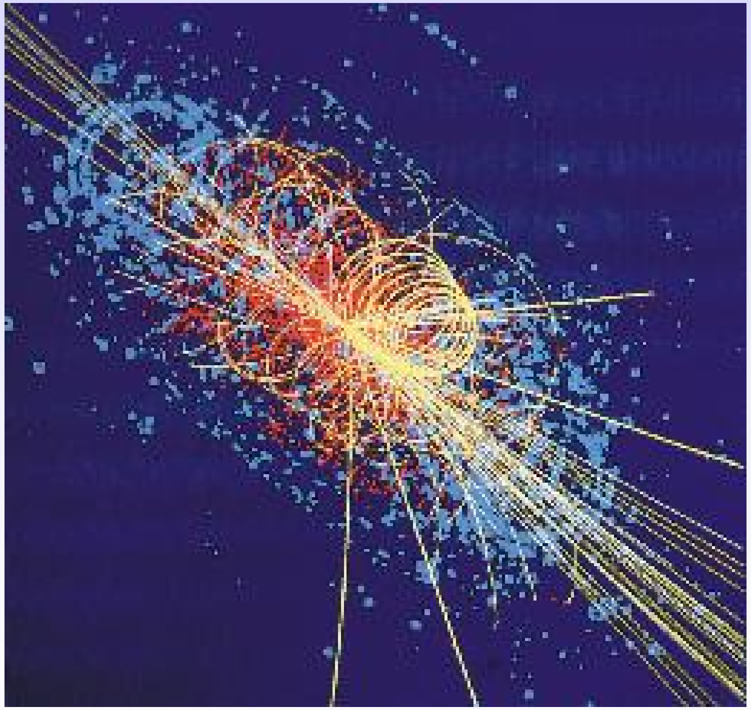
Physics at Hadron Colliders

Part 2

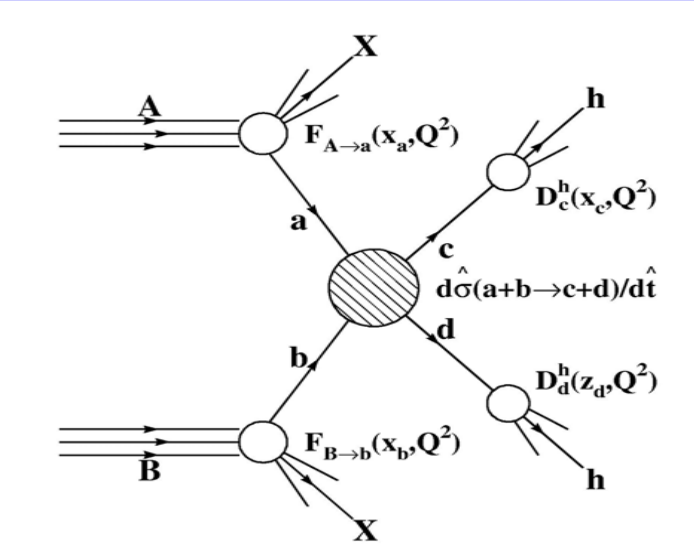


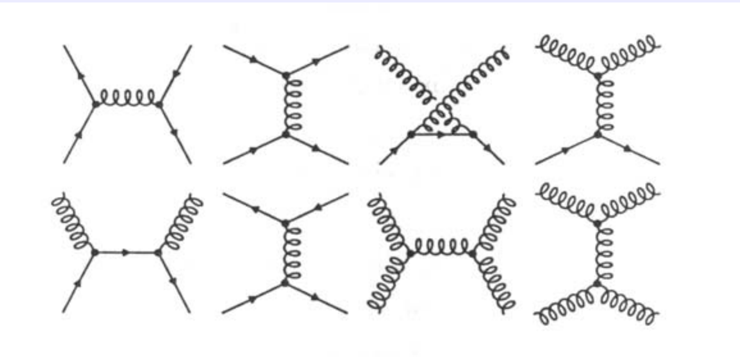
Standard Model Physics

Test of Quantum Chromodynamics
- Jet production
- W/Z production
- Production of Top quarks

Precision measurements
- W mass
- Top-quark mass

QCD processes at hadron colliders



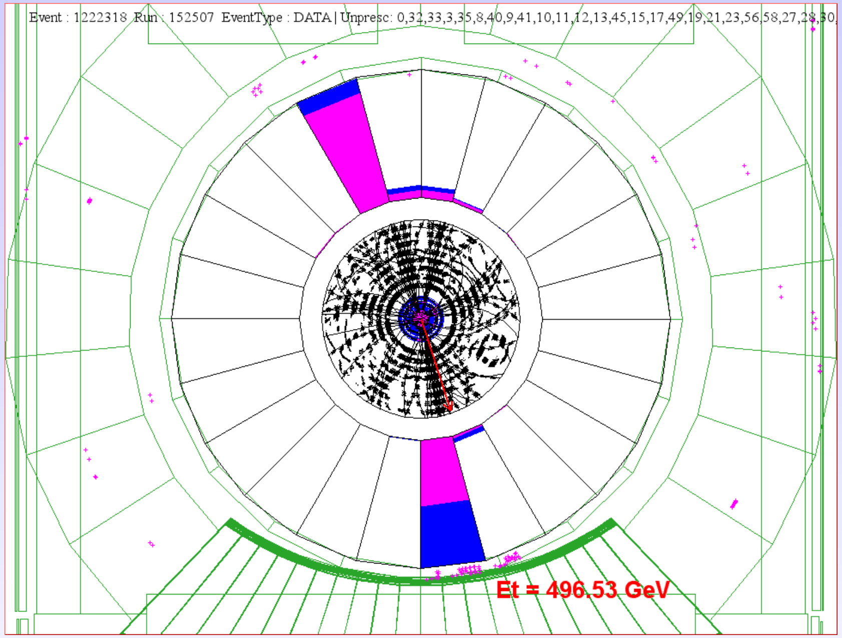


- Hard scattering processes are dominated by QCD jet production
- Originating from quark-quark, quark-gluon and gluon-gluon scattering
- Due to fragmentation of quarks and gluons in final state hadrons
  → Jets with large transverse momentum P_T in the detector
- Cross sections can be calculated in QCD (perturbation theory)

Comparison between experimental data and theoretical predictions constitutes an important test of the theory.

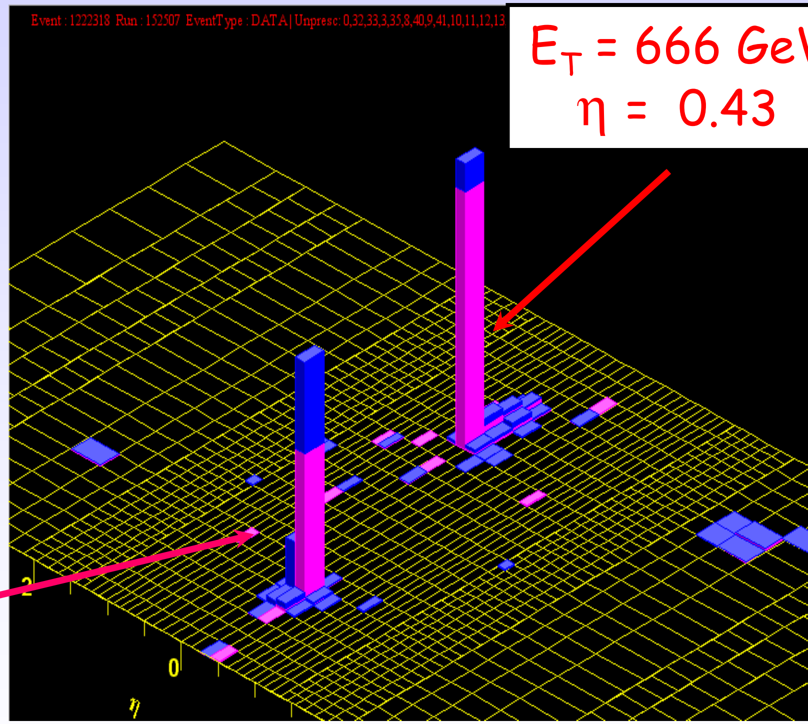
Deviations? → Problem in the experiment ?
Problem in the theory (QCD) ?
New Physics, e.g. quark substructure ?

A two jet event at the Tevatron (CDF)



CDF (ϕ-r view)

