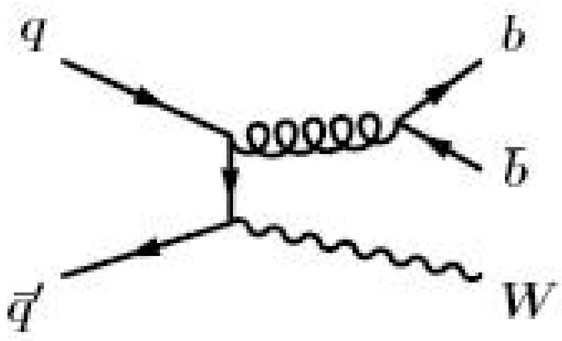
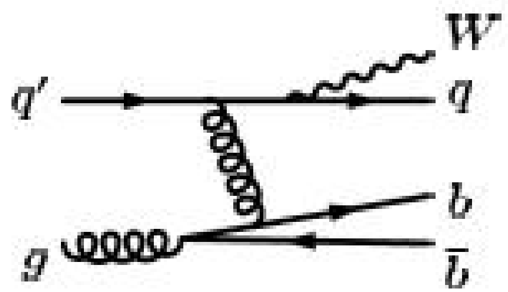
Measurement of the *b*-jet Cross Section in Events with a *W* Boson in ppbar Collisions at $\sqrt{s}$ =1.96 TeV

arXiv.0909.1505, submitted to PRL





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Northwest Terascale Research Projects
W/Z+ b-quark physics at the LHC
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University of Oregon

Motivation

Accurate model of *W*+*b*-jet production is essential for searches for rare processes that have the same signature

Calculation	Prediction (pb)
MCFM NLO	1.22±0.14
PYTHIA	1.10
ALPGEN	0.78 $Q^2 = M_W^2 + p_{T,W}^2$

Progress in NLO calculations

***Wbb* 1999, 2006** Ellis, Veseli PRD 60, 011501
Cordero, Reina, Wackeroth PRD 74, 034007

***Wbj* 2007** Campbell, Ellis, Maltoni, Willenbrock PRD 75, 054015

***Wb* 2009** Campbell, Ellis, Cordero, Maltoni, Reina, Wackeroth, Willenbrock PRD 79, 034023

Note well: rare $WH \to \ell\nu bb$ searches (0.042 pb at m_H=115 GeV/c^2):

- ***W*+*b*-jet uncertainty same size as 10x expected *WH* events**
- **Multivariate discrimination depends on model of *W*+*b*-jet kinematics from ALPGEN (leading-order)**

We present first measurement of the W+b-jet production rate with better than 20% accuracy (arXiv.0909.1505, submitted to PRL)

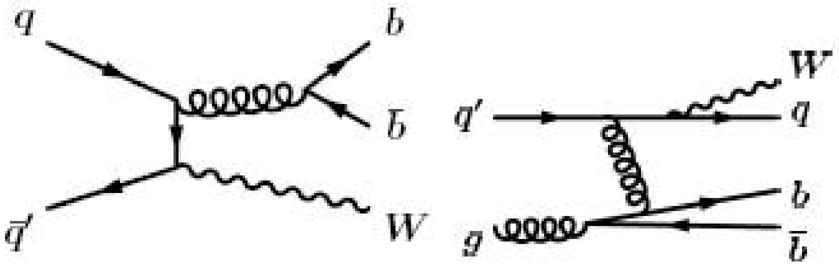
How we quote the measurement

NB: We quote our measurement in a restricted region of phase space

- **Avoids large extrapolation of our measurement to experimentally inaccessible regions (*i.e.* low jet E_T, large jet η)**
- **Any theorist can compare their new result with our measurement based on a clear definition of the phase space**

We also quote our measurement as a jet-level cross section

- **Avoids model-dependent correction for number of b jets per event**



Phase space requirements are made on stable final state particles from *W*+*b*-jet production and are coincident with our reconstructed event selection:

- **Lepton p_T>20 GeV/*c* with $|\eta|$<1.1, and neutrino p_T>25 GeV/*c***
- **One or two hadron-level jets with E_T>20 GeV and $|\eta|$<2.0**
- **Hadron-level jets (SPARTYJET) use final state particles and same cone algorithm as our reconstructed jets**

Theoretical predictions are jet-level & have same phase requirements imposed

- i.e. 1.22 pb x 1900 pb^{-1} = 2320 *b* jets in events passing phase space requirements

Event Selection

Focus on leptonic *W* decays, $W \to \ell\nu$ where $\ell = e, \mu$

Online event trigger:

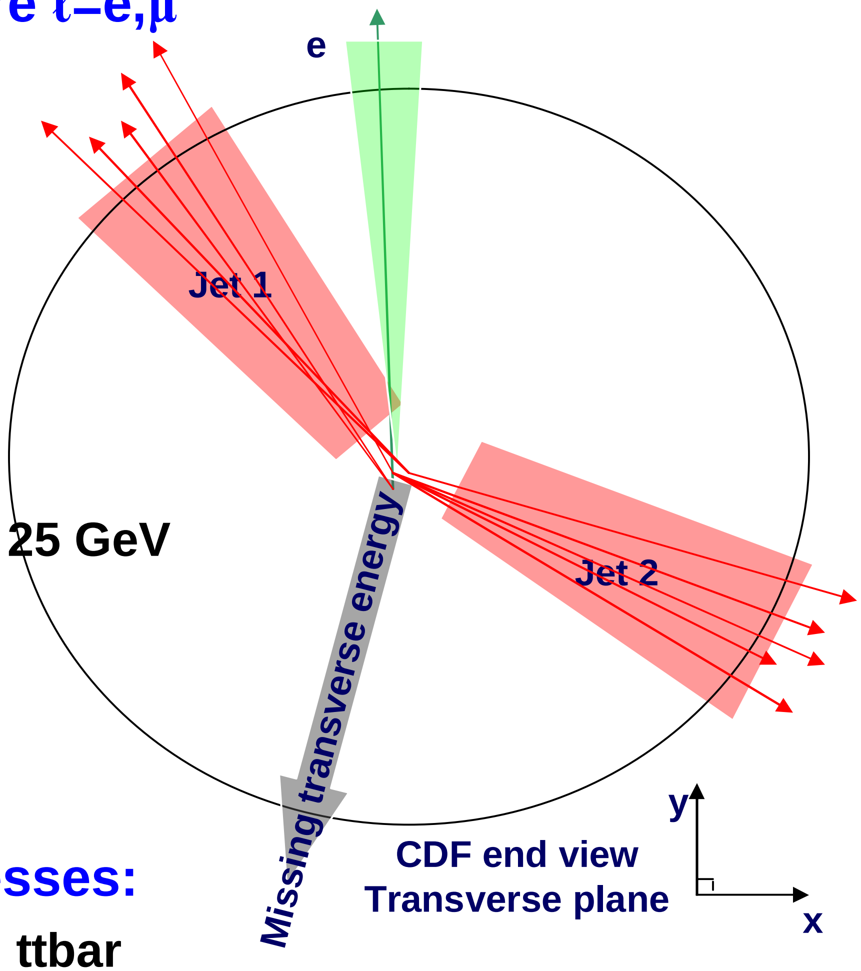
- **18 GeV $|\eta| < 1.1$ electron OR**
- **18 GeV $|\eta| < 0.6$ muon OR**
- **18 GeV $0.6 < |\eta| < 1.0$ muon**

***W* selection:**

- **$p_T > 20$ GeV/c isolated central lepton**
- **Large missing transverse energy: MET > 25 GeV**

Jet selection:

- **Exactly 1 or 2 $E_T > 20$ GeV, $|\eta| < 2.0$ jets**
- **JetClu clustering with R=0.4**

