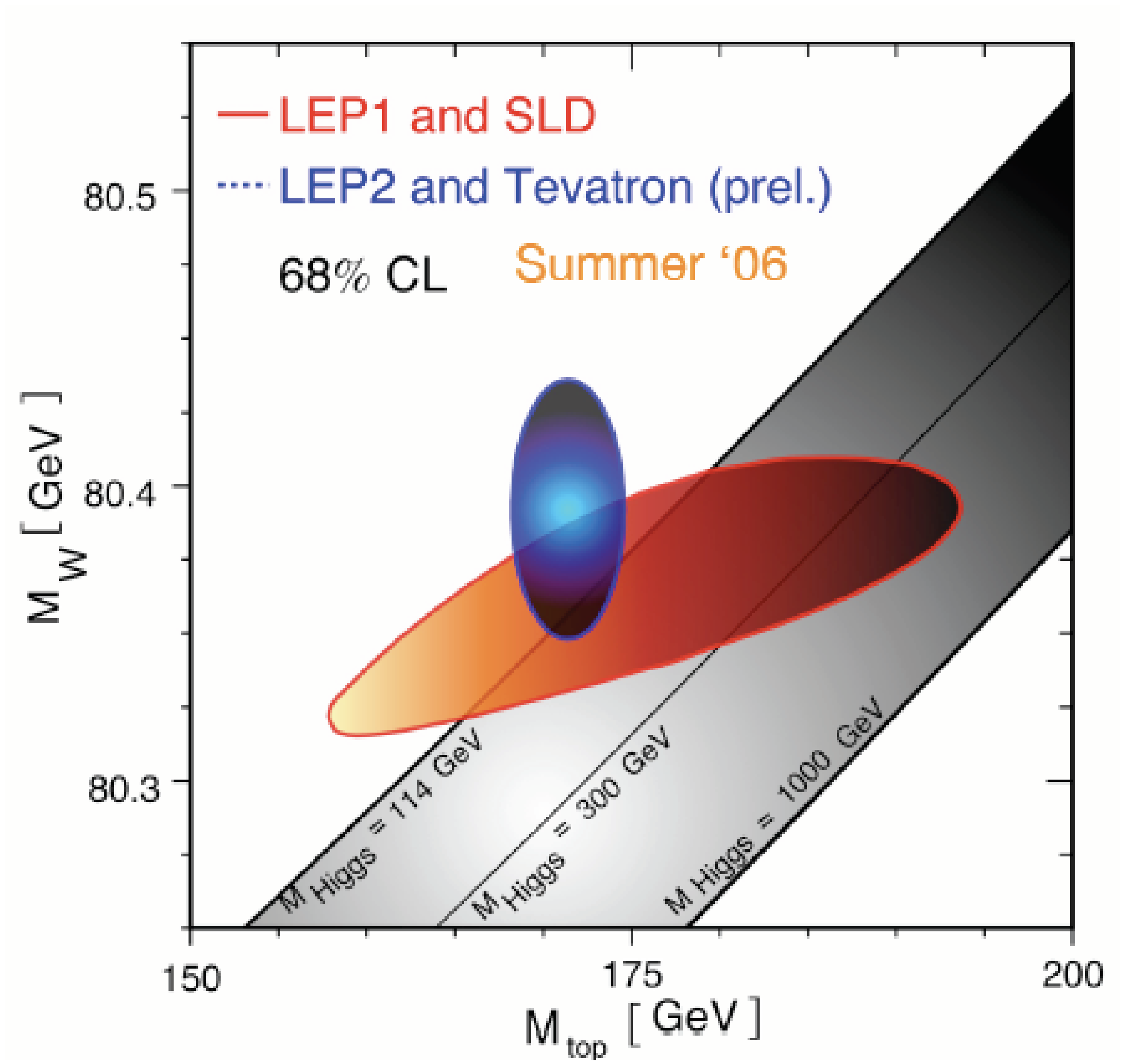
- Two [or more] Calorimeter Jets
- Exactly two Isolated Energetic Leptons (e or μ)
- Significant Missing Transverse Energy > 20GeV
- pT>20GeV required for jets/leptons
- 2 possible jet/parton assignments; life-time tagging information to increase S/B

Backgrounds:

- WW, Z+jets production
- Instrumental background due to fake leptons (WZ production)

The Top Quark Mass

- The top quark mass is a free parameter of the Standard Model
- The top quark is by far the heaviest of the six known quarks
- Its suspiciously high mass suggests a special role of the top quark in the Standard Model yet to be revealed
- Precision measurements of the top quark and W boson masses constrain the mass of the Higgs boson via radiative corrections
- With 4-8fb^{-1} of Tevatron data: $\delta m_t \sim 1.5$ GeV (CDF and DØ combined)



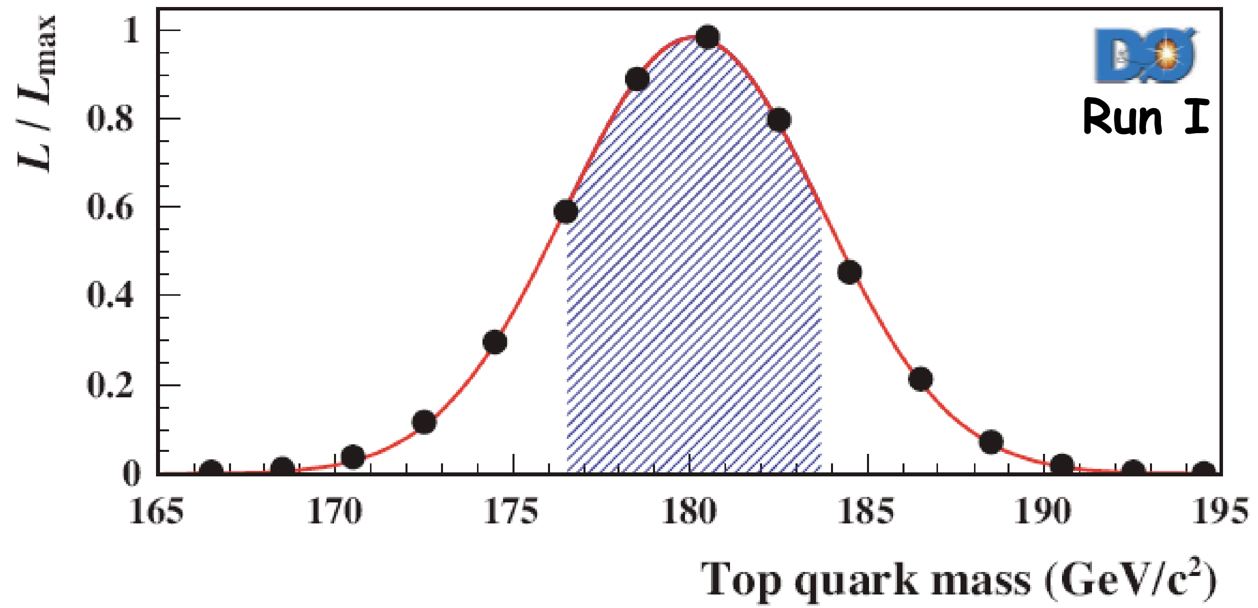
Tevatron top quark mass measurements will be relevant for many years, even after LHC turnon

The Matrix Element Method

- Developed during Run I, Application to D0 Lepton+Jets dataset yielded most precise Tevatron Run I result:

m_{top} = 180 ± 5.3 GeV
(±3.6 (stat.) ± 3.9 (syst.) GeV)

Nature **429**, 638 (2004)



- Applied to 370 pb^{-1} of D0 Run II Data (Lepton+Jets) to yield most precise D0 result
  - ★ FERMILAB-THESIS 2005-46 (320 pb^{-1}, topological analysis)
  - ★ Phys.Rev. D74, 092005, 2006 (370 pb^{-1}, topological + b-tagging)
- Application to 940 pb^{-1} CDF Run II Data (Lepton+Jets) yields world's best measurement
- Application to 1.03 fb^{-1} of CDF Run II Data (Dilepton) yields world's best measurement in the Dilepton channel
  - ★ Phys.Rev.Lett. 96,152002, 2006

Basics of the ME Method

- Use each event's full kinematic information to calculate its probability to originate from t-tbar production, as a function of the top mass m_t.
- Calculate its probability to be produced via the background process (W+jjjj) accordingly, and combine both to an event probability P_{evt}:

$$P_{evt}(x;m_t) = f_{sgn} P_{sgn}(x;m_t) + (1 - f_{sgn}) P_{bkg}(x)$$

f_{sgn}: signal fraction
x : event's kinematic variables

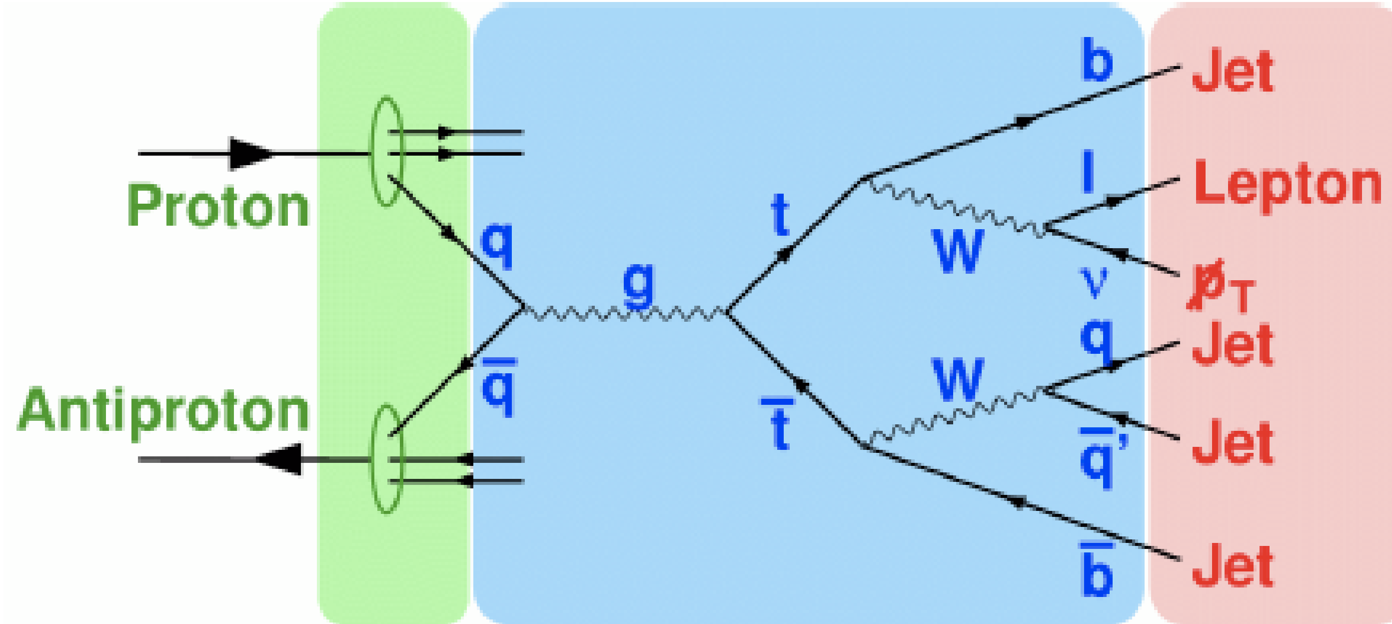
- Combine Event Probabilities of all n events in the dataset into a log likelihood:

$$-\ln L(x_1,\ldots,x_n;m_t,f_{sgn}) = \Sigma_i \ln P_{evt}(x_i;m_t,f_{sgn})$$

- Measure top quark mass by minimizing log likelihood w.r.t. m_t and f_{sgn}.
- Achieve optimal use of statistical information by treating events individually: well measured events contribute more than poorly measured events.
- The instrumental background from misidentified leptons in All-Jets events is not explicitly modeled, expected to be Wjjjj-like, the difference QCD/Wjjjj is treated as a systematic uncertainty

P_{sgn} Probability Calculation

- Integration over parton phasespace
- Assume all angles (jets, lepton) to be well measured, as well as the energy of the electron
- Parametrize Detector-Resolution of jets and muons using Monte Carlo (transfer function W(x,y))
- Calculate remaining 5(6)-dimensional integral using MC techniques (VEGAS)



$$\mathcal{P}_{t\bar{t}}(\vec{x}, m_t) = \underbrace{\frac{1}{\sigma_{t\bar{t}}(m_t)}}_{\text{Normalisation}} \int \underbrace{dp_q dp_{\bar{q}} f(p_q) f(p_{\bar{q}})}_{\text{PDFs}} \underbrace{d\sigma_{t\bar{t}}(\vec{y}, m_t)}_{\text{diff. xsec}} \underbrace{W(\vec{x}, \vec{y})}_{\text{det. resolutions}}$$

MATRIX ELEMENT

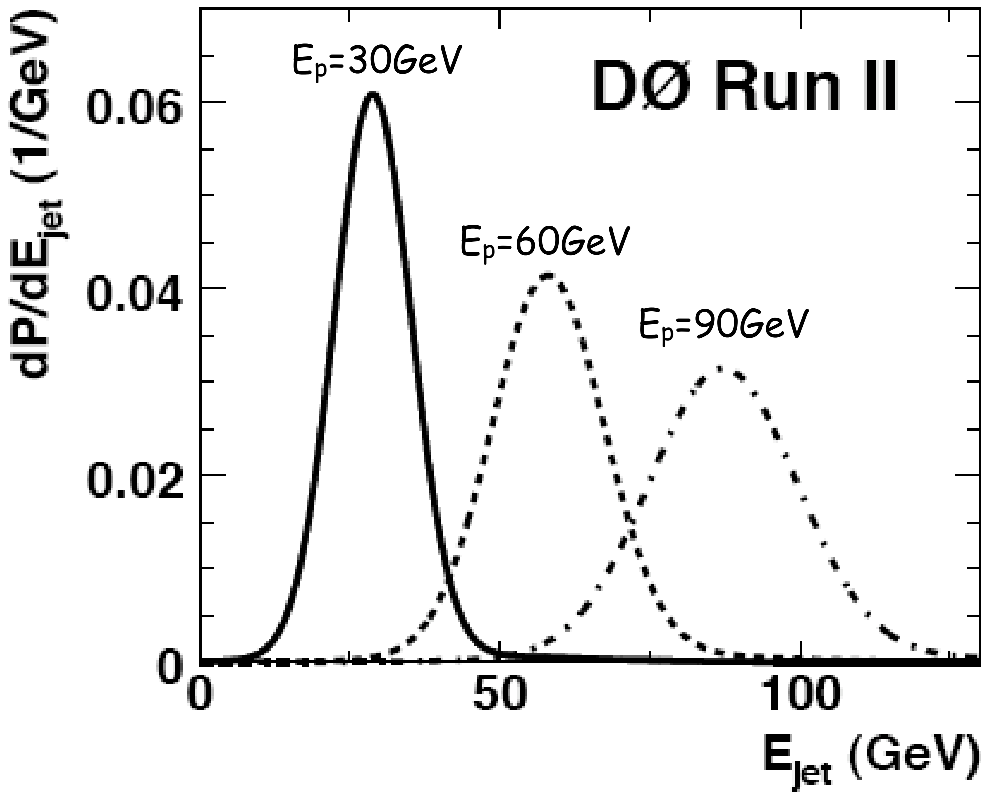
- Consider all 12 relevant jet-parton assigments
  - ⋆ 24 possible combinations, exclude permutations where the two hadronic W daughters are exchanged
- Presence of the escaping neutrino creates a quadratic ambiguity in the kinematic solution of each event: consider both neutrino solutions.

