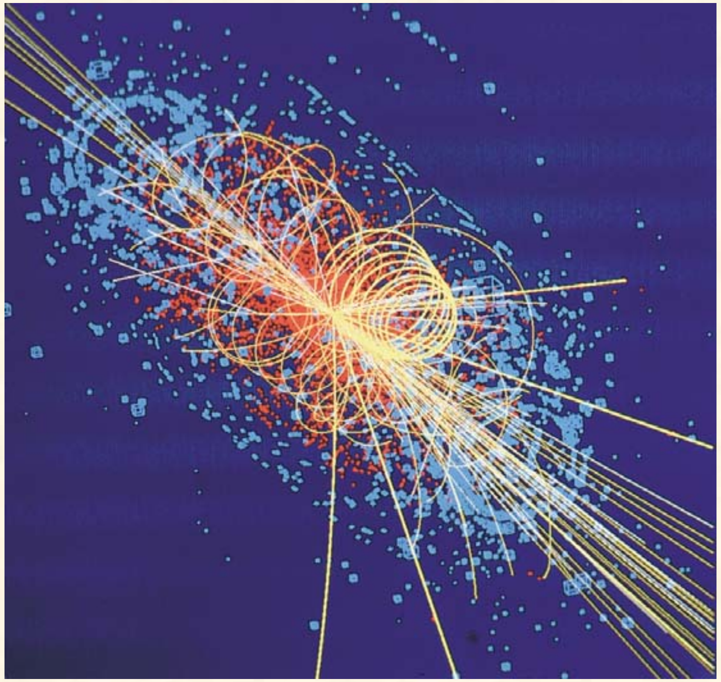
Physics at Hadron Colliders

Part 2

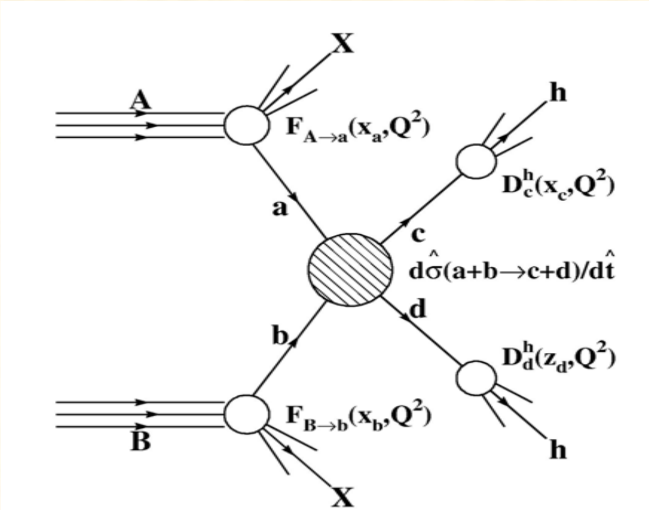


Standard Model Physics

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

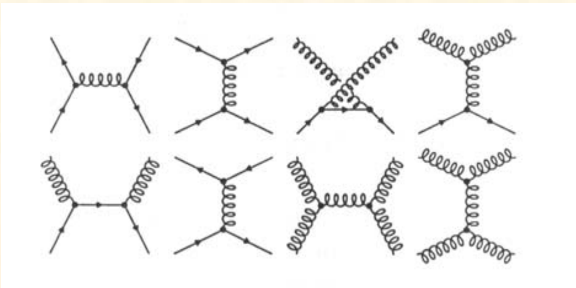
Electroweak measurements
- W mass
- Top-quark mass and other properties
- Single top production

QCD processes at hadron colliders

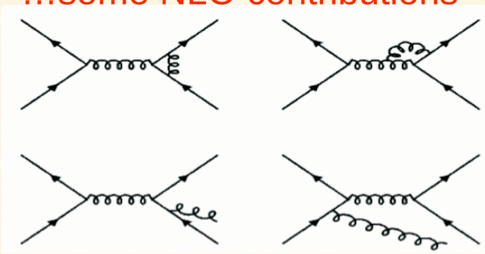


- Hard scattering processes are dominated by QCD jet production
- Originating from qq, qg and gg scattering
- Cross sections can be calculated in QCD (perturbation theory)

Leading order



…some NLO contributions



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

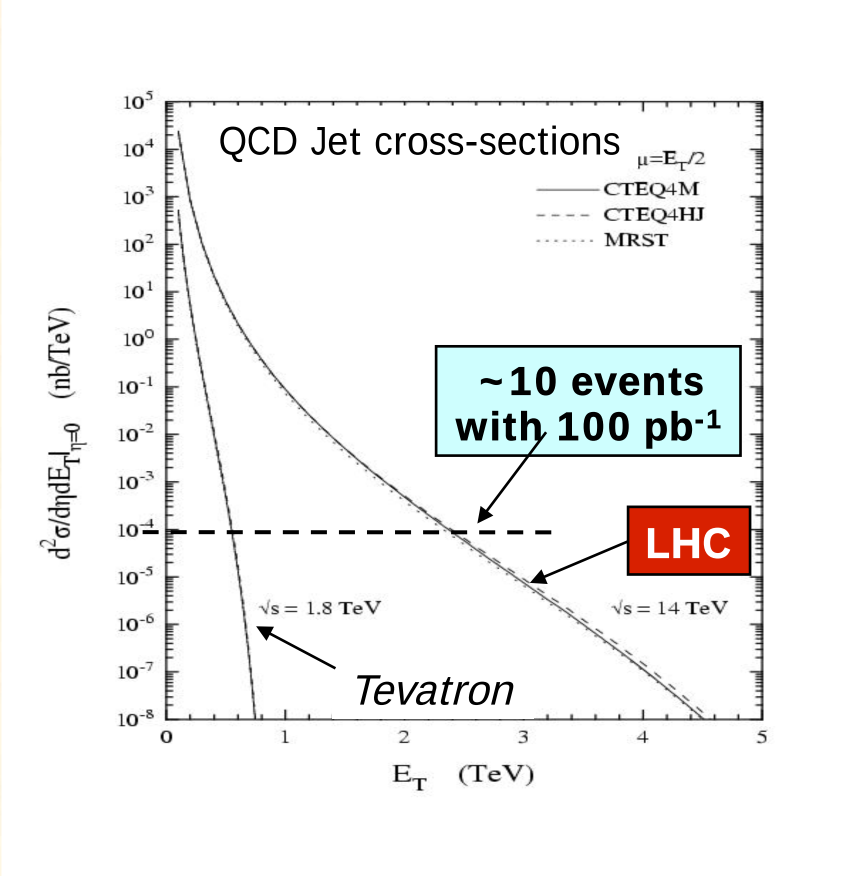
Deviations?
→ Problem in the experiment ?
Problem in the theory (QCD) ?
New Physics, e.g. quark substructure ?

Jets from QCD production: Tevatron vs LHC

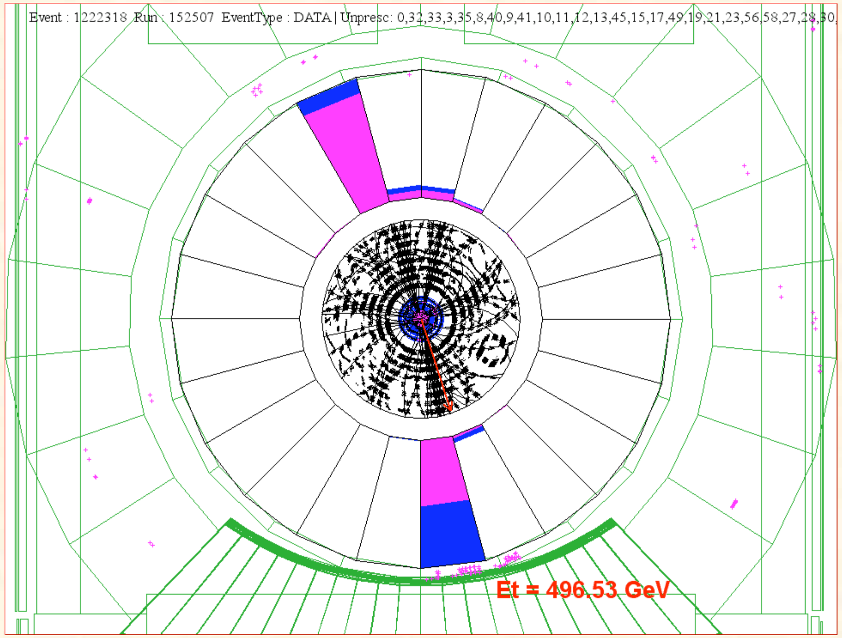
- Rapidly probe perturbative QCD in a new energy regime (at a scale above the Tevatron, large cross sections)

- Experimental challenge: understanding of the detector
  - main focus on jet energy scale
  - resolution

- Theory challenge:
  - improved calculations…
    (renormalization and factorization scale uncertainties)
  - pdf uncertainties

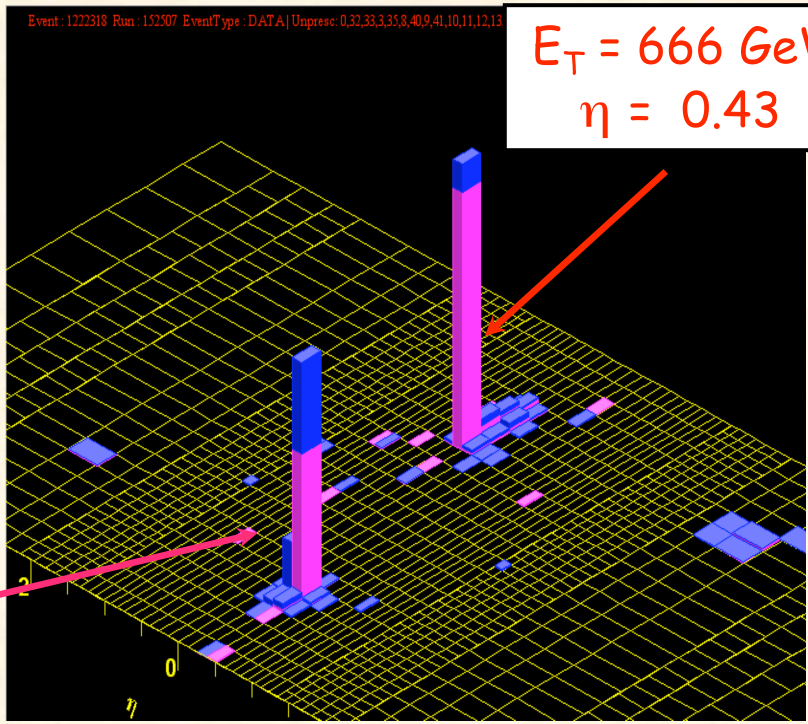


A two jet event at the Tevatron (CDF)



CDF (φ-r view)

Dijet Mass = 1364 GeV/c^2



E_T = 666 GeV
η = 0.43

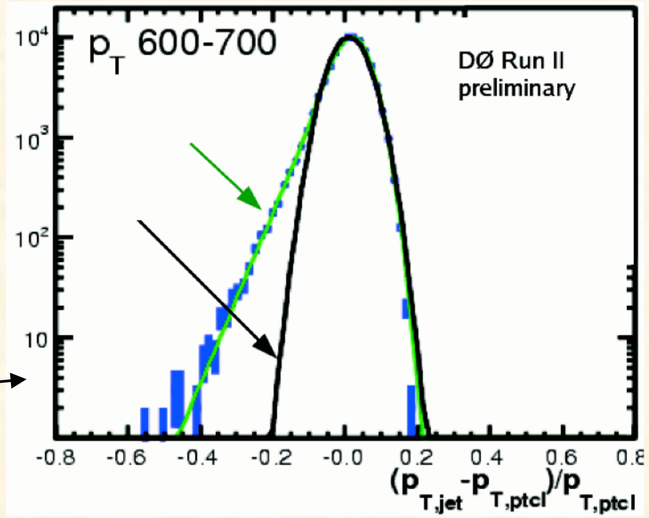
E_T = 633 GeV
η = -0.19

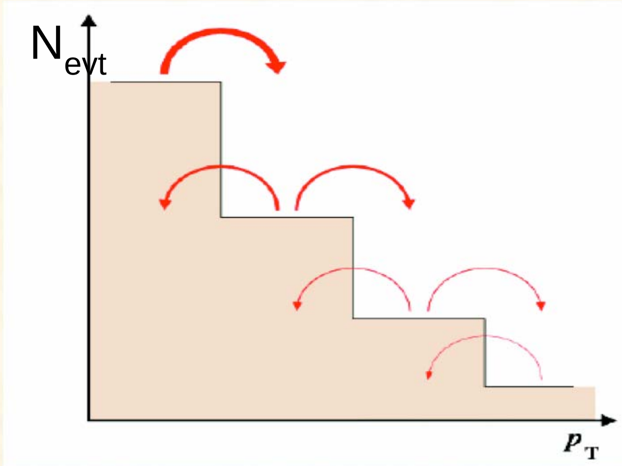
Jet measurements

$$d^2\sigma / dp_T\, d\eta \;=\; N \;/\; (\varepsilon \cdot L \cdot \Delta p_T \cdot \Delta\eta)$$

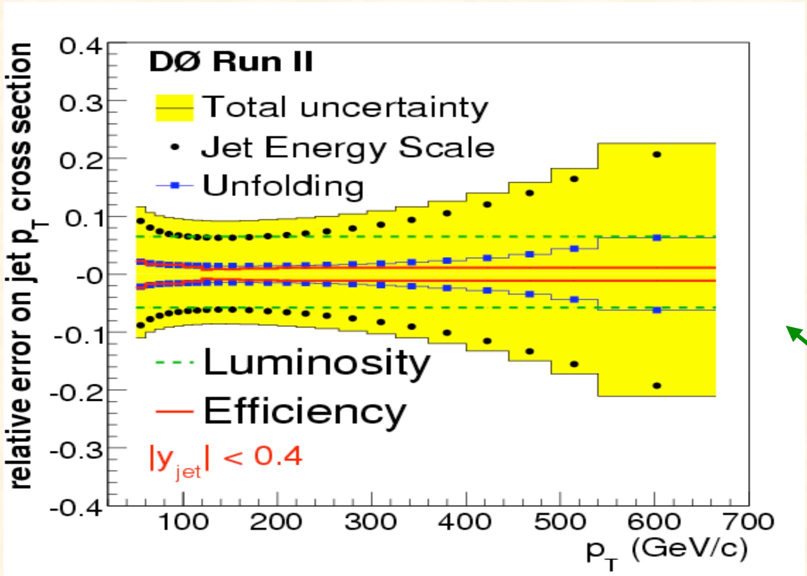
- In principle a simple counting experiment

- However, steeply falling p_T spectra are sensitive to jet energy scale uncertainties and resolution effects (migration between bins)
  → corrections (unfolding) to be applied





- Sensitivity to jet energy scale uncertainty:
  DØ: 1% energy scale error
  → 10% cross section uncert. at $|\eta|<0.4$



Major exp. errors:
energy scale, luminosity (6%),…

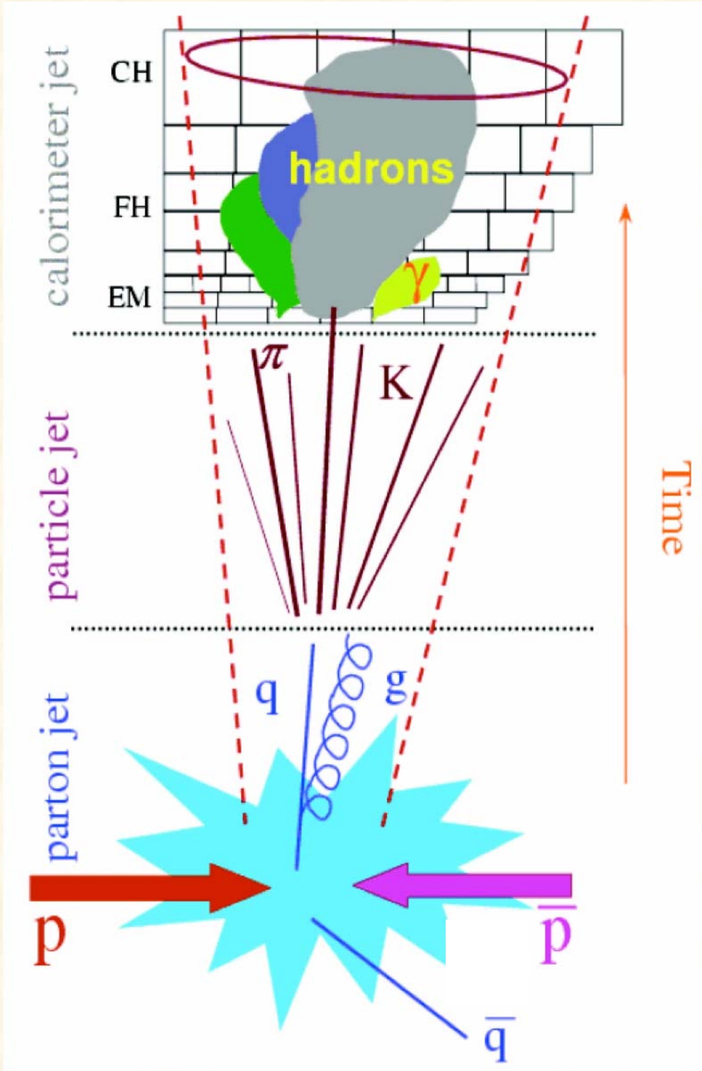
Jet reconstruction and energy measurement

- A jet is NOT a well defined object
  (fragmentation, gluon radiation, detector response)

- The detector response is different for particles interacting electromagnetically (e,γ) and for hadrons
  → for comparisons with theory, one needs to correct back the calorimeter energies to the „particle level“ (particle jet)
  Common ground between theory and experiment

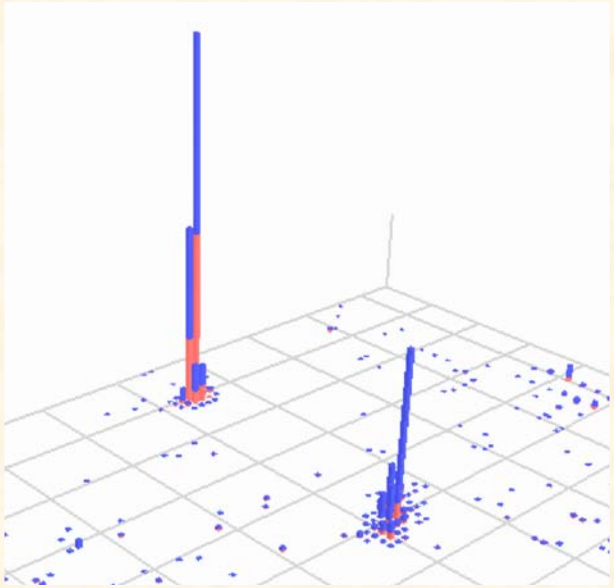
- One needs an algorithm to define a jet and to measure its energy
  conflicting requirements between experiment and theory (exp. simple, e.g. cone algorithm, vs. theoretically sound (no infrared divergencies))

