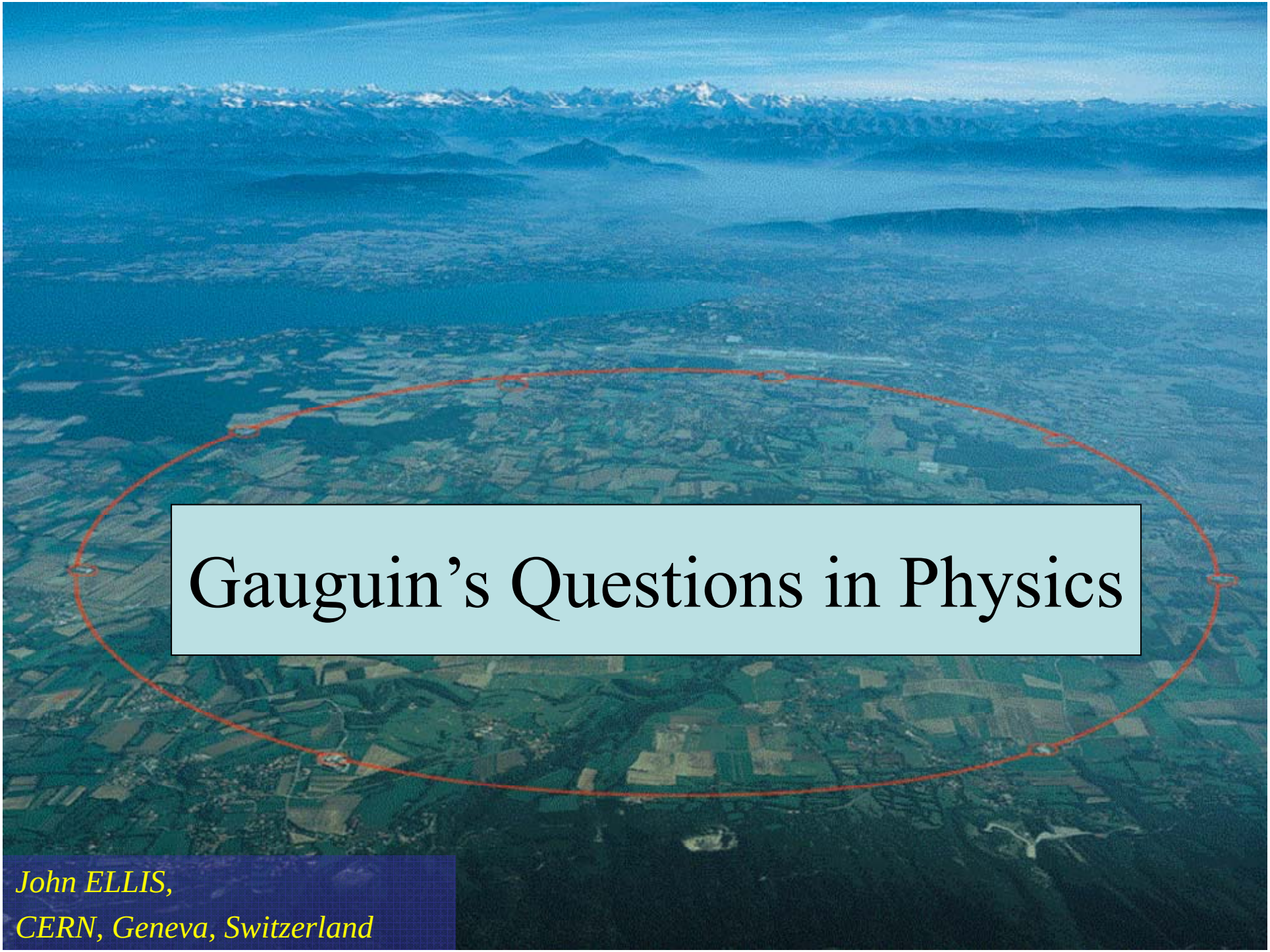


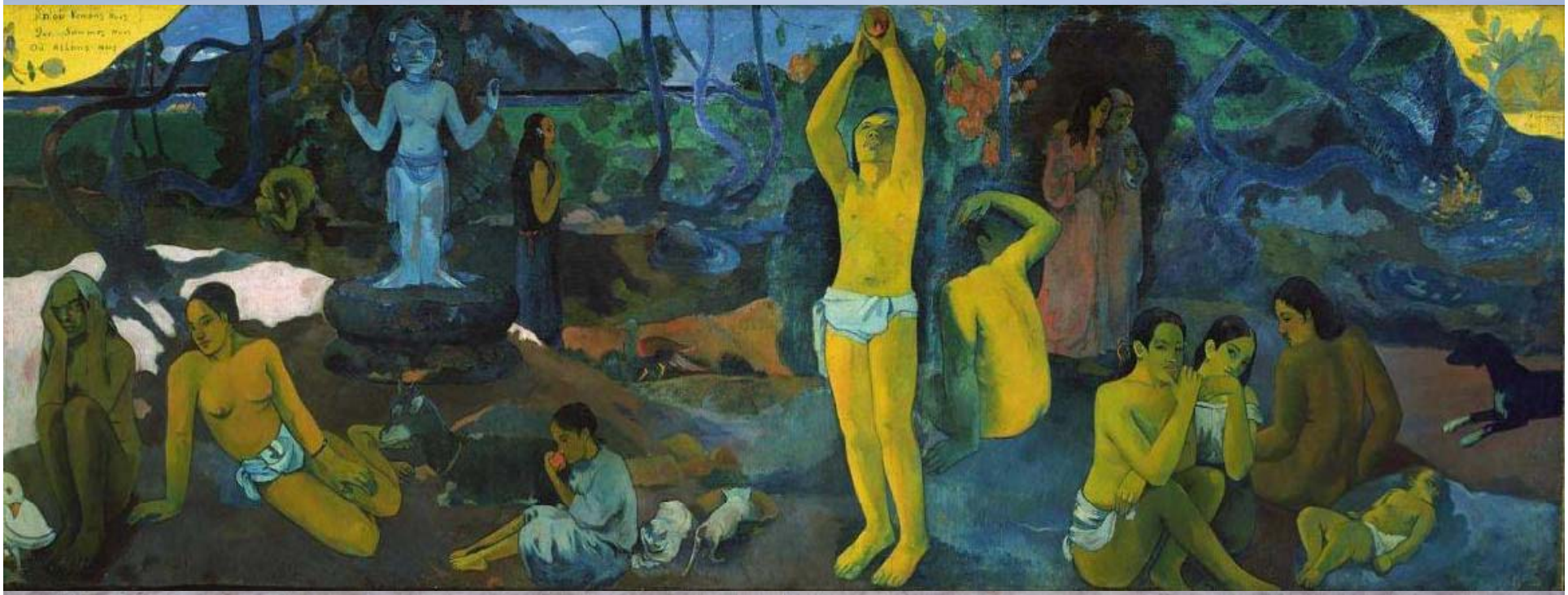
Gauguin's Questions in Physics

John ELLIS,
CERN, Geneva, Switzerland

Where do we come from?

What are we?

Where are we going?



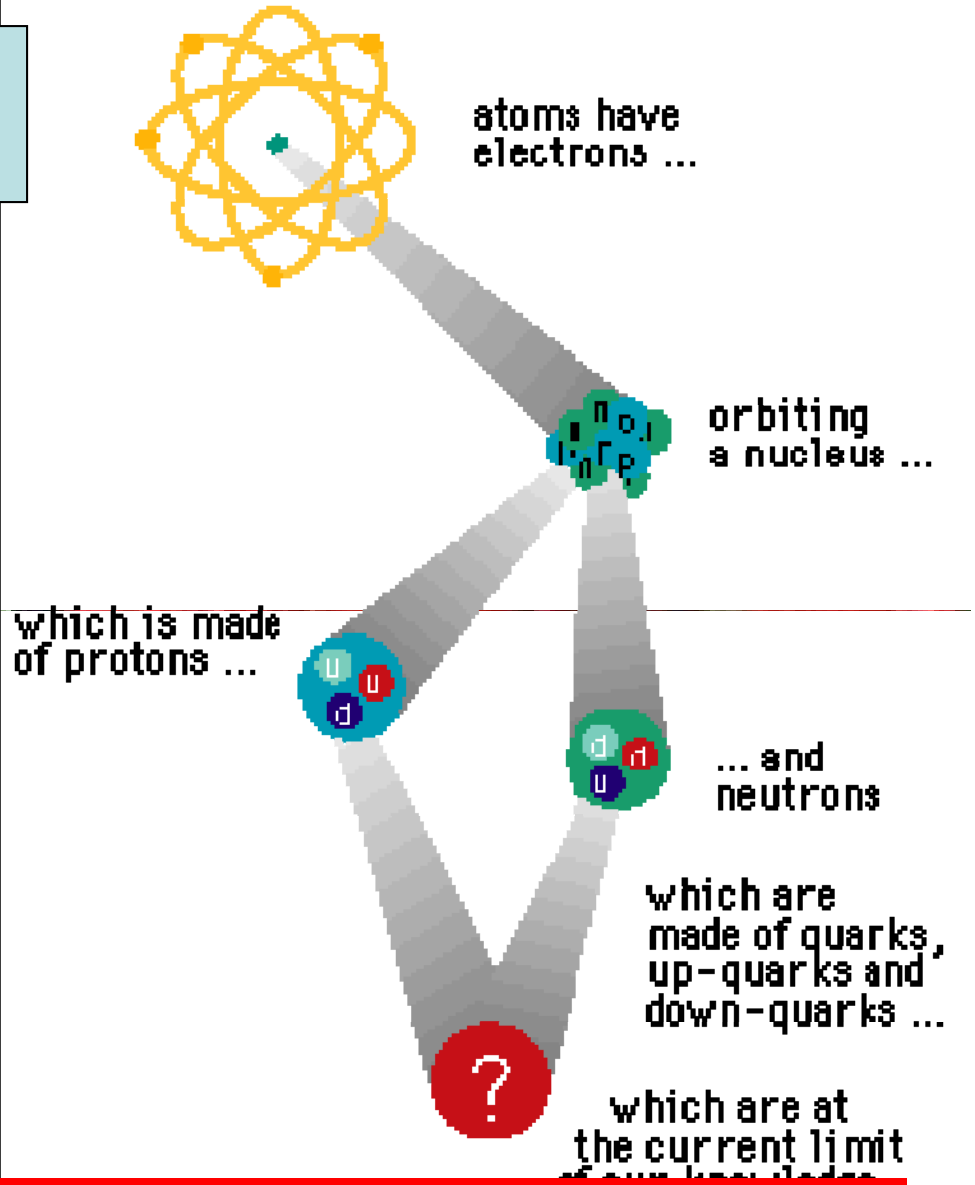
The aim of particle physics, CERN & the LHC:
What is the Universe made of?

Gauguin's Questions in the Language of Particle Physics

- What is matter made of?
- Why do things weigh?
- What is the dark matter that fills the Universe?
- How does the Universe evolve?
- What is the origin of matter?
- Why is the Universe so big and old?
- Are there additional dimensions of space?

Our job is to ask - and answer - these questions

Inside Matter

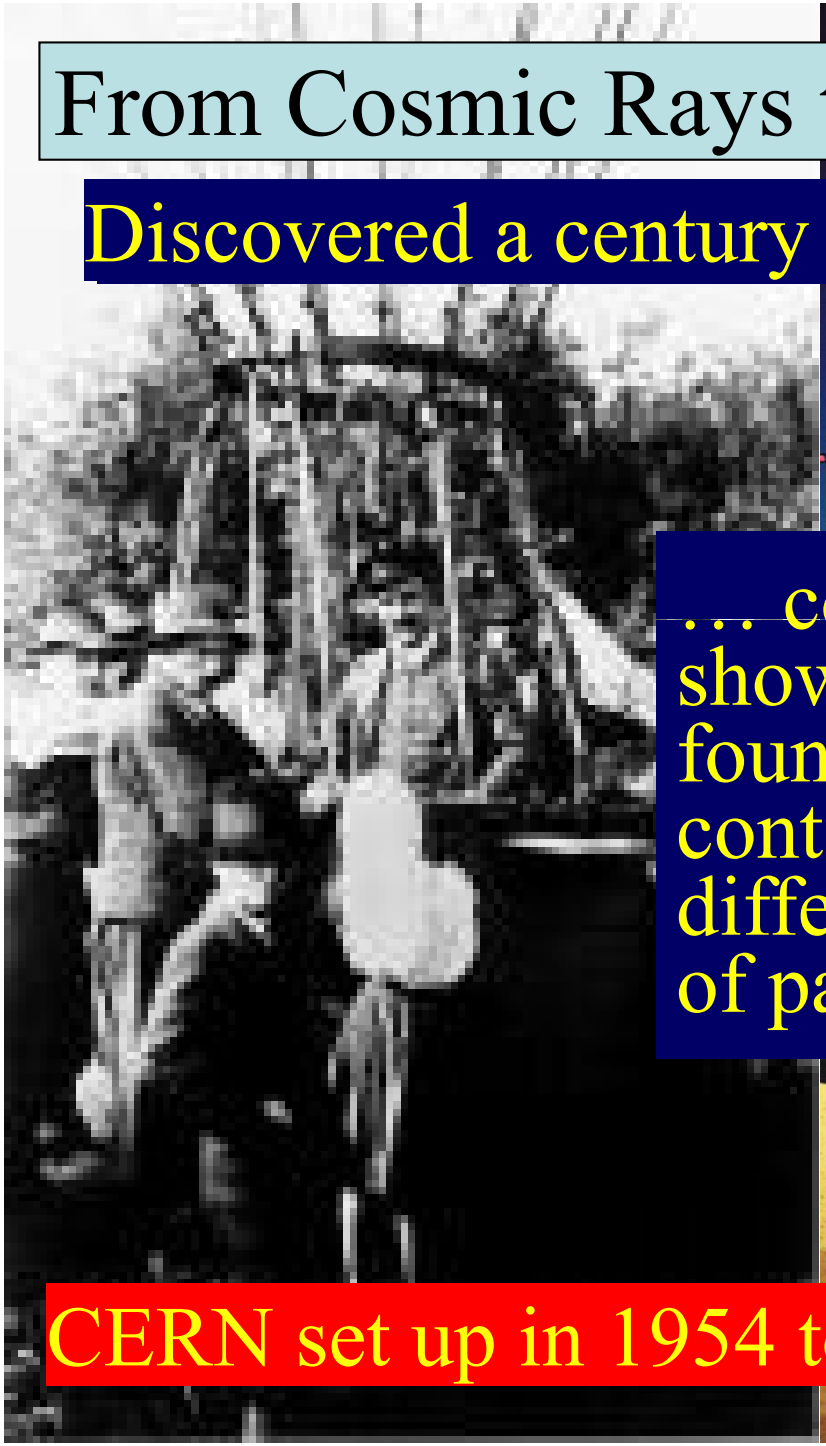


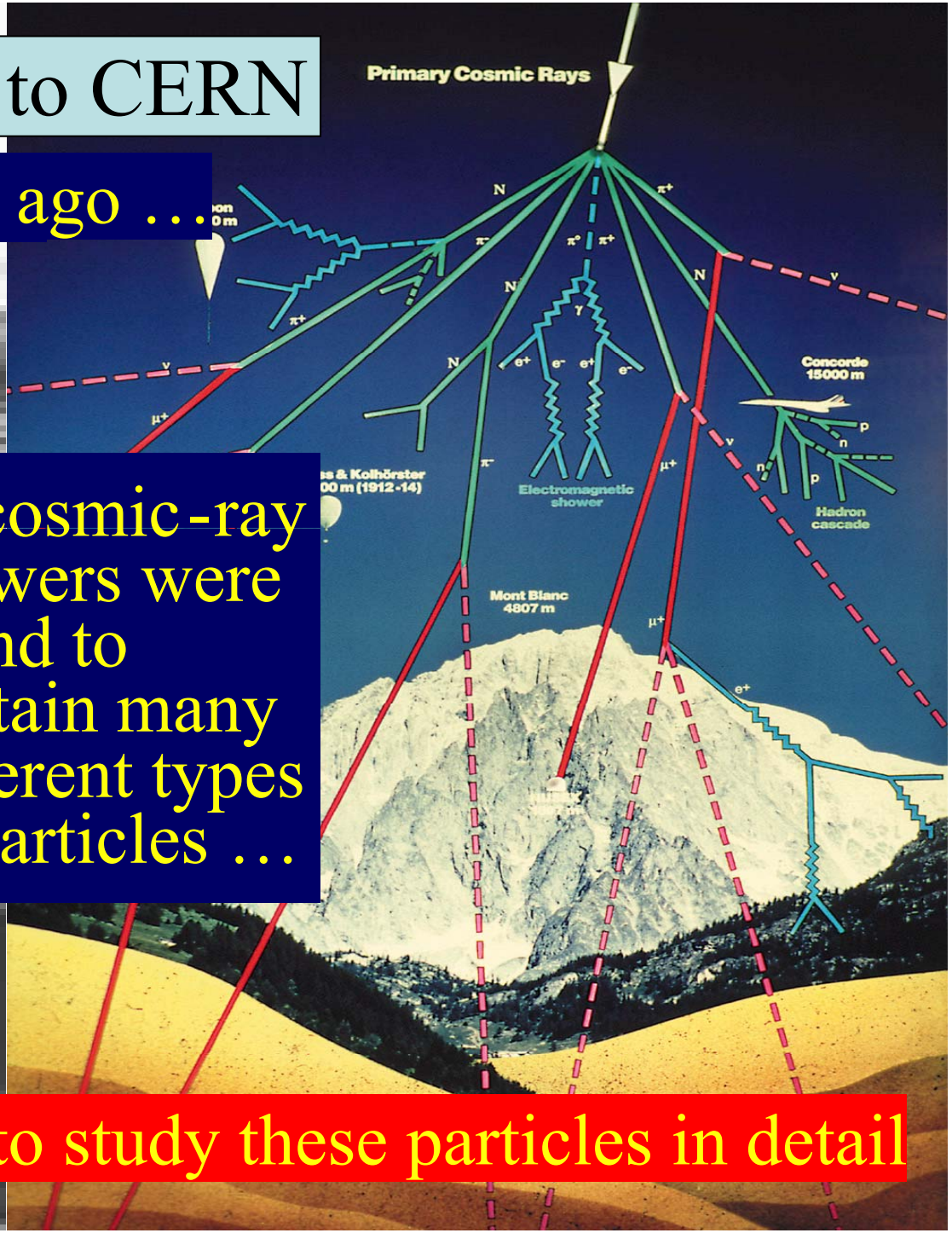
All matter is made of the same constituents

What are they?
What forces between them?

From Cosmic Rays to CERN

Discovered a century ago …





… cosmic-ray showers were found to contain many different types of particles …

CERN set up in 1954 to study these particles in detail

The ‘Standard Model’

= Cosmic DNA

The matter particles

The fundamental interactions

Gravitation electromagnetism weak nuclear force strong nuclear force

Why do Things Weigh?

Newton:

Weight proportional to Mass

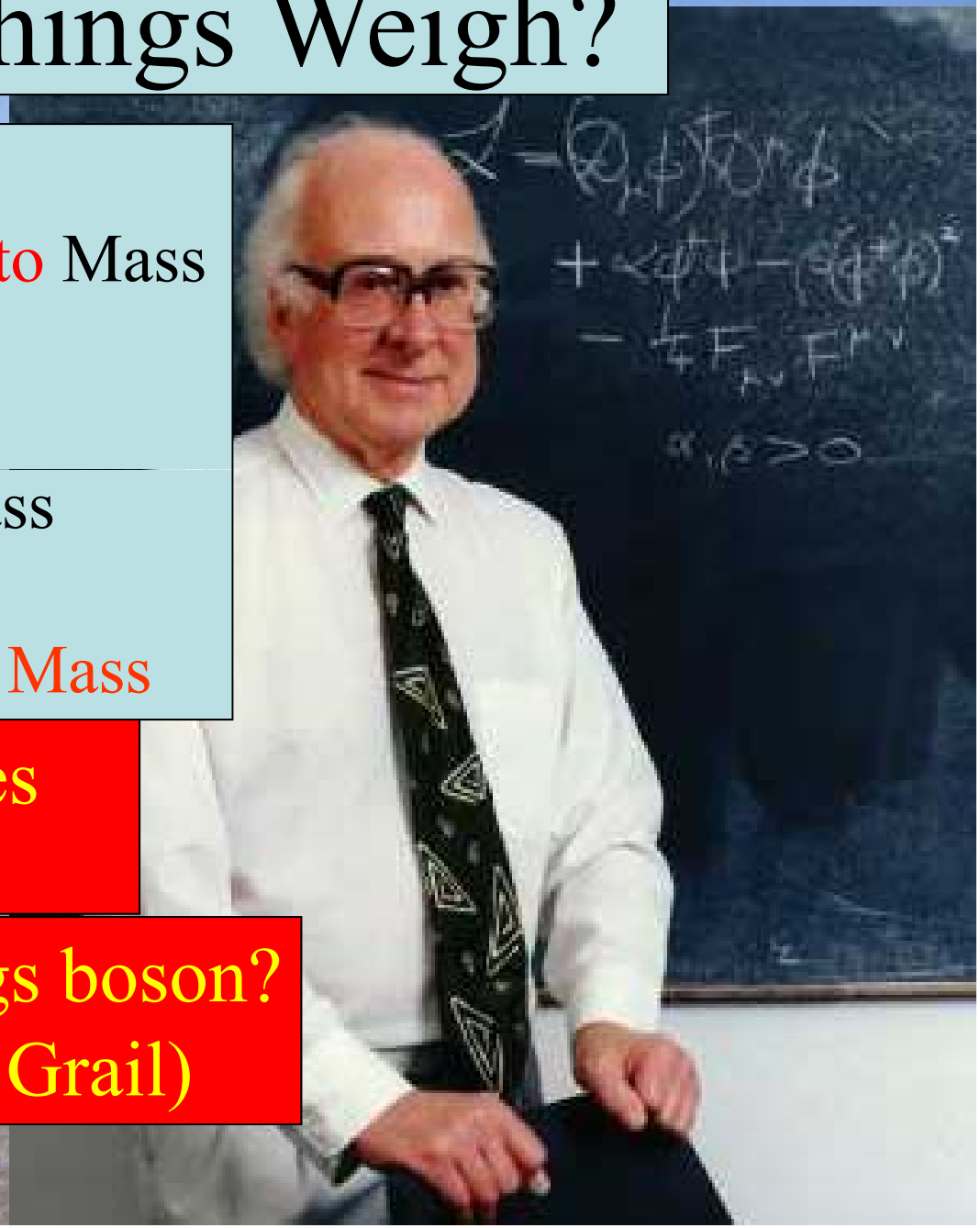
Einstein:

Energy related to Mass

Neither explained origin of Mass

Where do the masses come from?

Are masses due to Higgs boson? (the physicists' Holy Grail)



Think of a Snowfield

Skier moves fast:
Like particle without mass
e.g., photon = particle of light

Snowshoer sinks into snow,
moves slower:
Like particle with mass
e.g., electron

The LHC will look for the snowflake: The Higgs Boson

Hiker sinks deep,
moves very slowly:
Particle with large mass

How Heavy is the Higgs Snowflake?

- Direct search limit from LEP:

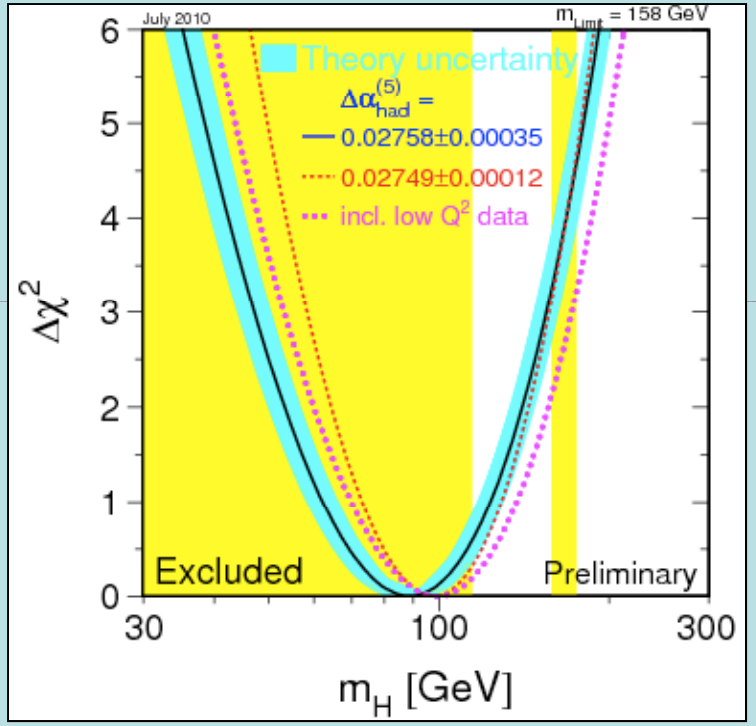
  $m_H > 114.4$ GeV
- Electroweak fit sensitive to m_t

  (Now $m_t = 173.1 \pm 1.3$ GeV)
- Best-fit value for Higgs mass:

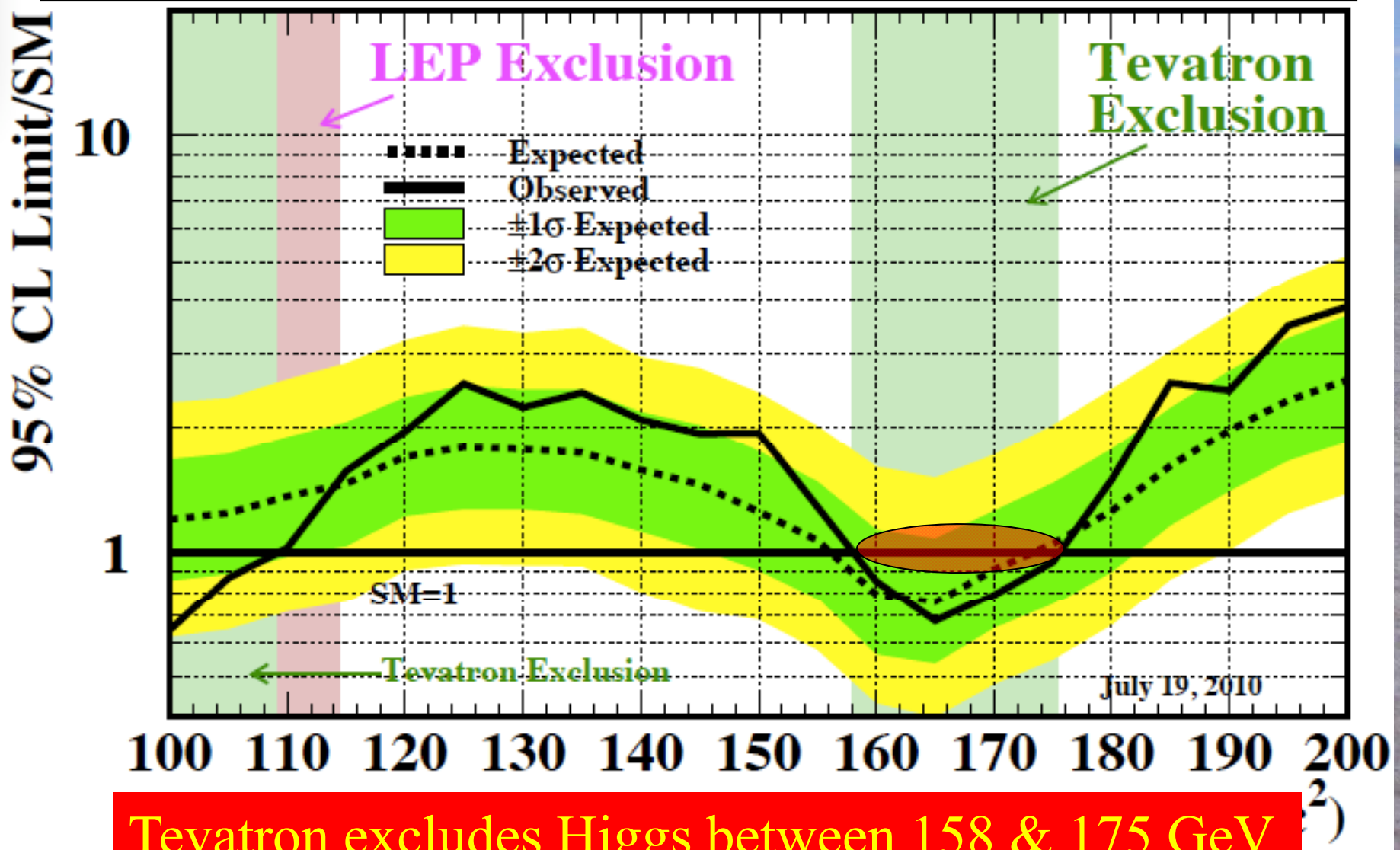
  $m_H = 89^{+35}_{-26}$ GeV
- 95% confidence-level upper limit:

  $m_H < 158$ GeV, or 185 GeV including LEP direct limit
- Tevatron exclusion:

  $m_H < 158$ GeV or > 175 GeV

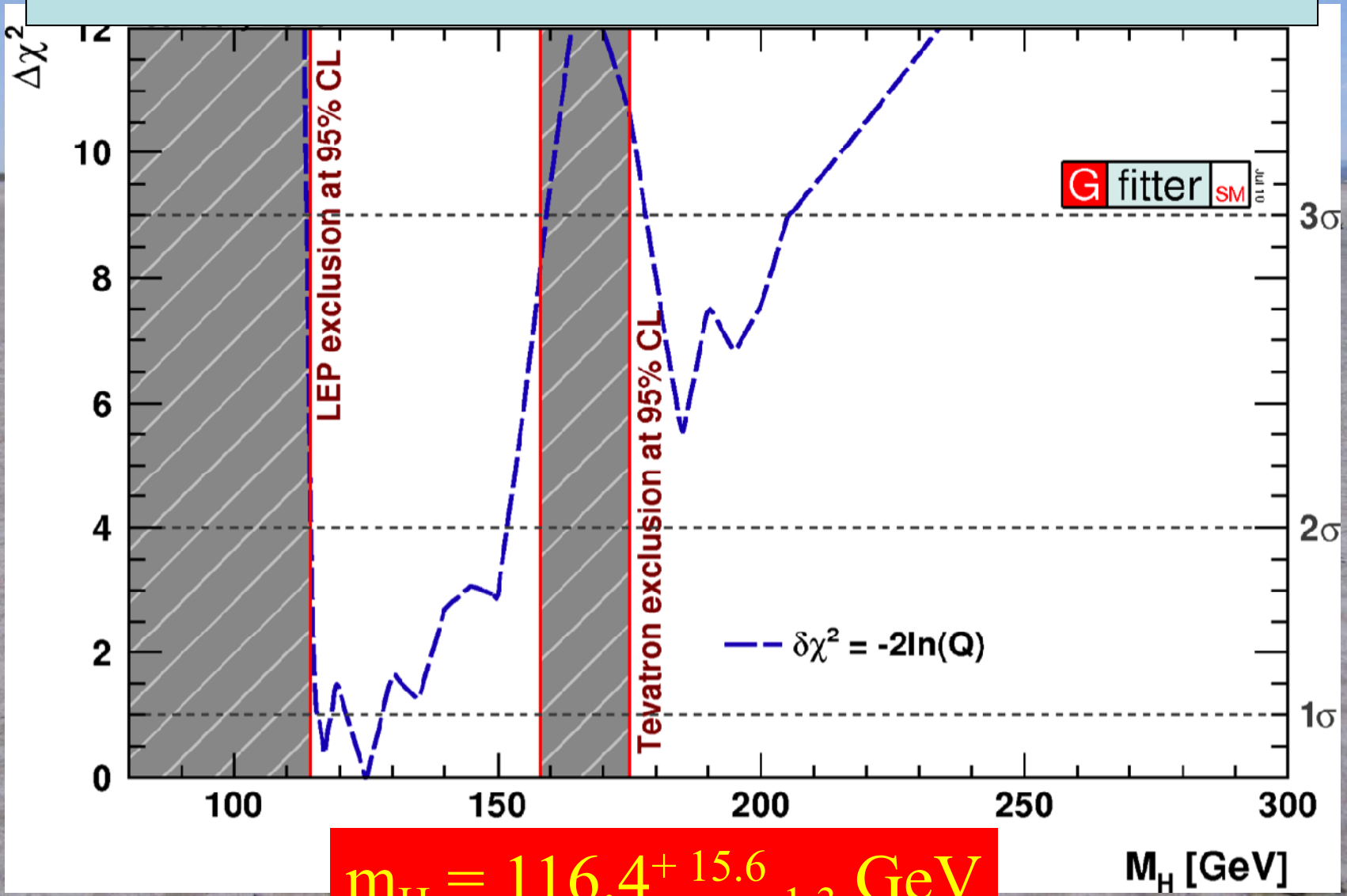


Higgs Search @ Tevatron



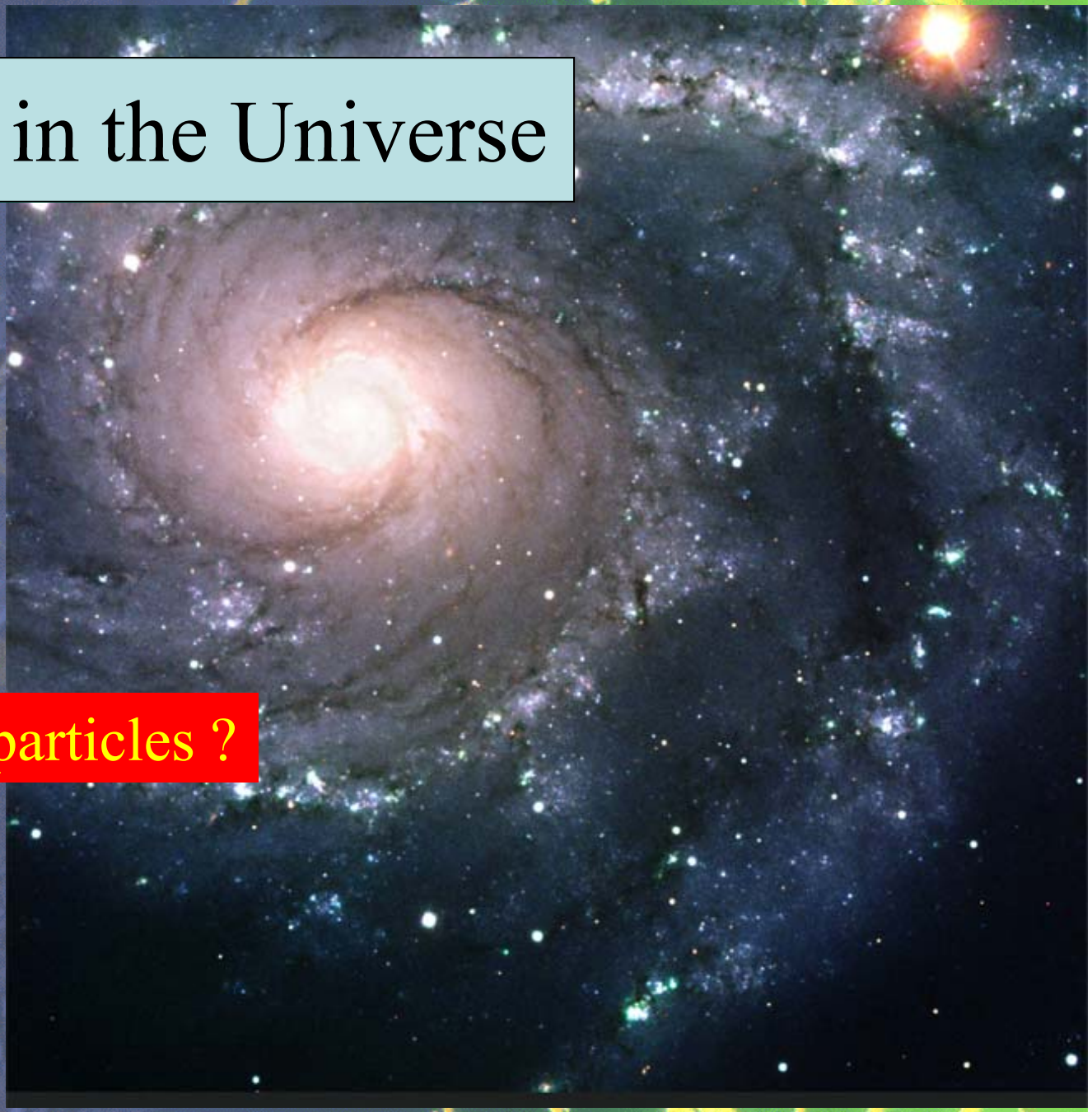
Tevatron excludes Higgs between 158 & 175 GeV

Combining the Higgs Information



$m_H = 116.4^{+15.6}_{-1.3}$ GeV

Dark Matter in the Universe



Astronomers say that most of the matter in the Universe is invisible Dark Matter

'Supersymmetric' particles ?

We shall look for them with the LHC

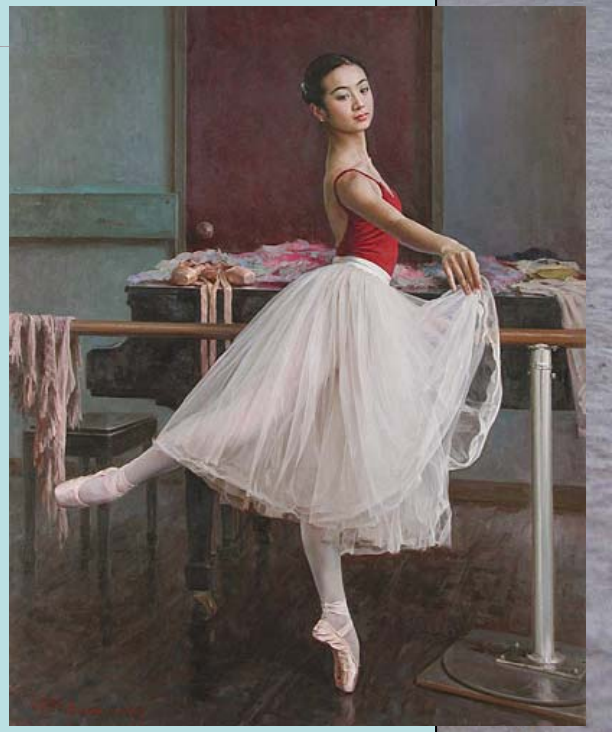
Supersymmetry?

- Would unify matter particles and force particles
- Related particles spinning at different rates

  0 - ½ - 1 - 3/2 - 2

  Higgs - Electron - Photon - Gravitino - Graviton

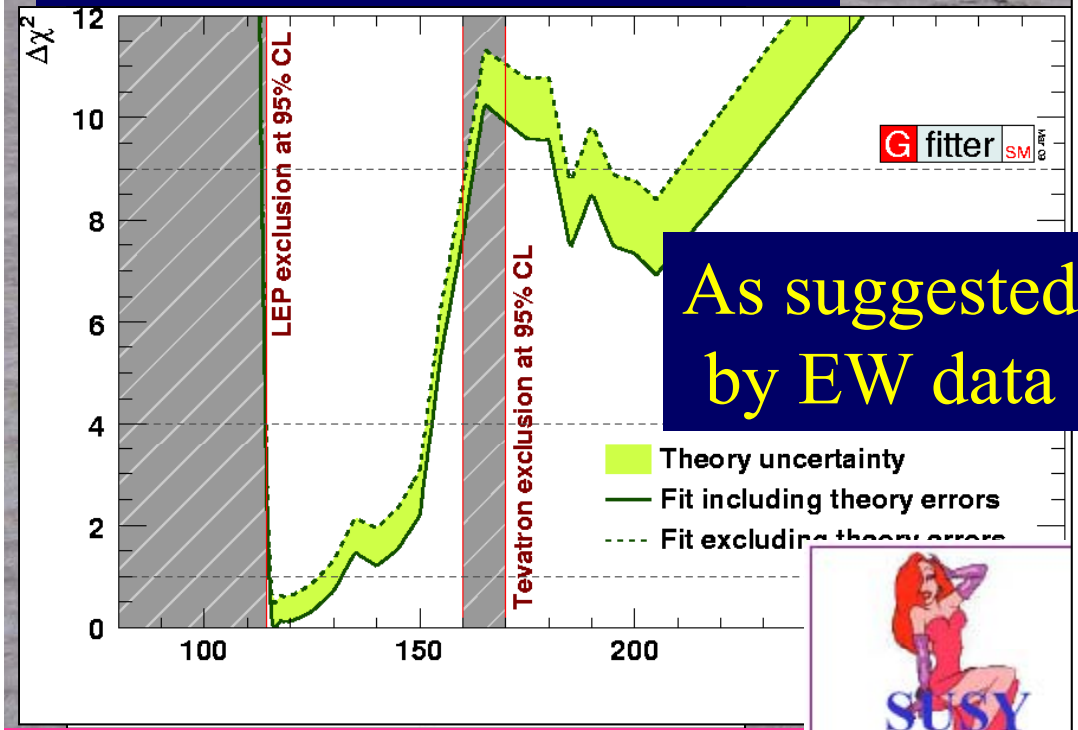
  (Every particle is a 'ballet dancer')
- Would help fix particle masses
- Would help unify forces
- Predicts light Higgs boson
- **Could provide dark matter for the astrophysicists and cosmologists**



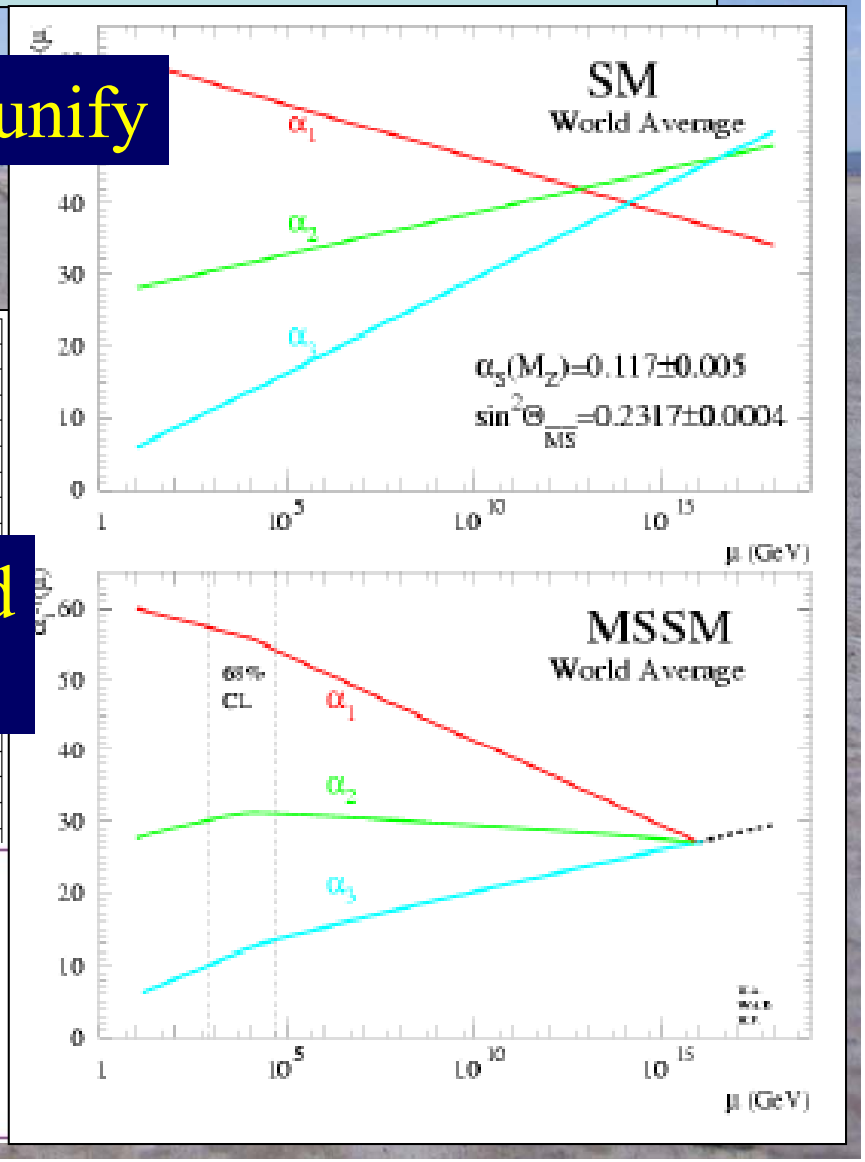
Other Reasons to like Susy

It enables the gauge couplings to unify

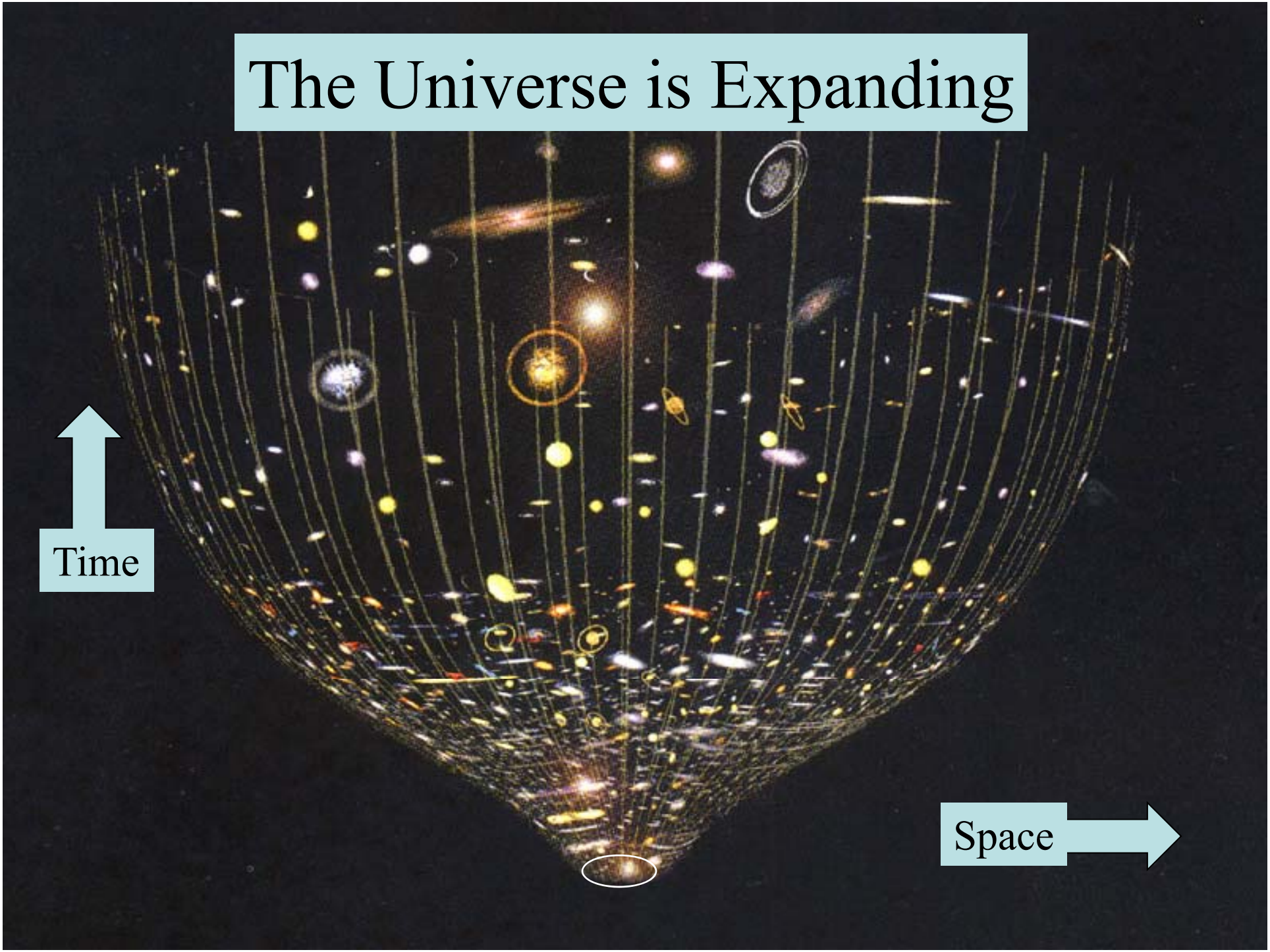
It predicts $m_H < 150$ GeV



As suggested by EW data



Provided by Fabiola Gianotti


The Universe is Expanding
Time
Space

300,000 years

Formation of atoms

3 minutes

Formation of nuclei

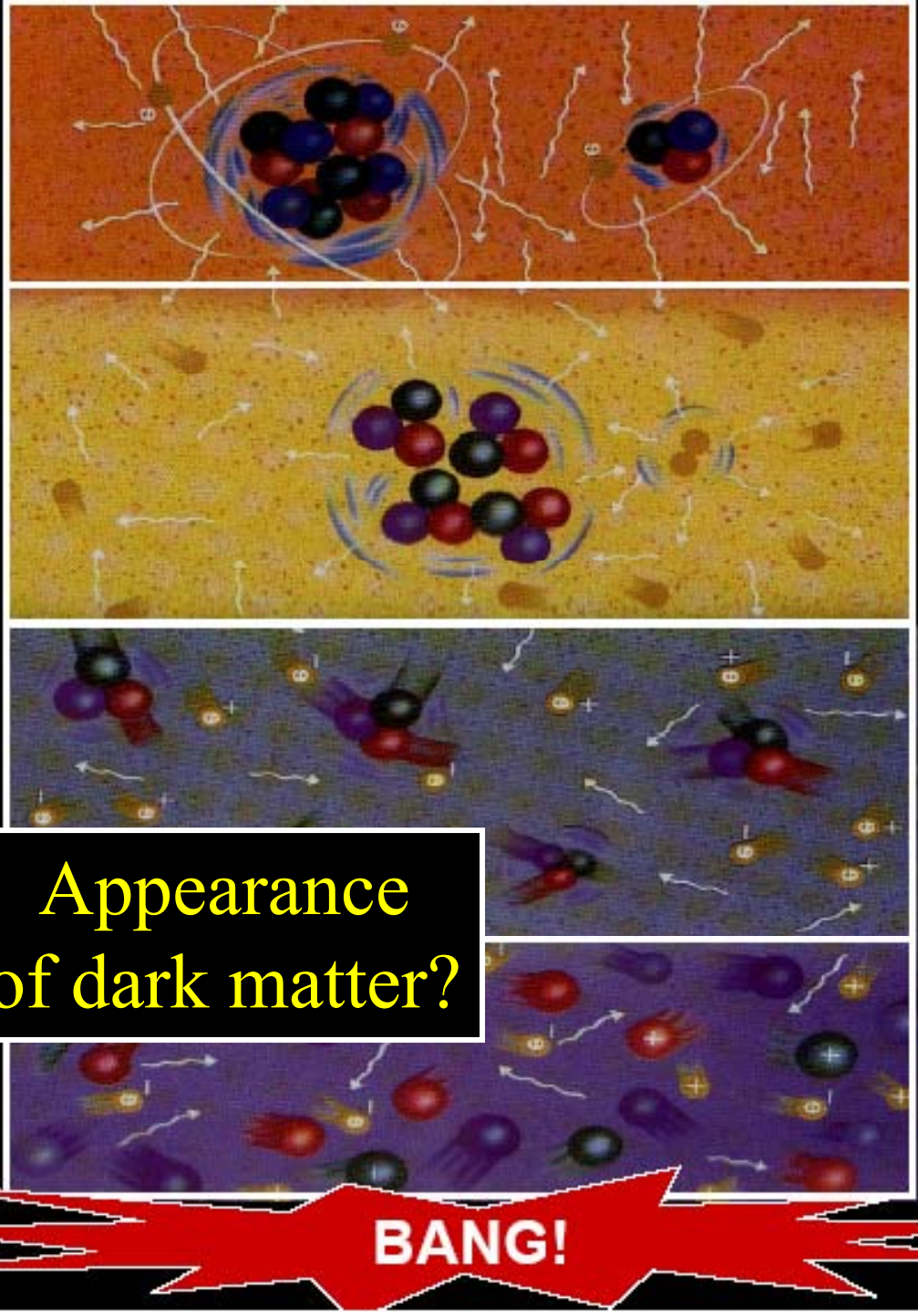
1 micro-second

Formation of protons & neutrons

Appearance of dark matter?

1 pico-second

Appearance of mass?



Where does the Matter come from?

Dirac predicted the existence of antimatter:
- same mass
- opposite internal properties:
  - electric charge, …

Discovered in cosmic rays

Studied using accelerators

Matter and antimatter not quite equal and opposite: WHY?

2008 Nobel Physics Prize: Kobayashi & Maskawa

Is this why the Universe contains mainly matter, not antimatter?

LHC experiments will look for answer

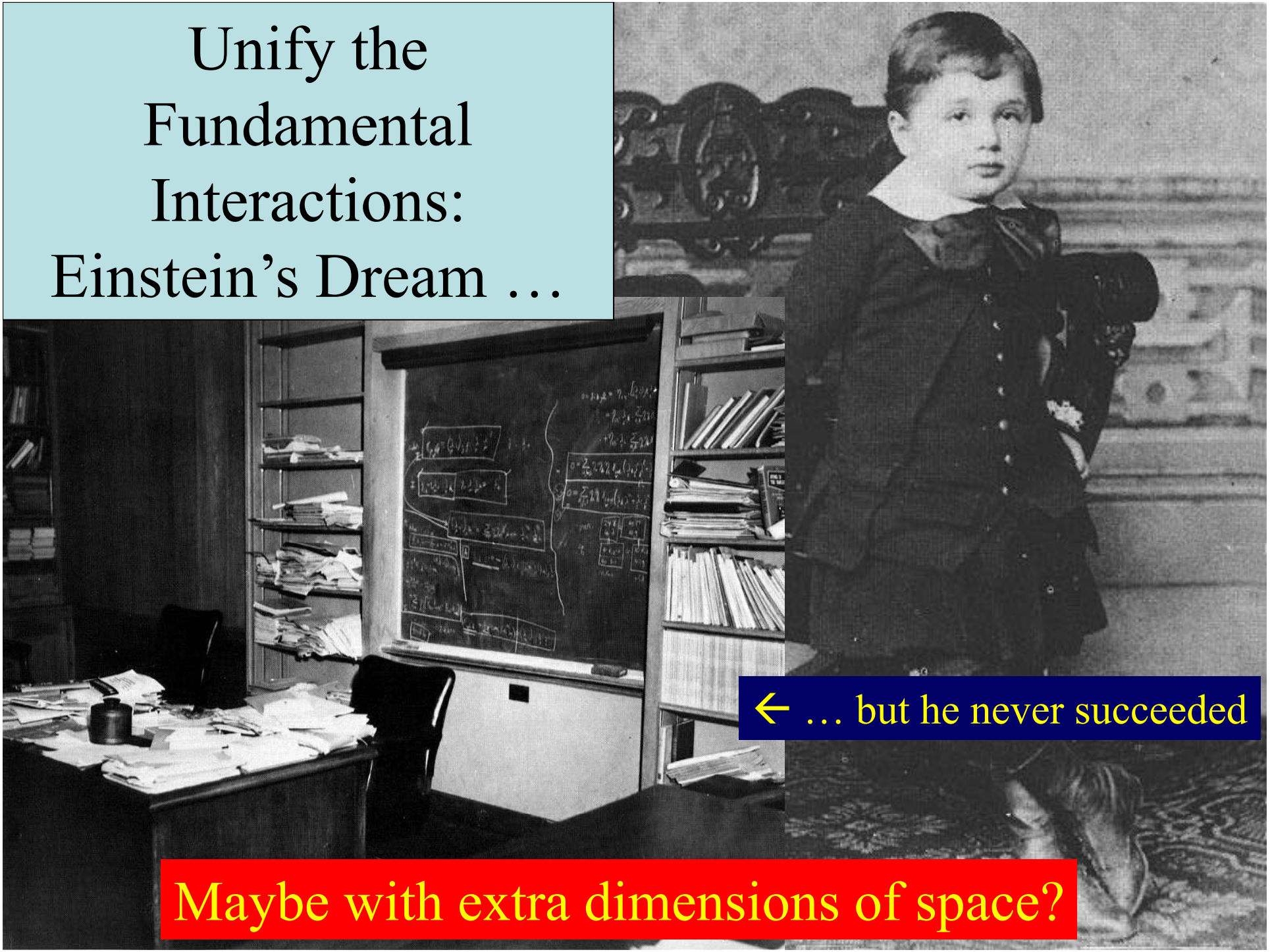
How to Create the Matter in the Universe?

Sakharov

- Need a difference between matter and antimatter
  observed in the laboratory
- Need interactions that make matter
  present in unified theories
  not yet seen by experiment
- Must break thermal equilibrium
  Possible in the early Universe

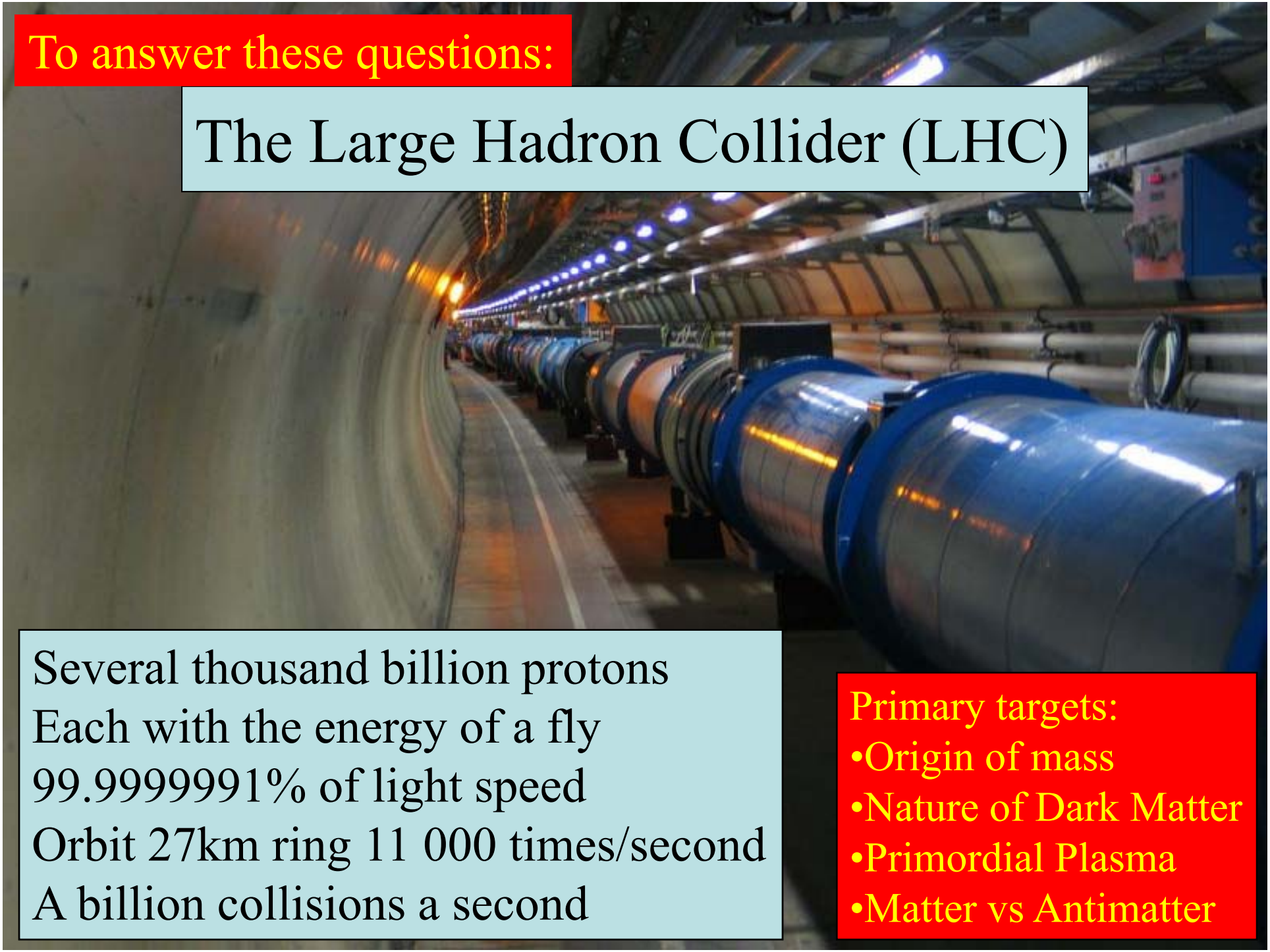
Will we be able to calculate using laboratory data?

