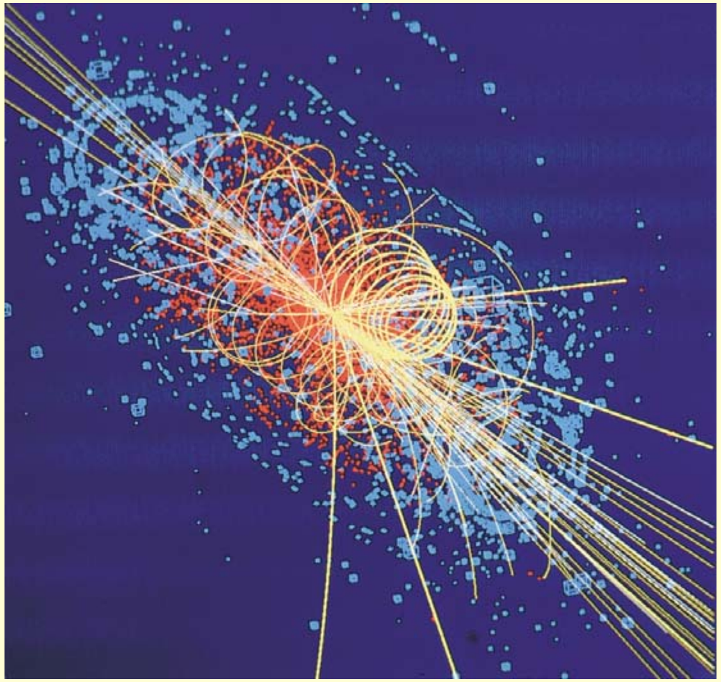
Physics at Hadron Colliders

Part 2



Standard Model Physics

Test of Quantum Chromodynamics

- Jet production
- W/Z production
- Production of Top quarks

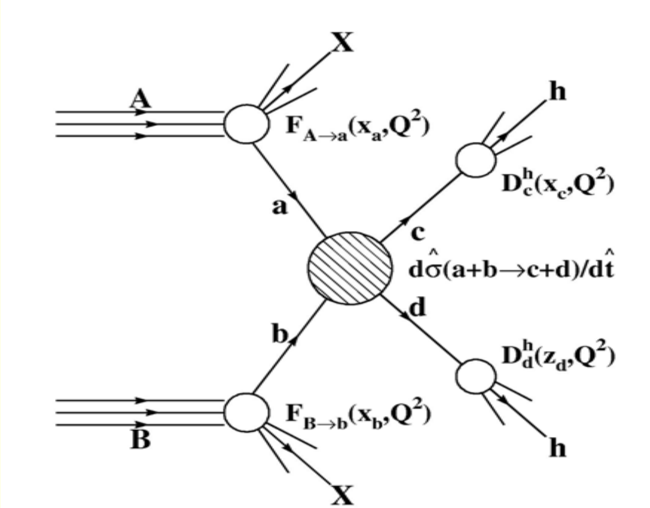
Electroweak measurements

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

Search for a SM Higgs Boson

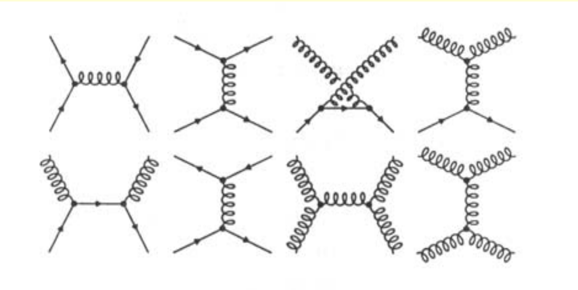
- Introduction
- Tevatron results

QCD processes at hadron colliders

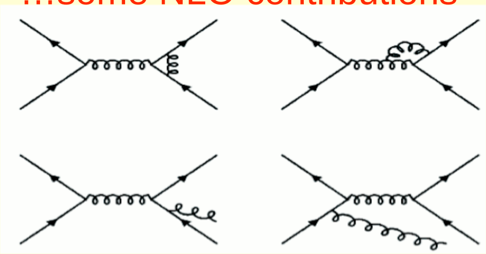


- Hard scattering processes are dominated by QCD jet production
- Originating from qq, qg and gg scattering
- Cross sections can be calculated in QCD (perturbation theory)

Leading order



…some NLO contributions



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

Deviations?

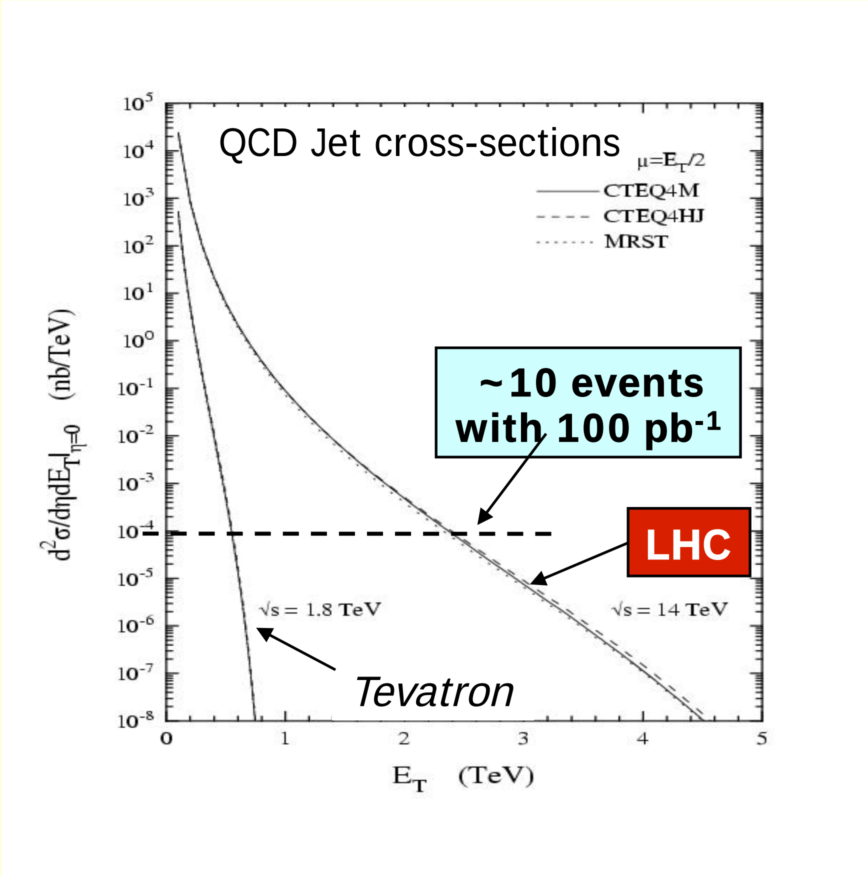
→ Problem in the experiment ?
Problem in the theory (QCD) ?
New Physics, e.g. quark substructure ?

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

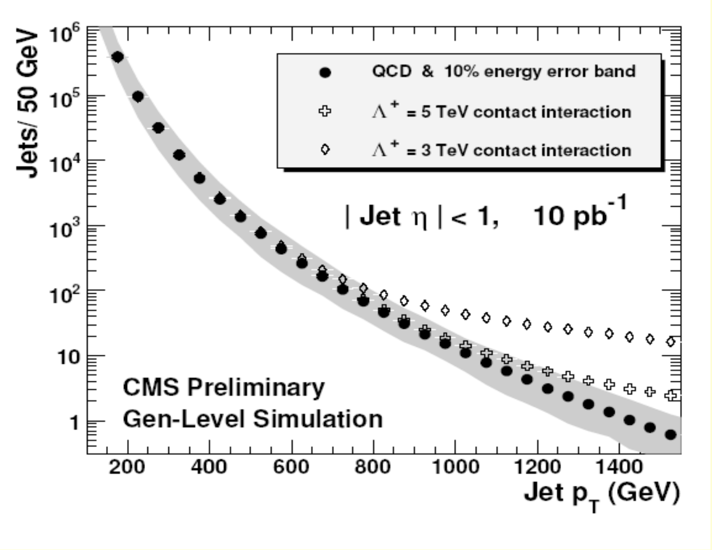


In addition to QCD test: Sensitivity to New Physics

- 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

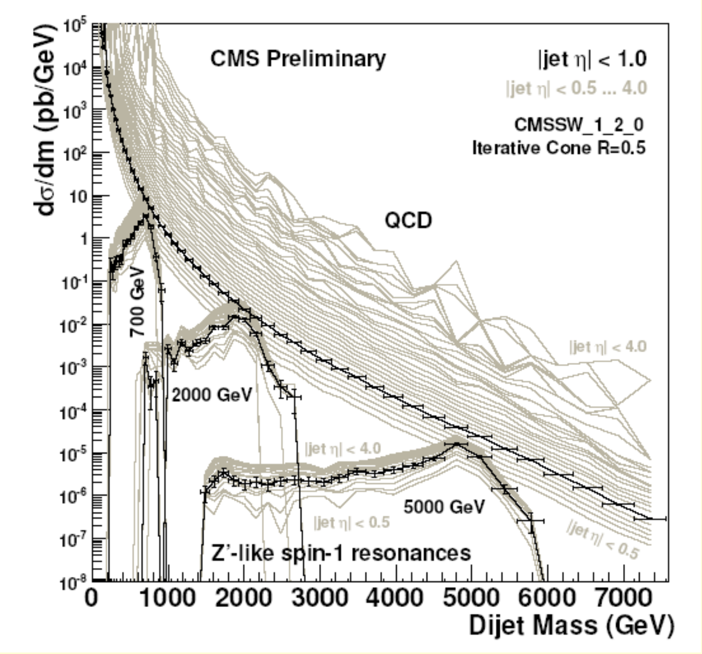
Search for deviations from QCD in the high p_T region



- Heavy resonances decaying into jets

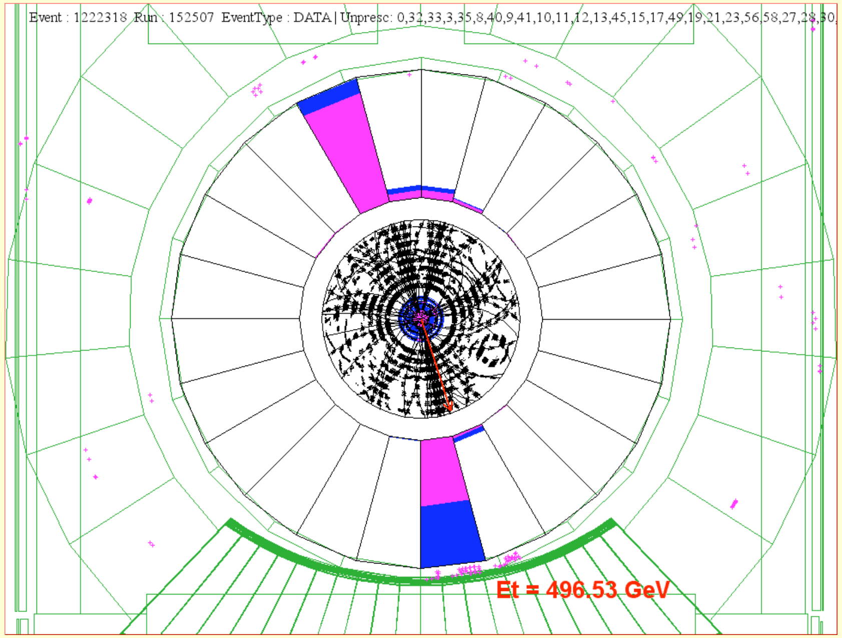
e.g. $Z' \rightarrow qq$

Search for resonant structures in dijet invariant mass spectrum

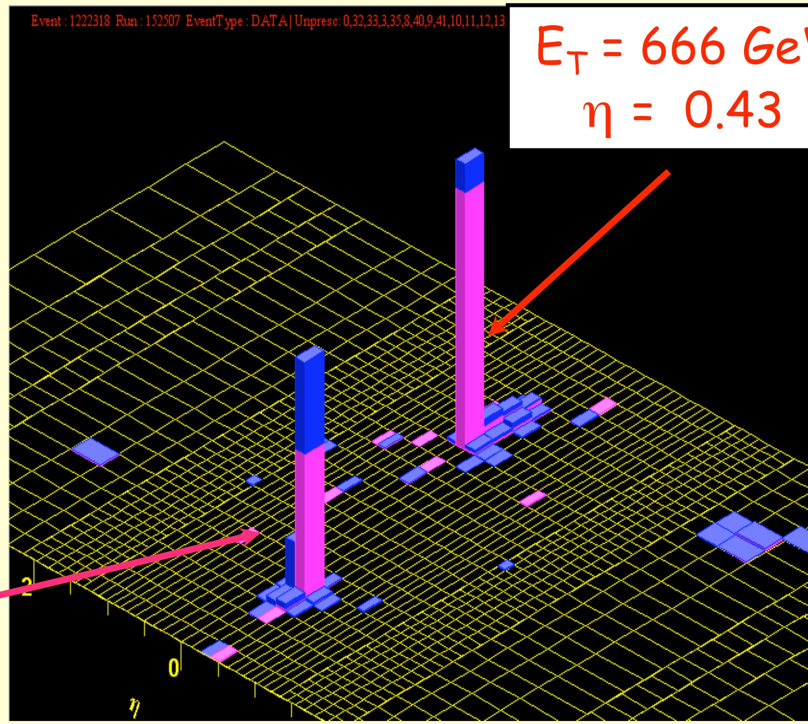


→ Results on Friday

A two jet event at the Tevatron (CDF)



Dijet Mass = 1364 GeV/c^2



E_T = 666 GeV
η = 0.43

CDF (ϕ-r view)

E_T = 633 GeV
η = -0.19

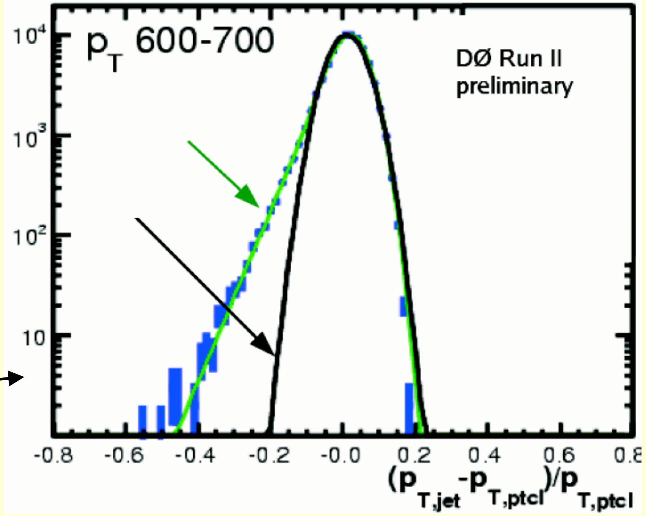
Jet measurements

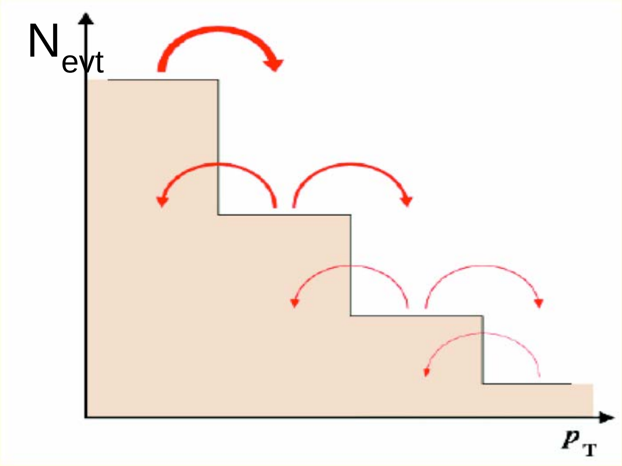
$$d^2\sigma / dp_T\, d\eta = N / (\varepsilon \cdot L \cdot \Delta p_T \cdot \Delta\eta)$$

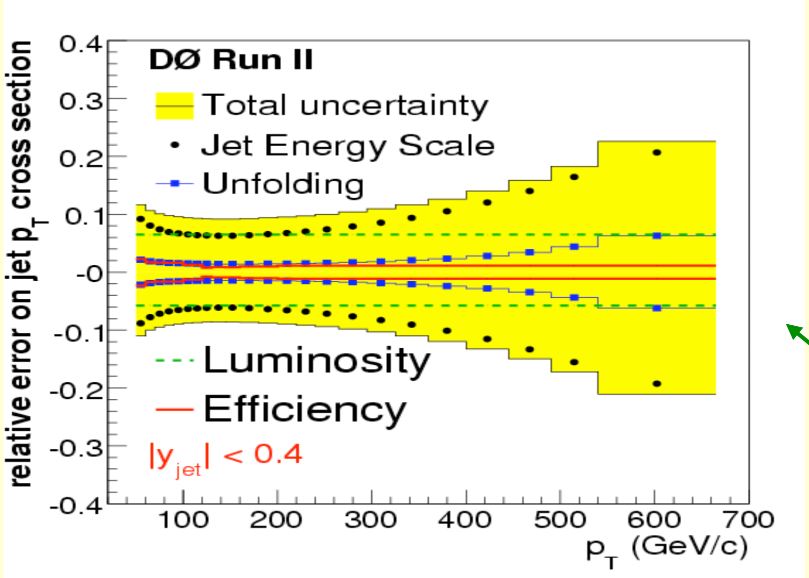
- In principle a simple counting experiment

- 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 $|\eta|<0.4$

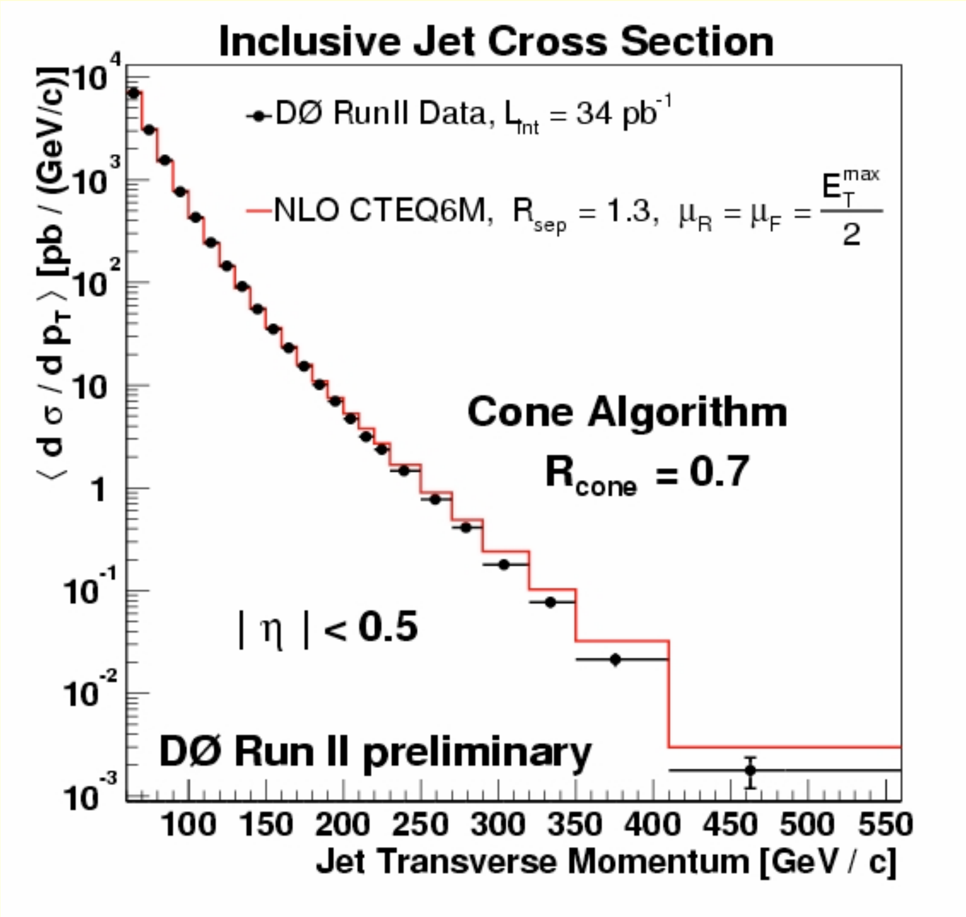






Major exp. errors:
energy scale, luminosity (6%),…

Test of QCD Jet production



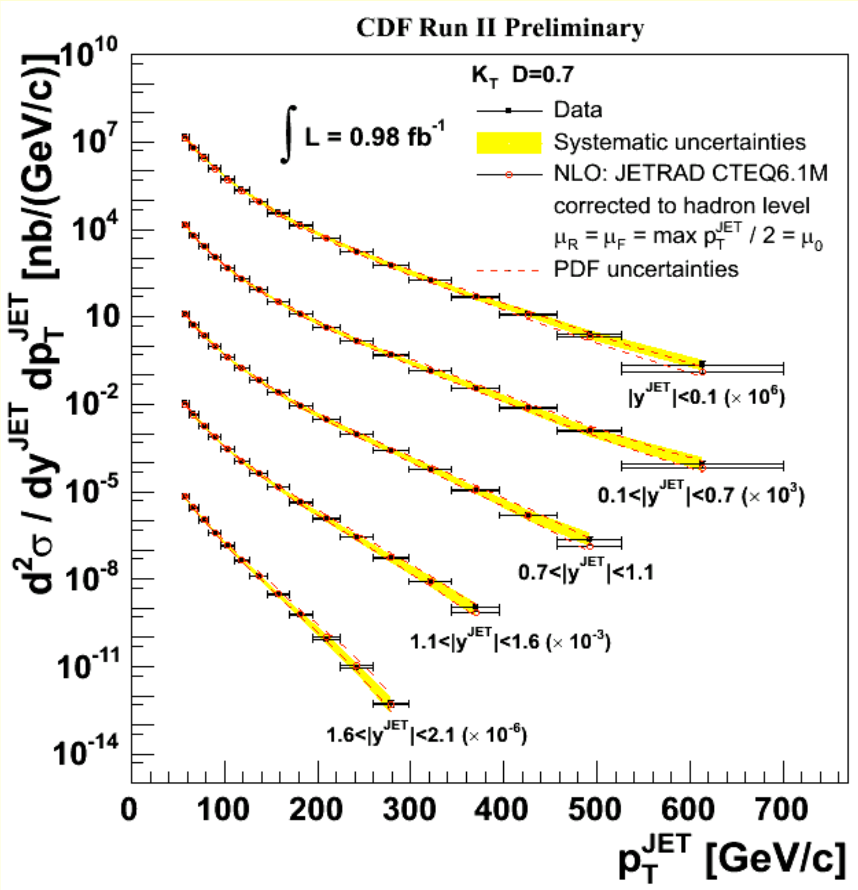
An **"early"** result from the DØ experiment (34 pb^{-1})

Inclusive Jet spectrum as a function of Jet-P_T

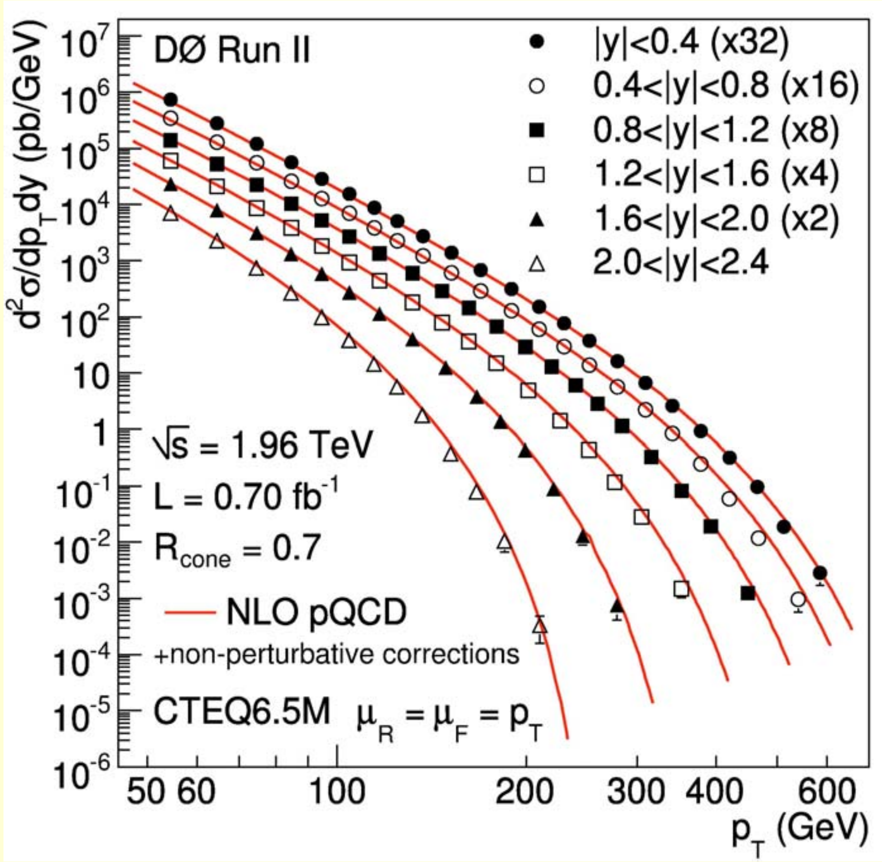
very good agreement with NLO pQCD calculations over many orders of magnitude !

