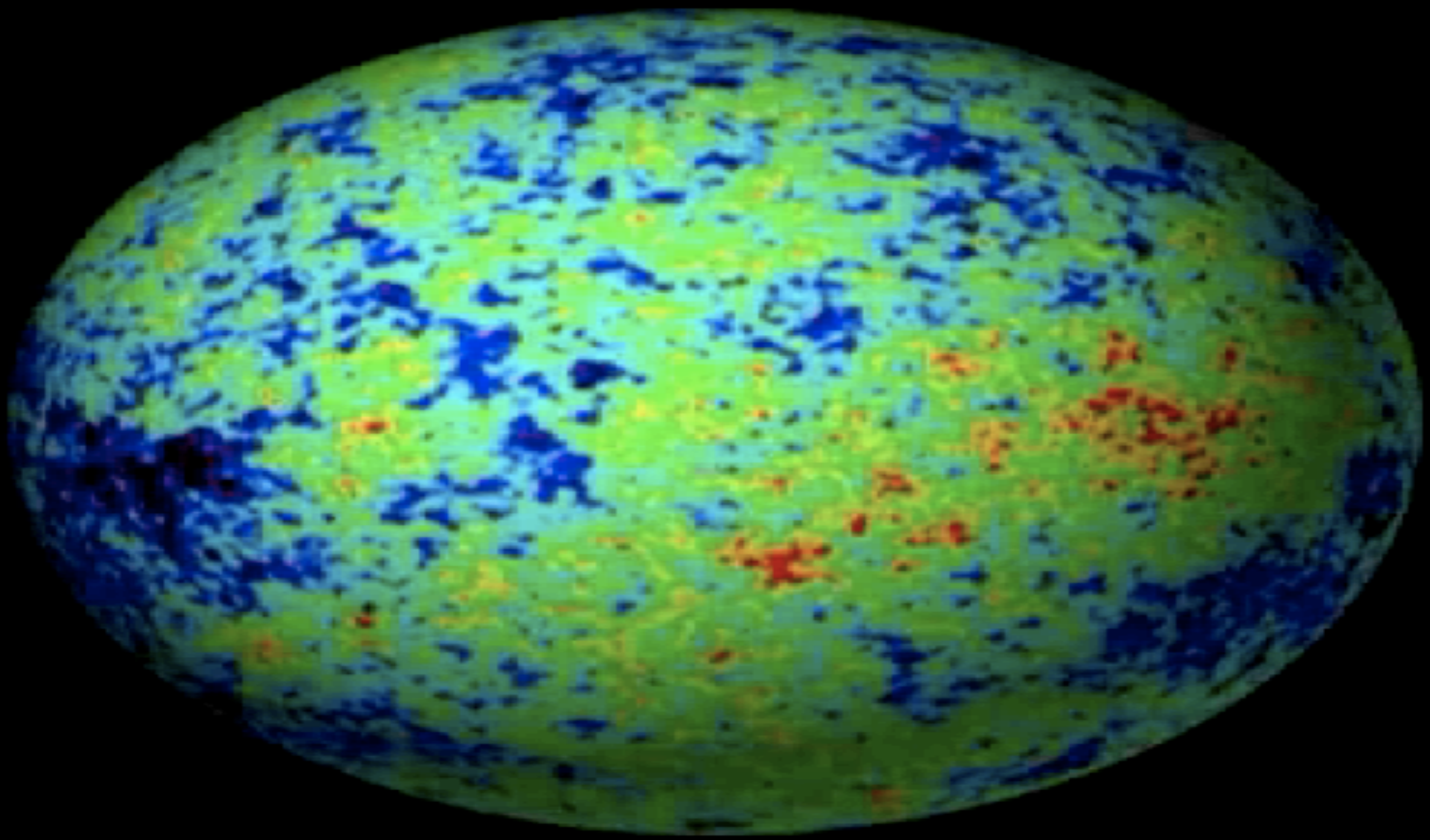
Particle Physics & Cosmology in Light of the LHC



John Ellis
King's College London & CERN

The 'Standard Model'

= Cosmic DNA

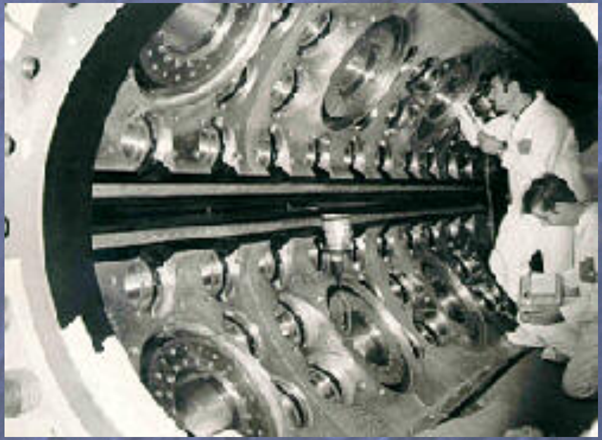
The matter particles

The fundamental interactions

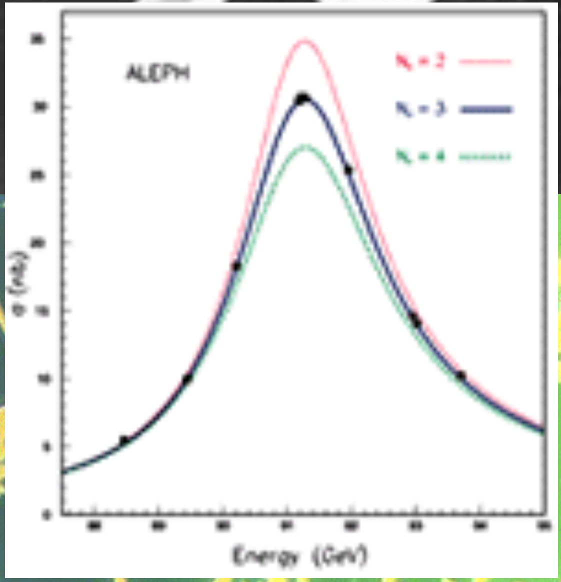
Gravitation electromagnetism weak nuclear force strong nuclear force

The ‘Standard Model’ of Particle Physics

Proposed byAbdus Salam, Glashow and Weinberg



Tested by experiments at CERN



Perfect agreement between theory and experiments in all laboratories

Open Questions beyond the Standard Model

- Why do particles have mass?
  - Higgs boson? Supersymmetry?
- Why so many types of matter particles?
- Are the fundamental forces unified?
  - Supersymmetry?
- Quantum theory of gravity?
  - String theory?

All → Cosmology

LHC project @ CERN

Why do Things Weigh?

Newton:

Weight **proportional to** Mass

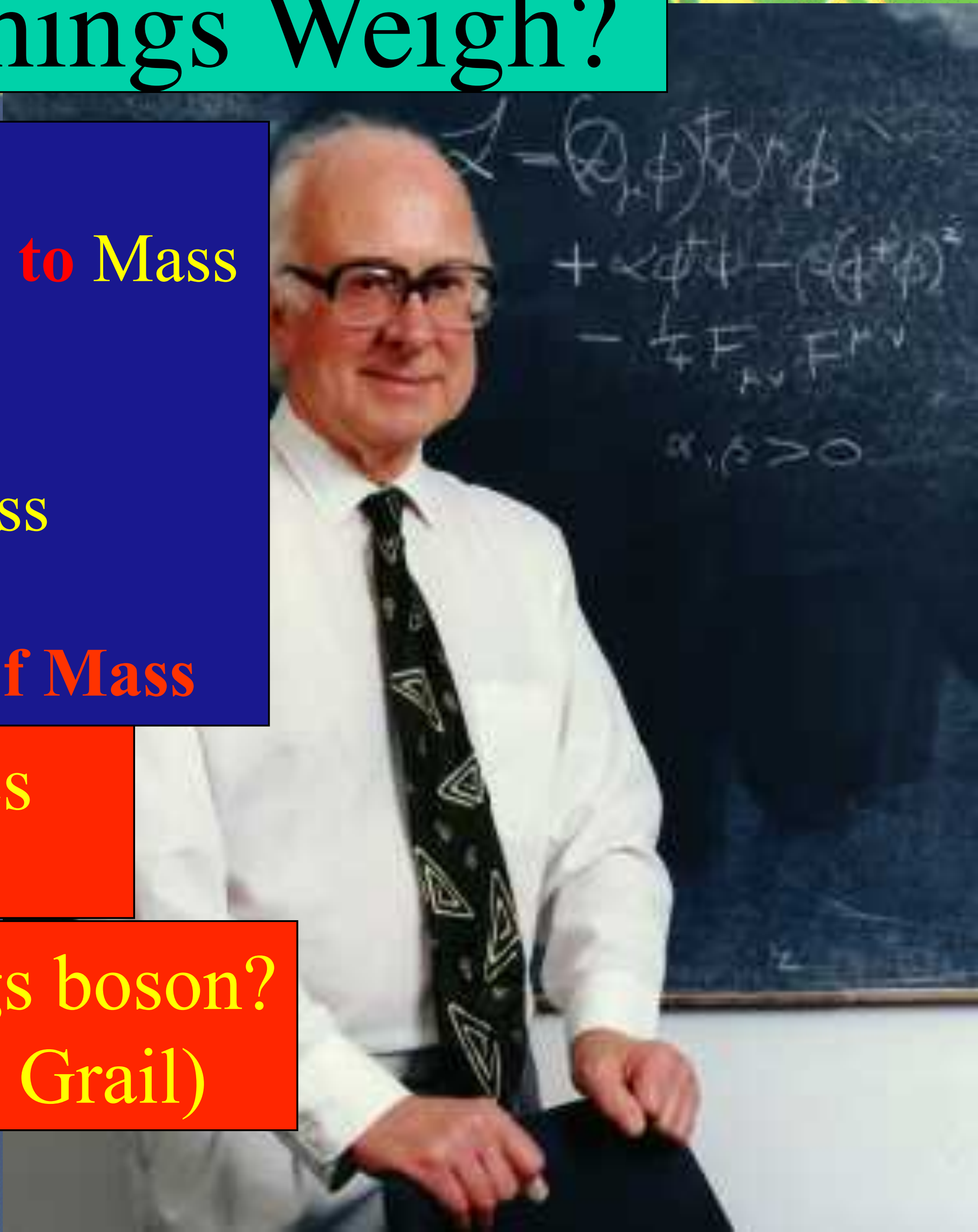
Einstein:

