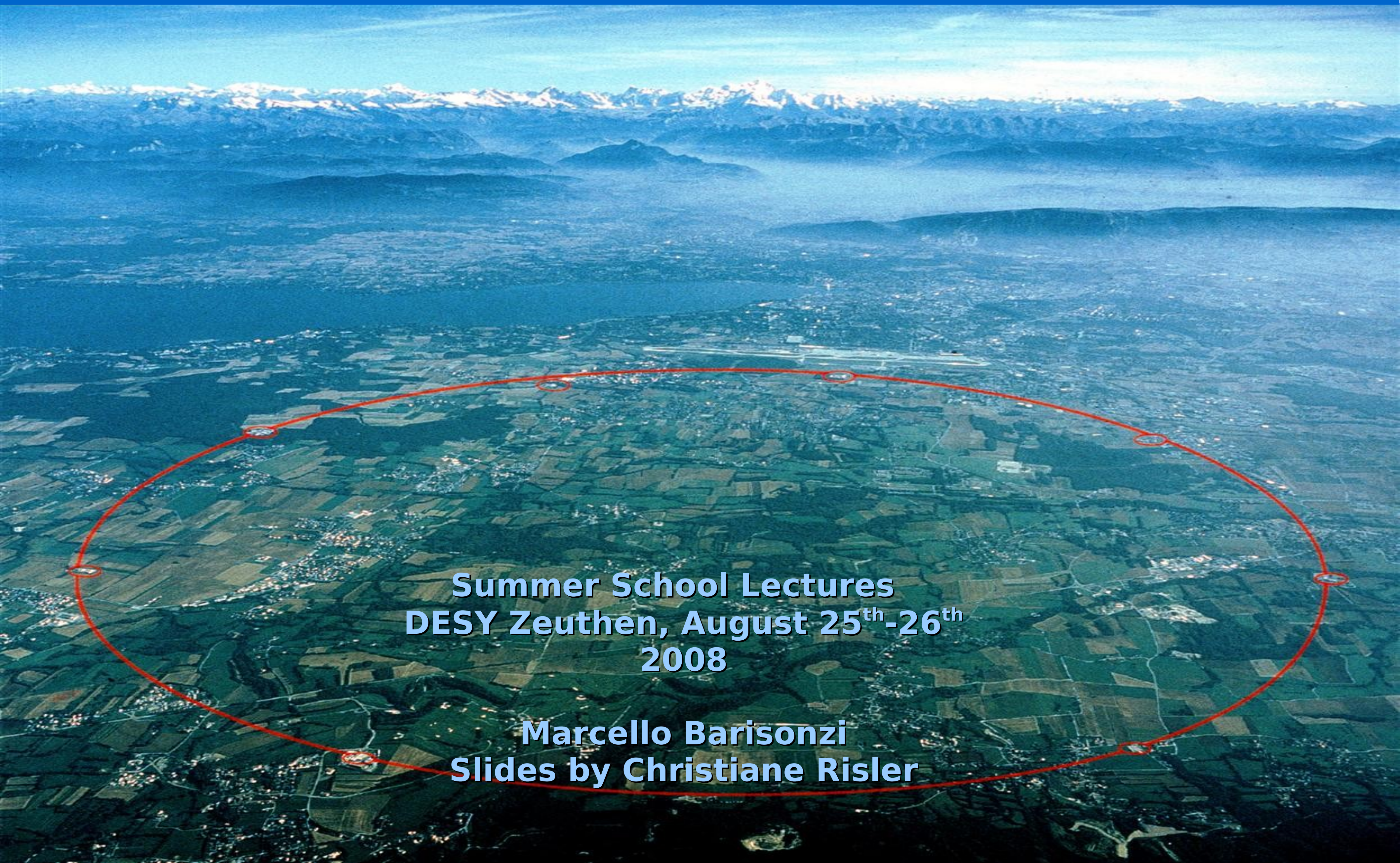
Physics at the LHC experiments



Summer School Lectures
DESY Zeuthen, August 25th-26th
2008

Marcello Barisonzi
Slides by Christiane Risler

Outline of part2

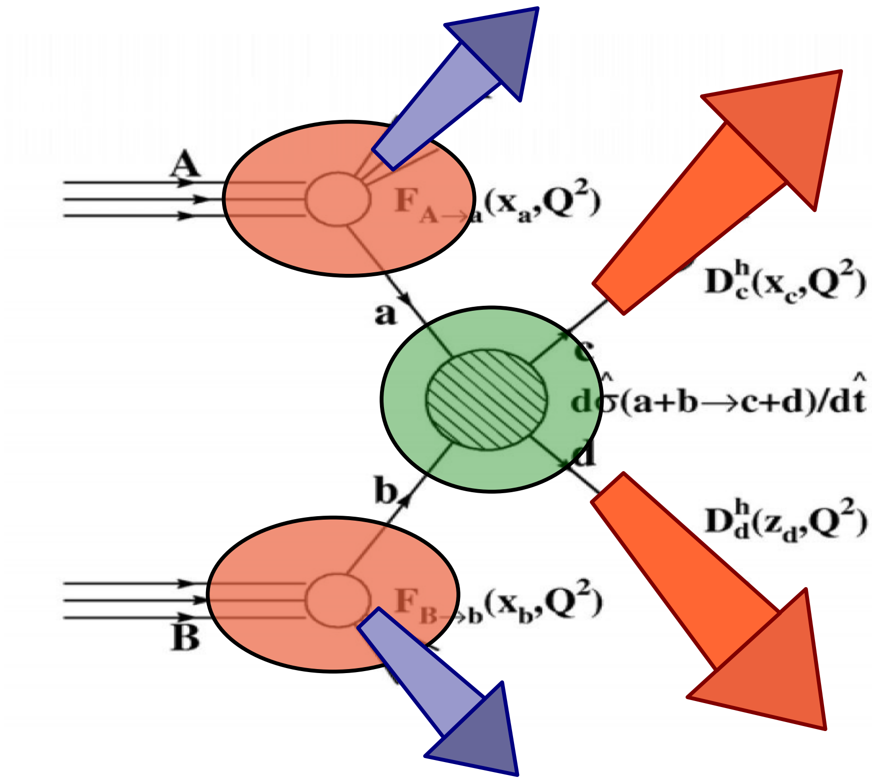
- **Tests of the Standard Model (QCD)** using
  - **jets**
  - **top quarks**
  - **W/Z – bosons**

- **high precision measurements of the W boson mass and top quark mass**

tests of the Standard Model (QCD) : jets in pp collisions

Why do we want to study Jets ?

QCD Jets at LHC: **Motivation : why jets ?**



Reminder: pp collisions
hard and **soft** QCD

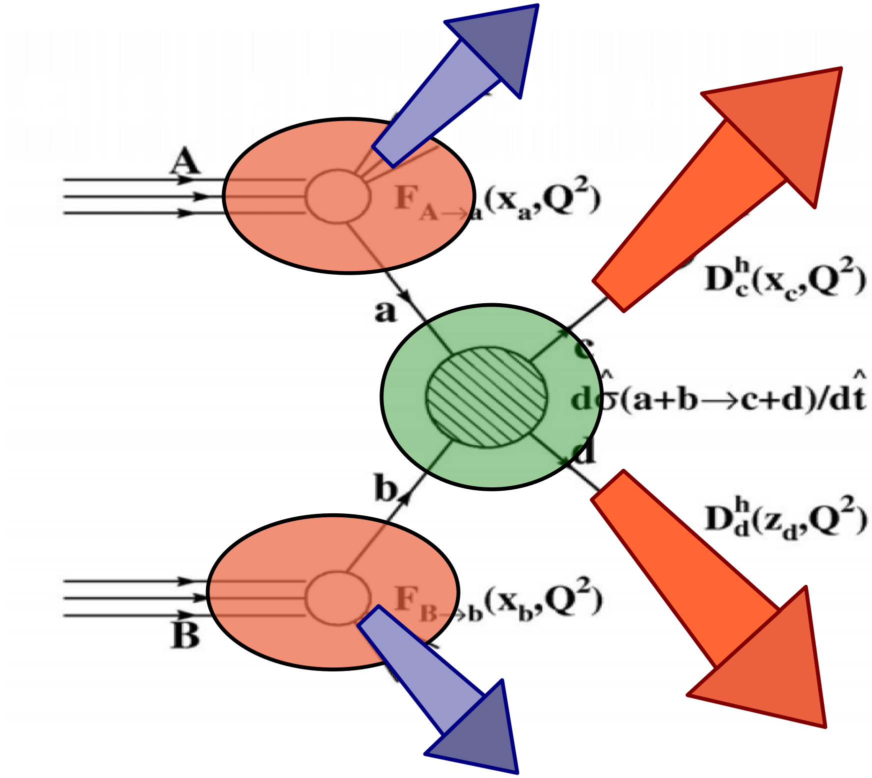
- hard QCD subprocess :
  hard (=perturbative=calculable) QCD gives us partons
- Jet = collimated bundle of particles
- jets are formed in fragmentation
  colorless
  ≠ partons

However:

- Jets = footprints of partons
  sensitive to hard subprocess
  parton dynamics
- study QCD – look at jets

Why do we want to study Jets ?

QCD Jets at LHC: Motivation : why hard QCD ?

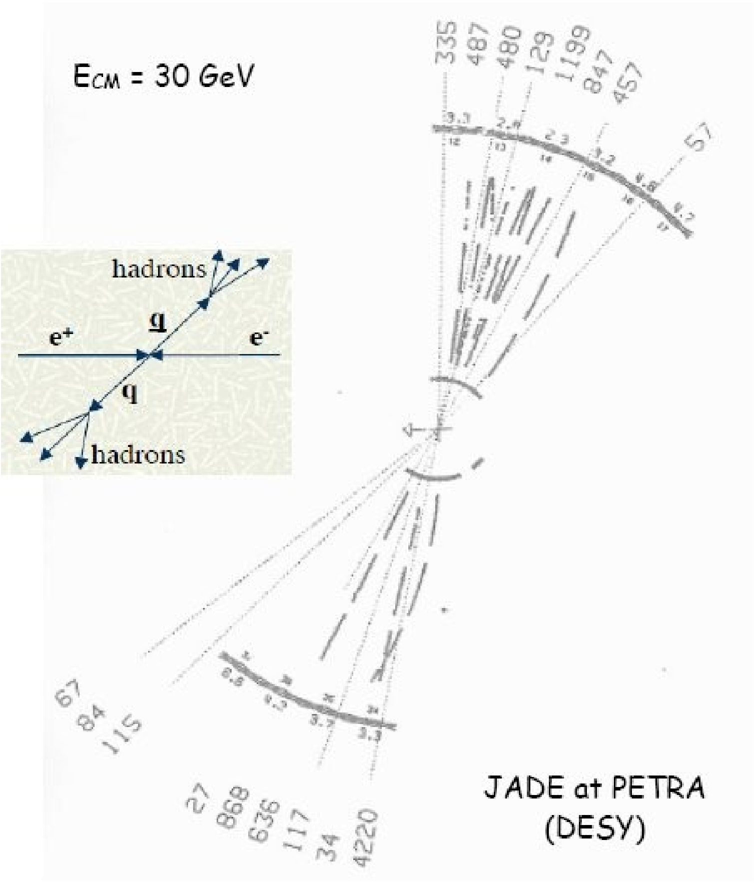


- cross section of hard subprocess and jet cross section calculable
- compare data and theory = test of Standard Model, test of QCD

  - find problems in theory ?
  - Hints of new physics ?
    e.g. quarks substructure ?
    known: not down to 10^{-18} m

  - Need to understand QCD jets in out detector, in order to find new physics
  "yesterdays signal = tomorrows bgr"

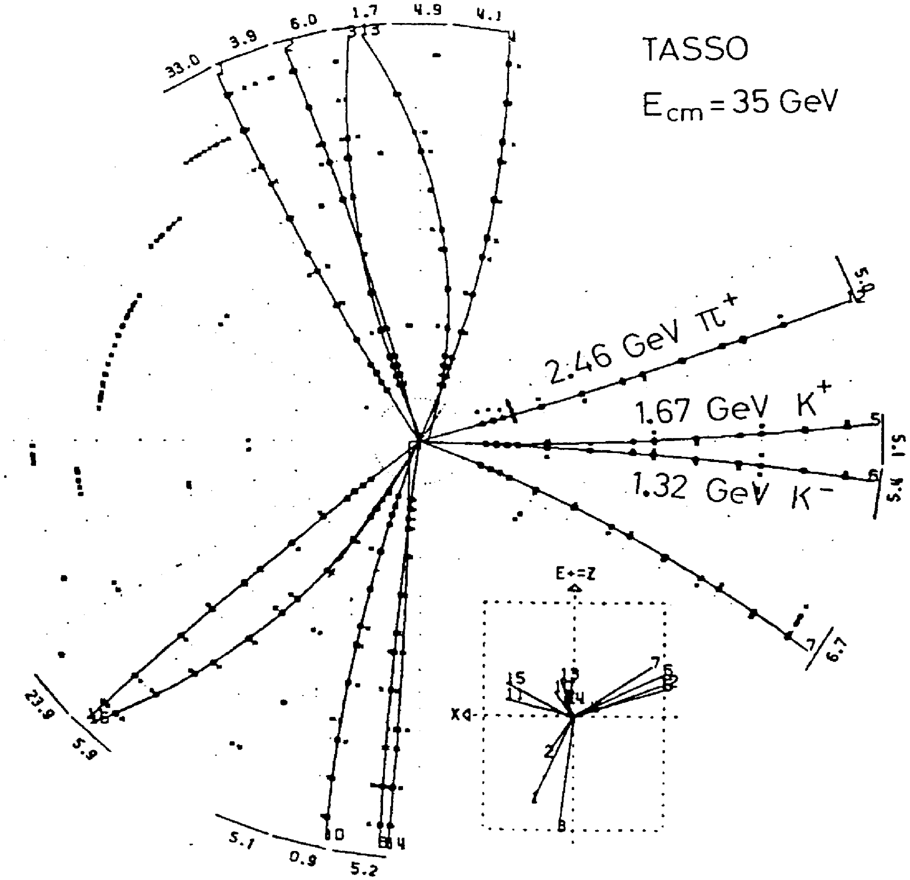
What do jets look like?



Di-Jet event JADE at PETRA

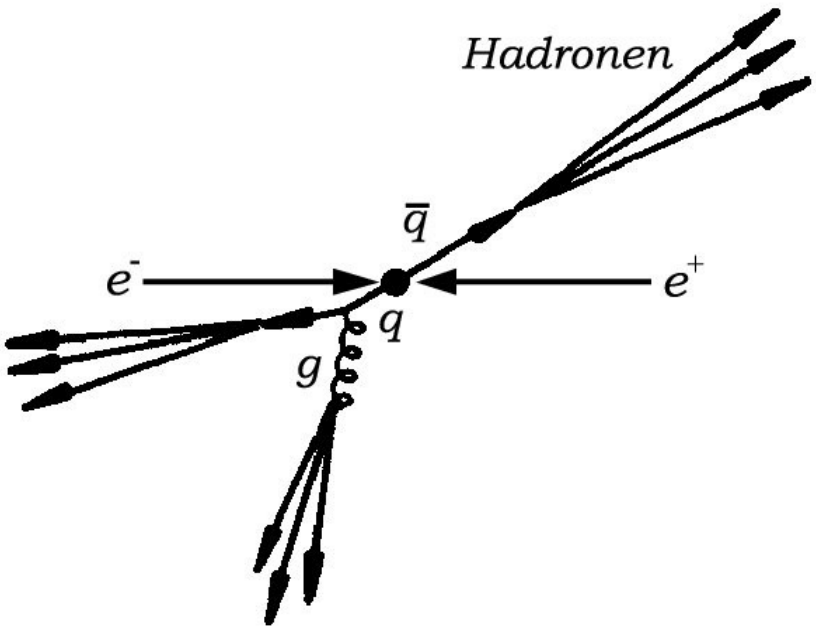
e+e- collisions at $\sqrt{s}$ = 30 GeV

What do jets look like?



