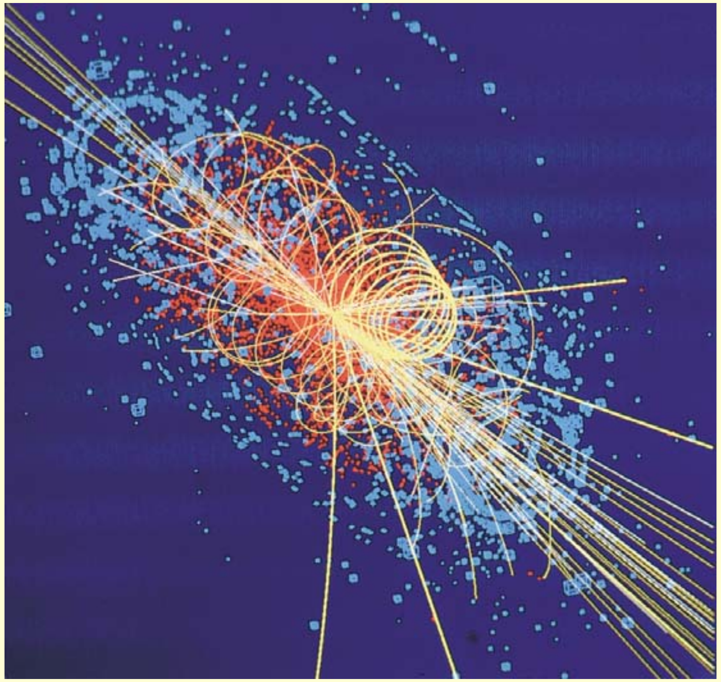
Physics at Hadron Colliders

Part 2

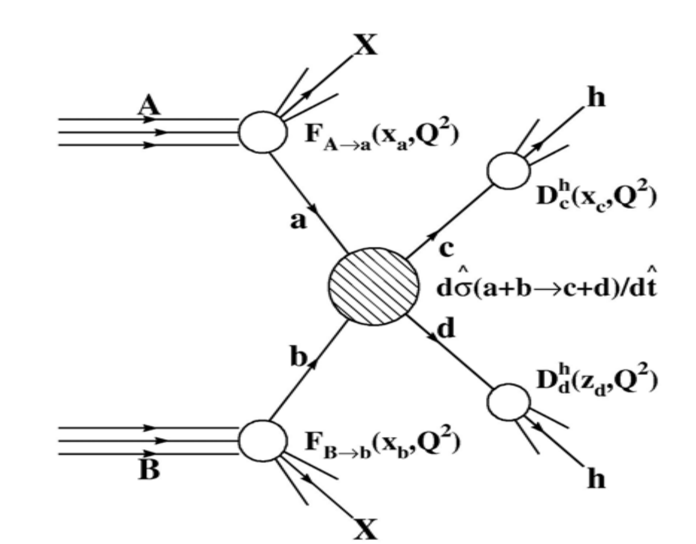


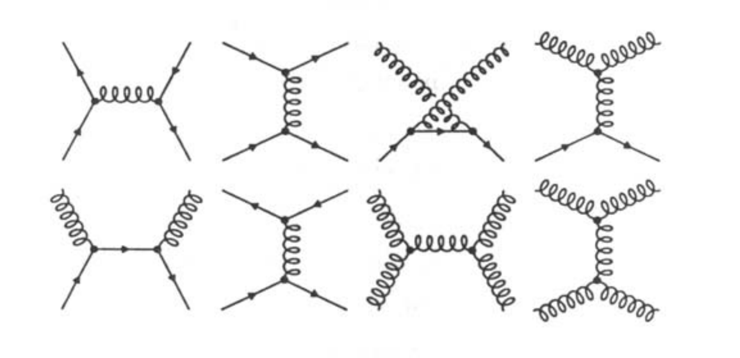
Standard Model Physics

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



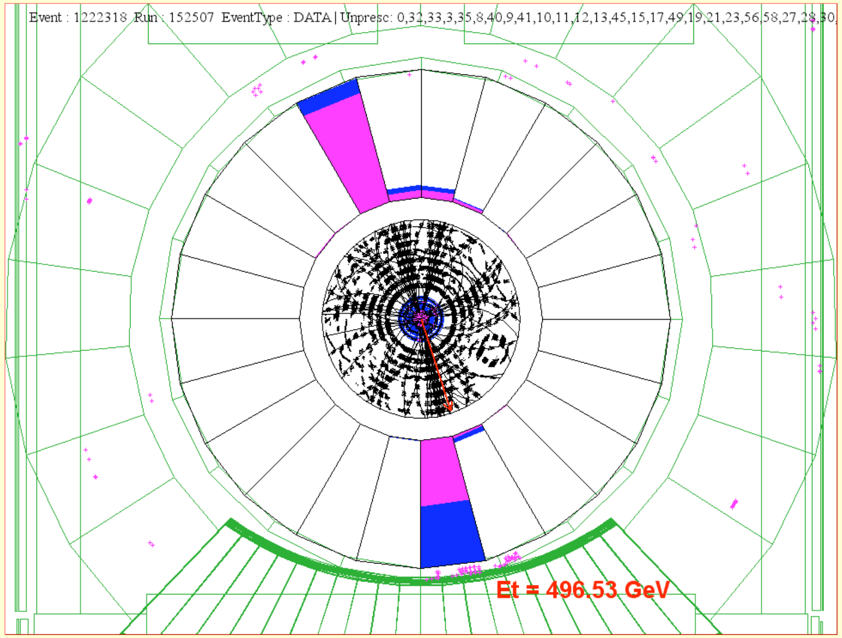


- Hard scattering processes are dominated by QCD jet production
- Originating from quark-quark, quark-gluon and gluon-gluon scattering
- Due to fragmentation of quarks and gluons in final state hadrons
  $\to$ Jets with large transverse momentum P_T in the detector
- Cross sections can be calculated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

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

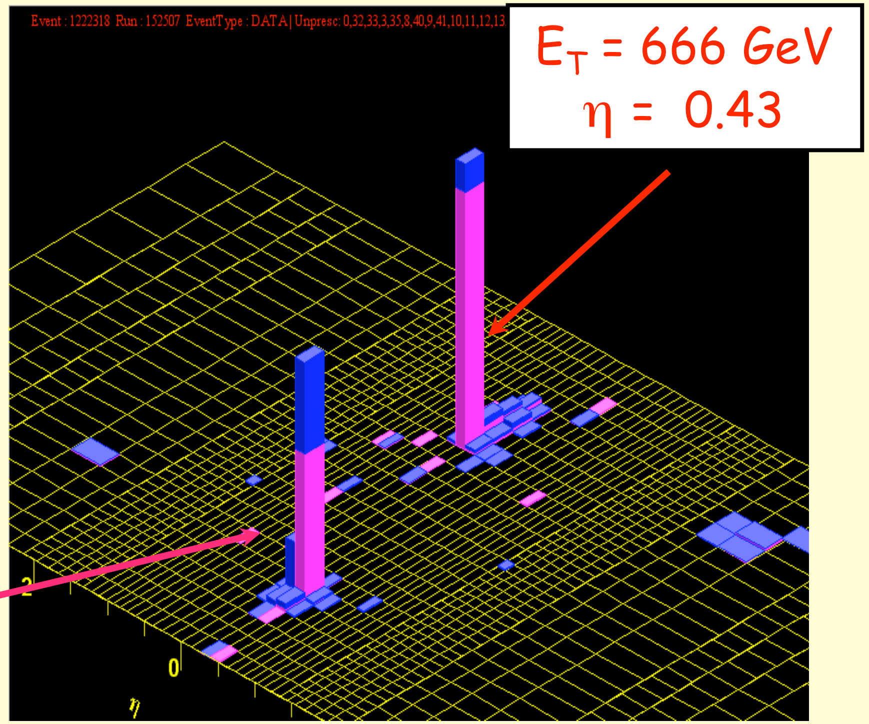
Deviations? $\to$ Problem in the experiment ?
Problem in the theory (QCD) ?
New Physics, e.g. quark substructure ?

A two jet event at the Tevatron (CDF)



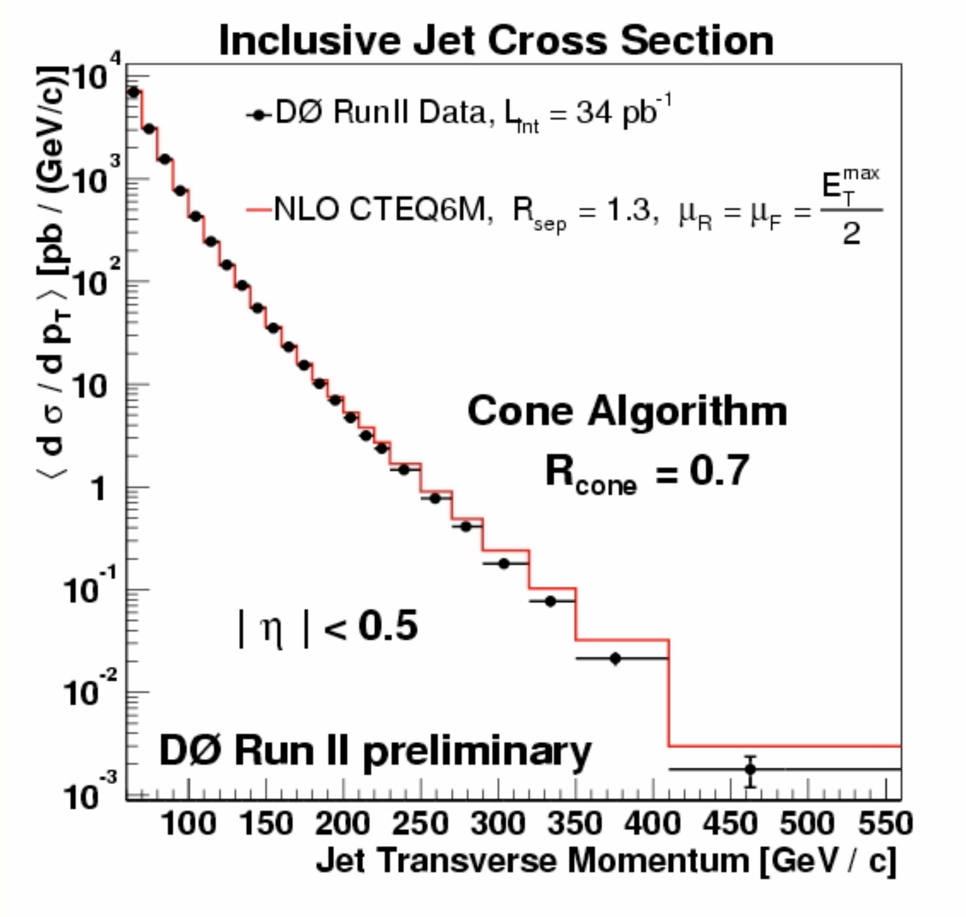
CDF (ϕ-r view)

Dijet Mass = 1364 GeV/c^2



E_T = 633 GeV
η = -0.19

Test of QCD Jet production



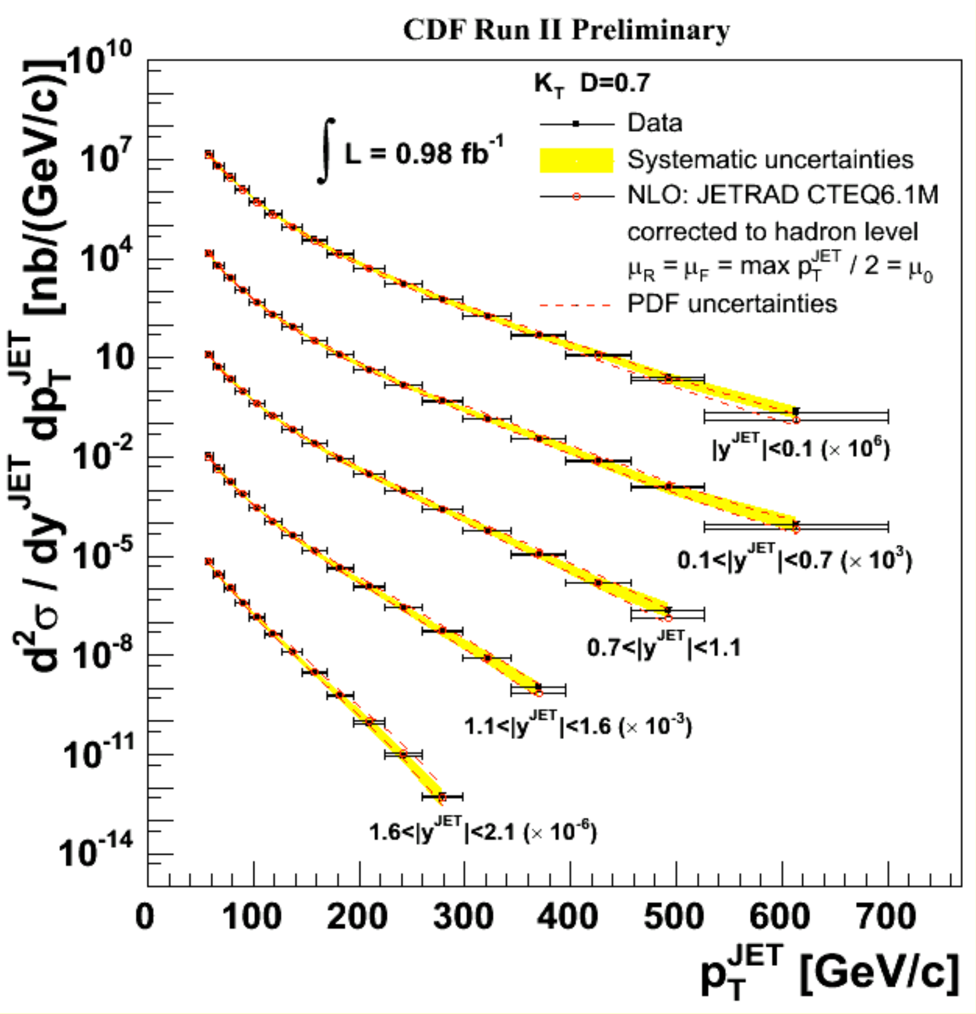
Data from the DØ experiment (Run II)

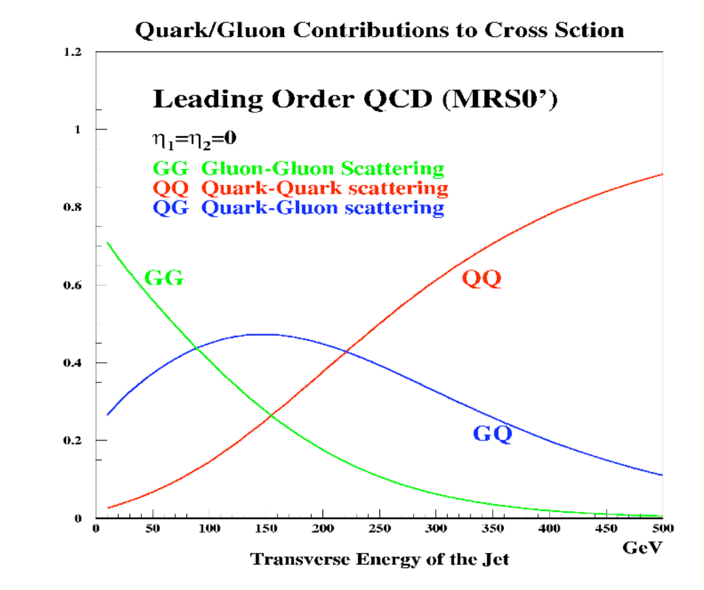
Inclusive Jet spectrum as a function of Jet-P_T

very good agreement over many orders of magnitude !

within the large theoretical and experimental uncertainties

Similar data from the CDF experiment





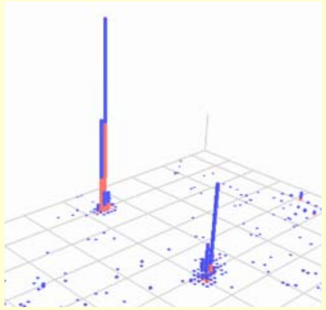
contributions of the various sub-processes to the inclusive jet cross section

