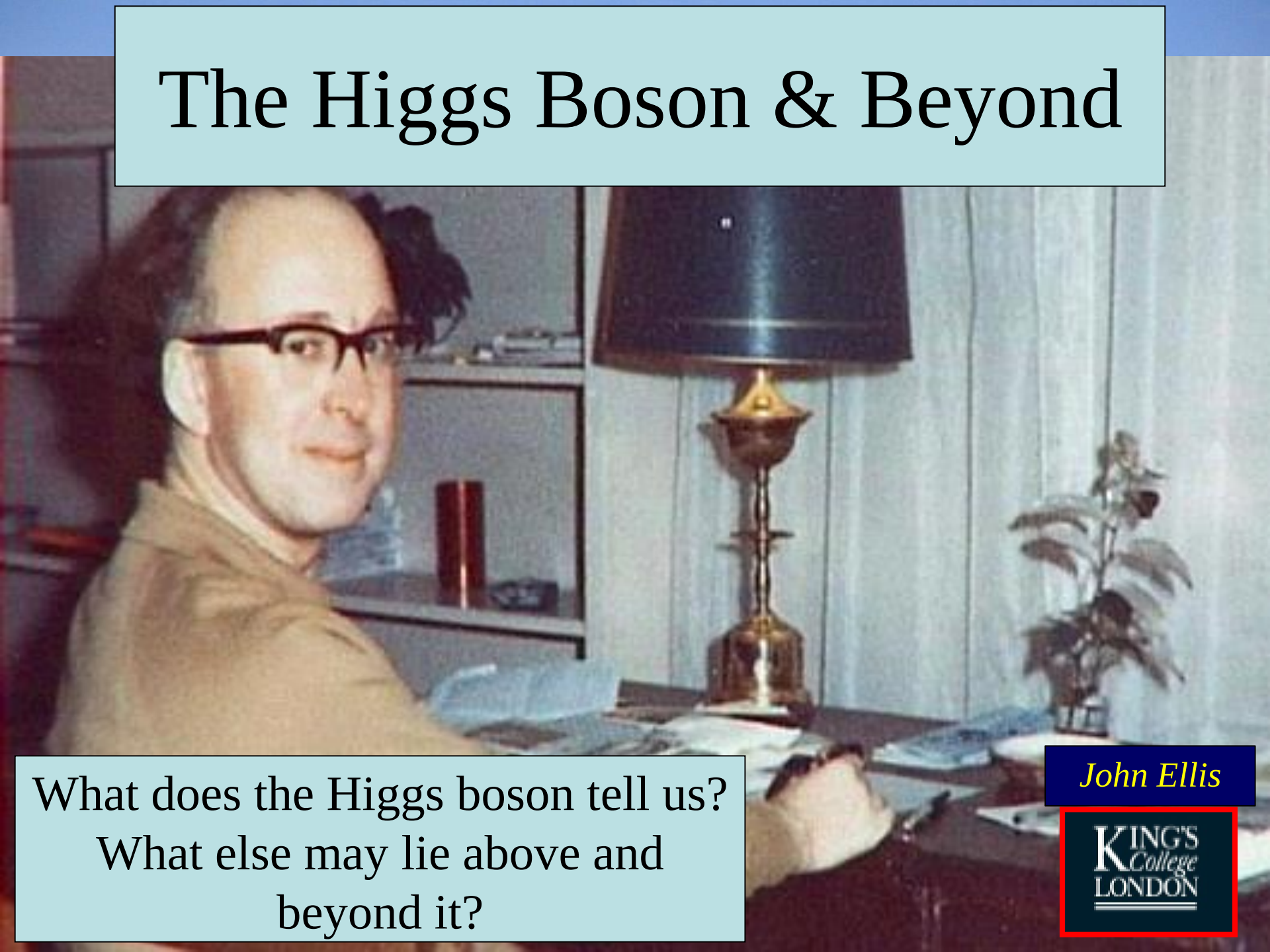
The Higgs Boson & Beyond



What does the Higgs boson tell us? What else may lie above and beyond it?

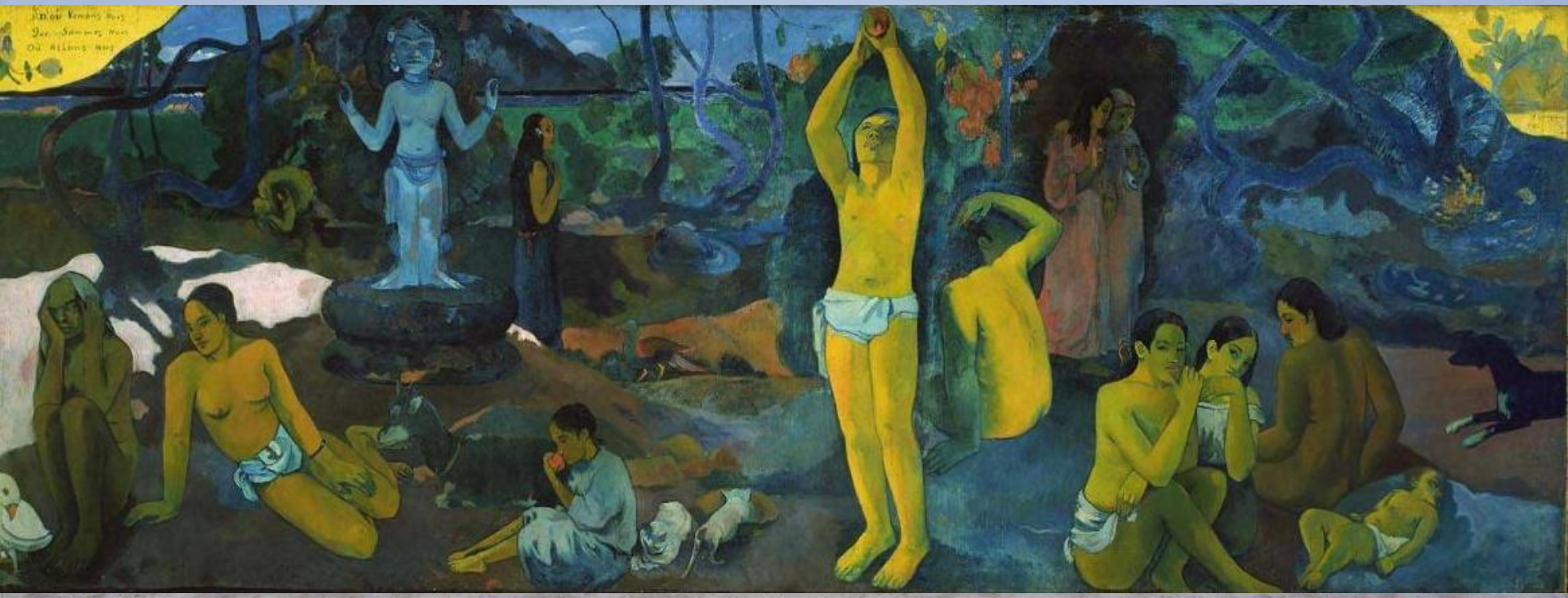
John Ellis

KING'S College LONDON

“Where do we come from?

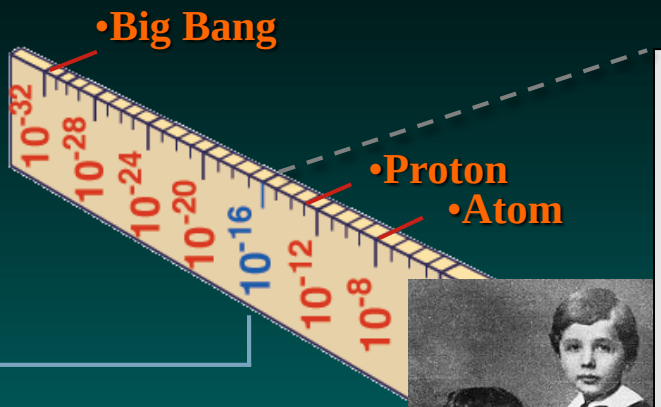
What are we?

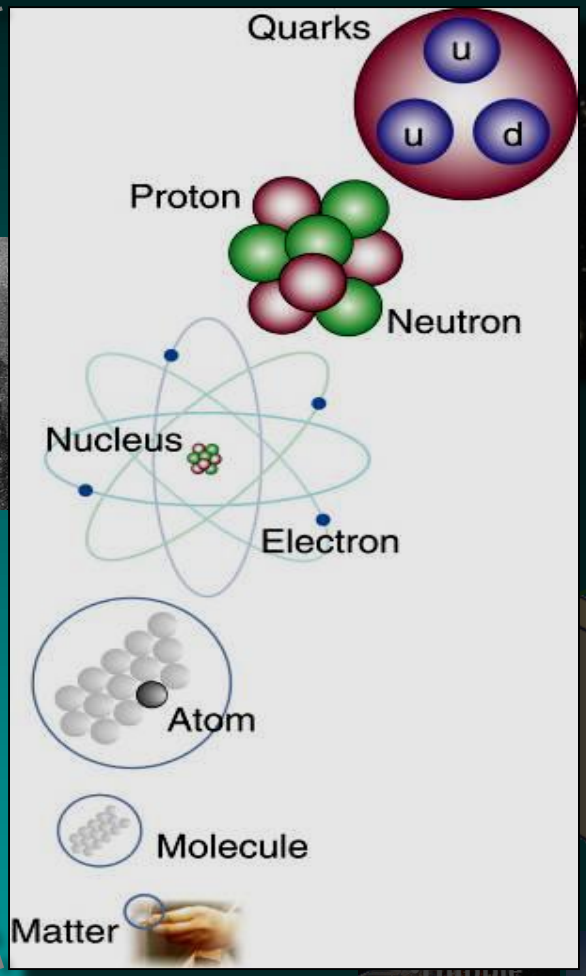
Where are we going?”



