Physics at (Anti)Proton-Proton Colliders

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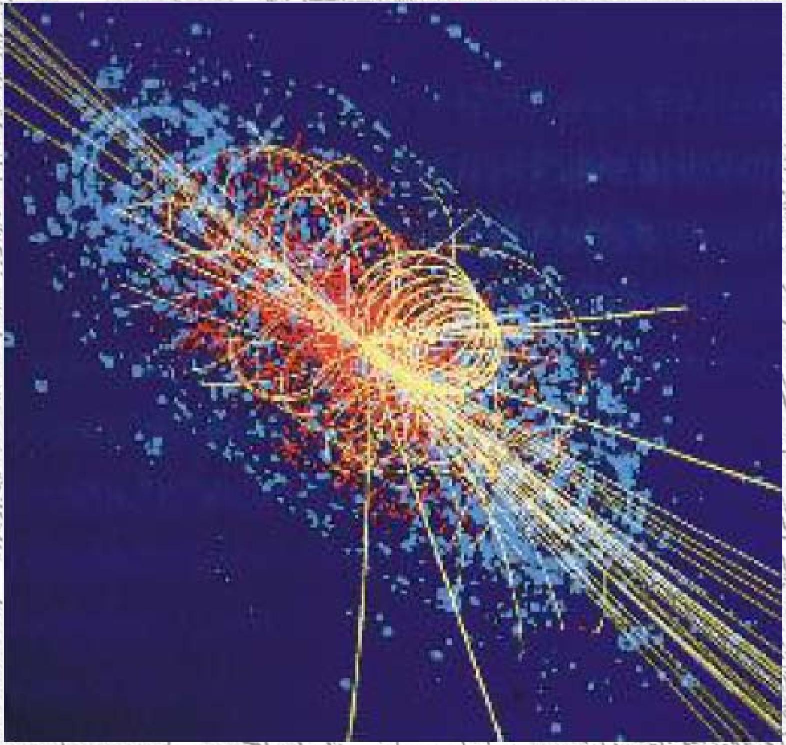
Introduction

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)



Today‘s Questions and Problems

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

- **Why are there 3 families?**

- **Are there additional forces and gauge bosons?**

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

- **What is dark matter (≈ 20% of the universe) and dark energy (≈ 75%)?**

- …

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

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

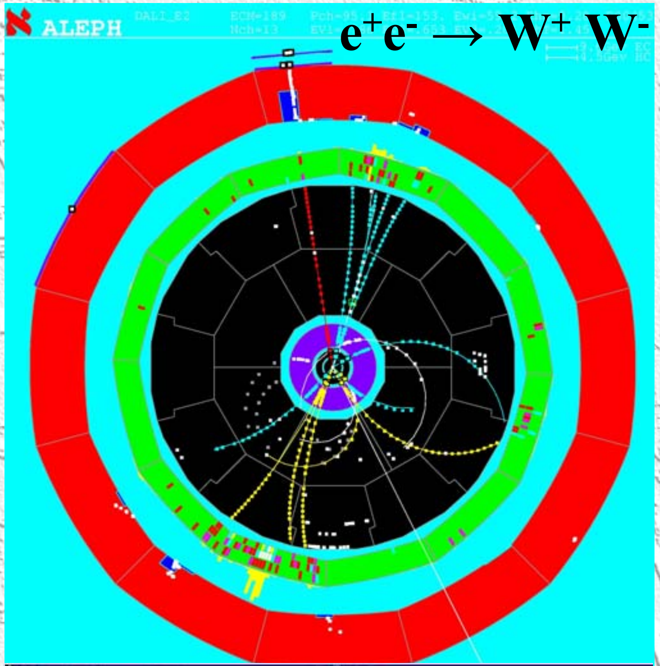
- **Why a proton collider like the LHC?**

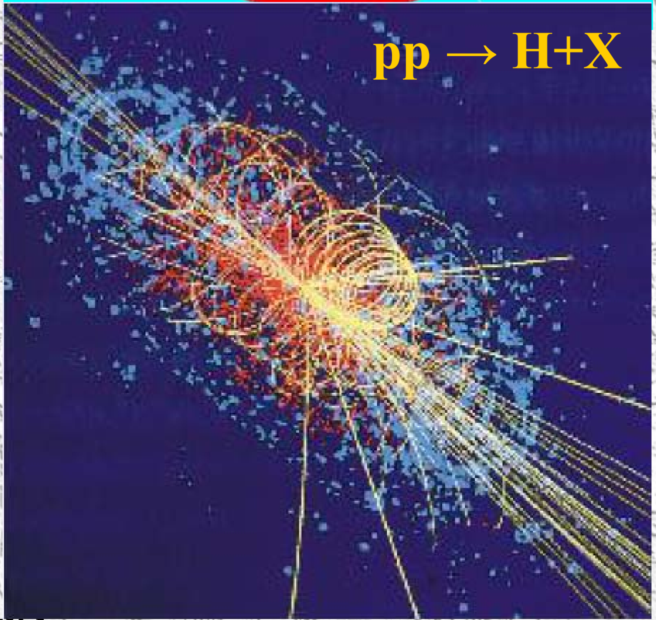
  e^+e^- machines like LEP are ideal machines for precision emasurements:

  - **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:

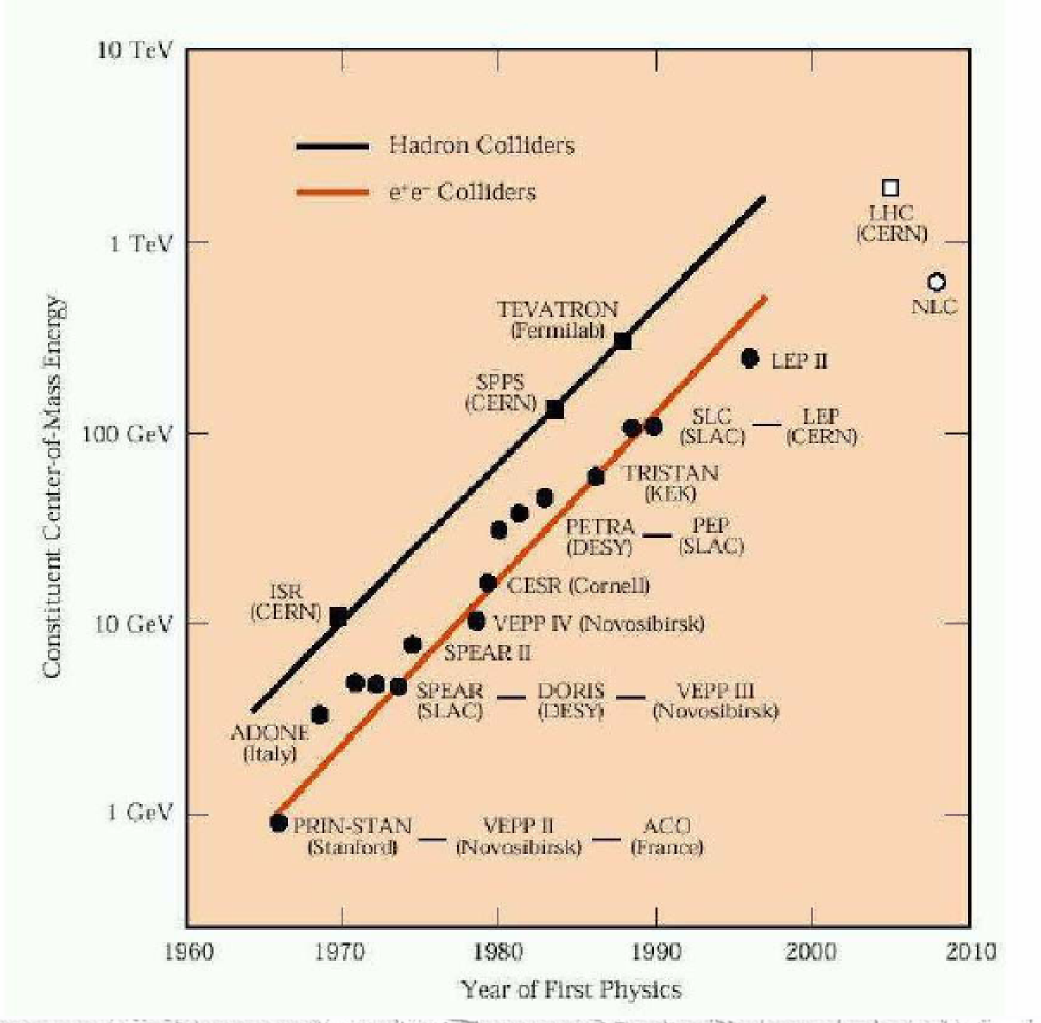
- **protons are not elementary**
- **hard scattering of partons (quarks & gluons)**
- **underlying event**
- **use only part of the beam energy**
- **event kinematics only partially constraint**





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
  $\int$Ldt = 125 pb-1

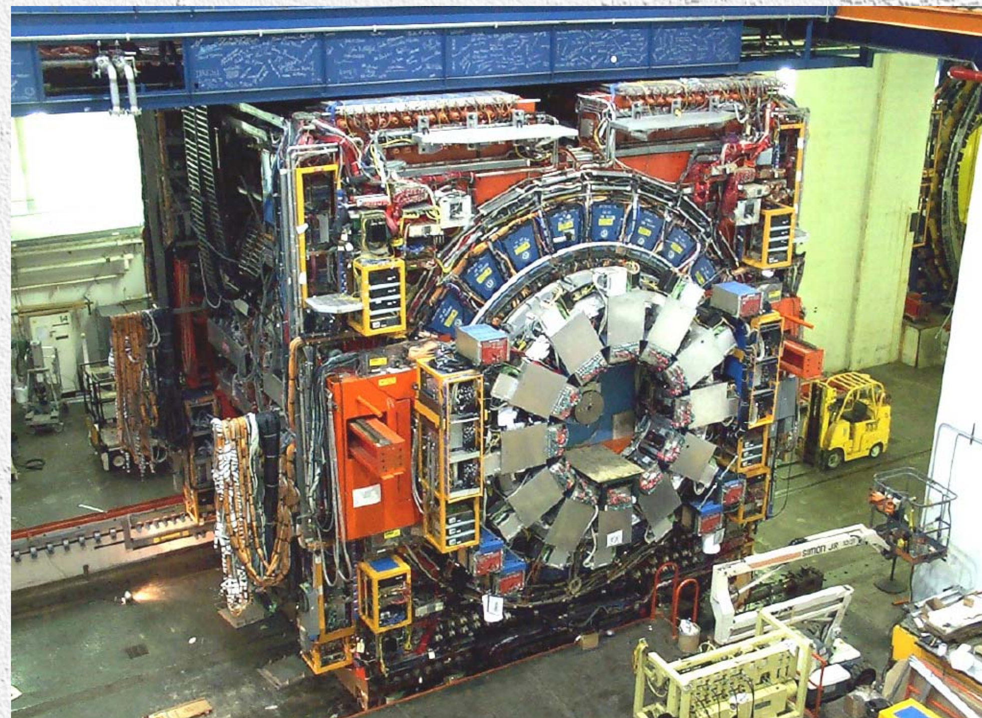
- **1996 – 2001 Upgrade**
  - new injector, antiproton recycler
    → higher luminosity
  - detector improvements

- **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

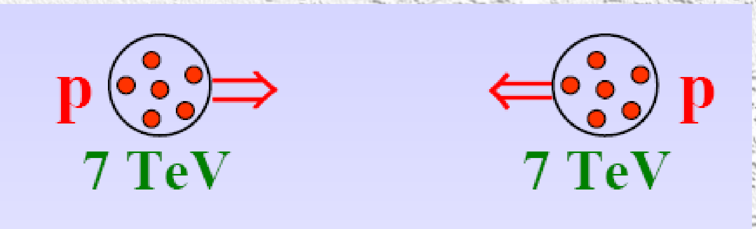
The D0 detector

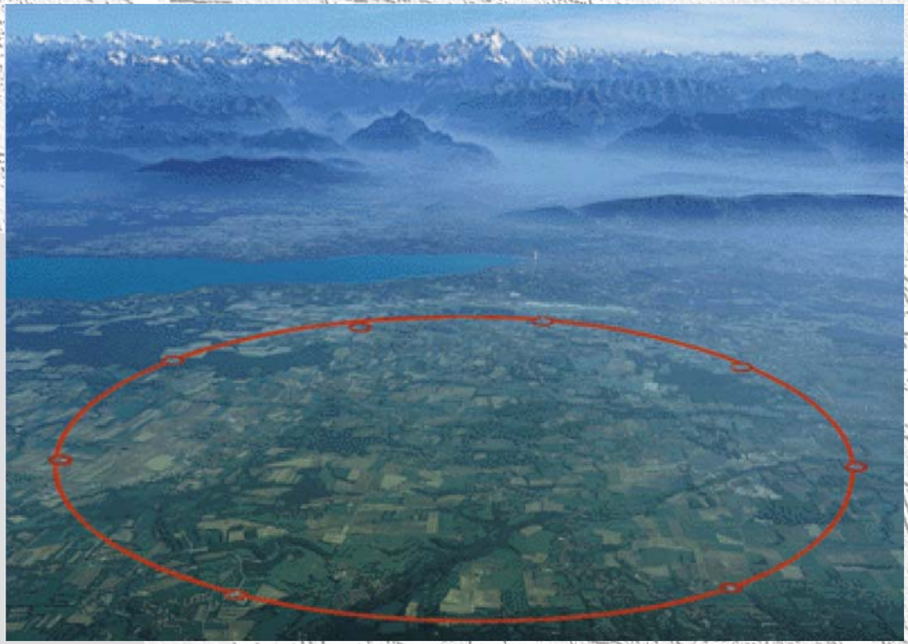
institutes from 19 countries
≈ 700 physicists

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

The Large Hadron Collider (LHC) at CERN

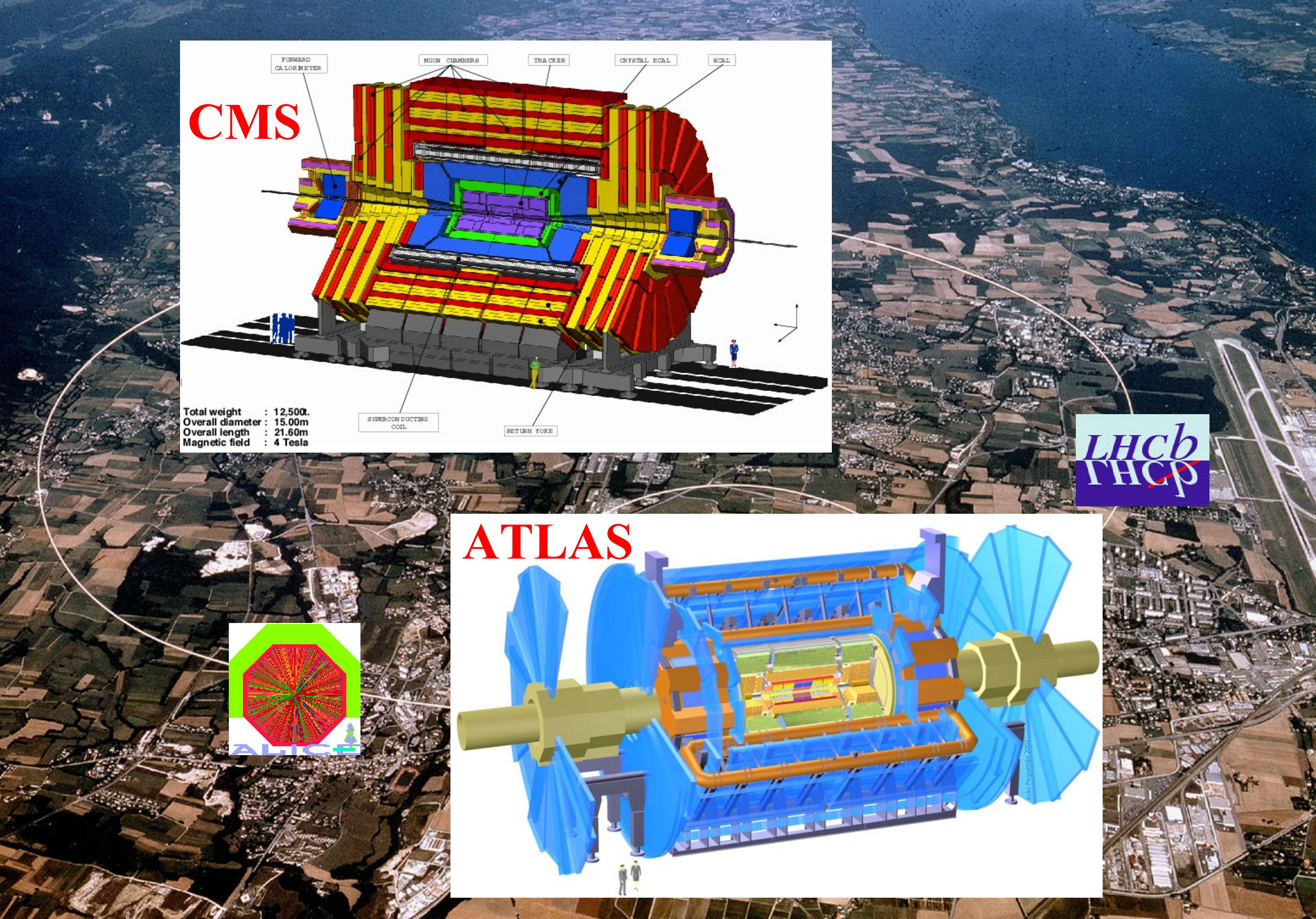
- Proton-proton collider in the former LEP tunnel at CERN (Geneva)





- 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 2008

The Large Hadron Collider LHC



Challenges for the LHC

- Superconducting dipole magnets to keep 7 TeV protons on circular path (r ≈ 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

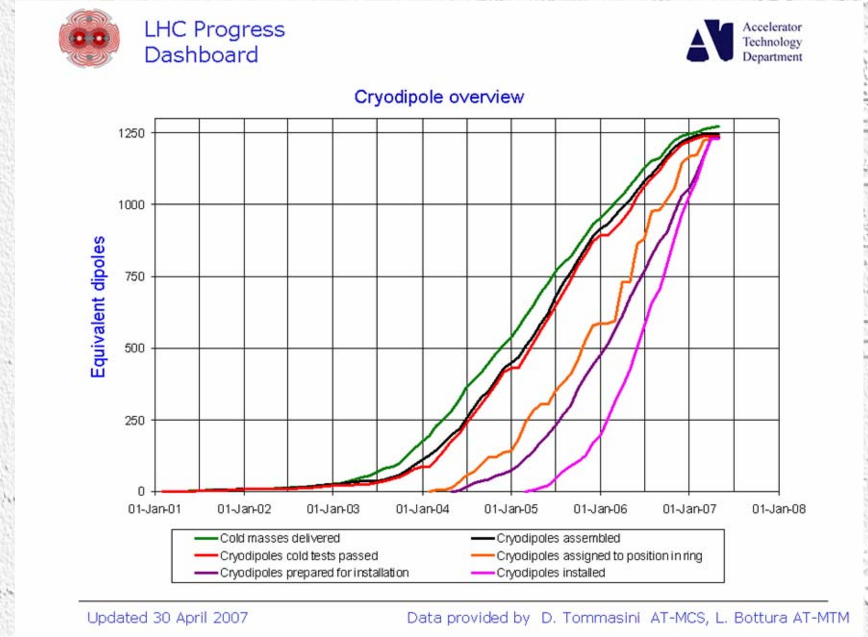
  corresponds to a
  40 t truck at 50 km/h!

- LHC dipole design
  incoporates reversed field for oppositely rotating proton beam

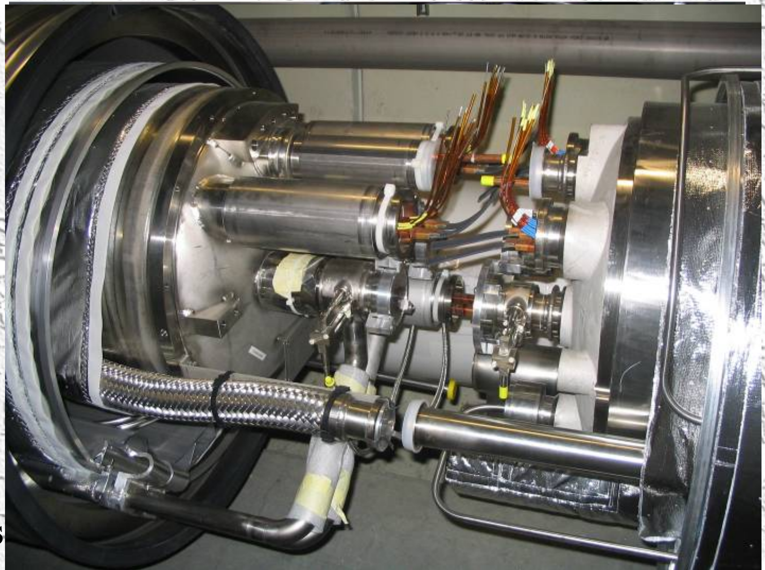
BTW:
the stored energy in the LHC proton beams is 350 MJ
enough to melt 500 kg of copper!

