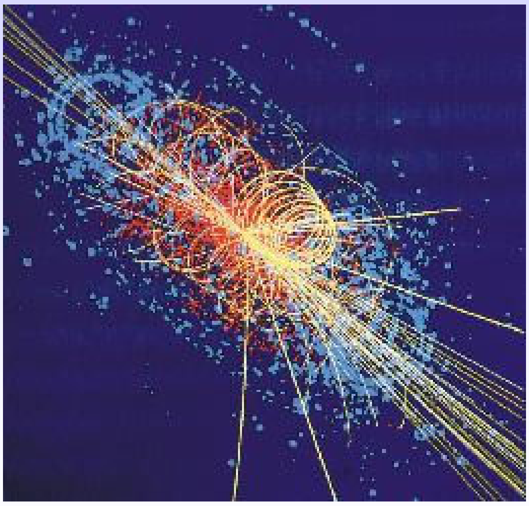
Physics at Hadron Colliders

Part 2

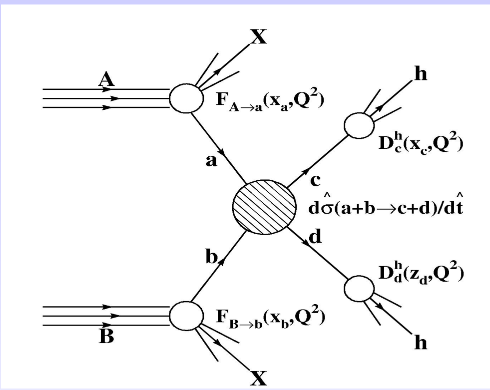


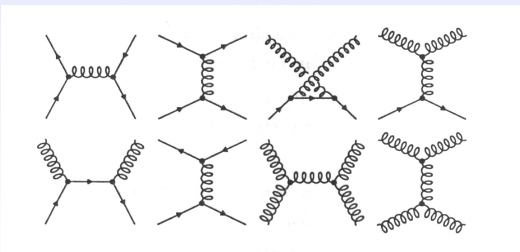
Standard Model Physics

Test of Quantumchromodynamics
(Jet production, W/Z production, top-quark production,....)

Precision measurements
(W mass, top-quark mass, ...)

QCD processes at hadron colliders



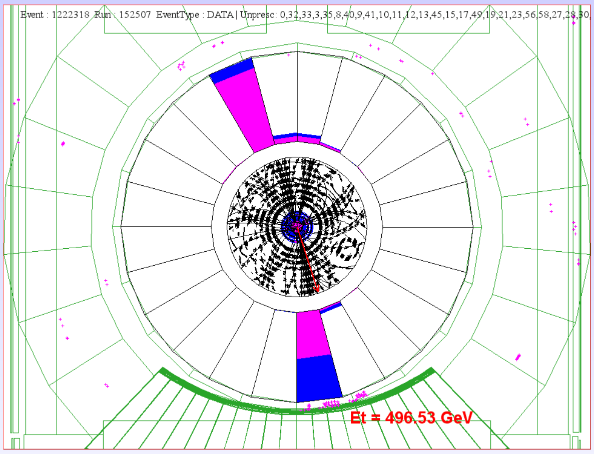


- Hard scattering processes are dominated by QCD jet production
- originating from quark-quark, quark-gluon and gluon-gluon scattering
- Due to fragmentation of quarks and gluons in final state hadrons
  → Jets with large transverse momentum P_T in the detector
- Cross sections can be calculated in QCD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

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

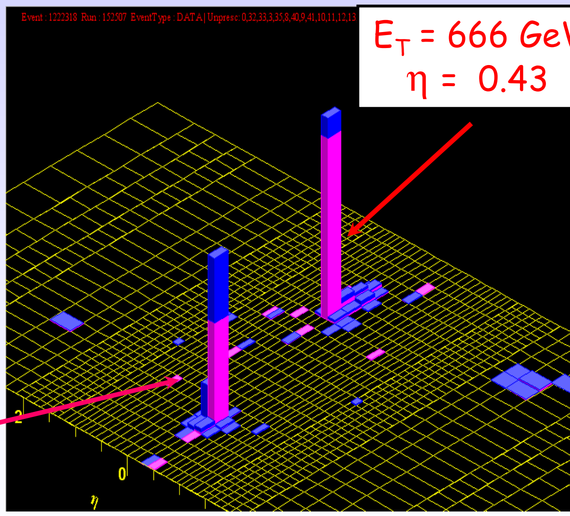
Deviations? → Problem in the experiment ?
Problem in the theory (QCD) ?
New Physics, e.g. quark substructure ?

A two jet event at the Tevatron (CDF)



CDF (ϕ-r view)