Transfer Functions

- Transfer functions describe the detector resolution of jets and muons: W(x,y) yields the Probability of a parton state y to be reconstructed as detector state x
- x and y are the respective kinematic variables; since angles are assumed to be well measured, transfer functions need to be derived for jet and muon energies.
- **Jet** Parametrization: $W(E_{jet},E_{parton}) = F(E_{jet}-E_{parton}) = F(\delta)$:

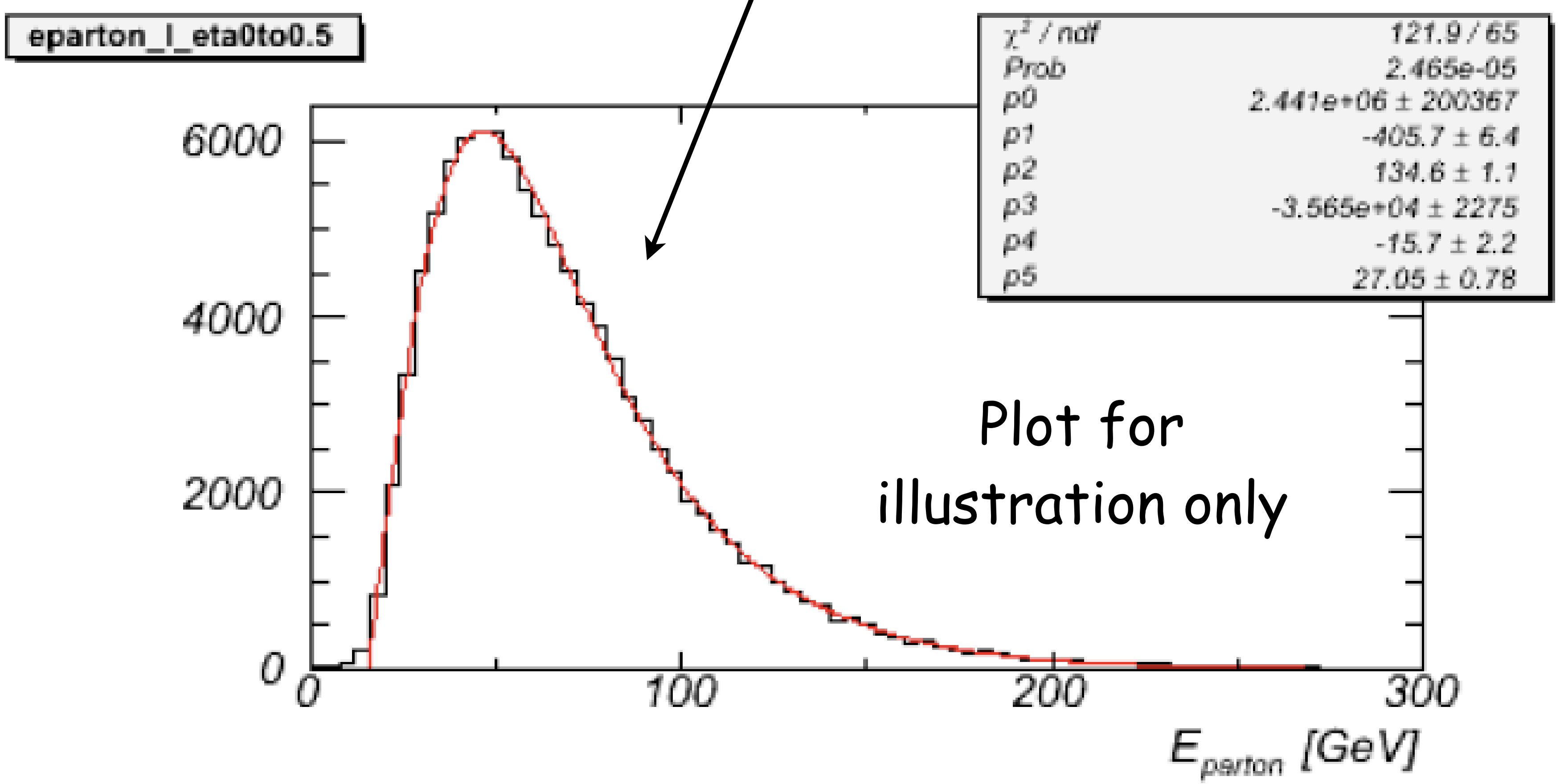
$$F(\delta) = \frac{1}{\sqrt{2\pi}(p_2 + p_3 p_5)}[\exp\frac{-(\delta - p_1)^2}{2p_2^2} + p_3 \exp\frac{-(\delta - p_4)^2}{2p_5^2}]$$

- Assume $p_i = a_i + b_i E_{parton}$ and derive the 10 parameters with a likelihood fit from t-tbar Monte Carlo Events for light, b-, and b(→μ) - jets
- **Muons**: $1/p_T$ parametrized as Gaussian with |η| - dependent width

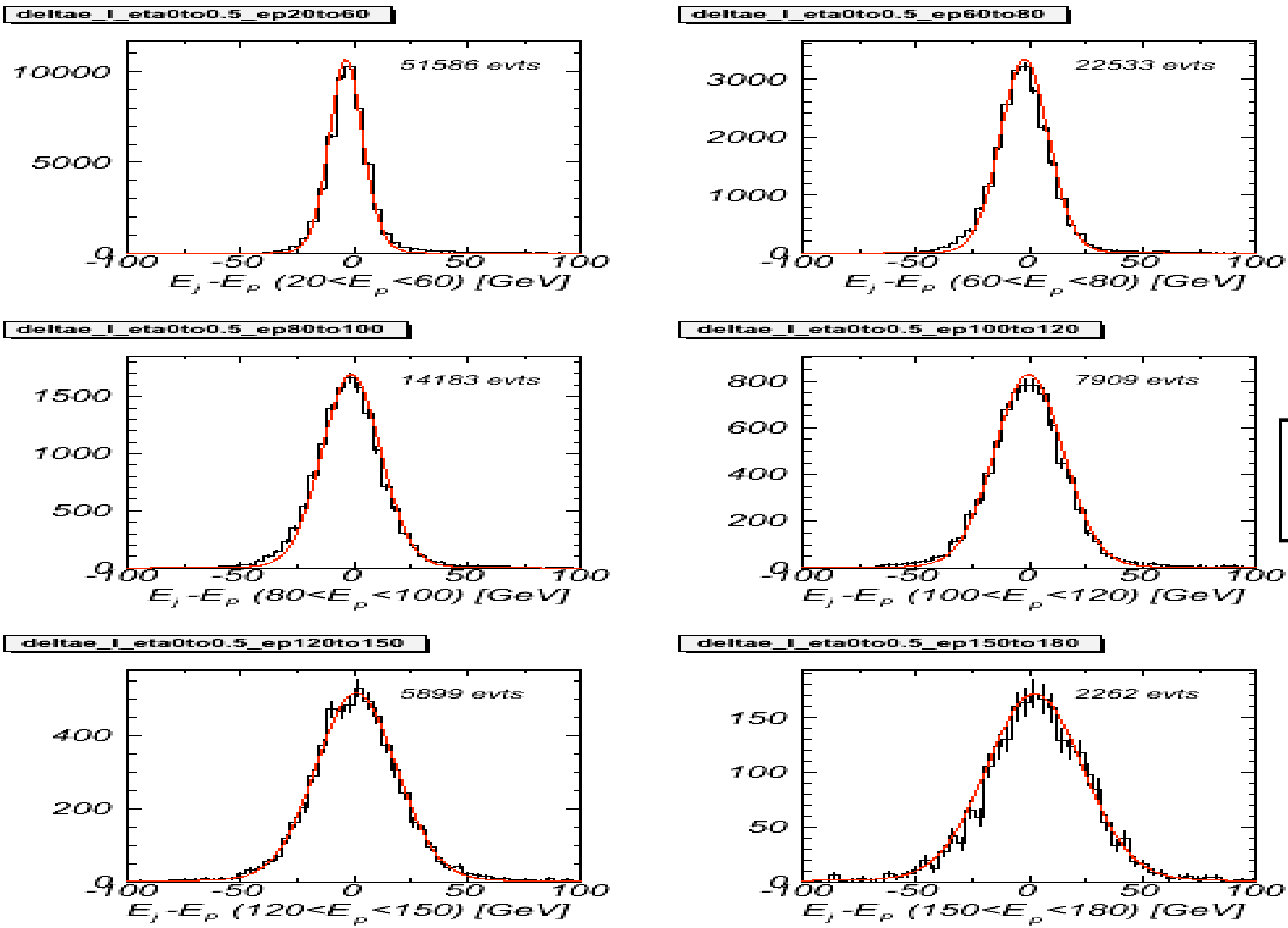


- To cross-check the derived parameters, compare MC jet energies with the prediction from the transfer functions
- The transfer function prediction H(δE) is computed by integration over Ep:

$$H(\delta E) = \int_{E_p^{min}}^{E_p^{max}} dE_p\, n(E_p)\, W(E_p, E_p + \delta E)$$



Transfer Function Cross-Check (2)



Plots for Illustration only

Monte Carlo
TF Prediction

$E_{jet} - E_{parton}$

Jet Energy Scale

- The Jet Energy Scale is by far the dominant systematic uncertainty for a top mass measurement
- The Jet Energy Scale for D0 RunII is derived independently from photon+jets events as a function of p_T and η.
- If this calibration is off by a global scale factor "JES", than this global factor can be introduced in the ME likelihood function as an additional parameter
  - ★ sensitivity comes from hadronic W decay in Lepton+Jets events: variation of the W mass value translates to a variation of the global JES scale factor
  - ★ Define "JES" such that it is 1.0 if the Jet Energy Scale calibration function is spot on
  - ★ It must be considered that the shape of the calibration might be off as well. "Residual JES uncertainty" (Turns out to be small).
  - ★ Minimization of the extended log likelihood

$$-\ln L(x_1,\ldots,x_n;m_t,JES,f_{sgn}) = \Sigma_i \ln P_{evt}(x_i;m_t,JES,f_{sgn})$$

    yields the statistical + JES error of the measurement!

