Search for Large Extra Dimensions Using Missing Energy
BLESSING

Kevin Burkett
Harvard University
Maria Spiropulu
University of Chicago

Exotics Meeting
October 17, 2002

- Introduction
- Background Monte Carlos and Normalization
- Comparison of Data to Standard Model Predictions
- Signal Systematics
- Extraction of Limit

Theoretical Motivation

New solution to the hierarchy problem

Model of Arkani-Hamed, Dimopoulos, Dvali

- n toroidal e.d. compactified at radius R
- Standard Model constrained to 4 dim. wall
- Gravity exists in 4+n dim. “bulk”
- New effective Planck scale, M_D

$$M^2_{Planck} \sim R^n M_D^{2+n}$$

Collider Signatures of Extra Dimensions

- Real Graviton Emission, Virtual Exchange
- Graviton emission: 3 processes

$$q\overline{q} \rightarrow gG,\ qg \rightarrow qG,\ gg \rightarrow gG$$

- Graviton $\Rightarrow$ Missing Energy

Implemented in Pythia 6.1

- Collaboration with J. Lykken and K. Matcheev
- Uses ADD model
- Calculations of Giudice, Ratazzi, and Wells
- 3 processes handled separately
- Choose # extra dimensions, M_D

List of Backgrounds

- $Z \to \nu\overline{\nu}$ + jets (Looks like the signal)
- $W \to \tau\nu$ + jets
- $W \to \mu\nu$ + jets
- $W \to e\nu$ + jets
- QCD di-jets
- Dibosons
- $t\overline{t}$, single top

General Strategy:

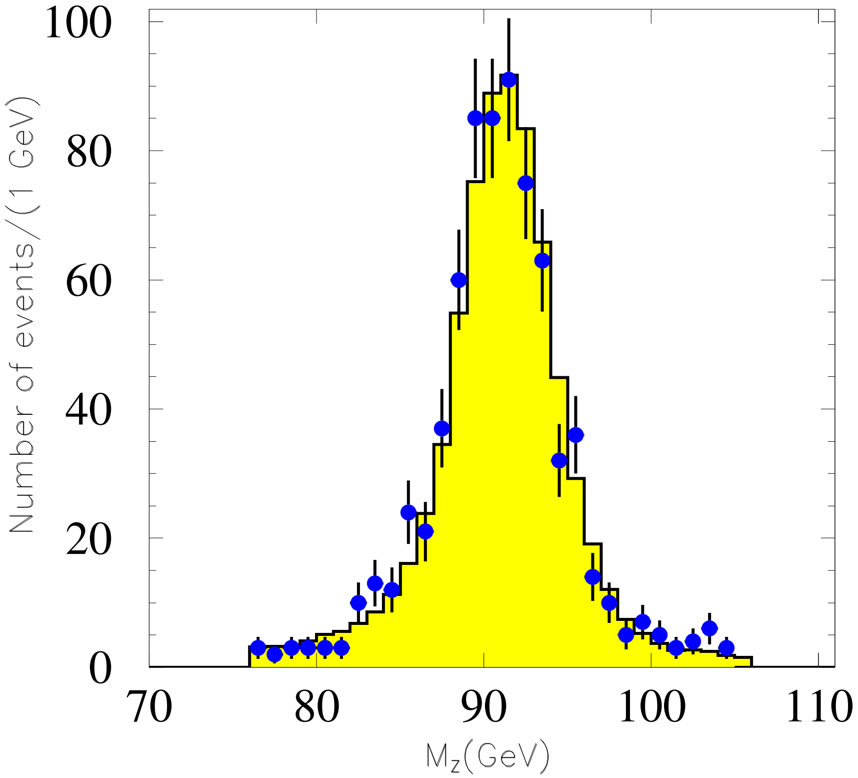
- Generate background processes in MC
- Normalize MC to data using other signals

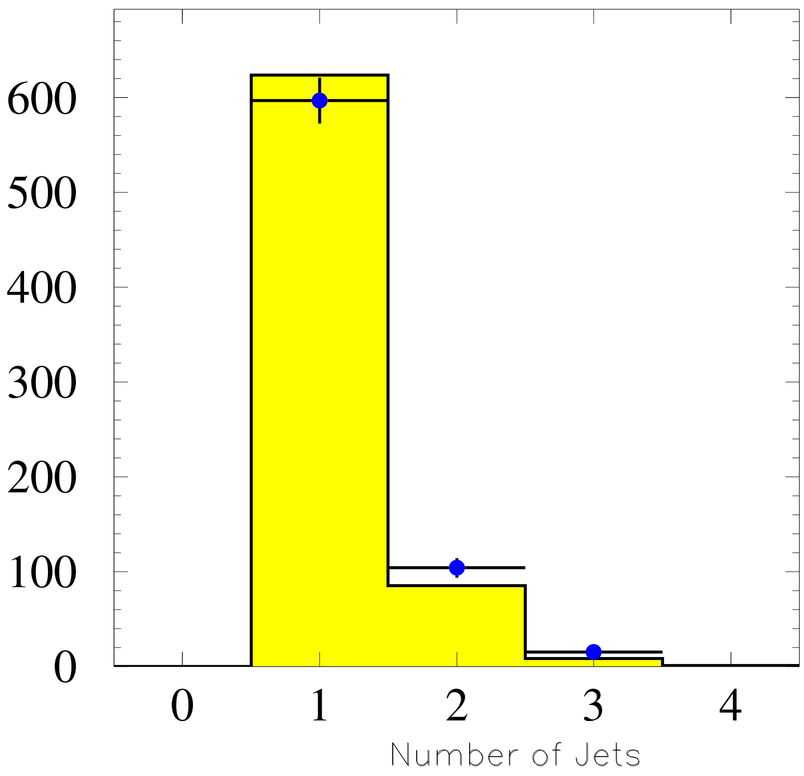
For W and Z Backgrounds:

- Generate PYTHIA Z + jets, W + jets
- 2→2 processes
- For Z + jets, turn off γ/Z interference
- Generate $Z \to ee + jets$, $W \to e\nu + jets$
- Select Z and W using Duke cuts
- Compare to $Z \to ee{+}jets$, $W \to e\nu{+}jets$ data
- Normalize MC based on # of $Z \to ee + jets$ in data

Z+jets Background

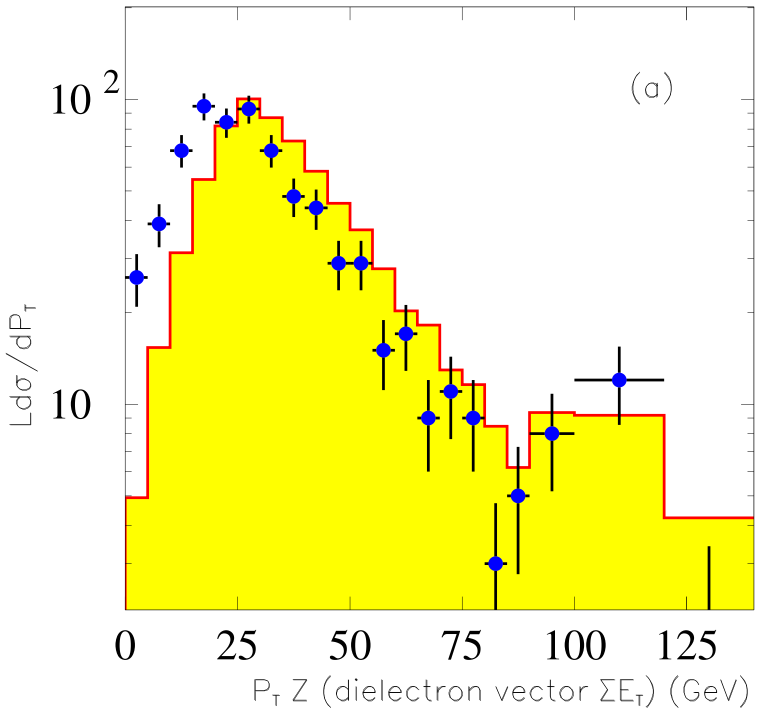
- Points: Data, Histogram: Pythia MC
- (a): $m(Z)$, (b): N_{jet}