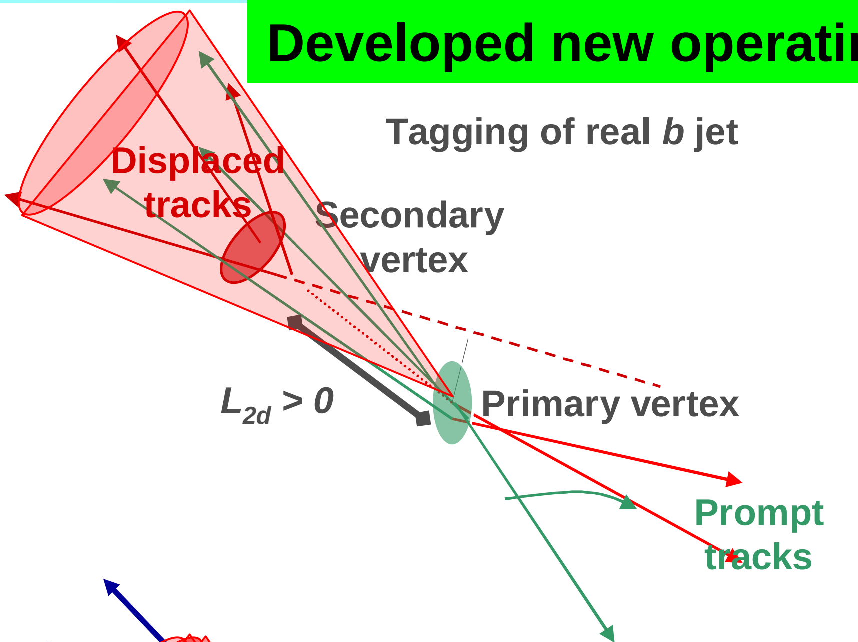


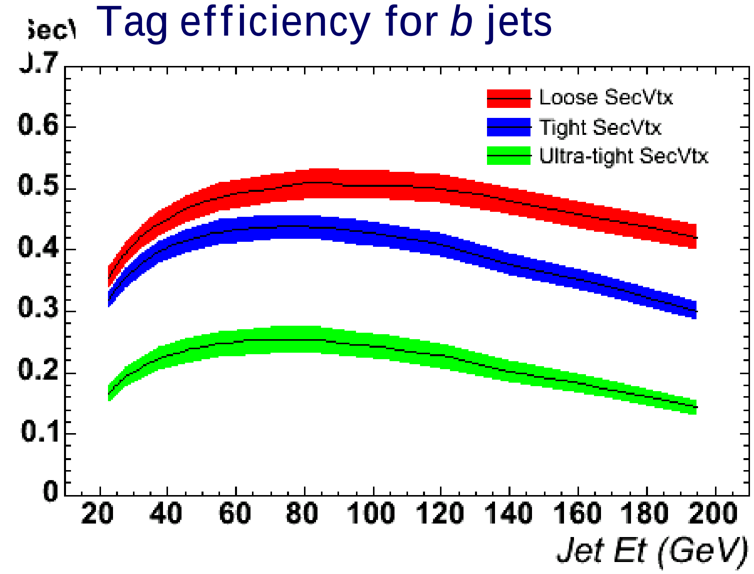
Do not consider events from other processes:

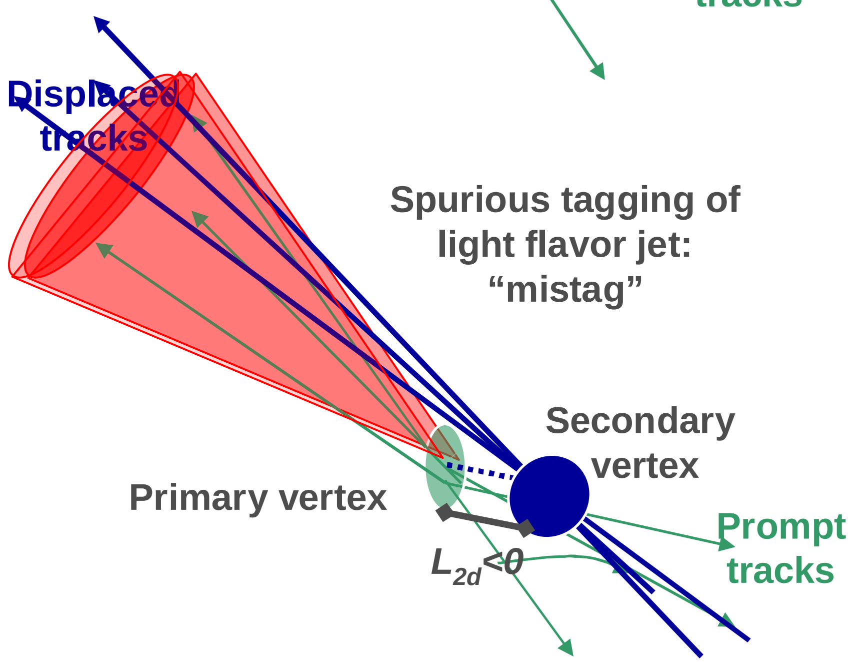
- **Veto events w/ 2 high p_T leptons to avoid ttbar**
- **Reject $Z \to \ell\ell$ production with one lepton not fully reconstructed**
- **Remove cosmic rays, events with objects from different interactions**
- **Veto fake *W* events**

