Measurements of Z+jets production cross sections at CDF

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Workshop on Vector Boson plus Jets Production,

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Outline

- Physics Motivation
- The Tevatron and the CDF experiment
- Results
- Summary and Conclusions

Measurement of Inclusive Jet Cross Sections in $Z/\gamma^{*}(\rightarrow e^{+}e^{-})$+jets Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

T. Aaltonen,[23] J. Adelman,[13] T. Akimoto,[54] M.G. Albrow,[17] B. Álvarez González,[11] S. Amerio,[42] D. Amidei,[34]
A. Anastassov,[51] A. Annovi,[19] J. Antos,[14] M. Aoki,[24] G. Apollinari,[17] A. Apresyan,[47] T. Arisawa,[56] A. Artikov,[15]
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W. Badgett,[17] A. Barbaro-Galtieri,[28] V.E. Barnes,[47] B.A. Barnett,[25] S. Baroiant,[7] V. Bartsch,[30] G. Bauer,[32]
P.-H. Beauchemin,[33] F. Bedeschi,[45] P. Bednar,[14] S. Behari,[25] G. Bellettini,[45] J. Bellinger,[58] A. Belloni,[22]
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D. Bortoletto,[47] J. Boudreau,[46] A. Boveia,[10] B. Brau,[10] A. Bridgeman,[24] L. Brigliadori,[5] C. Bromberg,[35]
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K. L. Byrum,[2] S. Cabrera[r],[16] M. Campanelli,[35] M. Campbell,[34] F. Canelli,[17] A. Canepa,[44] D. Carlsmith,[58]
R. Carosi,[45] S. Carrillo[l],[18] S. Carron,[33] B. Casal,[11] M. Casarsa,[17] A. Castro,[5] P. Catastini,[45] D. Cauz,[53]
M. Cavalli-Sforza,[3] A. Cerri,[28] L. Cerrito[p],[30] S.H. Chang,[27] Y.C. Chen,[1] M. Chertok,[7] G. Chiarelli,[45]
G. Chlachidze,[17] F. Chlebana,[17] K. Cho,[27] D. Chokheli,[15] J.P. Chou,[22] G. Choudalakis,[32] S.H. Chuang,[51]
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M.E. Convery,[17] J. Conway,[7] B. Cooper,[30] K. Copic,[34] M. Cordelli,[19] G. Cortiana,[42] F. Crescioli,[45]
C. Cuenca Almenar[r],[7] J. Cuevas[o],[11] R. Culbertson,[17] ...
P. de Barbaro,[48] S. De Cecco,[50] A. Deisher,[28] G. De Lento ...
J. Deng,[16] M. Deninno,[5] D. De Pedis,[50] P.F. Derwen ...

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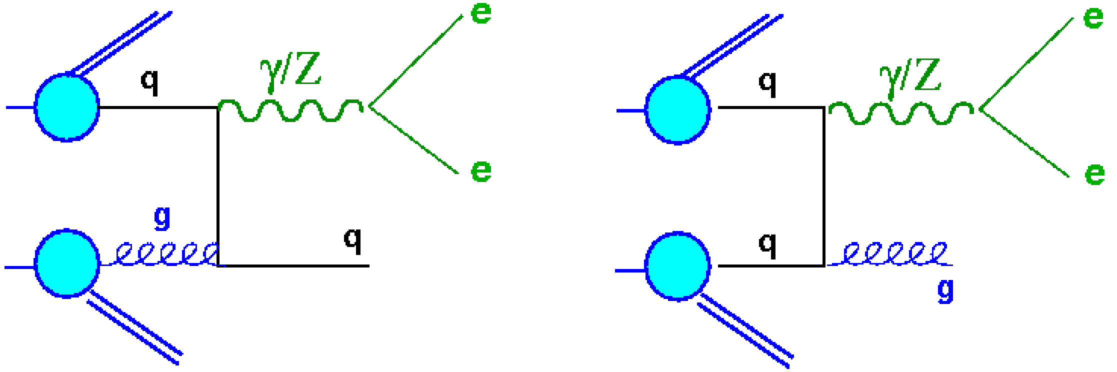
Physics Motivations



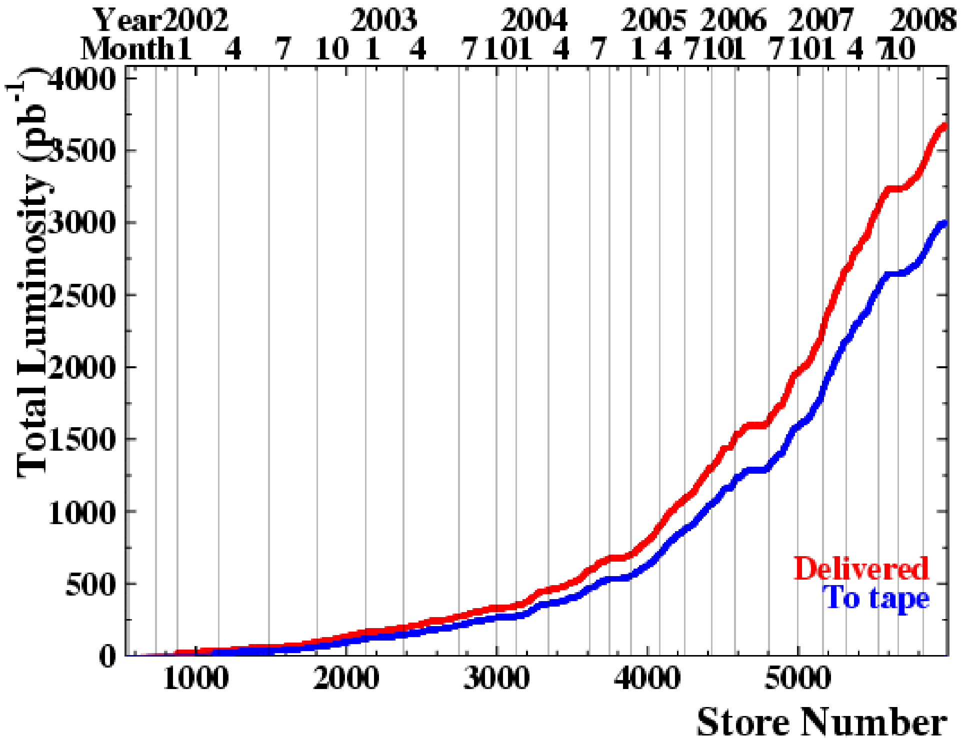
+ PS

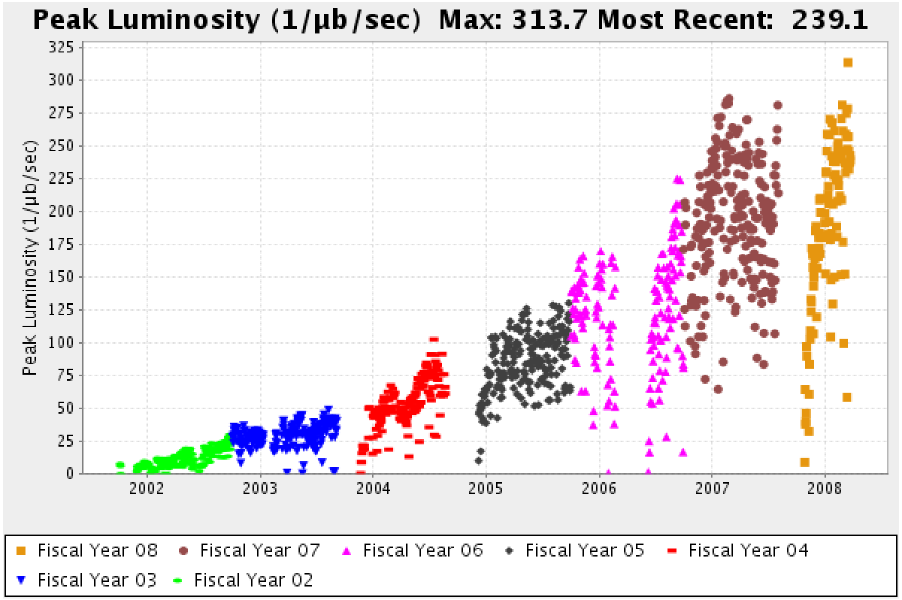
- Test-ground for perturbative QCD:
  - Presence of a boson ensures **high Q^2**
  - Large BR into leptons
- **No missing E_T**: can be used to validate MC predictions without compromising searches for new physics
- Clean signature: almost background free.
- Cross section is ~10 times less than W+jets, but with ~ 2 fb^{-1} of data, enough statistics to make studies on Z+jets.
- Sensitive to **Underlying Event** and **Hadronization** modeling

The Tevatron

Highest-energy accelerator currently operational

Peak luminosity → > **3 *10^{32} cm^{-2} s^{-1}**
Integrated luminosity/week
→ **~ 25-35 pb^{-1}**

