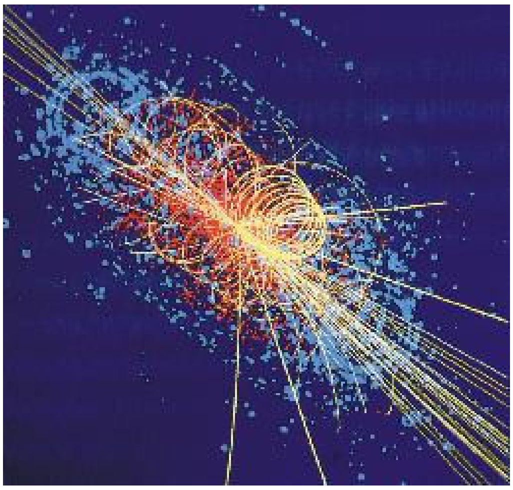
Physics at Hadron Colliders
- From the Tevatron to the LHC -



- **Introduction**
- **The present and future Hadron Colliders**
  - The status at the Tevatron
  - The LHC machine
- **QCD and Electroweak Physics**
  - **Jet production**
  - W- and top-Quark mass measurements
- **Search for the Higgs Boson**
- **Search for New Phenomena**

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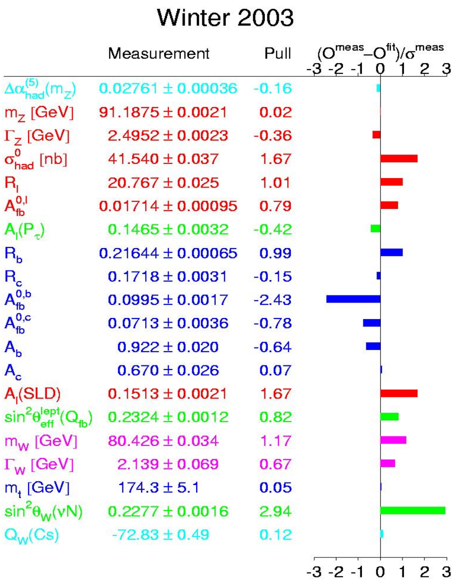
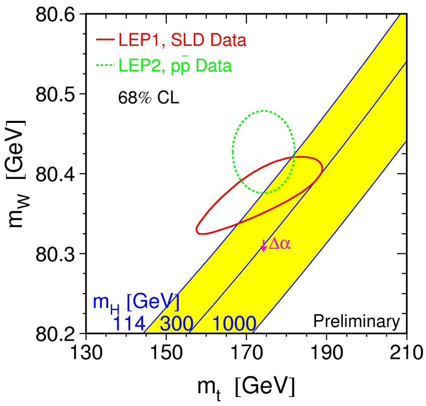
Universität Freiburg / Germany

Results from the LEP precision measurements



W-mass depends on top-quark mass and Higgs boson mass via radiative corrections:



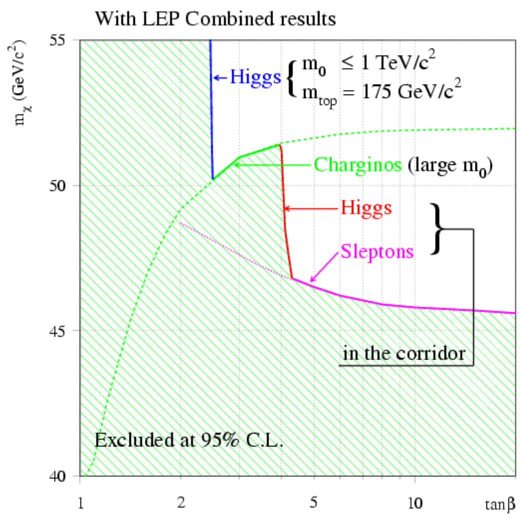
Incredible precision,

but the Standard Model is still alive……

Results of the precision el.weak measurements: (LEWWG-2003):

M_H = 91 (+58) (-37) GeV/c^2
M_H < 211 GeV/c^2 (95 % CL)

SUSY is still not found….



In the MSSM the mass of the

Lightest SUSY Particle (LSP)

is constrained to be

larger than ~45 GeV / c^2

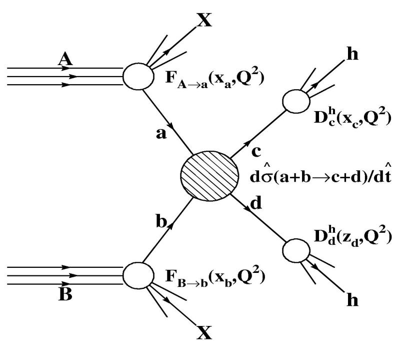
The role of *Hadron Colliders:*

Discovery machines

energy → explore the TeV range

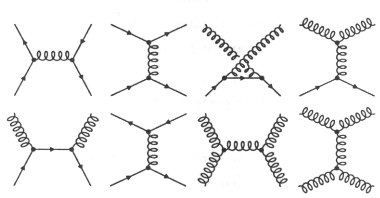
Precision (SM tests, large rates)

Physics at Hadron Colliders



Dominant hard scattering cross section:

„QCD Jet Production“ quark/gluon scattering



$$\sigma = \sum_{ij} \int dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \hat{\sigma}_{ij}\left(\alpha_s^m(\mu_R^2), x_1 P_1, x_2 P_2, \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$

Sum over initial states

Parton Distributions

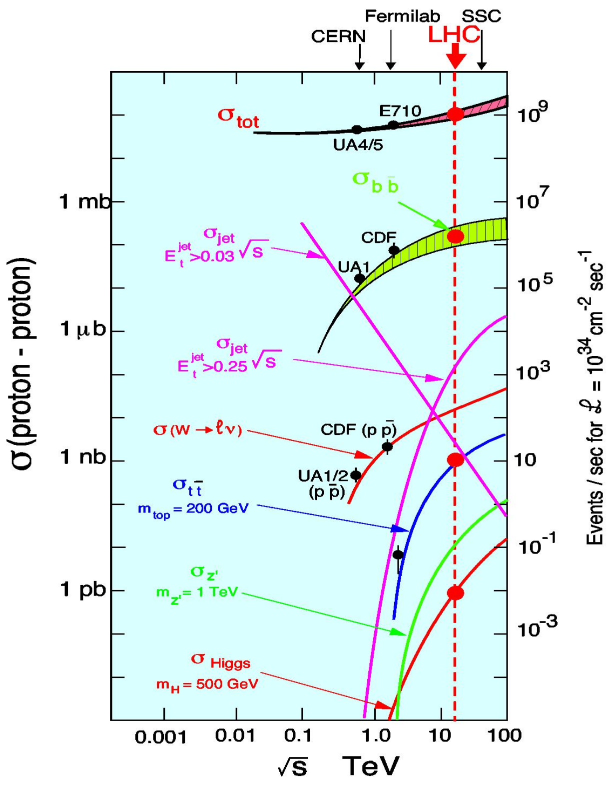
Factorization Scale

Point Cross Section

Order α_s^m

Renormalization Scale

Cross Sections and Production Rates



Rates for $L = 10^{34}$ cm^{-2} sec^{-1}: (LHC)

• Inelastic proton-proton reactions:	10^9 / sec
• bb pairs	5 10^6 / sec
• tt pairs	8 / sec
• W → e ν	150 / sec
• Z → e e	15 / sec
• **Higgs (150 GeV)**	**0.2 / sec**
• **Gluino, Squarks (1 TeV)**	**0.03 / sec**

Interesting physics processes are rare:

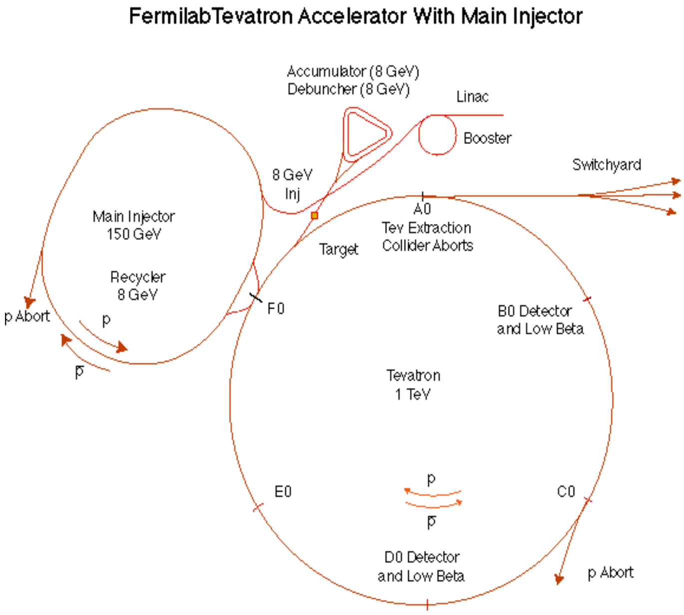
⇒ high luminosity,
⇒ extremely challenging detectors
(to suppress the huge backgrounds)

The Tevatron collider at Fermilab

Proton-antiproton collider

- **1992 - 1996: Run I, 2 experiments**
  CDF und D0, √s = 1800 GeV
  ∫ L dt = 125 pb $^{-1}$
- **1996 - 2001: Upgrade program**
  Machine: new injector
  Antiproton recycler
  (under commissioning)
  + Detectors
- **since March 2001: Run II a,**
  √s = 1960 GeV, 2 fb^{-1}
- **2006 - LHC: Run II b,**
  √s = 1960 GeV, 10-20 fb^{-1}
  0.8 → 5 x 10^{32} cm^{-2} s^{-1}

Tevatron accelerator complex



New for Run II:

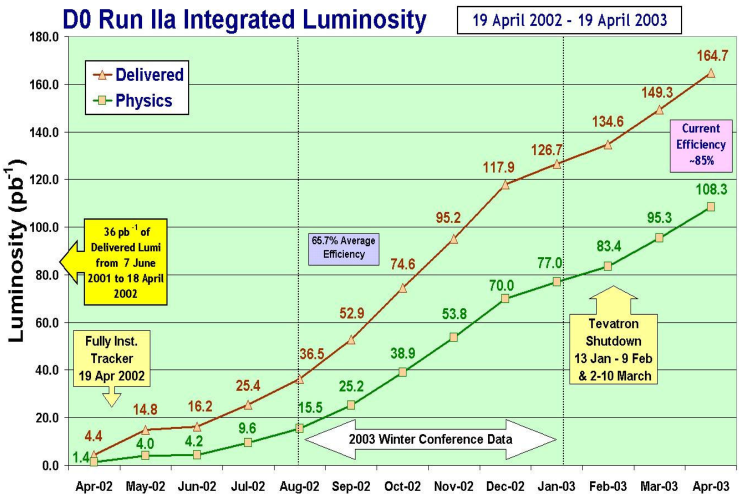
Main injector (150 GeV proton storage ring) replaces main ring

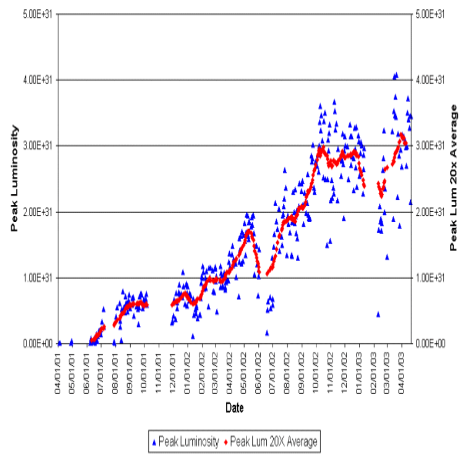
New permanent magnet storage ring for anti-proton accumulation (under commissioning)

Increased center-of-mass energy (1.8 $\Rightarrow$ 1.96 TeV)

More bunches (6 $\Rightarrow$ 36, 396 ns crossing time)

Integrated and peak luminosities





Peak luminosity

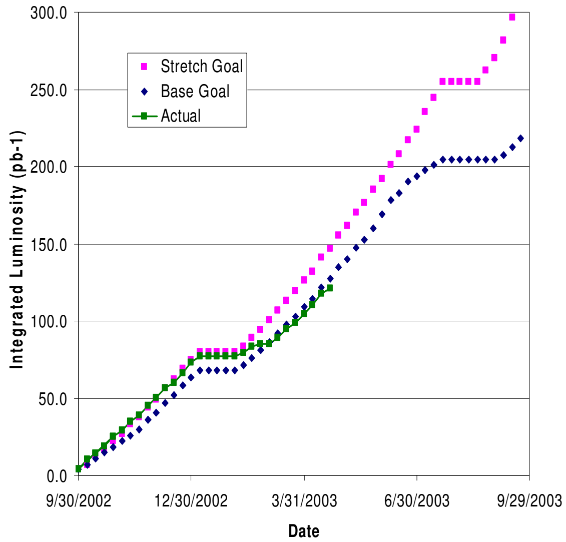
Run II goal: **5 x 10^{32} cm^{-2} s^{-1}**

Run II maximum: **4.1 x 10^{31} cm^{-2} s^{-1}**
(to date)

Run I maximum: **2.4 x 10^{31} cm^{-2} s^{-1}**

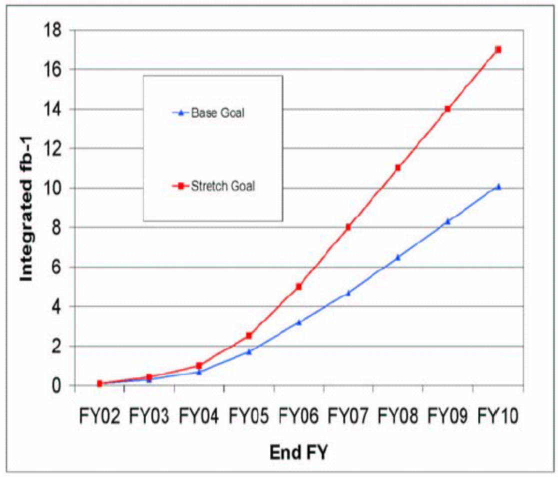
Luminosity Goals

Short term



>200 pb^{-1} by Sept. 2003

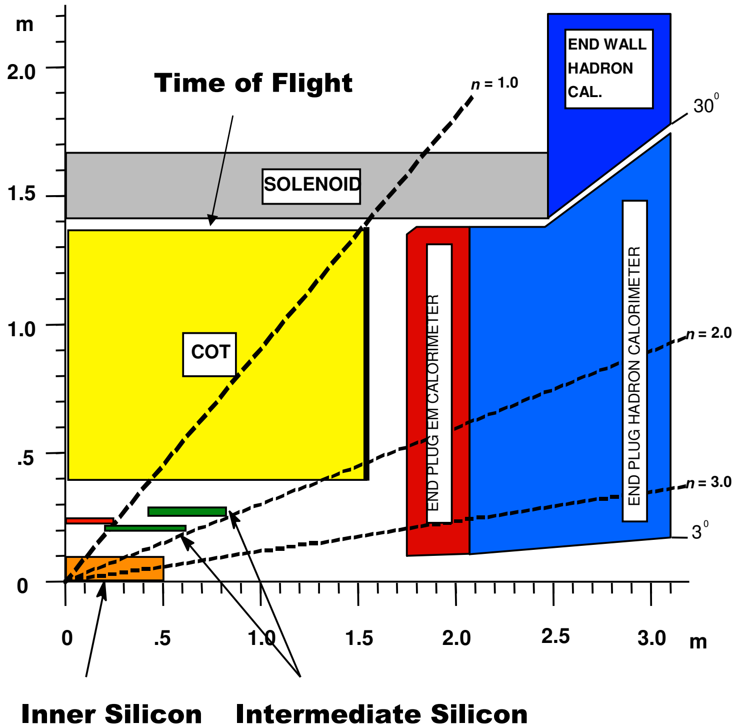
Long term



~ 9 -15 fb^{-1} by Sept. 2009

(The plan is currently being reviewed,
a revised plan will be submitted
to DOE in June 2003)

CDFII Detector



Retained from Run I
- Solenoid (1.4 Tesla)
- Central calorimeters
- Central muon detectors

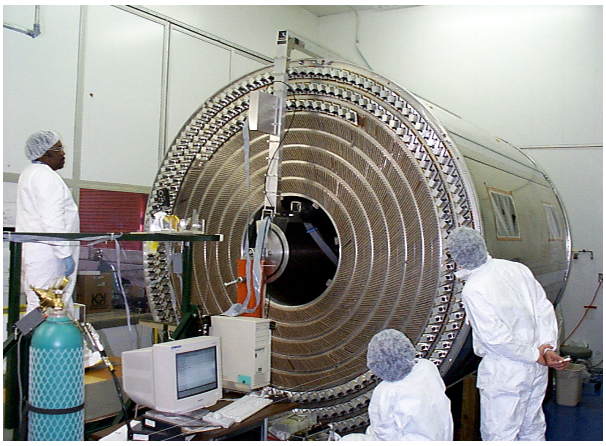
New in Run II

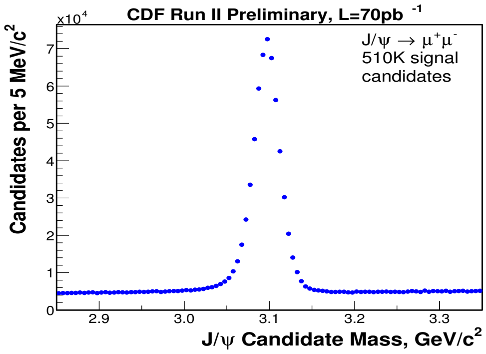
Tracking system
- Silicon vertex detector (SVXII)
- Intermediate silicon layers
- Central outer tracker (COT)

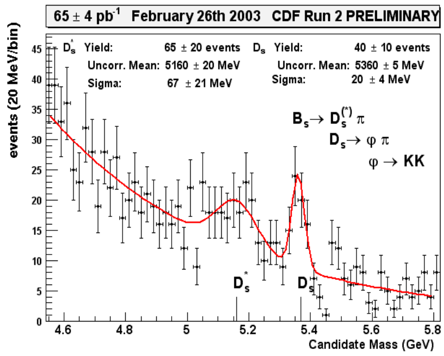
End plug calorimeter
Time of flight system

Front-end electronics
Trigger and DAQ systems

Tracker Performance



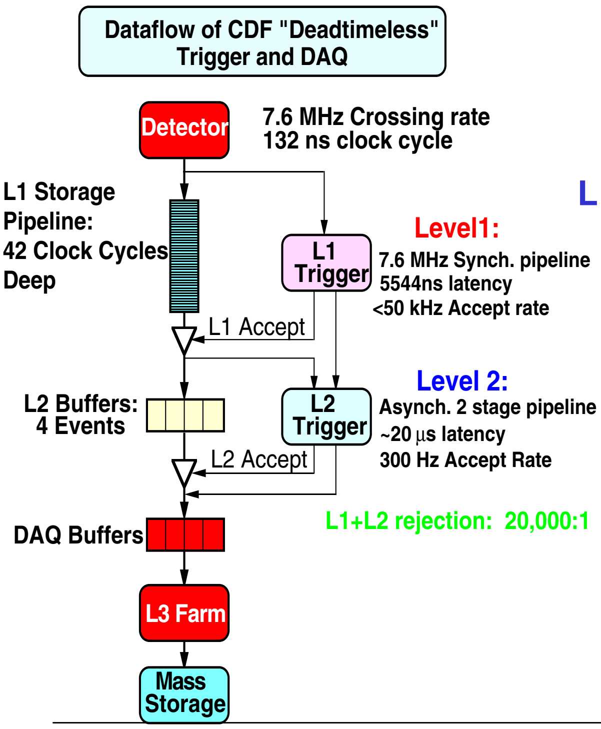




$\Delta p_T/p_T = 0.13\%\ p_T\ (GeV/c)$

Power of $B\ell^2$ (~2 T m^2)

Trigger and DAQ



Data on tape:
~ 160+ pb^{-1}
(including commissioning data)