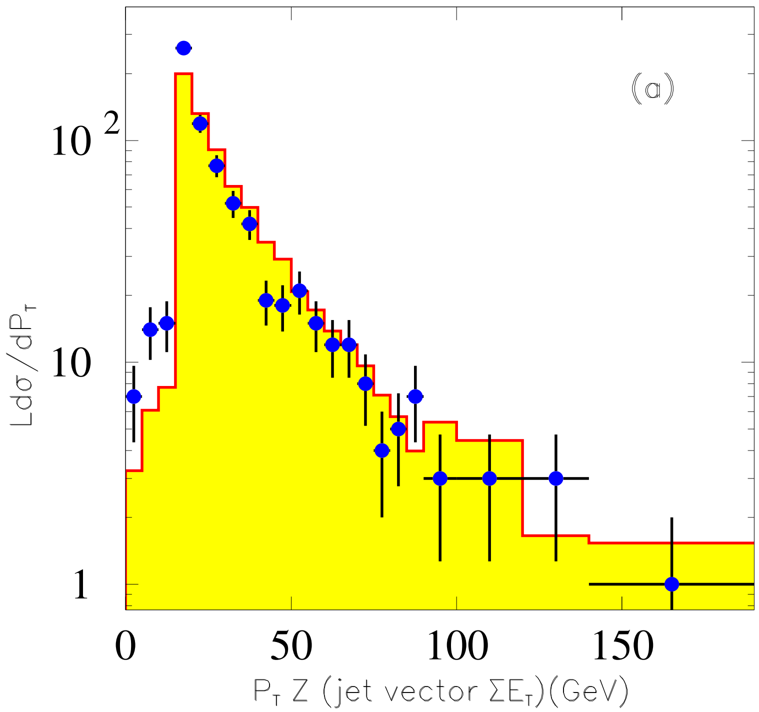




Check Kinematics of W,Z Pythia Monte Carlo

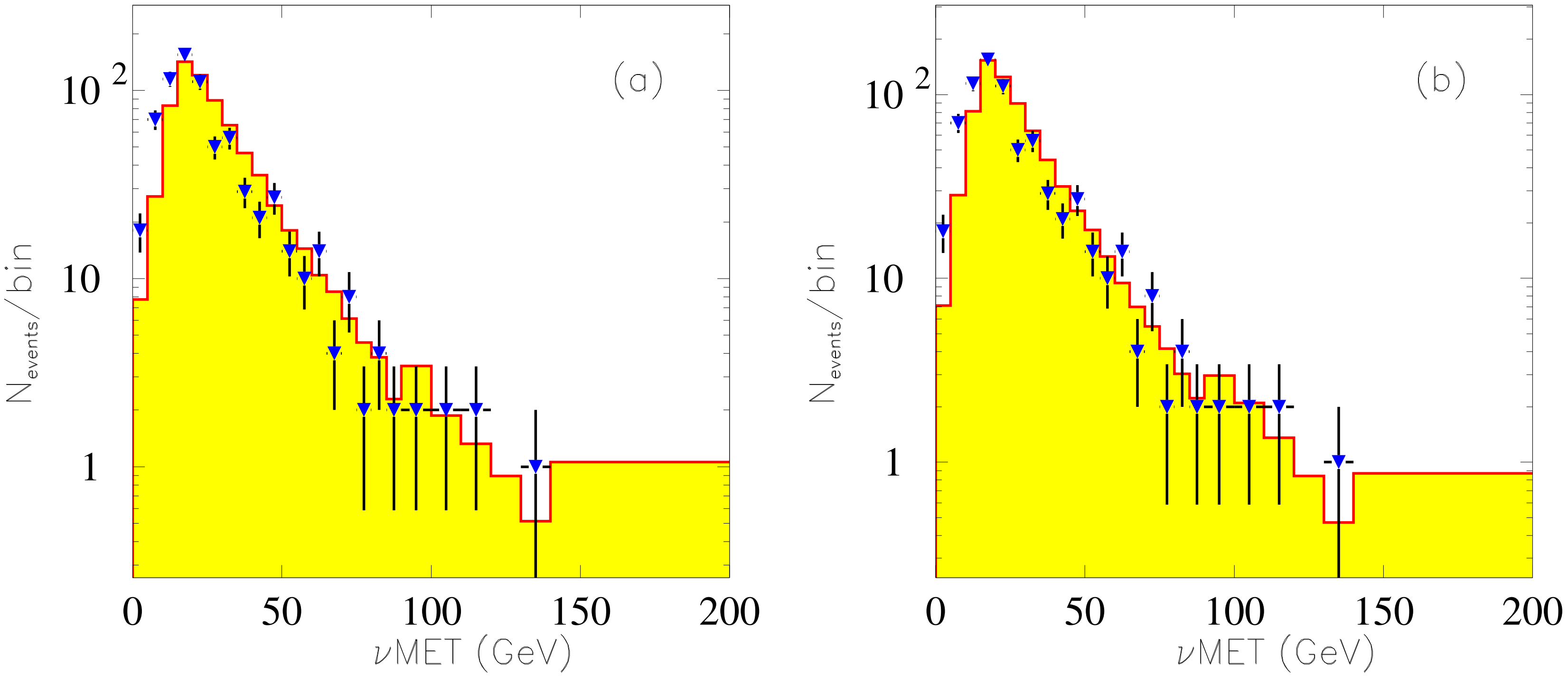
- Left: $P_T(Z)$ from electrons, Right: $P_T(Z)$ from jets
- Hist = Pythia $Z \rightarrow ee+ \geq 1j$ MC, Points = $Z \rightarrow ee+ \geq 1j$ Data





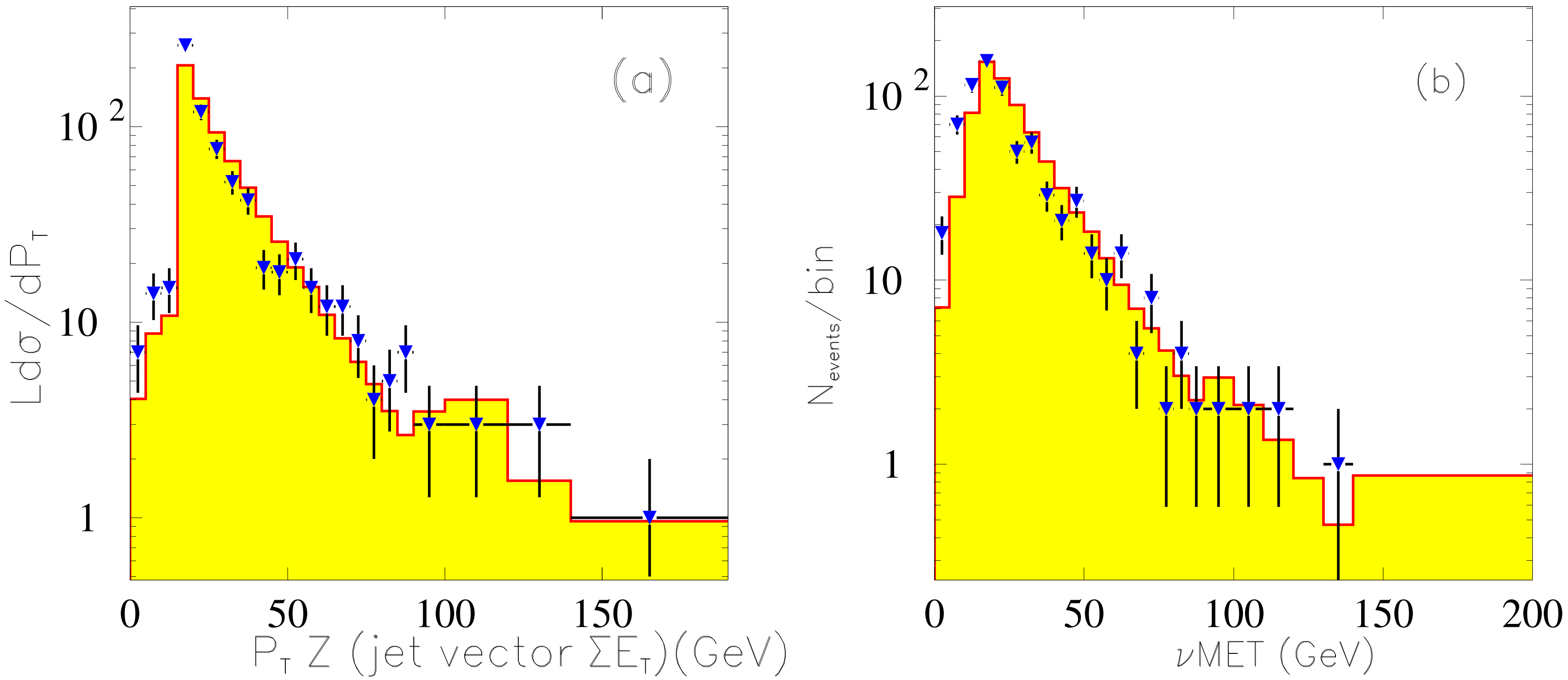
Check Kinematics of W,Z Pythia Monte Carlo

- $\nu MET = \not{E}_T + \Sigma\ E_T(e)$
- Left: Hist = Pythia $Z \rightarrow ee+ \geq 1j$, Points = $Z \rightarrow ee+ \geq 1j$ Data
- Right: Hist = Pythia $Z \rightarrow \nu\nu+ \geq 1j$, Points = $Z \rightarrow ee+ \geq 1j$ Data