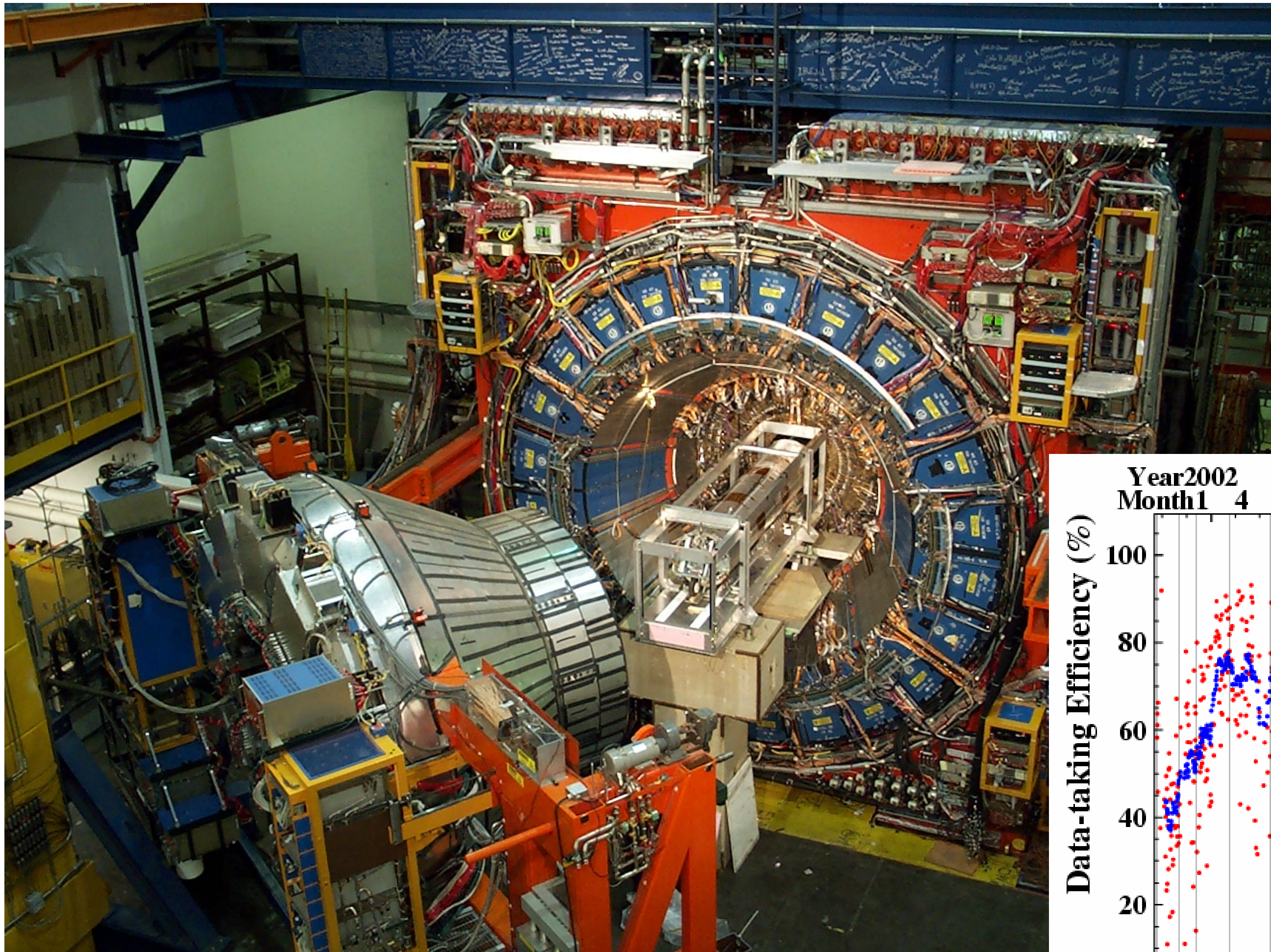




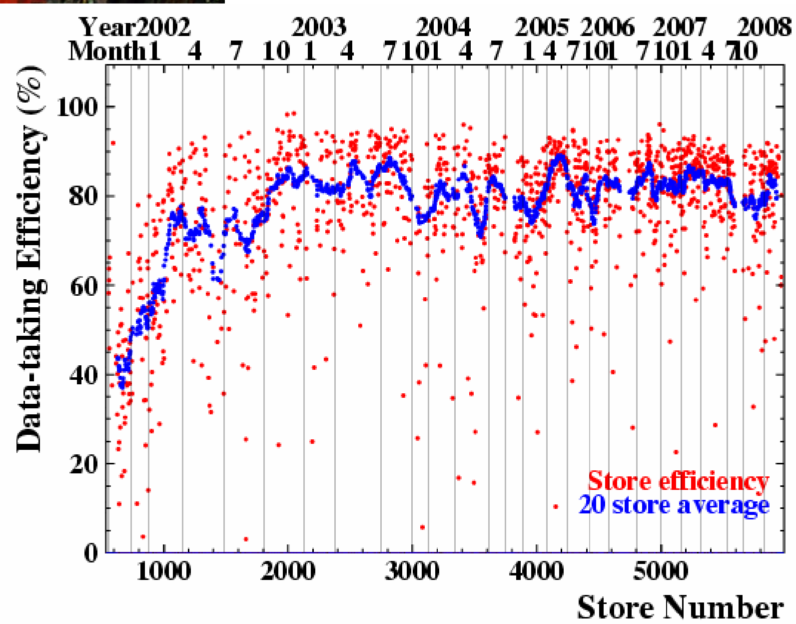
More than **3.7 fb^{-1}** delivered, **3 fb^{-1}** recorded on tape by CDF

Analysis shown here use **1.7 fb $^{-1}$**

The CDF experiment



Recording data with high **efficiency (80-85%)** and making full use of detector capabilities.



Measurement definition

- Inclusive **differential cross sections** measured as a function of jet transverse momentum (**p_T^{jet}**) and jet rapidity (**Y^{jet}**)
- **Total cross section** measured as a function of jet multiplicities **N_{jets}**.

Measurement performed in a well-defined kinematic region:

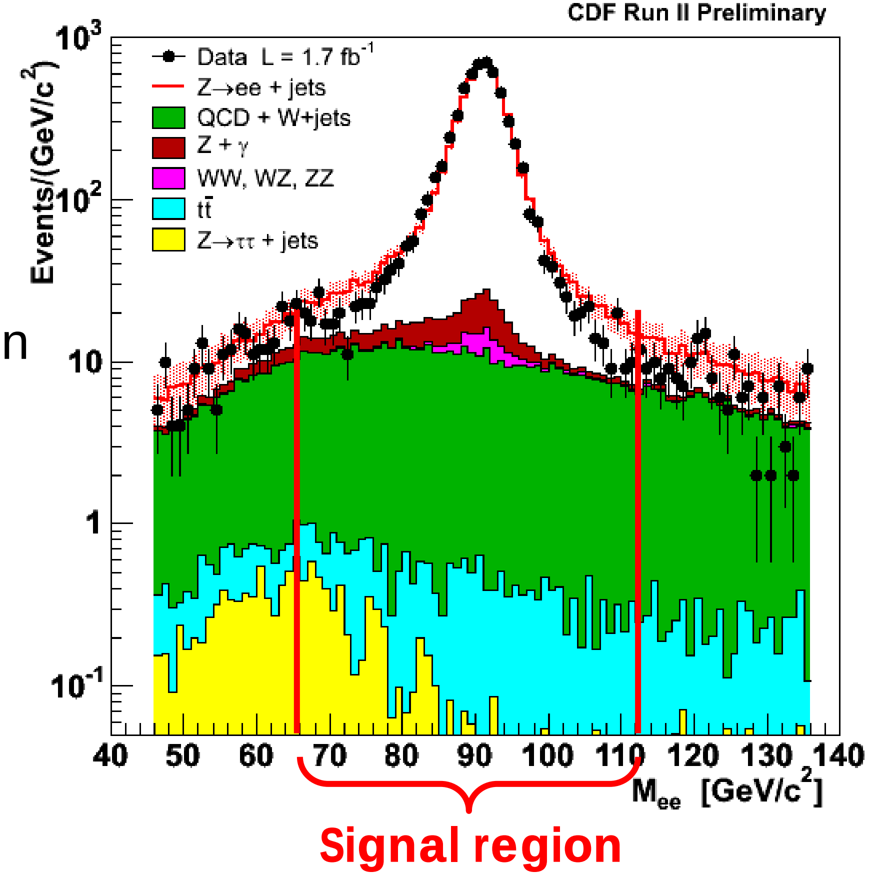
- Z selection
  - E_T(ele)>25 GeV
  - $|\eta_1^e| < 1.0$, $|\eta_2^e| < 1.0$ || $1.2 < |\eta_2^e| < 2.8$
  - M_{e+e-} in [66-116] GeV/c^2:
- Jet selection:
  - MidPoint, cone R = 0.7
  - $p_T^{corr} > 30$ GeV/c, $|Y| < 2.1$
  - Jets corrected for:
    - relative calorimeter response in Y
    - Multiple Particle Interaction
    - absolute energy scale
  - ΔR(e,jet) > 0.7

- Electron towers removed before clustering the jets.
- No isolation cuts applied to the electrons to avoid possible bias at very high pT

$Z/\gamma^*(\rightarrow e^+e^-)$+jets Backgrounds

- Relatively small background.
  - $Z/\gamma^*+\geq 1$ jet bkg contribution : **12%**
  - $Z/\gamma^*+\geq 2$ jets bkg contribution : **16%**
- Estimated from data and MC simulation
  - From data →
    Fakes (dominant): QCD jets, W+jets
  - From MC simulation →
    - Dibosons: WW, WZ and ZZ
    - Z+γ
    - tt production
    - Z→ττ+jets

    } < 1%



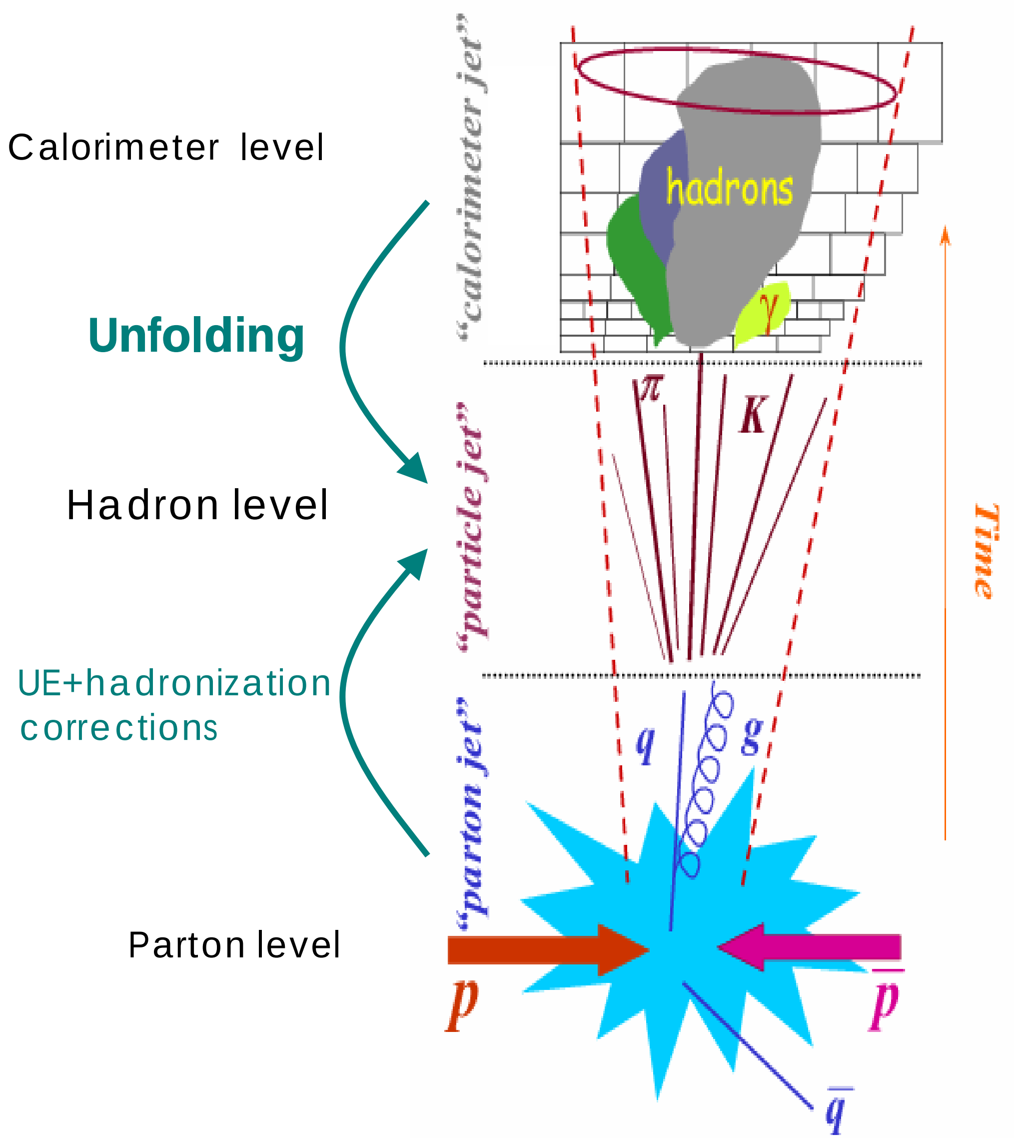
- Good agreement between data and background predictions

$Z/\gamma^*(\rightarrow e^+e^-)$+jets at Hadron Level

The cross section is defined at the level of stable particles (**hadron level**).

