Physics at (Anti)Proton-Proton Colliders

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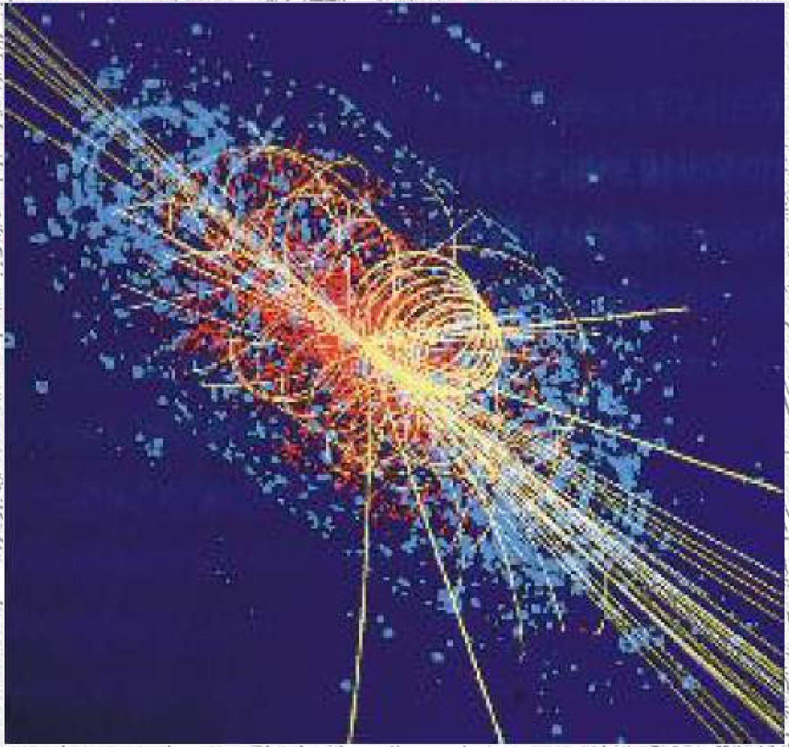
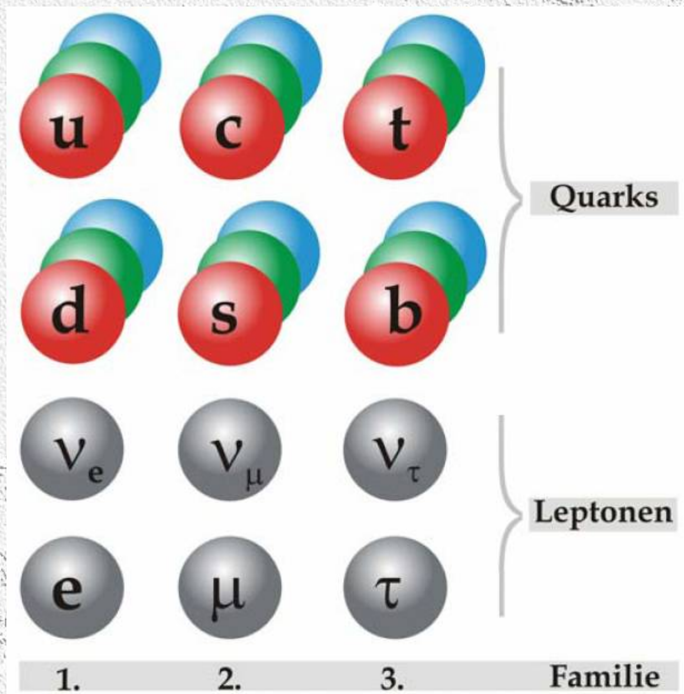
Introduction

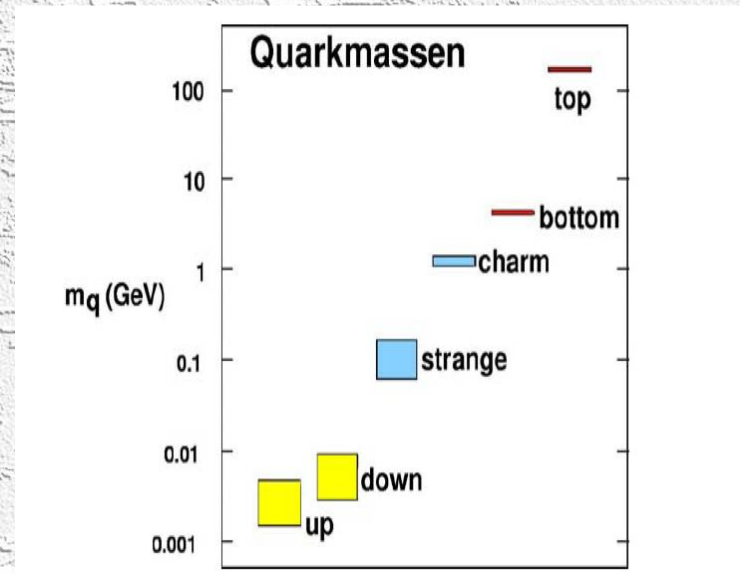
Outline:
- Reminder particle physics
- Proton versus electron collider
- Tevatron and LHC
- Physics at proton colliders
- LHC experiments
- Standard Model physics
- Higgs searches
- New phenomena (e.g. SUSY)



The Standard Model

Fermions: the building blocks of matter





$m(e) = 0{,}000511\ \mathrm{GeV}/c^2$
$m(\tau) = \sim 1{,}8\ \mathrm{GeV}/c^2$

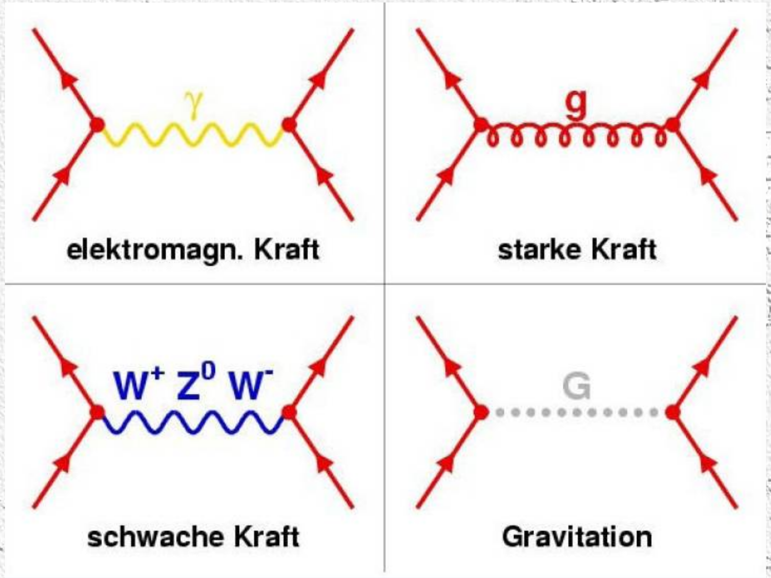
$m(u) = 0{,}005\ \mathrm{GeV}/c^2$
$m(t) = \sim 174\ \mathrm{GeV}/c^2$

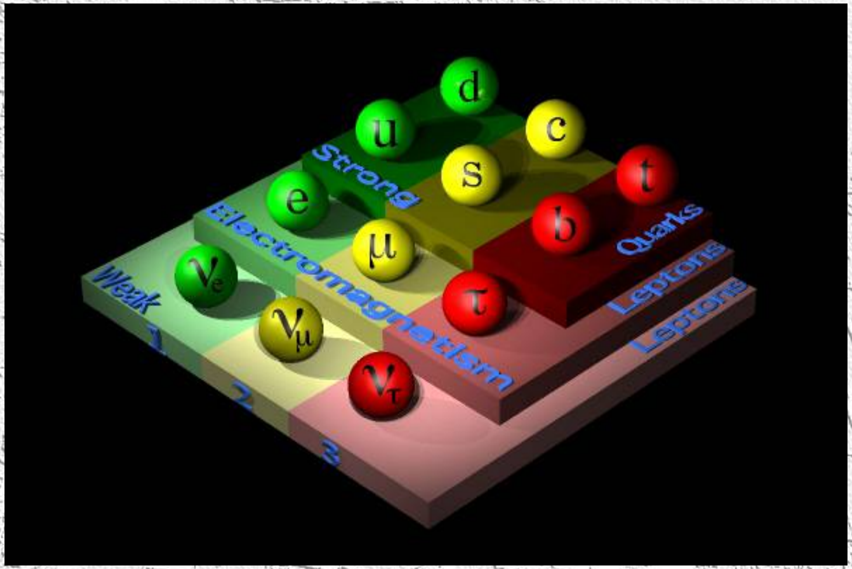
Three families (or generations) of quarks and leptons

Very different fermion masses

The Standard Model

Bosons: the carriers of forces (interactions)





Electroweak interactions $SU(2)_L \times U(1)$: γ, Z, W±
Strong interactions QCD SU(3)c: g
Gravitation?

$m_\gamma = m_g = 0$

$m_Z = 91.1875 \pm 0.0021$ GeV
$m_W = 80.329 \pm 0.029$ GeV

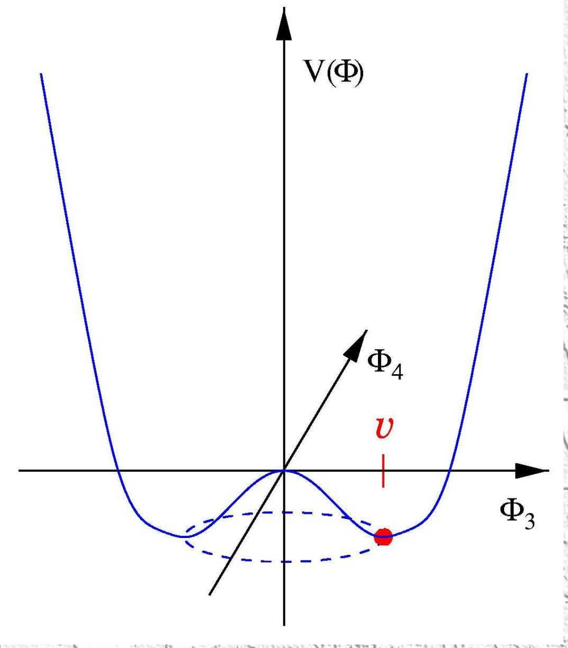
The Origin of Mass

- **Why are the fermion masses so different?**
  ranging from $m_{\nu e} < 2$ eV … $m_t = 175$ GeV

- **Massive gauge bosons Z, W±**
  a priori inconsistent with local gauge symmetries

- **Partial answer: Higgs mechanics**
  spontaneous symmetry breaking

  - Predicts the existence of a neutral, spin 0 boson
  - Last missing particle of the Standard Model
  - Mass m_H is a free parameter
    once measured, all properties of the Higgs boson are fixed in the theory



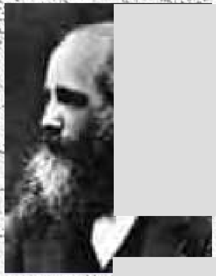
Today's knowledge about the Higgs mass

114.4 GeV < m_H <≈ 1 TeV
(experiment) (theory)

Unification of Forces

• Is there a universal force (interaction) at some high energy?

• Historical examples



Maxwell‘s unification of electric and magnetic forces (1864)

Electroweak interaction unification of electromagnetic and weak interations

Glashow-Salam-Weinberg model

- prediction of W and Z bosons
- Higgs mechanism is a cornerstone of the model

Unknown Types of Matter

Are there other, not yet discovered types of matter?

The answer is yes!

From studies of

- rotational curves of galaxies
- the cosmic microwave background
- very distant supernovae

the universe consists of

≈ 5% baryonic matter

≈ 25% dark matter (neutral, weakly interacting)

≈ 70% dark energy???

Supersymmetry (SUSY) is a popular SM extension

- candidate for dark matter
- unification of forces possible

Quark	Squark
Top	Stop
Electron	Selectron
Wino	W
Higgsino	H

Supersymmetric partners of SM particles

Spin differs by 1/2

Other Questions and Problems

Are quarks and leptons really elementary?
e.g. structureless, pointlike objects?

Why are there 3 families?

What is the origin of the matter-antimatter asymmetry in the universe?
What is the origin of CP violation?

Are there additional forces and gauge bosons?

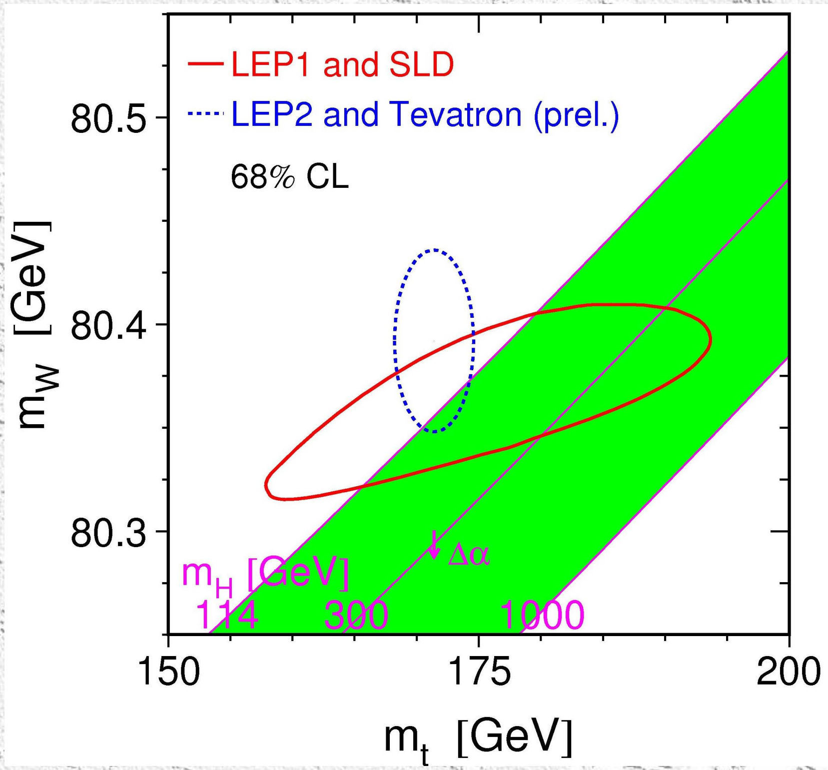
…

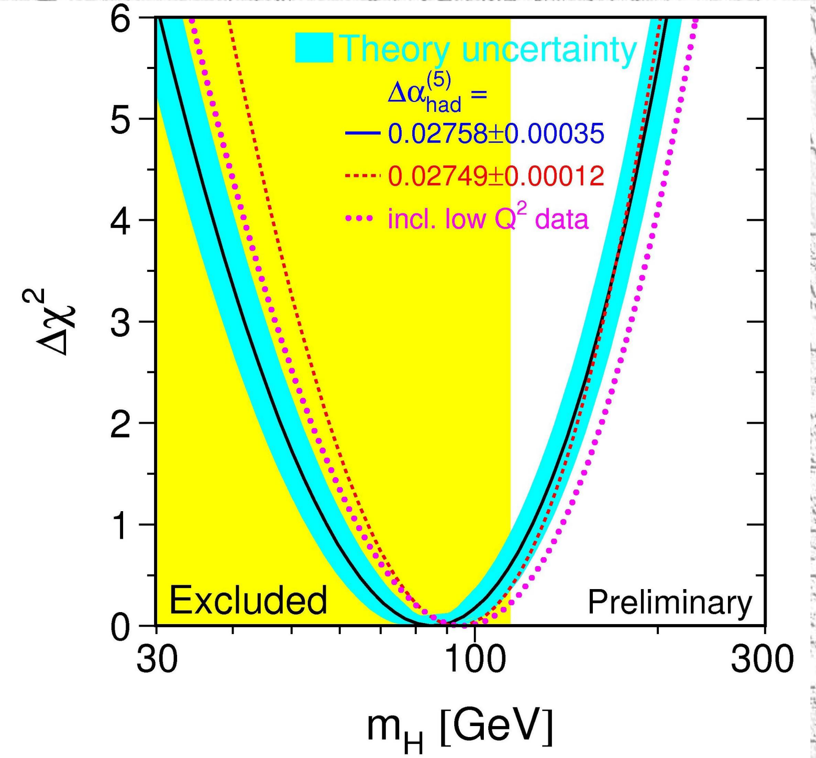
Answers to these questions need
- experiments at high energy
- and with high precision

State of the Art

Many experiments at the LEP & SLC e+e- colliders, the Tevatron pp collider etc. have explored the energy range up to O(100 GeV) with high precision

the Standard Model is correct to the 1-loop level
no evidence for new phenomena (e.g. SUSY)
the Higgs boson, if it exists, is probably light





Future

Discoveries

- Increase collision energy to explore TeV region

  explore the allowed Higgs mass range

  search for Supersymmetry

  and other new physics phenomena

  be prepared for the unexpected

LHC

Precision measurements and tests of the SM

measure SM parameters m_W, m_t

measure properties of new particles (Higgs, SUSY)

and check consistency of the model

LHC & ILC

Proton Collider

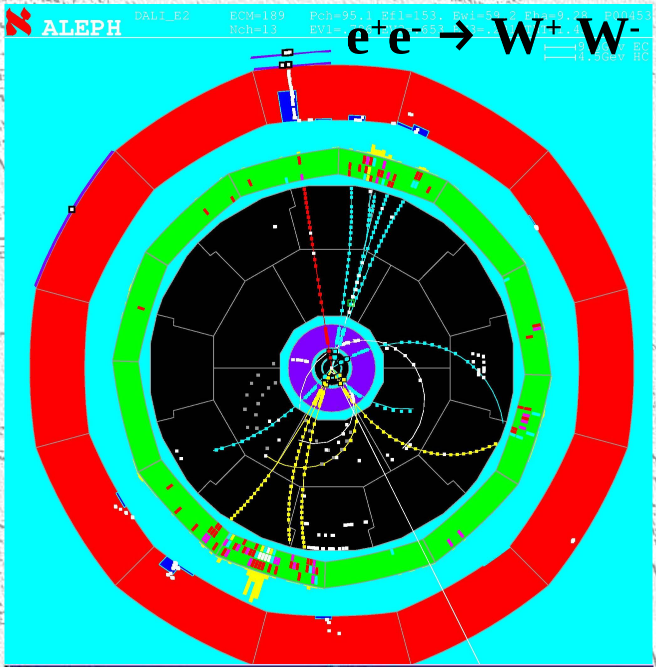
Why a proton collider like the LHC?

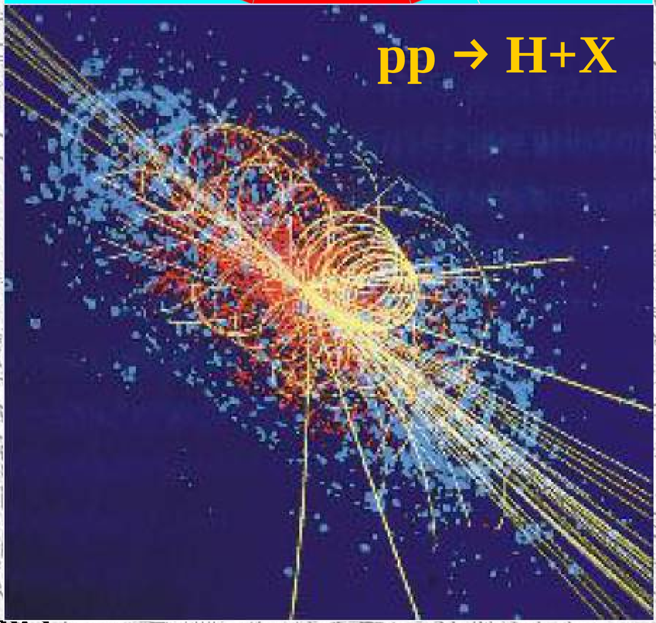
e^+e^- machines like LEP are ideal machines for precision emasurements:

- **$e^+/e-$ are point-like, no substructure**
  very clean events
- **centre-of-mass system**
- **event kinematics completely fixed**

Events at proton collider are much more complex:

- **protons are not elementary**
- **hard scattering of partons (quarks & gluons)**
- **underlying event**
- **use only part of the beam energy**
- **event kinematics only partially constraint**





Problem of Electron Storage Rings

Drawback of circular electron colliders like LEP:
Energy loss due to synchrotron radiation
(Accelerated charge do radiate photons!)

- **Radiated power P (in synchrotron photons) ring with radius R and energy E**

$$P = \frac{2\,e^2\,c}{3\,R^2}\left(\frac{E}{mc^2}\right)^4$$

- **Energy loss per turn**

$$-\Delta E \approx \frac{4\,\pi\,e^2}{3\,R}\left(\frac{E}{mc^2}\right)^4$$

- **Ratio of energy loss between electrons and protons**

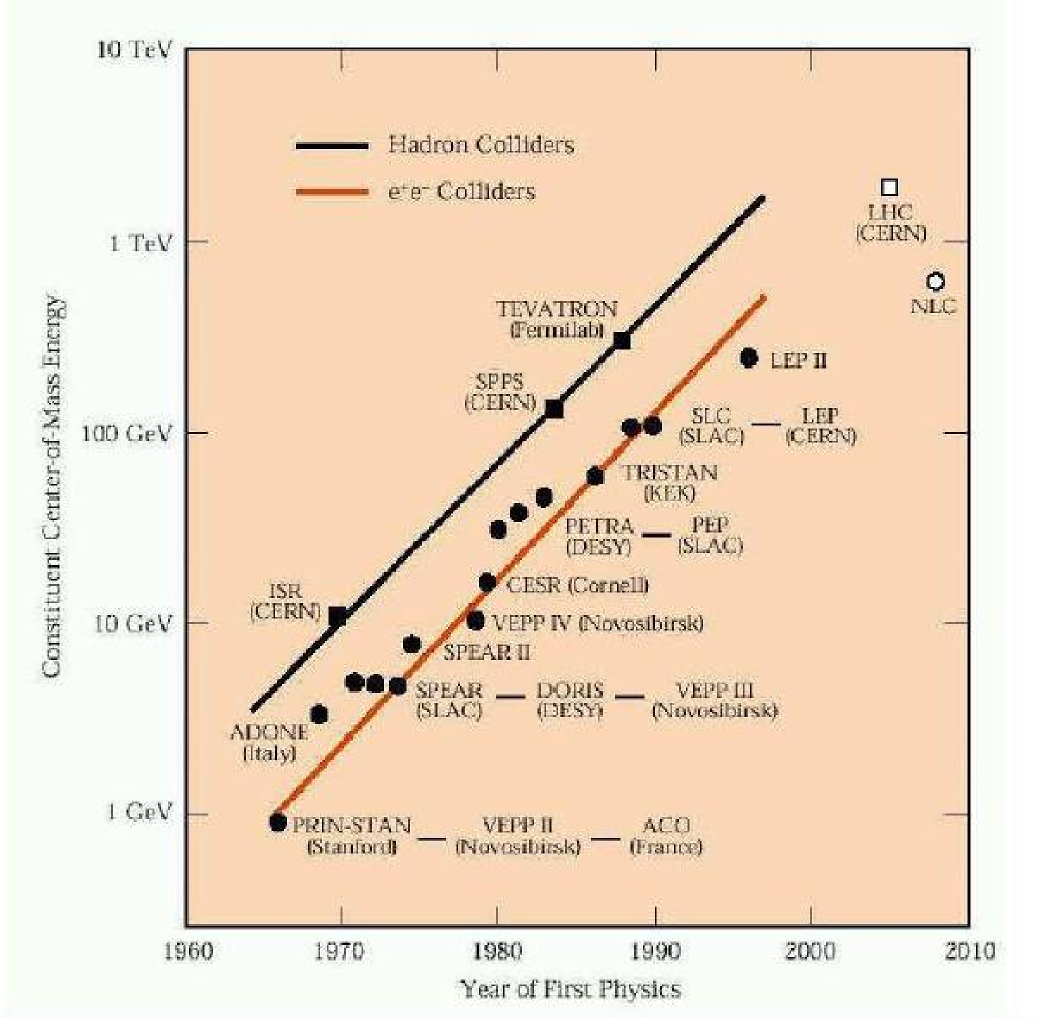
$$\frac{\Delta E(e)}{\Delta E(p)} = \left(\frac{m_p}{m_e}\right)^4 \sim 10^{13}$$

To reach higher energies at future colliders:

a) Linear electron-positron colliders (→ ILC)
b) Proton colliders (→ LHC)
LHC uses existing LEP tunnel!