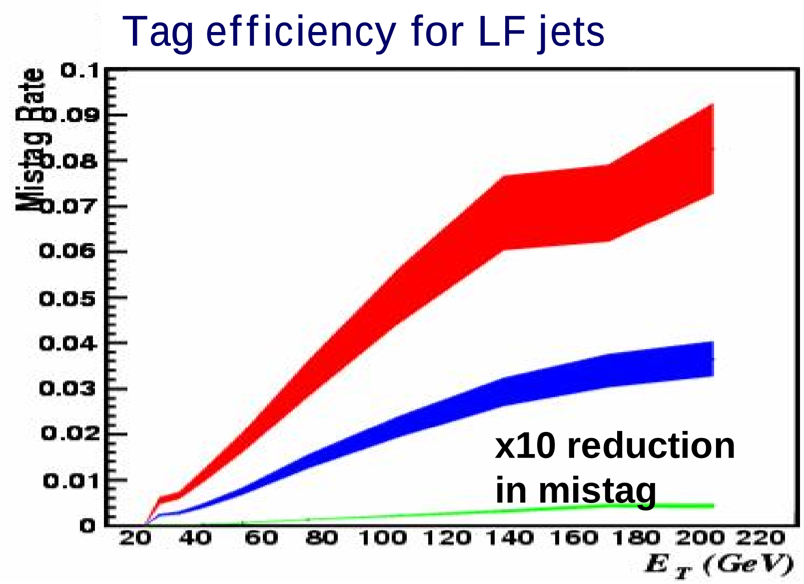
b-jet identification: Ultra-tight

Developed new operating point of SecVtx to reduce mistags



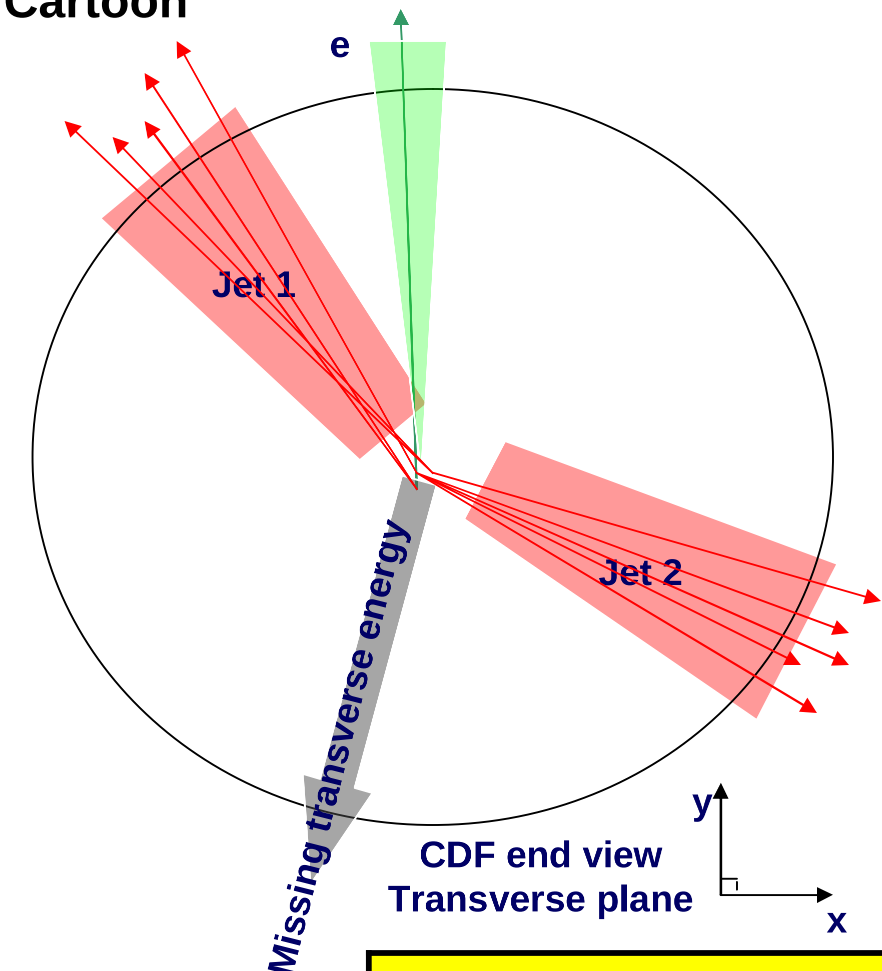




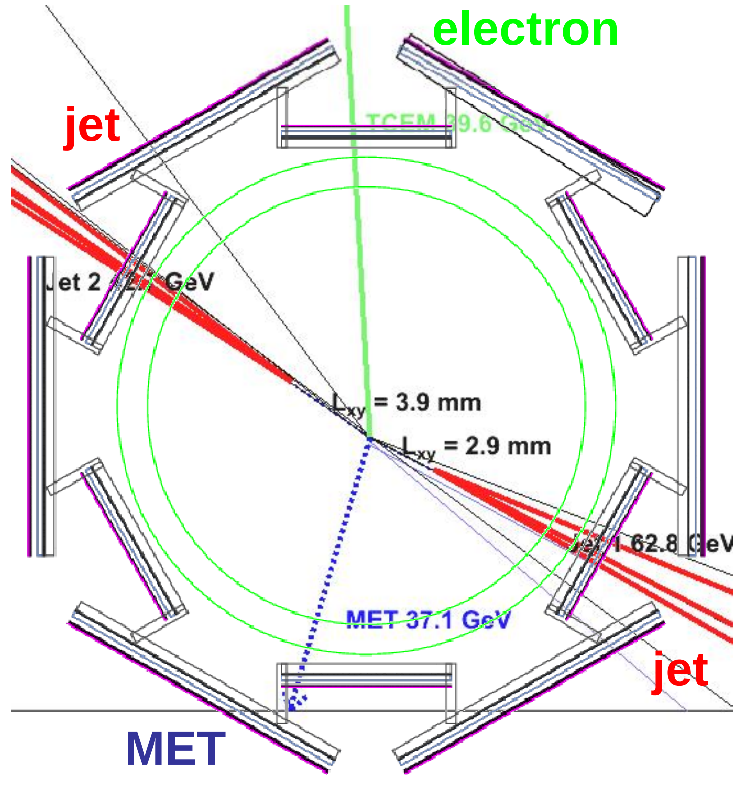


Events & jets in 1.9 fb^{-1}

Cartoon



The real thing: event recorded 10/2005



Event has 2 tagged jets!

Selected events	175,712
Total jets	199,670
Tagged jets	943

Ultratight SECVTX (UT) has lower yield but increased purity.

W+b jets: Measurement Strategy

$$\sigma_{b\,jets} \times B(W \to \ell\nu) = \frac{n_{\text{tag}} \cdot f^{b} - n_{\text{bkg}}^{b\,\text{jets}}}{\sum_{e,\mu} L \cdot A_{W+b}^{b\,\text{jets}} \cdot \varepsilon_{\text{tag}}^{b} \cdot \varepsilon}$$

Where do various pieces come from?

Discriminate *b* jets from *c*/LF jets in tagged sample using **vertex mass** $n_{\text{tag}} \cdot f^{b}$

Determine contribution from **background** with tagged *b* jets and subtract from overall yield $n_{\text{bkg}}^{b\,\text{jets}}$

Calculate **acceptance** for *W+b*-jet events $A_{W+b}^{b\,\text{jets}}$

Measure **tag efficiency** for *b* jets in *W+b*-jet production in MC and correct to match data $\varepsilon_{\text{tag}}^{b}$

Luminous region, trigger efficiency, lepton id SF ε

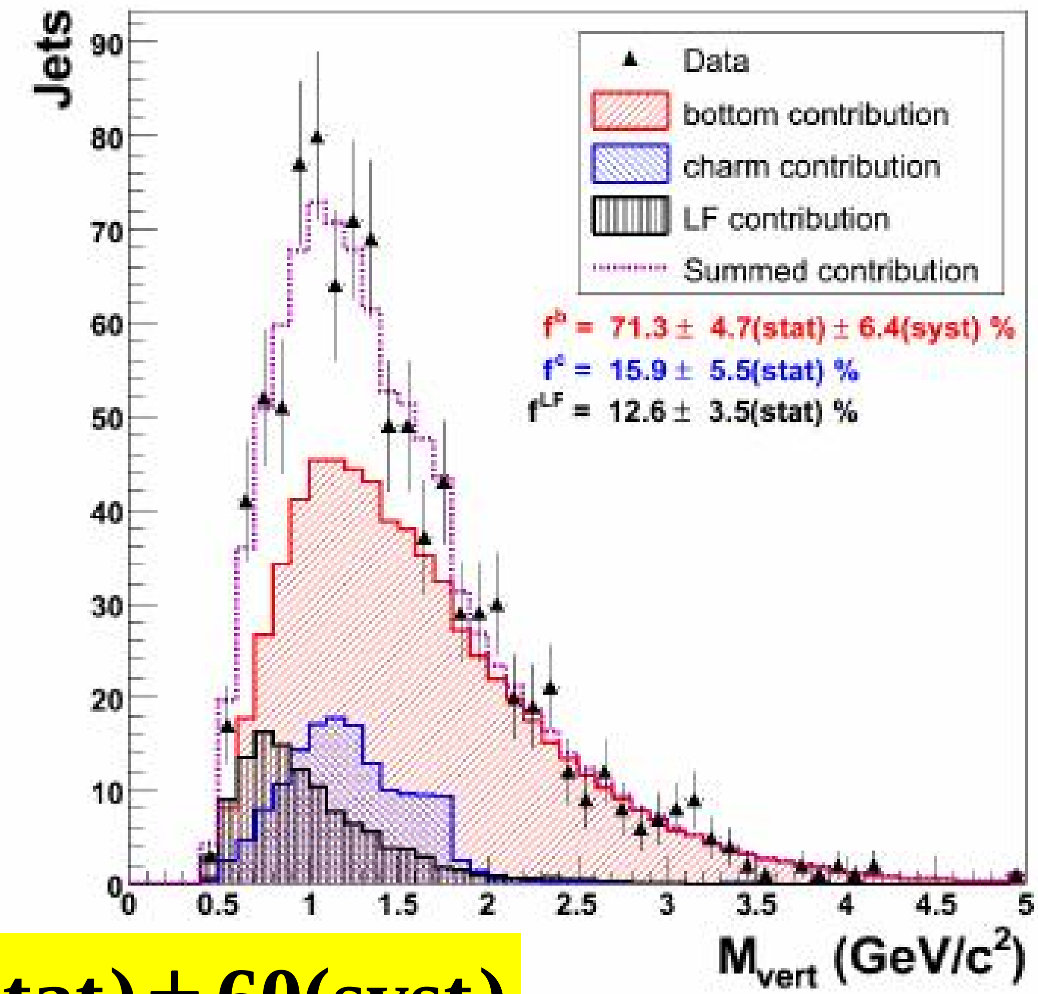
Discrimination with vertex mass

Invariant mass of charged particle tracks in secondary vertex correlated to mass of parent hadron

b-jet distribution: b-matched tagged jets in simulation for W+b jets, ttbar, single top with weighted contributions, all have very similar shapes

c-jet distribution: c-matched tagged jets in simulation for W+c-jets (W+c, W+ccbar)

LF-distribution: non-HF matched tagged jets in simulation for dijets (Jet50) for higher statistics



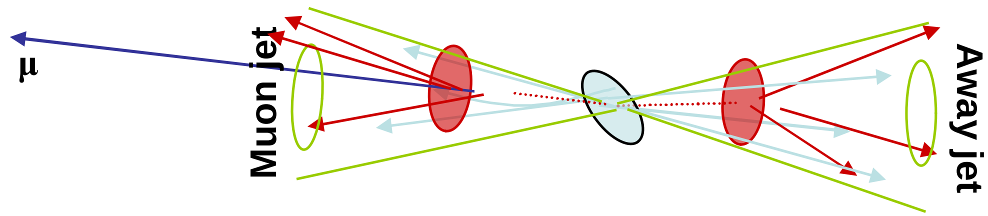
$$n_{tag} \cdot f^b = 670 \pm 44(\text{stat}) \pm 60(\text{syst})$$