within the large theoretical and experimental uncertainties

Double differential distributions in p_T and η



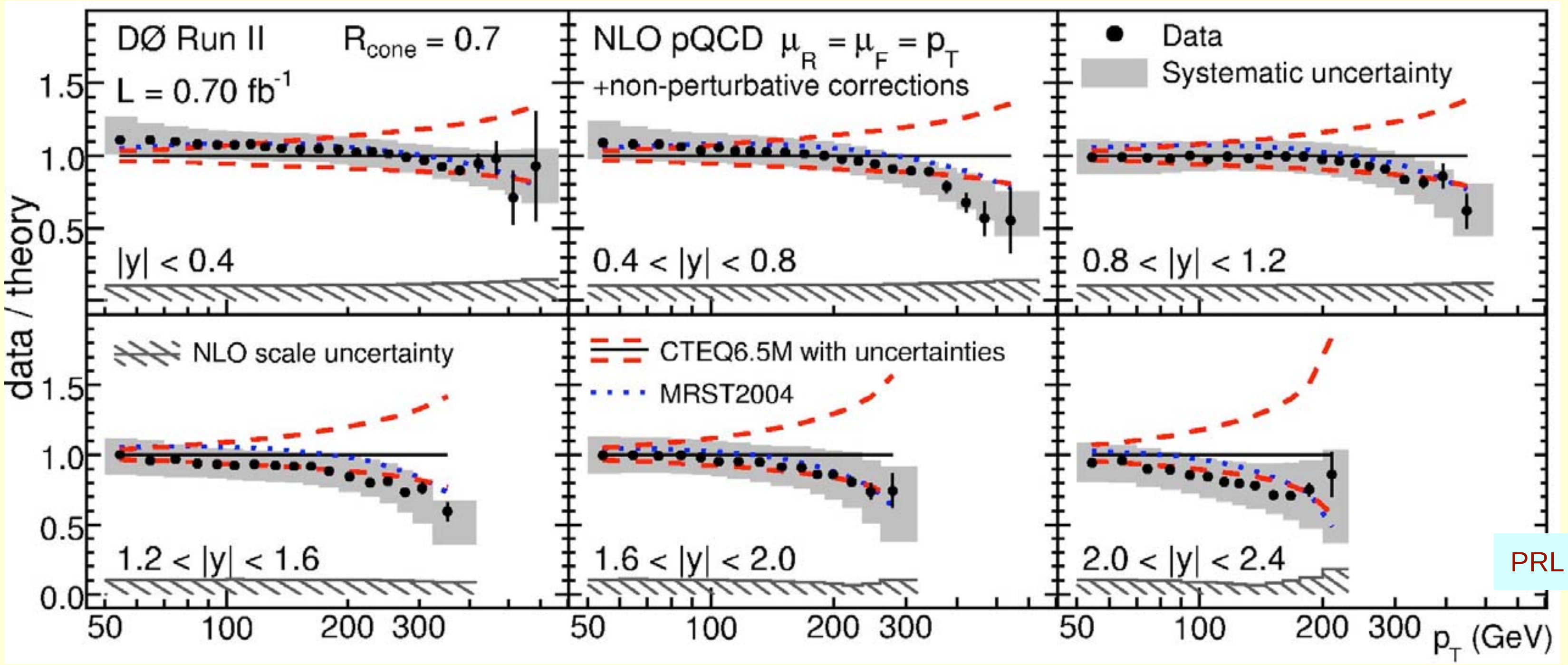
PRD 78 052006 ('08)



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

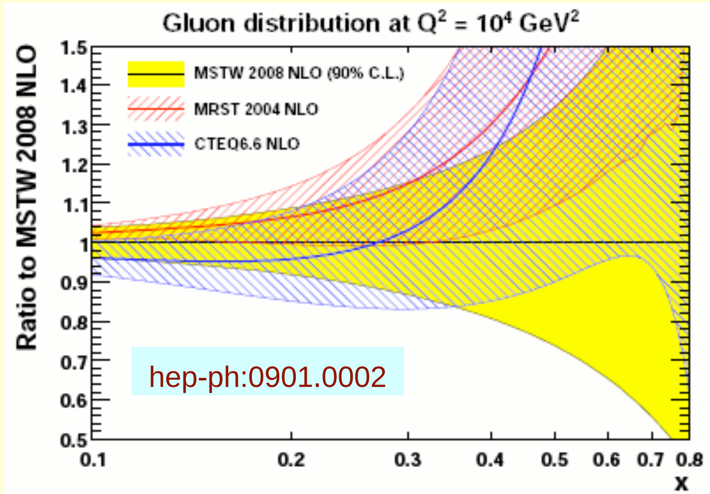


PRL 101 062001 ('08)

- **CDF and DØ agree within uncertainties**

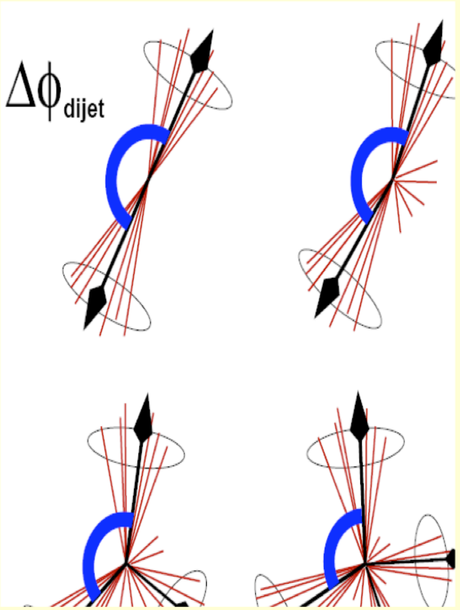
- Experimental uncertainties are smaller than the pdf uncertainties
  (in particular large for large x, gluon distribution)

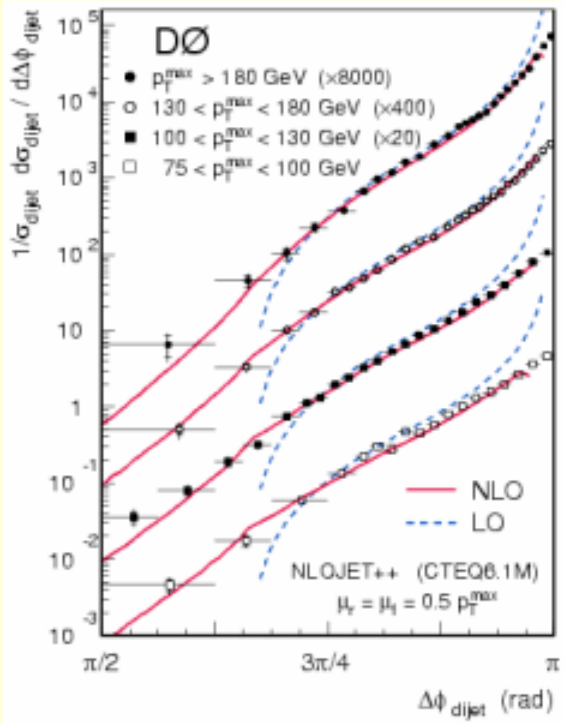
- Wait for updated (2009) parametrizations
  (plans to include Tevatron data, to better constrain the high x-region)

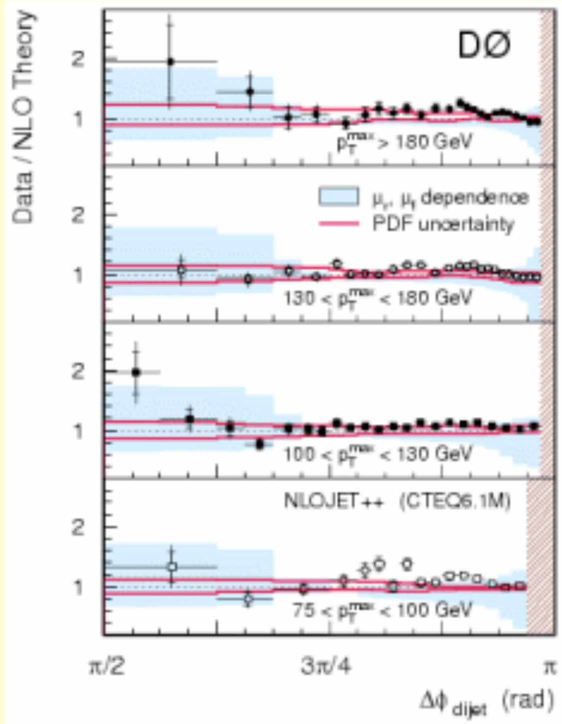


Di-jet angular distributions

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

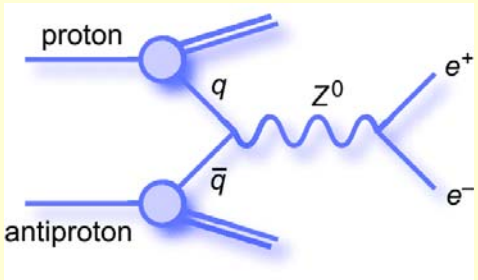




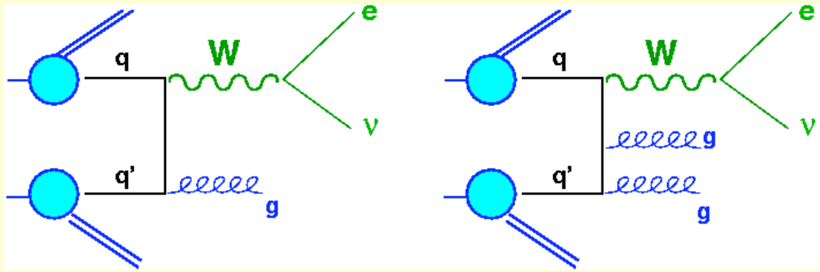


Good agreement with
Next-to-leading order QCD-predictions

QCD aspects in W /Z (+ jet) production



QCD at work

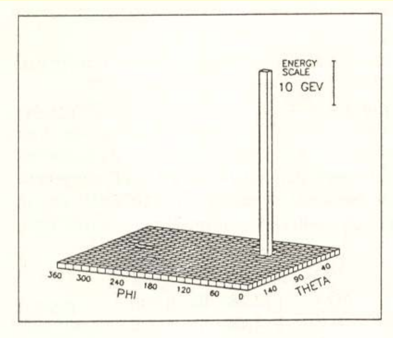


- Important test of NNLO Drell-Yan QCD prediction for the total cross section
- Test of perturbative QCD in high p_T region
  (jet multiplicities, p_T spectra,….)
- Tuning and „calibration“ of Monte Carlos for background predictions in searches at the LHC

How do W and Z events look like ?

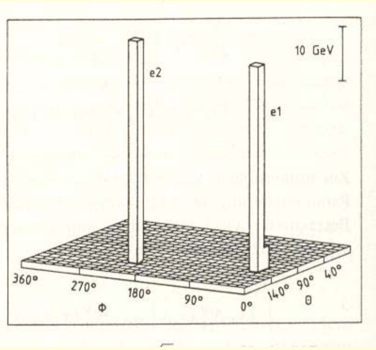
As explained, leptons, photons and missing transverse energy are key signatures at hadron colliders

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

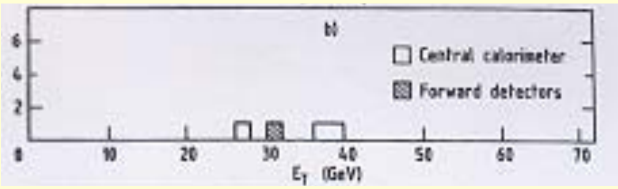


A bit of history: one of the first W events seen; UA2 experiment

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

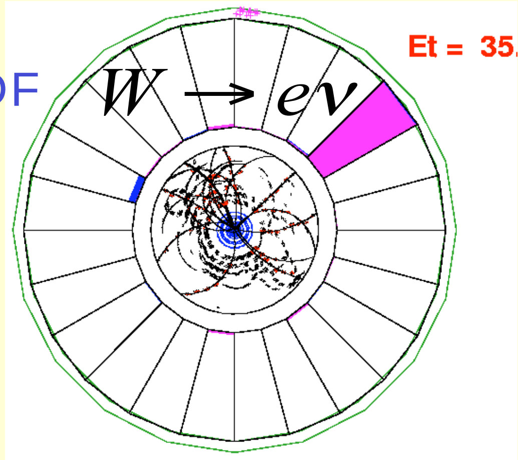


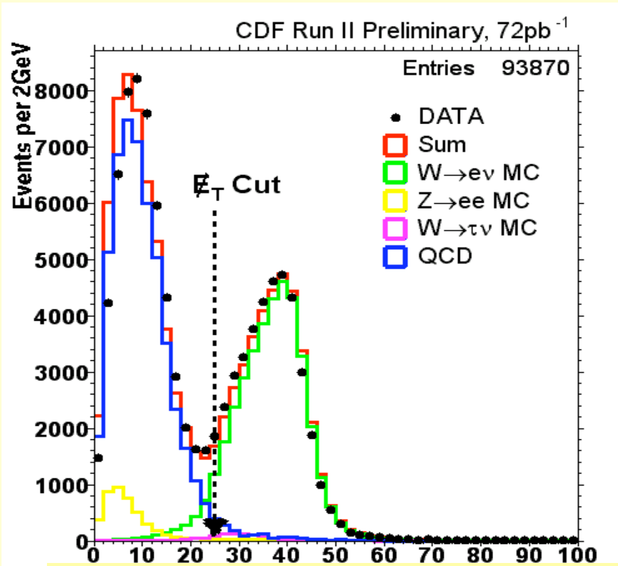
Transverse momentum of the electrons



Today's W / Z $\rightarrow$ 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

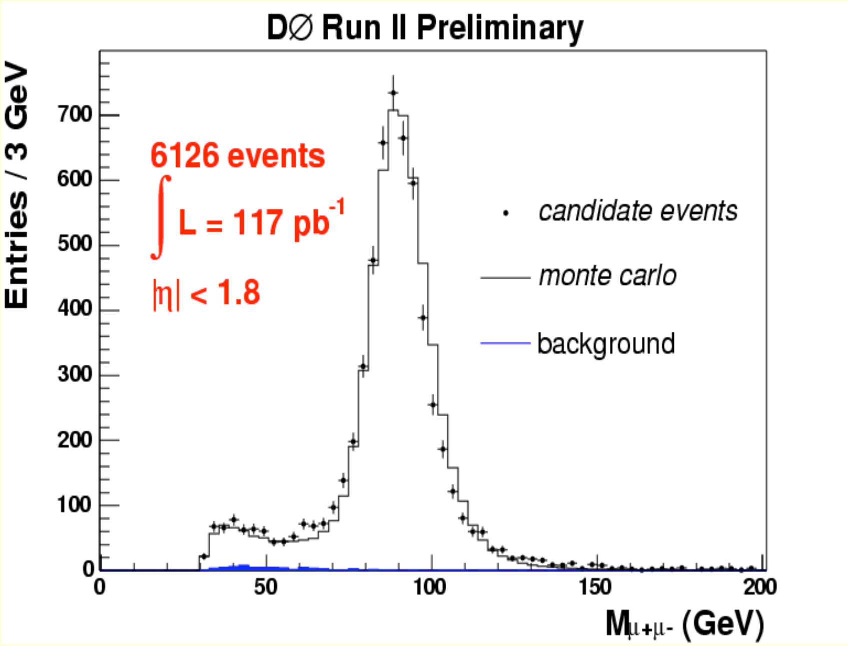
Z $\rightarrow$ ee

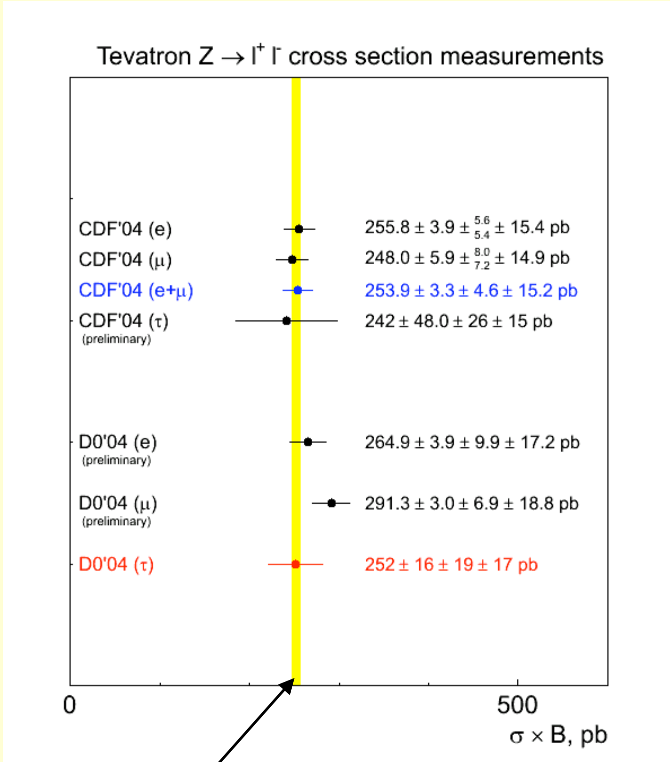
- 70 GeV/c^2 < m_{ee} < 110 GeV/c^2

W $\rightarrow$ eν

- Missing transverse momentum > 25 GeV/c

Z→ ℓℓ cross sections

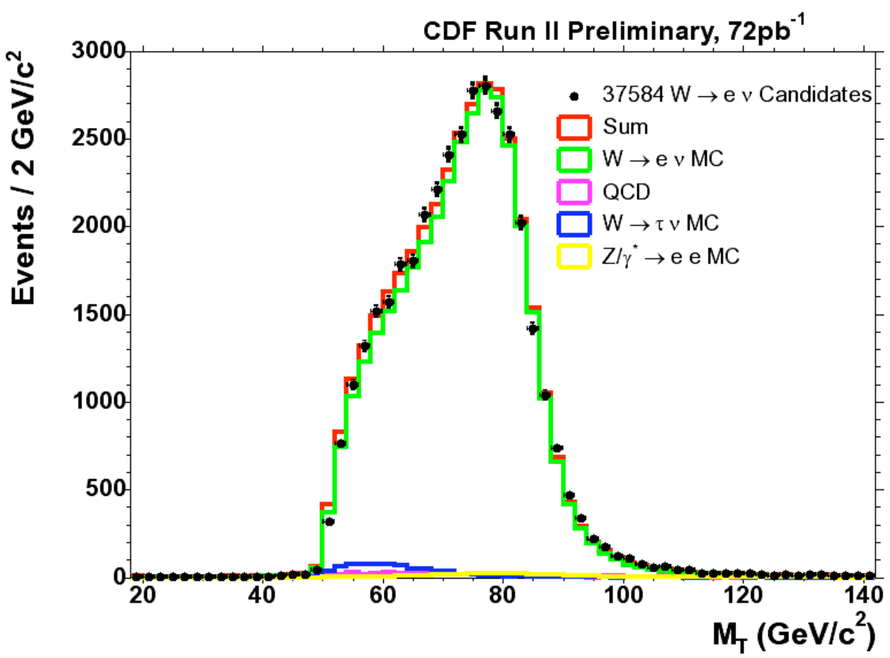


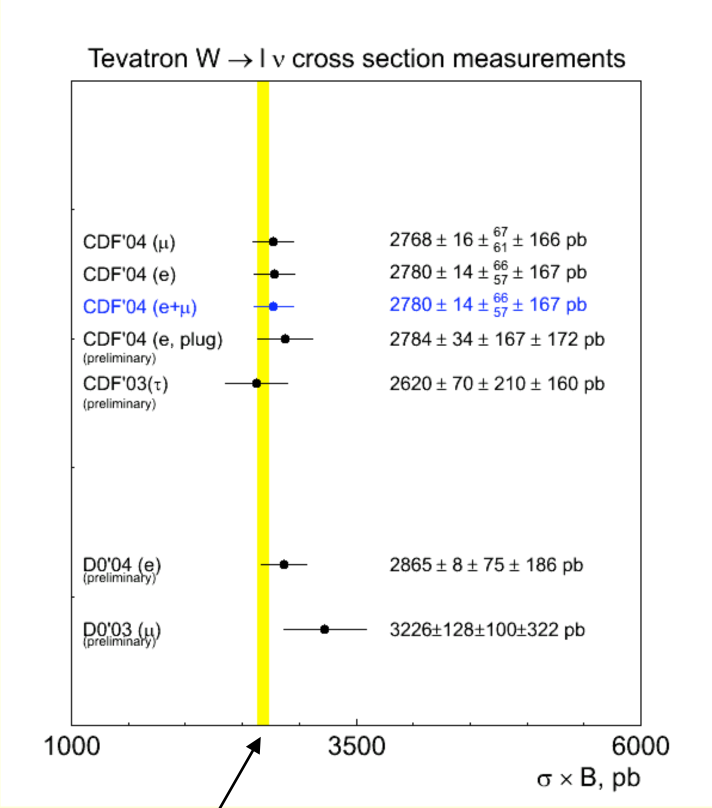


Good agreement with
NNLO QCD calculations,
QCD corrections are large: factor 1.3-1.4
C.R.Hamberg et al, Nucl. Phys. B359 (1991) 343.