History of Colliders

Comparison of past and future electron and proton colliders:



The Tevatron Collider at Fermilab

Proton-Antiproton Collider

1992 - 1996
Run I with 2 experiments CDF and D0
$\sqrt{s}$ = 1.8 TeV
$\int L dt$ = 125 pb-1

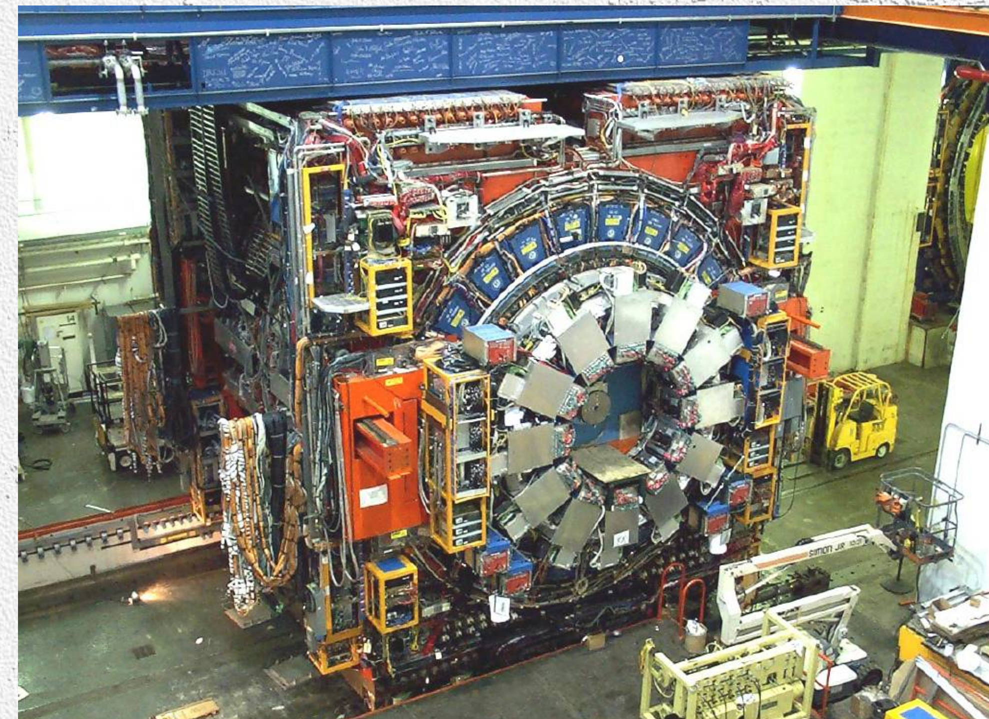
1996 – 2001 Upgrade
- **new injector, antiproton recycler**
  → higher luminosity
- **detector improvements**

since March 2001
Run II, $\sqrt{s}$ = 1.96 TeV

Both experiments are running collecting & analysing data

Experiments at the Tevatron

The CDF detector



Upgrades for Run II:
- tracking system
  large Si-strip detector
- forward calorimeter
- trigger and DAQ systems

≈ 700 physicists

Experiments at the Tevatron

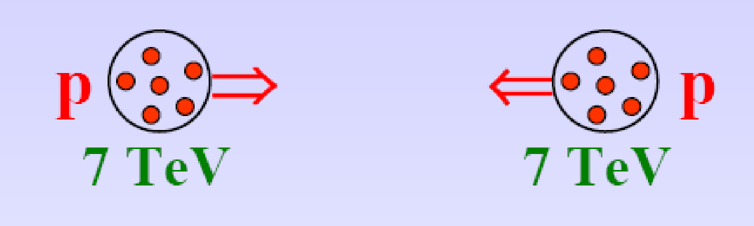
The D0 detector

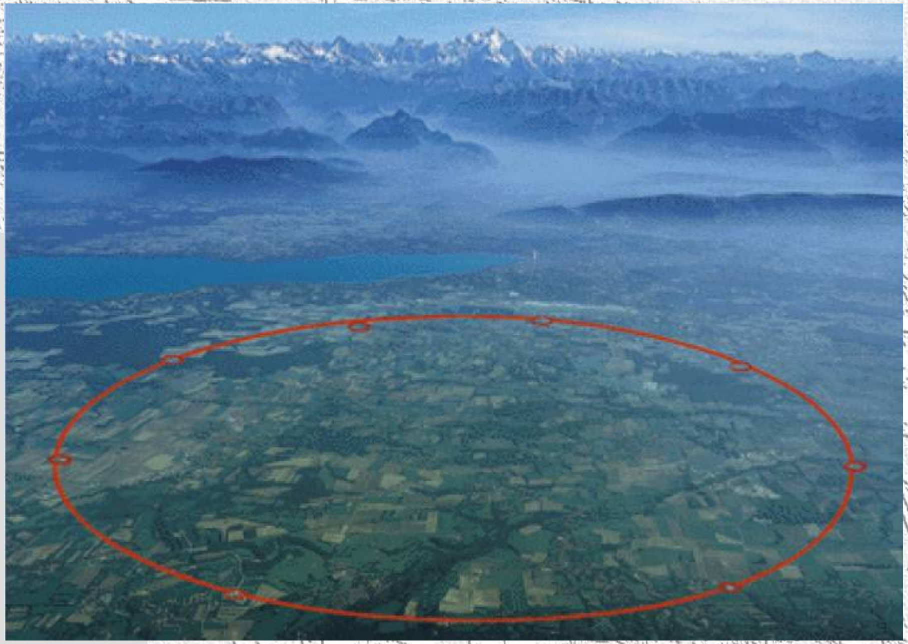
institutes from 19 countries
≈ 700 physicists

Upgrades for Run II:
- inner detector
- magnetic field
- forward muon
- trigger and DAQ systems

The Large Hadron Collider (LHC) at CERN

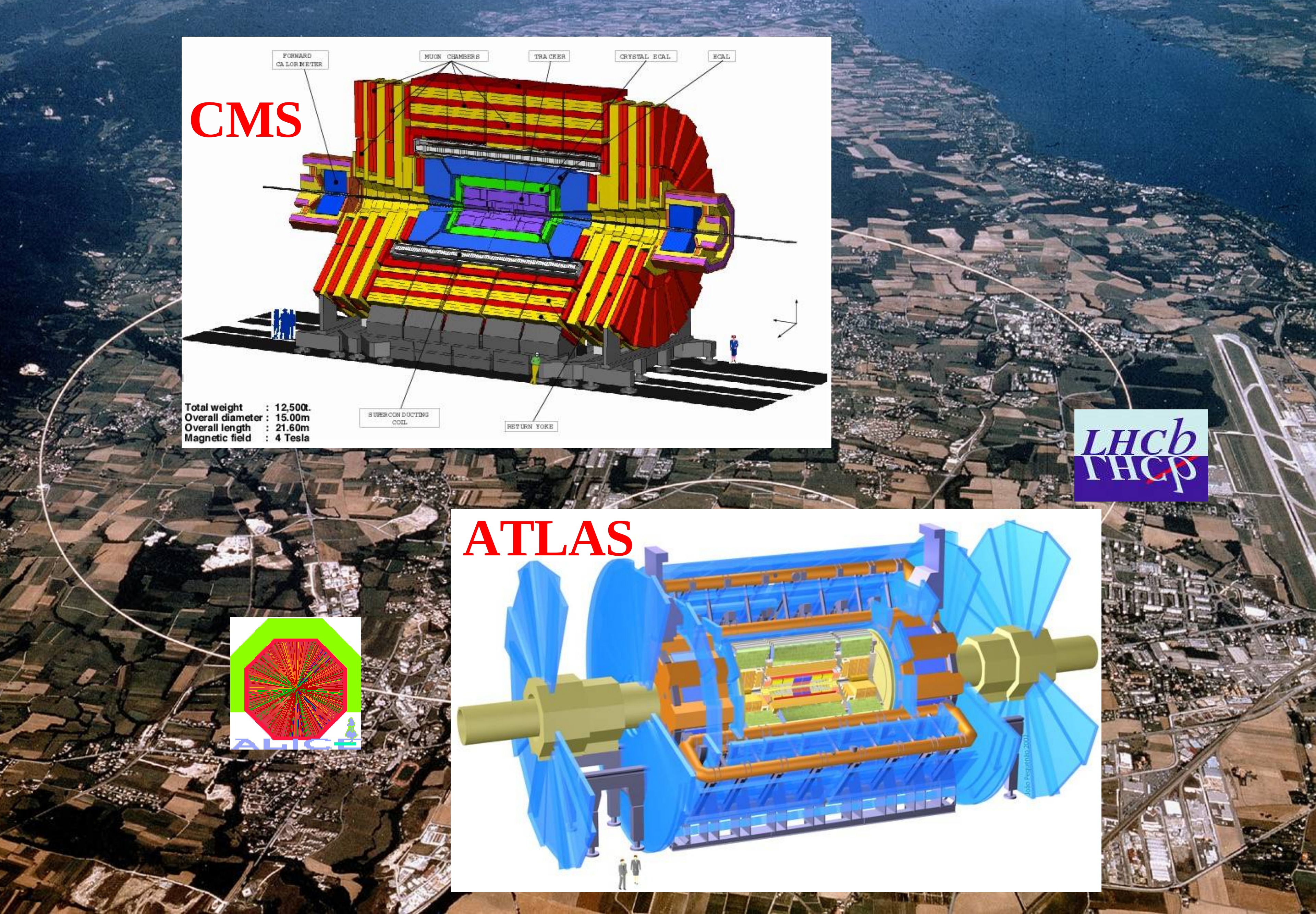
Proton-proton collider in the former LEP tunnel at CERN (Geneva)





Highest ever energy per collision
14 TeV in the pp-system
Conditions as $10^{-13} - 10^{-14}$ s after the Big Bang
4 experiments:
ATLAS
CMS
LHC-B specialised on b-physics
ALICE specialised for heavy ion collisons
Constructed in a worldwide collaboration
Start planned for 2007

The Large Hadron Collider LHC



Challenges for the LHC

Superconducting dipole magnets
to keep 7 TeV protons on circular
path (r $\approx$ 3 km)

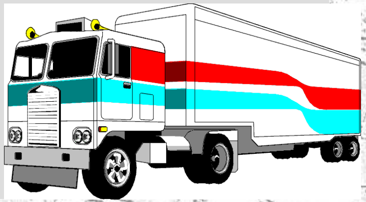
|B| = 8.33 Tesla

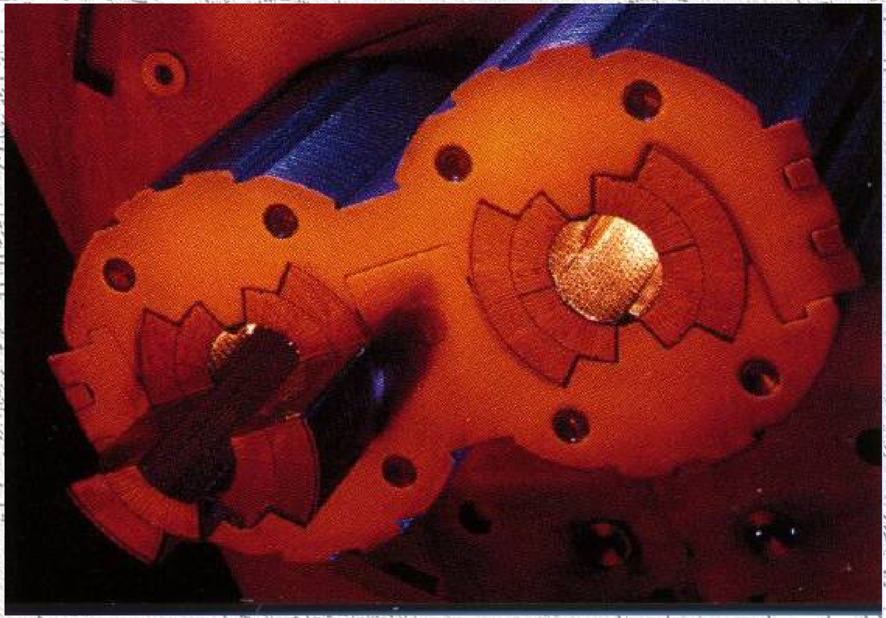
1232 dipole magnets are needed
(+ quadrupole, sextupoles etc.)
each dipole is 15 m long

1.9 K operating temperature
supraliquid He
largest cyrogenic facility in the world

Quench protection
stored energy in one dipole: 8 MJ

corresponds to a
40 t truck at 50 km/h!





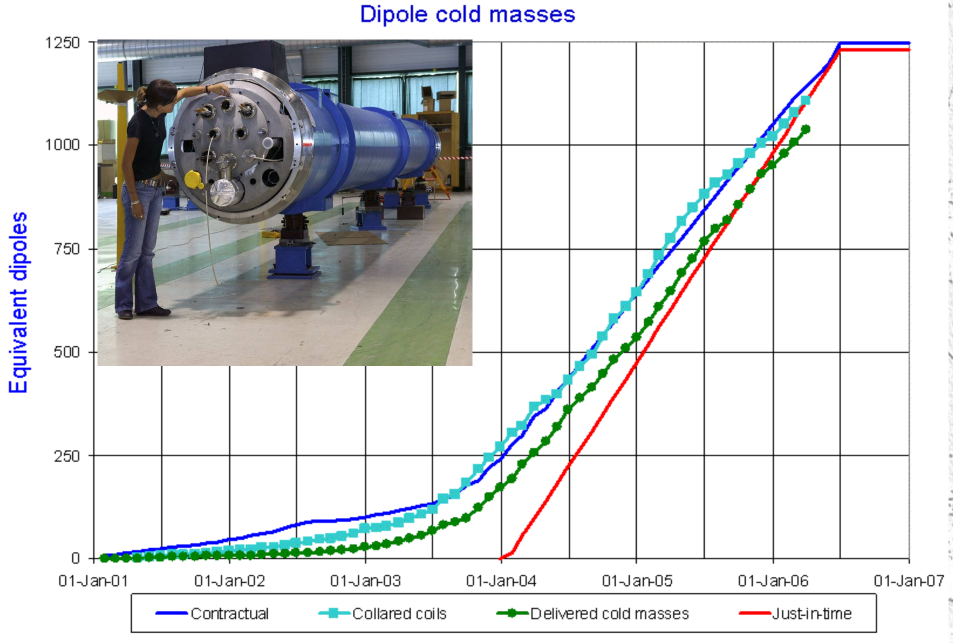
LHC dipole design
incoporates reversed field for
oppositely rotating proton beam

BTW:
the stored energy in the LHC
proton beams is 350 MJ
enough to melt 500 kg of copper!

Status of the LHC

LHC schedule: - first beam in 2007
- pilot run end 2007
- first full physics year in 2008

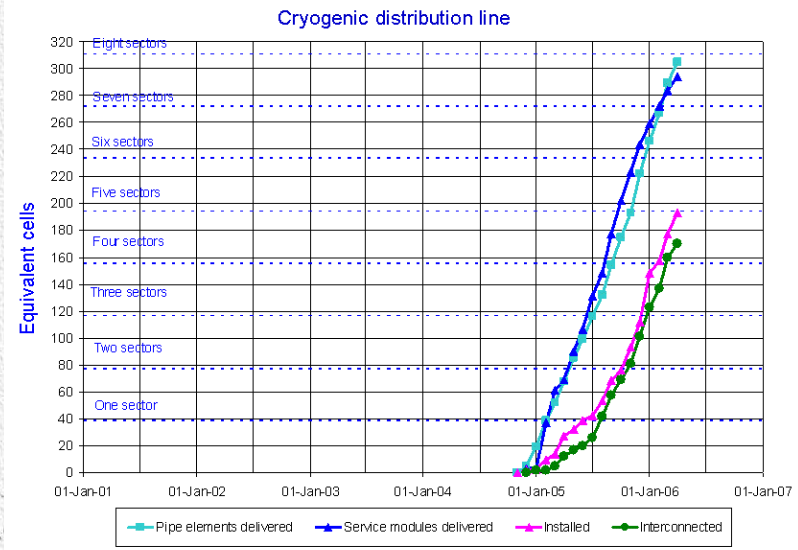
Progress:
Example dipole cold masses



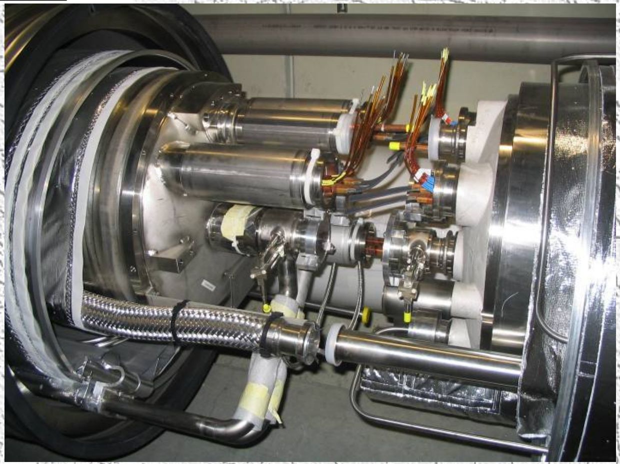
Storage of cold masses on CERN site

Installation in the LHC Tunnel

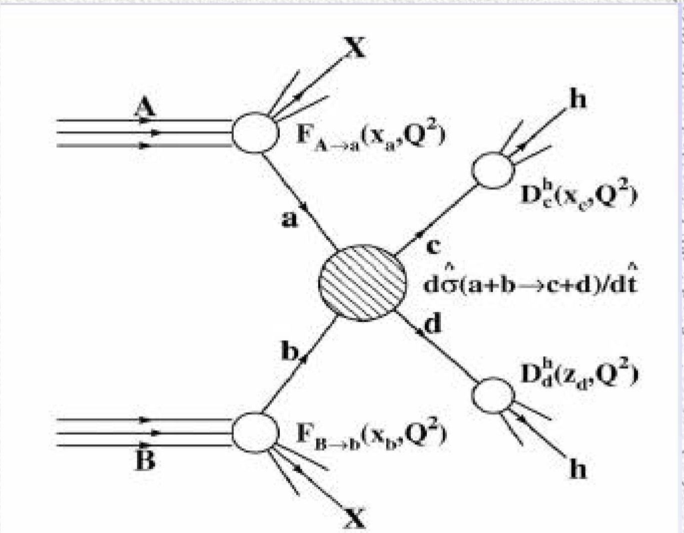
Installation of cryogenic lines delayed in 2004 due to manufacturing problem



Installation of magnets
after cryogenics
transport & interconn.
time consuming
on critical path

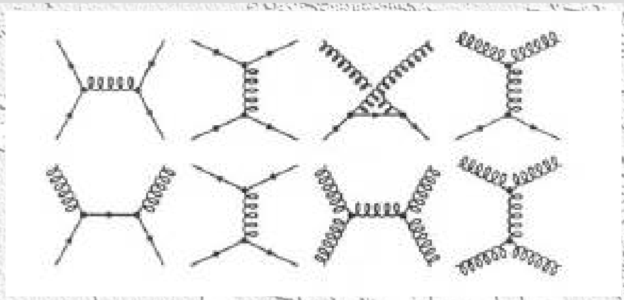


Physics at Proton Colliders



Protons are composite, complex objects
- partonic substructure
- quarks and gluons

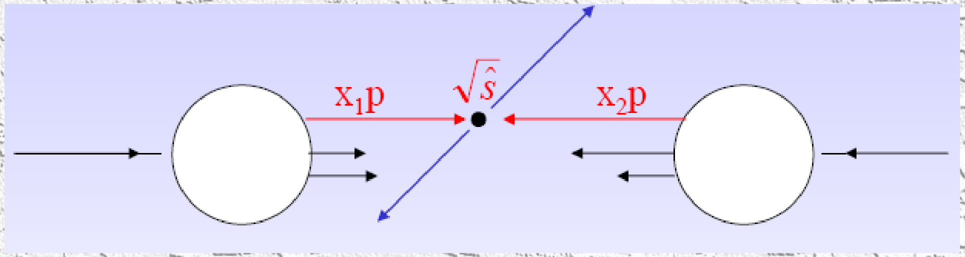
Interesting hard scattering processes
quark-(anti)quark
quark-gluon
qluon-gluon



However, hard scattering (high momentum transfer) processes are only a small fraction of the total cross section
- total inelastic cross section ≈ 70 mb (huge!)
- dominated by events with small momentum transfer

Proton-ProtonCollisions

Proton beam can be seen as beam of quarks and gluons with a wide band of energies
The proton constituents (partons) carry only a fraction $0 \leq x \leq 1$ of the proton momentum



The effective centre-of-mass energy $\sqrt{\hat{s}}$ is smaller than $\sqrt{s}$ of the incoming protons

$$\left.\begin{aligned} p_1 &= x_1\, p_A \\ p_2 &= x_2\, p_B \\ p_A &= p_B = 7\ \text{TeV} \end{aligned}\right\} \quad \sqrt{\hat{s}} = \sqrt{x_1\, x_2\, s} = x\sqrt{s} \quad (\text{if } x_1 = x_2 = x)$$

Note:
the component of the parton momentum parallel to the beam can vary from 0 to the proton momentum ($0 \leq x \leq 1$)
the variation of the transverse component is much smaller (of order the proton mass)

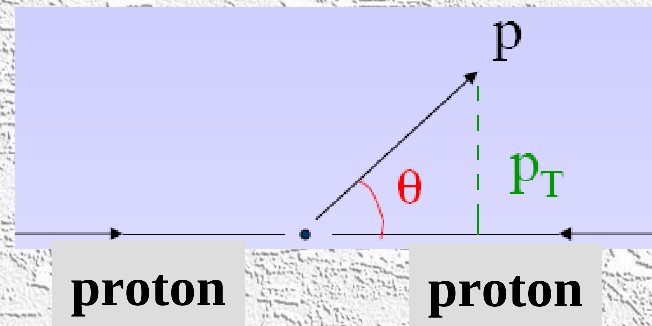
To produce a particle of mass		
mass	LHC	Tevatron
100 GeV	$x \approx 0.007$	$x \approx 0.05$
5 TeV	$x \approx 0.36$	---

Variables in pp Collisions

Kinematics fully defined only in transverse plane

Transverse momentum p_T

$p_T = p \sin\theta$

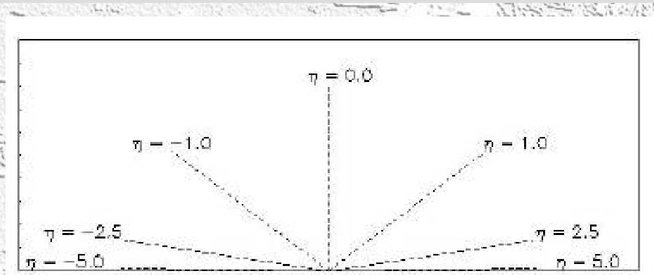


Rapidity: $$y = \frac{1}{2}\ln\frac{E + p_L}{E - p_L}$$

Differences in y are invariant under Lorentz boosts

Pseudo-rapidity: $$\eta = -\ln\frac{\theta}{2}$$

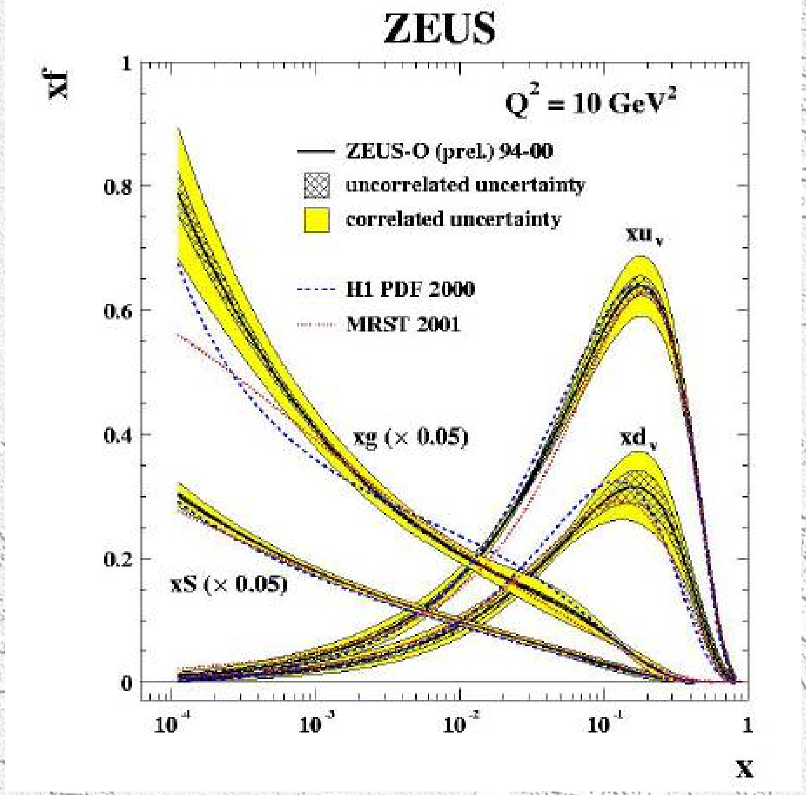
handy approximation, do not need to know the particle mass

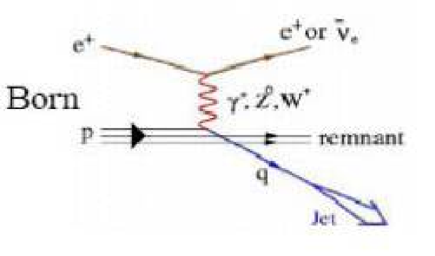


θ = 90°	η = 0
θ = 10°	η ≈ 2.4

Parton Density Functions

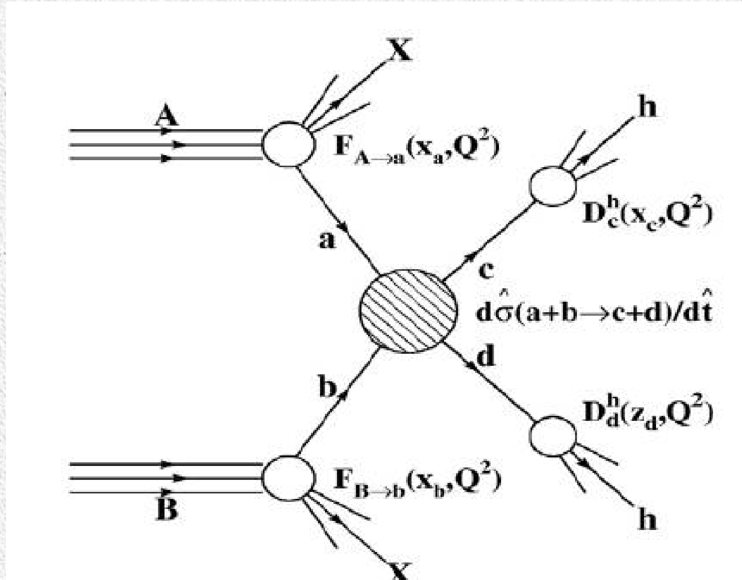
How do the distributions of the x-values look like?
Measured at HERA in ep-scattering, e.g.:





u- and d-quarks at large x-values
gluons dominate at small x
large uncertainties for gluons

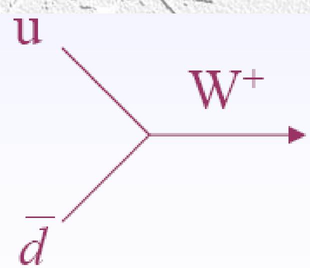
Cross Section Calculation



$$\sigma = \sum_{a,b} \int dx_a\, dx_b\, f_a(x_a, Q^2)\, f_b(x_b, Q^2)\, \hat{\sigma}_{ab}(x_a, x_b)$$

sum over initial states a,b
$f_i(x_i,Q^2)$ = parton density functions

Example: W production in leading order



$\sigma(pp\to W) \approx 150$ nb $\approx 2\cdot 10^{-6}\, \sigma_{tot}$

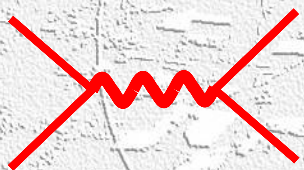
Parton Density Functions at the LHC

LHC is a proton-proton collider

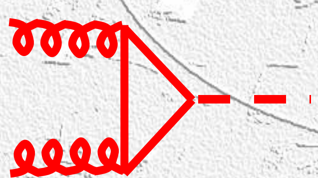
But fundamental processes are the scattering of

- **Quark – Antiquark**
- **Quark – Gluon**
- **Gluon – Gluon**

Examples:

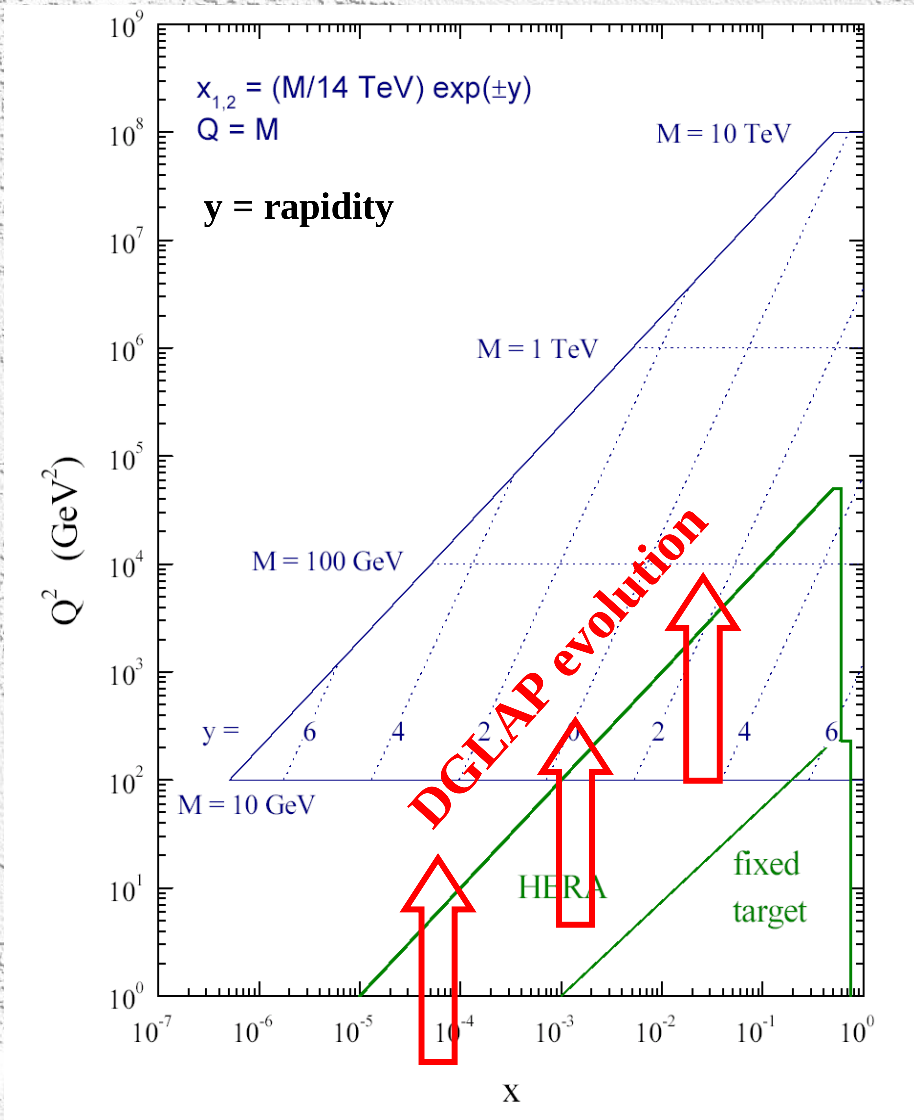


$\bar{q}q$ W lν



gg H

⇒ **need precise PDF(x,Q²)**
+ QCD corrections (scale)