Energy related to Mass

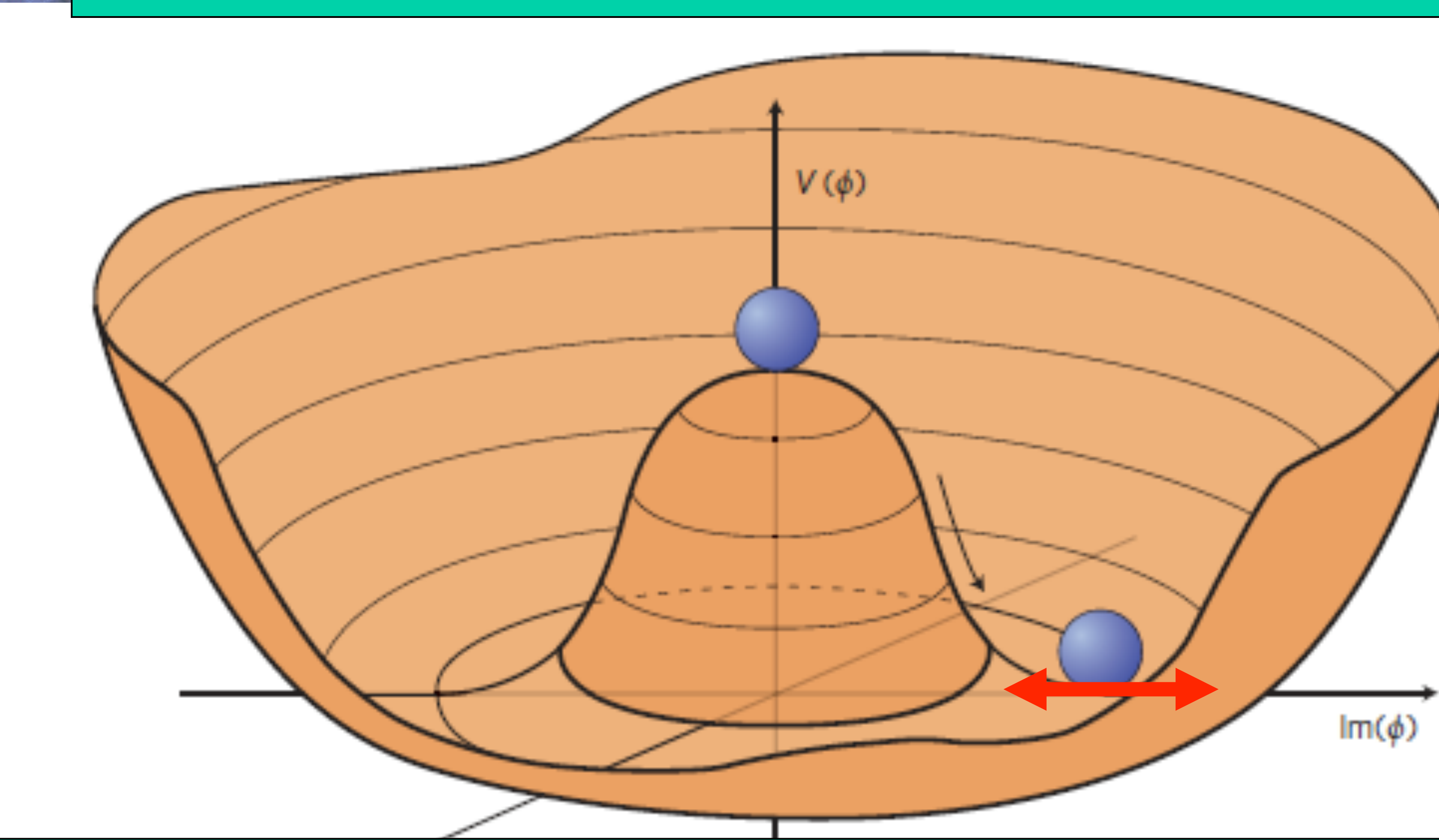
Neither explained origin of Mass

Where do the masses come from?

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



Mysterious Higgs Potential



Vertical scale ~ 10^{60} × dark energy

Mass^2 of Higgs ~ curvature of potential at minimum

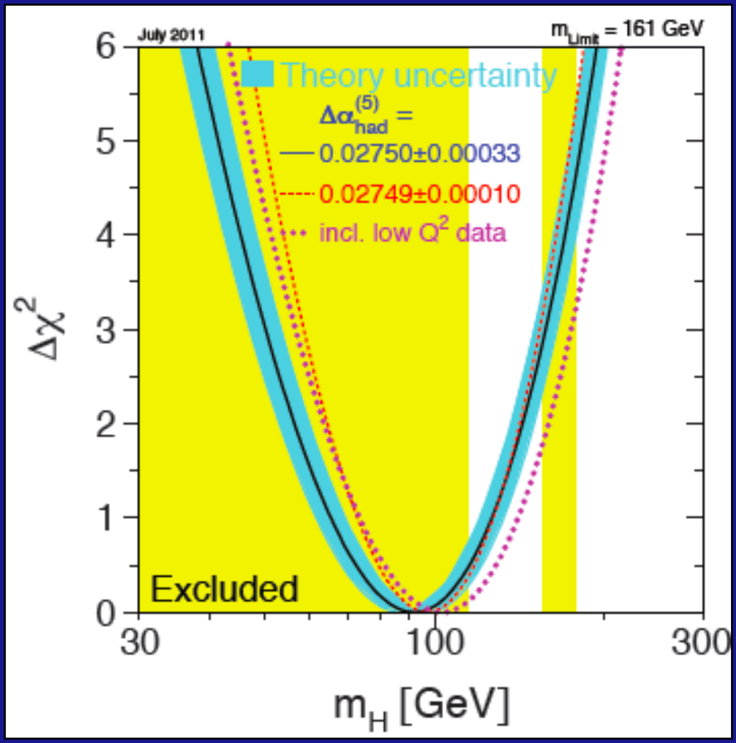
The State of the Higgs Earlier in 2011

- High-energy search:
  - Limit from LEP:

$$m_H > 114.4 \text{ GeV}$$

- High-precision electroweak data:
  - Sensitive to Higgs mass:

$$m_H = 96^{+30}_{-24} \text{ GeV}$$



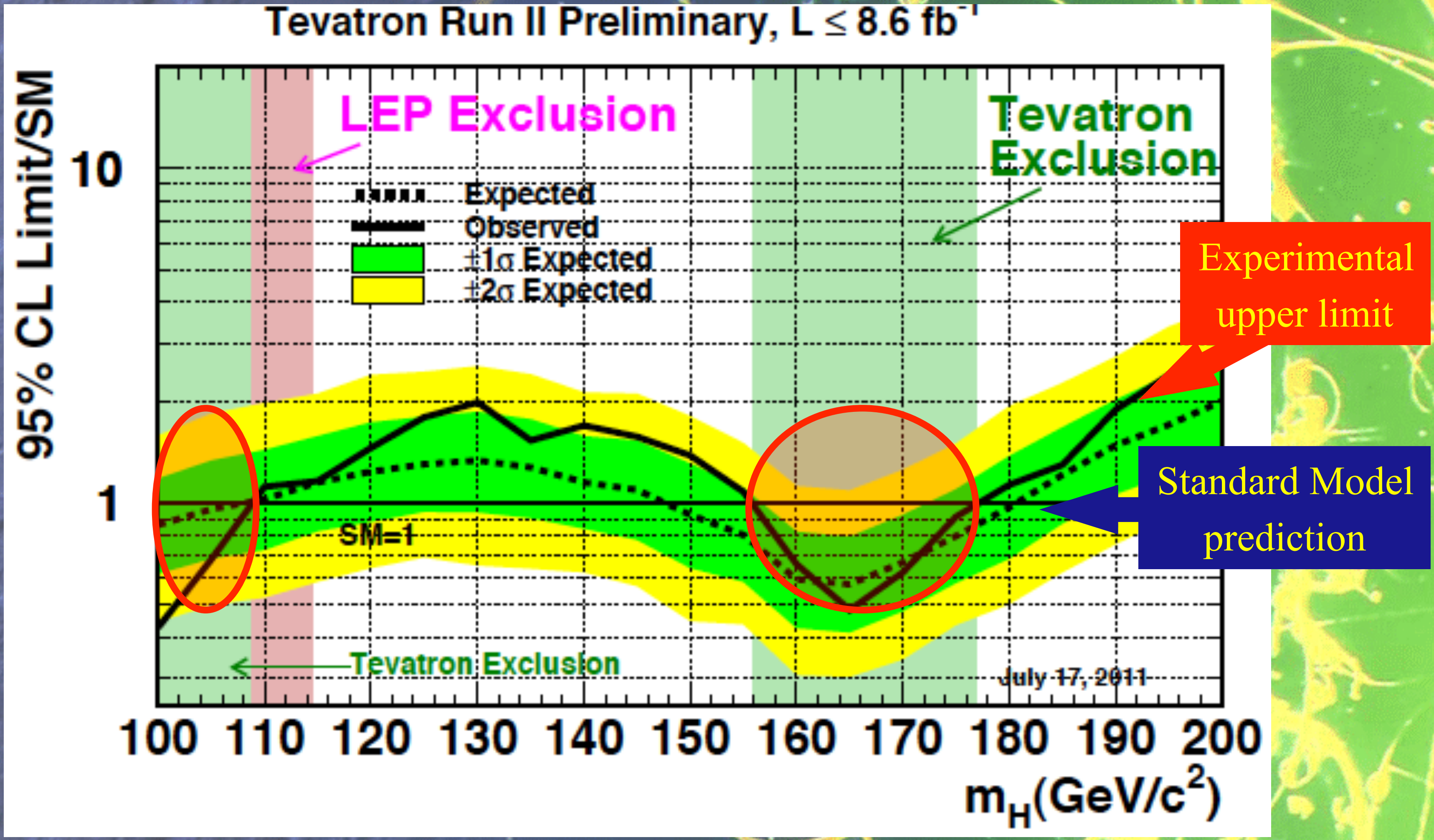
- Combined upper limit:

$m_H < 161$ GeV, or 190 GeV including direct limit

- Exclusion from high-energy search at Tevatron:

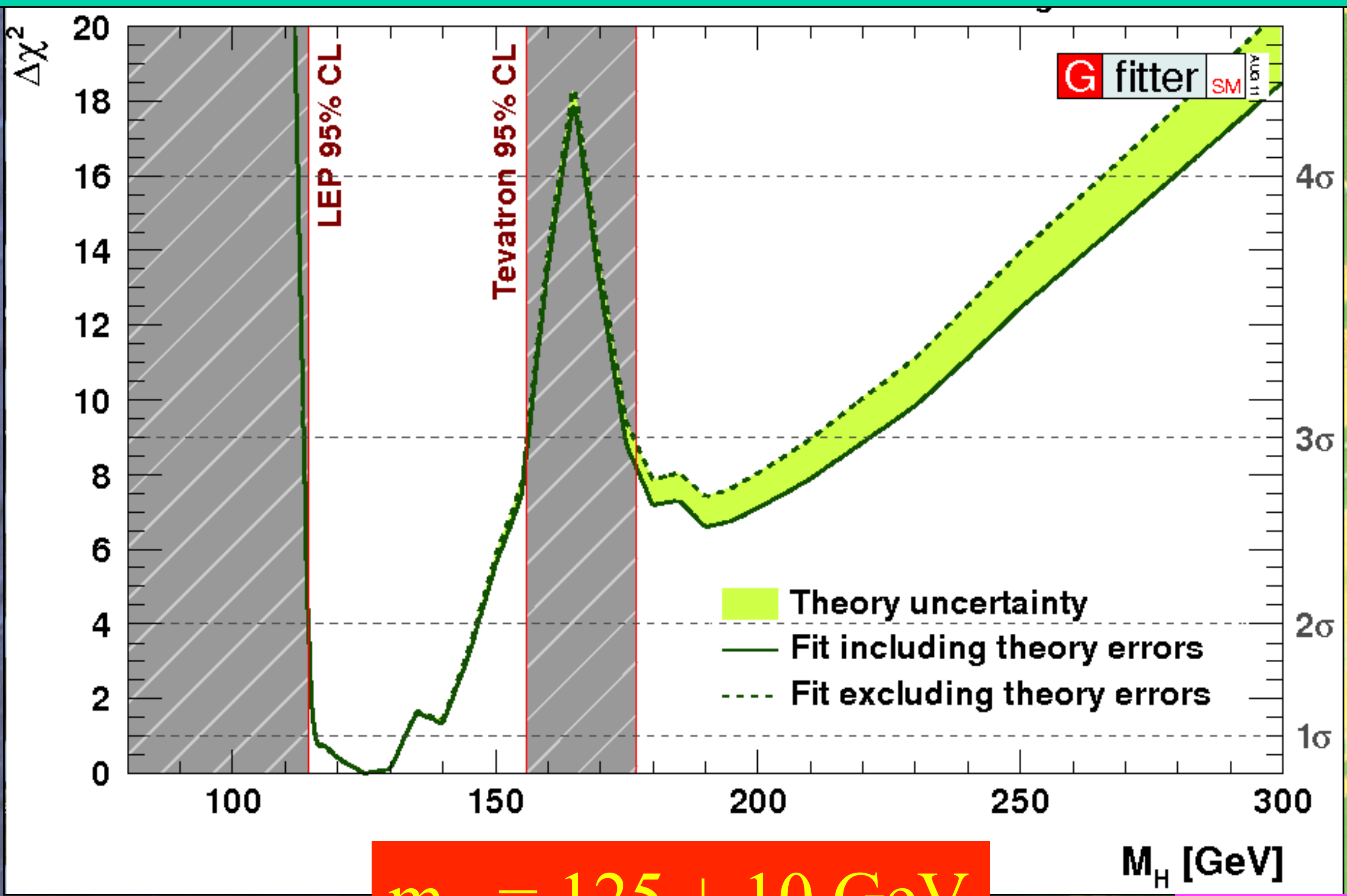
$m_H < 158$ GeV or > 173 GeV

Latest Higgs Searches @ Tevatron



Exclude (100,109); (156,177) GeV

Combining the Information from Previous Direct Searches and Indirect Data



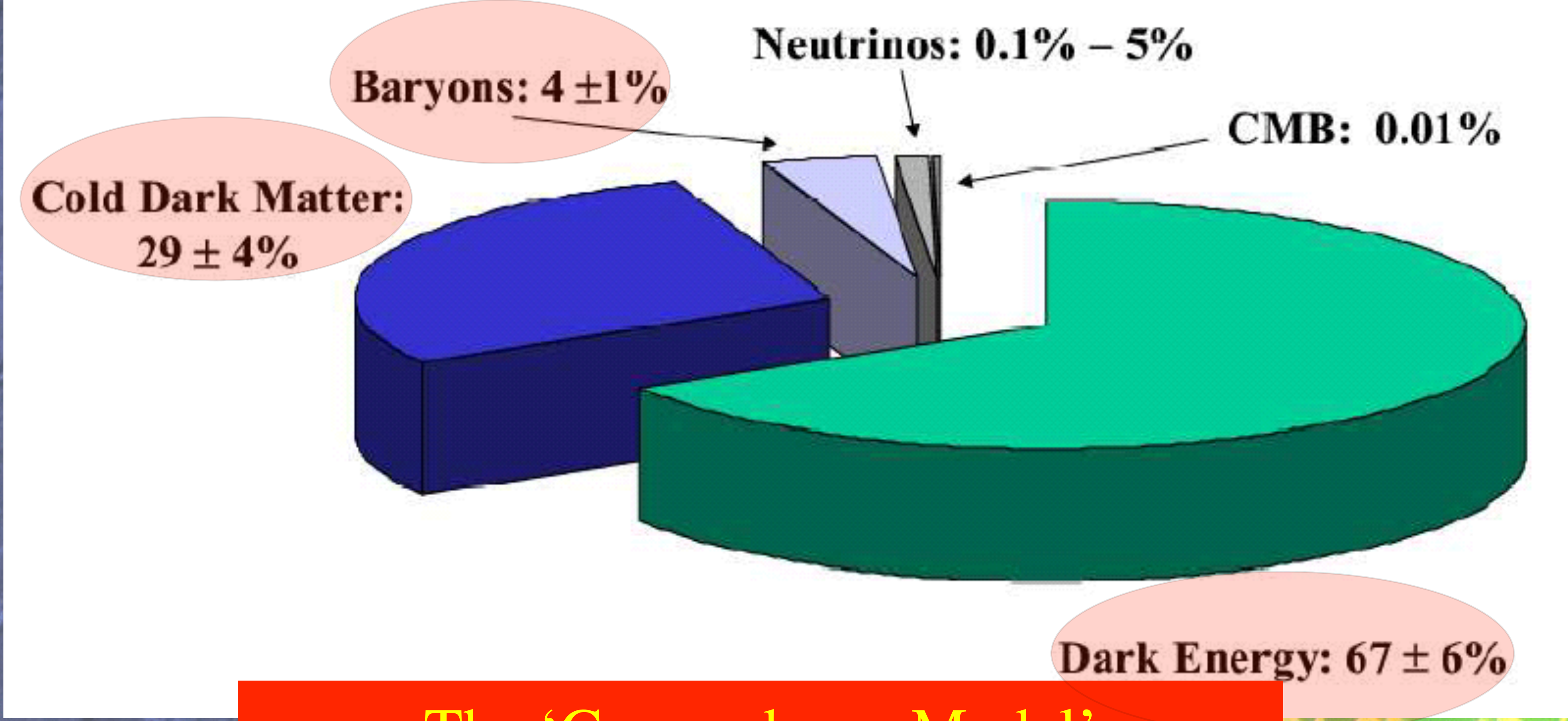
$m_H = 125 \pm 10$ GeV

Gfitter collaboration

The Higgs Boson and Cosmology

- Changed the state of the Universe when it was about 10^{-12} seconds old
- May have generated then the matter in the Universe
- Contributes (too much) to today's dark energy
- A related inflaton might have expanded the Universe when it was about 10^{-35} seconds old

A Strange Recipe for a Universe



The 'Concordance Model'
prompted by astrophysics & cosmology

Open Cosmological Questions

- Where did the matter come from?
  1 proton for every 1,000,000,000 photons
- What is the dark matter?
  Much more than the normal matter
- What is the dark energy?
  Even more than the dark matter
- Why is the Universe so big and old?
  Mechanism for cosmological inflation

Need particle physics to answer these questions

The Very Early Universe

- Size: $a \rightarrow$ zero
- Age: $t \rightarrow$ zero
- Temperature: $T \rightarrow$ large

  $T \sim 1/a$, $t \sim 1/T^2$
- Energies: $E \sim T$
- Rough magnitudes:

  $T \sim$ 10,000,000,000 degrees

  $E \sim$ 1 MeV $\sim$ mass of electron

  $t \sim$ 1 second

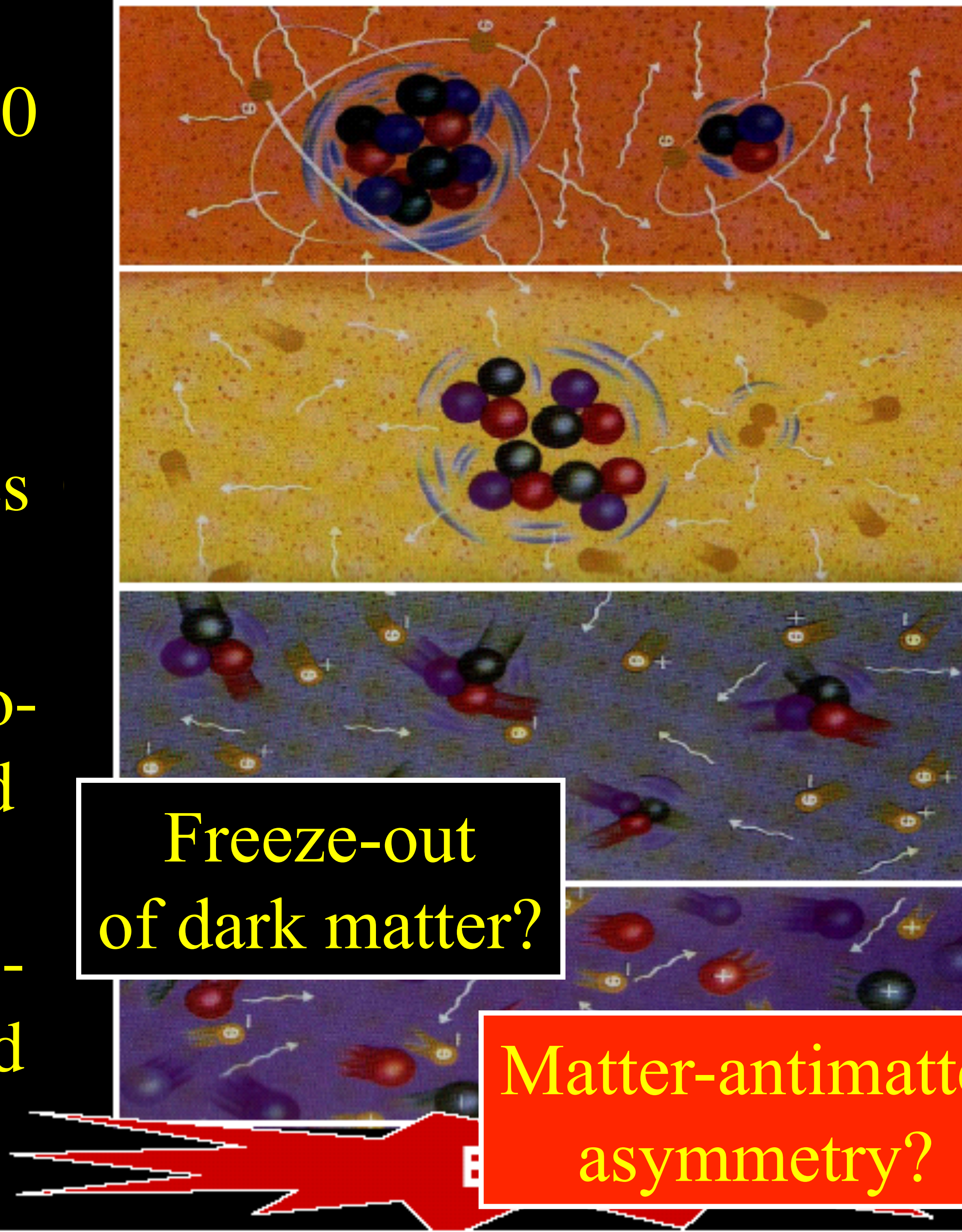
Need particle physics to describe earlier history
LHC physics @ TeV: $t \sim$ 1 picosecond

380,000 years — Formation of atoms

3 minutes — Formation of nuclei

1 micro-second — Formation of protons & neutrons

1 pico-second — Appearance of mass?

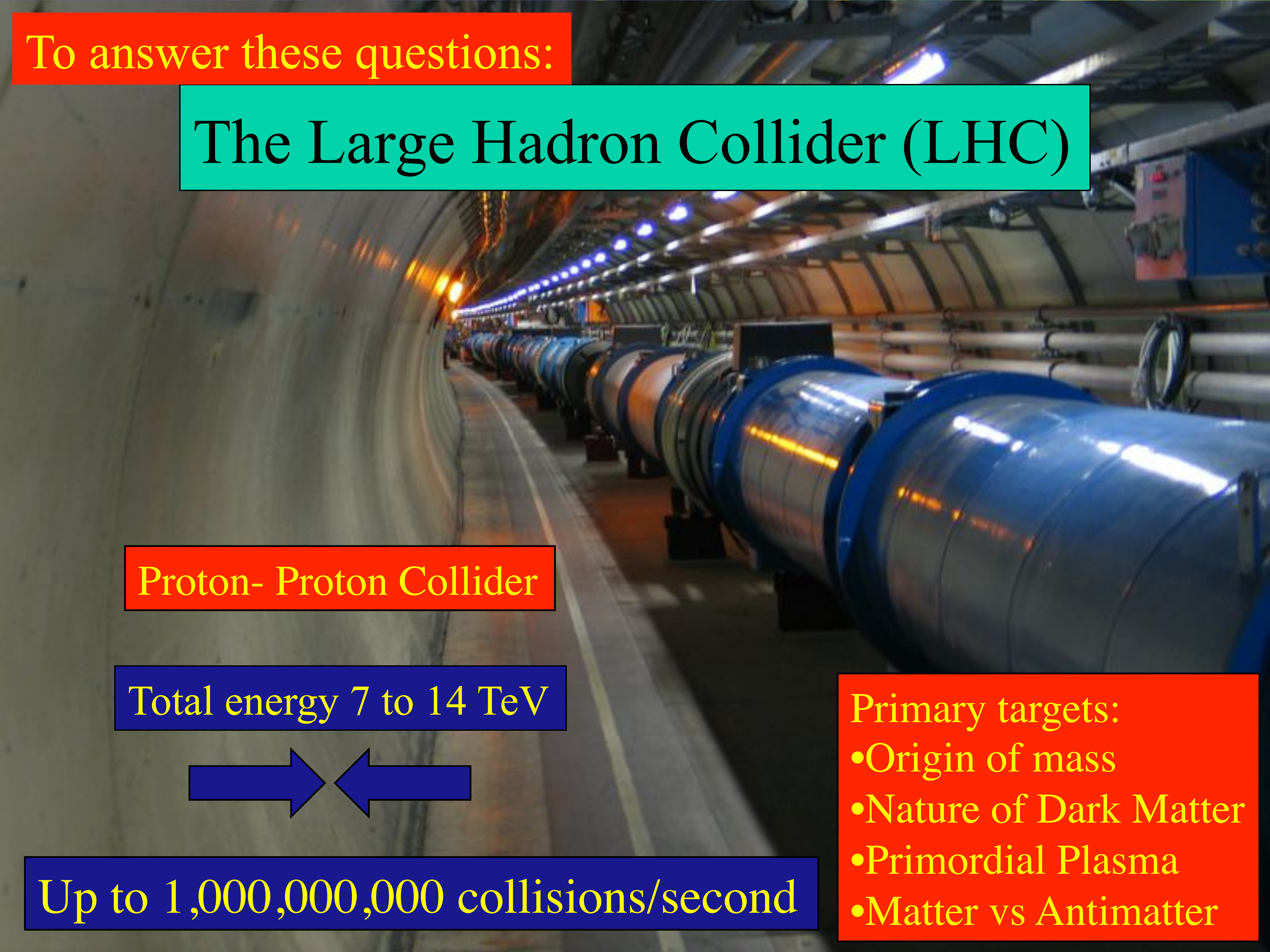


Freeze-out of dark matter?