  - ★ The "JES" variables is introduced to the event probability via the Transfer Function:

$$W(E_j,E_p;JES) = W(E_j/JES-E_p) / JES$$

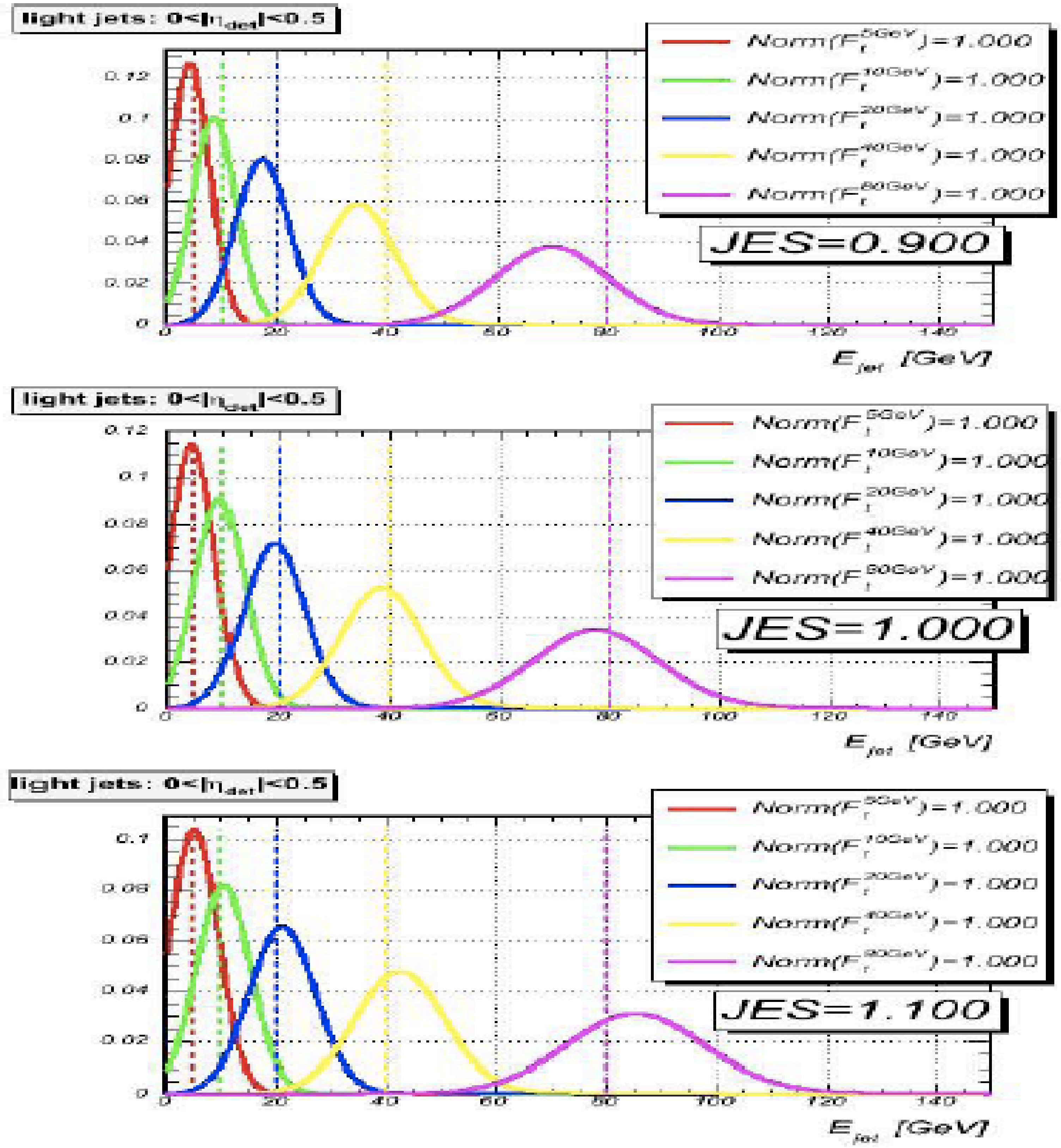
JES in Transfer Function

- Illustration of how the JES global scale parameter is absorbed by the Transfer Function Parameters
- For JES<1.0, the most likely Ejet for a fixed Eparton decreases, the Gaussian “moves to the left”
- For JES>1.0, the most likely Ejet for a fixed Eparton increases, the Gaussian “moves to the right”
- To convince yourself of the overall factor 1/JES, consider

$$\int W(Ej,Ep)\, dEj = 1$$

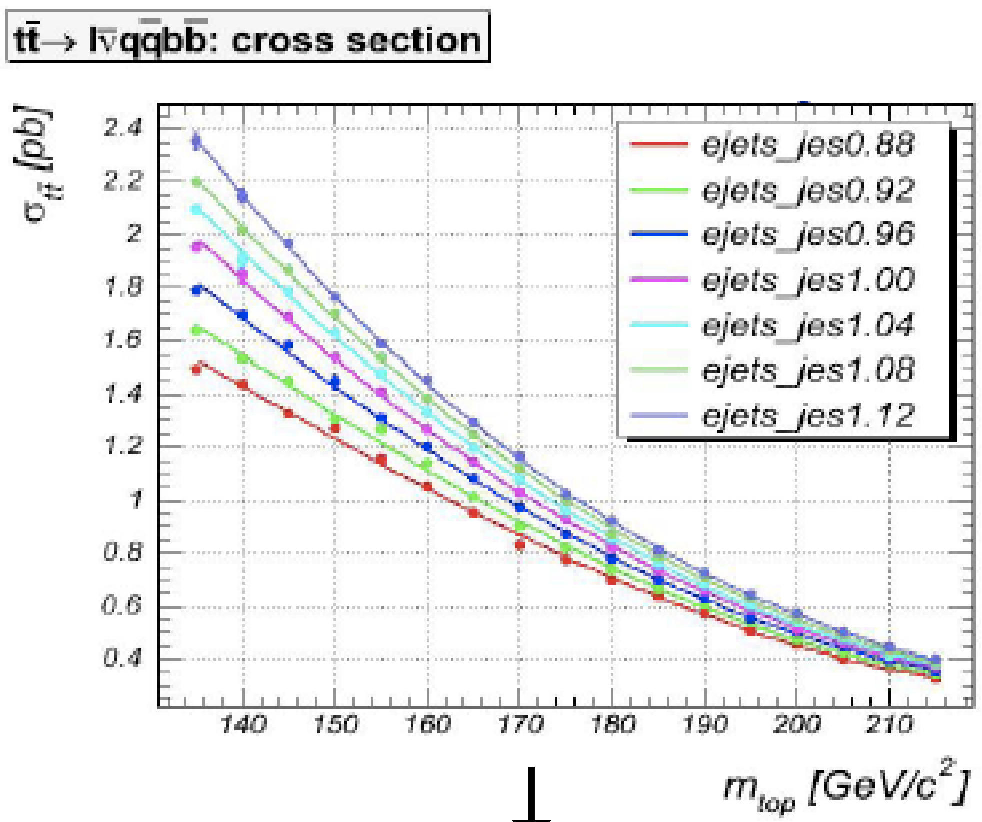
and

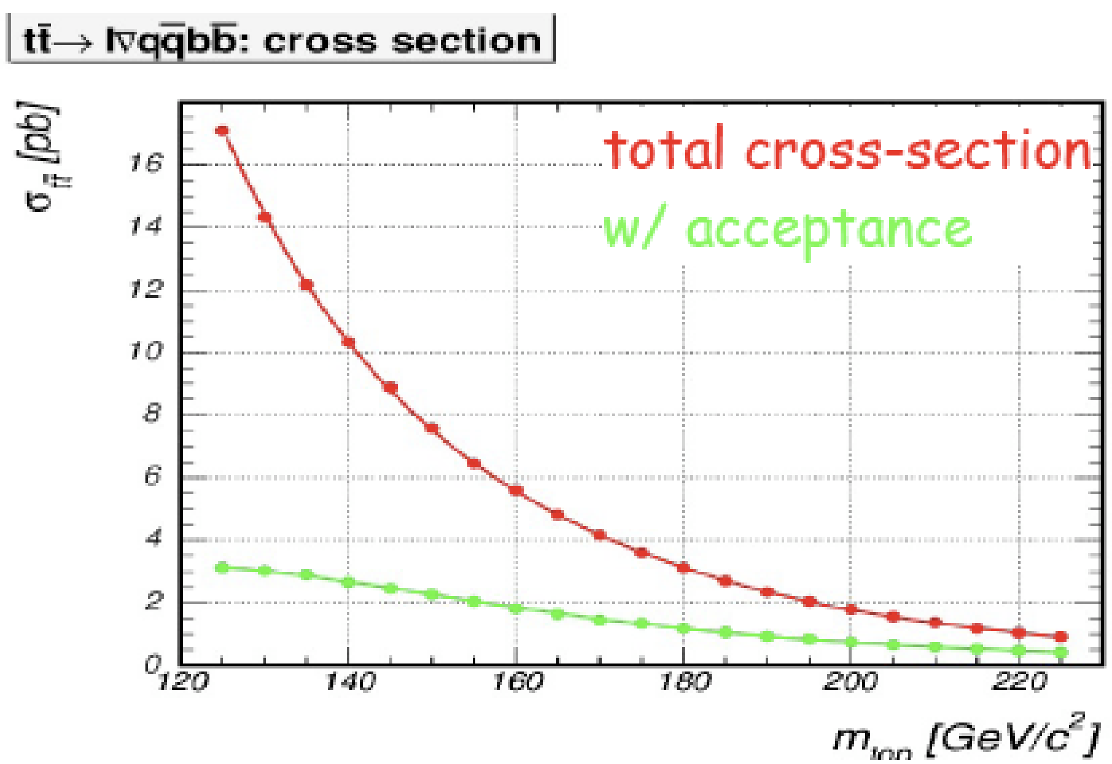
$$\int f(ax)\, dx = 1/a \int f(u)\, du,\ u=ax$$

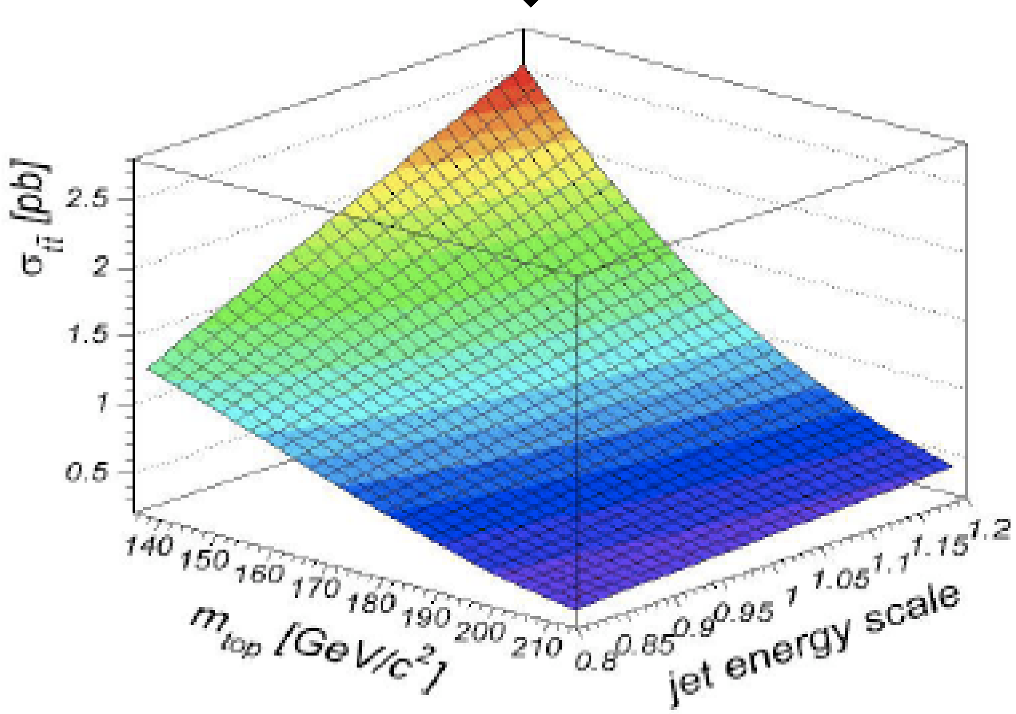


P_{sgn} Normalization

- Normalization = cross-section of the LO Matrix Element, taking the event selection efficiency into account!
- Monte Carlo Integration over Parton Phasespace, plus Jet/Muon Energies: 16 + 4 + 1 = 21 dim. Integral.
- Transfer Function provide Eparton/Ejet mapping during integration: relation between kinematic selection and parton phasespace, take kinematic selection into account!
- The normalization is (via the kinematic selection cuts!) also a function of the global Jet Energy scale Factor "JES", 2D Parametrization





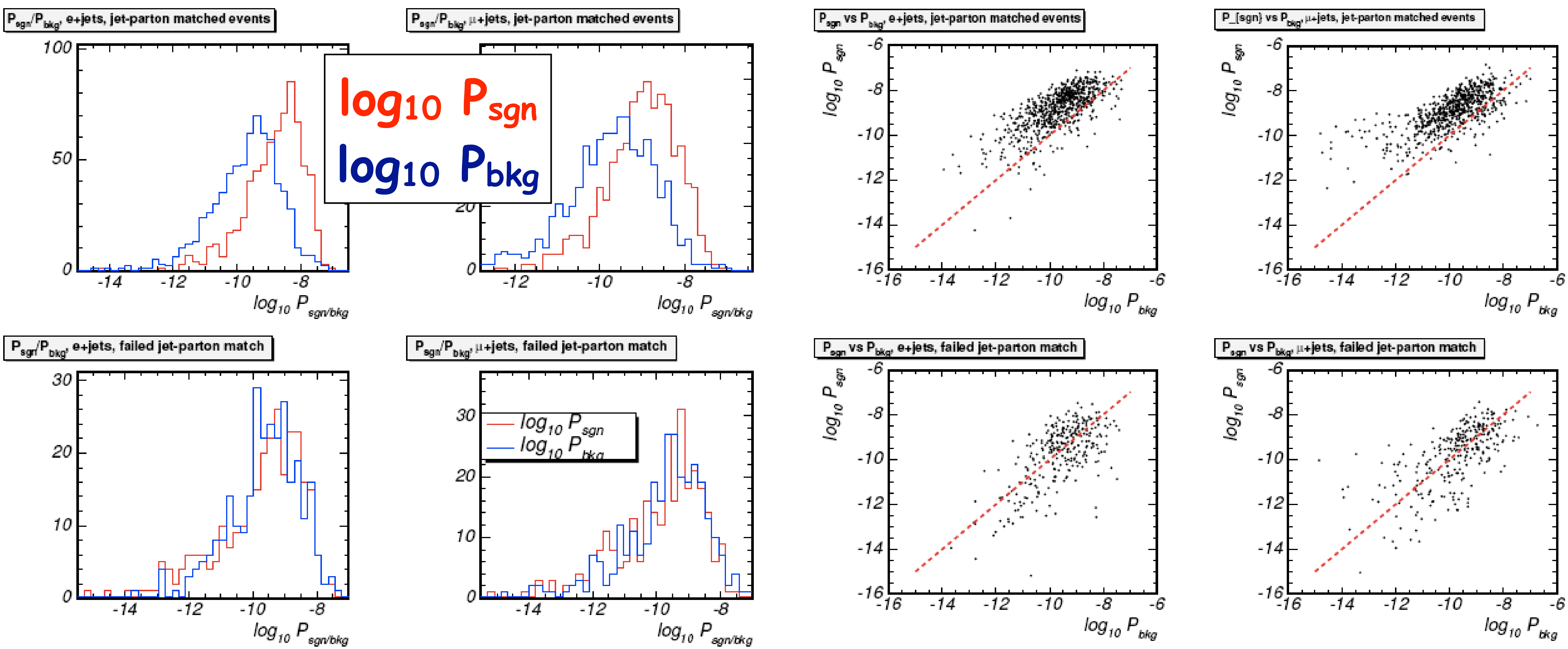


P_{bkg} Normalization

- The correct normalization of the Background (W+jjjj) Probability ensures an unbiased estimate of the sample composition in the fit (f_{sgn}).
- Crucial! Systematic over-estimation leads to top-mass bias, under-estimation to non-optimal use of the statistical information of the top events in the sample!
- This Normalization is not derived by calculating the cross-section integral; instead, an iterative calibration procedure is applied to MC events such that the fit produces the correct f_{sgn} estimate on average for the expected signal fraction in the dataset
- As demonstrated on the next slide, t-tbar events affected by Radiation don't behave "signal-like": the calculated Psgn is smaller than the calculated Pbkg.
- We identify this class of events in Monte Carlo by not being able to match all reconstructed jets to the partons from the LO-ME. (Consequently, "good events" are labeled "jet-parton matched events")
- By only using jet-parton matched events in the Pbkg calibration, the "bad" events are effectively treated as background, significantly improving the bias and pull of the likelihood fit.

