Boson+jets production at CDF

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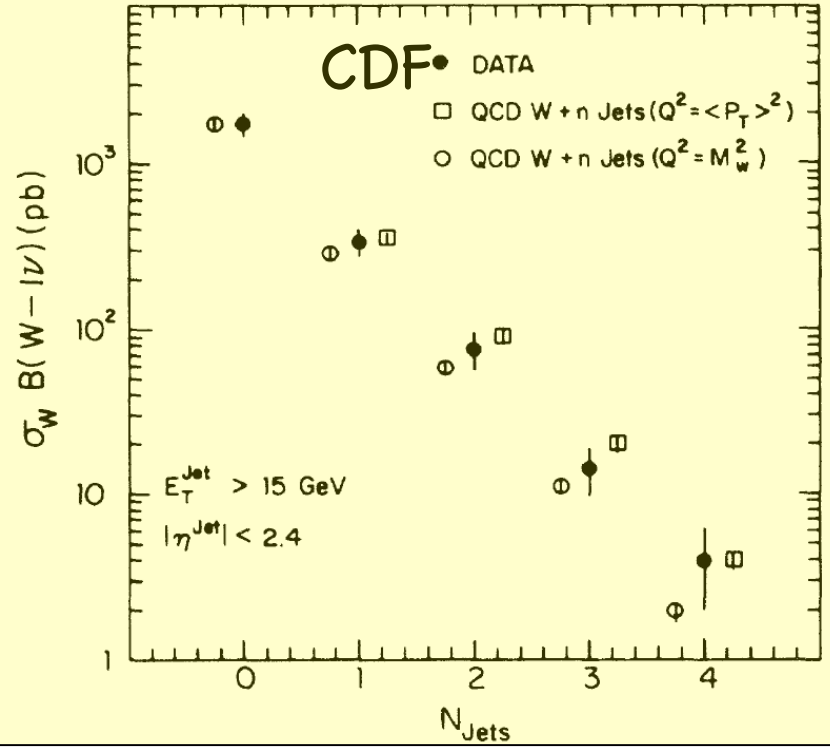
OUTLINE

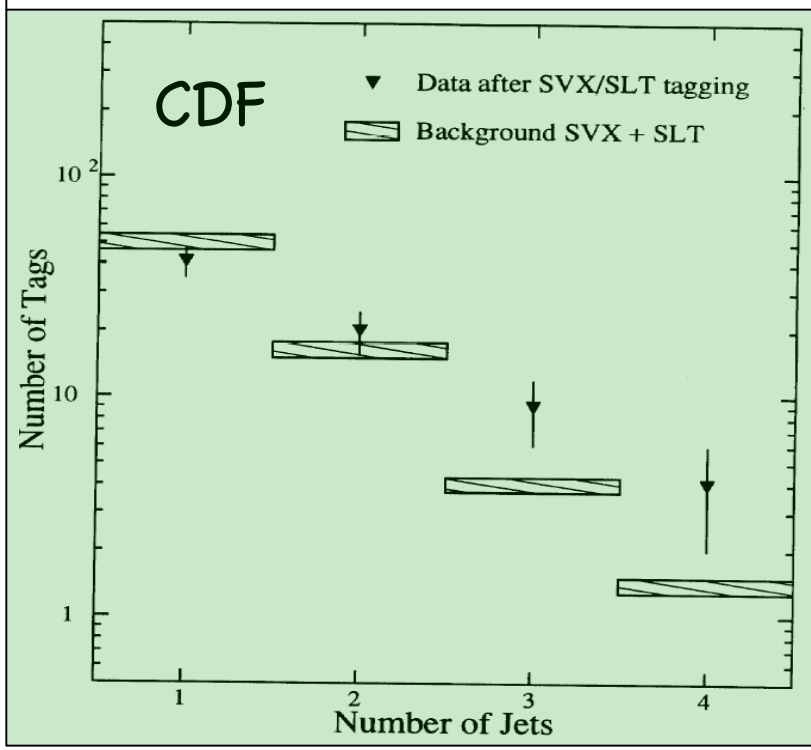
- Why boson+jets
- Experimental environment
- W+jets: a measurement in detail
- Comparison with theory
- Z+jets
- Boson+heavy flavor
- conclusions

Introduction

First W + jet paper
(Phys.Rev.Lett.70:4042-4046,1993)
Less than 10 pb^{-1} ≈ 2500 W

...one year later top evidence
Less than 20 pb^{-1}
≈ 10 t-tbar candidates





PHYSICAL REVIEW D VOLUME 50, NUMBER 5 1 SEPTEMBER 1994

Evidence for top quark production in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV

Abstract

We present the results of a search for the top quark in 19.3 pb^{-1} ... Under the assumption that the excess yield over background is due to $t\bar{t}$, constrained fitting on a subset of the events yields a mass of $174 \pm 10^{+13}_{-12}$ GeV/c^2 for the top quark. The $t\bar{t}$ cross section, using this top quark mass to compute the acceptance, is measured to be $13.9^{+6.1}_{-4.8}$ pb.

Motivation

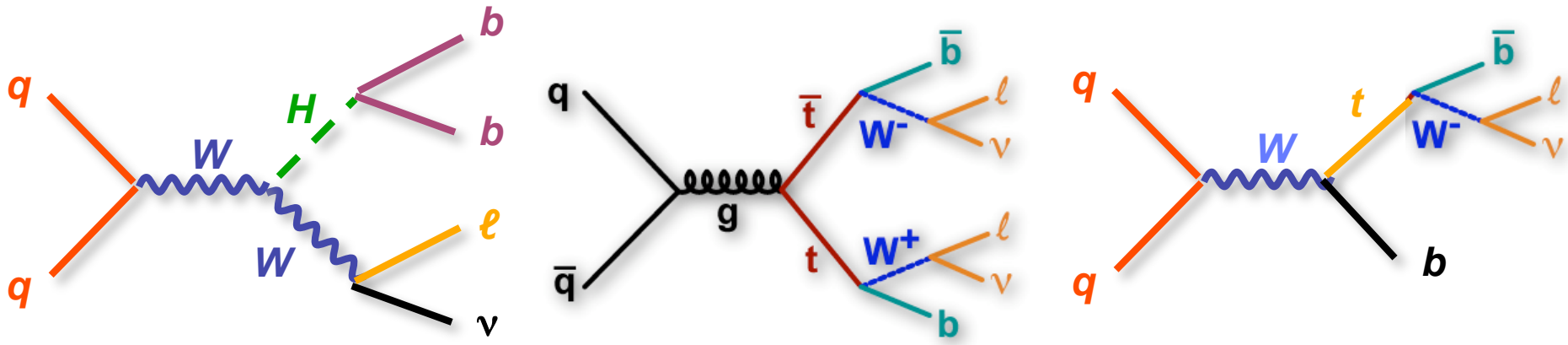
Testing ground for pQCD in multijet events

✓ The presence of a boson:
- Ensures high Q^2 - pQCD
- Large BR into leptons - easy to detect

✓ Key sample to test LO and NLO calculations
- Pythia, Herwig: shower, ME(W & W + 1parton)
- Alpgen, Ariadne, Helac Sherpa, MadEvent: W + multi-parton ME & matching algorithm (ckkw/Lonnblad/MLM) with shower
- Vecbos CompHep, Gr@PPA: W + multi-parton ME with shower
- MCFM: NLO ME W + 1 or 2 partons
- MC@NLO: W+X (NLO ME + herwig shower)

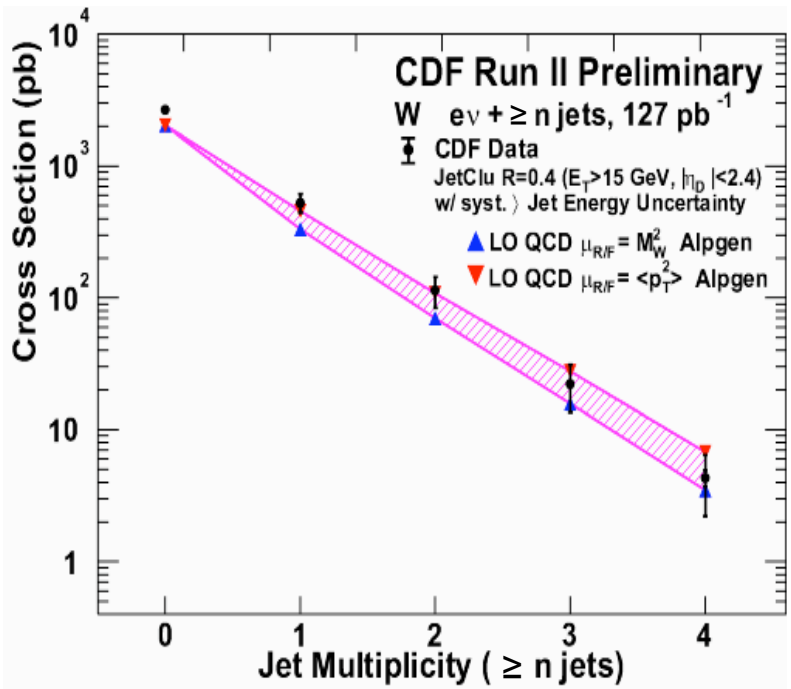
A lot of work done by our theory colleagues!!!

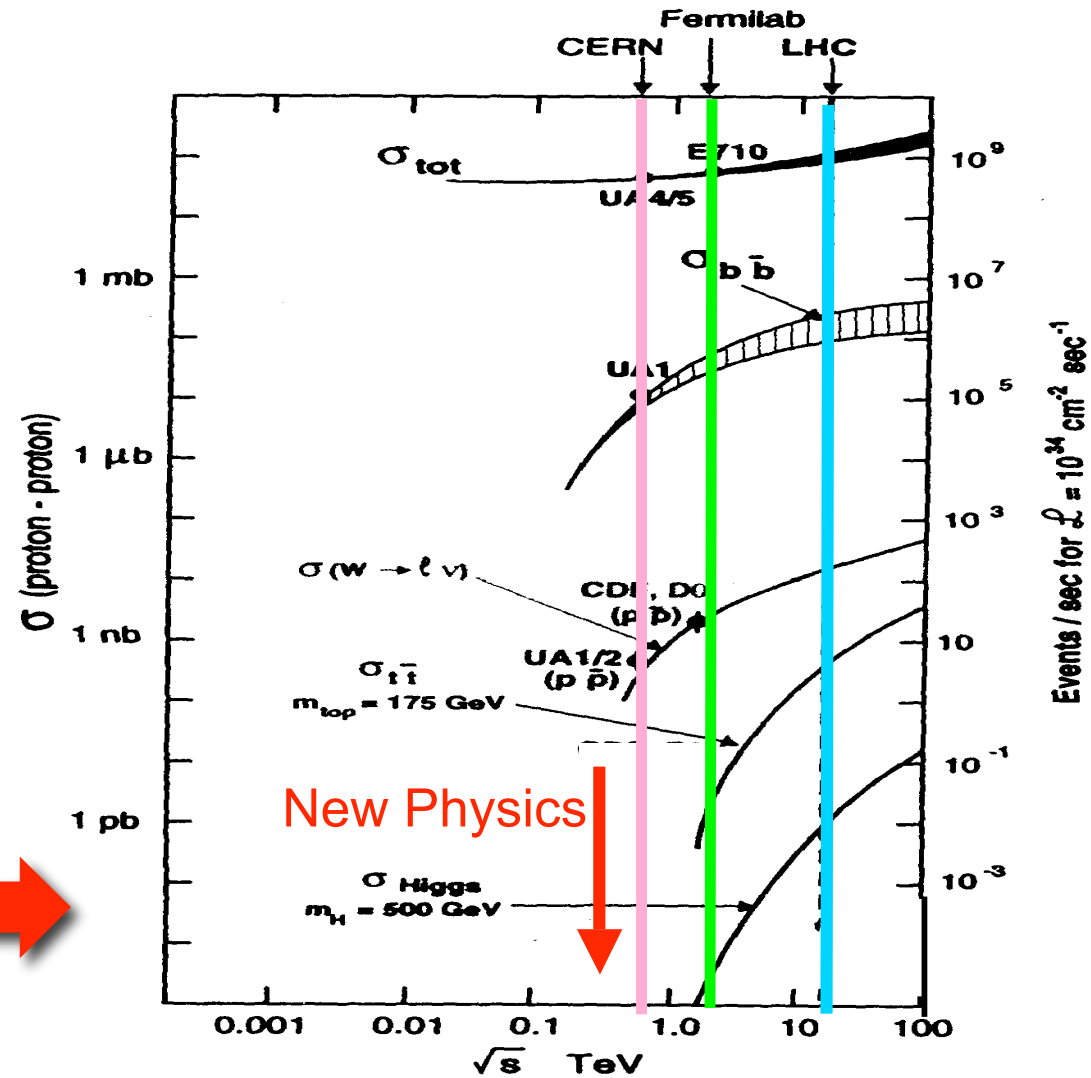
Motivation



- ✓ Boson + jets is the signature for a number of high p_T physics processes:
  - Top pair & single top production
  - Higgs boson searches
  - Searches for super-symmetric particles
- ✓ All these signals are overwhelmed by a large QCD production of boson + jets
- ✓ It is crucial to have a good understanding of such a process

Some cross sections…

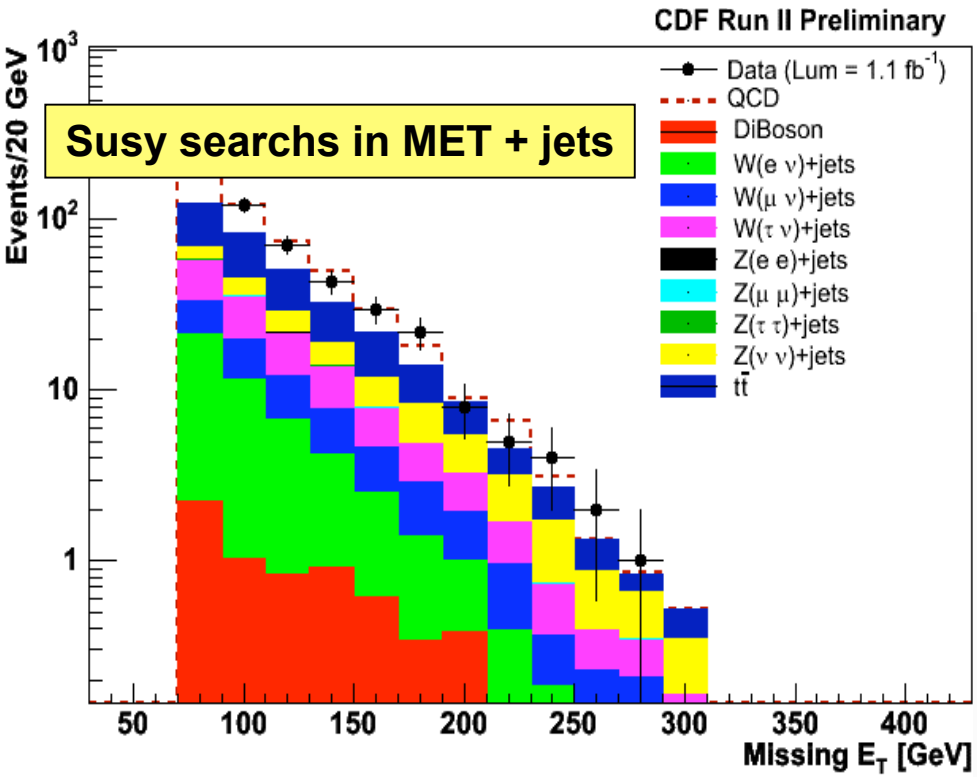


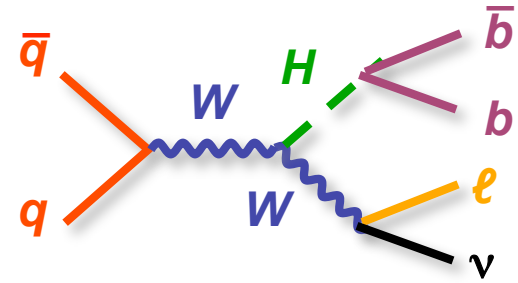


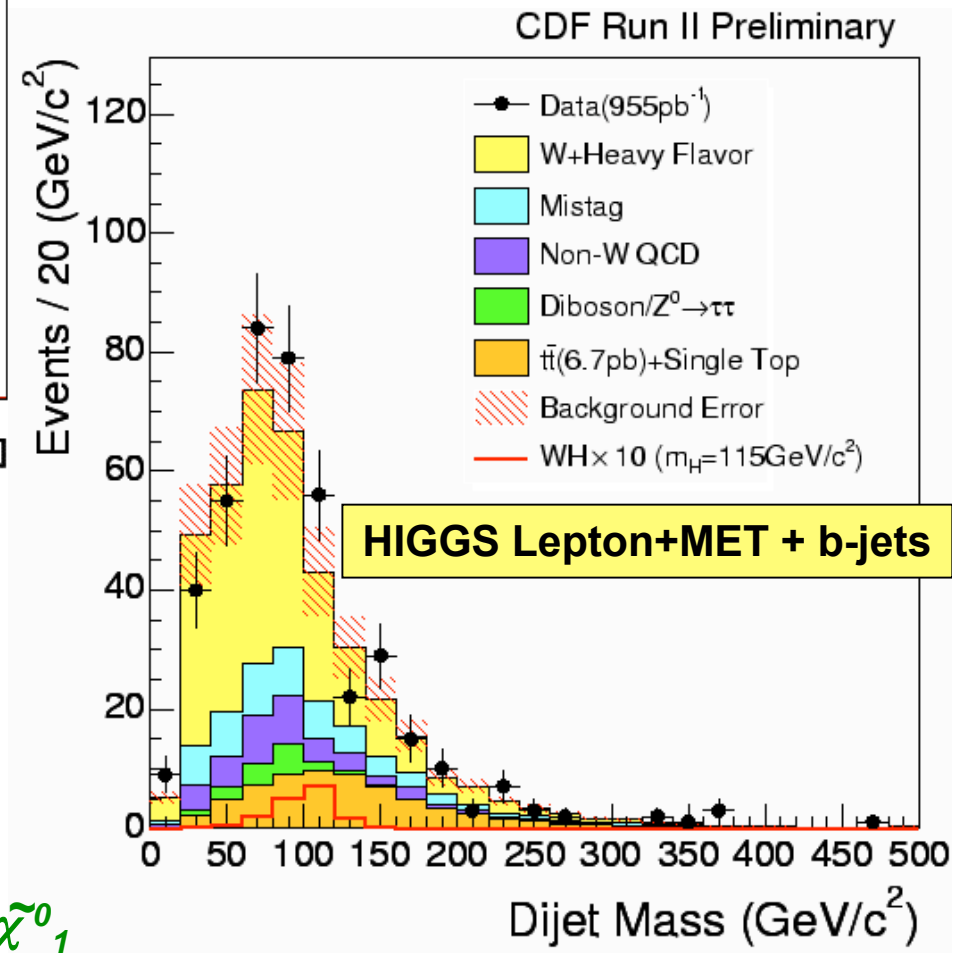
Each additional jet costs a factor of O(10) (α_s)

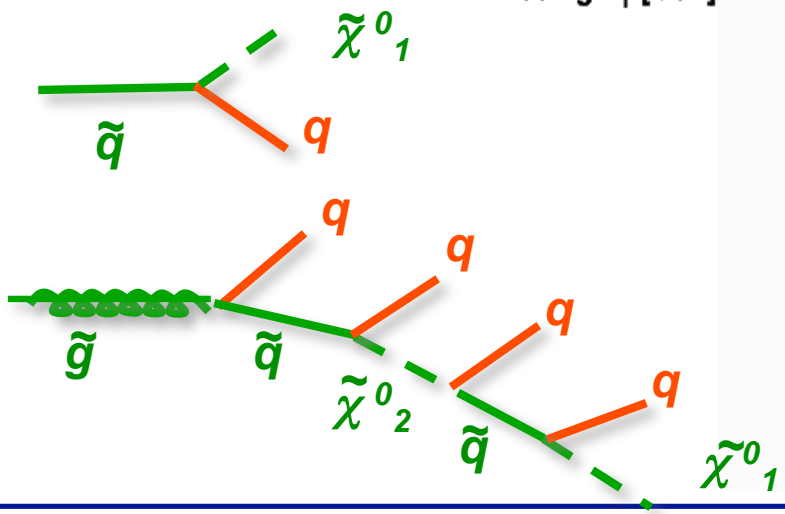
$\sigma(Z \to ee)/\sigma(W \to e\nu) \approx 0.1$