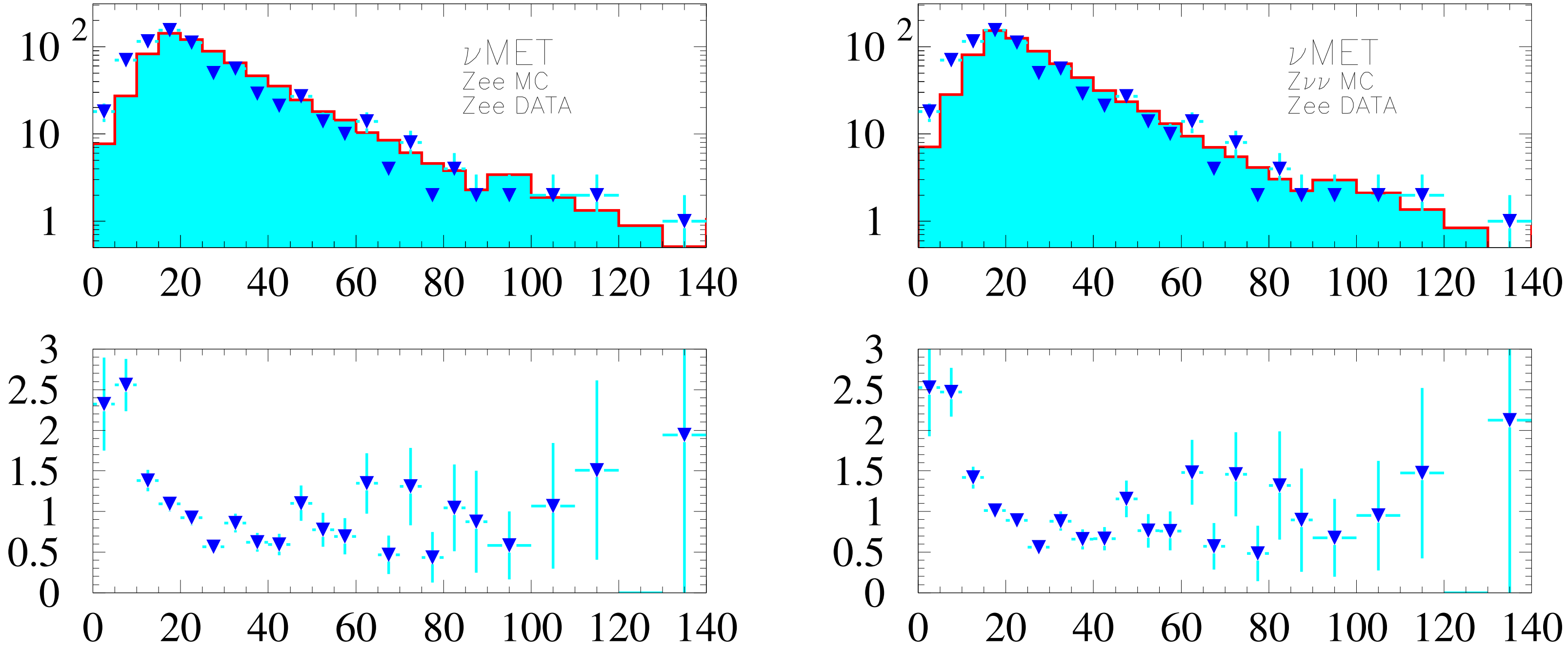
Check Kinematics of W,Z Pythia Monte Carlo

- Left: $P_T(Z)$ Hist = Pythia $Z \to \nu\nu + \geq 1j$, Points = $Z \to ee + \geq 1j$ Data
- Right: $\not{E}_T$ Hist = Pythia $Z \to \nu\nu + \geq 1j$, Points = $Z \to ee + \geq 1j$ Data



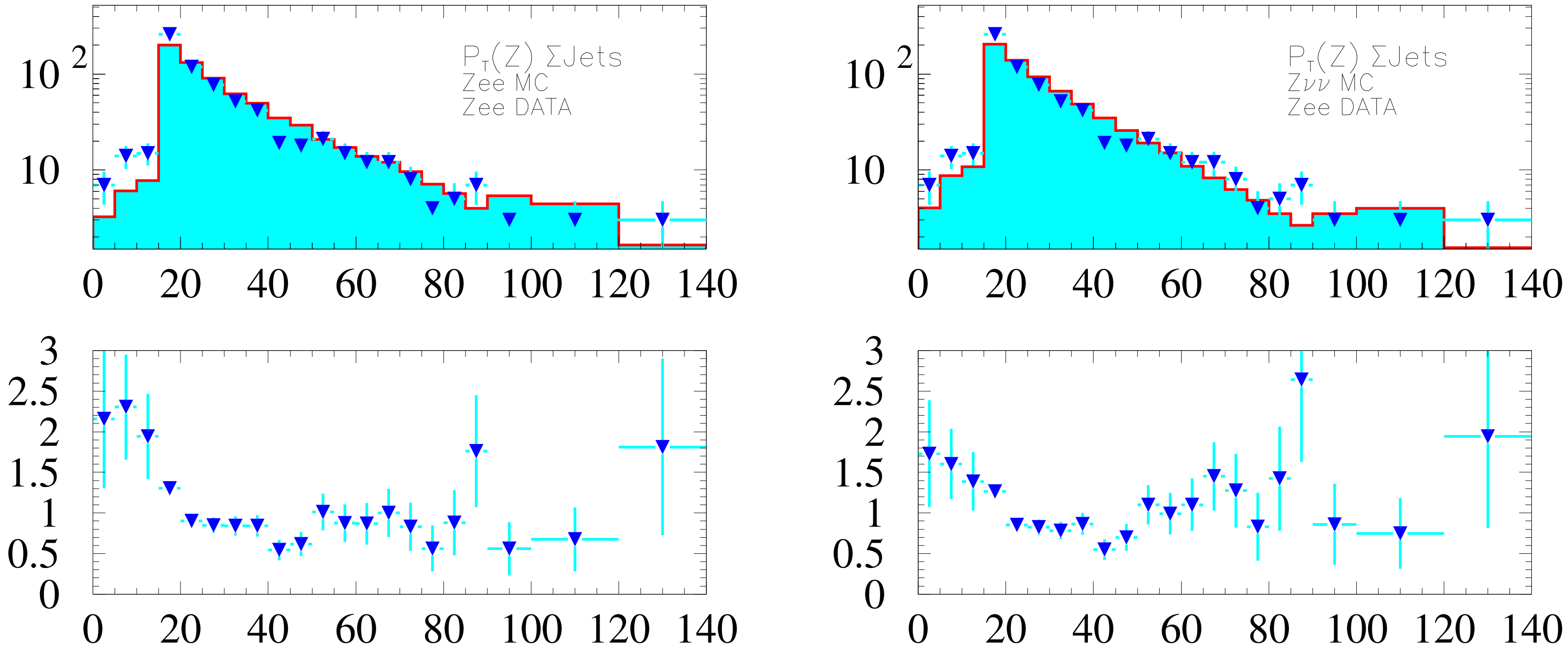
Comparison of νMET Spectra

- Left: Hist = Pythia $Z \rightarrow ee+ \geq 1j$, Points = $Z \rightarrow ee+ \geq 1j$ Data
- Right: Hist = Pythia $Z \rightarrow \nu\nu+ \geq 1j$, Points = $Z \rightarrow ee+ \geq 1j$ Data