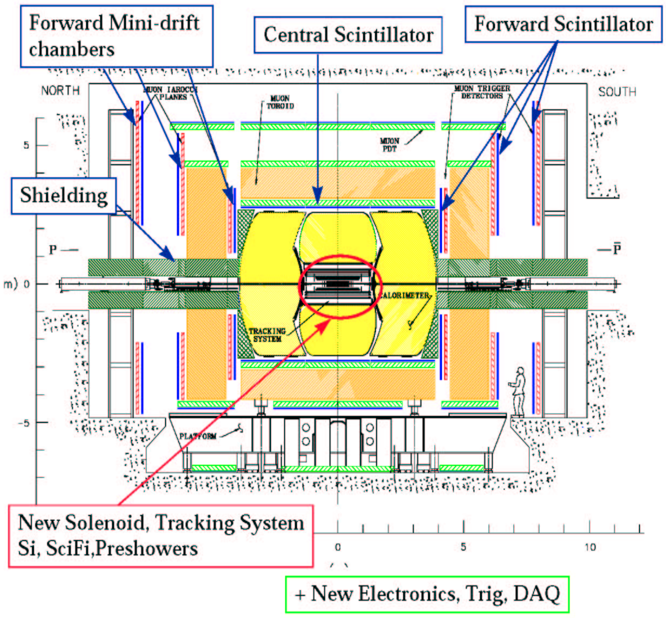
Rate at
$L \sim 3 \times 10^{31}$ cm^{-2} s^{-1}

12 kHz — Calorimeter energy, Central tracker, Muon stubs

250 Hz — Cal Energy-track match, E/P, EM shower max, Silicon secondary vertex, Multi object triggers

50 Hz — Farm of PC's running fast versions of Offline Code ➔ more sophisticated selections

DØ Run II Detector



Retained from Run I

LrAr calorimeter
Central muon detector
Muon toroid

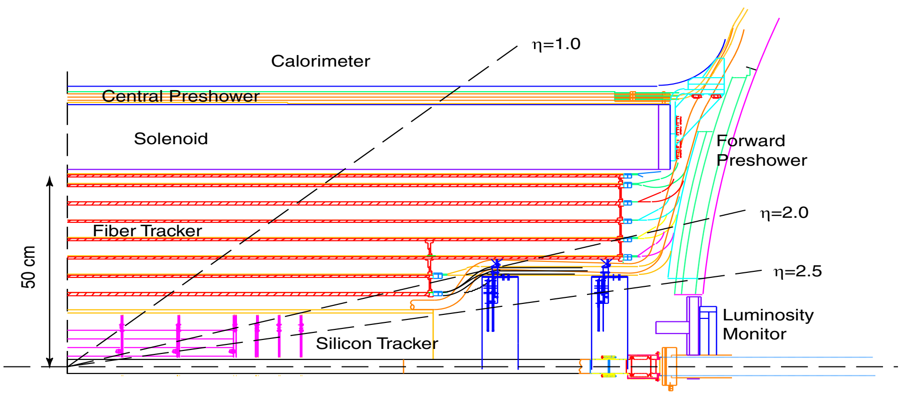
New for Run II

Inner detector (tracking)

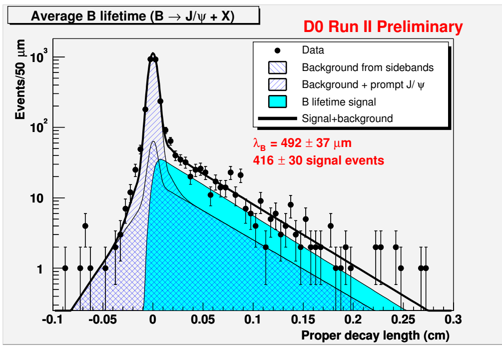
Preshower detectors
Forward muon detector

Front-end electronics
Trigger and DAQ

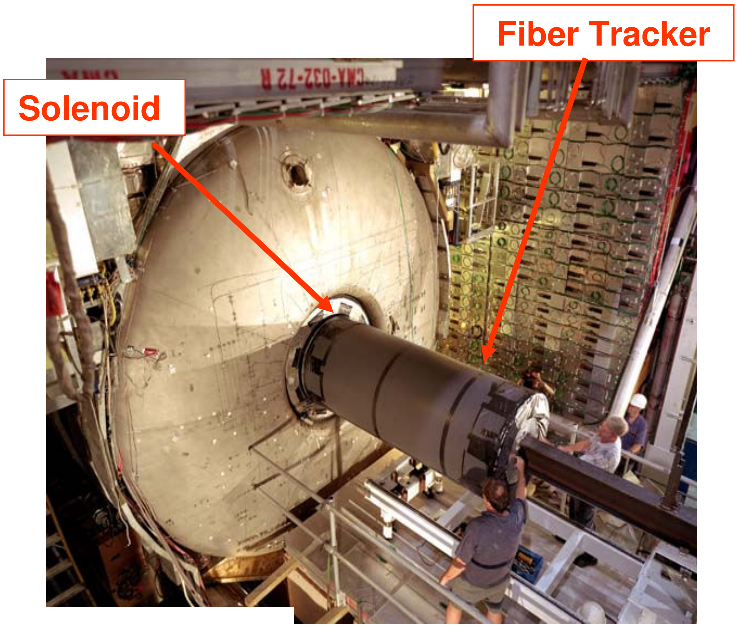
The Upgraded DØ Tracking Detector



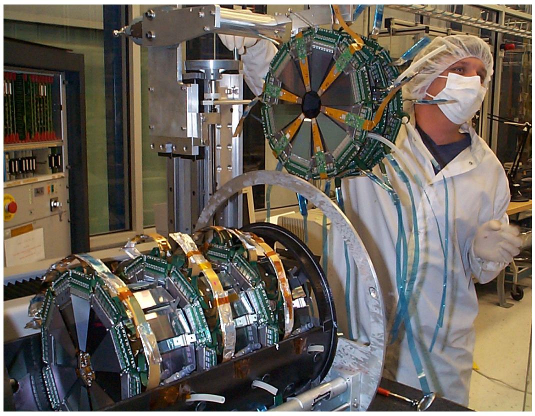
- First time charged particle tracking added to a major "non-magnetic" detector!
  - 2T solenoid
  - >100K scintillating fibers
  - >700K silicon strips



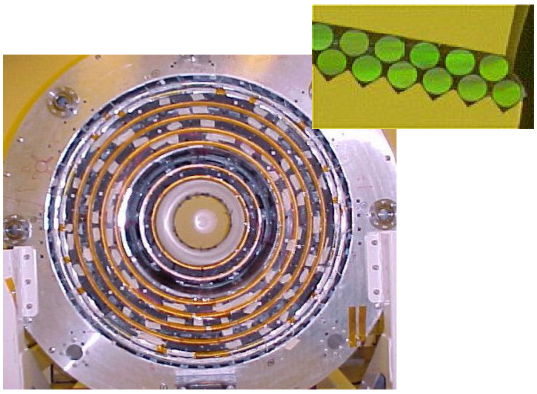
DØ Detector

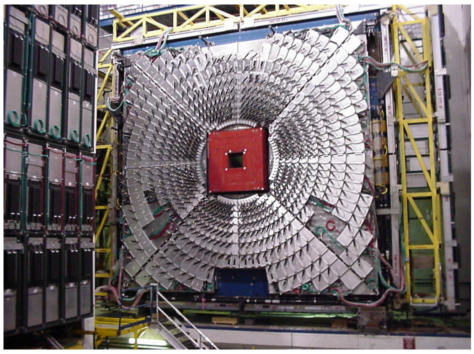


Silicon Detector

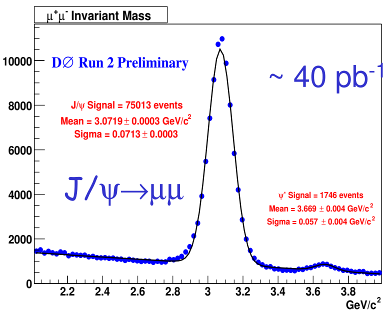


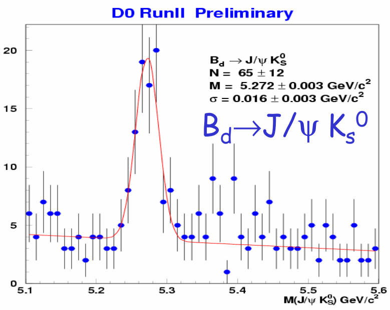
Tracking Performance



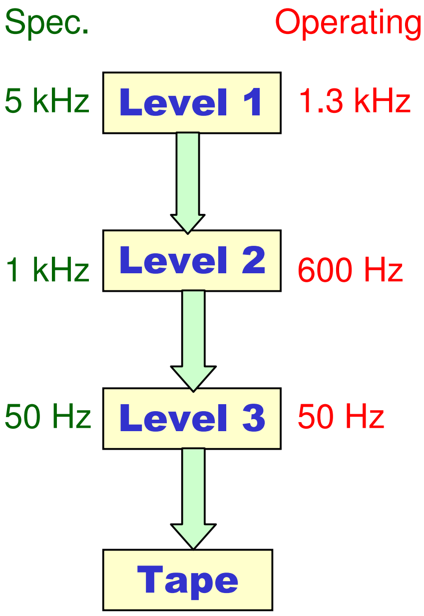


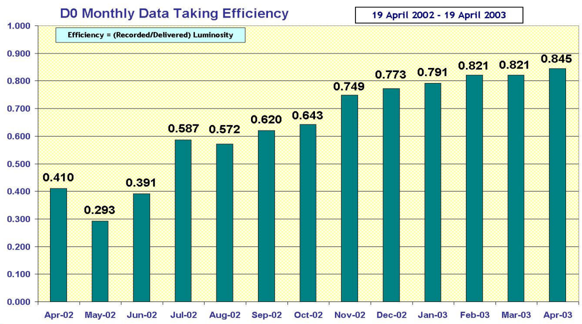
$B\ell^2 \sim 0.5$ T m²

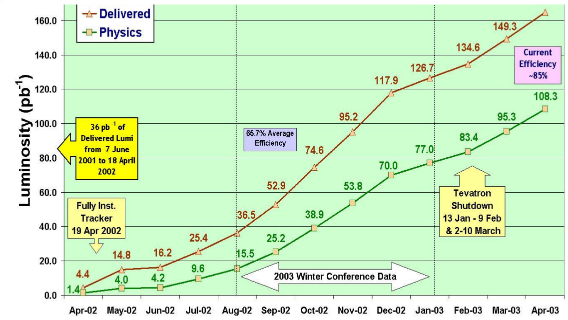




Trigger and DAQ





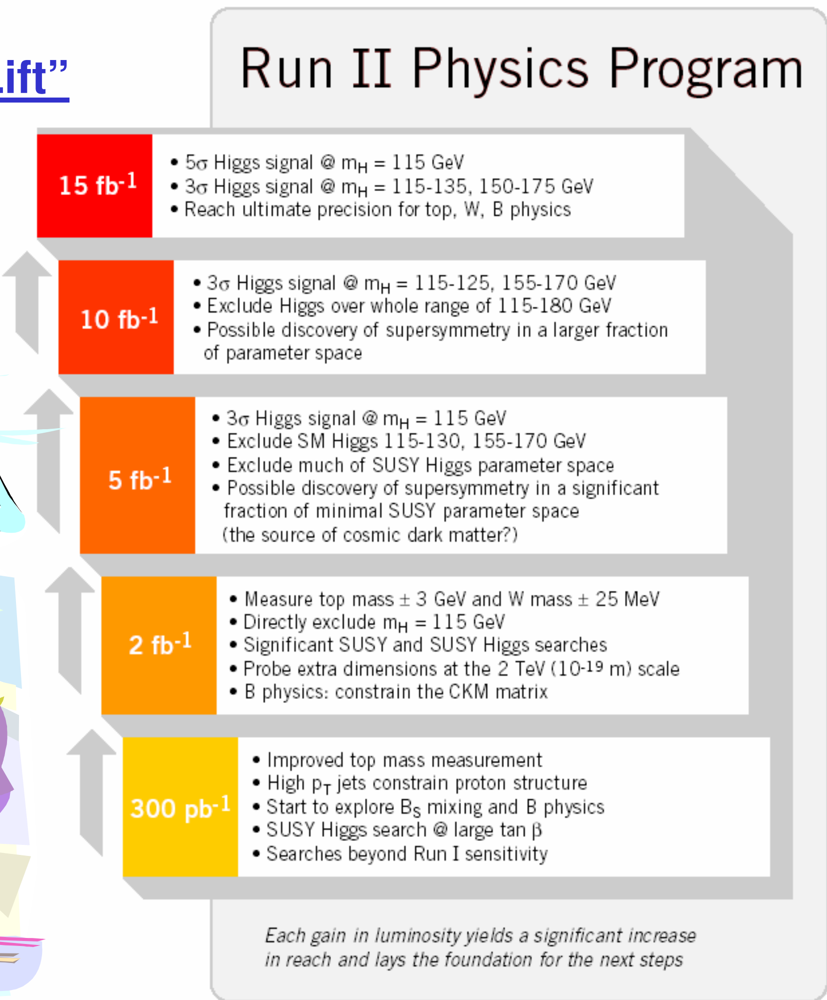


Track and vertex triggers integration underway

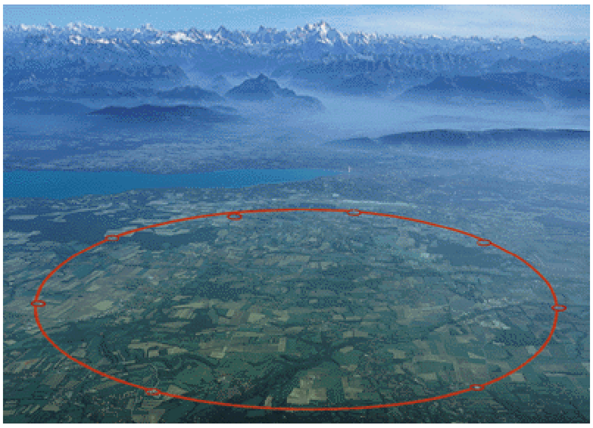
DAQ efficiency improved significantly, running routinely at ~85% now…

The "Luminosity Lift"

New physics panoramas open up each time we take the "Luminosity Lift"



The Large Hadron Collider (LHC)



- **Revised Time Schedule:**

Dec. 2006 — Ring closed and cold

Jan. - Mar. 2007 — Machine commissioning

Spring 2007 — First collisions , pilot run.
L=5x10^{32} to 2x10^{33} cm^{-2} sec^{-1},
≤ 1 fb^{-1}
Start detector commissioning,
~ 10^5 Z → ℓℓ, W → ℓν, tt events

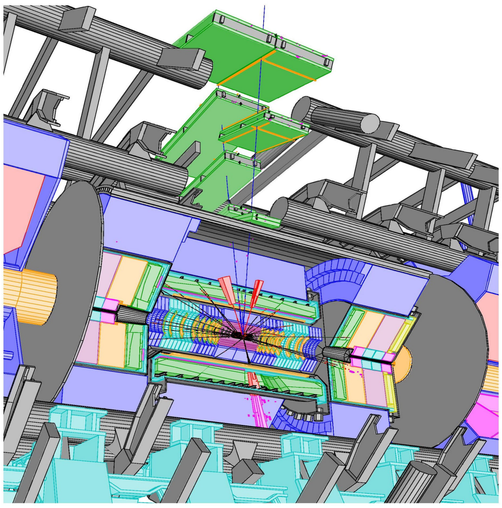
June - Dec. 2007 — Complete detector commissioning,
Physics run

→ 2009 — L=1-2 x10^{34}, 100 fb^{-1} per year
(high luminosity LHC)

low luminosity: **L = 1x10^{33} cm^{-2} sec^{-1}**
10 fb^{-1} / year

high luminosity: **L = 1x10^{34} cm^{-2} sec^{-1}**
100 fb^{-1} / year

Detector Requirements



- Good measurement of leptons and photons

momentum range: ~ GeV (b → l ν c, H→ℓℓℓℓ)
~ TeV (W' → l ν)

lepton energy / momentum scale: 0.1 % → 0.02%,
large statistics for calibration, Z → ℓℓ,
m_Z is close to m_W

- Good measurement of missing transverse energy (E_T^{miss})

and

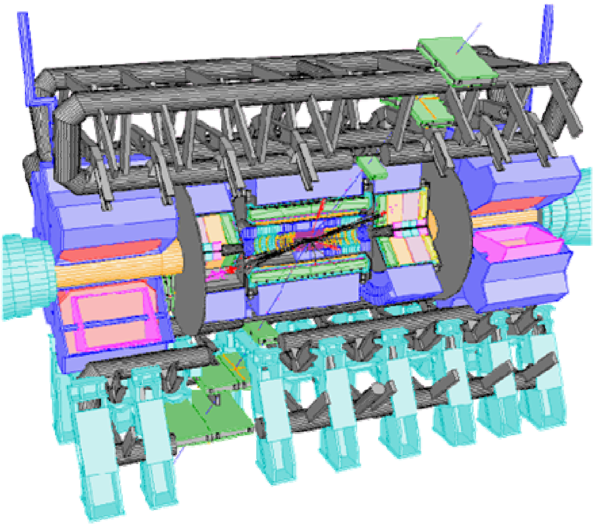
Jet energy measurements and jet-tagging in forward region
⇒ calorimeter coverage down to η ~ 5
Jet energy scale: 1% (relevant for m_{top} , SUSY)

- Efficient b-tagging and τ identification (silicon strip and pixel detectors)

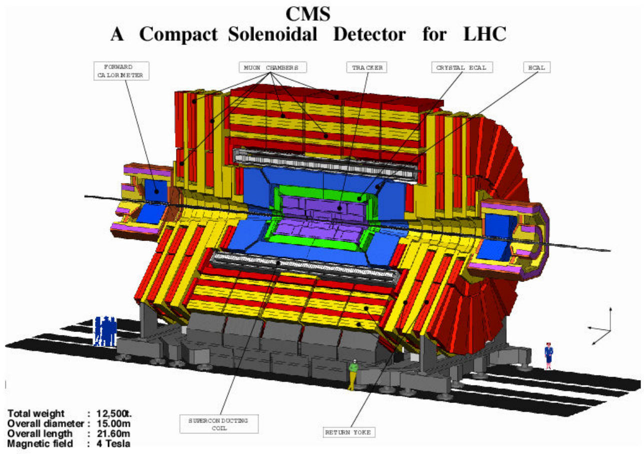
- Fast (25 ns bunch crossing) and rad. hard detectors and electronics