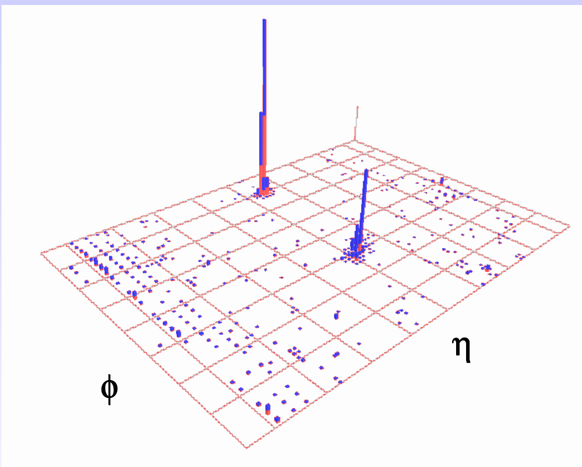
Dijet Mass = 1364 GeV/c^2

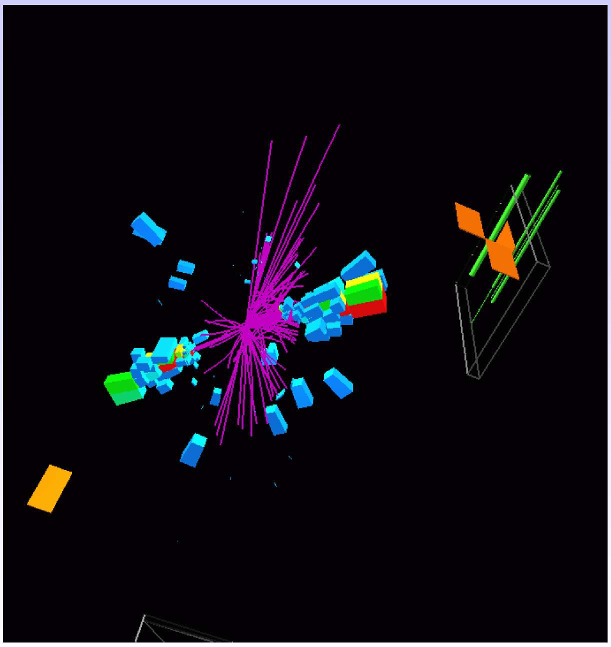


E_T = 666 GeV
η = 0.43

E_T = 633 GeV
η = -0.19

A two jet event in the DØ experiment



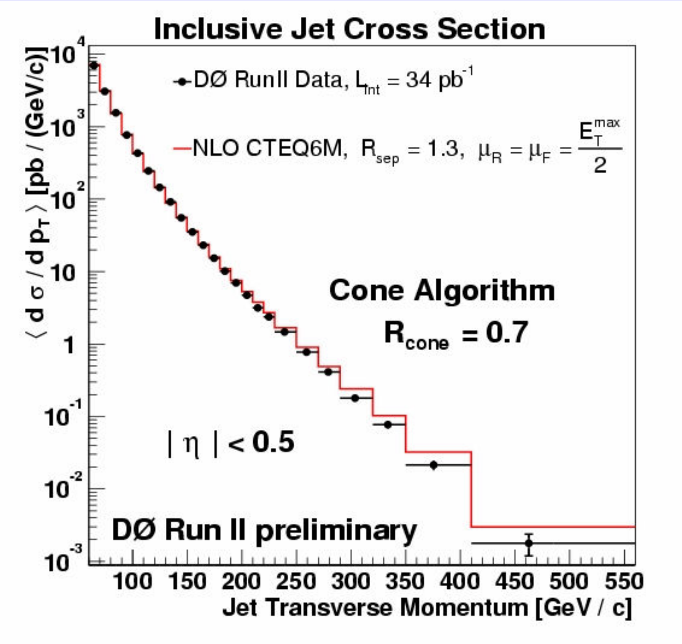


M_{jj} = 838 GeV/c^2

$p_T(1)$ = 432 GeV/c

$p_T(2)$ = 396 GeV/c

Test of QCD Jet production



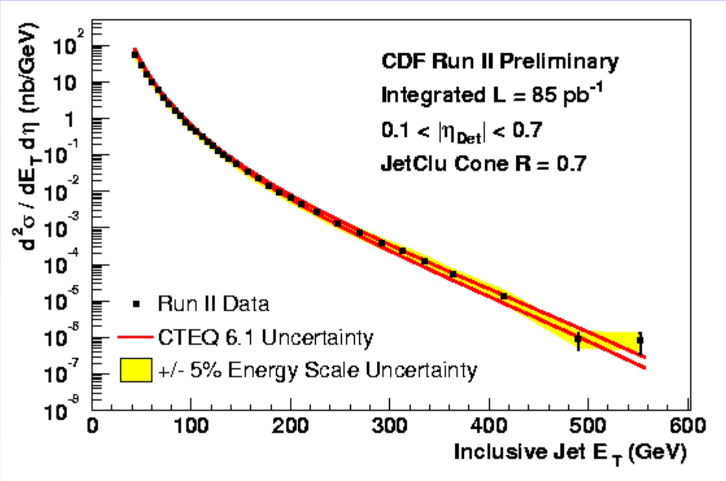
Data from the DØ experiment (Run II)

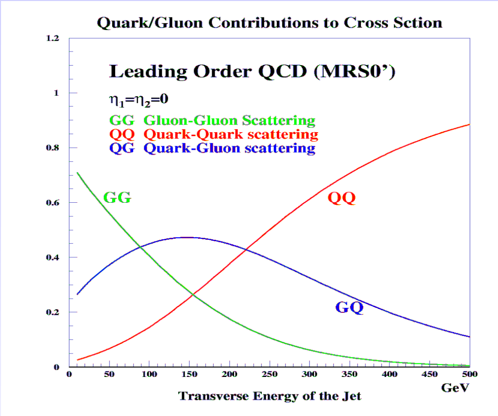
Inclusive Jet spectrum as a function of Jet-P_T

very good agreement over many orders of magnitude !

within the large theoretical and experimental uncertainties

Similar data for the CDF experiment





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

Main experimental systematic uncertainty: Jet Energy Scale

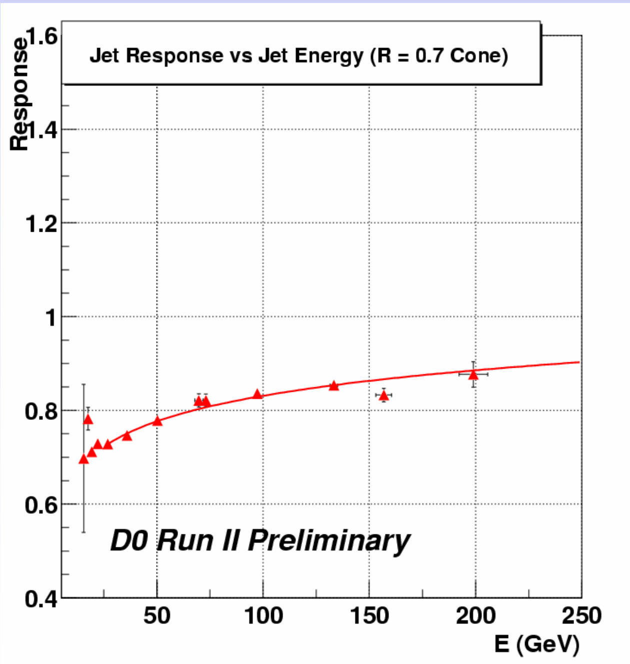
- A Jet is NOT a well defined object (fragmentation, detector response)
  - one needs an algorithm to define a jet, to measure its energy
  (e.g., a cone around a local energy maximum in the calorimeter, cone size adapted such that a large fraction of jet energy is collected,
  typical values: $\Delta R = \sqrt{\Delta\Phi^2 + \Delta\eta^2} = 0.7$

- Cluster 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 in/out of cone
  (corrected with jet data + Monte Carlo simulations)

Main experimental systematic uncertainty: Jet Energy Scale

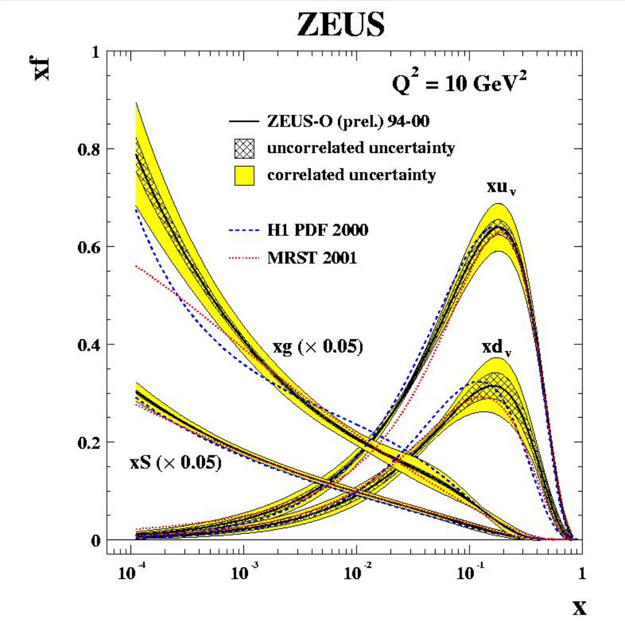


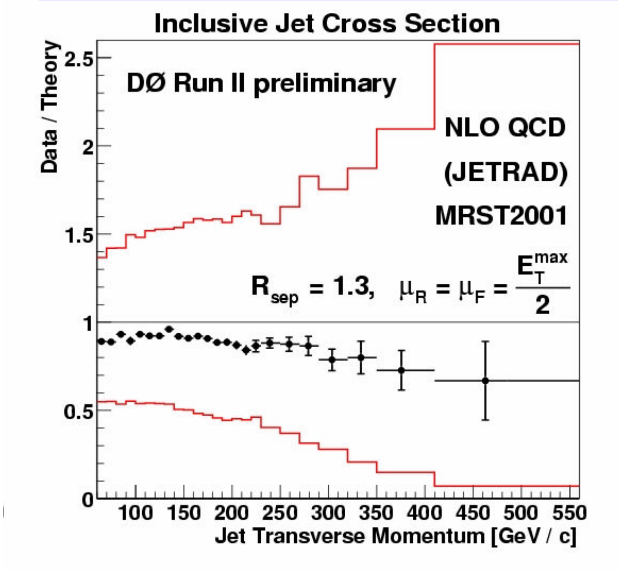
Jet response correction in DØ:

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

Comparison with Theory

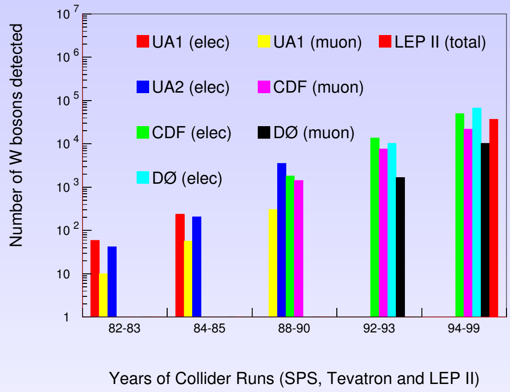
– Fully corrected inclusive jet cross section

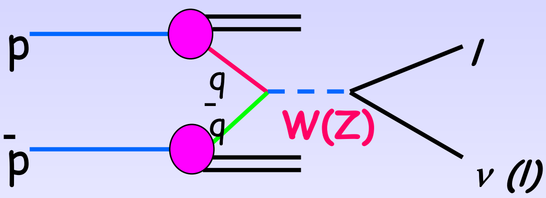




Test of W and Z production

Number of detected W-bosons:





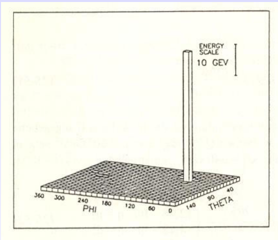
Tevatron: expected rates for 2 fb^{-1}: 3 Mio W → ℓ ν events

