Measurements of the Top Anti-Top Production Cross Section and Top Quark Mass in the Hadronically Decaying τ + Jets Decay Channel at CDF

Daryl Hare
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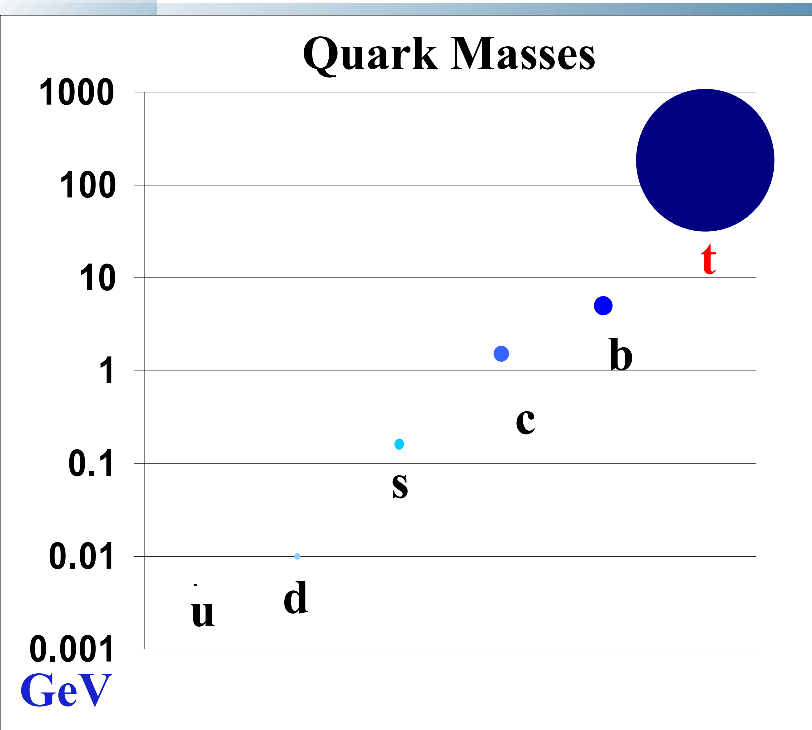
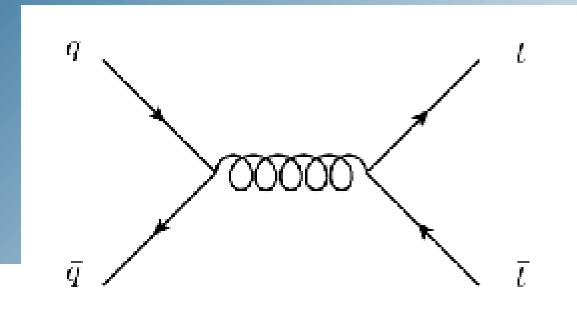
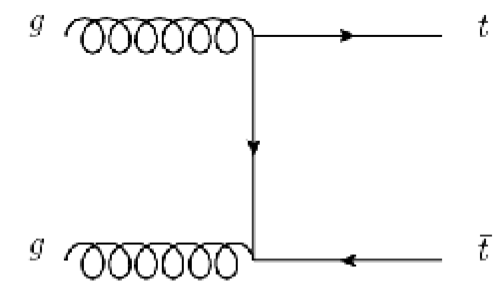
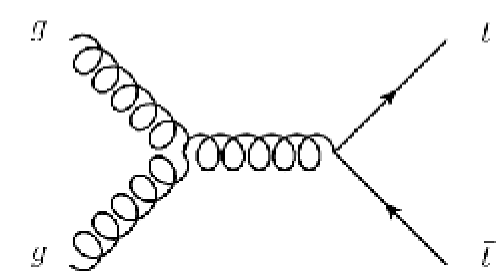
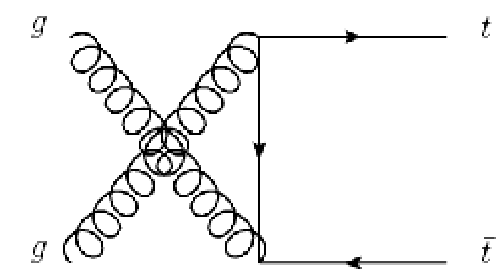


Top Quark





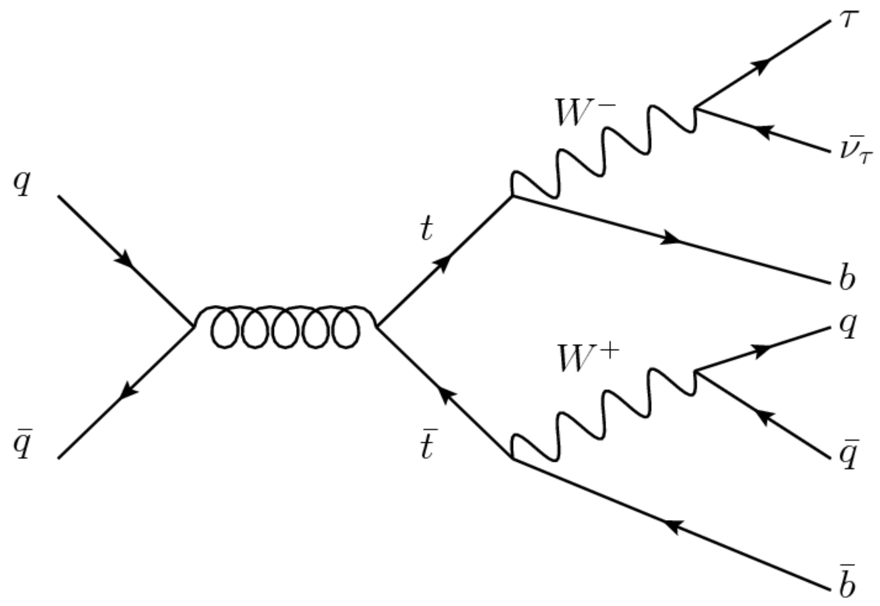


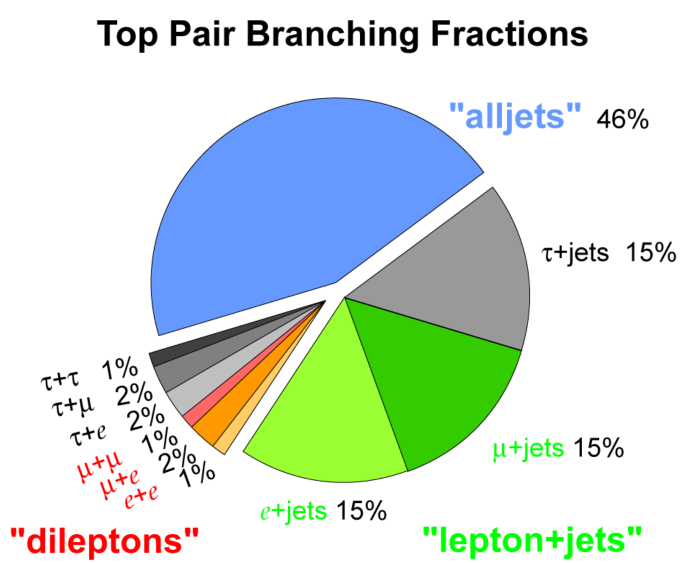


- Discovered during Run I at the Tevatron in 1995
- Produced via qq annihilation (~85%) or gg fusion (~15%)
- Most massive particle in SM
- Only quark to decay (10^{-25}s) before it hadronizes(10^{-24}s)
  - Allows us a unique chance to study it based on daughter particles
- Has a Yukawa coupling to the Higgs of ~1
- Constrains the Higgs mass along with W

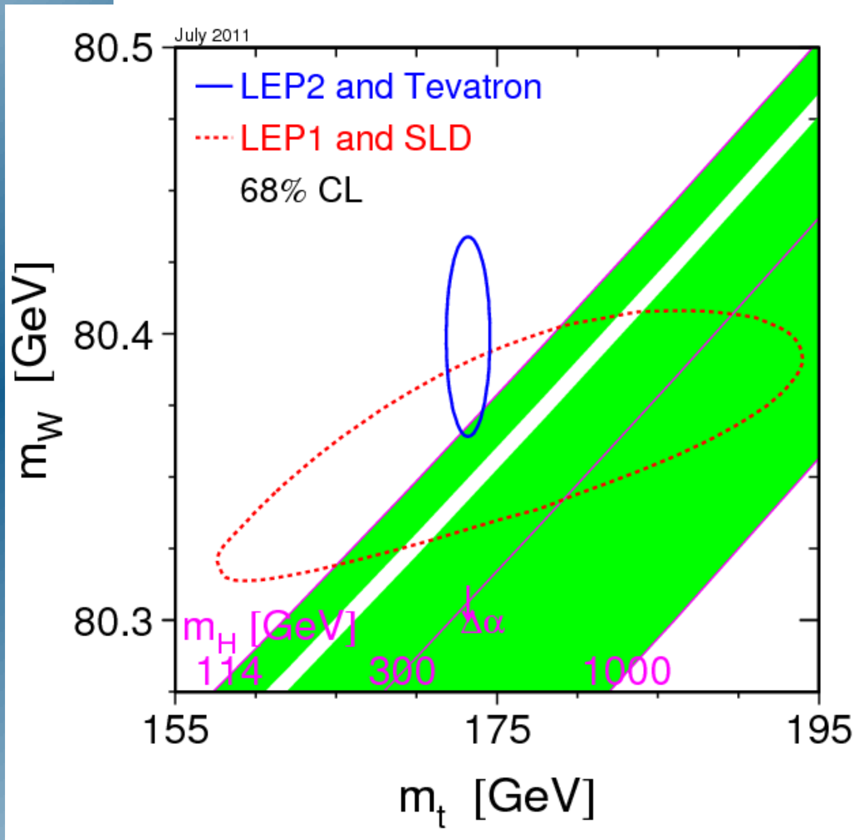
Top Quark Decay

- Top decays to Wb ~100%
- W decays:
  - leptonically (l + ν) - 32.6%
  - hadronically (q + q) - 67.6%
- 3 decay modes of ttbar
  - All Hadronic (“all jets”)
    - Both W's decay hadronically
    - 6 q's (2 b's)
  - Dileptonic
    - Both W's decay leptonically
    - 2 l, 2 ν, 2 b's
  - Semi-leptonic (“lepton + jets”)
    - 1 leptonic and 1 hadronic W decay
    - 1 lep, 1 ν, 4 q's (2 b's)



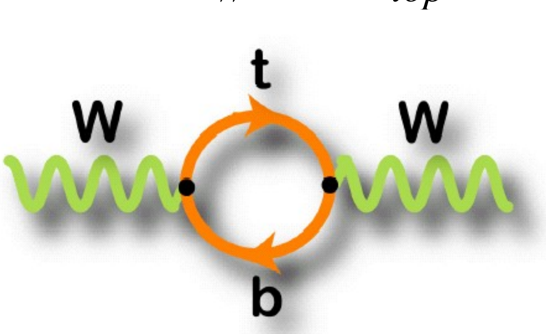


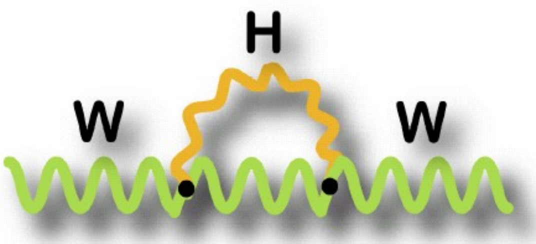
Precision Top Mass



- Particles get mass through interaction with Higgs boson
- Top and W mass constrain the Higgs mass through 1st order loop corrections:

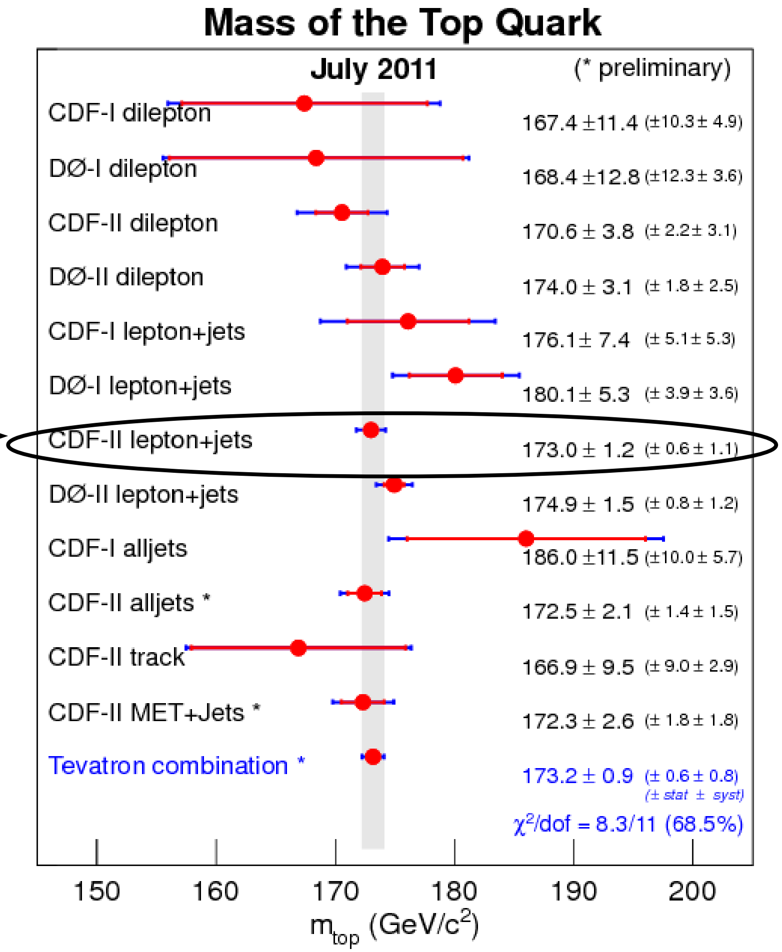
$$\delta M_W \propto M_{top}^2 \qquad \delta M_W \propto \ln M_{Higgs}$$





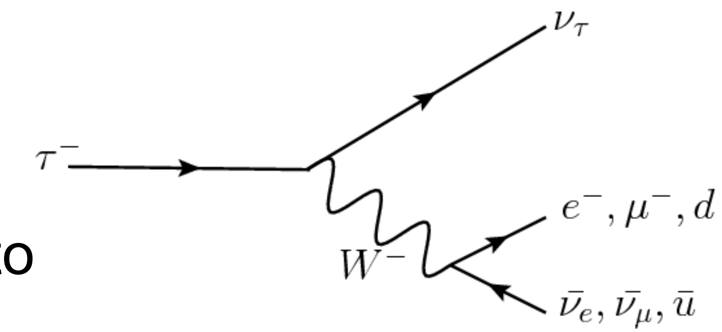
Precision Top Mass Measurements

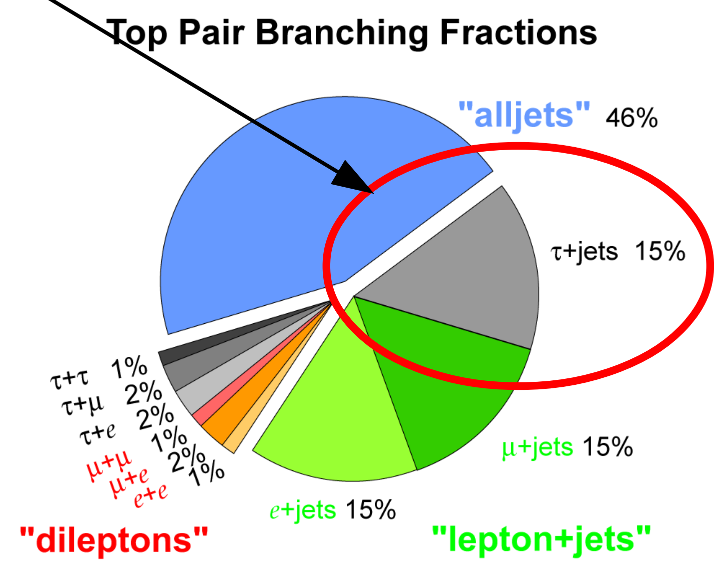
- No direct measurements with tau decay channels
- Lepton + Jets matrix element measurement leads combination



Tau's and Top Decay

- Tau is heaviest of the leptons
  - Kinematically favorable decay for new massive particles
    - Ex: low mass Higgs prefer decay to bb or ττ
- Relatively unexplored section of Top sector
  - 1st top mass measurement in tau decay channel
  - 2nd cross section measurement (D0)
    - We have much purer signal sample
- Test Lepton Universality
- Provide answers for questions about top
  - Is top really top?
  - Is something else (higgs or t') hiding behind the top quark





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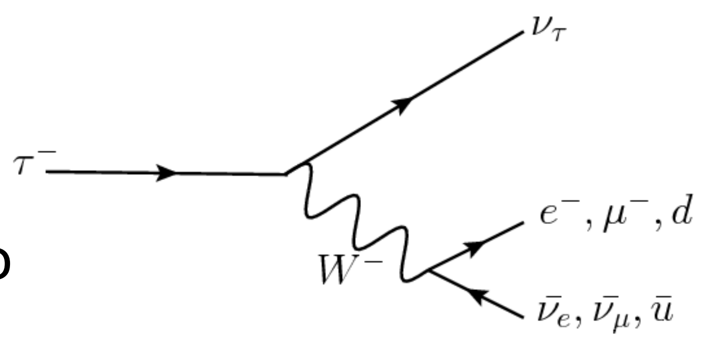
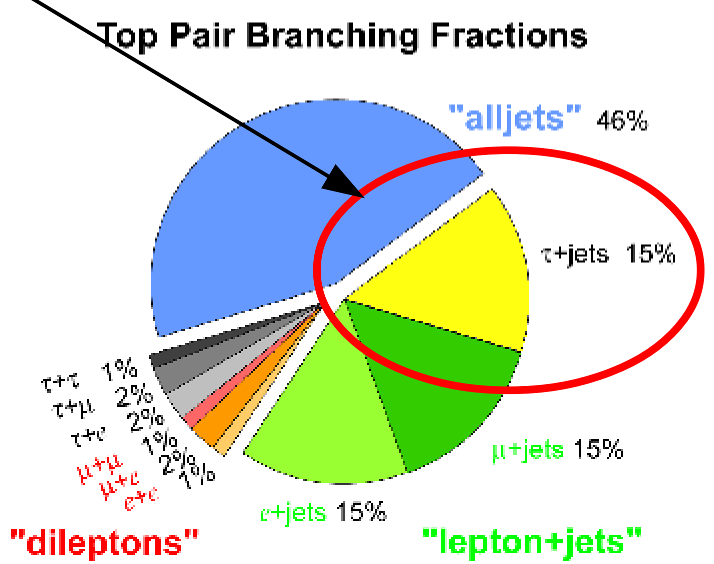
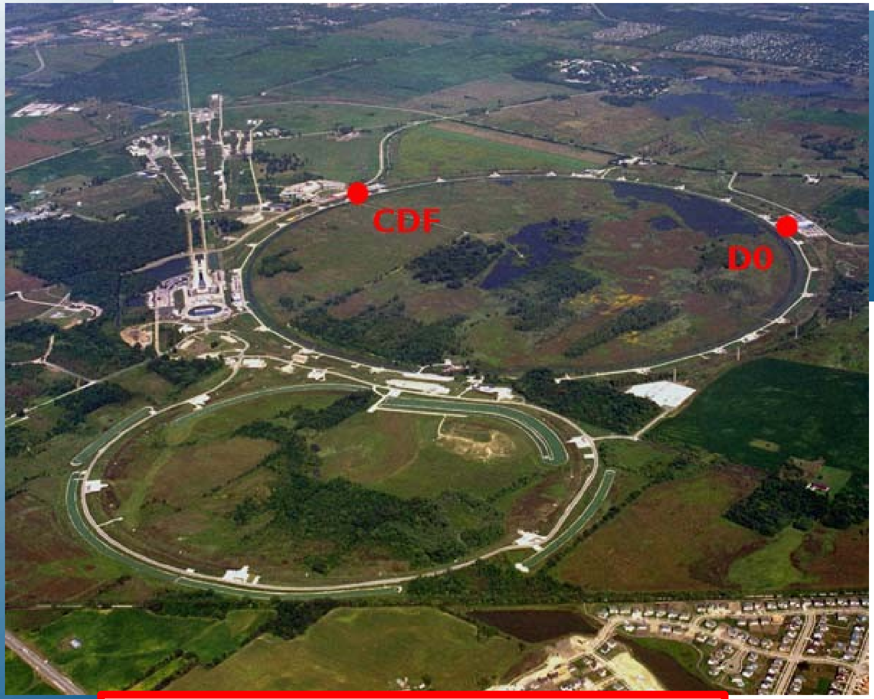
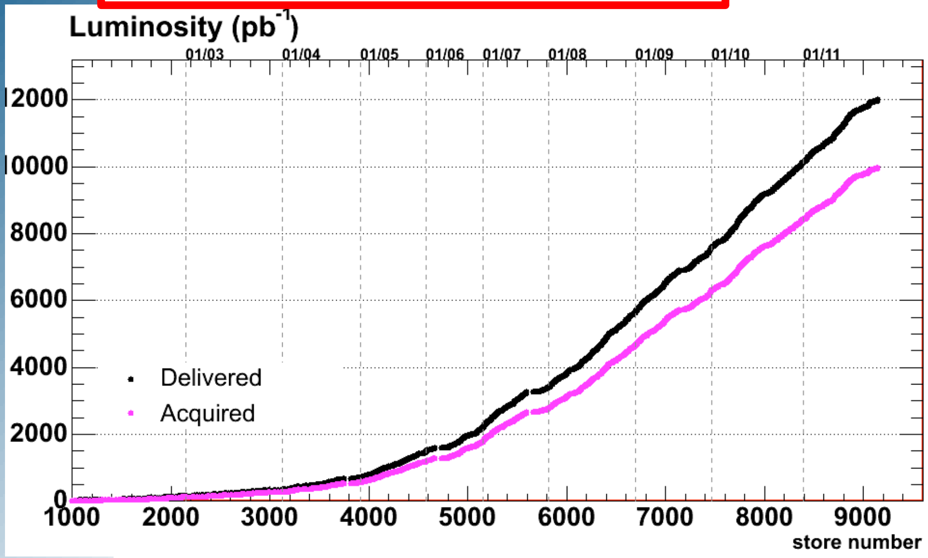




Tevatron

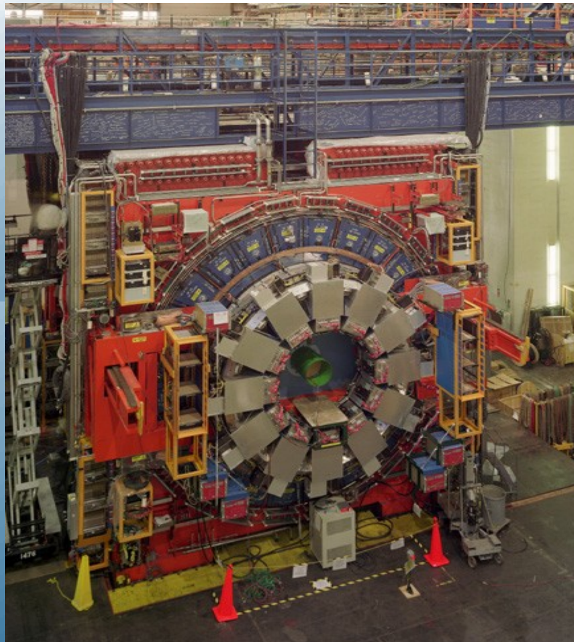


Luminosity:
Delivered: 12.0 fb^{-1}
Acquired: 10.0 fb^{-1}

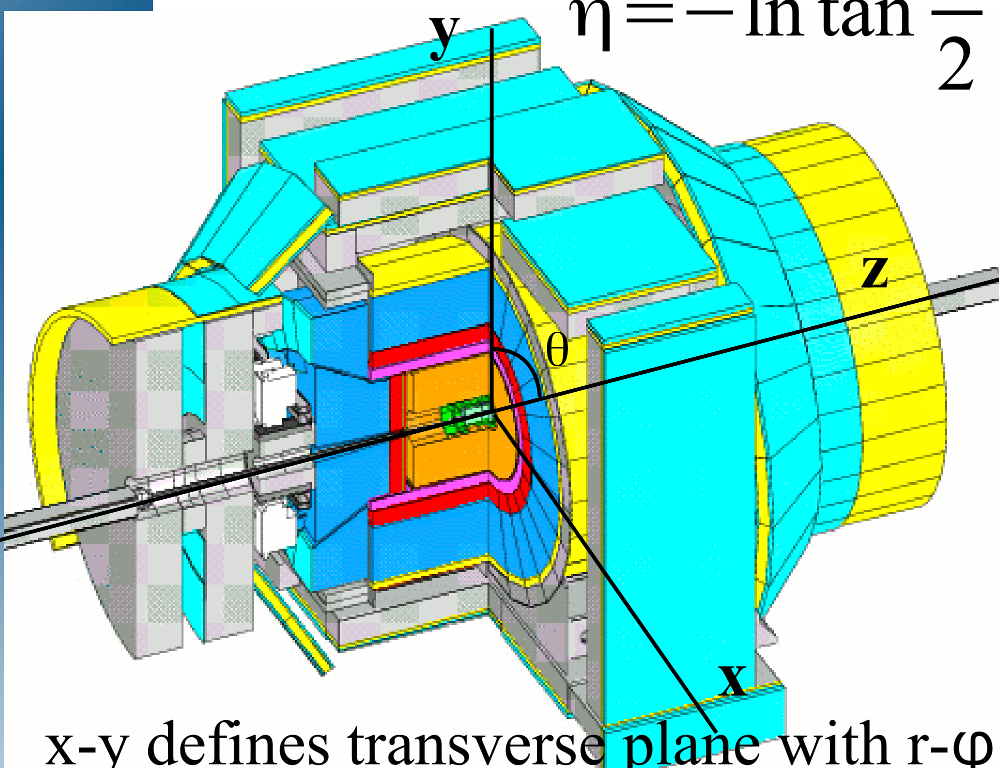


- Require large accelerators with high energy to create top quarks
- Tevatron provided p-pbar collisions at beam energies of 980 GeV for a collision energy, E_{cm},of 1.96 TeV.
- 1 km radius. Particles complete one revolution in ~21 μs.
- 36 bunches of protons and antiprotons circulate in the beam pipe.
- 2 intersection points located at CDF and D0.
- Run II ended Sept 30th, 2011
  - Tevatron performed well to the end

CDF Detector



$$\eta = -\ln \tan \frac{\theta}{2}$$



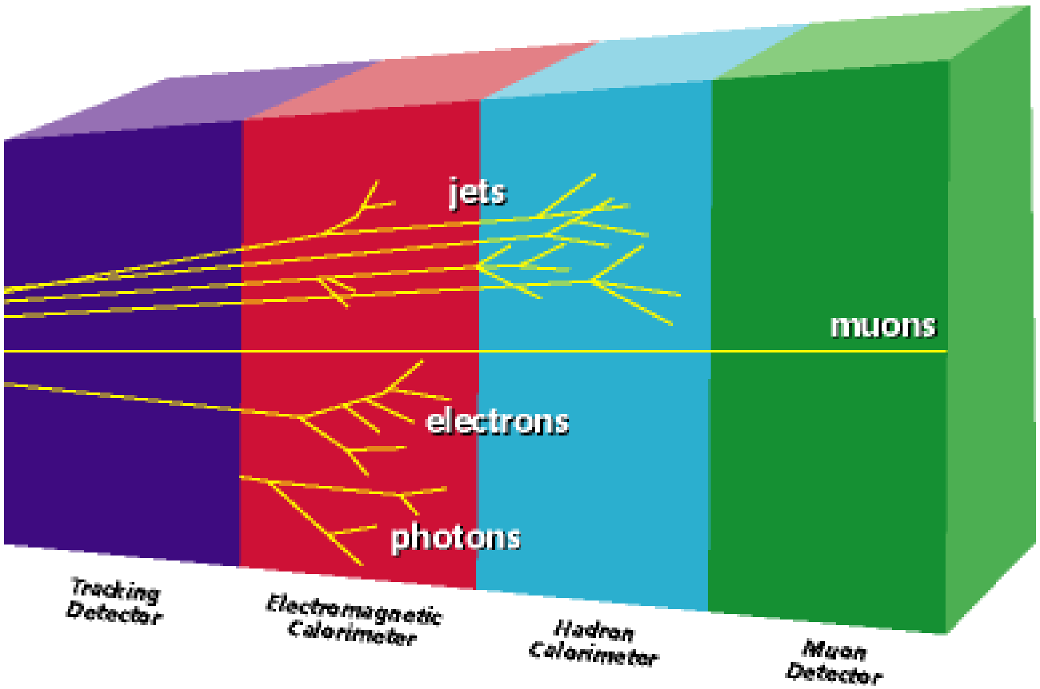
x-y defines transverse plane with r-φ

- Silicon Detector (Green)
  - high precision tracking and secondary vertex detection
- COT (Orange)
  - Drift chamber used for tracking in central region
- Solenoid (Purple)
  - Provides magnetic field of ~1.4 T
- ElectroMagnetic (Red) and Hadronic (Dark Blue) Calorimeters
  - Scintillator detector measuring shower energies
- Muon detection systems (cyan and yellow)
  - Small wire chambers for identifying muon “stubs”
  - Scintillators for triggering and timing of muon events

