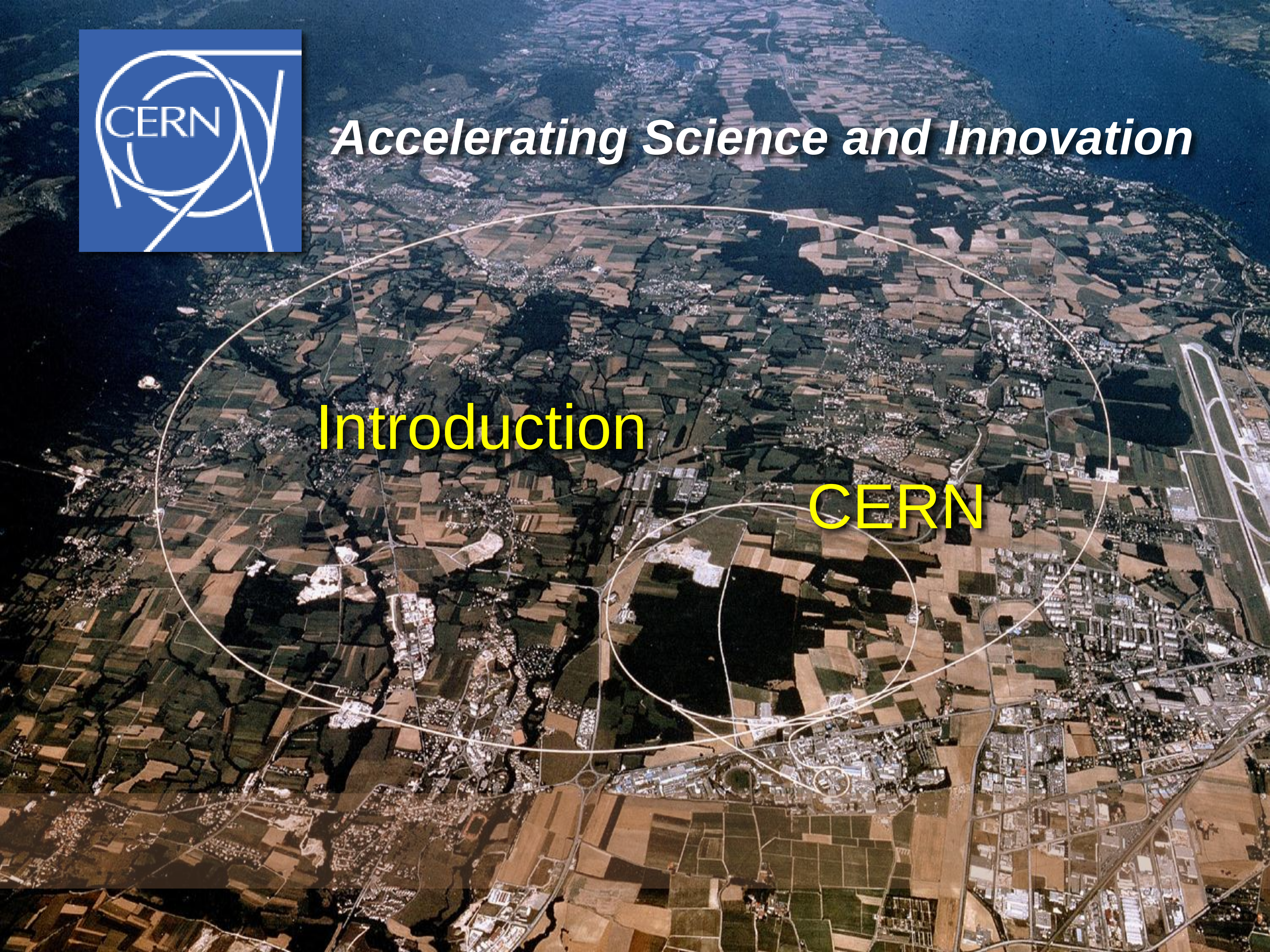
Accelerating Science and Innovation

Particle Physics at CERN

Introduction

Science

A Forward Look

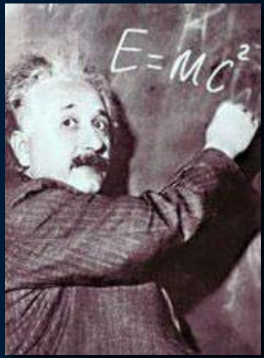

Accelerating Science and Innovation
Introduction
CERN

Innovation
Education
CERN
uniting people
Research

The Mission of CERN

- **Push forward** the frontiers of knowledge

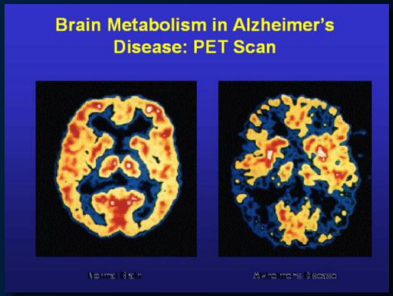
  E.g. the secrets of the Big Bang …what was the matter like within the first moments of the Universe’s existence?



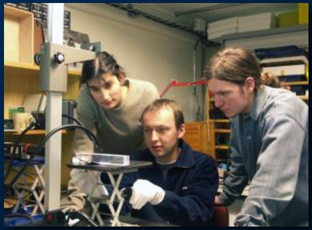
- **Develop** new technologies for accelerators and detectors

  Information technology - the Web and the GRID

  Medicine - diagnosis and therapy



- **Train** scientists and engineers of tomorrow



- **Unite** people from different countries and cultures

CERN was founded 1954: 12 European States

"Science for Peace"

Today: 20 Member States

~ 2300 staff
~ 1050 other paid personnel
~ 11000 users

Budget (2012) ~1000 MCHF

Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, the Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom

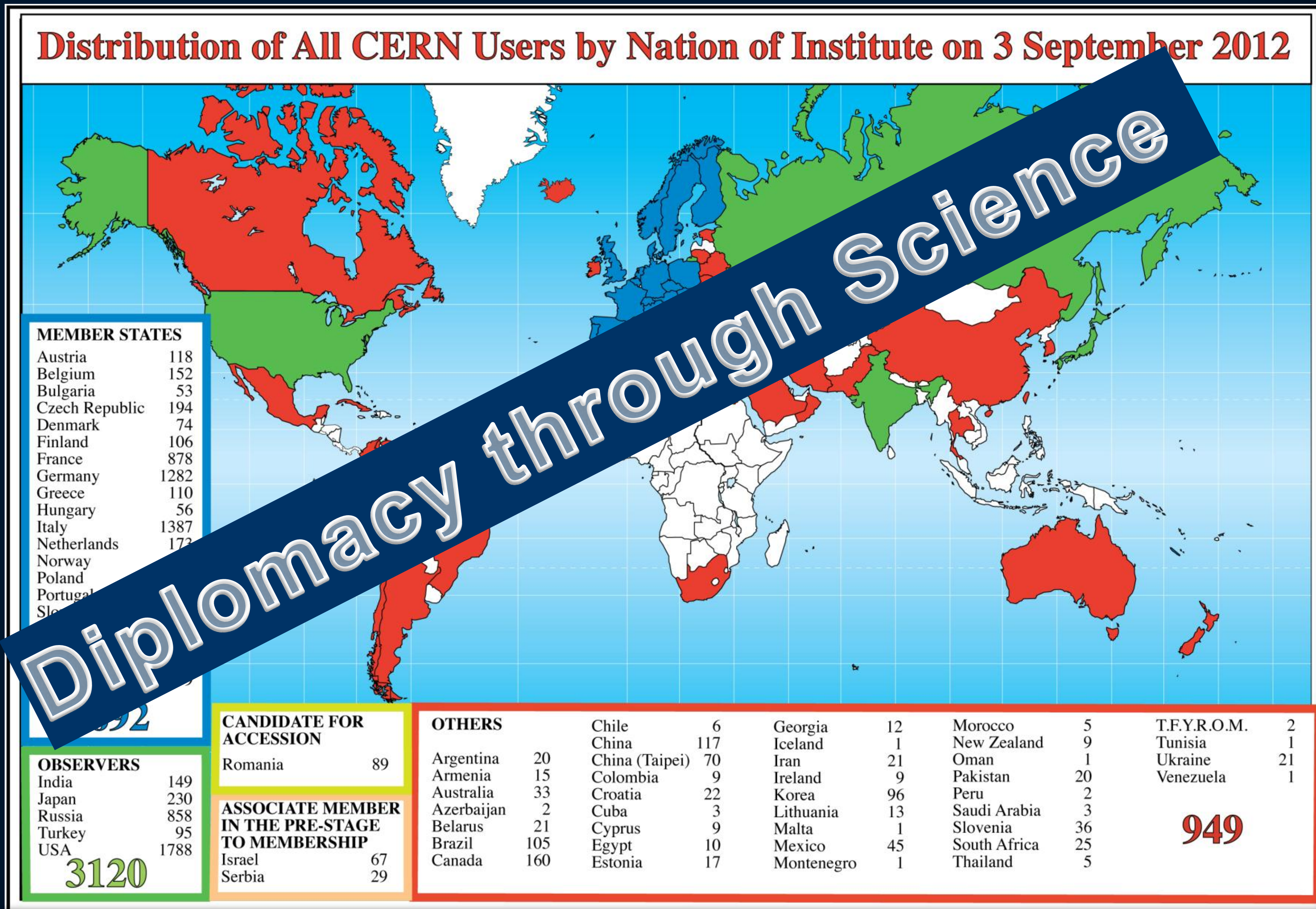
Candidate for Accession: Romania

Associate Members in the Pre-Stage to Membership: Israel, Serbia

Applicant States: **Cyprus**, Slovenia, Turkey

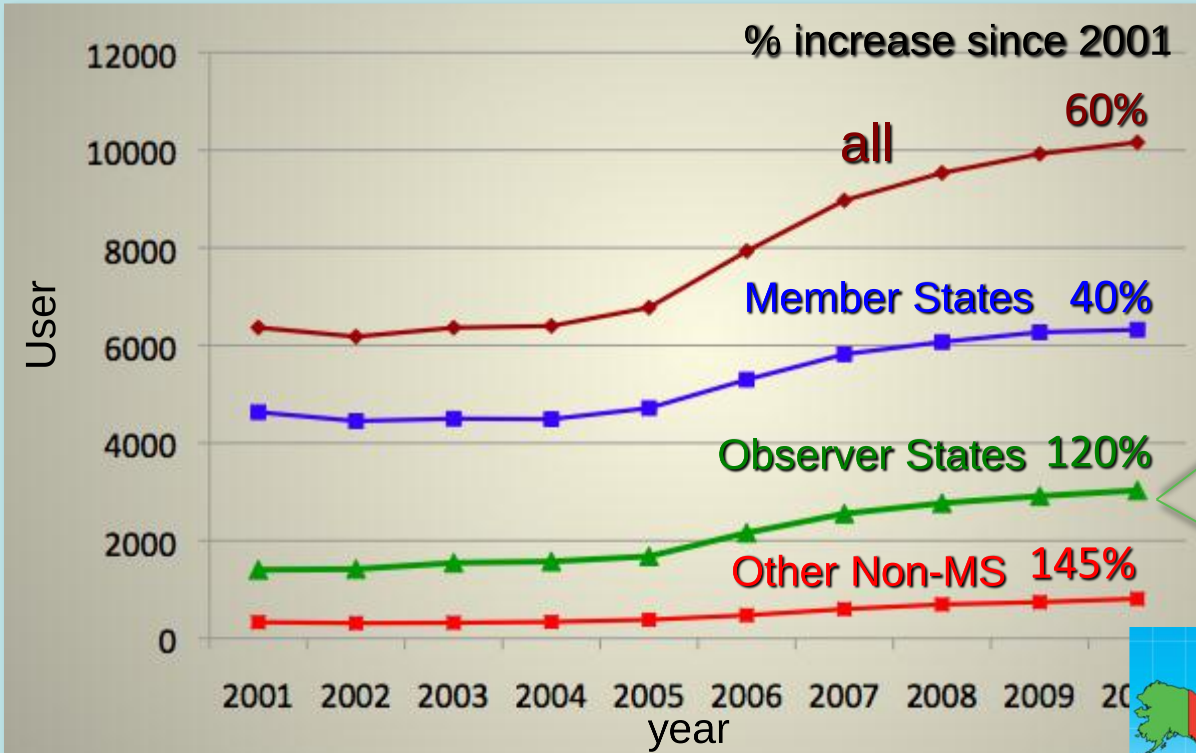
Observers to Council: India, Japan, the Russian Federation, the United States of America, Turkey, the European Commission and UNESCO

Science is getting more and more global

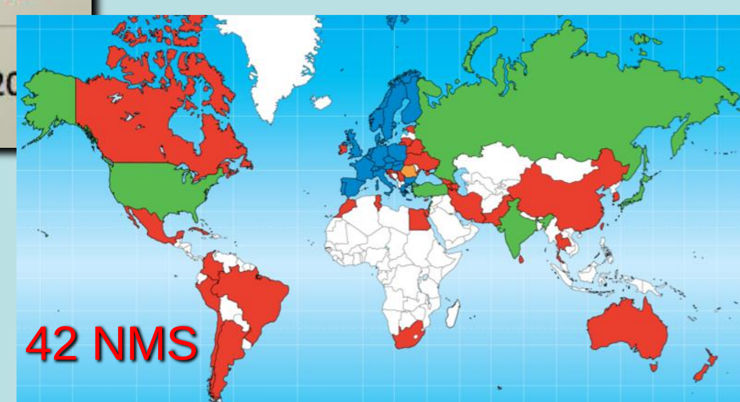


Impact of LHC on Evolution of CERN Users

Evolution of the number of CERN users by geographical location of the home institute: 2001-2010



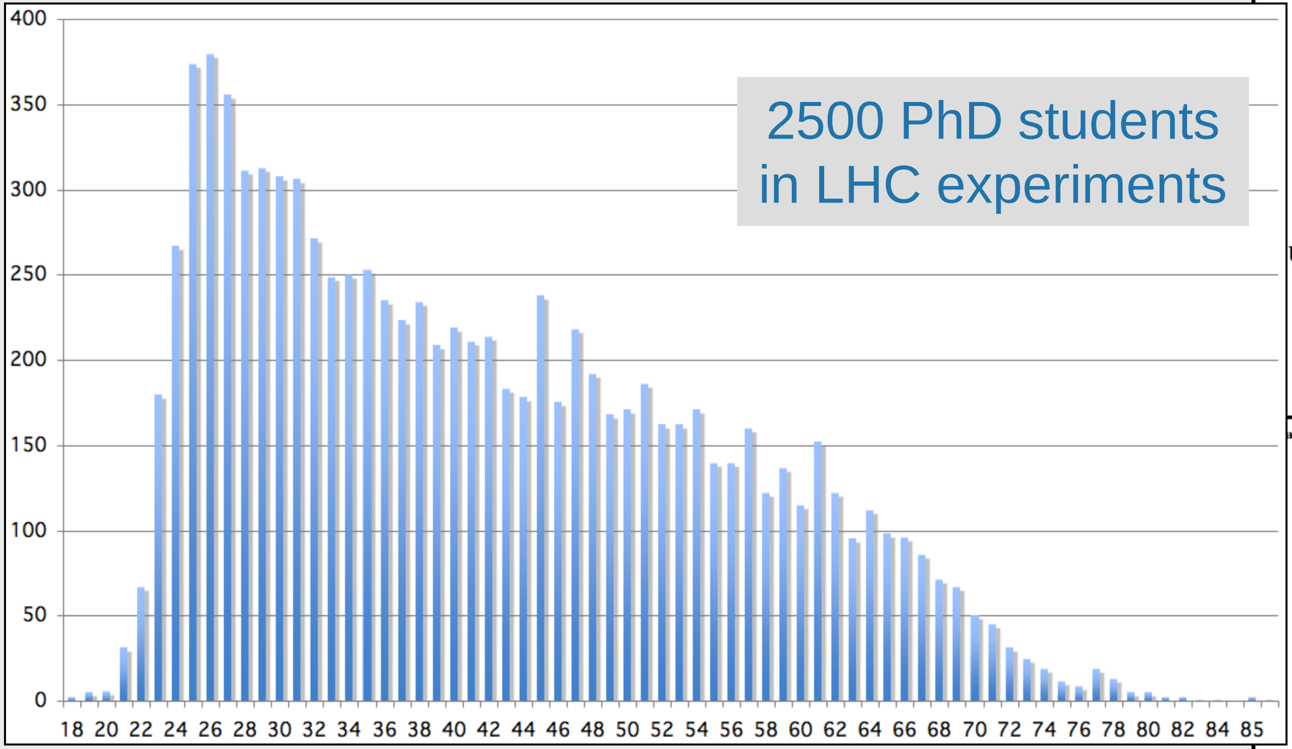
6 Observer States:
India, Israel, Japan,
Russia, Turkey, USA



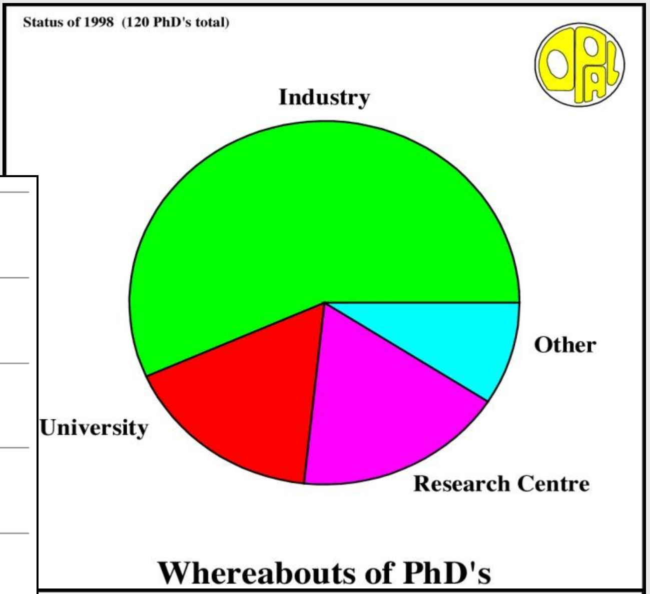
Age Distribution of Scientists

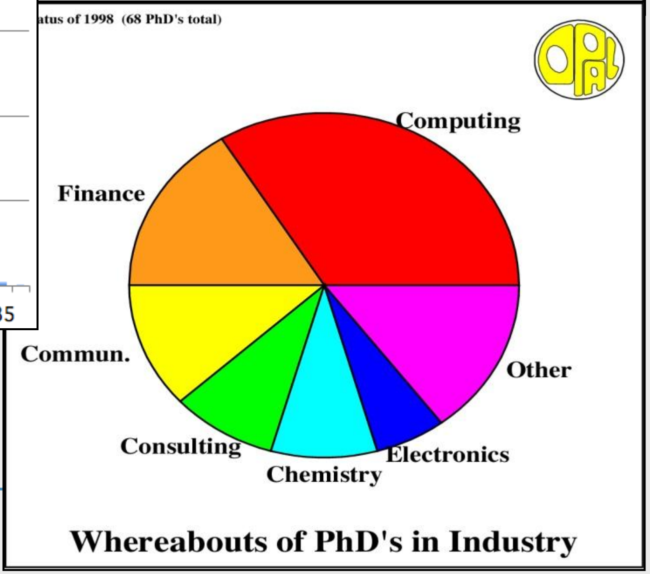
- and where they go afterwards

Survey in March 2009



2500 PhD students in LHC experiments





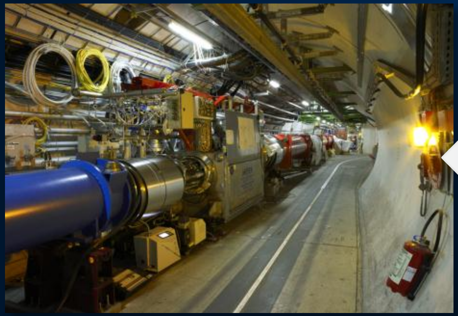
They do not all stay: where do they go?

Innovation
Education
CERN
uniting people
Research

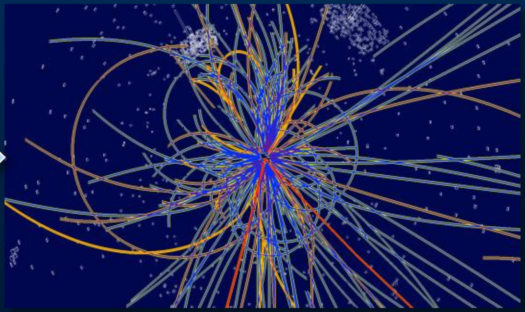
CERN: Particle Physics and Innovation

- Interfacing between fundamental science and key technological developments

- CERN Technologies and Innovation



Accelerating particle beams



Detecting particles

Large-scale computing (Grid)

Innovation
Education
CERN
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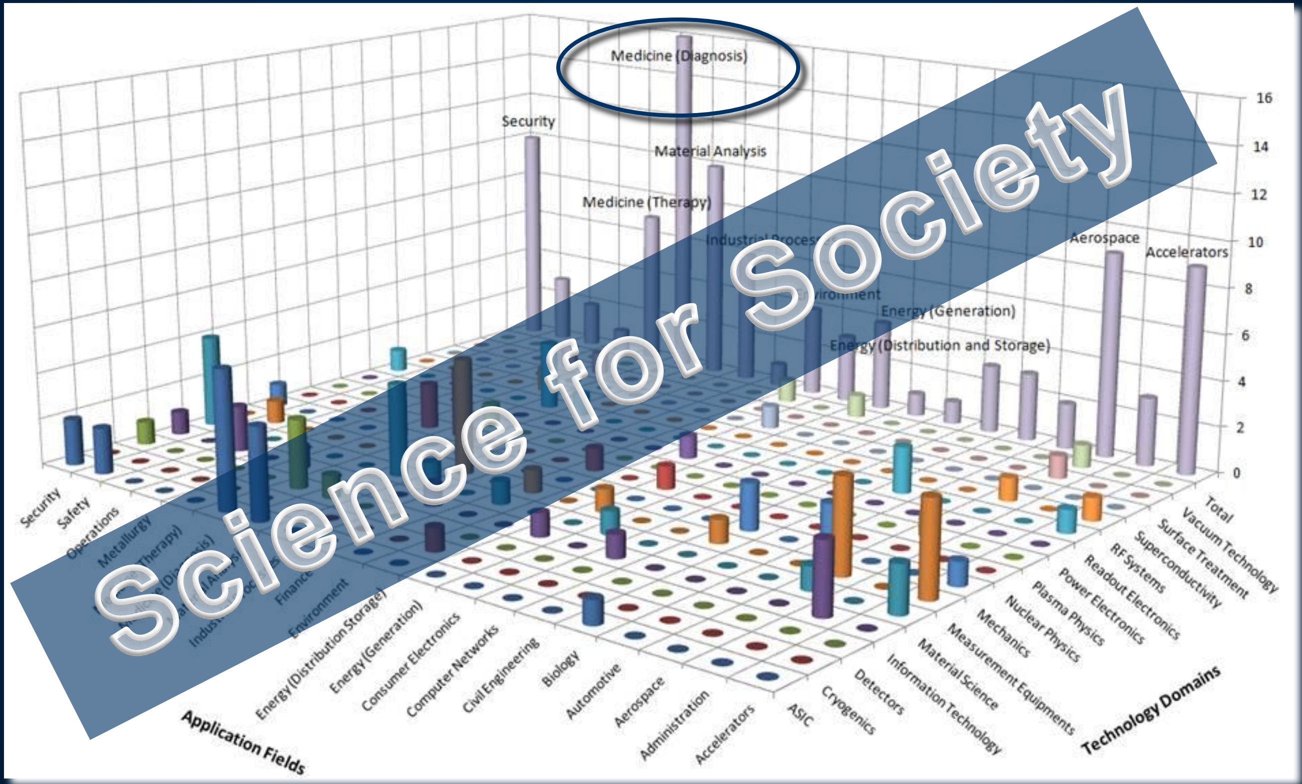
Research