- Energy corrections for losses of fragmentation products outside jet definition and underlying event or pileup energy inside

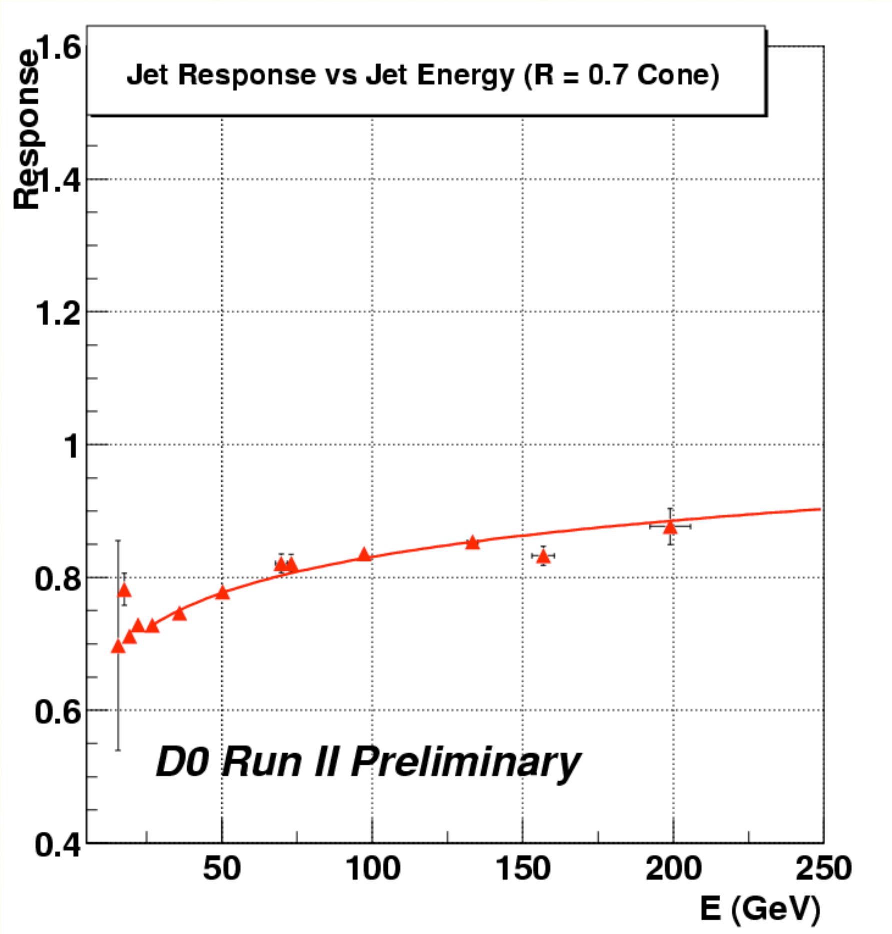


Main corrections:

- In general, calorimeters show different response to electrons/photons and hadrons
- 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)

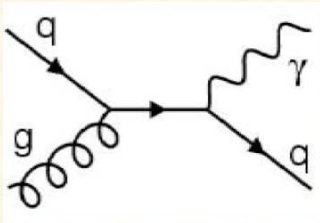


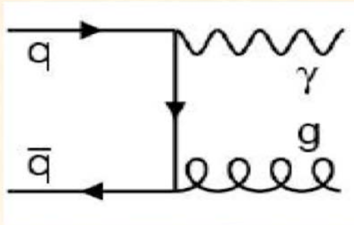
Jet Energy Scale



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





- Achieved jet energy scale uncertainty:

DØ: $\Delta E / E$ ~1-2%
(excellent result, a huge effort)

Jet energy scale at the LHC

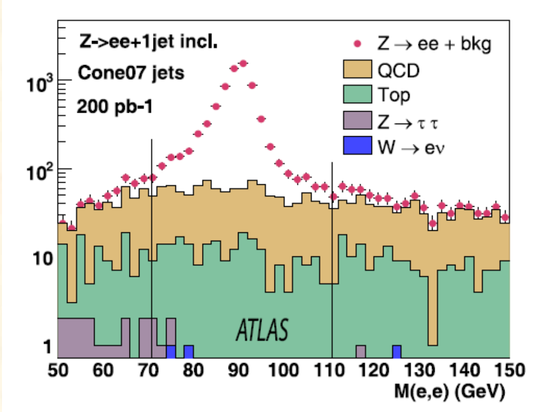
- A good jet-energy scale determination is essential for many QCD measurements (arguments similar to Tevatron, but kinematic range (jet p_T) is larger, ~20 GeV – ~3 TeV)

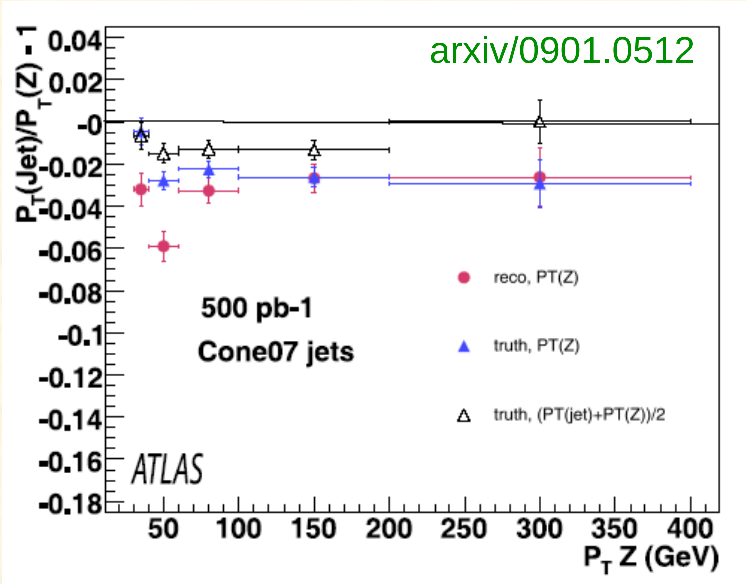
- Propagate knowledge of the em scale to the hadronic scale, but several processes are needed to cover the large p_T range

Measurement process	Jet p_T range
Z + jet balance	$20 < p_T < 100 - 200$ GeV
γ + jet balance	$50 < p_T < 500$ GeV (trigger, QCD background)
Multijet balance	500 GeV $< p_T$

Reasonable goal: 5-10% in first runs (1 fb^{-1})
1- 2% long term

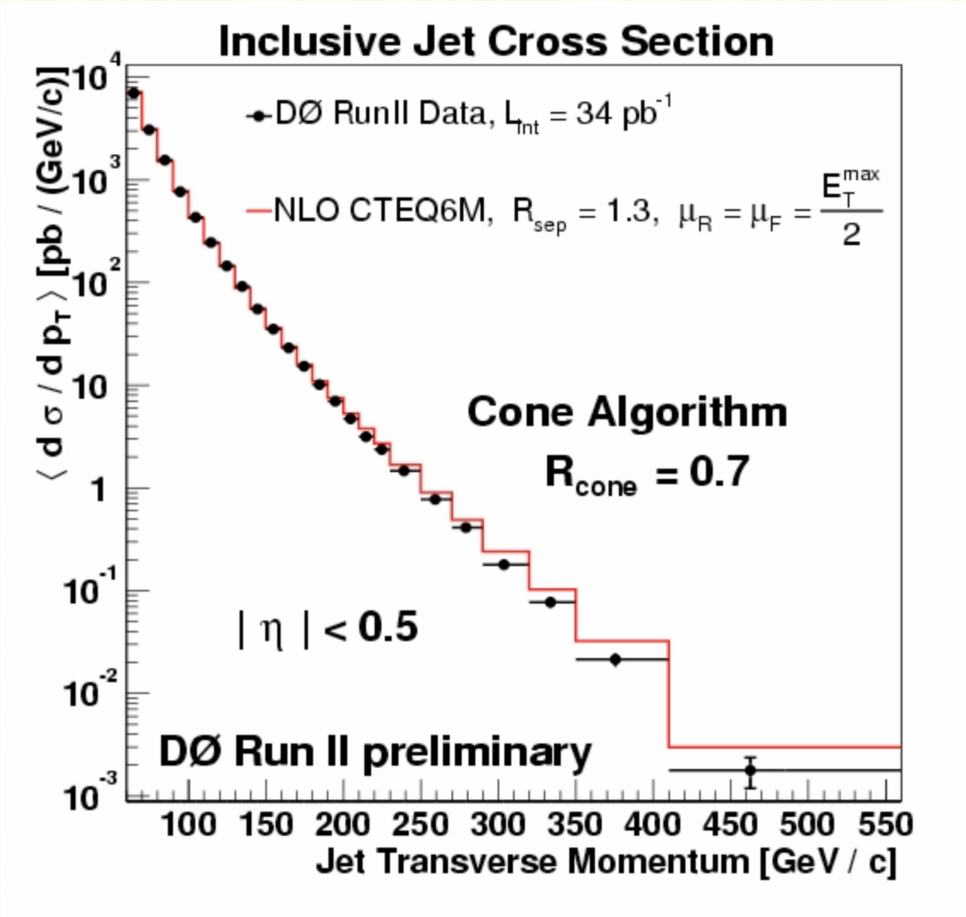
Example: Z + jet balance





Stat. precision (500 pb^{-1}): 0.8%
Systematics: 5-10% at low p_T, 1% at high p_T

Test of QCD Jet production



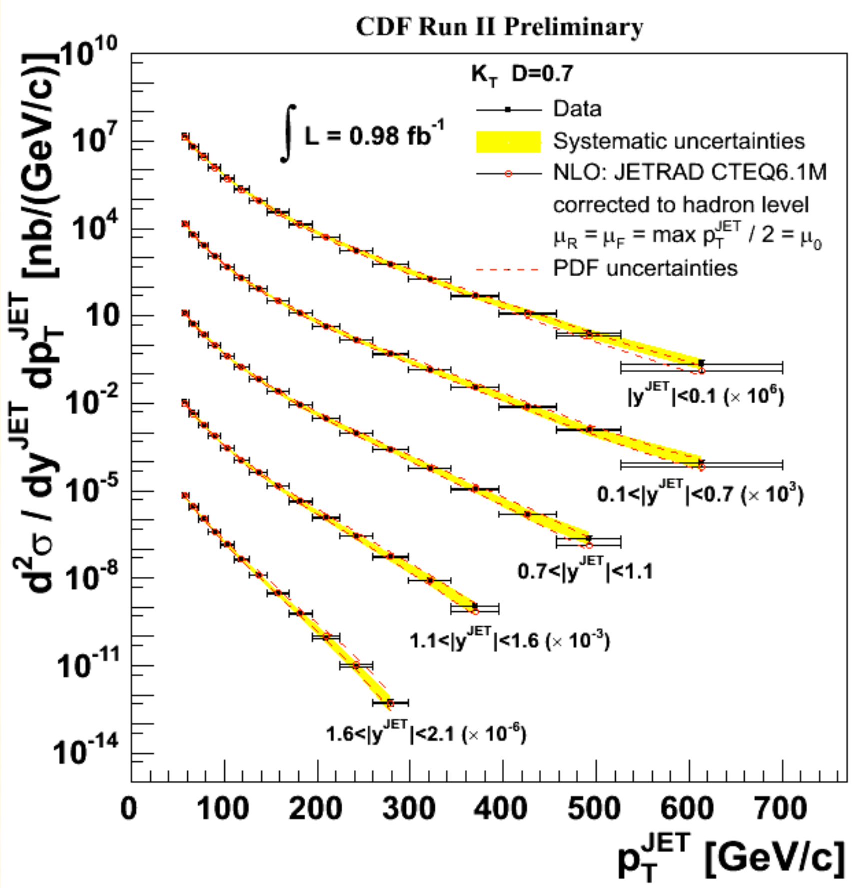
An **"early"** result from the DØ experiment (34 pb^{-1})

Inclusive Jet spectrum as a function of Jet-P_T

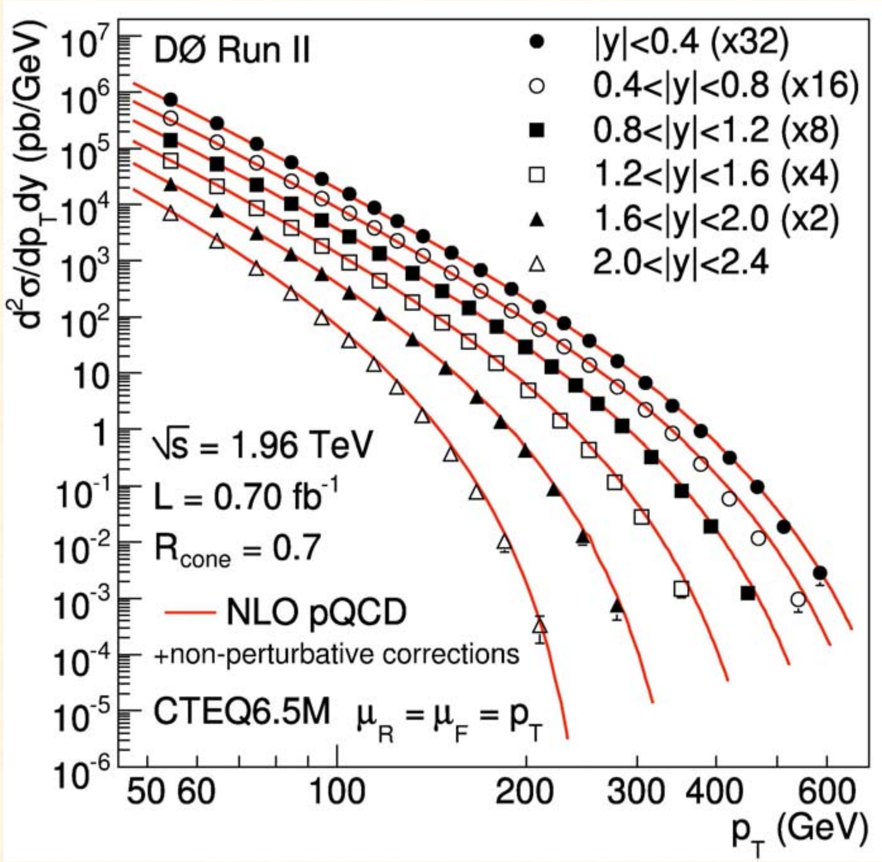
very good agreement with NLO pQCD calculations over many orders of magnitude !

within the large theoretical and experimental uncertainties

Double differential distributions in p_T and η



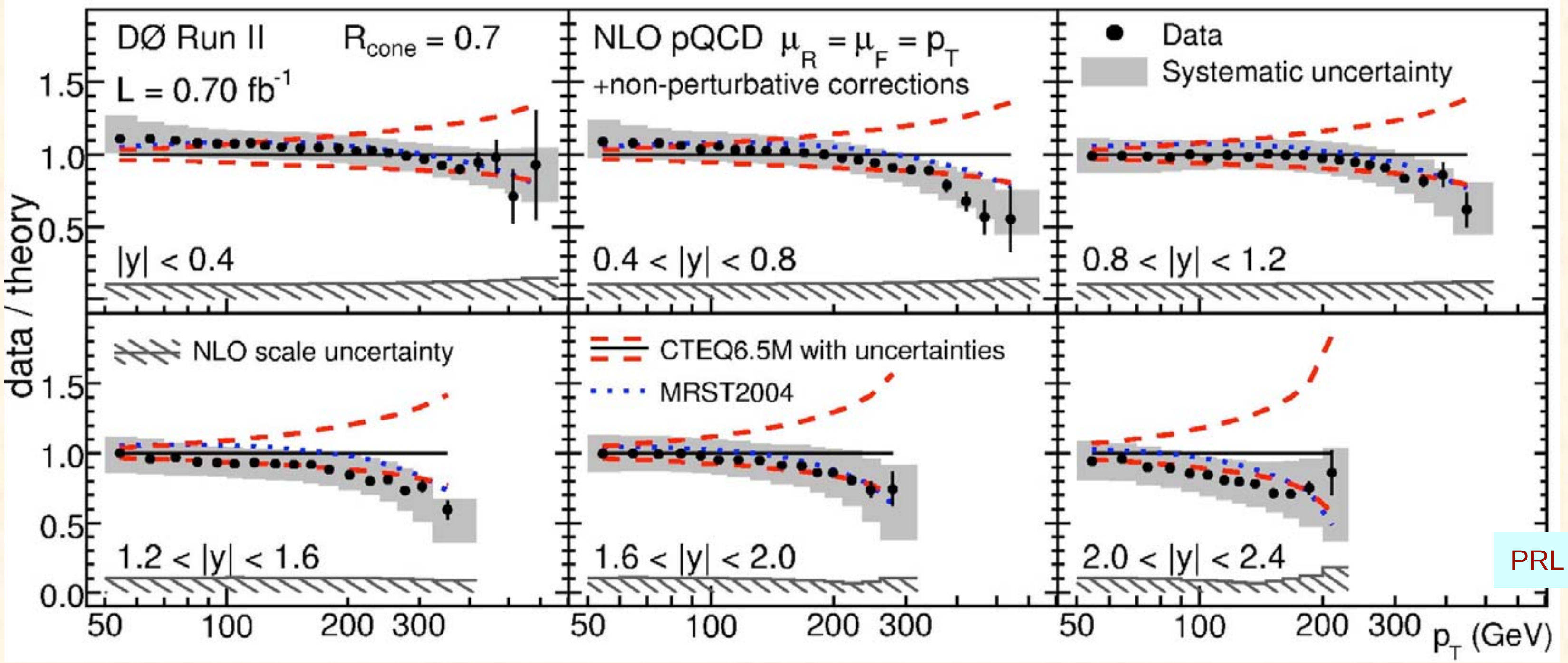
PRD 78 052006 ('08)



PRL 101 062001 ('08)

- Measurement in 5-6 different rapidity bins, over 9 orders of magnitude, up to p_T ~650 GeV
- Data corresponding to ~ 1 fb^{-1} (CDF) and 0.7 fb^{-1} (DØ)