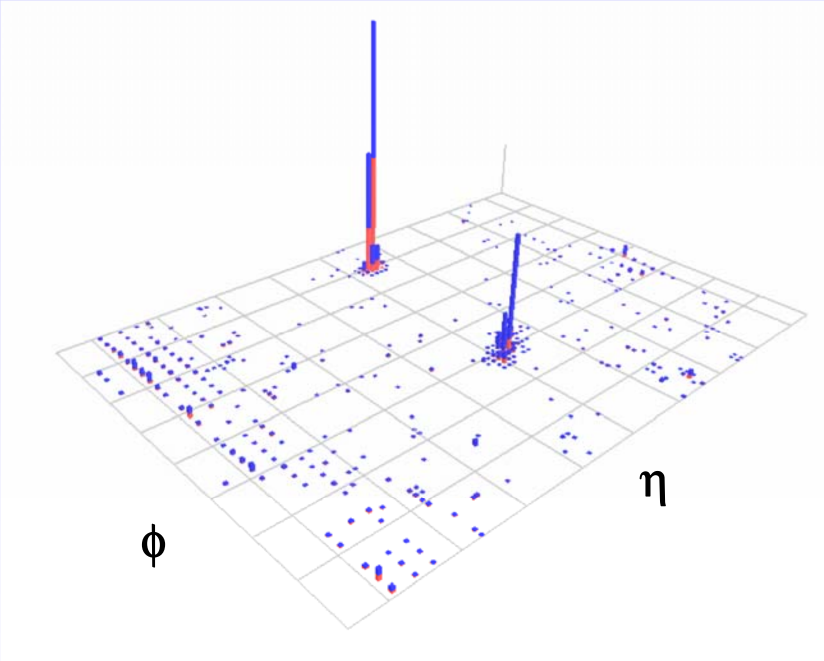
Dijet Mass = 1364 GeV/c^2

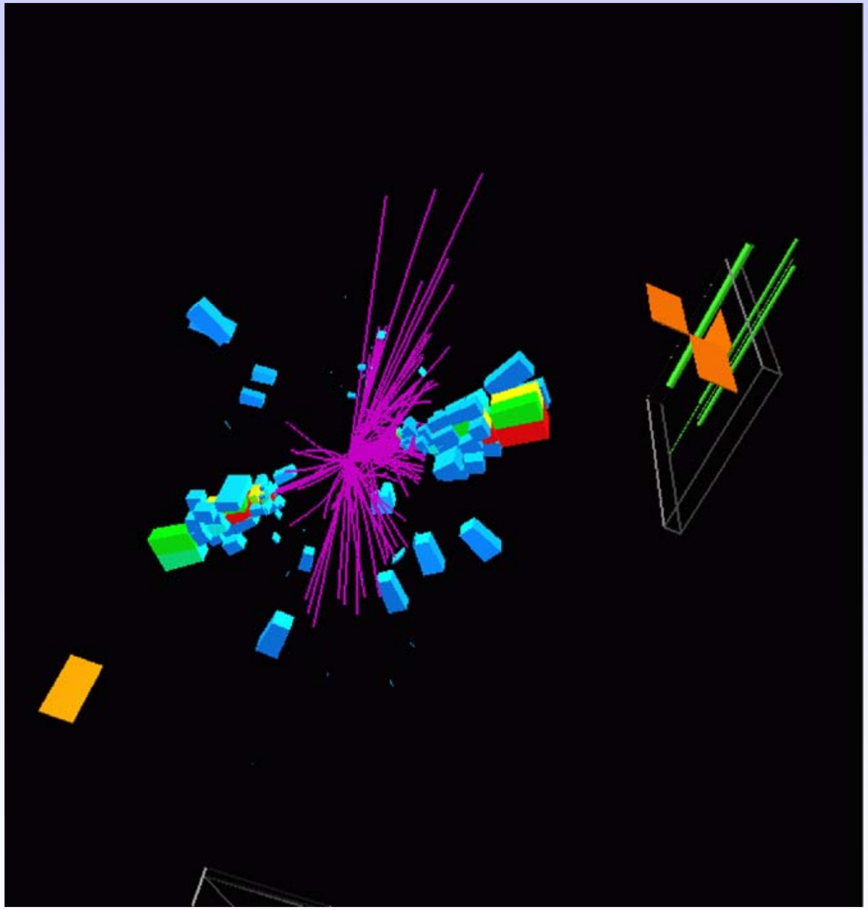


E_T = 666 GeV
η = 0.43

E_T = 633 GeV
η = -0.19

A two jet event in the DØ experiment



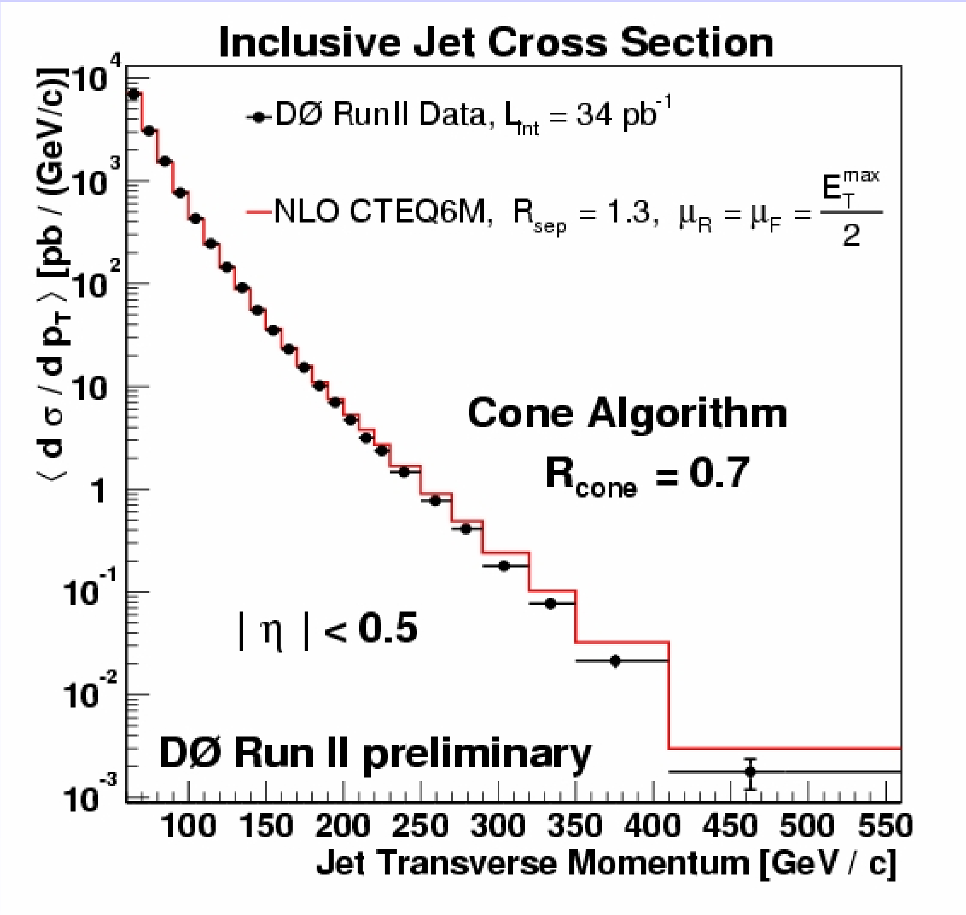


M_{jj} = 838 GeV/c^2

$p_T(1)$ = 432 GeV/c

$p_T(2)$ = 396 GeV/c

Test of QCD Jet production



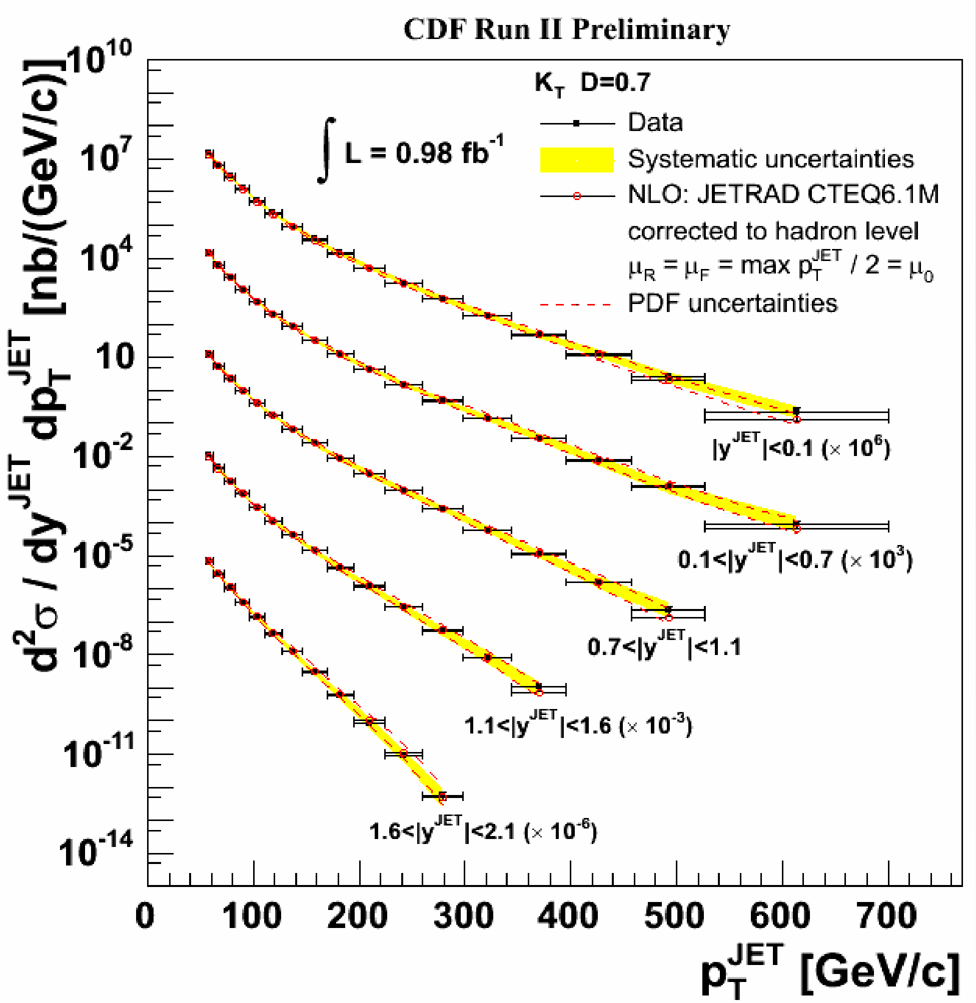
Data from the DØ experiment (Run II)

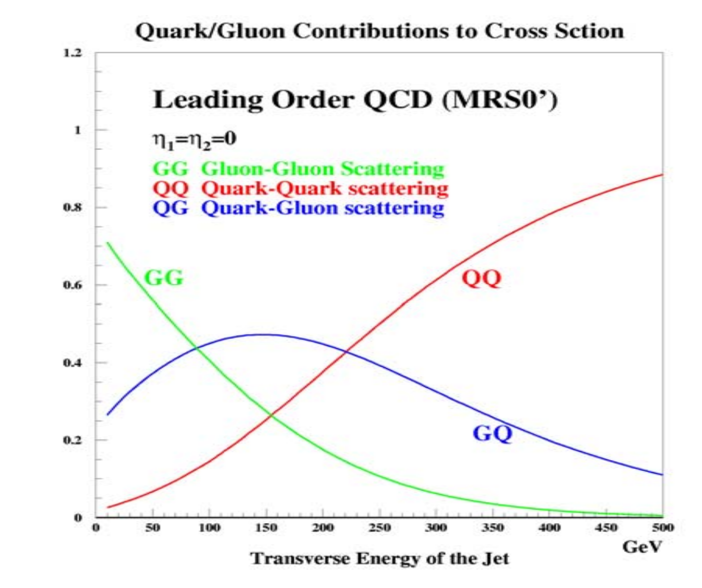
Inclusive Jet spectrum as a function of Jet-P_T

very good agreement over many orders of magnitude !

within the large theoretical and experimental uncertainties

Similar data from the CDF experiment





contributions of the various sub-processes to the inclusive jet cross section

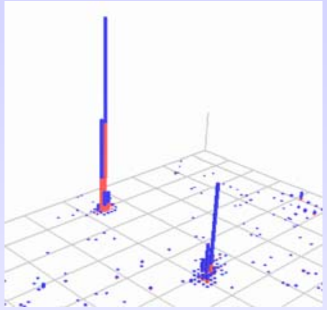
Data corresponding to ~1 fb^{-1}

Double differential distributions in P_T and η

Main experimental systematic uncertainty: Jet Energy Scale

- A Jet is NOT a well defined object (fragmentation, detector response)

  - one needs an algorithm to define a jet, to measure its energy
  (e.g., a cone around a local energy maximum in the calorimeter, cone size adapted such that a large fraction of jet energy is collected,
  typical values: $\Delta R = \sqrt{\Delta\Phi^2 + \Delta\eta^2} = 0.7$

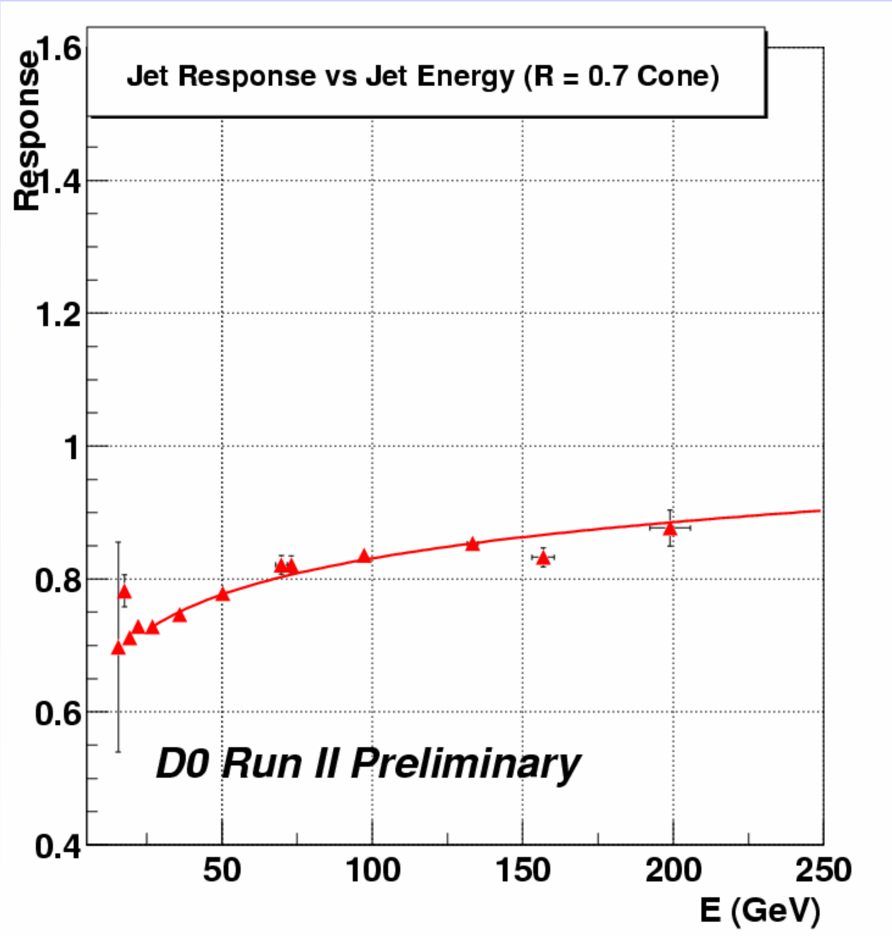


- Cone energy ≠ parton energy

Main corrections:

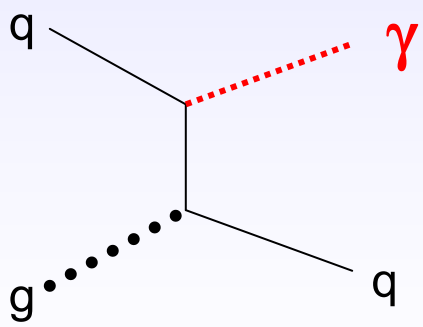
- In general, calorimeters show different response to electrons/photons and hadrons (see lectures on detector physics)
- Subtraction of offset energy not originating from the hard scattering
  (inside the same collision or pile-up contributions, use minimum bias data to extract this)
- Correction for jet energy out of cone
  (corrected with jet data + Monte Carlo simulations)

Main experimental systematic uncertainty: Jet Energy Scale



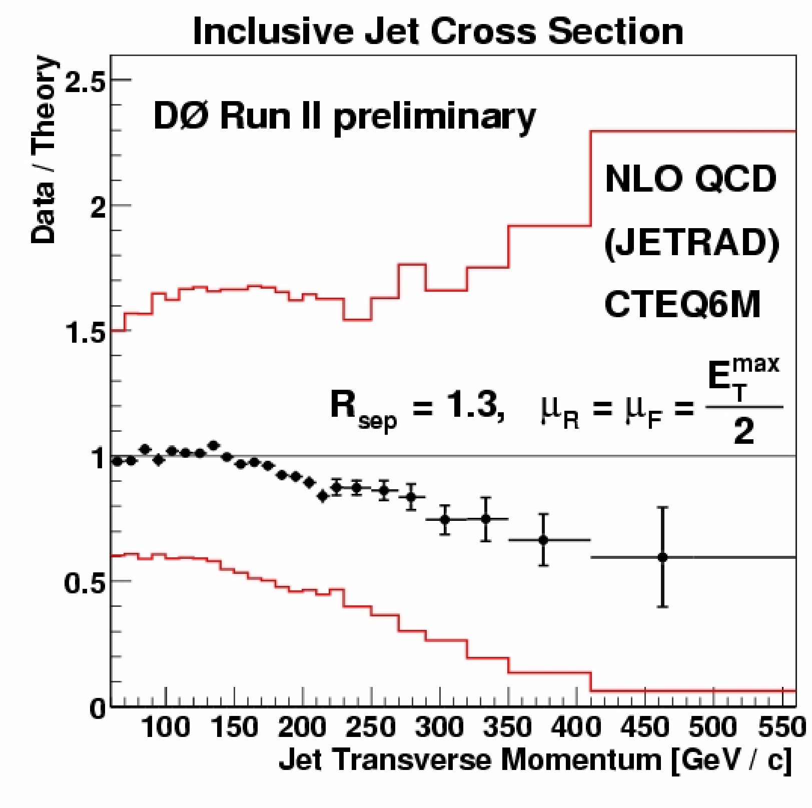
Jet response correction in DØ:

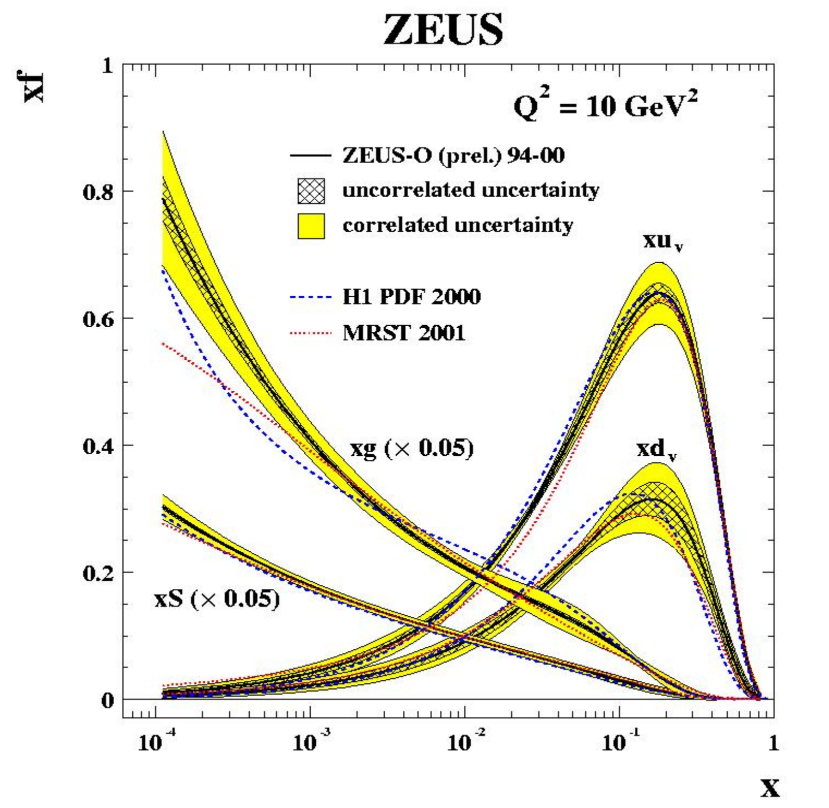
- measure response of particles making up the jet
- use photon + jet data - calibrate jets against the better calibrated photon energy



Comparison with Theory

– Fully corrected inclusive jet cross section

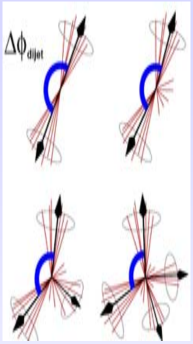


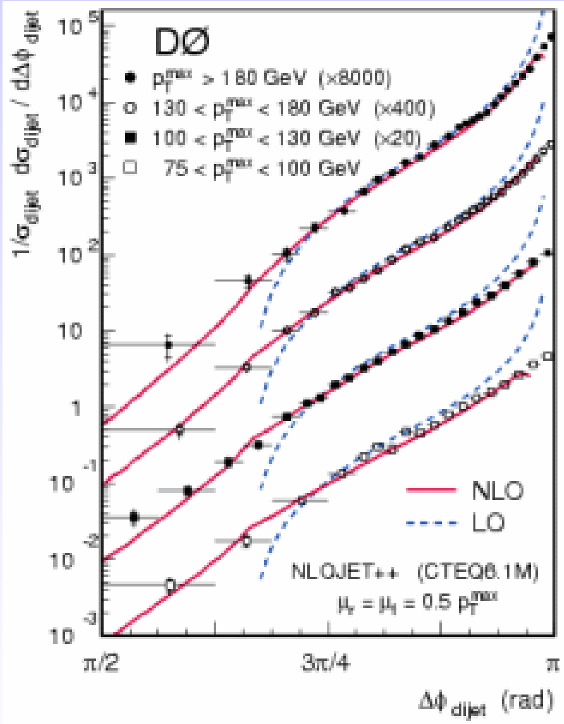


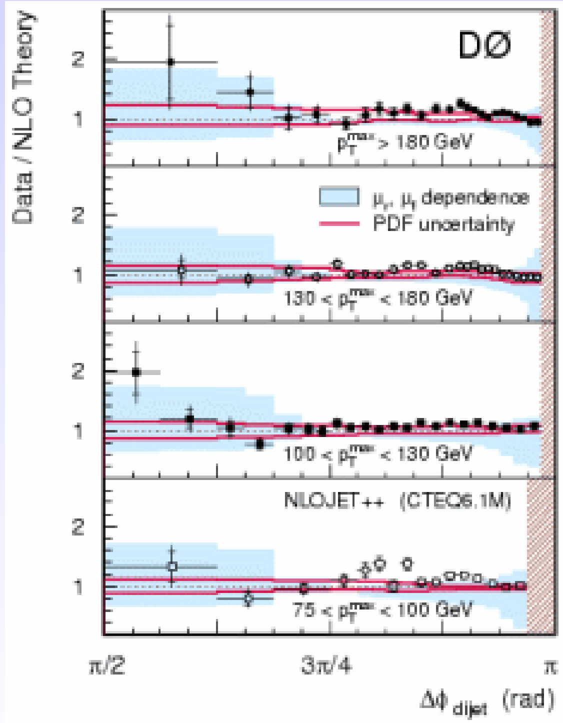
Systematic uncertainties: - jet energy scale (red band)
- parton density functions
- theory: renormalization scale

Di-jet angular distributions:

- reduced sensitivity to Jet energy scale
- sensitive to higher order QCD corrections



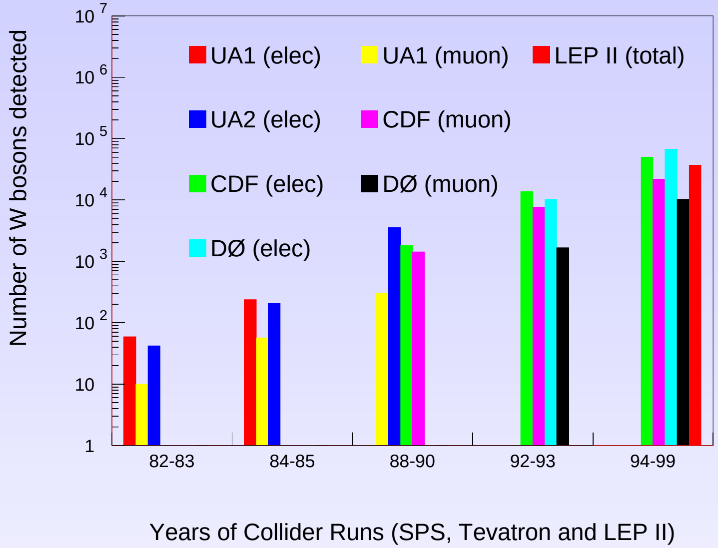


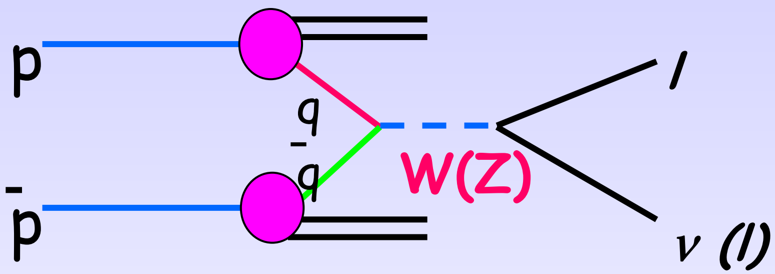


Good agreement with
Next-to-leading order QCD-predictions

Test of W and Z production

Number of detected W-bosons:





Drell-Yan production process (leading order)

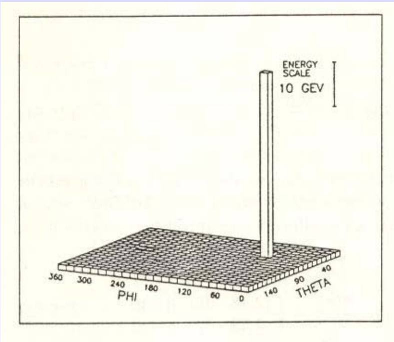
Tevatron: expected rates for 2 fb^{-1}: 3 Mio $W \to \ell \nu$ events

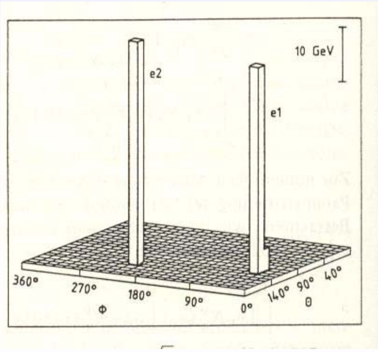
LHC: expected rates for 10 fb^{-1}: 60 Mio $W \to \ell \nu$ events

How do W and Z events look like ?

As explained, leptons, photons and missing transverse energy are key signatures at hadron colliders

→ Search for leptonic decays: $W \to \ell \nu$ (large $P_T(\ell)$, large P_T^{miss})
$Z \to \ell \ell$



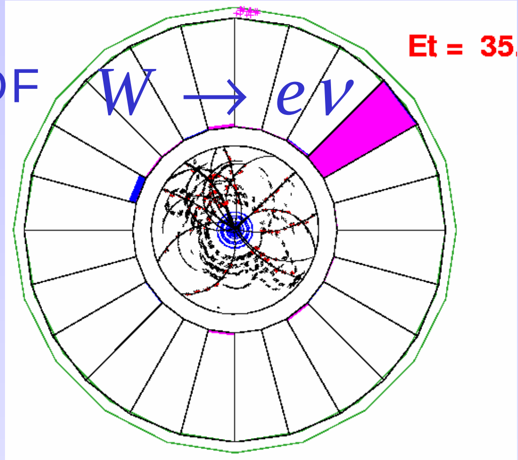


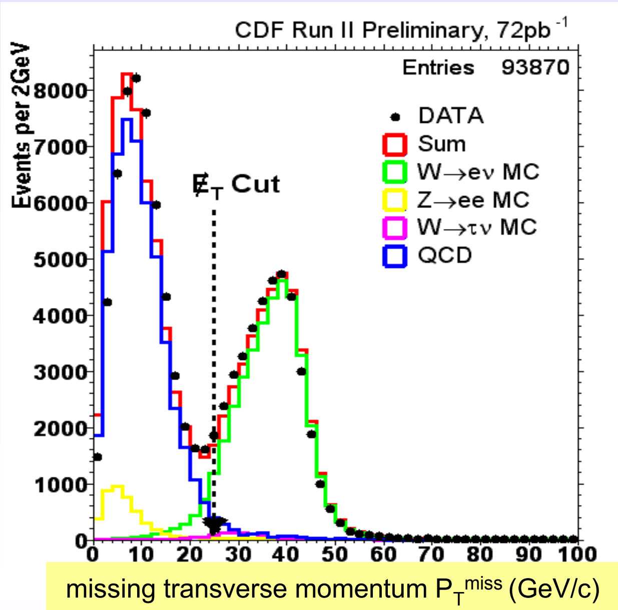
A bit of history: one of the first W events seen; UA2 experiment

W/Z discovery by the UA1 and UA2 experiments at CERN (1983/84)

Today's W / Z $\rightarrow$ eν / ee signals

CDF





Trigger:

- **Electron candidate > 20 GeV/c**

Electrons

- **Isolated el.magn. cluster in the calorimeter**
- **P_T> 25 GeV/c**
- **Shower shape consistent with expectation for electrons**
- **Matched with tracks**

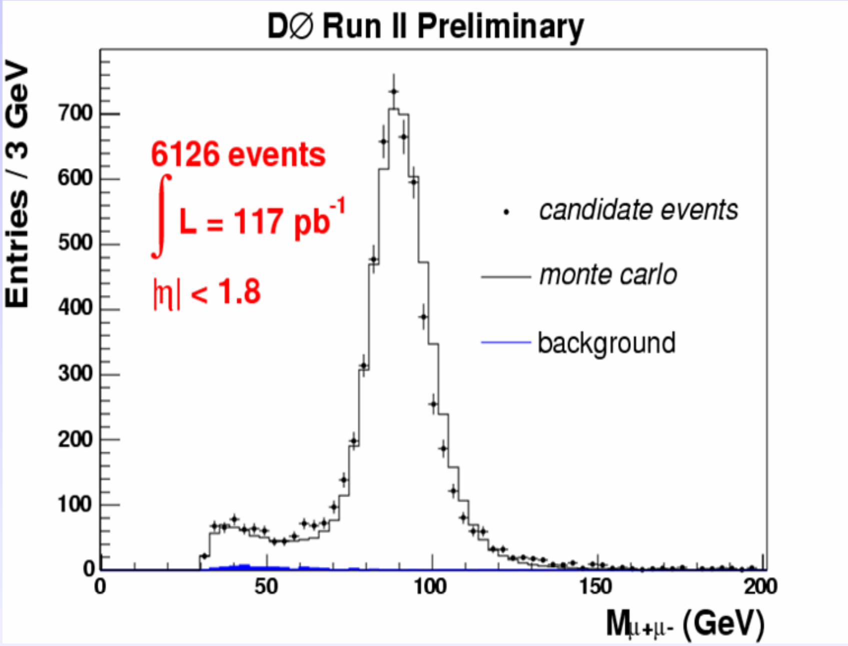
Z → ee

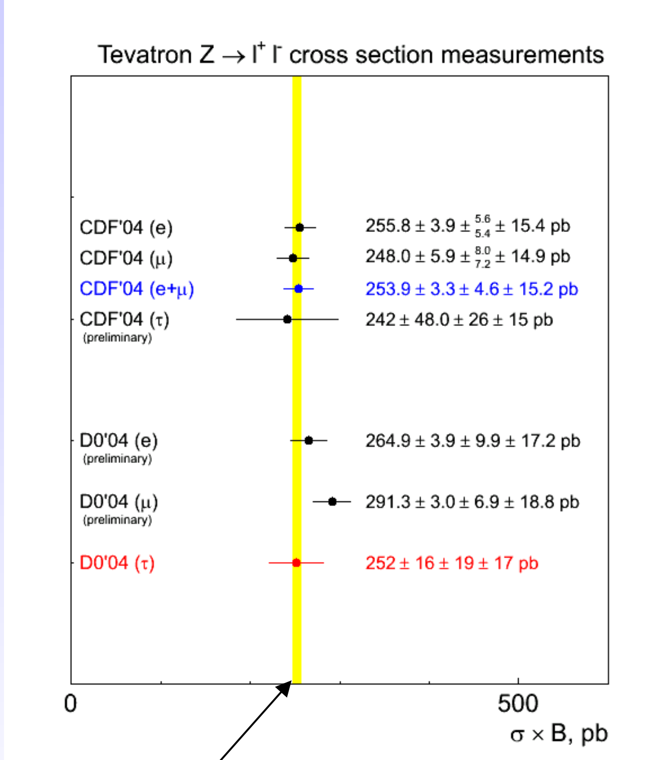
- **70 GeV/c² < m_{ee} < 110 GeV/c²**

W → eν

- **Missing transverse momentum > 25 GeV/c**

Z→ ℓℓ cross sections

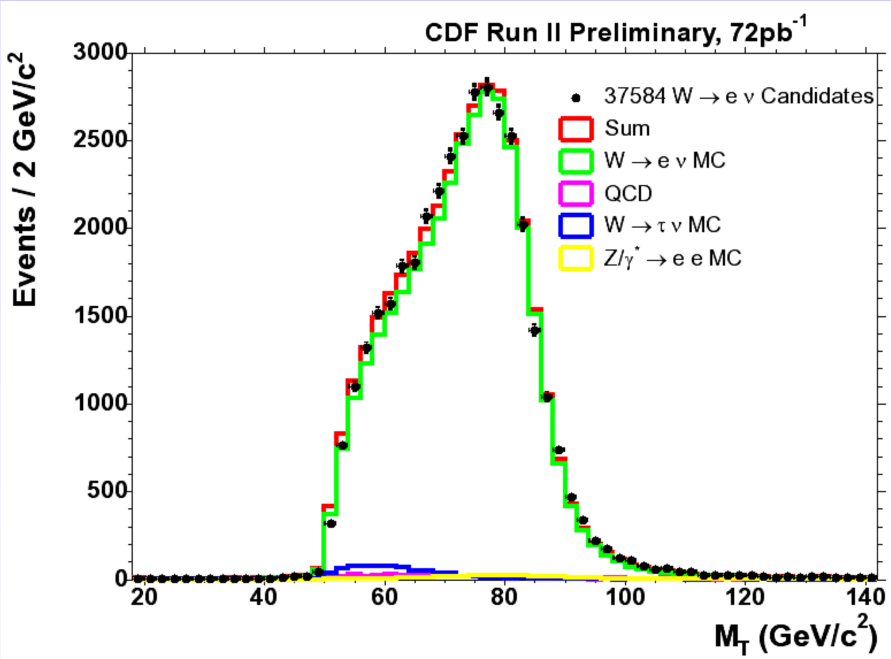


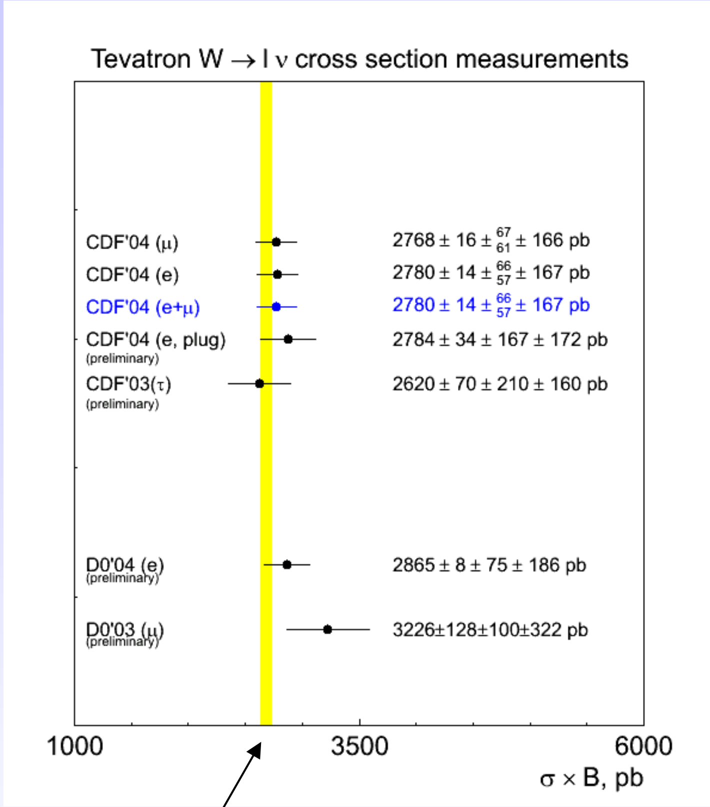


Good agreement with NNLO QCD calculations
C.R.Hamberg et al, Nucl. Phys. B359 (1991) 343.

Precision is limited by systematic effects (uncertainties on luminosity, parton densities,...)

W → ℓν Cross Section





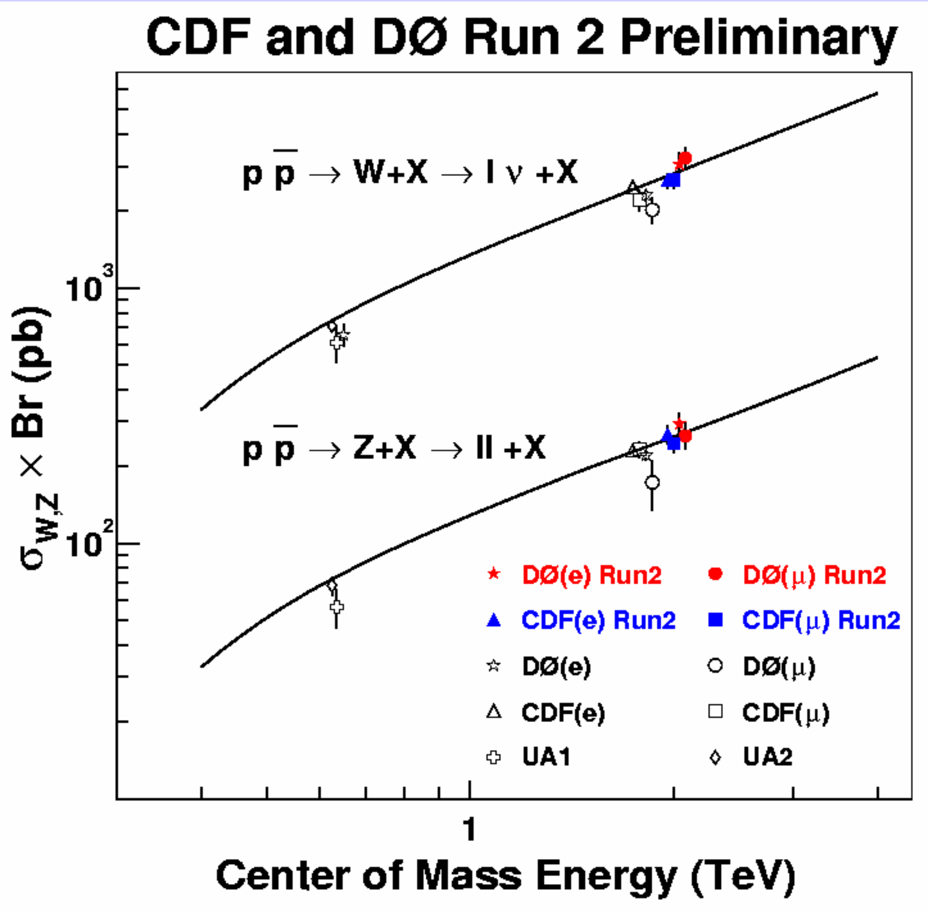
$$M_W^T = \sqrt{2 \cdot P_T^l \cdot P_T^\nu \cdot \left(1 - \cos \Delta\phi^{l,\nu}\right)}$$

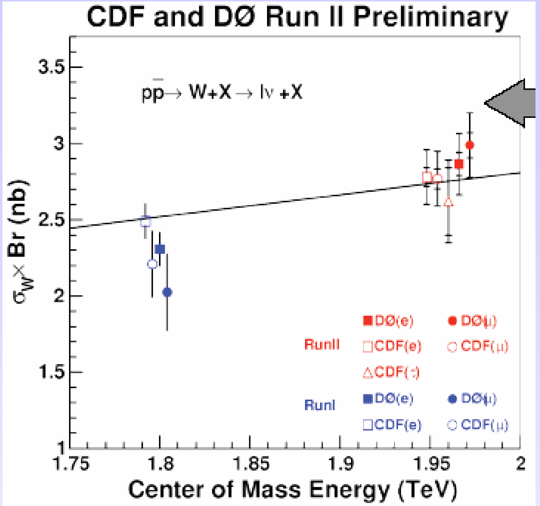
Good agreement with NNLO QCD calculations
C.R.Hamberg et al, Nucl. Phys. B359 (1991) 343.