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

W → ℓν Cross Section





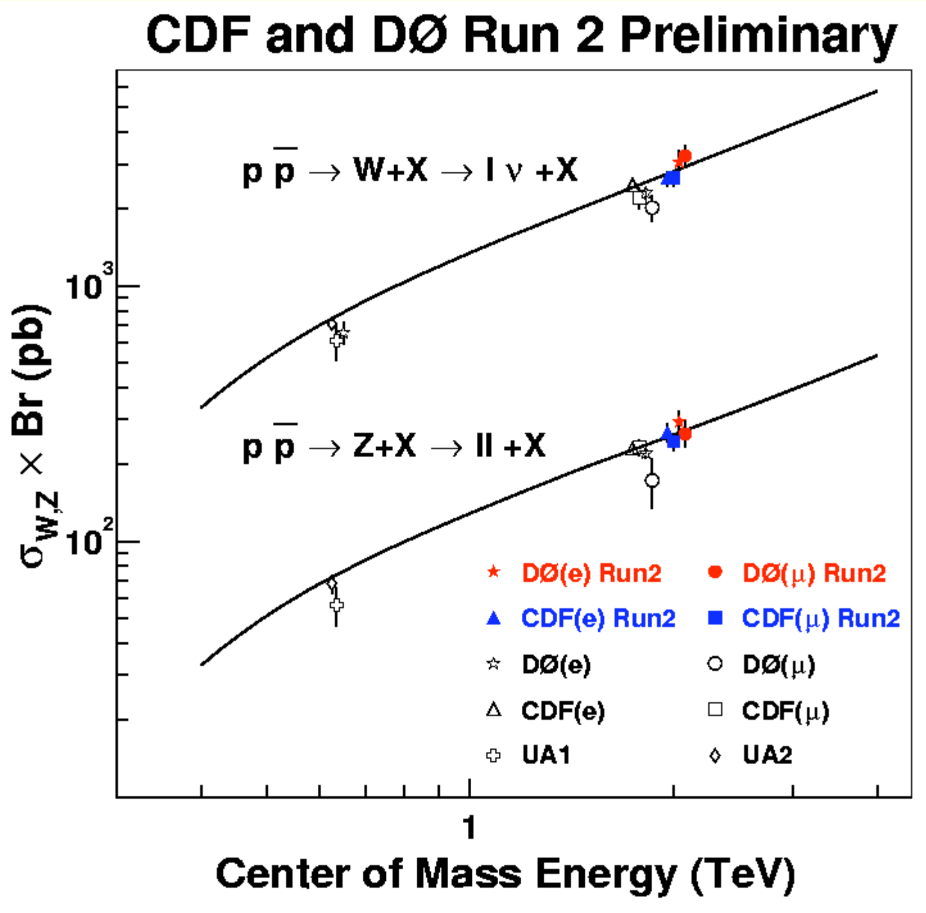
$$M_W^T = \sqrt{2 \cdot P_T^l \cdot P_T^\nu \cdot \left(1 - \cos \Delta\phi^{l,\nu}\right)}$$

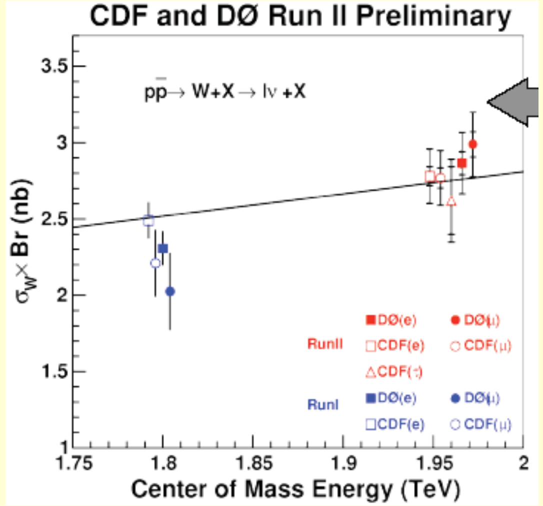
Note: the longitudinal component of the neutrino cannot be measured
→ only transverse mass can be reconstructed

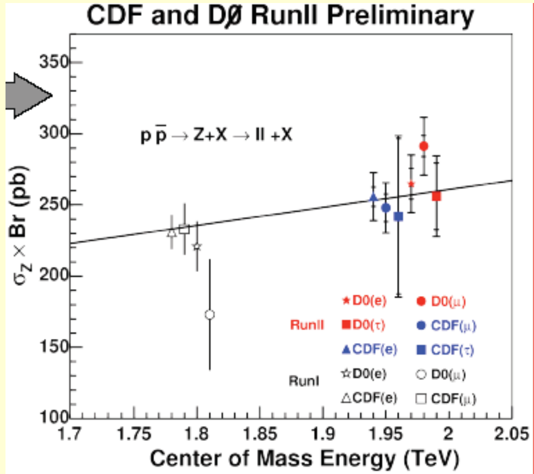
Good agreement with NNLO QCD calculations
C.R.Hamberg et al, Nucl. Phys. B359 (1991) 343.

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

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

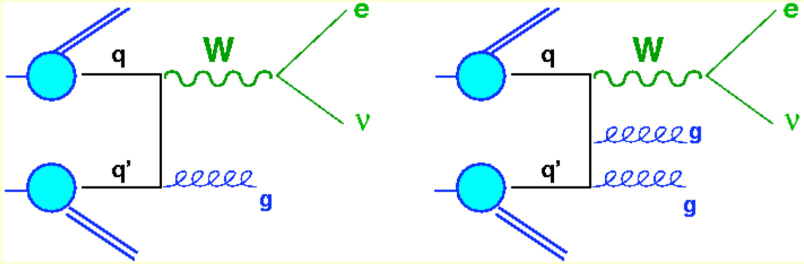






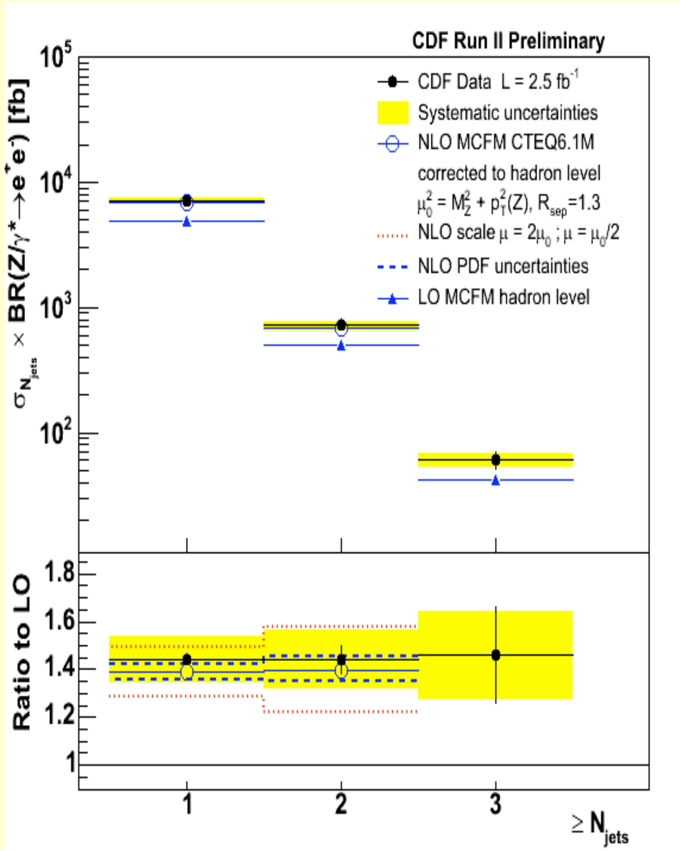
C. R. Hamberg, W.L. van Neerven and T. Matsuura, Nucl. Phys. B359 (1991) 343

QCD Test in W/Z + jet production

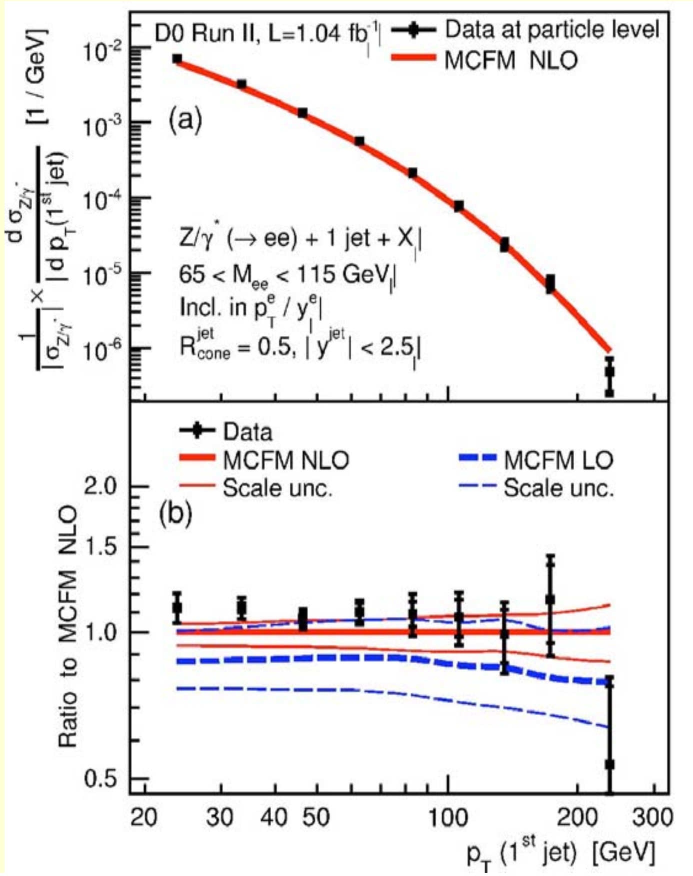


- LO predictions fail to describe the data;
- Jet multiplicities and p_T spectra in agreement with NLO predictions within errors; NLO central value ~10% low

Jet multiplicities in Z+jet production

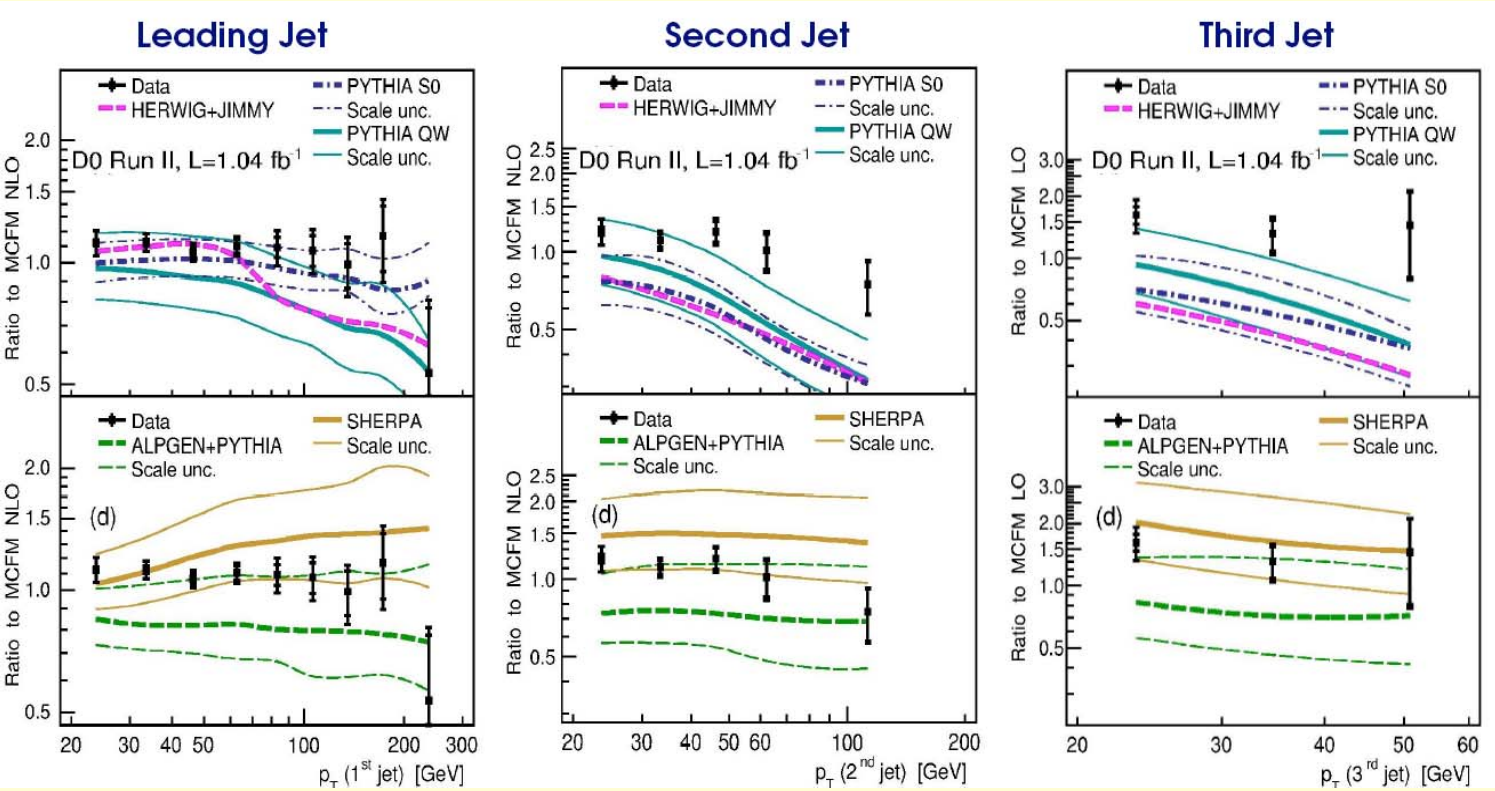


p_T spectrum of leading jet



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)



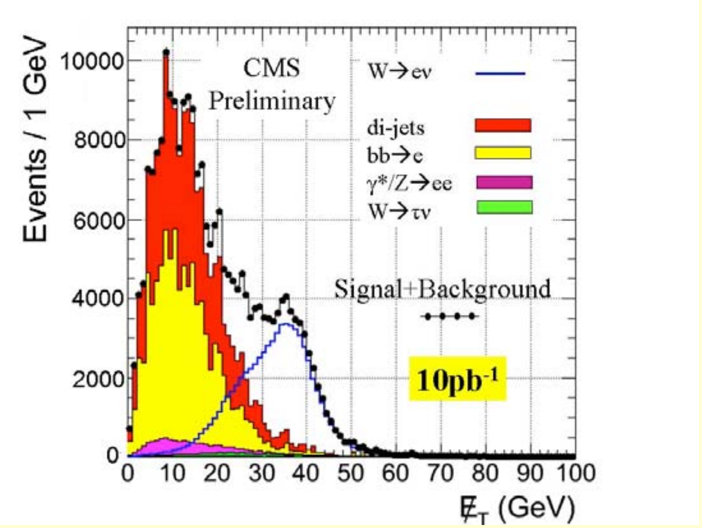
- Conclusions: (important for LHC)
  - Parton shower Monte Carlos fail to describe the higher jet p_T spectra;
  - Better agreement for ALPGEN and SHERPA, parameters can be tuned to describe them, but uncertainties -linked to the underlying tree level calculations- remain large;
  - It would be desirable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

W and Z Cross sections at the LHC

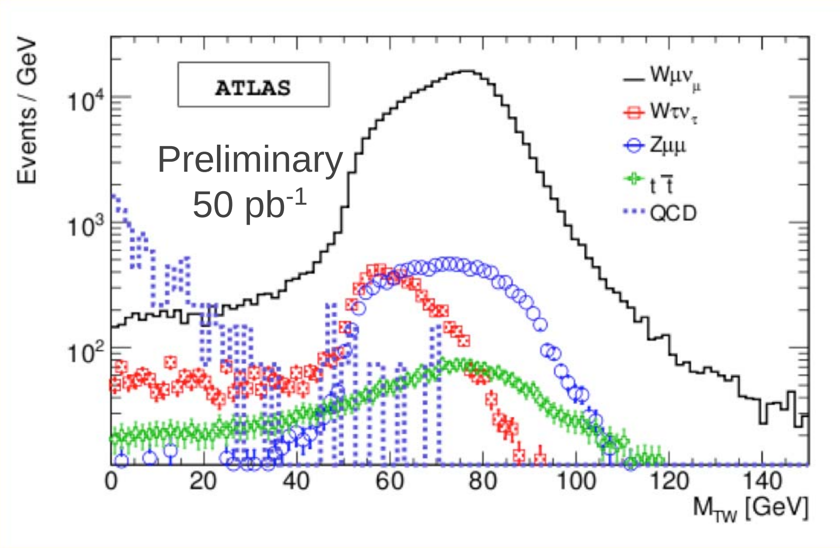
Even with early data (10-50 pb^{-1}),
high statistics of W and Z samples

→ data-driven cross-section measurements

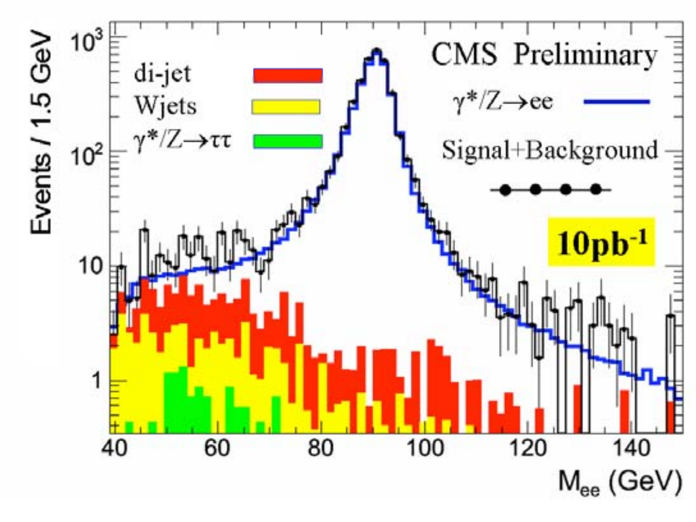
W → e ν



W → μ ν



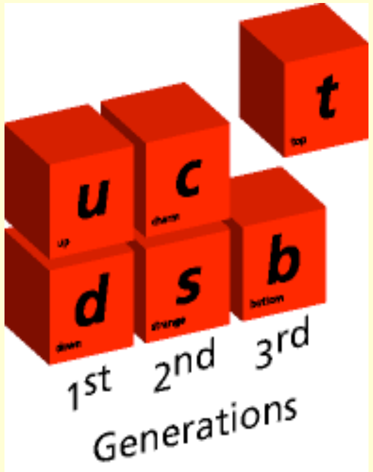
Z → ee

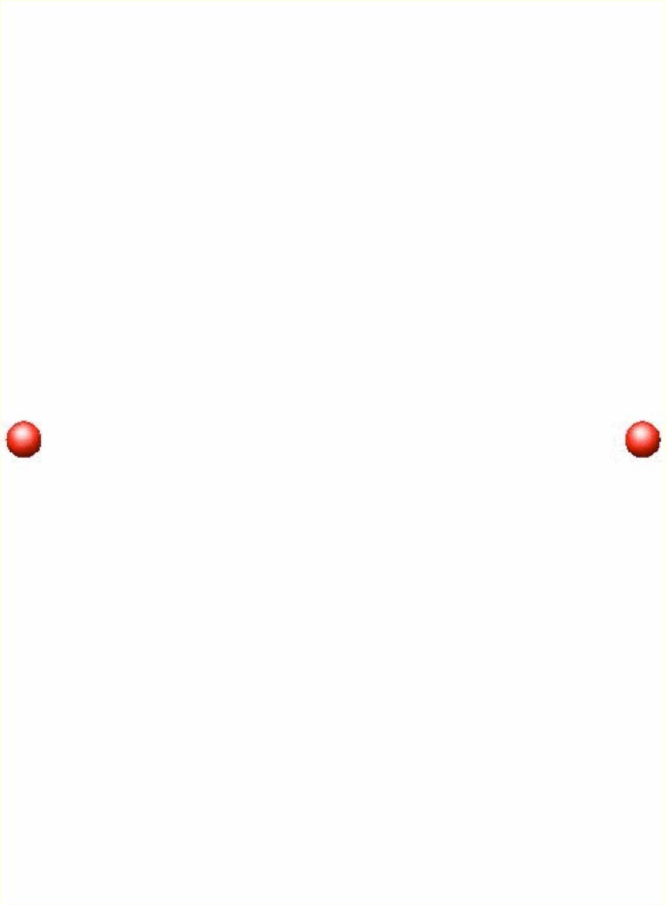


Limited by luminosity error: ~ 5-10% in first year,
Longer term goal ~ 2-3%

(process might be used later for luminosity measurement)

Top Quark Physics





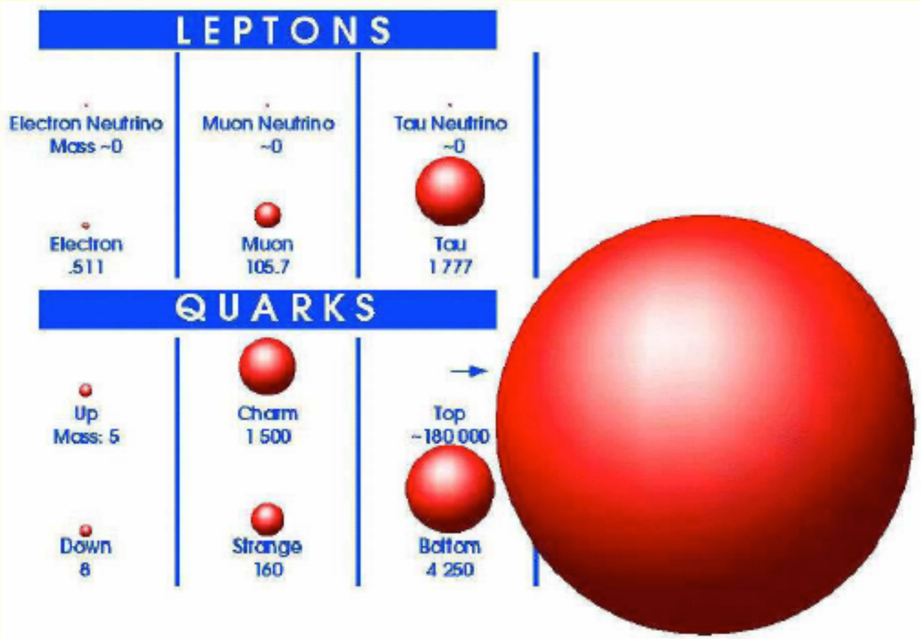
- Discovered by CDF and DØ collaborations at the Tevatron in 1995

- 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 ??

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

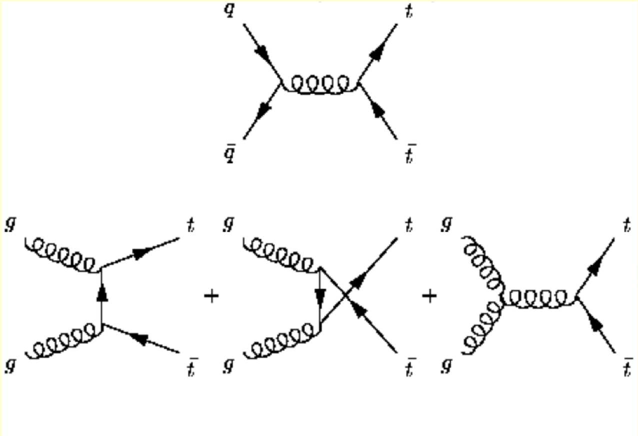
$$\Rightarrow \lambda_t = \frac{M_t}{173.9\,\mathrm{GeV}/c^2}$$

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

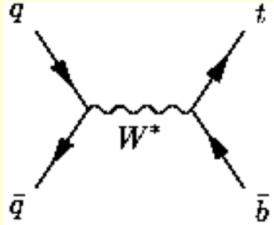
- A unique quark: decays before it hadronizes, lifetime ~10^{-24} s
  no "toponium states"
  remember: bb, bd, bs….. cc, cs….. Bound states (Mesons)

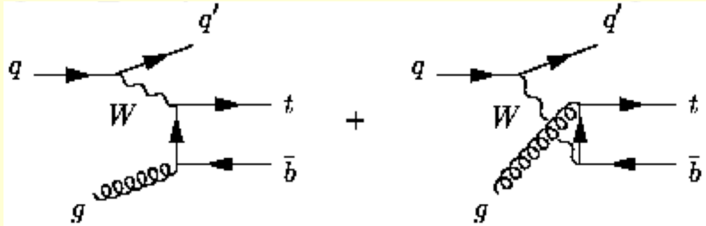
Top Quark Production

Pair production: qq and gg-fusion



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



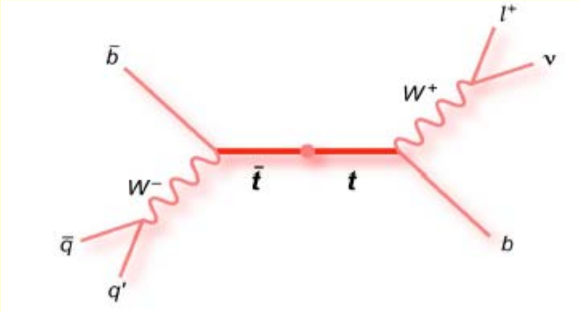


recently discovered by CDF and DØ at Fermilab

	Tevatron 1.96 TeV	LHC 14 TeV
qq gg	85% 15%	5% 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:

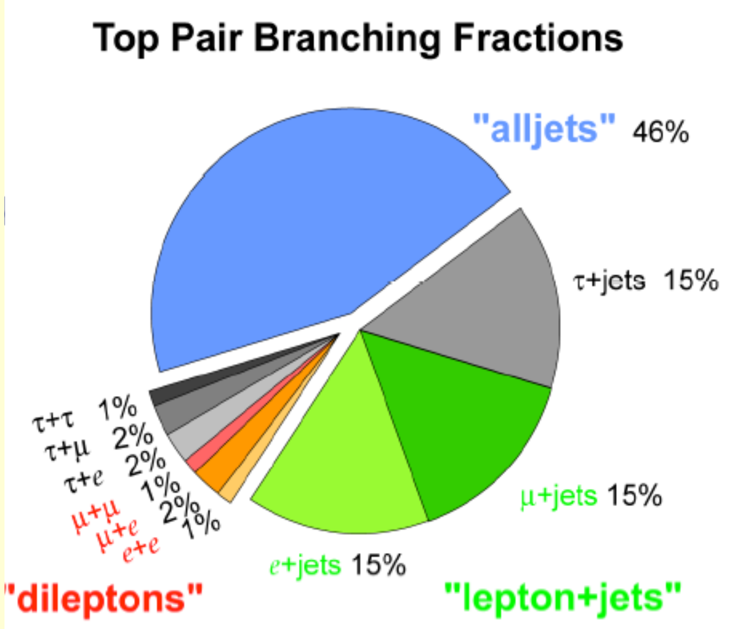
Both W's decay via $W \to \ell\nu$ (ℓ=e or μ; 4%)