The LHC Experiments

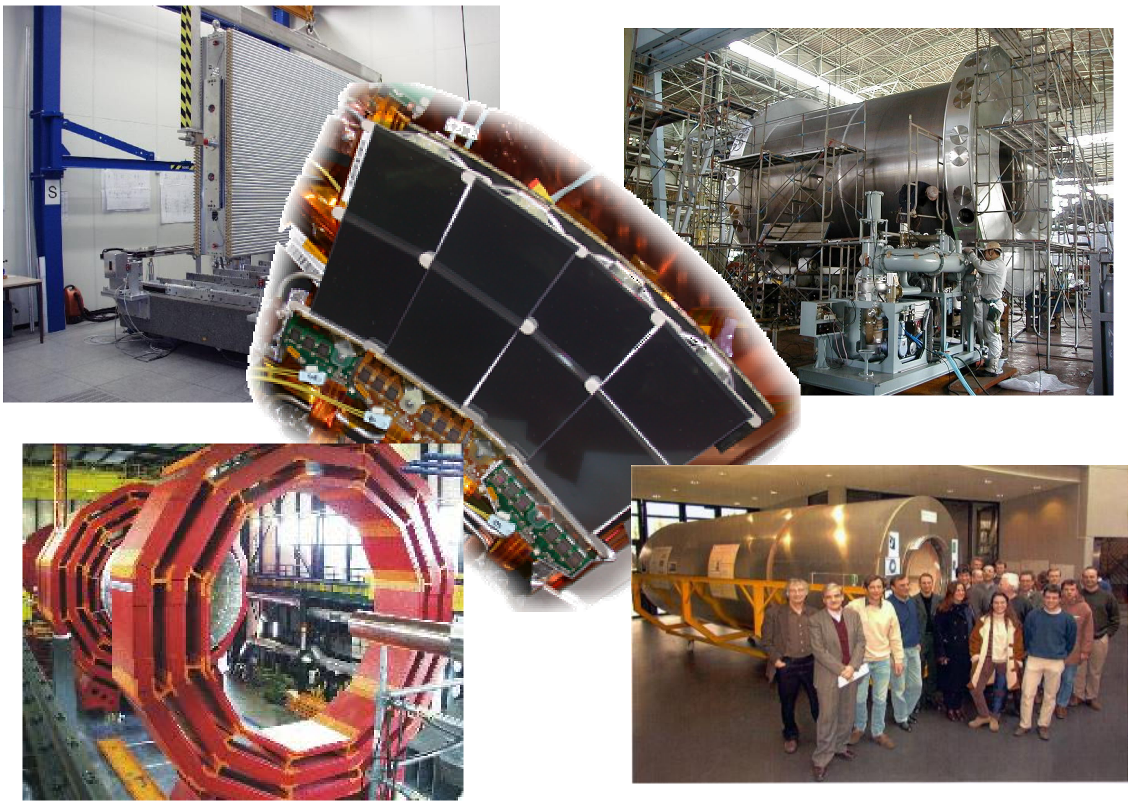
ATLAS



CMS



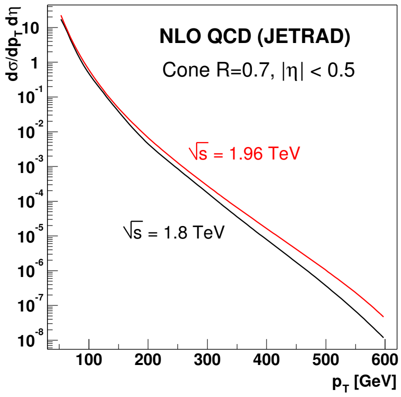
ATLAS and CMS detector construction



QCD Studies

- Jet production cross section

  (significant increase of cross section with energy; factor 2 for P_T(jet) = 400 GeV / c)

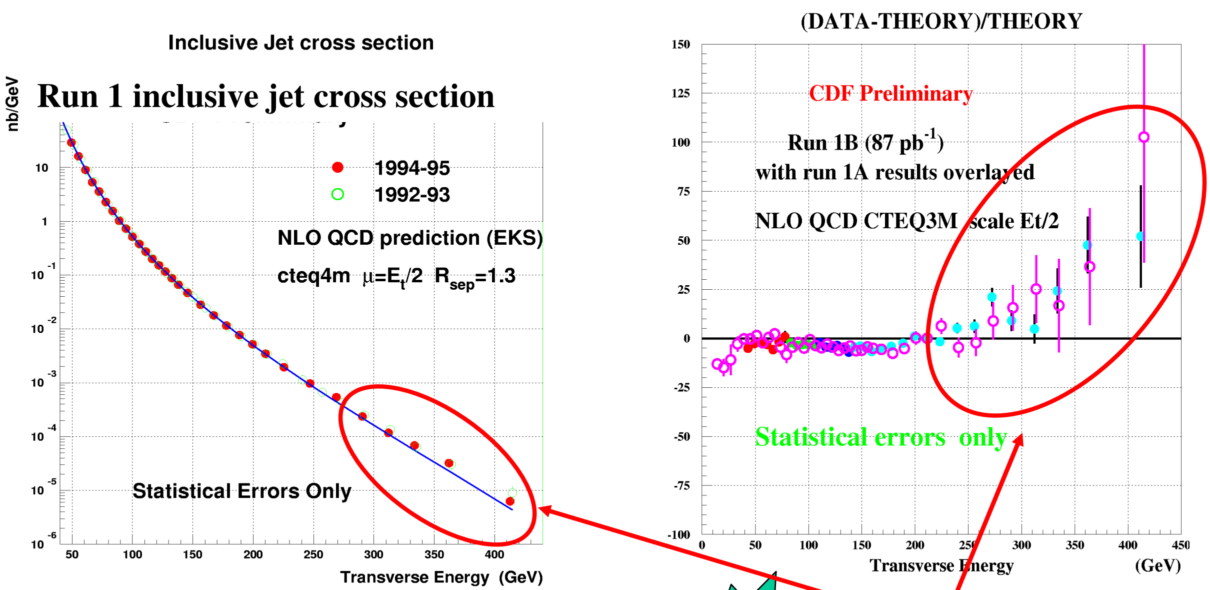


- Test of perturbative QCD in W/Z production
  (NLO corrections, constrain the PDFs)

- Better understanding of the experiment
  – efficiencies, backgrounds, luminosity
  – use these signals to tune triggers & algorithms

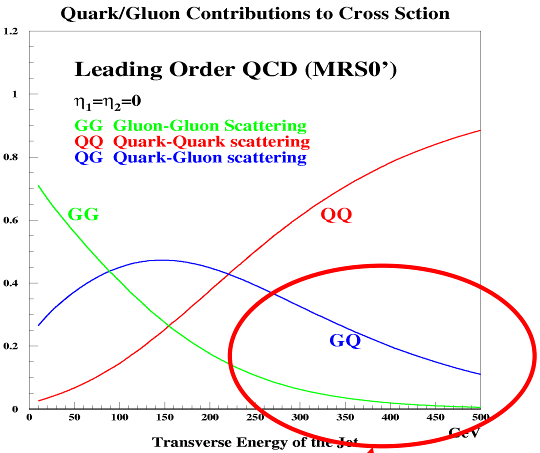
Reminder: CDF Inclusive Jet Cross-section in Run I

Vital to understand QCD in order to perform precision/search physics



Consistent over 7 orders of magnitude BUT deviation at high Et

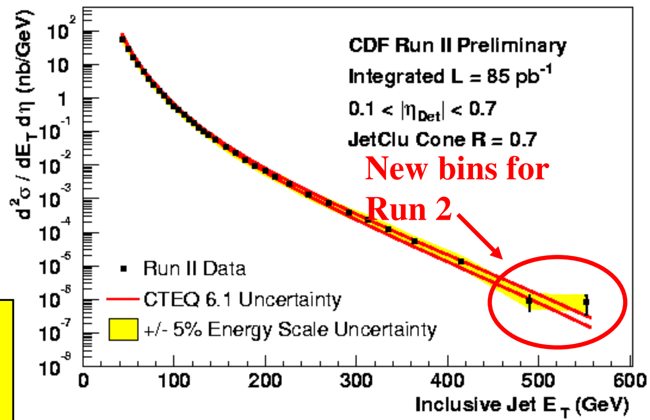
Possible Standard Model explanation



Run 2 - more high Et jets:

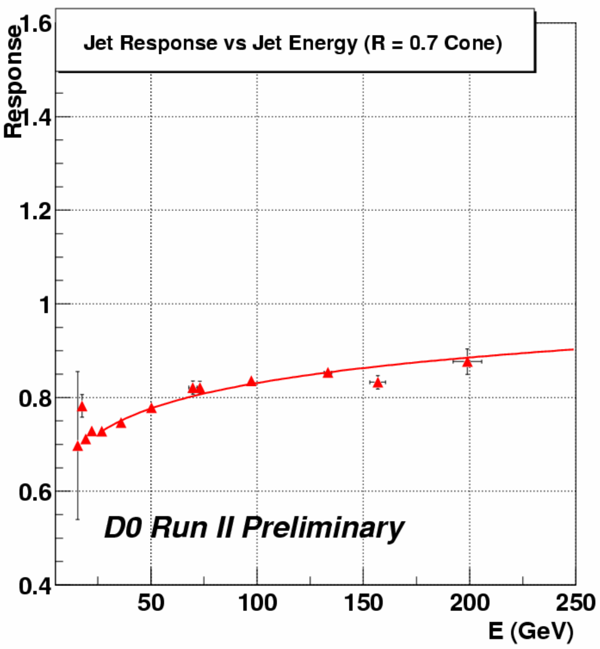
Test QCD at high Et

Discriminate between new physics and gluon PDF



Important gluon-gluon and gluon-quark contributions at high Et
Gluon PDF @ high x not well known.

Main systematic uncertainty: Jet Energy Scale



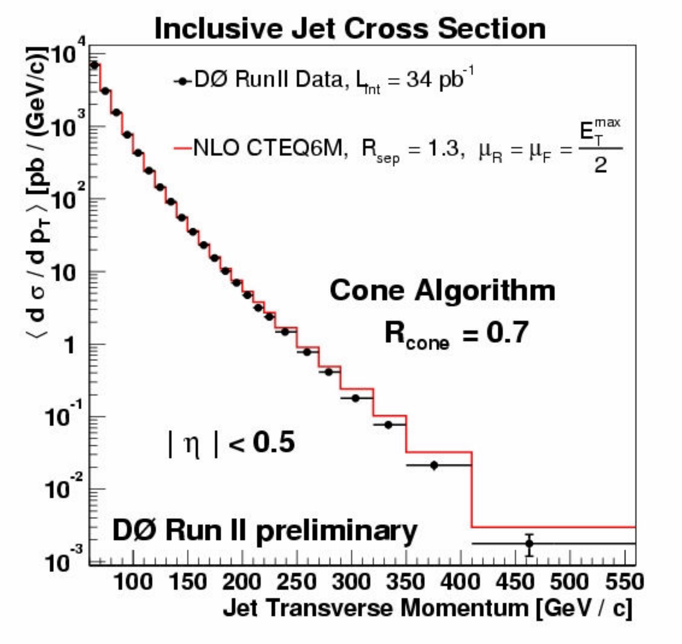
Jet Response:

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

Jet Energy Scale

- Main corrections:
  - Subtraction of offset energy not originating from the hard scattering
    - use minimum bias data (only requirement is an inelastic interaction) to extract this
  - Correction for jet energy in/out of cone
    - detector effect of jet calorimeter energies showering out of cone or different jet showering energy into cone
    - corrected with jet data + MC
- Current level of uncertainty
  - 9% for central jets between 50-200 GeV
  - Dominated by response measurement
    - statistics
    - electromagnetic scale

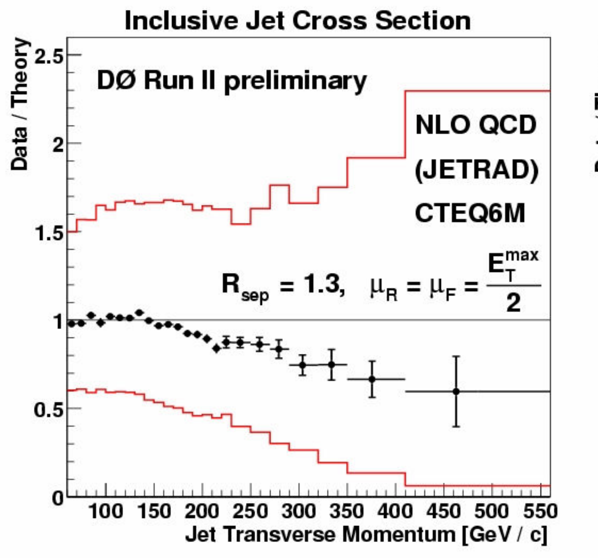
D0-Run II inclusive Jet Cross Section

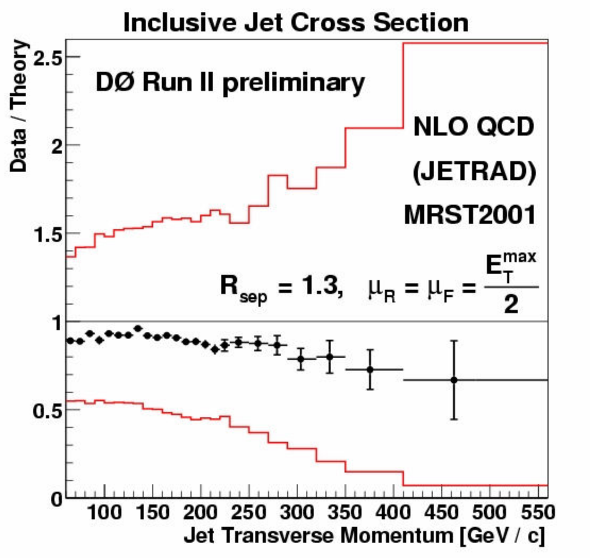


- Finally…
  after all corrections

Comparison with Theory

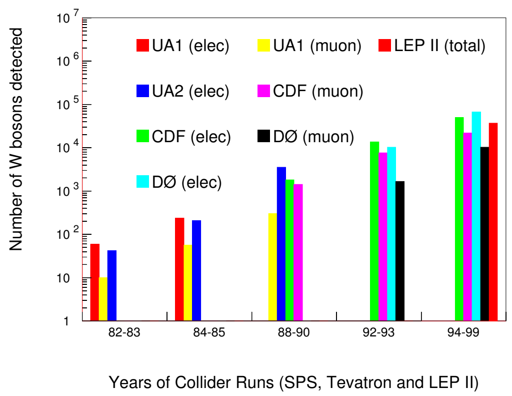
– Fully corrected inclusive jet cross section

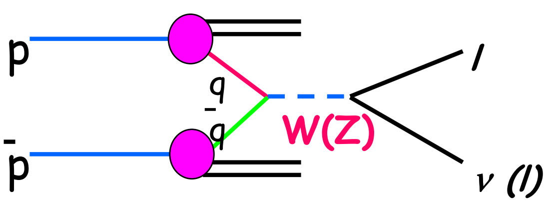




W and Z production

Number of detected W-bosons:

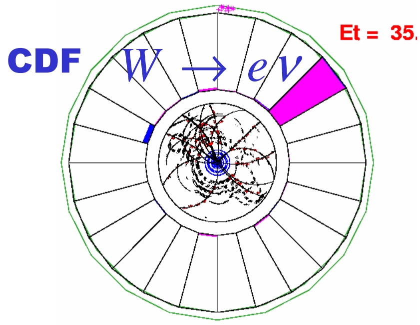




Tevatron: expected rates for 2 fb^{-1}: 3 Mio W → ℓ ν events

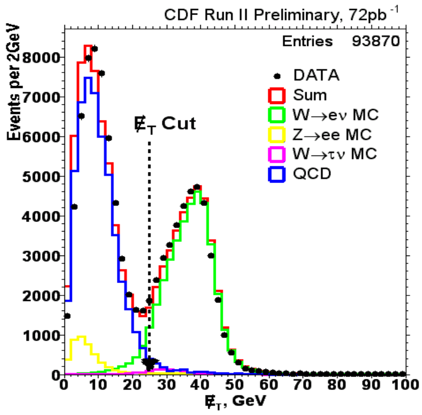
LHC: expected rates for 10 fb^{-1}: 60 Mio W → ℓ ν events

W / Z $\rightarrow$ eν / ee event selection



Trigger:

- L1: 1 calorimeter tower > 10 GeV (or 2 > 5 GeV)
- L3: Electron candidate > 20 GeV, shower shape cut



Electrons

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

Z→ee

- 70 GeV < m_{ee} < 110 GeV

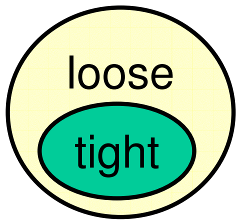
W→eν

- Missing transverse energy > 25 GeV
- Matched with central tracks

First results on W $\rightarrow$ e ν from the Tevatron Run II

- **Dominant (although small) background from QCD jet events**
- **Estimated from data, using different selections**

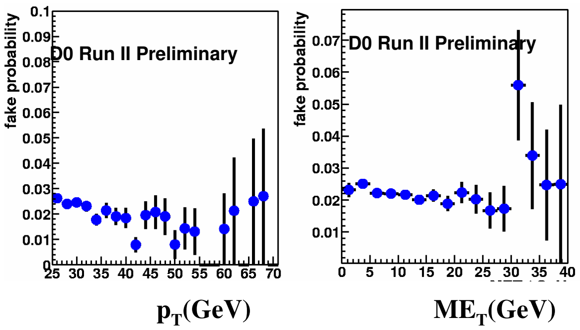
(loose: calorimeter cuts, tight add. matching of a track in the central detector)



$$N_{loose} = N_W + N_b$$
$$N_{tight} = N_W \varepsilon_{trk} + N_b \varepsilon_f$$

Solve for N_W

From QCD dijet sample

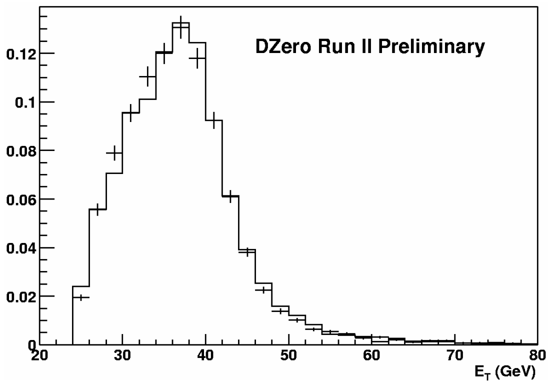


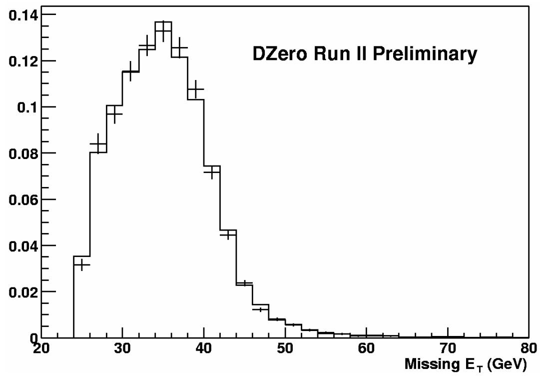
Other backgrounds:

- W → τν → eννν (1.5 %, MC)
- Z → ee (very small)

W → eν Cross Section

Background subtracted distributions compared to PYTHIA MC prediction



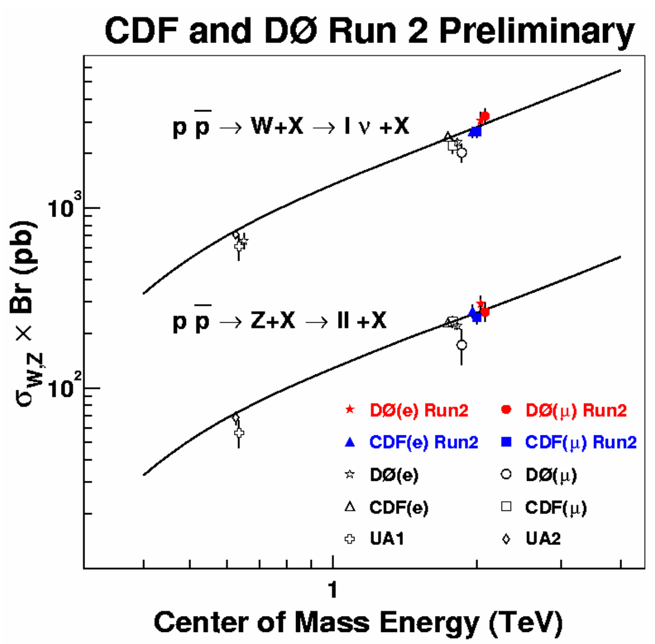


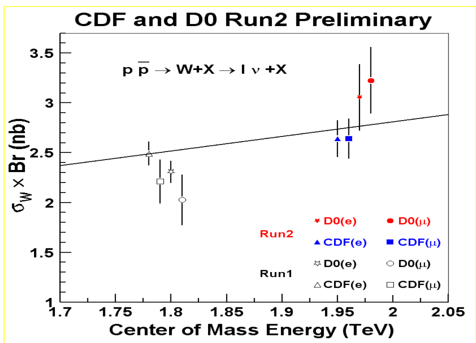
27370 Candidates in $\int Ldt = 42\ pb^{-1}$

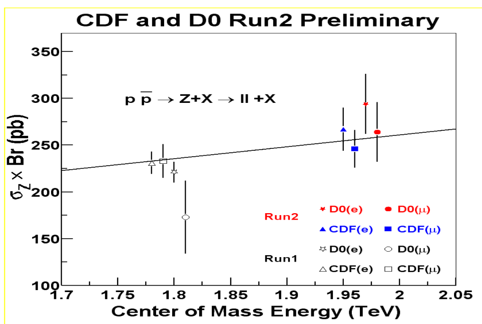
σ BR (W → eν) = 3054 ± 100 (stat.) ± 86 (syst.) ± 305 (lumi) pb