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

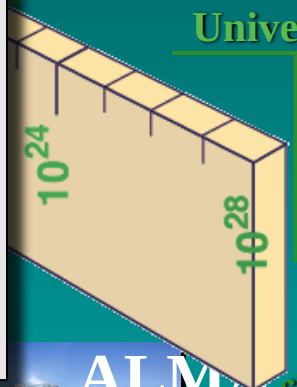
•/Users/johne/Desktop/YoungEinsteins.png

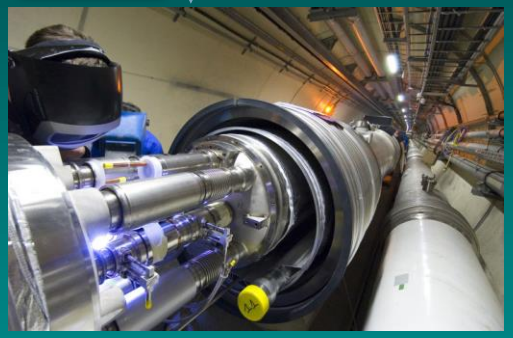




Radius of Galaxies

Universe





LHC

Super-Microscope

Study physics laws of first moments after Big Bang

increasing Symbiosis between Particle Physics,

Astrophysics and Cosmology

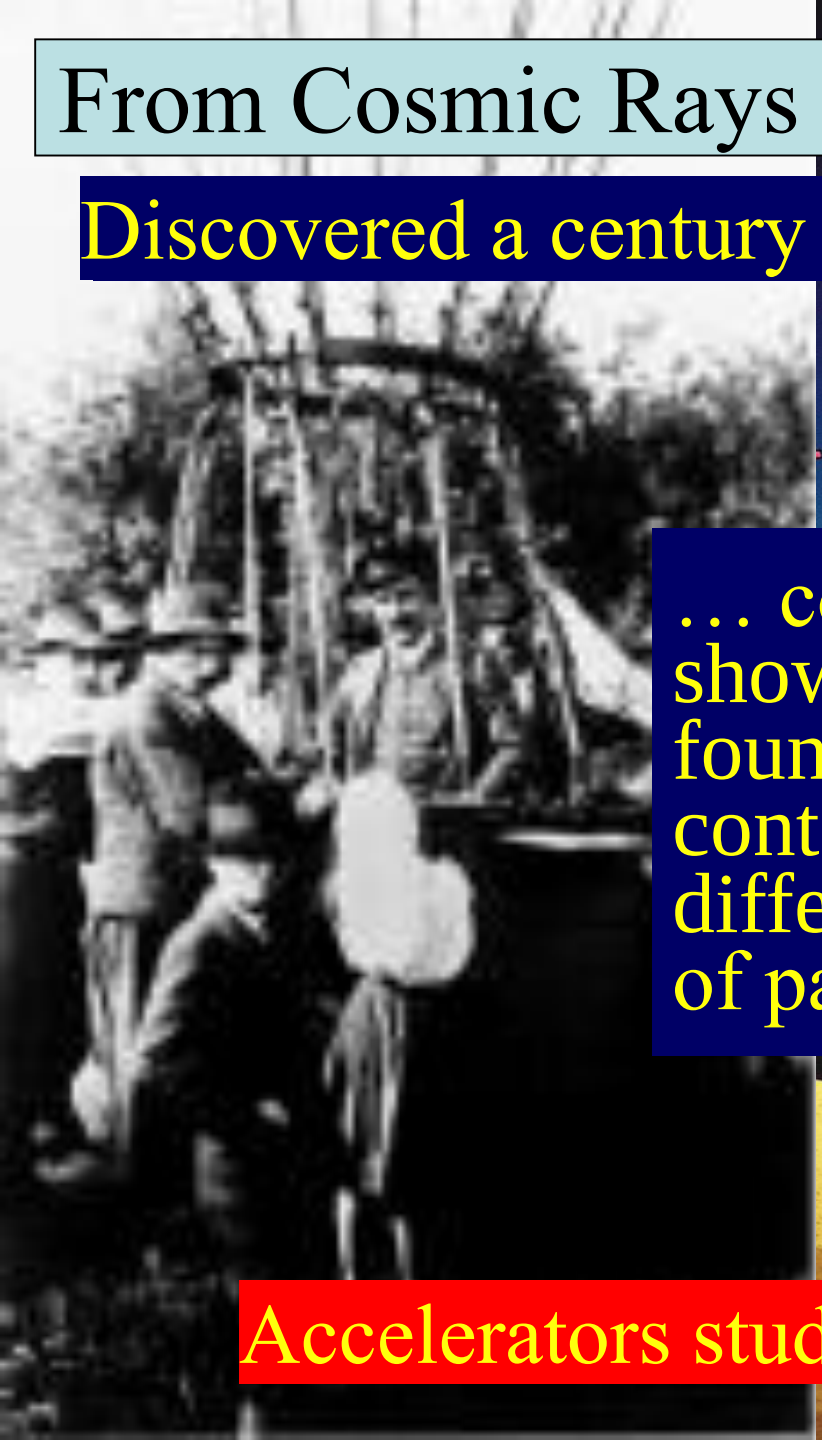
AMS

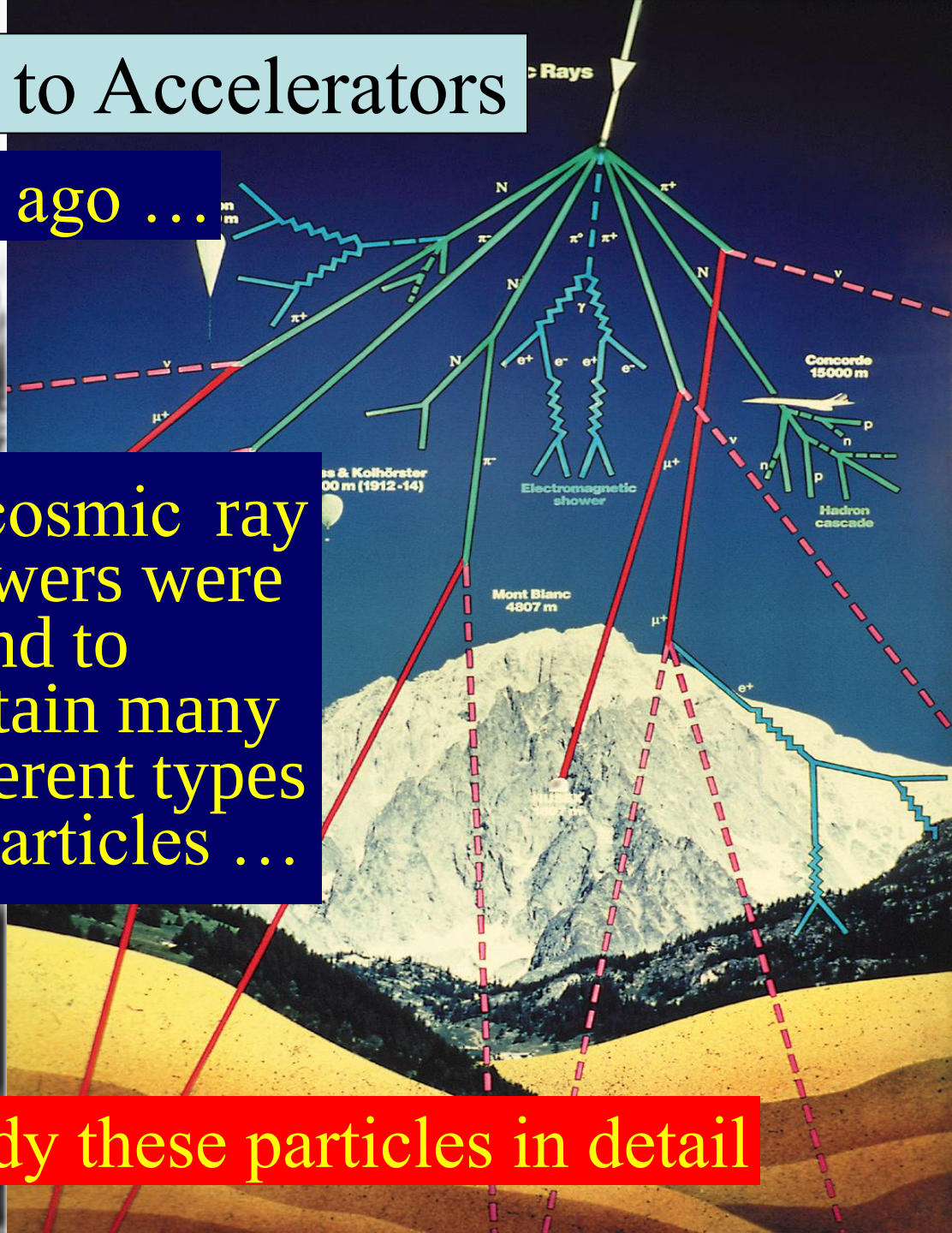
ALMA.cm

VLT

From Cosmic Rays to Accelerators

Discovered a century ago …





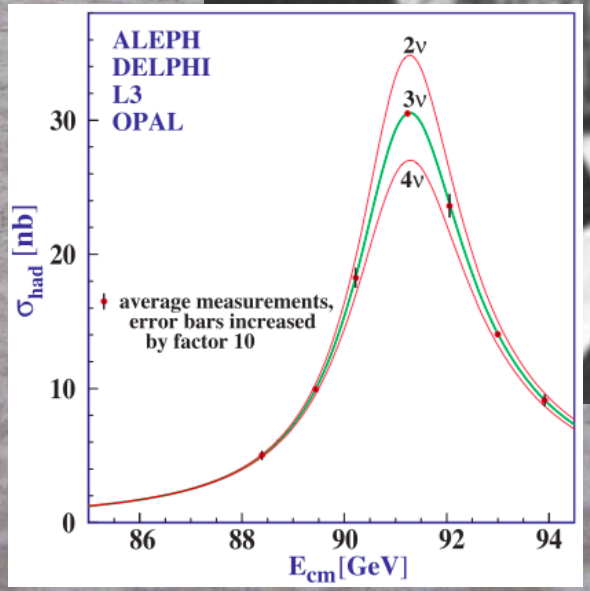
… cosmic ray showers were found to contain many different types of particles …

Accelerators study these particles in detail

The ‘Standard Model’ of Particle Physics

Proposed by Abdus Salam, Glashow and Weinberg

Tested by experiments at CERN

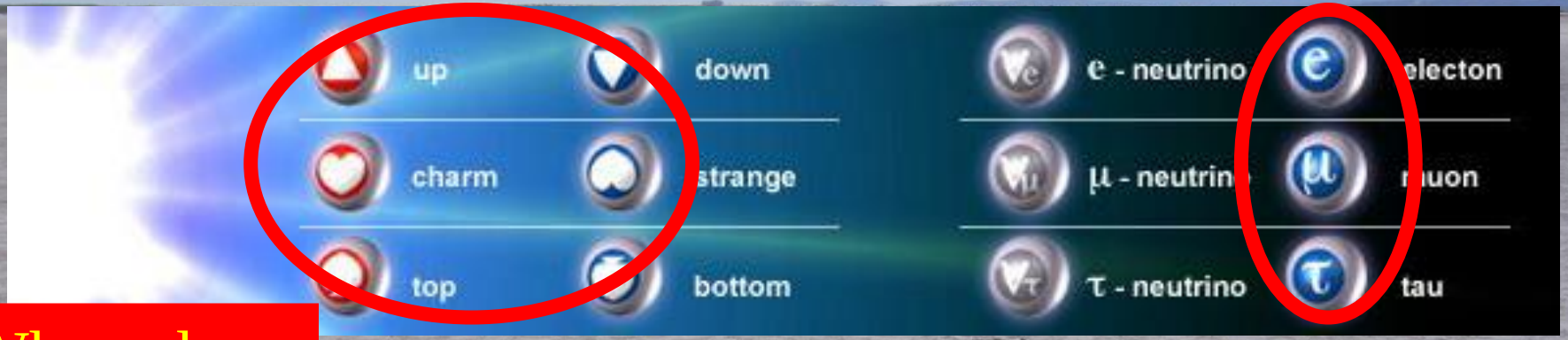


Perfect agreement between theory and experiments in all laboratories

The ‘Standard Model’