Unify the Fundamental Interactions: Einstein's Dream …



← … but he never succeeded

Maybe with extra dimensions of space?



To answer these questions:

The Large Hadron Collider (LHC)

Several thousand billion protons
Each with the energy of a fly
99.9999991% of light speed
Orbit 27km ring 11 000 times/second
A billion collisions a second

Primary targets:
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

F.A.Q.s ABOUT THE HADRON COLLIDER

Q: How does the Hadron Collider work?

A: You didn't even understand eleventh-grade math, so why are you asking?

Q: What would happen if I went inside it?

A: Just. Don't.

Q: How many miles of pipes and whatnot are in it?

A: A bajillion.

Q: How much did it cost?

A: Forty squillion.

Q: What does this thing do?

A: Don't touch that.

Q: What would happen if you, like, put a cat inside it?

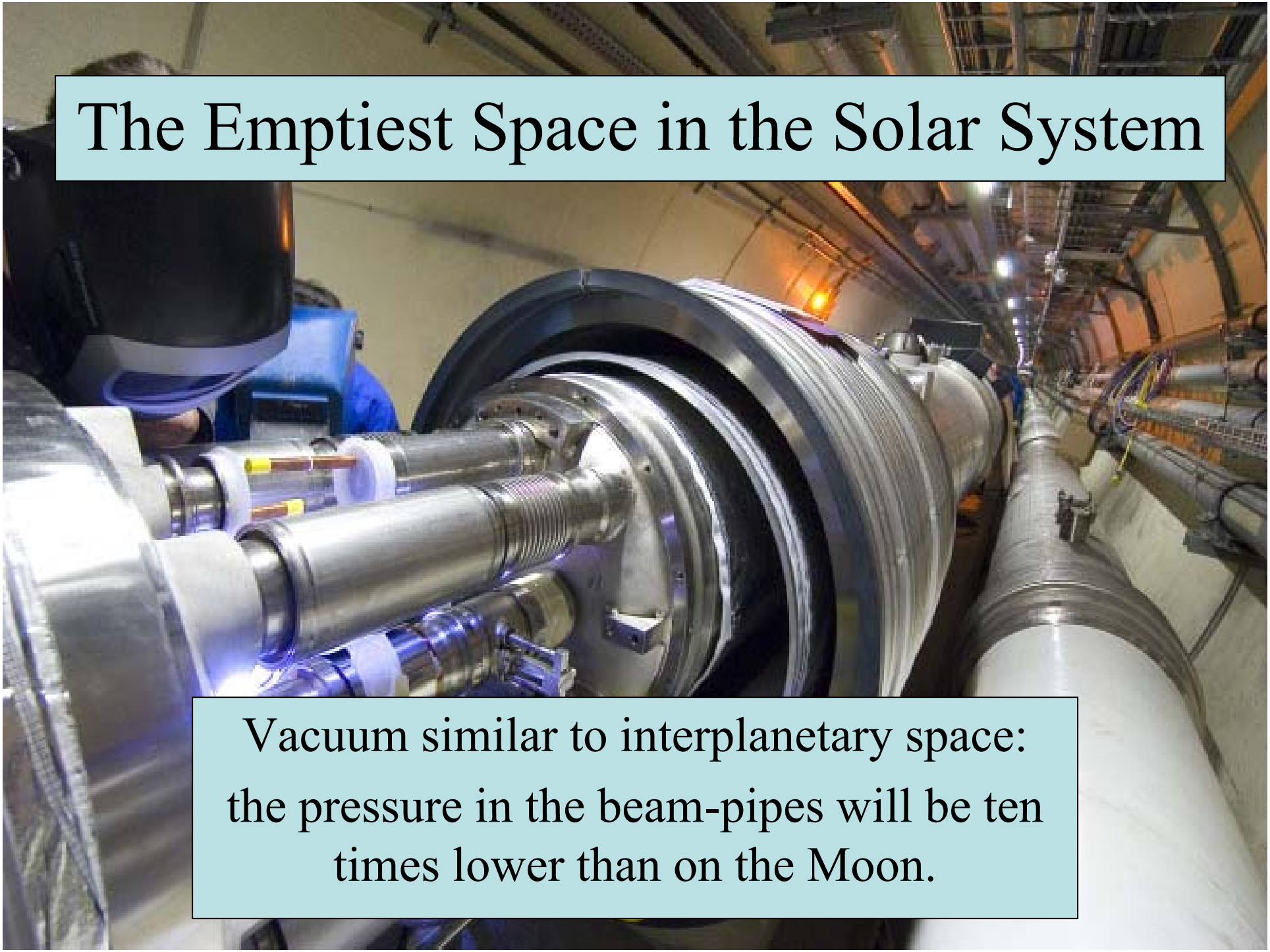
A: I *don't know.*

Q: If I concentrate ultra-hard, will I ever be able to understand it?

A: No.

R. Chast

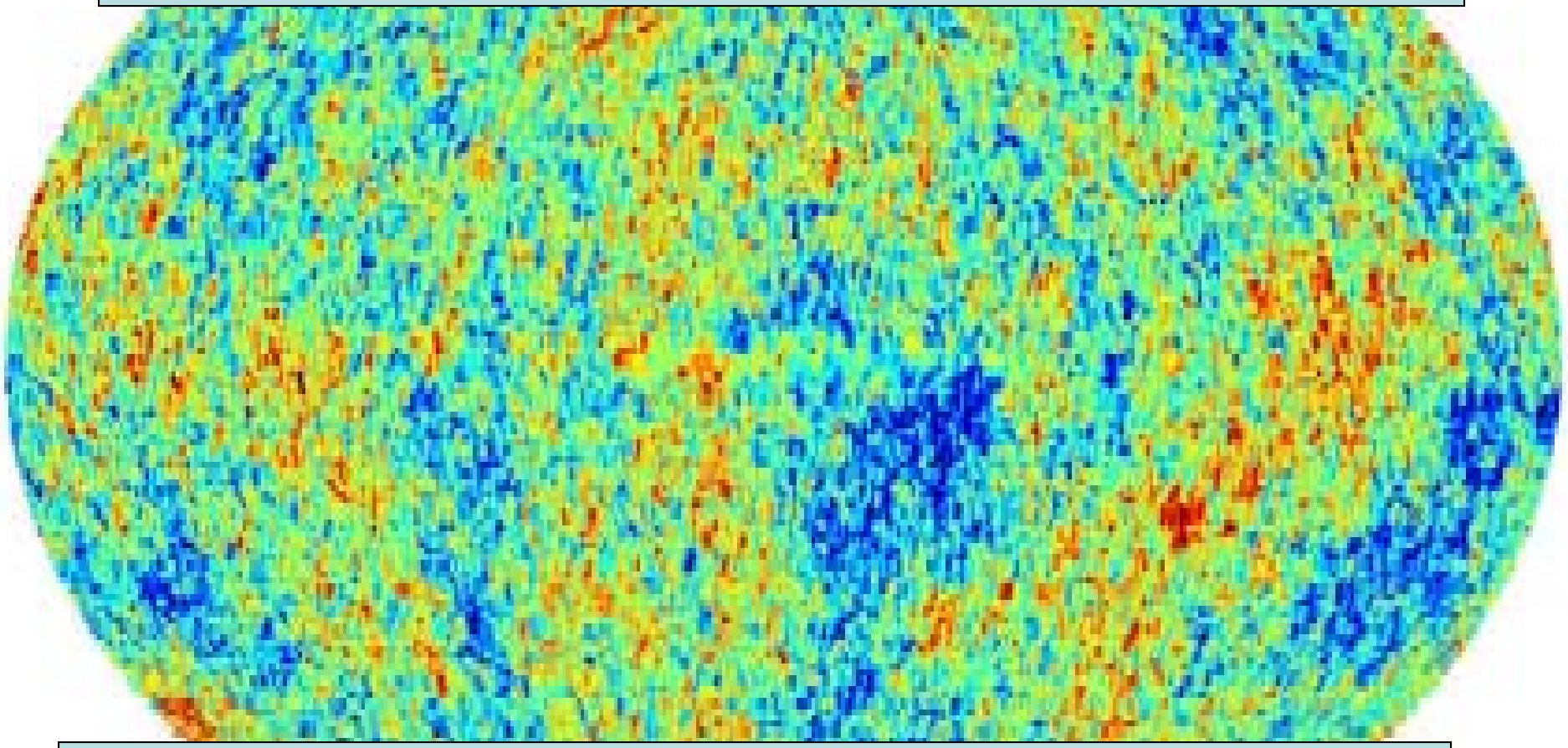
The Emptiest Space in the Solar System



Vacuum similar to interplanetary space:

the pressure in the beam-pipes will be ten times lower than on the Moon.

Colder than Outer Space

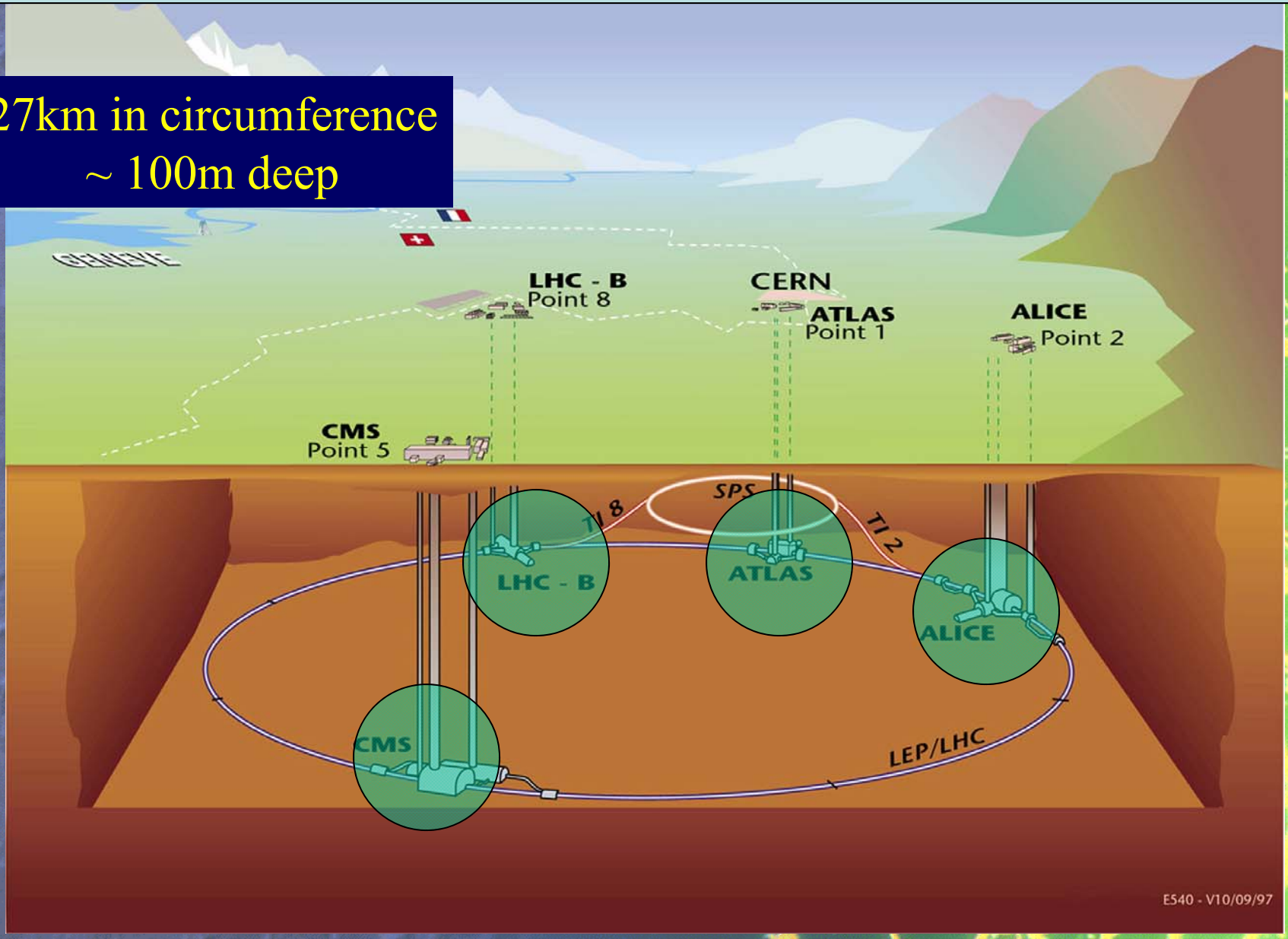


LHC 1.9 degrees above absolute zero = - 271 C

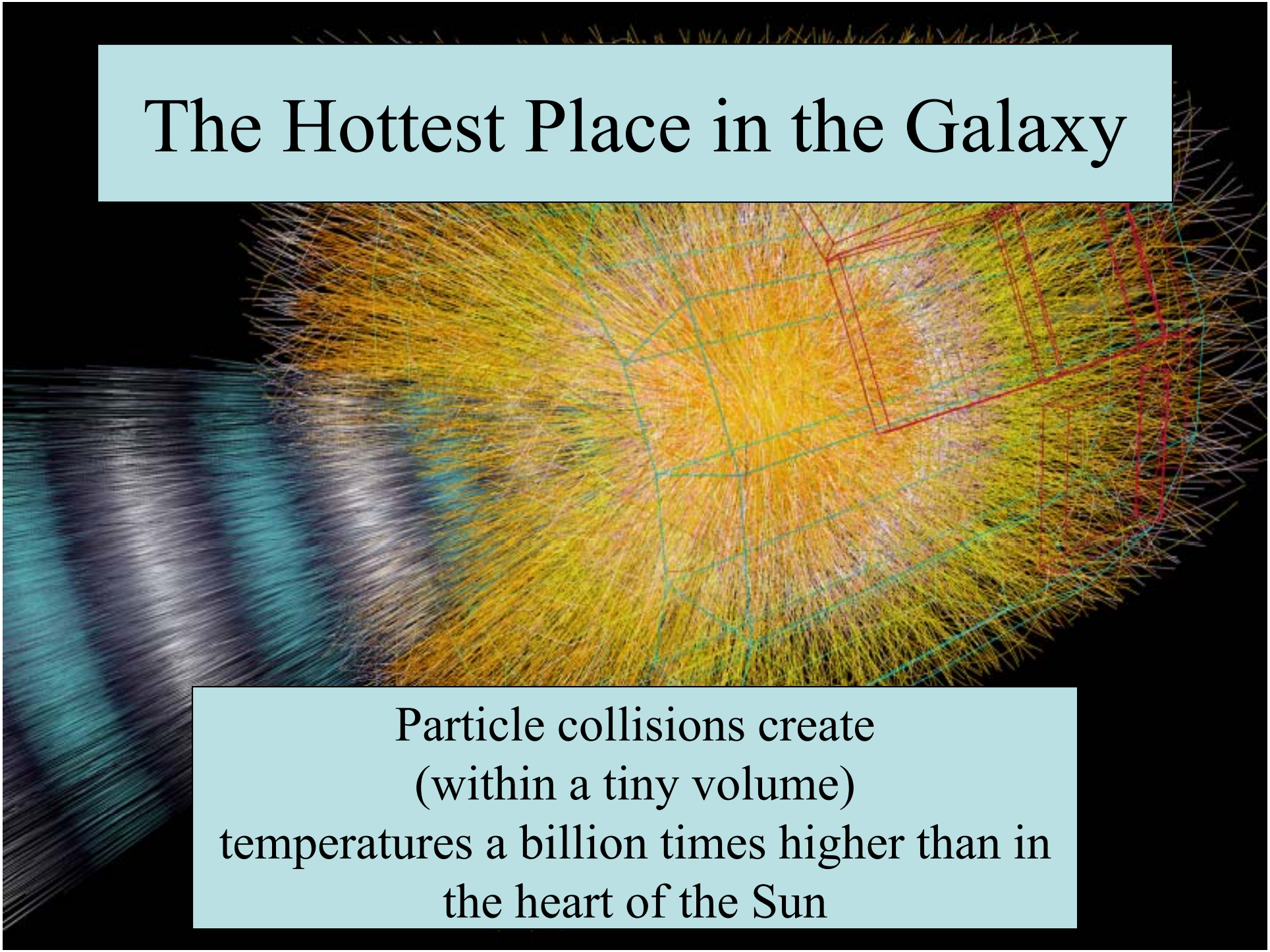
Outer space 2.7 degrees above zero = - 270 C

General View of LHC & its Experiments

27km in circumference
~ 100m deep

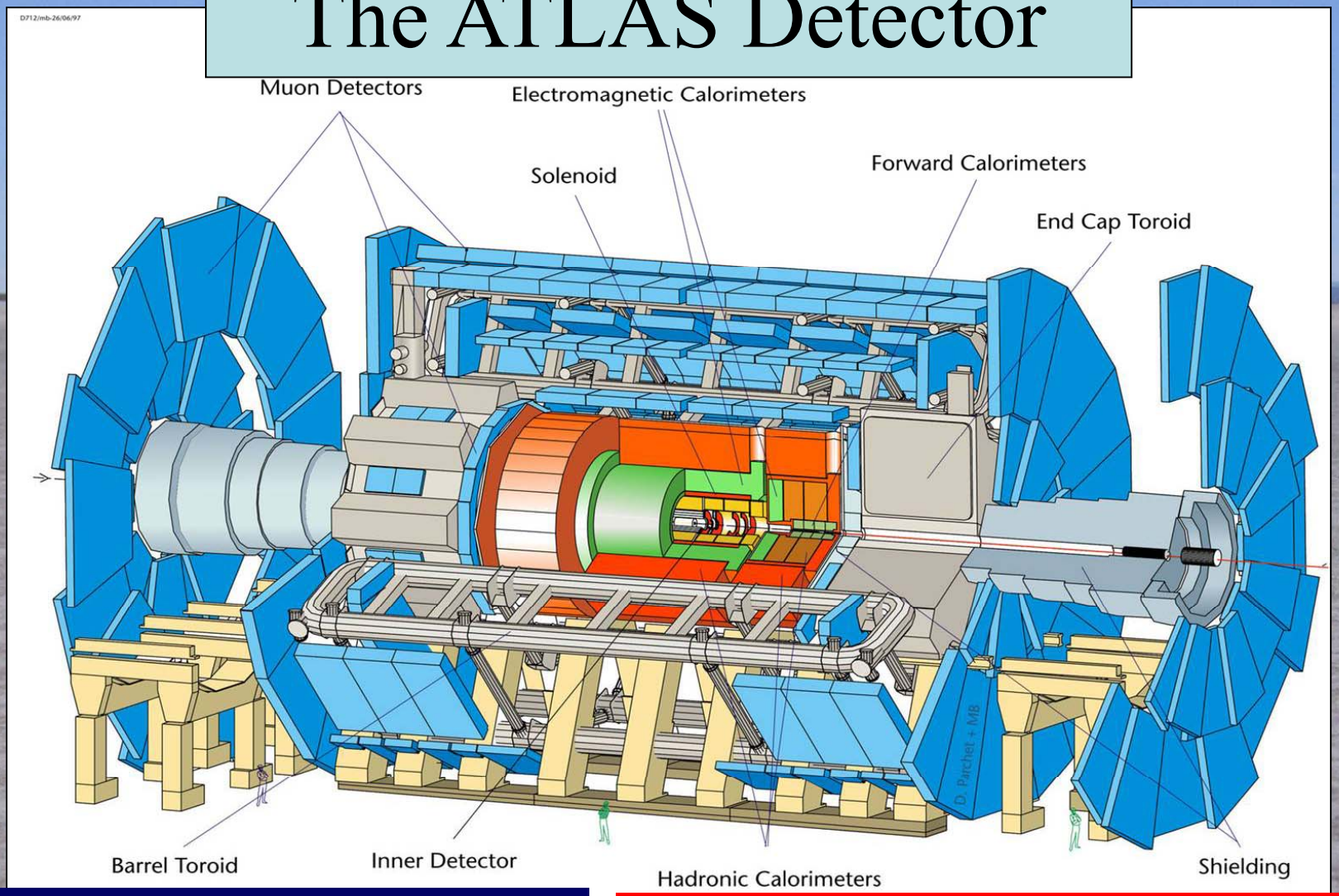


The Hottest Place in the Galaxy



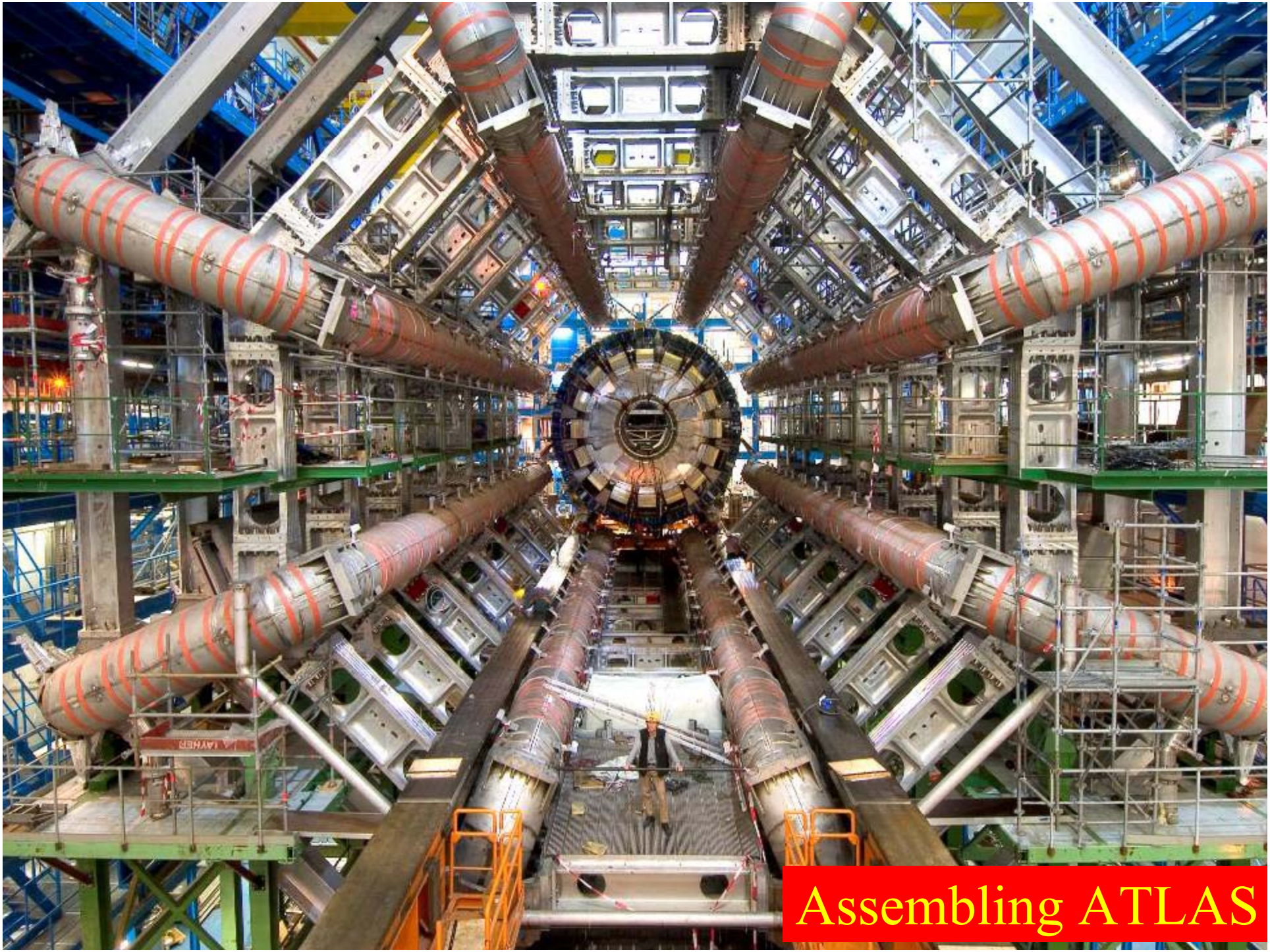
Particle collisions create
(within a tiny volume)
temperatures a billion times higher than in
the heart of the Sun

The ATLAS Detector



Diameter	25 m
Total length	46 m
Overall weight	7000 tons

Over 2000 scientists and engineers
Nearly 40 countries
More components than a moon rocket


Assembling ATLAS

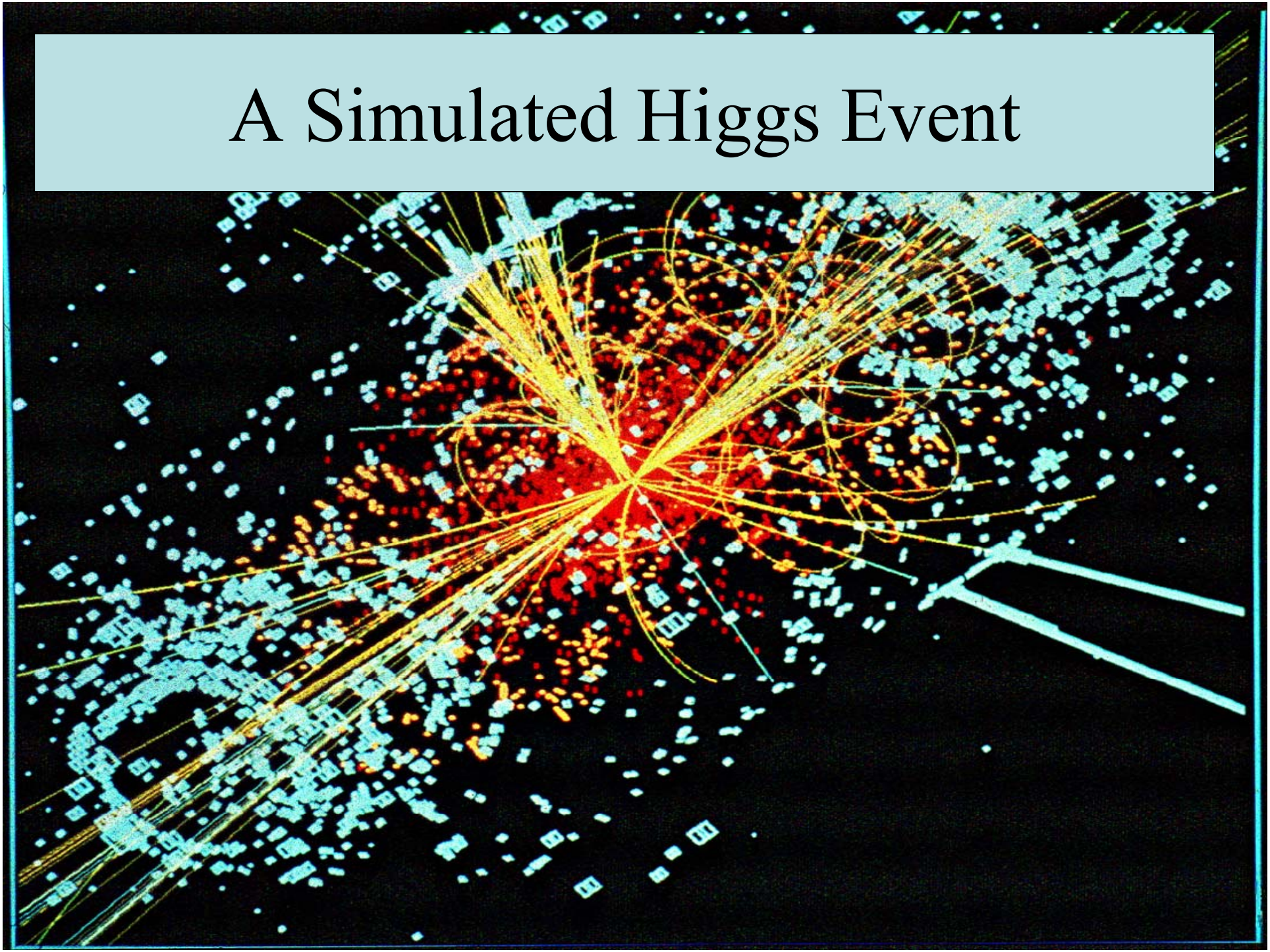
A Global Adventure: over 10000 Scientists from Around the World

MEMBER STATES 6405	
AUSTRIA	111
BELGIUM	102
BULGARIA	85
CZECH REPUBLIC	180
DENMARK	69
FINLAND	104
FRANCE	809
GERMANY	1113
GREECE	159
HUNGARY	64
ITALY	1681
NETHERLANDS	171
NORWAY	75
POLAND	241
PORTUGAL	141
SLOVAKIA	85
SPAIN	333
SWEDEN	72
SWITZERLAND	211
UNITED KINGDOM	599