Lepton + jet channel:

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

Full hadronic channel:

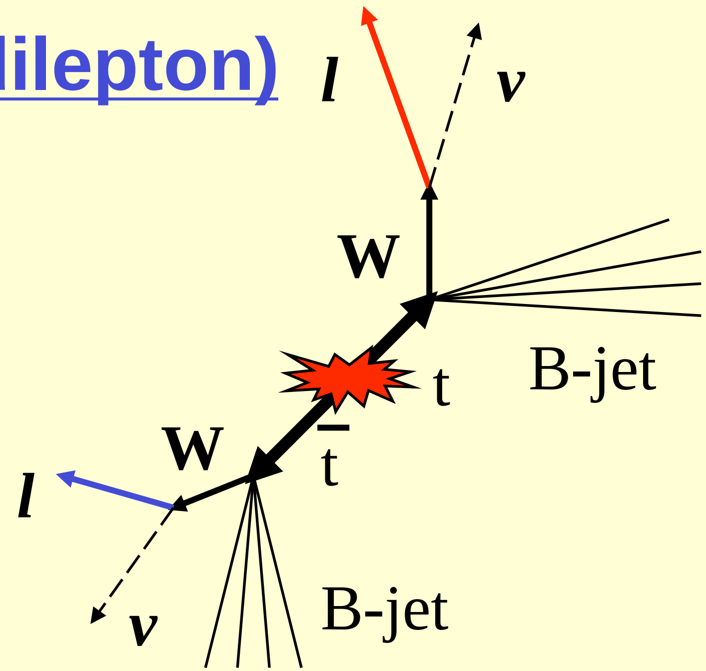
Both W's decay via $W \to qq$ (46%)



Important experimental signatures: : - Lepton(s)

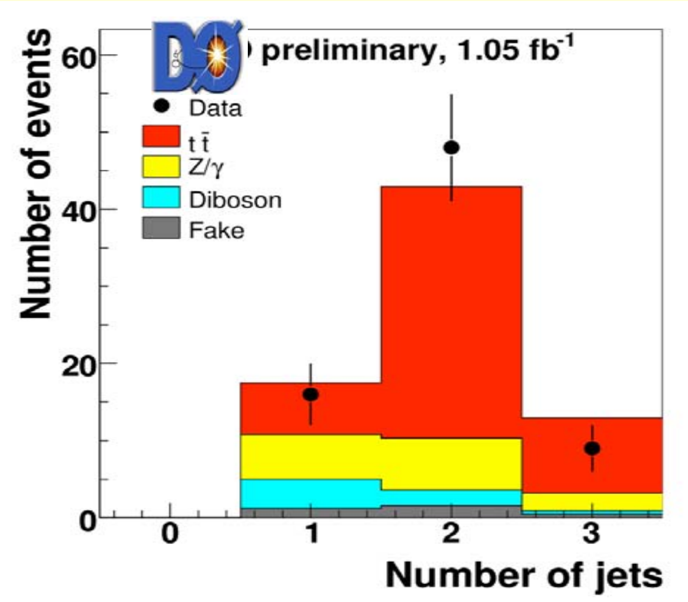
- Missing transverse momentum
- b-jet(s)

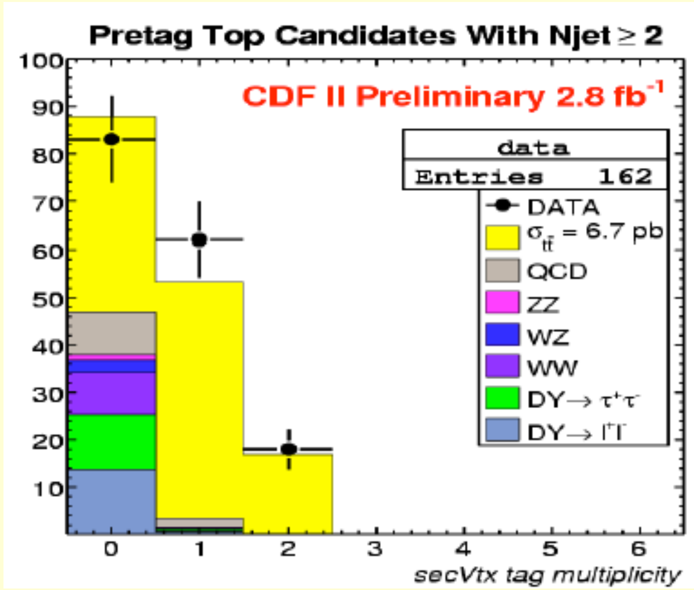
tt cross section (dilepton)



- 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

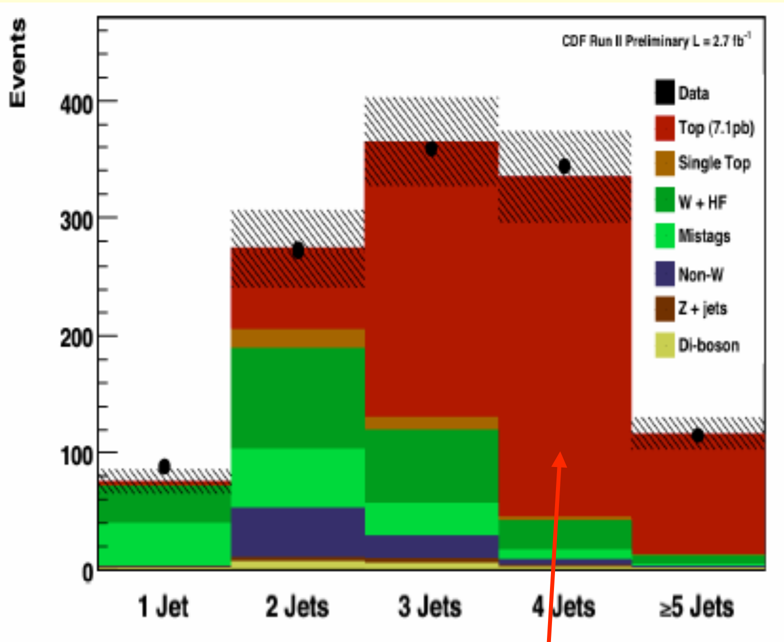
$t\bar{t}$ cross section (lepton + jets)   (including b-tagging)

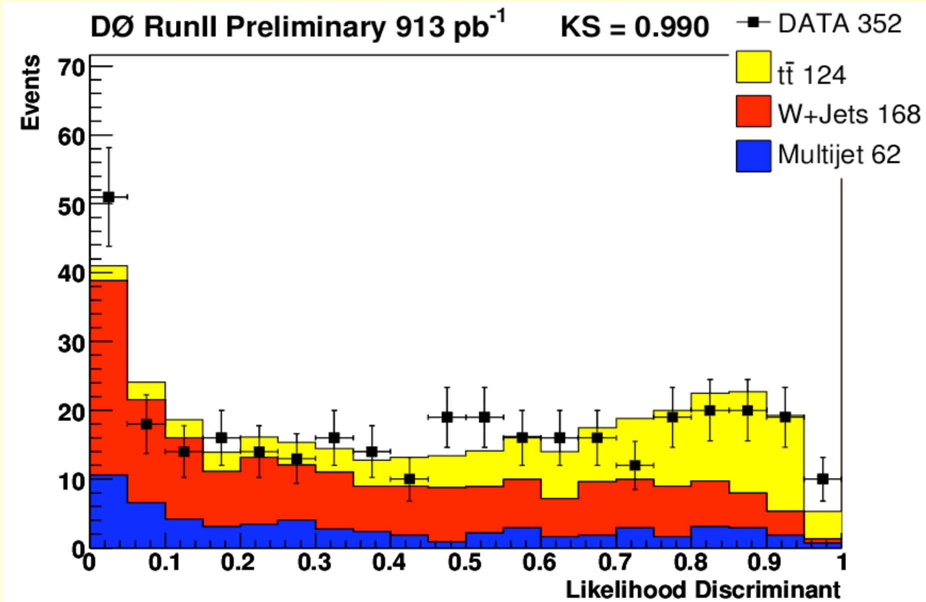
b-tag selection:

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

Kinematic selection:

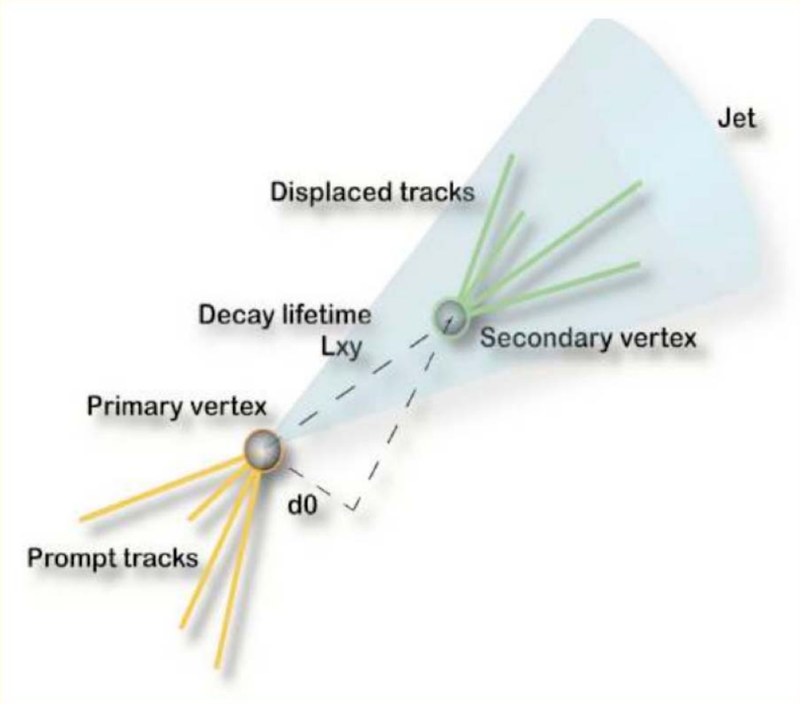
- One high P_T lepton (e, μ)
- Significant E_T^{miss}
- $\geq$ 4 jets
- Likelihood discriminant ($t\bar{t}$ vs. W+jets)

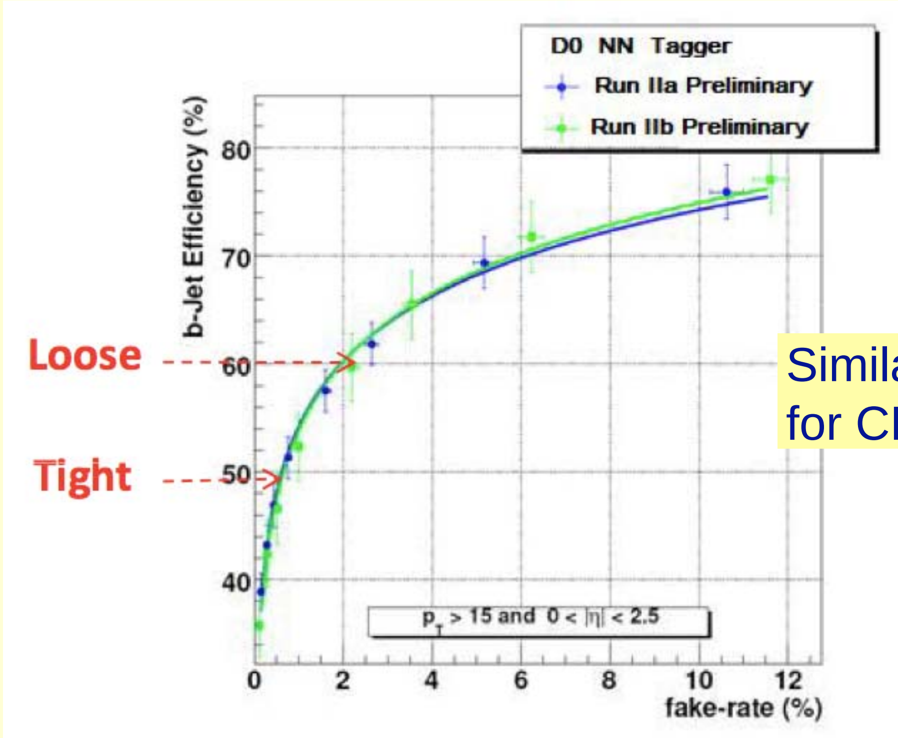




Clear excess above the W+ jet background in events with high jet multiplicity

Tevatron b-tagging performance

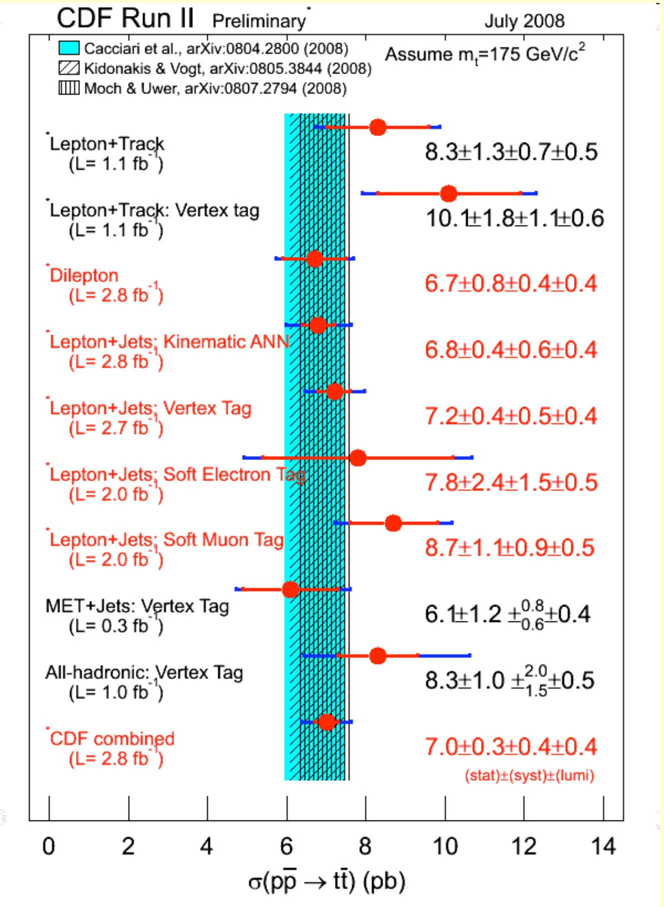


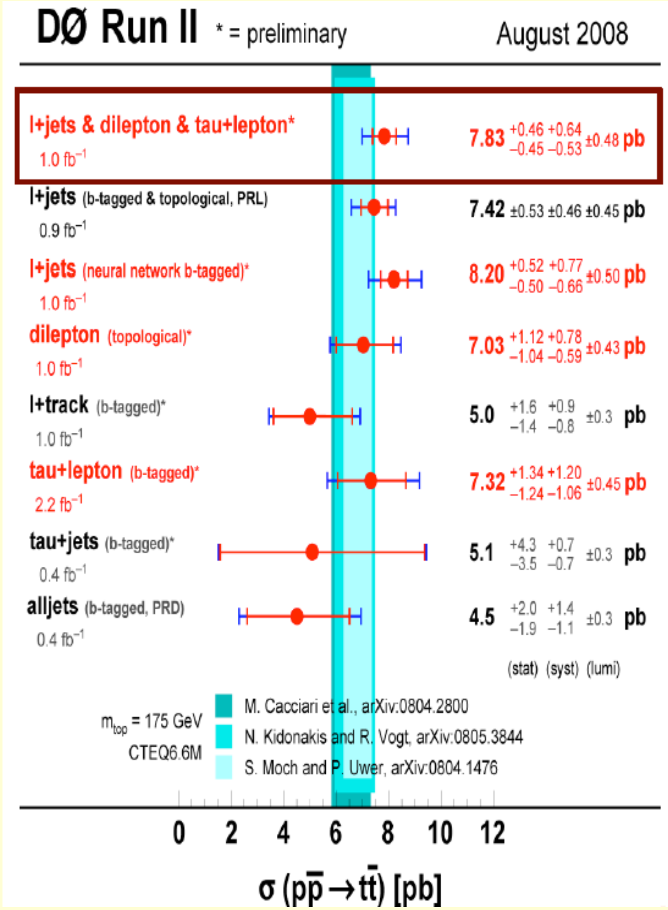


Similar for CDF

Neural networks are used for optimal combination of tagging information

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

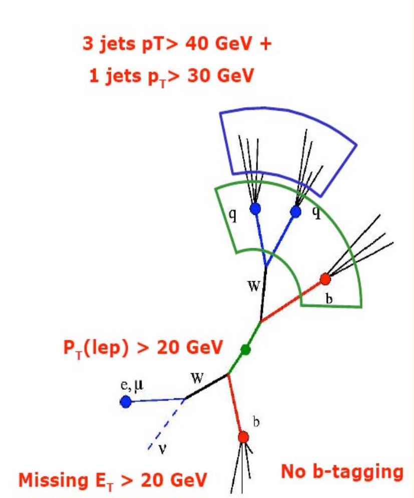
CDF Run II Preliminary L=2.7 fb^{-1}

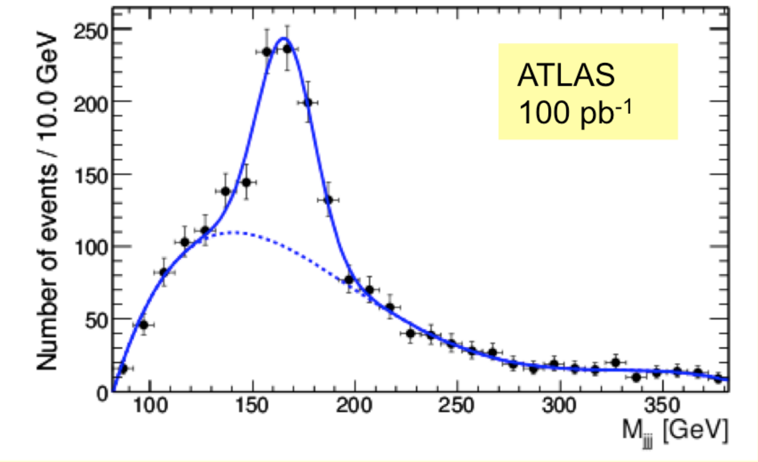
Good agreement:
- among various exp. measurements (two experiments)
- and with NLO + LL QCD prediction
- Systematic uncertainties at the 10% level (luminosity, b-tagging)

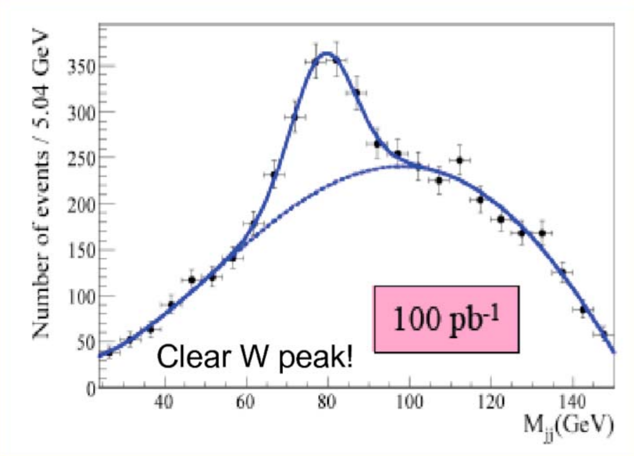
Top cross section in early LHC data

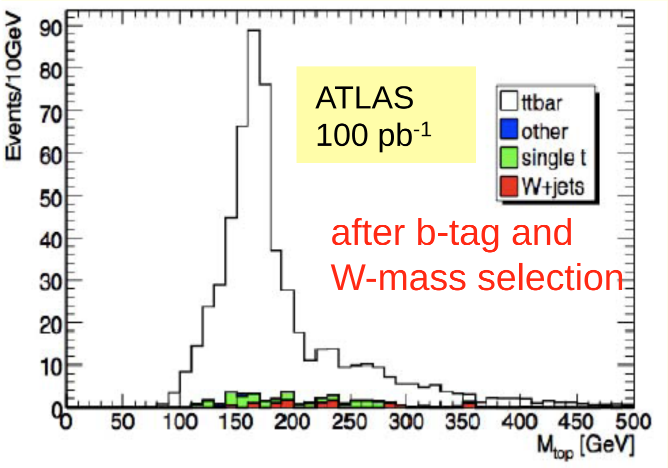
Large cross section: ~ 830 pb at √s = 14 TeV

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

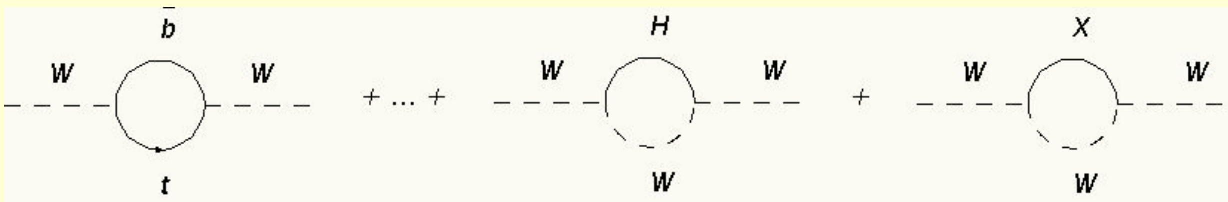
weak mixing angle
measured at
LEP/SLC

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

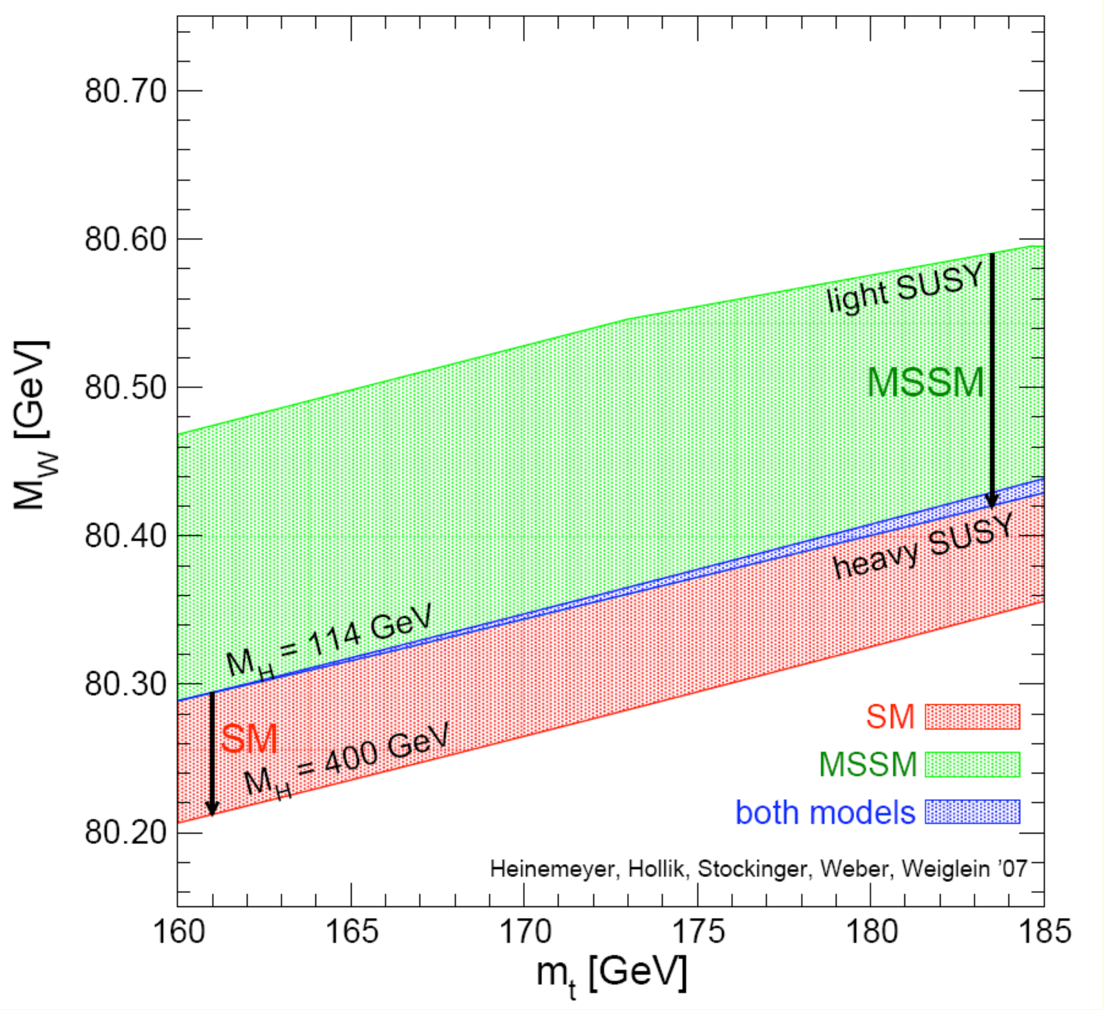
G_F, α_{EM}, $\sin\theta_W$

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)