Some search examples in boson+jets…





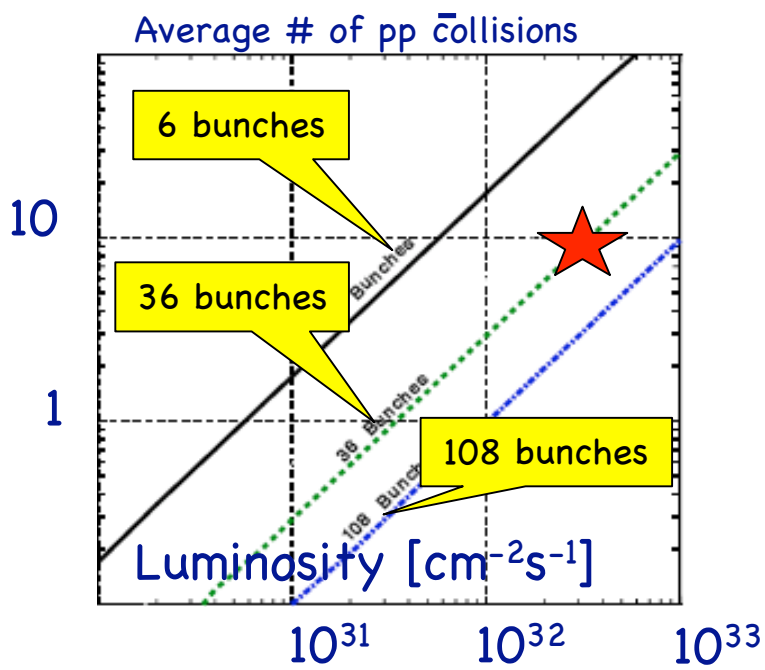


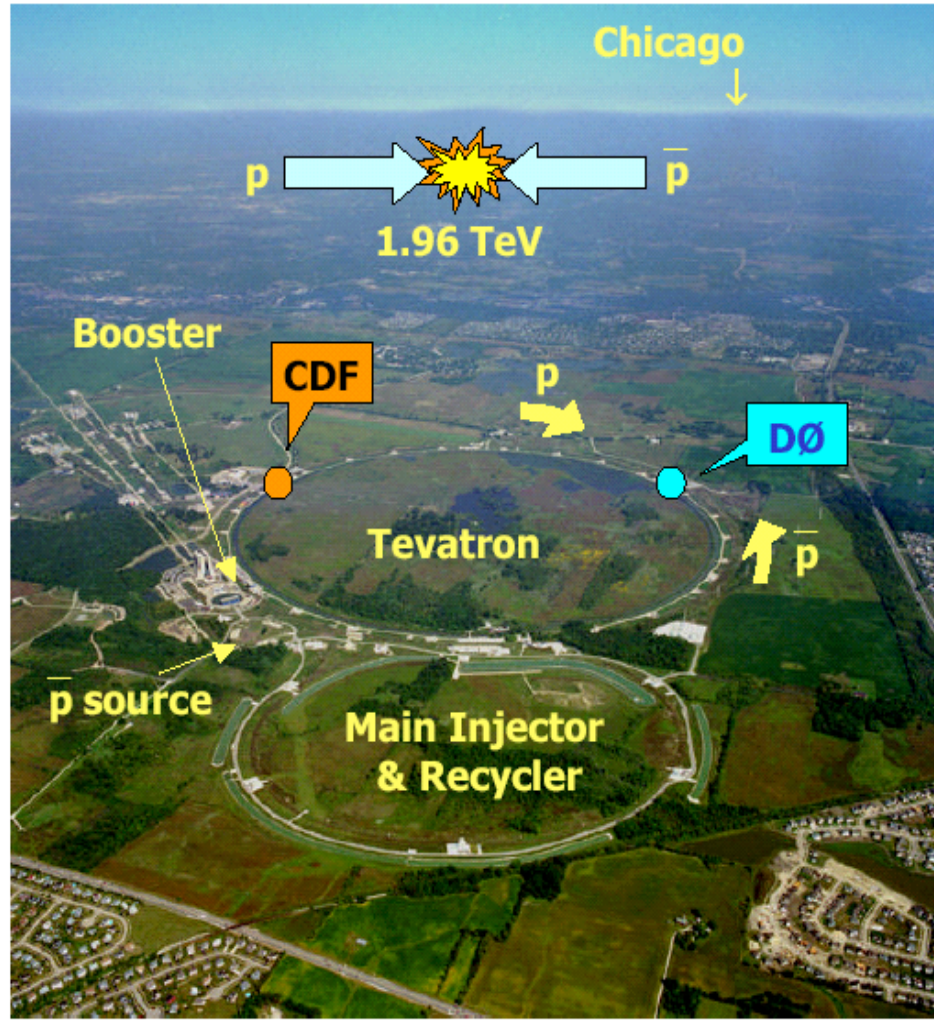


EXPERIMENTAL ENVIROMENT

The TeVatron Collider

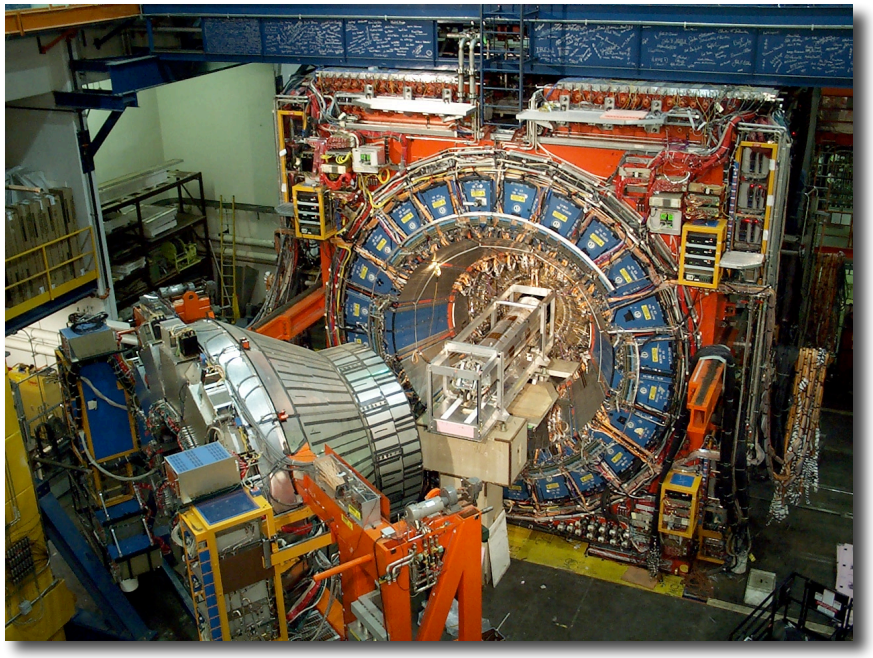
- p-$\bar{p}$ collisions
  $\sqrt{s}$=1.96 TeV (RunI 1.8)
- 36 bunches, 396 ns
- record peak Lum. 3×10^{32}[$cm^{-2}s^{-1}$]
  - ✓ Recycler (as $\bar{p}$ accumulator)
  - ✓ @ 3×10^{32} ≈ 7 <interactions>/BC
- ≈ 25 pb^{-1}/week (6×10^{4} W)





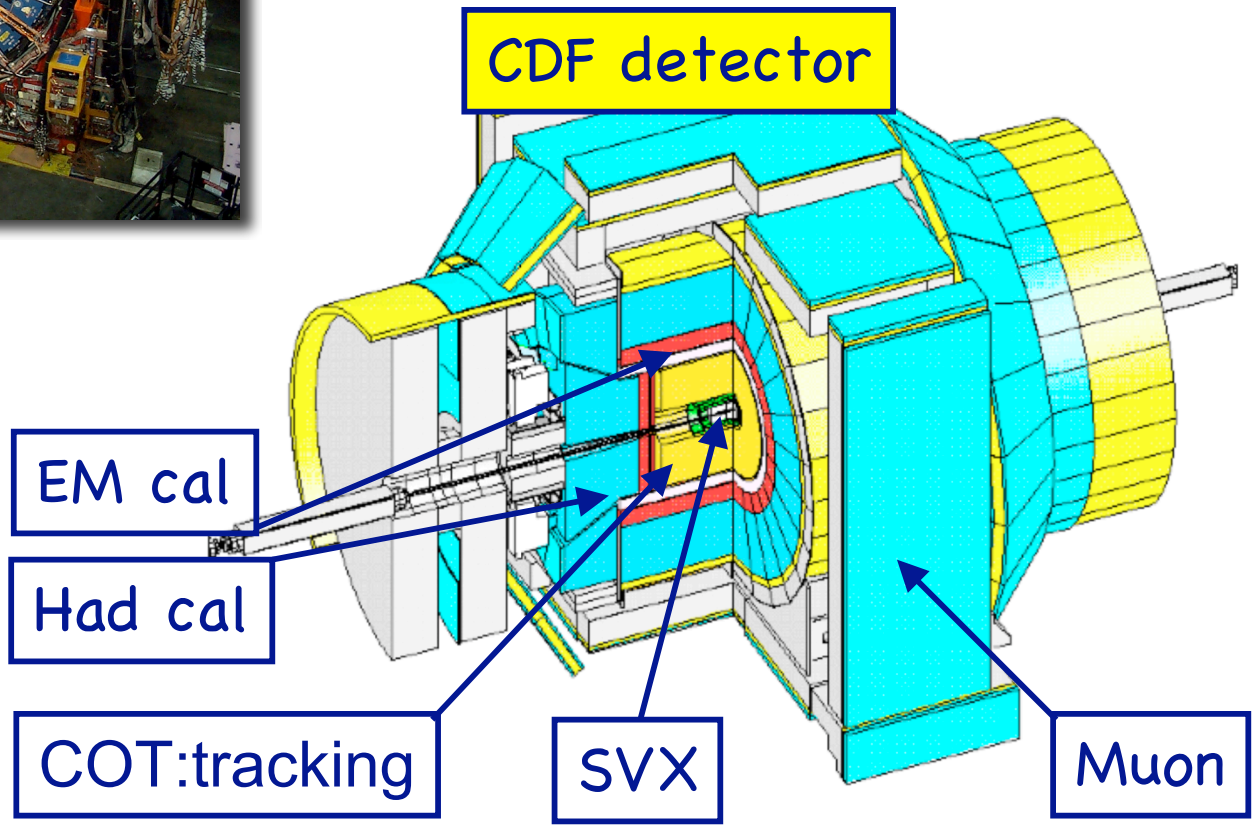
3.3 fb^{-1} delivered, 2.7 fb^{-1} on tape (CDF)
6 to 7 fb^{-1} expected by 2009.

Collider Detector at Fermilab



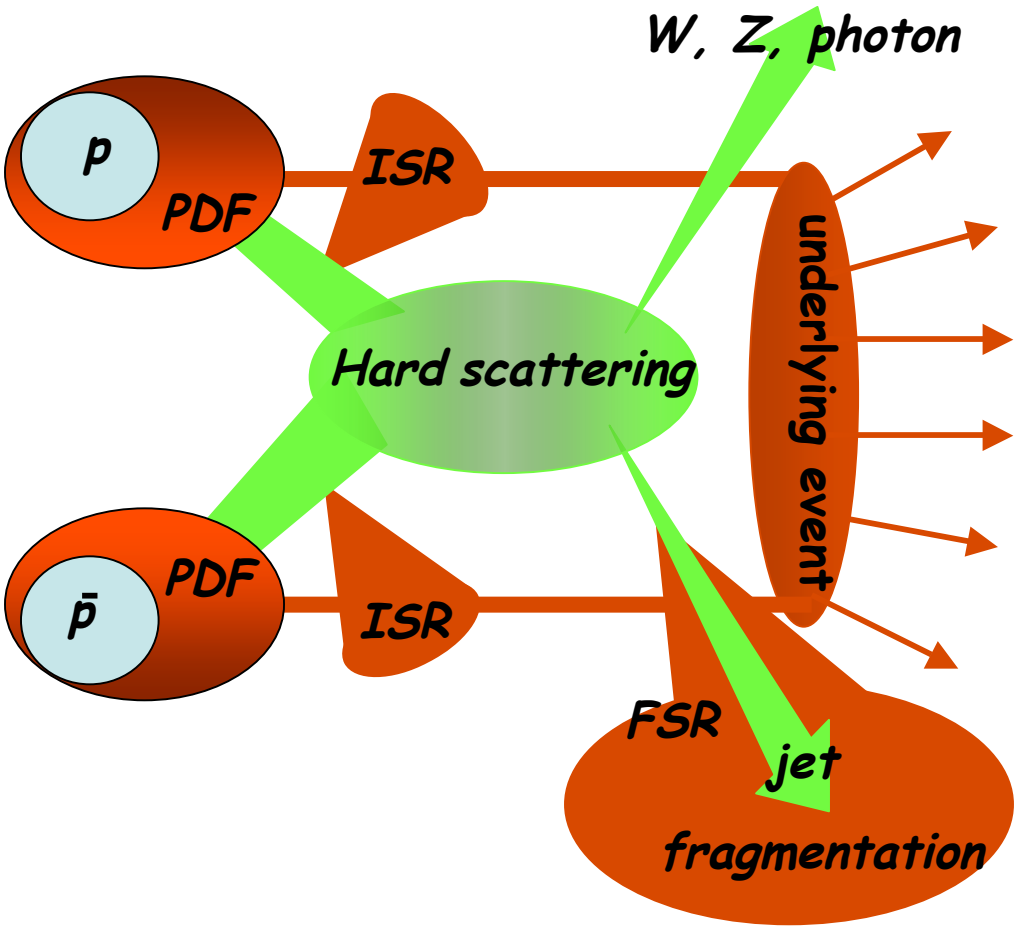
Multi-purpose detector:
- Precision measurements
- Search for new physics

- Silicon detector (SVX):
  top event b-tag: ~55%
- COT: drift chamber
  Coverage: $|\eta|<1$
  $\sigma_{Pt} / P_T \sim 0.15\% P_T$
- Calorimeters:
  Coverage: $|\eta|<3.6$
  EM: $\sigma_E / E \sim 14\% /\sqrt{E}$
  HAD: $\sigma_E / E \sim 80\% /\sqrt{E}$
- Muon:
  muon ID up-to $|\eta|=1.5$



High p_T Physics @ Tevatron

A typical Tevatron event consists of:



- Production QCD related
- Hard scattering:
  - ✓ perturbative regime
- Underlying event & soft physics:
  - ✓ phenomenological models

Jet reconstruction

A jet is a composite object:

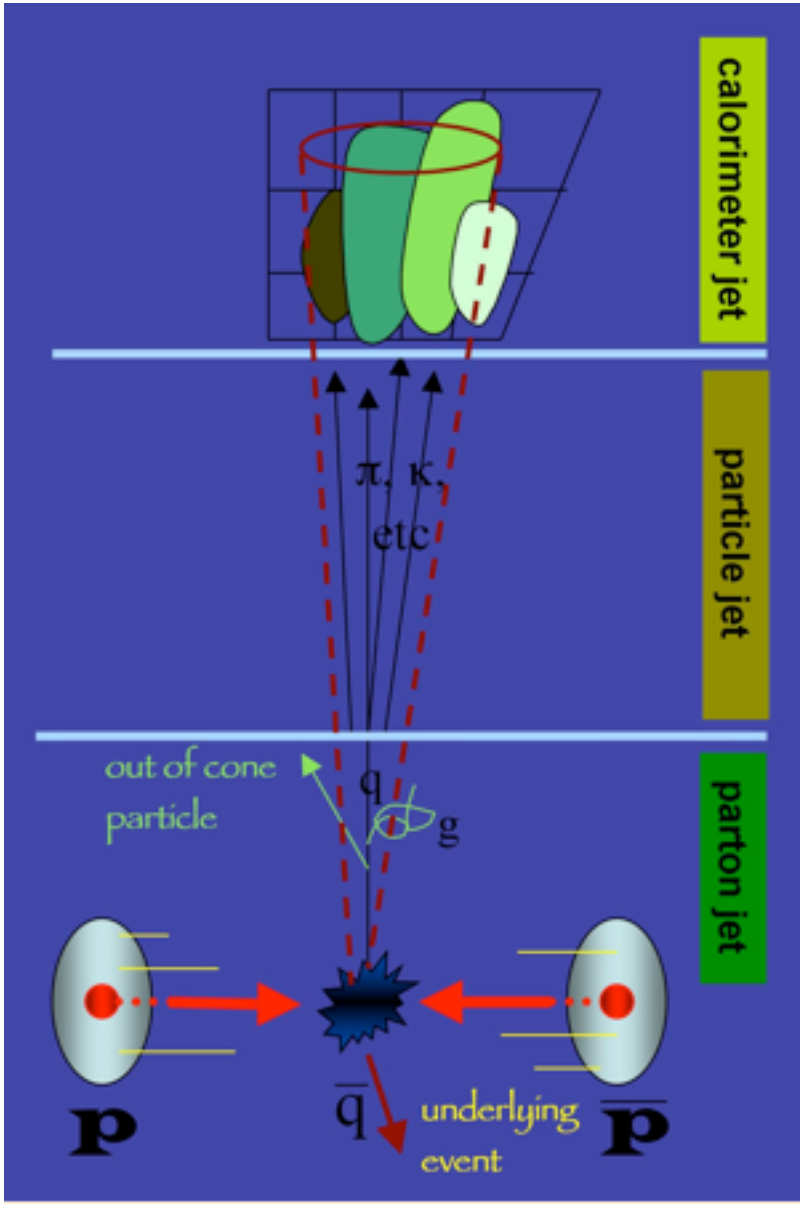
- complex underlying physics
- Depend on the clustering algorithm
- depends on detector properties

✓ Instrumental effects:

- Calorimeter response to hadron
- Detector resolution and efficiency
- Pile-up interactions (on average 3.6 interactions @ $10^{32}cm^{-2}s^{-1}$)

✓ Soft physics:

- Underlying event
- Fragmentation/hadronization
  - Monte Carlo model based
    - Need to be tuned on data!!! using many different observable

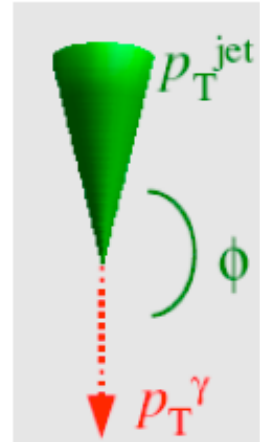


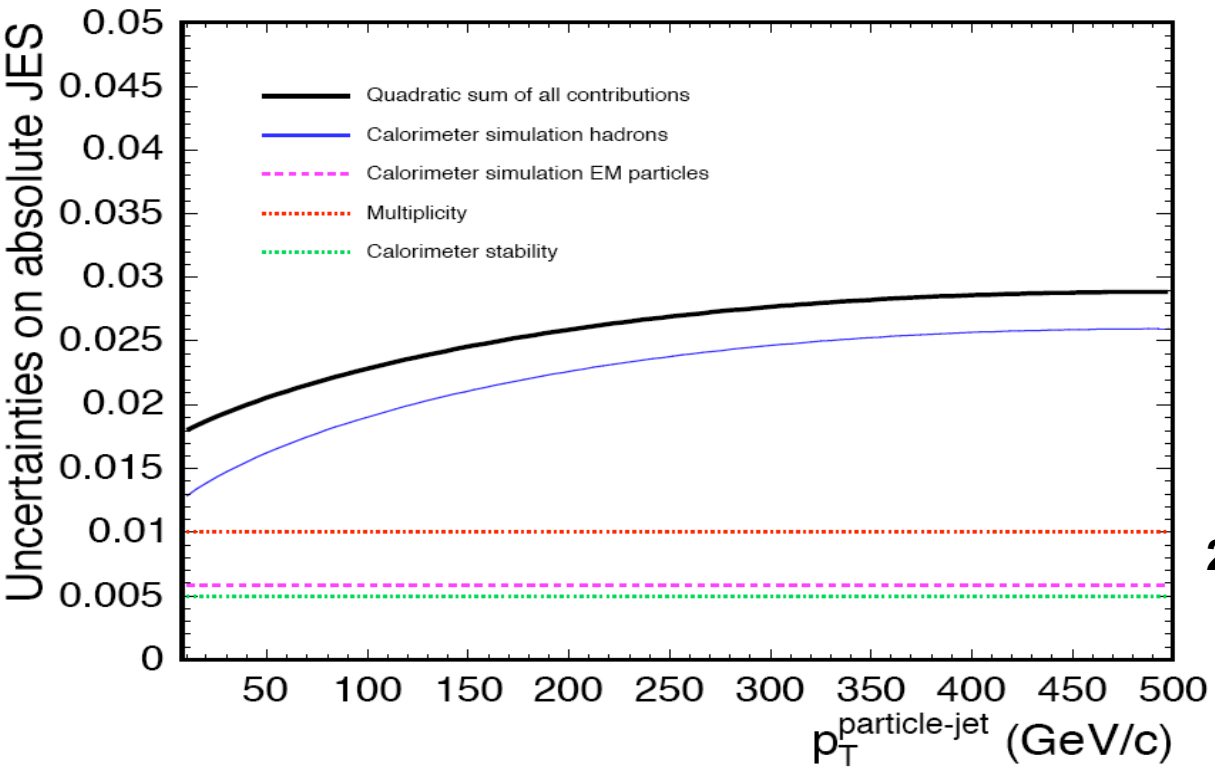
Jet energy correction method

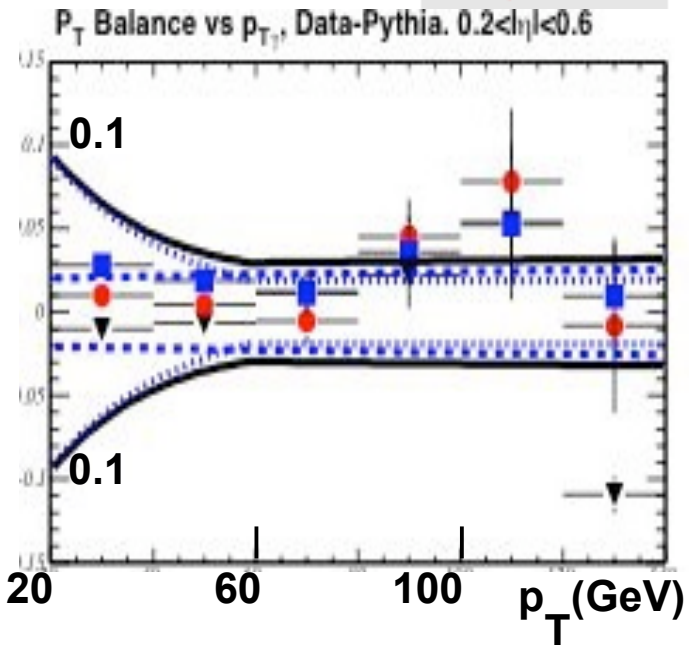
Correction for detector effects:

$$P_{T\ jet}(\eta, P_{Tjet}^{raw}) = [P_{T\ jet}^{raw}(\eta) \times f_{rel}(\eta) - MPI(vtx)] \times f_{abs}(P_{Tjet}^{raw}, \eta)$$

