Boson+jets Measurements at CDF

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for the CDF Collaboration

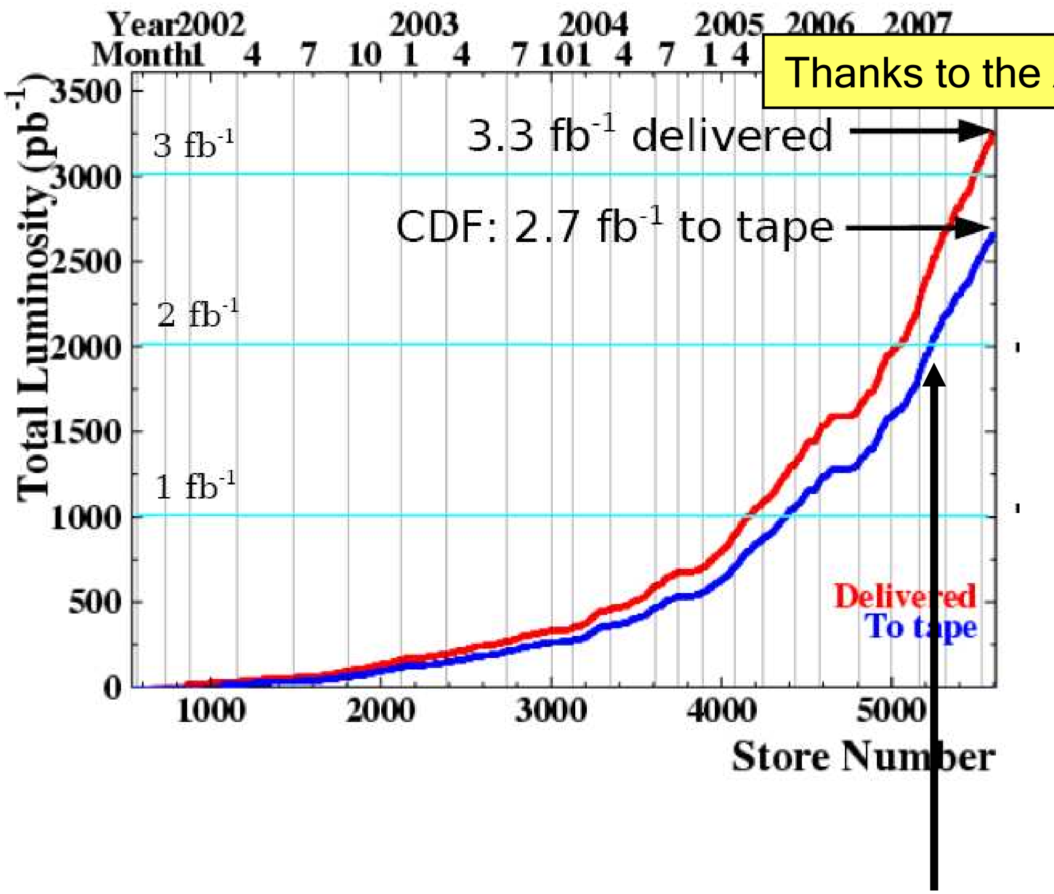
Wine & Cheese Seminar August 24, 2007

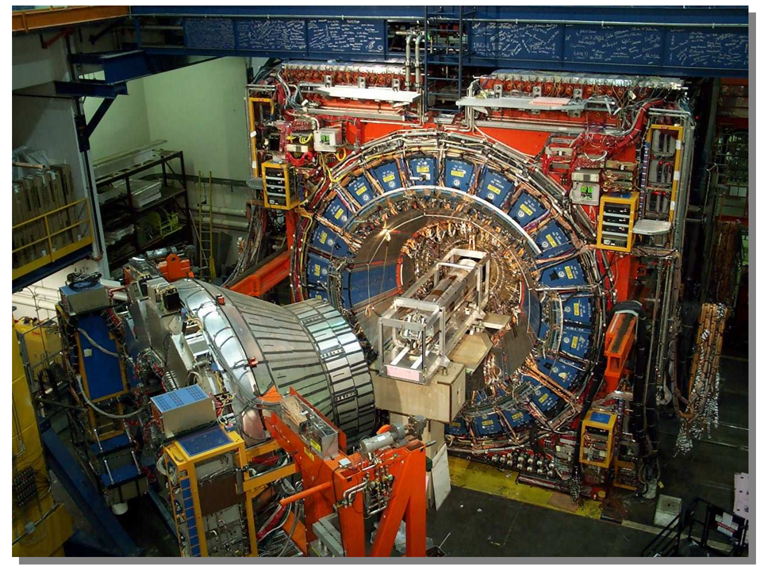
Outline

- Introduction
- Boson+jets
  - Z/γ+jets
  - W+jets
- Boson+Heavy Flavor Jets
  - Z/γ+b
  - W+c
  - W+b
  - Further develpments:
    - NN Heavy Flavor Tagger
- Boson+jets with 6 fb^{-1}
- Summary

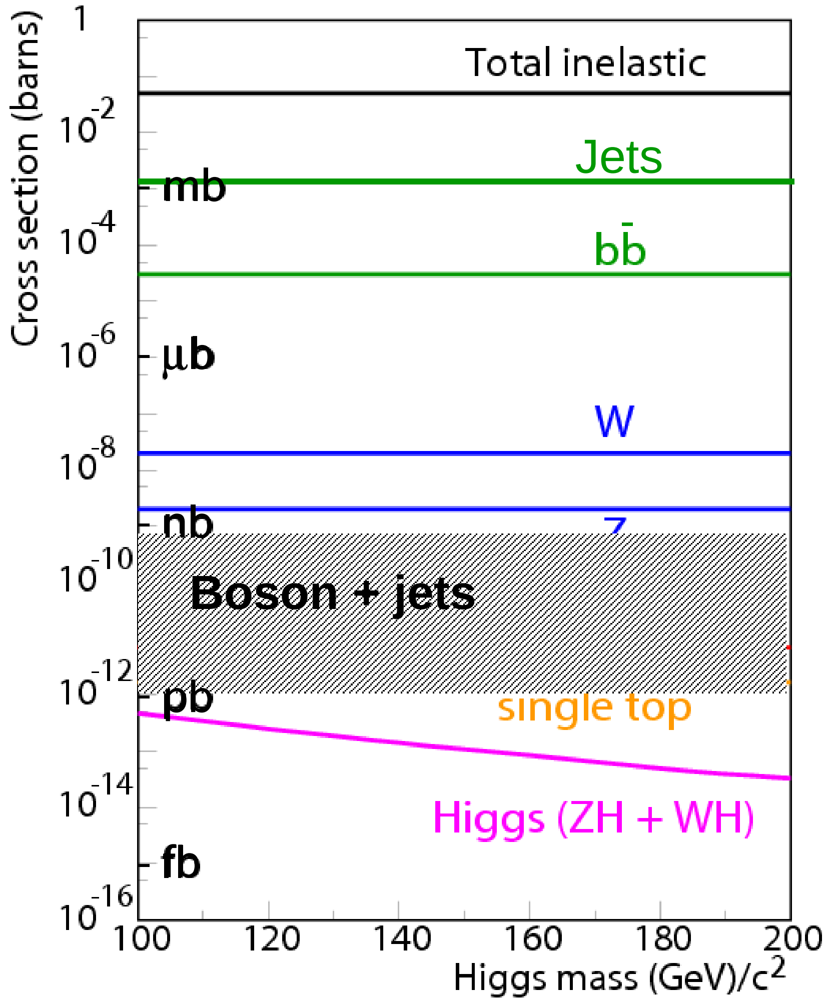
"Particles, particles, particles."

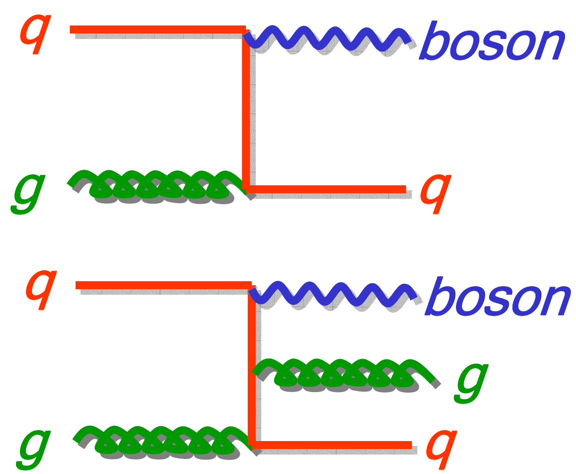
CDF Detector

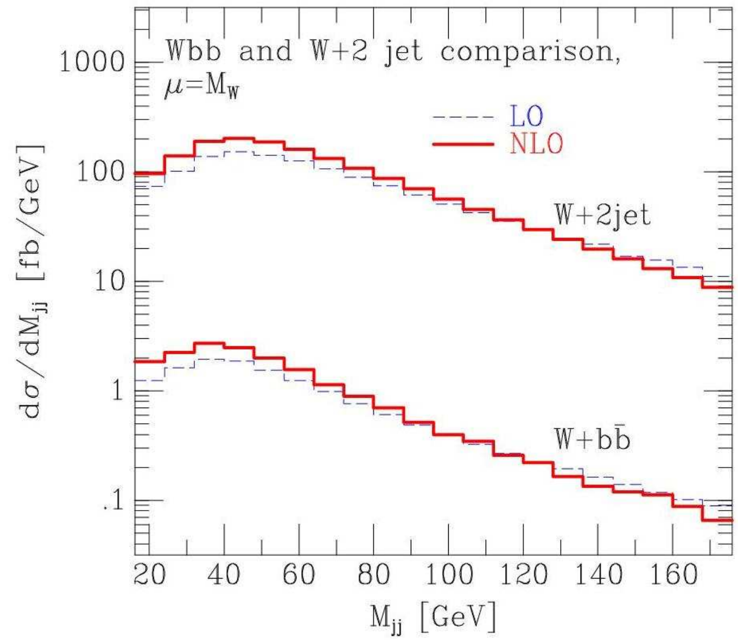




Measurements that will be presented here are using close to 2 fb^{-1} of data.


Cross section (barns)
Total inelastic
Jets
mb
bb̄
µb
W
Z
nb
Boson + jets
pb
single top
Higgs (ZH + WH)
fb
Higgs mass (GeV)/c²


q
boson
g
q
q
boson
g
g
q

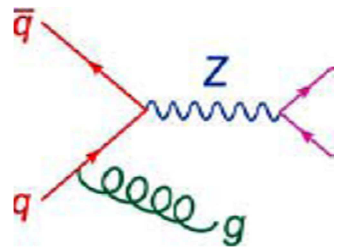

Wbb and W+2 jet comparison,
μ=M_W
LO
NLO
W+2jet
W+bb̄
dσ/dM_jj [fb/GeV]
M_jj [GeV]

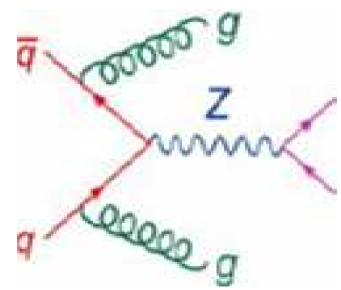
Stringent test of pQCD predictions.

- The mass of the boson provides the necessary hard scale to perform pQCD calculations.

NLO pQCD predictions available for Boson + up to 2 jets.

Also sensitive to any new physics decays to Boson+jets.



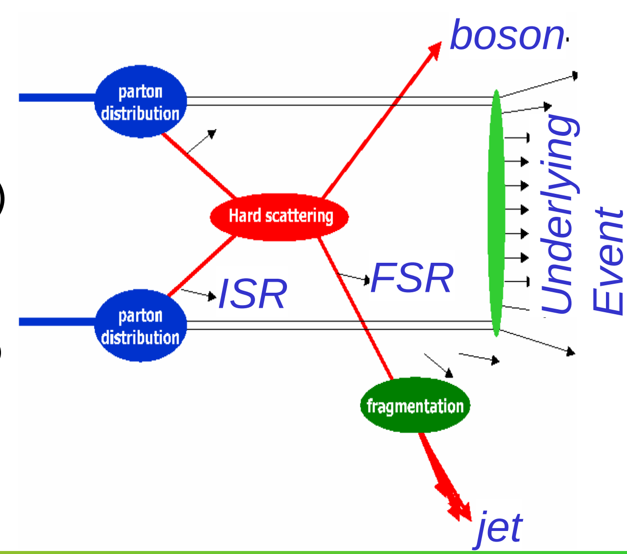


Test Ground for techniques matching Matrix Elements and Parton Shower (ME+PS).

- Special matching algorithms (MLM, CKKW) are used to avoid double counting on ME+PS interface.

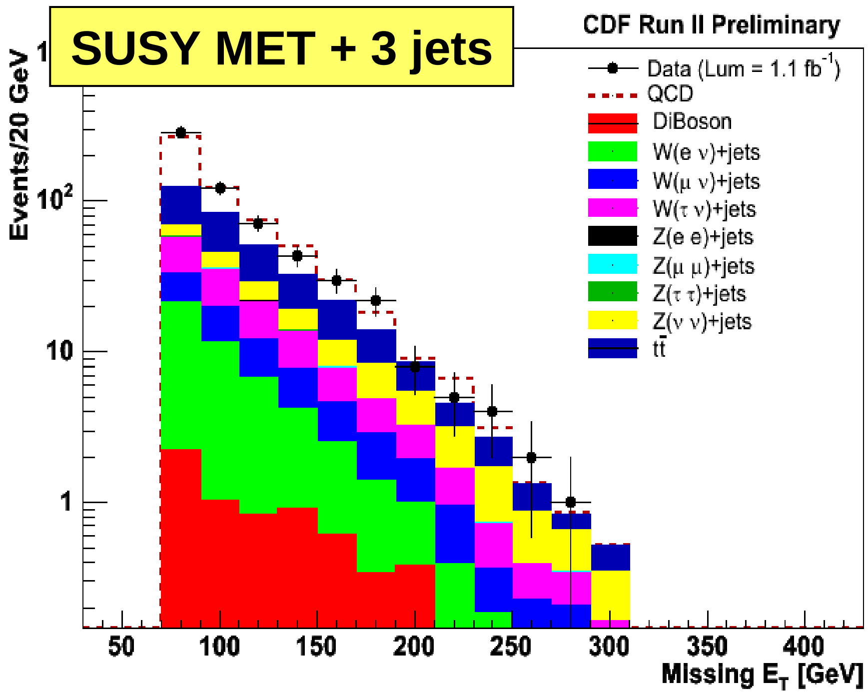
Test non-perturbative QCD modeling.