CERN Technologies and Innovation

Cutting edge Research Infrastructures play a key role in a knowledge driven society

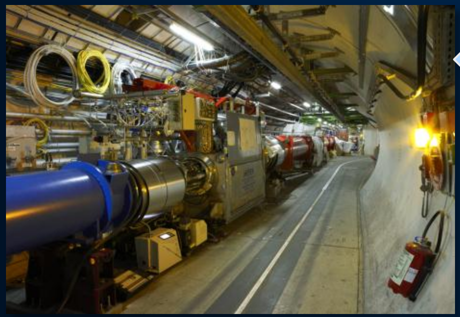


Knowledge is − and will be more and more − the most precious resource for a sustainable development

Innovation
Education
CERN
uniting people
Research

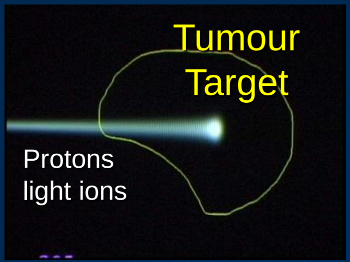
CERN Technologies and Innovation
Example: Medical applications

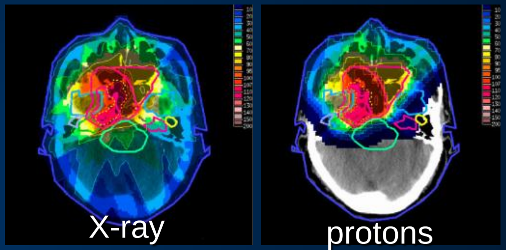
Combining Physics, ICT, Biology and Medicine to fight cancer



Accelerating particle beams
~30’000 accelerators worldwide
~17’000 used for medicine

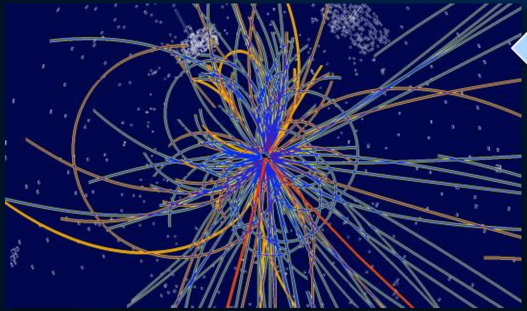
Hadron Therapy





Leadership in Ion Beam Therapy now in Europe and Japan

>70’000 patients treated worldwide (30 facilities)
>21’000 patients treated in Europe (9 facilities)

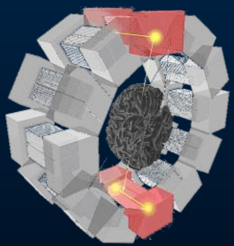


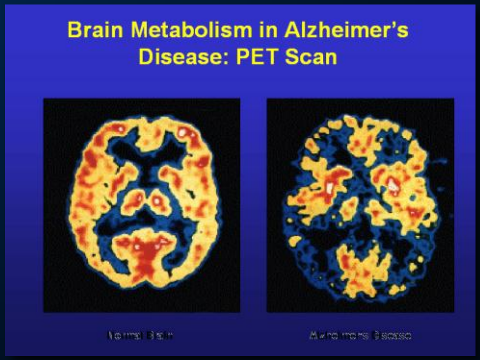
Detecting particles

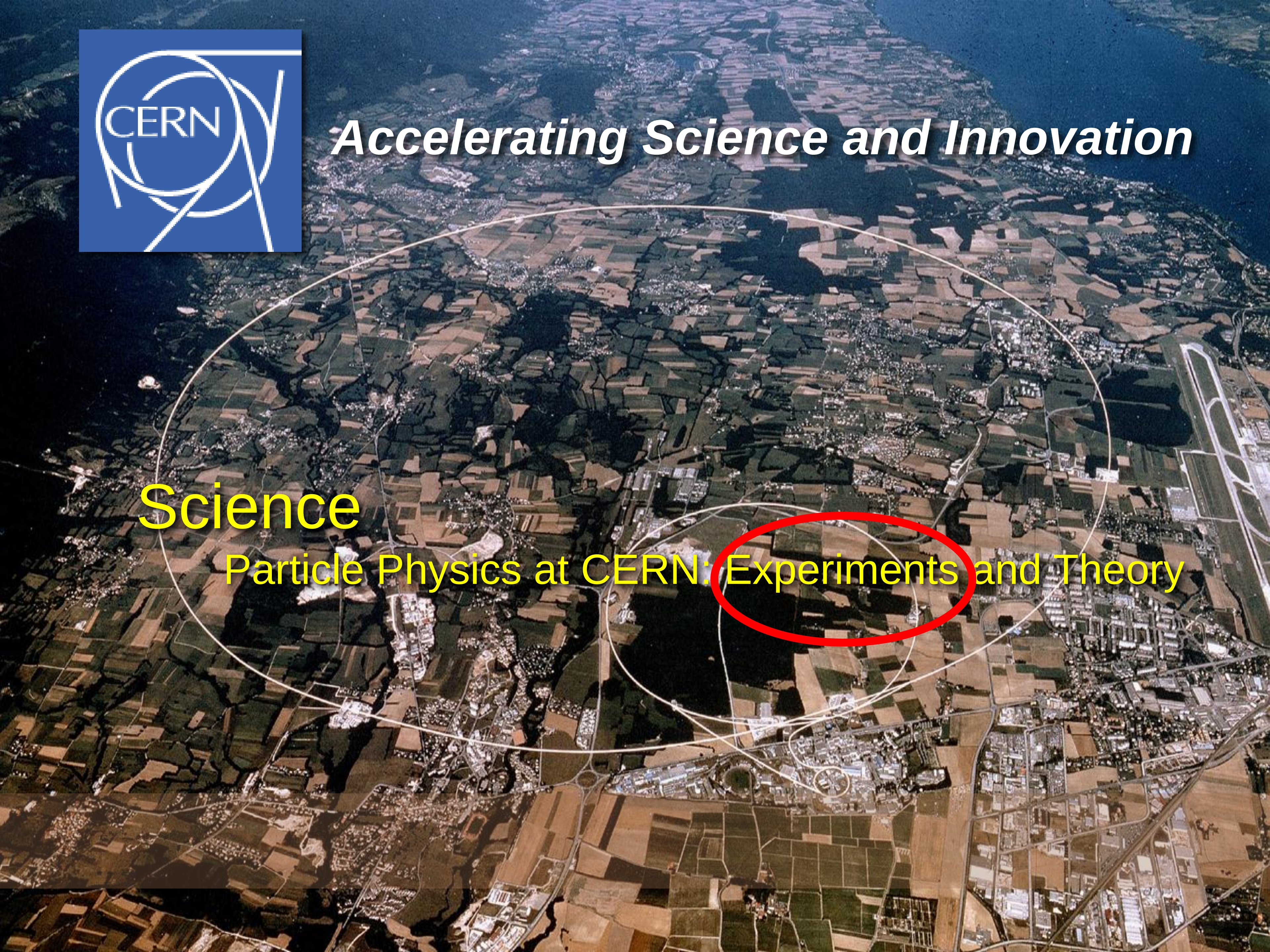
Imaging

PET Scanner

Clinical trial in Portugal for new breast imaging system (ClearPEM)



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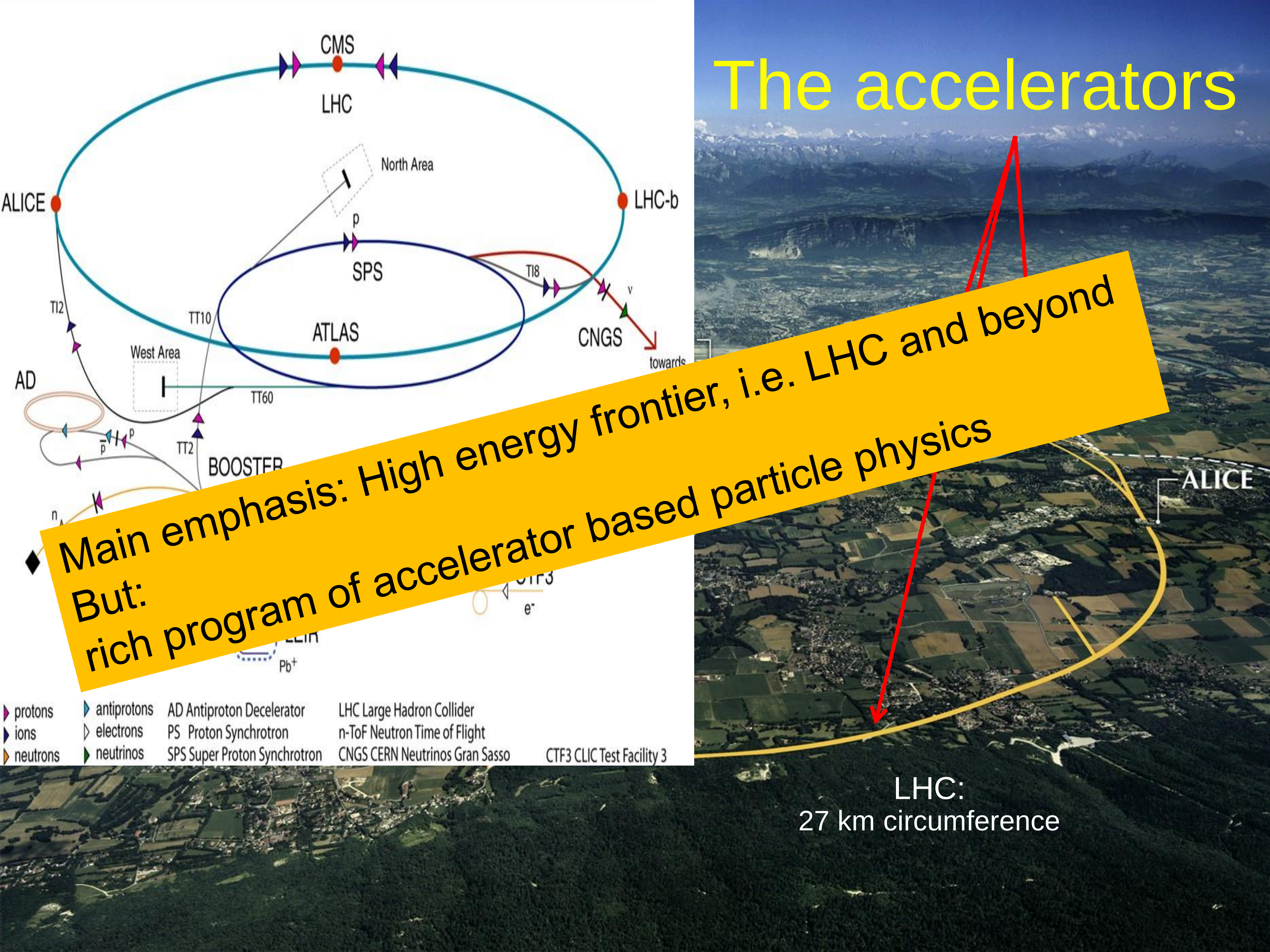
Science
Particle Physics at CERN: Experiments and Theory


The accelerators
CMS
LHC
North Area
ALICE
LHC-b
p
SPS
TI8
TI2
TT10
ATLAS
CNGS
towards
West Area
AD
TT60
TT2
BOOSTER
n
e-
Pb+
protons
ions
neutrons
antiprotons
electrons
neutrinos
AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron
LHC Large Hadron Collider
n-ToF Neutron Time of Flight
CNGS CERN Neutrinos Gran Sasso
CTF3 CLIC Test Facility 3
Main emphasis: High energy frontier, i.e. LHC and beyond
But:
rich program of accelerator based particle physics
ALICE
LHC:
27 km circumference

The Particle Physics Landscape at CERN

High Energy Frontier
LHC

Hadronic Matter
deconfinement
non-perturbative QCD
hadron structure

Low Energy
heavy flavours / rare decays
neutrino oscillations
anti-matter

Non-accelerator
dark matter
astroparticles

Multidisciplinary
climate, medicine

Non-LHC Particle Physics = o(1000) physicists / o(20) experiments

In the past 1.5 year

Several breakthroughs !

Steady progress of other programs

New mid-term and long-term projects started or in discussion

Fixed Target Physics

Antiproton Physics

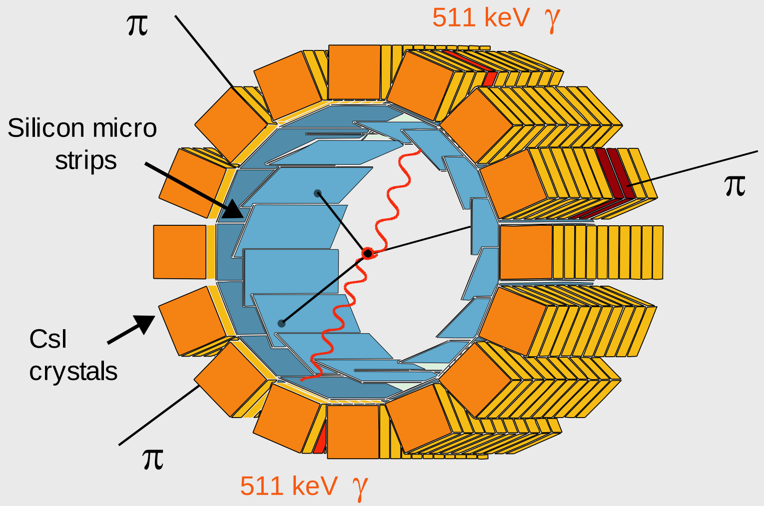
Cold antiprotons
("manufacturing anti-matter")

1. PS $p \rightarrow \bar{p}p$ 10^{-6}/collision
2. AD deceleration + cooling
   stochastic + electron
3. Extraction @ ~ 0.1*c*
4. Produce thousands of *anti-H*

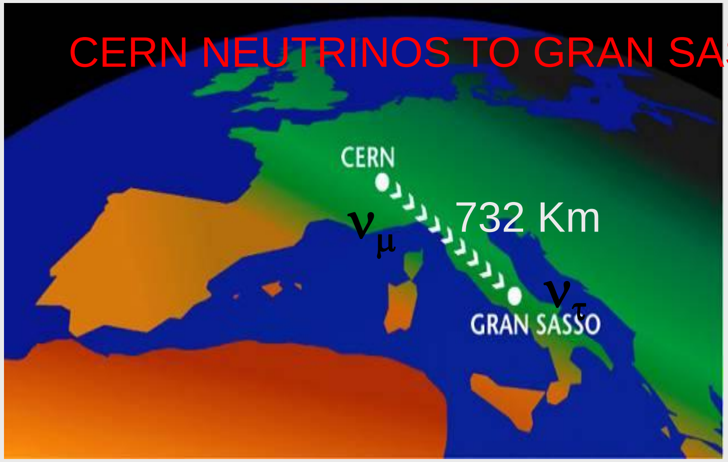
Anti-H annihilations detected

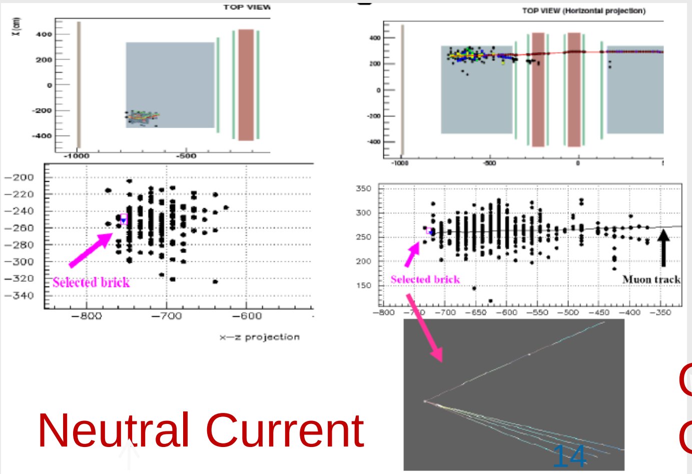
ATHENA (→ ALPHA)

anti-H ($\bar{p}e^+$) + matter → $\pi^+\pi^- + \gamma\gamma$



Neutrino Physics





OPERA

Charge Current

Breakthroughs… ALPHA

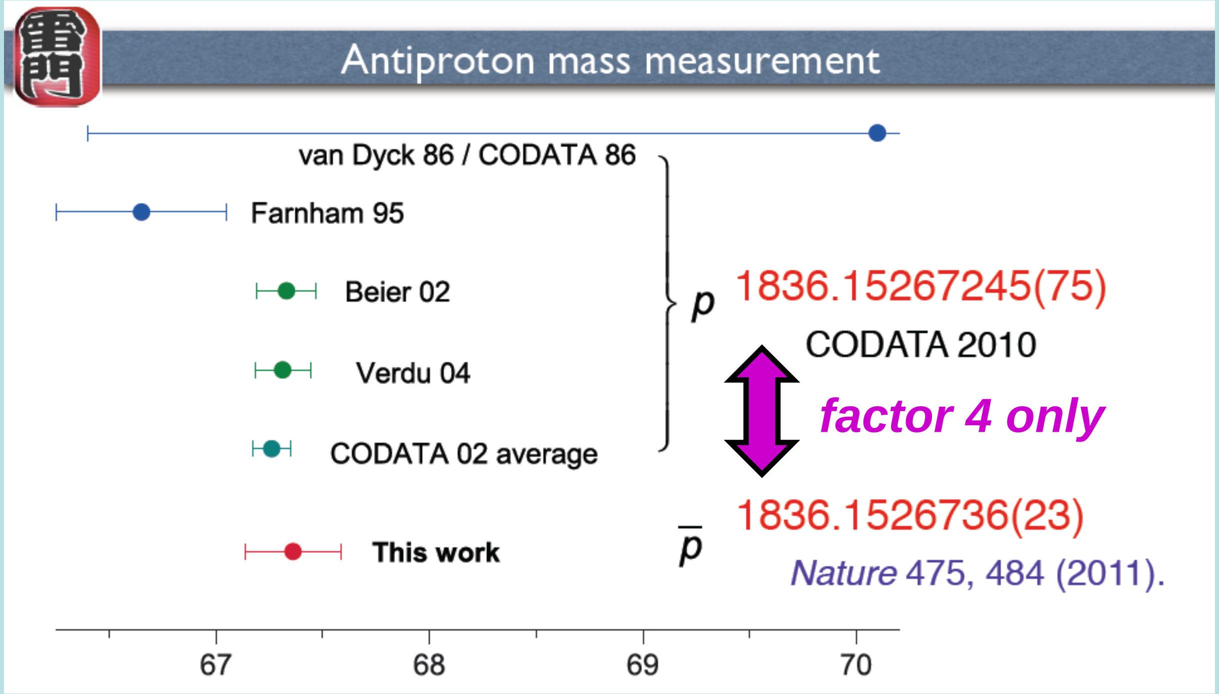
nature

First successful trapping of Anti-Hydrogen atoms

Trapping times of more than 15mn regularly achieved

Breakthroughs… ASACUSA

nature

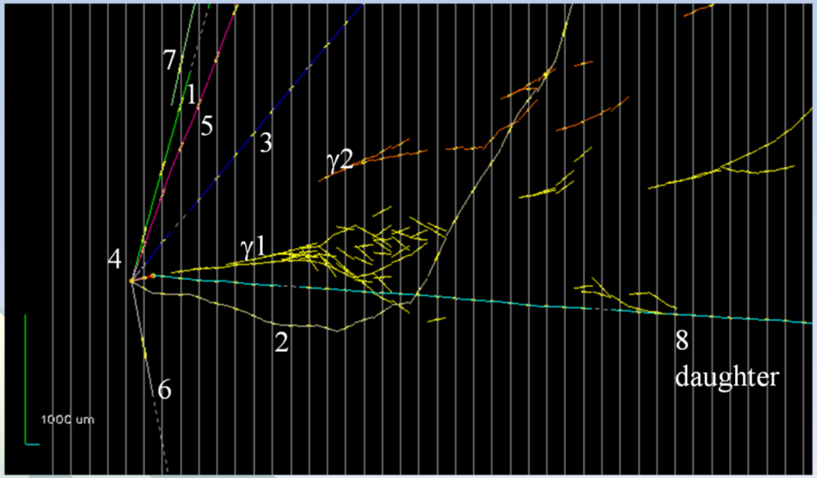


Parallel talk by Marilisa De Serio

OPERA ν_τ appearance

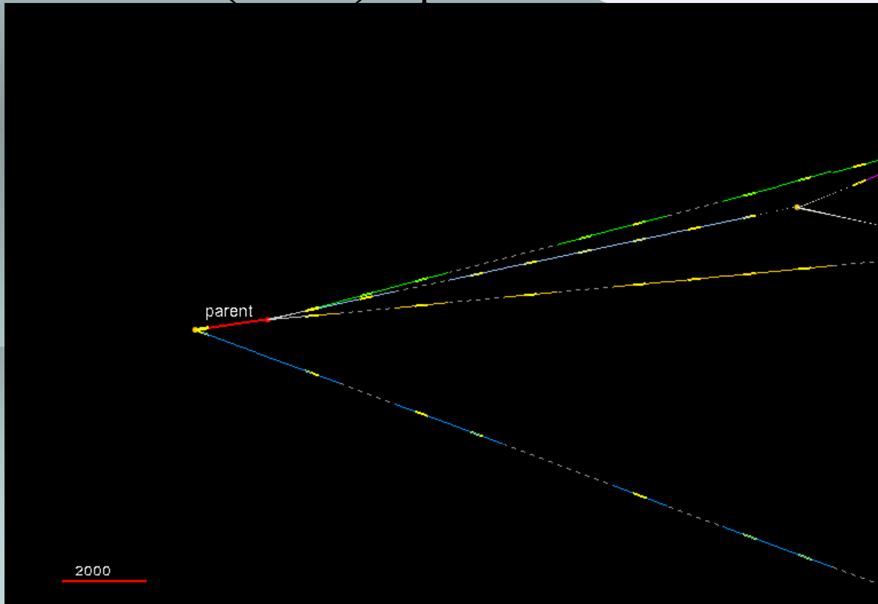
- Status of the analysis
  - 2 candidate events so far (expected 2.1 with 0.2 background events)
  - A few more events are under study.
  - Progress in estimating detection efficiency and BG.