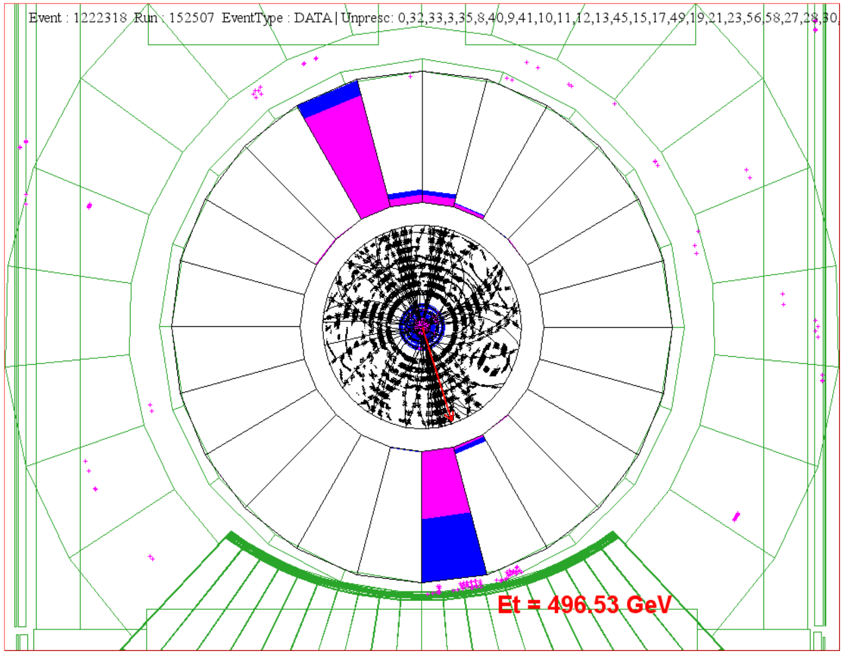
Famous three jet event from PETRA

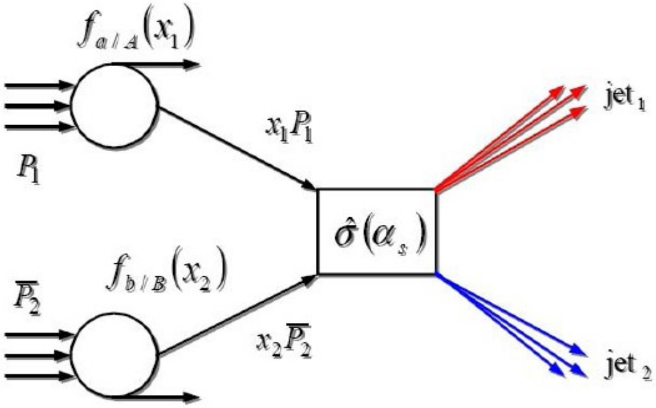
first hint of gluons

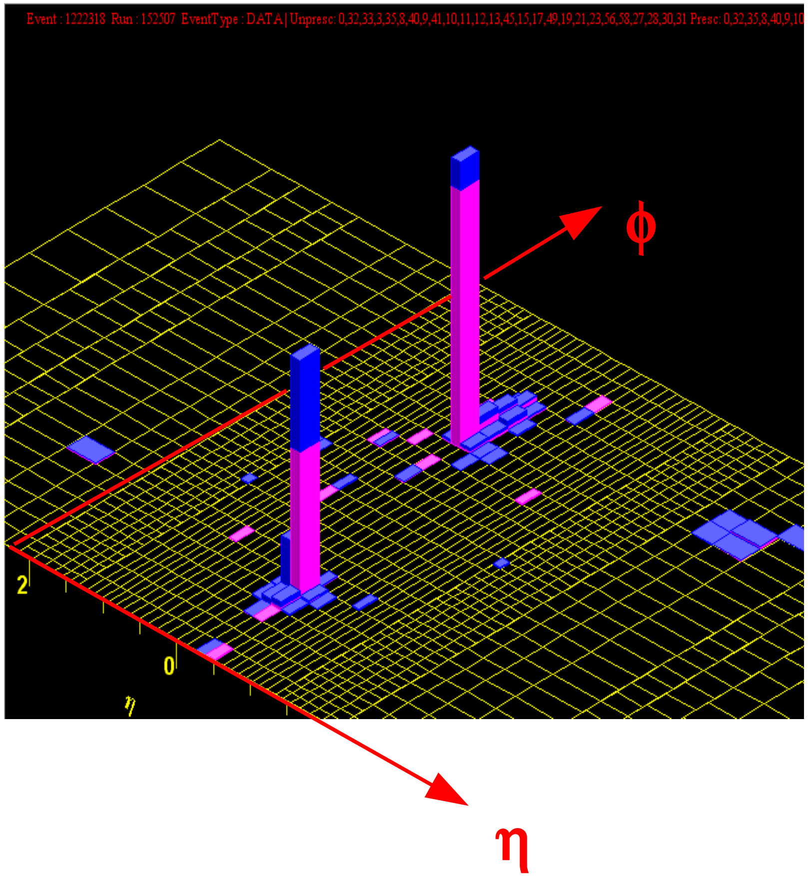


What do jets look like?

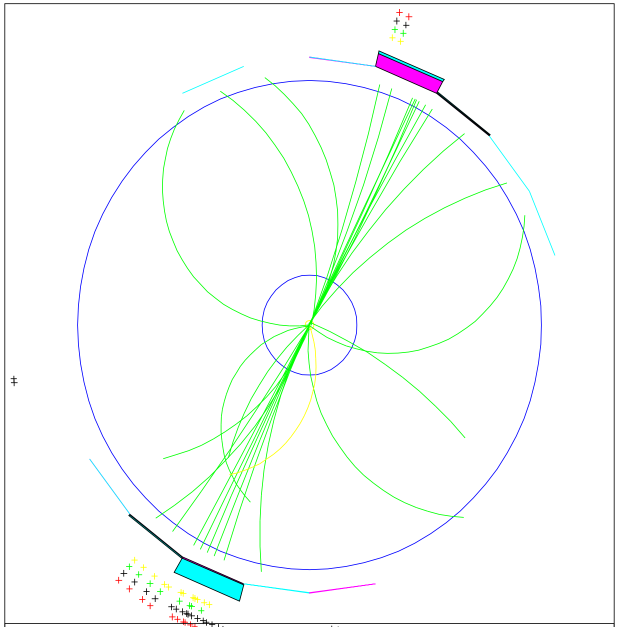
Dijet event in CDF

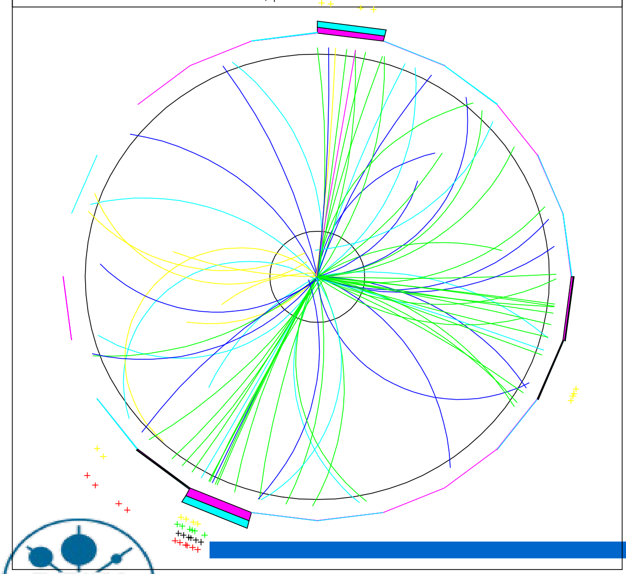






Jet Events in the CDF track detector



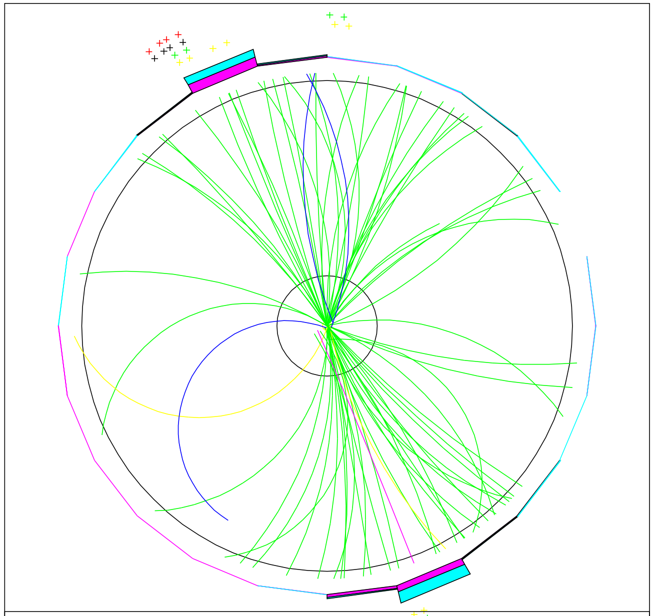


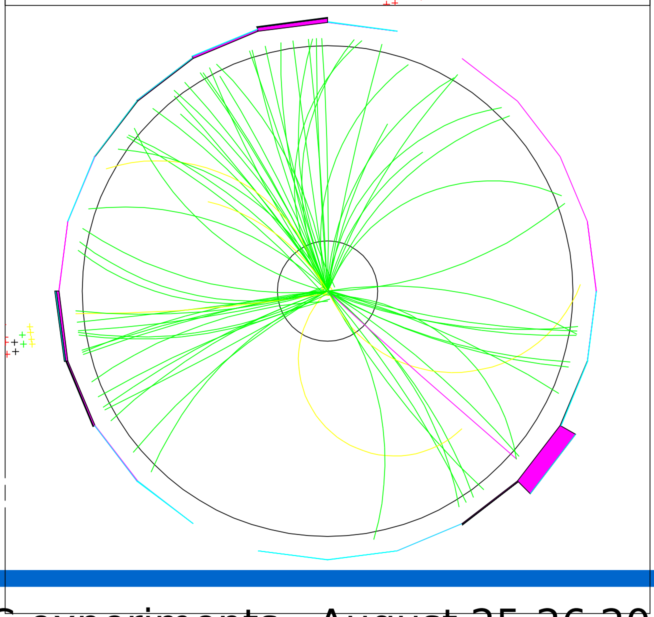
2 jet event

Multijets not so clearly seen by unaided eye

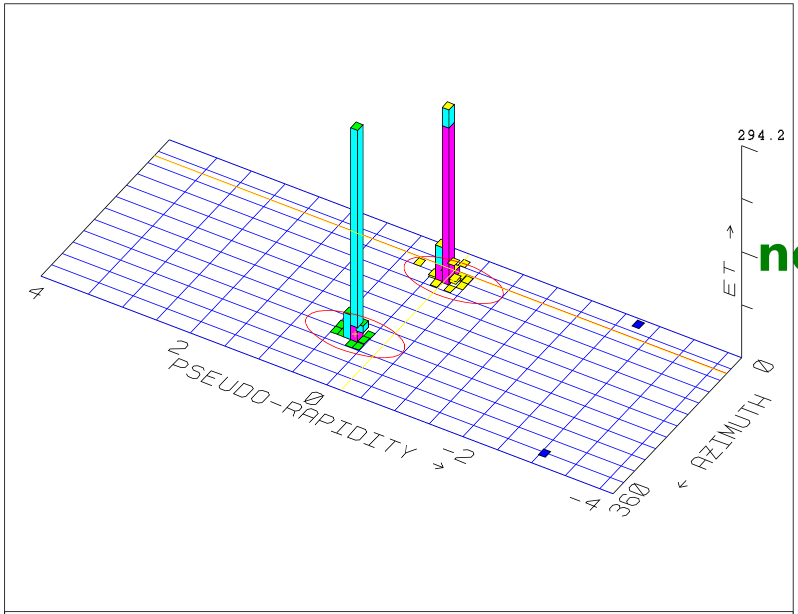
helps: calo info!

