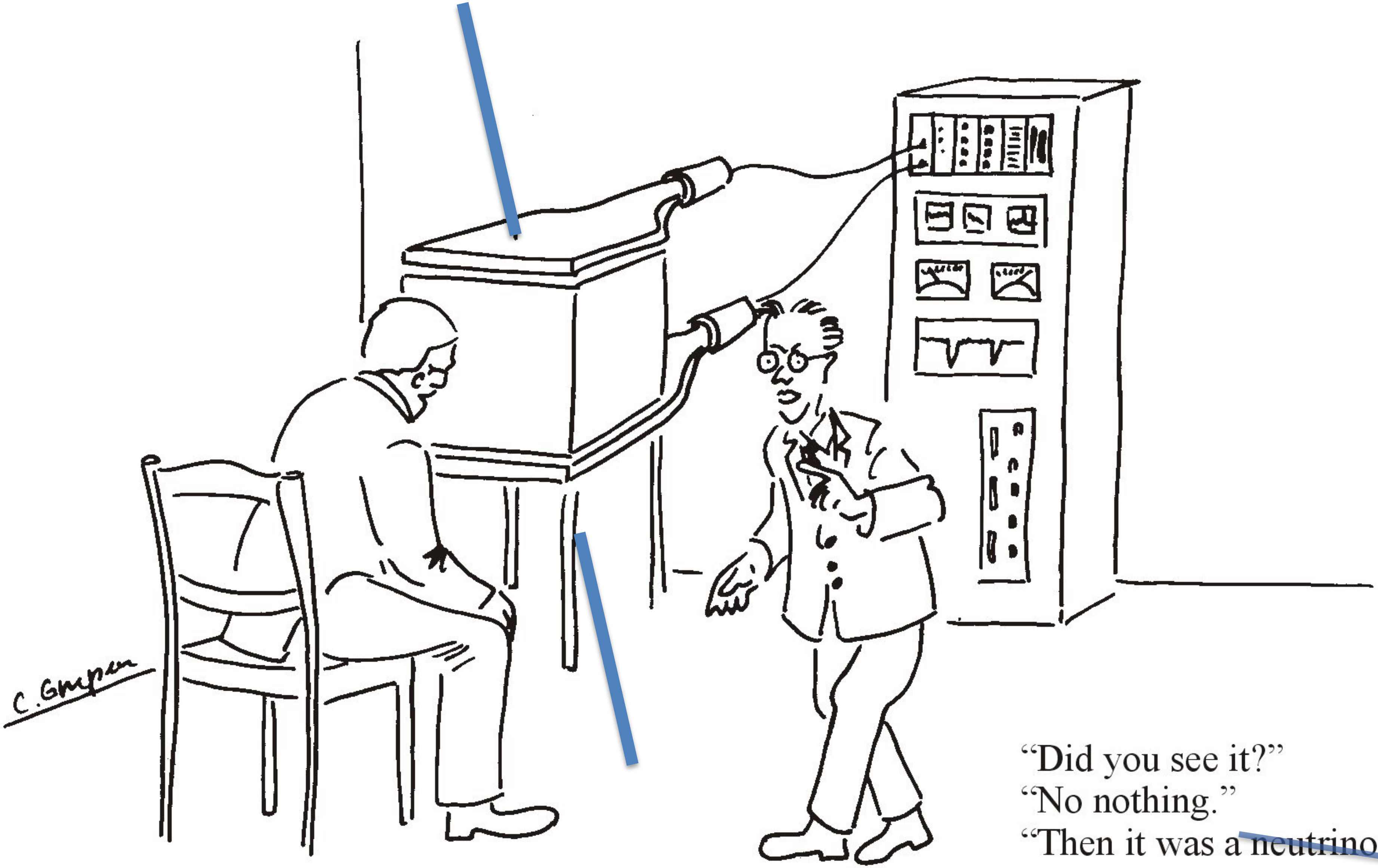
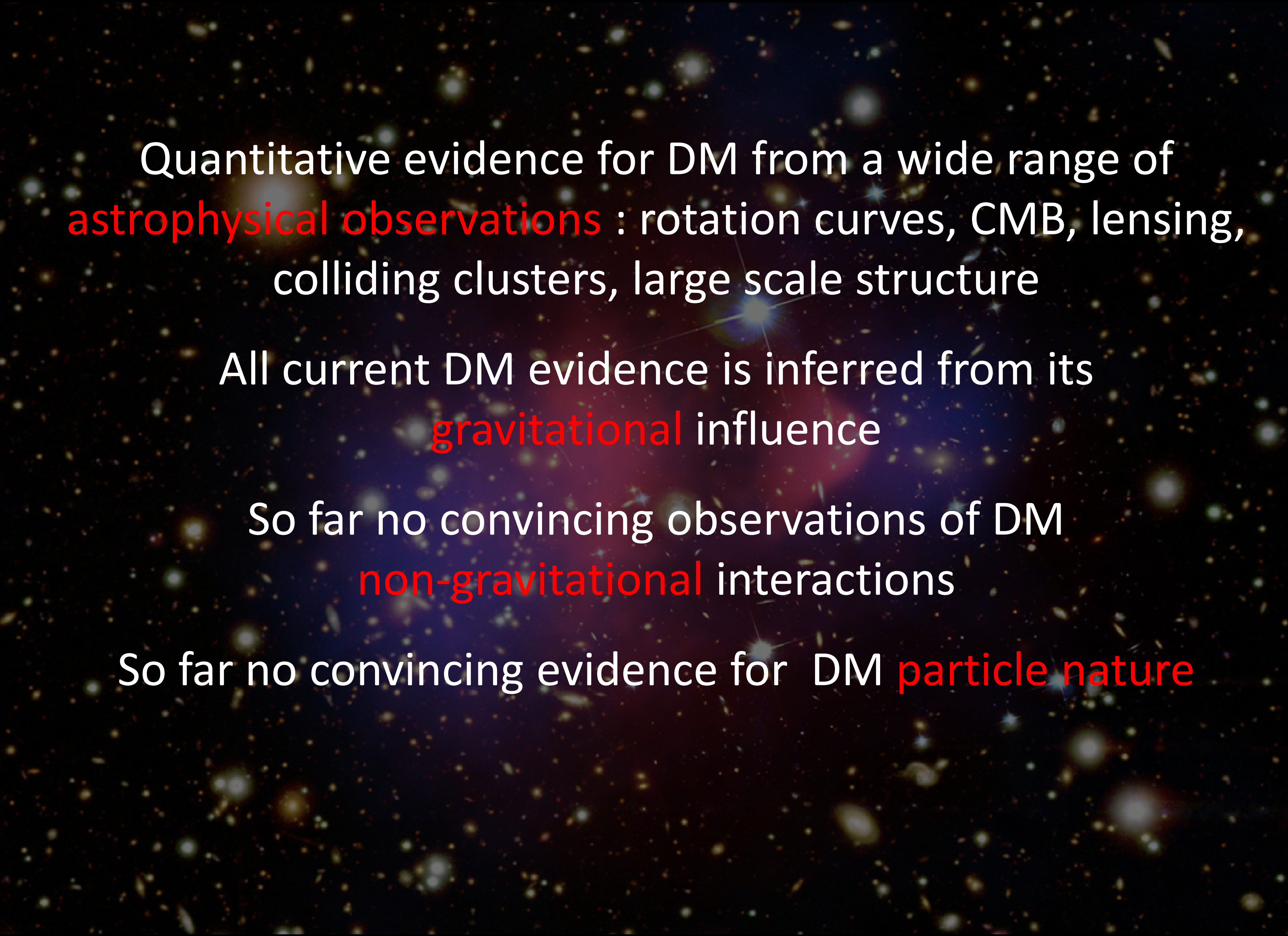
# Make your own Blue Matter – In Principle and in Practice

Karlheinz Meier
Kirchhoff-Institut für Physik
Astronomisches Kolloquium Heidelberg 2010



“Did you see it?”
“No nothing.”
“Then it was a ~~neutrino~~!”

DM particle



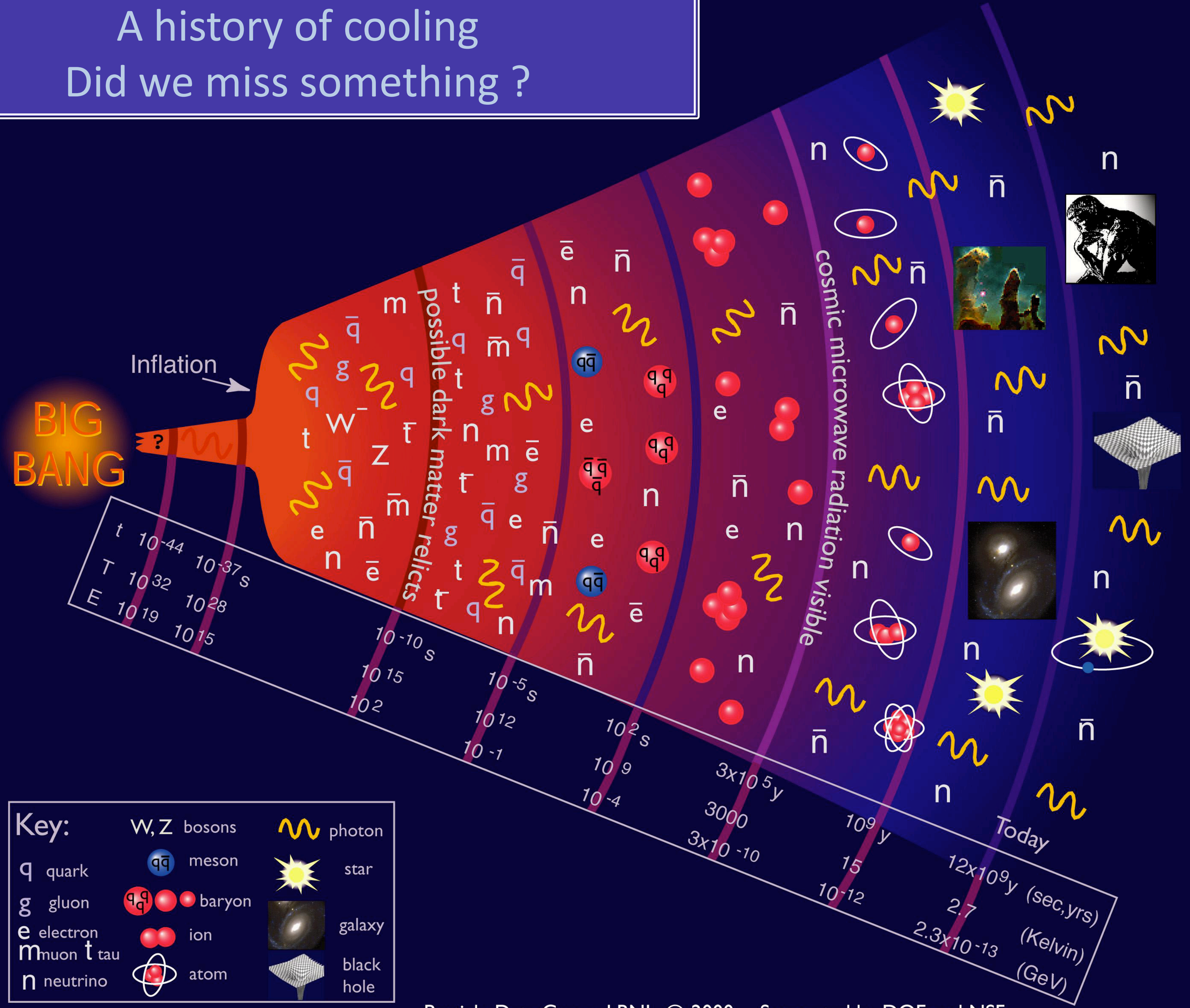
Quantitative evidence for DM from a wide range of astrophysical observations : rotation curves, CMB, lensing, colliding clusters, large scale structure

All current DM evidence is inferred from its gravitational influence

So far no convincing observations of DM non-gravitational interactions

So far no convincing evidence for DM particle nature

# A history of cooling
# Did we miss something ?



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

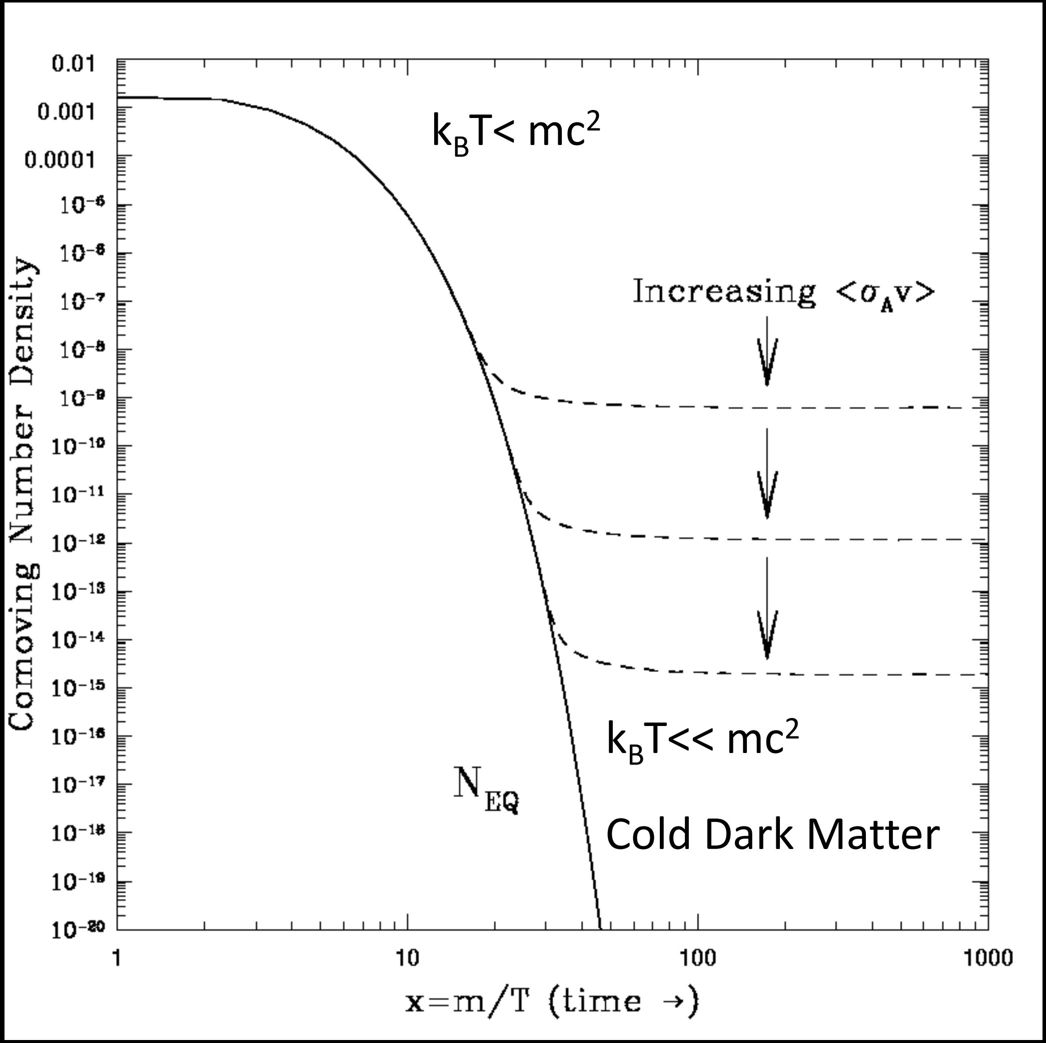
Following the thermal freeze-out process, a KNOWN, MEASURED relic density of DM is left over

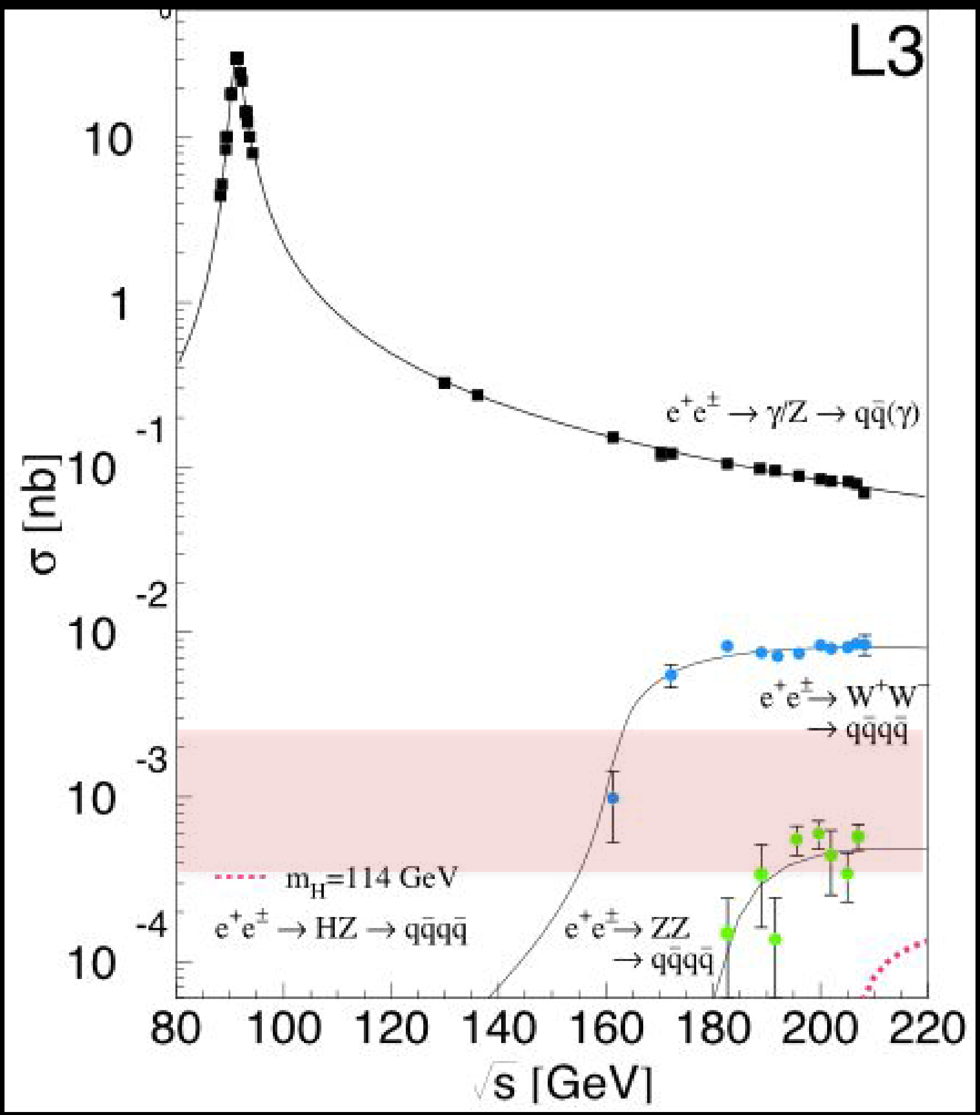
$$\Omega \sim x / \langle\sigma v\rangle$$