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

W/Z Cross Sections







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

Electroweak Physics

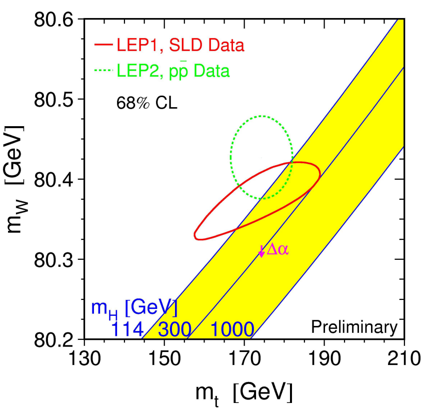
- Measurement of the W-boson and top-quark mass
  (fundamental parameters, precision)
- Test of anomalous couplings (W and top sector)

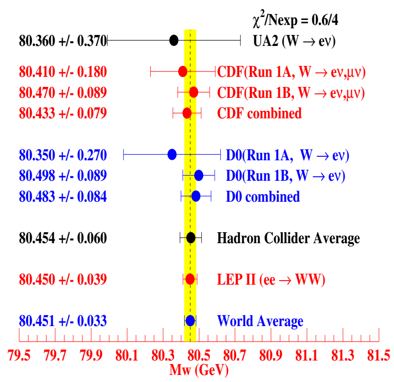
The W-mass measurement

The W-mass is a fundamental parameter of the Standard Model

Present precision: $\Delta M_W = \pm 33$ MeV (LEP + Tevatron)

In order to match the precision with the top rad. corrections, the W mass should be known with a precision of ± 15 MeV (goal of the LHC)

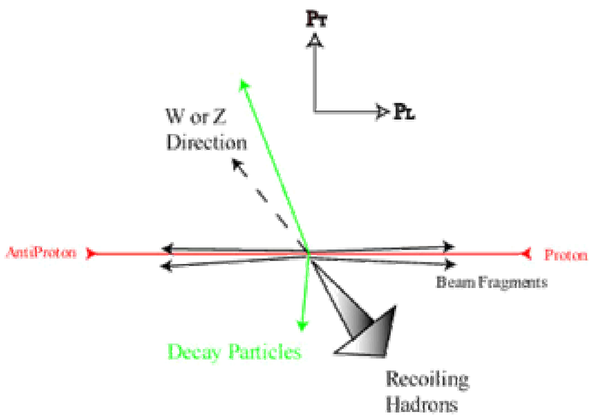


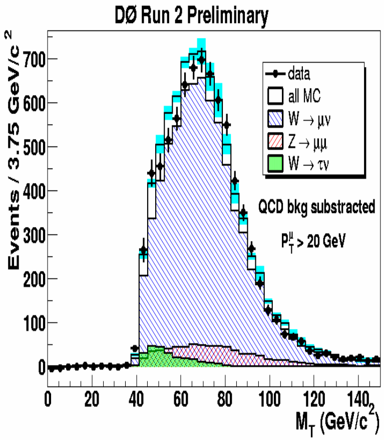


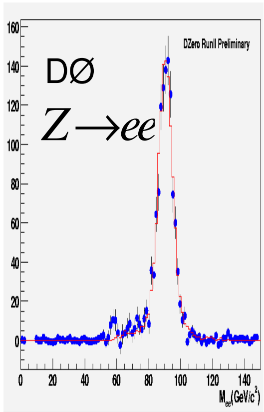
Ultimate test of the Standard Model: comparison between the direct Higgs mass (from observation, hopefully) and predictions from rad. corrections….

Technique used for W-mass measurement at hadron colliders:

Event topology:







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

$\Rightarrow$ **$P_T(\nu)$ = - ($P_T(e)$ + $P_T(had)$)** long. Component can not be measured

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

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

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

Source of syst.	CDF Run 1b	ATLAS	Comments
Lepton scale	75 MeV	15 MeV	<40MeV at Run II
Lepton resolution	25 MeV	5 MeV	Known to <1.5%
$P_T(W)$	15 MeV	5 MeV	Constrain with $P_T(Z)$
Recoil model	37 MeV	5 MeV	Constrain with Z data
W width	10 MeV	7 MeV	
PDFs	15 MeV	< 10 MeV	Constraints from the LHC
Radiative decays	20 MeV	< 10 MeV	Theor. calculations
Total	92 MeV	< 25 MeV	per lepton species

- Total error per lepton species and per experiment at the **LHC** is estimated to be **± 25 MeV**
  at the **Tevatron** **± 40 MeV**
- Main uncertainty: lepton energy scale (goal is an uncertainty of ± 0.02 %)
- Many systematic uncertainties can be controlled in situ, using the Z → $\ell\ell$ sample ($P_T(W)$, recoil model, resolution)

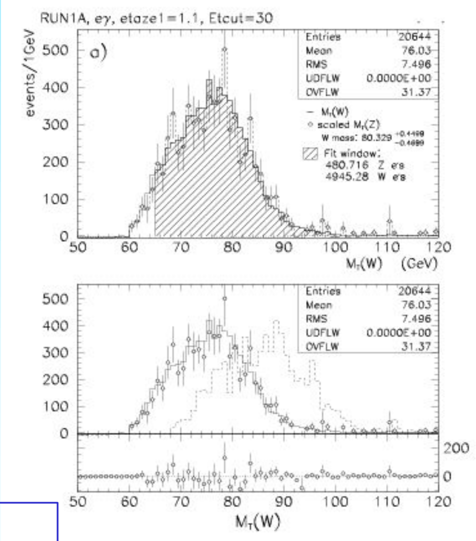
Combining both experiments (ATLAS + CMS, 10 fb^{-1}), both lepton species and assuming a scale uncertainty of ± 0.02% **⇒ Δm_W ~ ± 15 MeV**

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

Alternative method (new): W / Z mass ratio

Alternate Measurement of M_W

Extraction of W Mass from W/Z M_T ratio



Ratio of W and Z distributions
That are correlated to IVB mass.

- Treat $Z\rightarrow ee$ as $W\rightarrow e\nu$ by discarding one of the two Z electrons
- The scale factor between equivalent Z and W distributions gives M_W / M_Z

Possible Distributions:

- M_T
- P_T^e
- P^e

DØ Run 1a W Mass	Stat	Sys	
M_T: 80.350	+- 0.140	+- 0.165	+- 0.160
Ratio: 80.160	+- 0.360	+- 0.075	

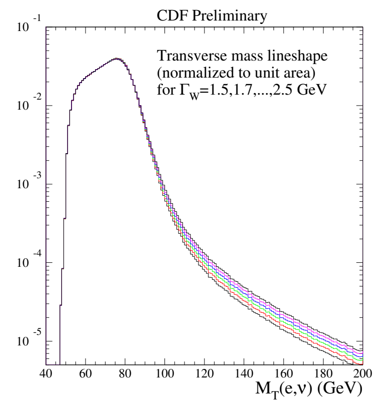
Measurement of the W-width

Indirect measurement: from the ratio of W/Z production cross section times branching ratio

$$R \equiv \frac{\sigma(p\bar{p}\rightarrow W+X)\times BR(W\rightarrow l\nu)}{\sigma(p\bar{p}\rightarrow Z+X)\times BR(Z\rightarrow ll)}$$

$$= \frac{\sigma(W)}{\sigma(Z)} \times \frac{\Gamma(Z)}{\Gamma(Z\rightarrow ll)} \times \frac{\Gamma(W\rightarrow l\nu)}{\Gamma(W)}$$

Perturbative QCD — LEP — SM



Run I result (CDF + D0 combined) :

Γ_W = 2.171 +- 0.021 (stat) +- 0.047 (syst.) GeV

Direct method: use the transverse mass spectrum

Run I result (CDF):

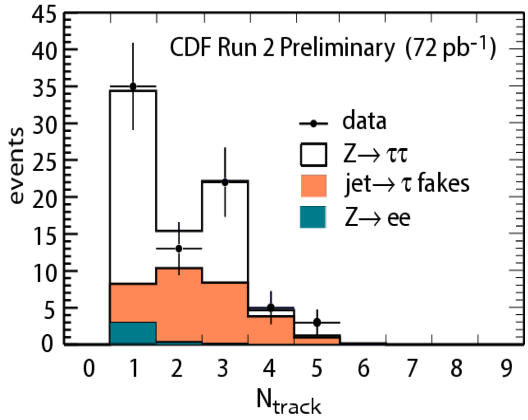
Γ_W = 2.055 +- 0.100 (stat) +- 0.075 (syst.) GeV

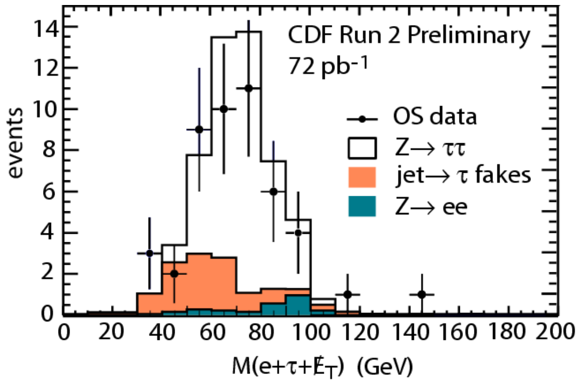
expected Run II sensitivity (CDF + D0 combined with 10 fb^{-1} each: $\Delta\Gamma_W$ ~ 10 MeV

SM prediction: 2.093 +- 0.003 GeV

$Z^0 \rightarrow \tau_e \tau_h$ signal in Run II

- CDF and D0 have clear $Z^0 \rightarrow \tau_e \tau_h$ signals.
- Further study of backgrounds is underway.
- Goal is to have a preliminary cross section measurement by summer.

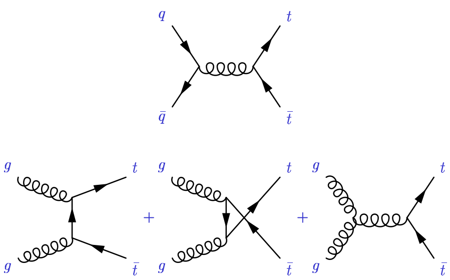




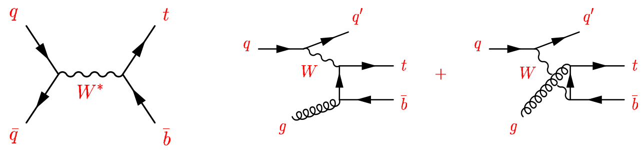
Not only interesting as an EWK measurement, it is important for Higgs and SUSY searches.

Top Quark Physics

Pair production: qq and gg-fusion



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



	Run 1 1.8 TeV	Run II 1.96 TeV	LHC 14 TeV
qq gg	90% 10%	85% 15%	5% 95%
σ (pb)	5 pb	7 pb	600 pb

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

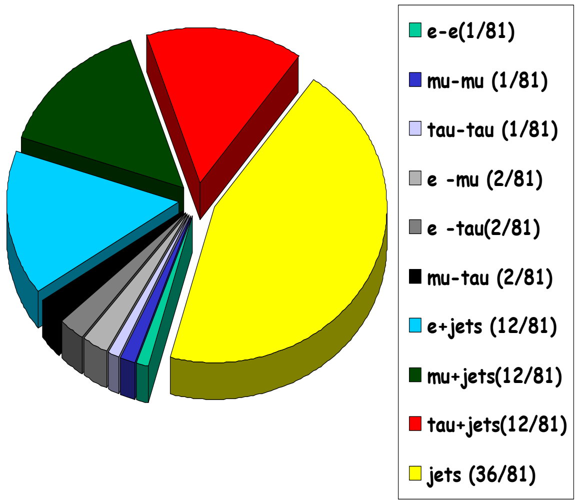
Top Quark Decays

BR (t→Wb) ~ 100%

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

One W decays via W→lν (l=e or μ;30%)
lepton+jets

Both W's decay via W→qq (44%)
all hadronic



Important exp. signatures: : - Lepton(s) (Trigger)
- Missing transverse momentum
- b-jet (tagging)

Cross section measurement

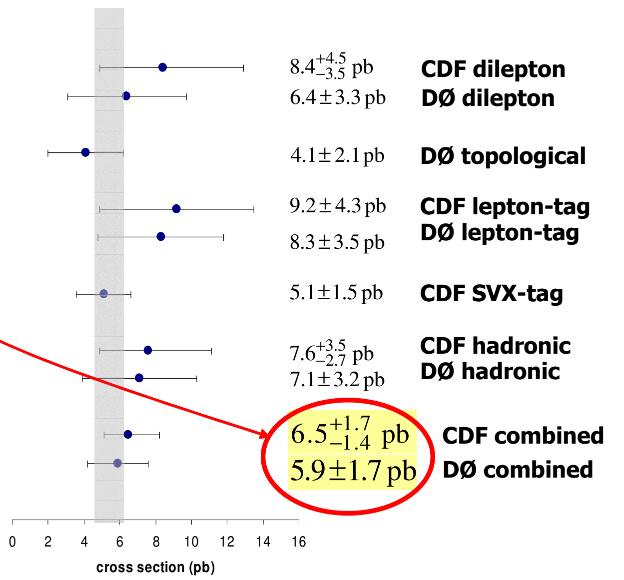
$$\sigma(t\bar{t}) = \frac{N_{obs} - N_{bkg}}{A \int L}$$

Acceptance×Efficiency

Integrated luminosity

Measured in Run I in all decay channels and using different techniques:
b tagging, kinematic selection, Neural Networks

Run I cross section results ~100 events



$\sigma(t\bar{t})$ in the dilepton channel, Run II

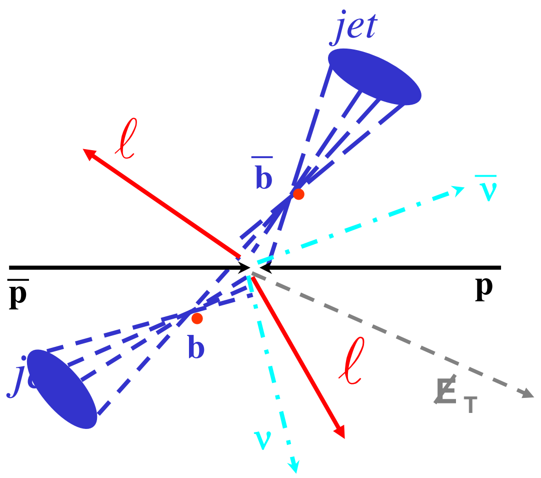
Event selection (similar to Run I):

- 2 high P_T isolated charged leptons (e,μ)
- Neutrinos: large missing E_T
- At least 2 jets
- Large transverse energy

Backgrounds:

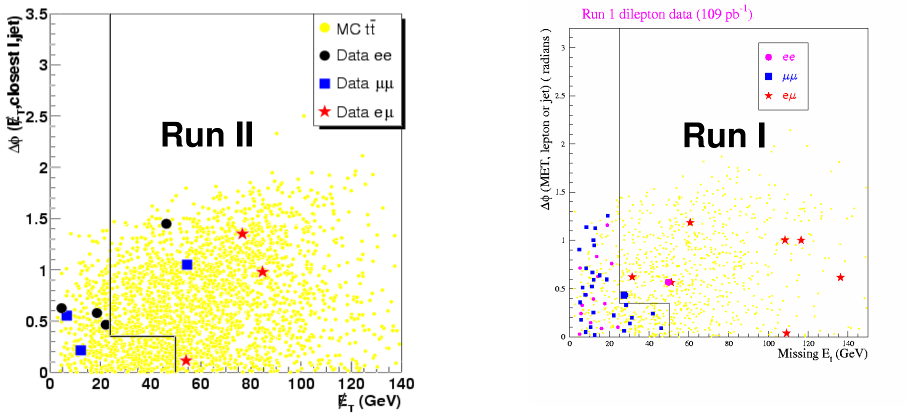
- Physics: WW/WZ,
  Drell Yan ($Z/\gamma^* \rightarrow ee,\mu\mu$), $Z \rightarrow \tau\tau$
- Instrumental: fake leptons in W+jets and QCD

- Smaller yield
- Cleaner signal (2 high P_T leptons)



$t(\rightarrow W^+b)\ t(\rightarrow W^-b)$
$\hookrightarrow e^+,\mu^+$ $\hookrightarrow e^-,\mu^-$

$\sigma(t\bar{t} \rightarrow ll + jets)$, CDF Run II



Source	ee	μμ	eμ	ll
Background	0.103±0.056	0.093±0.054	0.100±0.037	0.30±0.12
tt→lνlνbb	0.47±0.05	0.59±0.07	1.44±0.16	2.5±0.3
SM expectation	0.57±0.08	0.68±0.09	1.5±0.2	2.8±0.3
Data	1	1	3	5

$\sigma(t\bar{t})$ in the lepton+jets channel, Run II

- Larger yield, and still relatively clean

Event preselection:

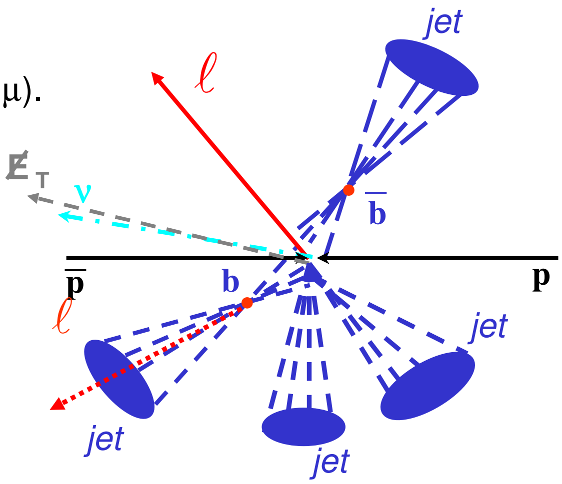
- 1 high P_T isolated charged lepton (e,μ).
- Neutrinos: large missing E_T
- di-lepton veto

Backgrounds:

- W+jets and fake leptons in QCD

Further selection & techniques:

- jet multiplicity:
  ≥ 4 jets (DØ)
- tag b jets with displaced VTX
  ≥ 3 jets, ≥ 1 b tag (CDF)
- tag b jets with Soft Lepton Tag
  ≥ 3 jets, ≥ 1 SLT tag (DØ)



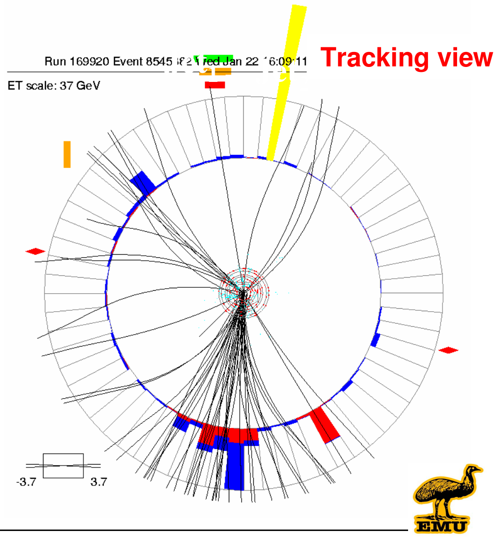
$t(\rightarrow W^{\pm}b)\ \bar{t}(\rightarrow W^{\pm}\bar{b})$
$\quad\hookrightarrow e^{\pm},\mu^{\pm} \quad \hookrightarrow q\bar{q}$

$\sigma(t\bar{t} \rightarrow ll + jets)$ and candidate, DØ Run II

	33pb^{-1}	42pb^{-1}	48.2pb^{-1}
	eμ	μμ	ee
$Z\rightarrow\tau\tau\rightarrow ll$ $WW\rightarrow ll$	0.02 ± 0.01 0.001± 0.001	0.02 ± 0.02 0.00 ± 0.00	0.02 ± 0.02 0.001 ± 0.001
$Z\rightarrow ll$ $DY\rightarrow ll$ QCD, W+jets	-- -- 0.05 ± 0.01	0.20 ± 0.12 0.20 ± 0.21 0.18 ± 0.18	0.98 ± 0.48
All BG	0.07 ± 0.01	0.60 ± 0.30	1.00 ± 0.48
Expected Signal	0.50 ±0.01	0.3 ± 0.04	0.25 ± 0.02
Observed	1	2	4

