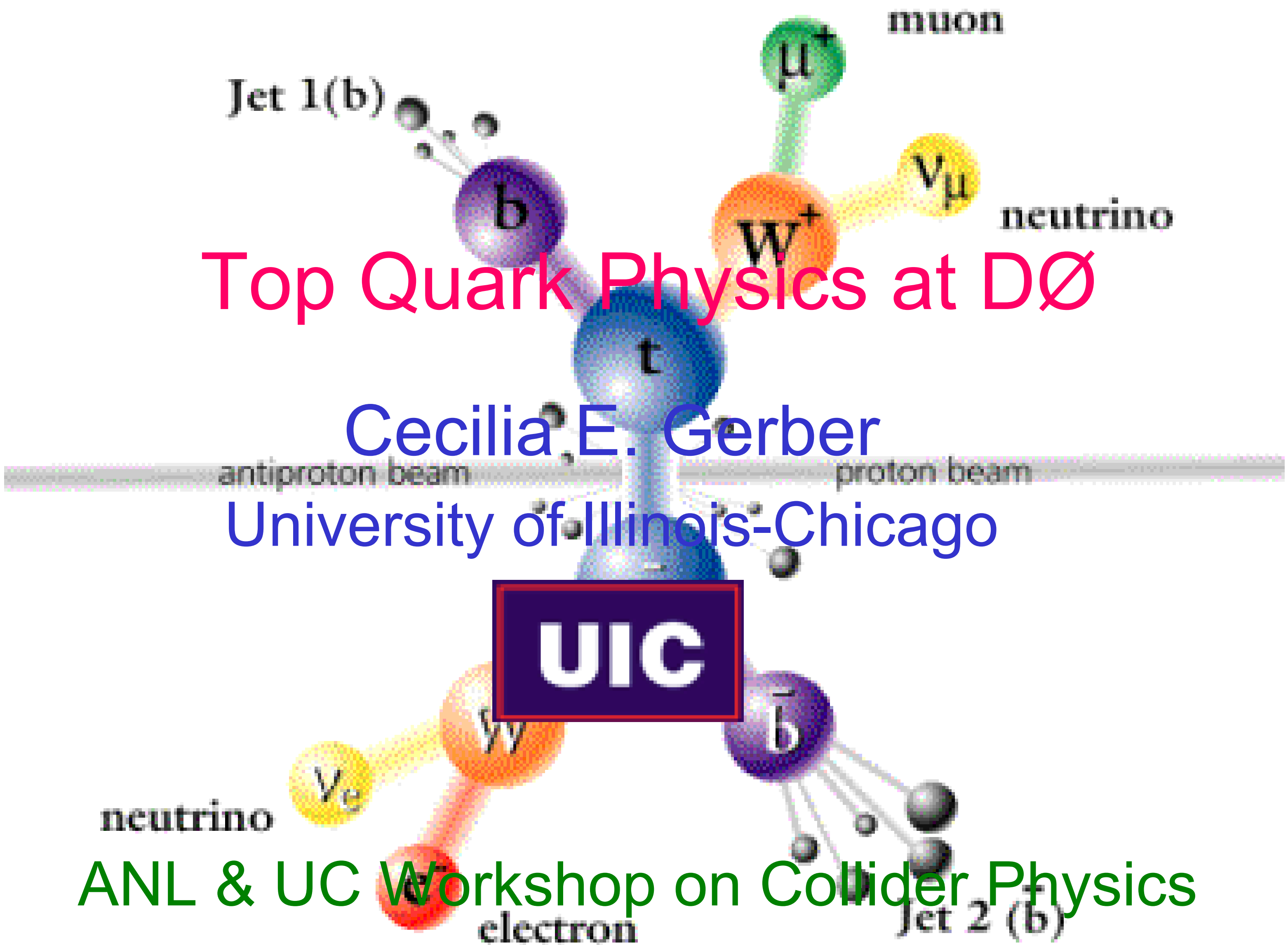
# Top Quark Physics at DØ


Cecilia E. Gerber

University of Illinois-Chicago


ANL & UC Workshop on Collider Physics

May 10, 2006

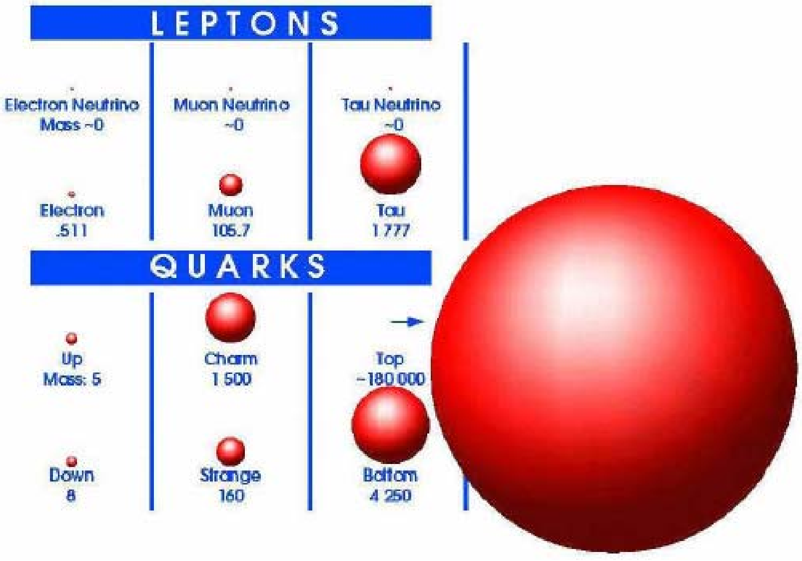


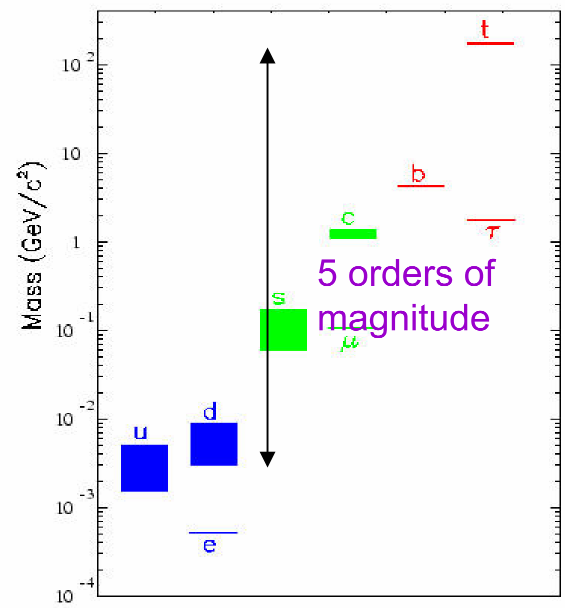
# Outline

- Introduction
- New results (since March 06)
  - Cross sections
  - Mass
- Food for thought
  - on systematic errors beyond JES
- Conclusions and Outlook

# Why study the Top Quark?

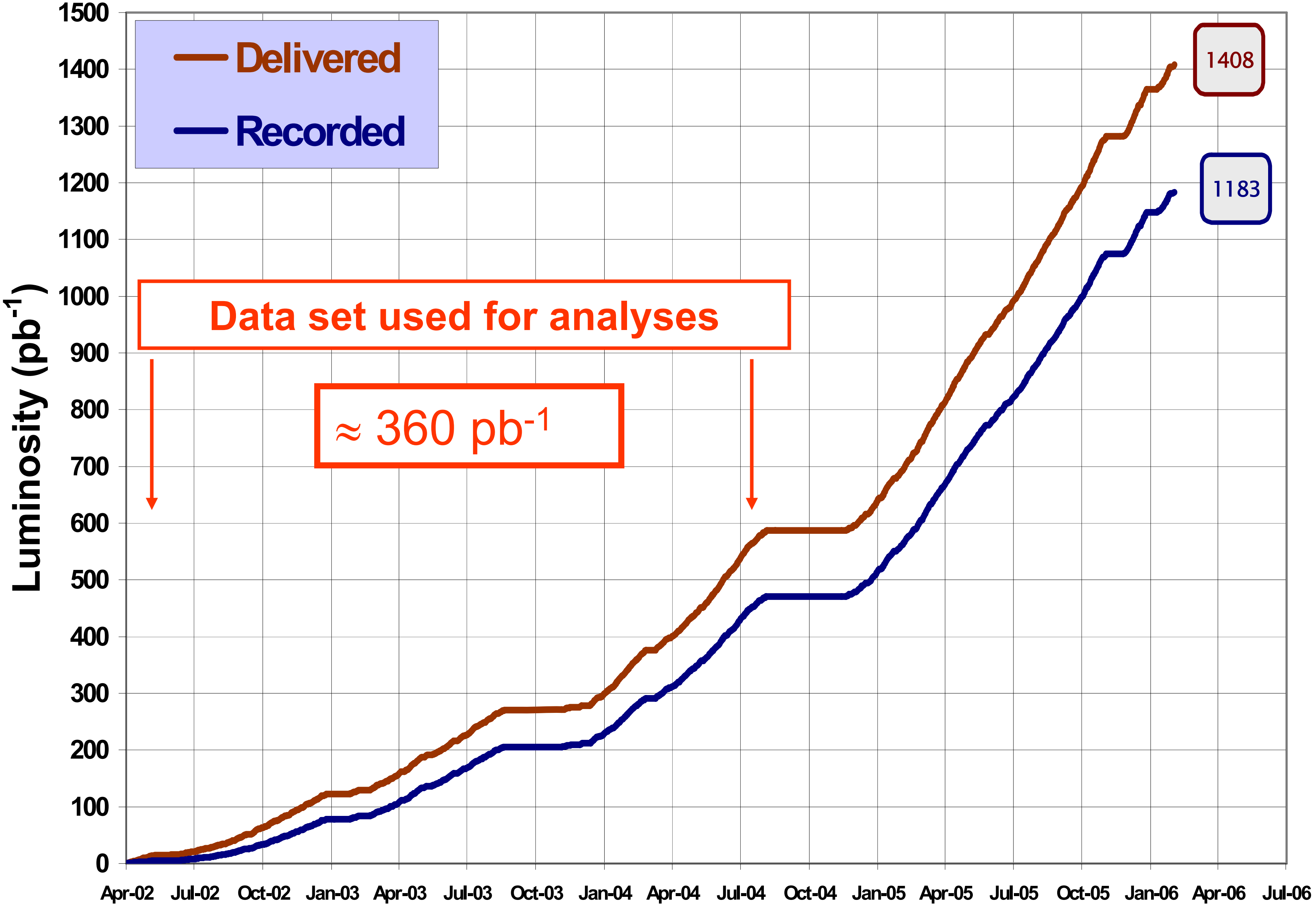
- Predicted by the SM and Discovered in 1995 by CDF and DØ
- $m_t$ ~ 175 GeV vs $m_b$~ 5 GeV
- Top-Higgs Yukawa coupling $\lambda_t \approx 1$
  - may help identify the mechanism of EWSB and mass generation.
  - may serve as a window to new physics that might couple preferentially to top.
- Know very little about top
  - Indirect constraints from low energy data, or statistically limited direct measurements from the Tevatron
    - Plenty of room for new Physics
  - Even if we find no surprises, precision top measurements will allow for stringent tests of the SM.