For a hypothetical particle with a 100 GeV mass this corresponds to a thermally averaged annihilation cross section of

$$\langle\sigma v\rangle \sim \text{picobarn}$$

Typical ELECTROWEAK INTERACTION cross-section





Measured electroweak pair production cross-sections (LEP at CERN)

Experimental Particle Physics could possibly RECREATE

Weakly Interacting

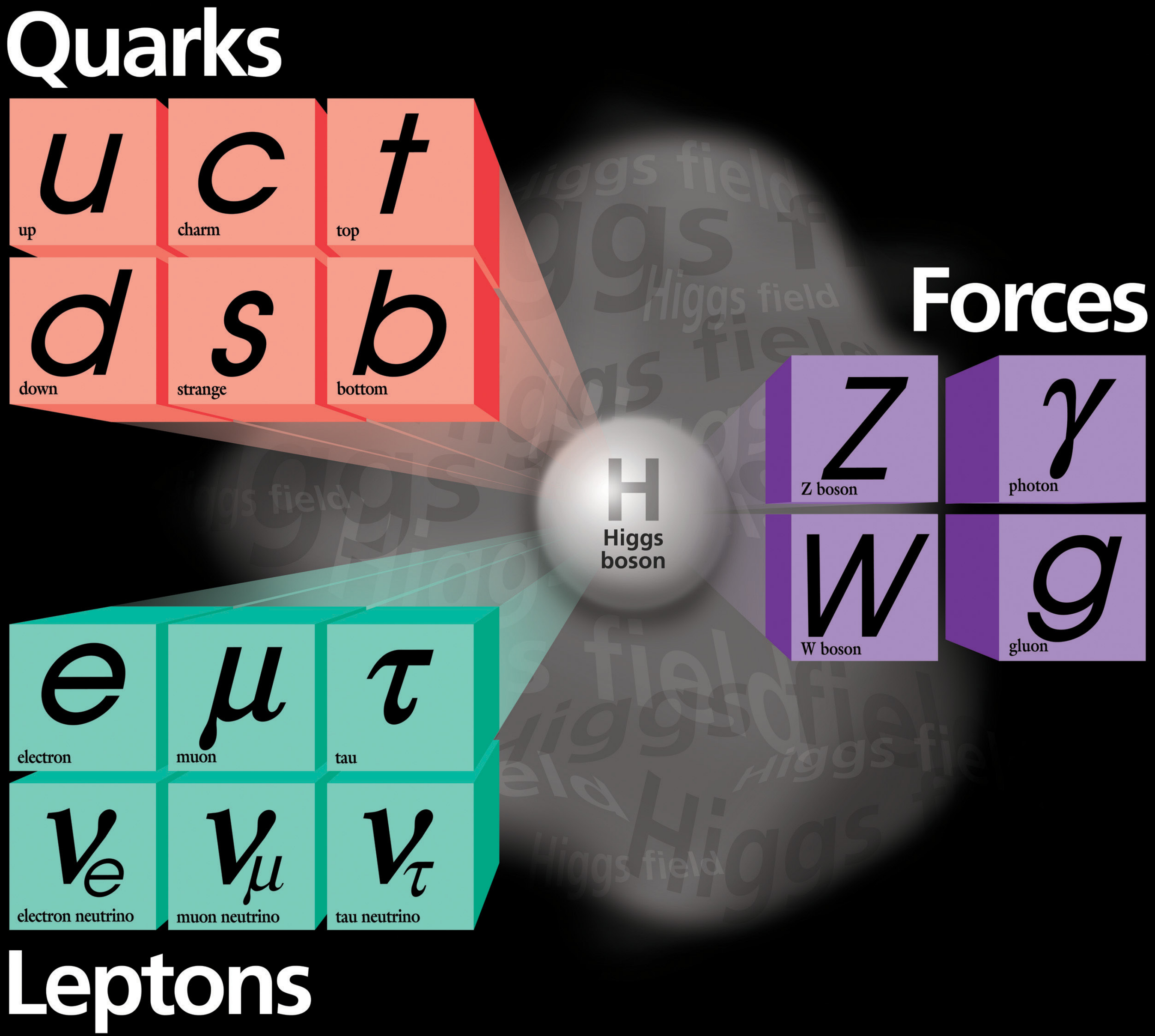
Massive

Particles

that are even Stable …. !

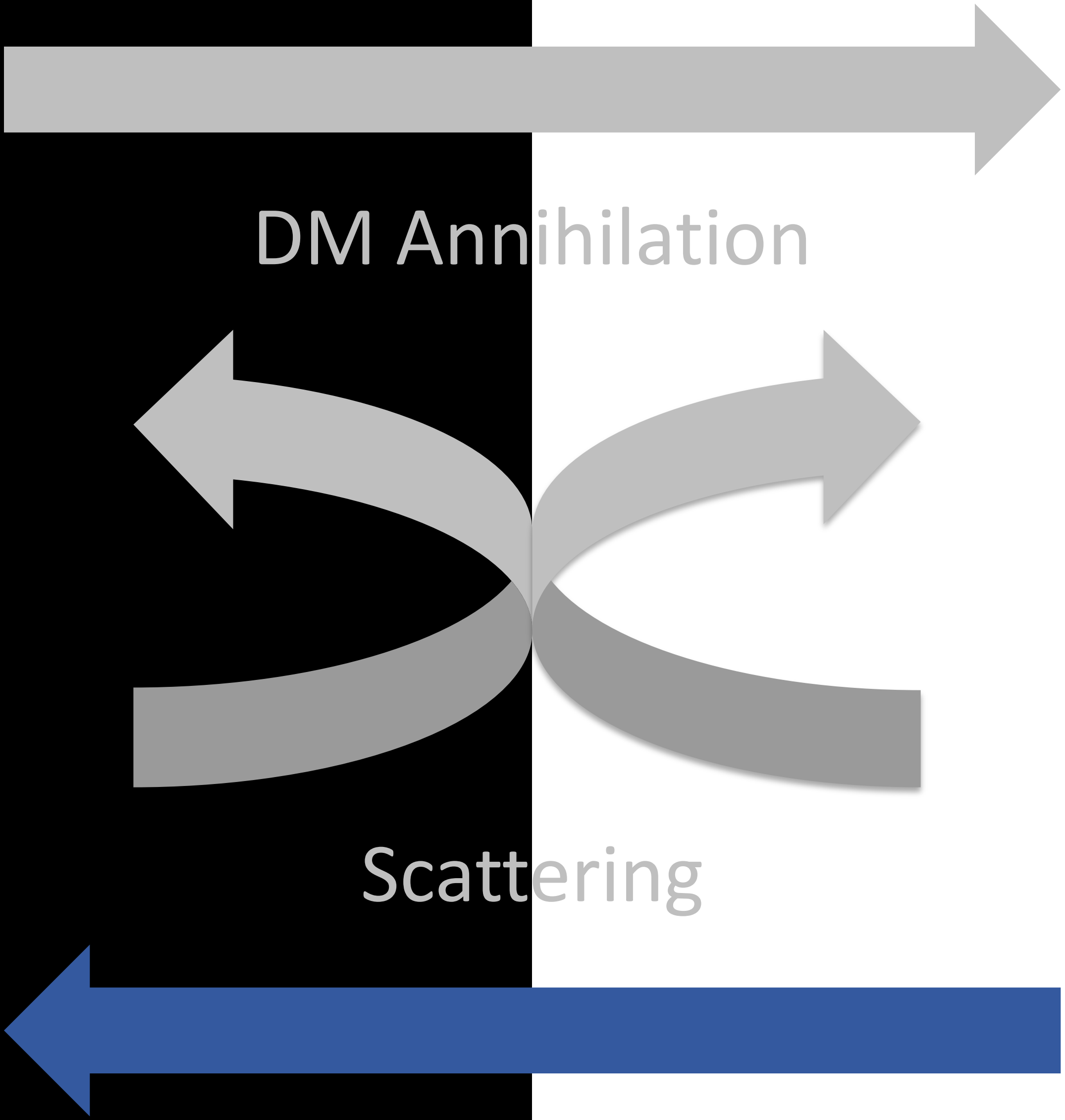
**Axions, Neutralinos, Gravitinos, Axinos, Kaluza-Klein Photons, Kaluza-Klein Neutrinos, Heavy Fourth Generation Neutrinos, Mirror Photons, Mirror Nuclei, Stable States in Little Higgs Theories, WIMPzillas, Cryptons, Sterile Neutrinos, Sneutrinos, Light Scalars, Q-Balls, D-Matter, Brane World Dark Matter, Primordial Black Holes, …**

# What we really KNOW – From our World to the Electroweak Scale



DARK
SIDE

KNOWN
SIDE



DM Annihilation

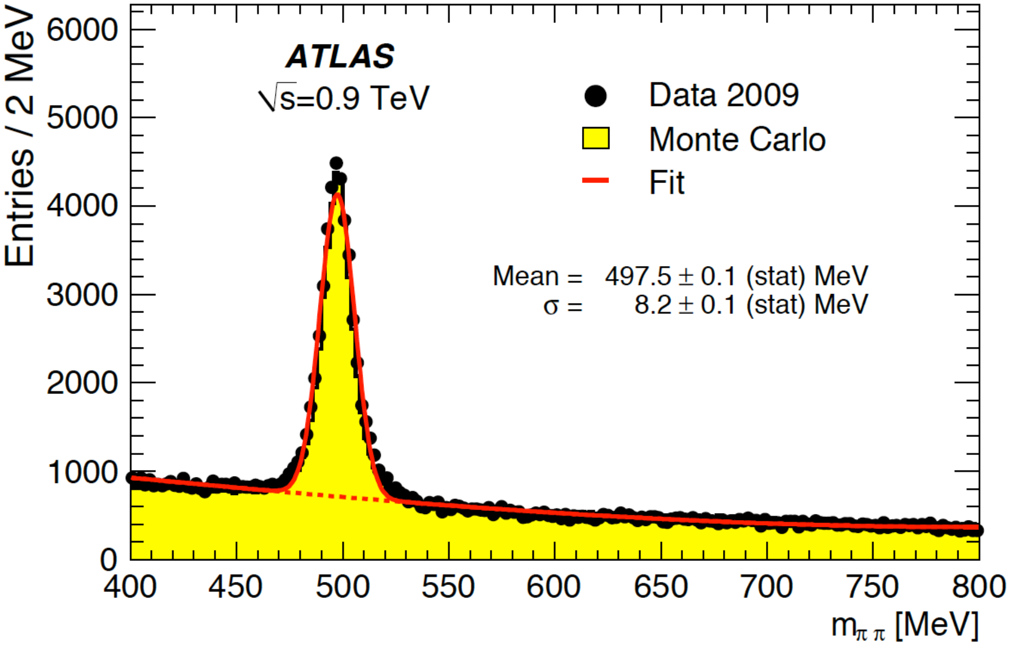
Scattering

DM Creation, or „Make Your Own ...“

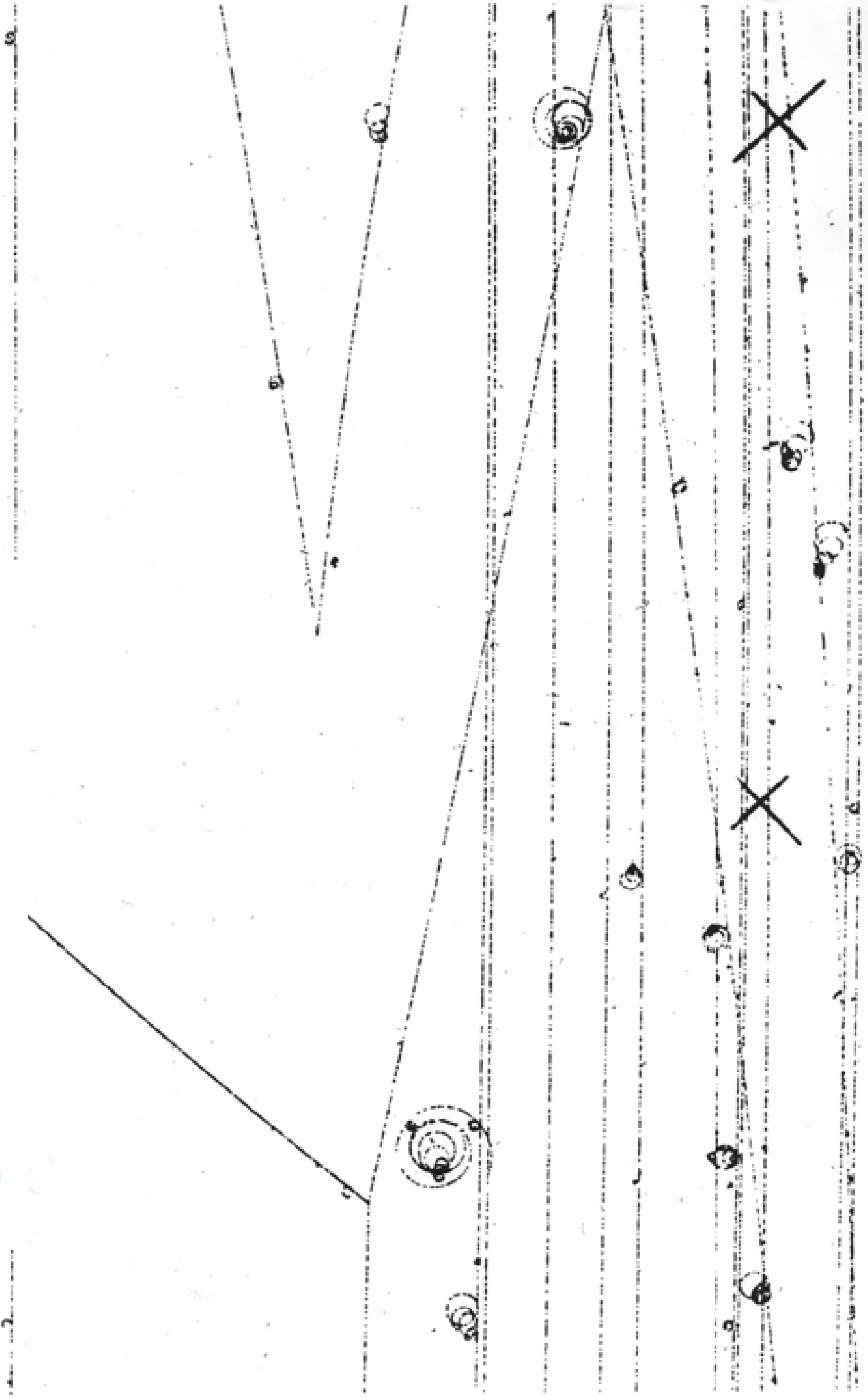
„Long-lived“, „exotic“, neutral artificially produced particles ?

A well known thing in particle physics
From the 1950s to latest LHC results

.... but this one sees weak AND strong interactions, also it is not really stable ....

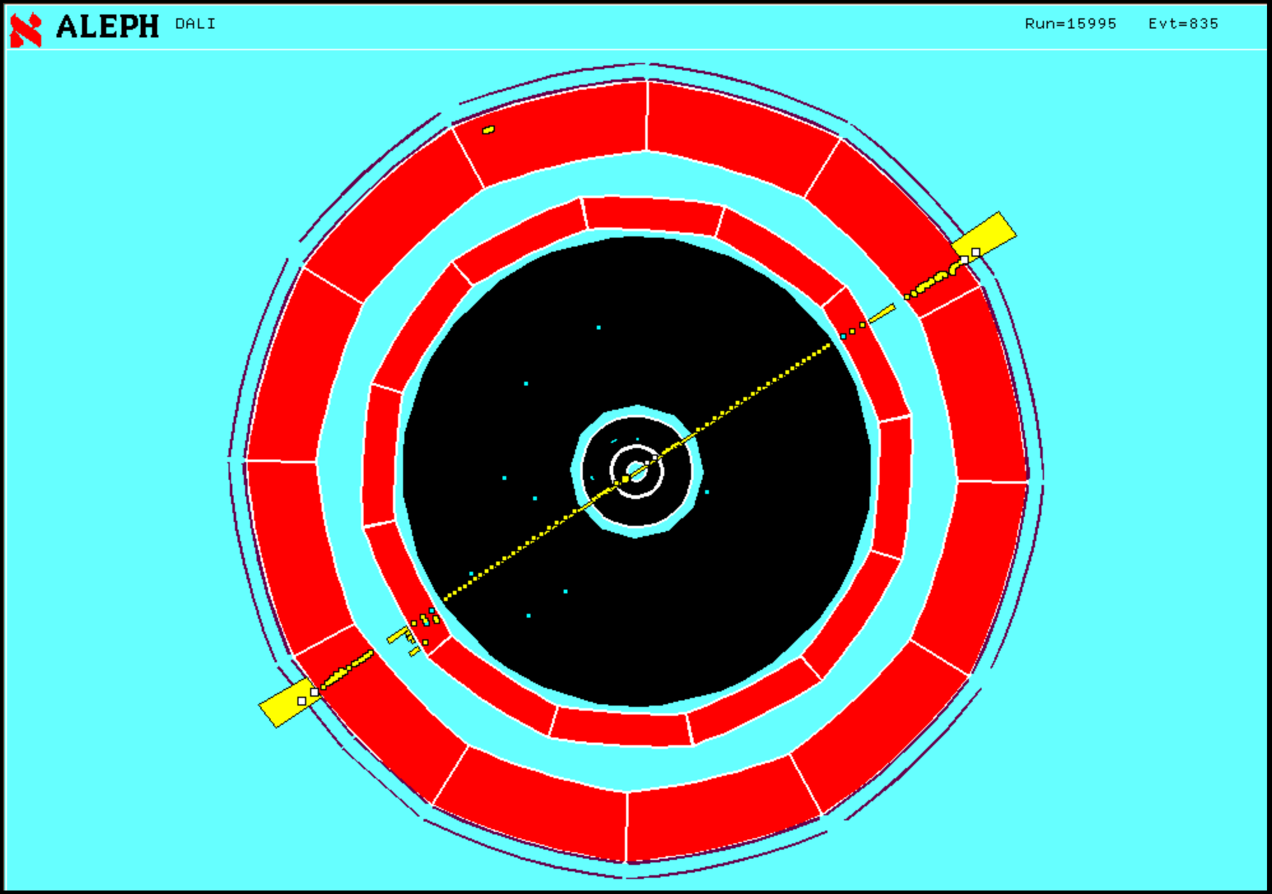


ATLAS Collaboration, Journal of High Energy Physics, Volume 2010, article id. #56, 2010