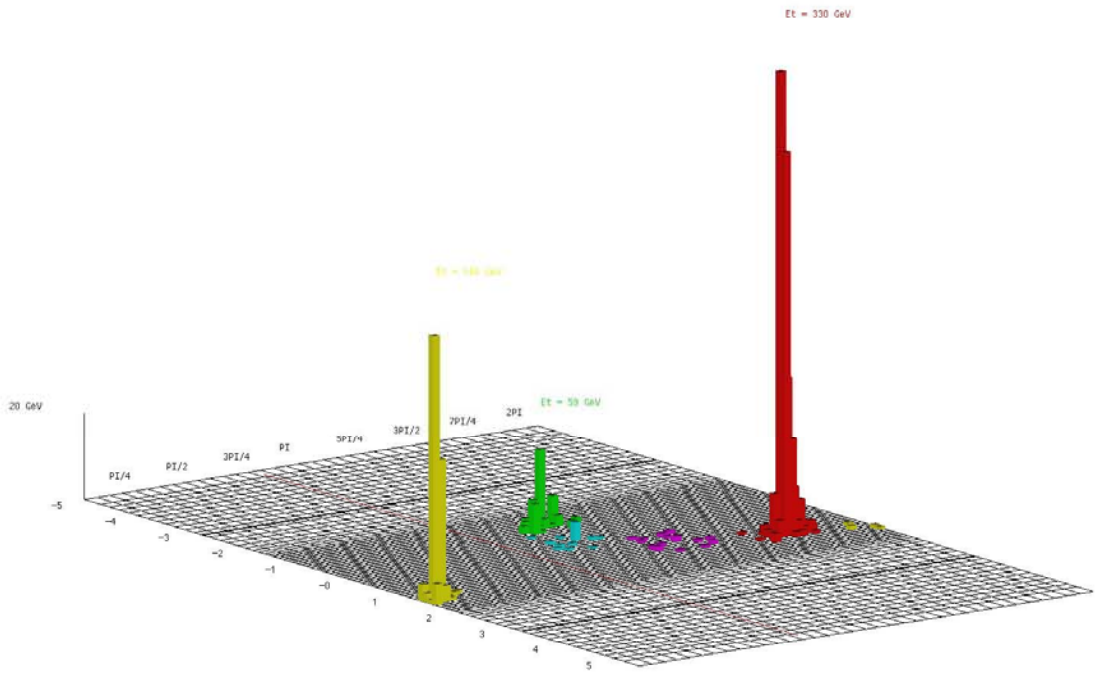
OBSERVER STATES 2530	
INDIA	191
ISRAEL	48
JAPAN	209
RUSSIA	983
TURKEY	103
USA	996

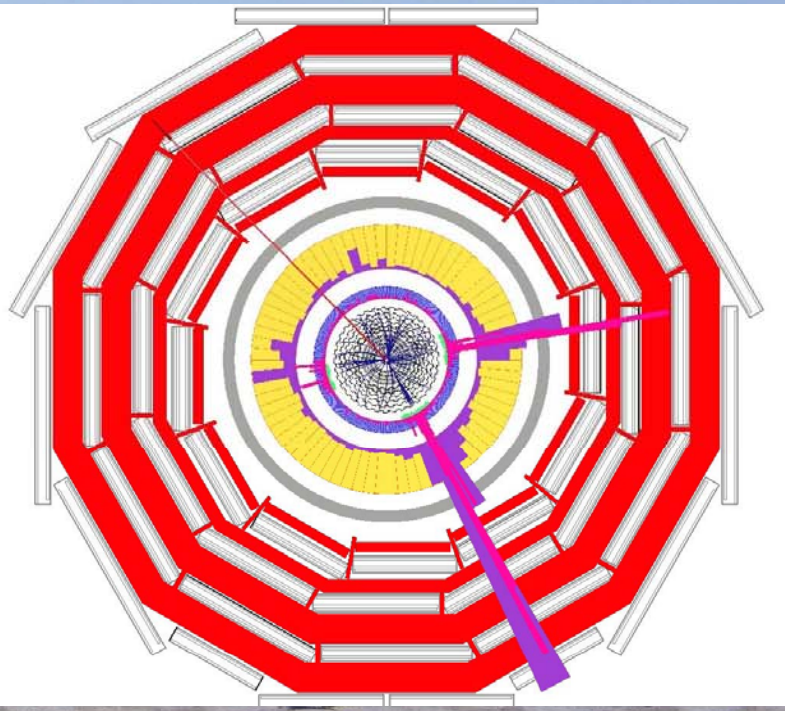
OTHERS 1280											
		BRAZIL	79	ESTONIA	12	KOREA REP.	86	MONGOLIA	1	SINGAPORE	3
		CANADA	151	ETHIOPIA	1	KYRGYZSTAN	1	MOROCCO	17	SLOVENIA	26
ALBANIA	3	CHILE	3	GEORGIA	35	LEBANON	8	NEPAL	3	SOUTH AFRICA	10
ALGERIA	9	CHINA	203	GIBRALTAR	2	LITHUANIA	14	NEW ZEALAND	8	SRI LANKA	6
ARGENTINA	10	CHINA (TAIPEI)	38	HONG KONG	2	LUXEMBOURG	4	PAKISTAN	41	SYRIA	2
ARMENIA	21	COLOMBIA	25	ICELAND	1	LIBYA	1	PALESTINE (O.T.).	2	TANZANIA	1
AUSTRALIA	18	COSTA RICA	1	INDONESIA	2	MACEDONIA F.Y.R.	1	PERU	2	THAILAND	3
AZERBAIJAN	5	CROATIA	21	IRAN	21	MADAGASCAR	3	QATAR	1	TUNISIA	6
BANGLADESH	3	CUBA	4	IRAQ	1	MALAYSIA	8	ROMANIA	100	UKRAINE	46
BELARUS	37	CYPRUS	13	IRELAND	23	MALTA	2	SAN MARINO	1	UZBEKISTAN	2
BOLIVIA	2	ECUADOR	2	JORDAN	3	MAURITIUS	1	SAUDI ARABIA	3	VENEZUELA	7
BOSNIA AND HERZEGOVINA	1	EGYPT	7	KENYA	1	MEXICO	49	SENEGAL	1	VIET NAM	8
		EL SALVADOR	1	KOREA, D.P.R.	3	MOLDOVA	2	SERBIA	36		

A Simulated Higgs Event



Looking for Dark Matter

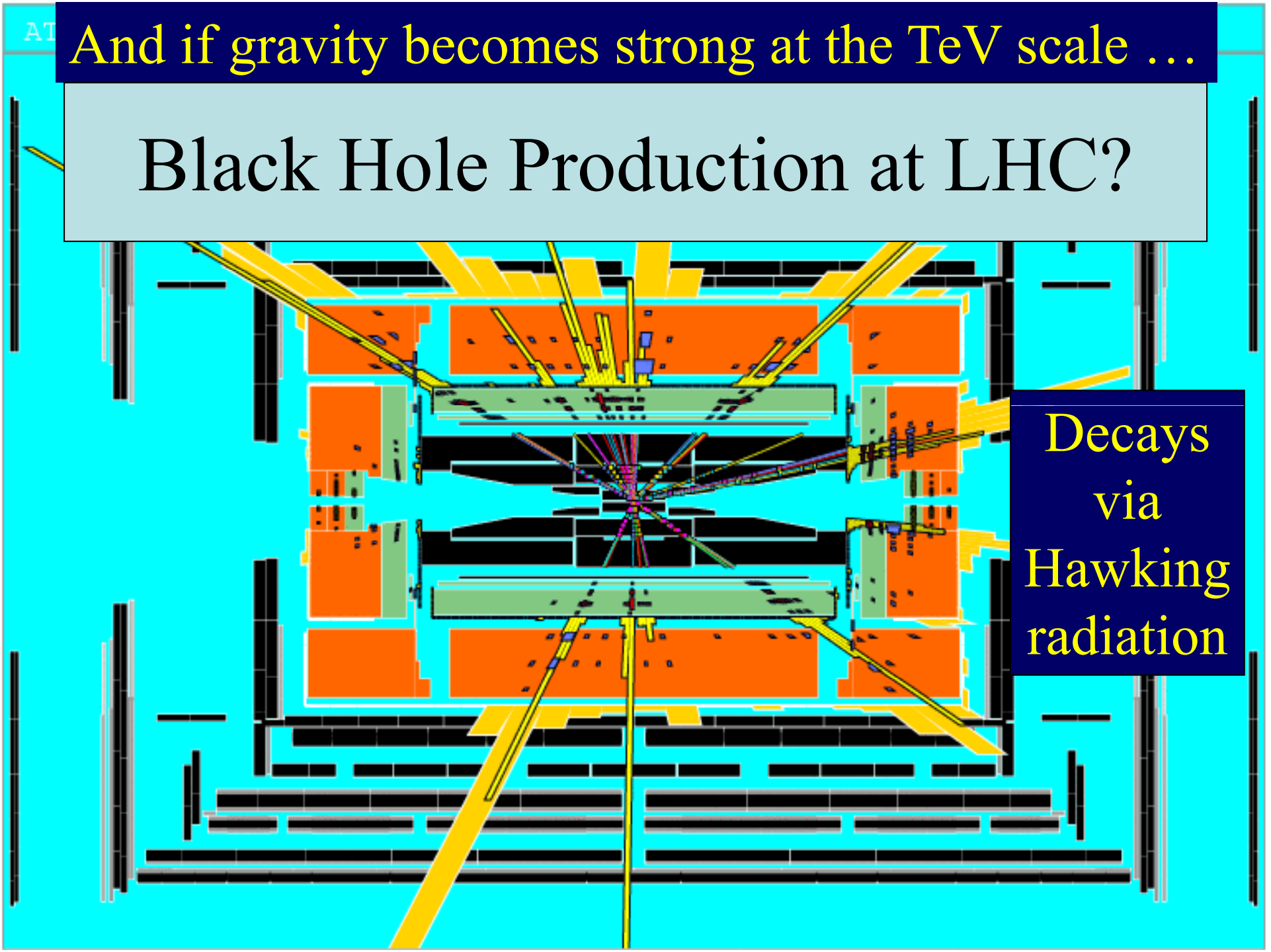




Missing energy
taken away by dark matter particles

And if gravity becomes strong at the TeV scale …

Black Hole Production at LHC?



Decays via Hawking radiation


Google
A billion people watched on TV

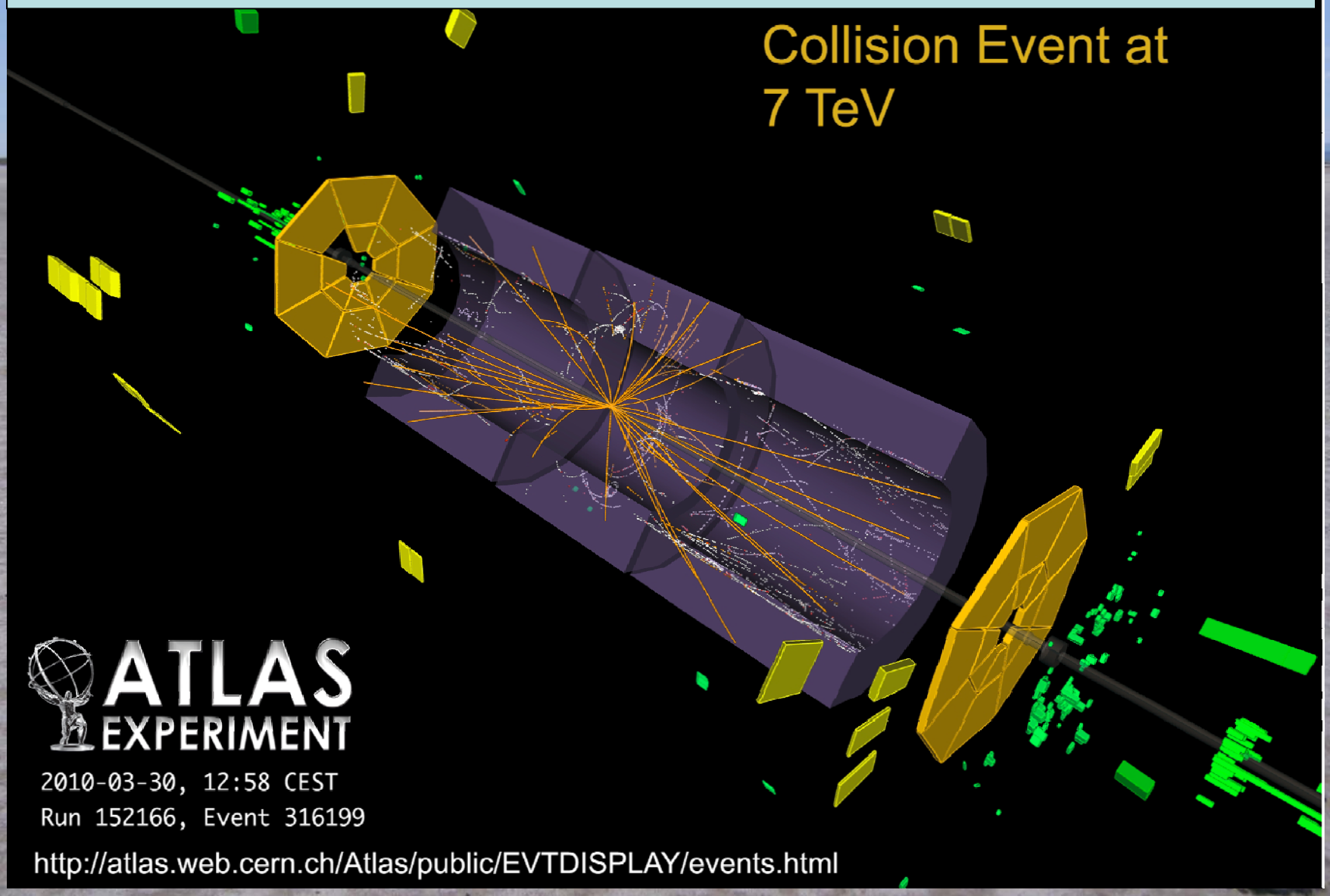
The LHC Enters Popular Culture

Concentration, Anxiety …

… and tense anticipation

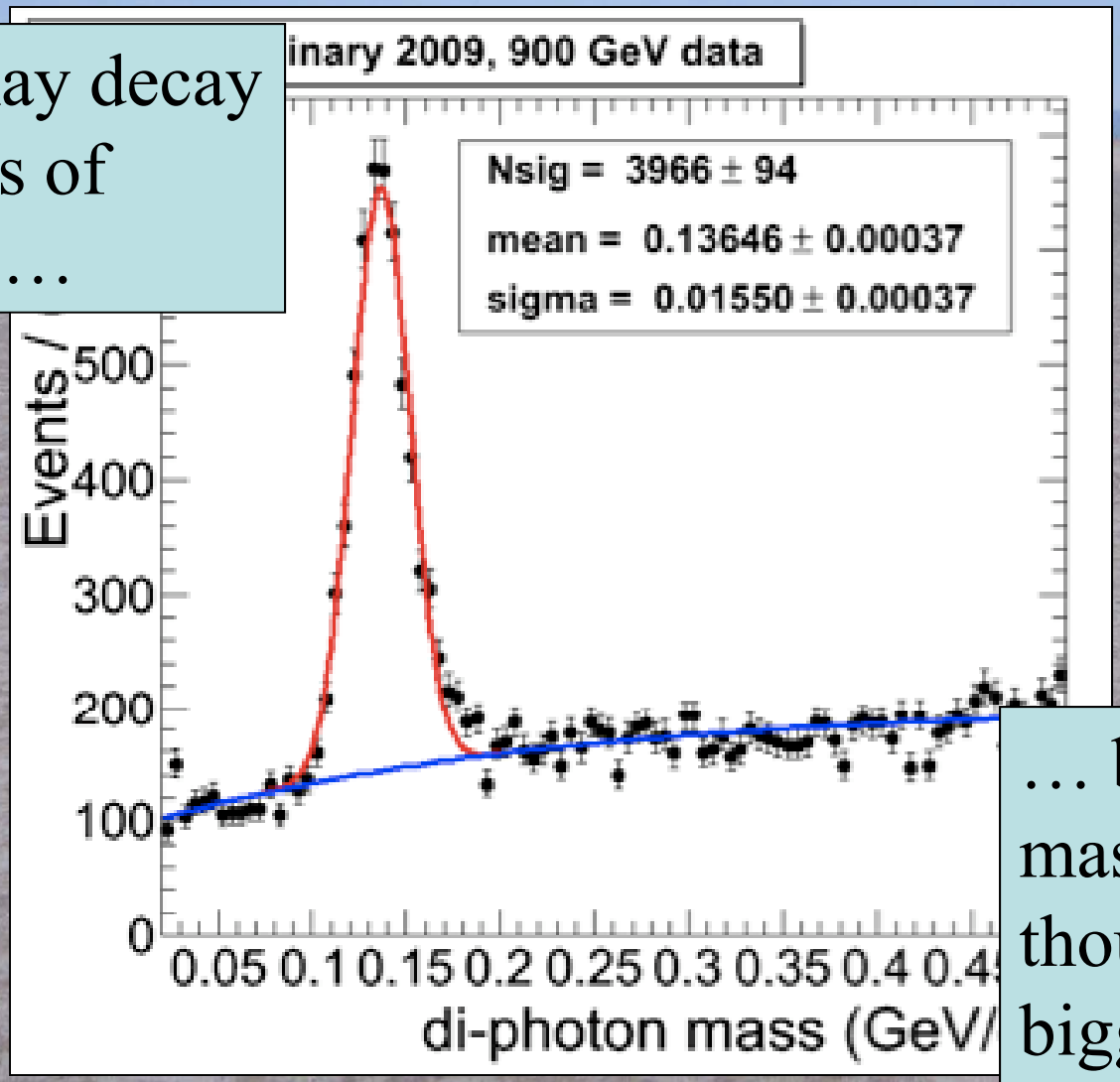
Nov. 20th 2009: Jubilation

First High-Energy LHC Collision

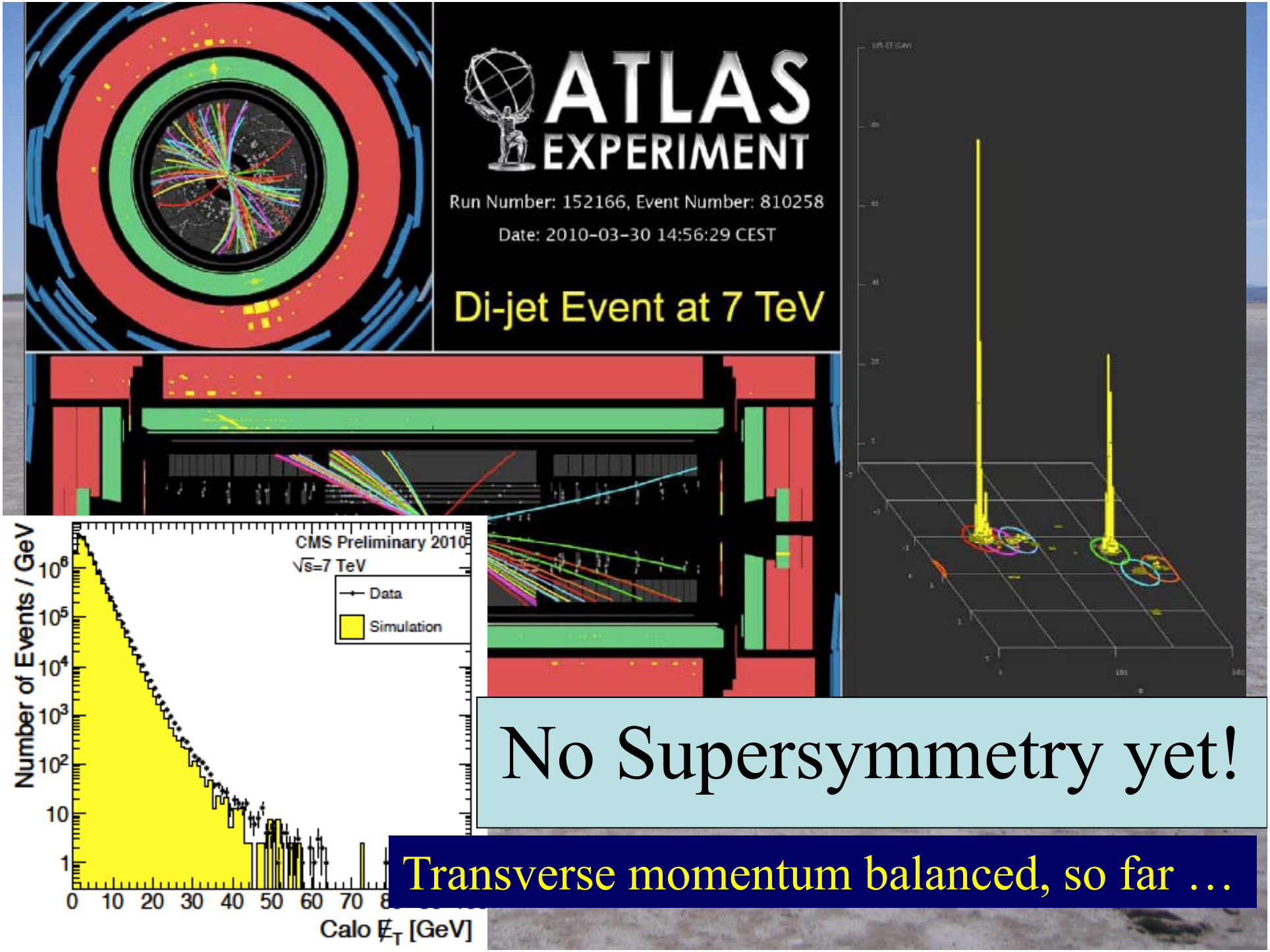


No Higgs yet!

Higgs may decay into pairs of photons …

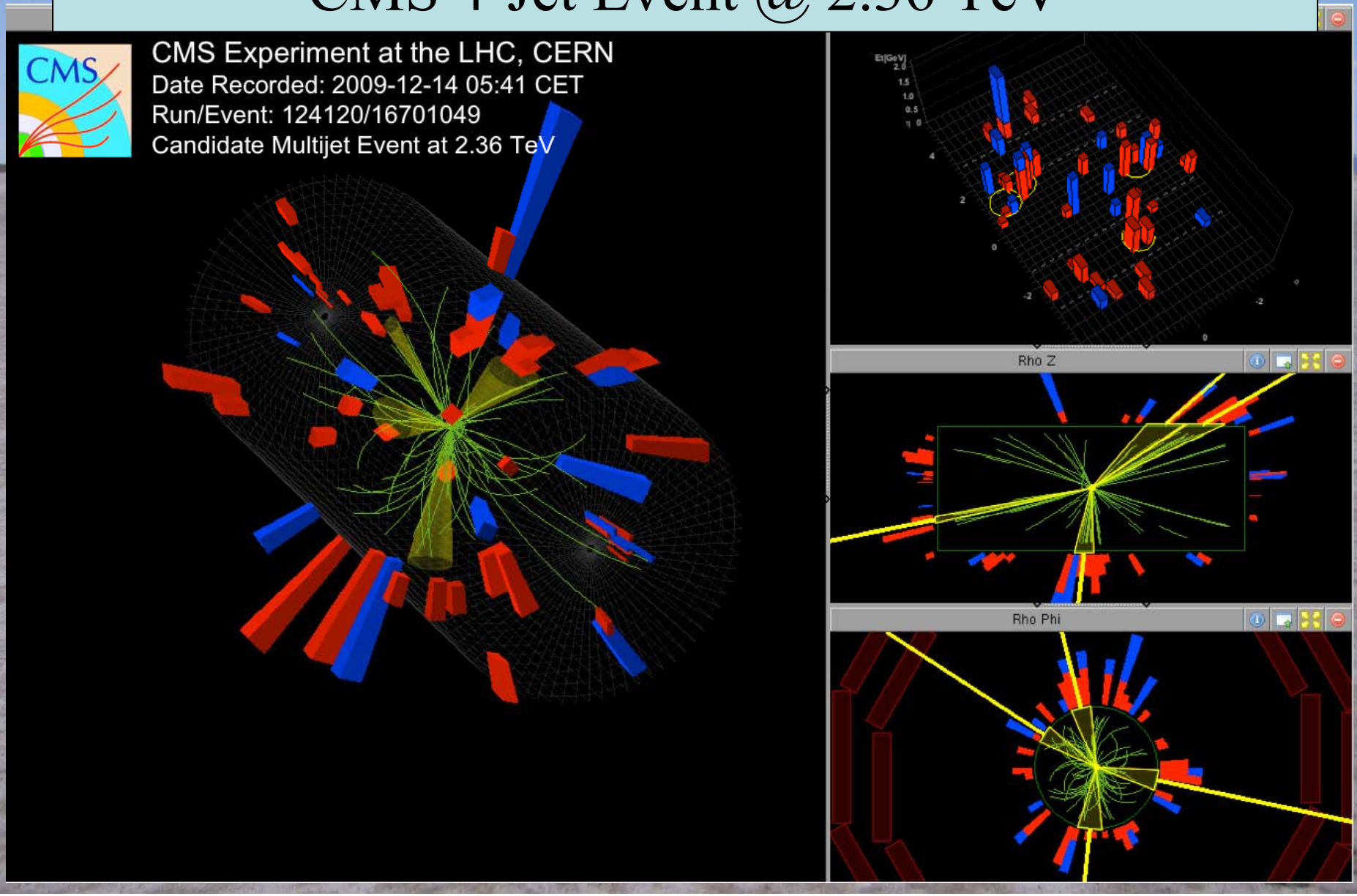


… but the Higgs mass is about a thousand times bigger!

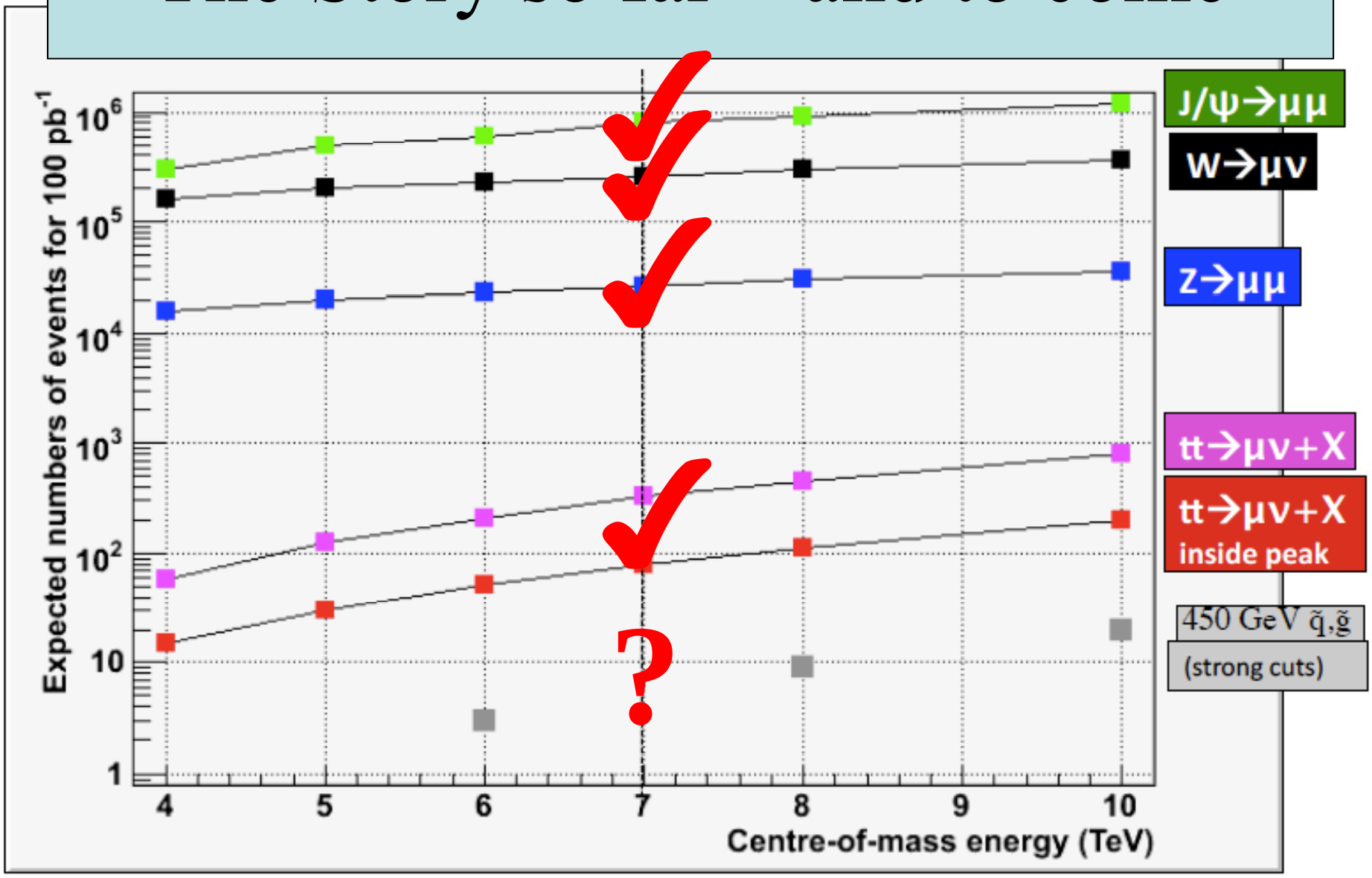

ATLAS
EXPERIMENT
Run Number: 152166, Event Number: 810258
Date: 2010-03-30 14:56:29 CEST
Di-jet Event at 7 TeV
CMS Preliminary 2010
√s=7 TeV
Data
Simulation
Number of Events / GeV
Calo $\not\!\!E_T$ [GeV]
No Supersymmetry yet!
Transverse momentum balanced, so far …

No Black Holes yet!

