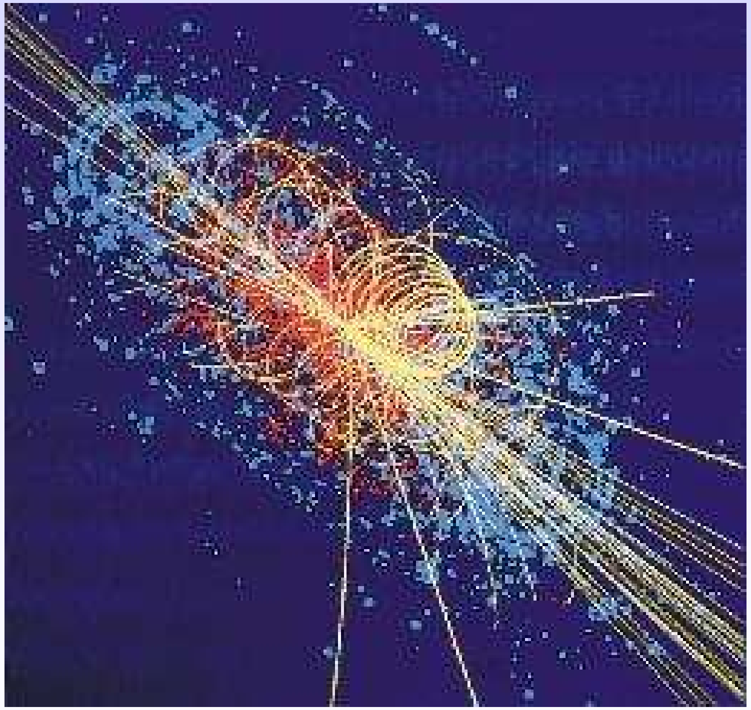
Physics at Hadron Colliders

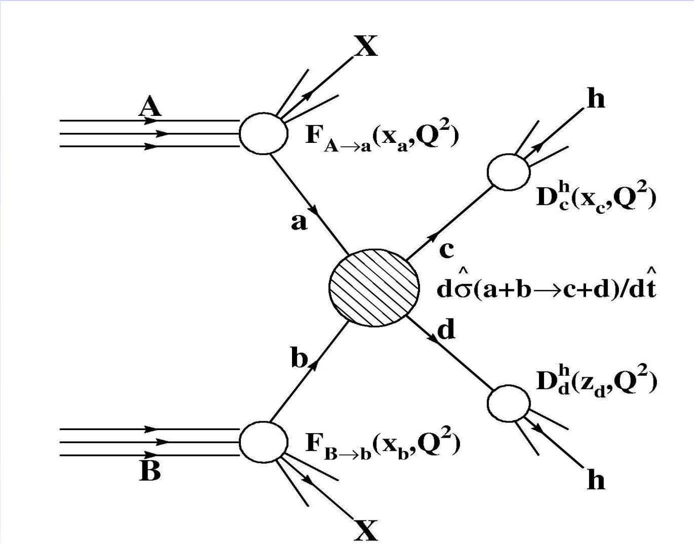
2. Test of the Standard Model

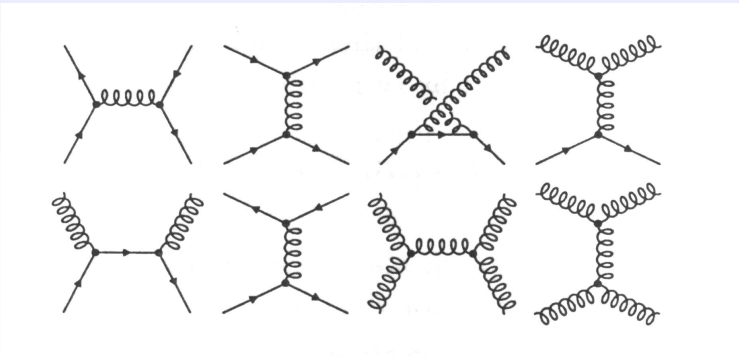


Tests of QCD
- Jet production
- W/Z production
- Top-quark production

Precision measurements
- W mass
- Top-quark mass

QCD processes at hadron colliders

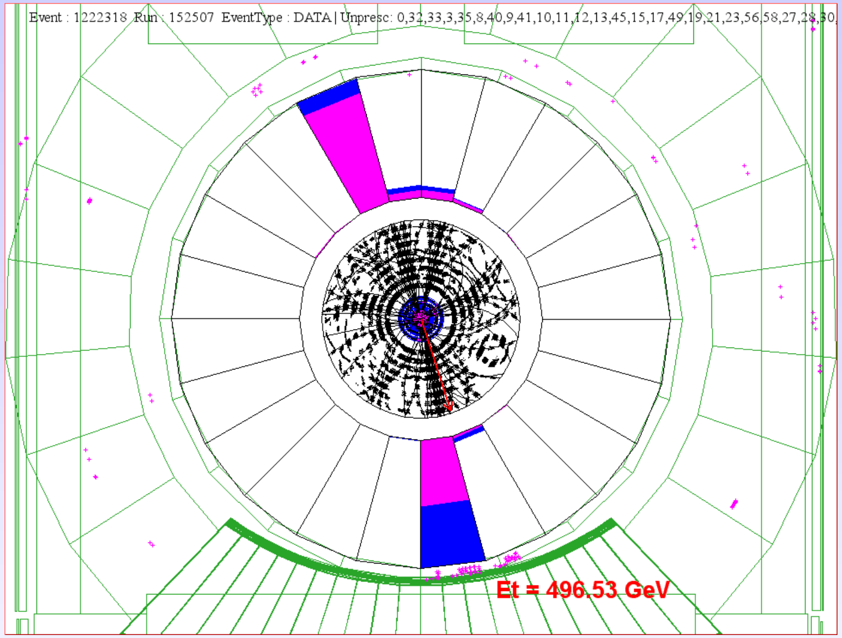




- Hard scattering processes are dominated by QCD jet production
- Originating from quark-quark, quark-gluon and gluon-gluon scattering
- Due to fragmentation of quarks and gluons in final state hadrons
  → Jets with large transverse momentum P_T in the detector
- Cross sections can be calculated in QCD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

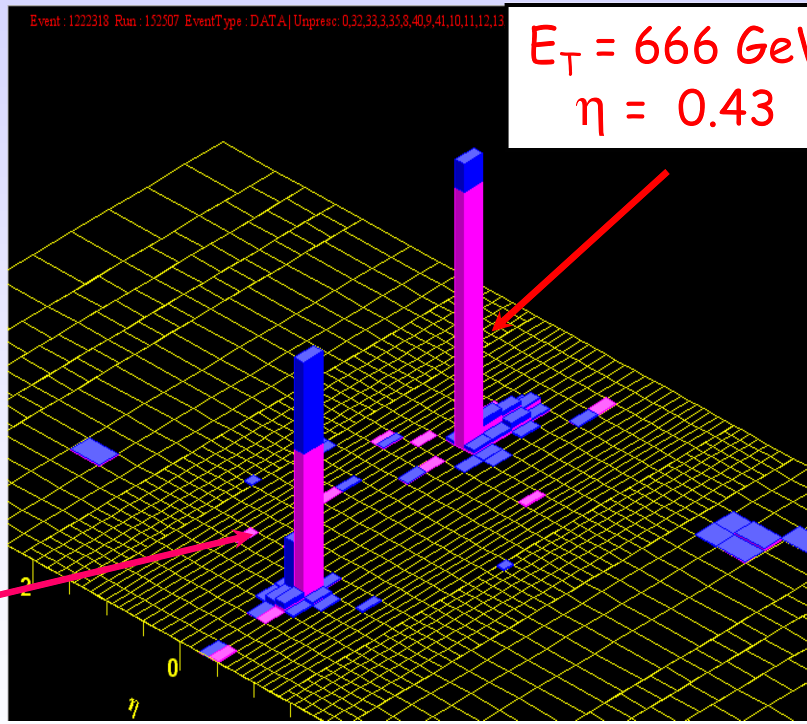
Comparison between experimental data and theoretical predictions constitutes an important test of the theory.

A two jet event at the Tevatron (CDF)



CDF (ϕ-r view)