Luminosity

Rate of produced events for a given process

$$\boxed{N = \sigma L}$$

σ cross section [barn = 10^{-24} cm^2]
L luminosity [1/cm^2/s]

luminosity depends on machine parameters:
number of protons stored, beam focus at the interaction point, …
luminosity should be high to achieve acceptable rates for rare processes

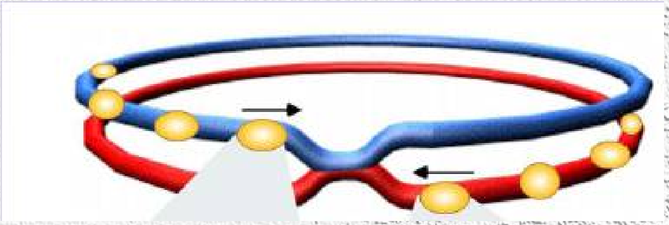
Comparison of colliders:

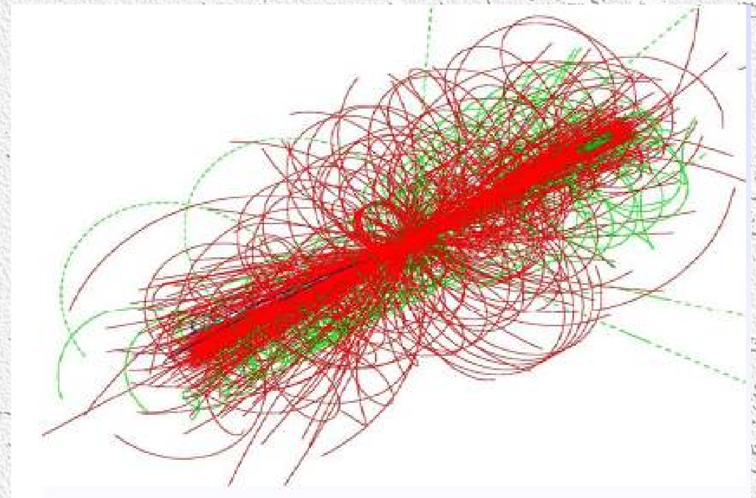
- 10^{31}/cm^2/s LEP
- $2\cdot 10^{32}$/cm^2/s Tevatron Run II design
- 10^{33}/cm^2/s LHC initial phase ($\approx$ 3 years)
- 10^{34}/cm^2/s LHC design luminosity (> 2010)

1 experimental year is about 10^7 s

- 10 fb^{-1} per year in the initial LHC phase
- 100 fb^{-1} per year later

Proton-Proton Collisions at the LHC





2835 + 2835 proton bunches
separated by 7.5 m
→ collisions every 25 ns
= 40 MHz crossing rate

10^{11} protons per bunch

at $10^{34}/\mathrm{cm}^2/\mathrm{s}$
≈ 25 pp interactions per crossing
<u>pile-up</u>

→ ≈ 10^9 pp interactions per second !!!

in each collision
≈ 1600 charged particles produced

enormous challenge for the detectors

Cross Section of Various SM Processes

⇒ **Low luminosity phase**

10^{33}/cm²/s = 1/nb/s

approximately

10^8 pp interactions

10^6 bb events

200 W-bosons

50 Z-bosons

1 tt-pair

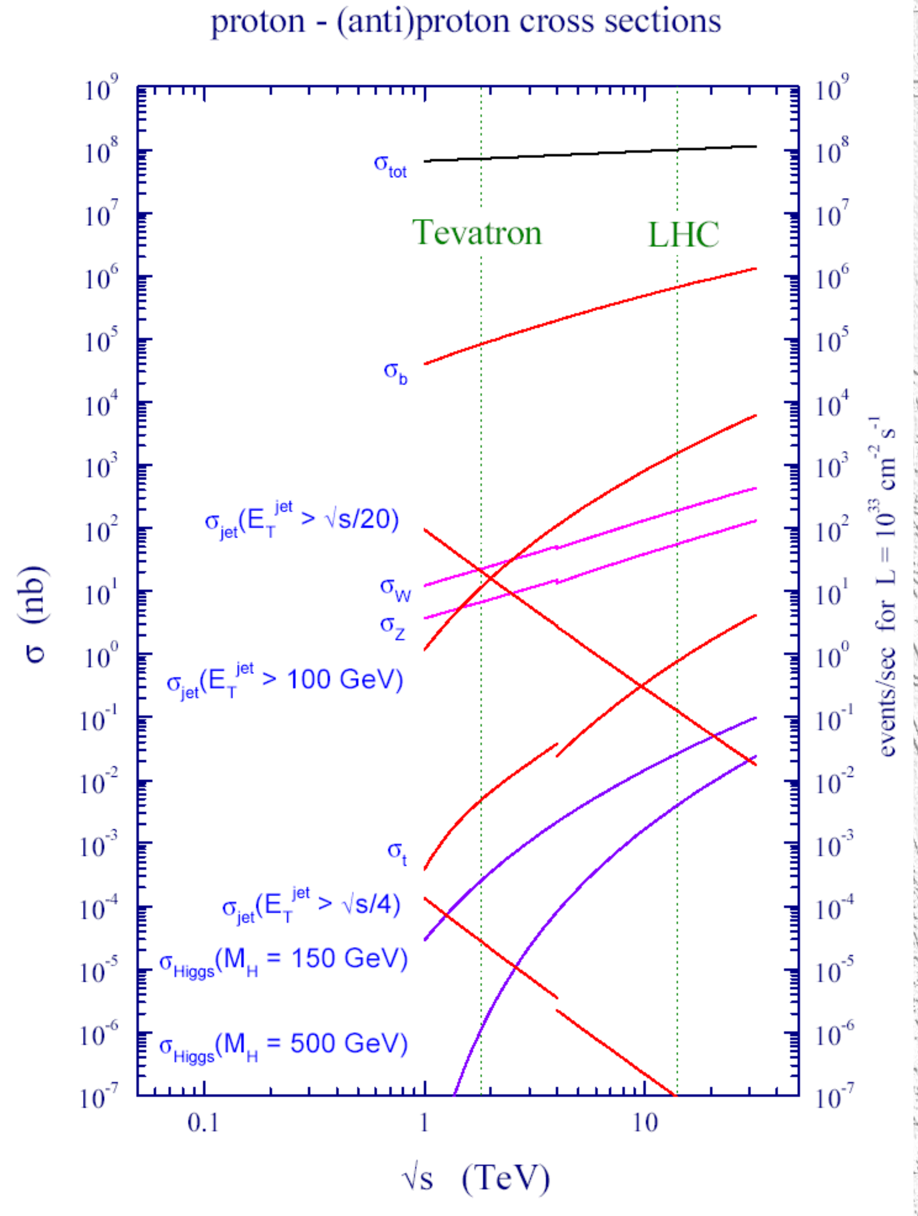
will be produced per second and

1 light Higgs

per minute!

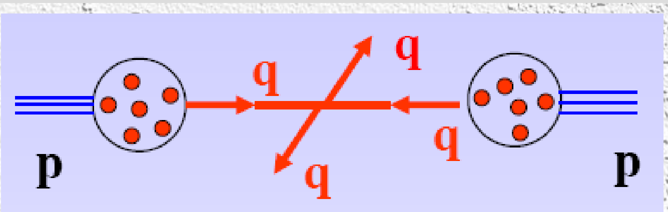
The LHC is a b, W, Z, top, Higgs, … factory!

The problem is to detect the events!



Experimental Signatures

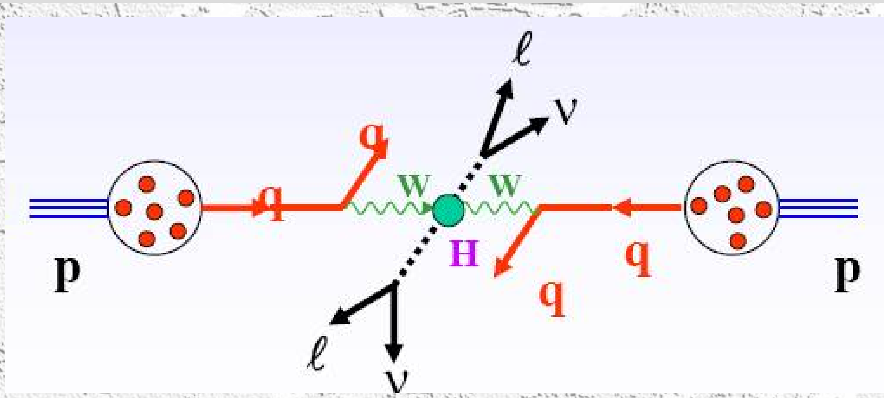
1. Hadronic final states, e.g. quark-quark



no high p_T leptons or photons in the final state

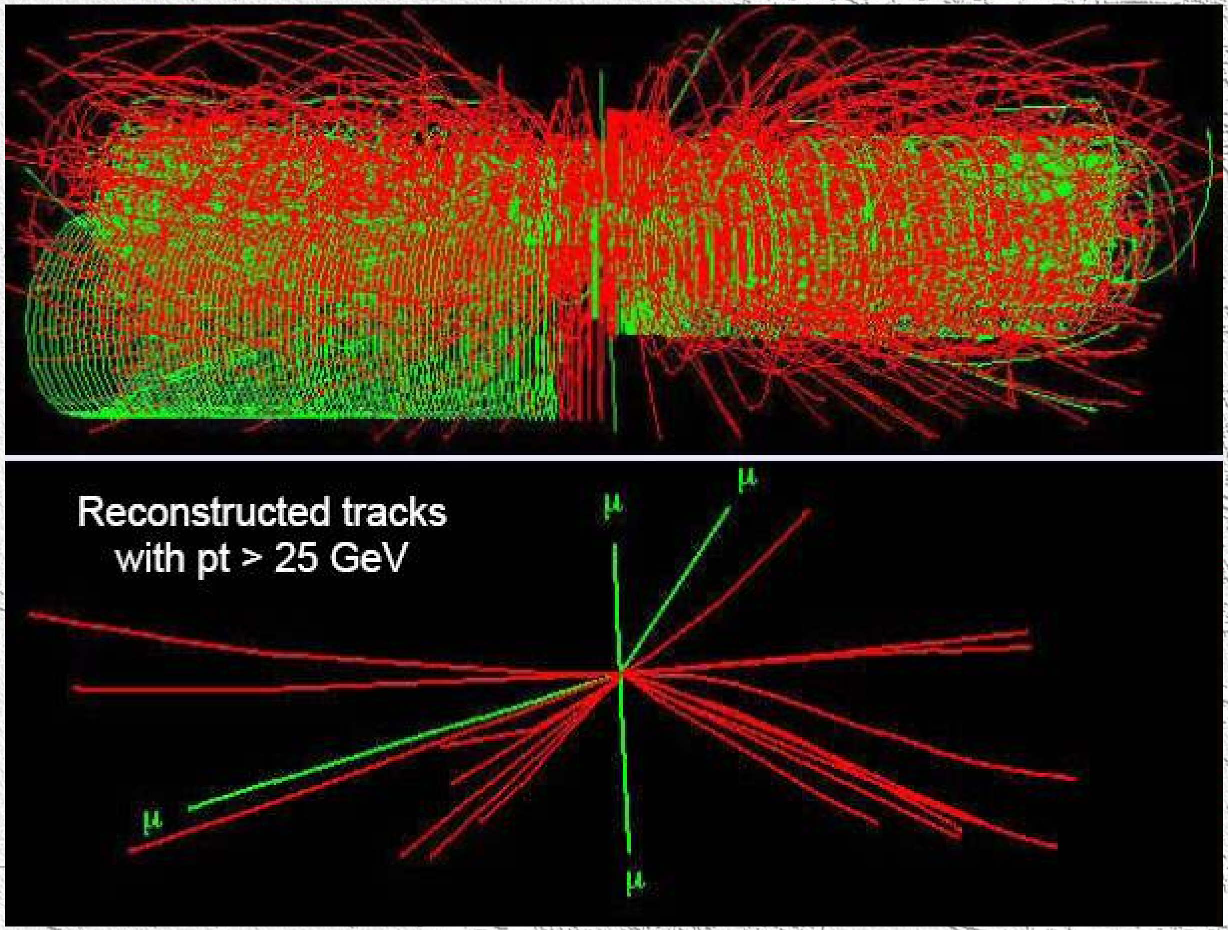
holds for the bulk of the total cross section

2. Lepton/photons with high p_T, example Higgs production and decay



Important signatures for interesting events:
- leptons and photons
- missing transverse energy

Suppression of Background



with 25 pile-up events

removing tracks with p_T < 25 GeV

requires high granularity (many channels)
good position, momentum and energy resolution

Detector Design Aspects

good measurement of leptons (high p_T)

muons: large and precise muon chambers
electrons: precise electromagnetic calorimeter and tracking

good measurement of photons

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

requires in particular good hadronic energy measurements down to small angles, i.e. large pseudo-rapidities ($\eta \approx 5$, i.e. $\theta \approx 1°$)

in addition identification of b-quarks and τ-leptons

precise vertex detectors (Si-pixel detectors)

Very important: radiation hardness

e.g. flux of neutrons in forward calorimeters 10^{17} n/cm^2 in 10 years of LHC operation

Online Trigger

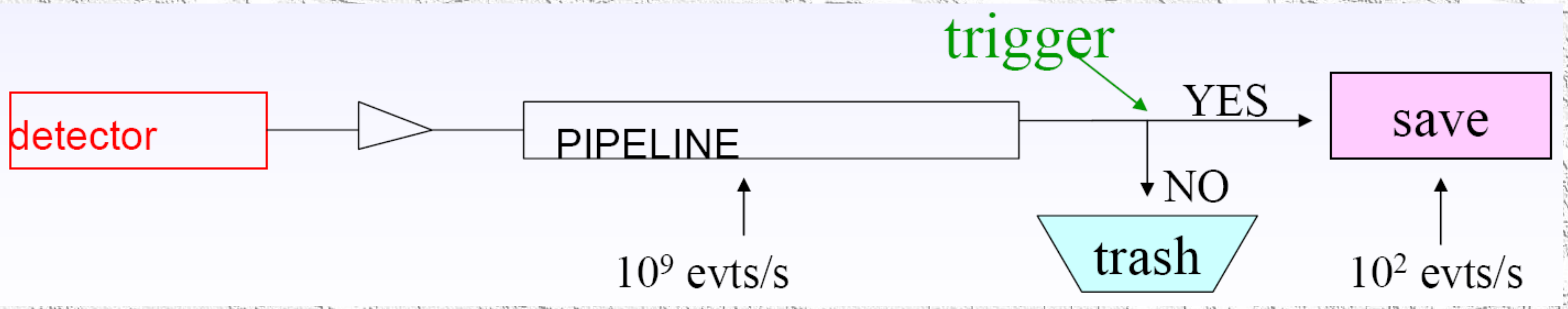
Trigger of interesting events at the LHC is much more complicated than at e^+e^- machines

interaction rate: $\approx 10^9$ events/s
max. record rate: ≈ 100 events/s **event size $\approx$ 1 MByte $\Rightarrow$ 1000 TByte/year of data**

$\Rightarrow$ trigger rejection $\approx 10^7$

collision rate is 25 ns (corresponds to 5 m cable delay)
trigger decision takes $\approx$ a few μs

$\Rightarrow$ store massive amount of data in front-end pipelines while special trigger processors perform calculations



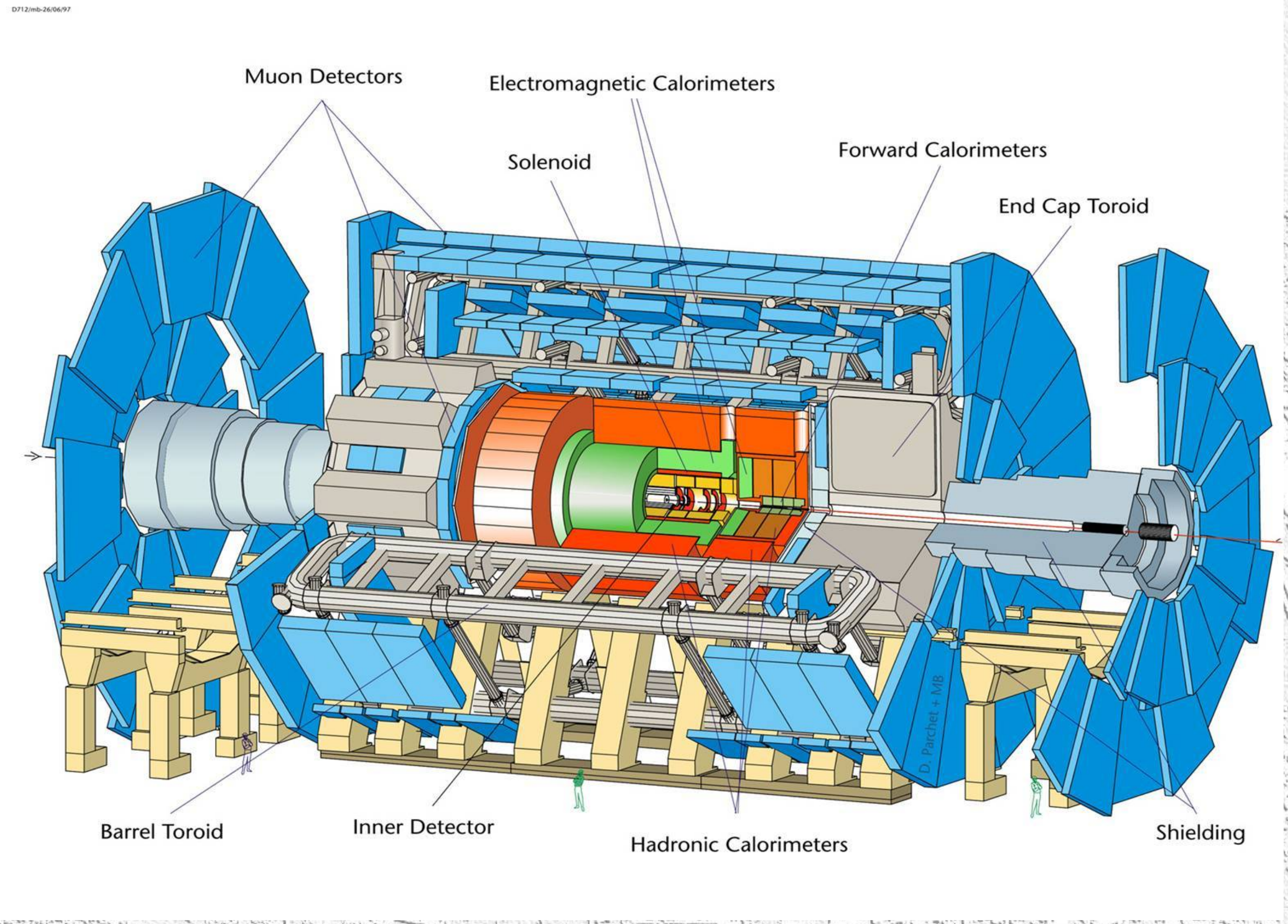
The ATLAS experiment

A Toroidal LHC ApparatuS

ATLAS in a nutshell:
- Large air toroid with μ chambers
- HCAL: steel & scintillator tiles
- ECAL: LAr
- Inner solenoid (2 T)
- Tracker: Si-strips & straw tubes (TRD)
- Si-pixel detector

10^8 channels

15 μm resolution



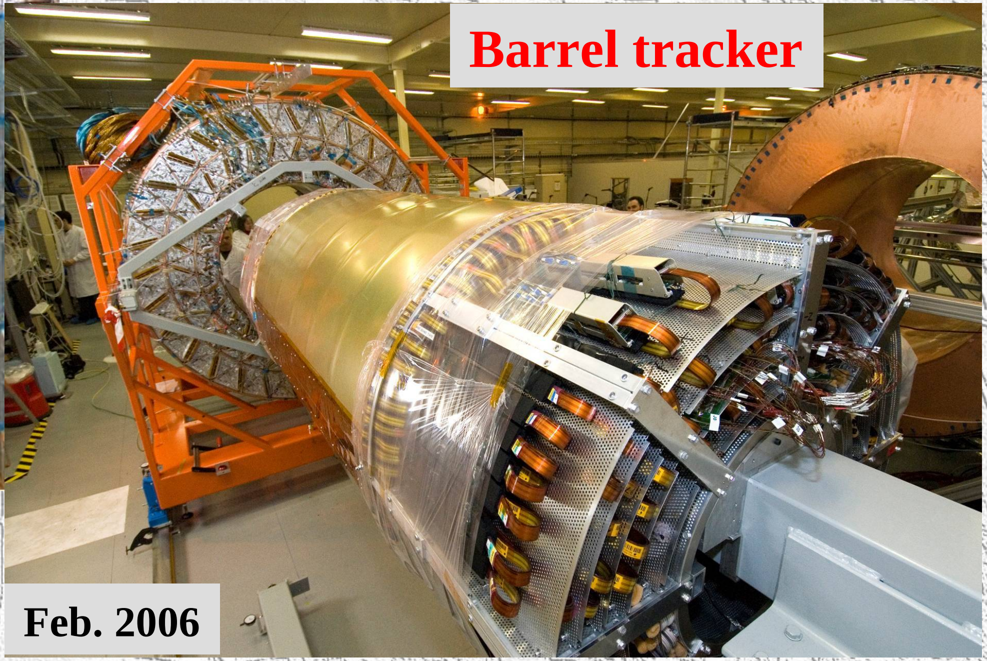
Status of ATLAS

Major structures assembled underground

August 2005: 8/8 toroid coils installed

Status of ATLAS

Examples of major detector components

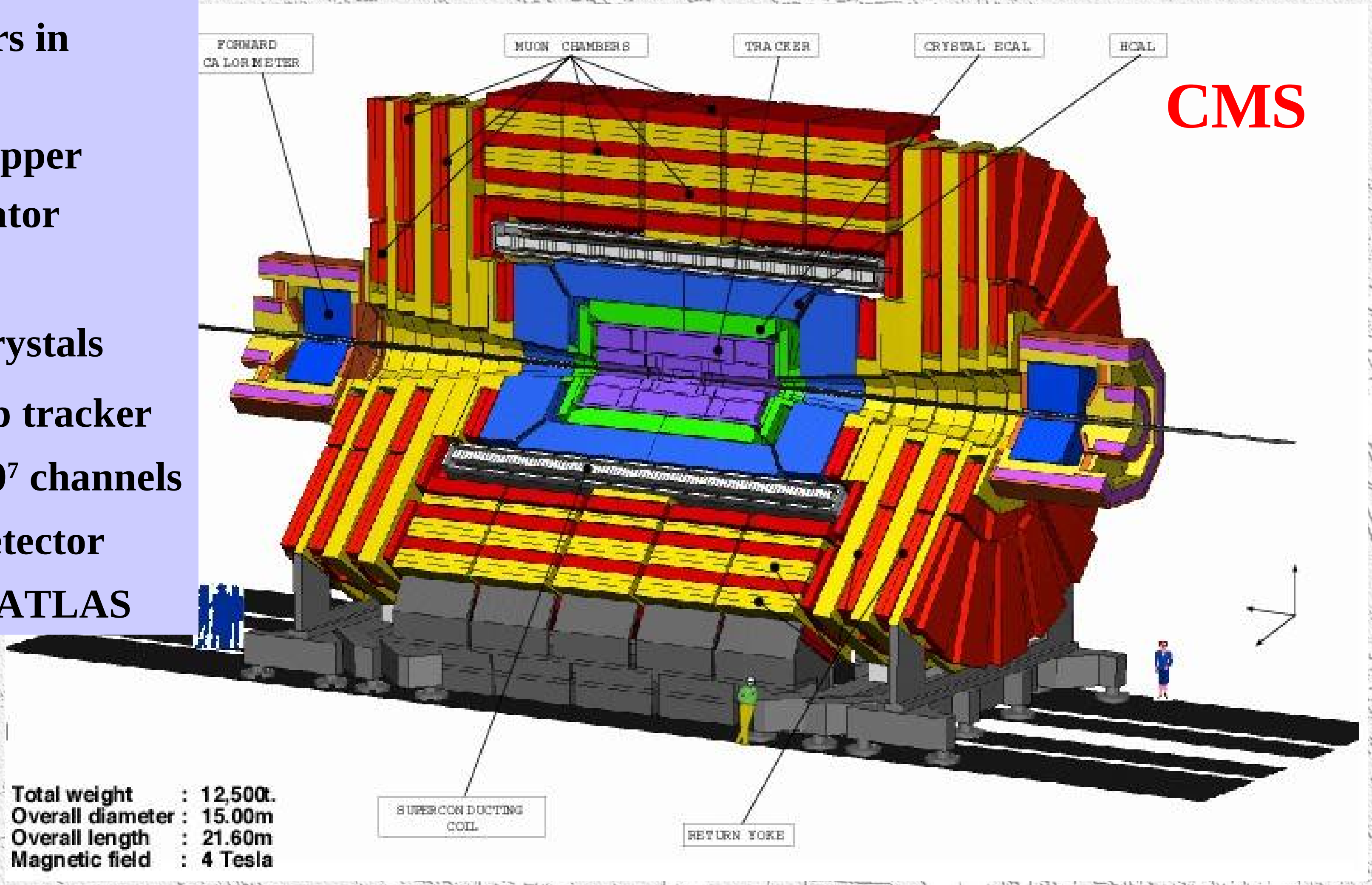


On schedule for 2007
- some smaller detector components deferred
- stagging of DAQ

The CMS experiment

Compact Muon Solenoid

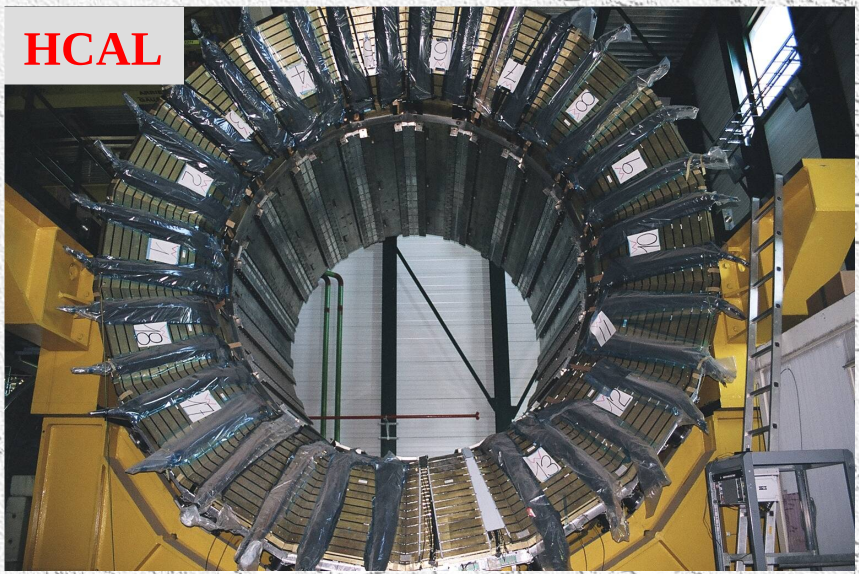
CMS in a nutshell:
- 4 T solenoid
- μ chambers in iron yoke
- HCAL: copper & scintillator
- ECAL: $PbWO_4$ crystals
- All Si-strip tracker 220 m², 10^7 channels
- Si-pixel detector similar to ATLAS