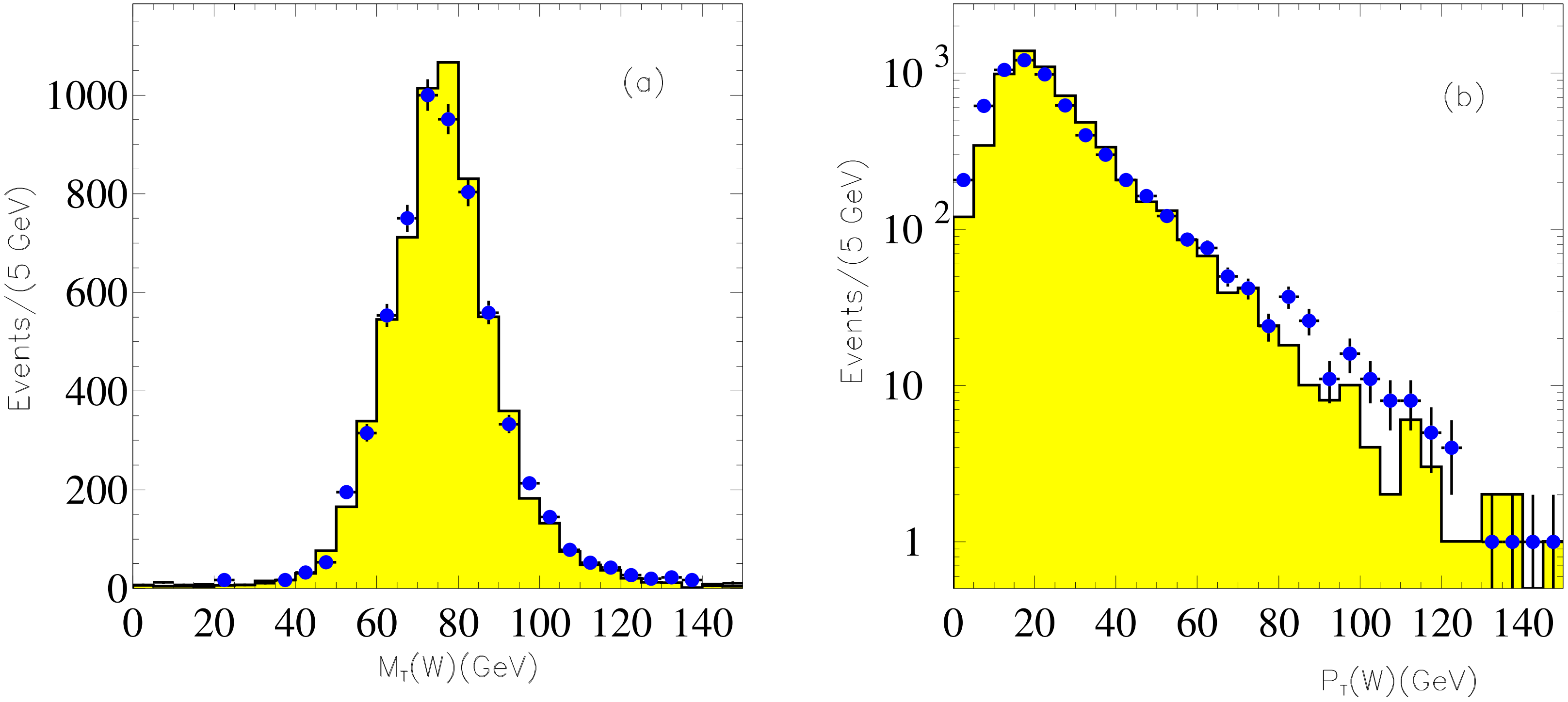
Comparison of $P_T(Z)$ Summing Jets

- Left: Hist = Pythia $Z \to ee + \geq 1j$, Points = $Z \to ee + \geq 1j$ Data
- Right: Hist = Pythia $Z \to \nu\nu + \geq 1j$, Points = $Z \to ee + \geq 1j$ Data



W+jets Background

- **Points:Data, Histogram: Pythia MC**
- **(a):** $m_T(W)$, **(b):** $P_T(W)$



Normalization of Z and W Backgrounds

Normalize $Z \to ee + jets$ MC to data

- Select $Z \to ee$+jets in data and MC
- MC sample luminosity from ratio of MC/data
- MC $\sigma(Z \to ee)$ using luminosity
- $\sigma(Z \to \nu\overline{\nu}) \;=\; 6 \times \sigma(Z \to ee)$
- Use $\sigma(Z \to \nu\overline{\nu})$ in normalizing $Z \to \nu\overline{\nu}$ MC

Normalize $W \to e\nu + jets$ MC with W/Z ratio

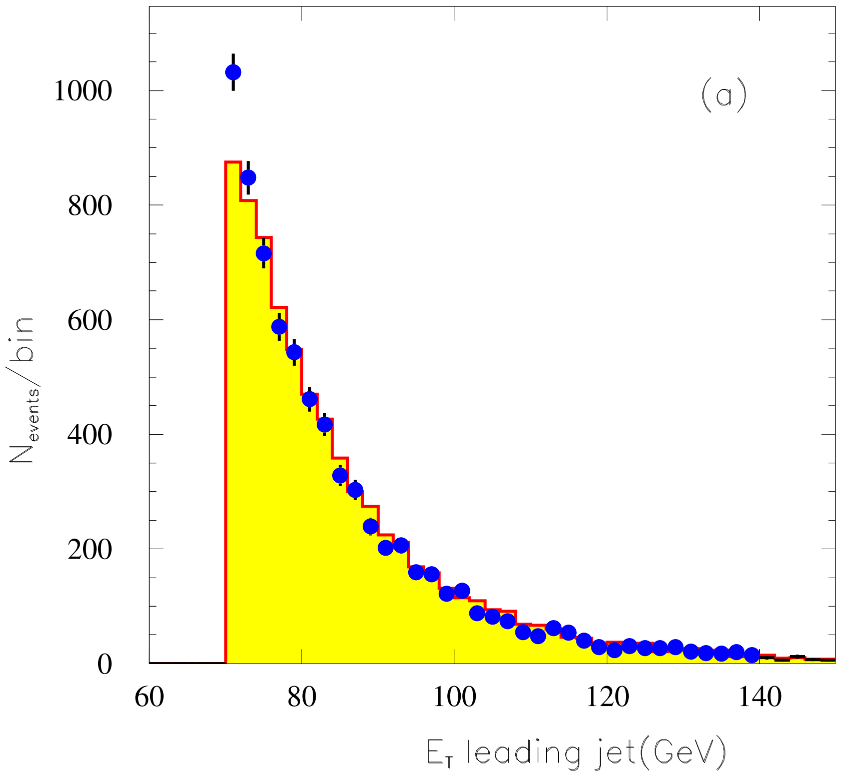
- Normalize $W \to e\nu + jets$ and $Z \to ee + jets$ MC samples to same luminosity using Pythia cross-sections
- Obtain ratio of found W/Z in MC
- Multiply with data-normalized $\sigma(Z \to ee)$ to obtain $\sigma(W \to e\nu)$
- Use ratio before trigger efficiency to avoid double-counting efficiency
- Cross check with normalization to $W \to e\nu$ data
  - Agrees to within 3%

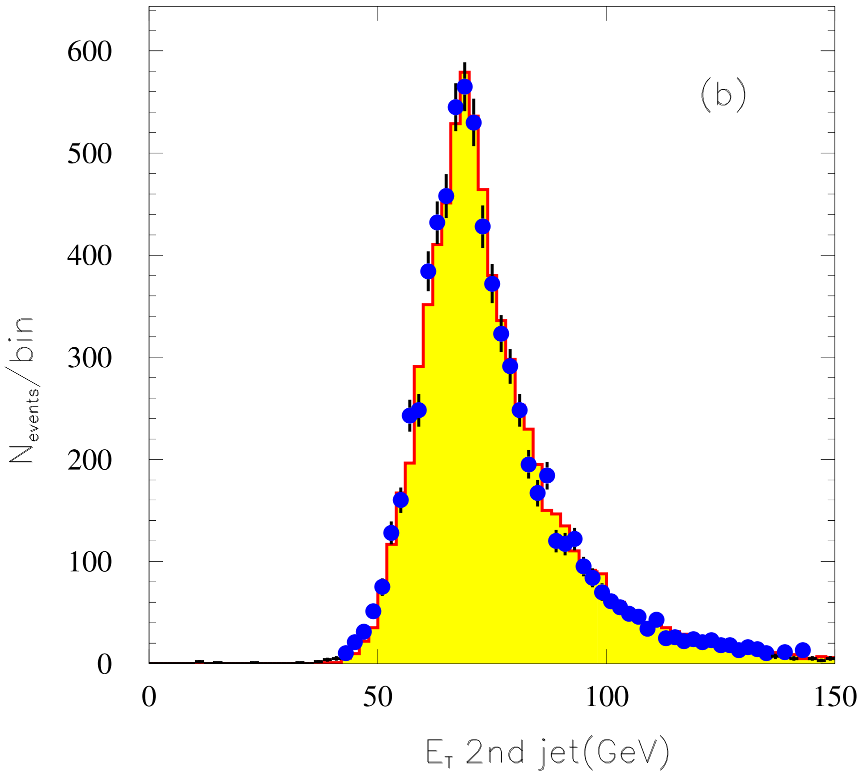
QCD Background

- Generate Herwig Jet50 Monte Carlo
- Actually two samples:
  - Default has Jet $E_T > 50$ GeV
  - Second sample requires $\not\!\!E_T > 40$ GeV to fill out $\not\!\!E_T$ tails
- For normalization and validation of MC, select dijets:
  - Exactly 2 jets
  - $E_T > 80$ GeV
  - $\not\!\!E_T < 20$ GeV
  - $\Delta\phi(jet - jet) > 2.7$
- Normalize $\#$ of dijets in MC to $\#$ in Jet50 Data
- Check normalization by reversing $\not\!\!E_T$ cut and seeing that it still holds.

Normalization of QCD MC with Dijets

- Points: Jet50 Data, Histogram: Herwig
- (a): $E_T(1)$, (b): $E_T(2)$





Data Selection

Initial Cuts

- SEL1 selection
  - $\not{E}_T \geq 35$ GeV
  - $EOT \leq 10$
  - $NOT \leq 5$
- SEL2 selection
  - $\geq 1\ jet,\ |\eta_d| < 0.7$
  - $ECHF \geq 0.1775$
  - $EEMF \geq 0.1$
- Remove bad runs, jets near cracks

Graviton Selection

- Keep 1 jet events and 2 jet events with high P_T 2nd jet
  - $1 \leq N_{jet} \leq 2$
  - $E_T(jet1) > 80$ GeV
  - If 2 jets, $E_T(jet2) > 30$ GeV
- Indirect Lepton Removal
  - EMF(jet) $\leq$ 0.9
  - No Isolated Stiff Tracks