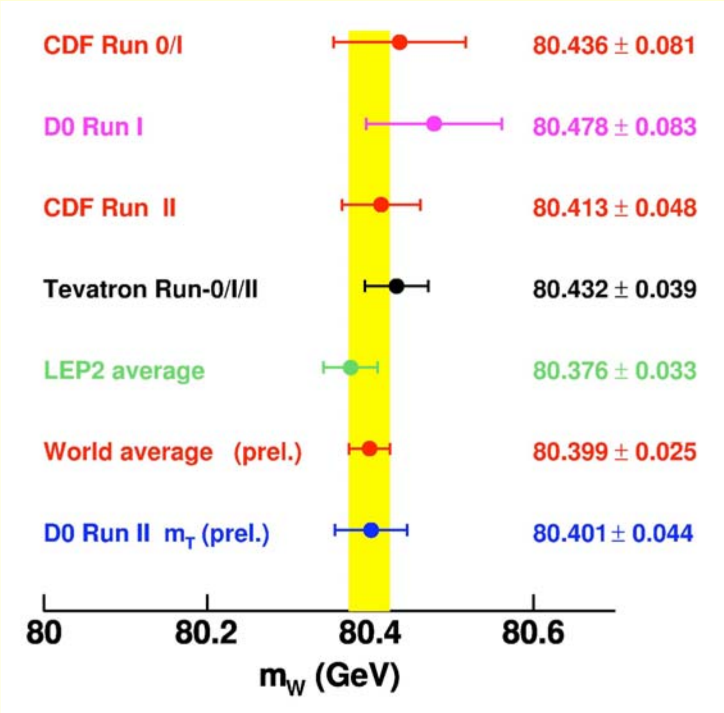


Relation between m_W, m_t, and m_H



The W-mass measurement

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

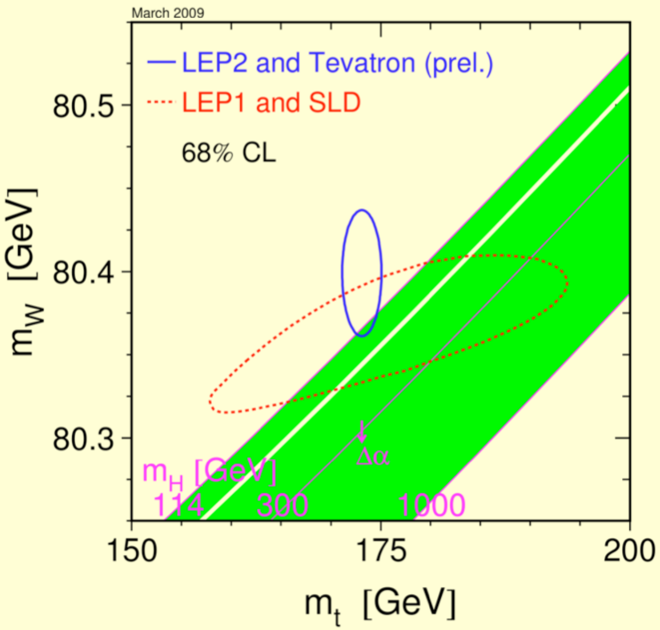


m_W (from LEP2 + Tevatron) = 80.399 ± 0.025 GeV

$3 \cdot 10^{-4}$

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

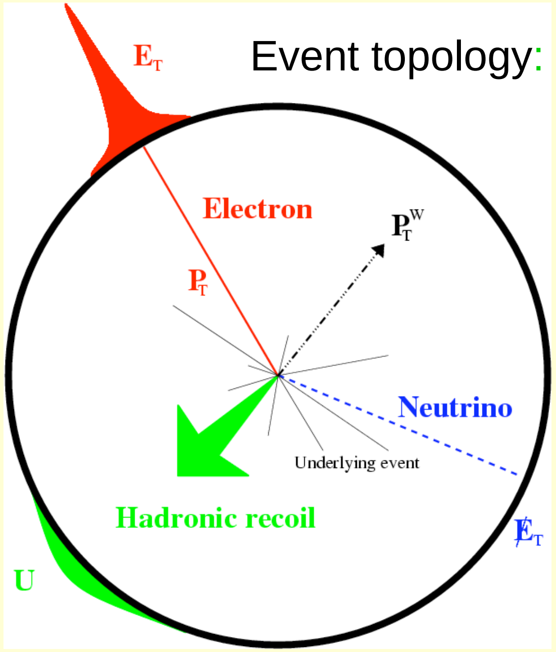
0.8%

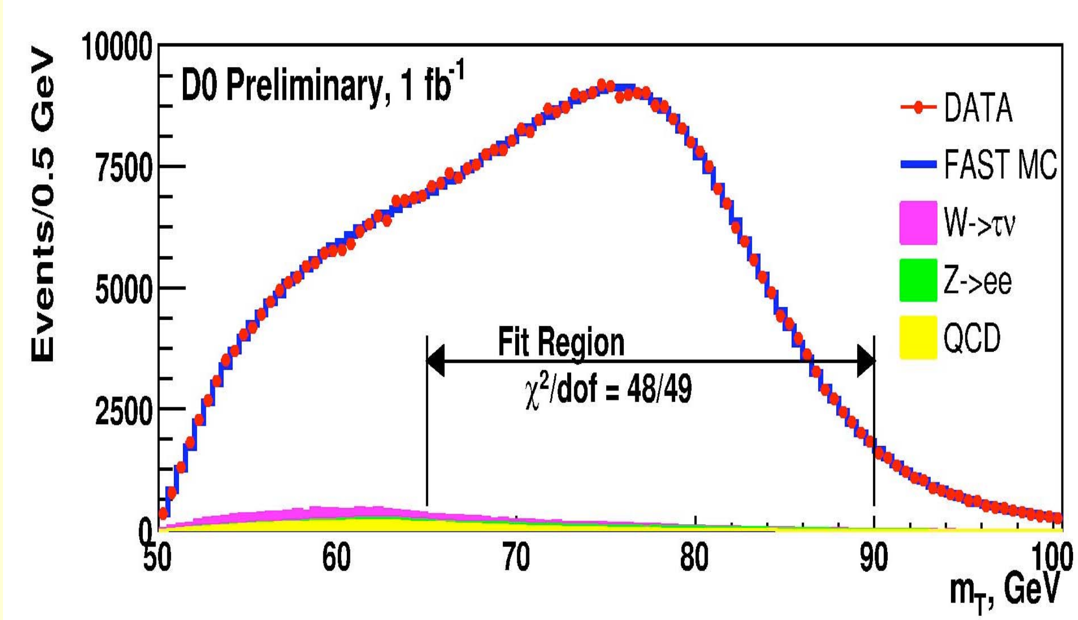


A light Higgs boson is favoured by present measurements

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

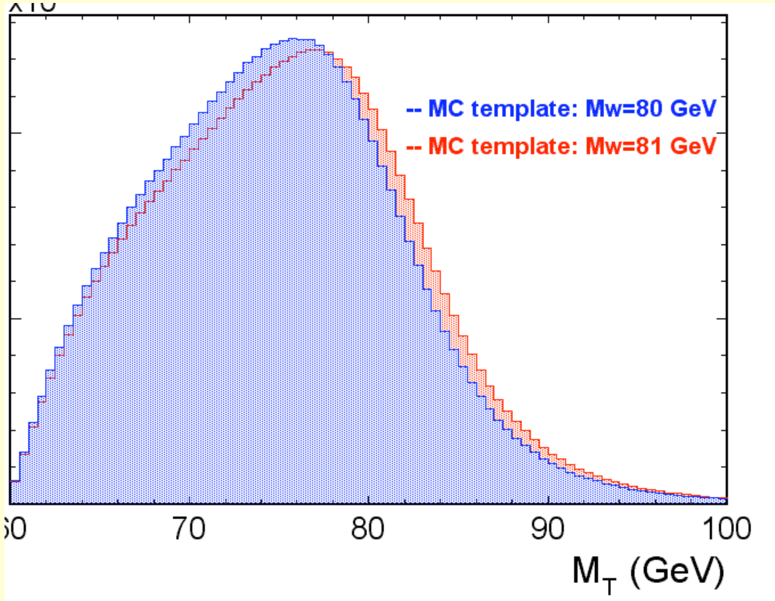
$\Rightarrow$ $P_T(\nu)$ = - ($P_T(e)$ + $P_T(had)$)

long. component cannot be measured

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

In general the transverse mass M_T is used for the determination of the W-mass (smallest systematic uncertainty).

Shape of the transverse mass distribution is sensitive to m_W, the measured distribution is fitted with Monte Carlo predictions, where m_W is a parameter



Main uncertainties:

Ability of the Monte Carlo to reproduce real life:

- Detector performance
  (energy resolution, energy scale, ….)
- Physics: production model
  $p_T(W)$, Γ_W, …..
- Backgrounds

Systematic Uncertainties (Tevatron measurements)

CDF II : 200 pb^{-1}

m_T Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	9	9	9
Recoil Resolution	7	7	7
$u_{\|\|}$ Efficiency	3	1	0
Lepton Removal	8	5	5
Backgrounds	8	9	0
$p_T(W)$	3	3	3
PDF	11	11	11
QED	11	12	11
Total Systematic	39	27	26
Statistical	48	54	0
Total	62	60	26

Total	**48**

D0 Preliminary : 1 fb^{-1}

Source	$\sigma(m_W)$ MeV m_T
Experimental	
Electron Energy Scale	34
Electron Energy Resolution Model	2
Electron Energy Nonlinearity	4
W and Z Electron energy loss differences	4
Recoil Model	6
Electron Efficiencies	5
Backgrounds	2
Experimental Total	35
W production and decay model	
PDF	9
QED	7
Boson p_T	2
W model Total	12
Total	37

Statistical	23
Total	**44**

Dominant error: knowledge of the lepton energy scale of the detector !

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

Numbers for a single decay channel

$W \to e\nu$

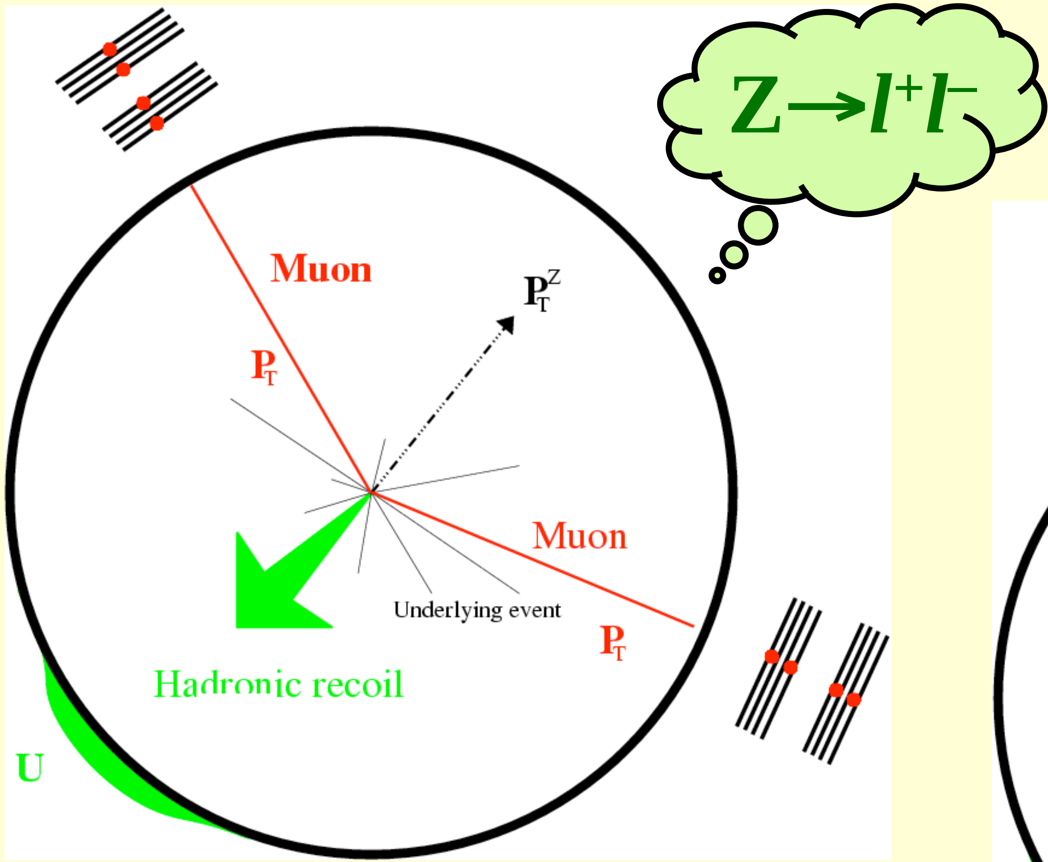
Int. Luminosity	CDF $0.2\ fb^{-1}$	DØ $1\ fb^{-1}$	LHC $10\ fb^{-1}$
Stat. error	**48 MeV**	**23 MeV**	**2 MeV**
Energy scale, lepton res.	30 MeV	34 MeV	4 MeV
Monte Carlo model (P_T^W, structure functions, photon-radiation….)	16 MeV	12 MeV	7 MeV
Background	8 MeV	2 MeV	2 MeV
Tot. Syst. error	**39 MeV**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

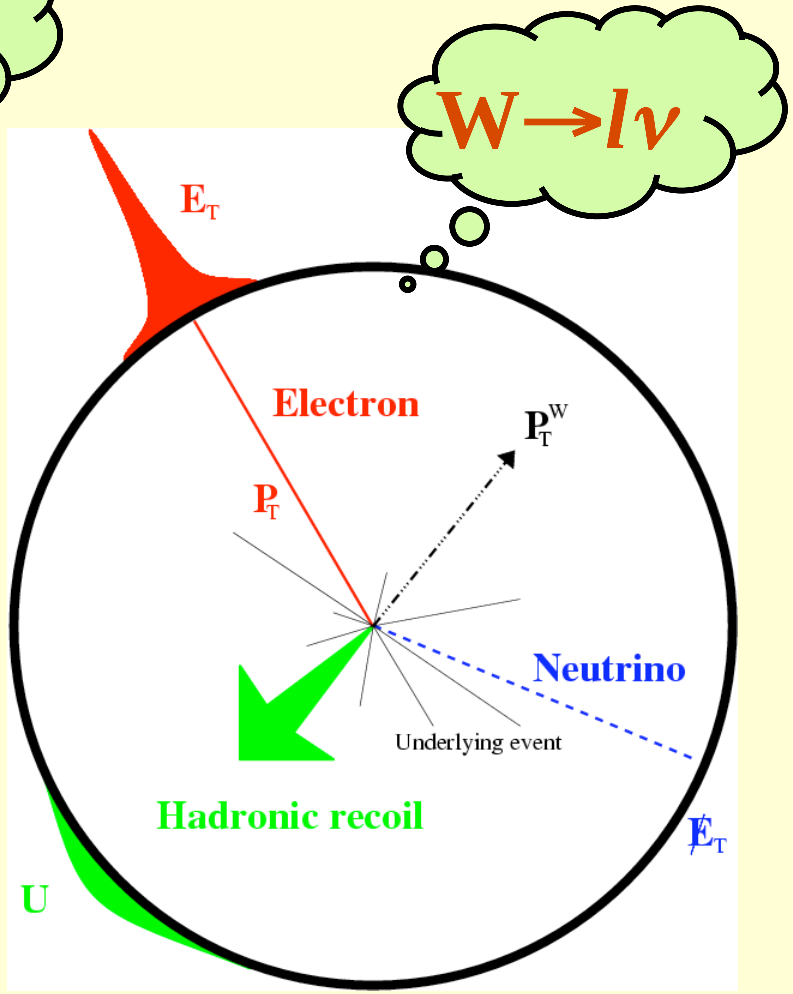
- Tevatron numbers are based on real data analyses
- LHC numbers should be considered as „ambitious goal“
  - Many systematic uncertainties can be controlled in situ, using the large $Z \to \ell\ell$ sample ($p_T(W)$, recoil model, resolution)
  - Lepton energy scale of ± 0.02% has to be achieved to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

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

Signature of Z and W decays





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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

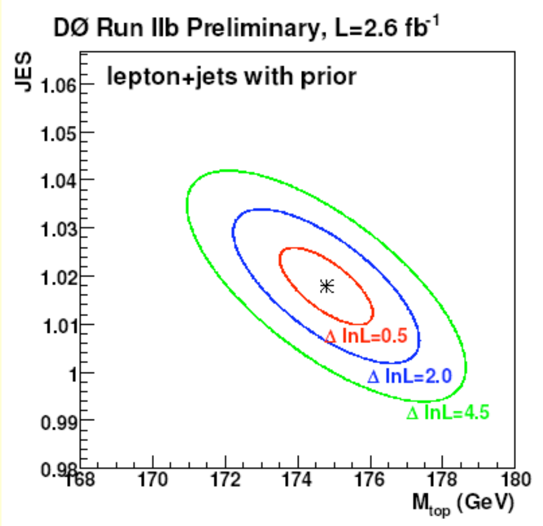
  → template methods,…
  matrix element method…

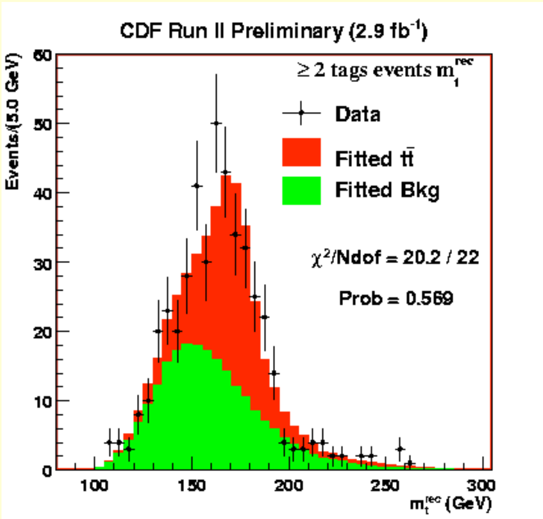
Most precise single measurements:

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)