Status of the LHC

- Example dipoles:
  all 1232 dipoles built and installed



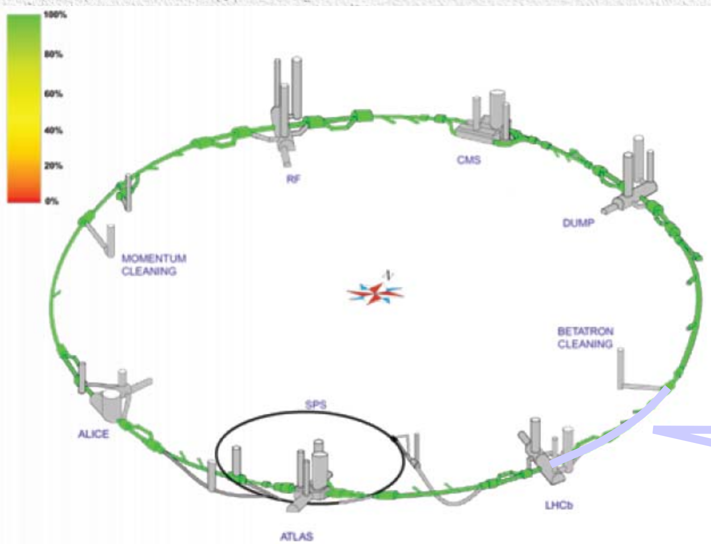
- Last dipole lowered on April 26, 2007



- All magnets prepared on schedule
- Interconnections on-going in 6 sectors
  - sector 7-8 ready
  - closure of 4-5 and 8-1 upcoming

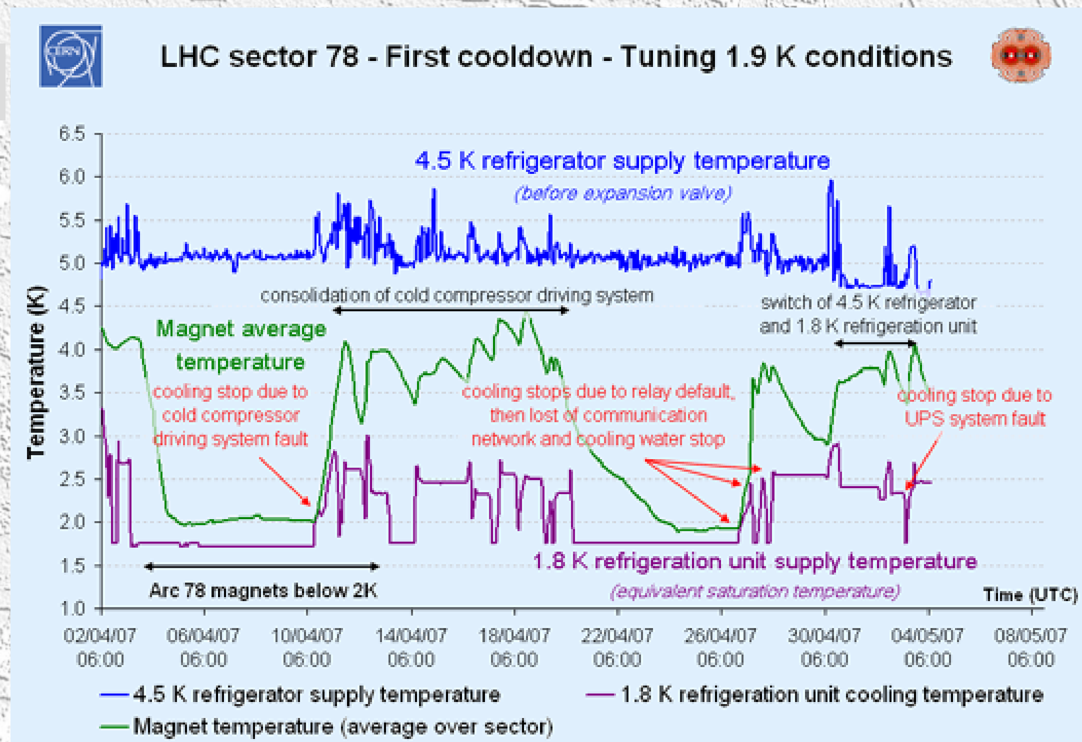
LHC schedule: first beam in 2008

Status of the LHC



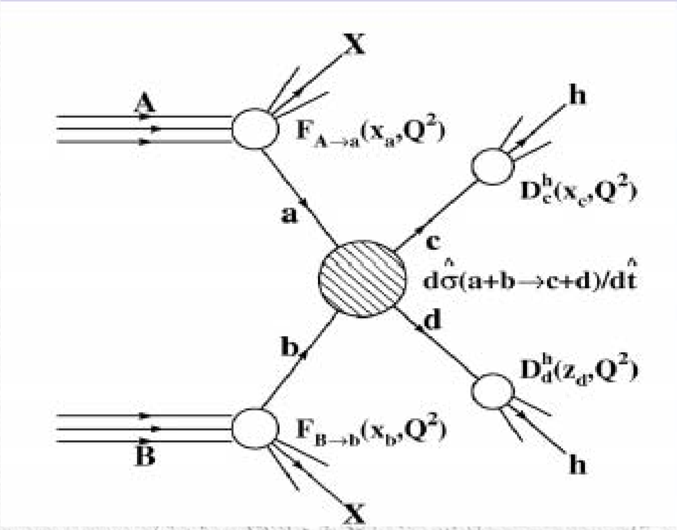
- Cryogenics complete

- First cooldown April 2007:



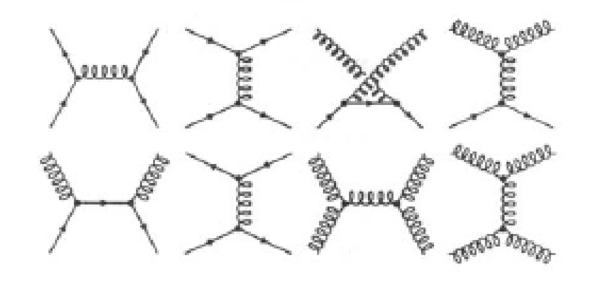
- 1.9 K: The coldest place in the universe!

Physics at Proton Colliders



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

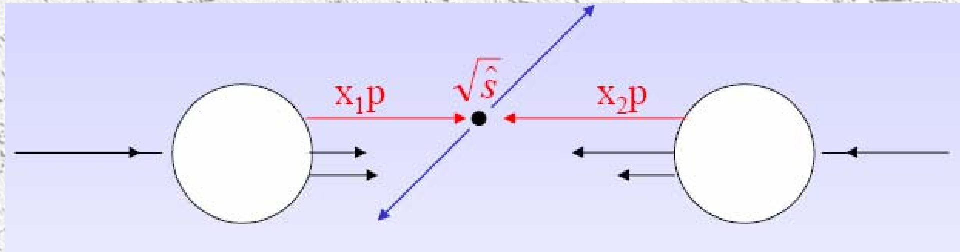
- **Interesting hard scattering processes**
  quark-(anti)quark
  quark-gluon
  qluon-gluon



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)

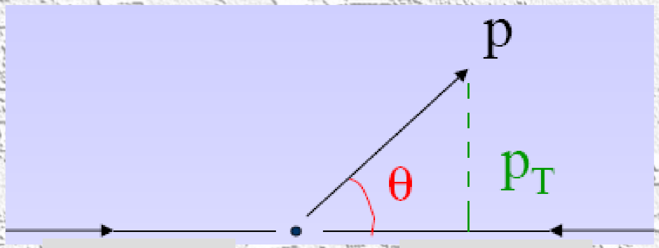
To produce a particle of mass		
mass	LHC	Tevatron
100 GeV	$x \approx 0.007$	$x \approx 0.05$
5 TeV	$x \approx 0.36$	---

Variables in pp Collisions

Kinematics fully defined only in transverse plane

Transverse momentum p_T

$p_T = p \sin\theta$

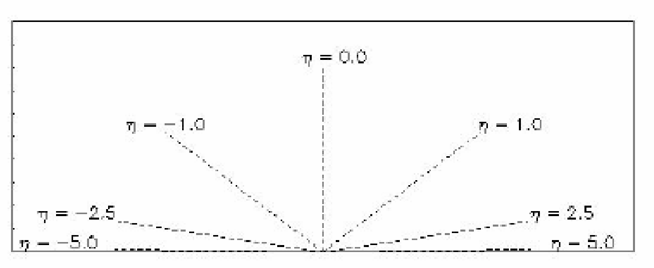


Rapidity: $y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L}$

Differences in y are invariant under Lorentz boosts

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

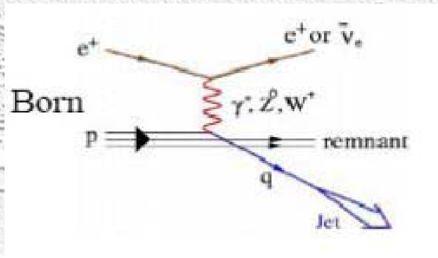
handy approximation, do not need to know the particle mass

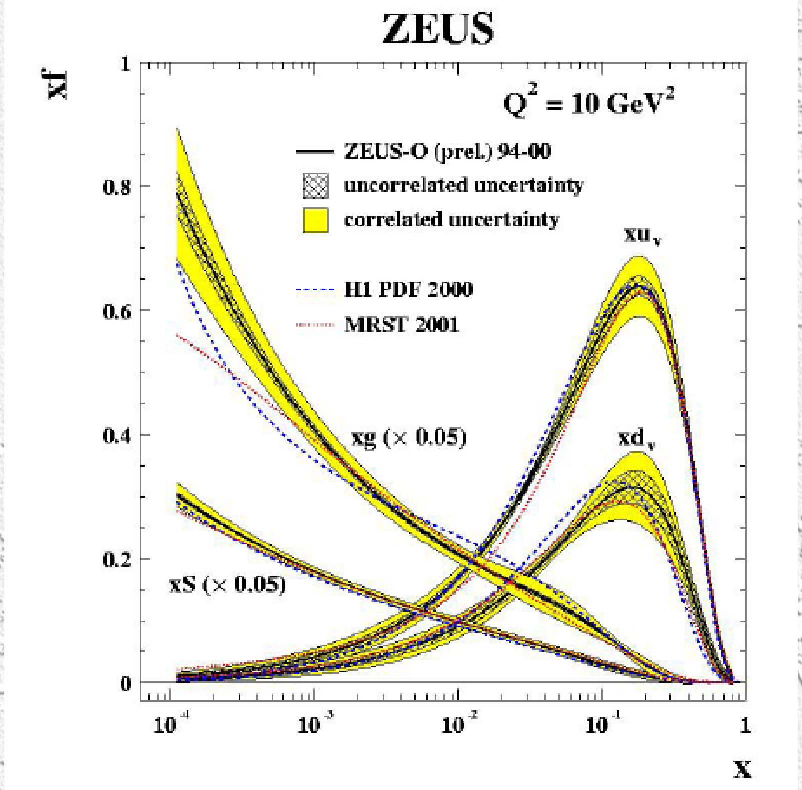


$\theta = 90°$	$\eta = 0$
$\theta = 10°$	$\eta \approx 2.4$

Parton Density Functions

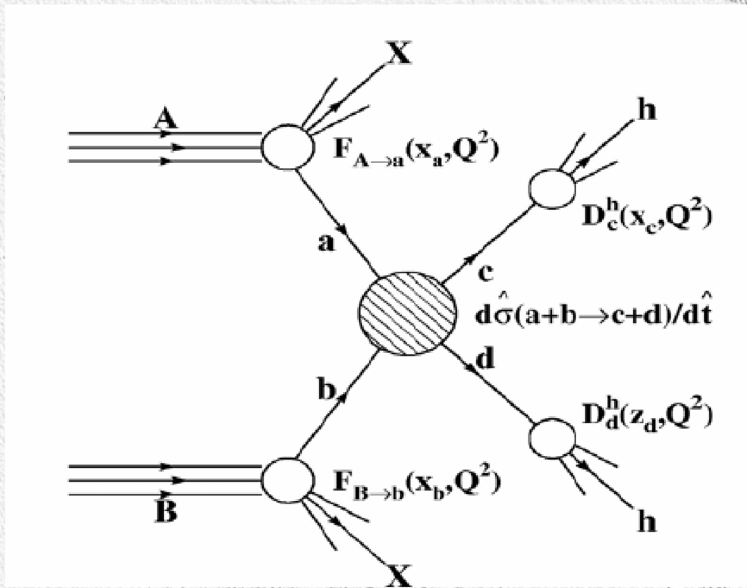
How do the distributions of the x-values look like?
Measured at HERA in ep-scattering, e.g.:





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

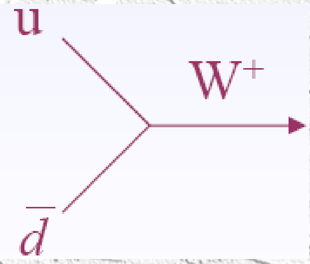
Cross Section Calculation



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

- 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 $\approx 2\cdot 10^{-6}\,\sigma_{tot}$

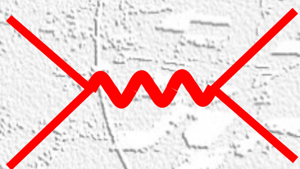
Parton Density Functions at the LHC

LHC is a proton-proton collider

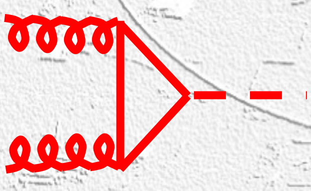
But fundamental processes are the scattering of

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

<u>**Examples:**</u>

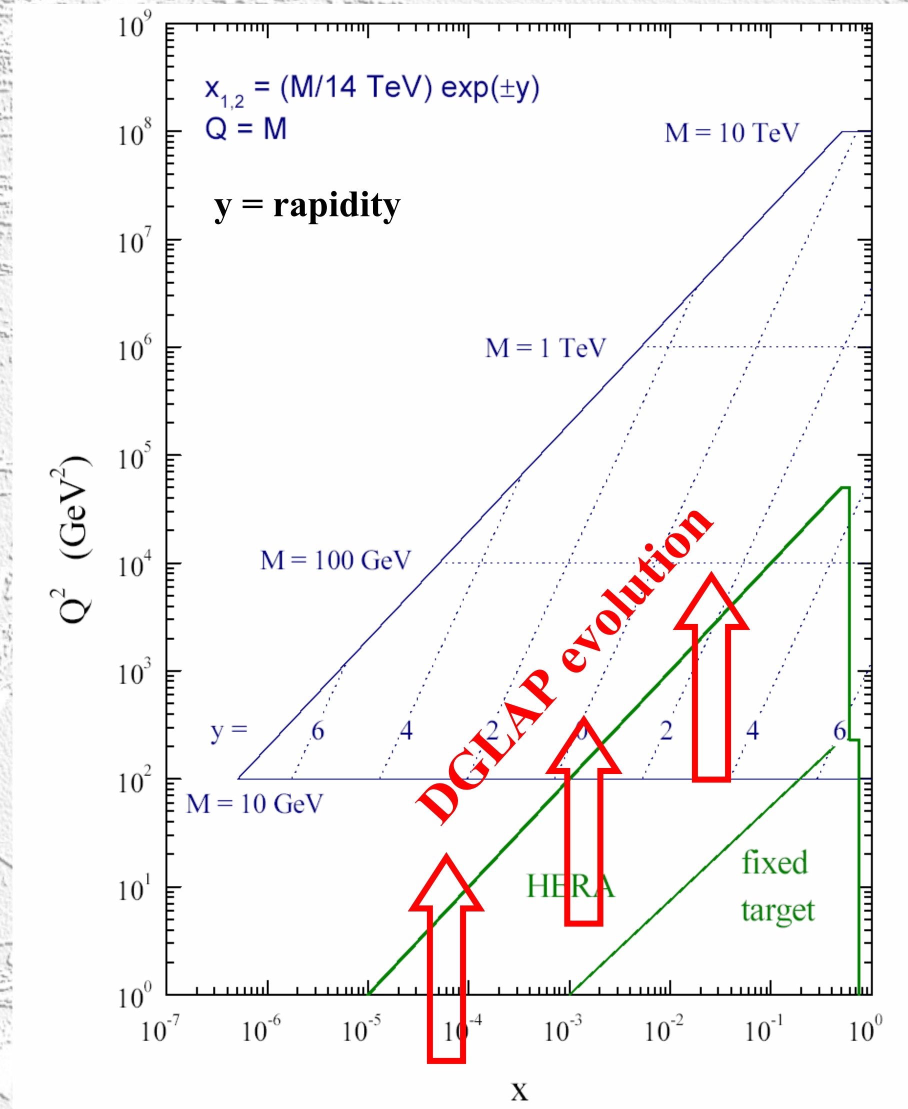


$q\bar{q} \rightarrow W \rightarrow l\nu$



$gg \rightarrow H$

$\Rightarrow$ need precise PDF(x,Q^2)
+ QCD corrections (scale)



Luminosity

Rate of produced events for a given process

$$N = \sigma L$$

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

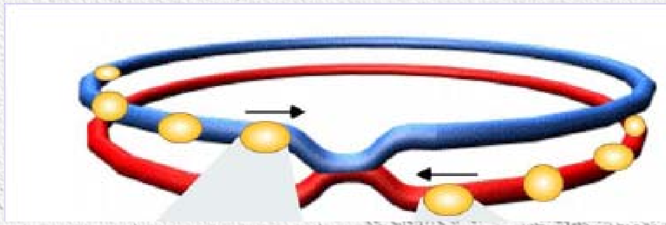
Comparison of colliders:

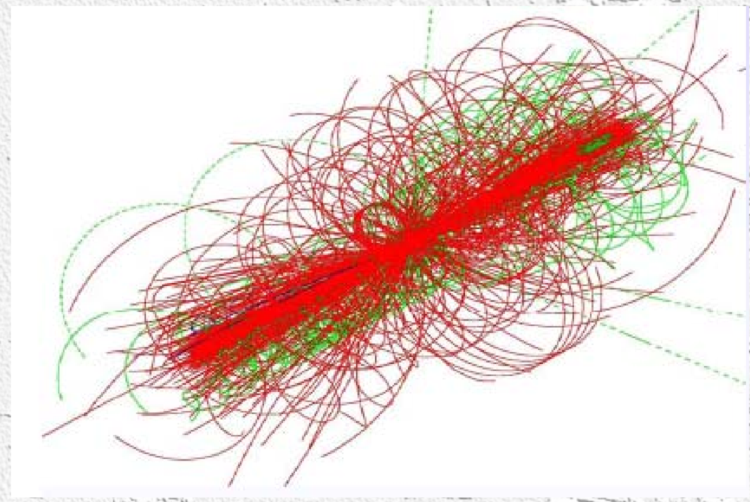
- 10^{31}/cm^2/s LEP
- $2\cdot10^{32}$/cm^2/s Tevatron Run II design
- 10^{33}/cm^2/s LHC initial phase (≈ 3 years)
- 10^{34}/cm^2/s LHC design luminosity (> 2010)

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}/cm²/s
  ≈ 35 pp interactions per crossing
  pile-up

→ ≈ 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**

$10^{33}/cm^2/s = 1/nb/s$

approximately

- **10^8 pp interactions**
- **10^6 bb events**
- **200 W-bosons**
- **50 Z-bosons**
- **1 tt-pair**

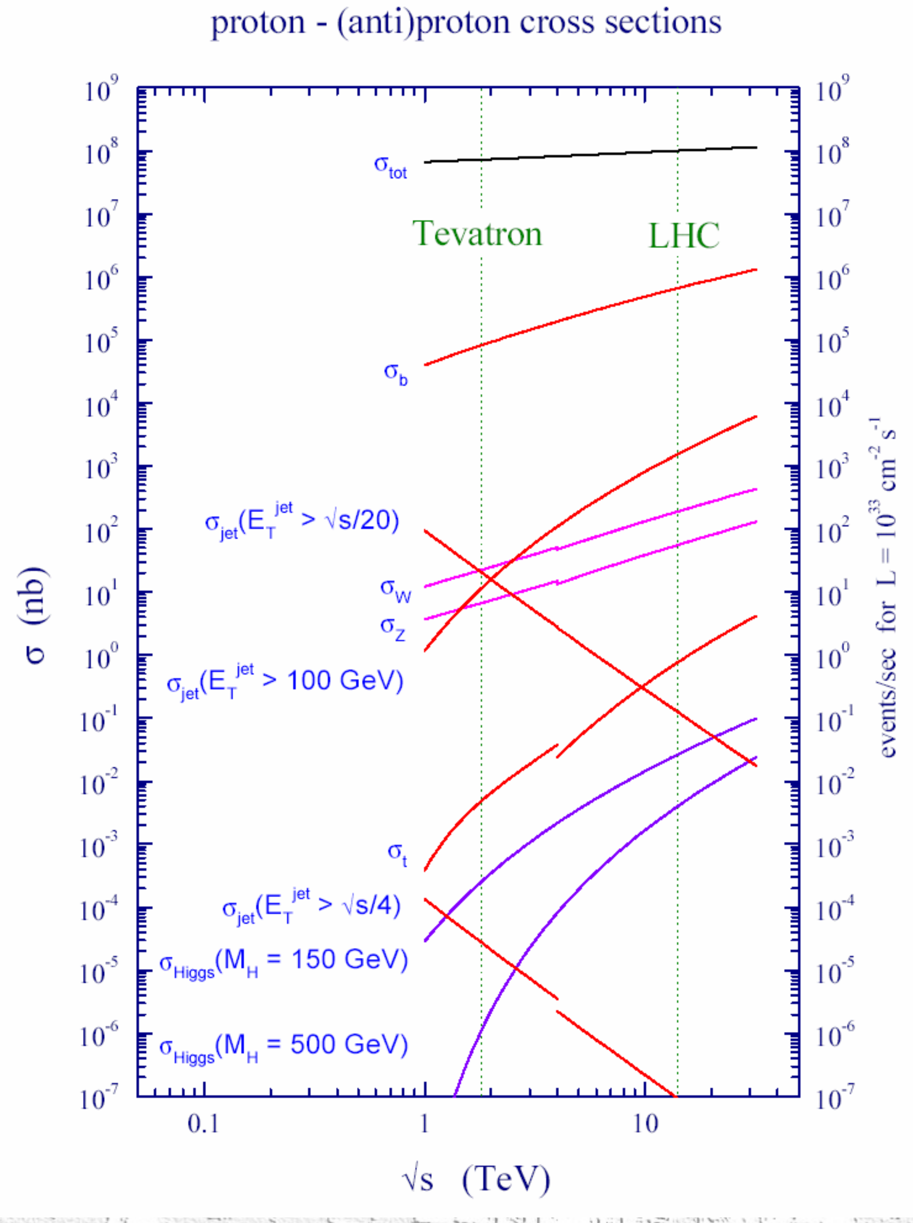
will be produced per second and

- **1 light Higgs**

per minute!