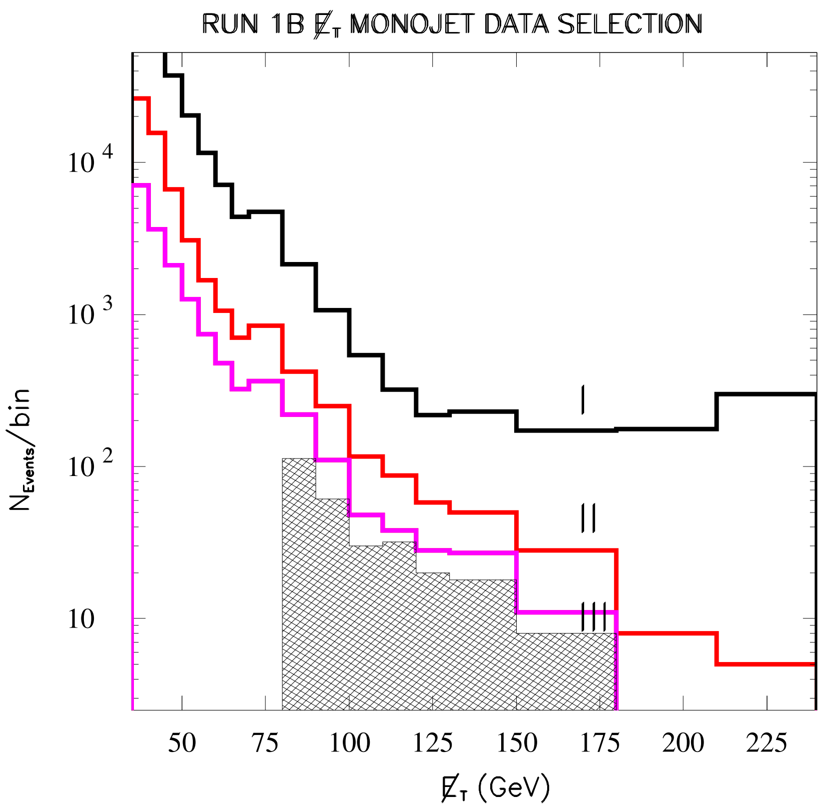
    ($p_T > 10$ GeV, $\sum_{tracks} p_T \leq 2$ GeV)
- $\not{E}_T > 80$ GeV
- $\Delta\phi_{min}(Jet - \not{E}_T) > 0.3$

Summary of Backgrounds

- $Z \to \nu\nu$, $W \to \ell\nu$, QCD, $t\bar{t}$, single top, dibosons
- Normalized either to data or with theoretical cross section
- Uncertainties are statistical plus systematic
- If normalized to data, uncertainty includes 4% uncertainty on luminosity
- Additional 13.5% uncertainty on QCD due to jet resolution.
- Numbers for W's slightly changed from pre-blessing - down 3%

Background	
$Z \to \nu\bar{\nu}$	160.3 ± 11.5
$W \to \tau\nu_\tau$	46.6 ± 5.5
$W \to \mu\nu_\mu$	23.8 ± 5.0
$W \to e\nu_e$	18.1 ± 4.3
top, dibosons	3.9 ± 0.2
Total EWK	252.5 ± 14.4
QCD	21.7 ± 6.7
Total predicted	274.1 ± 15.9

Data After Final Selection

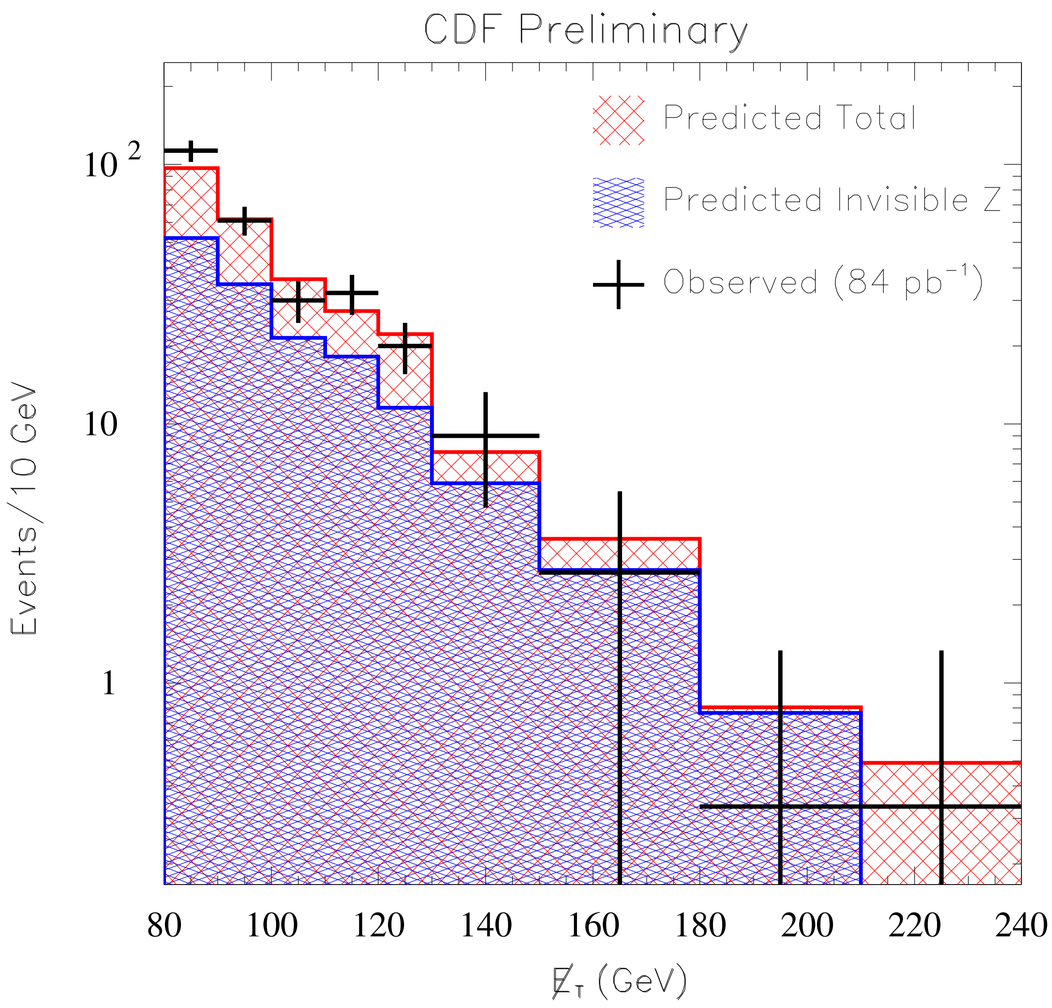


Requirement	Events passing
Pre-Selection	300945 **(I)**
1≤N$_{jet}$ ≤2 (cone .7,E_T≥ 15) $\lvert\eta_d\rvert(1\ or\ 2) < 1.1$ fiducial 2nd jet	50792**(II)**
EMF(1),EMF(2)≤ 0.9,N_{trk}^{iso}=0	20269
$\lvert vertex\rvert \le\ 60\ cm$,$\delta\phi_{min} \ge 0.3$	16459 **(III)**
E_T(1)≥80GeV If two jets E_T(2)≥30GeV	897
$\not\!E_T$ ≥80	284

Data vs. Predicted Backgrounds

Background	
$Z \to \nu_i\bar{\nu}_i$	160.3 ± 11.5
$W \to \tau\nu_\tau$	46.6 ± 5.5
$W \to \mu\nu_\mu$	23.8 ± 5.0
$W \to e\nu_e$	18.1 ± 4.3
top, dibosons	3.9 ± 0.2
QCD	21.7 ± 6.7
Total Predicted	274 ± 16
Data Observed	284

Data vs. Predicted Backgrounds



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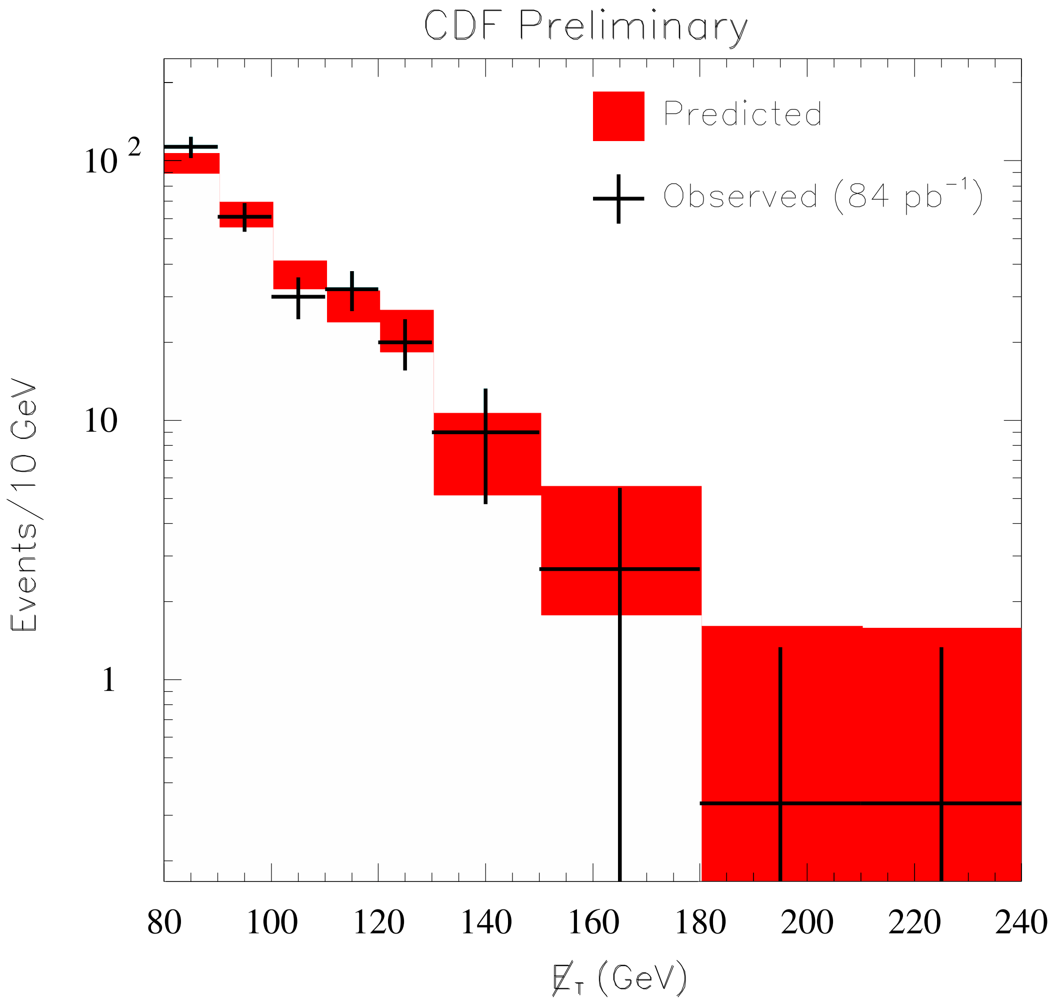

