The Large Hadron Collider:
Shedding Light on the Dark Universe

Particle Physics and the Early Universe

The Large Hadron Collider (LHC)

The LHC and the Dark Universe

R.-D. Heuer, CERN

Berlin, July 12, 2010

Particle Physics at accelerators

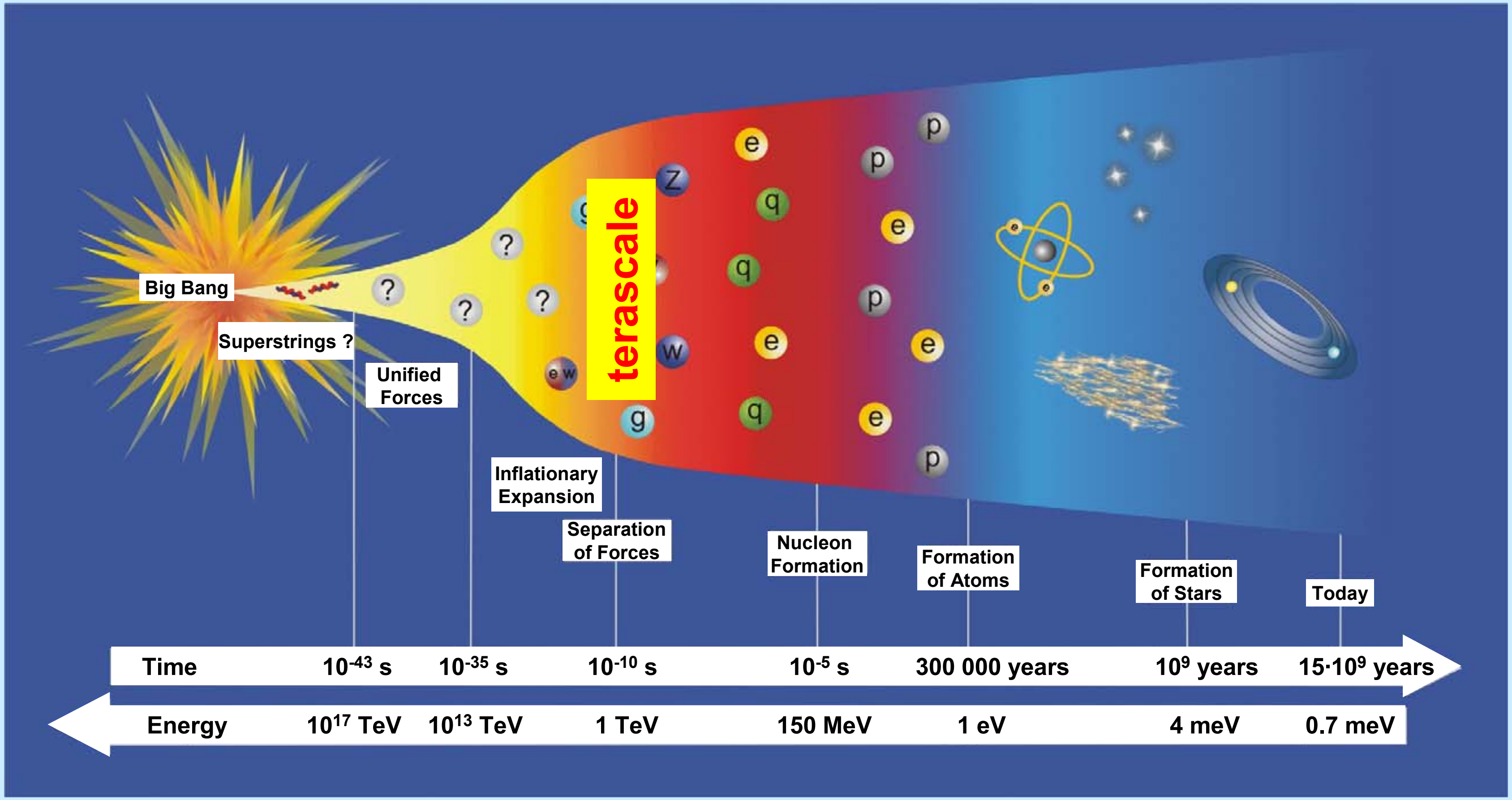
Explore the innermost structure of matter :

- Which are the fundamental constituents of matter ?
- Which forces interact between them ?

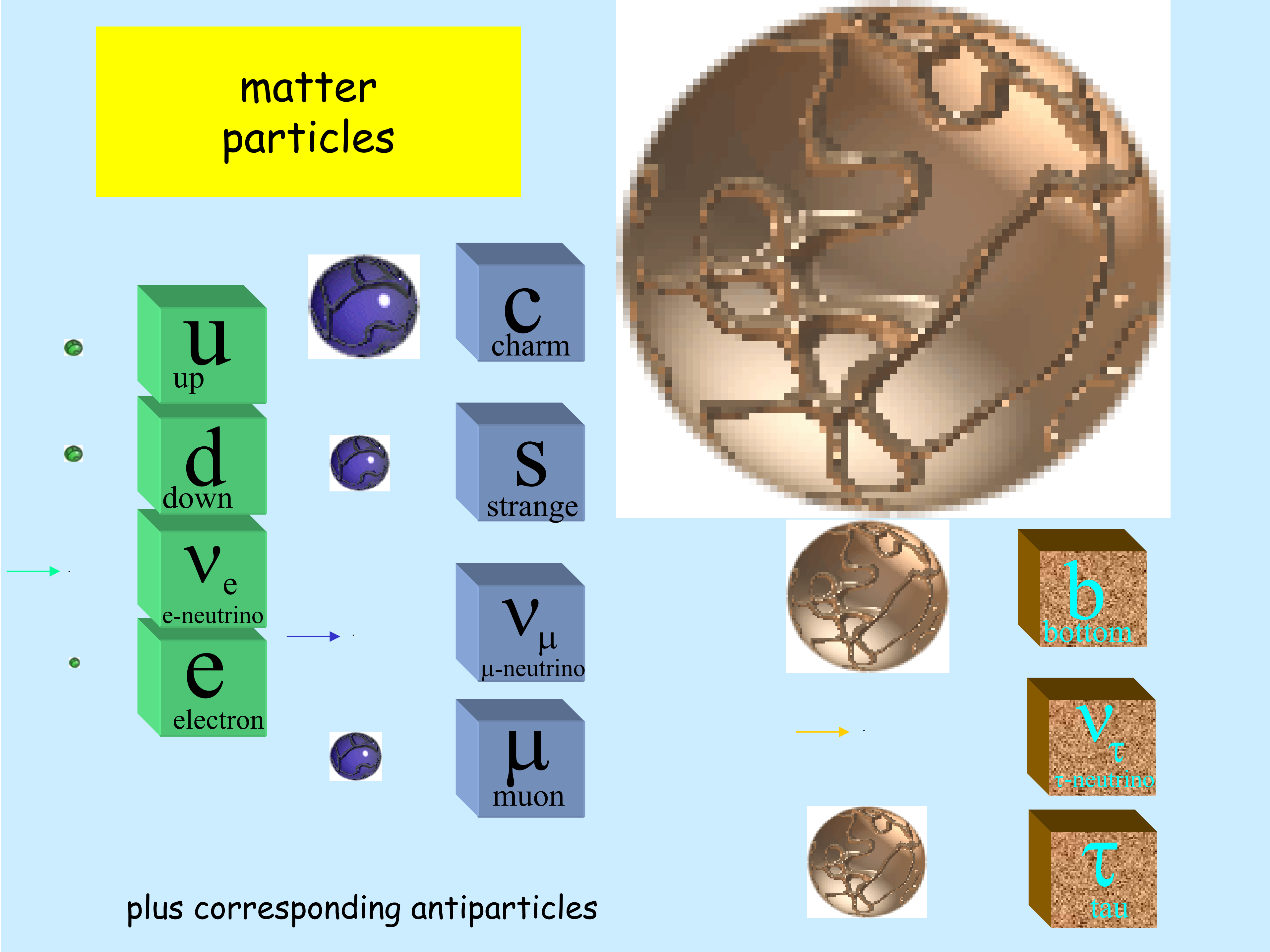
Investigating the Structure of Matter
↓
Understanding the Early Universe

Vision

- **Revolutionary advances in understanding the microcosm**
- **Connect microcosm with early Universe**



Particle Physics at the Energy Frontier with highest collision energies ever will change our view of the universe


matter
particles
u
up
d
down
ν_e
e-neutrino
e
electron
c
charm
s
strange
ν_μ
μ-neutrino
μ
muon
b
bottom
ν_τ
τ-neutrino
τ
tau
plus corresponding antiparticles

Electron-Positron Collider LEP:

Number of Families

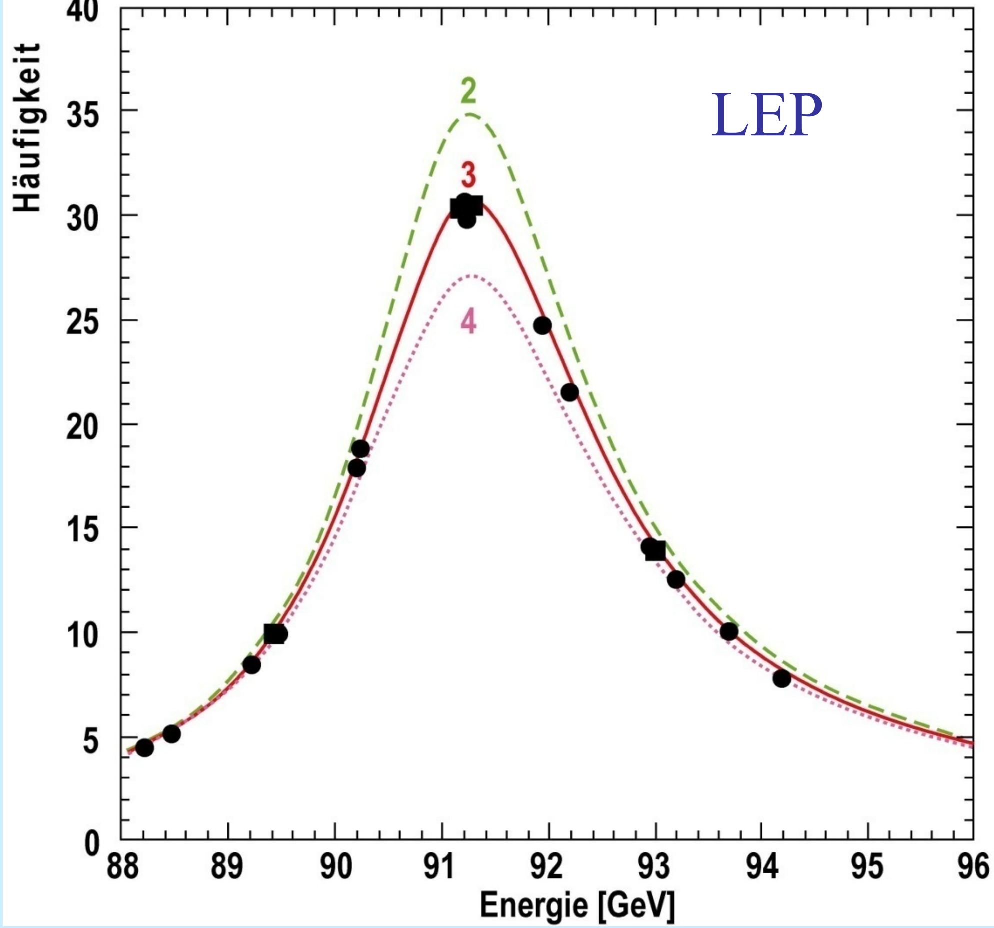
$e^+e^- \longrightarrow Z^0 \longrightarrow f\,\bar{f}$
where $f=q,l,\nu$

σ_Z and Γ_Z depend on number of (light) neutrinos

number of families:

$N = 2.984 \pm 0.008$

resonance curve Z-Boson



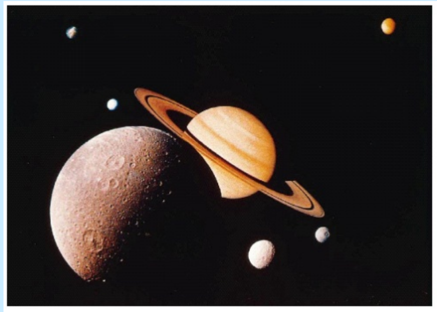
Structure of Matter I

Matter (Stars <=> living organisms) consists of
3 families of *Quarks* and *Leptons*

Matter around us: only 1 of the 3 families
Matter at high energies:
‚democratic', all 3 families present

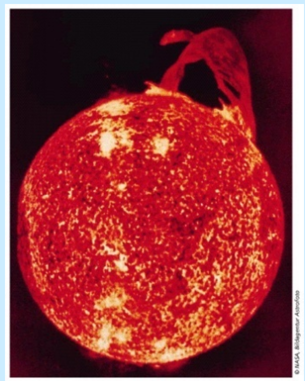
—> Situation fraction of seconds after the creation of the Universe
—> Study of Matter at High Energies
knowledge about Early Universe

Forces



Gravitation
(acts on mass, energy)

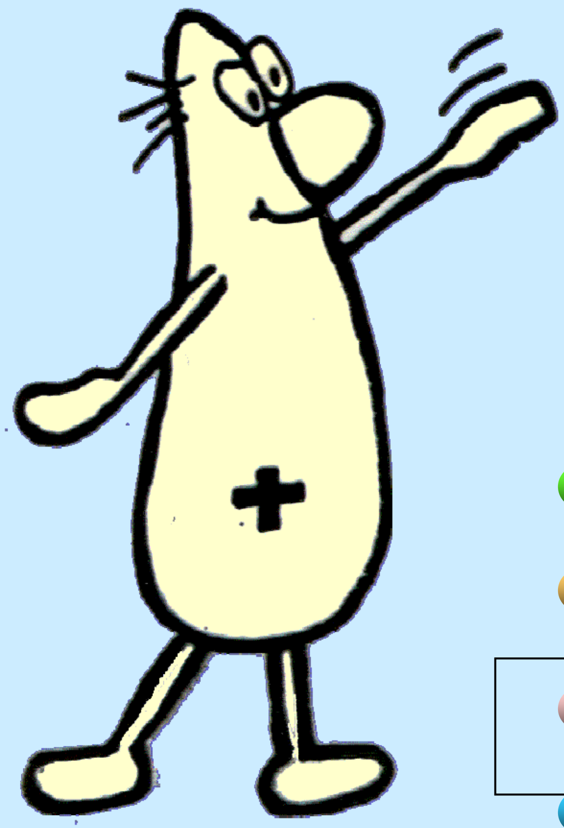
Electromagnetic Force
(acts on el.charge)



Weak Force
(acts on leptons, quarks)

Strong Force
(acts on quarks)

Force Carriers = Gauge Bosons



- Graviton
- Photon
- $W^{+/-}, Z^{0}$
- Gluon

The Forces in Nature

Type	rel. Strength	Force Carrier	acts on
Strong Force	1	Gluon g m = 0	Quarks Nuclei
Electro-magnet. Force	~ 1/137	Photon γ m = 0	Electric Charge Atoms, Chemistry
Weak Force	$\sim 10^{-14}$	W, Z Bosons m = 80 , 91 GeV	Leptons, Quarks Radioactive Decays (β-decay)
Gravitation	$\sim 10^{-40}$	Graviton ? m = 0	Mass, Energy

Force Carriers (Bosons) mediate the forces

Structure of Matter II

4 fundamental *forces* act between *Matter Particles* through the exchange of Gauge Bosons (Gluon, W und Z, Photon, Graviton)

Within our Energy regime:

resp. strengths of forces very different

At high Energies:

all forces of same strength → one force ?

—> Situation fraction of seconds after creation of the Universe

—> Study of the forces of Nature
knowledge about Early Universe

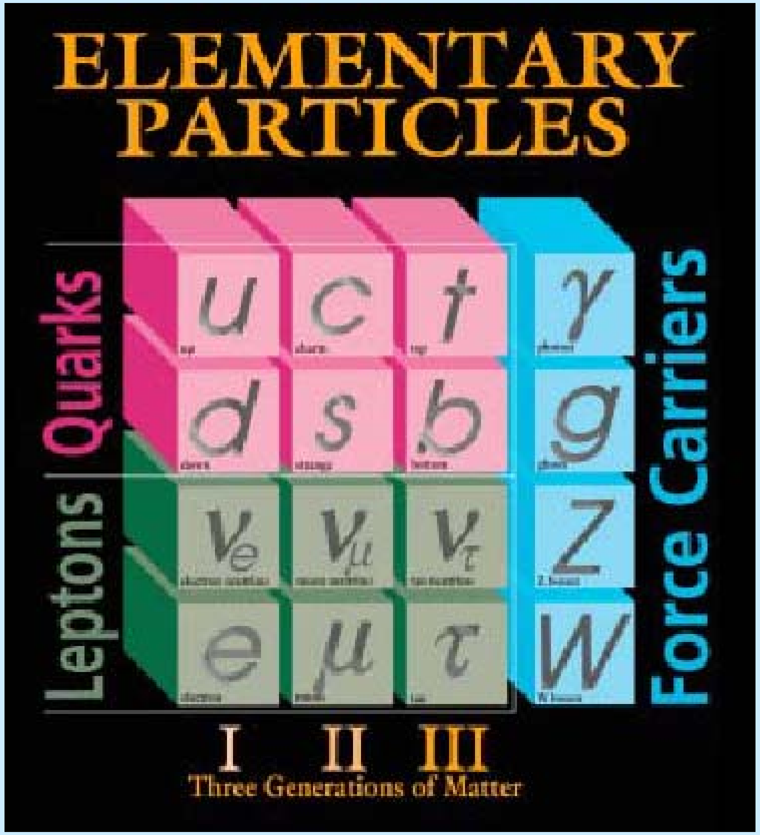
What have we learned the last 40 years
or
Status of the **Standard Model**

The physical world is

composed of
Quarks and Leptons

interacting via
force carriers
(Gauge Bosons)

Last entries: top-quark 1995
tau-neutrino 2000



Past few decades

"Discovery" of Standard Model

through synergy of

hadron - hadron colliders (e.g. Tevatron)

lepton - hadron colliders (HERA)

lepton - lepton colliders (e.g. LEP)

Structure of Matter III

Standard Model of Particle Physics

Mathematical formalism describing all interactions mediated through weak, electromagnetic and strong forces