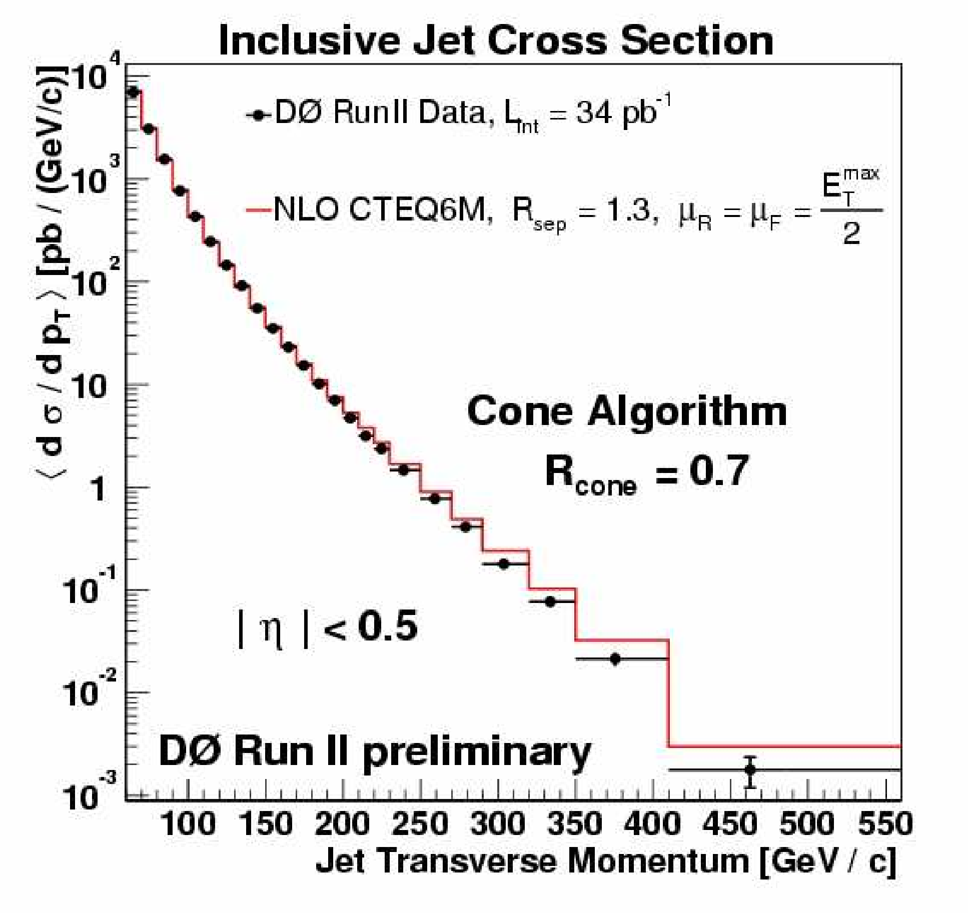
Dijet Mass = 1364 GeV/c^2



E_T = 666 GeV
η = 0.43

E_T = 633 GeV
η = -0.19

Test of QCD Jet production



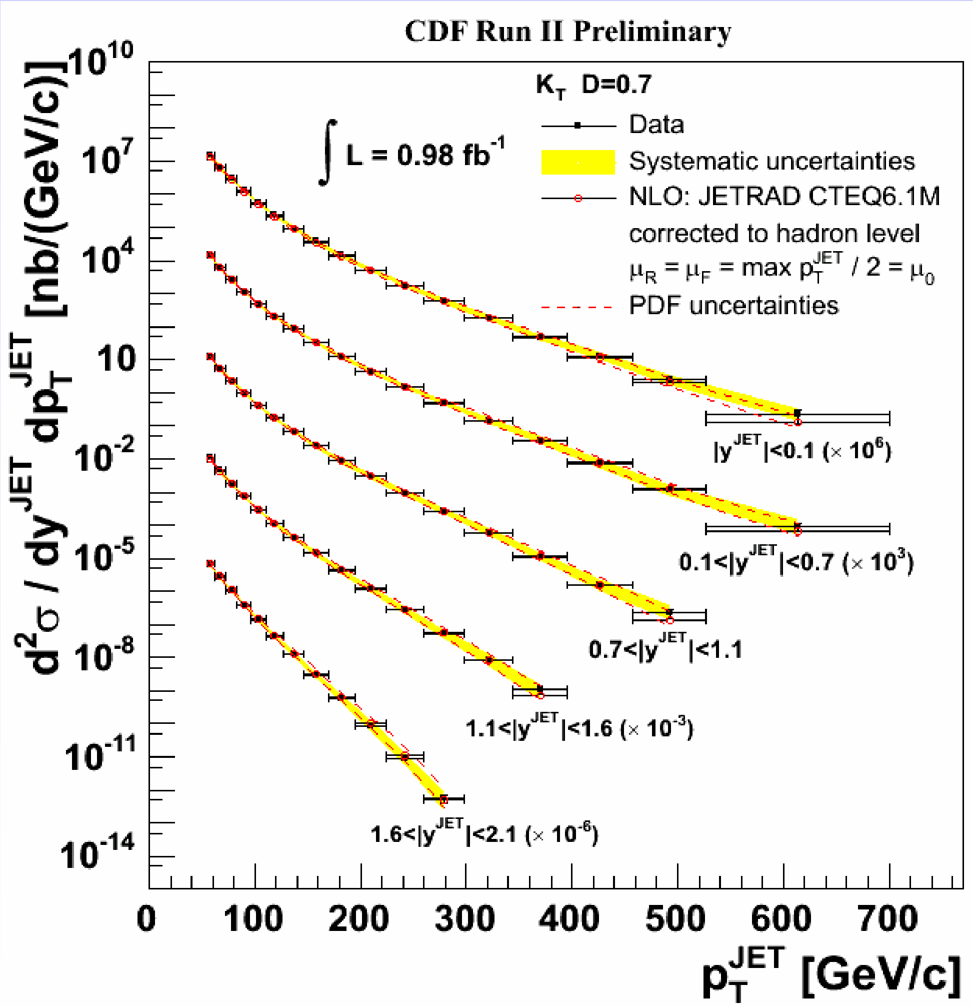
Inclusive Jet spectrum as a function of Jet-PT

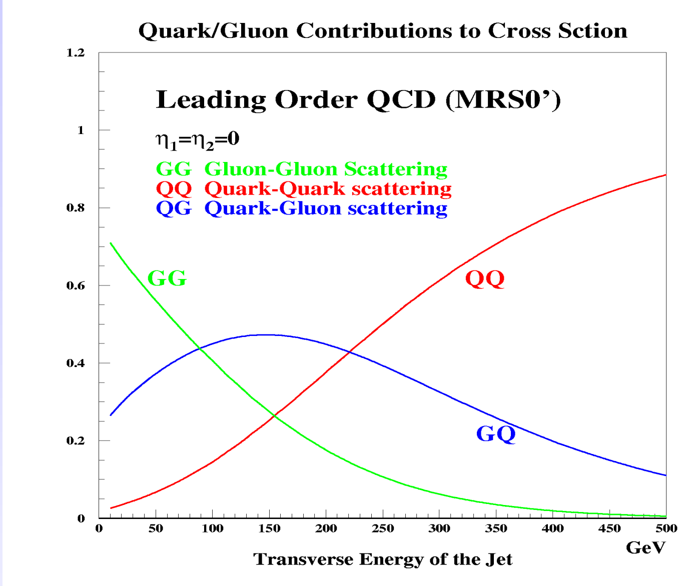
Data from the DØ experiment (Run II)

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

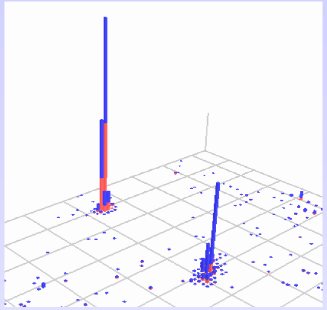
Data corresponding to ~1 fb^{-1}

Double differential distributions in P_T and η

Main experimental systematic uncertainties

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

  - one needs an algorithm to define a jet (e.g., a cone around a local energy maximum in the calorimeter)
  typical cone values: $\Delta R = \sqrt{\Delta\Phi^2 + \Delta\eta^2} = 0.5$



- Cone energy ≠ parton energy

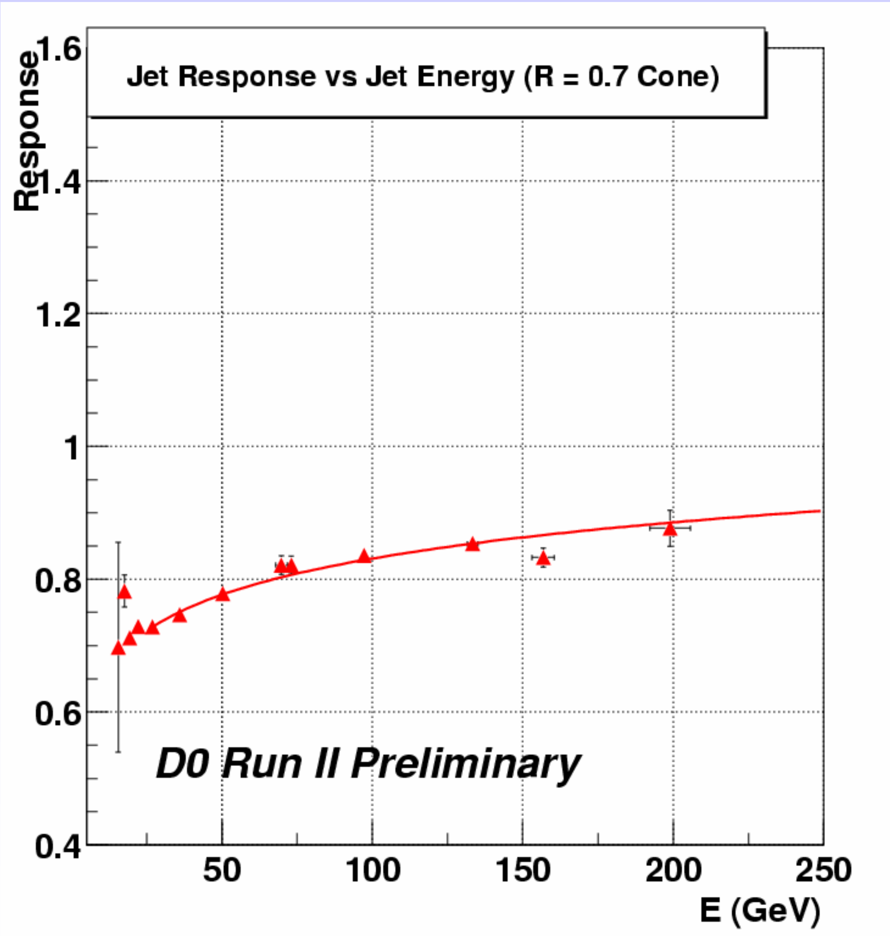
Main corrections:

– Calorimeters show different response to e, γ and hadrons

– Subtraction of energy not originating from the hard scattering

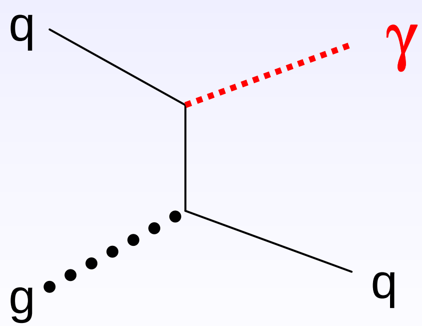
– Correction for jet energy outside the cone