First cand. ($\tau\rightarrow$1had kink) reported in 2010



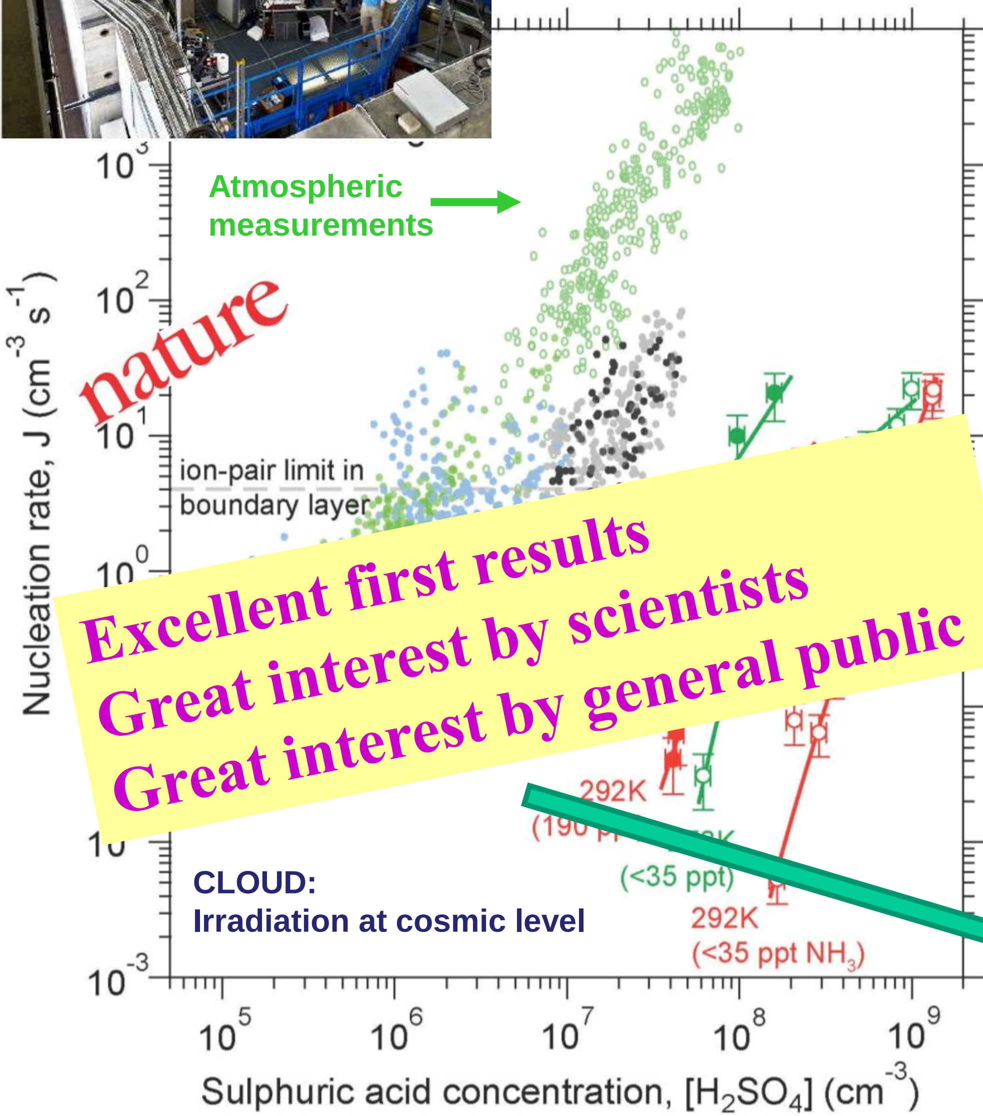
Years	Status	# of events for Decay search	Expected ν_τ (Preliminary)	Observed ν_τ Candidate Events	Expected BG for ν_τ (Preliminary)
2008-2009	Finished	2783		1	
2010-2011	In analysis	1343		1	
2012	Started				
Total		4126	2.1	2	0.2

2nd Cand ($\tau\rightarrow$3h) reported in June 2012

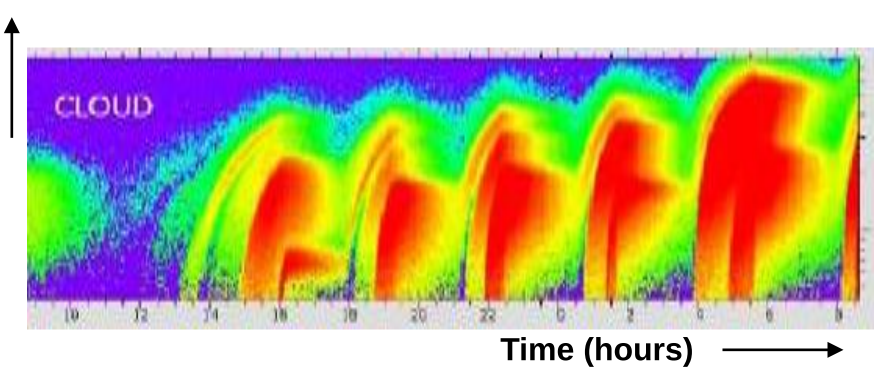


Breakthroughs… CLOUD

Aerosol nucleation under controlled conditions



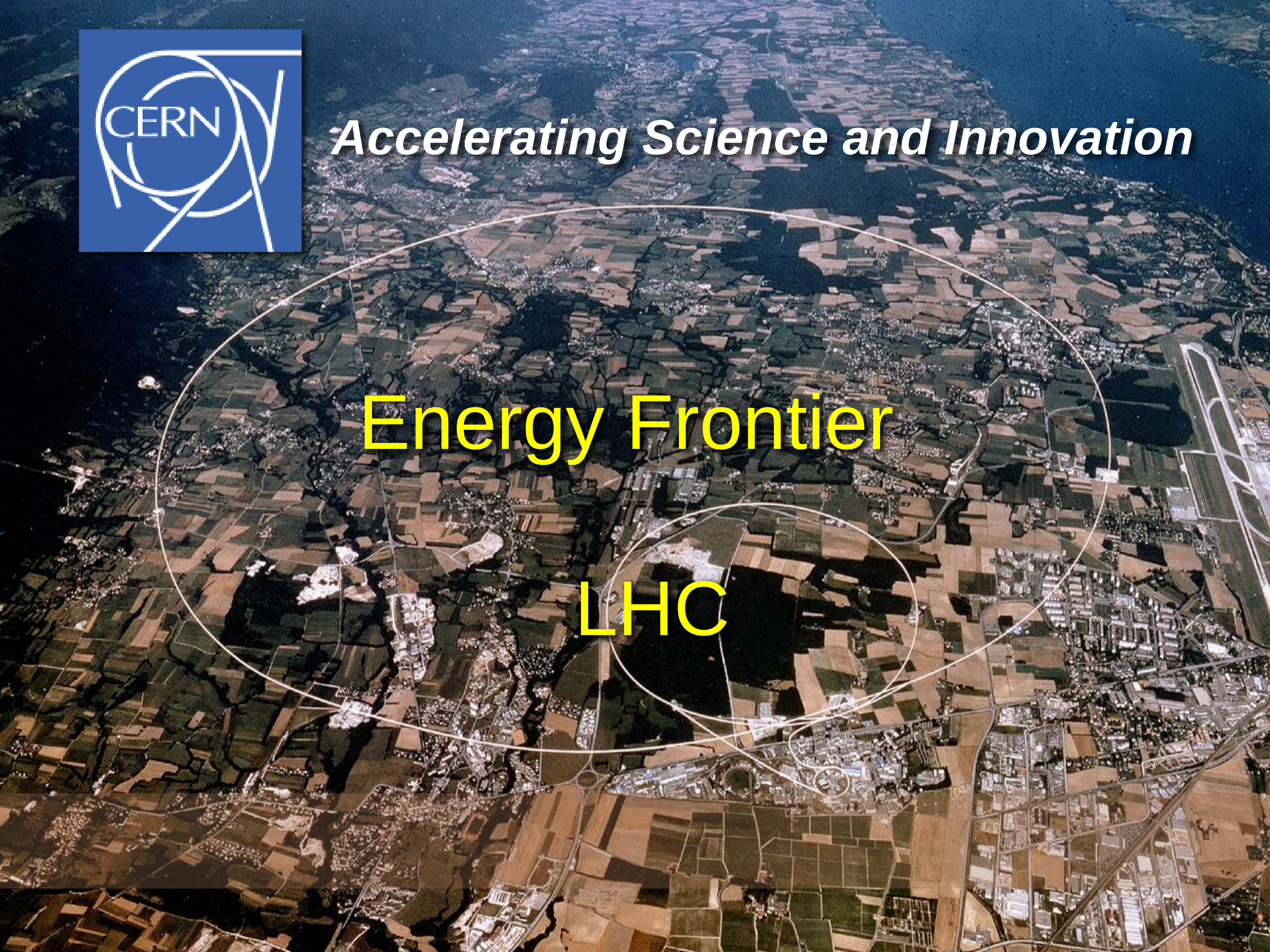
Excellent first results
Great interest by scientists
Great interest by general public



Nucleation depends on traces of organic vapors (tertiary process) and is sensitive to cosmic rays ionization

Atmospheric nucleation rates however not reproduced with $H_2SO_4 + NH_3$ only, other (yet unknown) organic compounds needed.

More studies ongoing at lower temperature


CERN
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Energy Frontier
LHC

Past few decades

"Discovery" of Standard Model

through synergy of

hadron - hadron colliders (e.g. Tevatron)

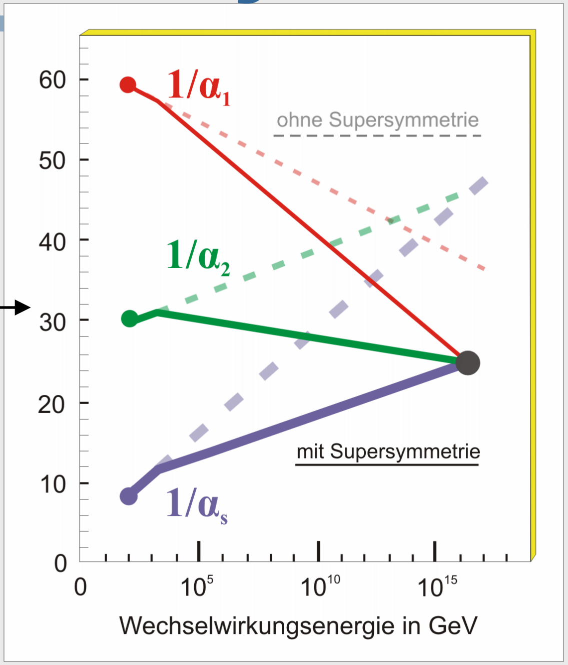
lepton - hadron colliders (HERA)

lepton - lepton colliders (e.g. LEP)

Key Questions of Particle Physics

origin of mass/matter or
origin of electroweak symmetry breaking

unification of forces



fundamental symmetry of forces and matter

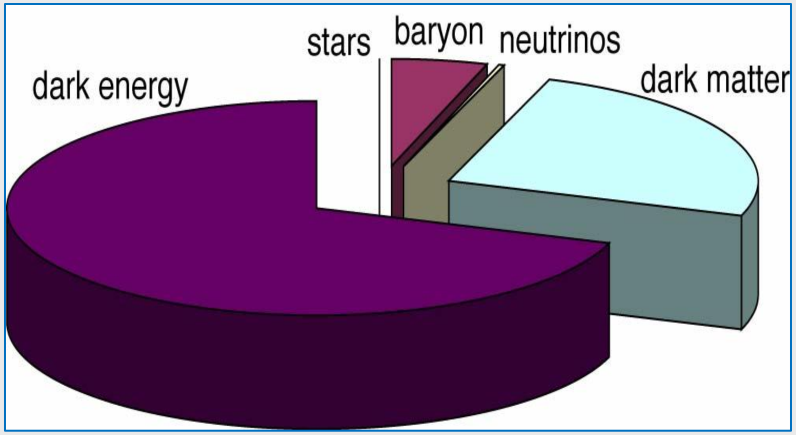
where is antimatter

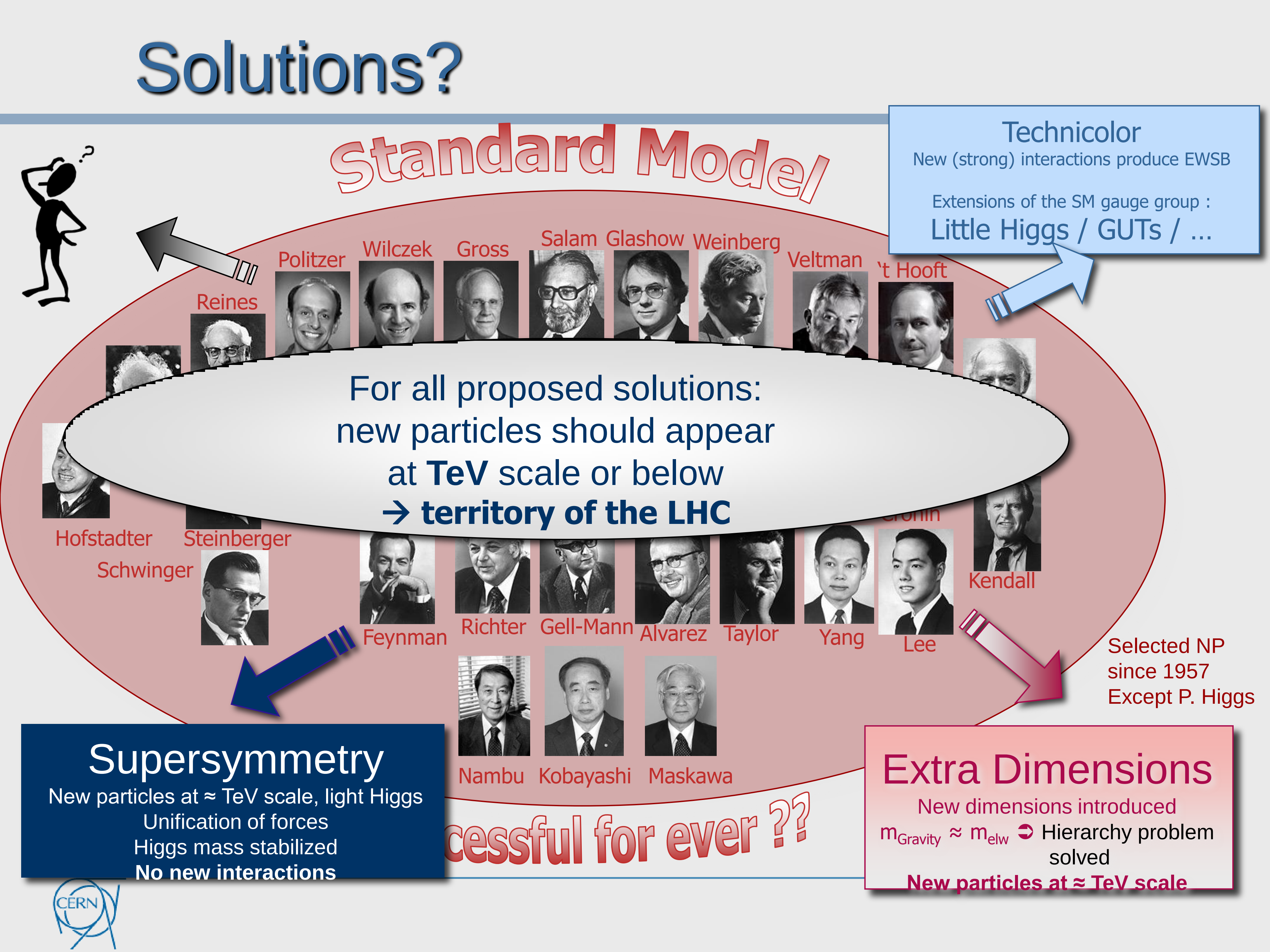
unification of quantum physics and general relativity

number of space/time dimensions

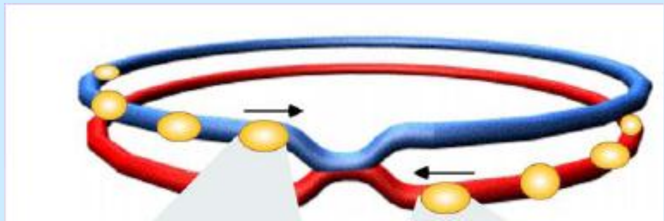
what is dark matter

what is dark energy



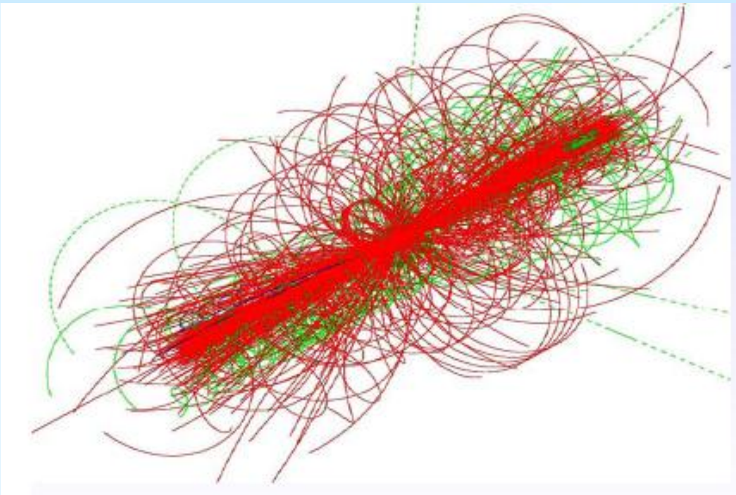

Solutions?
Standard Model
Technicolor
New (strong) interactions produce EWSB
Extensions of the SM gauge group :
Little Higgs / GUTs / ...
Politzer
Wilczek
Gross
Salam
Glashow
Weinberg
Veltman
't Hooft
Reines
For all proposed solutions:
new particles should appear
at **TeV** scale or below
→ territory of the LHC
Hofstadter
Steinberger
Schwinger
Feynman
Richter
Gell-Mann
Alvarez
Taylor
Yang
Lee
Kendall
Nambu
Kobayashi
Maskawa
Selected NP
since 1957
Except P. Higgs
cessful for ever ??
Supersymmetry
New particles at ≈ TeV scale, light Higgs
Unification of forces
Higgs mass stabilized
No new interactions
Extra Dimensions
New dimensions introduced
$m_{Gravity} \approx m_{elw}$ ➲ Hierarchy problem solved
New particles at ≈ TeV scale
CERN

Proton-Proton Collisions at the LHC



Design Energy:
7 + 7 = 14 TeV

Today: 4 + 4 = 8 TeV



- 2808 + 2808 proton bunches

Today: 1400 + 1400 bunches
20 MHz crossing rate

→ ...
= 40 MHz crossing rate

- 10^{11} protons per bunch

- at 10^{34}/cm²/s

Today: 6.5×10^{33}

≈ 35 pp interactions per crossing
pile-up

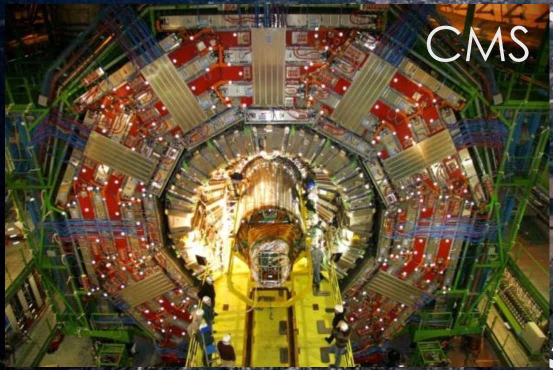
→ ≈ 10^9 pp interactions per second !!!

- in each collision
≈ 1600 charged particles produced

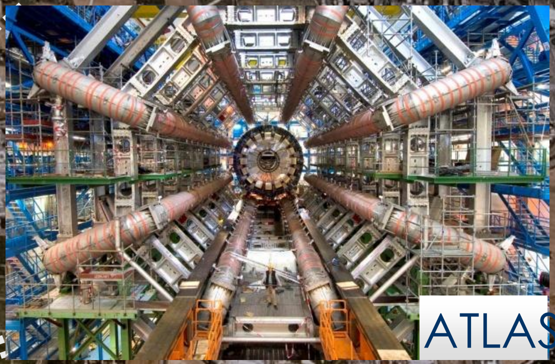
enormous challenge for the detectors
and for data collection/storage/analysis

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.

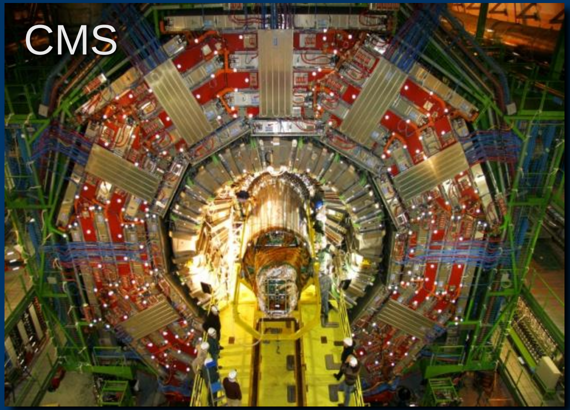


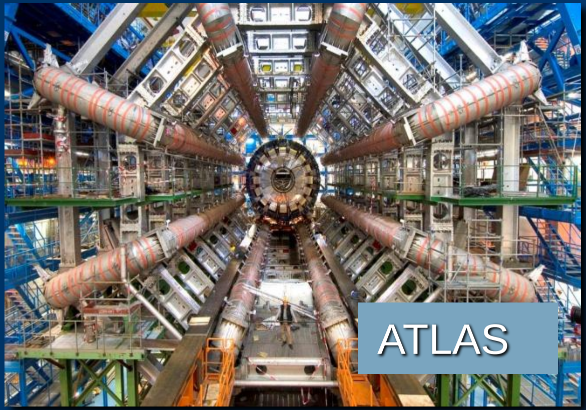
Exploration of a new energy frontier
Proton-proton and Heavy Ion collisions
at E_{CM} up to 14 TeV



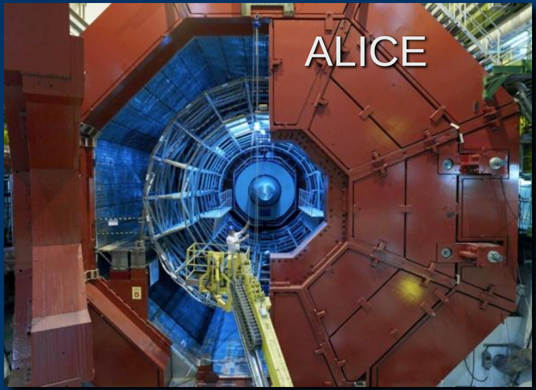
LHC Experiments → complementary

Specialised detector to study b-quarks → CPV





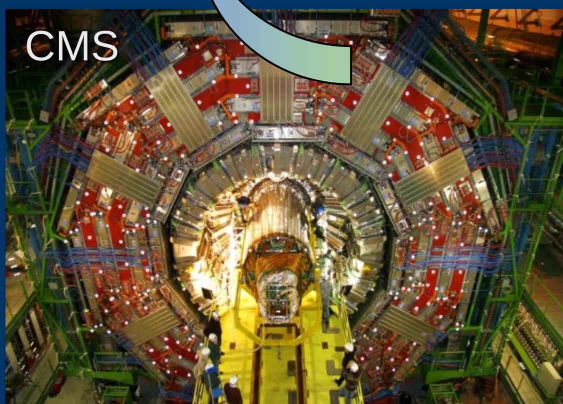
General purpose detectors

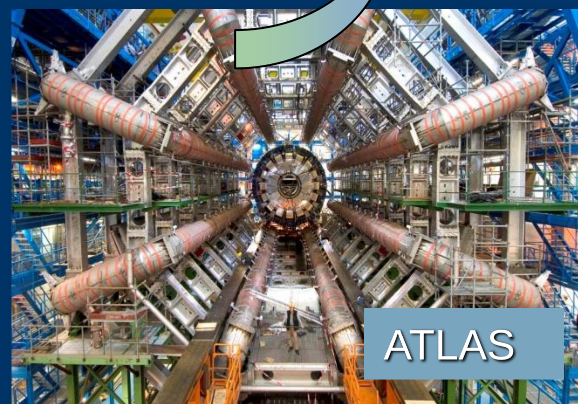


Specialised detector to study heavy ion collisions

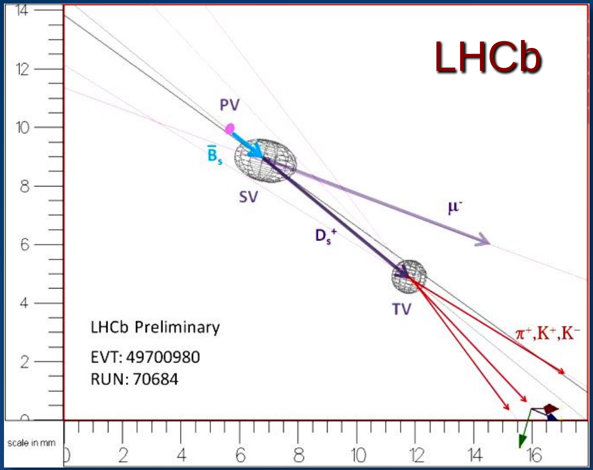
LHC Experiments → complementary

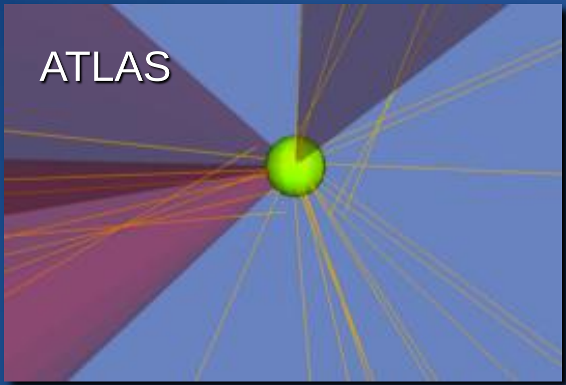
Overlap in physics reach





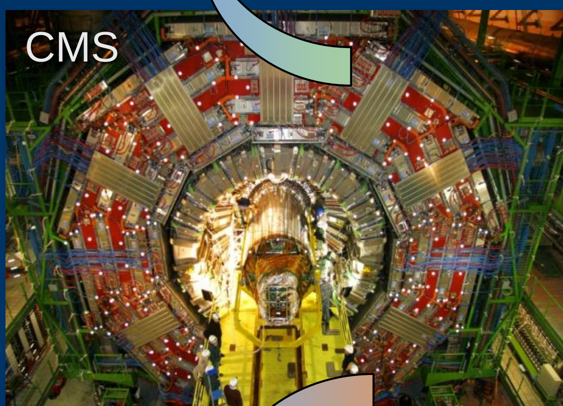
Key feature: reconstruct secondary vertex