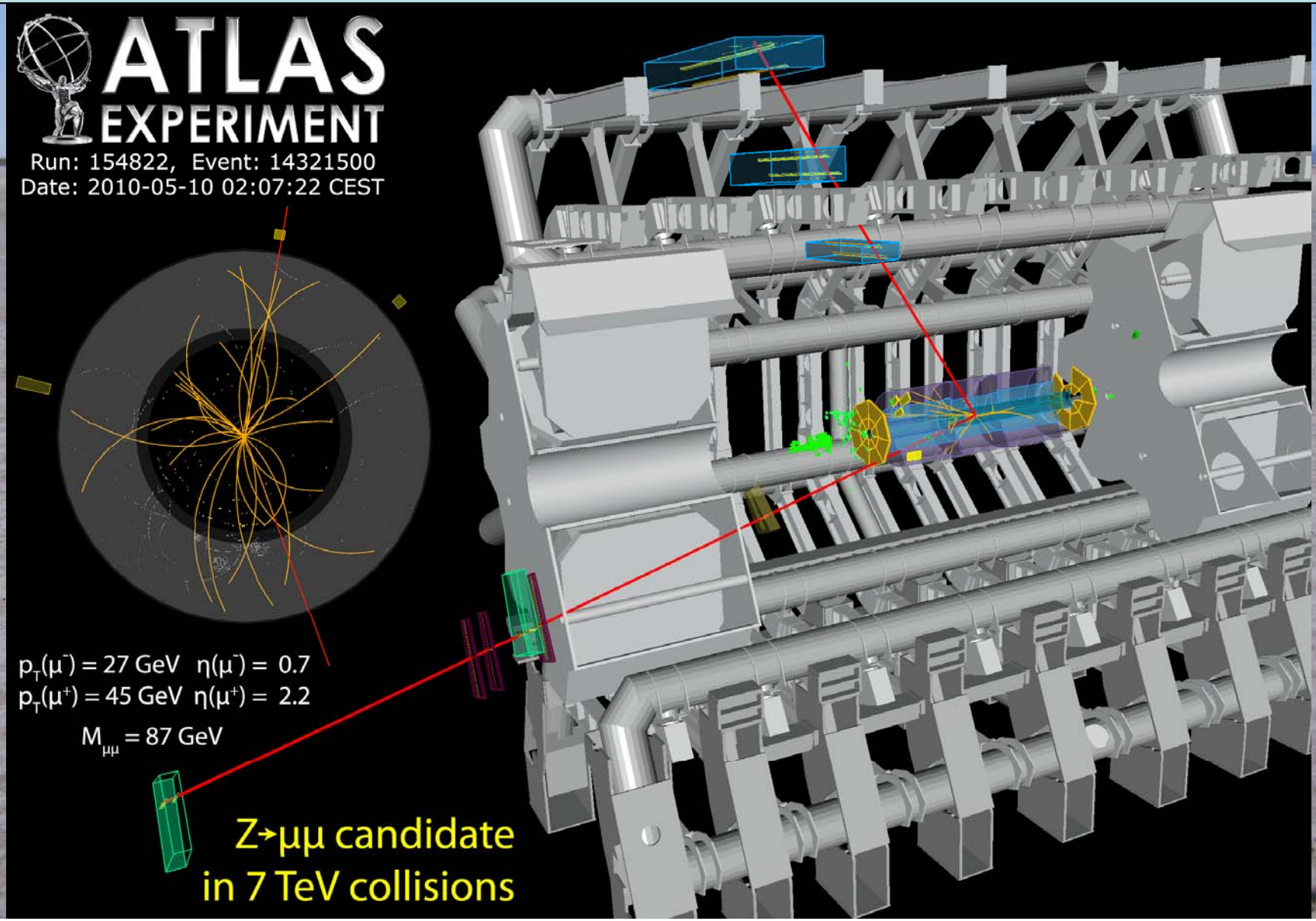
CMS 4-Jet Event @ 2.36 TeV



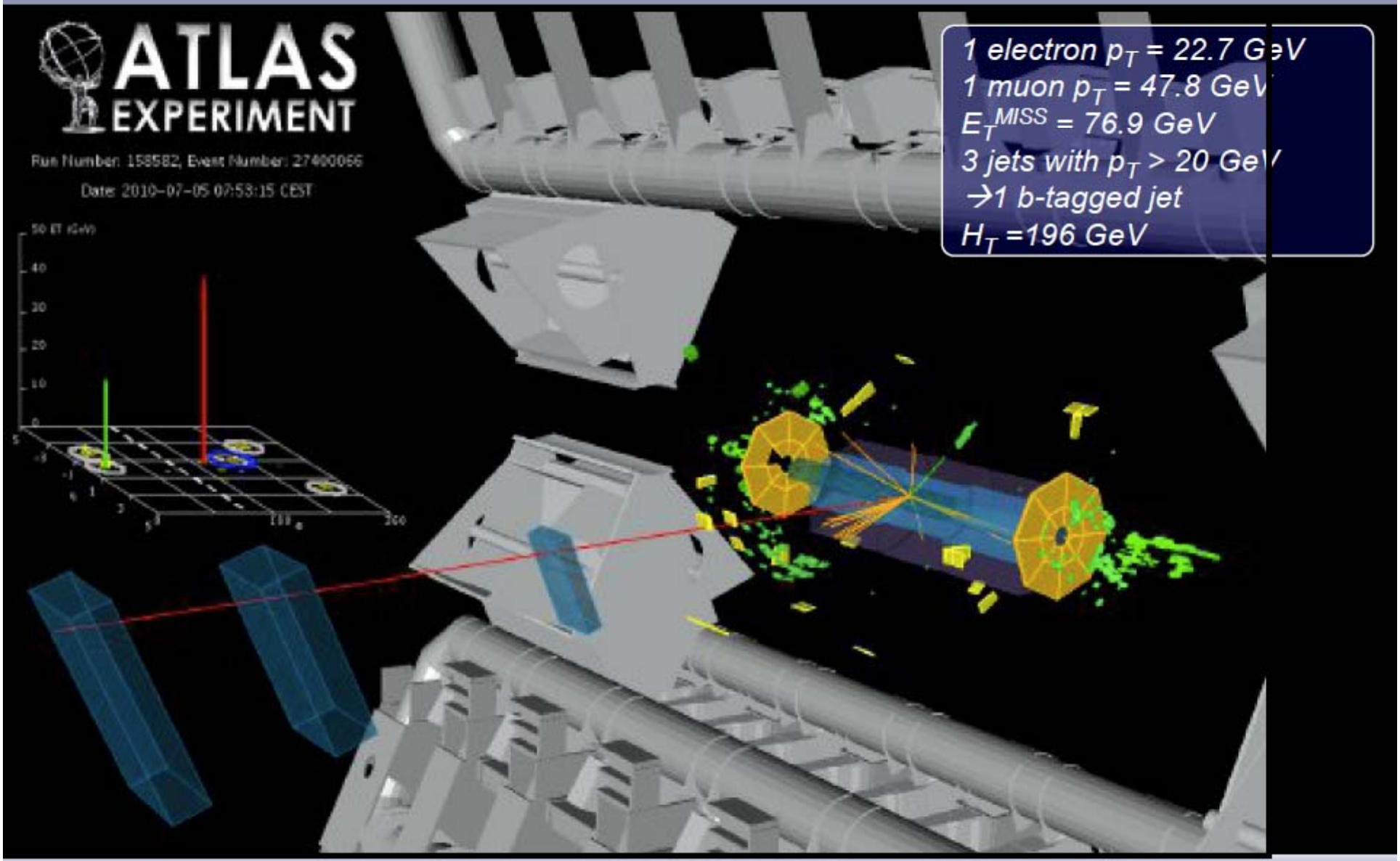
The Story so far – and to come



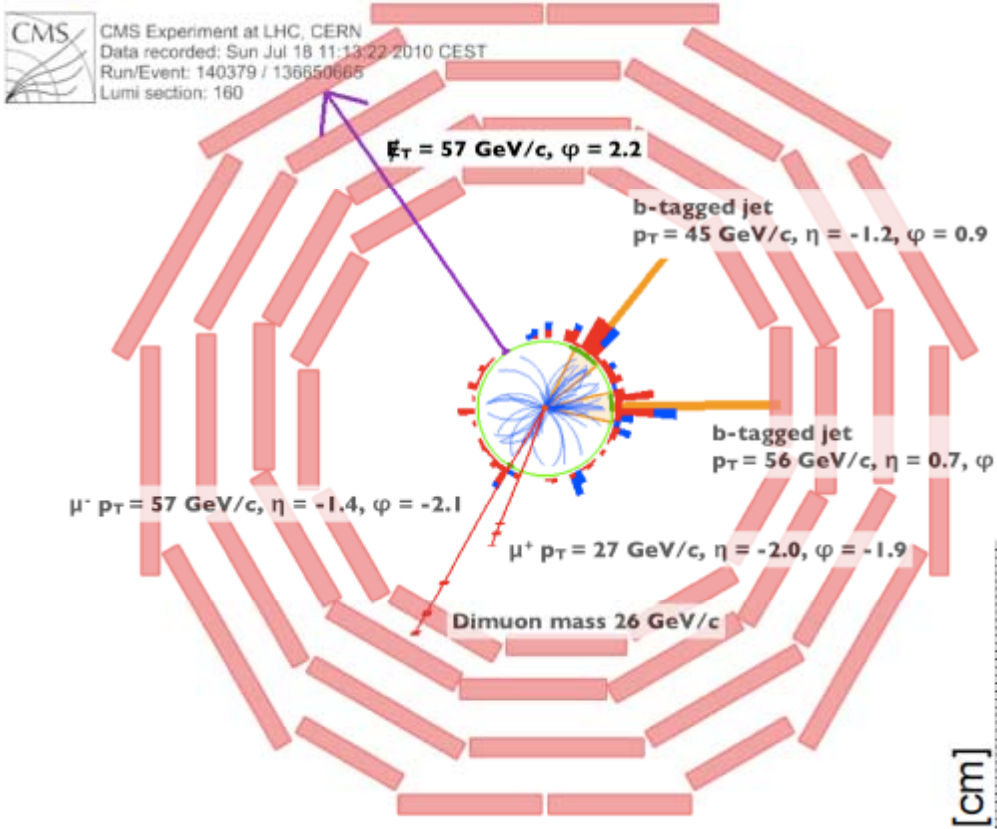
The Story so Far …



Top Pair Candidate in ATLAS



Top Pair Candidate in CMS

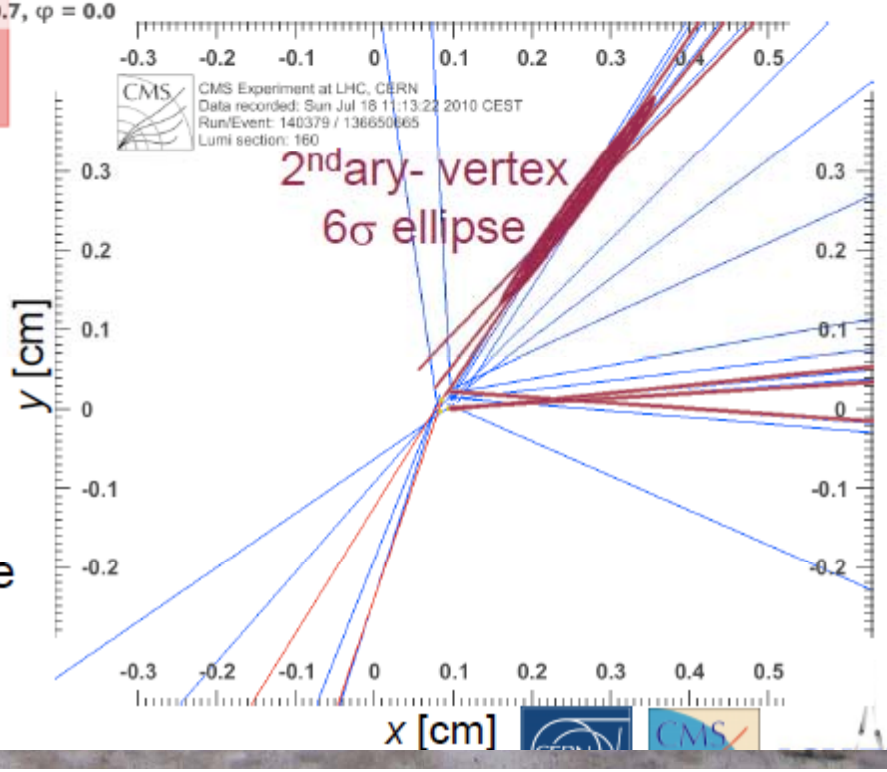


$m(\mu\mu) = 26\ \text{GeV}/c^2$

Preliminarily reconstr. mass is in the range 160–220 GeV/c^2 (consistent with m_{top})

Event passes all cuts of full selection:

2 muons with opposite charge
2 jets, both w/ good/clear *b*-tags (and secondary vertices!)
significant MET (>50 GeV)

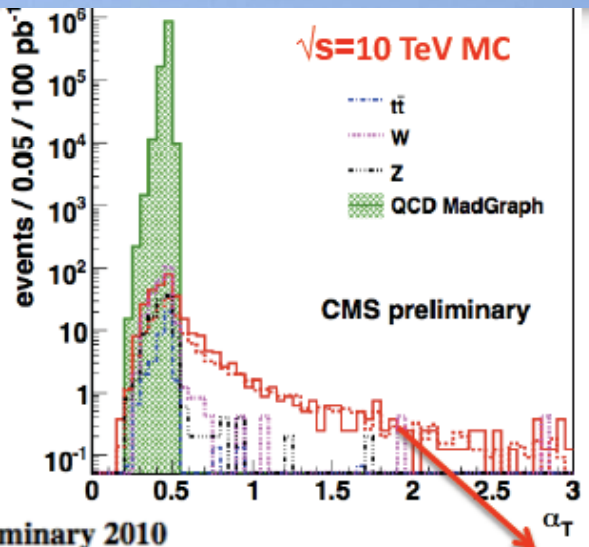


Supersymmetry Search in CMS

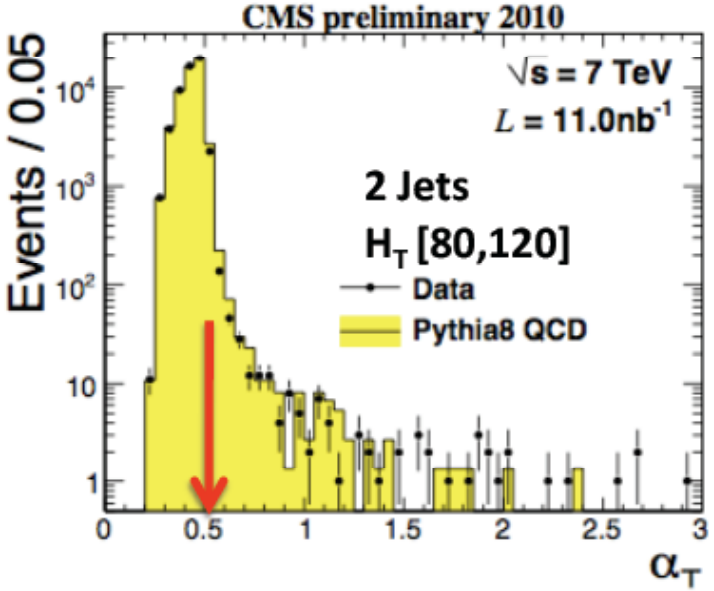
- A powerful variable for suppressing mis-measured QCD

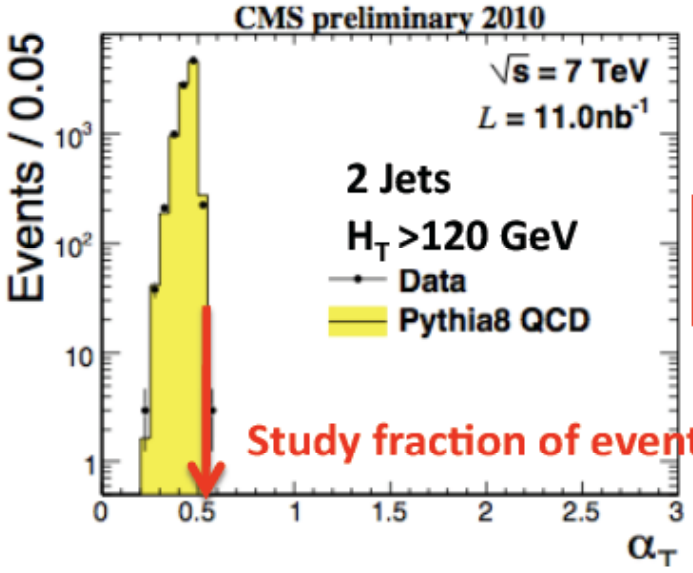
$$\alpha_T \equiv \frac{p_{T2}}{M_T} \qquad \alpha_T = \frac{\sqrt{p_{T2}/p_{T1}}}{\sqrt{2(1-\cos\Delta\phi)}}$$

- Well measured back-to-back di-jet system $\alpha_T \approx 0.5$, if one jet is mis-measured $\alpha_T < 0.5$



SUSY





$$H_T = \sum_i p_T(\text{jet}_i)$$

Study fraction of events with $\alpha_T > 0.55$

CERN's Basic Missions

- **Scientific research**

  & discovery!

- **Technological innovation**

  Spin-offs & industrial collaboration

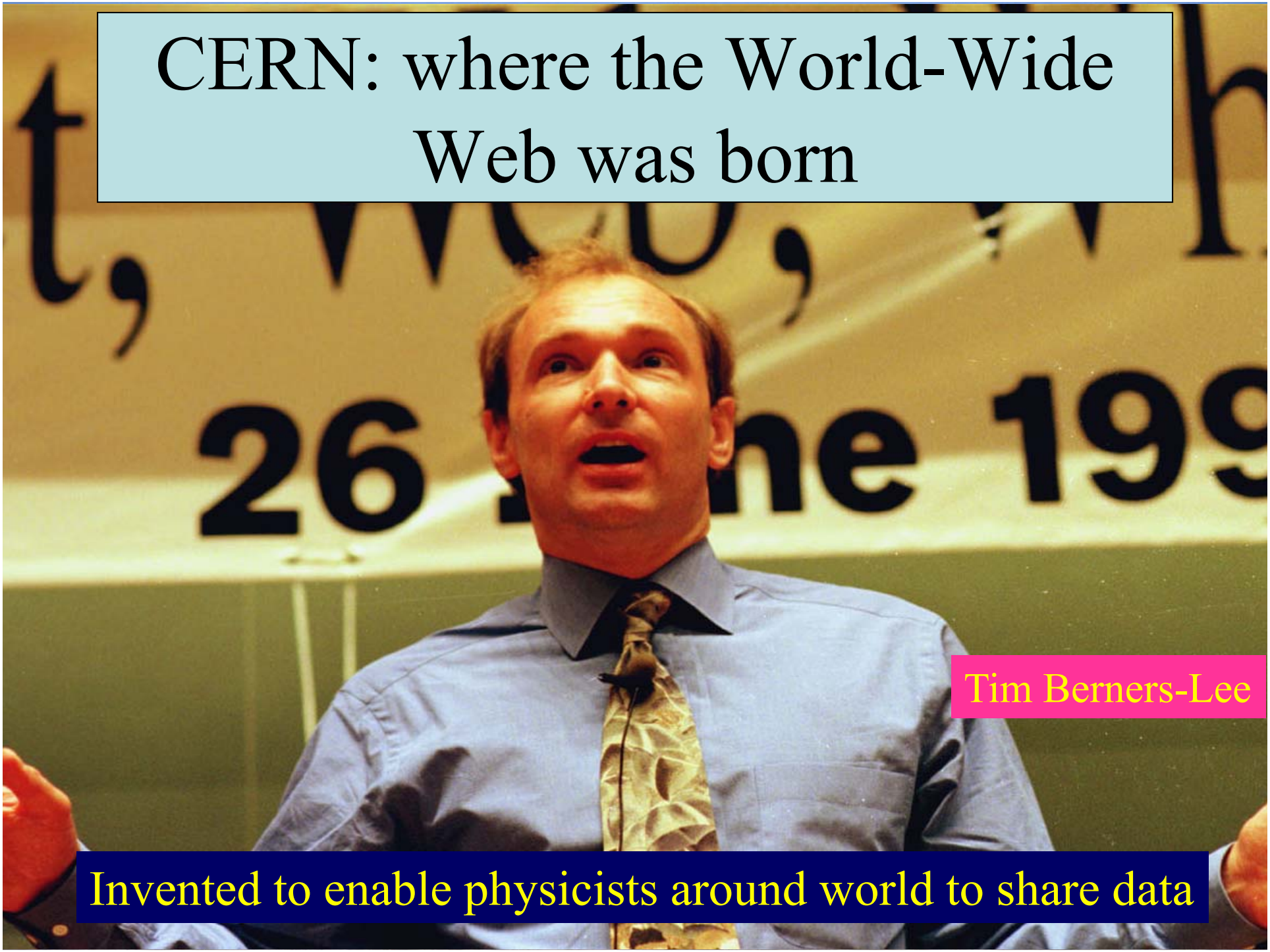
- **Advanced training**

  Many aspects of human resource development

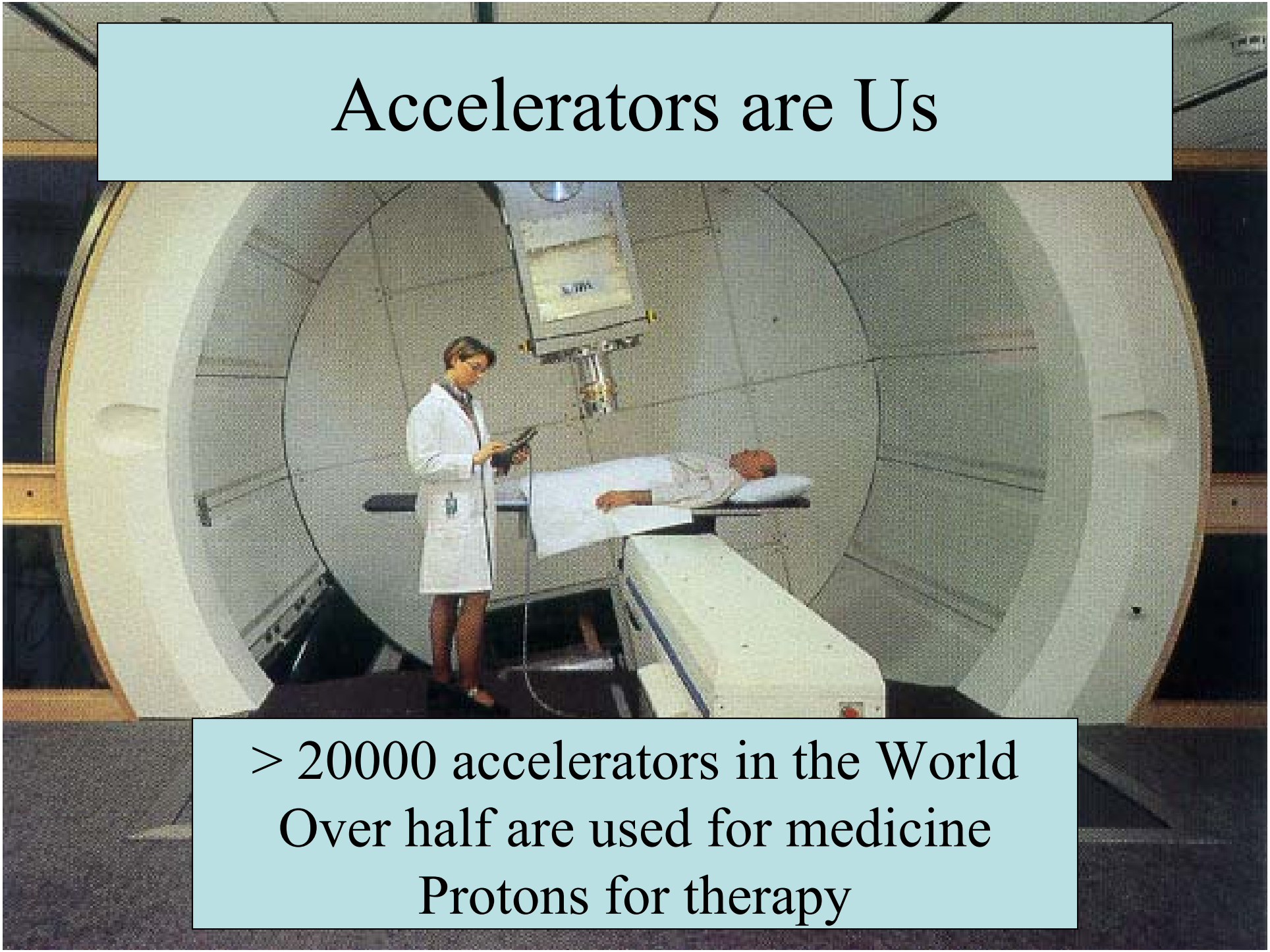
- **International collaboration**

  Member and non-member states

CERN: where the World-Wide Web was born

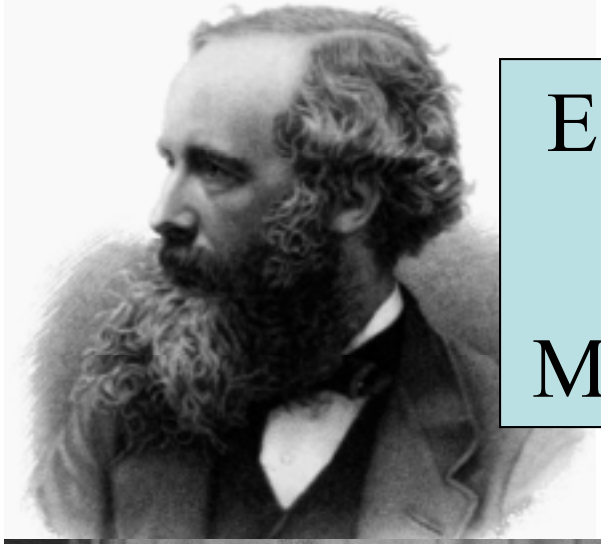


Accelerators are Us

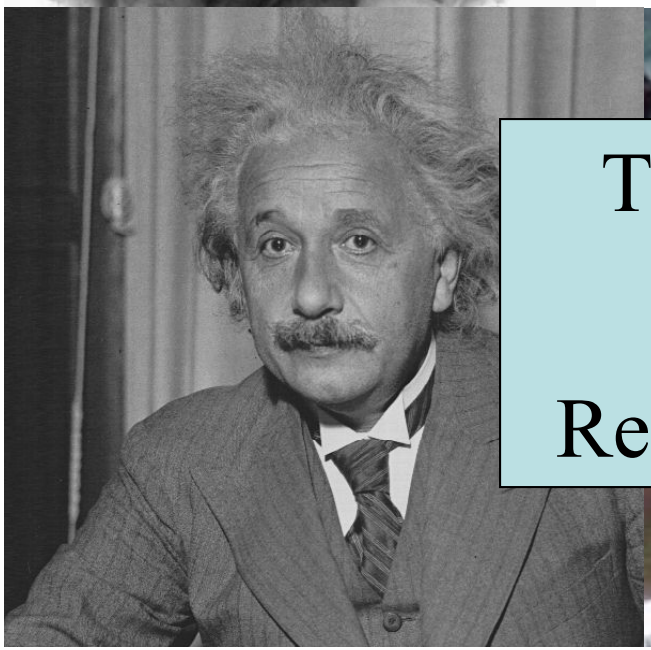


> 20000 accelerators in the World
Over half are used for medicine
Protons for therapy

