Experiments at the
Large Hadron Collider

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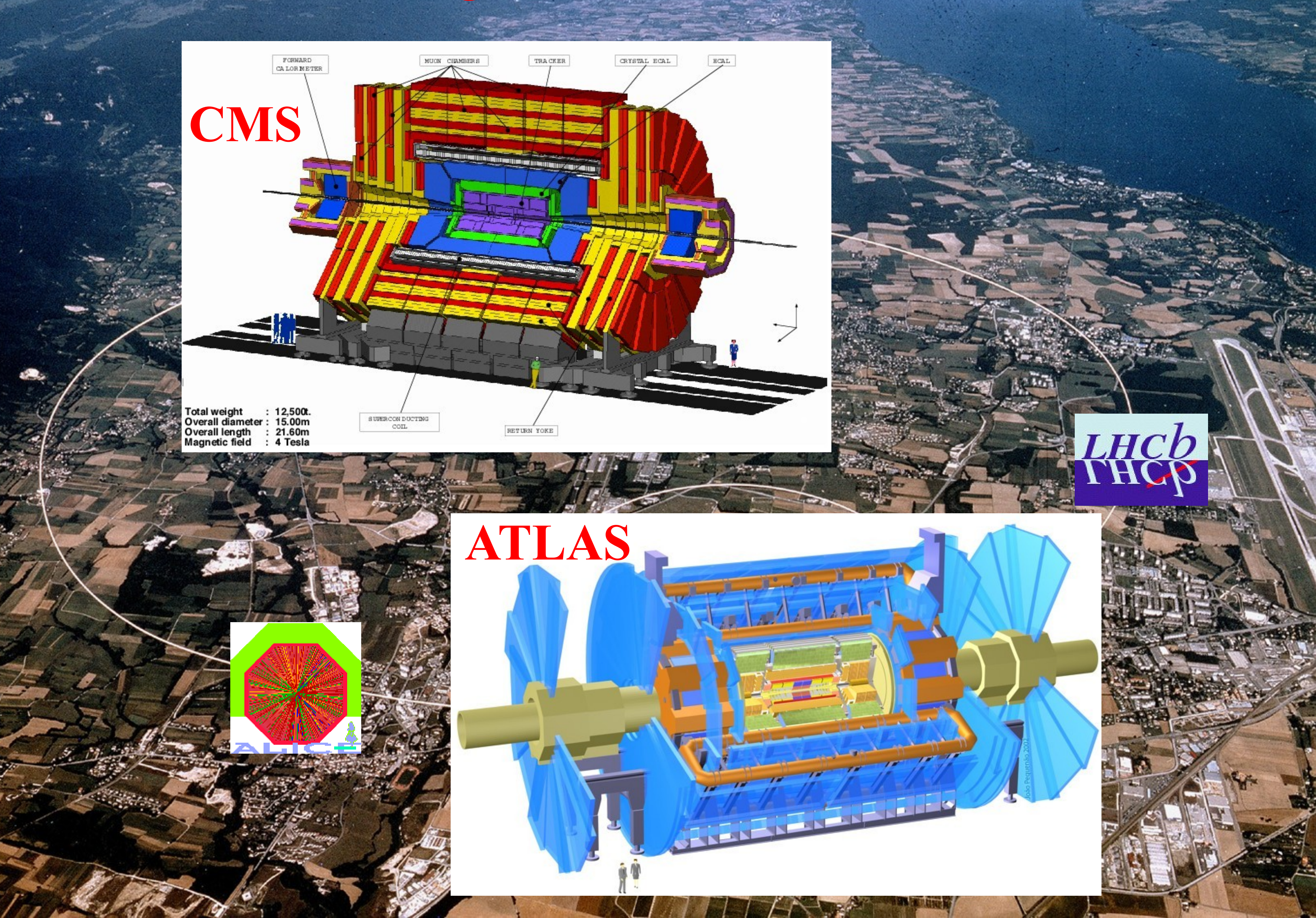
Outline

- The Large Hadron Collider
- The experiments
- Some examples for (early) physics
  - SM tests
  - SM Higgs search
  - SUSY(MSSM)
- LHC status and prospects

The Large Hadron Collider LHC



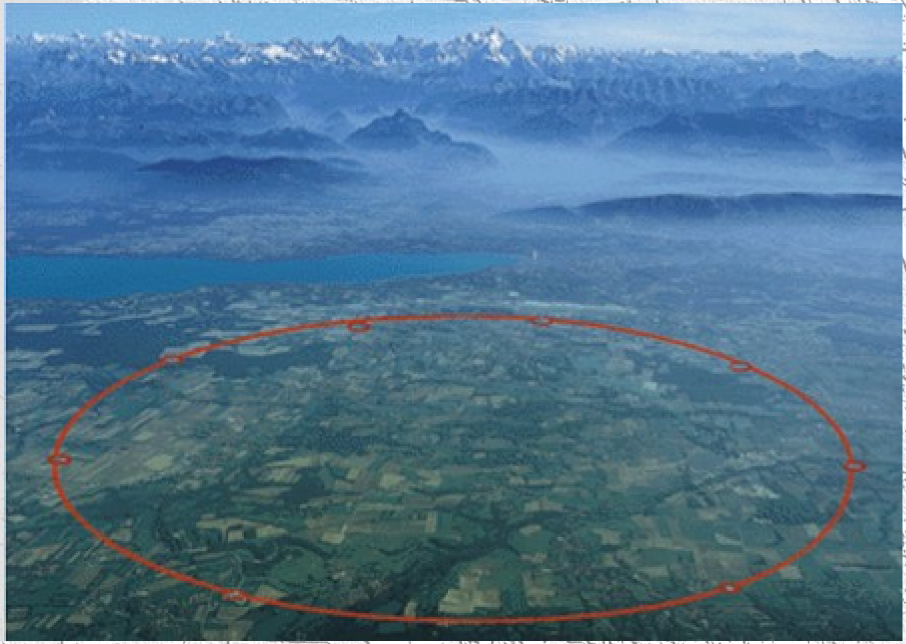
The Large Hadron Collider (LHC)

- Proton-proton collider in the former LEP tunnel
- Highest ever energy per collission

  14 TeV in the pp-system

  cf. Tevatron at 2 TeV
- High luminosity

  up to $10^{34}/cm^2/s$
- Conditions as $10^{-13} – 10^{-14}$ s after the Big Bang
- 4 experiments:
  ATLAS
  CMS
  LHCb specialised on b-physics
  ALICE specialised for heavy ion collisions
- LHC and experiments were constructed in global collaborations



The Large Hadron Collider (LHC)

LHC time table:

- Early 1980's: first ideas about a multi-TeV proton collider at CERN
- Oct 1990: ECFA workshop on LHC in Aachen
- 16 Dec 1994: CERN council approves the LHC
- Feb 1996: approval of ATLAS and CMS
- Apr 1998: start civil engineering
- 7 Mar 2005: first dipole magnet installed
- 26 Apr 2007: last dipole installed
- 10 Sep 2008: first circulating beams
- Oct 2009: first pp-collisions expected

Challenges for the LHC: Magnets

- **Superconducting dipole magnets to keep 7 TeV protons on a circular path (r ≈ 3 km)**

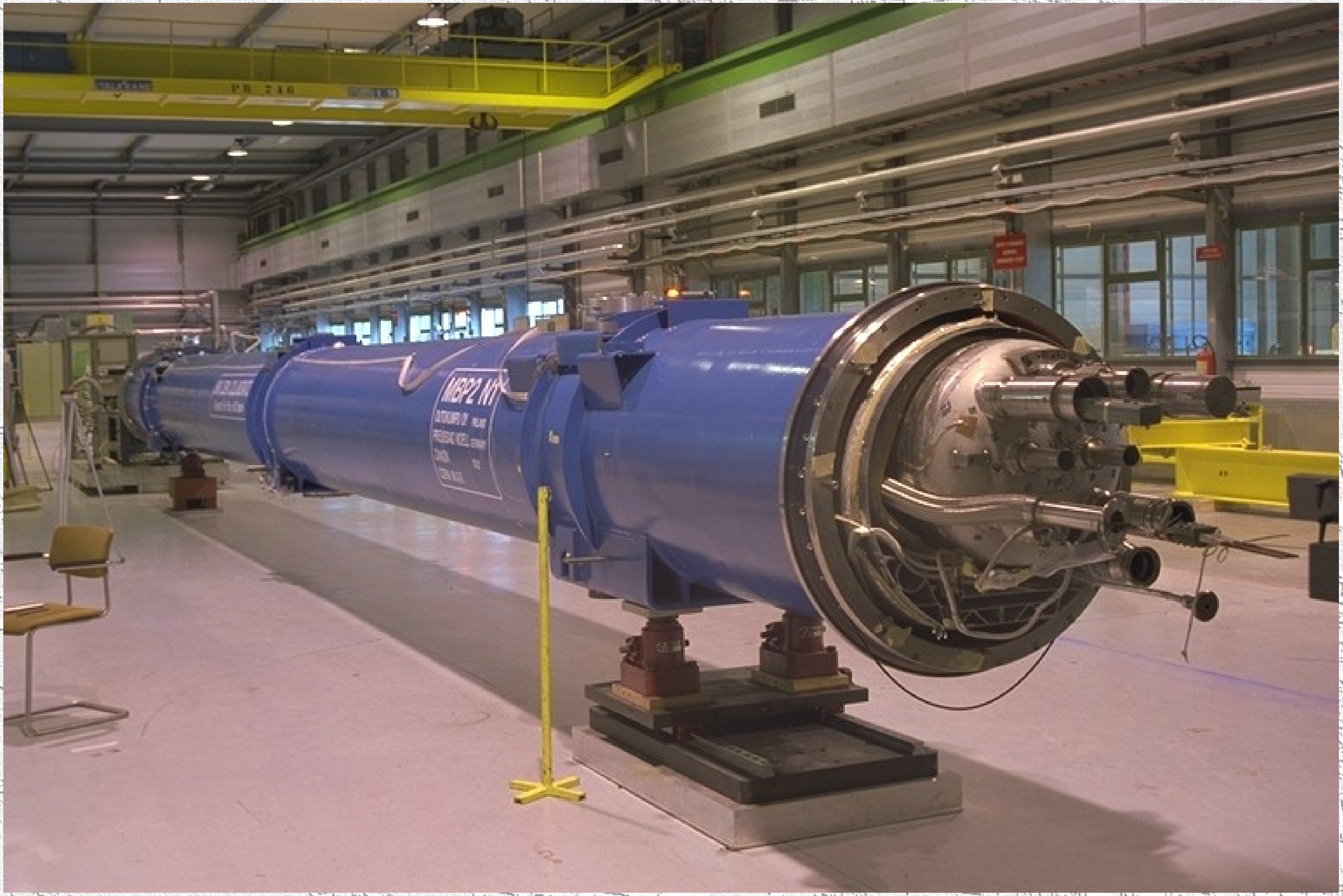
  |B| = 8.33 Tesla

- **1232 dipole magnets needed each is 15 m long (+ quadrupoles, sextupoles, etc.)**
  - **1.9 K operating temperature**
  - **Supraliquid Helium**
  - **Largest cryogenic 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 incorporates reversed field for oppositely rotating proton beams

LHC Dipoles

- **Around 1999: construction of dipoles start**

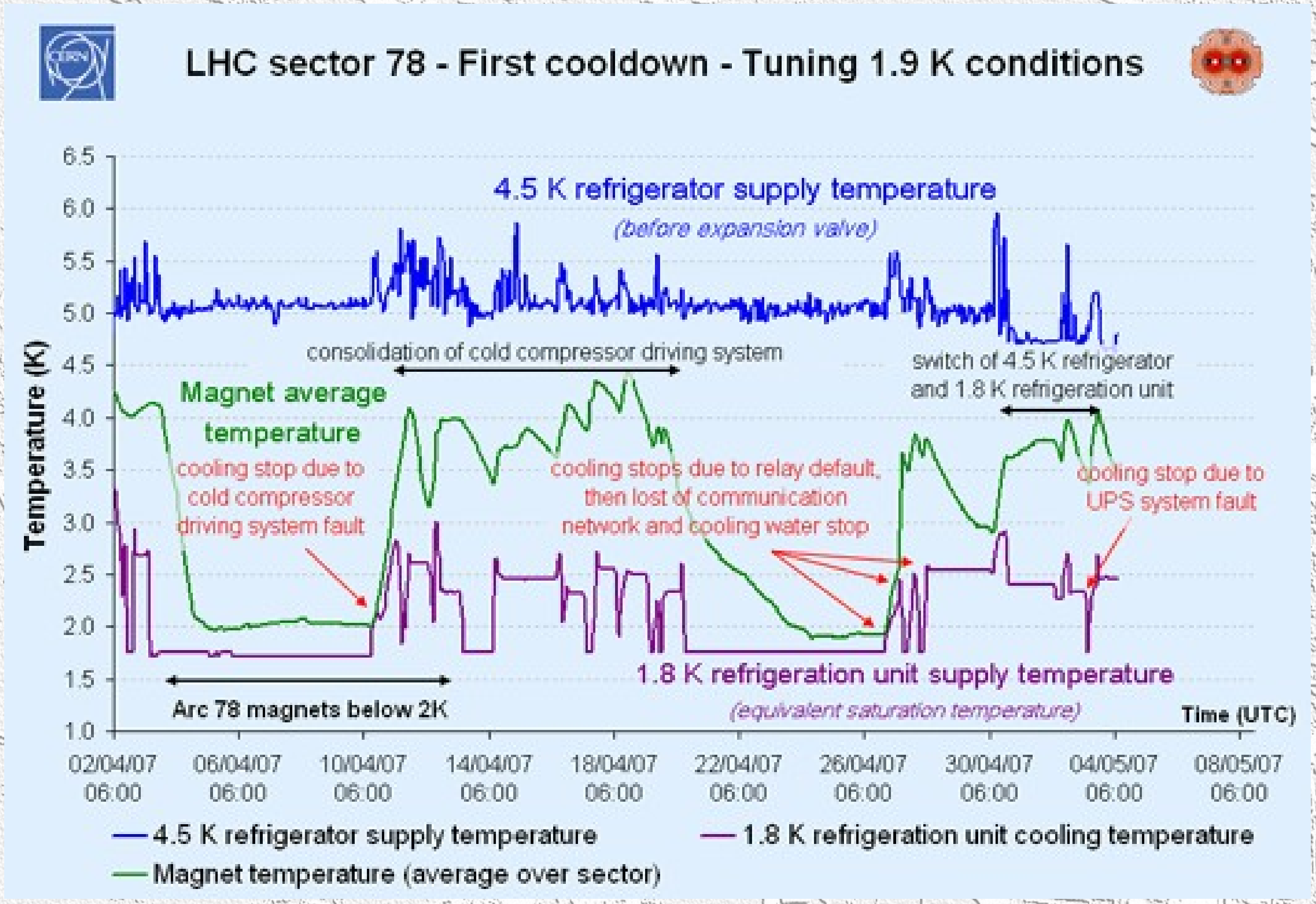


LHC Dipoles

Dipoles in the LHC Tunnel

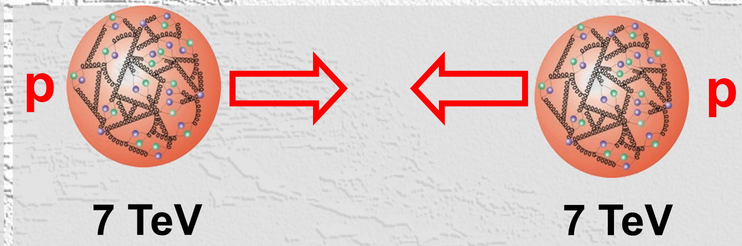
Cryogenics

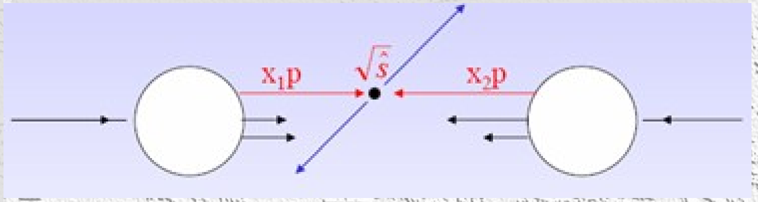
- First cool down of an LHC sector (> 3 km) in April 2007
- 1.9 K: coldest place in the universe

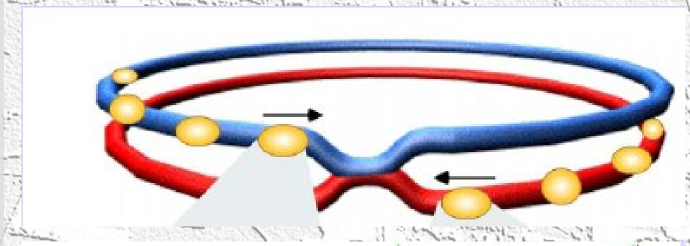


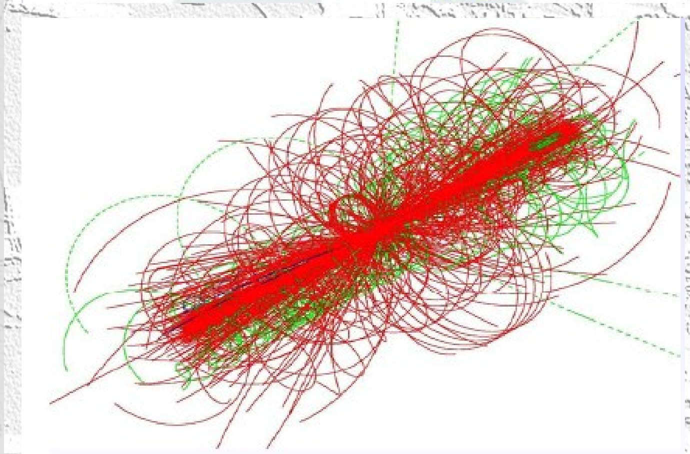
Challenges for LHC Detectors

- **Protons are composite particles**
  - LHC collides protons on protons
  - But collisions of quarks and gluons are the fundamental processes
  - Screened by interactions of other quarks & gluons (underlying event)
- **LHC is filled with 2835 + 2835 proton bunches**
  - Collisions every 25 ns
    40 MHz crossing rate
- **10^{11} protons per bunch**
  - 25 pp interactions per crossing (pile-up)
  - Each bunch collision produces ≈ 1600 charged particles

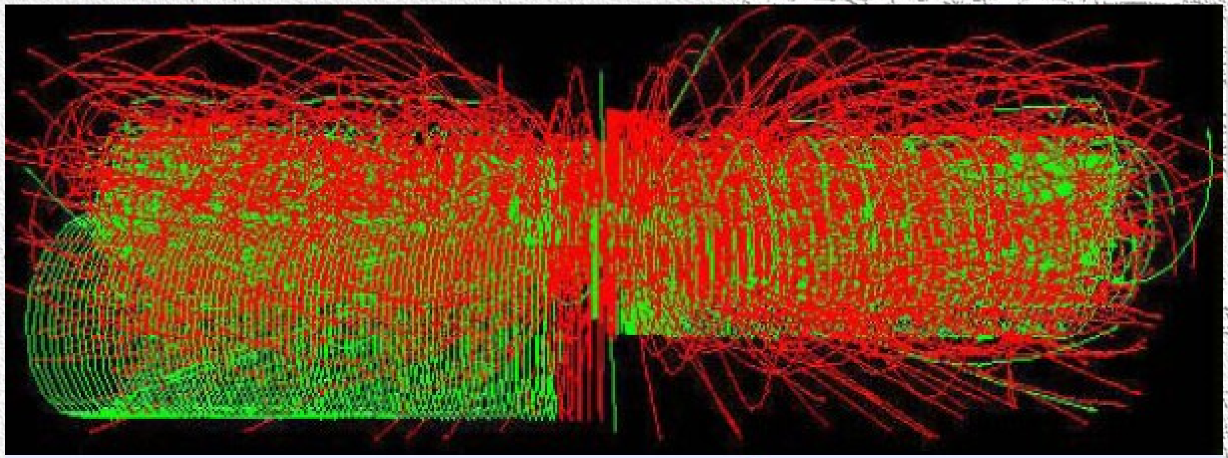




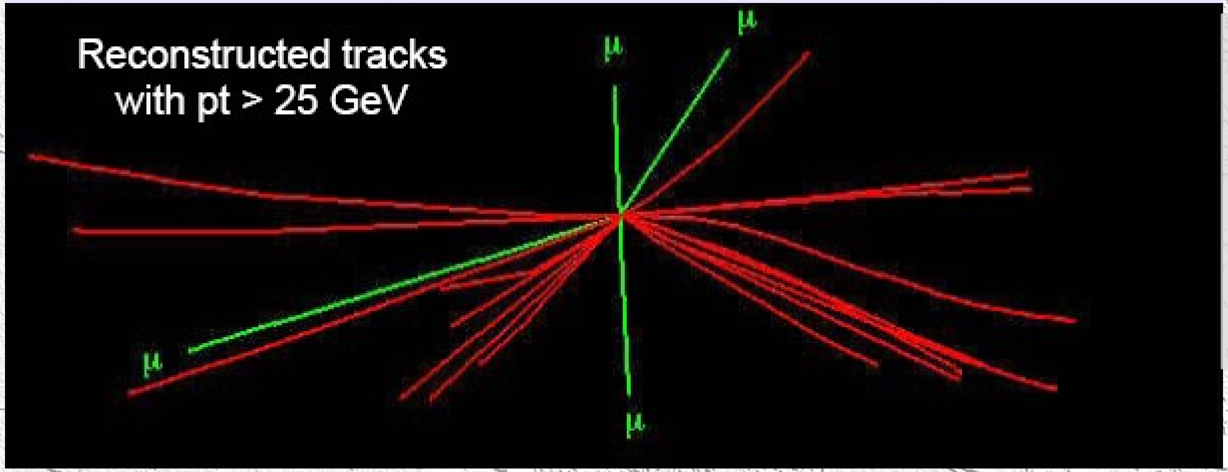




A Collision Producing a Higgs Boson



- with 25 pile-up interactions

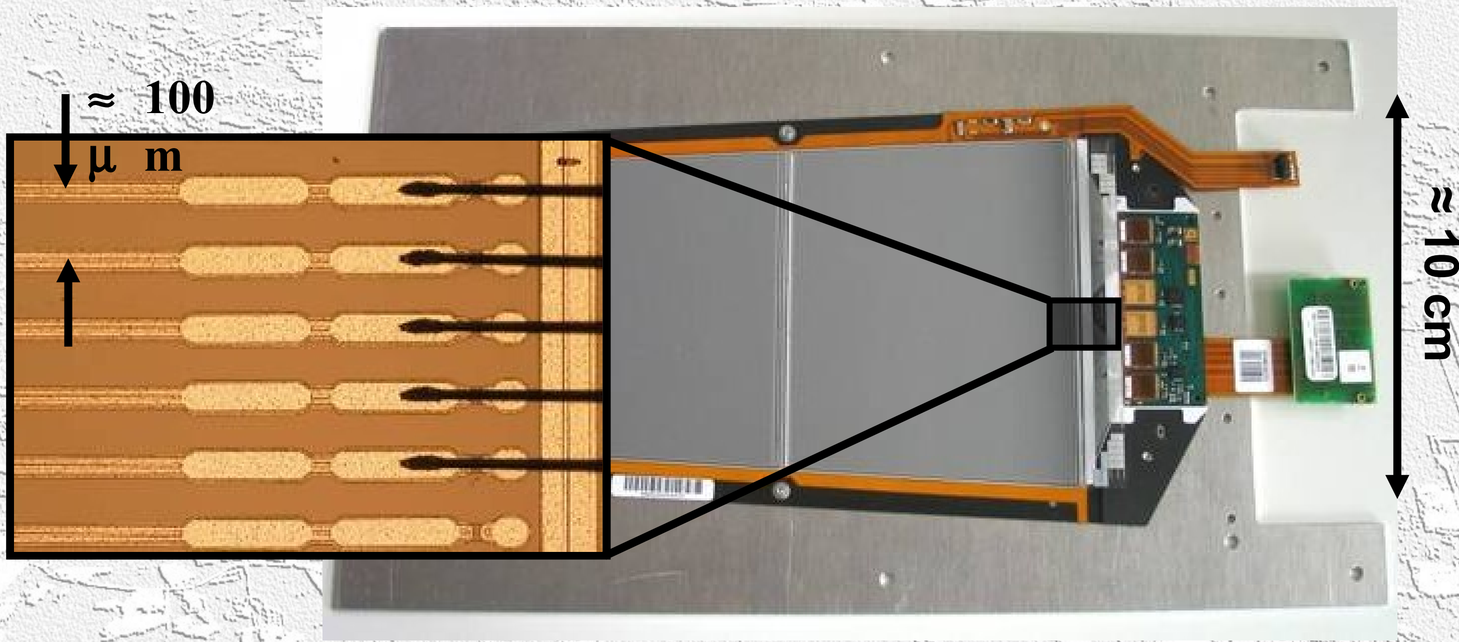


- Remove low energy tracks (p_T < 25 GeV)
- H → ZZ → 4 muons

- **Identify each track** **requires a highly granular detector**
- **Reconstruct every track** **takes a lot of computing power**

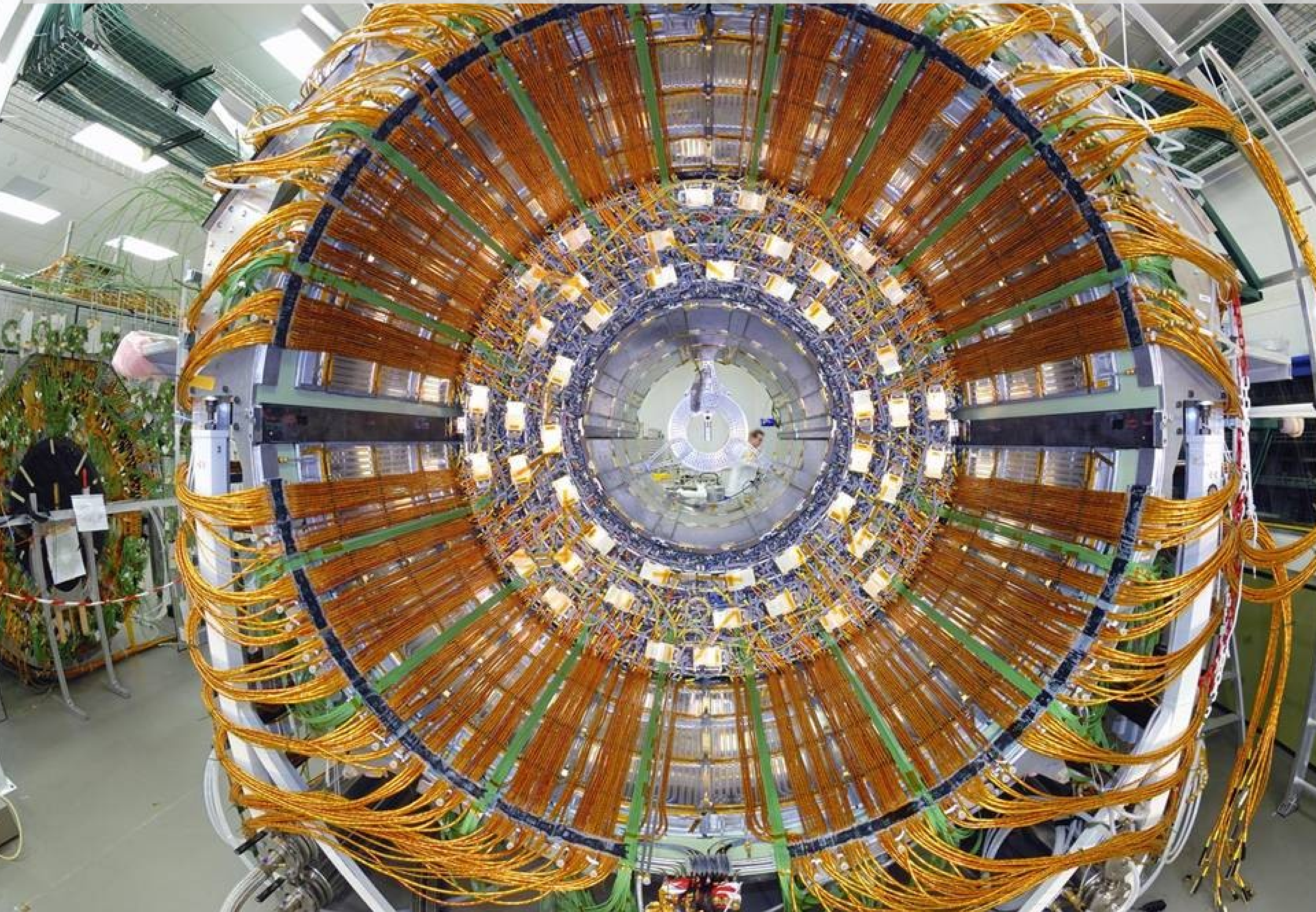
Example: CMS Tracking Detector

- **Silicon strip detector**



- 16000 such modules built
- 220 m^2 of silicon surface (almost a tennis court…)
- Largest silicon detector ever built

A Dream Becomes Reality...