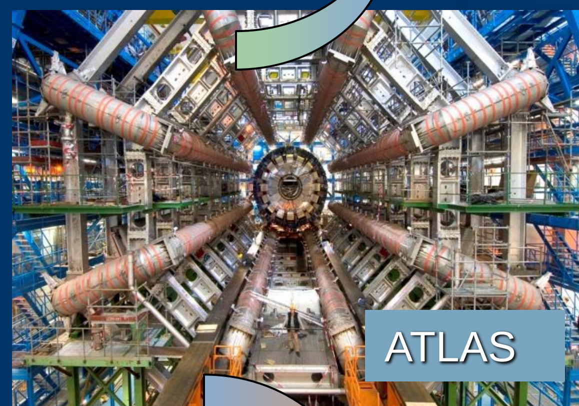


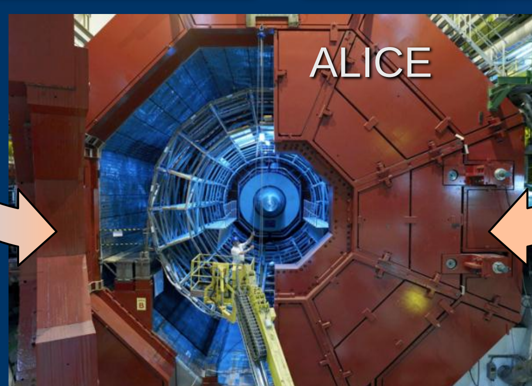


LHC Experiments → complementary

Overlap in physics reach

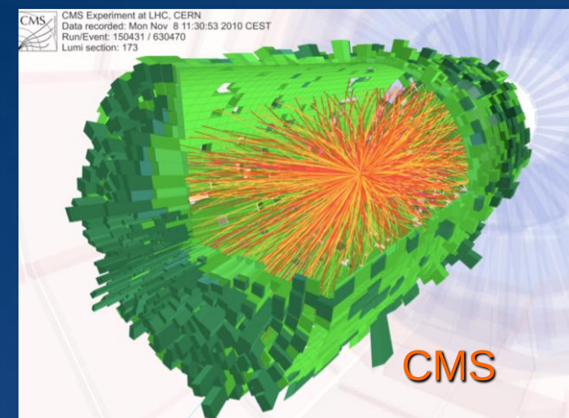


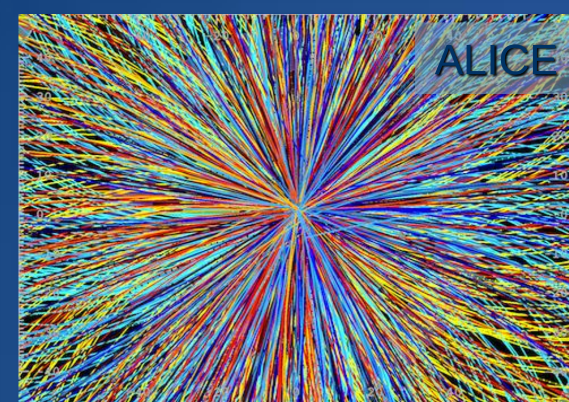




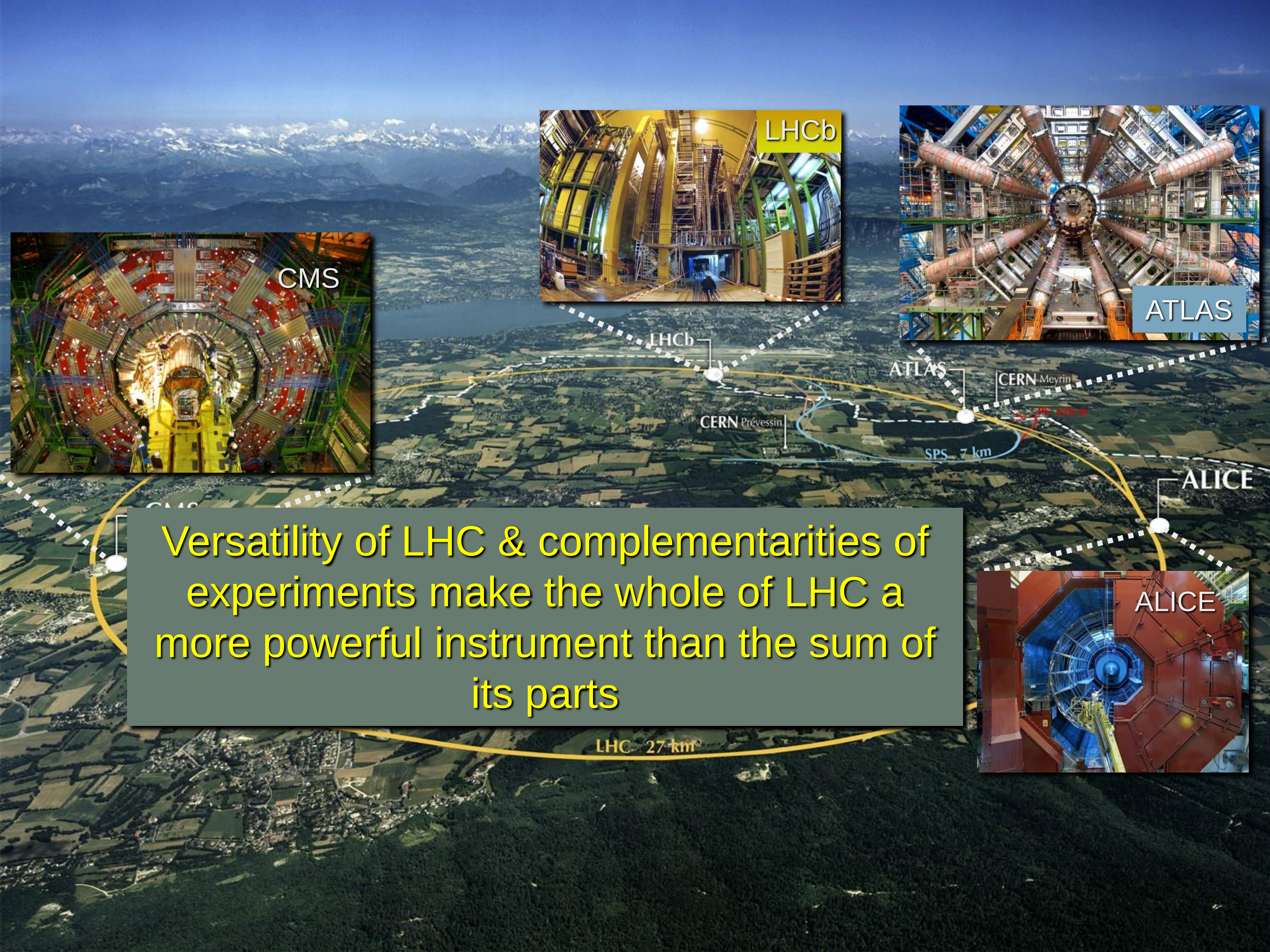
Overlap in physics reach

Key feature: reconstruct > 20’000 charged tracks in one event

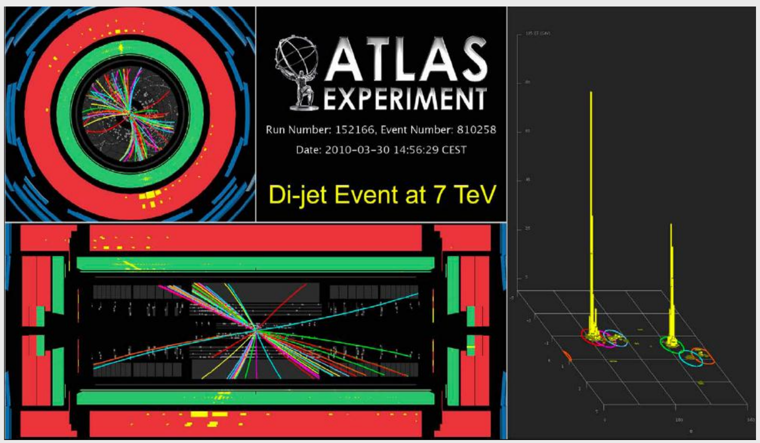


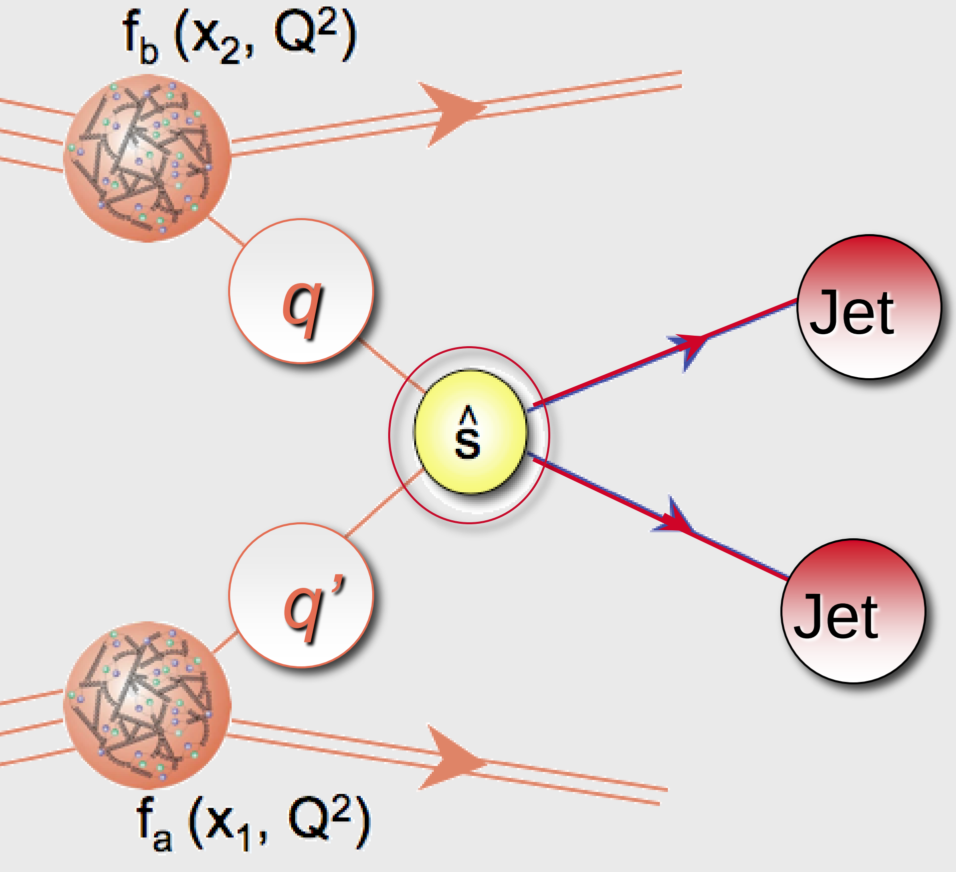


Versatility of LHC & complementarities of experiments make the whole of LHC a more powerful instrument than the sum of its parts