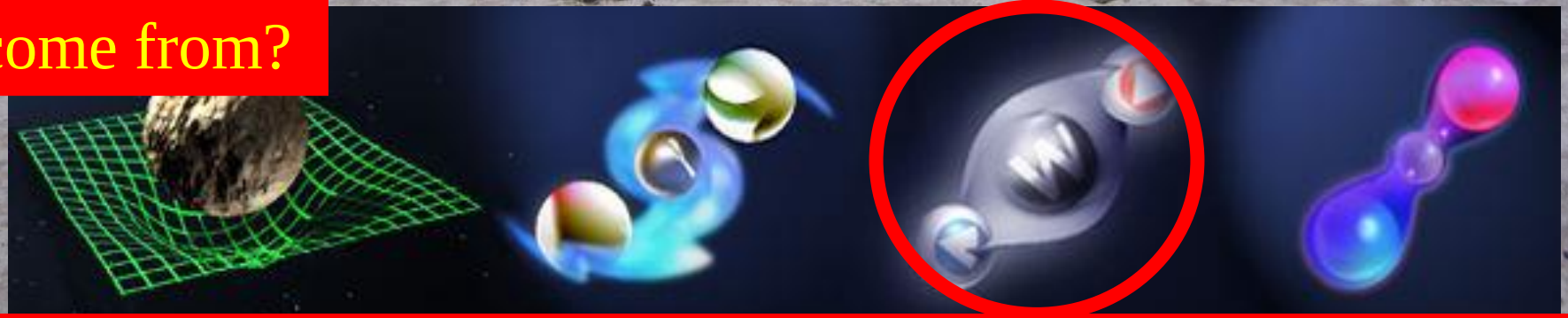
= Cosmic DNA

The matter particles



Where does mass come from?

The fundamental interactions



Gravitation electromagnetism weak nuclear force strong nuclear force

Gauguin's Questions in the Language of Particle Physics

- What is matter made of?
  - Why do things weigh?

- What is the origin of matter? LHC Run 2
- What is the dark matter that fills the U LHC Run 2
- How does the Universe evolve?
- Why is the Universe so big and old? LHC Run 2
- What is the future of the Universe? LHC Run 2

Our job is to ask - and answer - these questions

Why do Things Weigh?

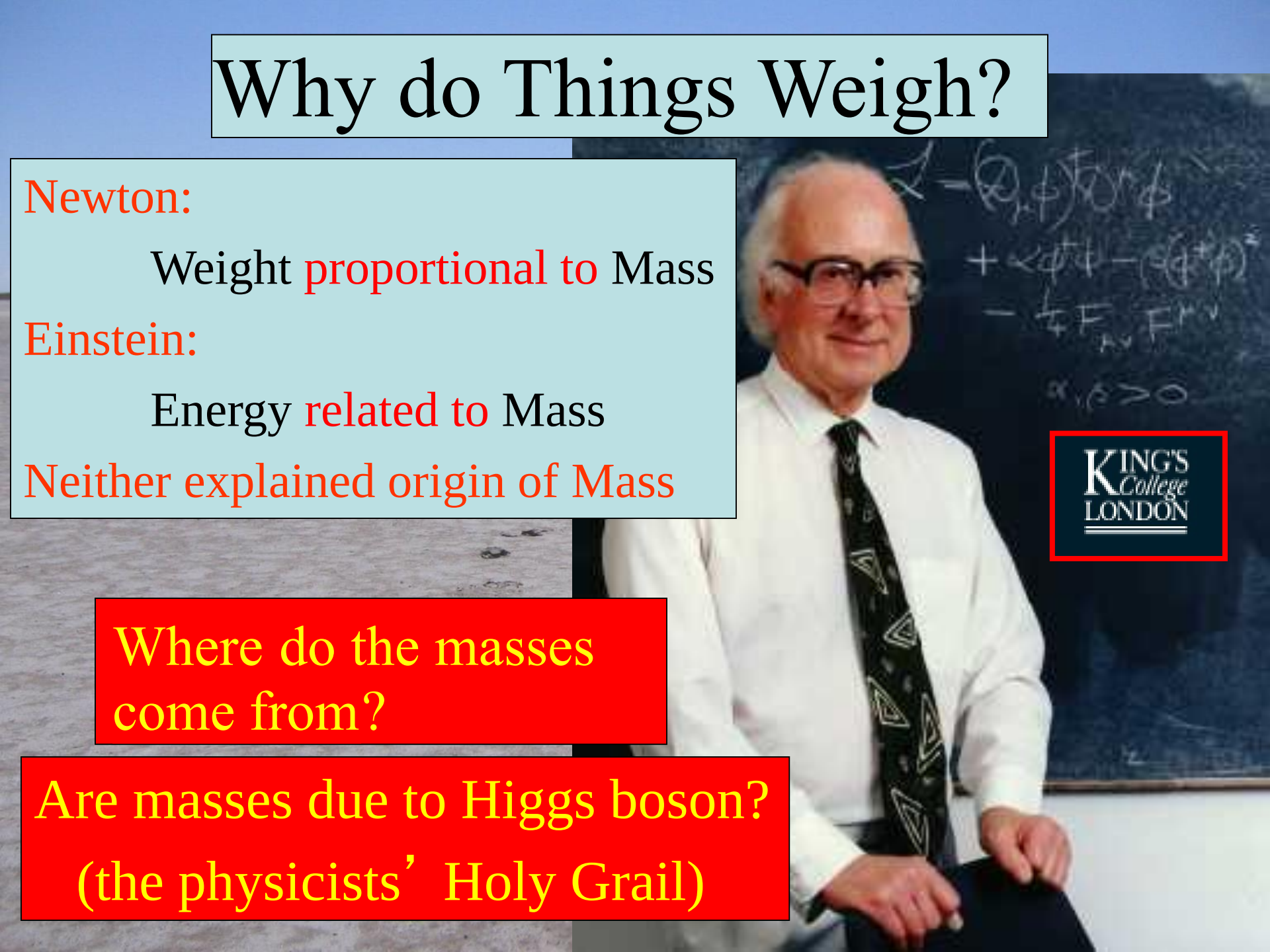
Newton:

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

The LHC looked for the snowflake: The Higgs Boson

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

Hiker sinks deep,

moves very slowly:

Particle with large mass

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

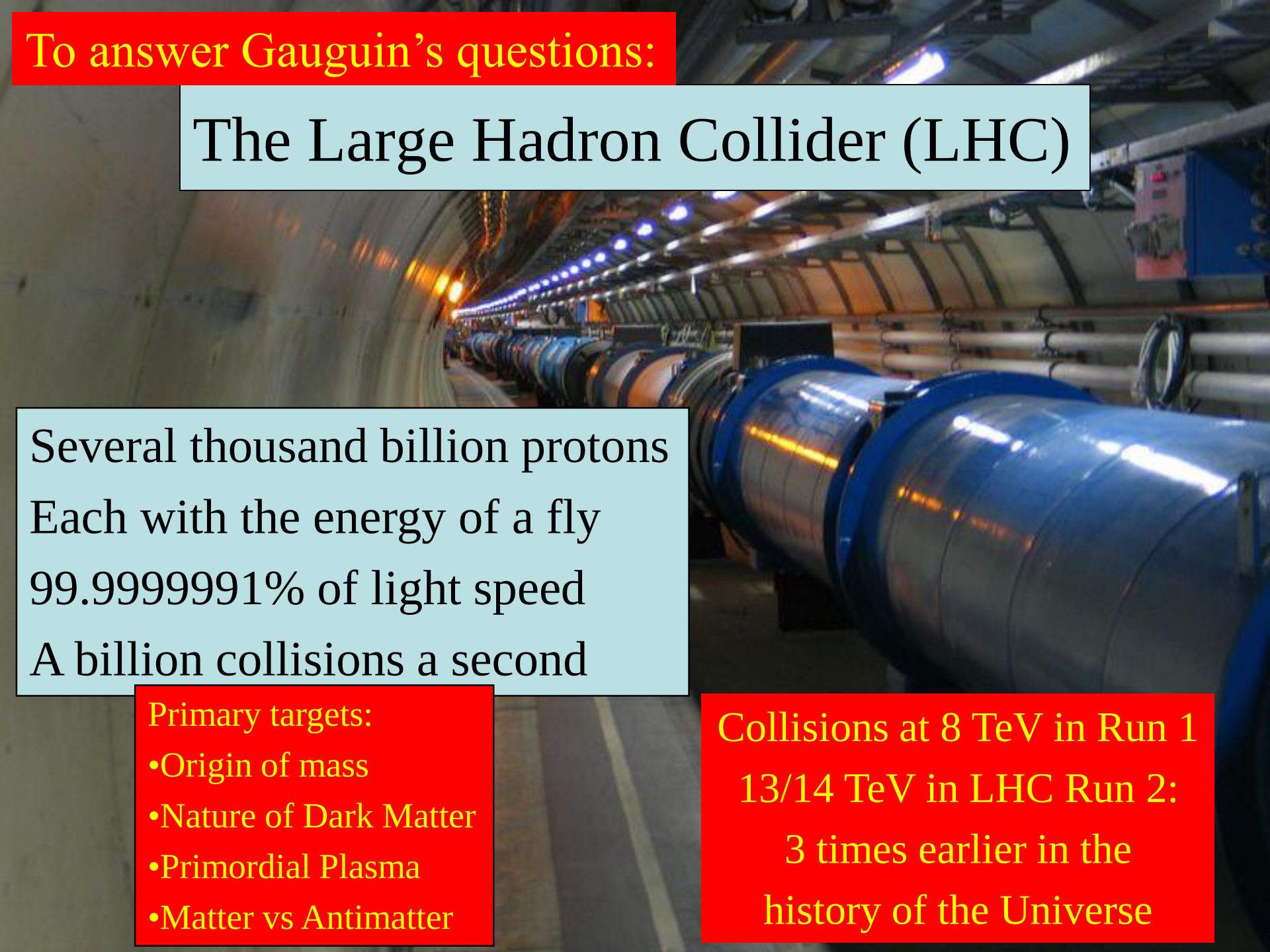
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.