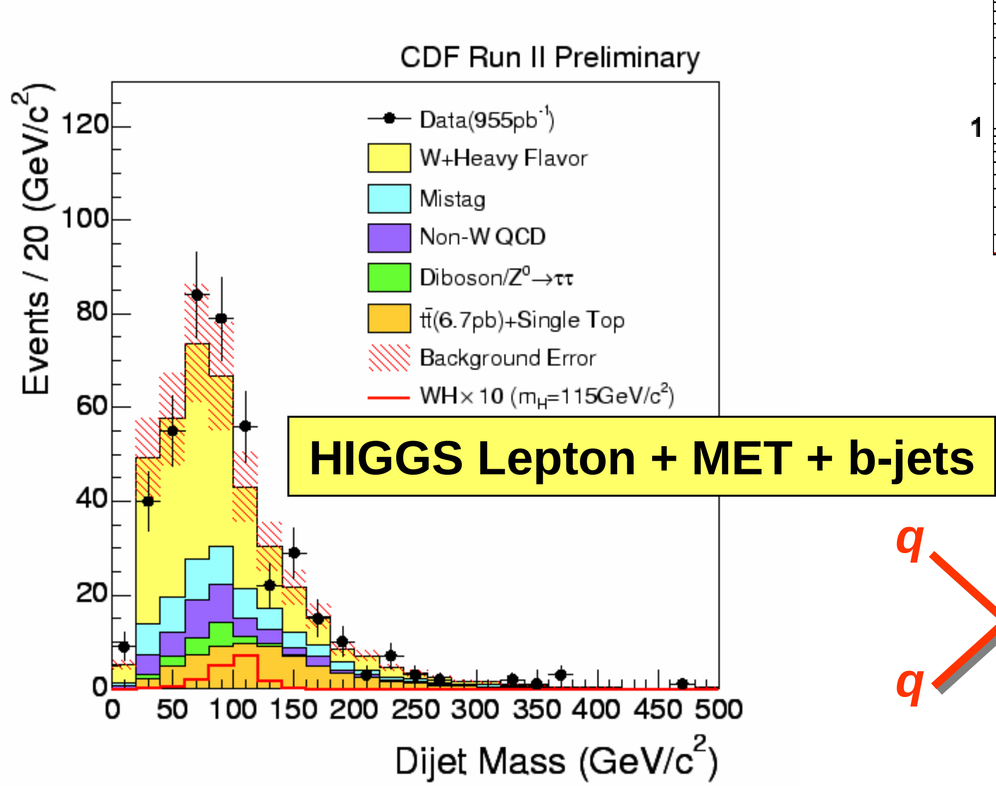
- The comparison of measured cross sections (hadron level) with fixed-order pQCD predictions requires a good modeling of the Underlying Event (interaction between the proton remnants) and the fragmentation of the partons into hadrons.

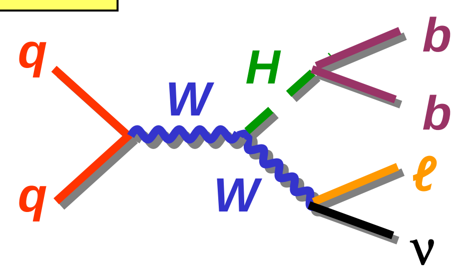


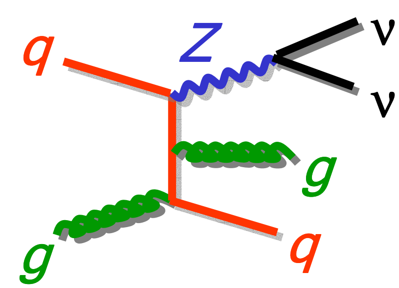
Introduction

Boson+jets constitute irreducible backgrounds for interesting SM processes (top production) and searches for new physics (SUSY and Higgs searches)

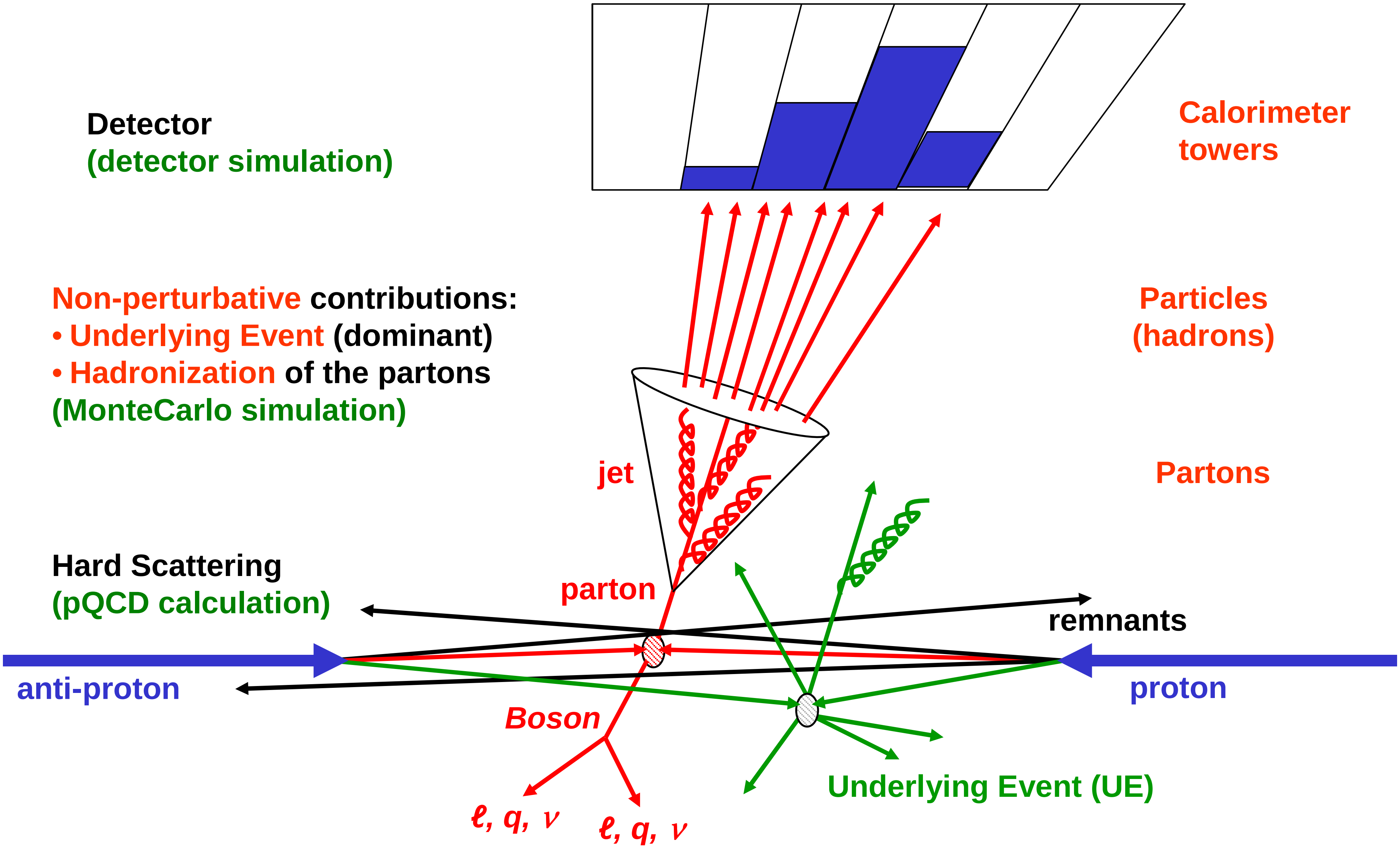








Boson+jets in Hadronic Collisions



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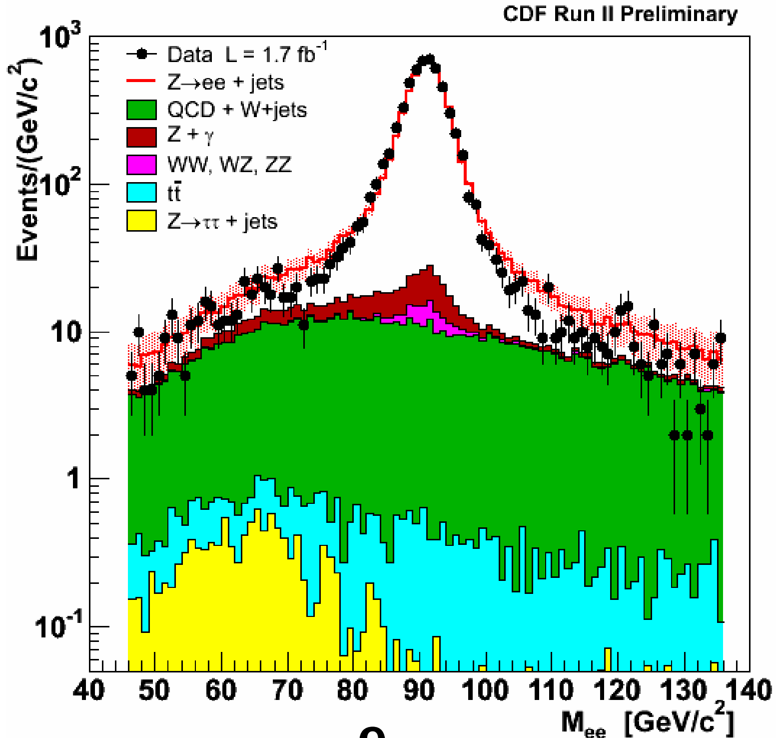
1.7 fb^{-1}

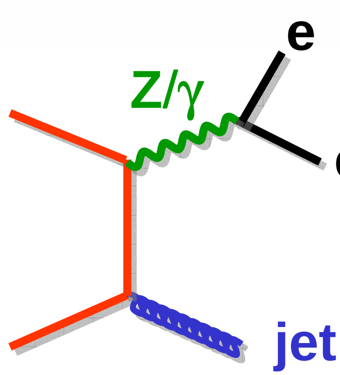


Z/γ→ee + jets is a very clean signal.

- No missing E_T
- Almost background free.

Z/γ→ee + jets does not constitute a background to MET+jets (SUSY searches) but allows validation of MC predictions for the rest of Z+jets and W+jets final states.

With more than 2 fb^{-1} of data differential jet measurements are possible.



Z/γ→ee+jets Cross Section

The measurements are performed in a well defined kinematic region.

Z/γ→ee branching ratio

- $66 < M_{ee} < 116$ GeV/c^2
- $E_T^e > 25$ GeV
- $|\eta_1^e| < 1.0$ $|\eta_2^e| < 1.0$ || $1.2 < |\eta_2^e| < 2.8$

Jets reconstructed with MidPoint Cone algorithm (R = 0.7)

-$p_T^{jet} > 30$ GeV/c $|y^{jet}| < 2.1$ $\Delta R(e,jet) > 0.7$

NLO pQCD prediction by MCFM.

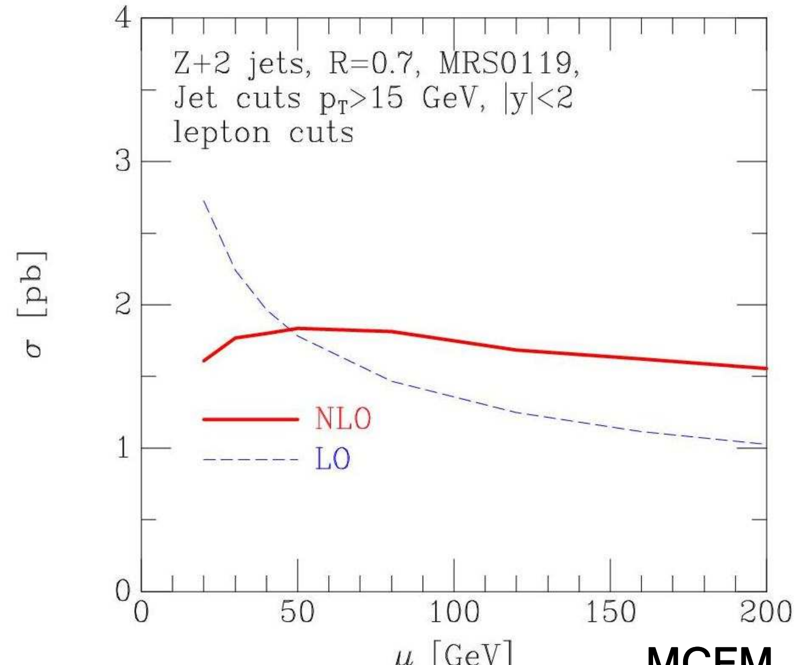
-PDF set: CTEQ6.1M, $R_{sep} = 1.3$

-Dynamic renormalization and factorization scale:

- $\mu^2 = M^2(Z) + p_T^2(Z)$

-Up to 3 jets in the final state (inclusive Z+≥2 jets)

-Corrected for non-perturbative contributions (Underlying Event and fragmentation into hadrons)



MCFM

from J.Campbell and R.K.Ellis: hep-ph/0202176

Z/γ→ee+jets Backgrounds

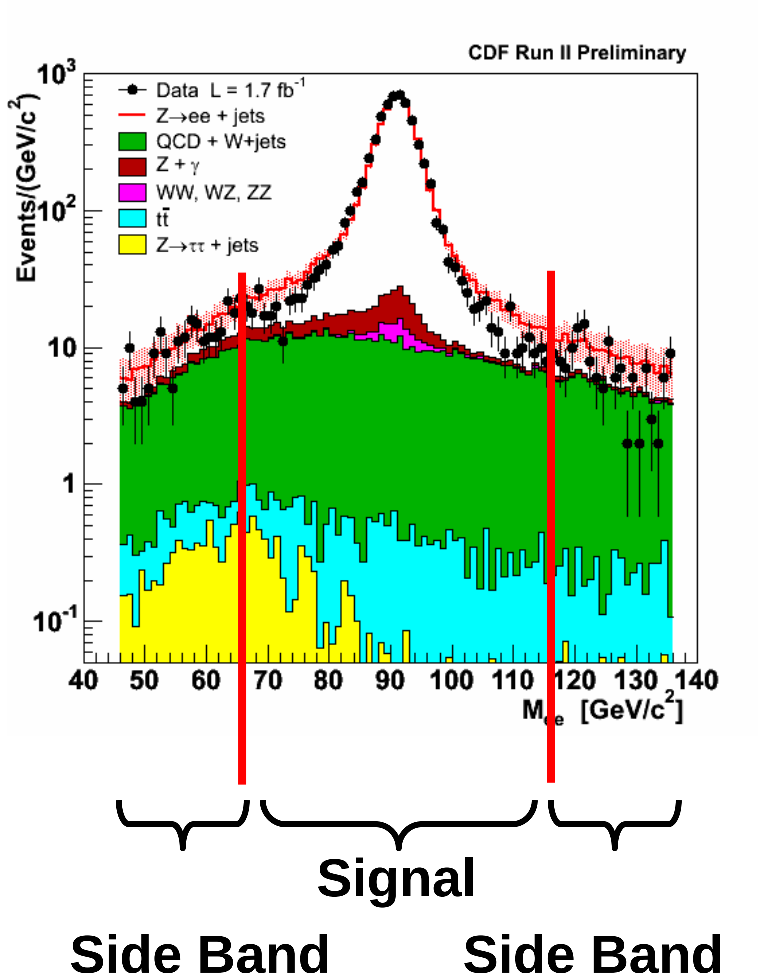
The background contributes a small fraction of the total number of events in the signal region.