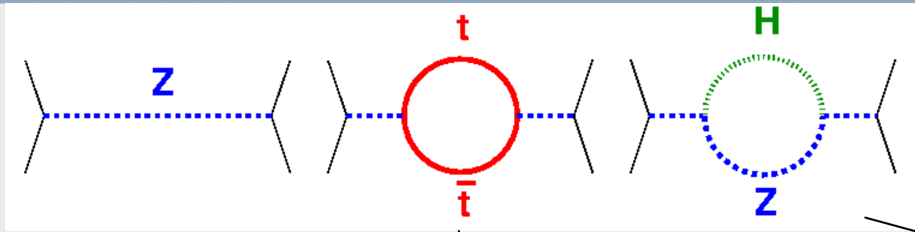
Test of predictions with very high precision

experimental validation

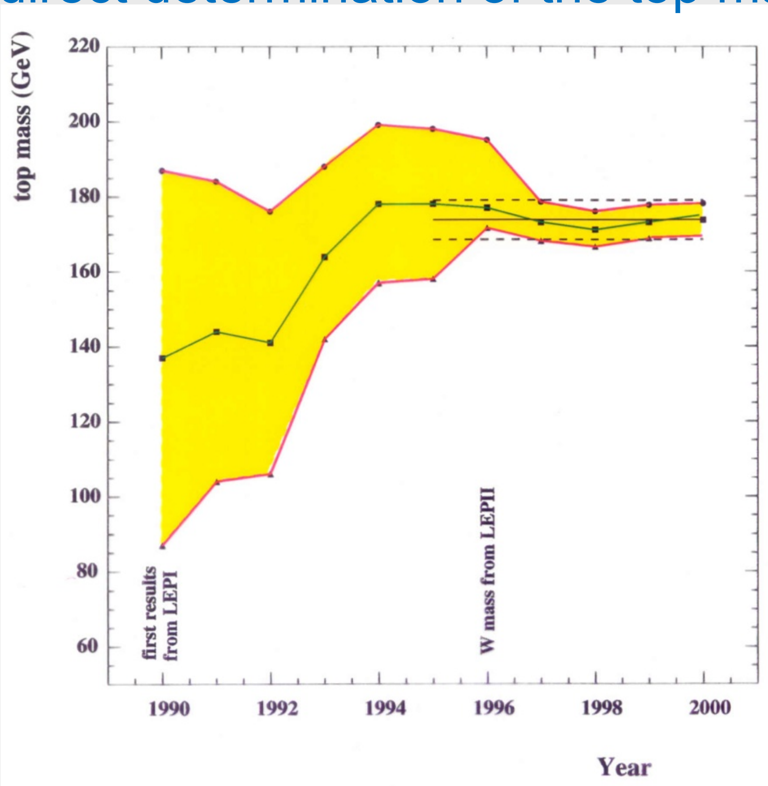
down to $\sim 10^{-18}$ m

or up to O(100 GeV)

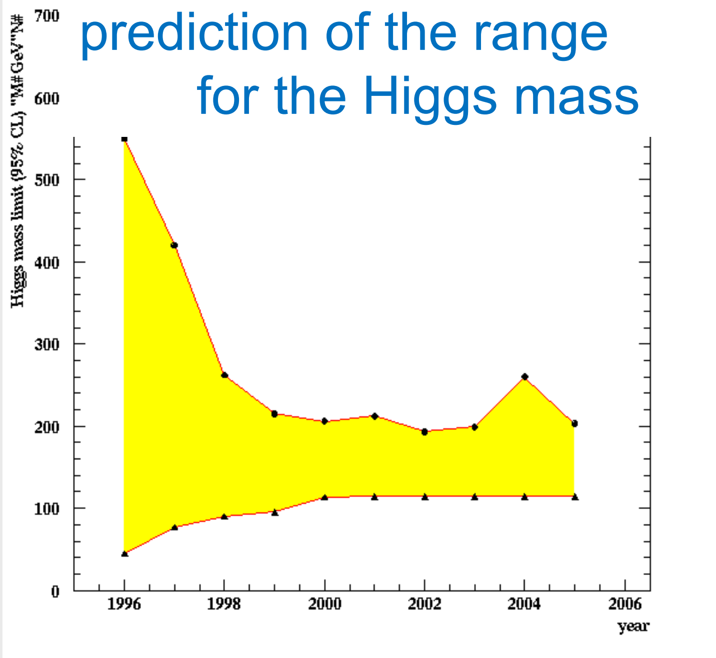
Test of the SM at the Level of Quantum Fluctuations



indirect determination of the top mass



prediction of the range for the Higgs mass



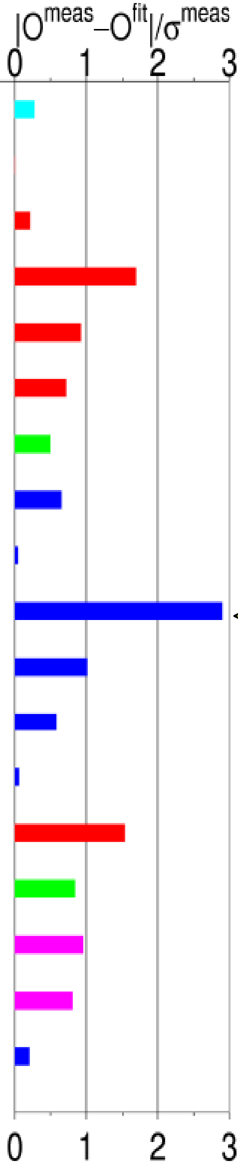
possible due to
- precision measurements
- known higher order electroweak corrections

$$\propto \left(\frac{M_t}{M_W}\right)^2, \ln\left(\frac{M_h}{M_W}\right)$$

Status recent Summer Conferences

Standard Model Analysis

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3



Fit to 17 high-Q^2 observables plus $\Delta\alpha_{had}$:

χ^2/ndof = 18.2/13 (15.1%)

Largest χ^2 contribution:
A_l(SLD) vs. $A_{fb}b$(LEP)

Decided in favour of leptons by m_W

Without this point, the fit is *too* good!

Afb(b) has largest pull: 2.9σ!

however . . .

. . . one piece missing
within Standard Model

THE missing cornerstone of the Standard Model

What is the origin of mass of elementary particles?

Possible solution:

Mass = property of particles with energy E to move with velocity $v/c = (1-m^2/E^2)^{1/2}$

➔ introduction of a scalar field (Higgs-Field)

particles acquire mass through interaction with this Higgs-Field

Self interaction —> Higgs-Particle

named after Peter Higgs

Nobel Prize 2008 to Nambu ---> „foundation“ for Higgs et al.

THE missing cornerstone of the Standard Model

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Self interaction —> Higgs-Particle

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Higgs-Particle = last missing cornerstone within SM

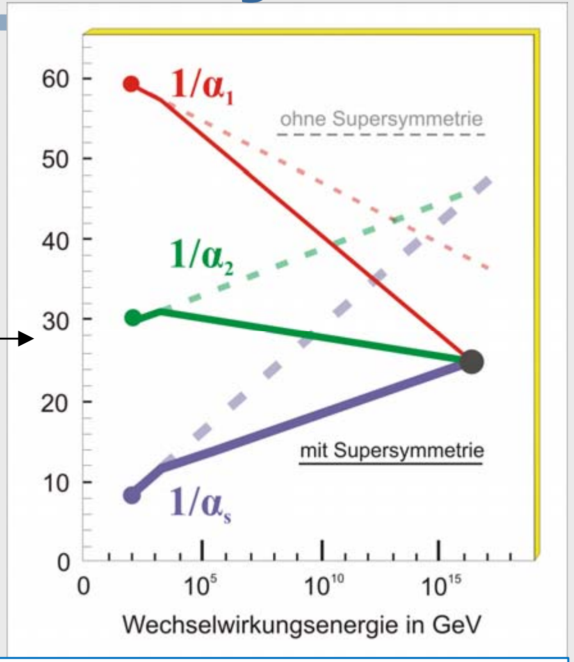
but:

Does the Higgs-Particle exist at all ??

Key Questions of Particle Physics

origin of mass/matter or
origin of electroweak symmetry breaking

unification of forces



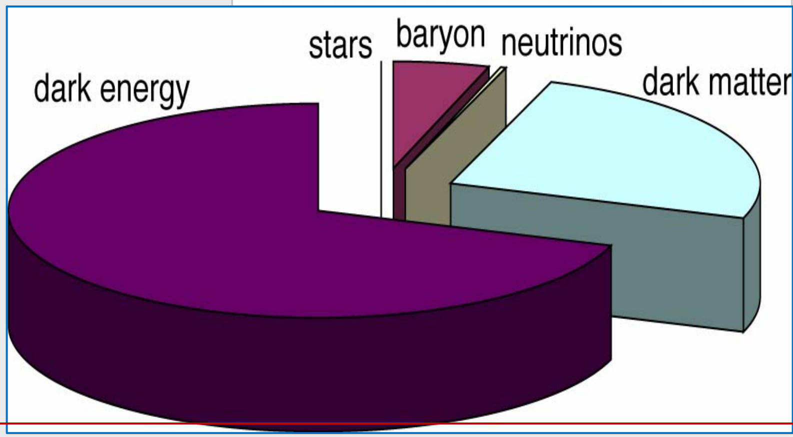
fundamental symmetry of forces and matter

unification of quantum physics and general relativity

number of space/time dimensions

what is dark matter

what is dark energy



→ with the Large Hadron Collider
at the Terascale now entering the 'Dark Universe'

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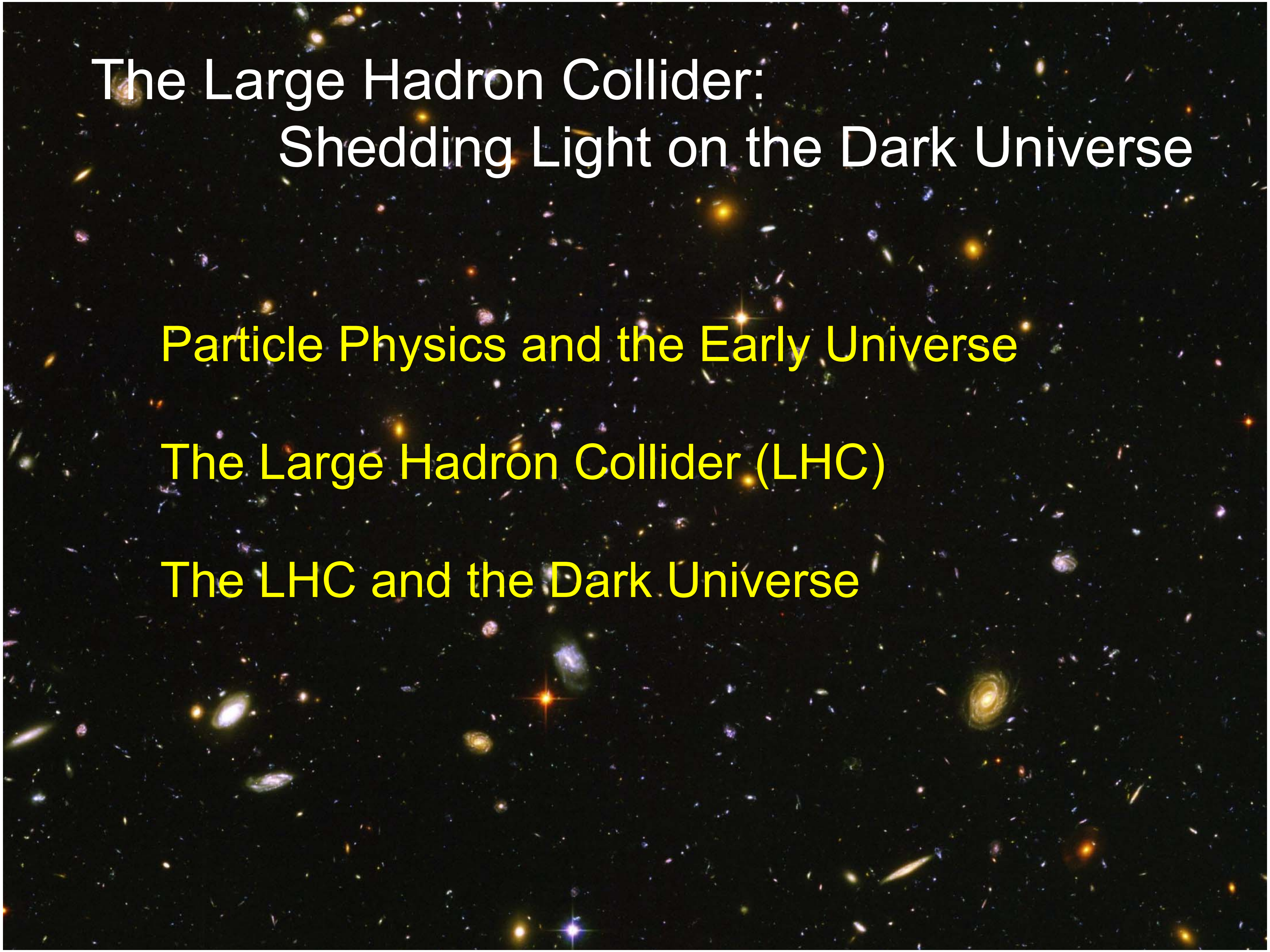
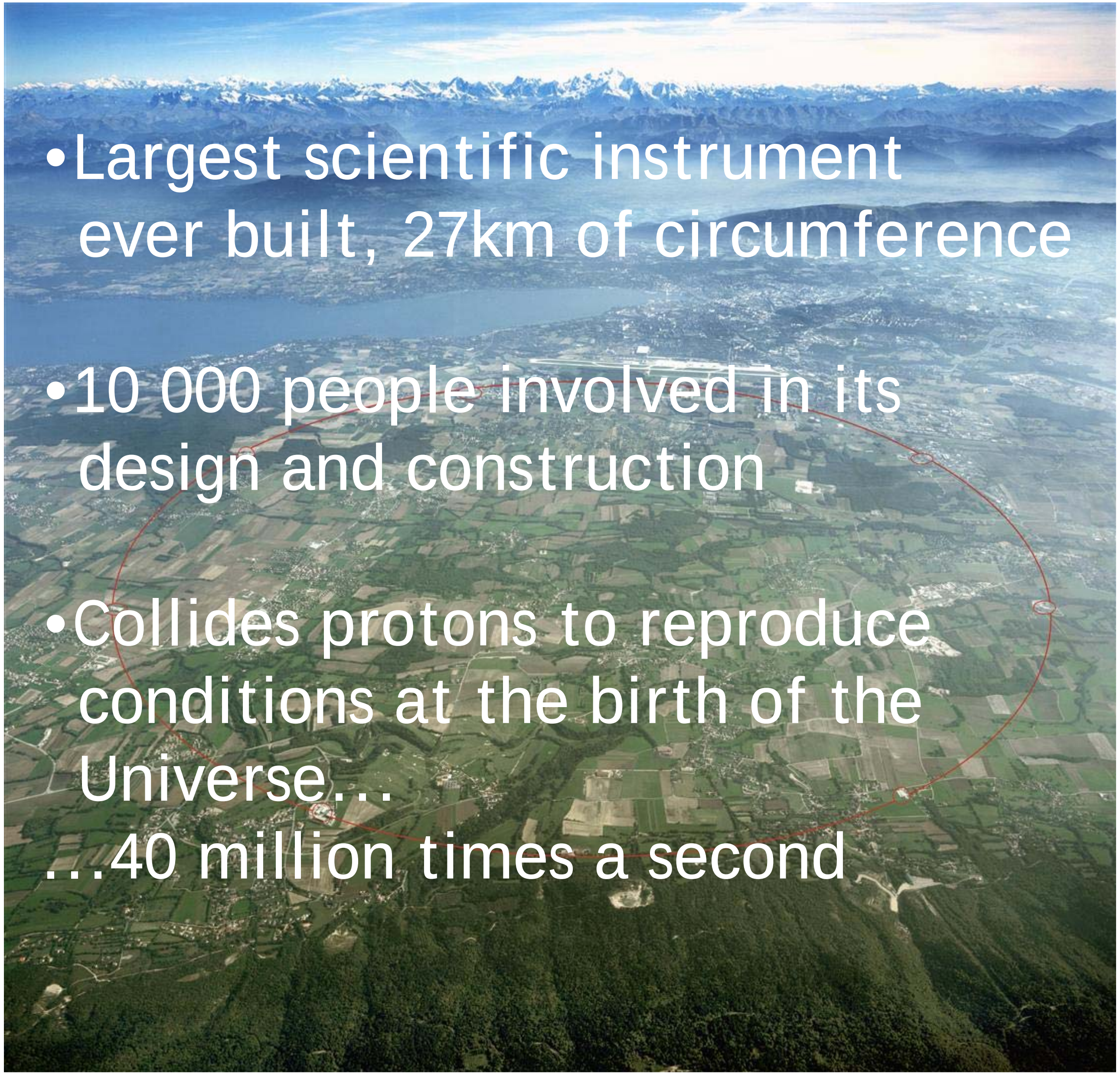
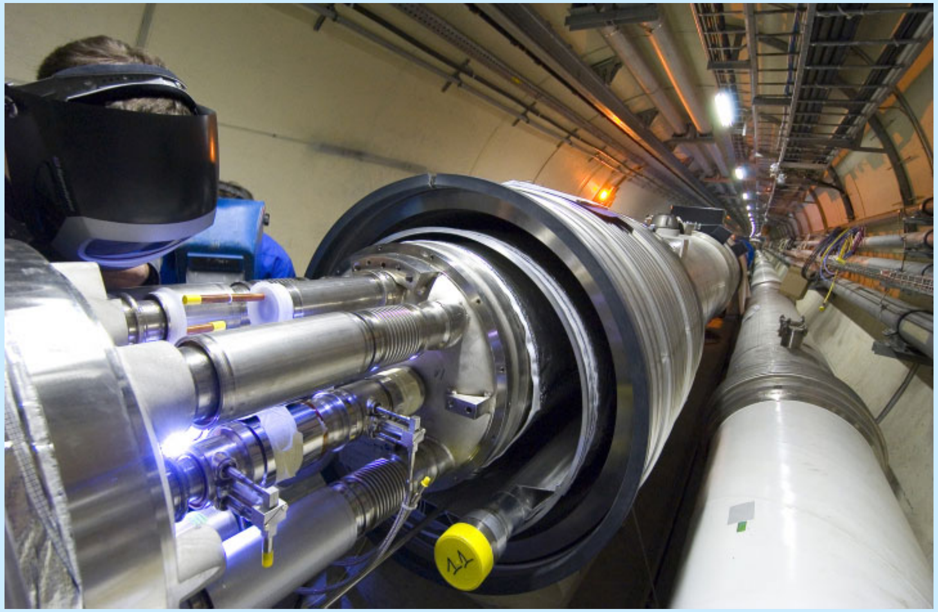
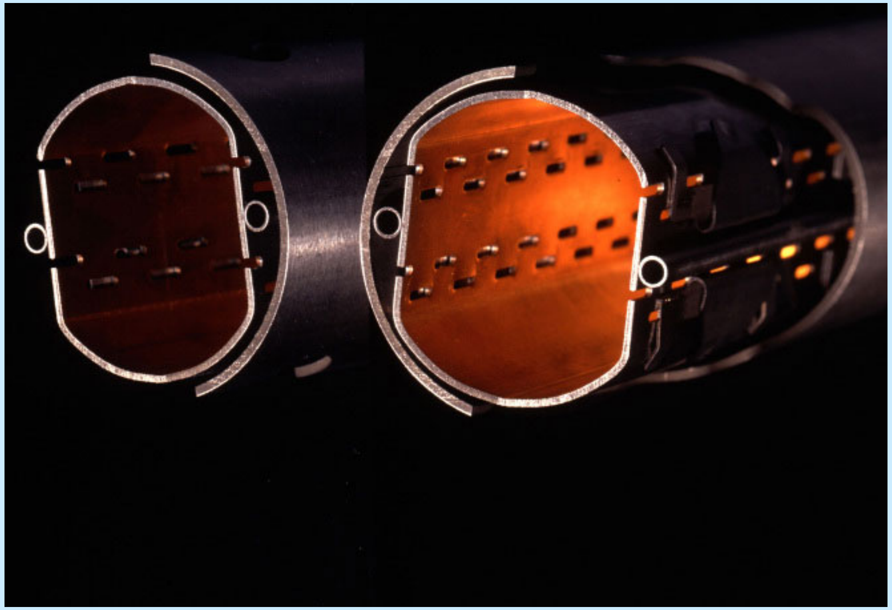