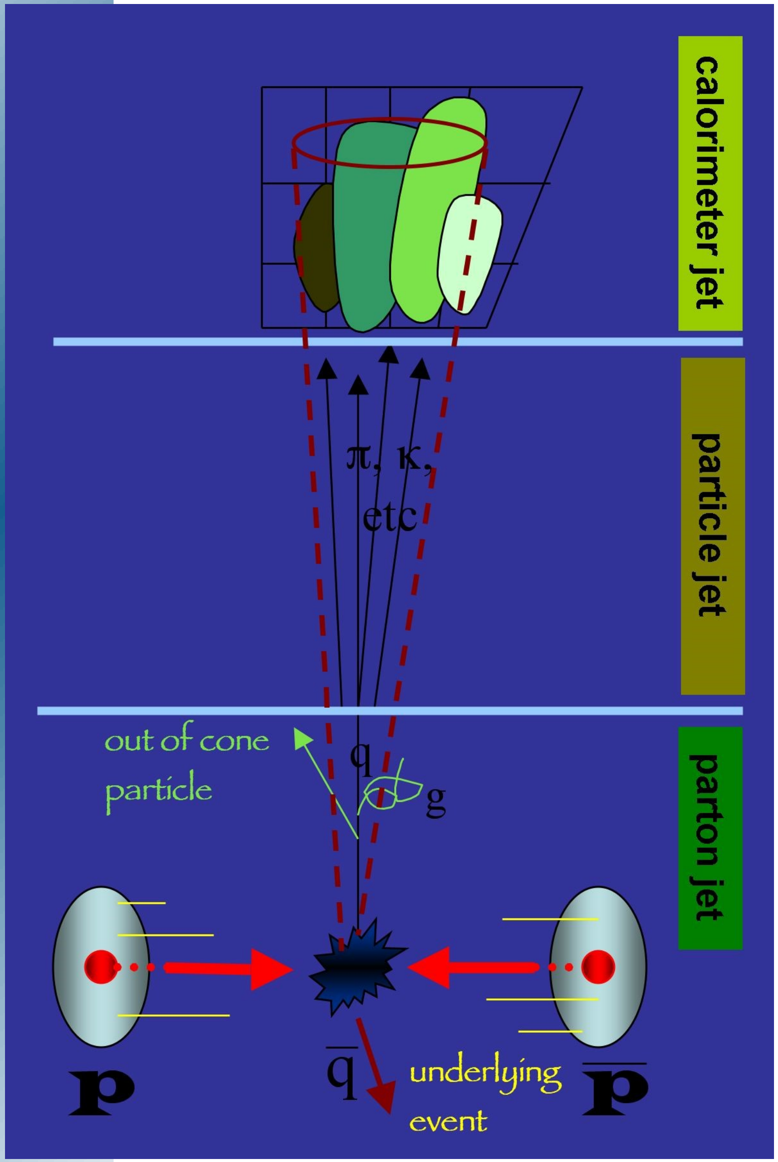
Particle Signature

- Hadronic tau decays to $\pi^{\pm}$ and π^{0}
  - $\pi^{\pm} \rightarrow$ charged track + hadronic calorimeter
  - $\pi^{0} \rightarrow \gamma\gamma$
- Neutrinos:
  - No direct signature
  - Define missing E_T as indicator of missing particles:

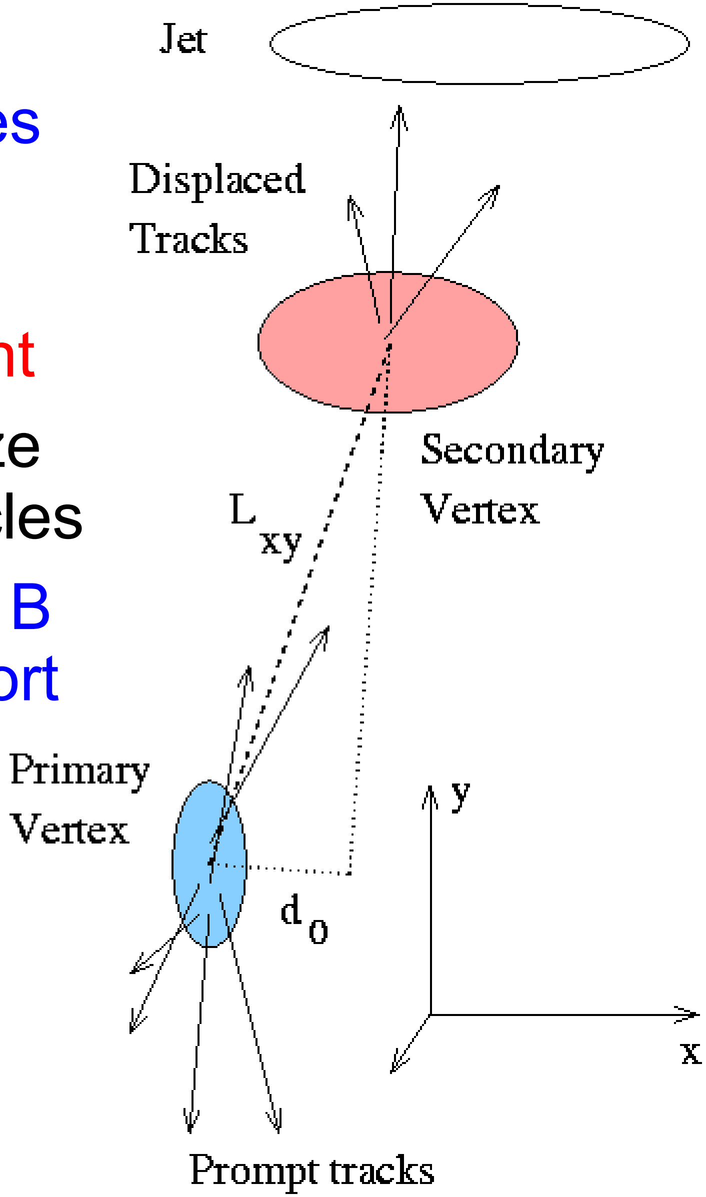
$$\vec{\not{E}}_{\mathrm{T}} = -\sum_{i}^{towers} E_{Ti} \hat{n}_{Ti}$$



What is a Jet?

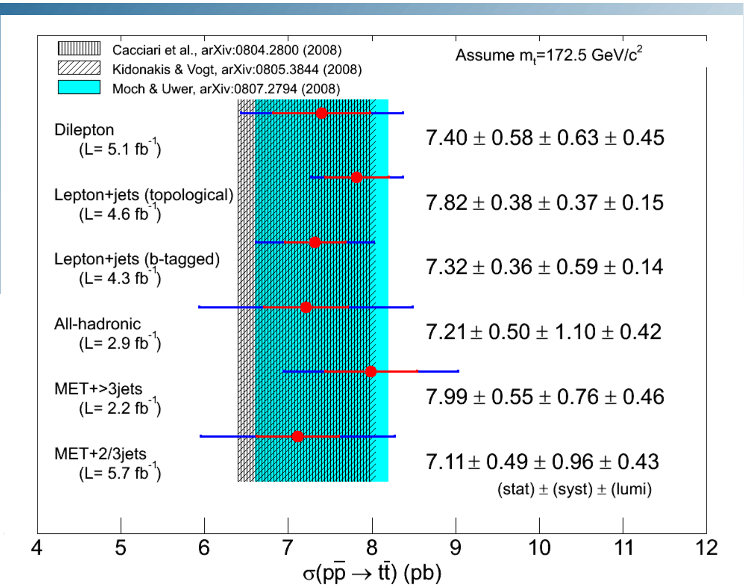


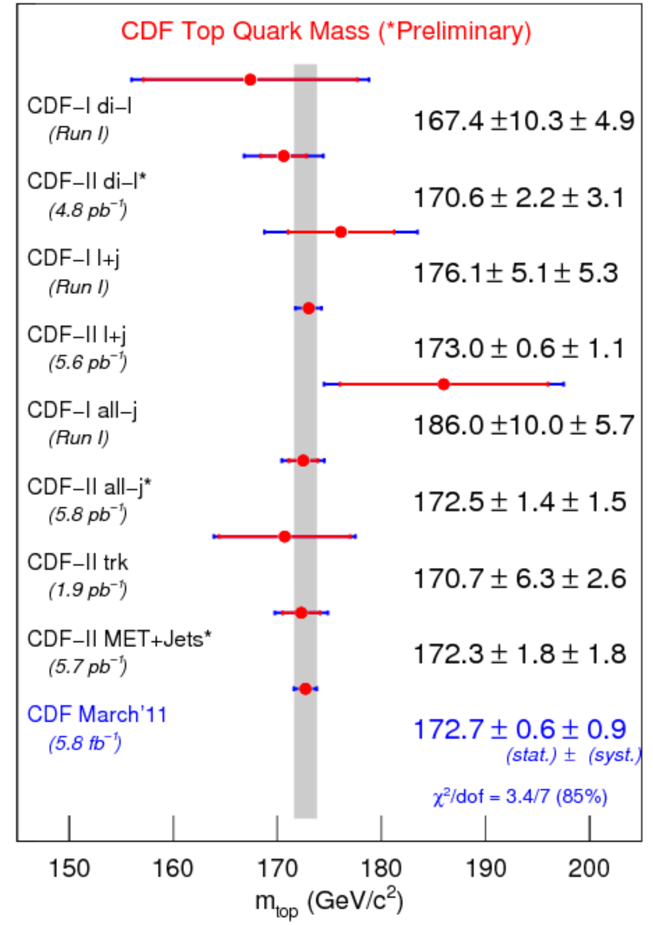
- Strong force does not allow bare quarks
  - Confinement
- Quarks hadronize into jets of particles
- b quarks lead to B hadrons with short lifetimes



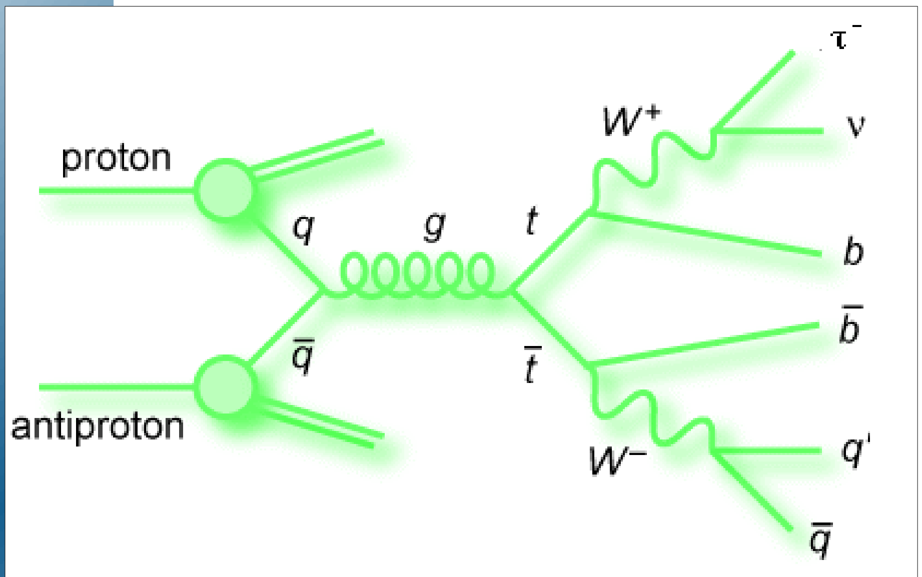
Top Quark Measurements

- Cross Section:
  - CDF Cross Section Combination with 4.6 fb^{-1}
    7.5 ± 0.5 pb
    assuming M_{top} = 172.5 GeV
  - D0 ttbar → τ + jets cross section with 1.0 fb^{-1}
    6.9 ± 2.2 pb
    assuming M_{top} = 170.0 GeV
- Mass:
  - July 2011 Tevatron Combination with 5.8 fb^{-1}
    173.2 ± 0.9 GeV

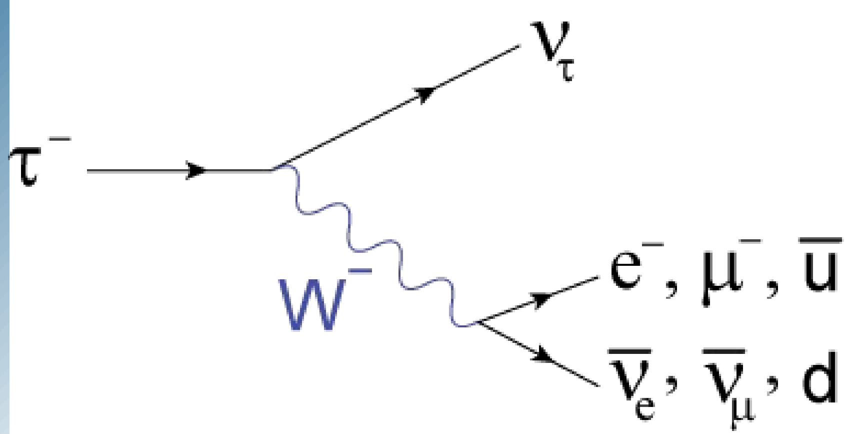




Event Selection
2.2 fb^{-1}



- **Looking for hadronic τ + jets ttbar decay:**
  - 4 jets with E_t > 20 GeV
    - at least 1 b-tagged
  - Missing E_t > 20 GeV
  - **1 hadronically decaying τ**
    - **E_t > 25 GeV**
    - **Looks like narrow jet**
    - **1 or 3 tracks**
- Do not accept leptonically decaying taus:
  - May be included in standard lepton analyses



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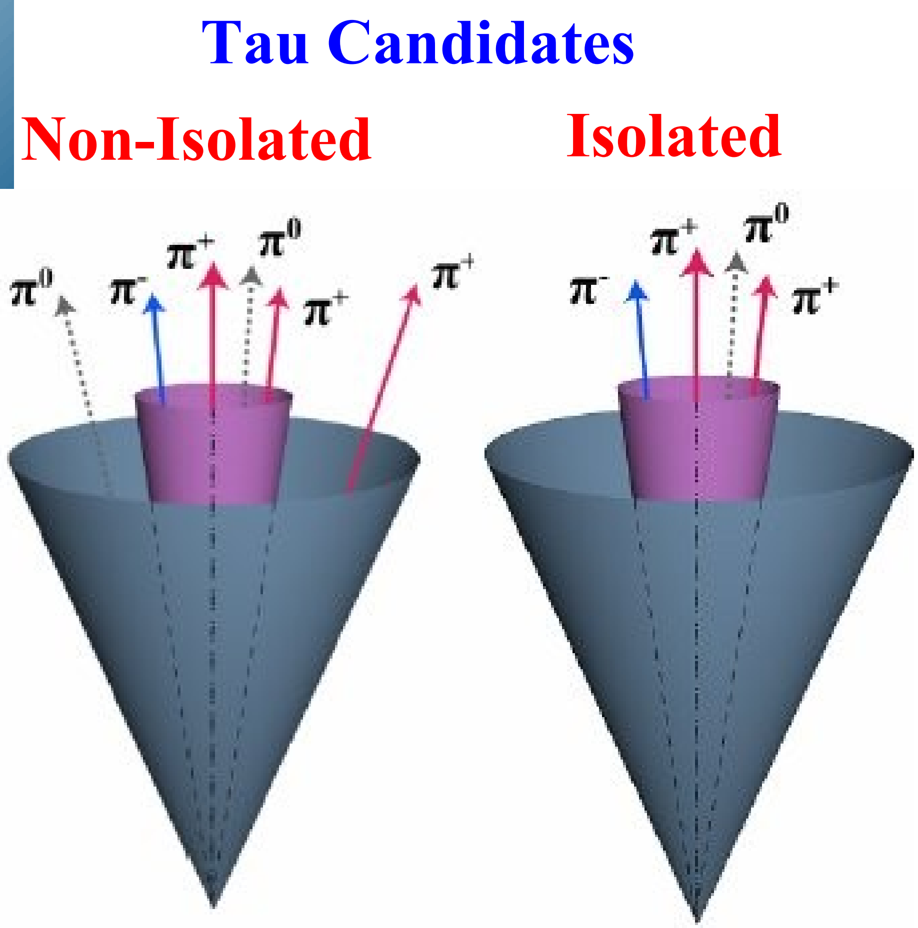
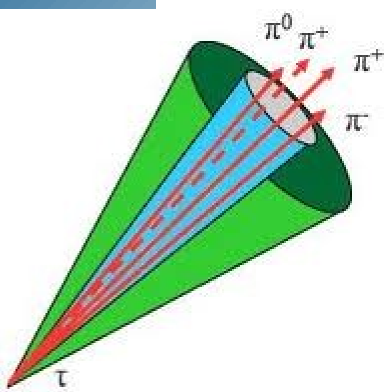
Tau Identification



- Hadronic taus usually decay to $\pi^{\pm}$ and π^{0}.
- Show up as a narrow jet with an odd number of tracks
- We look for narrow calorimeter clusters with a matching "seed" track.
- Define a variable size signal cone around the seed track and a 30 degree isolation annulus around the signal cone.
  - Variable size allows for better jet discrimination

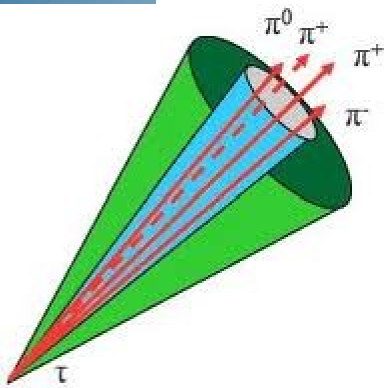
What is Different About Taus?

- **Hadronically decaying tau is essentially a narrow jet**
  - Large QCD Background
- **Taus are harder to measure than e or μ**
  - Hadronically decaying tau includes a neutrino
  - Now ttbar decay has 2 neutrinos

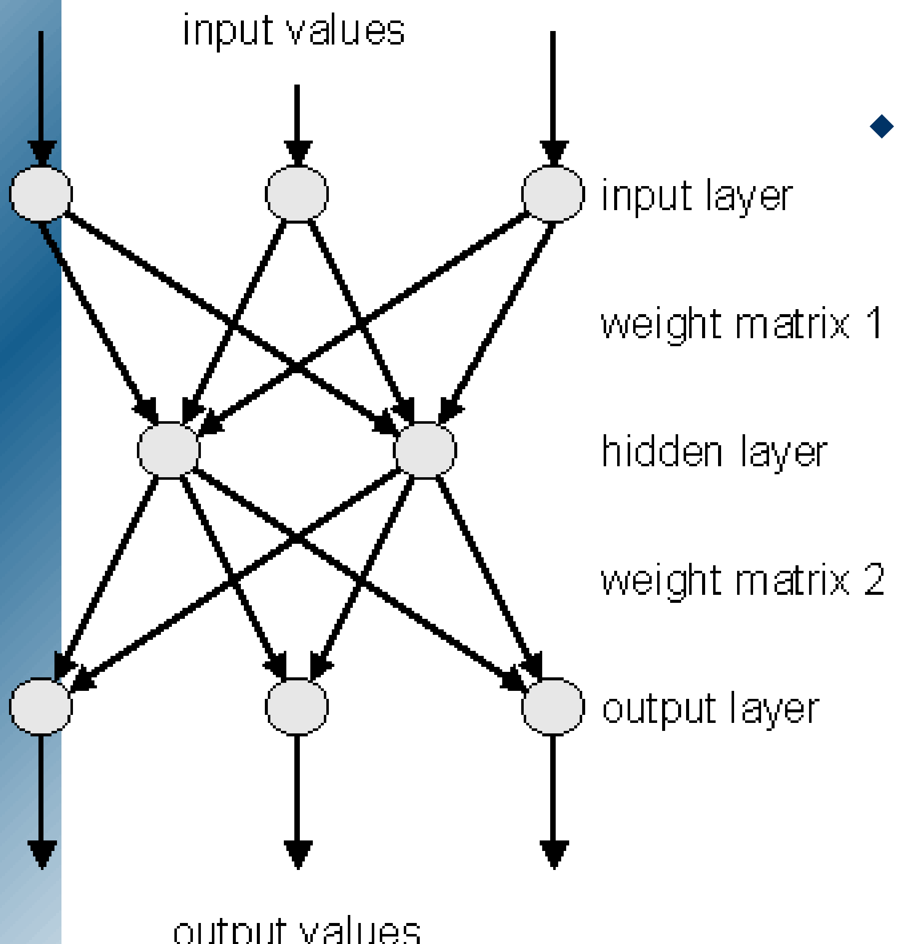


What is Different About Taus?

- **Hadronically decaying tau is essentially a narrow jet**
  - Large QCD Background
  - **Solution: Neural Network to Remove QCD**
- **Taus are harder to measure than e or μ**
  - Hadronically decaying tau includes a neutrino
  - Now ttbar decay has 2 neutrinos
  - **Relevant to tau energy, but not identification. Will revisit this when discussing mass measurement.**



Neural Network

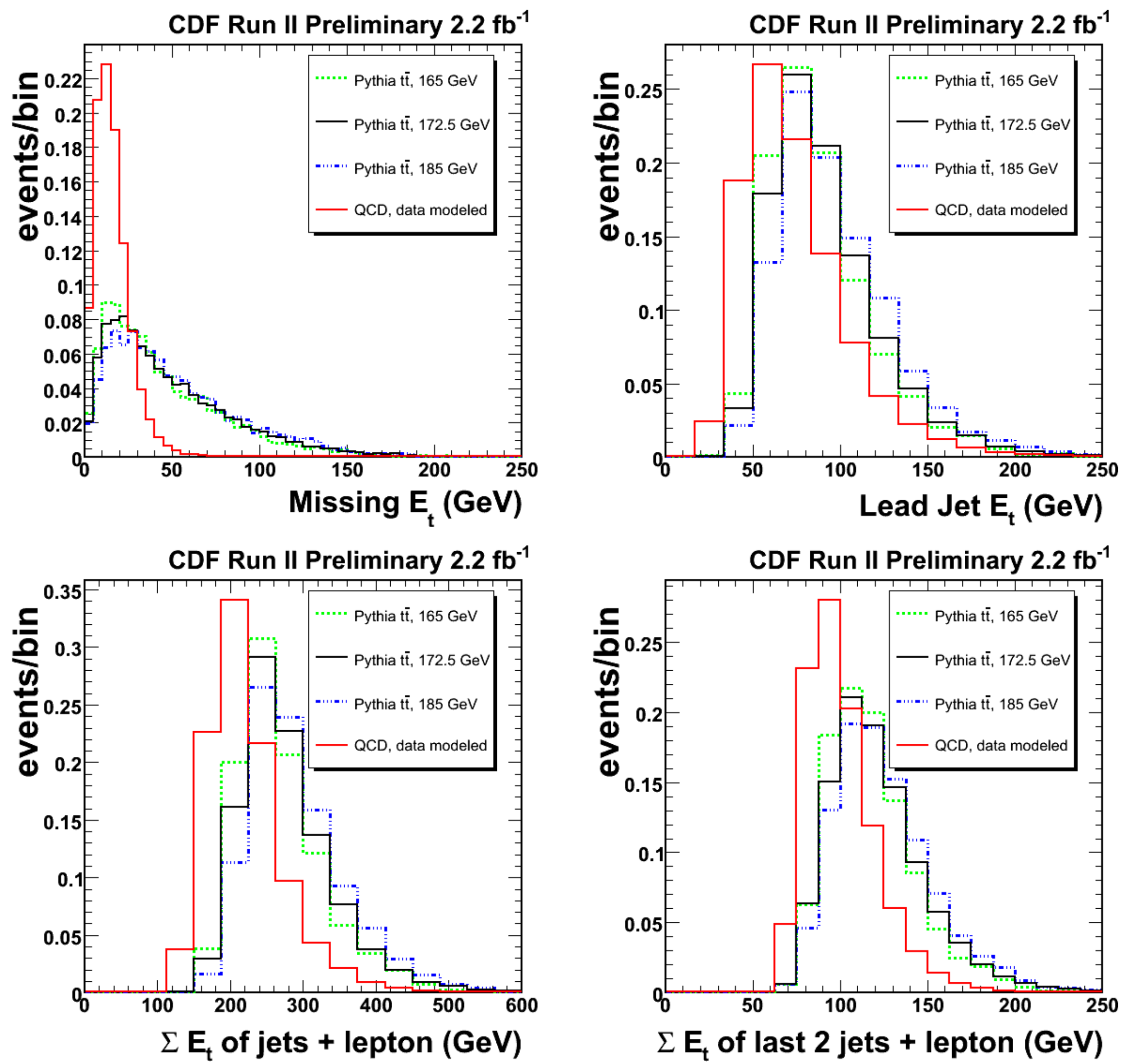


- NN very useful for signal discrimination
- Trained a NN to distinguish ttbar from QCD in tau + 4 jet events
- Trained events before missing Et and tagging requirements
- QCD tau fakes set as type 0, ttop25 type 1
- Ratio of ttbar:QCD events = 1:1
- Used a TMultilayerPerceptron network
  - 2 hidden layers with 10 and 4 nodes