Measurements unfolded back to the hadron level using the detector simulation and **Pythia Tune A** MC:

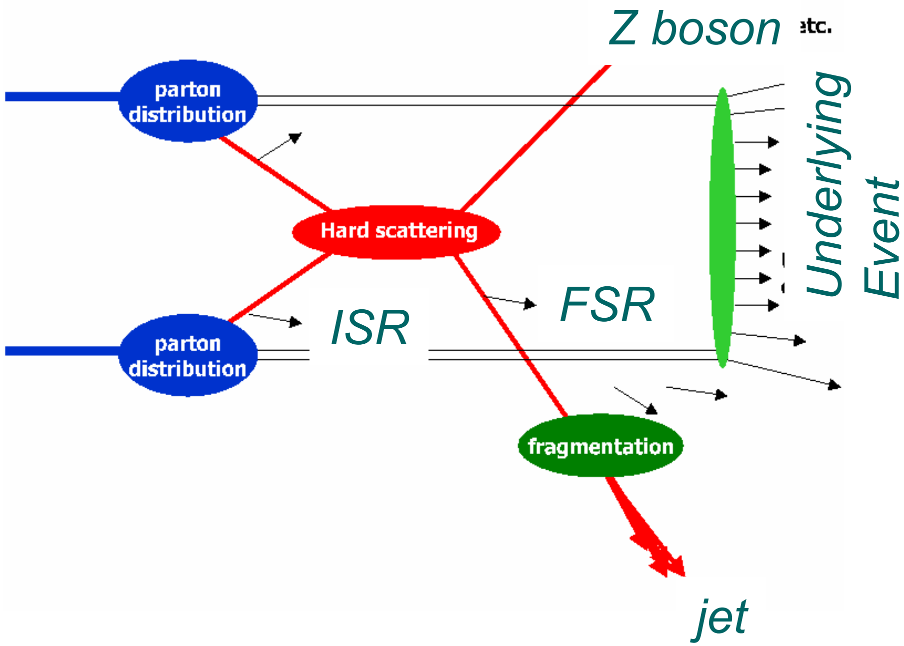
- Re-weight p_T distribution to avoid bias due to PDF (CTEQ5L) used in MC
- Unfolding factors → between **2 and 2.3**, mainly dominated by Z boson reconstruction efficiency



NLO pQCD prediction

- **MCFM**
  - NLO predictions up to 2 jets in final state
  - CTEQ6.1M PDF
  - Renormalization and factorization scale:

    $\mu_0 = M_Z^2 + p_T^2(Z)$
  - Jets reconstructed using MidPoint algorithm with $R_{sep} = 1.3$
  - Cross section at parton level:
    - needs correction for UE and hadronization effects



$$C_{HAD} = \frac{\left.\frac{d\sigma}{dp_T^{jet}}\right|_{Hadron\ level}}{\left.\frac{d\sigma}{dp_T^{jet}}\right|_{Parton\ level\ (no\ UE)}}$$

Corrections for non-pQCD effects are made using MC Pythia Tune A (Pythia Tune DW used to evaluate systematic uncertainties)

A number of measurements are performed to validate the MC modeling of the UE and fragmentation

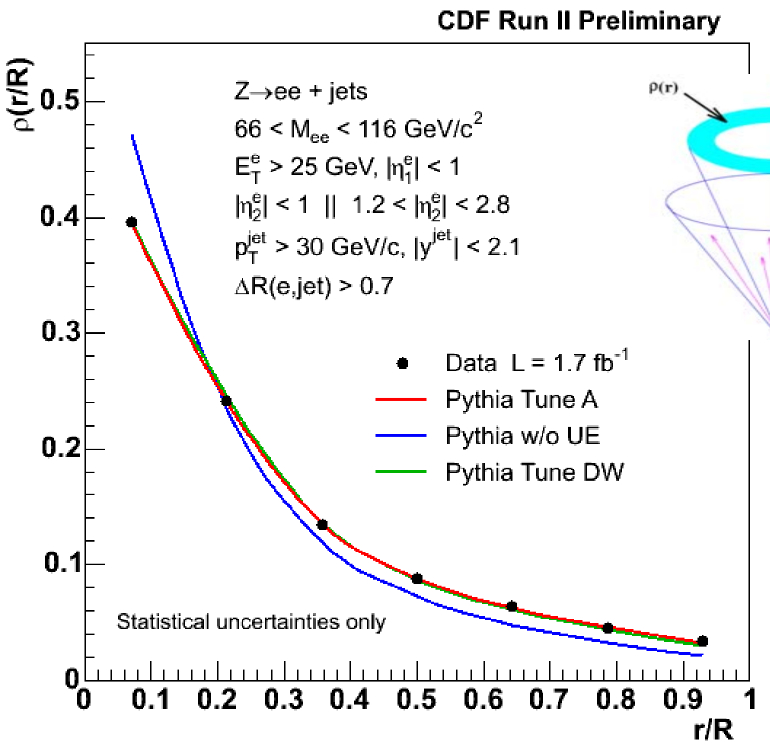
Underlying Events in Z+jets

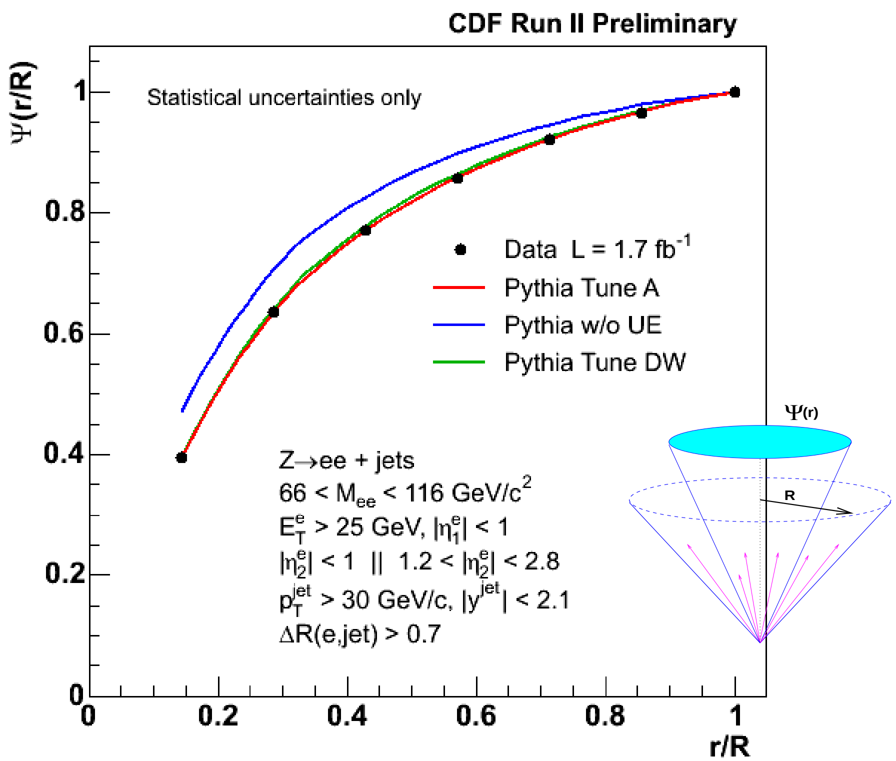
Jet shapes

sensitive to **fragmentation** and **underlying event** modeling.

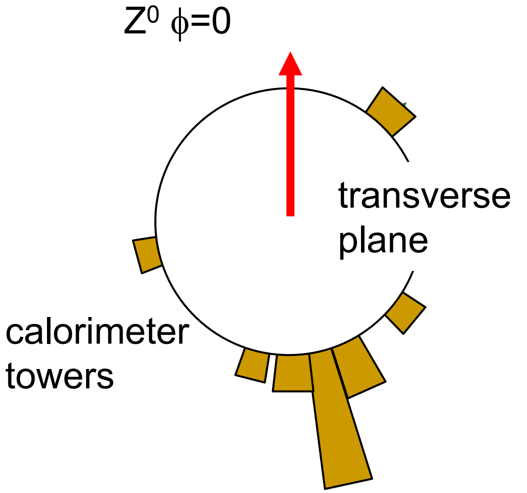
→ very accurately described by Pythia Tune A

(same that also describes the jet shapes in inclusive jet production)