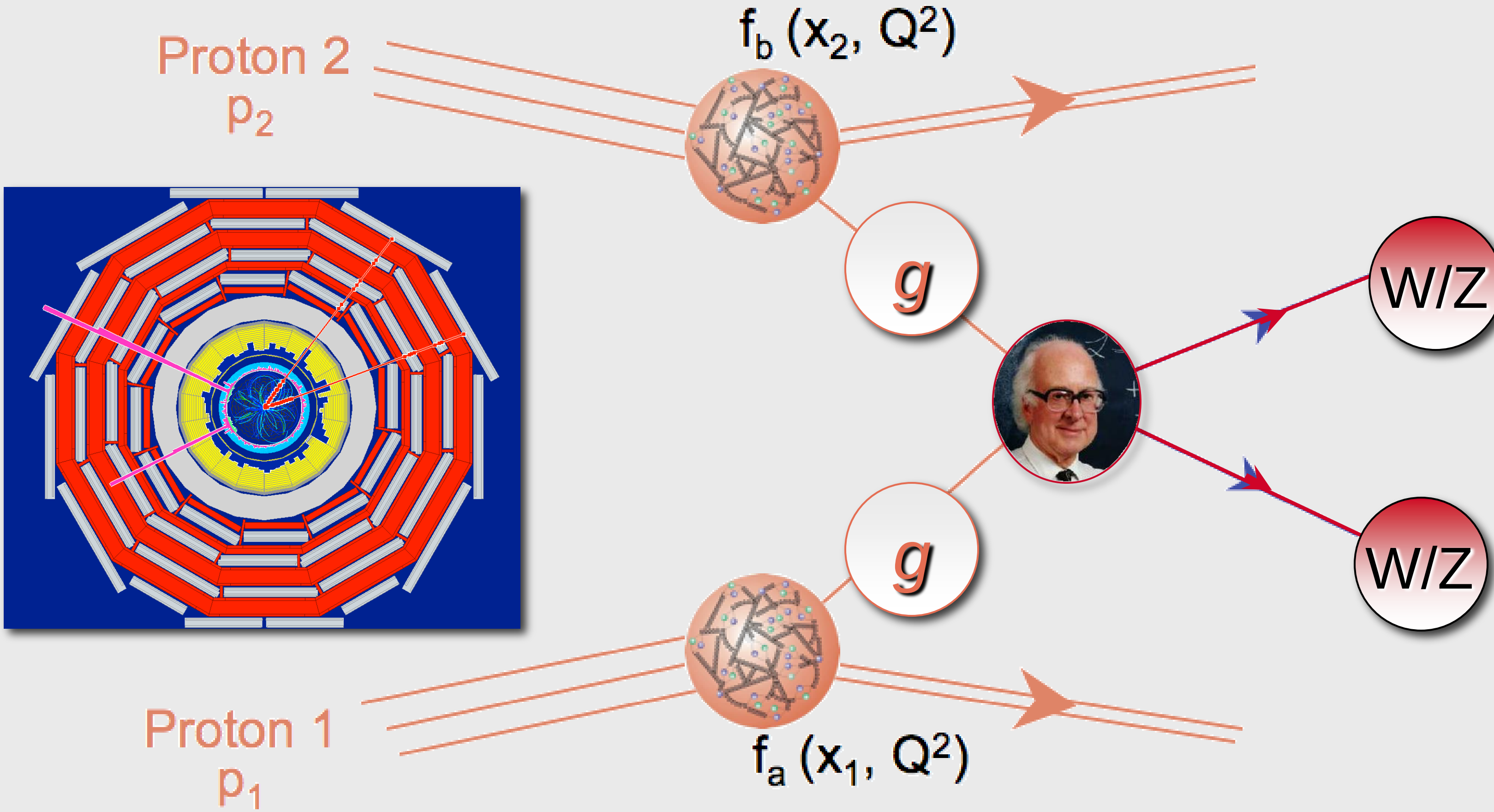


Basic processes at LHC

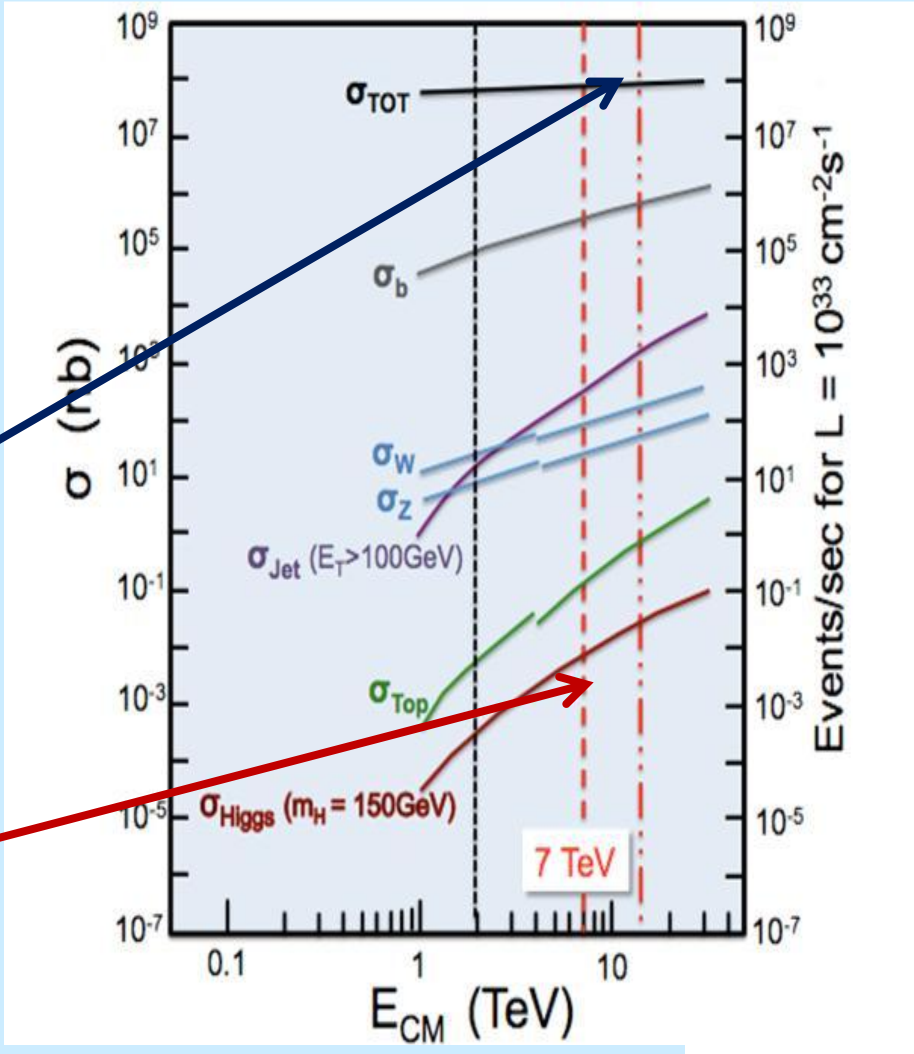




Basic processes at LHC



Cross Section („Production Rate“) of Various Processes



More than 10 orders of magnitude difference between

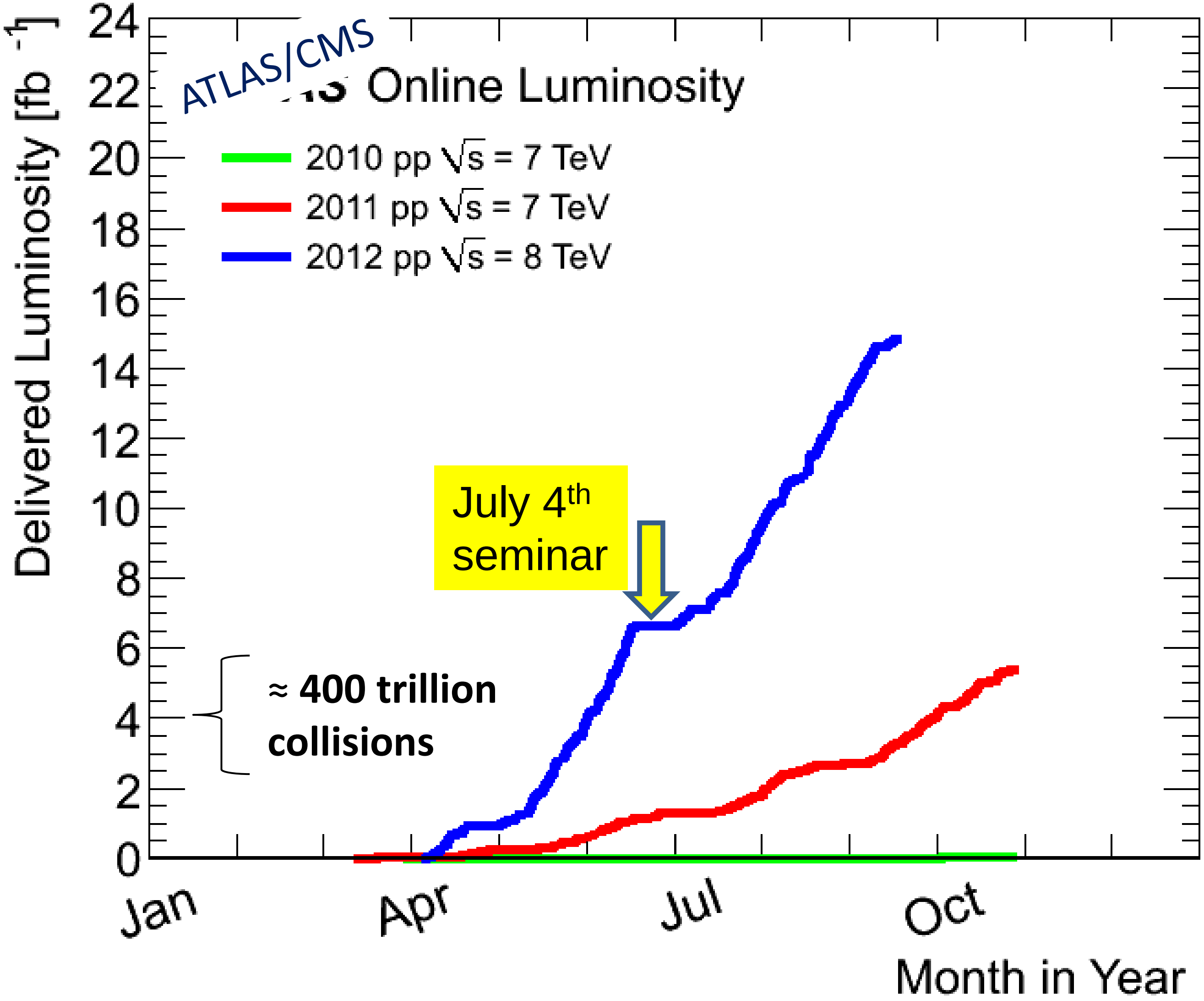
total reaction rate

and

rate of new physics

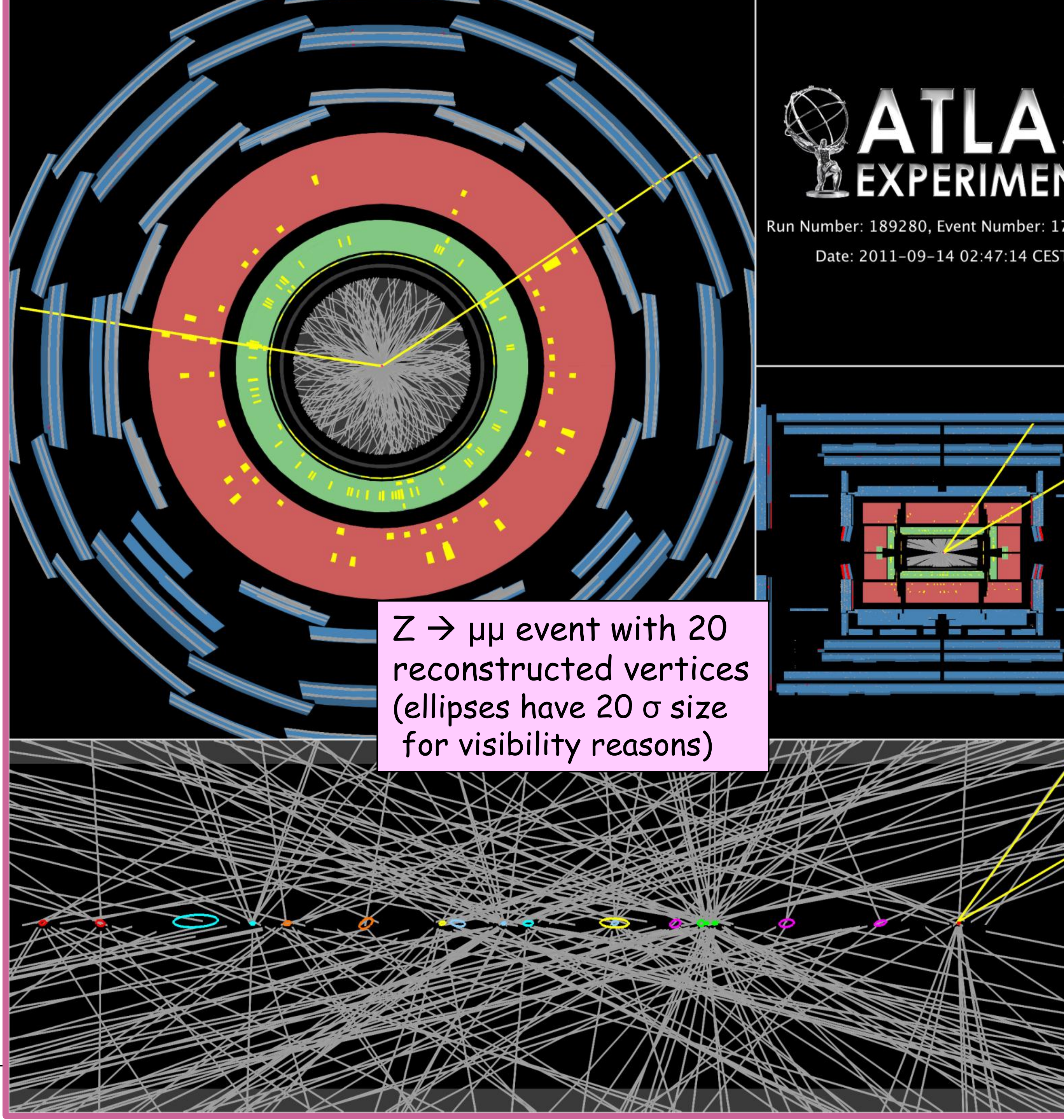
select 1 out of much more than 10 billion . . .

Evolution of Integrated Luminosity (September 13)



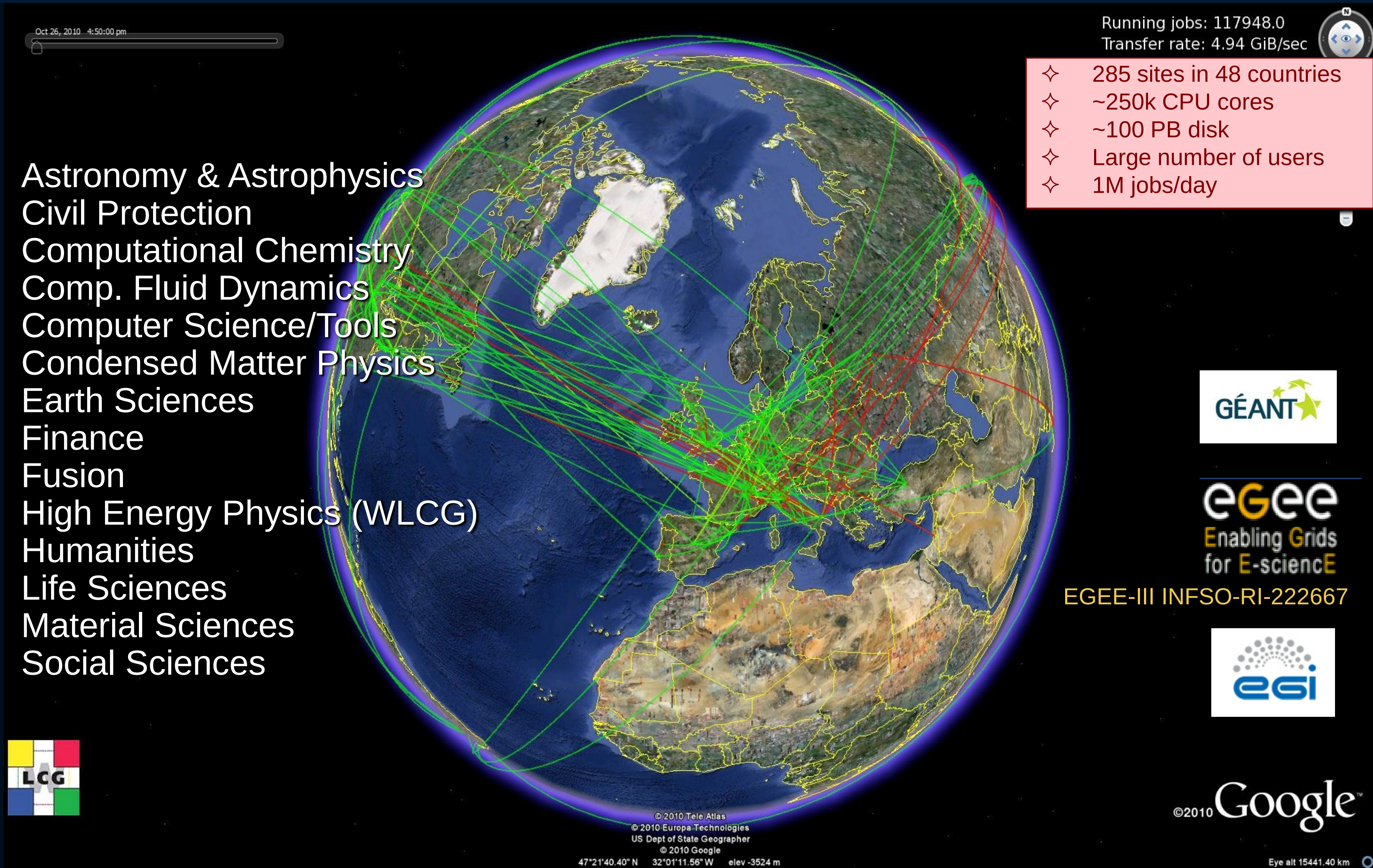
Pile-up

Experiments record data of **high quality** with **high efficiency** at luminosities not expected at such an early stage



Z → μμ event with 20 reconstructed vertices (ellipses have 20 σ size for visibility reasons)

Grid Computing and CERN



- 285 sites in 48 countries
- ~250k CPU cores
- ~100 PB disk
- Large number of users
- 1M jobs/day

Astronomy & Astrophysics
Civil Protection
Computational Chemistry
Comp. Fluid Dynamics
Computer Science/Tools
Condensed Matter Physics
Earth Sciences
Finance
Fusion
High Energy Physics (WLCG)
Humanities
Life Sciences
Material Sciences
Social Sciences

GÉANT

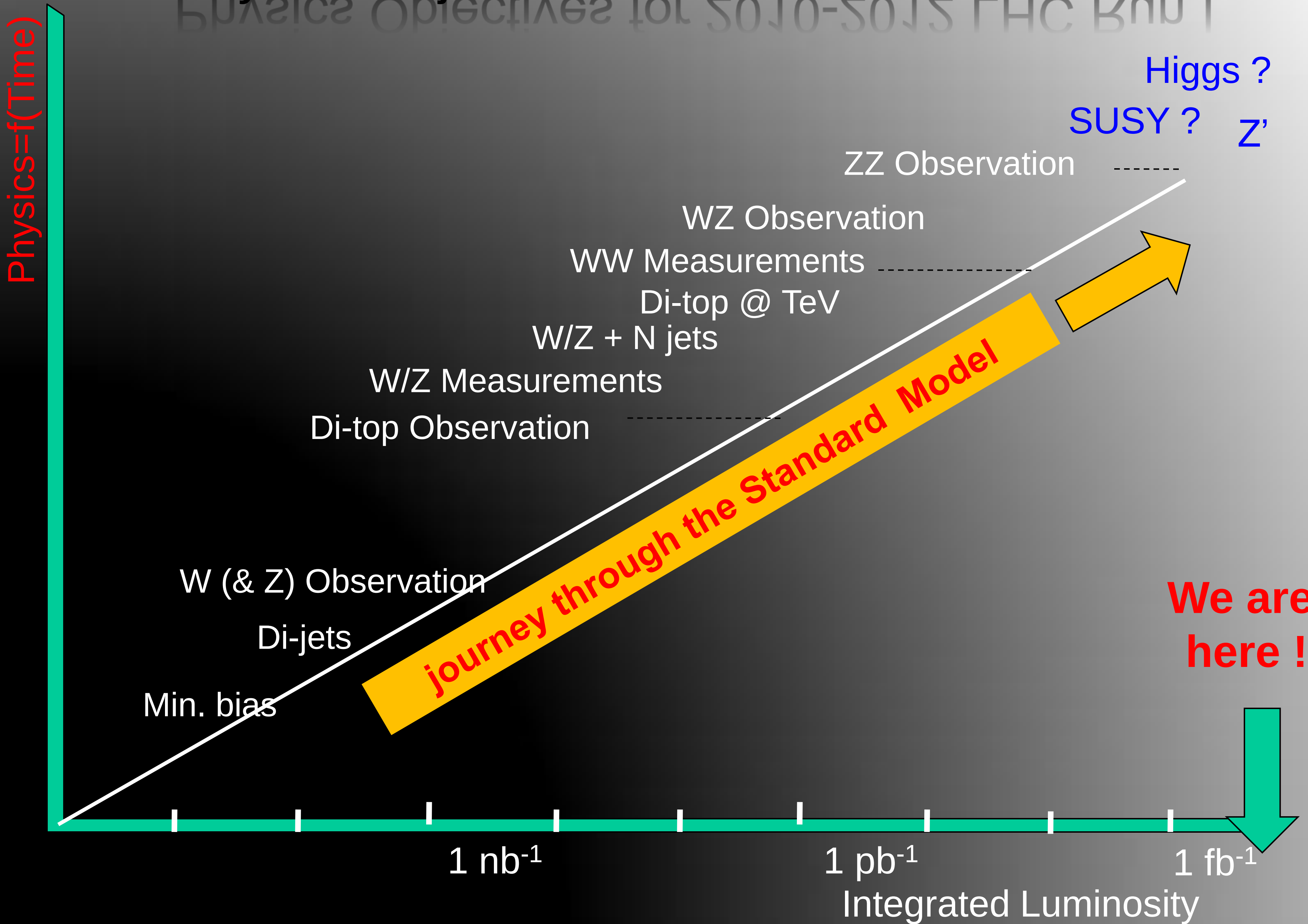
EGEE Enabling Grids for E-sciencE

EGEE-III INFSO-RI-222667

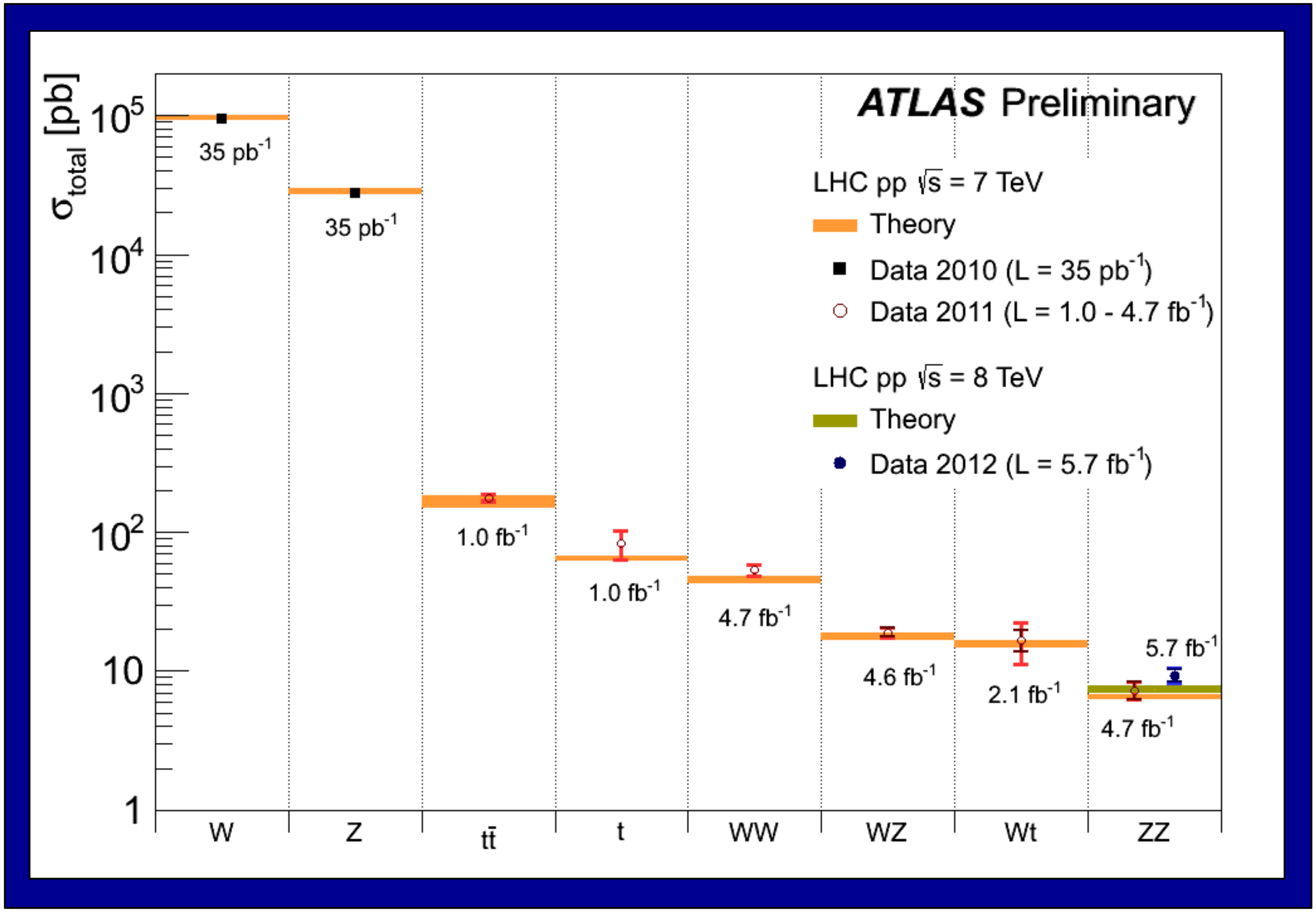
EGI

LCG

Physics Objectives for 2010-2012 LHC Run I



Most recent electroweak and top cross-section measurements

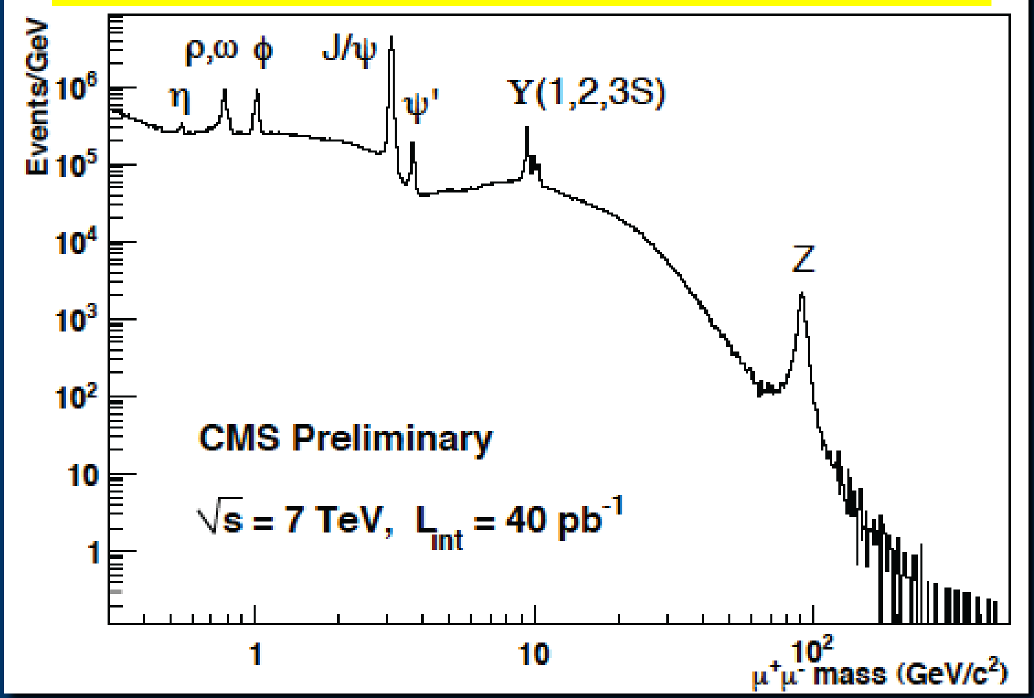


Inner error: statistical
Outer error: total

- Important on their own and as foundation for Higgs searches
- Most of these processes are reducible or irreducible backgrounds to Higgs
- Reconstruction and measurement of challenging processes (e.g. fully hadronic tt, single top, ..) are good training for some complex Higgs final states

Excellent performance……

re-discovery of the Standard Model



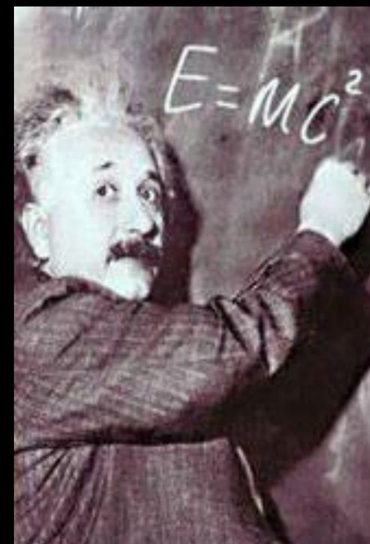
- **Experiments have about completed their journey through the Standard Model …**

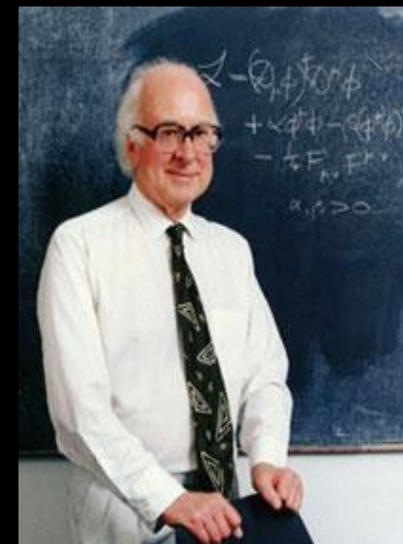
  and have started to take us into new territories …

The New Territory

We are poised to tackle

some of the most profound questions in physics:





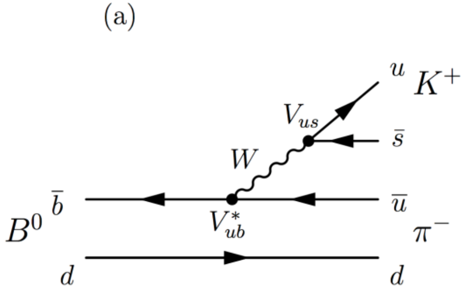
"Newton's" unfinished business… what is mass?

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

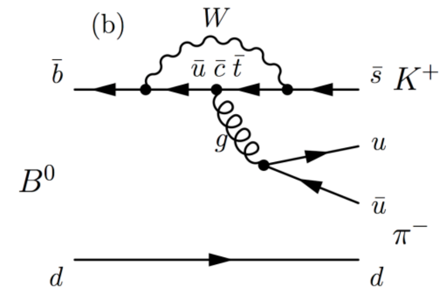
The secrets of the Big Bang… what was matter like within the first moments of the Universe's life?