- Energy scale in central cal. with test beam, tracking (E/p)
- transfer energy scale in forward cal. with jet P_T balance



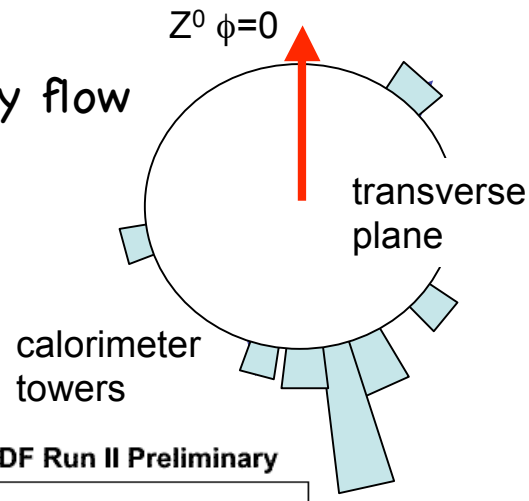


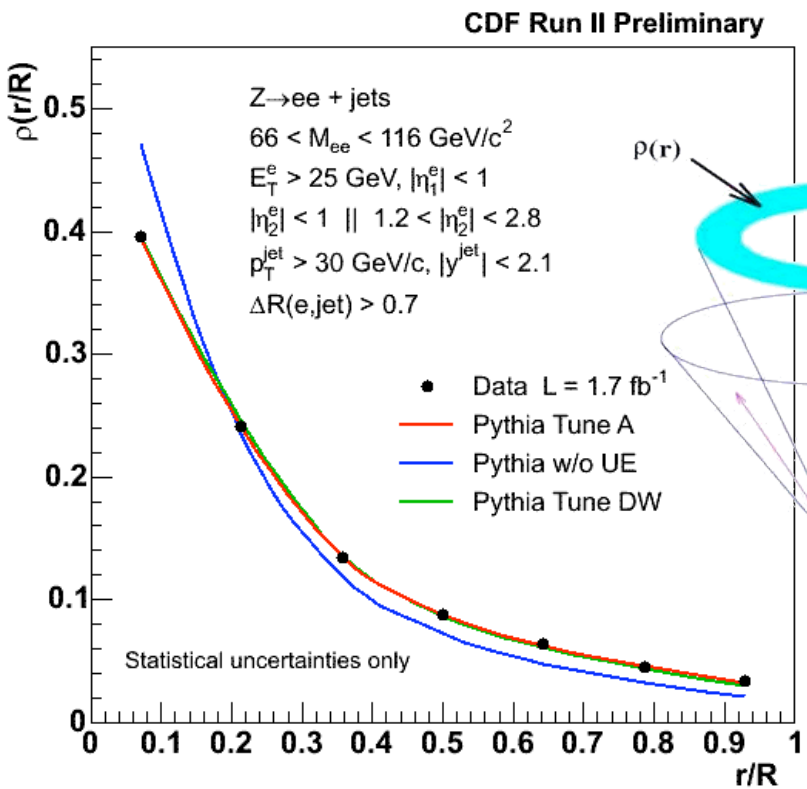


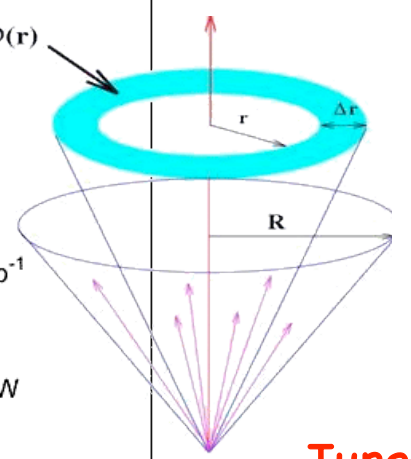
γ+jets, Z+jets used to check jet energy scale.

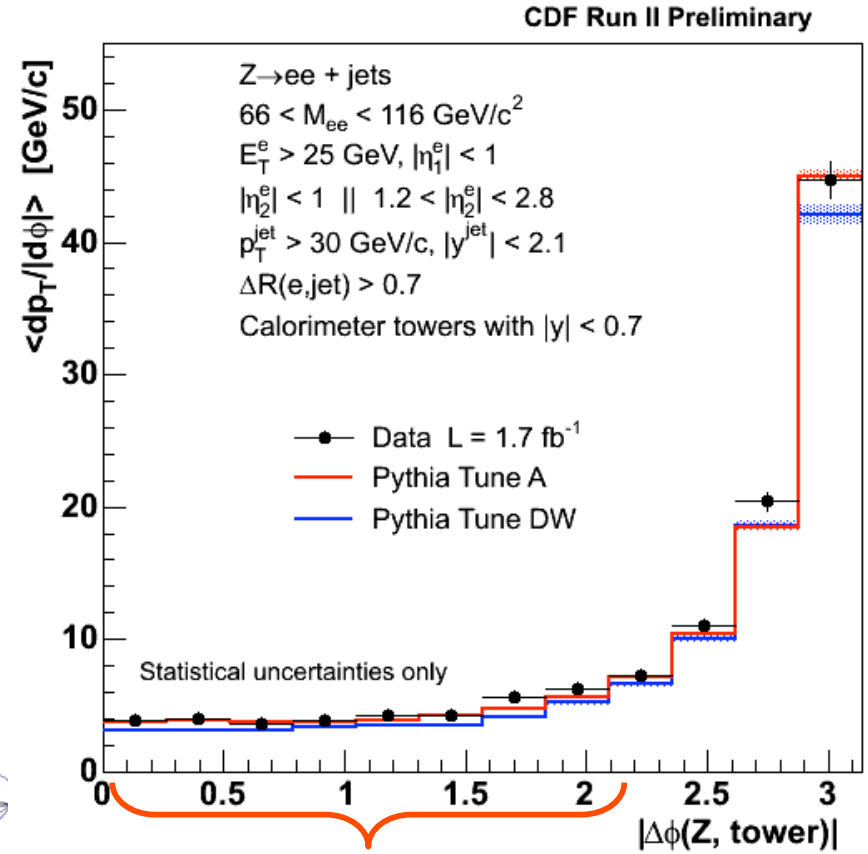
Closer look into jets

Jet shapes & energy flow are sensitive to the Underlying Event & hadronization.







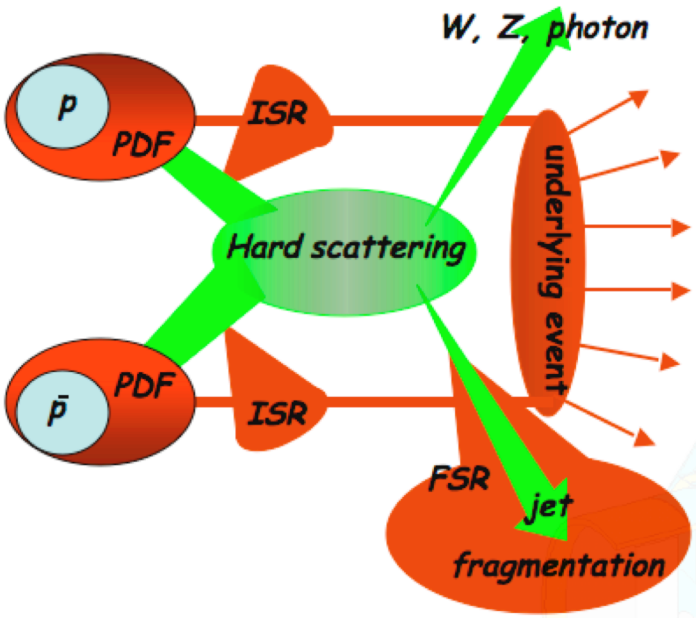


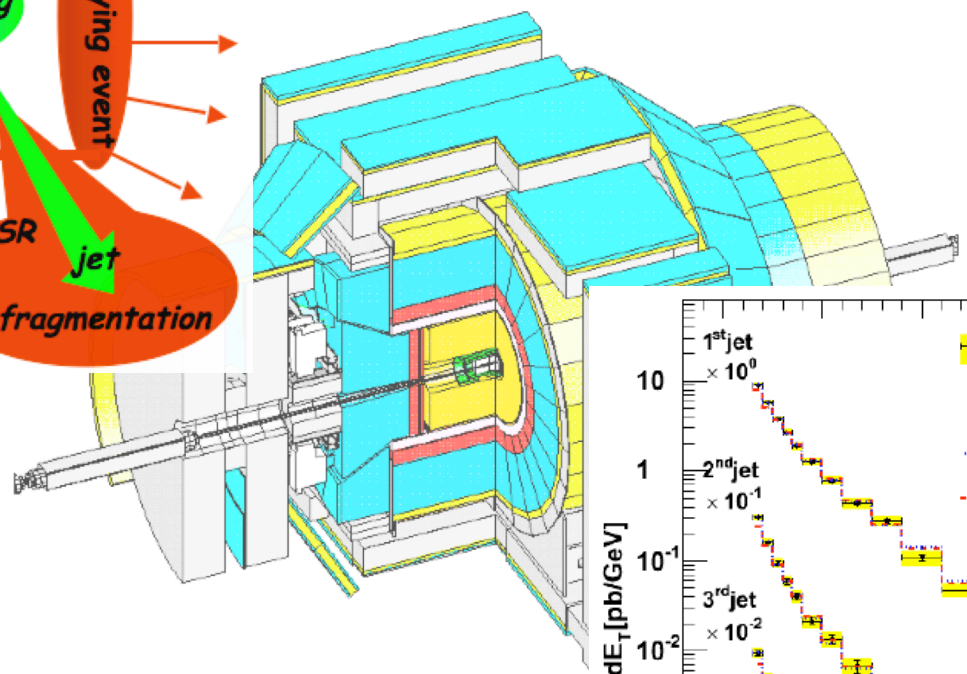
Dominated by the Underlying Event

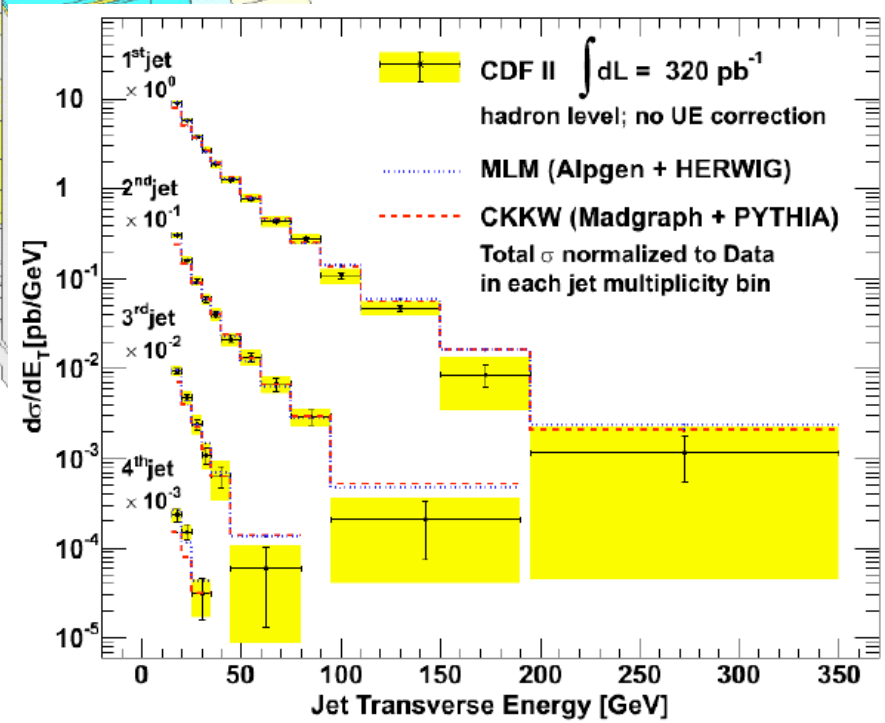
Tune A & Tune DW are different tunings of the Underlying Event in Pythia.

Both describe accurately soft physics.

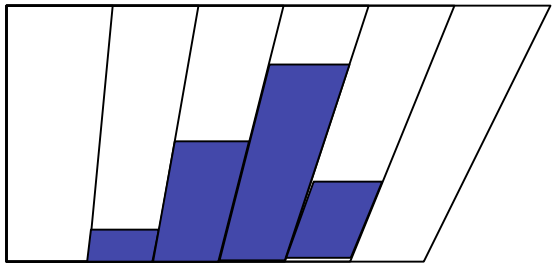
W + jet: a measurement in detail







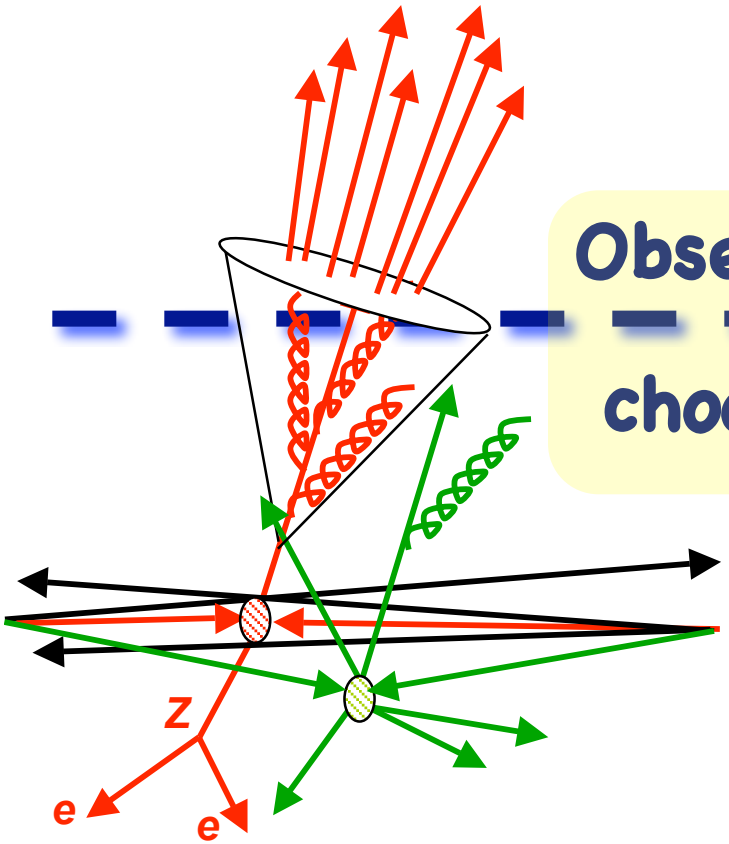
Observable definition



Observable: experimental challenges

Unfold detector effect
- correct for them, assign systematic otherwise

Estimate backgrounds



Observable defined at particle level

choosing a jet clustering algorithm

Observable: Theory description

Hard Scattering
(Perturbative-calculable)

Soft contribution
(Model-tuned on data)

W + jet measurement definition

- ✓ σ(W->eν + jet) vs jet E_T, jet-jet DR and invariant mass.

$$\frac{\delta\sigma\left[\begin{array}{l} P_T^e > 20GeV, M_T > 20GeV \\ P_T^\upsilon > 30GeV, |\eta^e| < 1.1 \end{array}\right]}{\delta E_T^j}$$

Restrict W xsec to the measurable phase space

Jets corrected hadron level
JETCLU 0.4
E_T^{corr}>15 GeV; $|\eta|$<2.0

- ✓ The W is a clean signal for high Q^2 events within which we can examine jet kinematics.

W + jet measurement definition

High P_T electron trigger →
- Identify W:
  - E_t^{ele}>20GeV; Met>30GeV;M_T^W>20GeV
- Reconstruct jets:
  - jetclu R=0.4 $|\eta|$<2 E_t^{jet}>20GeV

✓ In each bin of the jet E_T distribution compute:

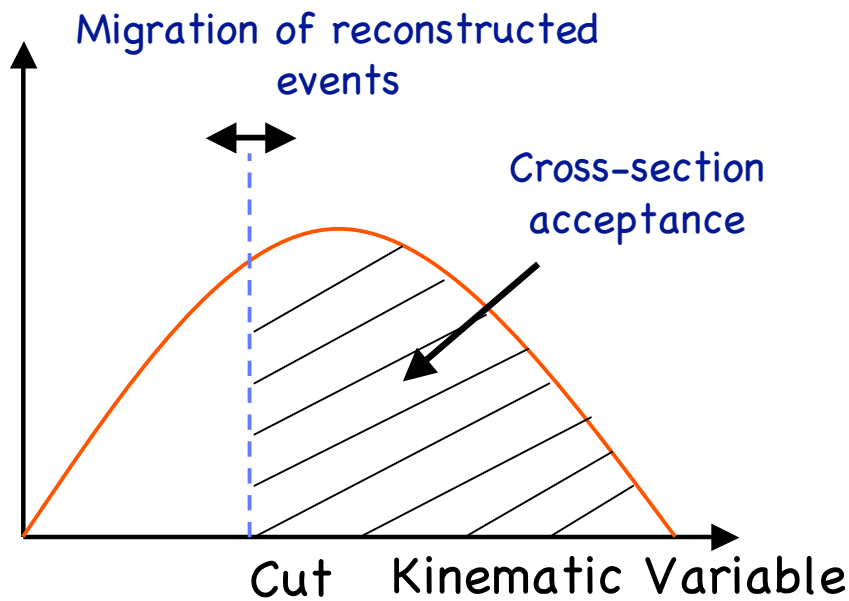
$$\sigma = \frac{N^{cand} - N^{bkgd}}{A \bullet \varepsilon_{ID} \bullet L} \bullet C_{unfold}^{calorimeter}$$

✓ Main backgrounds: QCD, top, W->$\tau\nu$

Acceptance and Efficiency

- ✓ Define cross section phase space as the W detector acceptance

Events migrate across acceptance boundary: convolution of local shape and resolution



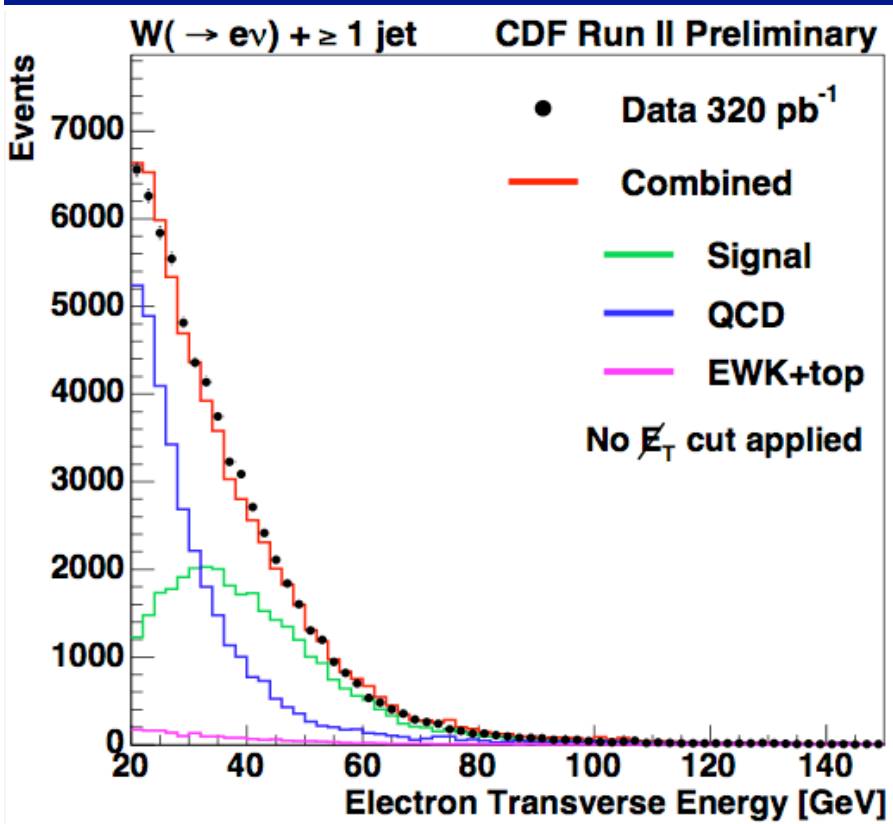
- ✓ Use MC for acceptance and electron ID efficiency
  - Systematic on ID efficiency comparing Z MC and data
  - Systematic on acceptance from different MC models