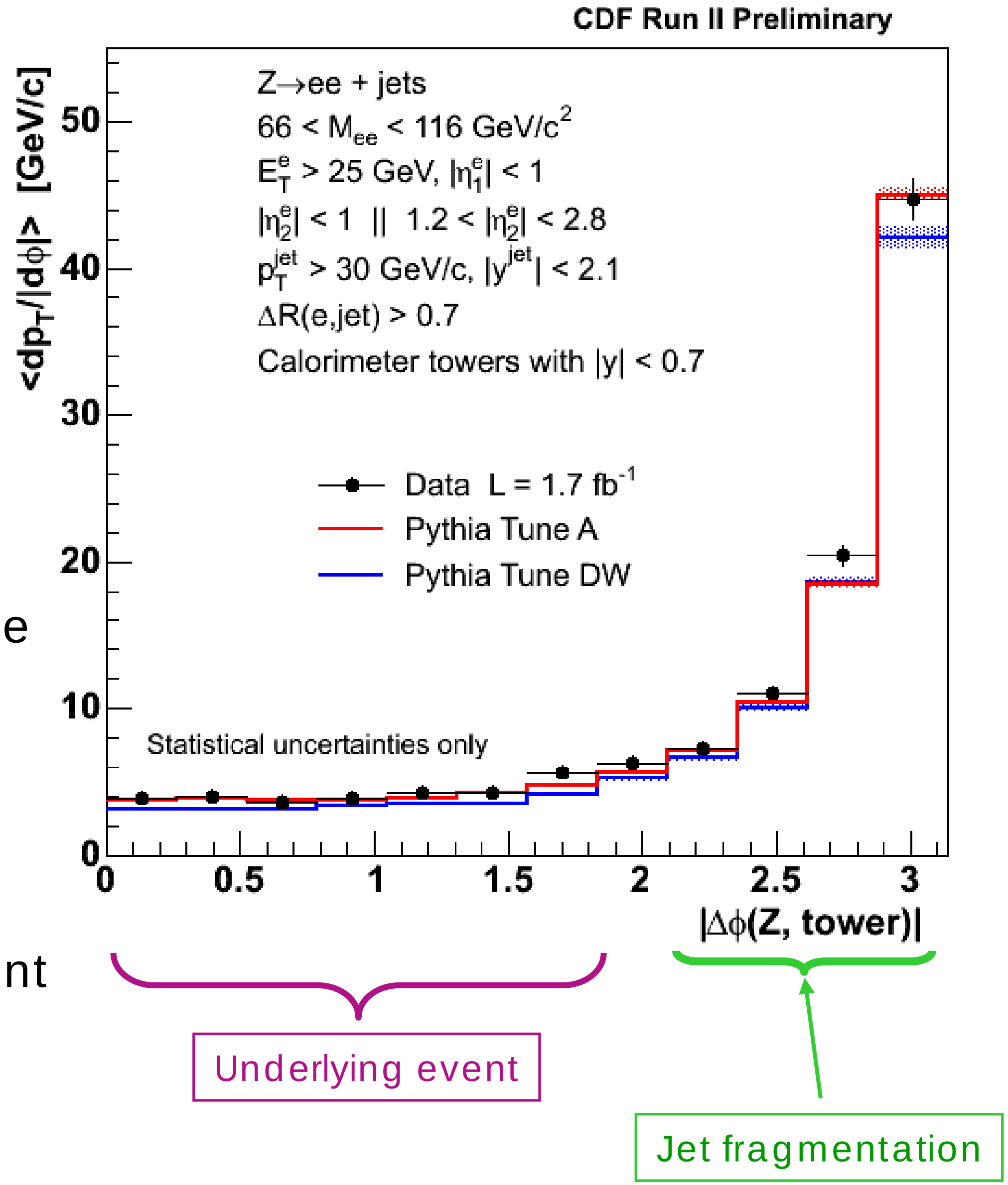




Energy flow

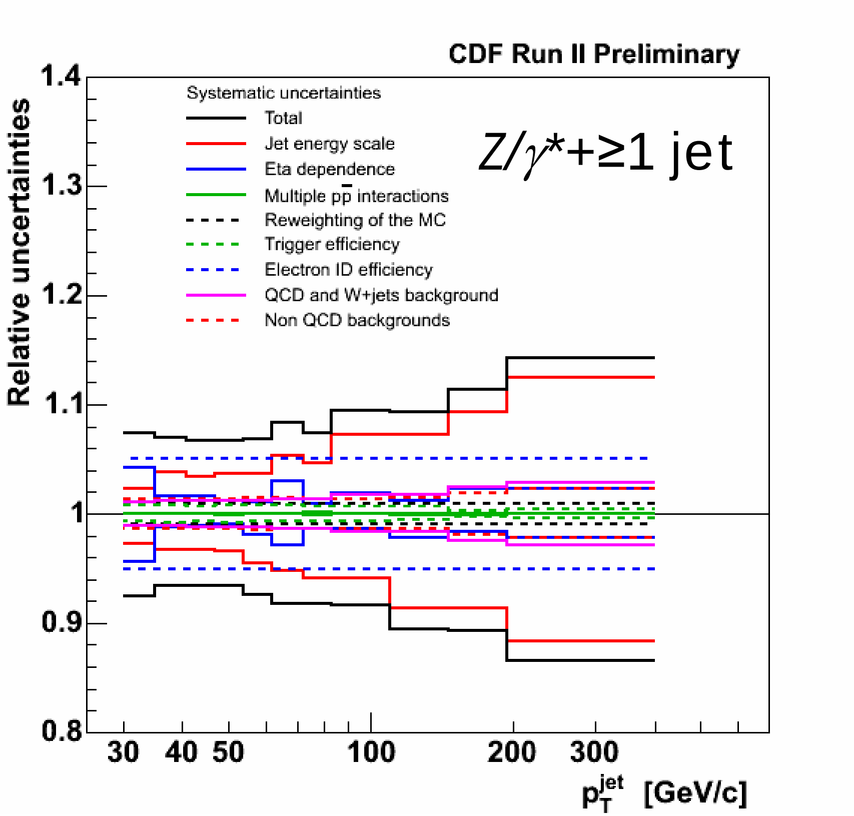


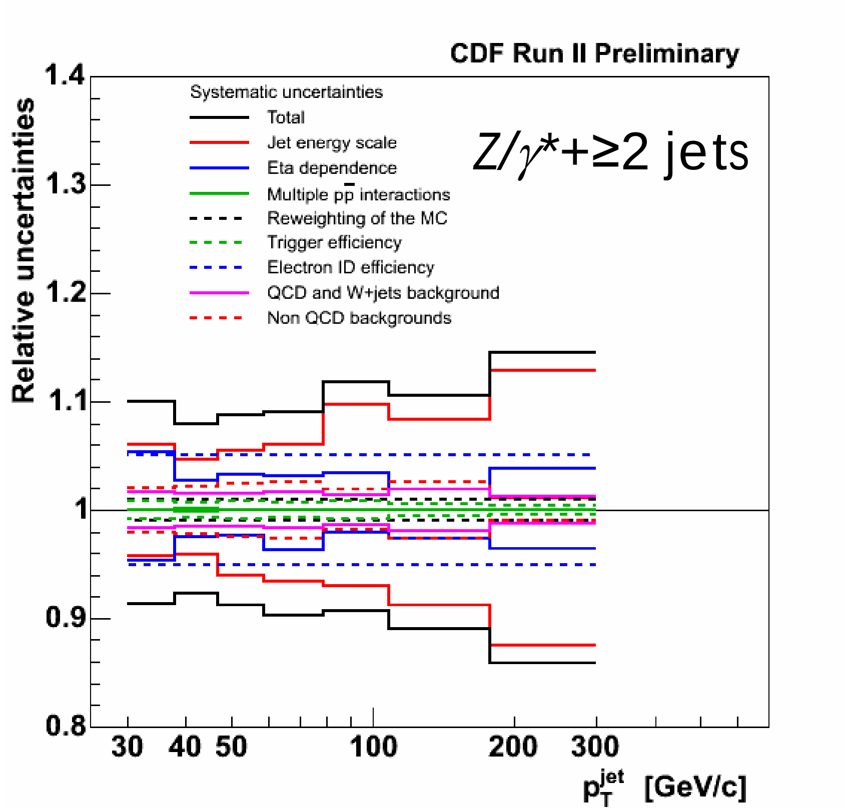
- p_T flow of particles in the transverse plane w.r.t the Z Boson
- Jet is described very accurately
- Very good agreement in the part dominated by the underlying event



Total systematic uncertainties (I)

Dominated by the uncertainty on the absolute **jet energy scale** (~3%), followed by a **5%** uncertainty on the **electron ID efficiency**.



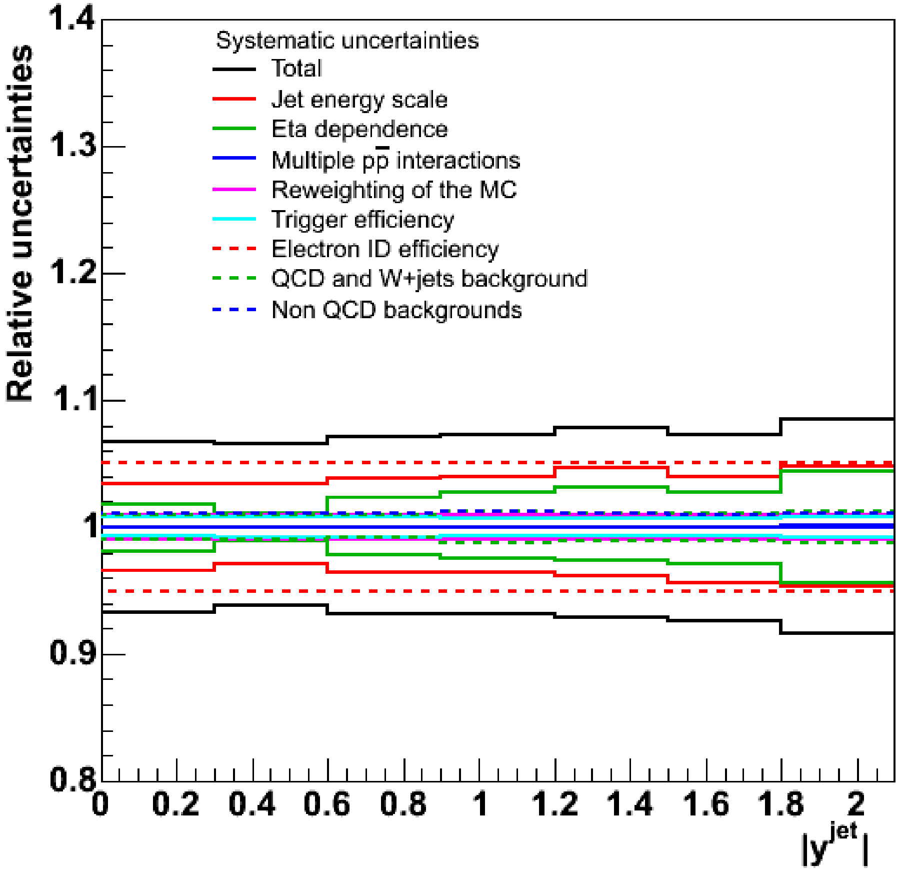


Total systematic uncertainties: ~ **10%** at low p_T^{jet}, up to **15%** at high p_T^{jet}.