Pbkg Normalization (2)

"Bad" t-tbar events bias the mass estimate and increase the pull



These effects can be minimized by appropriate P_{bkg} normalization

b-tagging

- b-tagging can be incorporated in the analysis via the kinematic selection: requiring at least one jet to be b-tagged significantly enhances the signal fraction (CDF)
- Optimal use of the statistical information is achieved if events with 0, 1, or 2 b-tags are treated as individual samples (**w.r.t. f_{sgn}!**) and then combined:

$$L = \prod_{0\,tags} P_{evt}^{0tag}(x; m_{top}, JES) \prod_{1\,tag} P_{evt}^{1tag}(x; m_{top}, JES) \prod_{2\,tag} P_{evt}^{2tag}(x; m_{top}, JES)$$

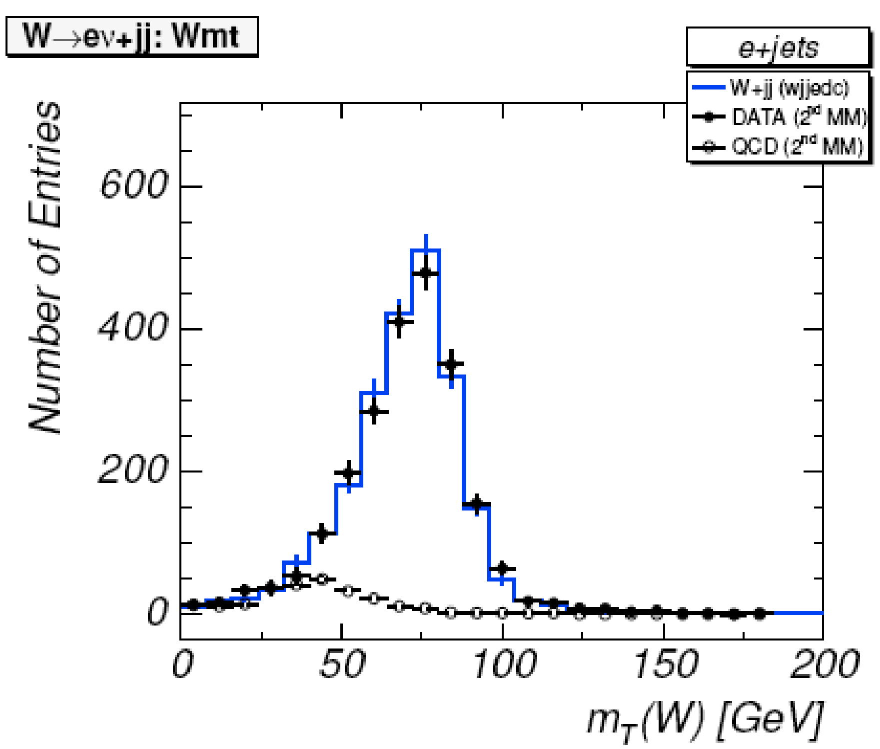
- Moreover, all possible jet parton assignments can be weighted according to the b-tagging information for further statistical gain
  - ★ A permutation with a b-tag corresponding to a b quark gets a high weight
  - ★ A permutation with a b-tag corresponding to a light quark gets a low weight (>0, charm!)
- For the 370 pb-1 Lepton-Jets sample, this technique amounts to ...
  - ★ ... a 20% improvement in statistical sensitivity w.r.t. the topological analysis
  - ★ ... a 30% improvement in statistcal sensitivity w.r.t. a ">=1 b-tag" selection requirement

The Data Sample

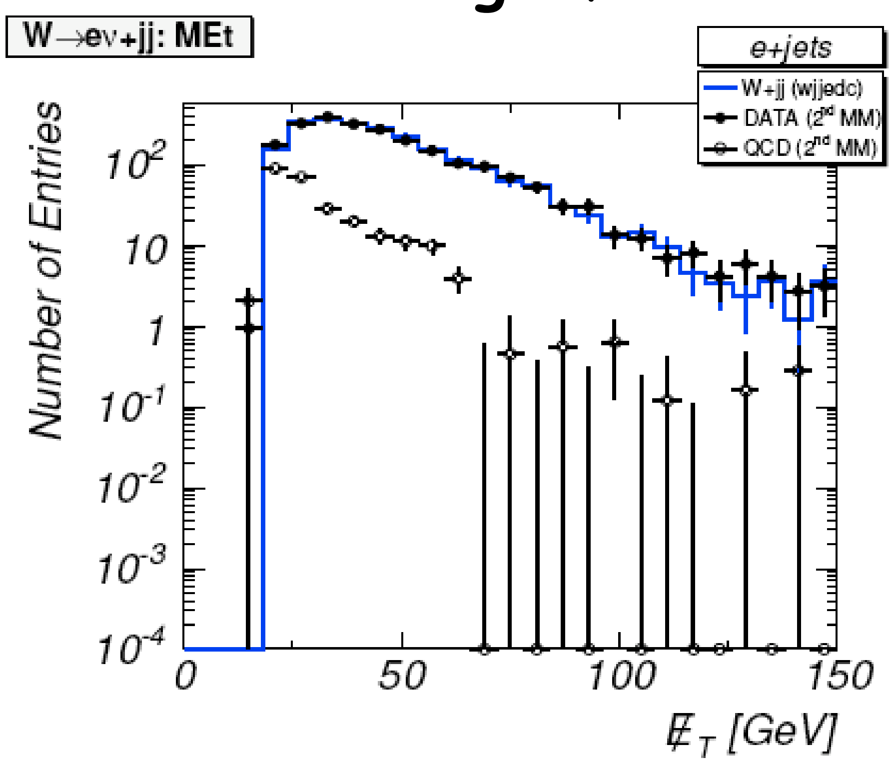
- Since the method is calibrated with Monte Carlo events, it is of course crucial to ensure that the recorded data sample is indeed accurately described by our simulation
- Therefore, we select W+**n**-jets events and compare them to the Monte Carlo for jet multiplicities n=1,2,3, and >=4 (the signal bin). The instrumental background is substracted with a special technique from the data before comparison to MC.
- Good agreement for all jet multiplicities for all relevant kinematic quantities leaves us with the necessary confidence that W+jets production is well described by our simulation, and that we can quantify the contribution from instrumental background