Comparison between data and theory

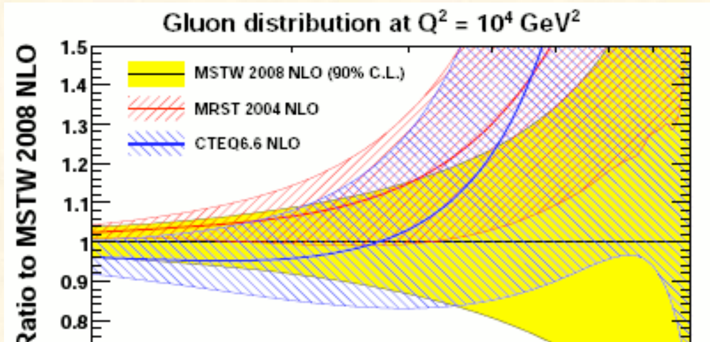


PRL 101 062001 ('08)

- **CDF and DØ agree within uncertainties**

- Experimental uncertainties are smaller than the pdf uncertainties
  (in particular large for large x, gluon distribution)

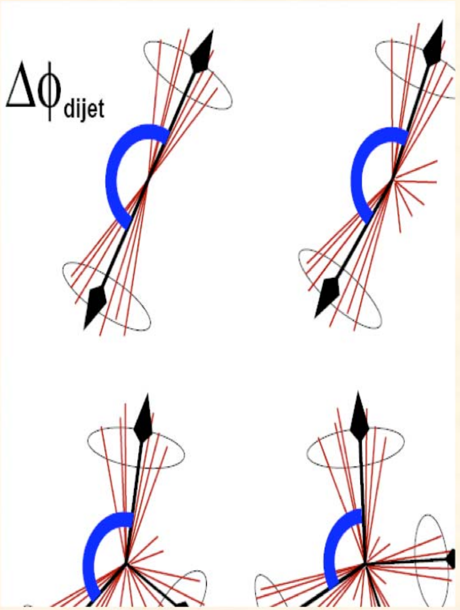
- Wait for updated (2009) parametrizations
  (plans to include Tevatron data, to better constrain the high x-region)

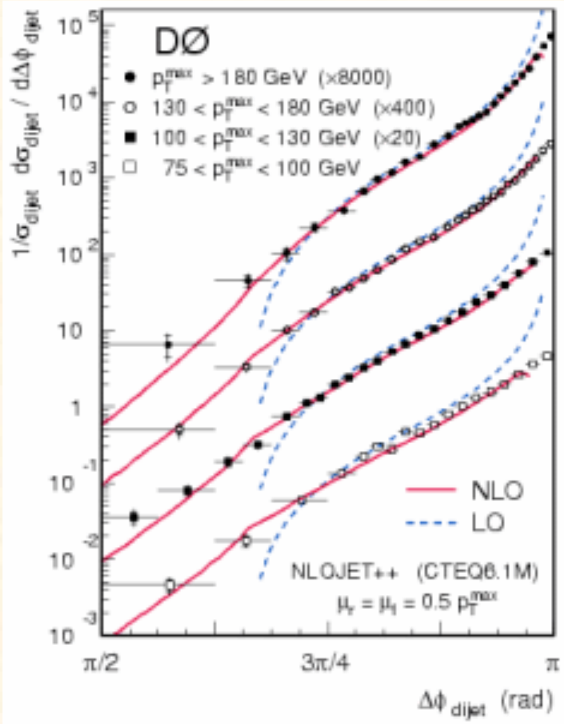


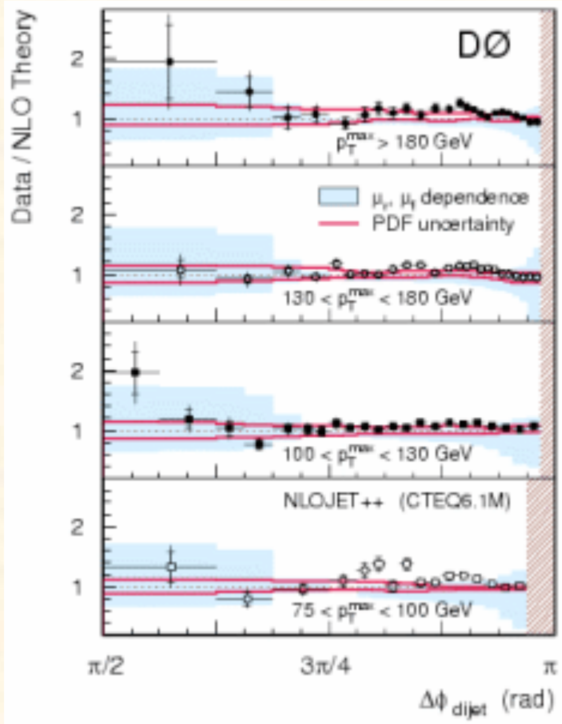
hep-ph:0901.0002

Di-jet angular distributions

- *reduced sensitivity to Jet energy scale*
- *sensitivity to higher order QCD corrections preserved*







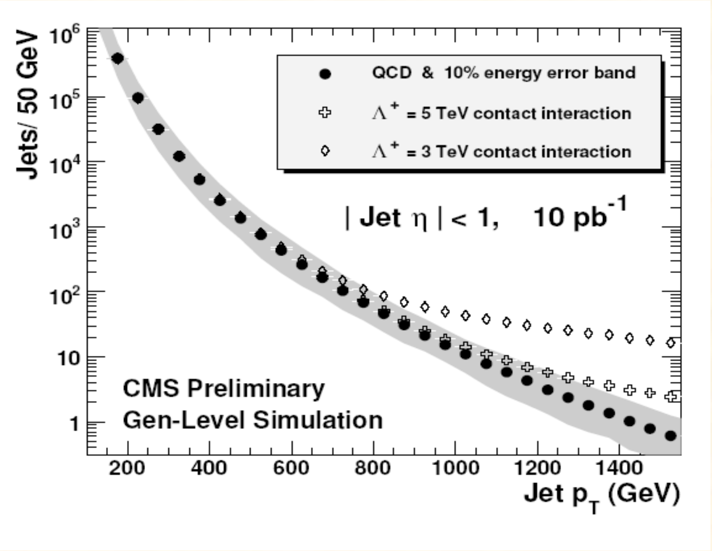
Good agreement with
next-to-leading order QCD predictions

In addition to QCD test: Sensitivity to New Physics

- Contact interactions:

  Despite the relatively large jet energy scale uncertainties (5-10%) expected with **early data**, the LHC has large sensitivity to contact interactions parametrized by a scale parameter Λ

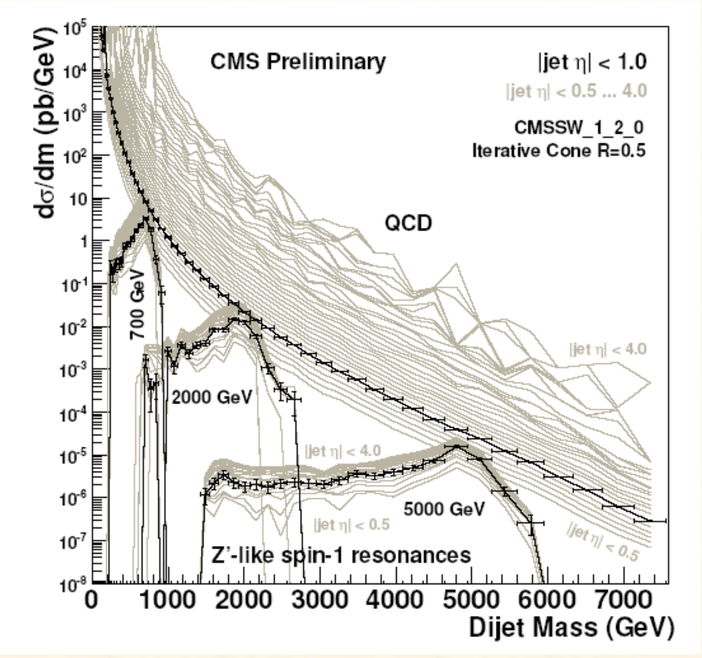
  Search for deviations from QCD in the high p_T region



- Heavy resonances decaying into jets

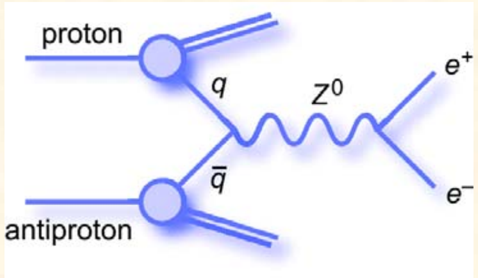
  e.g. $Z' \rightarrow qq$

  Search for resonant structures in dijet invariant mass spectrum

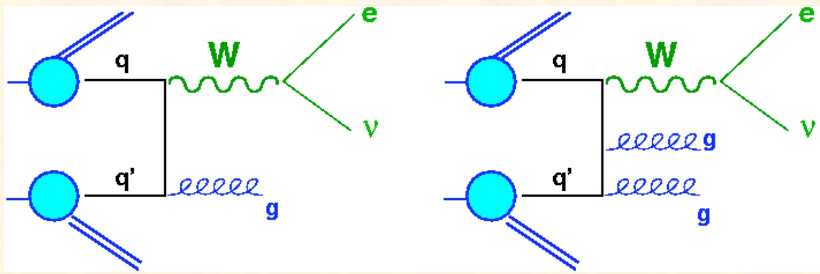


→ estimates tomorrow

QCD aspects in W/Z (+ jet) production



QCD at work



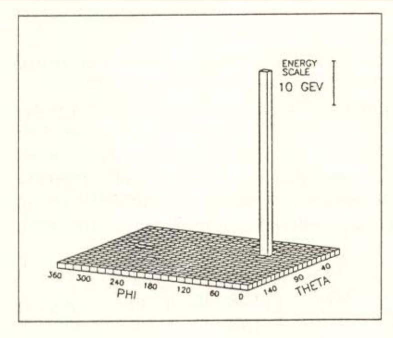
- Important test of NNLO Drell-Yan QCD prediction for the total cross section
- Test of perturbative QCD in high p_T region (jet multiplicities, p_T spectra,….)
- Tuning and „calibration“ of Monte Carlos for background predictions in searches at the LHC

How do W and Z events look like ?

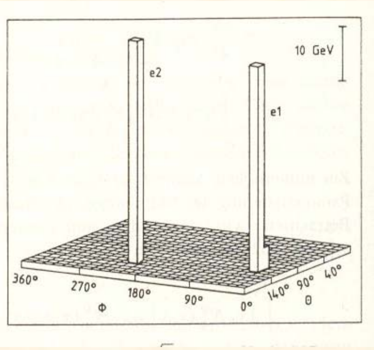
As explained, leptons, photons and missing transverse energy are key signatures at hadron colliders

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

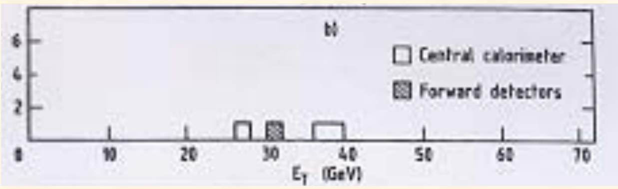
A bit of history: one of the first W events seen; UA2 experiment



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

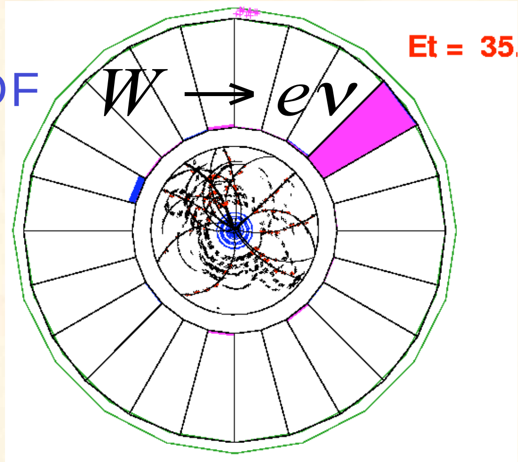


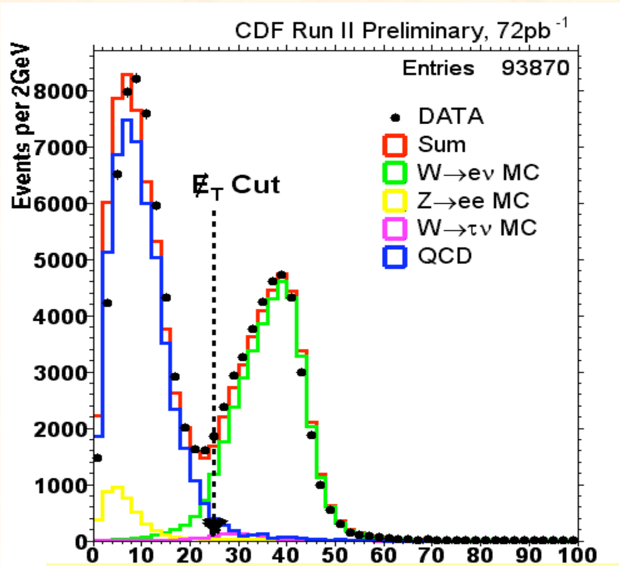
Transverse momentum of the electrons



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

CDF





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

Trigger:

- Electron candidate > 20 GeV/c

Electrons

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

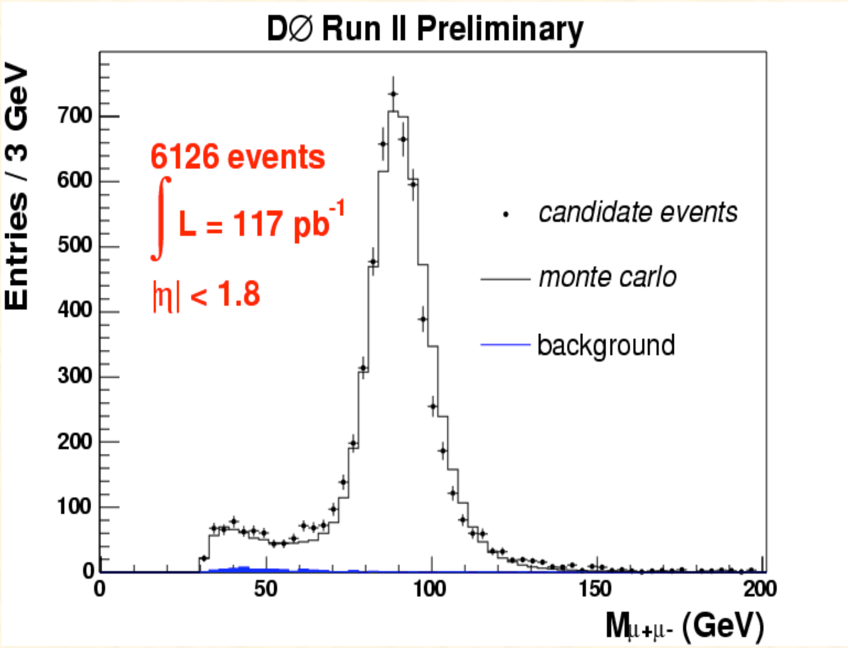
Z $\rightarrow$ ee

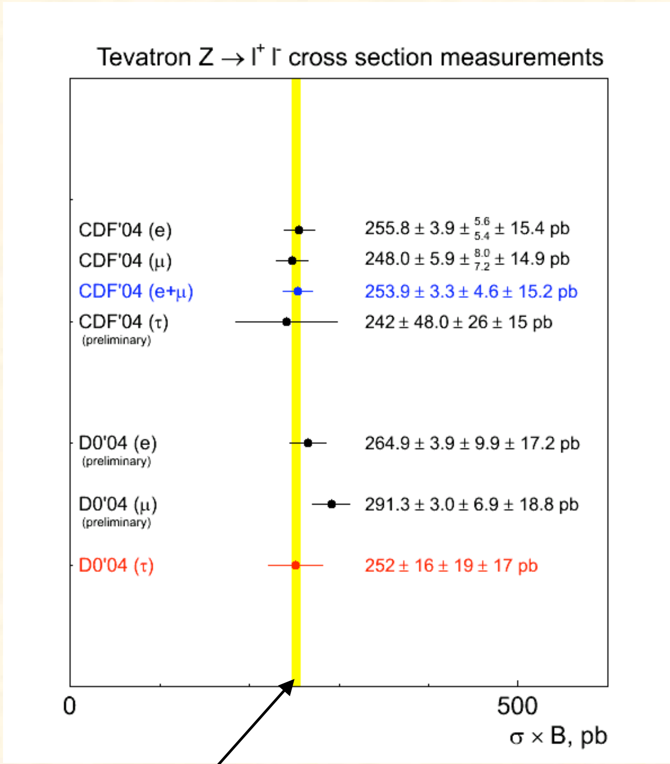
- 70 GeV/c^2 < m_{ee} < 110 GeV/c^2

W $\rightarrow$ eν

- Missing transverse momentum > 25 GeV/c

Z→ ℓℓ cross sections

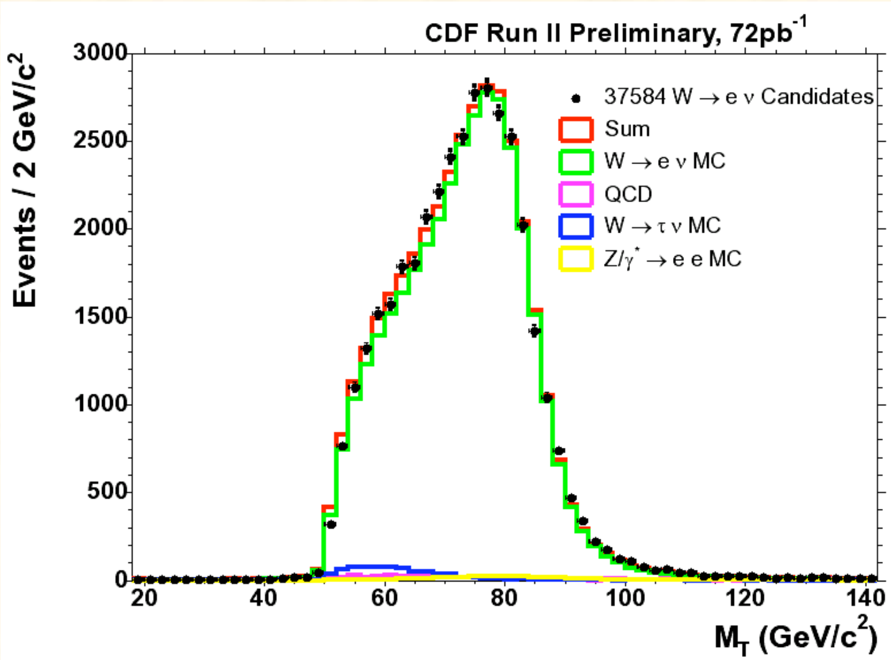


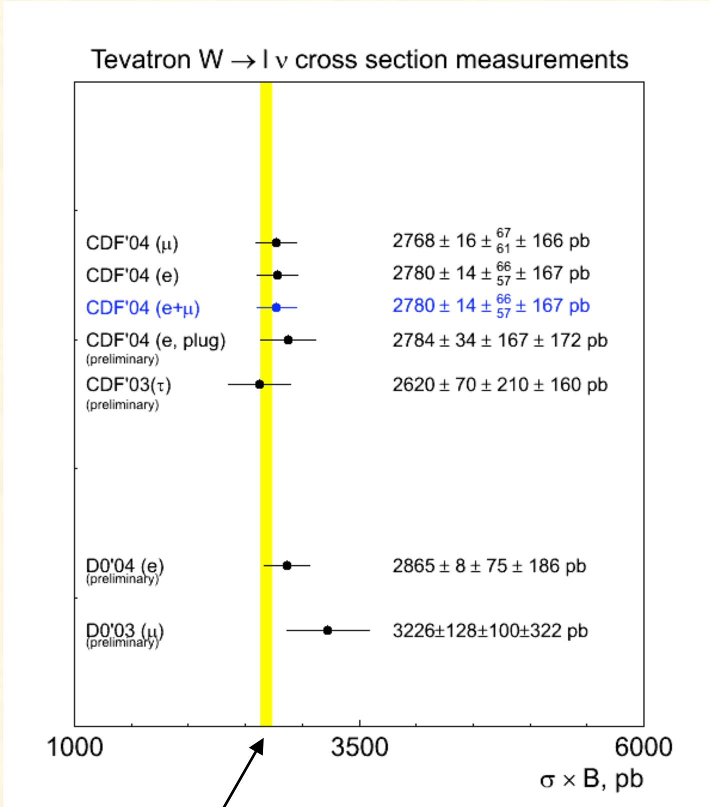


Good agreement with
NNLO QCD calculations,
QCD corrections are large: factor 1.3-1.4
C.R.Hamberg et al, Nucl. Phys. B359 (1991) 343.