Matter-antimatter asymmetry?

To answer these questions:

The Large Hadron Collider (LHC)

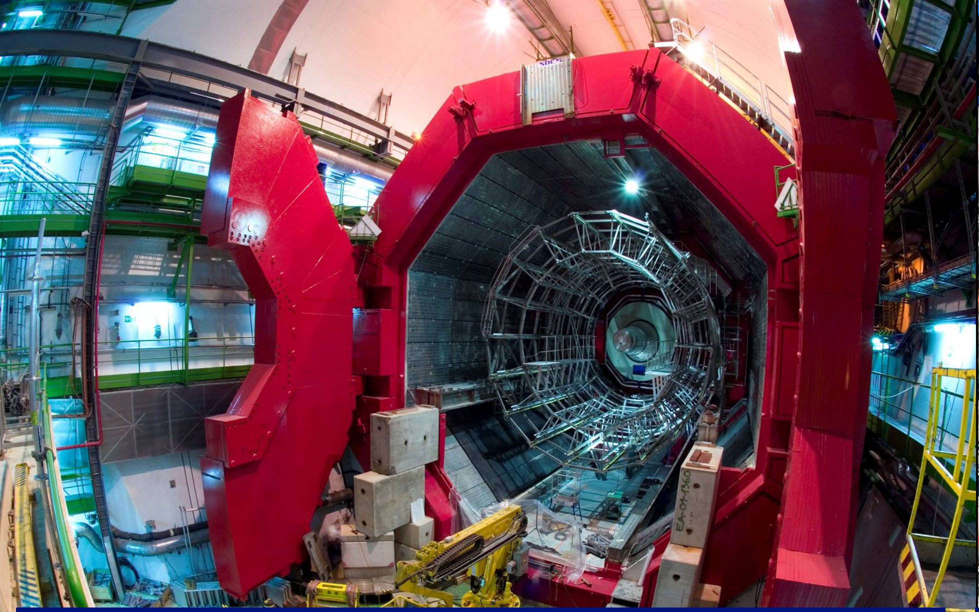


Proton- Proton Collider

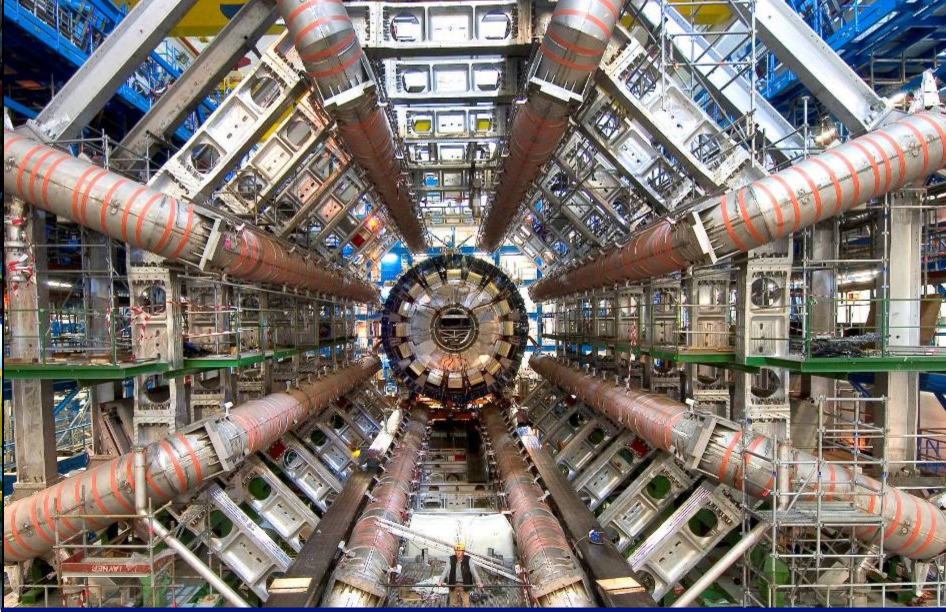
Total energy 7 to 14 TeV

Up to 1,000,000,000 collisions/second

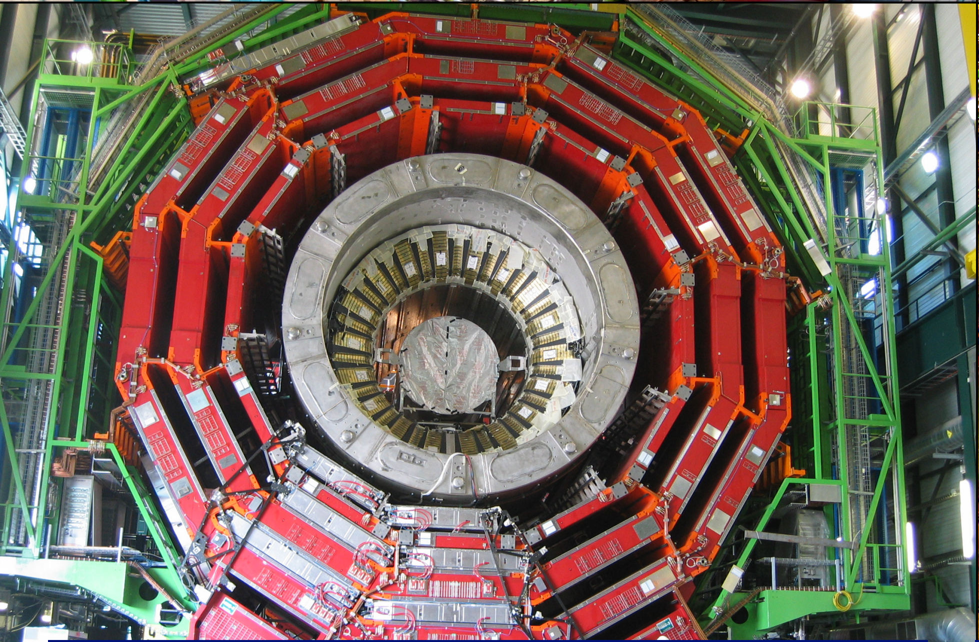
Primary targets:
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter



ALICE: Primordial cosmic plasma



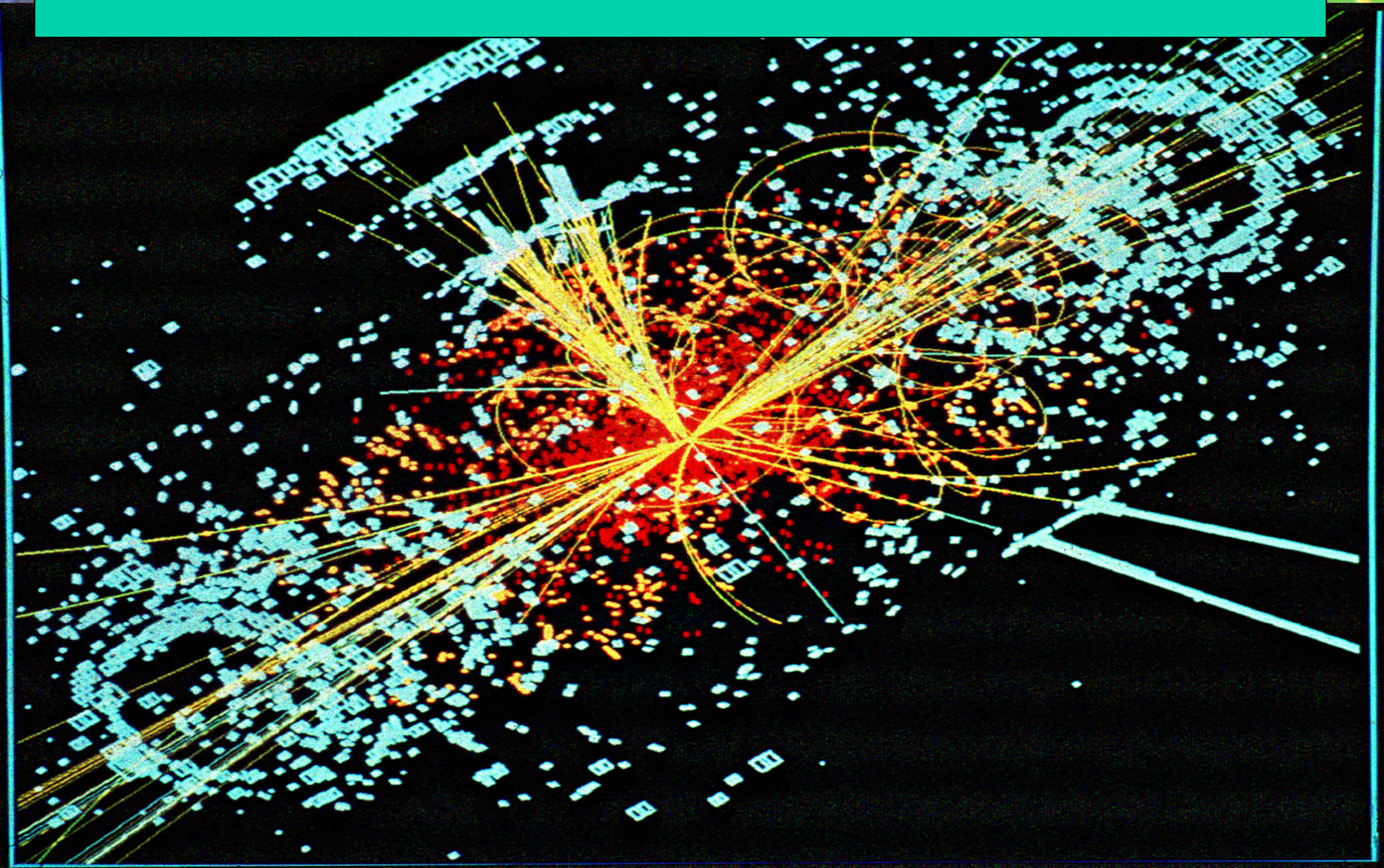
ATLAS: Higgs and supersymmetry



CMS: Higgs and supersymmetry

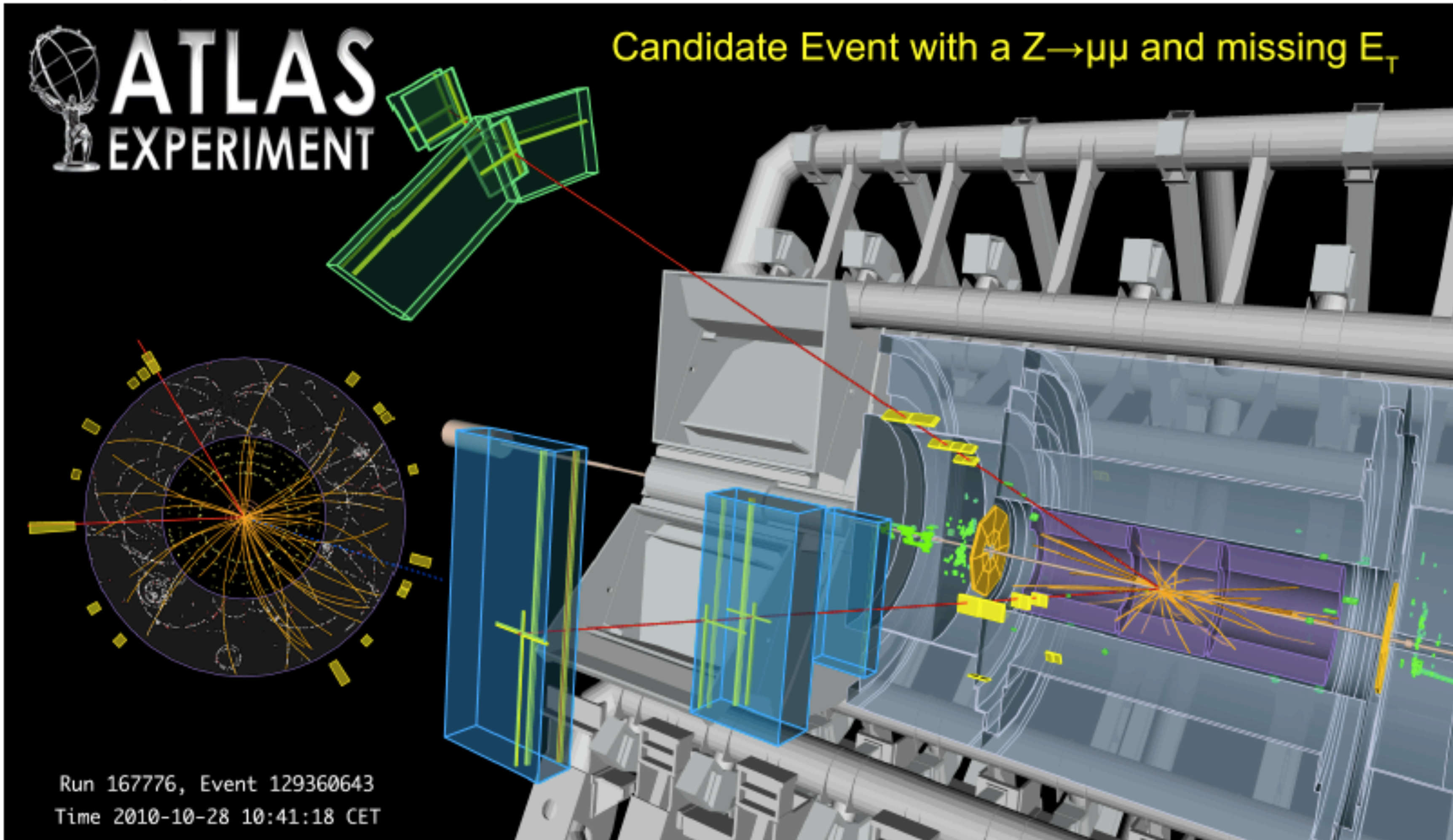
LHCb: Matter-antimatter difference

Simulated Production of a Higgs Boson



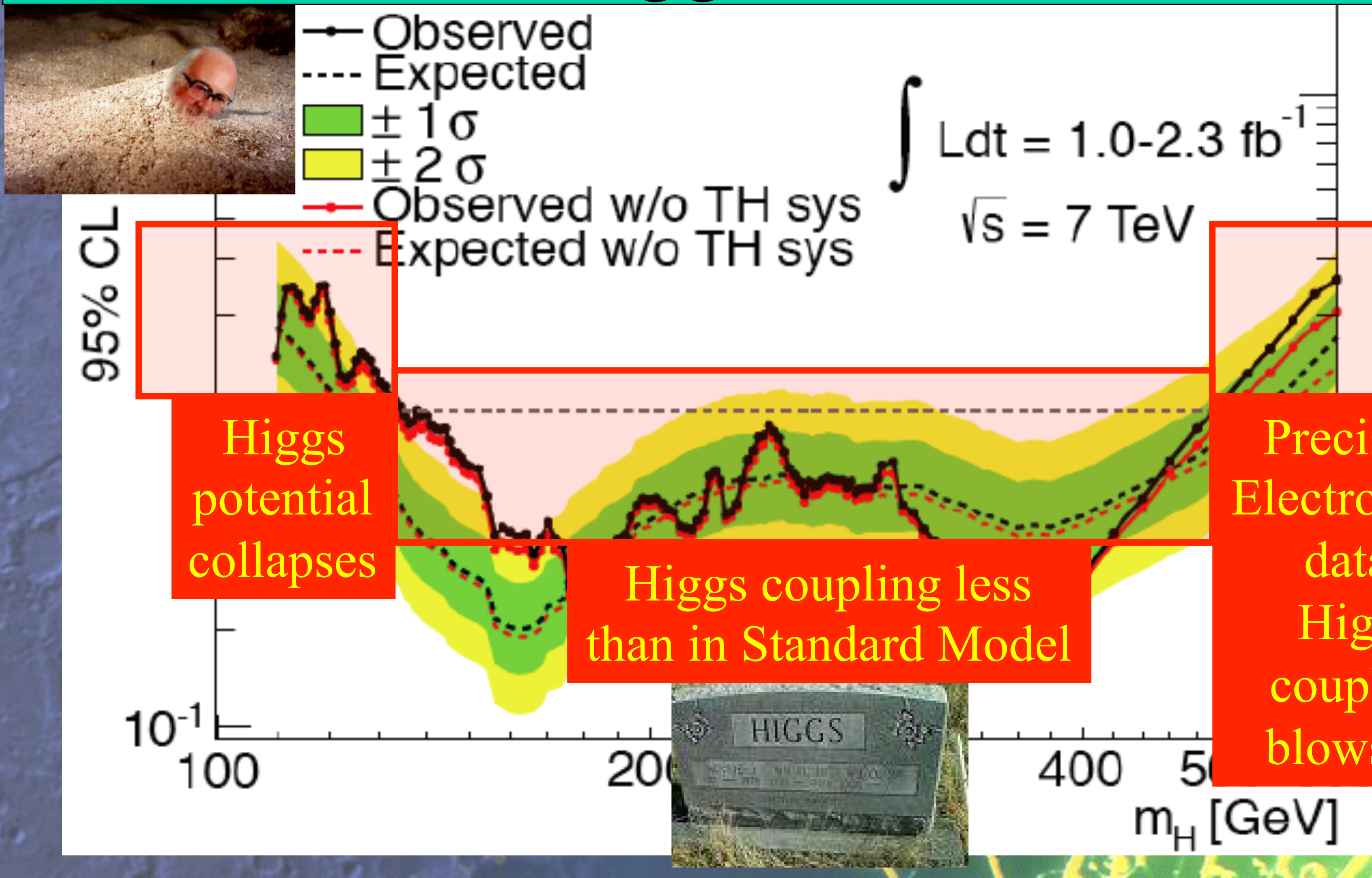
Interesting Events

$m_{\mu\mu}$ 94 GeV, E_T^{miss} = 161 GeV



Compilation from Friday Nov. 18th

There must be New Physics beyond the Higgs Boson



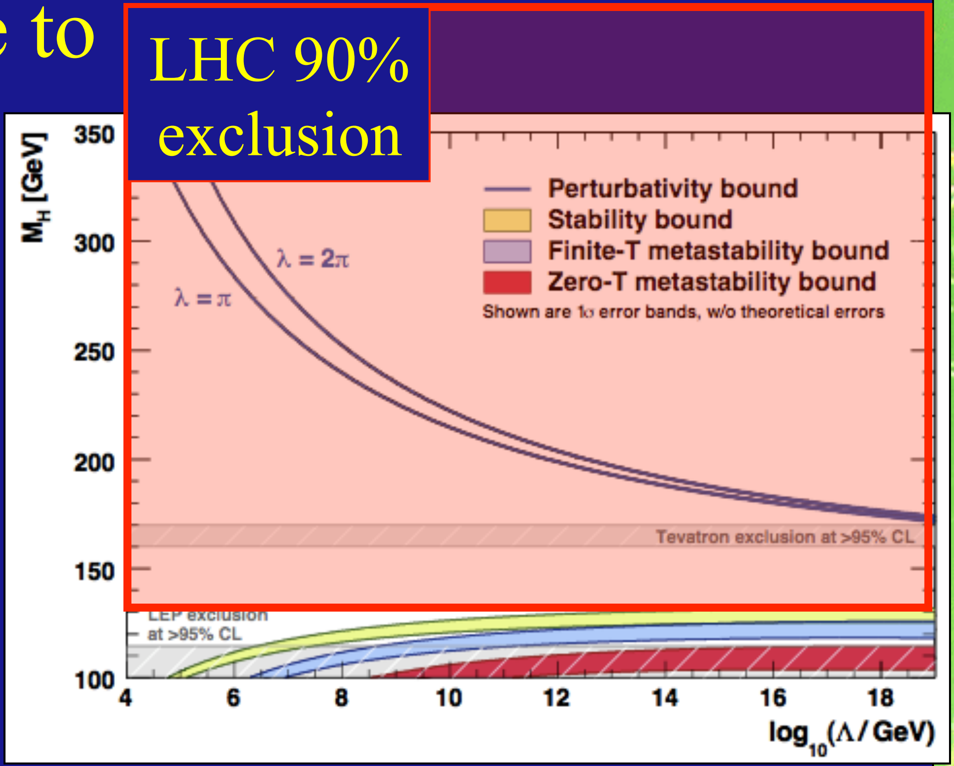
Higgs potential collapses

Higgs coupling less than in Standard Model

Precision Electroweak data? Higgs coupling blows up

Theoretical Constraints on Higgs Mass

- Large M_h → large self-coupling → blow up at low-energy scale Λ due to renormalization
- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable
- Bounds on Λ depend on Higgs mass



Espinosa, JE, Giudice, Hoecker, Riotto, arXiv0906.0954

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 stabilize vacuum
- Would help fix particle masses
- Would help unify forces
- Predicts light Higgs boson
- **Could provide dark matter for the astrophysicists and cosmologists**

Lightest Supersymmetric Particle

Fayet

- 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

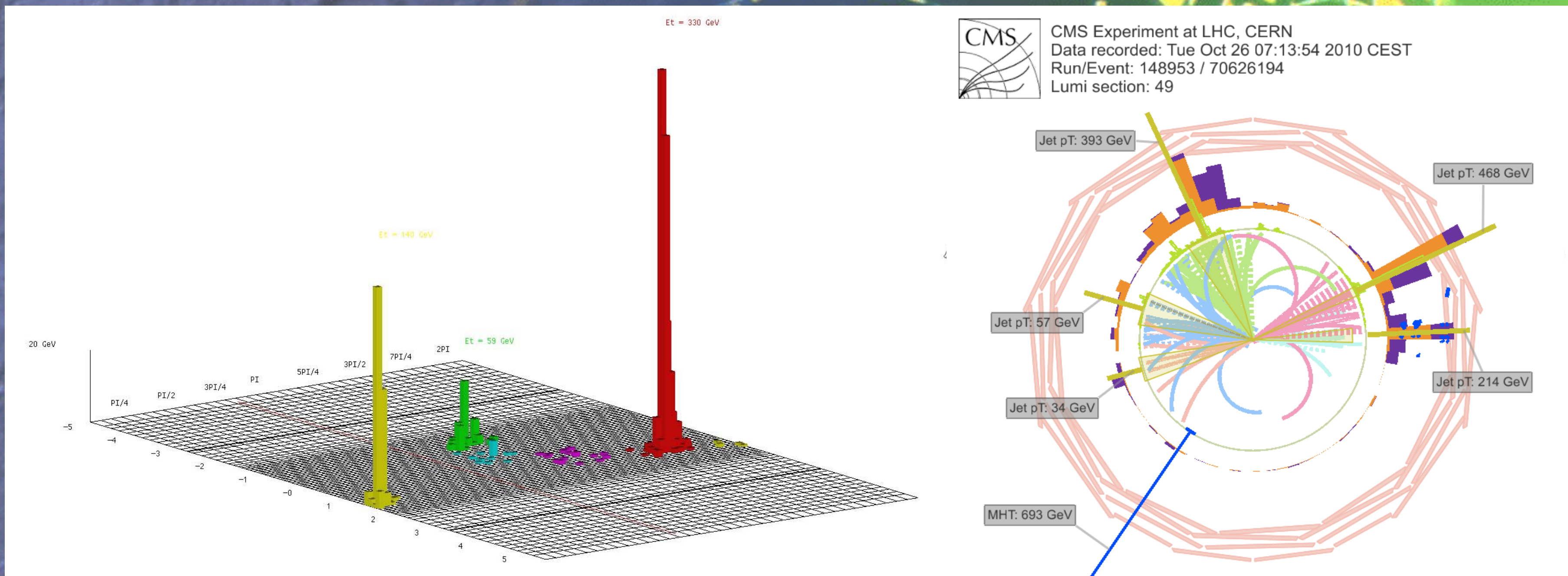
  Heavier sparticles → lighter sparticles