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**

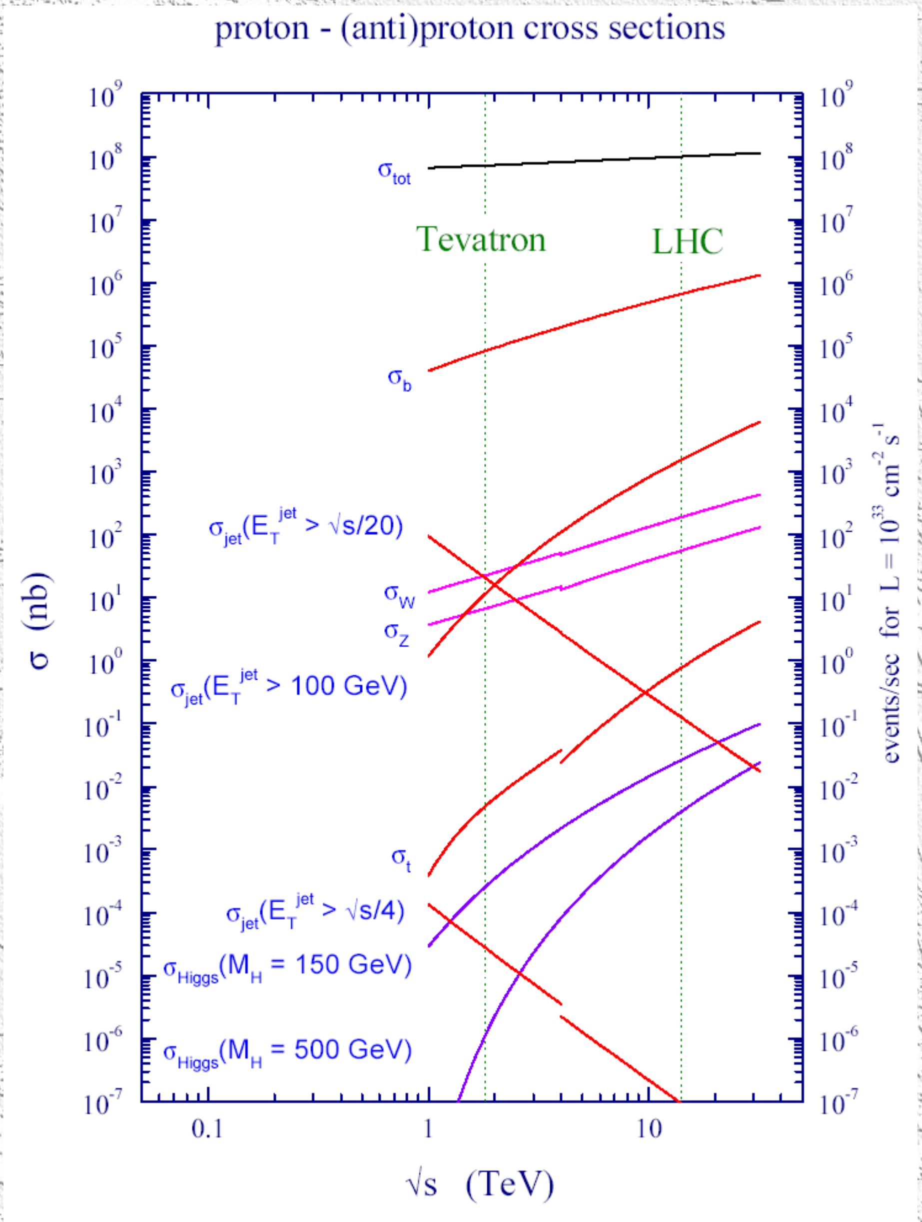
will be produced per second and

- **1 light Higgs**

per minute!

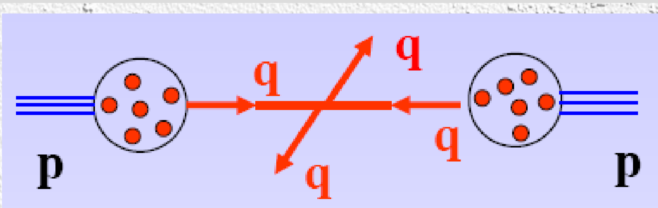
The LHC is a b, W, Z, top, Higgs, … factory!

The problem is to detect the events!



Experimental Signatures

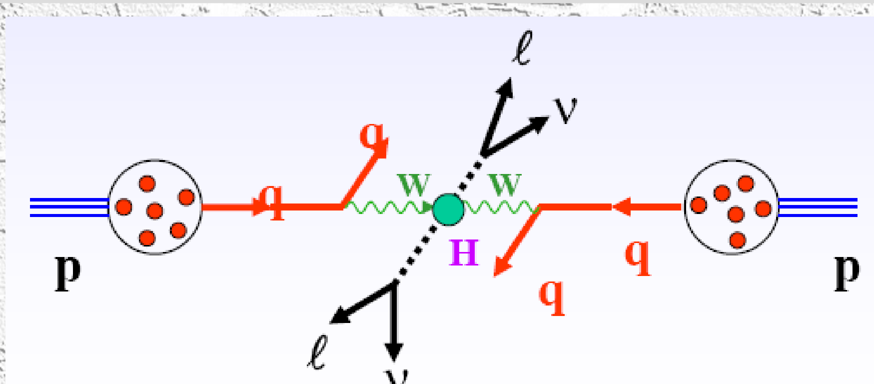
1. Hadronic final states, e.g. quark-quark



no high p_T leptons or photons in the final state

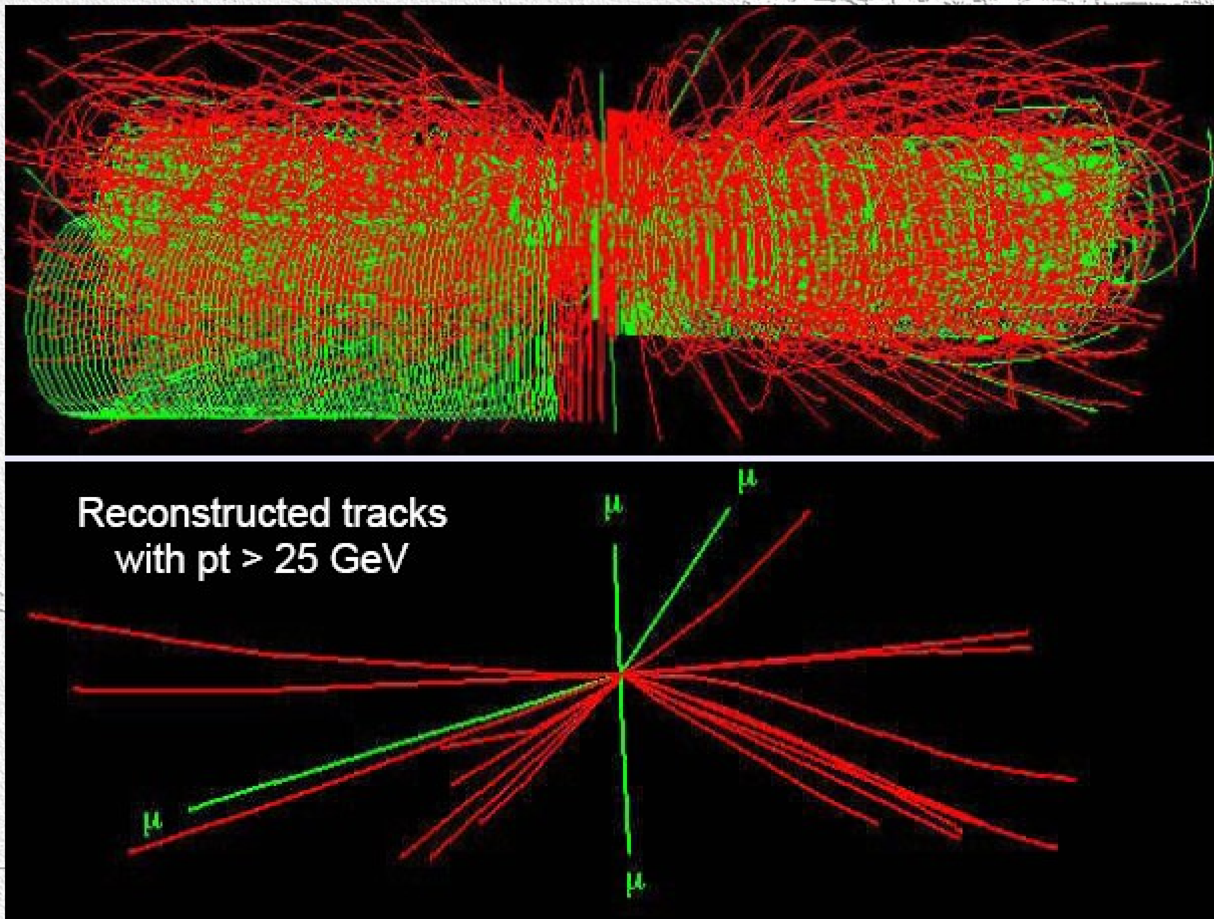
holds for the bulk of the total cross section

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

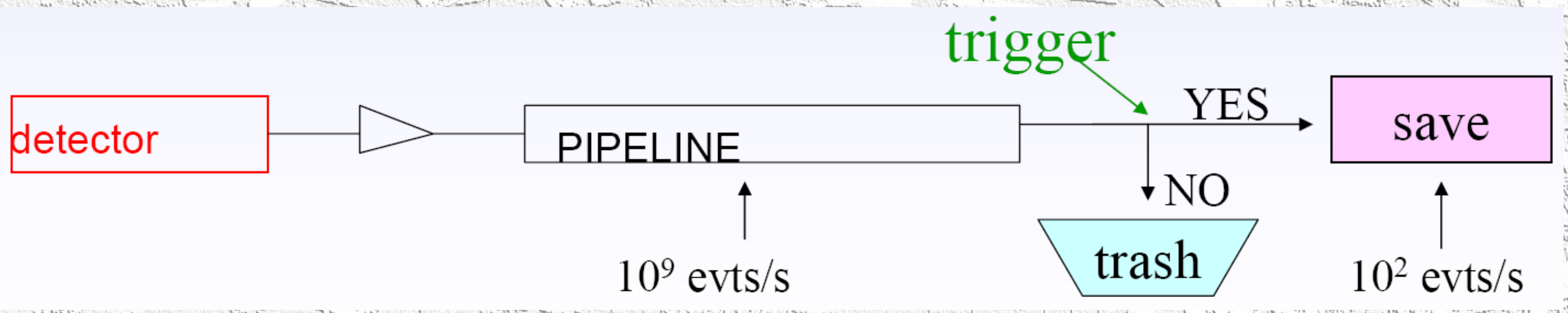
Trigger of interesting events at the LHC is much more complicated than at e^+e^- machines

- interaction rate: ≈ 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



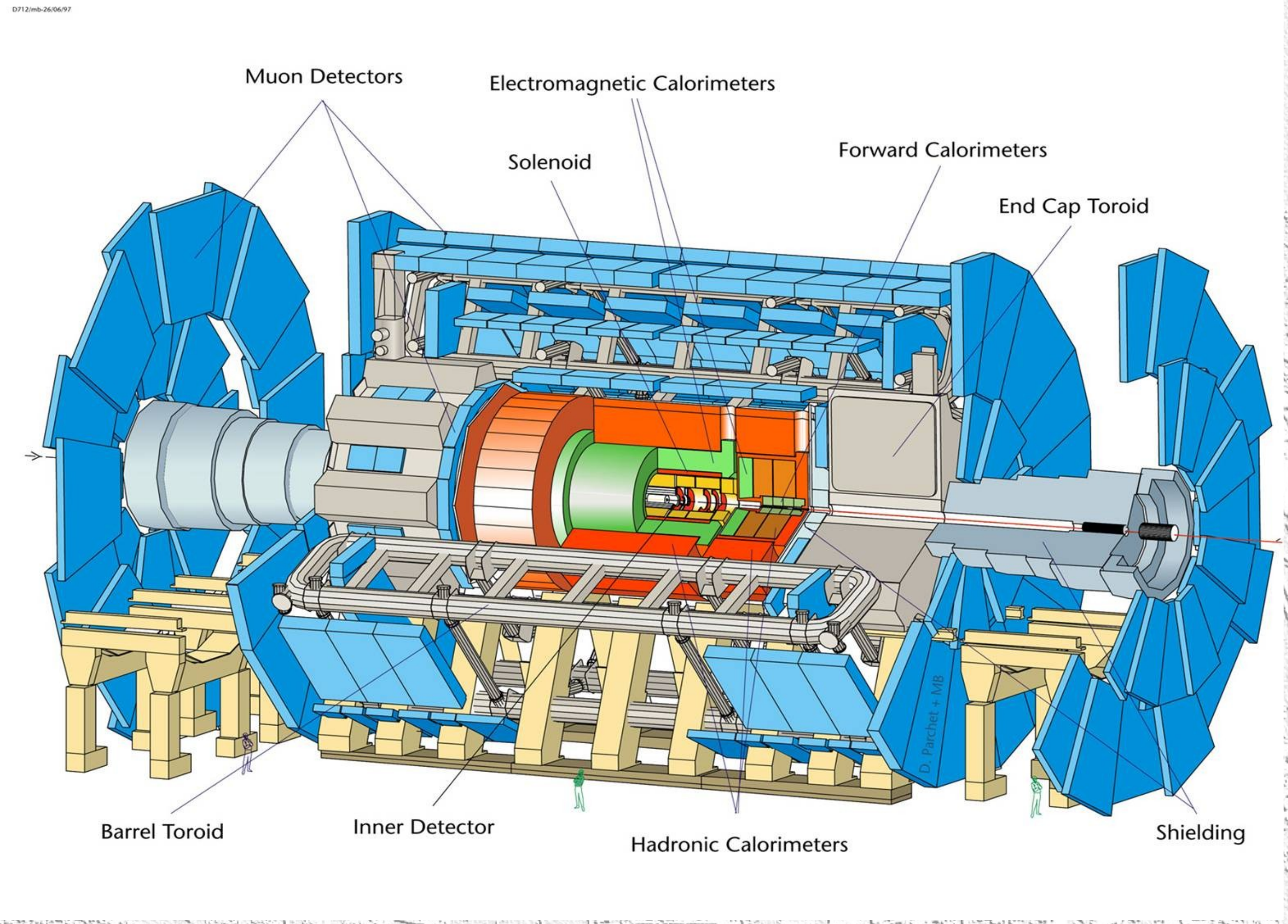
The ATLAS experiment

A Toroidal LHC ApparatuS

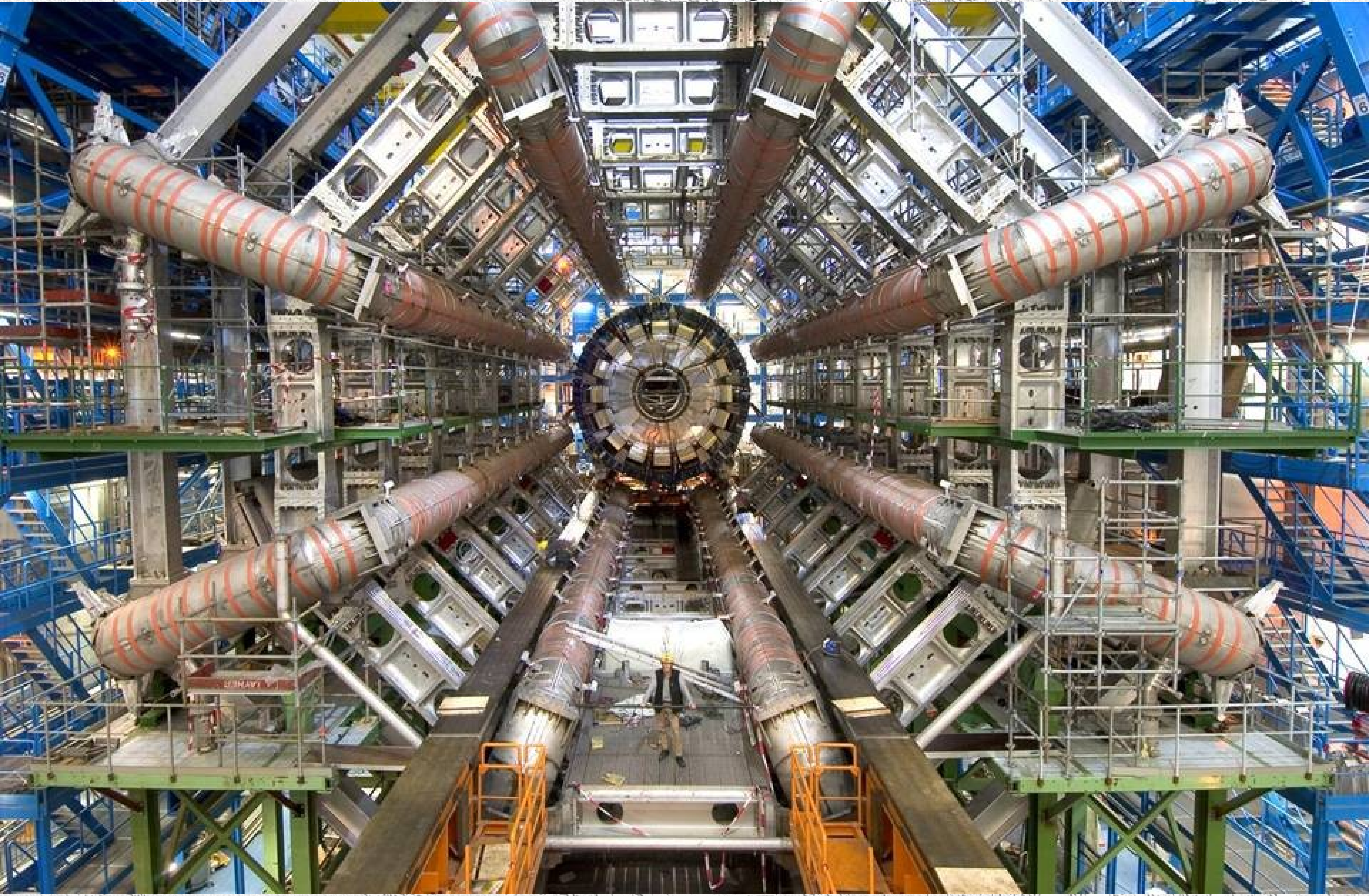
ATLAS in a nutshell:
- Large air toroid with μ chambers
- HCAL: steel & scintillator tiles
- ECAL: LAr
- Inner solenoid (2 T)
- Tracker: Si-strips & straw tubes (TRD)
- Si-pixel detector