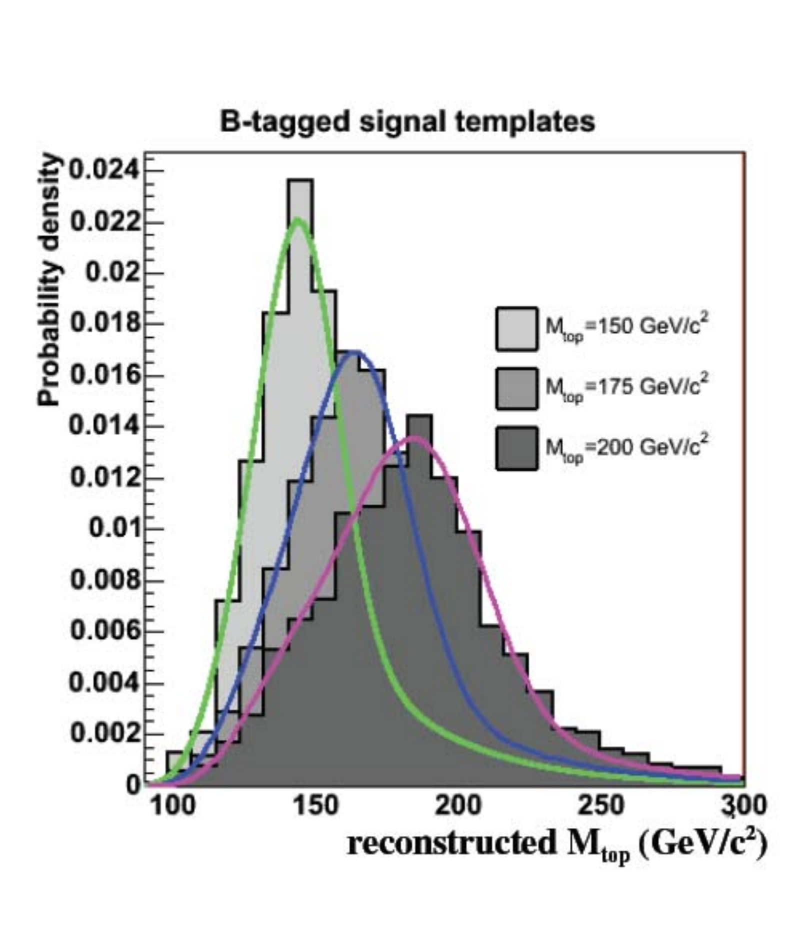




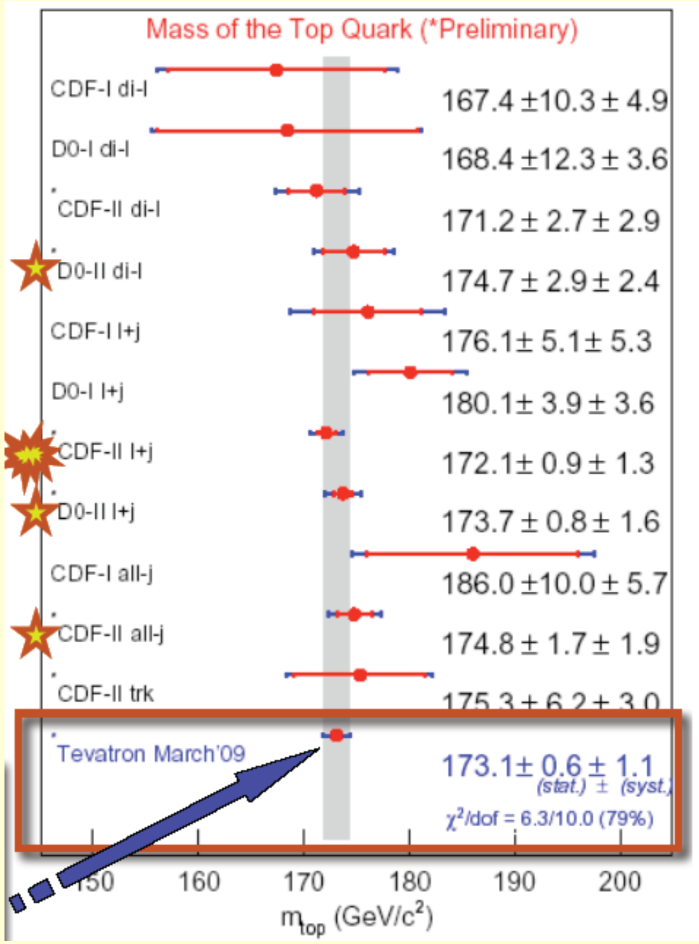
full hadronic channel

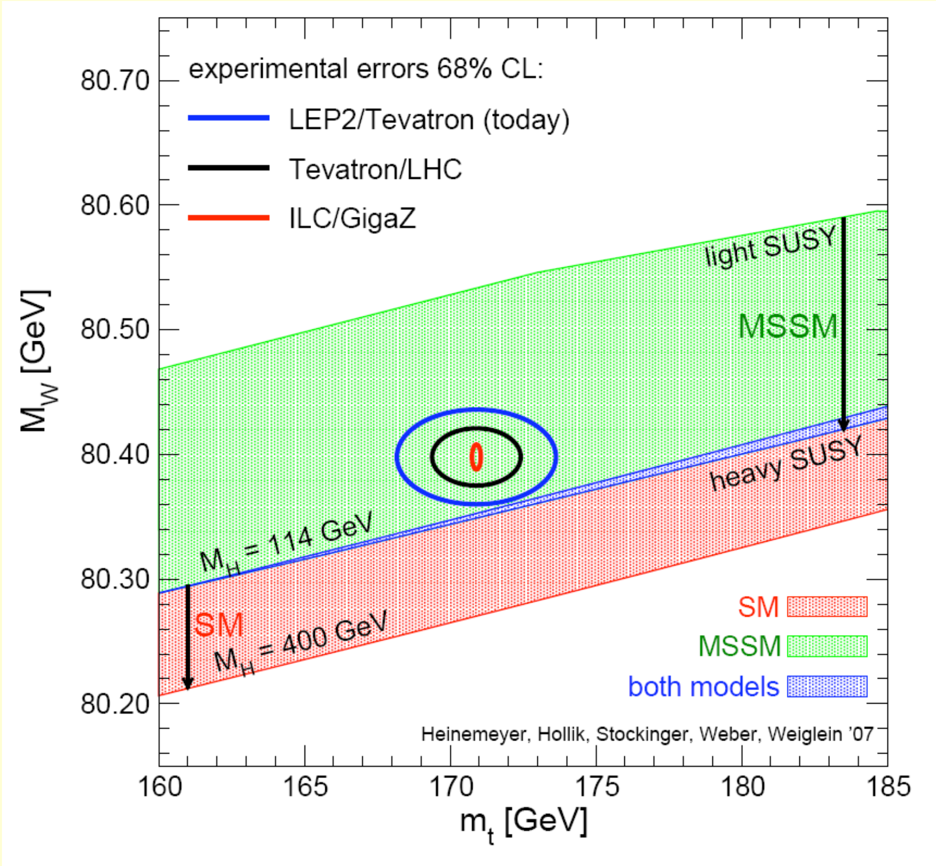
Example: template method

- 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



Future Prospects for the top quark mass measurement

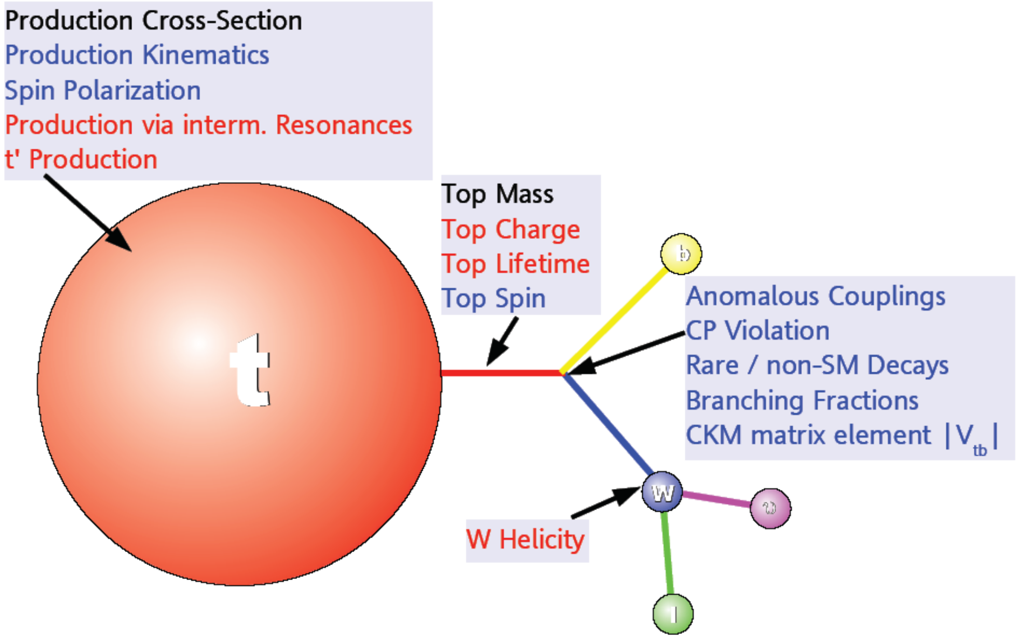




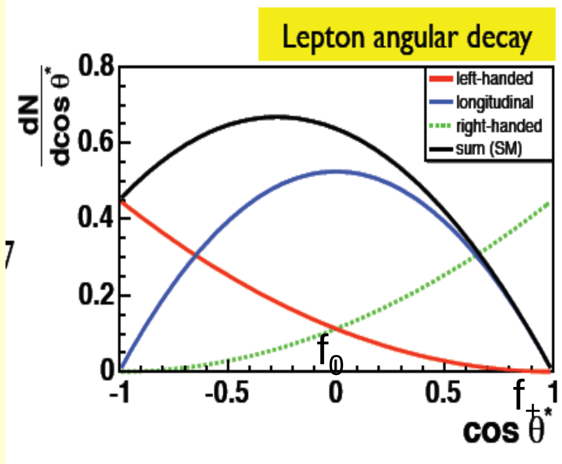
Expected LHC precision for 10 fb^{-1}:
(Combination of several methods, maybe somewhat conservative)

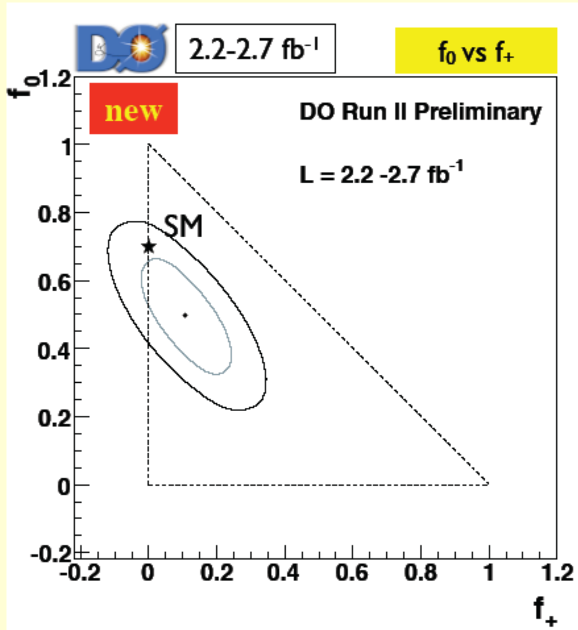
< ~ 1 GeV/c^2

Other top properties

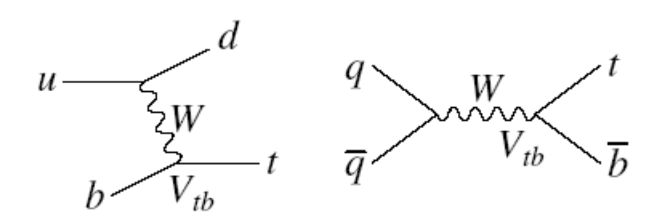


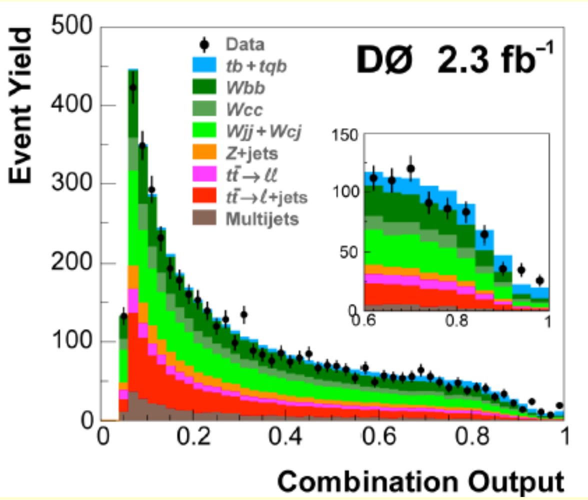
	Tevatron Result	luminosity (fb^{-1})
Mass	173.1 ± 1.3 GeV	~ 3.0
W helicity	CDF: f_0 = 0.66 ± 0.16, f_+ = -0.03 ± 0.07 DØ: f_0 = 0.49 ± 0.14 f_+ = 0.11 ± 0.08	1.9 2.2 – 2.7
Charge Lifetime V_{tb} BR(t→Wb) / BR(W→Wq) BR (t → Zq)	rule out Q = +4/3 (90.% C.L.) Γ_t < 13.1 GeV (95% C.L.) V_{tb} > 0.89 (95%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

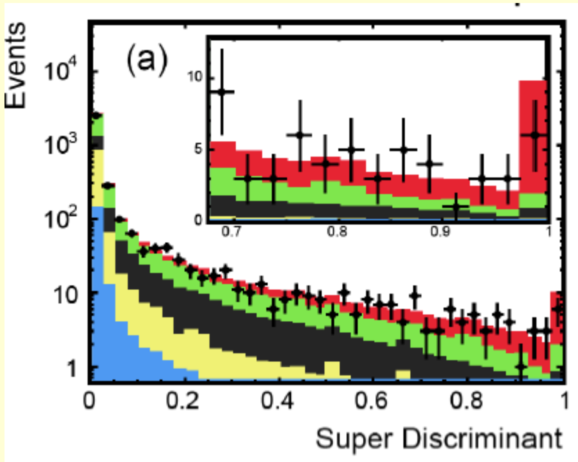




First observation of Single Top Production at the Tevatron

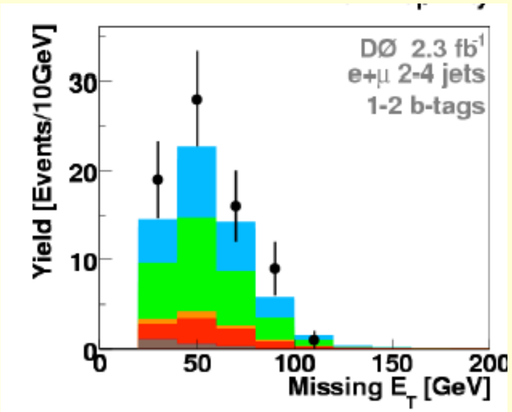


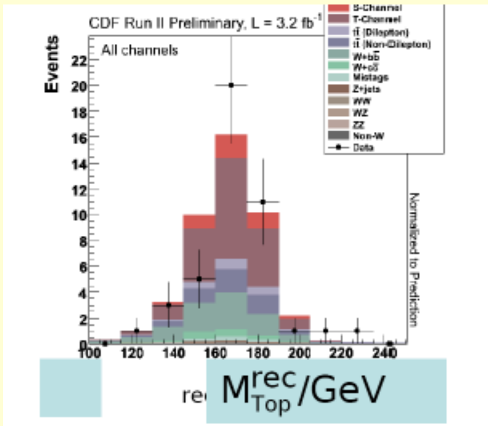


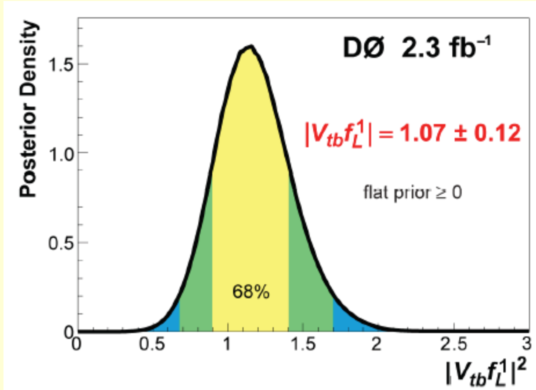


Combined Results

	$\mathcal{L}$ [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	$2.3^{+0.6}_{-0.5}$





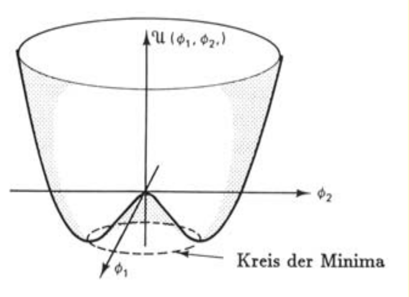


$|V_{tb}f_{L1}| = 1.07 \pm 0.12$,
$|V_{tb}| > 0.78$ at 95% CL

Where is the

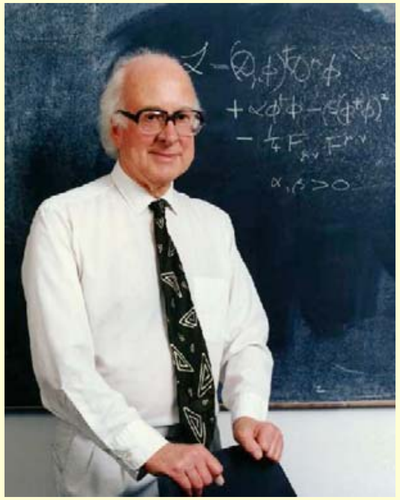
Higgs Boson ?

The Search for the Higgs Boson



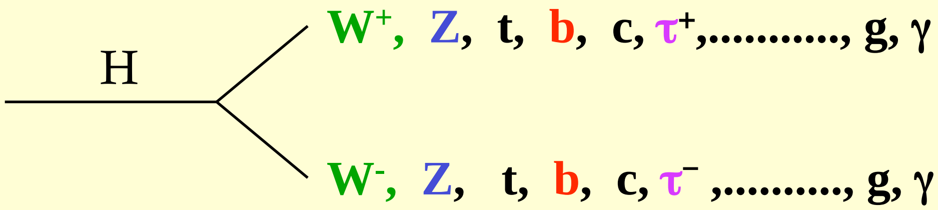
- „Revealing the physical mechanism that is responsible for the breaking of electroweak symmetry is one of the key problems in particle physics"

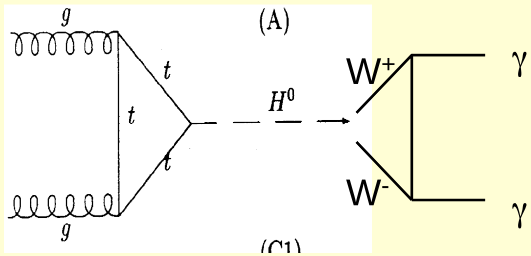
- „A new collider, such as the LHC must have the potential to detect this particle, should it exist."



Properties of the Higgs Boson

- The decay properties of the Higgs boson are fixed, if the **mass** is known:





$$\Gamma(H \to f\bar{f}) = N_C \frac{G_F}{4\sqrt{2}\pi} m_f^2(M_H^2)\, M_H$$

$$\Gamma(H \to VV) = \delta_V \frac{G_F}{16\sqrt{2}\pi} M_H^3 \,(1 - 4x + 12x^2)\, \beta_V$$

where: $\delta_Z = 1, \delta_W = 2, \quad x = M_V^2/M_V^2, \quad \beta = \text{velocity}$

$$\Gamma(H \to gg) = \frac{G_F\, \alpha_s^2(M_H^2)}{36\sqrt{2}\pi^3} M_H^3 \left[1 + \left(\frac{95}{4} - \frac{7N_f}{6}\right)\frac{\alpha_s}{\pi}\right]$$

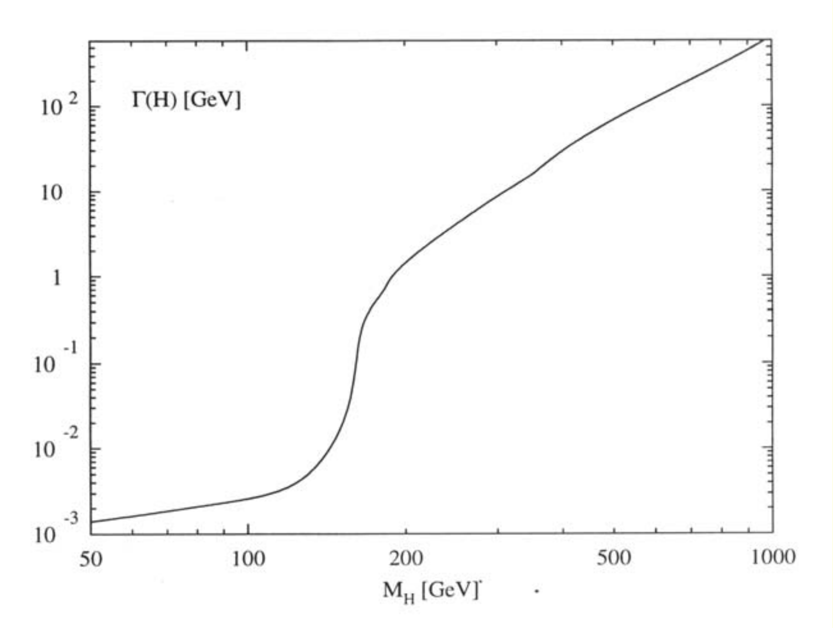
$$\Gamma(H \to \gamma\gamma) = \frac{G_F\, \alpha^2}{128\sqrt{2}\pi^3} M_H^3 \left[\frac{4}{3} N_C e_t^2 - 7\right]^2$$

Higgs boson likes mass:

It couples to particles proportional to their mass

→ decays preferentially in the heaviest particles kinematically allowed

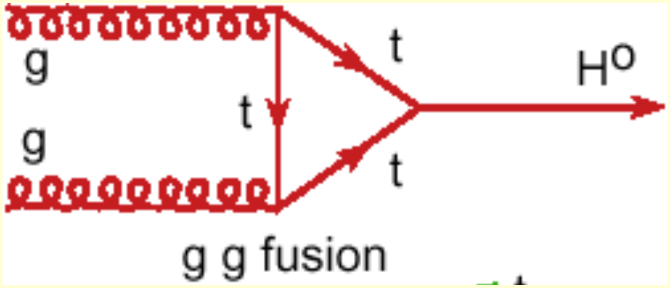
Properties of the Higgs Boson



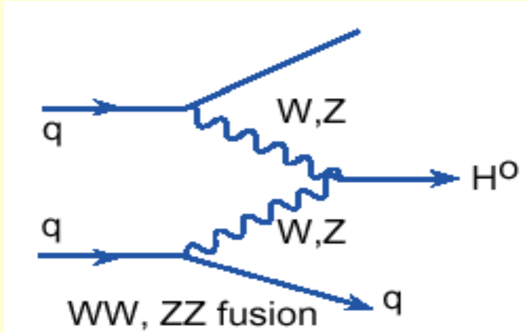
Upper limit on Higgs boson mass: from unitarity of WW scattering **$M_H < 1$ TeV/c^2**

Higgs Boson Production at Hadron Colliders

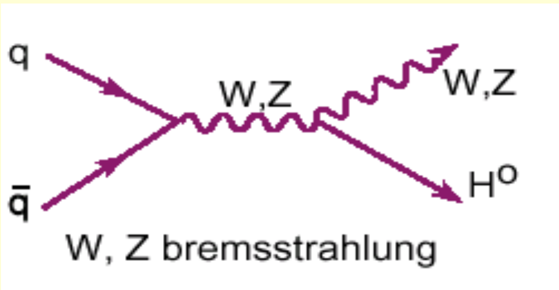
(i) Gluon fusion

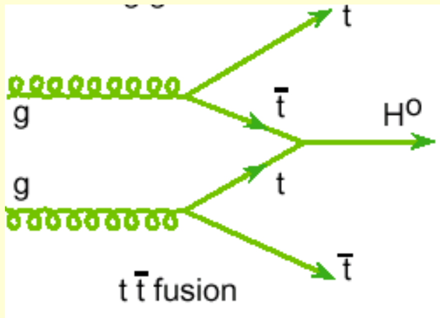


(ii) Vector boson fusion



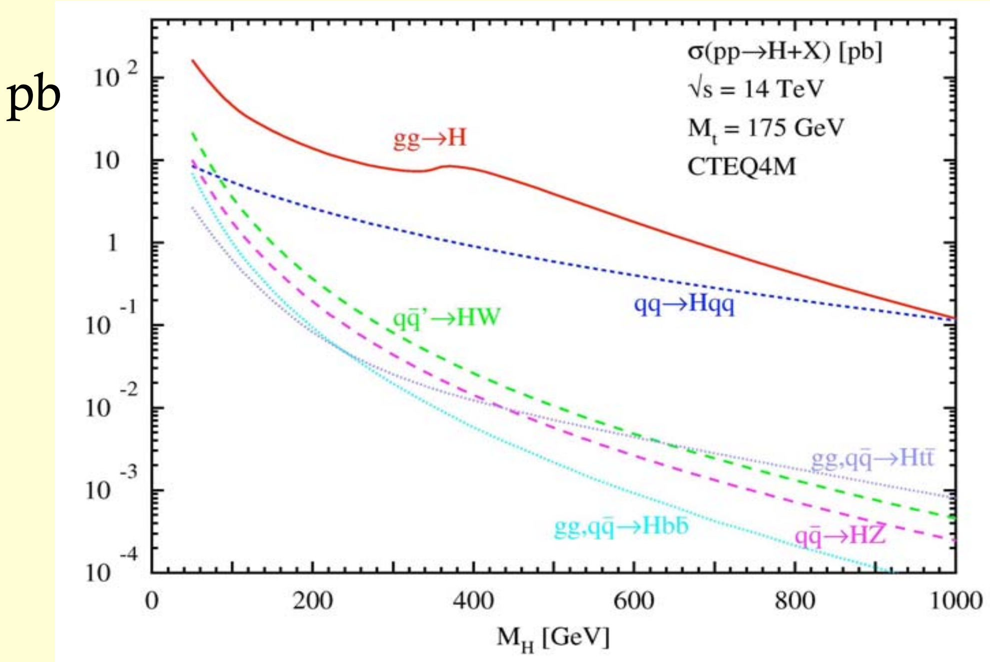
(iii) Associated production (W/Z, tt)



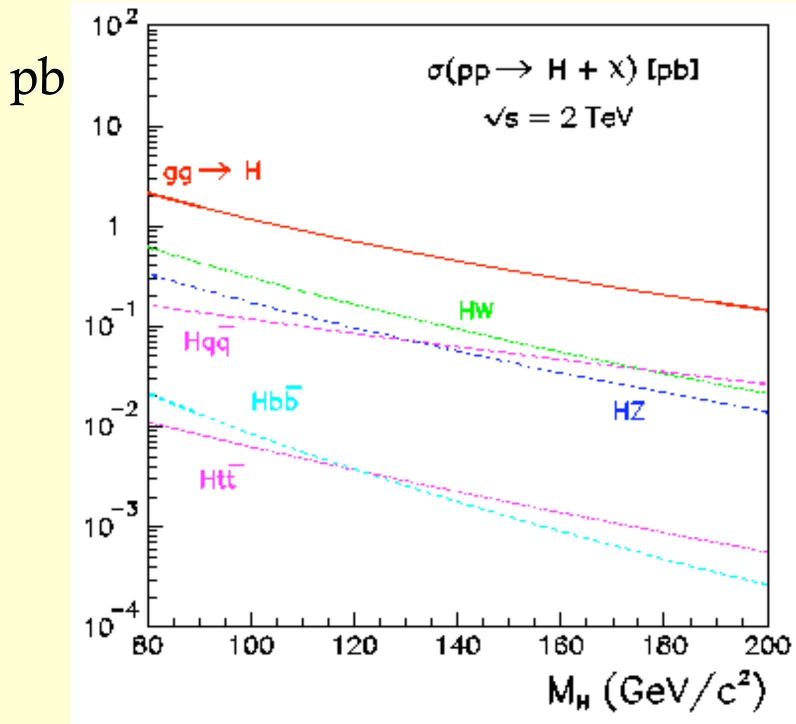


Higgs Boson Production cross sections

LHC M. Spira et al.