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: $\Delta R = \sqrt{\Delta\Phi^2 + \Delta\eta^2} = 0.7$

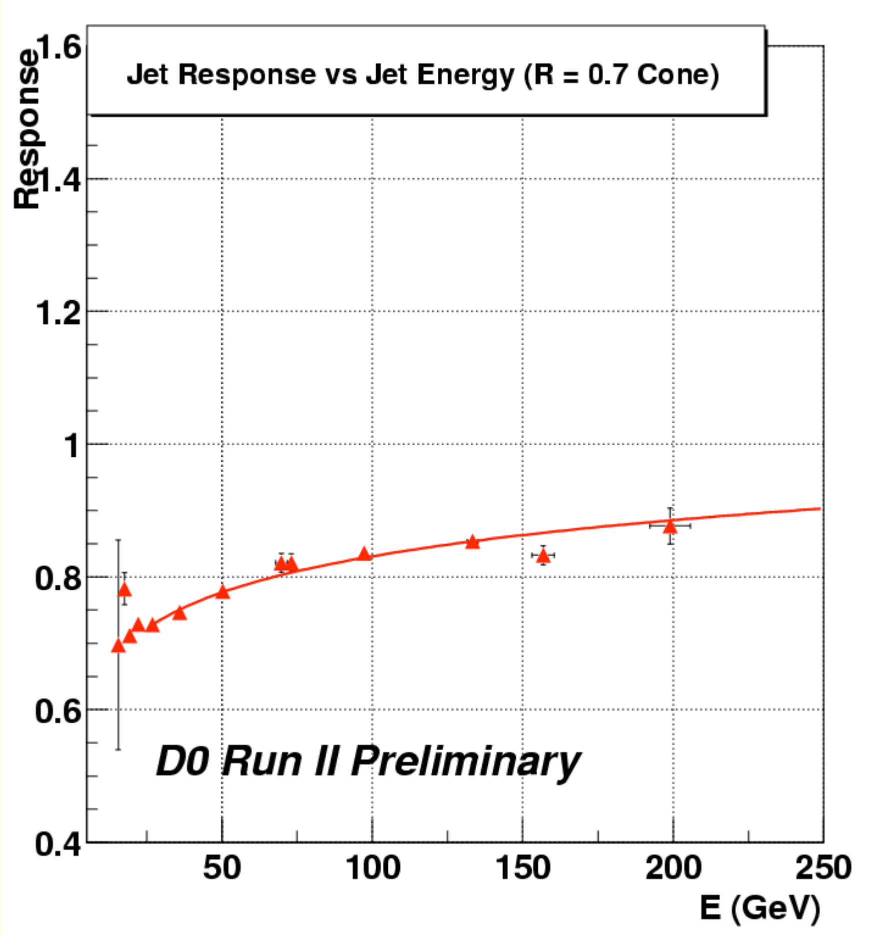


- Cone energy ≠ parton energy

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)

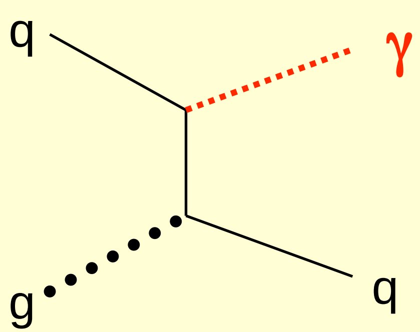
Main experimental systematic uncertainty: Jet Energy Scale



Jet response correction in DØ:

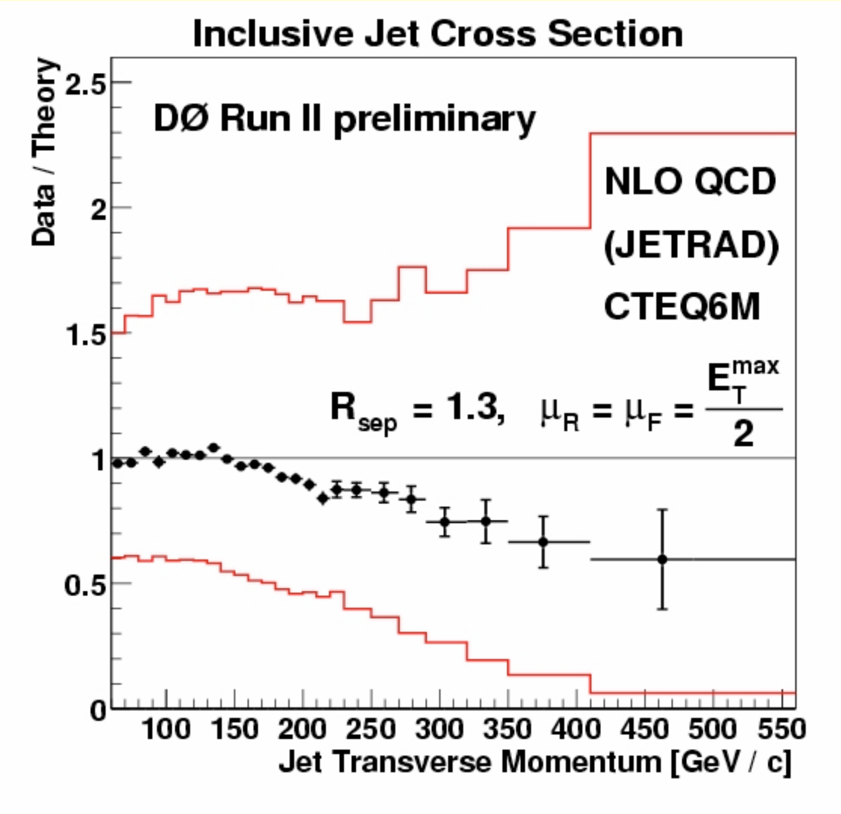
- measure response of particles making up the jet

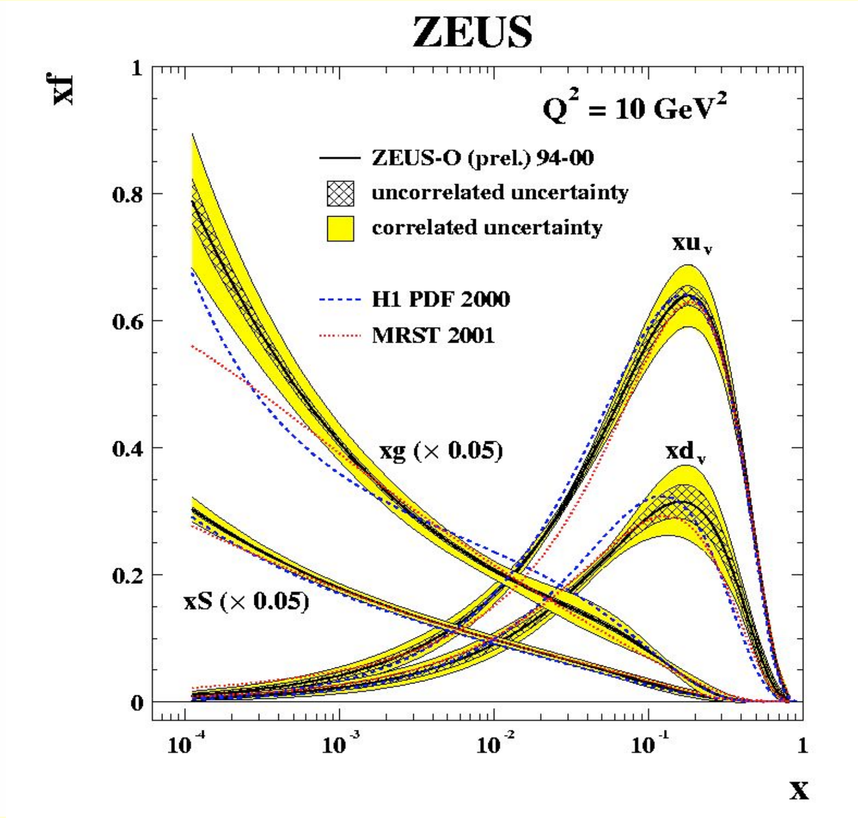
- use photon + jet data - calibrate jets against the better calibrated photon energy



Comparison with Theory

– Fully corrected inclusive jet cross section

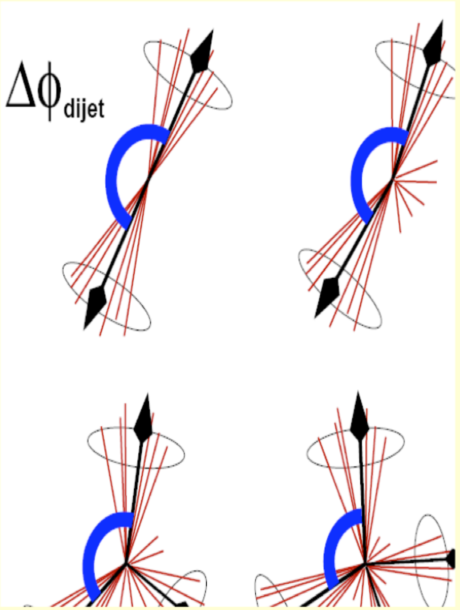


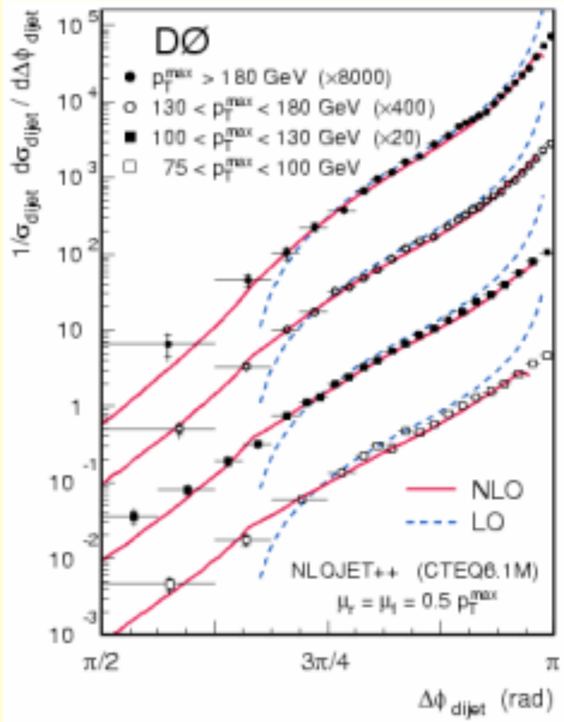


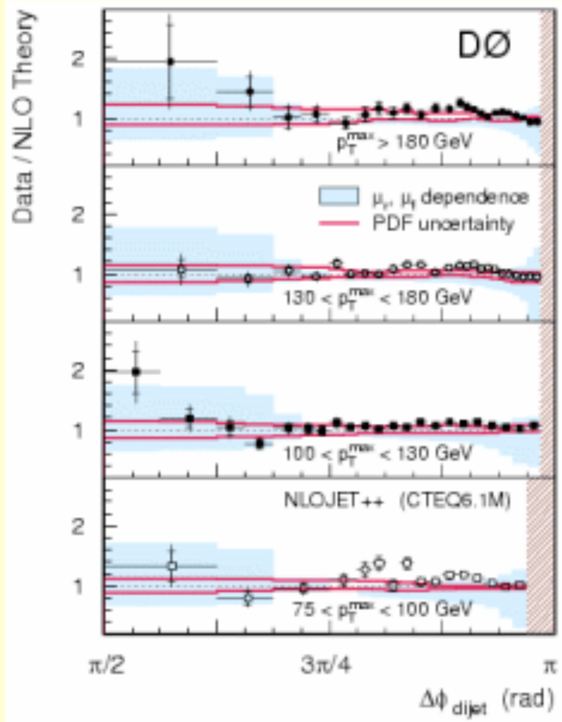
Systematic uncertainties: - jet energy scale (red band)
- parton density functions
- theory: renormalization scale

Di-jet angular distributions:

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

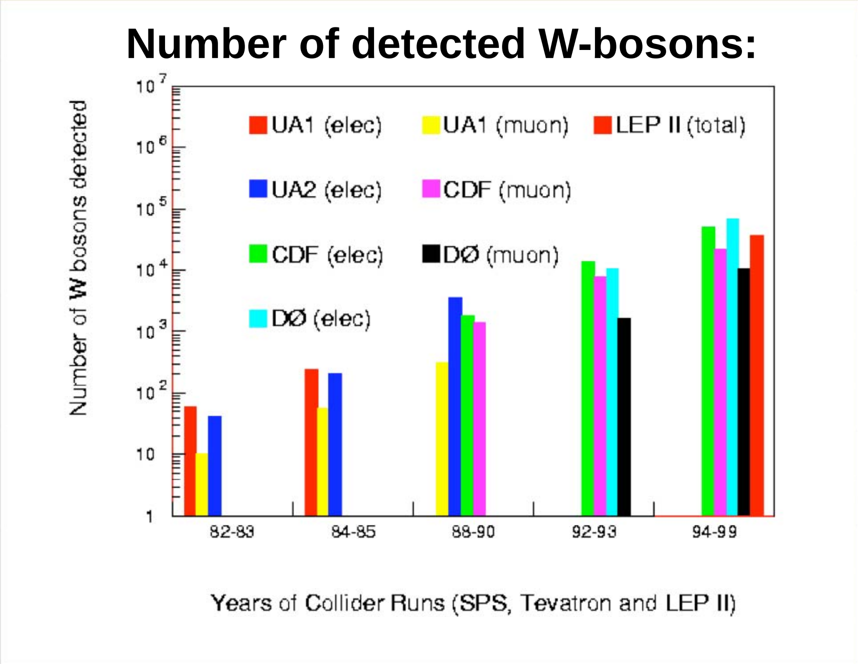


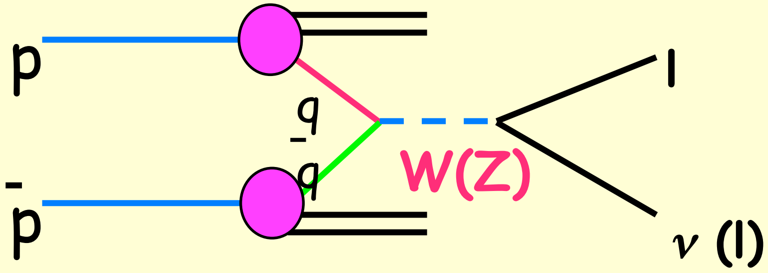




Good agreement with
Next-to-leading order QCD-predictions

Test of W and Z production





Drell-Yan production process (leading order)

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

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

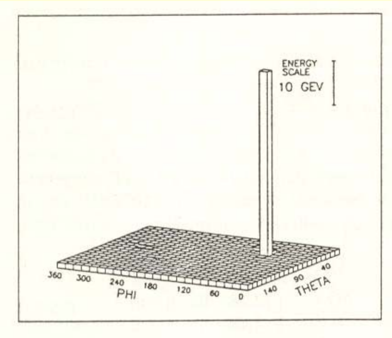
How do W and Z events look like ?