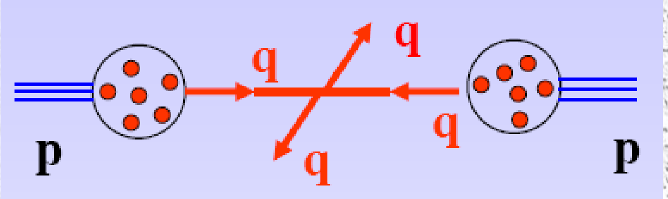
The LHC is a b, W, Z, top, Higgs, … factory!

The problem is to detect the events!



Experimental Signatures

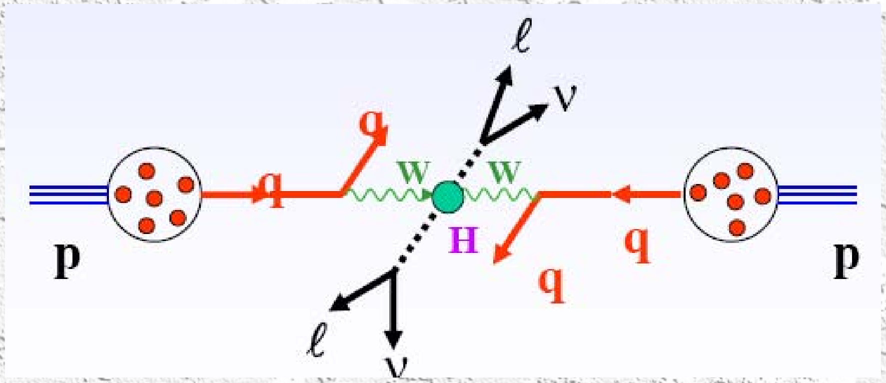
1. Hadronic final states, e.g. quark-quark



no high p_T leptons or photons in the final state

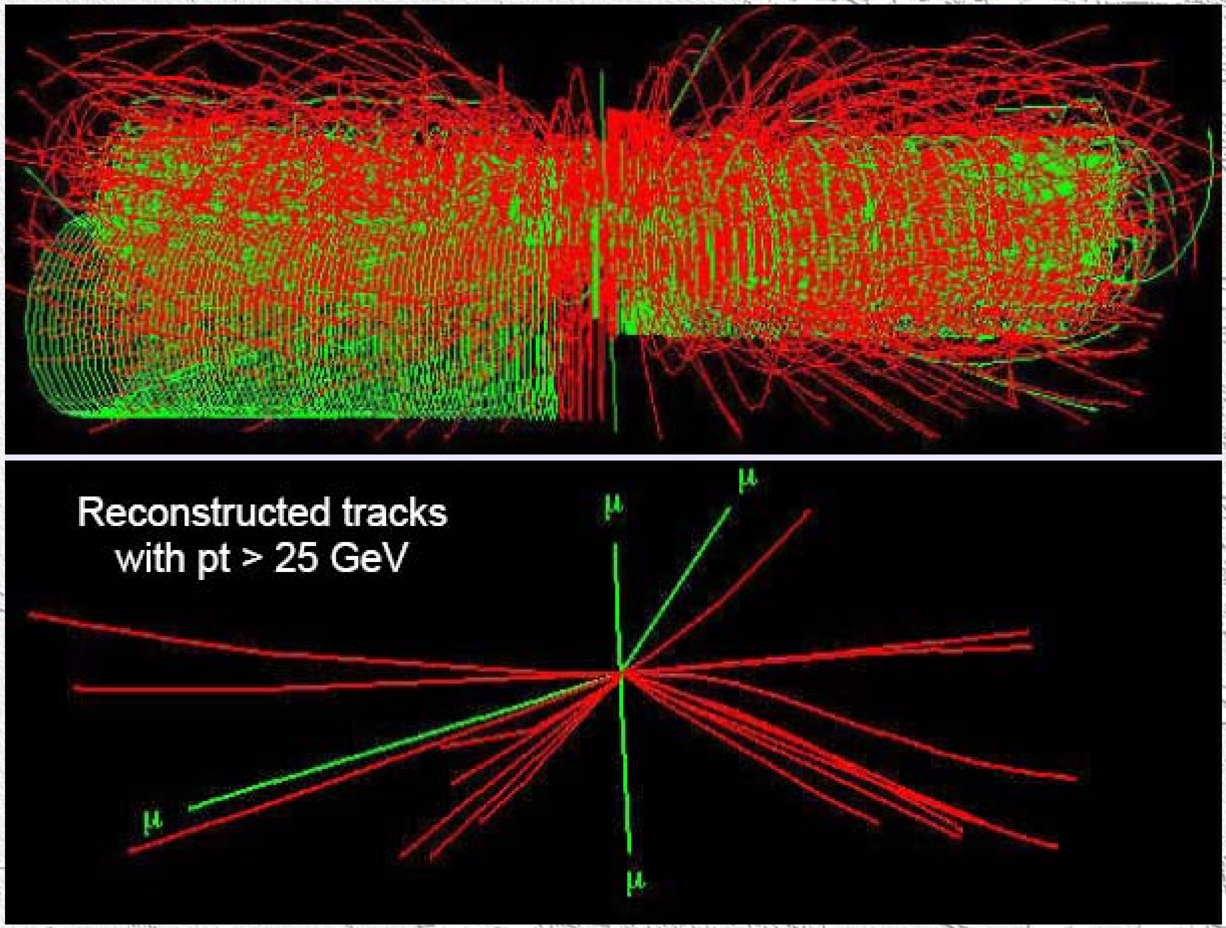
holds for the bulk of the total cross section

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

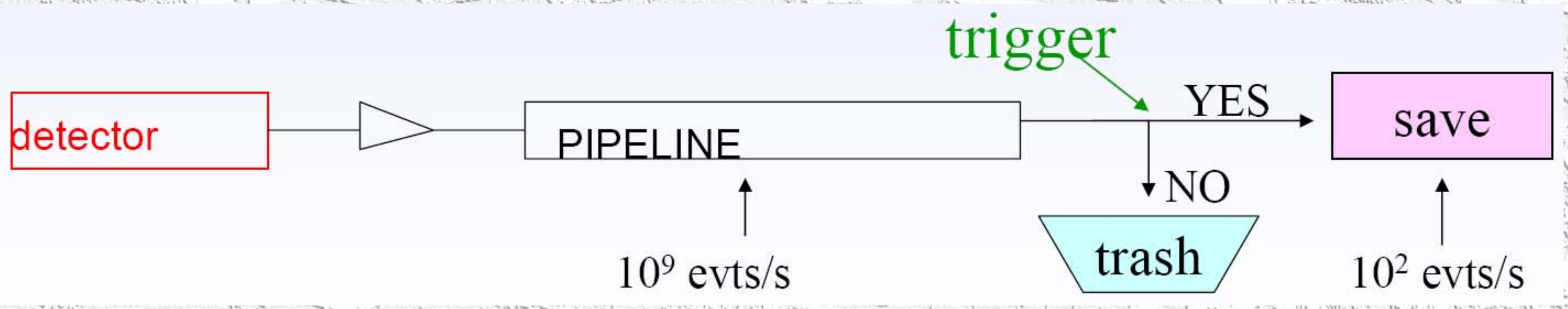
Trigger of interesting events at the LHC is much more complicated than at e^+e^- machines

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

⇒ trigger rejection ≈ 10^7

- **collision rate is 25 ns (corresponds to 5 m cable delay)**
- **trigger decision takes ≈ a few µs**

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



The ATLAS experiment

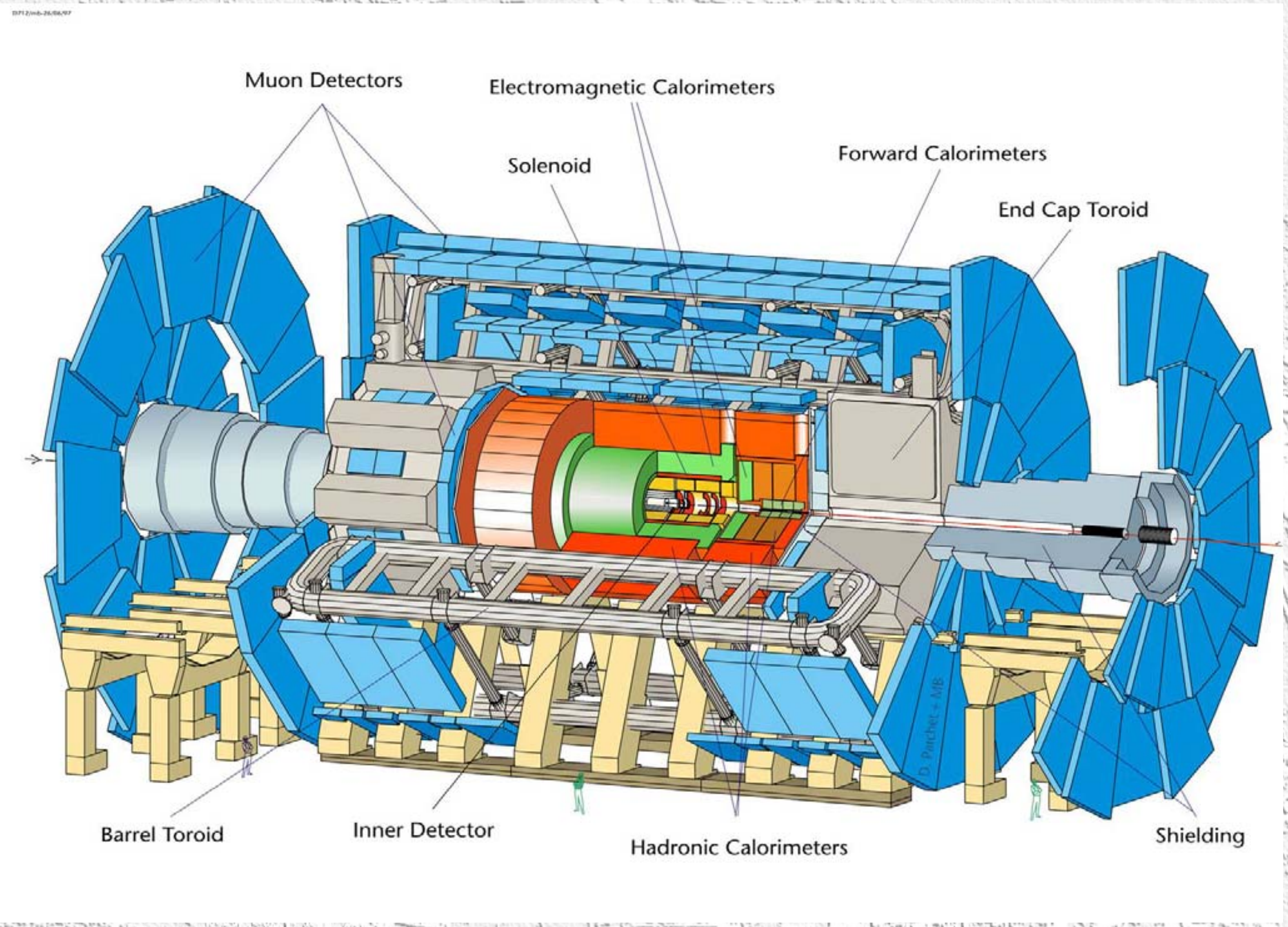
A Toroidal LHC ApparatuS

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

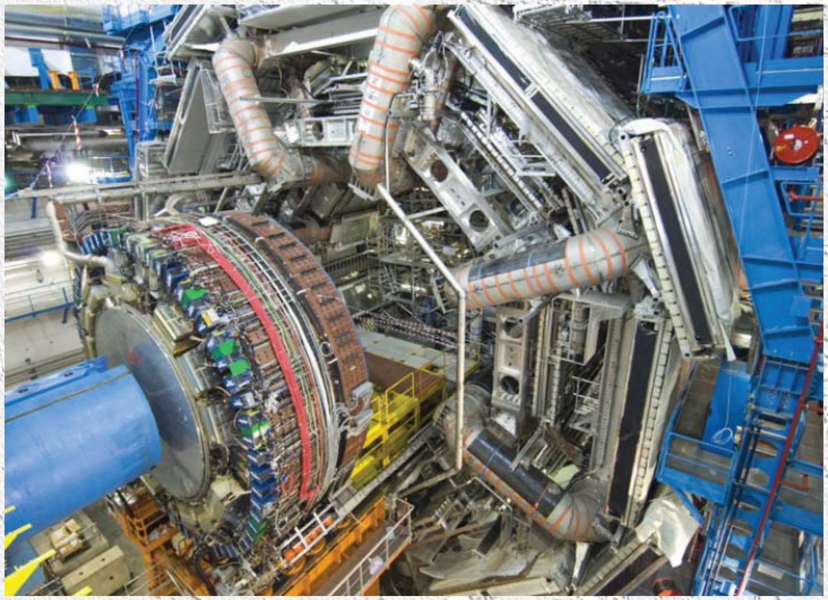
15 μm resolution



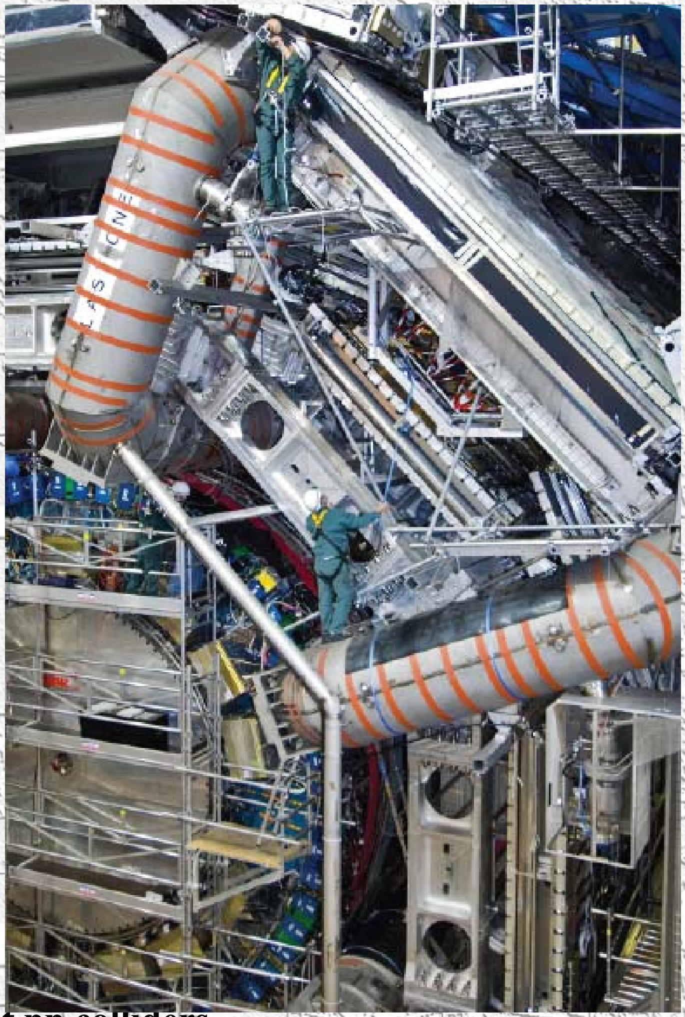
Status of ATLAS

Major structures assembled underground

- all calorimeters installed



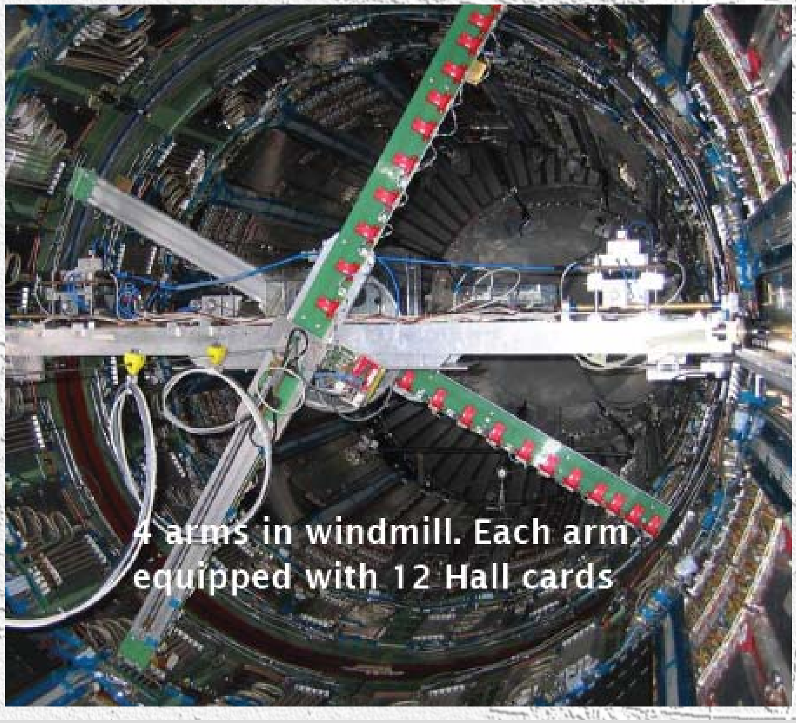
- 99% of barrel μ chambers installed



ATLAS: on track for LHC physics

Status of ATLAS

- Magnets
  - barrel toroid tested sucesfully (11/06)
  - inner solenoid:
    tested & field map taken

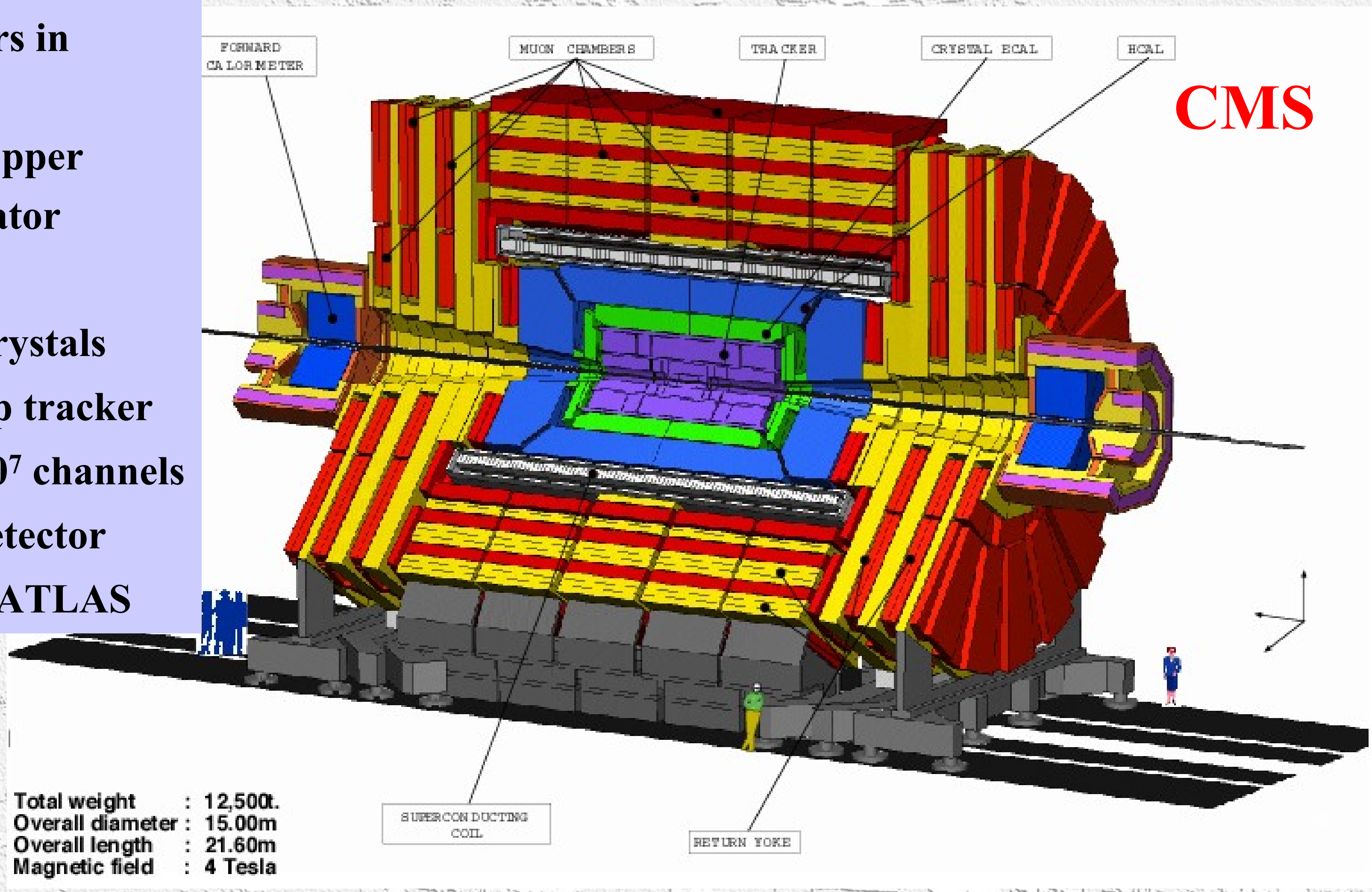


- 1 endcap toroid sucessfully tested (03/07)
  moved to IP1
- 2nd followed in June