Examples from W(→eν)+jj

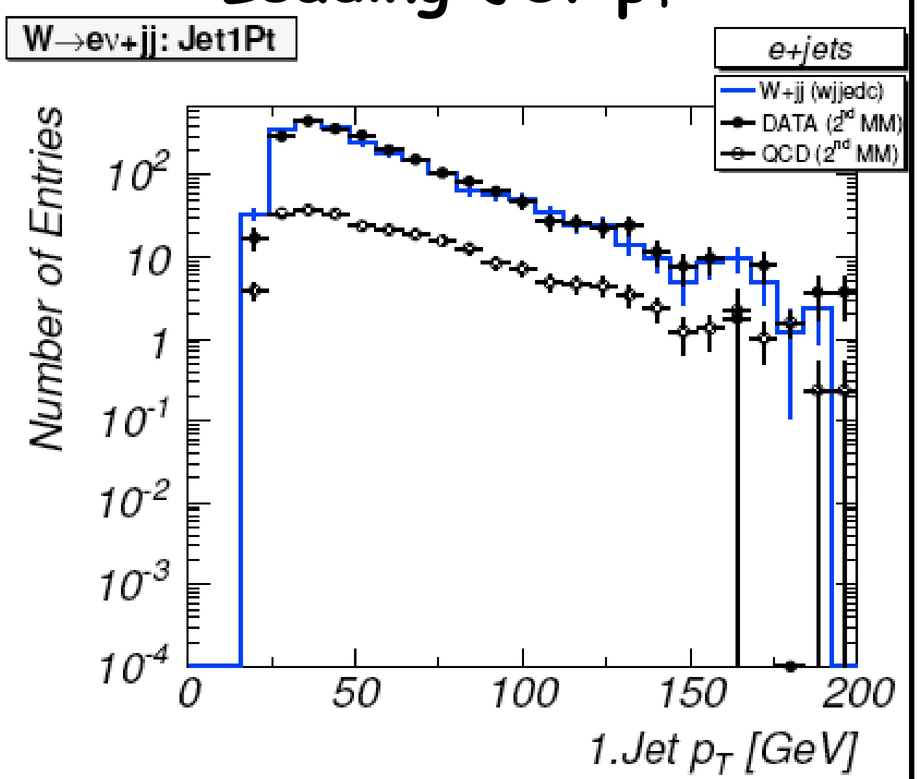
Transverse W mass



Missing E_T



Leading Jet p_T

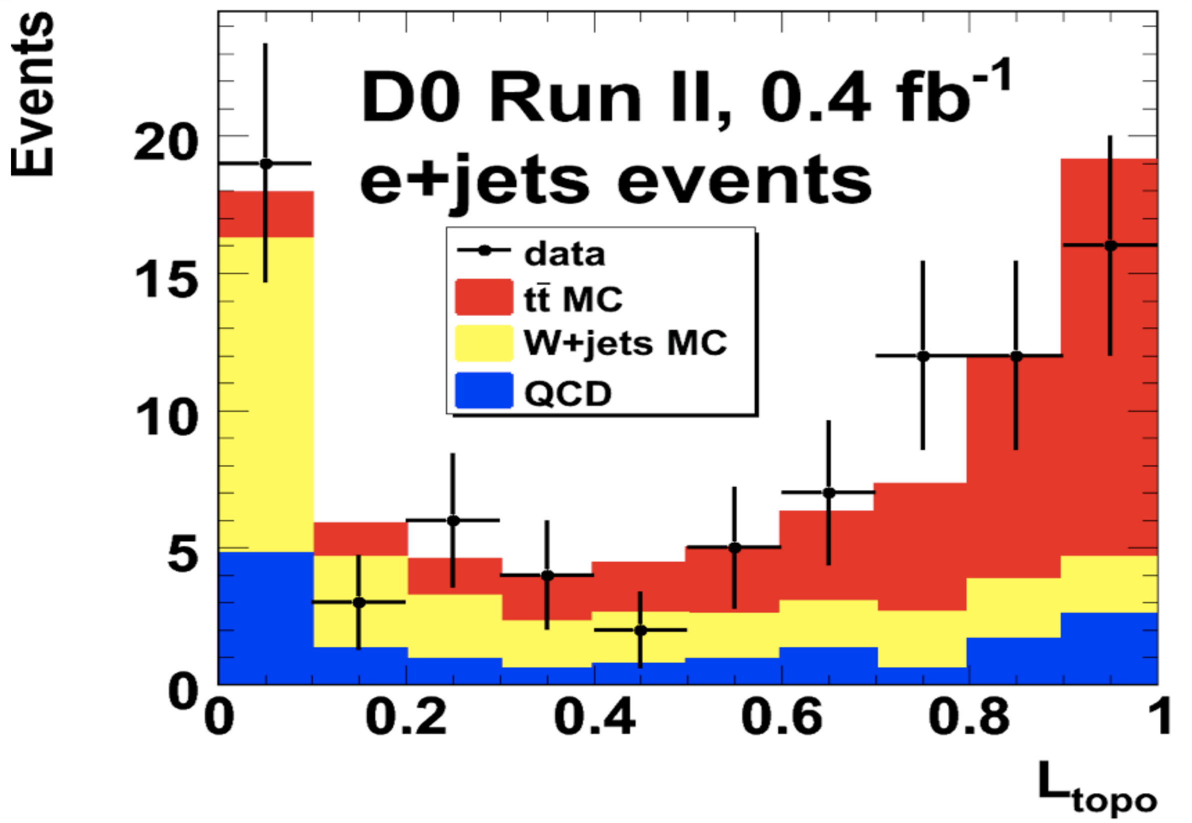


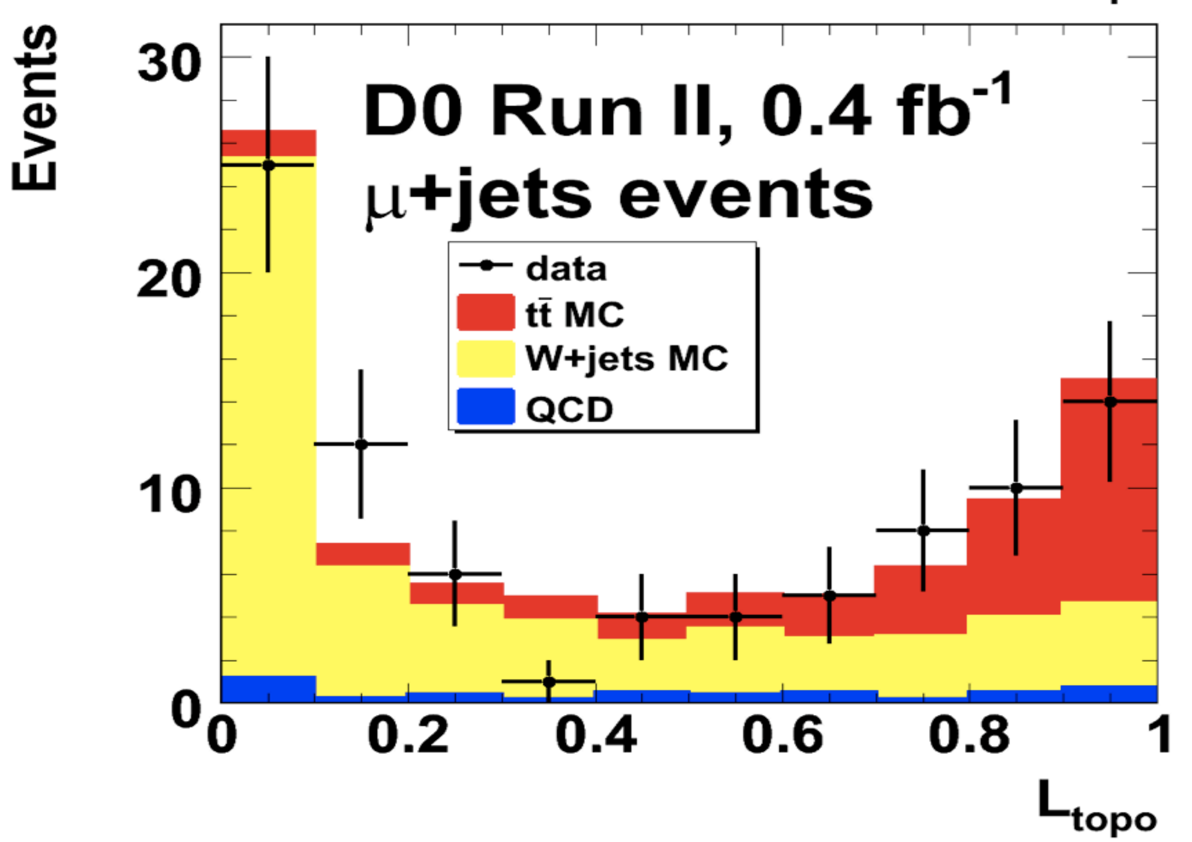
Data Sample Composition

- Before the P_{bkg}-Normalization is performed and MC ensembles for the calibration of the method are drawn, the sample composition of the 370 pb^{-1} is estimated
- Use a template-fit method based on a topological likelihood, developed for the D0 t-tbar cross-section measurement in the Lepton+Jets dataset

channel	N_{evts}	f_{top}^{topo}	N_{top}^{topo}	f_{QCD}^{topo}
e+jets	86	$47.2\,^{+10.9}_{-10.6}\,\%$	$40.6\,^{+9.4}_{-9.1}$	$17.6\,^{+2.4}_{-2.2}\,\%$
μ+jets	89	$29.0\,^{+9.7}_{-9.1}\,\%$	$25.8\,^{+8.6}_{-8.1}$	$5.1\,^{+0.9}_{-0.8}\,\%$
ℓ+jets	175	$37.9\,^{+7.3}_{-7.0}\,\%$	$66.4\,^{+12.7}_{-12.2}$	$11.3 \pm 1.2\,\%$

- Note that these estimates don't enter the measurement directly as a constraint, but are merely used to calibrate the method with realistically drawn ensembles!

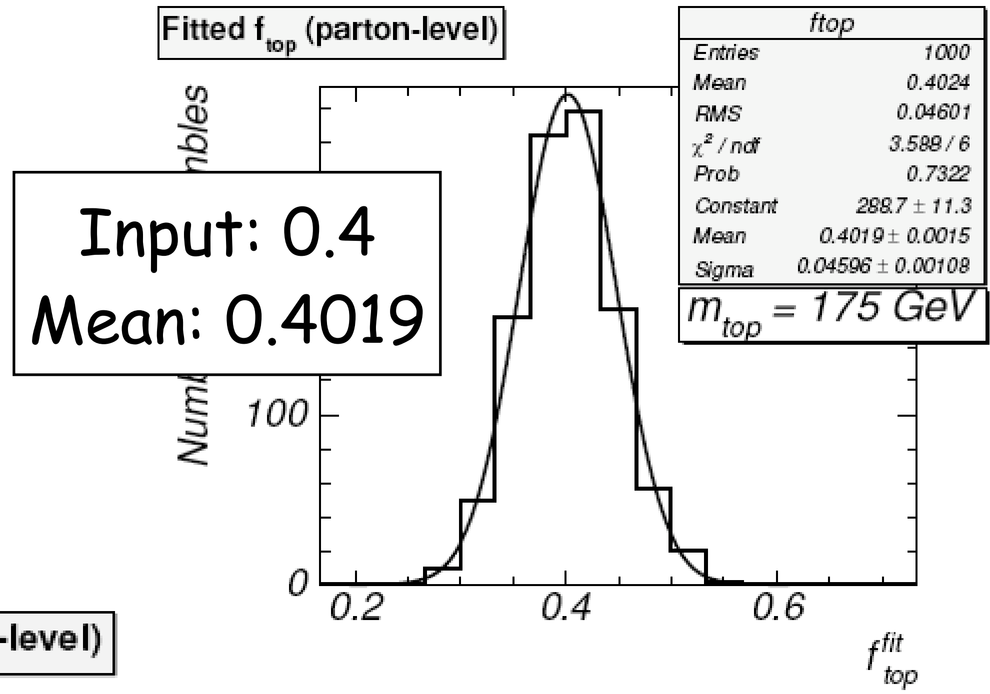


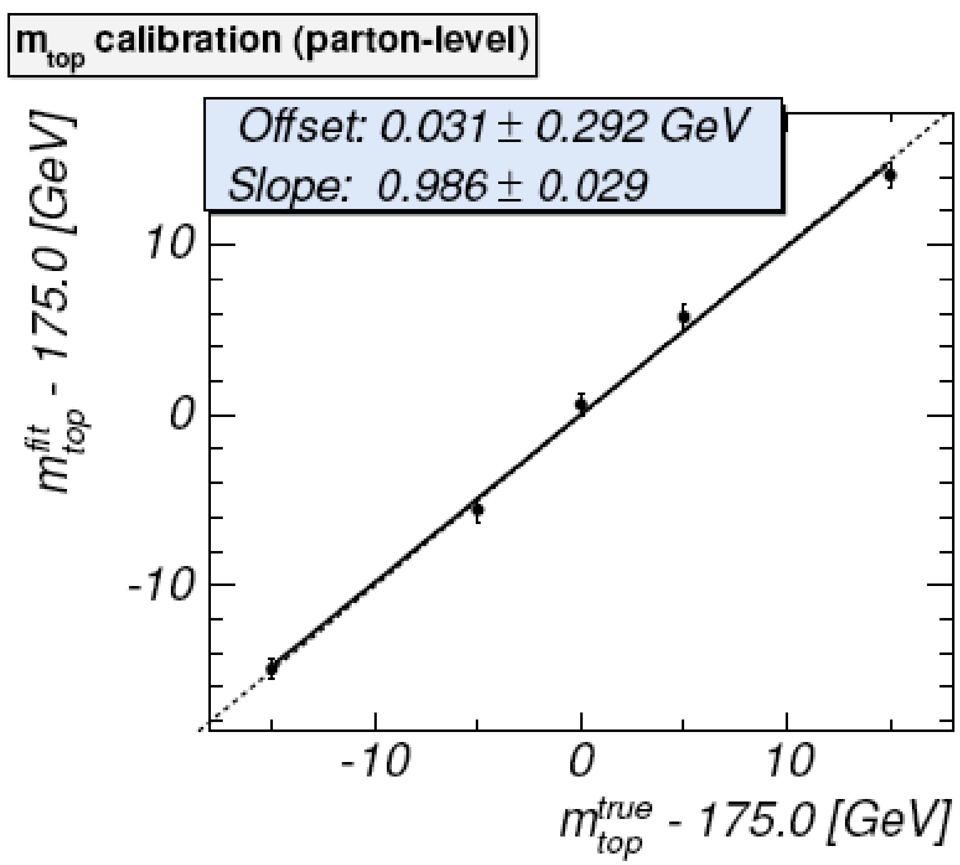


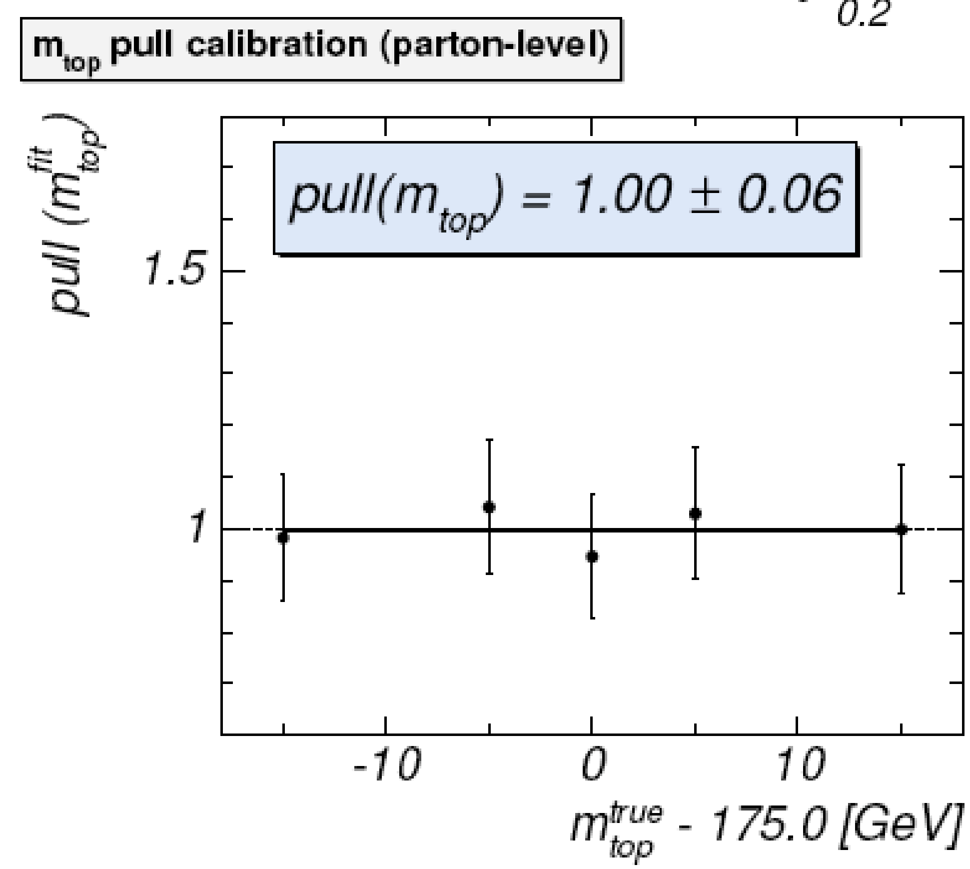
MC Calibration: Parton-Level

- First, the method is tested in Ensembe-Tests using Parton-Level events: generated with LO ME (MadGraph), energies smeared accordina to transfer-function parameters

- The idealized assumptions are therefore all valid:
  - ★ Leading-Order production, no radiation
  - ★ jet and lepton angles well measured
  - ★ Resolution parametrization exact