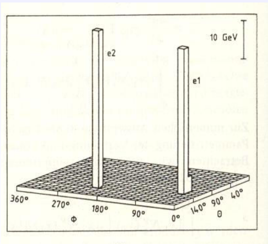
LHC: expected rates for 10 fb^{-1}: 60 Mio W → ℓ ν events

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
Z → ℓ ℓ



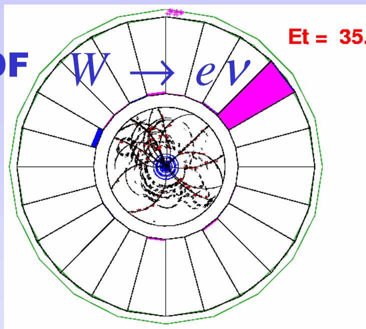


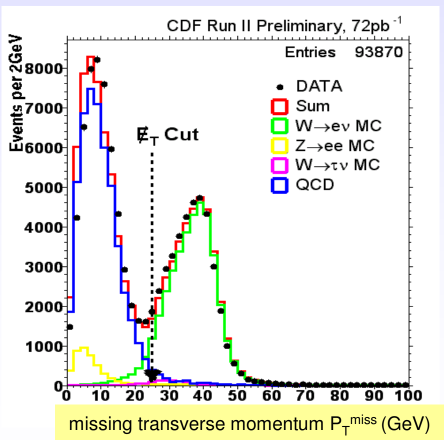
A bit of history: one of the first W events seen; UA2 experiment

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

Today's W / Z → eν / ee signals

CDF





Trigger:

- **Electron candidate > 20 GeV, shower shape cut**

Electrons

- **Isolated EM Cluster in the Calorimeter**
- **E_T> 25 GeV with large EM fraction**
- **Shower shape consistent with MC expectation**
- **Matched with tracks**

Z → ee

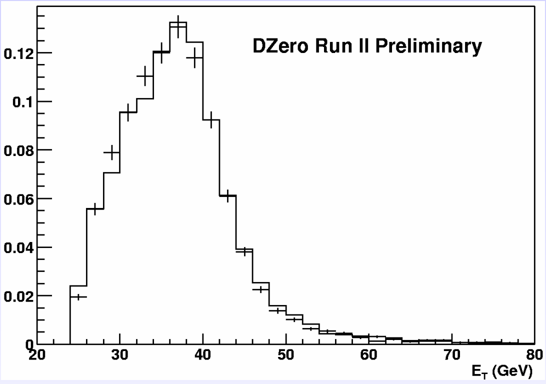
- **70 GeV < m_{ee} < 110 GeV**

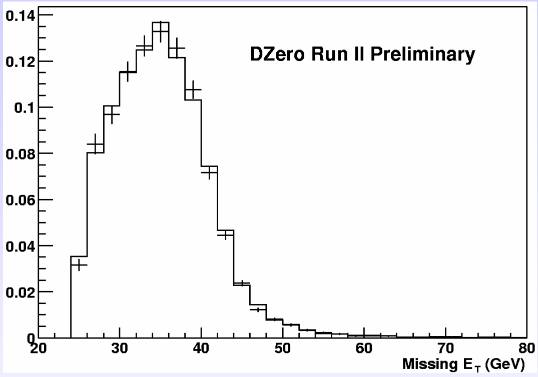
W → eν

- **Missing transverse momentum > 25 GeV**

W → eν Cross Section

Background subtracted distributions compared to Monte Carlo predictions

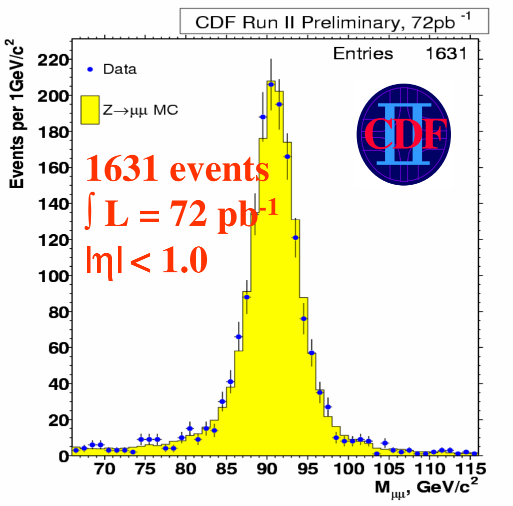


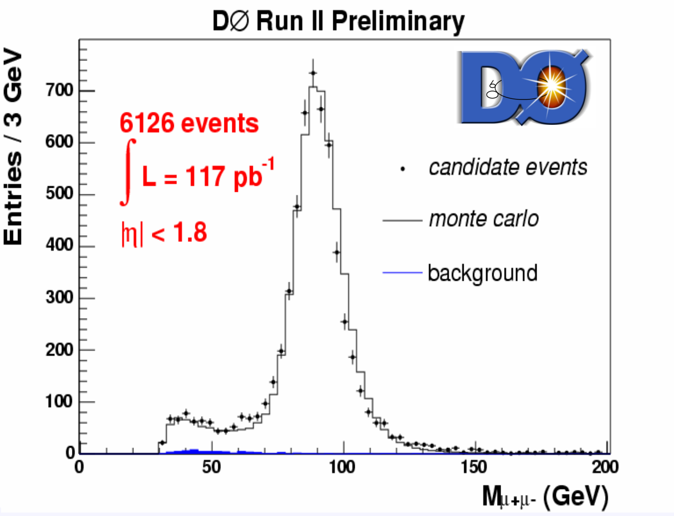


27370 Candidates in $\int Ldt = 42\ pb^{-1}$

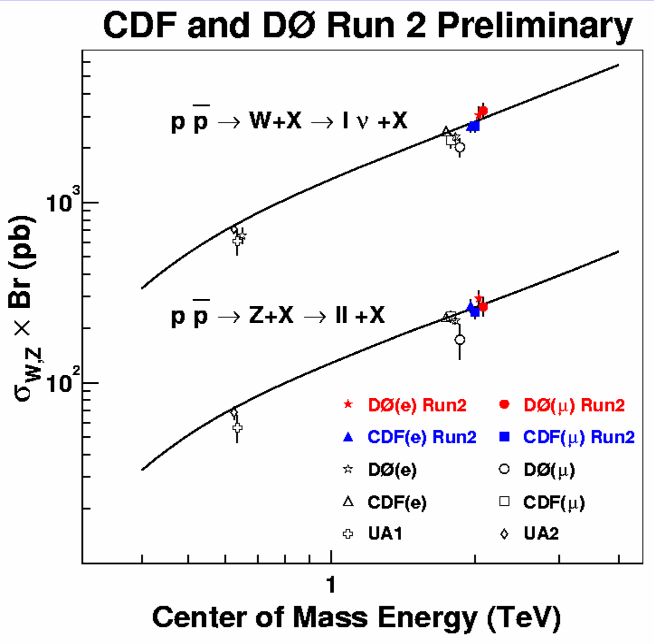
σ BR (W → eν) = 3054 ± 100 (stat.) ± 86 (syst.) ± 305 (lumi) pb
σ BR (W → μν) = 3226 ± 128 (stat.) ± 100 (syst.) ± 323 (lumi) pb

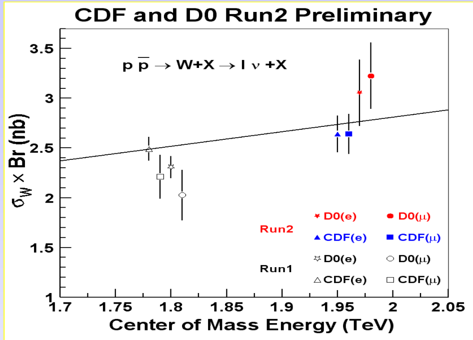
Recent CDF and DØ Z→ μμ event sample

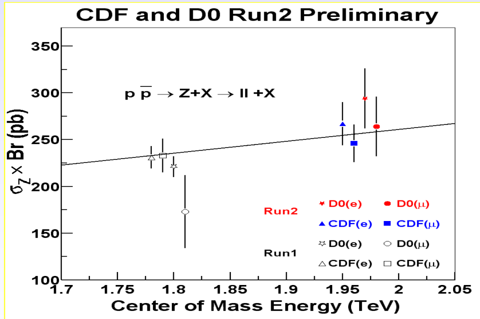




Comparison between measured W/Z cross sections and theoretical prediction (QCD)