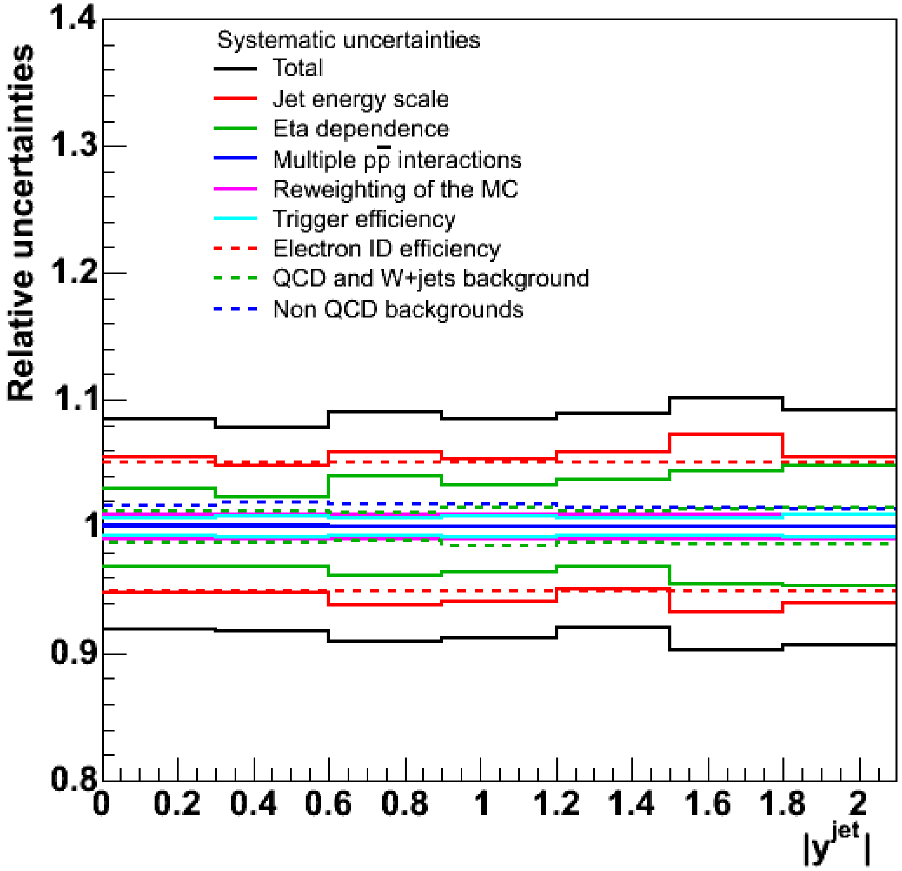
Total Systematic Uncertainty (II)

- Flat in rapidity : **~ 8%**

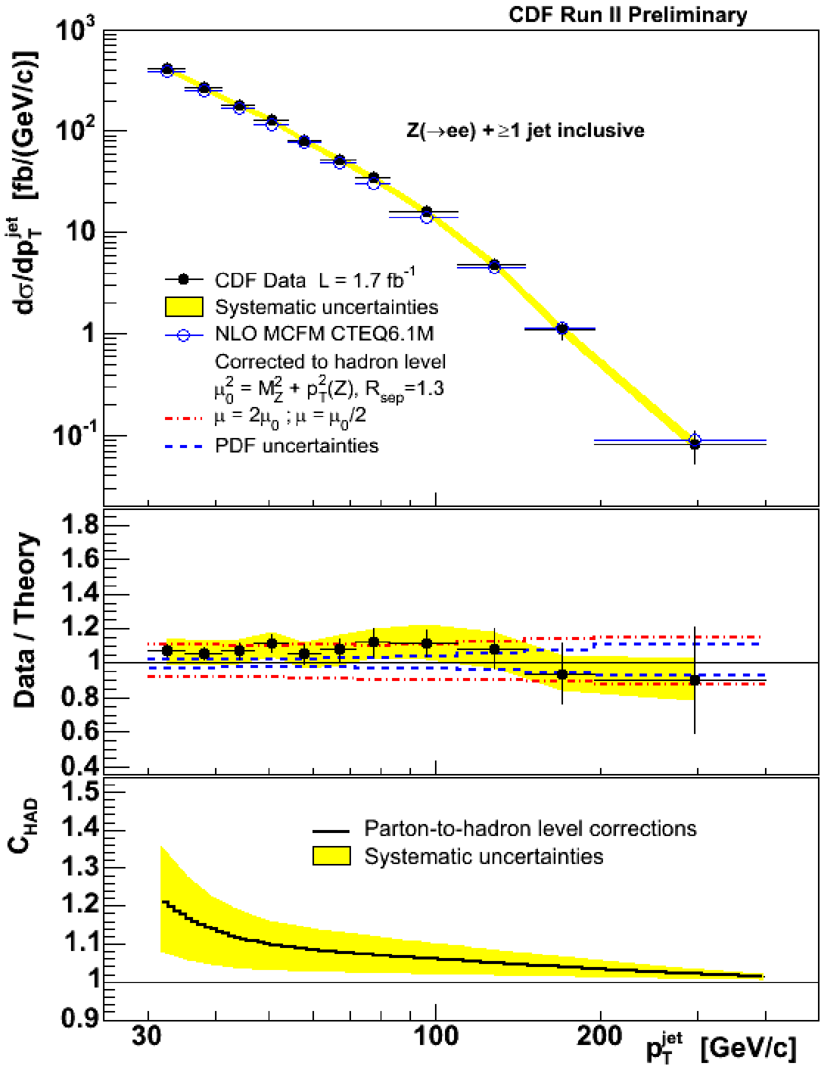
$Z/\gamma^{*}+\geq 1$ jet



$Z/\gamma^{*}+\geq 2$ jets

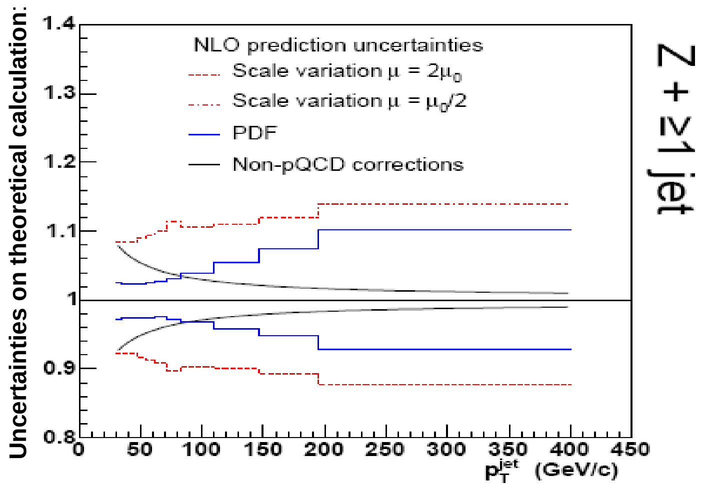


Cross Section Z+ ≥ 1 jet



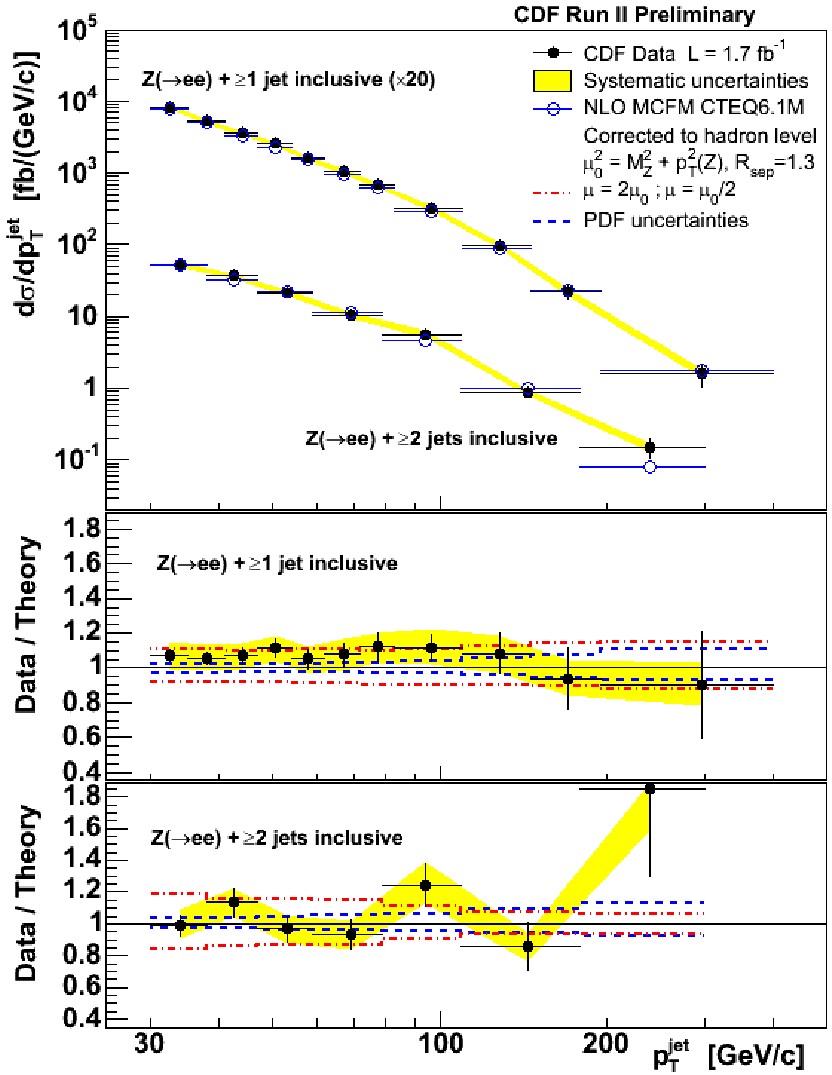
Uncertainties on theoretical calculation:

- PDF uncertainties:
  - using Hessian method: 3-10%
- Renormalization and factorization scale variation (run at $2\mu_0$ and $1/2\mu_0$):
  - 10-15% variation in the prediction
- Uncertainties on non-pQCD factors:
  - Up to 8% at low p_T ^{jet}