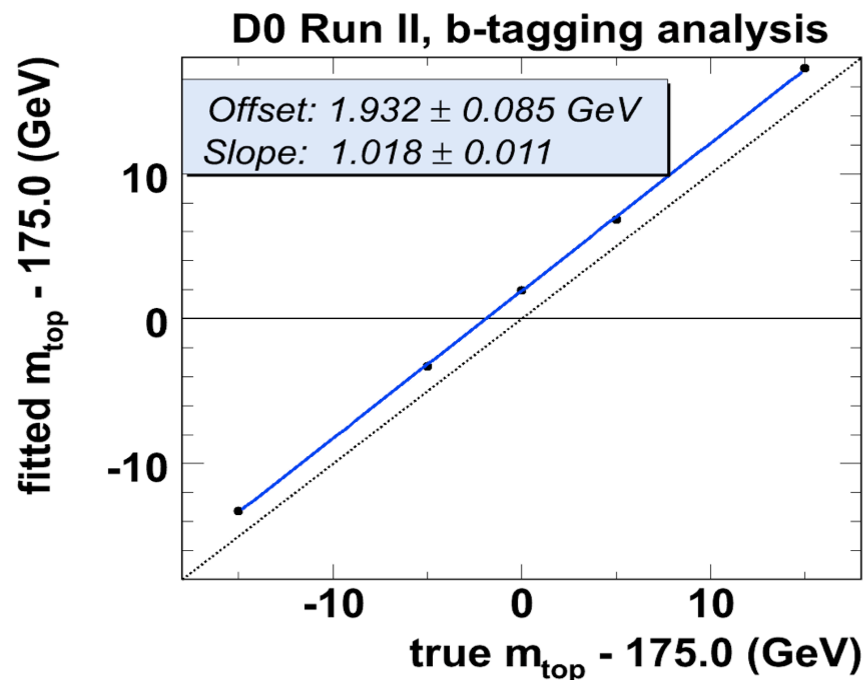


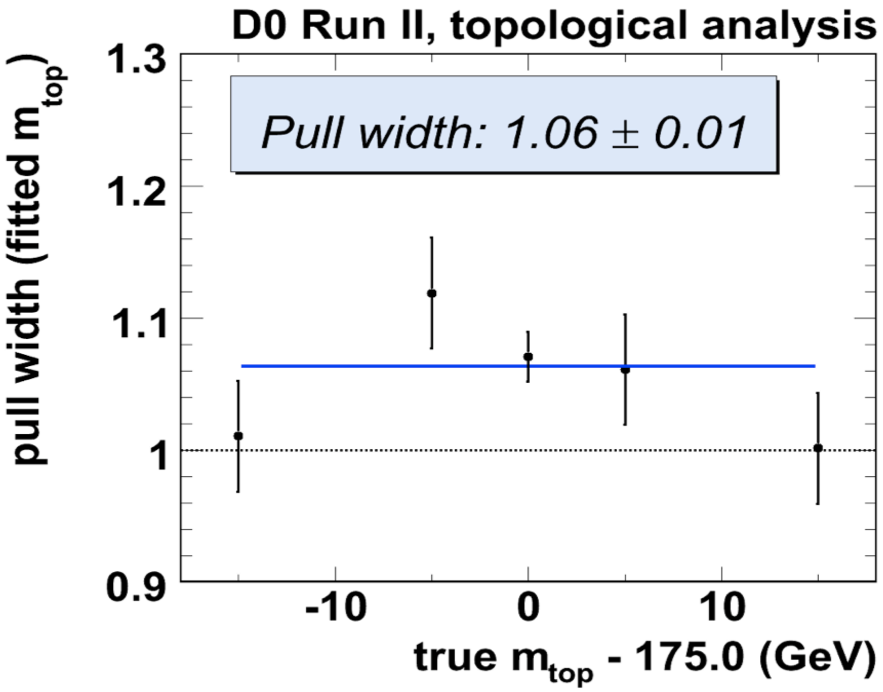


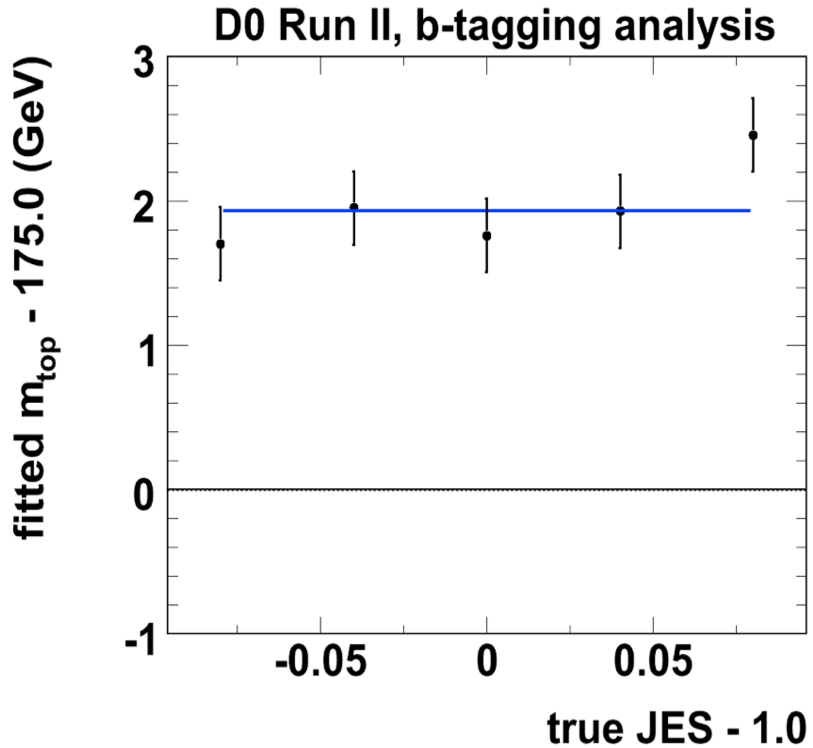


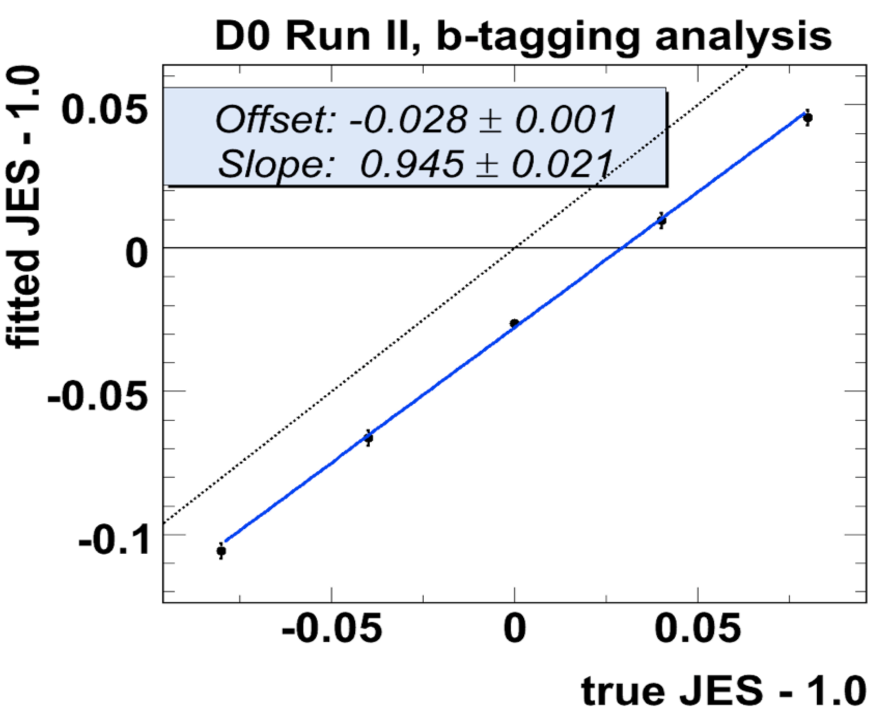
MC Calibration

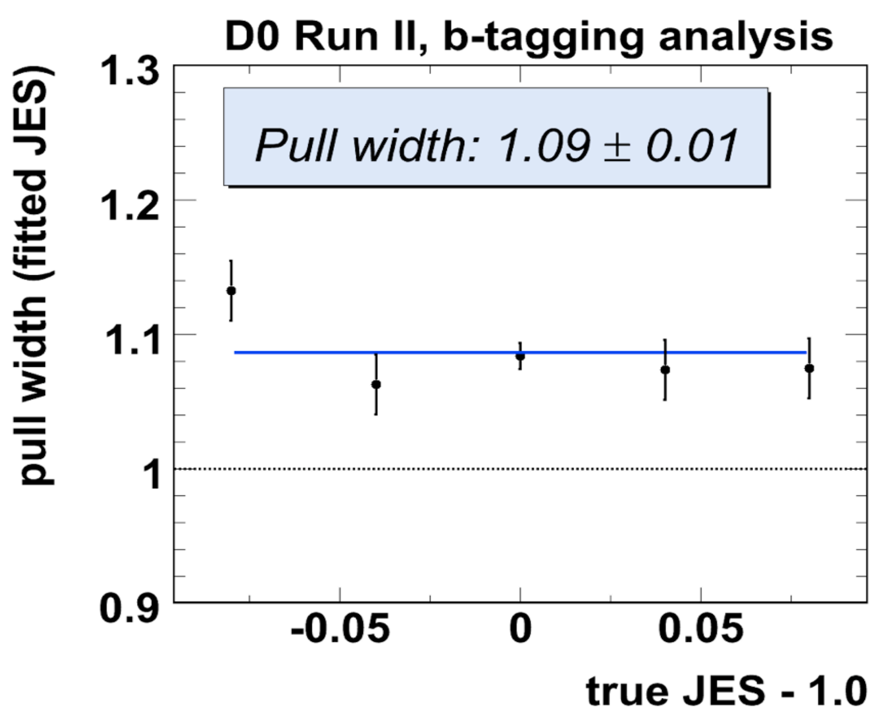
- The calibration for the data measurement is derived from Monte Carlo events processed with the full D0 simulation chain
- The data result is corrected for the observed bias and the pull deviation from 1.0