# Pairwise Creation of New Matter (LEP at CERN)

$e^+e^- \to \mu^+\mu^-$



The heavier sisters of the electron (x 200)

Known since 1937 as the dominant component of „cosmic“ rays on the earths surface

Creation of a quantum number not existing at our moderate temperatures ($L_\mu$)

# Particle Physics : Space - Time – Matter

$$\Delta x \cdot \Delta p \geq \hbar$$

*Werner Heisenberg*

Small Structures – Small Distances

$$E = m \cdot c^2$$

*Albert Einstein*

New and Heavy Matter

$$\langle E \rangle \approx k_b \cdot T$$

*Ludwig Boltzmann*

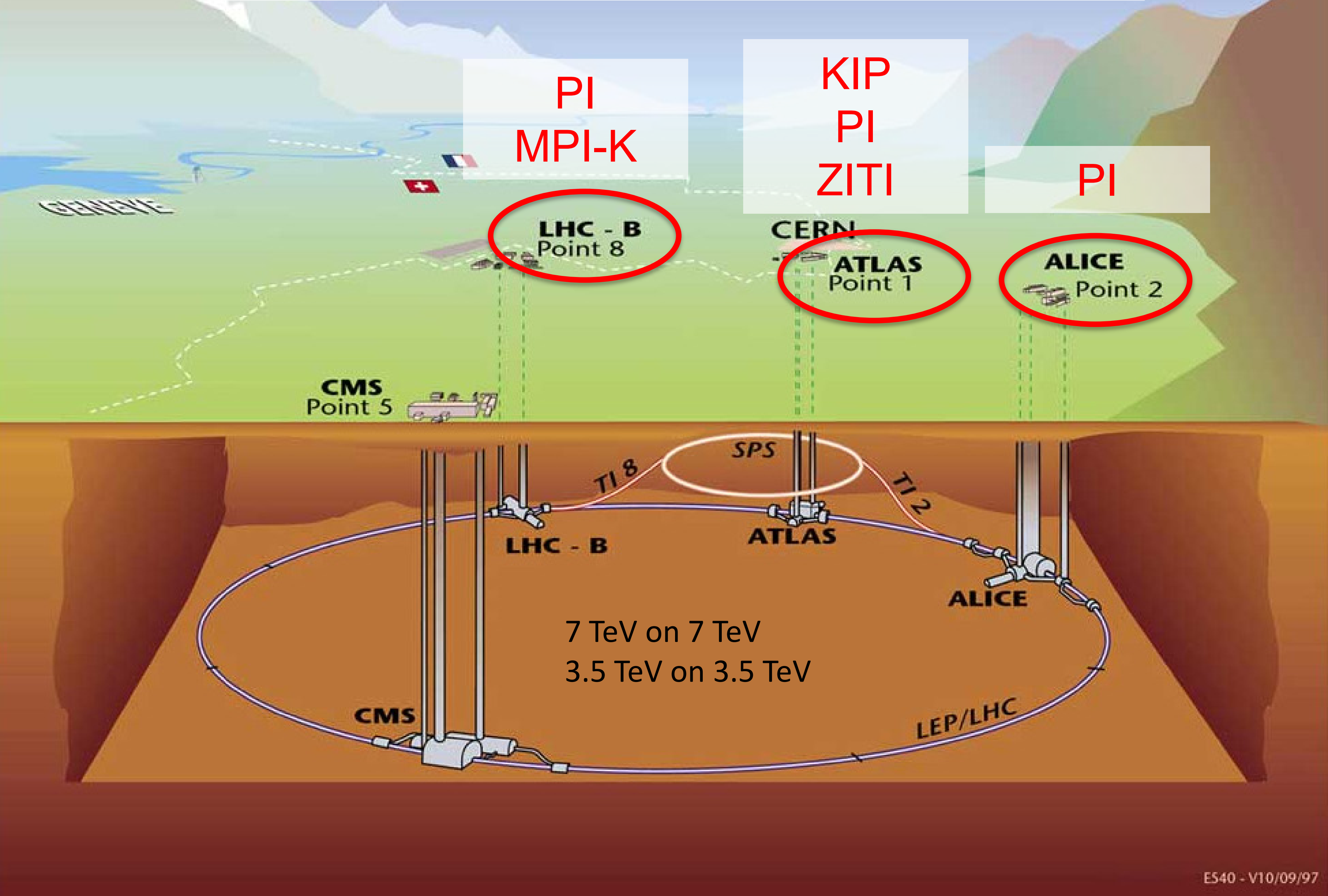
High Temperatures

Temperature of the Universe drops with Time

ENERGY is the Key !

The Large Hadron Collider at CERN

# Heidelberg at the Large Hadron Collider



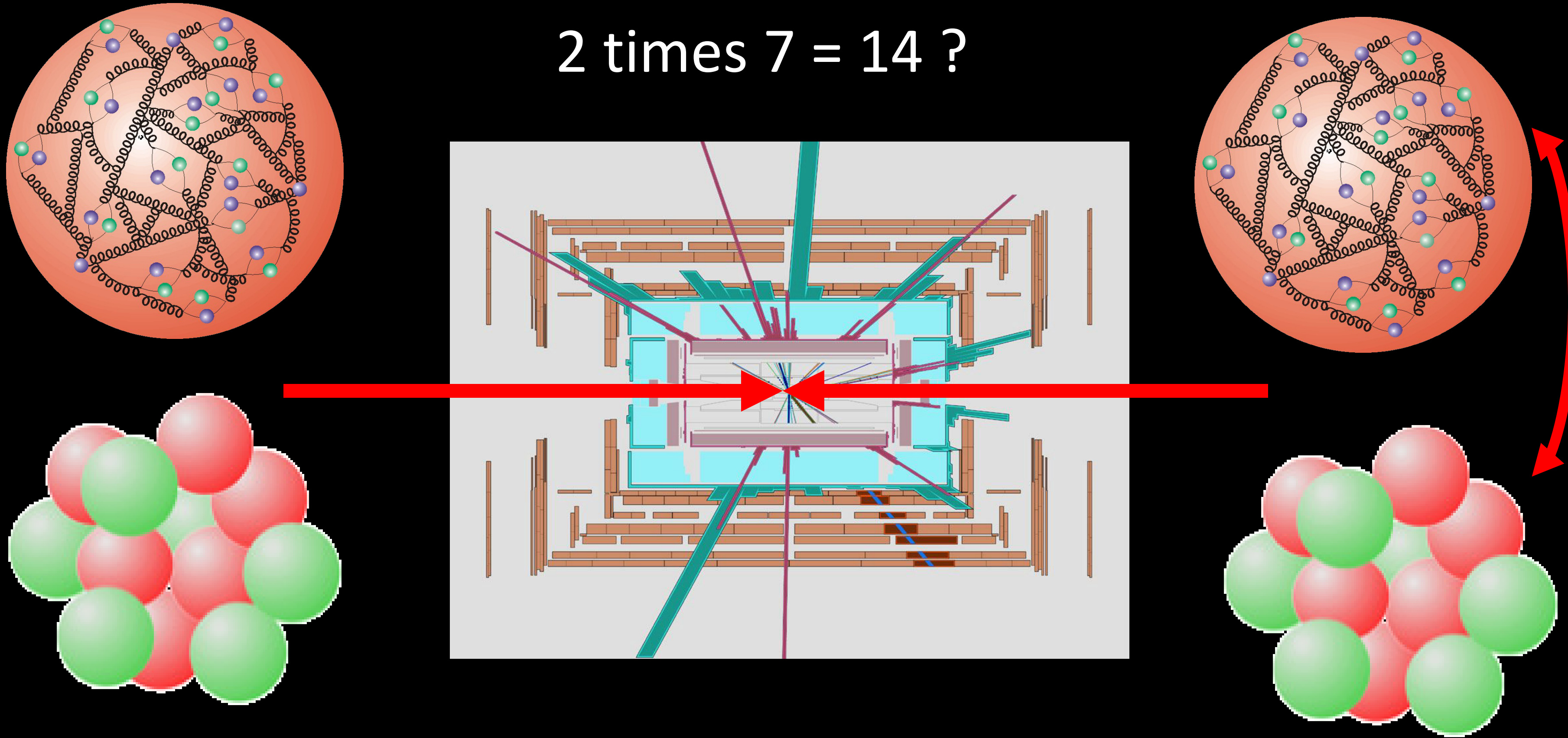
PI
MPI-K

KIP
PI
ZITI

PI

7 TeV on 7 TeV
3.5 TeV on 3.5 TeV

# 2 times 7 = 14 ?

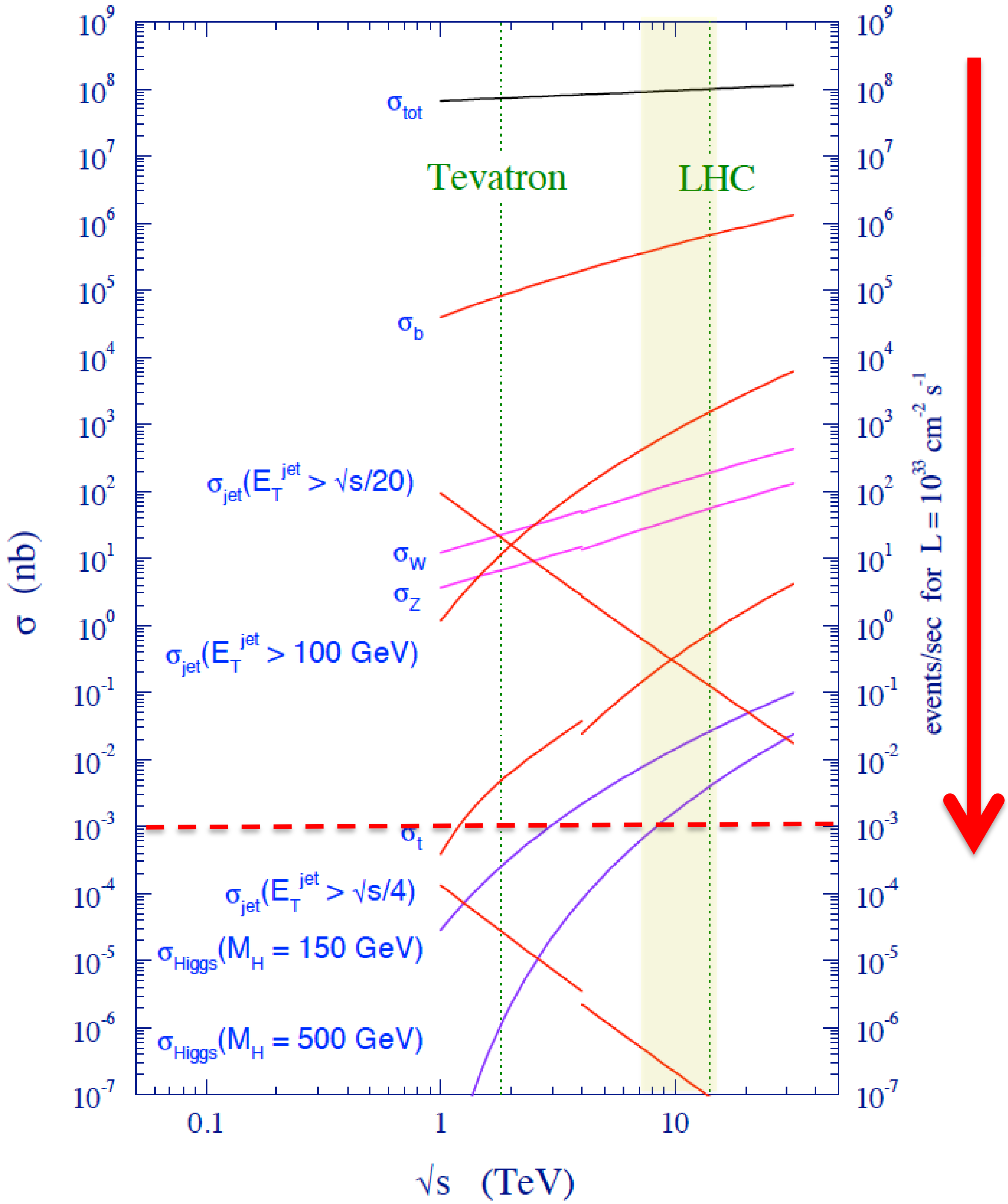


## Two avenues towards LHC physics :

1 TeV in collisions of „partons“ in the proton (*THE TERASCALE*)

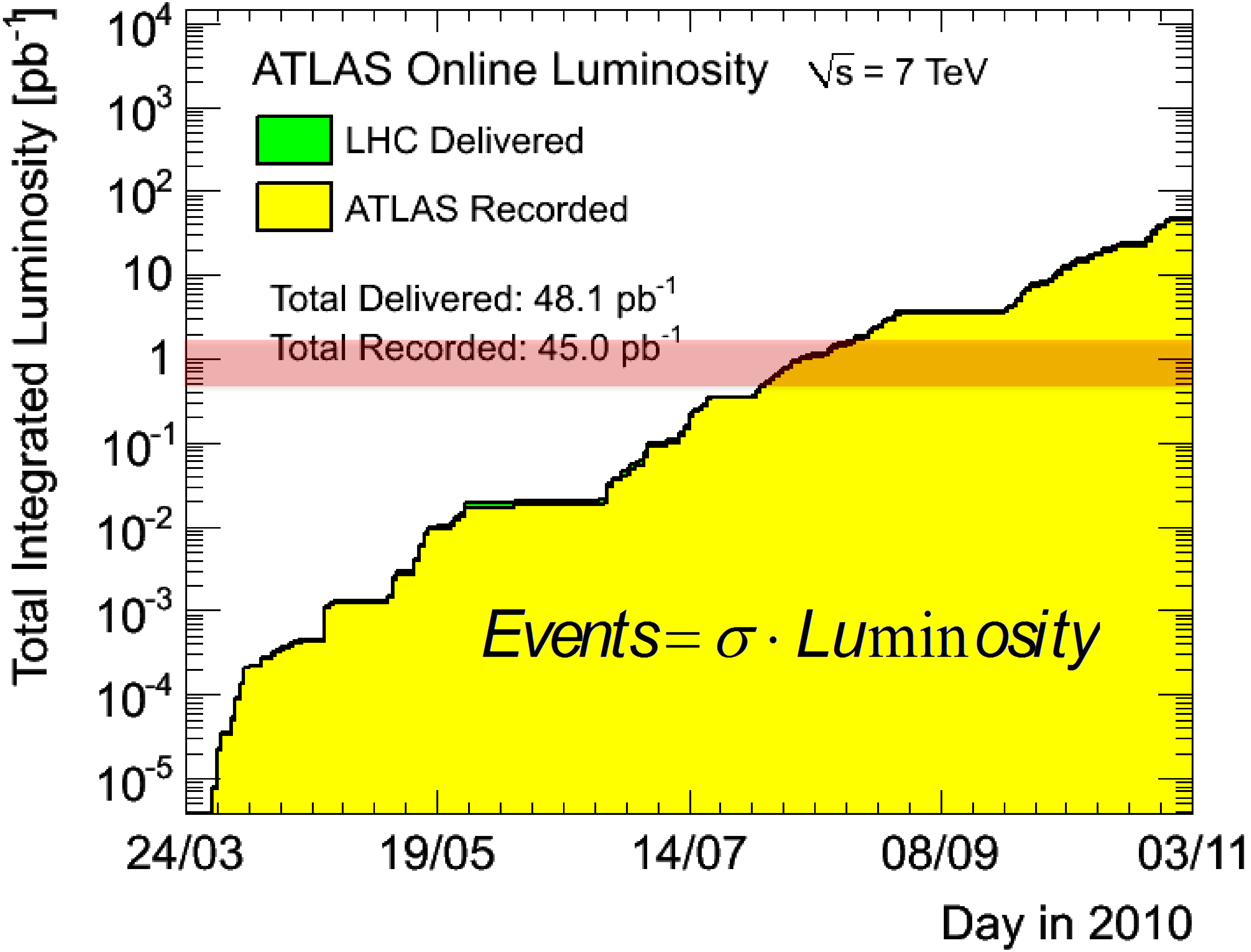
5.5 TeV in collisions of nucleons in lead nuclei

# LHC :
# The Cross-Section Challenge



Task :

- Check everything
- Select the RARE



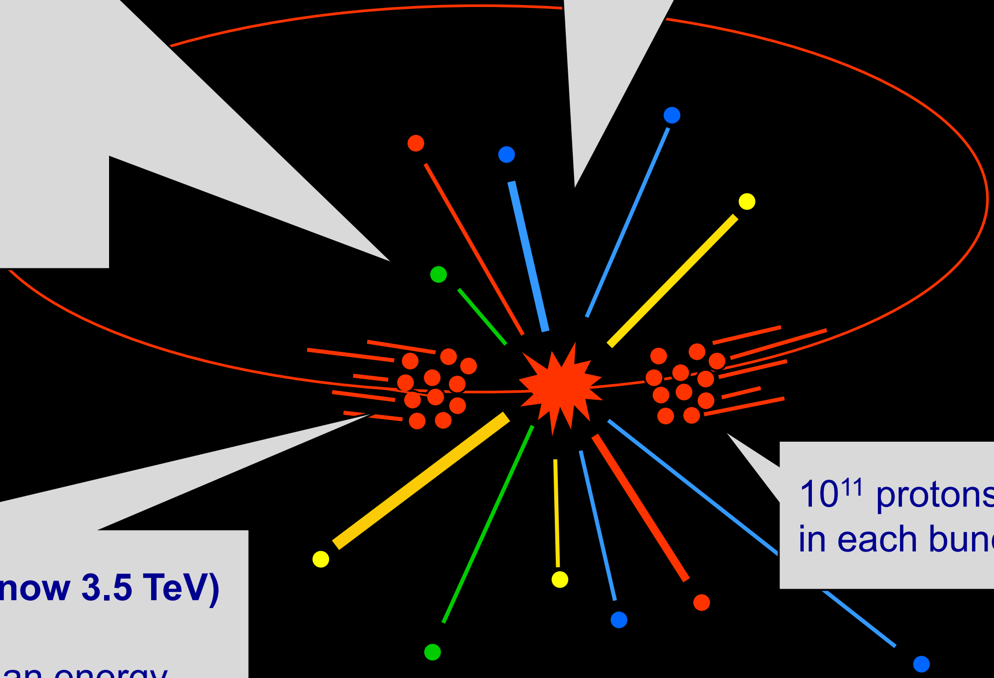
$$Events = \sigma \cdot Luminosity$$

Collision products are recorded by surrounding detector.