Main experimental systematic uncertainty: Jet Energy Scale

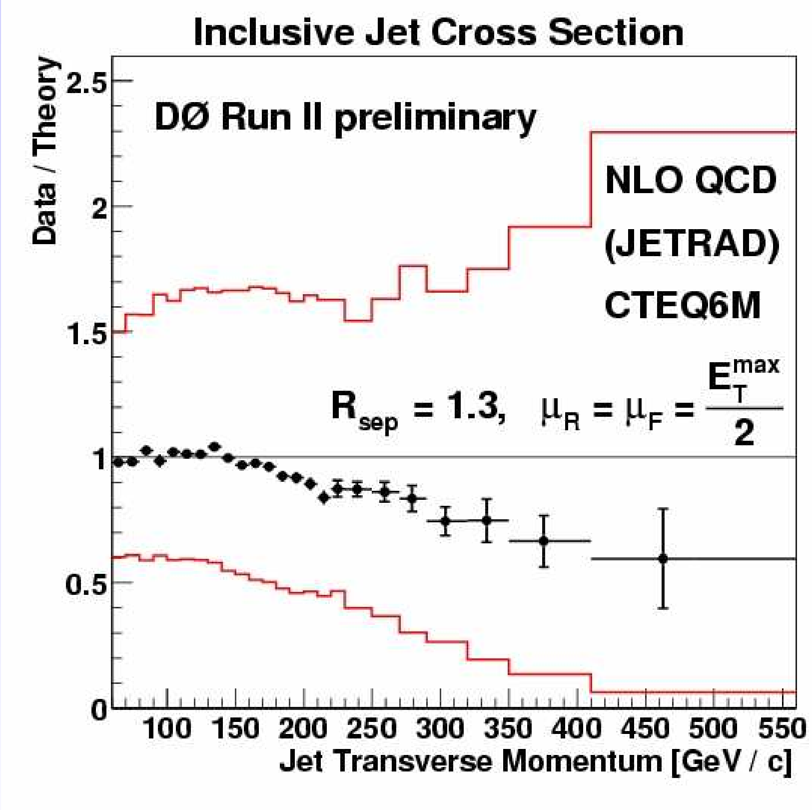


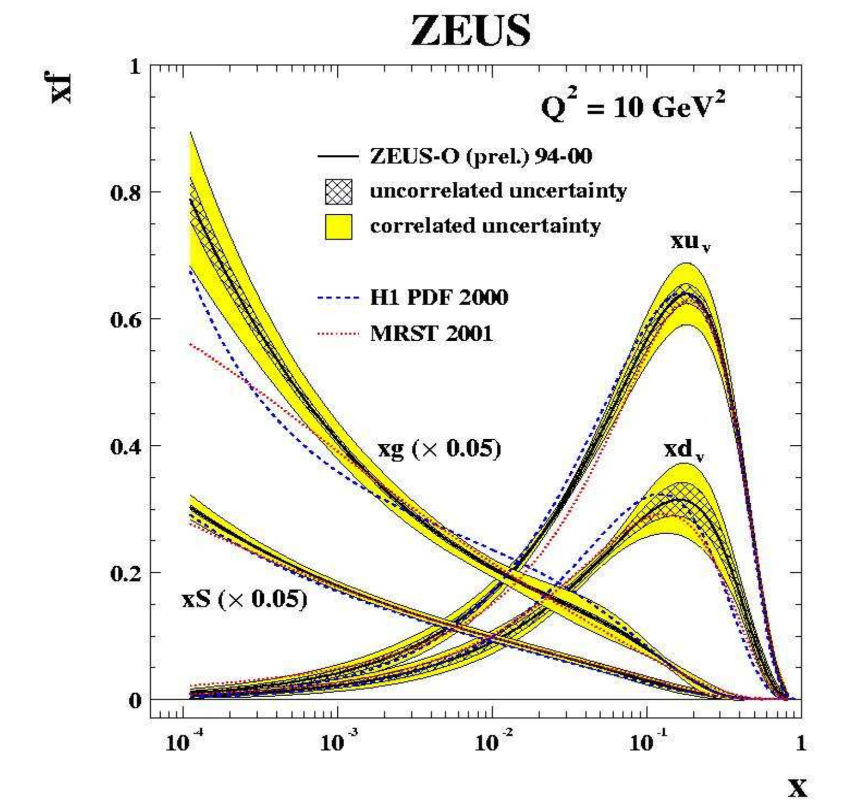
Jet response correction in DØ:

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



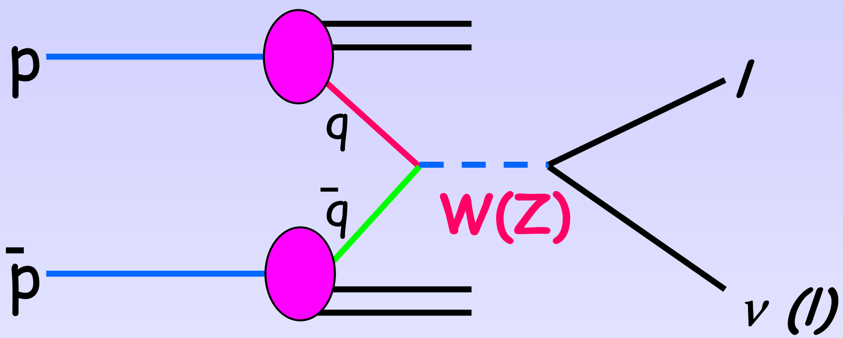
Comparison with Theory





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

Test of W and Z production



Drell-Yan production process

Tevatron: expected rates for 2 fb^{-1}: 3 Mio W → ℓ ν events

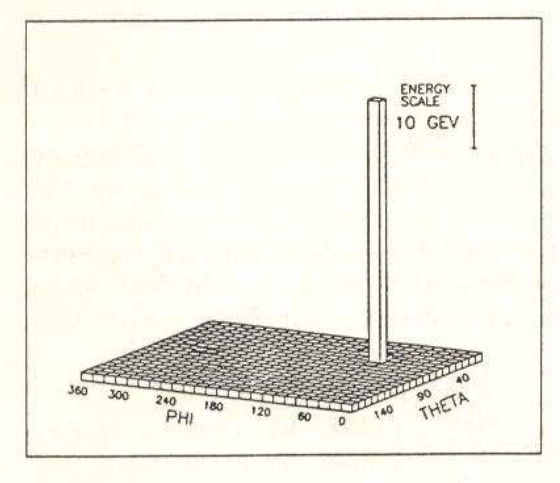
LHC: expected rates for 10 fb^{-1}: 60 Mio W → ℓ ν events

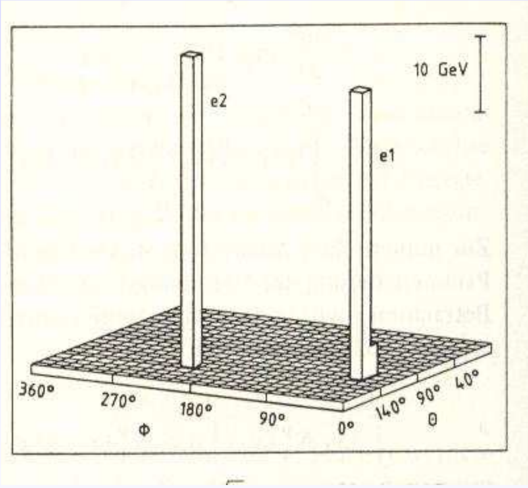
LEP II: recorded events: 40 000 W → ℓ ν events

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 → ℓ ν** large P_T (ℓ), large P_T^{miss}
Z → ℓ ℓ 2 leptons with large P_T (ℓ)

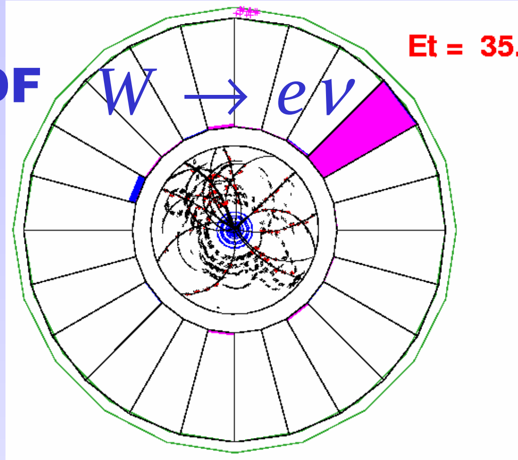


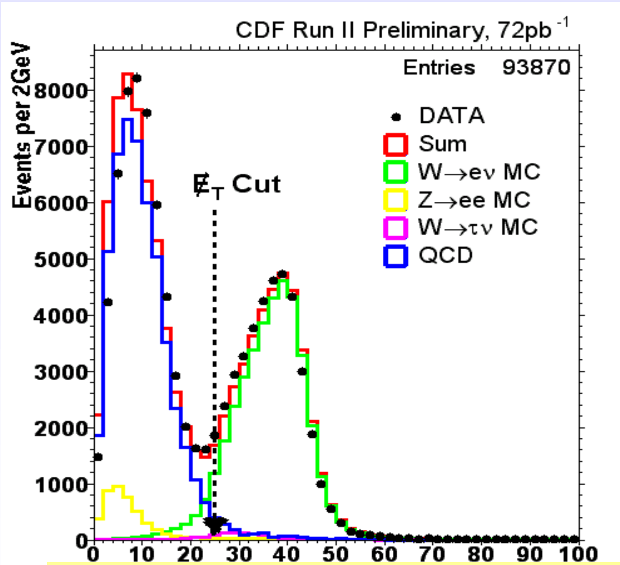


W/Z discovery by the UA1 and UA2 experiments at CERN (1983/84)

W / Z → eν / ee signals

CDF





missing transverse momentum P_T^{miss} (GeV/c)

Trigger:

- Electron candidate > 20 GeV/c

Electrons

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

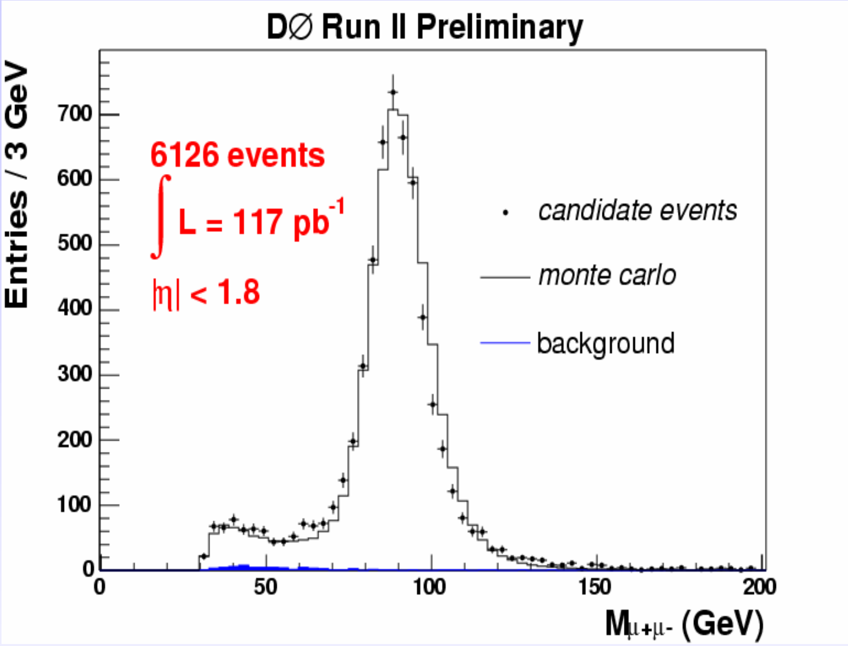
Z → ee

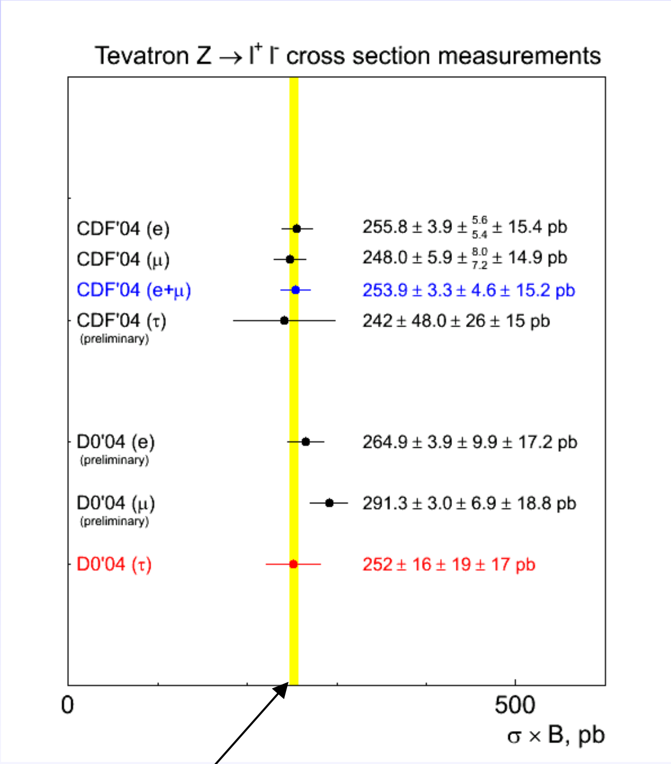
- 70 GeV/c² < m_{ee} < 110 GeV/c²

W → eν

- Missing transverse momentum > 25 GeV/c

Z→ ℓℓ cross section

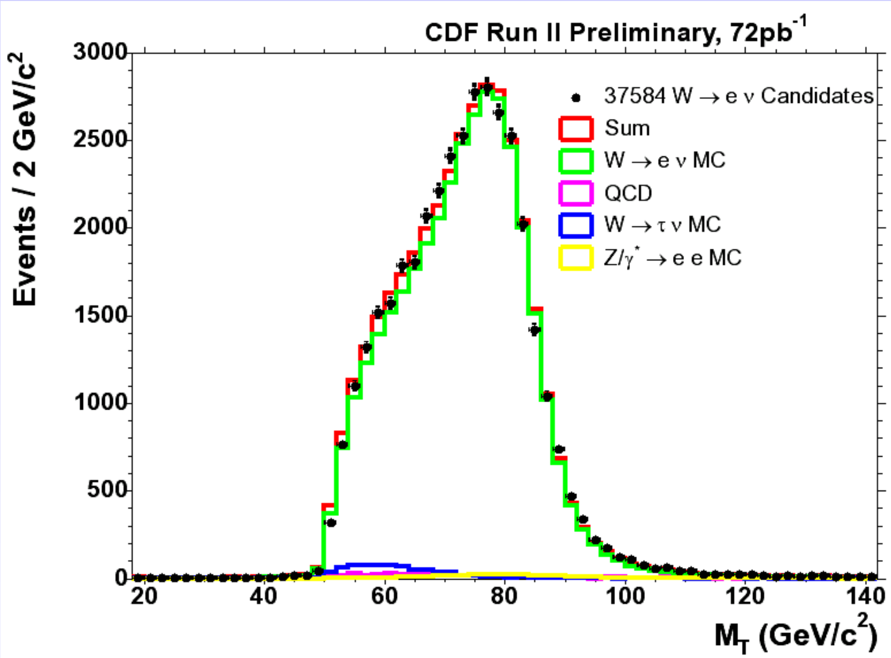


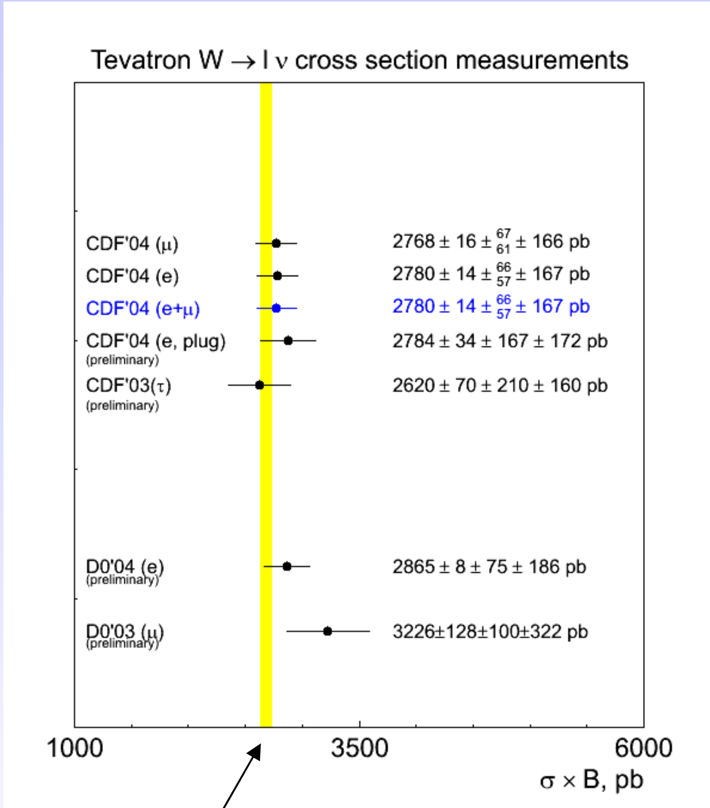


Good agreement with NNLO QCD calculations

C.R.Hamberg et al, Nucl. Phys. B359 (1991) 343.

W → ℓν Cross Section





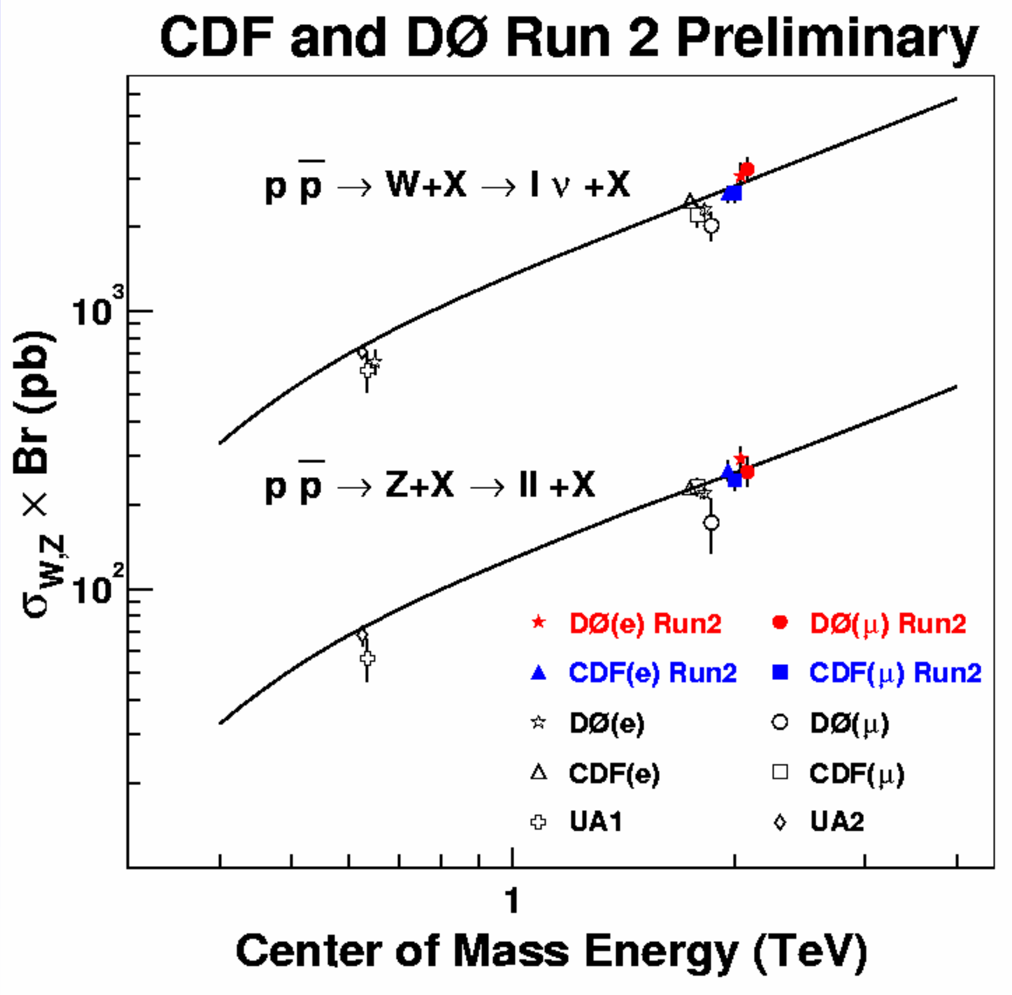
$$M_W^T = \sqrt{2 \cdot P_T^l \cdot P_T^\nu \cdot \left(1 - \cos \Delta\phi^{l,\nu}\right)}$$

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

Good agreement with NNLO QCD calculations

C.R.Hamberg et al, Nucl. Phys. B359 (1991) 343.

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

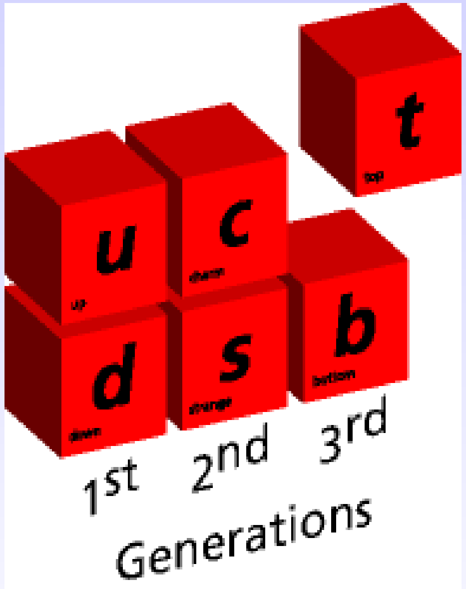


Top Quark Physics

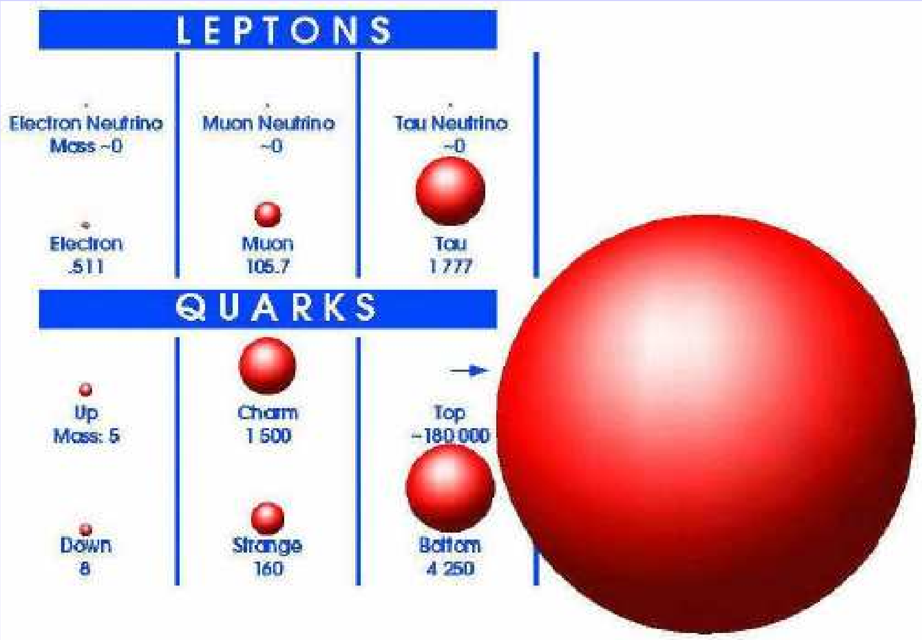
• Discovered by CDF and DØ collaborations at the Tevatron in 1995

• 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



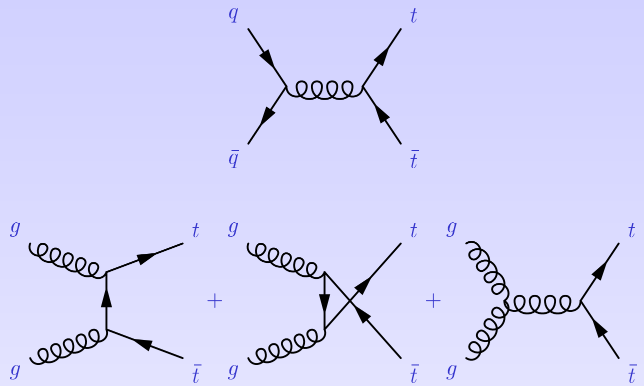
Why is Top-Quark so important ?