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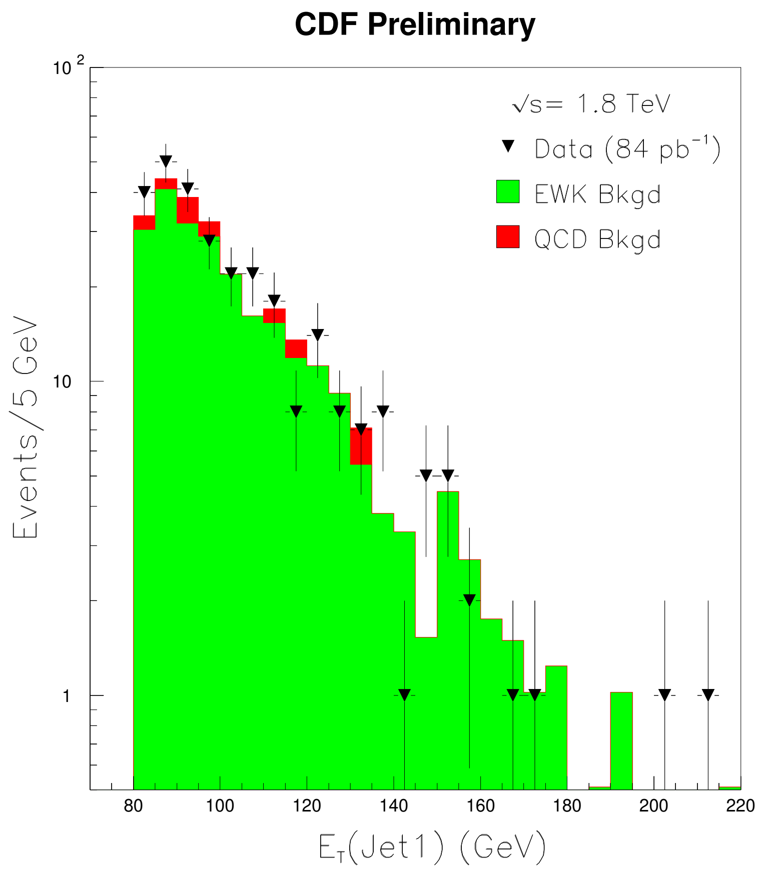
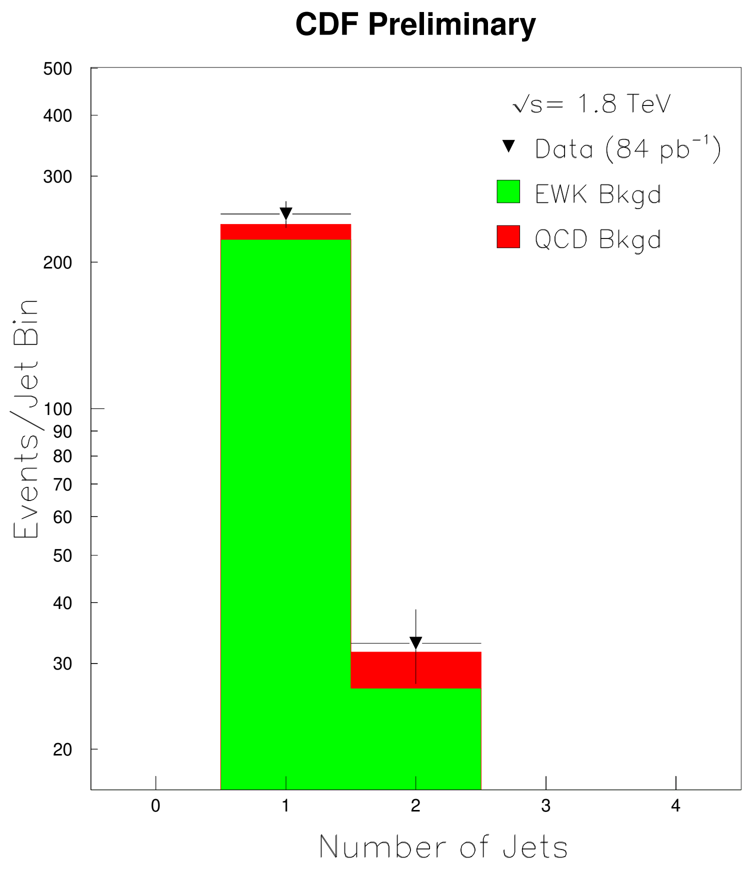
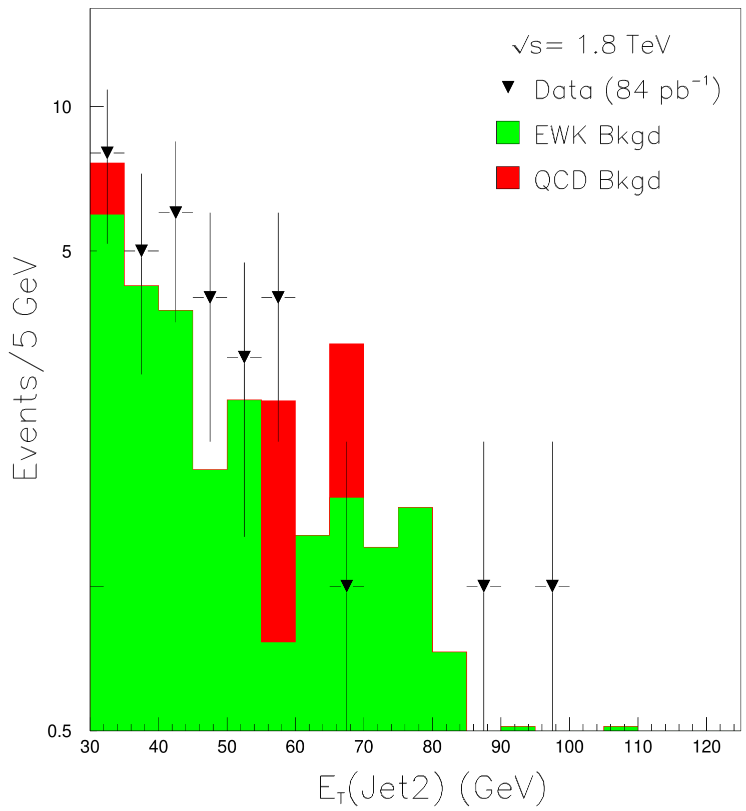




Data vs. Predicted Backgrounds

CDF Preliminary



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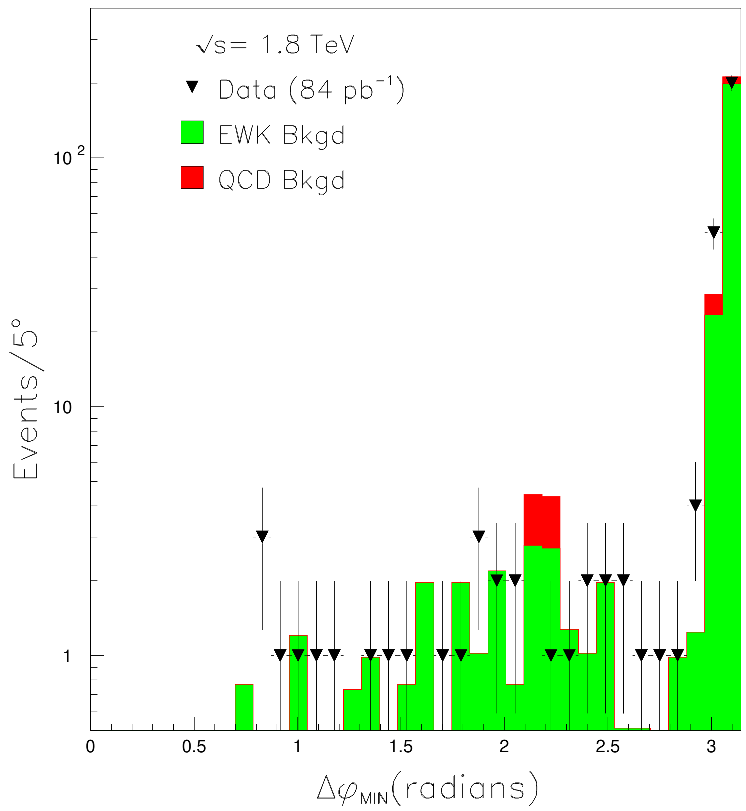