The CMS experiment

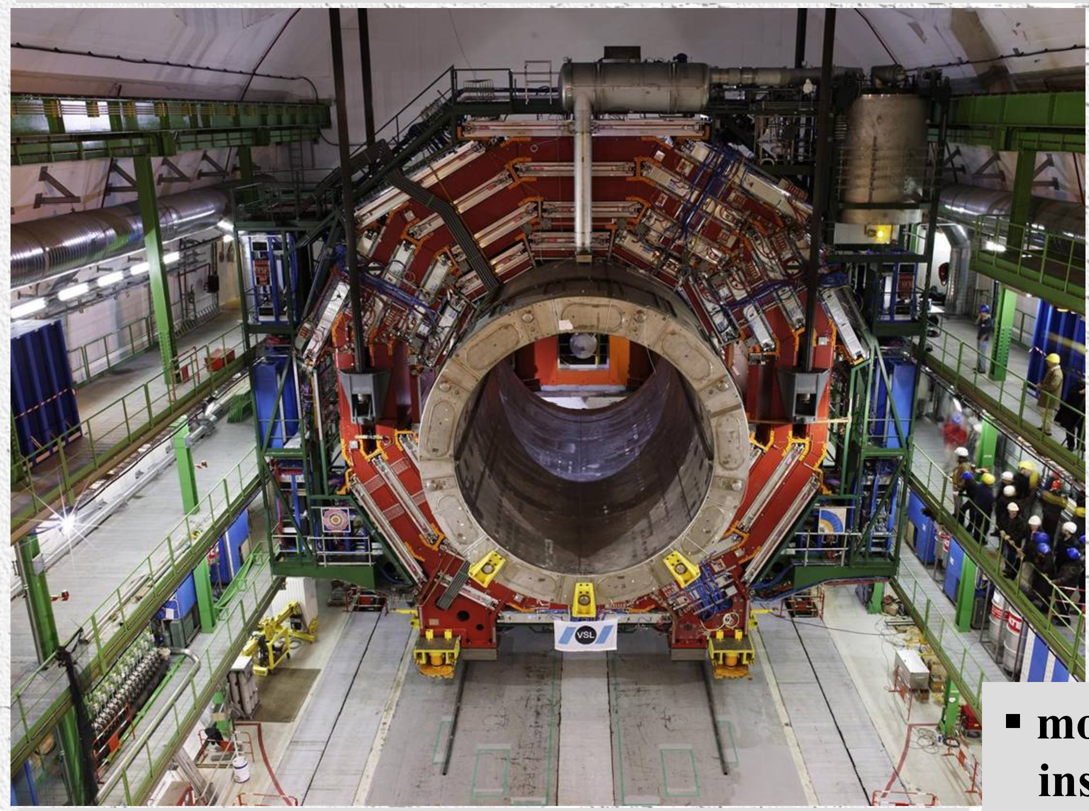
Compact Muon Solenoid

CMS in a nutshell:
- 4 T solenoid
- μ chambers in iron yoke
- HCAL: copper & scintillator
- ECAL: $PbWO_4$ crystals
- All Si-strip tracker $220\ m^2$, 10^7 channels
- Si-pixel detector similar to ATLAS

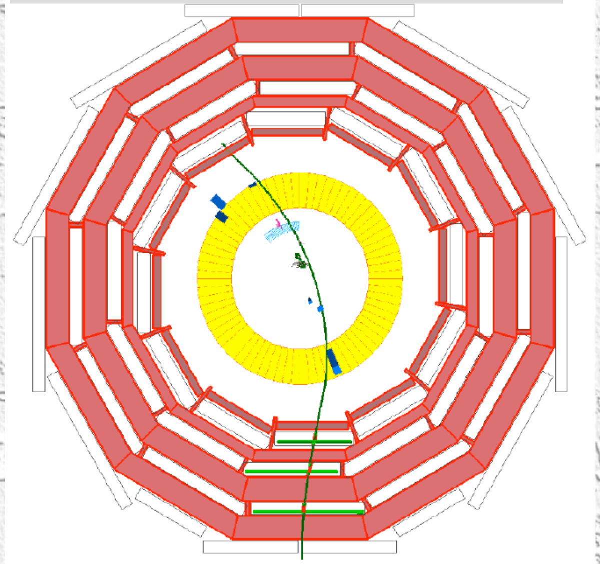


Status of CMS

CMS: major structures assembled on surface
- solenoid sucessfully operated at 4 Tesla (11/06), field map
- lowering of central magnet slice (YB0) on February 28th



Cosmic from magnet test



- most μ chambers installed

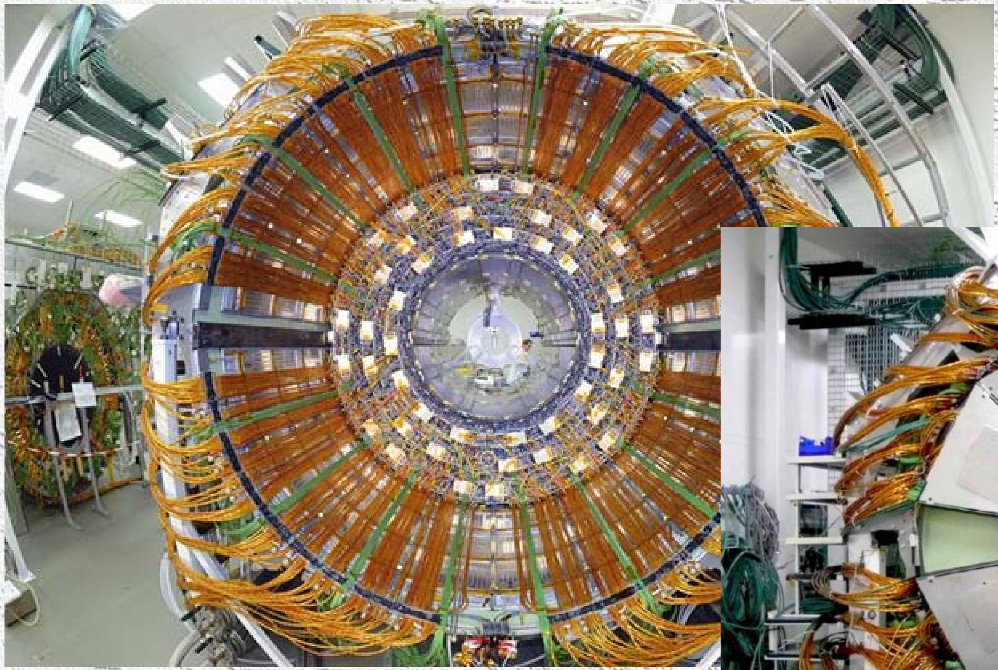
- 5/13 heavy pieces still to be lowered but all of known type
- 2nd endcap cabled, tested & commissioned on surface

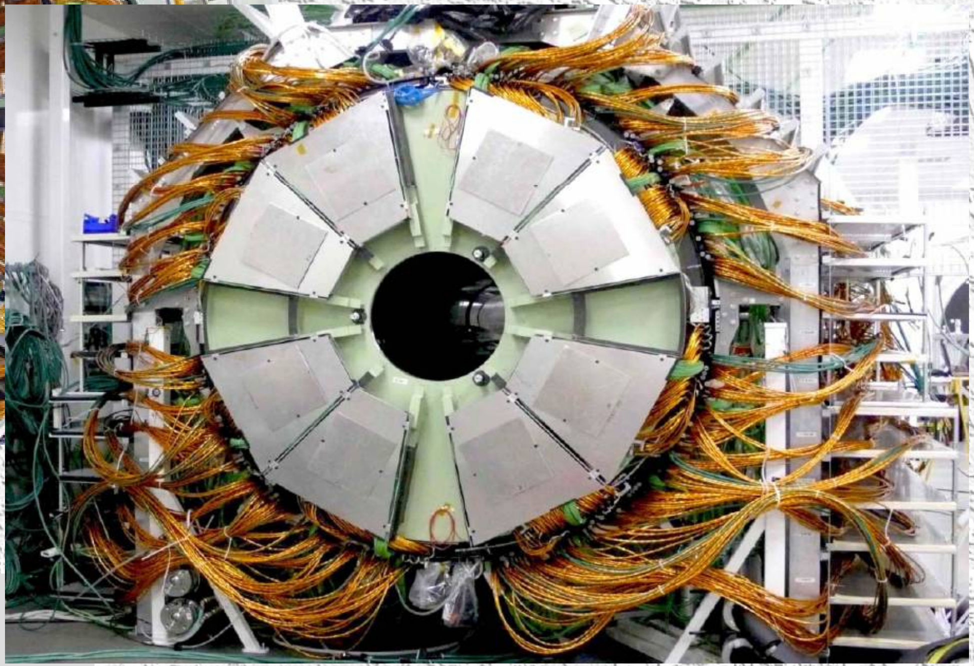
CMS: on track for LHC physics

Status of CMS

- Silicon tracker ready
  - under test at surface
  - to be installed in August 2007

CMS tracker:
- ≈ 220 m^2 of Si sensors
- 10.6 million Si strips
- 65.9 million Si pixel





- Pixel detector:
  - 2/3 of modules produced
  - ready for installation end 2007

Comparison of ATLAS and CMS

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

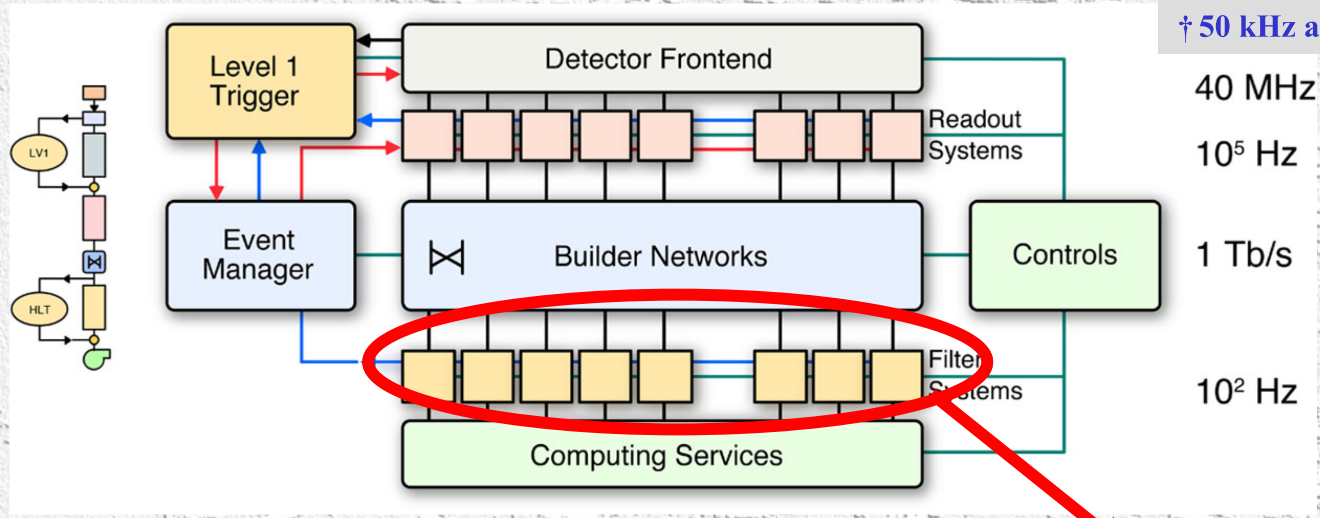
Trigger & DAQ system

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)



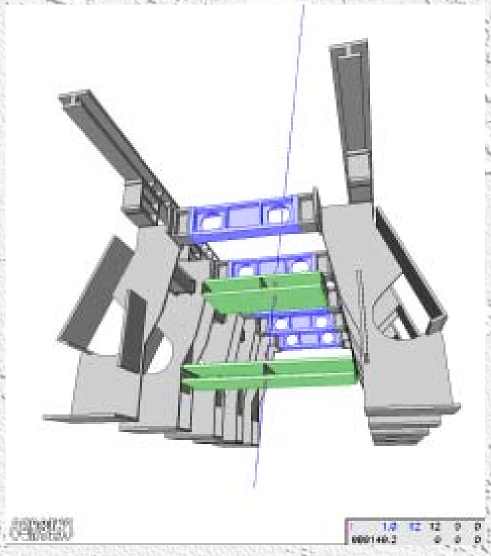
Filter farm:

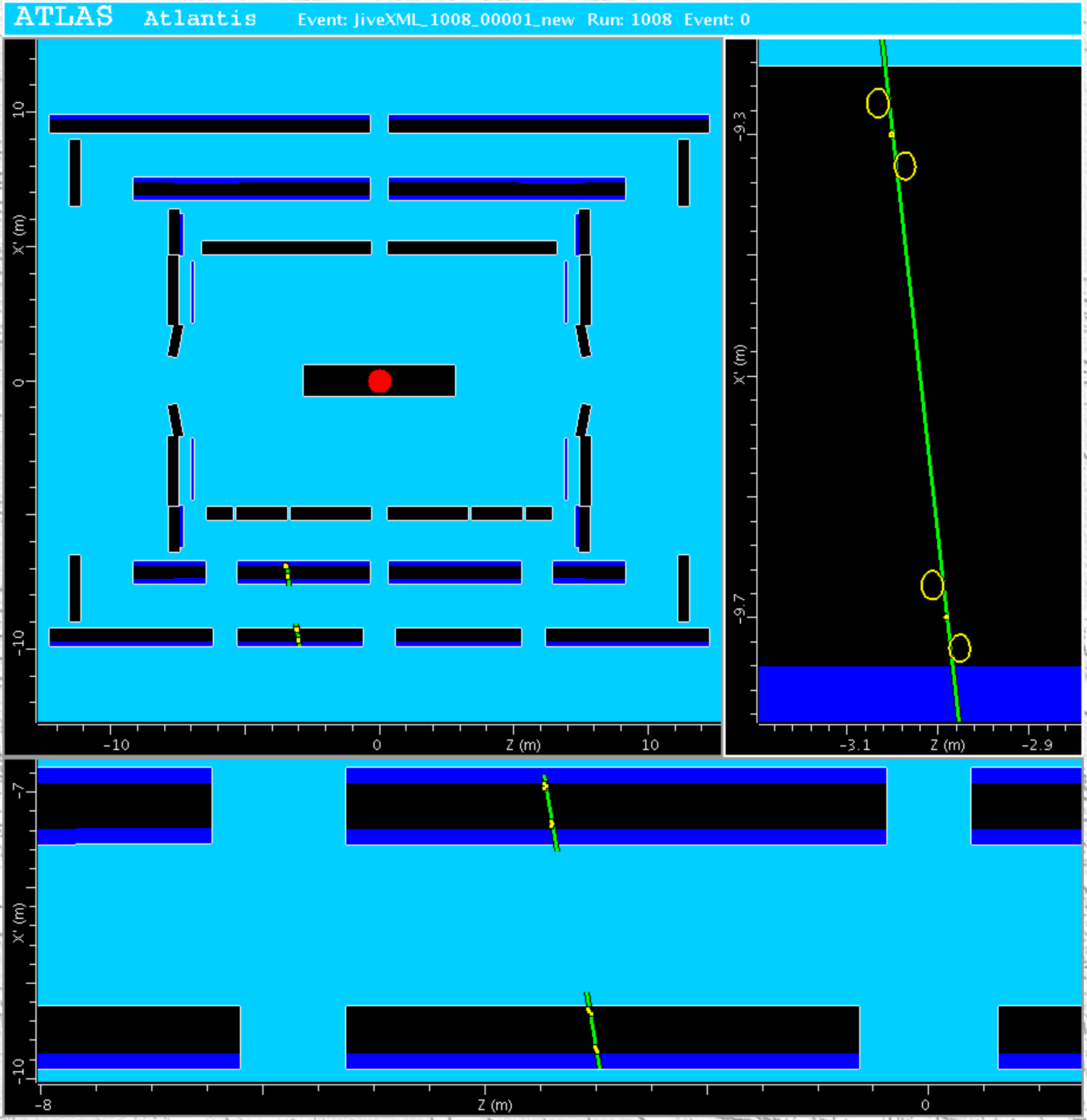
- approx. 2000 CPUs
- easily scaleable
- staged (lower lumi & saves money)
- uses offline software

The longest journey starts with the first step…

Just before Christmas:

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





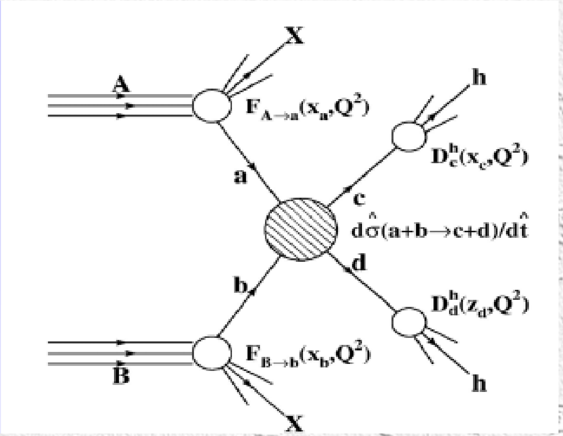
Possible LHC Schedule

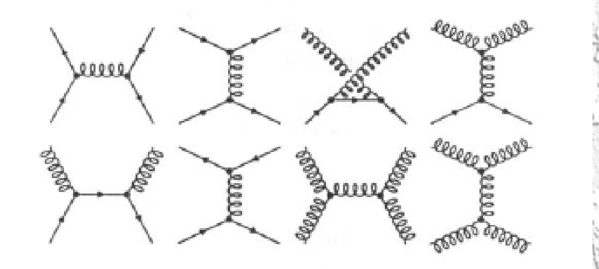
- 2008 first physics year
  - machine closure April
  - first collisions in summer
    at 7 TeV proton energy
  - try to reach few × $10^{32}/cm^2/s$
  - $\leq 1\ fb^{-1}$
- 2008 - 2010 three years at 1 - $2 \cdot 10^{33}/cm^2/s$
  - $\geq 30\ fb^{-1}$ in total
  - important for precision physics and discoveries
- ≥ 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

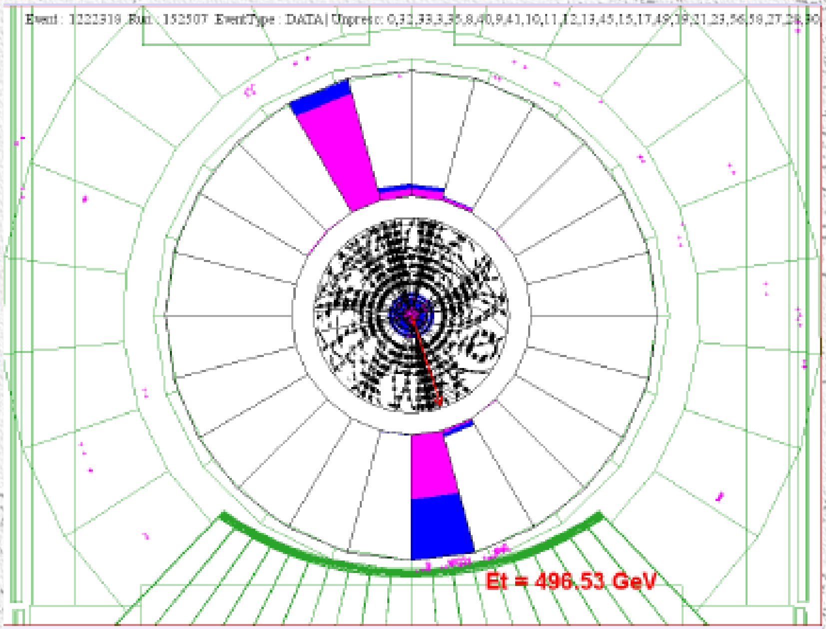




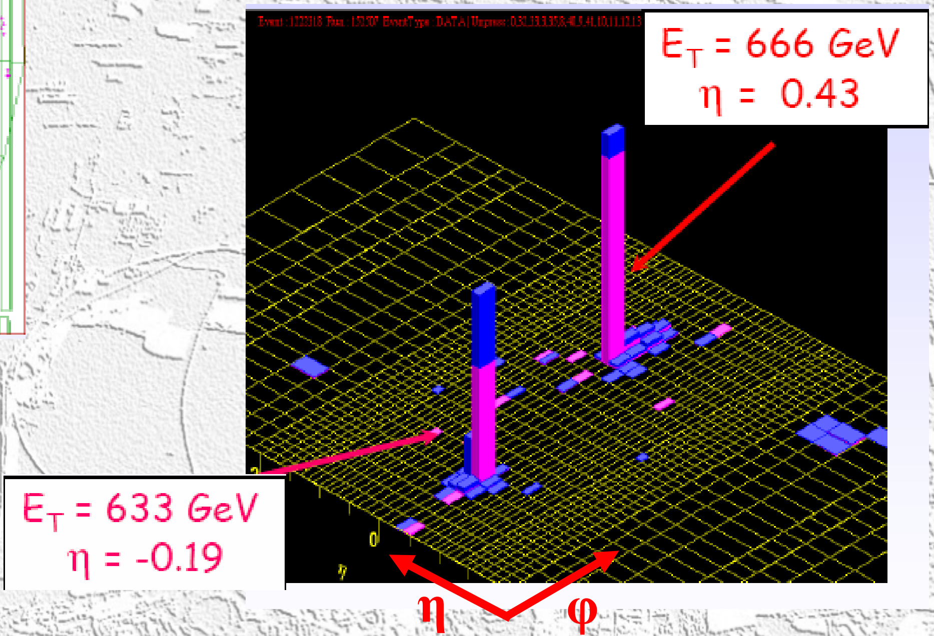
- Hard scattering processes dominated by QCD jet production
- Originating from quark-quark, quark-gluon and gluon-gluon scattering
- colored objects fragment
  → observation of jets with high p_T in the detectors
- Studies of jet production is important
  - test of the experiment
  - test of the theory, down to the smallest distances
  - new physics, e.g. quark substructure?