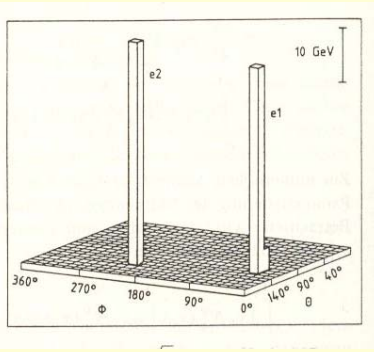
As explained, leptons, photons and missing transverse energy are key signatures at hadron colliders

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

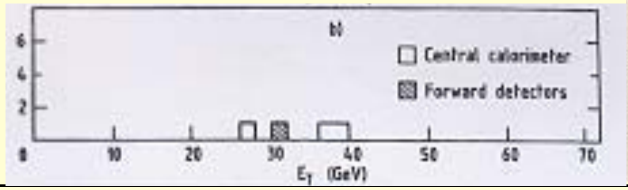
A bit of history: one of the first W events seen; UA2 experiment

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

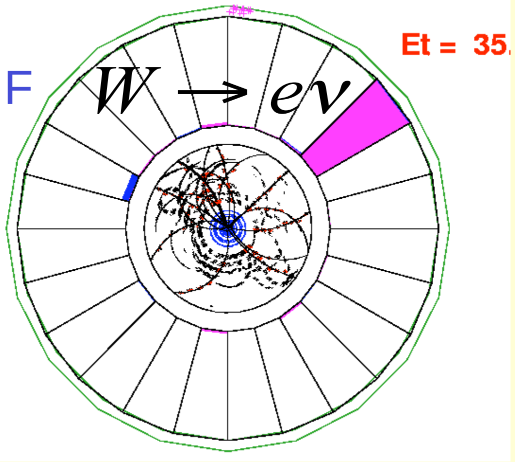




Transverse momentum of the electrons

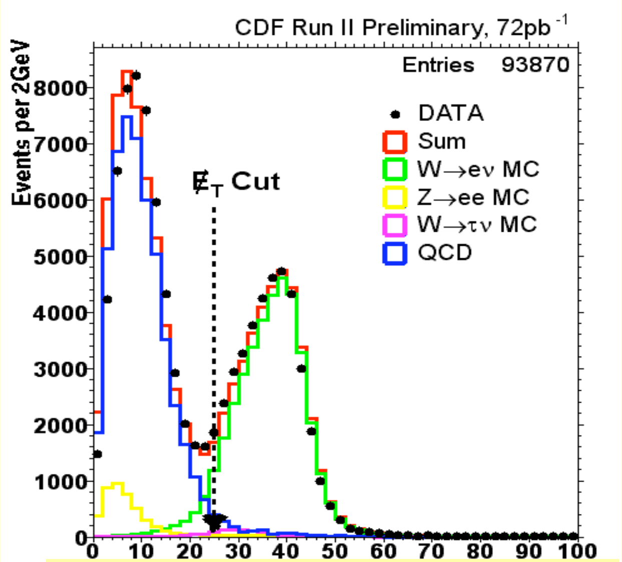


Today's W / Z → eν / ee signals



Trigger:

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



missing transverse momentum P_T^{miss} (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**

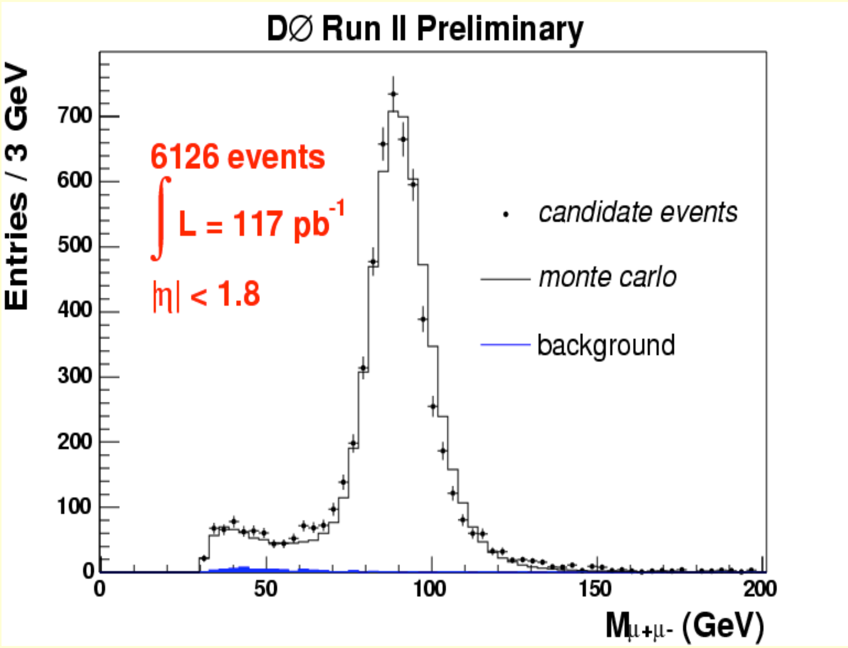
Z → ee

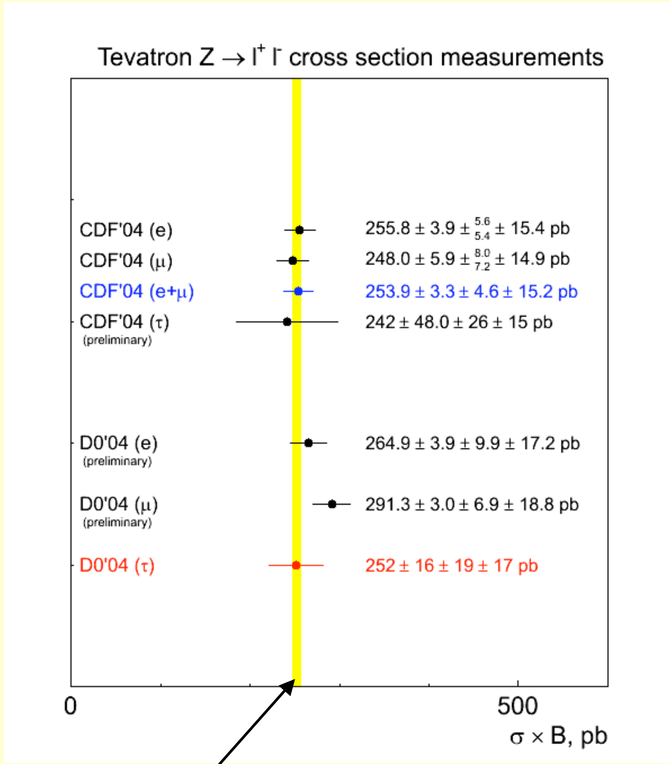
- **70 GeV/c^2 < m_{ee} < 110 GeV/c^2**

W → eν

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

$Z \rightarrow \ell\ell$ cross sections

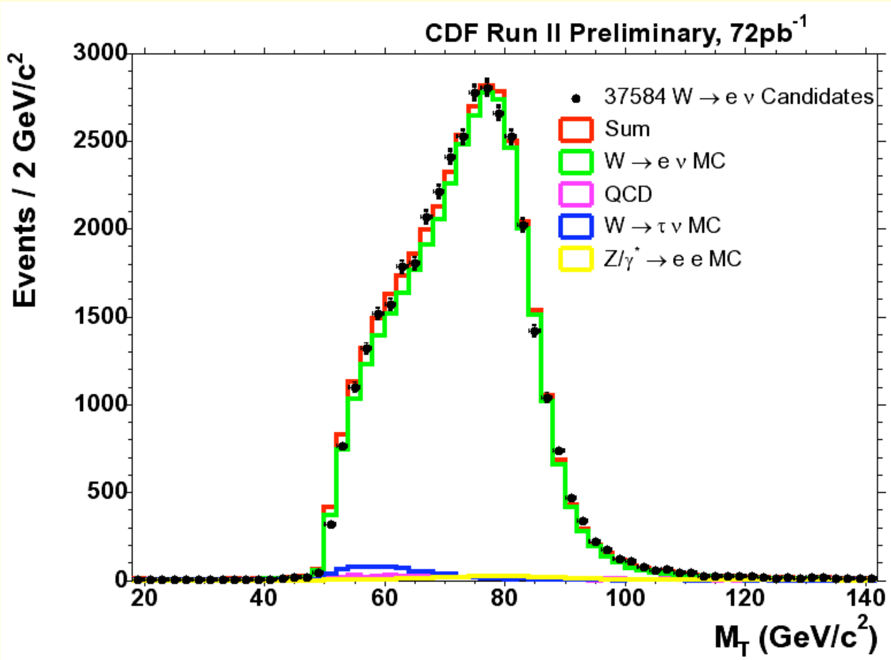


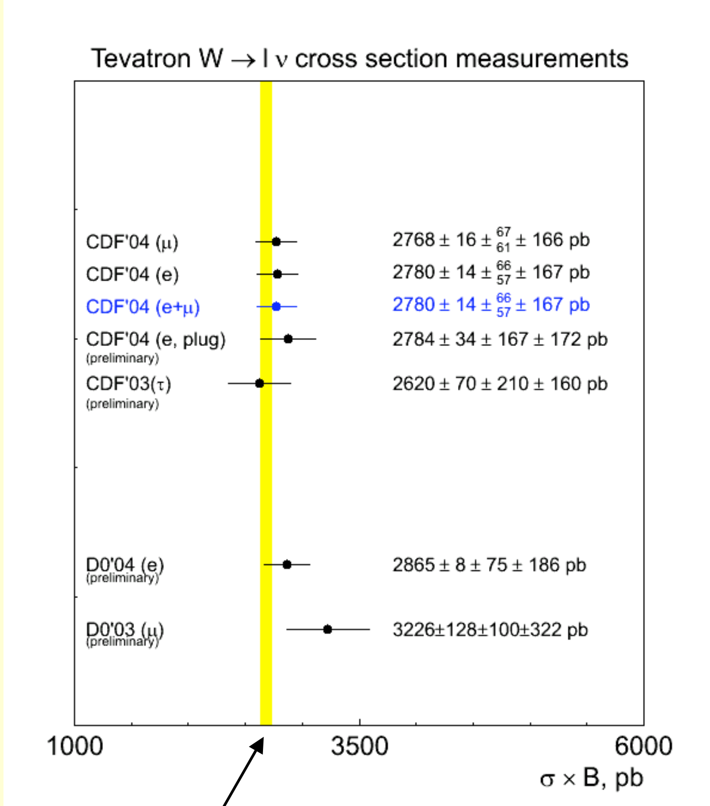


Good agreement with
NNLO QCD calculations,
QCD corrections are large: factor 1.3-1.4
C.R.Hamberg et al, Nucl. Phys. B359 (1991) 343.

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

W → ℓν Cross Section





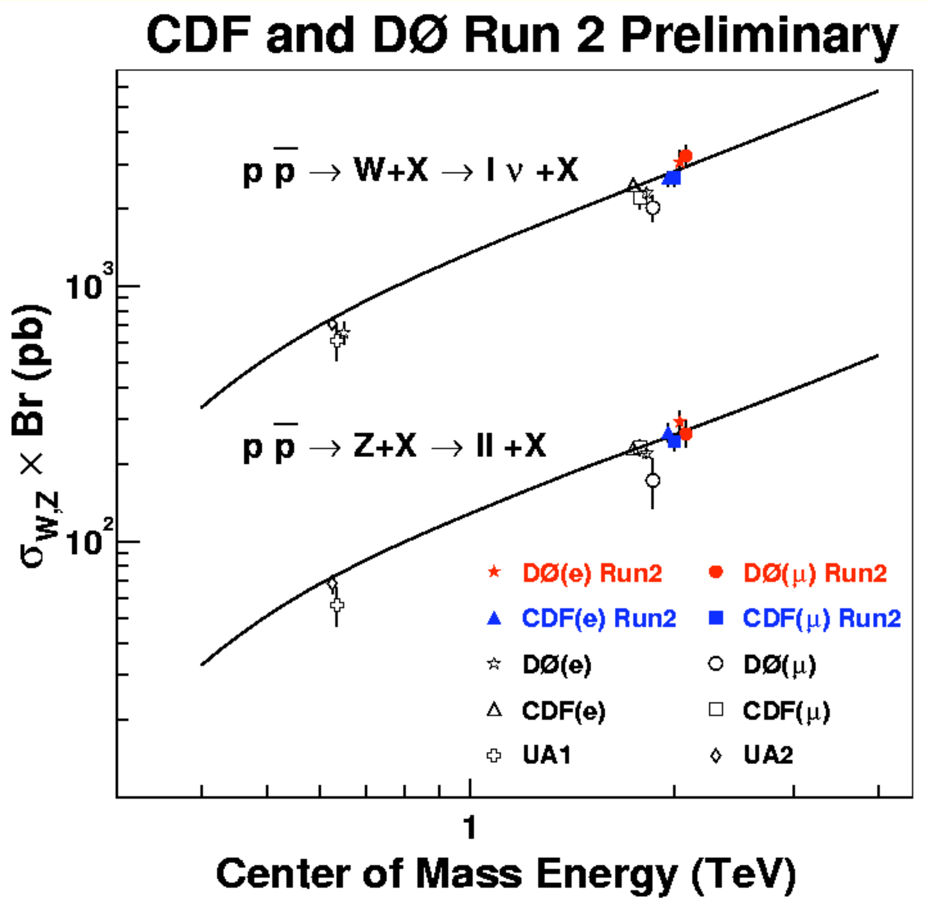
$$M_W^T = \sqrt{2 \cdot P_T^l \cdot P_T^\nu \cdot \left(1 - \cos \Delta\phi^{l,\nu}\right)}$$

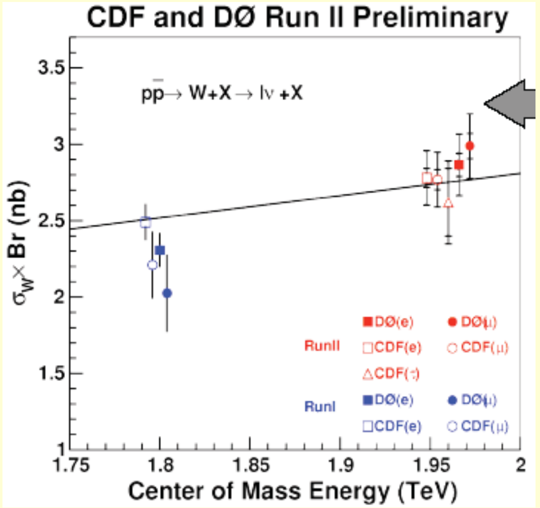
Note: the longitudinal component of the neutrino cannot be measured
→ only transverse mass can be reconstructed

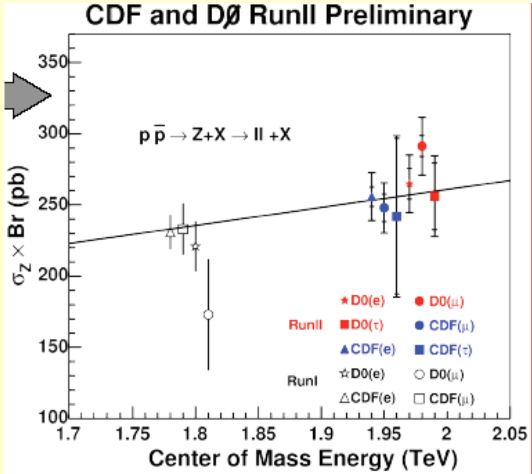
Good agreement with NNLO QCD calculations
C.R.Hamberg et al, Nucl. Phys. B359 (1991) 343.