CMS Solenoid

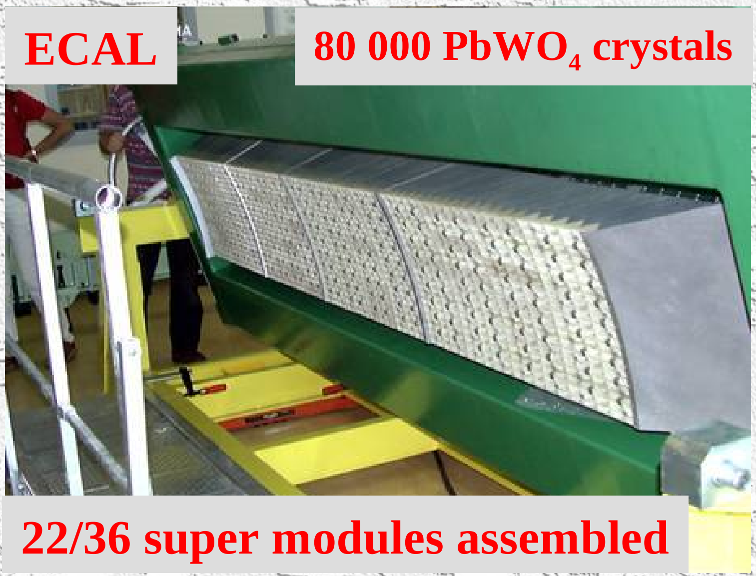
Examples of major detector components

HCAL



ECAL

80 000 $PbWO_4$ crystals



22/36 super modules assembled

Si-tracker

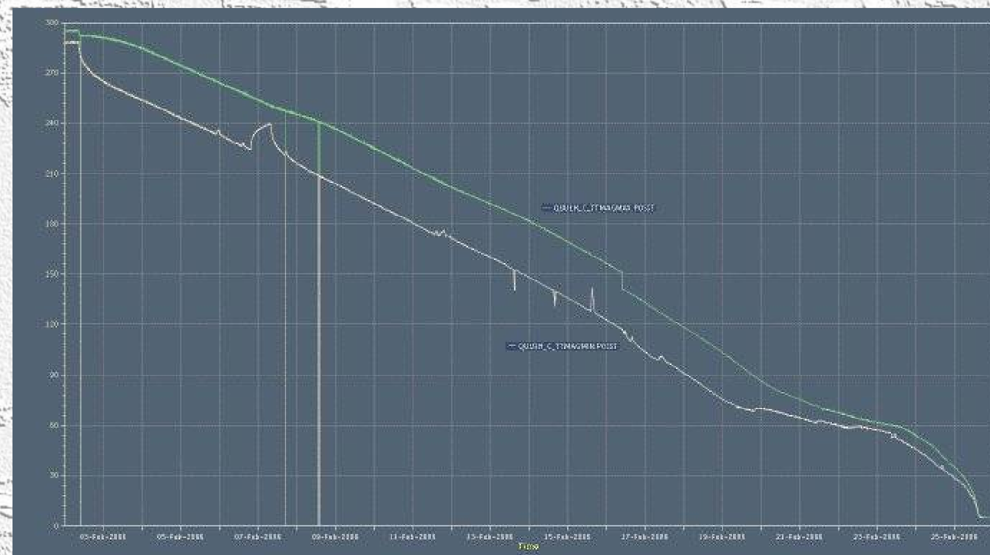
Mostly on schedule for 2007
- delays in ECAL and Tracker
- prob. deferred installation of ECAL endcaps
- stagging of pixel & DAQ

Status of CMS

Major structures assembled on surface
Detector slices to be lowered in cavern

September 2005: coil inserted in yoke

Coil cooled down to 4.5°K February 2006

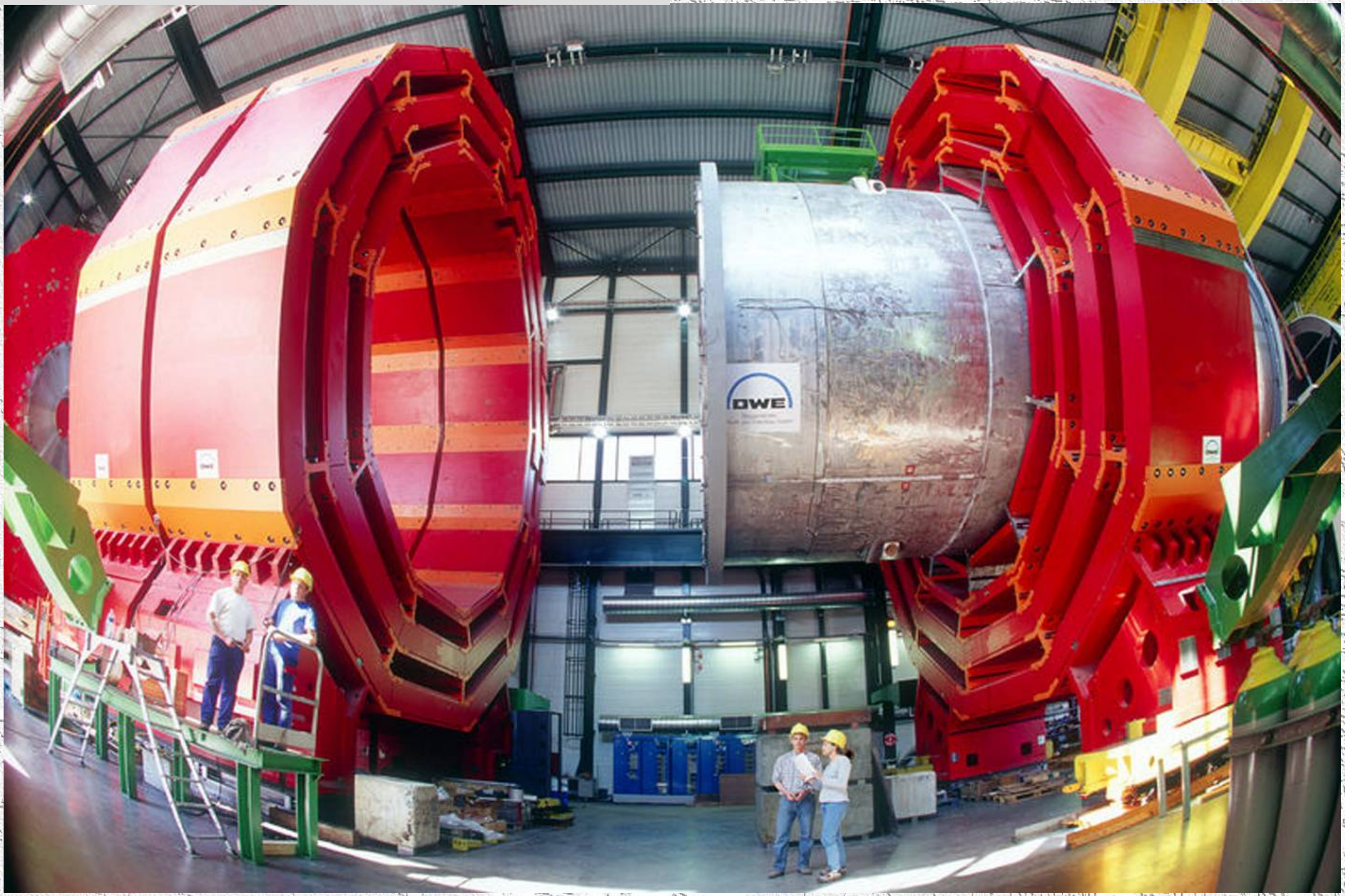


Test on surface is currently going on
3.95 Tesla reached last week!

Large fraction of muon chambers installed

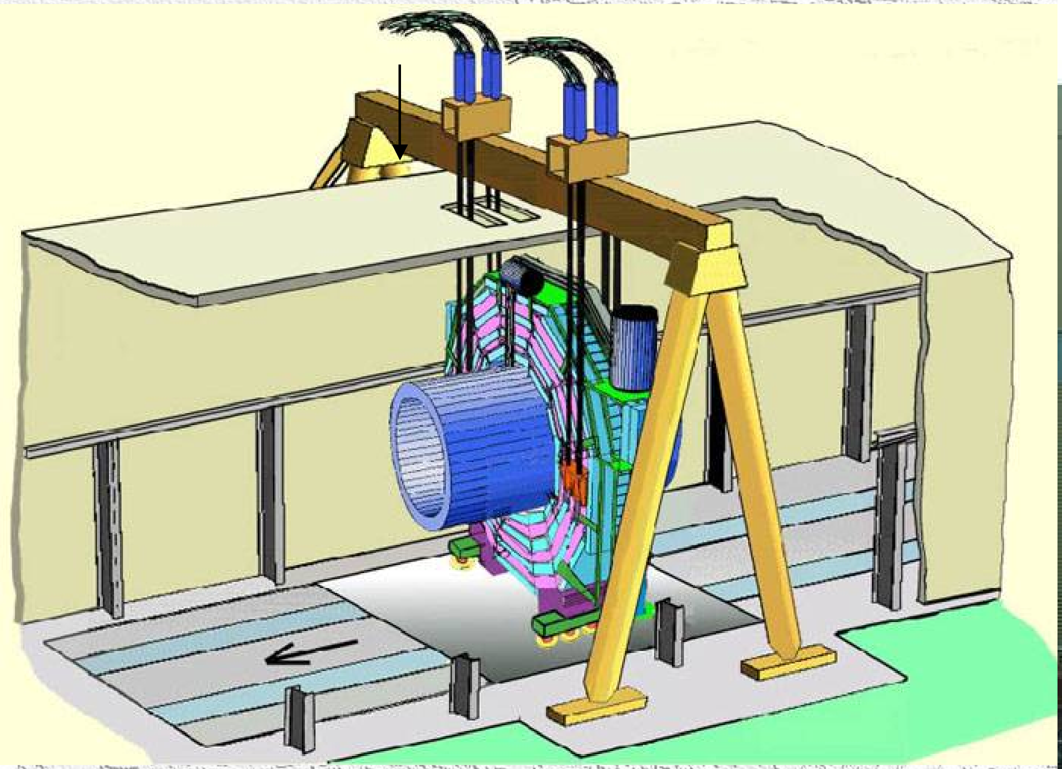
Layout of CMS

11 slices: 5 barrel and 2*3 endcaps



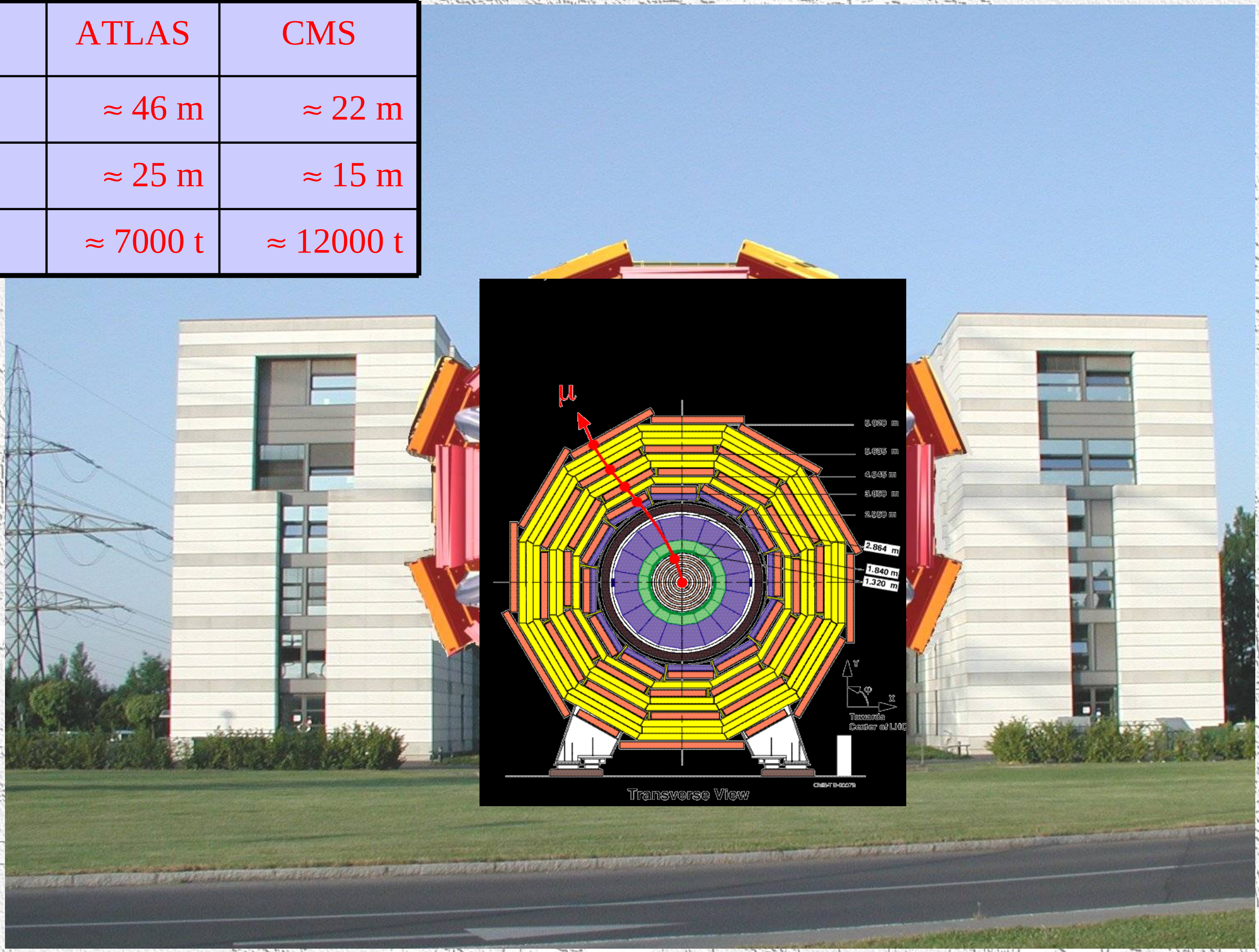
Lowering of CMS

Crane installed
Lowering starts in autumn 2006



Comparison of ATLAS and CMS

	ATLAS	CMS
length	≈ 46 m	≈ 22 m
diameter	≈ 25 m	≈ 15 m
weight	≈ 7000 t	≈ 12000 t



Comparison of ATLAS and CMS

Physics performance:
comparison in terms of mass resolutions

Table 8
Mass resolution for various states in the different experiments (at a luminosity of $2 \times 10^{33}\ \mathrm{cm^{-2}\,s^{-1}}$ in the case of ATLAS and CMS)

	ATLAS ($\mathrm{GeV}\,c^{-2}$)	CMS ($\mathrm{GeV}\,c^{-2}$)	LHCb ($\mathrm{GeV}\,c^{-2}$)	ALICE ($\mathrm{GeV}\,c^{-2}$)
$\mathrm{B} \to \pi\pi$	0.070	0.031	0.017	—
$\mathrm{B} \to J/\psi \mathrm{K_S^0}$	0.019	0.016	0.010	—
$\Upsilon \to \mu\mu$	0.152	0.050	—	0.107
$\mathrm{H}(130\ \mathrm{GeV}\,c^{-2}) \to \gamma\gamma$	1.55	0.90	—	—
$H(150\ \mathrm{GeV}\,c^{-2}) \to ZZ^* \to 4\mu$	1.60	1.35	—	—
$\mathrm{A}(500\ \mathrm{GeV}\,c^{-2}) \to \tau\tau$	50.0	75.0	—	—
$\mathrm{W} \to$ jet jet	8.0	10.0	—	—
$\mathrm{Z}'(3\ \mathrm{TeV}\,c^{-2}) \to \mu\mu$	240	170	—	—
$\mathrm{Z}'(1\ \mathrm{TeV}\,c^{-2}) \to \mathrm{ee}$	7.0	5.0	—	—

From T. Virdee, Phys. Rep. 403-404 (2004) 401

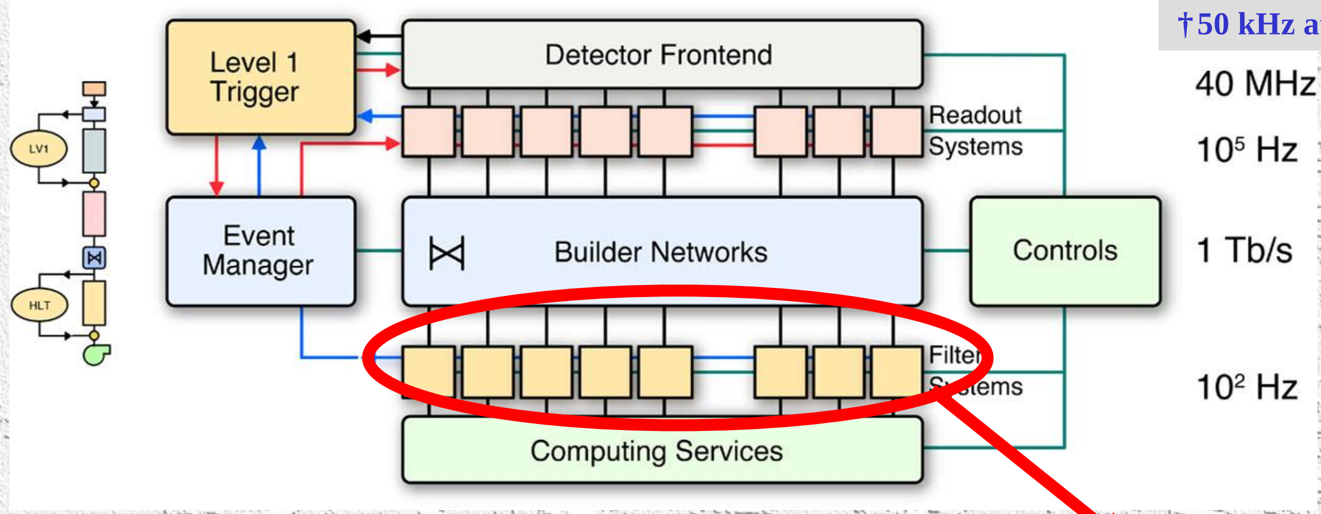
Trigger & DAQ system

Similar design for ATLAS & CMS

Example CMS:

Collision rate	40 MHz
Level-1 max. trigger rate	100 kHz†
Average event size	≈ 1 Mbyte

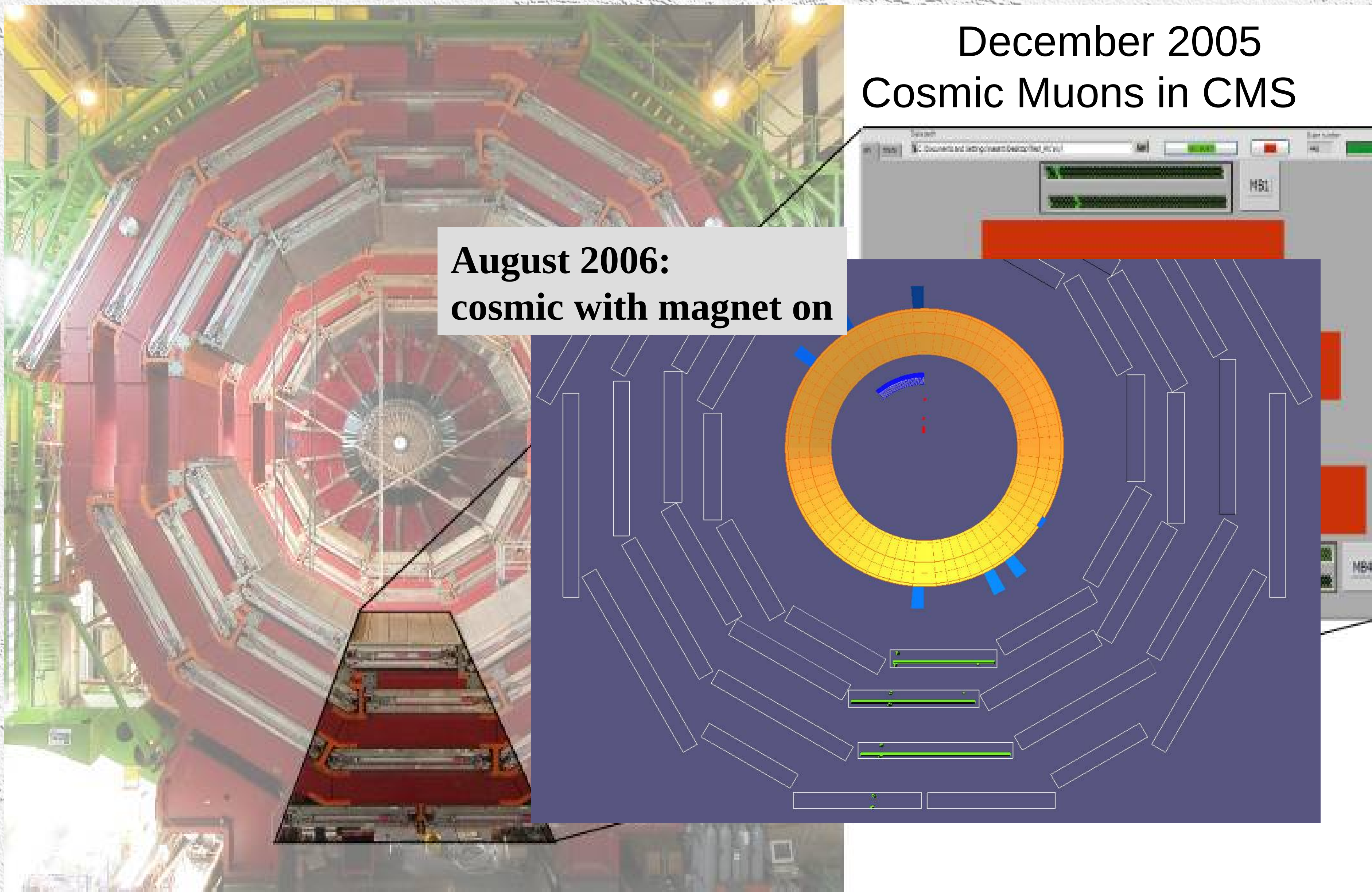
†50 kHz at startup (DAQ staging)



Filter farm:
- approx. 2000 CPUs
- easily scaleable
- staged (lower lumi & saves money)
- uses offline software

The longest journey starts with the first step…

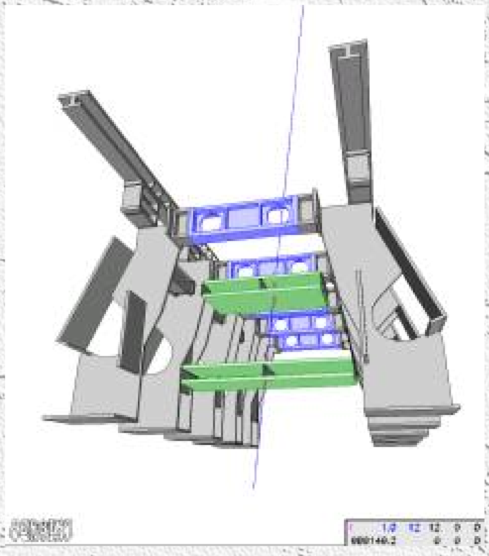
Cosmic data taking with assembled detector components…

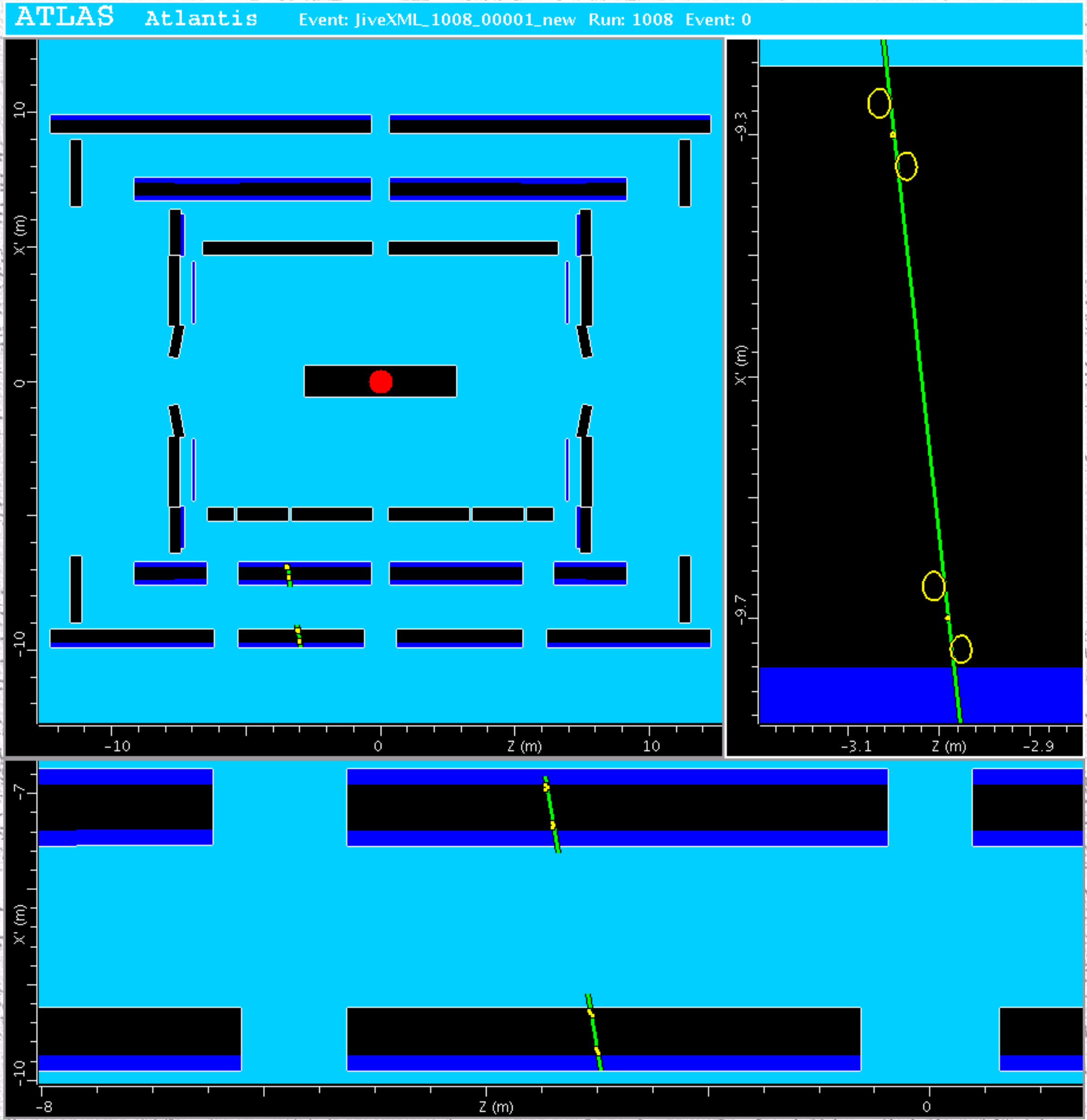


Cosmic Data Taking ATLAS

Just before Christmas:

First cosmics muons registered in the stations installed in the bottom sector of the spectrometer





Possible LHC Schedule

2007 LHC startup
- single beam operation
- collisions: pilot run with low luminosity, $\approx$ 1 month
- at low beam energy: 450 GeV, perhaps up to $\approx$ 1 TeV

2008 first physics year
- at 7 TeV proton energy
- try to reach 10^{33}/cm^2/s
- 1 -10 fb^{-1}

2008 - 2010 three years at 1 - 2$\cdot 10^{33}$/cm^2/s
- $\geq$ 30 fb^{-1} in total
- important for precision physics and discoveries

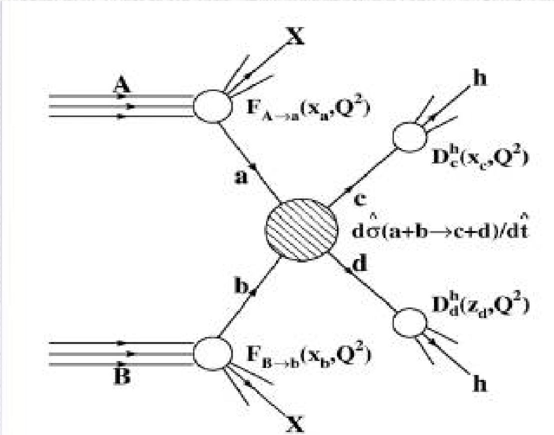
$\geq$ 2011 high luminosity running at 10^{34}/cm^2/s
- 100 fb^{-1} per year

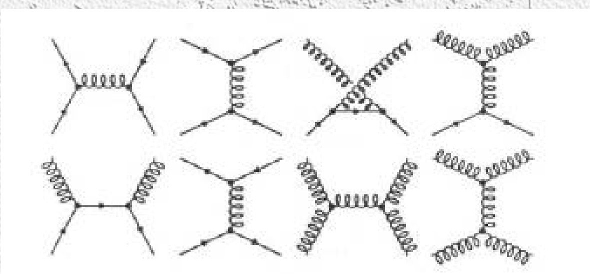
2015 Upgrade to Super LHC 10^{35}/cm^2/s
- under discussion
- requires major machine and detector upgrades