The Large Hadron Collider (LHC) at CERN



The most empty place in the solar system……





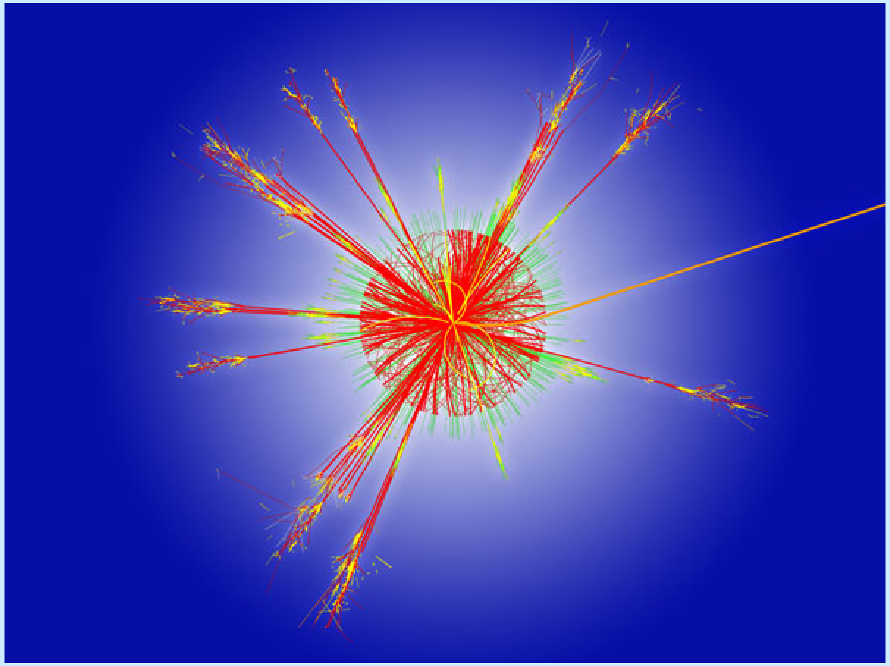
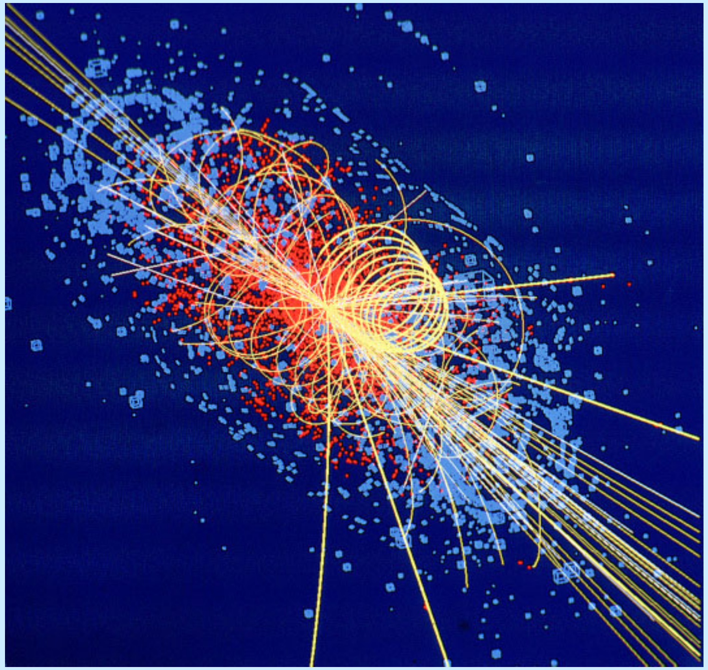
In order for particles to circulate in the LHC, a vacuum similar to that in interstellar space is needed.

The pressures in the vacuum tubes of the LHC are below those on the surface of the moon.

One of the most coldest places in the Universe...

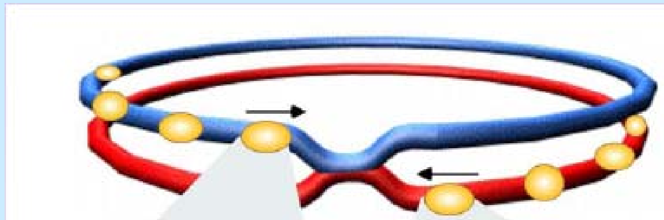
With a temperature of -271 C, or 1.9 K above absolute zero, the LHC is colder than outer space.

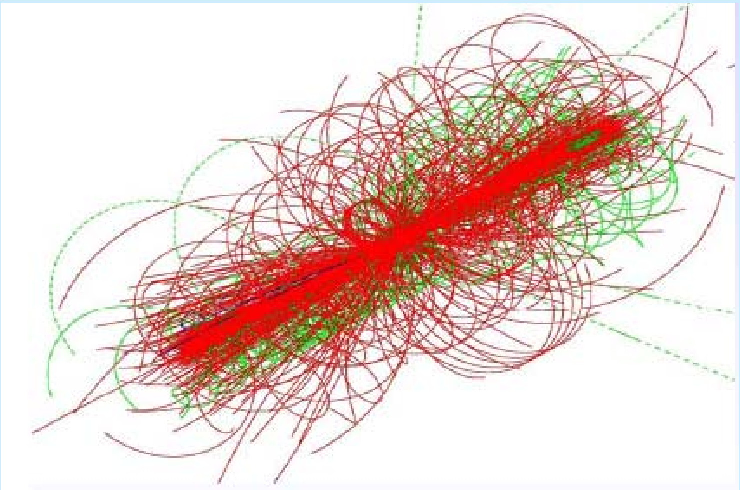
One of the **hottest** places in the galaxy...

The collision of two proton beams generates temperatures 1000 million times larger than those at the centre of the Sun, but in a much more confined space.

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

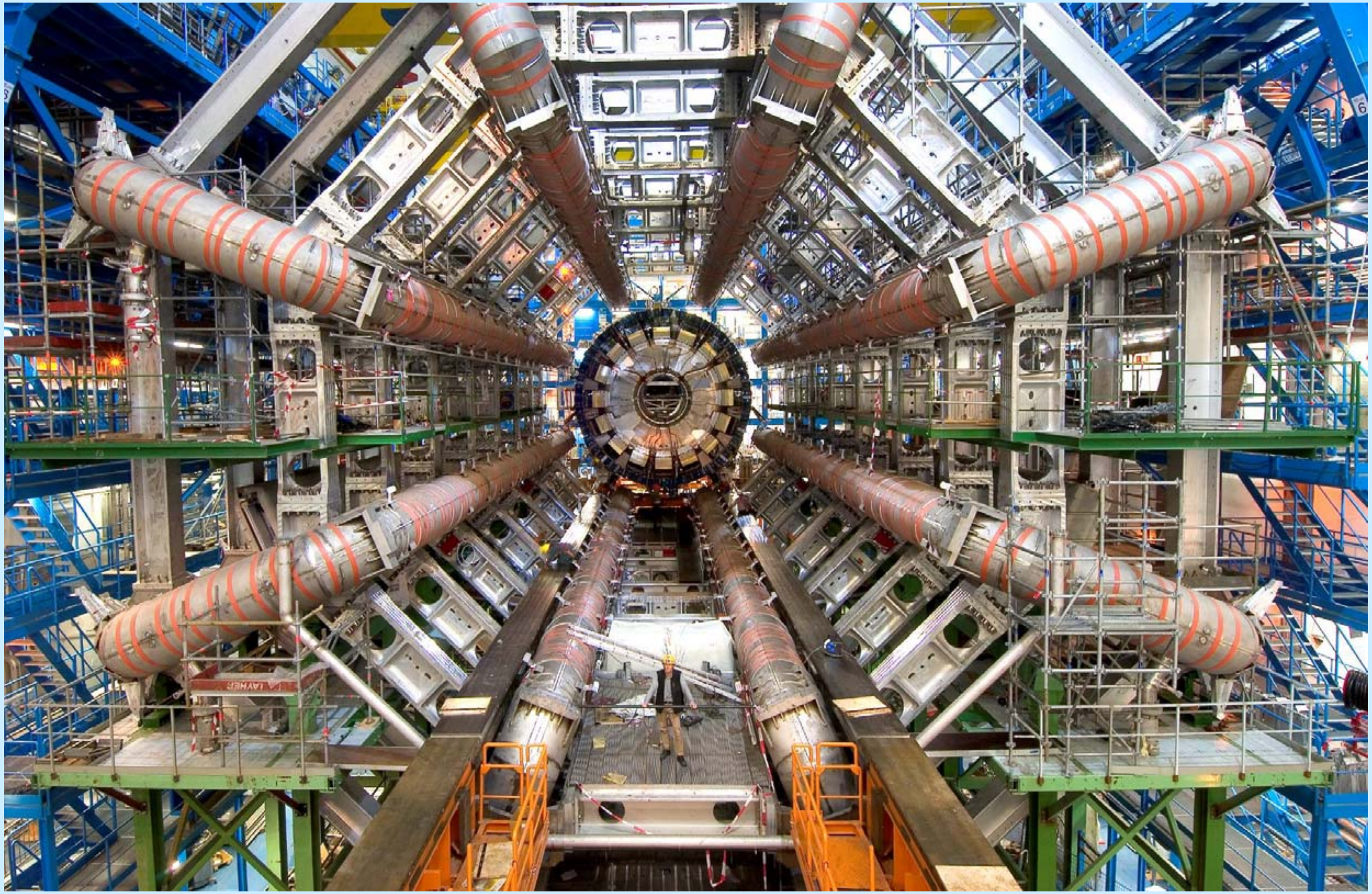
- at 10^{34}/cm^2/s
  ≈ 35 pp interactions per crossing
  pile-up

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

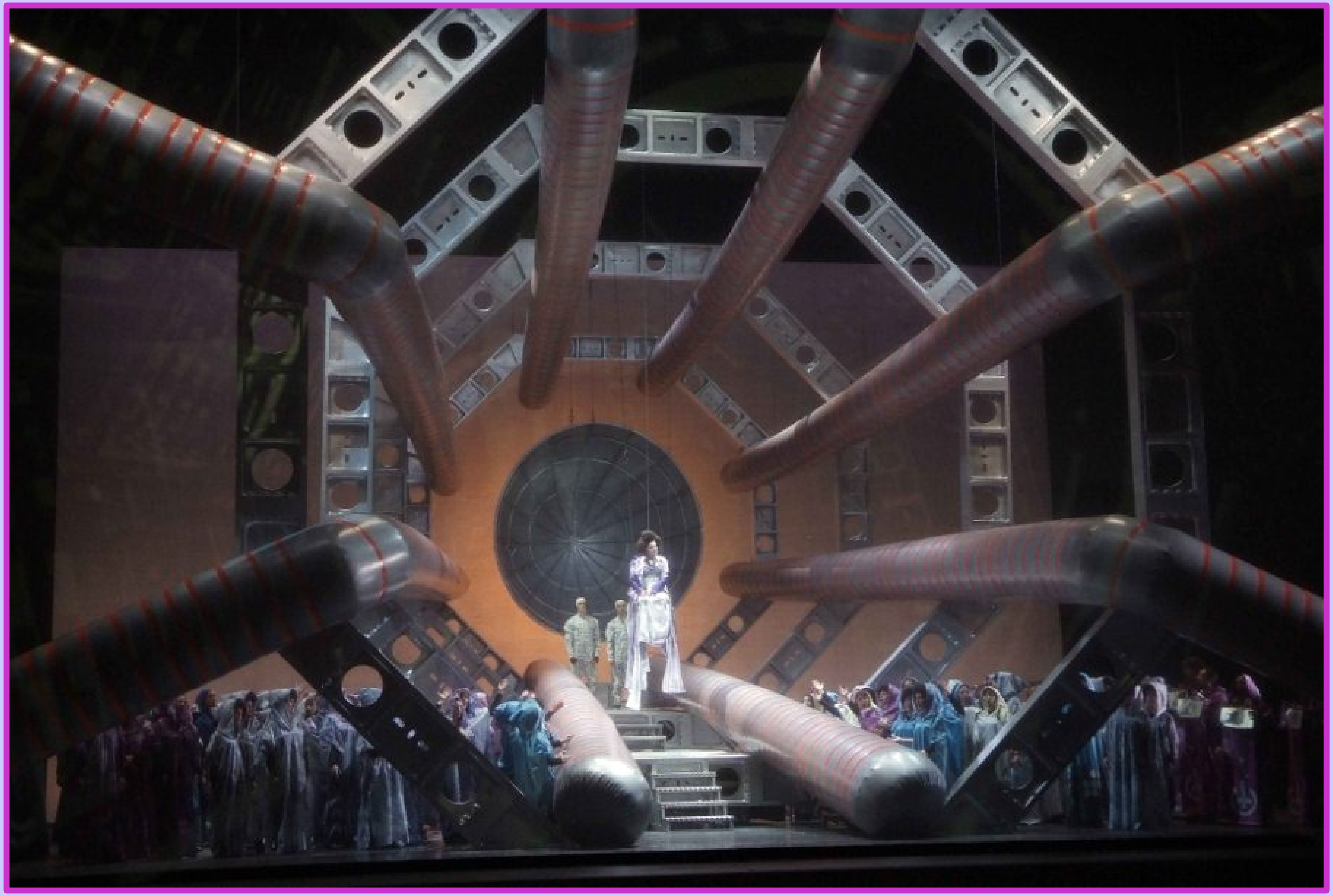
- in each collision
  ≈ 1600 charged particles produced

  enormous challenge for the detectors

the largest and most complex detectors

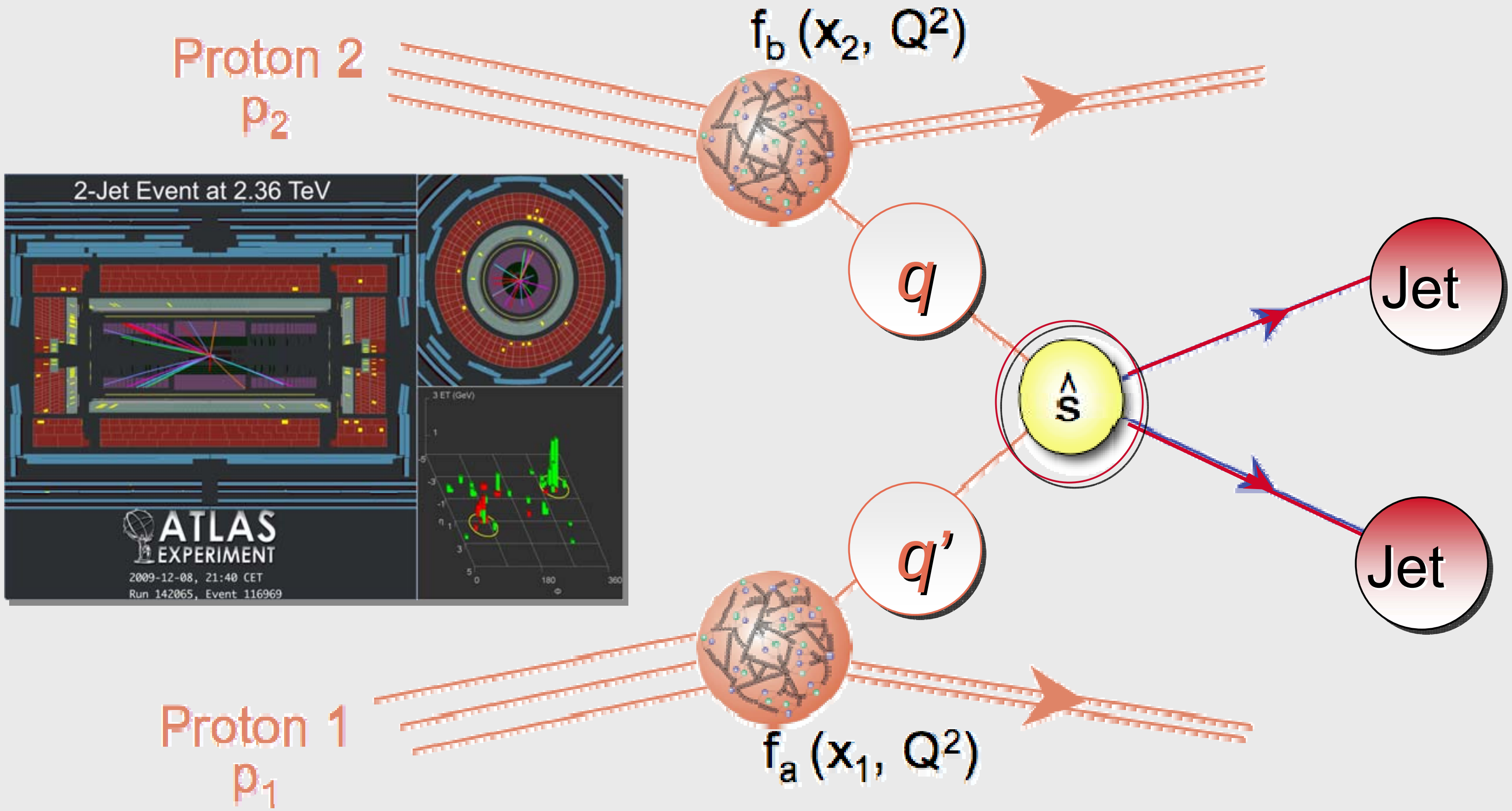


To select and record the signals from the 600 million proton collisions every second, huge detectors have been built to measure the particles traces to an extraordinary precision.