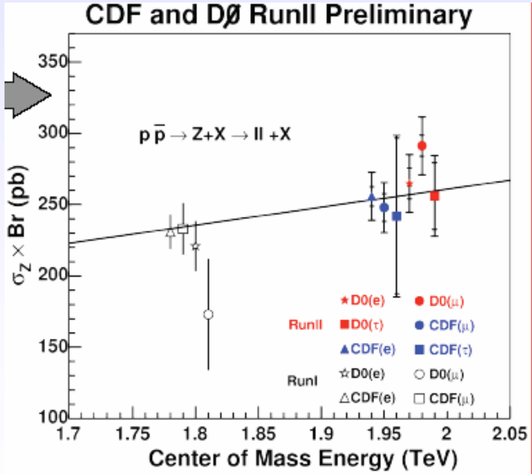
Note: the longitudinal component of the neutrino cannot be measured
→ only transverse mass can be reconstructed

Precision is limited by systematic effects (uncertainties on luminosity, parton densities,...)

Comparison between measured W/Z cross sections and theoretical prediction (QCD)

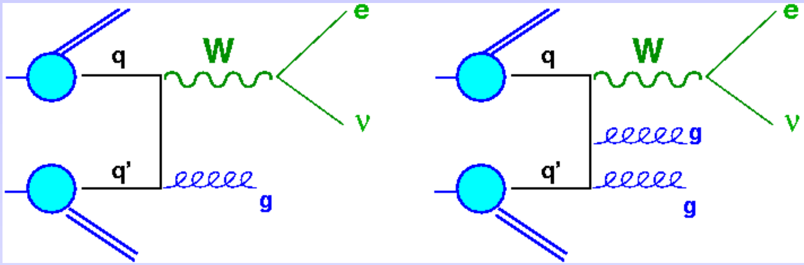


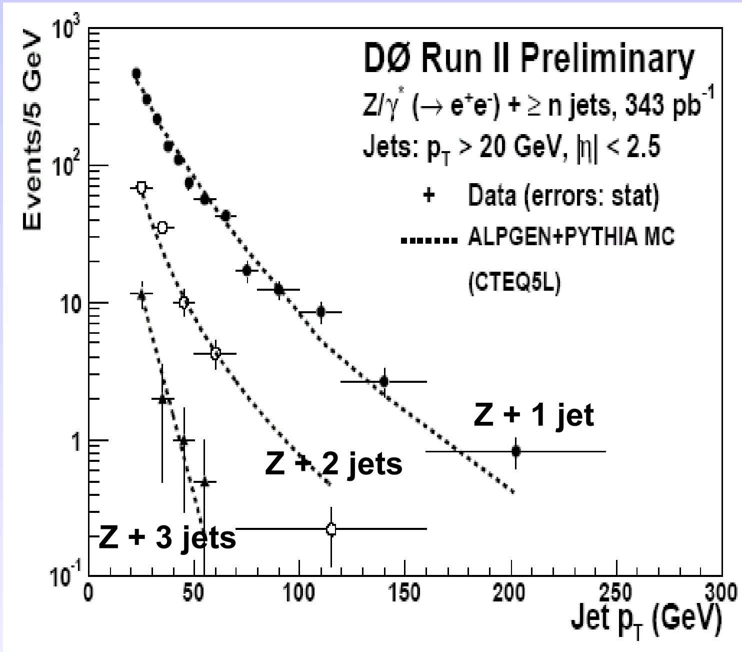


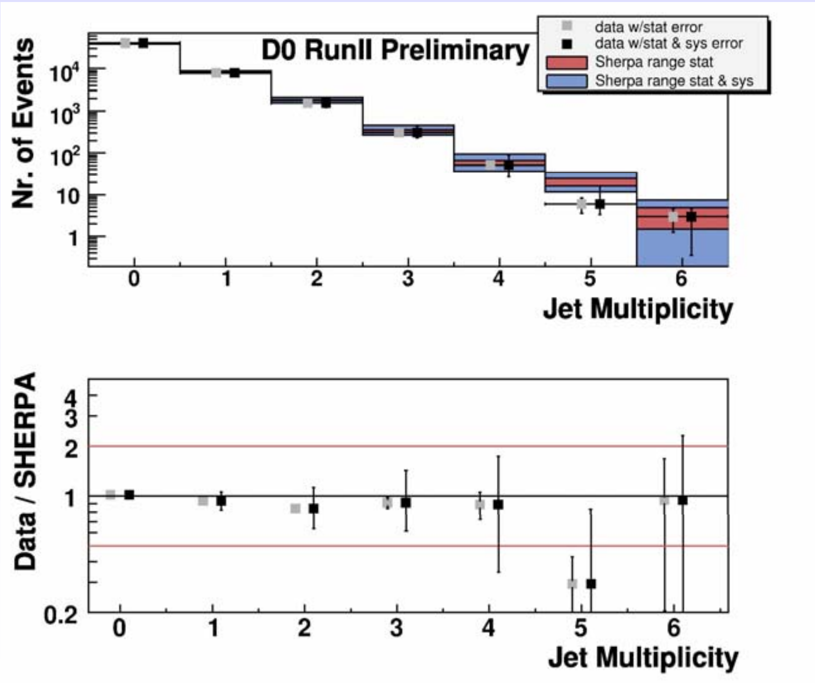


C. R. Hamberg, W.L. van Neerven and T. Matsuura, Nucl. Phys. B359 (1991) 343

QCD Test in W/Z + jet production

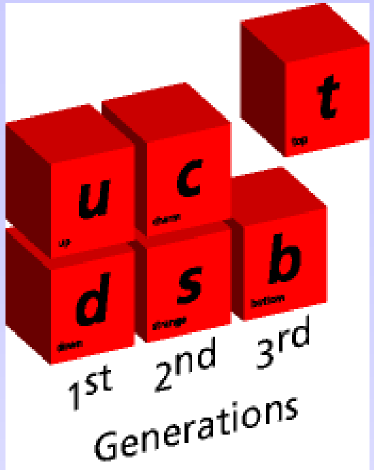


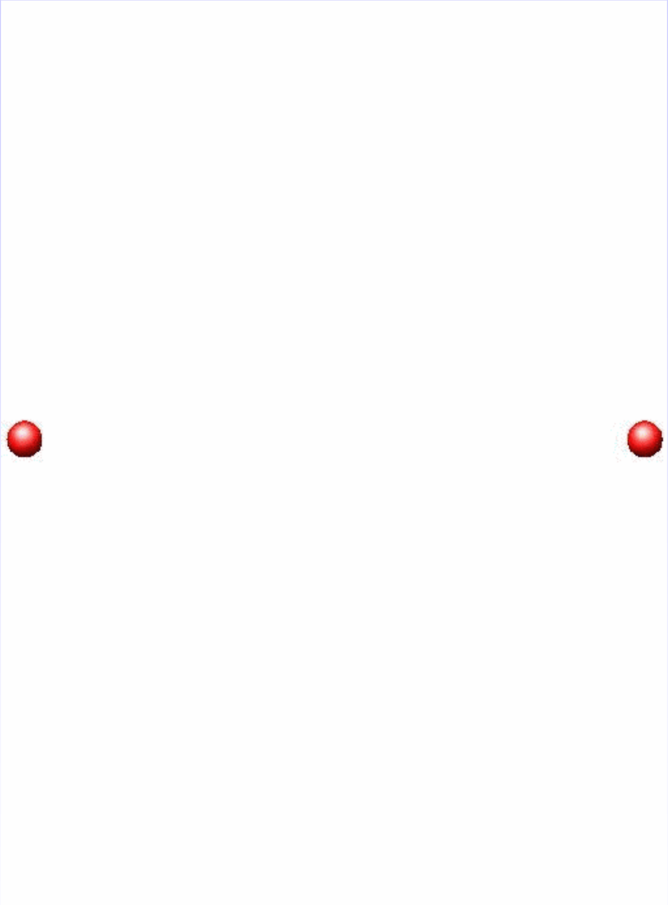




Compare # of W/Z + n jet events
(data versus QCD Monte Carlo Models
-SHERPA, ALPGEN-)

Top Quark Physics

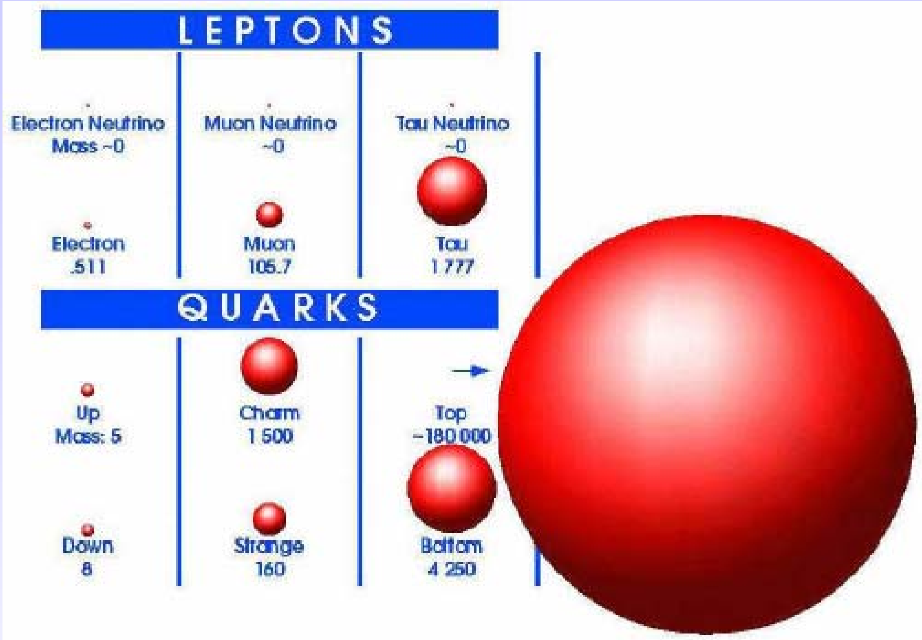




- Discovered by CDF and DØ collaborations at the Tevatron in 1995
- Run I top physics results are consistent with the Standard Model

  (Errors dominated by statistics)
- Run II top physics program will take full advantage of higher statistics
  - Better precision
  - Search for deviations from Standard Model expectations

Why is Top-Quark so important ?



- The top quark may serve as a window to ***New Physics*** related to the electroweak symmetry breaking;
  Why is its Yukawa coupling ~ 1 ??

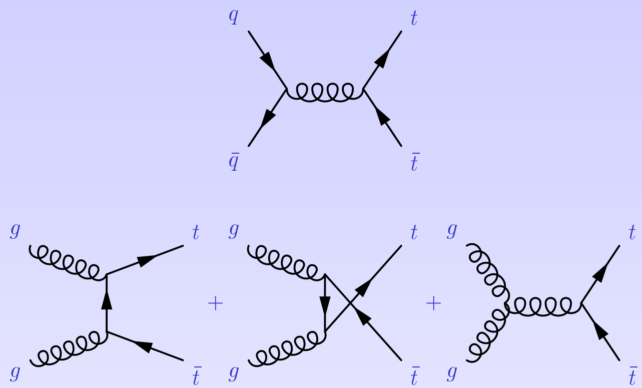
$$M_t = \frac{1}{\sqrt{2}} \lambda_t v$$

$$\Rightarrow \lambda_t = \frac{M_t}{173.9\ \mathrm{GeV}/c^2}$$

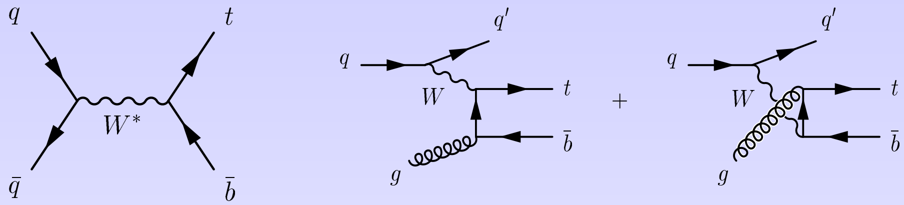
- We still know little about the properties of the top quark:
  mass, spin, charge, lifetime, decay properties (rare decays), gauge couplings, Yukawa coupling,…

Top Quark Production

Pair production: qq and gg-fusion



Electroweak production of single top-quarks (Drell-Yan and Wg-fusion)



	Run I 1.8 TeV	Run II 1.96 TeV	LHC 14 TeV
qq gg	90% 10%	85% 15%	5% 95%
σ (pb)	5 pb	7 pb	600 pb

	Run I 1.8 TeV	Run II 1.96 TeV	LHC 14 TeV
σ (qq) (pb) σ (gW) (pb) σ (gb) (pb)	0.7 1.7 0.07	0.9 2.4 0.1	10 250 60

Top Quark Decays

BR ($t \rightarrow Wb$) ~ 100%

Both W's decay via $W \rightarrow \ell\nu$ (ℓ=e or μ; 5%)

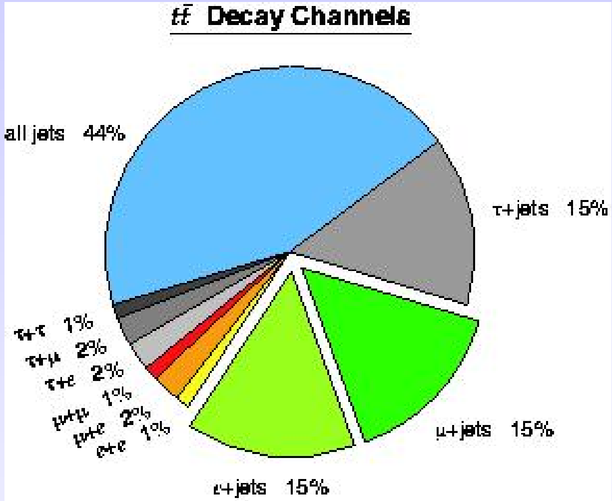
dilepton channel

One W decays via $W \rightarrow \ell\nu$ (ℓ=e or μ; 30%)

lepton + jet channel

Both W's decay via $W \rightarrow qq$ (44%)