Neural Network Input Variables

- Red: QCD
- Black: ttbar MC
  - M_{top} = 172.5 GeV
- Blue: ttbar MC
  - M_{top} = 185 GeV
- Green: ttbar MC
  - M_{top} = 165 GeV

ttbar shapes largely independent of top mass



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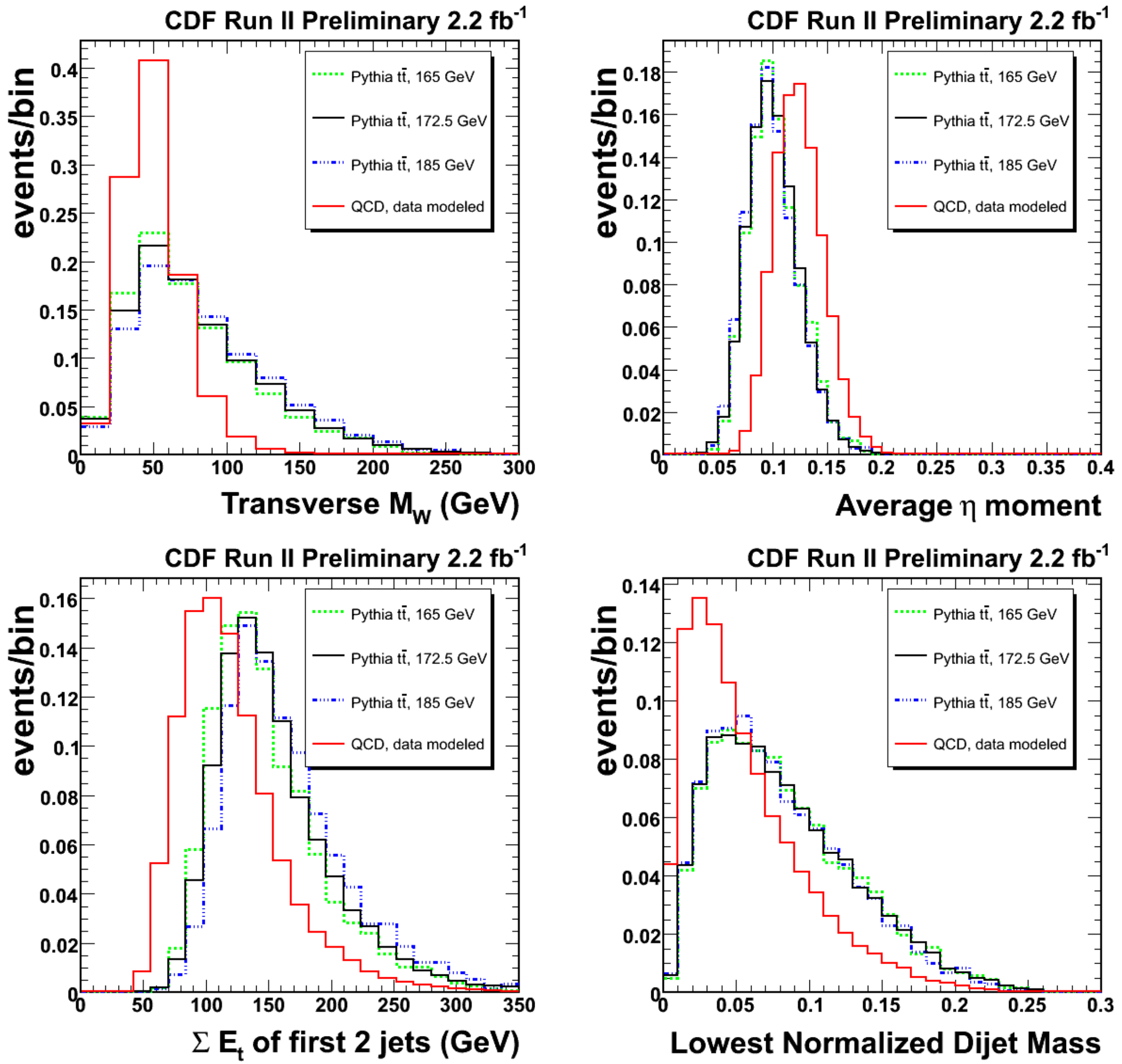
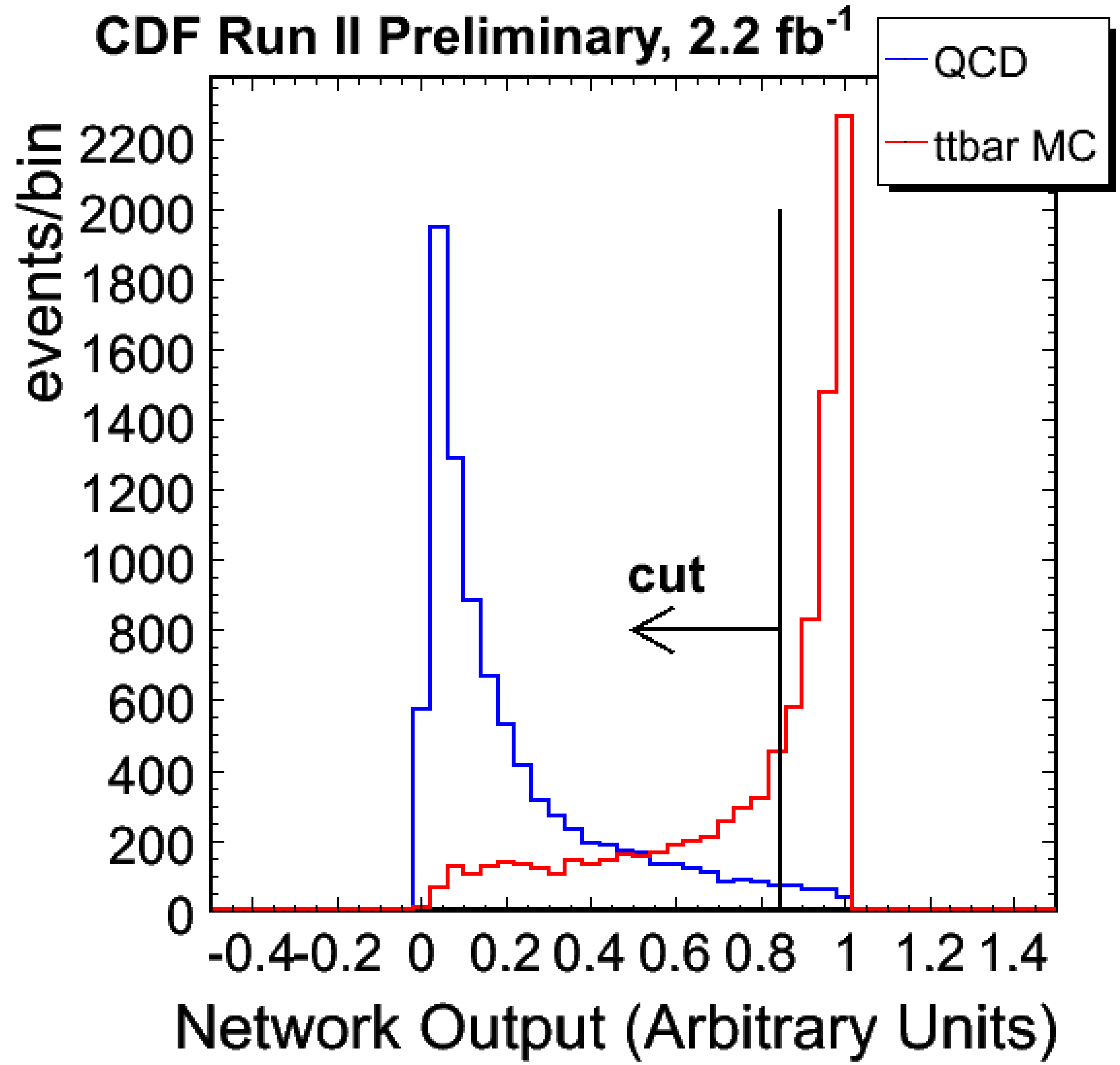


Neural Network Output

- Cut on NN to reduce QCD
- Optimize NN cut to maximize

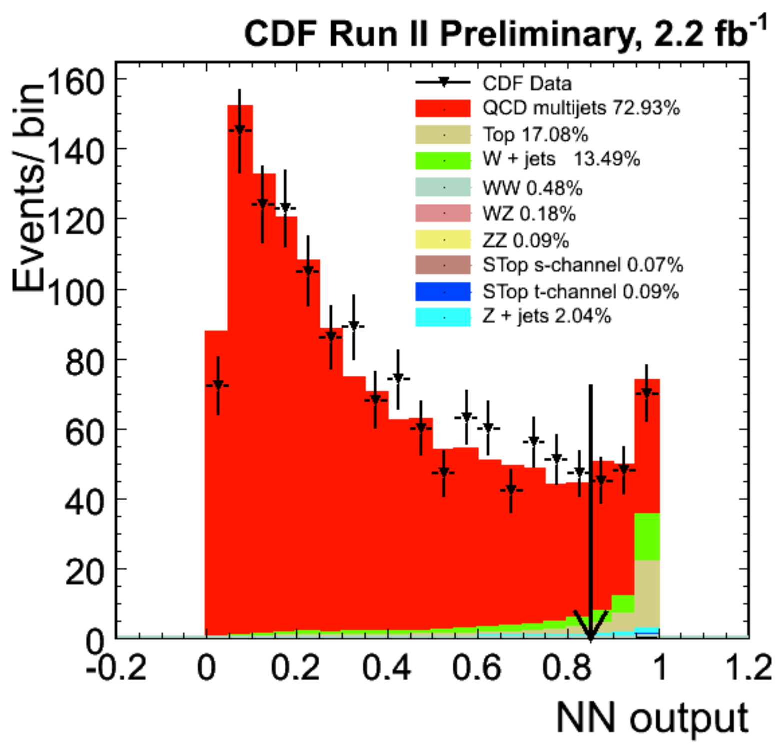
$$\frac{S}{\sqrt{S+B}}$$

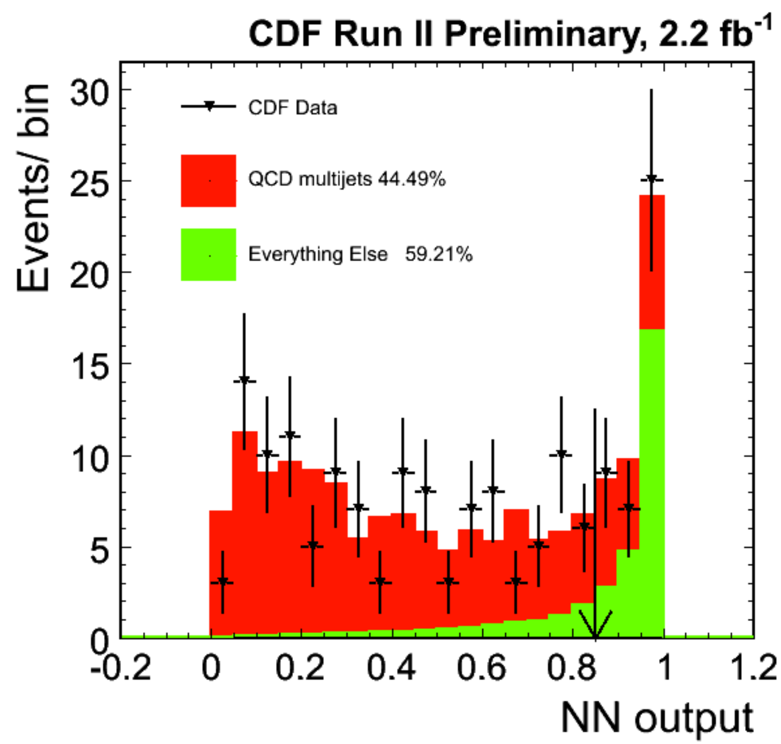
- Find optimal NN cut at 0.85



Fitting the Neural Network Output

- Diboson, Single top, Z+jets, and ttbar contributions determined by cross section and MC acceptance
- QCD and W+jets contributions determined by fitting shapes of NN output to data in non b-tag and b-tag samples





Assume ttbar xsec of 7.4 pb and top mass of 172.5 GeV

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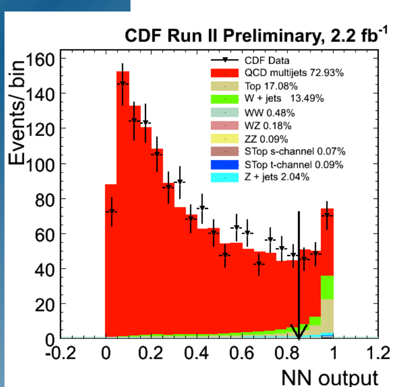
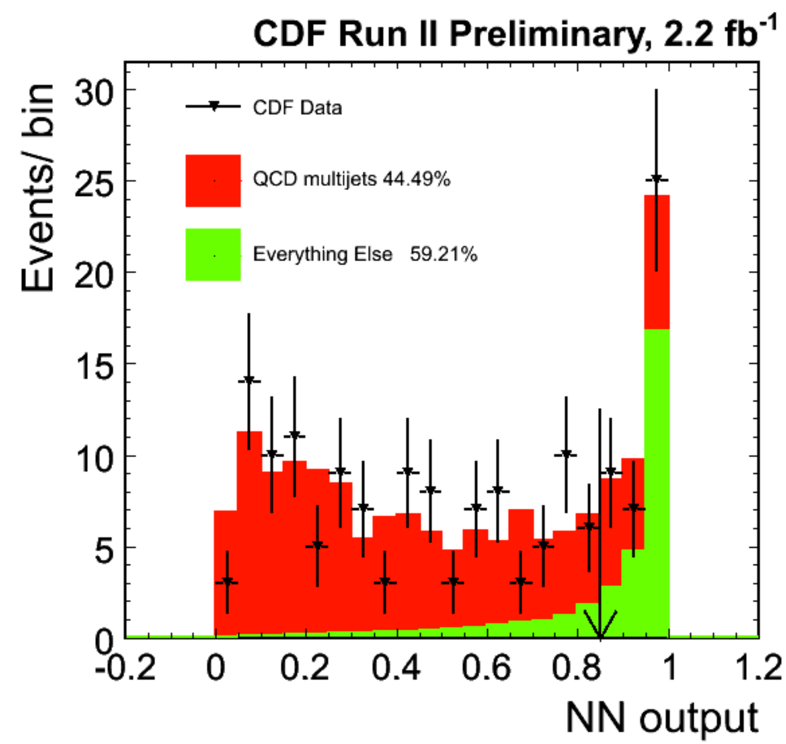


CDF Run II Preliminary 2.2 fb^{-1}			
Source	**Number of Events**		
Diboson	0.2	±	< 0.1
Single Top	0.2	±	< 0.1
Z + jets	0.3	±	< 0.1
Wbb	0.6	±	0.5
Wcc	0.3	±	0.3
Wc	0.2	±	0.1
W+jets (light)	0.5	±	0.6
QCD	18.2	±	4.1
ttbar	18.2	±	2.8
Total Prediction	38.7	±	5.1
Observed	41.0		



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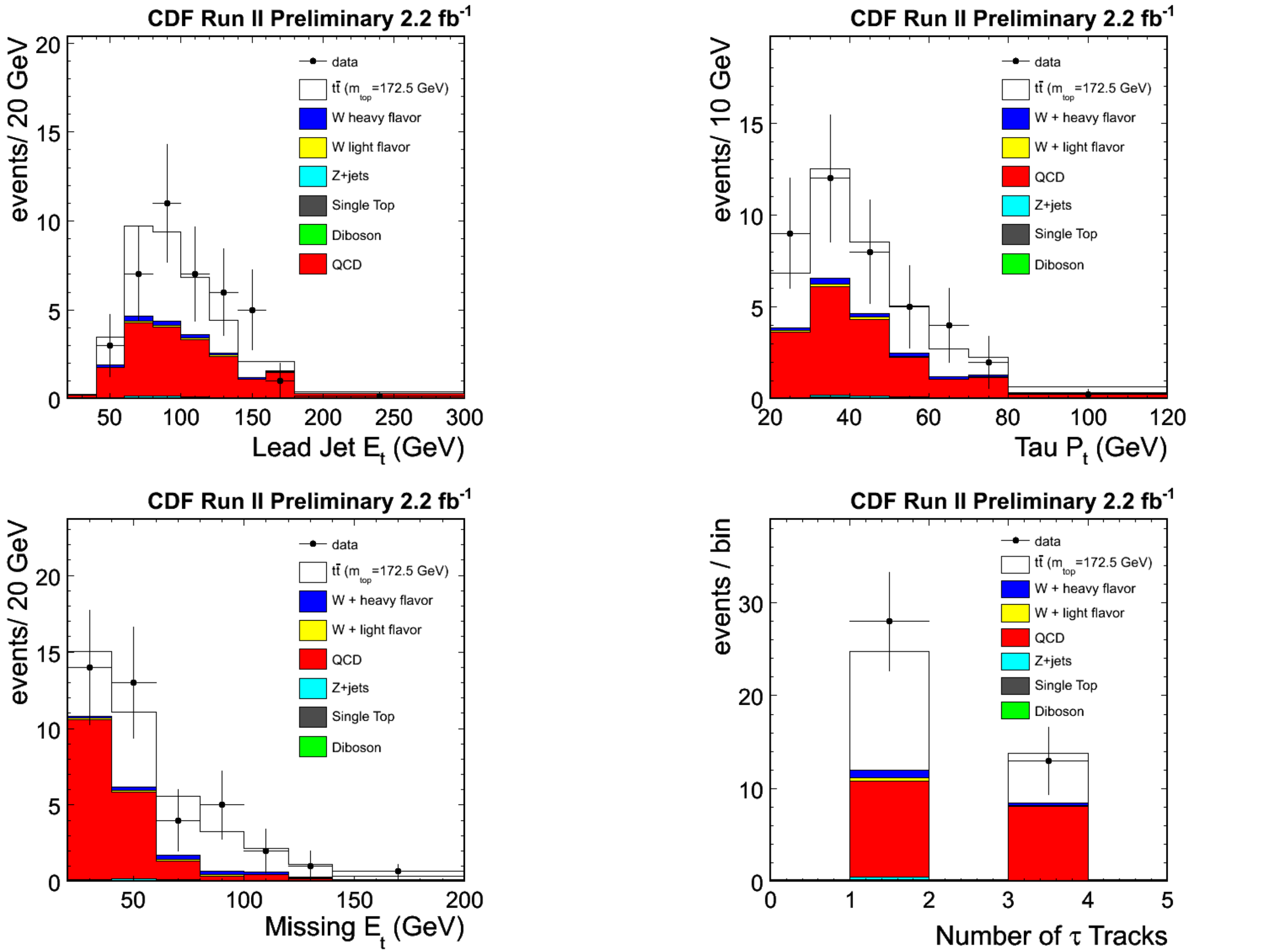
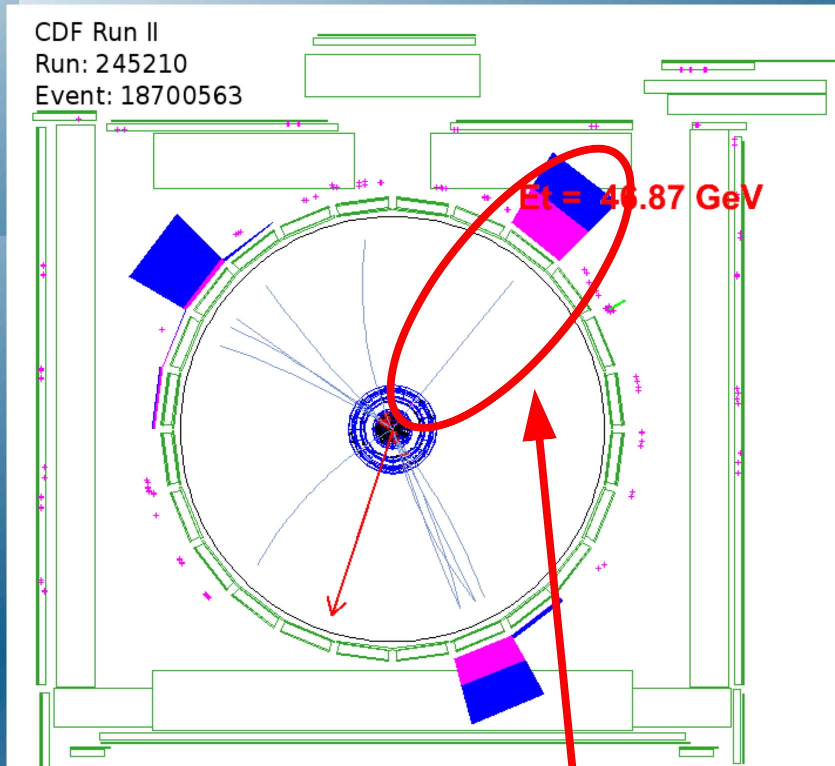
Kinematic Distributions

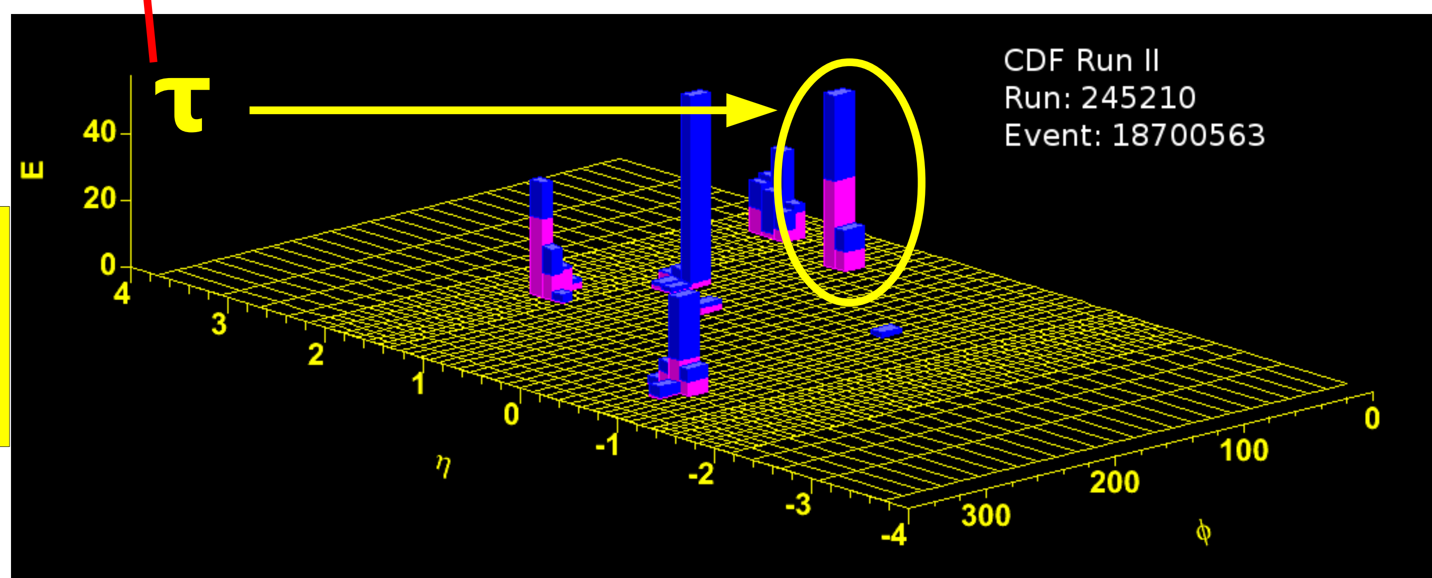


τ + jets Event Display



CDF Run II Preliminary 2.2 fb^{-1}

	Pt	Eta	Phi
Tau	65.6	0.82	50.6
Btagged Jet	53.6	-0.69	295.6
Jet	59.6	1.13	146.8
Jet	47.6	1.70	37.3
Jet	36.8	1.63	218.5



This event gives M_{top}: 173.7 GeV

Cross Section Measurement

- Cross section is calculated as: $$\sigma = \frac{N_{data} - N_{bkgd}}{A \cdot \epsilon \cdot \mathcal{L}}$$
- Note: in this analysis, N_{bkgd} depends on the ttbar cross section.
- Build a Poison Likelihood Function:
  - Compare number of observed events, N_{data}, with number of events expected assuming xsec σ_{ttbar}

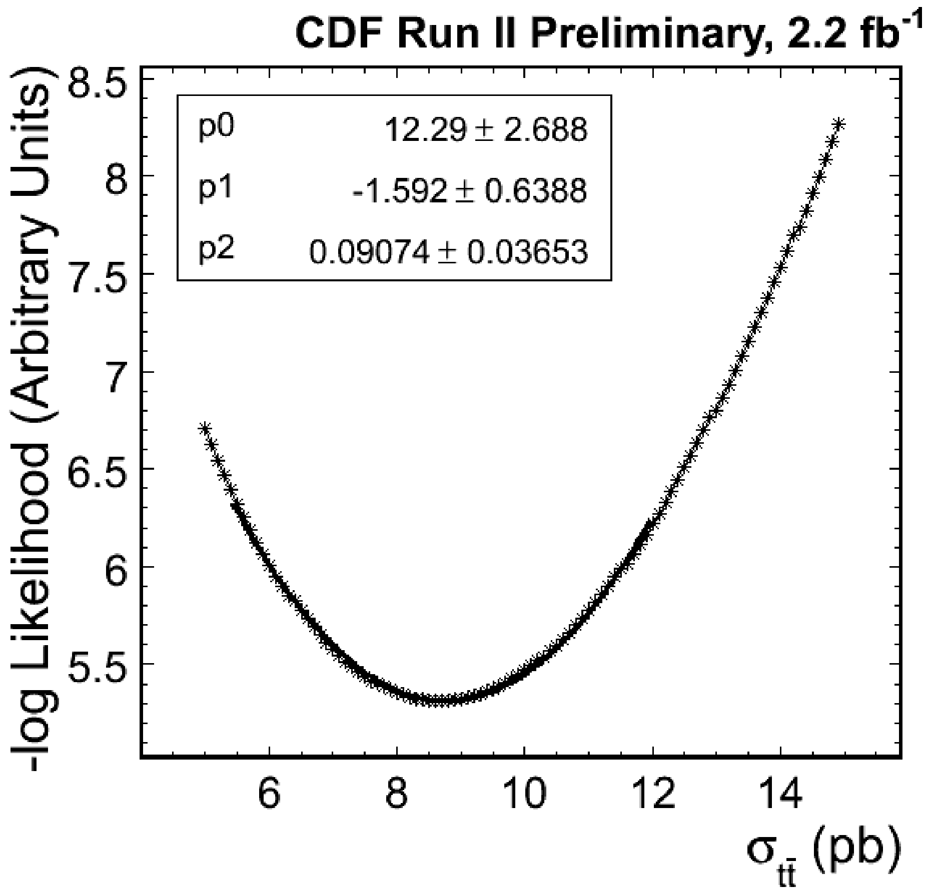
$$-2 \cdot lnL = -2 \cdot (N_{data} \cdot ln(\sigma_{t\bar{t}} \cdot D + N_b(\sigma_{t\bar{t}})) - ln(N_{data}!) - (\sigma_{t\bar{t}} \cdot D + N_b(\sigma_{t\bar{t}})))$$

where D = $A \cdot \epsilon \cdot \mathcal{L}$

- Scan a range of potential ttbar cross sections and fit with 2nd order polynomial

Cross Section Result

- **Hadronic τ + jets Result (2.2 fb^{-1}):** assuming M_{top} 172.5 GeV
  - 8.8 ± 3.3 (stat) ± 2.2 (syst) pb
  - CDF Combination (4.6 fb^{-1}): 7.5 ± 0.5 pb



Systematic	$\delta\sigma$ (pb)	$\delta\sigma/\sigma$ (%)
Jet Energy Scale	0.6	6.9
IFSR	0.5	5.7
Color Reconnection	0.4	4.6
Tagging	0.4	4.6
Mistag Matrix	0.1	1.1
QCD Fraction	1.8	20.5
K-Factor	0.1	1.1
Parton Showering	0.5	6.0
Lepton ID	0.2	2.3
Trigger Efficiency	0.1	1.1
PDF	0.5	5.7
Luminosity	0.5	6.0
Total	2.2	25.0

QCD Uncertainty

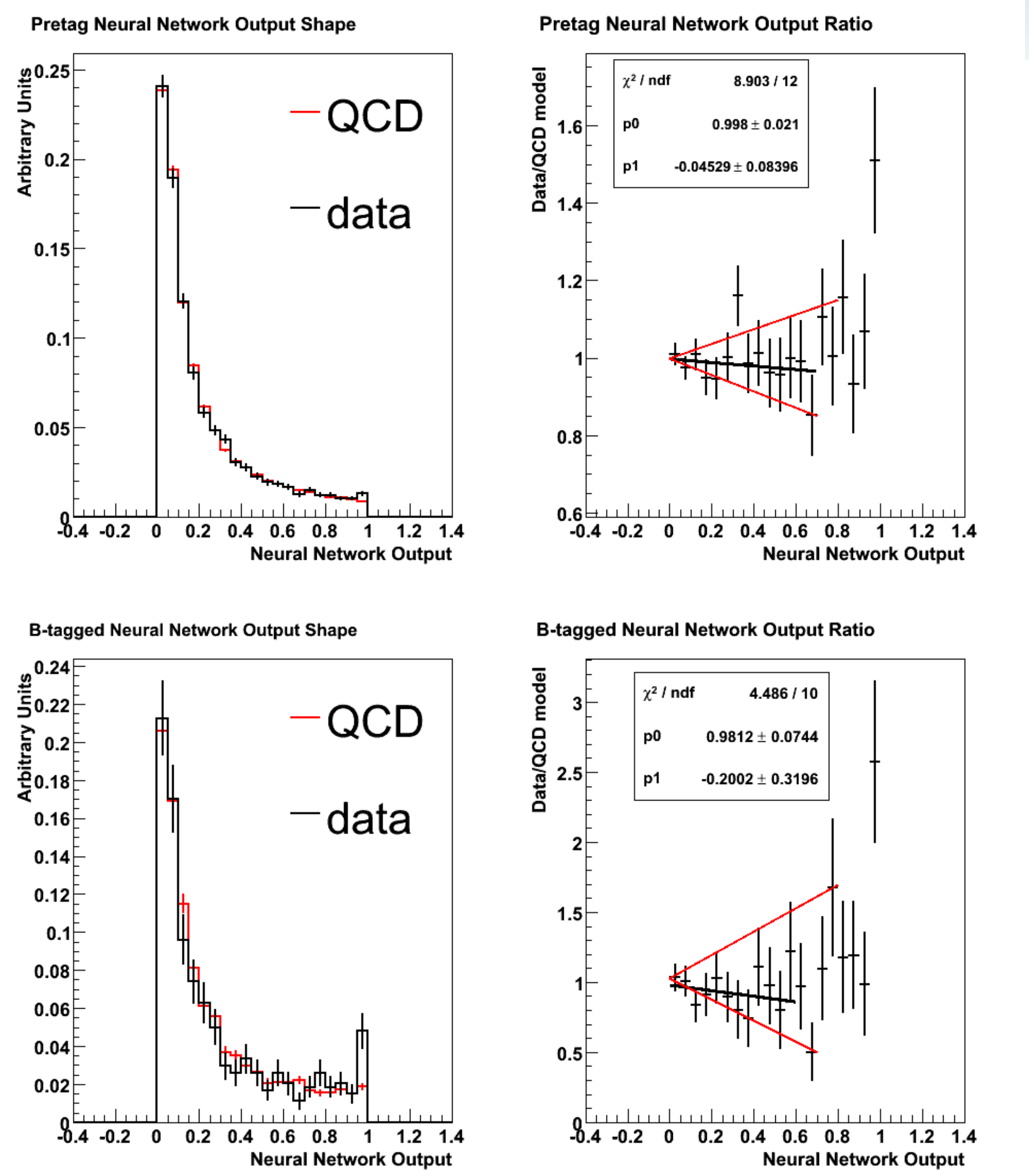
Data with no missing Et or NN cut is QCD dominated.