3 jet event



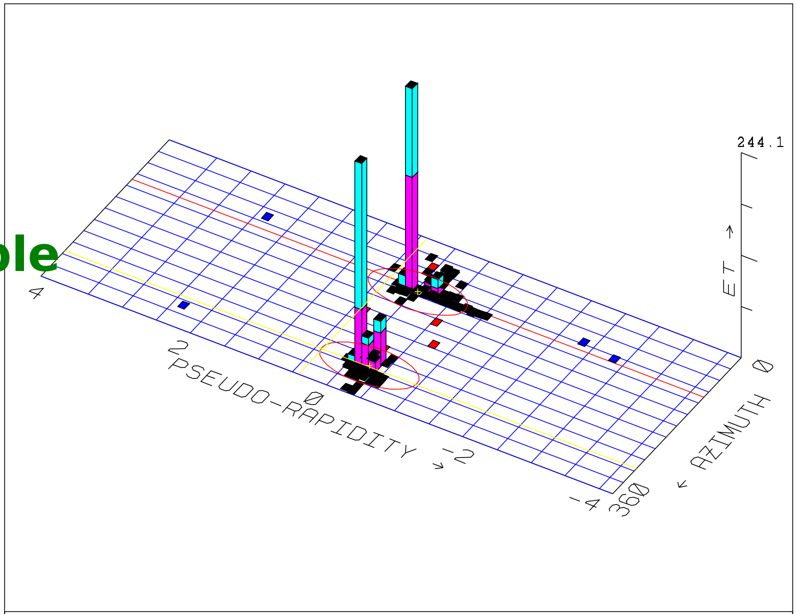


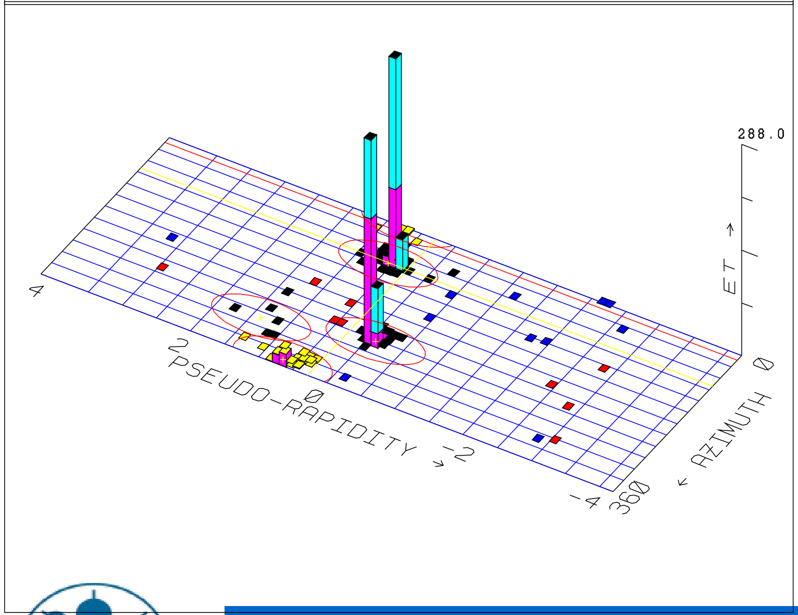
Jet Events in the CDF calorimeter



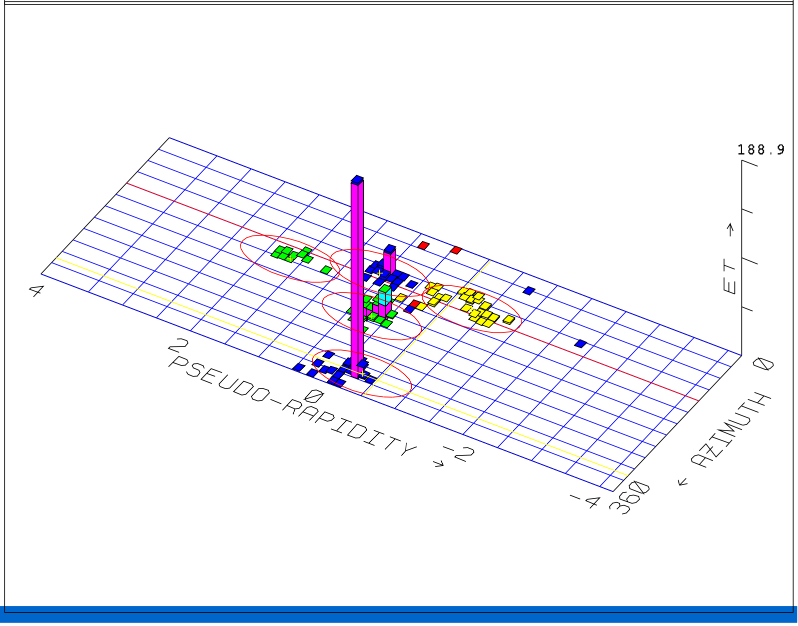
Same events as before

now jets clearly visible



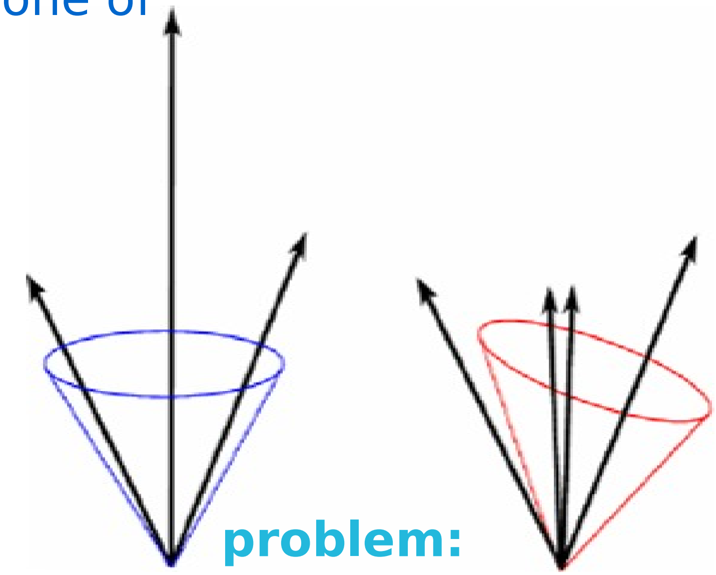


but anyway:
dont want to do this by eye, need algorithm !
many, introduce just 2 on the next pages...



Jet algorithm1: Cone algorithm

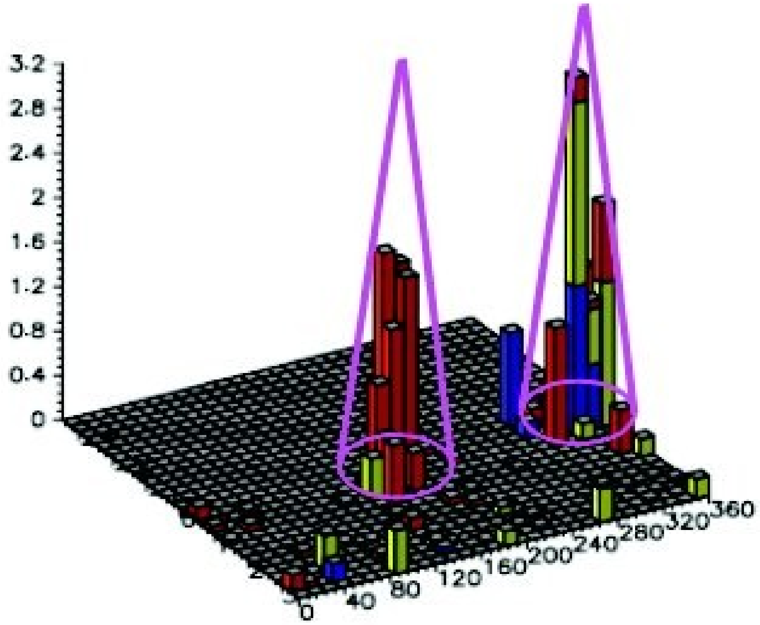
Sum over all calorimeter activities within a certain cone of radius R around a high energetic cluster



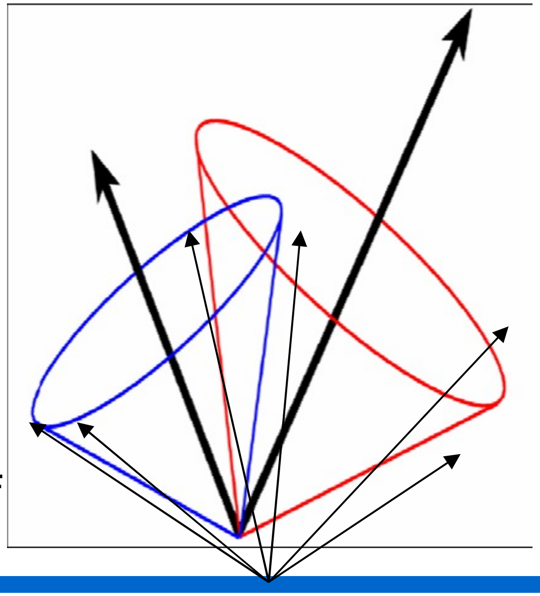
cut criteria for jet-cone:

$$R = \sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2} < y(cut)$$

y(cut) typically 0.5 … 1.0
jet definition depends on y



problem: overlapping jets



Merge or split ?

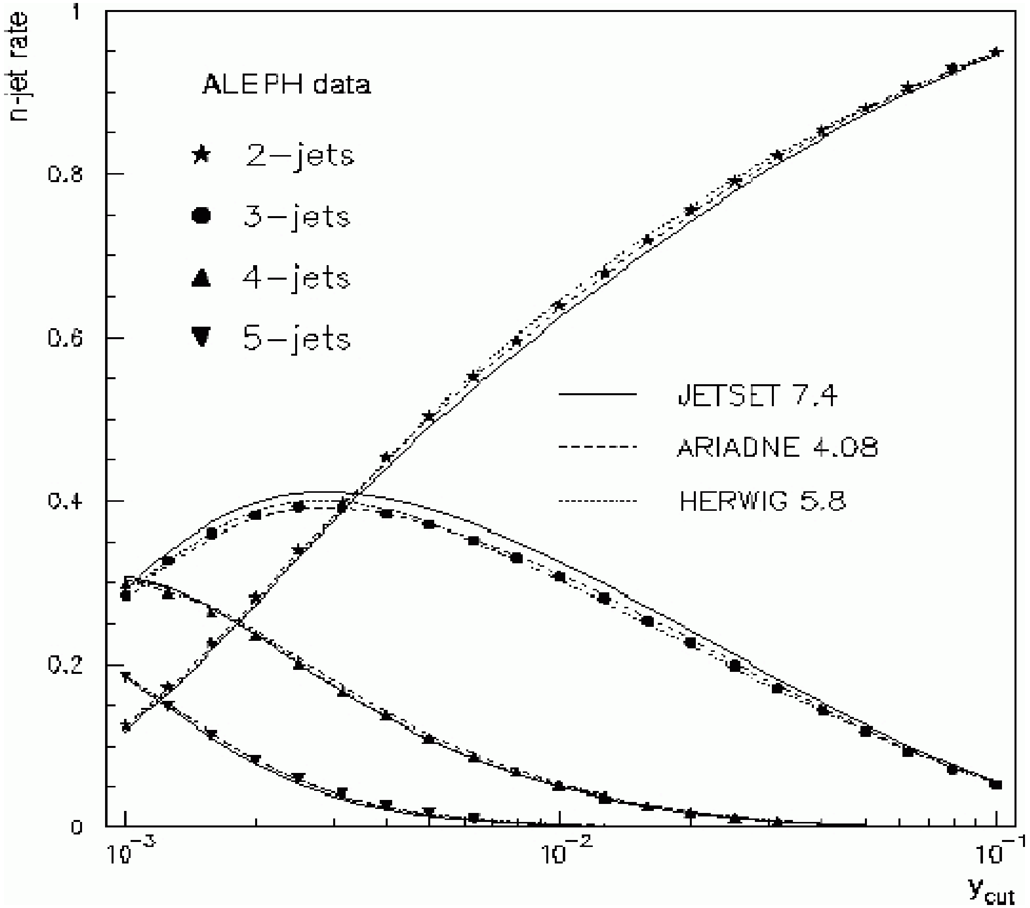
$E_{overlap}/E_{tot}$

> f   merge

< f   split

additional parameter f

Jet algorithm1: # of jets vs y-cut



Jet not well defined physical object
but depend on definition
e.g. "cone algorithm with a given y-cut"

Jet algorithm2: k_T algorithm

Make a list of all particles
(e.g. calorimeter clusters)

Calculate for each particle: $$d_i = p_{T,i}^2$$

Calculate for each pair particle:

$$d_{ij} = \min(p_{T,i}^2, p_{T,j}^2) \cdot R_{i,j}^2$$

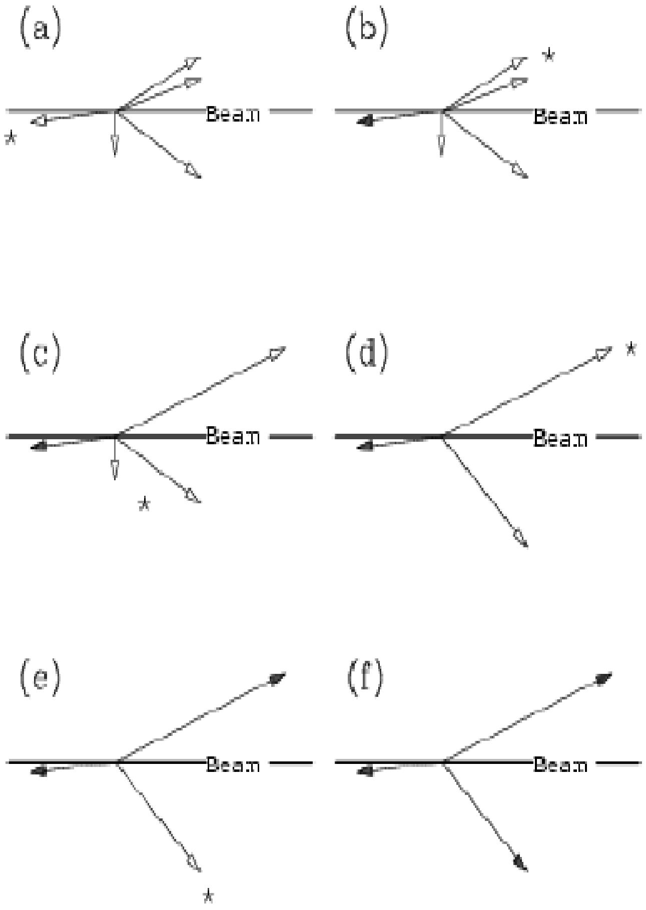
where

$$R_{i,j}^2 = (\Delta\eta_{i,j}^2 + \Delta\phi_{i,j}^2)$$

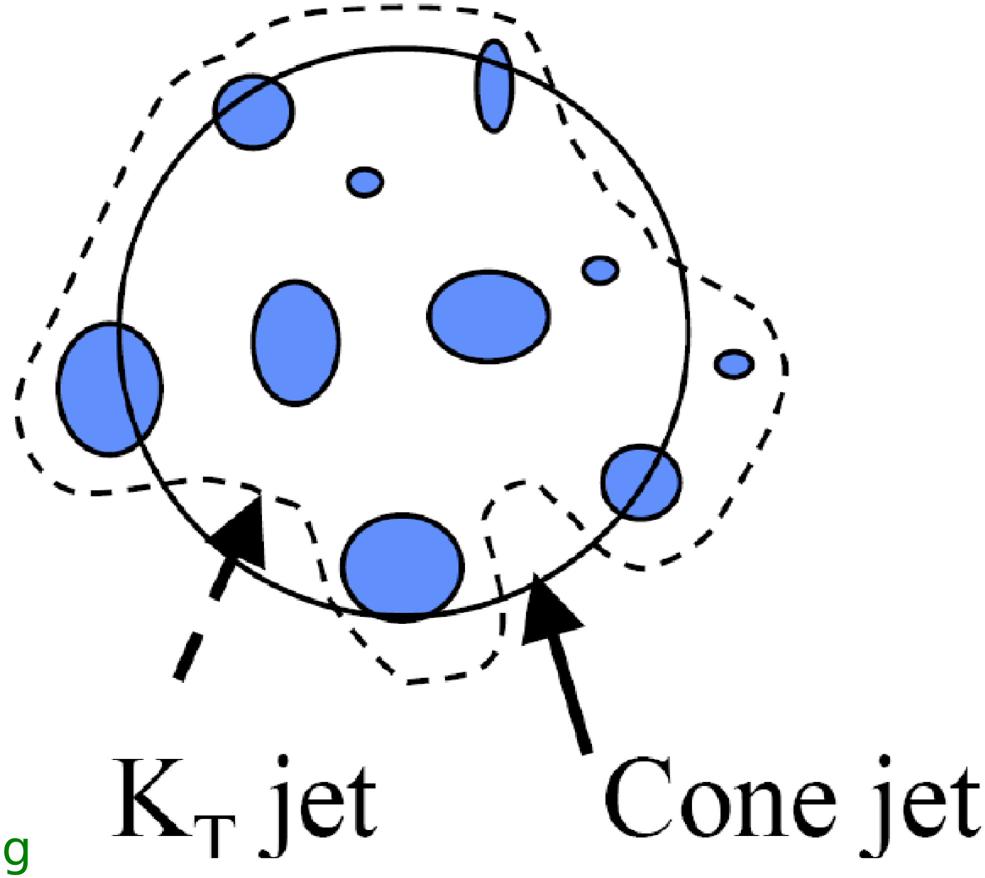
is $d_{i,j} < d_i$ **?**

Yes: add clusters i and j to the same jet
No: put cluster i on the list of new jets