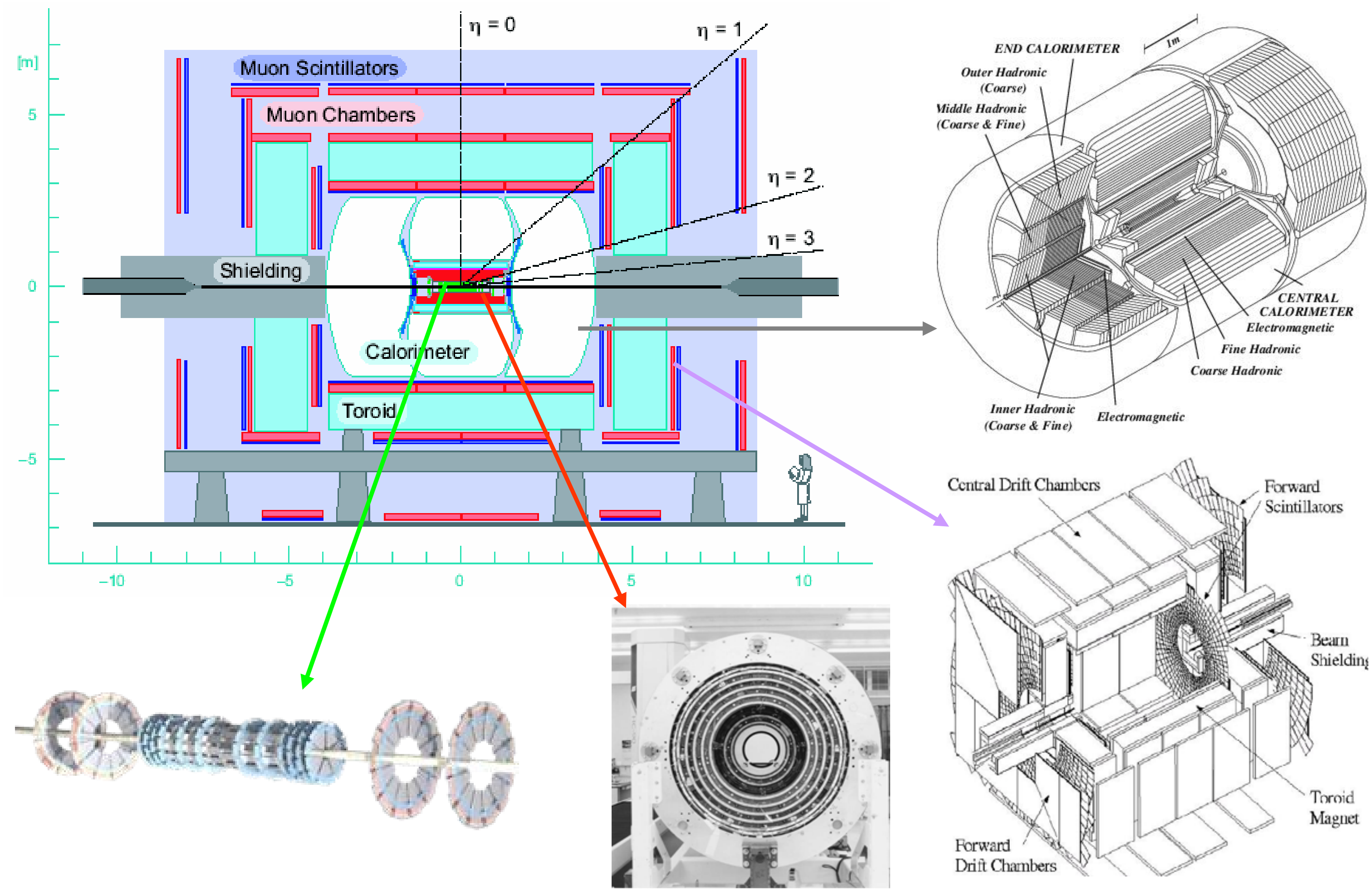



# Run II Integrated Luminosity

19 April 2002 - 19 February 2006



# Run II DØ Detector

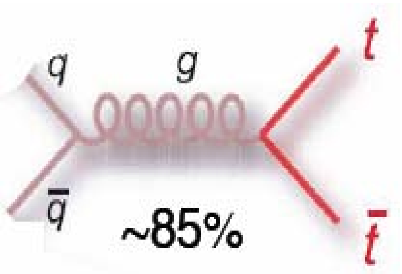


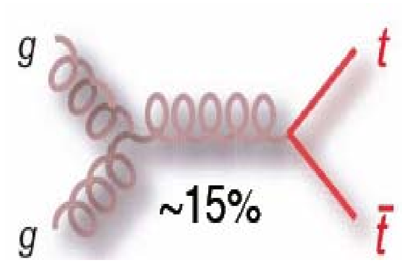

+ three tiered trigger system (rate reduction from 1.7 MHz to 50 Hz)

# Top quark production at the Tevatron

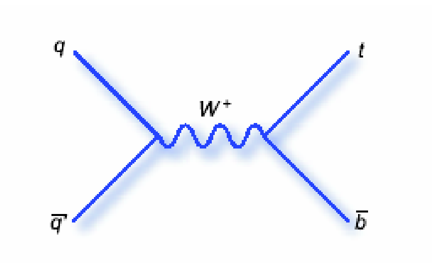
- Top quarks are mainly produced in pairs, via the strong interaction

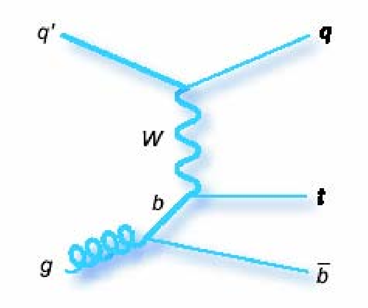
$\sigma_{tt}$=6.8±1.2pb (theory)




- EW Single Top production not yet observed




***s*-channel**
**$\sigma_s$~0.9 pb**

***t*-channel**
**$\sigma_t$~2.0 pb**

**DØ Preliminary 370 pb$^{-1}$ exp/obs**
**(updated Summer 2005)**

*s-channel* 3.3/5.0 pb
*t-channel* 4.3/4.4 pb

**Published 230 pb$^{-1}$ (Phys. Let. B 622)**

*s-channel* 4.5/6.4 pb
*t-channel* 5.8/5.0 pb

Experimentally challenging due to large W+jets background in lower jet multiplicities that pair production

# Top Quark Decay

$m_t > m_W + m_b \Rightarrow$ dominant 2-body decay $t \rightarrow Wb$

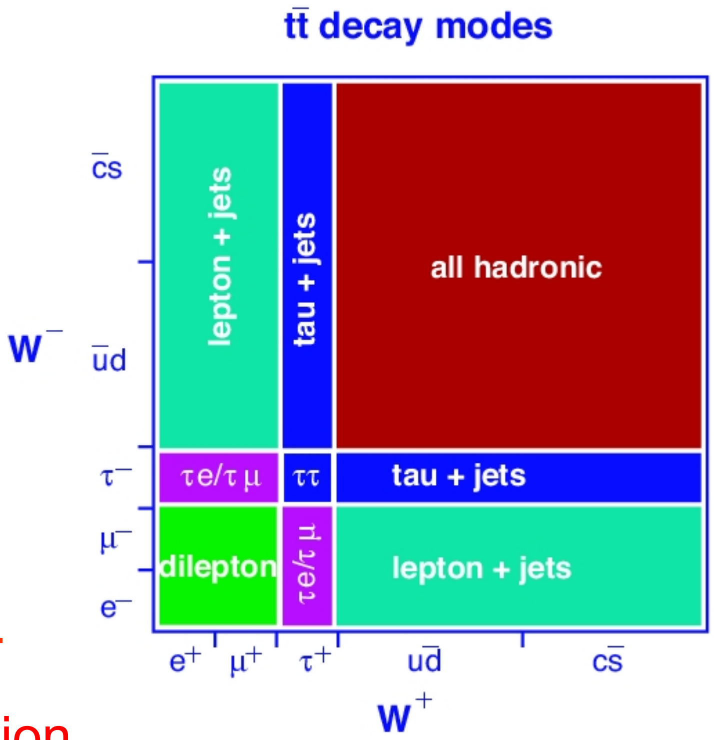
Assuming unitarity of 3-generation CKM matrix