QCD and Jet Physics

A two-jet event at the Tevatron (CDF)



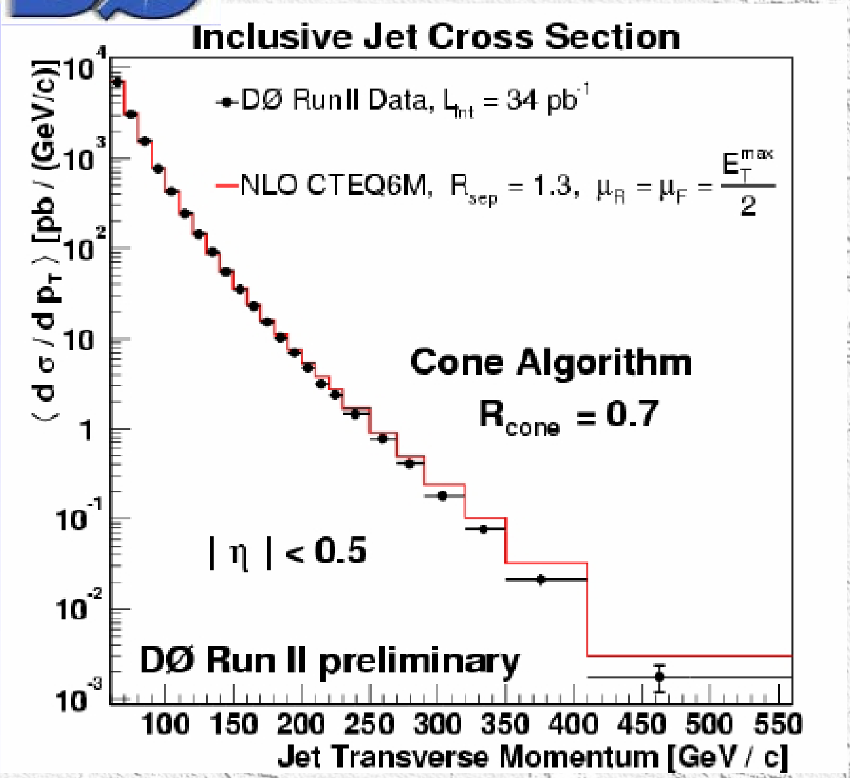
Lego-plot:
- project objects on ηφ -plane
- height of tower ~ energy



Mass of the di-jet system:

1.364 TeV

QCD and Jet Physics



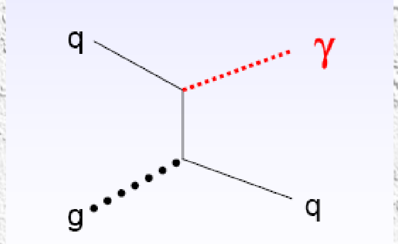
- Measured jet cross section versus ET:
  - comparison to theory
  - good agreement over many orders of magnitude

- theoretical errors
  - QCD higher order (difficult)
  - pdf

  measurement can be used to check pdf

- experimental errors
  - jet energy scale

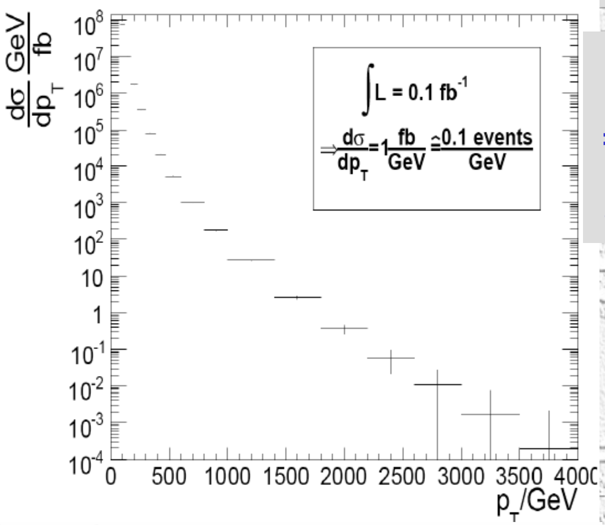
Calibration processes: γ+jet



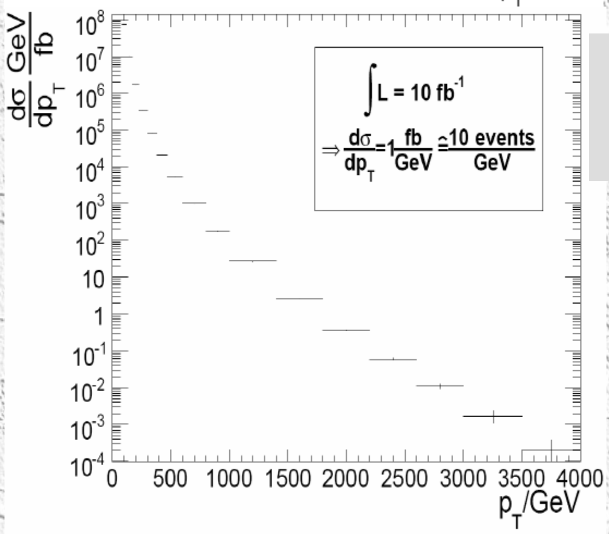
A jet is not a very well defined object:
- need algorithm to define it
- relation to parton energy → correction
- pile-up (LHC)

LHC Jet Physics

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

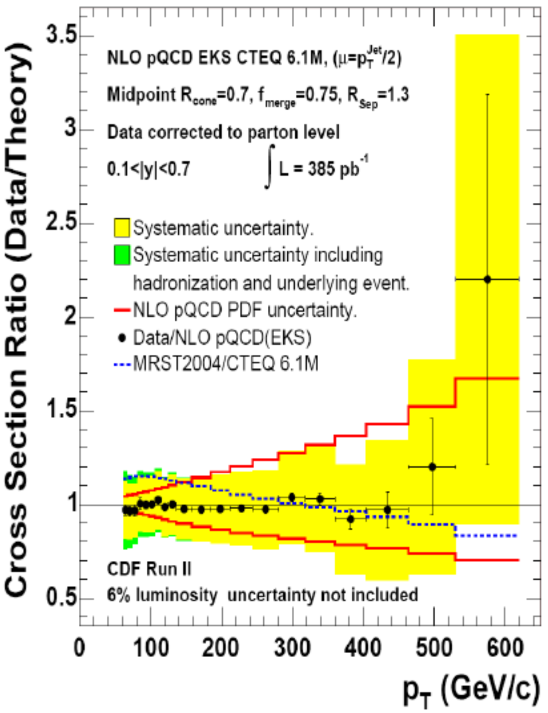


100 pb-1
= few weeks
at 14 TeV



10 fb-1
= 1 year

- compare to CDF result run II



- detector systematic effects expected to be similar to Tevatron

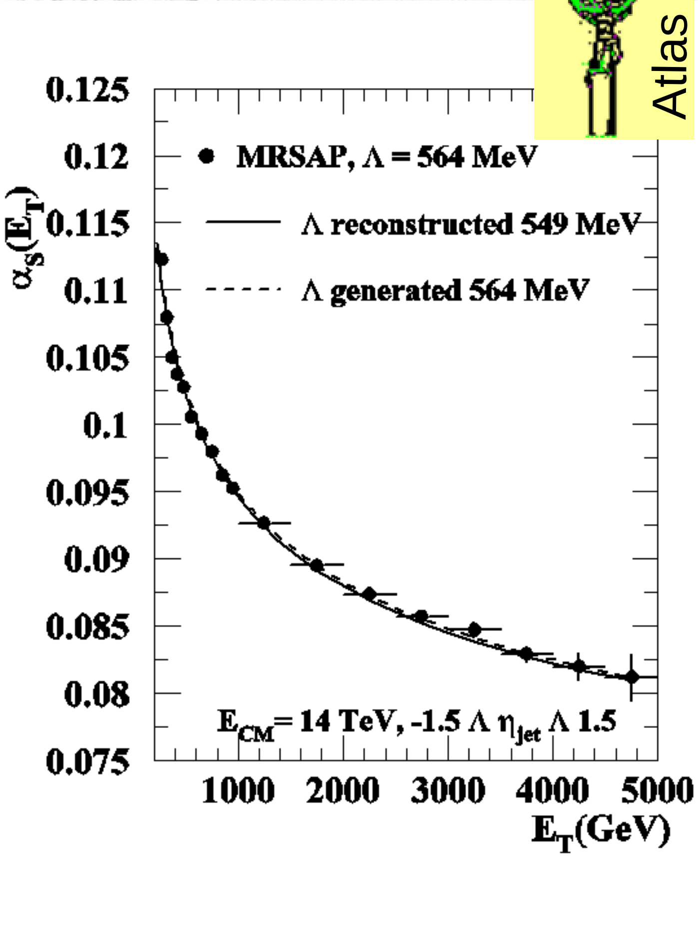
QCD

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
- ➢ **$\alpha_s = 0.118$ at m_Z**
- ➢ **$\alpha_s \approx 0.082$ at 4 TeV (QCD expectation)**

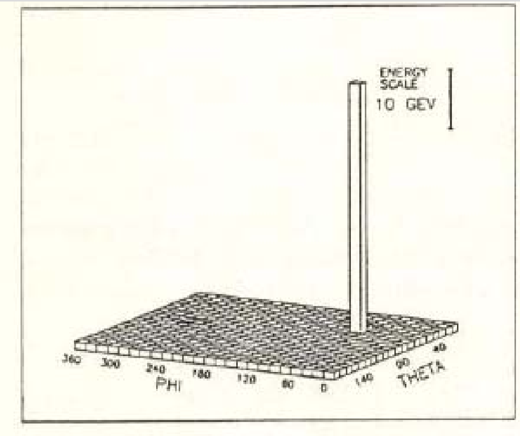


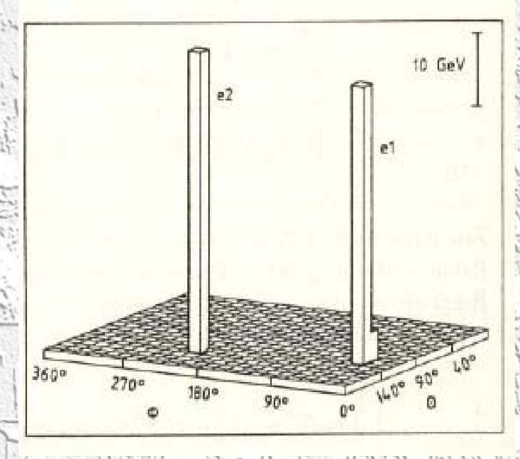
Atlas

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





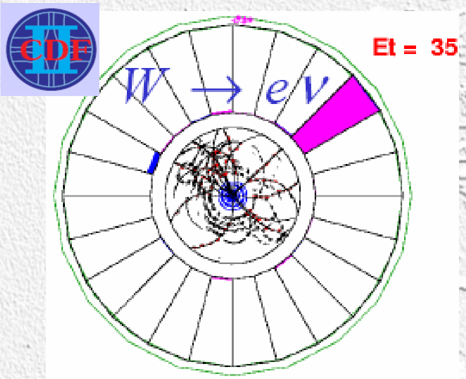
How do W/Z events look like at proton colliders?

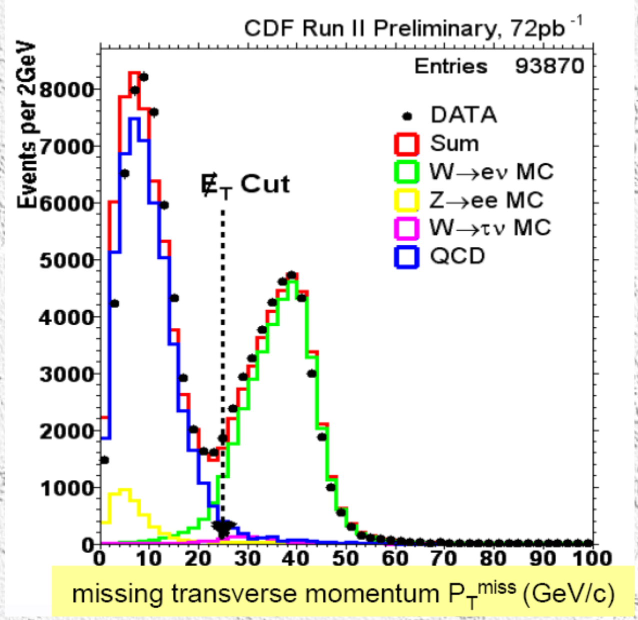
Use leptonic decays (electrons & muons)

- **W →lν** — **high p_T lepton + missing E_T**
- **Z → 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

$Z \to ee$

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

$W \to e\nu$

- Missing transverse momentum > 25 GeV/c

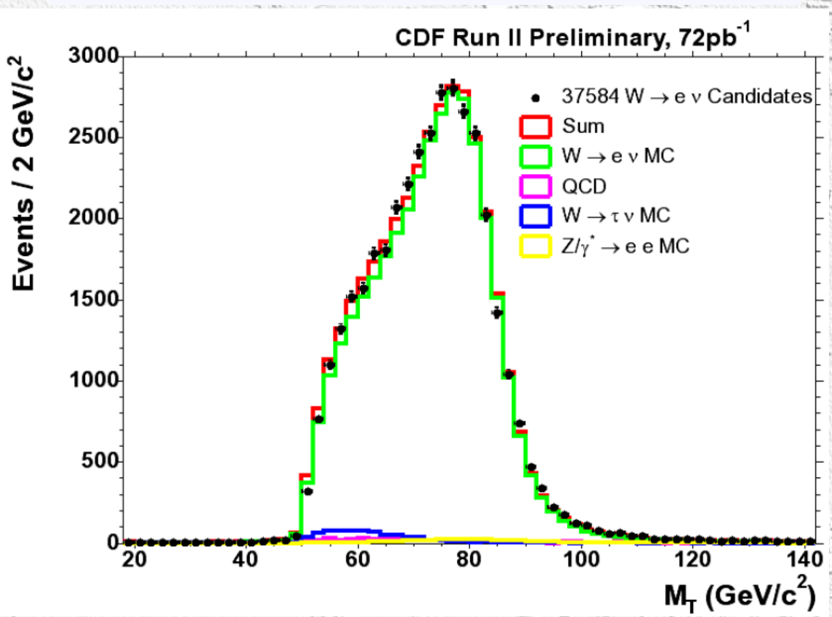
Separation of $W \to l\nu$ events from background

Mass of the W

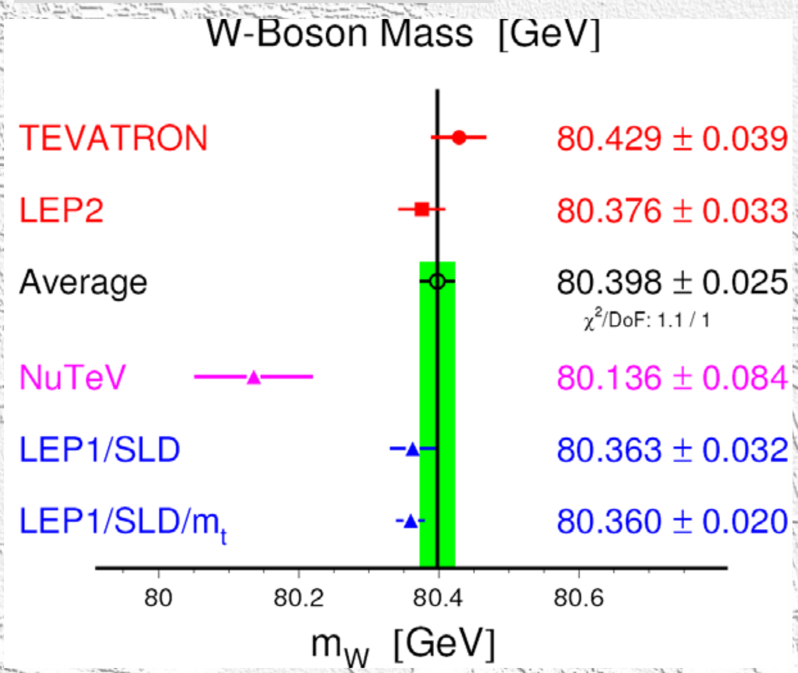
- precision measurement at proton colliders possible
- results competitive to LEP experiments

- 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

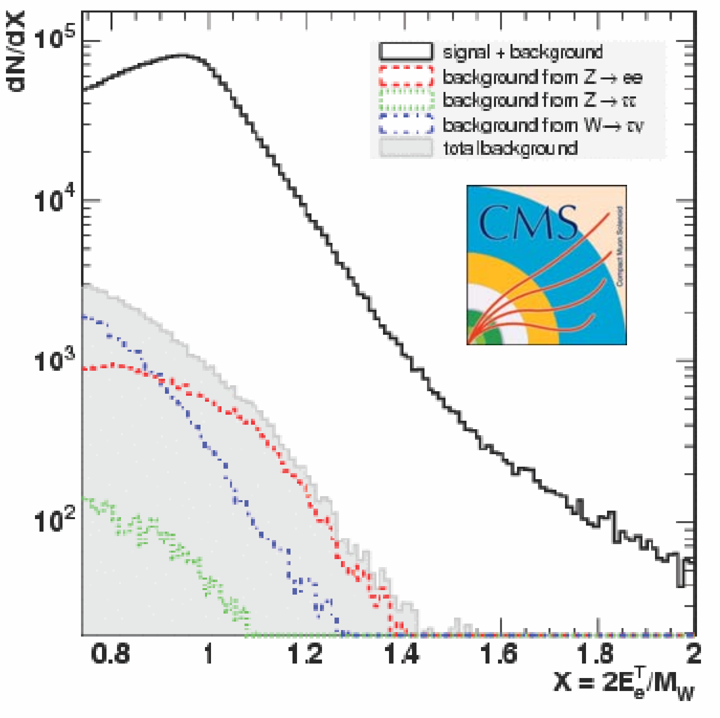


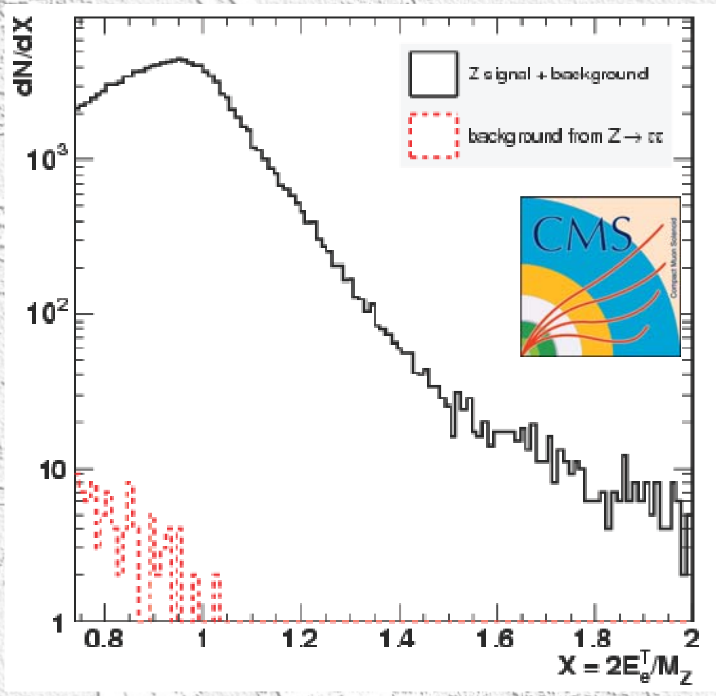
- $3 \cdot 10^{-4}$ rel. precision on m_W
- Tevatron results will improve with increasing Run II statistics

- main challenge: electron/muon energy scale
- use $Z \to ee$, $\mu\mu$ 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

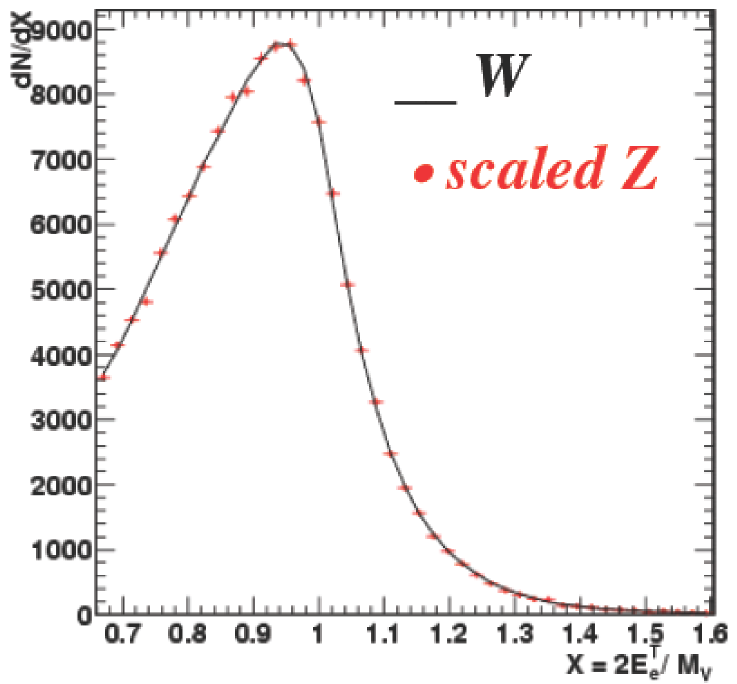
$O_V = E^T, M^T$ distributions are scaled according to

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

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

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

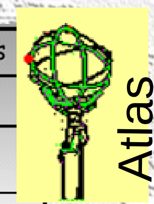
- NNLO calculations (p_T spectra) probably needed to achieve the required precision



W Mass at the LHC

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

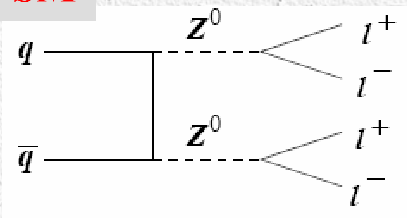
2007: $m_W = 80\,398 \pm 25$ MeV **LEP & Tevatron Run I/II**

2009: $m_W \approx 80\ \ldots\ \pm 20$ MeV ($2.5 \cdot 10^{-4}$) **expected after Tevatron Run II**

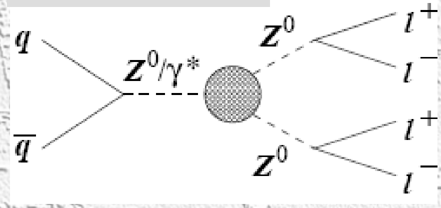
Di-Boson Production at the LHC

- very interesting: WW,ZZ final states not yet observed at the Tevatron
  first WZ events observed early 2007
- test triple gauge boson couplings (TGC)
  - γWW and ZWW precisely fixed in SM
  - γZZ and ZZZ do not exist in SM!