repeat until the list is finished



Cone vs k_T algorithm



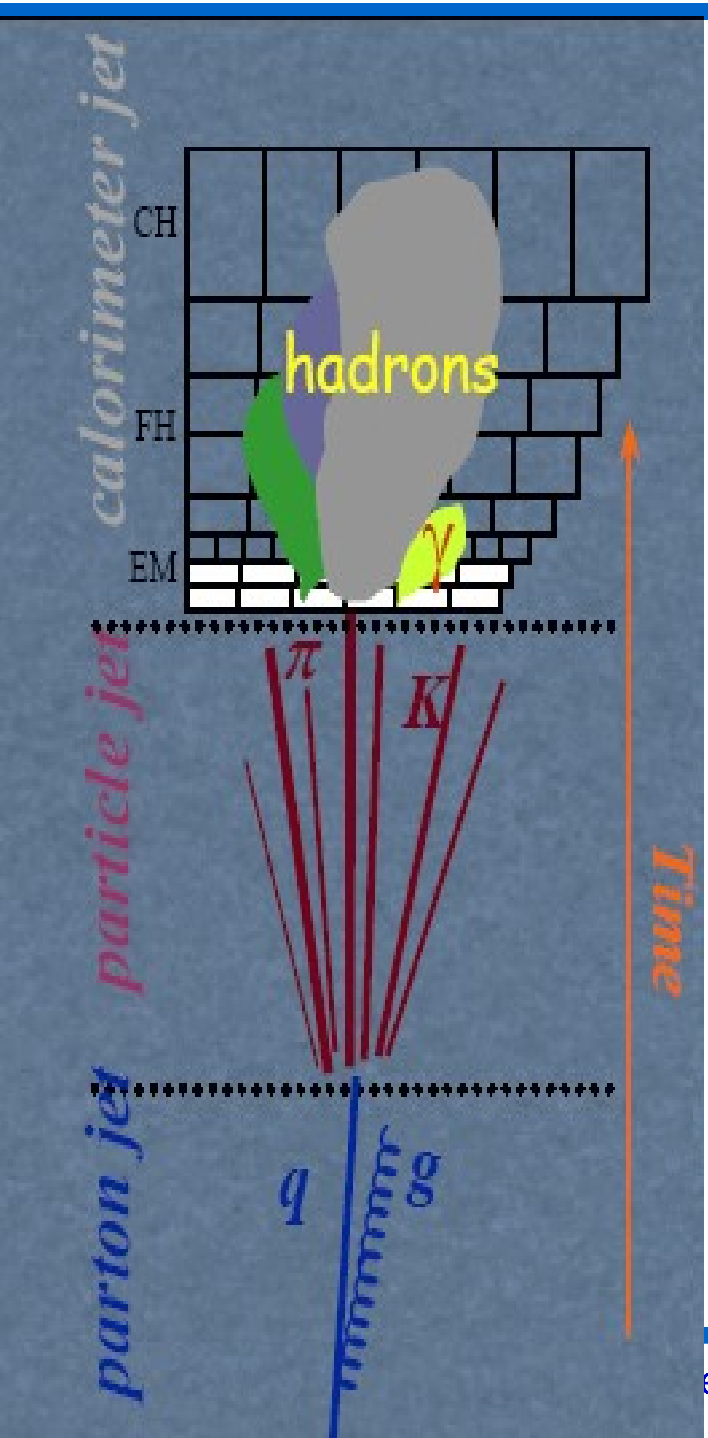
☺ unambiguous mapping particles -- jets
soft particles at edges neglected

☹ complicated boundary
(speed ~ N^3 meanwhile: implementation with ~ N lnN avaiblable, ok!)

☺ (speed)
simple shape of jets

☹ max. procedure not unique
overlap of jets

Jet Energy Scale (JES)



correct from measured energy to
energy of the jet of hadrons

take into account:

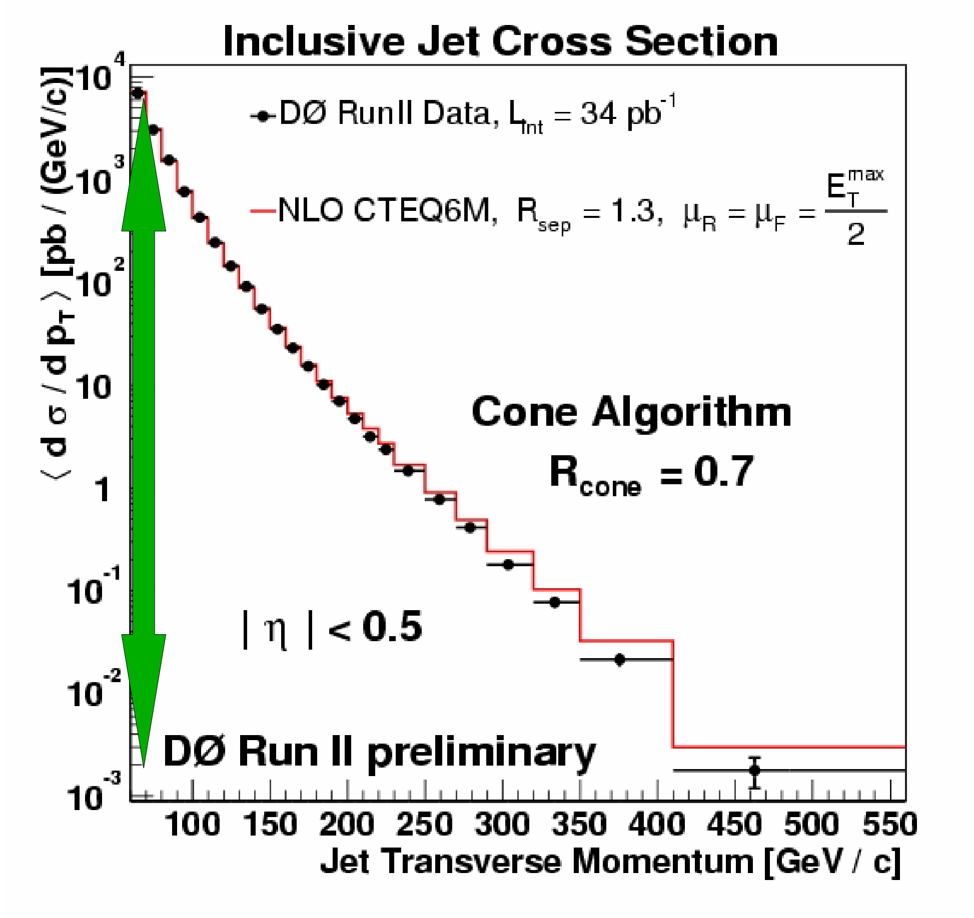
- offset due to underlying event, pile- up, ...
  subtract E, that does not belong to this jet : E_0
- leakage in/out cone of jet R_{OOC}
- calorimeter response to Jet R_{jet}
  different for electrons / photons and hadrons

$$E_{jet} = \frac{E_{meas} - E_0}{R_{jet} R_{ooc}}$$

JES = main experimental uncertainty
typical uncertainty of JES : few %

QCD jet production : example from Tevatron

Inclusive Jet spectrum as a function of Jet-P_T



data from the DØ experiment (Run II)

compared to QCD prediction

very good agreement over many orders of magnitude !

QCD jet production : example from Tevatron

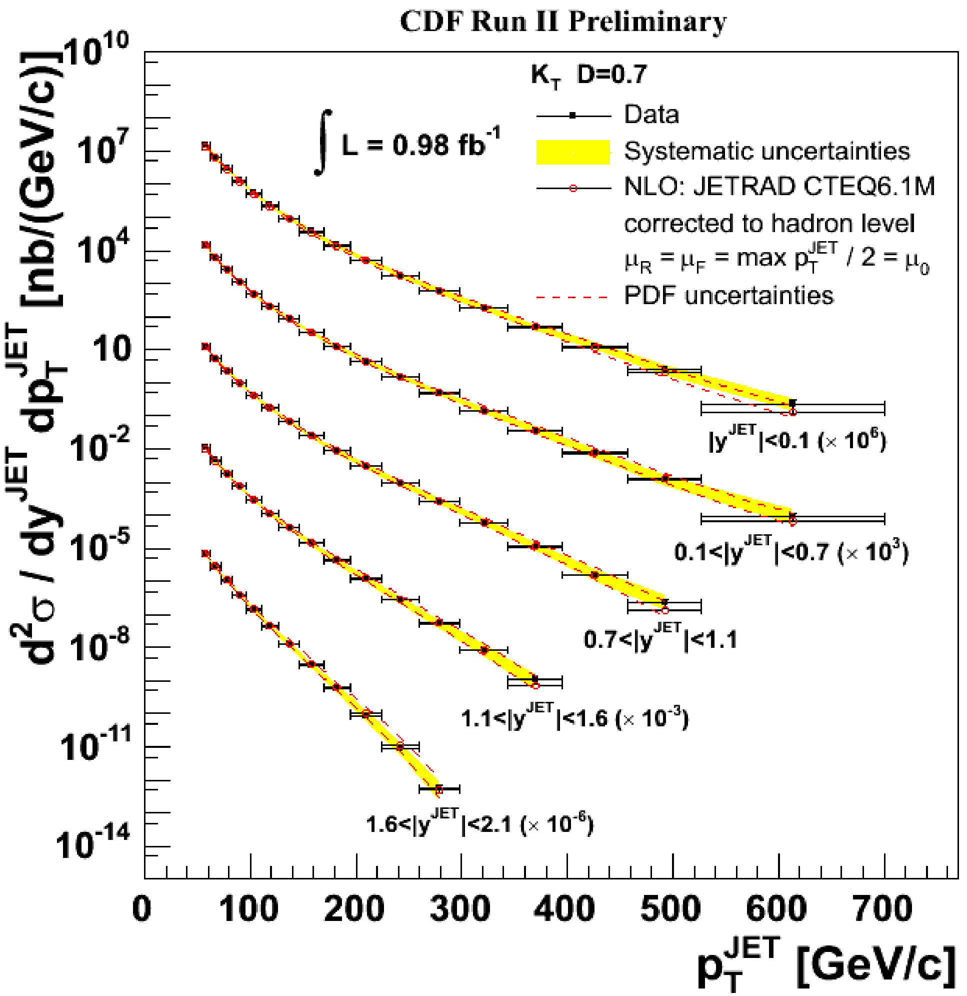
similar analysis by CDF

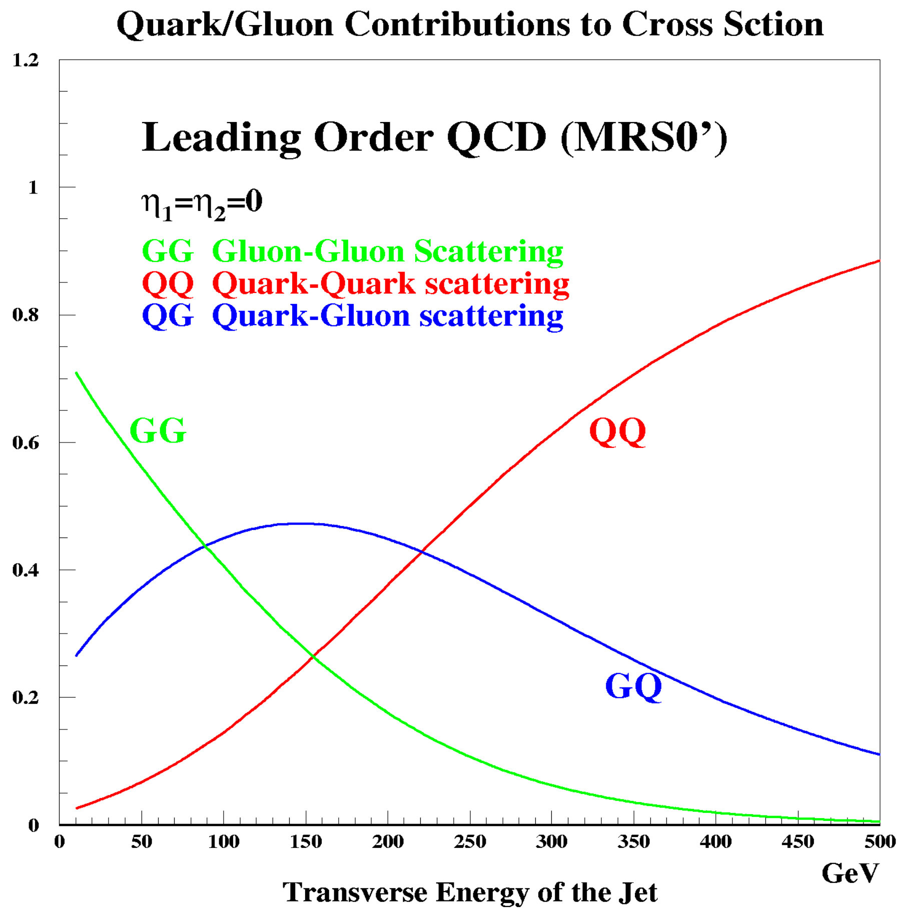
data corresponding to ~1 fb^{-1}

double differentially in P_T and η

Jets = footprints of partons ?

contributions of the various hard subprocesses to the inclusive jet cross section at different p_T^{JET}

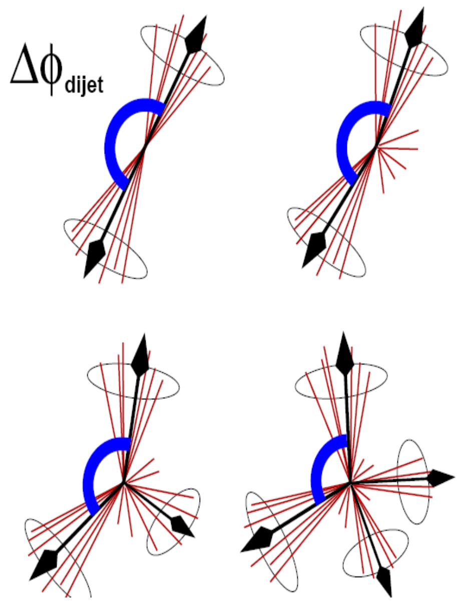


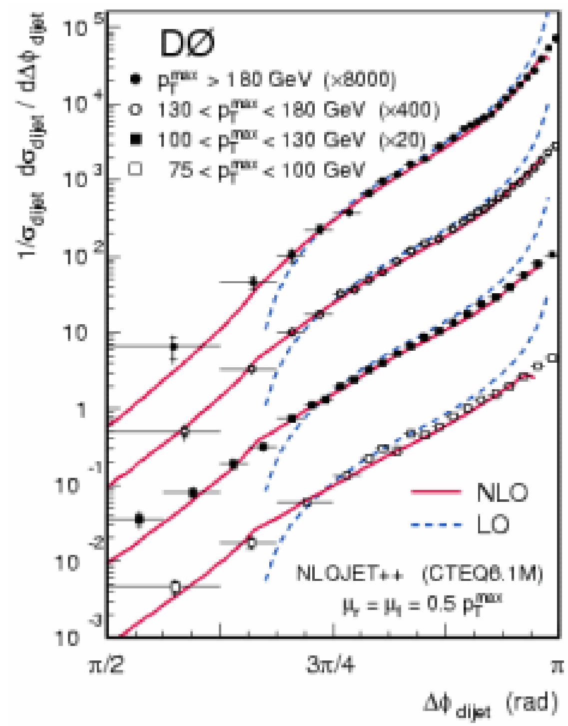


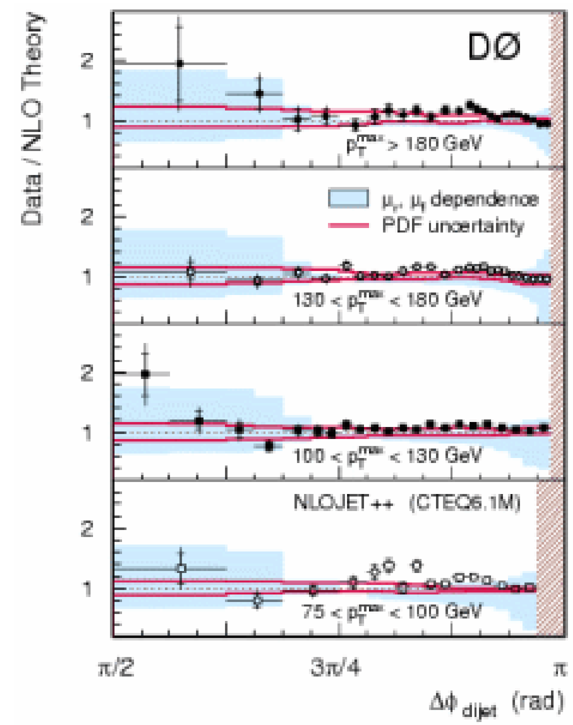
Angular correlation in di-jet events

Study angular correlations between jets

- reduced sensitivity to JES
- sensitive to higher orders of QCD
  - 2 partons - 2 jets : back- to-back $\Delta\phi = 180°$ “leading order QCD”
  - additional hard partons = “higher orders of QCD”
    not back-to-back any more! smaller $\Delta\phi$ between 2 hardest partons/jets





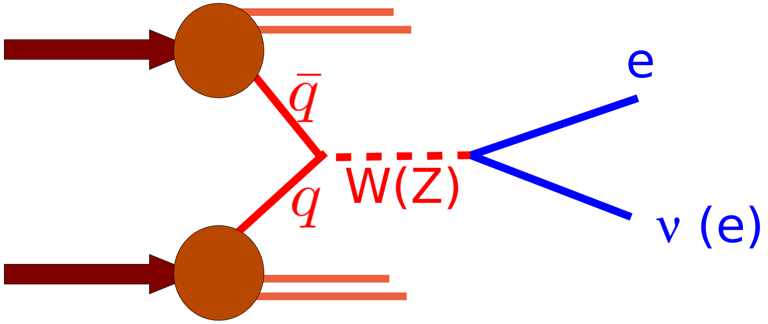


Good agreement with QCD-predictions
if higher orders are included!