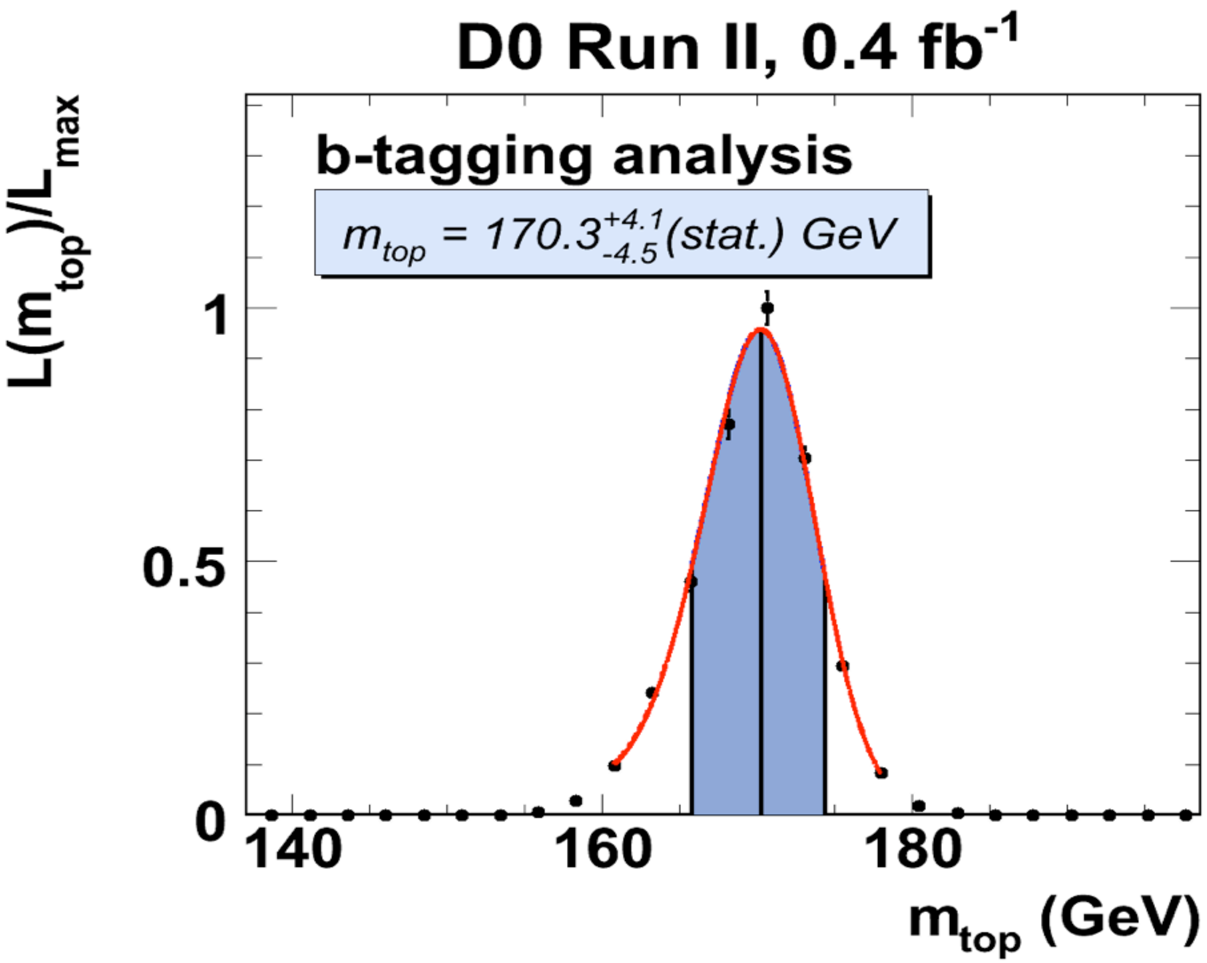


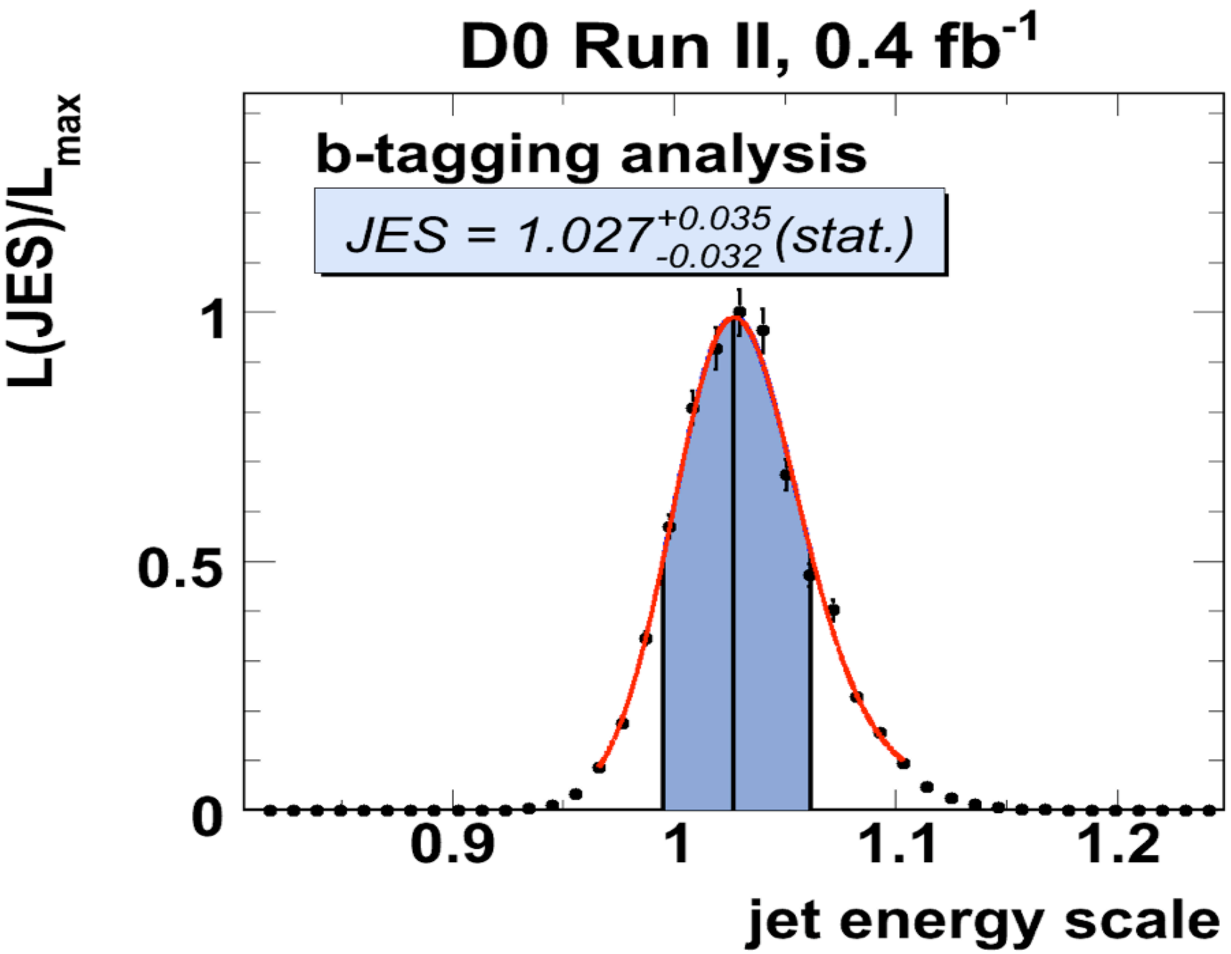


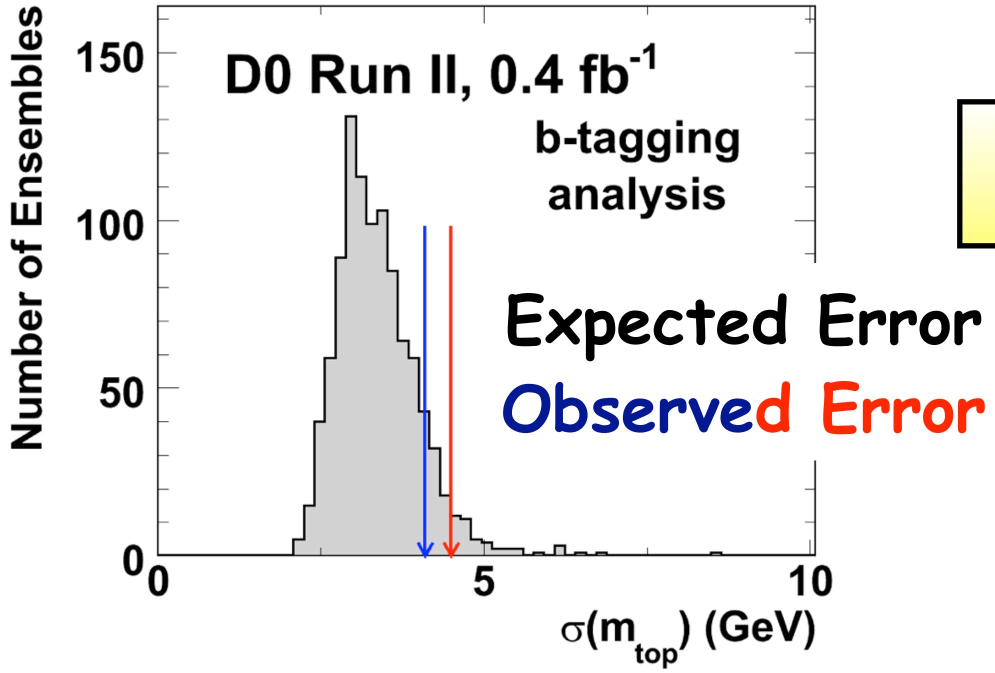












$m_t = 170.6^{+4.0}_{-4.7}$ (stat.+JES) ± 1.4 (syst.) GeV

Most precise D0 Top Mass Measurement

Systematics: D0 Lepton+Jets

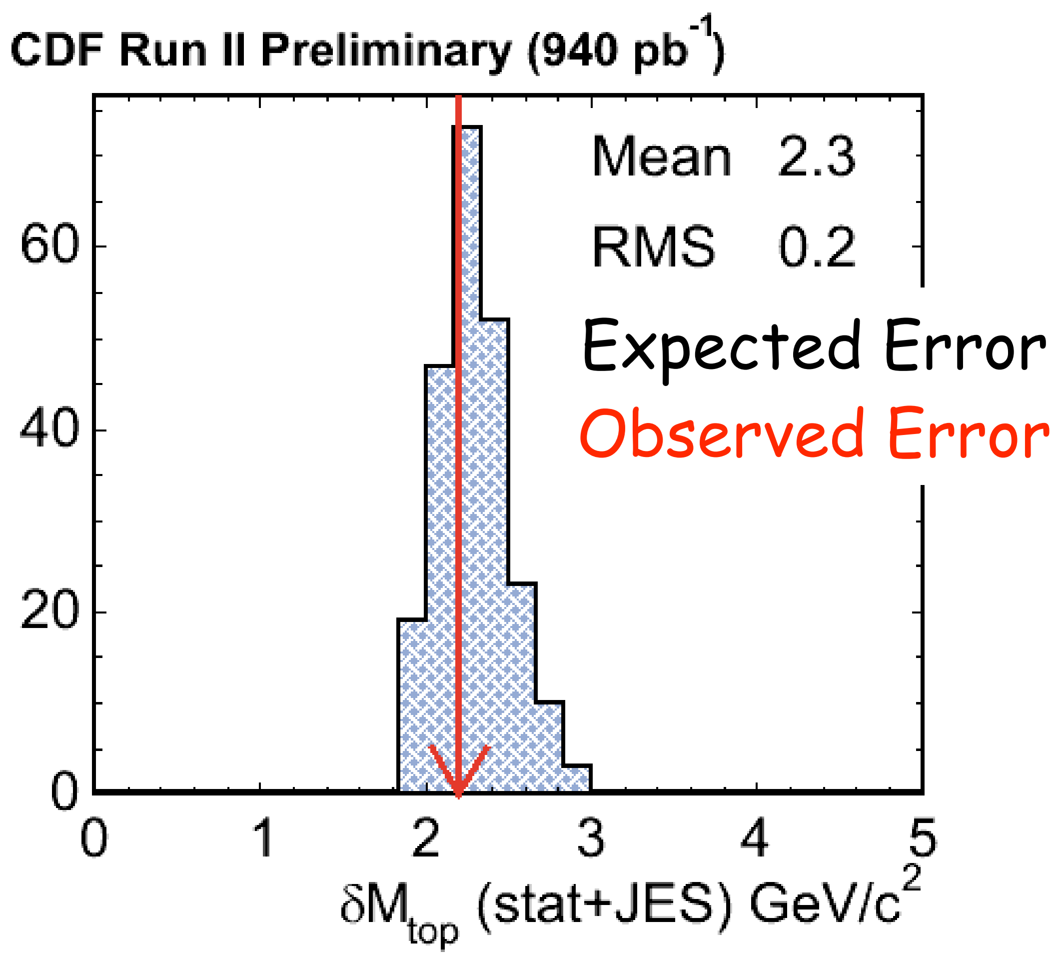
The Jet Energy Scale uncertainty is included in the error derived from the 2D log-likelihood minimization, its contribution is ~3.0 GeV

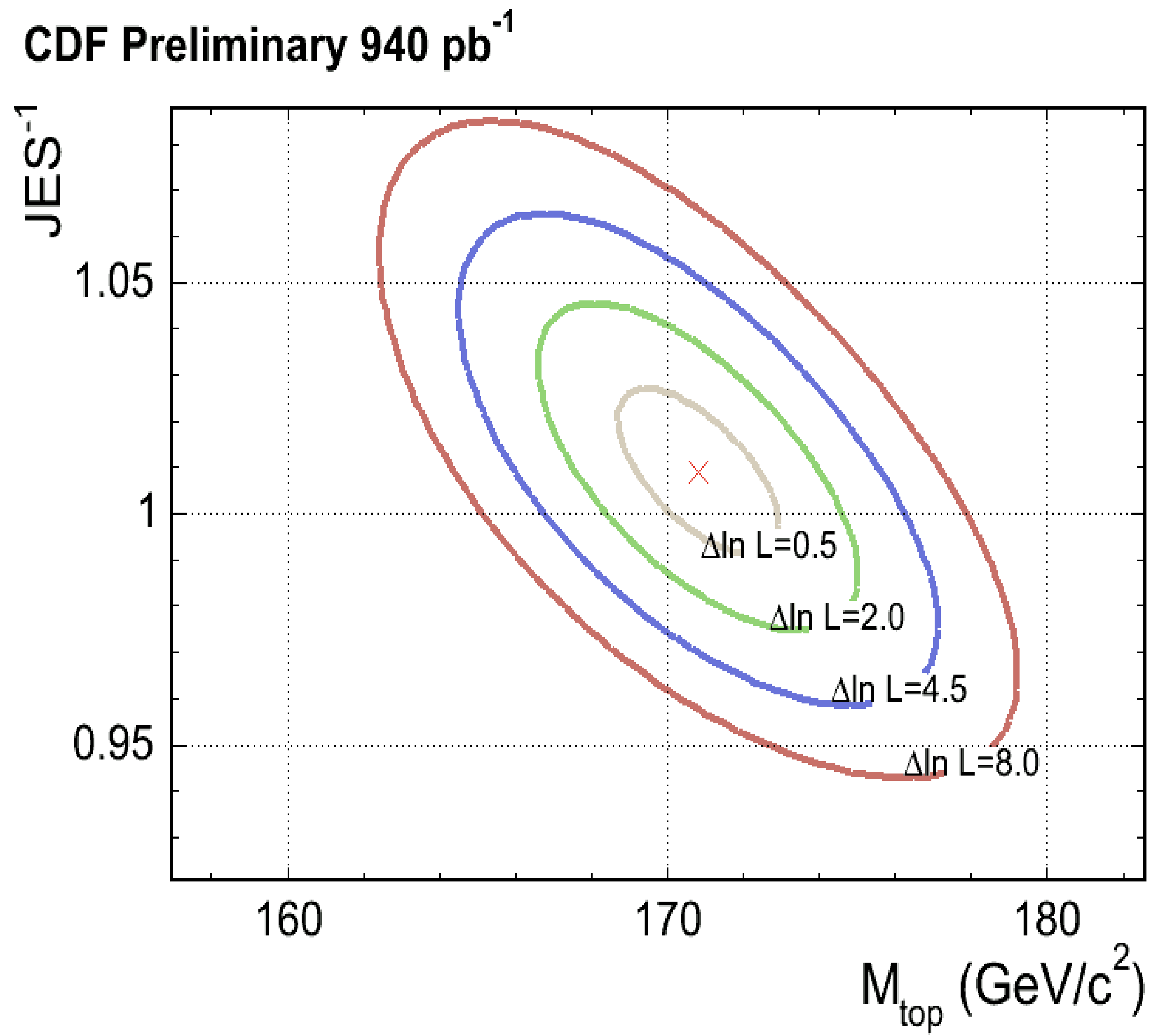
	Systematic	GeV
physics modeling	signal modeling	± 0.46
	background modeling	± 0.32
	PDF Uncertainty	± 0.07
	b fragmentation	± 0.71
	b/c semilpetonic decays	± 0.07
detector modeling	Residual Jet Energy Scale	± 0.25
	b response	± 0.80
	trigger	± 0.08
	b-tagging	± 0.24
method	signal fraction	± 0.15
	QCD contamination	± 0.29
	MC Calibration	± 0.48
	TOTAL	**± 1.4**