The detector should:

- have large coverage (catch most particles)
- be precise
- be fast

Each meeting of two bunches results in about 23 proton-proton collisions. Average number of particles created in such collisions is about 1500.

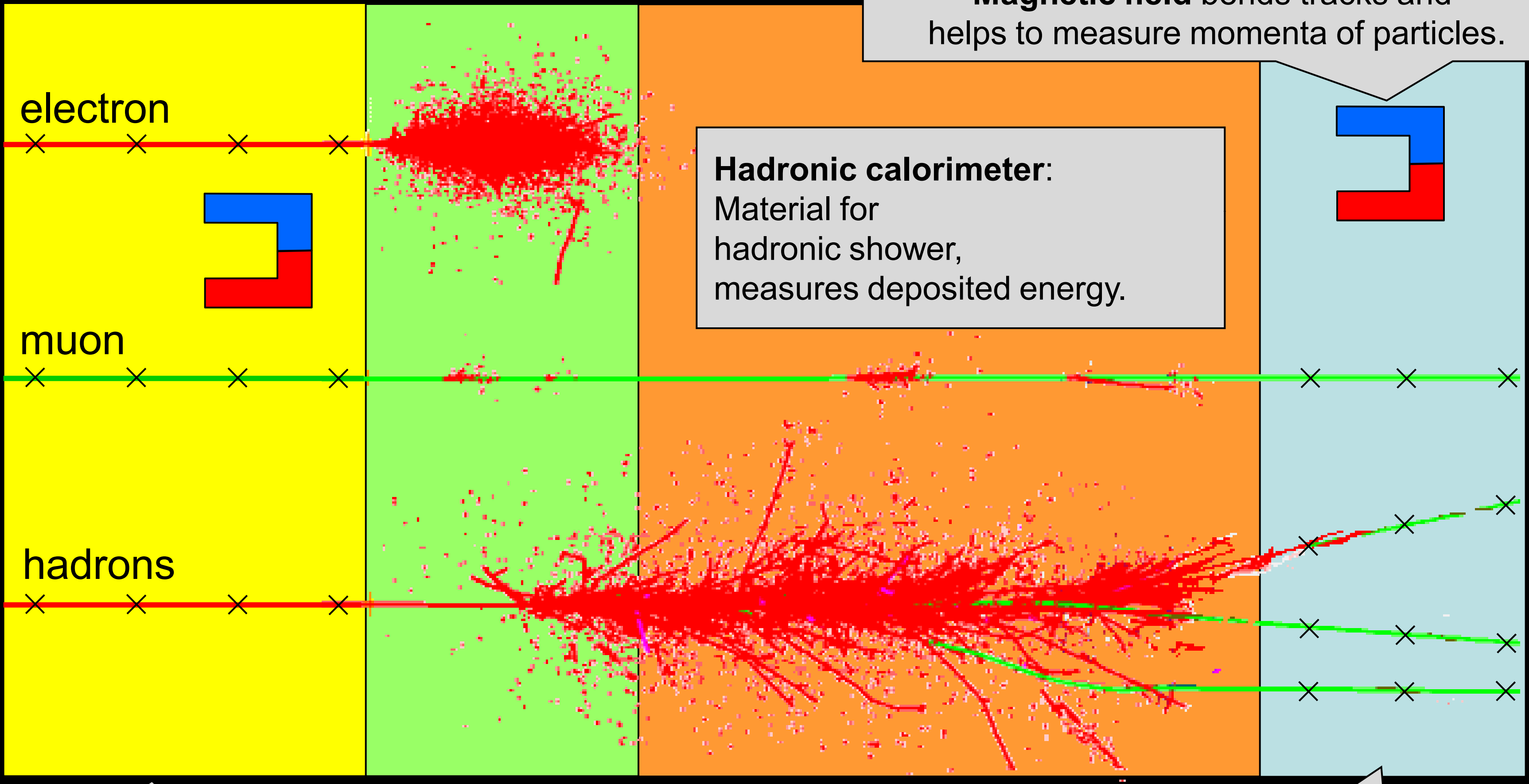


$10^{11}$ protons in each bunch

**Each proton carries energy 7 TeV (now 3.5 TeV)**

Each bunch with $10^{11}$ protons carries an energy of $10^{11} \times 7 \times 10^{12}$ eV = $7 \times 10^{23}$ eV = 44 kJ.
This is a macroscopic !
Corresponds to a bike at 30 km/h …

# The strategy of a detector : To catch almost all particles:



**Magnetic field** bends tracks and helps to measure momenta of particles.

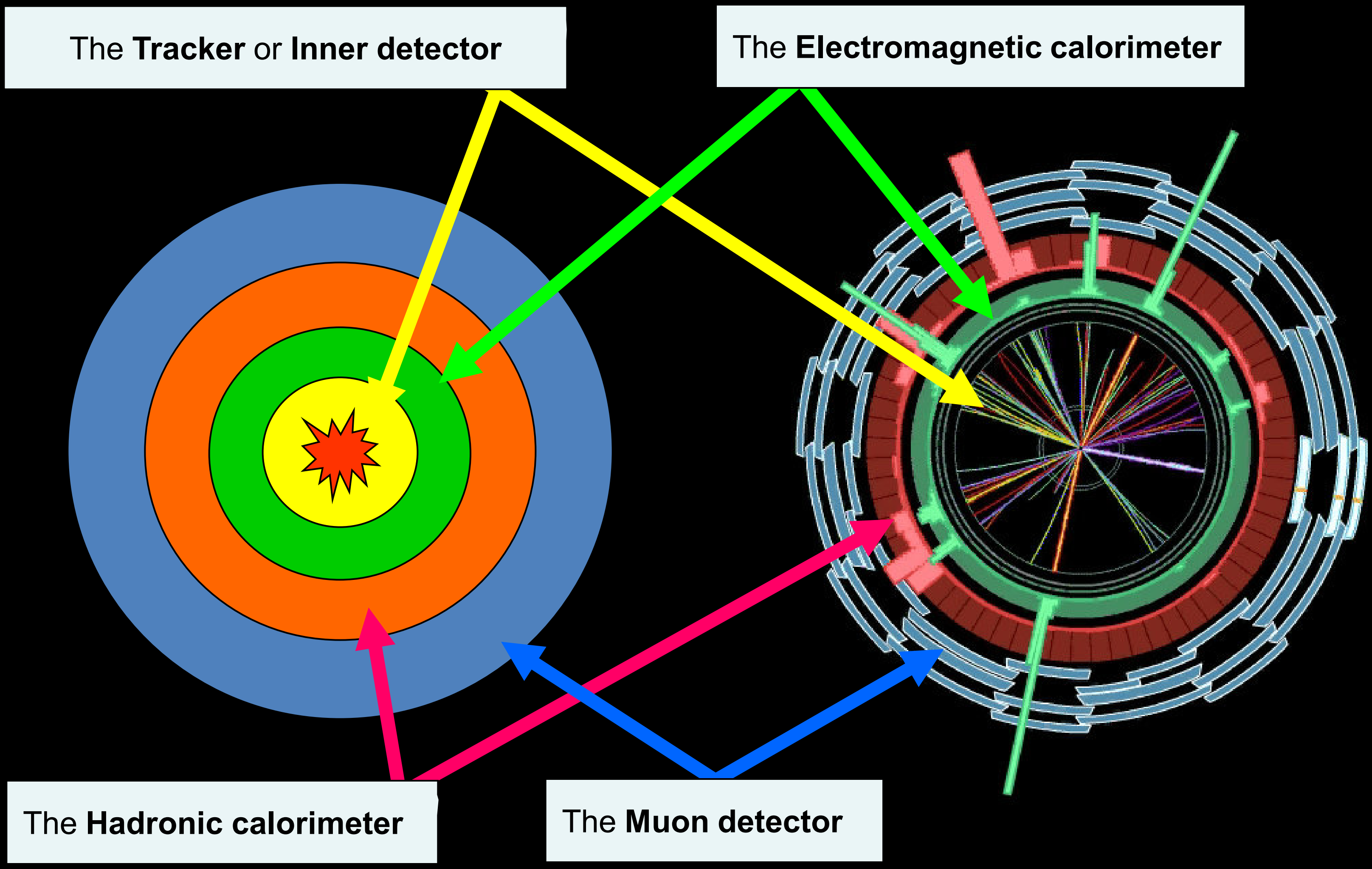
**Hadronic calorimeter**:
Material for
hadronic shower,
measures deposited energy.

**Tracker**: Not much material, finely segmented detectors measure precise positions of points on tracks.

**Electromagnetic calorimeter**: Material for electromagnetic shower, measures deposited energy.

**Muon detector**: Measures muon tracks.

# Detectors are wrapped around the beam pipe and the collision point – A schematic and less schematic cut through the ATLAS detector