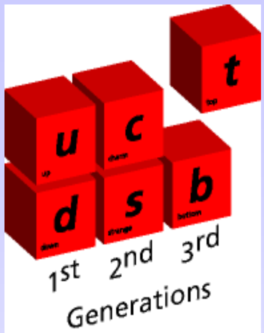


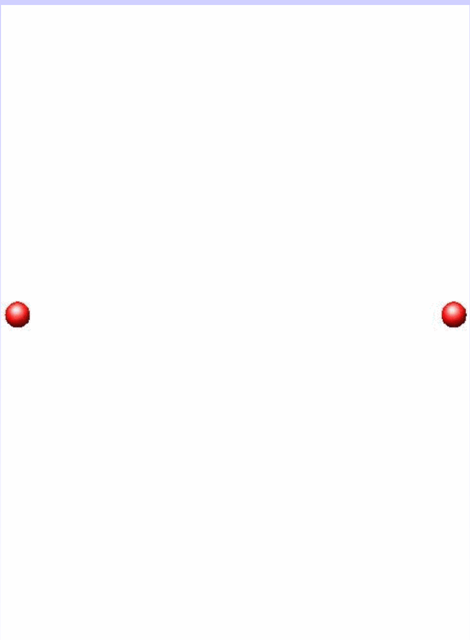




C. R. Hamberg, W.L. van Neerven and T. Matsuura, Nucl. Phys. B359 (1991) 343

Top Quark Physics

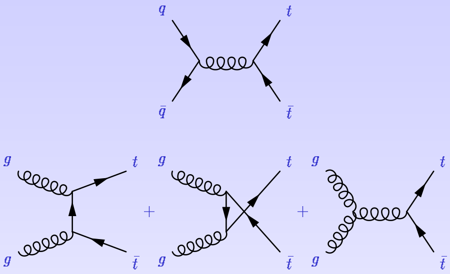




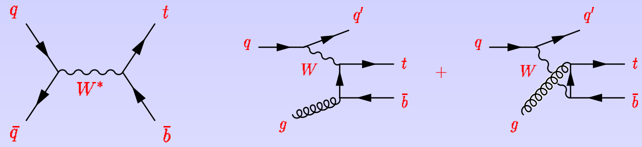
- Discovered by CDF and DØ collaborations at the Tevatron in 1995
- Run I top physics results are consistent with the Standard Model
  (Errors dominated by statistics)
- Run II top physics program will take full advantage of higher statistics
  - Better precision
  - Search for deviations from Standard Model expectations

Top Quark Production

Pair production: qq and gg-fusion



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



	Run 1 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 1 1.8 TeV	Run II 1.96 TeV	LHC 14 TeV
σ (qq) (pb)	0.7	0.9	10
σ (gW) (pb)	1.7	2.4	250
σ (gb) (pb)	0.07	0.1	60

Top Quark Decays

BR (t→Wb) ~ 100%

Both W's decay via W→ ℓν (ℓ=e or μ; 5%)

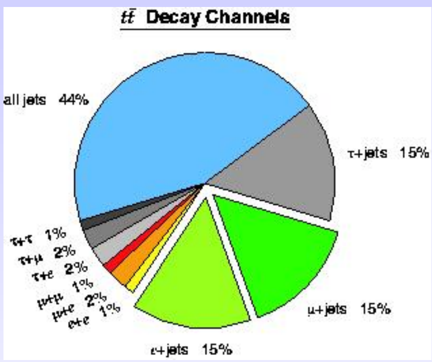
dilepton channel

One W decays via W→ℓν (ℓ=e or μ; 30%)

lepton + jet channel

Both W's decay via W→qq (44%)

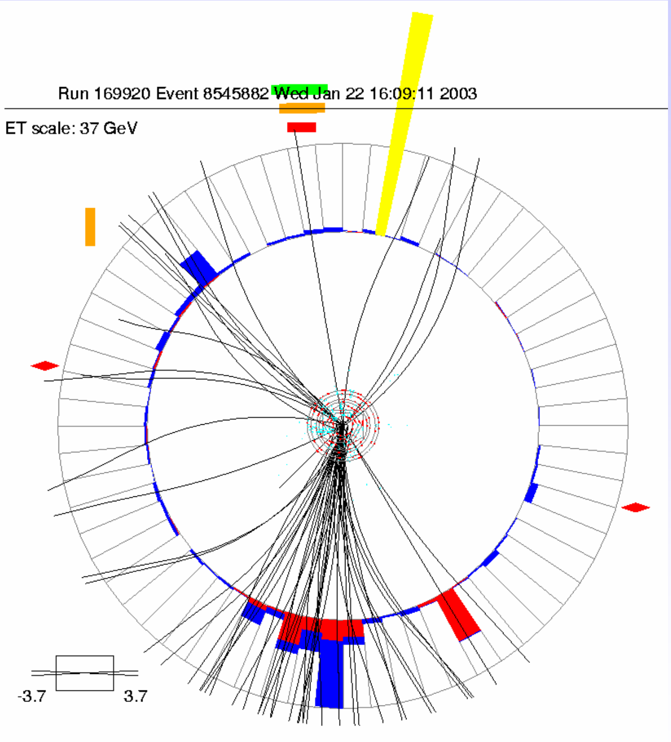
all hadronic, not very useful



Important experimental signatures: : - Lepton(s)

- Missing transverse momentum
- b-jet(s)

DØ top candidate event with two leptons



$p_T(e)$ = 20.3 GeV/c²

$p_T(\mu)$ = 58.1 GeV/c²

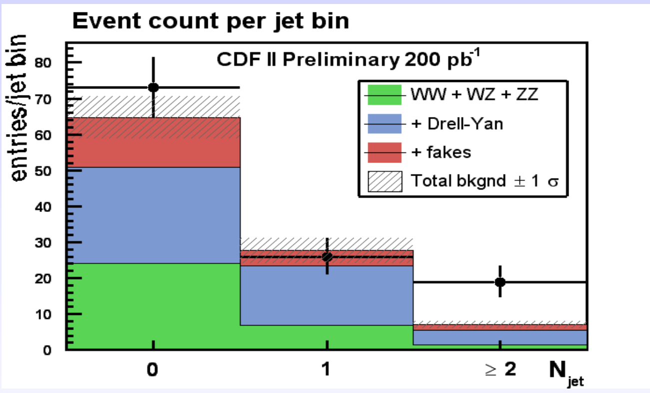
E_T^j = 141.0, 55.2 GeV

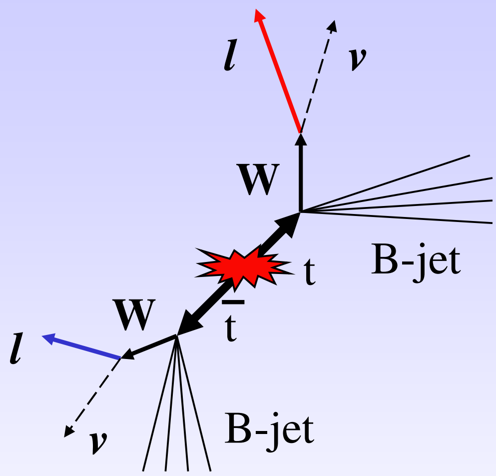
$\not{E}_T$=91 GeV

$t\bar{t}$ cross section (dilepton)