W and Z bosons

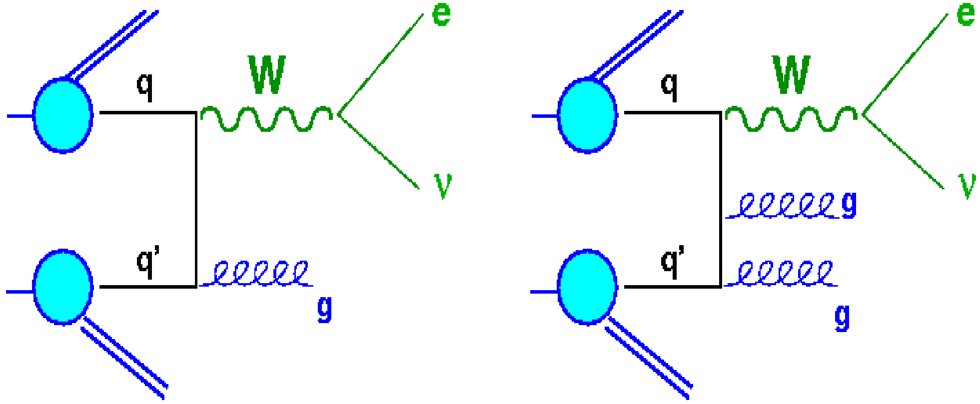
W and Z bosons

Production in Drell-Yan process



comparison of data with theory
- test of model
- test of pdf!
- pdf uncertainties!

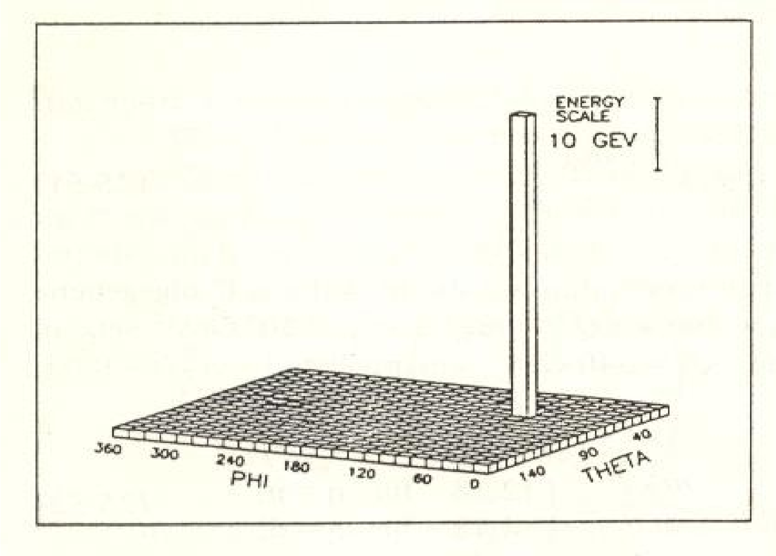
QCD production



QCD production
W(Z) + jets
W/Z = “clean” probe of hard subprocess

test of QCD

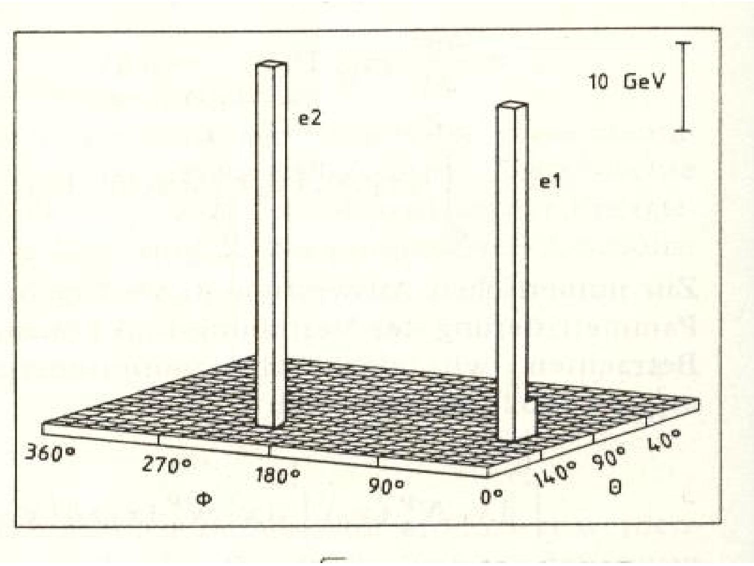
Discovery of W and Z bosons



predicted by electroweak theory
as result of Higgs mechanism
needed to explain weakness of interaction

discovery in proton-antiproton collisisions
at $Sp\bar{p}S$ at CERN by UA1 and UA2

W and Z event in UA2 experiment



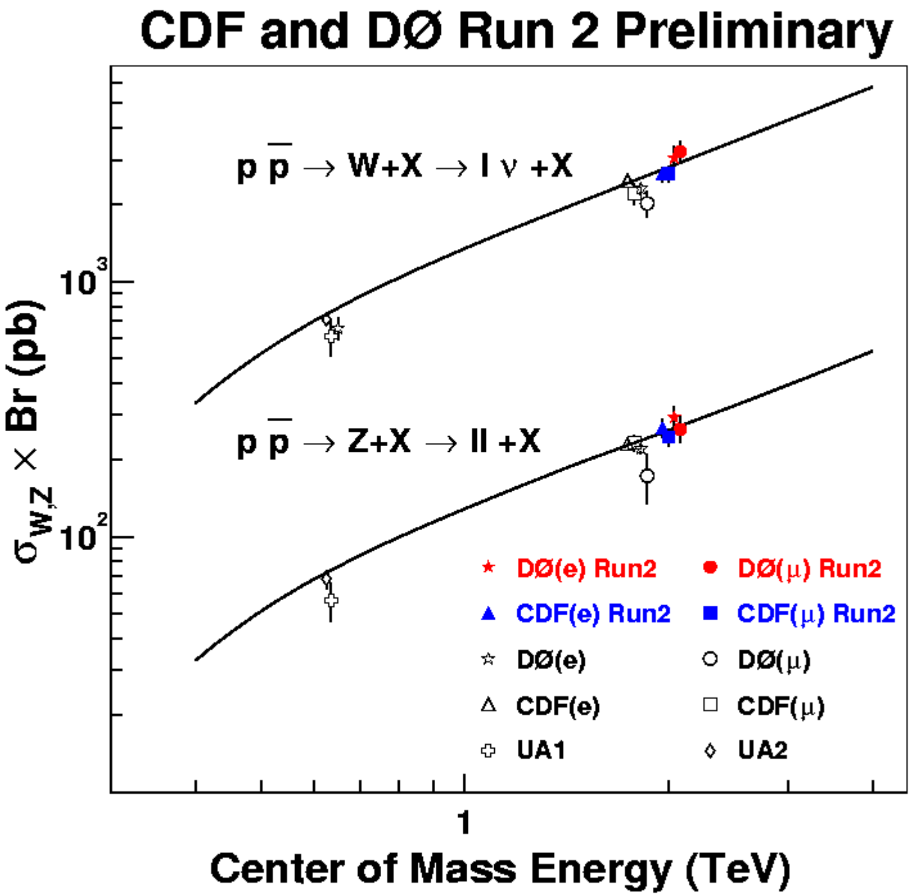
Nobel Prize 1984
Rubbia, van der Meer

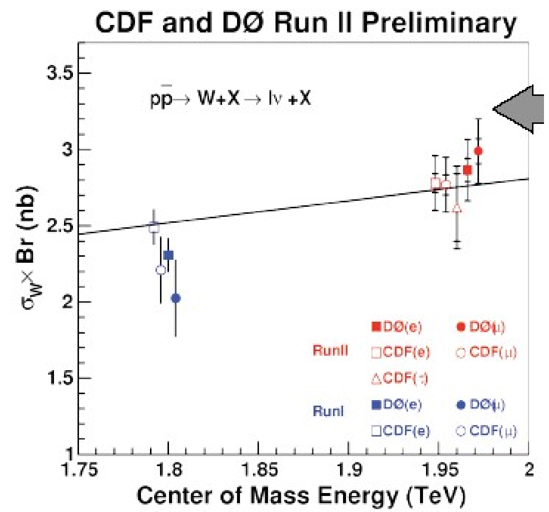
W/Z cross sectoin - comparison with theory

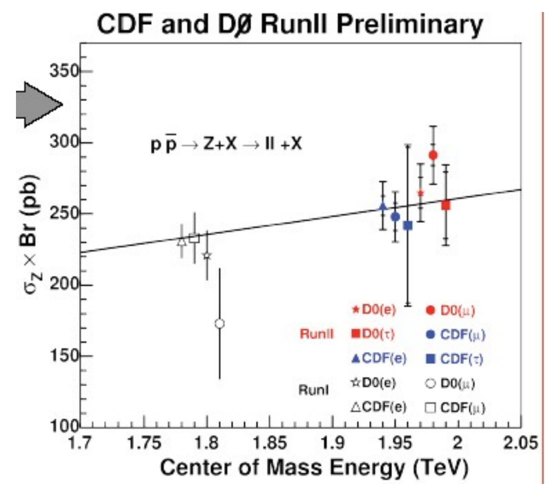
CDF and DØ at Tevatron measure inclusive cross section for

$$W \rightarrow l\nu \text{ and } Z \rightarrow ll$$

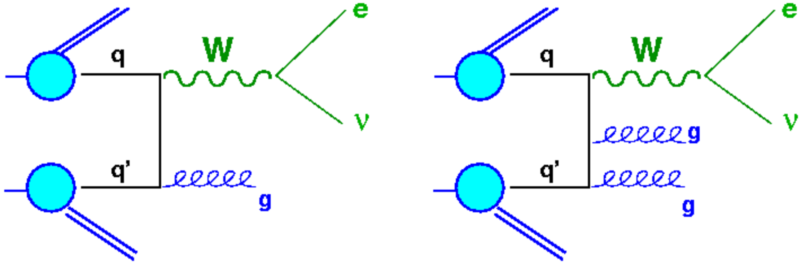
compared to theory



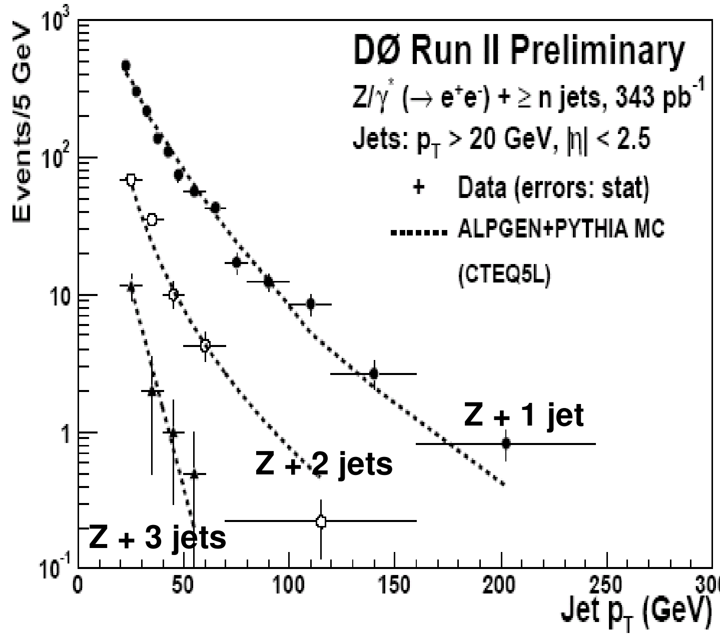




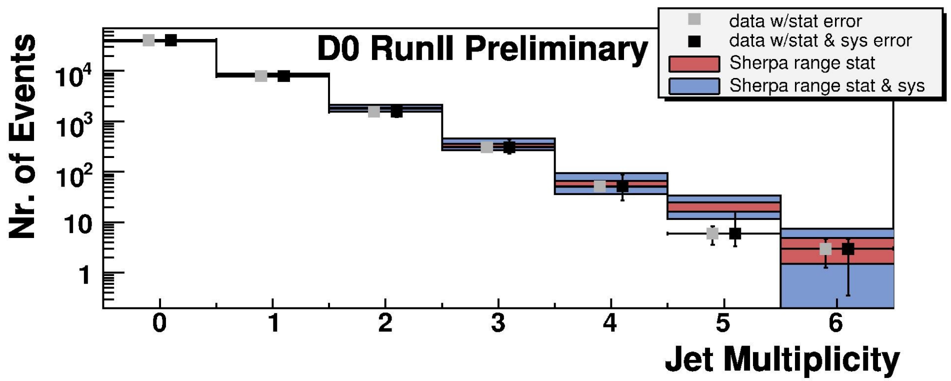
W/Z +jets = test of QCD

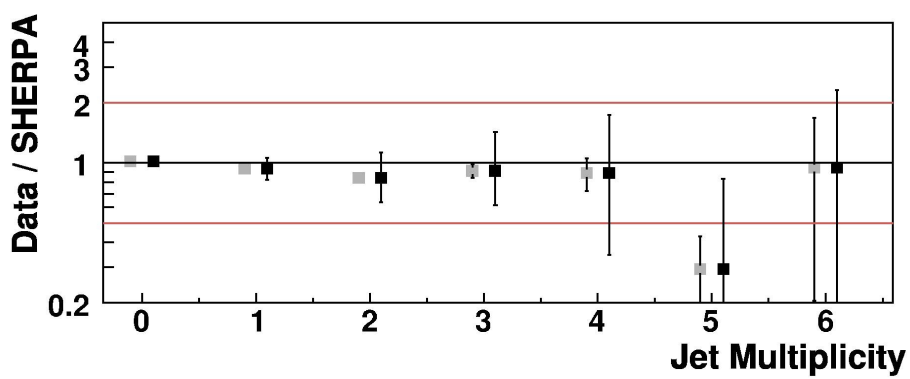


Z + jets pT distribution



Z+jets: jet multiplicity



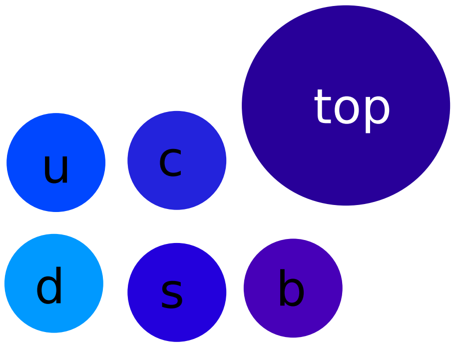


comparison with models
MC generator SHERPA

Top quark physics

Top Quark Physics

the top quark is the HEAVIEST fermion in the standard model!
... and the least well known