10^8 channels

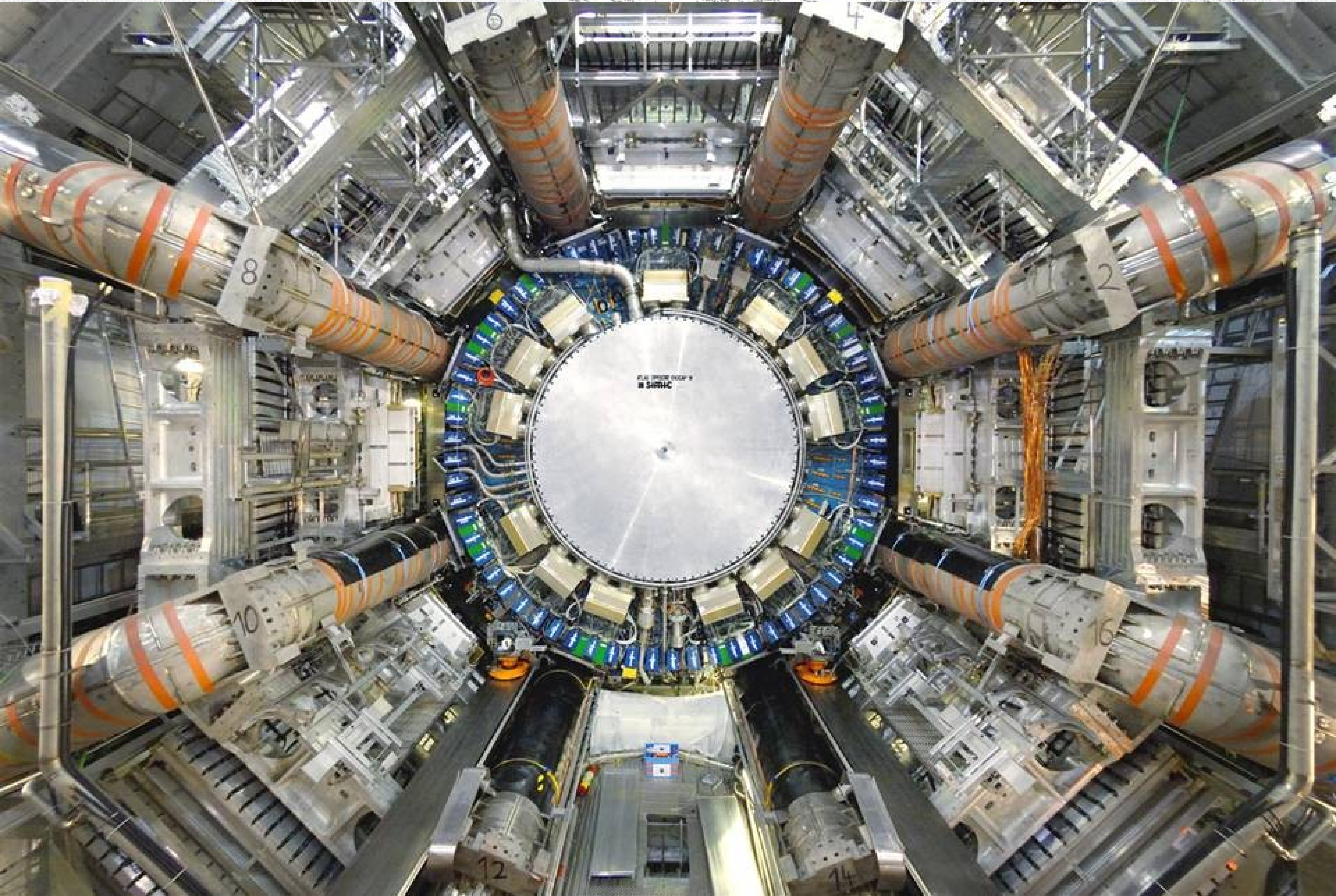
15 μm resolution



ATLAS



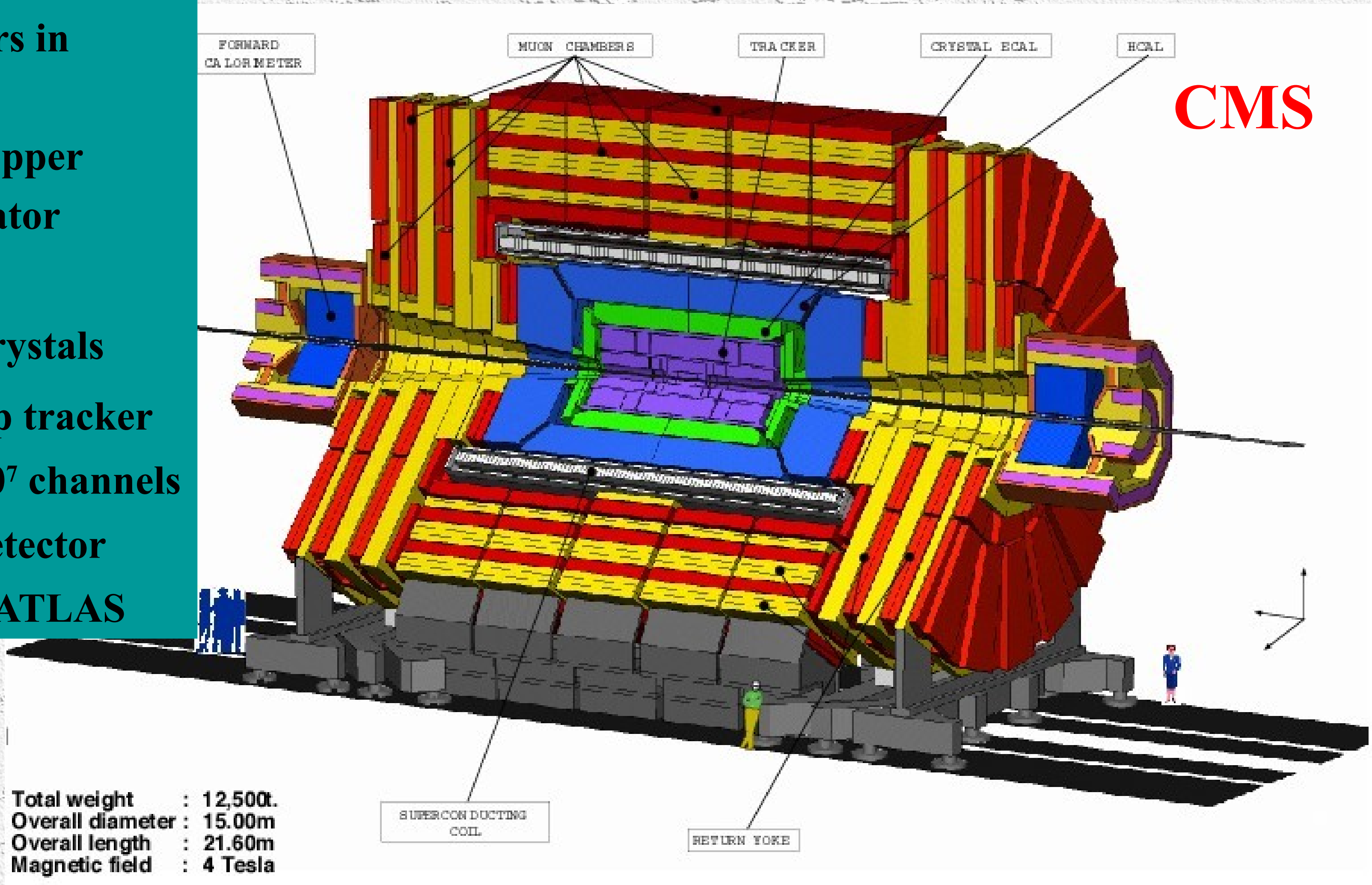
ATLAS with inner Detectors



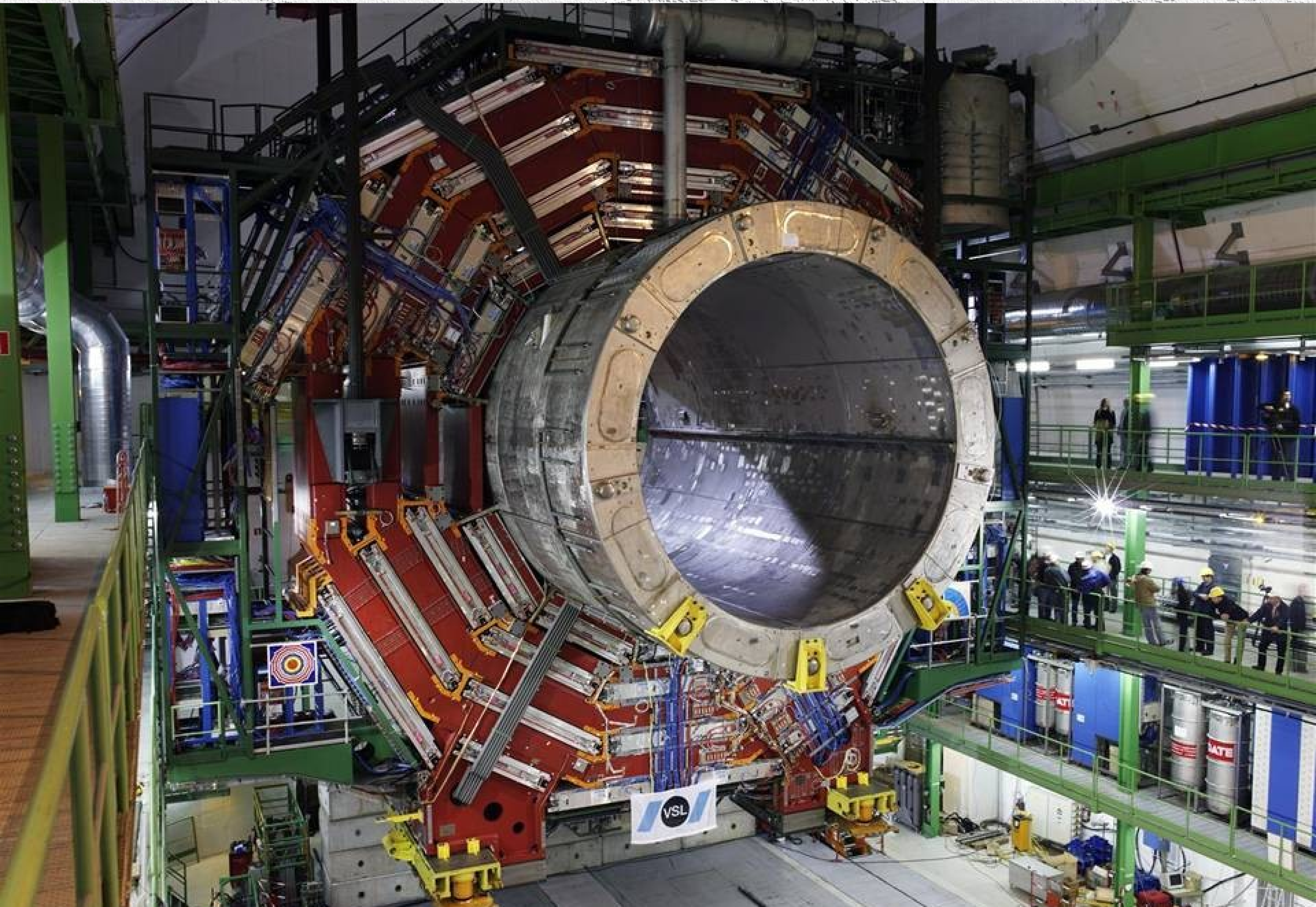
The CMS experiment

Compact Muon Solenoid

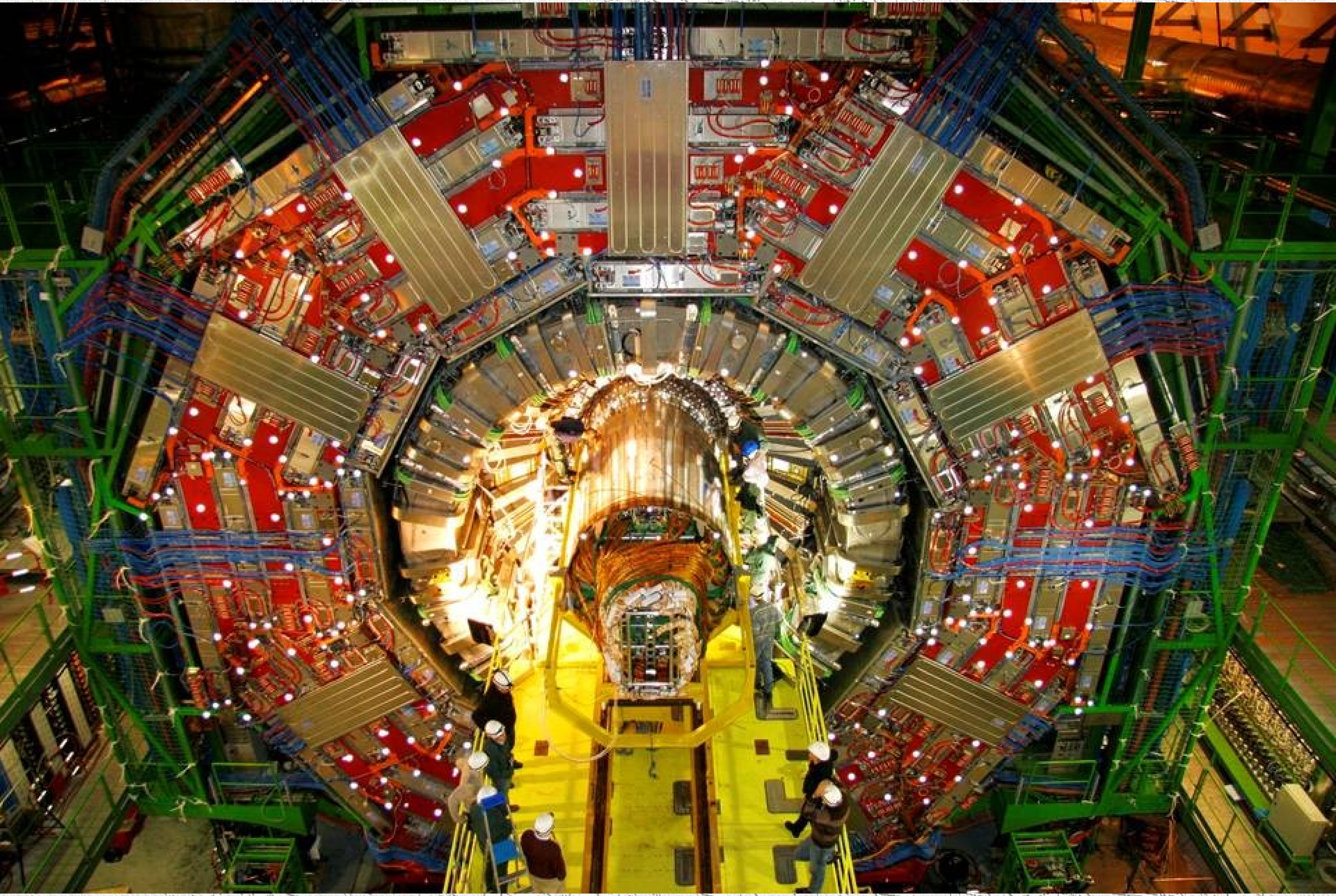
CMS in a nutshell:
- 4 T solenoid
- μ chambers in iron yoke
- HCAL: copper & scintillator
- ECAL: $PbWO_4$ crystals
- All Si-strip tracker $220\ m^2$, 10^7 channels
- Si-pixel detector similar to ATLAS



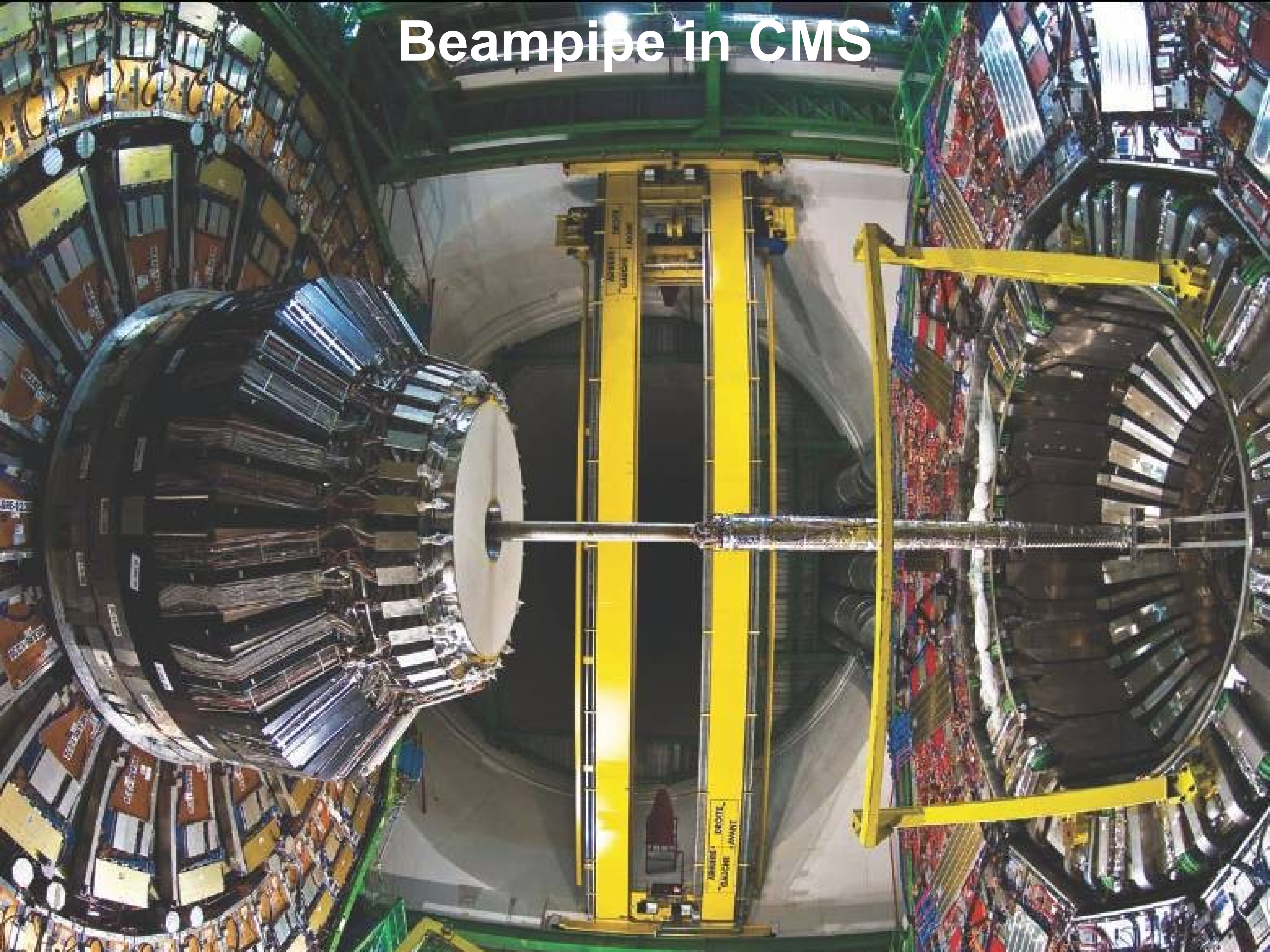
CMS: Compact Muon Solenoid



CMS

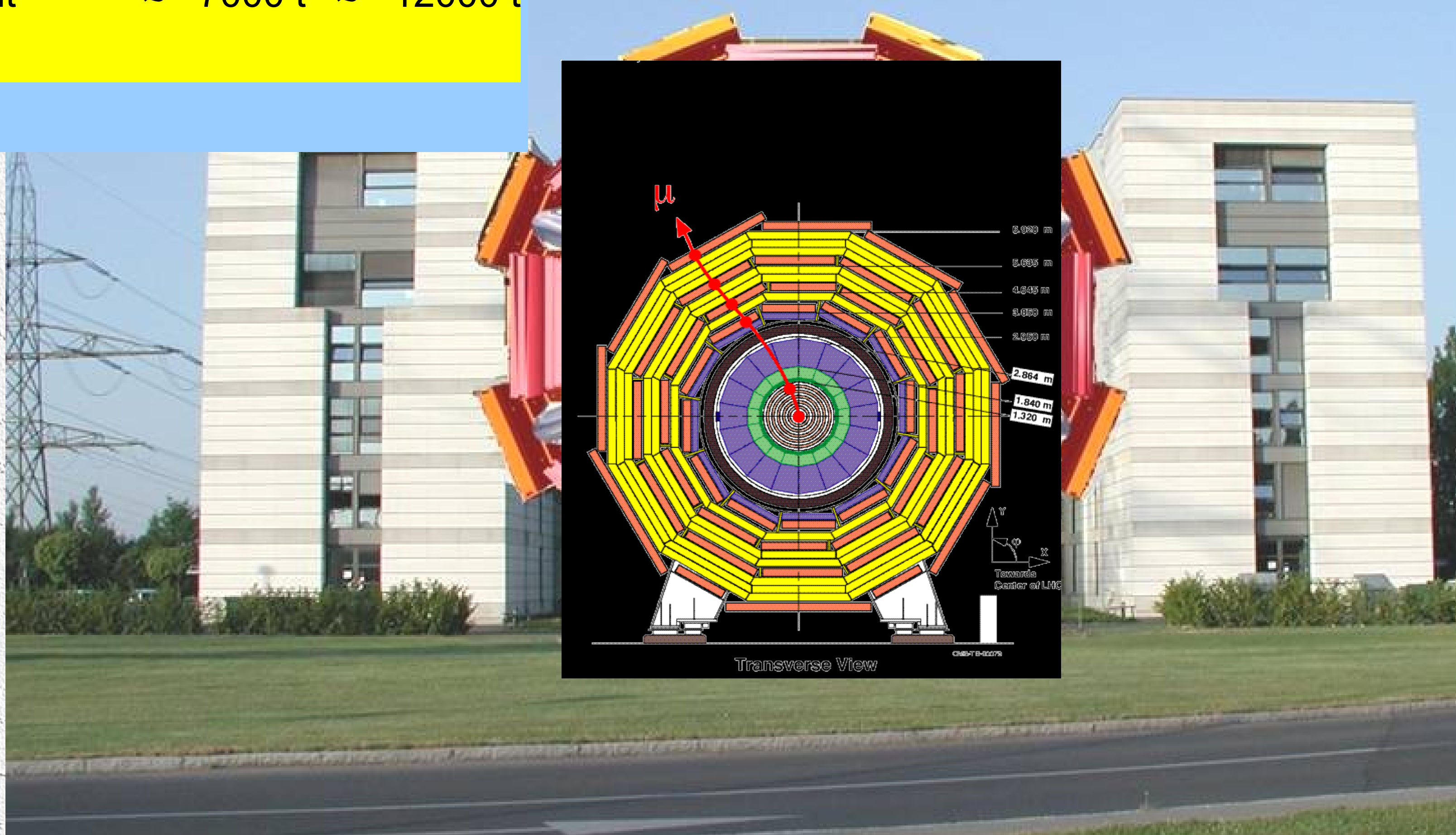


Beampipe in CMS



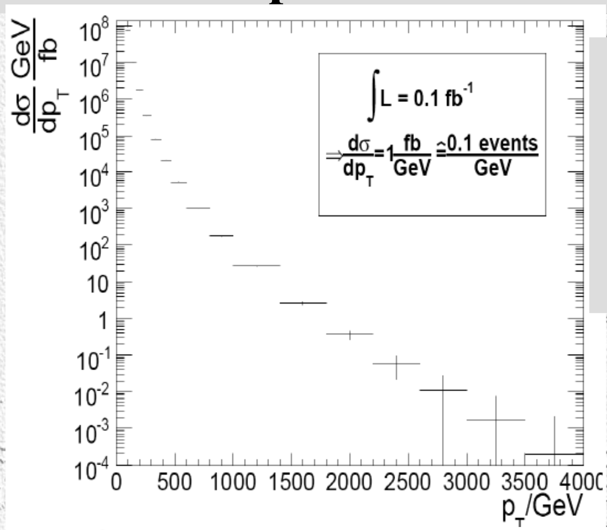
Comparison ATLAS and CMS

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

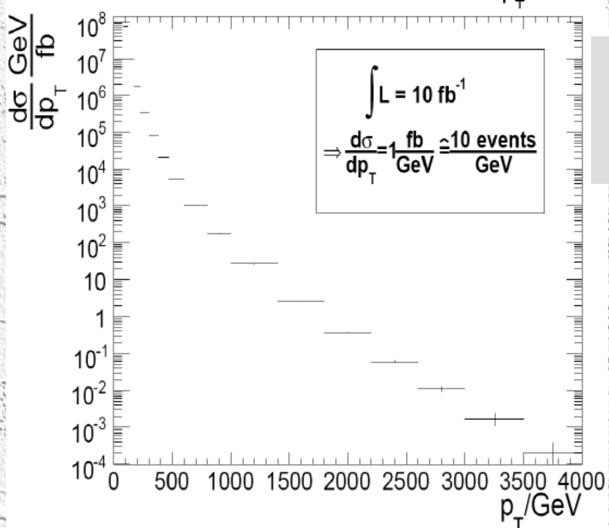


LHC Jet Physics

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

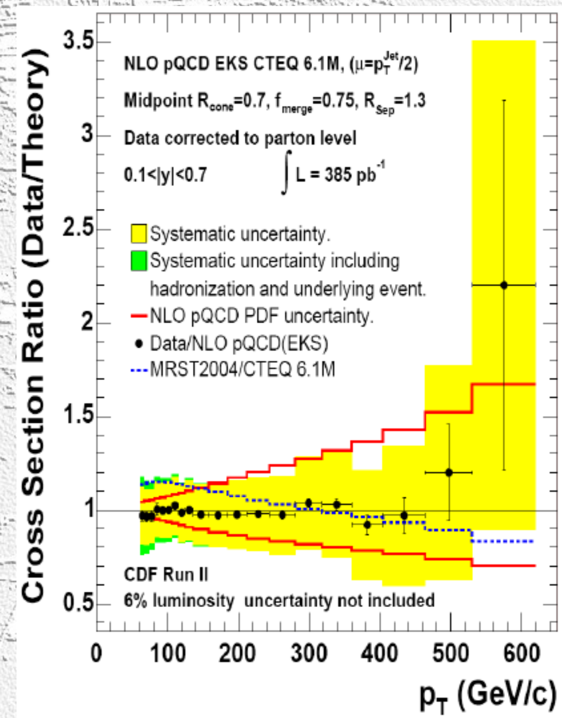


100 pb^{-1}
= few weeks
(or months)
at 14 TeV



10 fb^{-1}
= 1 year

- compare to CDF result run II

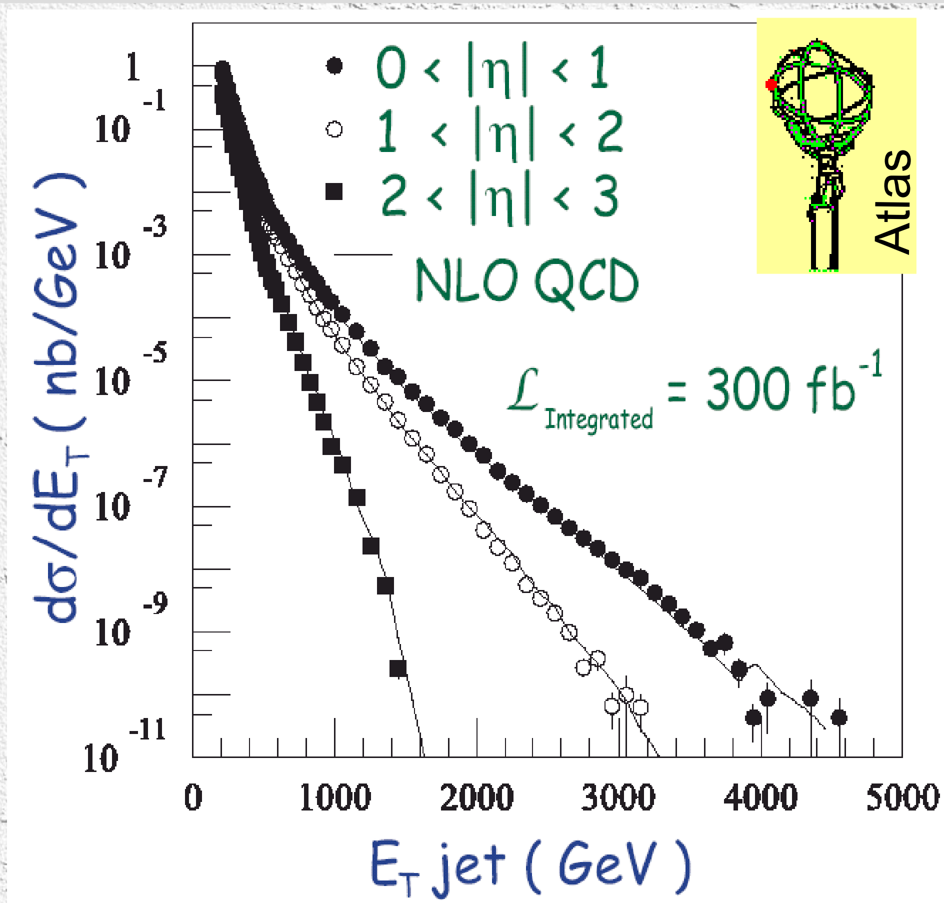


- detector systematic effects expected to be similar to Tevatron
- provides handle on PDF