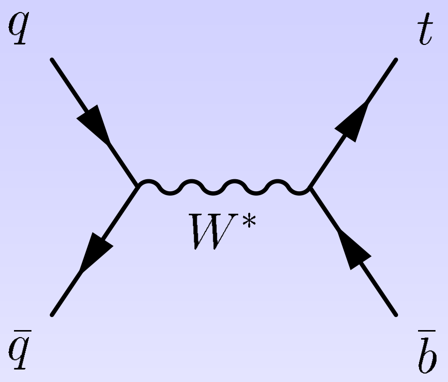
We still know experimentally very little about the properties of the top quark:
mass, spin, charge, lifetime, decay properties (rare decays), gauge couplings, Yukawa coupling,…

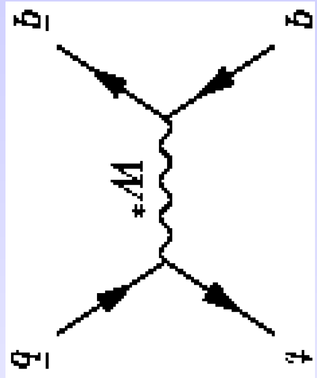
Top Quark Production

Pair production: qq and gg-fusion



single top-quarks qq, qb and gb-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)	0.7	0.9	10
σ (qb) (pb)	1.7	2.4	250
σ (gb) (pb)	0.07	0.1	60

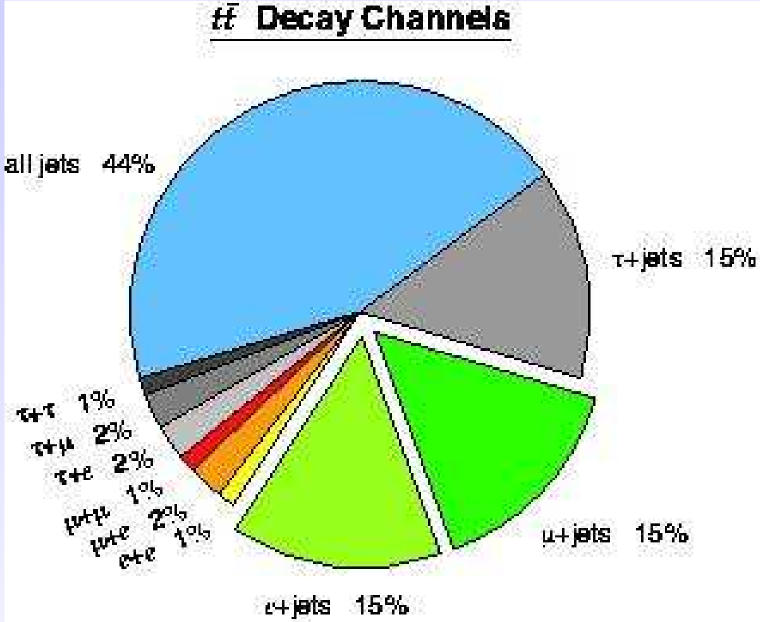
Top Quark Decays

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

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

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

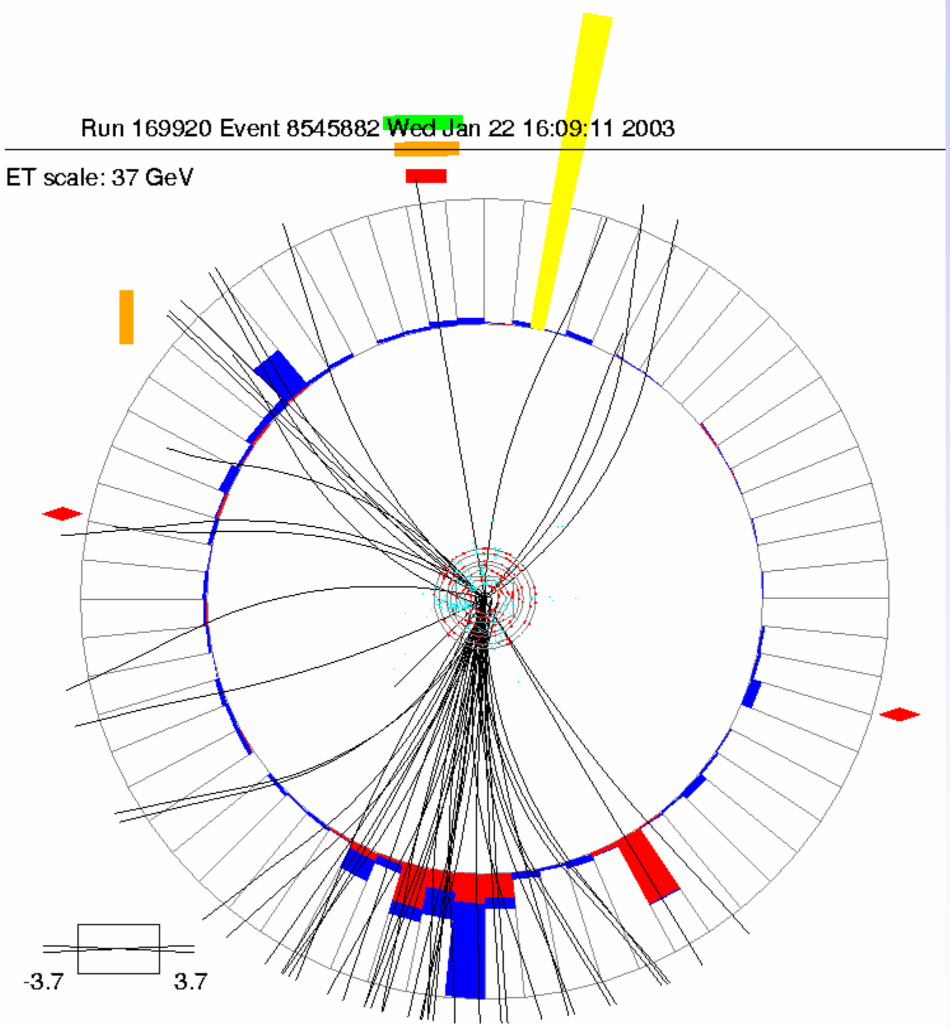
Both W's decay via $W \rightarrow qq$ (44%)
all hadronic, not very useful



Important experimental signatures: : - Lepton(s)

- Missing transverse momentum
- b-jet(s)