$p_T(e) = 20.3$ GeV/c^2
$p_T(\mu) = 58.1$ GeV/c^2
$E_T^j = 141.0, 55.2$ GeV
$\not{E}_T = 91$ GeV
$H_T(e) = 216$ GeV

Tracking view

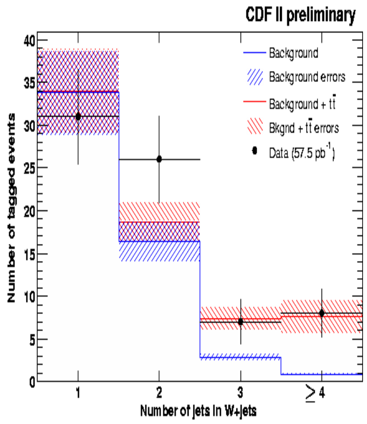


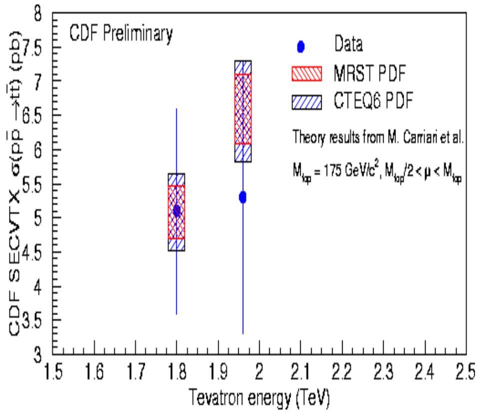
$e^+\mu^-$ + 2 jets

$\sigma(t\bar{t} \rightarrow l + \text{jets})$, CDF Run II

57.5 pb^{-1}

Source	W+ 1jet	W+ 2jets	W+ 3jets	W+ ≥4jets
Background	33.8±5.0	16.4±2.4	2.88±0.05	0.87±0.2
SM Bkgnd + $t\bar{t}$	34.0±5.0	18.65±2.4	7.35±1.4	7.62±2.0
Events before tagging	4913	768	99	26
Events after tagging	31	26	7	8

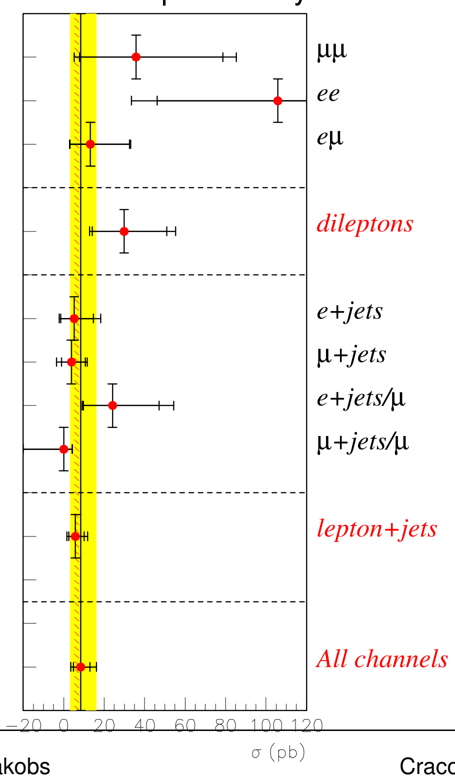




$$\sigma(t\bar{t}) = 5.3 \pm 1.9(\text{stat}) \pm 0.8(\text{sys}) \pm 0.3(\text{lumi}) \text{ pb}$$

$\sigma(t\bar{t})$, DØ Run II combined

DØ Run II preliminary



lepton+jets channels only

$$\sigma(t\bar{t}) = 5.8\,^{+4.3}_{-3.4}\,(\text{stat})\,^{+4.1}_{-2.6}\,(\text{sys}) \pm 0.6(\text{lumi}) \text{ pb}$$

all combined

$$\sigma(t\bar{t}) = 8.5\,^{+4.5}_{-3.6}\,(\text{stat})\,^{+6.3}_{-3.5}\,(\text{sys}) \pm 0.8(\text{lumi}) \text{ pb}$$

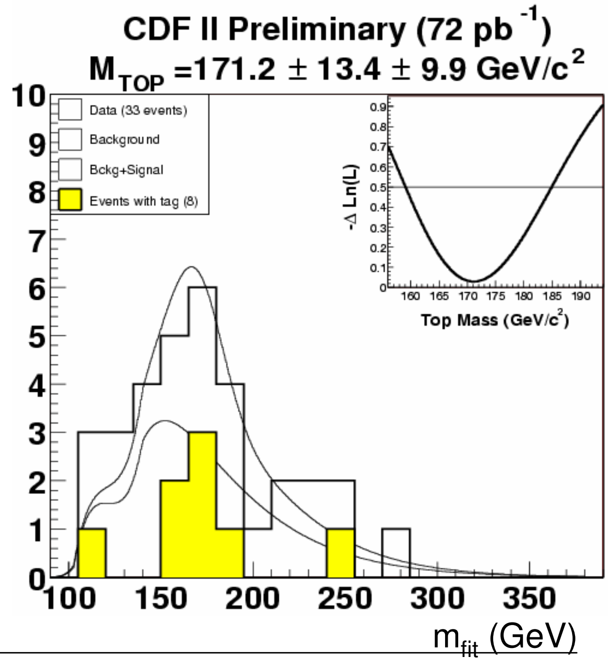
Top quark mass, CDF Run II

33 candidates after event selection

- 2C fit, mass constraints
- Maximum likelihood fit

Will improve with detector understanding

Source	Uncertainty (GeV/c^2)
Jet Energy Measurement	9.3
Initial and Final State Radiation	2.4
Background Shape	0.3
Parton Distribution Functions	1.8
Monte-Carlo Generators	1.8
Total	9.9



Summary of the present Tevatron top-status:

Cross section from Run II (CDF), dilepton and l+jets

$\sigma(t\bar{t}) = 5.3 \pm 1.9(\text{stat}) \pm 0.8(\text{sys}) \pm 0.3(\text{lumi})$ pb

$\sigma(t\bar{t}) = 13.2 \pm 5.9(\text{stat}) \pm 1.5(\text{sys}) \pm 0.8(\text{lumi})$ pb

Cross section from Run II (DØ), combined

$\sigma(t\bar{t}) = 8.5^{+4.5}_{-3.6}(\text{stat})^{+6.3}_{-3.5}(\text{sys}) \pm 0.8(\text{lumi})$ pb

Mass from Run II (CDF)

$m_{top} = 171.2 \pm 13.4\ (\text{stat}) \pm 9.9(\text{sys})\,\text{GeV}/c^2$

Run II has started, re-establishing signals and preparing for the top physics of larger datasets

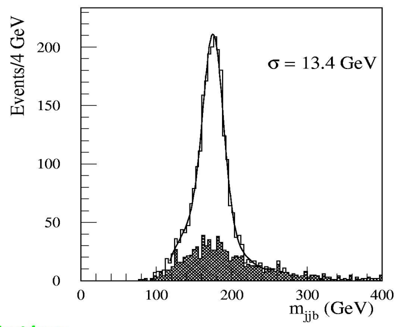
Prospects for top-quark mass measurements at the LHC

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

Best channel for mass measurement:

$tt \rightarrow Wb \quad Wb \rightarrow \ell \nu b$ jet jet b

(trigger) (mass measurement)



Experimental numbers:

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

estimated syst. uncertainties:

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

Syst. uncertainties dominated by final state radiation effects

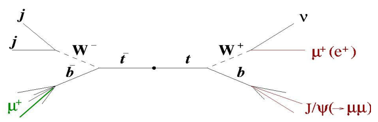
Additional Methods

- Full reconstruction applying kinematical constraints

$m_{jj} = m_{\ell\nu} = m_W$ and $m_{jjb} = m_{\ell\nu b}$

Precision of ~ ± 1 GeV seems possible

- Using ℓ-J/ψ final states:



Reconstruct $m_{\ell\text{-}J/\Psi}$

- BR = 10^{-5}: low rate, but clean signature
- Statistical error: ±0.9 GeV (for 500 fb^{-1})
- Different systematic uncertainties (dominated by b-fragmentation: ~ 0.4 GeV)

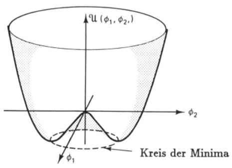
combination of various methods: $\Delta m_{top} < \sim \pm 1$ GeV

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.

- To establish the Higgs mechanism:
  1. Discovery
  2. Parameter measurements
  3. Demonstration of Higgs boson self-coupling (potential)

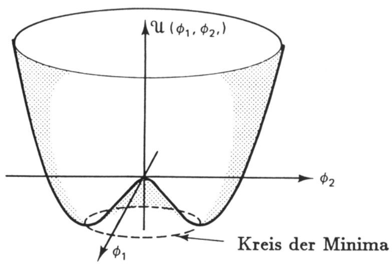


The Higgs-Mechanism

- Essential ingredient of the Standard Model:

  complex scalar field with potential

$$\mathcal{U}(\phi) = \mu^2(\phi^*\phi) + \lambda(\phi^*\phi)^2$$



- Used to break the el.weak symmetry......

$$M_{W^\pm} = \frac{1}{2}vg \qquad M_Z = \frac{1}{2}vg/\cos\theta_W = M_W/\cos\theta_W$$

..... and to generate fermion masses:

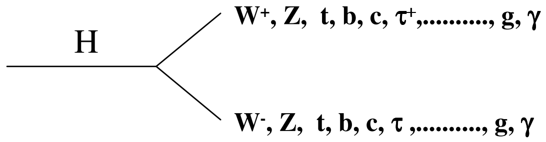
$$m_f = g_f\, v\, /\sqrt{2} \quad \Rightarrow \quad g_f = m_f\, \sqrt{2}\, /\, v$$

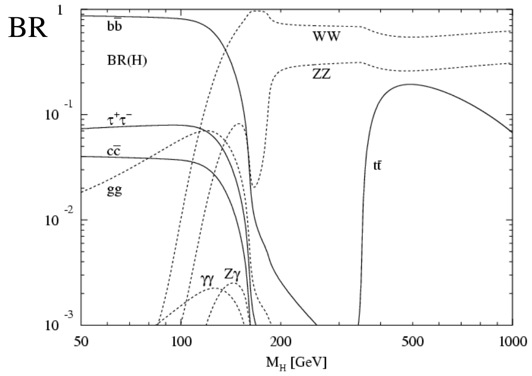
- Higgs particle $M_H = \sqrt{\lambda}\, v^2$

v = vacuum expectation value $v = (\sqrt{2}\ G_F)^{-½} = 246$ GeV

Properties of the Higgs Boson

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





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

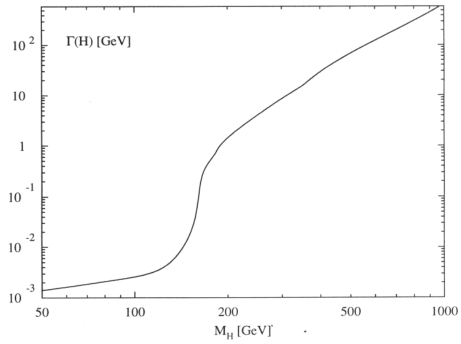
$$\Gamma(H \to VV) \;= \delta_V \frac{G_F}{16\sqrt{2}\pi} M_H^3 \;(1 - 4x + 12x^2)\; \beta_V$$

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

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

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

(+ W-loop contributions)

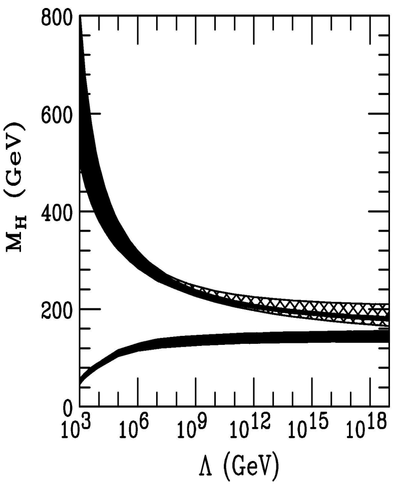


Higgs mass constraints:

Bounds on the Higgs-boson mass result from the energy dependence of the Higgs coupling $\lambda\ (Q^2)$

(if the SM is assumed to be valid up to some scale Λ)

$\lambda_0 = M_H^2 / v^2 \qquad \lambda\,(Q^2) = \lambda_0 \{ 1 + 3\lambda_0/2\pi^2 \log (2\,Q^2/v^2) + \ldots. -3g_t^4/32\pi^2 \log (2Q^2/v^2) + \ldots.\}$



Upper bound: diverging coupling (Landau Pole)

Lower bound: stability of the vacuum (neg. contribution from top quark dominates)

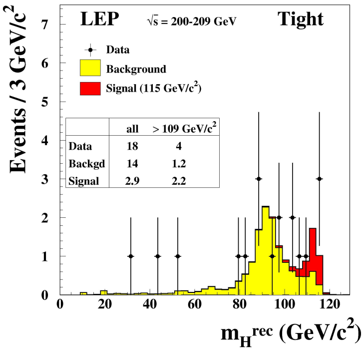
Mass bounds depend on scale Λ up to which the Standard Model should be valid

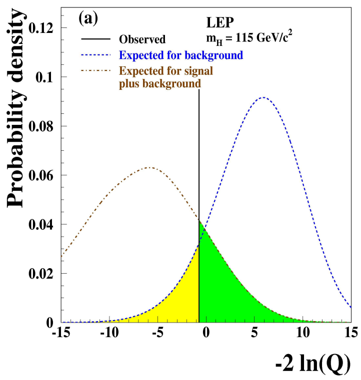
Hambye, Risselmann et al.

Final combined LEP result on Higgs boson searches

Decay modes searched for:

- Four Jet channel: HZ → bb qq
- Missing energy channel: → bb νν
- Leptonic channel: → bb ee, bb μμ
- Tau channels: → bb ττ, and ττ qq





$1-CL_B = 0.09$ ↔

Signal significance = 1.7 σ

	$1-CL_b$	CL_{s+b}
LEP	0.09	0.15
ALEPH	3.3×10^{-3}	0.87
DELPHI	0.79	0.03
L3	0.33	0.30
OPAL	0.50	0.14
Four-jet	0.05	0.44
All but four-jet	0.37	0.10

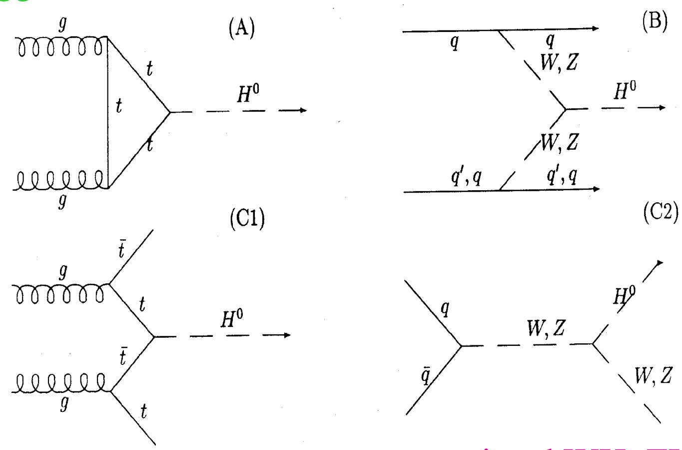
M_H > 114.4 GeV/c² (95% CL)

Expected mass limit: 115.3 GeV/c²

Higgs Boson Production at Hadron Colliders

gg fusion

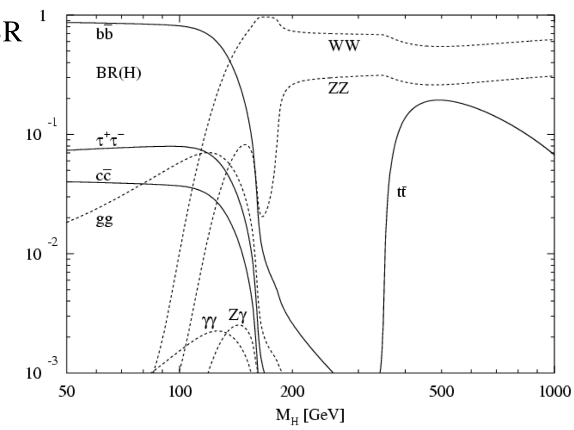
WW/ZZ fusion



associated $t\bar{t}H$

associated WH, ZH

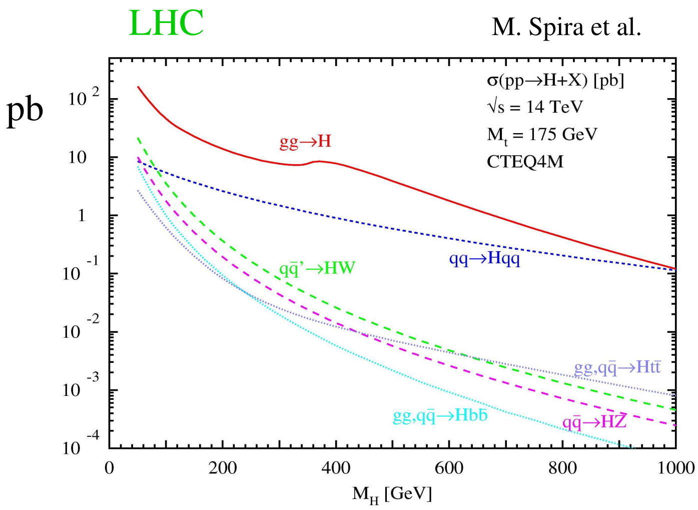
BR

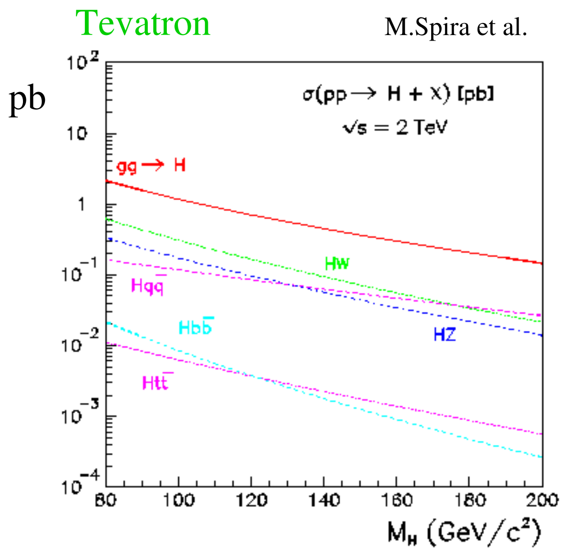


Lepton and Photon final states are essential (**via H → WW , ZZ, (ττ), γγ**) (QCD jet background)

bb decay mode only possible in associated production (W/Z, tt)

Higgs Boson Production cross sections

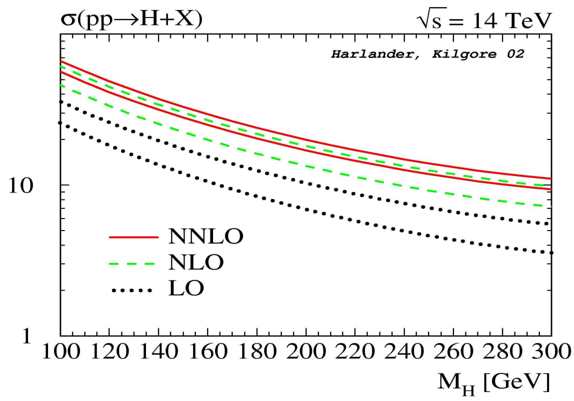




qq → W/Z + H   cross sections   ~10 x larger at the LHC
gg → H   ~70-80 x larger at the LHC

Status of higher order corrections

NLO corrections (K-factors) have meanwhile been calculated for all Higgs production processes   (huge theoretical effort !)