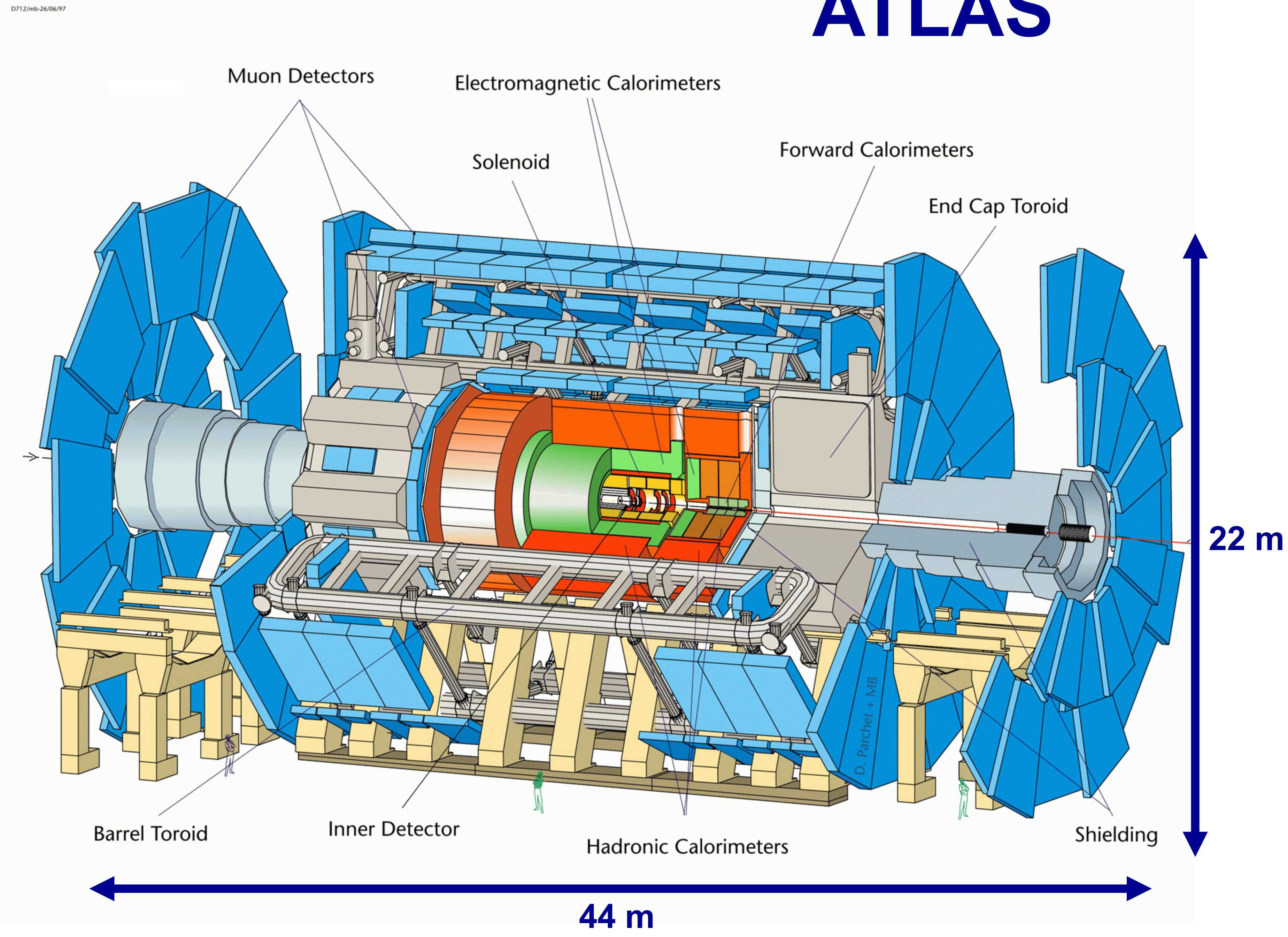
The **Tracker** or **Inner detector**

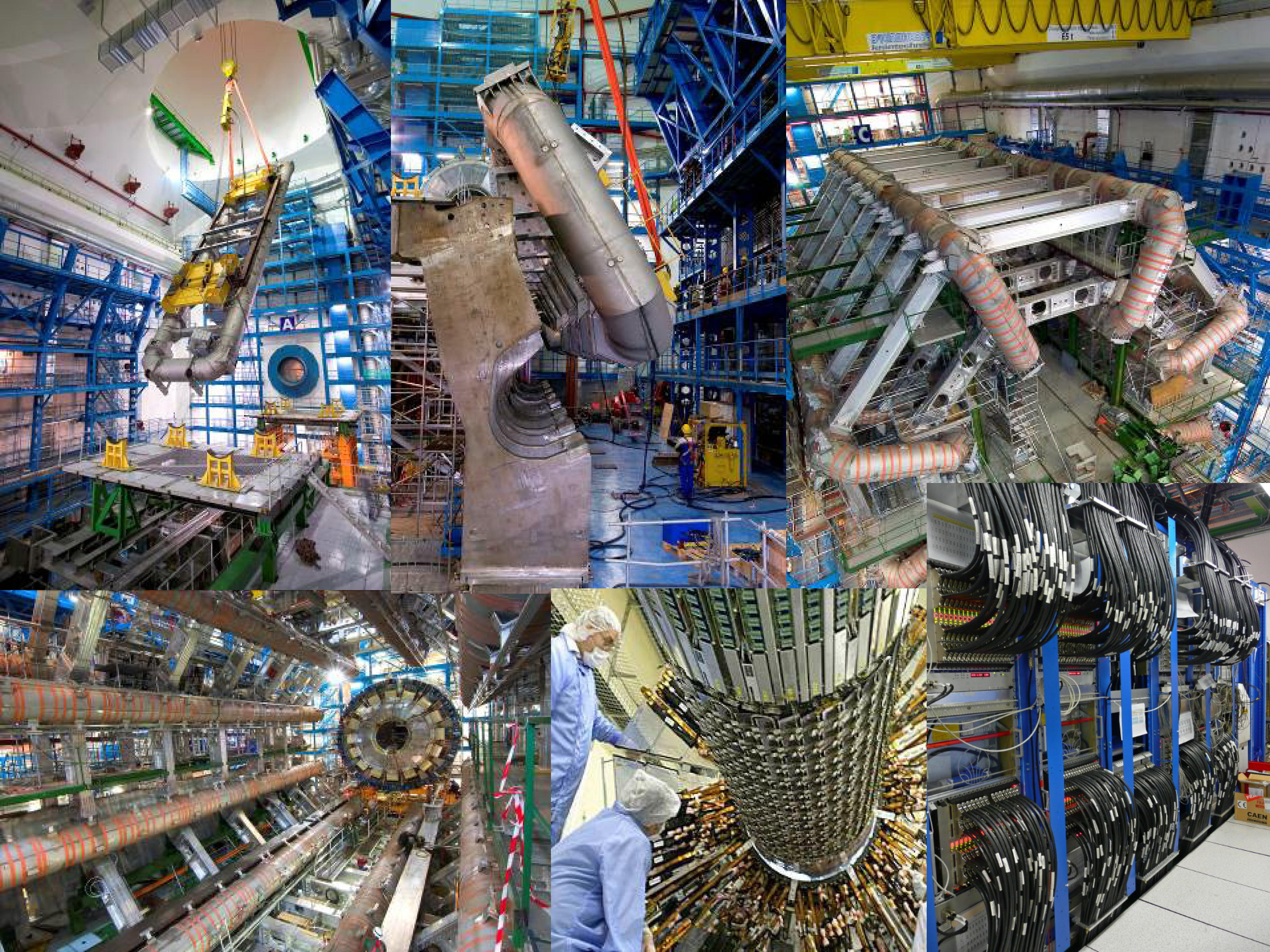
The **Electromagnetic calorimeter**

The **Hadronic calorimeter**

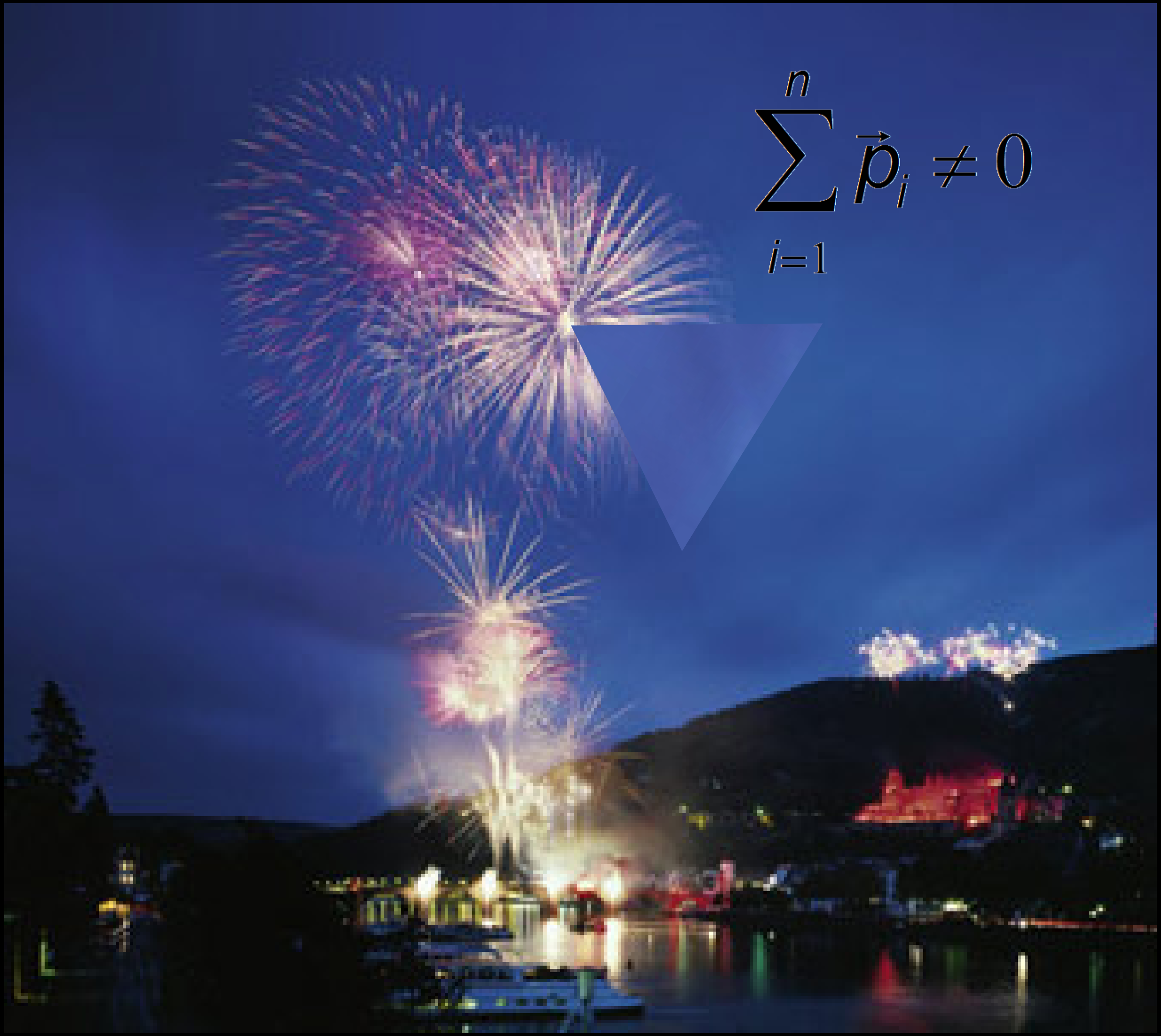
The **Muon detector**

# ATLAS

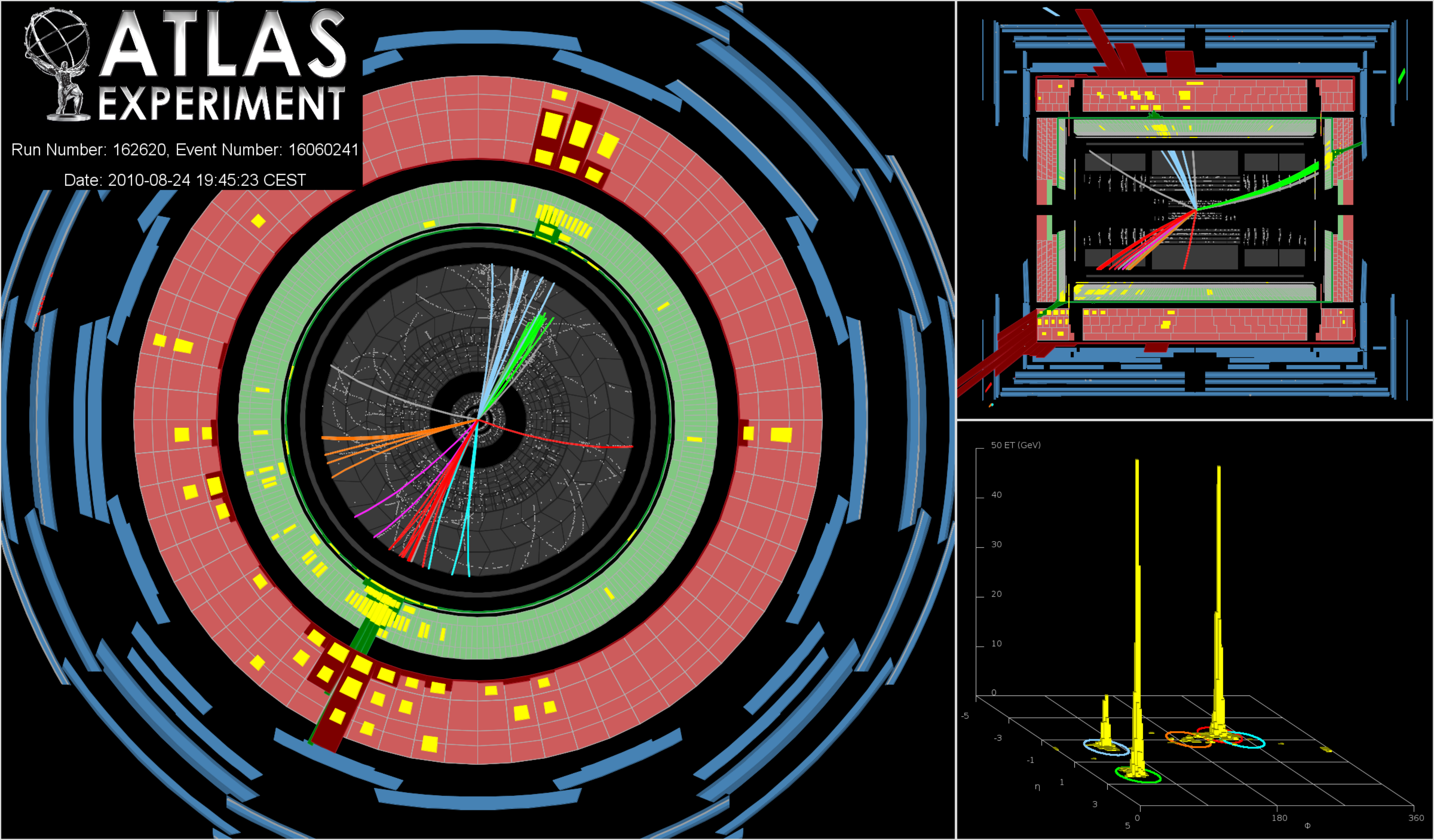

D712/mb-26/06/97
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
22 m
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
D. Parchet + MB
44 m


A
C
CAEN

$$\sum_{i=1}^{n} \vec{p}_i = 0$$



$$\sum_{i=1}^{n} \vec{p}_i \neq 0$$

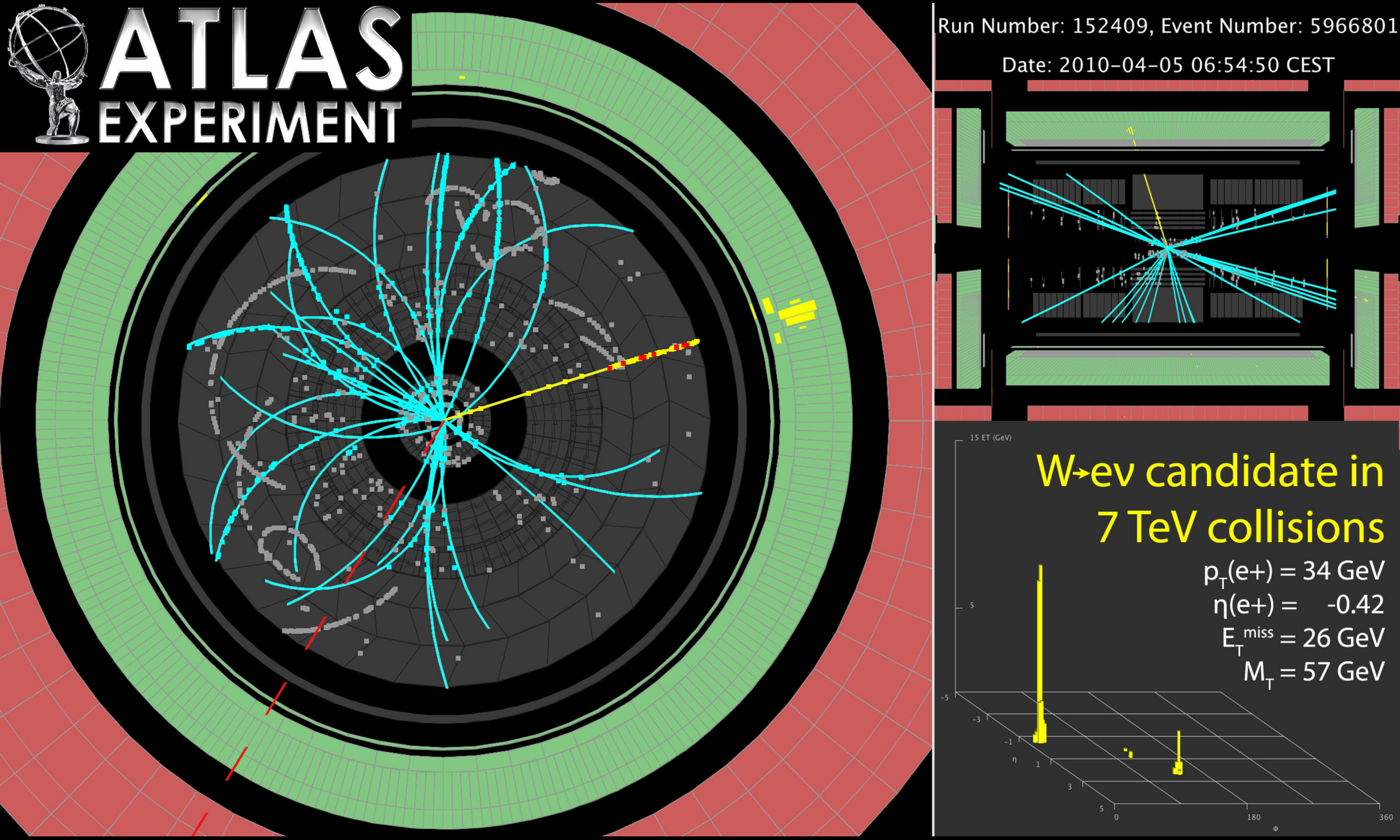

Run Number: 162620, Event Number: 16060241

Date: 2010-08-24 19:45:23 CEST

# „Missing $E_T$“ (MET)

$$\vec{p}_{T,miss} = (\sum p_x, \sum p_y)$$

$$p_{T,miss} = \sqrt{\left(\sum p_x\right)^2 + \left(\sum p_y\right)^2}$$



Run Number: 152409, Event Number: 5966801

Date: 2010-04-05 06:54:50 CEST

# W→eν candidate in 7 TeV collisions

$p_T(e+) = 34$ GeV
$\eta(e+) = -0.42$
$E_T^{miss} = 26$ GeV
$M_T = 57$ GeV

# A historical problem : $E=mc^2$ for the electron

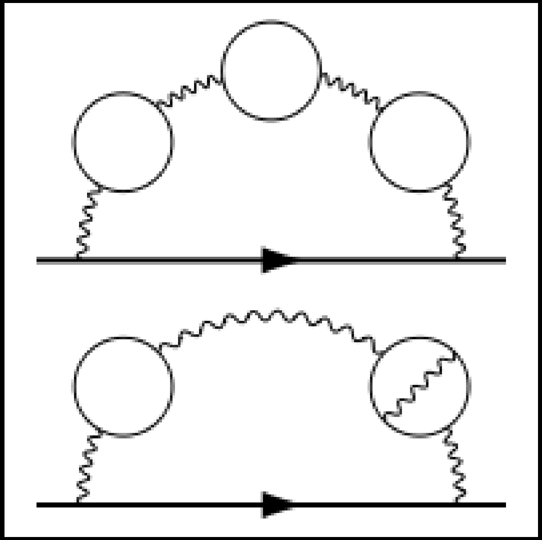
- Electron size < $10^{-18}$ cm !
- Electron repels itself
- Need at least $10^{10}$ eV of energy to pack electric charge tightly inside the electron
- But the observed mass of the electron is only $5\times10^5$ eV
- Electron cannot be smaller than $10^{-13}$ cm ?

- Breakdown of theory of electromagnetism

# New Anti-Matter helps - QED

- Loops of matter anti-matter creation/annihilation
- Electron annihilates the positron in the bubble

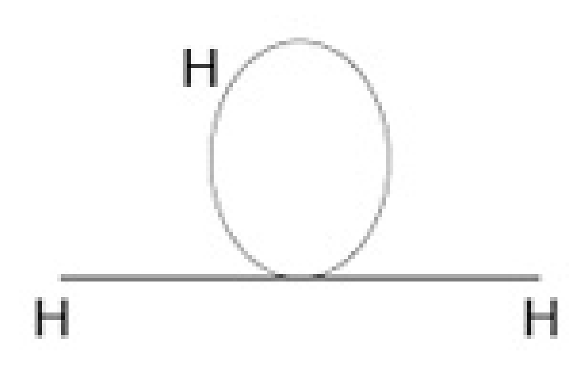
  $\Rightarrow$ reduction of mass



# Higgs repels itself, too

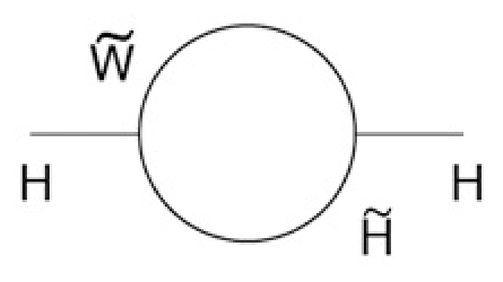
- Just like the electron repelling itself because of its charge, the Higgs boson also repels itself
- Requires a lot of energy to contain itself in its point-like size!

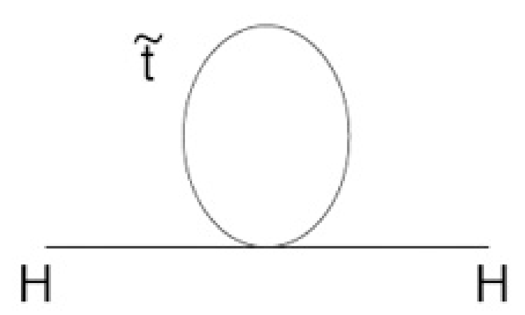
- Breakdown of theory of weak force



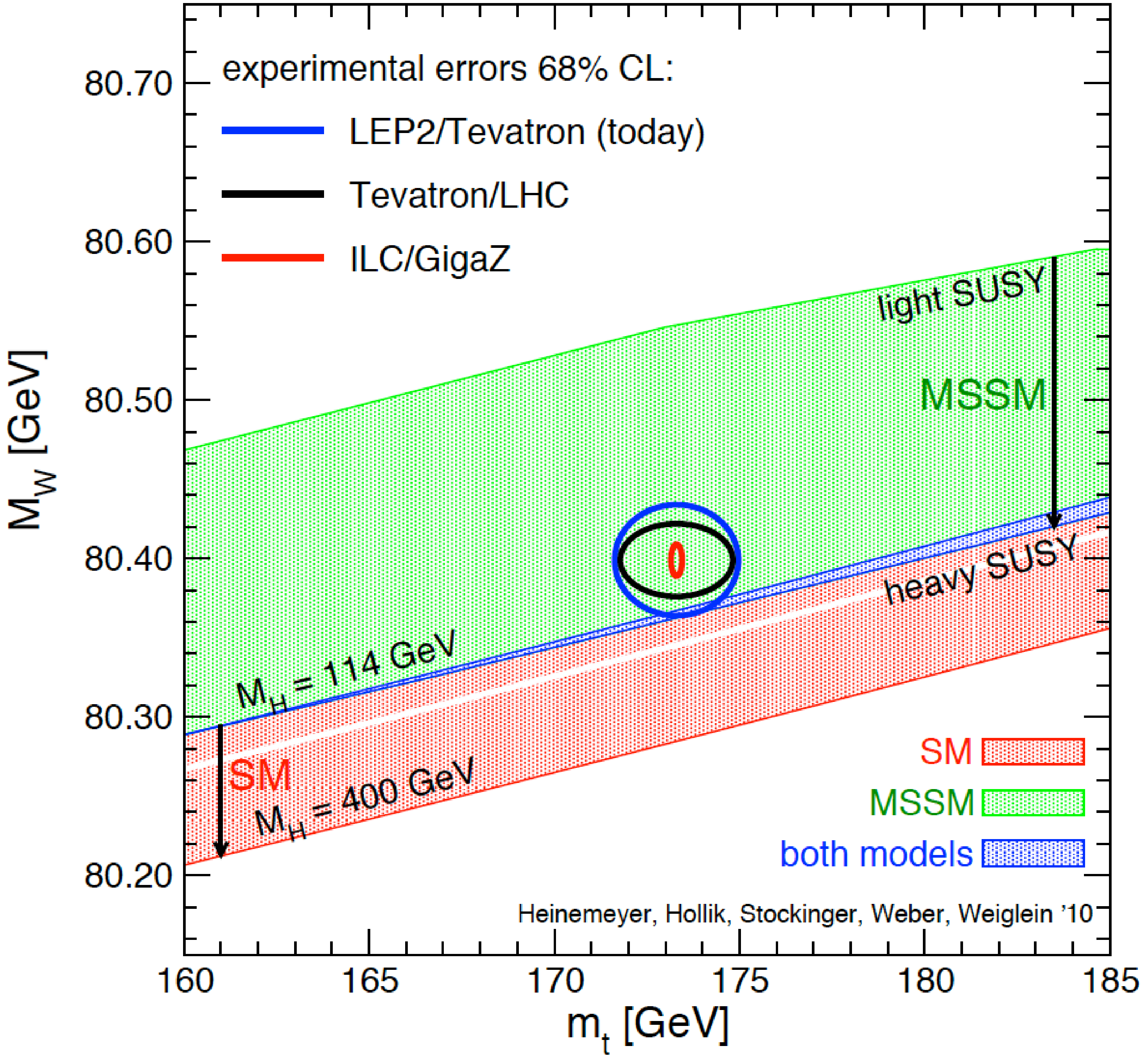
# Play the same trick again ?