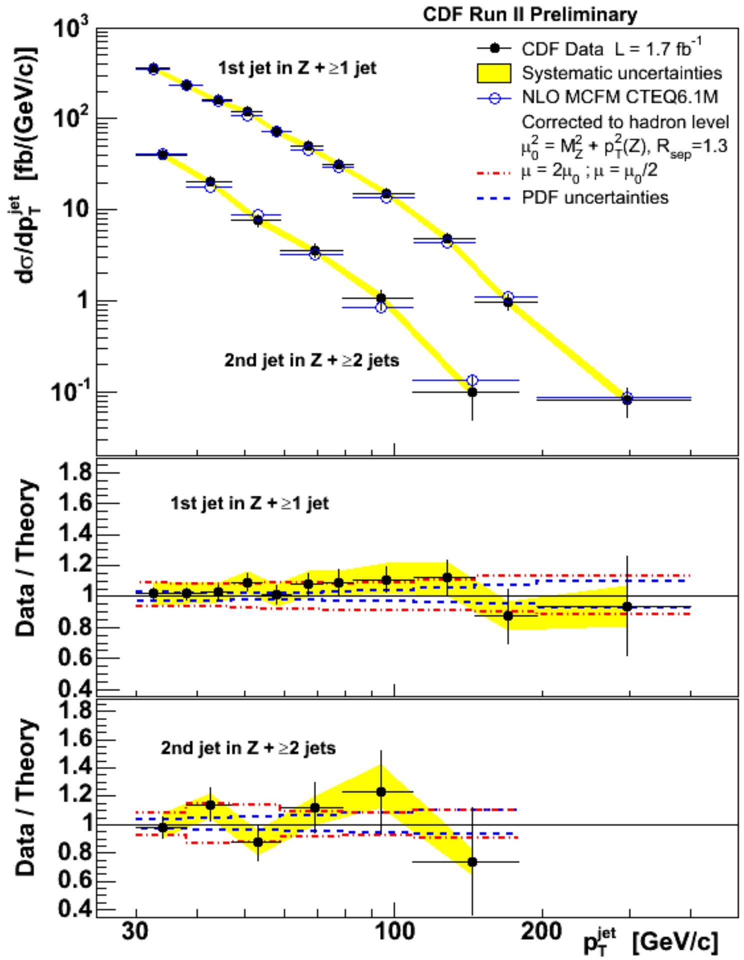


Good agreement between data and NLO pQCD

Cross Section Z+ jets



Good agreement between data and NLO pQCD



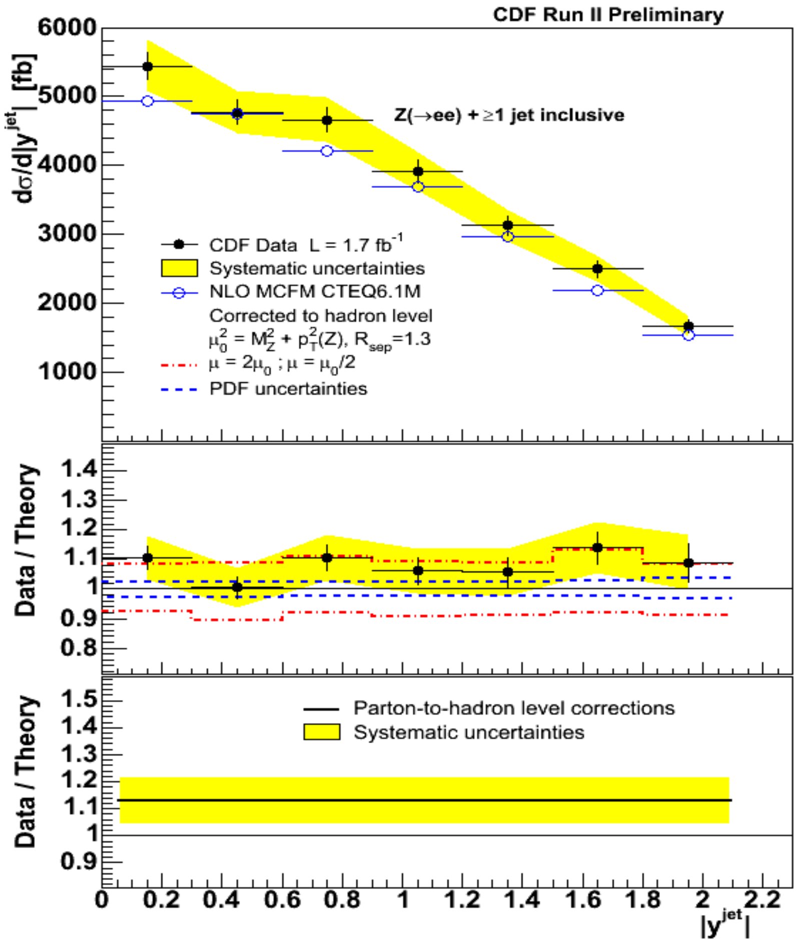
Table

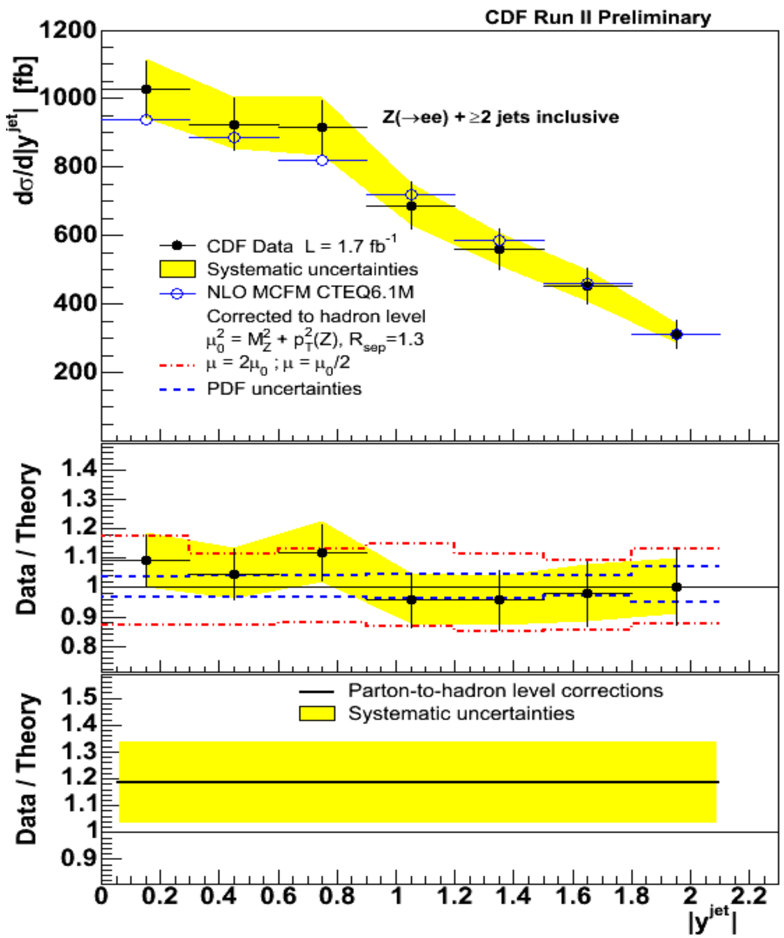
p_T^{jet} [GeV/c]	$\frac{d\sigma}{dp_T^{jet}} \pm$ (stat.) $\pm$ (syst.) $\pm$ (lum.) [fb/(GeV/c)]	$C_{had} \pm$ (stat.) $\pm$ (syst.) parton $\rightarrow$ hadron
$Z/\gamma^*(\rightarrow e^+e^-)$+jets ($N_{jet} \geq 1$)		
30 - 35	$413.3 \pm 13.3^{+30.4}_{-31.3} \pm 24.0$	$1.209 \pm 0.010 \pm 0.134$
35 - 41	$263.3 \pm 9.4^{+18.3}_{-17.4} \pm 15.3$	$1.146 \pm 0.010 \pm 0.096$
41 - 47	$178.3 \pm 7.5^{+12.0}_{-11.6} \pm 10.3$	$1.114 \pm 0.011 \pm 0.077$
47 - 54	$128.5 \pm 5.9^{+8.7}_{-8.4} \pm 7.5$	$1.097 \pm 0.012 \pm 0.066$
54 - 62	$80.5 \pm 4.3^{+5.5}_{-6.0} \pm 4.7$	$1.086 \pm 0.013 \pm 0.059$
62 - 72	$52.5 \pm 3.2^{+4.4}_{-4.3} \pm 3.0$	$1.078 \pm 0.013 \pm 0.053$
72 - 83	$34.2 \pm 2.4^{+2.5}_{-2.8} \pm 2.0$	$1.072 \pm 0.015 \pm 0.049$
83 - 110	$16.0 \pm 1.1^{+1.5}_{-1.3} \pm 0.9$	$1.063 \pm 0.012 \pm 0.043$
110 - 146	$4.9 \pm 0.5^{+0.5}_{-0.5} \pm 0.3$	$1.051 \pm 0.012 \pm 0.035$
146 - 195	$1.1 \pm 0.2^{+0.1}_{-0.1} \pm 0.06$	$1.040 \pm 0.008 \pm 0.027$
195 - 400	$0.08 \pm 0.03^{+0.01}_{-0.01} \pm 0.005$	$1.021 \pm 0.005 \pm 0.013$
$Z/\gamma^*(\rightarrow e^+e^-)$+jets ($N_{jet} \geq 2$)		
30 - 38	$52.9 \pm 3.5^{+5.3}_{-4.6} \pm 3.1$	$1.262 \pm 0.022 \pm 0.217$
38 - 47	$37.0 \pm 2.8^{+2.9}_{-2.8} \pm 2.1$	$1.207 \pm 0.024 \pm 0.169$
47 - 59	$21.2 \pm 1.8^{+1.9}_{-1.9} \pm 1.2$	$1.164 \pm 0.025 \pm 0.130$
59 - 79	$10.5 \pm 1.0^{+0.9}_{-1.0} \pm 0.6$	$1.123 \pm 0.024 \pm 0.093$
79 - 109	$5.7 \pm 0.6^{+0.7}_{-0.5} \pm 0.3$	$1.087 \pm 0.026 \pm 0.062$
109 - 179	$0.88 \pm 0.15^{+0.09}_{-0.10} \pm 0.05$	$1.052 \pm 0.020 \pm 0.030$
179 - 300	$0.15 \pm 0.04^{+0.02}_{-0.02} \pm 0.009$	$1.026 \pm 0.010 \pm 0.008$

The **table** includes **differential cross section** as a function of p_T^{jet} for $Z/\gamma^*(\rightarrow e^+e^-)$+≥1 jet and $Z/\gamma^*(\rightarrow e^+e^-)$+≥2 jets production with statistical, systematic and luminosity uncertainties.

The **C_{HAD} parton-to-hadron corrections** applied to the NLO pQCD predictions are included with their uncertainties.