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

W → ℓν Cross Section





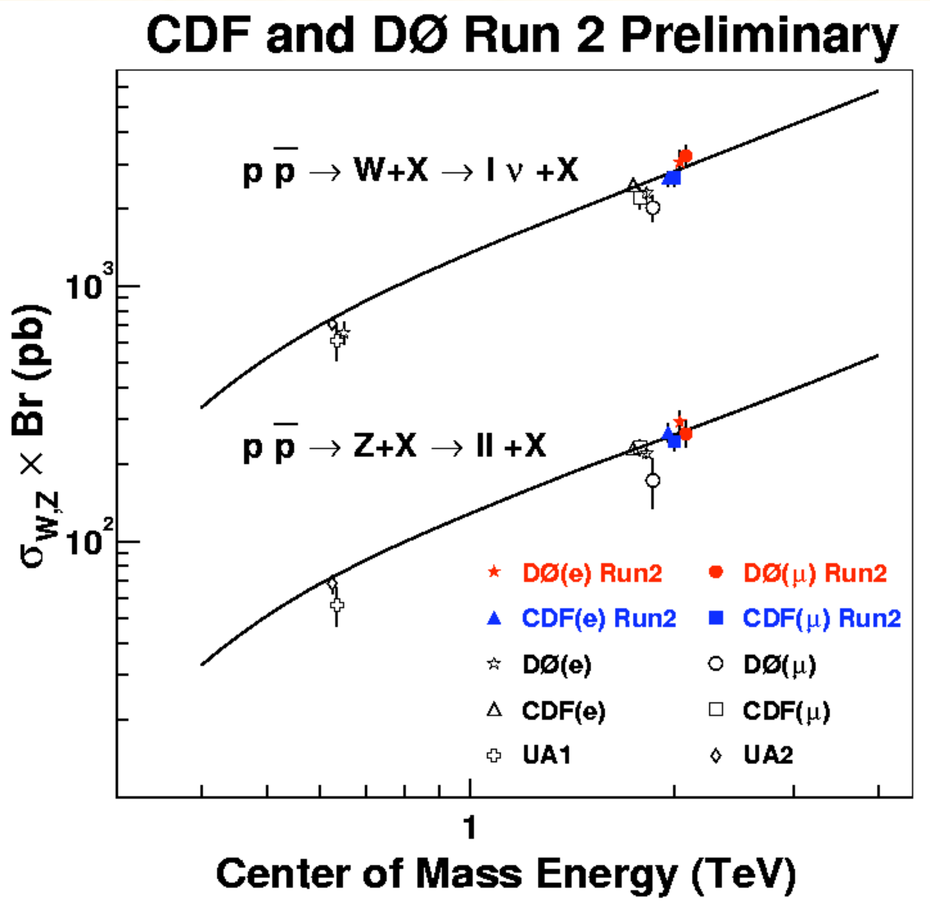
$$M_W^T = \sqrt{2 \cdot P_T^l \cdot P_T^\nu \cdot \left(1 - \cos \Delta\phi^{l,\nu}\right)}$$

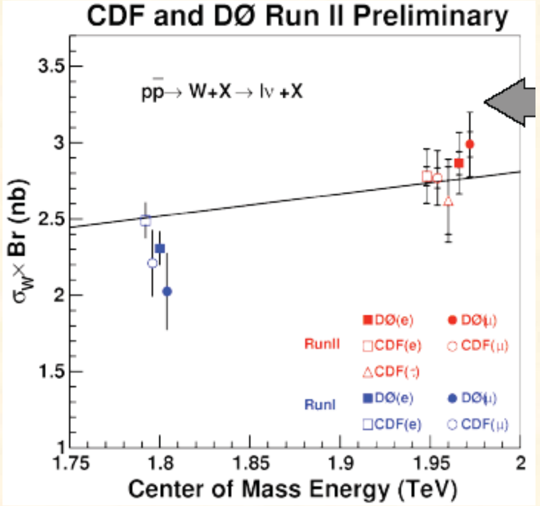
Note: the longitudinal component of the neutrino cannot be measured
→ only transverse mass can be reconstructed

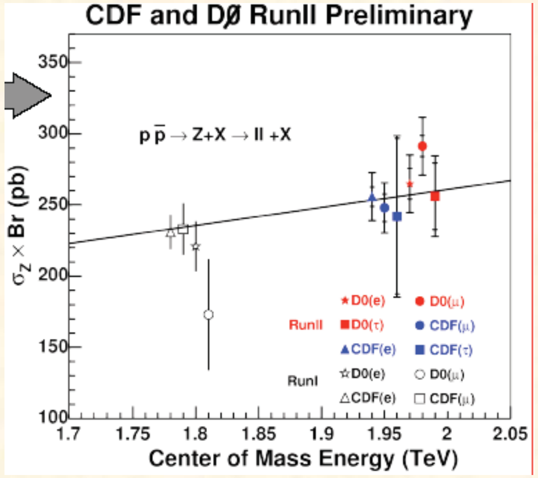
Good agreement with NNLO QCD calculations
C.R.Hamberg et al, Nucl. Phys. B359 (1991) 343.

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

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

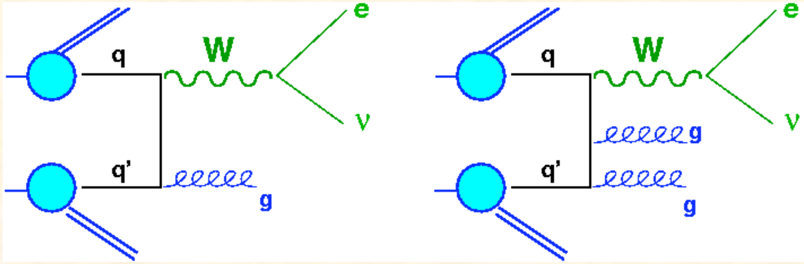






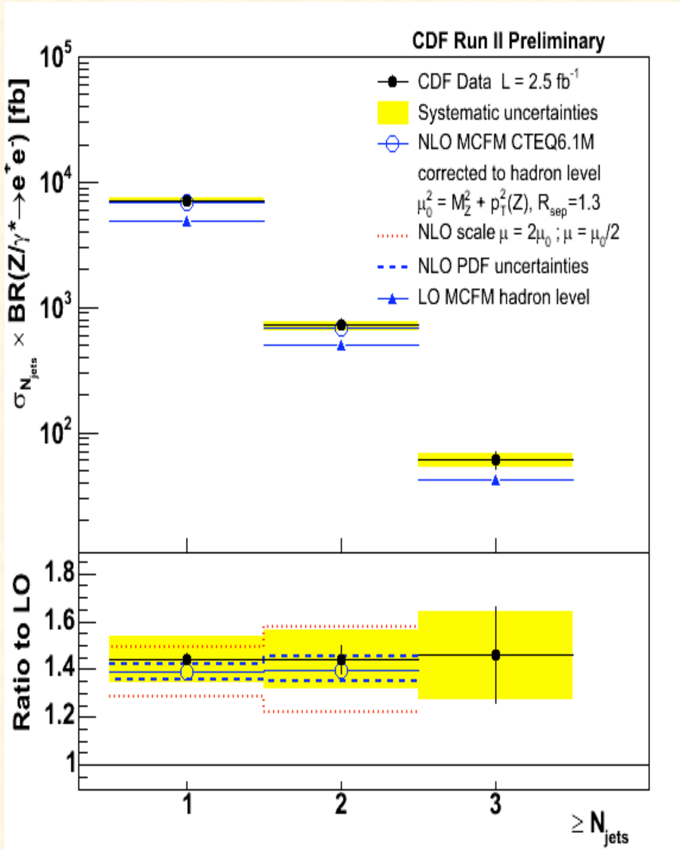
C. R. Hamberg, W.L. van Neerven and T. Matsuura, Nucl. Phys. B359 (1991) 343

QCD Test in W/Z + jet production

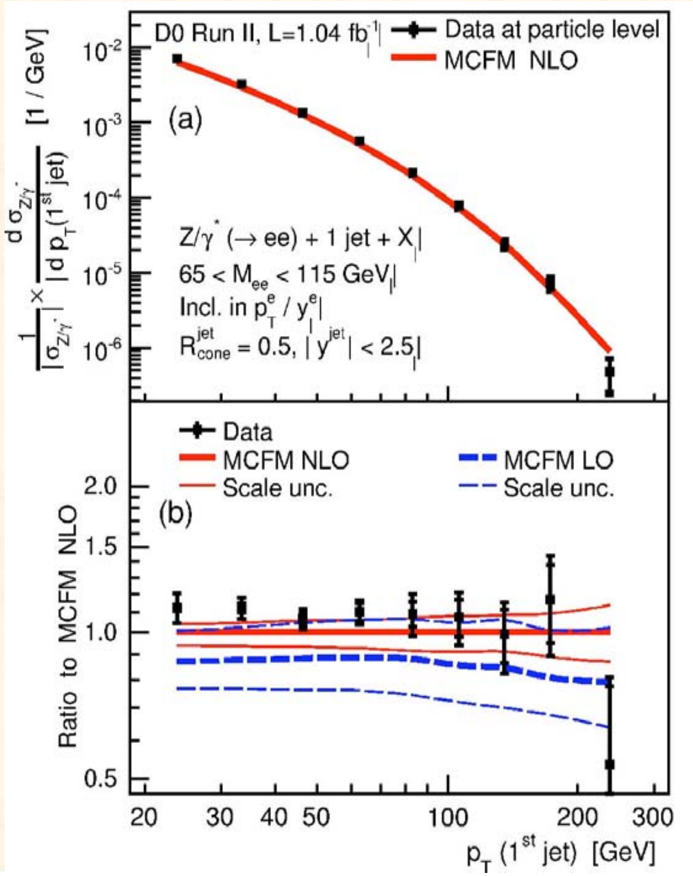


- LO predictions fail to describe the data;
- Jet multiplicities and p_T spectra in agreement with NLO predictions within errors; NLO central value ~10% low

Jet multiplicities in Z+jet production

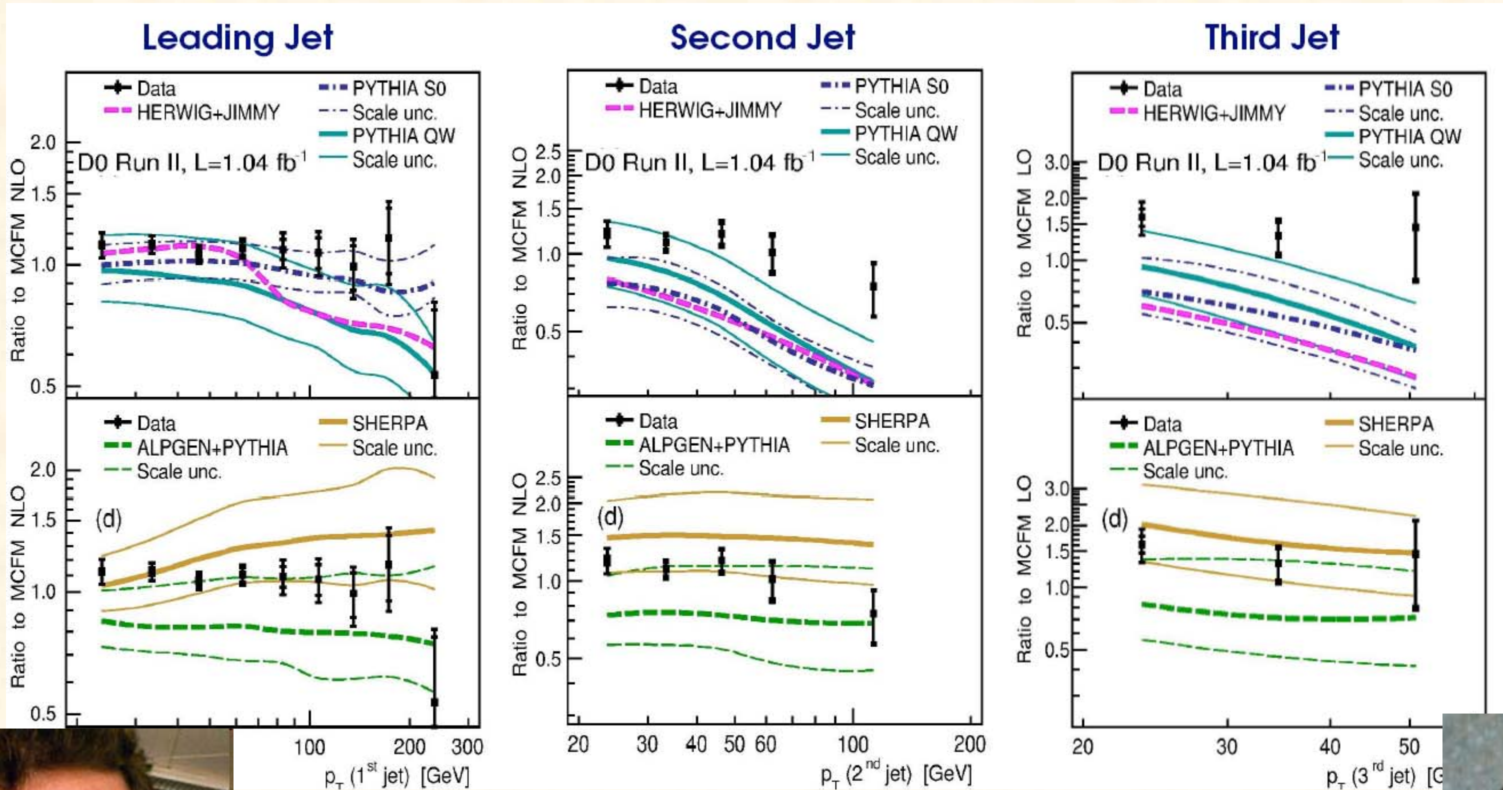


p_T spectrum of leading jet



comparison to different Monte Carlo predictions

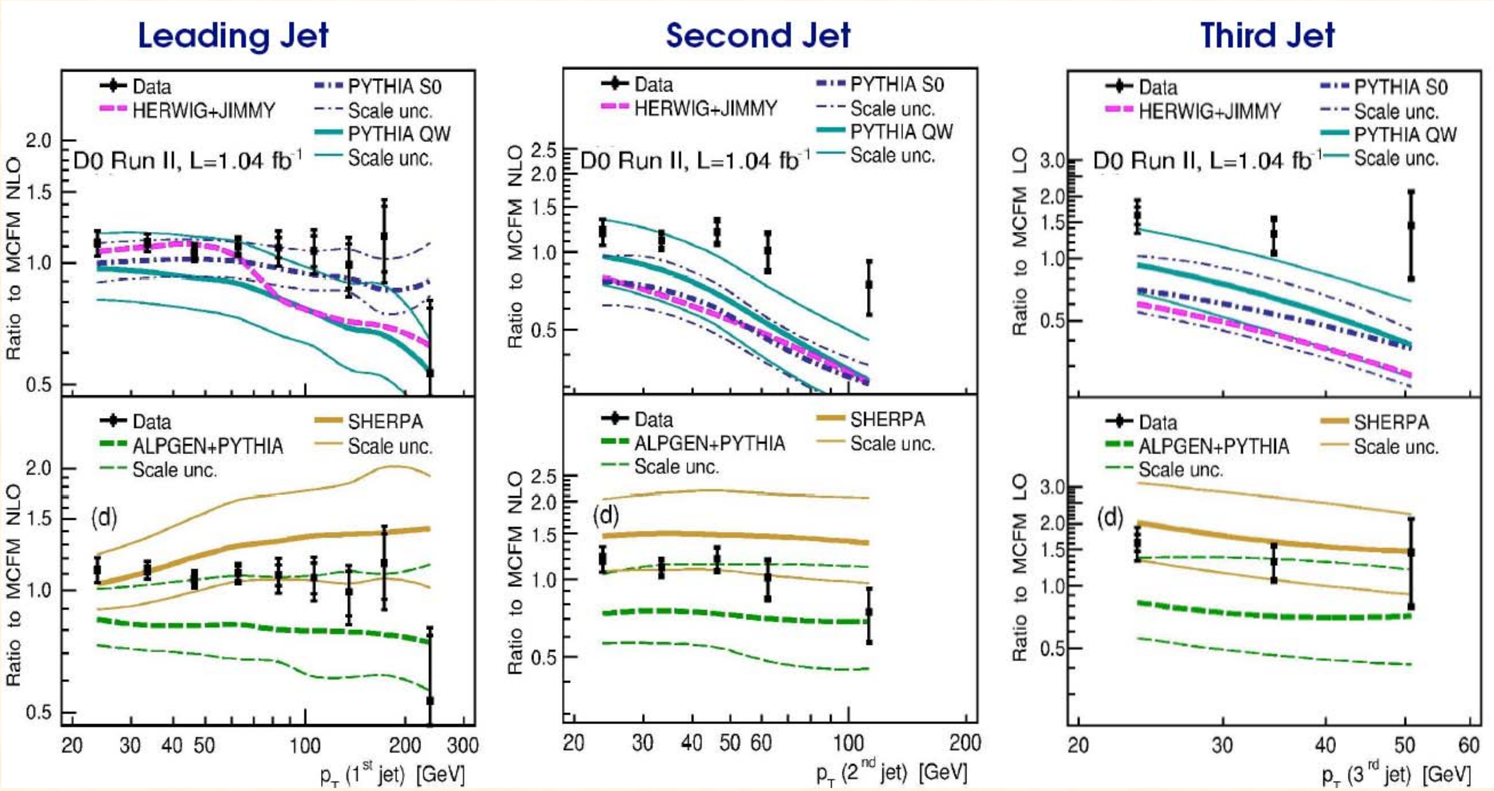
- Comparison of p_T spectra of leading, second and third jet in Z+jet events to
  - PYTHIA and HERWIG (parton shower based Monte Carlos)
  - ALPGEN and SHERPA (explicit matrix elements (tree level) matched to parton showers)