Jet Physics

Jet physics at the LHC

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

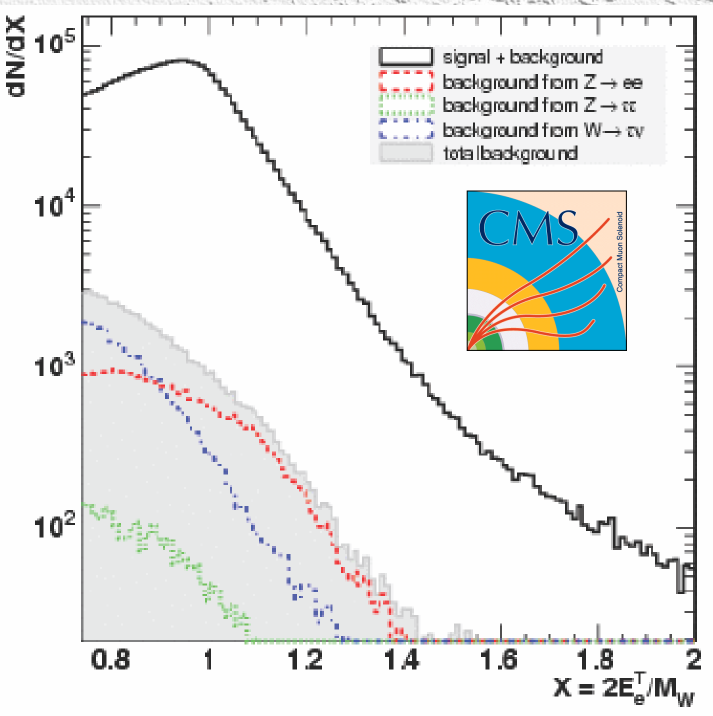


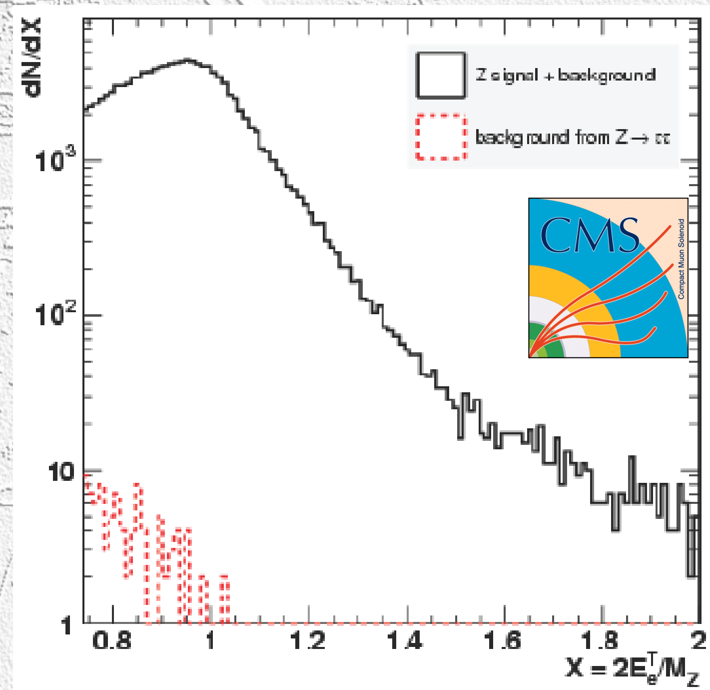
Inclusive jet rates for 300 fb^{-1}:

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

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

CMS: detailed study of statistical and systematic errors

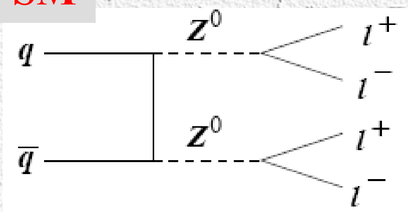
- **1 fb^{-1}: early measurement**
- **10 fb^{-1}: asymptotic reach, best calibrated & understood detector, improved theory etc.**

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

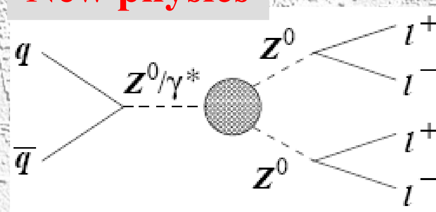
Di-Boson Production at the LHC

- 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!

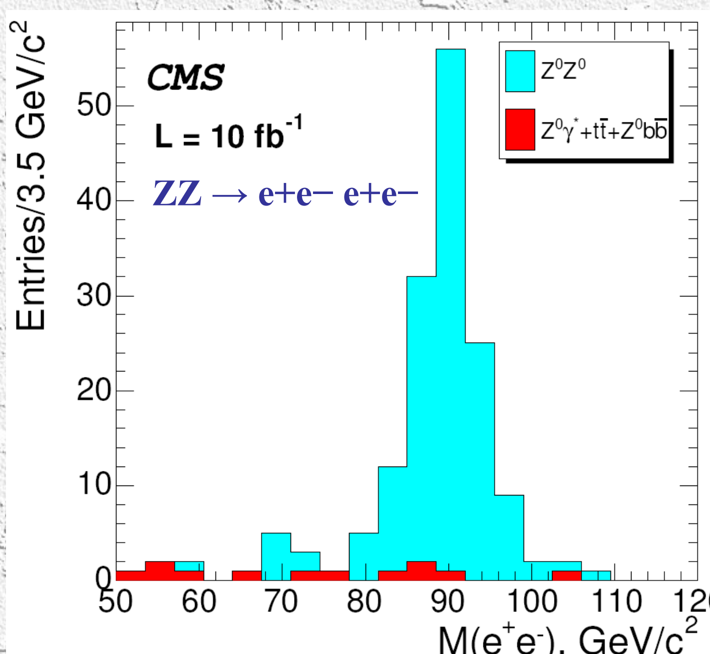
SM

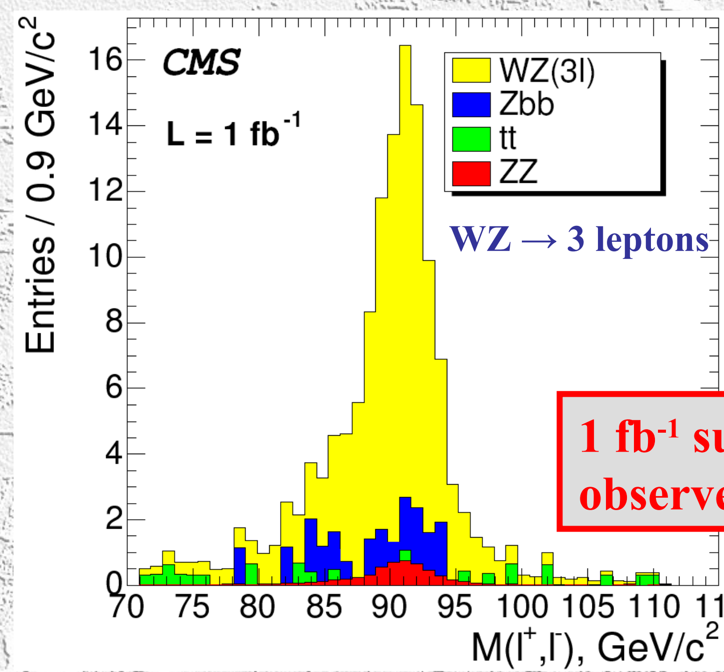


New physics



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

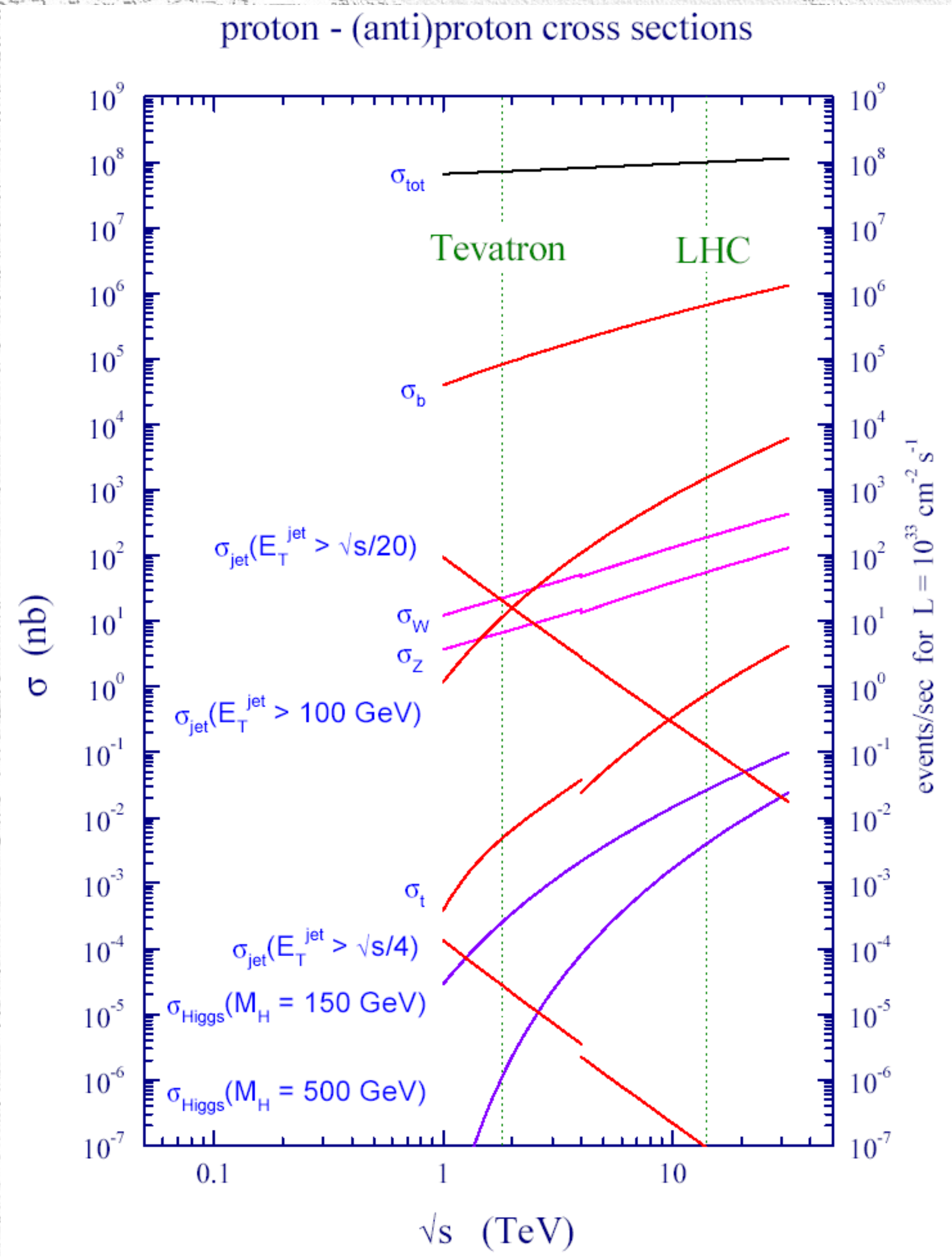




1 fb^{-1} sufficient to observe both processes

Top Physics at the LHC

- **LHC is a top factory**
  - **at 10^{33}/cm²/s**
    1 ttbar per second or
    10 million per year
- **Cross section ≈ 100 times larger than at the Tevatron**
  7 pb Tevatron
  > 800 pb LHC
- **LHC will eclipse existing knowledge on the top despite problems like**
  - **pile-up**
  - **less striking signatures**

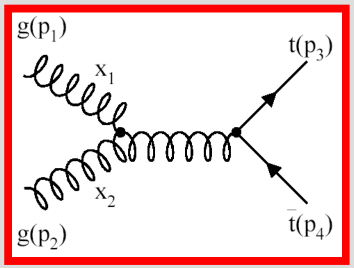


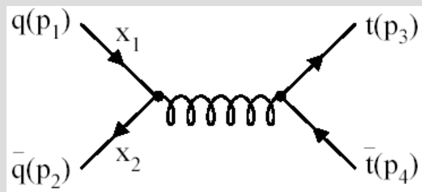
Why Top Physics at the LHC?

- **ttbar production is standard candle at high Q^2**
  - **relatively precisely measureable and calculable**
  - **cross checks impact of pdf, underlying event, pile-up, …**

- **ttbar production**

≈ 90% gluon fusion **≈ 10% quark annihilation**

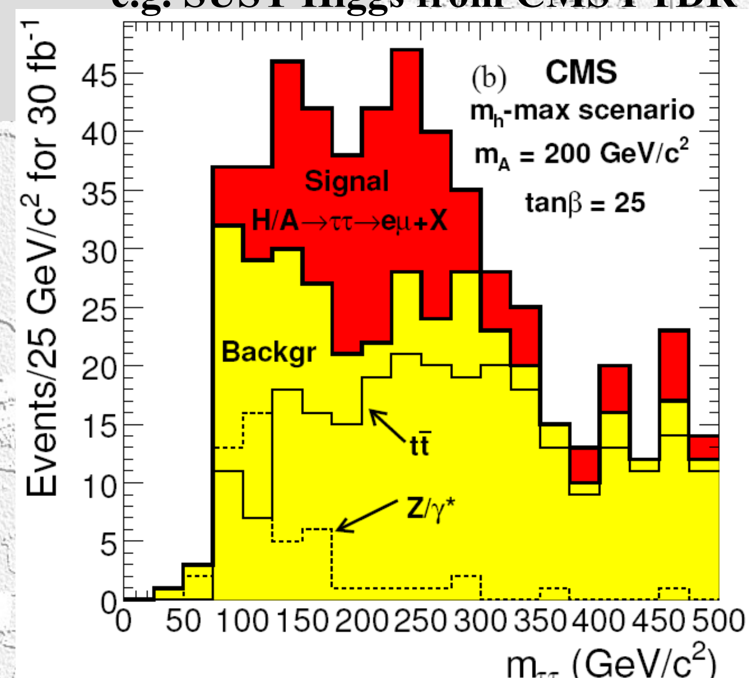




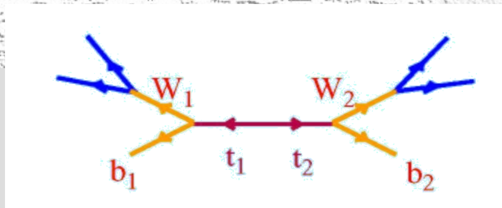
i.e. similar to e.g. Higgs production

- **Important background reaction for many New Physics channels**
  - **high cross section**
  - **presence of high p_T lepton(s)**
  - **multi-jet final states**

e.g. SUSY Higgs from CMS PTDR



Top Quark Decay

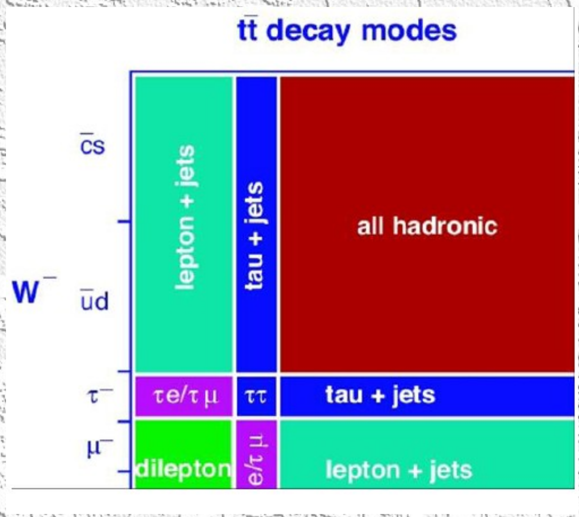


- Top decay: ≈ 100% t → bW
- Other rare SM decays:
  - CKM suppressed t → sW, dW: 10^{-3} –10^{-4} level
- & non-SM decays, e.g. t → bH^+

In SM topologies and branching ratios are fixed:

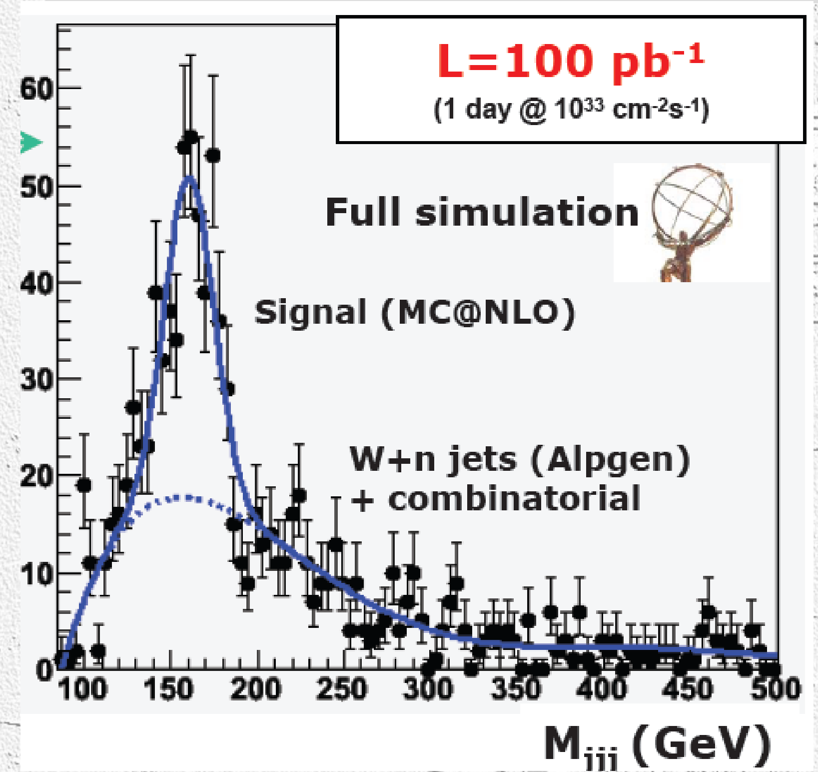
- expect two b-quark jets
- plus W^+W^- decay products:
  - 2 charged leptons + 2 neutrinos
  - 1 charged lepton + 1 neutrino + 2 jets
  - 4 jets (no b-quark!)

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

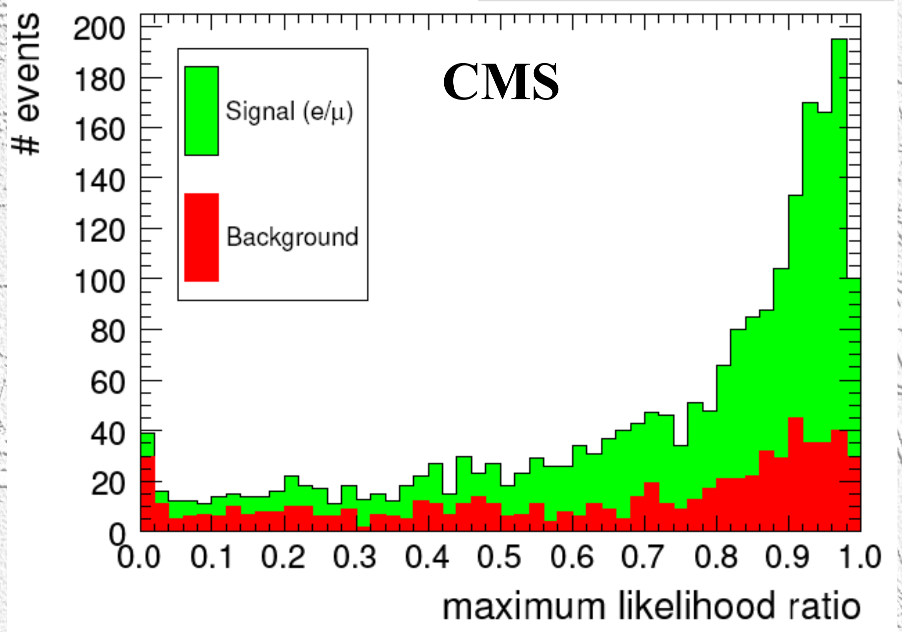


Top Pairs at the LHC

- Re-discovery of top possible with low luminosity (< 100 pb^{-1})
- Semi-leptonic events



S. Kasselmann, Ph.D. thesis



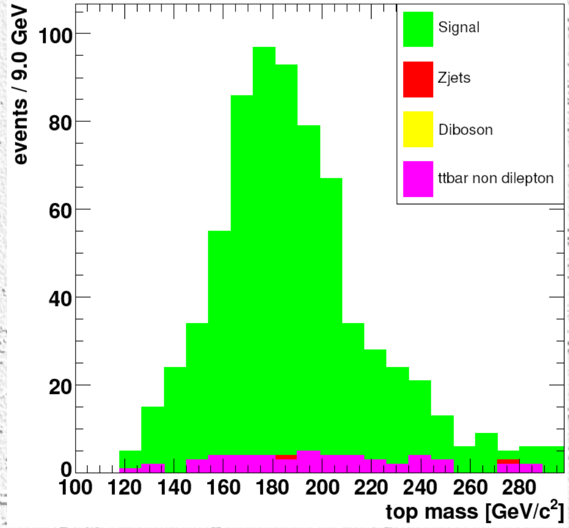
Observation of top quarks demonstrates that the full detector works:

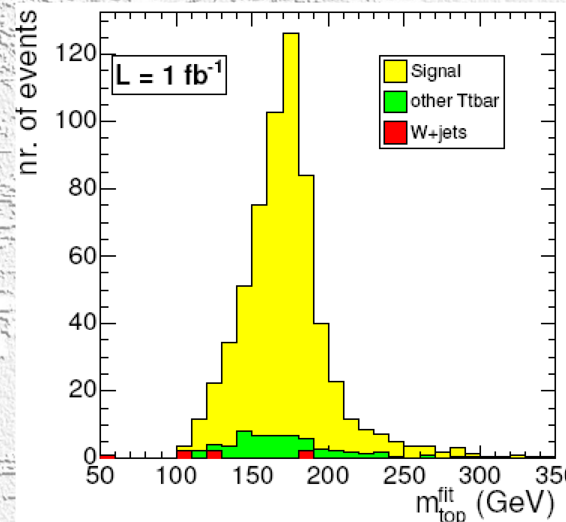
- electrons/ muons
- b-tagging
- jets
- missing ET

Top Mass at the LHC

Example: detailed studies by CMS:

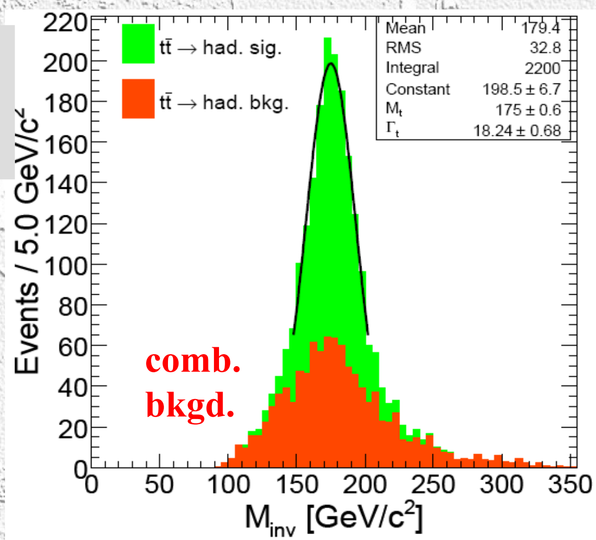
di-leptonic
± 1.2 GeV

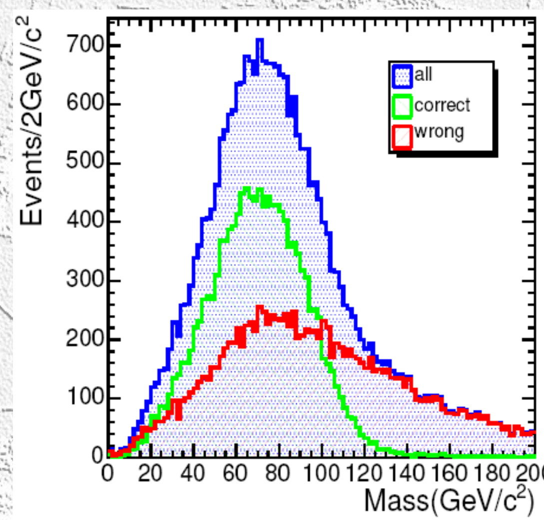




semi-leptonic
± 1.2 GeV

fully hadronic
± 2 GeV





$t \to J/\Psi + l + X$
± 1.5 GeV

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

Search for New Physics at the LHC

Some general considerations on LHC early phase

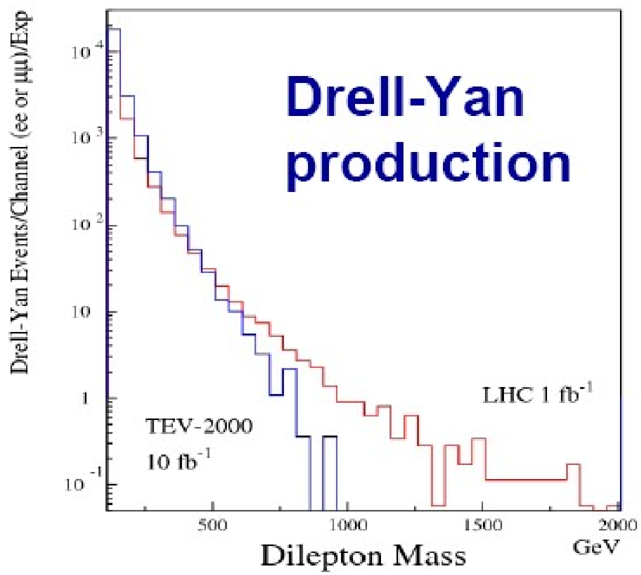
- time scale for discoveries not neceesarily determined by ramp-up of integrated luminosity
- but progress and level of detector understanding
  - malfunctions, calibration, alignment