$B(t \rightarrow Wb) \sim 100\%$

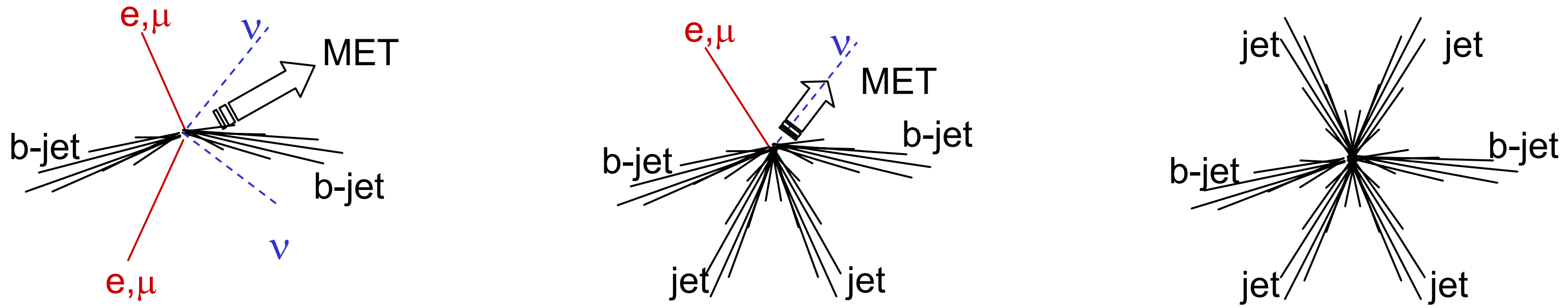
$\Gamma_t^{SM} \approx 1.4$ GeV at $m_t = 175$ GeV

Top decays before top-flavored hadrons or tt-quarkonium bound states can form.

Top quark spin transferred to the final state.




final state signatures in top quark pair production




***Dilepton***
(BR~5%, low bckg)

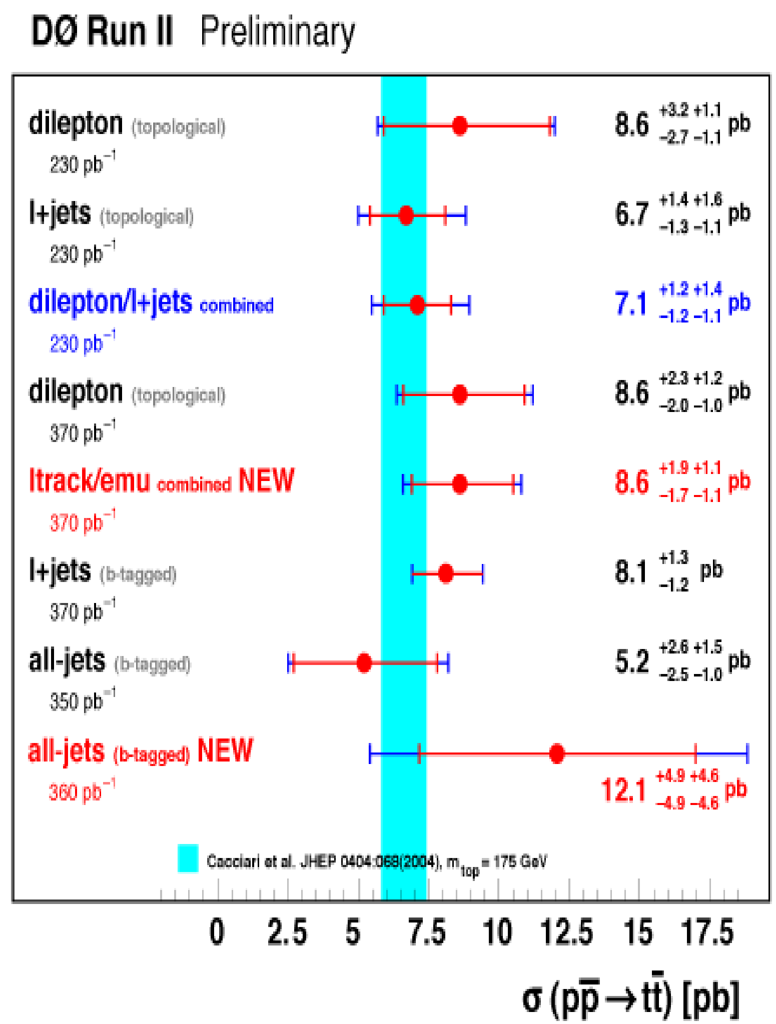
***Lepton+jets***
(BR~30%, moderate bckg)

***All-hadronic***
(BR~46%, huge bckg)

# Top Quark Pair Production x-section

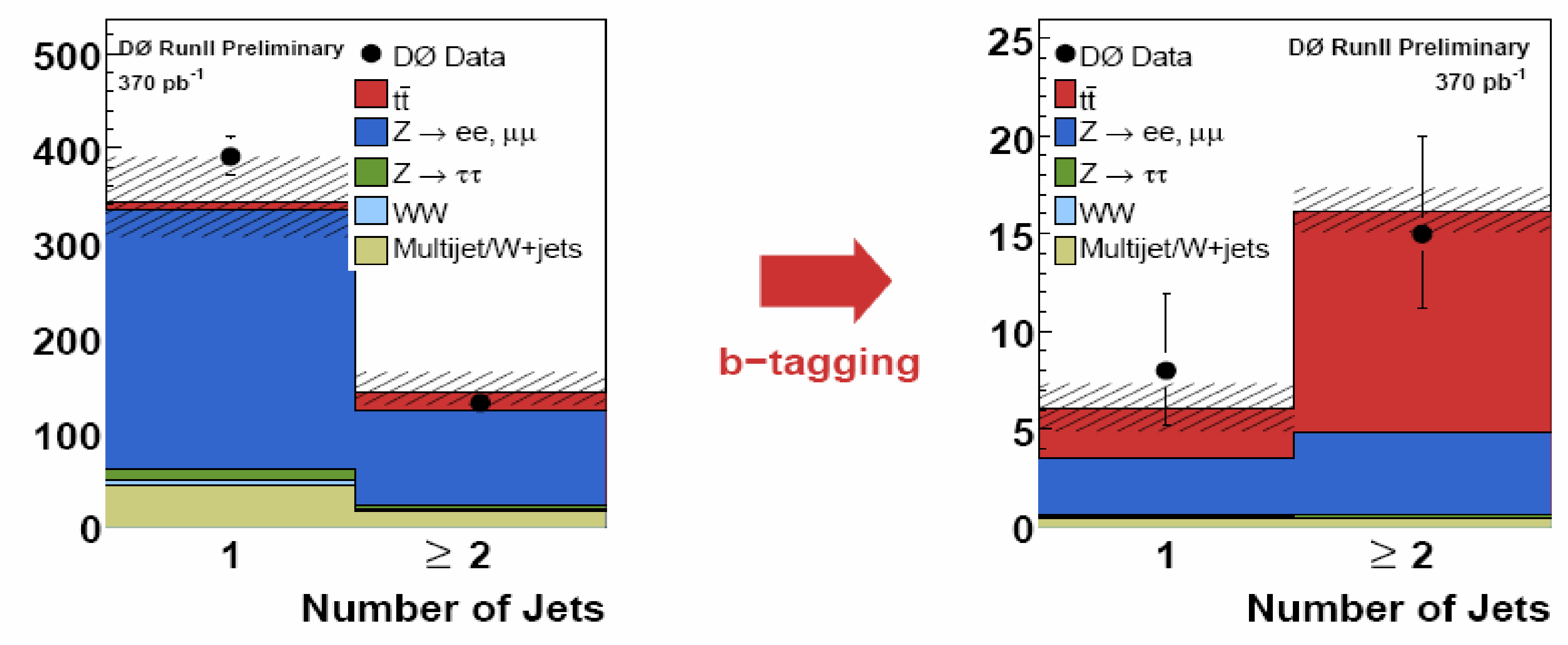
- Precise measurement of the top quark pair production cross section is a key element of the Top Physics program:
  - test of perturbative QCD
  - sensitive to New Physics (important to compare measurements in as many channels as possible)
- Well understood samples serve as basis of all top properties measurements
- Crucial input for searches for which top events are a dominant background.

- Run II measurements will be systematics-limited
  - jet energy scale, signal/background modeling, luminosity determination
  - Large data samples will allow to control many of these uncertainties



# Lepton + Track channel

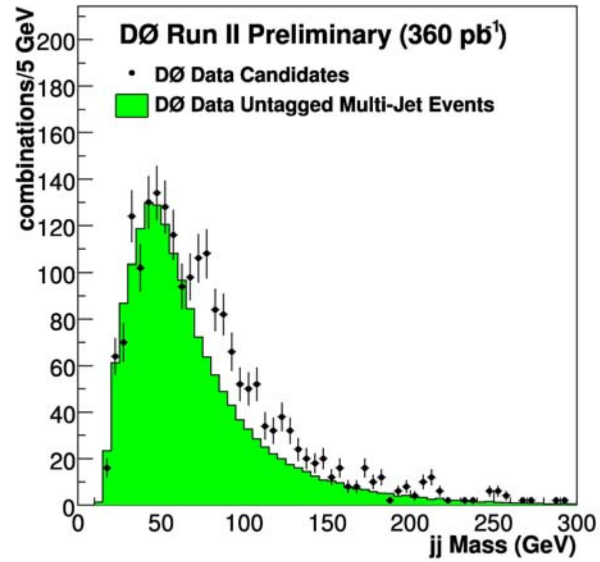
- Select events containing one lepton, 1 high pT isolated track, high Met and 1 or 2 jets
  - Recover some of the lepton detection inefficiency and pick up some tau decays
- Background is much higher than in a regular di-lepton analysis, dominated by Z → ℓ ℓ events
  - Can be controlled requiring that at least 1 jet in the event is a b-jet