Results: CDF Lepton+Jets

940 pb^{-1}

m_t = 170.9 ±2.2 (stat.+JES) ± 1.4 (syst.) GeV

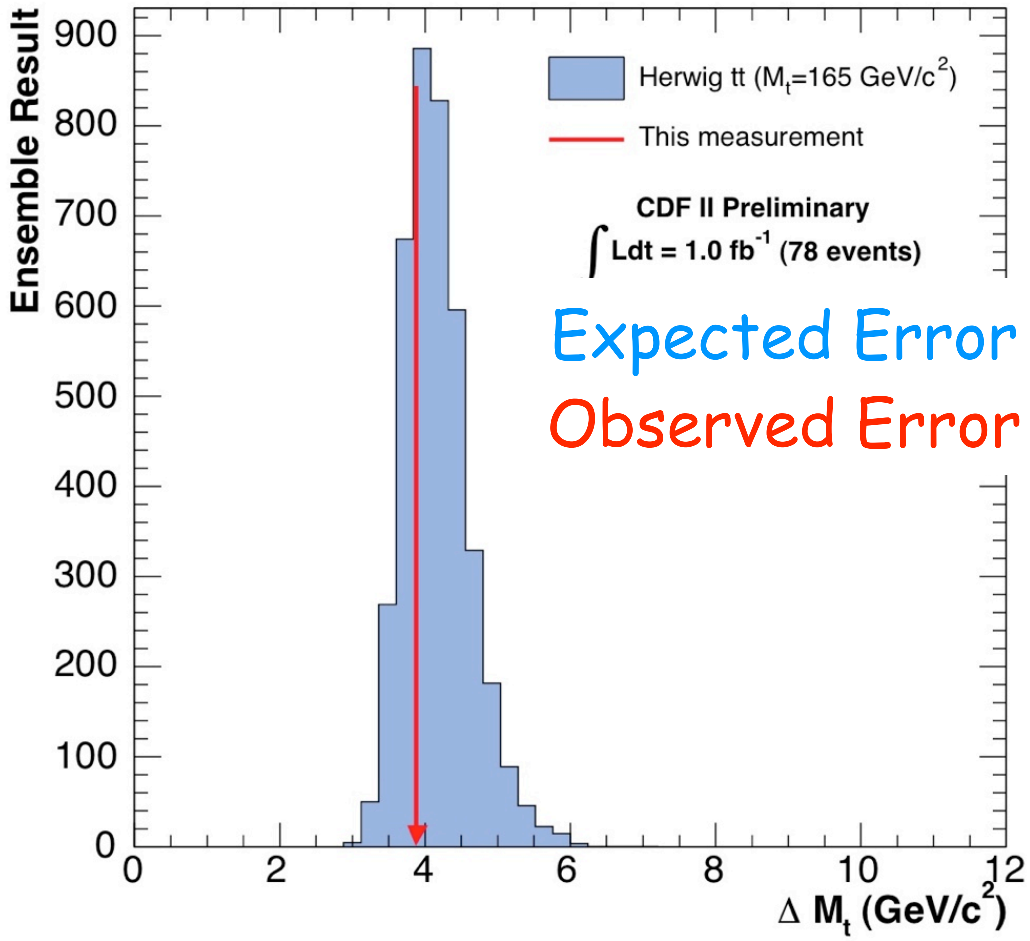


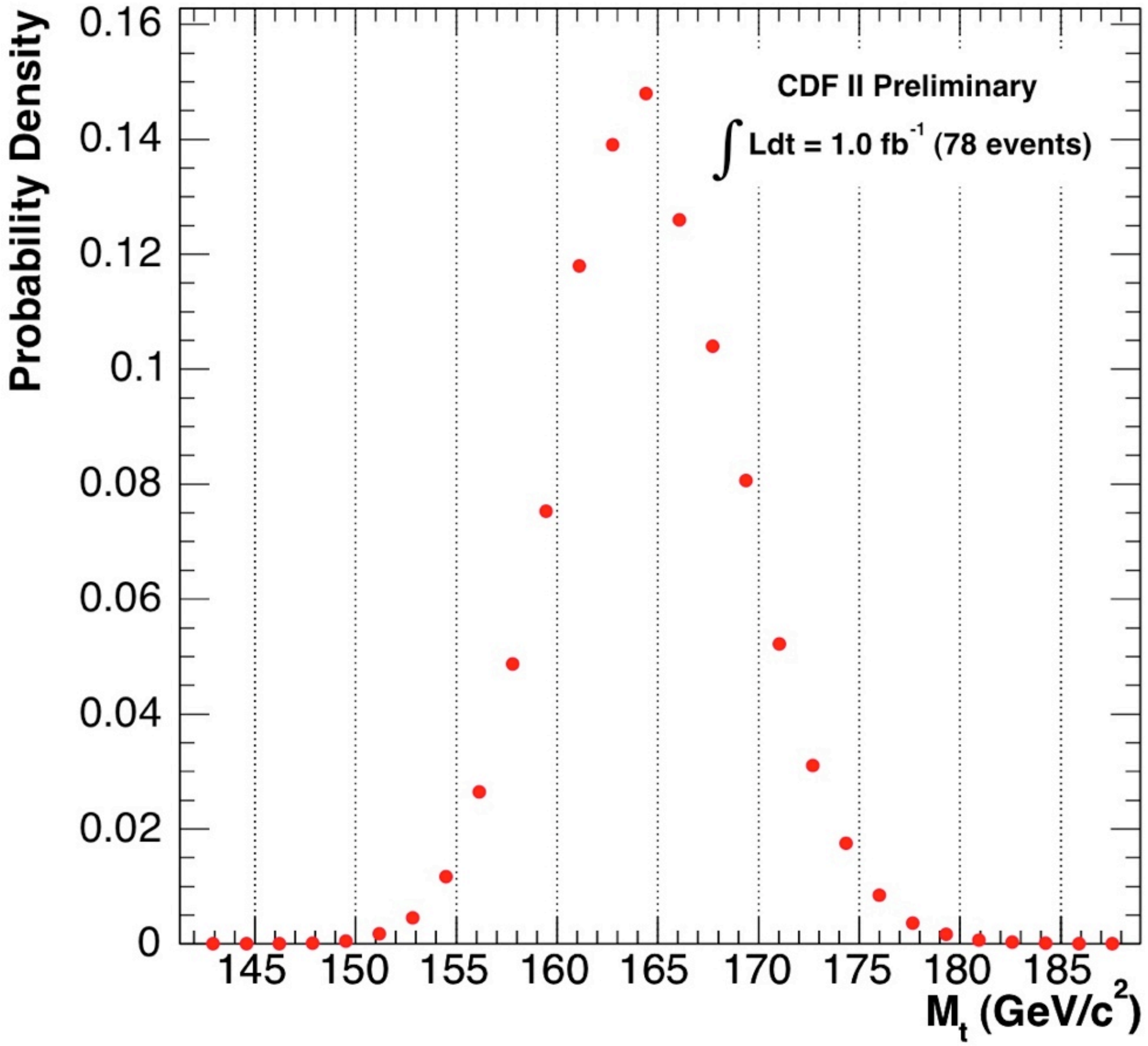


World's single most precise measurement of the top mass!

Results: CDF Dilepton

m_t = 164.5 ±3.9 (stat.) ± 3.9 (syst.) GeV

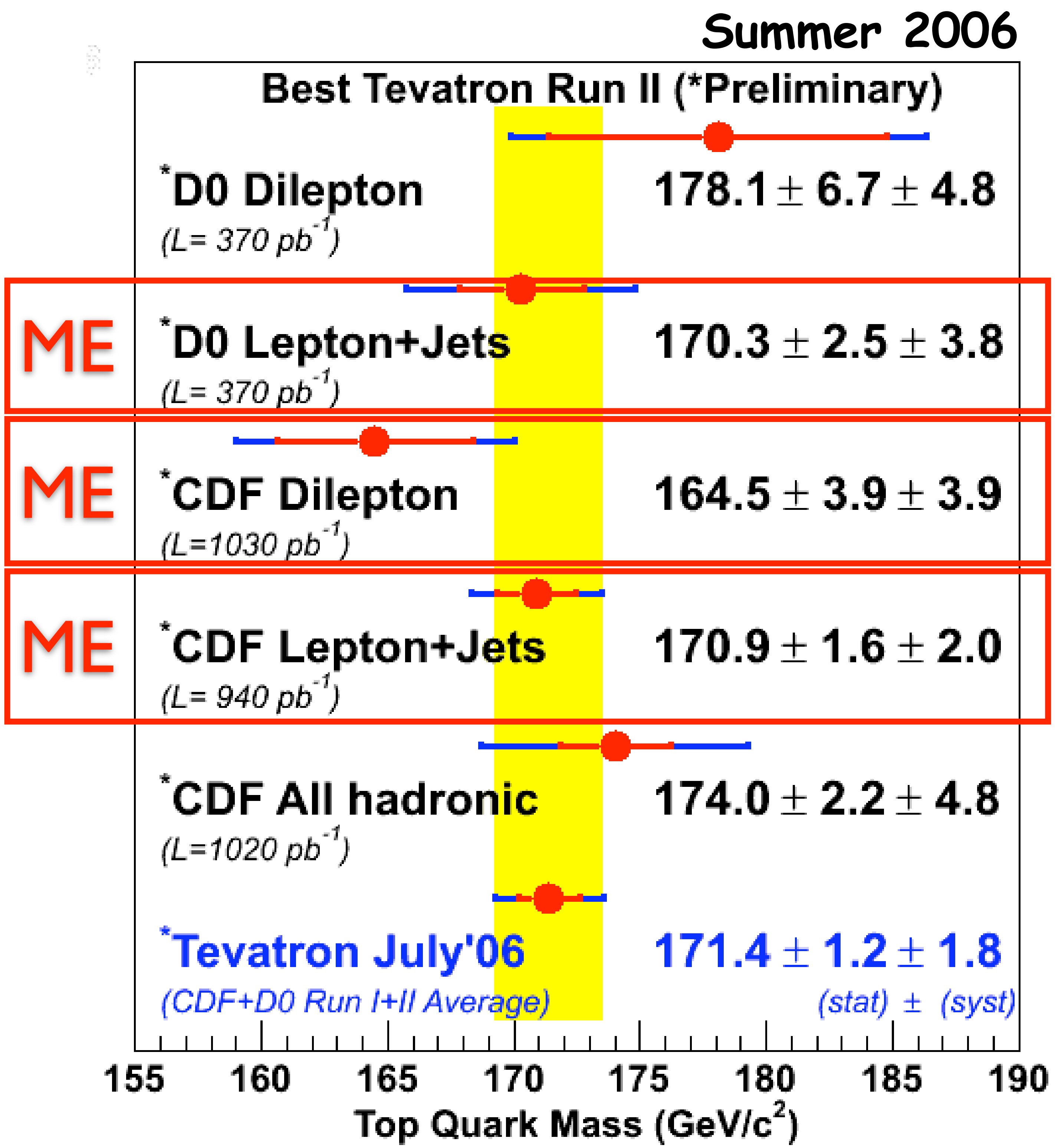




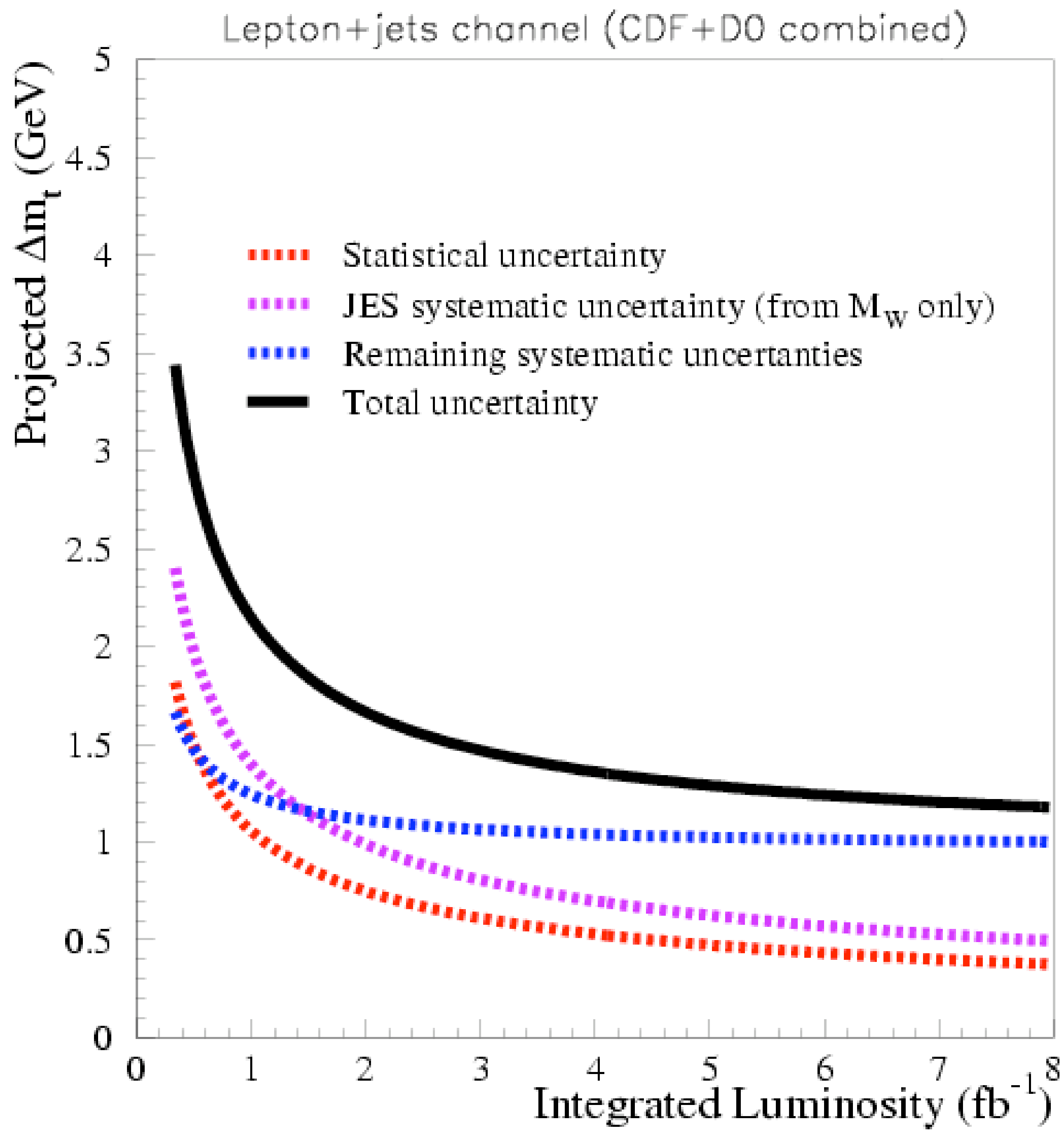
World's single most precise measurement of m_t in dilepton channel!

Top Mass: World Average

- RunII ME Analyses play a key role in the striking precision of the current world average!
- Already limited by systematic uncertainty
- Precision Measurement: δMt~1.3%
- For the 4-8 fb-1 future, a total uncertainty of ~1.5 GeV is projected
- The JES uncertainty is going to improve with rising statistics as well, thanks to The In-Situ calibration technique



Projected Future Top Mass Error



Conclusions

- The Matrix Element Method has been developed at D0 during Run I and yielded the most precise measurement of the top mass in Run I
- It is again successfully applied in Run II by both CDF and D0:

$m_t = 170.6^{+4.0}_{-4.7}$ (stat.+JES) ± 1.4 (syst.) GeV	D0, Lepton+jets, 370 pb-1
$m_t = 170.9 \pm 2.2$ (stat.+JES) ± 1.4 (syst.) GeV	CDF, Lepton+jets, 940 pb-1
$m_t = 164.5 \pm 3.9$ (stat.) ± 3.9 (syst.) GeV	CDF, Dilepton, 1030 pb-1

- Thanks in part to these and future applications of the method, combined with other methods developed by the Tevatron collaborations, the Tevatron total error on the top mass is projected to be as low as ~1.5 GeV
- It will not amount a small challenge for the LHC experiments to further improve the top mass precision