Cross Section vs Y(jets)

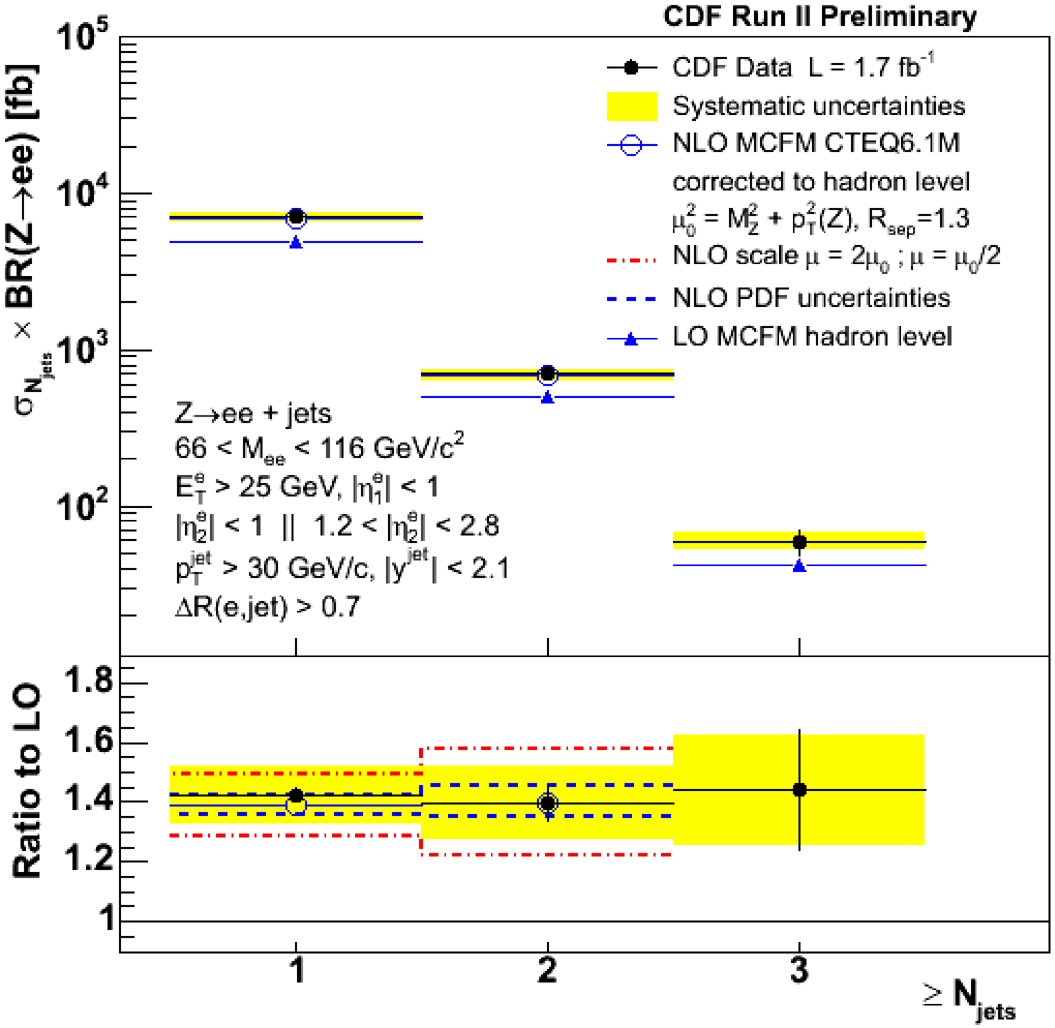




Good agreement with NLO predictions with non-perturbative contributions

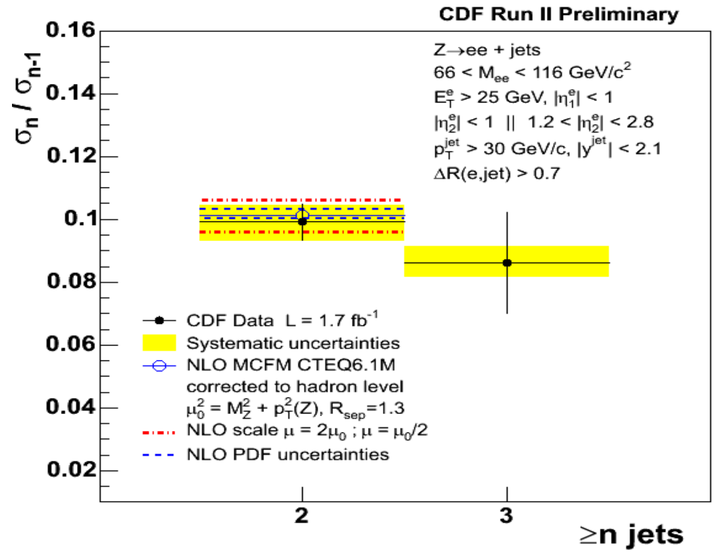
Jet Multiplicity

Cross Section w.r.t. the number of jets



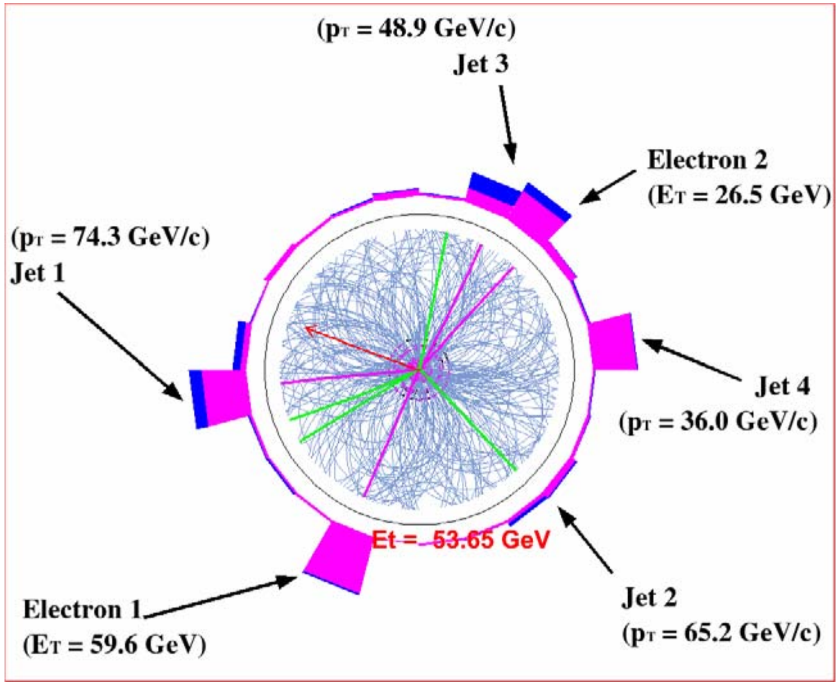
- Good agreement between data and NLO pQCD.
- k-factor (NLO/LO) is rather flat and around ~1.4
- ~ 15% more jets due to the non-pQCD effects.

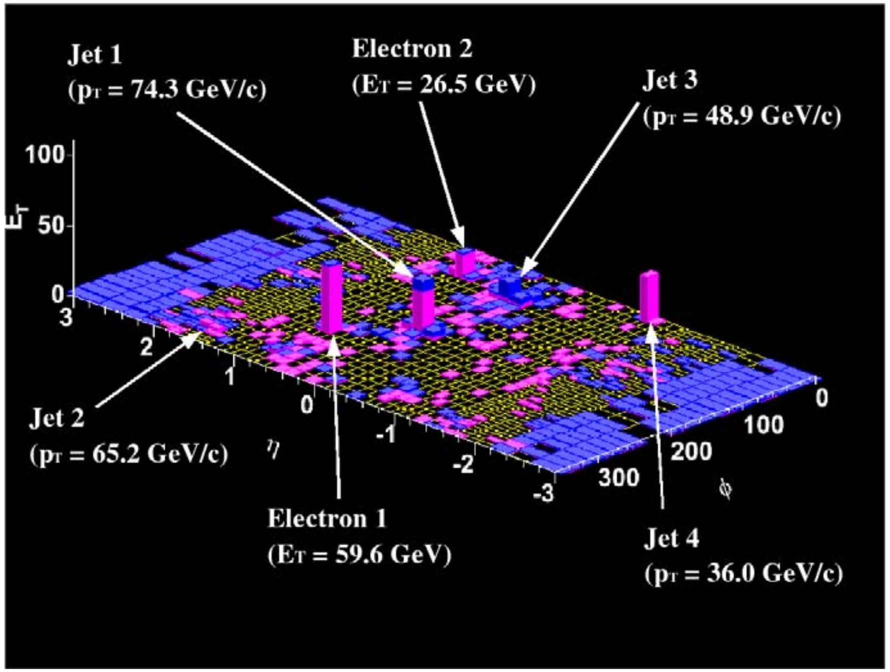
Cross Section ratios



Z+4 jets events

Found two events with a Z boson and 4 jets





View of the transverse plane (showing the tracks and the calorimeter towers) and a lego plot of the calorimeter towers of one of the **Z+4 jets** event.

Boson+jets as bkg. for new Physics (I)

- Boson+jets constitute an important backgrounds to
  - top production, Higgs searches
  - SUSY searches: **squark/gluino**

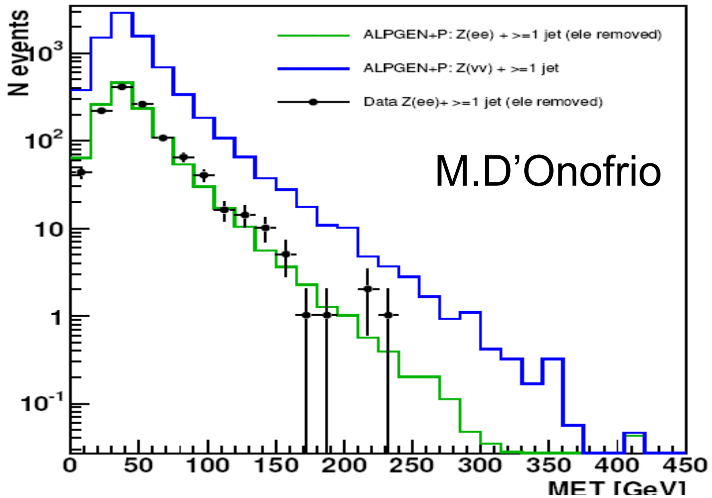
Signature: **energetic jets + MET (undetected LSP)**

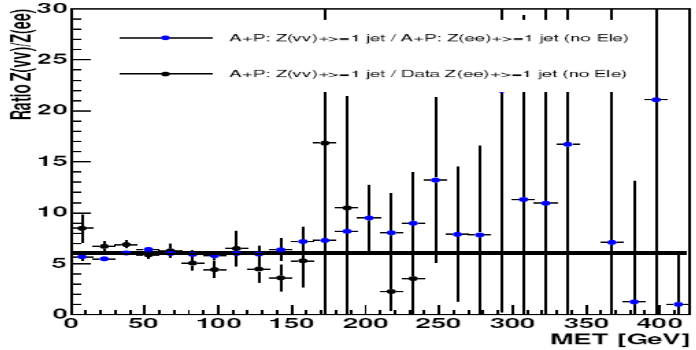
➢ Boson+jets one of the largest bkg, $Z \rightarrow \nu\nu$+jets irreducible