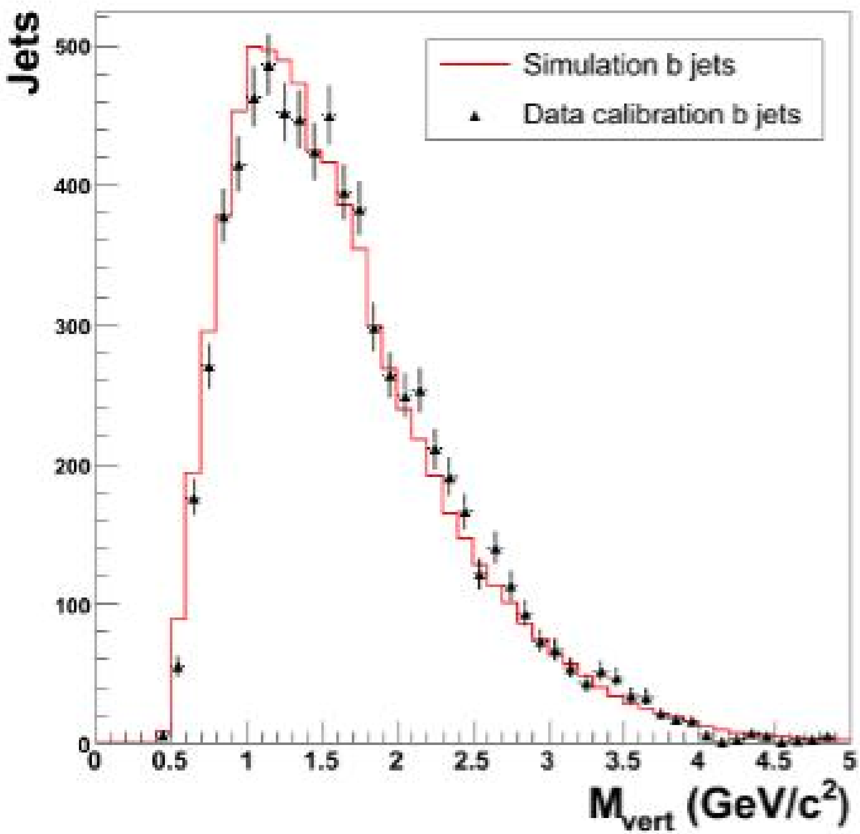
Calibration & Fit systematics

Data-based calibration of vertex mass distribution for *b* jets

Can construct a pure sample of Ultratight tagged *b* jets in data:

- **Trigger: p_T>8 GeV/*c* muon**
- **Back-to-back dijet system:**
  - **Muon jet: UT-tag, M_{vert}>1.7GeV/c^2**
  - **Away jet: UT-tag**
- **Away-jet *b* purity > 99% in Pythia**





- **Data-simulation *b*-jet difference gives a relative $\delta f_b/f_b$ systematic of 8%**

- ***c*, LF shape systematics have smaller effects of 1% and 3%**

Backgrounds with *b* jets

Of the 670 tagged *b* jets, some are from other processes with *b* jets

$$n_{\mathrm{bkg}}^{b\ \mathrm{jets}} = 177 \pm 22$$

MC-based estimate for top, diboson, Z+jets normalized to theoretical predictions

- **Small contribution from W→τν treated as background**

Data-based estimate for non-W

- **Eliminated as much as possible with non-W veto**
- **Use anti-electron sample as MET model**
- **Fit MET distribution to find non-W**
- **Fit vertex mass distribution in anti-electron sample to find fraction of tagged jets that are really *b* jets**

Process	n^b_{W+12j}
$t\bar{t}$	73.1 ± 10.1
s-channel	22.2 ± 9.6
t-channel	33.4 ± 15.0
WZ	9.1 ± 0.9
ZZ	0.28 ± 0.03
WW	0.83 ± 0.12
$W + bb$+Np, $W \to \tau\nu$	7.3 ± 0.8
$Z + bb$+Np, $Z \to e^+e^-$	0.67 ± 0.08
$Z + bb$+Np, $Z \to \mu^+\mu^-$	4.1 ± 0.4
$Z + bb+ \geq$Np, $Z \to \tau^+\tau^-$	1.48 ± 0.20
Non-W	24.5 ± 8.4
Total	176.8 ± 22.3

Acceptance and Phase Space

$$\mathcal{A}_{W+b}^{b\text{ jets}} = \frac{\#\text{ reconstructed } b\text{-matched jets in events passing selection } \&\text{ phase space}}{\#\text{ hadron } b\text{-matched jets in events passing phase space}} = 0.68 \pm 0.03$$

Acceptance factor from ALPGEN *W+b* jets MC corrects for two effects:

- Smearing from fragmentation effects, CDF detector resolution, lower energy for b-jets with semileptonic decays
- Reduction in sample through selection cuts that isolate signal
  - MC events only migrate out due to event vetoes

Recall, phase space requirements are made on stable final state particles and are coincident with our reconstructed event selection:

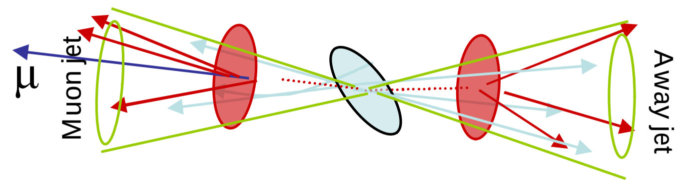
- Lepton p_T>20 GeV/c with $|\eta|$<1.1, and neutrino p_T>25 GeV/c
- One or two hadron-level jets with E_T>20 GeV and $|\eta|$<2.0
- Hadron-level jets (SPARTYJET) use final state particles and same cone algorithm; *b* jet is a jet matched within ΔR<0.4 to a *b* quark (after showering)

b-jet Identification Efficiency

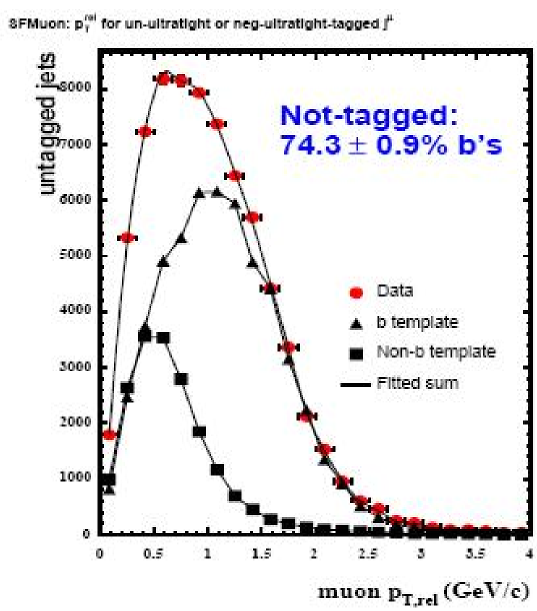
Measure tag efficiency for reconstructed *b* jets in ALPGEN *W+b* jet simulated samples passing event selection and correct with MC-to-data scale factor

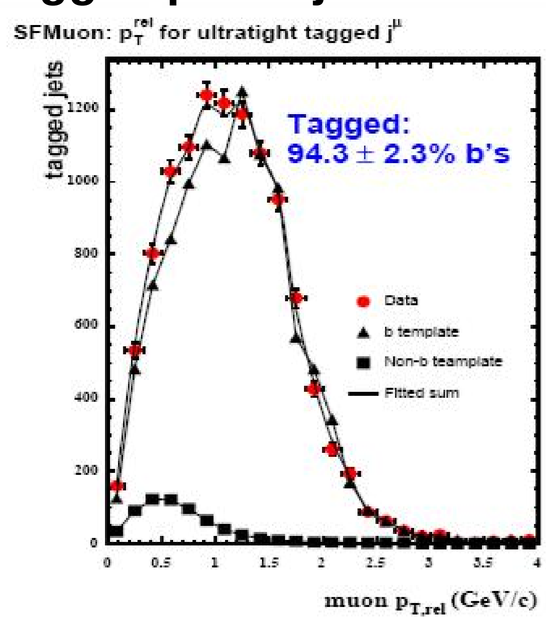
$$\varepsilon^{b}_{\mathrm{tag}} = 0.16 \pm 0.01\ (\mathrm{syst})$$

Measuring the tag efficiency in the data



- **Dijet events**
- **Enhance HF content with UT away-jet**
- **Require muon in probe jet**
- **Muon's momentum relative to jet discriminates *b* from non-*b***
- **Fits for *b* fraction in tagged, untagged probe jets to extract efficiency**





CDF Note 8640

W+b jets: Result

$$\sigma_{b\ jets} \times B(W \to \ell\nu) = \frac{n_{\mathrm{tag}} \cdot f^{b} - n_{\mathrm{bkg}}^{b\,\mathrm{jets}}}{L \cdot A_{W+b}^{b\,\mathrm{jets}} \cdot \varepsilon_{\mathrm{tag}}^{b} \cdot \varepsilon} = 2.74 \pm 0.27_{\mathrm{stat}} \pm 0.42_{\mathrm{syst}}\ \mathrm{pb}$$

Where do various pieces come from?