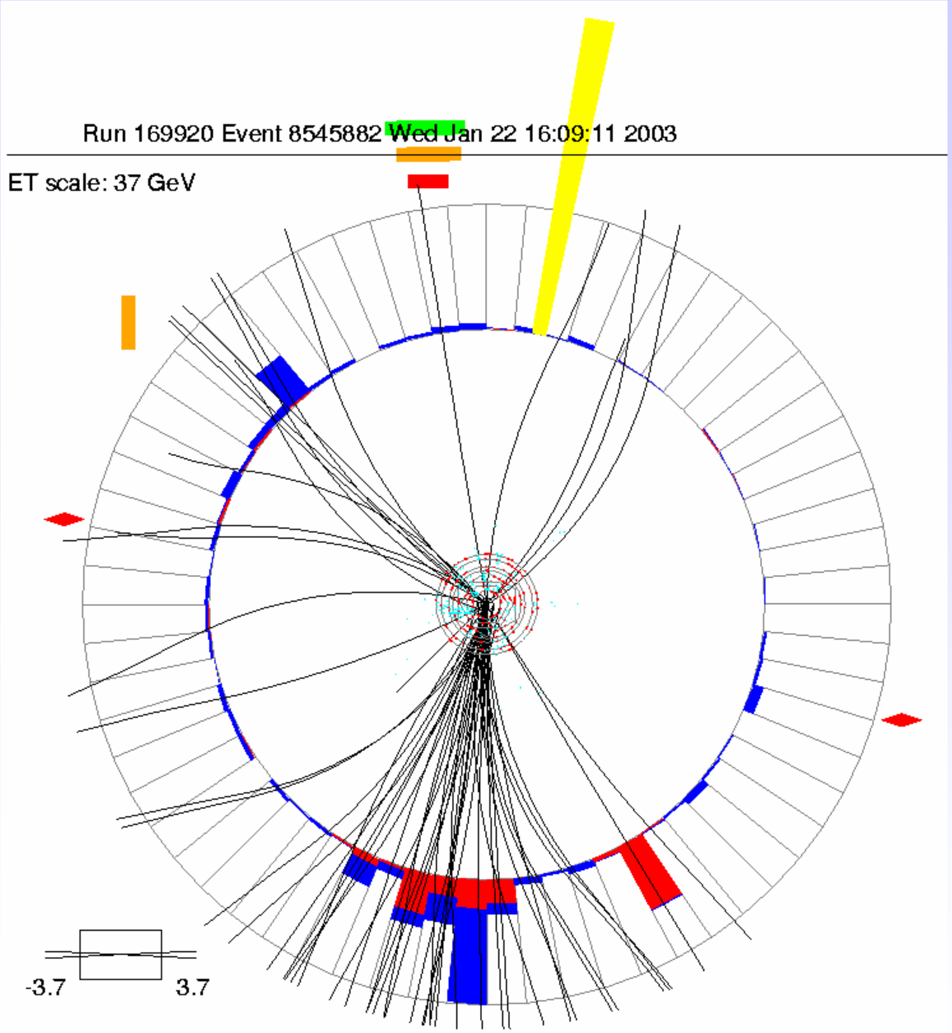
all hadronic, not very useful



<u>Important experimental signatures</u>: : - Lepton(s)

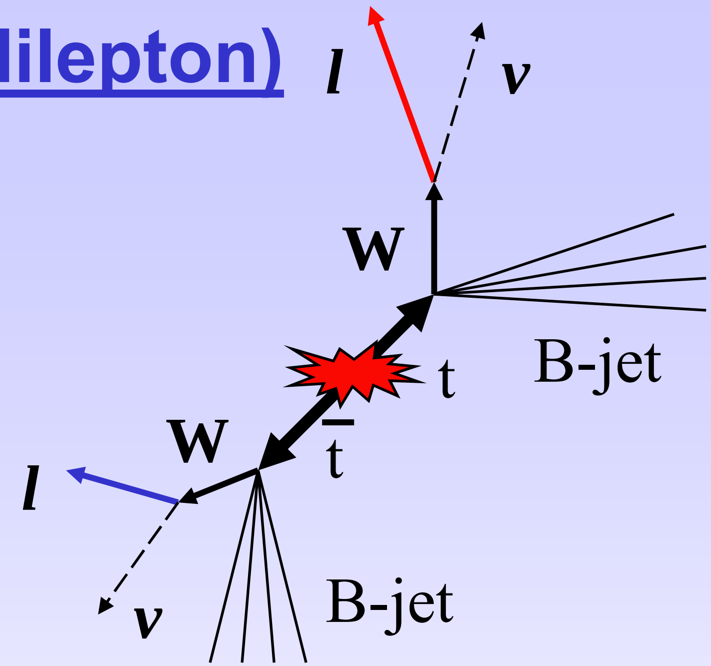
- Missing transverse momentum
- b-jet(s)

DØ top candidate event with two leptons



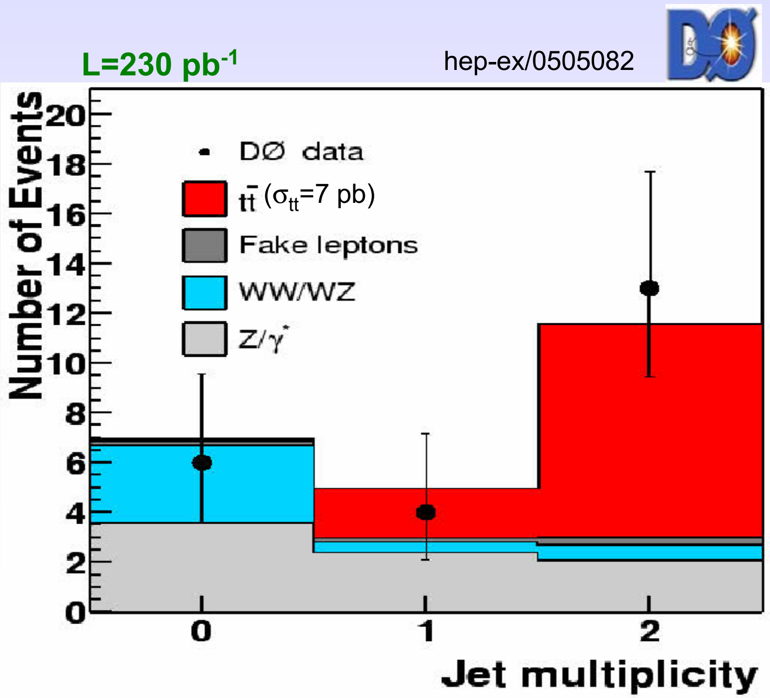
$p_T(e) = 20.3\ GeV/c^2$
$p_T(\mu) = 58.1\ GeV/c^2$
$E_T^j = 141.0, 55.2\ GeV$
$\not{E}_T = 91\ GeV$

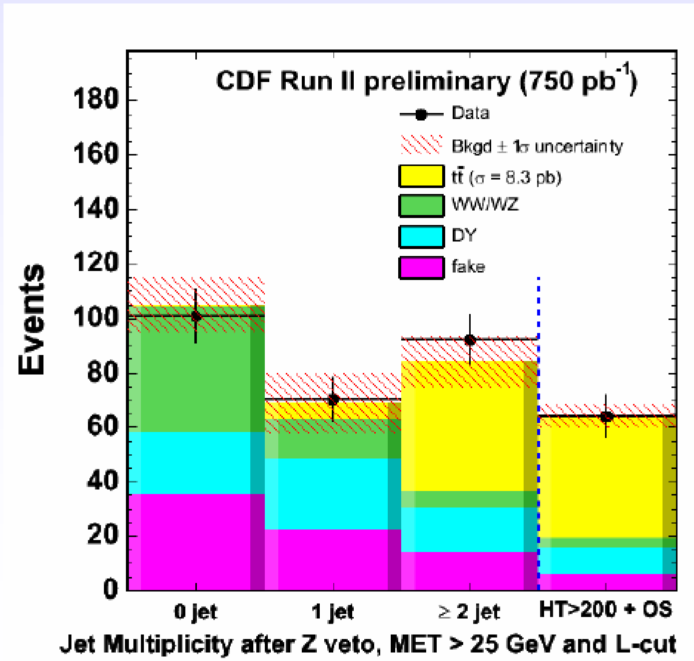
tt cross section (dilepton)



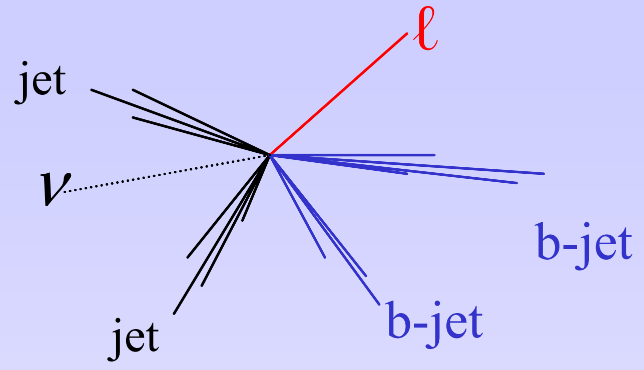
2 high-p_T isolated leptons

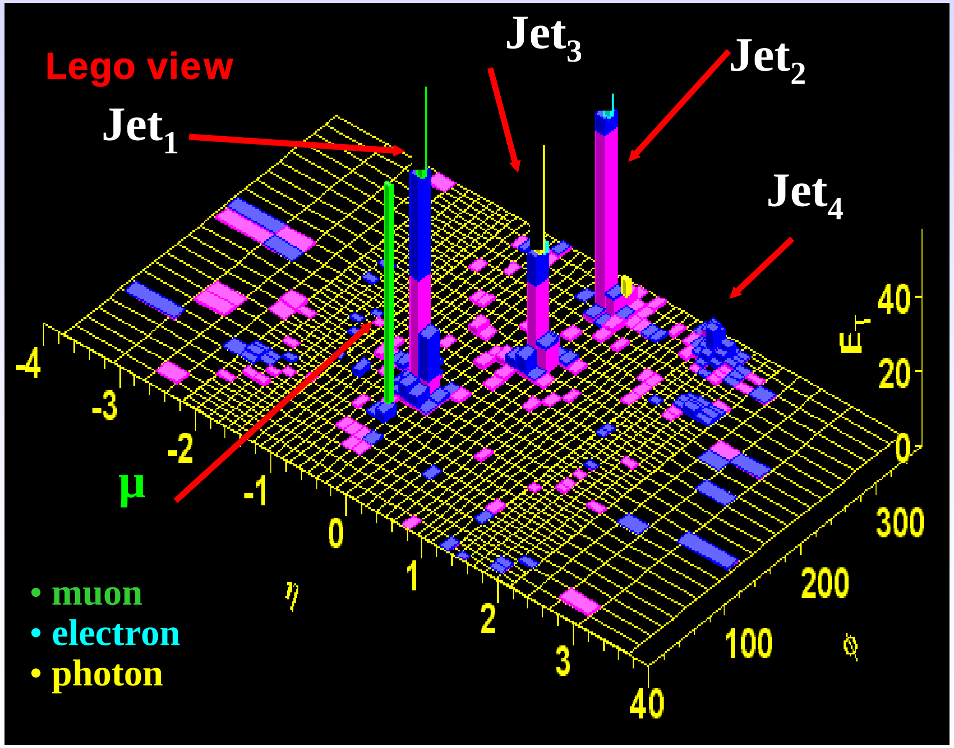
Large missing E_T , ≥ 2 jets

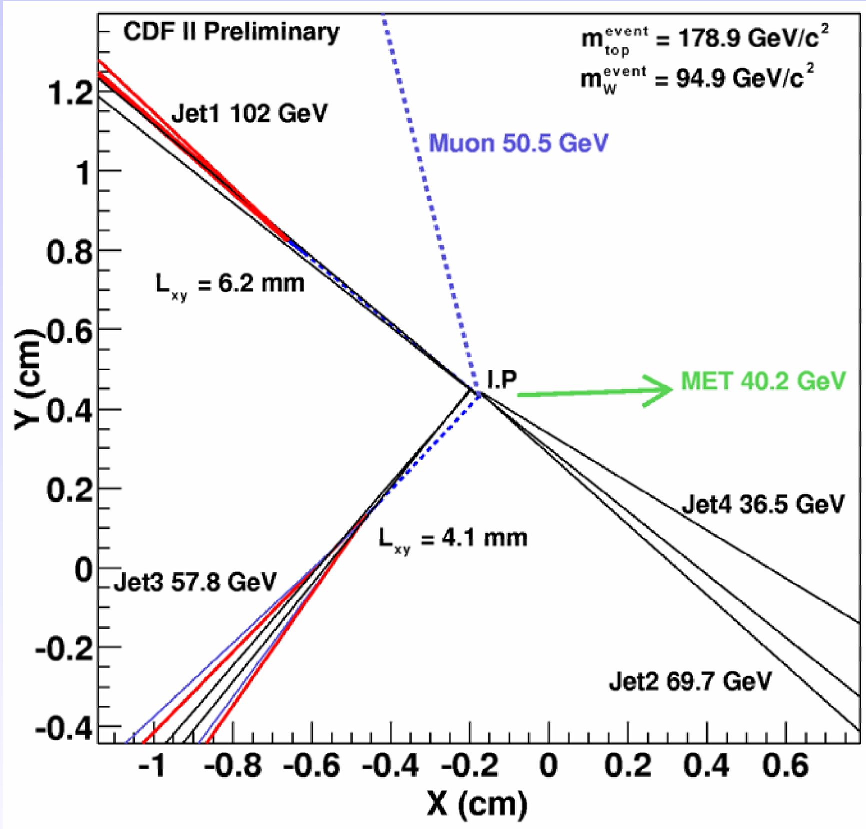




A CDF Lepton + Jet event







$p_T(\mu)$ = 54.4 GeV

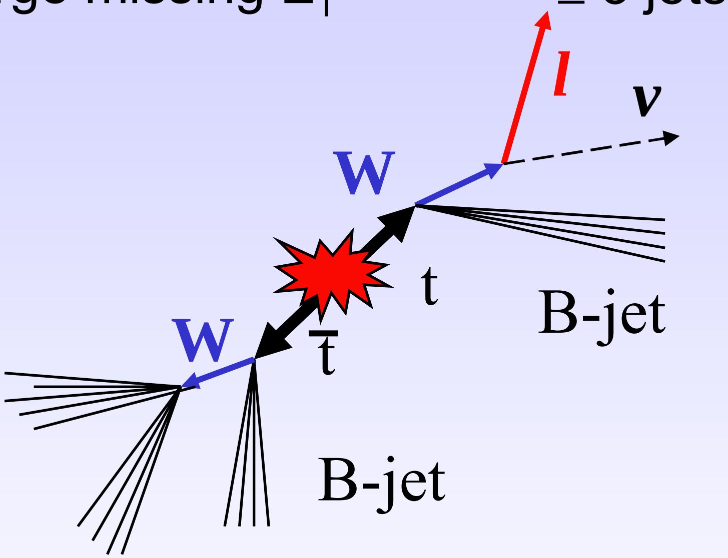
E_T^j = 96.7, 65,8, 54.8, 33.8 GeV

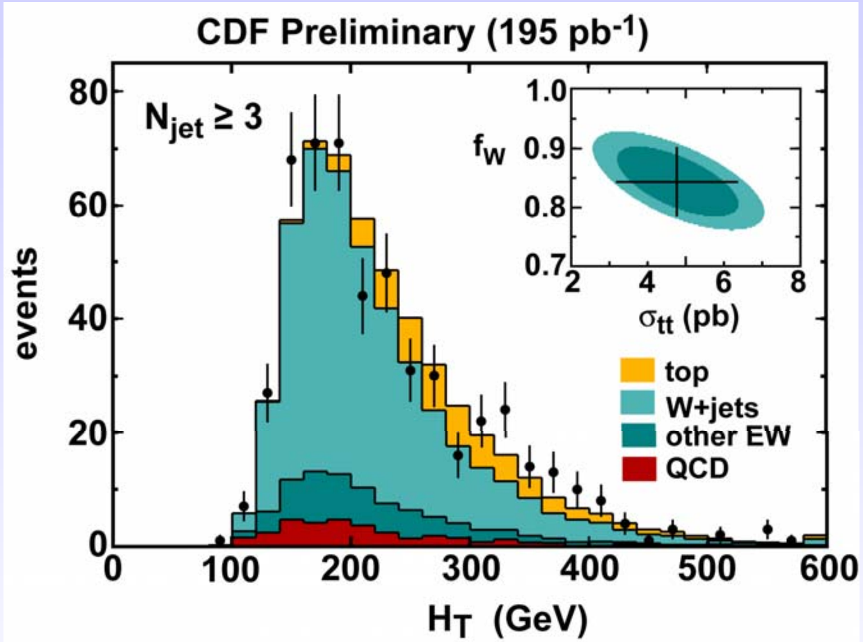
Missing E_T= 40.2 GeV

$t\bar{t}$ cross section (lepton + jets)
(topology, no b-jet identification)