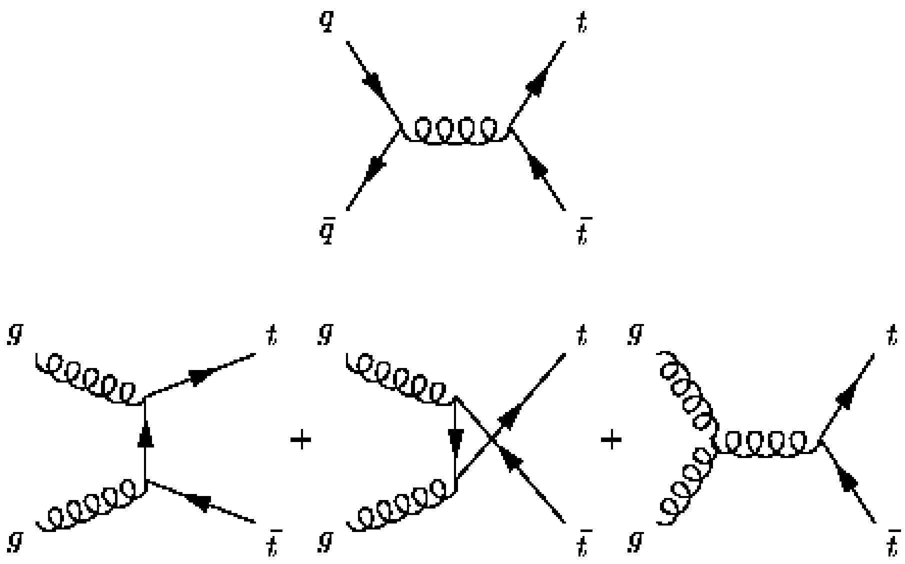


- discovered only 1995 at Tevatron: CDF and D0
- Tevatron data from RunI: consistent with SM .. so far
  statistics limited
- new Tevatron data (and LHC!) :
  better precision
  deviations from standard model ?
- Top and new physics:
  high mass – probe el. weak symmetry breaking
  and fermion mass generation
  other massive particles?
- Top at LHC: $\sigma(t\bar{t})\ 800\text{pb}$
  80 mio $t\bar{t}$ pairs per year (design Lumi)
- Background to searches for new physics

lepton masses				quark masses			[MeV]
electron	0.511	electron neutrino	0	up	5	down	8
muon	107	muon neutrino	0	charm	1500	strange	160
tau	1777	tau neutrino	0	top	**175 000**	beauty	4200

Top Production in pp collisions

Top pair production



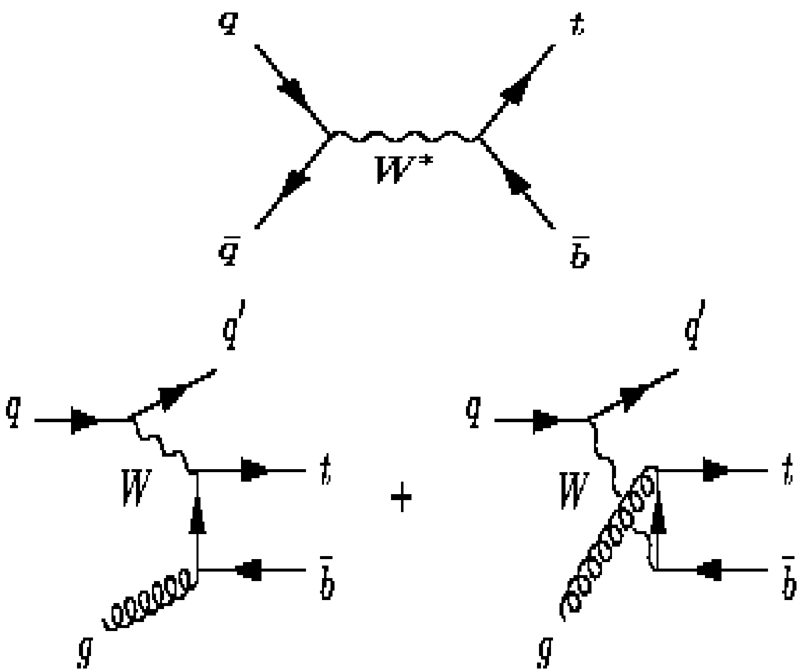
cross sections: at Tevatron ~ 5pb
at LHC ~ 800 pb

relative contribution qq-gg :

	qq	gg	
	90%	10%	at TeV
	5 %	95 %	at LHC

Single top production

Drell-Yan process and Wg fusion

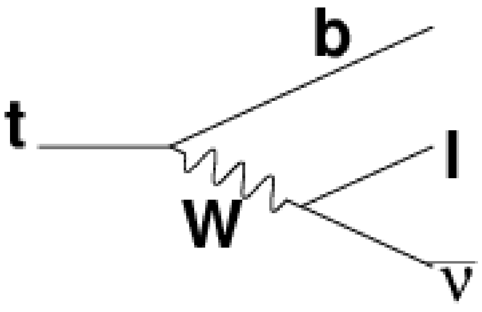


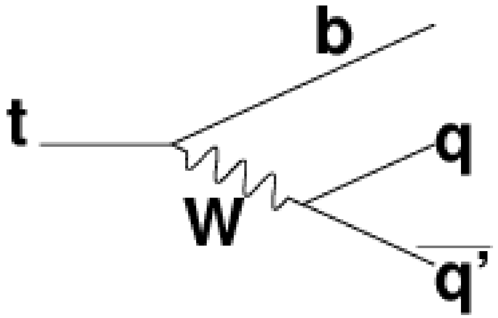
cross sections:

	Tevatron	LHC
σ (qq) (pb)	~1	10
σ (gW) (pb)	~2	250
σ (gb) (pb)	~0.1	60

Top Quark Decays

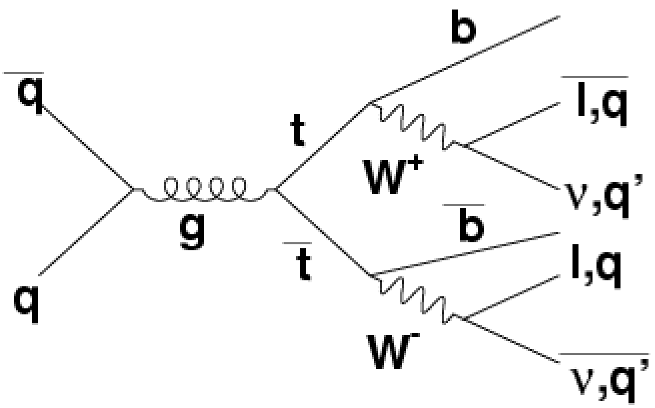
- top quark decays before it hadronises – no top mesons or baryons!
- decays to ~100 % into W bosons and beauty $t \to Wb$
  - dilepton channel
    both W decay into leptons
    $W \to l\,\nu$ l=e or μ, 5%
  - lepton + jets
    one W decays into lepton, the other hadronic
    $W \to l\,\nu$ $W \to q\bar{q}'$ l=e or μ, 30 %
  - All hadrons
    both W decay into quarks 44 %
    $W \to q\bar{q}'$

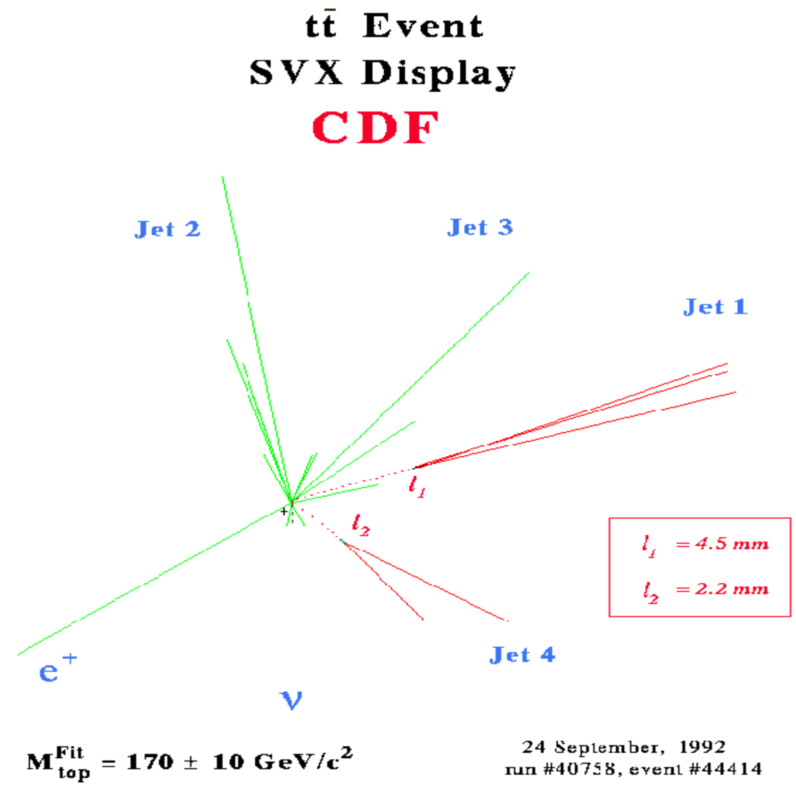




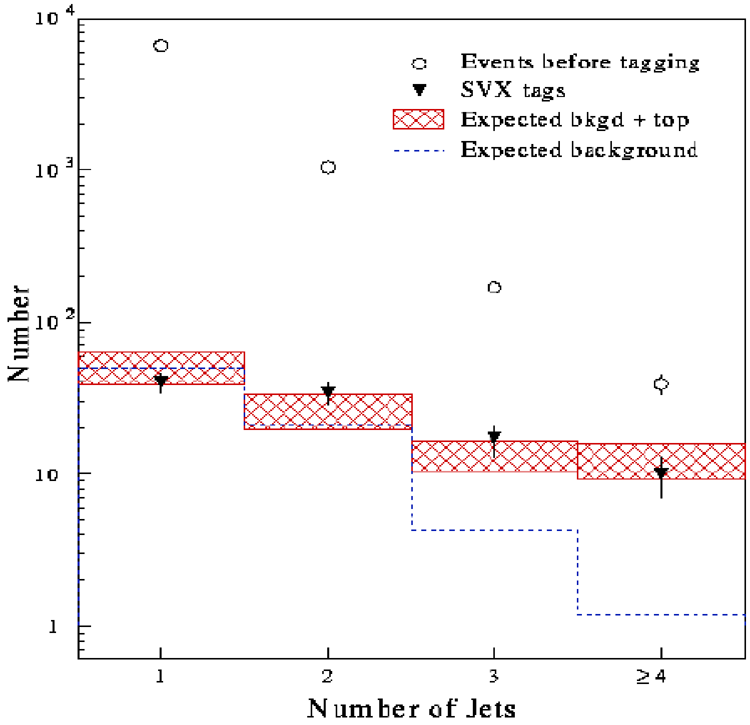
- signatures: leptons, missing ET, b-jets

Discovery of top Quark at Tevatron





b-quark lives for ~10^{-12} s
vertex displace by few mm



Njet distribution w and w/o
shifted vertex
compared to bgr+top

Discovery of top Quark at Tevatron

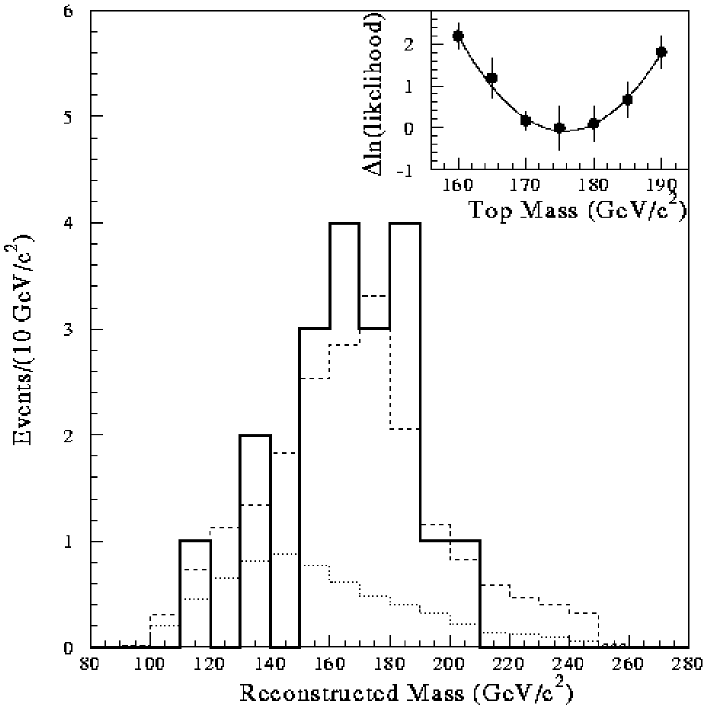
combining 3 techniques:

for lepton+jet events:
- shifted vertex of b-decay
- additional leptons from b decay

also
- dilepton events

Channel:	SVX	SLT	Dilepton
observed	27 tags	23 tags	6 events
expected background	6.7 ± 2.1	15.4 ± 2.0	1.3 ± 0.3
background probability	2×10^{-5}	6×10^{-2}	3×10^{-3}

The numbers of tags or events observed in the three channels along with the expected background and the probability that the background would fluctuate to the observed number or more.