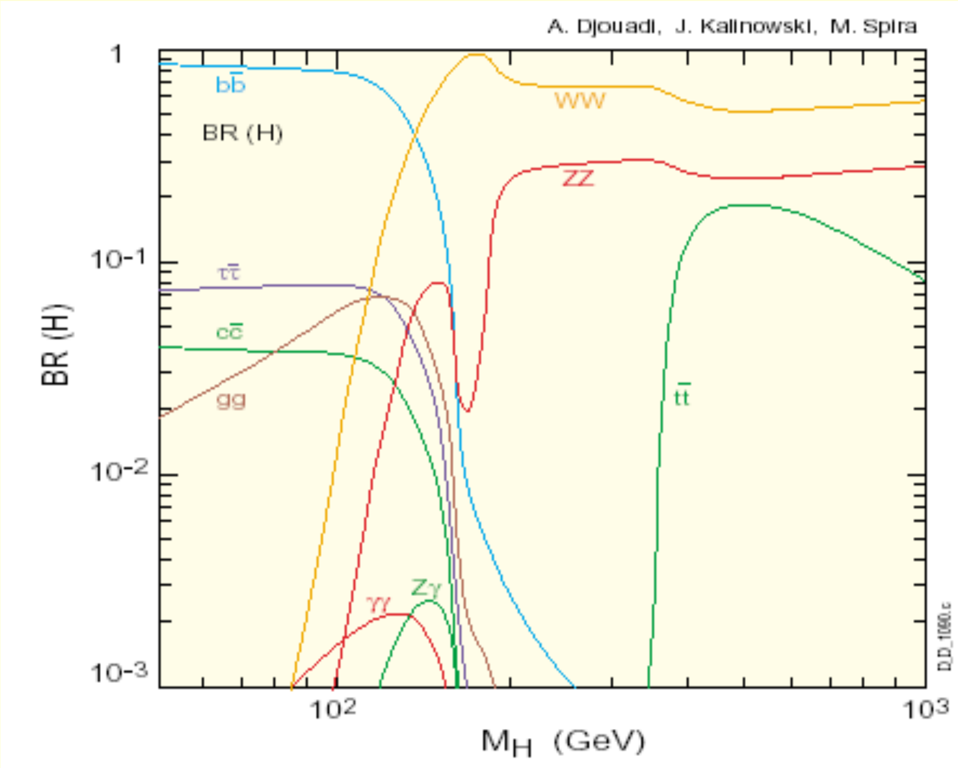
Tevatron M.Spira et al.



qq → W/Z + H cross sections **~10 x larger at the LHC**

gg → H **~70-80 x larger at the LHC**

Higgs Boson Decays at Hadron Colliders



at high mass:

Lepton final states are essential

(via $H \to WW$, ZZ)

at low mass:

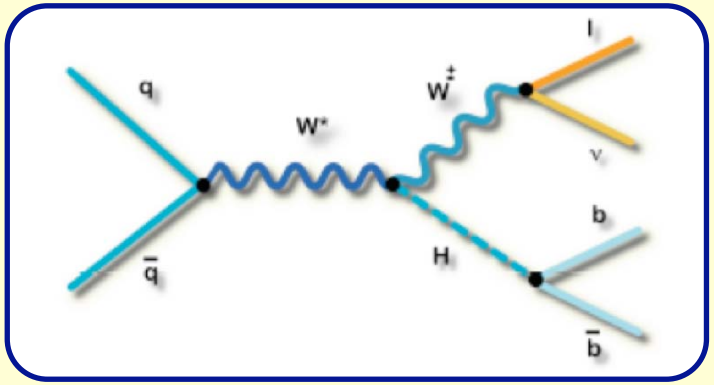
Lepton and Photon final states

(via $H \to WW^*$, ZZ^*)

Tau final states

The dominant **bb decay mode** is only useable in the associated production mode (ttH, W/Z H)
(due to the huge QCD jet background)

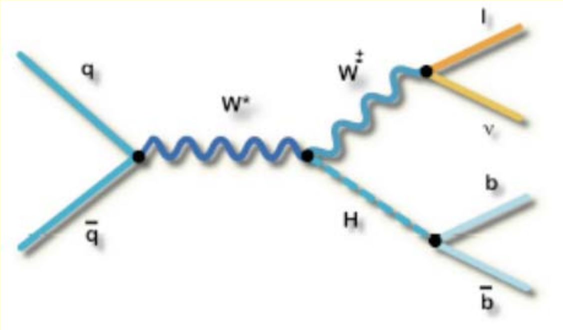
Searches for a low mass Higgs at the Tevatron



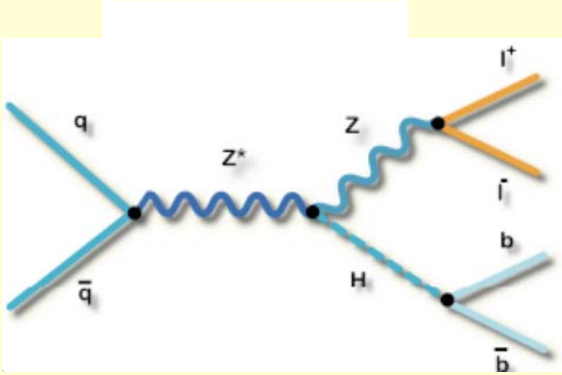
m_H < 135 GeV:

Associated production WH and ZH with H→bb decay

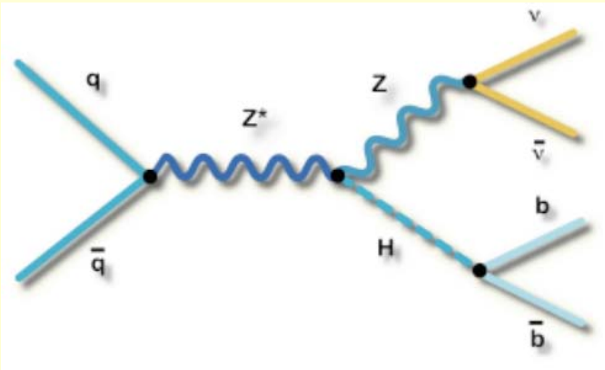
Main low mass search channels



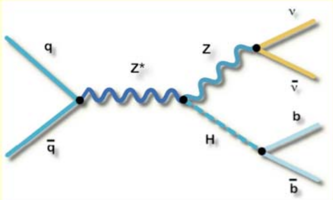
$\ell + E_T^{miss} + bb$: $WH \rightarrow \ell\nu bb$
Largest *VH* production cross section
More backgrounds than $ZH \rightarrow \ell\ell bb$



$\ell\ell$+bb: $ZH \rightarrow \ell\ell bb$
Less backgrounds
Fully constrained
Smallest Higgs signal



E_T^{miss} + bb: $ZH \rightarrow \nu\nu bb$
3x more signal than $ZH \rightarrow \ell\ell\, bb$
(+$WH \rightarrow \ell\nu\, bb$ when lepton missing)
Large backgrounds which are difficult to handle

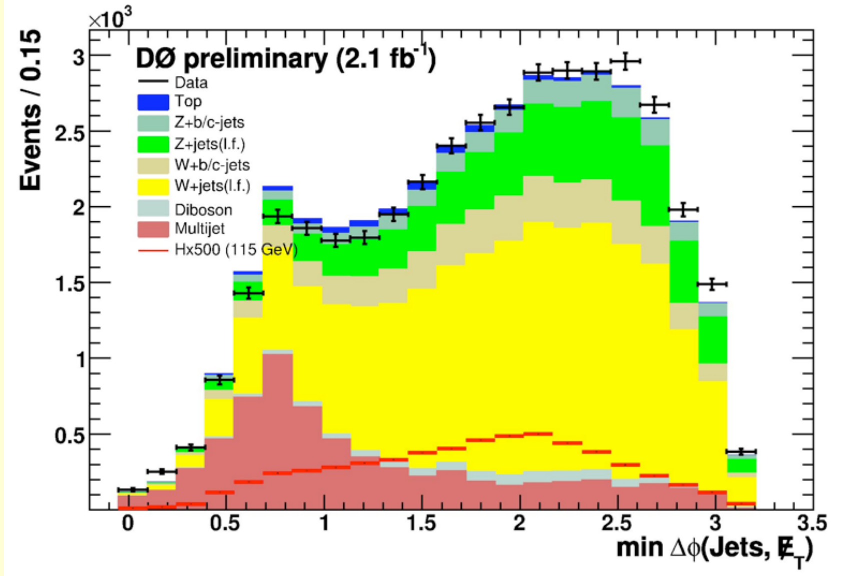


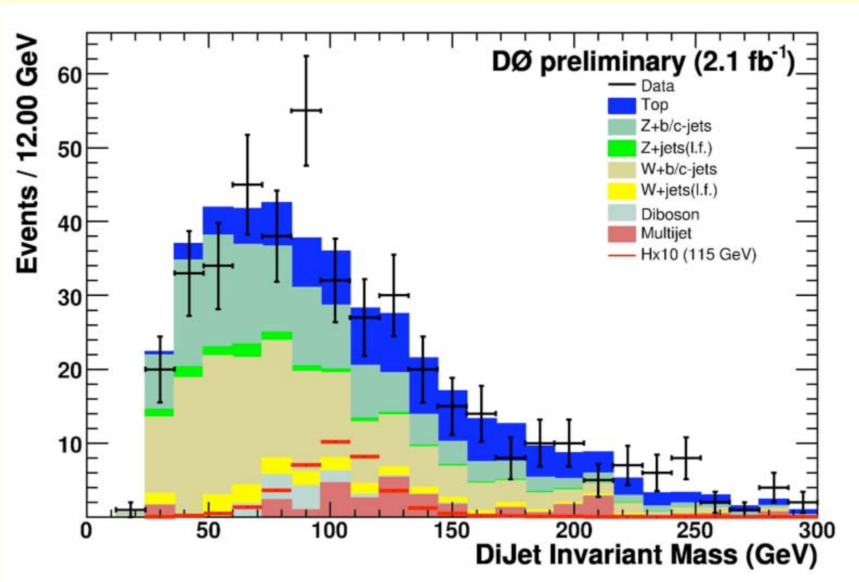
Example: ZH →νν bb

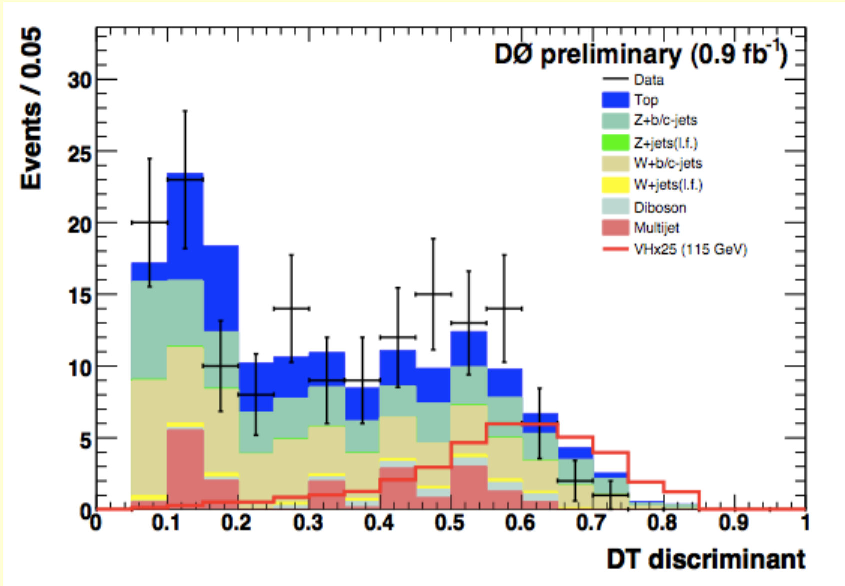
(i) Select events consistent with Z/W + 2 jets
(large W+jet and Z+jet backgrounds)

(ii) Apply b-tagging
(most discriminating variable: dijet inv. mass)

(i) Optimize separation power by multivariate discrimination
(→ Decision tree output)



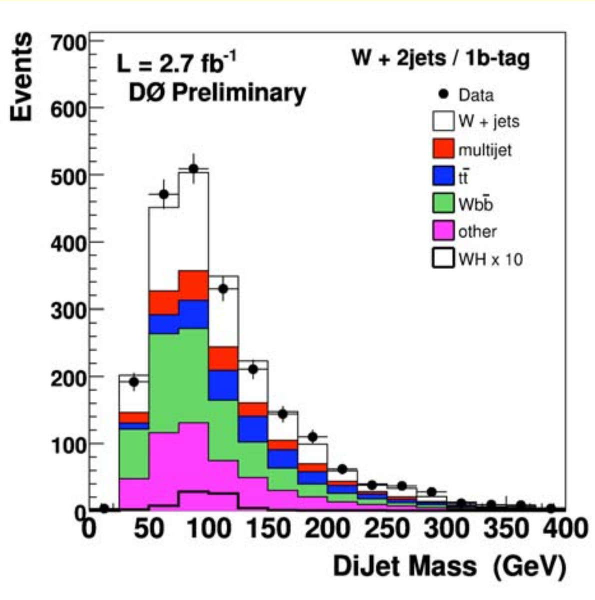


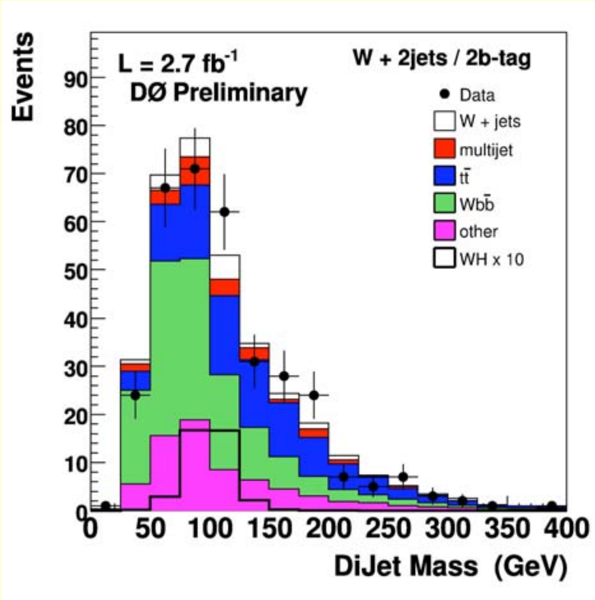


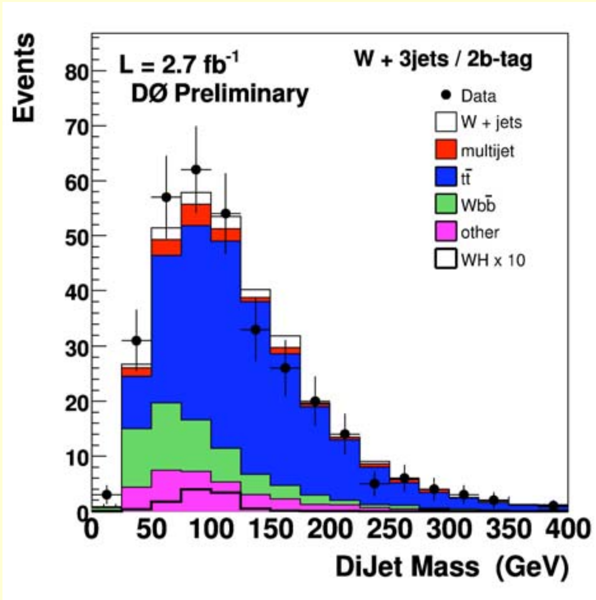
(iv) Split data into several sub-samples with different final state topologies

- maximize sensitivity due to S:B variations
- different background composition in the different classes

Example: WH → $\ell\nu$ bb

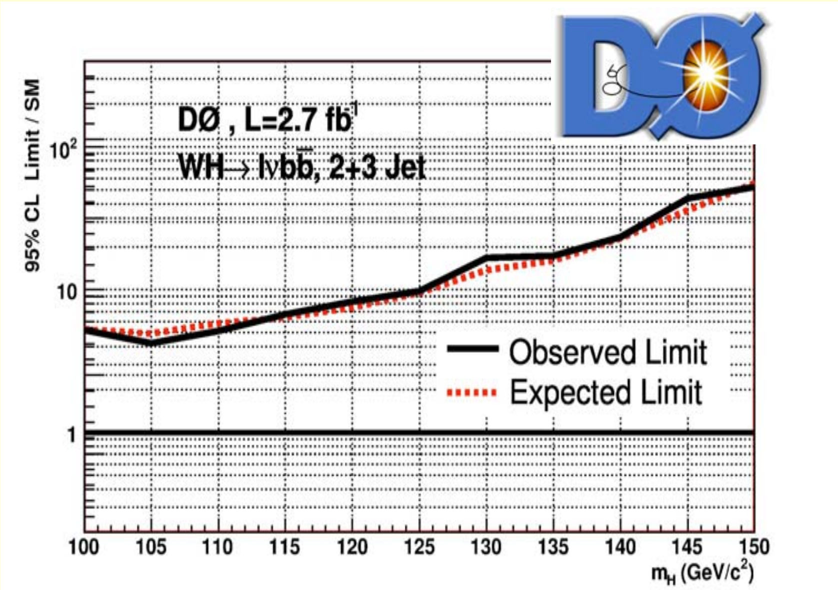


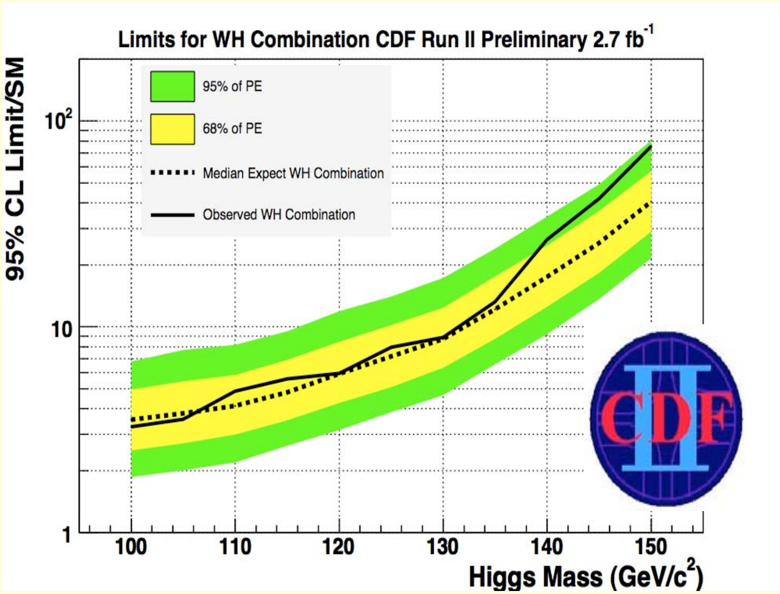




Sensitivity in individual channels

- Limits on individual channels a factor of 5-10 away from SM cross section at m_H = 115 GeV
- → The combination of all contributing channels is crucial

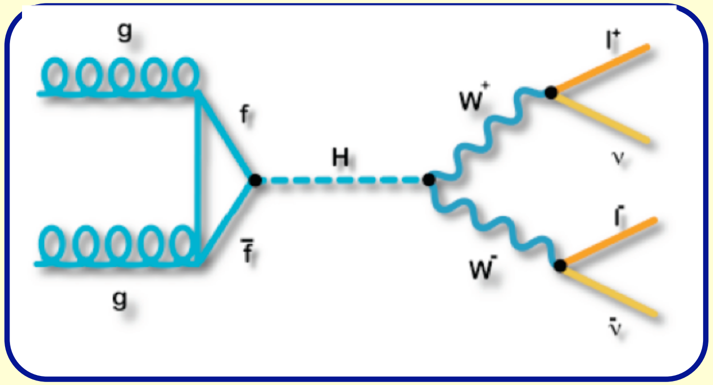




- Main systematic uncertainties for low mass channels:
  - Signal (total 15%): cross section, b-tagging, ID efficiencies
  - Background (total 25-30%): normalisation of W/Z+jets heavy flavour samples, modelling of the multijet and W/Z+jet backgrounds, b-tagging

- At high values of the discriminant output, S:B is typically 1/10 - 1/20 for the most sensitive low mass channels

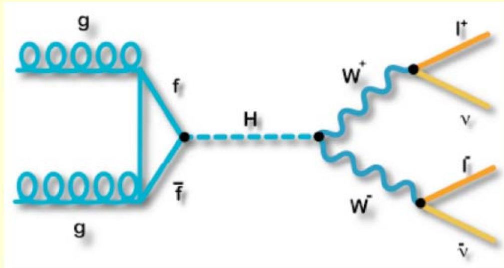
Searches for a high mass Higgs at the Tevatron



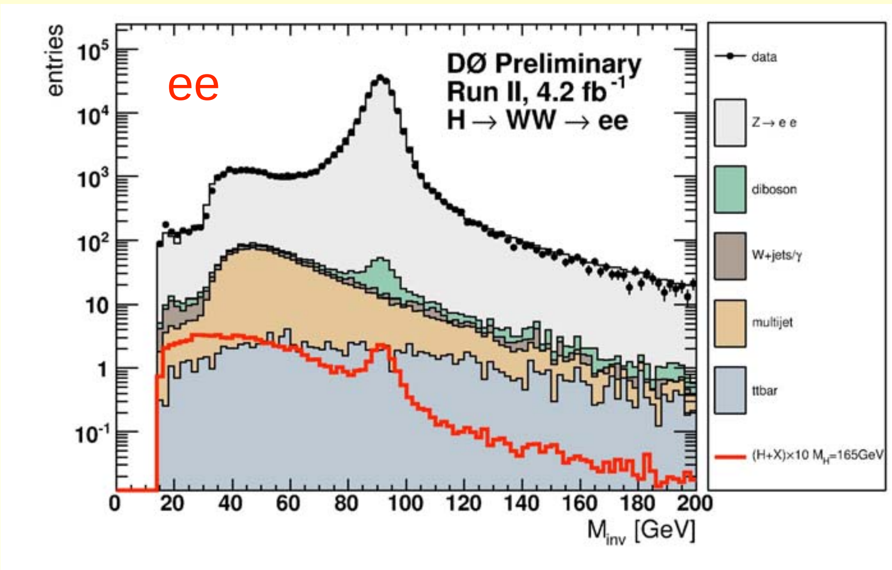
m_H > 135 GeV:

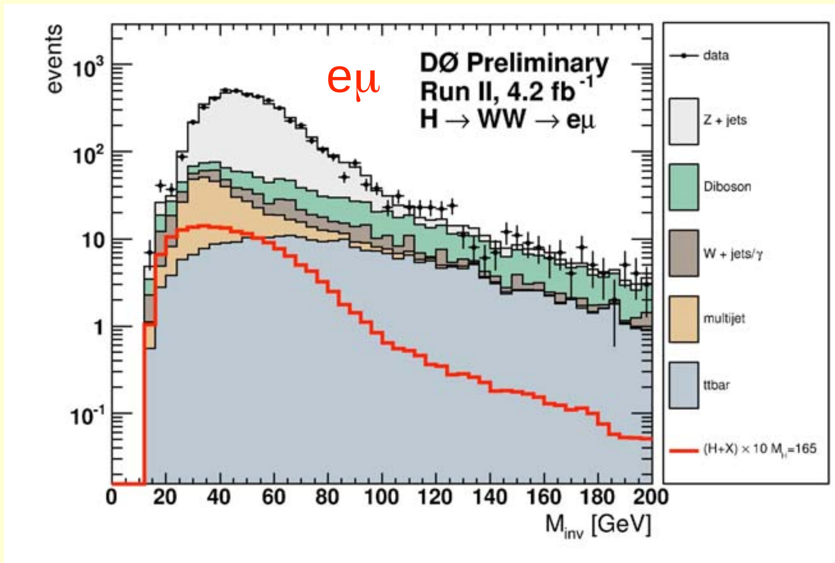
gg → H productionwith decay to WW

$H \to \ell^+\ell^- \nu\nu$



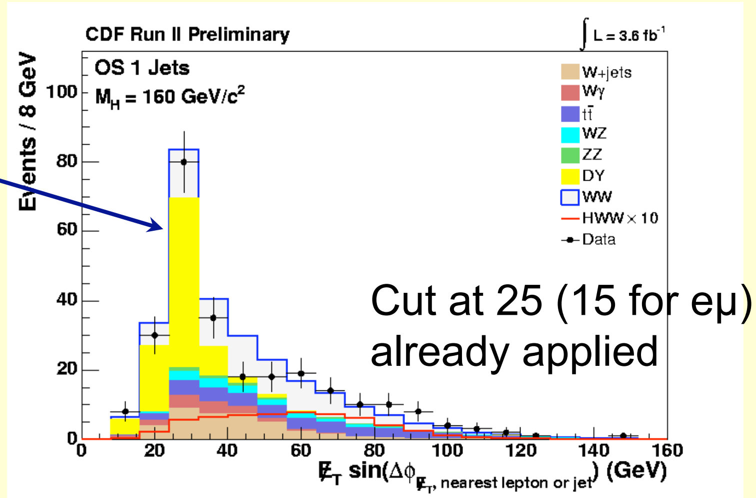
- Dominant decay for m_H >135 GeV: $H \to W^*W$
  Leptons in final state
  → exploitation of gg→H is possible
- Signal contribution also from $W/Z+H$, qqH production
  → Consider all sources of opposite sign di-lepton + missing E_T
  Split analysis in ee, μμ, and eμ final states
- Backgrounds: Drell-Yan, dibosons, tt, W+jet, multijet production