- Z+≥1 jet background contribution : 12%
- Z+≥2 jets background contribution : 16%

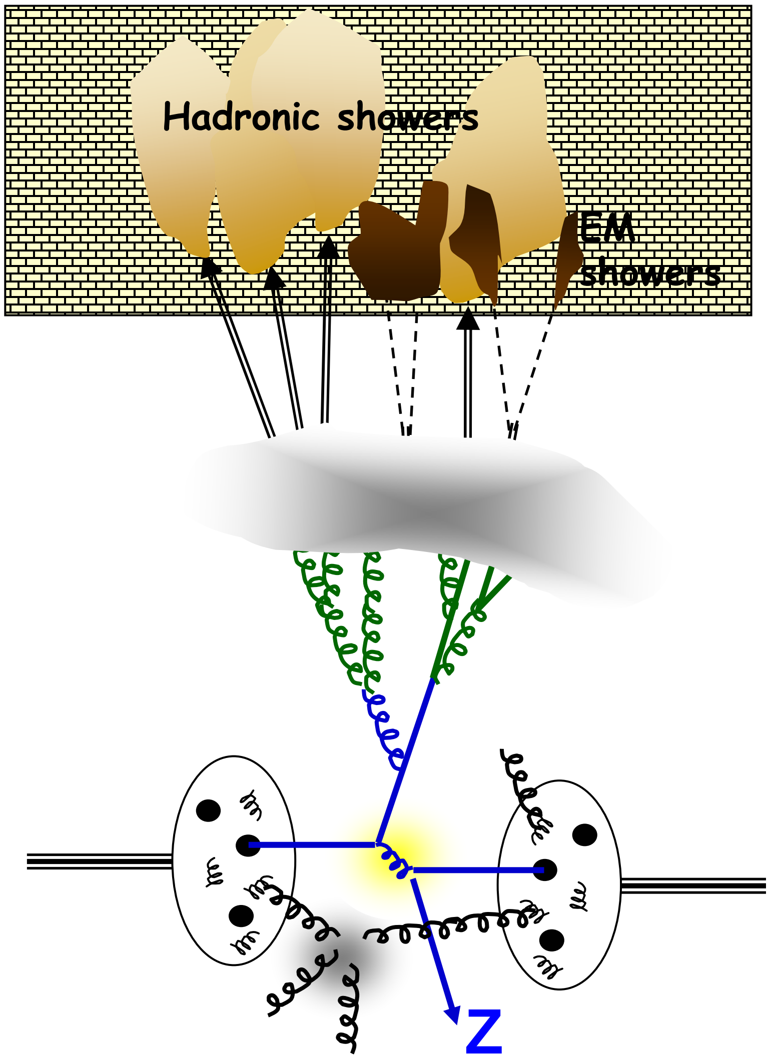
Estimated from data and MC simulation.

- From data:
  - Fakes. Dominant background
    - QCD jets
    - W+jets
- From MC simulation
  - Dibosons: WW, WZ and ZZ
  - Z+γ
  - tt production
  - Z→ττ+jets

The background estimation is cross-checked in the side bands of the Z mass distribution.



Z/γ→ee+jets at Hadron Level



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

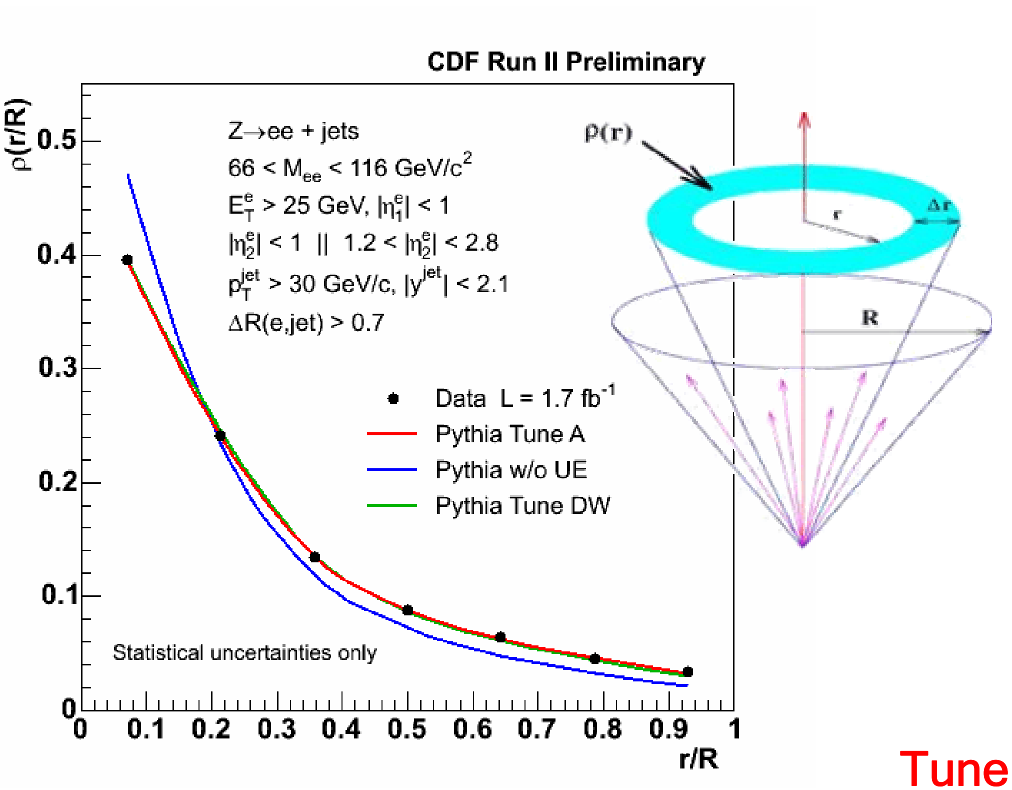
Measurements are unfolded back to the hadron level using the detector simulation.

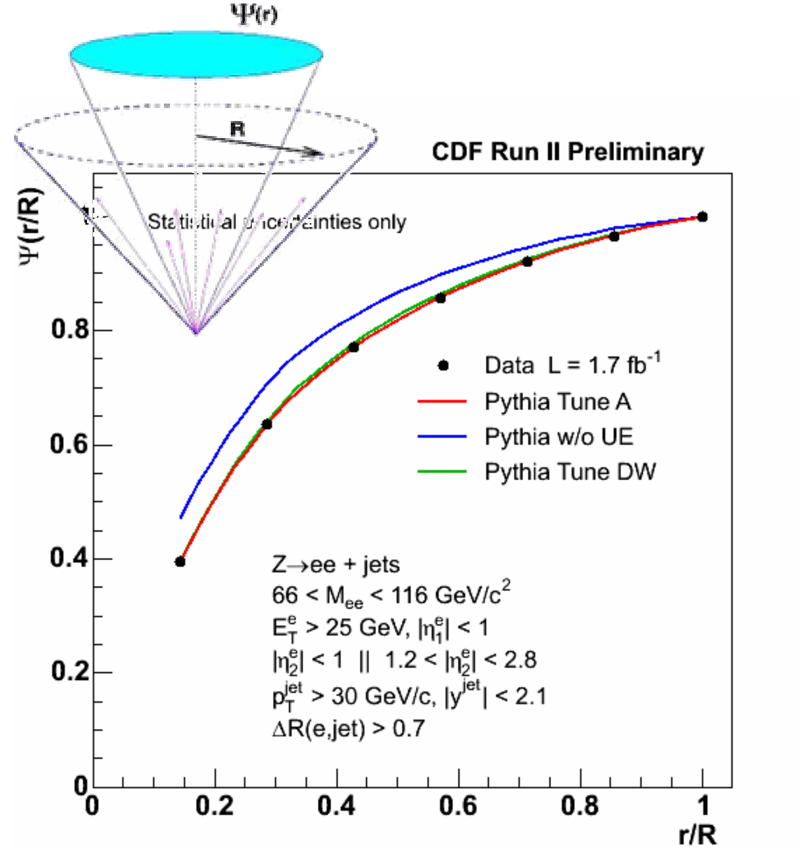
NLO pQCD prediction at parton level are corrected for non-perturbative QCD contributions.

This requires a good modeling of the Underlying Event (dominant contribution) and fragmentation into hadrons in the MC.

Jet Shapes

The observable is sensitive to the Underlying Event and the hadronization.





Jet shapes are very well described by the MC simulation.

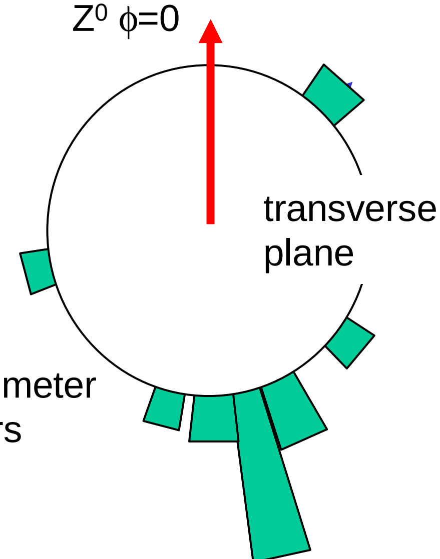
Tune A and Tune DW are two different tunings of the Underlying Event in Pythia.

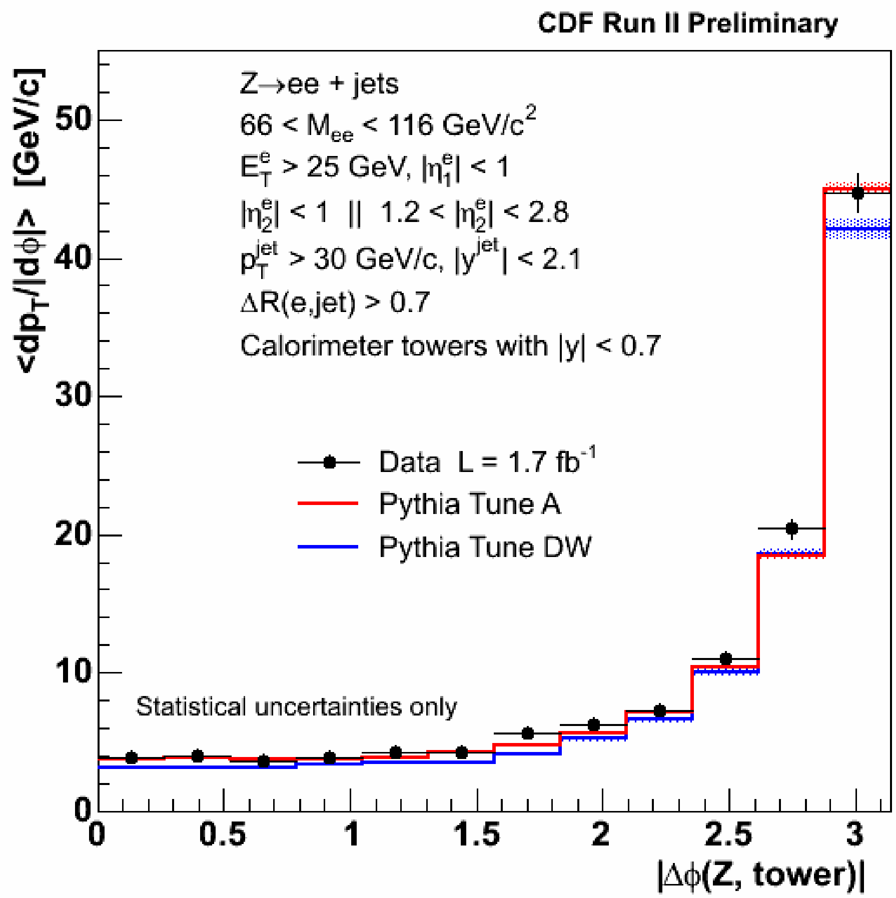
Both describe accurately the jet shapes.

As already seen, the jets are described accurately.

Also very good agreement in the region away from the jet dominated by the Underlying Event.

Both Tune A and Tune DW describe the energy flow in the data.

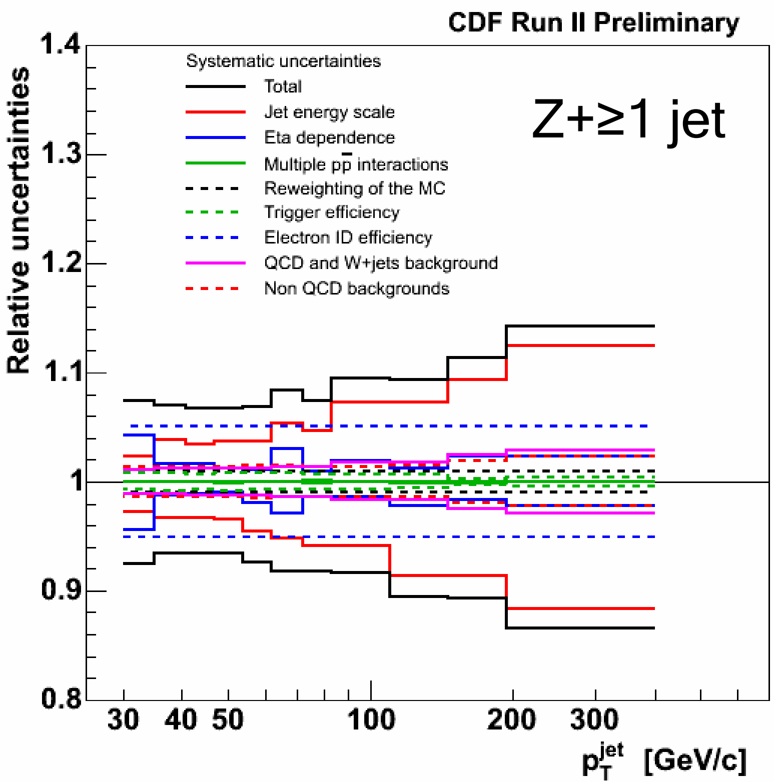


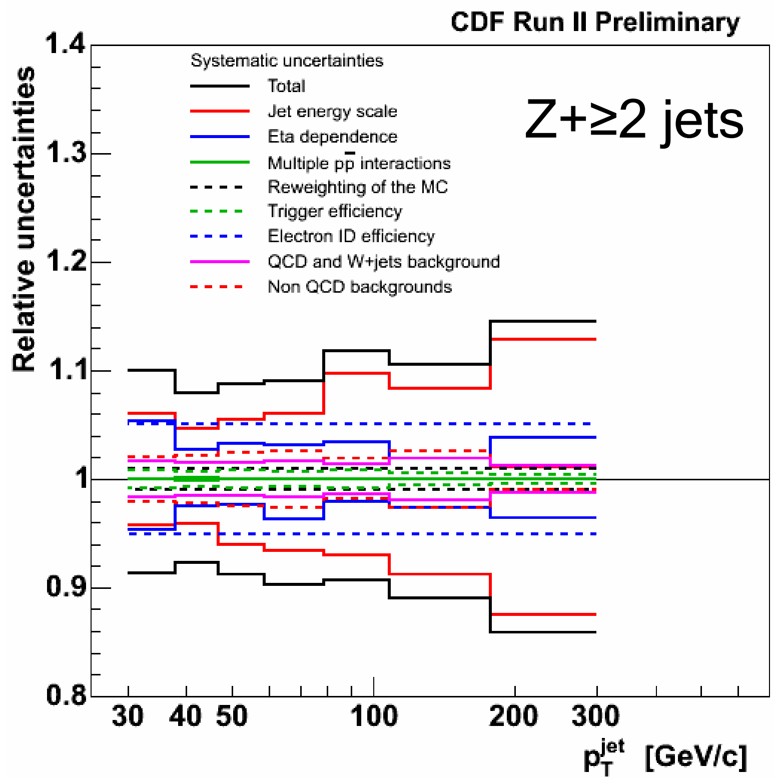


Dominated by the Underlying Event

Uncertainties

The total systematic uncertainty is dominated by the uncertainty on the absolute jet energy scale (≈3%), followed by a 5% uncertainty on the electron ID efficiency.





The total systematic uncertainty is about 10% at low p_T^{jet}, up to 15% at high p_T^{jet}.