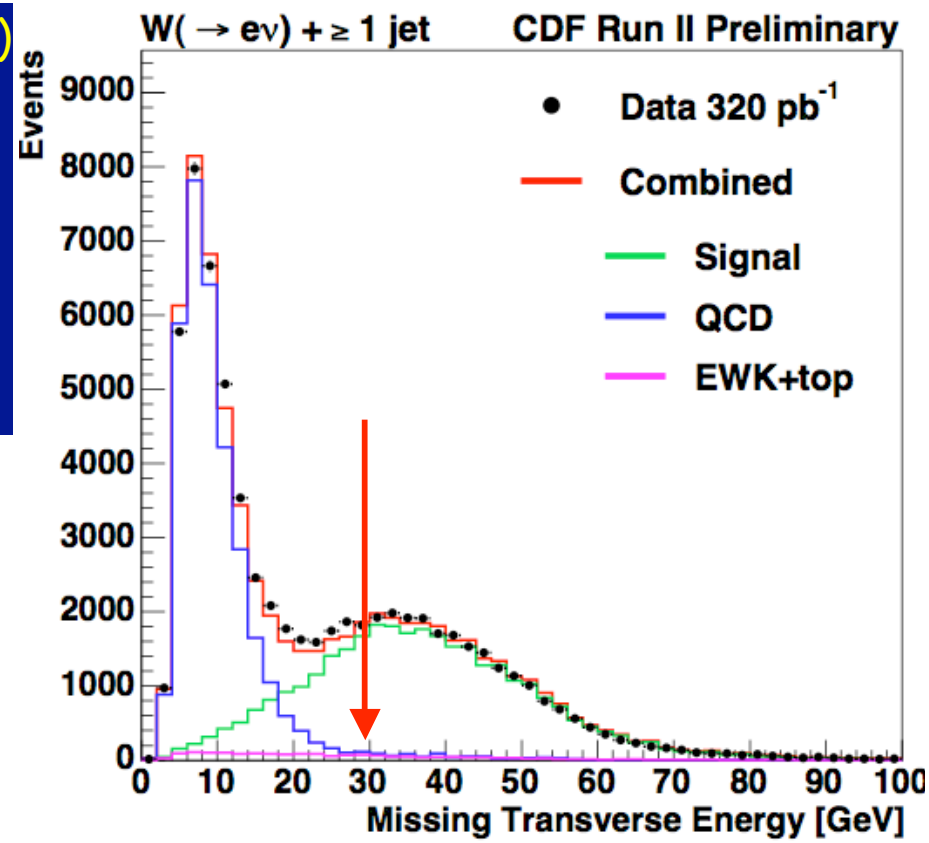
$$A \bullet \varepsilon_{ID} \approx 0.6 \pm 0.03$$

largely flat as function of jet kin

Background

- QCD from fake electron (antielectron)
- Use MC for EWK & top
- Relative normalization from MissE_T fit to data
- Very good agreement with data in other kinematic variables

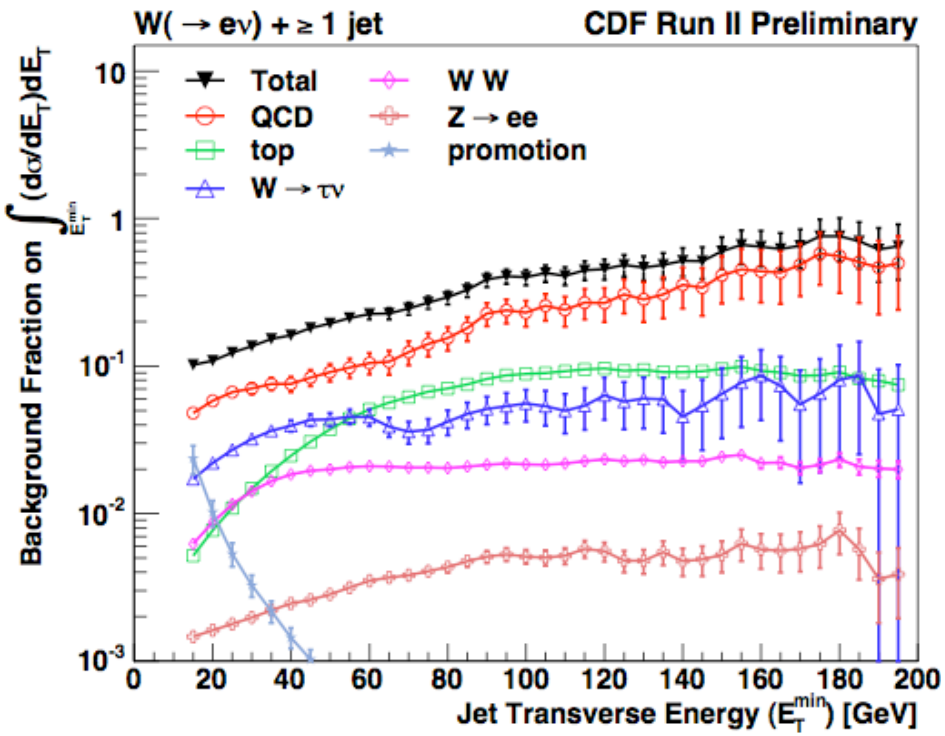


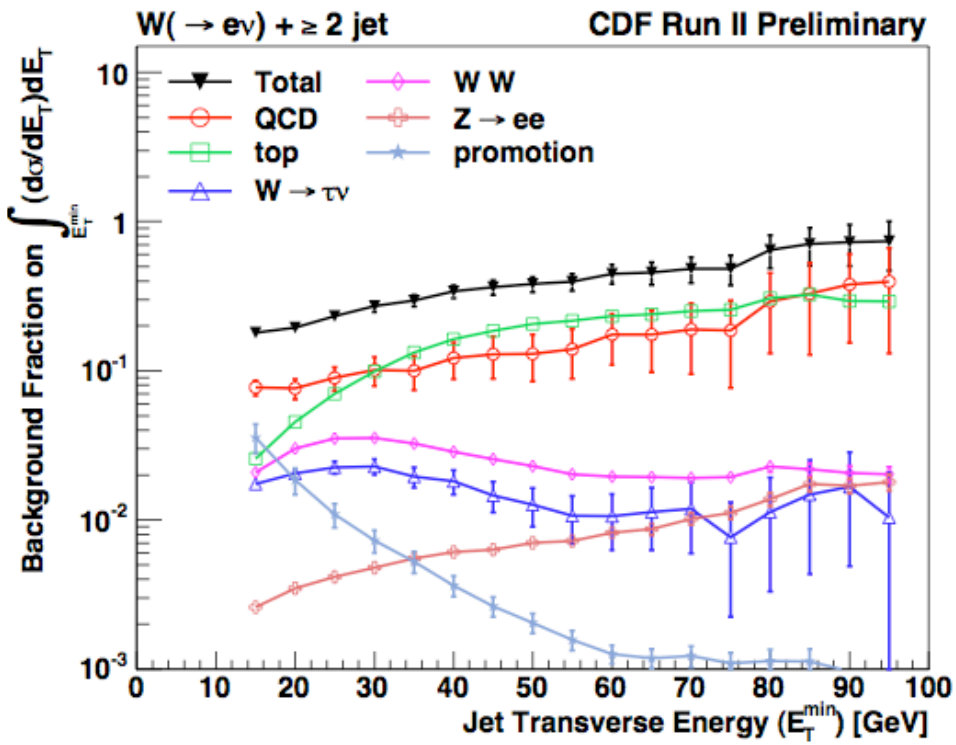


Systematics:

- antielectron statistic
- antielectron model (5-20%)
- Top cross section (10-20%)
- MC model (5%)

Background breakdown in jet E_T





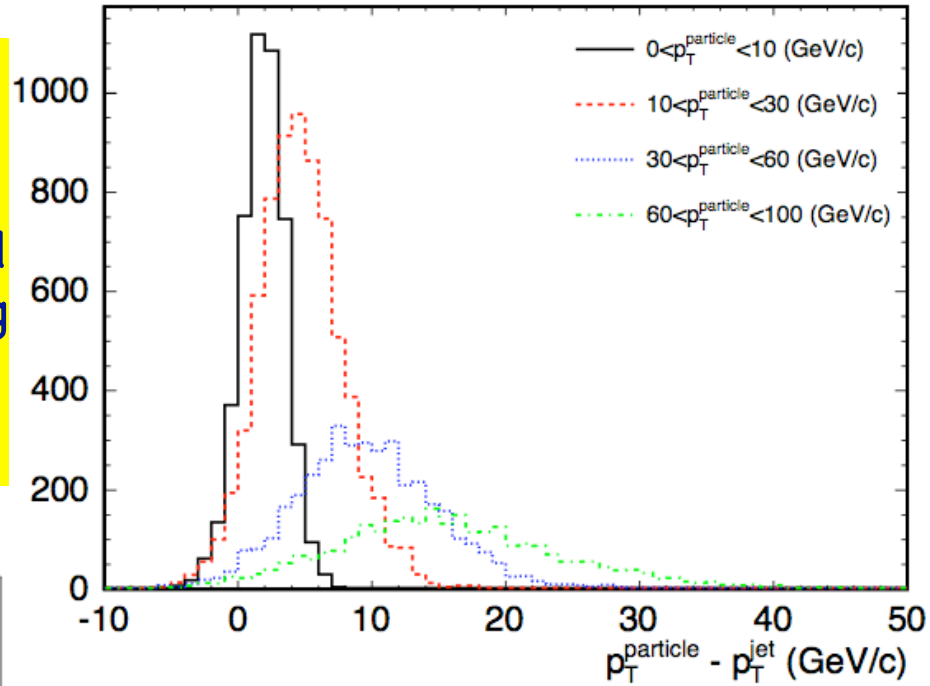
- ✓ QCD gives a substantial contribution to the background fraction
- ✓ In the tail of the distribution (high jet multpl., High E_T) top is dominant

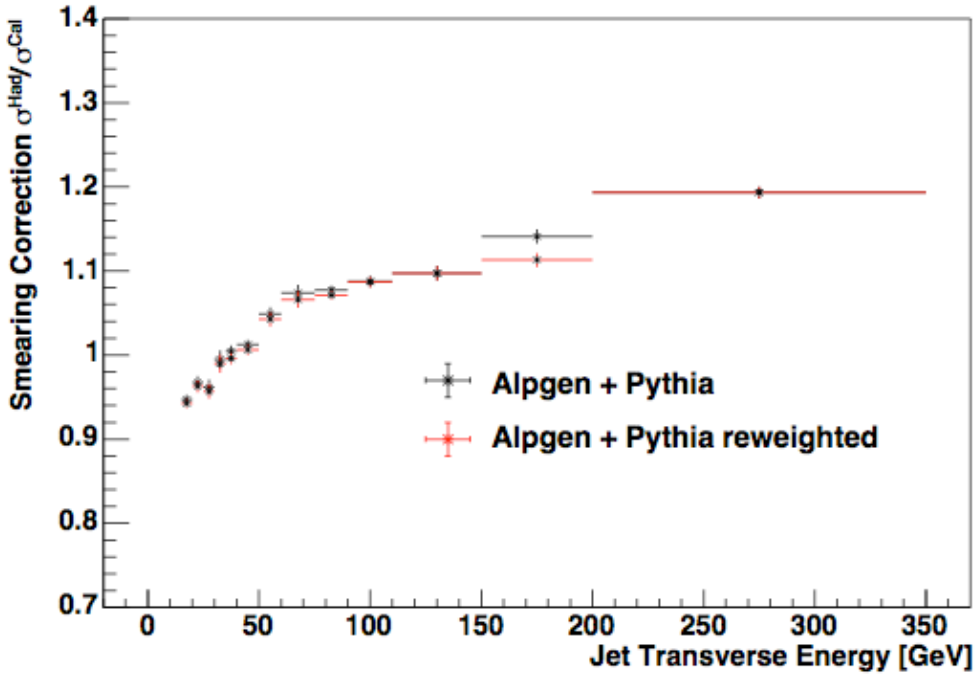
Promotion background (small contribution at low E_T):

- ✓ extra interaction produce jet not associated to the W -> wrong W jet-multipl.
- ✓ Estimate extra jet rate in MB, correct data on average as a function of # vtx

Calorimeter resolution unfolding

- Absolute scale corrects on average for calorimeter response.
- Resolution alters shape of measured E_T spectrum - necessitates unfolding correction.



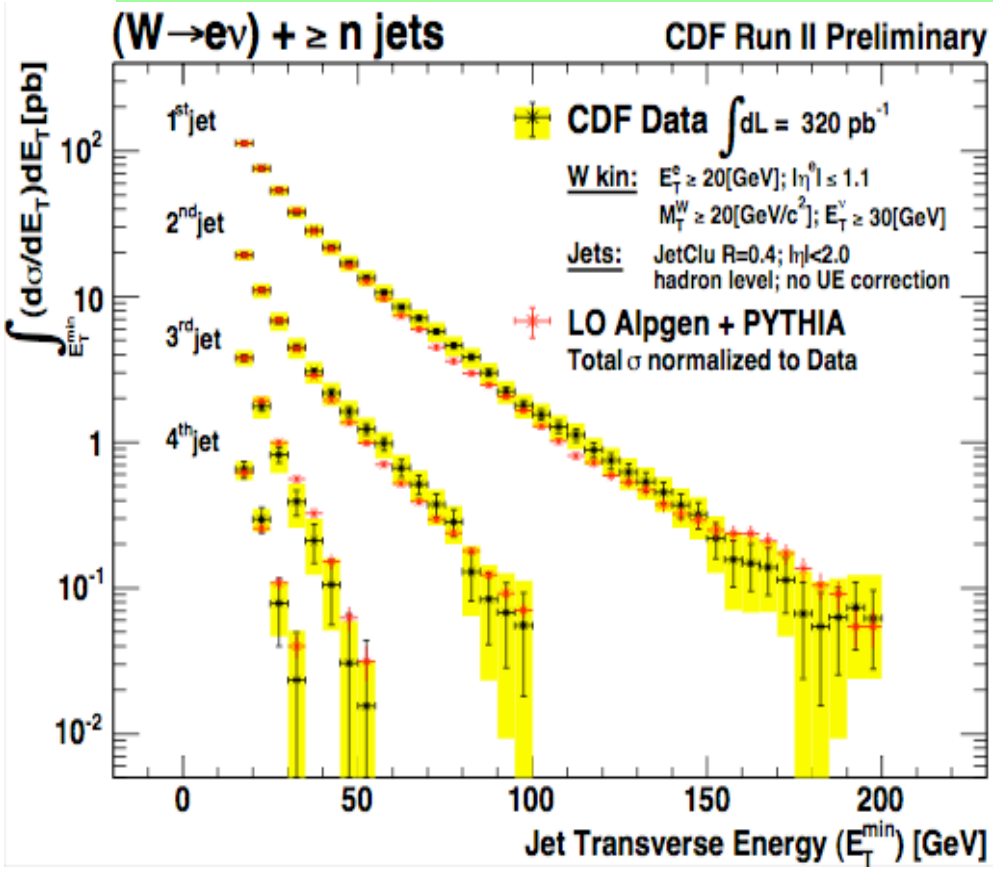


- Use detector simulated W+Jets MC events.
- Form jet E_T spectra at HAD level and at CAL level.
- Define unfolding factor in each bin as N_{HAD}/N_{CAL}.

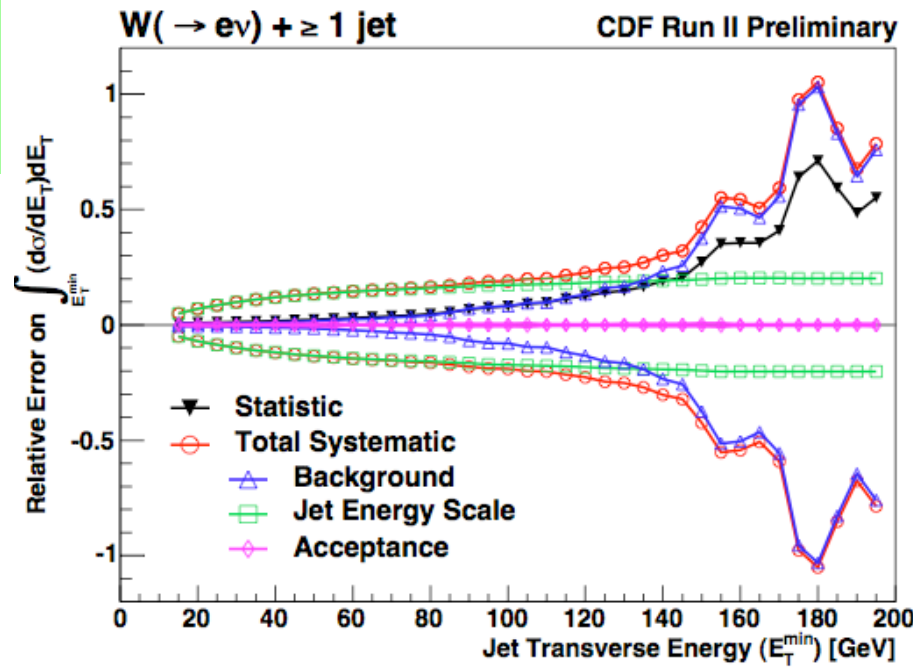
CDF W+jet cross section measurement

$$\int_{E_T^{min}} \frac{d\sigma_{W\to e\nu}}{dE_T} dE_T$$

For 1st, 2nd, 3rd and 4th Jet E_T



Errors on leading jet $\int_E d\sigma/dE_T$



At high E_T large statistic uncertainty. Systematic dominated by jet energy scale(3-4%) at low E_T, by background subtraction at high E_T.

MC has been normalized to inclusive data cross section in each jet sample!

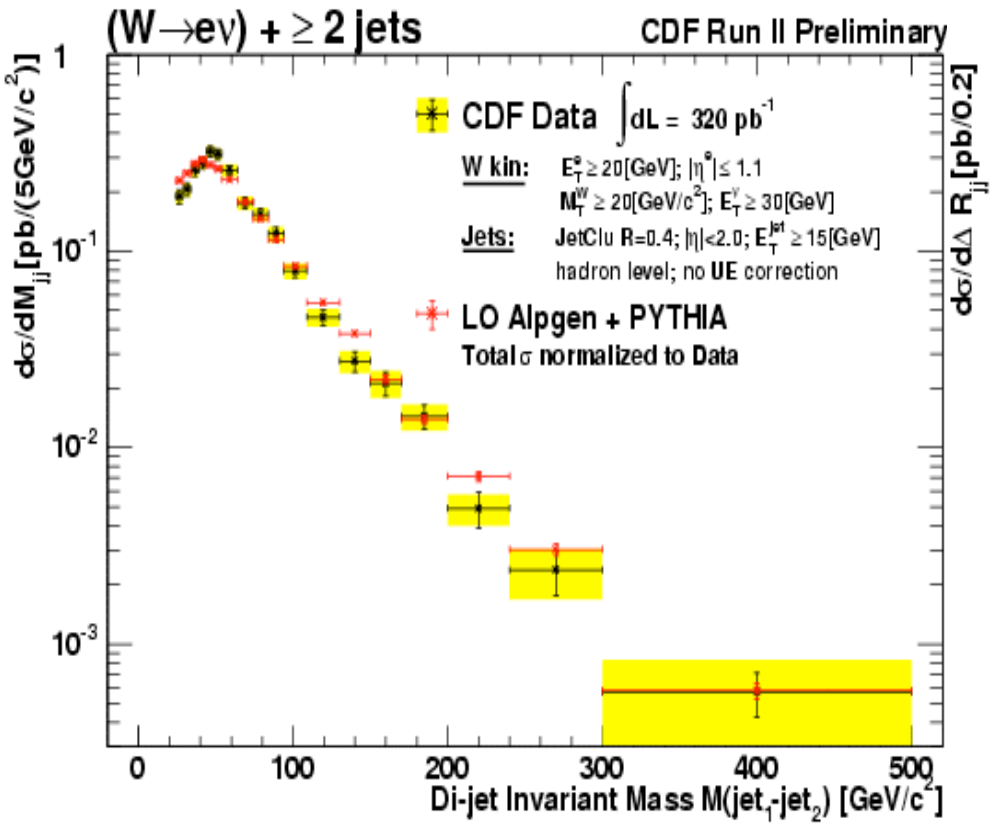
CDF W+jet cross section measurement

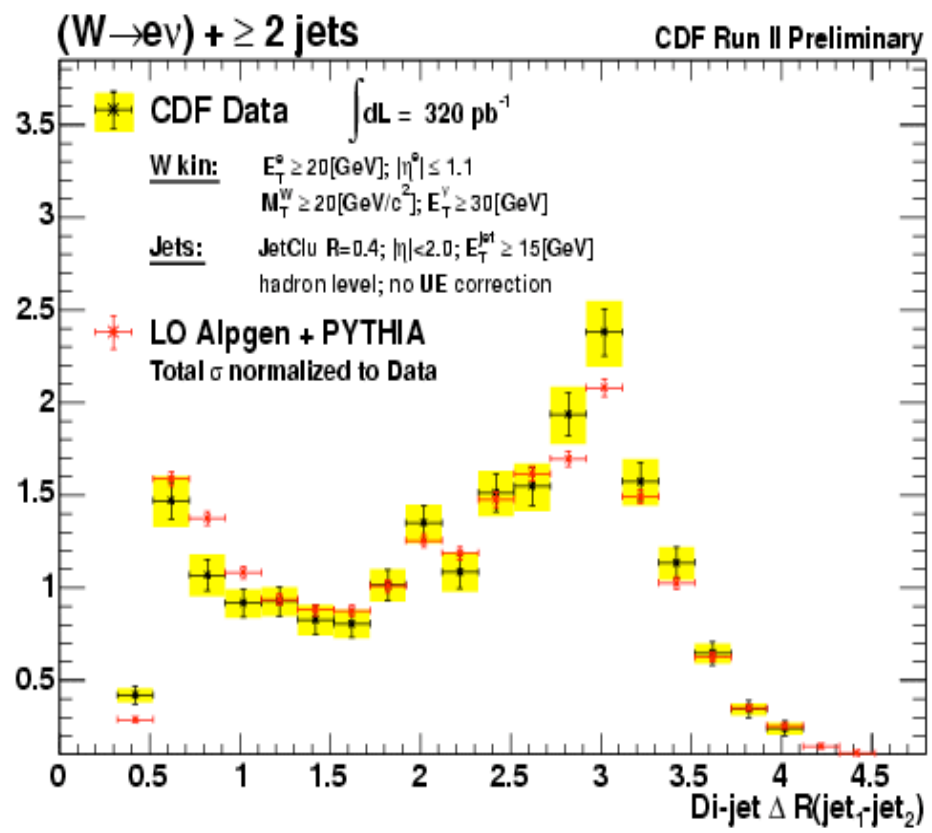
$$\frac{d\sigma_{W\to e\nu}}{dM_{jj}}$$

Differential σ w.r.t 1st-2nd jet invariant mass in the W + ≥ 2 jet sample

$$\frac{d\sigma_{W\to e\nu}}{d\Delta R_{jj}}$$

Differential σ w.r.t 1st-2nd jet ΔR in the W + ≥ 2 jet sample



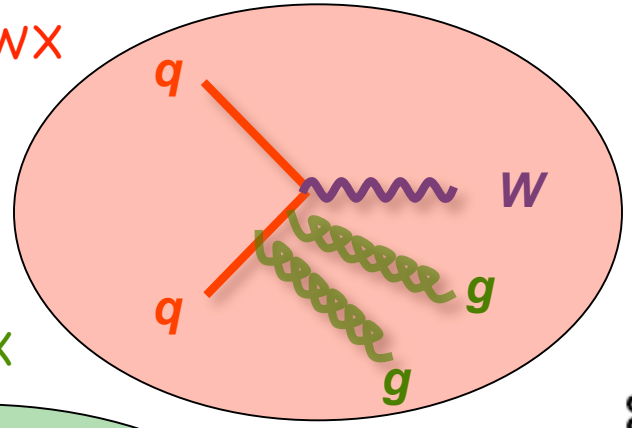


MC has been normalized to measured W+ ≥ 2 jet inclusive cross section!