2 high-p_T isolated leptons

Large missing E_T , ≥ 2 jets



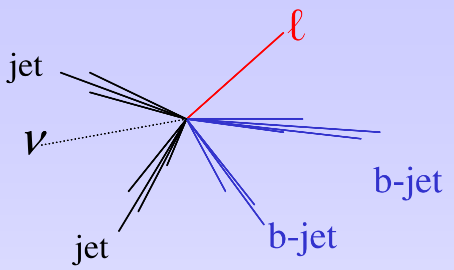


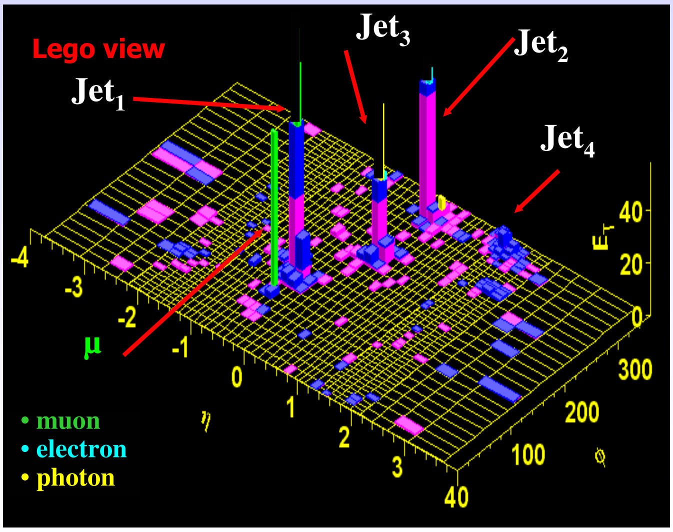
Run II preliminary

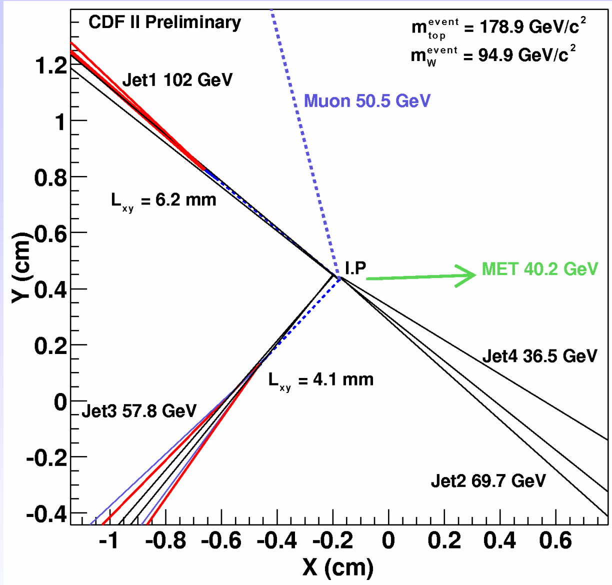
CDF (200 pb⁻¹): $\sigma_{t\bar{t}} = 6.9^{+2.7}_{-2.4}\,(\text{stat}) \pm 1.2\,(\text{syst}) \pm 0.4\,(\text{lumi})$ pb

DØ (100 pb⁻¹) : $\sigma_{t\bar{t}} = 8.7^{+6.4}_{-4.7}\,(\text{stat})\ ^{+2.7}_{-2.0}\,(\text{syst}) \pm 0.9\,(\text{lumi})$ pb

A CDF Lepton + Jet event







$p_T(\mu)$ = 54.4 GeV

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

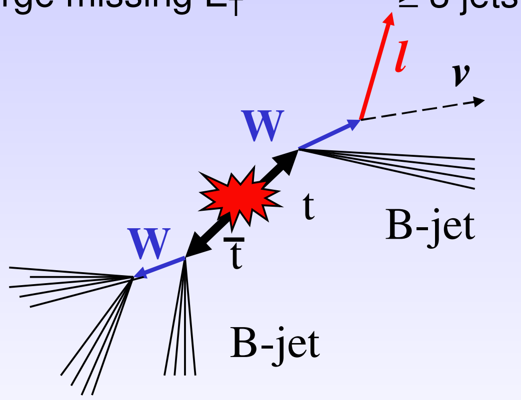
Missing E_T= 40.8 GeV

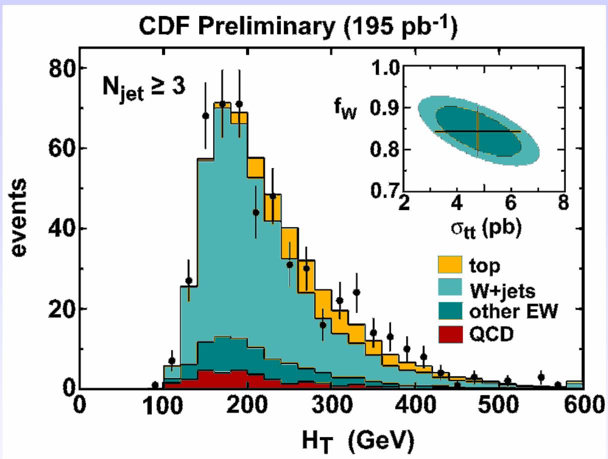
tt cross section (lepton + jets) (topology, no b-jet identification)

1 high-p_T isolated lepton

Large missing E_T

≥ 3 jets



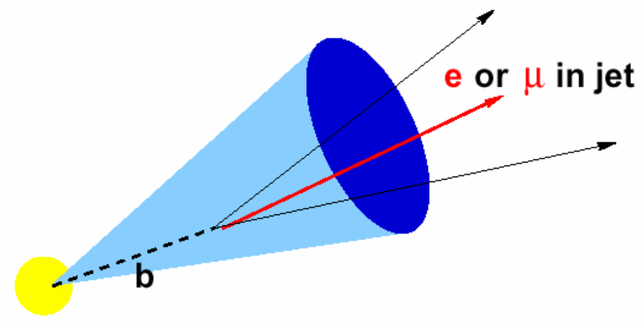


H_T = scalar sum of all high P_T objects (jets, leptons, E_T^{miss})

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

Tagging a b-quark

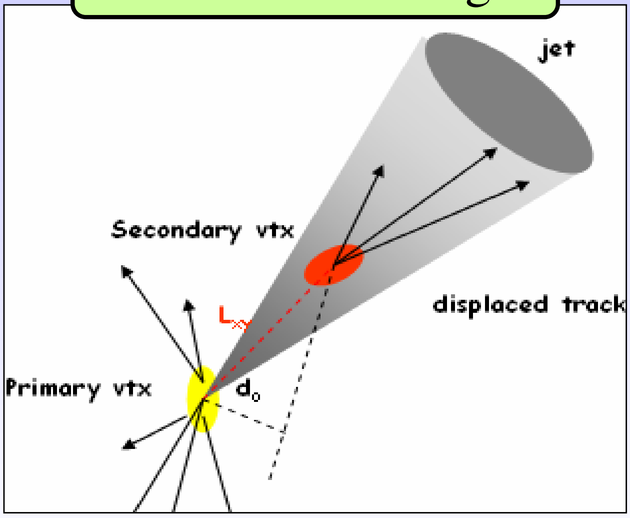
Soft lepton tagging



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

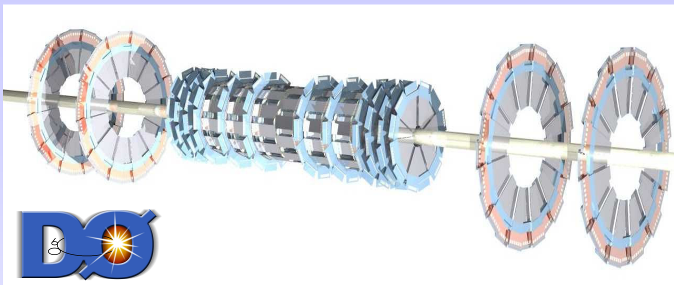
Search for non-isolated soft lepton in a jet

Silicon Vertex tag

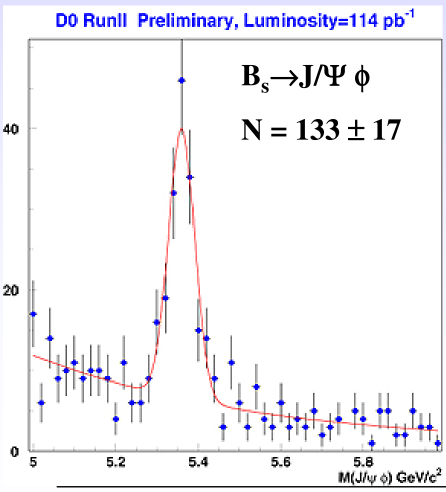


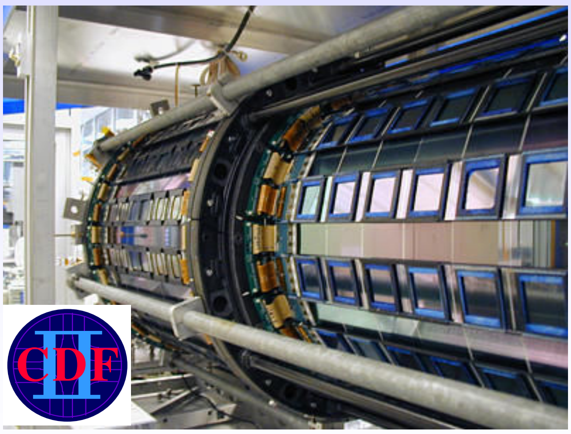
B mesons travel ~ 3 mm before decaying:
- Search for secondary vertex