1 high-p_T isolated lepton

Large missing E_T $\geq$ 3 jets



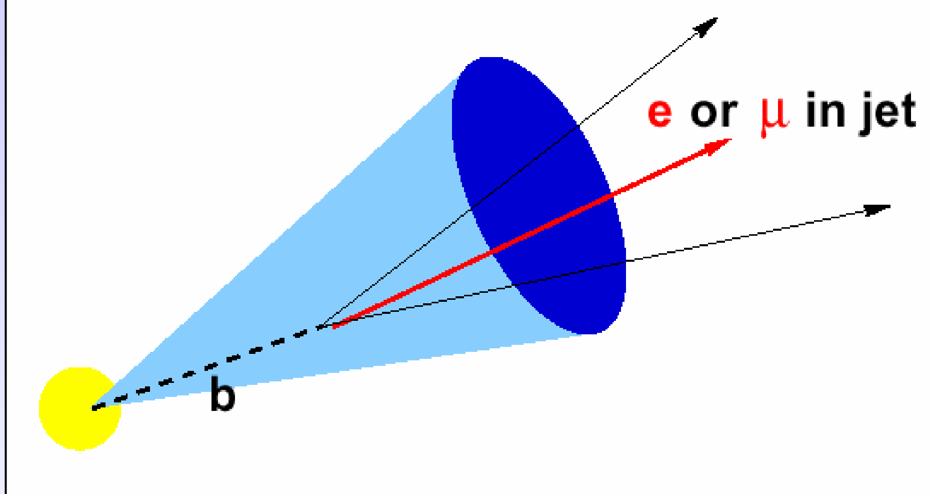


H_T = scalar sum of all high P_T objects (jets, leptons, E_T^{miss})

Before b-tagging: background from W+jet events clearly dominates

Tagging of b-quarks

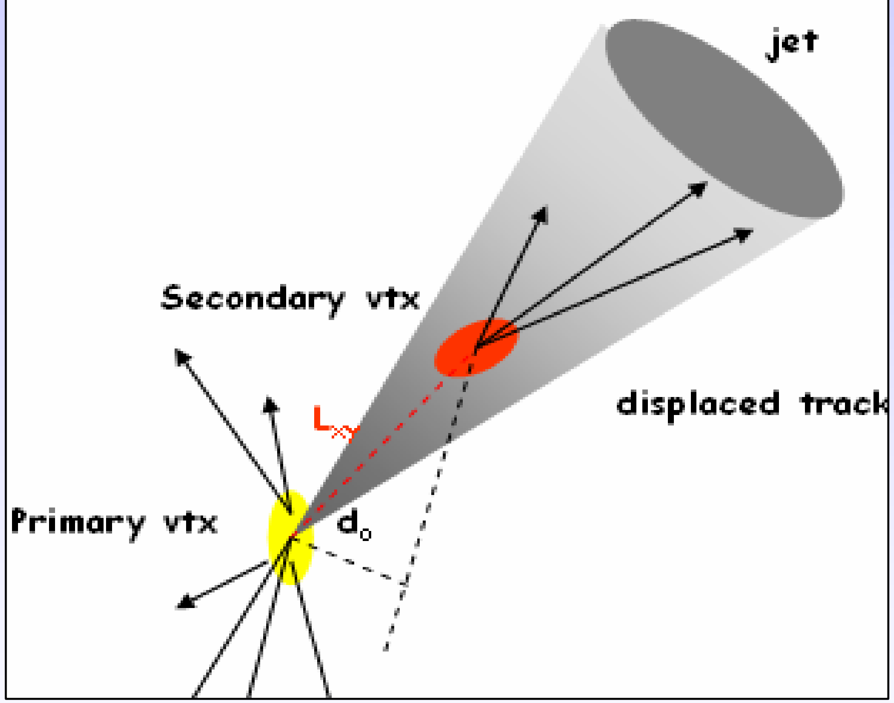
Soft lepton tagging



- $b \to \ell\nu c$ (BR ~ 20%)
- $b \to c \to \ell\nu s$ (BR ~ 20%)

Search for non-isolated soft lepton in a jet

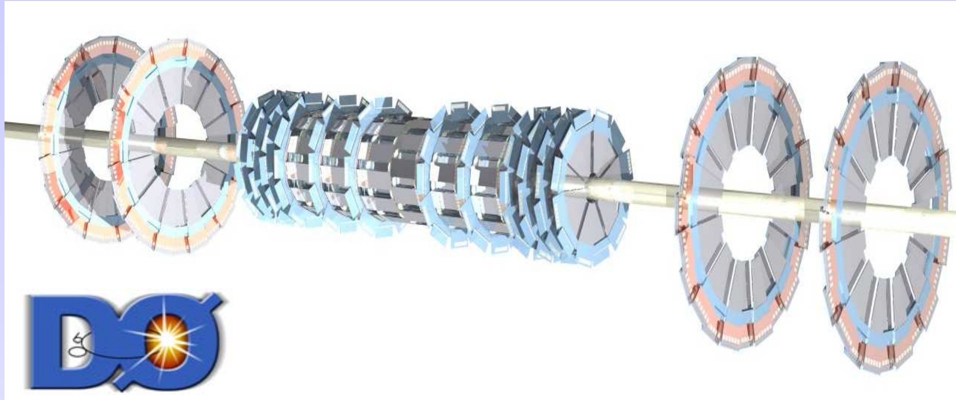
Silicon Vertex tag



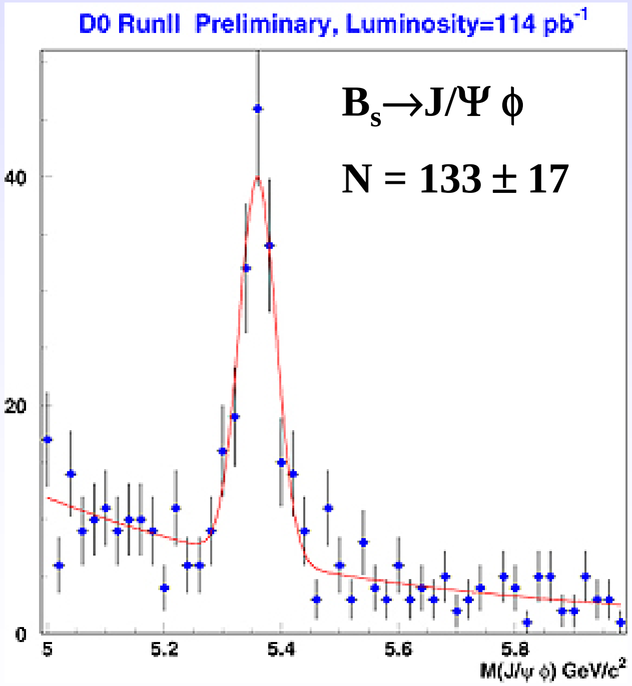
B mesons travel ~ 3 mm before decaying:

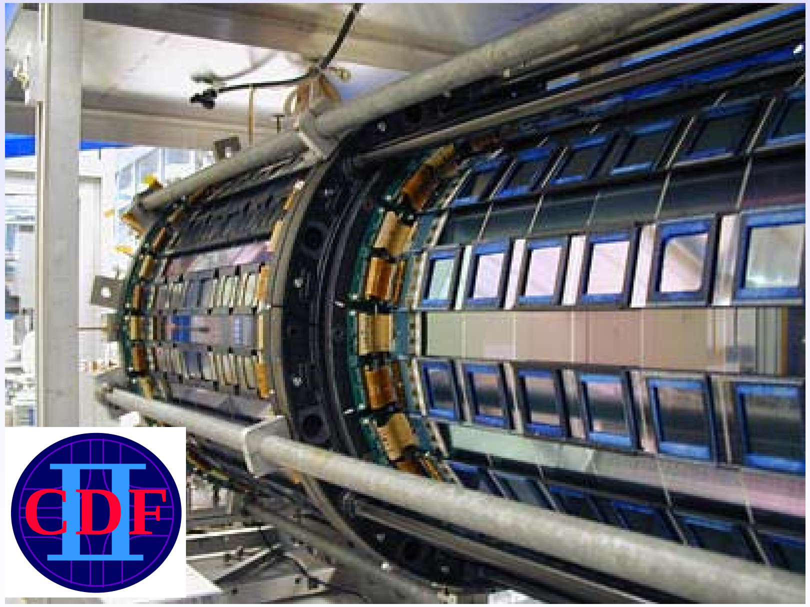
– Search for secondary vertex

Silicon detectors



Run II: silicon detectors cover a large region of acceptance

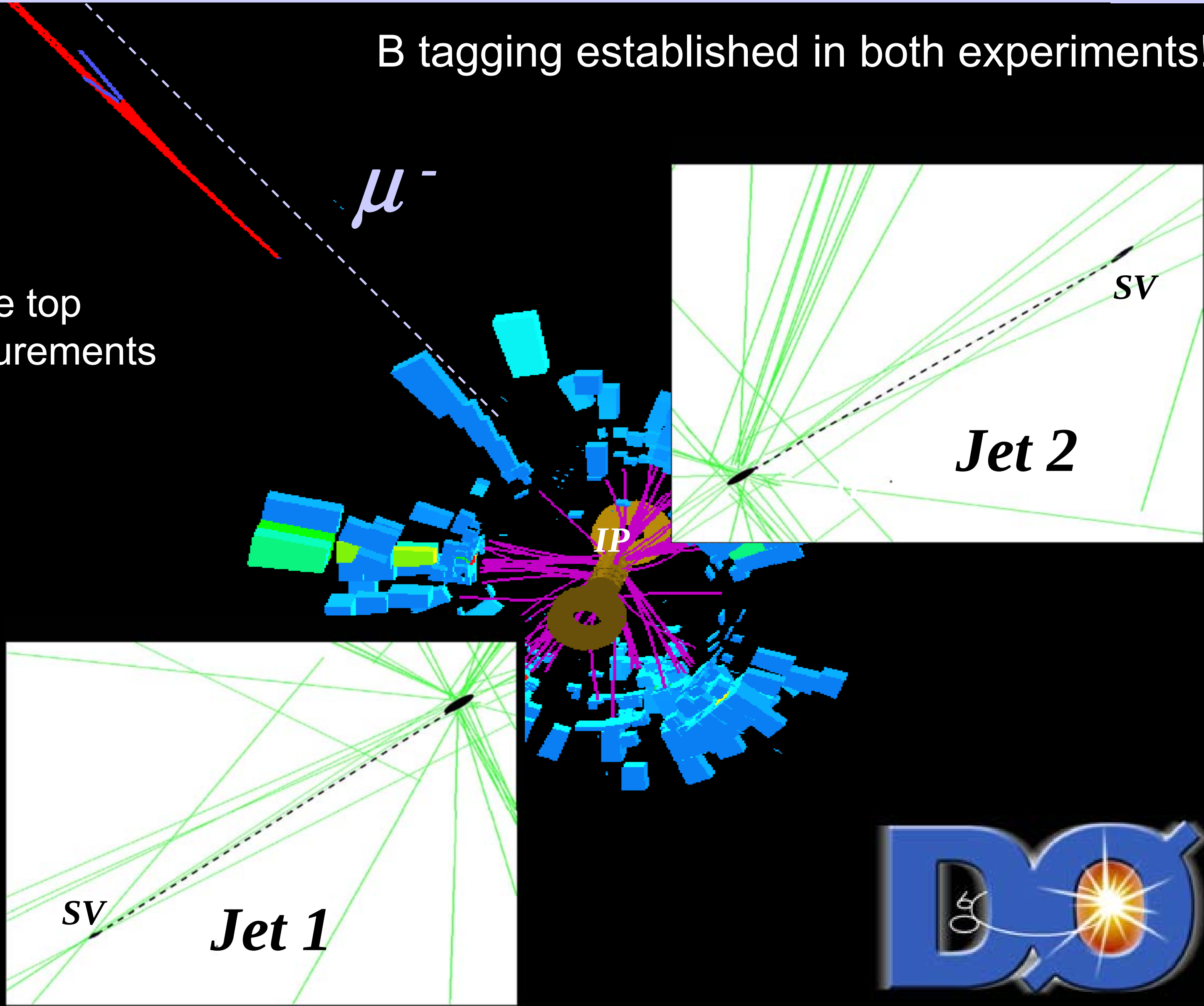




μ + jets double-tagged event

B tagging established in both experiments!

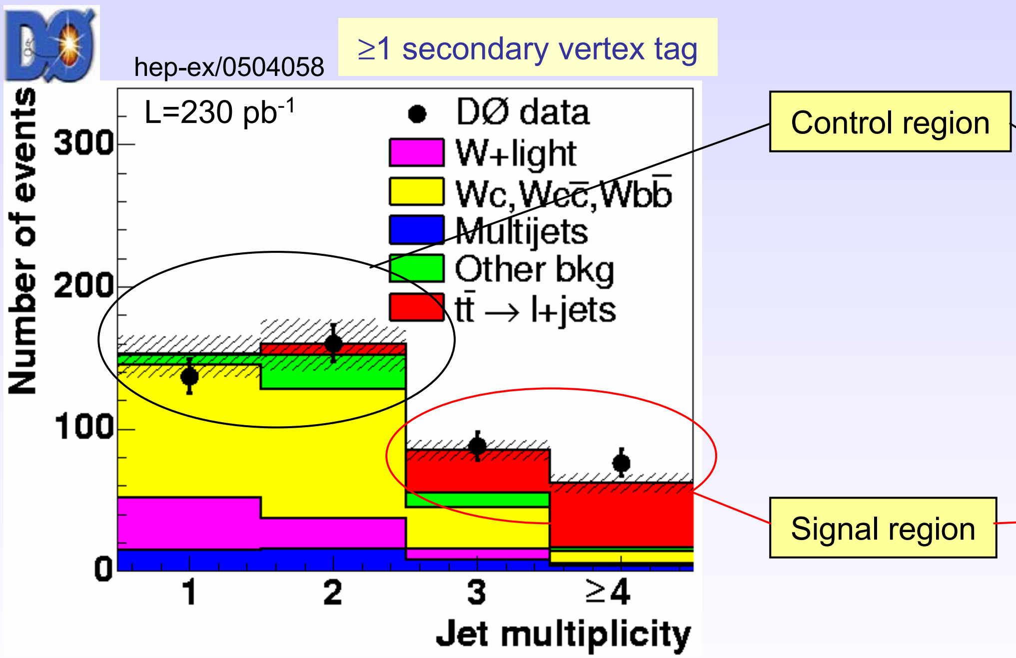
Important for the top physics measurements

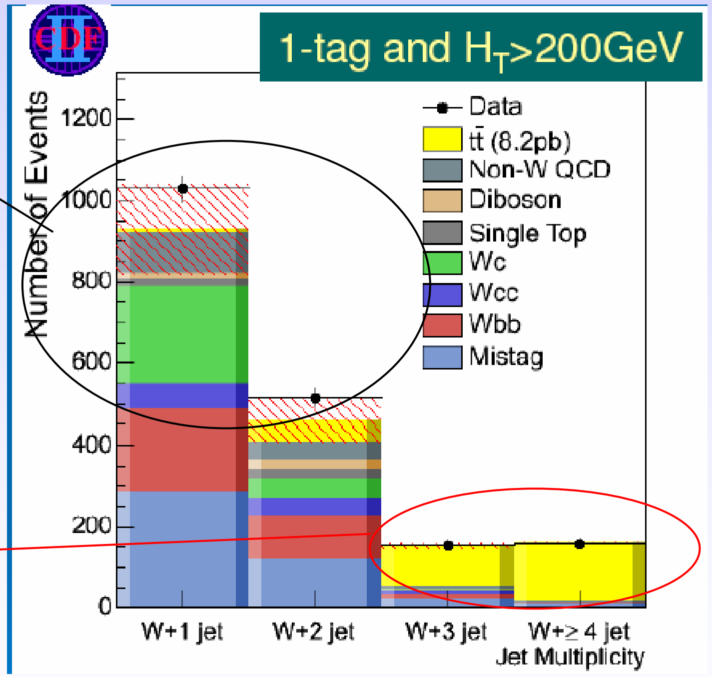


$t\bar{t}$ cross section (lepton + jets)   (including b-tagging)