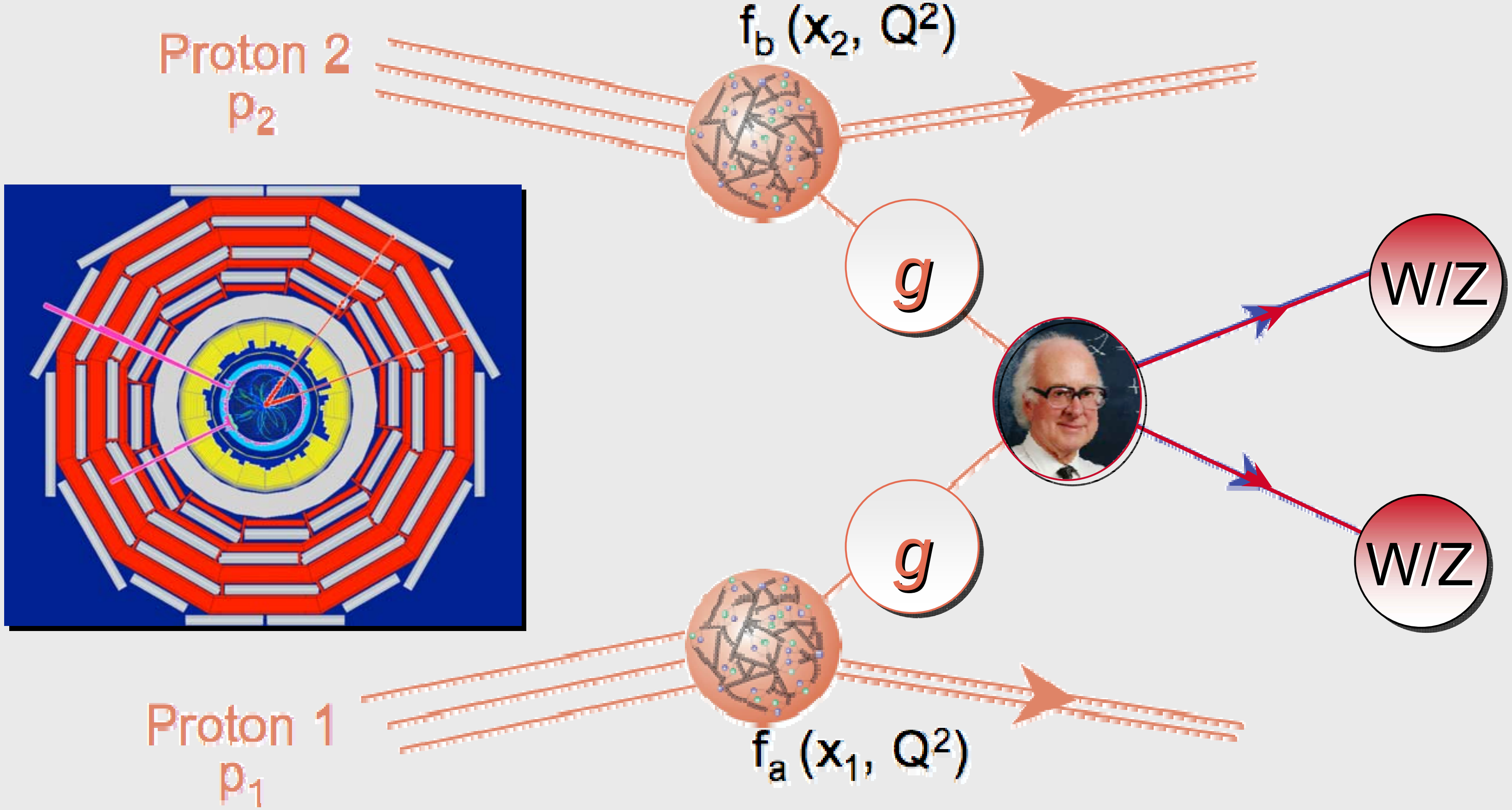
Hector Berlioz, “Les Troyens”, opera in five acts
Valencia, Palau de les Arts Reina Sofia, 31 October -12 November 2009

Basic processes at LHC

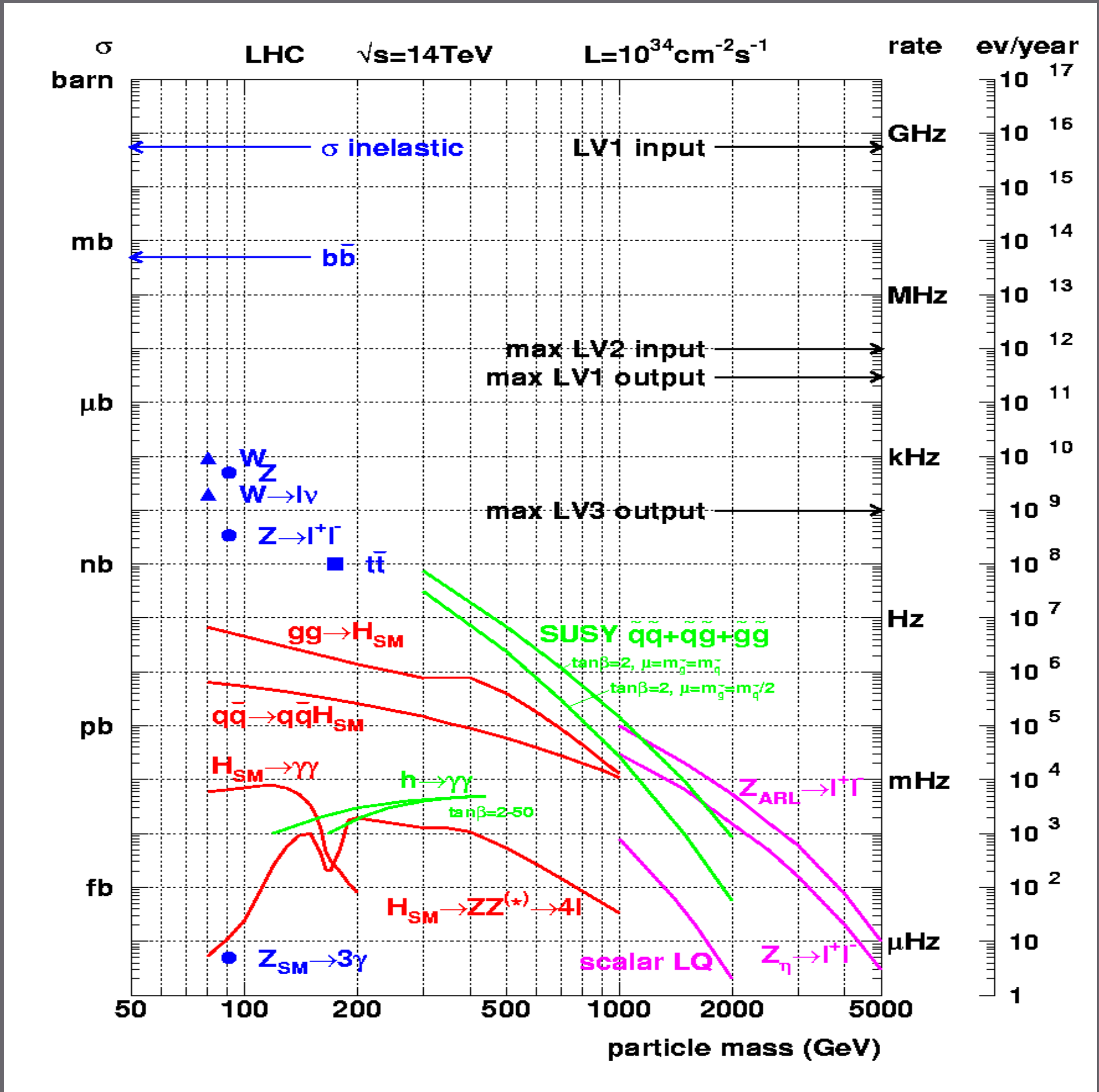


$$d\sigma(p_1 p_2 \to c\, d) = \int_0^1 dx_1 dx_2 \sum_{a,b} \left(f_a(x_1, Q^2)\, f_b(x_2, Q^2)\, d\hat{\sigma}^{ab\to cd}\right)$$

Basic processes at LHC



Cross sections at the LHC



"Well known" processes. Don't need to keep all of them …

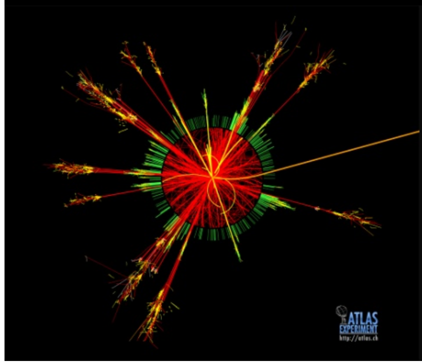
New Physics!!

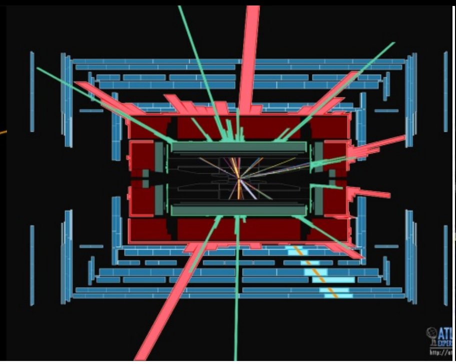
We want to keep!!

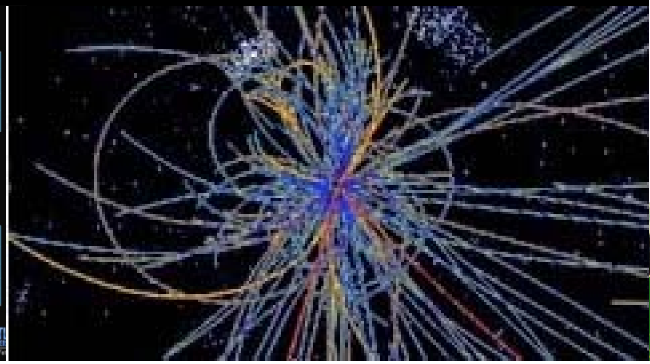
The LHC data

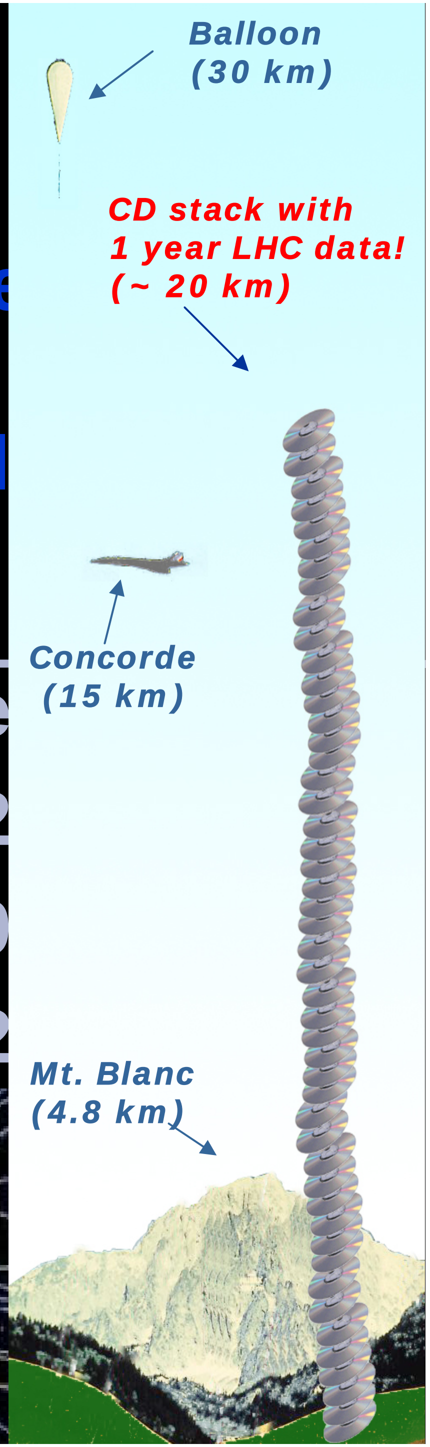
- **40 million events (pictures) per second**
- **Select (on the fly) the ~200 interesting e second to write on tape**
- **"Reconstruct" data and convert for anal "physics data" [→ the grid…]**

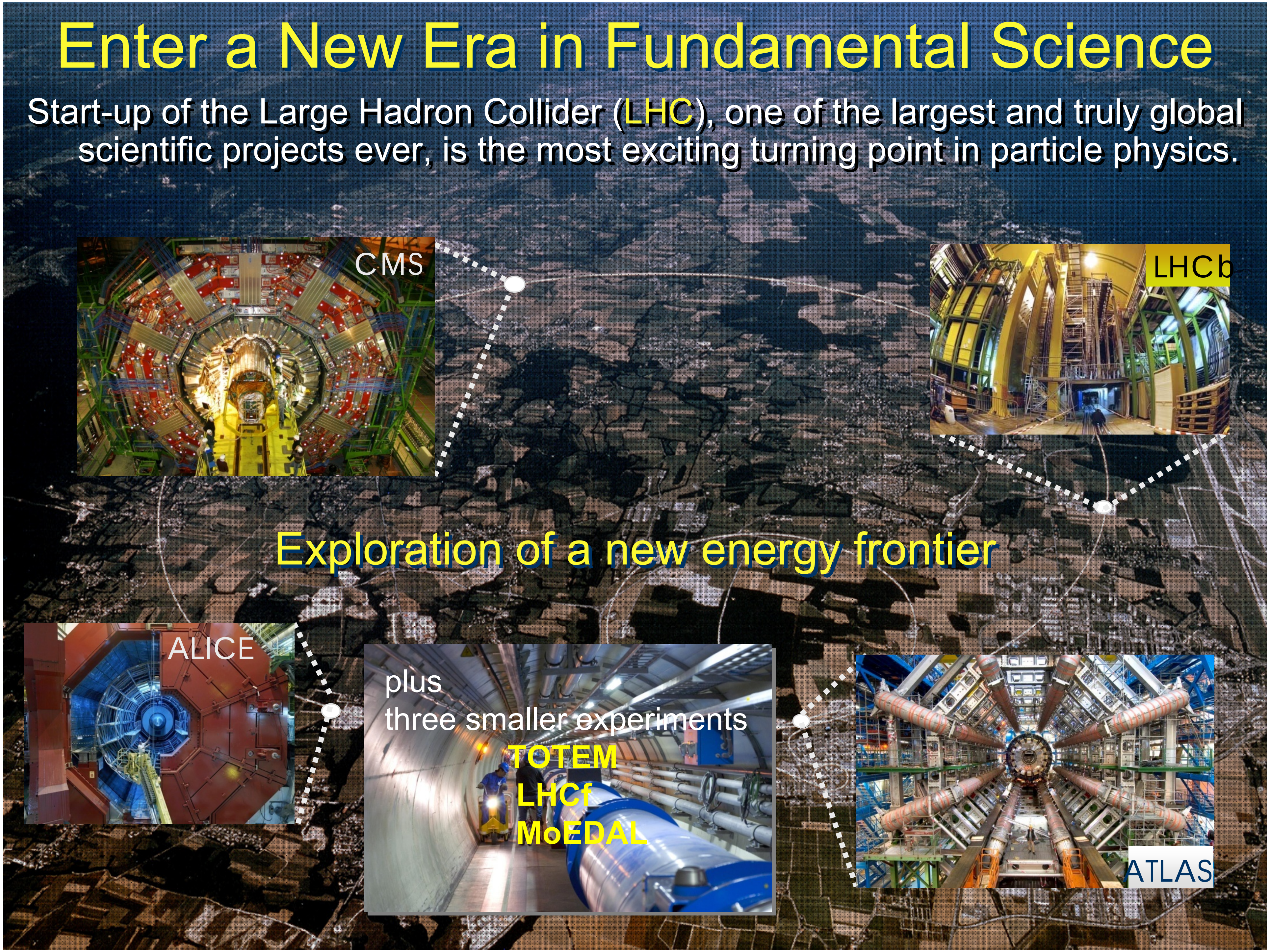
(x4 experiments x15 years)	Per event	Pe
Raw data	1.6 MB	32
Reconstructed data	1.0 MB	20
Physics data	0.1 MB	2



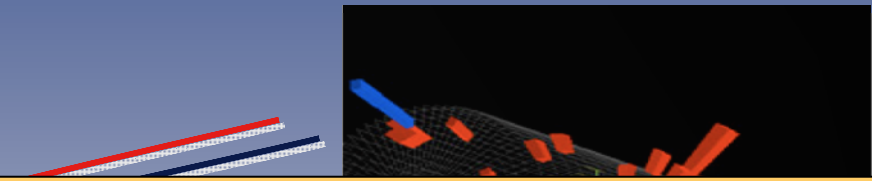







Enter a New Era in Fundamental Science
Start-up of the Large Hadron Collider (LHC), one of the largest and truly global scientific projects ever, is the most exciting turning point in particle physics.
CMS
LHCb
Exploration of a new energy frontier
ALICE
plus
three smaller experiments
TOTEM
LHCf
MoEDAL
ATLAS

First Collisions at LHC on 23 November 2009 at E_{CM} = 900 GeV



<u>Chronology of a fantastic escalation of events:</u>

2009

- 20 November: first beams circulating in the LHC
- 23 November: first collisions at $\sqrt{s}$ = 900 GeV
- 8, 14, 16 December: few hours of collisions at $\sqrt{s}$ = 2.36 TeV (the world record !)
- 16 December: end of first run
- 16 December- 26 February: technical stop

2010

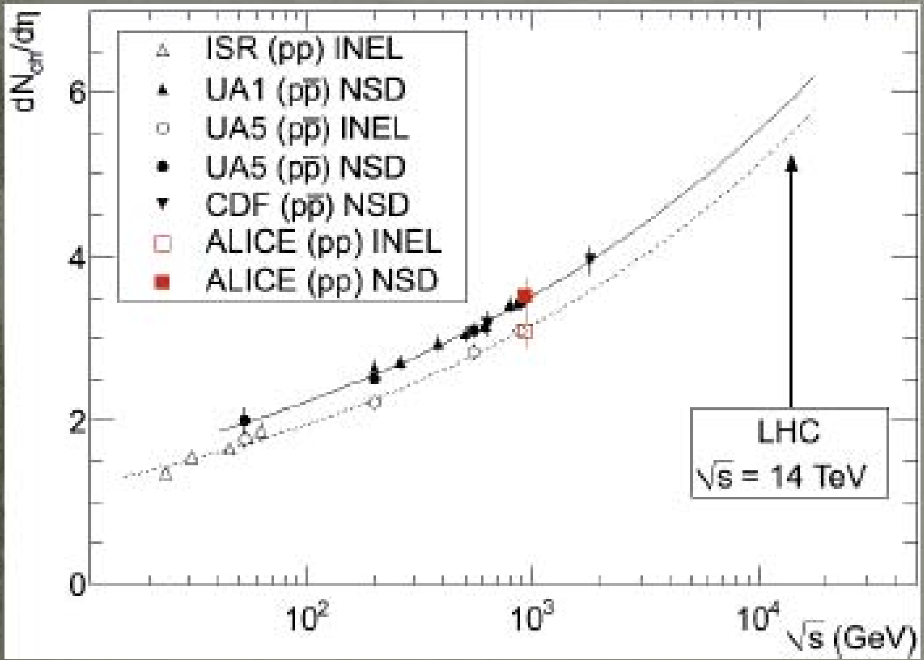
- 27 February : machine operation started again
- 19 March : first (single) beams ramped up to 3.5 TeV
- 30 March : first collisions at 3.5+3.5 TeV