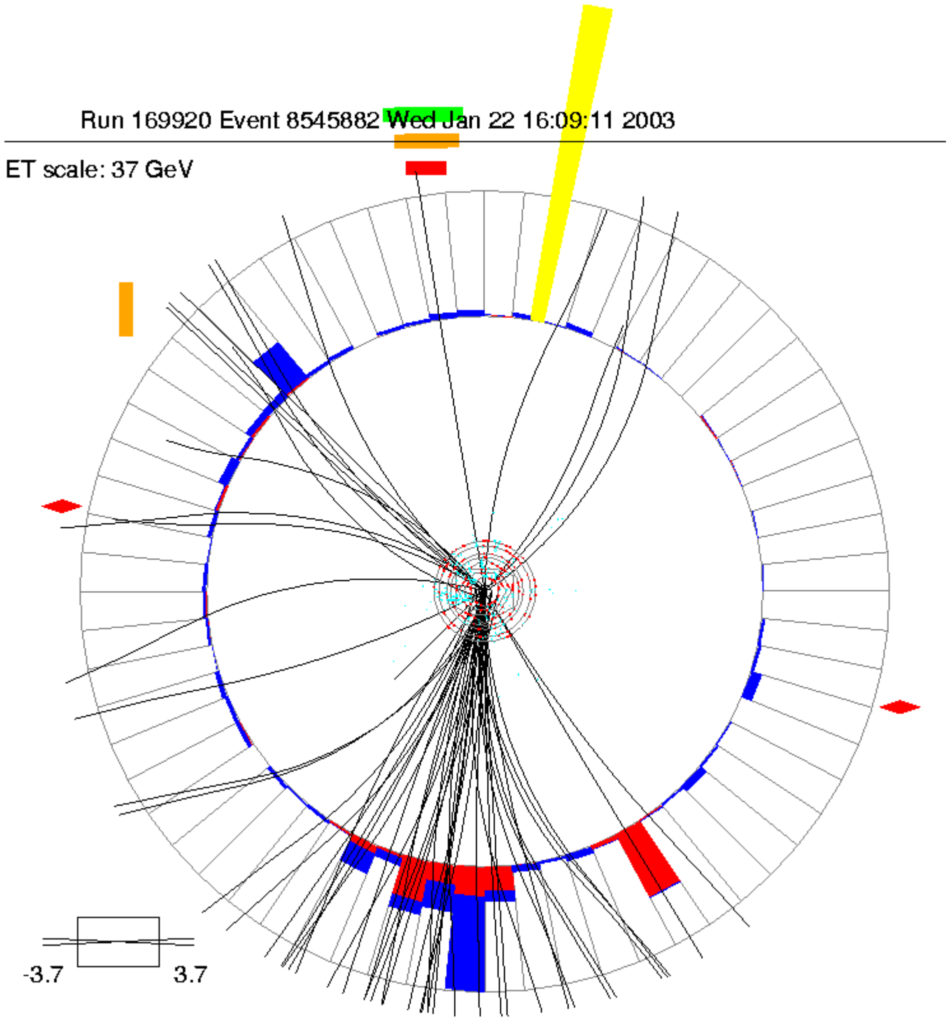
reconstructed mass of leptons + 4jets with b tag

$$M_{top} = 176 \pm 8 \pm 10 GeV/c^2$$

5 of the 6 dilepton events have a b-tag unlikely for non-t bgr!

combined bgr-probability 10^{-6}
corresponding to a 4.8 σ discovery

D0 top candidate with 2 leptons



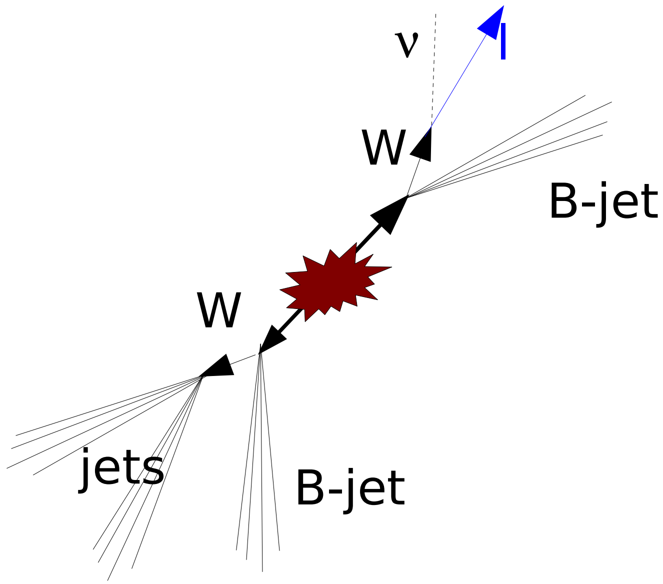
$p_T(e)$ = 20.3 GeV/c²

$p_T(\mu)$ = 58.1 GeV/c²

E_T^j = 141.0, 55.2 GeV

MET=91 GeV

tt cross section measurements at Tevatron

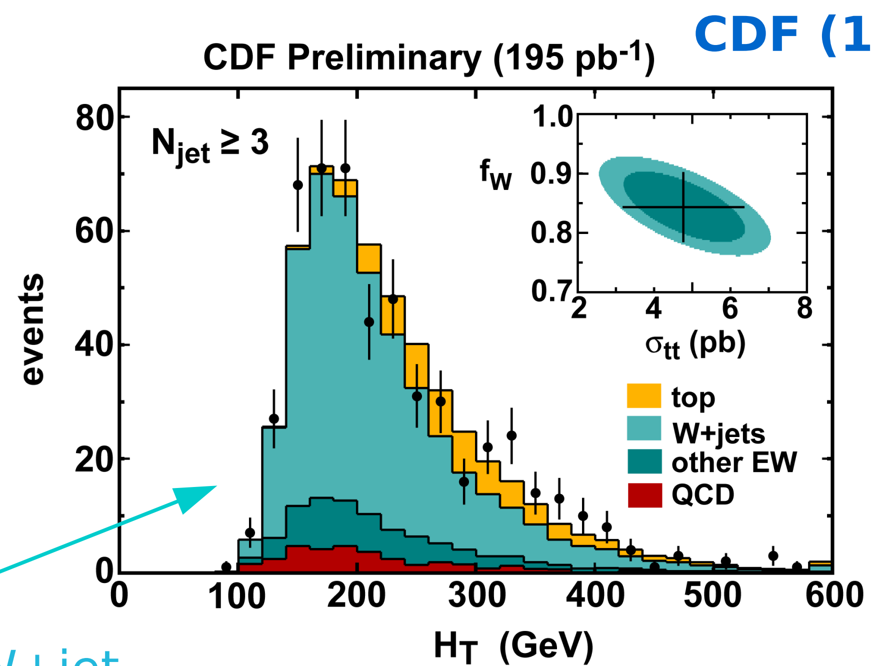


Lepton + jet channel

signature:
1 isolated high-pT lepton
large missing Et
at least 3 jets

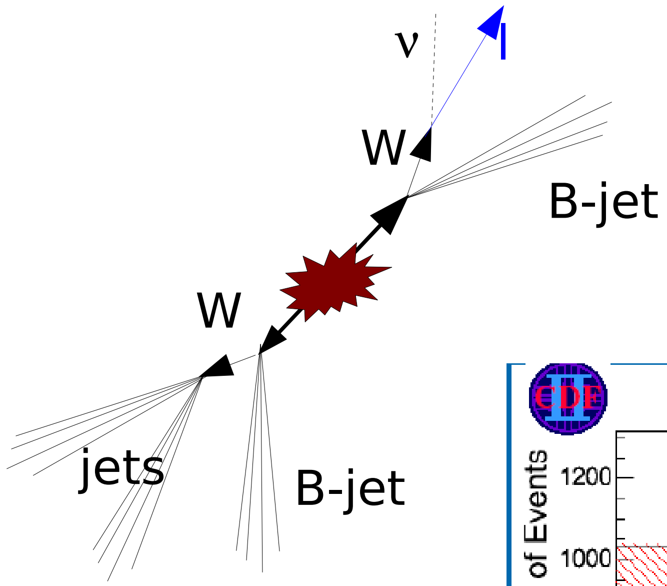
$$H_T = \sum_{jets,leptons} p_T + E_T^{miss}$$

CDF (195 pb^{-1})



background from W+jet
events can be removed
by requiring b-tags

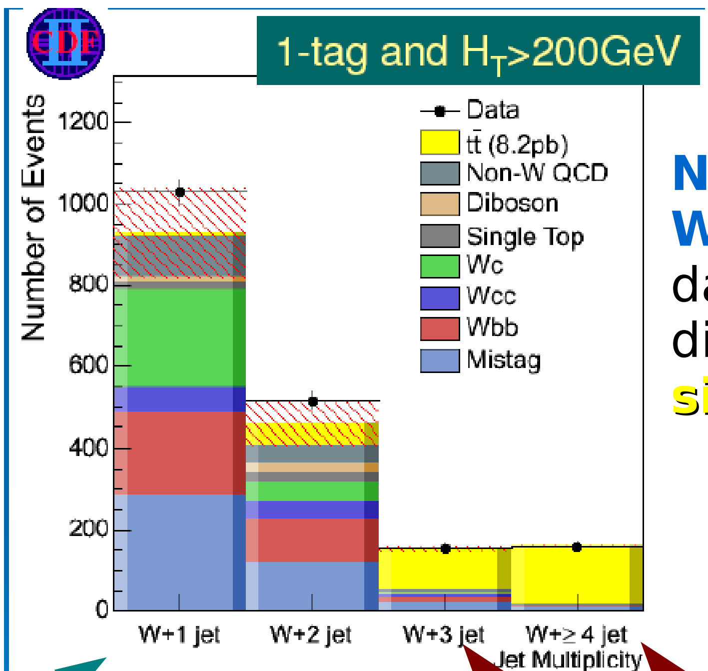
tt cross section measurements at Tevatron



Lepton + jet channel with b-tag

signature:
1 isolated high-pT lepton
large missing Et
at least 1 b-tagged jet

both CDF and D0:
b-tag using
silicon detectors

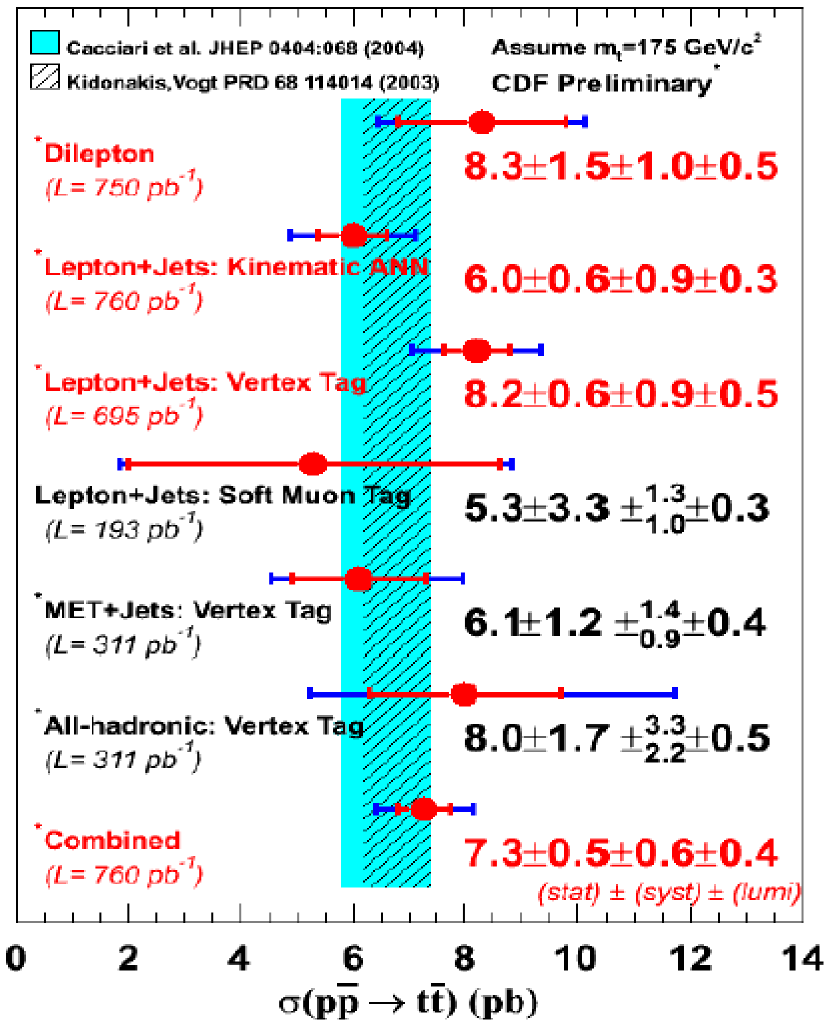


Number of Events with W+n jets:
data compared with
different MC distribution:
signal top MC and bgr MCs

W+1jet, W+2 jet :
control region
sum of bgr describes data

W+3 and more jets:
signal region, top enriched
very clean sample!

tt cross section measurements at Tevatron



Good agreement of different measurements and with QCD prediction (similar results for DØ)

Precision measurements of the W boson and top quark mass

Precision measurement of W and top mass

m_W

m_{top}

fundamental parameters of the standard model
relation between m_t, m_W and m_{Higgs}

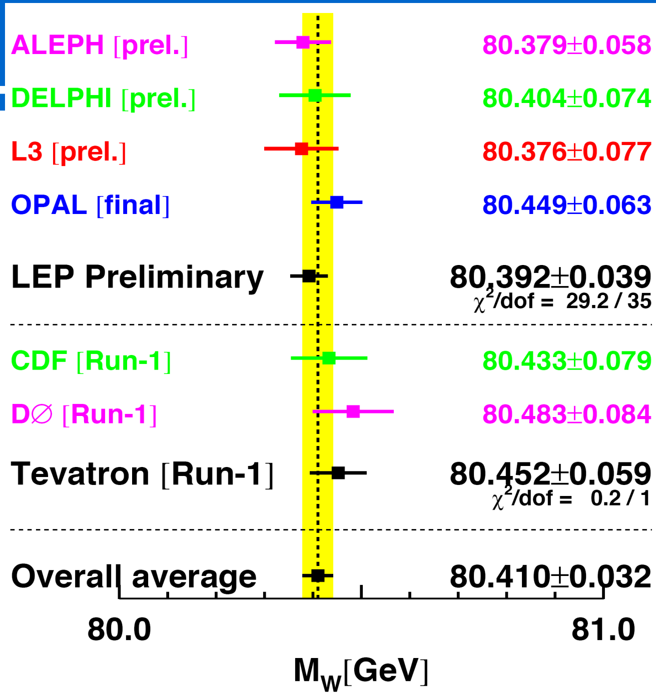
$$m_W = \left(\frac{\pi\alpha_{em}}{\sqrt{2}G_F}\right)\frac{1}{\sin\theta_W\sqrt{1-\Delta r}}$$

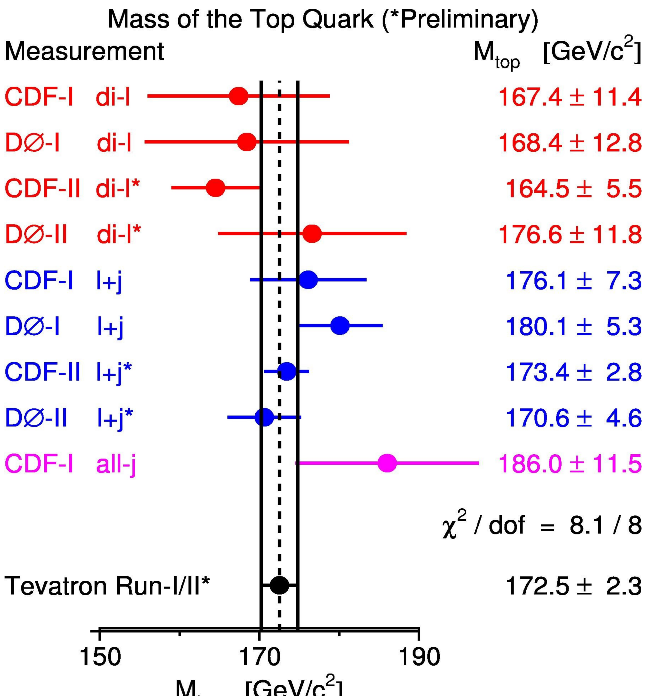
$\Delta r \;\; m_t^2 \text{and} \log m_H \;\; 3\%$

Fermi constant, α_{em} and weak mixing angle known precisely
(from muon decay, e+e-or atomic trans., LEP)

precise measurement of
m_W and m_{top} : constraints on Higgs mass
m_W, m_{top} and hopefully also m_{Higgs} : ultimate test of SM !!