1 high-p_T isolated lepton,   at least one b-tagged jet

Large missing E_T



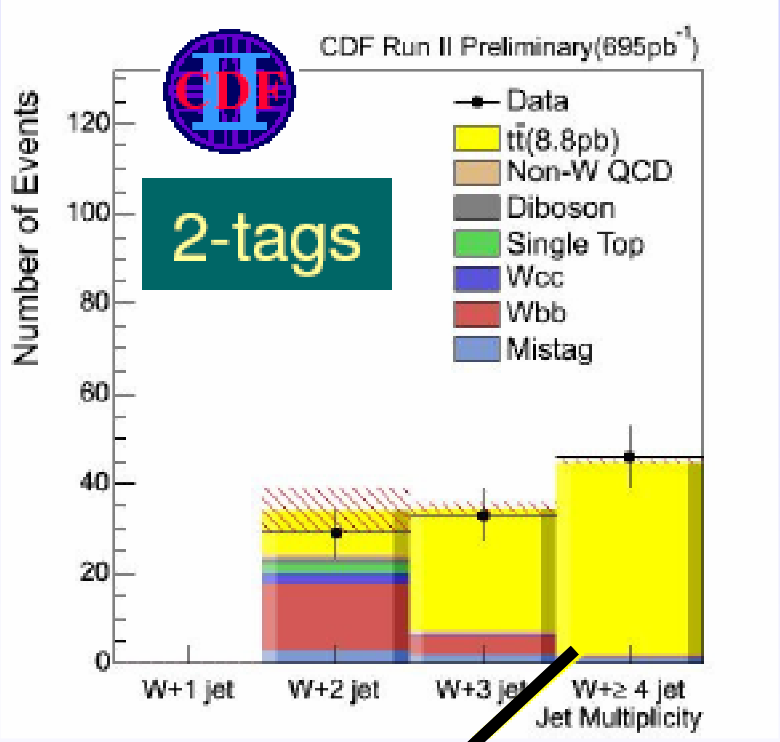


Excess above the W+ jet background in events with high jet multiplicity

$t\bar{t}$ cross section (lepton + jets) (including double b-tag)

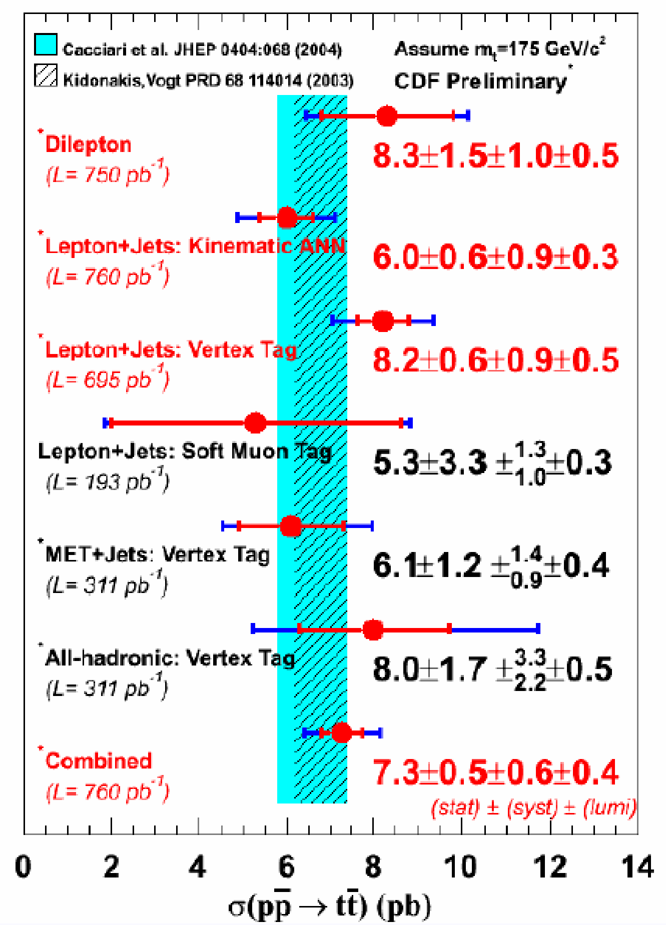
1 high-p_T isolated lepton + Two b-tagged jet

Large missing E_T



Very clean top sample

$t\bar{t}$ cross section summary (preliminary)



QCD prediction:

- Cacciari et al.,   hep-ph/0303085
- Kidonakis et al., hep-ph/0303086

Good agreement among various exp. measurements and with QCD prediction (similar results for DØ)

Precision measurements of m_W and m_{top}

Motivation:

W mass and top quark mass are fundamental parameters of the Standard Model;
The standard theory provides well defined relations between m_W, m_{top} and m_H

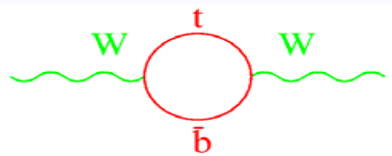
Electromagnetic constant
measured in atomic transitions,
e^+e^- machines, etc.

$$m_W = \left(\frac{\pi \, \alpha_{EM}}{\sqrt{2} \, G_F} \right)^{1/2} \frac{1}{\sin \theta_W \sqrt{1 - \Delta r}}$$

Fermi constant
measured in muon
decay

weak mixing angle
measured at
LEP/SLC

radiative corrections
$\Delta r \sim f\,(m_{top}^2, \log m_H)$
$\Delta r \approx 3\%$



G_F, α_{EM}, $\sin \theta_W$

are known with high precision

Precise measurements of the W mass and the top-quark mass constrain the Higgs-boson mass
(and/or the theory, radiative corrections)

The W-mass measurement

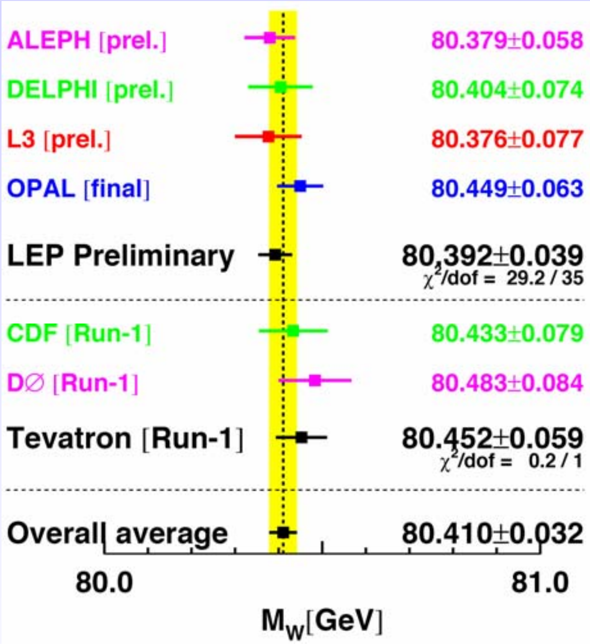
$$m_W = \left(\frac{\pi\,\alpha_{EM}}{\sqrt{2}\,G_F}\right)^{1/2} \frac{1}{\sin\theta_W\,\sqrt{1-\Delta r}}$$

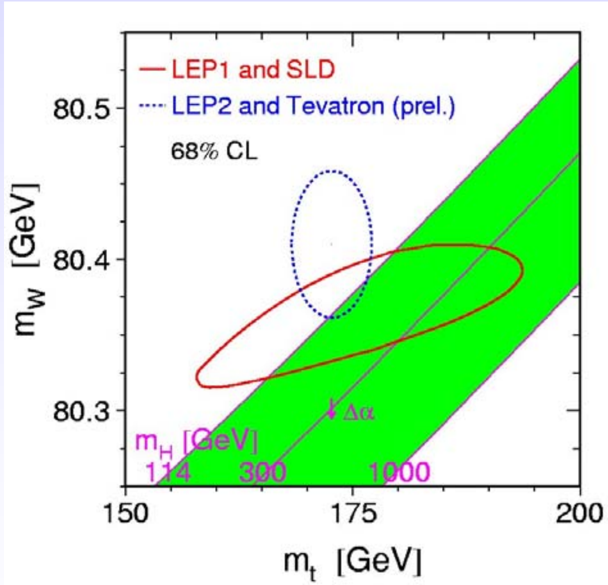
4·10^{-4}

m_W (from LEP2 + Tevatron) = 80.410 ± 0.032 GeV

m_{top} (from Tevatron) = 172.5 ± 2.3 GeV

1.4%

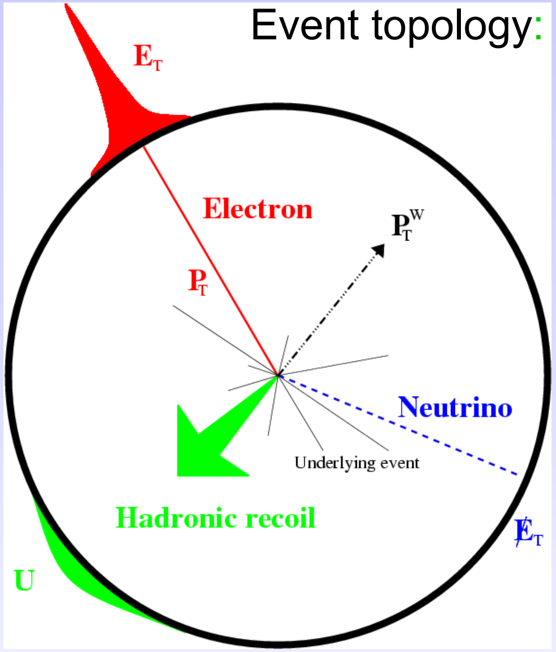


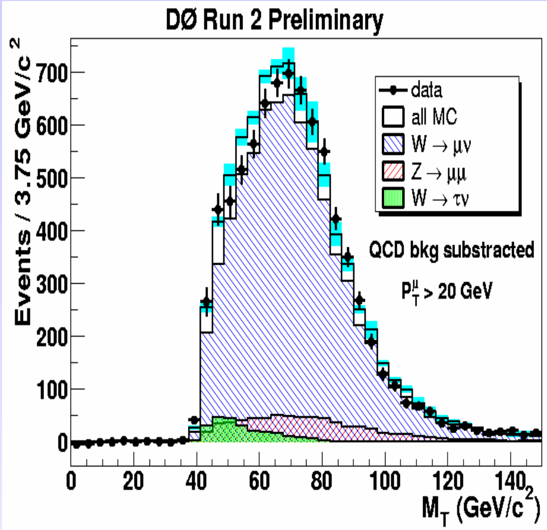


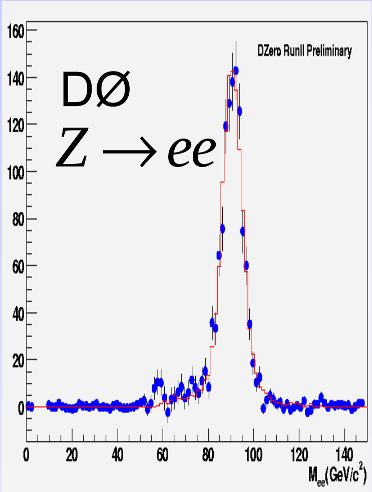
light Higgs boson is favoured by present measurements

Ultimate test of the Standard Model: comparison between the direct Higgs boson mass (from observation, hopefully) and predictions from rad. corrections….

Technique used for W-mass measurement at hadron colliders:







Observables: $P_T(e)$, $P_T(had)$

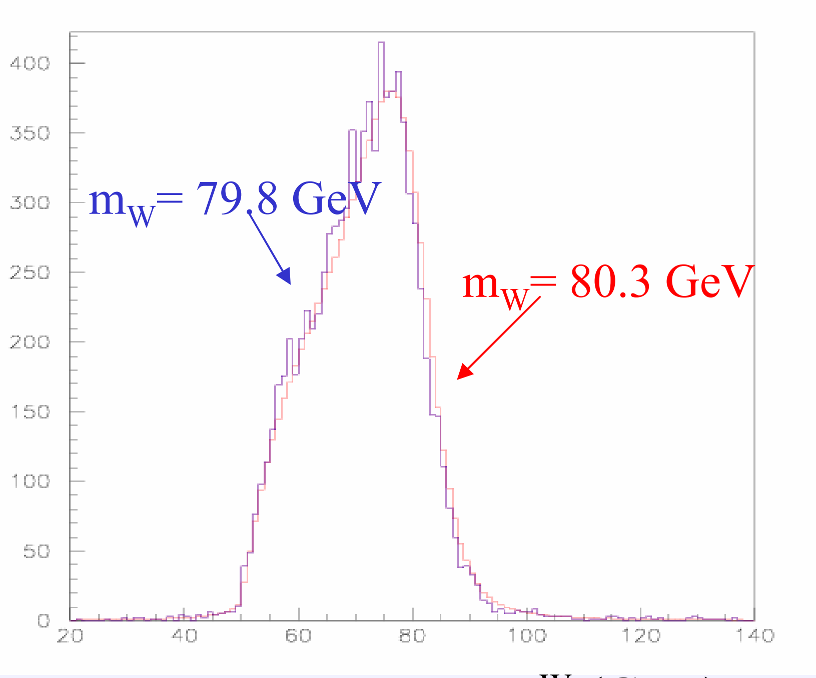
$\Rightarrow$ $P_T(\nu)$ = - ($P_T(e)$ + $P_T(had)$)

long. component cannot be measured

$$\Rightarrow \quad M_W^T = \sqrt{2 \cdot P_T^l \cdot P_T^\nu \cdot \left(1 - \cos \Delta\phi^{l,\nu}\right)}$$

In general the transverse mass M_T is used for the determination of the W-mass (smallest systematic uncertainty).

Shape of the transverse mass distribution is sensitive to m_W, the measured distribution is fitted with Monte Carlo predictions, where m_W is a parameter



m_T^W (GeV)

Main uncertainties:

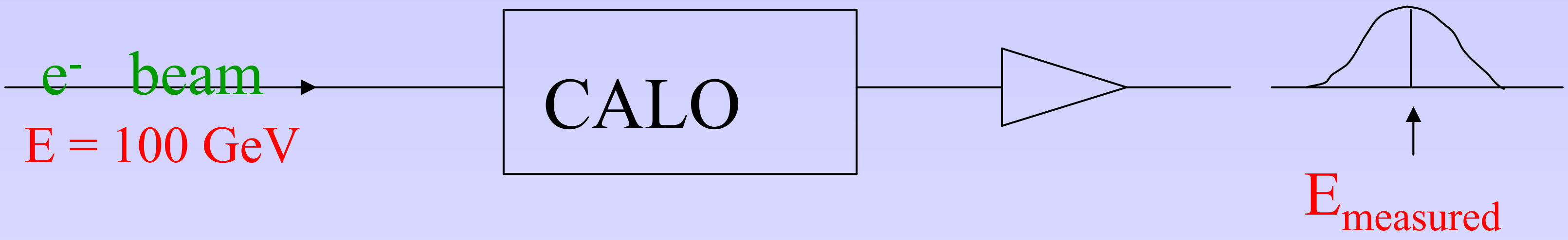
result from the capability of the Monte Carlo prediction to reproduce real life:

- detector performance
  (energy resolution, energy scale, ….)
- physics: production model
  $p_T(W)$, Γ_W, …..
- backgrounds

Dominant error (today at theTevatron, and most likely also at the LHC) :
Knowledge of lepton energy scale of the detector !