Inclusive Jet Cross Section

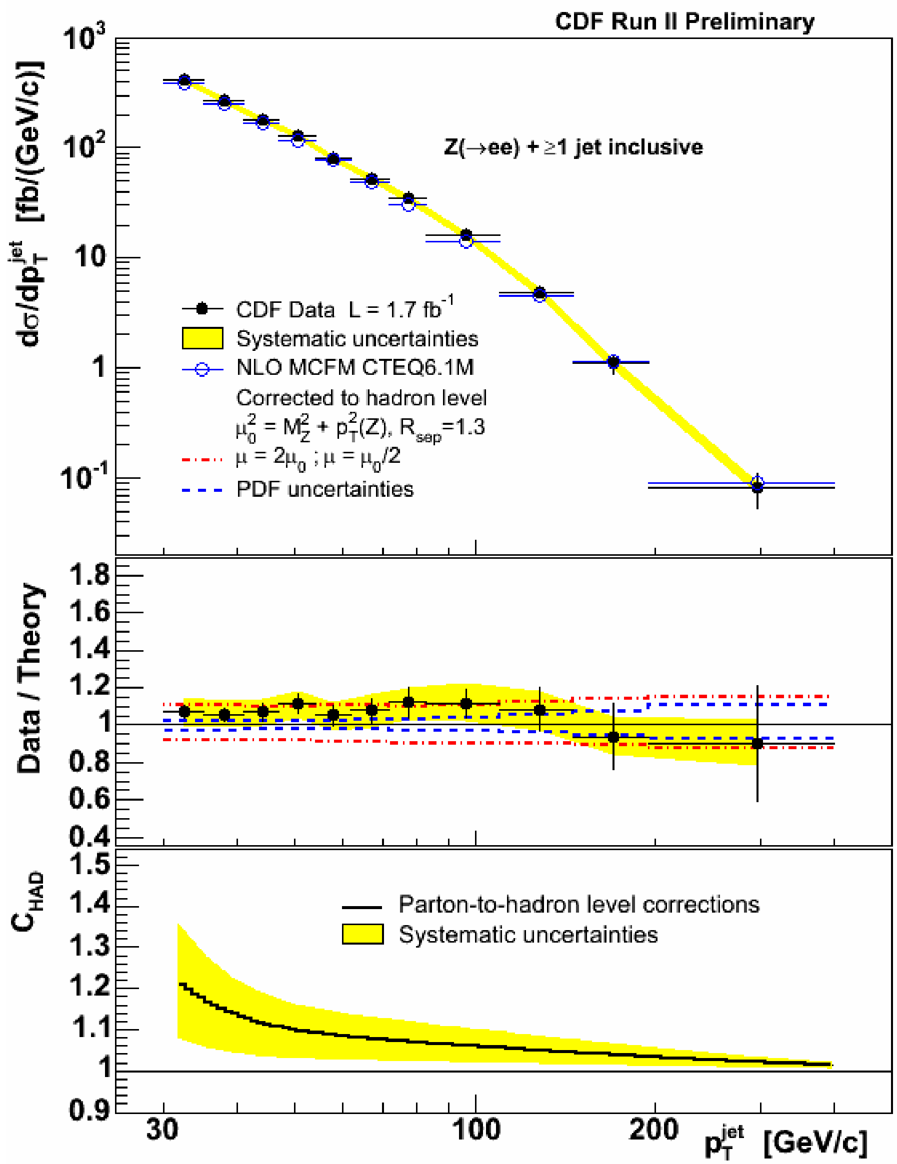
Inclusive jet cross section for Z+≥1 jet production compared to NLO pQCD.

PDF uncertainty varies between 3% at low p_T^{jet} and 10% at high p_T^{jet}.

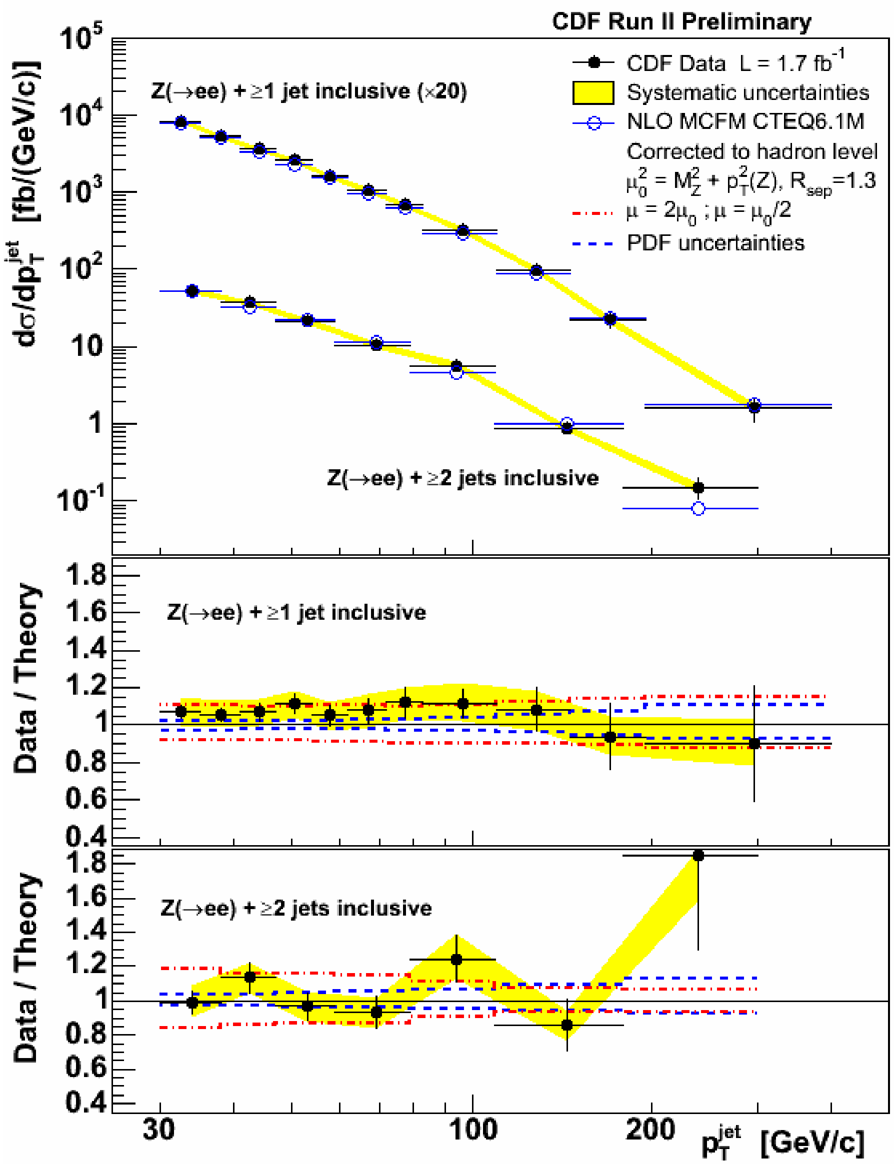
Uncertainty on cross section from the renormalization and factorization scale variation ranges between 10% and 15%.

$$C_{HAD} = \frac{\left(d\sigma / dp_T^{jet} \right)_{\text{HADRON LEVEL}}}{\left(d\sigma / dp_T^{jet} \right)_{\text{PARTON LEVEL (NO UE)}}}$$

Uncertainty estimated from the difference between Pythia Tune A and Tune DW.



Inclusive Jet Cross Section



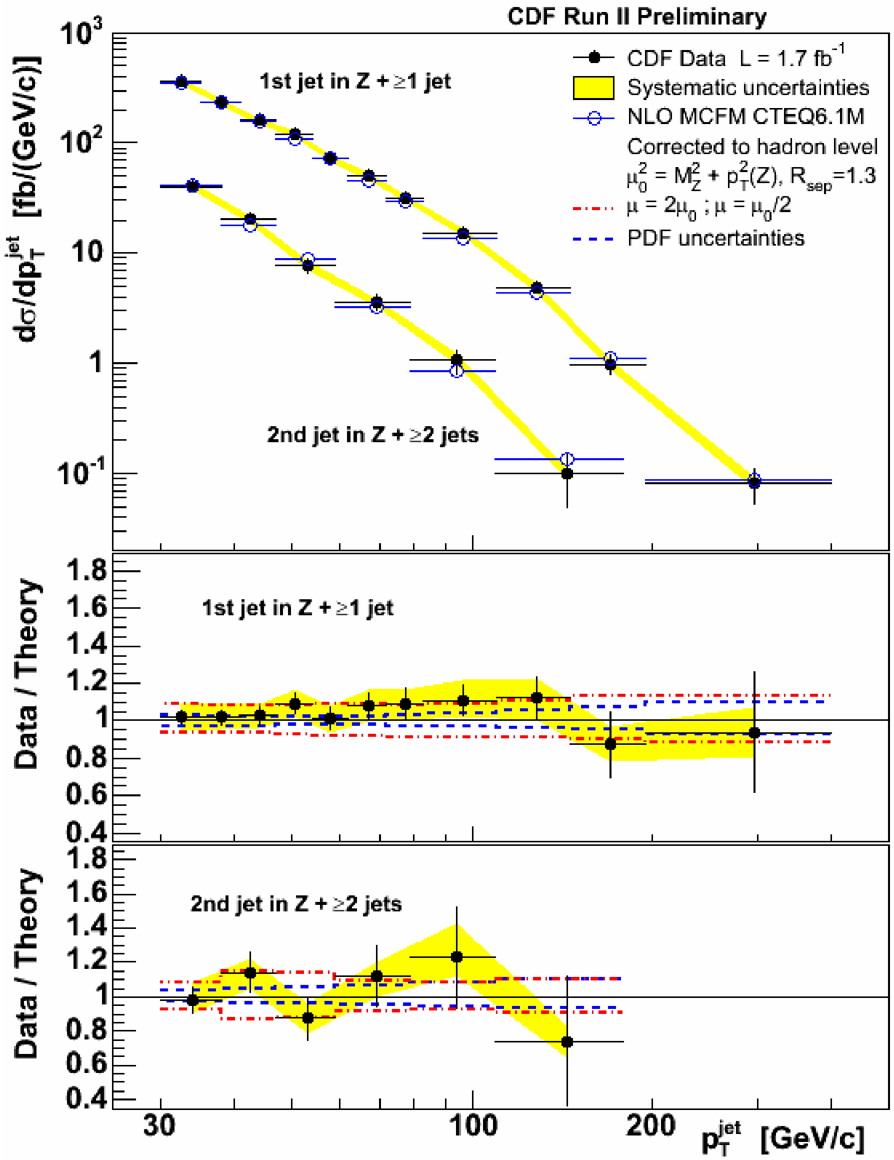
Measurement spans 4 orders of magnitude in cross section

Inclusive jet cross section for $Z+\geq 1$ jet and $Z+\geq 2$ jets production.

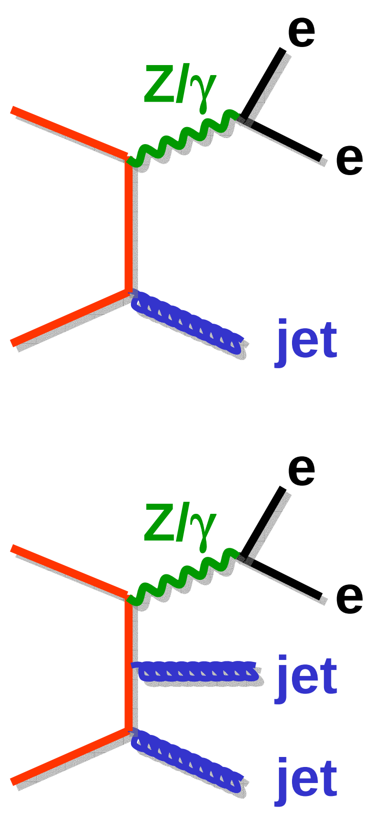
Very good agreement between Data and NLO pQCD predictions.

Uncertainties in Data and theory are comparable at low p_T^{jet} (≈10%).

Leading Jets Cross Section



Cross section as a function of the p_T of the N^{th} leading jet in inclusive Z+≥N jets production, N≥1, 2 jets.



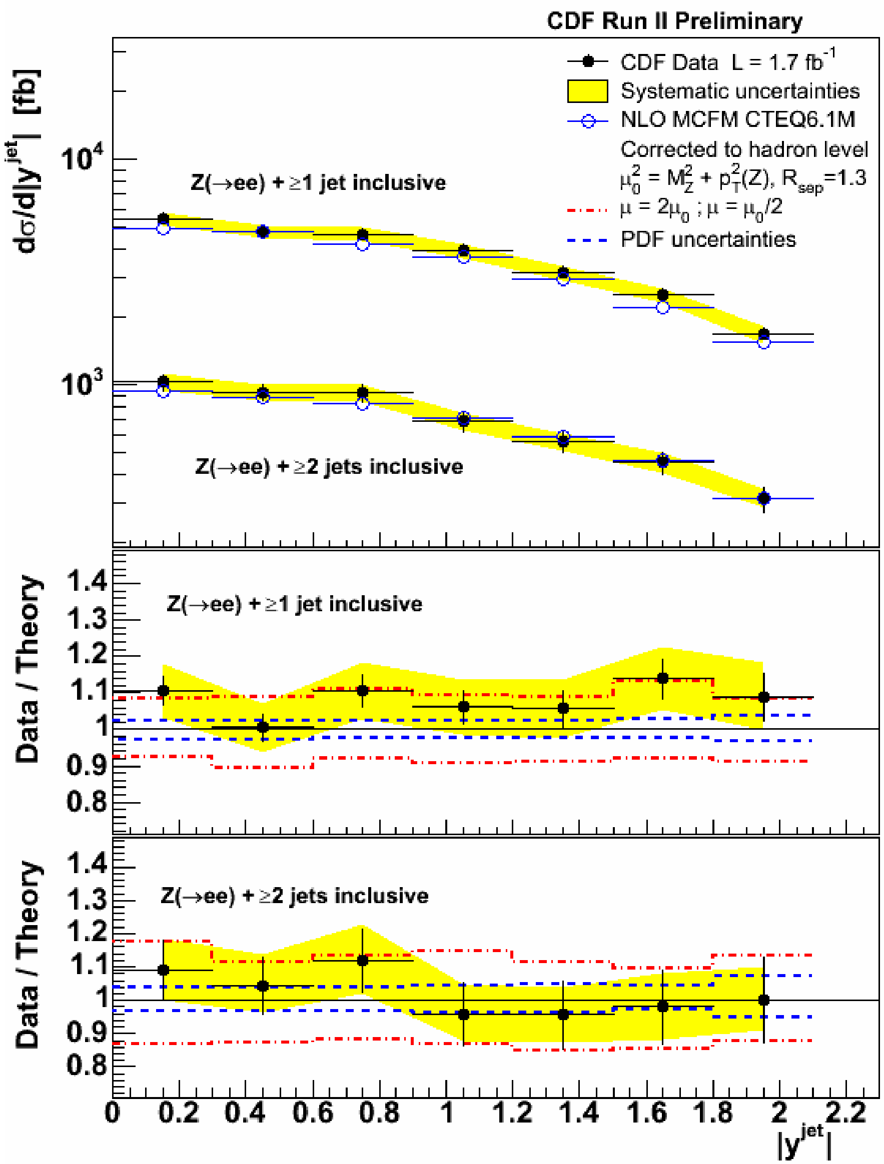
Inclusive Jet Cross Section

Inclusive jet differential cross section as a function of the jet rapidity.