….they might have to try harder

comparison to different Monte Carlo predictions

- Comparison of p_T spectra of leading, second and third jet in Z+jet events to
  - PYTHIA and HERWIG (parton shower based Monte Carlos)
  - ALPGEN and SHERPA (explicit matrix elements (tree level) matched to parton showers)



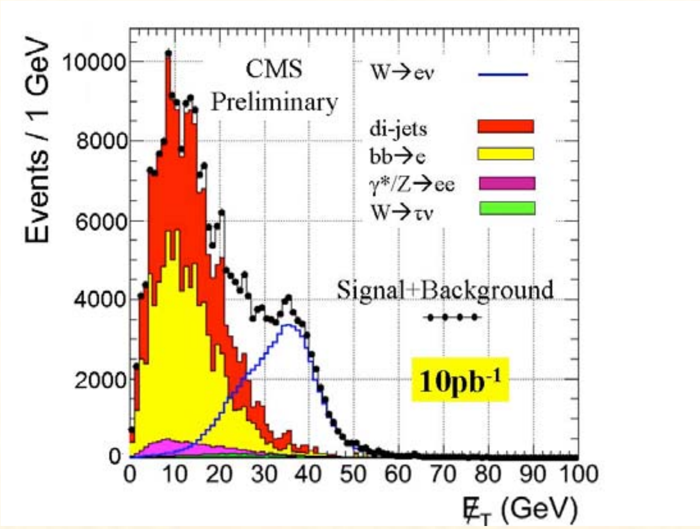
- Conclusions: (important for LHC)
  - Parton shower Monte Carlos fail to describe the higher jet p_T spectra;
  - Better agreement for ALPGEN and SHERPA, parameters can be tuned to describe them, but uncertainties -linked to the underlying tree level calculations- remain large;
  - It would be desirable to have NLO matched calculations

W and Z cross sections at the LHC

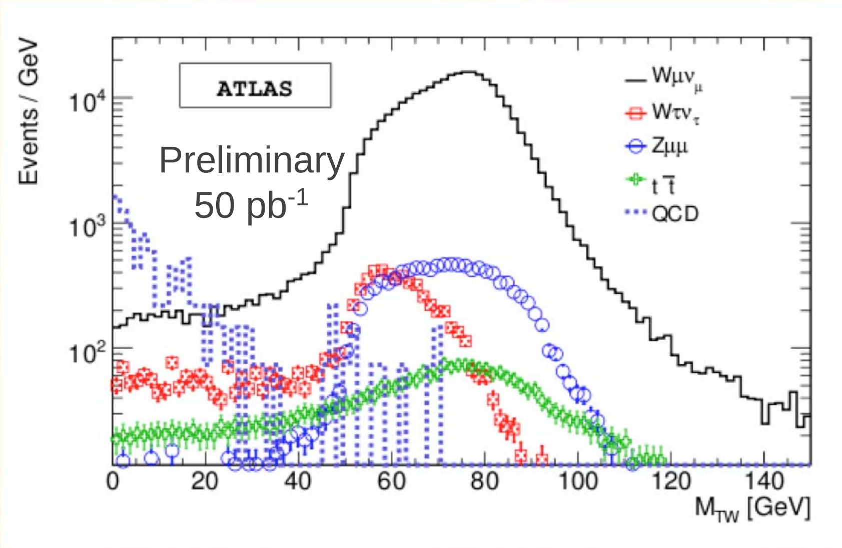
Even with early data (10-50 pb^{-1}),
high statistics of W and Z samples

→ data-driven cross-section measurements

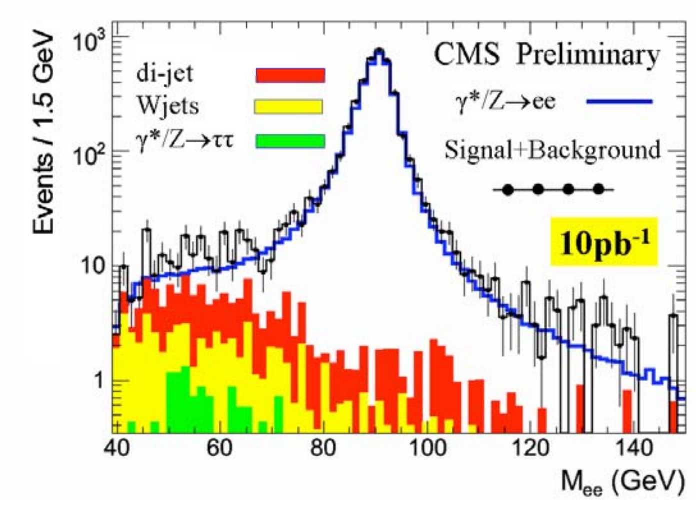
W → e ν



W → μ ν



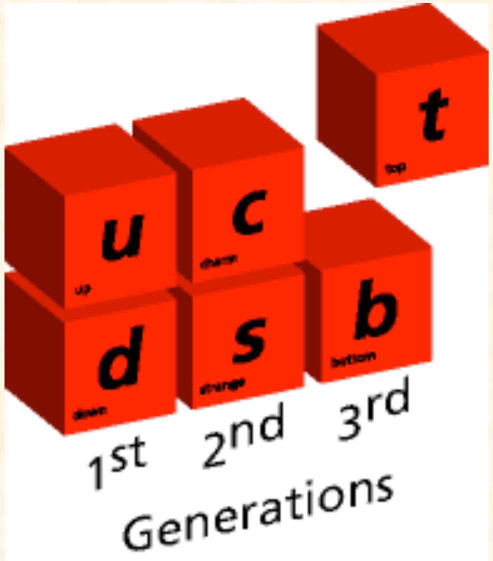
Z → ee



Limited by luminosity error: ~ 5-10% in first year,
Longer term goal ~ 2-3%

(process might be used later for luminosity measurement)

Top Quark Physics



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

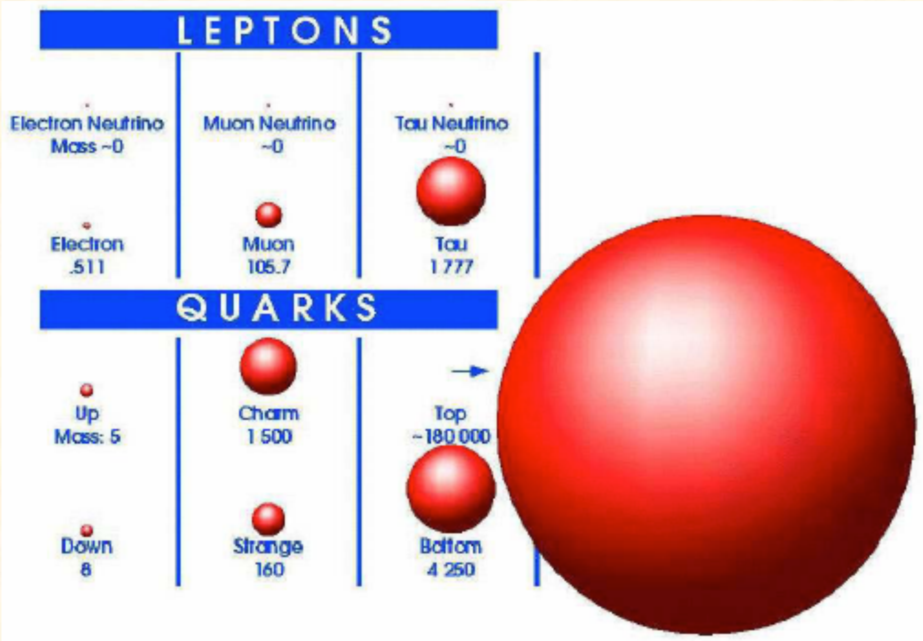
- Run I top physics results are consistent with the Standard Model

  (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 ??

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

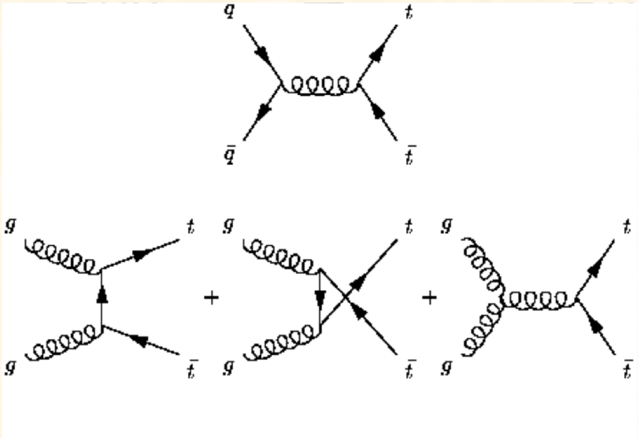
$$\Rightarrow \lambda_t = \frac{M_t}{173.9 \text{ GeV}/c^2}$$

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

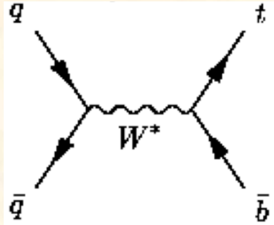
- A unique quark: decays before it hadronizes, lifetime ~10^{-24} s
  no “toponium states”
  remember: bb, bd, bs….. cc, cs….. bound states (mesons)

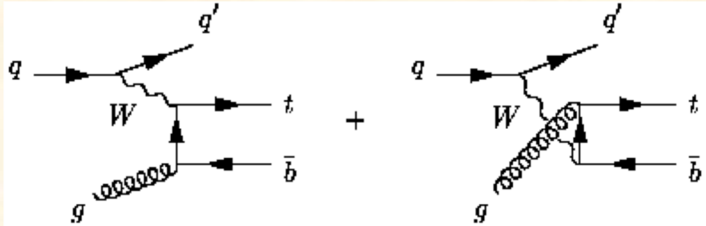
Top Quark Production

Pair production: qq and gg-fusion



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



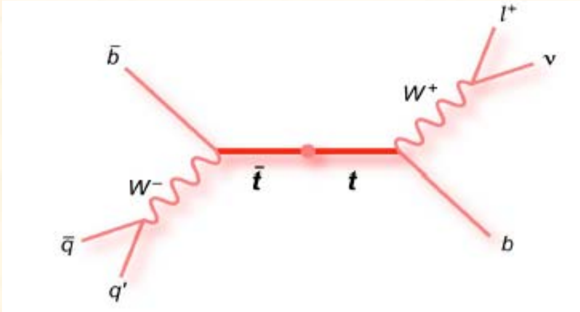


recently discovered by CDF and DØ at Fermilab

	Tevatron 1.96 TeV	LHC 14 TeV
qq	85%	5%
gg	15%	95%
σ (pb)	7 pb	830 pb

	Tevatron 1.96 TeV	LHC 14 TeV
σ (qq) (pb)	0.9	10
σ (gW) (pb)	2.4	250
σ (gb) (pb)	0.1	60

Top Quark Decays



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

Dilepton channel:

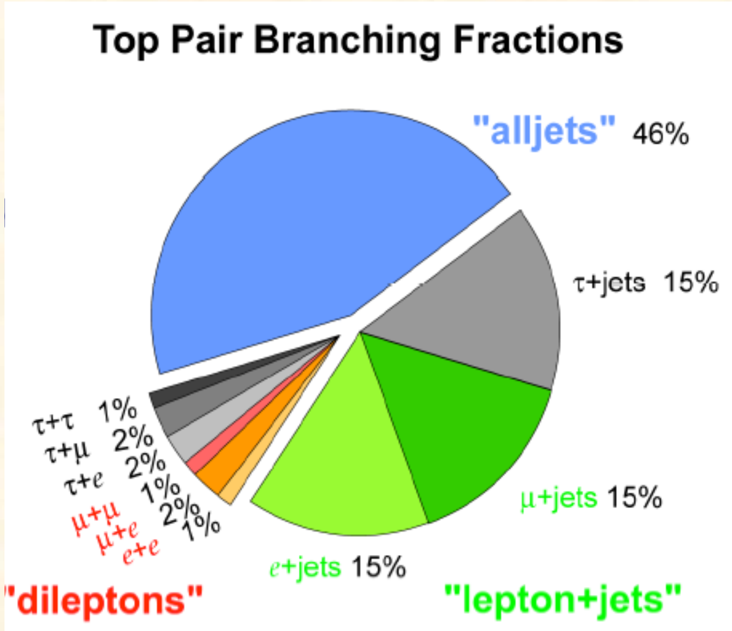
Both W's decay via $W \to \ell\nu$ (ℓ=e or μ; 4%)

Lepton + jet channel:

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

Full hadronic channel:

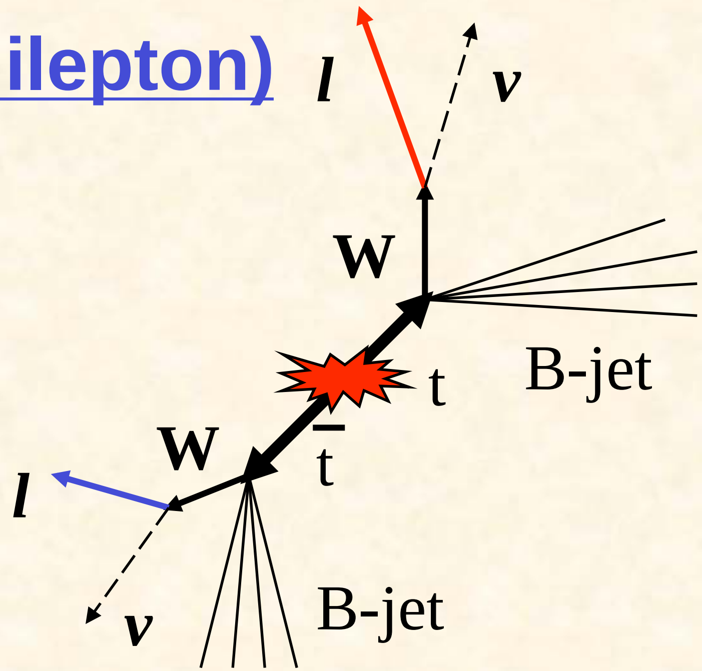
Both W's decay via $W \to qq$ (46%)



Important experimental signatures: : - Lepton(s)

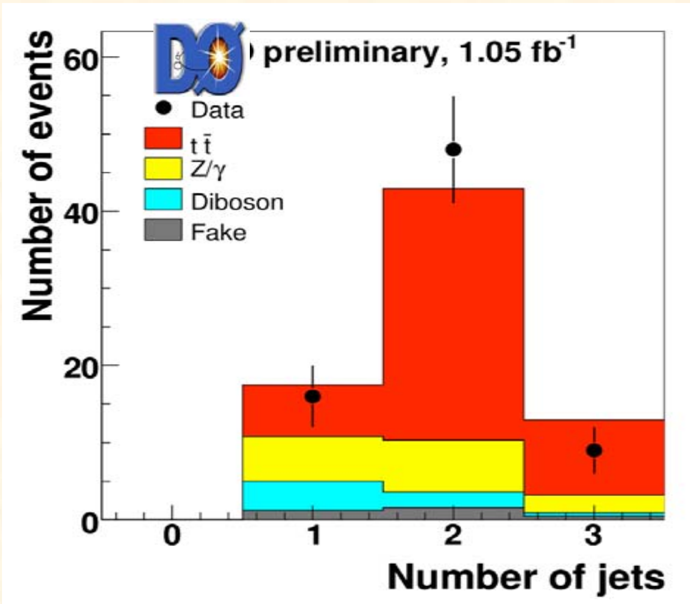
- Missing transverse momentum
- b-jet(s)

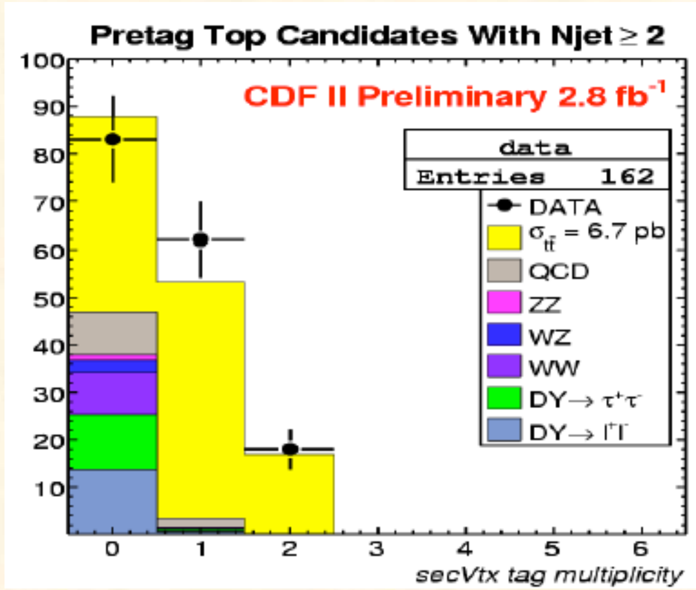
tt cross section (dilepton)