This allows us to better measure the uncertainty on the QCD background.

Compare NN output shape in data to QCD model.

Reweight QCD events and refit QCD fraction in method2

Use uncertainty from fit to predict QCD uncertainty



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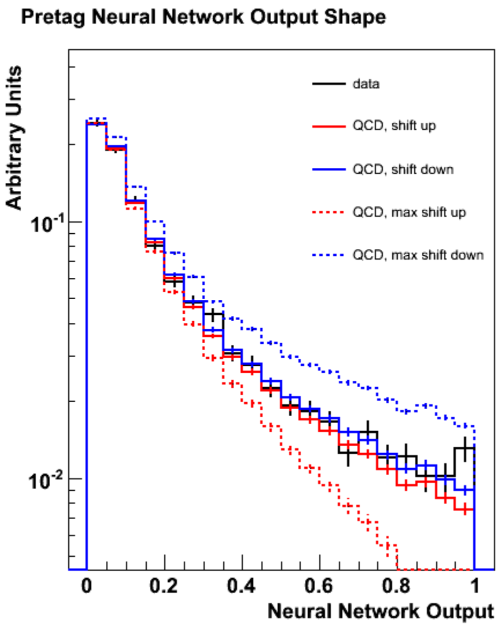
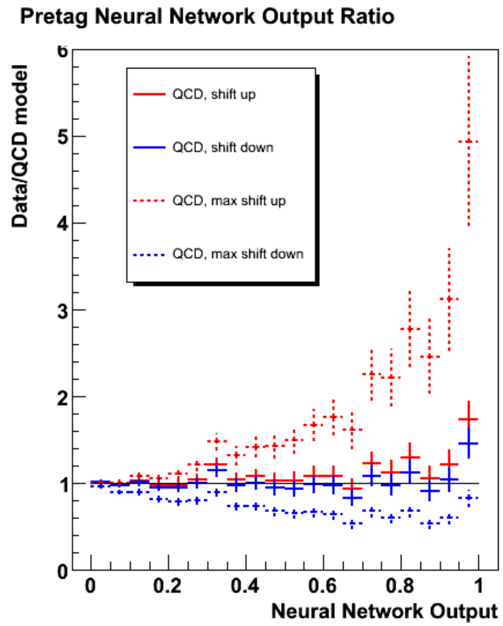
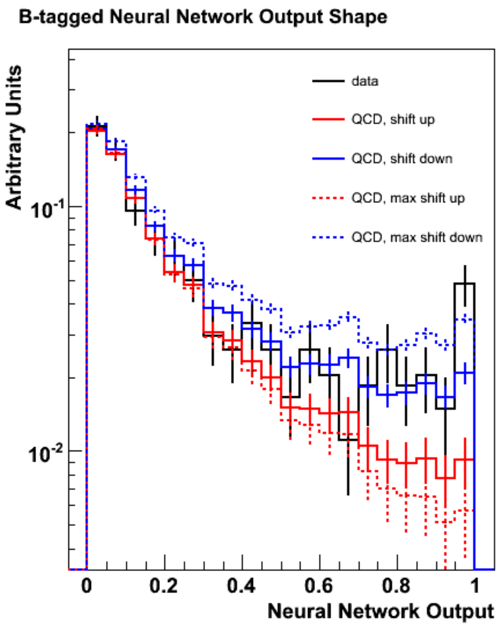
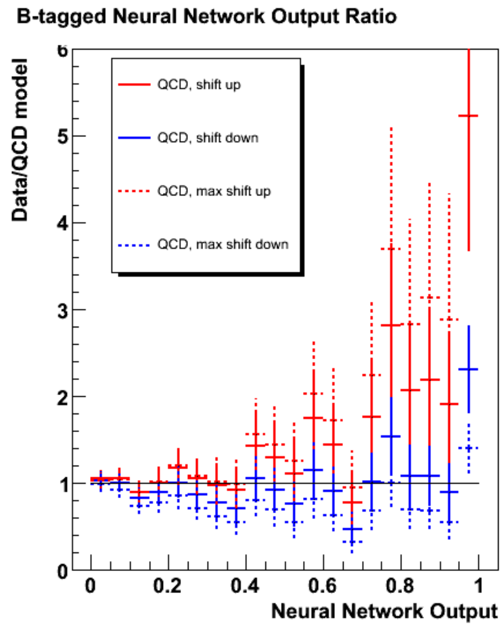
QCD Uncertainty









	Pretag fQCD	Tag fQCD
Max Up	0.816	0.618
Up	0.748	0.477
Nominal	0.729	0.445
Down	0.664	0.272
Max Down	0.618	0.184

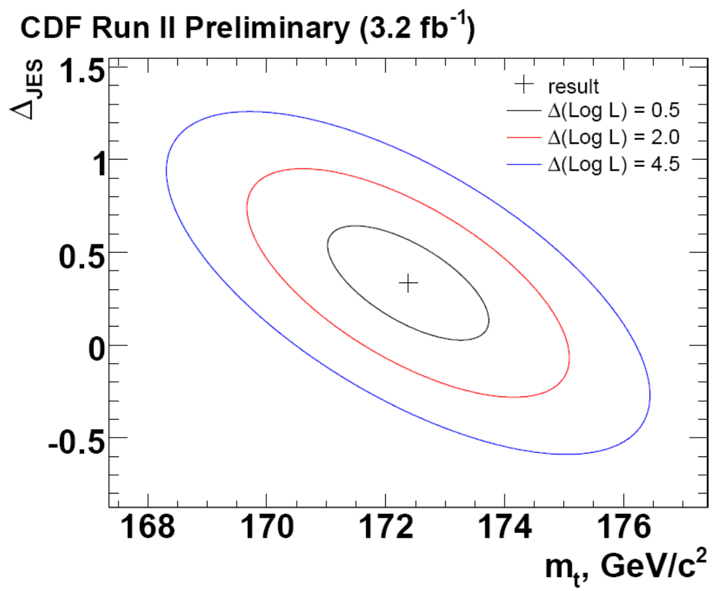
Maximum shifts don't agree well with the data

Use Up and Down shift to measure uncertainty

Pretag fQCD = 0.729 +/- 0.04
Tag fQCD = 0.445 +/- 0.10

Top Quark Mass Measurement

- ttbar cross section measurement consistent with SM
    - 8.8 ± 3.3 (stat) ± 2.2 (syst) pb
- Now move to mass measurement
  - Use ME method from e/mu + jets measurement
    - ArXiv 1108:1601 : Recently accepted to PRD RC
    - I was also a primary author on this paper



Using 3.2 fb^{-1}:

M_{top} = 172.4 ± 1.4 (stat + JES) ± 1.3 (syst) GeV

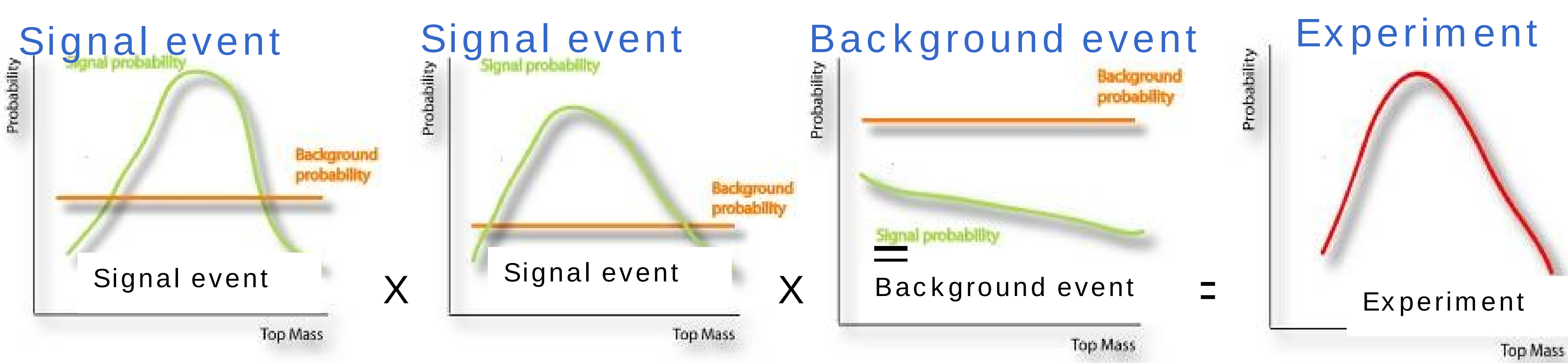
M_{top} = 172.4 ± 1.9 GeV

Matrix Element Technique

$$P(\vec{x};\alpha)=c_s P_{t\bar{t}}(\vec{x};M_{top})+A_{bkgd}(1-c_s)P_{W+jets}(\vec{x})$$

- **Build likelihood function from signal and bkgd probabilities**
- **Constrain c_s to expected signal fraction from slide 23**
- **Calculate P_{sig} by integrating over $d\sigma_{ttbar}$**

$$P(\vec{x};m_t)=\frac{1}{\langle Acc(m_t)\rangle * \sigma_{ttbar}}\int\sum_{soln}^{4}|M^2|\frac{f(\tilde{q}_1)f(\tilde{q}_2)}{|q_1||q_2|}\prod(W(\vec{x},\vec{y}))d\Phi$$



Matrix Element Technique

Normalization

PDFs

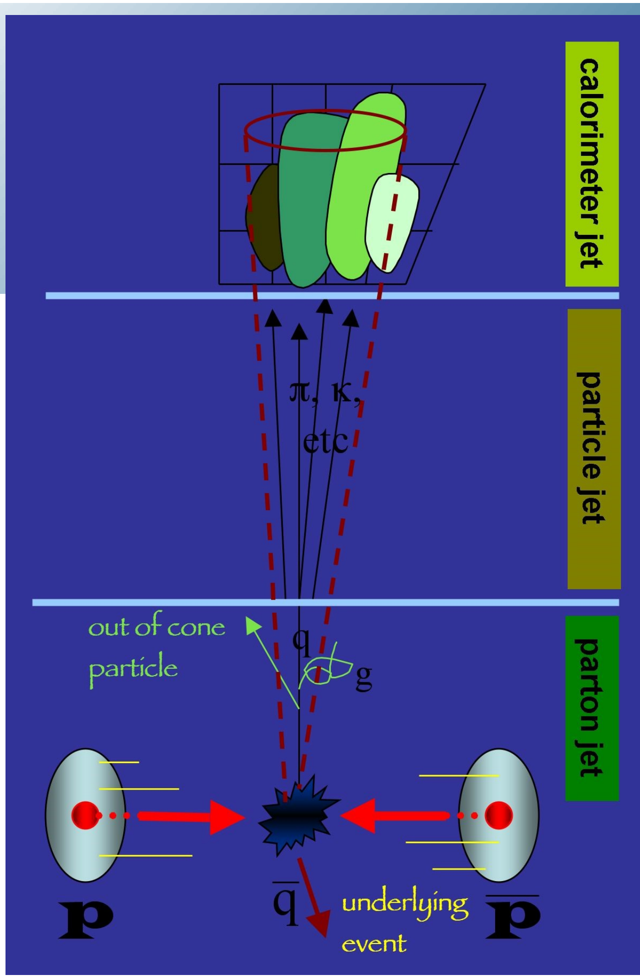
$$P(\vec{x};m_t)=\frac{1}{\langle Acc(m_t)\rangle * \sigma_{ttbar}}\int\sum_{soln}^{4}|M^2|\frac{f(\tilde{q}_1)f(\tilde{q}_2)}{|q_1||q_2|}\prod(W(\vec{x},\vec{y}))\,d\Phi$$

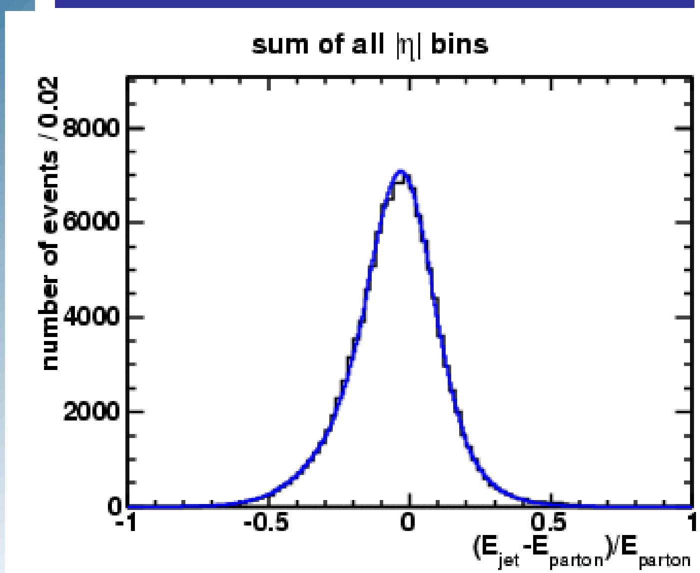
Matrix Element

Transfer Functions

- M calculated using parton level quantities from integration
  - Signal Probability uses Mahlon Parke ttbar cross section
    - hep-ph/9512264
- Integrate over m^2_{Whad}, m^2_{Wlep}, ρ_{jet1}, $\cos\alpha_{12}$, $\cos\alpha_{Wbhad}$
- Similar expression for background probability:
  - **Use VECBOS W+4jets matrix element**
  - **Integrate over E_{jet1}, E_{jet2}, E_{bhad}, E_{blep}, p^z_ν**

Transfer Functions

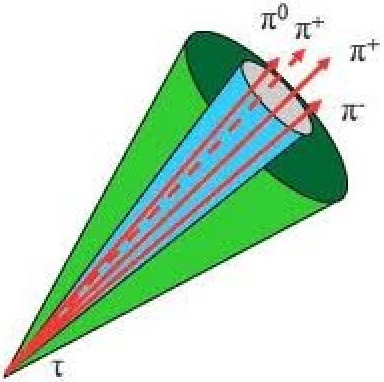




- Corrected jet energy is not equivalent to parton energy
- Transfer function returns probability that measured jet x resulted from parton y
- Rely on ttbar MC to fit
- Energy transfer functions
  - Separate for b and light quarks
- Found bias in angles between light quark jets from W
  - Added angular transfer function
  - Similar effect with hadronic side W and b

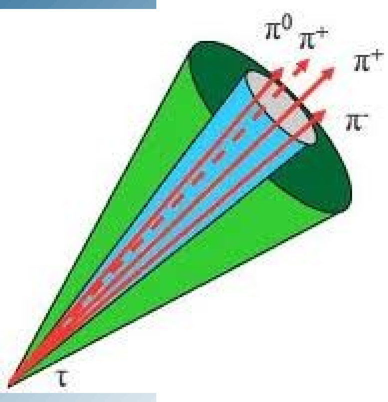
What is Different About Taus?

- **Hadronically decaying tau is essentially a narrow jet**
  - Large QCD Background
  - **Solution: Neural Network to Remove QCD**
- **Taus are harder to measure than e or μ**
  - Hadronically decaying tau includes a neutrino
  - Now ttbar decay has 2 neutrinos

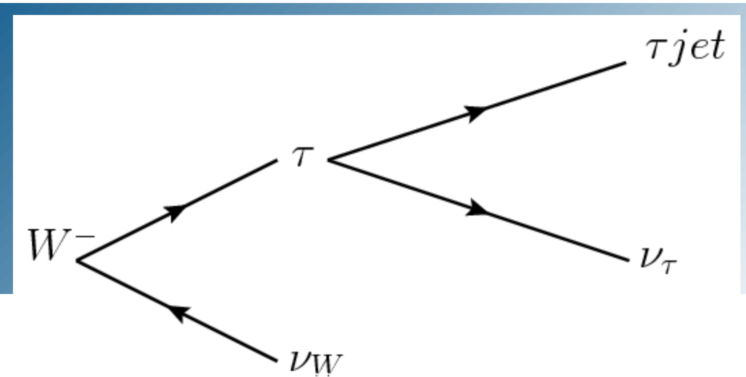


What is Different About Taus?

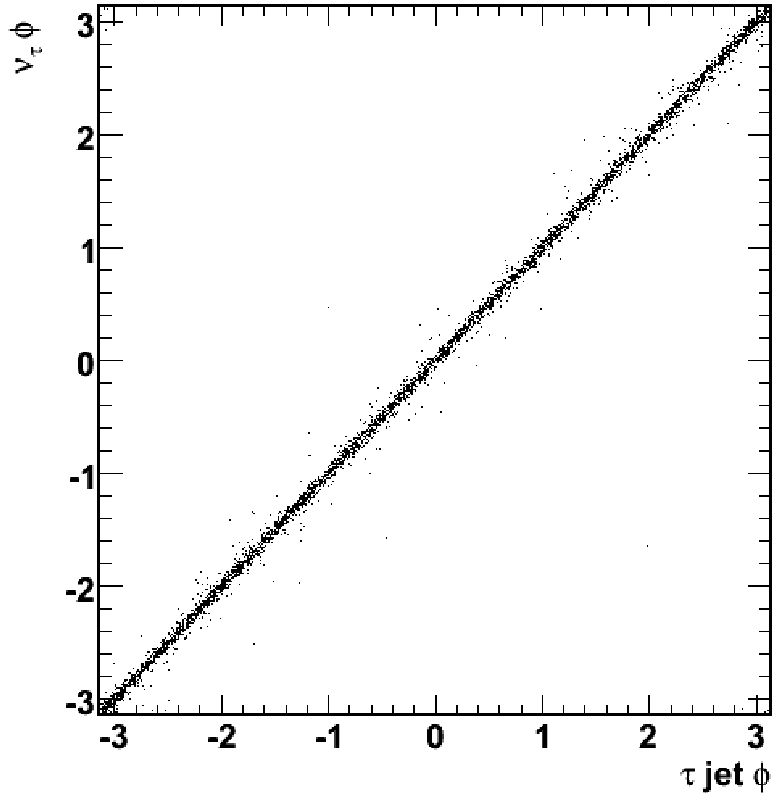
- **Hadronically decaying tau is essentially a narrow jet**
  - Large QCD Background
  - **Solution: Neural Network to Remove QCD**
- **Taus are harder to measure than e or μ**
  - Hadronically decaying tau includes a neutrino
  - Now ttbar decay has 2 neutrinos
  - **Solution: Scan Method to reconstruct neutrino from tau decay**
    - 4D scan over both neutrino angles $(\eta_1,\varphi_1,\eta_2,\varphi_2)$
    - Use W and τ mass to solve for ν^E_1 and ν^E_2
    - Compare predicted missing E_t to measured to determine most likely neutrino angles

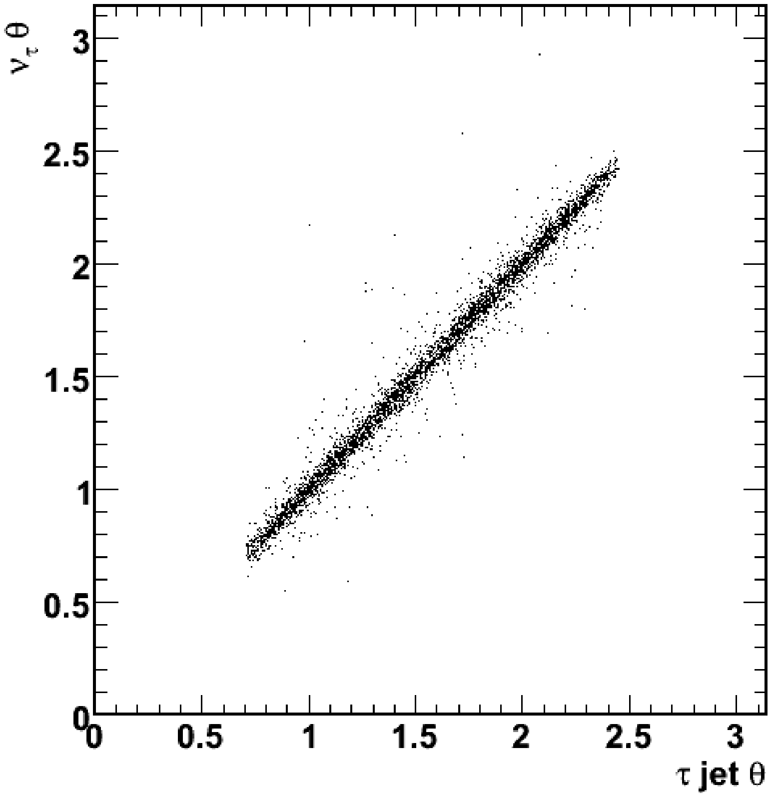


Neutrino Scan Method

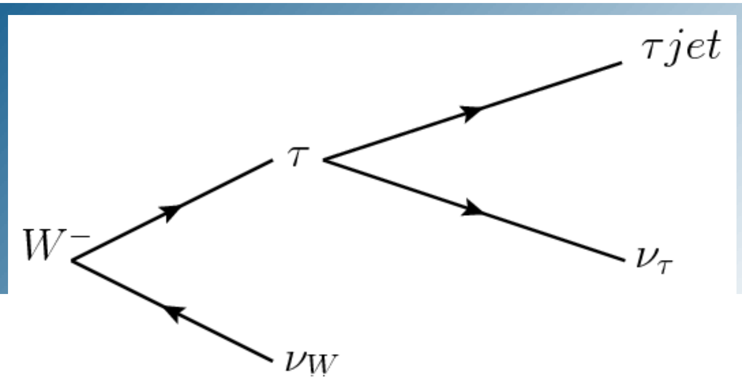


- Found that neutrino from tau is nearly collinear with tau "jet"

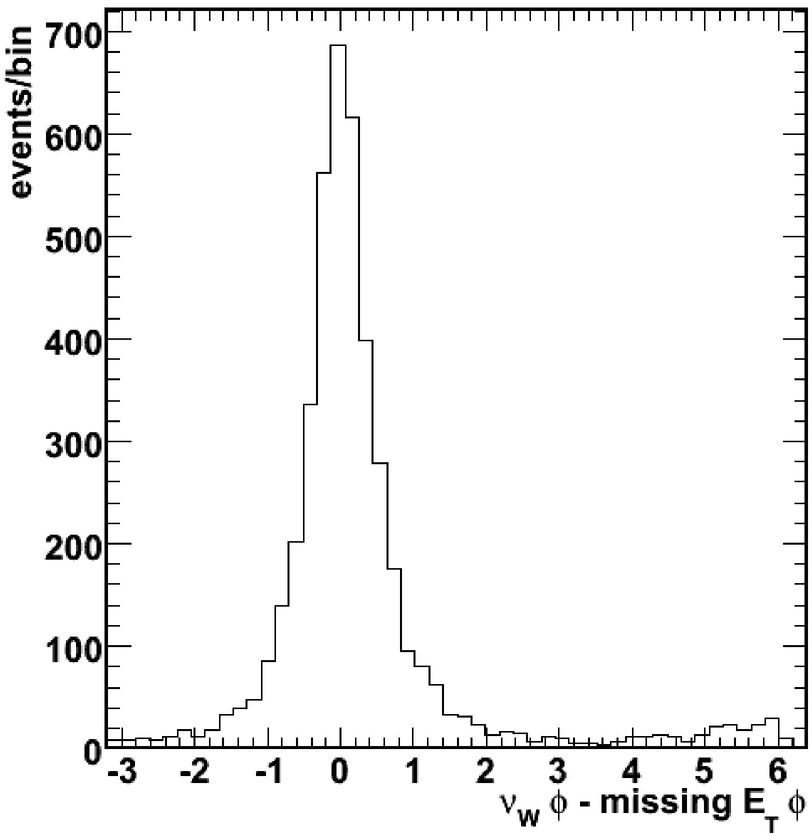




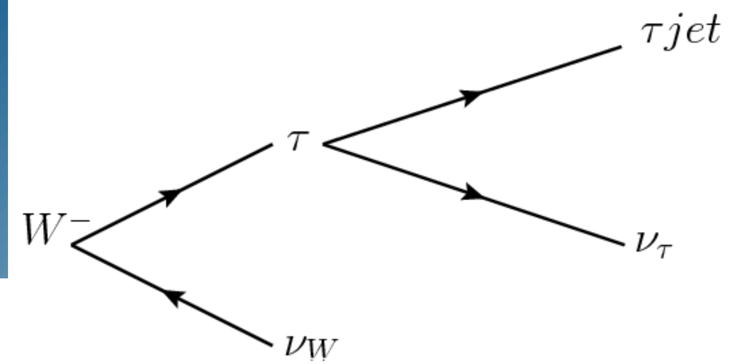
Neutrino Scan Method



- Found that neutrino from tau is nearly collinear with tau “jet” and neutrino from W tends to be close to missing Et direction in x-y plane.



Neutrino Scan Method



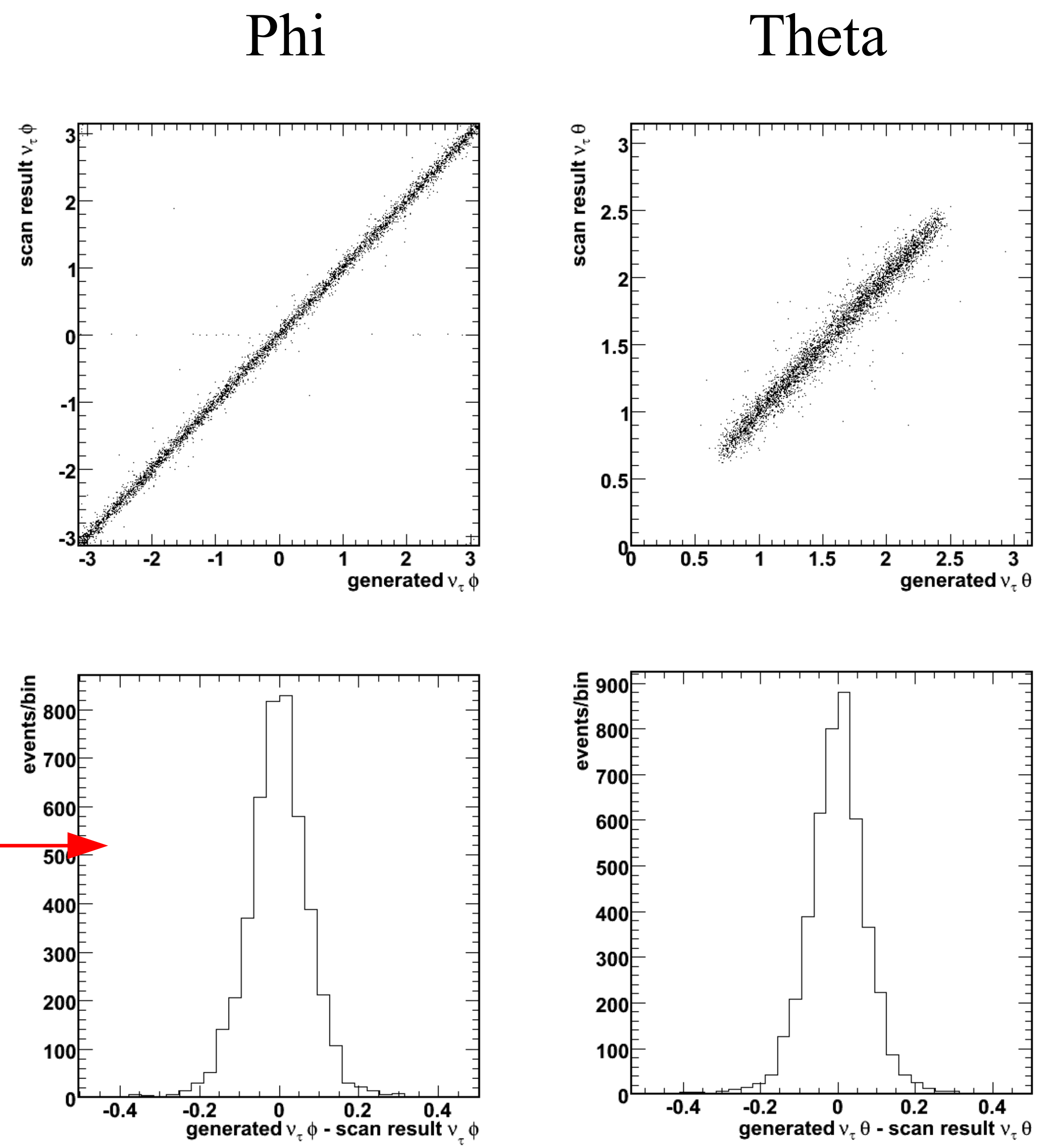
- Found that neutrino from tau is nearly collinear with tau "jet" and neutrino from W tends to be close to missing Et direction in x-y plane.
- Scan in 4D for the theta and phi angles of each neutrino
  - Scan +/- 0.1 in theta and phi around tau "jet" for tau neutrino (25 steps)
  - Scan +/- 1 around MET phi for W decay neutrino (50 steps)
  - Scan 0 to π for theta of W decay neutrino (50+ steps) [no handle]
- Use W and tau mass constraints to solve for neutrino momenta for each point in 4D space
- Build a probability function using Missing Et

$$P = \exp\frac{-\left(MET_x^{scan} - MET_x^{gen}\right)^2}{2\sigma^2}\exp\frac{-\left(MET_y^{scan} - MET_y^{gen}\right)^2}{2\sigma^2}$$