DØ top candidate event with two leptons



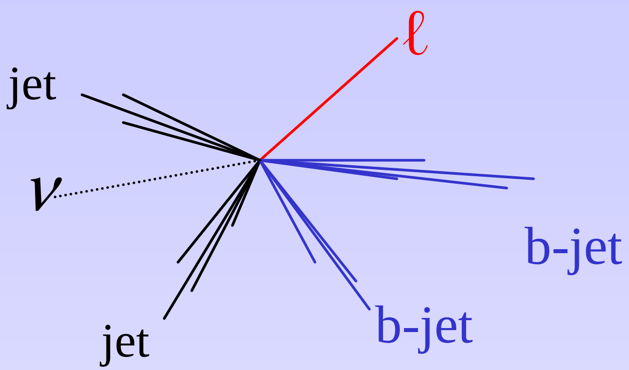
$p_T(e) = 20.3\ GeV/c^2$

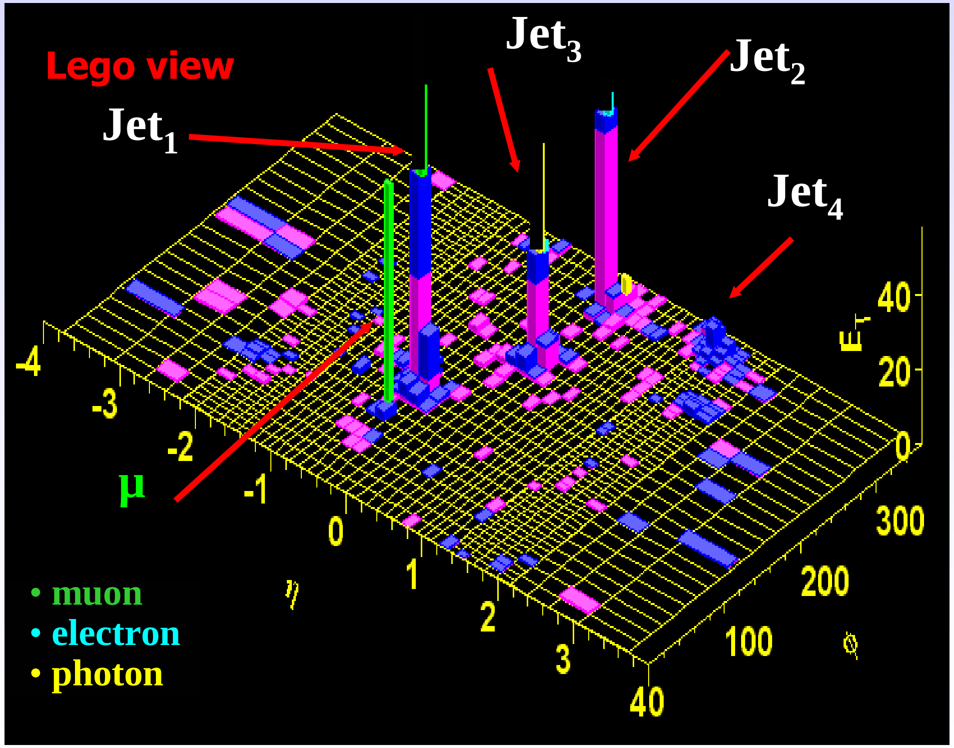
$p_T(\mu) = 58.1\ GeV/c^2$

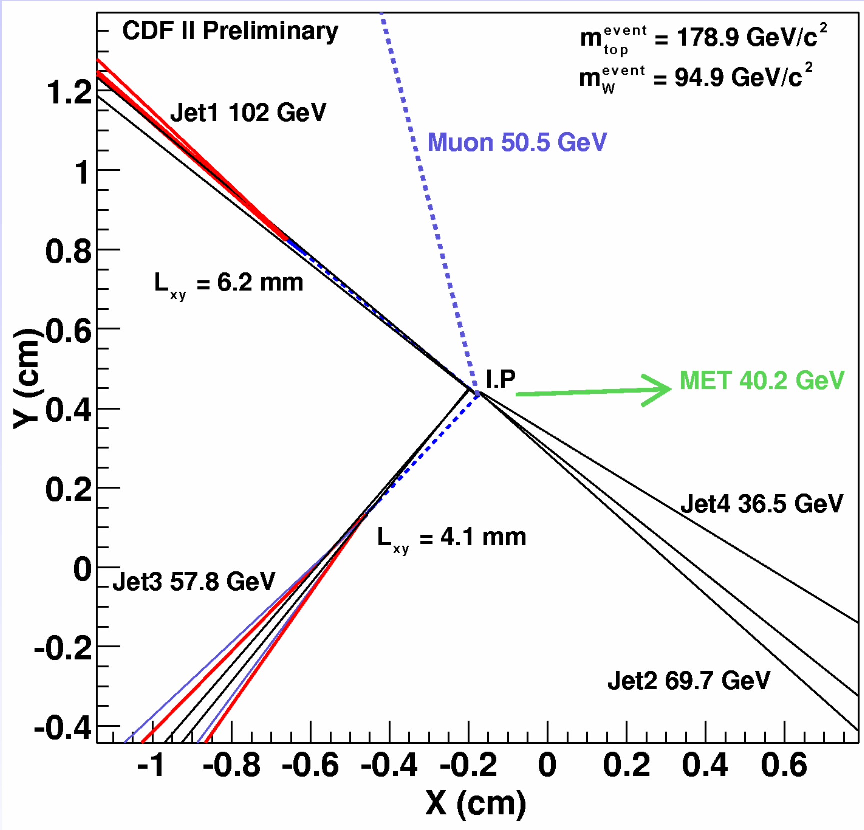
$E_T^j = 141.0, 55.2\ GeV$

E_T miss=91 GeV

A CDF Lepton + Jet event







$p_T(\mu)$ = 54.4 GeV

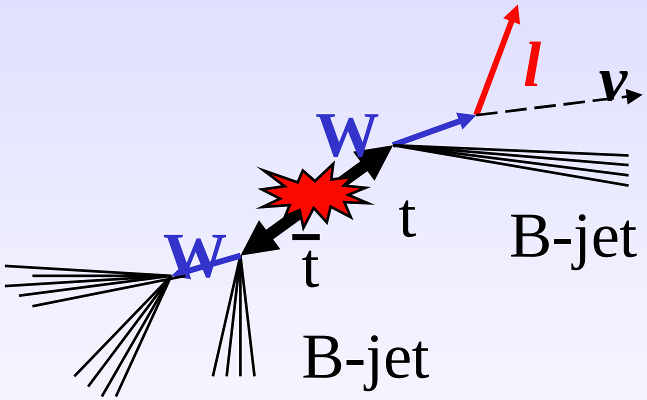
E_T^j = 96.7, 65,8, 54.8, 33.8 GeV

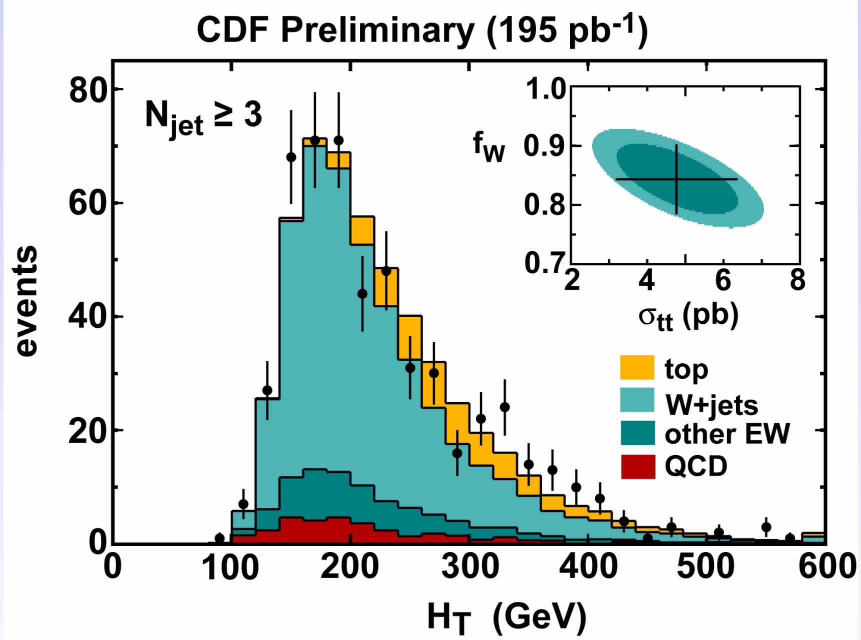
Missing E_T= 40.2 GeV

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

1 high-p_T isolated lepton

Large missing E_T + $\geq$ 3 jets



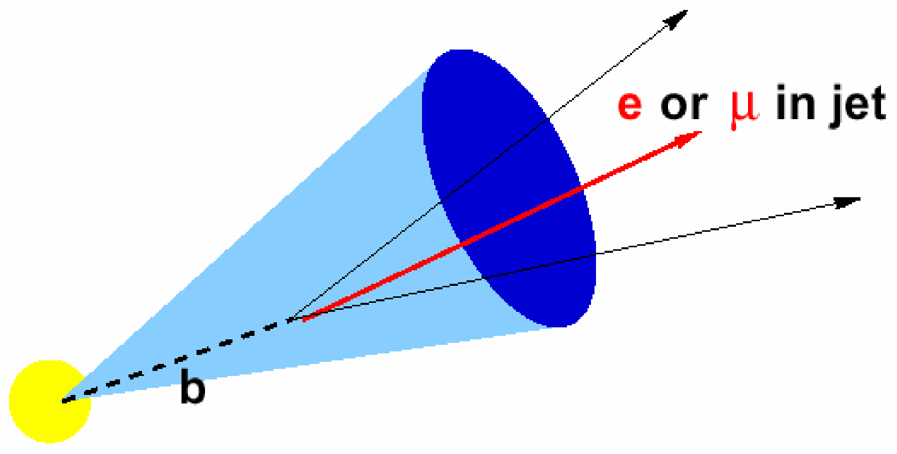


H_T = scalar sum of all high P_T objects (jets, leptons, E_T^{miss})

<u>Before b-tagging</u>: background from W+jet events clearly dominates

Tagging of b-quarks

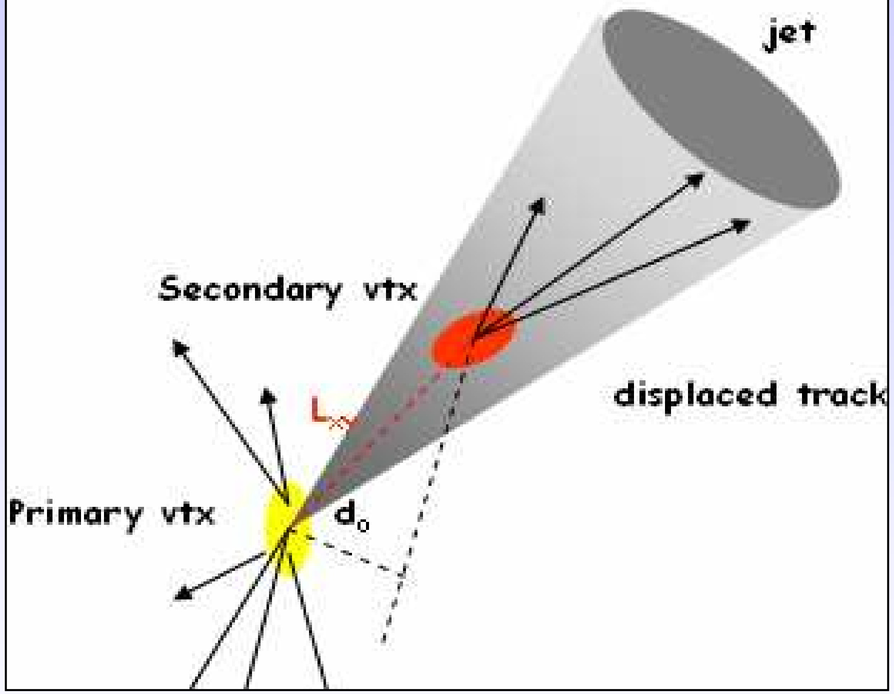
Soft lepton tagging



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

Search for non-isolated soft lepton in a jet

Silicon Vertex tag

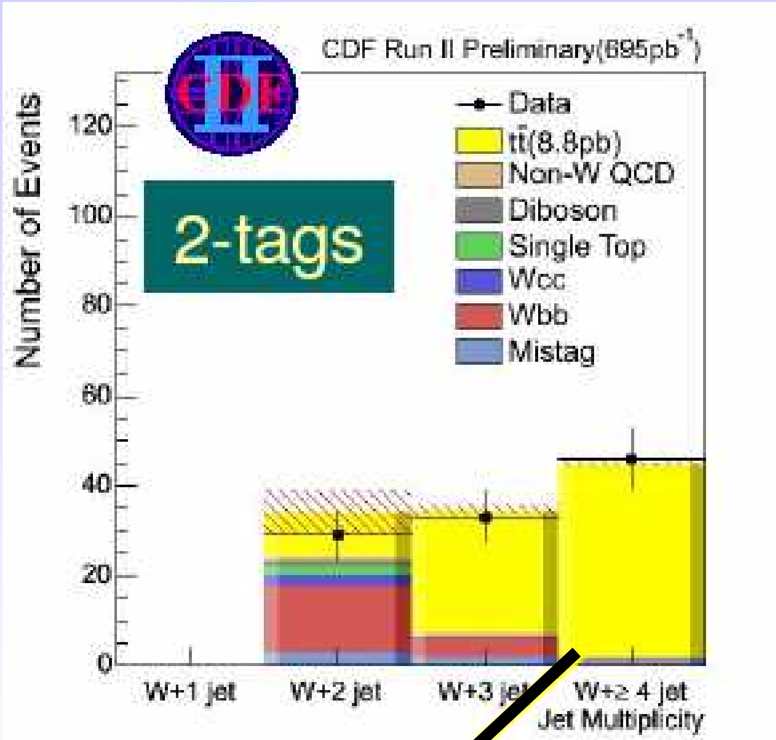


B mesons travel ~ 3 mm before decaying:

– Search for secondary vertex

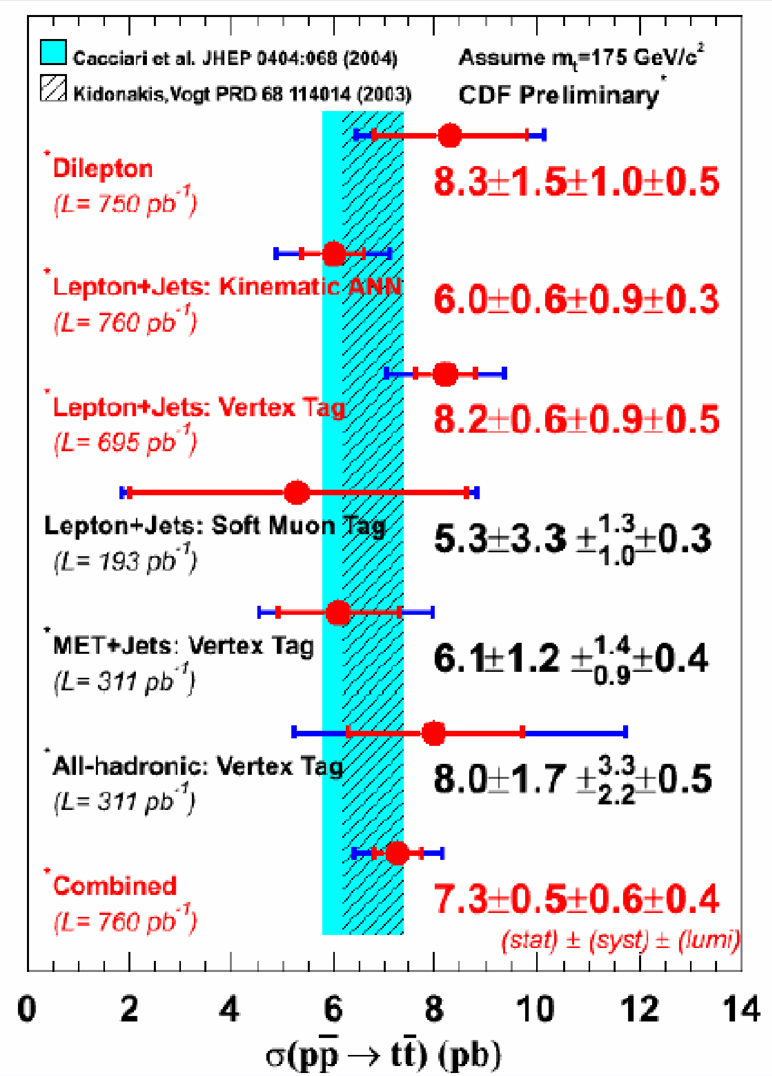
tt cross section (lepton + jets) (including double b-tag)

1 high-p_T isolated lepton + Large missing ET + Two b-tagged jet



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

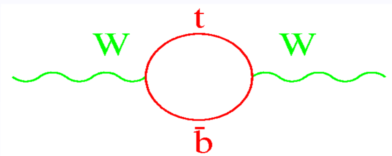
Electromagnetic constant
measured in atomic transitions

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

Fermi constant
measured in muon decay

weak mixing angle
measured at LEP/SLC

radiative corrections
$\Delta r = f\,(m_{top}^2, \log m_H)$



G_F, α_{EM}, $\sin \theta_W$

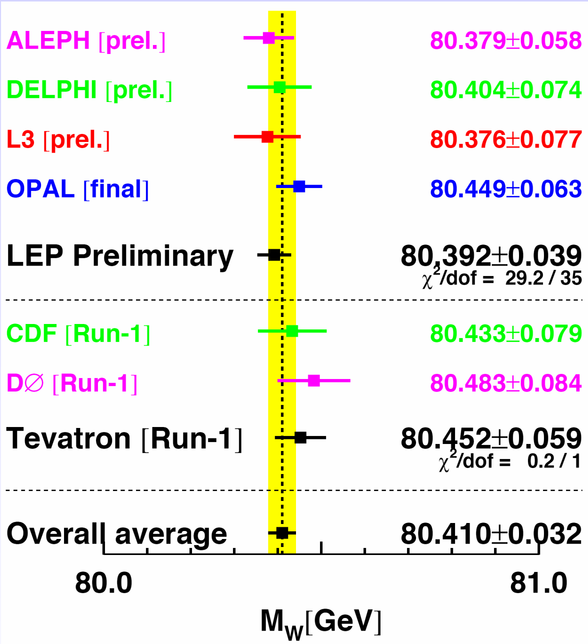
are known with high precision

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

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

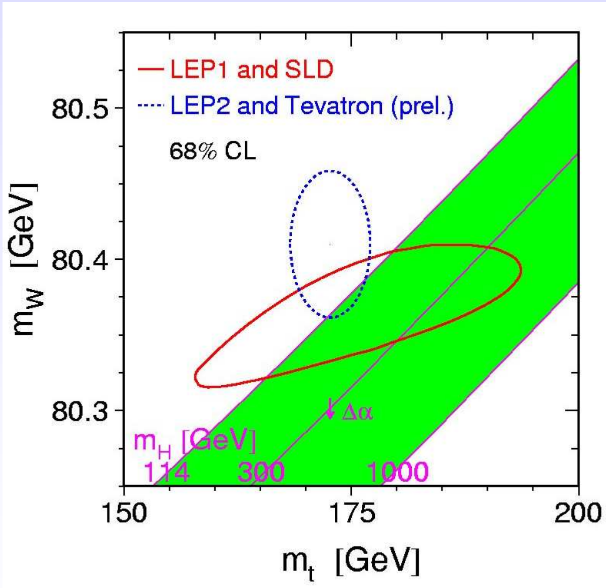
$4\cdot10^{-4}$



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

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

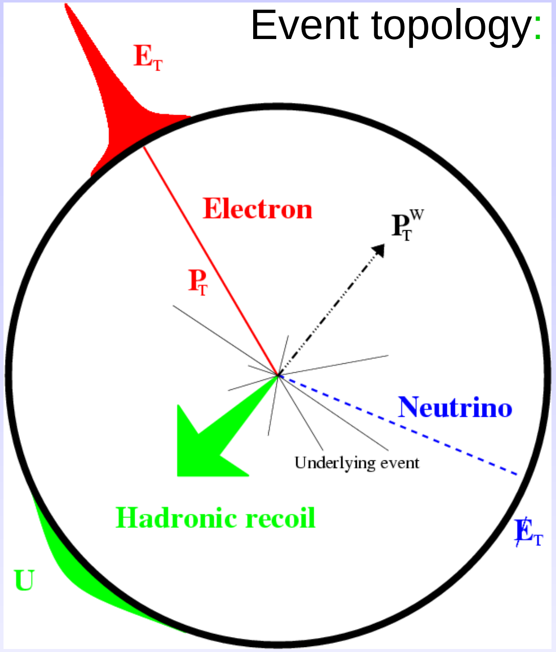
1.4%

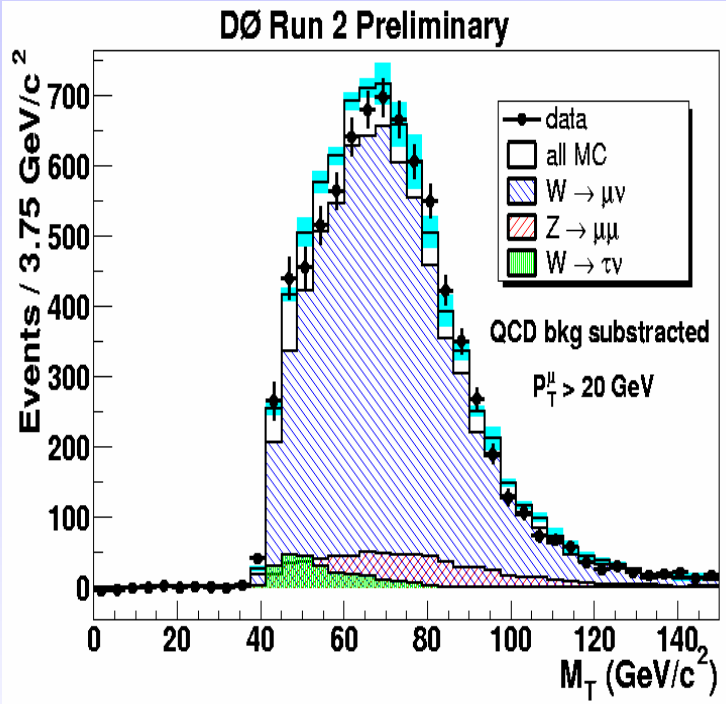


light Higgs boson
is favoured
by present
measurements

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:



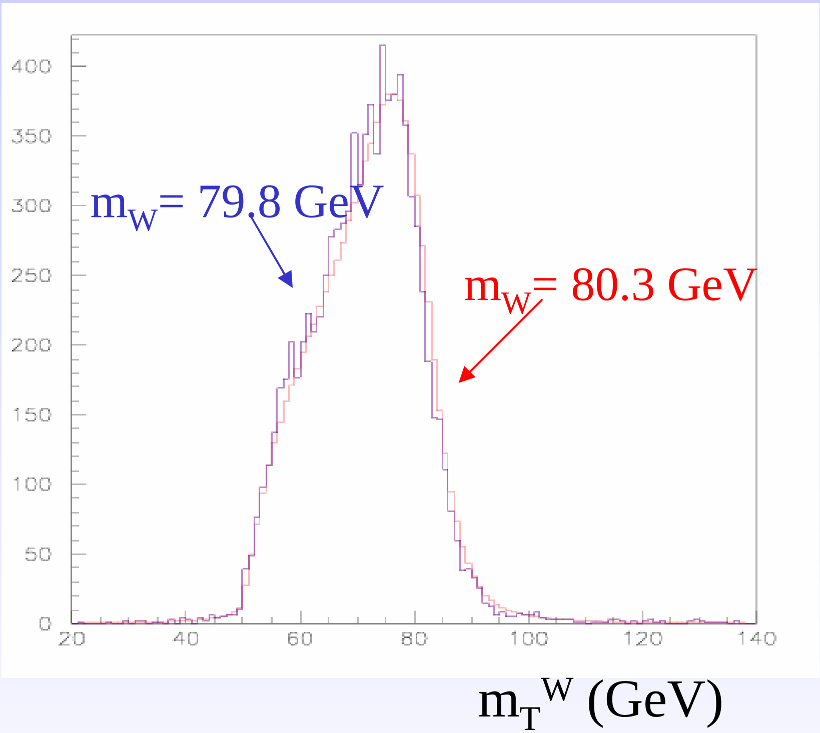


Observables: $P_T(e)$, $P_T(had)$ $\Rightarrow$ $P_T(\nu)$ = - ($P_T(e)$ + $P_T(had)$)