Calibration of the detector energy scale:

Example : EM calorimeter



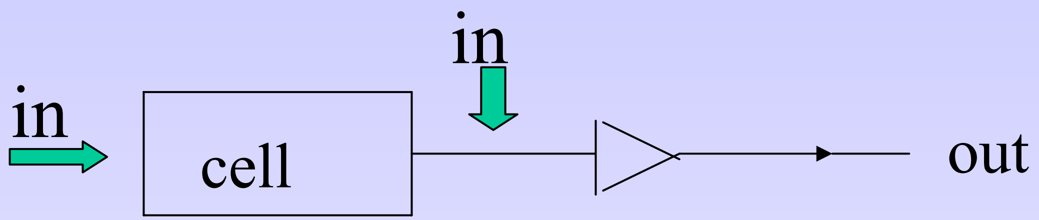
- if $E_{measured}$ = 100.000 GeV for all calorimeter cells
  $\rightarrow$ calorimeter is perfectly calibrated

- to measure m_W to ~ 20 MeV, need to know energy scale to 0.02%,
  i.e. if $E_{electron}$ = 100 GeV then 99.98 GeV < $E_{measured}$ < 100.02 GeV

$\Rightarrow$ one of most serious experimental challenges !!

Calibration strategy:

- detectors equipped with calibration systems which inject known pulses:



$\rightarrow$ check that all cells give same response: if not $\rightarrow$ correct

- calorimeter modules calibrated with test beams of known energy
  $\rightarrow$ set the energy scale

- inside LHC detectors: calorimeter sits behind Inner Detector
  $\rightarrow$ electrons lose energy in material of Inner Detector
  $\rightarrow$ need a final calibration " *in situ* " by using physics samples:

e.g. $Z \rightarrow e^+ e^-$ decays 1/s at low luminosity
constrain $m_{ee} = m_Z$

known to $\approx 10^{-5}$ from LEP

What precision can be reached in Run II and at the LHC ?

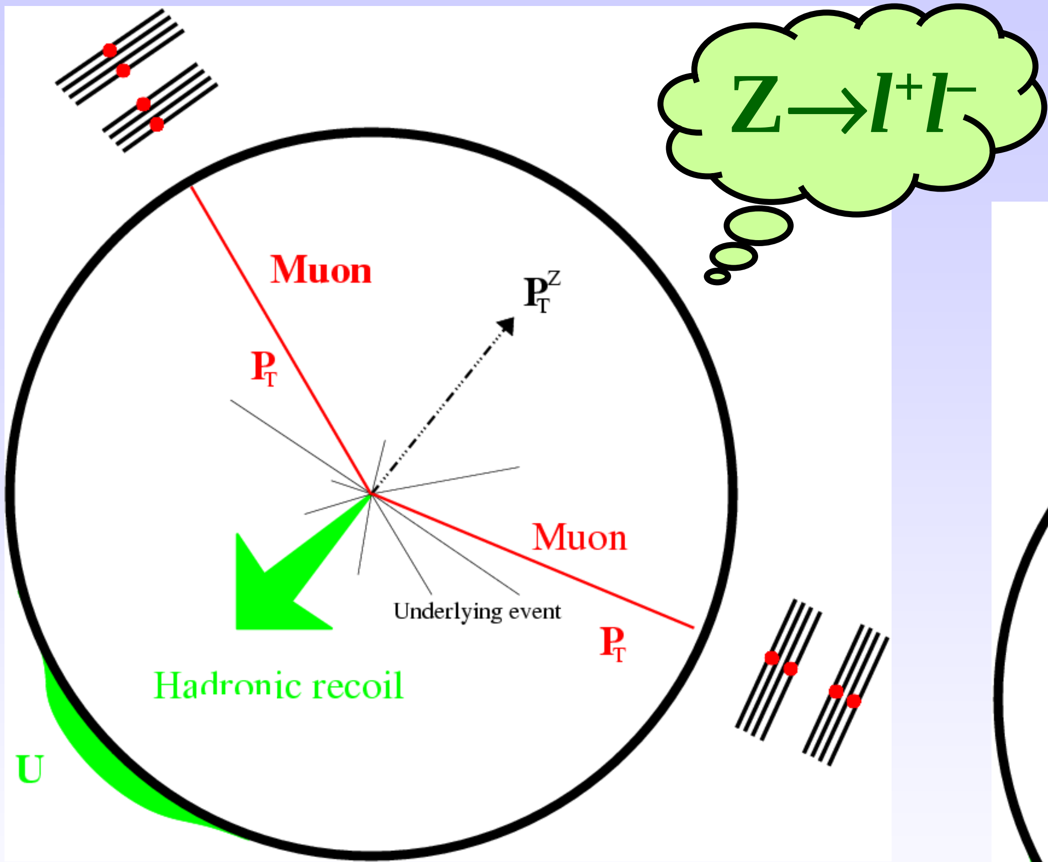
Int. Luminosity	0.08 fb^{-1}	2 fb^{-1}	10 fb^{-1}
Stat. error	96 MeV	19 MeV	2 MeV
Energy scale, lepton res.	57 MeV	20 MeV	16 MeV
Monte Carlo model (P_T^W, structure functions, photon-radiation….)	30 MeV	20 MeV	17 MeV
Background	11 MeV	2 MeV	1 MeV
Tot. Syst. error	66 MeV	28 MeV	24 MeV
Total error	**116 MeV**	**34 MeV**	**25 MeV**

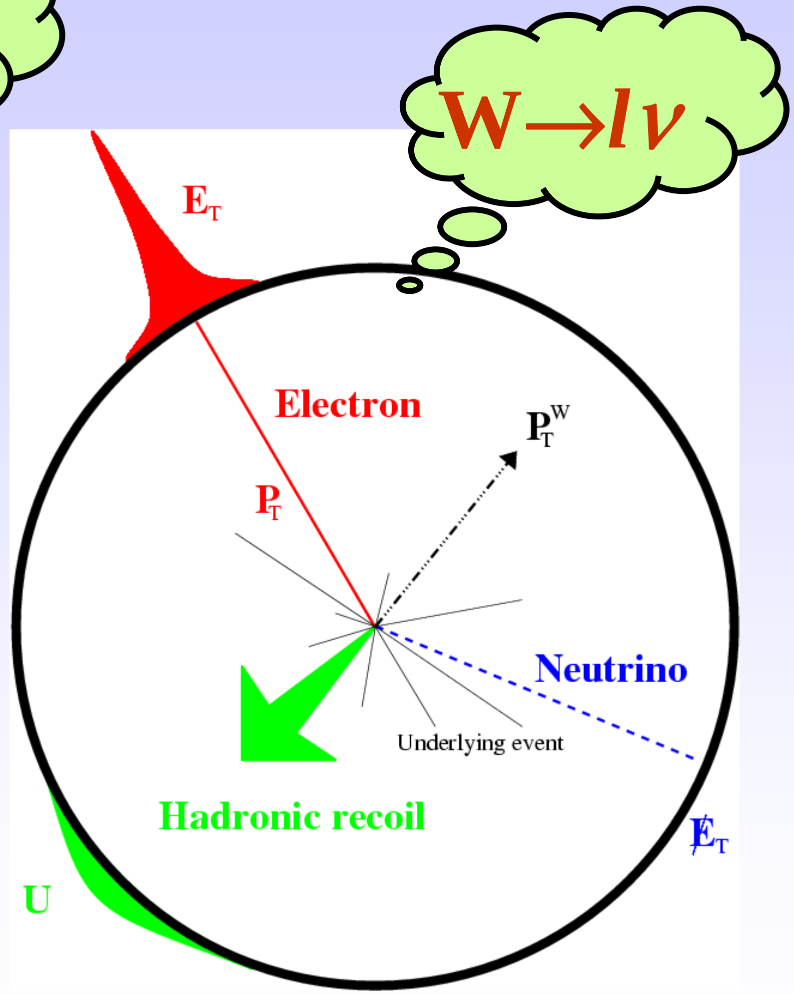
- Total error per lepton species and per experiment at the **LHC** is estimated to be **± 25 MeV**
  at the **Tevatron** **± 34 MeV**
- Main uncertainty: lepton energy scale (goal is an uncertainty of ± 0.02 %)
- Many systematic uncertainties can be controlled in situ, using the $Z \rightarrow \ell\ell$ sample (P_T(W), recoil model, resolution)

Combining both experiments (ATLAS + CMS, 10 fb^{-1}), both lepton species and assuming a scale uncertainty of ± 0.02% **⇒ $\Delta m_W \sim \pm 15$ MeV**

Tevatron: 2 fb^{-1}: **$\Delta m_W \sim \pm 30$ MeV**

Signature of Z and W decays





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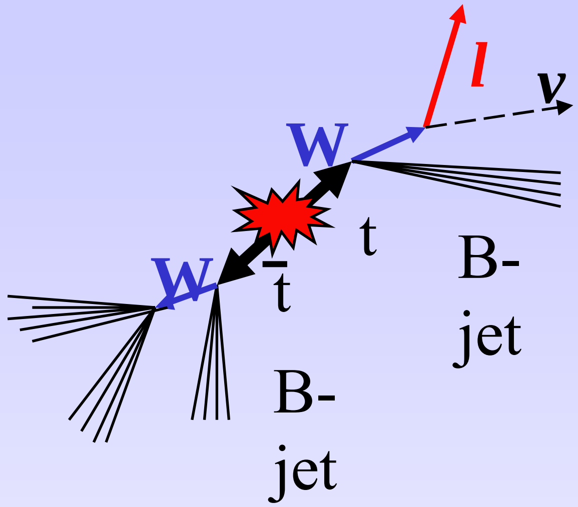
Top mass measurements

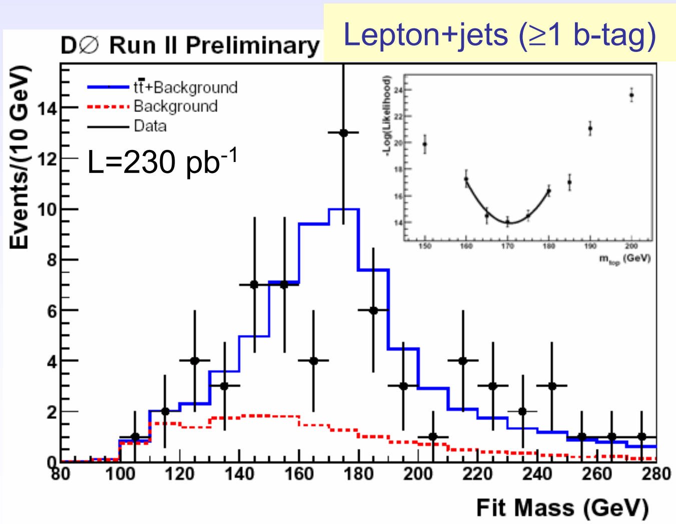
- Top mass calculation:
  - Kinematic fit under (tt) hypothesis
  - compute likelihood for observed events as a function of the top quark mass
    Maximum likelihood → m_{top}



Most precise single measurements:

m_{top} = 173.4 ±3.5 (stat+JES) ± 1.3 (syst) GeV/c^2 (CDF)

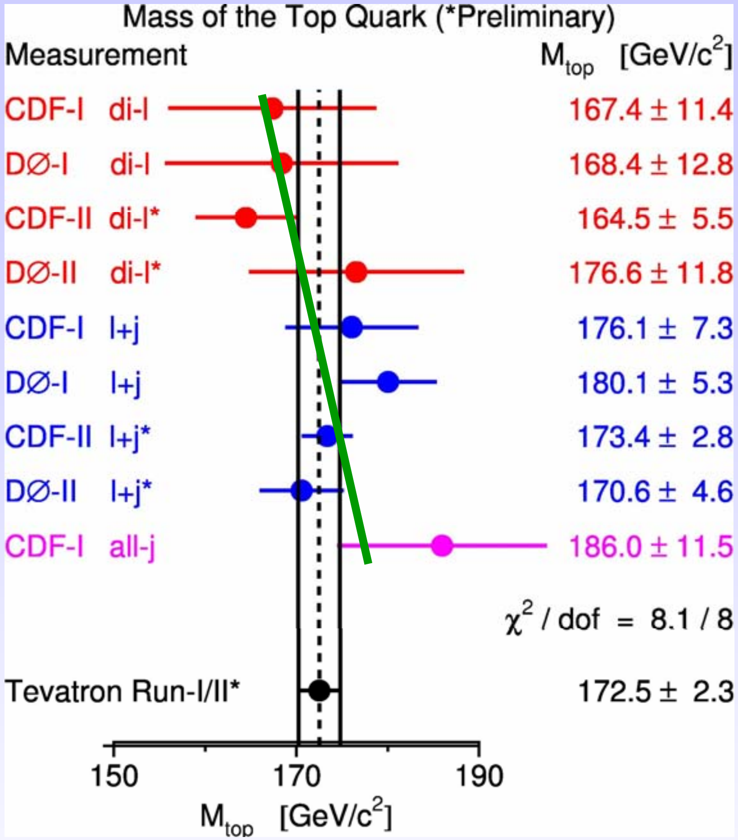
m_{top} = 170.6 ±4.4 (stat+JES) ± 1.4 (syst) GeV/c^2 (DØ)

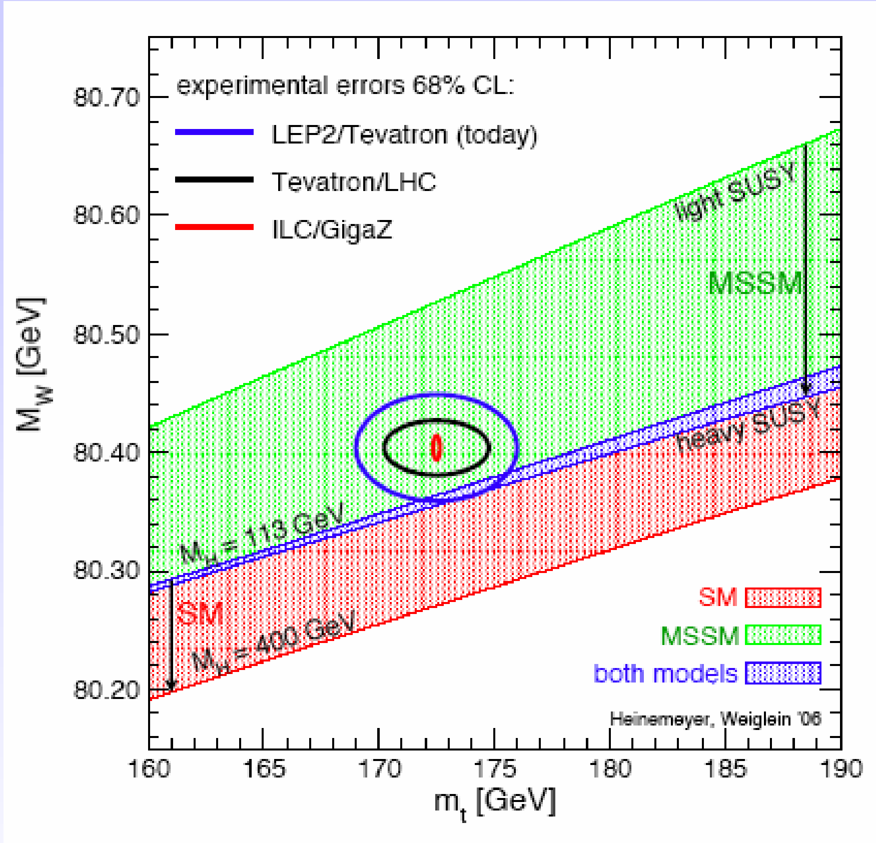


- Reduce JES systematic by using in-situ hadronic W mass in tt events

(simultaneous determination of m_t and JES from reconstructed m_t and M_W templates)

Future Prospects for the top quark mass measurement





1. Channel dependence ? still statistically consistent results; full hadronic channel is difficult

2. Expected Tevatron precision (full data set): $\pm$ 1.5 GeV/c^2

3. Expected LHC precision for 10 fb^{-1}: < ~ 1 GeV/c^2
   (Combination of several methods, maybe somewhat conservative)

Summary of the 2. Lecture

- **Hadron Colliders Tevatron and LHC play an important role in future tests of the Standard Model**

- **Predictions of Quantum Chromodynamics can be tested in**
  - **High P_T jet production**
  - **W/Z production**
  - **Top quark production**
  - **…….**

- **In addition, precise measurements of Standard Model parameters can be carried out.**

Examples: W mass can be measured to ~15 MeV
Top-quark mass to ~ 1 GeV

→ Higgs mass constrained indirectly to ~ 25%