To answer Gauguin's questions:

The Large Hadron Collider (LHC)

Several thousand billion protons
Each with the energy of a fly
99.9999991% of light speed
A billion collisions a second

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

Collisions at 8 TeV in Run 1
13/14 TeV in LHC Run 2:
3 times earlier in the
history of the Universe

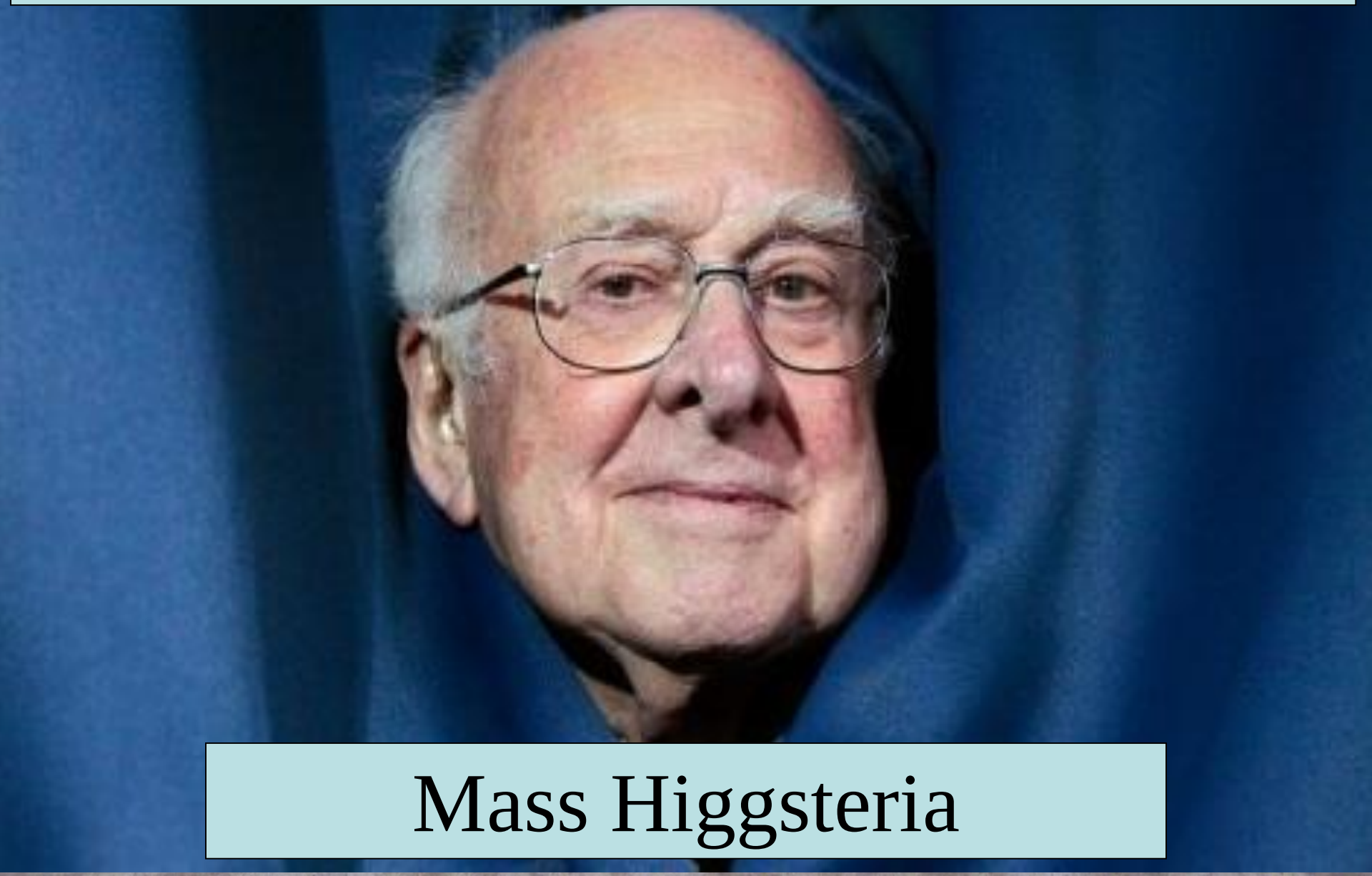
ALICE: Primordial cosmic plasma

ATLAS: Higgs and dark matter

CMS: Higgs and dark matter

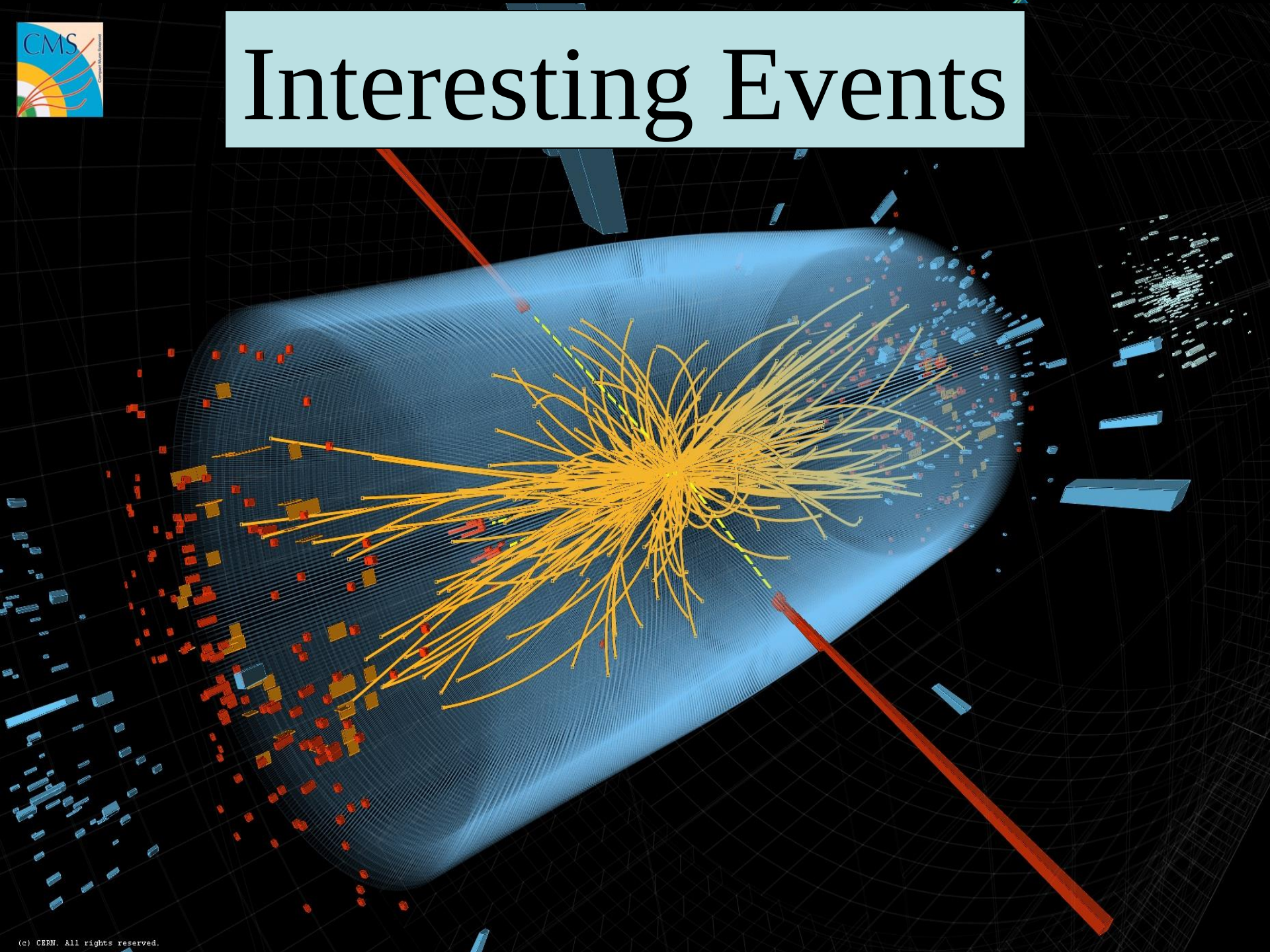
LHCb: Matter-antimatter difference