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

How to study antimatter at LHCb



+



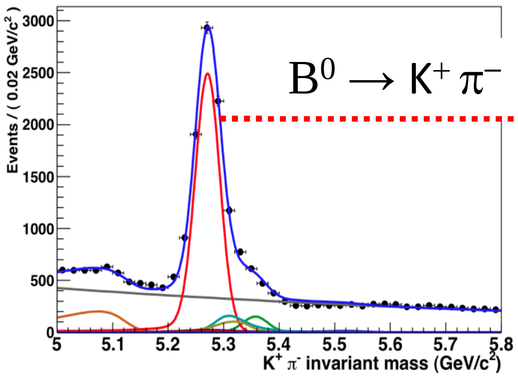
$B^0 \rightarrow K\pi$

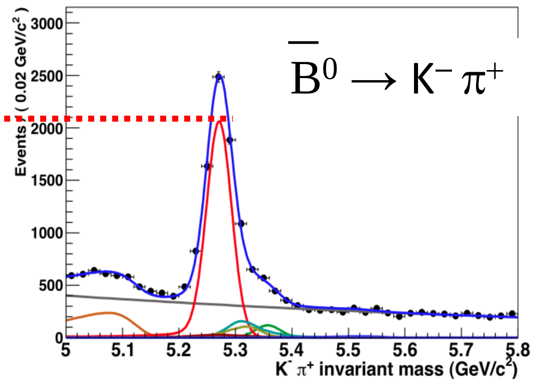
A_{CP} = -0.088 ± 0.011 ± 0.008

Most precise and first **5σ**

Observation of CP violation

in a hadronic machine



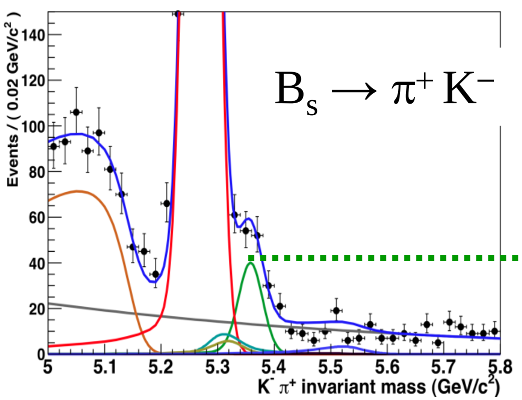


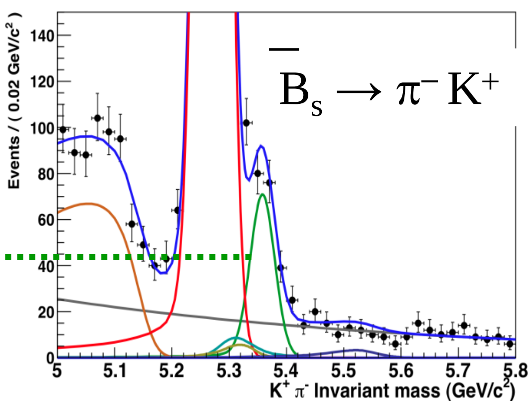
$B_s \rightarrow \pi K$

A_{CP} = 0.27 ± 0.008 ± 0.02

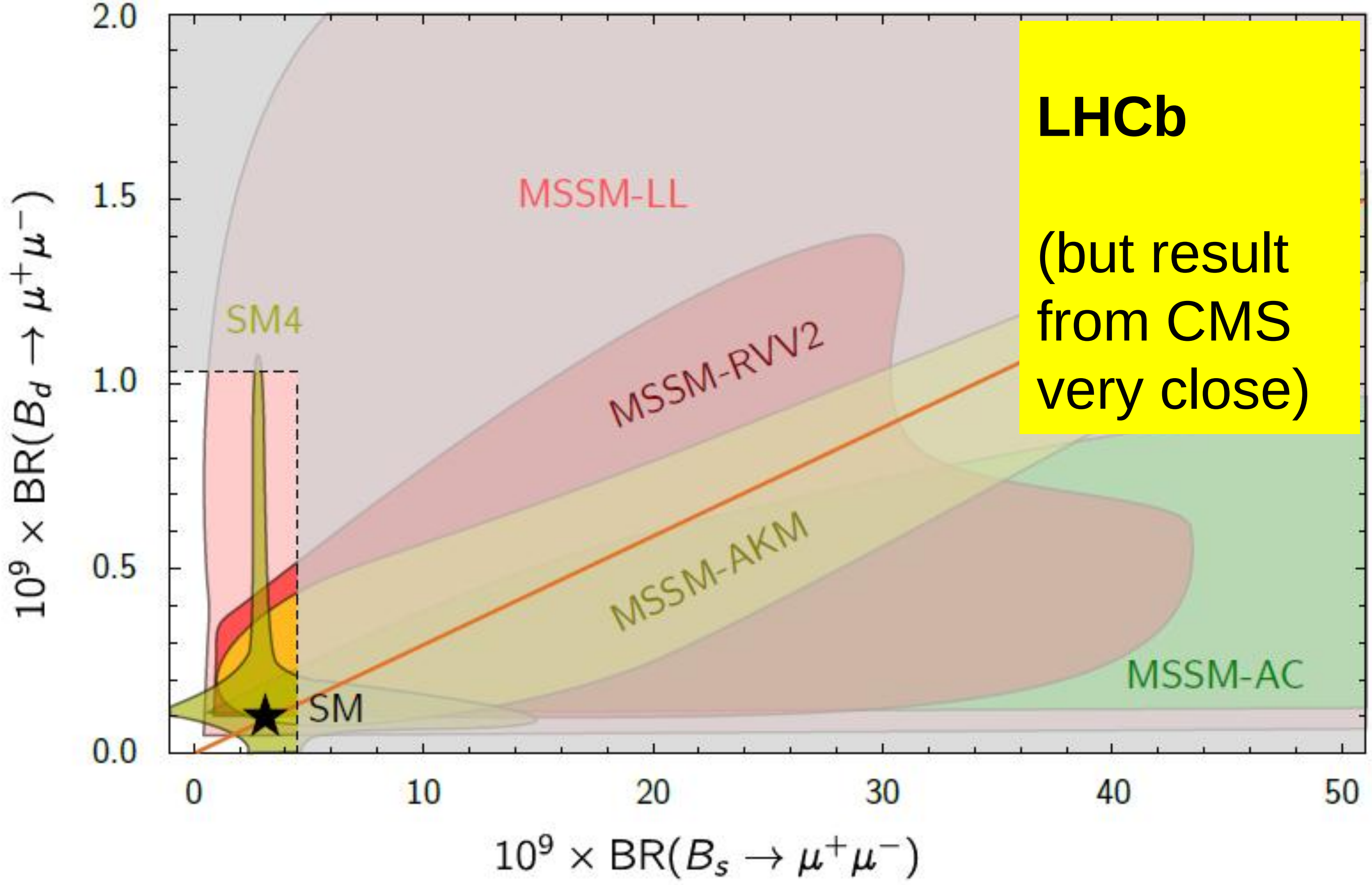
First **3σ** evidence for

CP asymmetry in Bs decays





$B_s \rightarrow \mu^+ \mu^-$: very sensitive to "New Physics"



LHCb

(but result from CMS very close)

New experimental bounds already exclude large part of constrained SUSY model parameter space

The “beauty” of charm

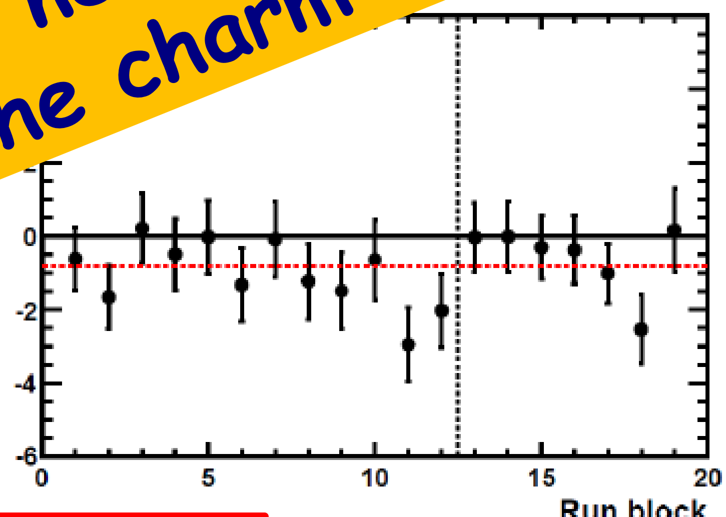
- LHCb can profit of the huge charm production cross section at the LHC (~6mb): LHC is a charm-factory !

- First Evidence of CP viol. in charm decays in the measurement of D→hh asymmetry

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) \ldots \to f)}{\ldots \to f)}$$

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+ \ldots$$

- Theoretical c... compatibi... ch... with... Mode...
- Ext... ...ng from “conve... ...ysics unlikely, but still poss...



Present status: excellent agreement with the Standard Model !
But: First evidence for new effects (beyond SM) seen in the charm sector

CDF confirms this result: (- 0.62 ± 0.21 ± 0.10) %

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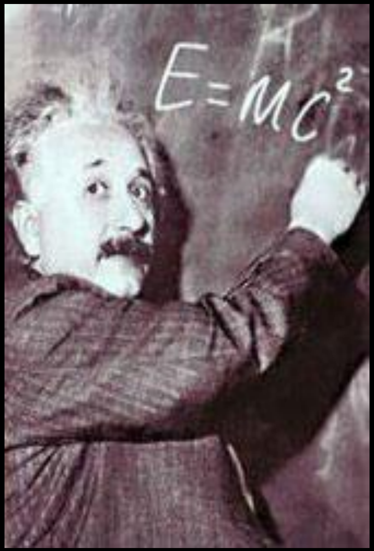

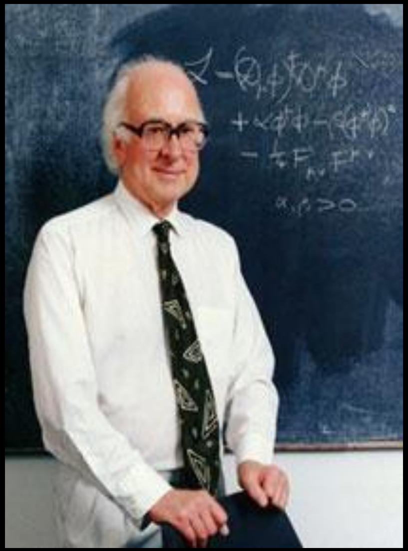

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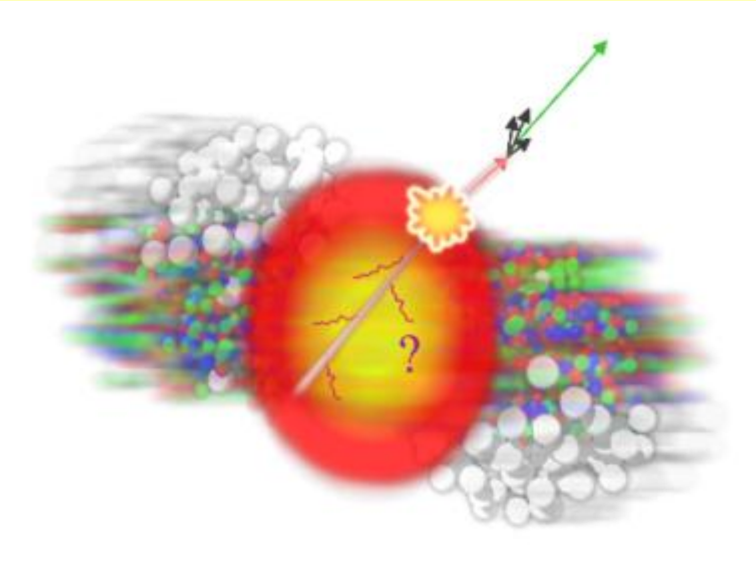
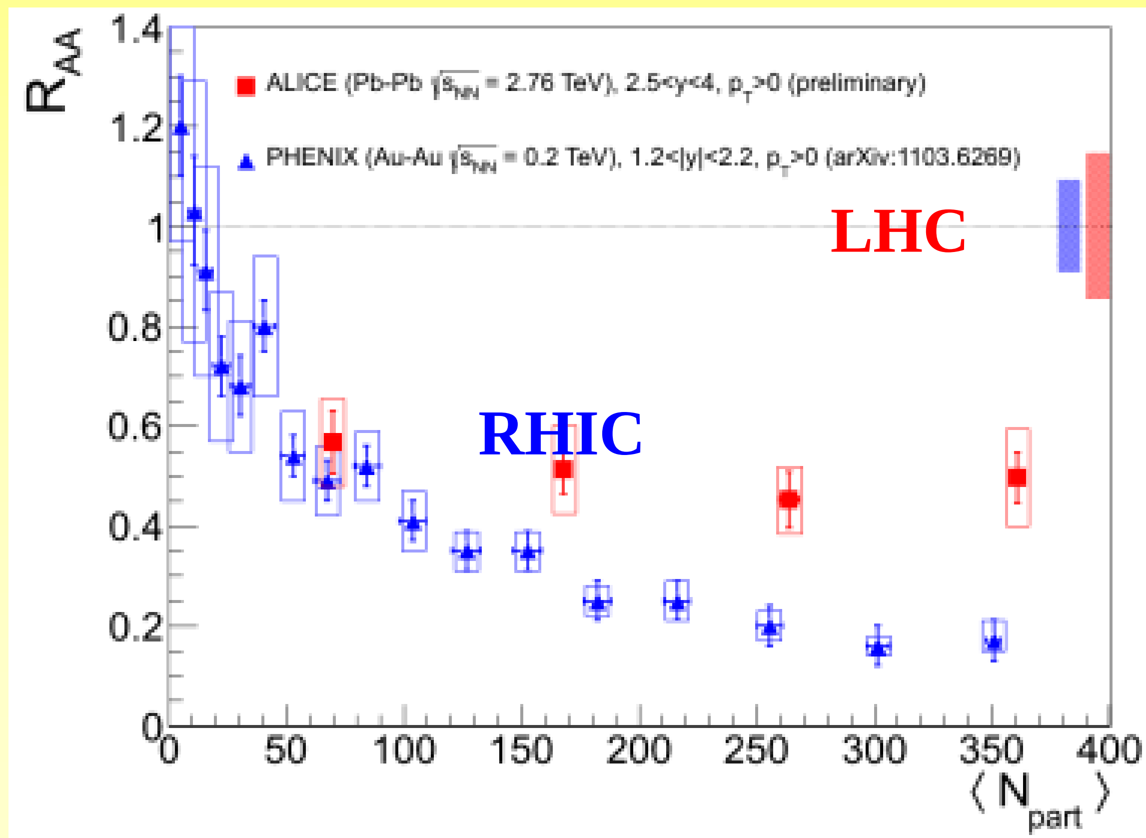


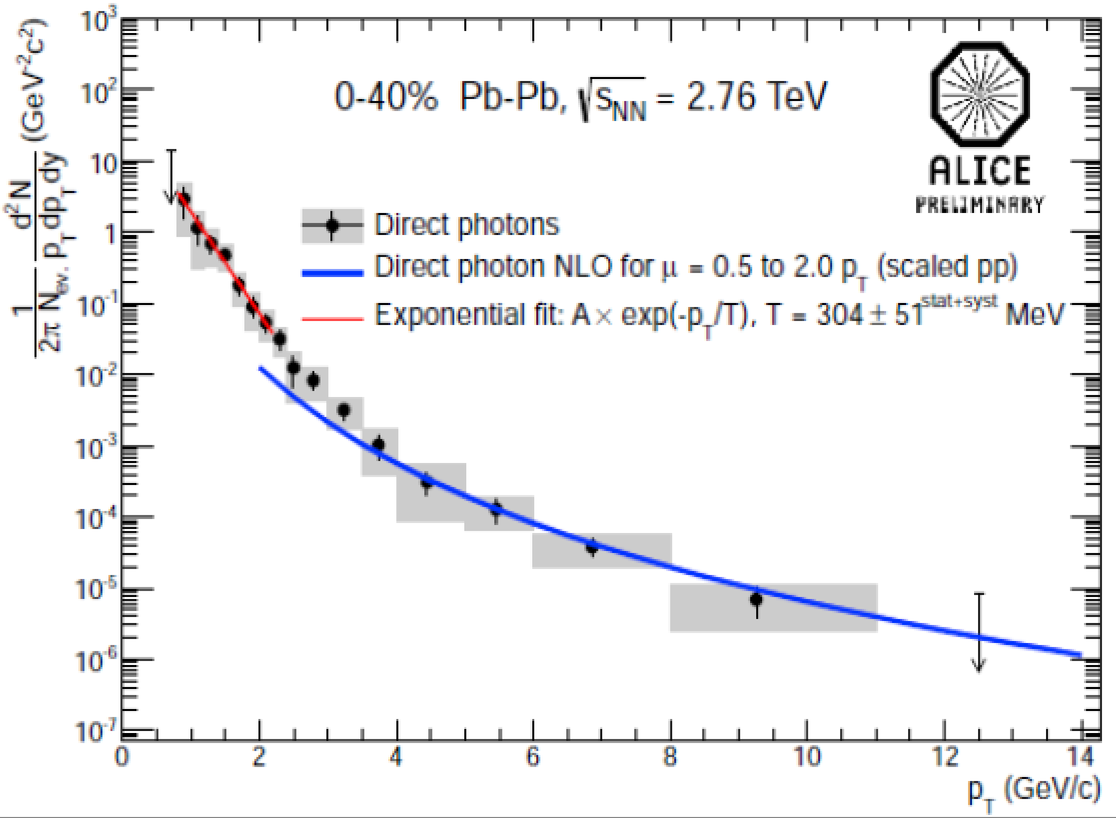
Selected PbPb results: R_{AA}

Interaction of Quarkonia with QGP

J/Ψ less supressed in then denser QGP ! Recombination ?



Low p_T direct photons → a direct thermometer for the temperature of the fireball



Integrated over fireball history: T = 304 MeV
initial temperature > 450 MeV
highest temperature ever measured in the laboratory

around 3.5×10^{12} K

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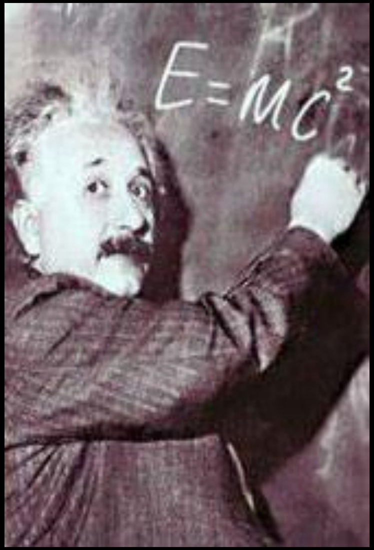

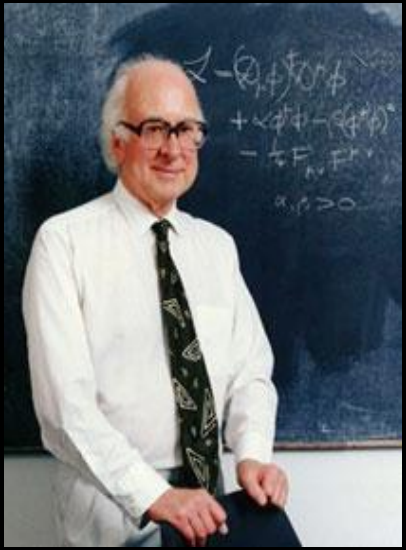

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Dark Matter

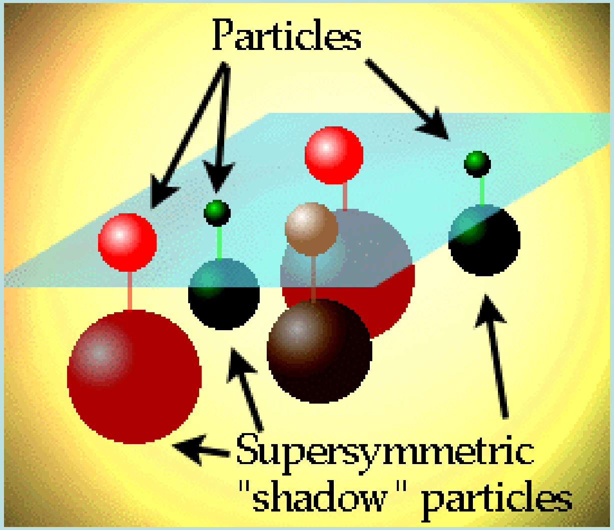
Astronomers & astrophysicists over the next two decades using powerful new telescopes will tell us how dark matter has shaped the stars and galaxies we see in the night sky.

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.

Supersymmetry



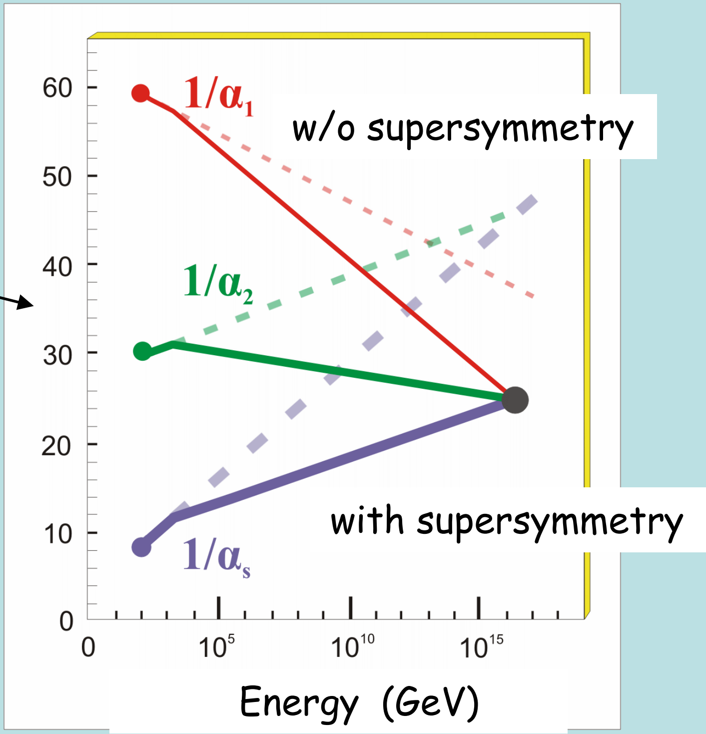
- unifies matter with forces

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

- allows to unify strong and electroweak forces

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

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

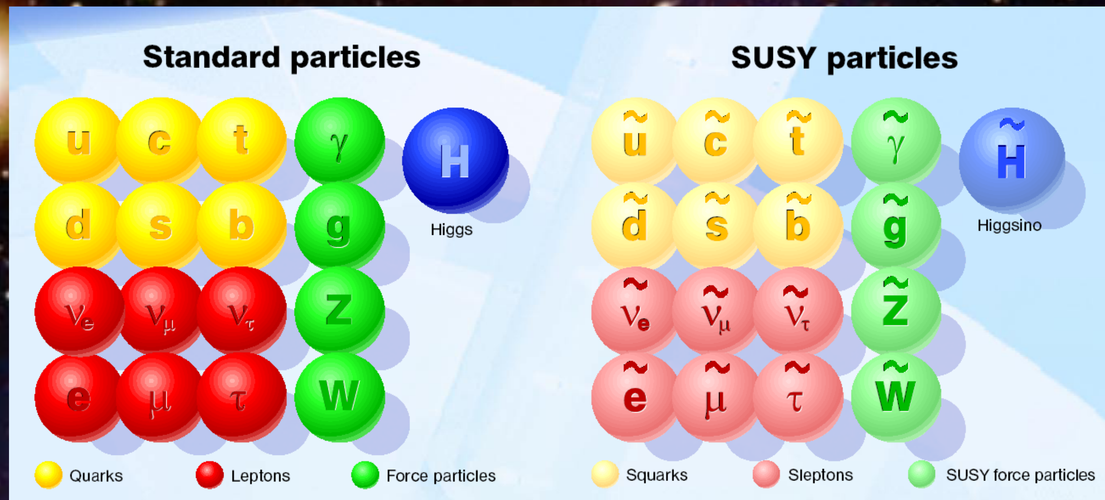


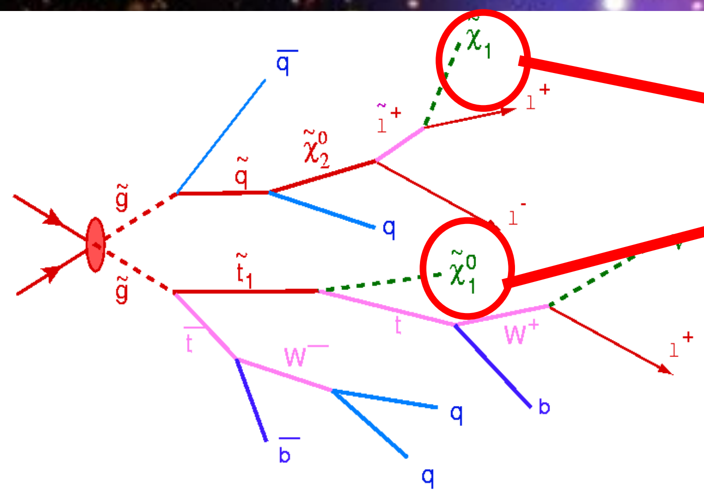
- provides link to string theories

- provides Dark Matter candidate

  (stable Lightest Supersymmetric Particle)