- Known particle loops
  $(100\ GeV)^2 = (10^{16}\ GeV)^2$ □□□$(10^{16}\ GeV)^2$
- Double particles : superpartners
- Loops of superpartners cancel the energy required to contain Higgs boson in itself

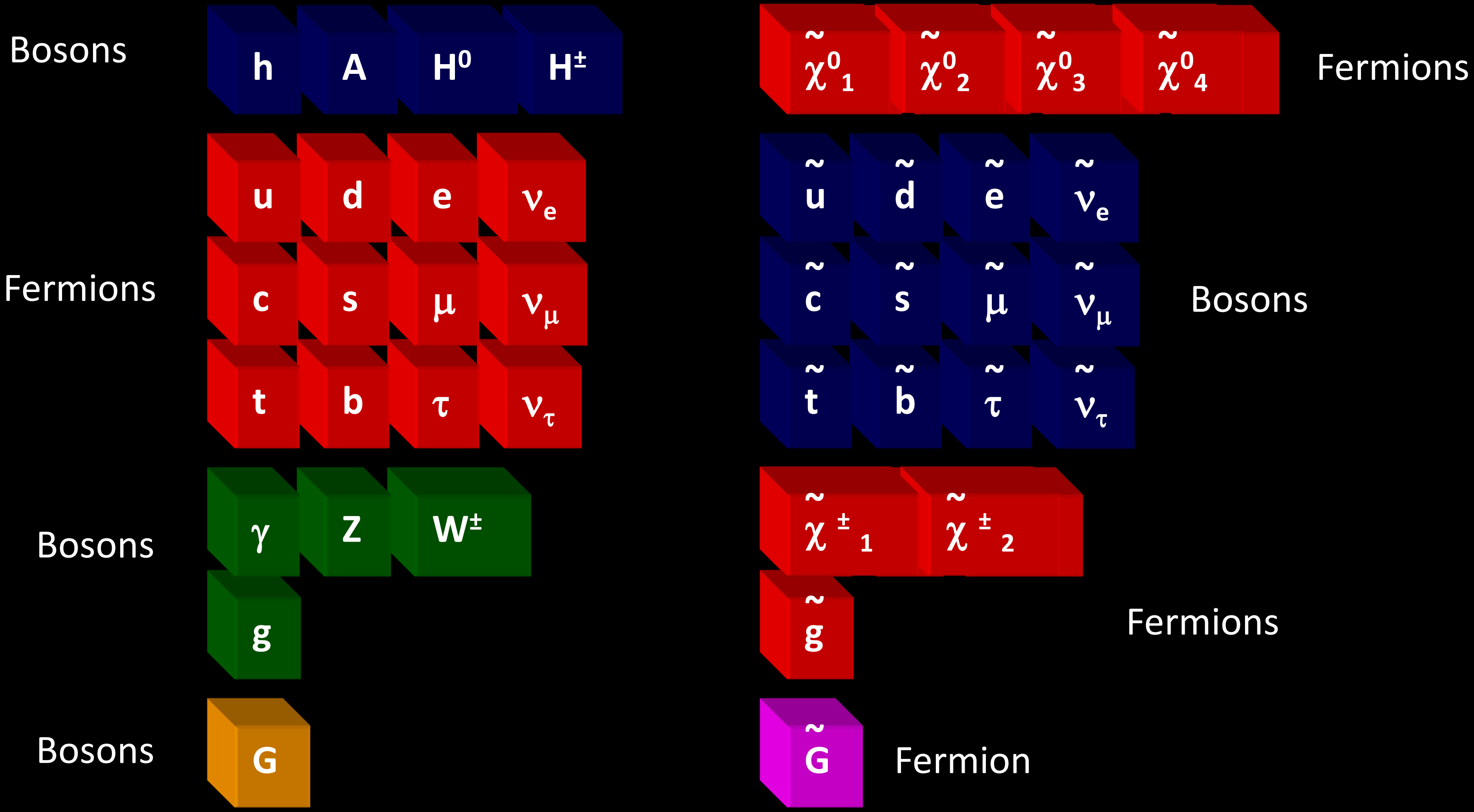




# The Billion Dollar Plot



# Supersymmetry gives rise to partners of known standard model states with opposite spin-statistic (Fermion – Boson)



Bosons

$h$ $A$ $H^0$ $H^\pm$

Fermions

$u$ $d$ $e$ $\nu_e$

$c$ $s$ $\mu$ $\nu_\mu$

$t$ $b$ $\tau$ $\nu_\tau$

Bosons

$\gamma$ $Z$ $W^\pm$

$g$

Bosons

$G$

$\tilde{\chi}^0_1$ $\tilde{\chi}^0_2$ $\tilde{\chi}^0_3$ $\tilde{\chi}^0_4$

Fermions

$\tilde{u}$ $\tilde{d}$ $\tilde{e}$ $\tilde{\nu}_e$

$\tilde{c}$ $\tilde{s}$ $\tilde{\mu}$ $\tilde{\nu}_\mu$

$\tilde{t}$ $\tilde{b}$ $\tilde{\tau}$ $\tilde{\nu}_\tau$

Bosons

$\tilde{\chi}^\pm_1$ $\tilde{\chi}^\pm_2$

$\tilde{g}$

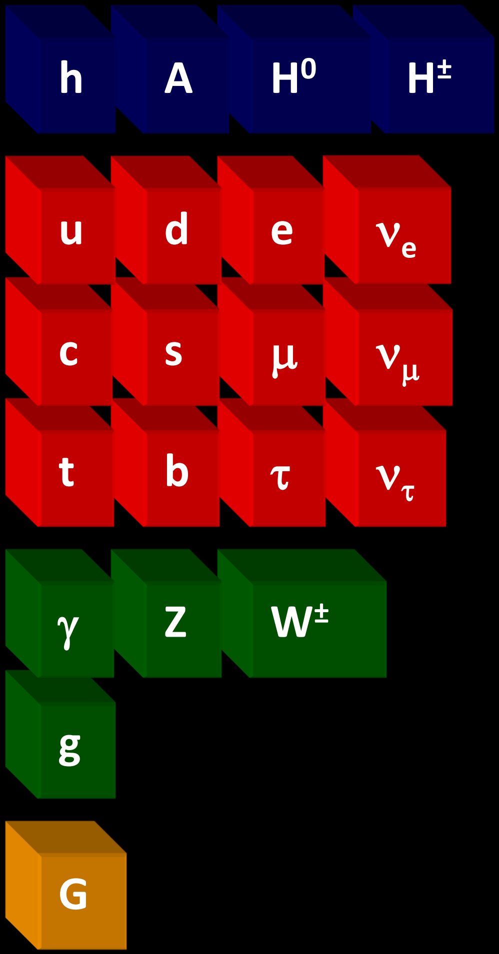
Fermions

$\tilde{G}$

Fermion

## Particles

## Sparticles



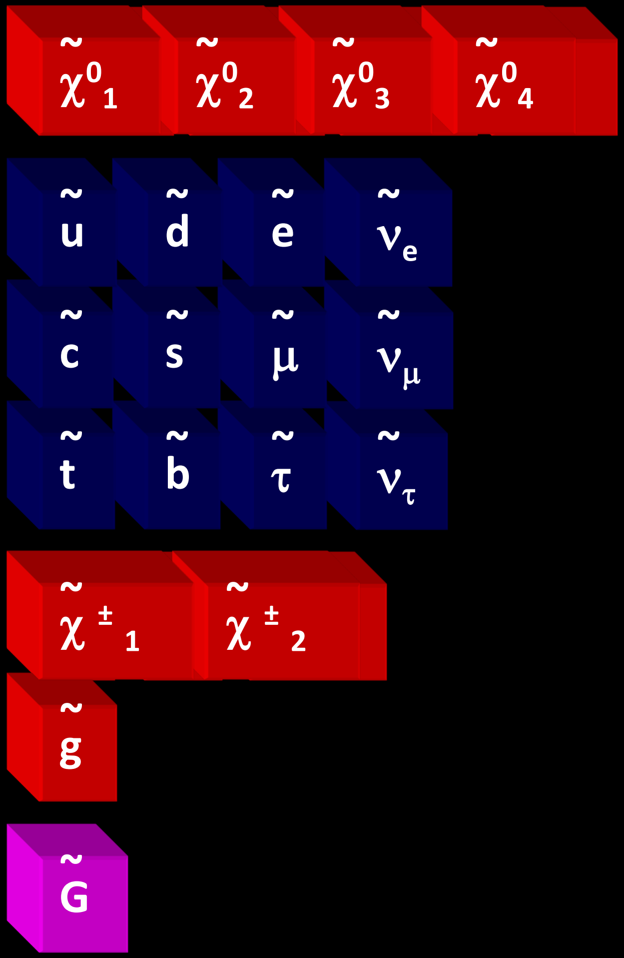
# Minimal SSM (1)

2 complex Higgs-doublets
8 free scalar parameters
5 physical Higgs fields:
$H^\pm$
$H_1^0$
$H_2^0$
$A^0$

## Minimal SSM (2)

Gauginos
mix with higgsinos
and therefore result in
4 *charginos*
and

*4 neutralinos !*



- 124 FREE PARAMETERS for masses and couplings !!

- Possibly conservation of R parity:
  $R = (-1)^{2S - L + 3B}$
  S = spin, L = lepton number, B = baryon number

- Particles have R = +1, sparticles R = -1:
  Sparticles produced in pairs
  Heavier sparticles → lighter sparticles

- Lightest supersymmetric particle (LSP) stable, candidate for particle interpretation of CDM

# From CDM to Supersymmetry

Non-baryonic matter density obtained from WMAP measurements:

$\mathbf{0.094 < \Omega_{DM}\, h^2 < 0.129}$

For any specific set of parameters of a supersymmetric R-parity conserving model, it is possible to compute the corresponding LSP relic density from the mass spectrum and the Big-Bang cosmology.

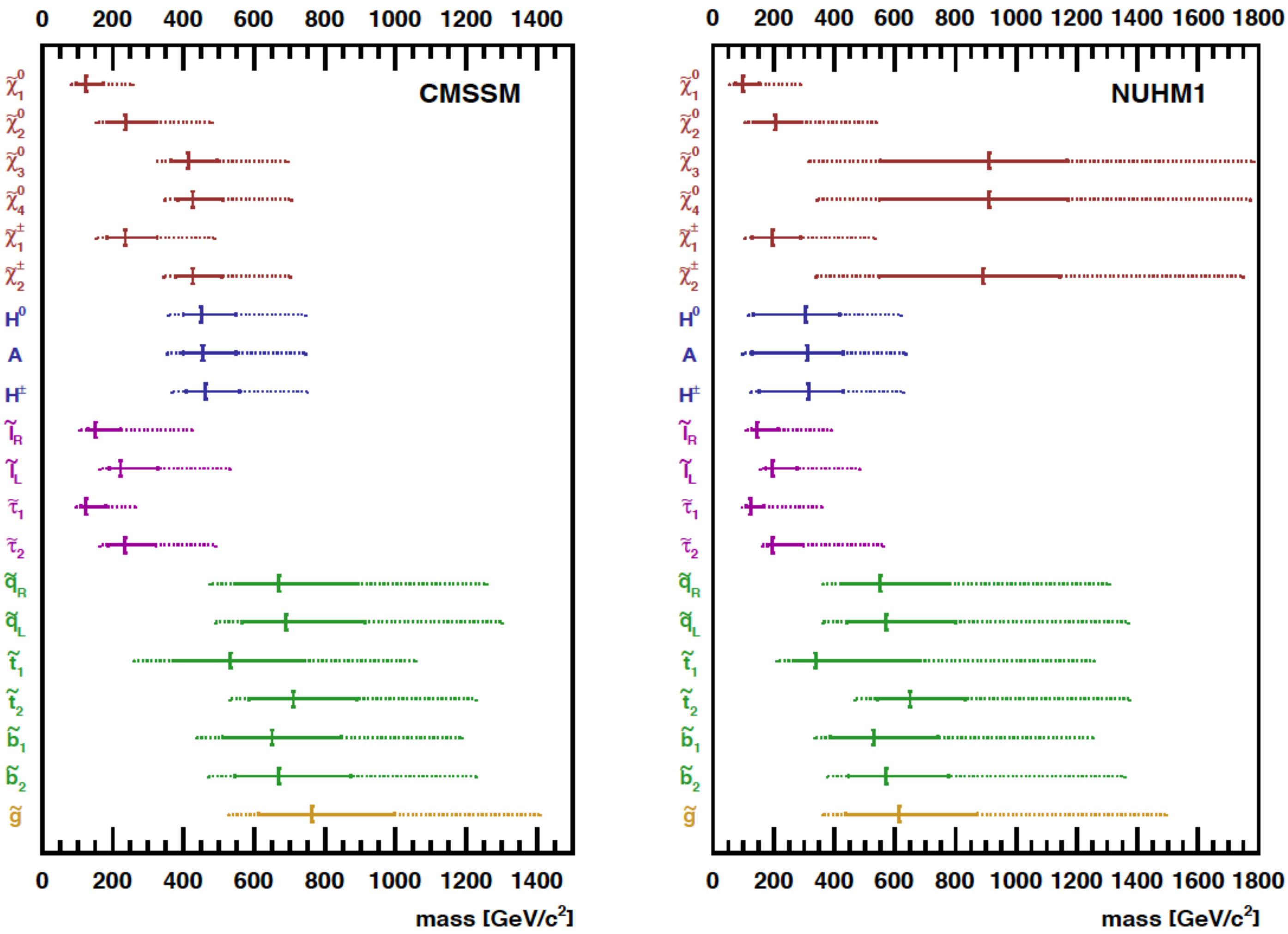
The relic density should be less than $\Omega_{DM}$ (if other contributions to the DM).

The WMAP measurement is a constraint that defines cosmologically interesting regions of the SUSY parameter space.

# … and back to CDM

Once (if ever …) we will have a measurement of the mass mass spectrum and the mixing angles, we can compute the relic density it corresponds to.

# Making the best (?) of theory, electroweak HEP data and cosmology .....



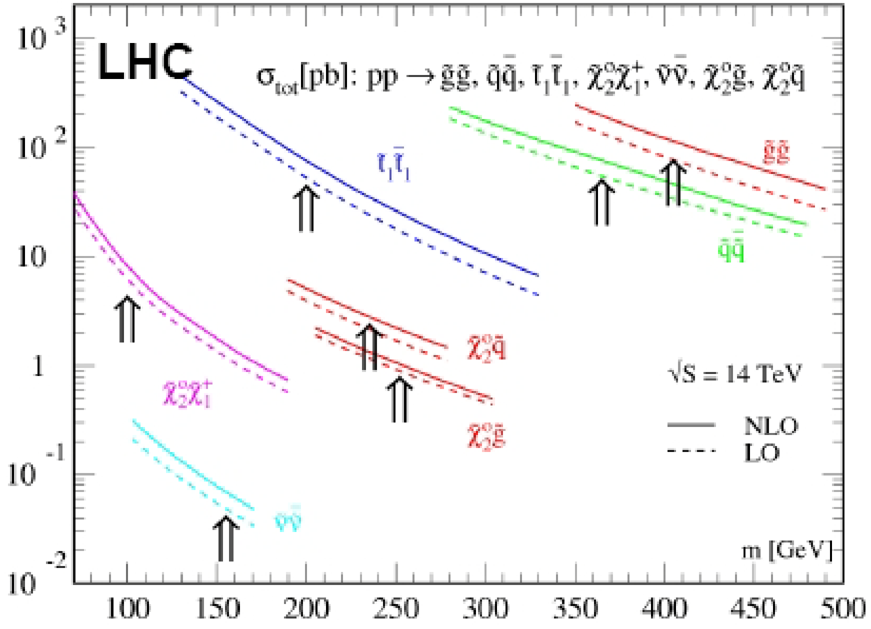
S. Heinemeyer and G. Weiglein, Nuclear Physics B, Volume 205, p. 283-288, 2010

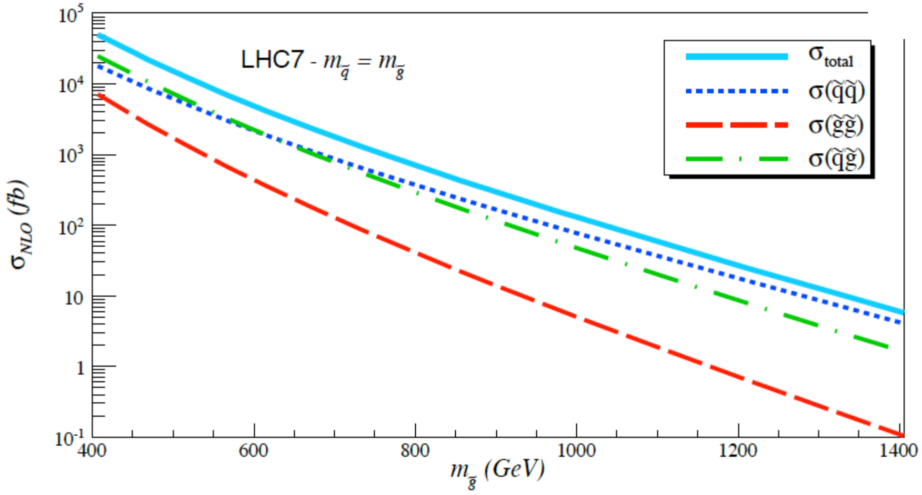
# SUSY Production at the LHC

Weak for light

Strong for heavy (and light ..)