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

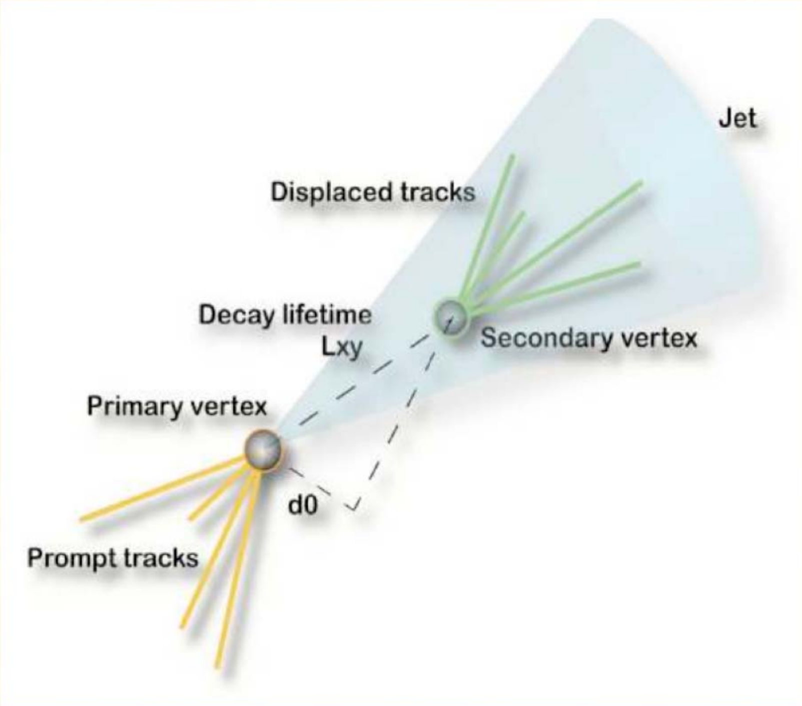
ee,eμ and μμ combined

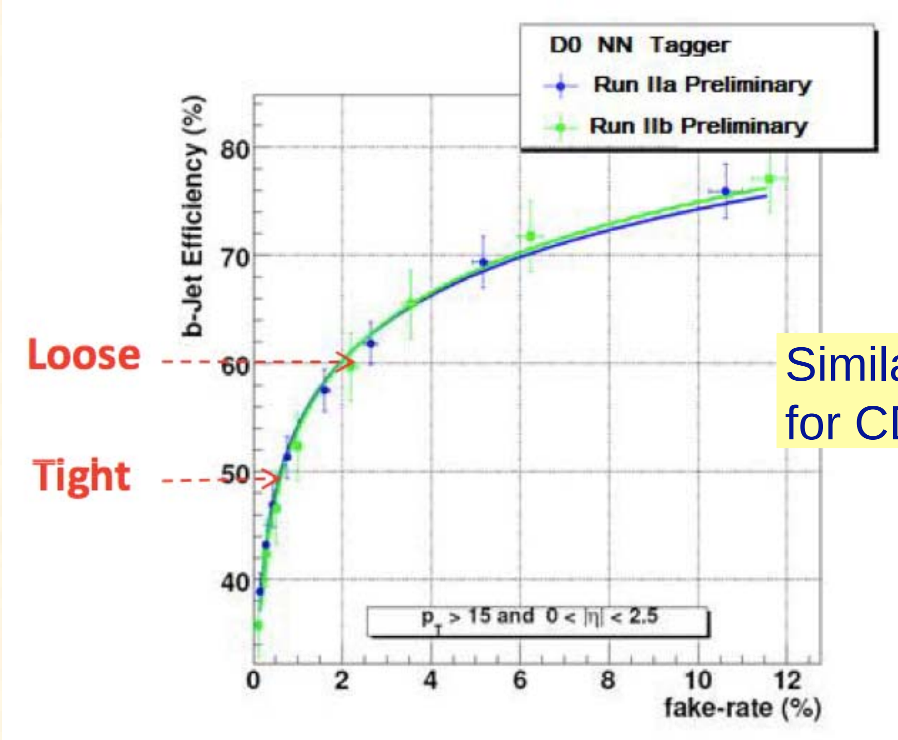




Top quark is needed to describe the
b-jet multiplicity distribution in dilepton events

Tevatron b-tagging performance





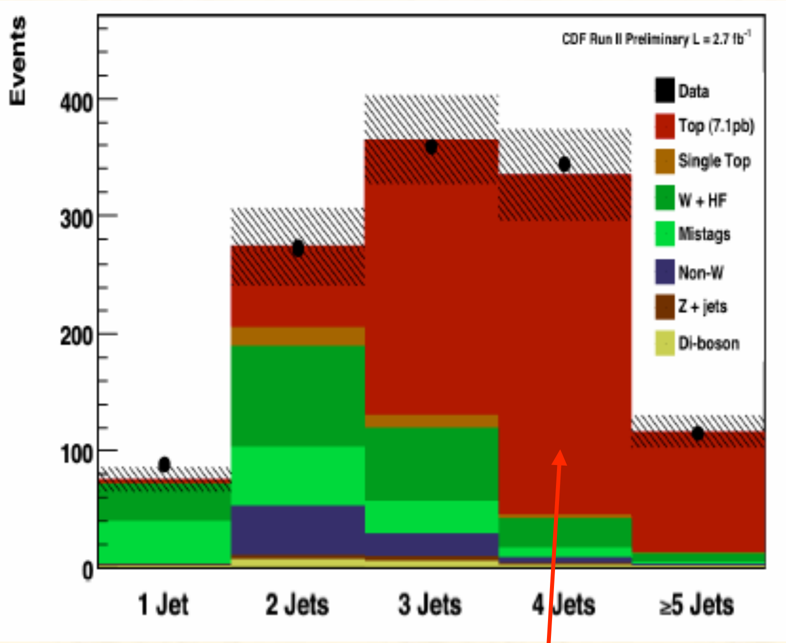
Similar for CDF

Neural networks are used for optimal combination of tagging information

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

b-tag selection:

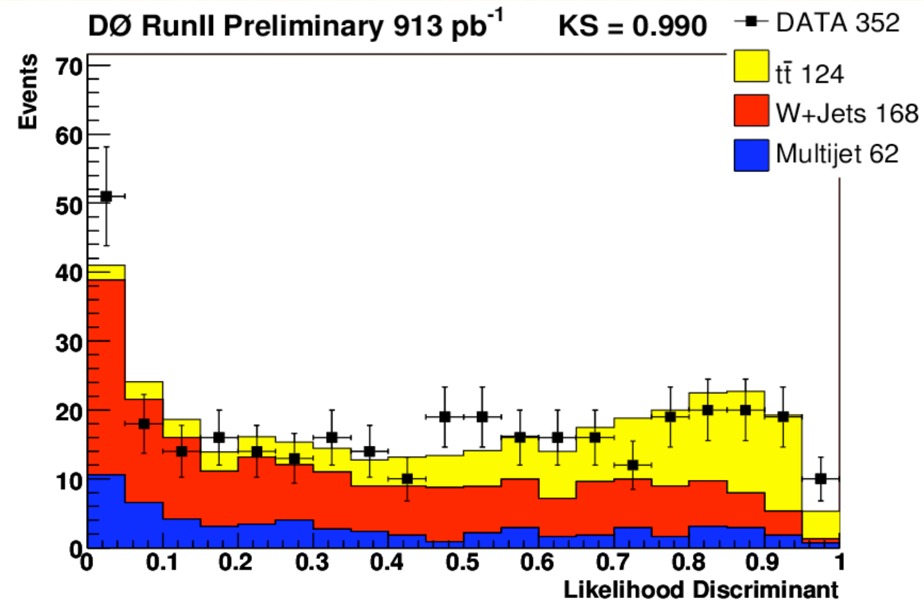
- One high P_T lepton (e, μ)
- Significant E_T^{miss}
- ≥ 1 b-tagged jet



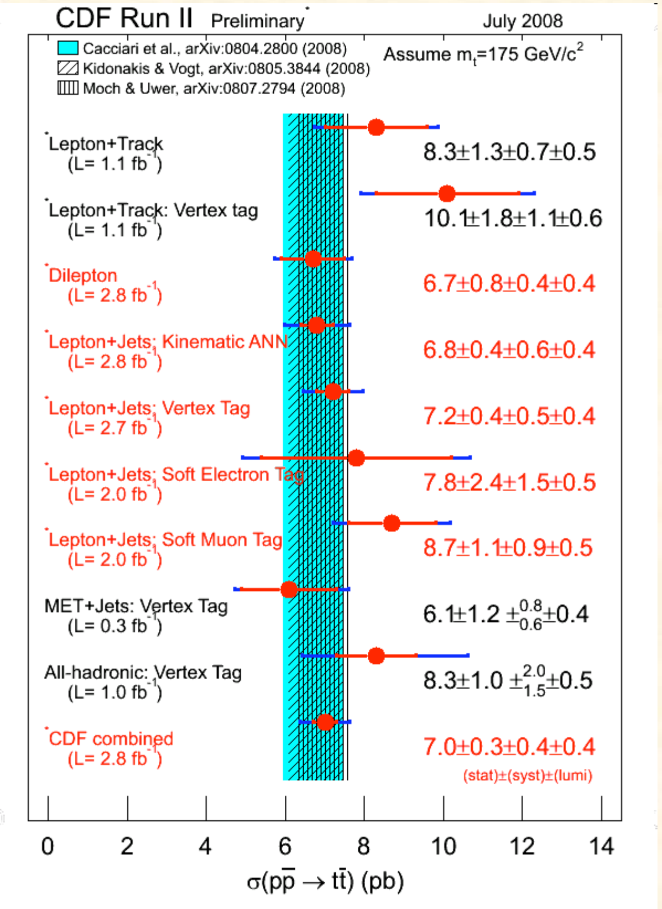
Clear excess above the W+ jet background in events with high jet multiplicity

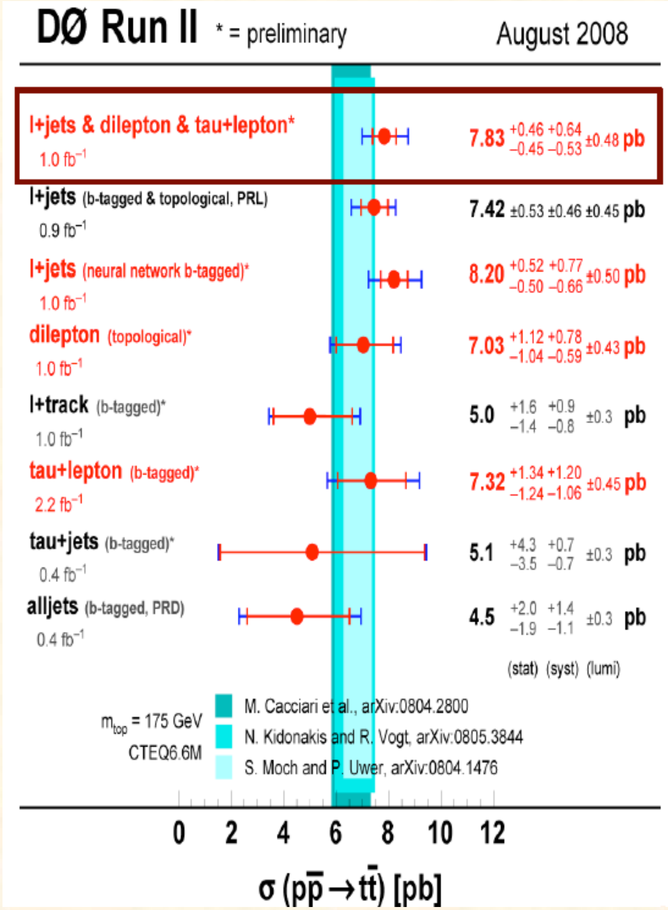
Kinematic selection:

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



tt cross section summary (preliminary)





Summary of syst. uncertainties

b-tag analysis (2.7 fb^{-1}):

SYSTEMATIC	$\Delta\ \sigma$ pb	$\Delta\ \sigma / \sigma$ %
JET ENERGY SCALE	0.16	2.2
BOTTOM TAGGING	0.38	5.2
CHARM TAGGING	0.08	1.1
MIS-TAGS	0.15	2.1
HEAVY FLAVOR CORRECTION	0.23	3.2
LUMINOSITY	0.42	5.8
QCD FRACTION	0.02	0.2
PARTON SHOWER MODELING	0.13	1.8
INITIAL/FINAL STATE RADIATION	0.04	0.6
TRIGGER EFFICIENCY	0.05	0.6
PDF	0.06	1.0
TOTAL	0.67	9.3

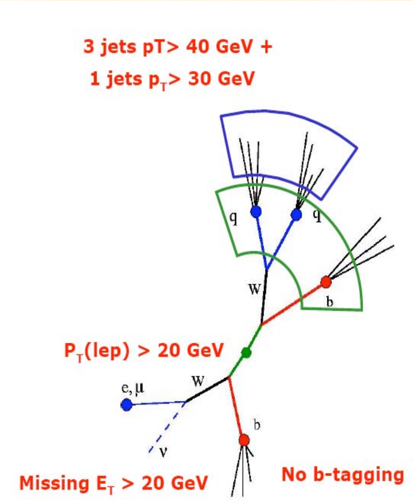
CDF Run II Preliminary L=2.7 fb^{-1}

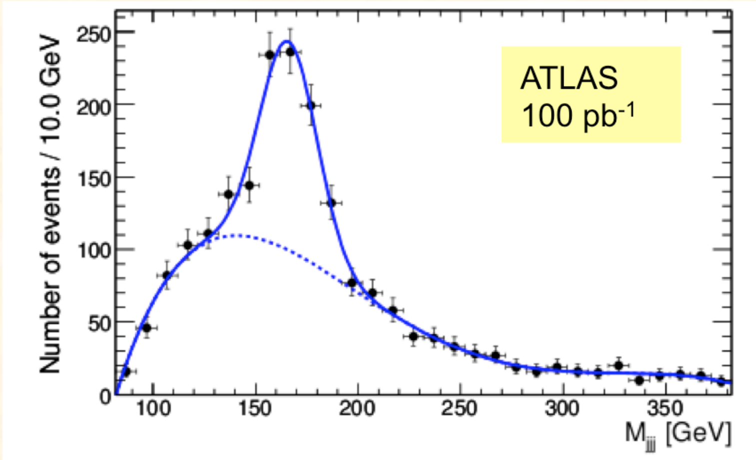
Good agreement:
- among various exp. measurements (two experiments)
- and with NLO + LL QCD prediction
- Systematic uncertainties at the 10% level
  (luminosity, b-tagging)

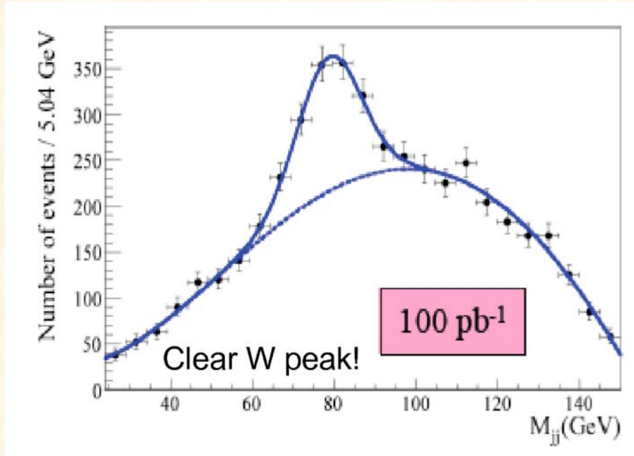
Top cross section in early LHC data

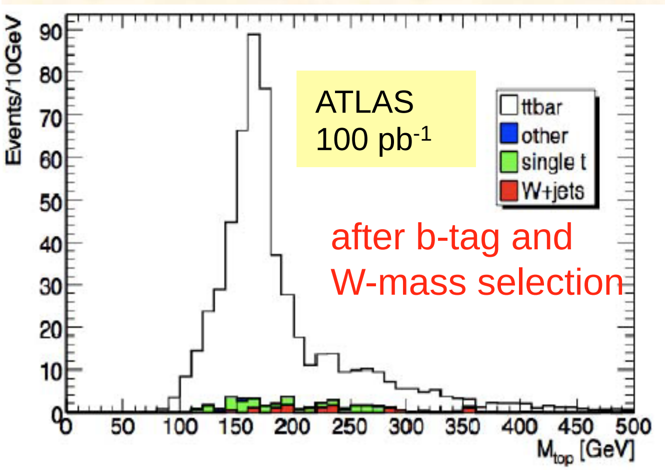
Large cross section: ~ 830 pb at √s = 14 TeV

Reconstructed mass distribution after a simple selection of **tt → Wb Wb → ℓνb qqb** decays:









- Cross section measurement (test of perturbative QCD) with data corresponding to 100 pb^{-1} possible with an accuracy of ±10-15%
- Errors are dominated by systematics
  (jet energy scale, Monte Carlo modelling (ISR, FSR),…)
- Ultimate reach (100 fb^{-1}): ± 3-5%
  (limited by uncertainty on the luminosity)