Innovation is based on Fundamental Science

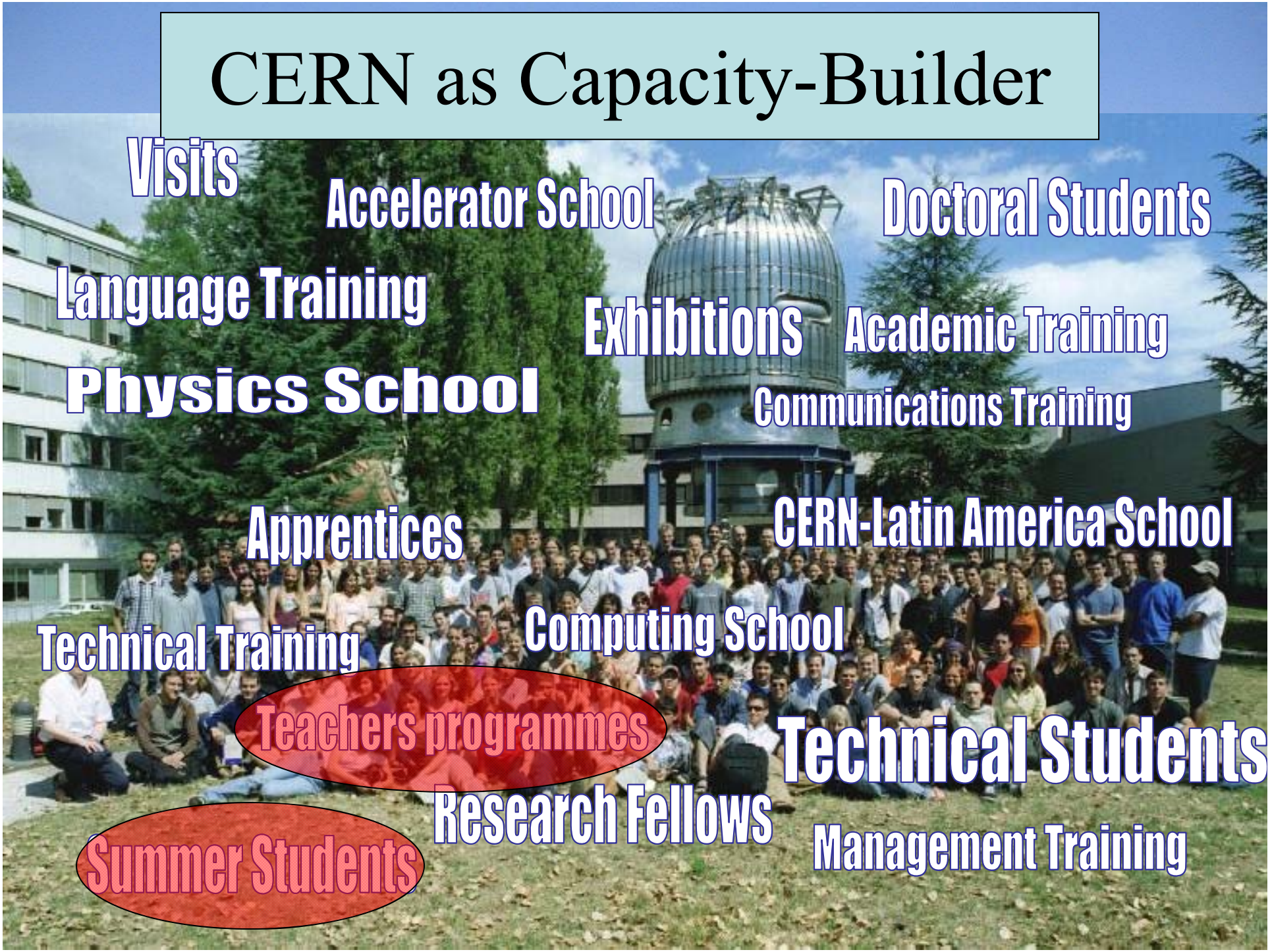


Electricity and Magnetism

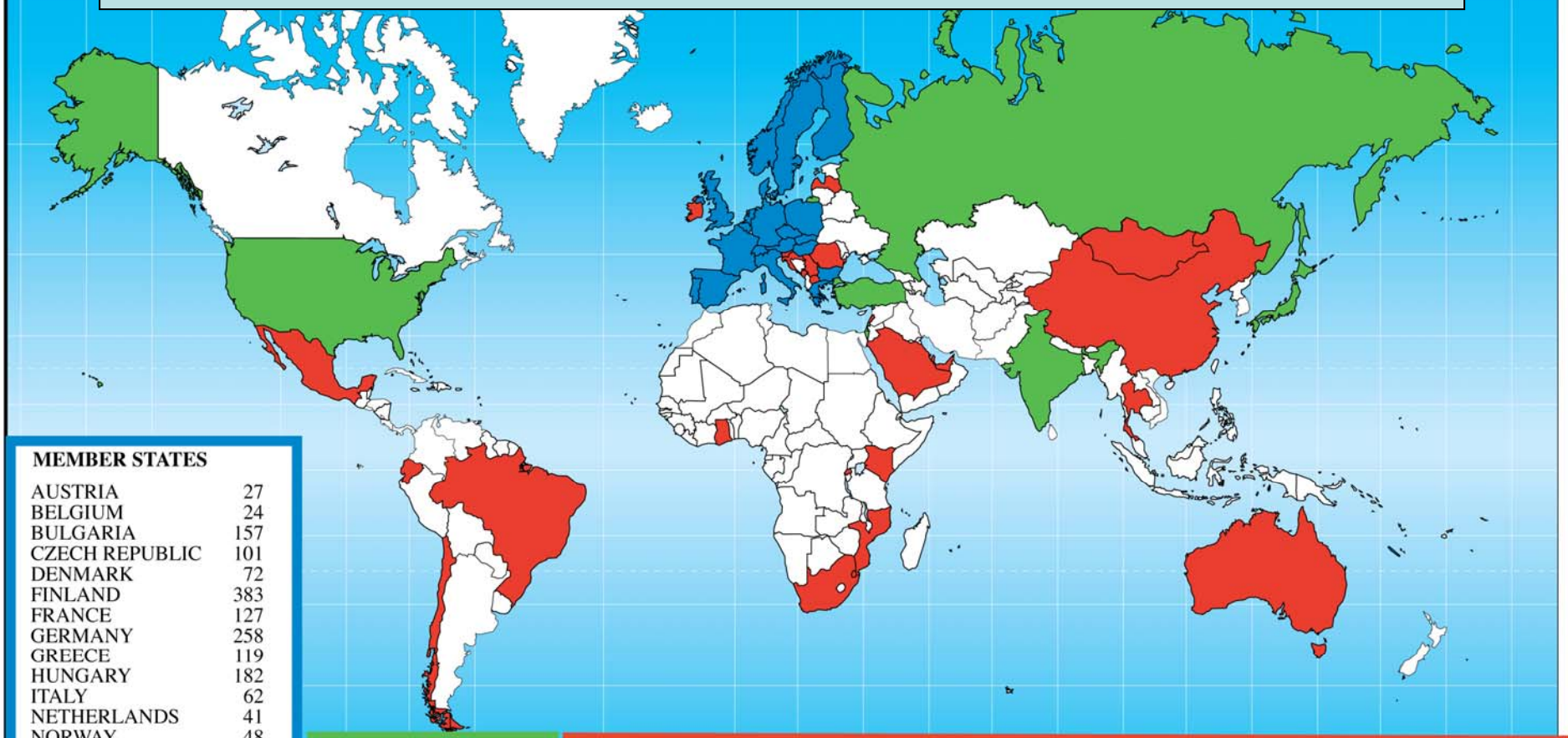


Theory of Relativity

CERN as Capacity-Builder



Teachers from around the World



MEMBER STATES

AUSTRIA	27
BELGIUM	24
BULGARIA	157
CZECH REPUBLIC	101
DENMARK	72
FINLAND	383
FRANCE	127
GERMANY	258
GREECE	119
HUNGARY	182
ITALY	62
NETHERLANDS	41
NORWAY	48
POLAND	460
PORTUGAL	167
SLOVAKIA	189
SPAIN	168
SWEDEN	79
SWITZERLAND	12
UNITED KINGDOM	567

3243

OBSERVER STATES

INDIA	2
ISRAEL	1
JAPAN	2
RUSSIA	48
TURKEY	2
USA	51

106

OTHERS

AUSTRALIA	1	IRELAND	3	MONTENEGRO	13	SLOVENIA	21
AZERBAIJAN	1	KENYA	1	MOZAMBIQUE	5	SOUTH AFRICA	6
BRAZIL	12	LATVIA	1	QATAR	1	SWAZILAND	1
CHILE	3	LEBANON	1	ROMANIA	7	THAILAND	2
CHINA	1	MACEDONIA	11	RWANDA	7	U.A.E.	1
CROATIA	1	MALTA	36	SAUDI ARABIA	1		
ECUADOR	1	MEXICO	5	SERBIA	10		
GHANA	2	MONGOLIA	1	SINGAPORE	2		

158

2010 Summer Students from around the World

MEMBER & OBSERVER STATES 157

AUSTRIA	3
BELGIUM	3
BULGARIA	3
CZECH REPUBLIC	6
DENMARK	6
FINLAND	2
FRANCE	14
GERMANY	20
GREECE	5
HUNGARY	2
ISRAEL	4
ITALY	11
JAPAN	5
NETHERLANDS	9
NORWAY	3
POLAND	5
PORTUGAL	3
SLOVAKIA	2
SPAIN	9
SWEDEN	7
SWITZERLAND	3
UNITED KINGDOM	15
USA	17

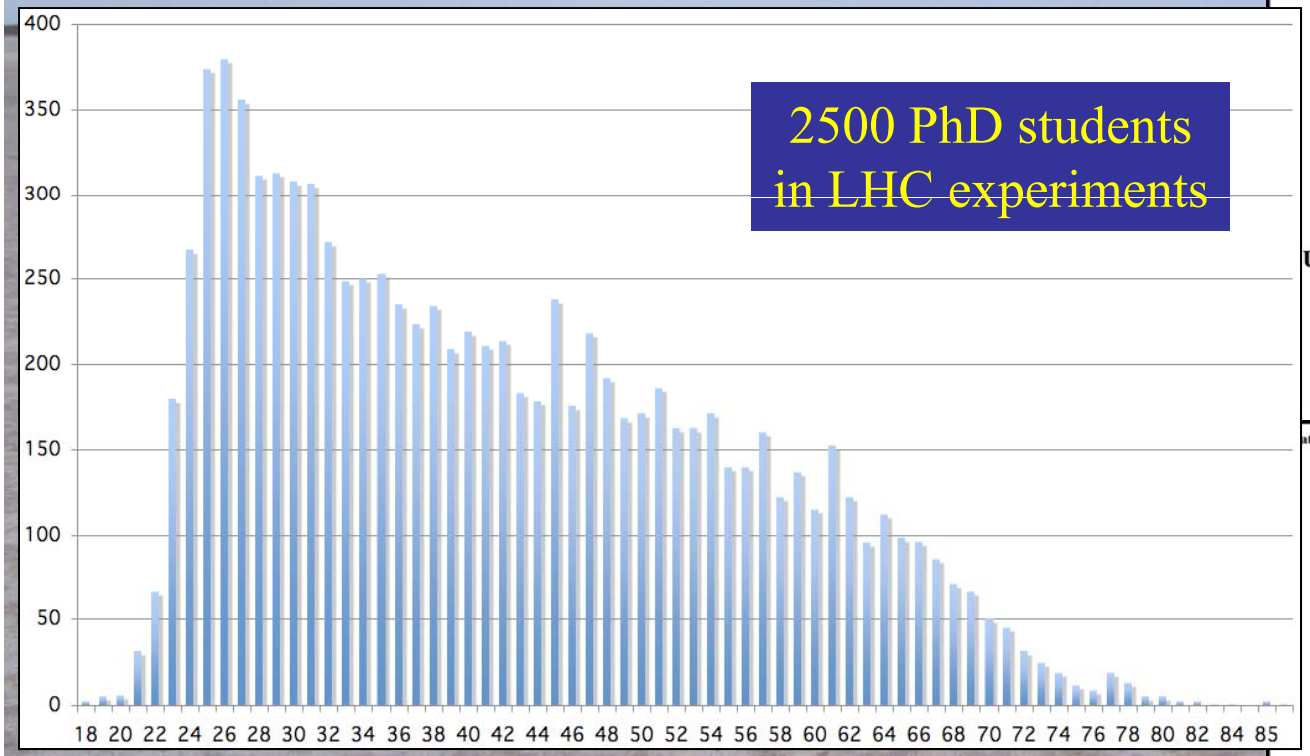
NON-MEMBER STATES 93

ALGERIA	2	CAMEROON	1	INDIA	8	MALTA	3	SERBIA	1
ARMENIA	2	CANADA	5	IRELAND	1	MEXICO	2	SINGAPORE	1
AUSTRALIA	2	CHINA	2	JORDAN	1	PAKISTAN	6	SLOVENIA	1
AZERBAIJAN	1	CROATIA	4	KAZAKHSTAN	1	PHILIPPINES	1	SOUTH AFRICA	1
BOLIVIA	1	EGYPT	1	LEBANON	1	ROMANIA	1	SOUTH KOREA	1
BOSNIA & HERZEGOVINA	2	ESTONIA	2	MACEDONIA	2	RUSSIA	9	THAILAND	2
BRAZIL	2	GHANA	1	MADAGASCAR	2	RWANDA	1	TURKEY	10
		GIBRALTA	1	MALAYSIA	1	SAUDI ARABIA	2	VIETNAM	4
		ICELAND	1						

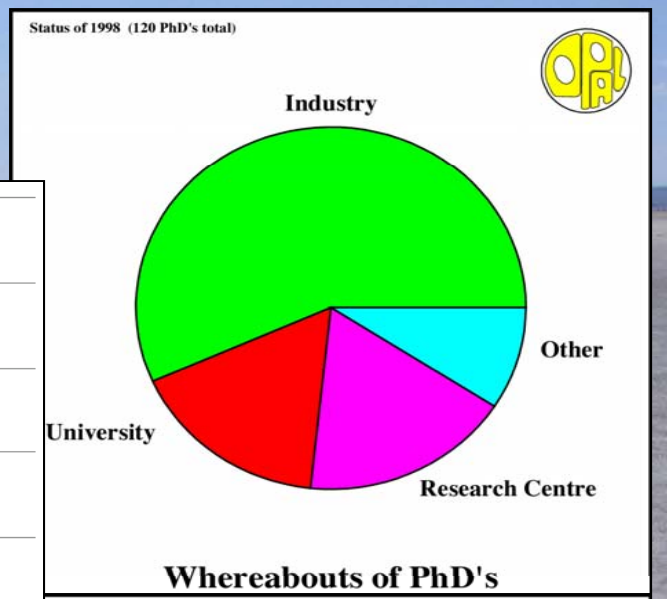
Age Distribution of Scientists

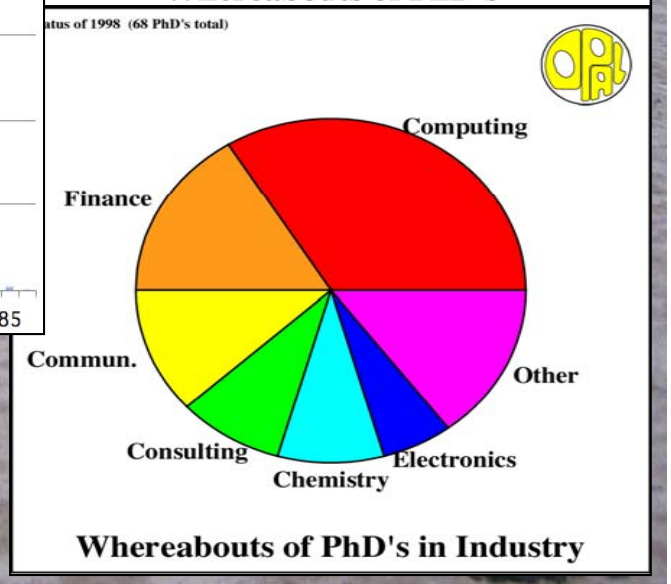
- and where they go afterwards

Survey in March 2009



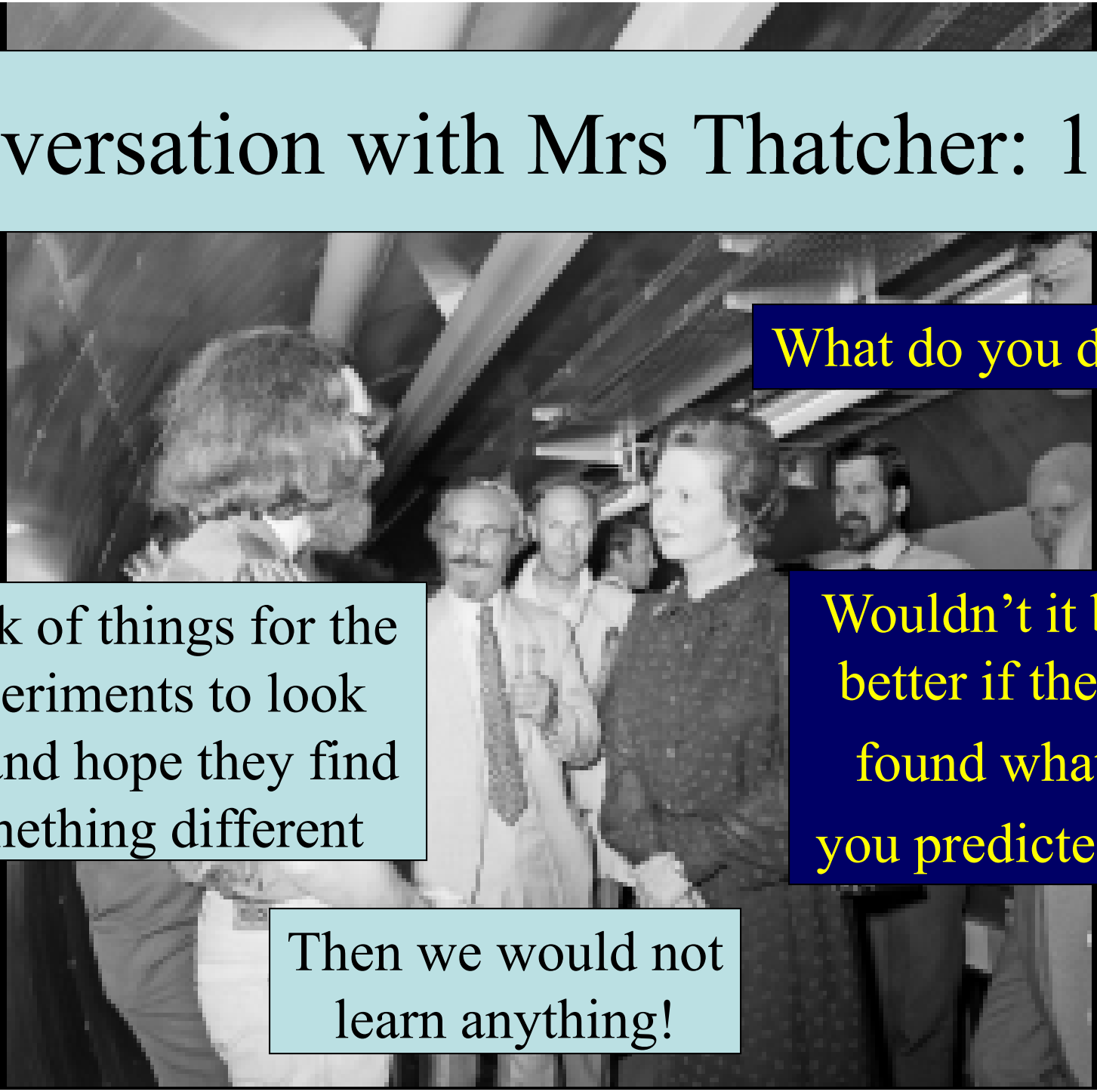
2500 PhD students in LHC experiments





They do not all stay: where do they go?

Conversation with Mrs Thatcher: 1982



What do you do?

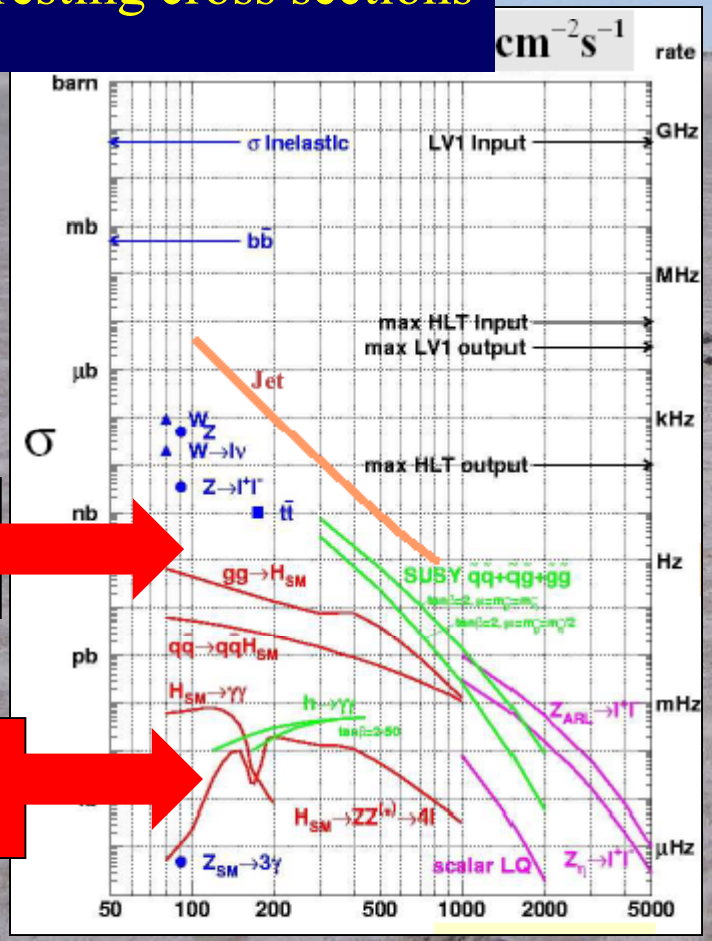
Think of things for the experiments to look for, and hope they find something different

Wouldn't it be better if they found what you predicted?

Then we would not learn anything!

The LHC Physics Haystack(s)

Interesting cross sections



Susy

Higgs

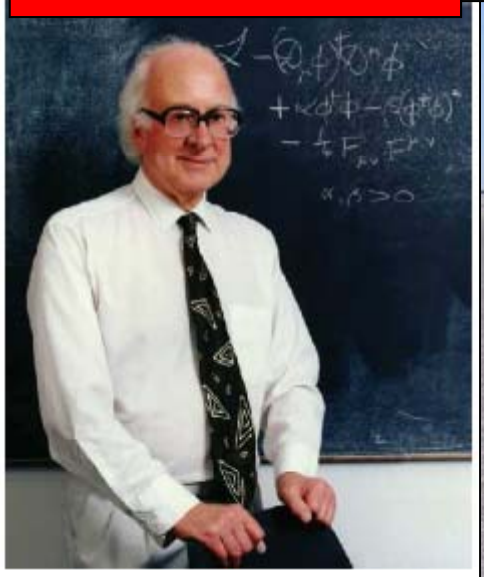
- Cross sections for heavy particles
  ~ 1 /(1 TeV)^2
- Most have small couplings ~ α^2
- Compare with total cross section
  ~ 1/(100 MeV)^2
- Fraction ~ 1/1,000,000,000,000
- Need ~ 1,000 events for signal
- Compare needle
  ~ 1/100,000,000 m^3
- Haystack ~ 100 m^3
- Must look in ~ 100,000 haystacks

The LHC Roulette Wheel

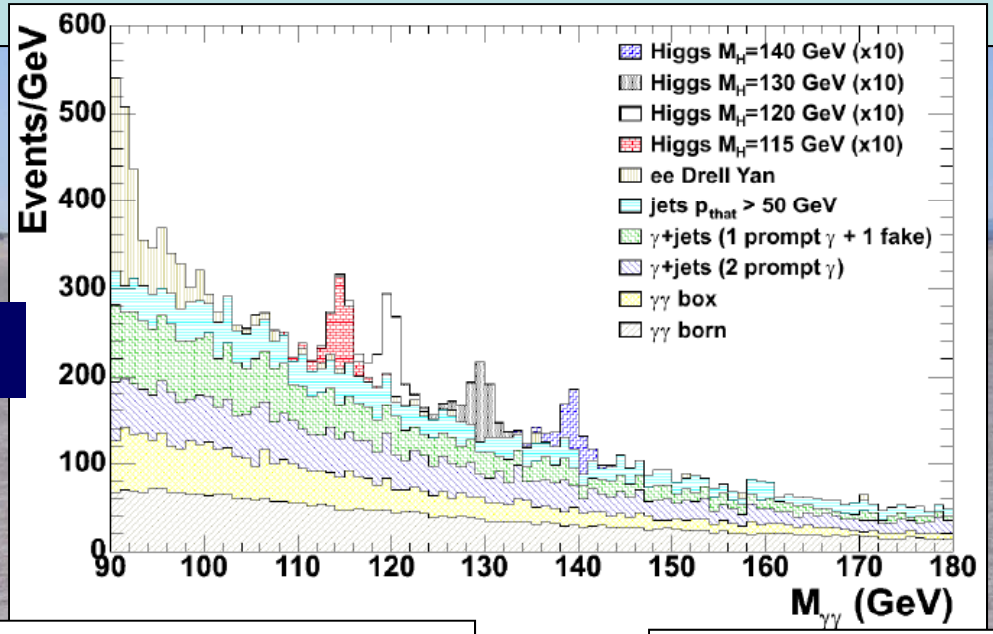
Higgs boson

A la recherche
du
Higgs perdu …

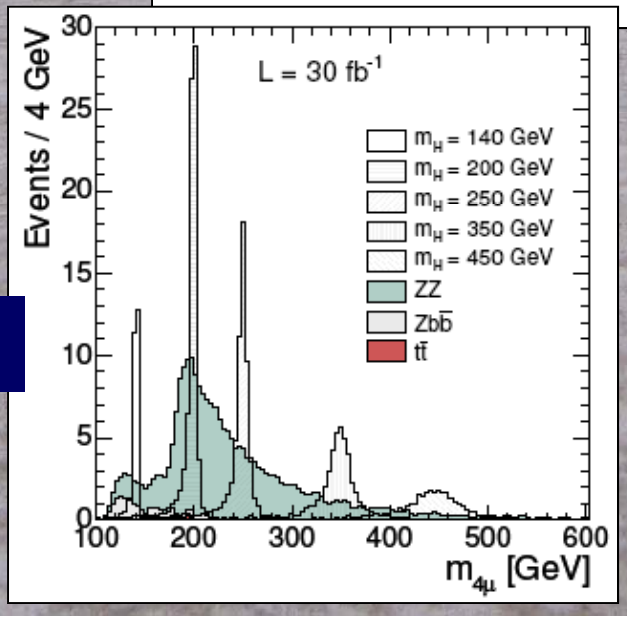
Some Sample Higgs Signals



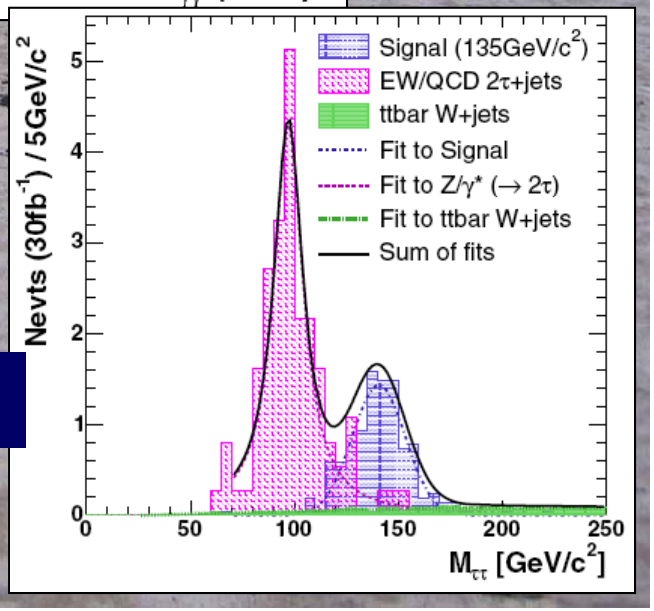
$\gamma\gamma$



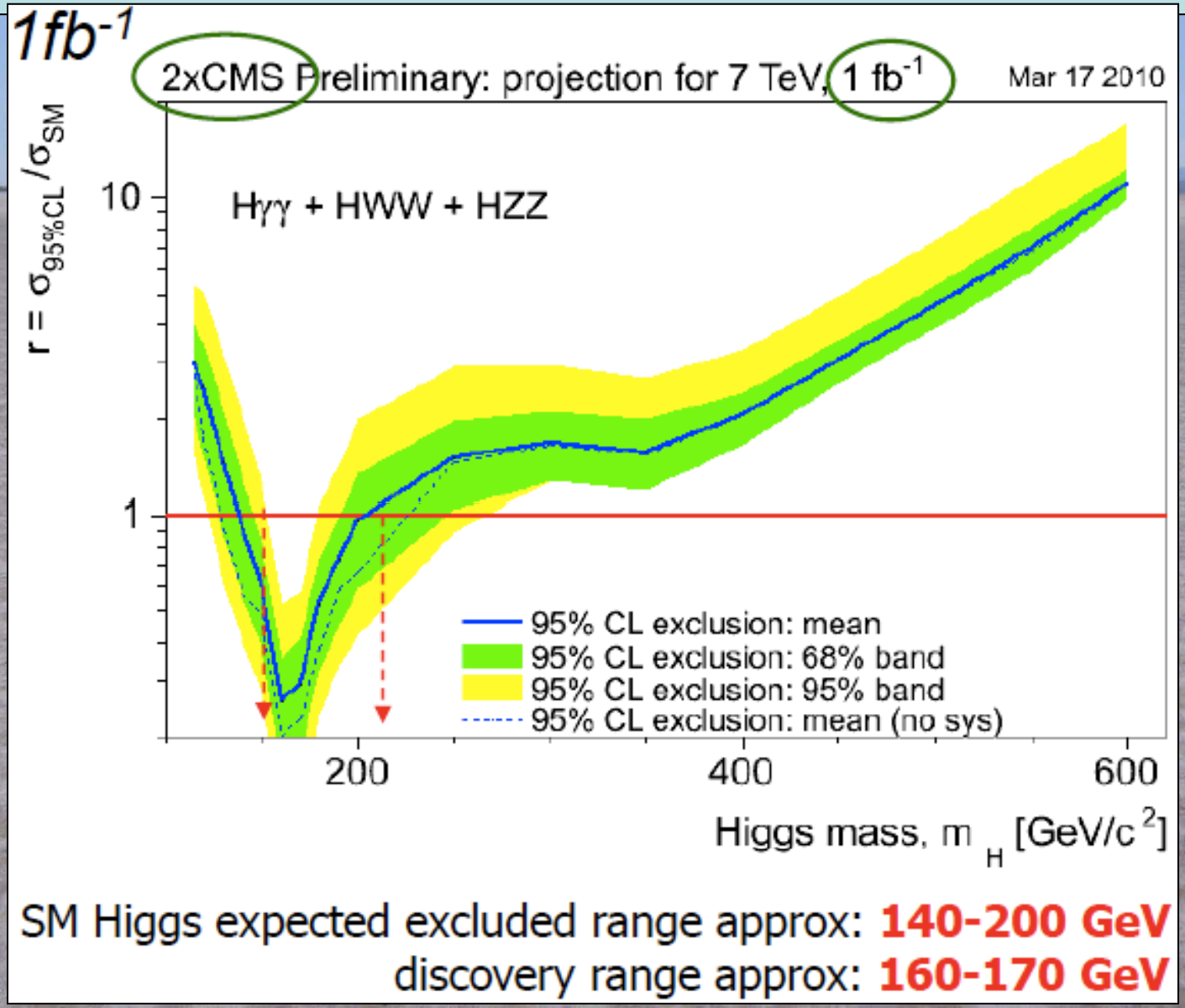
ZZ* -> 4 leptons



$\tau\tau$



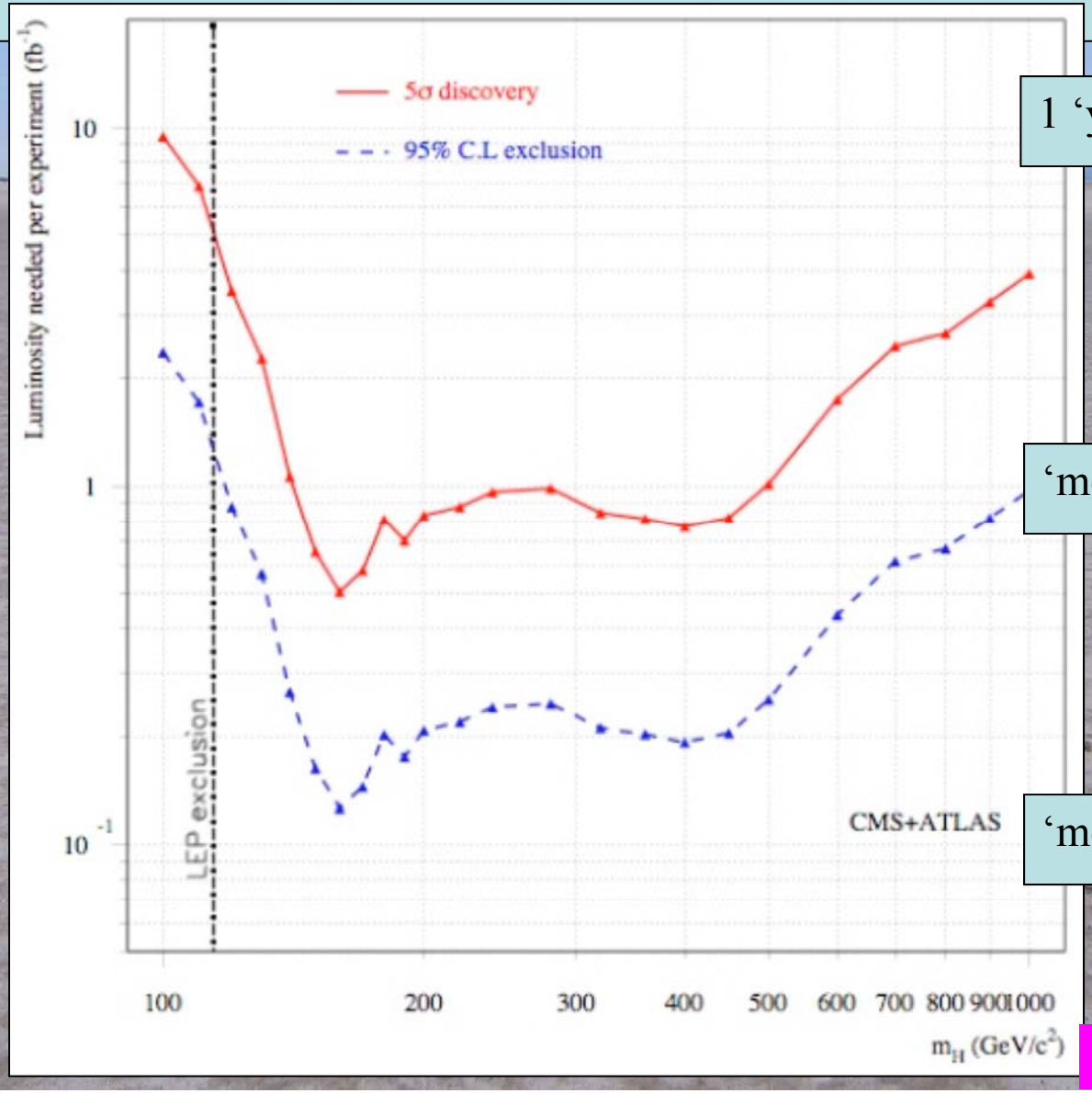
Higgs Search @ 7 TeV



SM Higgs expected excluded range approx: **140-200 GeV**

discovery range approx: **160-170 GeV**

When will the LHC discover the Higgs boson?