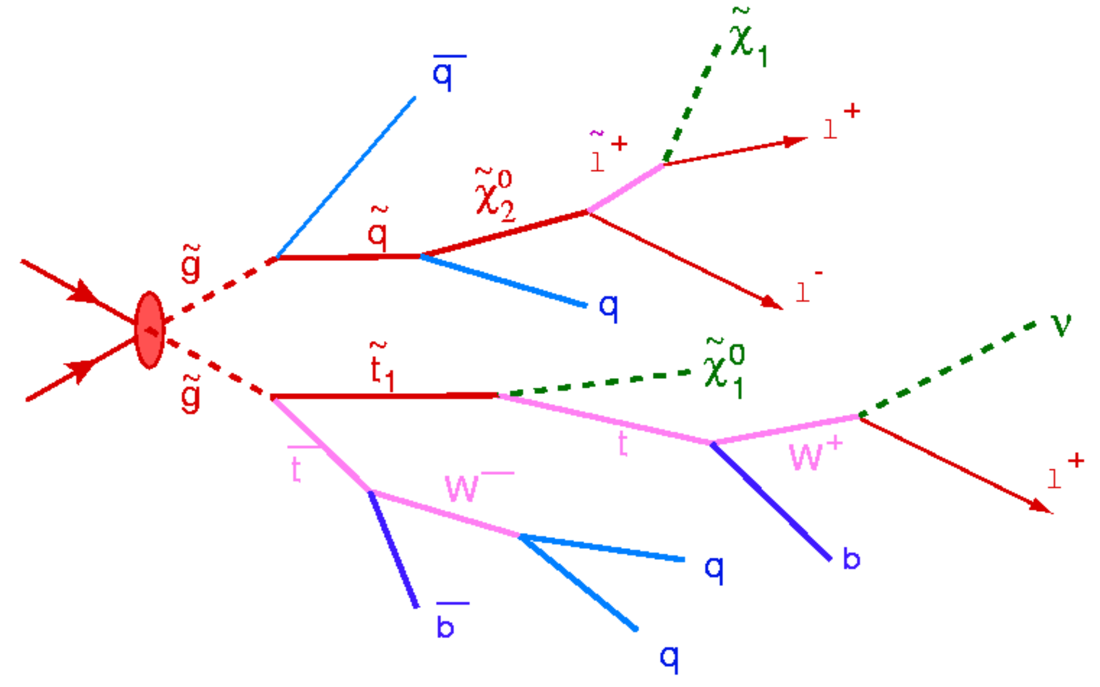
Strong for the beginning





Strong for less !

H.Baer et al., Capability of LHC to discover supersymmetry with sqrt {s} = 7{text{TeV}} and 1 fb$^{-1}$, Journal of High Energy Physics, Volume 2010, article id. #102

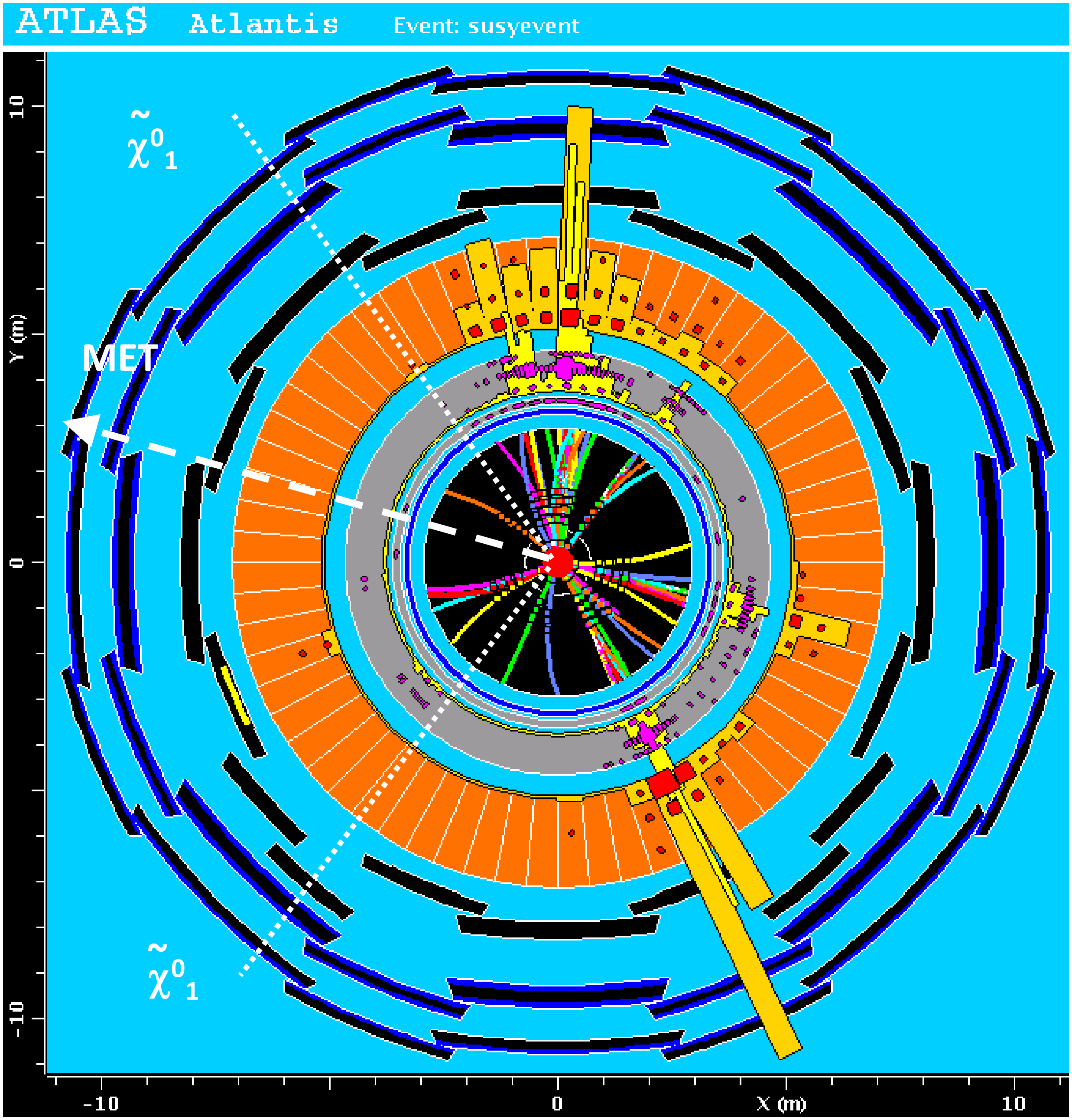


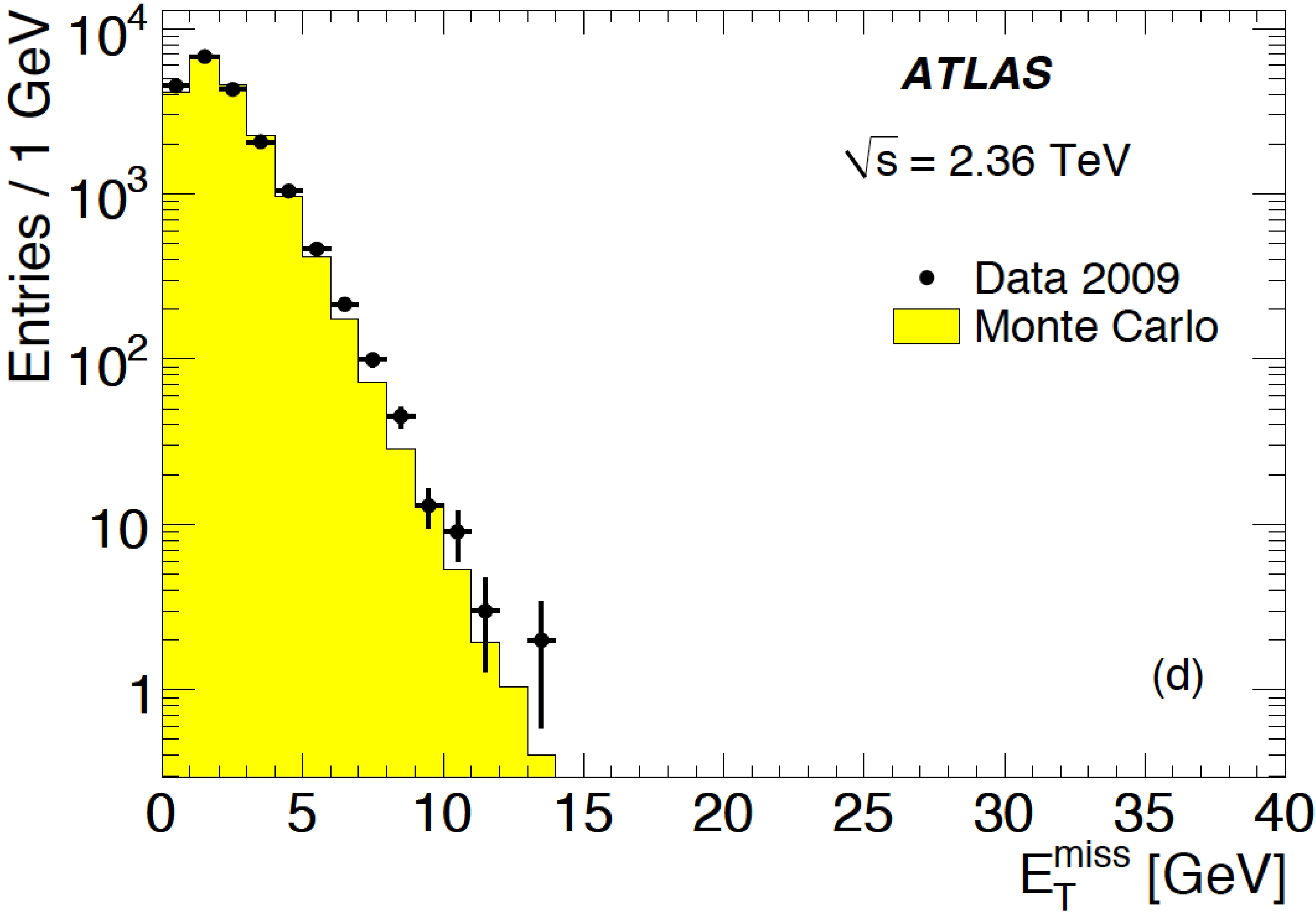
The LHC likes strong interactions !

Quarks and gluons in the initial state

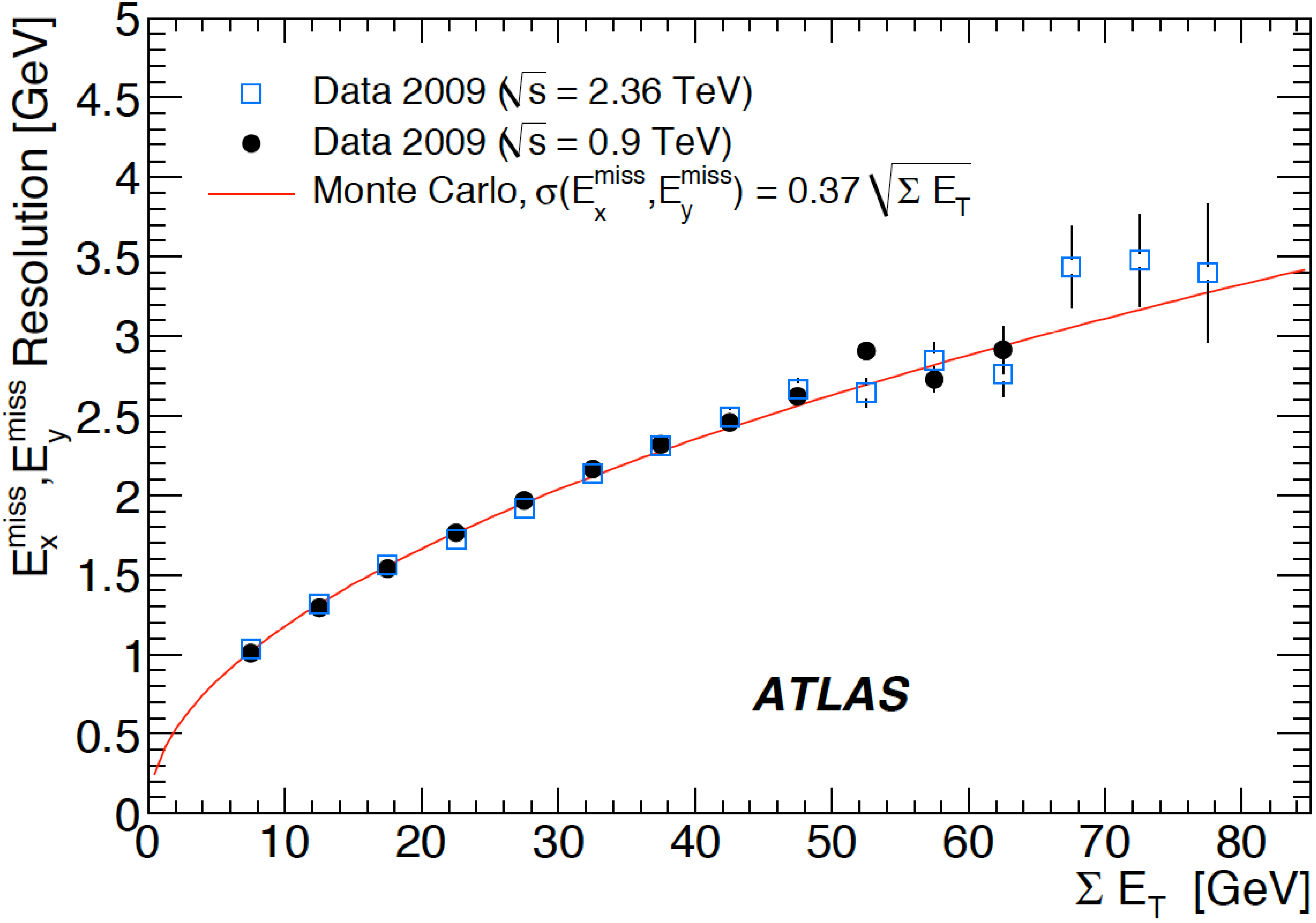
Squarks and gluinos are the objects to produce !

The last in the cascade (The *NEUTRALINO*) might be 23% of our universe ...


ATLAS
Atlantis
Event: susyevent
$\tilde{\chi}^0_1$
MET
$\tilde{\chi}^0_1$
Y (m)
10
0
-10
X (m)
-10
0
10



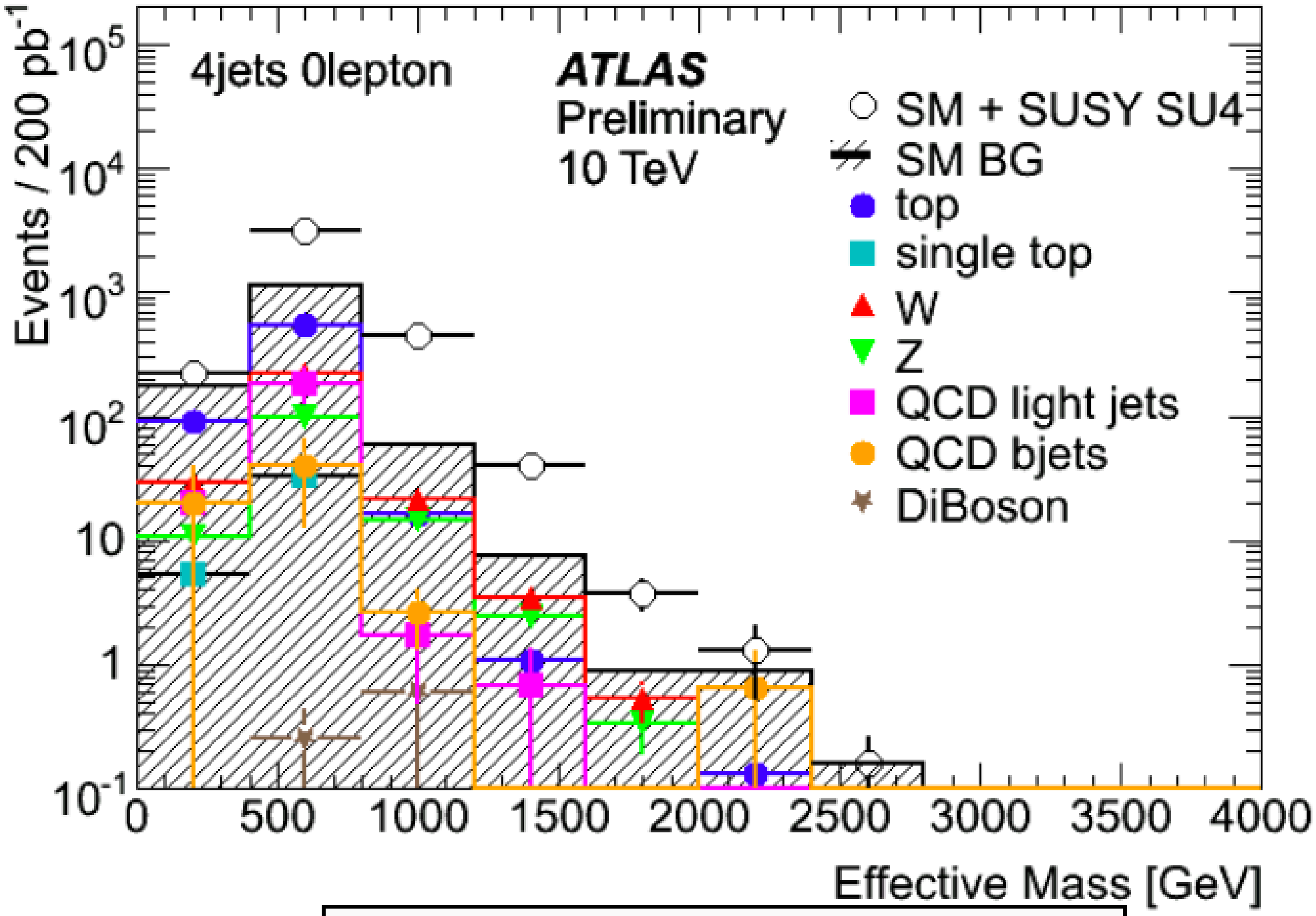
ATLAS Collaboration, Journal of High Energy Physics, Volume 2010, article id. #56, 2010



ATLAS Collaboration, Journal of High Energy Physics, Volume 2010, article id. #56, 2010