The Discovery of the Higgs Boson



Mass Higgsteria

Interesting Events



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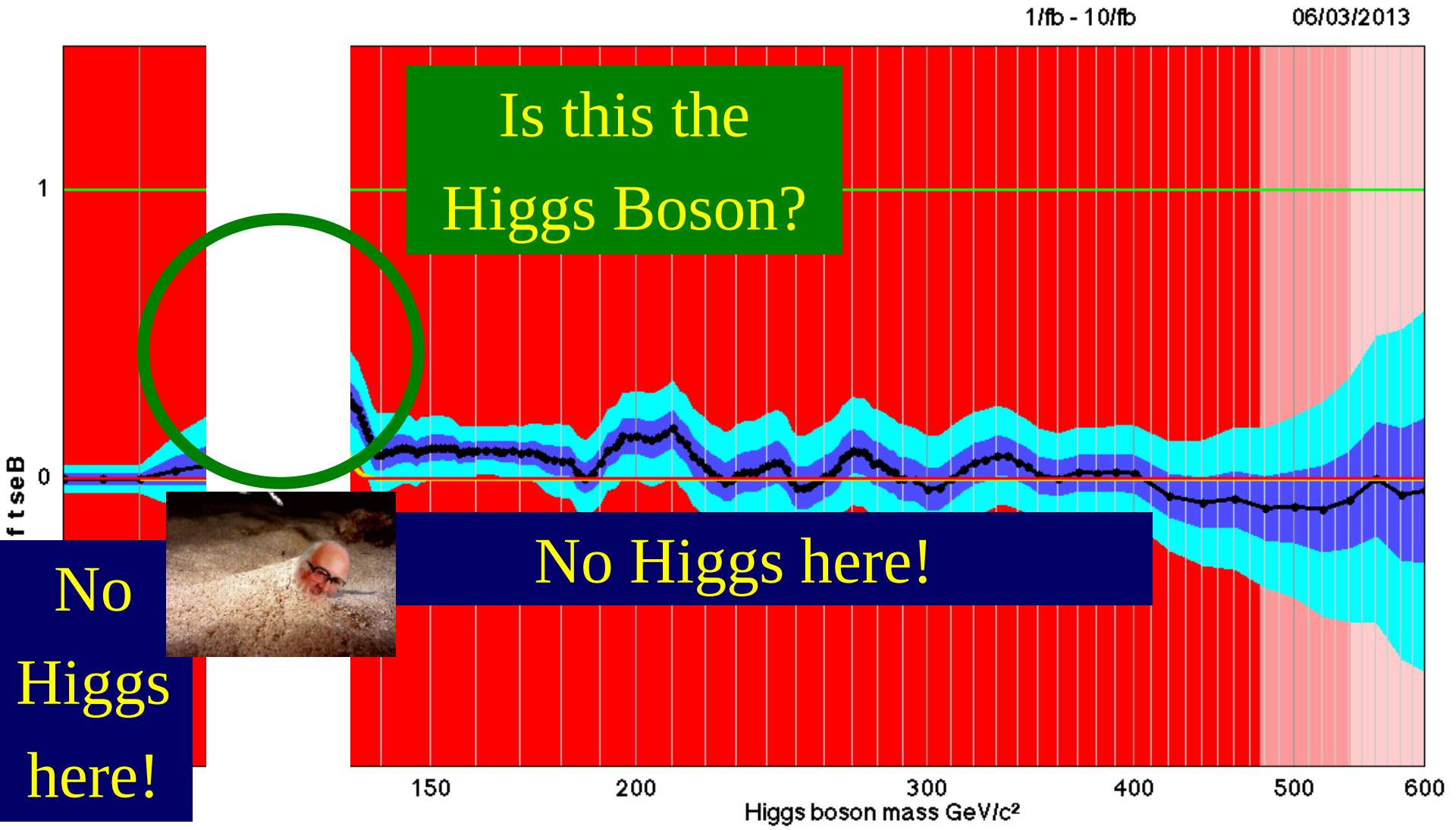
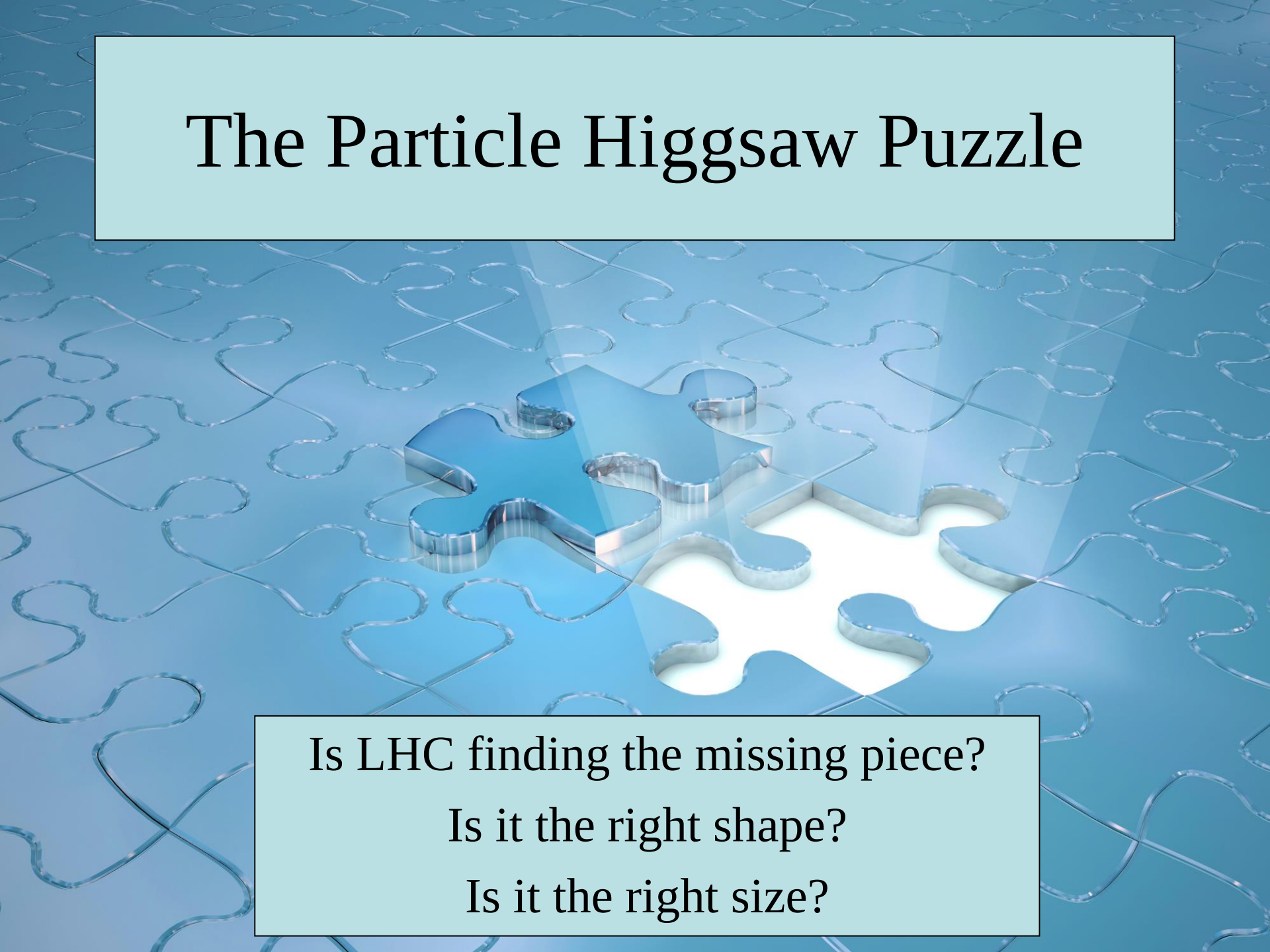
Higgsdependence Day!

Unofficial Combination of Higgs Data



The Particle Higgsaw Puzzle



Is LHC finding the missing piece?

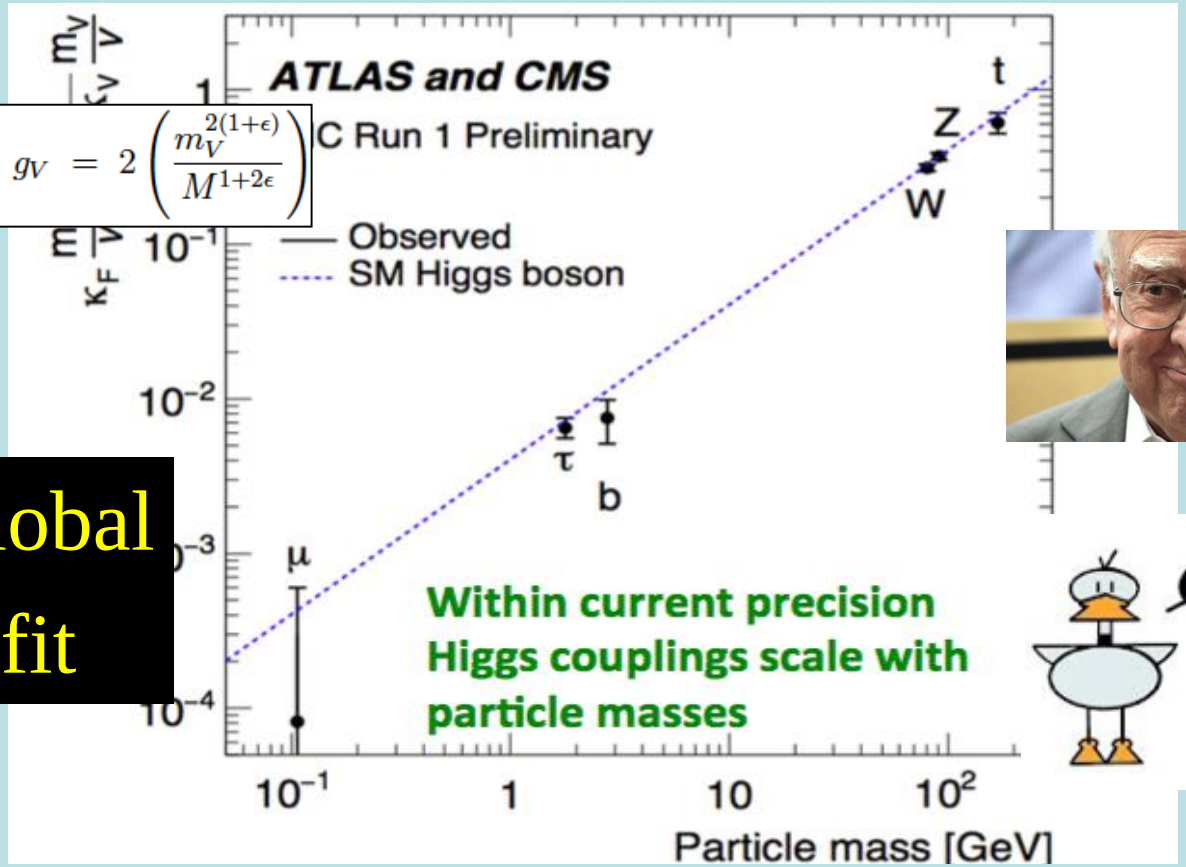
Is it the right shape?

Is it the right size?

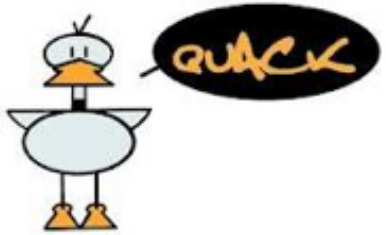
It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \; g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$