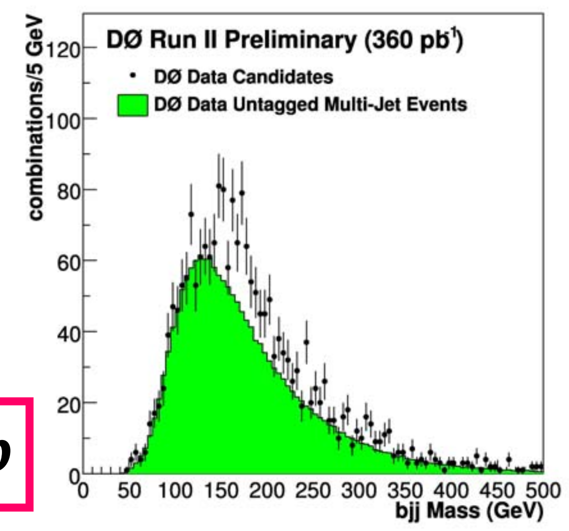



$$\sigma_{tt} = 7.1^{+2.6}_{-2.2}(\boldsymbol{stat}) \pm 1.3(\boldsymbol{syst}) \pm 0.5(\boldsymbol{lum})\,\boldsymbol{pb}$$

# All Jets channel

- Select events with 2 b-jets and 4 non-b jets
  - Overwhelmed with QCD multi-jet background
- Look for W and top candidates in mass spectra, using all jet combinations
  - Normalize background to candidate distribution in Mjj < 65GeV region
  - Use the W mass peak for an in-situ Jet Energy Scale calibration
- Extract cross section by counting number of candidates above background expectation

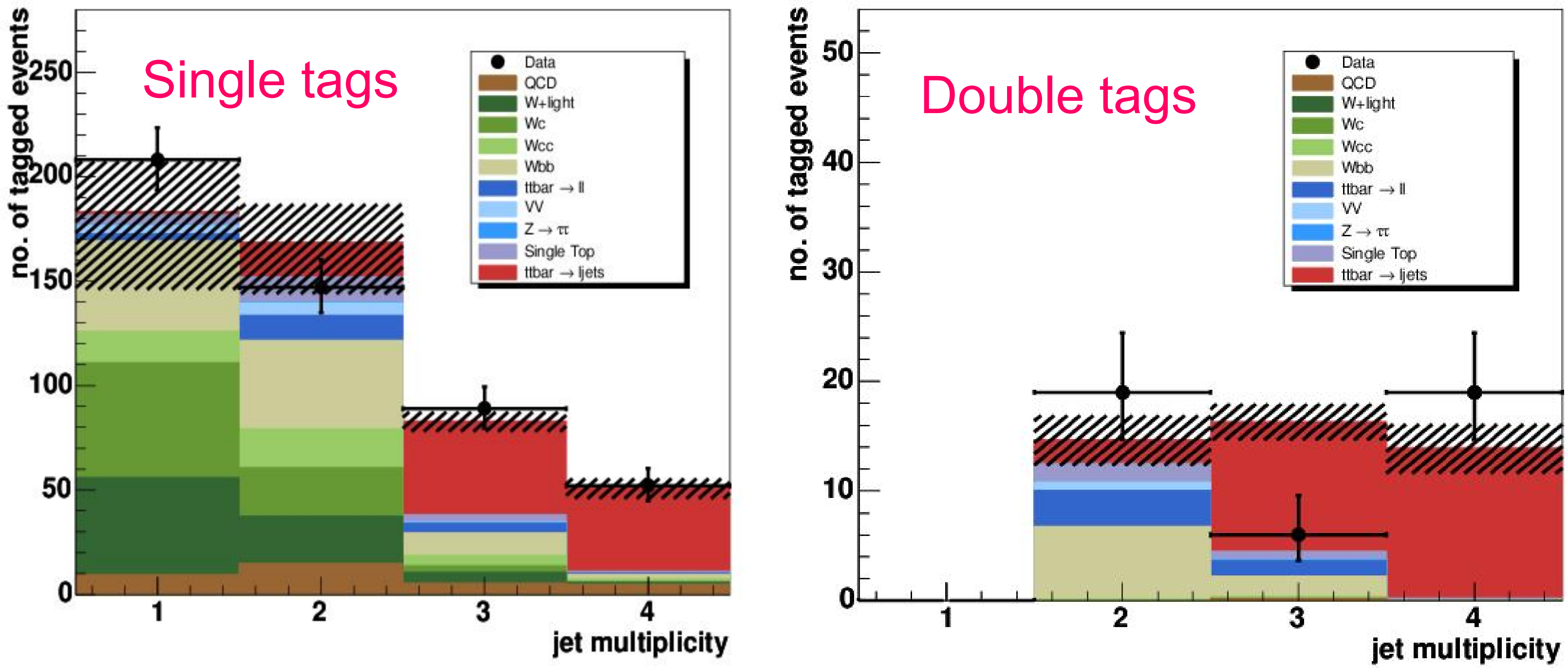



$$\sigma_{tt} = 12.1 \pm 4.9(\boldsymbol{stat}) \pm 4.6(\boldsymbol{syst}) \pm 0.5(\boldsymbol{lum})\, \boldsymbol{pb}$$

# Lepton + Jets channel

- Select events containing one lepton, high Met and ≥ 1 jet
  - Sample is dominated by W+jets events
- Apply lifetime b-tagging
  - 1st and 2nd jet bin are control samples.
  - Cross section is extracted from 3rd and 4th jet bin, in events with electrons and muons separately (8 channels)




$$\sigma_{tt} = 8.1^{+1.9}_{-1.7}(\boldsymbol{stat} + \boldsymbol{syst}) \pm 0.5(\boldsymbol{lum})\,\boldsymbol{pb}$$

# Lepton + Jets channel

Select events containing one lepton, high Met and ≥ 1 jet

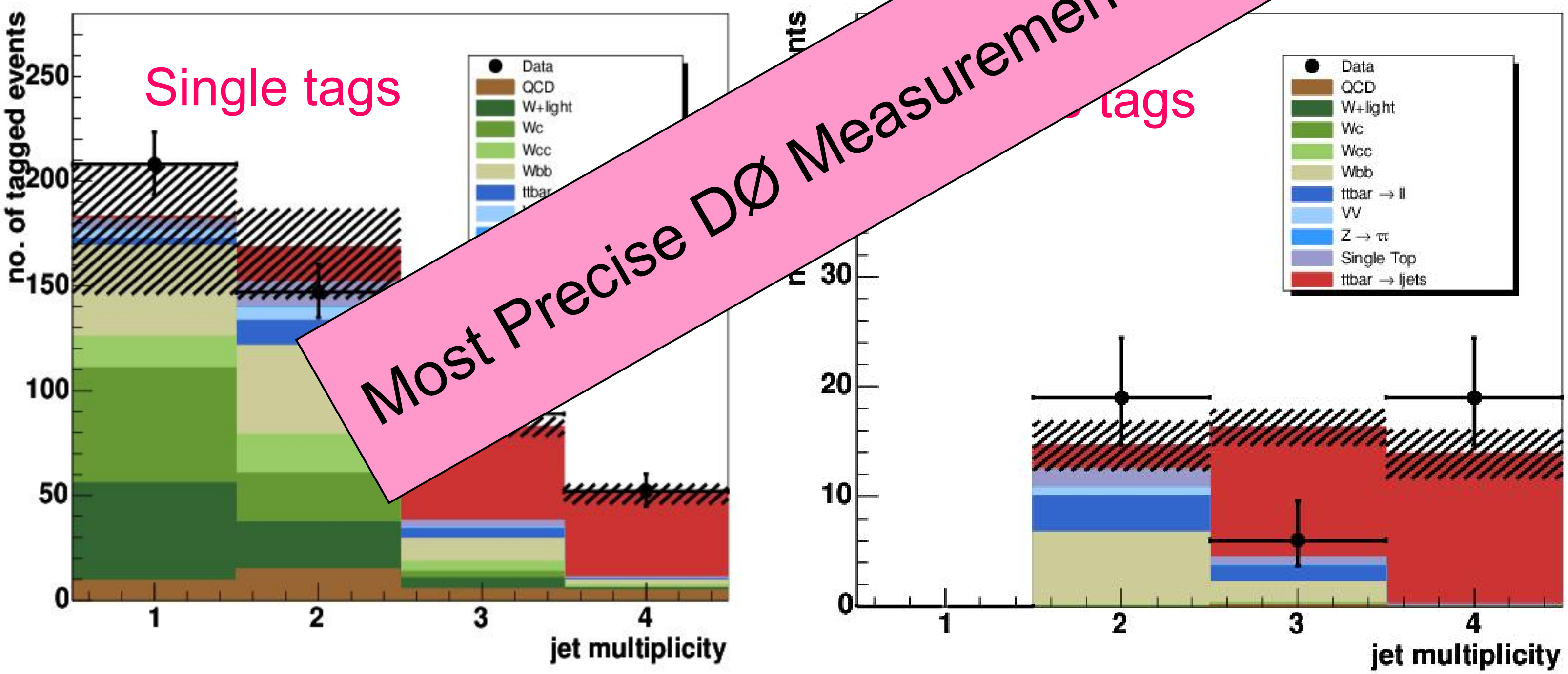
Sample is dominated by W+jets events

Apply lifetime b-tagging

1st and 2nd jet bin are control samples.