Supersymmetry: A New Symmetry in Nature

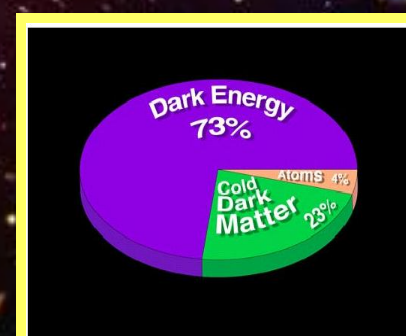




3 isolated leptons
+ 2 b-jets
+ 4 jets
+ E_t^{miss}

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

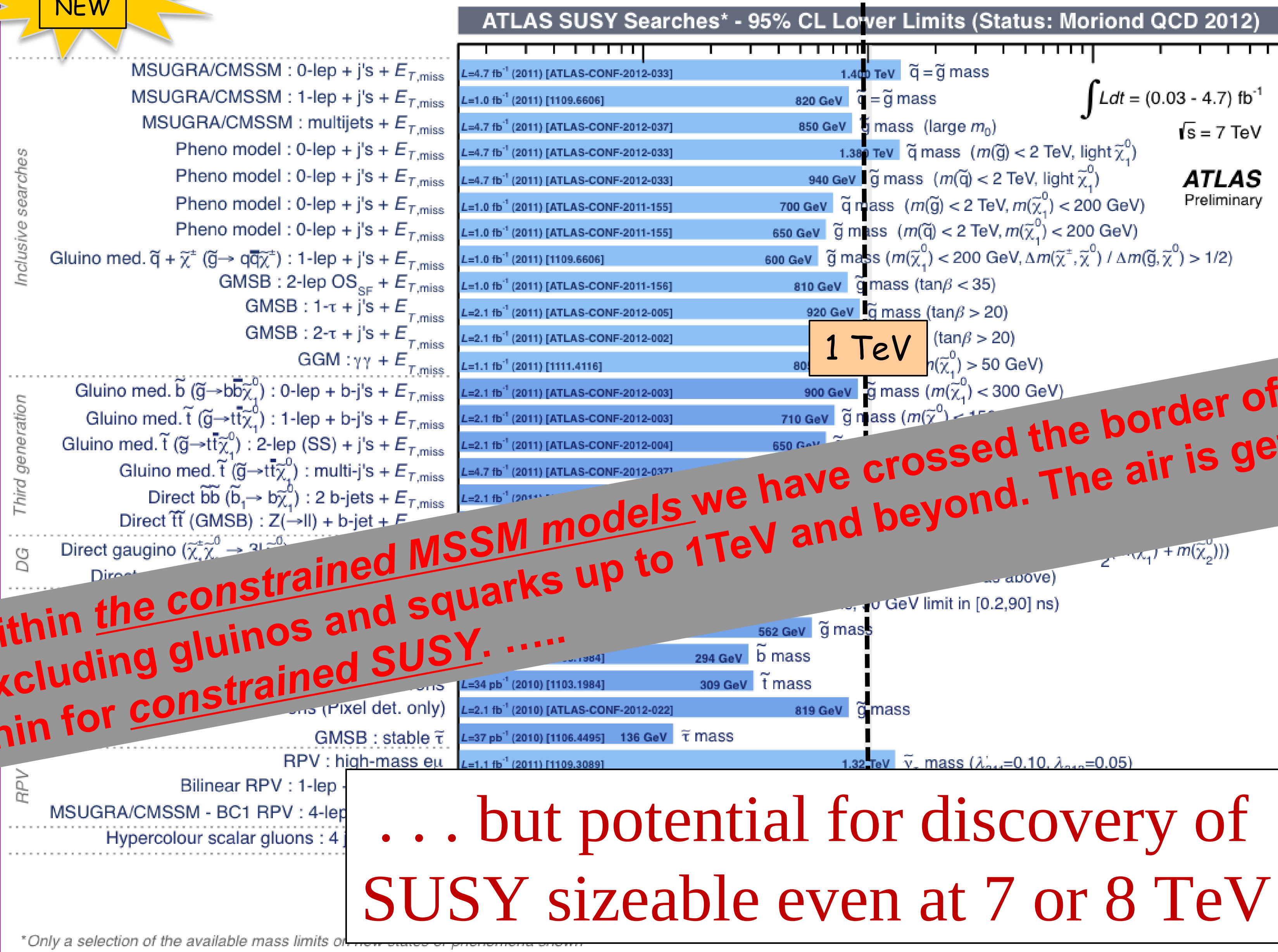
SUSY particle production at the LH



n Marusa Bradac

Main ATLAS results on SUSY searches

NEW



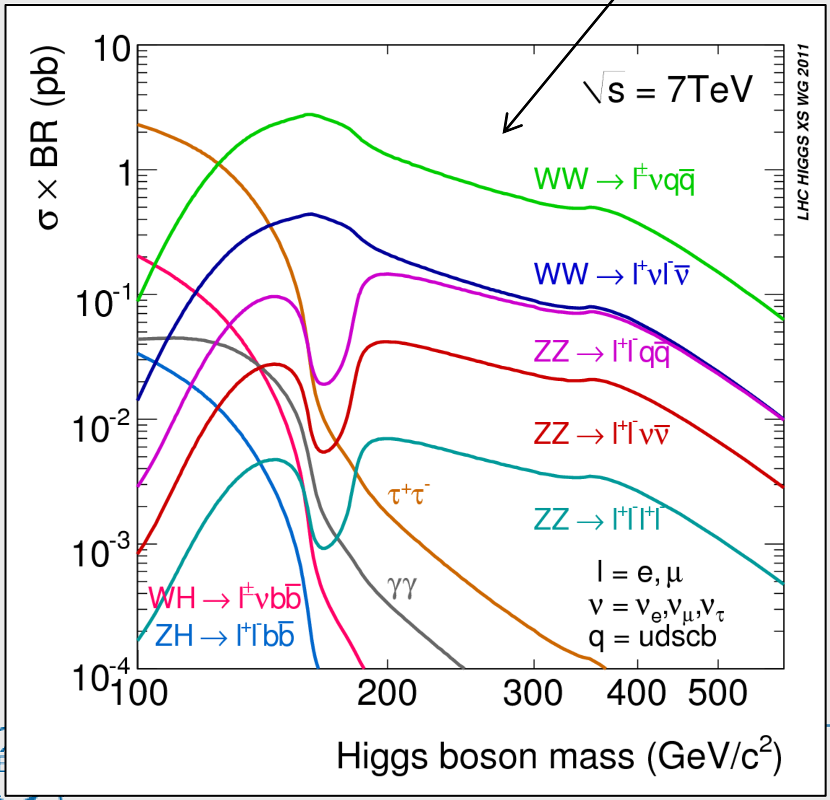
Within the constrained MSSM models we have crossed the border of excluding gluinos and squarks up to 1TeV and beyond. The air is getting thin for constrained SUSY. …..

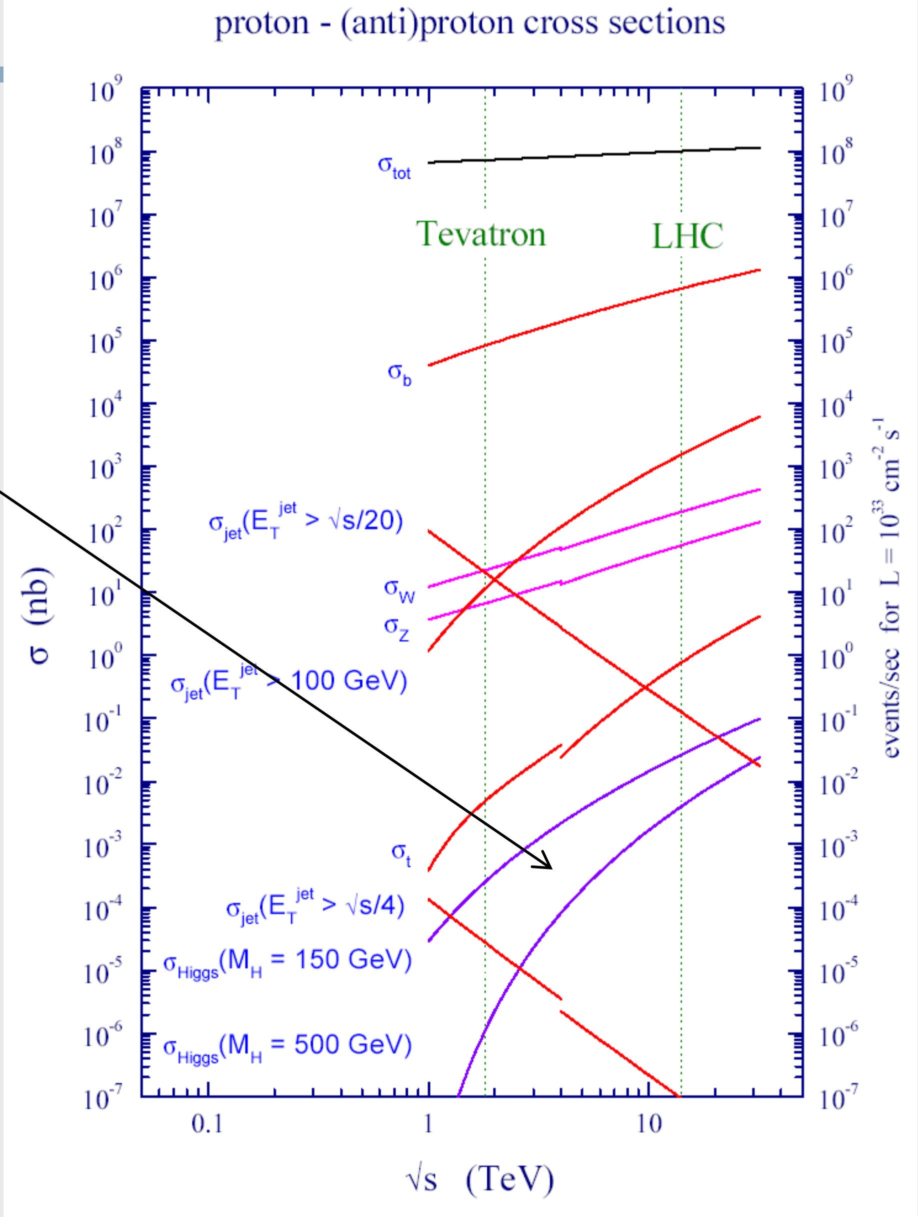
. . . but potential for discovery of SUSY sizeable even at 7 or 8 TeV

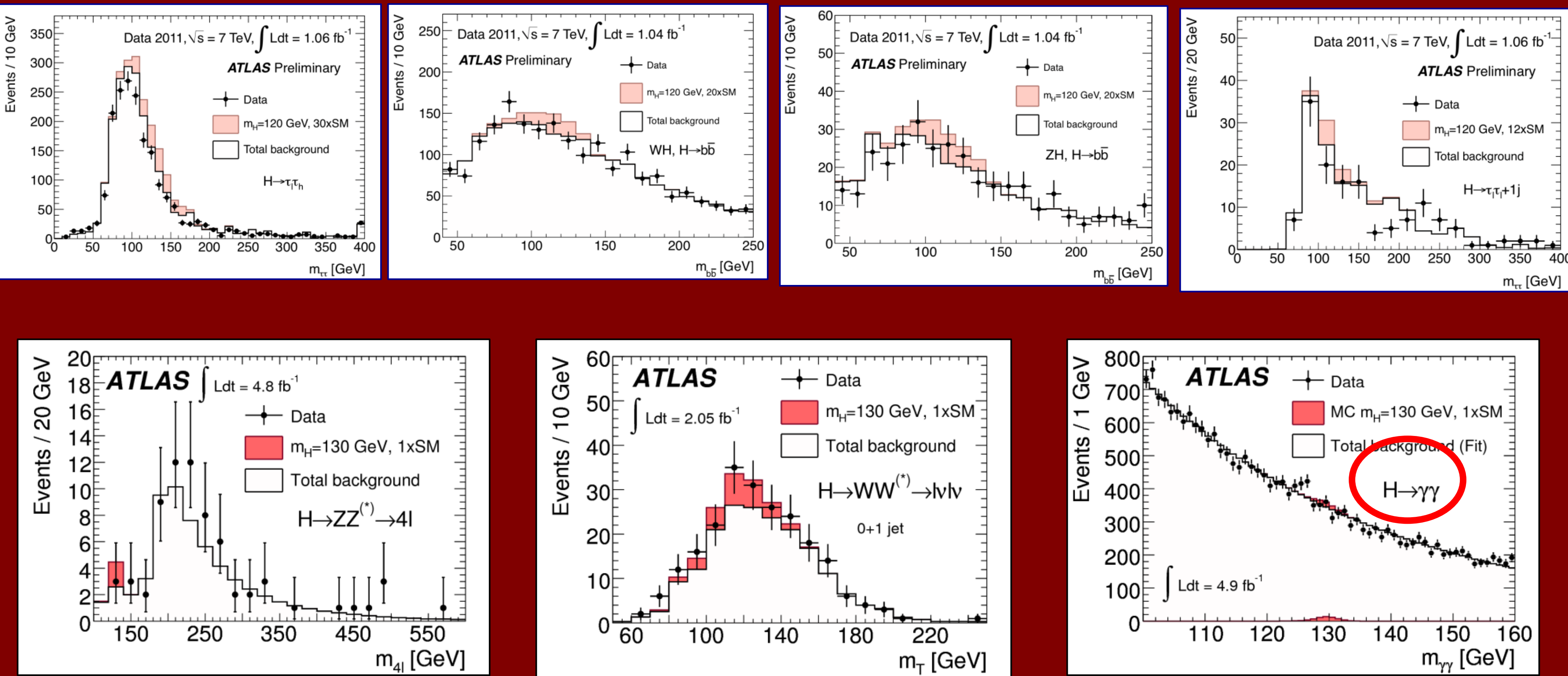
Search for the Higgs-Boson at the LHC

Production rate
of the Higgs-Bosons
depends on its mass

as well as its decay possibilities

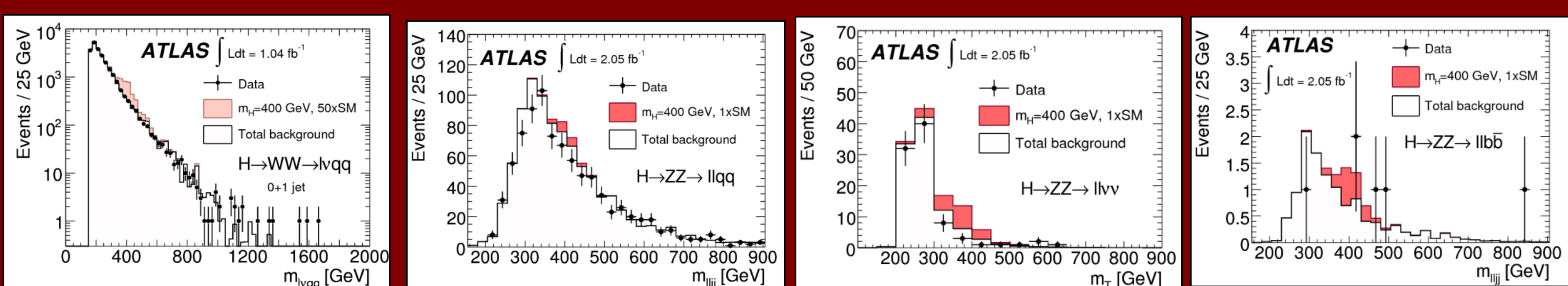






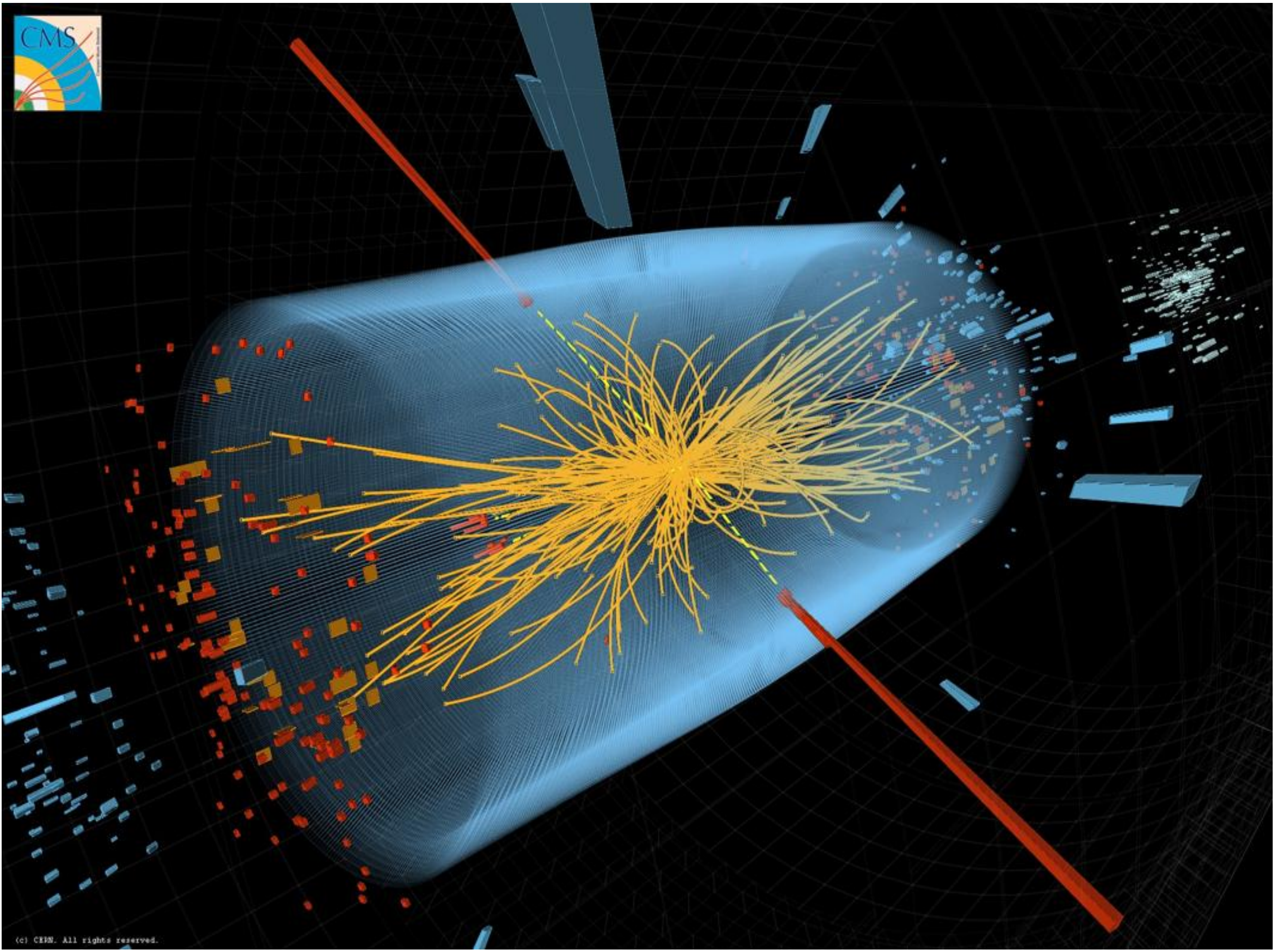
Data 2011, √s = 7 TeV, ∫Ldt = 1.06 fb⁻¹
ATLAS Preliminary
Data
m_H=120 GeV, 30xSM
Total background
H→τ_lτ_h
Events / 10 GeV
m_ττ [GeV]
Data 2011, √s = 7 TeV, ∫Ldt = 1.04 fb⁻¹
ATLAS Preliminary
Data
m_H=120 GeV, 20xSM
Total background
WH, H→bb̄
m_bb̄ [GeV]
Data 2011, √s = 7 TeV, ∫Ldt = 1.04 fb⁻¹
ATLAS Preliminary
Data
m_H=120 GeV, 20xSM
Total background
ZH, H→bb̄
m_bb̄ [GeV]
Data 2011, √s = 7 TeV, ∫Ldt = 1.06 fb⁻¹
ATLAS Preliminary
Data
m_H=120 GeV, 12xSM
Total background
H→τ_lτ_l+1j
Events / 20 GeV
m_ττ [GeV]
ATLAS ∫Ldt = 4.8 fb⁻¹
Data
m_H=130 GeV, 1xSM
Total background
H→ZZ(*)→4l
Events / 20 GeV
m_4l [GeV]
ATLAS
∫Ldt = 2.05 fb⁻¹
Data
m_H=130 GeV, 1xSM
Total background
H→WW(*)→lνlν
0+1 jet
Events / 10 GeV
m_T [GeV]
ATLAS
Data
MC m_H=130 GeV, 1xSM
Total background (Fit)
H→γγ
∫Ldt = 4.9 fb⁻¹
Events / 1 GeV
m_γγ [GeV]

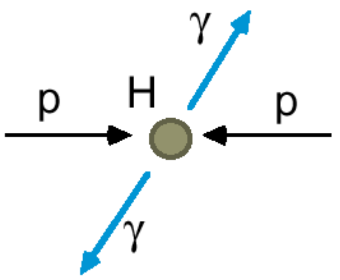
SM Higgs



ATLAS ∫Ldt = 1.04 fb⁻¹
Data
m_H=400 GeV, 50xSM
Total background
H→WW→lνqq
0+1 jet
Events / 25 GeV
m_lνqq [GeV]
ATLAS ∫Ldt = 2.05 fb⁻¹
Data
m_H=400 GeV, 1xSM
Total background
H→ZZ→ llqq
Events / 25 GeV
m_lljj [GeV]
ATLAS ∫Ldt = 2.05 fb⁻¹
Data
m_H=400 GeV, 1xSM
Total background
H→ZZ→ llνν
Events / 50 GeV
m_T [GeV]
ATLAS
∫Ldt = 2.05 fb⁻¹
Data
m_H=400 GeV, 1xSM
Total background
H→ZZ→ llbb̄
Events / 25 GeV
m_lljj [GeV]