1. gg fusion:

- large NLO QCD correction   **K ~ 1.7 – 2.0**
  [Djouadi, Spira, Zerwas (91)] [Dawson (91)]
- complete NNLO calculation ⇒
  evidence for nicely converging pQCD series
  (infinite top mass limit)
  [Harlander, Kilgore (02)] [Anastasiou, Melnikov (02)]

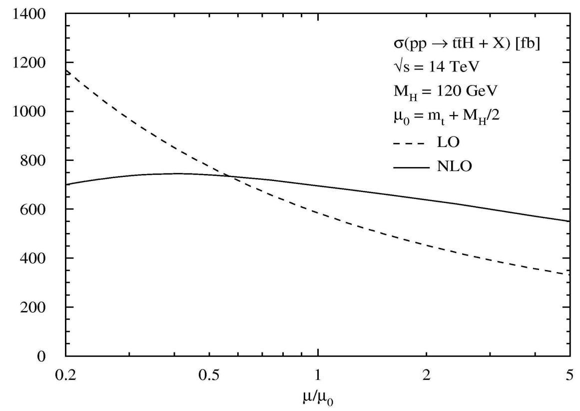
2. Weak boson fusion: K ~1.1
[Han, Valencia, Willenbrock (92)] [Spira (98)]

3. WH associated production: K ~ 1.3
(QCD corrections from Drell-Yan process)

Status of higher order corrections (cont.)

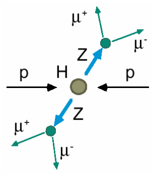
4. ttH associated production:

- full NLO calculation LHC: K ~ 1.2 scale: $\mu_0 = m_t + M_H/2$
  Tevatron: K ~ 0.8
- scale uncertainty drastically reduced
  [Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas (01)] [Dawson, Reina (01)]



$H \to ZZ^{(*)} \to \ell\ell\ell\ell$

Signal: σ BR = 5.7 fb (m_H = 100 GeV)



$P_T(1,2) > 20$ GeV
$P_T(3,4) > 7$ GeV
$|\eta| < 2.5$
Isolated leptons

Background: Top production

tt → Wb Wb → ℓν cℓν ℓν cℓν

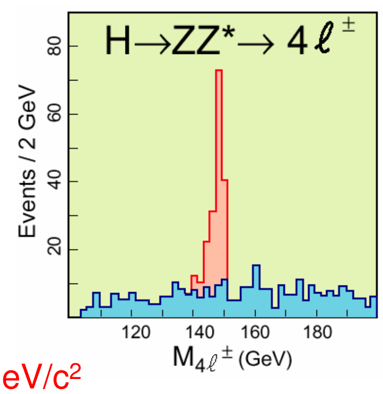
σ BR ≈ 1300 fb

Associated production Z bb

Z bb → ℓℓ cℓν cℓν

M(ll) ~ M_Z
M(l'l') ~ < M_Z

L = 100 fb^{-1}

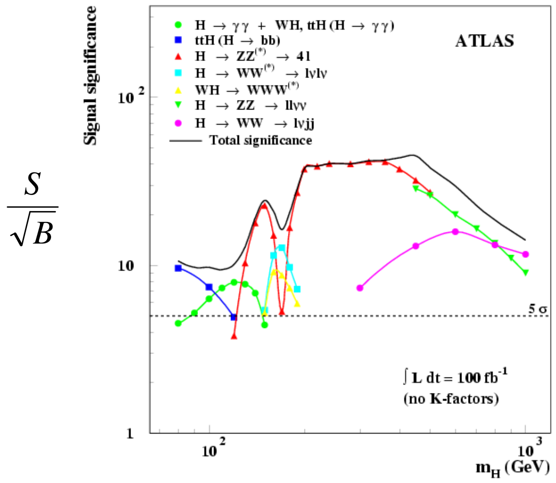


Background rejection: Leptons from b-quark decays
→ non isolated
→ do not originate from primary vertex
(B-meson lifetime: ~ 1.5 ps)

Dominant background after isolation cuts: ZZ continuum

Discovery potential in mass range from ~130 to ~600 GeV/c^2

The LHC Higgs discovery potential



10 fb^{-1}: Discovery possible over the full mass range, however, needs combination of ATLAS + CMS

M_H = 115 GeV: **$S/\sqrt{B}$ = 4.7**

$m_H < 2\, m_Z$: $t\bar{t}H \to \ell b\bar{b} + X$, $H \to \gamma\gamma$,
$H \to ZZ^* \to 4\ell$, $H \to WW^{(*)} \to \ell\nu\ell\nu$

$m_H > 2\, m_Z$: $H \to ZZ \to 4\ell$
$qqH \to qq\, ZZ \to qq\, \ell\ell\, \nu\nu$
$qqH \to qq\, ZZ \to qq\, \ell\ell\, jj$
$qqH \to qqWW \to qq\, \ell\nu jj$

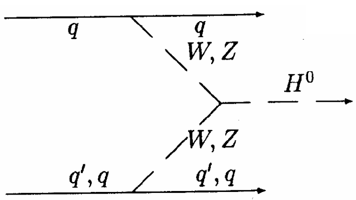
m_H > 300 GeV
forward jet tag

Higgs Boson Search using vector boson fusion at low mass

Motivation: Increase discovery potential at low mass
Improve measurement of Higgs boson parameter
(couplings to bosons, fermions (taus))

proposed by D.Rainwater and D.Zeppenfeld et al.:
(hep-ph/9712271, hep-ph/9808468 and hep-ph/9906218)

Distinctive Signature of:
- **two high P_T forward jets**
- **little jet activity in the central region**
  ⇒ **Jet Veto**

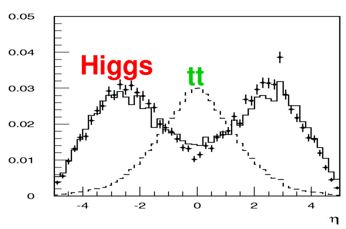


⇒ **Experimental Issues:**
- **Forward jet reconstruction**
- **Jets from pile-up in the central / forward region**

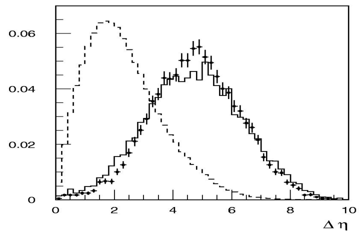
Channels studied: $qqH \to qqWW^* \to qq\, \ell\nu\, \ell\nu$
$qqH \to qq\, \tau\tau \to qq\, \ell\nu\nu\, \ell\nu\nu$
$\to qq\, \ell\nu\nu$ had ν

Forward jet tagging

Rapidity distribution of tag jets
VBF Higgs events vs. tt-background



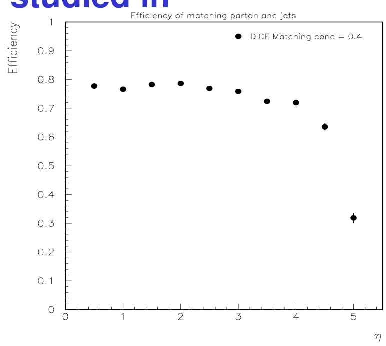
Rapidity separation



Forward tag jet reconstruction has been studied in full simulation in ATLAS

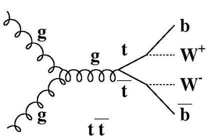
kin. eff. for tag jets = 51.9%
($P_T > 40/20$ GeV, $\Delta\eta > 3.6$)

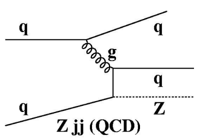
tag eff. per jet: around 75%



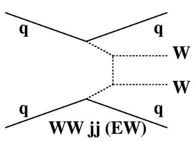
Background:

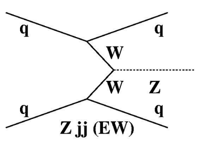
QCD backgrounds:
tt production Z + 2 jets





el.weak background:
WW jj production Z + 2 jets

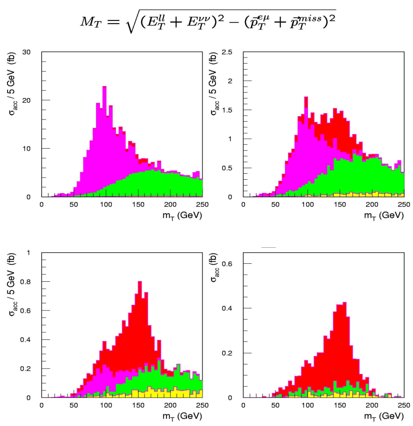




Background rejection:

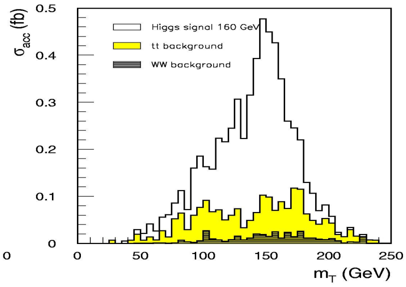
qqH → qqWW* → qq l ν l ν

- Lepton P_T cuts and tag jet requirements ($\Delta\eta$, P_T)
- Require large mass of tag jet system
- Jet veto
- Lepton angular and mass cuts

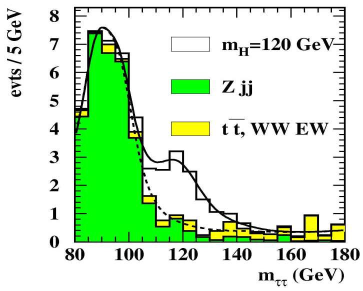


Higgs boson (m_H = 160 GeV)
tt background
γ* / Z + jets
el.weak WW jj

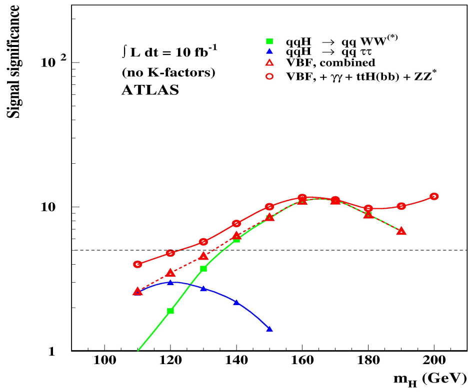
qq H → qq WW*
→ qq l ν l ν



qq H → qq τ τ
→ qq l ν ν l ν ν
→ qq l ν ν h ν



Combined significance of VBF channels for 10 fb^{-1}

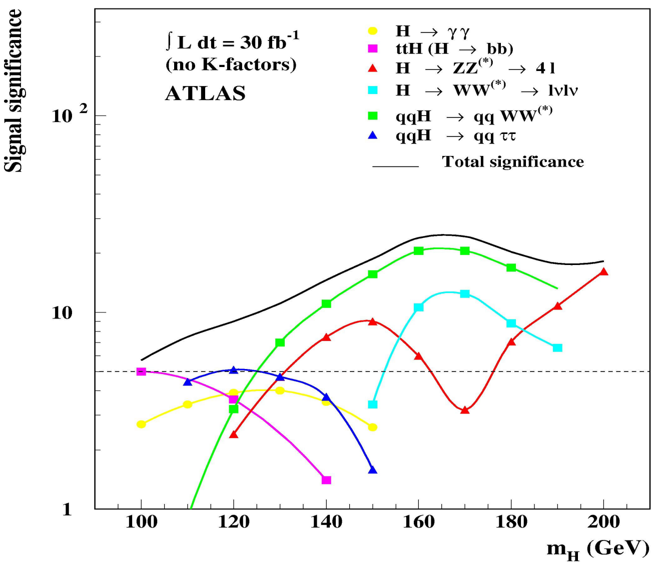


- VBF channels (in particular WW*) are discovery channels at low luminosity

- **For 10 fb^{-1} in ATLAS:**

5 σ significance for
$120 \leq m_H \leq 190$ GeV

ATLAS Higgs discovery potential for 30 fb^{-1}



- **Vector boson fusion channels improve the sensitivity significantly in the low mass region**
- **Several channels available over the full mass range**

The Higgs Sector in the MSSM

Two Higgs doublets: 5 Higgs particles **H, h, A** **H^+, H^-**

determined by two parameters: m_A, $\tan\beta$

fixed mass relations at tree level:
(Higgs self coupling in MSSM fixed by gauge couplings)

$$m^2_{H,h} = \frac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{(m_A^2+m_Z^2)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta}\right)$$

$$m_h^2 \le m_Z^2 \cos^2 2\beta \le m_Z^2$$

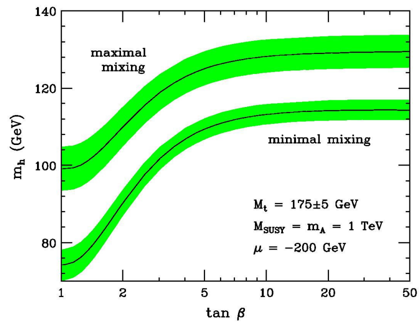
Important radiative corrections !! (tree level relations are significantly modified)
→ upper mass bound depends on top mass and mixing in the stop sector

$$m_h^2 \le m_Z^2 + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + x_t^2\left(1 - \frac{x_t^2}{12}\right)\right]$$

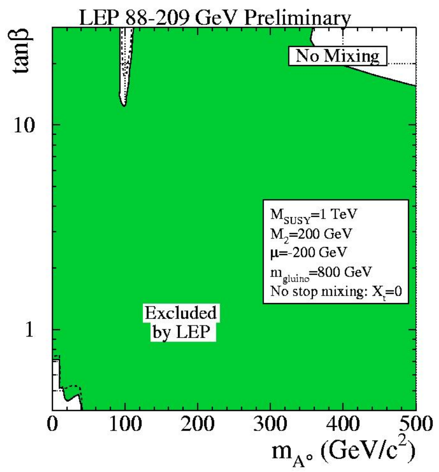
where: $M_S^2 = \frac{1}{2}\left(M_{\tilde t_1}^2 + M_{\tilde t_2}^2\right)$ and $x_t = (A_t - \mu\cot\beta)\ /\ M_S$

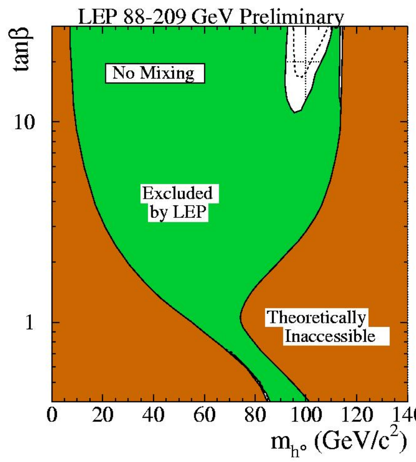
→ m_h < 115 GeV for minimal mixing
→ m_h < 135 GeV for maximal mixing

i.e., no mixing scenario: in LEP reach
max. mixing: easier to address at the LHC



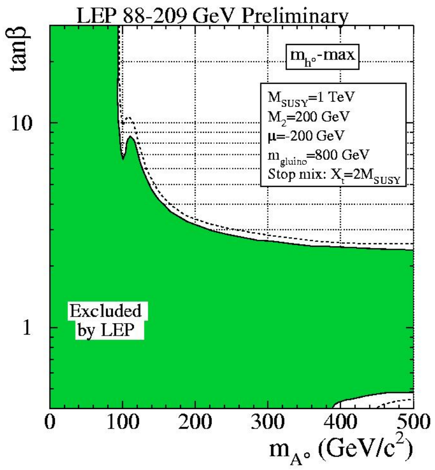
LEP results for the no-mixing scenario:

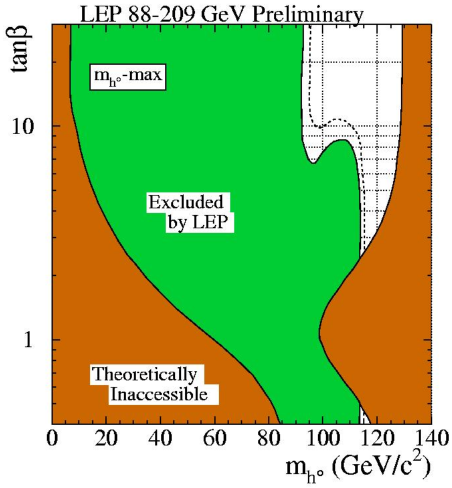




$M_h > 91.5$ GeV/c^2
$m_A > 92.2$ GeV/c^2
Excluded $\tan\beta$ range: $0.7 < \tan\beta < 10.5$

LEP results for the m_h-max scenario:





$M_h > 91.0$ GeV/c^2

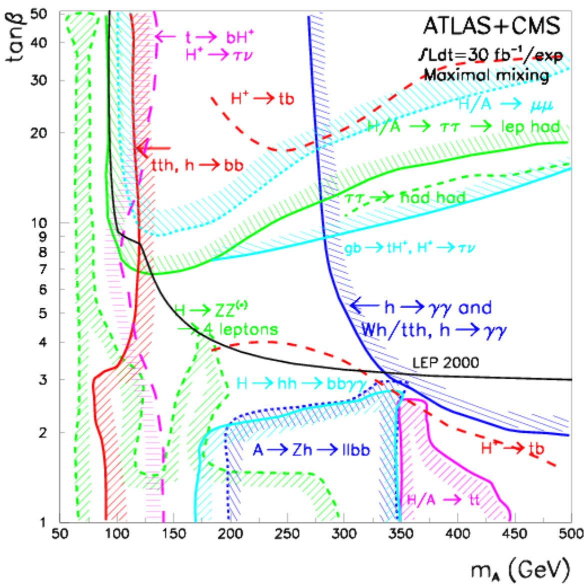
$m_A > 91.9$ GeV/c^2

Excluded tan β range: $0.5 < \tan\beta < 2.4$ (m_t =175 GeV/c^2)

< 1.9 (m_t = 179 GeV/c^2)

LHC can also discover MSSM Higgs bosons

5σ discovery in m_A – tan β plane

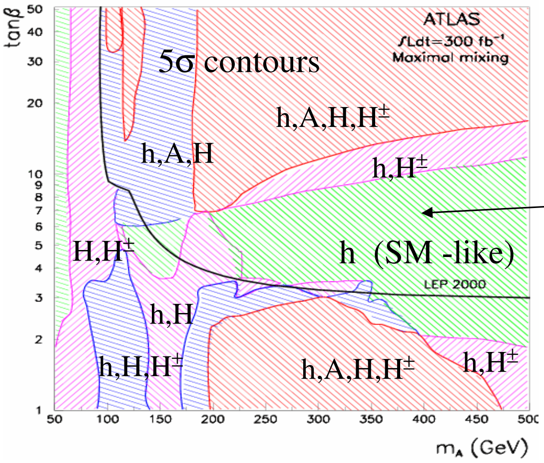


m_{SUSY} = 1 TeV, m_{top} = 175 GeV/c^2

Two or more Higgs can be observed over most of the parameter space → disentangle SM / MSSM

- Plane fully covered (no holes) at low L (30 fb^{-1})
- **Main channels : h → γγ , tth h → bb, A/H → μμ, ττ , $H^\pm$ → τ ν**

LHC discovery potential for MSSM Higgs bosons



4 Higgs observable
3 Higgs observable
2 Higgs observable
1 Higgs observable

Here only SM-like h observable if SUSY particles neglected.