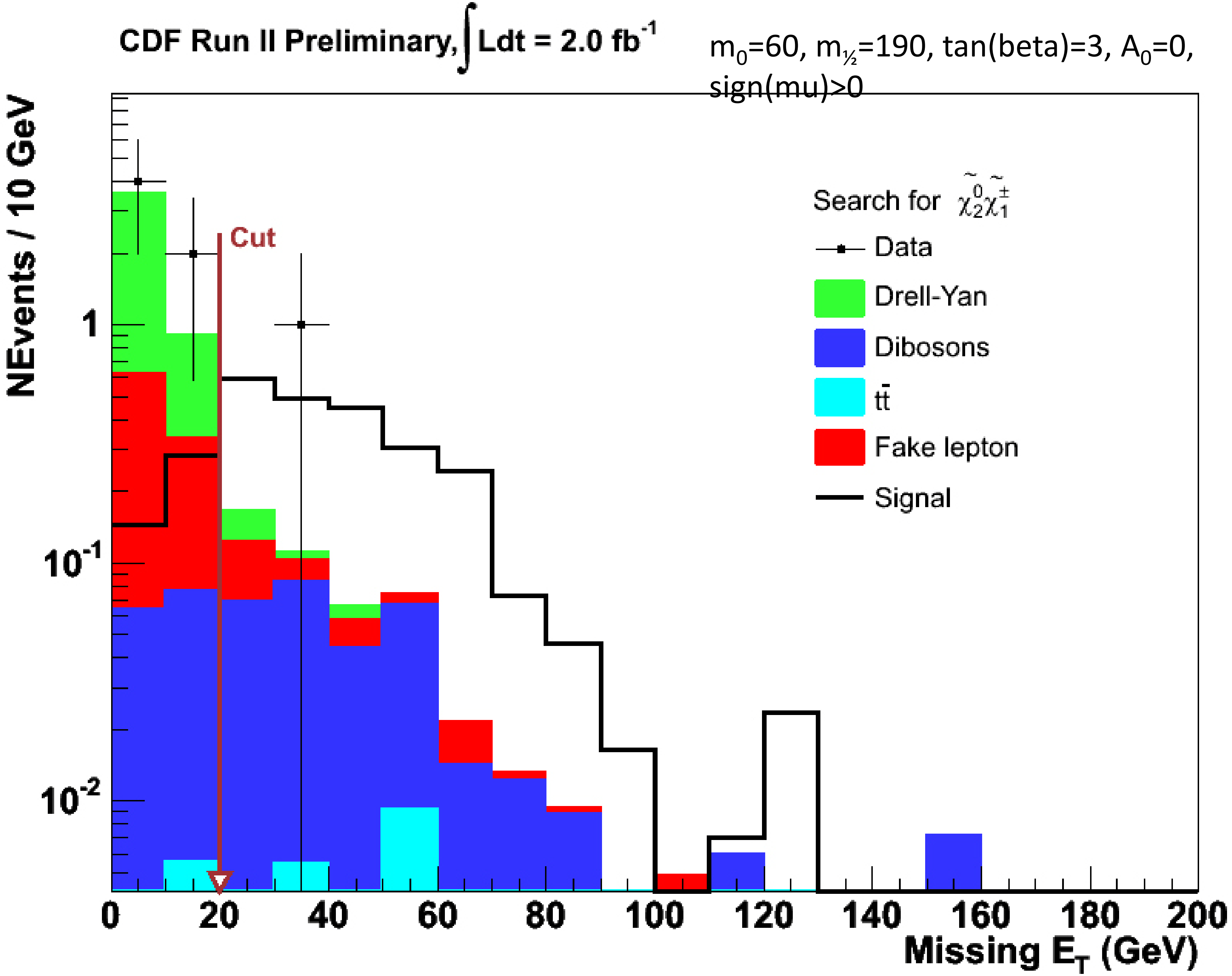
# But when it comes to RARE topologies there will be COMPETITION !

## SIMULATED Example : $M_{\text{squark}} = M_{\text{gluiono}} = 410$ GeV

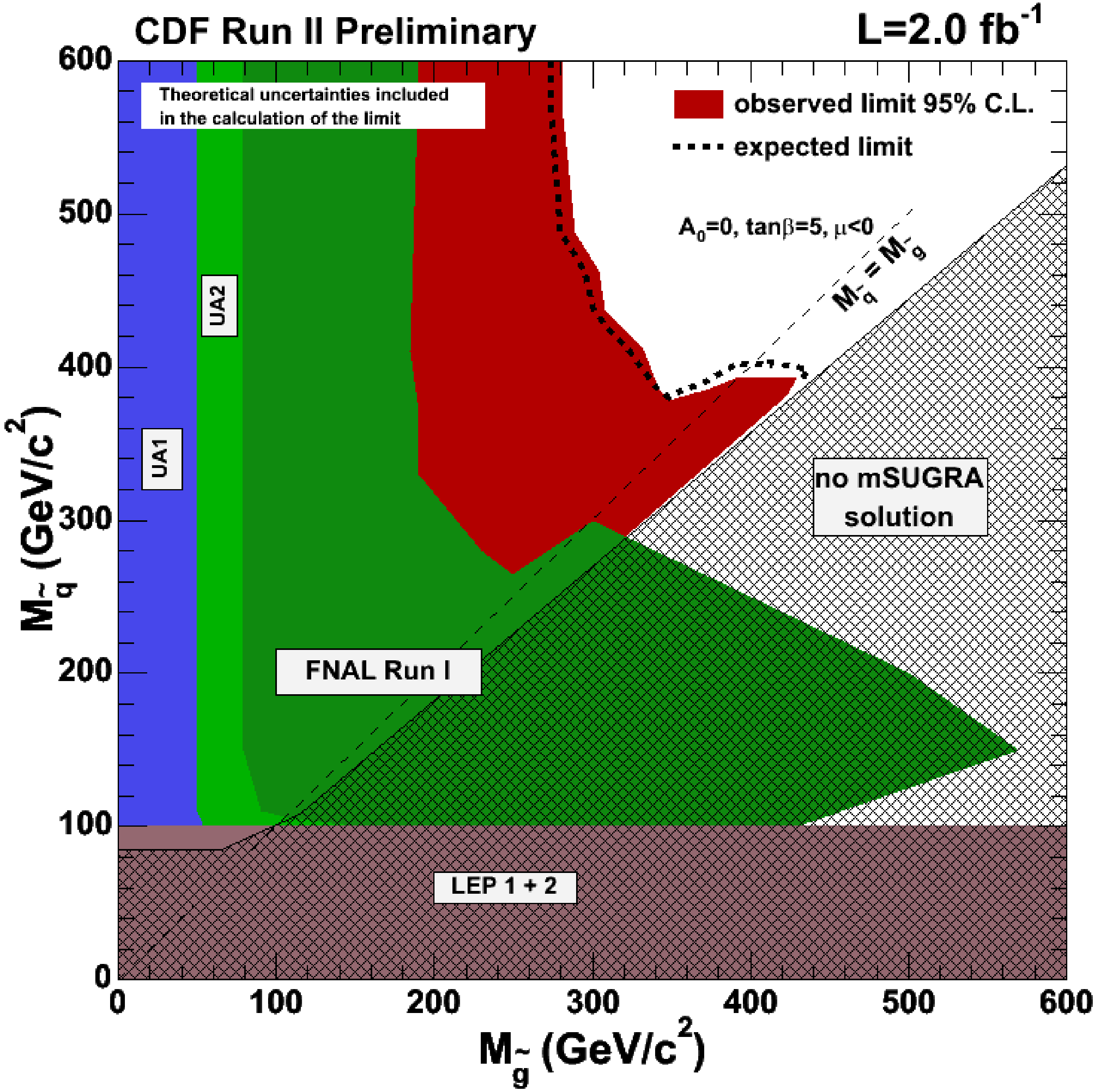


$$M_{\text{eff}} \equiv \sum_{i=1}^{4} p_T^{\text{jet},i} + \sum_{i=1} p_T^{\text{lep},i} + E_{\text{T}}^{\text{miss}}$$

Can you spot the signal ?

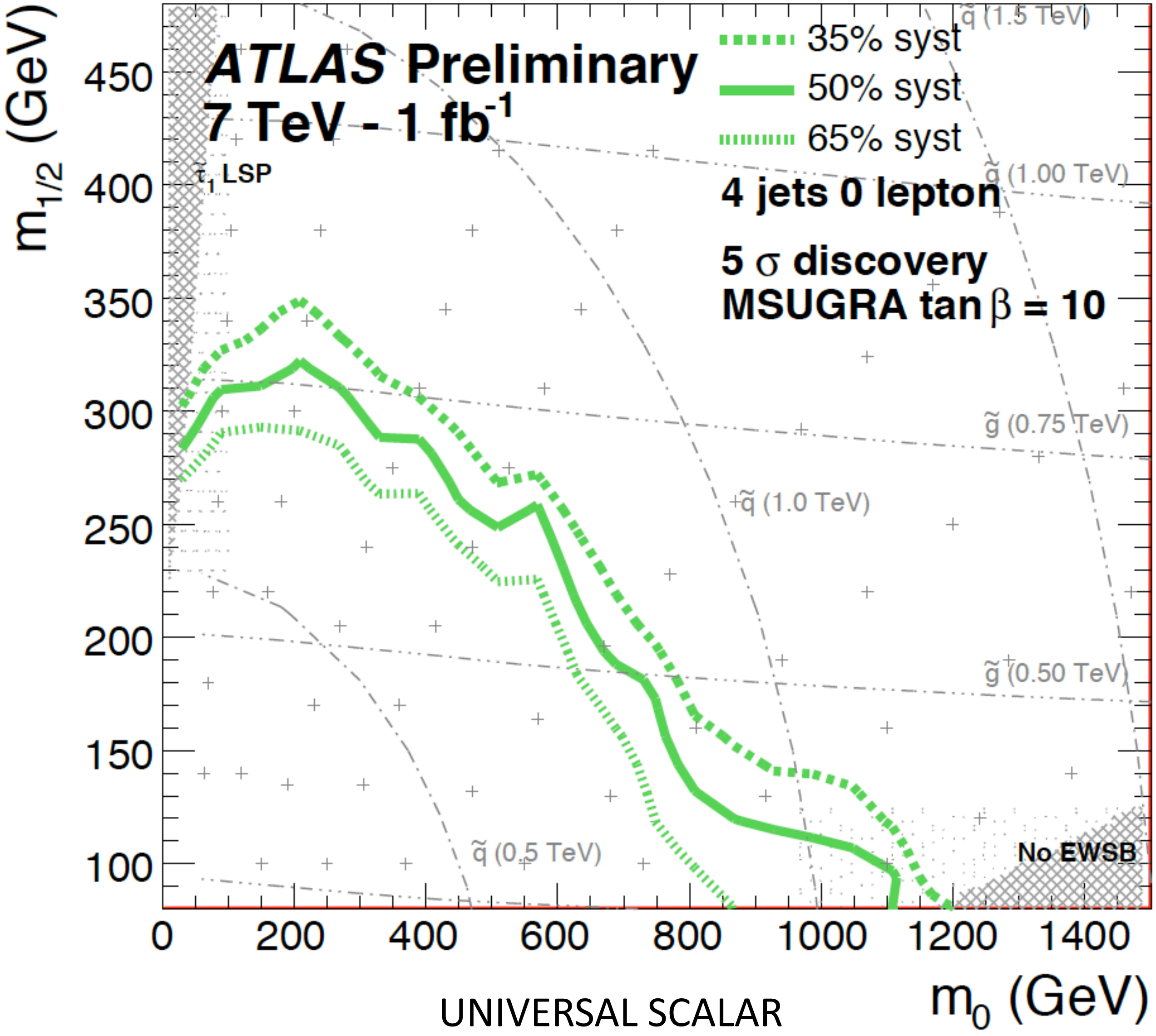


$m_0$=60, $m_{½}$=190, tan(beta)=3, $A_0$=0, sign(mu)>0



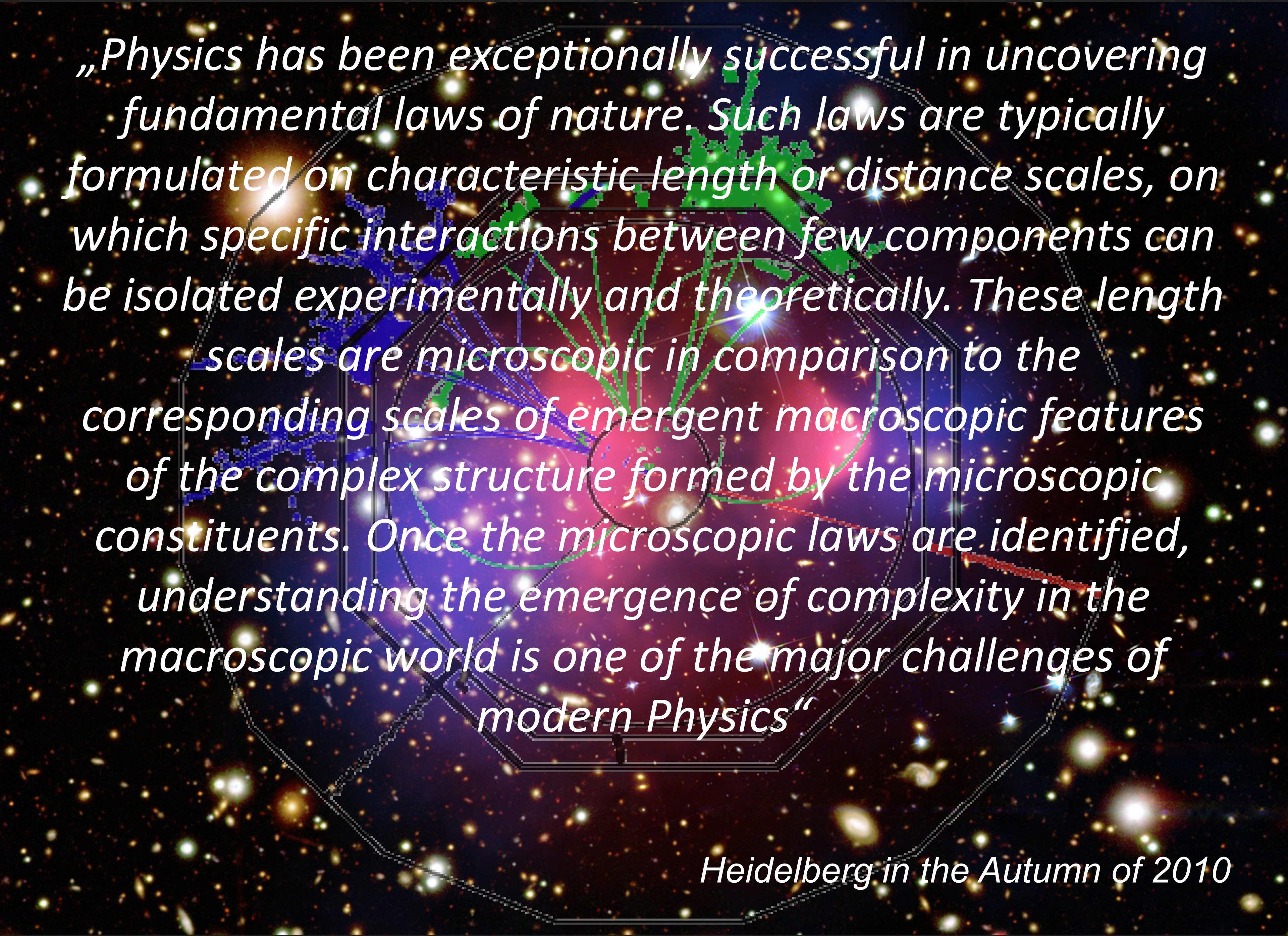
CDF Collaboration, PRL 102, 121801 (2009)

UNIVERSAL GAUGINO



UNIVERSAL SCALAR

ATLAS Collaboration, http://cdsweb.cern.ch/record/1278474/files/ATL-PHYS-PUB-2010-010.pdf

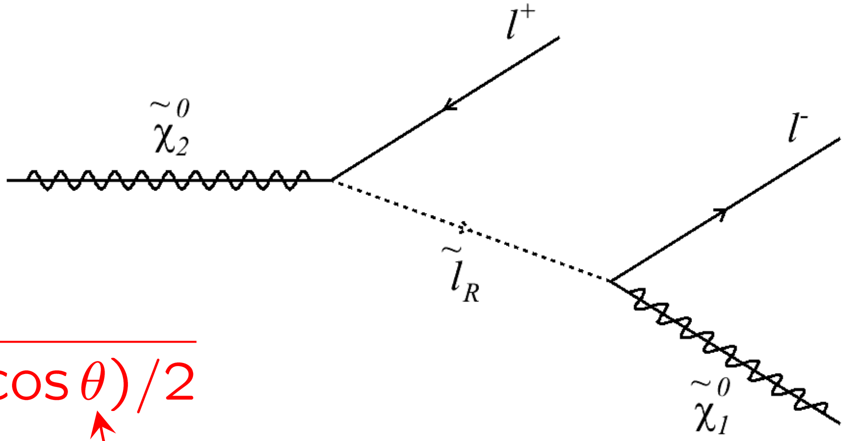


*„Physics has been exceptionally successful in uncovering fundamental laws of nature. Such laws are typically formulated on characteristic length or distance scales, on which specific interactions between few components can be isolated experimentally and theoretically. These length scales are microscopic in comparison to the corresponding scales of emergent macroscopic features of the complex structure formed by the microscopic constituents. Once the microscopic laws are identified, understanding the emergence of complexity in the macroscopic world is one of the major challenges of modern Physics“*

*Heidelberg in the Autumn of 2010*

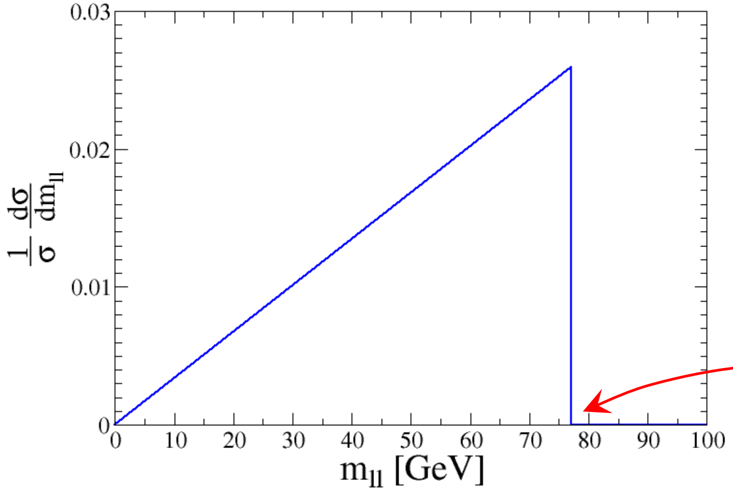
# Exclusive Reconstruction of Supersymmetric Particle Masses

e.g. consider the decay



$$m_{ll} = m_{ll}^{\max}\sqrt{(1-\cos\theta)/2}$$

angle between leptons



$m_{ll}$ is maximised when leptons are back-to-back in slepton rest frame

$$\left(m_{ll}^{\max}\right)^2 = \left(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2\right)\left(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2\right)/m_{\tilde{l}_R}^2$$