A Collision with two Photons

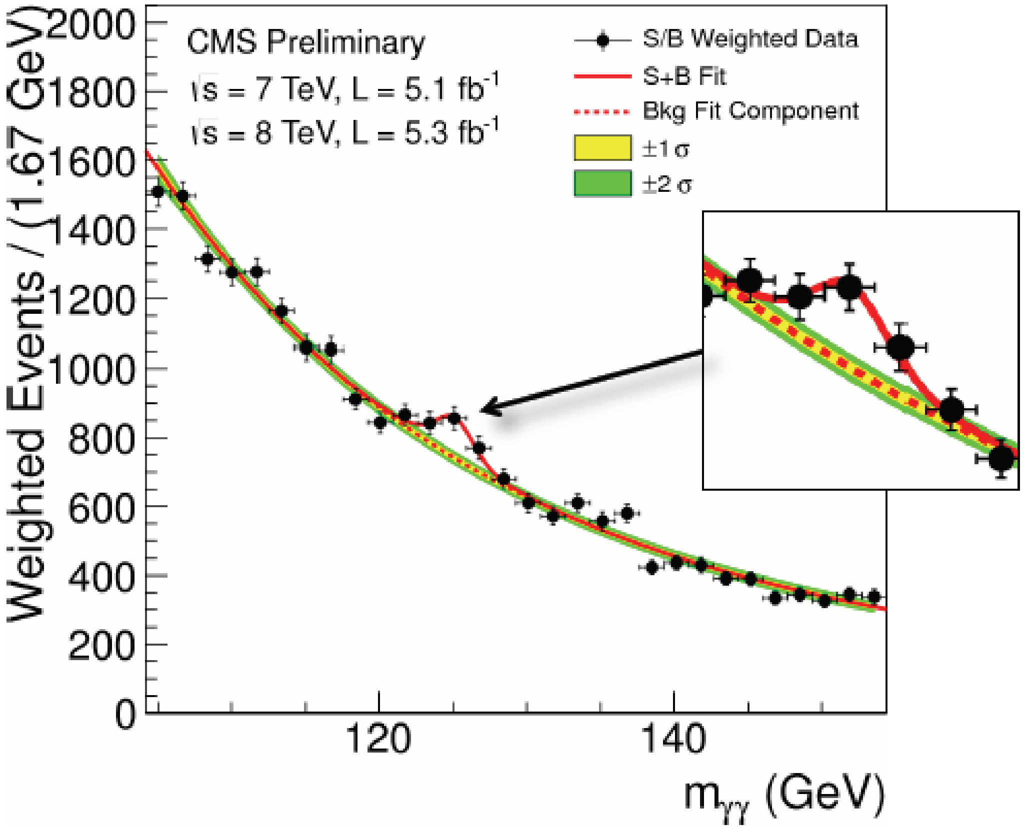




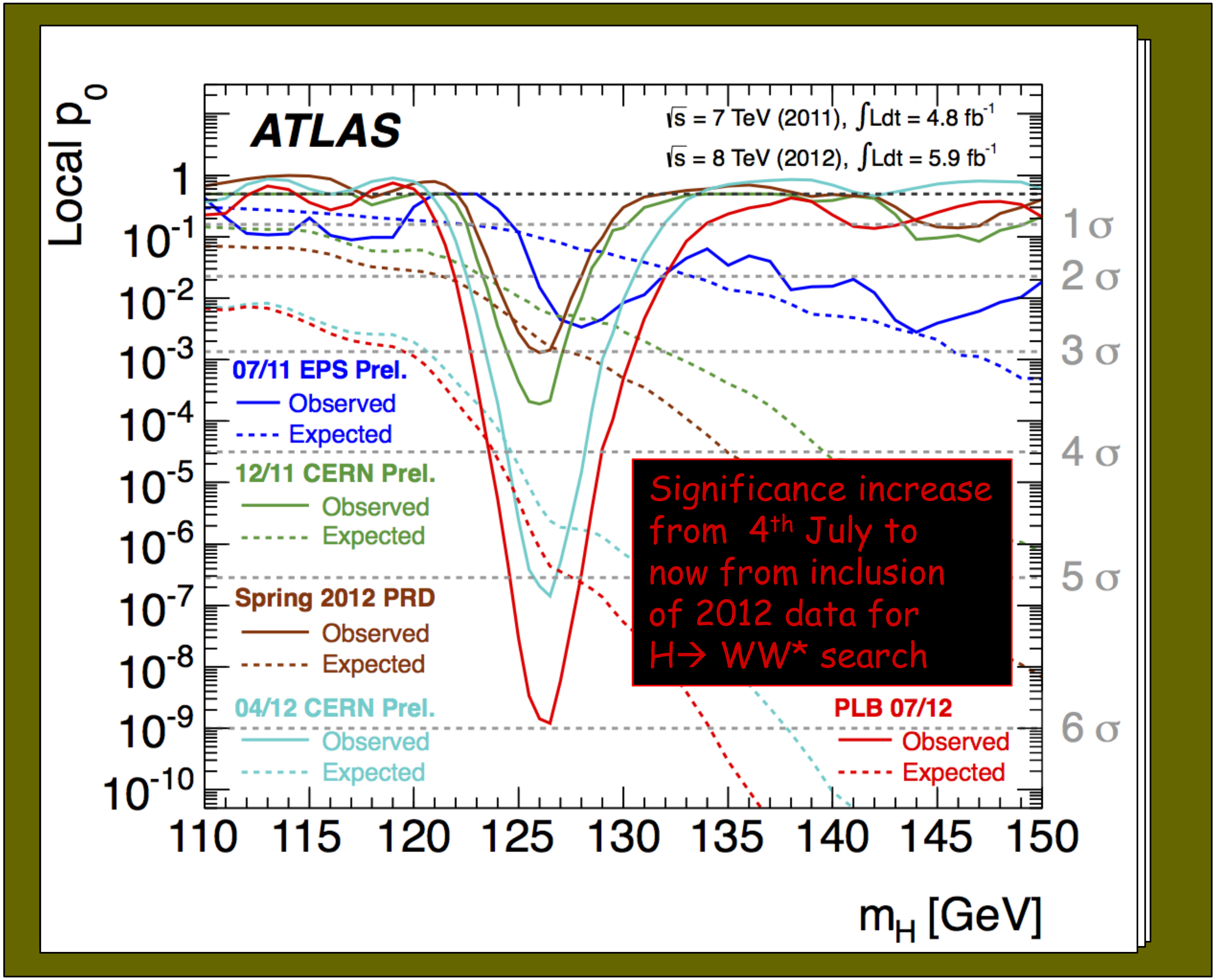
A Higgs or
a ‘background’
process without
a Higgs?

S/B Weighted Mass Distribution

- Sum of mass distributions for each event class, weighted by S/B
  - B is integral of background model over a constant signal fraction interval

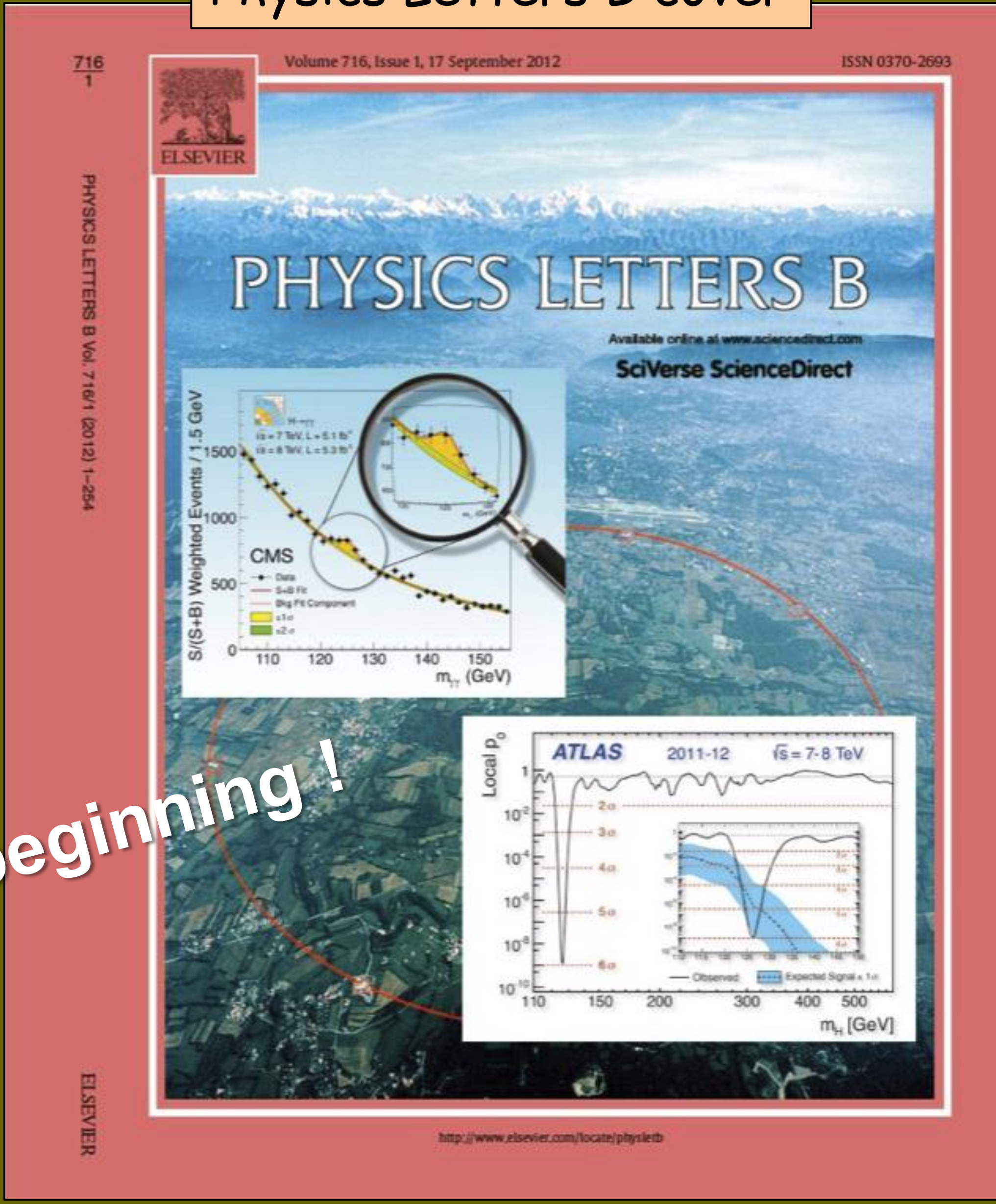


Evolution of the excess with time



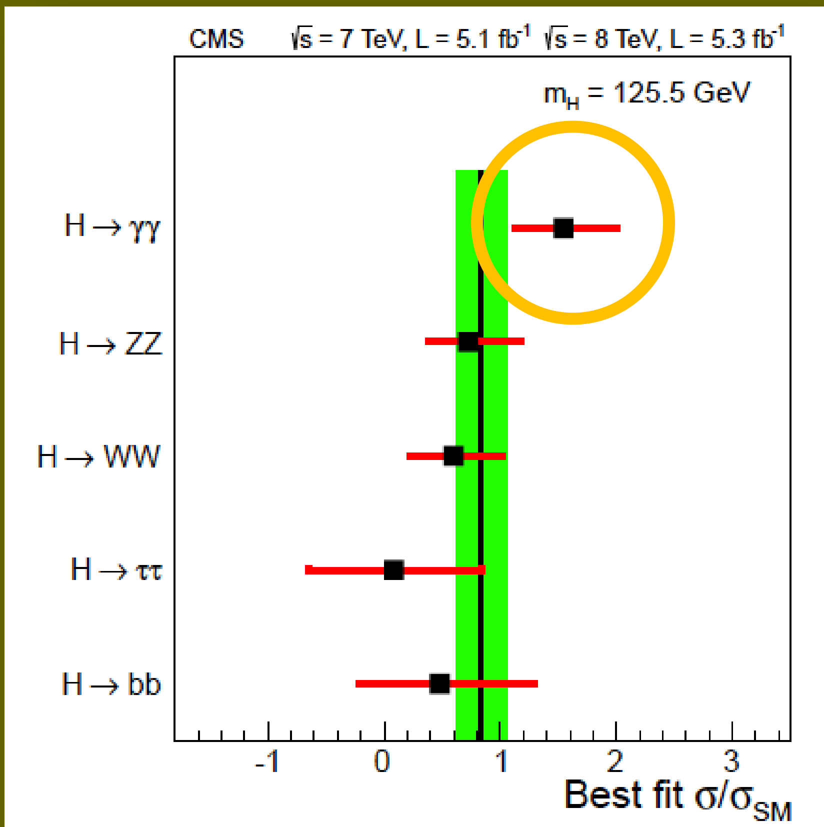
Physics Letters B cover

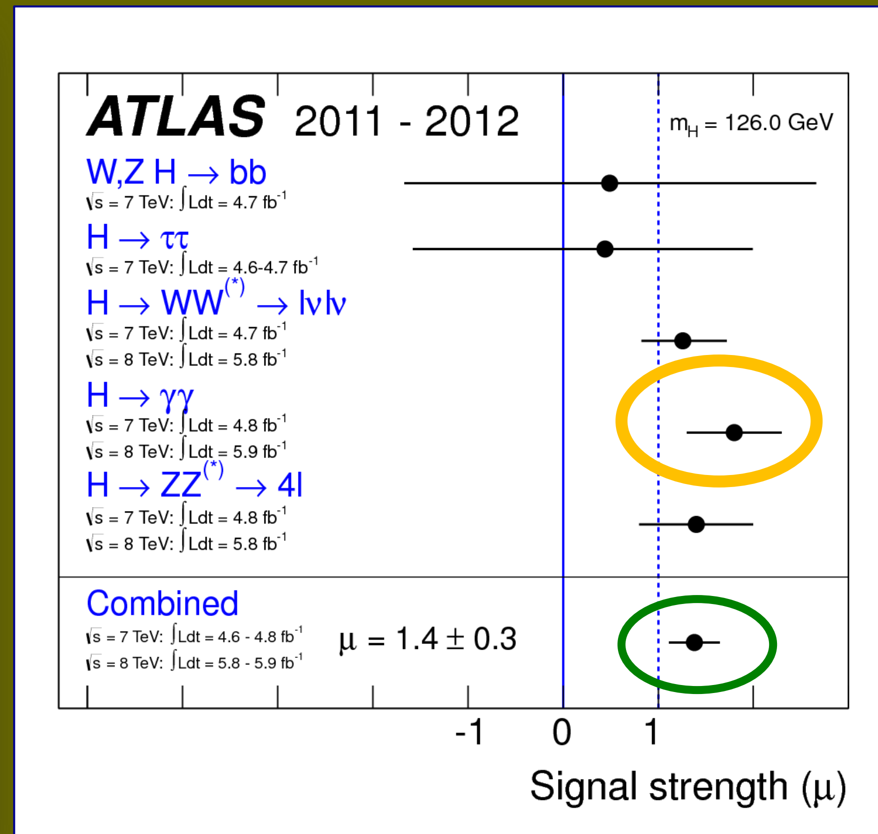
ATLAS and CMS “Higgs discovery” papers published side by side in Phys. Lett. B716 (2012)



… but that’s only the beginning !
What’s next ?

How does it "interact" with all the other particles?





… is it a scalar particle ?

… is it *the* Higgs Boson?
or one of several?

… its properties could give information
on Dark Matter

… its properties could give first hints
on Dark Energy

our understanding of the Universe
is about to change

Road beyond Standard Model

- *At the energy frontier:*

through synergy of

hadron - had… …ders

… - hadron colliders

lepton - lepton colliders

LHC results will guide the way at the energy frontier

Key message

There is a program at the energy frontier with the LHC for at least 20 years:

8 TeV

14 TeV design luminosity

14 TeV high luminosity (HL-LHC)


beyond LHC ?

Choices at the energy frontier

High Energy Hadron Collider (HE – LHC)

(≈ 33 TeV in the LHC tunnel, or larger tunnel?)

Lepton - Hadron Collider (LHeC)

Lepton Collider (ILC/CLIC)

Linear e^+e^- Colliders: ILC / CLIC

Both projects are global endeavours, now under one umbrella

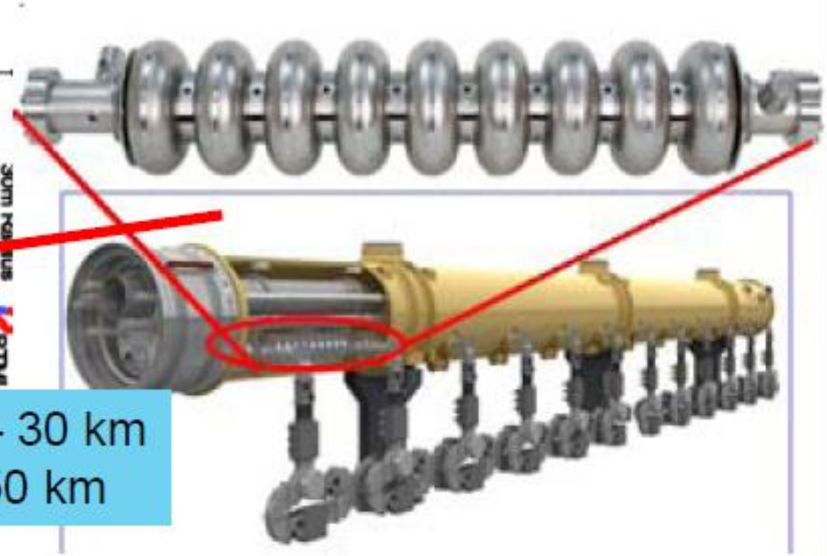
Wide range of Physics Topics, e.g.

- Higgs couplings, in particular **self coupling**
- precision studies of Z, W, and **Top**
- new physics phenomena

Very interesting after the discovery of the Higgs-like Boson

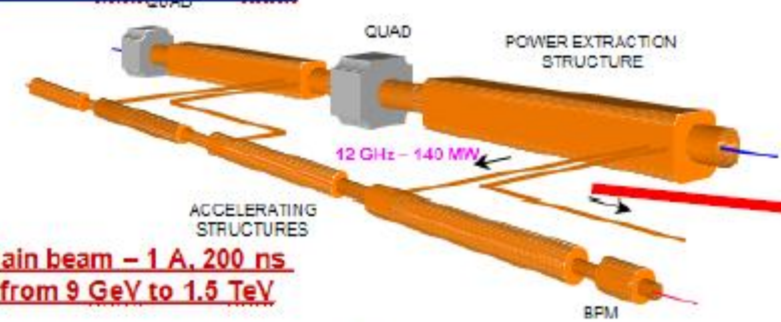
Linear Collider layouts

http://www.linearcollider.org/cms   http://clic-study.web.cern.ch/CLIC-Study/

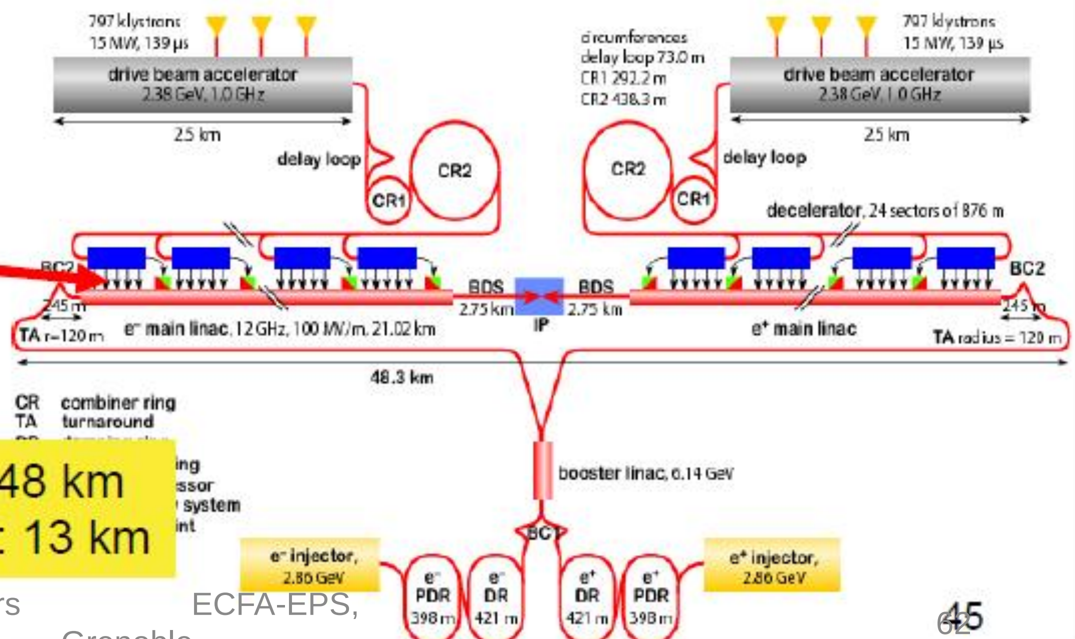


ILC 0.5 TeV – 30 km
ILC 1 TeV – 50 km

Drive beam - 95 A, 300 ns from 2.4 GeV to 240 MeV



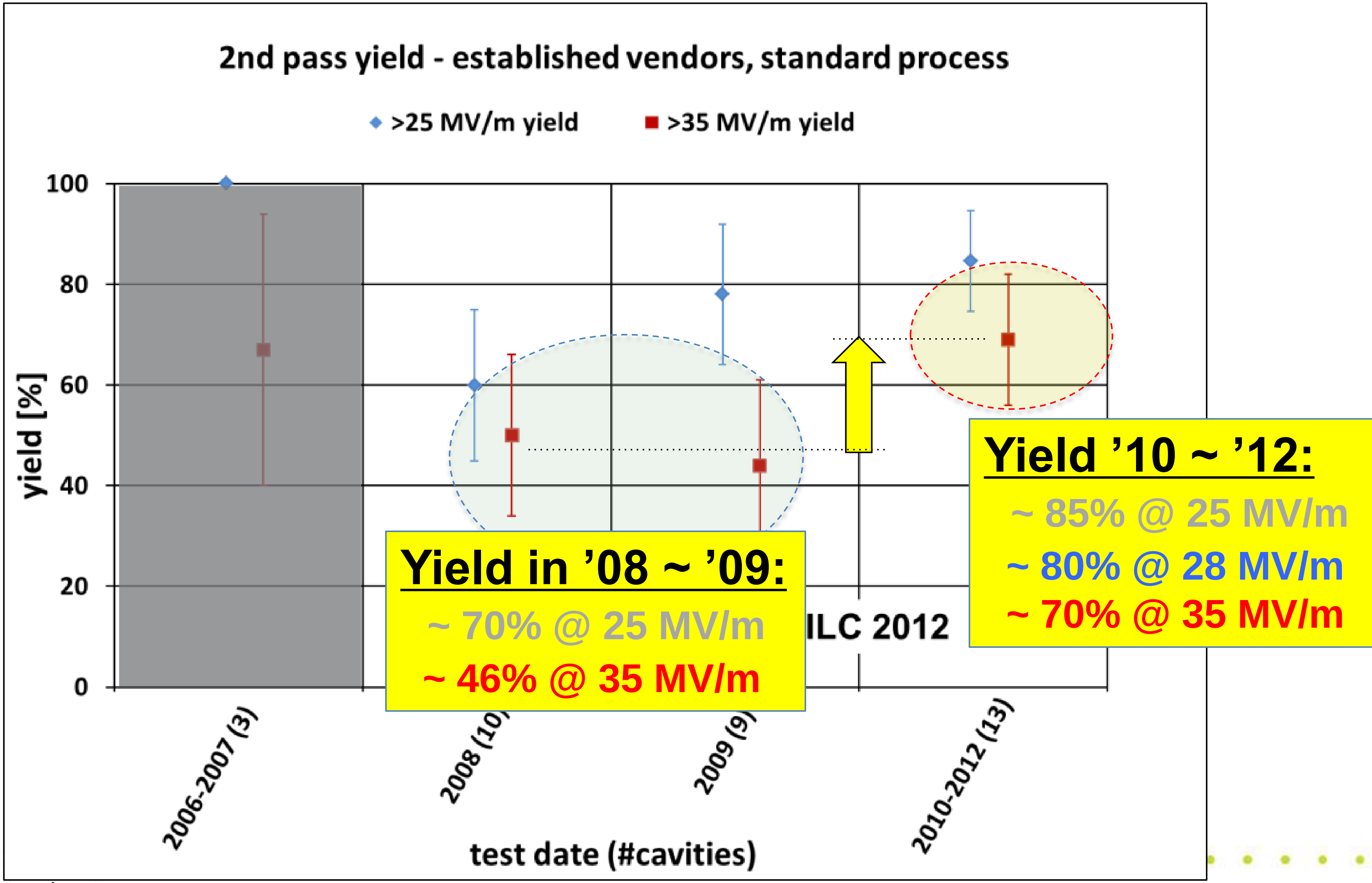
Main beam – 1 A, 200 ns from 9 GeV to 1.5 TeV



CLIC 3 TeV: 48 km
CLIC 0.5 TeV: 13 km

Yearly Progress in Cavity Gradient Yield

as of April 24, 2012



from Choices ? *to* Choice !

- Roadmap (Japan) just published

- Roadmap discussion (US) next year

- Update of the European Strategy for Particle Physics in 2012/13 ≡ Strategy of Europe in a global context
  - Several Meetings with **international participation**
    → bottom-up process: community input important
  - Finalization: May 2013

CERN today….into the future

- CLIC conceptual design report 2012
- Participation in all LC activities
- LHeC conceptual design report 2012
- R&D [illegible] high-field magnets (towards HE-LHC)
- Generic R&D (high-power SPL, Plasma Acc)
- Participation in Neutrino-Projects studied

Position CERN as Laboratory at the energy frontier

CERN: opening the door…

- Membership for Non-European countries
- New Associate Membership defined
- CERN participation in global projects independent of location

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

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exciting prospects