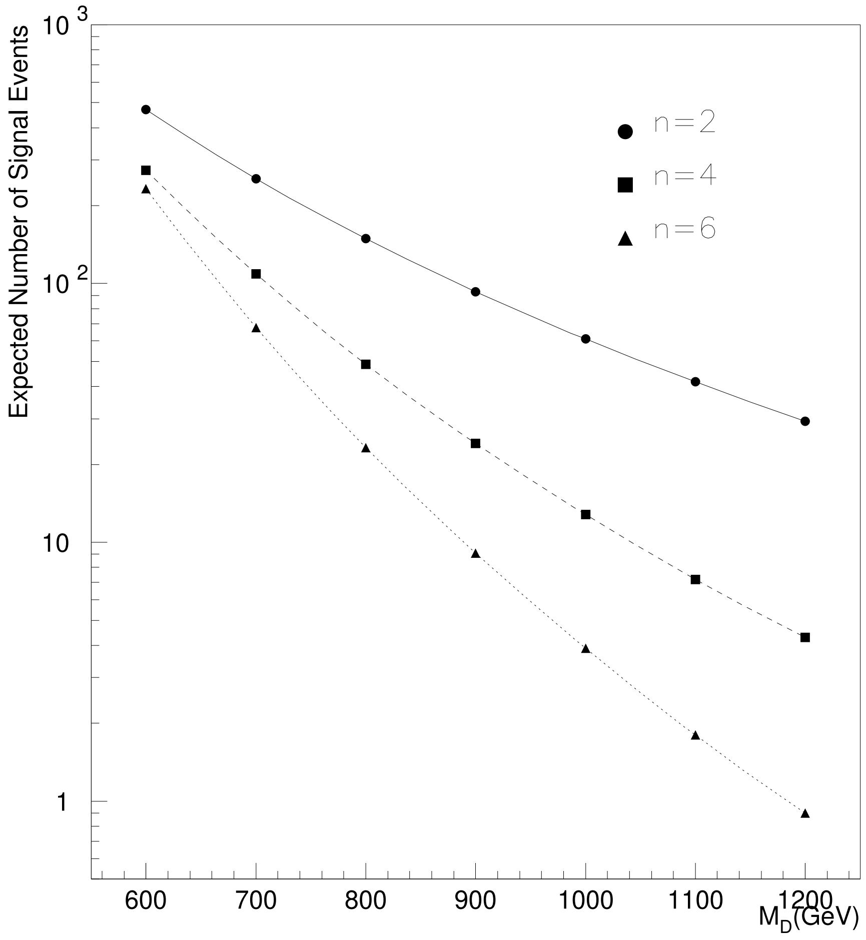
Signal Acceptance After Final Selection

Requirement	Signal Acceptance(%)
Preselection, $\not{E}_T > 35$ GeV 1≤N$_{jet}$ ≤2 (cone .7,E_T≥ 15 GeV) $\lvert\eta_d\rvert(1\ or\ 2) < 1.1$ fiducial 2nd jet	30
EMF(1),EMF(2)≤ 0.9,N_{trk}^{iso}=0	28
$\lvert vertex\rvert \leq\ 60\ cm$,$\delta\phi_{min} \geq 0.3$	28
E_T(1)≥80GeV If two jets E_T(2)≥30GeV	6
$\not{E}_T$ ≥80	5

Requiring $E_T(2) \geq 30$ GeV lowers acceptance from 5.6% to 5%

Expected Signal After Final Selection

Signal events vs M_D for n = 2, 4, 6



M_D(GeV)	n=2	n=4	n=6
600	471	274	232
700	254	109	68
800	149	49	23
900	93	24	9
1000	61	13	4
1100	42	7	2
1200	29	4	1

Signal Systematics

- Jet Energy Scale
  - Vary jet energies by $\pm 5\%$
  - Systematic: 11%
- Q^2 Scale
  - Default is $Q_0 = \frac{1}{2}m_{KK}^2 + P_T^2$
  - Vary to $2 * Q_0$ and $\frac{1}{2} * Q_0$
  - Systematic: 8%
- ISR/FSR
  - Default is ISR ON / FSR ON
  - Compare with OFF/OFF, OFF/ON, and ON/OFF
  - Systematic: 21%
- PDF's
  - Default MRSD-, Check with CTEQ2M
  - Systematic: 2%
- Trigger Efficiency
  - Systematic: 2%
- Total = 25%

Signal Systematics

Source	% Uncertainty
ISR/FSR	21
Jet Energy Scale	11
Q^2 Scale	8
PDF's	2
Trigger Efficiency	2
Total	25

Setting a Limit

- Events Predicted:274 $\pm$ 16
- Observed in Data:284
- Uncertainty on Signal Acceptance: 25%

Upper Limit (95%CL): 62 events

Convert to Limit on M_D

- n=2 $M_D \geq$ 995 GeV
- n=4 $M_D \geq$ 768 GeV
- n=6 $M_D \geq$ 707 GeV

Comparison with Other Limits

	n=2	n=4	n=6
CDF $\not{E}_T$ +jet	995	768	707
D0 $\not{E}_T$ +jet(K=1.34)	987	728	646

Setting a Limit

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Upper Limit (95%CL): 62 events

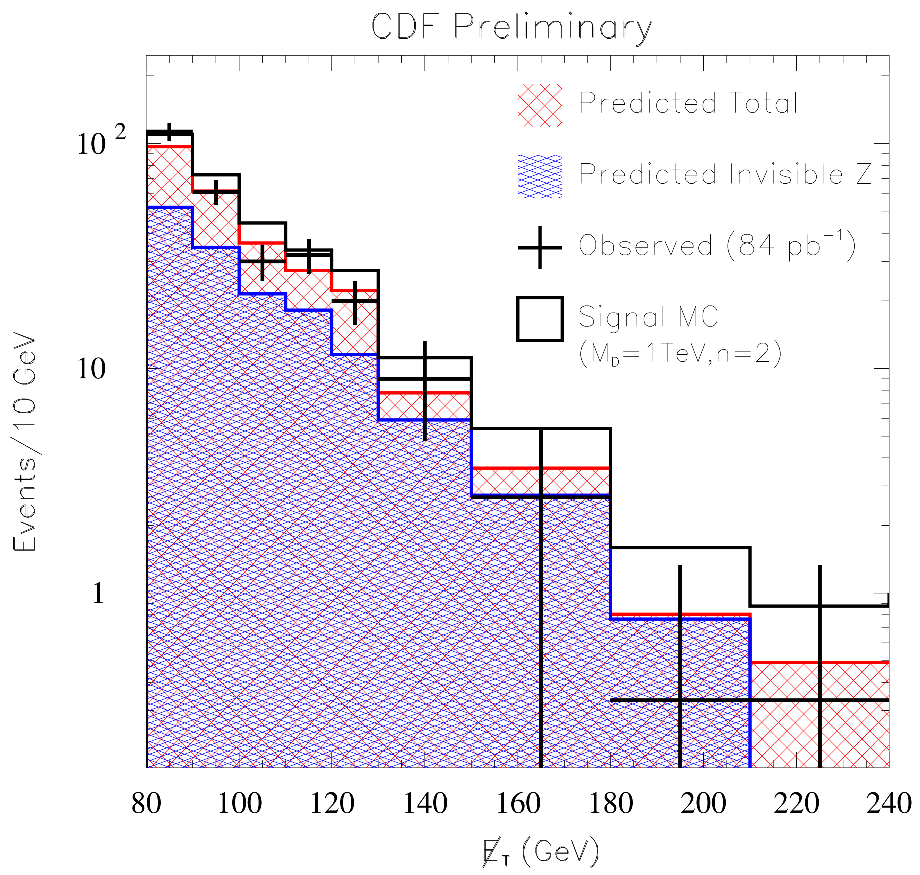
Comparison with Other Limits

	n=2	n=4	n=6
CDF $\not\!\!E_T$ +jet	995	768	707
D0 $\not\!\!E_T$ +jet(K=1.34)	987	728	646
CDF γ+jet	—	549	581