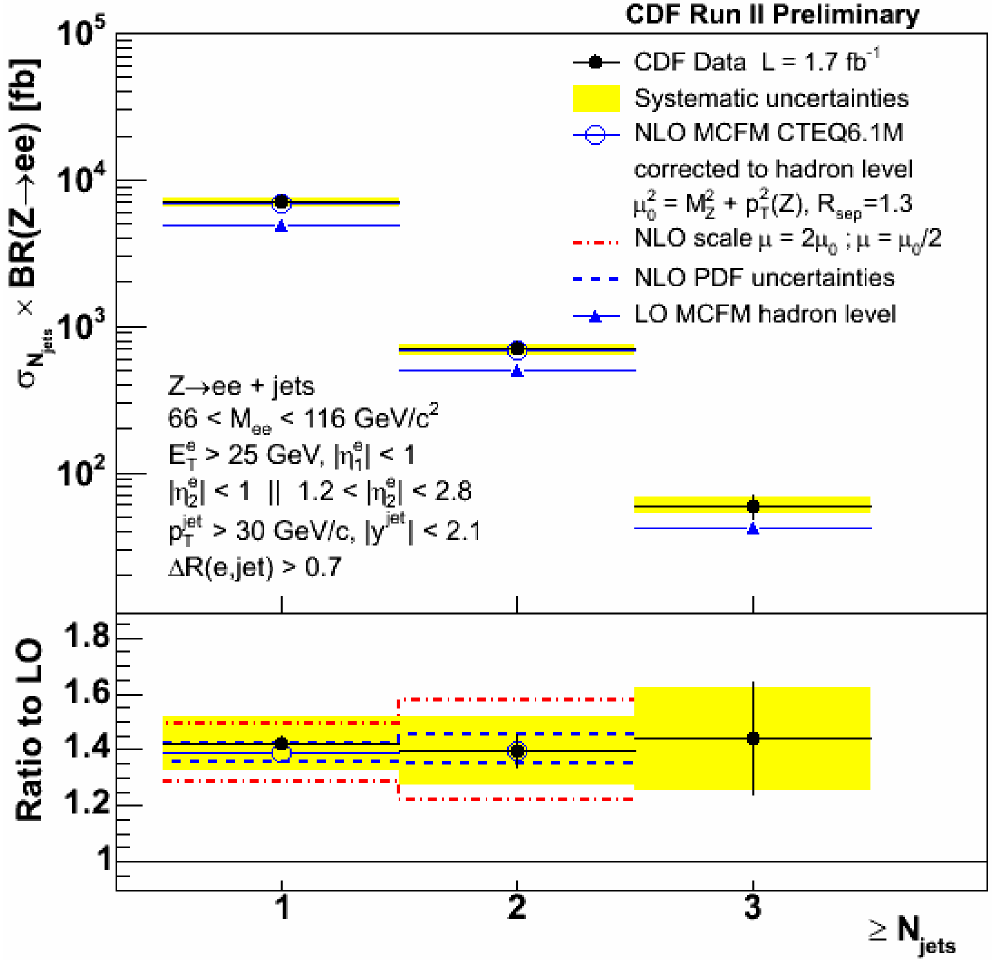
Good agreement between Data and NLO pQCD in the whole rapidity range.

Uncertainties in the theory prediction dominated by the dependence on the scale (10% in Z+≥1 jet and 15% in Z+≥2 jets).

PDF uncertainties are at the level of 3%.



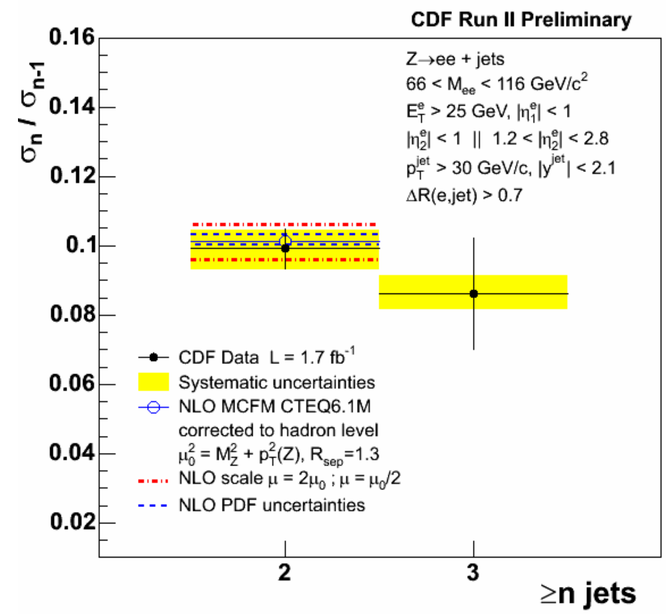
Total Cross Section for $Z+\geq N_{jet}$



LO pQCD underestimates the cross section by a factor 1.4

NLO pQCD (when available) in very good agreement with the measured cross section.

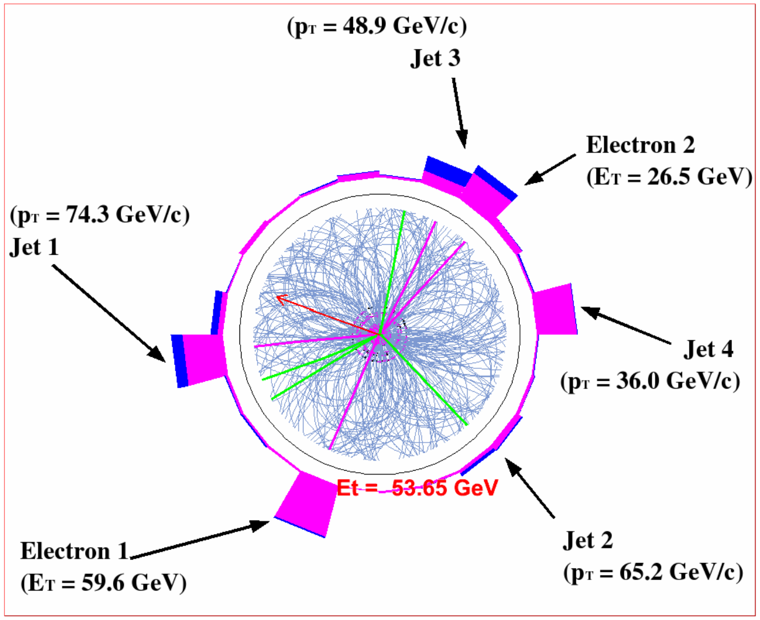
Data suggest a constant NLO/LO k-factor for up to 3 jets in the final state

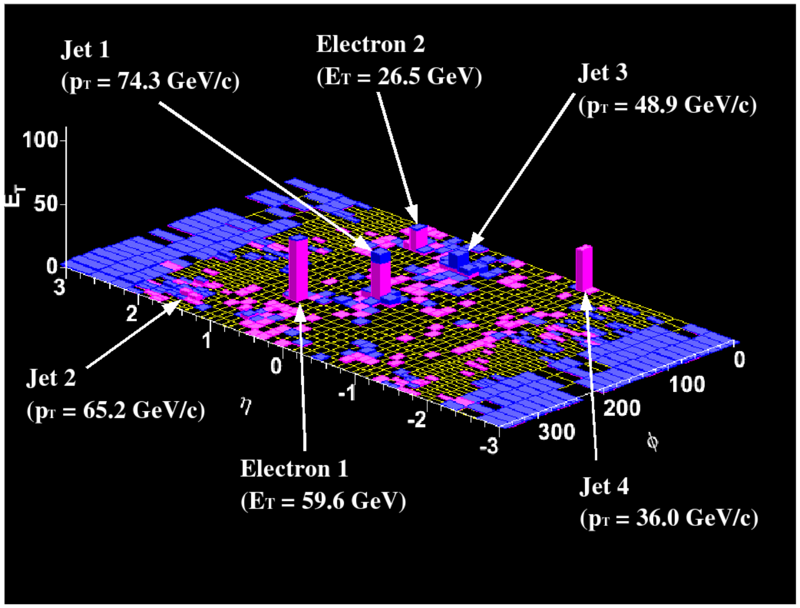


Very good agreement Data-NLO pQCD

Both, LO and NLO, predictions include a ≈15% contribution from non-pQCD effects.

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.

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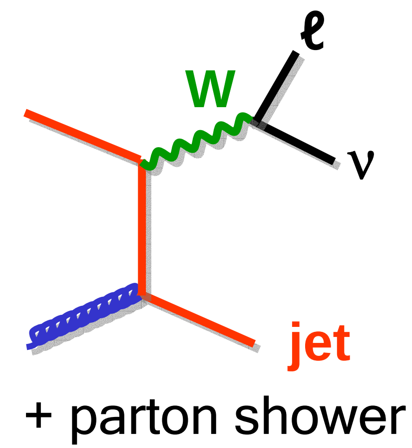
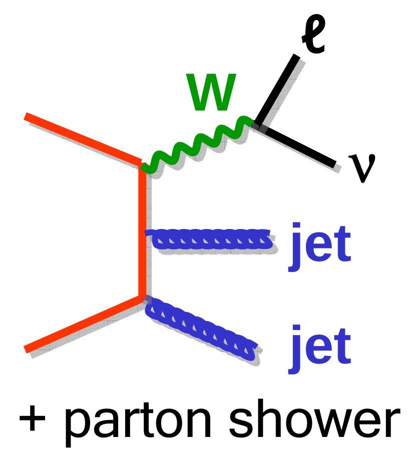
W+jets Cross Section

Measurement of the W(→eν)+jets cross section at hadron level for jets with E_T > 15GeV and |η| < 2; and W decay products: E_T^e > 20GeV, $|\eta^e|$ < 1.1, E_T^ν > 30GeV and M_T^W > 20 GeV/c^2.



The shapes of the cross section are compared to MC samples generated with LO Matrix Element matched with the parton shower (Alpgen+Herwig and Madgraph+Pythia) using the MLM and the CKKW matching algorithms to avoid double counting of the gluon radiation.



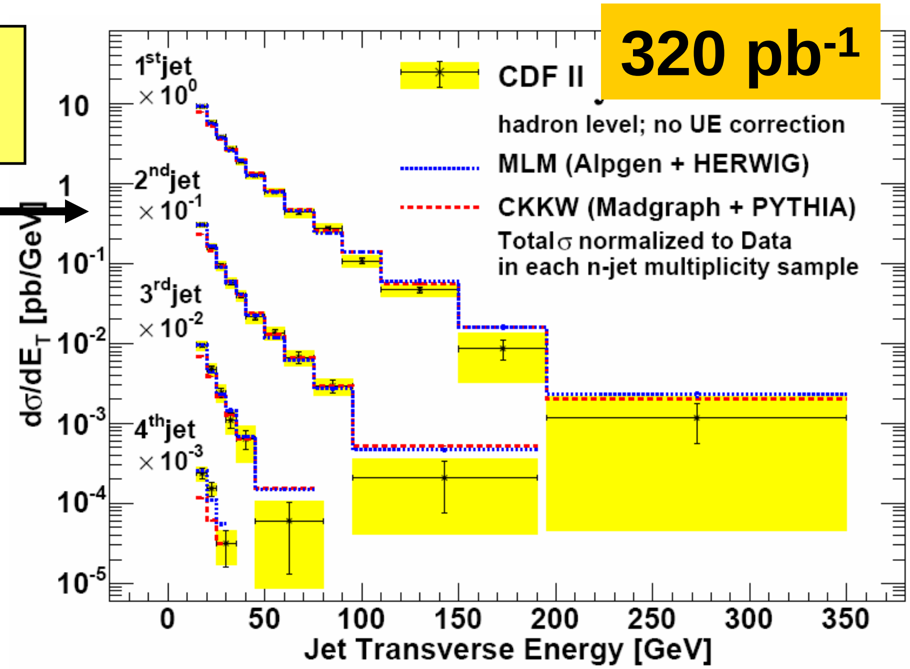
With 10 times more cross section than Z+jets detailed studies on W+2 jets topologies are possible.

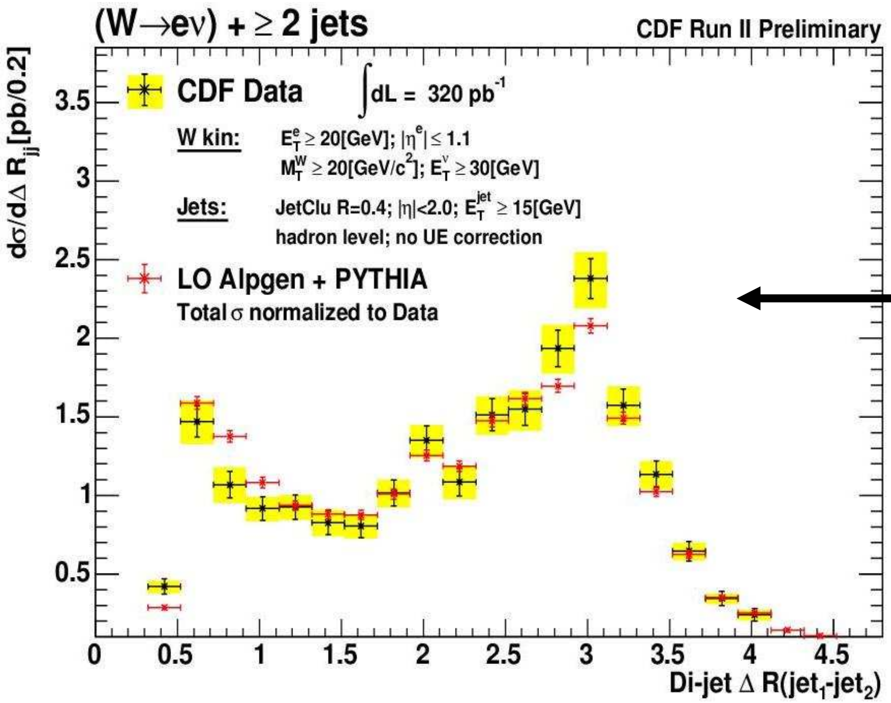
W+jets Cross Section

MC samples are normalized to the inclusive cross section for each jet multiplicity

Differential cross section of the nth leading jet in W+≥N jets for up to N≥4 jets.

ME+PS give a good description of the shapes in the data.





ΔR in (η,ϕ) between the two leading jets in W+≥2 jets events.

The distribution is sensitive to the modeling of the soft gluon radiation in the MC.

Looking forward to an updated measurement with more statistics.

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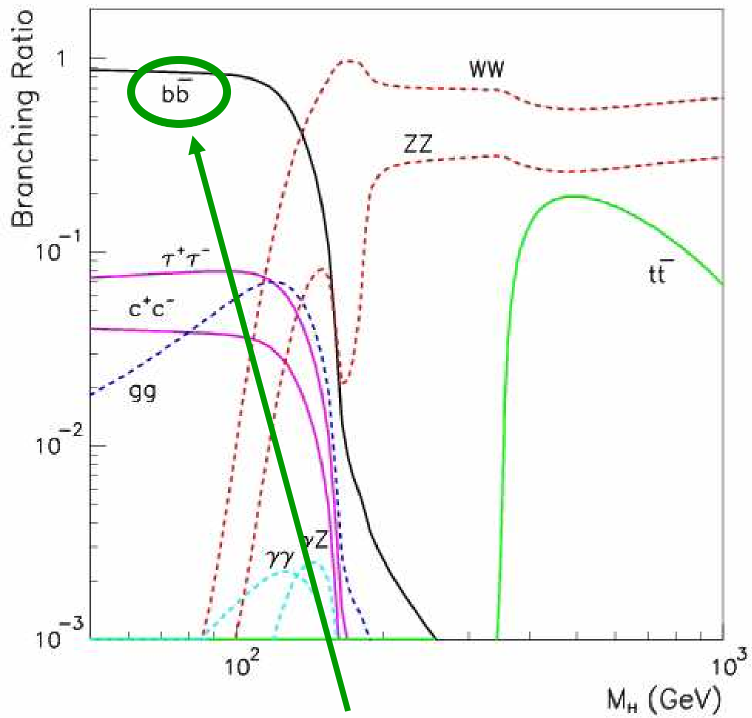
Boson + Heavy Flavor Jets

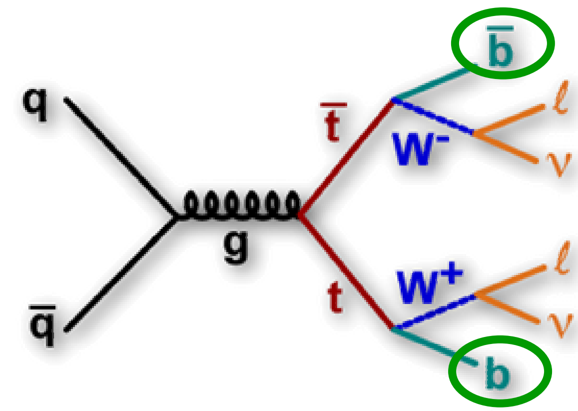
There is special interest in Boson+HF jets processes.