Discriminate *b* jets from *c*/LF jets in tagged sample using **vertex mass**

$$n_{\mathrm{tag}} \cdot f^{b} = 670 \pm 44$$

Determine contribution from **background** with tagged *b* jets and subtract from overall yield

$$n_{\mathrm{bkg}}^{b\ \mathrm{jets}} = 177 \pm 22$$

Calculate **acceptance** for *W*+*b*-jet events

$$A_{W+b}^{b\ \mathrm{jets}} = 0.68 \pm 0.03$$

Measure **tag efficiency** for *b* jets in *W*+*b*-jet production in MC and correct to match data

$$\varepsilon_{\mathrm{tag}}^{b} = 0.16 \pm 0.01$$

Luminous region, trigger efficiency, lepton id

$$\varepsilon = 0.88 \pm 0.006$$

Summary of systematics

Source	$\frac{\delta_{\sigma_{b-\text{jets}} \times BR}}{\sigma_{b-\text{jets}} \times BR}$ (%)
b shape modeling	8
c shape modeling	1
LF shape modeling	3
UT tag efficiency	6
Luminosity	6
Top Cross Sections	2
Fake $W^{\pm}$ $\not{E}_T$ fits	1
Tagged Fake $W^{\pm}$ b fraction	1
Jet Energy Scale	3
Q^2	3
PDF	2
$\lvert z_0 \rvert$ efficiency	<1
Trigger efficiency	<1
Lepton ID efficiency	<1

Reduced modeling systematics thanks to ultra-tight b-tag that yields purer sample 6% on 71% b fraction instead of 33% b fraction

Very small uncertainty from non-W thanks to veto, anti-electron method, fit for b-fraction

Conclusions & Future Work

First publication on *W+b*-jets production from CDF, better than 20% precision with 1.9 fb^{-1}

$$\sigma_{b\,jets} \times B(W \to \ell \nu) = 2.74 \pm 0.27_{\text{stat}} \pm 0.42_{\text{syst}}\ \text{pb}$$

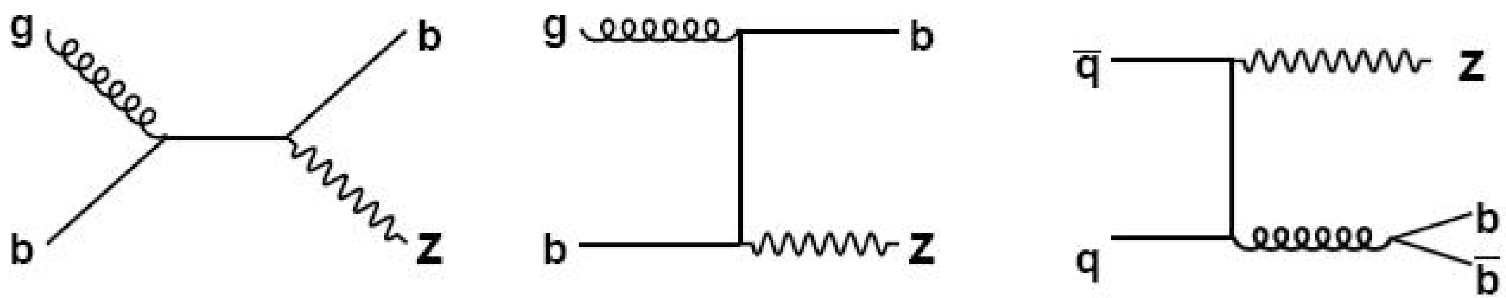
Find 2-3 times larger than predictions

- **MCFM NLO: 1.22±0.14 pb (private communication with authors)**
- **PYTHIA: 1.10 pb**
- **ALPGEN: 0.78 pb (CDF default Q^2 scale)**

Next plan to measure differential cross section with 5 fb^{-1}

- **Important test of model of *W+b*-jets kinematics: an accurate model is critical for robust searches for WH using multivariate techniques that exploit kinematic differences**
- **CDF *Z+b*-jets measurement found indications that default CDF scale set for ALPGEN is not a good model: is the same true for *W+b* jets?**

Measurement of the *b*-jet Cross Section in Events with a *Z* Boson in ppbar Collisions at $\sqrt{s}$ =1.96 TeV



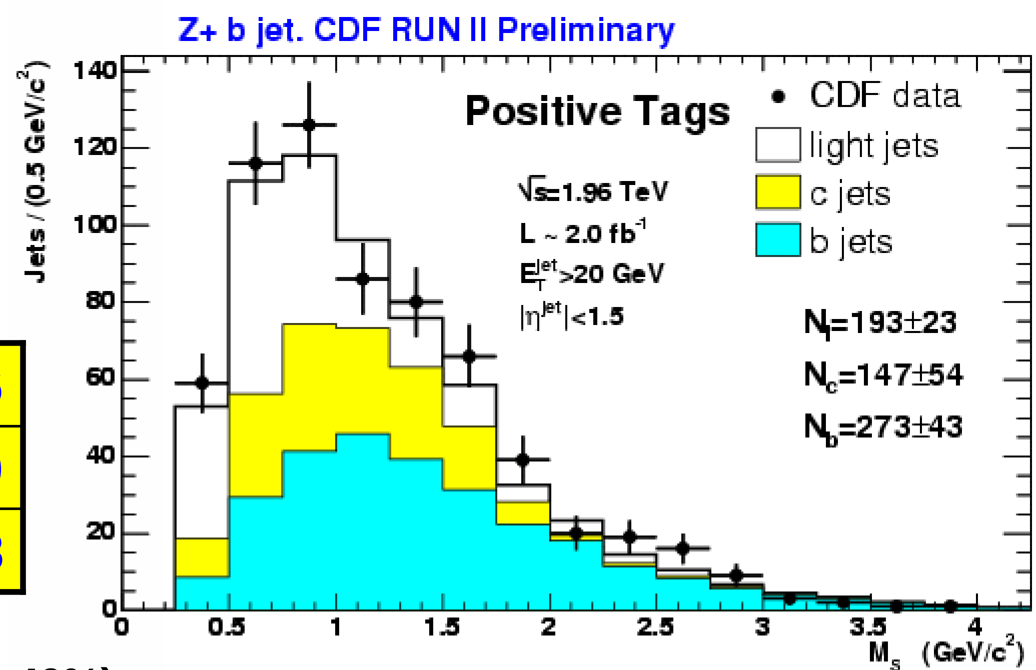
Dedicated measurement of production rate and ratio to inclusive Z production, with differential rates, published in PRD 79, 052008 (2009)

(Z+b jet)/Z= 3.32 $\pm$ 0.53 (stat) $\pm$ 0.42 (syst) x10^{-3}

Z+b-jets

- §Dilepton (ee, μμ) with invariant mass [76,106] GeV/c^2
- §Jet selection: E_T>20 GeV and |η|<1.5 with cone size of 0.7

Selected Z events	295,716
Selected Z+j events	47,450
Tagged jets	648



Using default SECVTX, x2 efficiency (30-40%) but x4 contamination from charm and x10 from light flavor relative to ultratight (note "46%" *b-* jet fraction here)

But can exploit by also fitting negative tags to constrain light flavor

Smaller backgrounds from other processes with b-jets (35.2 ±8.6 jets) so constrain in fit rather than subtracting after fit as for W+jets

b-jet backgrounds	e^+e^-	$\mu^+\mu^-$
ZZ	6.5 ± 1.3	4.3 ± 0.9
$t\bar{t}$	1.3 ± 0.3	1.4 ± 0.3
$Z \rightarrow \tau^+\tau^-$ / WW	0.2 ± 0.1	0.1 ± 0.1
fake lepton	16.4 ± 8.2	5.0 ± 2.2

Z+b-jets: Systematics

Source	Uncertainty (%)
E_T, η model	8.0, 2.8
Track efficiency	5.7
b fragmentation	0.8
b to bb jets, c to cc	3.8
Light flavor	1.7
b-tag efficiency	5.3
Jet energy scale	2.4
Fake lepton bkg	1.9
Other bkg	0.8
Total	**12.7**

Vertex mass model: 11% No independent data check for b model. Instead re-weight simulation to match data jet E_T, η; also vary reconstruction and simulation parameters

Results

Ratio of Z+b-jet to Z:

$$\frac{\sigma^{\text{jet}}(Z+b\,\text{jet})}{\sigma(Z)} = (3.32 \pm 0.53(\text{stat.}) \pm 0.42(\text{syst.})) \times 10^{-3}.$$

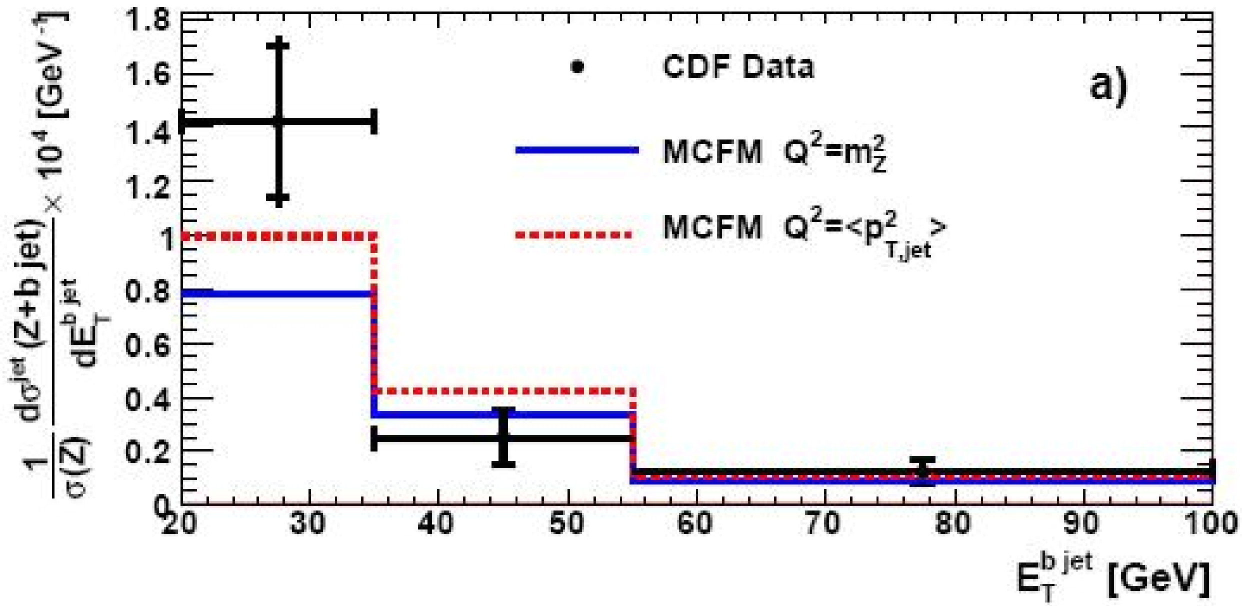
In reasonable agreement with theory, preference for a lower scale