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

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

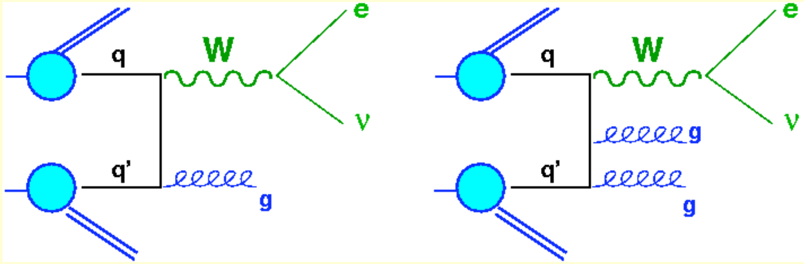


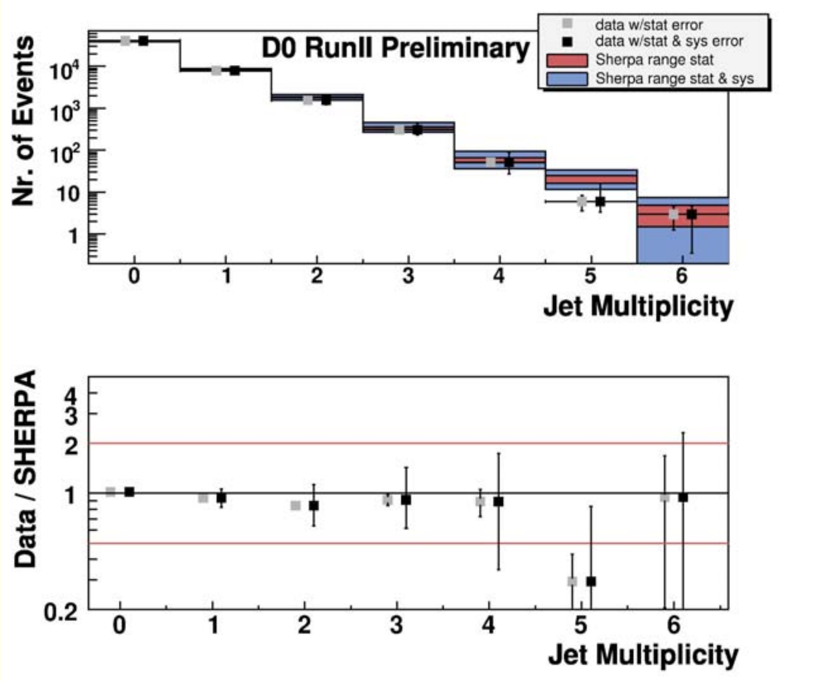


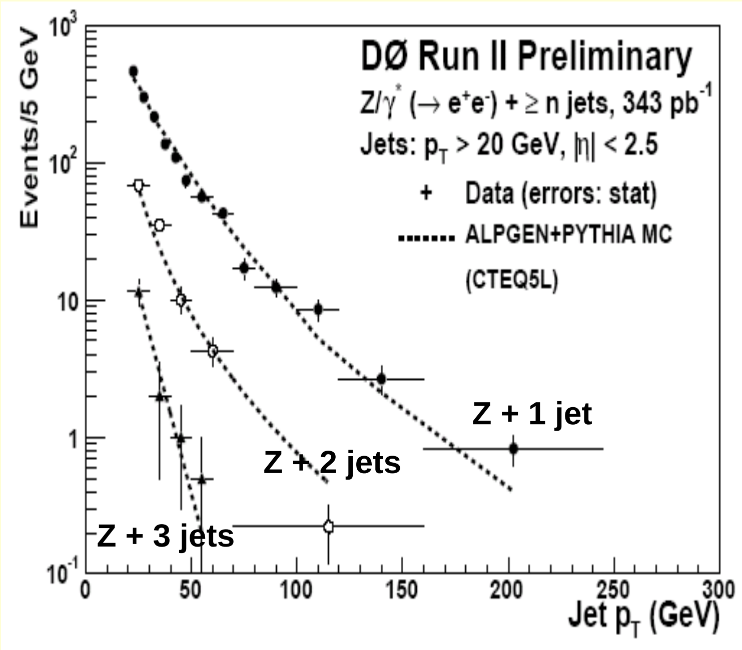


C. R. Hamberg, W.L. van Neerven and T. Matsuura, Nucl. Phys. B359 (1991) 343

QCD Test in W/Z + jet production

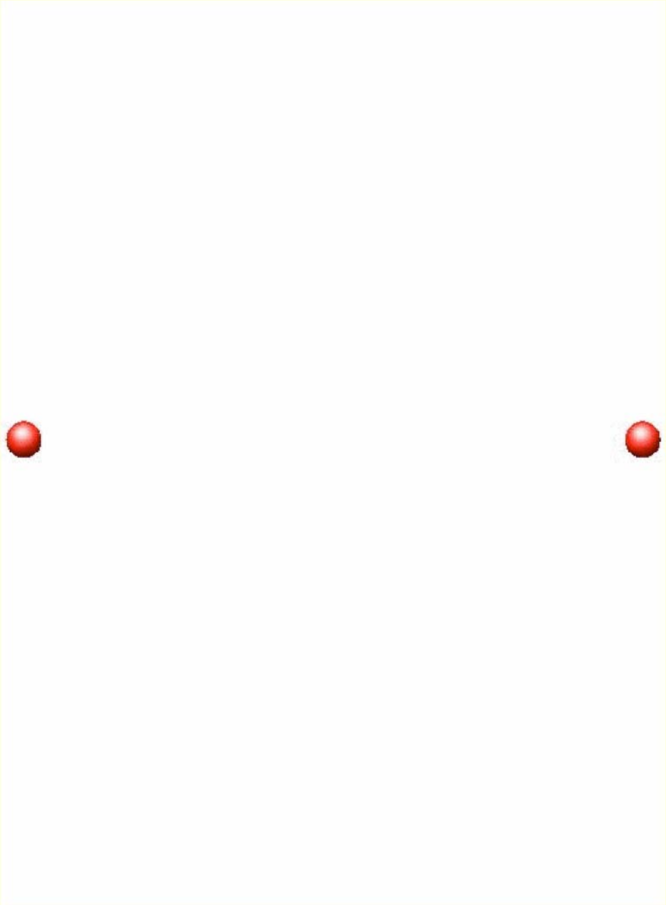






Compare # of W/Z + n jet events
(data versus QCD Monte Carlo Models
-SHERPA, ALPGEN-)

Top Quark Physics



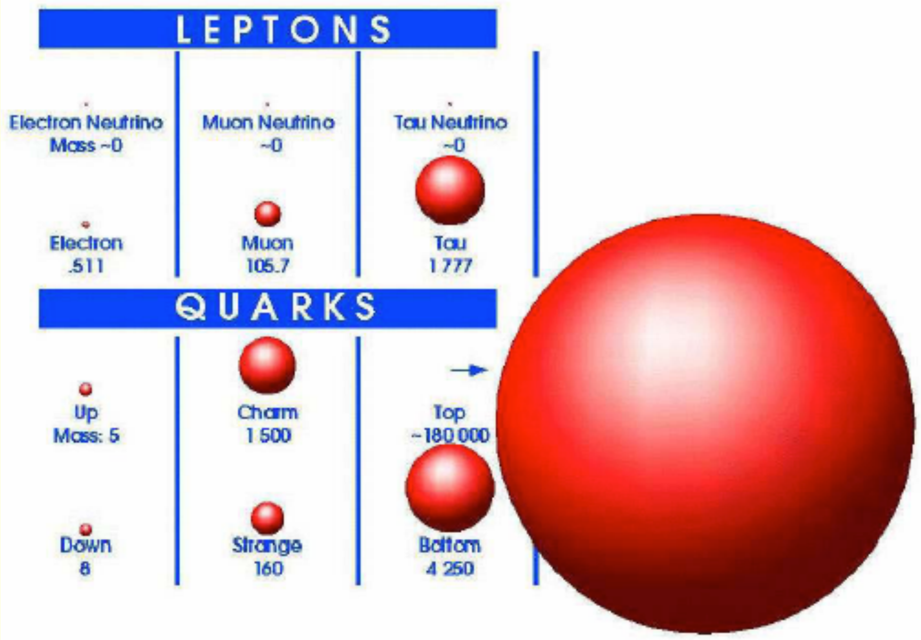
- Discovered by CDF and DØ collaborations at the Tevatron in 1995

- 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 ??

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

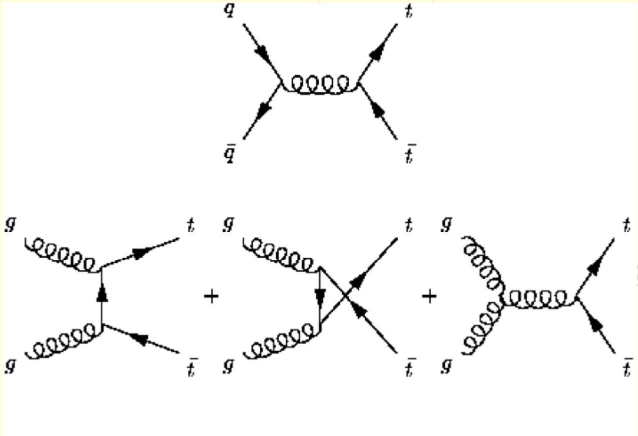
$$\Rightarrow \lambda_t = \frac{M_t}{173.9\ \mathrm{GeV}/c^2}$$

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

- A unique quark: decays before it hadronizes, lifetime ~10^{-24} s
  no "toponium states"
  remember: bb, bd, bs….. cc, cs….. Bound states (Mesons)

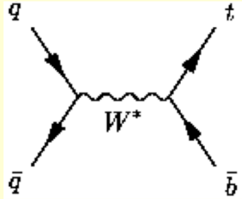
Top Quark Production

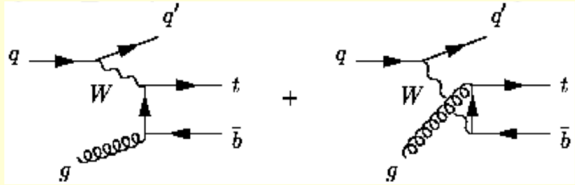
Pair production: qq and gg-fusion



	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

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





	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%)

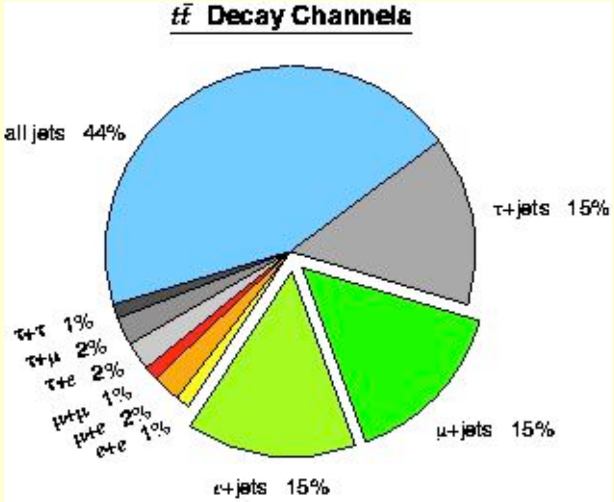
dilepton channel

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%)

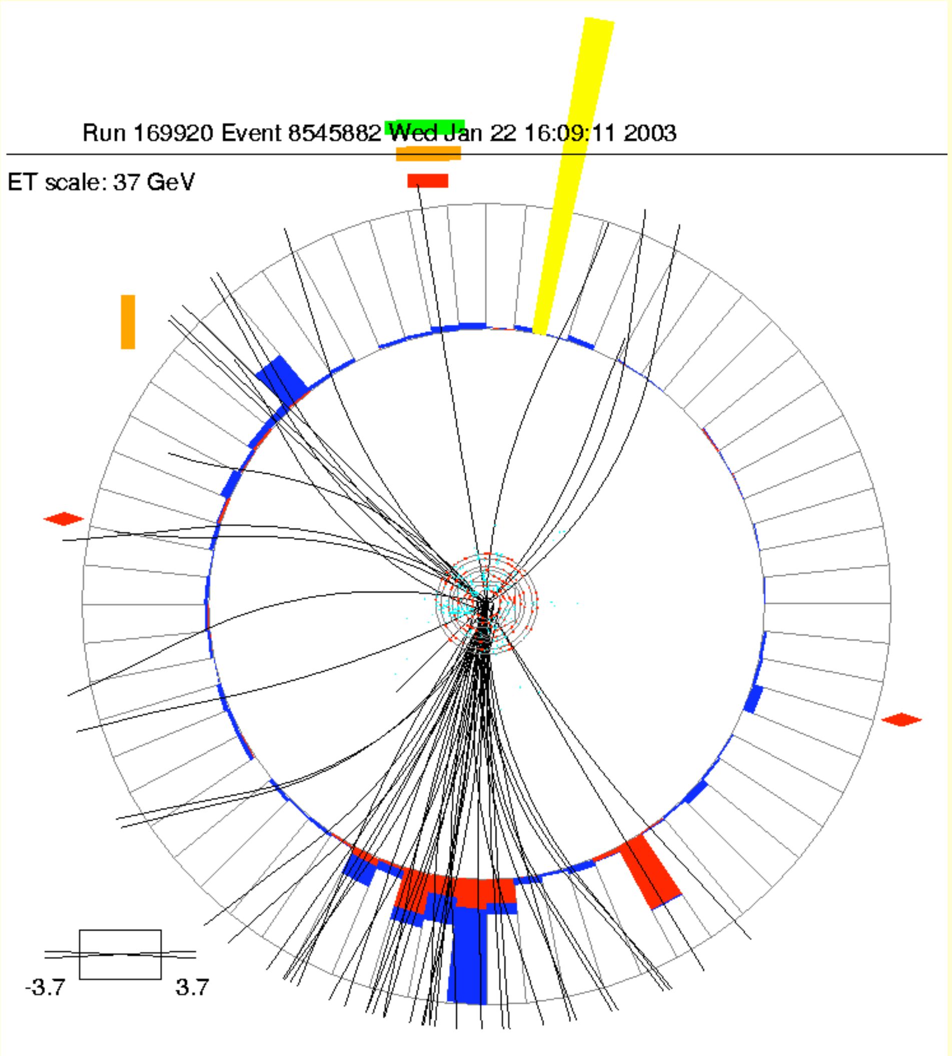
all hadronic, not very useful



Important experimental signatures: : - Lepton(s)

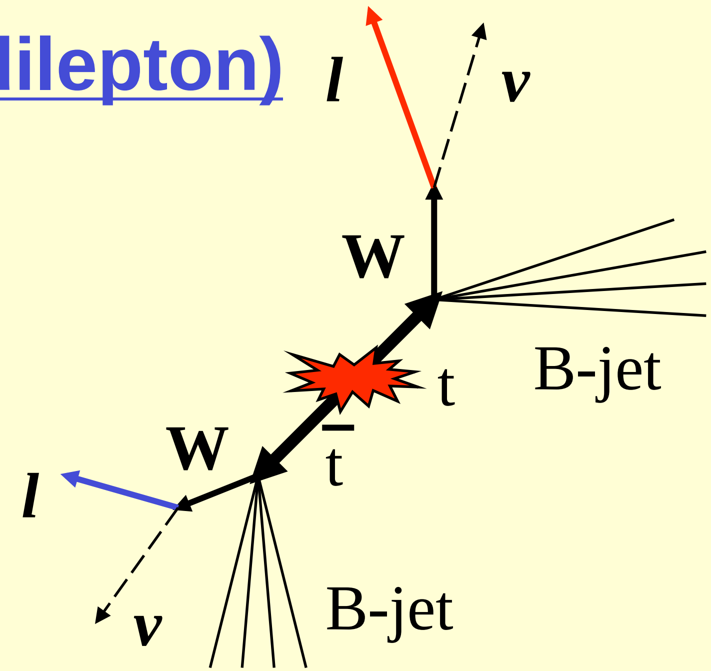
- Missing transverse momentum
- b-jet(s)

DØ top candidate event with two leptons



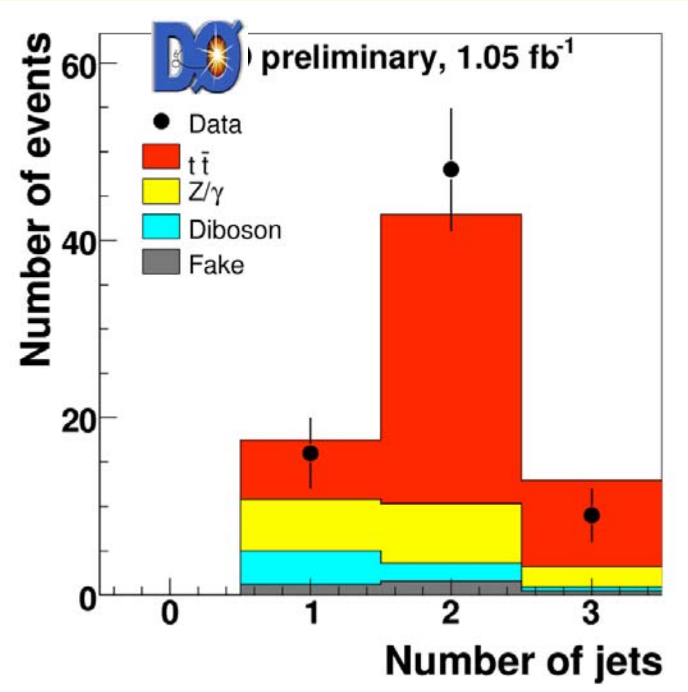
$p_T(e)$ = 20.3 GeV/c^2
$p_T(\mu)$ = 58.1 GeV/c^2
E_T^j = 141.0, 55.2 GeV
$\not{E}_T$=91 GeV