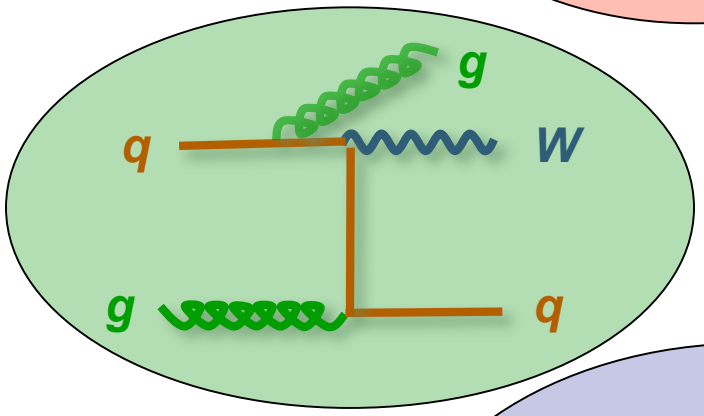
COMPARISON WITH THEORY

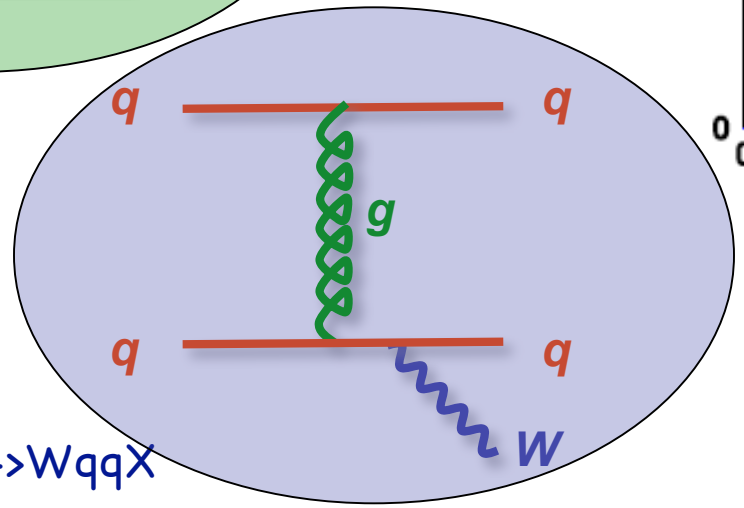
W+jet at the parton level: multi-parton ME

Proc 1 = qq->WX

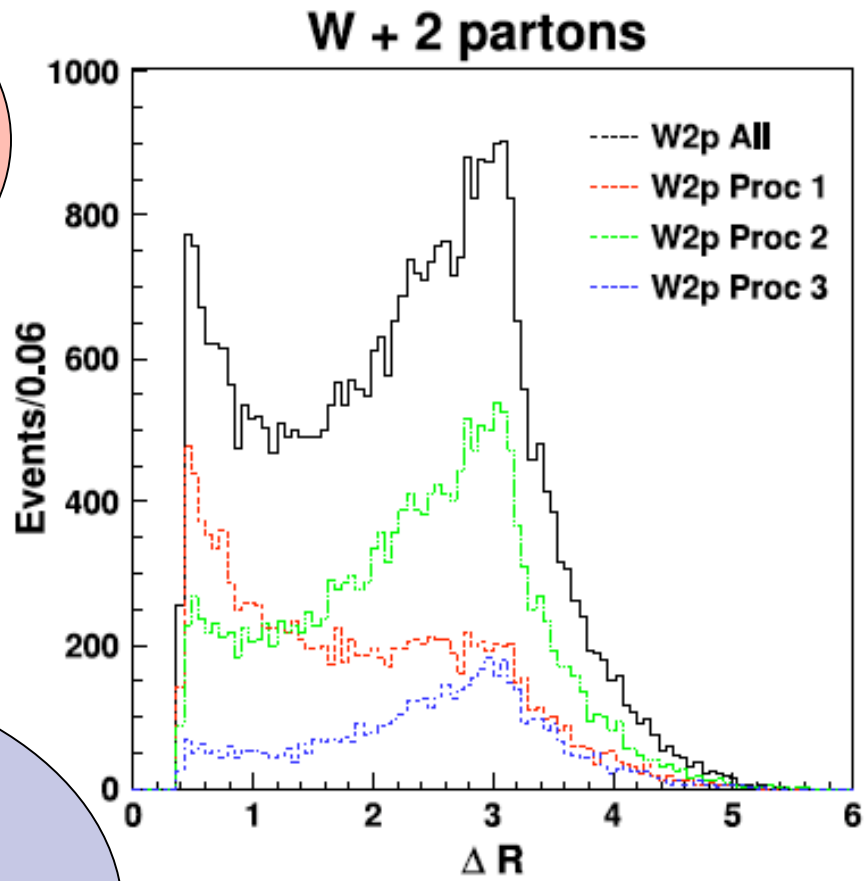


Proc 2 = qg->WqX

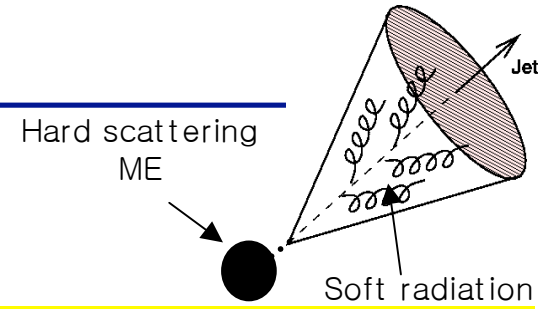




Proc 3 = qq(gg)->WqqX



ME & PS matching



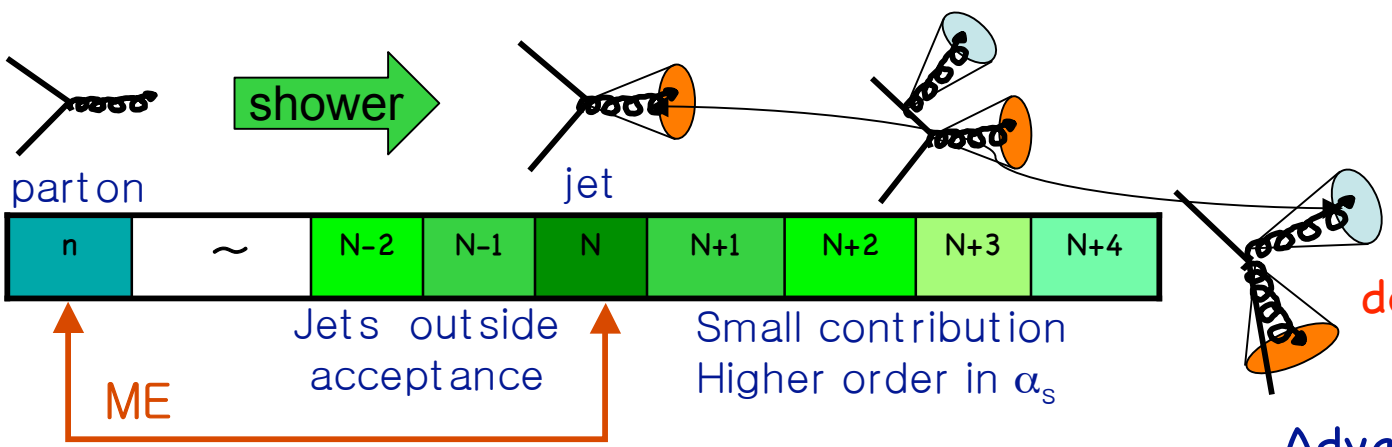
ME

1. Parton-level description
2. Fixed order calculation
3. Interference exact
4. Valid when partons are hard and well separated
5. Necessary for multi-jet description

PS

1. Showering & hadronization description
2. Resums large logs
3. Valid when partons are collinear and/or soft
4. Necessary for realistic studies

Complementary approaches



2 topologies ≈ $O(\alpha)$
Same jet multiplicity

double counting
depends on parton-level cuts

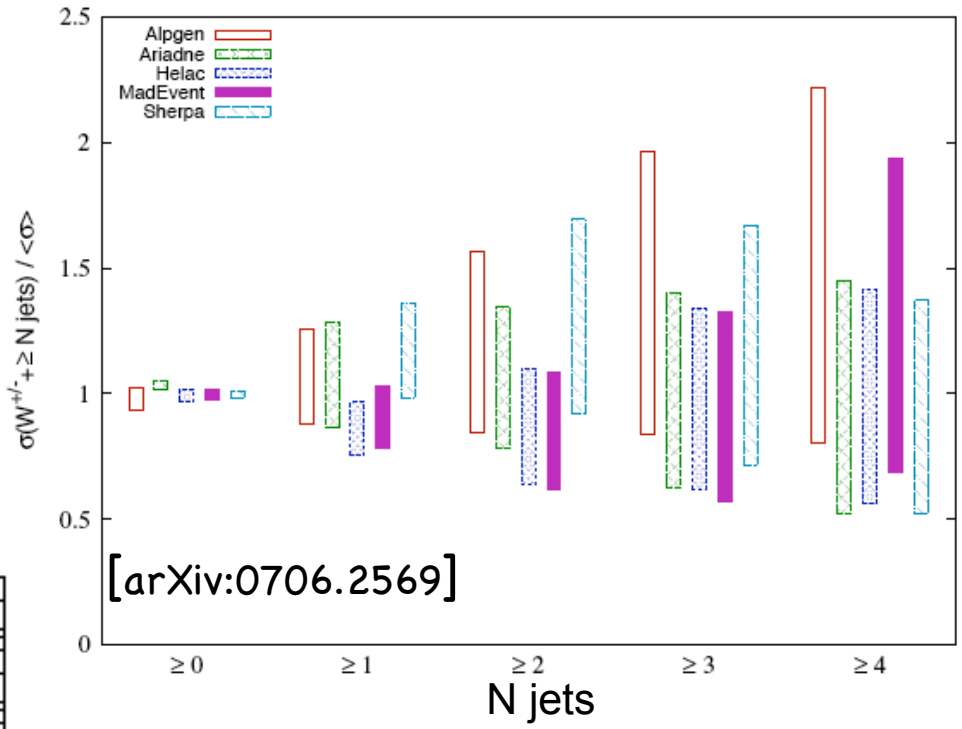
Advances:
ME-PS matching

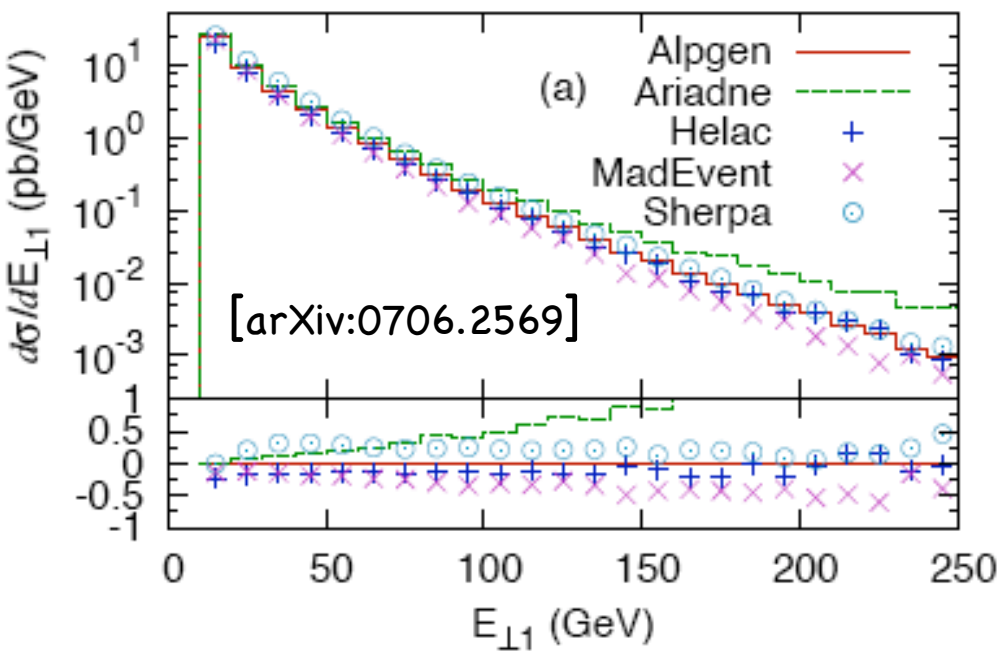
...new ME-PS merging tools

Many new tools: Alpgen, Ariadne, Helac, MadEvent, Sherpa [arXiv:0706.2569]

Separate multijet phase-space

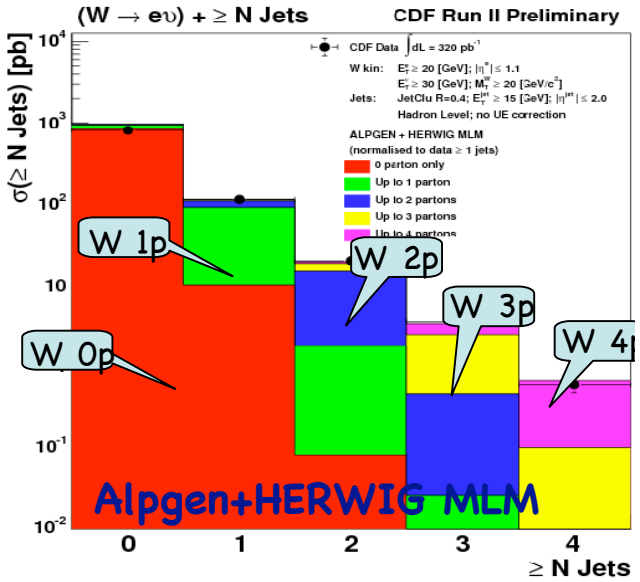
- Matrix element domain
- Parton shower domain

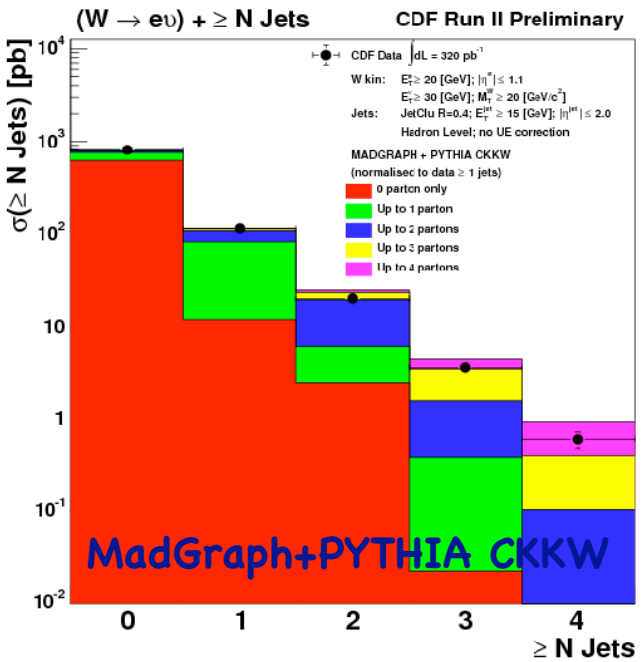


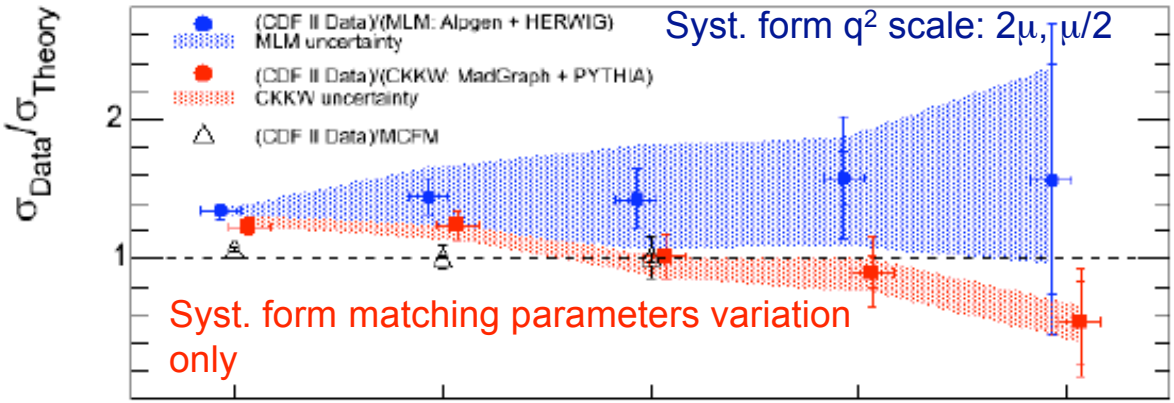


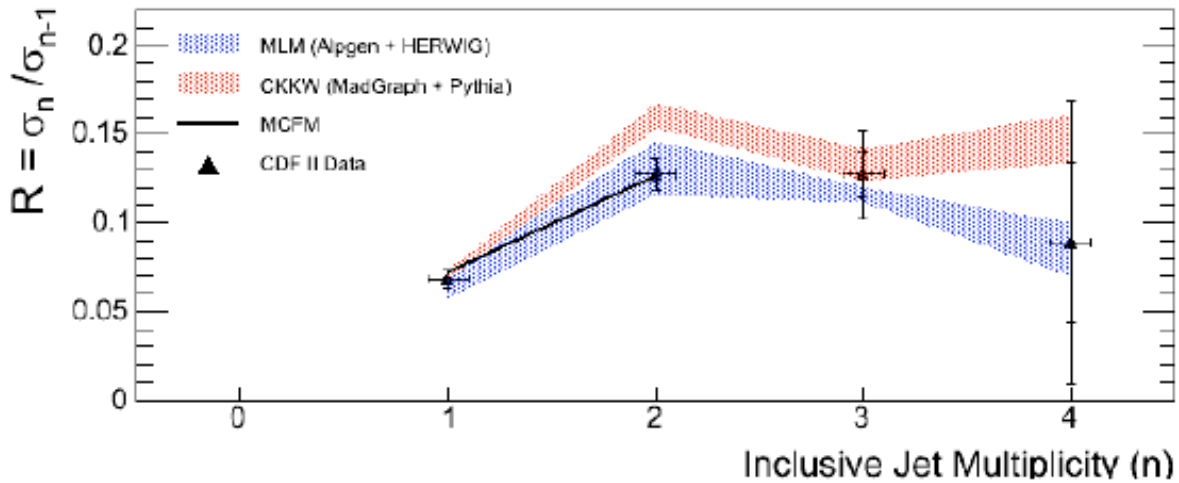
Important to validate/tune these tools against data.