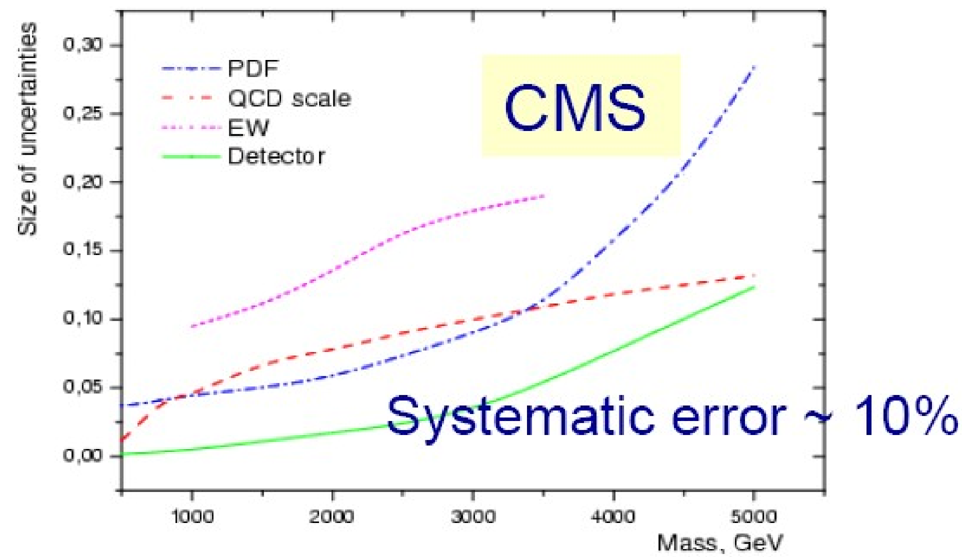
- difficult issues
  - jets
  - missing ET
  - forward detectors

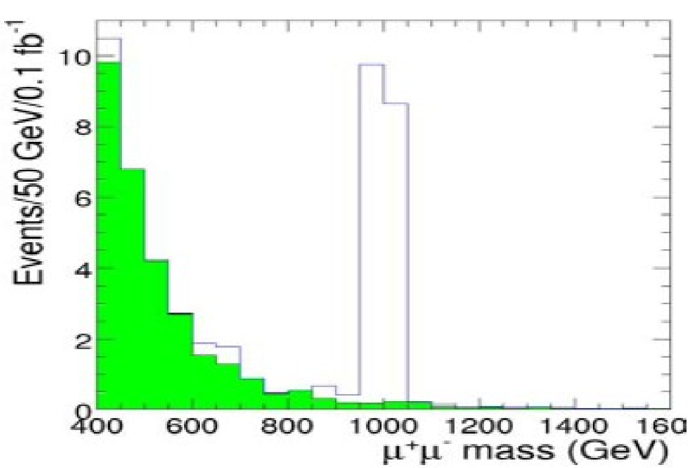
- less critical
  - lepton based measurements
    in particular muons

Understanding of the Detector

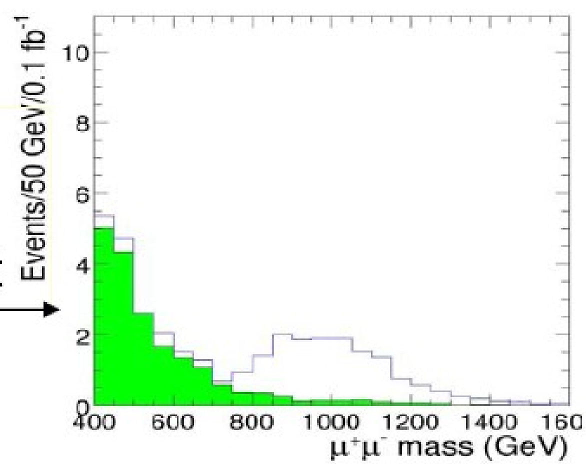
- **Example for an easy case: muon pairs**







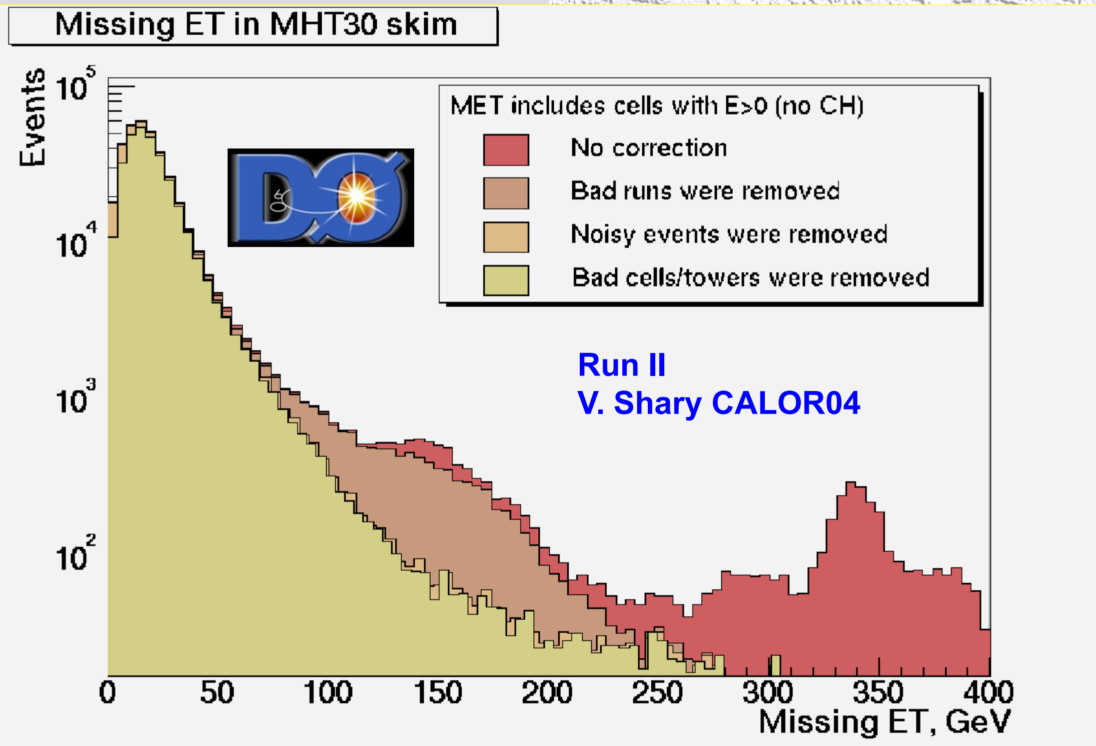
At **100 pb**$^{-1}$:
1 TeV Z' with
initial alignment



Understanding of the Detector

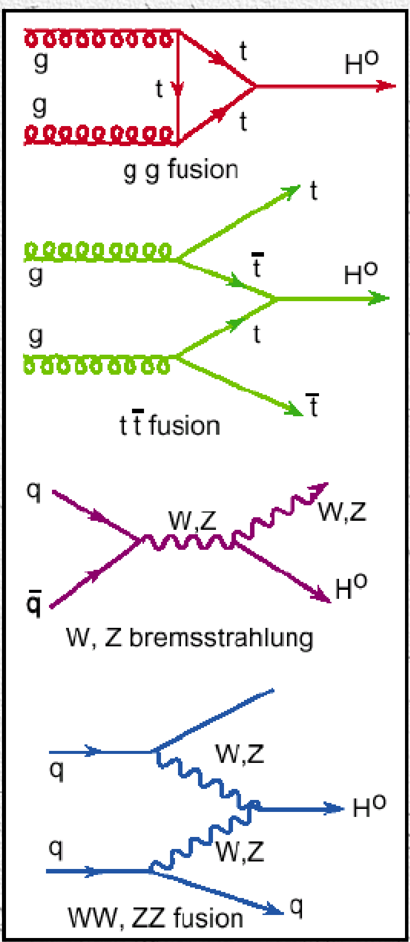
Difficult example: missing ET

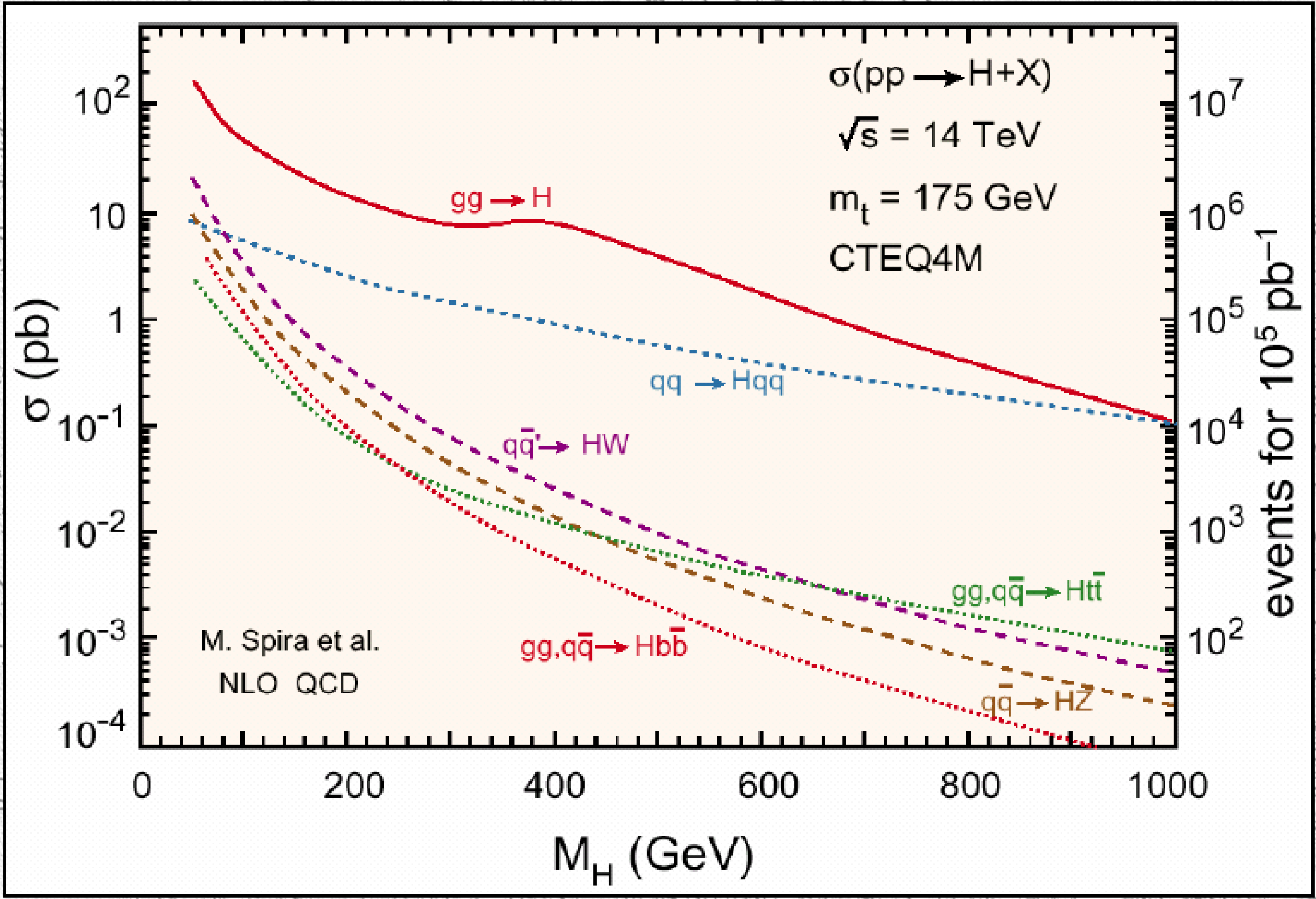
- is a very powerful tool to look for new physics
- but very complicated variable and difficult to understand:
- collison effects
  - pile-up
  - underlying event
- beam related background
  - beam halo
  - cosmic muons
- detector effects
  - instrumental noise
  - dead/hot channels
  - inter-module calibration



SM Higgs Boson Production at the LHC

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



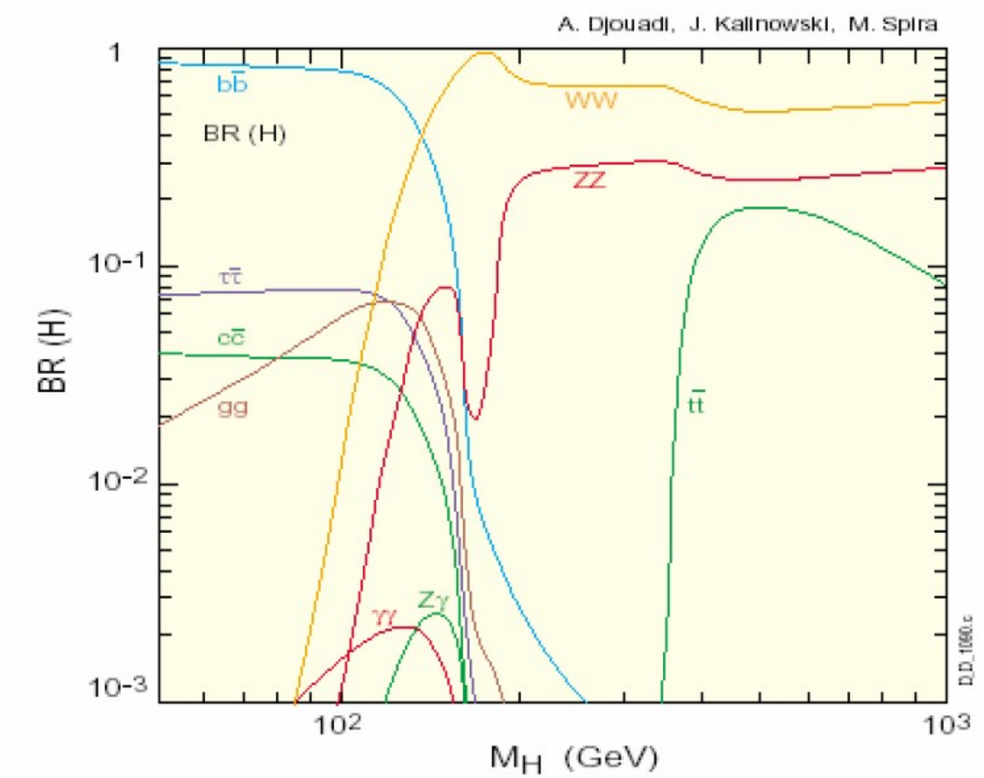


- **Gluon-gluon fusion and W, Z fusion are dominant**
- **Cross section at the Tevatron almost factor 100 smaller!**

Higgs Boson Decay

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

Branching ratio versus m_H:

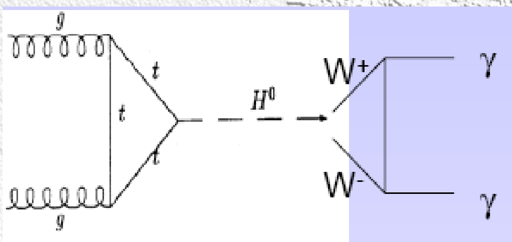


- **Low mass (115 < m_H < 140 GeV**
  H → bb make up most of the decays problem at the LHC because of the huge QCD background !
- **Intermediate (140 < m_H < 180 GeV)**
  H → WW opens up use leptonic W decay modes
- **High mass (m_H > 180 GeV)**
  H → ZZ → 4 leptons golden channel!

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

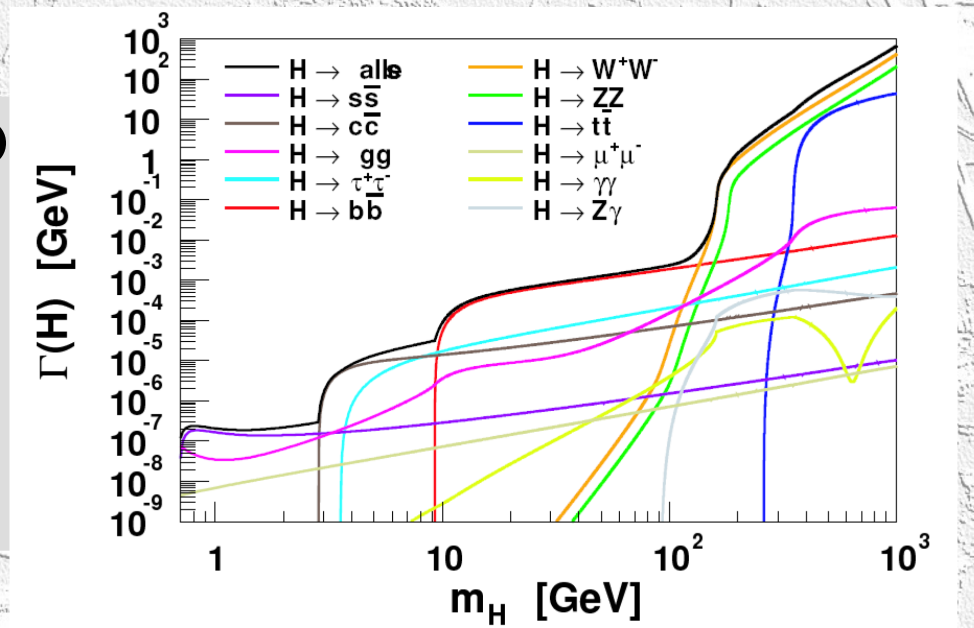
Total width of the Higgs (= inverse lifetime)

- 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

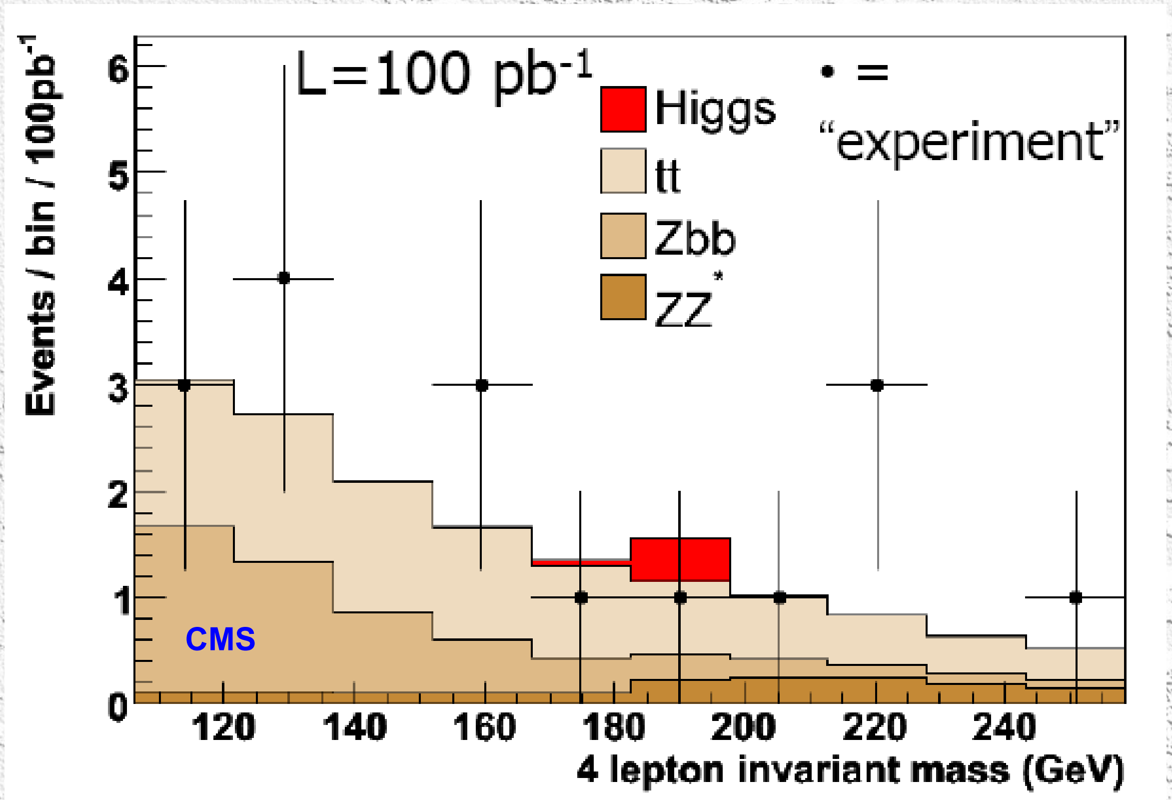
$$\Gamma_H \approx m_H$$



Early Higgs Searches

Early Higgs searches

- e.g. $H \rightarrow ZZ \rightarrow ee\mu\mu$ with 0.1 fb^{-1}



Search for the Higgs Boson at LHC

Possible future Higgs discovery plots:

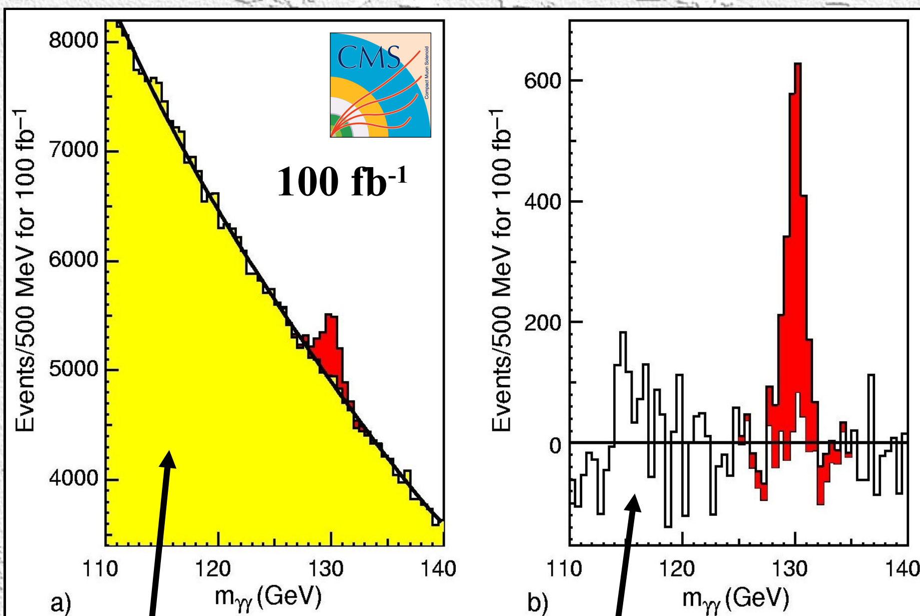
$H \rightarrow \gamma\gamma$:

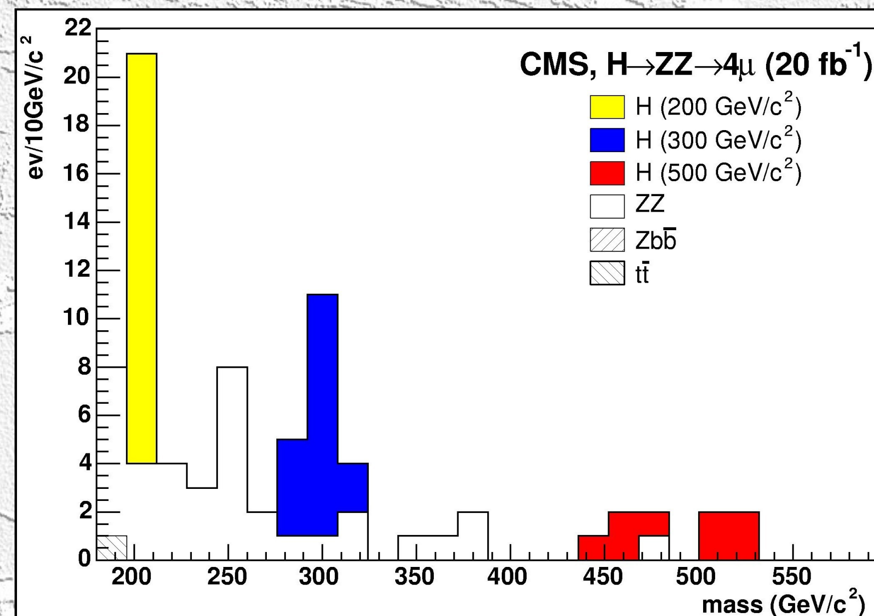
m_H = 130 GeV

$\sigma_{mH} \approx$ 1 GeV

$H \rightarrow ZZ \rightarrow 4\mu$:

m_H = 200 (300, 500) GeV





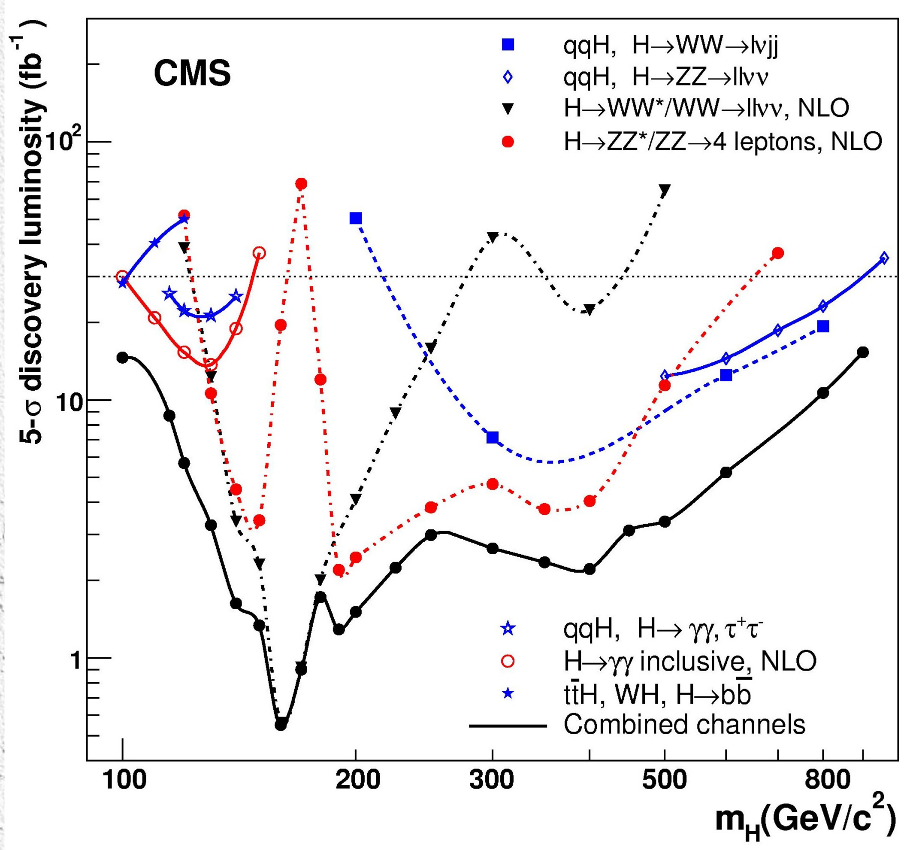
large combinatorial background

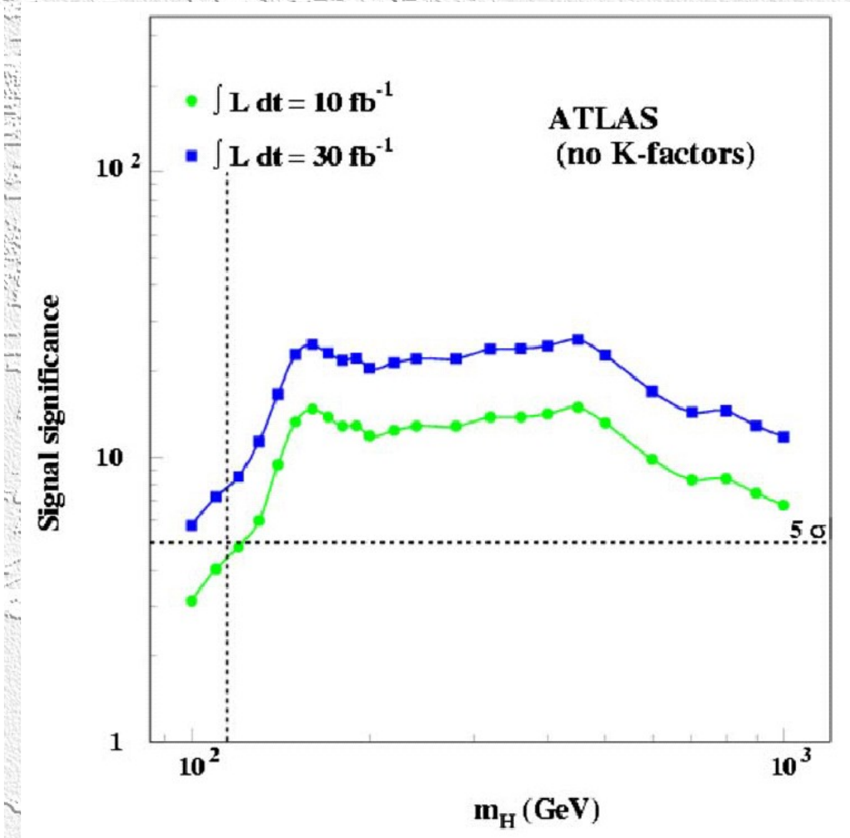
background subtracted

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:





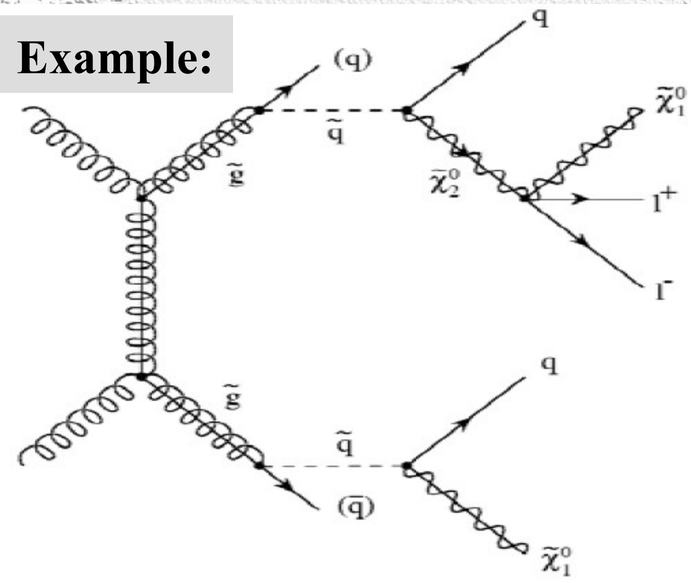
10 fb^{-1} sufficient for 5 σ discovery of the Higgs corresponds to 1 year at a luminosity of 10^{33}/cm^2/s

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 produced, 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!)

Squarks and Gluinos

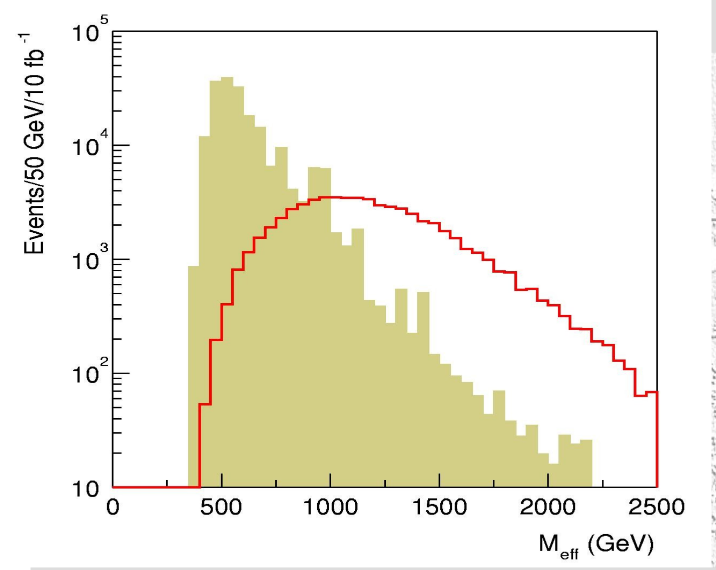
- Strongly produced, cross sections comparable to QCD cross sections at the same mass scale

- If R-parity conserved, cascade decays produce distinctive events: multiple jets, leptons, and E_T^{miss}

- Typical selection: $N_{jet} > 4$, $E_T > 100, 50, 50, 50$ GeV, $E_T^{miss} > 100$ GeV

$$M_{eff} = E_T^{miss} + P_T^1 + P_T^2 + P_T^3 + P_T^4$$

- (effective mass)



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

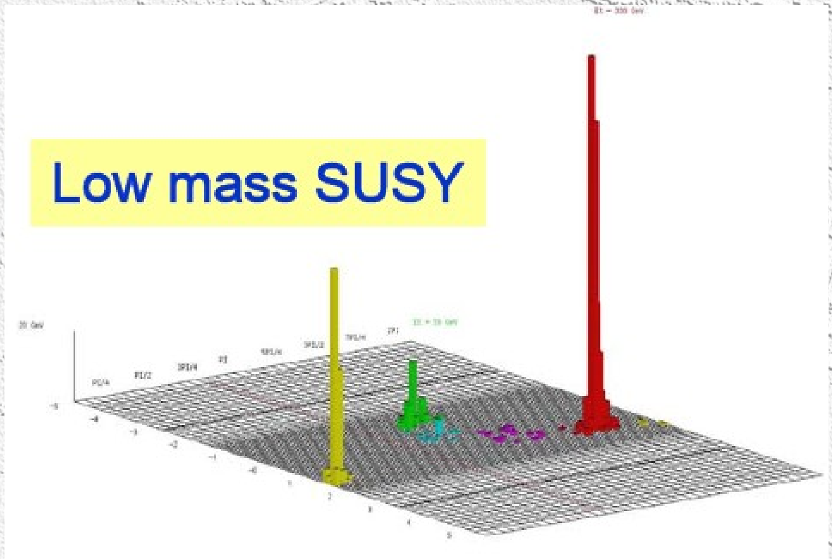
LHC reach for Squark- and Gluino masses:

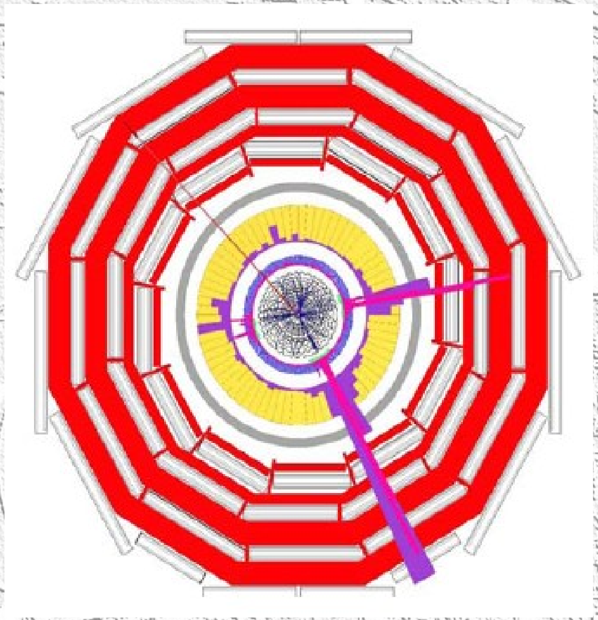
1 fb^{-1}	⇒	M ~ 1500 GeV
10 fb^{-1}	⇒	M ~ 1900 GeV
100 fb^{-1}	⇒	M ~ 2500 GeV

TeV-scale SUSY can be found rather quickly !

Early SUSY Searches

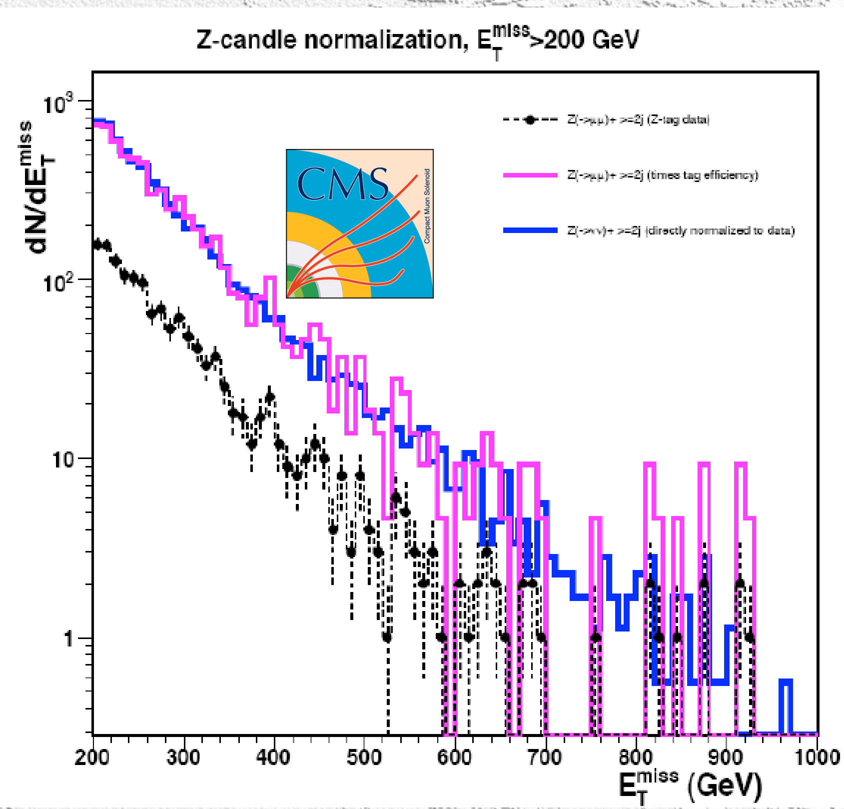
- Low mass SUSY (M_{sp} ≈ 500 GeV) accessible with O(100 pb^{-1})
- However time to discovery will be determined by
  - time to understand detector performance, e.g. E_T^{miss}
  - time to collect control samples e.g. W+jets, Z+jets, top,…



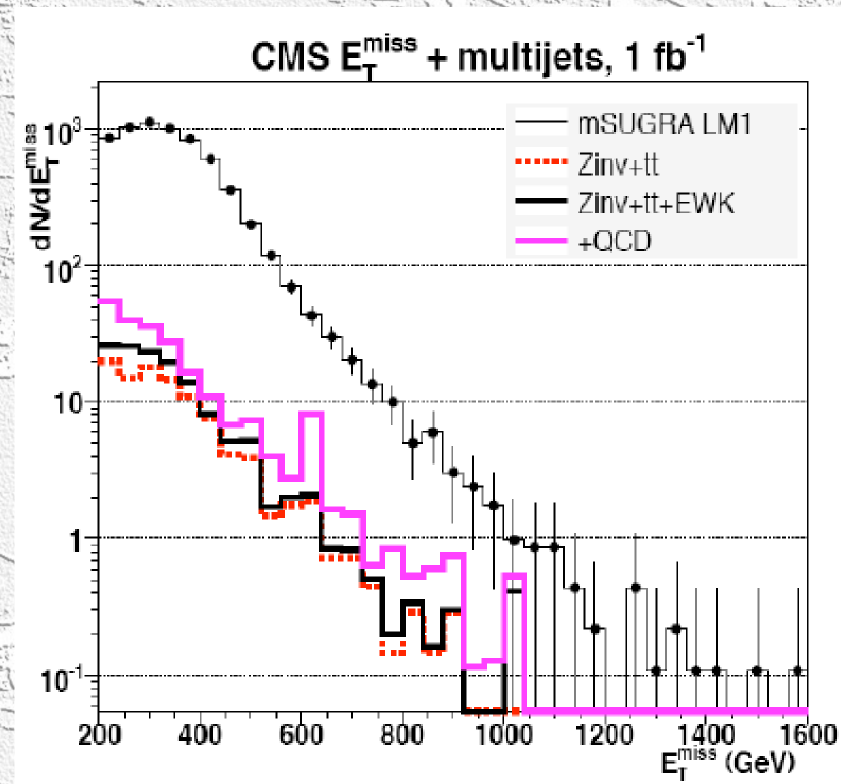


Early SUSY Searches

- Control over physics background
- Example E_t^{miss} + jets:
  - background from Z → νν (+jets)
  - normalise to Z→ μμ (+jets)

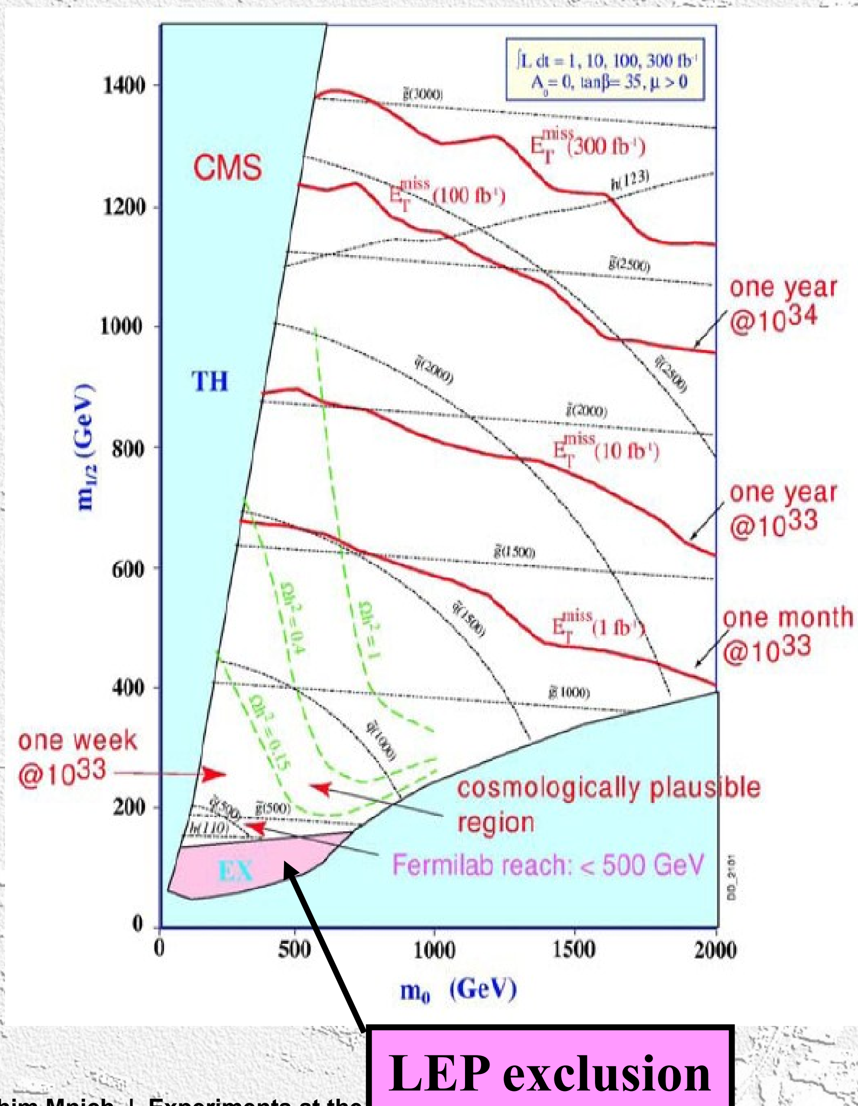


- Inclusive searches for 1 fb^{-1}



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

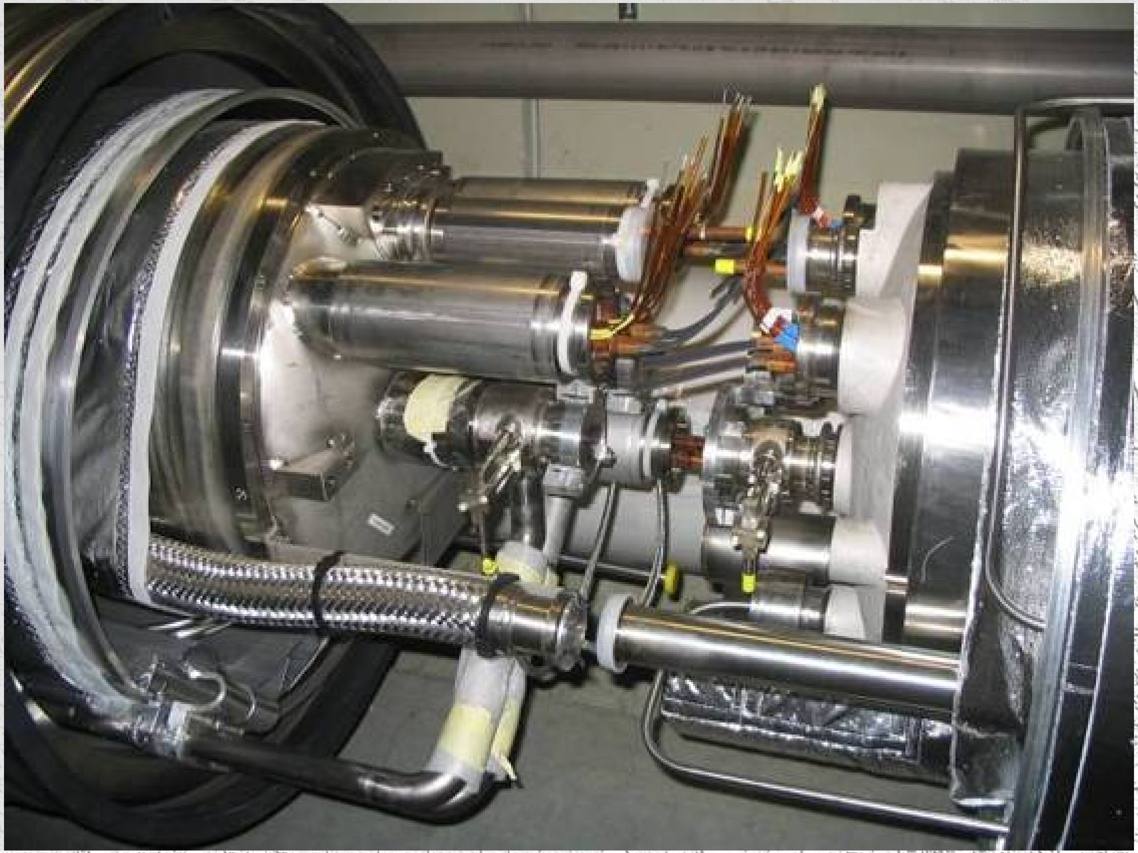
Conclusion:
- LHC will eclipse today's limits on SUSY particles and parameters
- or discover SUSY if it exists at the TeV scale

Where are we today? Status and Expectations

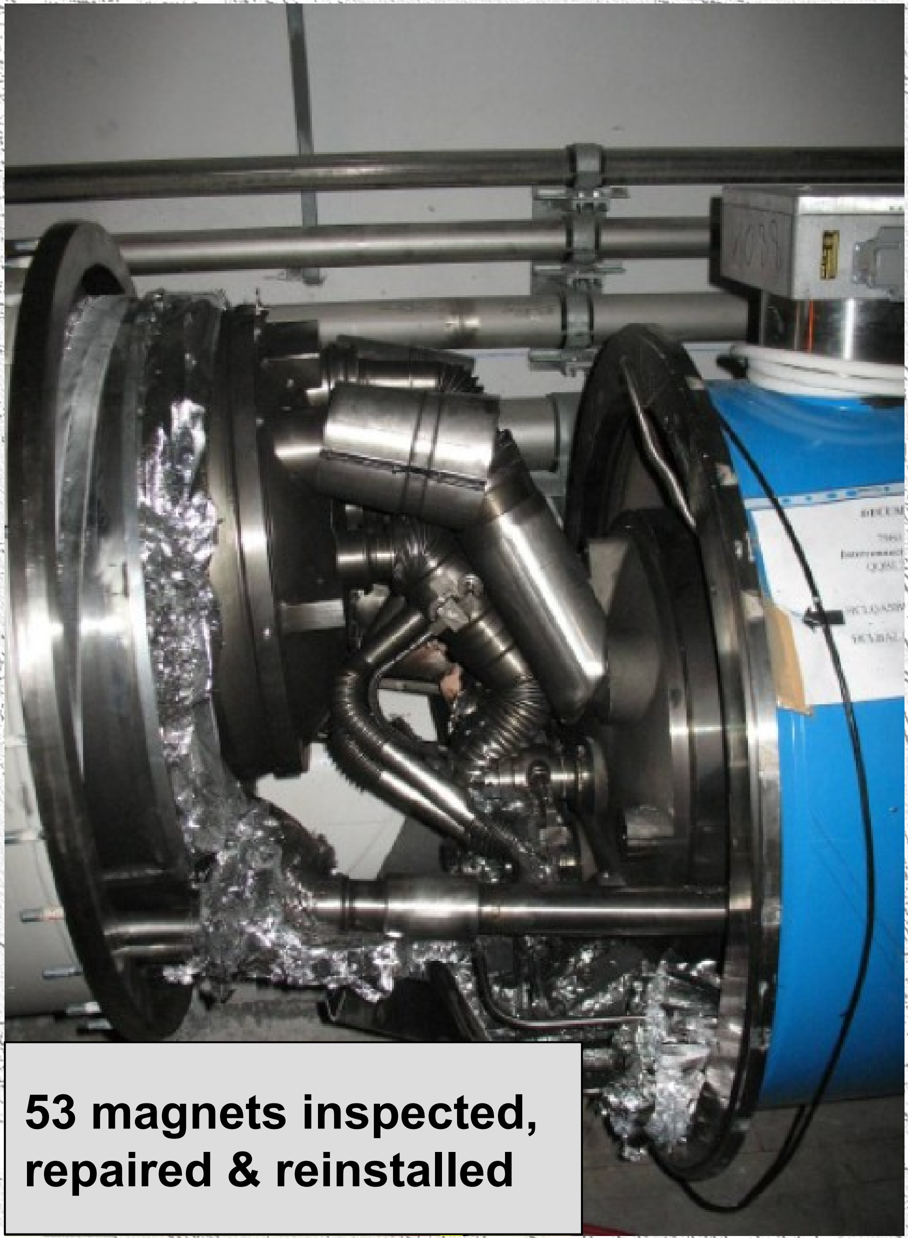
- **First circulating beams on**

LHC Accident

- **Major accident on September 19, 2008**
  - Bad connection between 2 magnets (resistance >> 1 nΩ)
  - Heat load ≈ 10 W cannot be cooled away
  - Thermal runaway
- **Quench protection of magnets worked well**
- **But light arc between magnets**
  - Destroyed a Helium vessel
  - 2 tons of He effused
  - Shock wave in tunnel