The transverse mass M_T is used for the determination of the W-mass

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

The shape of the transverse mass distribution is sensitive to m_W



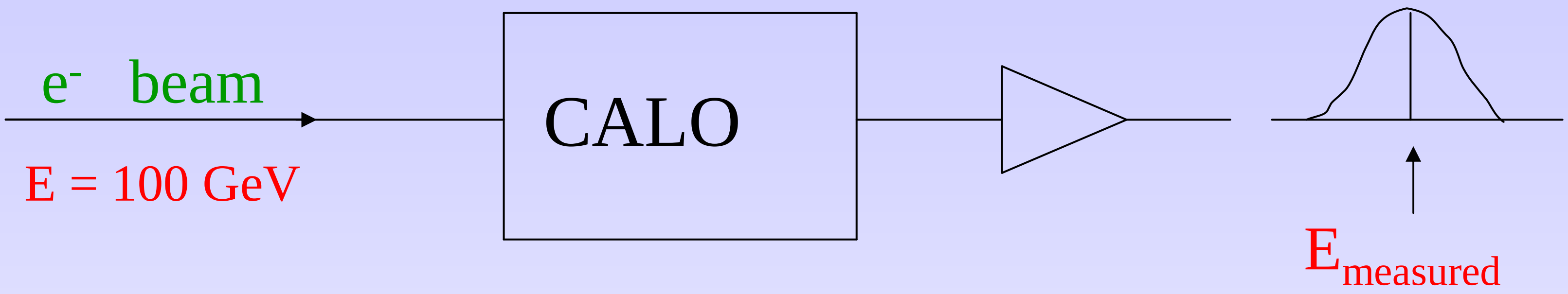
Main uncertainties:

- detector performance
  (energy resolution, energy scale, ….)
- theory: 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



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

⇒ one of most serious experimental challenges !!

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)	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**

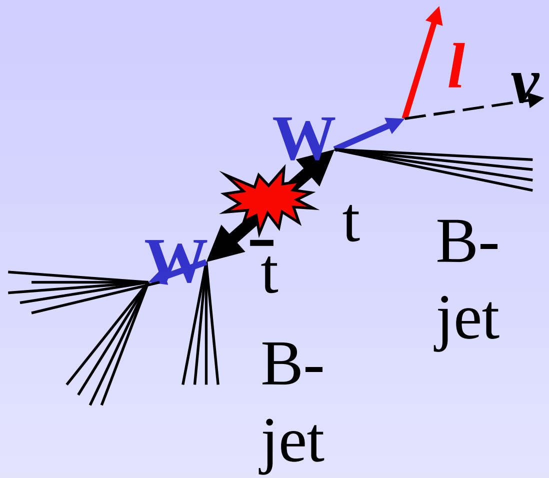
- Total error per lepton species and per experiment at the **LHC** is estimated to be **± 25 MeV**
  at the **Tevatron** **± 34 MeV**
- Main uncertainty: lepton energy scale (goal is an uncertainty of ± 0.02 %)

Combining both experiments (ATLAS + CMS, 10 fb^{-1}), both lepton species and assuming a scale uncertainty of ± 0.02% **⇒ Δm_W ~ ± 15 MeV**

Tevatron: 2 fb^{-1}: **Δm_W ~ ± 30 MeV**

Top mass measurements

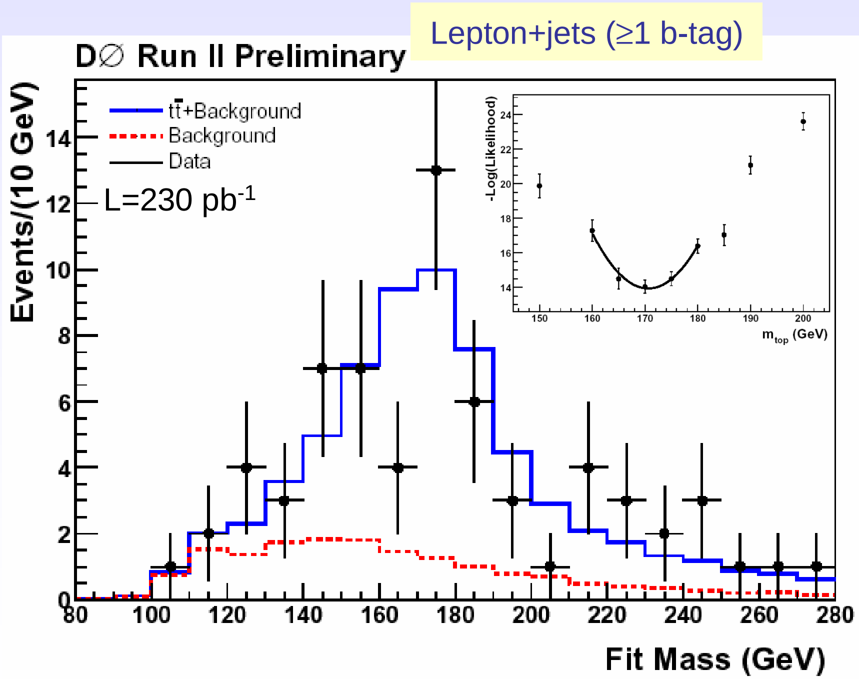
- Kinematic fit under (tt) hypothesis
- compute likelihood for observed events as a function of the top quark mass



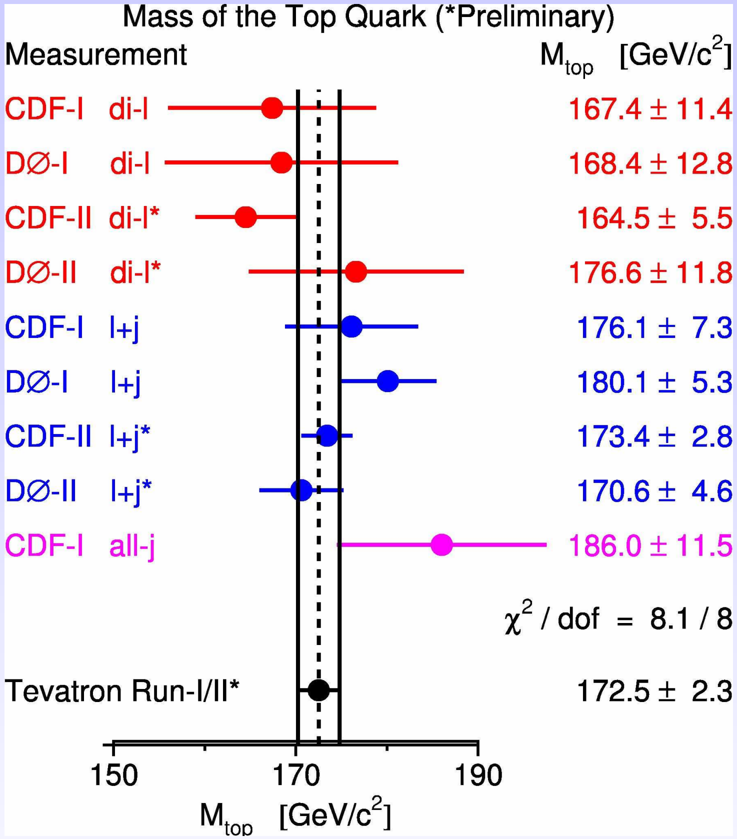
Most precise single measurements:

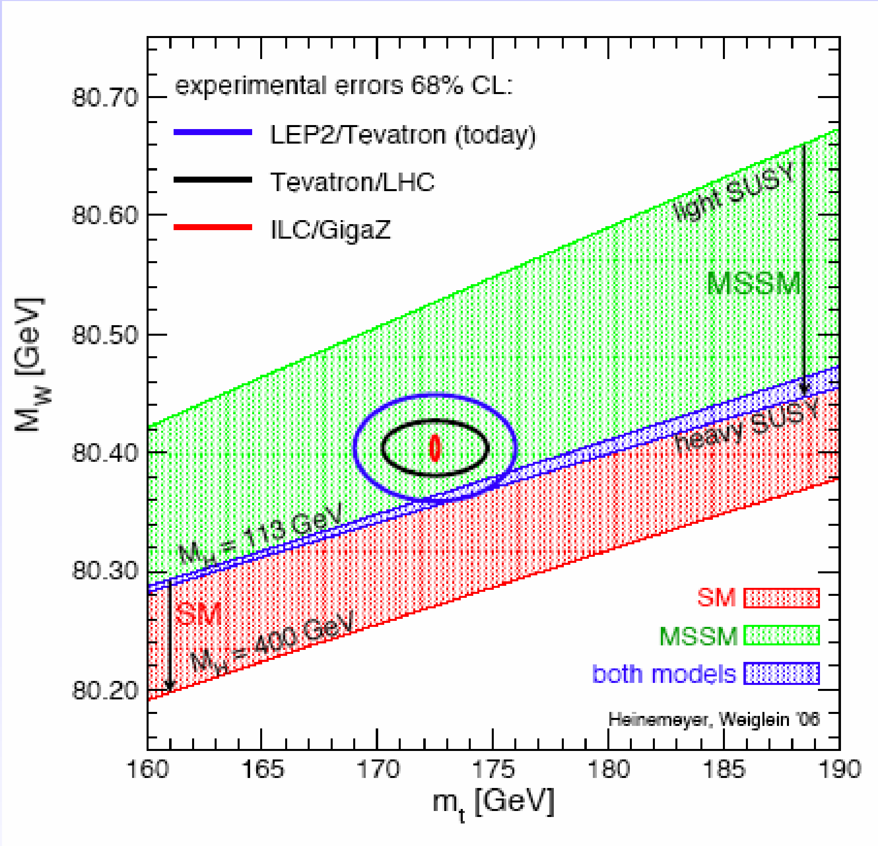
m_{top} = 173.4 ±3.5 (stat) ± 1.3 (syst) GeV/c^2 (CDF)

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



Future Prospects for the top quark mass measurement





- Expected Tevatron precision : $\pm$ 1.5 GeV/c^2
- Expected LHC precision : ~ 1 GeV/c^2
- Expected ILC precision : ~ 0.1 GeV/c^2

Summary of the 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**

- **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