- Lightest supersymmetric particle (LSP) stable

Possible Nature of LSP

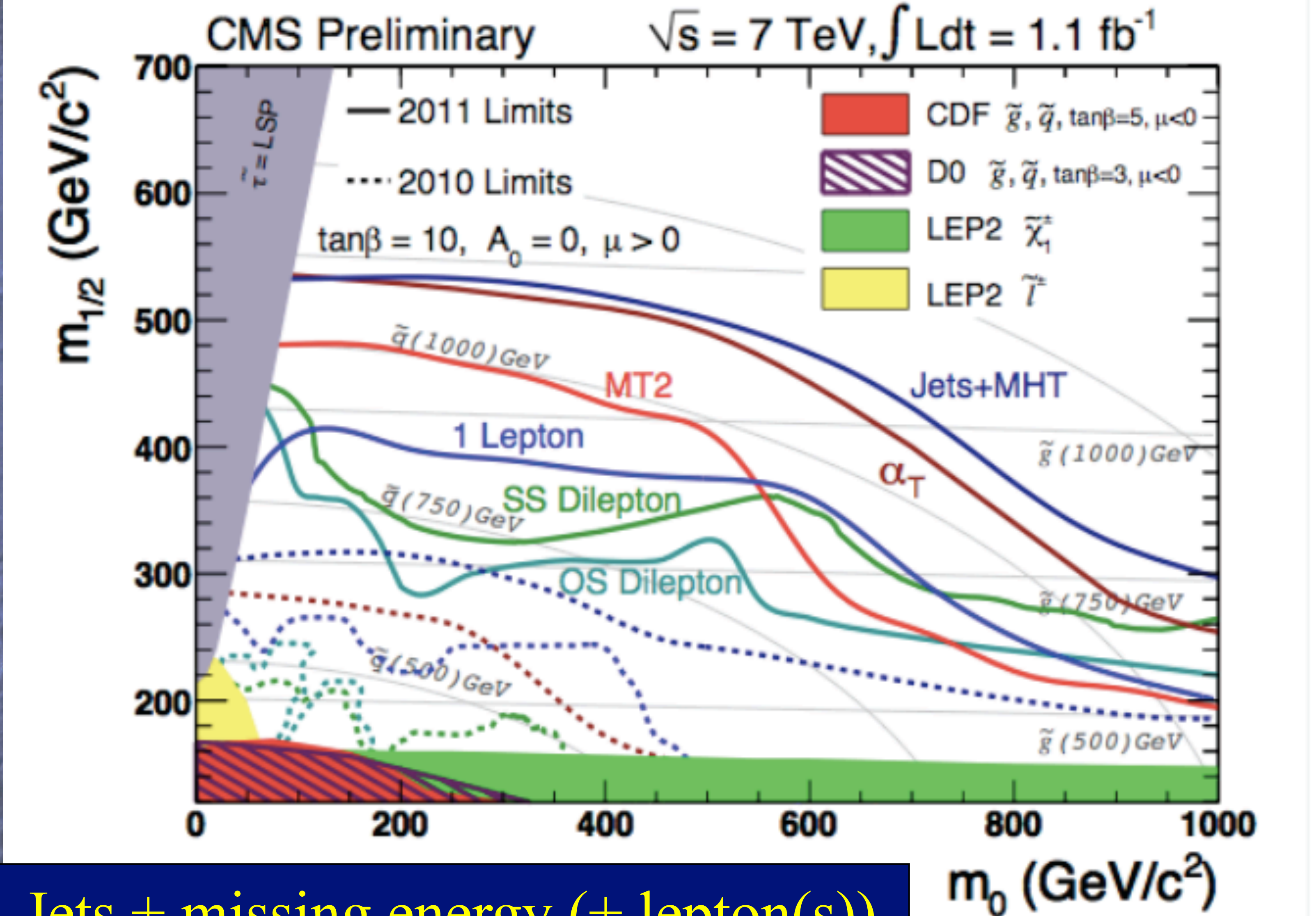
- No strong or electromagnetic interactions
  - Otherwise would bind to matter
  - Detectable as anomalous heavy nucleus
- Possible weakly-interacting scandidates
  - Sneutrino
    - (Excluded by LEP, direct searches)
  - Lightest neutralino χ (partner of Z, H, γ)
  - Gravitino
    - (nightmare for astrophysical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

Supersymmetric Signature @ LHC



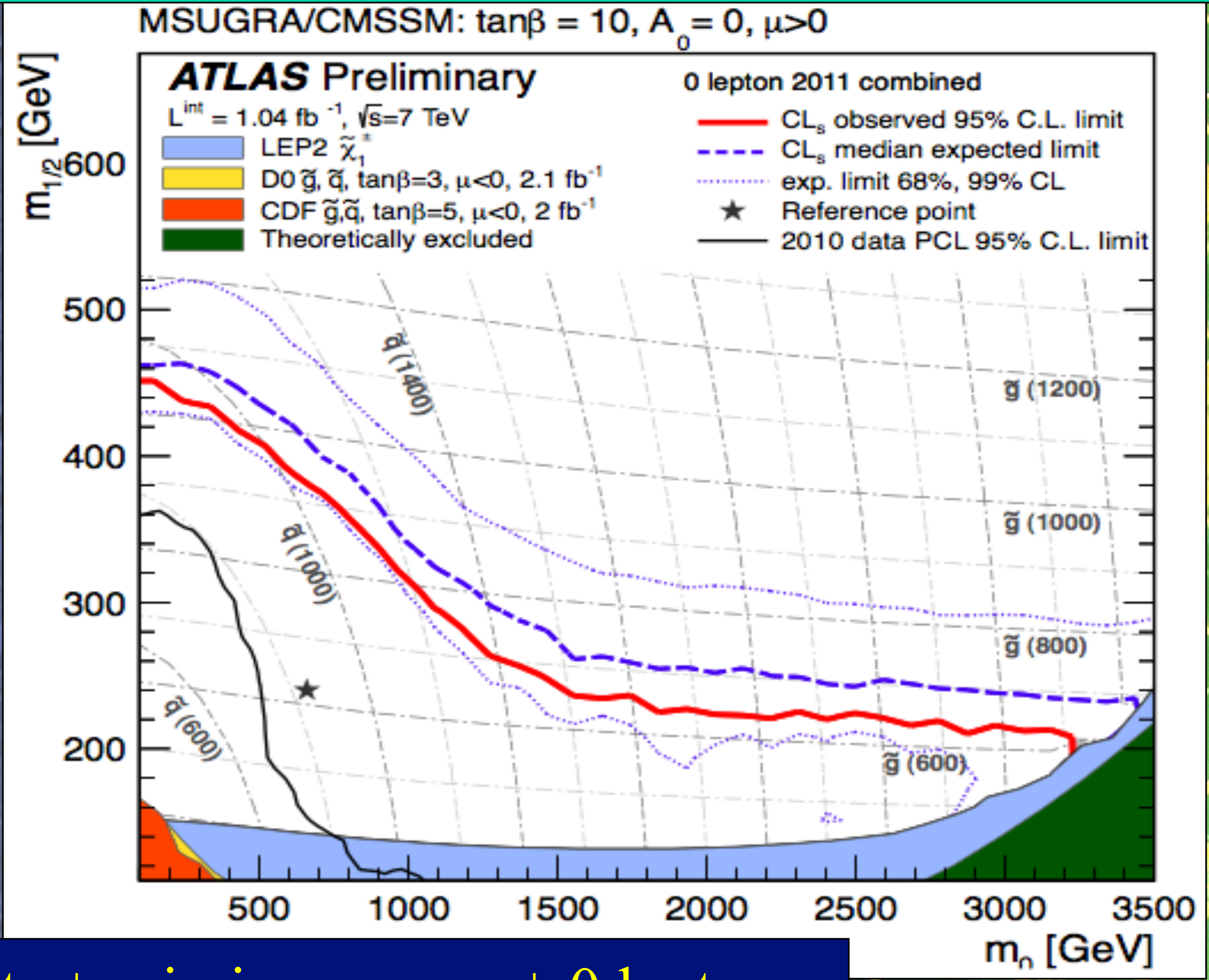
Missing transverse energy carried away by dark matter particles

Supersymmetry Searches in CMS



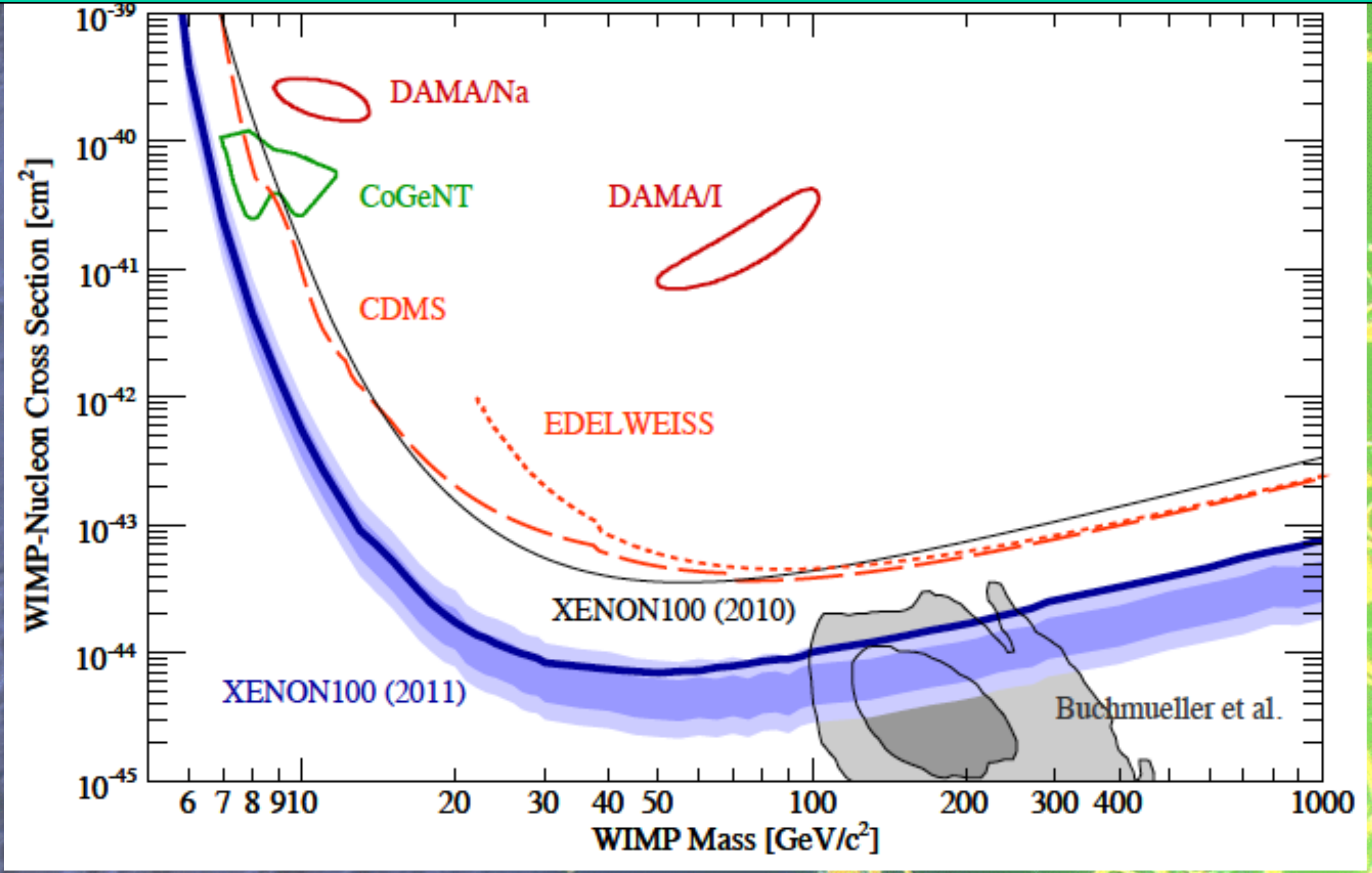
Jets + missing energy (+ lepton(s))