1 'year' @ 10^{33}

'month' @ 10^{33}

'month' @ 10^{32}

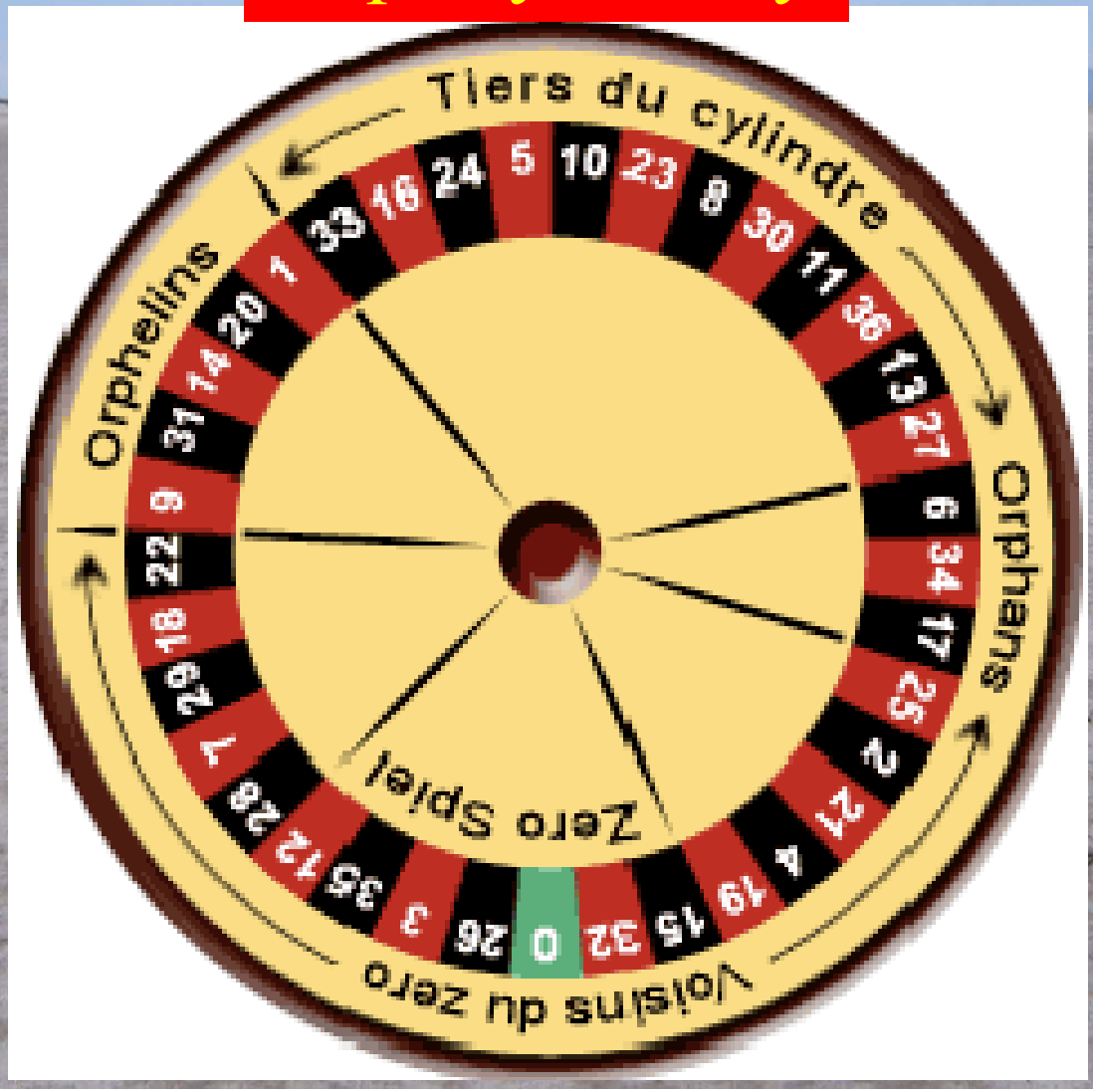
Blaising, JE et al: 2006

The Stakes in the Higgs Search

- How is particle symmetry broken?
- Is there an elementary scalar field?
- What is the fate of the Standard Model?
- Did mass appear when the Universe was a picosecond old?
- Did Higgs help create the matter in the Universe?
- Did a related inflaton make the Universe so big and old?
- Why is there so little dark energy?

The LHC Roulette Wheel

Supersymmetry



Constraints on Supersymmetry

- Absence of sparticles at LEP, Tevatron

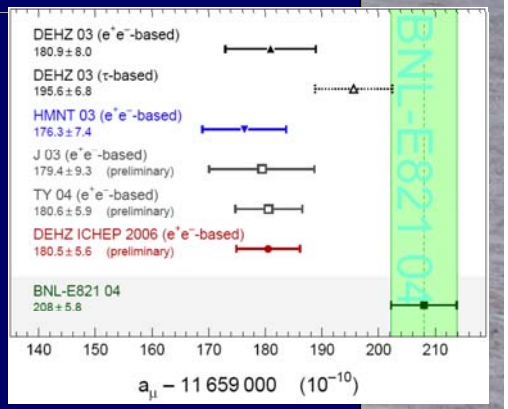
  selectron, chargino > 100 GeV

  squarks, gluino > 300 GeV

- Indirect constraints

  Higgs > 114 GeV, $b \rightarrow s\,\gamma$

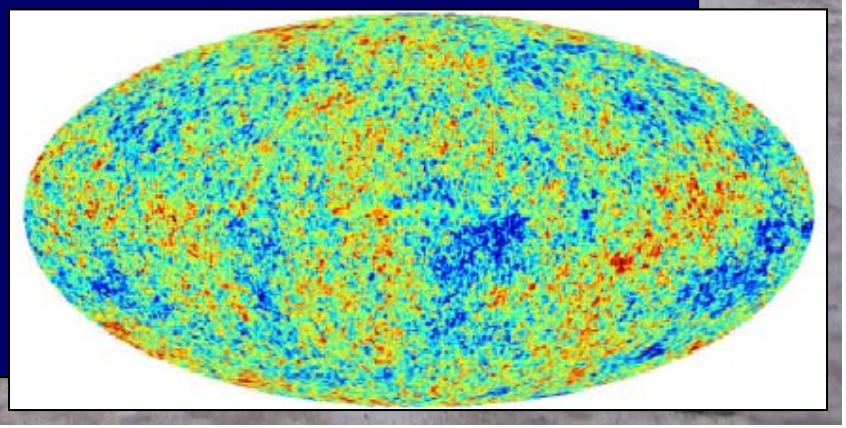
  3.3 σ effect in $g_\mu - 2$?



- Density of dark matter

  lightest sparticle χ:

  $0.094 < \Omega_\chi h^2 < 0.124$



Current Constraints on CMSSM

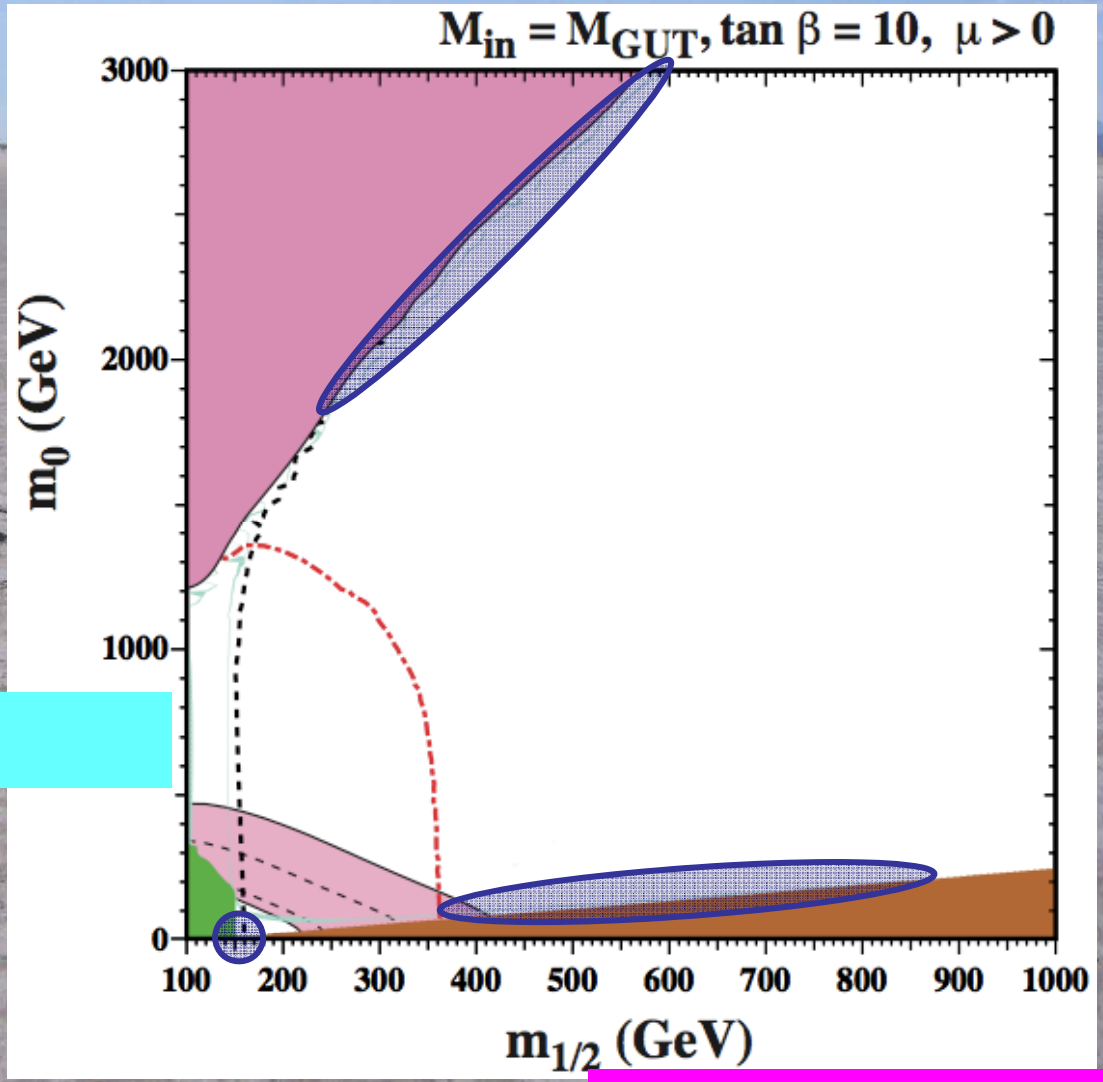
Assuming the lightest sparticle is a neutralino

Excluded because stau LSP

Excluded by b → s gamma

WMAP constraint on relic density

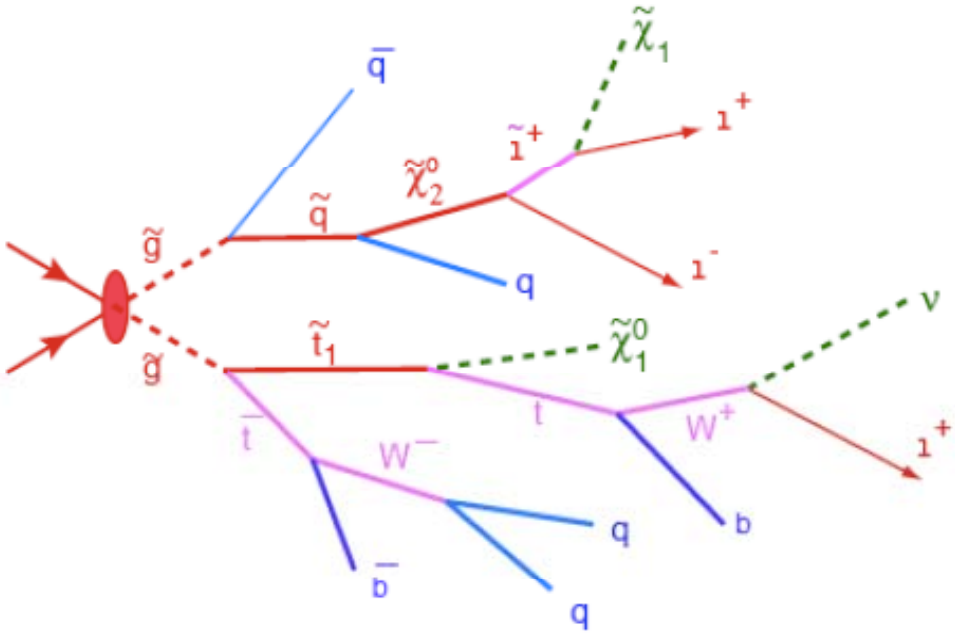
Preferred (?) by latest g - 2



JE + Olive + Santoso + Spanos

What we are Looking for

Lots of missing energy, many jets, and possibly leptons in the final state



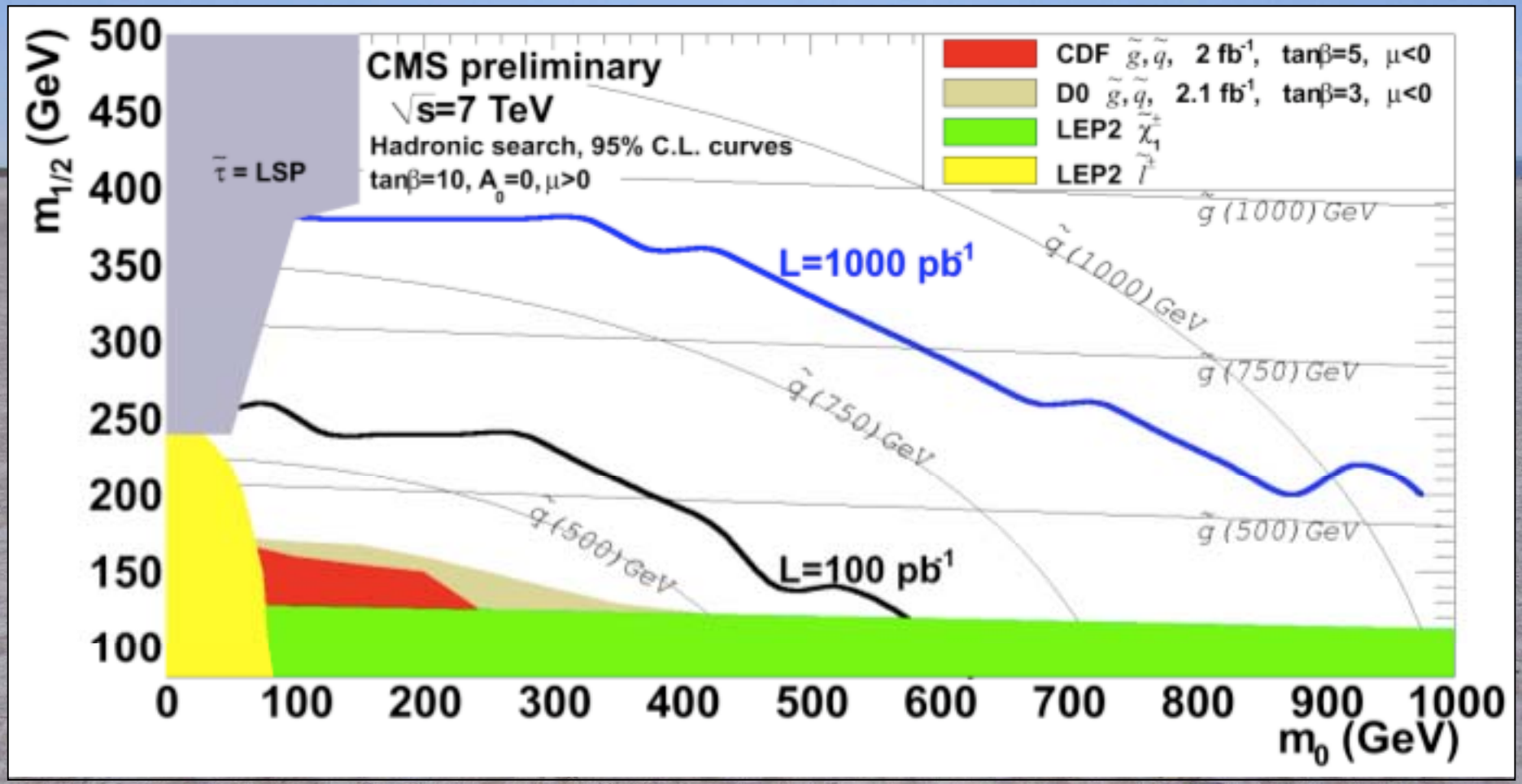
Missing Energy:
- *from LSP*

Multi-Jet:
- *from cascade decay (gaugino)*

Multi-Leptons/photons:
- *from decay of charginos/neutralios*

Start with dijets + missing E_T ,
then multijets,
then events with (di)leptons

LHC Sensitivity @ 7 TeV



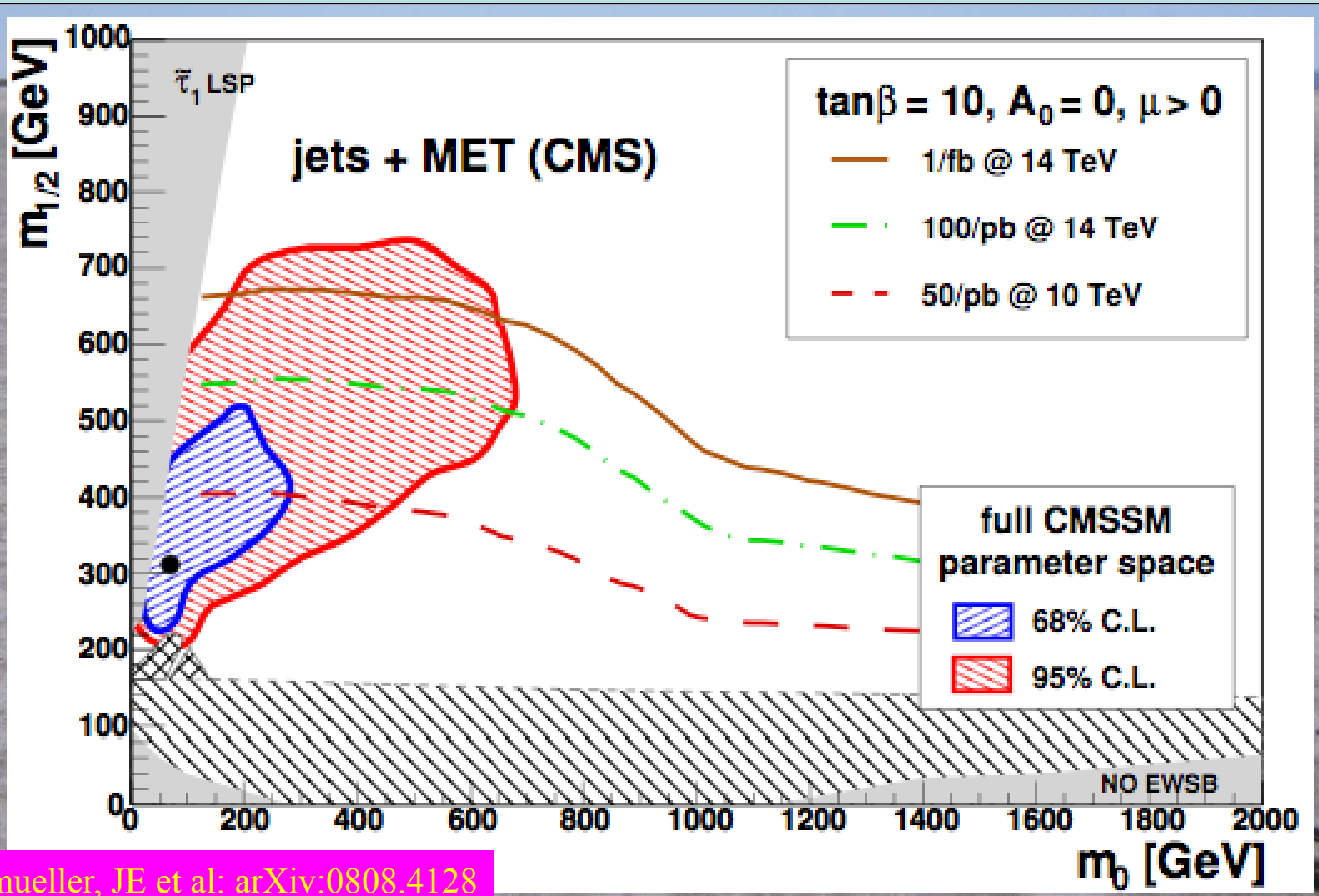
Compared with previous searches @ LEP, Tevatron

Global Supersymmetric Fit

- Frequentist approach
- Data used:
  - Precision electroweak data
  - Higgs mass limit
  - cold dark matter density
  - B decay data ($b \to s\,\gamma$, $B_s \to \mu^+\mu^-$)
  - $g_\mu - 2$ (optional)
- Combine likelihood functions

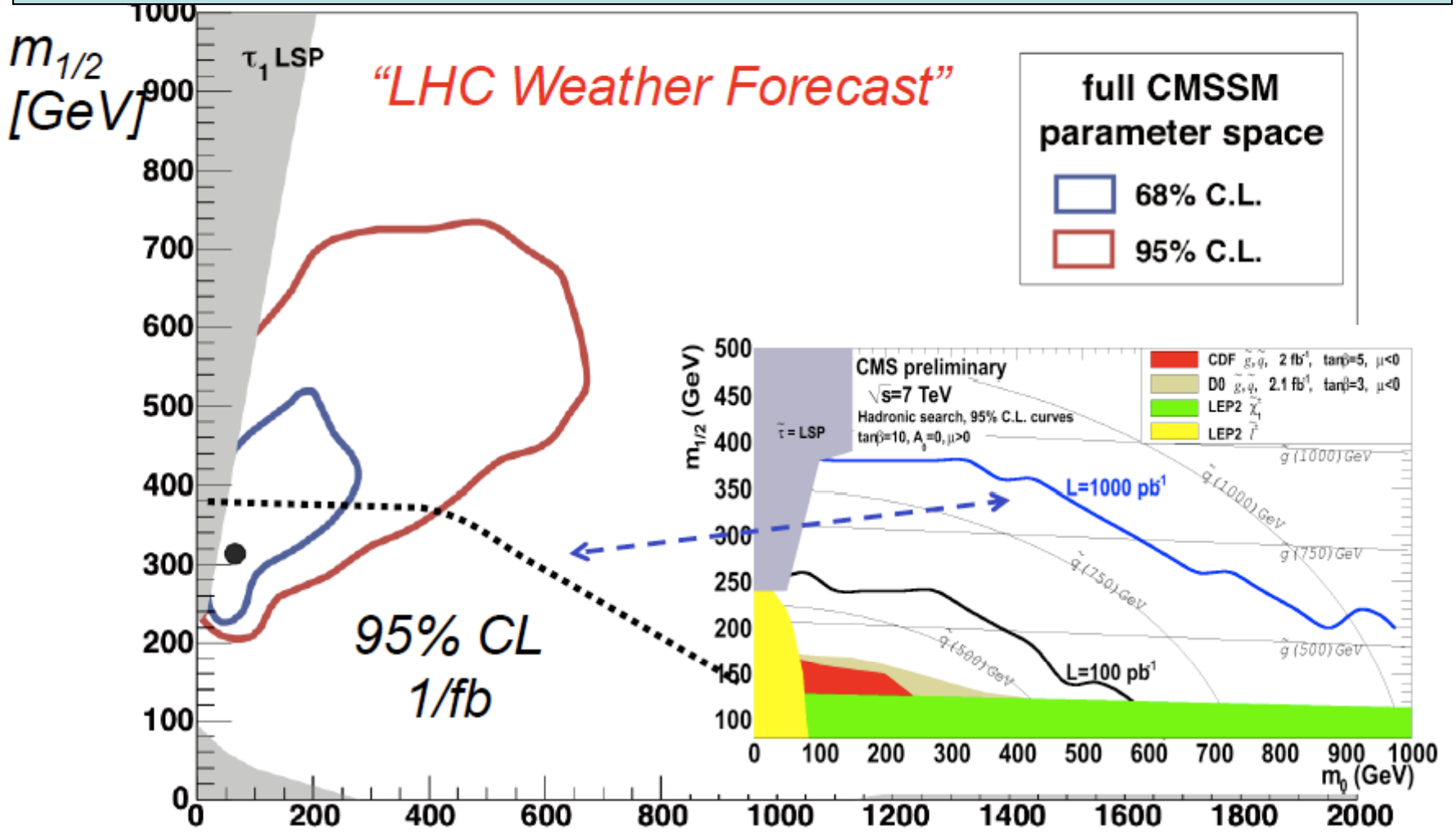
O.Buchmueller, JE et al: arXiv:0808.4128, 0907.5568, 0912.1036

How Soon Might the CMSSM be Detected?



O.Buchmueller, JE et al: arXiv:0808.4128

LHC Sensitivity @ 7 TeV



Compared with 'most likely' region for CMSSM

Strategies for Detecting Supersymmetric Dark Matter

- Annihilation in galactic halo

  $\chi - \chi \rightarrow$ antiprotons, positrons, …?

- Annihilation in galactic centre

  $\chi - \chi \rightarrow \gamma + \ldots$?