Merging tools vs data: Njet distribution



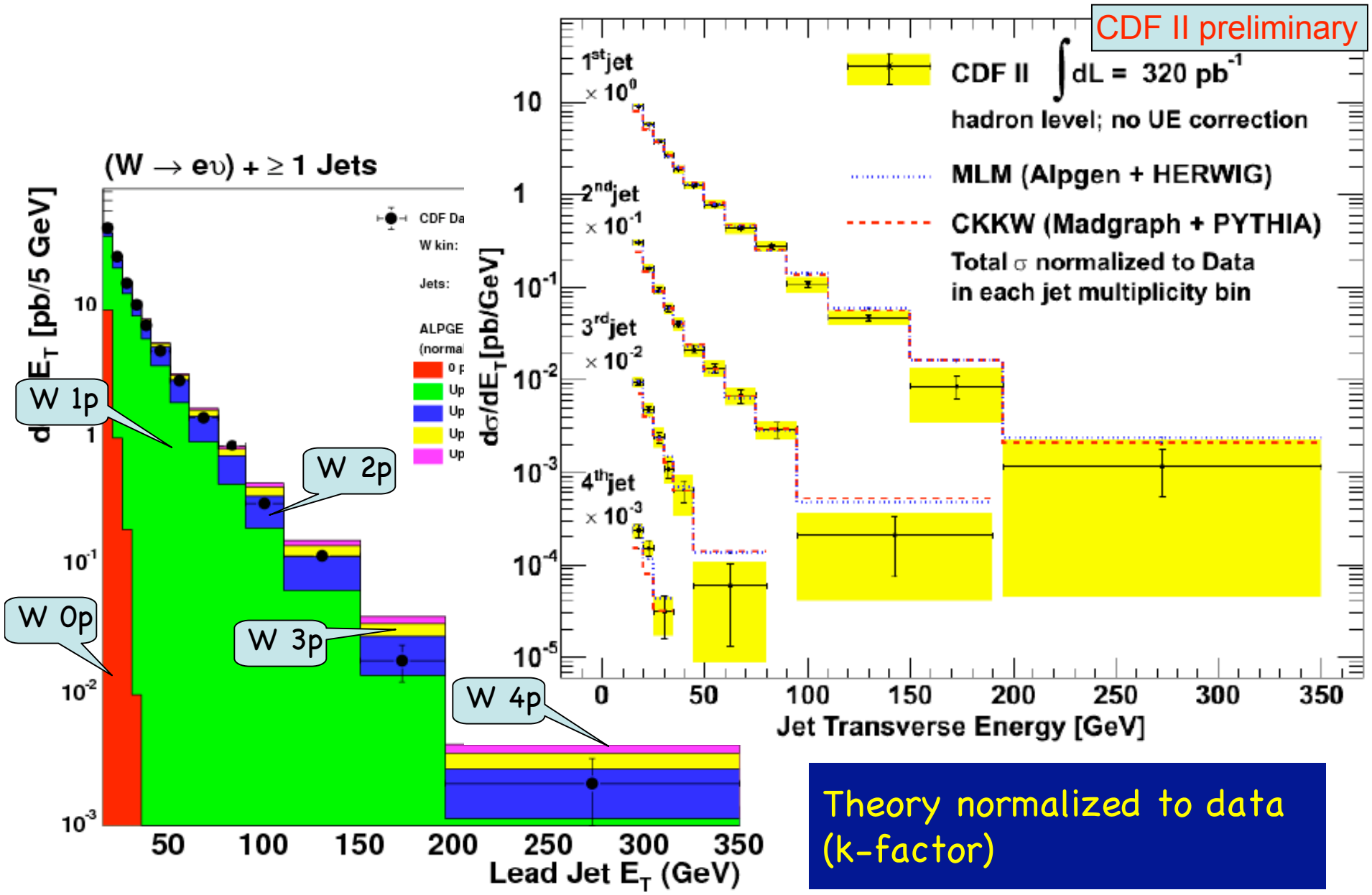






K-factor as large as 50% Theory models dependent on renormalization scale and ME-PS matching parameters

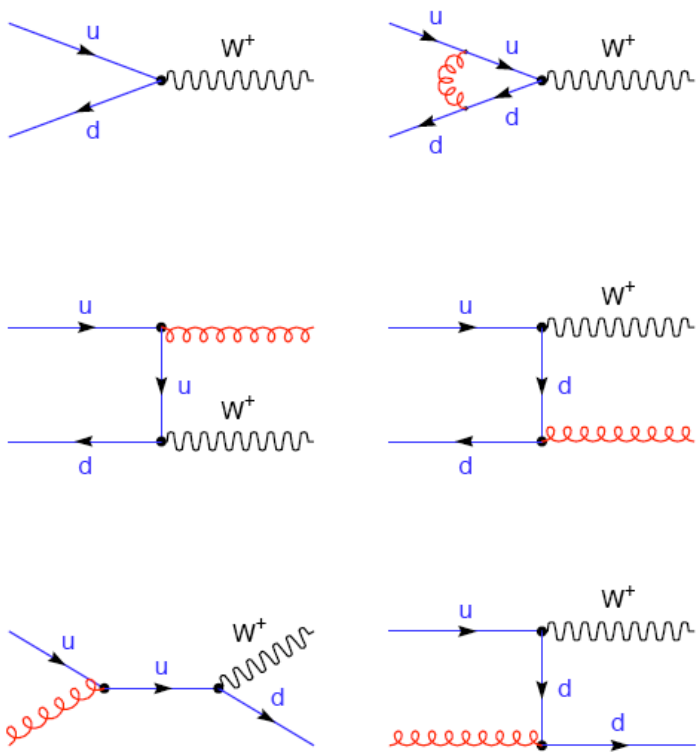
Merging tool vs data: E_t^{jet} spectra:

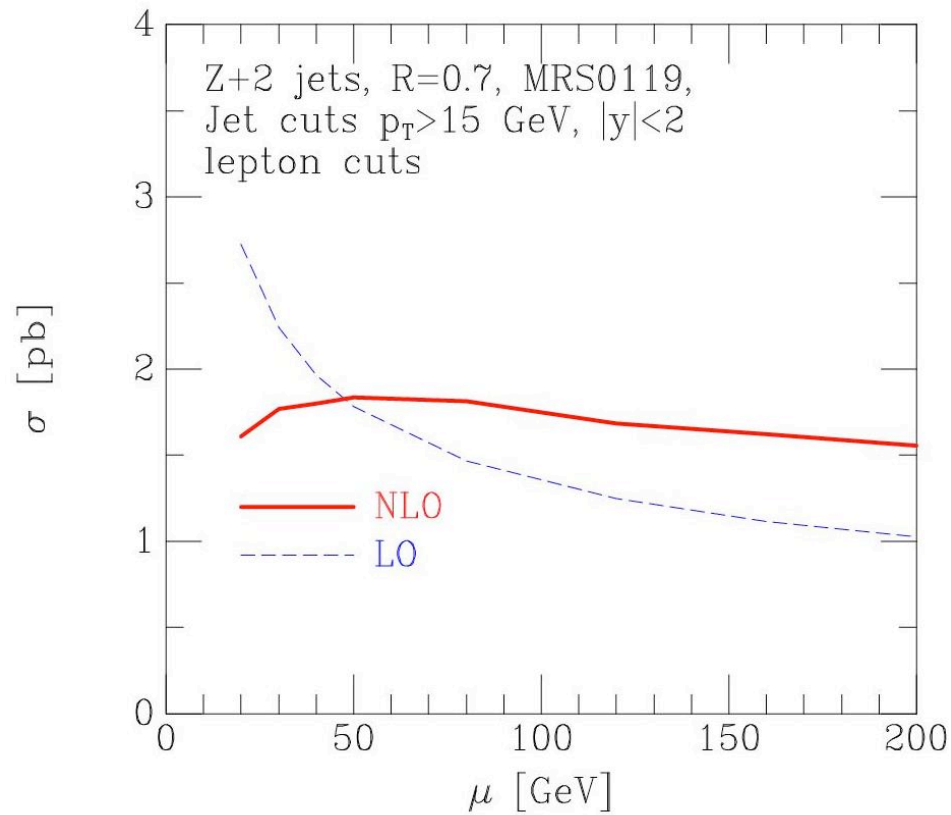


Theory normalized to data (k-factor)

Next to leading order

→Complementary approach to LO and parton shower generators
→Gives a prediction of **total cross section** and distribution at parton level but is not a fully implemented event generator

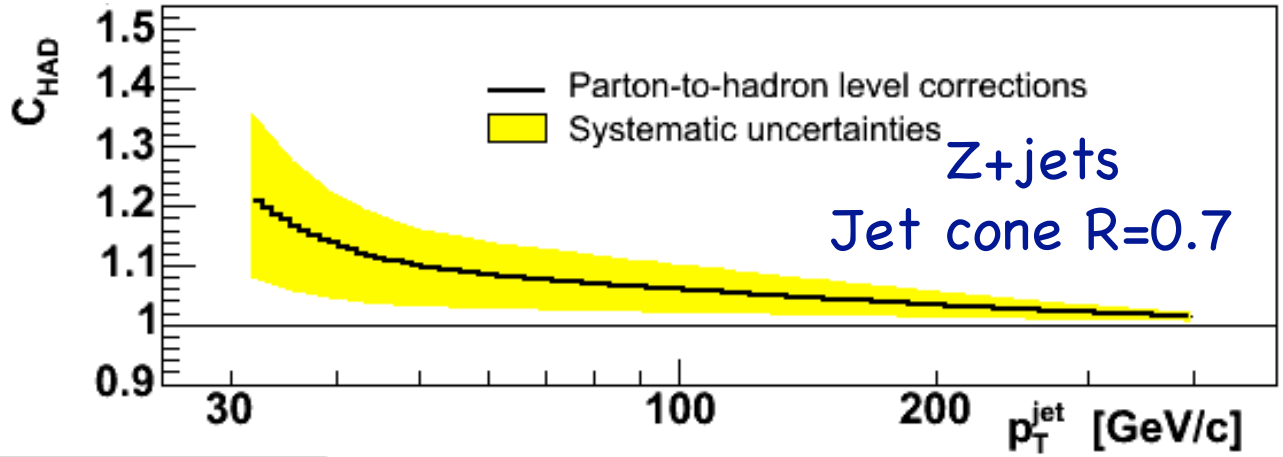


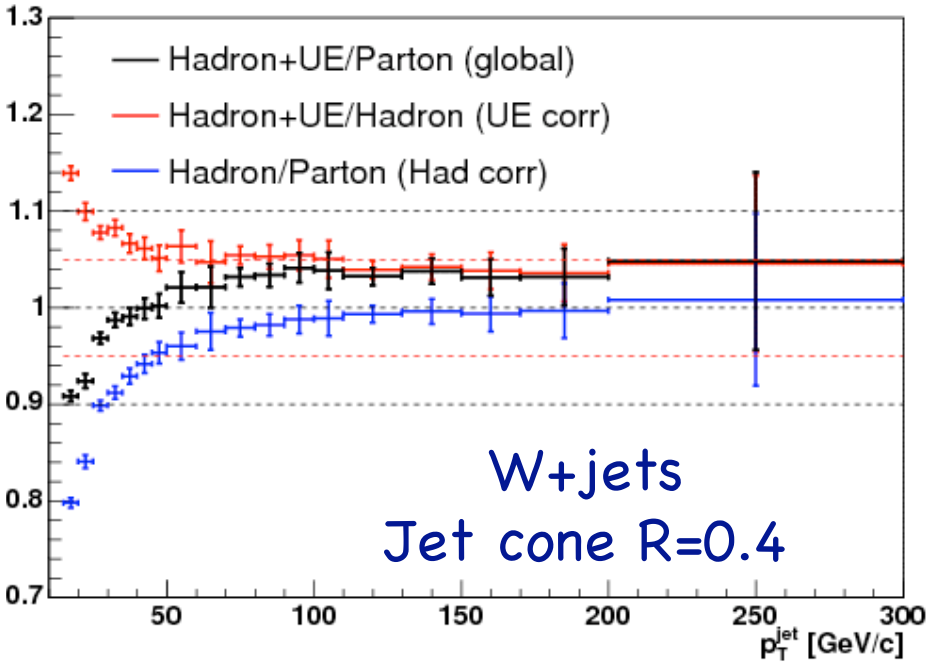


Non perturbative correction

To compare with data need to estimate non perturbative effects:

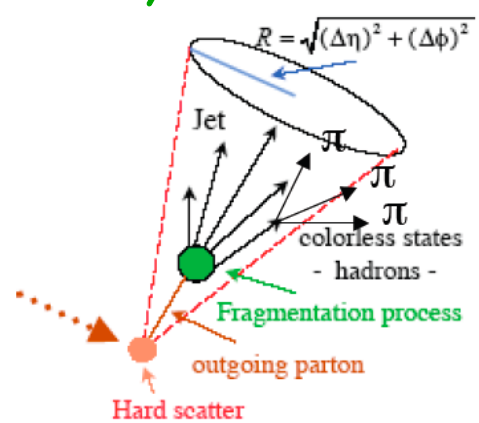
1. Hadronization
2. Underlying event





Relying on phenomenological models tuned on data.

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

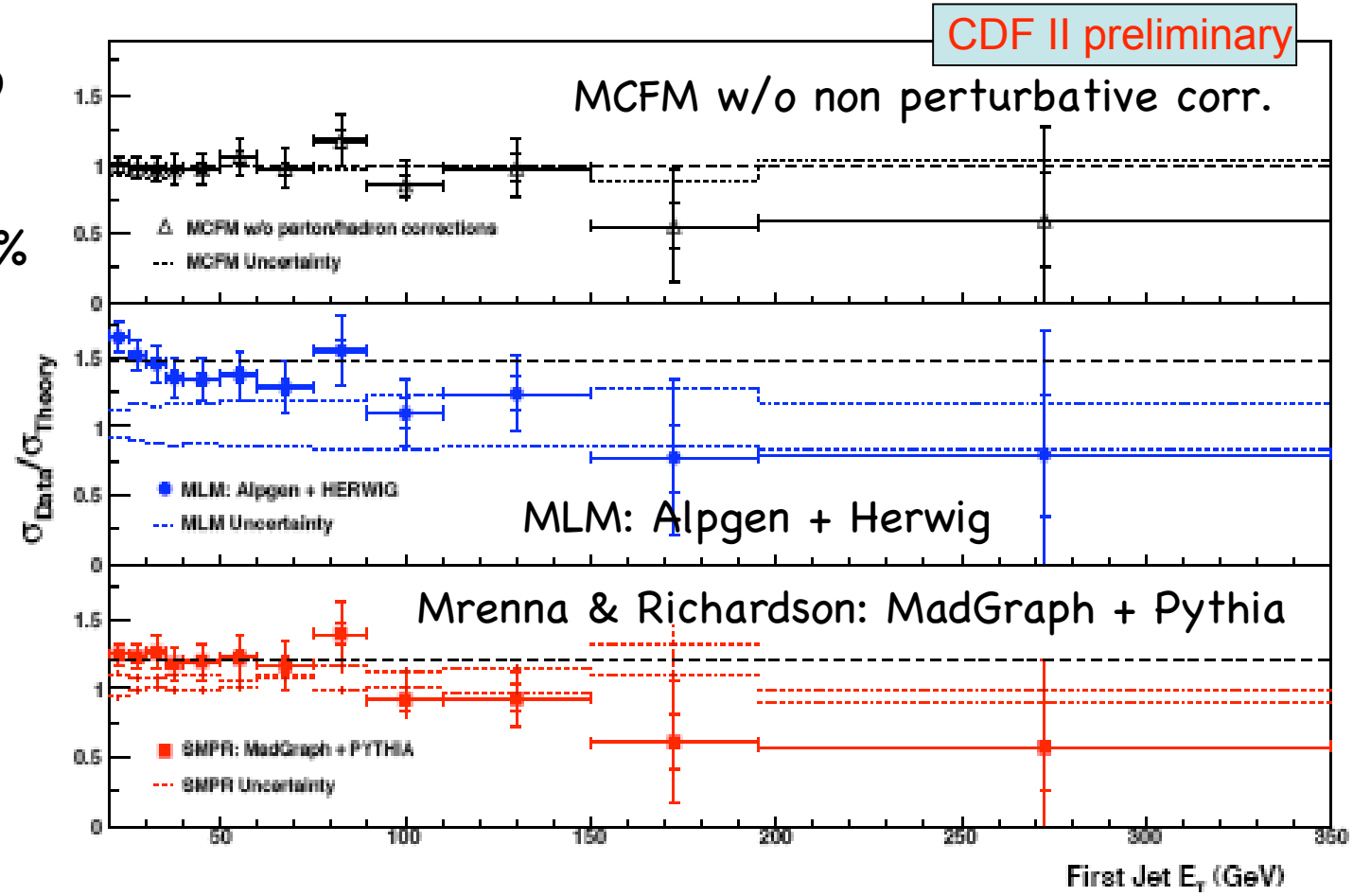


Data theory ratios:

Good agreement NLO
$Q^2=(p_T^{jet})^2$
PDF =CTEQ6.1
Non perturbative ≈5%

Effect of the UE at low E_t^{jet}
PDF=CTEQ5L

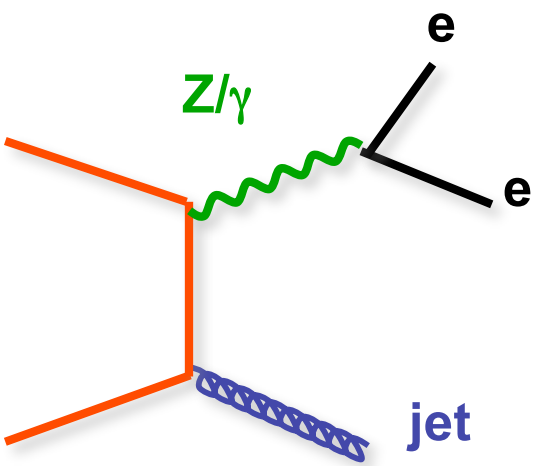
Pythia has a better model of the UE, better agreement with data
PDF=CTEQ5L

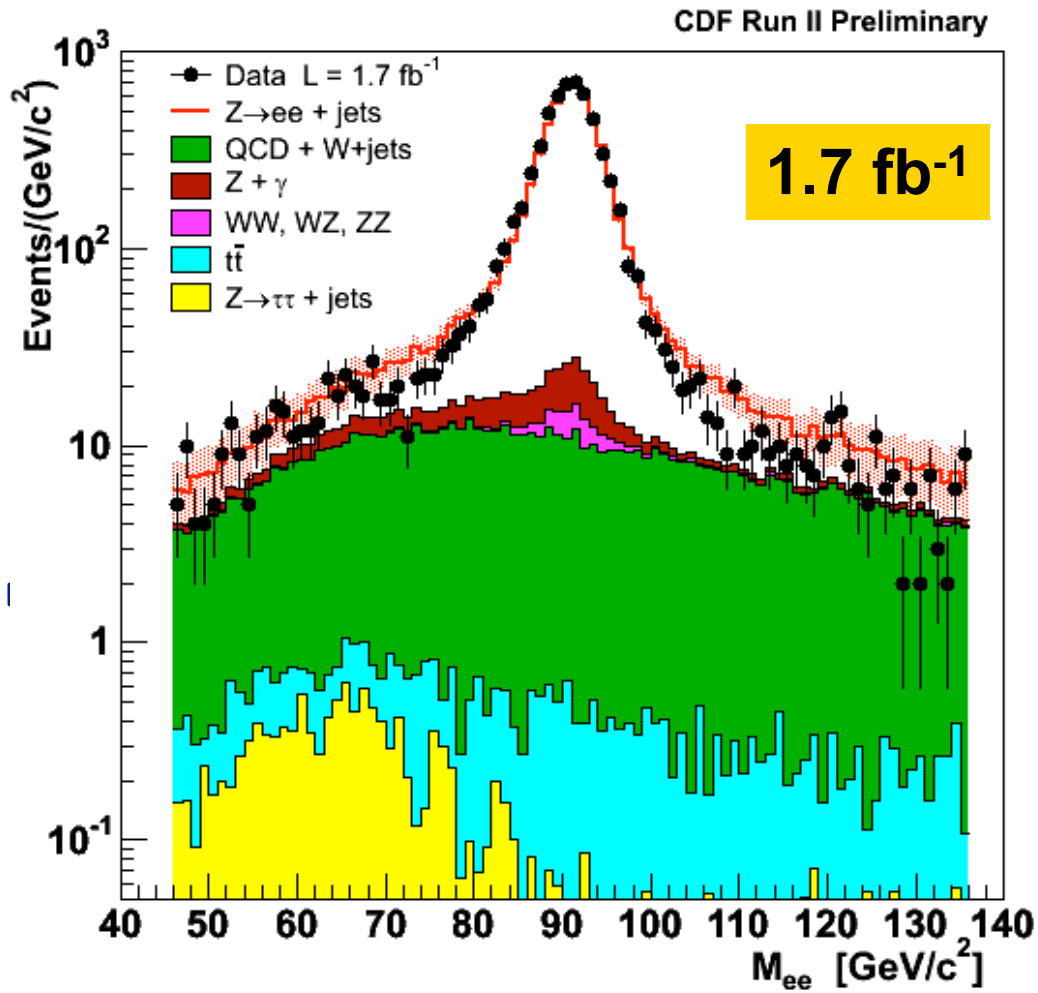


Z+jets measurement

Z+jets measurement

$Z/\gamma \rightarrow ee$ + jets is a very clean signal: background < 10%





Measurement performed in a well defi
kinematic region.