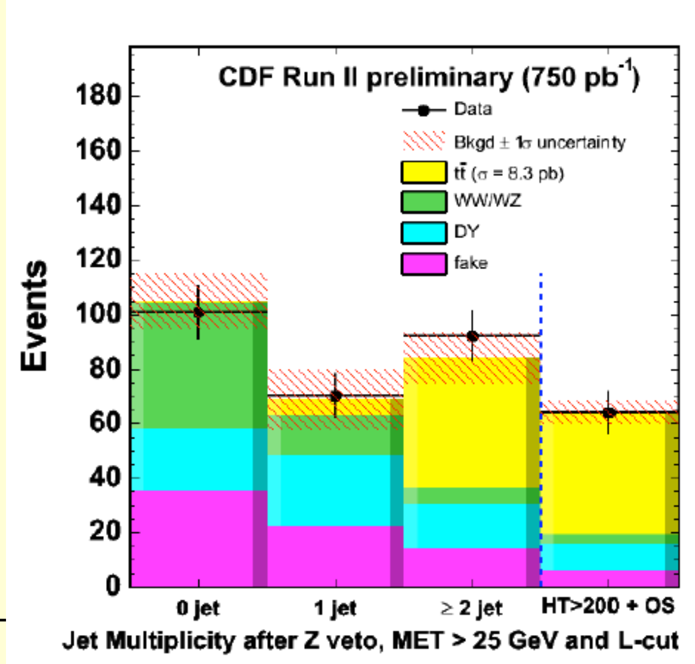
$t\bar{t}$ cross section (dilepton)



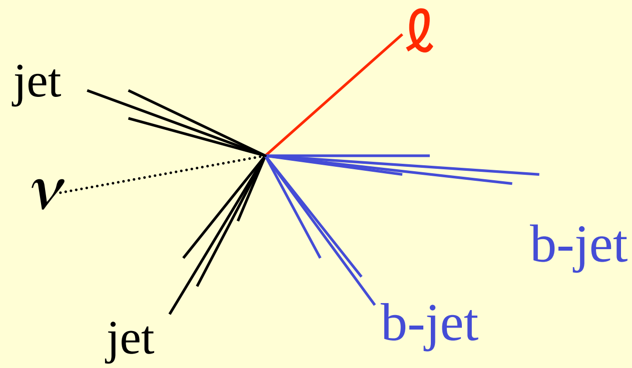
- Two high P_T leptons (opposite charge)
  ee, eμ, μμ
- Significant missing transverse momentum
- ≥ 1 jet (eμ), ≥ 2 jets (ee, μμ)

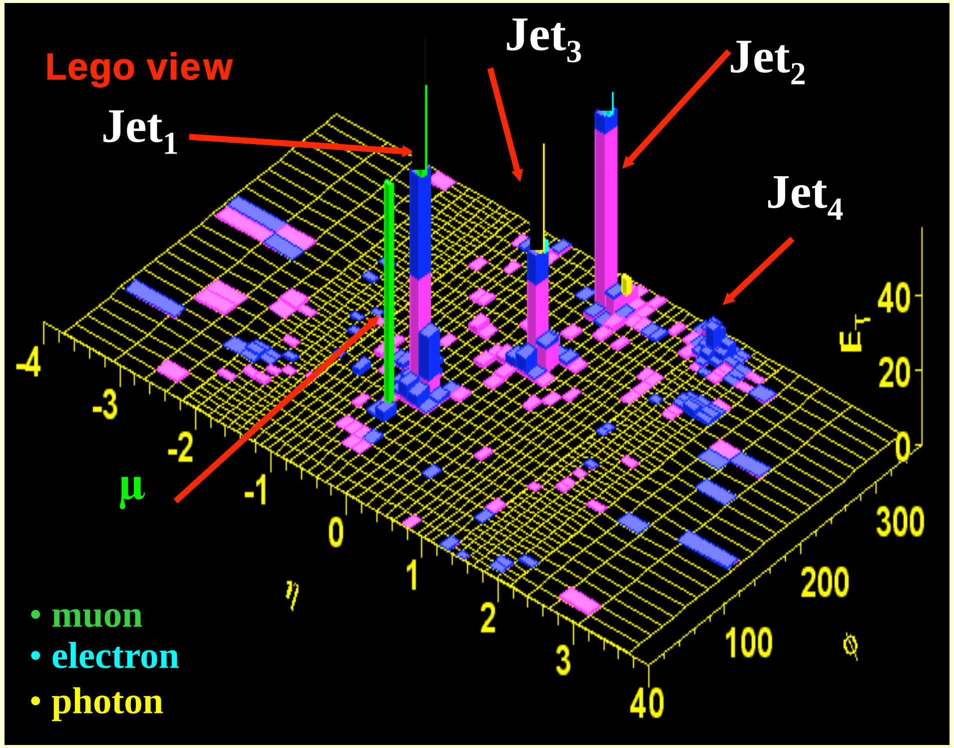
ee,eμ and μμ combined

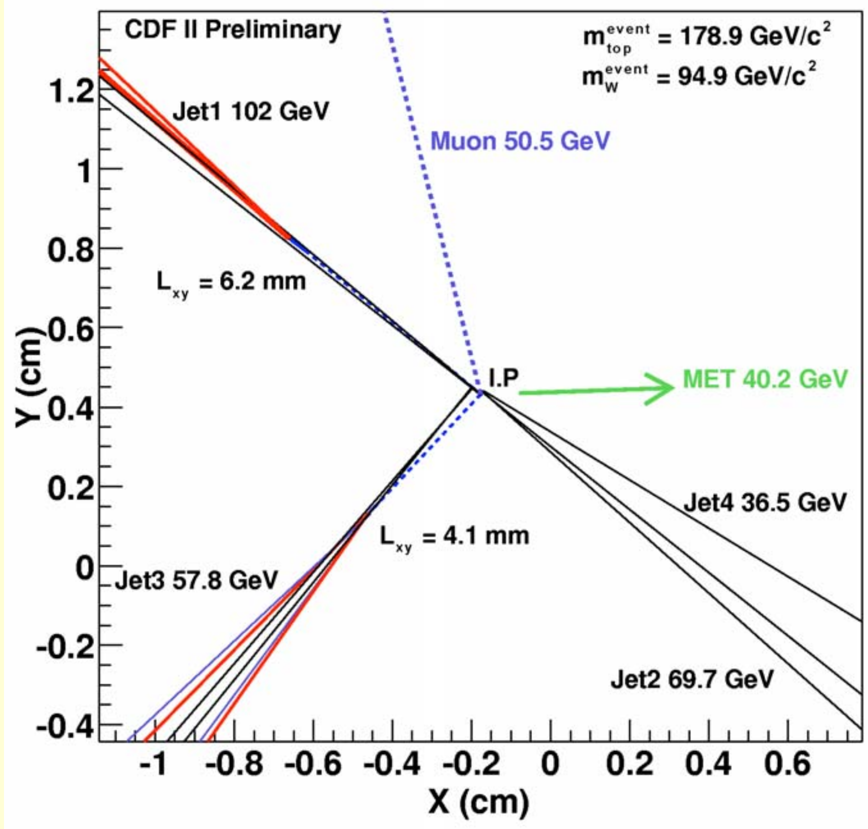




A CDF Lepton + Jet event







$p_T(\mu)$ = 54.4 GeV

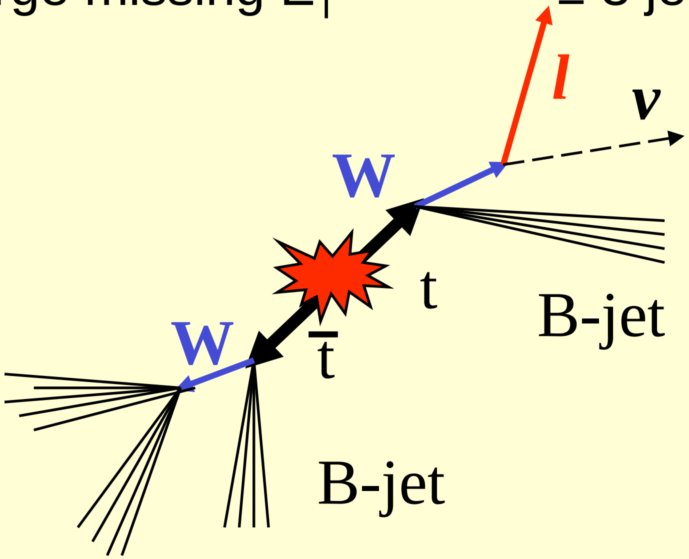
E_T^j = 96.7, 65,8, 54.8, 33.8 GeV

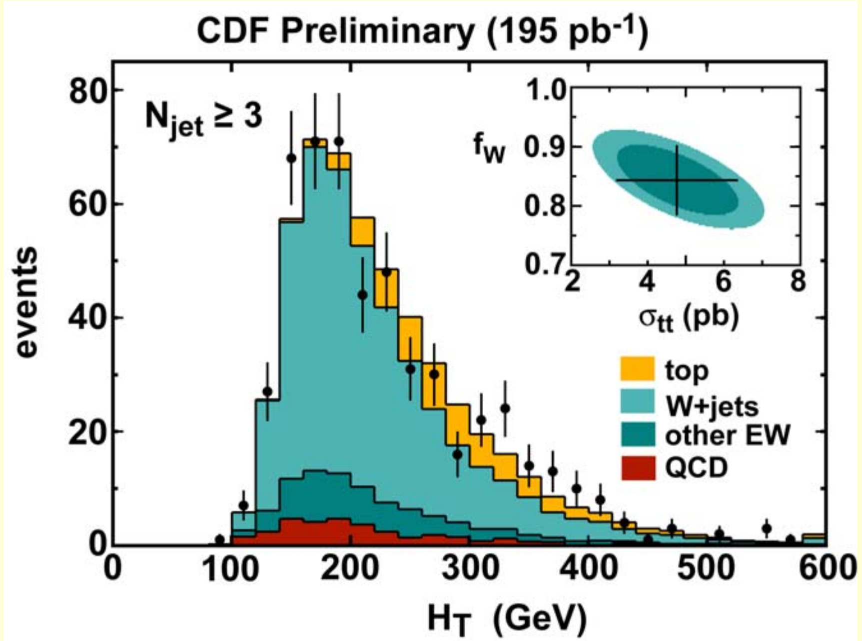
Missing E_T= 40.2 GeV

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

1 high-p_T isolated lepton

Large missing E_T



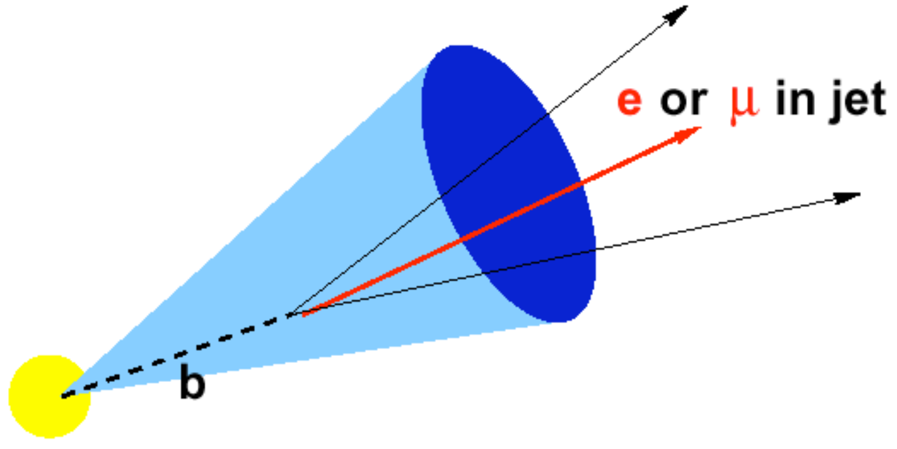


H_T = scalar sum of all high P_T objects (jets, leptons, E_T^{miss})

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

Tagging of b-quarks

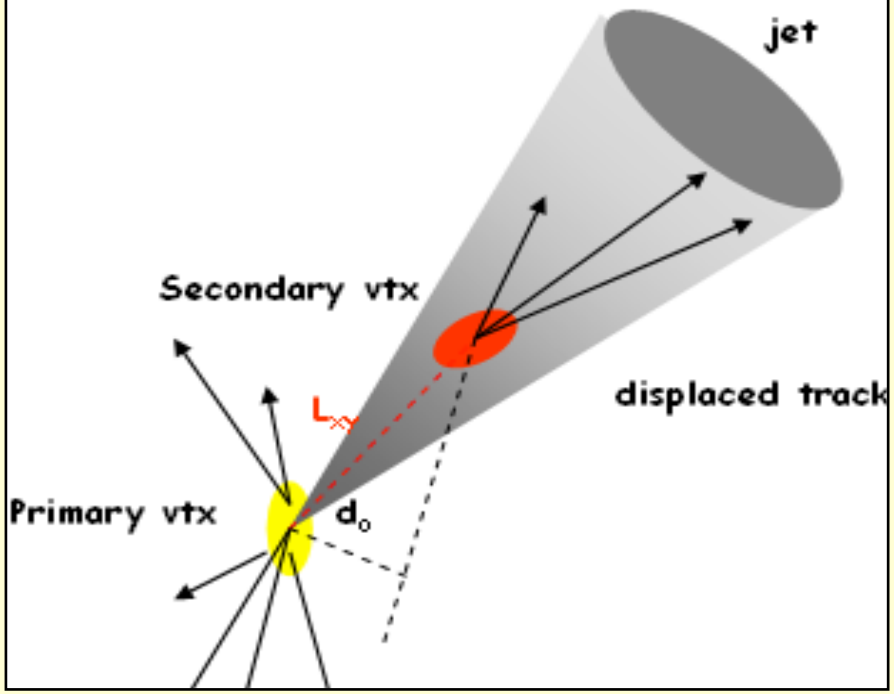
Soft lepton tagging



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

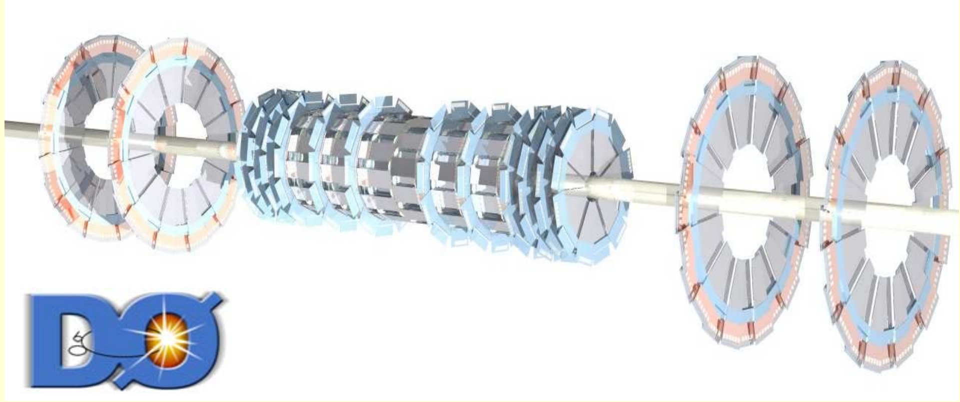
Search for non-isolated soft lepton in a jet