Assuming decays to SM particles only

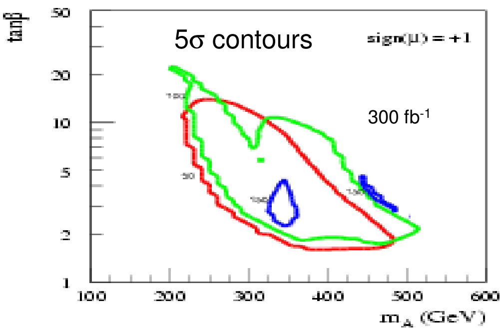
- Region at large m_A and moderate tan β only covered by h; difficult to detect other Higgs bosons

Possible coverage: * via SUSY decays (model dependent, under study)
* luminosity (only moderate improvement)

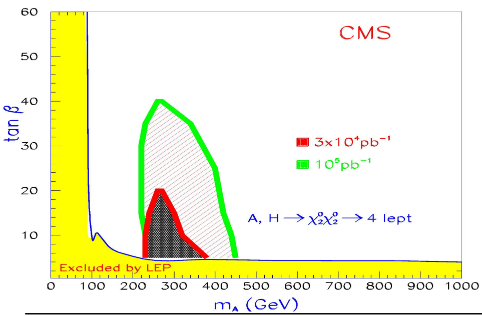
Higgs decays via SUSY particles

If SUSY exists : search for

$H/A \rightarrow \chi^0_2\chi^0_2 \rightarrow \ell\ell\chi^0_1\ \ell\ell\chi^0_1$



ATLAS: SUGRA scan
m_0 = 50 - 250 GeV
$m_{1/2}$ = 100 - 300 GeV
tan β = 1.5 - 50
A_0 = 0

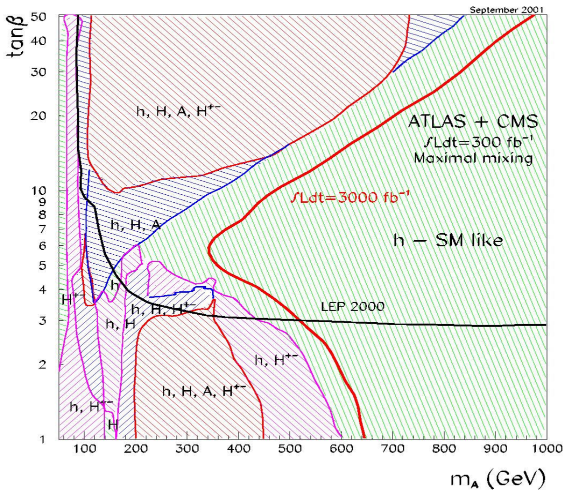


CMS: special choice in MSSM (no scan)
M_1 = 60 GeV
M_2 = 110 GeV
μ = -500 GeV

Exclusions depend on MSSM parameters (slepton masses, μ)

MSSM discovery potential for Super-LHC

ATLAS + CMS, 2 x 3000 fb^{-1}



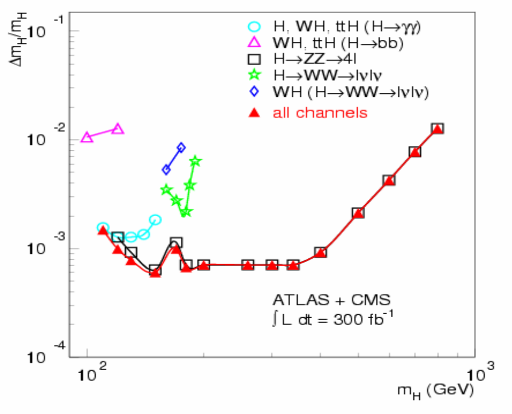
- Situation can be improved, in particular for m_A < ~400 GeV
- But: (S)LHC can not promise a complete observation of the heavy part of the MSSM Higgs spectrum ....

  .... although the observation of sparticles will clearly indicate that additional Higgs bosons should exist.

Determination of Higgs Boson Parameters

1. Mass
2. Couplings to bosons and fermions
   (impact of vector boson fusion channels)
3. Higgs self coupling

Measurement of the Higgs boson mass



No theoretical error, e.g. mass shift for large Γ_H
(interference resonant/non-resonant production)

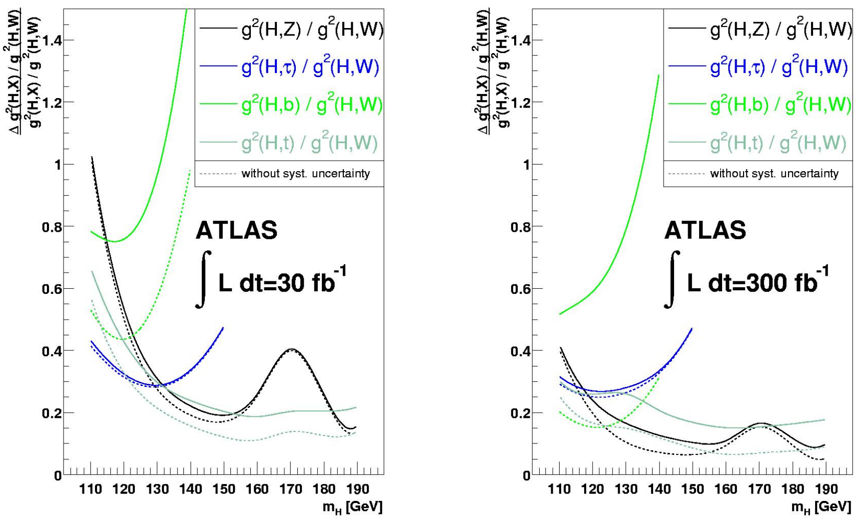
Dominant systematic uncertainty: γ / ℓ E scale.
Assumed 1‰
Goal 0.2‰
Scale from $Z \to \ell\ell$ (close to light Higgs)

Higgs boson mass can be measured with a precision of 0.1%
over a large mass range (130 - ~450 GeV / c^2)

Measurement of Higgs Boson Couplings

Global likelihood-fit (at each possible Higgs boson mass)
Input: measured rates, separated for the various production modes

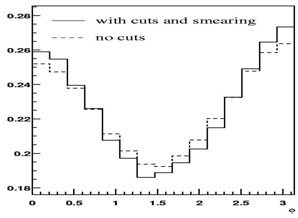
Output: Higgs boson couplings, normalized to the WW-coupling

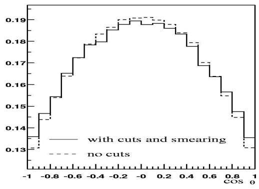


Relative couplings can be measured with a precision of 10-20% (for 300 fb^{-1})

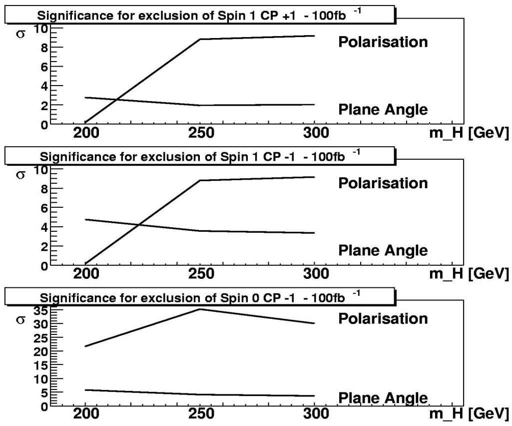
Higgs Boson spin ?

- Angular distributions in the decay channel $H \to ZZ^{(*)} \to 4\,\ell$ are sensitive to spin and CP eigenvalue
- azimuthal angle ϕ, defined as angle between the decay planes of the two Z-bosons in the restframe of the Higgs
- polar angle θ, defined as angle of neg. charged lepton in the restframe of the Z to the direction of motion of the Z in the restframe of the Higgs



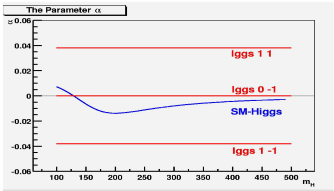


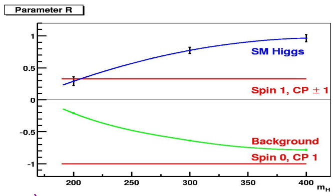
Expected results:



Fit to $F(\phi) = \alpha \cos(\phi) + \beta \cos(2\phi)$

$F(\theta) = T\,(1+\cos^2\theta) + L \sin^2\theta$ $\qquad R = (L-T) / (L+T)$



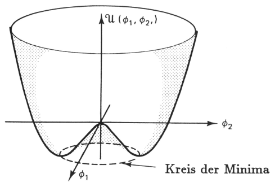


(J.R. Dell´Aquila, C.A. Nelson)

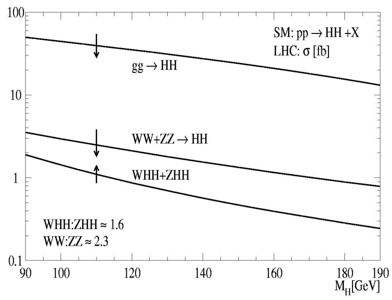
Higgs Bosons Self-coupling ?

to establish the Higgs mechanism the Higgs boson self-coupling has to be measured:

$$\lambda^{SM}_{HHH} = 3\,\frac{m_H^2}{v}\,, \quad \lambda^{SM}_{HHHH} = 3\,\frac{m_H^2}{v^2}$$



Cross sections for HH production:



small signal cross sections, large backgrounds from tt, WW, WZ, WWW, tttt, Wtt,...

$\Rightarrow$ no significant measurement possible at the LHC

need Super LHC $L = 10^{35}$ cm^{-2} sec^{-1}, 6000 fb^{-1}

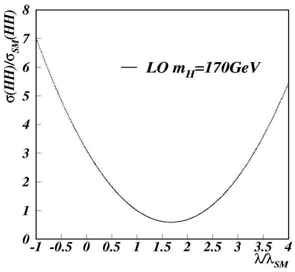
Most sensitive channel: $gg \to HH \to WW\ WW \to \ell\nu\ jj\ \ell\nu\ jj$

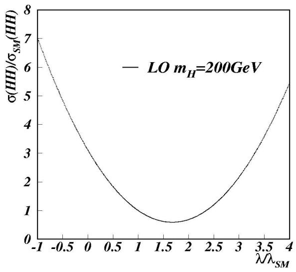
- accessible in mass range 160 GeV - 200 GeV
- bb-decay mode at lower masses is hopeless

Selection:

- 2 isolated, high P_T, like sign leptons (from different Higgs bosons)
- 4 high P_T jets, compatible with W-mass

m_H	Signal	$t\bar{t}$	$W^{\pm}Z$	$W^{\pm}W^{+}W^{-}$	$t\bar{t}W^{\pm}$	$t\bar{t}t\bar{t}$	$S/\sqrt{B}$
170 GeV	350	90	60	2400	1600	30	5.4
200 GeV	220	90	60	1500	1600	30	3.8





6000 fb $^{-1}$ $\Rightarrow$ $\Delta\lambda_{HHH}/\lambda_{HHH}$ = 19 % (stat.) (for m_H = 170 GeV)
$\Delta\lambda_{HHH}/\lambda_{HHH}$ = 25 % (stat.) (for m_H = 200 GeV)

Search channels at the Tevatron

- important production modes: associated WH and ZH
  gluon fusion with $H \to WW \to \ell\nu\ \ell\nu$
- hopeless: gluon fusion in $H \to \gamma\gamma$, 4 ℓ (rate limited)
  σ BR ($H \to ZZ \to 4\ \ell$) = 0.07 fb (M_H=150 GeV)

Mass range 110 - 130 GeV: LHC

- **WH → lν bb** (✔) weak
- **ZH → l⁺l⁻ bb** weak
- **ZH → νν bb** ∅ (trigger)
- **ZH → bb bb** ∅ (trigger)
- **ttH → lν b jjb bb** ✔

Triggering:

slightly easier at the Tevatron:

- better P_T^{miss}-resolution
- track trigger at level-1 (big challenge)

Mass range 150 - 180 GeV: LHC

- **H → WW$^{(*)}$ → lν lν** ✔
- **WH → WWW$^{(*)}$ → lν lν lν** ✔
- **WH → WWW$^{(*)}$ → l⁺ν l⁺ν jj** ✔

Background:

electroweak production:
~10 x larger at the LHC
QCD production (e.g, tt):
~ 100 x larger at the LHC

Detector acceptance: larger at Fermilab (central production)

Signal and background ratios after detector acceptance:

	low mass	high mass
	$WH \to \ell\nu\ b\bar{b}$ $ZH \to \ell\ell\ \ b\bar{b}$	$H \to WW^{(*)} \to \ell\nu\ell\nu$ (M_H = 160 GeV)
S (14 TeV) / S (2 TeV)	≈ 5	≈ 30
B (14 TeV) / B (2 TeV)	≈ 25	≈ 6
S/B (14 TeV) / S/B (2 TeV)	≈ 0.2	≈ 5
S/√B (14 TeV) / S/√B (2 TeV)	≈ 1	≈ 10

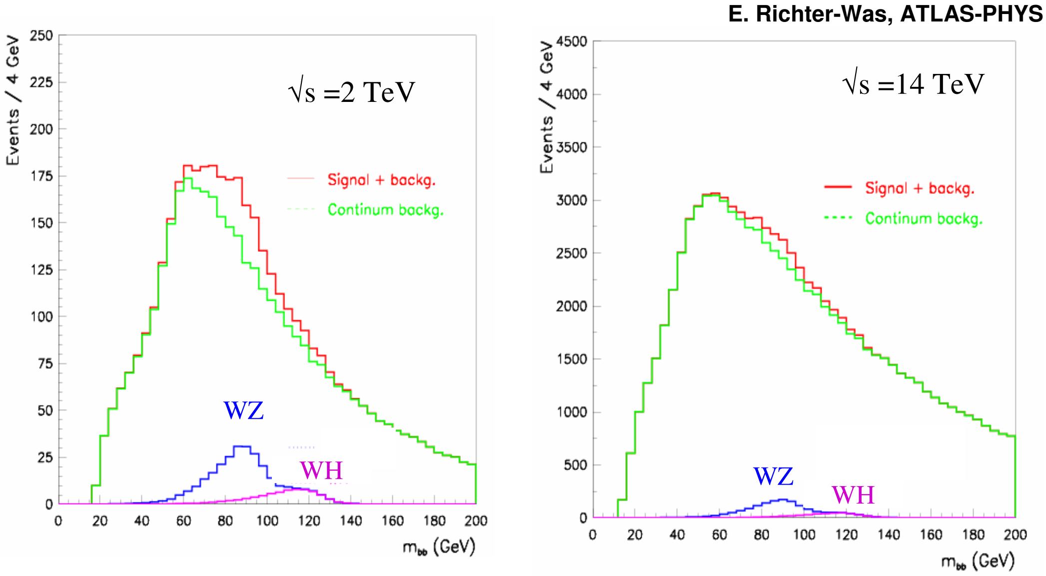
➡ -- comparable discovery potential for WH and ZH:
- larger signal at the LHC
- better S/B-ratio at theTevatron
- difficult at both colliders

-- significantly better LHC potential for $H \to WW^{(*)} \to \ell\nu\ell\nu$

WH Signals at the LHC and the Tevatron

M_H = 120 GeV, 30 fb^{-1}

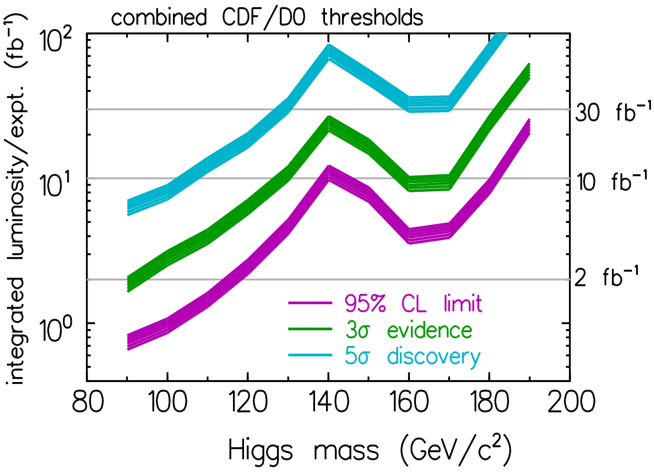
E. Richter-Was, ATLAS-PHYS



most important: control of the background shapes

Tevatron discovery potential for a light Higgs Boson

combination of both experiments and all channels
(discovery in a single channel not possible)



For 10 fb^{-1} :

(i) 95% CL exclusion of a SM Higgs boson is possible over the full mass range (M_H < 185 GeV)

(ii) 3-σ evidence for M_H < 130 GeV and 155 GeV < M_H < 175 GeV

Für 30 fb^{-1} (optimistic) :

(i) 3-σ evidence for the SM Higgs boson is possible over the full mass range (M_H < 185 GeV)

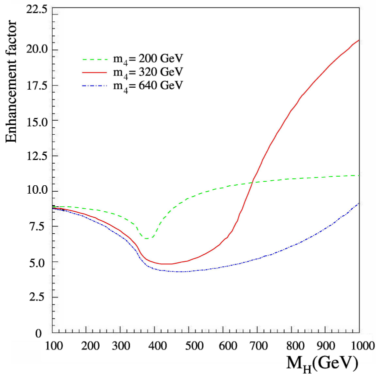
Results of studies with more detailed detector simulations are consistent with previous simulations.

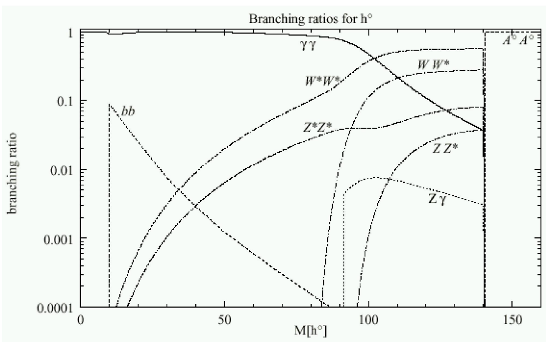
First steps towards the Higgs search at the Tevatron

With present integrated luminosity, no sensitivity yet for a SM Higgs boson:
⇒ study the backgrounds
⇒ search for **exotic Higgs bosons**

Higgs boson production rates can be enhanced in Exotic Models:

* 4th SM family enhance Higgs cross sections by a factor of ~8.5 for a Higgs boson mass between 100-200 GeV
* Fermiophobic / Topcolor Higgs: BR (H → V V) >98% for $m_H \geq$ 100 GeV

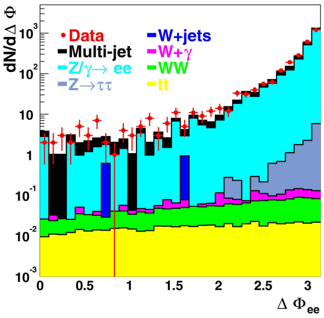


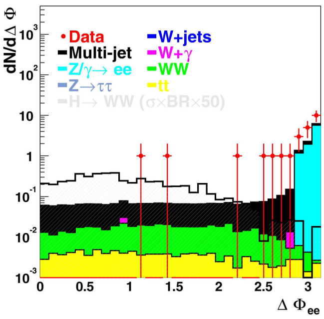


D0´s first look at: $H \to WW \to e \nu e \nu$

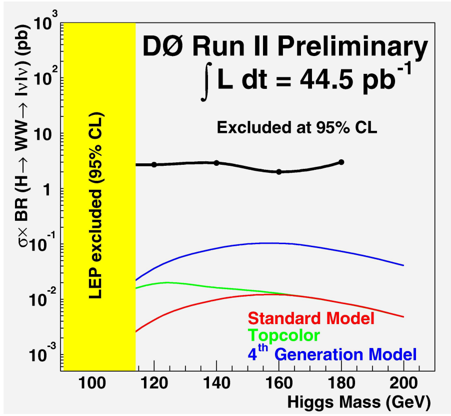
Search for ee + P_T^{miss} events,
Study of $\Delta\phi$ ($\ell\ell$) distribution at various level of the cuts:

luminosity
44.5 pb^{-1}





Require good e^+e^- ,
missing E_T



Data are consistent with background expectations

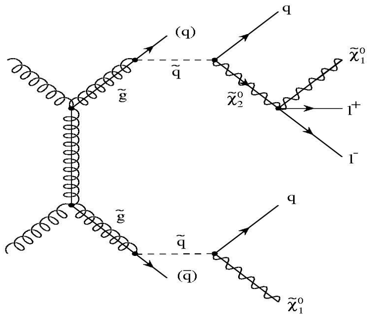
Search for Physics Beyond the Standard Model

1. Supersymmetry
2. New Gauge Bosons
3. Leptoquarks

Search for Supersymmetry

- If SUSY exists at the electroweak scale, a discovery at the LHC should be easy
- Squarks and Gluinos are strongly produced

  They decay through cascades to the lightest SUSY particle (LSP)