Neutrino Scan Method

- Using this probability function, we select the most probable point in the 4D space.
- Probability generally returns correct angles for the neutrino from the tau decay

Difference between HEPG and Scan value



Neutrino Scan Method

- Using this probability function, we select the most probable point in the 4D space.
- Probability generally returns correct angles for the neutrino from the tau decay
  - We use these angles with the tau mass constraint to solve for the neutrino and reconstruct the original tau lepton.
  - **This tau lepton can now be treated like a standard lepton in the Matrix Element mass analysis**
- Due to the lack of a handle for theta of the neutrino from the W decay, we do not tend to find the correct angles for this neutrino
  - Cannot reconstruct this neutrino well with scan method
  - **Not a problem as this neutrino is already solved for in the Matrix Element method.**

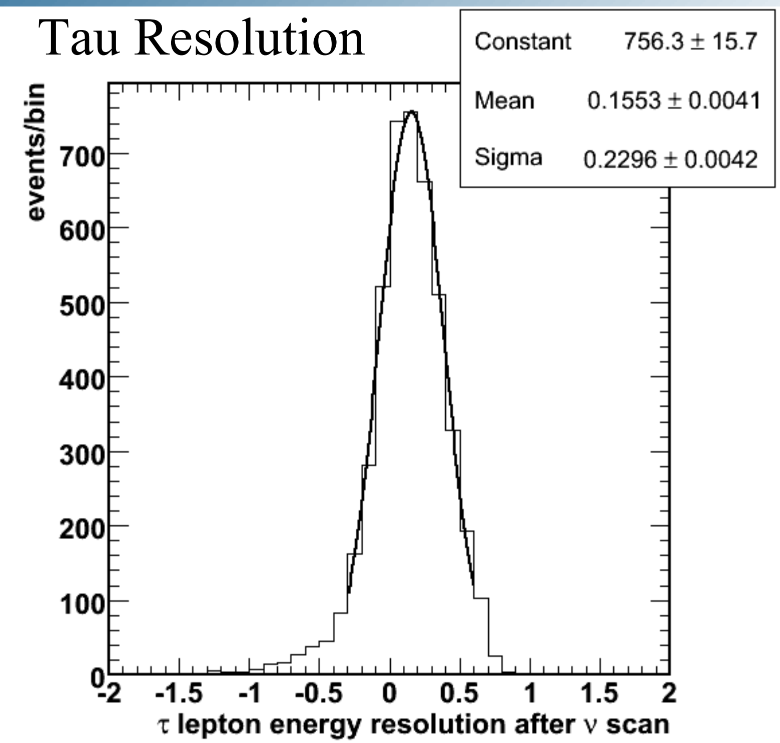
Tau Energy Resolution

- Neutrino scan improve tau energy resolution, but still far from a delta function like electrons or muons.
- How much of an effect does this energy resolution have on the top quark mass measurement?
- Test with smeared electron test

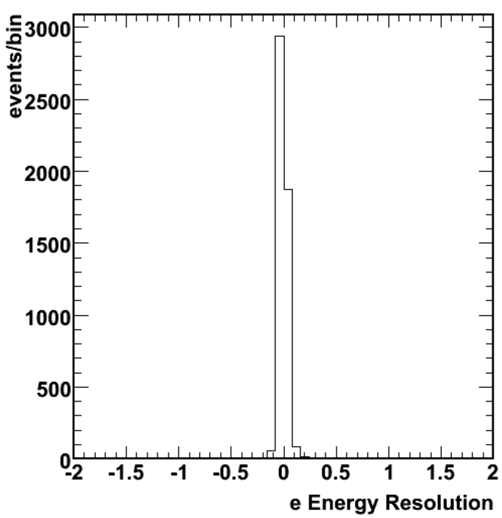
Energy Resolution

- Fit Gaussian to tau energy resolution
- Use this function to smear the electron energy in a sample of MC ttbar → e + 4 jets events
- Using previous version of this analysis, measure top quark mass with smeared electrons and compare result to unsmeared electrons

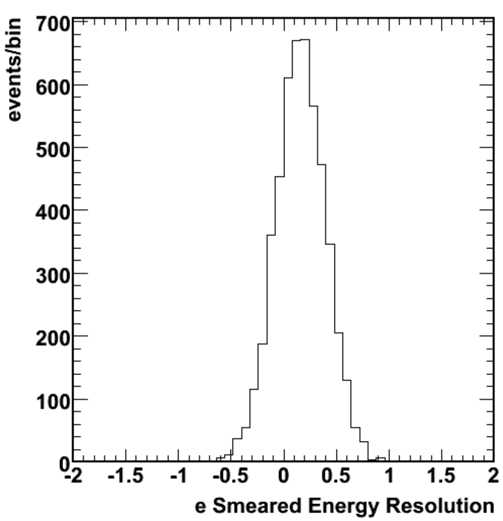
Tau Resolution



Unsmeared e's:

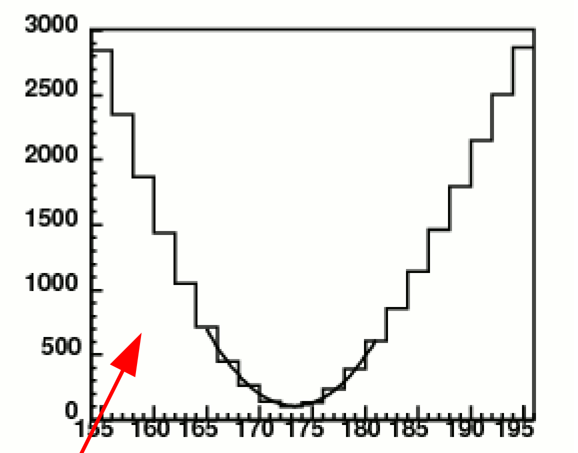


Smeared e's:



Smeared Electron Results

- Using previous version of analysis, measure top quark mass with smeared and unsmeared electrons



Only Signal Probability

Mass	events	Unsmeared Result		Smeared Result	
		Cs	Mass	Cs	Mass
180	2000	0.982	179.4 +/- 0.5	0.983	182.0 +/- 0.5
175	6000	0.982	174.7 +/- 0.3	0.979	176.6 +/- 0.3
170	2000	0.978	170.5 +/- 0.5	0.971	172.7 +/- 0.5

Turn on Background Probability (cleans up bad events in signal sample)

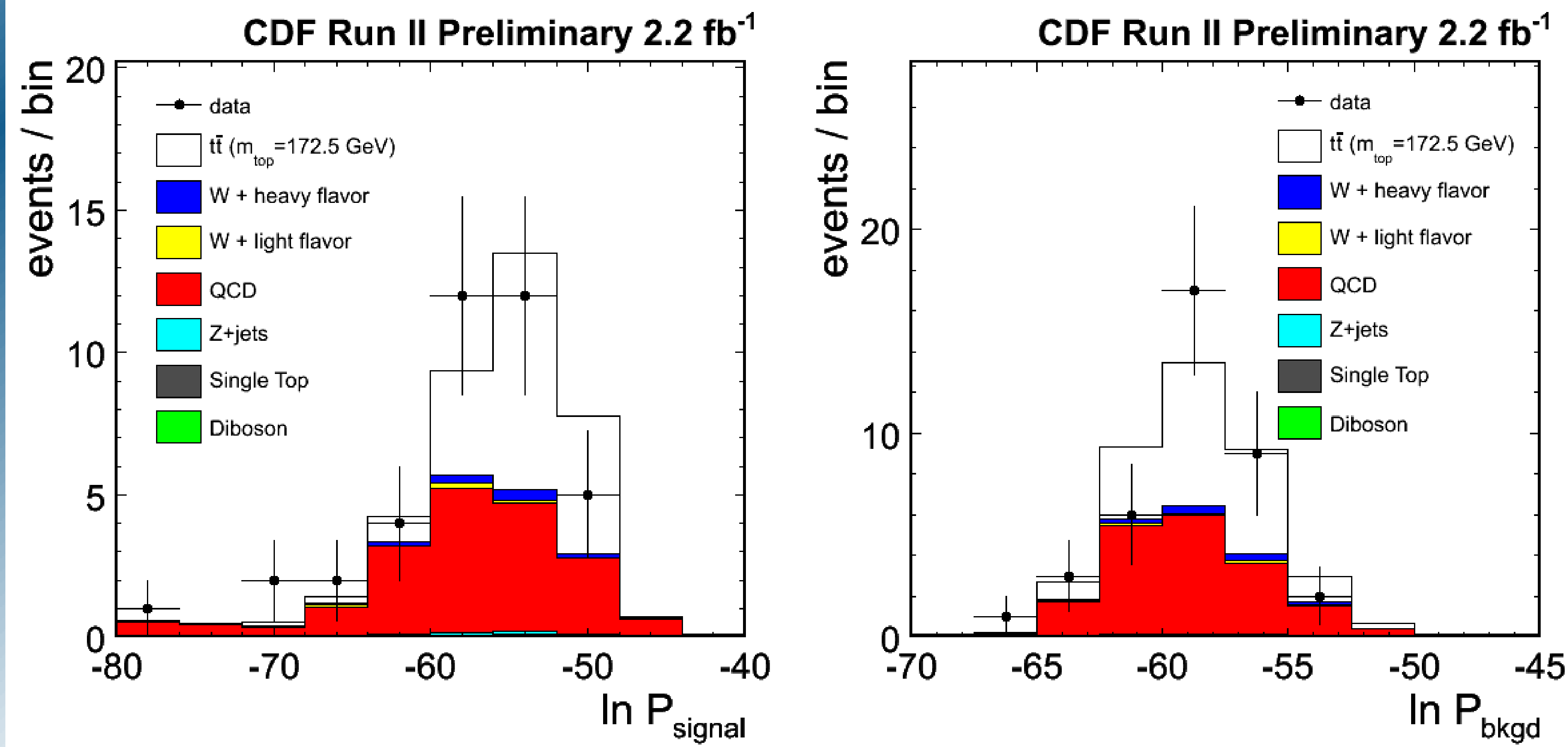
Mass	events	Unsmeared Result		Smeared Result	
		Cs	Mass	Cs	Mass
180	2000	0.740	179.4 +/- 0.5	0.680	180.1 +/- 0.6
175	6000	0.763	173.8 +/- 0.3	**0.699**	**174.3 +/- 0.3**
170	2000	0.773	169.9 +/- 0.5	0.720	170.4 +/- 0.5

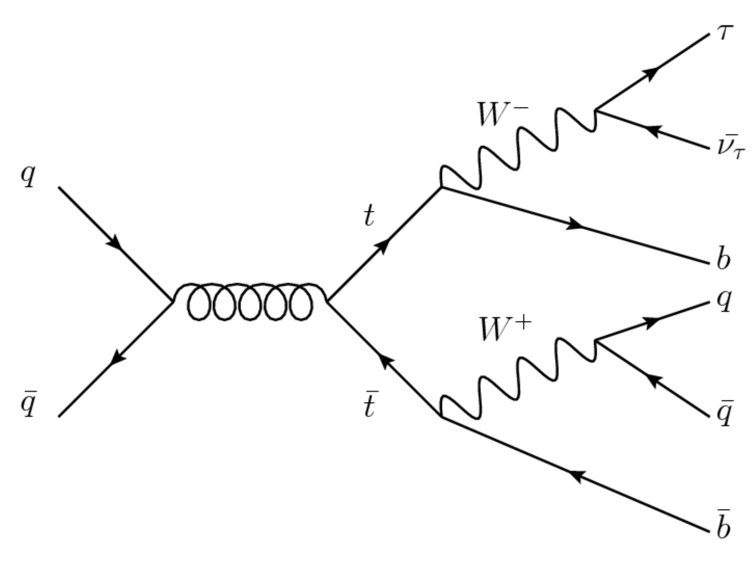
We find a small linear bias from the energy resolution which can be corrected when calibrating the method

Data Probabilities

Signal and Background Probabilities:

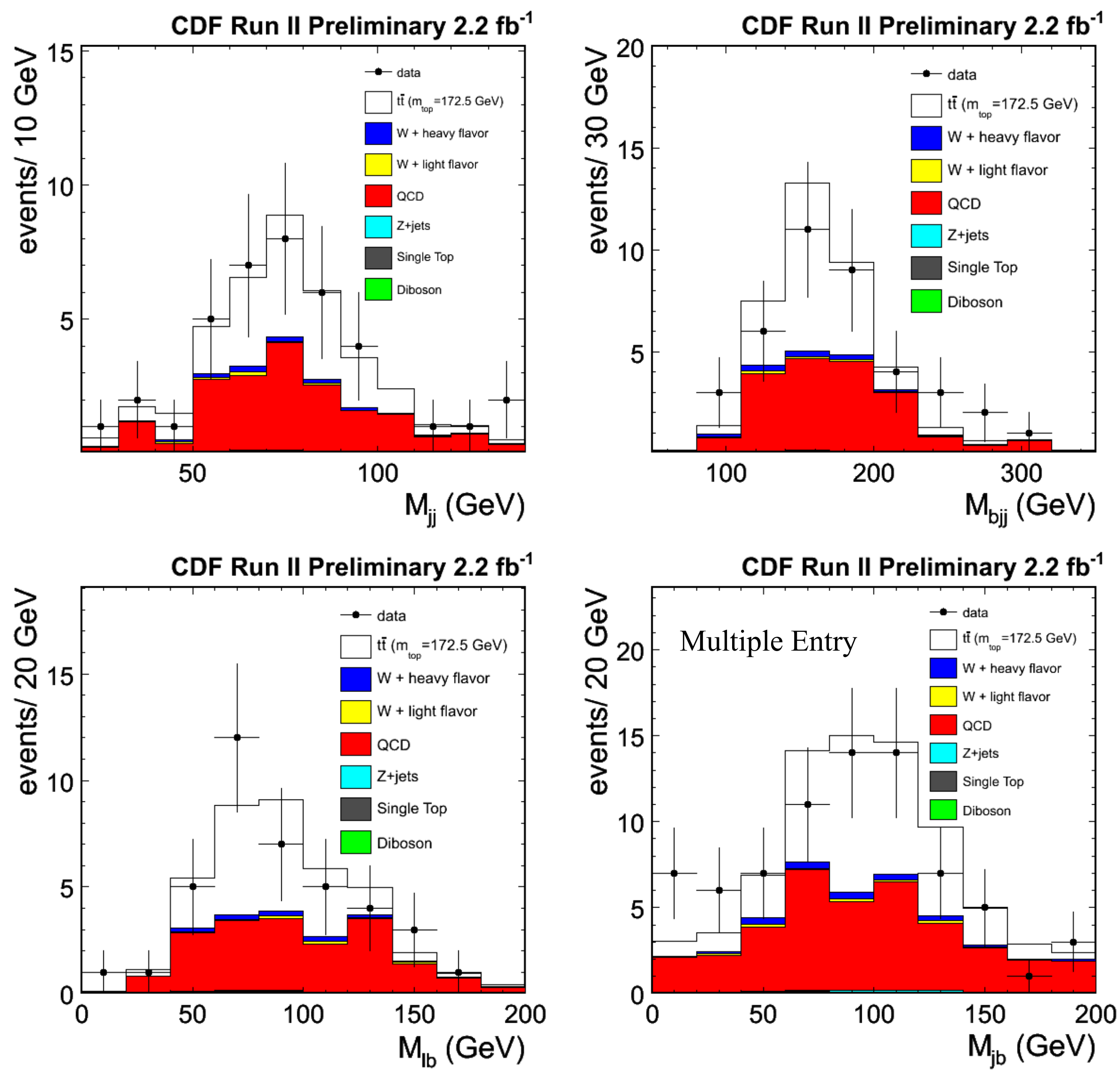
Signal is taken from highest probability point in M_{top}





Matrix Element Validation

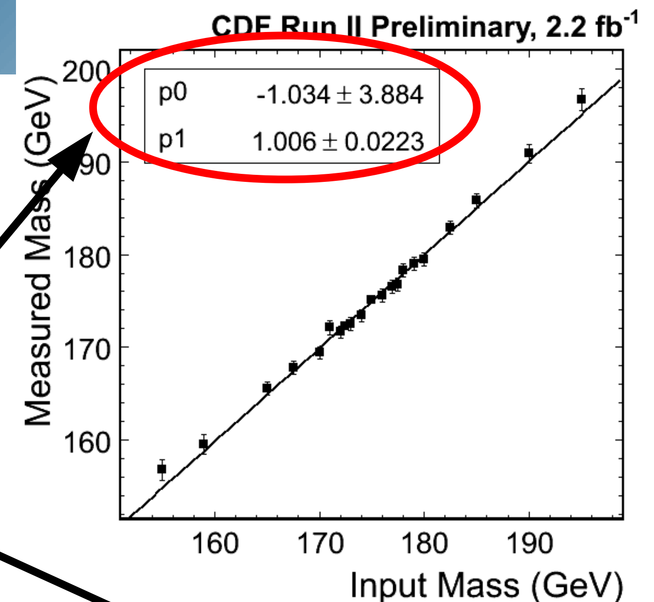
- Select most probable jet combination from signal probability
- Look at interesting mass variables:
  - Hadronic side W
  - Hadronic side Top
  - Mass of lepton and lep side b
  - Mass of lq jet and hadronic side b

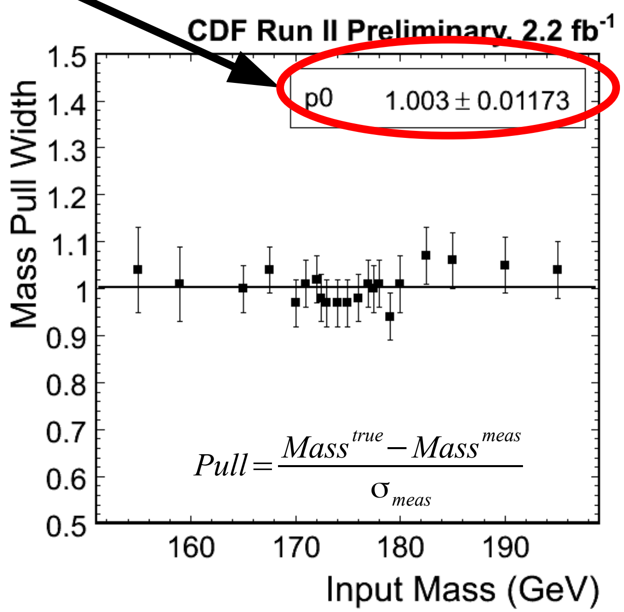


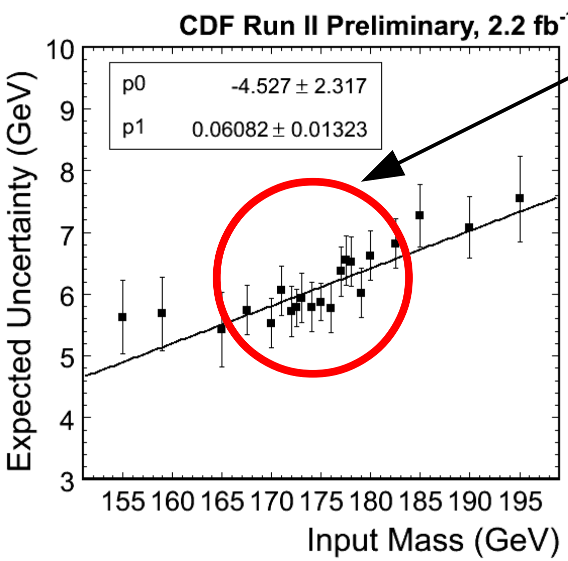
Daryl Hare, Rutgers University

Linearity Checks and Expected Uncertainty

- Use 21 MC samples with mass ranging from 155 to 195 GeV
- Throw pseudo-experiments with fully simulated backgrounds
  - **Mass measurement is unbiased**
  - **Pull widths consistent with 1**
- **At M_{top} = 172.5 GeV expect statistical uncertainty of ~6 GeV**







Systematic Uncertainties

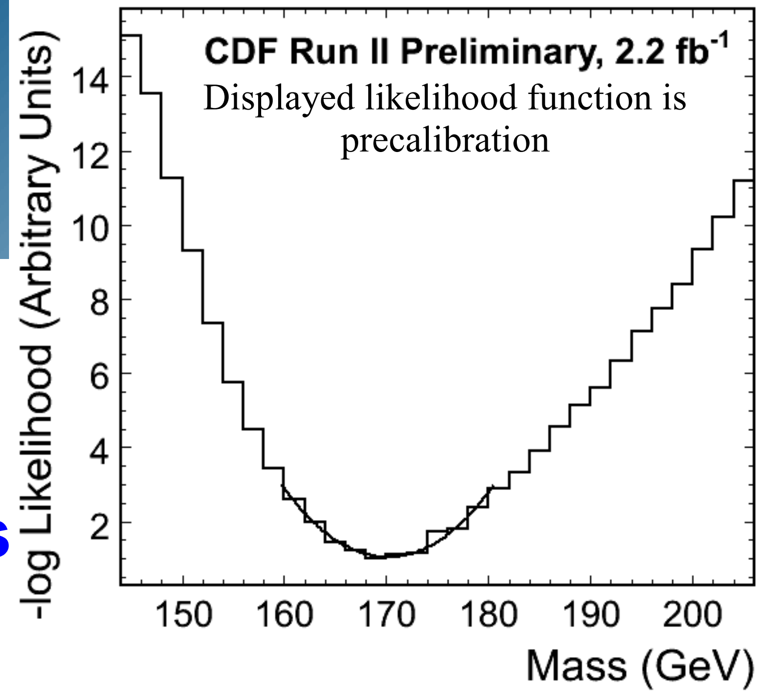
CDF Run II Preliminary, 2.2 fb^{-1}

Source	Result (GeV)
JES	3.37
MC Generator	0.50
ISR/FSR	0.34
Color Reconnection	0.50
Background Fraction	0.47
MC Statistics	0.14
PDF	0.12
gg fusion	0.17
B-jet	0.39
Lepton p_T	0.19
Pileup	0.95
Calibration	0.17
Total	3.7

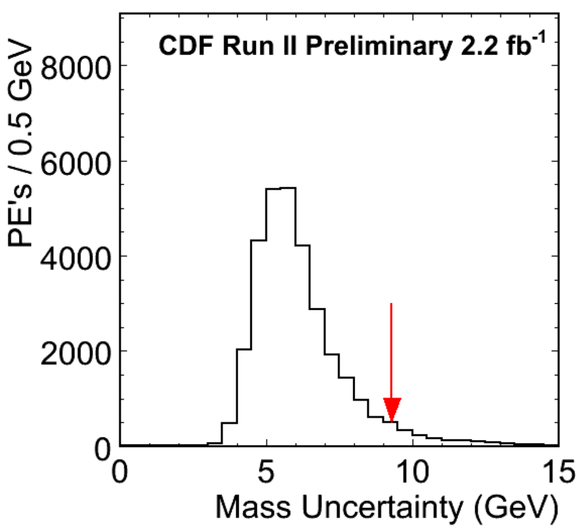
Systematic uncertainty dominated by Jet Energy Scale

Top Mass Result

- **First measurement of the top quark mass in hadronic τ + jets channel**
- **Result (2.2 fb^{-1}):**
  - **172.7 ± 9.3 (stat) ± 3.7 (syst) GeV**
  - **172.7 ± 10.0 GeV**
- Summer 2011 Tevatron Average (5.8 fb^{-1}):
  - 173.2 ± 0.9 GeV
- **Demonstrates that we can do complicated physics with taus**



Expected Statistical Uncertainty from PE's at 172.5 GeV



Conclusion

- **ttbar Cross Section measured in τ + jets channel**
  - **8.8 ± 3.3 (stat) ± 2.2 (syst) pb**
- **First top mass measurement using directly identified hadronic tau events (2.2 fb^{-1} of data)**
  - **172.7 ± 9.3 (stat) ± 3.7 (syst) GeV**
  - **172.7 ± 10.0 GeV**
  - Measurements agree with CDF and Tevatron Averages
  - Agree with measurements in other decay channels
- **We can use taus even in high jet multiplicity environments**
- **Taus are useful tools for identifying new physics**

http://www-cdf.fnal.gov/physics/new/top/2011/meatv3_tau_public/index.html

BACKUP

Tau Selection Requirements

Kinematic
- Visible $E_t > 25$
- Cluster $E_t > 20$

Fiducial
- $|\text{Cluster Eta}_{Det}| < 1$
- |Tracks Eta| < 1
- 9 < |ZCES| < 230

Seed Track Quality
- Seed Track $P_t > 10$
- >= 3 Axial Segments
- >= 2 Stereo Segments
- d0 < 1
- |Seed Track Vertex| < 60

Jet Rejection
- Visible Mass < 1.8

Isolation
- 0 tracks in 10 to 30 degree
- (Calorimeter E_t isolation)/E_t < 0.1

Electron Rejection
- ξ' > 0.1

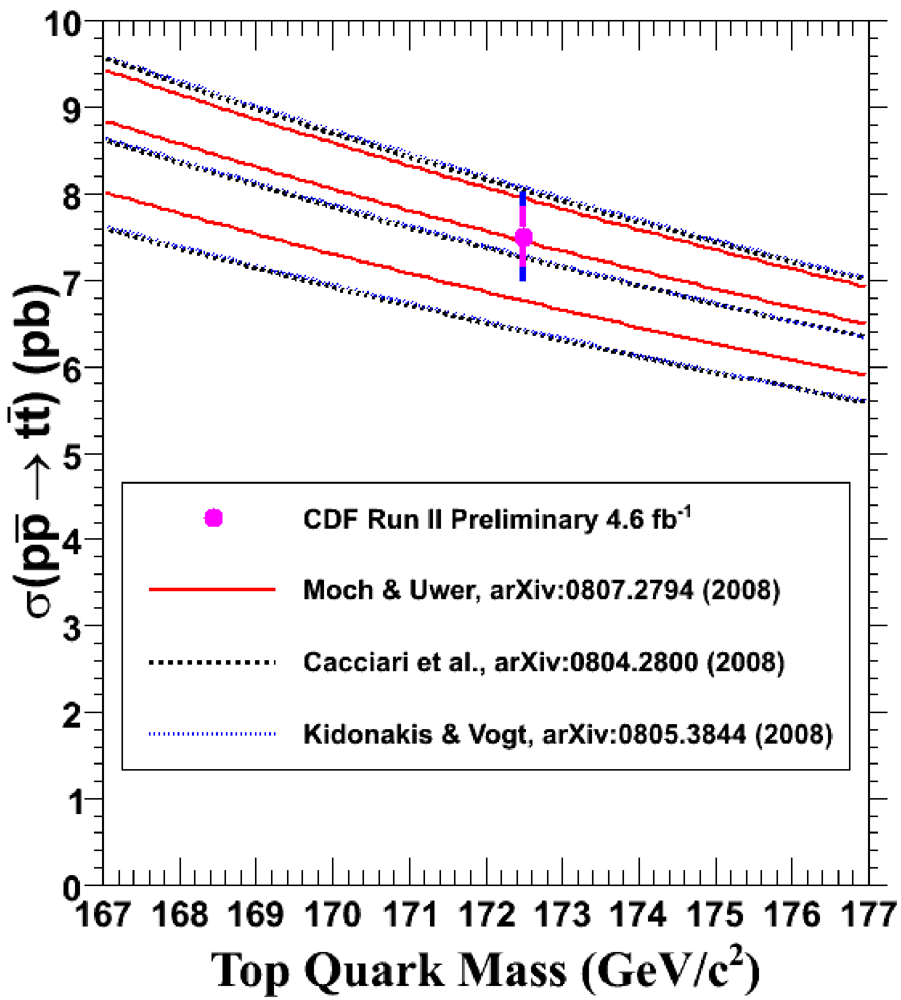
$$\xi' = \frac{E_{tot}}{\sum |\vec{p}|}\left(0.95 - \frac{E_{EM}}{E_{tot}}\right)$$

NN Input Variables

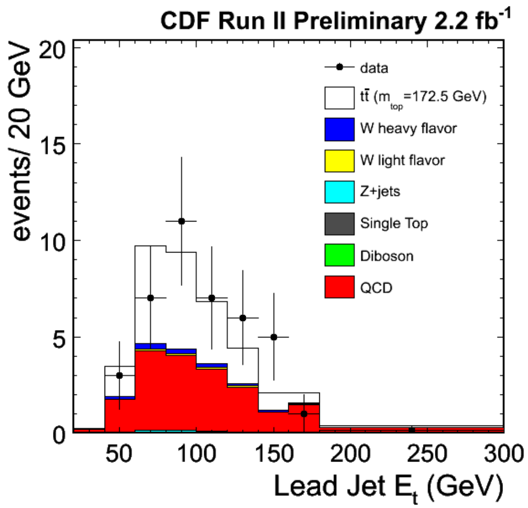
Use 8 varibles:

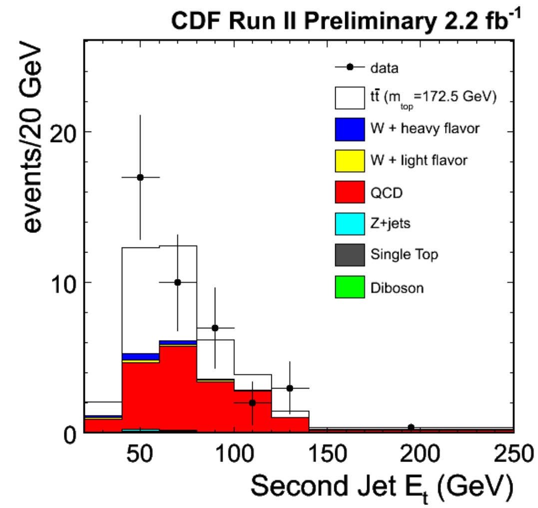
- MEt
- Σ Et tau + jets
- Σ Et tau + 2 lowest jets
- Σ Et 2 hardest jets
- Transverse M_w
- Lead Jet Et
- Average Eta Moment
  - Consider non btagged jets
- Lowest Dalitz Variable

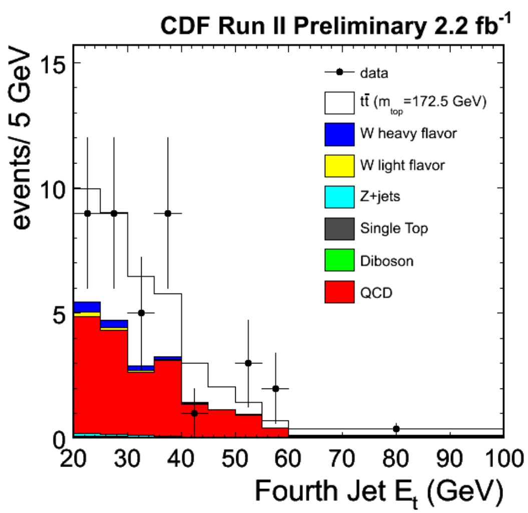
Cross Section Vs Mass

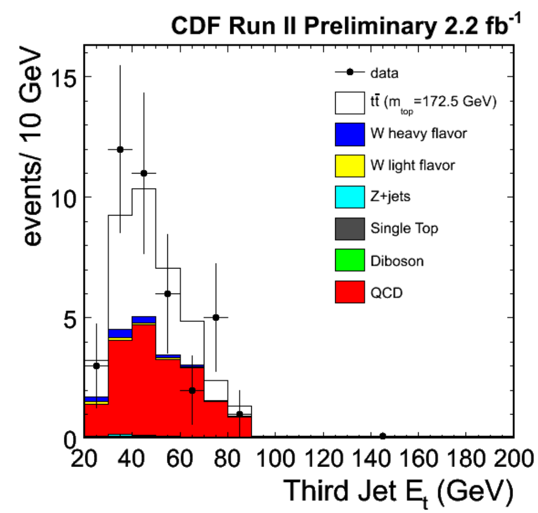


Event Variables









Parton Showering Systematic

- Compared cross section measurement with Pythia (ttop25) and Herwig (dtops0) ttbar MC.
  - **Found a 20.5% systematic uncertainty coming from the acceptance**
    - **Xsec Central Value with Pythia MC: 8.8 pb**
    - **Xsec Central Value with Herwig MC: 7.0 p**

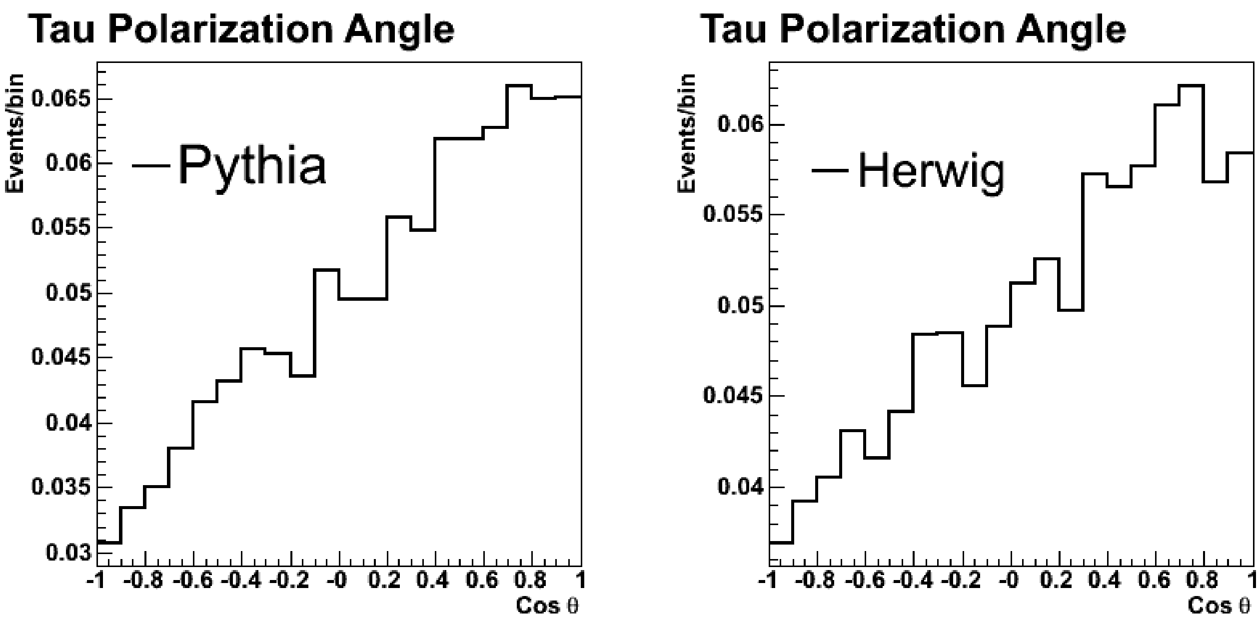
	Pythia		Herwig		Effect
Generated	5274981		4401272		
Total Accepted (No Matching)	8858	0.156%	9080	0.206%	32%
Matched tau	6114	0.116%	5434	0.123%	6%
Matched tau + jets	4242	0.080%	3695	0.084%	5%

Something in Herwig is faking taus

Check Tau Polarization

Do both MC's properly model tau polarization?

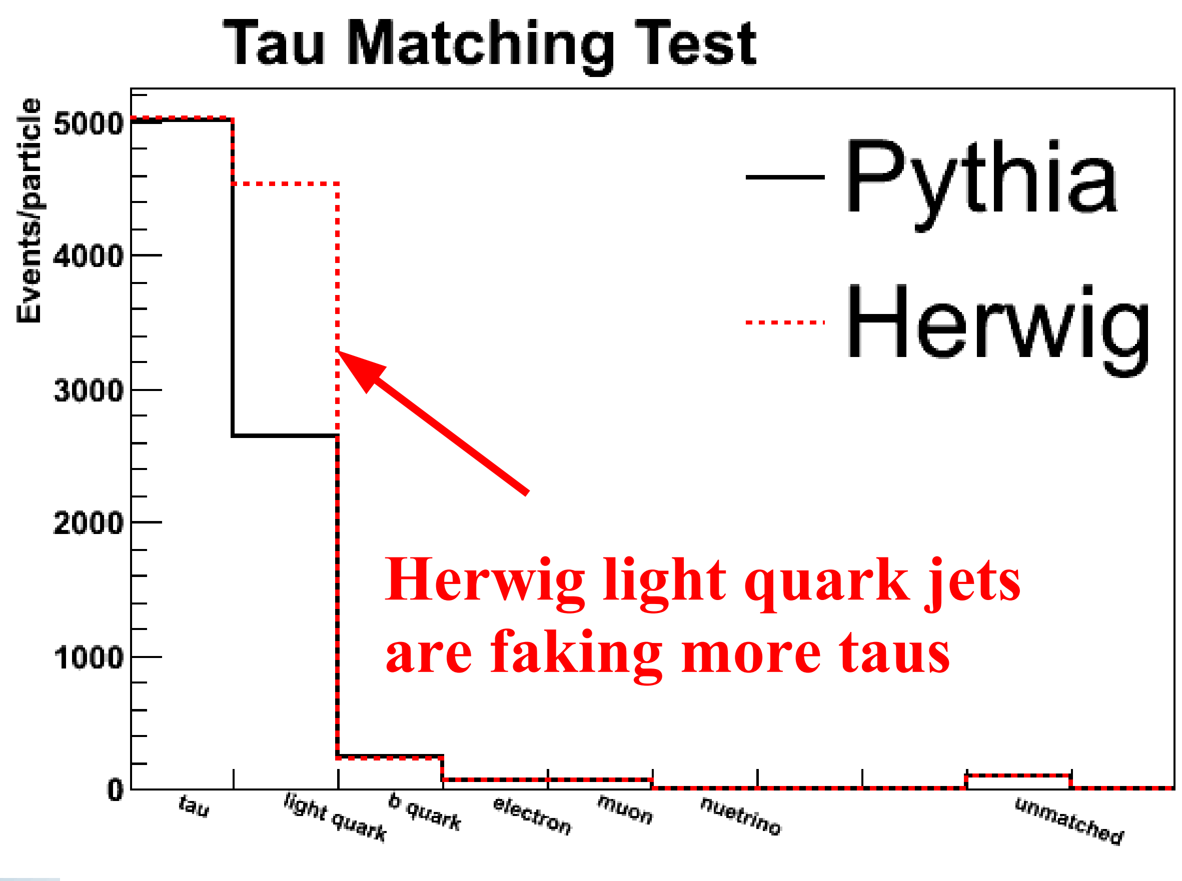
- What do we expect:
  - Polarized:
    - W couples to left handed taus
    - Neutrinos are left handed
    - Cos of polarization angle favors 1 over -1
  - Unpolarizated
    - Cos of polarization angle is random (flat distribution)



Generated taus have proper polarization in both MC's

Tau Matching

- Suspect that Herwig jets are better at faking taus
  - Match reco tau to 6 ttbar daughters
  - Rescale herwig plot so first bin (matched taus) equal:



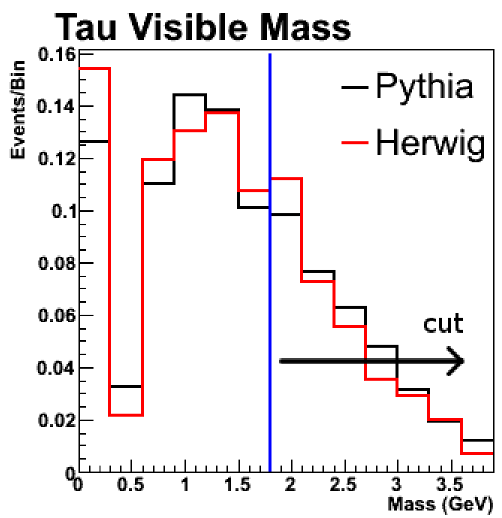
- Matched to:
  - Bin 1: taus
  - **Bin 2: light quarks**
  - Bin 3: b quarks
  - Bin 4: electrons
  - Bin 5: muons
  - Bin 6: nutrino
  - Bin 9: unmatched to a top daughter

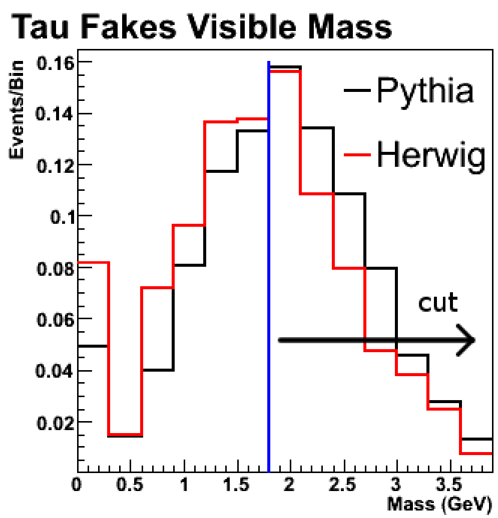
N – 1 Plots

Left: N-1 plot for all taus
Right: N-1 plot for taus matched to light quarks

- Main culprits are jet rejection cuts:
  - Visible Mass (Pi0's + Trks)

    → SMOKING GUN





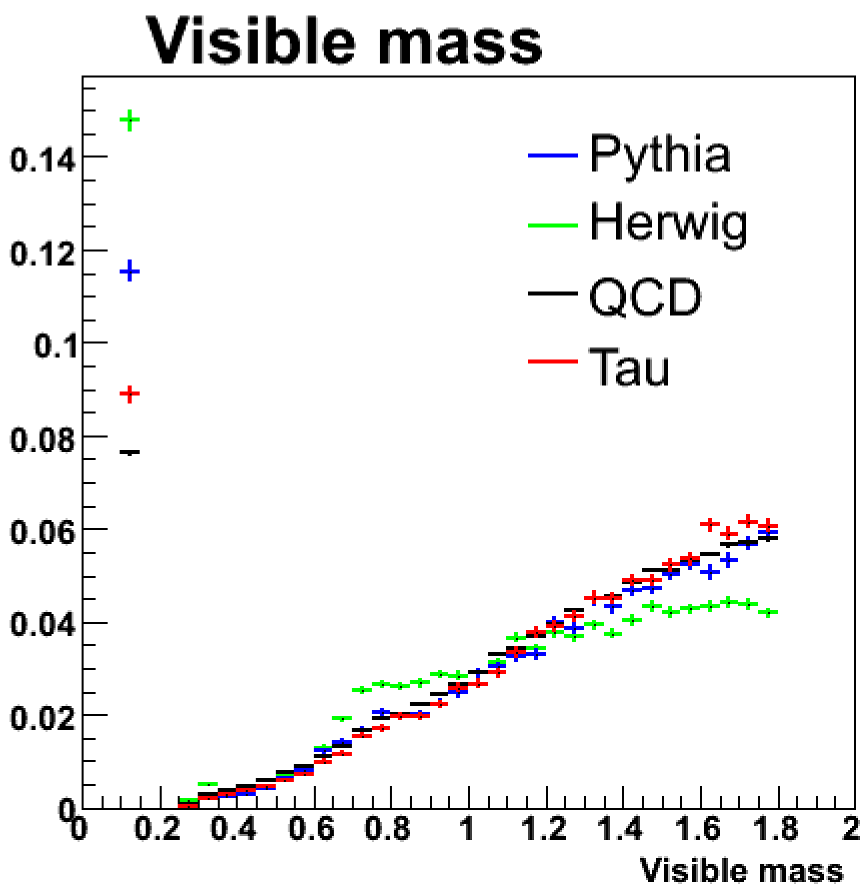
- Herwig jets:
  - Lower Pi0's

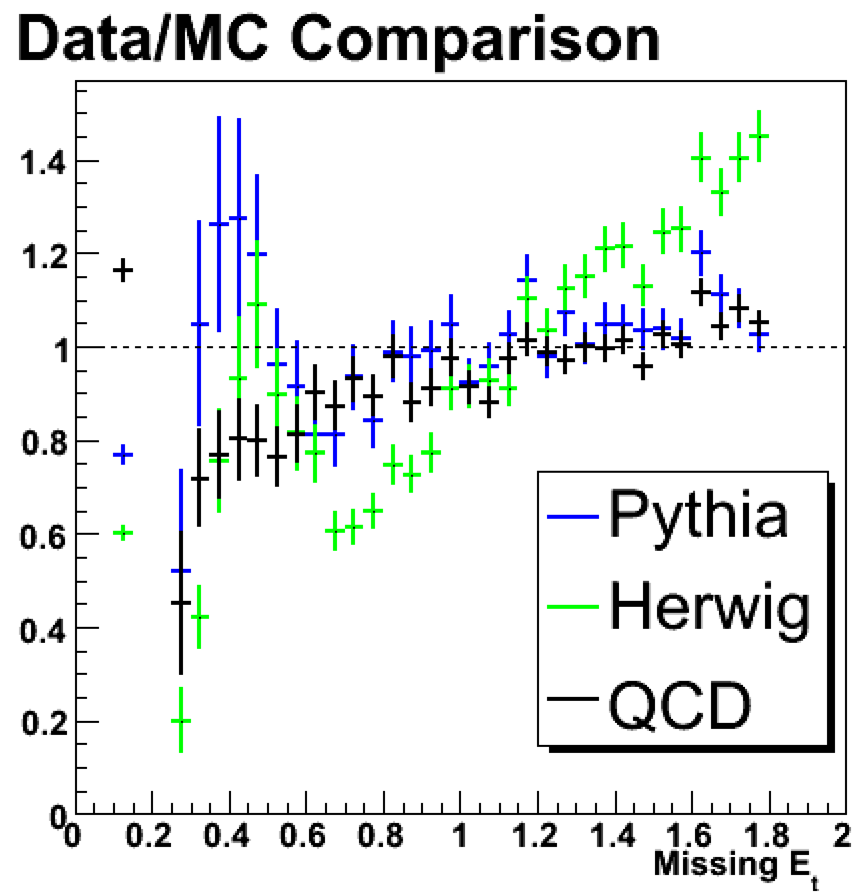
    → Lower EM fraction

    → Lower mass tau fakes
- **But is this effect real?**
  - Discussed this effect with Rick Field and Herwig authors Bryan Webber and Mike Seymour
  - They generally agreed that the charge/neutral particle ratio in jets at low Pt has a large disagreement between models. Both models fit LEP well, but they are not well tuned for hadron colliders

Tau Visible Mass

- Defined as mass of tracks + pi0s





Reweighting Results

Pretag	Acc	% Diff
Pythia	0.001885	---
Herwig	0.002350	**24.7 %**
Herwig RW	0.001961	**4.0%**

Tag	Acc	% Diff
Pythia	0.001209	---
Herwig	0.001494	**23.6 %**
Herwig RW	0.001247	**3.1%**

Final	Xsec (pb)	% Diff
Pythia	8.8	---
Herwig	7.0	**20.5 %**
Herwig RW	8.5	**3.4%**

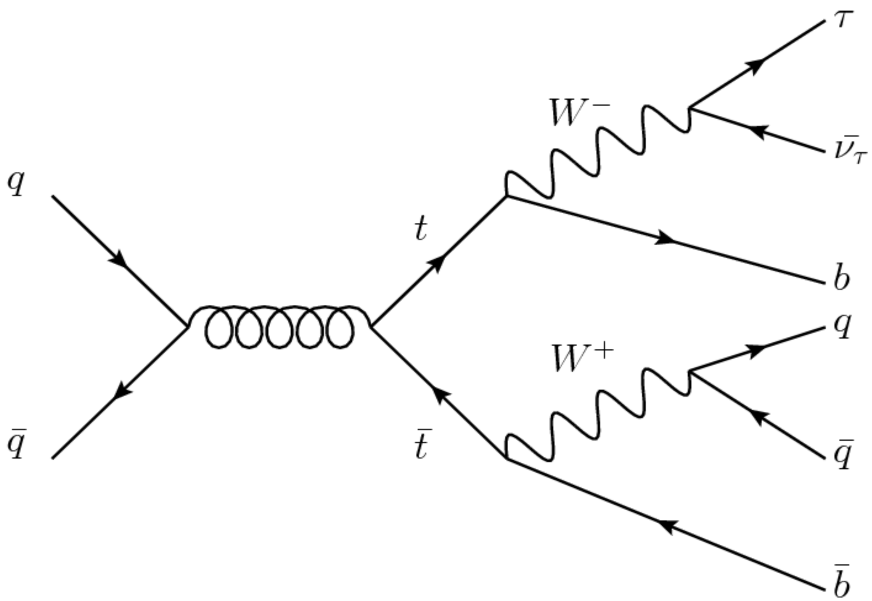
Reweight Herwig to match Pythia in visible mass

Removing visible mass difference brings the effect down to 3.4%

Similar to effect for e/mu analyses

Conservatively take a 6% uncertainty = 0.5 pb

Mahlon Parke Matrix Element



$$|M|^2 = \frac{g_s^4}{9} F\bar{F}\left(2 - \beta^2 sin^2\theta_{qt}\right)$$

g_s = strong coupling constant

β = relativistic velocity

θ_{qt} = top production angle in ttbar rest frame

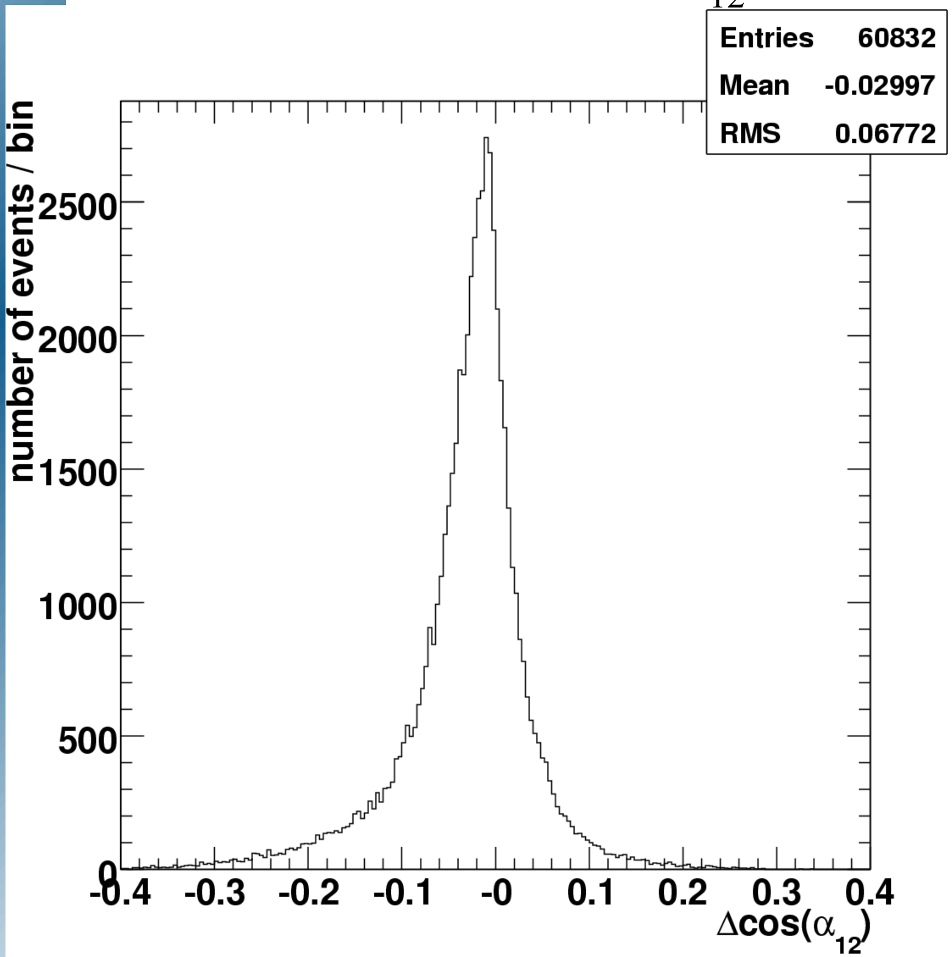
hep-ph/9512264

$$F = \frac{g_W}{4} \frac{(m_t^2 - m_{\bar{\tau}\nu}^2)}{(m_{b\bar{\tau}\nu}^2 - m_t^2)^2 + m_t^2\Gamma_t^2} \frac{m_t^2 \left(1 - c_{\bar{\tau}b}^2\right) + m_{\bar{\tau}\nu}^2 \left(1 + c_{\bar{\tau}b}\right)^2}{(m_{\bar{\tau}\nu}^2 - m_W^2)^2 + m_W^2\Gamma_W^2}$$

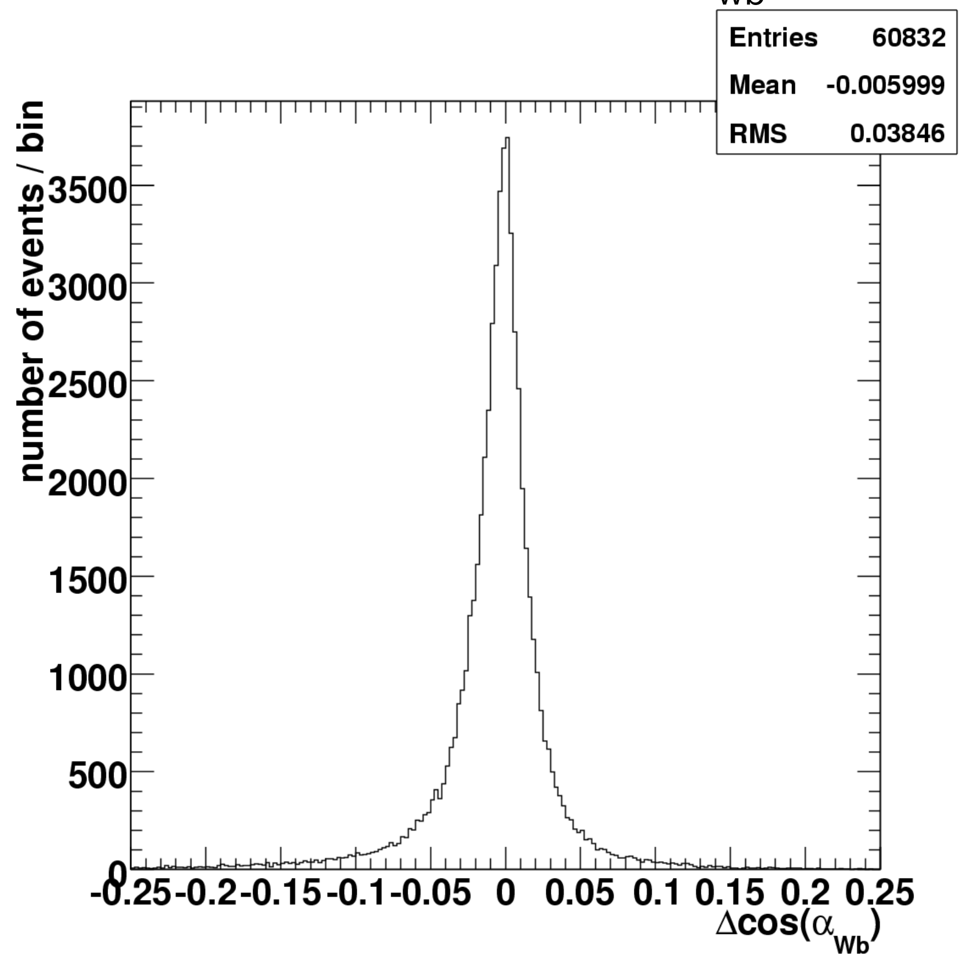
$$\bar{F} = \frac{g_W}{4} \frac{(m_t^2 - m_{d\bar{u}}^2)}{\left(m_{\bar{b}d\bar{u}}^2 - m_t^2\right)^2 + m_t^2\Gamma_t^2} \frac{m_t^2 \left(1 - c_{d\bar{b}}^2\right) + m_{d\bar{u}}^2 \left(1 + c_{d\bar{b}}\right)^2}{(m_{d\bar{u}}^2 - m_W^2)^2 + m_W^2\Gamma_W^2}$$