➢ can "simulate" MET as from $Z \rightarrow \nu\nu$ in data artificially removing electro-magnetic clusters associated with reconstructed $Z \rightarrow ee$ Boson

- Data compared to:
  Alpgen+Pythia $Z \rightarrow ee$+jets
  Alpgen+Pythia $Z \rightarrow \nu\nu$+jets

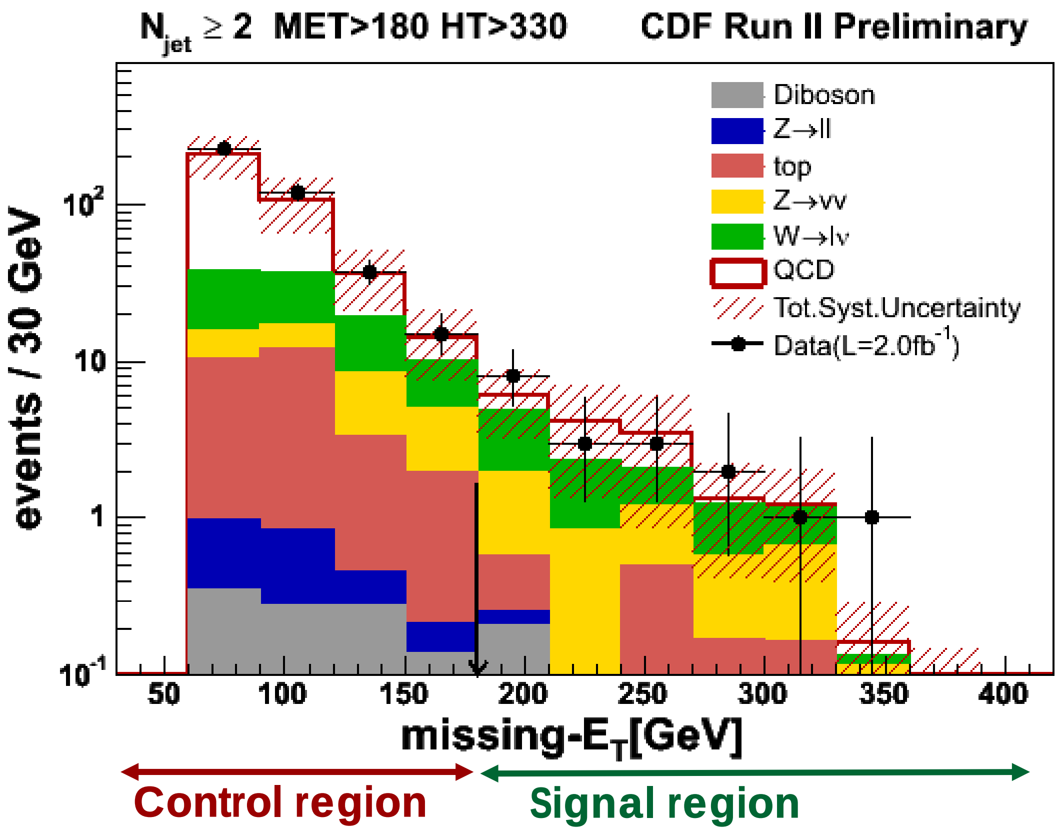
A+P $Z(\nu\nu)$ / A+P $Z(ee)$ = 6.11 ± 0.19
A+P $Z(\nu\nu)$ / Data $Z(ee)$ = 5.98 ± 0.08
Expected from PDG: ~ 6





Boson+jets as bkg. for new Physics (II)

- Boson+jets background processes well reproduced with ME+PS (ALPGEN + PYTHIA in this case) once normalized to measured DY cross section



- We will need more statistics to further test MC generators and compare their predictions with data

Summary

- Tevatron and CDF experiment performing well:
  - > 3 fb^{-1} data on tape (~ 80-85% efficiency)
- Boson+jets are fundamental to test pQCD, underlying Event and new LO ME calculations + Parton Shower Monte Carlo generators.
- Important background for top, Higgs and SUSY searches
- Z+jets cross section:
  - Compared to NLO pQCD calculations.
  - p_T , Y and Jet multiplicity distributions in inclusive Z+jets production.
  - Non-pQCD corrections are sizeable (~15% more jets).
- More statistics will be used for further studies to test MC generators.

Back up

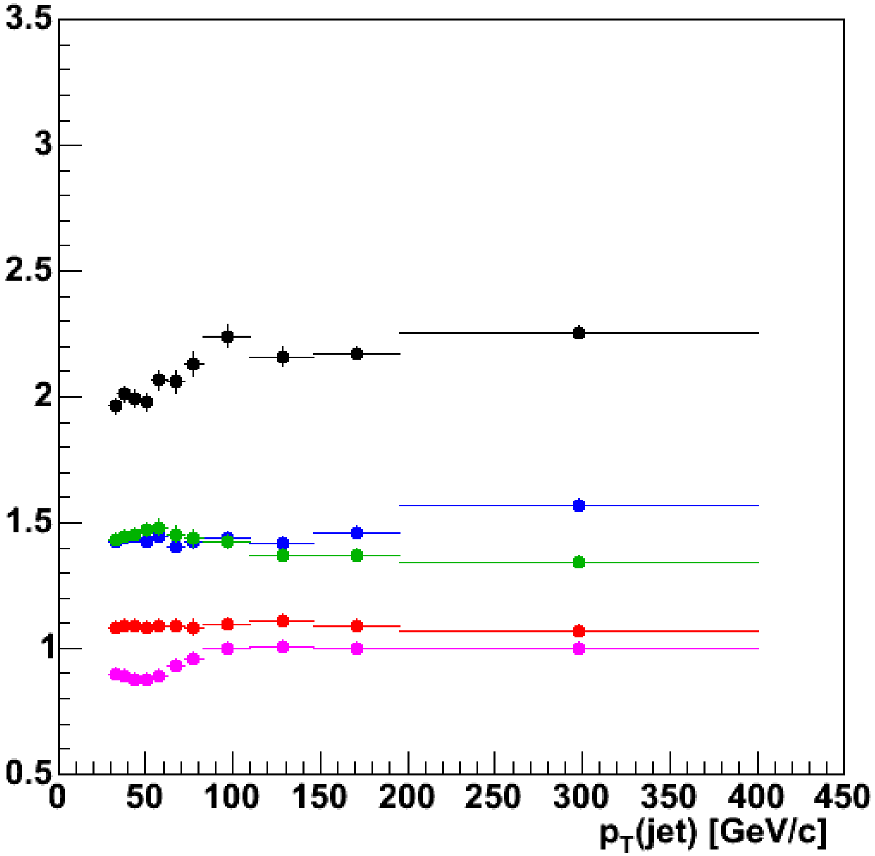
Z+jets Electron Selection

- **Tight Central Electron**
  - $|\eta| < 1.0$
  - $|z_0| < 60$ cm
  - $p_T > 10$ GeV/c
  - $E_T > 25$ GeV
  - Track quality cuts
    - > 3 Stereo SL w/ hits ≥ 5
    - > 2 Axial SL w/ hits ≥ 5
  - Iso4 – Leak $< 0.1 \cdot E_T$
  - HadEm $< 0.055 + 0.00045 \cdot E_T$
  - E/p < 2.0 OR $p_T < 50$ GeV/c
  - Lshr < 0.2
  - $\chi^2_{CES} < 10.0$
  - -3.0 cm $< Q \cdot \Delta x <$ 1.5 cm
  - $|\Delta z| < 3.0$ cm
  - Fiduciality == 1

- **Loose Central Electron**
  - $|\eta| < 1.0$
  - $|z_0| < 60$ cm
  - $p_T > 10$ GeV/c
  - $E_T > 25$ GeV
  - Track quality cuts
    - > 3 Stereo SL w/ hits ≥ 5
    - > 2 Axial SL w/ hits ≥ 5
  - Iso4 – Leak $< 0.1 \cdot E_T$
  - HadEm $< 0.055 + 0.00045 \cdot E_T$
  - Fiduciality == 1

- **Plug Electron**
  - $1.2 < |\eta| < 2.8$
  - $E_T > 25$ GeV
  - Iso4 < 4
  - HadEm < 0.05
  - $\chi^2_{PEM} <= 10.0$

Unfolding breakdown



- All the intermediate steps are flat and smooth in p_T.
- As expected the **reclustering** has a larger effect at low p_T jets

- Total
- Particle to Calorimeter

$$\frac{Z\left[gen: E_T^e, \eta^e, M_{ee}\right] + \geq n\ hadron\ \ jets\left[p_T, \eta\right]}{Z\left[rec: E_T^e, \eta^e, M_{ee}\right] + \geq n\ \ jets\left[p_T^{CORR}, \eta\right]}$$

- Apply fiduciality and trk cuts to electrons

$$\frac{Z\left[rec: E_T^e, \eta^e, M_{ee}\right] + \geq n\ \ jets\left[p_T^{CORR}, \eta\right]}{Z\left[rec: E_T^e, \eta^e, M_{ee}, p_T^{trk},\ fid\right] + \geq n\ \ jets\left[p_T^{CORR}, \eta\right]}$$

- Apply ID and vtx cuts to the electrons

$$\frac{Z\left[rec: E_T^e, \eta^e, M_{ee}, p_T^{trk},\ fid\right] + \geq n\ \ jets\left[p_T^{CORR}, \eta\right]}{Z\left[rec: E_T^e, \eta^e, M_{ee}, p_T^{trk},\ fid, ID\ cuts, vtx\right] + \geq n\ \ jets\left[p_T^{CORR}, \eta\right]}$$

- Effect of reclustering the jets

$$\frac{Z\left[rec: E_T^e, \eta^e, M_{ee}, p_T^{trk},\ fid, ID\ cuts, vtx\right] + \geq n\ \ jets\left[p_T^{CORR}, \eta\right]}{Z\left[rec: E_T^e, \eta^e, M_{ee}, p_T^{trk},\ fid, ID\ cuts, vtx\right] + \geq n\ RC\ \ jets\left[p_T^{CORR}, \eta\right]}$$

Pythia Tunes

Parameter	Tune A	Tune DW
MSTP(81)	1	1
MSTP(82)	4	4
PARP(82)	2.0 GeV	1.9 GeV
PARP(83)	0.5	0.5
PARP(84)	0.4	0.4
PARP(85)	0.9	1.0
PARP(86)	0.95	1.0
PARP(89)	1.8 TeV	1.8 TeV
PARP(90)	0.25	0.25
PARP(62)	1.0	1.25
PARP(64)	1.0	0.2
PARP(67)	4.0	2.5
MSTP(91)	1	1
PARP(91)	1.0	2.1
PARP(93)	5.0	15.0