⇒ combination of Jets, Leptons, E_T^{miss}

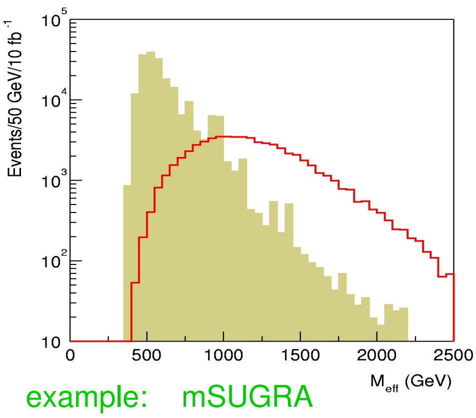
1. Step: Look for deviations from the Standard Model
   Example: Multijet + E_T^{miss} signature

2. Step: Establish the SUSY mass scale use inclusive variables, e.g. effective mass distribution

3. Step: Determine model parameters (difficult)
   Strategy: select particular decay chains and use kinematics to determine mass combinations

Squarks and Gluinos

- Strongly produced, cross sections comparable to QCD cross sections at same Q^2
- If R-parity conserved, cascade decays produce distinctive events: multiple jets, leptons, and E_T^{miss}
- Typical selection: $N_{jet} > 4$, E_T > 100, 50, 50, 50 GeV, E_T^{miss} > 100 GeV
- Define: $M_{eff} = E_T^{miss} + P_T^1 + P_T^2 + P_T^3 + P_T^4$ (effective mass)



example: mSUGRA
m_0 = 100 GeV, $m_{1/2}$ = 300 GeV
tan β = 10, A_0 = 0, μ > 0

LHC reach for Squark- and Gluino masses:

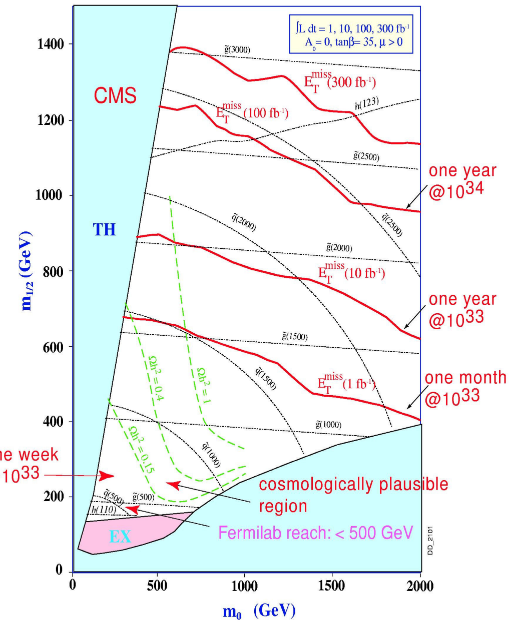
1 fb^{-1}	⇒	M ~ 1500 GeV
10 fb^{-1}	⇒	M ~ 1900 GeV
100 fb^{-1}	⇒	M ~ 2500 GeV

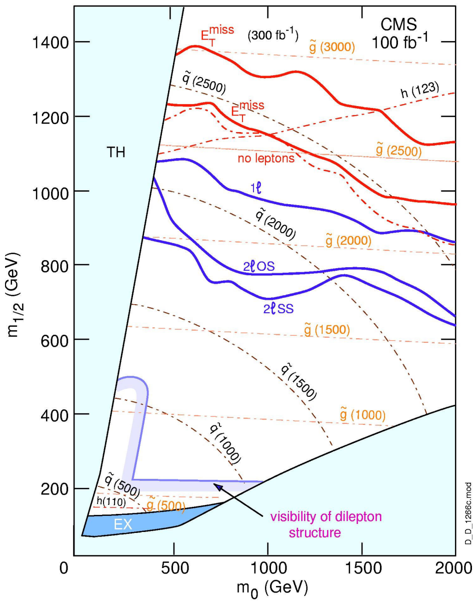
TeV-scale SUSY can be found quickly !

LHC reach in the m_0 - $m_{1/2}$ mSUGRA plane:

Multijet + E_T^{miss} signature

SUSY cascade decays give also rise to many other inclusive signatures: **leptons, b-jets, τ's**





Expect multiple signatures for TeV-scale SUSY

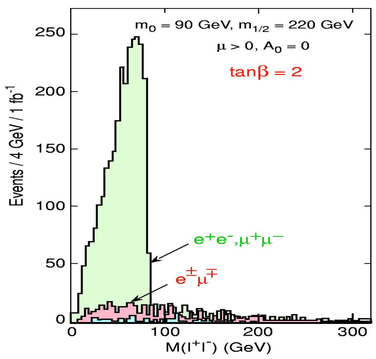
Determination of model parameters

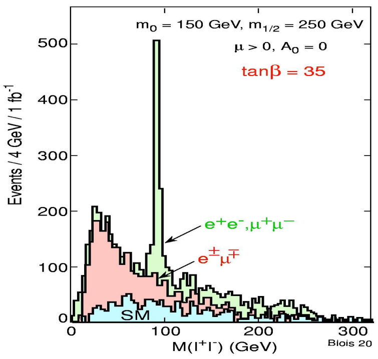
- Invisible LSP ⇒ no mass peaks, but kinematic endpoints
  ⇒ mass combinations

- Simplest case: $\chi^0_2 \rightarrow \chi^0_1\ \ell^+ \ell^-$ endpoint: $M_{\ell\ell} = M(\chi^0_2) - M(\chi^0_1)$

(significant mode if no $\chi^0_2 \rightarrow \chi^0_1 Z$, $\chi^0_1 h$, $\tilde{\ell}\ell$ decays)

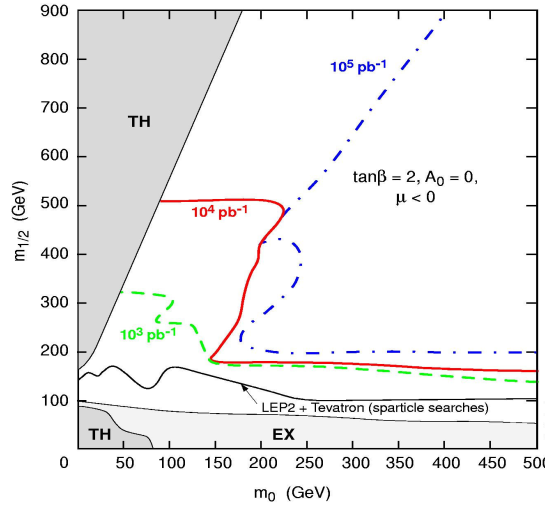
- Require: 2 isolated leptons, multiple jets, and large E_T^{miss}





Modes can be distinguished

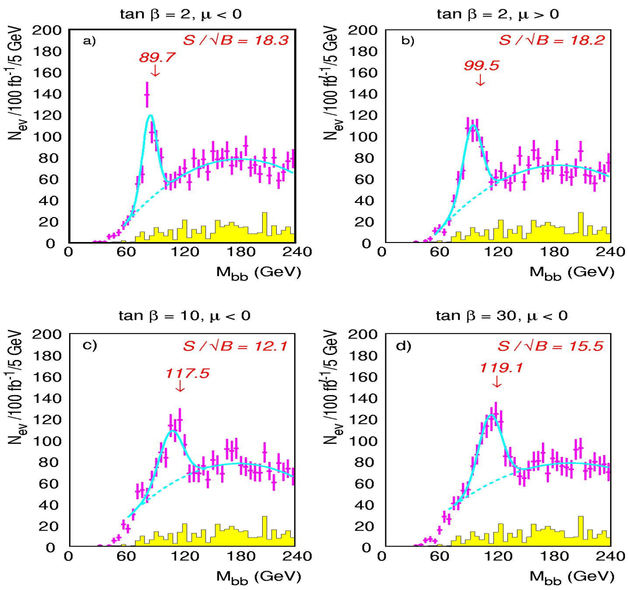
using shape of ℓℓ-spectrum



$\ell\ell$ - endpoint can be observed over a significant fraction of the parameter space

(covers part of the SUGRA region favored by cold dark matter (Ellis et al.))

$h \rightarrow bb$:



important if $\chi^0_2 \rightarrow \chi^0_1 h$ is open;

bb peak can be reconstructed in many cases

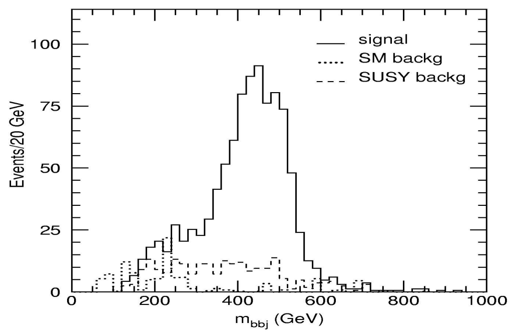
Could be a Higgs discovery mode !

SM background can be reduced by applying a cut on E_T^{miss}

work backwards the decay chain:
example: SUGRA study point 5

$pp \to \tilde{q}_L \tilde{q}_R$: $\tilde{q}_R \to \tilde{\chi}^0_1 q$
$\tilde{q}_L \to \tilde{\chi}^0_2 q \to \tilde{\chi}^0_1 h q \quad \to \tilde{\chi}^0_1 b\bar{b} q$

combine $h \to bb$ with jets to determine other masses



$\tilde{q} \longrightarrow \tilde{\chi}^0_1 h q$ endpoint

Strategy in SUSY Searches at the LHC:

- Search for multijet + E_T^{miss} excess
- If found, select SUSY sample (simple cuts)
- Look for special features (γ's , long lived sleptons)
- Look for $\ell^{\pm}$, $\ell^+ \ell^-$, $\ell^{\pm} \ell^{\pm}$, b-jets, τ's
- End point analyses, global fit

Models other than SUGRA

GMSB:

- LSP is light gravitino
- Phenomenology depends on nature and lifetime of the NLSP
- Generally longer decay chains, e.g. $\tilde{\chi}^0_2 \to \tilde{\ell}^{\pm} \ell^{\mp} \to \tilde{\chi}^0_1 \ell^+ \ell^- \to \tilde{G} \gamma \ell^+ \ell^-$

- ⇒ models with prompt NLSP decays give add handles and hence are easier than SUGRA

- NLSP lifetime can be measured:
  - For $\tilde{\chi}^0_1 \to \tilde{G}\gamma$, use Dalitz decays (short lifetime) or search for non-pointing photons
  - Quasi stable sleptons: muon system provides excellent „Time of Flight“ system

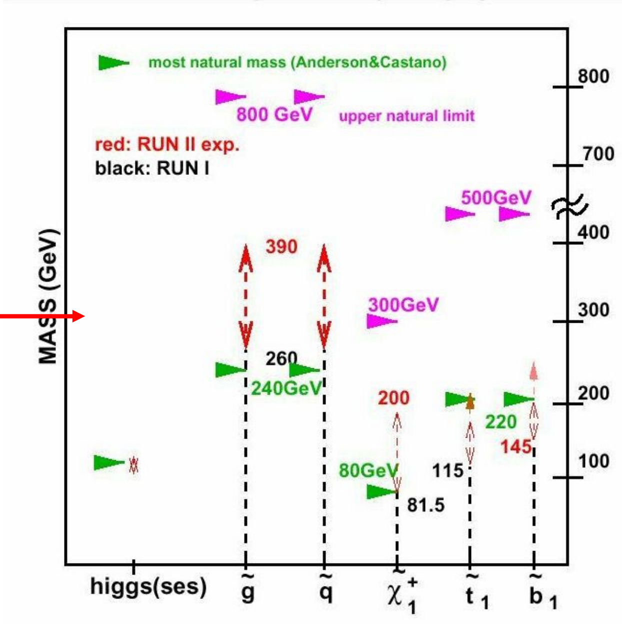
RPV :

- R-violation via $\chi^0_1 \to \ell\ell\nu$ or $qq\ell$, $qq\nu$ gives additional leptons and/or E_T^{miss}

- R-violation via $\chi^0_1 \to cds$ is probably the hardest case; (c-tagging, uncertainties on QCD N-jet background)

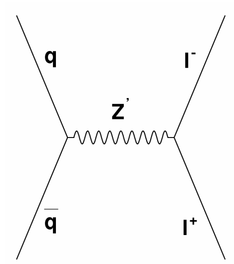
The Reach for SUSY at the Tevatron

SUSY:
Extend reach for SUSY particle masses

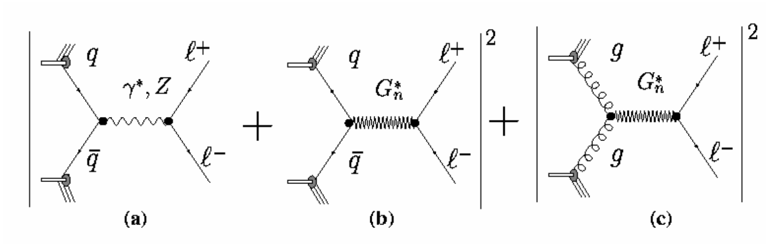


Fermilab Search for New Resonances in High Mass Di-leptons

- **Neutral Gauge Boson Z'**
  - SM Coupling assumed



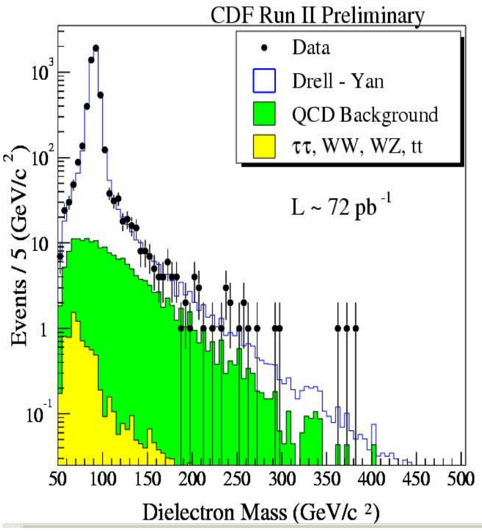
- **Randall-Sundrum narrow Graviton resonances decaying to di-leptons**
  - Gravitons in extra dimensions
  - Free parameters:
    - Mass M_G
    - Coupling $\mathbf{k}/M_{PL}$



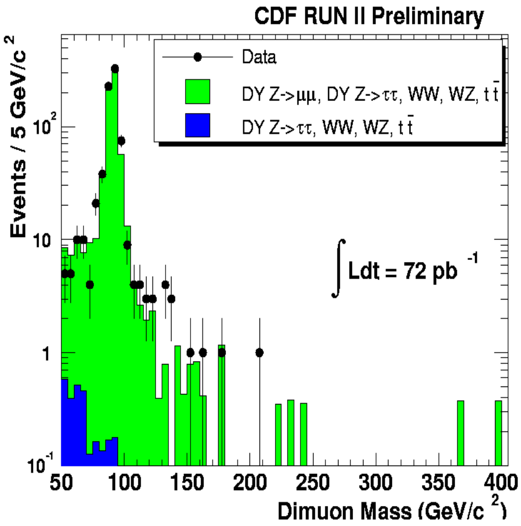
Main background from Drell-Yan pairs

Search for New Resonances in High Mass Di-leptons

Di-electron Invariant Mass



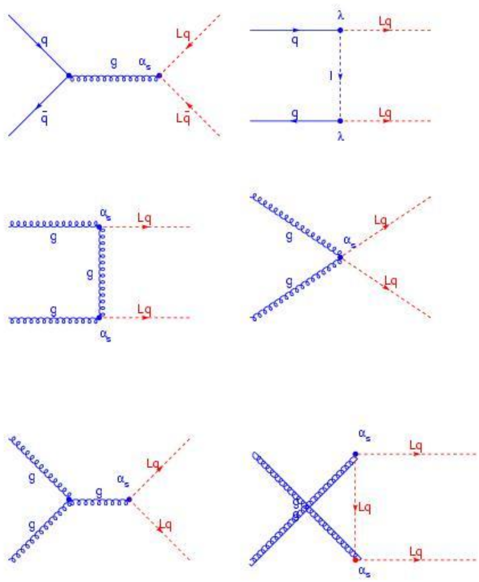
Di-muon Invariant Mass



Data are consistent with SM background. No excess observed.

Search for 1. Generation scalar Leptoquarks

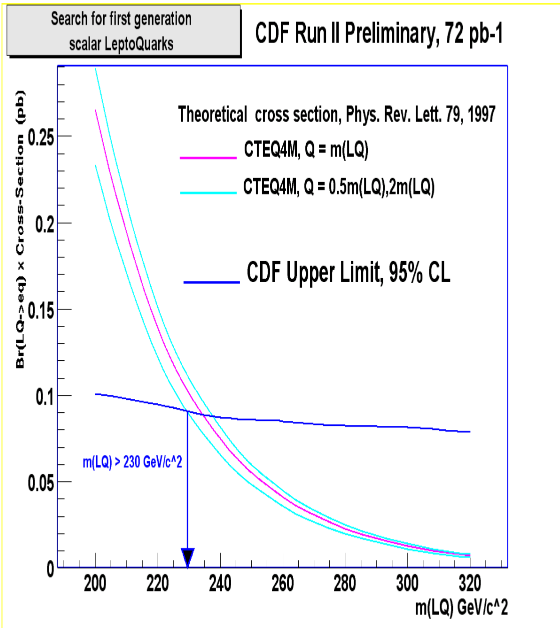
- **Production**
  - qg → LQ + LQ
  - gg → LQ + LQ
  - qq → LQ + LQ
- **Decay**
  - LQLQ → l^+l^-qq,
  - LQLQ → $l^\pm\nu$qq,
  - LQLQ → ννqq
- **Experimental signature**
  - 2 high pt isolated leptons + jets
  - one isolated lepton + MET + jets
  - MET + jets



Search for First Generation scalar LQ

- **Event Selection:**
  - 2 central electrons with E_T > 25 GeV
  - 2 jets with $E_T(j_1)$ > 30 and $E_T(j_2)$ > 15 GeV
  - Z veto
  - Cuts on *sum* of jet and electron E_T's to reject SM backgrounds
- **Expected Bkg:** 3.4 ± 3.2 events
  (DY+2 jet events, tt)

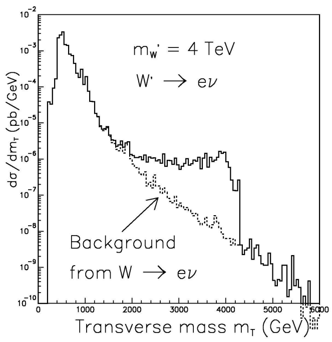
0 events observed in 72 pb-1.
M(LQ) > 230 GeV/c² @ 95% CL
(Run I: 220 GeV/c²)



LHC reach for exotic particles
(a few examples)

Excited quarks: $q^* \to q\gamma$, up to:	m ~6 TeV
Leptoquarks, up to:	m ~1.5 TeV
Monopoles: $pp \to \gamma\gamma pp$, up to:	m ~20 TeV
Lepton flavour viol. $\tau \to \mu\gamma$:	$10^{-6} - 10^{-7}$
Compositeness, up to: from di-jet and Drell-Yan, needs calorimeter linearity better than 2%	$\Lambda \sim 40$ TeV
$Z' \to ll, jj$, up to:	m ~5 TeV
$W' \to l\nu$, up to:	m ~6 TeV

$\int \mathcal{L}dt = 100\ fb^{-1}$



Conclusions

1. Experiments at Hadron Colliders have a huge discovery potential

- SM Higgs: full mass range, already at low luminosity
  Vector boson fusion channels improve the sensitivity significantly

- MSSM Higgs: parameter space covered; new scenarios investigated at present
- SUSY: discovery of TeV-scale SUSY should be easy,
  determination of model parameters is more difficult

- Exotics: experiments seem robust enough to cope with new scenarios

2. Experiments have also a great potential for precision measurements
   - m_W to ~15 MeV
   - m_{top} to ~ 1 GeV
   - $\Delta m_H / m_H$ to 0.1% (100 - 600 GeV)
   + gauge couplings and measurements in the top sector ....

Transparencies under: (after Tuesday next week)

http://www.uni-mainz.de/~jakobs/atlas/zakopane-2003.pdf

K. Jakobs Cracow School of Theoretical Physics, Zakopane, Poland, June 2003