Silicon detectors

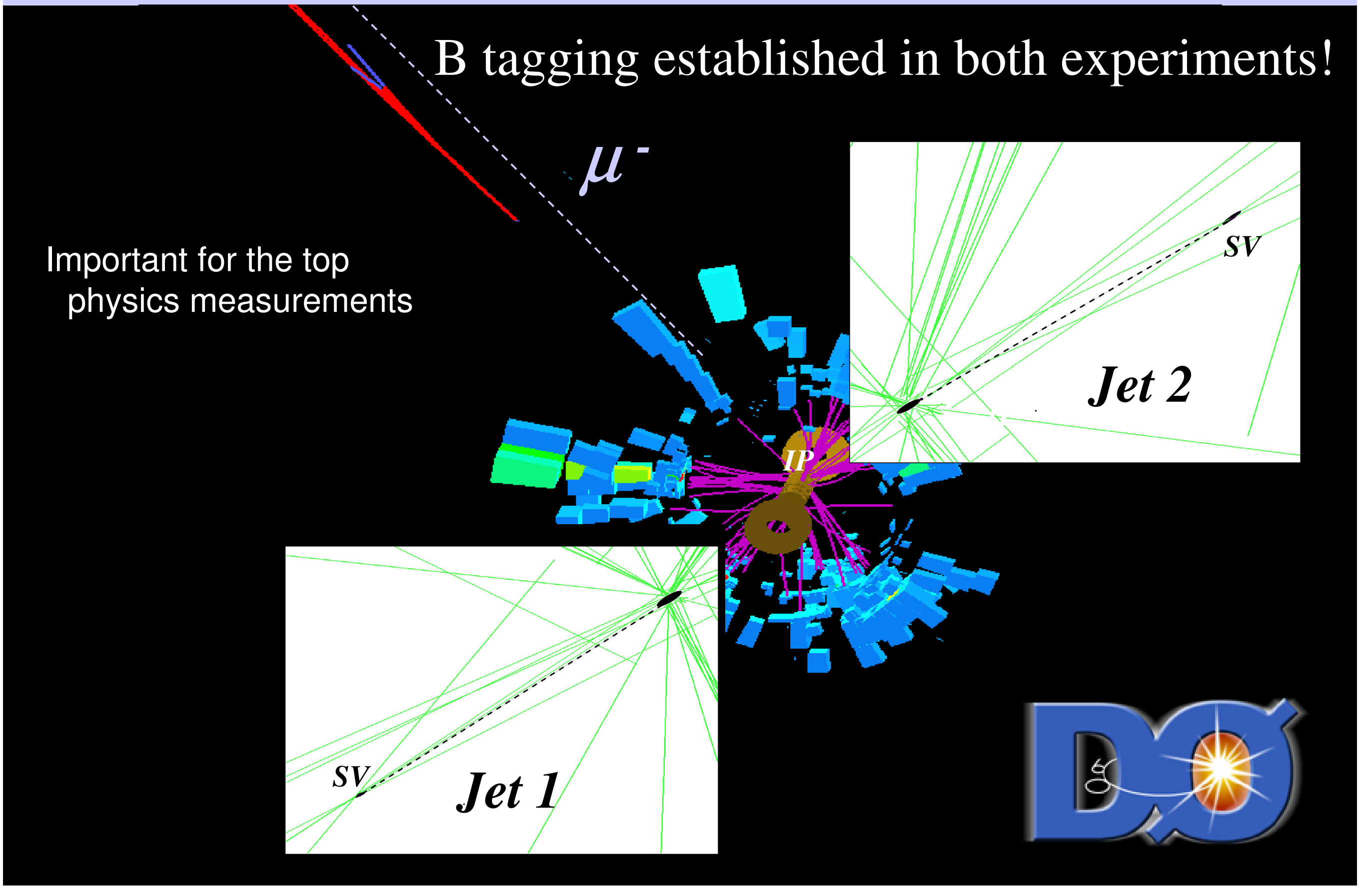


Run II: silicon detectors cover a large region of acceptance





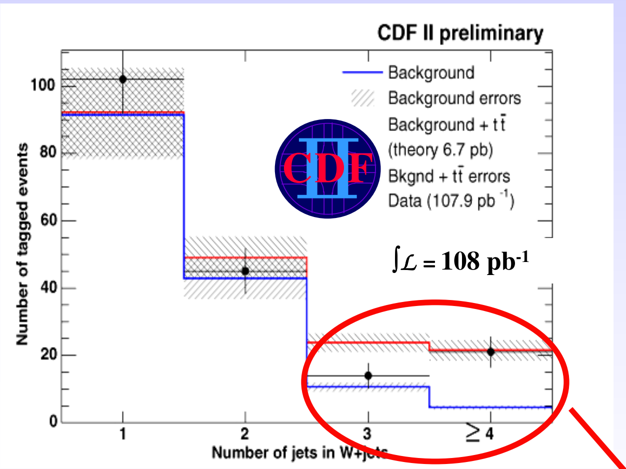
μ + jets double-tagged event

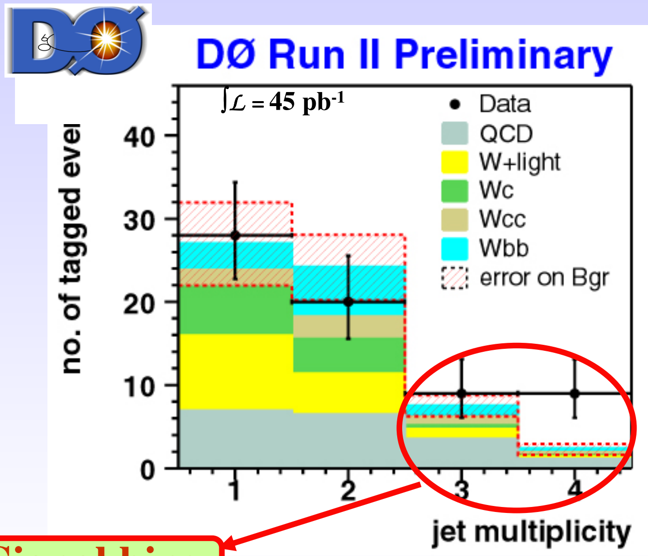


tt cross section (lepton + jets)   (including b-tagging)

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

Large missing E_T

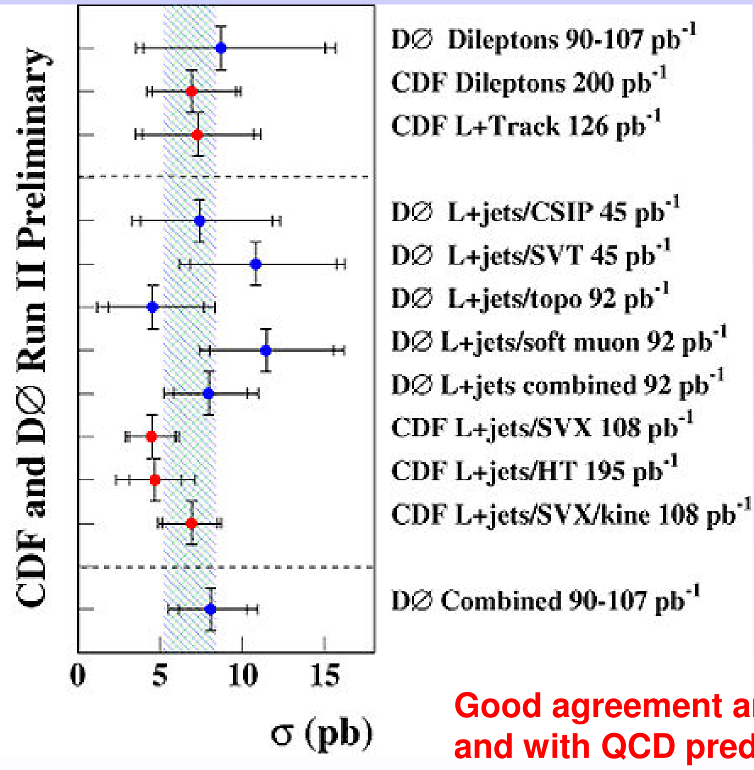




Signal bins

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

tt cross section summary (preliminary)



QCD prediction:

Cacciari *et al.* **hep/ph0303085**

Kidonakis **hep-ph/0303086**

$8.1^{+2.2}_{-2.0}\,(\mathrm{stat})^{+1.6}_{-1.4}\,(\mathrm{syst}) \pm 0.8(\mathrm{lum})$

Good agreement among various exp. measurements and with QCD prediction

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

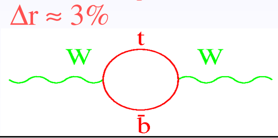
Electromagnetic constant measured in atomic transitions, e^+e^- machines, etc.