Silicon Vertex tag

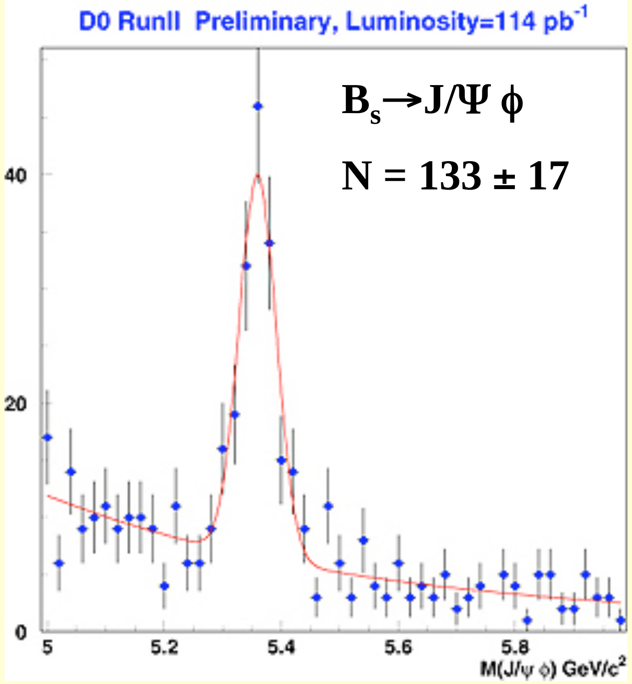


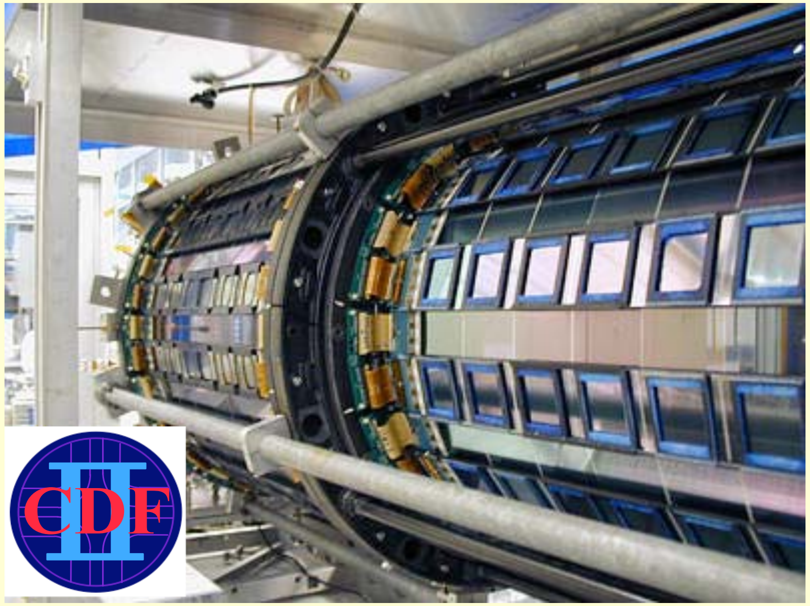
B mesons travel ~ 3 mm before decaying:
- Search for secondary vertex

Silicon detectors



Run II: silicon detectors cover a large region of acceptance

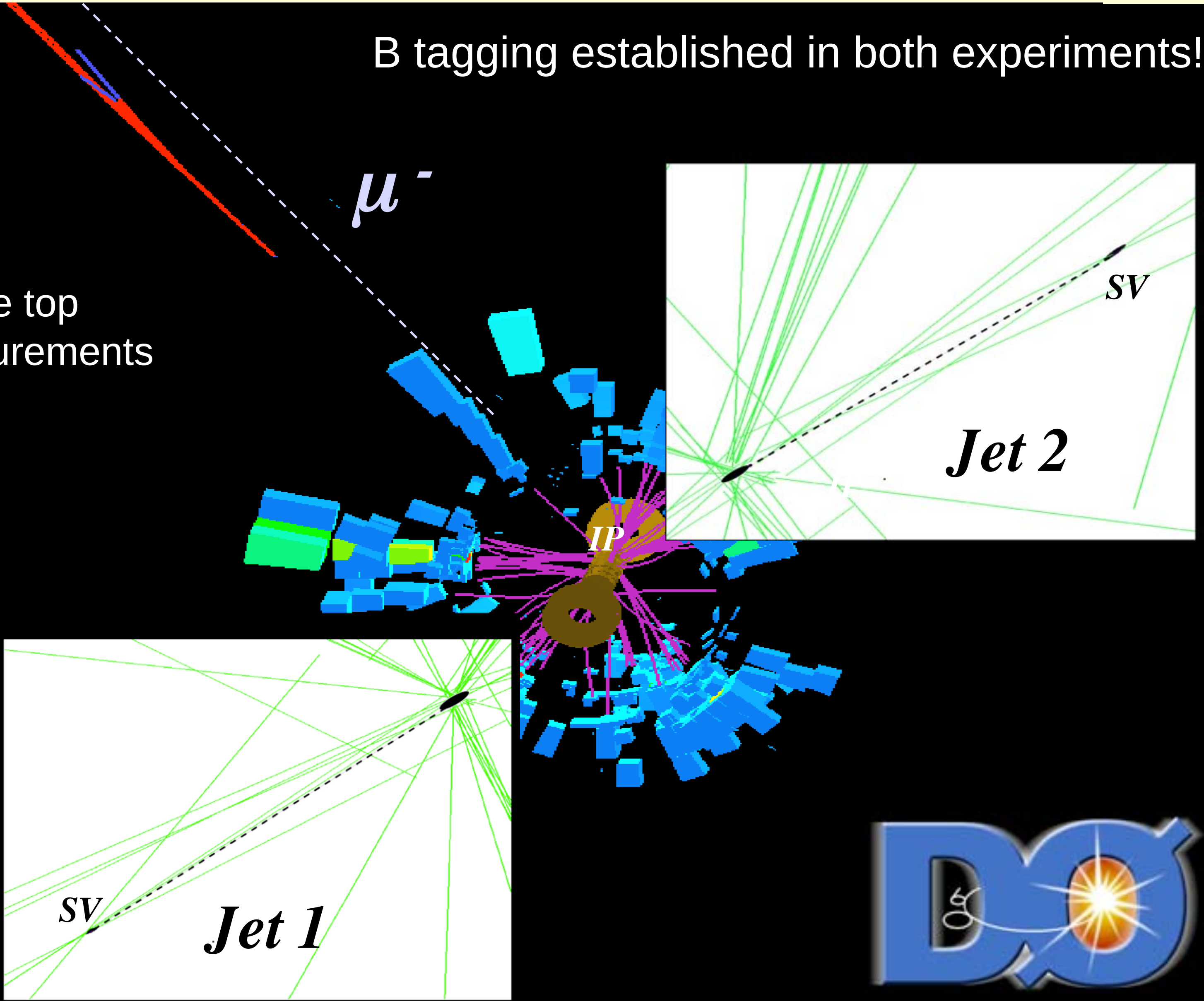




μ⁻μ + jets double-tagged event

B tagging established in both experiments!

Important for the top physics measurements



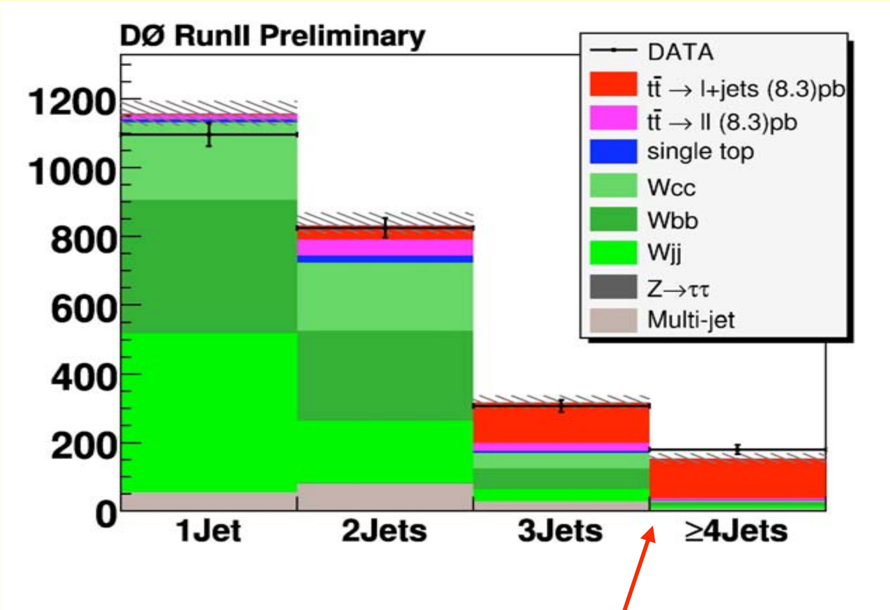
$t\bar{t}$ cross section (lepton + jets) (including b-tagging)

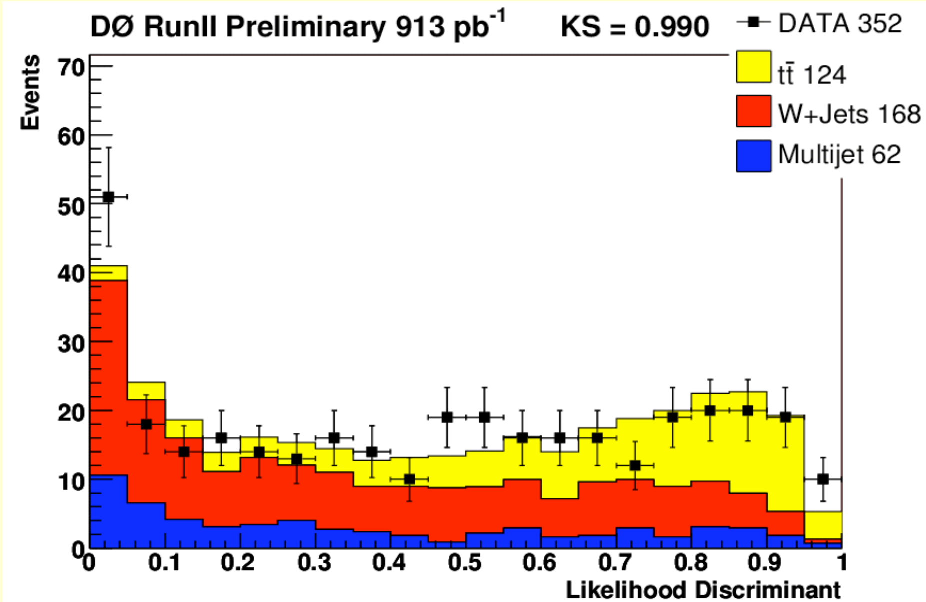
b-tag selection:

- One high P_T lepton (e, μ)
- Significant P_T^{miss}
- ≥ 1 b-tagged jet

Kinematic selection:

- One high P_T lepton (e, μ)
- Significant P_T^{miss}
- ≥ 4 jets
- Likelihood discriminant (tt vs. W+jets)



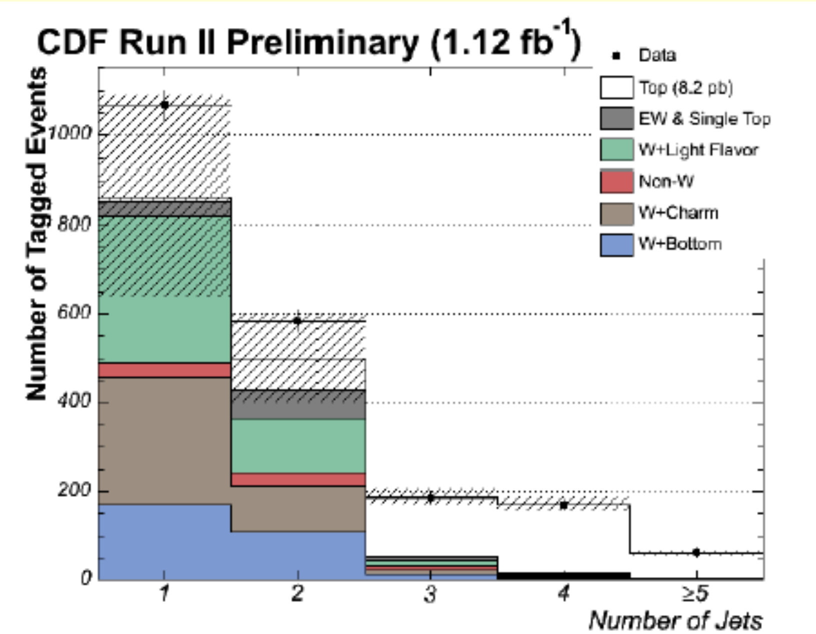


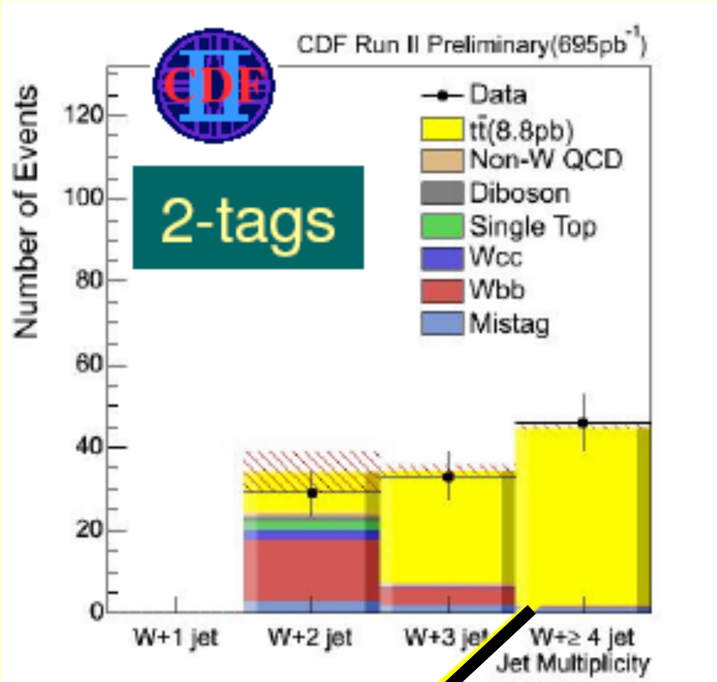
Excess above the W+ jet background in events with high jet multiplicity

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

1 high-p_T isolated lepton + 1 or 2 b-tagged jet(s)

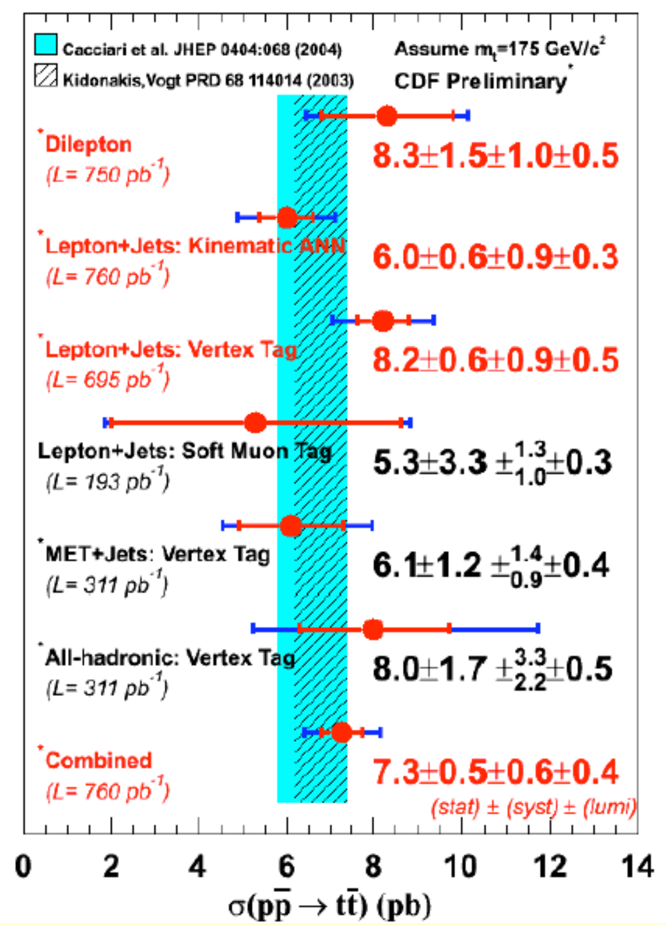
Large missing E_T





Very clean top sample

tt cross section summary (preliminary)



QCD prediction:

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

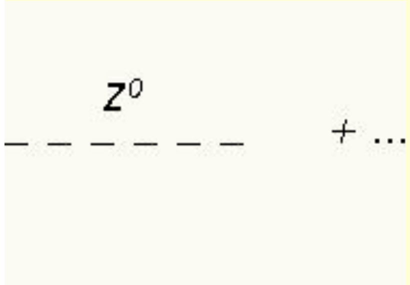
Good agreement among various exp. measurements and with QCD prediction (similar results for DØ)