$Z/\gamma \rightarrow ee$ 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; $|y^{jet}|<2.1$; DR(e,jet)>0.7

Z+jet inclusive cross section - p_T^{jet}

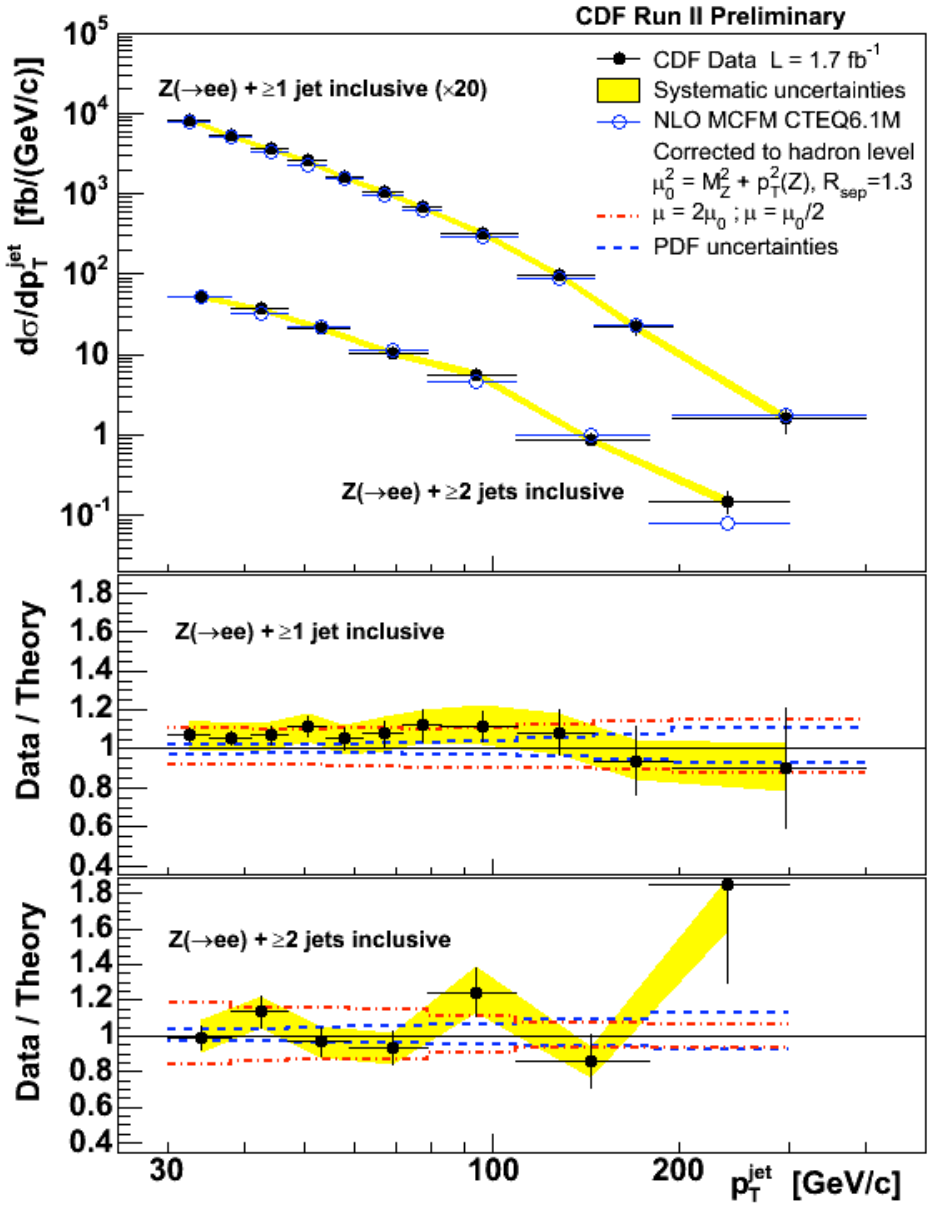
Inclusive jet cross section for Z+≥1 jet and Z+≥2 jets production.

Good agreement between Data and NLO pQCD predictions.

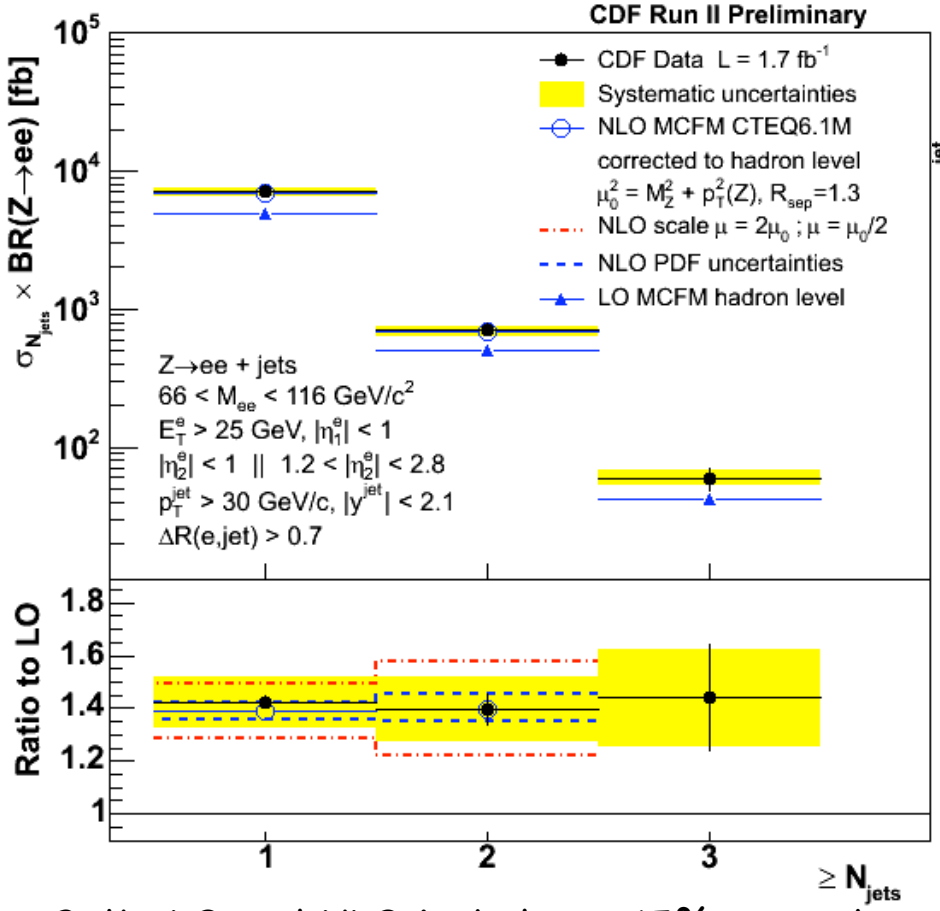
Main systematic at high p_T^{jet} jet energy scale (up to 15%)
ele ID (5%) flat

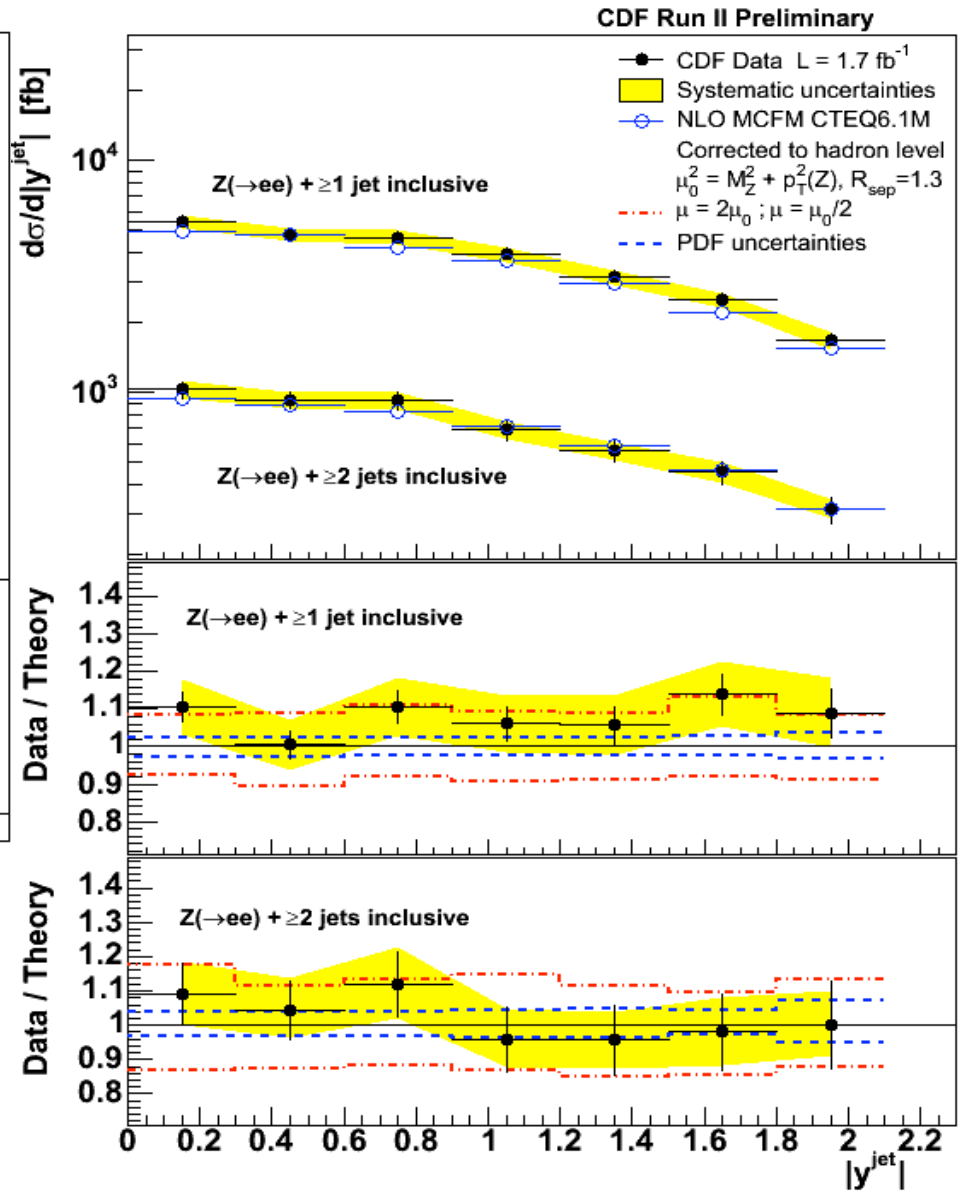
PDF uncertainty varies between 3% @ low p_T^{jet} and 10% @ high p_T^{jet}.

renormalization and factorization scale variation ranges between 10% and 15%.



Z+jet inclusive cross section: N_{jet} & y^{jet}





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

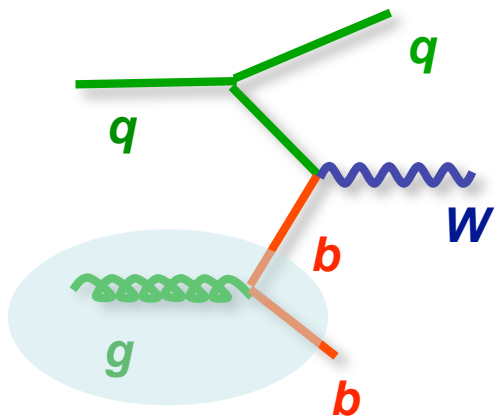
LO underestimates the data by a factor 1.4.

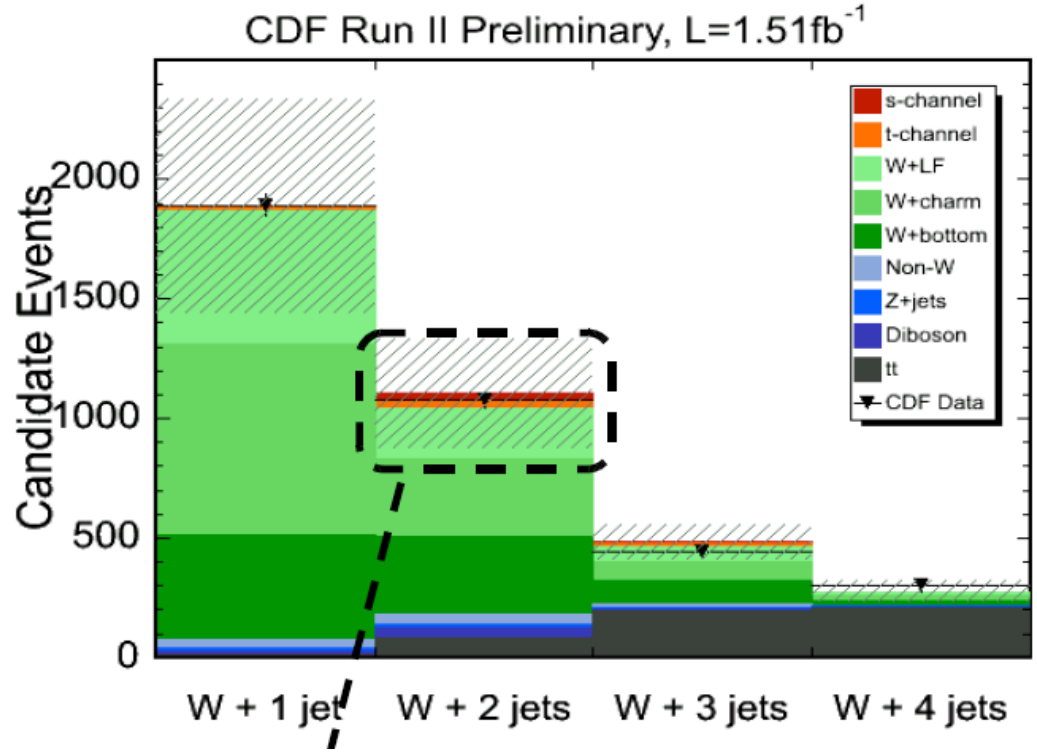
NLO in good agreement with the data.

Data suggest a constant k-factor.

Boson + heavy flavor jets measurement

Motivation

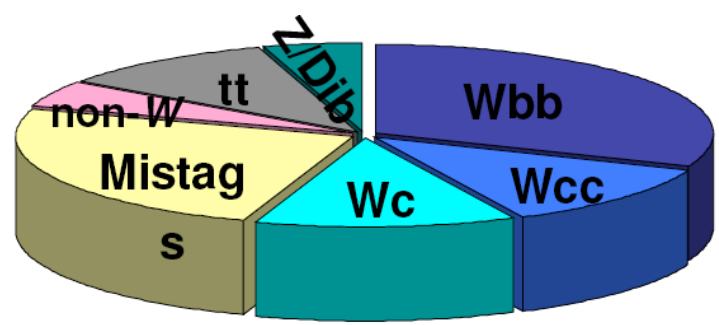




Sensitive to production mechanisms & heavy quarks content in the proton.

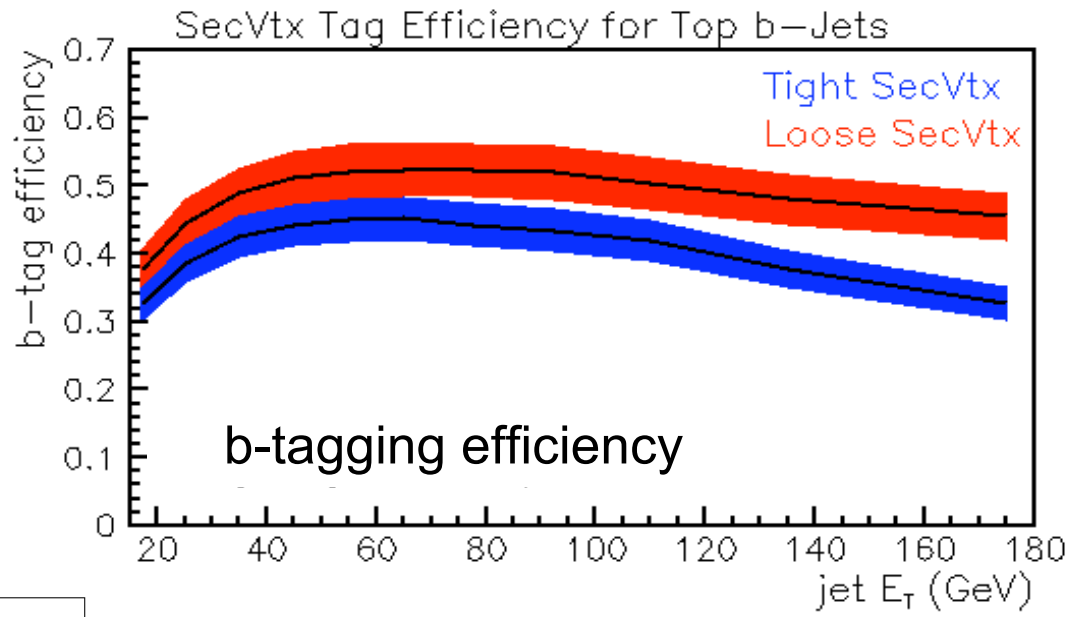
Large uncertainty on W+X. It is crucial to have all these contributions under control for new discoveries.

Boson + heavy flavor processes are the main backgrounds to many new physics searches.

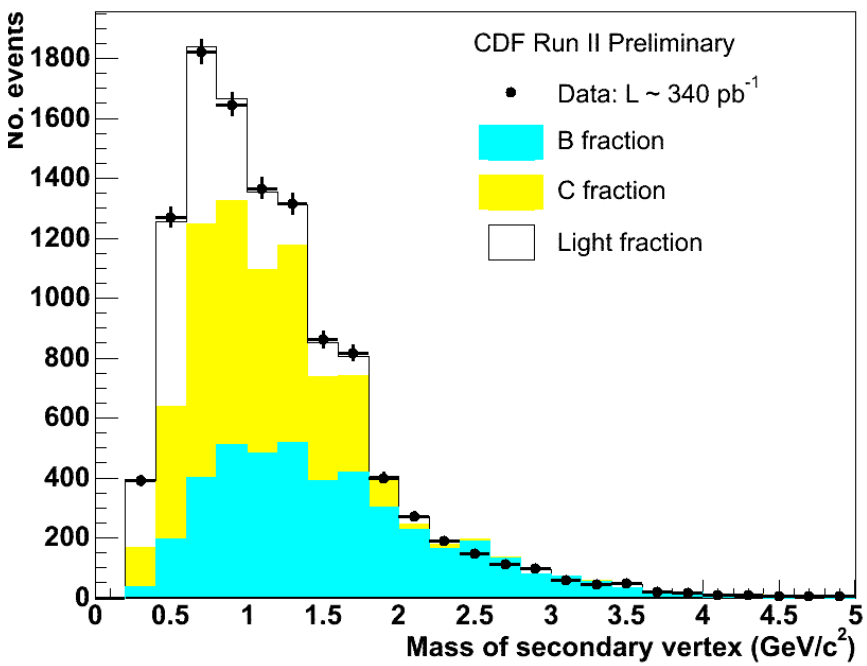


Heavy Flavor Jets: SecVtx tagging

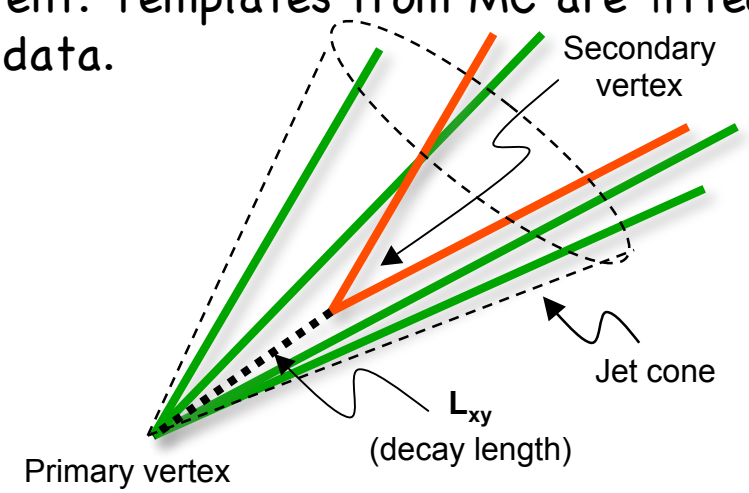
(SecVtx) reconstructs secondary vertices inside jets. Cutting on the distance between the primary and secondary vertices rejects most of light flavor jets.



Templates fitted to the data

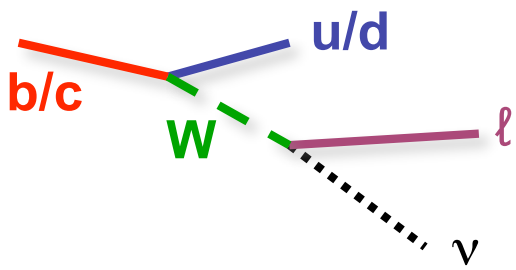


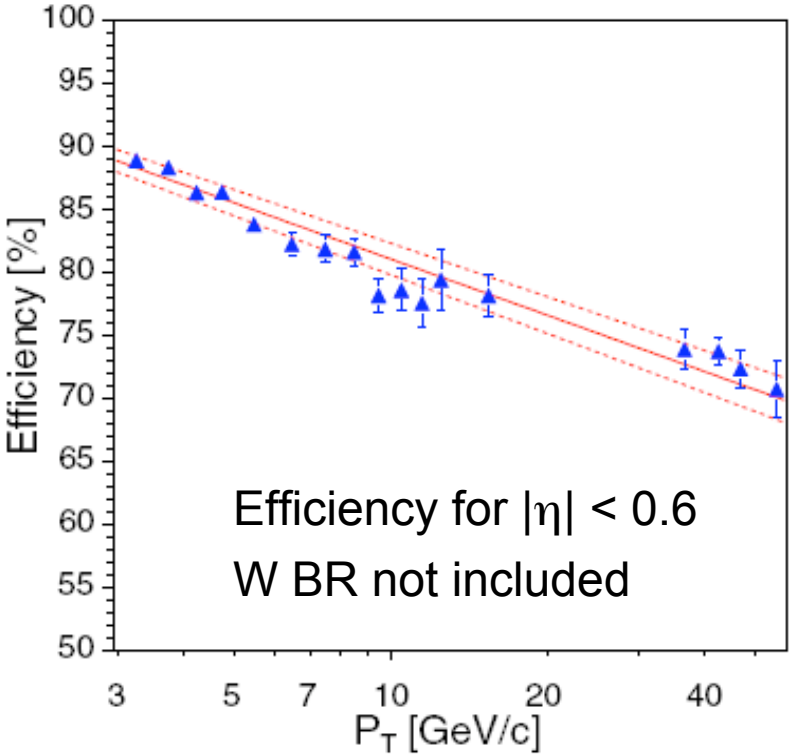
The mass of the secondary vertex is a powerful discriminant to extract the b-jet content. Templates from MC are fitted to the data.