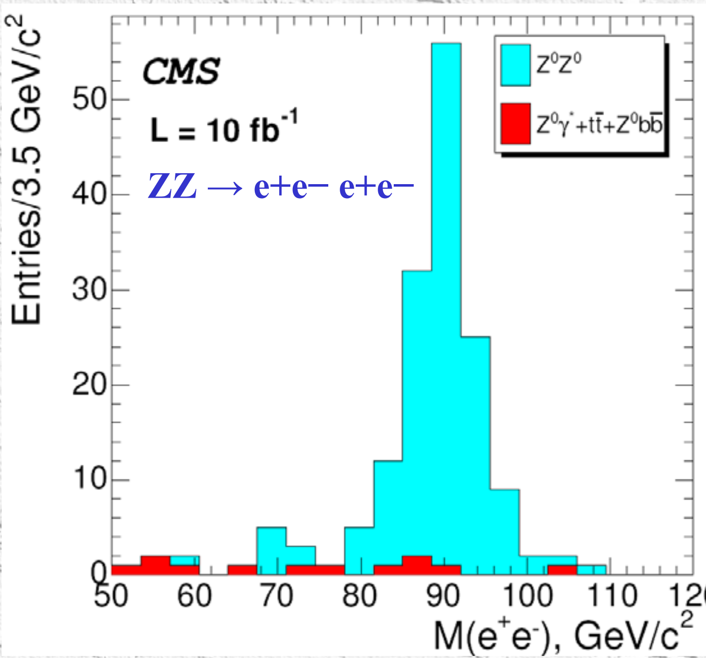
SM

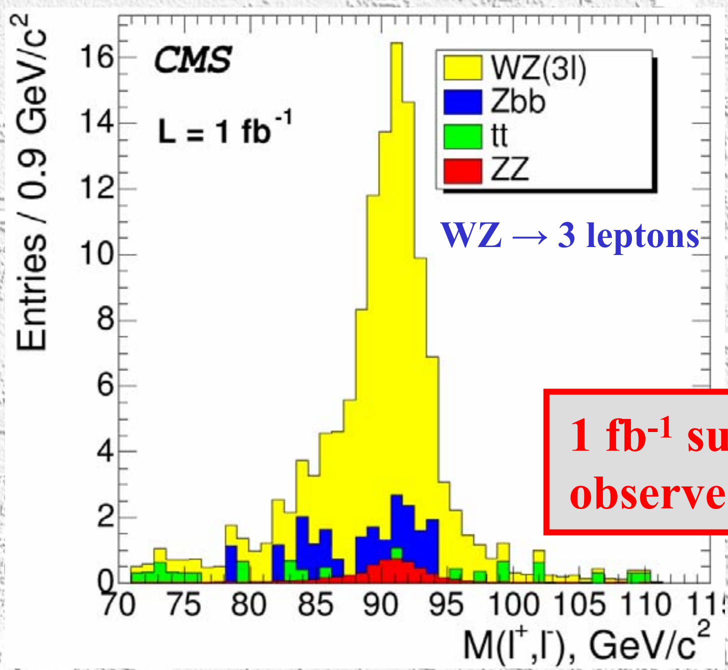


New physics



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



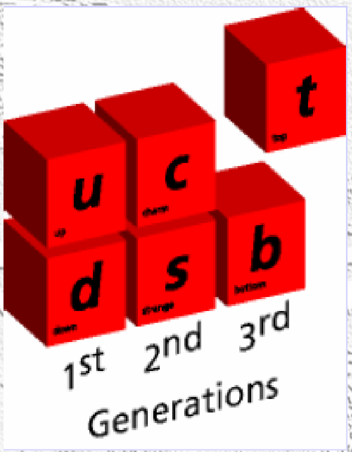


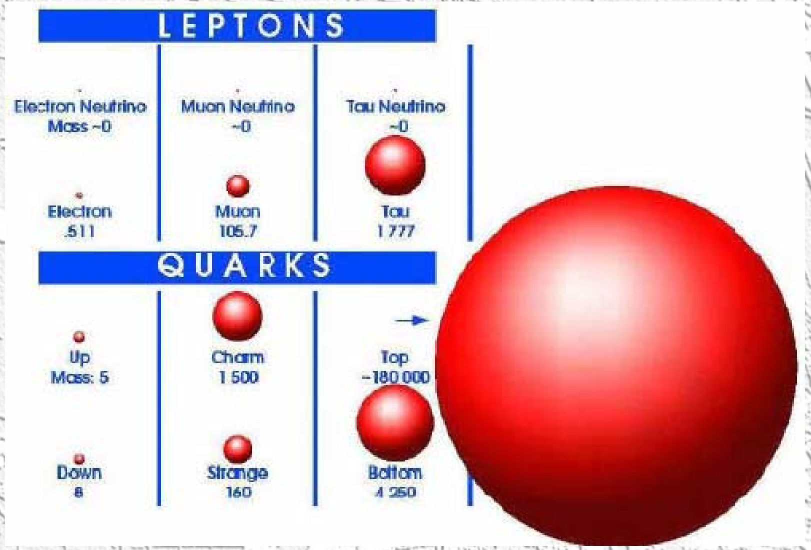
1 fb^{-1} sufficient to observe both processes

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 its decay products

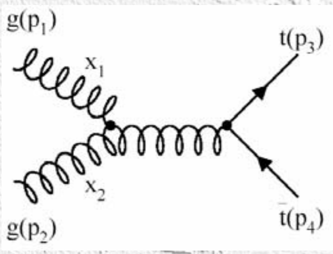


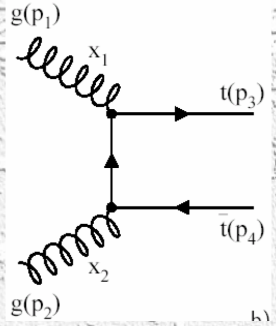


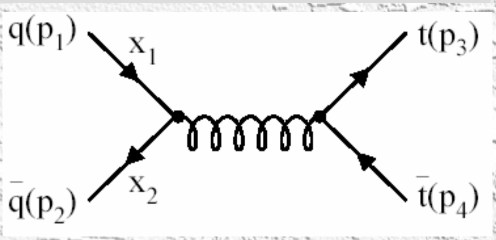
Top Quark Production

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

gluon fusion **quark annihilation**





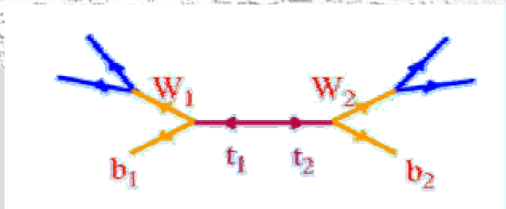


Tevatron: mainly quark annihihaltion O(90%)
LHC: mainly gluon fusion O(90%)

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

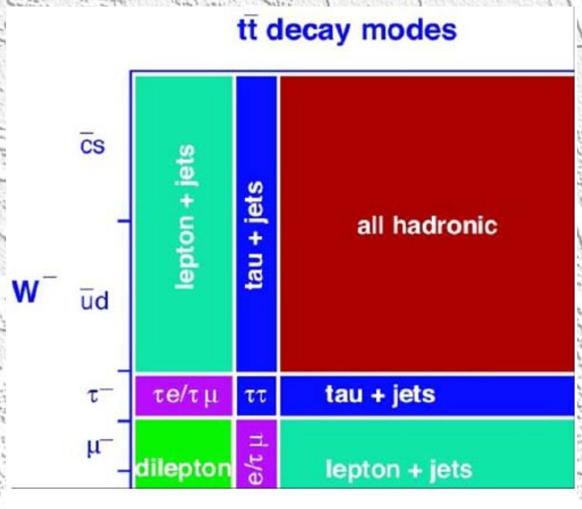


- Top decay: ≈ 100% $t \rightarrow bW$
- Other rare SM decays:
  - CKM suppressed $t \rightarrow sW, dW$: $10^{-3} - 10^{-4}$ level
  - $t \rightarrow bWZ$: $O(10^{-6})$

    difficult, but since $m_t \approx m_b + m_W + m_Z$ sensitive to m_t
- & non-SM decays, e.g. $t \rightarrow bH^+$

In SM topologies and branching ratios are fixed:

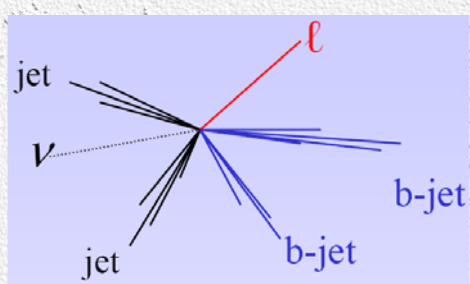
- expect two b-quark jets
- plus W^+W^- decay products:
  - 2 charged leptons + 2 neutrinos
  - 1 charged lepton + 1 neutrino + 2 jets
  - 4 jets (no b-quark!)



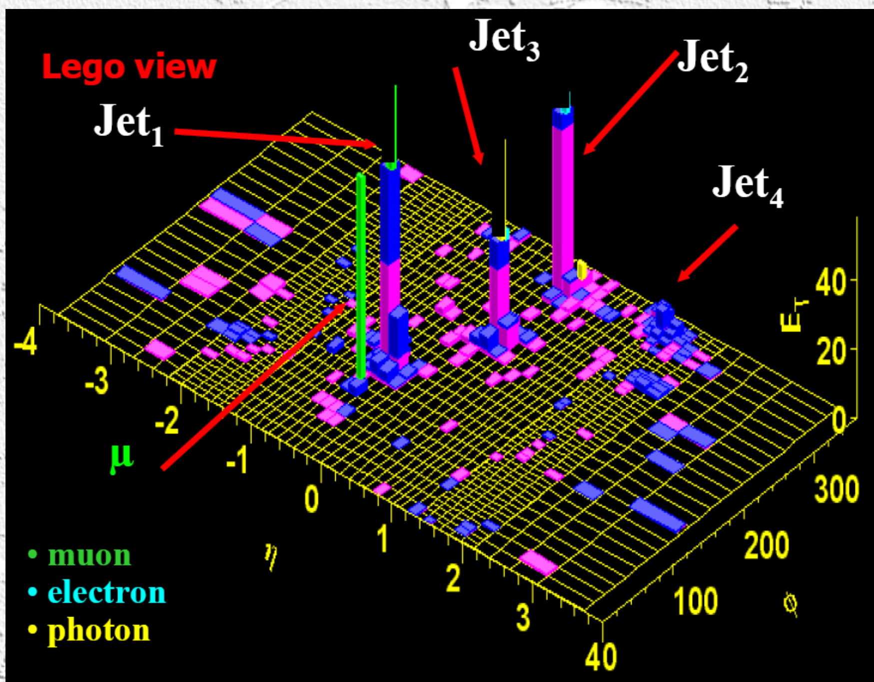
$t\bar{t} \rightarrow l\nu l\nu bb$	5%	$(e+\mu)$
$t\bar{t} \rightarrow l\nu qqbb$	30%	$(e+\mu)$
$t\bar{t} \rightarrow qqqqbb$	46%	

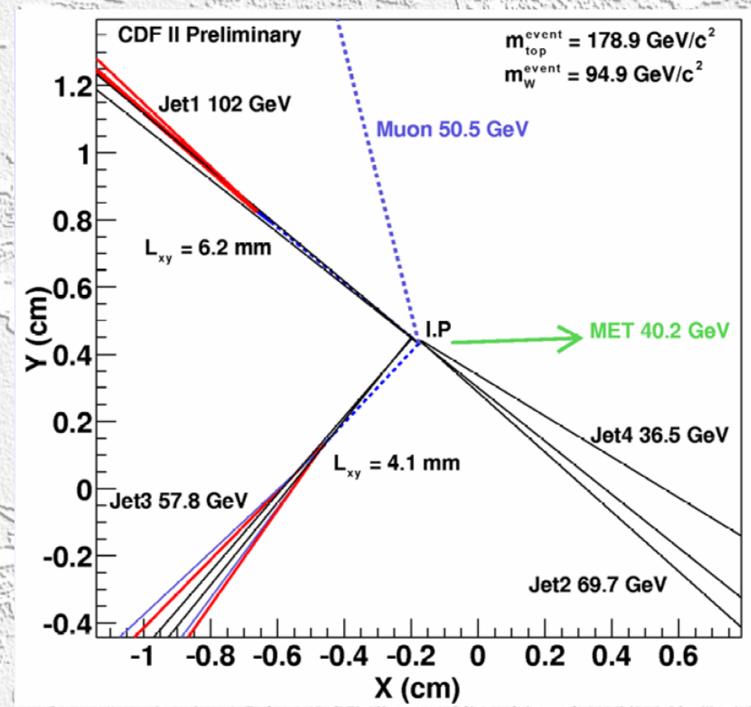
A Top-Pair Event at CDF

- semi-leptonic channel



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



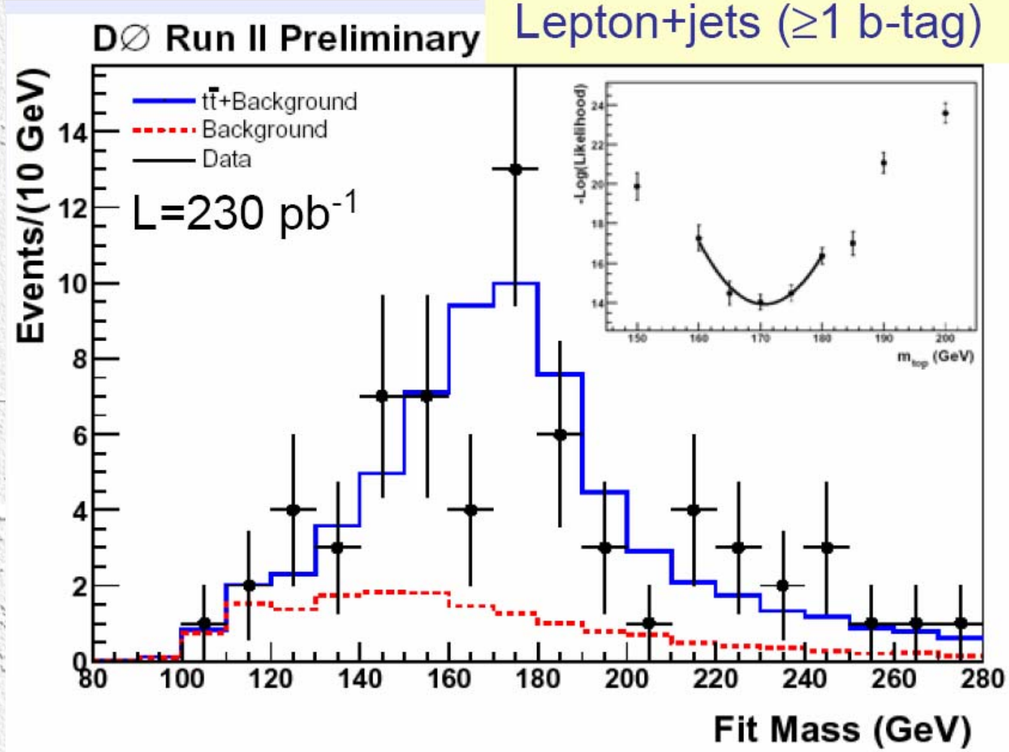


Top Mass Measurement

- 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

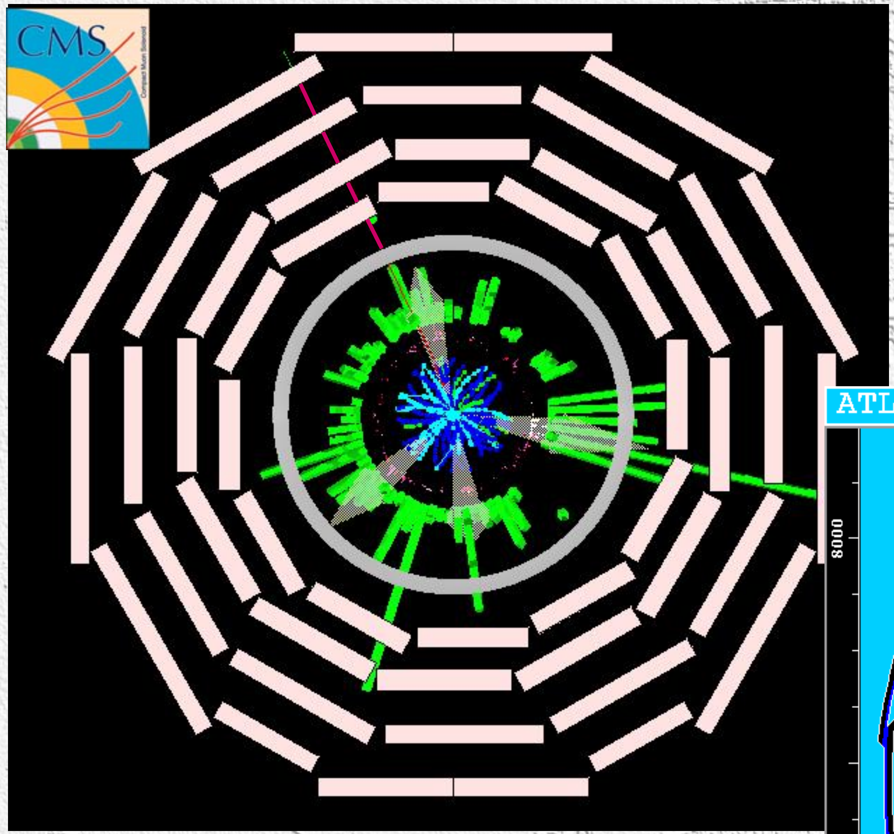
Result from D0:



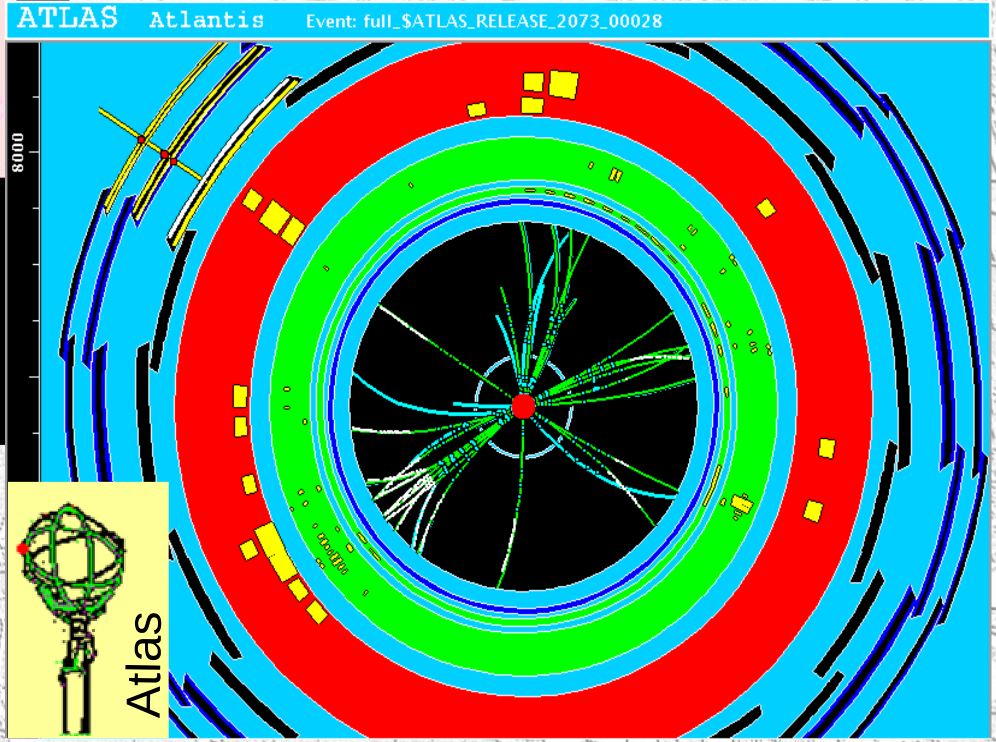
Combined Tevatron measurement

$m_t = 170.9 \pm 1.8$ GeV

Top Quarks at the LHC



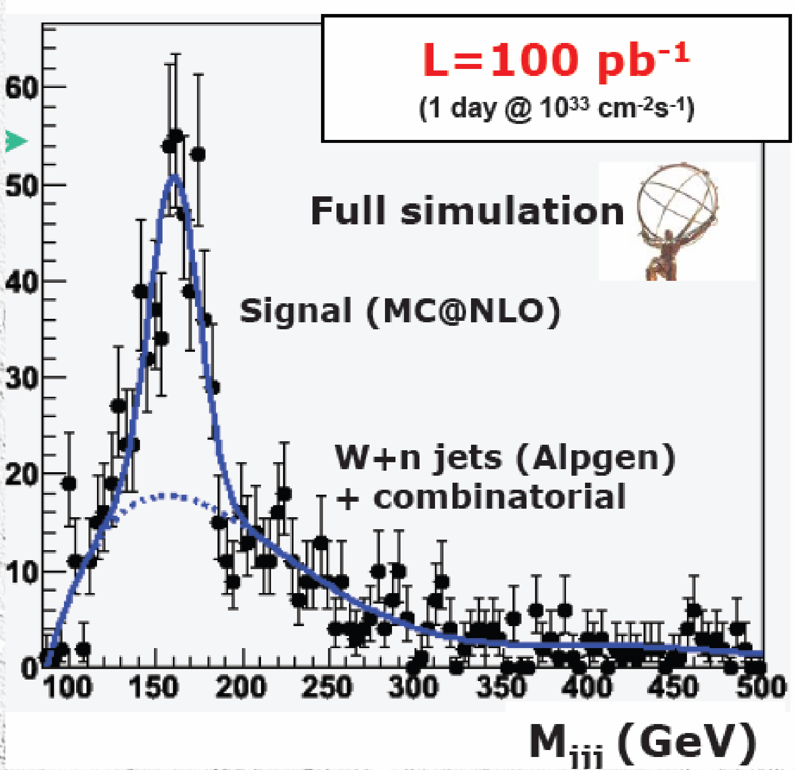
Examples of simulated tt → bb qq μν events from CMS & ATLAS