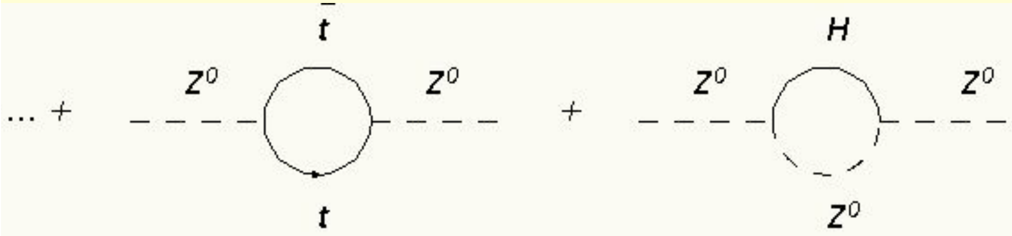
Precision measurements

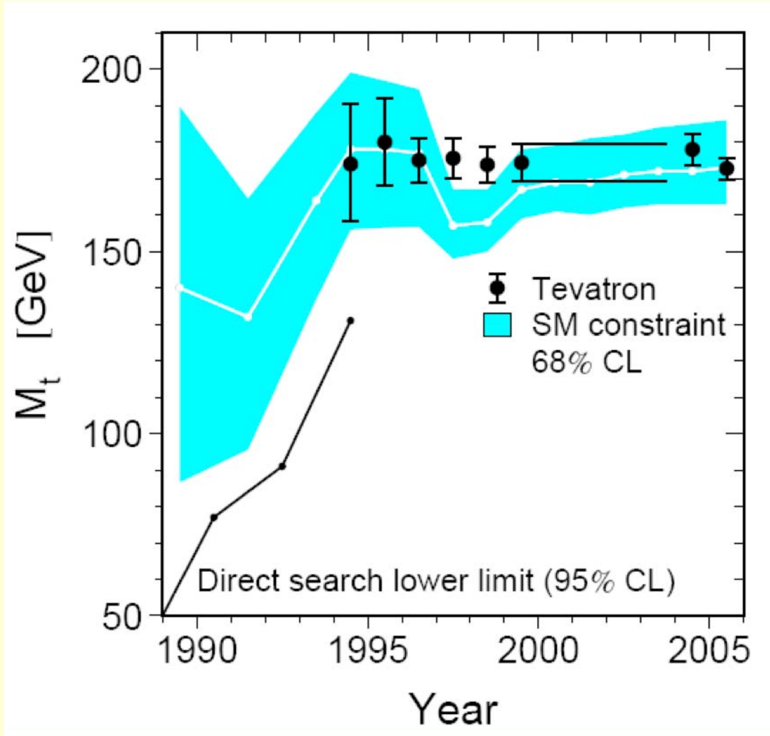
→ **Sensitivity to New Particles**

via Quantum Corrections

Top-mass predictions via precision measurements of the Z-boson parameters







$$m_Z^2 = m_Z^2(0.) \cdot (1 + \Delta(m_t, m_H, \ldots))$$

$$\Delta = \ldots. + c_1 \cdot m_t^2 + \ldots. + c_2 \cdot \ln m_H + \ldots.$$

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

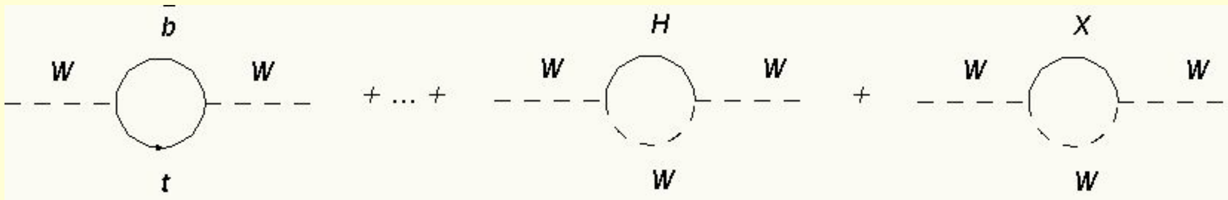
weak mixing angle
measured at
LEP/SLC

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

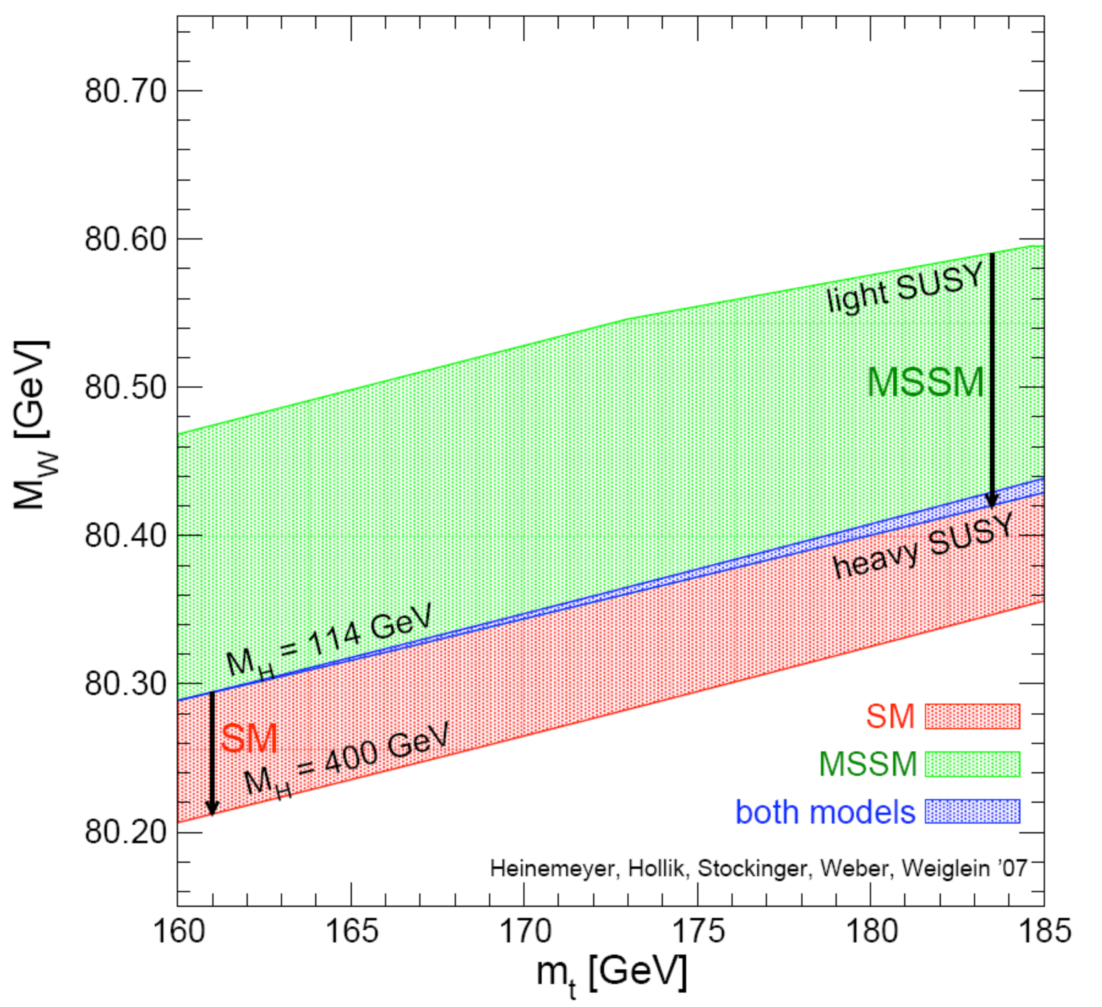
G_F, α_{EM}, $\sin\theta_W$

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)



Relation between m_W, m_t, and m_H



The W-mass measurement

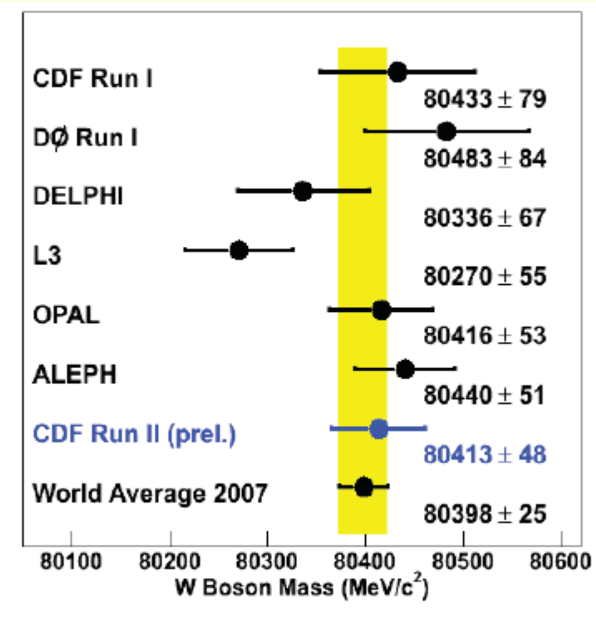
$$m_W = \left(\frac{\pi \alpha_{EM}}{\sqrt{2}\, G_F} \right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

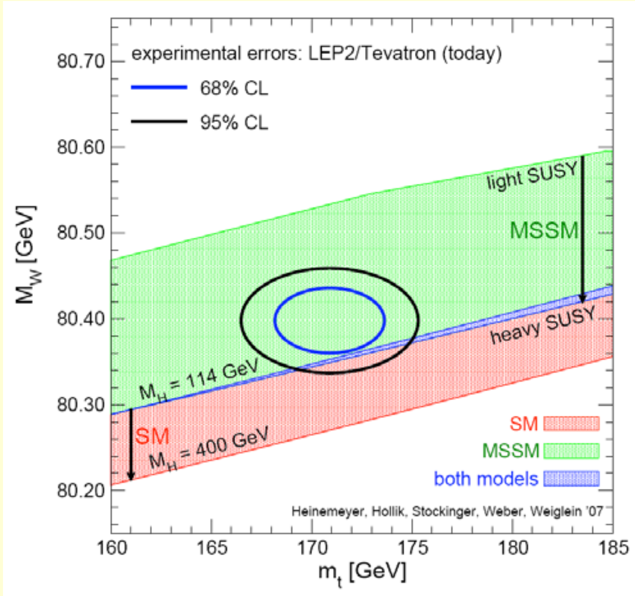
3•10⁻⁴

m_W (from LEP2 + Tevatron) = 80.398 ± 0.025 GeV

m_{top} (from Tevatron) = 170.9 ± 1.8 GeV

1.1%

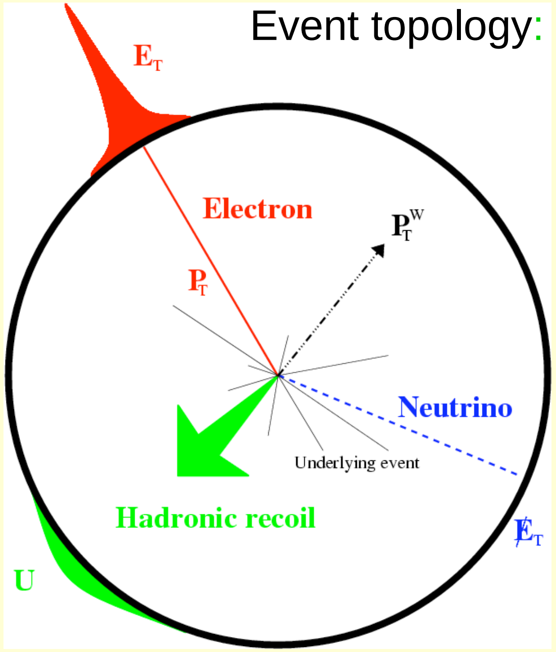


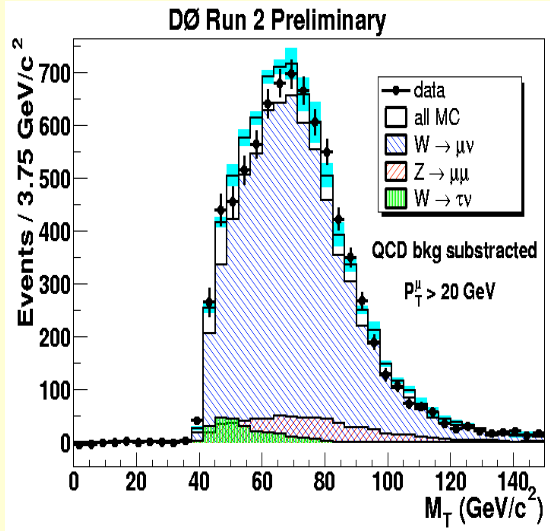


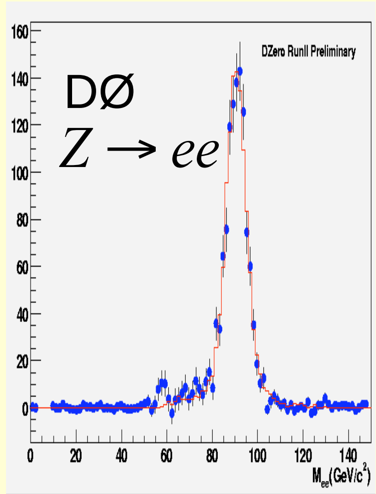
light Higgs boson is favoured by present measurements

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

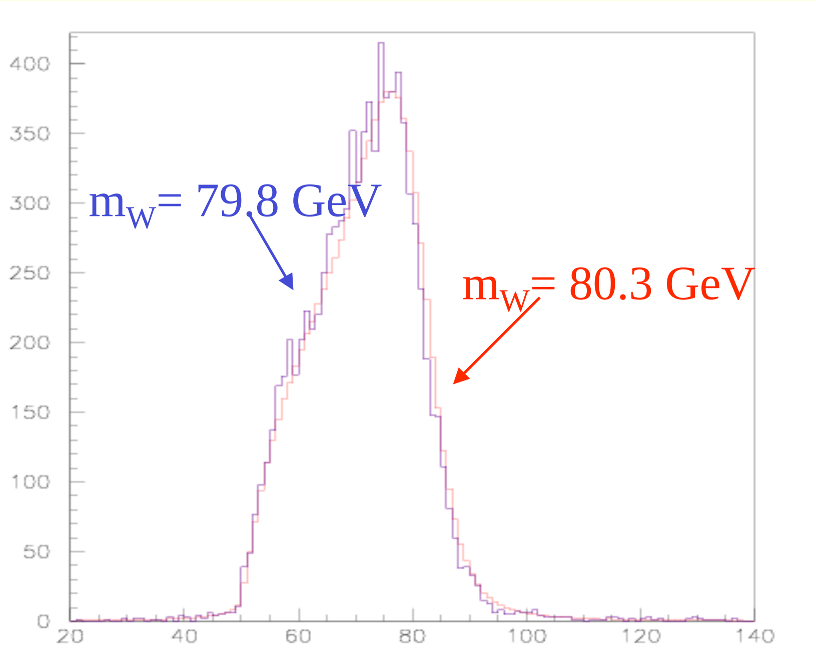
$\Rightarrow$ $P_T(\nu)$ = - ($P_T(e)$ + $P_T(had)$)

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

long. component cannot be measured

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 !