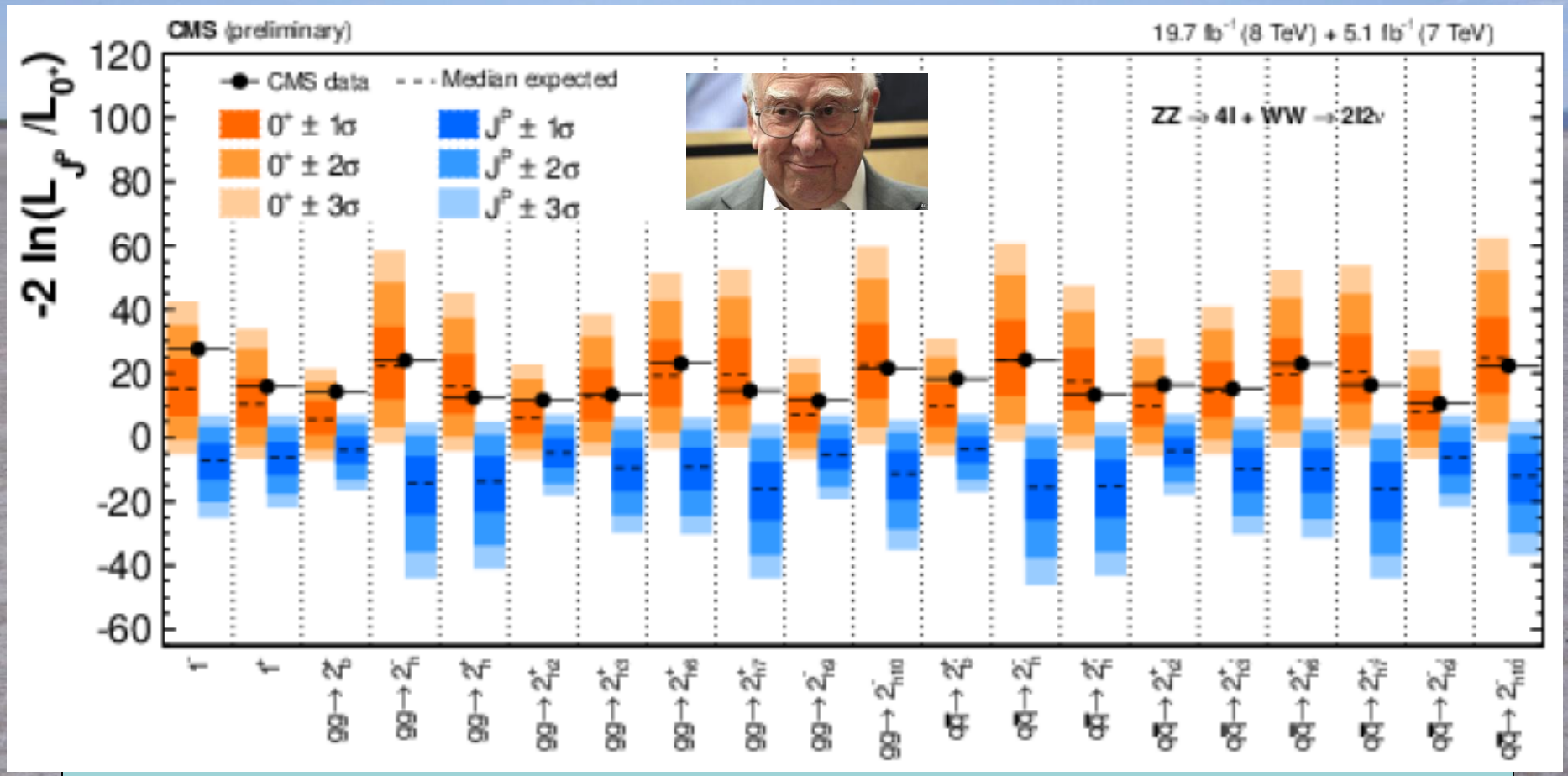


Global fit



- **Blue** dashed line = Standard Model

The ‘Higgs’ has Spin 0



- Alternative spin-parity hypotheses disfavoured

Without Higgs …

… there would be no atoms

- massless electrons would escape at the speed of light

… there would be no heavy nuclei

… weak interactions would not be weak

- Life would be impossible: everything would be radioactive

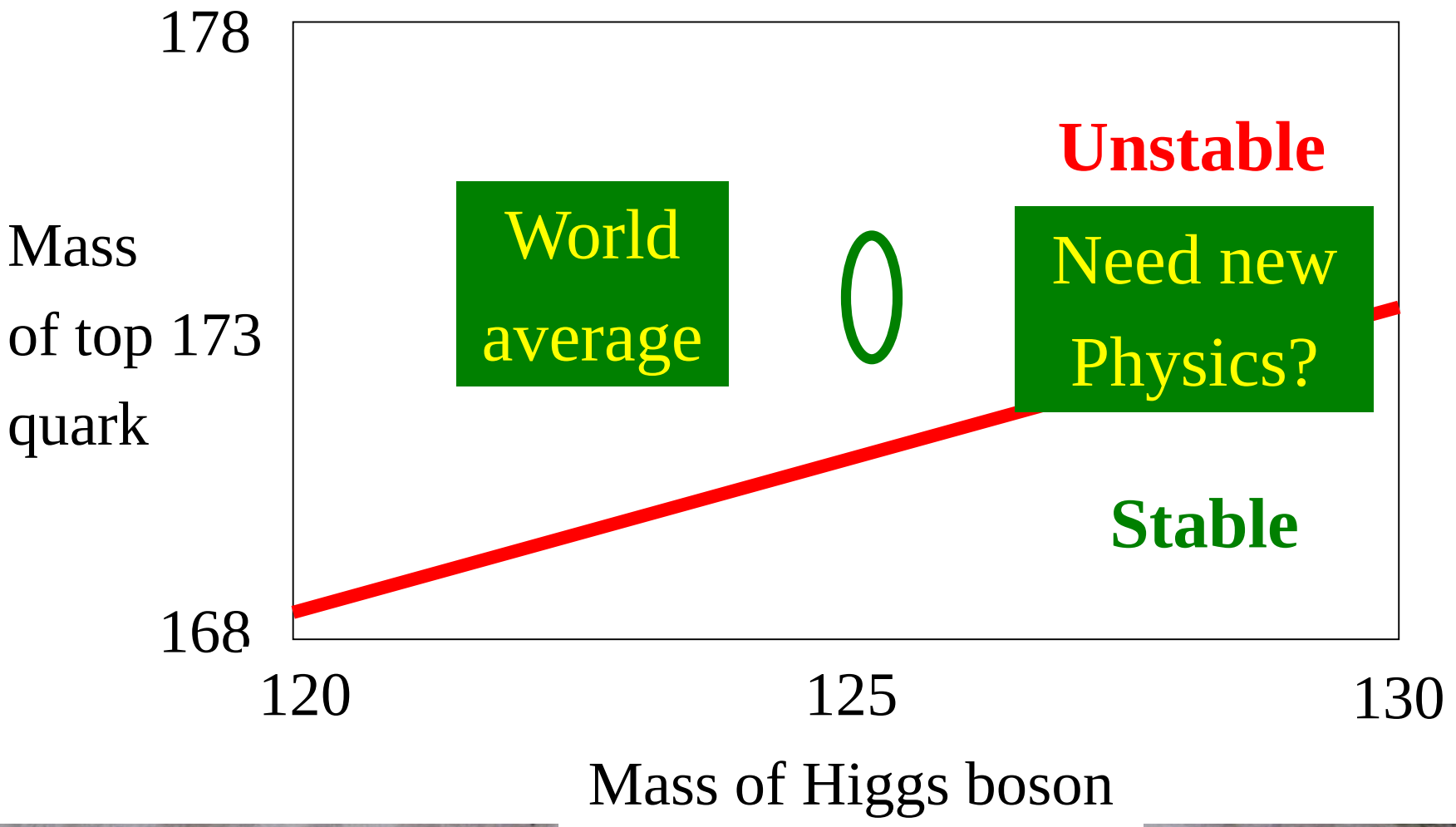
Its existence is a big deal!

- « Empty » space is u — LHC Run 2
- Dark matter — LHC Run 2
- Origin of matter — LHC Run 2
- Masses of neutrinos
- Hierarchy problem — LHC Run 2
- Inflation — LHC Run 2
- Quantum gravity — SUSY
- …

- The Standard Model

Is “Empty Space” Unstable?

- Depends on masses of Higgs boson and top quark



Should it have Collapsed already?

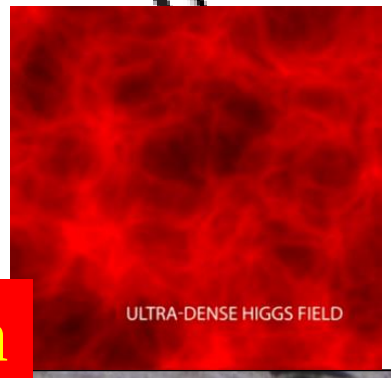
Fluctuate over barrier in the early Universe?

Not if supersymmetry: infinite barrier

We are here

Tunnel through barrier now?

Quantum fluctuations



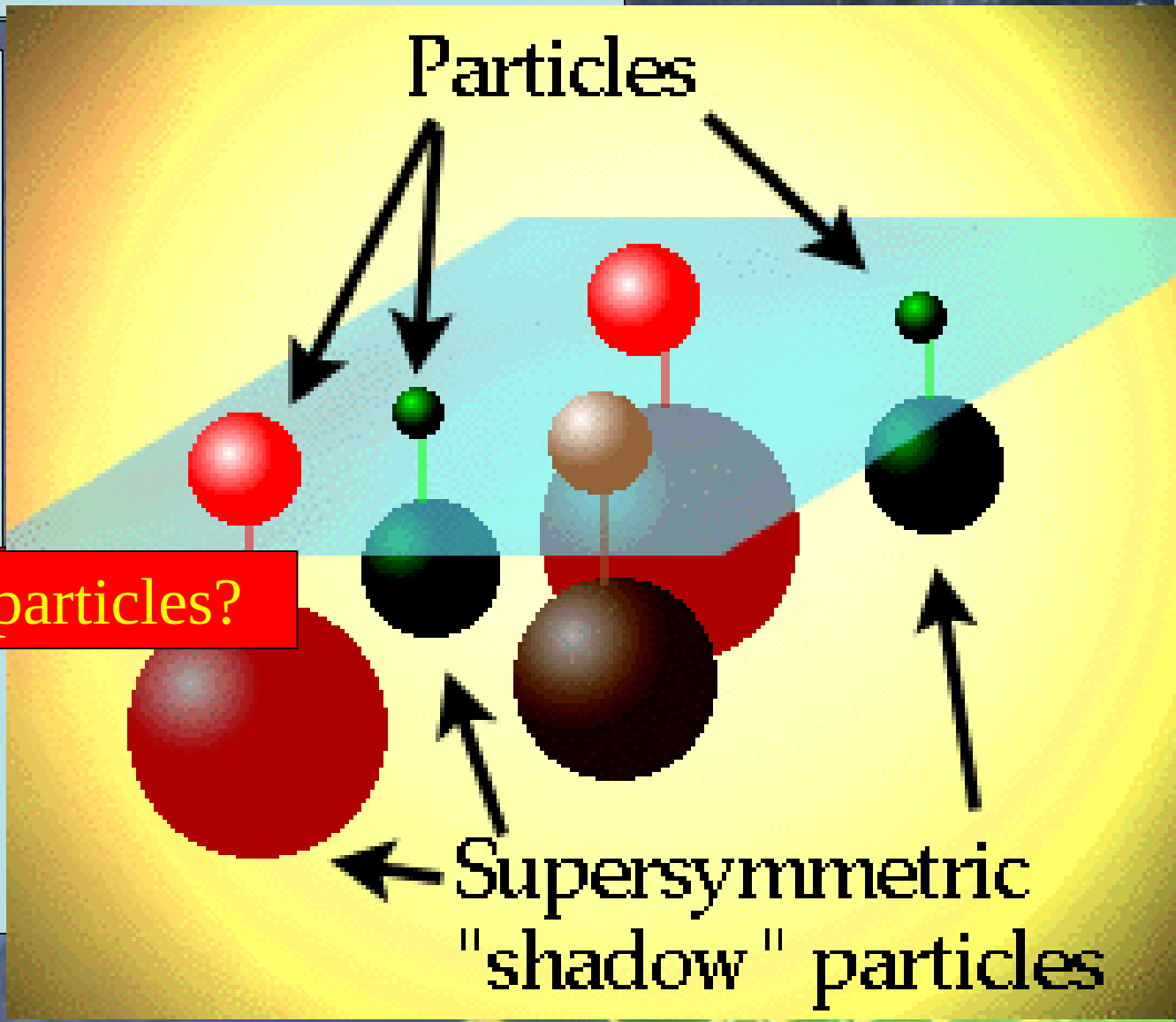
The Big Crunch

Dark Matter in the Universe

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

Supersymmetric particles?