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

Fermi constant measured in muon decay

weak mixing angle measured at LEP/SLC

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



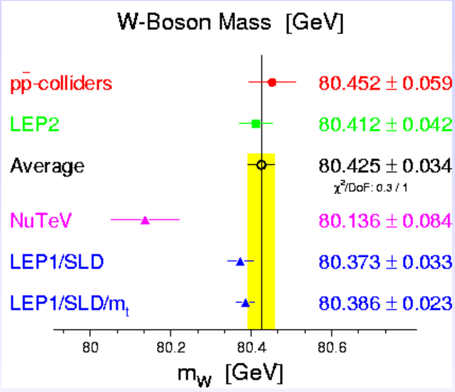
G_F, α_{EM}, $\sin\theta_W$

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

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

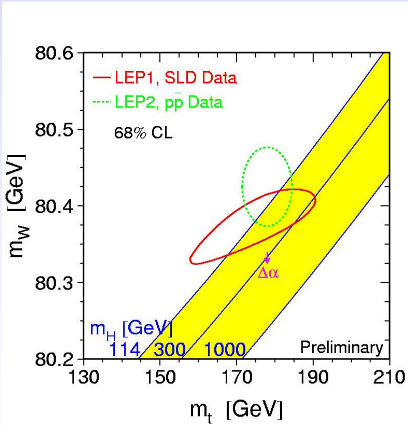


4·10^{-4}

m_W (from LEP2 + Tevatron) = 80.425 ± 0.034 GeV

m_{top} (from Tevatron) = 178.0 ± 4.3 GeV

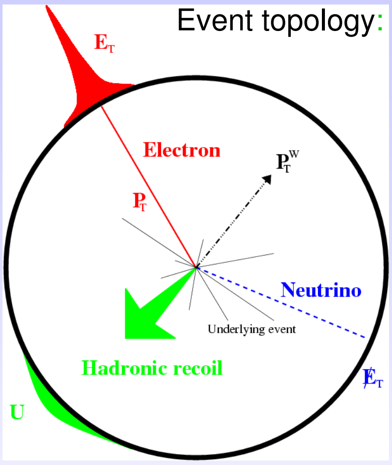
2.4%

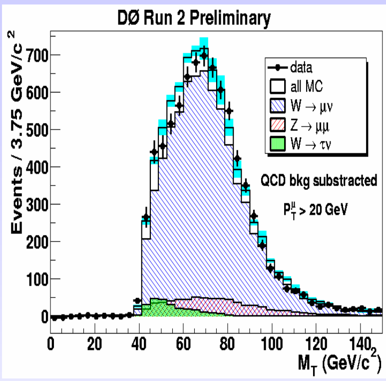


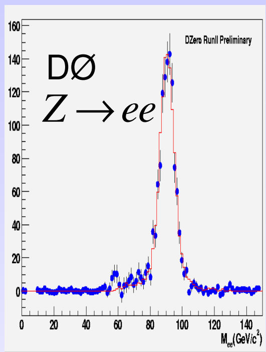
light Higgs boson is favoured by present measurements

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

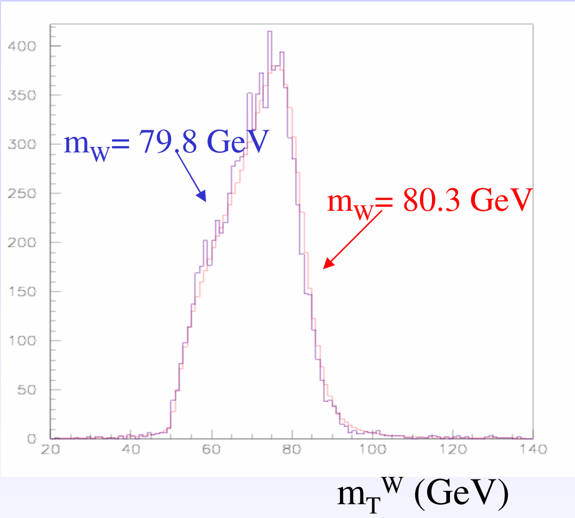
$\Rightarrow$ $P_T(\nu)$ = - ($P_T(e)$ + $P_T(had)$)

long. component can not 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



Main uncertainties:

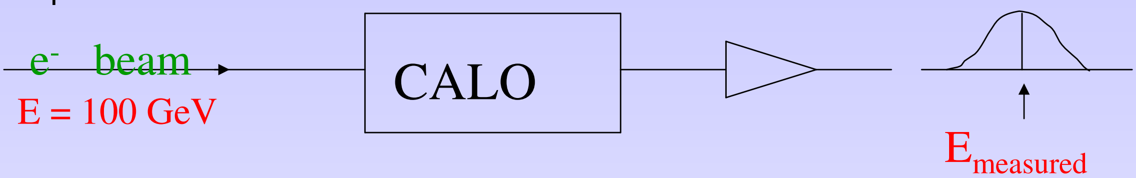
result from the capability of the Monte Carlo prediction to reproduce real life:

- 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 !
(if measurement of the lepton energy wrong by 1%, then measured m_W wrong by 1%)

Calibration of the detector energy scale:

Example : EM calorimeter



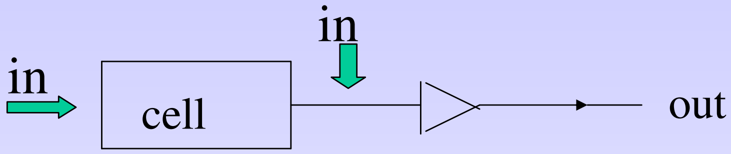
- if $E_{measured}$ = 100.000 GeV for all calorimeter cells
  → calorimeter is perfectly calibrated

- to measure m_W to ~ 20 MeV, need to know energy scale to 0.2 ‰ ,
  i.e. if $E_{electron}$ = 100 GeV then 99.98 GeV < $E_{measured}$ < 100.02 GeV

⇒ one of most serious experimental challenges

Calibration strategy:

- detectors equipped with calibration systems which inject known pulses:



→ check that all cells give same response: if not → correct

- calorimeter modules calibrated with test beams of known energy
  → set the energy scale

- inside LHC detectors: calorimeter sits behind Inner Detector
  → electrons lose energy in material of Inner Detector
  → 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 ≈ 10^{-5} from LEP