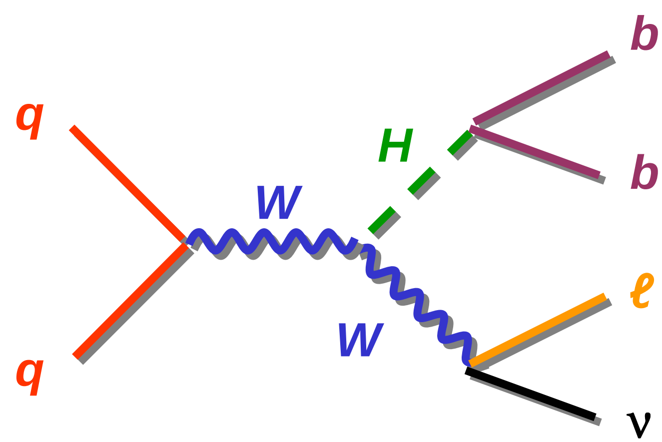
They are background to some of the most interesting processes.



Light Higgs prefers to decay in bb

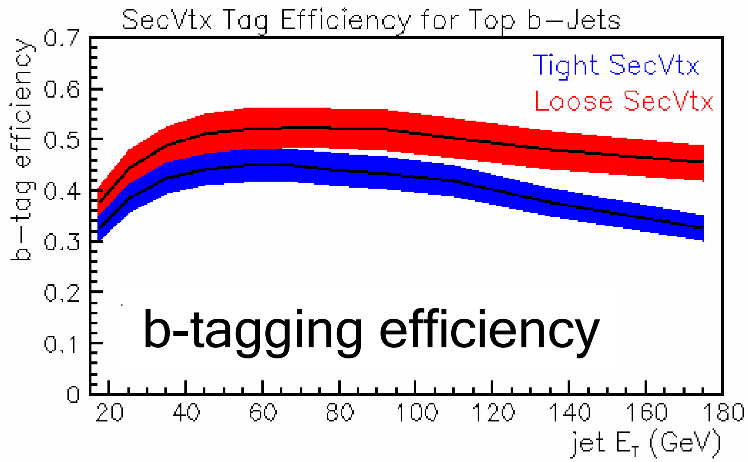
Background to top production

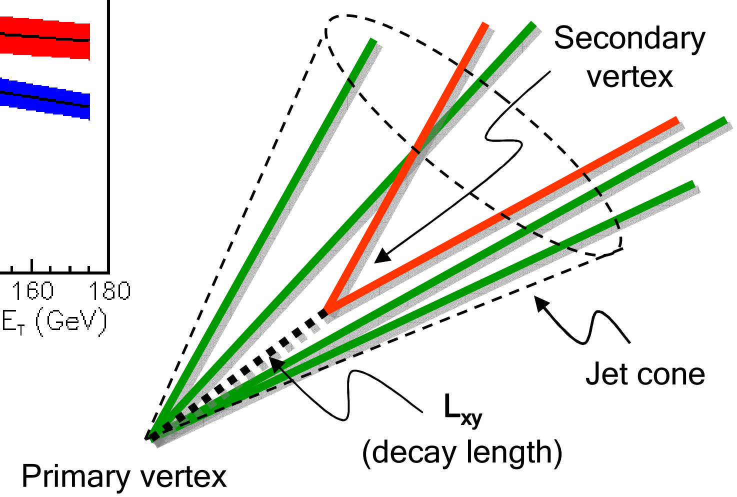




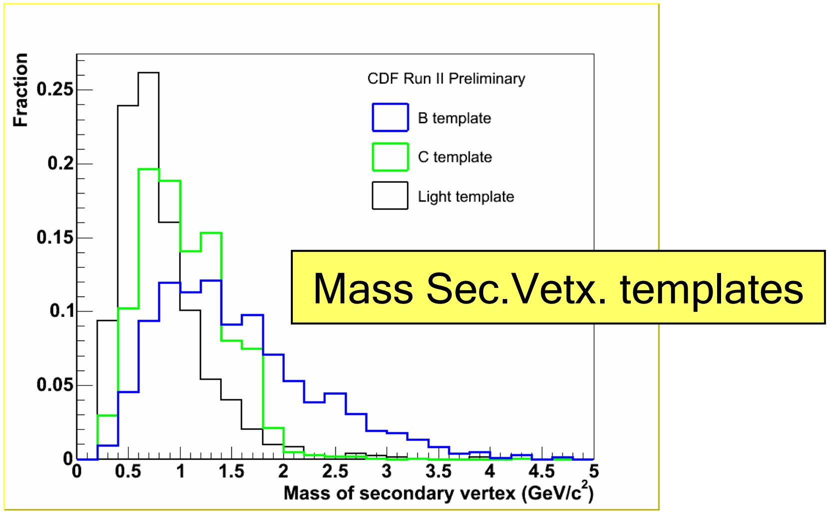
Heavy Flavor Jets (SecVtx)

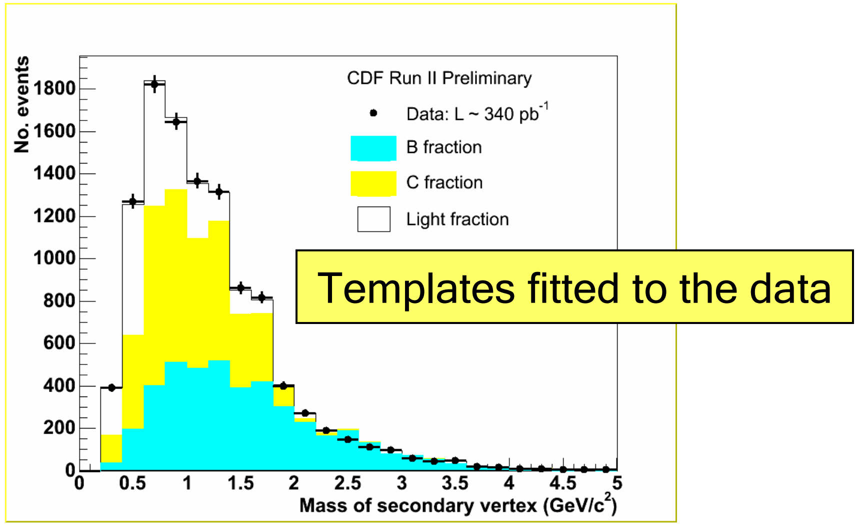
Secondary Vertex algorithm (SecVtx) reconstructs secondary vertices inside jets. Cutting on the distance between the primary and secondary vertices rejects most of light flavor jets.





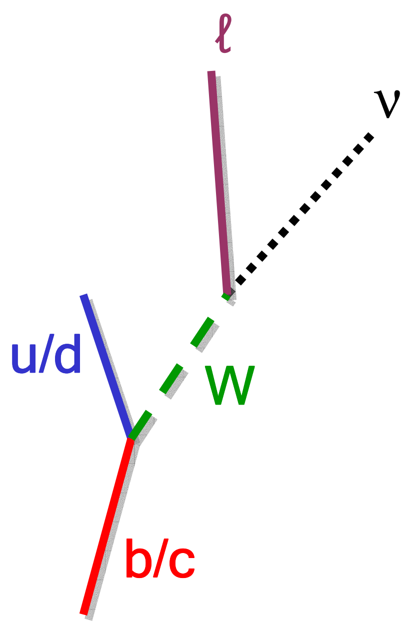
The mass of the secondary vertex is a powerful discriminant to extract the b-jet content. Templates from MC are fitted to the data.



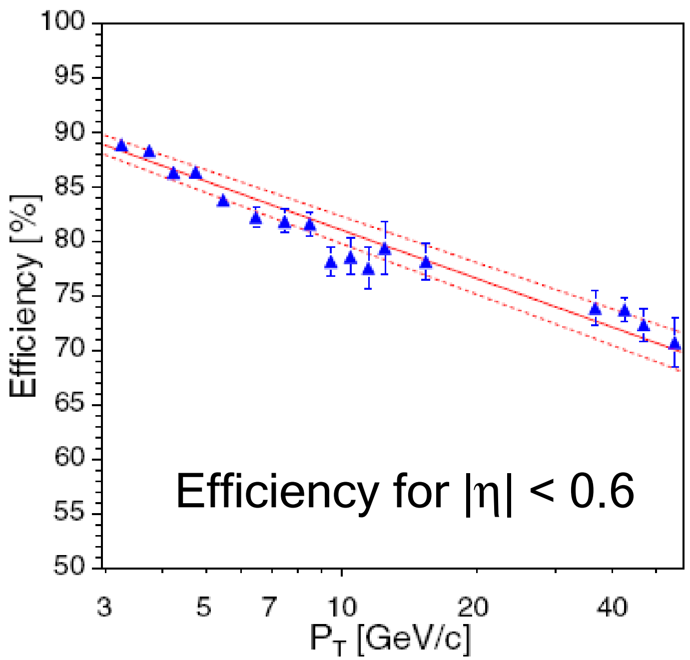


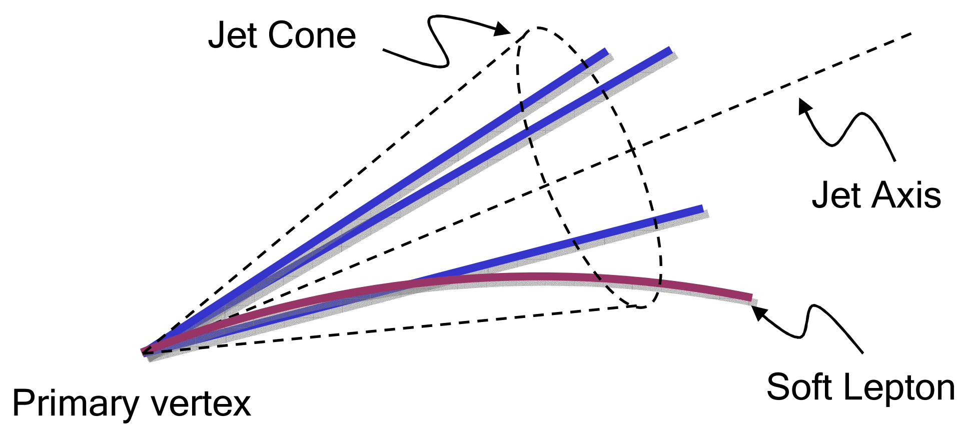
Heavy Flavor Jets (SLT)

Heavy Flavor jets can be identified by the presence of a low p_T lepton (soft lepton (electron or muon)) inside the jet coming from the semi-leptonic decay of a heavy quark.



In the μ case, a jet is tagged if the μ p_T>3GeV/c and it goes in the direction of the jet, and passes some track quality cuts.





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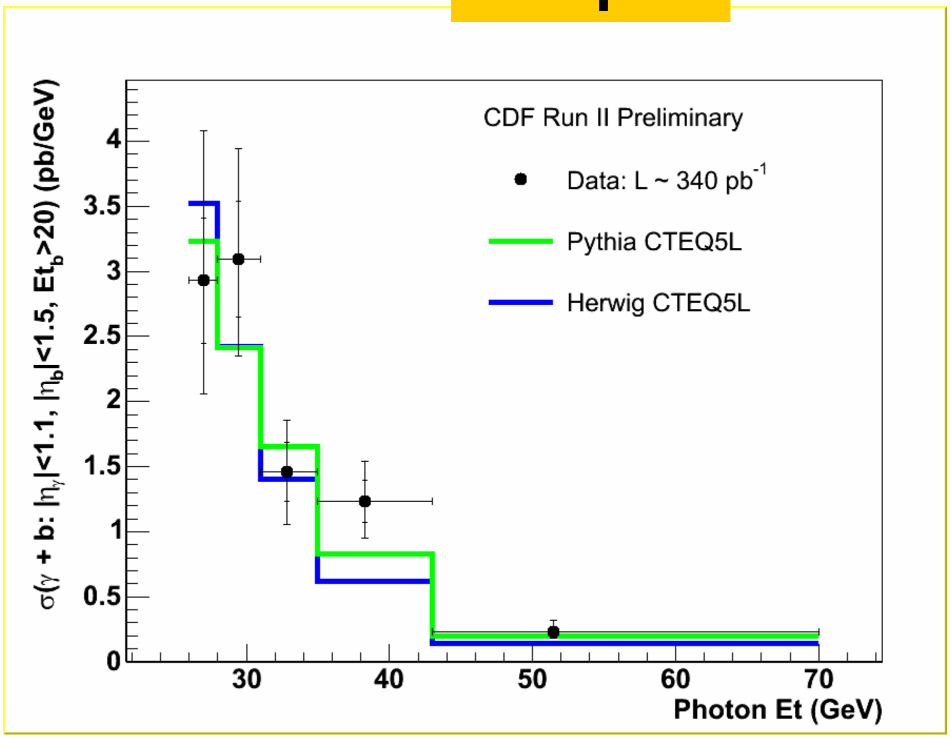
γ+b Cross Section

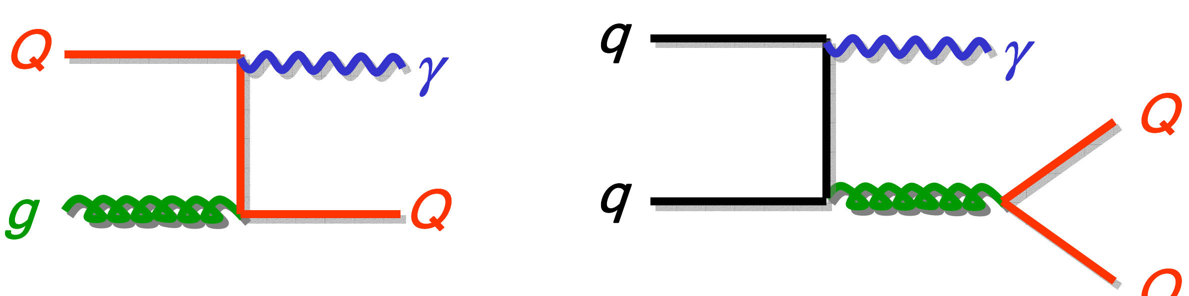
Measurement of the γ+b cross section for jets with $E_T^{jet}>20GeV$ and $|\eta^{jet}|<1.5$ and photons with $E_T^{\gamma}>26GeV$ and $|\eta^{\gamma}|<1.1$

Test of b production mechanisms and sensitive to b-quark PDF in the proton.

Compared to LO Pythia and Herwig that describe the data reasonably well.

340 pb^{-1}





Comparison with NLO predictions (JETPHOX) is expected soon.