Supersymmetry Searches in ATLAS



Jets + missing energy + 0 lepton

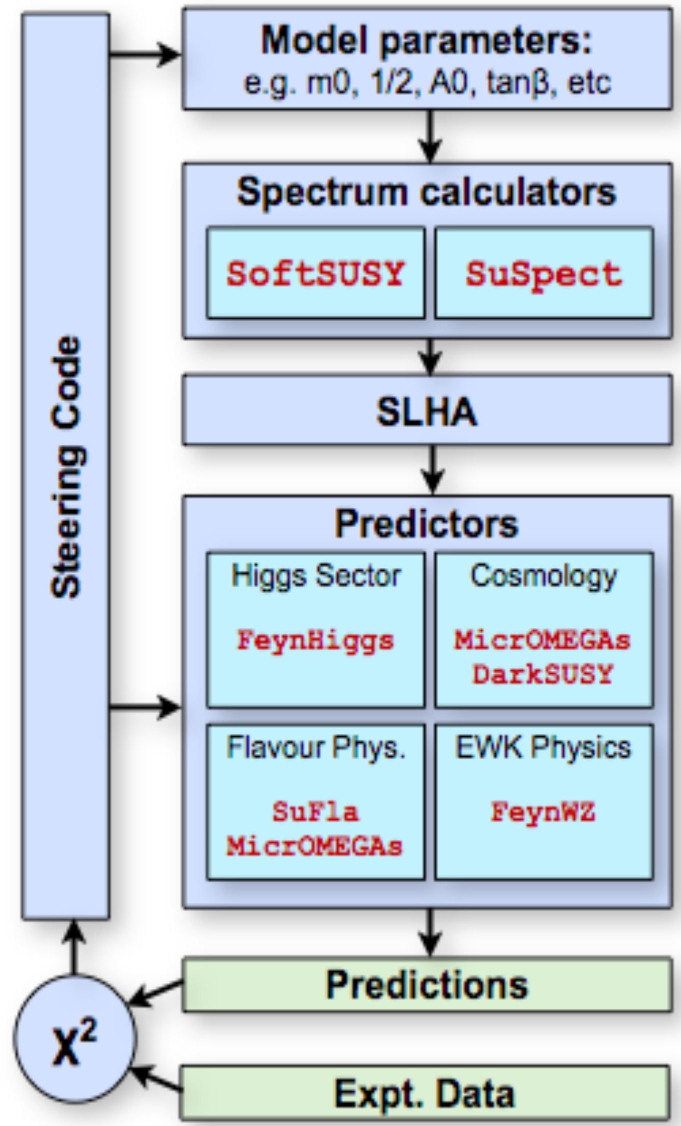
XENON100 Experiment



Aprile et al: arXiv:1104.2549

MasterCode

- **Combines diverse set of tools**
  - different codes : all state-of-the-art
    - Electroweak Precision (FeynWZ)
    - Flavour (SuFla, micrOMEGAs)
    - Cold Dark Matter (DarkSUSY, micrOMEGAs)
    - Other low energy (FeynHiggs)
    - Higgs (FeynHiggs)
  - different precisions (one-loop, two-loop, etc)
  - different languages (Fortran, C++, English, German, Italian, etc)
  - different people (theorists, experimentalists)
- **Compatibility is crucial! Ensured by**
  - close collaboration of tools authors
  - standard interfaces

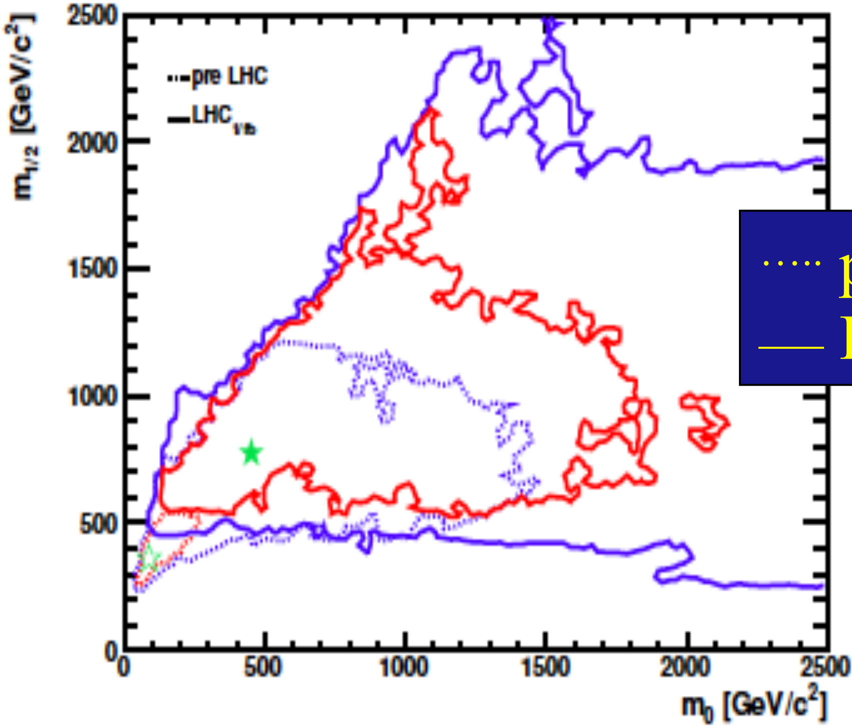


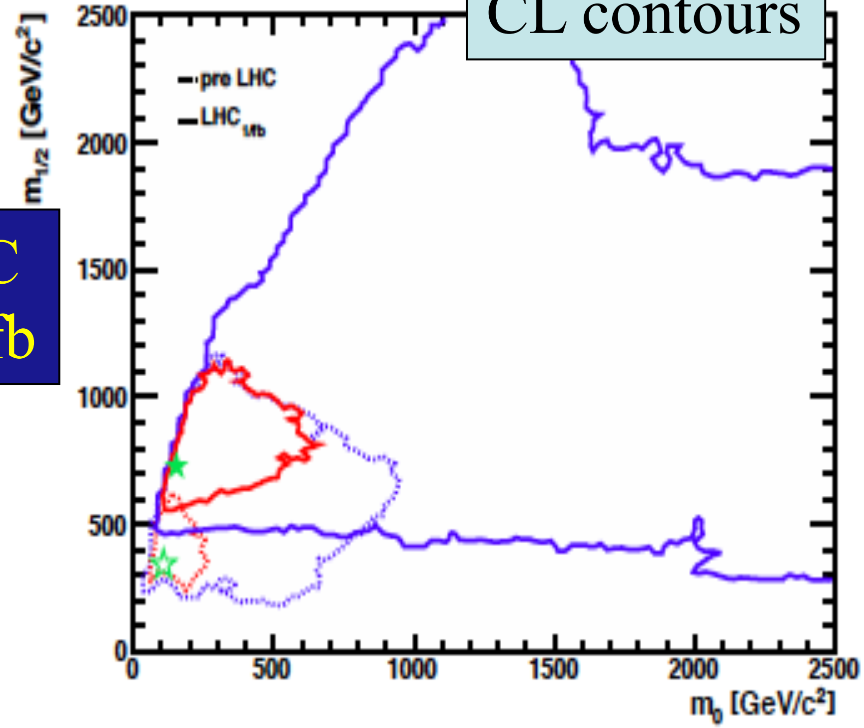
O. Buchmueller, R. Cavanaugh, D. Colling, A. de Roeck, M.J. Dolan, J.R. Ellis, H. Flaecher, S. Heinemeyer, G. Isidori, D. Martinez Santos, K.A. Olive, S. Rogerson, F.J. Ronga, G. Weiglein

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data

68% & 95% CL contours





····· pre-LHC
— LHC 1/fb

CMSSM

60 million points sampled

NUHM1

70 million points sampled

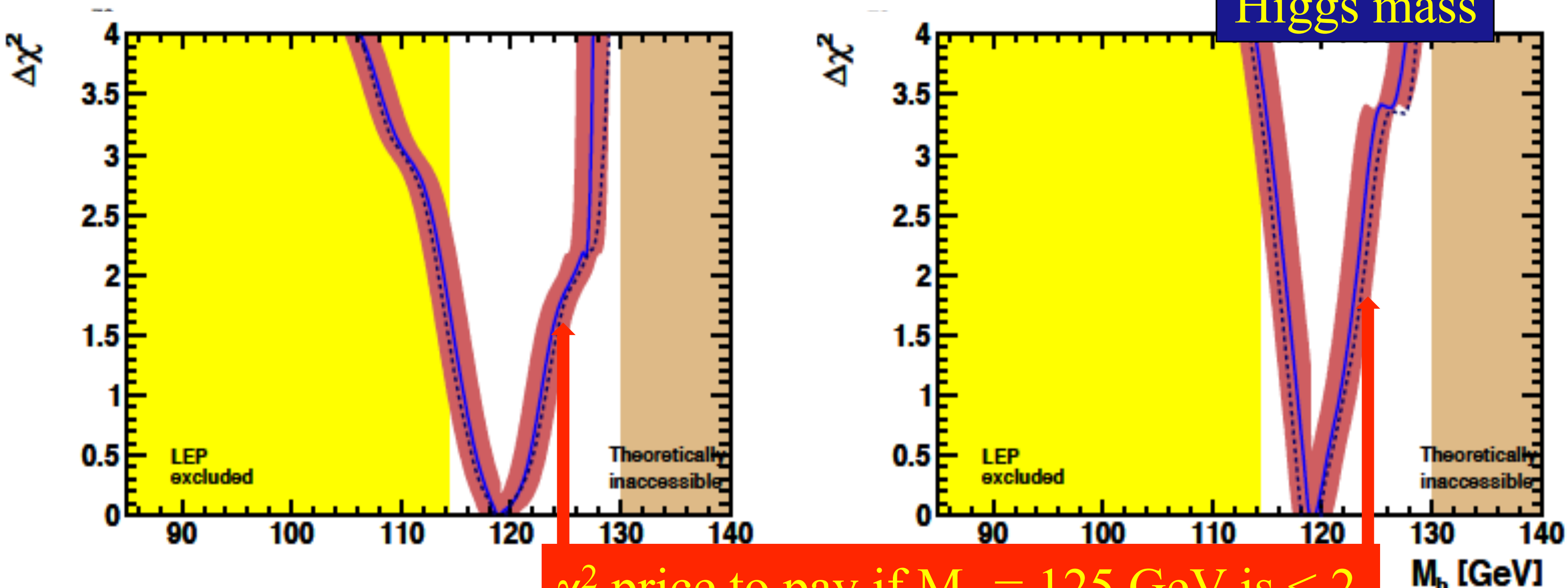
Red and blue curves represent $\Delta\chi^2$ from global minimum, located at ☆

Preferred region "opens up" at cost of worsening global χ^2 value!

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data

Higgs mass



χ^2 price to pay if M_h = 125 GeV is < 2

CMSSM

60 million points sampled

NUHM1

70 million points sampled

Buchmueller, JE et al: arXiv:1112.3564

Favoured values of M_h ~ 119 GeV:
Range consistent with evidence from LHC !