Standard Model Physics

Not a complete survey
Just a few examples of
- Tevatron results and
- LHC prospects
on QCD, W&Z bosons
and top physics

QCD and Jet Physics





Hard scattering processes dominated by QCD jet production

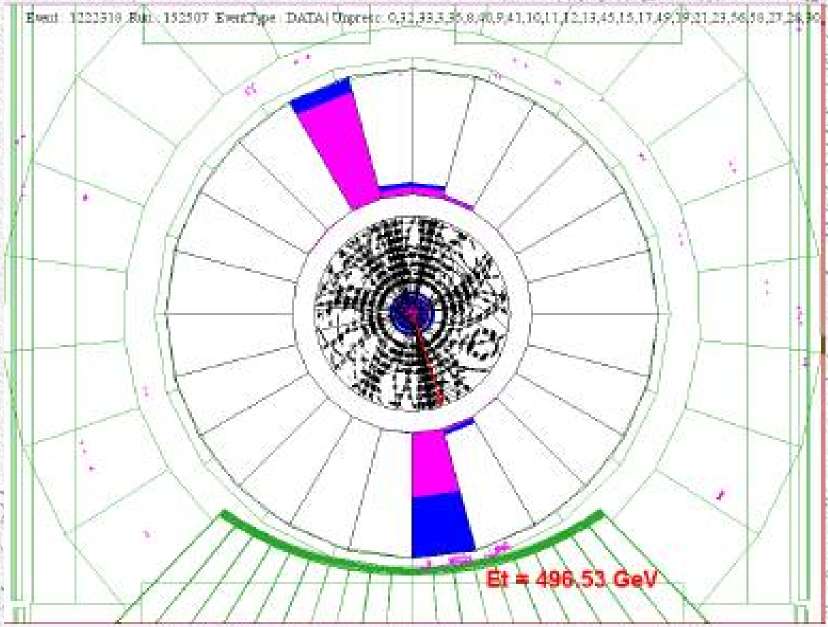
Originating from quark-quark, quark-gluon and gluon-gluon scattering

colored objects fragment
→ observation of jets with high p_T in the detectors

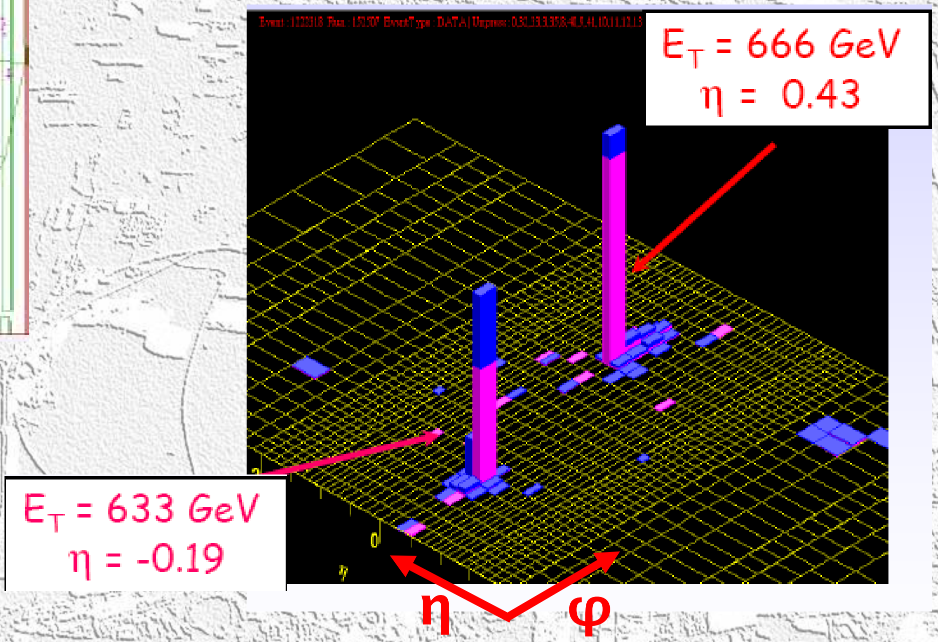
Studies of jet production is important
- test of the experiment
- test of the theory, down to the smallest distances
- new physics, e.g. quark substructure?

QCD and Jet Physics

A two-jet event at the Tevatron (CDF)



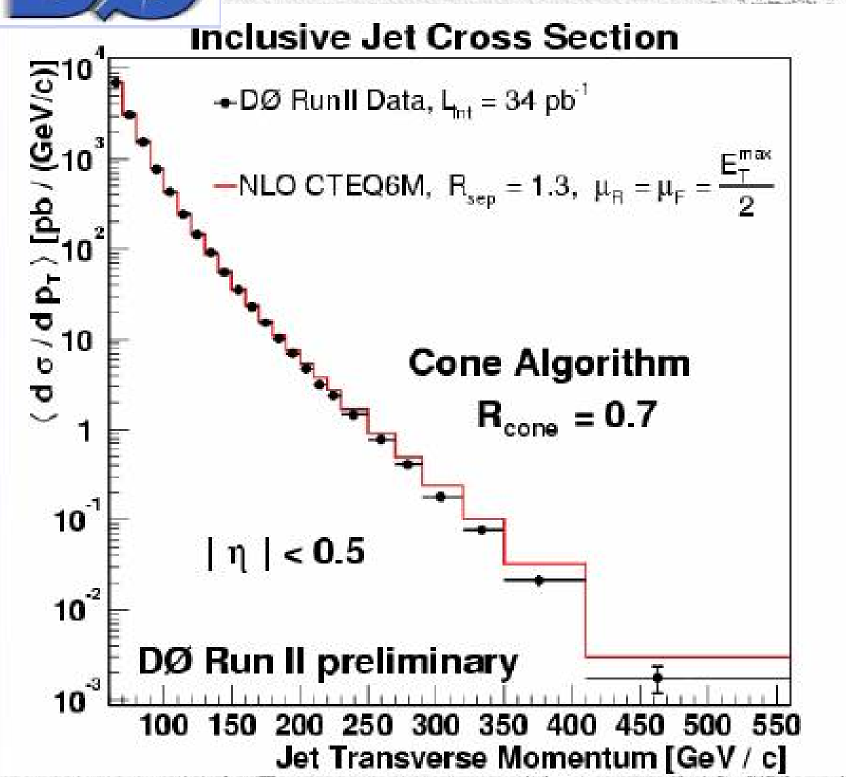
Lego-plot:
- project objects on ηφ-plane
- height of tower ~ energy



Mass of the di-jet system:

1.364 TeV

QCD and Jet Physics



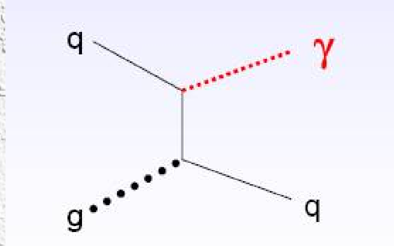
Measured jet cross section versus ET:
- comparison to theory
- good agreement
  over many orders of magnitude

theoretical errors
- QCD higher order (difficult)
- pdf
  measurement can be used to check pdf

experimental errors
- jet energy scale

A jet is not a very well defined object:
- need algorithm to define it
- relation to parton energy → correction
- pile-up

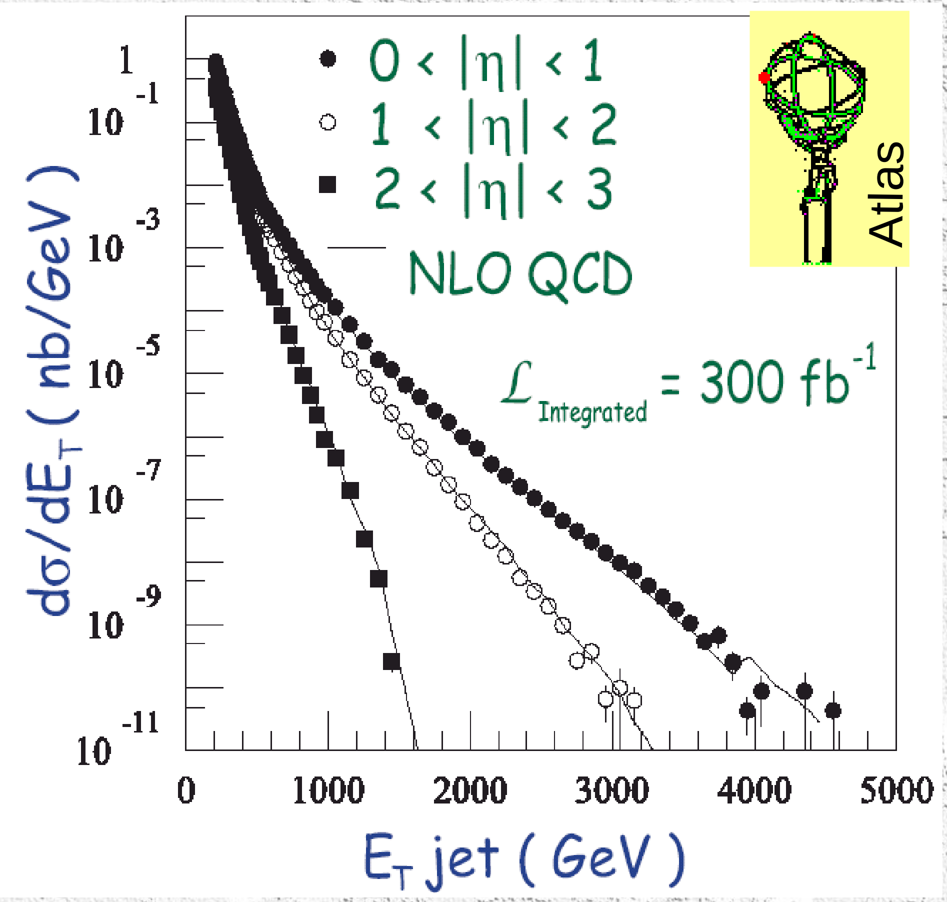
Calibration processes: γ+jet



Jet Physics

Jet physics at the LHC

- **E_T spectrum, rate varies over 11 orders of magnitude**
- **Test QCD at the multi-TeV scale**

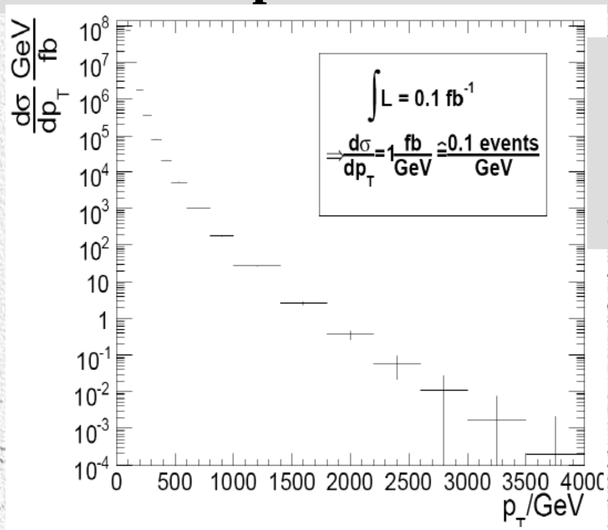


Inclusive jet rates for 300 fb^{-1}:

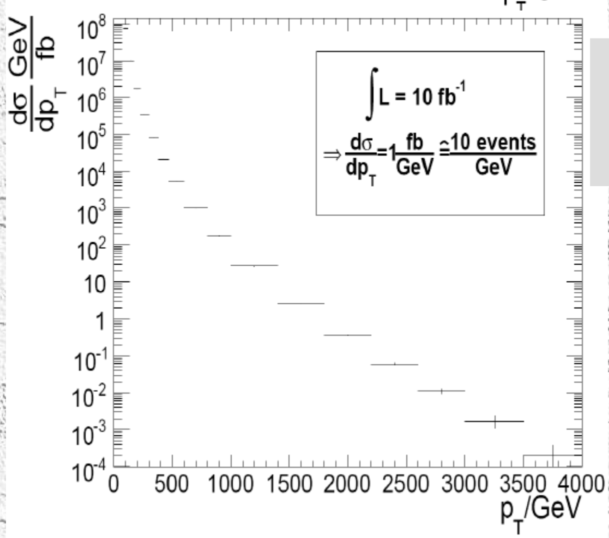
E_T of jet	Events
> 1 TeV	$4 \cdot 10^6$
> 2 TeV	$3 \cdot 10^4$
> 3 TeV	400

LHC Jet Physics

Jet rates will be one of the first LHC result:
statistical precision

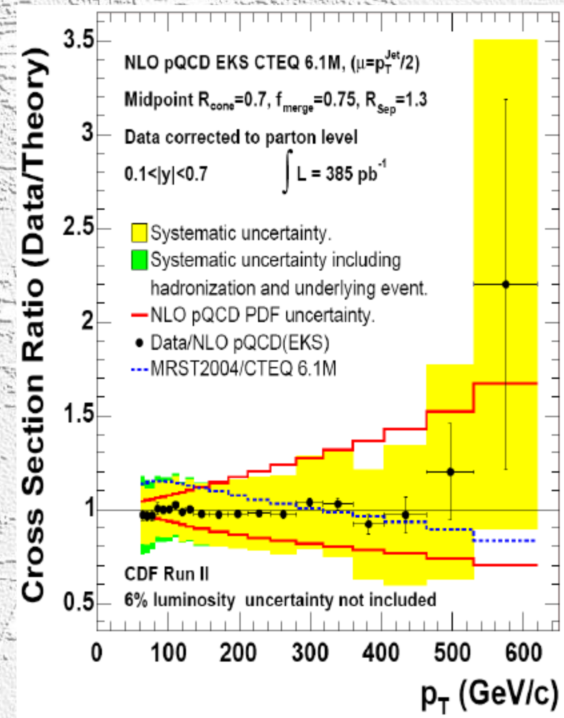


100 pb-1
= few weeks
at 14 TeV



10 fb-1
= 1 year

compare to CDF result run II



detector systematic effects expected to be similar to Tevatron

QCD

Measurement of α_s at LHC limited by

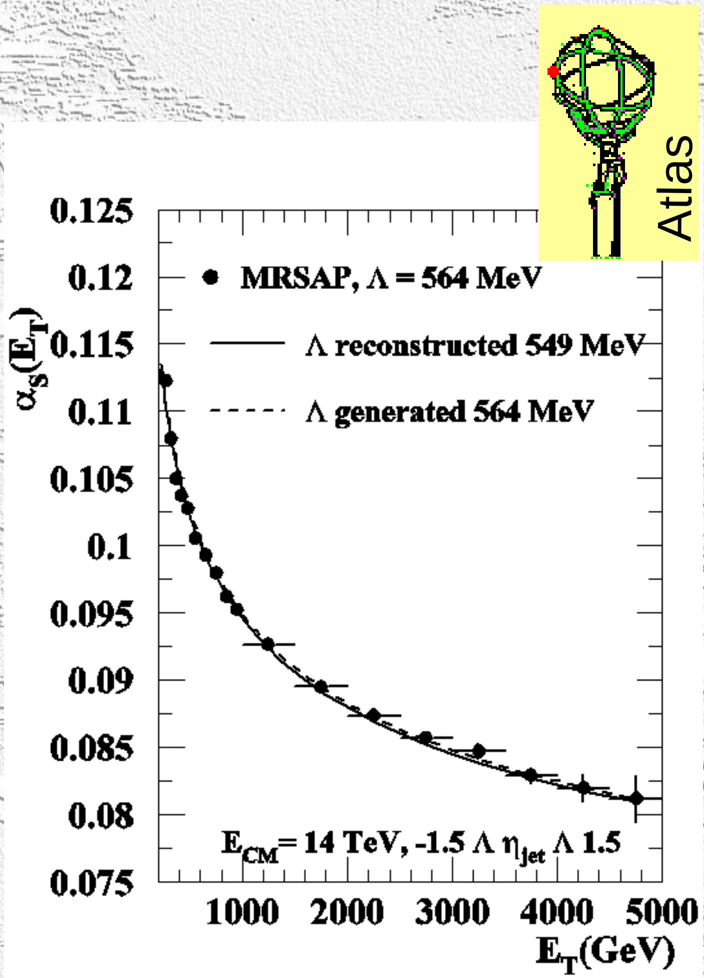
PDF (3%)
Renormalisation & factorisation scale (7%)
Parametrisaton (A,B)

$$\frac{d\sigma}{dE_T} \sim \alpha_S^2(\mu_R) A(E_T) + \alpha_S^3(\mu_R) B(E_T)$$

10% accuracy $\alpha_s(m_Z)$ from incl. jets
Improvement from 3-jet to 2-jet rate?

Verification of running of α_s and test of QCD at the smallest distance scale

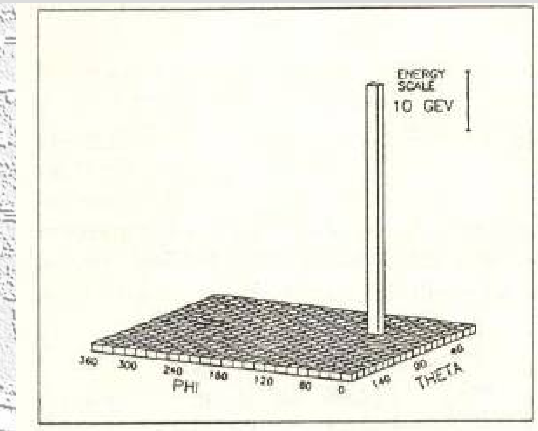
α_s = 0.118 at m_Z
$\alpha_s \approx$ 0.082 at 4 TeV (QCD expectation)

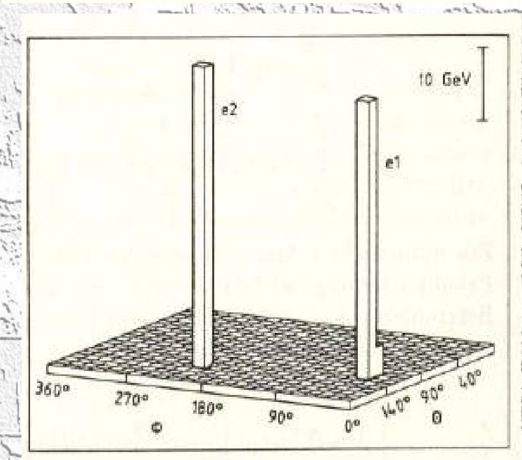


Electroweak Physics (W and Z Bosons)

W and Z bosons were discovered in proton-antiproton collisions
1983: UA1 & UA2 at the SppS collider at CERN

Examples of early W/Z events





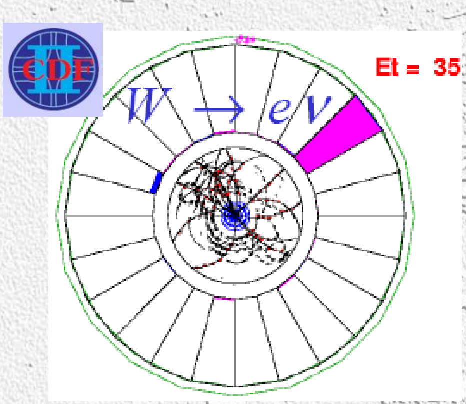
How do W/Z events look like at proton colliders?

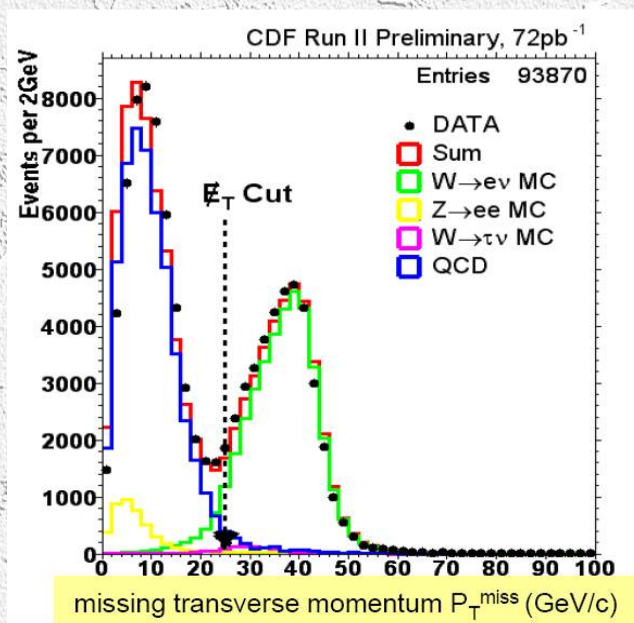
Use leptonic decays (electrons & muons)

$W \to l\nu$	**high p_T lepton + missing E_T**
$Z \to ll$	**2 oppositely charged, high p_T leptons**

W and Z Bosons

Example from the Tevatron:





Electrons

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

Z → ee

- 70 GeV/c² < m_{ee} < 110 GeV/c²

W → eν

- Missing transverse momentum > 25 GeV/c

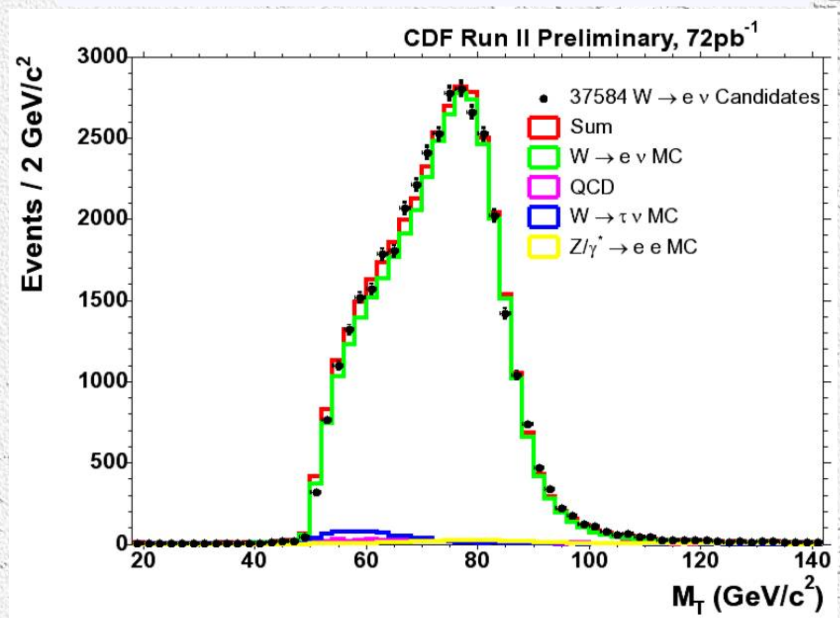
Separation of W → lν events from background

Mass of the W

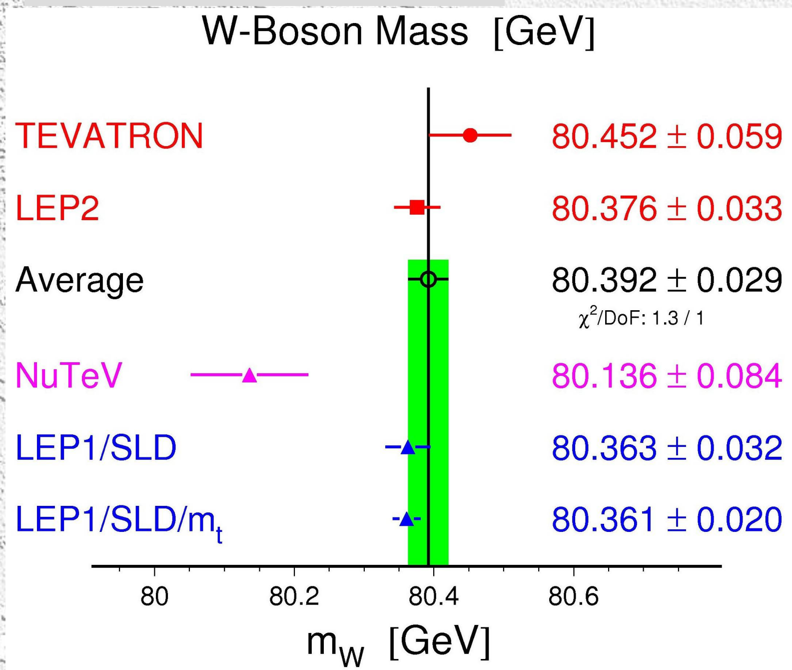
precision measurement at proton colliders possible
results competitive to LEP experiments

define transverse mass from missing E_T

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



Latest results on m_W



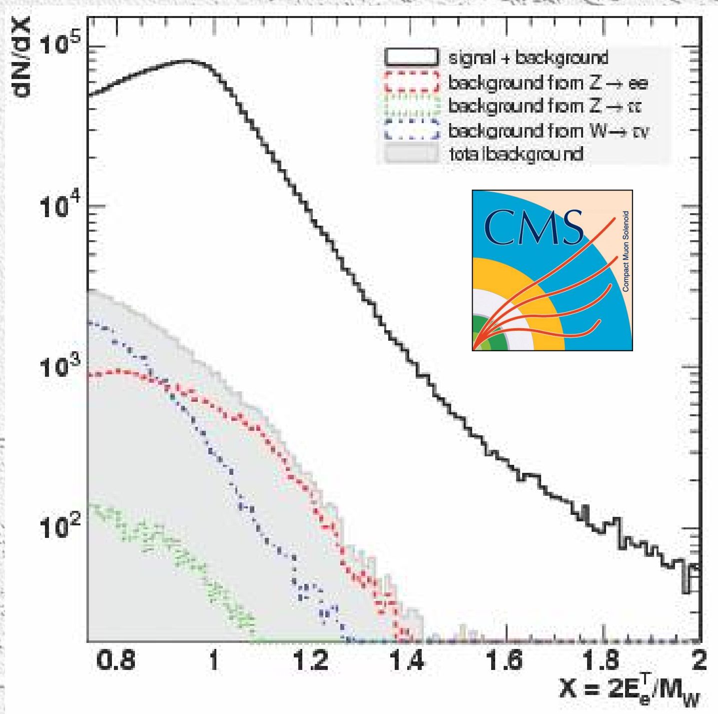
$4 \cdot 10^{-4}$ rel. precision on m_W

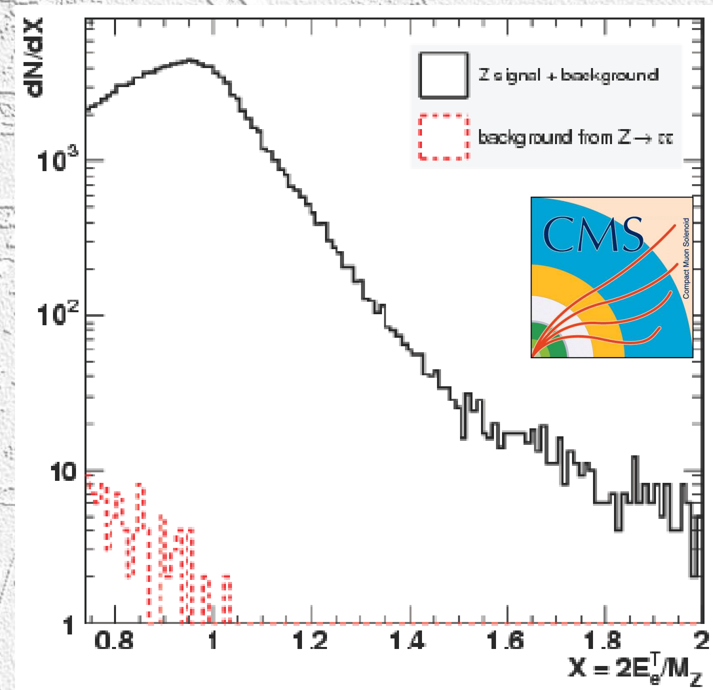
Tevatron results will improve with increasing Run II statistics

main challenge: electron/muon energy scale
use Z→ee, μμ events and precise m_Z from LEP

W/Z Physics at the LHC

Very clean selection of W and Z boson possible
e.g. CMS study of W→ eν and Z → ee





Recall rates (initial phase 10^{33}/cm^2/s):
≈ 200 W/s → ≈ 20 W→eν /s
≈ 50 Z/s → ≈ 1.5 Z → ee /s
plus the same rates for muon decays!