Z+b Cross Section

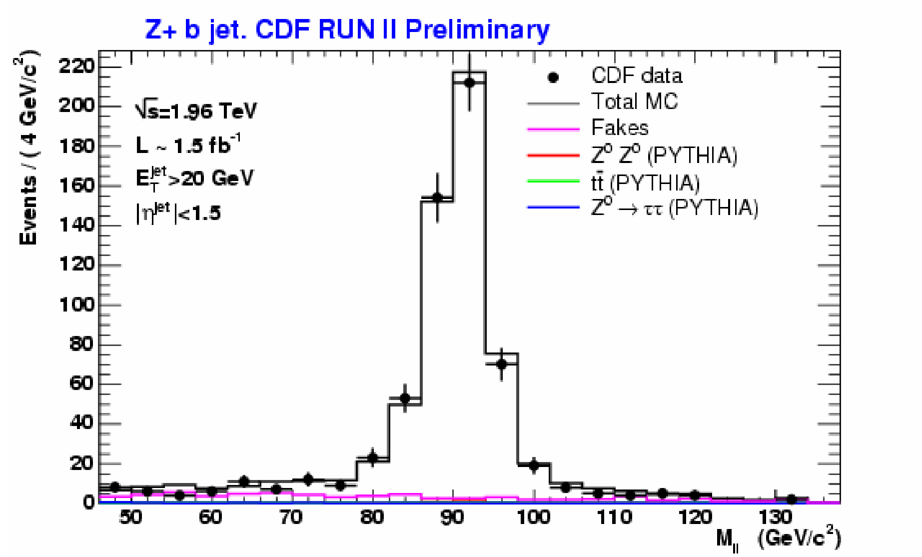
Measurement of the Z+b-jets cross section at hadron level for jets with E_T^{jet}>20 GeV and $|\eta|$<1.5

NLO pQCD calculation by MCFM.

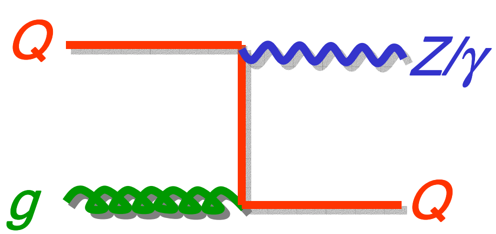
- CTEQ6M PDFs
- $\mu_R^2 = \mu_F^2 = M_Z^2 + p_T^2$

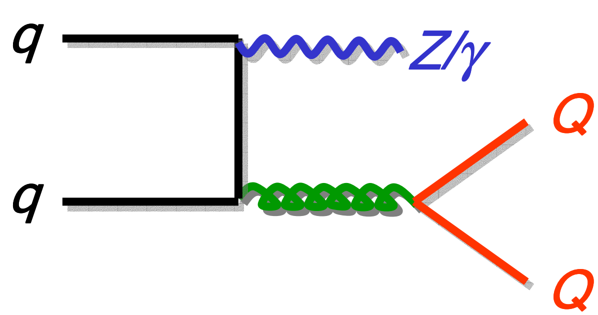
The measurement is sensitive to the production mechanisms and to the heavy quarks content in the proton.

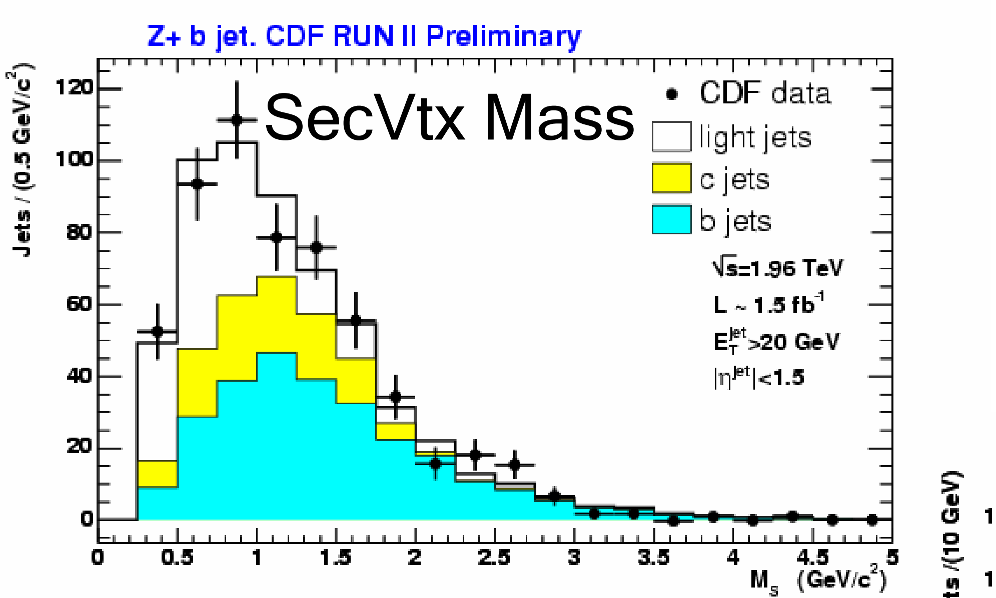
1.5 fb^{-1}



Measured using the Z→ee and Z→μμ channels



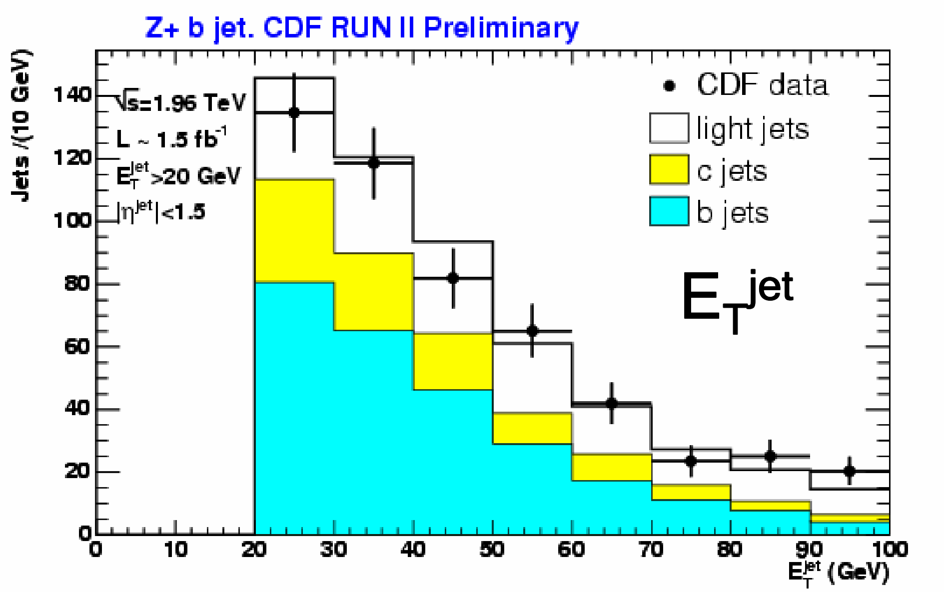




Fraction of jet flavors (Data/MC):

$$\begin{cases} \rho_b = 1.06 \pm 0.16 \\ \rho_c = 0.97 \pm 0.52 \\ \rho_l = 1.76 \pm 0.38 \end{cases}$$

Fraction of b-jets obtained by fitting the invariant mass of the tracks of the secondary vertex with the templates of the light, c and b jet contributions.



Z+b Cross Section

E_T^{jet}>20 GeV, $\lvert\eta^{jet}\rvert$<1.5 R_{jet}=0.7	CDF Run II Preliminary measurement	PYTHIA	MCFM NLO	MCFM NLO + UE + hadr.
σ(Z+*b*-jet)/σ(Z)	0. 369 ± 0.057 ± 0.055 %	0.35 %	0.21 %	0.23 %
σ(Z+*b*-jet)	0.94 ± 0.15 ± 0.15 pb	n.a.	0.51 pb	0.56 pb
σ(Z+*b*-jet)/σ(Z+jet)	2.35 ± 0.36 ± 0.45 %	2.18 %	1.88 %	1.77 %

$$\frac{\sigma(Z+\text{bjet})}{\sigma(Z)} = \rho_b \cdot \frac{N^{\text{MCHad}}_{Z+\text{bjet}}}{N^{\text{MCHad}}_{Z}} \cdot \frac{N^{\text{MC}}_{Z}}{N^{\text{Data}}_{Z}}$$

$$\sigma(Z \to \ell\ell + \text{bjet}) = \frac{\sigma(Z+\text{bjet})}{\sigma(Z)} \cdot \sigma_{measured}(Z \to \ell\ell)$$

$$\frac{\sigma(Z+\text{bjet})}{\sigma(Z+\text{jet})} = \rho_b \cdot \frac{N^{\text{MCHad}}_{Z+\text{bjet}}}{N^{\text{MCHad}}_{Z+\text{jet}}} \cdot \frac{N^{\text{MC}}_{\text{jet}}}{N^{\text{Data}}_{\text{jet}}}$$

Underlying Event and hadronization contributions obtained from Pythia (+10% and -1%)

Data are well described by Pythia but is underestimated by the NLO prediction.

Outline

- Introduction
- Boson+jets
  - Z/γ+jets
  - W+jets
- **Boson+Heavy Flavor Jets**
  - Z/γ+b
  - **W+c**
  - W+b
  - Further develpments:
    - NN Heavy Flavor Tagger
- Boson+jets with 6 fb^{-1}
- Summary

"Particles, particles, particles."

W+c Cross Section

1.8 fb^{-1}

First direct measurement of this cross section.

Probes the gluon and s-quark PDF in the proton.

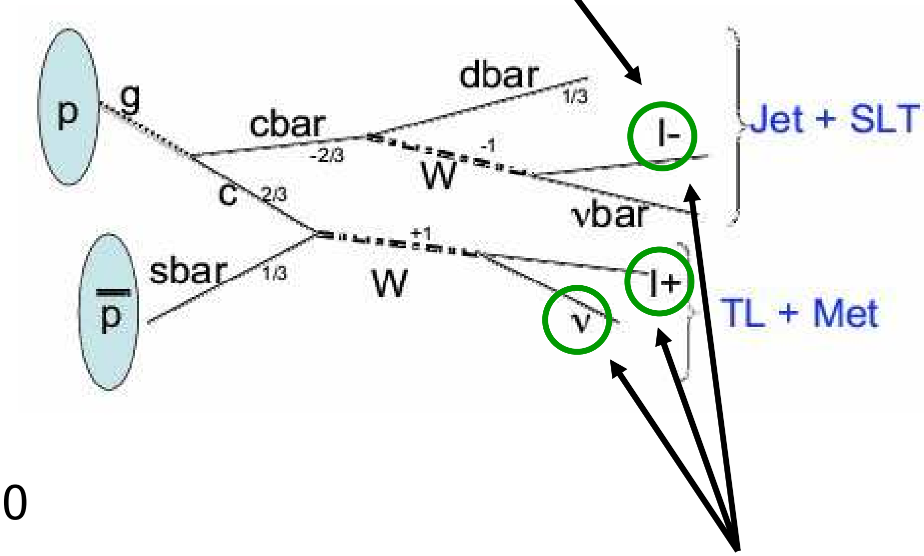
For W+c, the soft muon in the SLT jet and the lepton from the W must have opposite sign.

Observable: N^{OS}-N^{SS}

- Used to distinguish the signal from W+cc and W+bb, where $N^{OS}-N^{SS} \approx 0$
- Definition of Asymmetry:

$$A = \frac{N^{OS} - N^{SS}}{N^{OS} + N^{SS}}$$

c-jets identified by the presence of a soft muon inside the jet from the semi-leptonic decay of the c quark (SLT_{μ} jet)

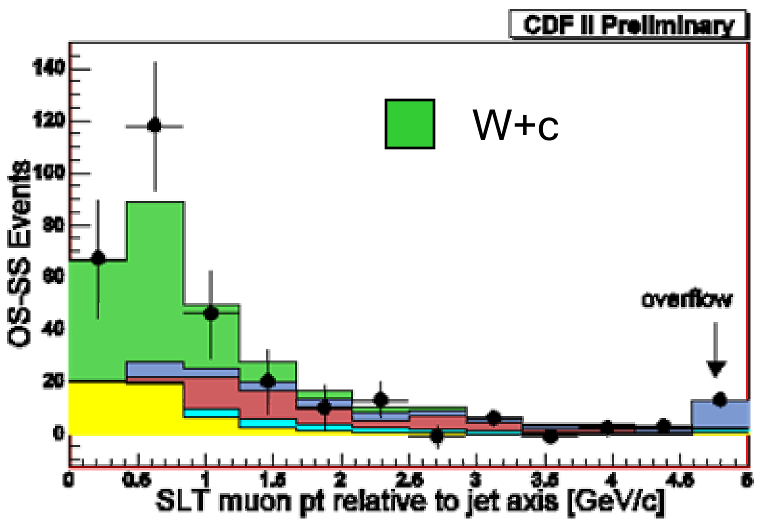


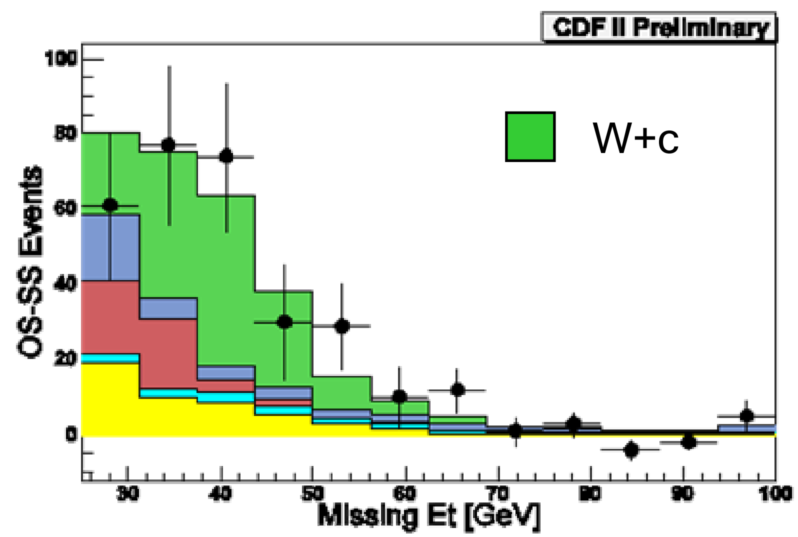
Events selected by the presence of a SLT jet, in addition to a charged lepton and MET from the W decay.

W+c Cross Section

$$\left(N^{OS} - N^{SS}\right)_{measured} = 147.0 \pm 42.1(stat) \pm 15.4(sys)$$

W+c contribution scaled to the number of (OS-SS) observed





$$\sigma_{Wc} = \frac{N_{tot}^{OS-SS} - N_{bkg}^{OS-SS}}{A \cdot Acc \cdot \int L}$$

Asymmetry

Cross section for $p_T(c) > 8$ GeV/c and $|\eta(c)| < 3$

$$\sigma_{Wc} \times BR(W \to \ell\nu) = 28.5 \pm 8.2(stat)\,^{+4.1}_{-4.4}(sys) \pm 1.6(lum)\,pb$$

in agreement with ALPGEN prediction: $22.2 \pm 1.2(PDF)\,^{+3.8}_{-3.0}(scale)\,pb$

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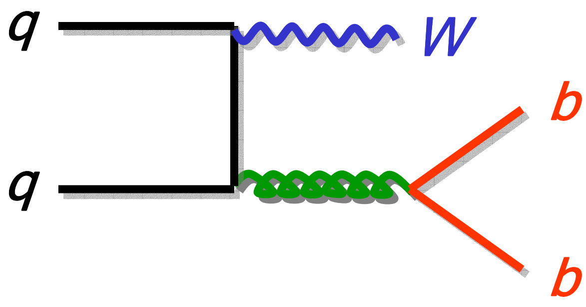


Important background to WH, single top.