- immediate data taking by all experiments with high efficiency
- first publications accepted

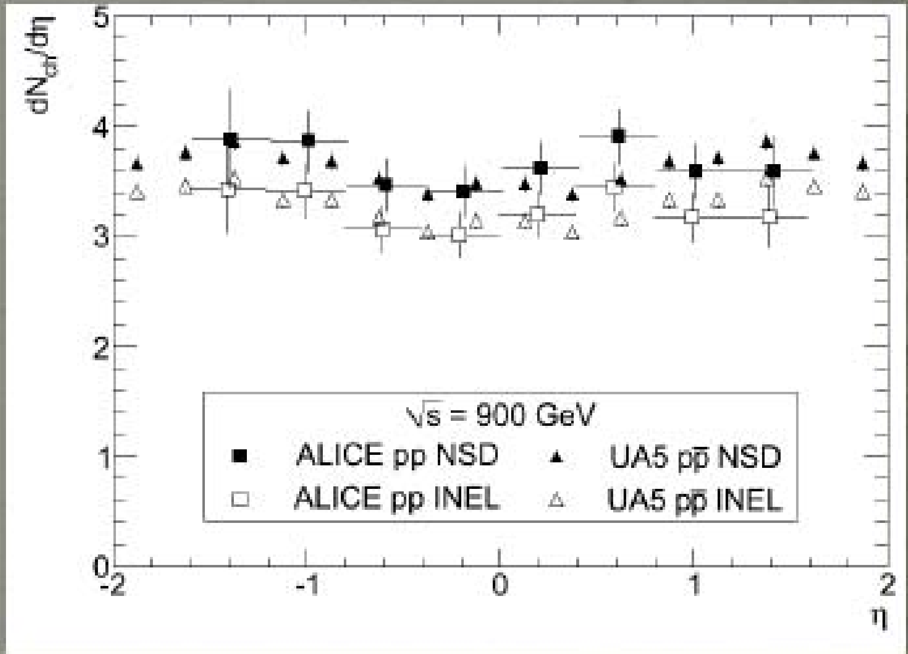
… after more than a year of repairs and improvements

First paper (submitted 28/11)

- $dN_{ch}/d\eta$ for $|\eta| < 0.5$



- $dN_{ch}/d\eta$ vs η

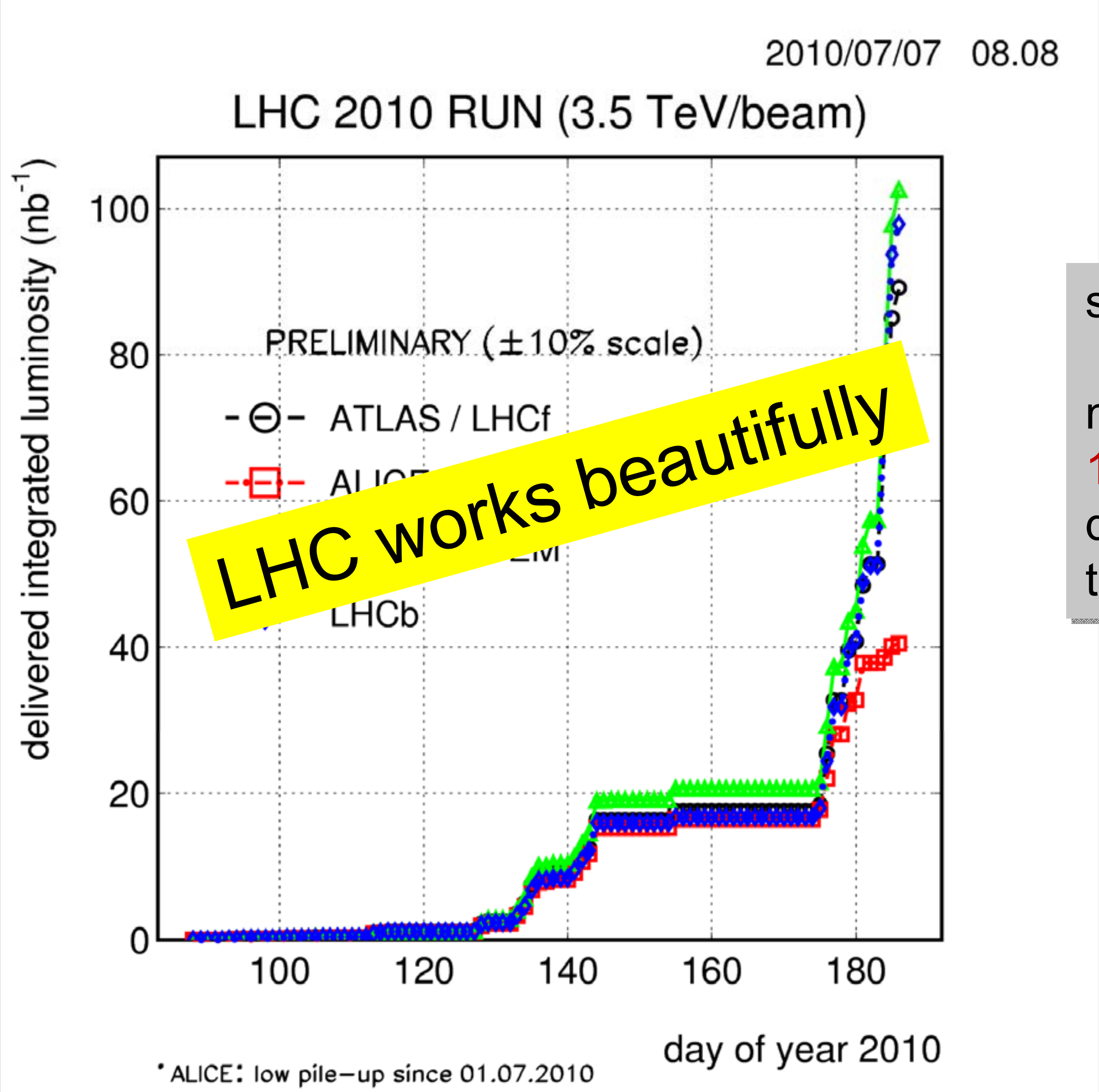


K. Aamodt et al. (ALICE), Eur. Phys. J C 65 (2010) 111

2010

- 30 March: first collisions at 3.5TeV/beam
- 19 April: order of magnitude increase in luminosity
    - doubling the number of particles/bunch
    - β * from 11 to 2m (4b/beam) L ~2x10^{28}.
    - Beam lifetimes of ~1000 hours
- 22 May another order of magnitude:
    - 13 bunches in each beam (L~ 3x10^{29})
- 26 May: Design intensity bunches were brought into collision at 3.5TeV/beam.

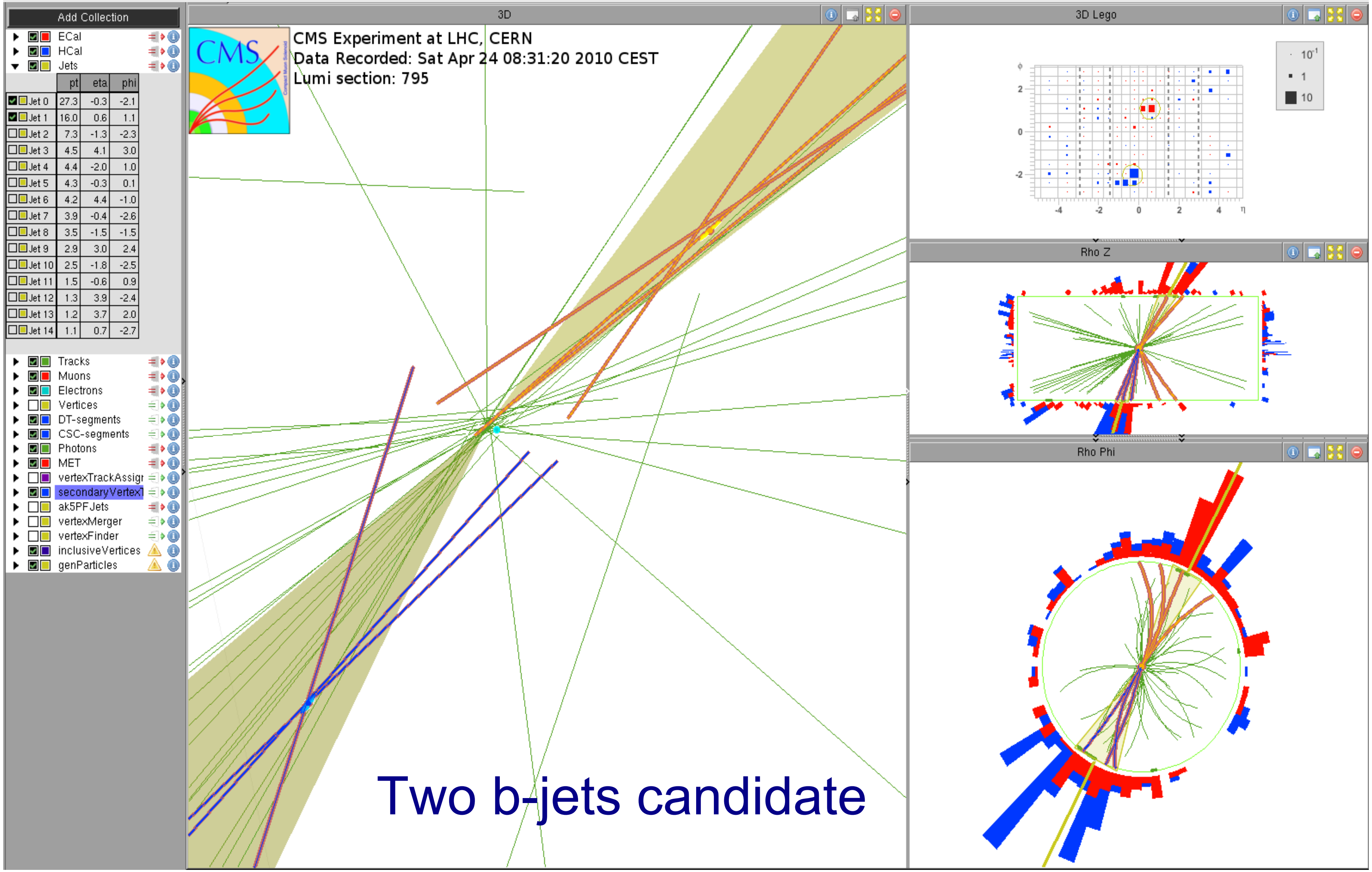
Integrated Luminosity (Linear Scale)



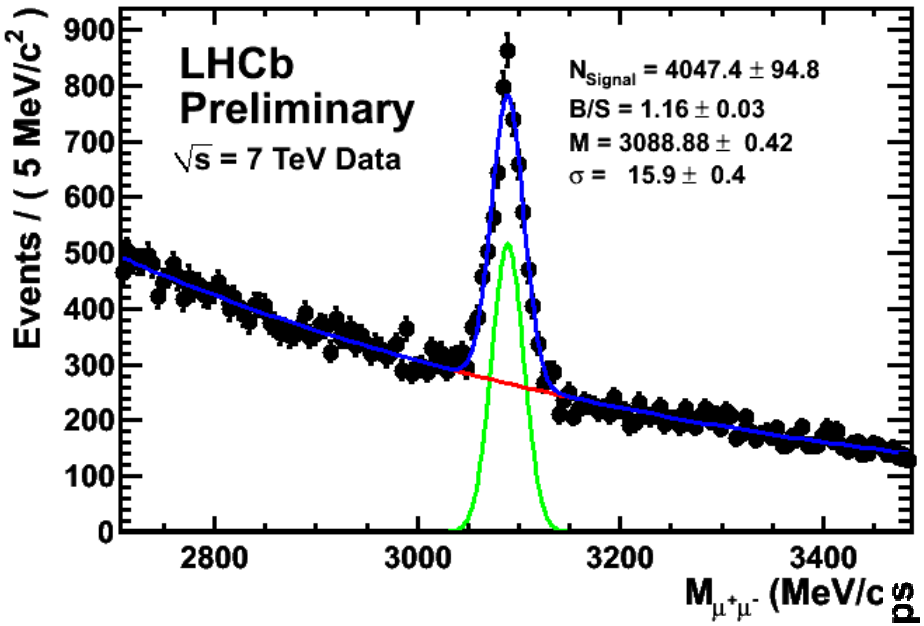
status today:

more than
100/nb
delivered
to the experiments

Ready for b physics (and b-tagging in general)

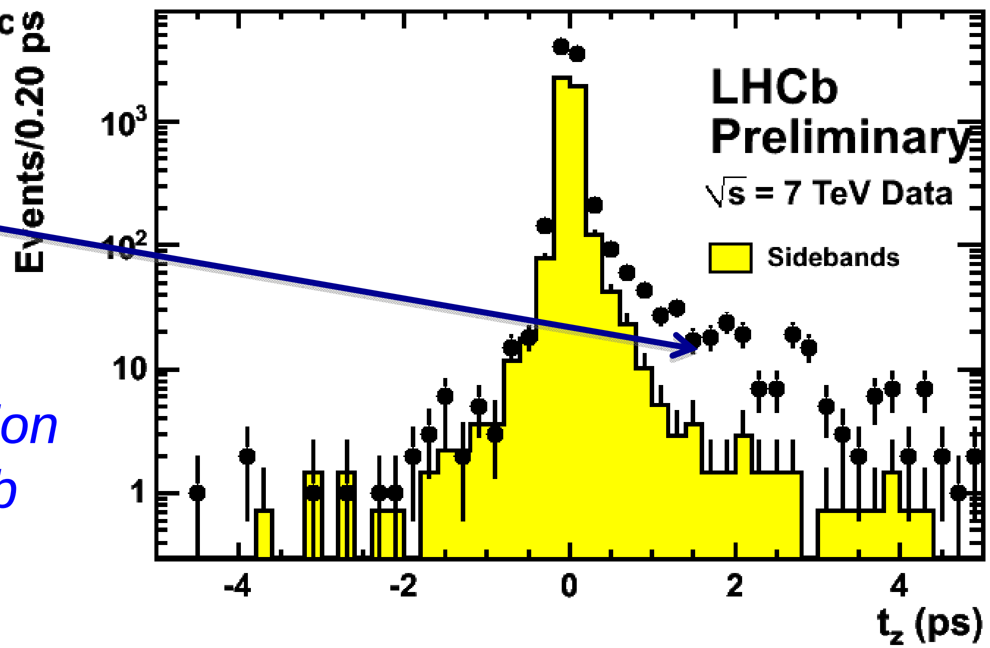


J/psi Effective Lifetime



A total of 4000 J/ψ → $\mu\mu$ decays reconstructed

Signal window & normalized sideband



Proper life time distribution shows clear evidence for J/ψ produced in B decays

Solid prospects to measure production cross-sections for prompt J/ψ and bb at $\sqrt{s}$ = 7 TeV

After pre-selection:

-- $W \to e\nu$:

loose $e^{\pm}$, $E_T > 20$ GeV

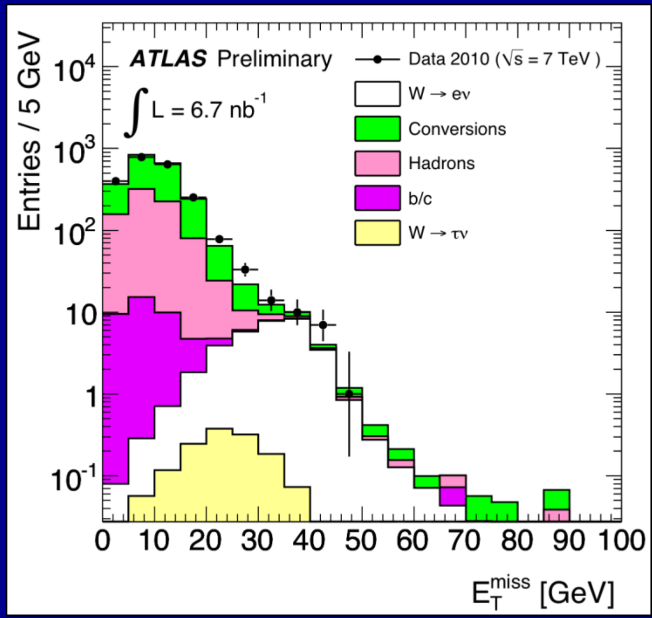
-- $W \to \mu\nu$:

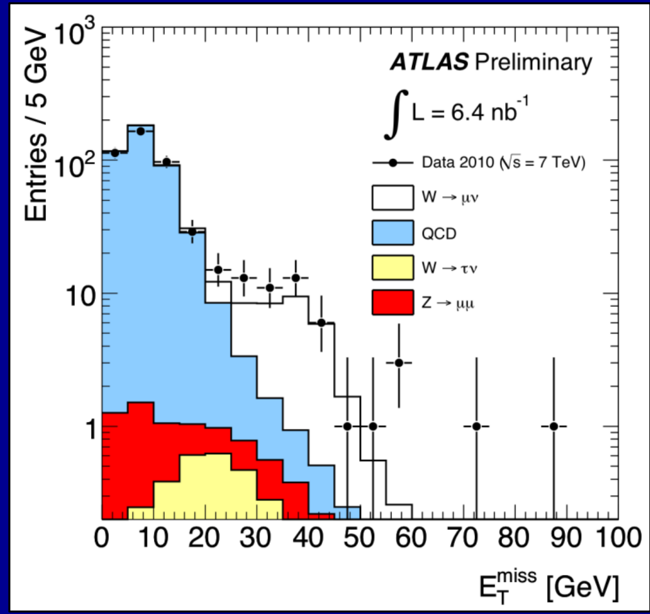
$p_T(\mu) > 15$ GeV

$|\Delta p_T(\text{ID-MS})| < 15$ GeV

$|Z_\mu - Z_{vtx}| < 1$ cm

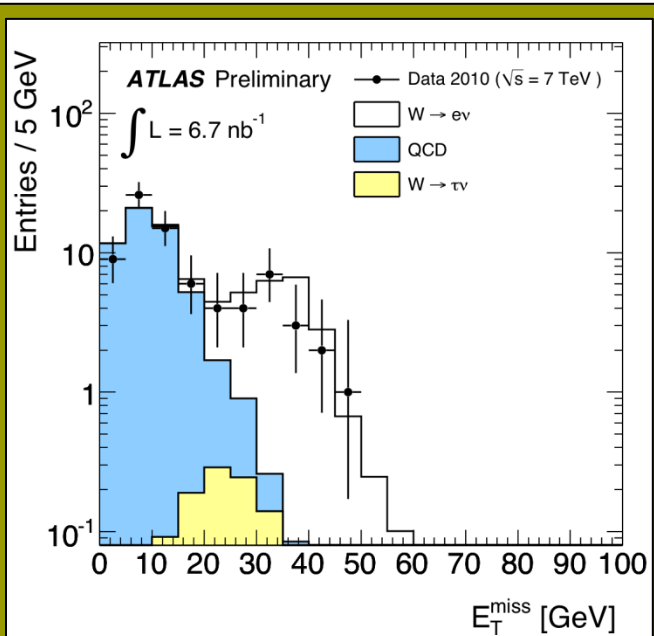
MC: normalised to data (total number of events)