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

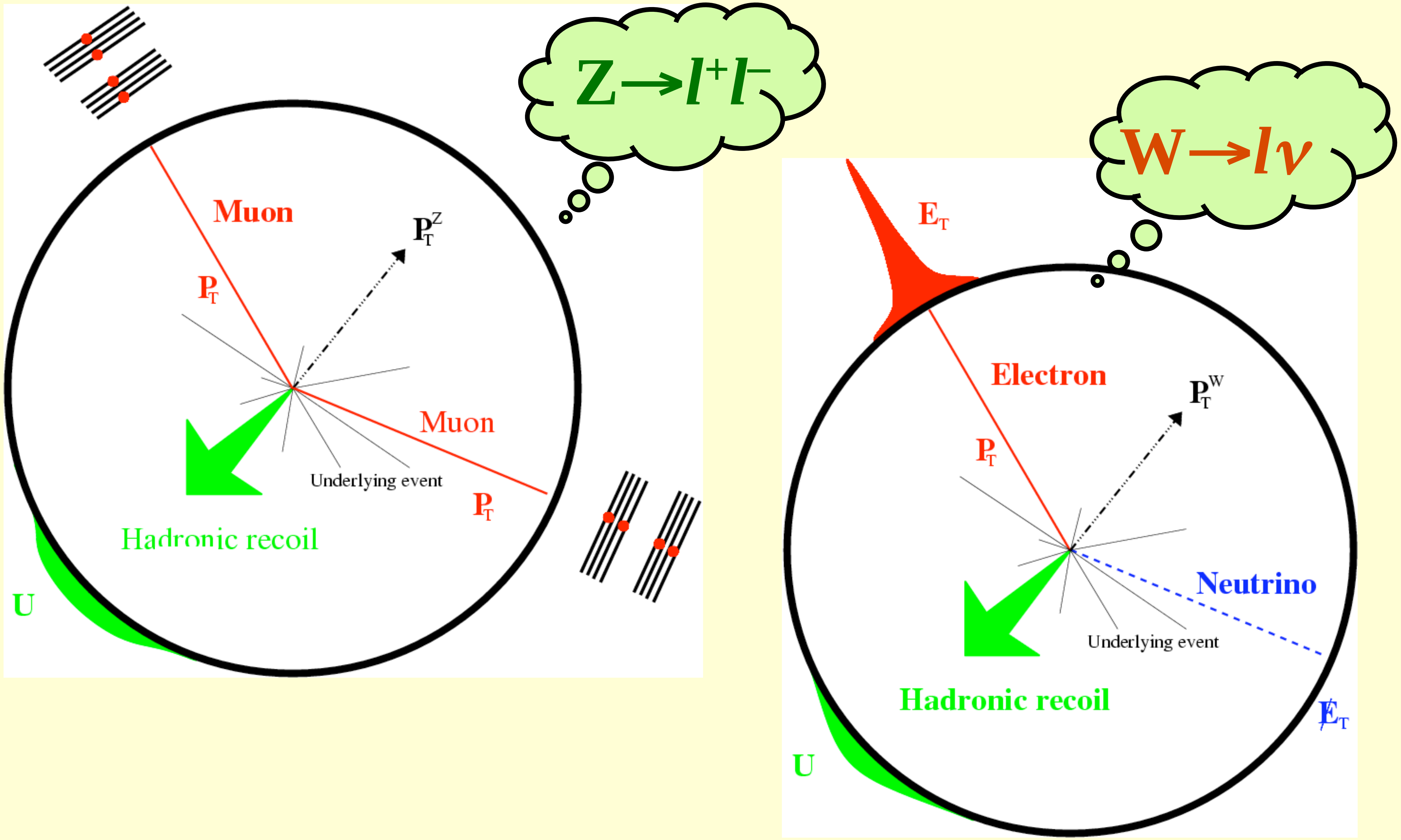
Int. Luminosity	0.08 fb^{-1}	2 fb^{-1}	10 fb^{-1}
Stat. error	**96 MeV**	**19 MeV**	**2 MeV**
Energy scale, lepton res.	57 MeV	20 MeV	16 MeV
Monte Carlo model (P_T^W, structure functions, photon-radiation….)	30 MeV	20 MeV	17 MeV
Background	11 MeV	2 MeV	1 MeV
Tot. Syst. error	**66 MeV**	**25 MeV**	**24 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% **$\Rightarrow$ $\Delta m_W \sim \pm$ 15 MeV**

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

Signature of Z and W decays



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)

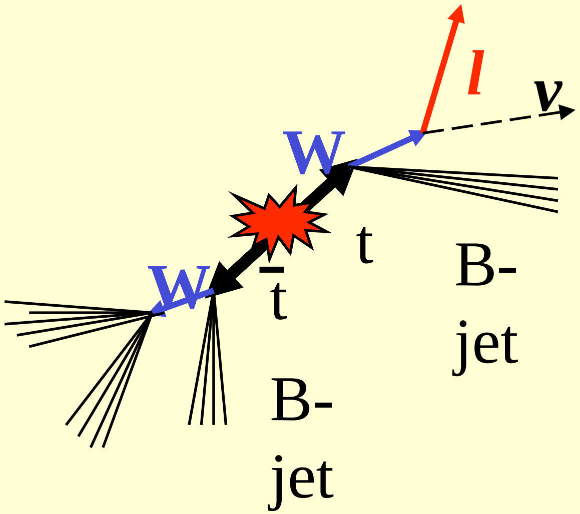
Combining both experiments (ATLAS + CMS, $10\ fb^{-1}$), both lepton species and assuming a scale uncertainty of ± 0.02% **⇒ Δm_W ~ ± 15 MeV**

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

Top mass measurements

- Top mass determination:
  No simple mass reconstruction possible,
  Monte Carlo models needed

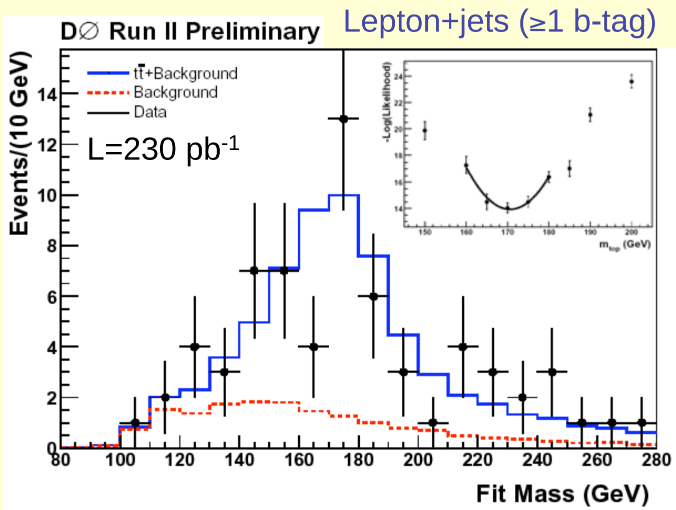
  → template methods,…
  matrix element method…



<u>Most precise single measurements</u>:

m_{top} = 170.9 ± 1.6 (stat) ± 2.0 (syst) GeV/c^2 (CDF)

m_{top} = 170.5 ± 1.6 (stat) ± 2.2 (syst) GeV/c^2 (DØ)

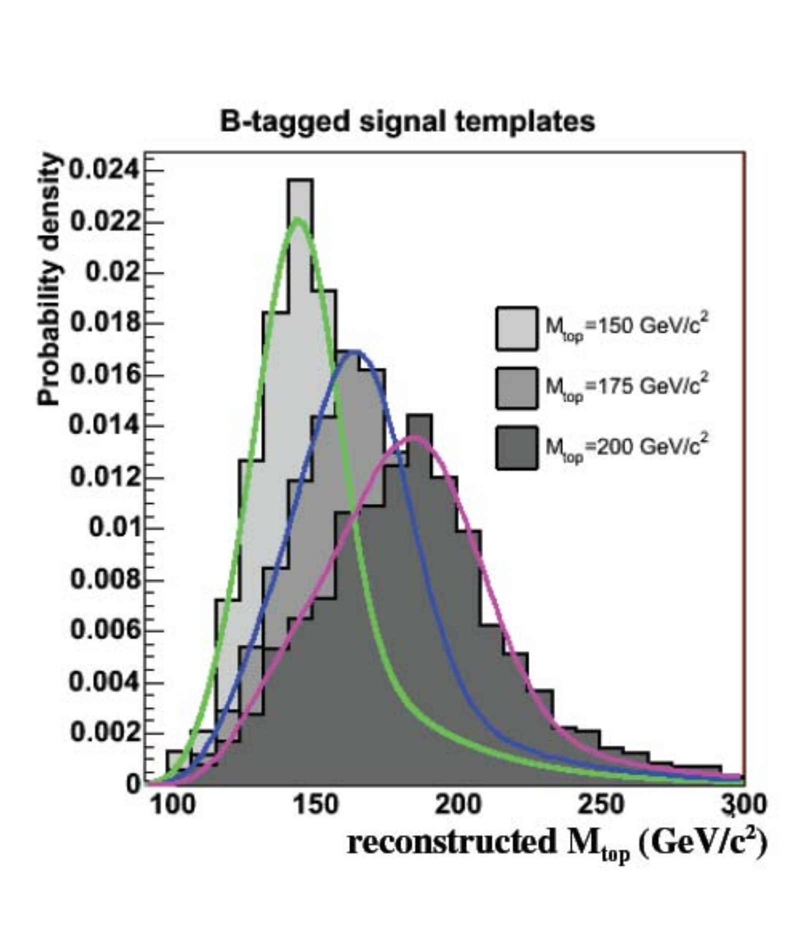


- Reduce JES systematic by using in-situ hadronic W mass in tt events

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

Example: template method

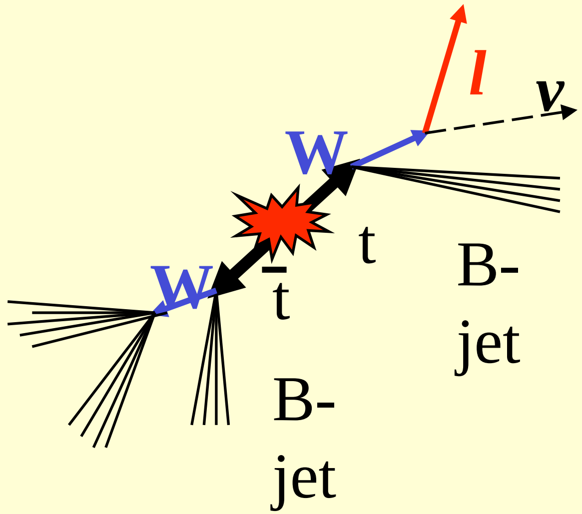
- Calculate a per-event observable that is sensitive to m_t
- Make templates from signal and background events
- Use pseudo-experiments (Monte Carlo) to check that method works
- Fit data to templates using maximum likelihood method



Top mass measurements

- Top mass determination:
  No simple mass reconstruction possible,
  Monte Carlo models needed

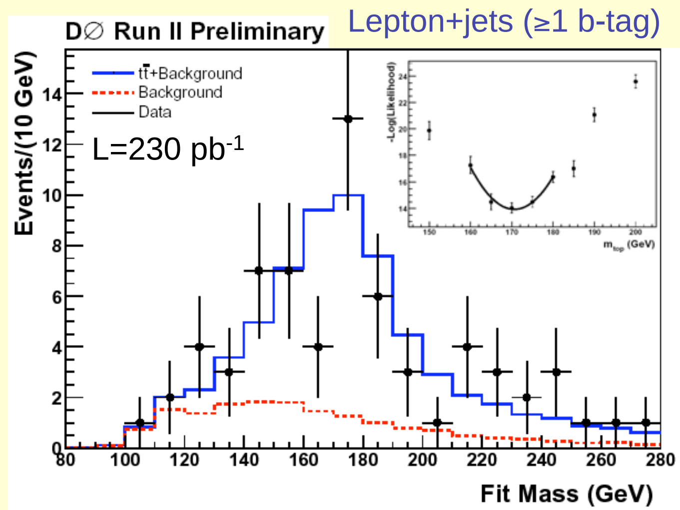
  → template methods,…
  matrix element method…



Most precise single measurements:

m_{top} = 170.9 ± 1.6 (stat) ± 2.0 (syst) GeV/c^2 (CDF)

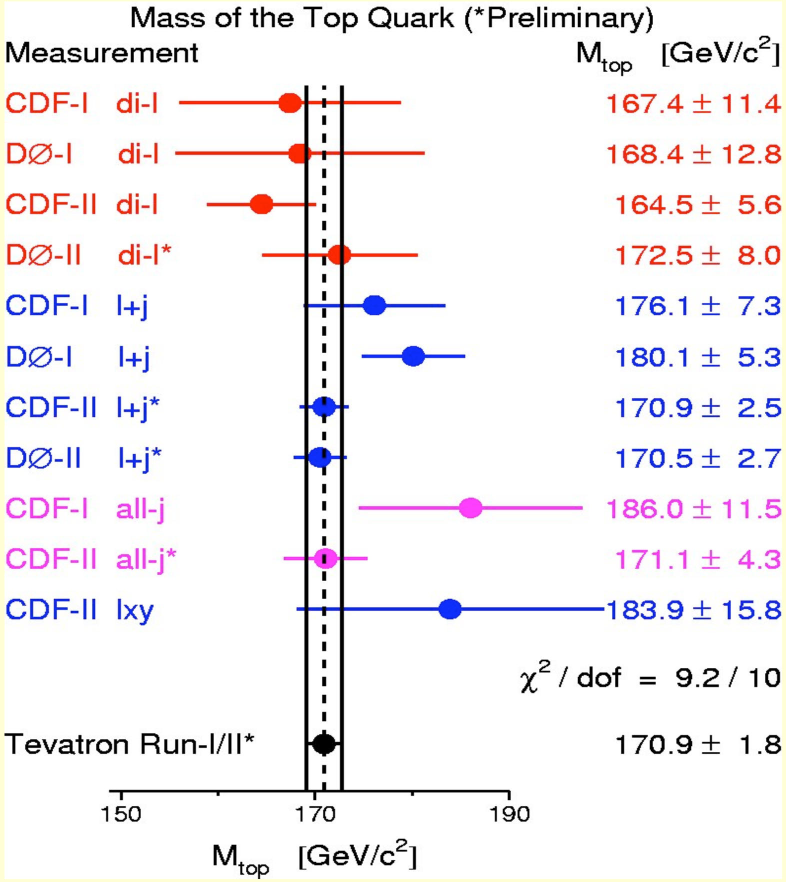
m_{top} = 170.5 ± 1.6 (stat) ± 2.2 (syst) GeV/c^2 (DØ)

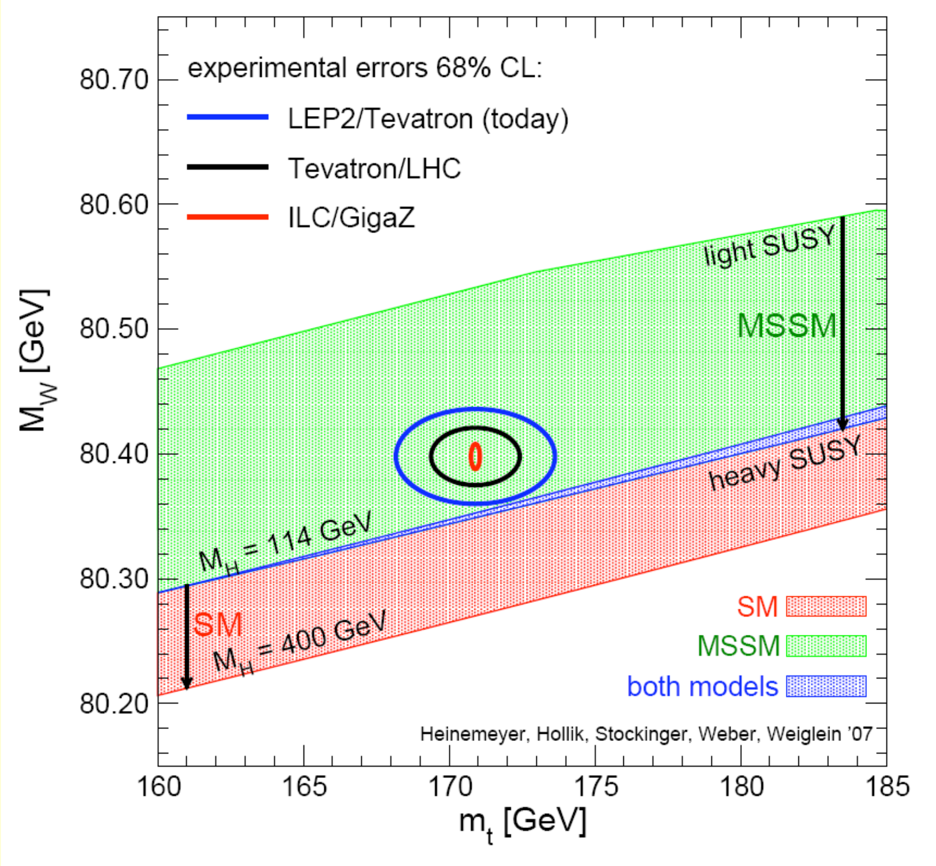


- Reduce JES systematic by using in-situ hadronic W mass in tt events

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

Future Prospects for the top quark mass measurement





Expected Tevatron precision (full data set): ± 1.5 GeV/c^2

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 better than ~ 1 GeV

→ Higgs mass constrained indirectly to ~ 25%