W and Z events will provide an excellent tool for detector calibration

W Mass at the LHC

Any improvement at the LHC requires control of systematic error to 10^{-4} level

take advantage from large statistics $Z \to e^+e^-, \mu^+\mu^-$

most experimental and theoretical uncertainties cancel in W/Z ratio

e.g. Scaled Observable Method

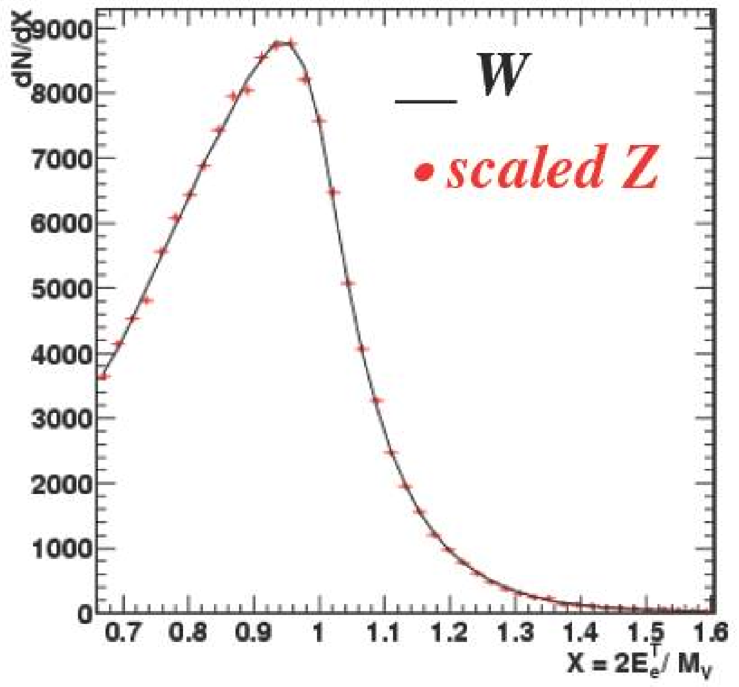
$O_V = E^T, M^T$ distributions are scaled according to

$$\boxed{\frac{d\sigma^W}{dO_W}(O_W = XM_W) = \frac{M_Z}{M_W} R(X) \frac{d\sigma^Z}{dO_Z}(O_Z = XM_Z)}$$

T.Giele, S.Keller, PR D57 (1998)

$$R(X) = \frac{d\sigma^W / dX_W}{d\sigma^Z / dX_Z}$$

NNLO calculations (p_T spectra) probably needed to achieve the required precision



W Mass at the LHC

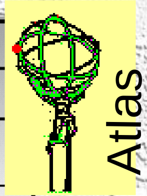
CMS: detailed study of statistical and systematic errors
1 fb-1: early measurement
10 fb-1: asymptotic reach, best calibrated & understood detector, improved theory etc.

Source of uncertainty	uncertainty with 1 fb^{-1}	ΔM_W [MeV/c^2] with 1 fb^{-1}	uncertainty with 10 fb^{-1}	ΔM_W [MeV/c^2] with 10 fb^{-1}
scaled lepton-p_T method applied to W$\rightarrow e\nu$				
statistics		**40**		**15**
background	10%	10	2%	2
electron energy scale	0.25%	10	0.05%	2
scale linearity	0.00006/ GeV	30	<0.00002/ GeV	<10
energy resolution	8%	5	3%	2
MET scale	2%	15	<1.5%	<10
MET resolution	5%	9	<2.5%	< 5
recoil system	2%	15	<1.5%	<10
total instrumental		**40**		**<20**
PDF uncertainties		20		<10
Γ_W		15		<15
p_T^W		30		30 (or NNLO)
transformation method applied to W$\rightarrow \mu\nu$				
statistics		**40**		**15**
background	10%	4	2%	negligible
momentum scale	0.1%	14	<0.1%	<10
$1/p^T$ resolution	10%	30	<3%	<10
acceptance definition	η-resol.	19	$< \sigma_\eta$	<10
calorimeter E_T^{miss}, scale	2%	38	≤1%	<20
calorimeter E_T^{miss}, resolution	5%	30	<3%	<18
detector alignment		12	–	negligible
total instrumental		**64**		**<30**
PDF uncertainties		≈20		<10
Γ_W		10		< 10

W Mass at the LHC

ATLAS study:

Source	CDF Run Ib	ATLAS or CMS	$W \to l\,\nu$, one lepton species
	30K evts, 84 pb^{-1}	60M evts, 10fb^{-1}	
Statistics	**65 MeV**	**< 2 MeV**	
Lepton scale	**75 MeV**	**15 MeV**	most serious challenge
Energy resolution	25 MeV	5 MeV	known to 1.5% from Z peak
Recoil model	33 MeV	5 MeV	scales with Z statistics
W width	10 MeV	7 MeV	$\Delta\Gamma_W \approx 30$ MeV (Run II)
PDF	**15 MeV**	**10 MeV**	
Radiative decays	**20 MeV**	**<10 MeV**	(improved Theory calc)
$P_T(W)$	45 MeV	5 MeV	$P_T(Z)$ from data, $P_T(W)/P_T(Z)$ from theory
Background	5 MeV	5 MeV	
TOTAL	**113 MeV**	**≤ 25MeV**	Per expt, per lepton species



Combine both channels & both experiments

$\Rightarrow$ **$\Delta m_W \leq$ 15 MeV (LHC)**

Compare to

2006: $m_W = 80\,392 \pm 29$ MeV **LEP & Tevatron Run I/II**

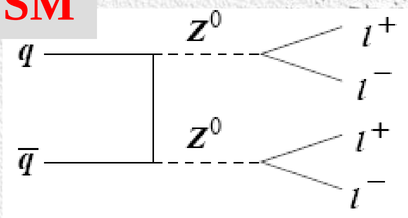
2007: $m_W \approx 80$ ... ± 20 MeV (2.5 $\cdot 10^{-4}$) **expected after Tevatron Run II**

Di-Boson Production at the LHC

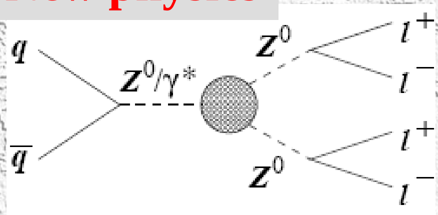
very interesting: WW,WZ,ZZ final states not yet observed at the Tevatron
test triple gauge boson couplings (TGC)

- γWW and ZWW precisely fixed in SM
- γZZ and ZZZ do not exist in SM!

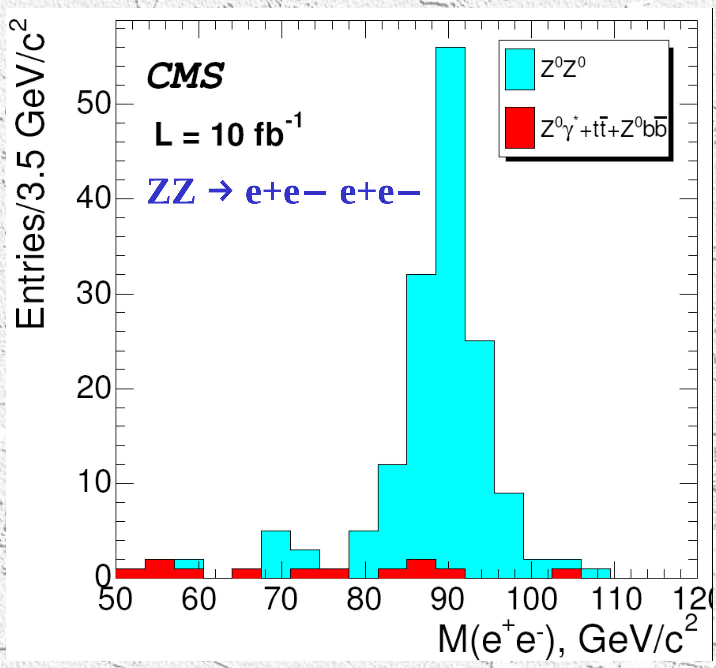
SM

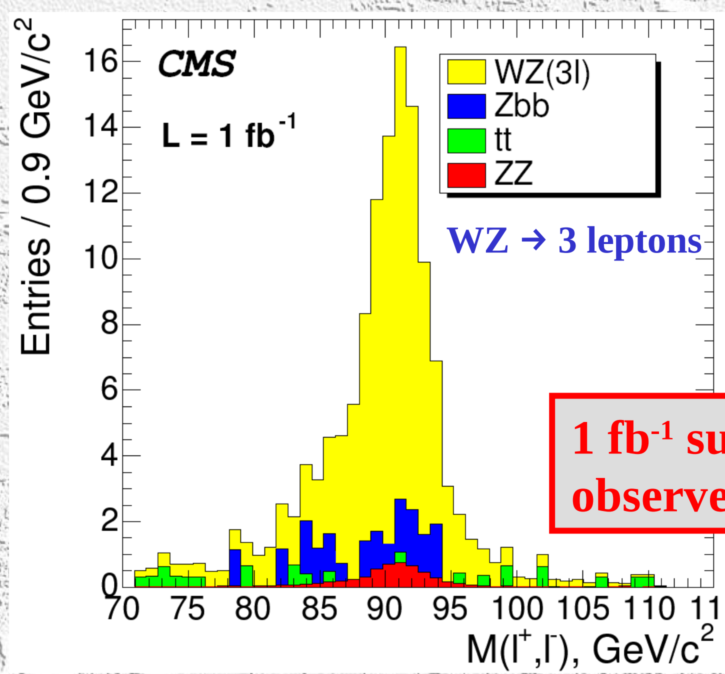


New physics



deviations from SM are amplified with E
also Wγ and Zγ final states can be used



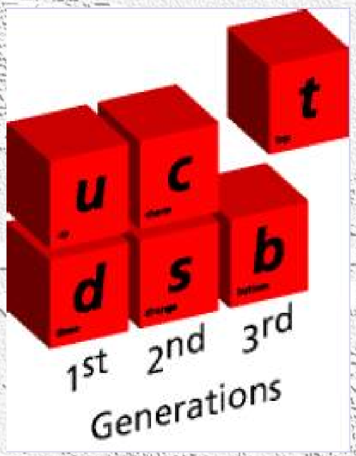


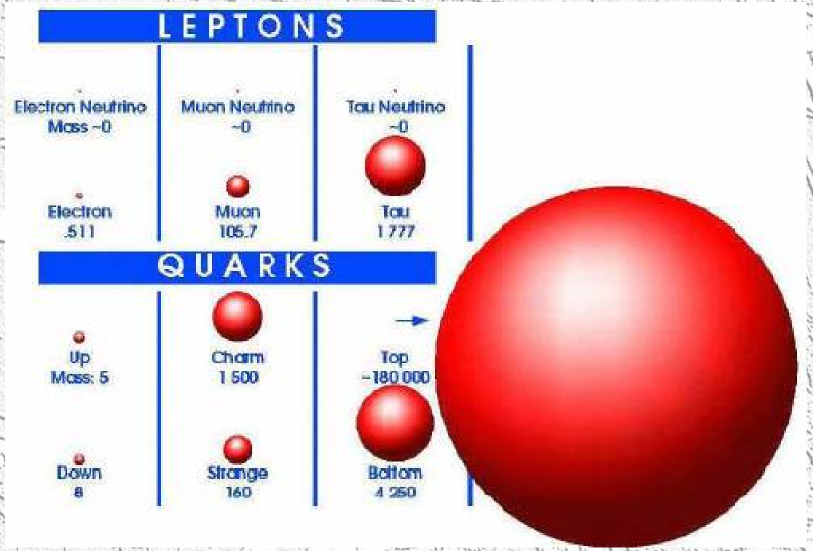
1 fb^{-1} sufficient to observe both processes

Top Physics

Why is the top quark so interesting special?

- by far the heaviest fermion
- could provide window to New Physics
  (mass generation)
- discovered 1995 at the Tevatron
  O(100) events observed in Run I
- still we know very little about it (mass)
  would like to measure all other properties
- top has a very short lifetime
  the <u>only</u> quark that decays before forming hadrons
  → can determine spin, polarisation from ist decay products

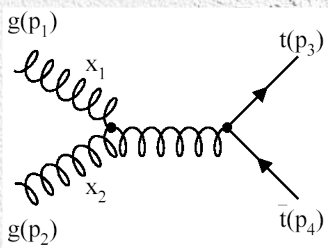


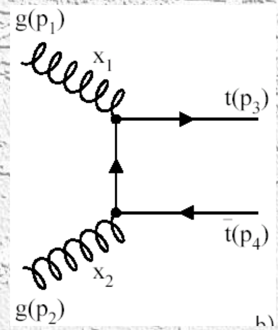


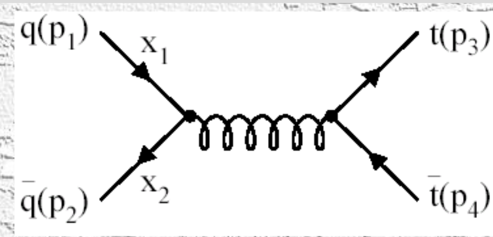
Top Quark Production

Top quarks are mainly produced in pairs (top-antitop) two main mechanisms:

gluon fusion **quark annihilation**







Tevatron: mainly quark annihihaltion O(90%)
LHC: mainly gluon fusion O(90%)

Cross sections:

≈ 7 pb (Tevatron)
≈ 800 pb (LHC)

→ approx. 1 $t\bar{t}$-pair per second at $10^{33}/cm^2/s$

LHC is a top factory!

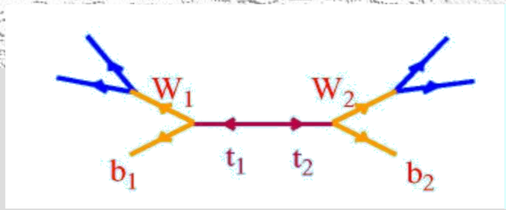
Top Quark Decay

Top decay: ≈ 100% t bW

Other rare SM decays:

- **CKM suppressed t sW, dW: $10^{-3} - 10^{-4}$ level**
- **t bWZ: $O(10^{-6})$**
- **difficult, but since $m_t \approx m_b + m_W + m_Z$ sensitive to m_t**

& non-SM decays, e.g. t bH$^+$

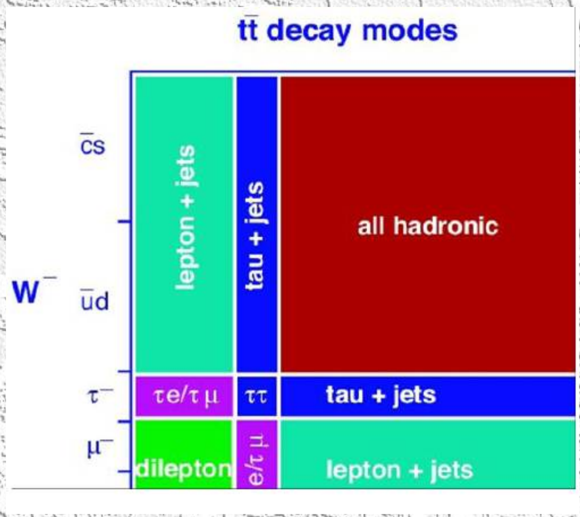


In SM topologies and branching ratios are fixed:

expect two b-quark jets

plus W+W- decay products:

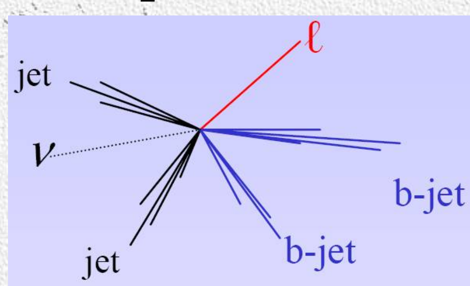
- **2 charged leptons + 2 neutrinos**
- **1 charged lepton + 1 neutrino + 2 jets**
- **4 jets (no b-quark!)**



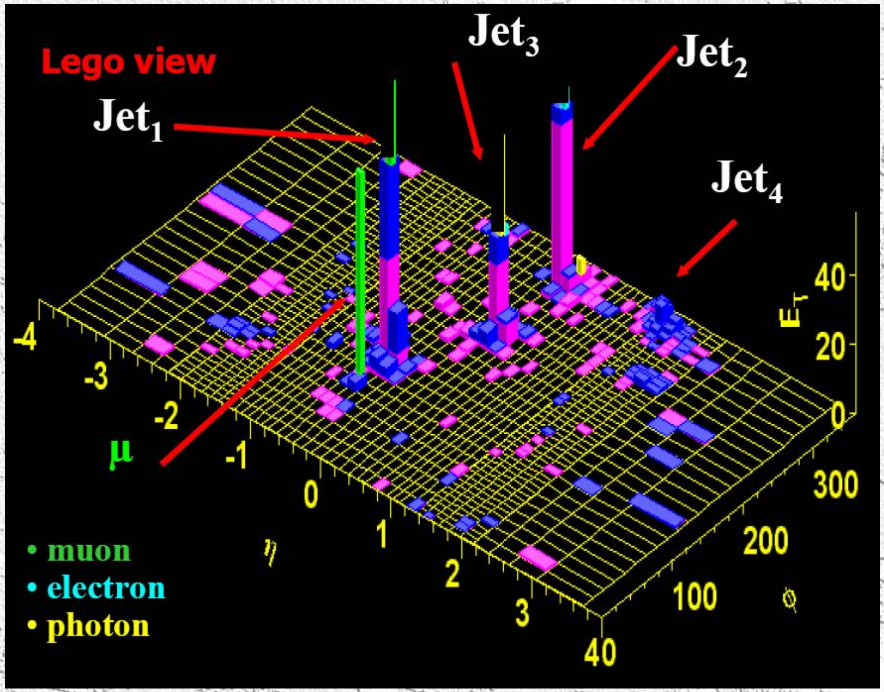
$t\bar{t} \rightarrow l\nu l\nu bb$	5%	$(e+\mu)$
$t\bar{t} \rightarrow l\nu qqbb$	30%	$(e+\mu)$
$t\bar{t} \rightarrow qqqqbb$	46%	

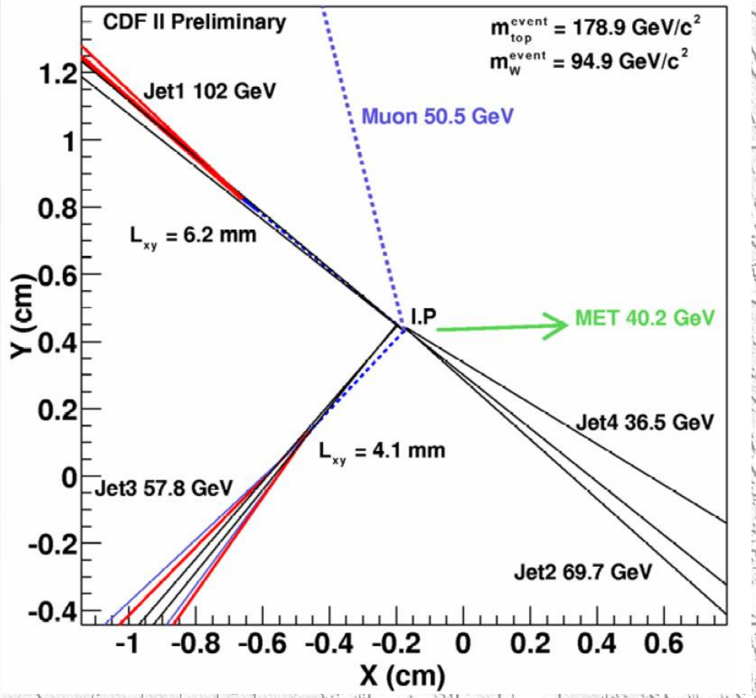
A Top-Pair Event at CDF

semi-leptonic channel



1 muon
1 neutrino (missing E_T)
2 light quark jets
2 b-quark jets
tagged by displaced vertices



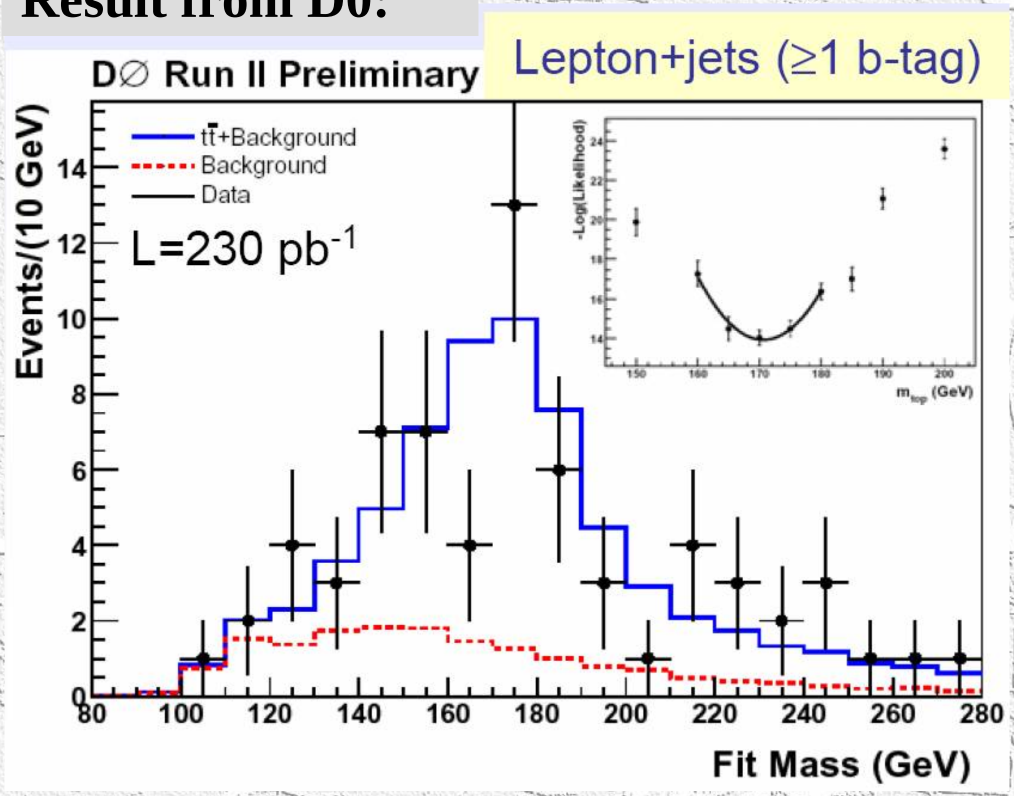


Top Mass Measurement

select top pair events
perform kinematic fit to improve resolution
use W mass to fix jet energy scale

perform maximum likelihood fit to all observed events

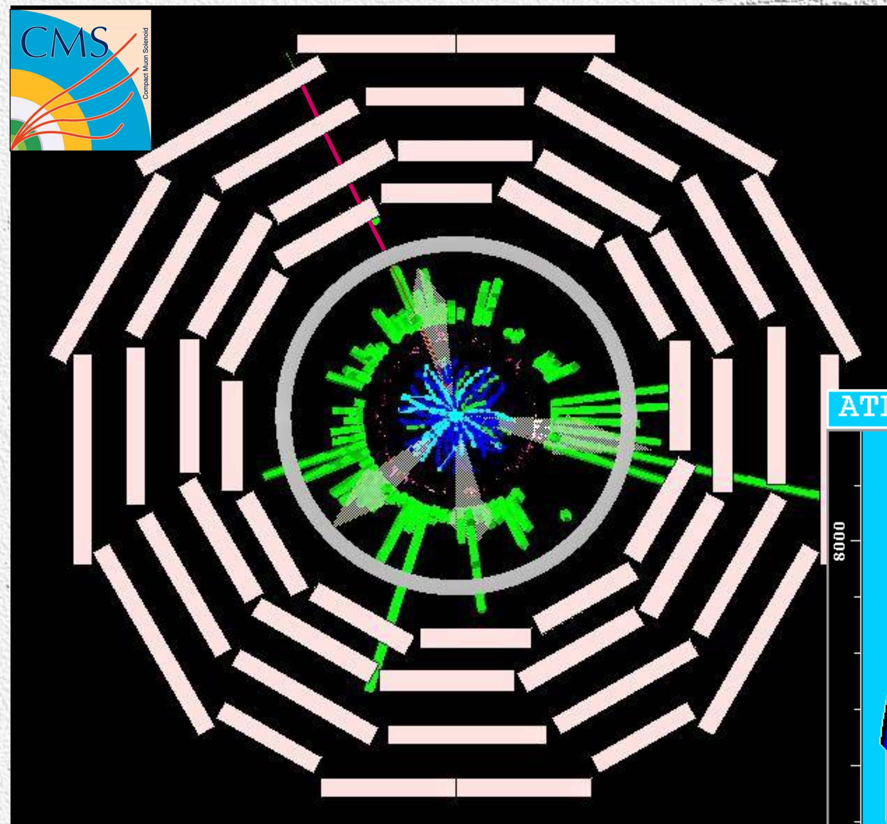
Result from D0:



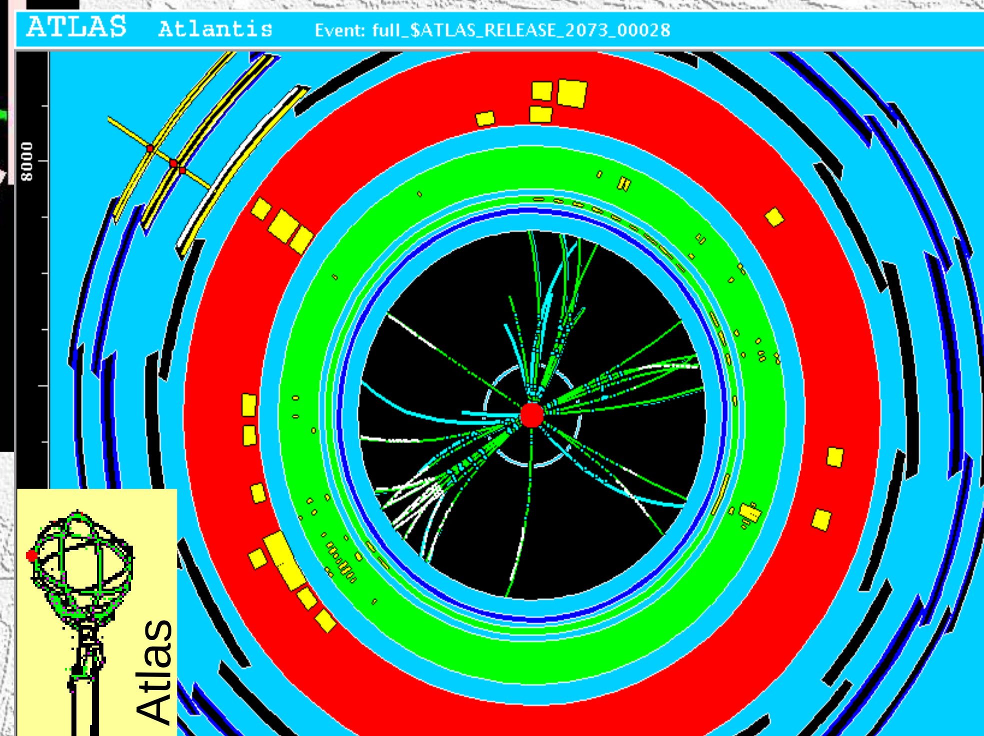
Combined Tevatron measurement

$m_t = 171.4 \pm 2.1$ GeV

Top Mass at the LHC



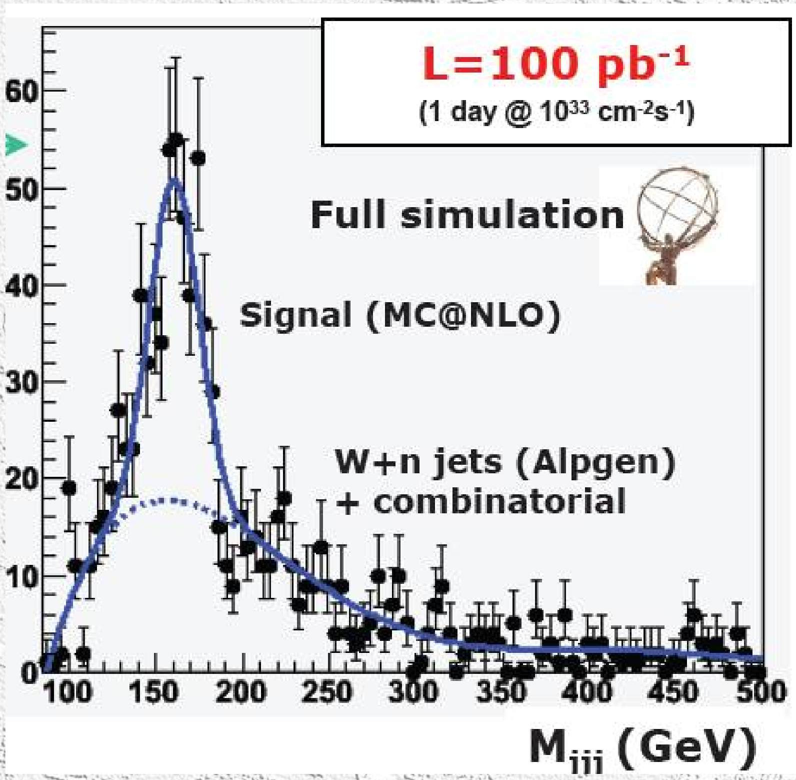
Examples of simulated
tt bb qq μν events
from CMS & ATLAS