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

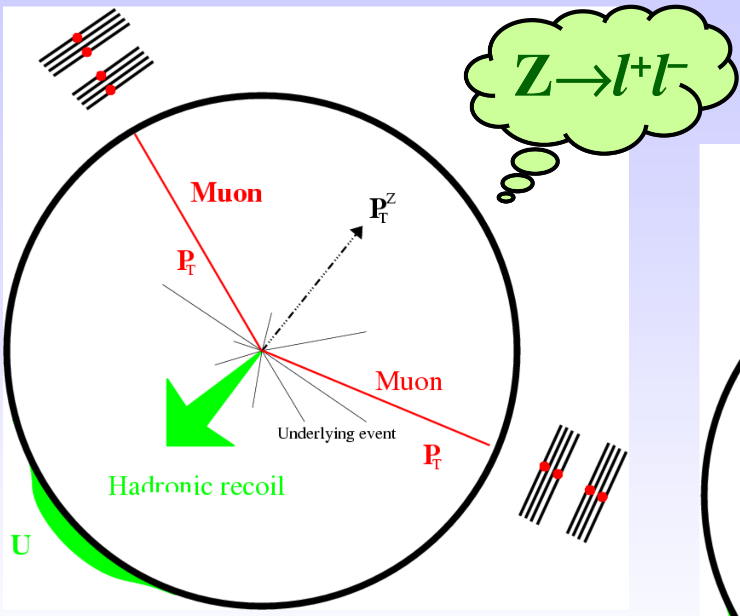
Int. Luminosity	0.08 fb^{-1}	2 fb^{-1}	10 fb^{-1}
Stat. error	**96 MeV**	**19 MeV**	**2 MeV**
Energy scale, lepton res.	57 MeV	20 MeV	16 MeV
Monte Carlo model (P_T^W, structure functions, photon-radiation….)	30 MeV	20 MeV	17 MeV
Background	11 MeV	2 MeV	1 MeV
Tot. Syst. error	**66 MeV**	**28 MeV**	**24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

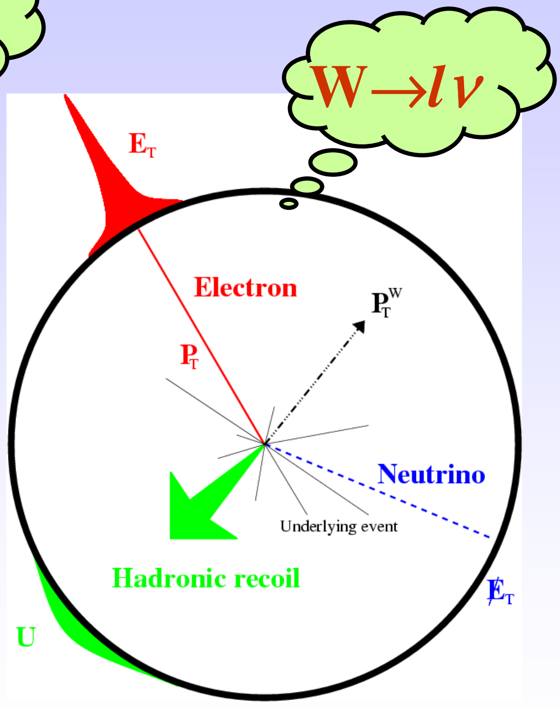
- Total error per lepton species and per experiment at the **LHC** is estimated to be **± 25 MeV**
  at the **Tevatron** **± 34 MeV**
- Main uncertainty: lepton energy scale (goal is an uncertainty of ± 0.02 %)
- Many systematic uncertainties can be controlled in situ, using the $Z \rightarrow \ell\ell$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

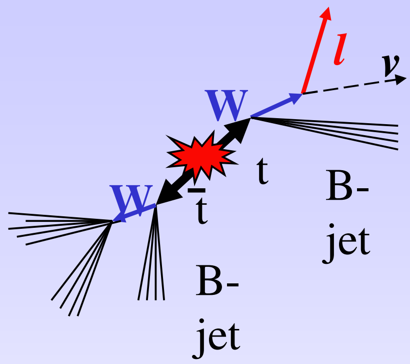
Signature of Z and W decays





Top mass measurement (CDF) (preliminary)

- 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}

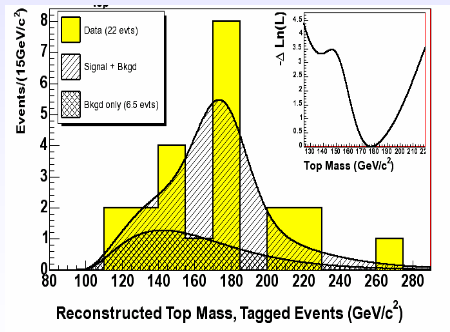


$\int \mathcal{L} = 108\ \text{pb}^{-1}$

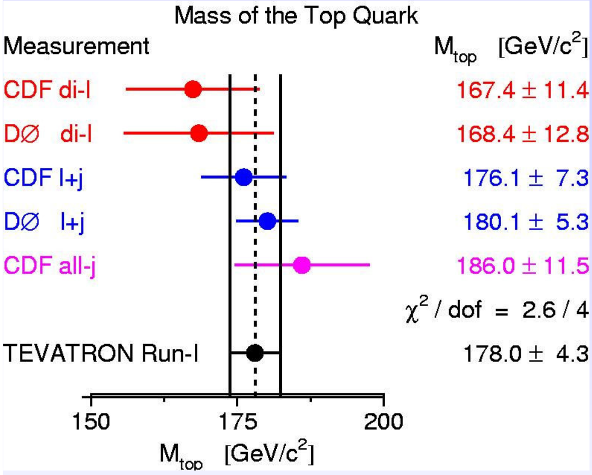
- $177.5^{+12.7}_{-9.4}\,(\text{stat}) \pm 7.1(\text{syst})\ \text{GeV/c}^2$

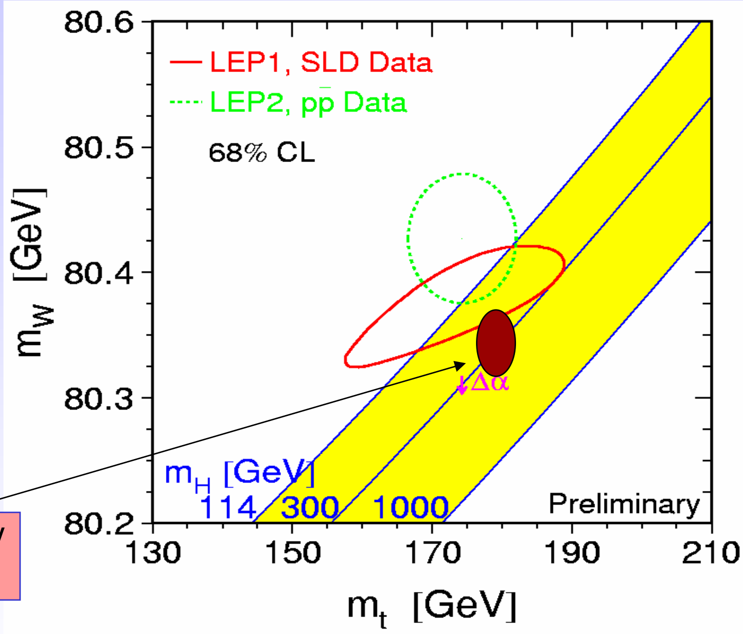
$\int \mathcal{L} = 124\ \text{pb}^{-1}$

- $175.0^{+17.4}_{-16.9}\,(\text{stat}) \pm 7.9(\text{syst})\ \text{GeV/c}^2$



Tevatron results on the top quark mass





expected precision in 2007: ± 1.5 -2 GeV
(Tevatron)

expected LHC precision for 10 fb^{-1}: < ~ ± 1 GeV
(combination of several methods)

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%

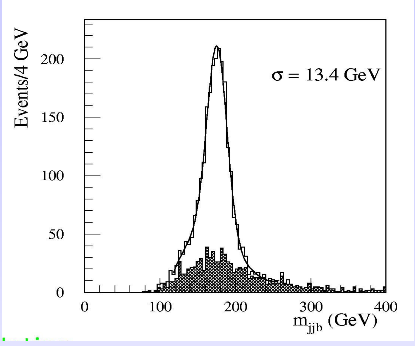
Prospects for top-quark mass measurements at the LHC

Year 2007: Δm_{top} ~ 2-3 GeV (Tevatron)

Best channel for mass measurement:

tt → Wb Wb → ℓ ν b jet jet b

(trigger) (mass measurement)



Experimental numbers:

- Production cross section: 590 pb
- After exp. cuts: 130.000 tt events in 10 fb[-1] S/B ~ 65

estimated syst. uncertainties:

Contribution	Δm_{top} (GeV)
statistics	< 0.07
u,d,s jet scale	0.3
b-jet scale	0.7
b-fragmentation	0.3
initial state rad.	0.3
final state rad.	1.2
background	0.2
Total	~ 1.5 GeV

Syst. uncertainties dominated by final state radiation effects

combination of various methods: Δm_{top} < ~ ± 1 GeV