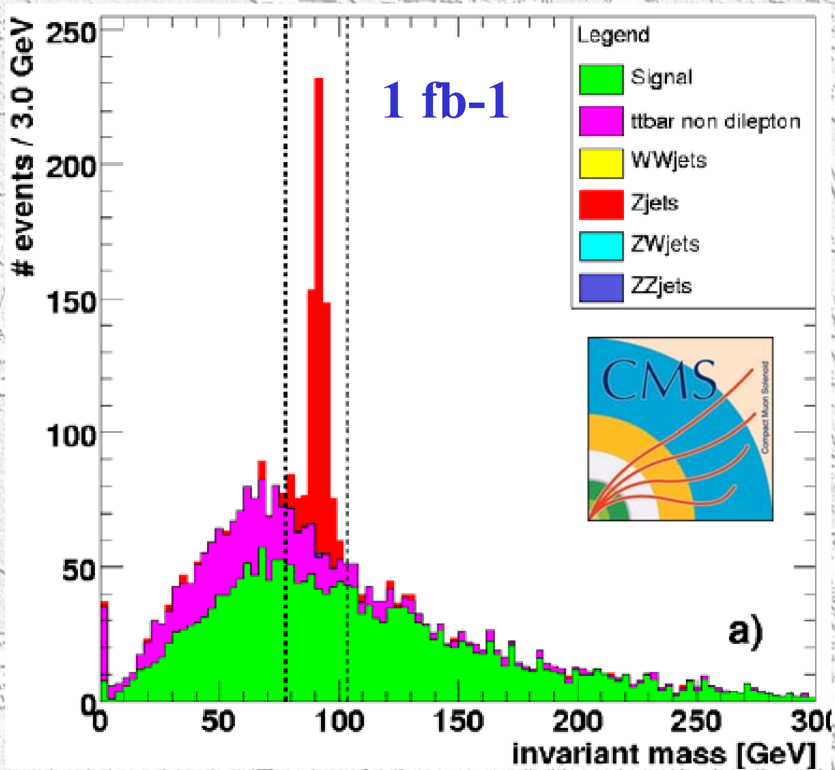
Top Mass at the LHC

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

- **Semi-leptonic events**



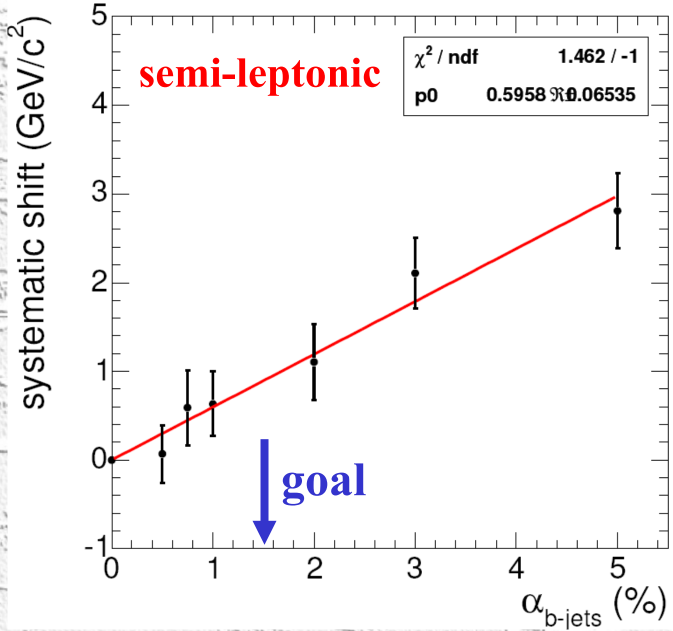
- **Di-leptonic events**

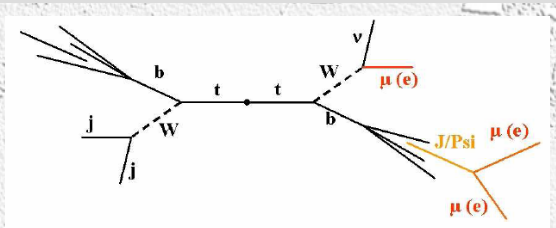


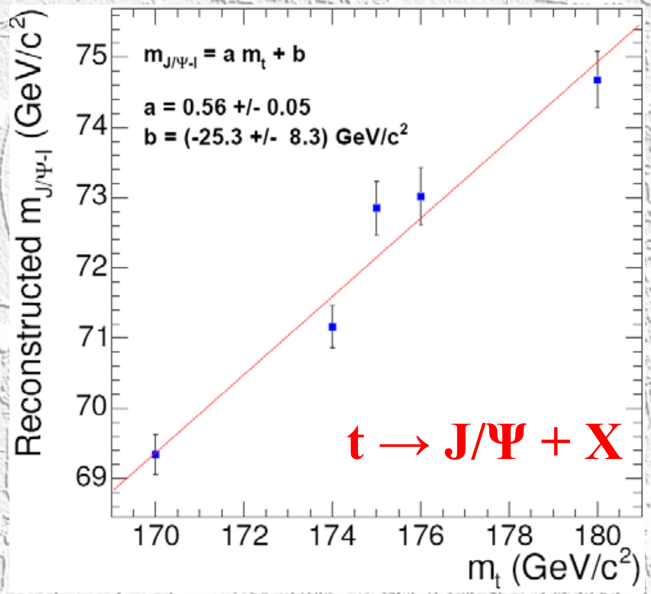
Top Mass at the LHC

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 $t \rightarrow J/\Psi + X$ decays**
  low stat., but different systematic
  partial reconstruction J/Ψ + lepton from W





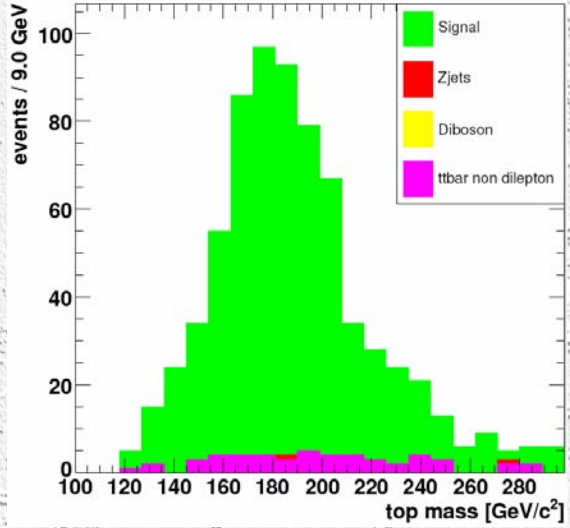


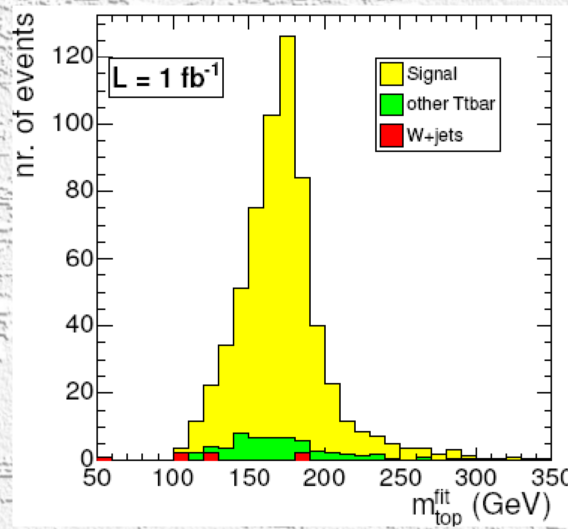
Top Mass at the LHC

Recent detailed studies by CMS:

di-leptonic

± 1.2 GeV



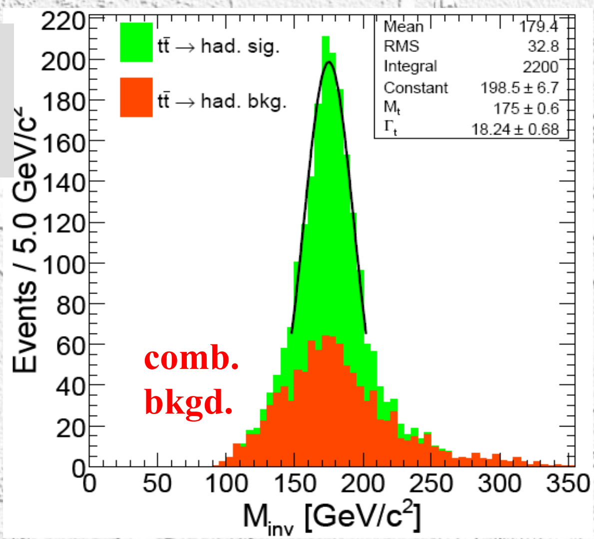


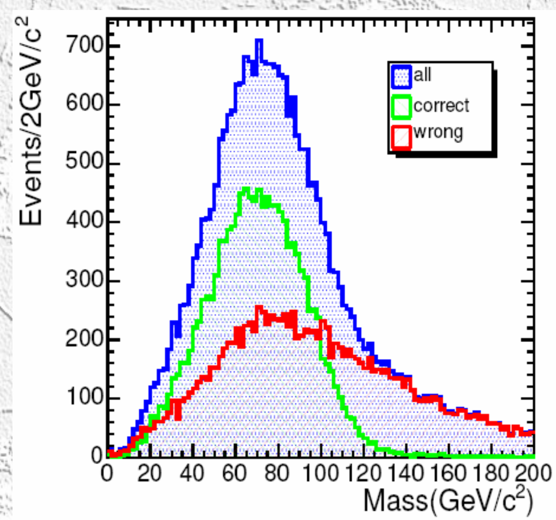
semi-leptonic

± 1.2 GeV

fully hadronic

± 2 GeV





$t \rightarrow J/\Psi + l + X$

± 1.5 GeV

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

Search for Higgs Bosons

Emphasis on SM Higgs

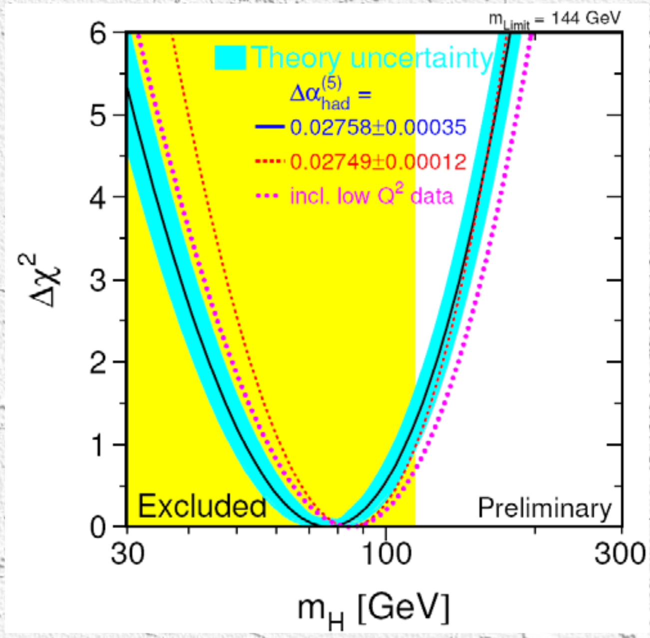
Standard Model Higgs Boson

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

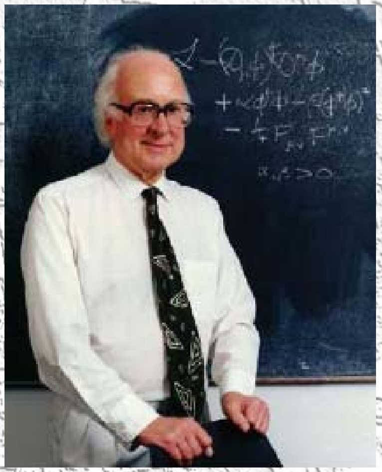
$$m_H > 114.4 \text{ GeV}$$

- electroweak precision measurements (incl. m_t measurement)



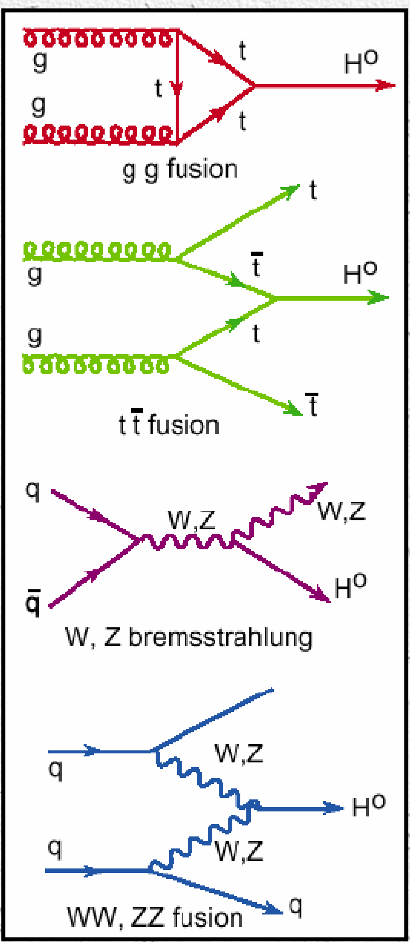
⇒ $m_H < 144$ GeV (95% CL)

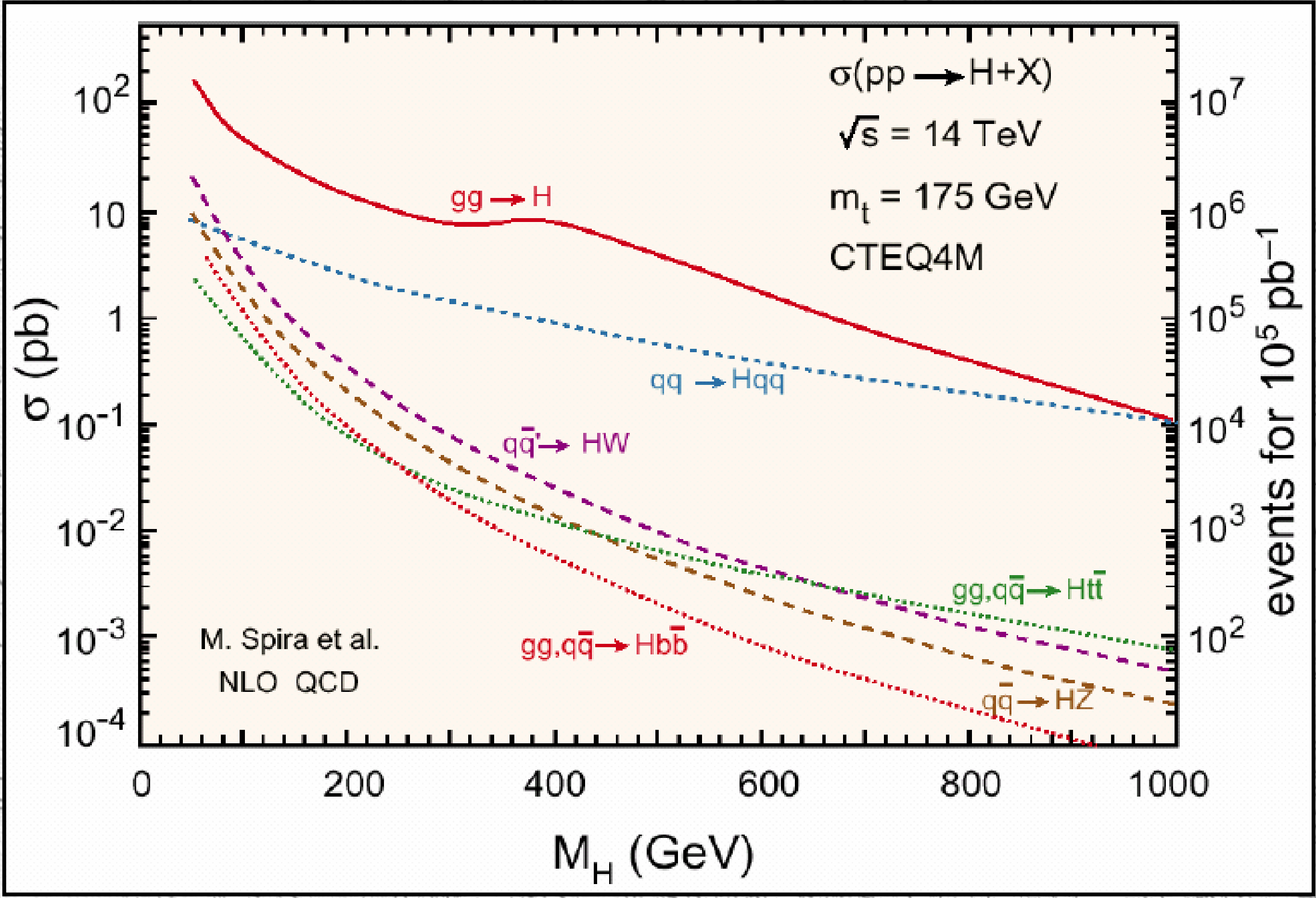
⇒ the Higgs should be around the corner!



Higgs Boson Production at the LHC

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



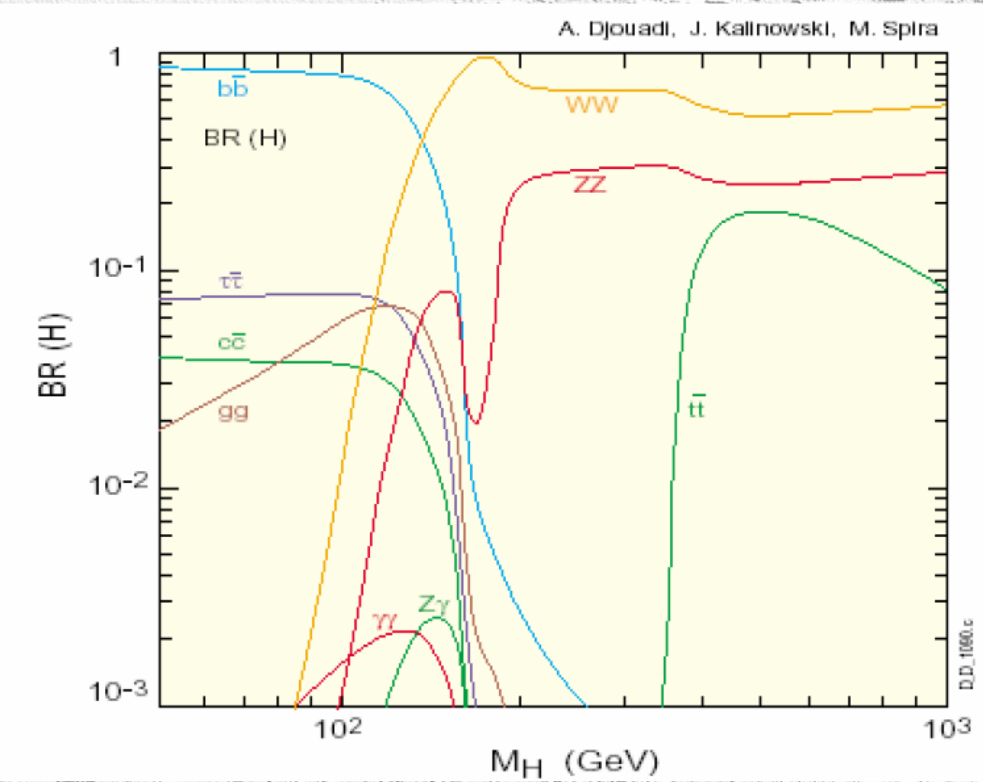


- **Gluon-gluon fusion and W, Z fusion are dominant**
- **Cross section at the Tevatron almost factor 100 smaller!**

Higgs Boson Decay

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

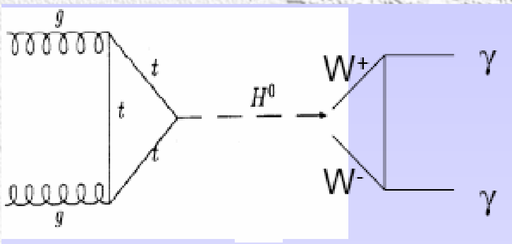
Branching ratio versus m_H:



- **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 preferred low mass region, i.e. $m_H < 140$ GeV?
- use $H \rightarrow \gamma\gamma$
- very low branching ratio $O(10^{-3})$
- but clean signature



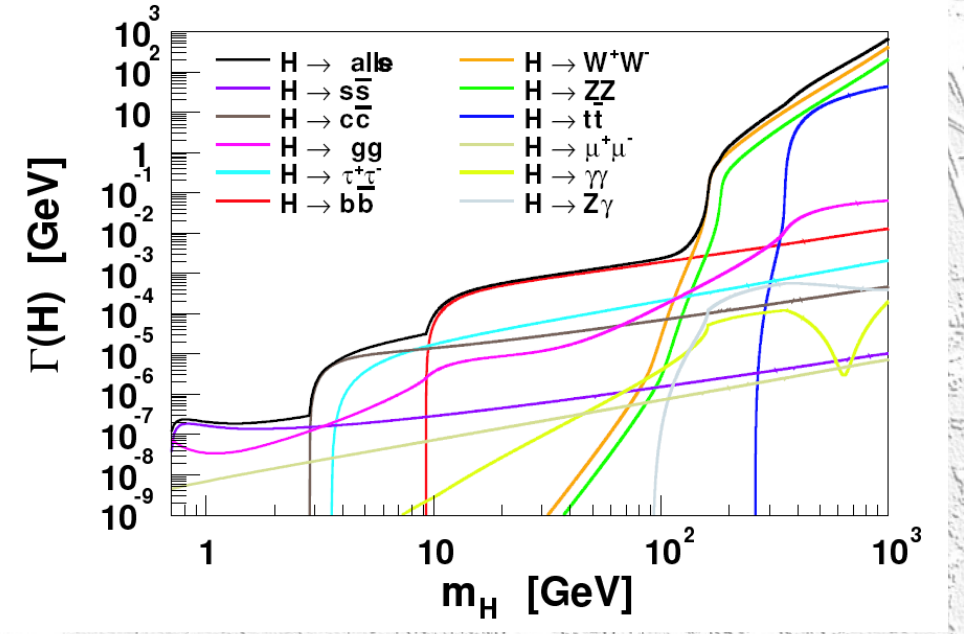
internal loop with heavy charged particle
W boson or top quark