Searching for them at the LHC



General Interest in Antimatter Physics

Physicists cannot make enough for Star Trek or Dan Brown!

How do Matter and Antimatter Differ?

Dirac predicted the existence of antimatter:

same mass

opposite internal properties:

electric charge, …

Discovered in cosmic rays

Studied using accelerators

Used in PET scanners

Matter and antimatter not quite equal and opposite: WHY?

Why does the Universe mainly contain matter, not antimatter?

Experiments at LHC and elsewhere looking for answers

What lies beyond the Standard Model?

Supersymmetry

New motivations
From LHC Run 1

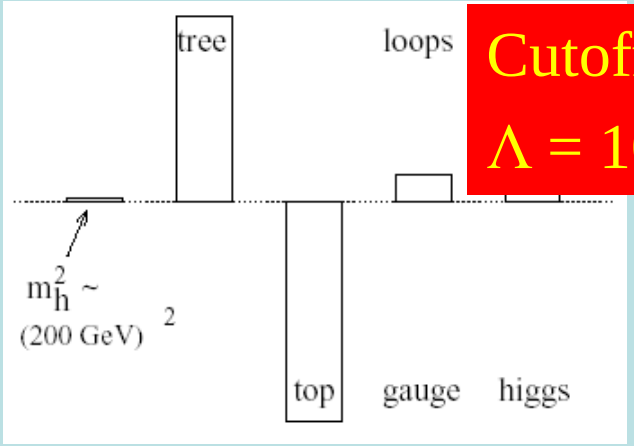
- **Stabilize electroweak vacuum**
- **Successful prediction for Higgs mass**
  - **Should be < 130 GeV in simple models**
- **Successful predictions for couplings**
  - **Should be within few % of SM values**
- Naturalness, GUTs, string, …, **dark matter**

Elementary Higgs or Composite?

- Higgs field:

  $\langle 0|H|0\rangle \neq 0$

- Quantum loop problems



Cutoff

Λ = 10 TeV

Cut-off Λ ~ 1 TeV with Supersymmetry?

- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- Top-antitop condensate? needed m_t > 200 GeV

New technicolour force?

- Heavy scalar resonance?
- Inconsistent with precision electroweak data?
- Little Higgs, …

Phenomenological Framework

- Assume custodial symmetry:

$$SU(2) \times SU(2) \to SU(2)_V \qquad (\rho \equiv M_W/M_Z \cos\theta_w \sim 1)$$

- Parameterize gauge bosons by 2 × 2 matrix Σ:

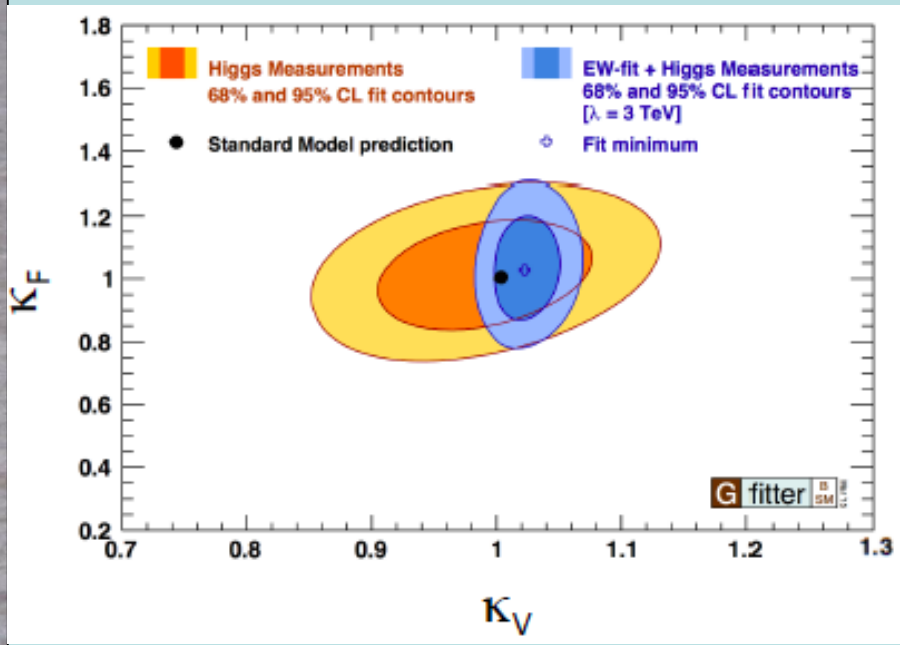
$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}D_\mu\Sigma^\dagger D^\mu\Sigma\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}+\ldots\right) - m_i\bar{\psi}^i_L\Sigma\left(1+c\frac{h}{v}+\ldots\right)\psi^i_R + \mathrm{h.c.}$$
$$+\frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}m_h^2h^2 + d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots \quad ,$$

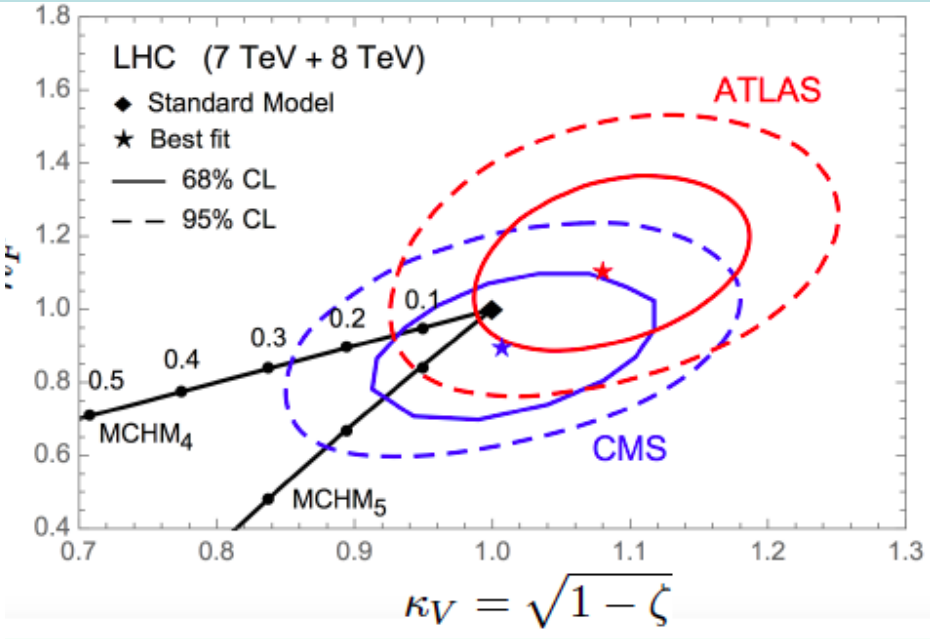
$$\Sigma = \exp\left(i\frac{\sigma^a\pi^a}{v}\right) \qquad \mathcal{L}_\Delta = -\left[\frac{\alpha_s}{8\pi}b_sG_{a\mu\nu}G_a^{\mu\nu} + \frac{\alpha_{em}}{8\pi}b_{em}F_{\mu\nu}F^{\mu\nu}\right]\left(\frac{h}{V}\right)$$

- Coefficients ***a = c = 1*** in Standard Model

Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by κ_V, to fermions by κ_f
- Standard Model: $\kappa_V = \kappa_f = 1$





- Consistency between Higgs and EW measurements
- **Must tune composite models to look like SM**

Minimal Supersymmetric Extension of Standard Model (MSSM)

- Double up the known particles:

$$\begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix} \; e.g., \; \begin{pmatrix} \ell \; (lepton) \\ \tilde{\ell} \; (slepton) \end{pmatrix} or \begin{pmatrix} q \; (quark) \\ \tilde{q} \; (squark) \end{pmatrix}$$

$$\begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix} \; e.g., \; \begin{pmatrix} \gamma \; (photon) \\ \tilde{\gamma} \; (photino) \end{pmatrix} \; or \; \begin{pmatrix} g \; (gluon) \\ \tilde{g} \; (gluino) \end{pmatrix}$$

- Two Higgs doublets
  - 5 physical Higgs bosons:
  - 3 neutral, 2 charged
- Lightest neutral supersymmetric Higgs looks like the single Higgs in the Standard Model

Lightest Supersymmetric Particle

- Stable in many models because of conservation of R parity:

  $R = (-1)^{2S - L + 3B}$

  where S = spin, L = lepton #, B = baryon #

- Particles have R = +1, sparticles R = -1:

  Sparticles produced in pairs

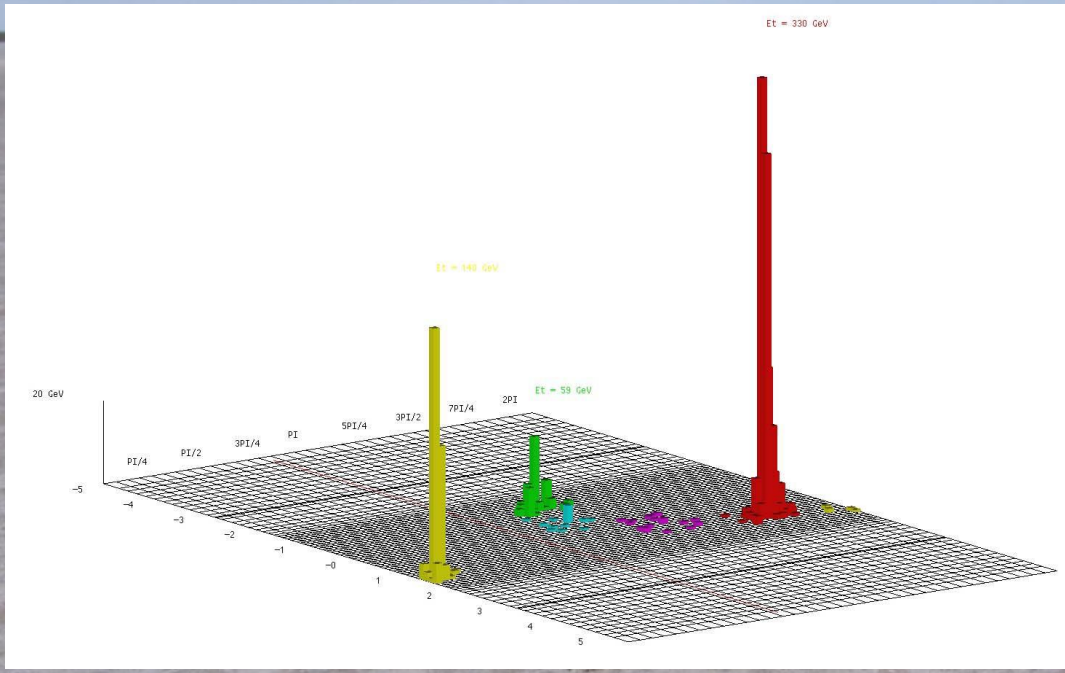
  Heavier sparticles → lighter sparticles