Electroweak parameters

- W mass
- Top Quark Mass & Properties
- Single top, V_{tb}

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

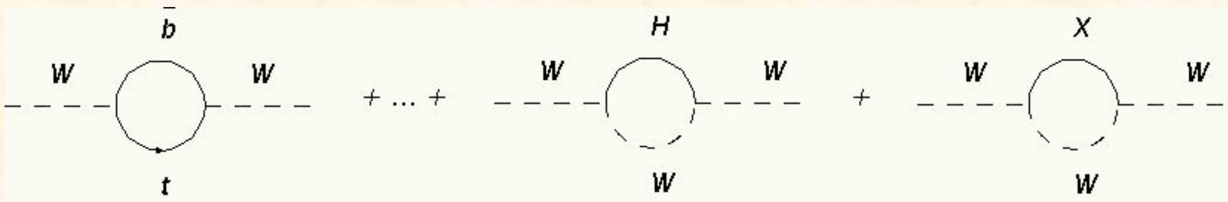
weak mixing angle
measured at
LEP/SLC

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

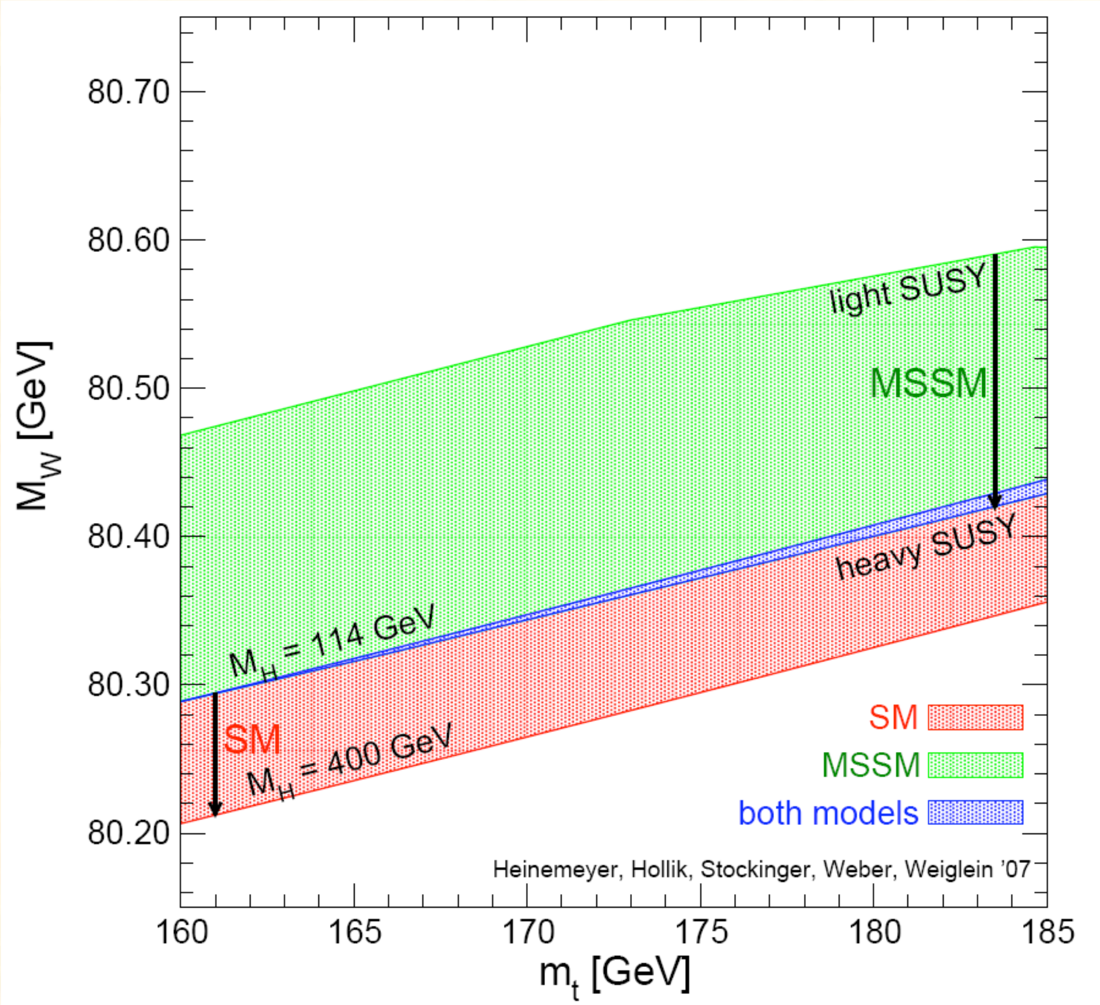
G_F, α_{EM}, $\sin\theta_W$

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

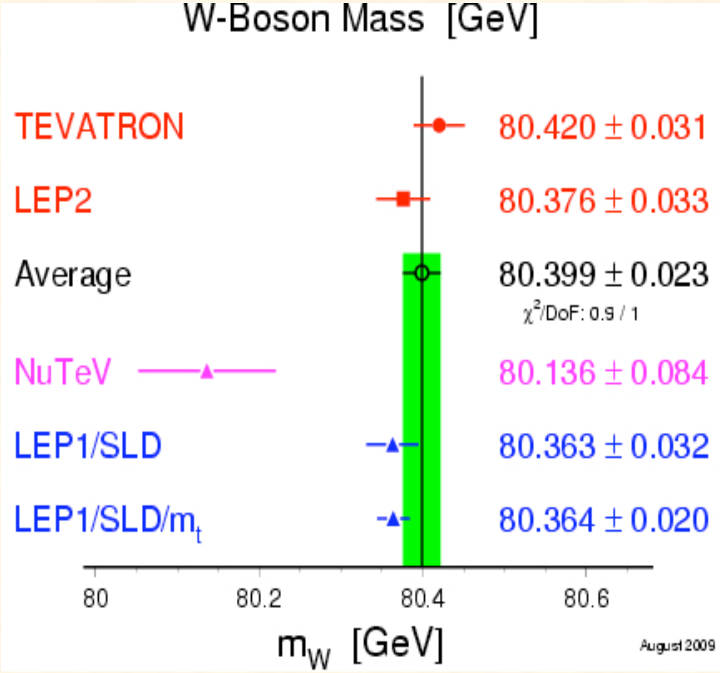
$$m_W = \left(\frac{\pi \alpha_{EM}}{\sqrt{2}\, G_F} \right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

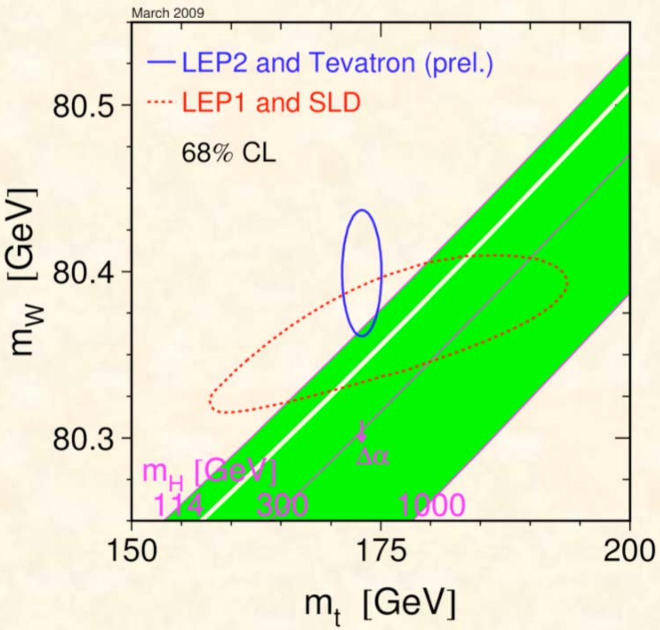
$3 \cdot 10^{-4}$

m_W (from LEP2 + Tevatron) = 80.399 ± 0.023 GeV

m_{top} (from Tevatron) = 173.1 ± 1.3 GeV

0.8%

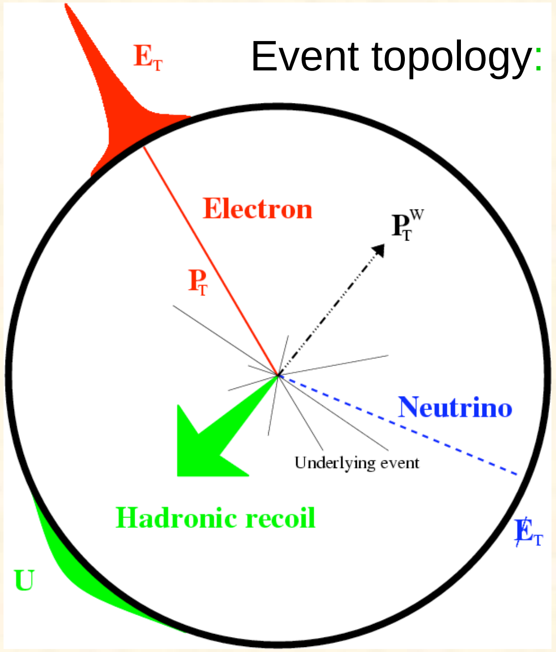


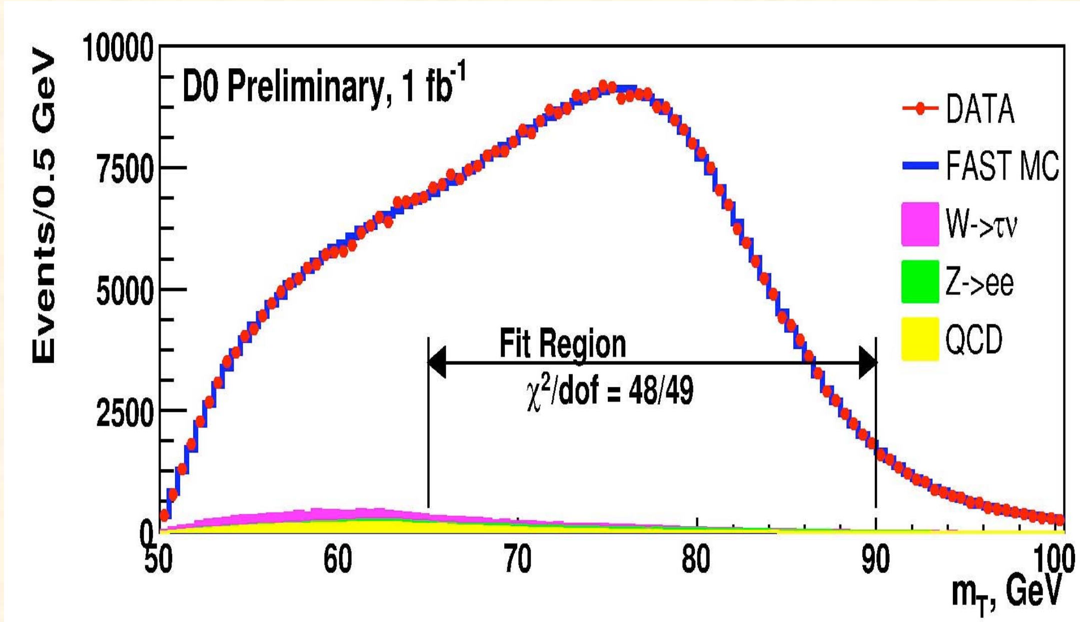


A light Higgs boson is favoured by present measurements

Ultimate test of the Standard Model: comparison between the direct Higgs boson mass and predictions from radiative corrections….

Technique used for W mass measurement at hadron colliders:





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

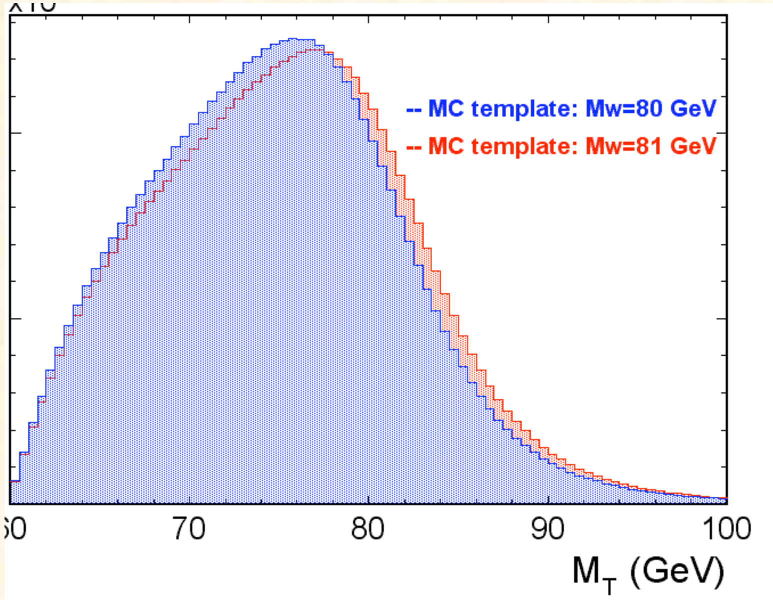
$\Rightarrow$ $P_T(\nu)$ = - ($P_T(e)$ + $P_T(had)$)

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

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



Main uncertainties:

Ability of the Monte Carlo to reproduce real life:

- Detector performance
  (energy resolution, energy scale, ...)

- Physics: production model
  $p_T(W)$, Γ_W, ...

- Backgrounds

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

Numbers for a single decay channel

$W \rightarrow e\nu$

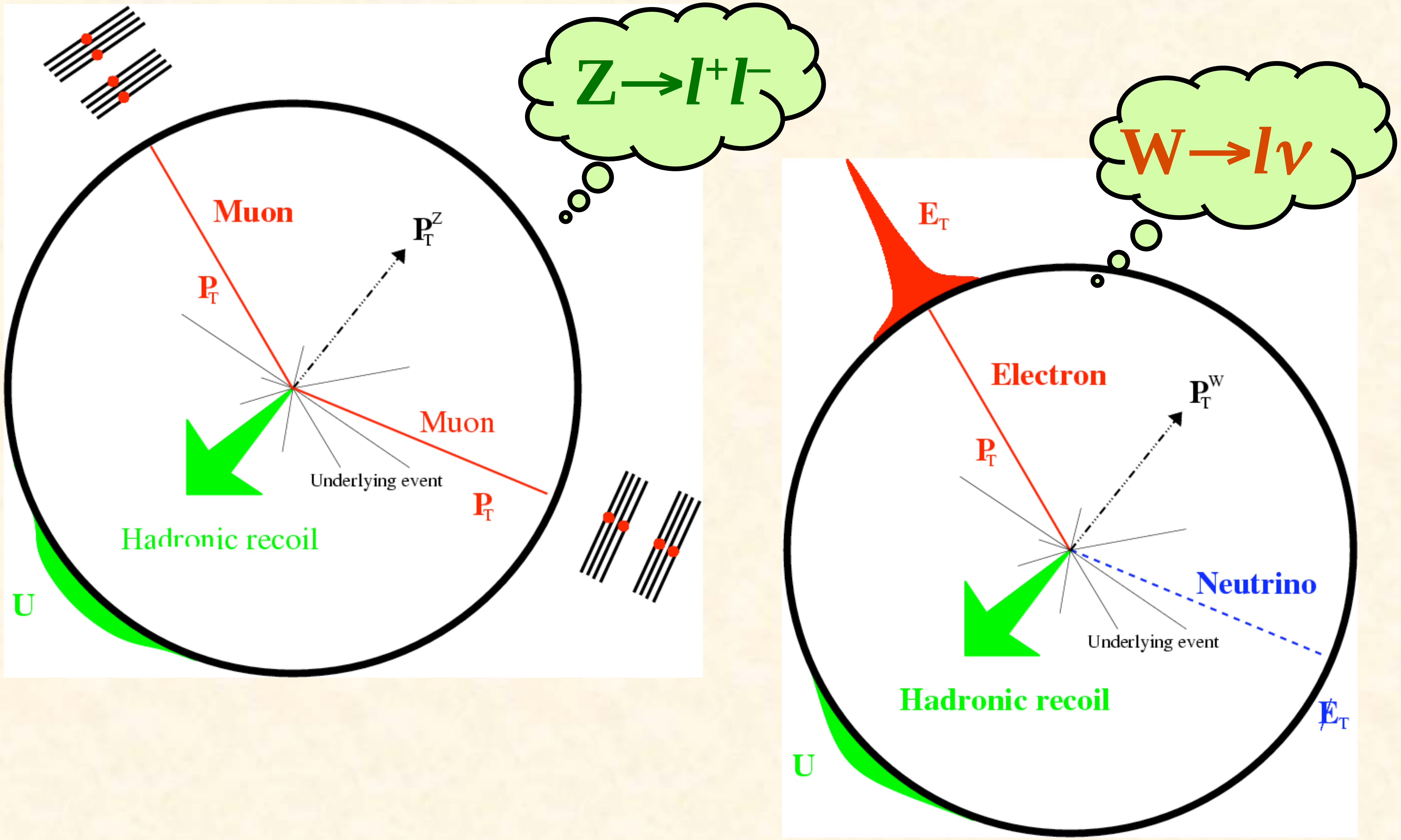
Int. Luminosity	CDF 0.2 fb^{-1}	DØ 1 fb^{-1}	LHC 10 fb^{-1}
Stat. error	**48 MeV**	**23 MeV**	**2 MeV**
Energy scale, lepton res.	30 MeV	34 MeV	4 MeV
Monte Carlo model (P_T^W, structure functions, photon-radiation….)	16 MeV	12 MeV	7 MeV
Background	8 MeV	2 MeV	2 MeV
Tot. Syst. error	**39 MeV**	**37 MeV**	**8 MeV**
Total error	**62 MeV**	**44 MeV**	**~10 MeV**

- Tevatron numbers are based on real data analyses
- LHC numbers should be considered as „ambitious goal“
  - Many systematic uncertainties can be controlled in situ, using the large $Z \rightarrow \ell\ell$ sample (p_T(W), recoil model, resolution)
  - Lepton energy scale of ± 0.02% has to be achieved to reach the quoted numbers

Combining both experiments (ATLAS + CMS, 10 fb^{-1}), both lepton species and assuming a scale uncertainty of ± 0.02% a total error in the order of

$\Rightarrow$ Δm_W ~ ± 10 - 15 MeV might be reached.

Signature of Z and W decays



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

Numbers for a single decay channel

$W \to e\nu$

Int. Luminosity	CDF 0.2 fb^{-1}	DØ 1 fb^{-1}	LHC 10 fb^{-1}
Stat. error	**48 MeV**	**23 MeV**	**2 MeV**
Energy scale, lepton res.	30 MeV	34 MeV	4 MeV
Monte Carlo model (P_T^W, structure functions, photon-radiation….)	16 MeV	12 MeV	7 MeV
Background	8 MeV	2 MeV	2 MeV
Tot. Syst. error	**39 MeV**	**37 MeV**	**8 MeV**
Total error	**62 MeV**	**44 MeV**	**~10 MeV**

- Tevatron numbers are based on real data analyses
- LHC numbers should be considered as „ambitious goal“
  - Many systematic uncertainties can be controlled in situ, using the large $Z \to \ell\ell$ sample (PT(W), recoil model, resolution)
  - Lepton energy scale of ± 0.02% has to be achieved to reach the quoted numbers

Combining both experiments (ATLAS + CMS, 10 fb^{-1}), both lepton species and assuming a scale uncertainty of ± 0.02% a total error in the order of

$\Rightarrow$ $\Delta m_W \sim \pm$ 10 - 15 MeV might be reached.