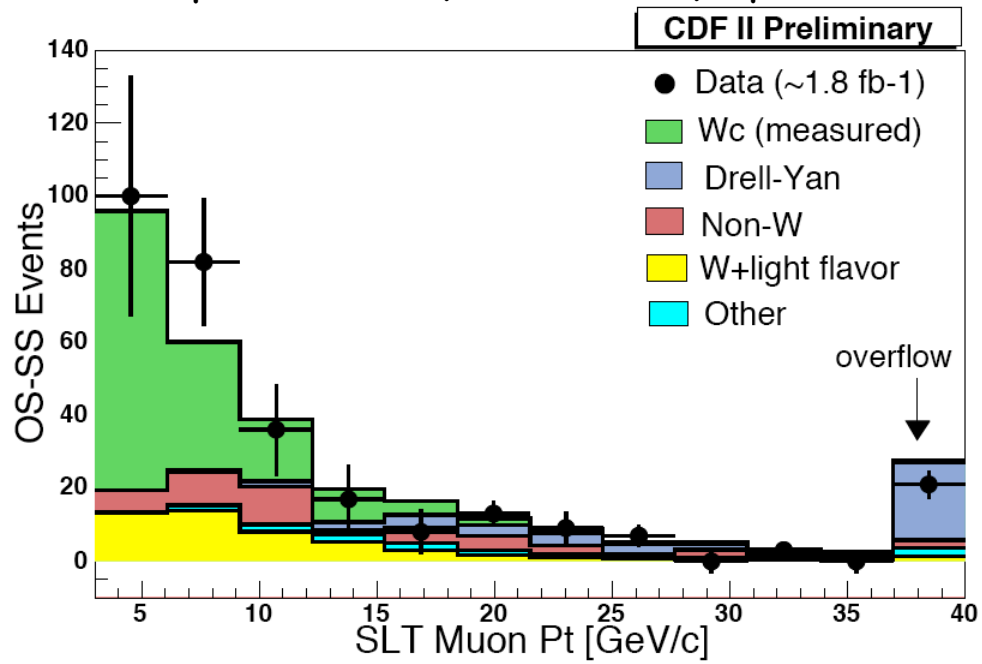


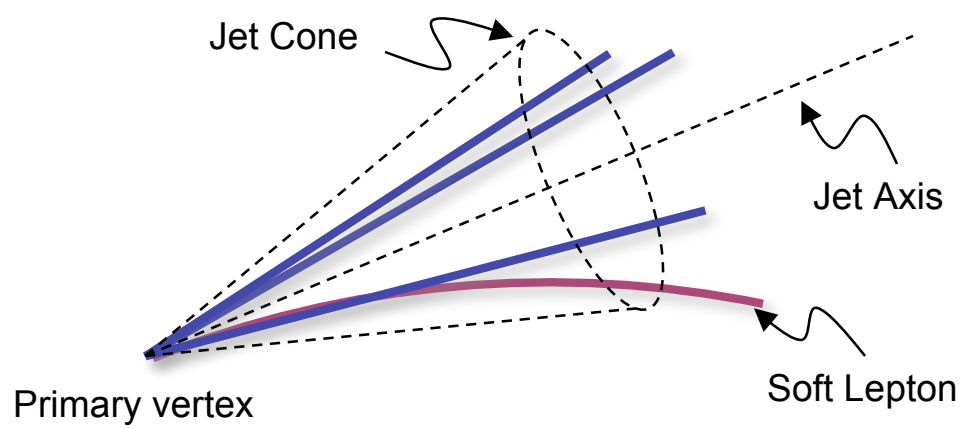
Heavy Flavor Jets: SLT tagging

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







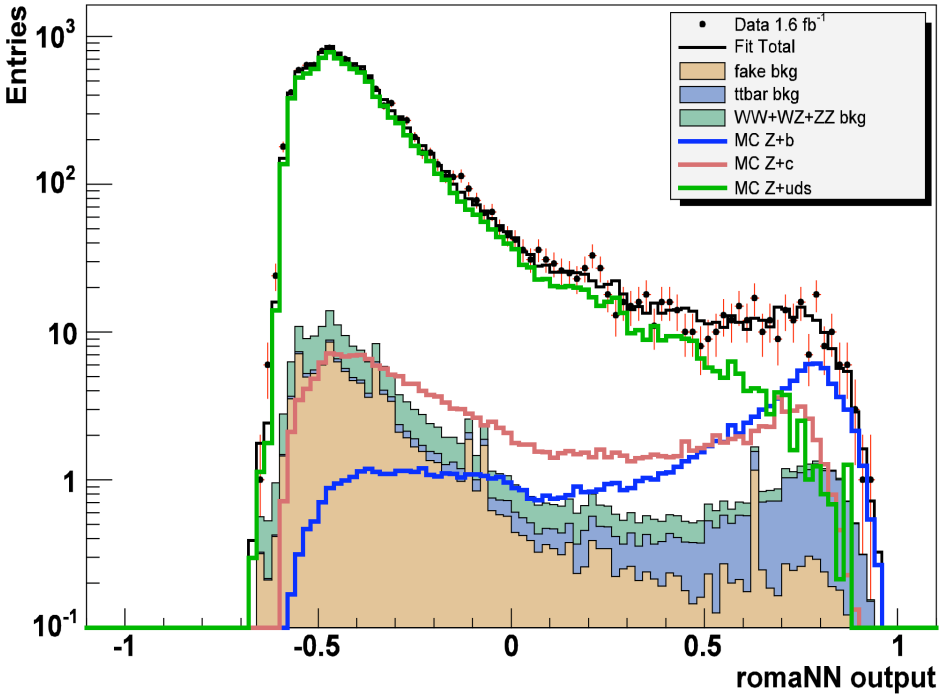


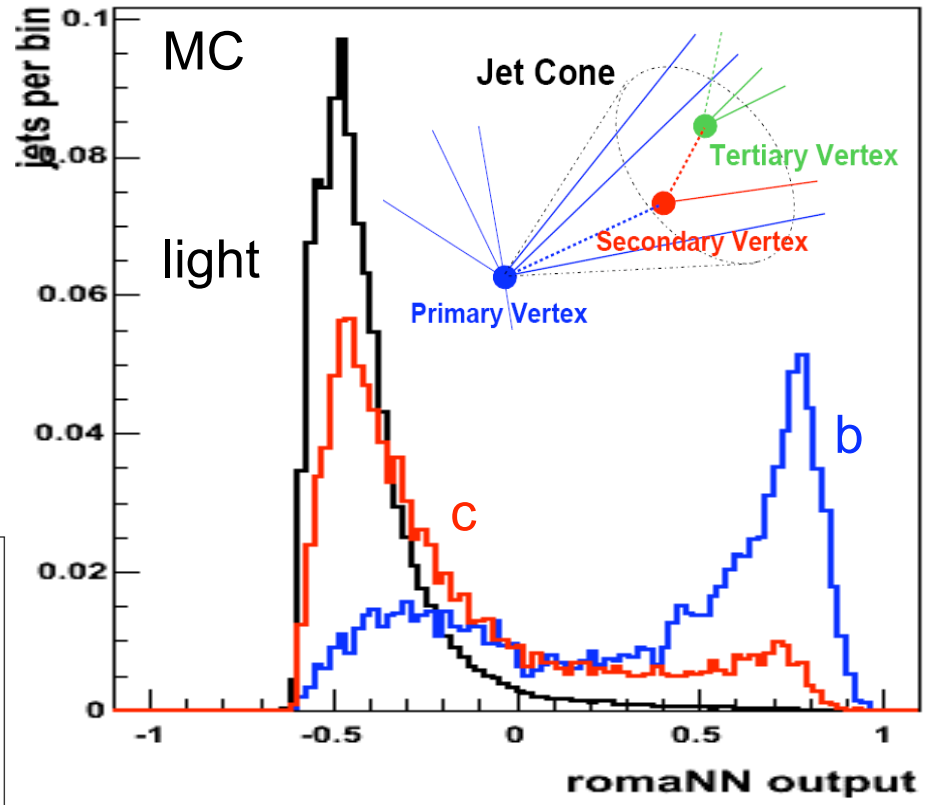
Heavy Flavor Jets: new NN-tagger

Use all the available information

- All the vertices in the jet and their invariant masses.
- displaced but un-vertexed tracks
- soft leptons, JetProb, global jet variables.

Combine all the information in a single variable using neural networks.





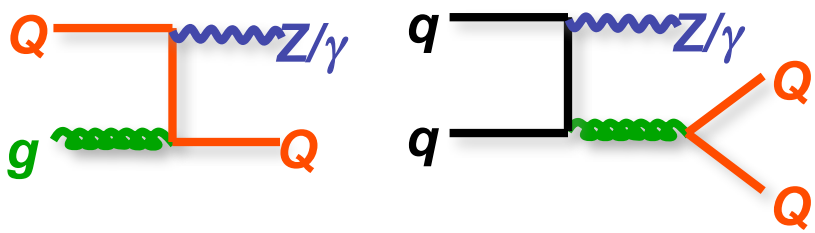
Neural network training performed in a generic sample and then used in the analyses.

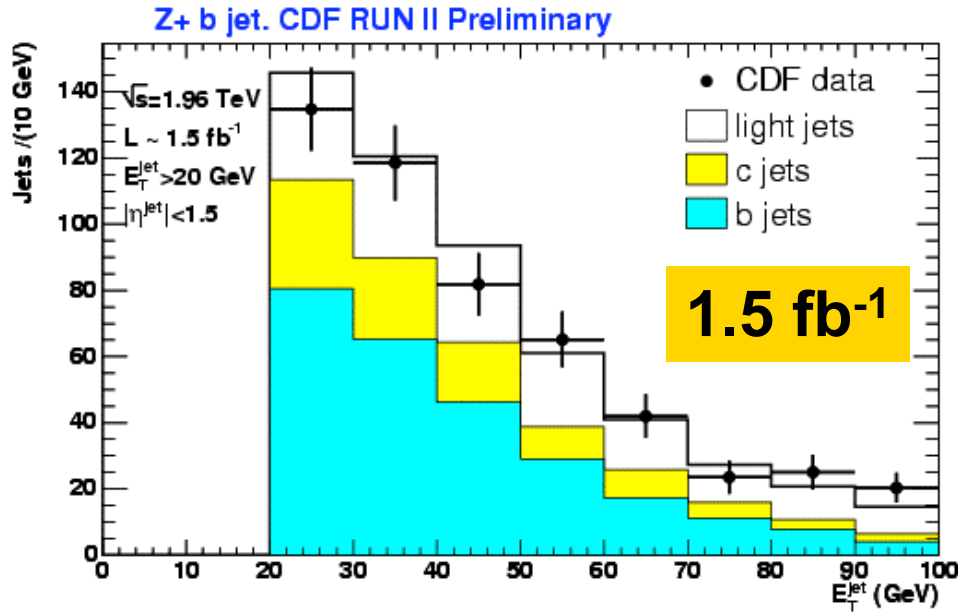
Output as a continuous tagging variable.

Good b-c-light statistical separation.

Work in progress…

Z+b Cross Section





Jets: E_T^{jet}>20 GeV and $|\eta|$<1.5

b, c, light fraction from template fit to the secondary vertex mass distribution.

NLO pQCD calculation by MCFM.

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

Data are well described by Pythia but are underestimated (2σ) by the NLO prediction.

E_T^{jet}>20 GeV, $|\eta^{jet}|$<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 %

W+c Cross Section

Sensitive to s-quark proton PDF

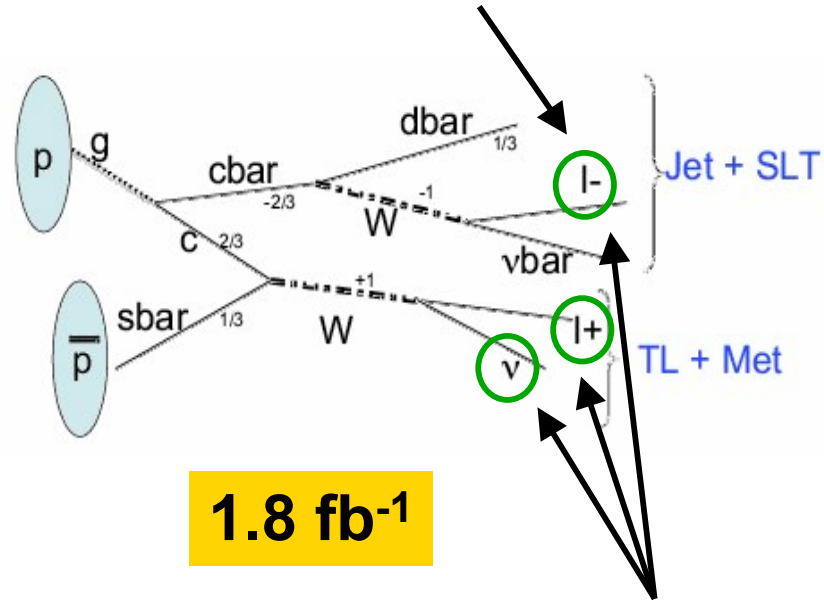
c-jet identified by the presence of a soft muon inside the jet.

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

Observable:

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

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



1.8 fb^{-1}

Events selection a SLT jet, a charged lepton and MET from the W decay.

$$\sigma_{Wc}(pt_c > 8, |\eta_c| < 3) \times BR(W \to \ell\nu)$$
$$= 28.5 \pm 8.2(\text{stat})^{+4.0}_{-4.3}(\text{syst}) \pm 1.7(\text{lum})\ \text{pb}$$

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

Conclusions

Boson+jets: 15 years balance

Make the measurement corrected for all know detector effects.

✓detector unfolding

...reduce as much as possible the model dependence

✓observable as close as possible to what is accessible by detector

more clean and easy comparison against theory.
Critical input to validate Monte Carlo models vastly employed in all kinds of measurements and new physics searches.

✓NLO & LO pQCD calculation are not complete, they serve different purposes and parameters need to be tuned on data.

✓NLO (when available) + non pQCD correction gives a good description of data.

✓LO ME with matching gives a good description of the kinematic, k-factor≈1.4.

✓Soft physics important at low E_t^{jet}. Tunings of Pythia give good description, but need always to be checked against data.

By 2009 with 6 fb^{-1} we expect new results to further improve our description of boson+jets processes and provide better inputs to the LHC experiments.

Boson + jets at LHC

Boson + jets cross sections at LHC at least x10 with respect to Tevatron.
This physics is definitely part of the early LHC physics programme!
After having:

- ✓ calibrated and understood the detectors
- ✓ measured efficiencies
- ✓ "re-understood" SM @ 14TeV (Minimum Bias, Underlying Event, jets, W, Z, top)

Measure main backgrounds to new physics boson+jets: & top

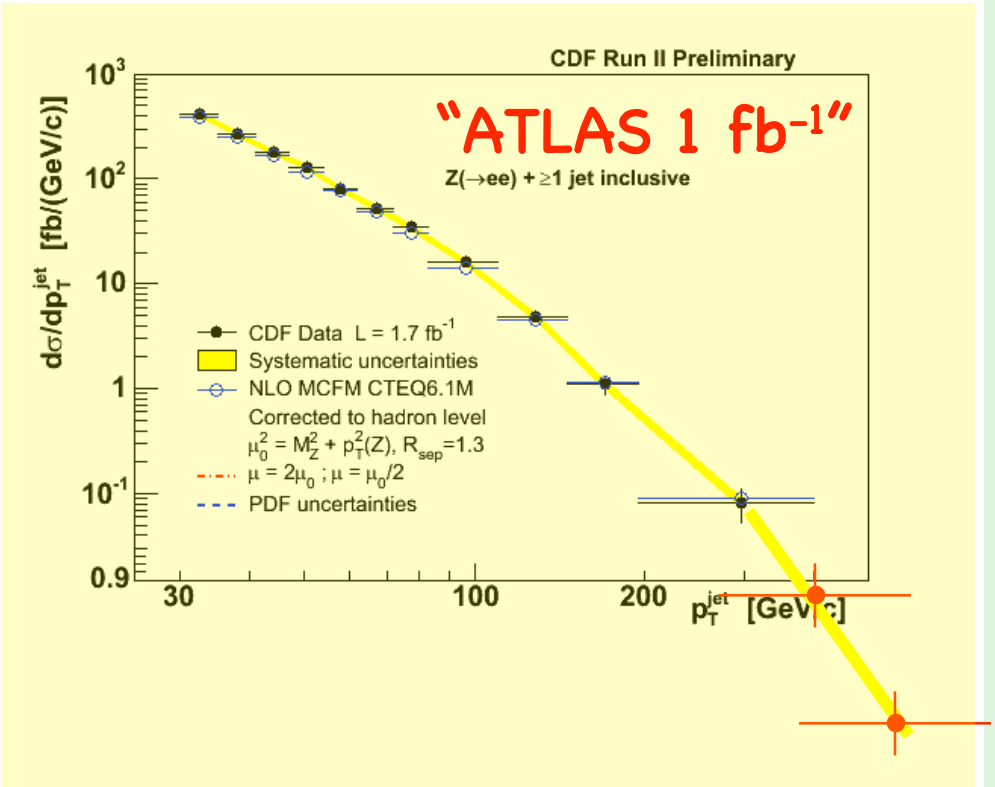
W+jets more difficult:

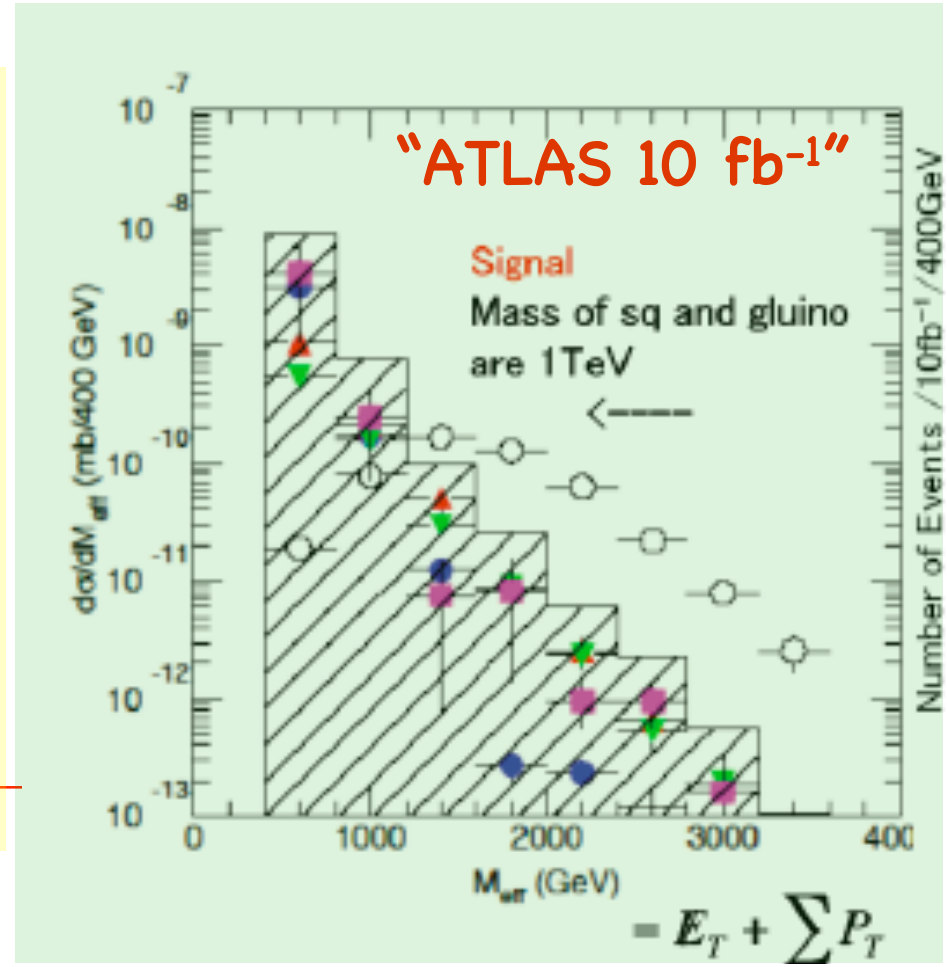
- ✓ Multi-jet background (higher jet σ)
- ✓ top background subtraction (top σ x100 than Tevatron)
- ✓ Understand Missing Energy

Z+jets easier:

- ✓ Z boson easier to reconstruct and select
- ✓ almost background free (<10%)

Boson + jets at LHC: a possible scenario





Summary

CDF has contributed a number of measurements to the understanding of boson production in association with jets, among others:

- ✓ W+jets cross sections (320pb^{-1}):
  - ✓ Extensive comparison against matched LO+parton shower predictions
  - ✓ LO shows a k-factor ≈ 1.4.
- ✓ New Z+jets cross sections (1.7 fb^{-1}):
  - ✓ NLO plus non-perturbative correction in good agreement with the measurements.
  - ✓ Pythia tunings describe non-perturbative physics.
- ✓ New Z+b-jets cross section (1.5 fb^{-1}):
  - ✓ Pythia describes the data.
  - ✓ NLO underestimates the data - under investigation.
- ✓ New W+c-jet cross section (1.8 fb^{-1}):
  - ✓ LO Alpgen + MLM matching in good agreement with data

Boson + jets will keep us busy in the next years both at the Tevatron and LHC