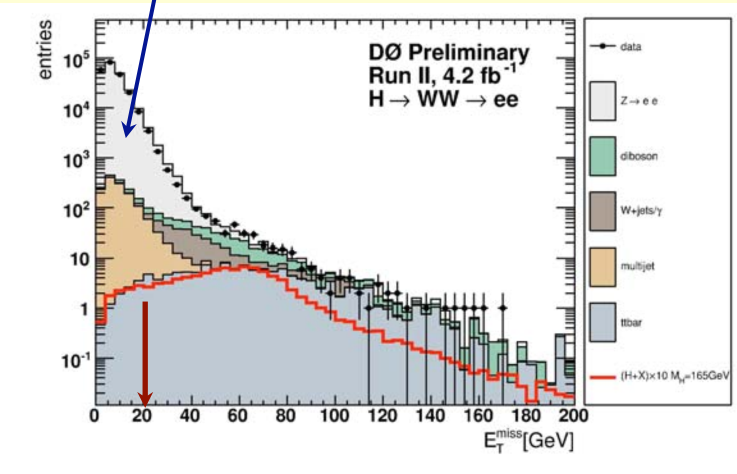




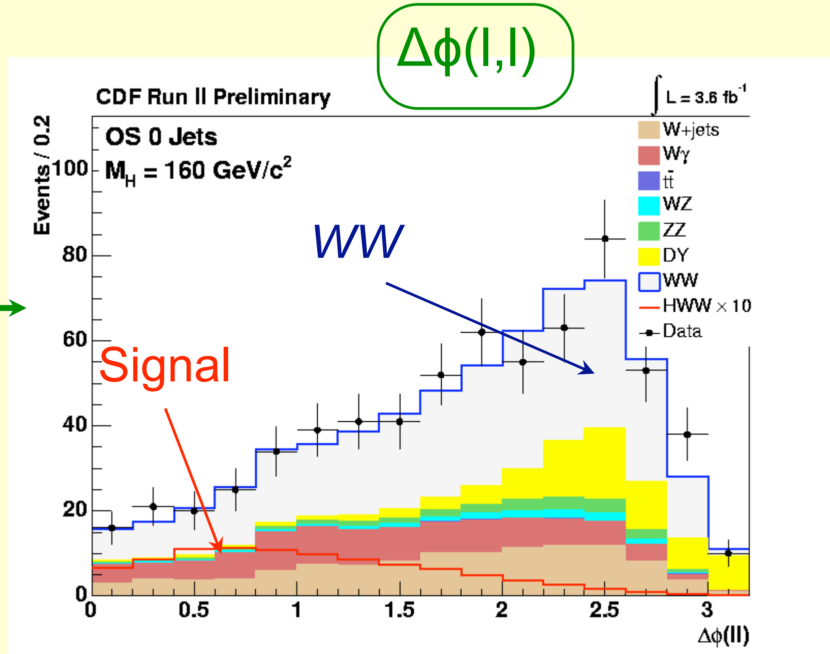
$H \rightarrow l^+l^- \nu\nu$

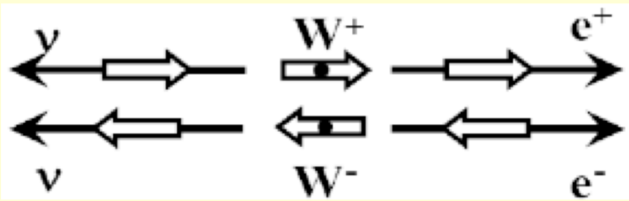
Dominant Drell-Yan background can be reduced with cuts on E_T^{miss} and its isolation (distance to nearest object)





Spin correlation gives main discrimination against irreducible background from non-resonant *WW* production



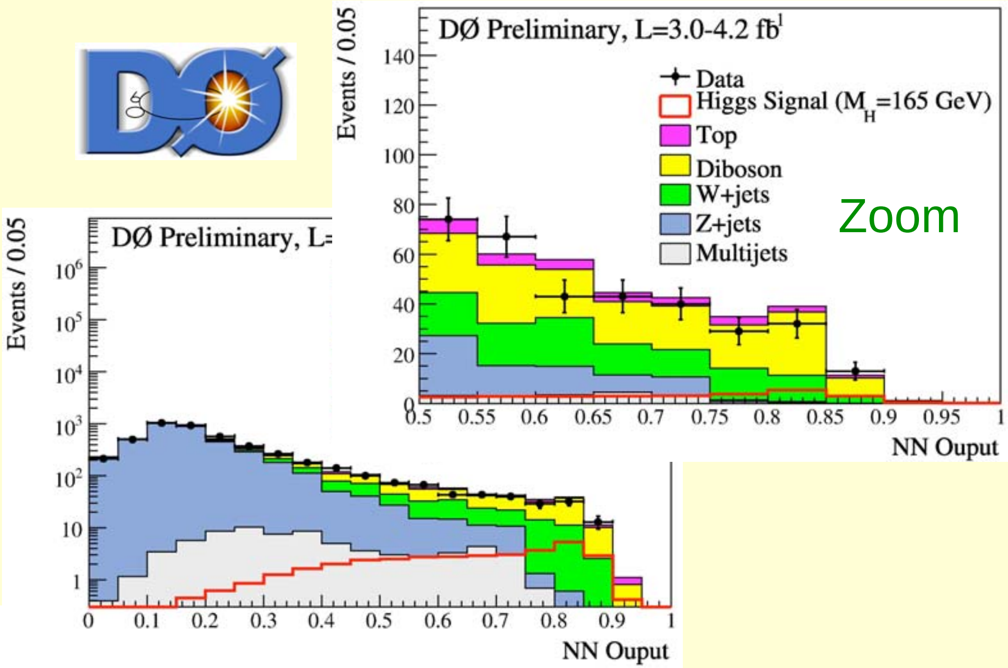


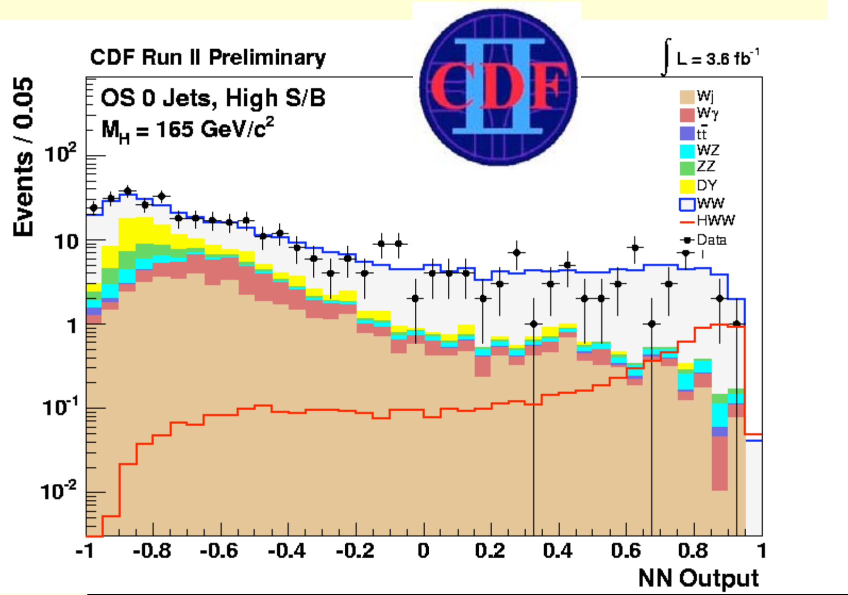
$H \rightarrow \ell^+\ell^- \nu\nu$

To increase sensitivity:

DØ: Split the samples according to lepton flavour and combine result

Neural Network with 11 kinematic and topological input variables

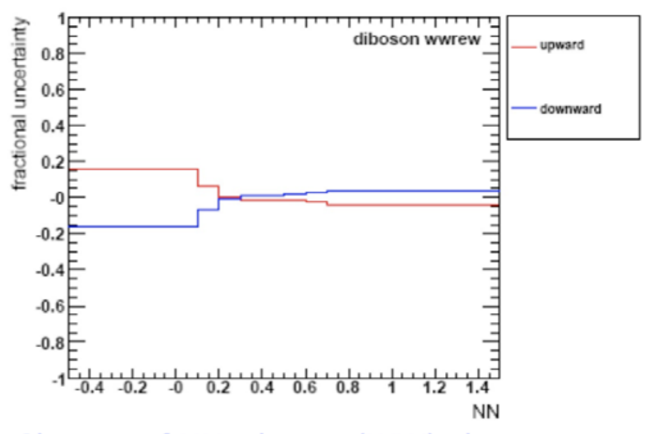




CDF: Split samples into jet multiplicity and lepton ID criteria: different signal and background composition

Veto events with tight b-tagged jet

Systematic uncertainties



Change of NN when $p_T(WW)$ changes

Main systematic uncertainties:

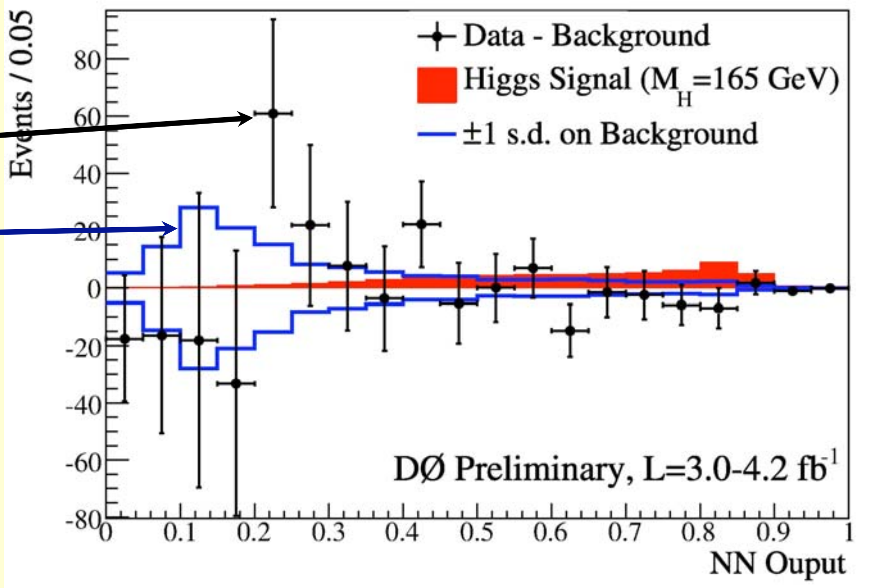
- Signal (total 10%): cross section, lepton ID/trigger
- Background (total 13%): cross sections, jet → lepton fake rate, jet ID/resolution/calibration

Systematic uncertainties change rate and shape of the signal and background predictions

SM signal expectation and data after background subtraction

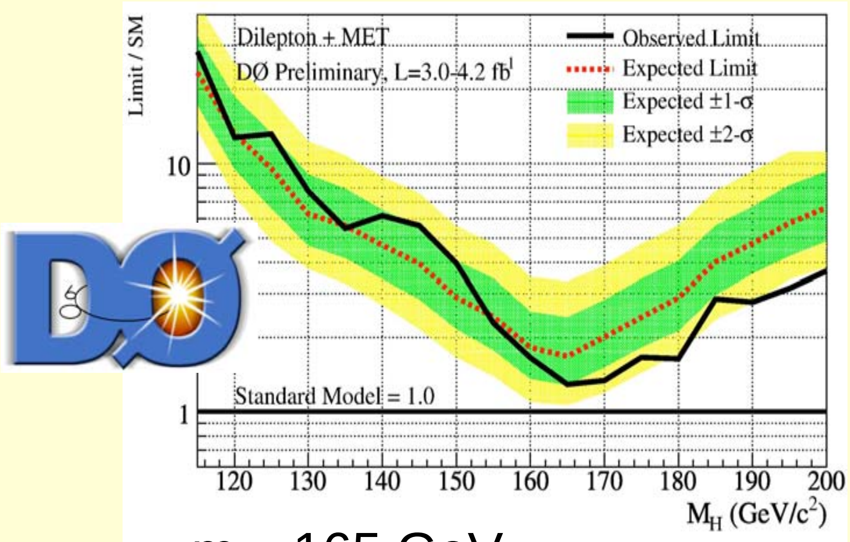
Constrained total systematic uncertainty

Expected 165 GeV SM Higgs signal would be visible over background uncertainty

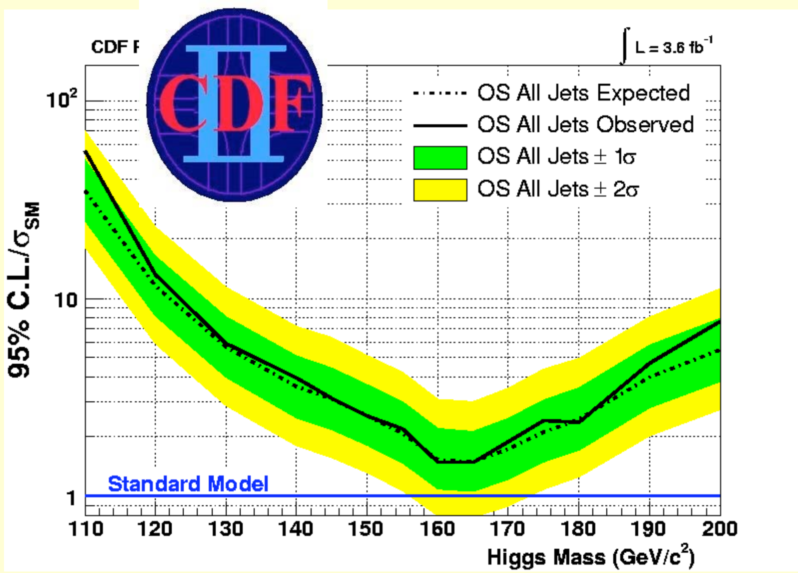


$H \rightarrow l^+l^- \nu\nu$

Exclusion limits per experiment:



m_H=165 GeV
Exp(Obs): 1.7(1.3) x σ_{SM}

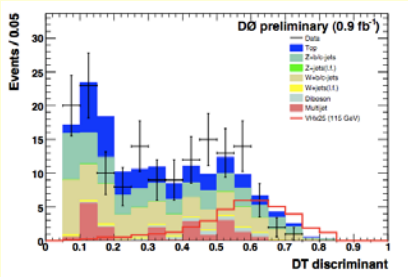


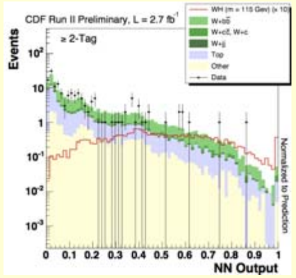
m_H=165 GeV
Exp(Obs): 1.4(1.5) x σ_{SM}

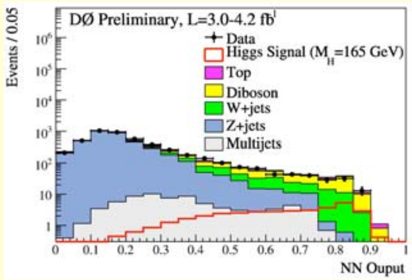
With additional luminosity expect single experiment exclusion around m_H = 165 GeV

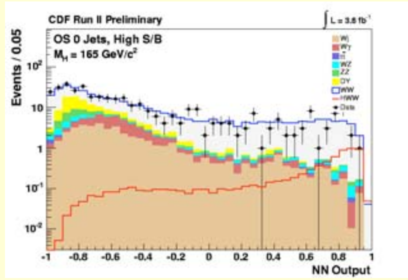
Combination → limit setting

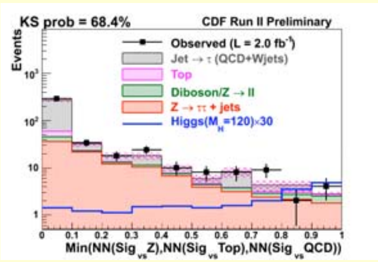
Combination of all channels and of the two experiments:
(note that exclusion is not possible in a single channel / experiment)

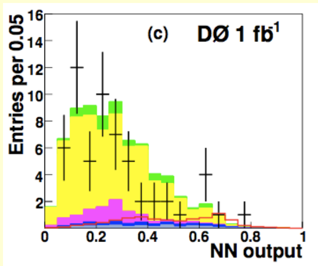


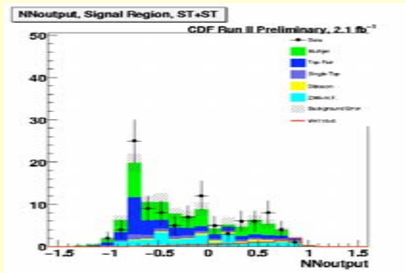


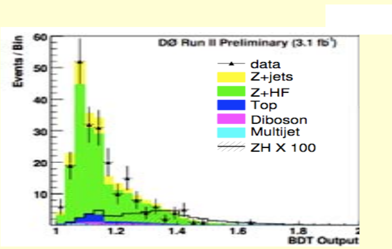


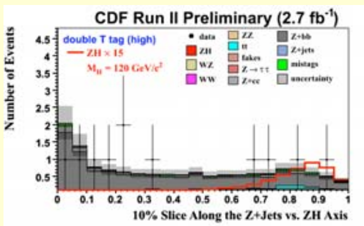


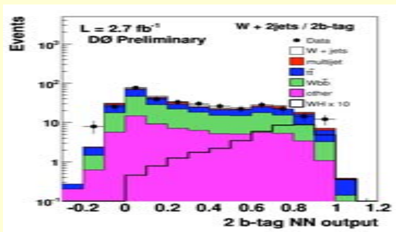


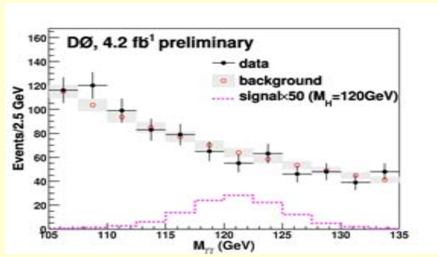




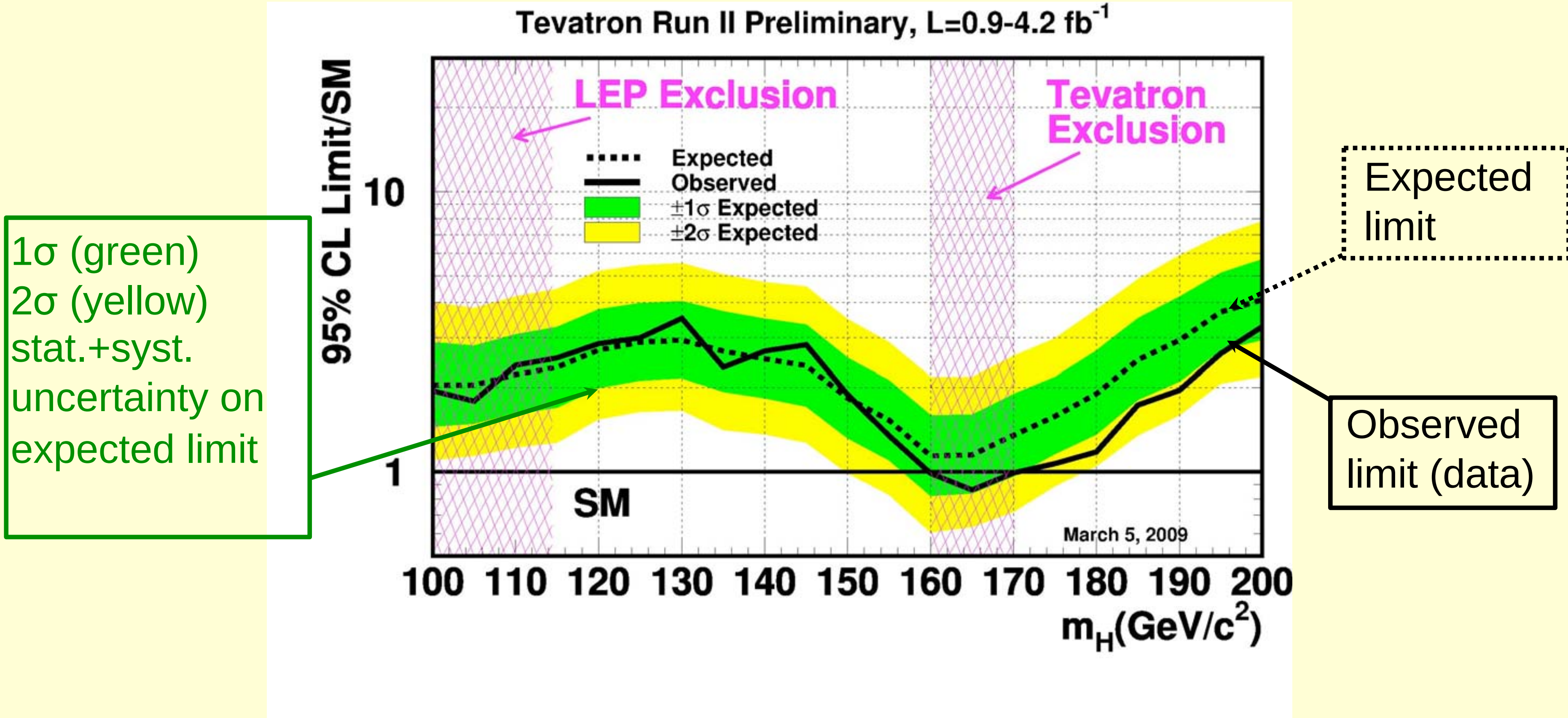








Combined Tevatron limits



A fluctuation in the data allows the Tevatron to set a 95% CL exclusion of a SM Higgs boson in the mass region around 160−170 GeV (first direct exclusion since LEP)

At m_H=115 GeV Expected limit: 2.4 x σ_{SM}

Observed limit: 2.5 x σSM

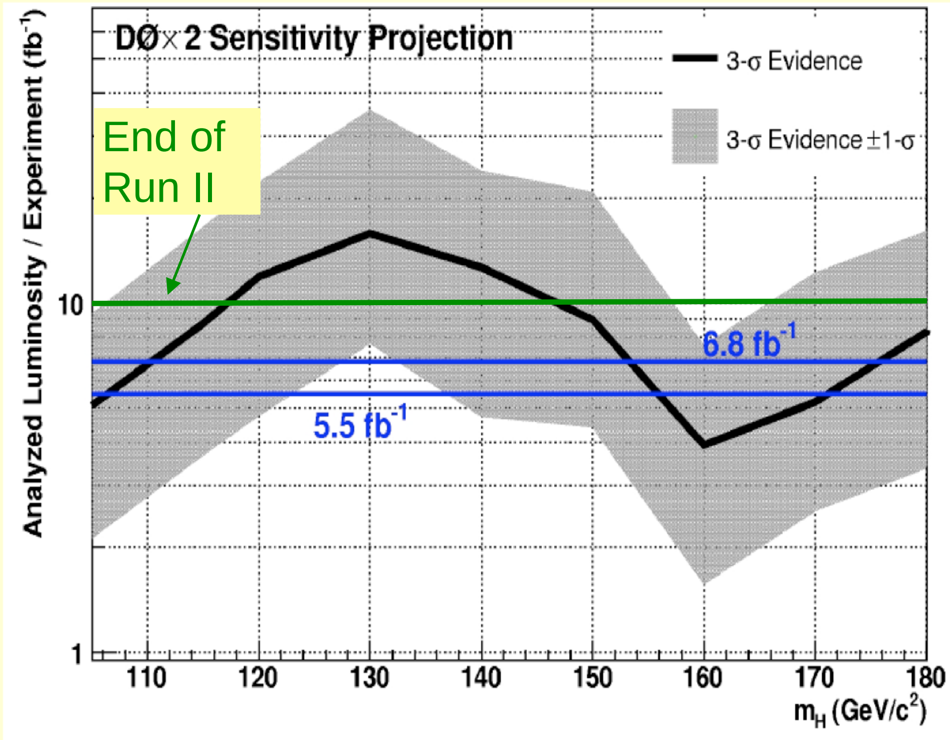
Conclusions on the Tevatron Higgs search

- The Tevatron experiments are about to reach sensitivity (expected limit) for the SM Higgs boson in the mass range around 160 GeV

- With increased luminosity the sensitivity in this region is expected to reach the 3σ level
  → either a large mass region can be excluded with 95% C.L. or first evidence (3σ) for a SM Higgs boson can be found;

- The Higgs search in the mass range below ~130 GeV is difficult (also at the LHC);

  Search for the bb final state will provide complementary information to the LHC Higgs search



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

- The Tevatron experiments are about to reach sensitivity for a SM Higgs boson in the mass range around 160 -170 GeV

  With an integrated luminosity of 10 fb^{-1} a 95% CL exclusion might be possible over the mass range up to ~180 GeV .or. 3s evidence in some mass regions