Todays precision



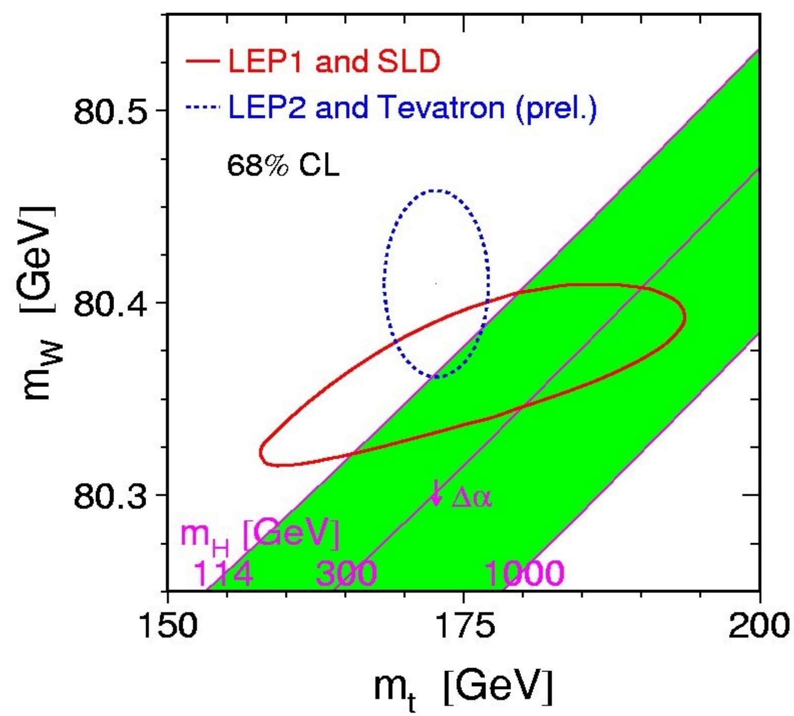


M_w (from LEP and Tevatron) = 80.410 ± 0.032

m_t (from Tevatron) = 172.5 2.3 GeV

precision : M_w : 4 ·10-4 and m_t : 1.4%

Constraining the Higgs mass…



How can W mass be measured?

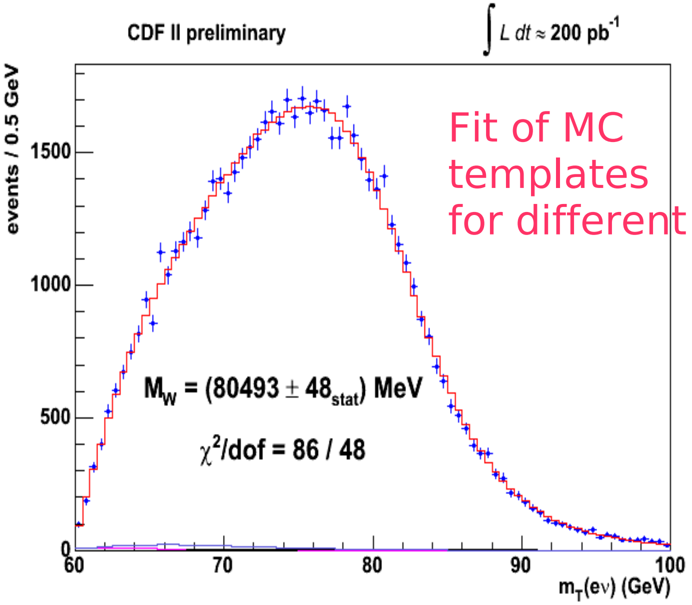
Decay $W \to \nu e \text{ and} W \to \nu\mu$

missing Et and lepton ID

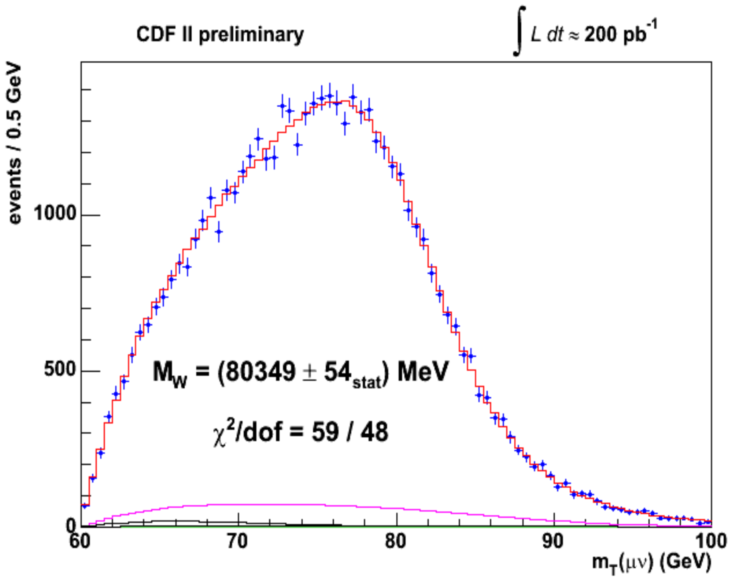
Use $p_T(e)$ and $p_T(had)$

$$p_T^\nu = -(p_T(e) + p_T(had))$$
$$M_W^T = \sqrt{2 \cdot p_T^l \cdot p_T^\nu \cdot (1 - \cos\Delta\phi(l,\nu))}$$

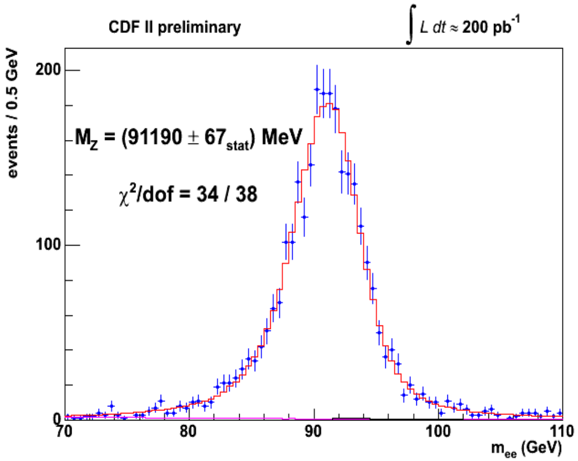
Transverse mass for eν and μν



Fit of MC templates for different Mw



Energy scale calibration using Z peak



Expected precision from future data

Sources of uncertainties and their expected contribution:

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**

- expected :

total error (per lepton flavor, experiment) at LHC ±25MeV
total error at Tevatron ± 34 MeV

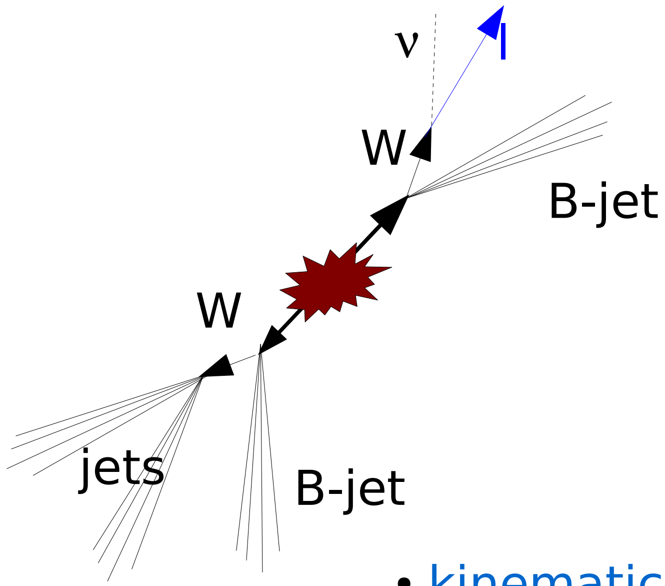
main uncertainty: lepton energy scale
systematic uncertainties – estimated by using $Z \to ll$ sample

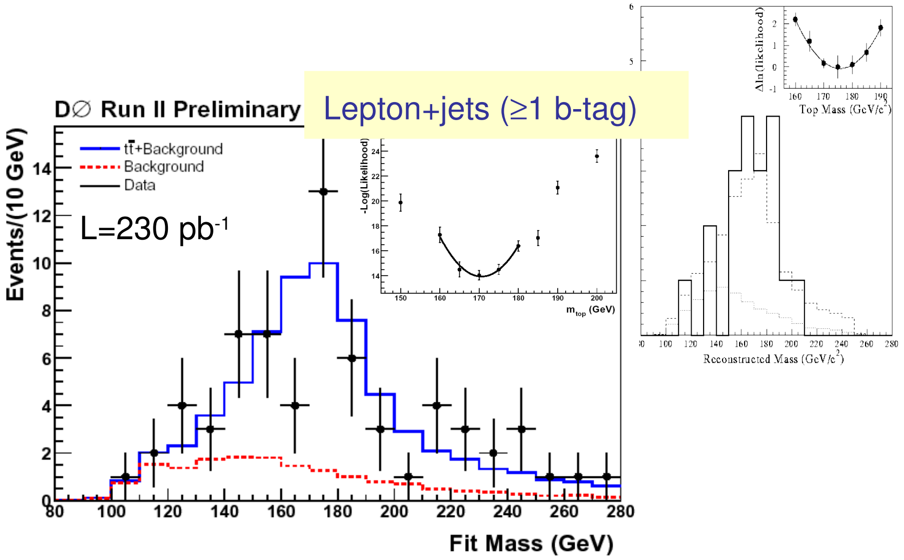
- combining ATLAS and CMS, 10 fb-1 each, e and μ and

assuming a lepton energy scale uncertainty of ± 0.02% will be reached
precision could be **Δm_W ~ ± 15 MeV**

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

How can top mass be measured?





- kinematic fit under tt-hypothesis (each event)
- likelihood for observed events as function of top mass
- -log(likelihood) has minimum at most likely top mass

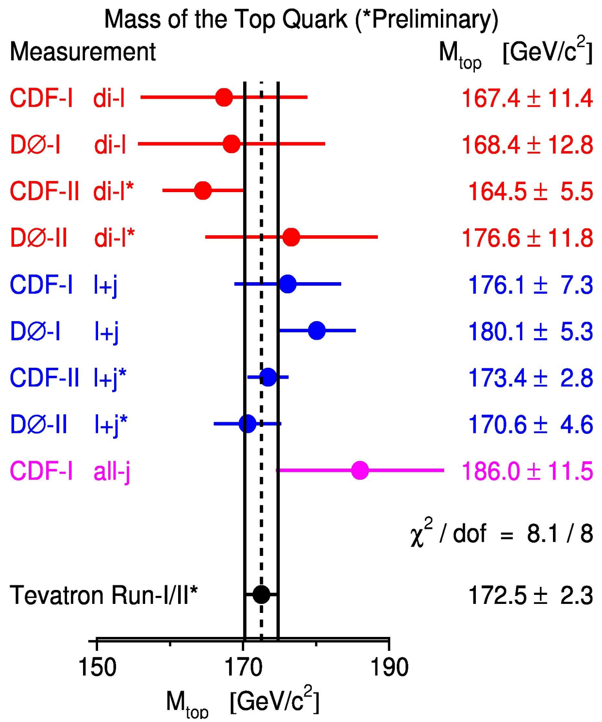
Measurements from D0 and CDF:

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

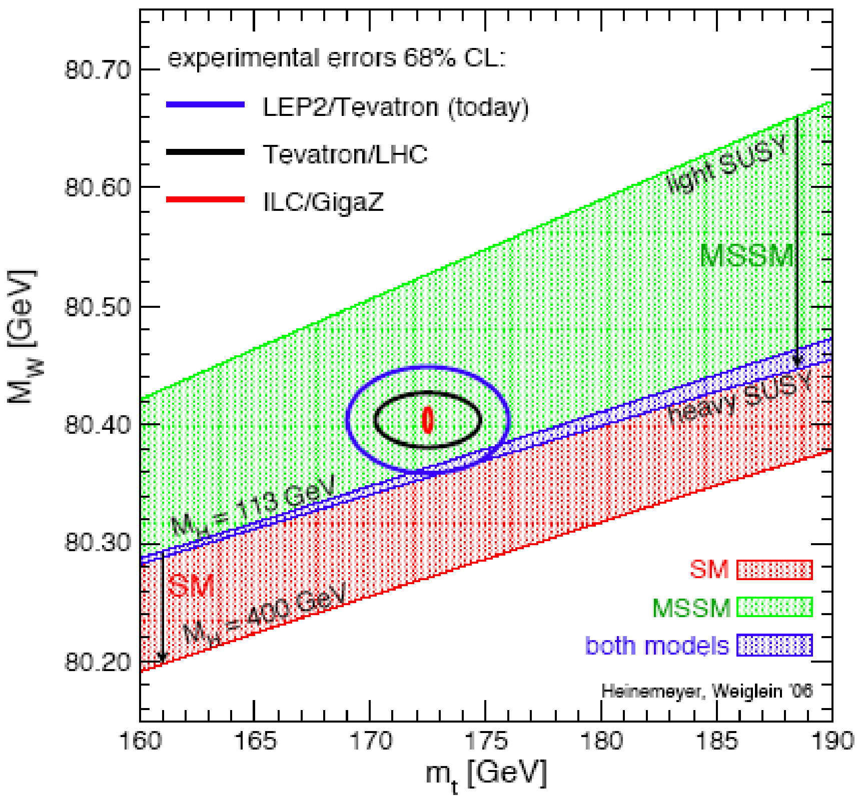
m_{top} = 170.6 ±4.4 (stat+JES) ± 1.4 (syst) GeV/c^2 (DØ)

statistical and JES uncertainty dominant error

Expected precision from future data



expected constraints on M_H:



current value 172.5 ± 2.4 GeV
Precision expected from full Tevatron data set: ± 1.5 GeV
expected precision with 10 fb-1 LHC data : ±~ 1 GeV

Summary

• Hadron colliders can provide future tests of the standard model

predictions of Quantum chronodymaics can be tested with
jets, W/Z boson production, top quark production

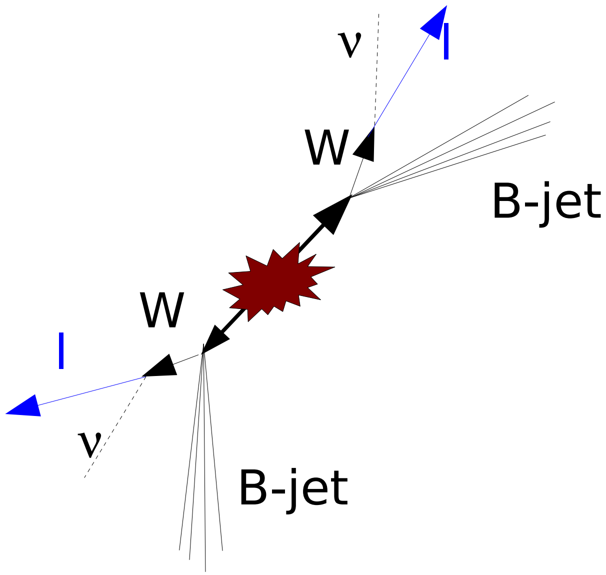
• also precise measurements of standard model parameters

W mass ~ 15 MeV

top quark mass ~ 1 GeV

providing indirect constraints on the Higgs mass (of ~25%)

tt cross section measurements at Tevatron



dilepton channel

signature:
2 isolated high-pT leptons from W decays
large missing Et
at least 2 jets