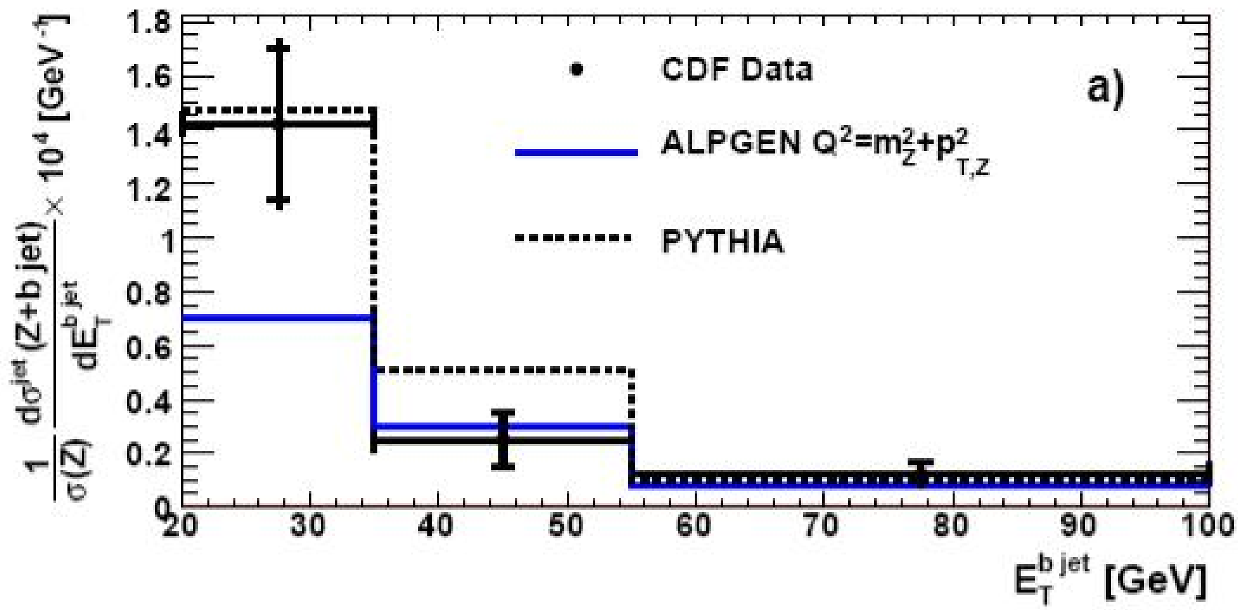
- **MCFM:** **$2.3\text{x}10^{-3}$** $Q^2 = M_Z^2 + p_{\mathrm{T},Z}^2$
- **MCFM:** **$2.8\text{x}10^{-3}$** $Q^2 = \langle p_{\mathrm{T,jet}}^2 \rangle$
- **ALPGEN:** **$2.1\text{x}10^{-3}$** $Q^2 = M_Z^2 + p_{\mathrm{T},Z}^2$
- **PYTHIA:** **$3.5\text{x}10^{-3}$**

$$\sigma_{b\,jets} \times B(Z \to aa) = \frac{\sigma^{\mathrm{jet}}(\mathrm{Z+b-jet})}{\sigma(\mathrm{Z})} \times 254.9 = 0.85 \pm 0.14_{\mathrm{stat}} \pm 0.12_{\mathrm{syst}}\ \mathrm{pb}$$

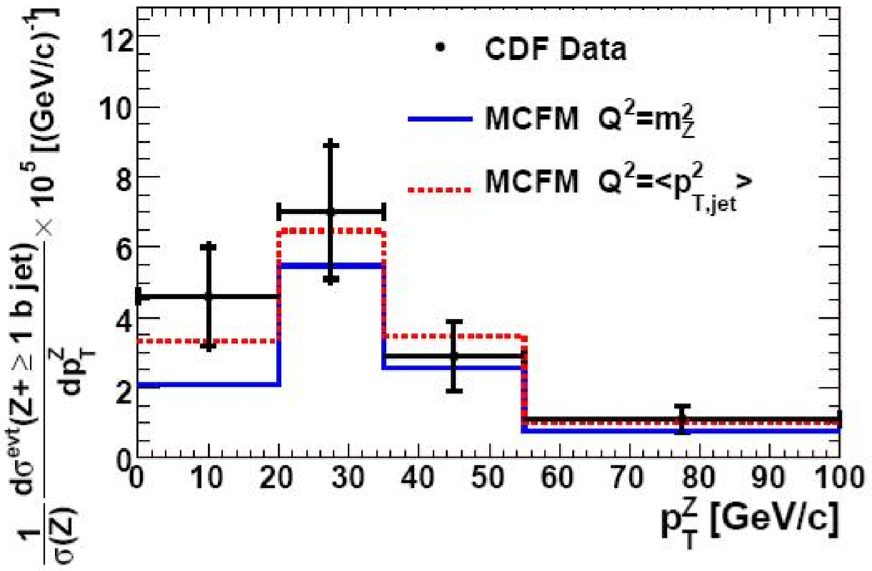
For jets with E_T>20 GeV and |η|<1.5 and cone of 0.7