Angular Bias

Resolution of $\cos(\alpha_{12})$

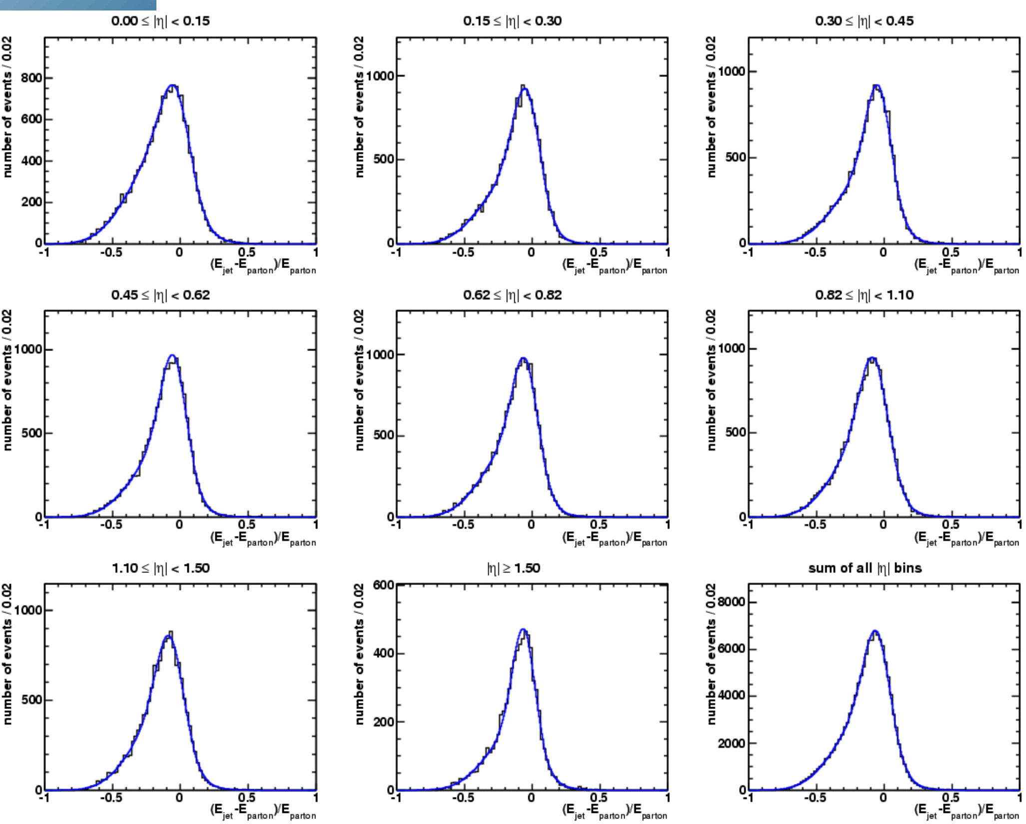


Resolution of $\cos(\alpha_{wb})$

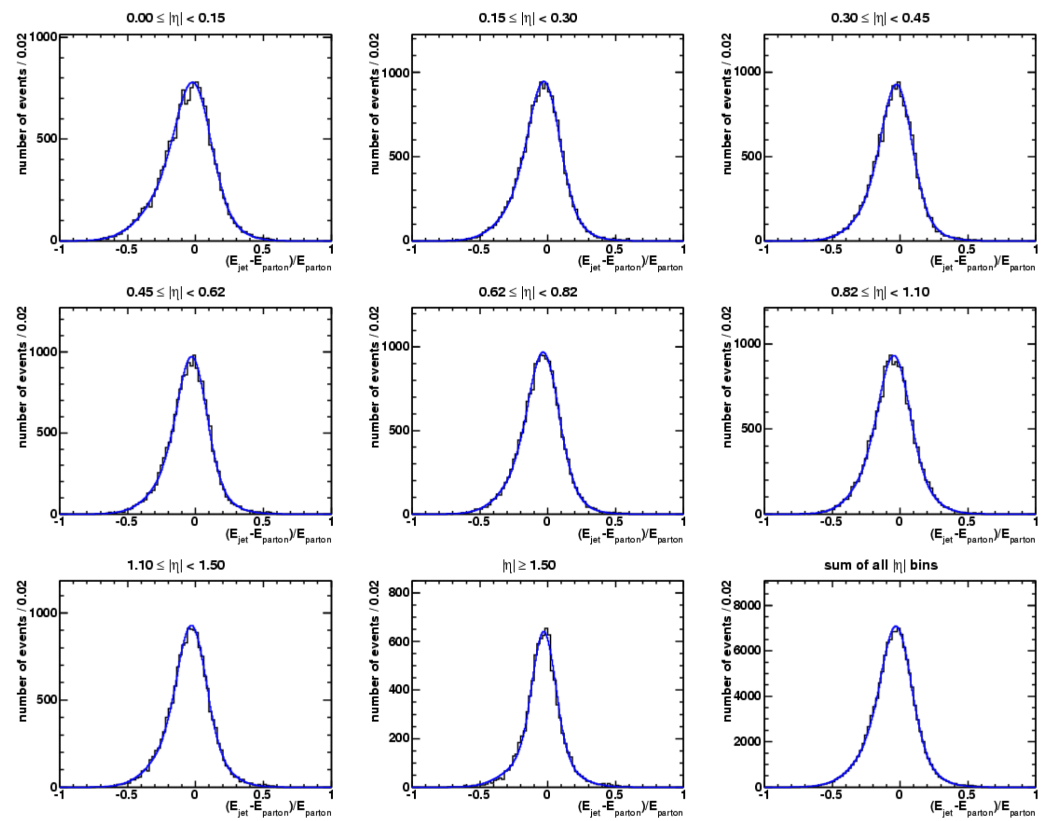


Jet Energy Transfer Functions

Light quark Energy TF

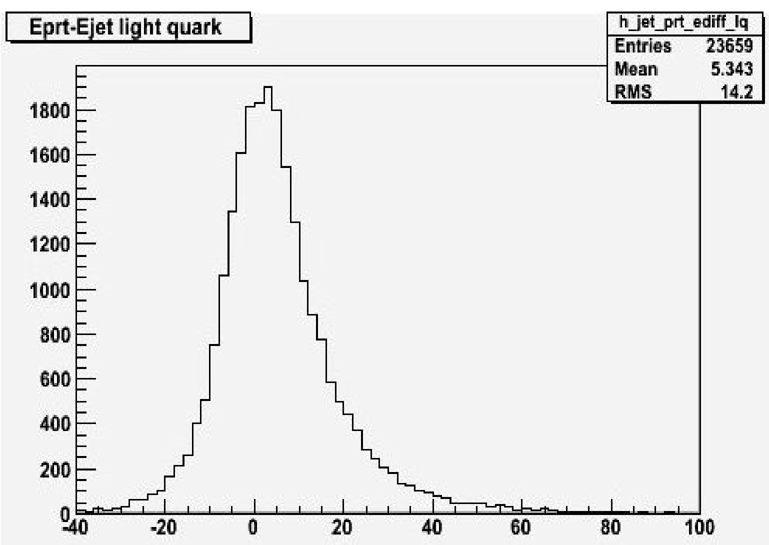


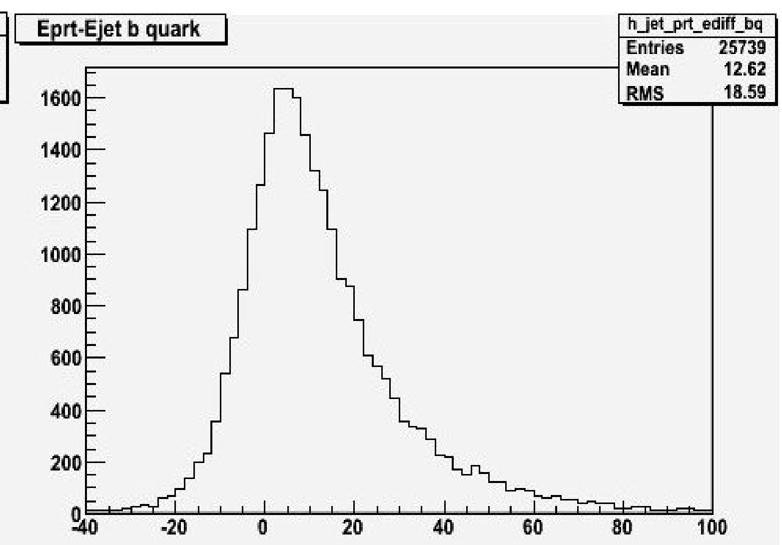
b quark Energy TF



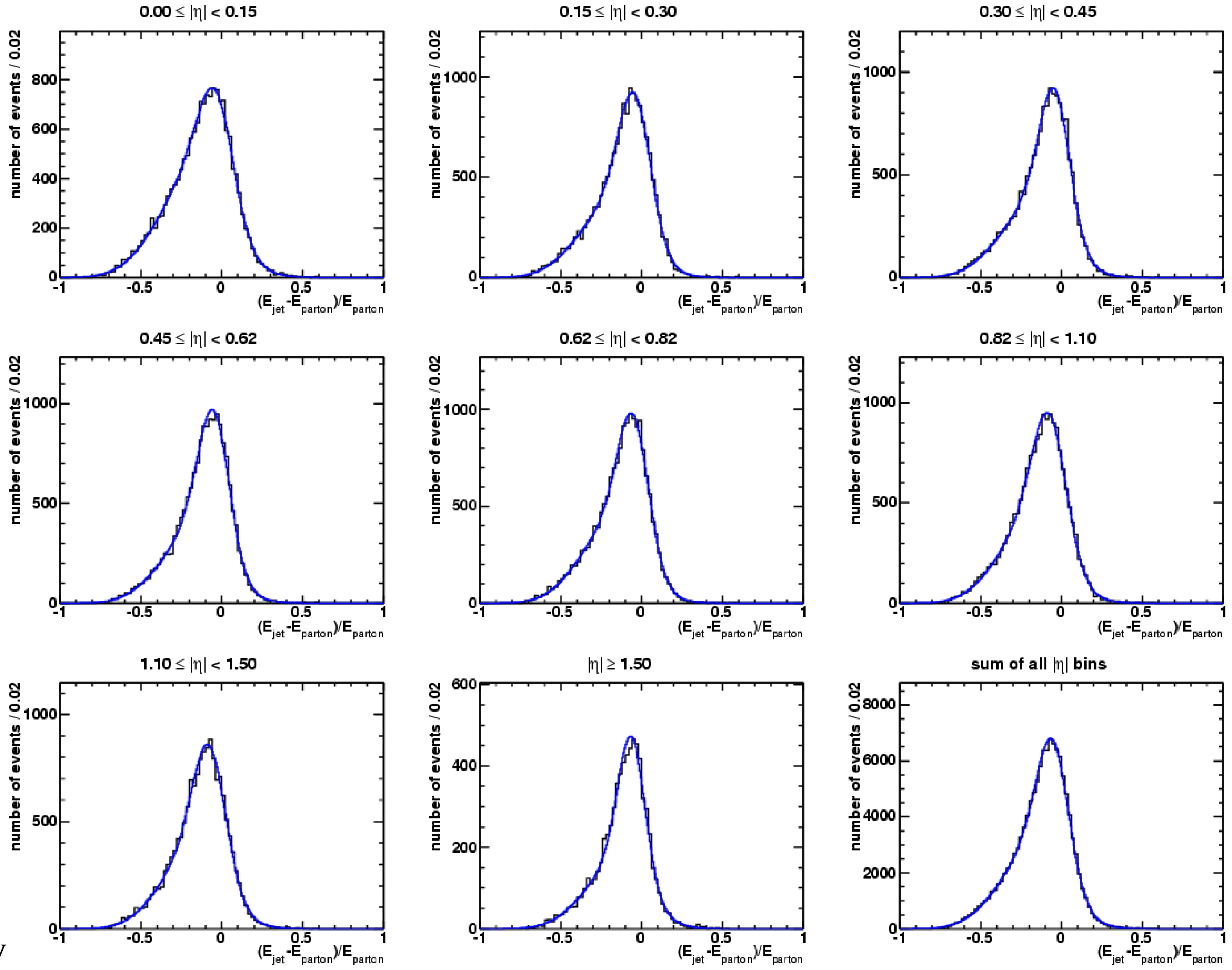
Jet Energy Transfer Functions

- Corrected jet energy not equivalent to parton energy
- Transfer function returns probability that measured jet x is the result of parton y
  - Sum of two Gaussians with 5 parameters, p_i
    - $p_i = a_i + b_i * E_{Parton}$
  - $$W_{jet}(E_{jet}, E_{parton}) = \frac{1}{\sqrt{2\pi}(p_2 + p_3 p_5)} [e^{\frac{-(\delta - p_1)^2}{2p_2^2}} + |p_3| e^{\frac{-(\delta - p_4)^2}{2p_5^2}}]$$
  - $\delta = E_{parton} - E_{jet}$

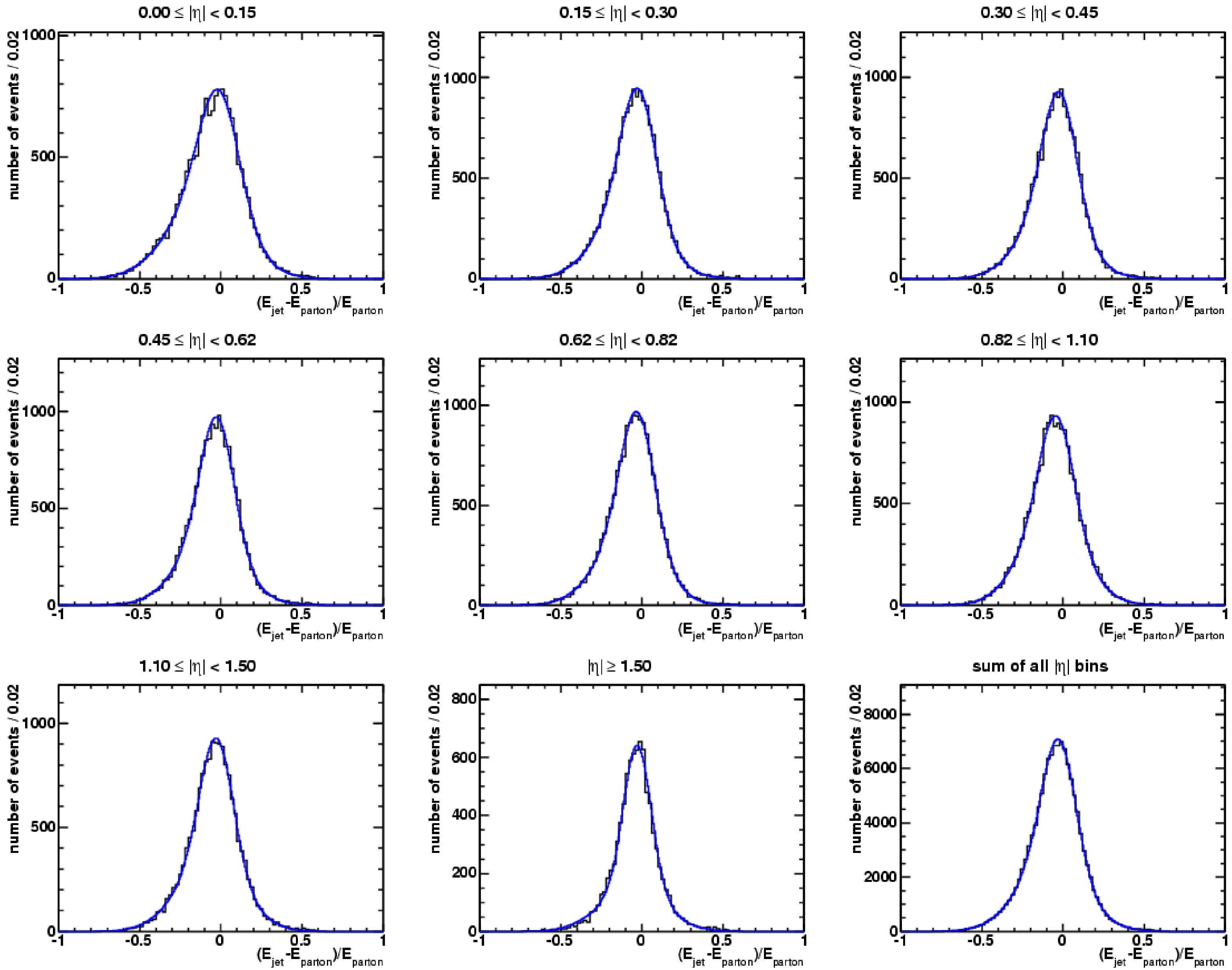




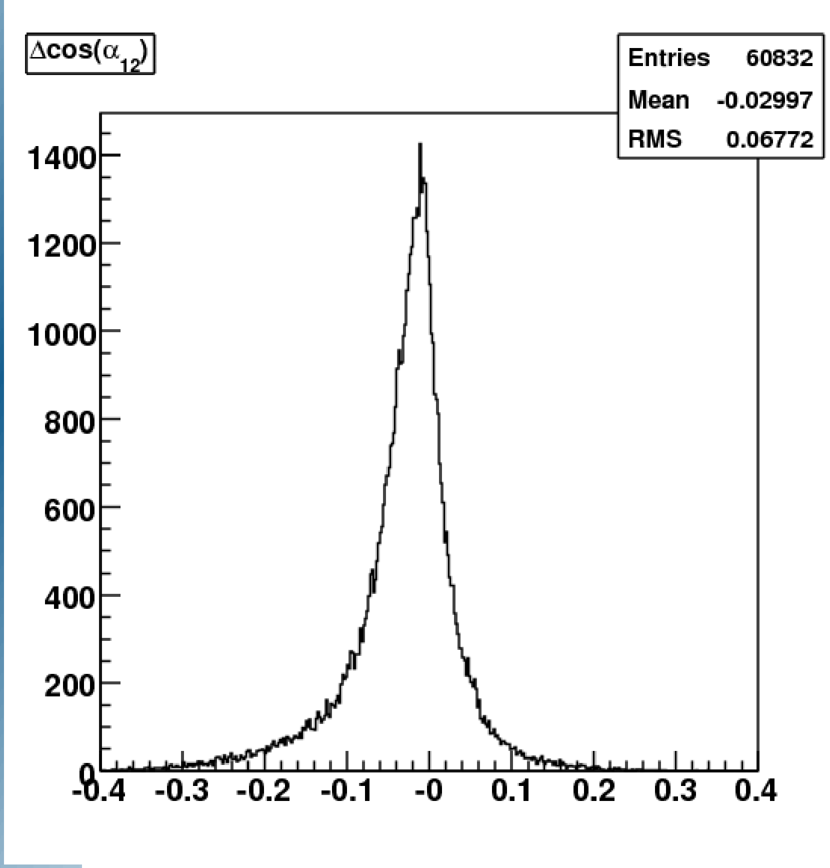
Jet Energy Transfer Functions: Light Quark



Jet Energy Transfer Functions: B Quark



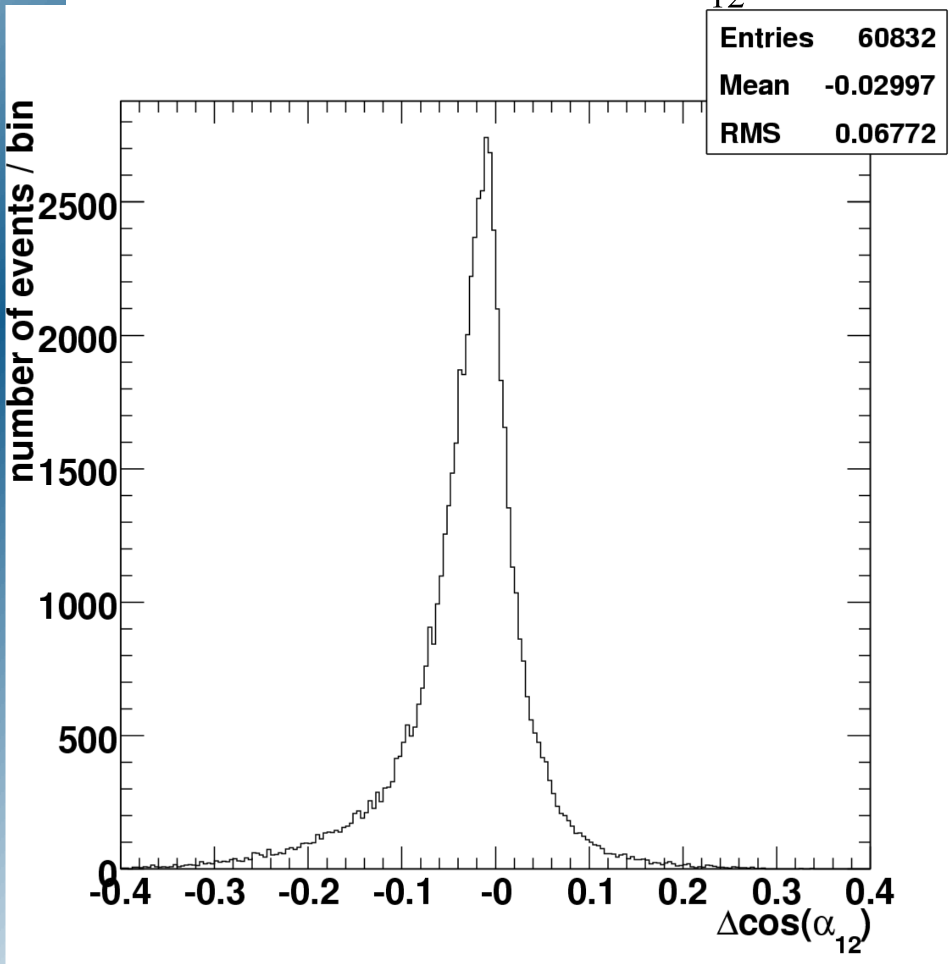
Angular Transfer Functions



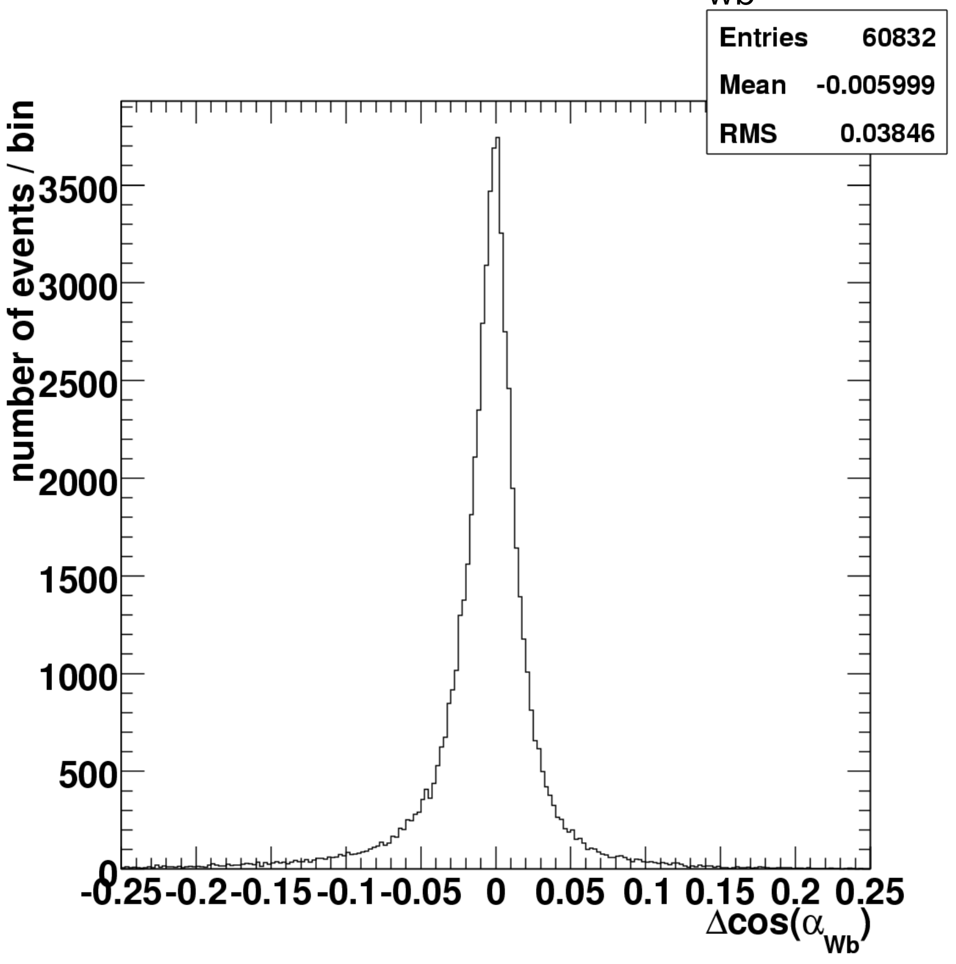
- Previously assumed jet angles were well measured
  - Seems valid when checking resolutions
- Further investigation shows bias in angle between the two jets from hadronic W
  - causes a 1 to 2 GeV shift down in M_{Whad}
  - very important value for in situ jet calibration

Angular Bias

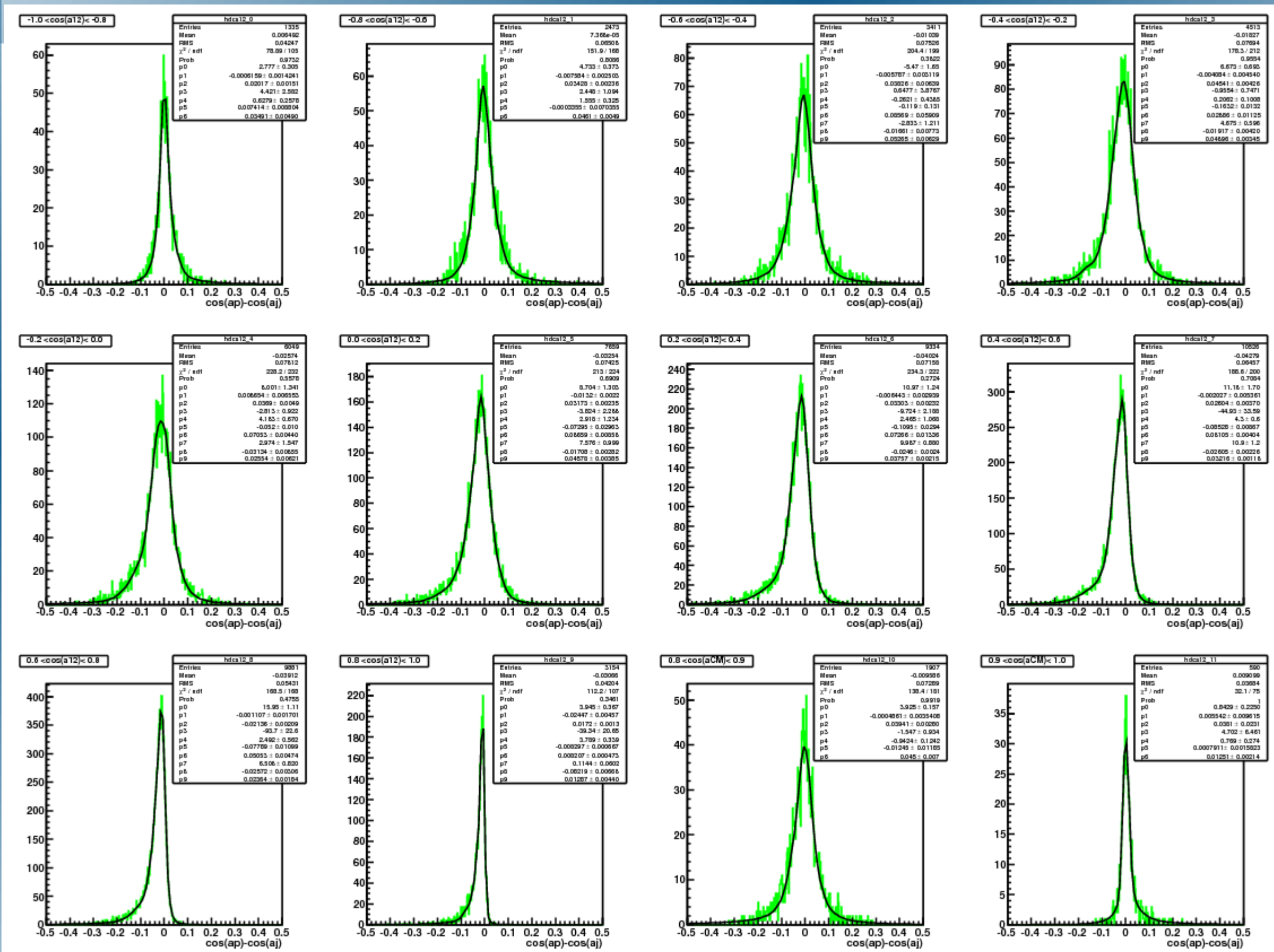
Resolution of cos(α_{12})



Resolution of cos(α_{wb})