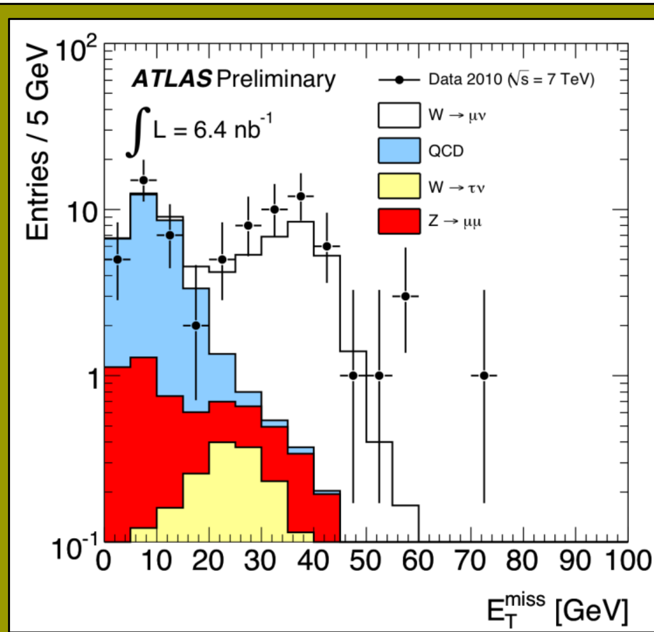




Observed events: 57

After all cuts but E_T^{miss} and m_T

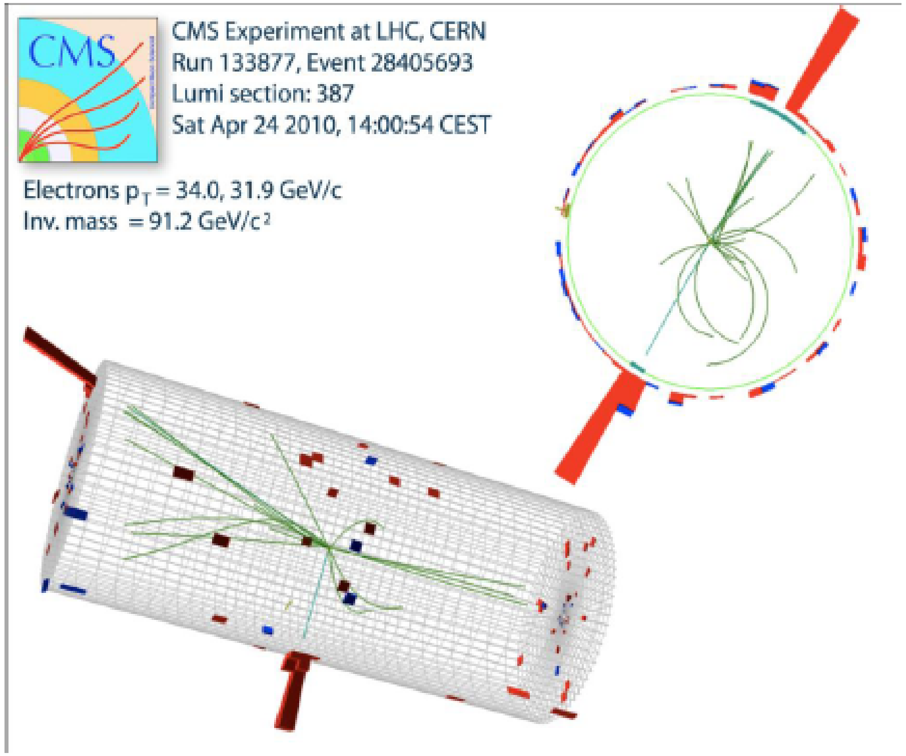




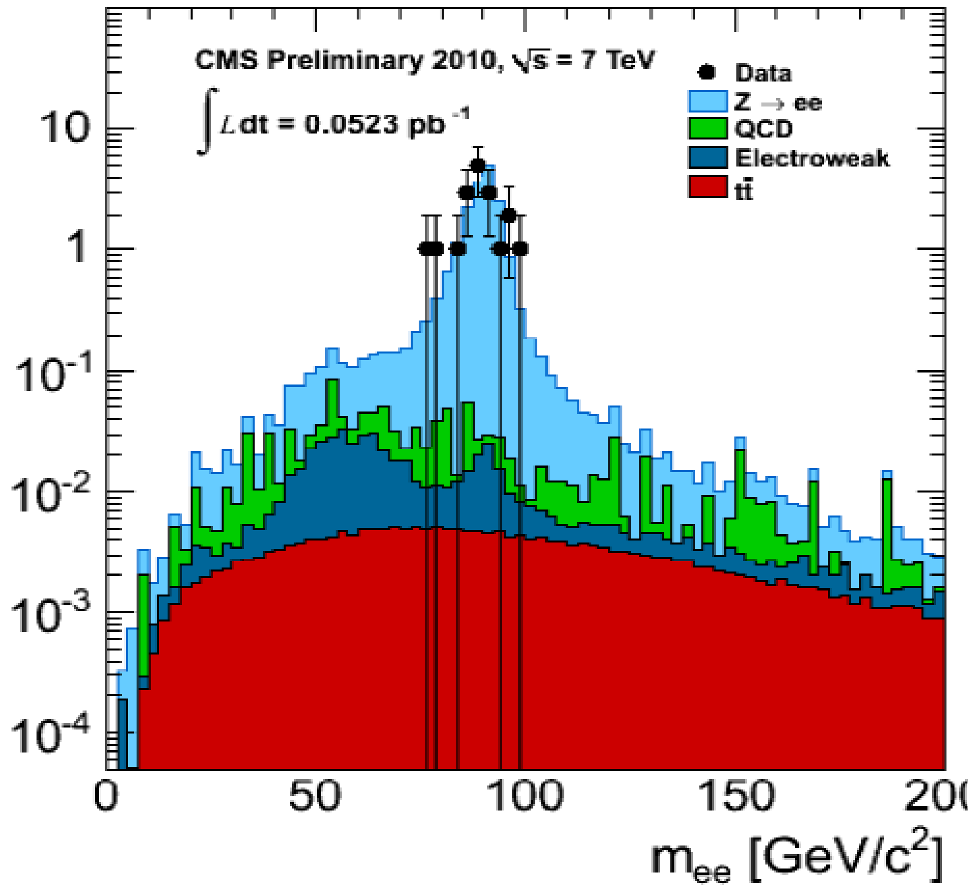
Final candidates inspected in detail → timing, lepton reconstruction quality, event topology …

$Z \rightarrow e^+e^-$ observation

- Event selection:
  - ➢ Two electrons with $E_T > 20$ GeV
- Monte Carlo: Event count normalized to integrated luminosity



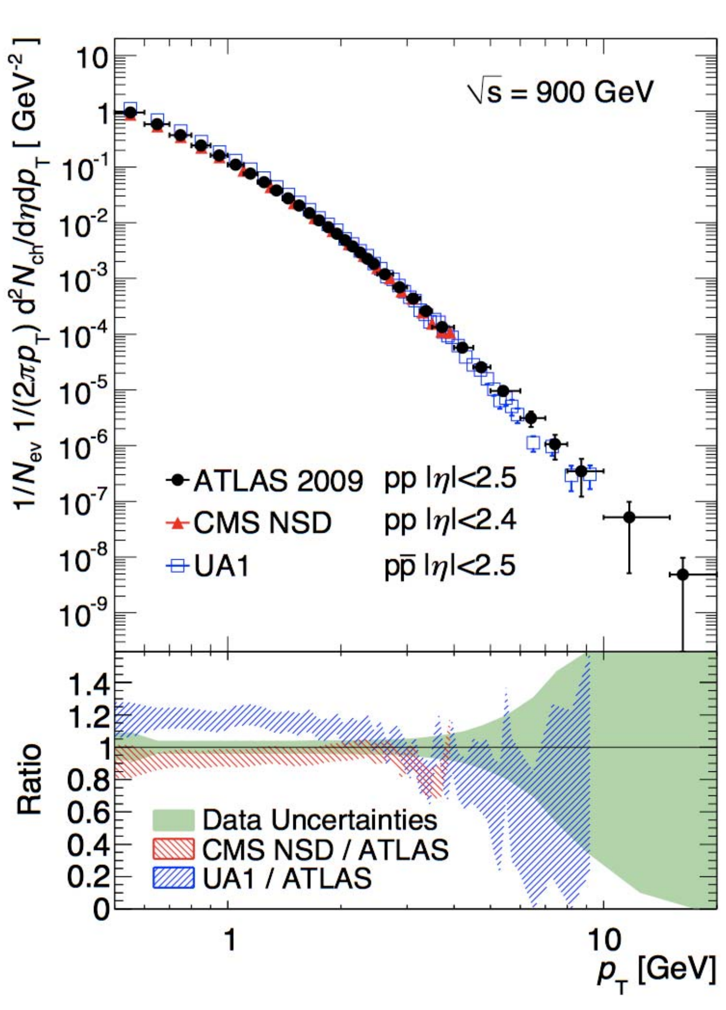
Z→ee candidate

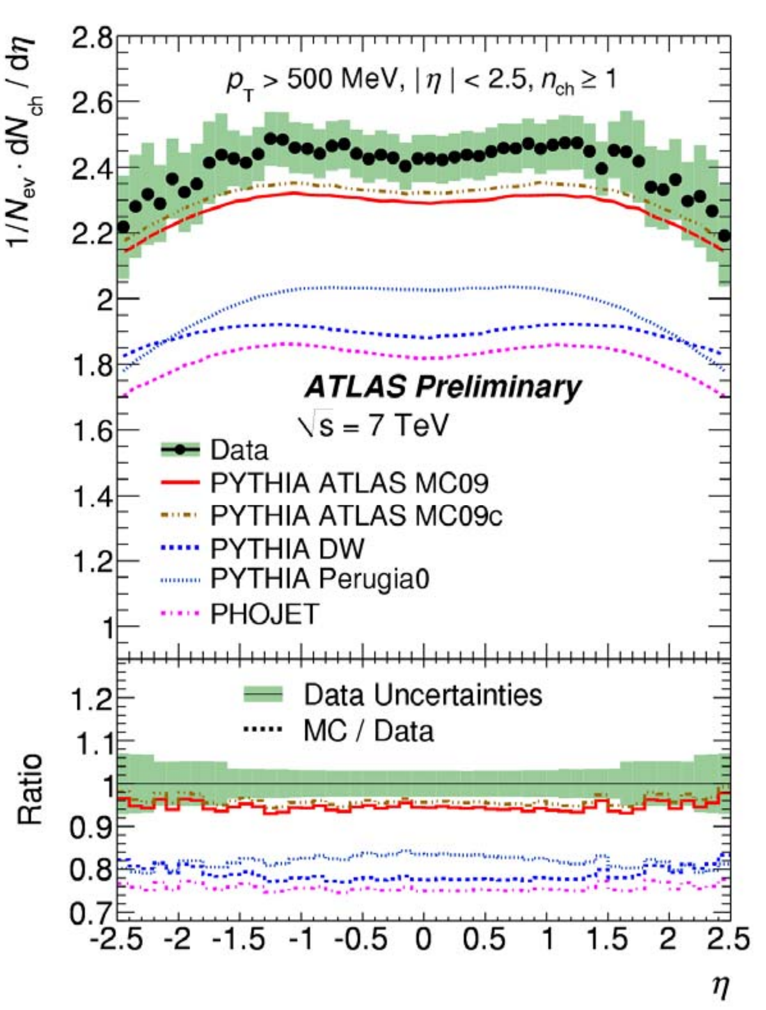


#of candidate = 18
#of expected signal = 19
#of expected background = 0.8

52 nb^{-1}

Charged Particle Multiplicities at $\sqrt{s}$=0.9, 7 TeV





Monte Carlo underestimates the track multiplicity seen in ATLAS

ALICE+CMS

Performance of Missing Transverse Energy ($0.3 nb^{-1}$)

Understanding of high ETmiss tails is crucial for NP

Hopefully very low rate of new physics events sitting in these ta

Test ETmiss up to 250 GeV of transverse energy
time stability within 3%

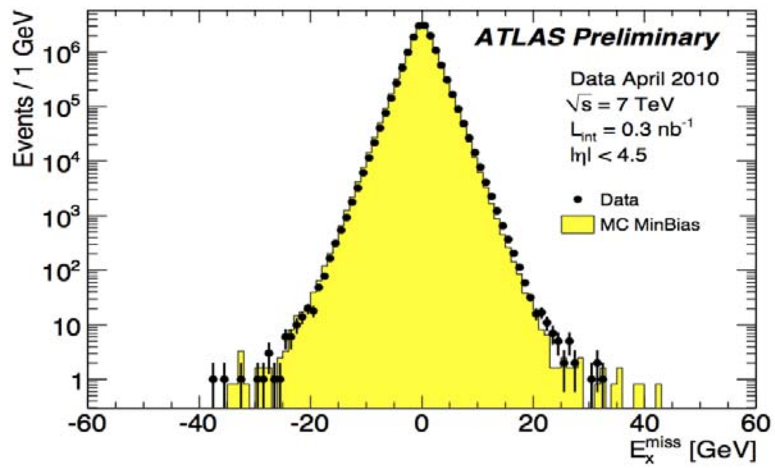
Event cleaning: find jets from noise burst or photons from cosmic muon bremsstrahlung.

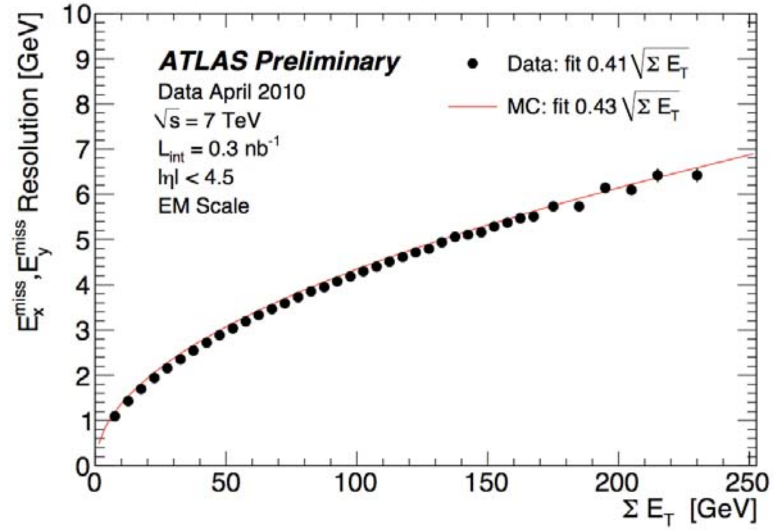
$$E_T^{miss} = -\sum E_{cell} \text{ (vector sum)}$$

Due to large granularity of calorimeter, use only cells belonging to 3D calorimeter "topo" cluster $4\sigma/2\sigma$ algorithm

Excellent agreement between data and MC at this early stage

More advanced computation of ETmiss including electrons, muons, taus, jets and their proper calibration under way





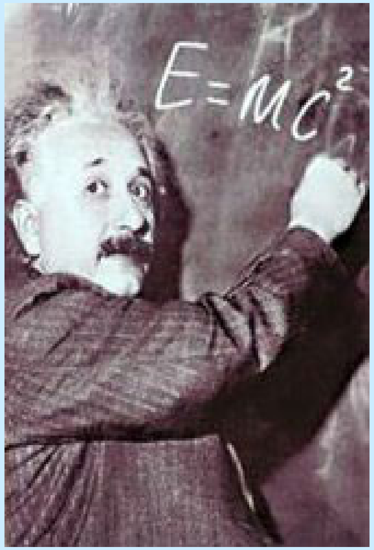
LHC Experiments Summary

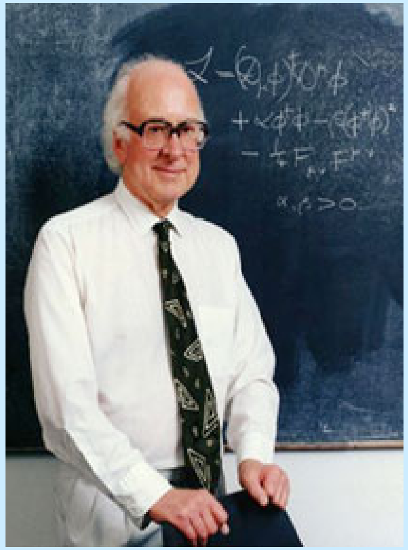
- So far, so good….
- Experiments tracking nicely the machine evolution, eagerly awaiting more data
- Computing infrastructure supports magnificently the swift data analysis
- Experiments are re-discovering the Standard Model (only top quark missing…..)
- …exciting times !

The Science

We are poised to tackle

some of the most profound questions in physics:





Newton's unfinished business… what is mass?

Nature's favouritism… why is there no more antimatter?

The secrets of the Big Bang… what was matter like within the first second of the Universe's life?