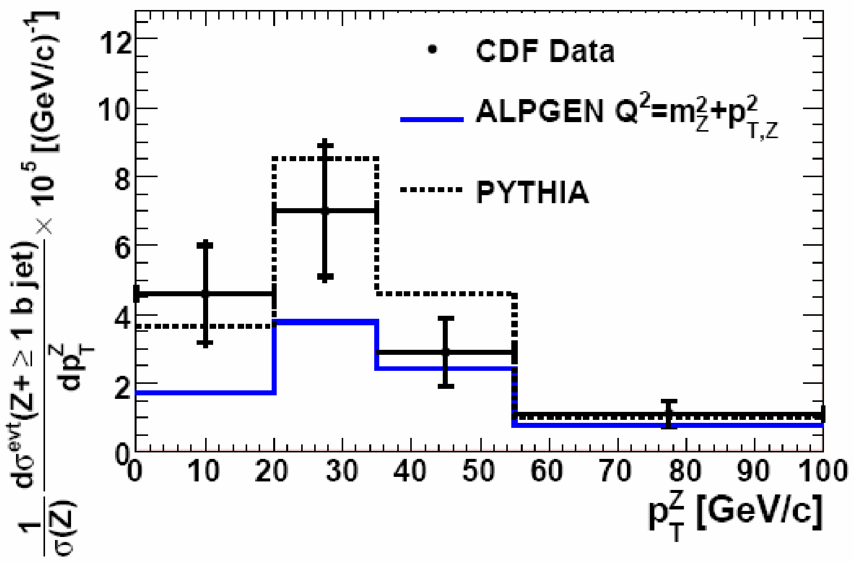
Differential rate vs jet E_T



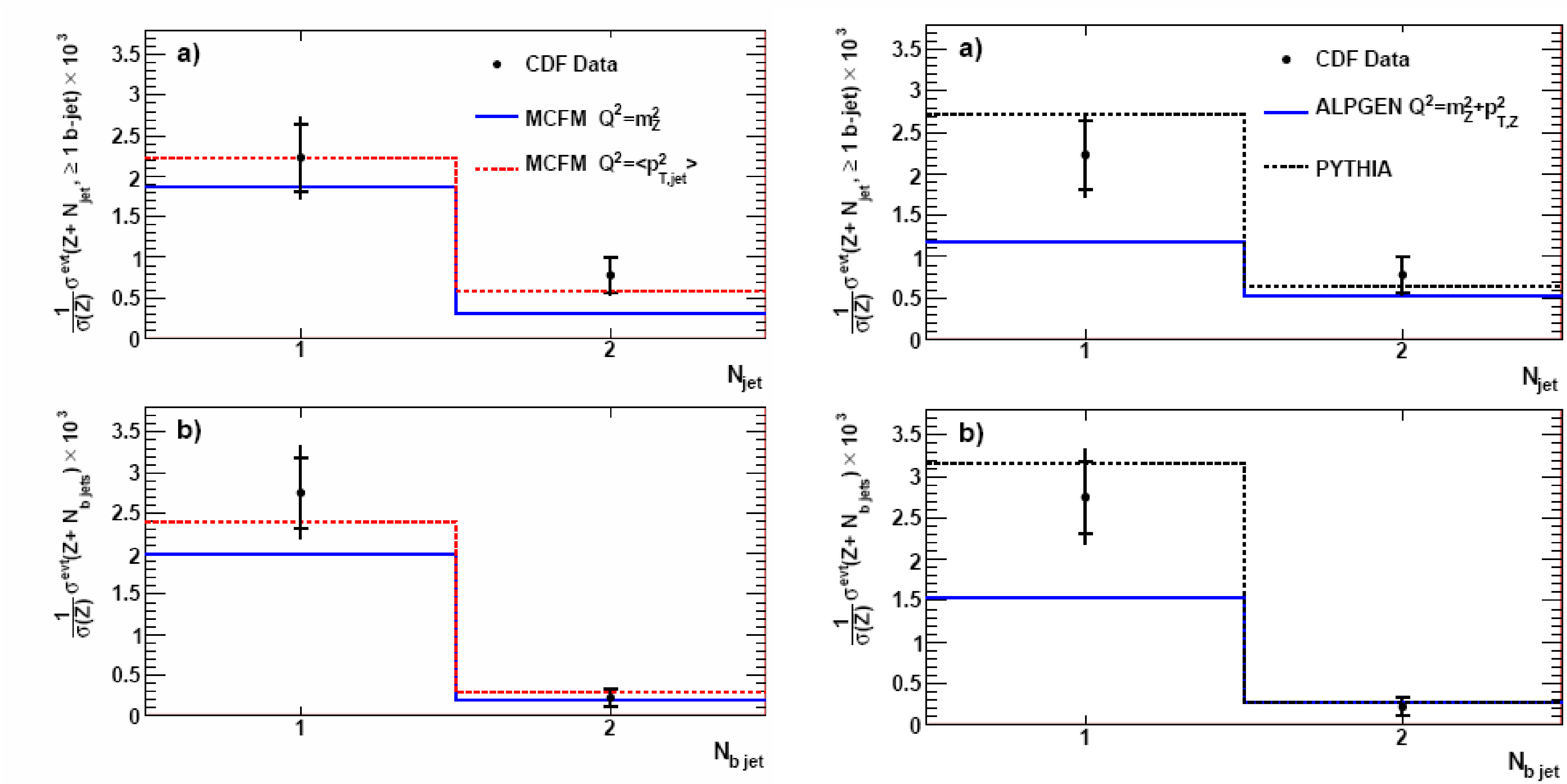


Differential rate vs Z boson p_T





Differential rate vs Number of jets

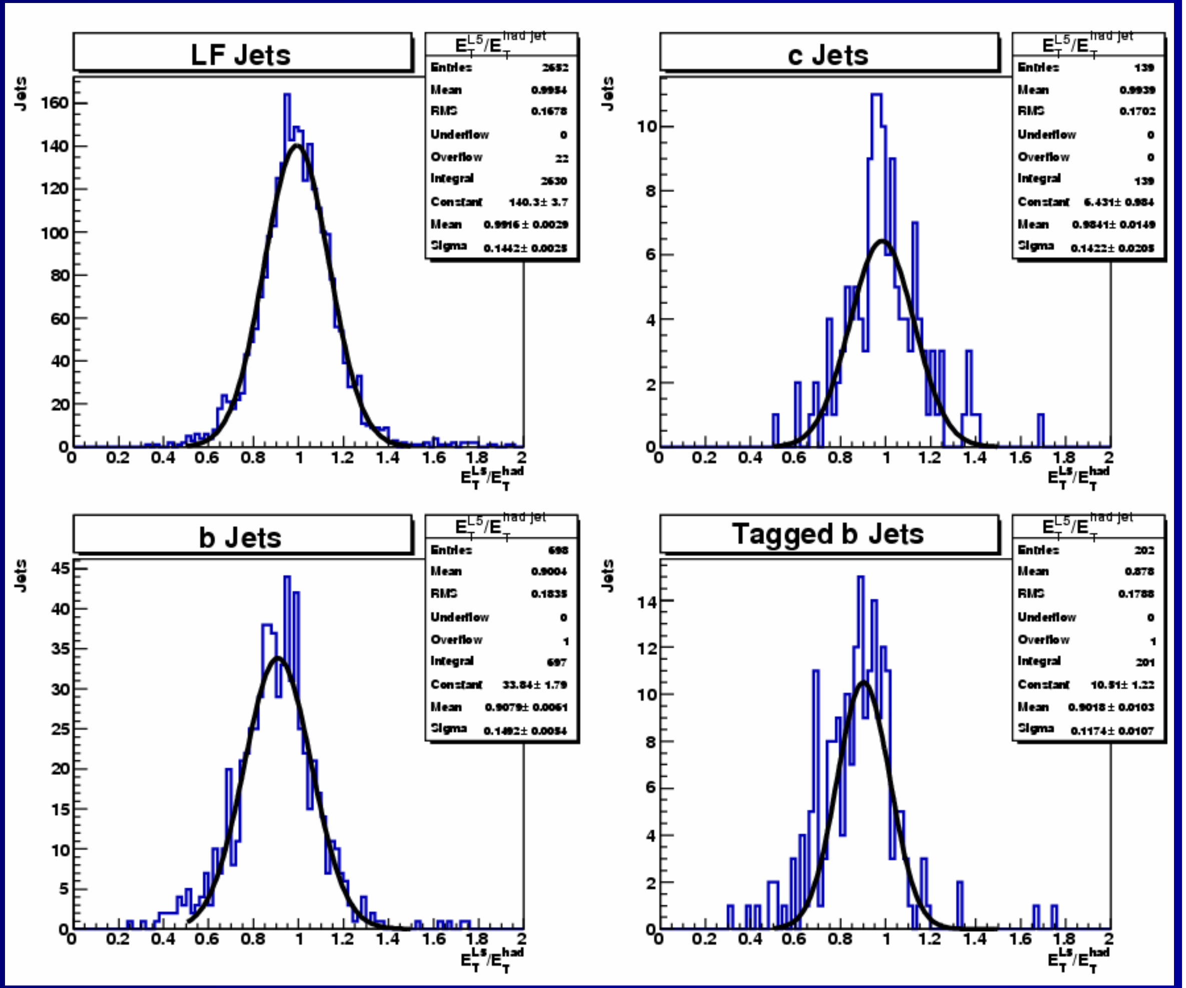


Summary

- W+b-jets rate 2-3 times higher than predictions
  - Differential rates will be measured soon
- Z+b-jets rate in reasonable agreement with predictions
  - Preference for lower scale than $Q^2 = M_Z^2 + p_{\mathrm{T},Z}^2$
  - Jet E_T quite different than default hadron collider ALPGEN prediction, which is used to construct multi-variate discriminant for ZH search

Hadron-level Jets

- Jets without the calorimeter!
  - SpartyJet: Software provides jet clustering on raw particles
  - Some knowledge of CDF geometry
  - Glimpse of "truth" jets
- Convention: exclude *W* daughters but make jets out of everything else
- Natural mismatch wrt measured jet E_Ts
  - effect largest for *b* jets



Measured b-jet energies are ~10% low on average wrt "truth".
Agreement better for LF, *c* jets.