Angular Transfer Functions



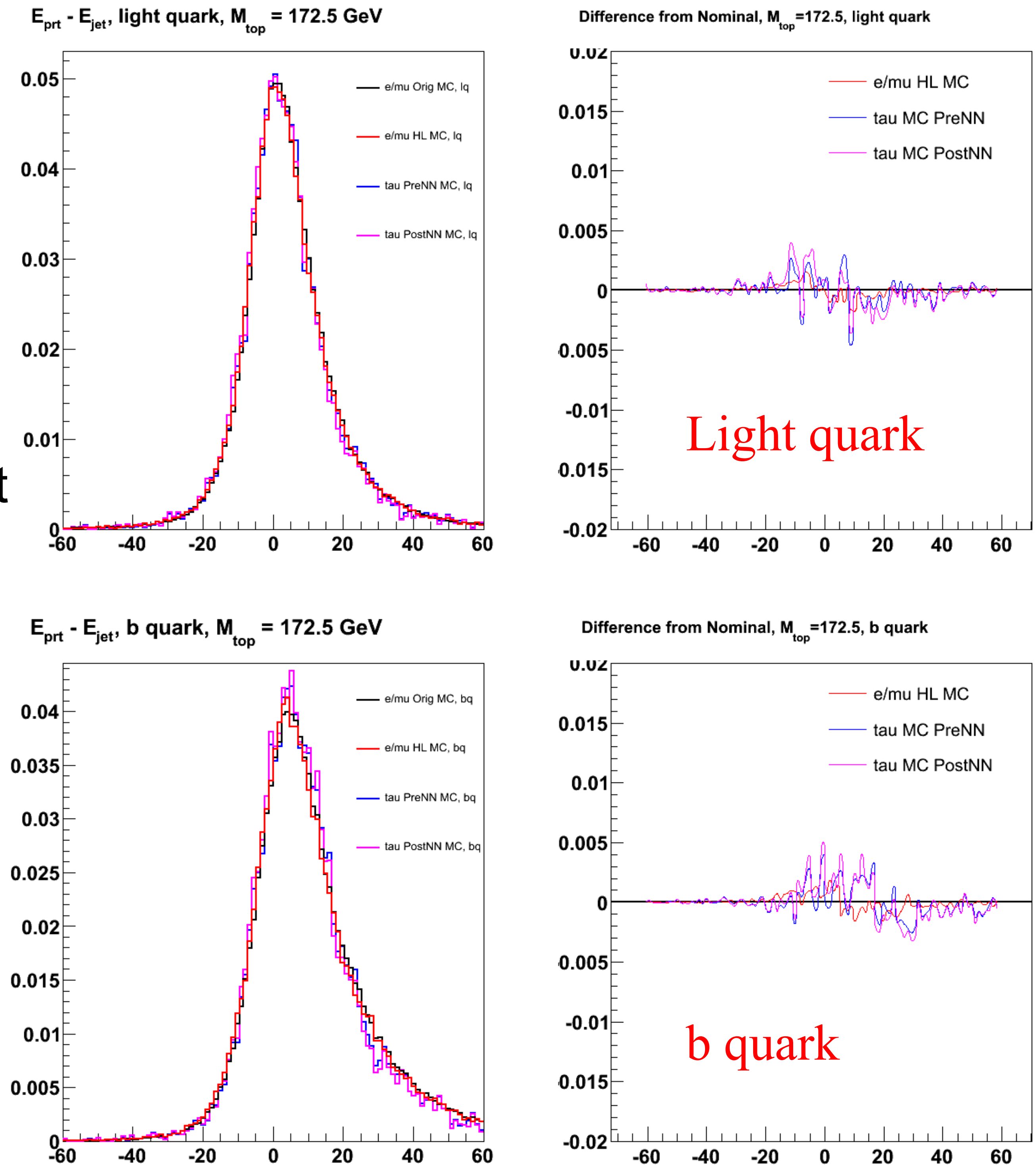
12 bins in $\cos|\alpha_{12}|$ and $\cos|\theta_{CM}|$

θ_{CM} = angle of the jets with respect to W direction in CM frame

- Parameterize transfer function in terms of α_{12}
- Add integral over α_{12} to Signal Probability calculation
- Repeat process for α_{Wb}

Energy TF 172.5

- Mass = 172.5
- Sanity check at another mass point
- Black – orig e/mu MC
- Red – high lumi MC
- Blue – preNN tau MC
- Pink – postNN tau MC



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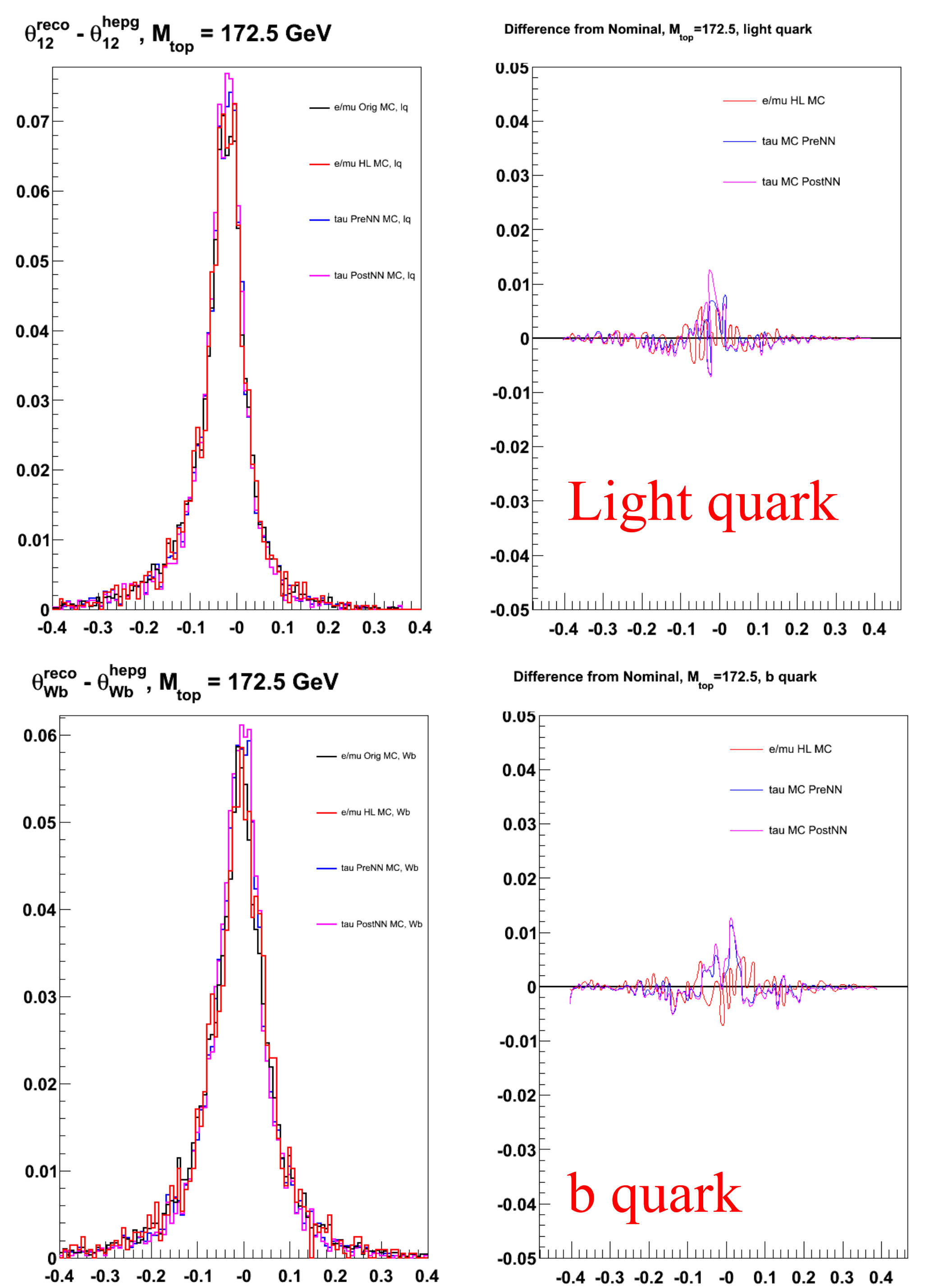


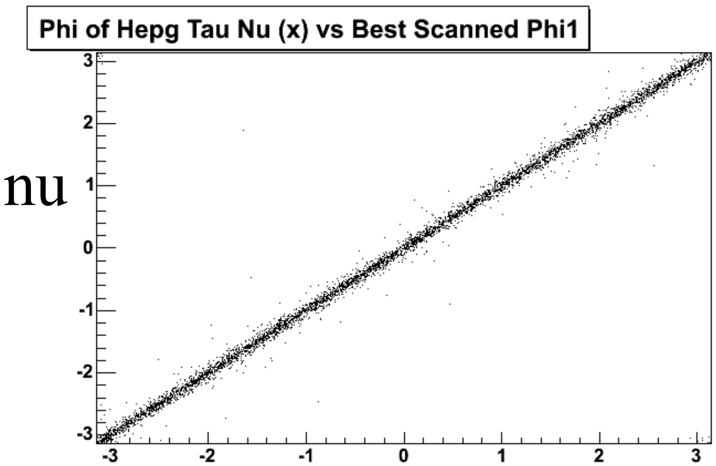
Scan Results

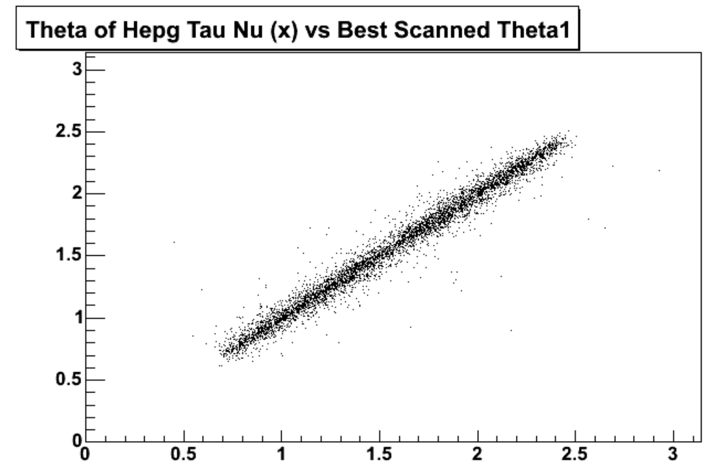
x = generated
y = reconstructed

Phi

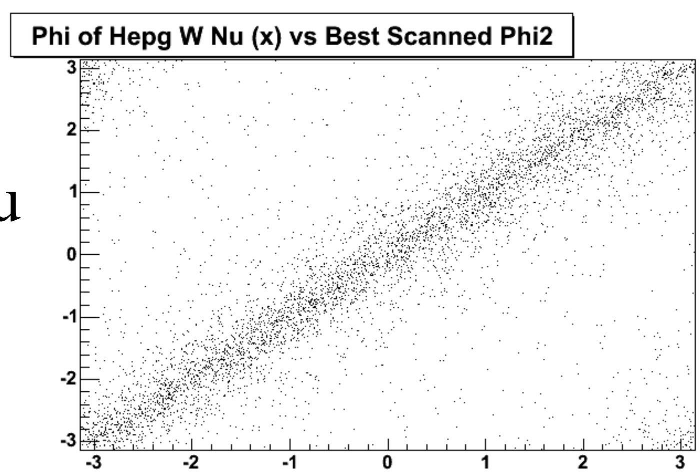
Theta

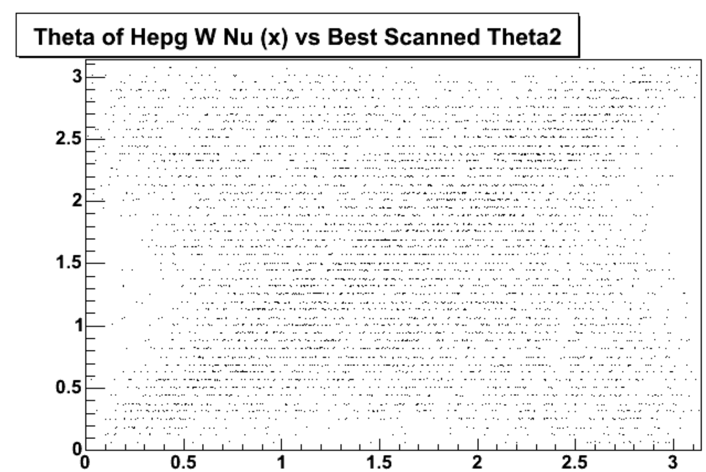
Tau decay nu





W decay nu

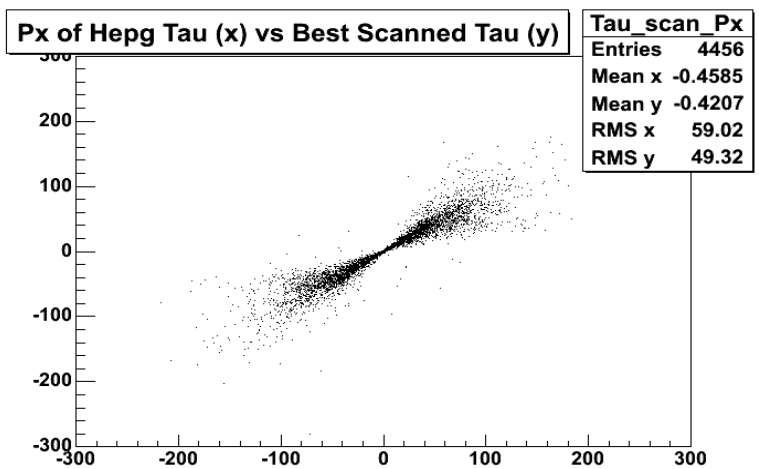




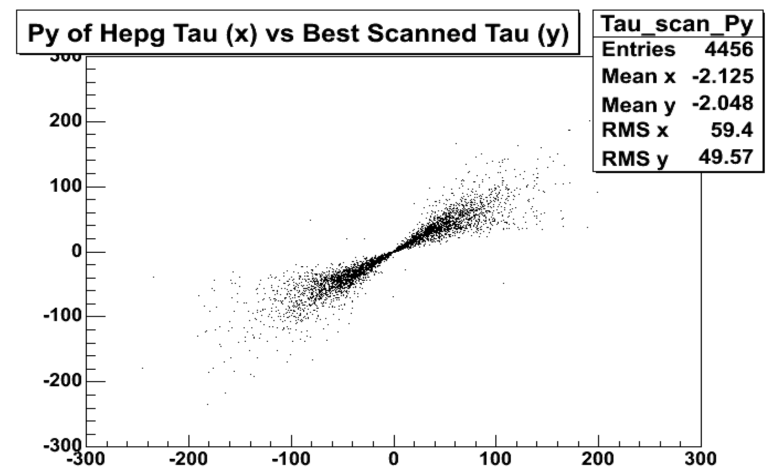
Tau Results

x = generated
y = reconstructed

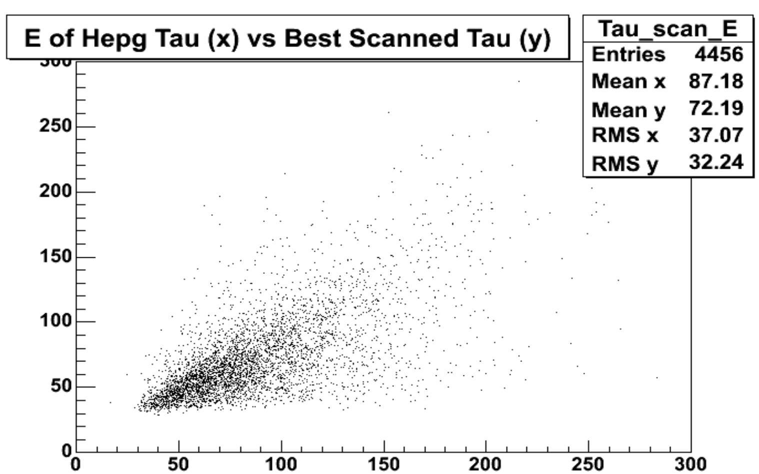
Px



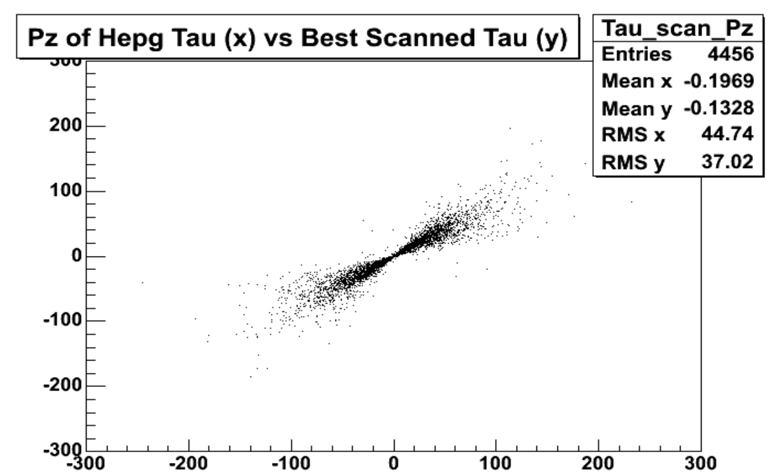
Py



E

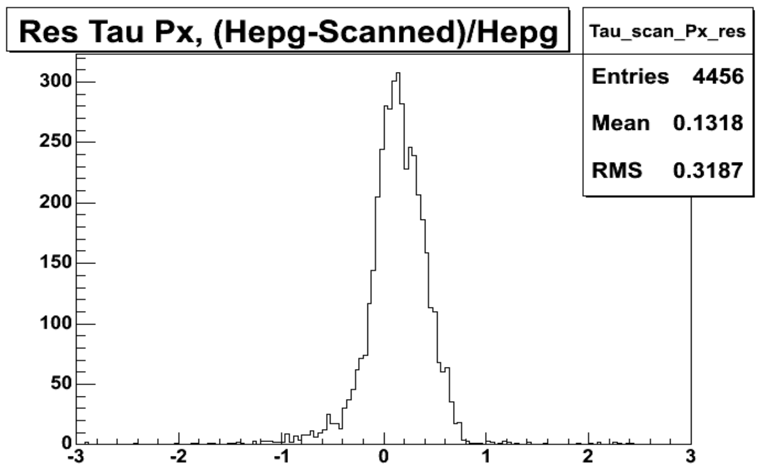


Pz

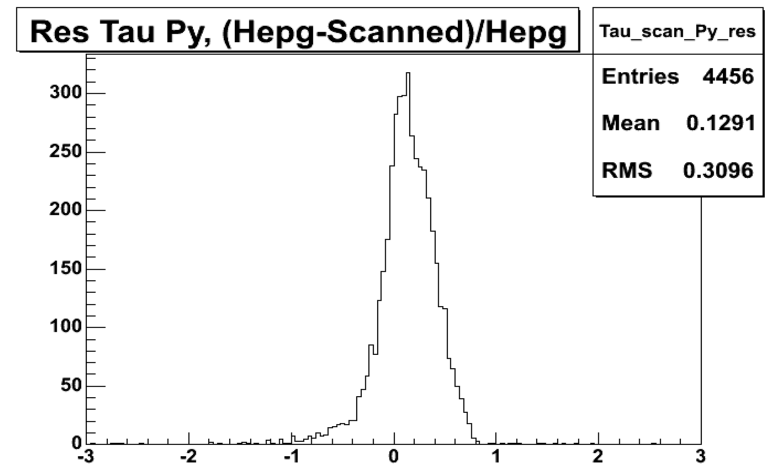


Tau Results

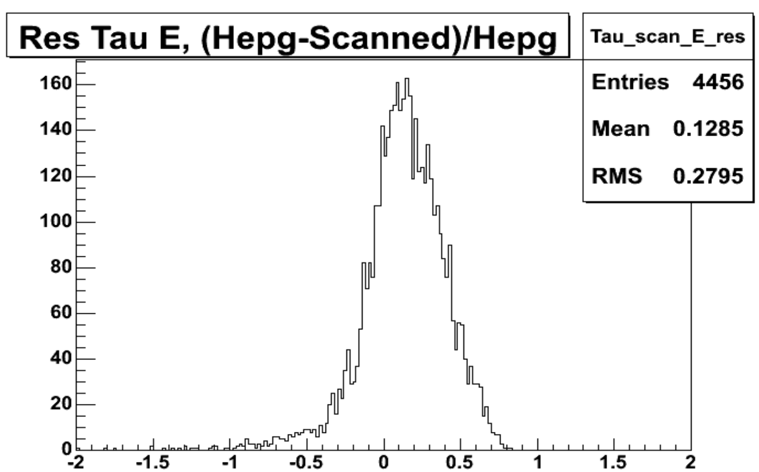
Px



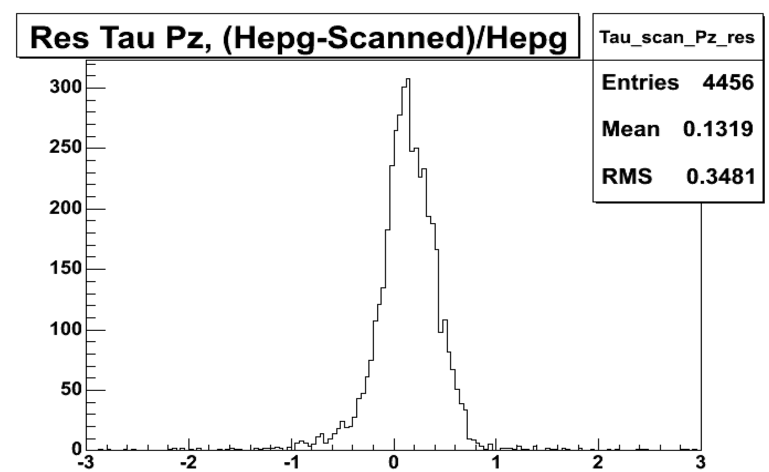
Py



E



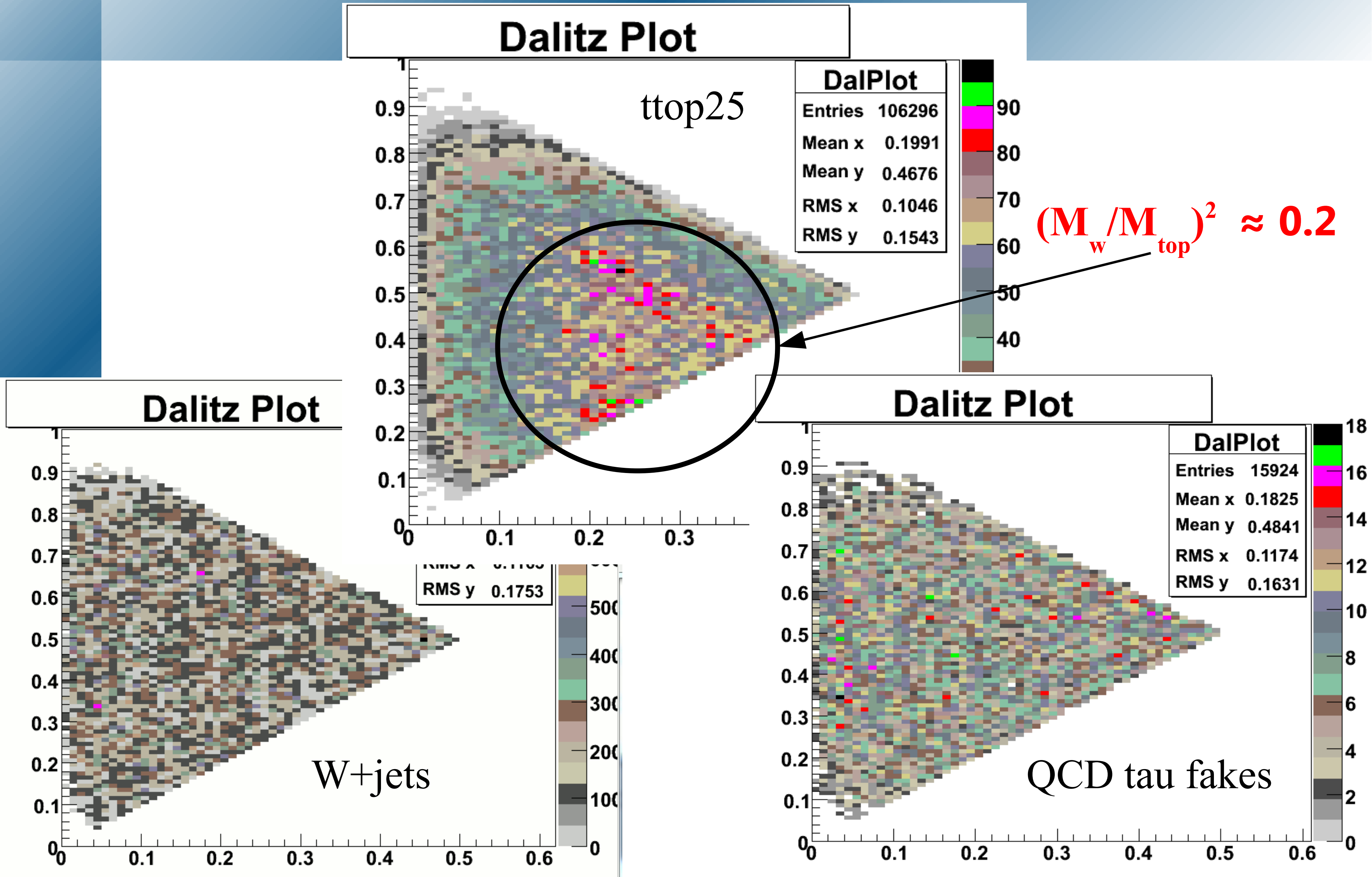
Pz



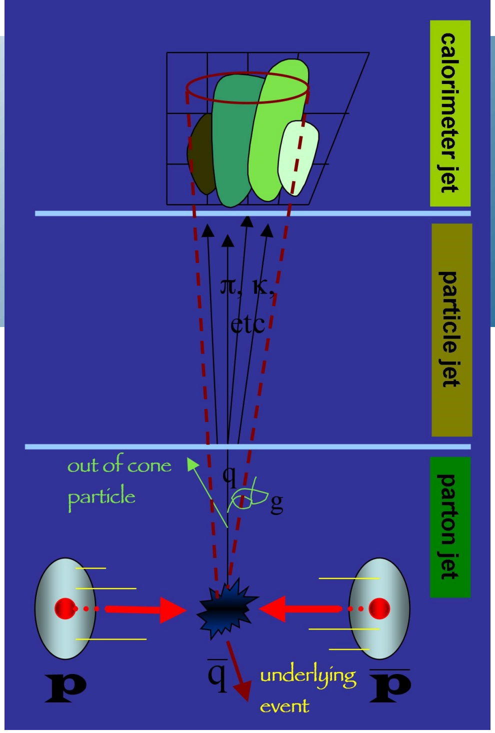
Dalitz Variables

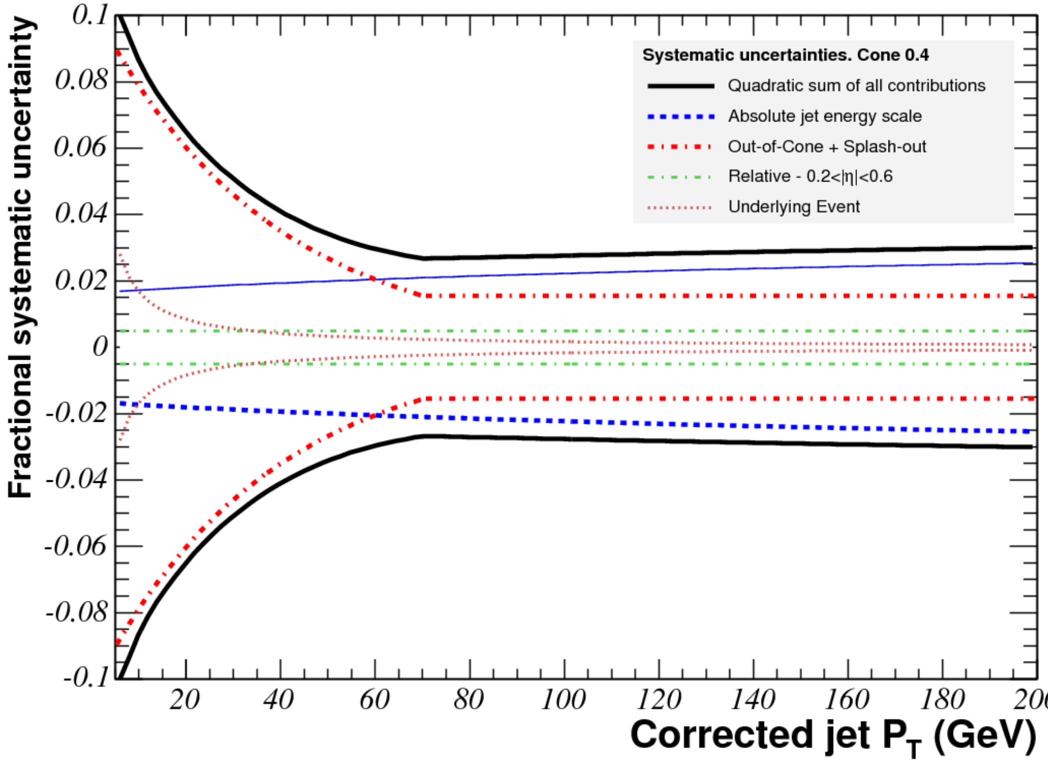
- For each jet triplet:
  - Make 3 normalized Dalitz Variables:
    - M(ij)^2 / [M(ijk)^2 + M(i)^2 + M(j)^2 + M(k)^2]
    - By definition, these variables sum to 1
  - Order the 3 variables from highest to lowest and plot:
    - Hi vs Med
    - Hi vs Low
    - Med vs Low
- If you make this plot for all triplets:
  - ttbar events: the ratio of W resonance to top resonance will stand out
  - Background events: random noise

Dalitz Plots



What is a Jet?





- CDF jet energy corrections to scale measured jet energy back to "particle level" jet
- "Particle level" not identical to "parton level"
  - Transfer Functions (later slide)
- Each correction also has an associated uncertainty
- We call quadrature sum of all uncertainties σ_{JES}