Science's little embarrassment… what is 96% of the Universe made of?

ready to enter the
Dark Universe

Dark Matter

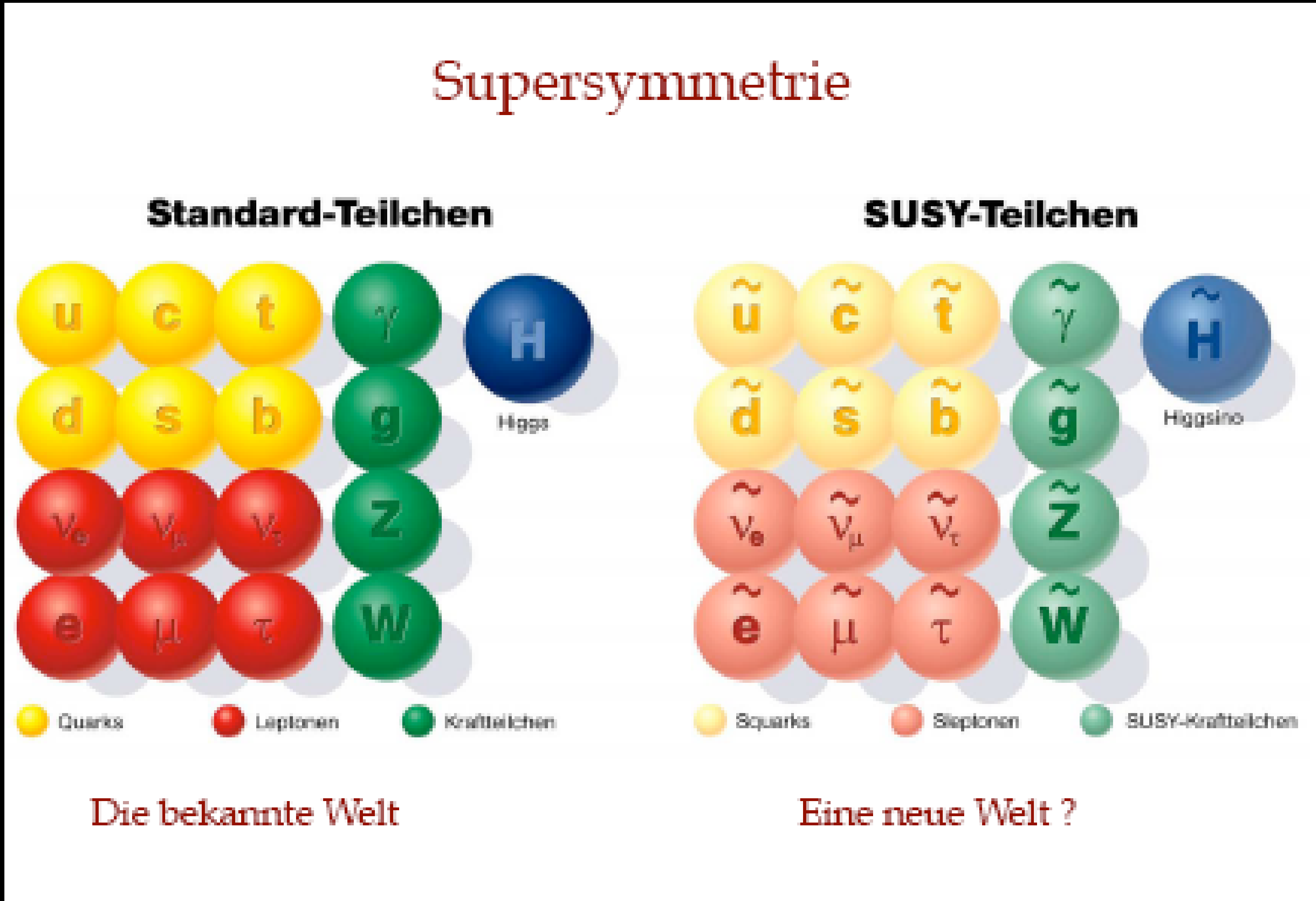
Astronomers & astrophysicists over the next two decades using powerful new telescopes will tell us how dark matter has shaped the stars and galaxies we see in the night sky.

Only particle accelerators can produce dark matter in the laboratory and understand exactly what it is.

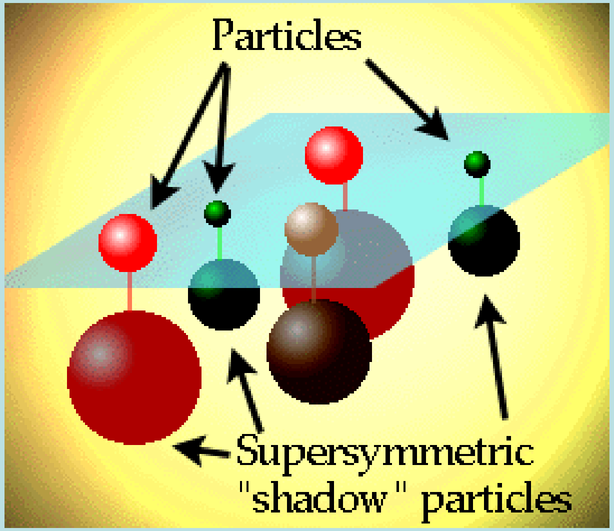
Composed of a single kind of particle
or
more rich and varied (as the visible world)?

LHC may be the perfect machine to study dark matter.

The favoured candidate:



Supersymmetry

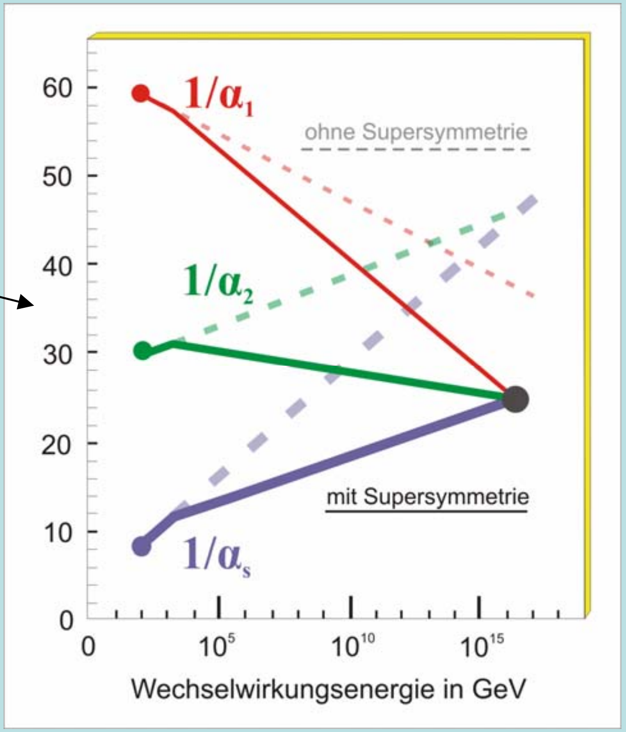


- unifies matter with forces

  for each particle a supersymmetric partner (*sparticle*) of opposite statistics is introduced

- allows to unify strong and electroweak forces

  $\sin^2\theta_W{}^{SUSY} = 0.2335(17)$
  $\sin^2\theta_W{}^{exp} = 0.2315(2)$

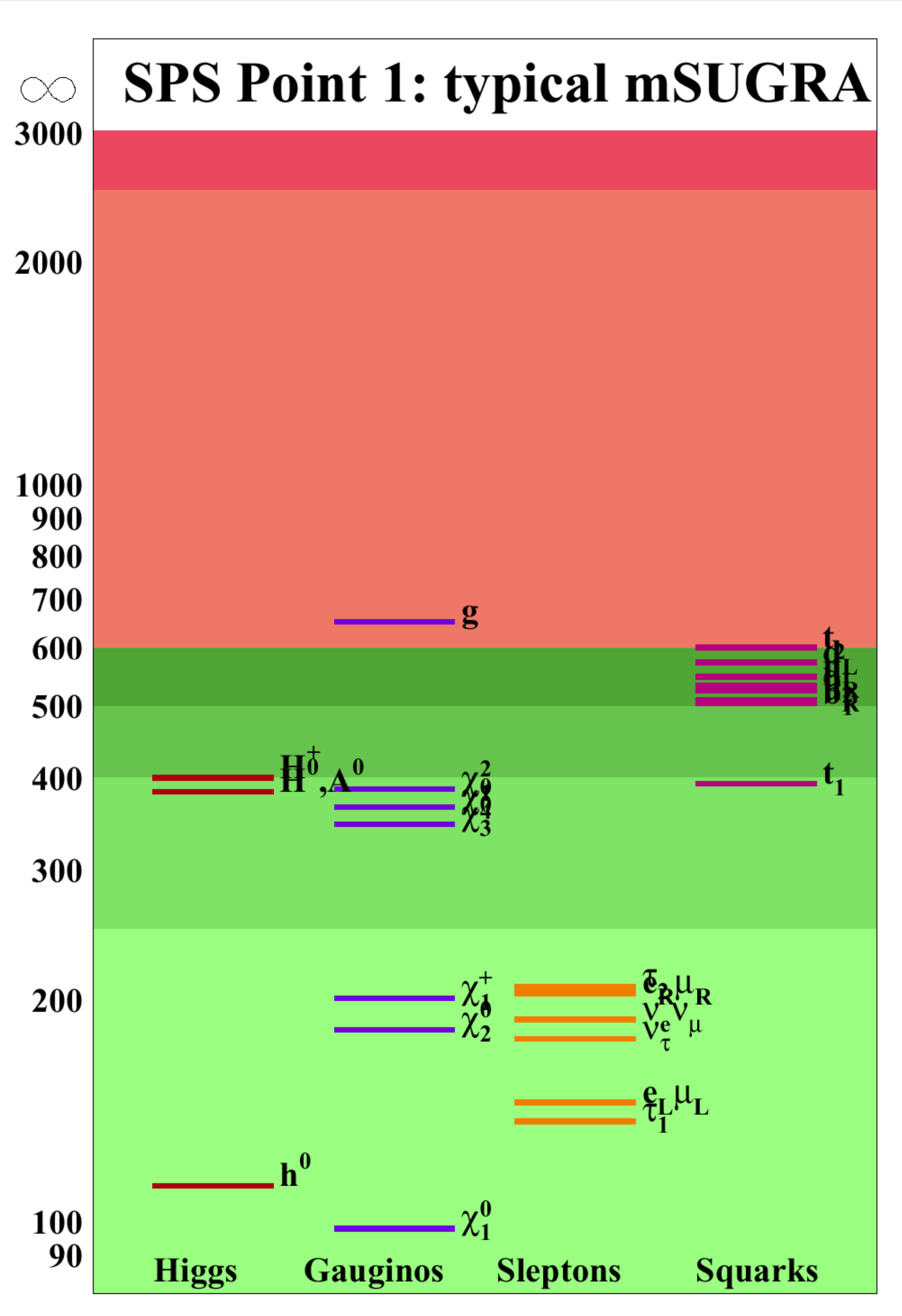


- provides link to string theories

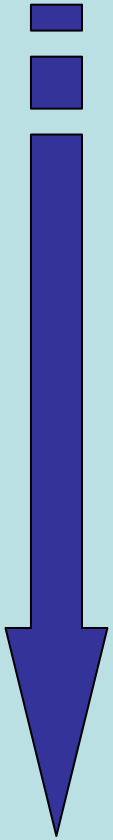
- provides Dark Matter candidate

  (stable Lightest Supersymmetric Particle)

Supersymmetry

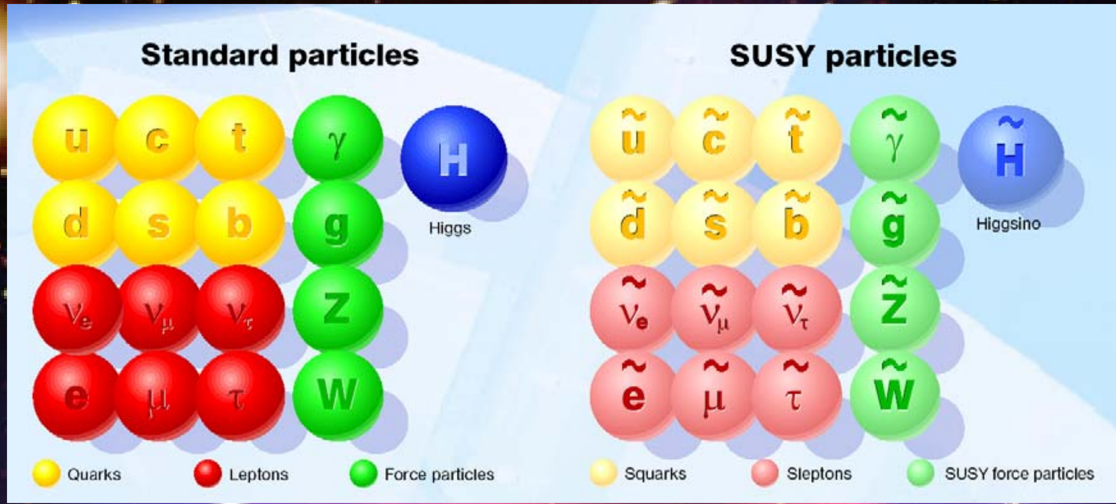


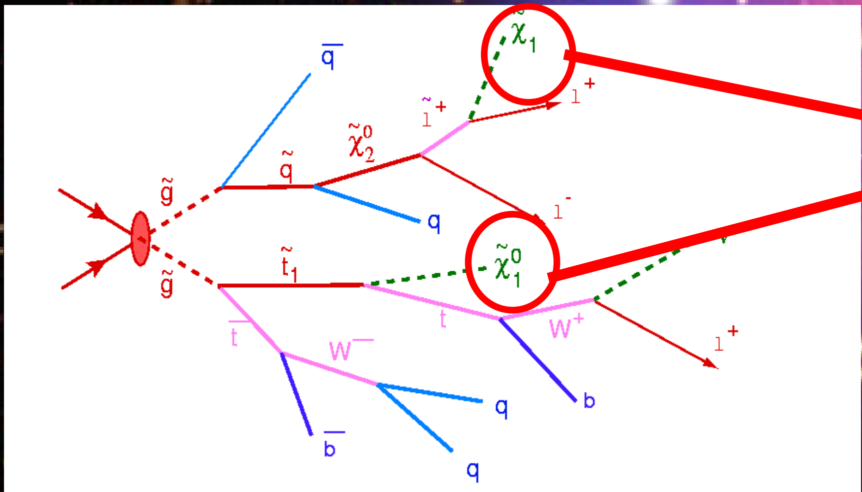
Mass spectra depend on choice of models and parameters...



Energy range of the LHC

Supersymmetry: A New Symmetry in Nature

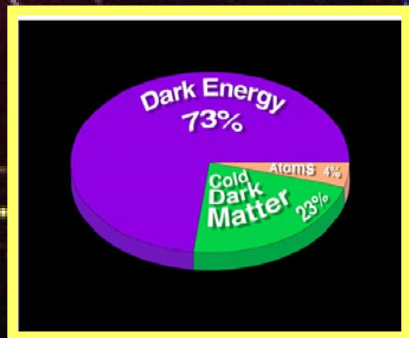




3 isolated leptons
+ 2 b-jets
+ 4 jets
+ E_t^{miss}

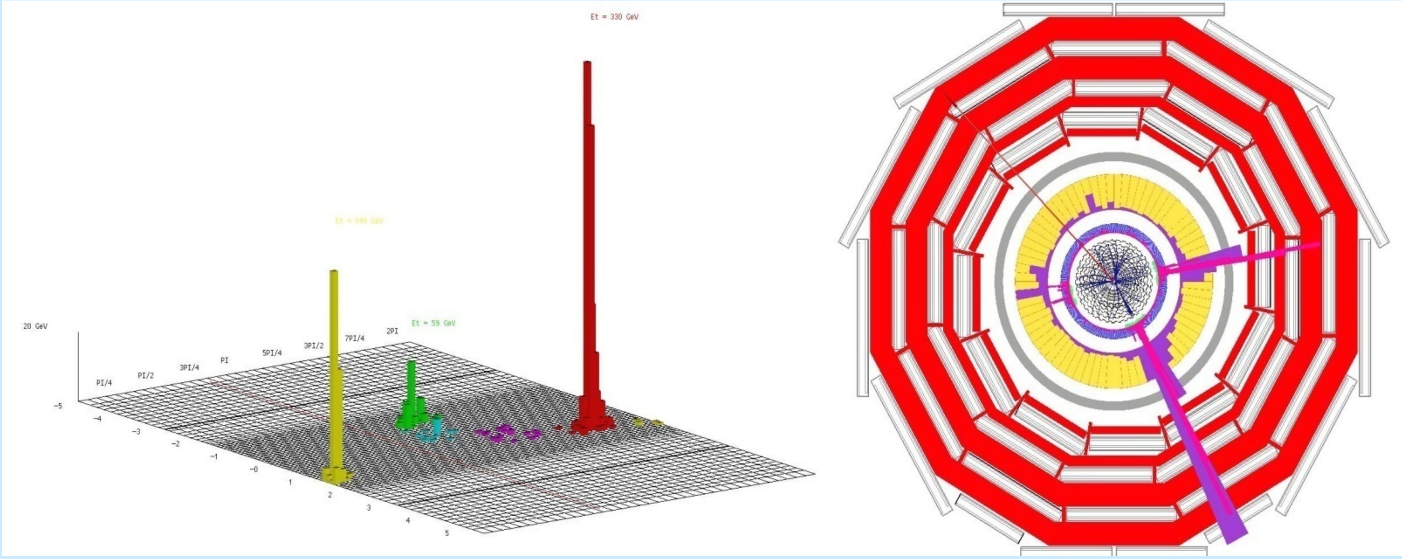
Candidate Particles for Dark Matter
⇒ Produce Dark Matter in the lab

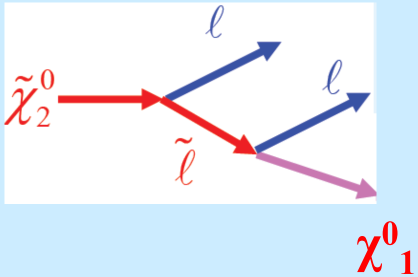
SUSY particle production at the LH

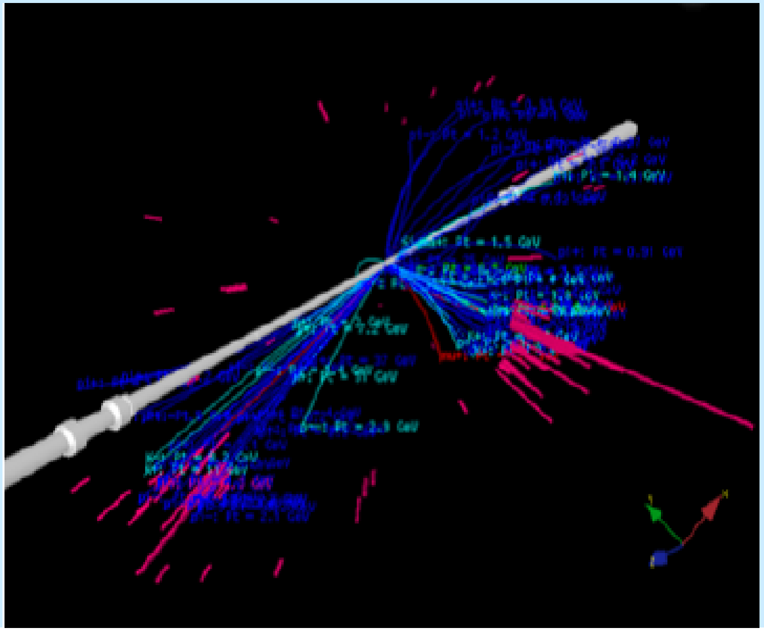


Marusa Bradac

Searching for SUSY







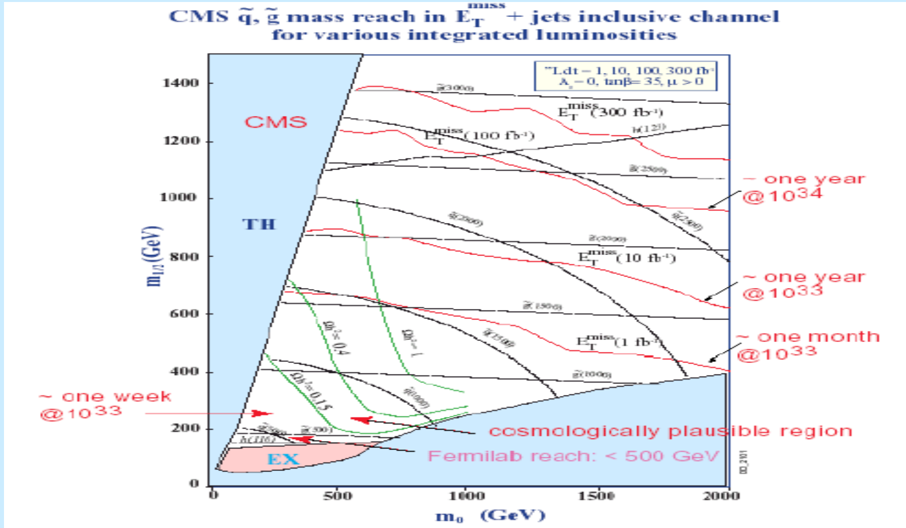
Key:

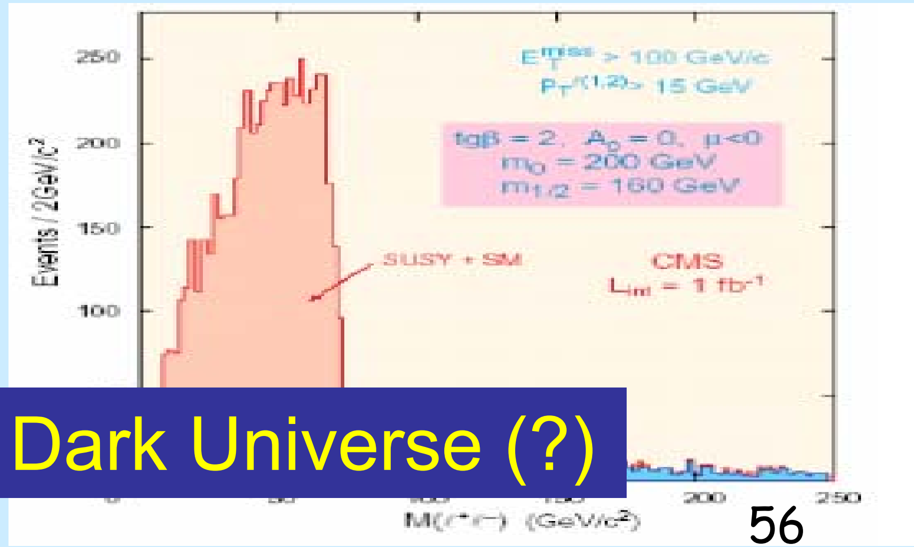
missing energy
missing momentum

Vital:
well understood
detectors

Search for SUSY at LHC Start-up

- Due to their high production cross-sections, squarks and gluinos can be produced in large numbers even at modest luminosities.
- Potential for discovery of SUSY is sizeable even at LHC start-up.

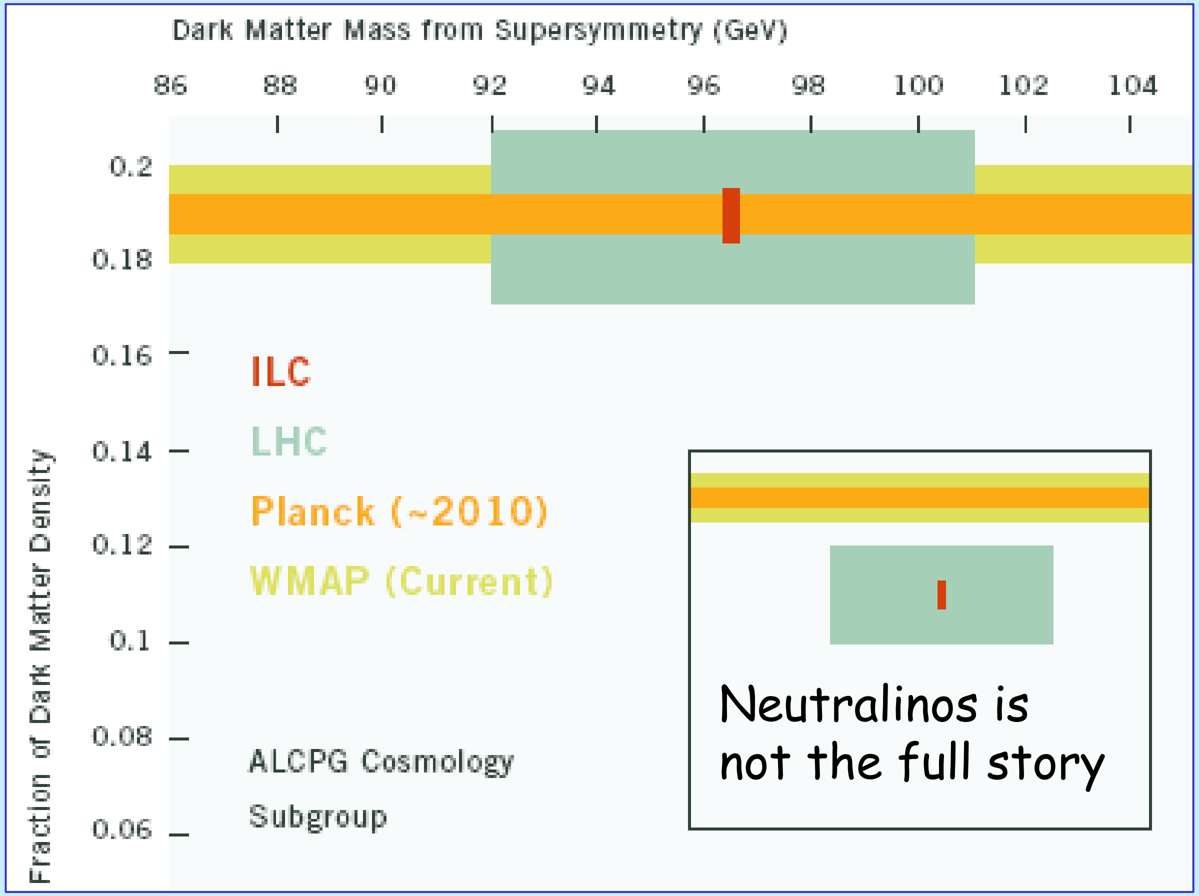




→ First light in the Dark Universe (?)

Dark Matter and SUSY

- Is dark matter linked to the Lightest Supersymmetric Particle?



Accel. and sat. data (WMAP and Planck):

complementary views of dark matter.

WMAP/Planck: sensitive to total density of dark matter.

LHC/LC: identify DM particle, measures its mass;

Together they establish the nature of dark matter.

LHC results should allow,
together with dedicated dark matter searches,
first discoveries in the dark universe

- around 73% of the Universe is in some mysterious "dark energy". It is evenly spread, as if it were an intrinsic property of space. It exerts negative pressure.

Challenge:
get first hints about the world of
dark energy in the laboratory

The Higgs is Different!

All the matter particles are spin-1/2 fermions.
All the force carriers are spin-1 bosons.

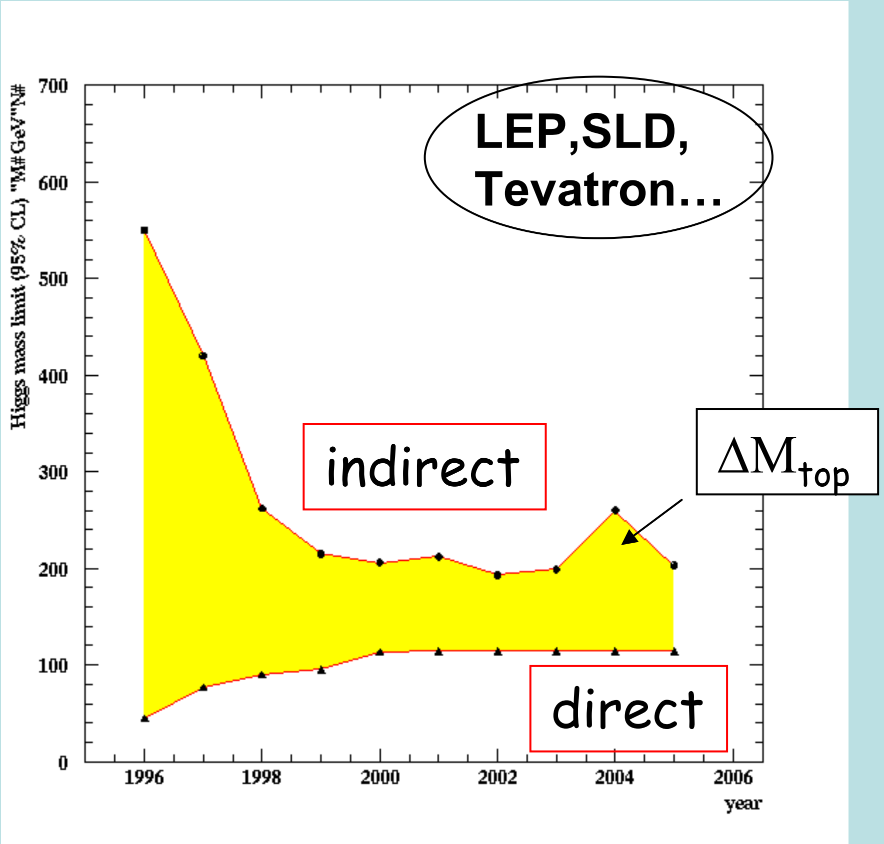
Higgs particles are spin-0 bosons (scalars).
The Higgs is neither matter nor force.
The Higgs is just different.
This would be the first fundamental scalar ever discovered.

The Higgs field is thought to fill the entire universe.
Could it give some handle of dark energy (scalar field)?

Many modern theories predict other scalar particles like the Higgs.
Why, after all, should the Higgs be the only one of its kind?

LHC can search for and study new scalars with precision.

Status of search for Higgs-Boson

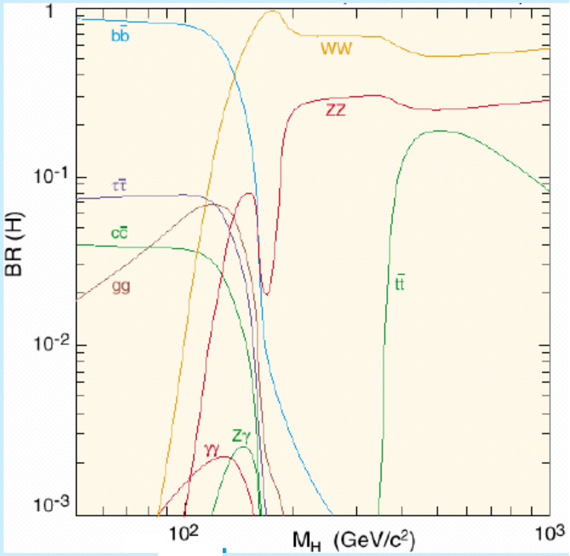


Time evolution of experimental limits on the Higgs boson mass

M_H between 114 and ~200 GeV

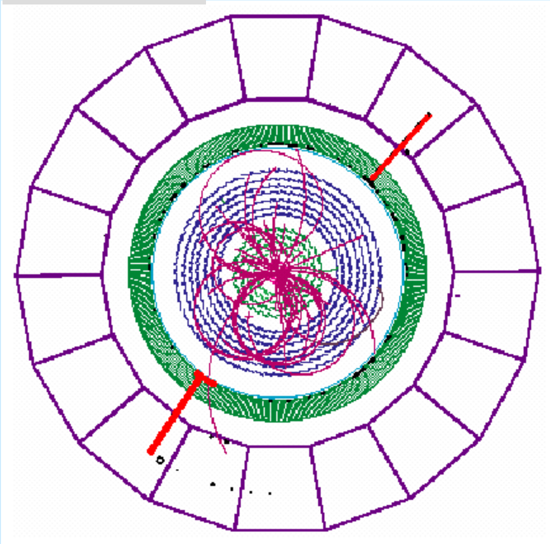
If the Higgs-Boson exists it will be found at the LHC

Search for the Higgs Boson

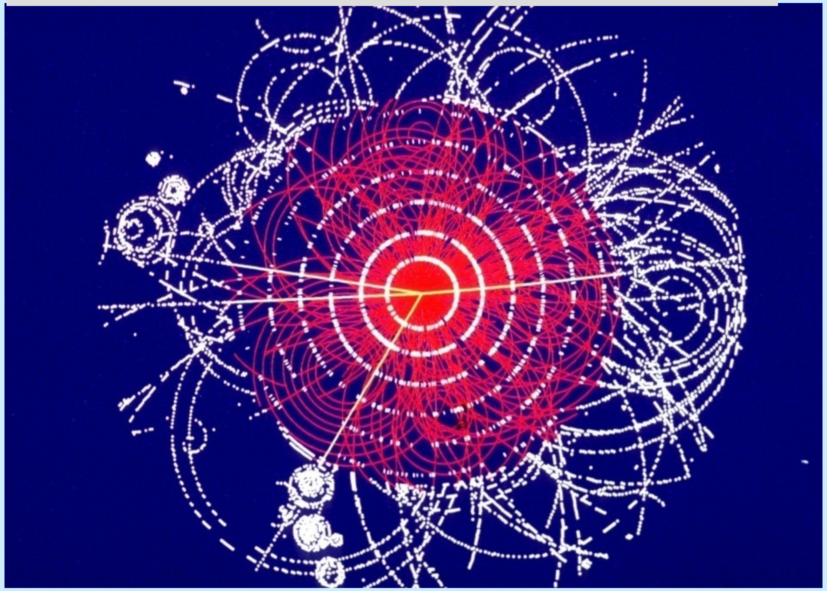


LEP:	LHC:	
$H \to bb$	$H \to bb$	enormous QCD bkgd
	$H \to \gamma\gamma$	low m_H (BR $\approx 10^{-3}$)
	$H \to W^+W^-$	medium m_H
	$H \to ZZ$	high m_H

$H \to \gamma\gamma$



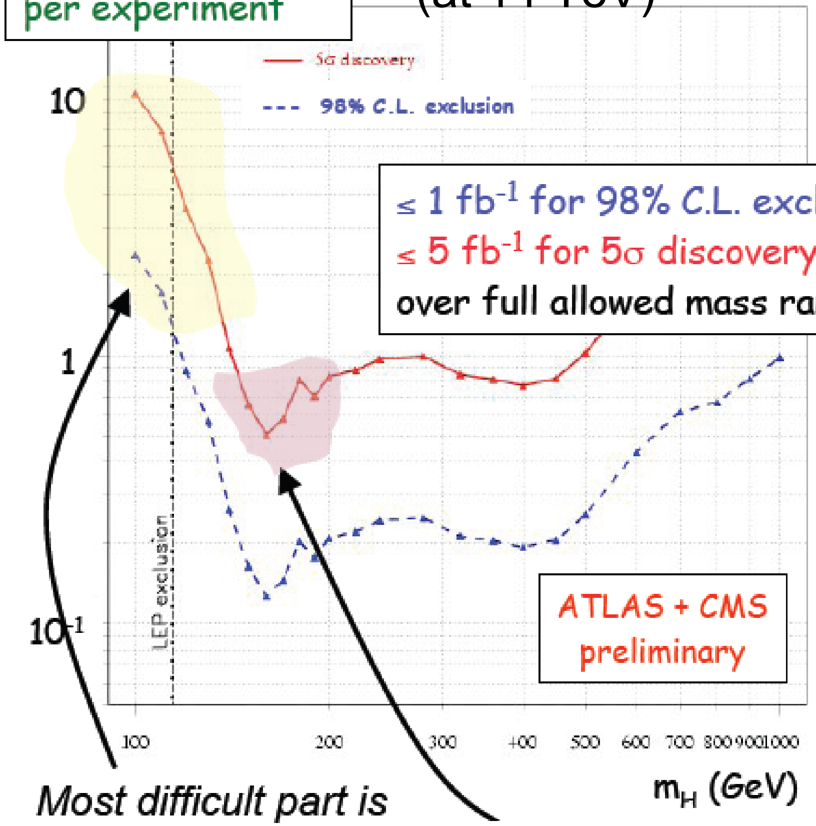
$H \to ZZ \to 4\mu$ (golden channel)



SM Higgs Reach

Needed ∫Ldt (fb^{-1}) per experiment

(at 14 TeV)

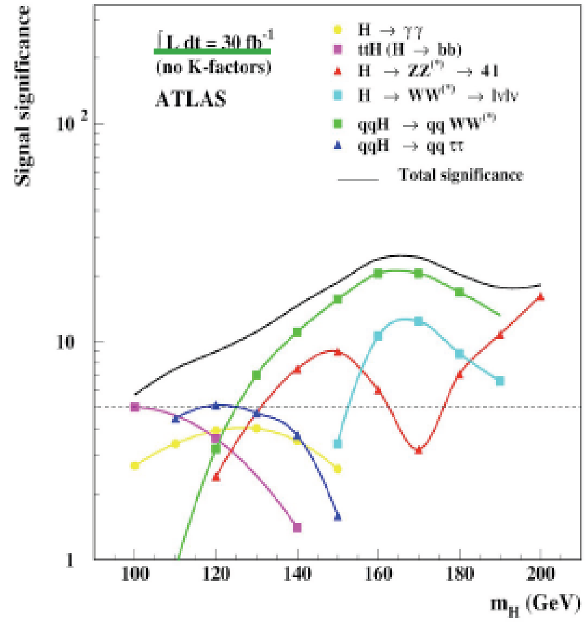


≤ 1 fb^{-1} for 98% C.L. exclusion
≤ 5 fb^{-1} for 5σ discovery
over full allowed mass range

ATLAS + CMS preliminary

Most difficult part is M_h~115 GeV

Early discovery already Possible with 1fb^{-1} $H \to WW^{(*)} \to 2l$



With 1fb^{-1} of understood data:

- *potential to exclude almost all m_h values*
- *potential to discover higgs with m_h~165 GeV*

LHC will give us an answer!

25/07/2007 HEP 2007 C

55

but it will take time. . .

In conclusion (G.Altarelli, LP09)

Is it possible that the LHC does not find the Higgs particle?

Yes, it is possible, but then must find something else

Is it possible that the LHC finds the Higgs particle but no other new physics (pure and simple SM)?

Yes, it is technically possible but it is not natural

Is it possible that the LHC finds neither the Higgs nor new physics?

LHC results will allow
to study the Higgs mechanism in detail and
to reveal the character of the Higgs boson

This would be the first investigation
of a scalar field

This could be the very first step to
understanding Dark Energy

Past decades saw precision studies of 5 % of our Universe → Discovery of the Standard Model

The LHC is delivering data

We are just at the beginning of exploring 95 % of the Universe

Past decades saw precision studies of 5 % of our Universe → Discovery of the Standard Model

The LHC will soon deliver data

We are just at the beginning of exploring 95 % of the Universe

the future is bright in the Dark Universe