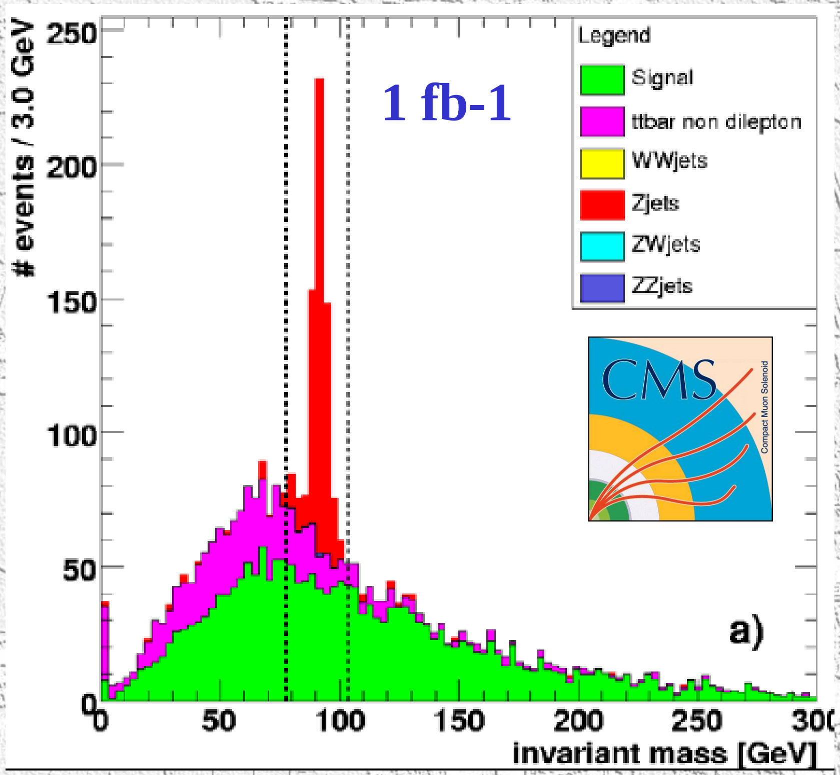
Top Mass at the LHC

Because of the high production rate results on m_t can be obtained with low/modest luminosity:

Semi-leptonic events



Di-leptonic events



Top Mass at the LHC

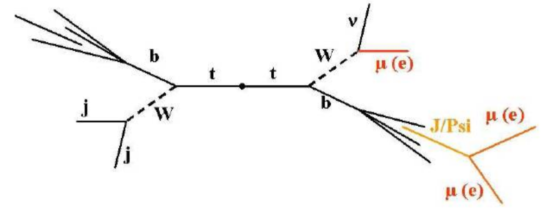
All decay topologies can be used:

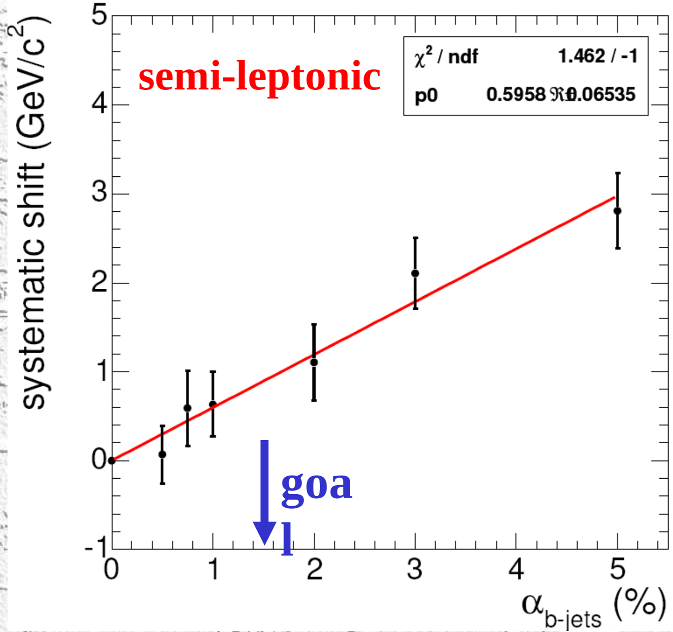
di-lepton events
kinematics underconstraint
but sensitive to m_t

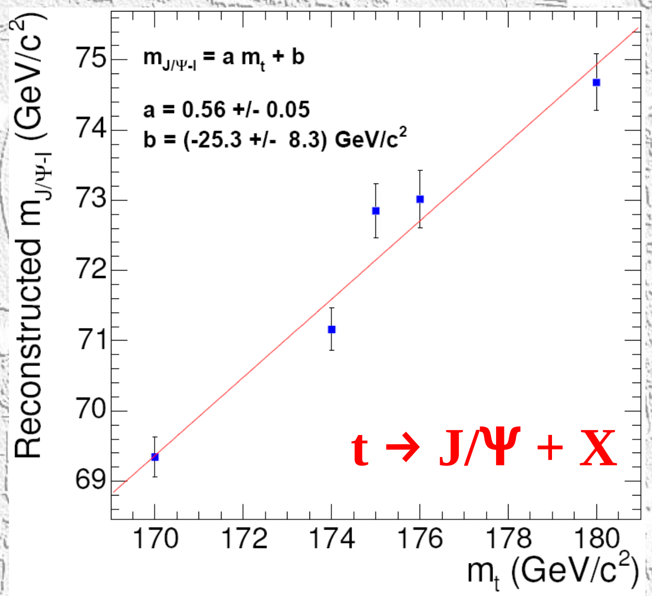
semi-leptonic events
golden channel, ideogramm method
limited by b-jet E-scale

fully hadronic top pairs
suffers from QCD and combinatorial background

exclusive t → J/Ψ + X decays
low stat., but different systematic
partial reconstruction J/ Ψ + lepton from W





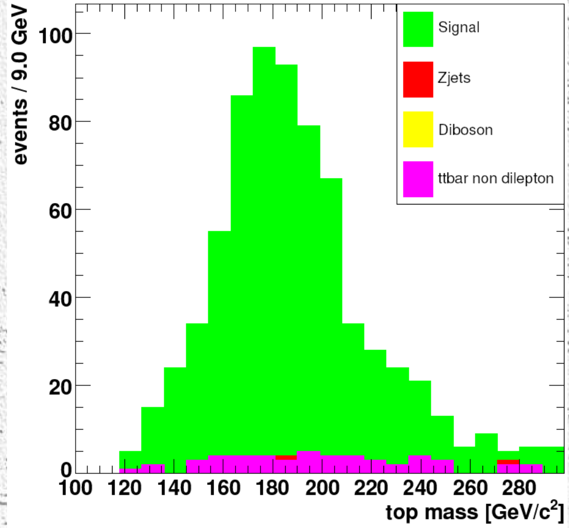


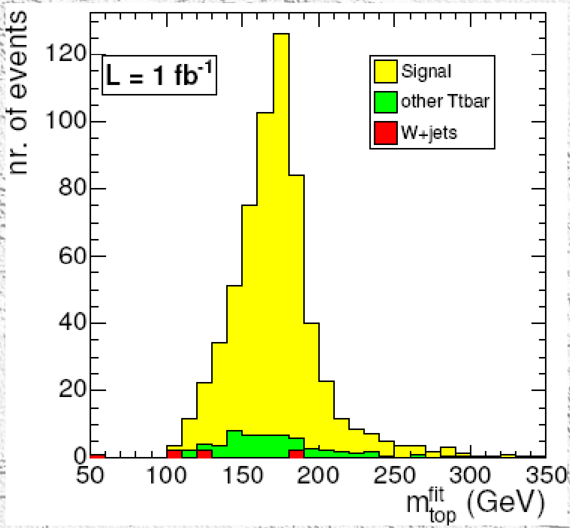
Top Mass at the LHC

Recent detailed studies by CMS:

di-leptonic

± 1.2 GeV



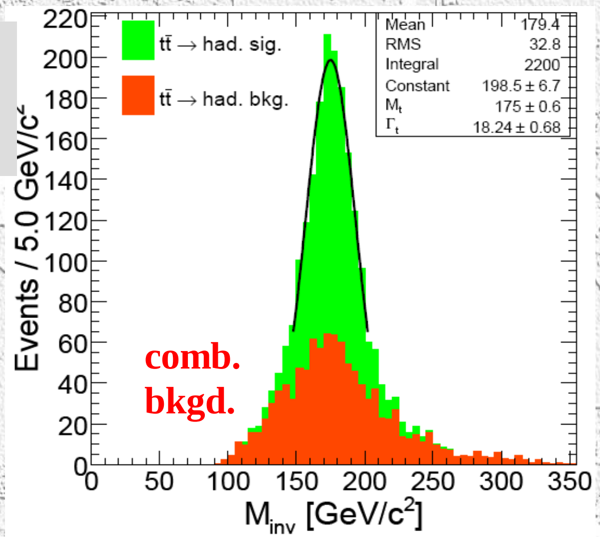


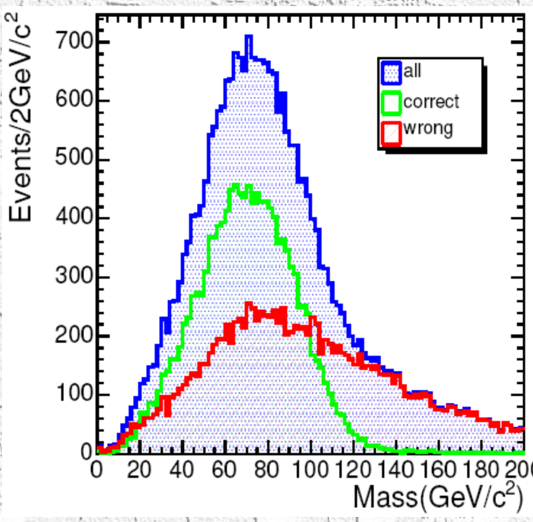
semi-leptonic

± 1.2 GeV

fully hadronic

± 2 GeV





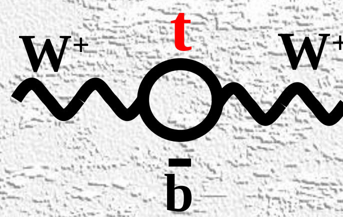
t→ J/Ψ + l + X

± 1.5 Ge

→ total top mass error ≤ 1 GeV possible with O(10 fb^{-1}) of well understood data

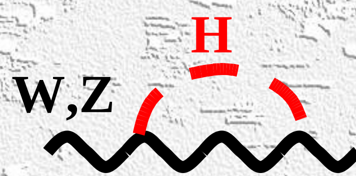
Importance of Top Mass

m_t enters quadratically in electroweak loop corrections

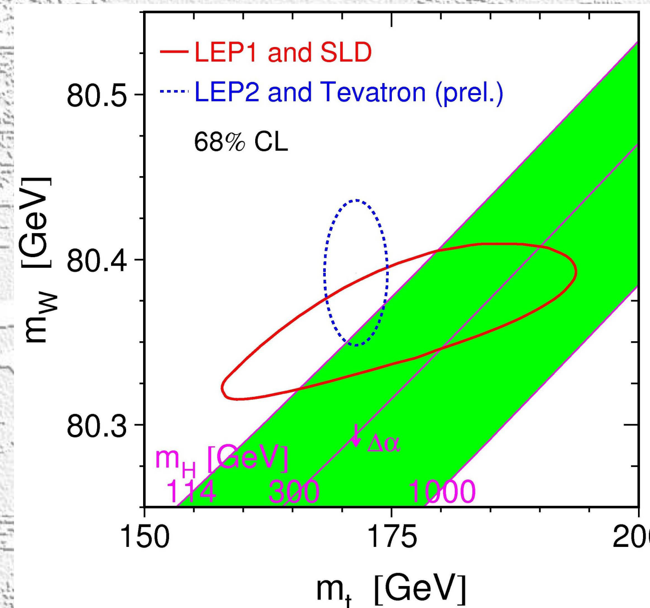


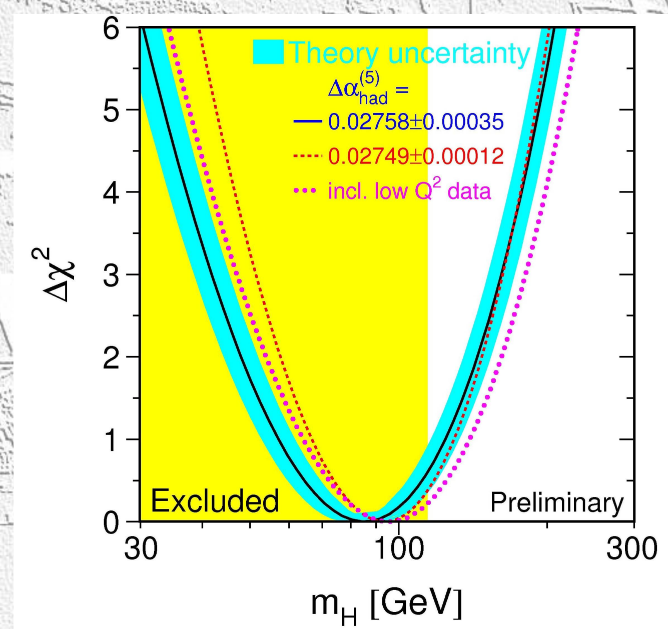
$\propto (m_t^2 - m_b^2)$

m_H only logarithmically



$\propto \log m_H/m_W$





All observables include the combined effect!

→ m_t plays a key role in precision test of the SM
to predict the Higgs mass
and once the Higgs is discovered to check the consistency of the model

Search for Higgs Bosons

Emphasis on SM Higgs

Standard Model Higgs Boson

What do we know today about the SM Higgs boson?

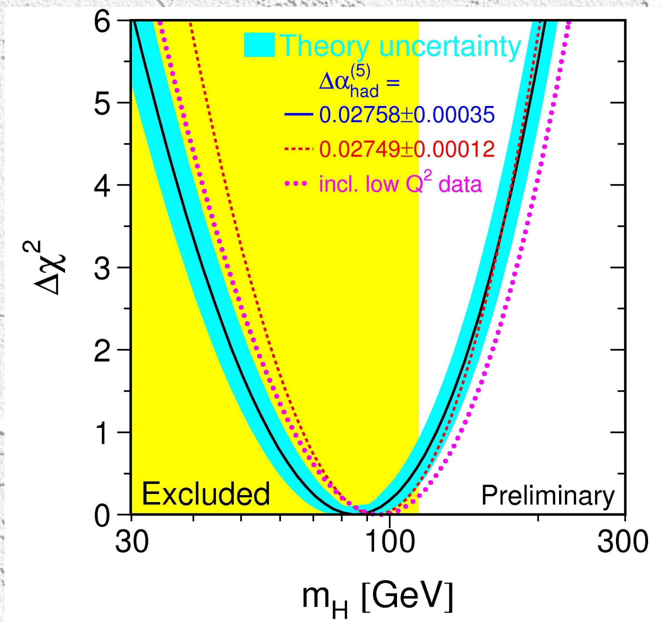
needed in the SM to accomodate masses (heavy gauge bosons and fermions)

mass is not predicted, except that $m_H < 1000$ GeV

direct searches at LEP

$m_H > 114.4$ GeV

electroweak precision measurements (incl. m_t measurement)

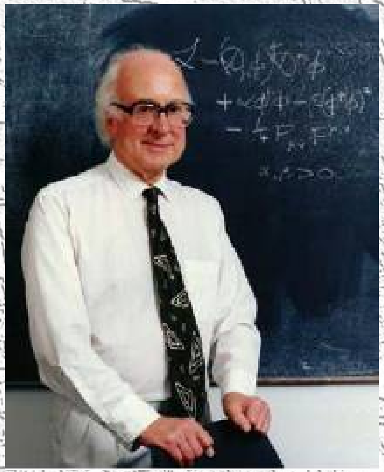


$$\log m_H/\mathrm{GeV} = 1.93^{+0.16}_{-0.17}$$

$$m_H = 85^{+39}_{-28}\ \mathrm{GeV}$$

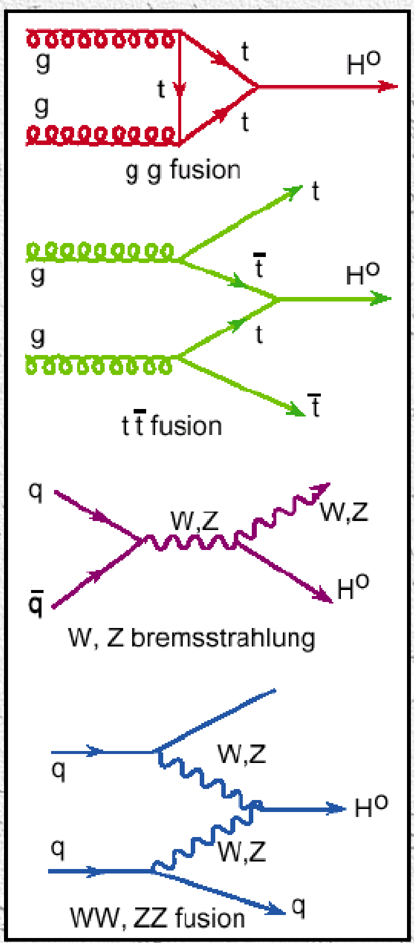
⇒ $m_H < 166$ GeV (95% CL)

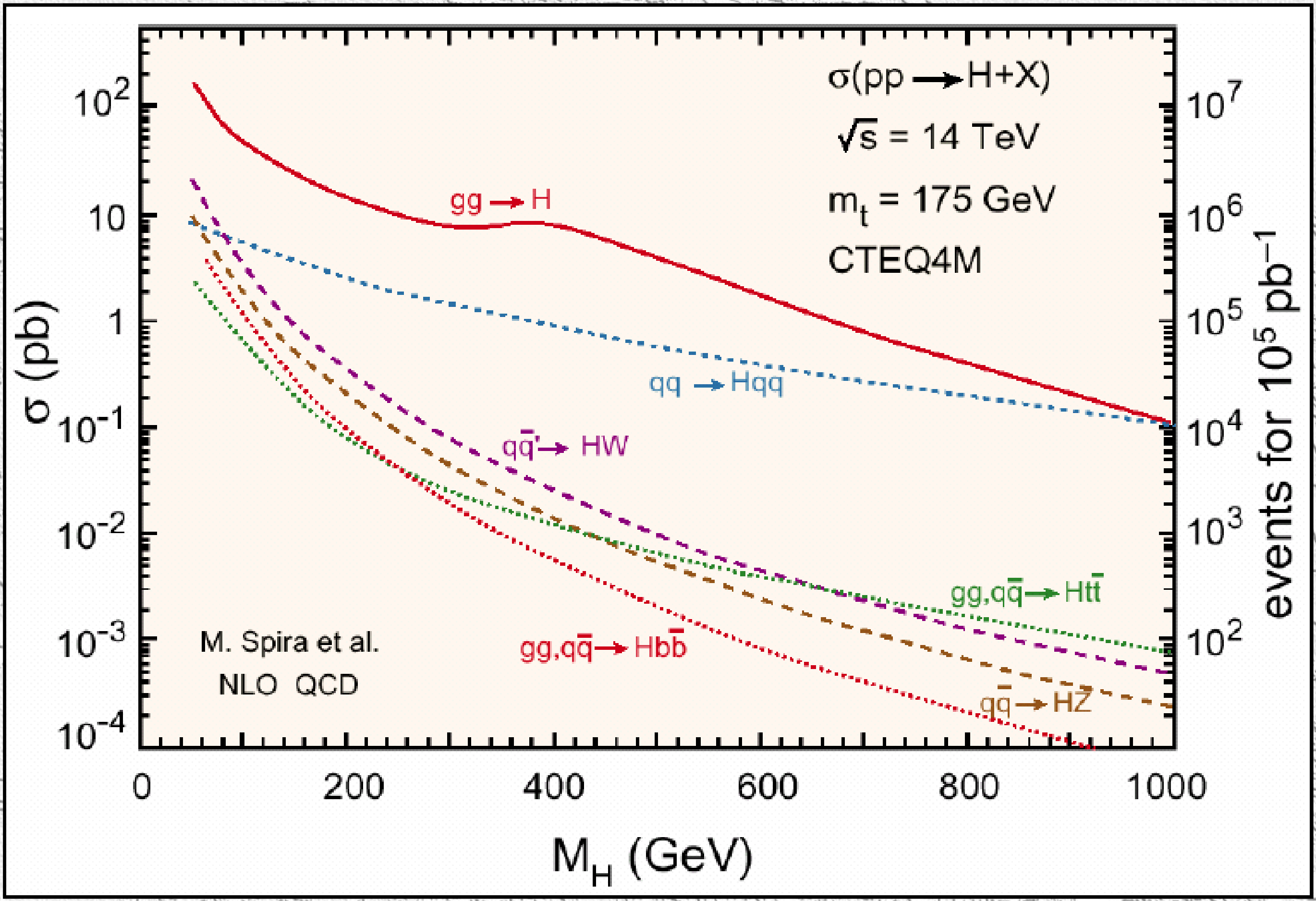
⇒ the Higgs should be around the corner!



Higgs Boson Production at the LHC

Once the mass is know all other Higgs properties are fixed!



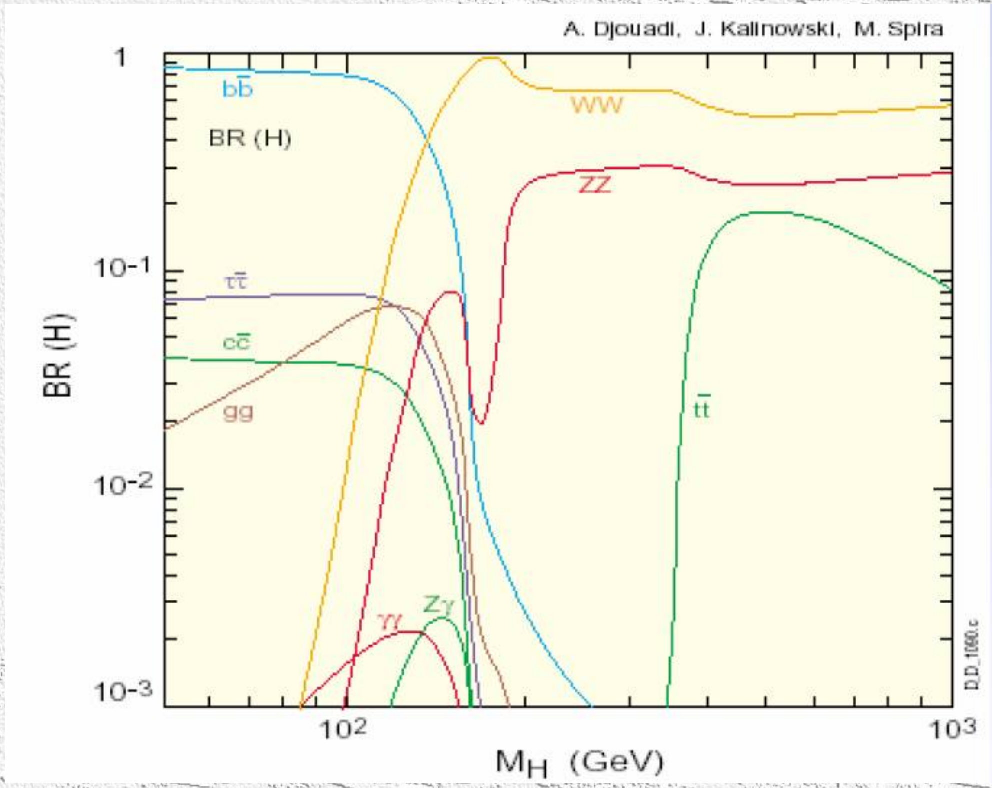


Gluon-gluon fusion and W, Z fusion are dominant
Cross section at the Tevatron almost factor 100 smaller!

Higgs Boson Decay

Higgs couples proportional to masses
⇒ preferentially decaying into heaviest particle kinematically allowed

Branching ratio versus m_H:



Low mass ($115 < m_H < 140$ GeV)
H → bb make up most of the decays problem at the LHC because of the huge QCD background !

Intermediate ($140 < m_H < 180$ GeV)
H → WW opens up
use leptonic W decay modes

High mass ($m_H > 180$ GeV)
H → ZZ → 4 leptons
golden channel!