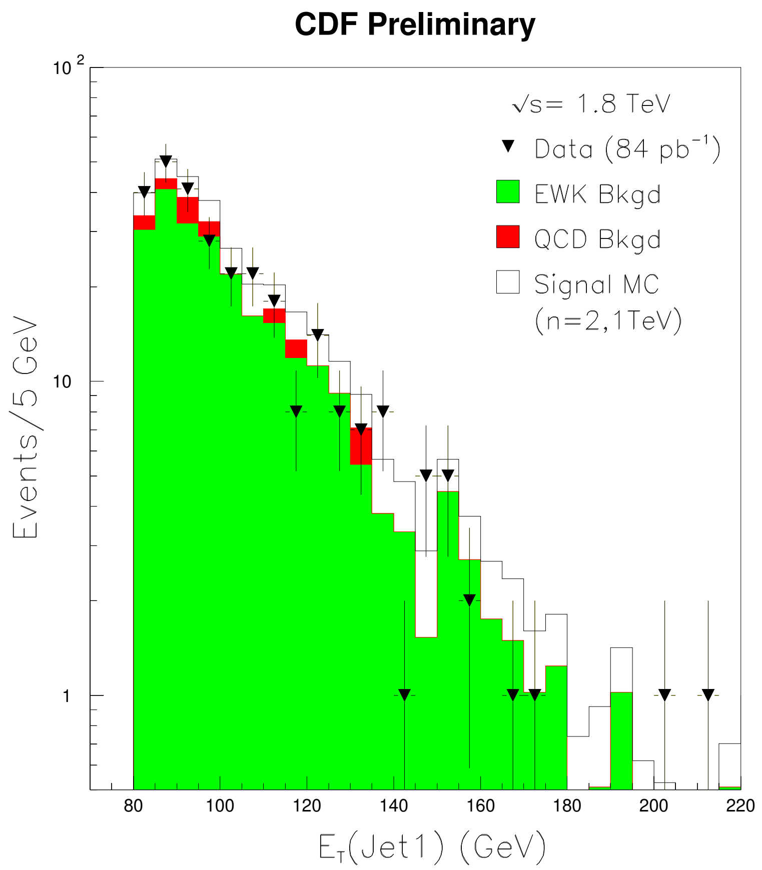
Convert to Limit on M_D

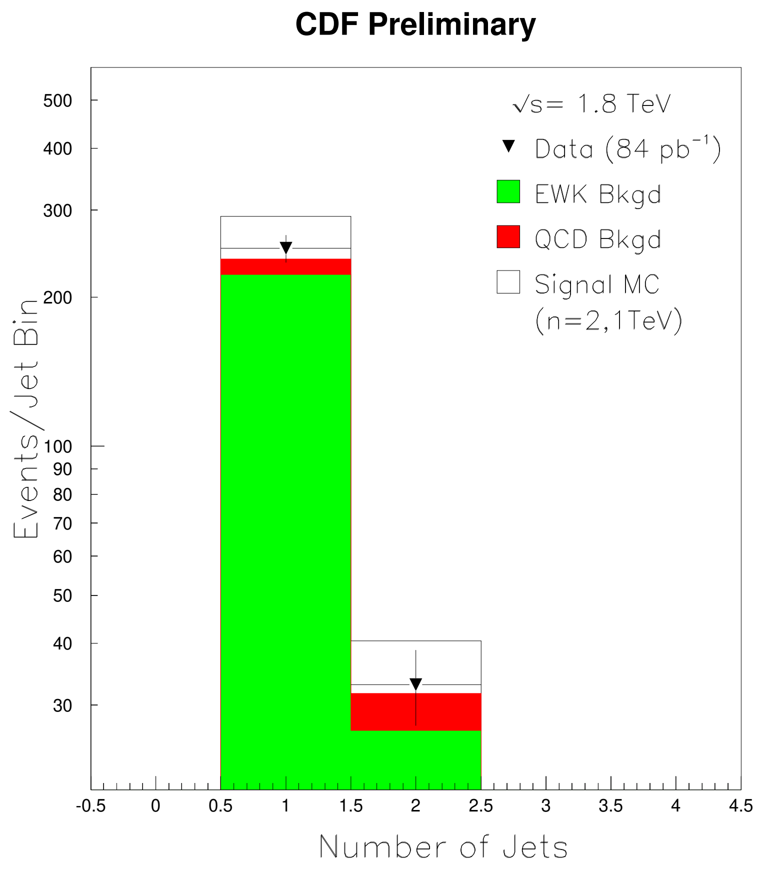
- n=2 $M_D \geq$ 995 GeV
- n=4 $M_D \geq$ 768 GeV
- n=6 $M_D \geq$ 707 GeV

Data Histograms with Signal Added



Data Histograms with Signal Added





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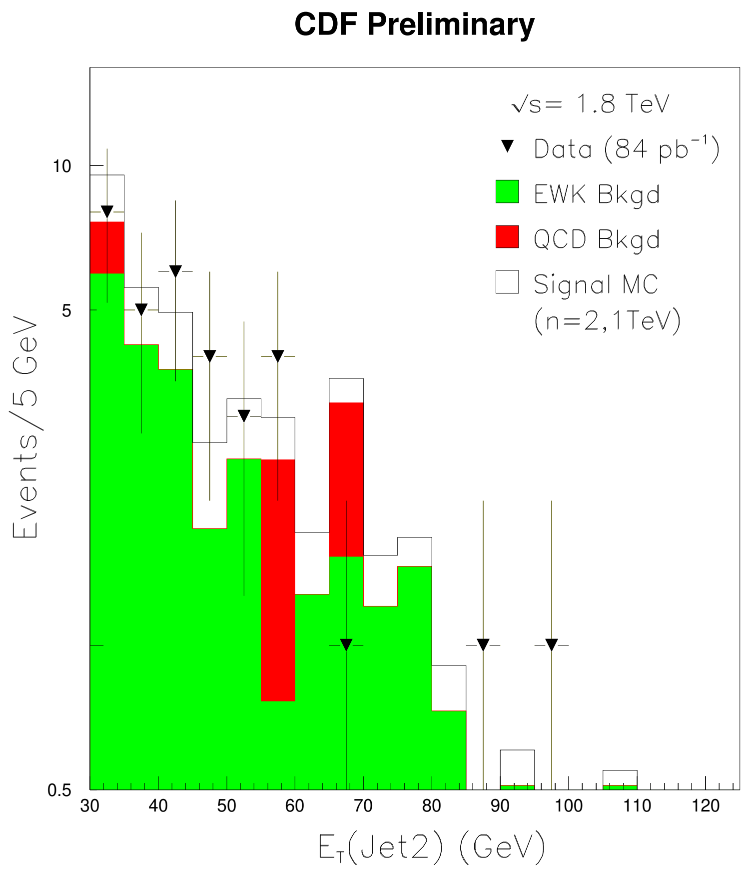

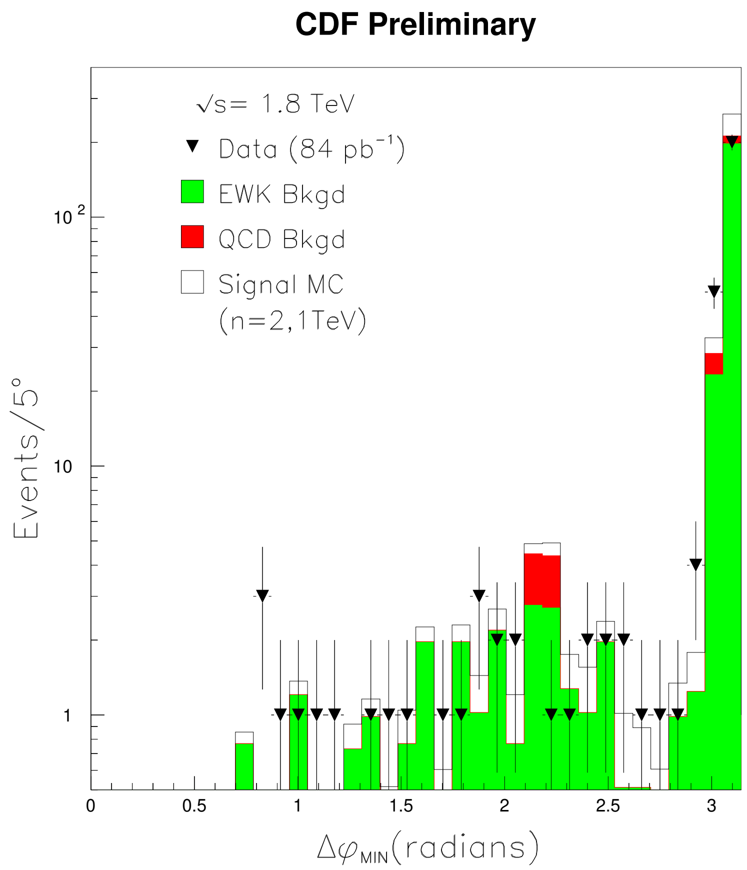

Conclusions

- Data is consistent with predicted SM backgrounds
- No evidence for large extra dimensions
- Limits set on extra dimensions in ADD model
  - n=2: $M_D \geq 995$ GeV
  - n=4: $M_D \geq 768$ GeV
  - n=6: $M_D \geq 707$ GeV
- Remaining items for paper:
  - Limit on Randall-Lykken model
  - Limits with K factor
  - Godparents, draft, etc.