Veto of Events with Fake *W* (aka NonW, aka QCD)

Keep event if…

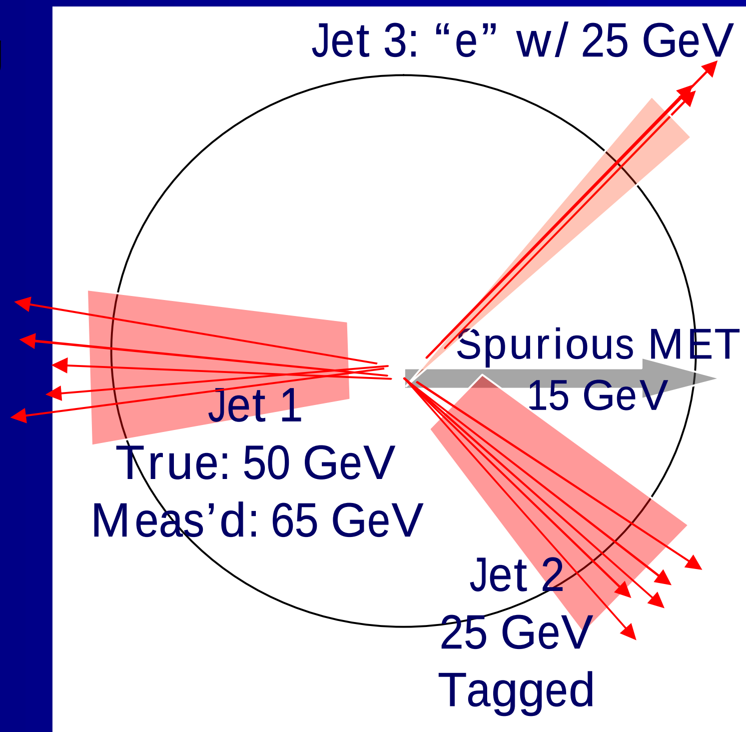
	1 Jet	2 Jet
CEM	• $M_T(W) > 20$ GeV • $S_{MET} \geq -0.05 * M_T(W) + 3.5$ • $S_{MET} \geq -7.6 + 3.2 * \Delta\varphi$(ª,j1)	• $M_T(W) > 20$ GeV • $S_{MET} \geq -0.05 * M_T(W) + 3.5$ • $S_{MET} \geq 2.5 - 3.125 * \Delta\varphi(MET,j2)$
CMUP	• $M_T(W) > 10$ GeV • $MET \geq -145 + 60 * \Delta\varphi$(ª,j1)	• $M_T(W) > 10$ GeV
CMX	• $M_T(W) > 10$ GeV	• $M_T(W) > 10$ GeV

- Seek to eliminate fake *W* events – mostly QCD multijets – hard to model
- Effective non-*W* removal developed by Karlsruhe group for 1.5+/fb single top analyses
- Exploits features of fake *W* events:
  - Low transverse mass of spurious *W*
  - MET from spurious *W* is less significant
  - Correlations between jets and leptons and MET

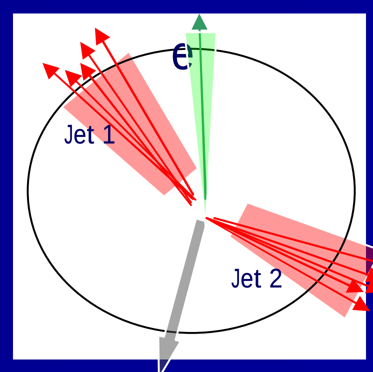
Background Sources of *b* Jets: *b* Jets in Fake *W* Events

- What are fake *W* events?
  - Mostly QCD multijet production mimicking isolated lepton w/ spurious missing energy from mismeasured jets
  - Tagged jets found elsewhere in the event
  - Characterized by:
    - small MET
    - large MET error
    - small W transverse mass
- Strategy here:
  - Remove as much as possible from the start
  - Model what remains using data
- Model for fake *W*: "antielectrons"
  - Most fake electrons *just barely* satisfy electron identification
  - Construct a sample of objects that nearly satisfy electron ID - marginal failures

Fake W Event:

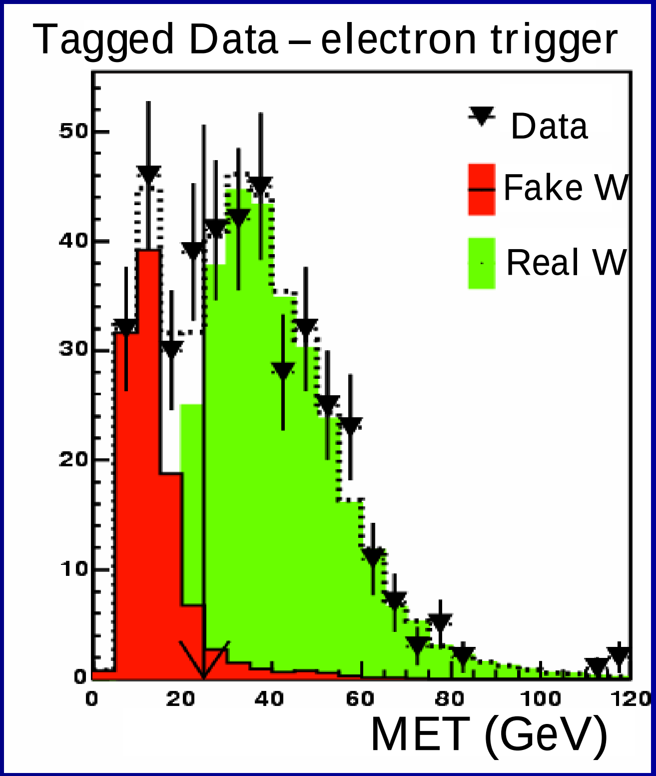


Recall, picture of real *W* event:



Background Sources of *b* Jets: *b* Jets in Fake *W* Events

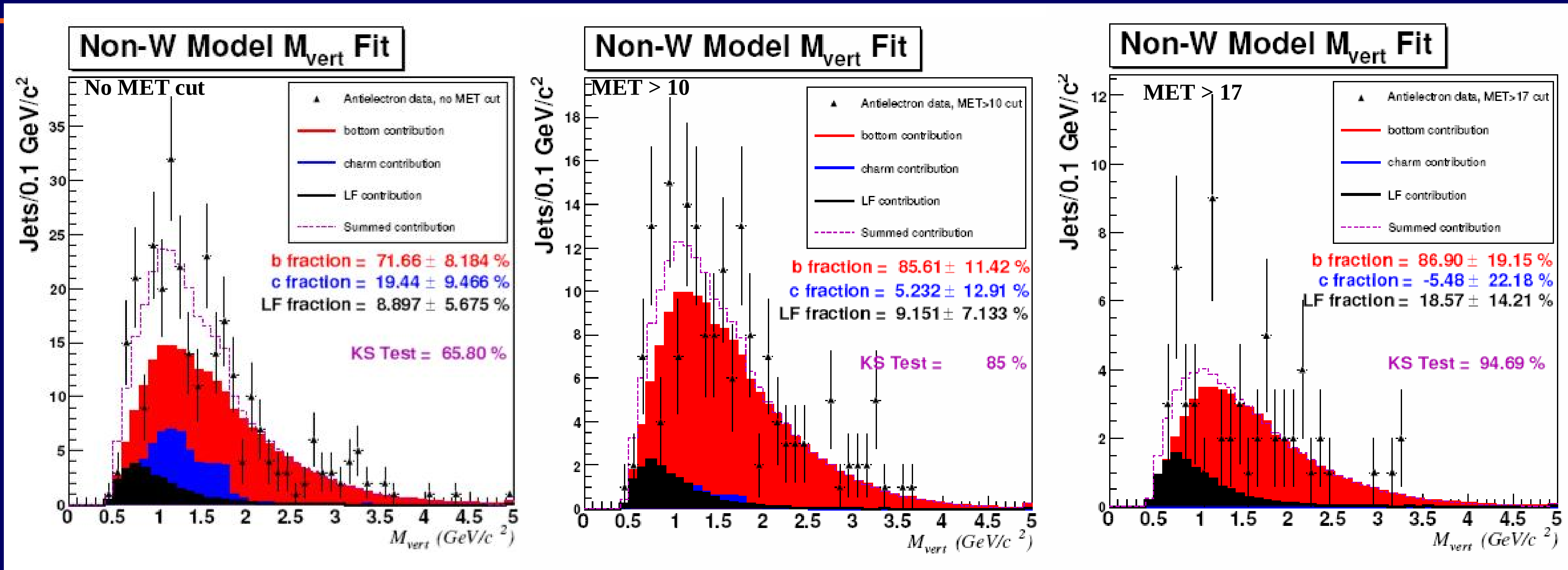
- With model in place can now determine how many tagged jets come from fake *W*
- Procedure:
  1. Use MET – discriminates between real and fake W events
  2. Relax MET cut (for lever arm)
  3. Fit entire data MET dist to shapes from top, single top, *W*+jets, Fake-*W*
  4. Return to MET>25 cut after fit and obtain Fake-*W* fraction
  5. Fit vertex mass of tagged jets to get *b* fraction



From this fit, fake *W* is responsible for 2.9% of tagged jets in electron trigger data.

NB: Here antielectron shape used to model fake W's in the muon trigger sample as well.

Background Sources of *b* Jets: *b* Jets in Fake *W* Events



- Step 5 fails – insufficient stats in antielectron sample with MET>25
- Step through different MET cuts, examine behavior
- As one tightens the MET cut f_b^{QCD} increases

	W + 1 jet	W + 2 jet	W + 1,2 jet
Fake W tags	11.8 +- 3.6	18.8 +- 6.3	**30.6 +- 7.4**
Fake W tagged b	9.4 +- 3.7	15.1 +- 6.3	24.5 +- 8.4

Fit errors only

- Reasonable choice: $f_b^{FakeW} = 0.8 \pm 0.2$