Damage

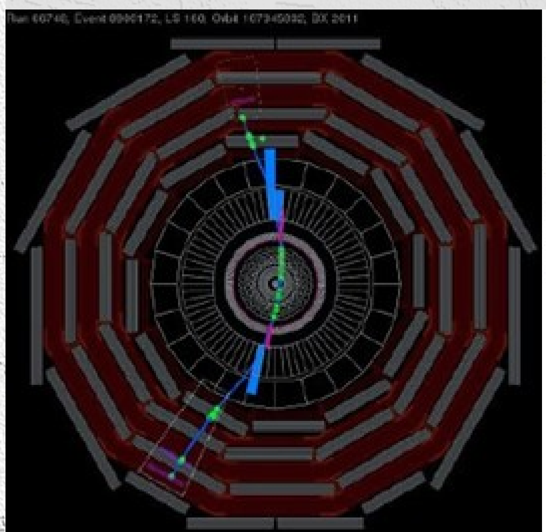


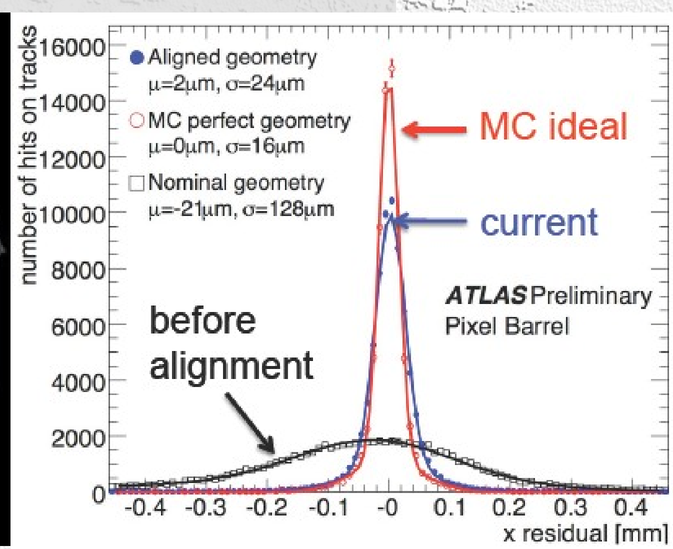
53 magnets inspected, repaired & reinstalled

Plans

- **Improve protection systems**
- **Restart LHC in September 2009**
- **First collisions in October 2009**
- **Operation until end 2010**
  - **reduced energy (4-5 TeV)**

- **Detectors are ready and preparing for data taking with cosmic rays**





Summary & Outlook

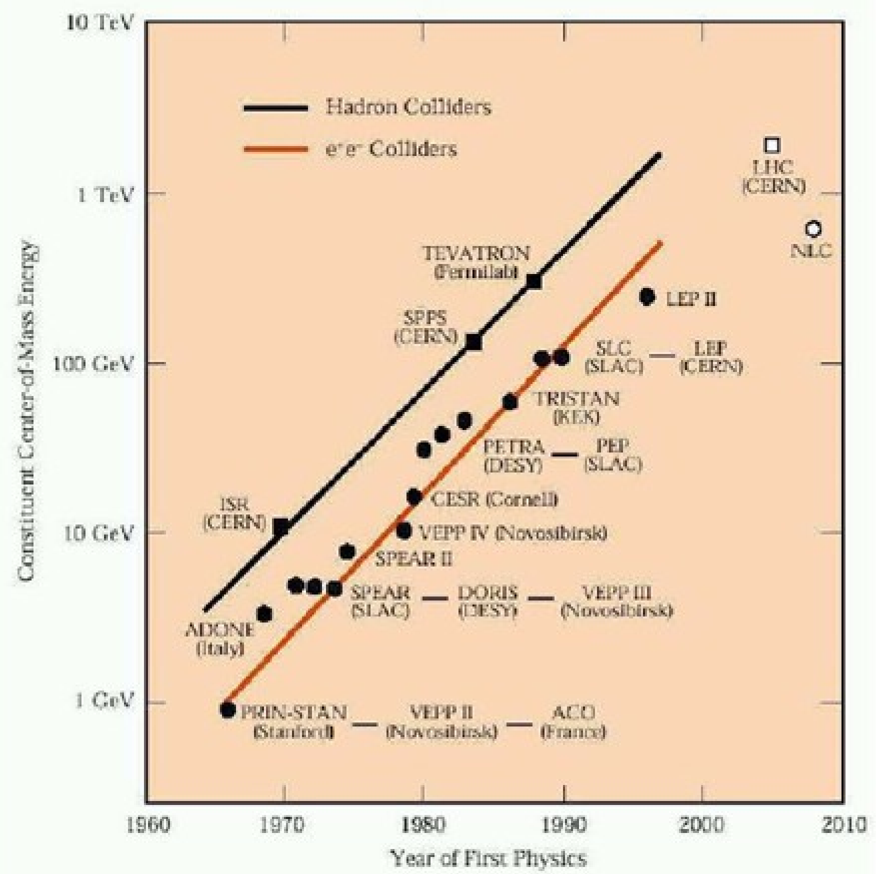
- LHC start second half 2009
  - Collisions at 4-5 TeV energy (single beam)
  - 1st run continously until end 2010
  - expected luminosity: a few 100 pb-1
- Detectors are ready for data taking
- The LHC experiments will
  - further improve knowledge on W boson, top quarks, QCD
  - will probe physics 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!

Backup slides

A Collider for the Terascale

- **Electron-Positron Collider**
  - Like DORIS & PETRA at DESY or LEP at CERN
  - Point-like particles
  - But limited in energy by synchrotron radiation
- **Proton-(anti)proton collider**
  - Higher energy reach limited by magnet bending power
  - But much harder for experiments



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 2×10^{33} cm^{-2} s^{-1} in the case of ATLAS and CMS)

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

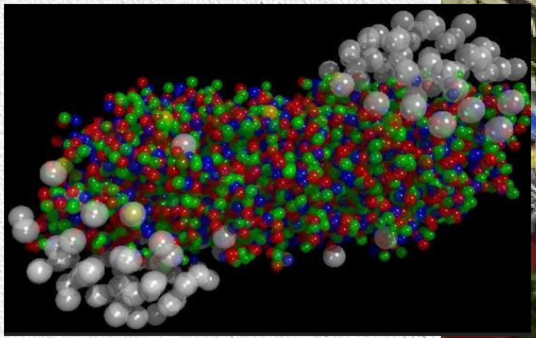
From T. Virdee, Phys. Rep. 403-404 (2004) 401

LHCb

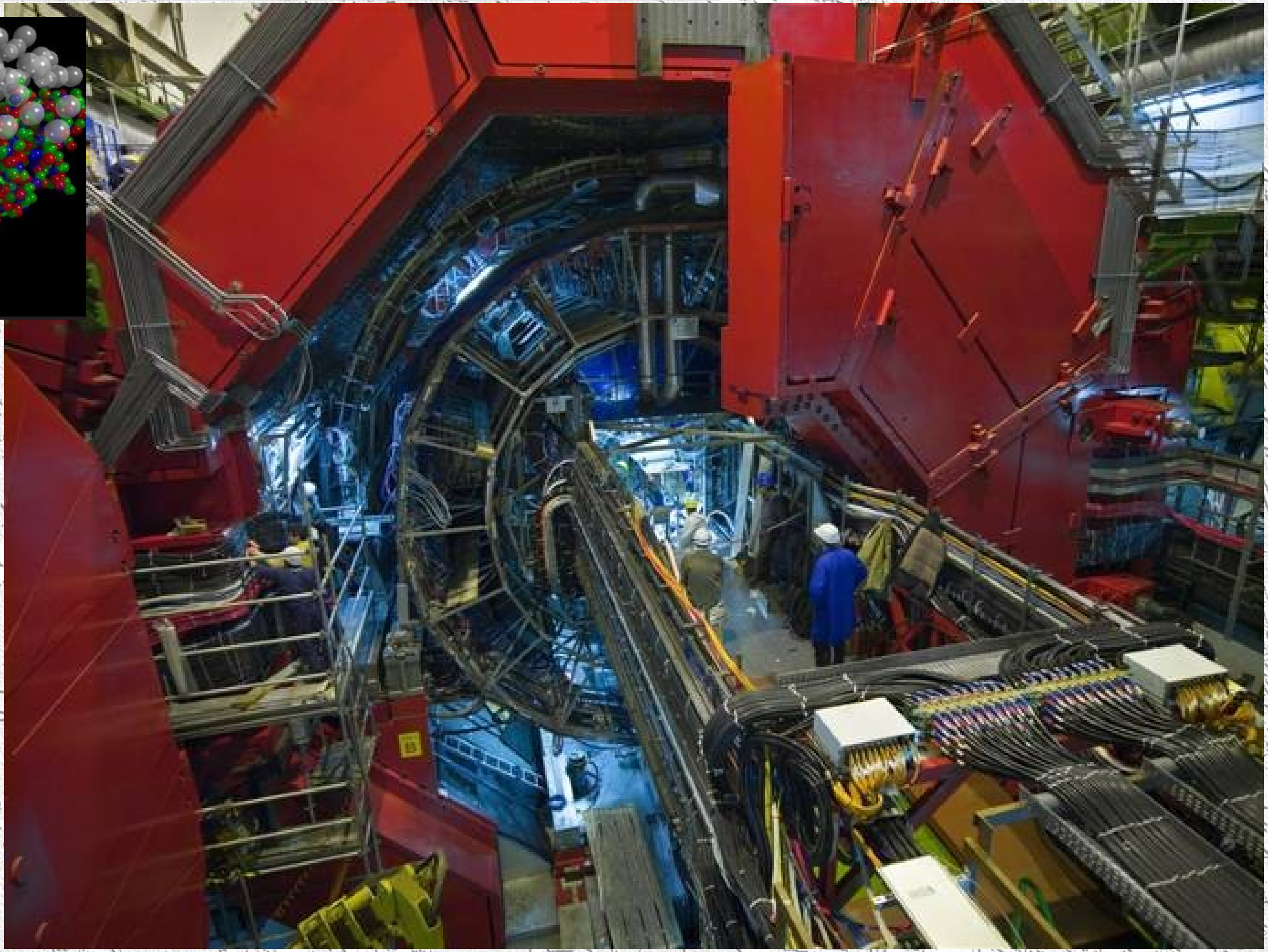
- **Experiment to address the question of matter-antimatter asymmetry**

ALICE

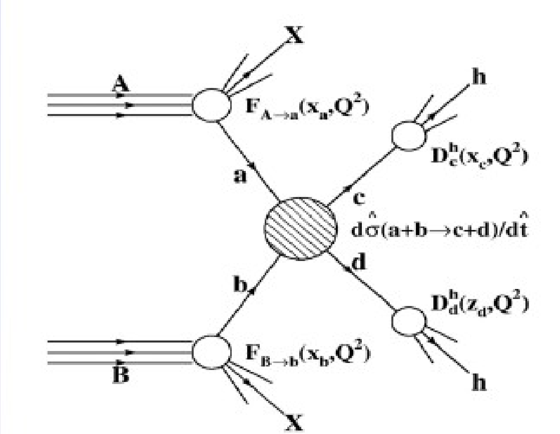
- **Experiment addresses new state of matter: the quark-gluon plasma**

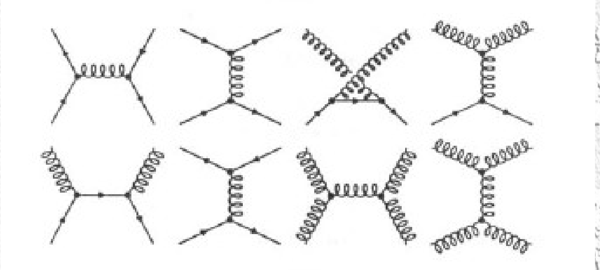


- Heavy ion collisions, eg. Pb-Pb



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

Measurement of α_s at LHC limited by

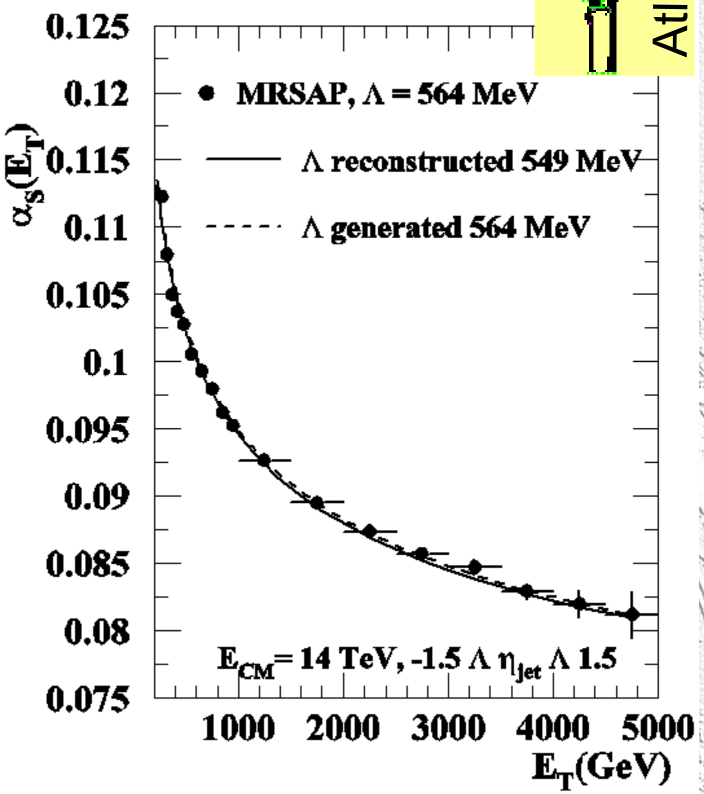
- **PDF (3%)**
- **Renormalisation & factorisation scale (7%)**
- **Parametrisaton (A,B)**

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

- **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

W Mass at the LHC

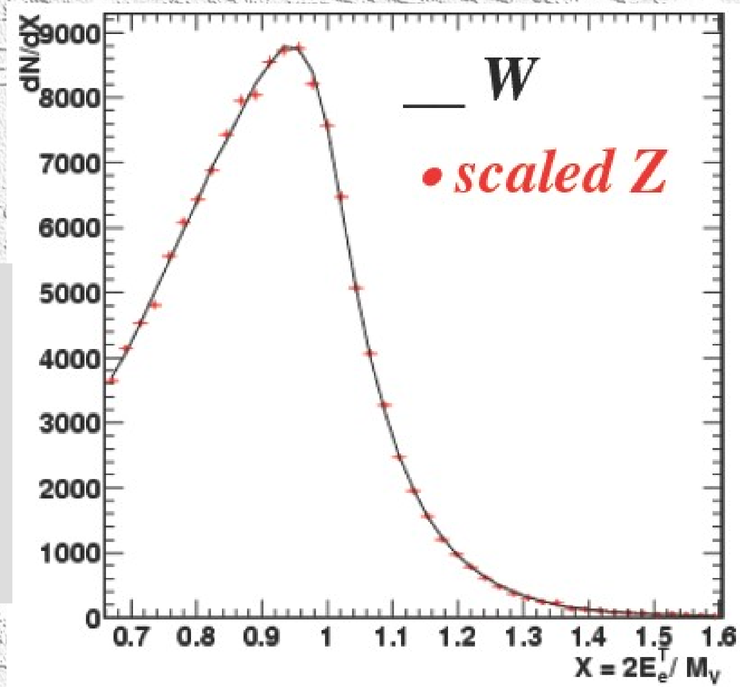
- Any improvement at the LHC requires control of systematic error to 10^{-4} level
  - take advantage from large statistics $Z \rightarrow e^+e^-, \mu^+\mu^-$
  - most experimental and theoretical uncertainties cancel in W/Z ratio
    e.g. Scaled Observable Method

$O_V = E^T, M^T$ 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)

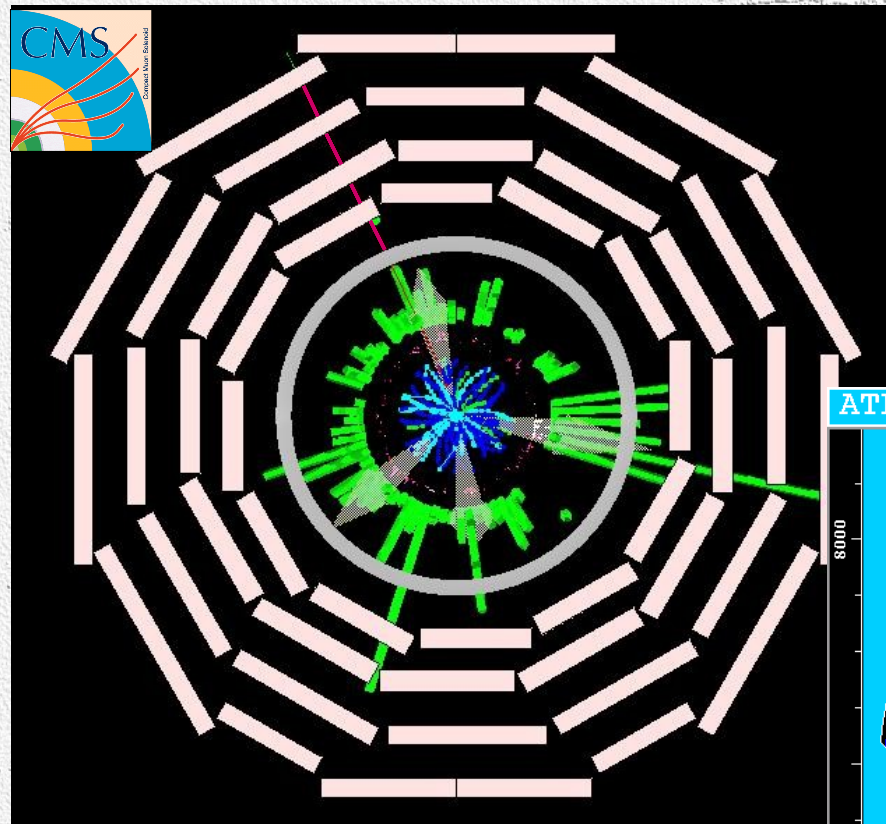
$$R(X) = \frac{d\sigma^W / dX_W}{d\sigma^Z / dX_Z}$$



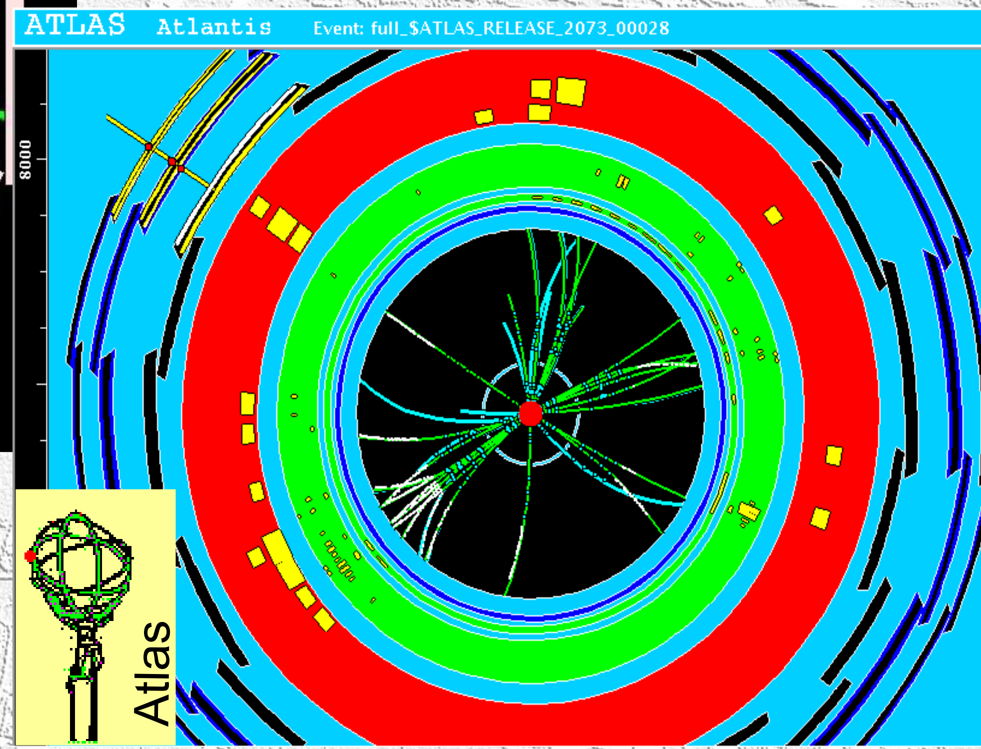
- Another method:
  generate $W \rightarrow e(\mu)\nu$ „Monte Carlo“ from data by removing a lepton from $Z \rightarrow e^+e^-, \mu^+\mu^-$ events

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

Top Quarks at the LHC



Examples of simulated
$tt \rightarrow bb\ qq\ \mu\ \nu$ events
from CMS & ATLAS

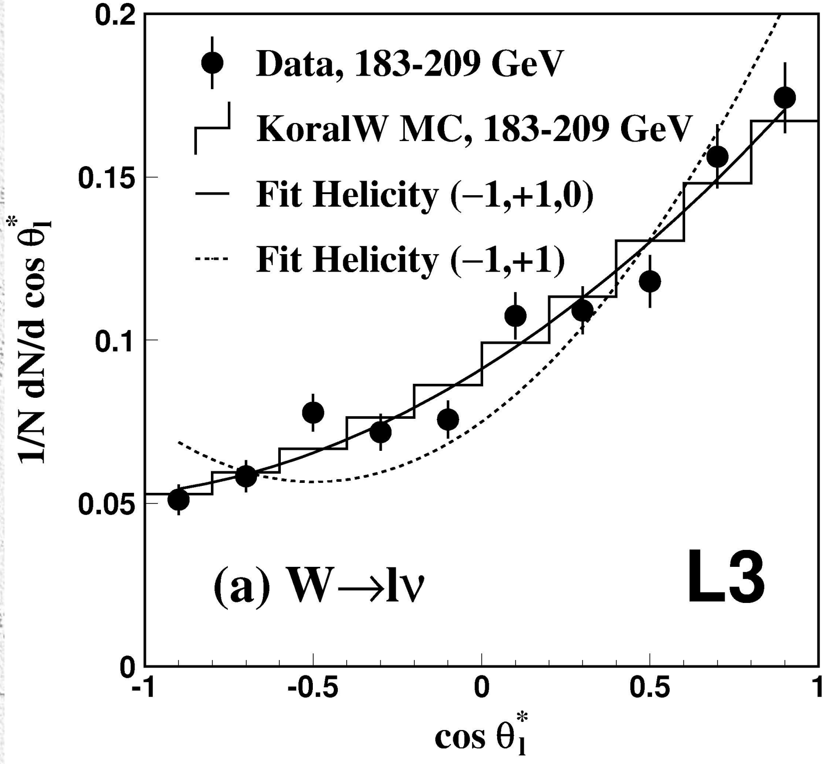


W Polarization

Massive gauge bosons have three polarization states

At LEP in $e^+e^- \to W^+W^-$:
determine W helicity from lepton (quark) decay angle in W rest frame θ^*

- $(1 \pm \cos\theta^*)^2$ transverse
- $\sin^2\theta^*$ longitudinal



⇒

- **Fraction of longitudinal W in $e^+e^- \to W^+W^-$**

  0.218 ± 0.031

  SM: 0.24

- **Tevatron: Longitudinal W in top decays**

  0.91 ± 0.52 CDF

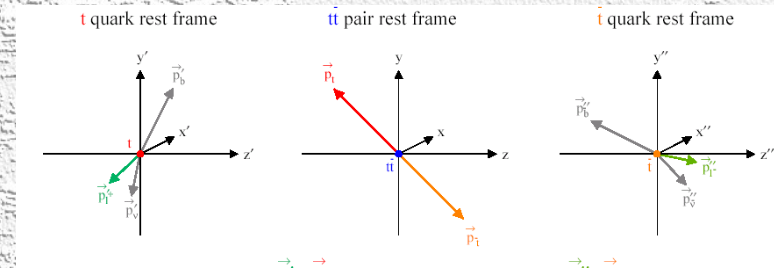
  0.56 ± 0.31 D0

  SM: 0.7

$t\bar{t}$ Spin Correlation

Very short lifetime, no top bound states

⇒ Spin info not diluted by hadron formation



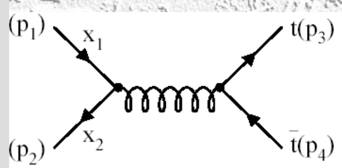
$$\cos\theta^*_{l^+} \equiv \frac{\vec{p}^{\,\prime}_{l^+} \cdot \vec{p}_t}{|\vec{p}^{\,\prime}_{l^+}||\vec{p}_t|} \qquad \cos\theta^*_{l^-} \equiv \frac{\vec{p}^{\,\prime\prime}_{l^-} \cdot \vec{p}_{\bar{t}}}{|\vec{p}^{\,\prime\prime}_{l^-}||\vec{p}_{\bar{t}}|}$$