Cross section is ...cted from 3rd and 4th jet bin, in... h electrons and muons ... nnels)

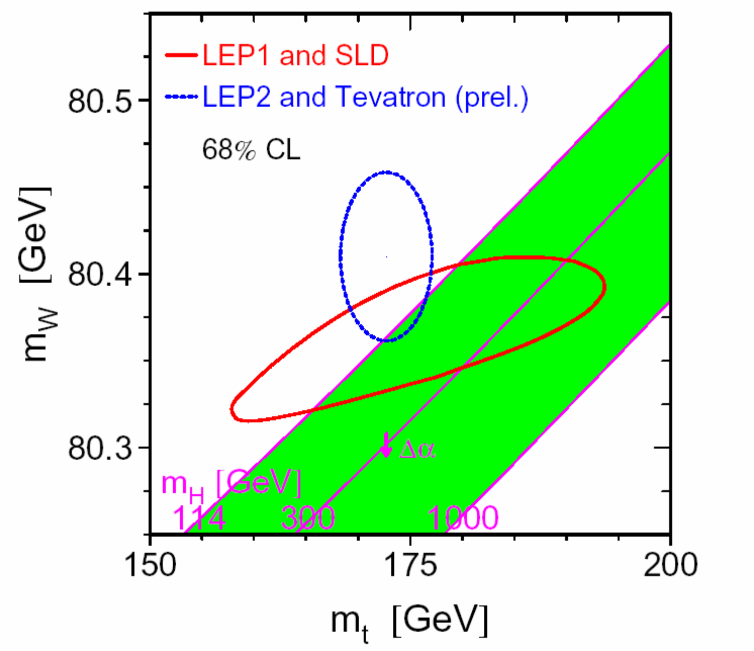
**Most Precise DØ Measurement to-date**

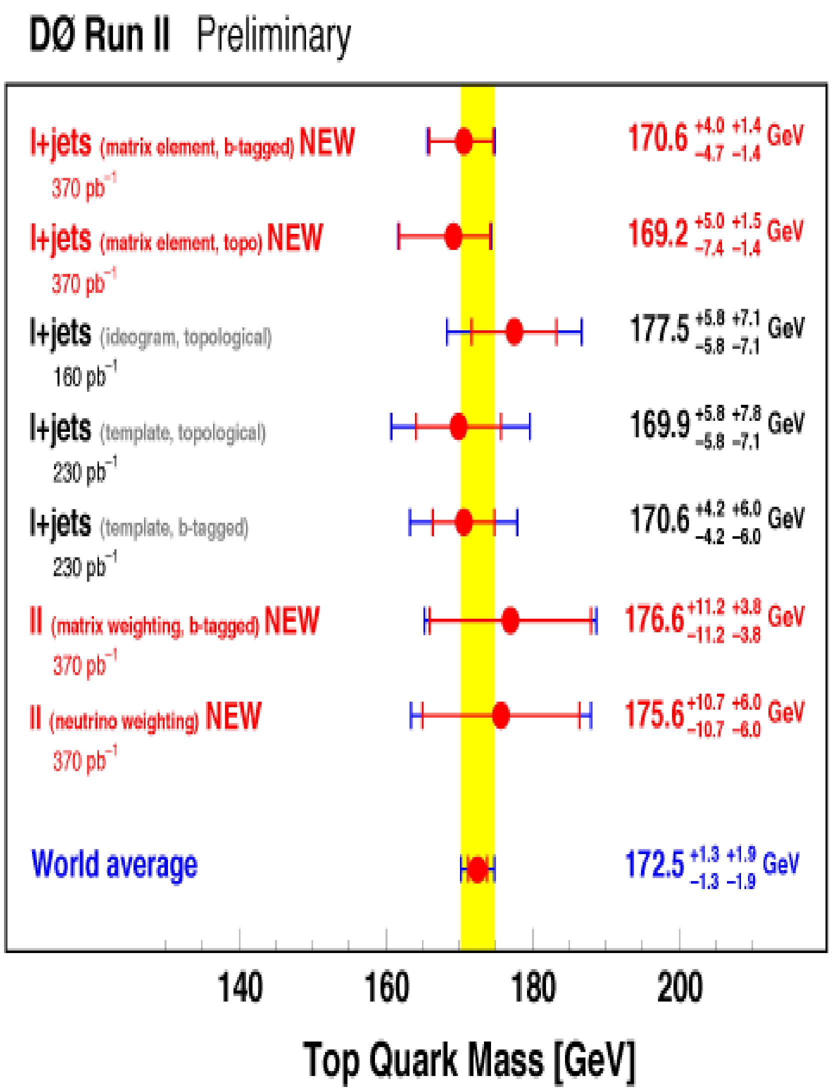



$$\sigma_{tt} = 8.1^{+1.9}_{-1.7}(\boldsymbol{stat} + \boldsymbol{syst}) \pm 0.5(\boldsymbol{lum})\,\boldsymbol{pb}$$

# Top Quark Mass

- Fundamental parameter of the Standard Model
  - Affects predictions of SM via radiative corrections
  - Together with the W Boson mass, places constraints on the Higgs mass



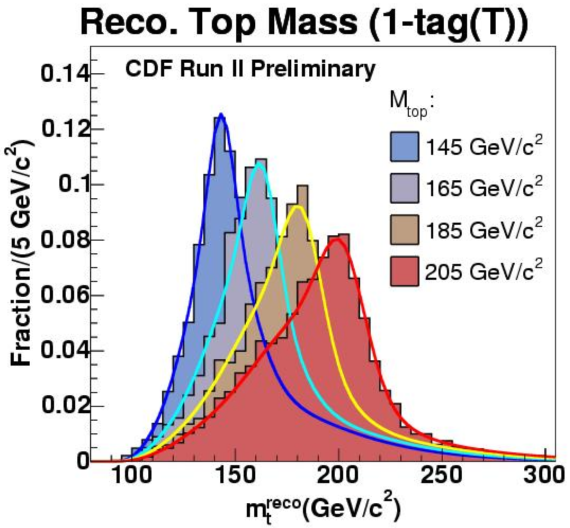
# Mass Measurement Methods

Precision measurement $\Rightarrow$ maximize statistical significance with sophisticated mass extraction techniques + minimize systematic uncertainties (jet energy scale, signal/background modeling).

Main mass extraction techniques:

Template methods:

typically, one mass per event from kinematic fit, compare data to MC templates.




Dynamical methods:

event by event weights according to quality of agreement with SM top and background differential cross-sections.

$$P(x;m_{top}) = \frac{1}{\sigma}\int d^n\sigma(y;m_{top})dq_1dq_2f(q_1)f(q_2)W(x|y)$$

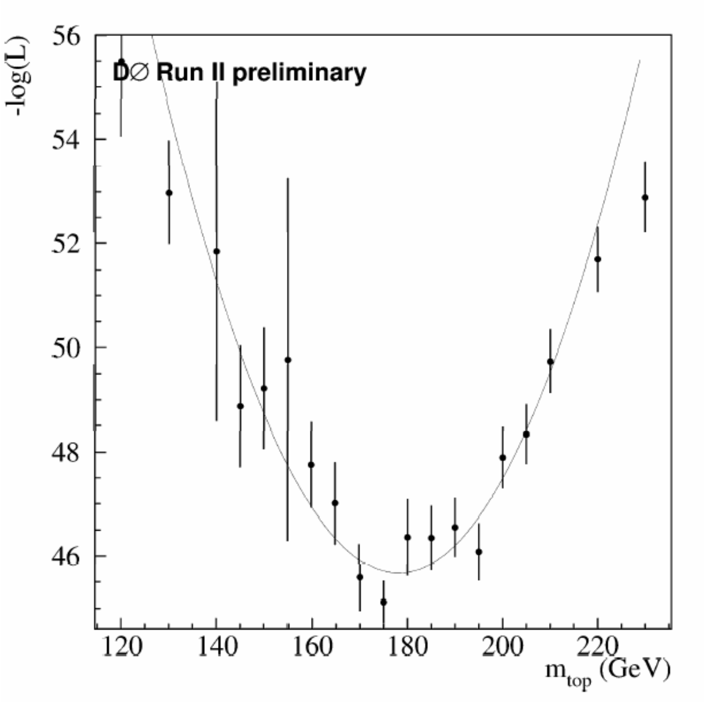
differential cross-section (LO matrix element)

PDF's

Transfer function: mapping from parton level variables (y) to reconstructed level variables (x)

# Mass in the ℓℓ + jets channel

Dilepton channels are underconstrained:
template methods assume values for certain variables in order to extract a solution, and assign weights to the different solutions.




Two analyses:

The **Matrix Weighting method** scans over top masses and assigns a weight to the solution based on the ME predictions for the lepton pT's.

b-tagging is used to increase S:B of sample.

$$M_{TOP} = 176.6 \pm 11.2(stat) \pm 3.8(syst)\ GeV$$

Extract x-sec from binned maximum likelihood fit to signal and background templates.

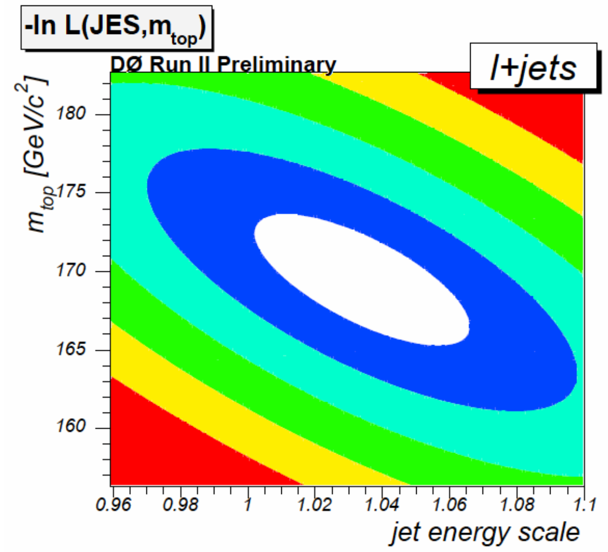
The **Neutrino Weighting method** scans over top masses and assigns a weight to the solution based on the agreement of the calculated neutrino pT's and the observed Missing $E_T$

$$M_{TOP} = 175.6 \pm 10.7(stat) \pm 6.0(syst)\ GeV$$

# Mass in the ℓ+jets channel

Simultaneous determination of Top mass and JES from reconstructed $m_{top}$ and $M_W$ templates

reduces JES error with in- situ calibration of the hadronic W mass in top decays

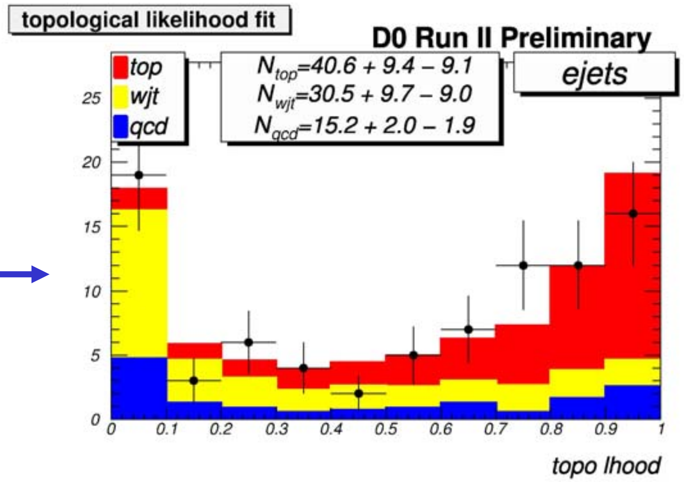



Two analyses:

Use b-tagging to reduce physics backgrounds and weigh different jet-parton assignment

$$M_{TOP} = 170.6^{+4.0}_{-4.7}(stat + JES) \pm 1.4(syst)\ GeV$$

Use kinematic properties of events to separate signal from background

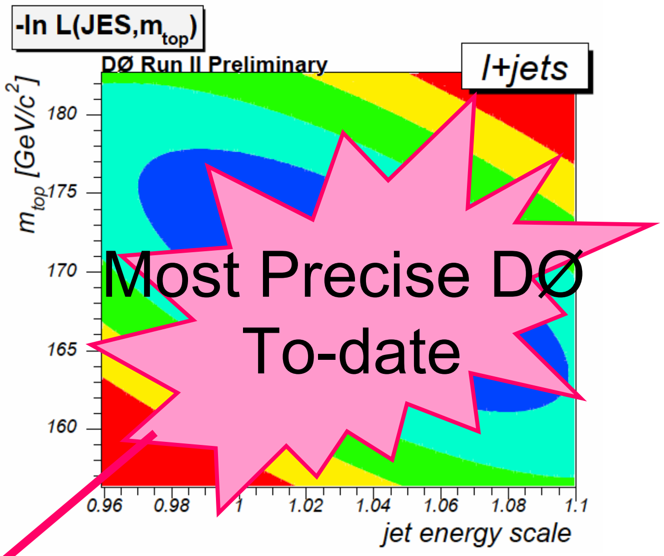



$$M_{TOP} = 169.2^{+5.0}_{-7.4}(stat + JES)^{+1.5}_{-1.4}(syst)\ GeV$$

# Mass in the ℓ+jets channel

Simultaneous determination of Top mass and JES from reconstructed $m_{top}$ and $M_W$ templates.

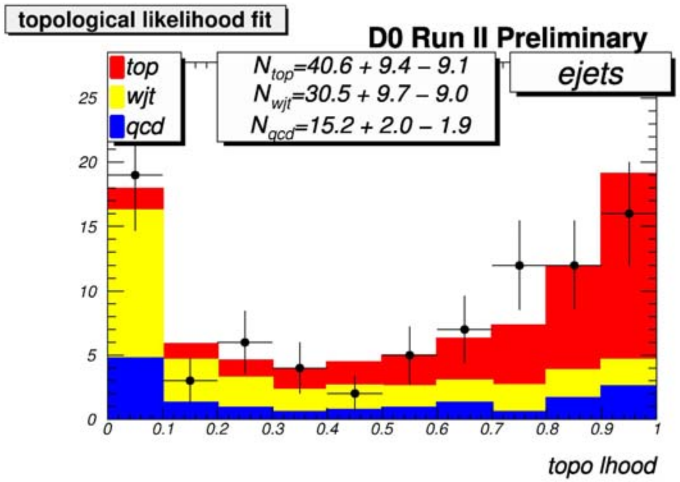
reduced JES error with in- situ calibration of the hadronic W mass in top decays




Two analyses:

Use b-tagging to reduce physics backgrounds and weigh different jet-parton assignment

$$M_{TOP} = 170.6^{+4.0}_{-4.7}(stat + JES) \pm 1.4(syst)\ GeV$$




Use kinematic properties of events to separate signal from background

$$M_{TOP} = 169.2^{+5.0}_{-7.4}(stat + JES)^{+1.5}_{-1.4}(syst)\ GeV$$

# Food for Thought

Top Quark Analyses benefit greatly from (lifetime) b-tagging.

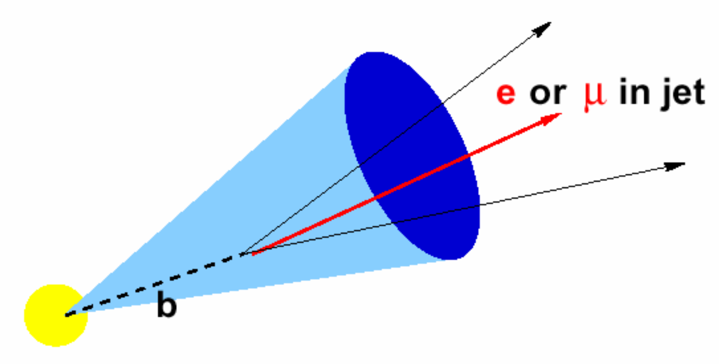
Uncertainties arising from the b-tagging methods are significant, and in some cases, the main source of error → work is needed to reduce them.

b-tagging at DØ:

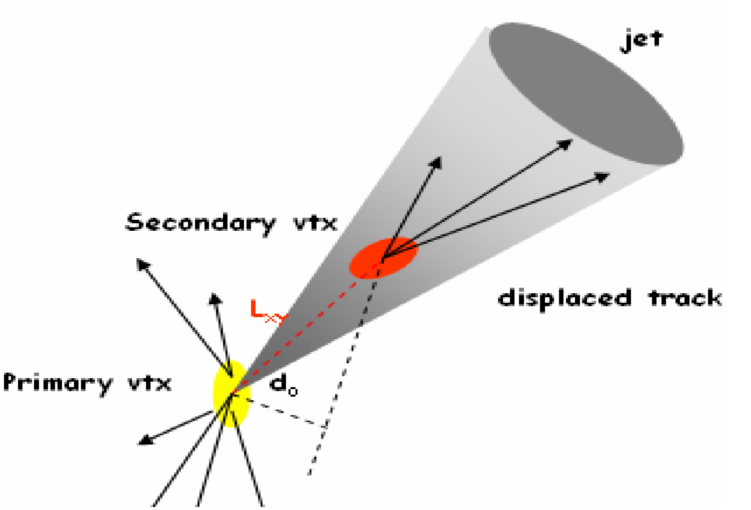
***b*-quarks hadronize into long lived (ct ~ 450mm) *B* mesons which travel a few millimeters before decaying.**

**Soft Lepton Tagging: lepton within a jet from semileptonic b decay**

**Lifetime Tagging: tracks significantly displaced from the PV**



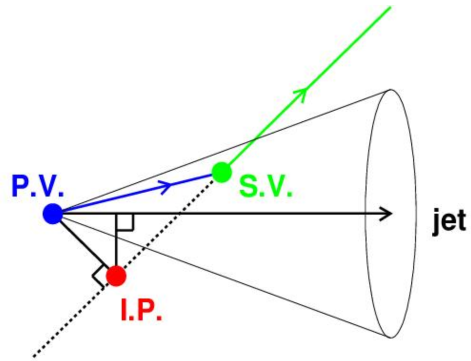

- $b \to \ell\nu c$ (BR ~ 20%)
- $b \to c \to \ell\nu s$ (BR ~ 20%)



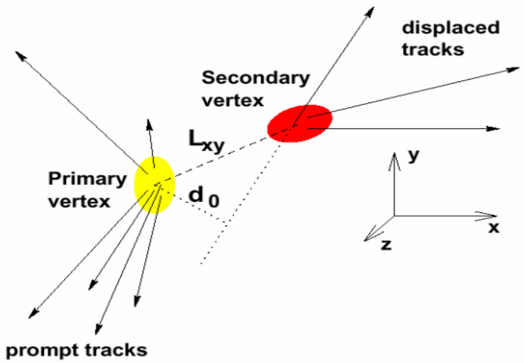
# Secondary Vertex Tagger Algorithm

The Secondary Vertex Tagger (SVT) is a lifetime tagger that explicitly reconstructs vertices which are displaced from the Primary Vertex

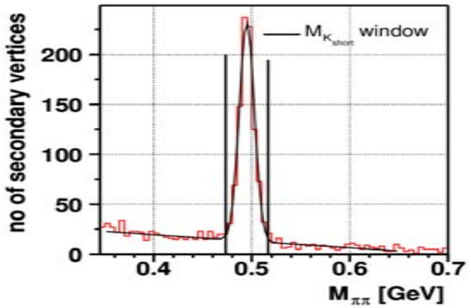
1) Use tracks with significant impact parameter with respect to the PV




2) Build-up method fits pairs of selected tracks within track-jets to find SV




3) Removes track pairs in the mass windows corresponding to $K^0_S$, $\Lambda^0$ and photon conversions ($\gamma \rightarrow e^+e^-$)