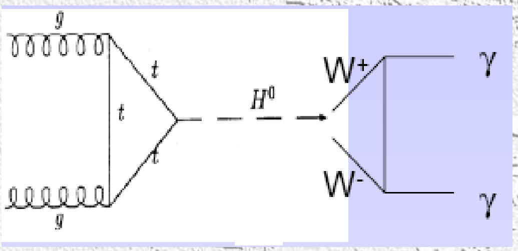
Higgs Boson Decay

What to do in the prefered low mass region, i.e. m_H < 140 GeV?

use H → γγ

very low branching ratio O(10^{-3})

but clean signature



internal loop with heavy charged particle
W boson or top quark

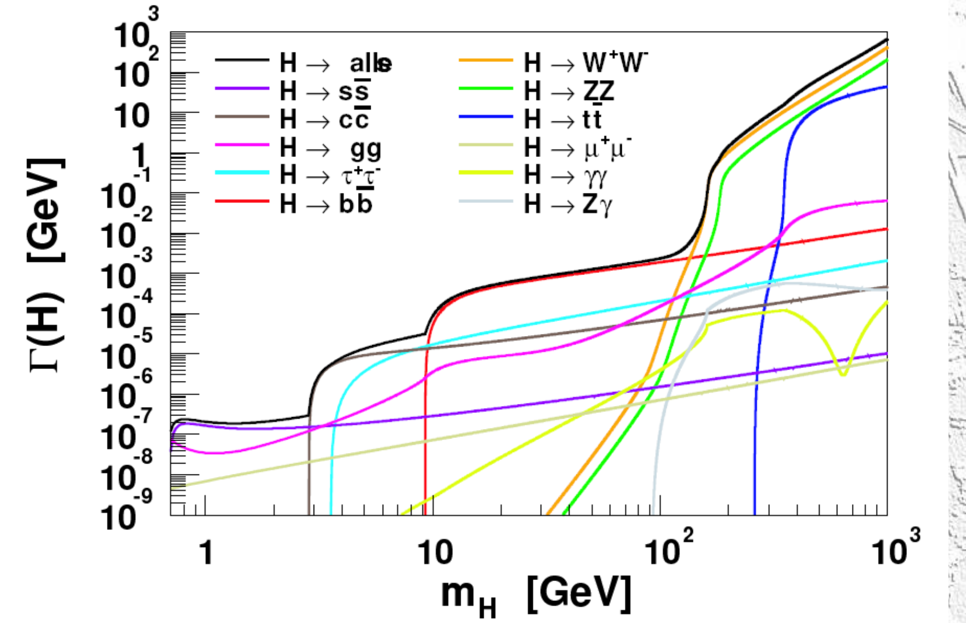
Total width of the Higgs (= inverse lifetime)

at low masses Higgs is a very sharp resonance

Γ_H << 1 MeV

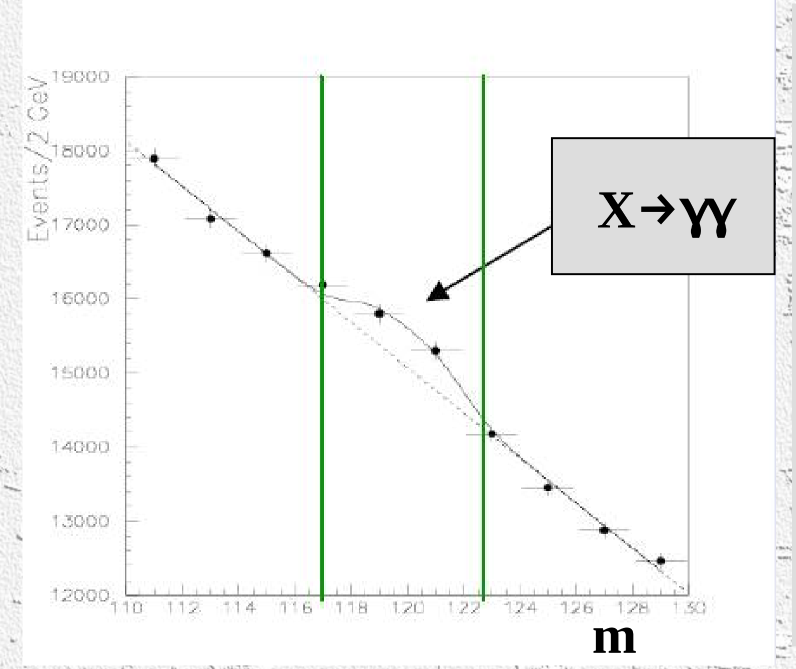
Γ_H explodes once H → WW, ZZ open up for m_H → 1 TeV

$\Gamma_H \approx m_H$



Higgs Discovery

How could we claim a Higgs discovery?
Suppose a narrow resonance decaying into 2 photons



Signal significance S:
count in signal region
(defined by Γ_X and resolution)
N_S number of signal events
N_B number of background events

$$S = N_S/\sqrt{N_B}$$

$\sqrt{N_B}$ fluctuation of background events
use Poisson for small N_B

Convention:
discovery if $S > 5$
Gaussian probability that background fluctuates up by more than 5 σ is 10^{-7}

Higgs Discovery

Two critical parameters to maximise S:

1. Improve, i.e. reduce, experimental resolution σ_m

if σ_m is worse by factor 2, N_B increases by factor 2

$\Rightarrow S = N_S/\sqrt{N_B}$ decreases by $1/\sqrt{2}$

$$\Rightarrow \; S \propto 1/\sqrt{\sigma_m}$$

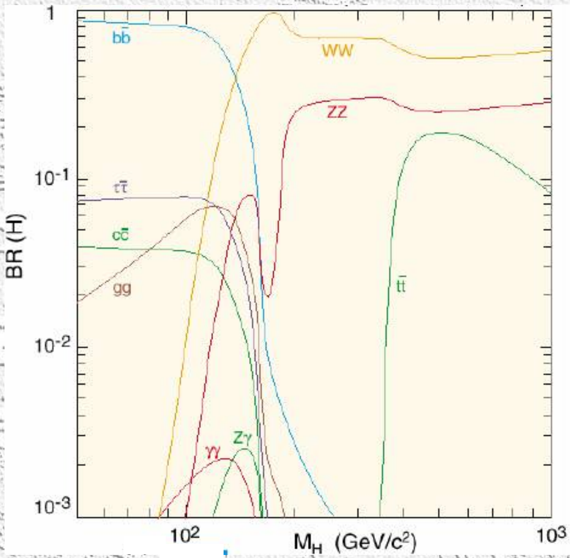
holds until $\sigma_m \approx \Gamma_X$

2. Luminosity

$N_S \propto L$ and $N_B \propto L$

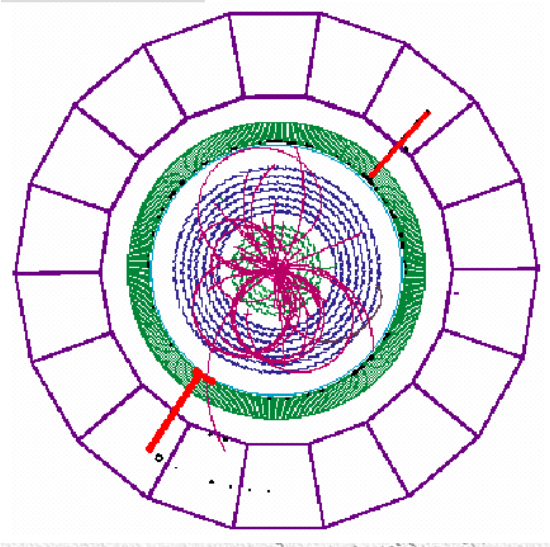
$$\Rightarrow \; S \propto \sqrt{L}$$

Search for the Higgs Boson

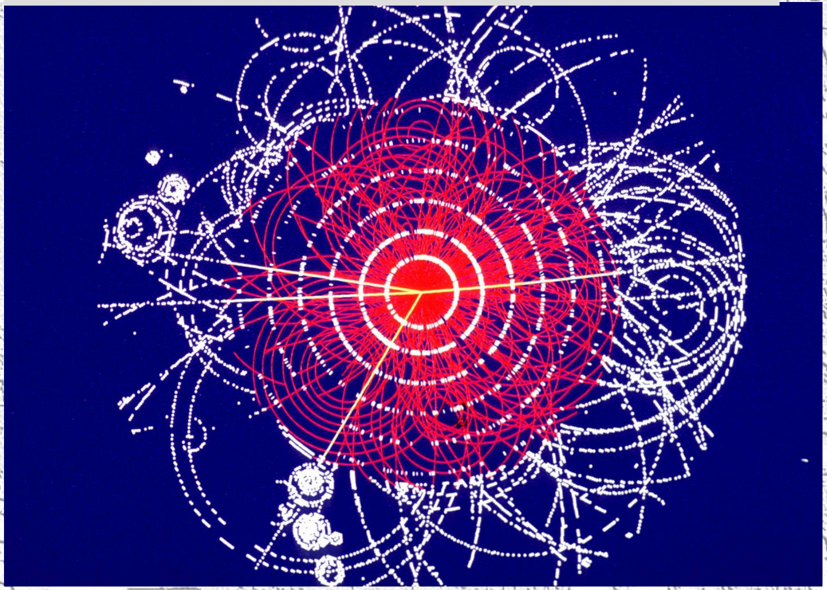


LEP:	LHC:	
$H \to bb$	$H \to bb$	enormous QCD bkgd
	$H \to \gamma\gamma$	low m_H (BR $\approx 10^{-3}$)
	$H \to W^+W^-$	medium m_H
	$H \to ZZ$	high m_H

$H \to \gamma\gamma$



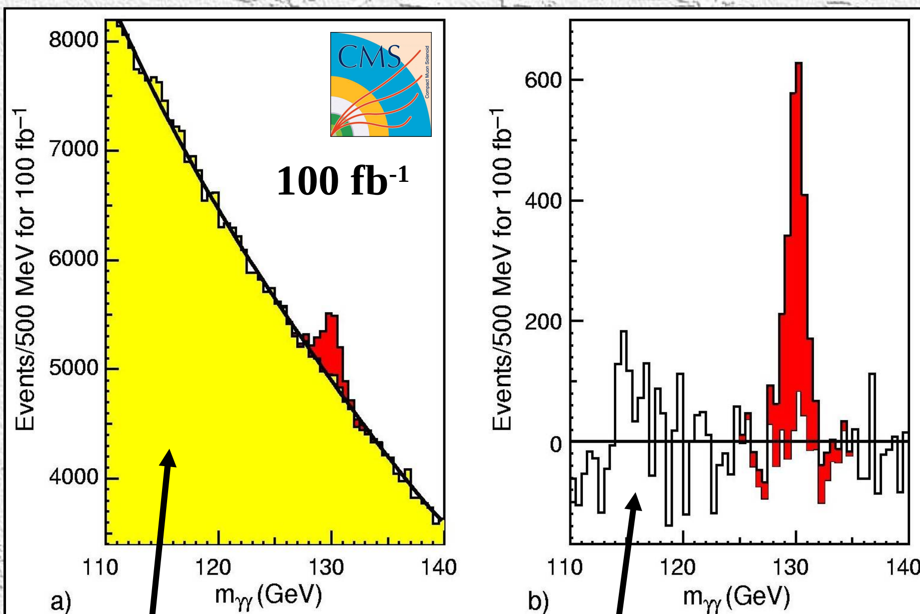
$H \to ZZ \to 4\mu$ (golden channel)



Search for the Higgs Boson at LHC

Possible future Higgs discovery plots:

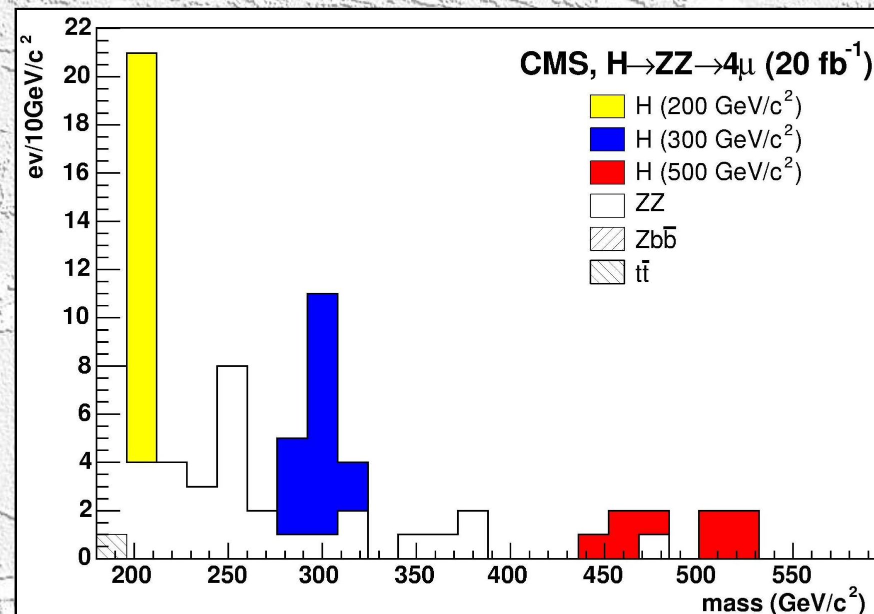
$H \rightarrow \gamma\gamma$:
m_H = 130 GeV
$\sigma_{mH} \approx$ 1 GeV



large combinatorial background

background subtracted

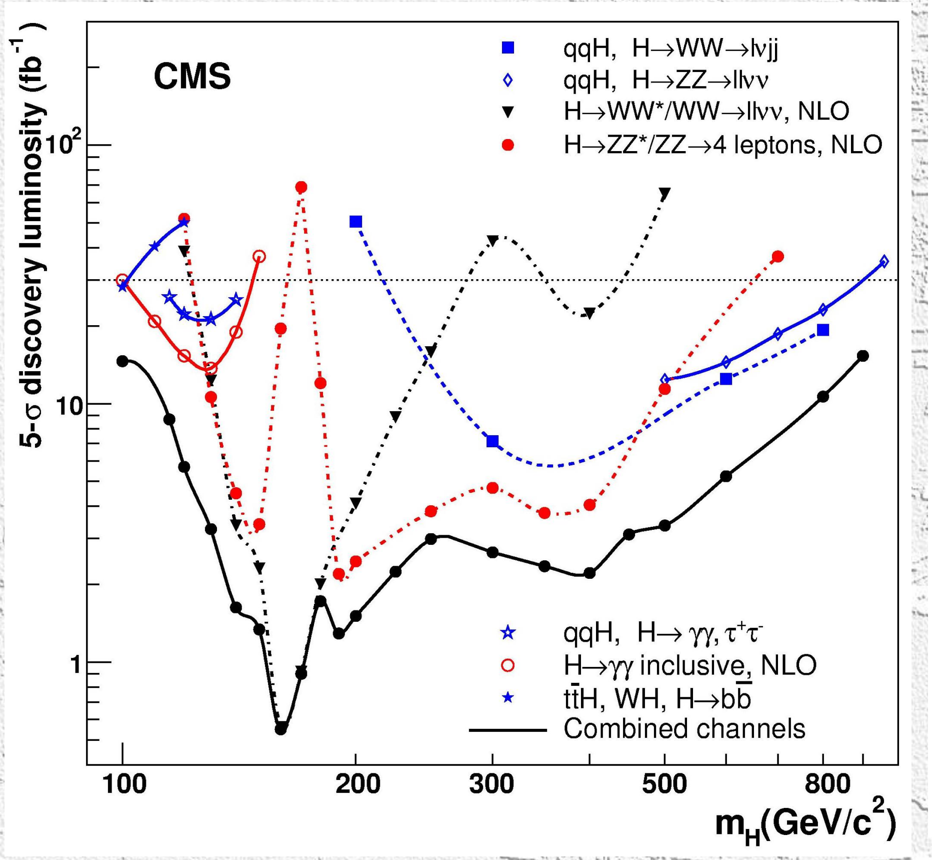
$H \rightarrow ZZ \rightarrow 4\mu$:
m_H = 200 (300, 500) GeV

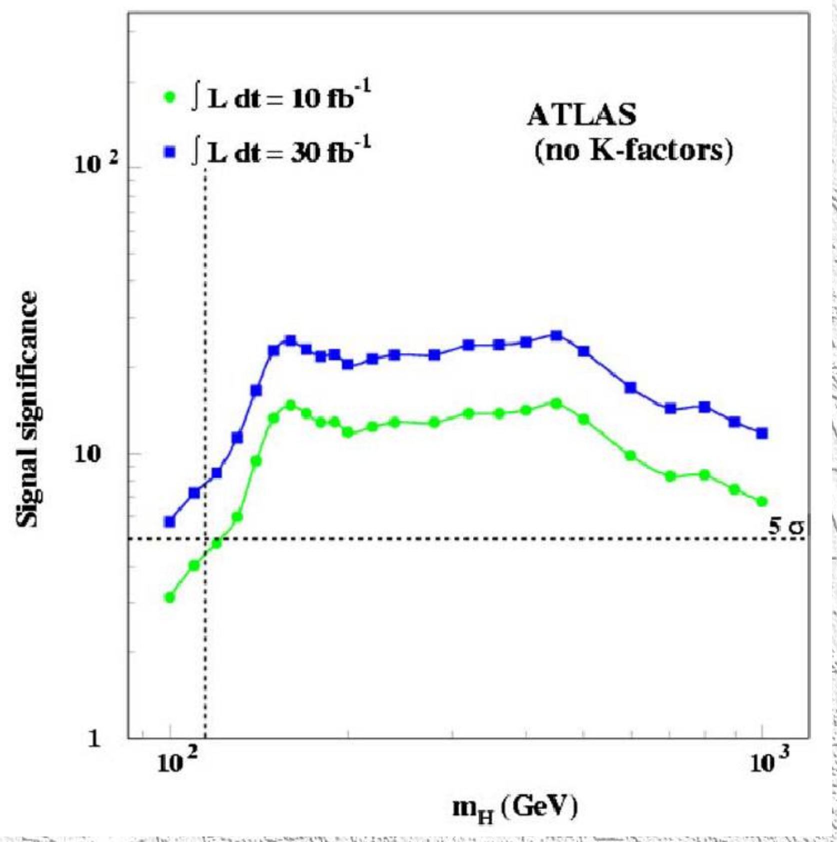


Note the increasing signal width

Search for the Higgs Boson at the LHC

Combine all search channels and determine expected significance as function of the luminosity and Higgs mass:





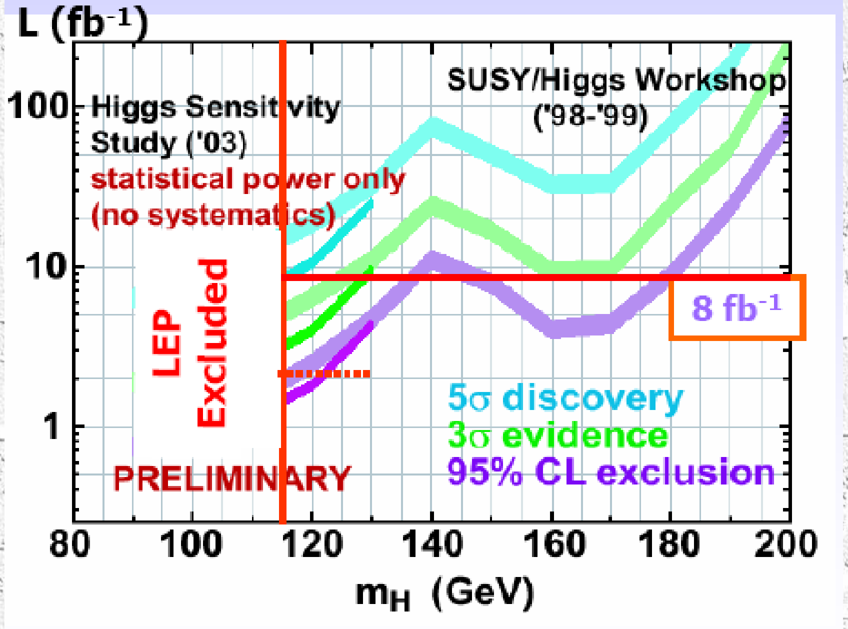
10 fb^{-1} sufficient for 5 σ discovery of the Higgs corresponds to 1 year at low luminosity 10^{33}/cm^2/s

Summary on Higgs search

The LHC will explore the entire Higgs mass region and definitely answer the question if there is a Higgs boson or not (holds for SM and MSSM)

The modest amount of 10 fb^{-1} of luminosity is required could be collected in 1-2 years

How about the Tevatron experiments?



For an estimated luminosity of 8 fb^{-1}

2 σ exclusion up to $m_H \approx 180$ GeV

3 σ evidence up to $m_H \approx 130$ GeV

Search for New Phenomena

Supersymmetry (MSSM)

SUSY Motivation

Why are we not satisfied with the Standard Model?

many open questions, gravity, dark matter, unification of couplings, hierachy problem, …

Need a more fundamental theory of which the SM is a `low energy` approximation:

Supersymmetry, Extra Dimensions, Technicolor, …

all predict new phenomena/particles at the TeV scale

Minimal Supersymmetric Model:

symmetry between fermion and bosons

for each SM particle there is a SUSY partner with $\Delta s = ½$

Ex. : q (s=1/2) $\rightarrow$ $\boxed{\tilde{q}}$ (s=0) squarks

g (s=1) $\rightarrow$ $\boxed{\tilde{g}}$ (s=1/2) gluino

MSSM Particle Spectrum

5 Higgs bosons : h, H, A, $H^{\pm}$

quarks	$\rightarrow$	squarks	$\tilde{q}$
leptons	$\rightarrow$	sleptons	$\tilde{e}, \tilde{\mu}, \tilde{\nu}$, etc.
$W^{\pm}$	$\rightarrow$	winos	$\rightarrow \chi^{\pm}_1, \chi^{\pm}_2$
$H^{\pm}$	$\rightarrow$	charged higgsino	2 charginos
γ	$\rightarrow$	photino	
Z	$\rightarrow$	zino	$\rightarrow \chi^0_{1,2,3,4}$ 4 neutralinos
h, H	$\rightarrow$	neutral higgsino	
g	$\rightarrow$	gluino	$\tilde{g}$

New multiplicative quantum number R-parity $R_{p:}$

R_p = +1 for SM particles

R_p = -1 for SUSY partners

R_p is conserved in most SUSY models, e.g. MSSM

SUSY particles are produced in pairs

lightest SUSY particle (LSP) is stable (χ^0_1)

LSP is candidate for dark matter

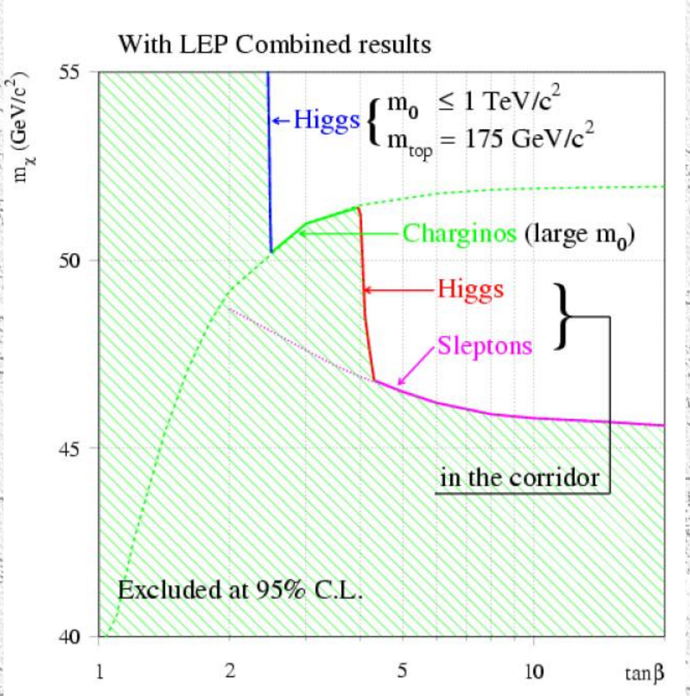
LSP interacts only weakly (like a neutrino)

$\Rightarrow$ SUSY signature: missing E_T

MSSM Particle Spectrum

What do we know about SUSY particles?
masses are not predicted, depend on a number of model parameters
experimental searches performed at LEP and Tevatron

m (sleptons, charginos)	>	90-103 GeV		LEP II
m (squarks, gluinos)	>	~	250 GeV	Tevatron Run 1
m (LSP, lightest neutralino)	>	~	45 GeV	LEP II



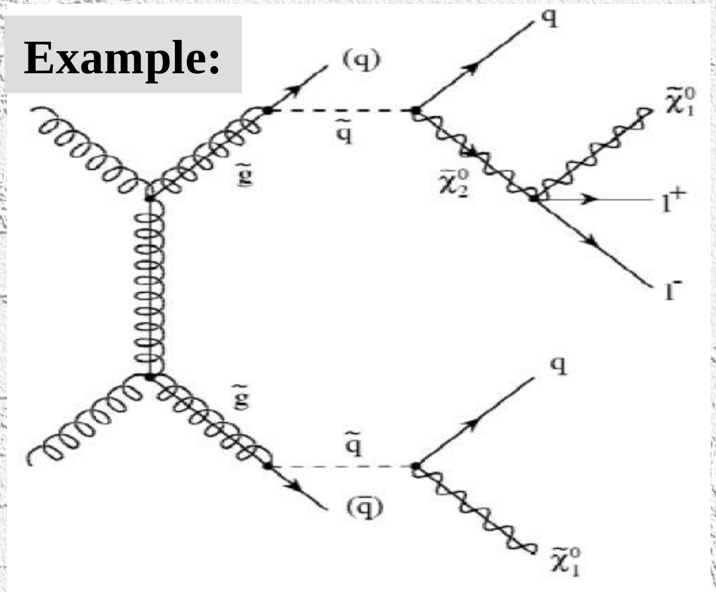
Example from LEP

SUSY Search at LHC

Production of SUSY particles at the LHC

- squarks and gluinos are pair-produced through strong interaction, i.e. high cross sections
- but also sleptons and other SUSY particles can be pair-produced
- SUSY particles decay in a chain to SM particles plus the LSP

Example:



Signature:

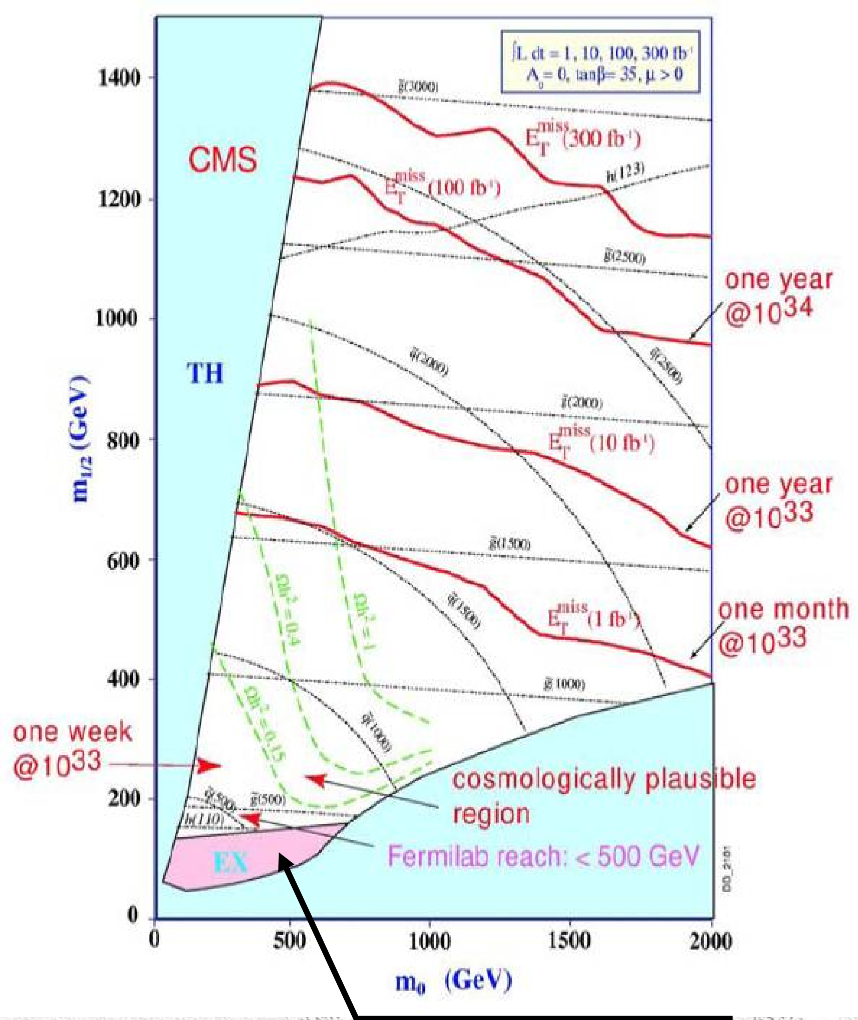
- leptons, jets and missing E_T
- depend of SUSY particles prodcued, on their branching ratios etc.

Strategy to discover SUSY at the LHC:

- look for deviation from SM in distributions
  - e.g. multi-jet + E_T^{miss}, multilepton+ E_T^{miss}
- establish SUSY mass scale
- try to determine model parameters (difficult!)

SUSY Search at LHC

Example: discovery reach as function of luminosity and model parameters which fix the mass scale of SUSY parameters



LEP exclusion

achievable limits exploiting E_T^{miss} signatures
requires very good understanding of detectors

Conclusion:
LHC will eclipse today's limits on SUSY particles and parameters or discover SUSY if it exists at the TeV scale

Conclusions

Experiments at proton colliders explore the highest energy frontier

- for discoveries of new particles and phenomena
- for precision meaurements

Standard Model is great, but cannot be the ultimate theory

pp experiments are testing and challenging the model

- Experiments at the Tevatron are collecting larger data samples
- LHC and the pp experiments ATLAS and CMS are will start next year to explore the TeV region

The LHC experiments will

- further improve knowledge on W boson, top quarks, QCD
- will probe physics at the smallest distance scale
- will answer the question if there is a Higgs boson or not
- probe models like SUSY on the (multi-)TeV scale

Very exciting times are ahead of us!
Come and join us now!

Questions & comments to Joachim.Mnich@desy.de