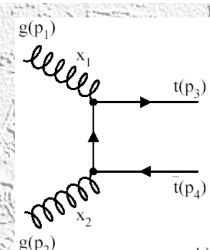
$$\mathcal{A} = \frac{N(t_L\bar{t}_L + t_R\bar{t}_R) - N(t_L\bar{t}_R + t_R\bar{t}_L)}{N(t_L\bar{t}_L + t_R\bar{t}_R) + N(t_L\bar{t}_R + t_R\bar{t}_L)}$$

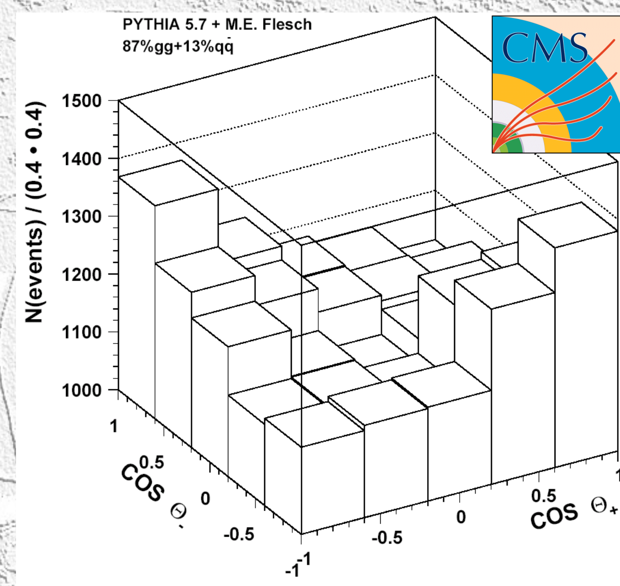
$$\frac{1}{N}\frac{d^2N}{d\cos\theta^*_{\ell+}\, d\cos\theta^*_{\ell-}} = \frac{1}{4}(1 - \mathcal{A}\cos\theta^*_{\ell+}\cos\theta^*_{\ell-})$$

Distinguishes between

- **quark annihilation**
  A = -0.469
- **and gluon fusion**
  A = +0.431





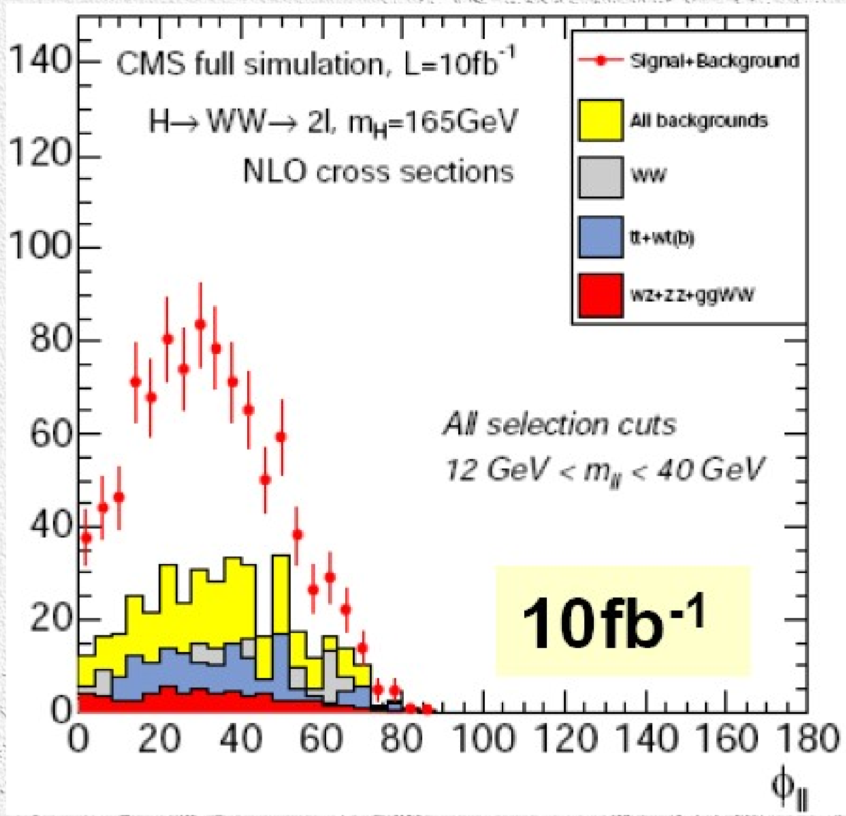


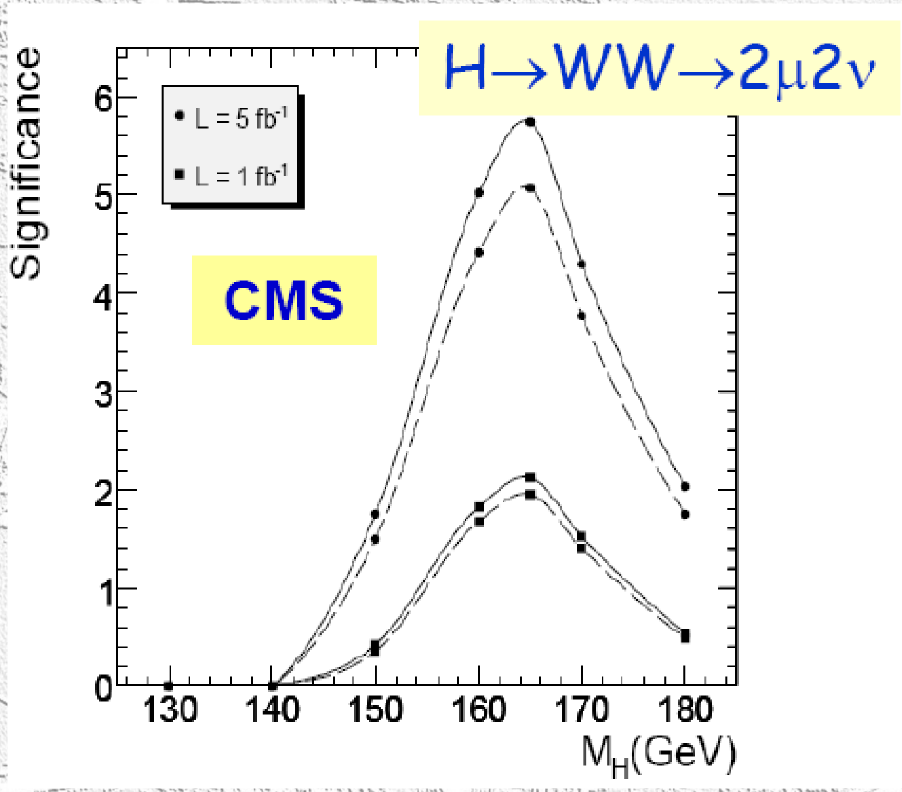
Use double leptonic decays
tt → bb lν lν

A= 0.311 ± 0.035 ± 0.028
(using 30 fb^{-1})

Early Higgs Searches

- Best chances around $m_H \approx 2\ m_W$ in $H \rightarrow WW \rightarrow 2l + 2\nu$ channel





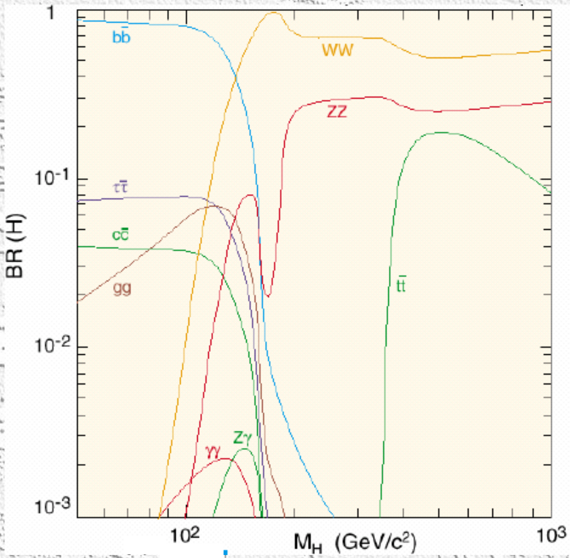
Search for the Higgs Boson

LEP:

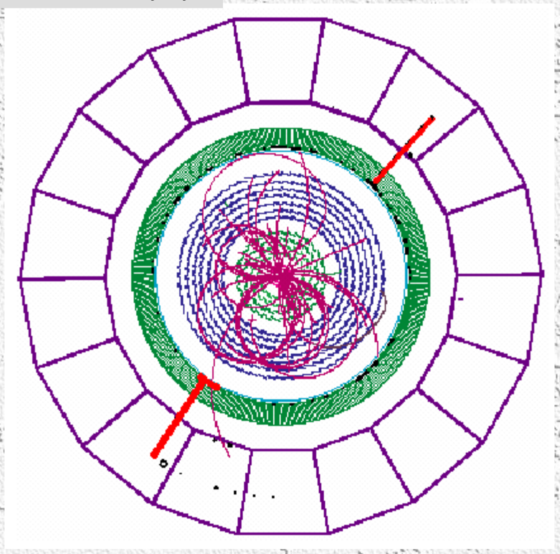
$H \rightarrow bb$

LHC:

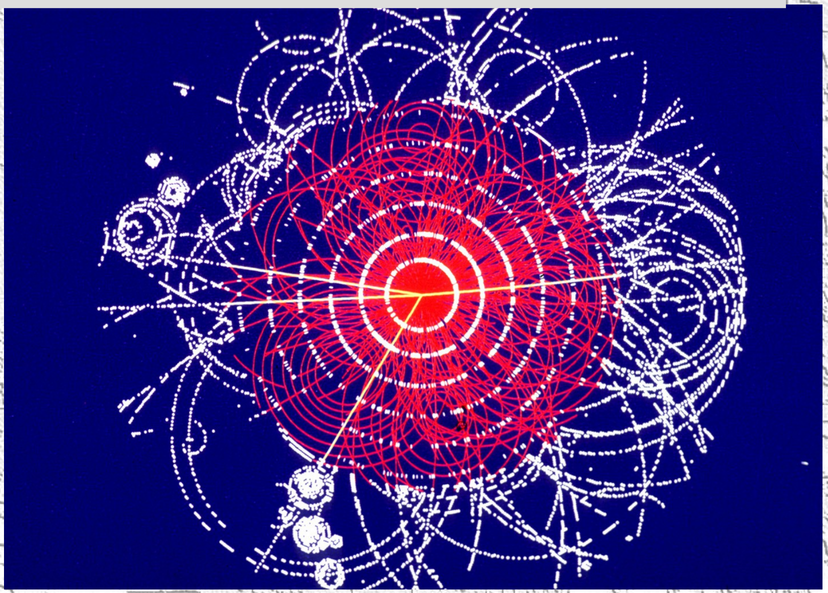
$H \rightarrow bb$	enormous QCD bkgd
$H \rightarrow \gamma\gamma$	low m_H (BR $\approx 10^{-3}$)
$H \rightarrow W^+W^-$	medium m_H
$H \rightarrow ZZ$	high m_H



$H \rightarrow \gamma\gamma$

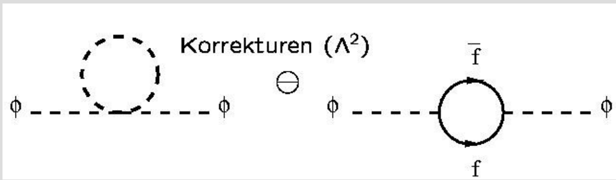


$H \rightarrow ZZ \rightarrow 4\mu$ (golden channel)



Why SUSY?

1. **Quadratically divergent quantum corrections to the Higgs boson mass are avoided**

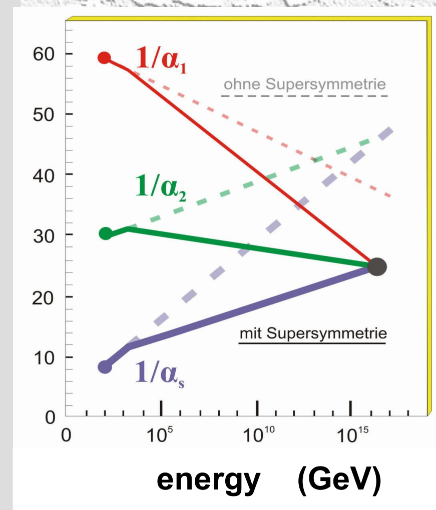


$$\Delta m_H = f(m_B^2 - m_f^2)$$

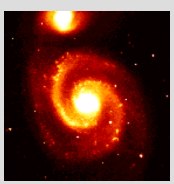
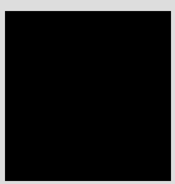
→ $m_{SUSY} \sim 1$ TeV

(Hierarchy or naturalness problem)

2. **Unification of coupling constants of the three interactions seems possible**

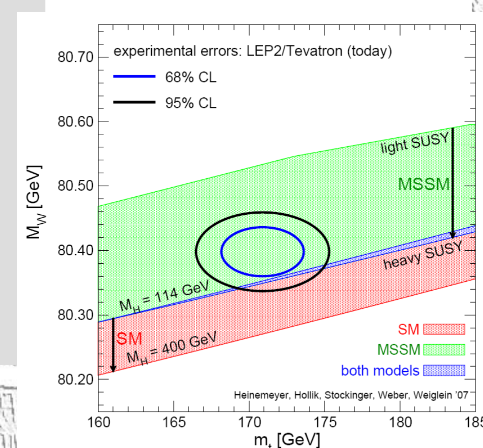


3. **SUSY provides a candidate for dark matter,**

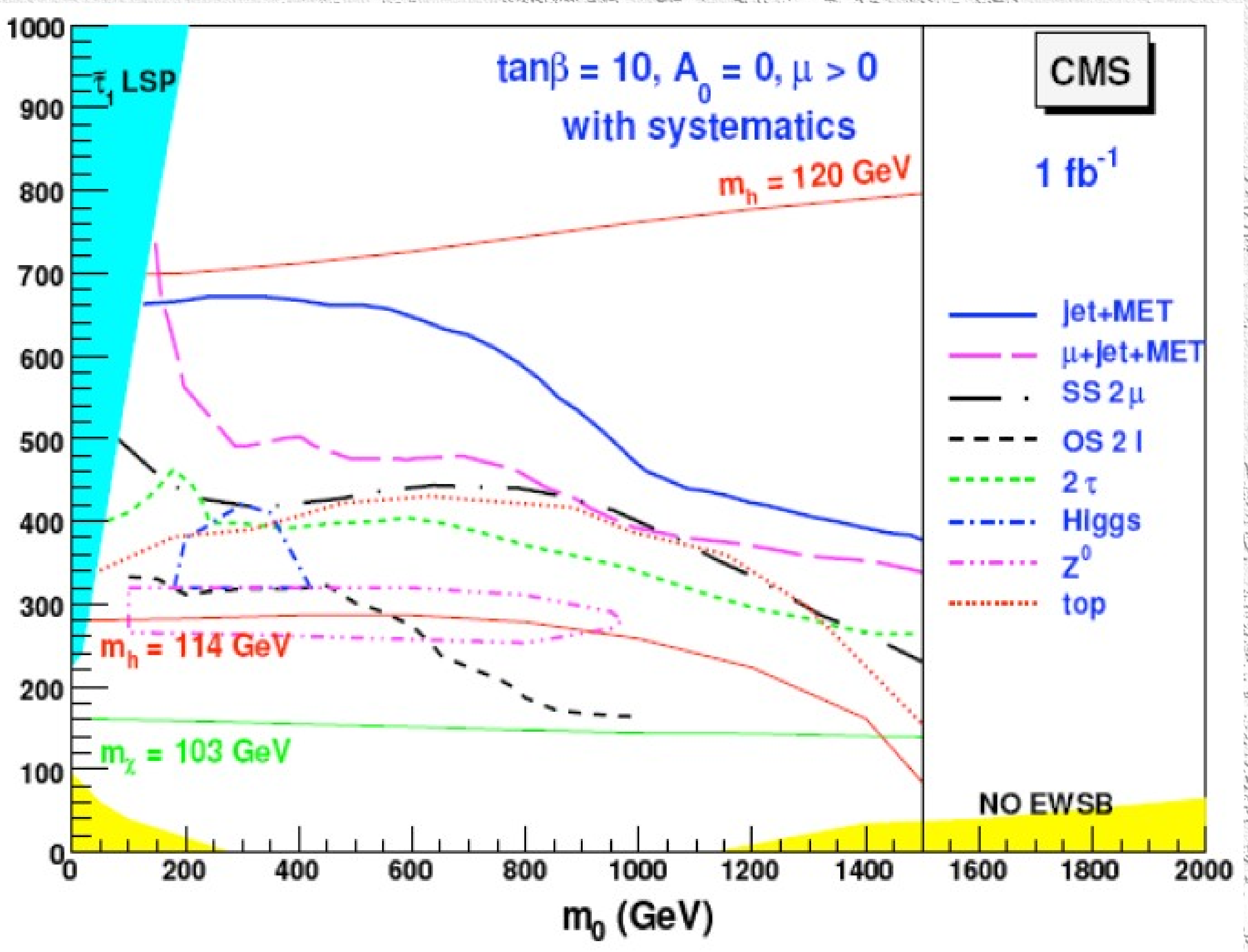
The lightest SUSY particle (LSP)

4. **A SUSY extension is a small perturbation, consistent with the electroweak precision data**



Early SUSY Searches

Inclusive searches for 1 fb-1



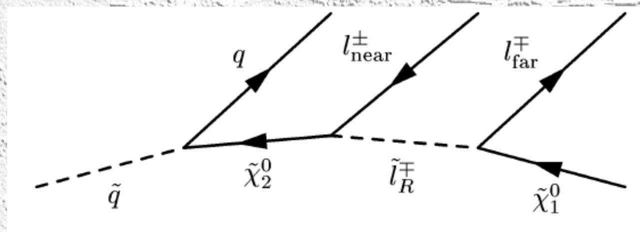
SUSY Searches

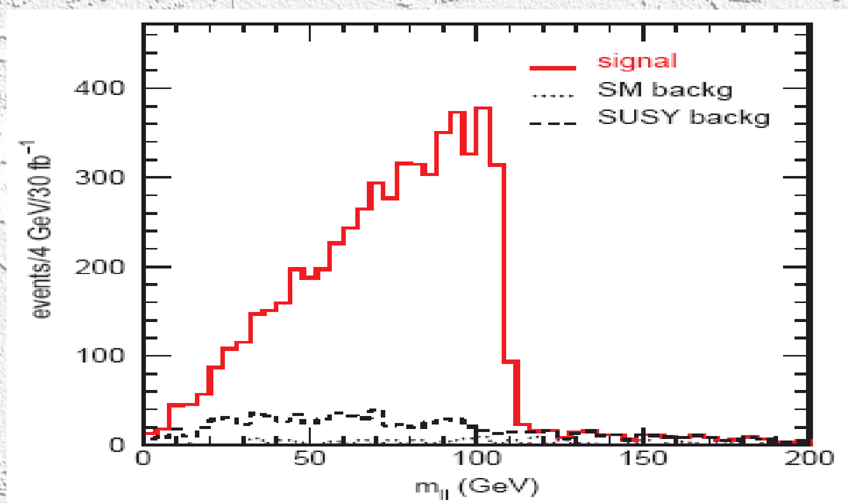
LHC Strategy: End point spectra of cascade decays

Example: $\tilde{q} \rightarrow q\tilde{\chi}_2^0 \rightarrow q\tilde{t}^{\pm}t^{\circ} \rightarrow qt^{\pm}e^{e}\tilde{\chi}_1^0$

$$M^{max}_{t^+t^-} = \frac{\sqrt{(m^2_{\chi_2^0} - m^2_{\tilde{t}})(m^2_{\tilde{t}} - m^2_{\chi_1^0})}}{m_{\tilde{e}}}$$

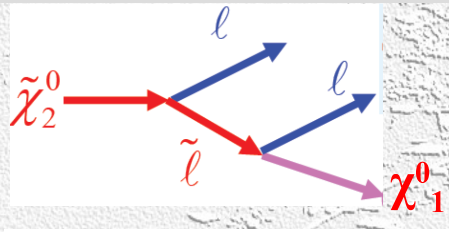
$$M^{max}_{t_1 q} = \frac{\sqrt{(m^2_{\chi_2^0} - m^2_{\tilde{e}})(m^2_{\tilde{q}} - m^2_{\chi_2^0})}}{m_{\chi_2^0}}$$

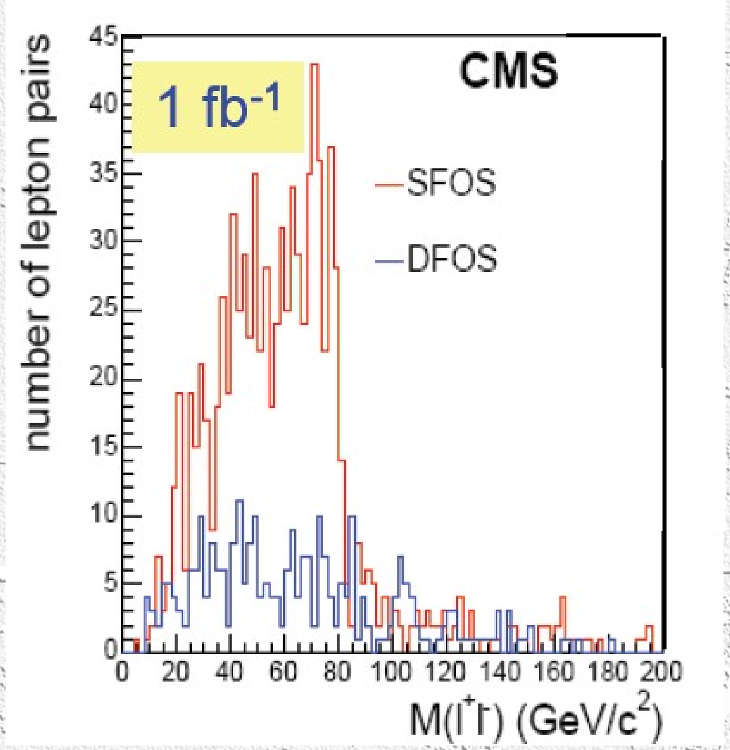




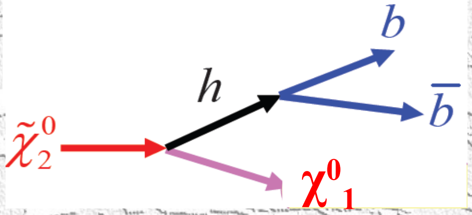
SUSY signals

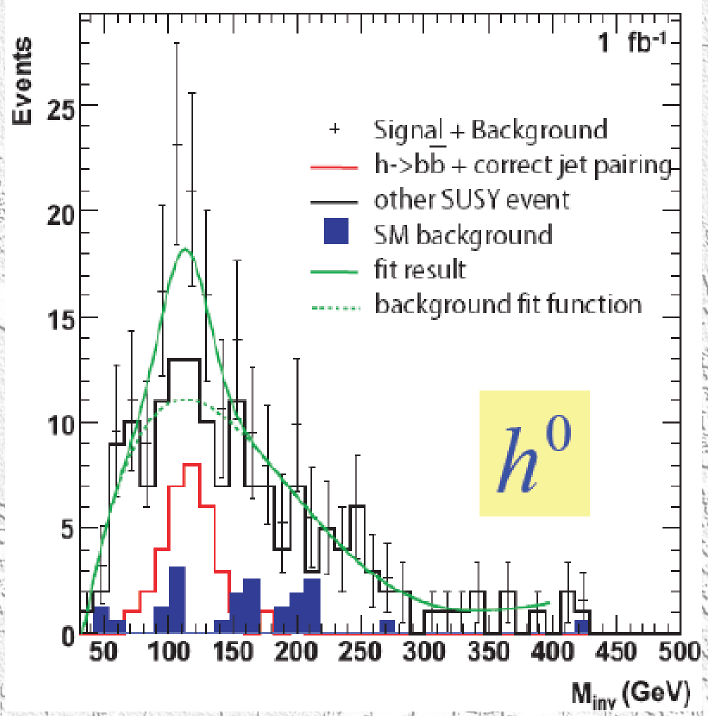
Second ligthest neutralino χ^0_2
- **cascade decay**
- **leptons + E_T^{miss}**





- **cascade decay with h**
- **b-jets + E_T^{miss}**





Extra Dimensions: Z´/ Randall-Sundrum

With 1 fb^{-1}:
- **Z´ discovery up to 2 - 2.5 TeV**
- **most of RS parameter space covered**