- Annihilation in core of Sun or Earth

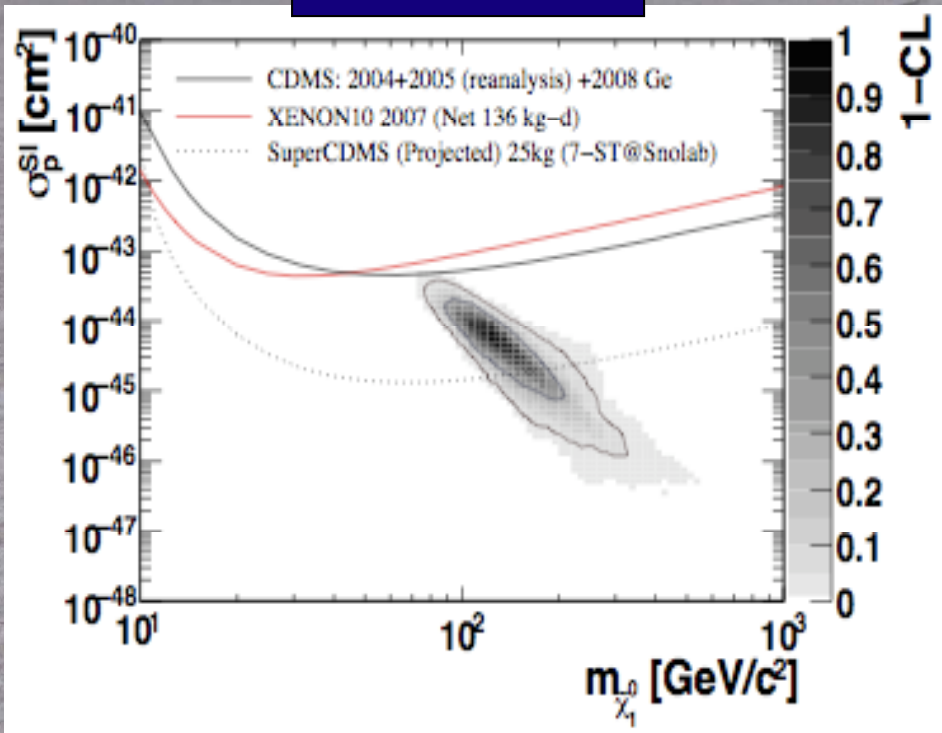
  $\chi - \chi \rightarrow \nu + \ldots \rightarrow \mu + \ldots$

- Scattering on nucleus in laboratory

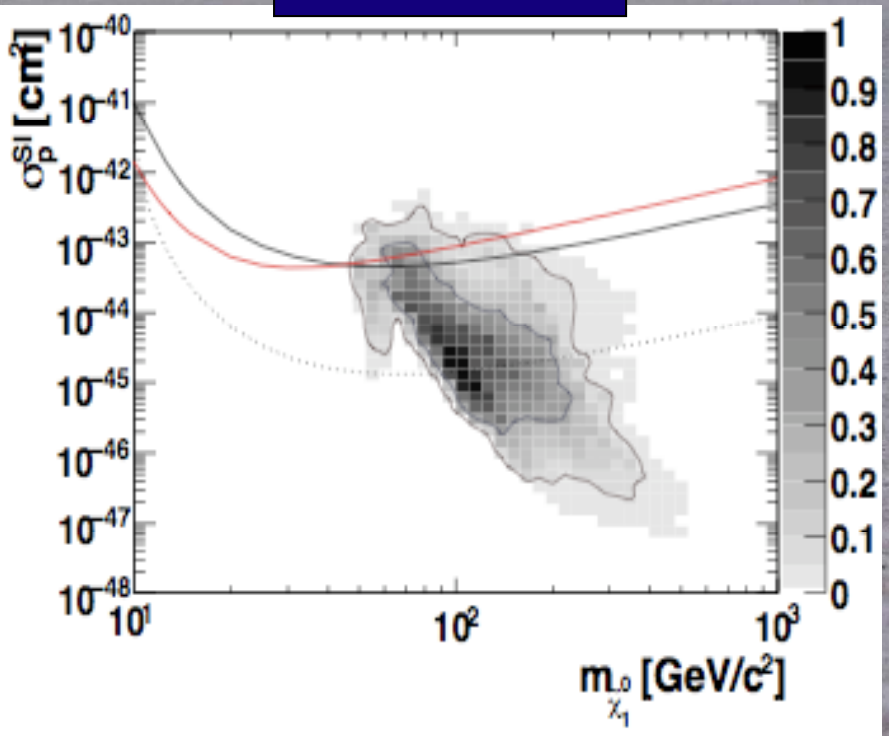
  $\chi + A \rightarrow \chi + A$

Elastic Scattering Cross Sections

CMSSM



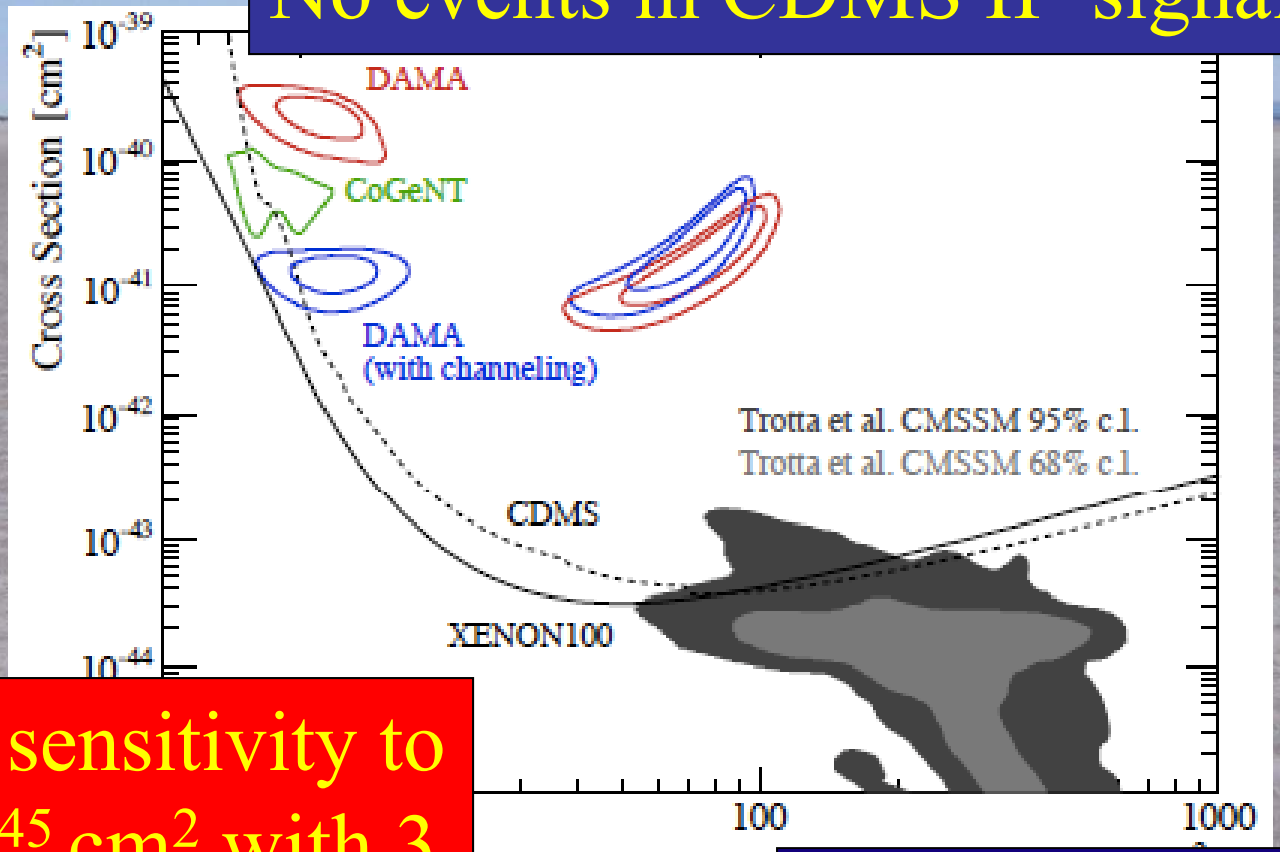
NUHM1



O.Buchmueller, JE et al: arXiv:0907.5568

Xenon100 Experiment

No events in CDMS II 'signal' region



Expect sensitivity to 2.10^{-45} cm^2 with 3 months of data

Aprile et al: arXiv:1005.0380

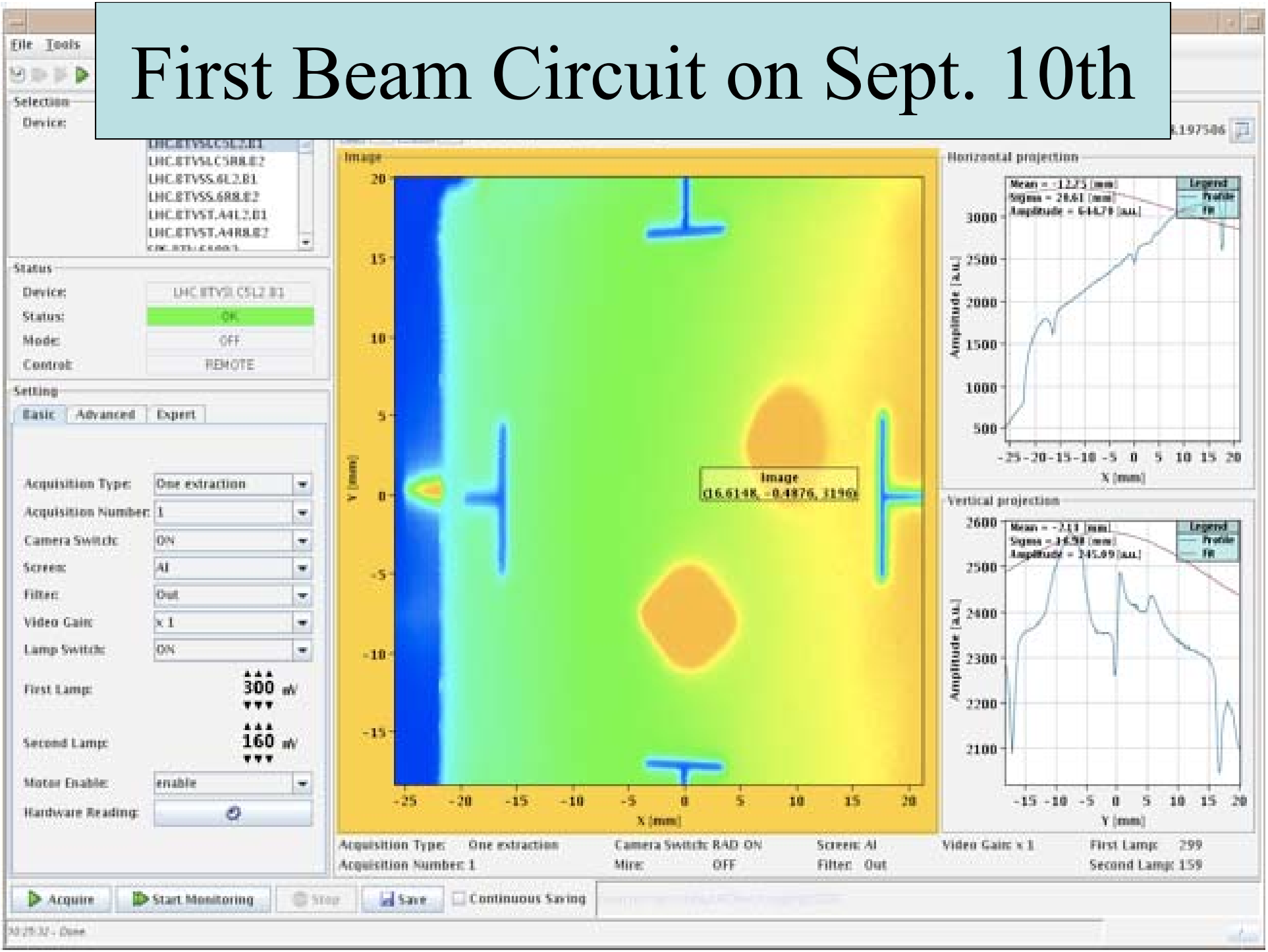
Similar sensitivity with 11 days of data


The LHC is not only the World's most powerful microscope, but also a telescope
Looking towards the beginning of time

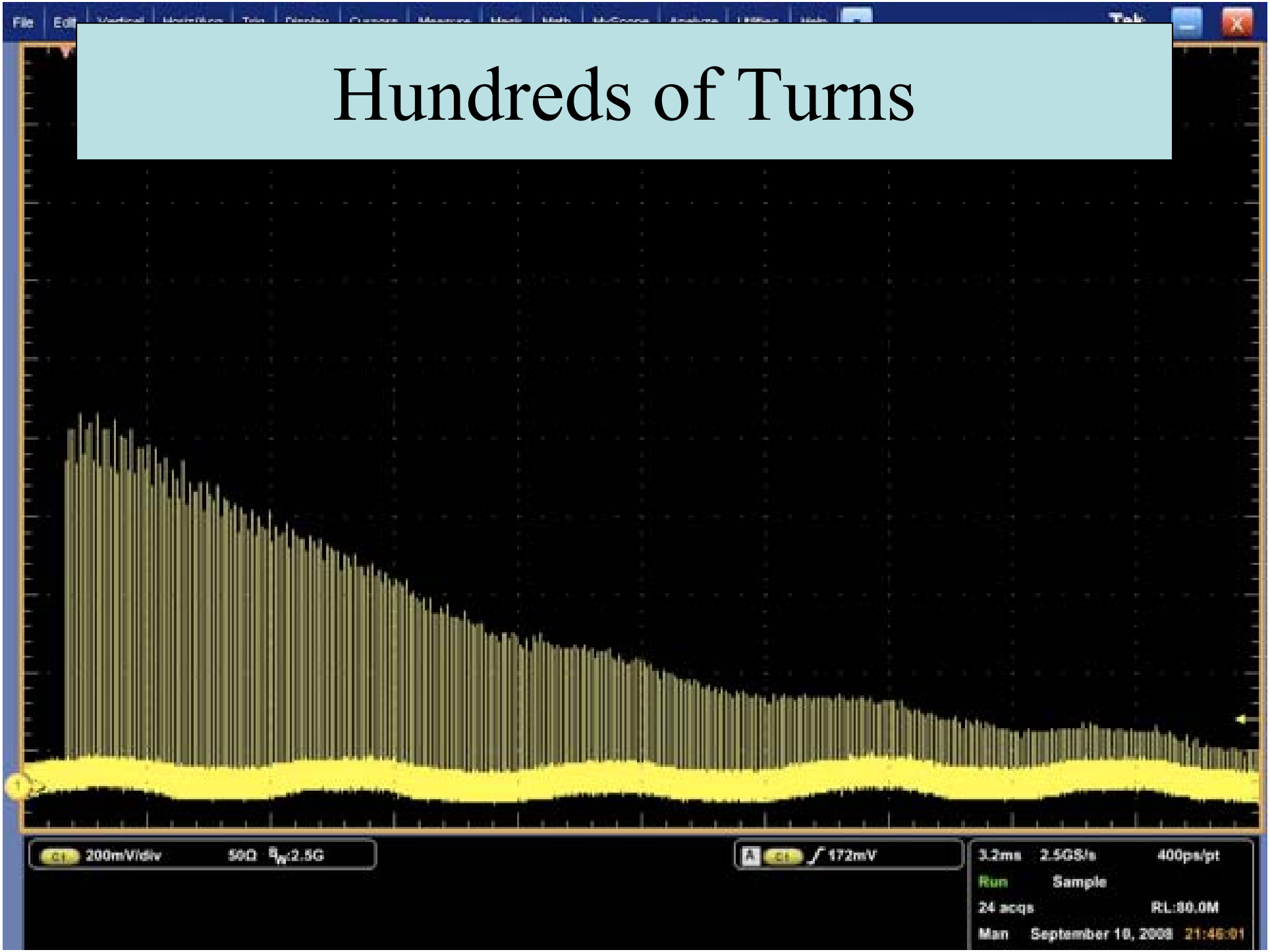
You are the basis for all we do

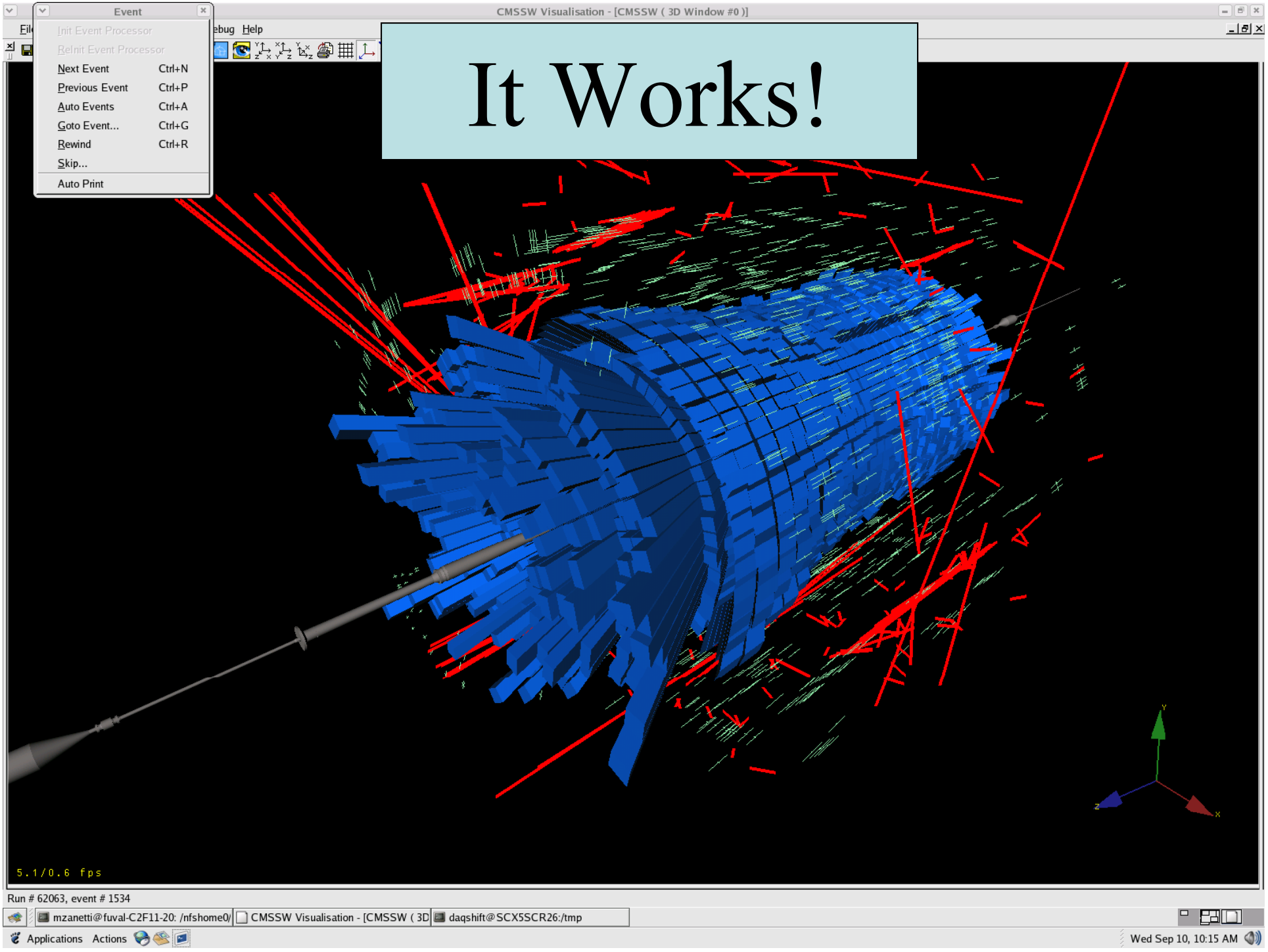
- Build up scientific literacy of society
- Enable evidence-based decision-making
- Inspire some students to undertake further studies in STEM subjects
- Some may continue into research
  - Not only in physics
    - Not necessarily in particle physics
- Many/most will not stay in research
- All will contribute to advancing society
- Thank you!

First Beam Circuit on Sept. 10th



Hundreds of Turns



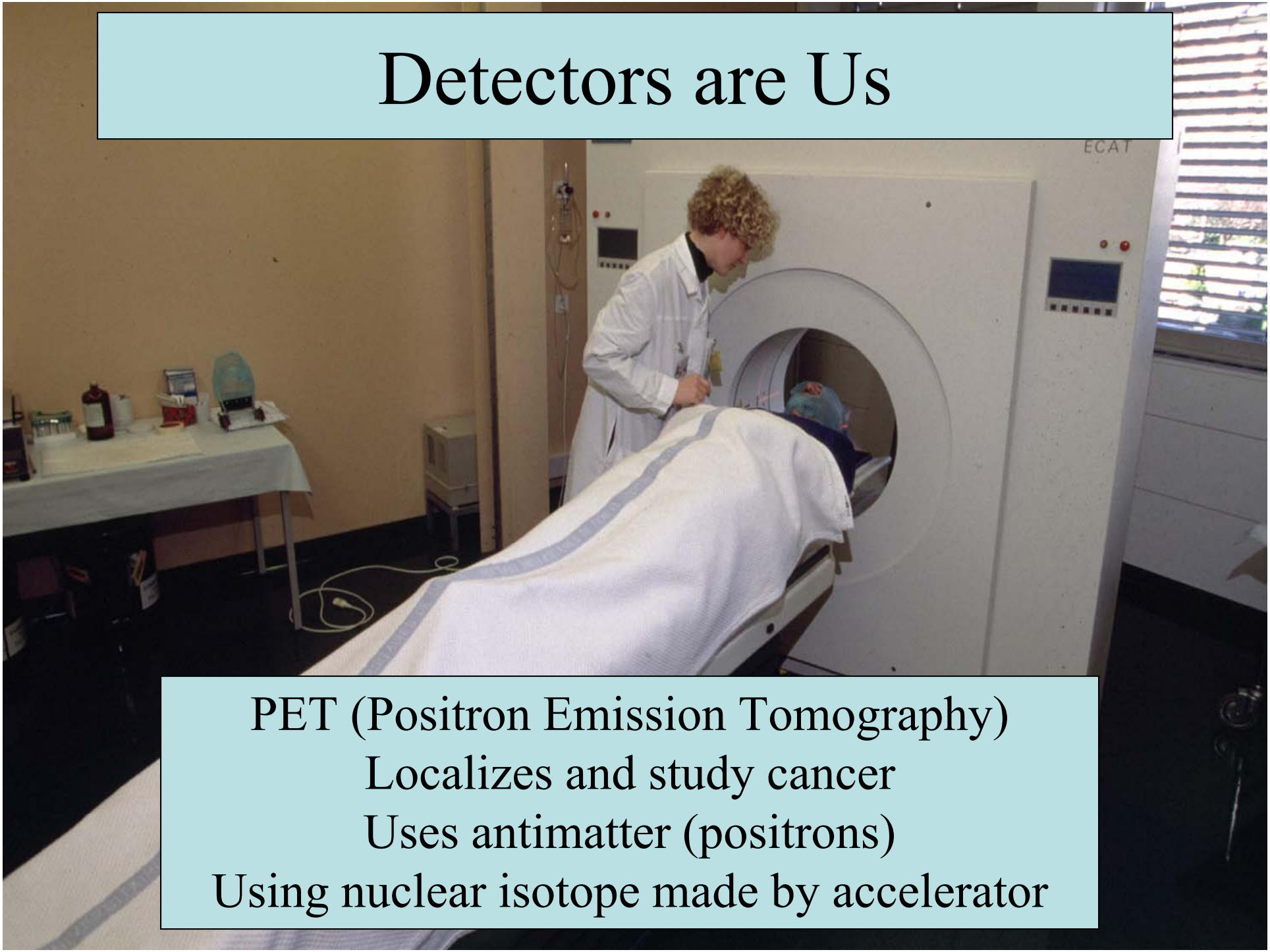

Event
Init Event Processor
Reinit Event Processor
Next Event Ctrl+N
Previous Event Ctrl+P
Auto Events Ctrl+A
Goto Event... Ctrl+G
Rewind Ctrl+R
Skip...
Auto Print
CMSSW Visualisation - [CMSSW (3D Window #0)]
File
Debug Help
It Works!
5.1/0.6 fps
Run # 62063, event # 1534
mzanetti@fuval-C2F11-20: /nfshome0/
CMSSW Visualisation - [CMSSW (3D
daqshift@SCX5SCR26:/tmp
Applications Actions
Wed Sep 10, 10:15 AM

Yes, it really Works!

The Lone LHC Protester

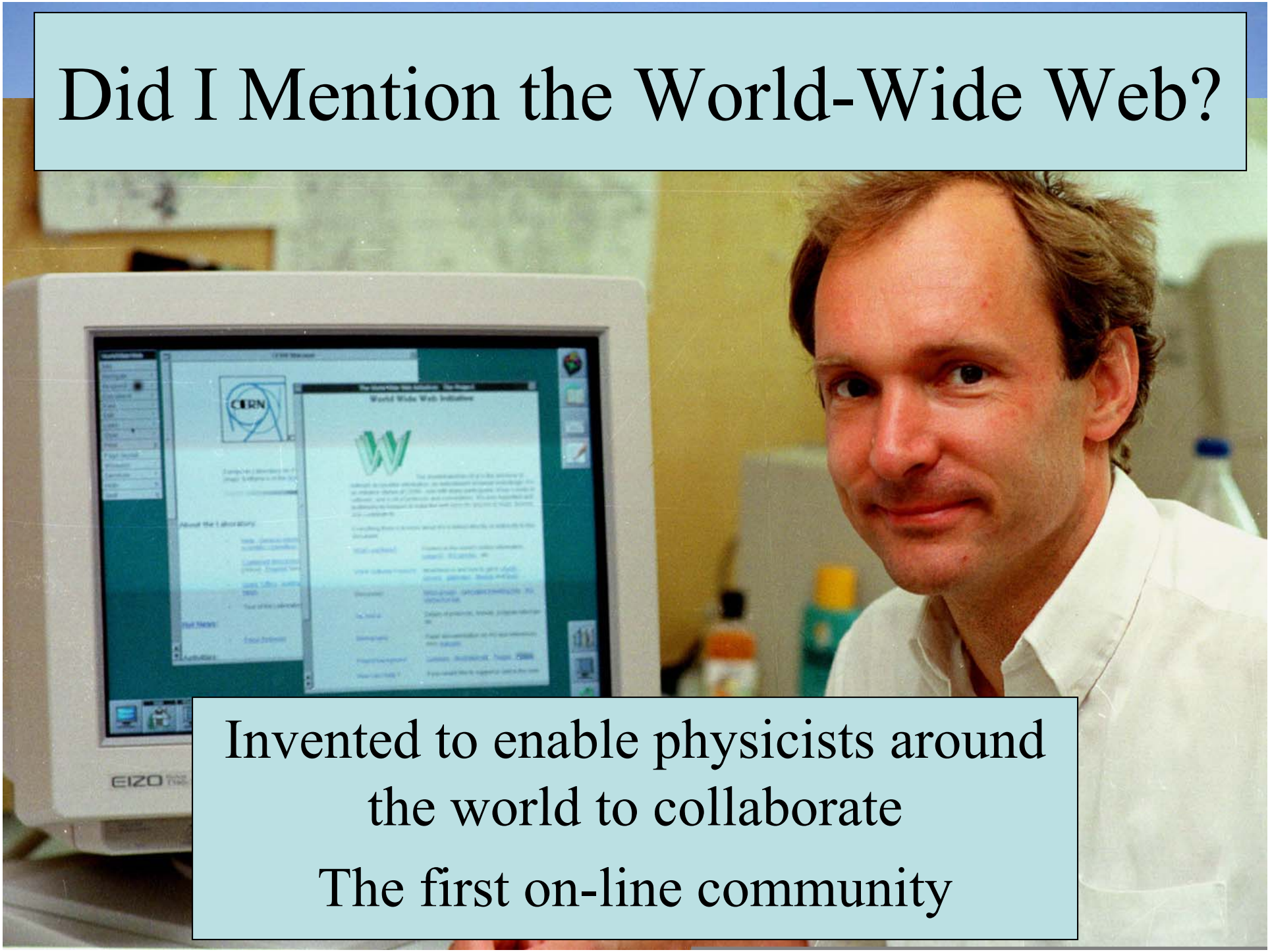

What is the use of it?

Detectors are Us



PET (Positron Emission Tomography)
Localizes and study cancer
Uses antimatter (positrons)
Using nuclear isotope made by accelerator

Did I Mention the World-Wide Web?

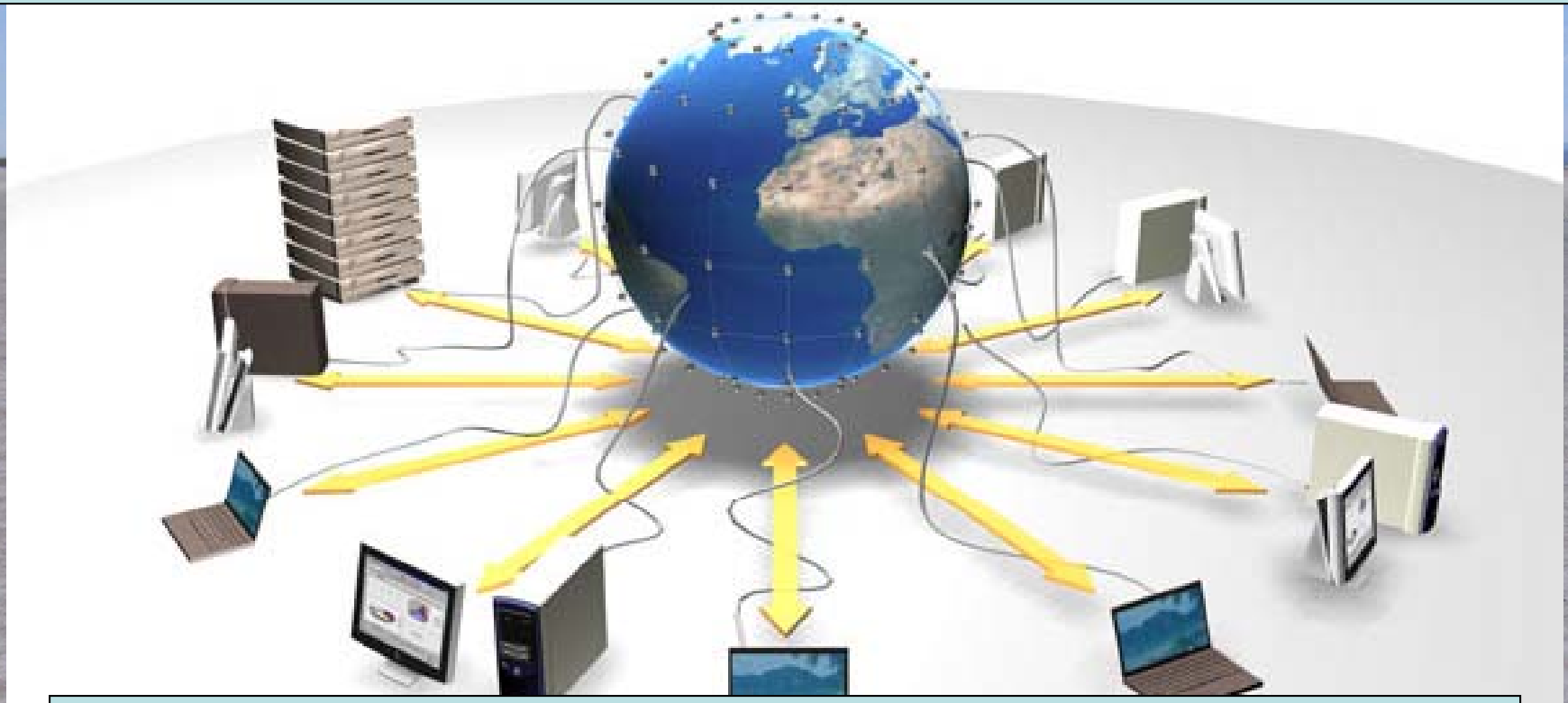


Invented to enable physicists around the world to collaborate

The first on-line community


QuickTime™ and a
decompressor
are needed to see this picture.

Largest Computer System in the World



100,000 computers all over the world
linked to analyse data from CERN
Grid is next advance in decentralised computing -
from laboratory that invented the World-Wide Web