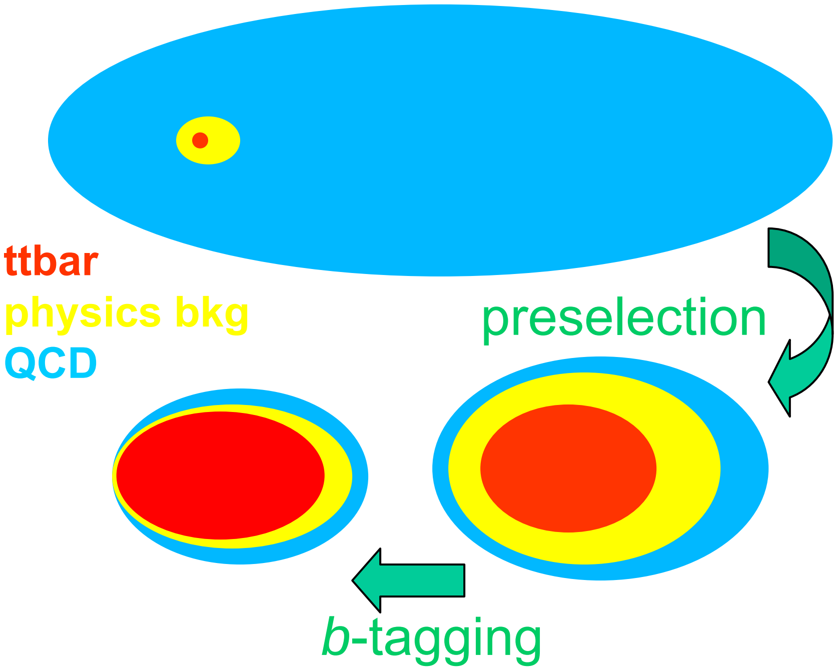

A jet is tagged if it contains a reconstructed Secondary Vertex

# Analysis Method

Original sample mostly QCD multi-jet events

Selecting isolated high $p_T$ leptons produces a sample dominated by W-like events (W+jets, top, Dibosons, $Z \rightarrow \tau\tau$)

b-tagging produces a sample dominated by top pairs (3&4 jets); (1&2 jets used as control bins)



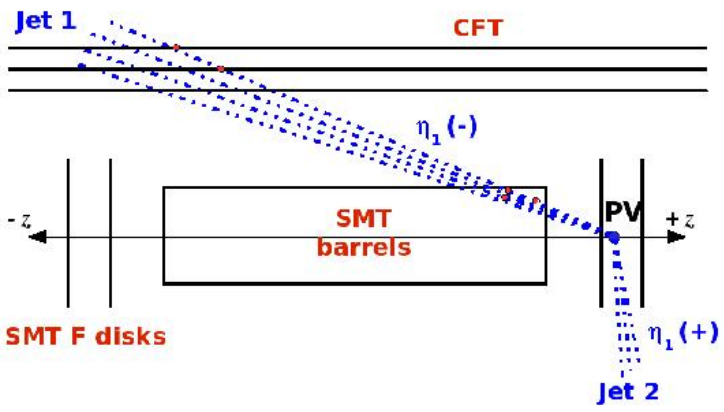

Need to determine the probability to tag a jet from a given flavor (b, c, light) & the flavor fractions of the backgrounds, to understand the sample composition of the tagged sample and extract the top pair content.

# Tagging Efficiencies

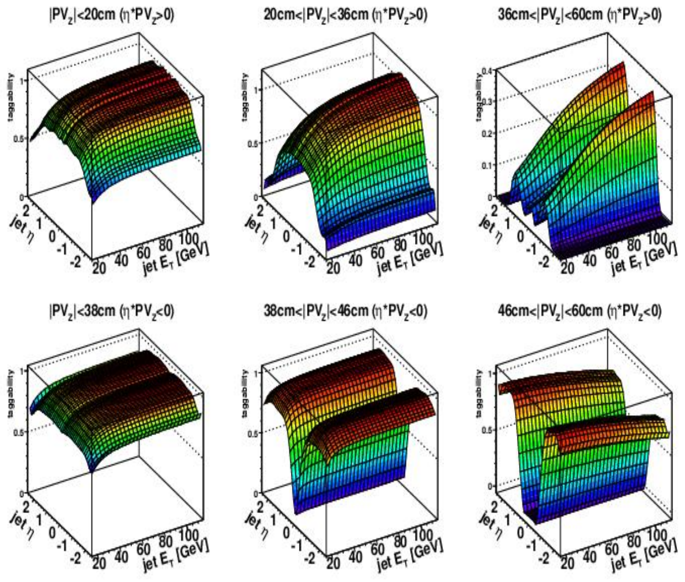
The probability for a jet to be tagged is split into

- Probability for a jet to be taggable (have at least two good tracks with hits in SMT)
- Probability for a taggable jet to be tagged
  - Decouple tagging efficiency from tracking inefficiencies & directly compare performances between different algorithms.

Taggability has strong geometric dependence: measure directly from pretagged sample




parameterize vs. y and $p_T$ of jet in 6 bins of ($PV_Z$, $y_{jet}$)



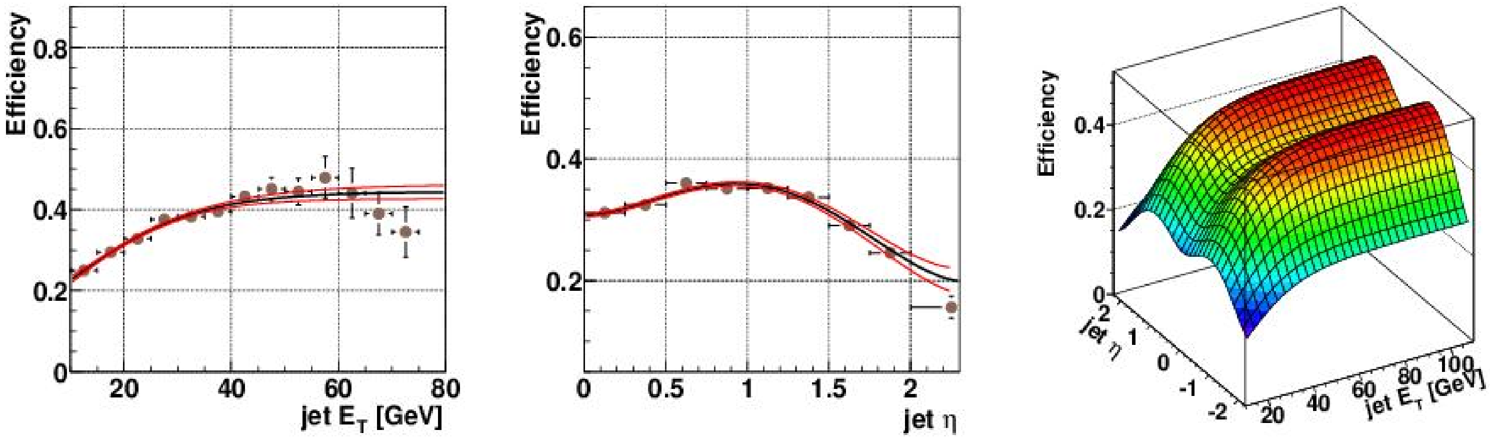
# Semileptonic b-tagging efficiency

Measured directly from data applying SVT and SLT to two samples with different fractions of heavy flavor jets

muon-in-jet

muon-in-jet away jet lifetime tagged (enriched in heavy flavor)

Parameterize in terms of $p_T$ and y of jet




Uncertainties arise from limited data statistics, measured correlations between SVT and SLT, and choice of $p_T$(rel) cut in SLT.
Total systematic error ≈ 5%

# Inclusive b & c-tagging efficiency

Inclusive b & c- tagging efficiency measured in ttbar MC

B-(C) mesons inside a jet determine the flavor of the jet

Efficiencies are corrected by a data-to-MC Scale Factor

$$SF_{b\rightarrow\mu}(p_T,\eta) = \frac{\epsilon^{data}_{b\rightarrow\mu}(p_T,\eta)}{\epsilon^{MC}_{b\rightarrow\mu}(p_T,\eta)}$$

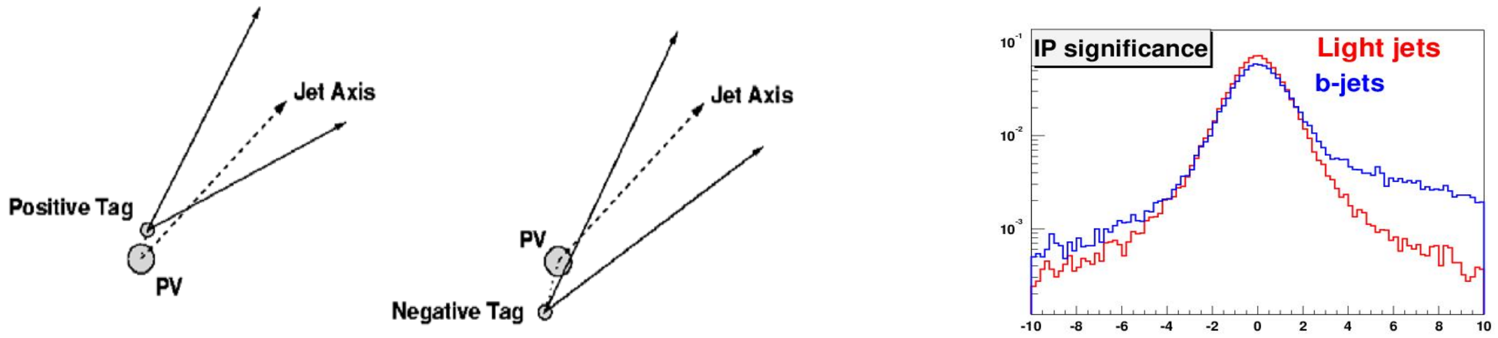
defined as the ratio of the semileptonic b-tagging efficiency measured in data, to the one measured in a bbar sample

The kinematic dependence of the tagging efficiencies are taken from the simulation, with the overall normalization determined from the data