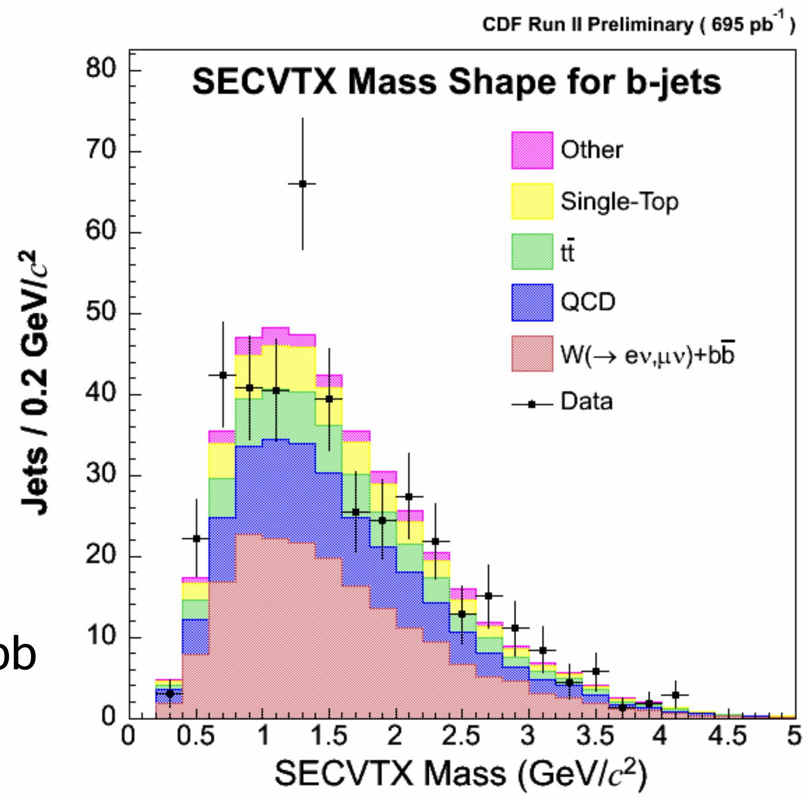
695 pb^{-1}

Look for leptonic W decay and 1 or 2 jets.

b-jet cross section for W+bb with E_T^{jet}>20GeV, $|\eta^{jet}|<2$, $p_T(\ell^\pm)>20$GeV/c, $|\eta(\ell^\pm)|<1.1$ and $p_T(\nu)>25$GeV/c.

$$\sigma_{b-jet} = 0.90 \pm 0.20(stat) \pm 0.30(sys)\text{pb}$$

in agreement with Alpgen prediction: 0.74±0.18pb



Significant effort towards understanding and reducing systematic uncertainties.
Expected relative uncertainty on measured W+b jet rate: 15%

Result with 2 fb^{-1} expected soon

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New HF Neural Network Tagger

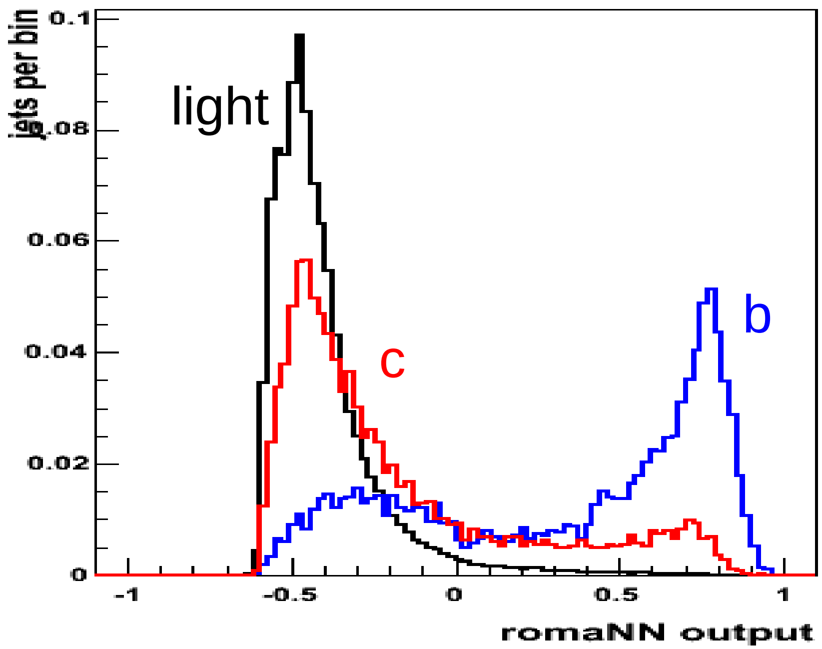
The underlying idea is to use all the information available to improve the tagging power

- All the vertices in the jet (primary, secondaries…) and their invariant masses.
- Tracks that are displaced but are not associated to any vertex.
- Information about soft leptons, JetProb, global jet variables.

Combine all the information together in a single discriminant using a series of neural networks.

Neural network training performed in a generic sample and then used in the analyses.

MC



Output provides a continuous tagging variable.

Good b-c-light fraction statistical separation.

Work in progress…

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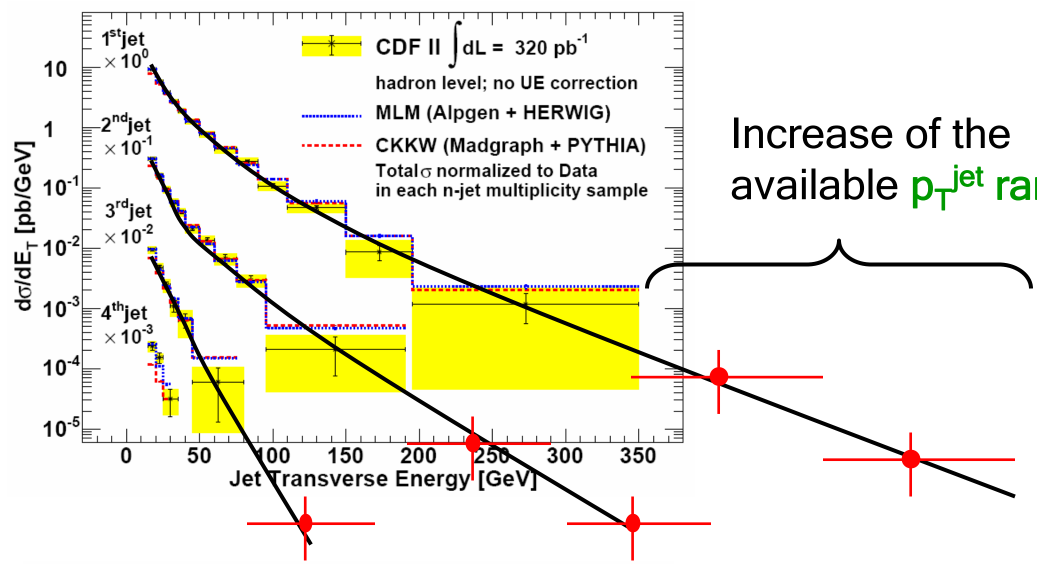
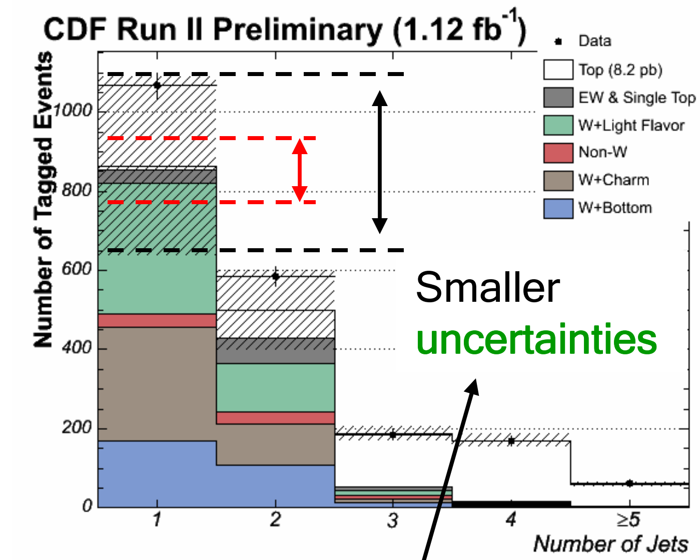
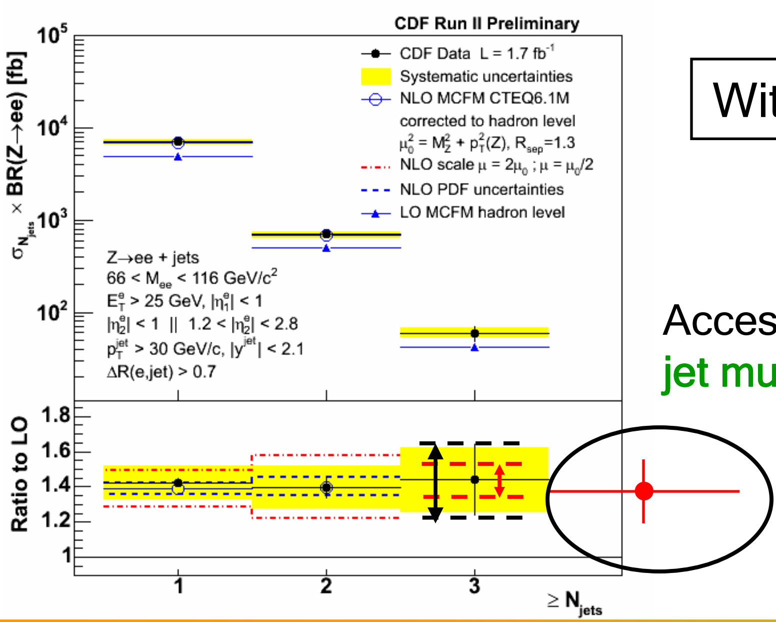
Boson+jets with 6 fb^{-1}



Increase of the available p_T^{jet} range



Smaller uncertainties



With more integrated luminosity

Access to higher jet multiplicities

Improvements in the analysis

+

New techniques

+

More precise measurements

Summary

- CDF is carrying out a number of measurements to understand in detail Boson+jets processes with and without heavy flavor jets in the final state.

- New Z+jets measurements already based on 2 fb^{-1} of data:
  - Have shown that the data can be described by a fixed-order (NLO) pQCD prediction plus non-perturbative contributions.
  - No new physics on Z+jets final states.

- Boson+jets measurements are used to validate ME+PS Monte Carlo models that are vastly employed in all kinds of measurements and searches for new physics.

- New results on Boson+b/c production and the development of new heavy flavor tagging techniques promise to improve the current understanding of SM QCD processes.

- With 6 fb^{-1} of data, we expect new and exiting results to further increase our knowledge of Boson+jets data.

Backup slides

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
  - $\chi^2_{PEM} <= 10.0$

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

MLM Matching

An alternative, simpler prescription to address this problem (a.k.a. MLM's matching, http://cepa.fnal.gov/patriot/mc4run2/MCTuning/15nov2002.html**)**

- **Generate parton-level configurations** for a given hard-parton multiplicity N_{part}, with partons constrained by
  - $p_T > p_{T\,min}$ $\Delta R_{jj} > R_{min}$
- **Perform the jet showering**, using the default Herwig/Pythia algorithms
- Process the showered event (**before hadronization**) with a **cone jet algorithm**, defined by $E_{T\,min}$ **and** R_{jet}
- **Match partons and jets:**
  - for each hard parton, select the jet with min $\Delta R_{j\text{-}parton}$
  - if $\Delta R_{j\text{-}parton} < R_{jet}$ the parton is "matched"
  - a jet can only be matched to a single parton
  - **if all partons are matched, keep the event, else discard it**
- This prescription defines an **inclusive sample** of $N_{jet} = N_{part}$ **jets**
- Define an **exclusive N-jet** sample by requiring that the number of reconstructed showered jets N_{jet} be equal to N_{part}
- After matching, combine the exclusive event samples to obtain an **inclusive sample containing events with all multiplicities**

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M.Mangano, Lund University, Oct 7, 2004

CKKW Matching Algorithm

CKKW* prescription in a nutshell

- Generate samples of N-jet configurations, defined by the $k_\perp$ algorithm, with a resolution parameter k_o
- Since all N-jets have to be resolved w.r.t. the beam, $k_o = p_T^{min}$.
- Cluster the partons using the $k_\perp$ algorithm, allowing only for physical branchings in the tree
- Reevaluate α_s at each vertex of the tree, using $k_\perp$ as a scale
- For each line in the tree, associate a Sudakov weight giving the probability that no emission takes place along this line
- Samples of different N-jet multiplicity can now be put together, and evolved through the vetoed shower

* Catani, Krauss, Kuhn, Webber, **JHEP 0111:063,2001**
L.Lonnblad **JHEP 0205:046,2002**

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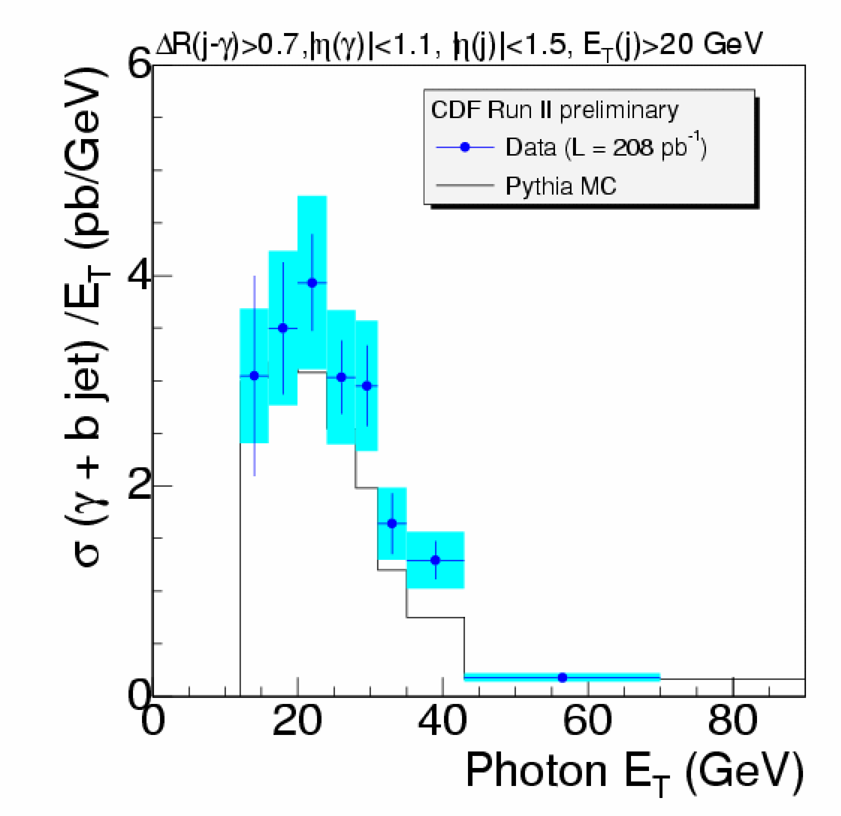
γ+b Cross Section

Secondary vertex triggered



208 pb^{-1}

Z+b Cross Section

Source of Uncertainty	Uncertainty (%)
jet energy scale	1.5
b jet energy scale	1.0
MC η^{jet} dependence	3.8
MC E_T^{jet} dependence	10
b tagging efficiency	4.1
single/double b/c quark in jet	4.6
track reconstruction efficiency	7.7
b hadron multiplicity	0.8
fake lepton background	2.4
other backgrounds	0.4
Z selection efficiency	1.8
luminosity	5.8
total	16