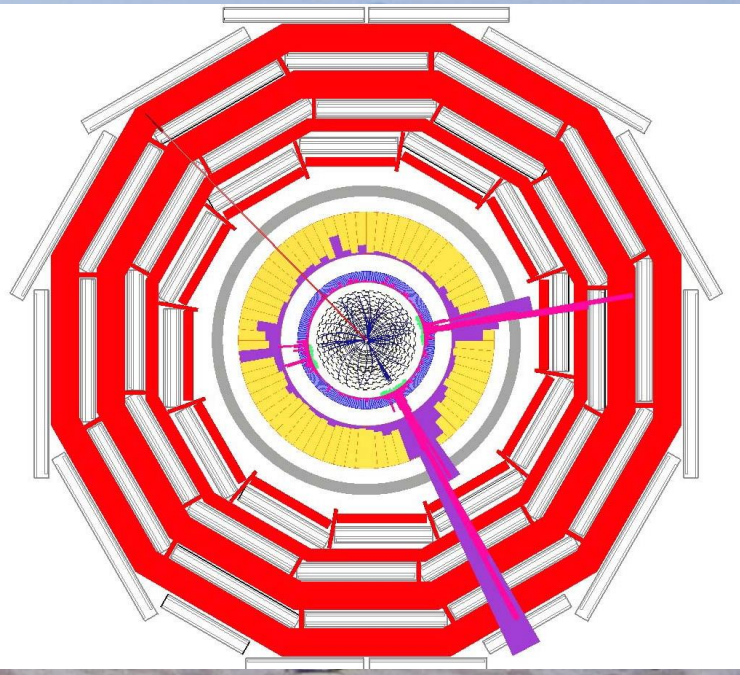
- **Lightest supersymmetric particle (LSP) stable**

LSP as Dark Matter?

- No strong or electromagnetic interactions
  Otherwise would bind to matter
  Detectable as anomalous heavy nucleus
- Possible weakly-interacting scandidates
  Sneutrino
  (Excluded by LEP, direct searches)
  Lightest neutralino χ (partner of Z, H, γ)
  Gravitino
  (nightmare for detection)

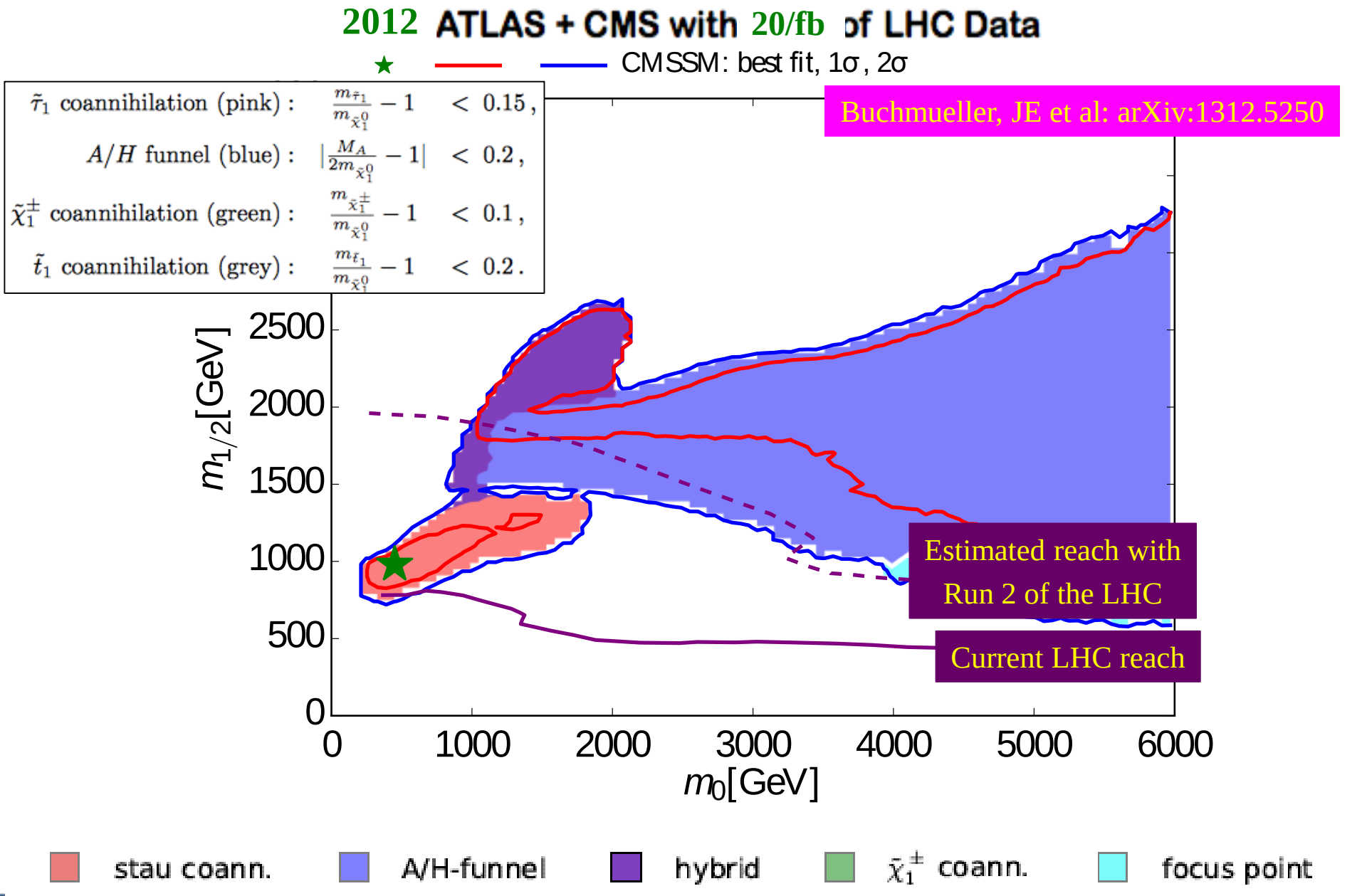
Classic Dark Matter Signature



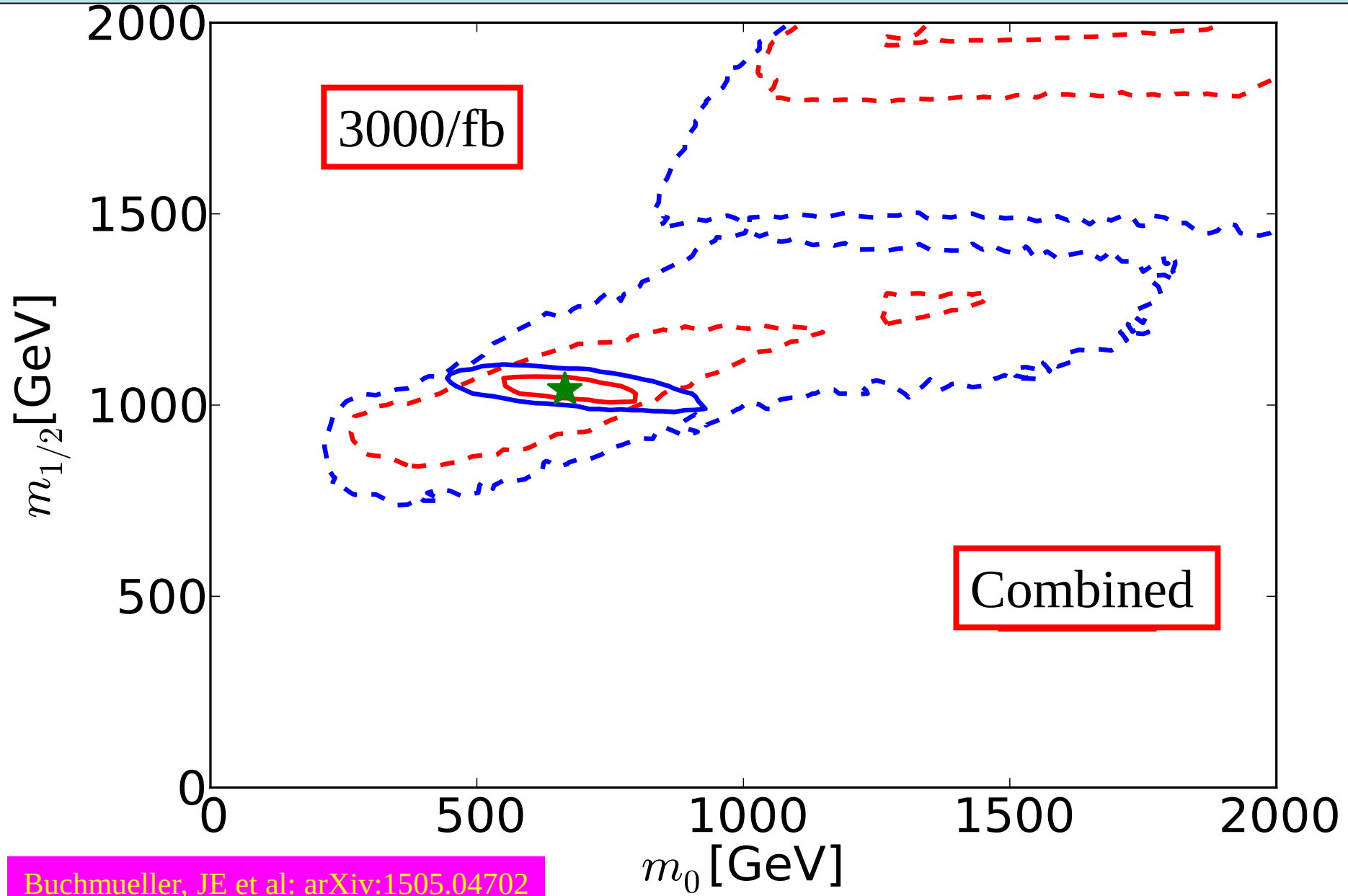


Missing transverse energy
carried away by dark matter particles

Dark Matter Density Mechanisms



Measuring the CMSSM with the LHC



Buchmueller, JE et al: arXiv:1505.04702

Standard Model Particles:

Years from Proposal to Discovery