Uncertainties arise from the choice of b-fragmentation models in the MC

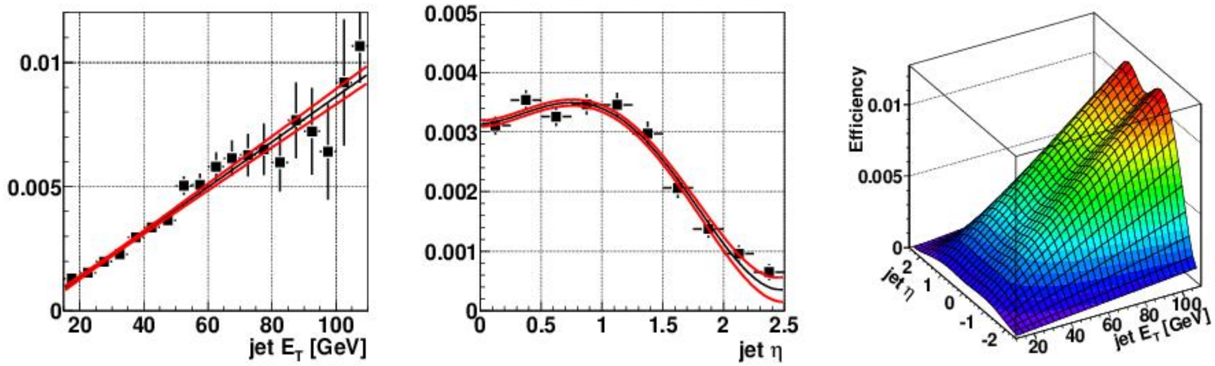
# Mistag Rate (probab to tag a light jet)

Originating from misreconstruction and resolution effects




Determined from the negative tagging efficiency measured in QCD data

- Corrected for heavy flavor contamination in the data sample and residual long loved particles ($K^0_s$, $\Lambda^0$) not present in the negative tagging rate



# Event Tagging Probability

Take the per-jet tagging probability

$$\mathcal{P}_\alpha(p_T,\eta) = P^{tagg,data}(p_T,\eta)\epsilon_\alpha(p_T,\eta)$$

$\alpha$ = *b*, *c*, *light*

Derive event tagging probabilities by weighting each jet in MC with the per-jet tagging probability

$$P^{tag}_{event}(\geq 1 \text{ tag}) = 1 - P^{tag}_{event}(0 \text{ tag}) = 1 - \prod_{j=1}^{N_{jets}} (1 - \mathcal{P}_{\alpha_j}(p_{T_j},\eta_j))$$

Single tag probability

$$P^{tag}_{event}(1 \text{ tag}) = \sum_{j=1}^{N_{jets}} \mathcal{P}_{\alpha_j}(p_{T_j},\eta_j) \prod_{i\neq j}(1 - \mathcal{P}_{\alpha_i}(p_{T_i},\eta_i))$$

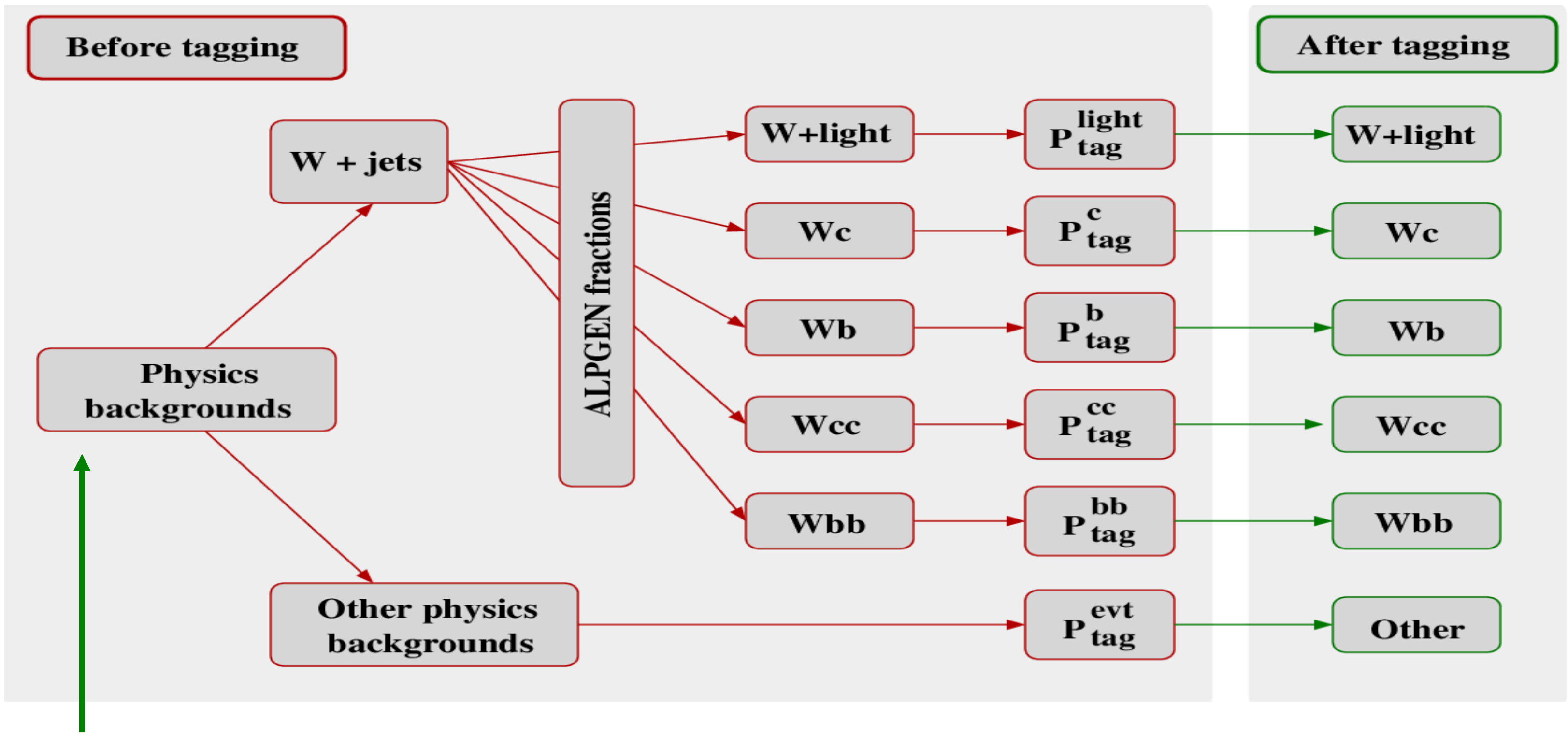
Double tag probability

$$P^{tag}_{event}(\geq 2 \text{ tag}) = P^{tag}_{event}(\geq 1 \text{ tag}) - P^{tag}_{event}(1 \text{ tag})$$

Estimate the number of tagged events

$$N^{tag}_{event} = N^{presel}_{event}\,\bar{P}^{tag}_{event}$$

# Composition of the tagged sample



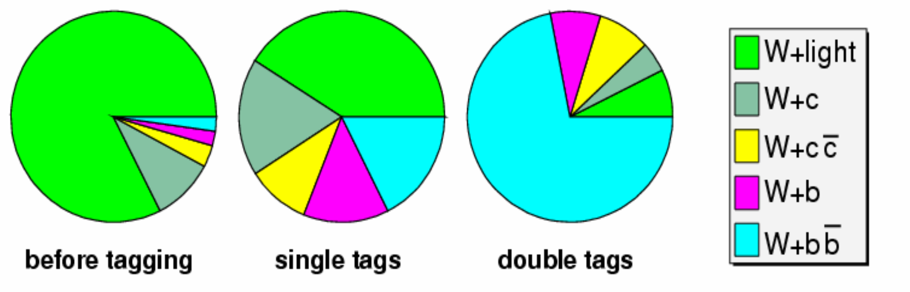

Overall normalization obtained from data.

W boson heavy flavor fraction computed from ALPGEN 1.3 followed by PYTHIA 6.2 to simulate the underlying event and the hadronization.

Number of QCD events in tagged sample measured directly from data, on a sample with leptons that fail the tight selection

# *W*+jets heavy flavor fractions

Approximation of the MLM matching used to avoid double counting of configurations leading to the same final state.




Uncertainties arise from choice of matching parameters, limited Monte Carlo statistics, and K factors. Total systematic error ≈ 6%

| Contribution | W + 1jet | W + 2jets | W + 3jets | W+ ≥ 4jets |
|---|---|---|---|---|
| $Wb\bar{b}$ | | $(1.23 \pm 0.08)\%$ | $(2.05 \pm 0.21)\%$ | $(2.84 \pm 0.16)\%$ |
| $Wc\bar{c}$ | | $(1.69 \pm 0.12)\%$ | $(2.94 \pm 0.37)\%$ | $(4.44 \pm 0.29)\%$ |
| $W(b\bar{b})$ | $(0.86 \pm 0.03)\%$ | $(1.46 \pm 0.09)\%$ | $(2.03 \pm 0.15)\%$ | $(2.99 \pm 0.24)\%$ |
| $W(c\bar{c})$ | $(1.23 \pm 0.05)\%$ | $(2.26 \pm 0.15)\%$ | $(3.08 \pm 0.24)\%$ | $(5.06 \pm 0.54)\%$ |
| $Wc$ | $(4.41 \pm 0.18)\%$ | $(6.25 \pm 0.43)\%$ | $(4.93 \pm 0.48)\%$ | $(4.30 \pm 0.23)\%$ |
| W + jets(mistags) | $(93.50 \pm 0.20)\%$ | $(87.10 \pm 0.70)\%$ | $(84.96 \pm 1.12)\%$ | $(80.36 \pm 0.64)\%$ |

*Table shows MC stat error only*

# b-tagging summary

Main b-tagging uncertainties arising from the semileptonic b-tagging efficiency measured in data and the W boson heavy flavor fractions

CDF efforts to measure the heavy flavor fractions in data give results 50% higher than ALPGEN, for both b and c jets (PRD 71, 52003 (2005)).

Will need concentrated experimental/theoretical effort on these fronts to reduce the errors

Important for precision measurements and searches, both at the Tevatron and the LHC

# Conclusions

Entering an era of precision top measurements:

- Sophisticated analyses methods in place
- Analyses based on 1fb$^{-1}$ of data forthcoming
- Expect many interesting results from Tevatron Run II

Stay Tuned…