Top mass measurements

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

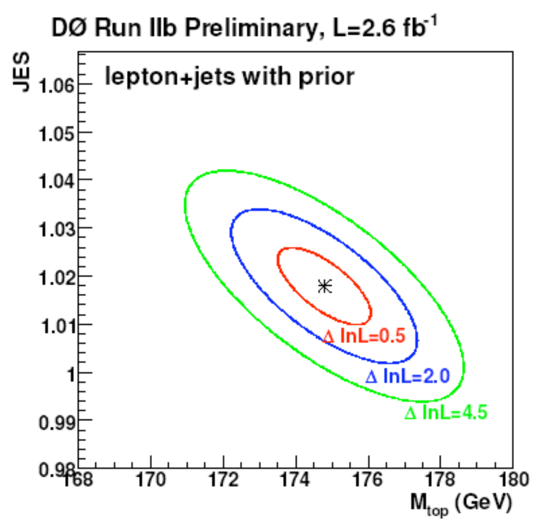
  → template methods,…
  matrix element method…

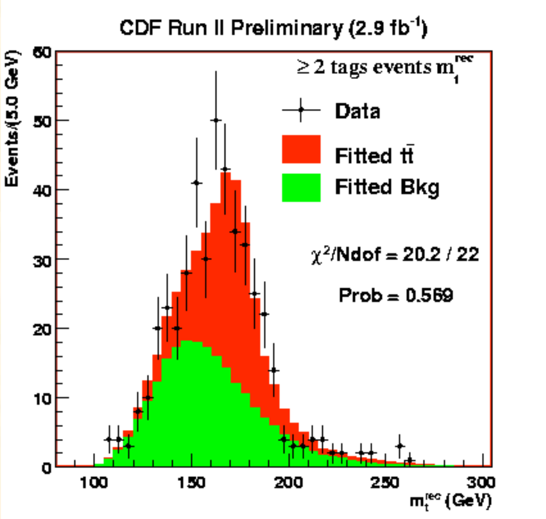
Most precise single measurements:

m_{top} = 172.1 ± 0.9 (stat) ± 1.3 (syst) GeV/c^2 (CDF)

m_{top} = 173.7 ± 0.8 (stat) ±1.6 (syst) GeV/c^2 (DØ)

- Reduce jet energy scale systematic by using in-situ hadronic W mass in tt events
  (simultaneous determination of m_t and energy scale)

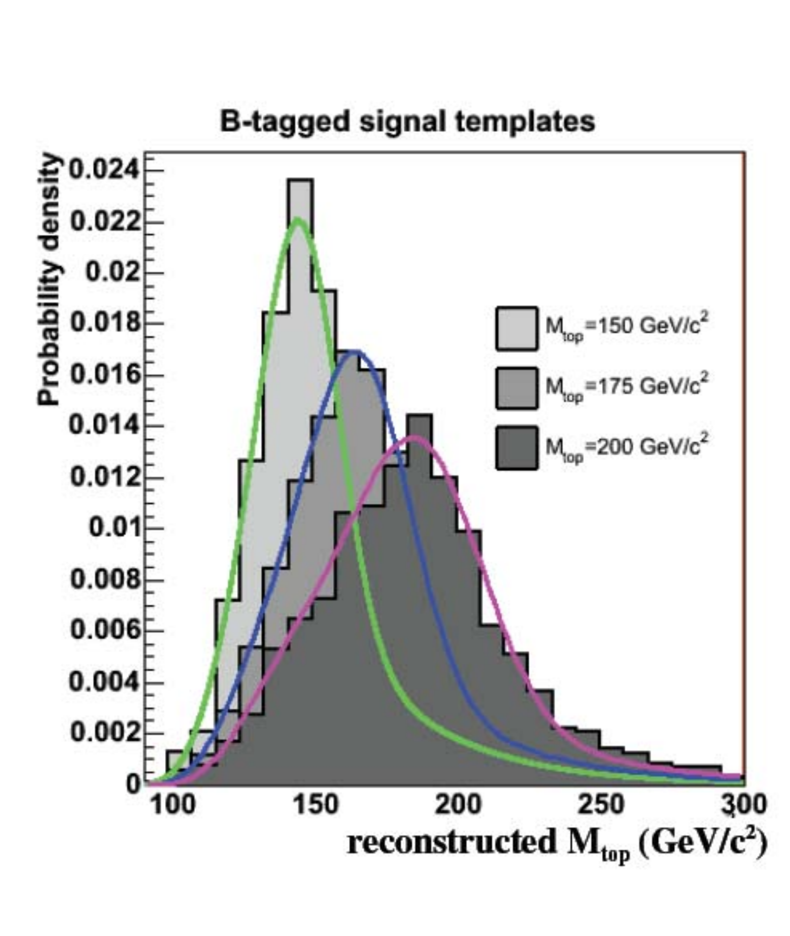




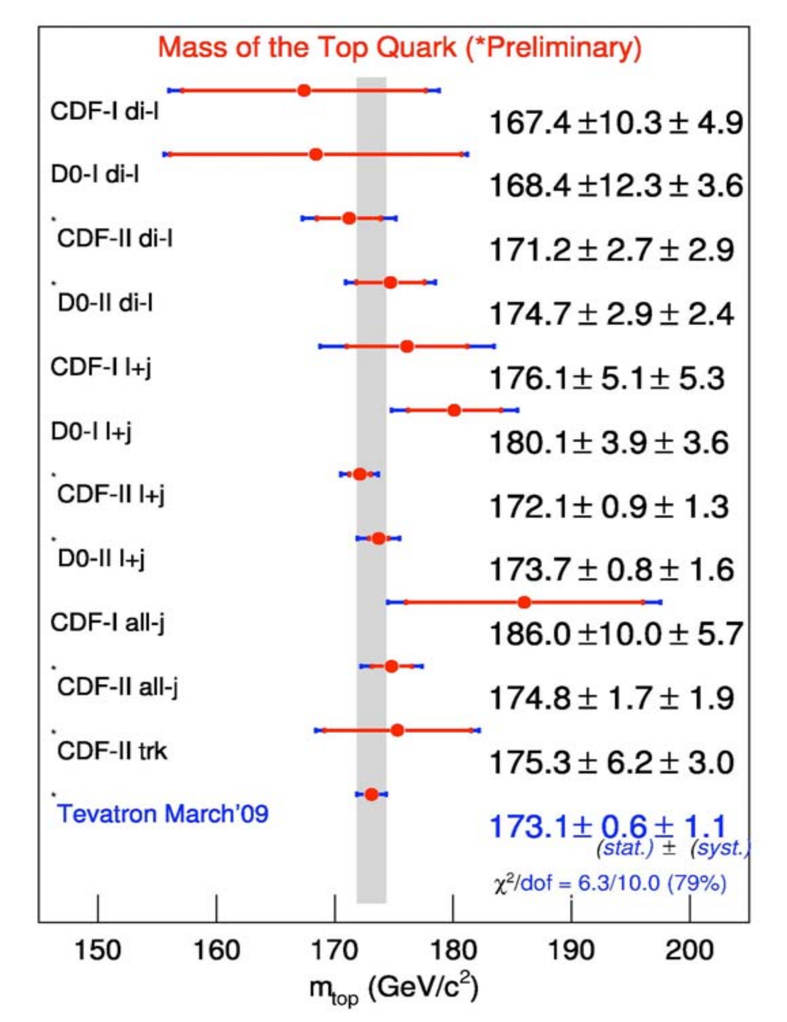
full hadronic channel

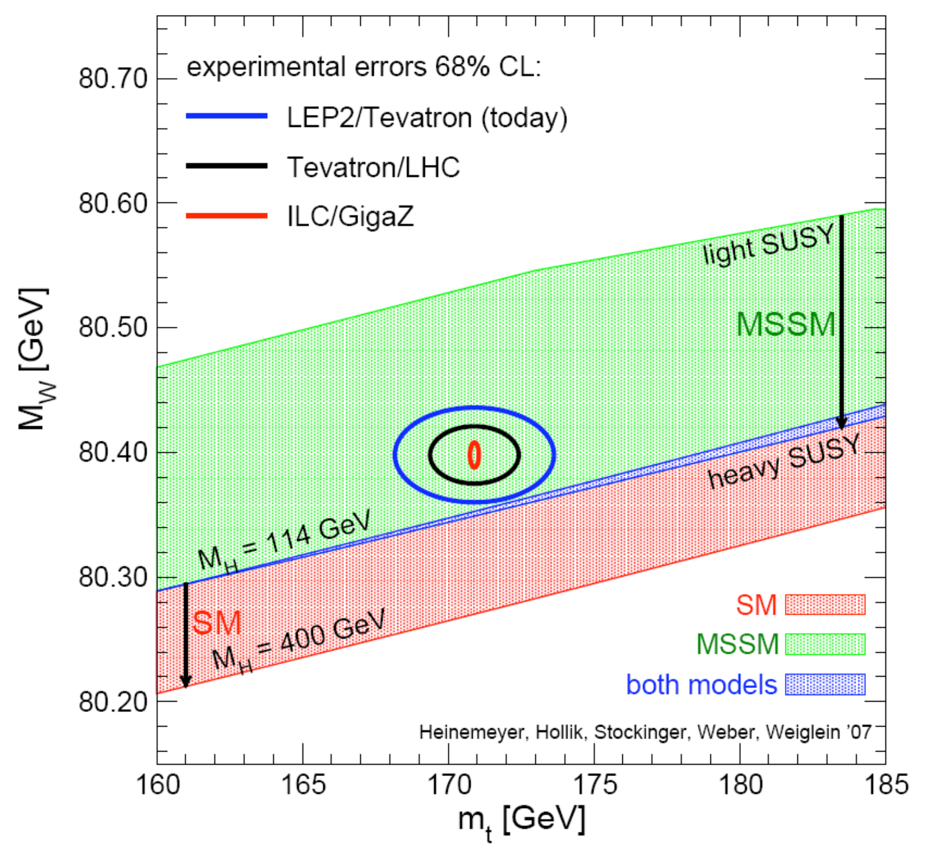
Example: template method

- 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



Summary of present results and future prospects

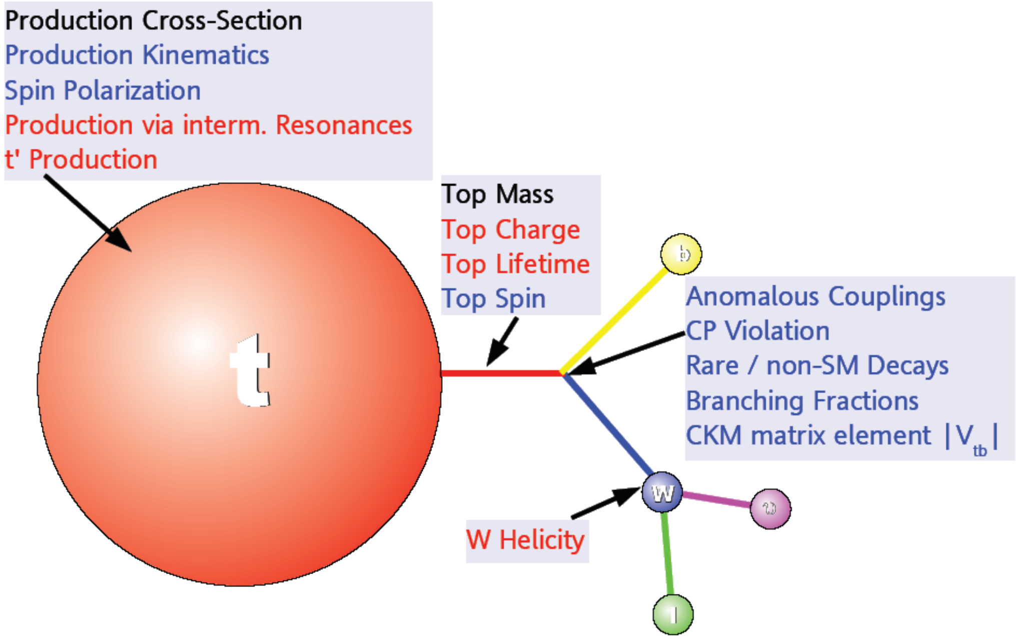


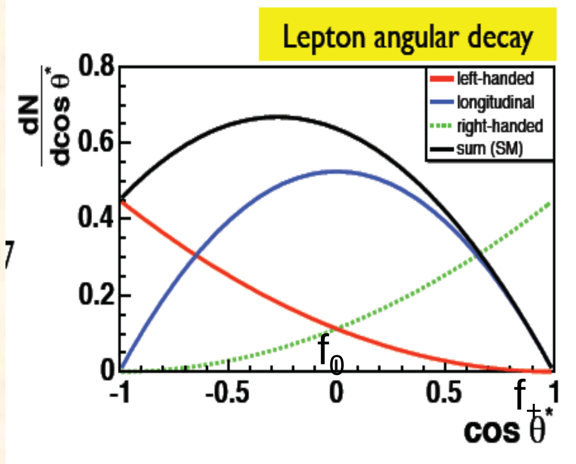


Expected LHC precision for 10 fb^{-1}:
(Combination of several methods, maybe somewhat conservative)

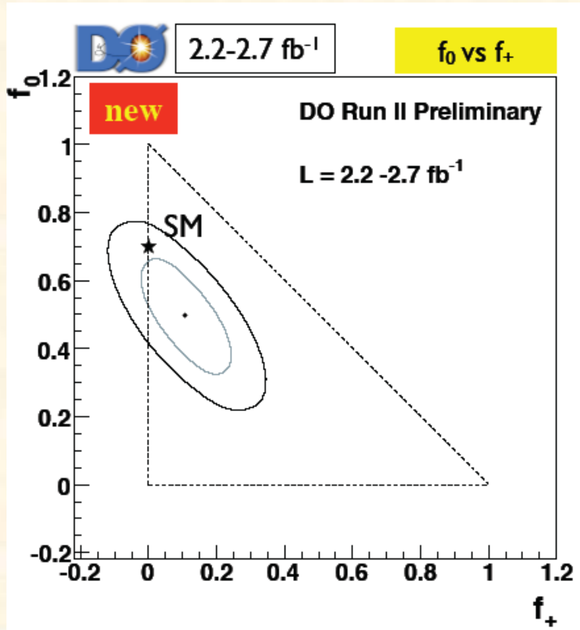
< ~ 1 GeV/c^2

Other top properties

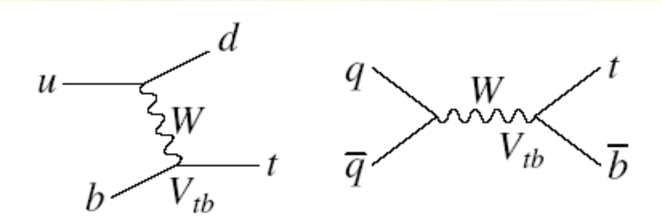


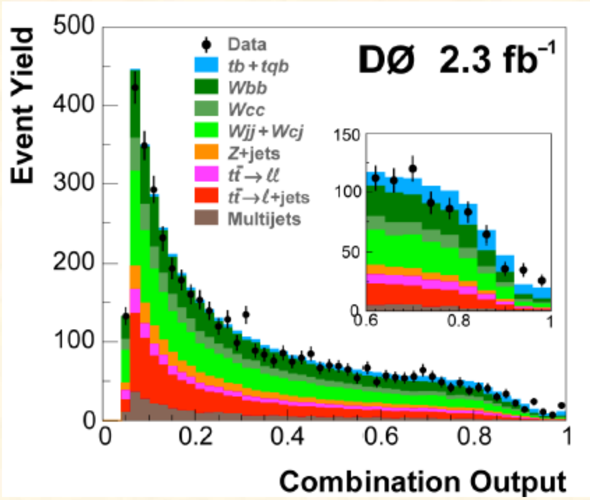


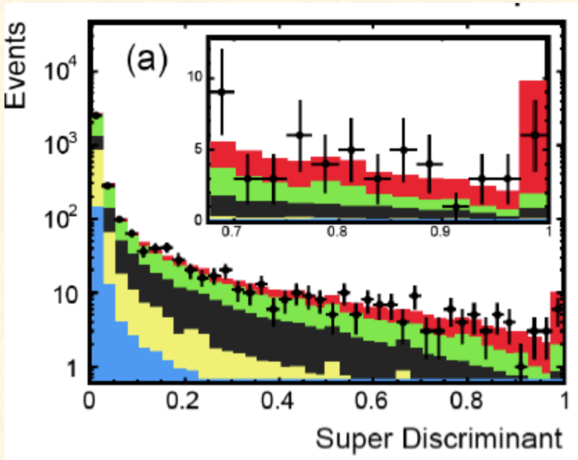
	Tevatron Result	luminosity (fb^{-1})
Mass	173.1 ± 1.3 GeV	~ 3.0
W helicity	CDF: f_0 = 0.66 ± 0.16, f_+ = -0.03 ± 0.07 DØ: f_0 = 0.49 ± 0.14 f_+ = 0.11 ± 0.08	1.9 2.2 – 2.7
Charge Lifetime $\mathbf{V_{tb}}$ BR(t→Wb) / BR(W→Wq) BR (t → Zq)	rule out Q = +4/3 (90.% C.L.) Γ_t < 13.1 GeV (95% C.L.) V_{tb} > 0.89 (95% C.L.) R = 0.97 (+0.09) (-0.08) < 3.7% (95% C.L.)	1.5 ~ 1.0 0.9



First observation of Single Top Production at the Tevatron

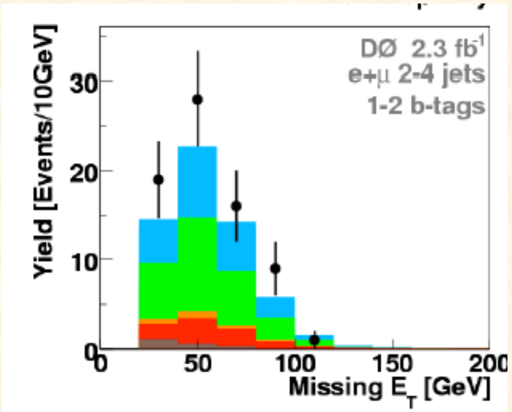


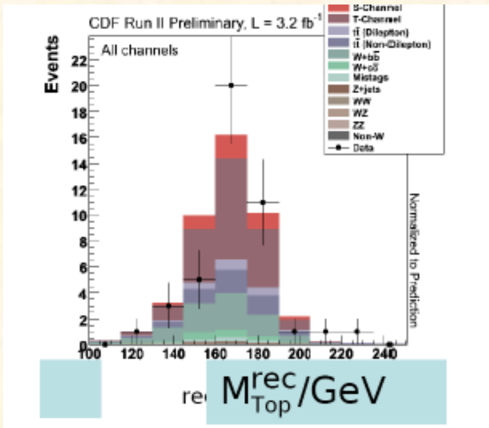


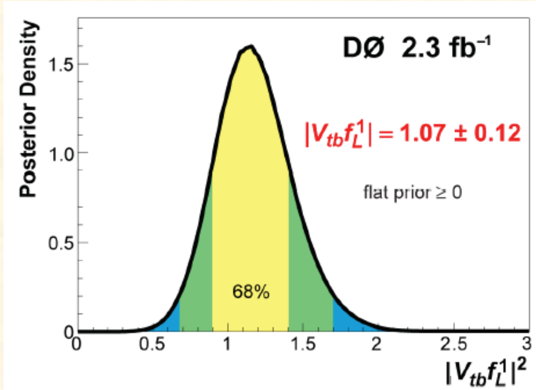


Combined Results

	$\mathcal{L}$ [fb^{-1}]	Significance Exp.	Significance Obs.	σ_{s+t} [pb]
DØ	2.3	4.5σ	5.0σ	$3.9^{+0.9}_{-0.9}$
CDF	3.2	5.9σ	5.0σ	$2.3^{+0.6}_{-0.5}$







$|V_{tb}f_{L1}| = 1.07 \pm 0.12$,
$|V_{tb}| > 0.78$ at 95% CL

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 ~10 - 15 MeV
Top-quark mass to better than ~ 1 GeV