Total width of the Higgs (= inverse lifetime)
- at low masses Higgs is a very sharp resonance

$$\Gamma_H << 1 \text{ MeV}$$

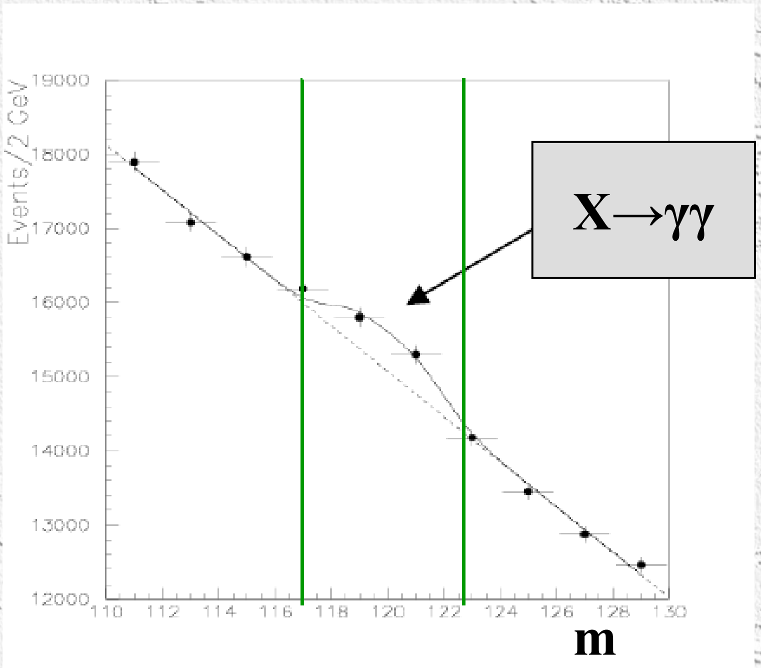
- Γ_H explodes once $H \rightarrow WW, ZZ$ open up for $m_H \rightarrow 1$ TeV

$$\Gamma_H \approx m_H$$



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 $1/\sqrt{2}$

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

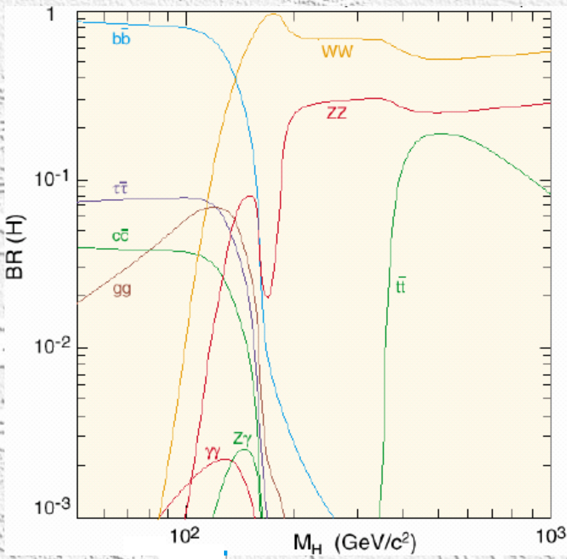
holds until $\sigma_m \approx \Gamma_X$

2. Luminosity

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

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

Search for the Higgs Boson



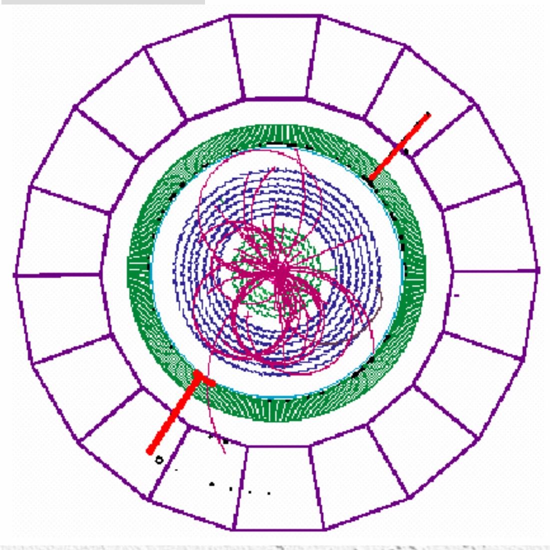
LEP:

$H \rightarrow bb$

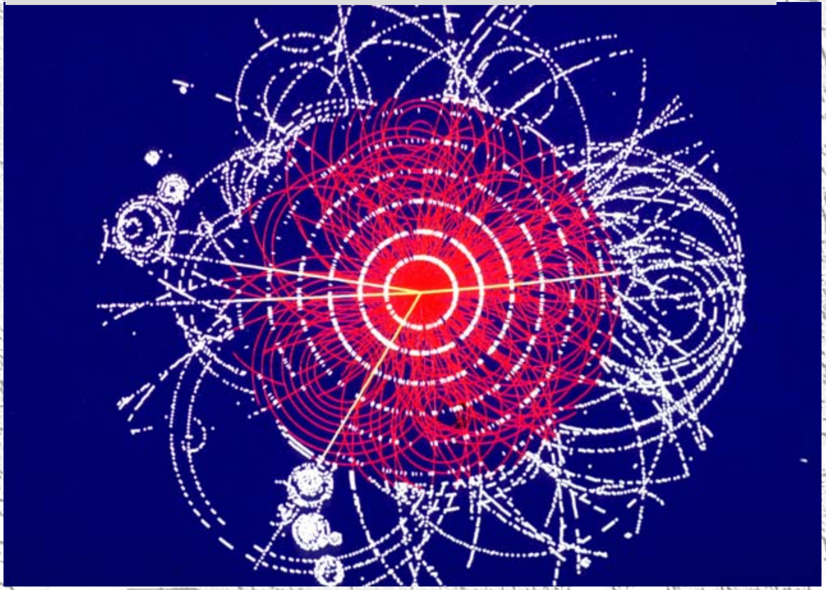
LHC:

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

$H \rightarrow \gamma\gamma$



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

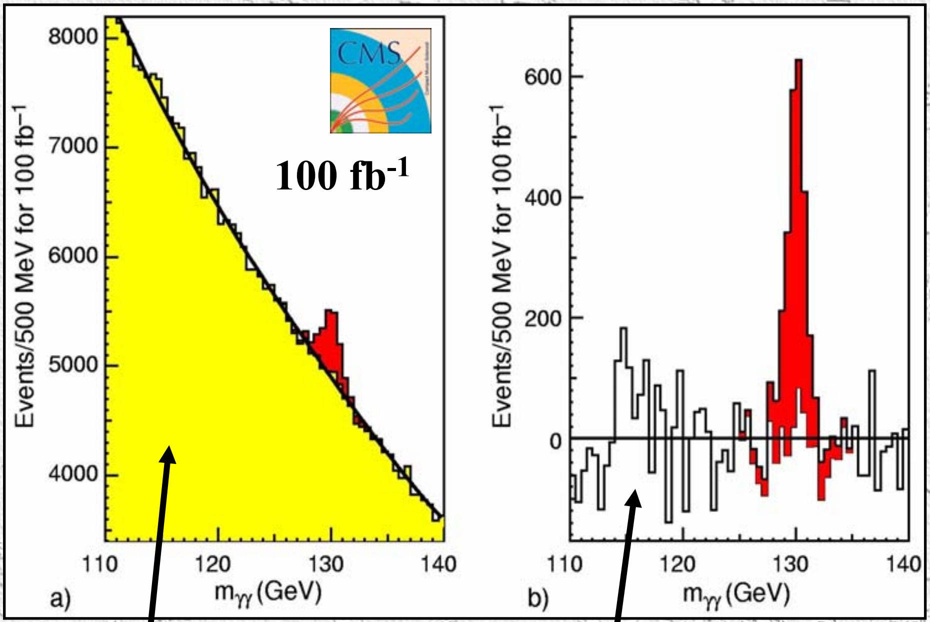


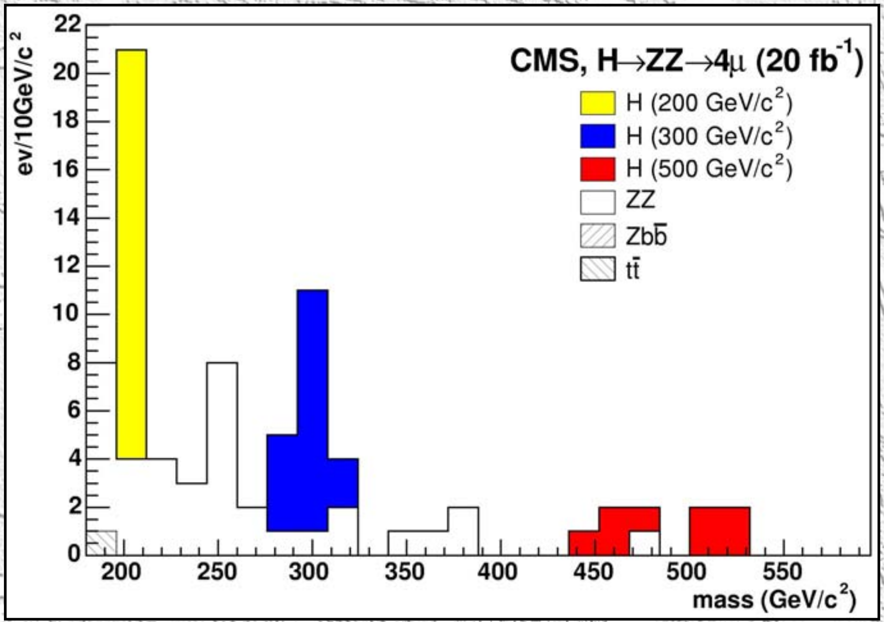
Search for the Higgs Boson at LHC

Possible future Higgs discovery plots:

H → γγ:
m_H = 130 GeV
$\sigma_{mH} \approx$ 1 GeV

H → ZZ → 4μ:
m_H = 200 (300, 500) GeV





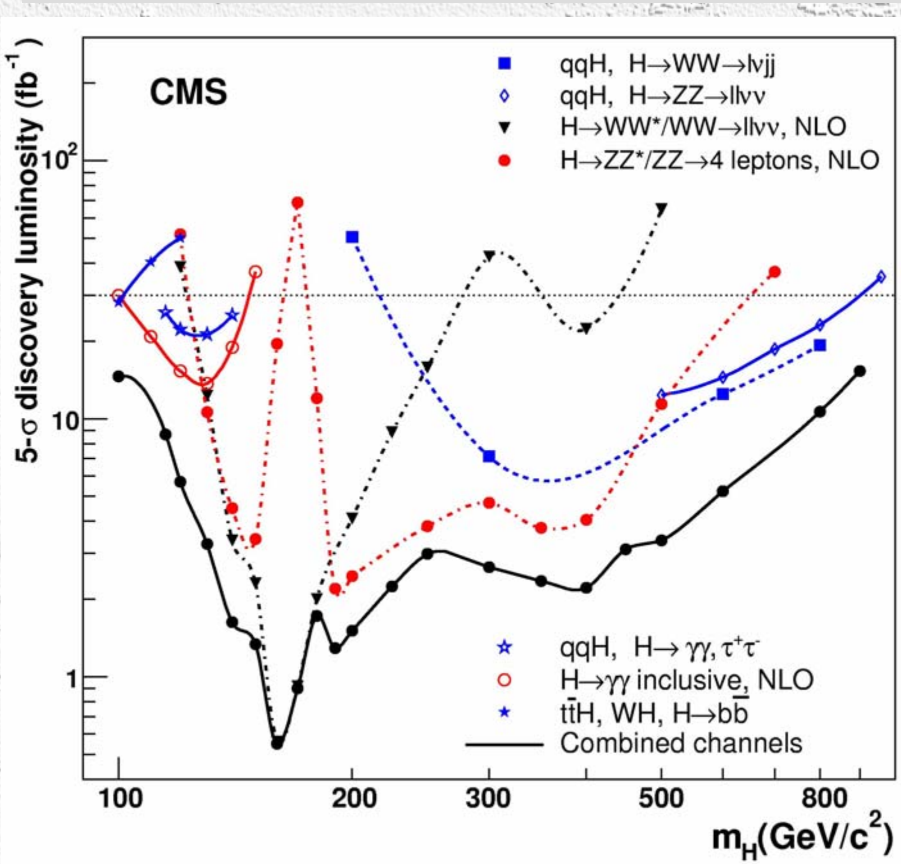
large combinatorial background

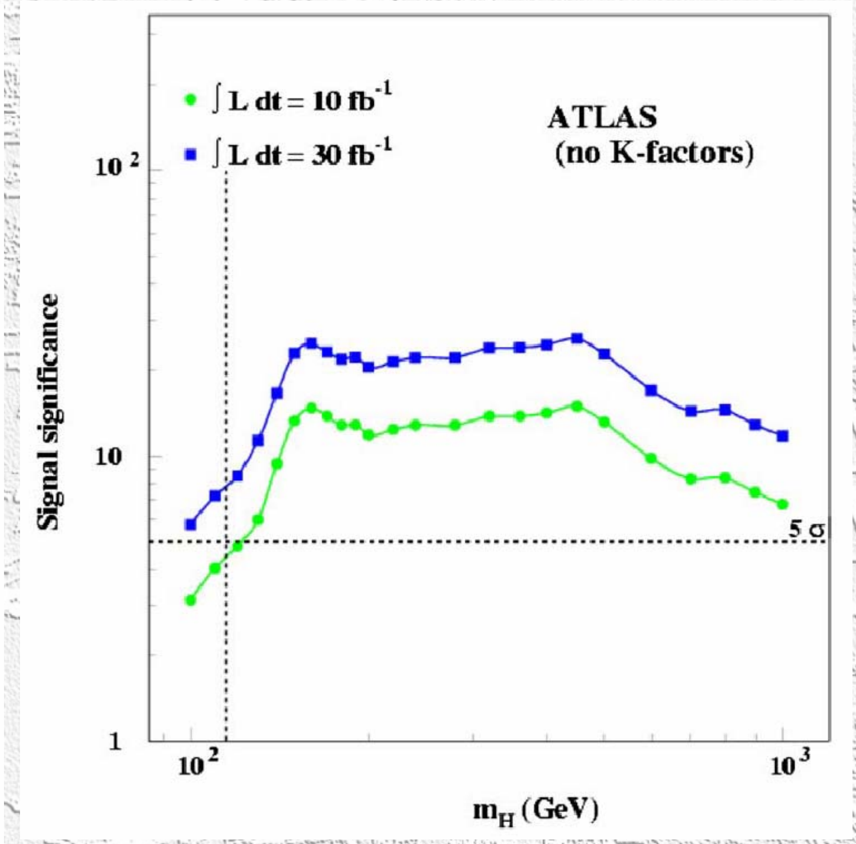
background subtracted

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:





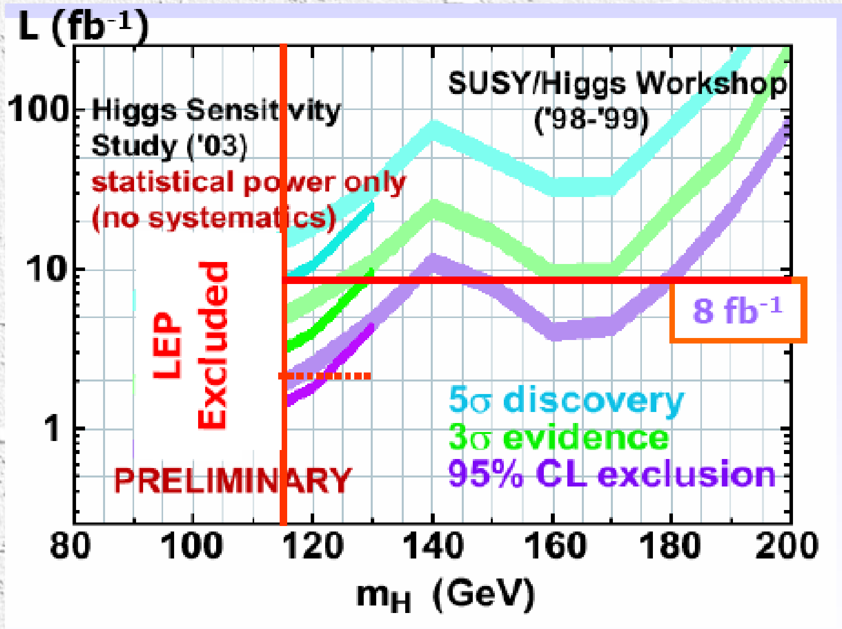
$10\ fb^{-1}$ sufficient for 5 σ discovery of the Higgs corresponds to 1 year at low luminosity $10^{33}/cm^2/s$

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 $\Delta s = ½$

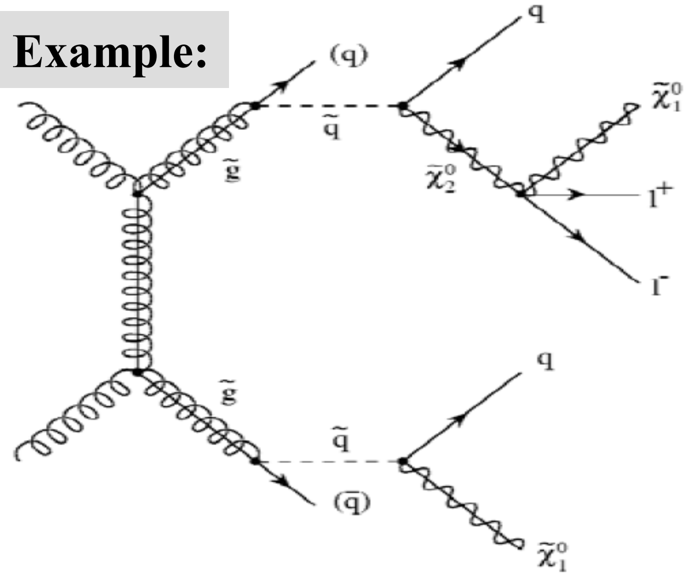
Ex. :	q (s=1/2)	$\rightarrow$	$\tilde{q}$	(s=0)	squarks
	g (s=1)	$\rightarrow$	$\tilde{g}$	(s=1/2)	gluino

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:

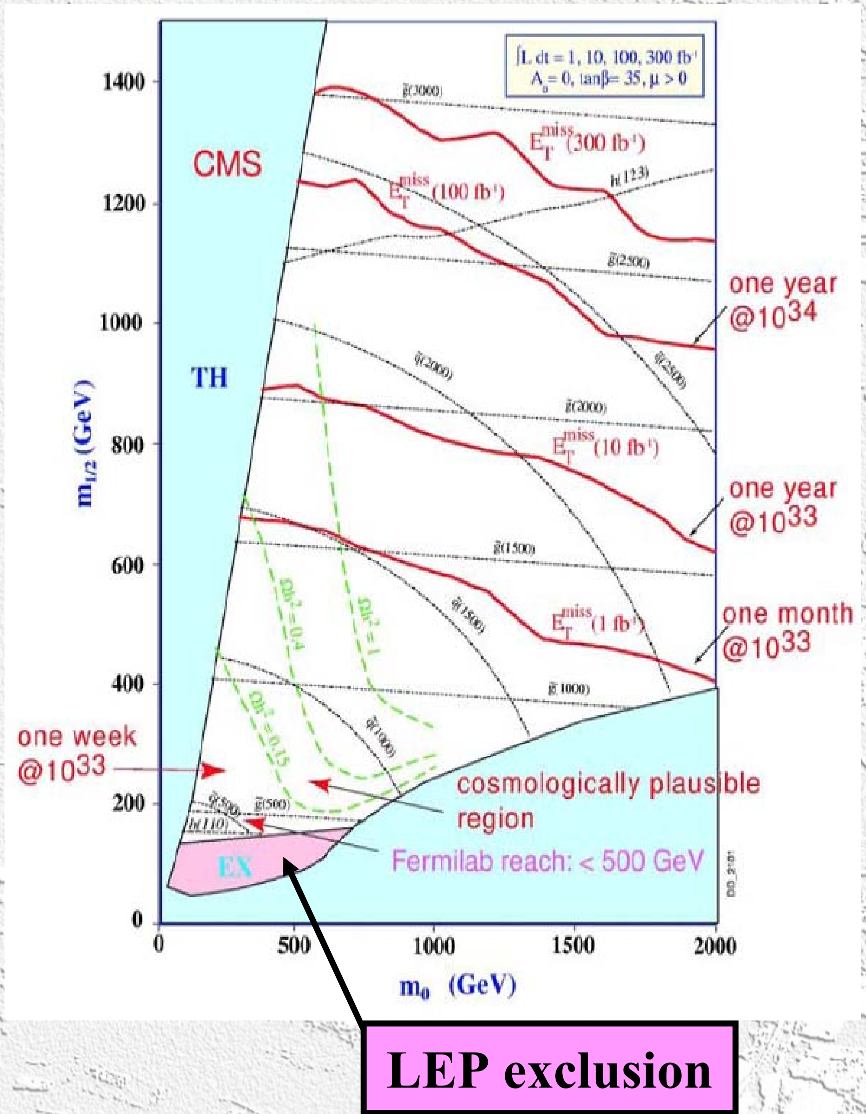
- leptons, jets and missing E_T
- depend of SUSY particles prodcued, on their branching ratios etc.

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



- **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