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13 December 2011 Last updated at 17:20 GMT   9.7K Share

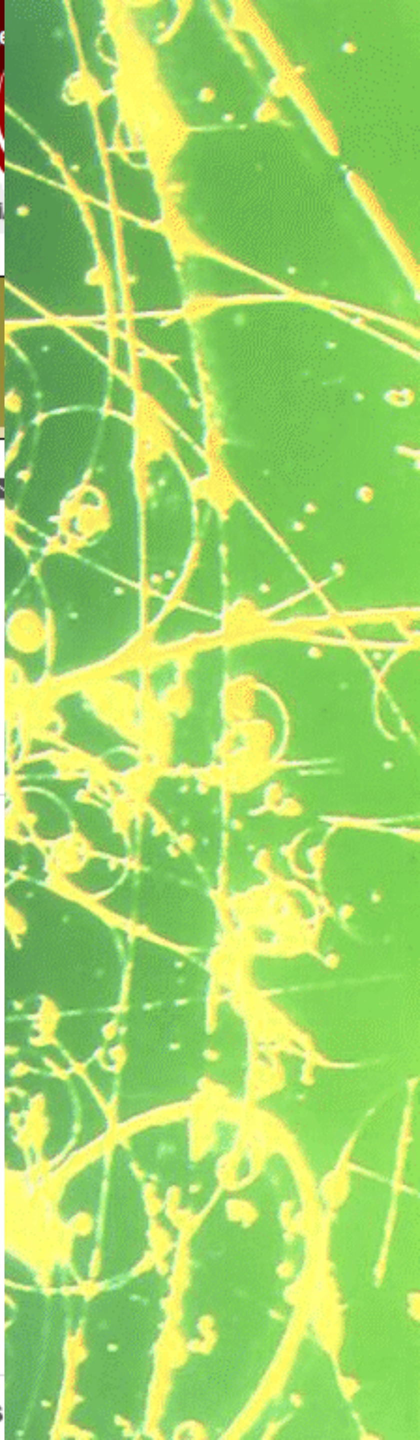
LHC: Higgs boson 'may have been glimpsed'

By Paul Rincon
Science editor, BBC News website, Geneva

Two teams at the LHC have seen hints of what may well prove to be the Higgs

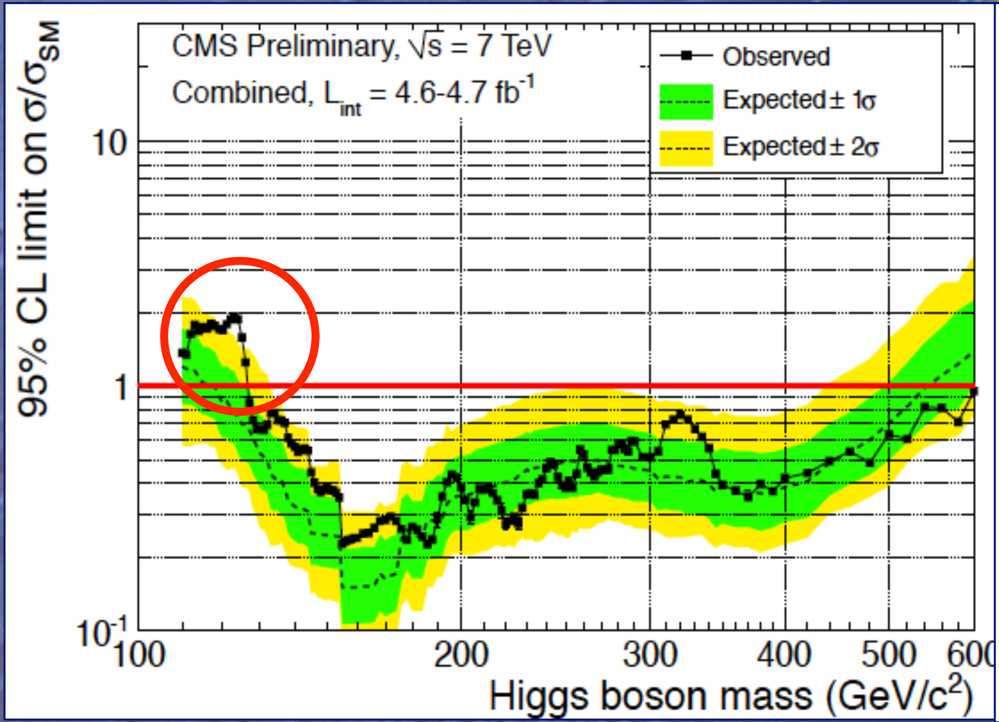
The most coveted prize in particle physics - the Higgs boson - may have been glimpsed, say researchers reporting at the Large Hadron

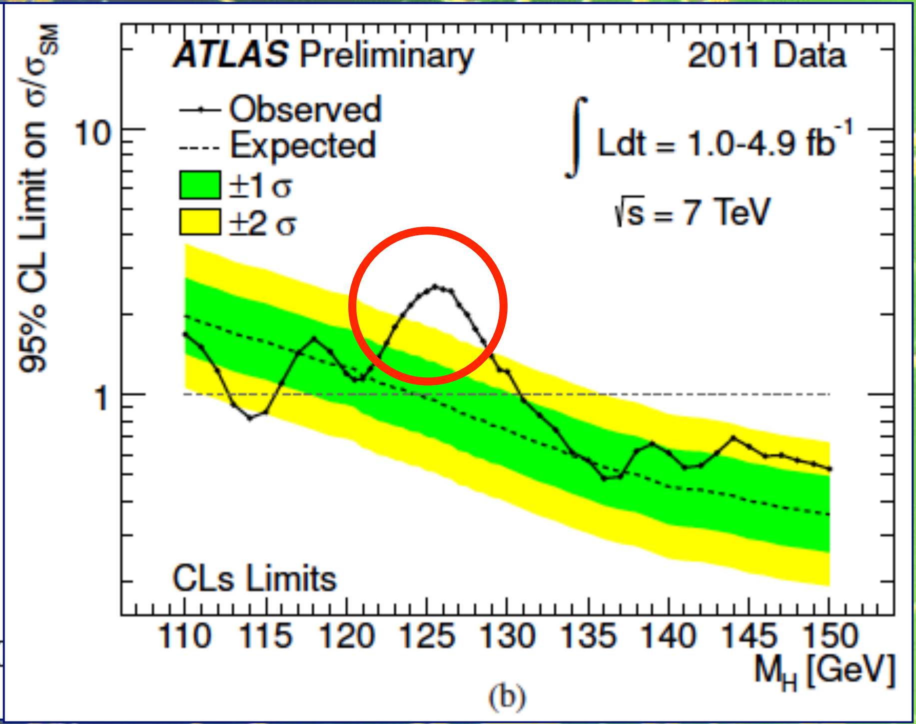
Related Stories



Has the Higgs Boson been Discovered?

Interesting hints around M_h = 125 GeV ?

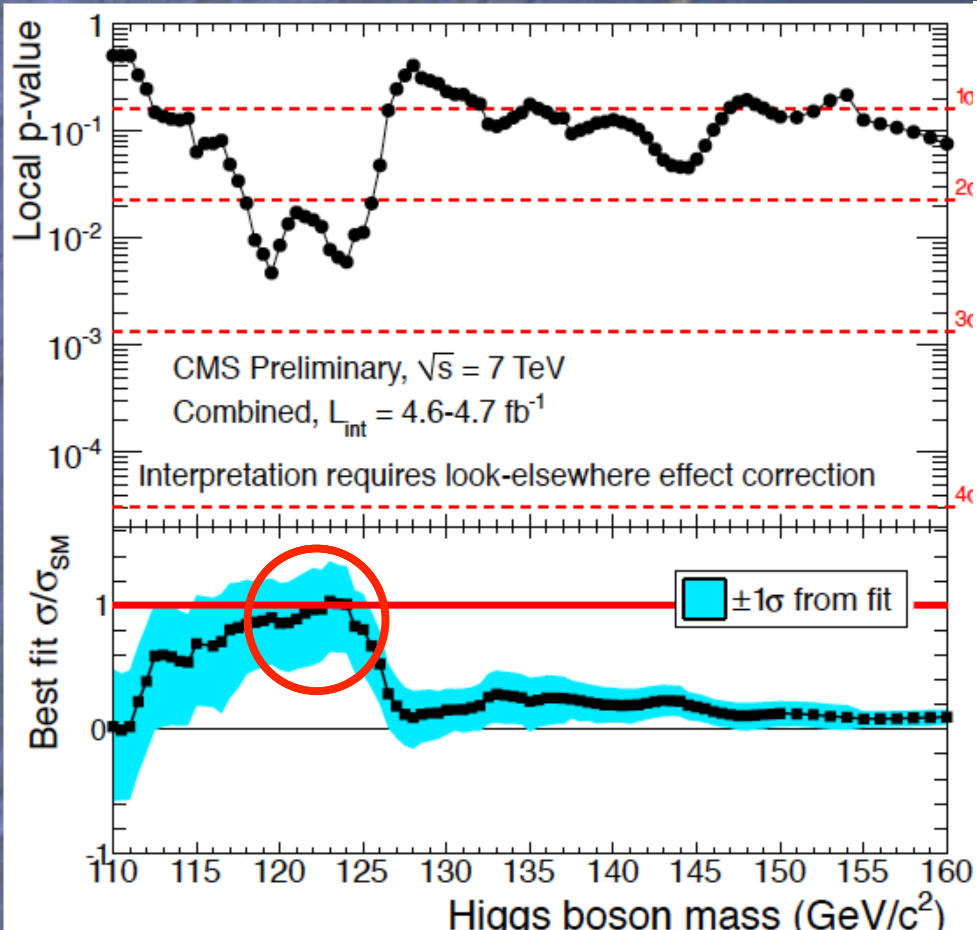


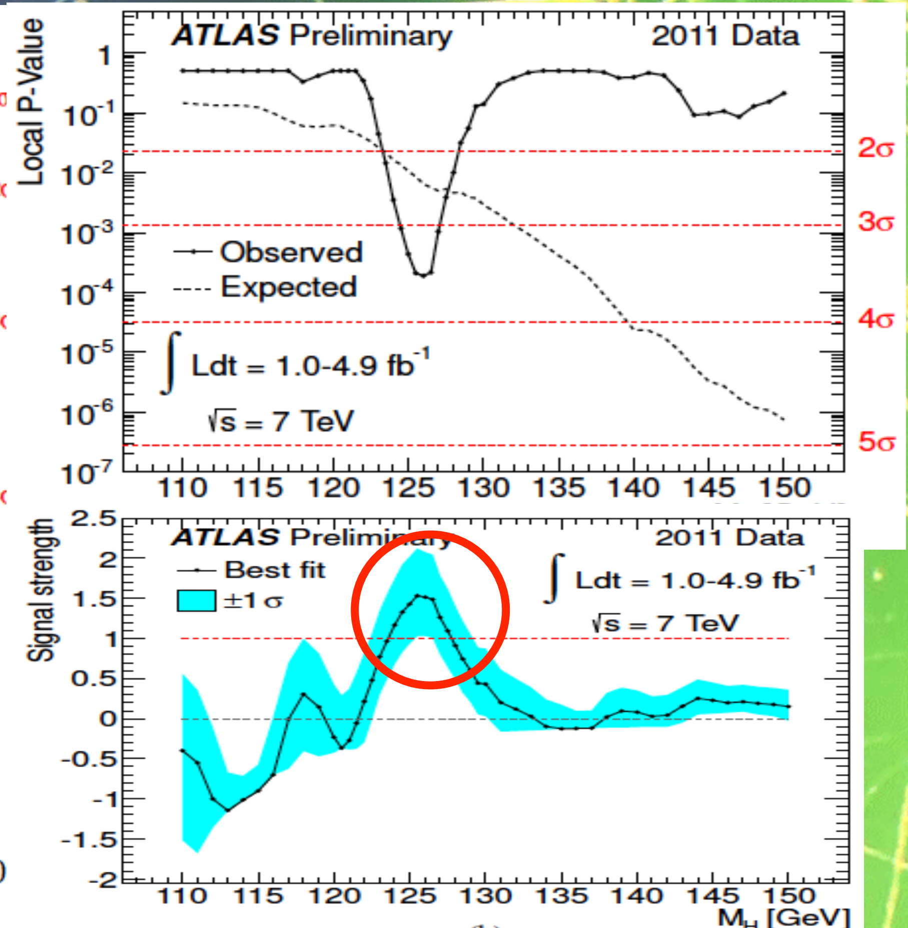


CMS sees broad enhancement

ATLAS prefers 125 GeV

Has the Higgs Boson been Discovered?



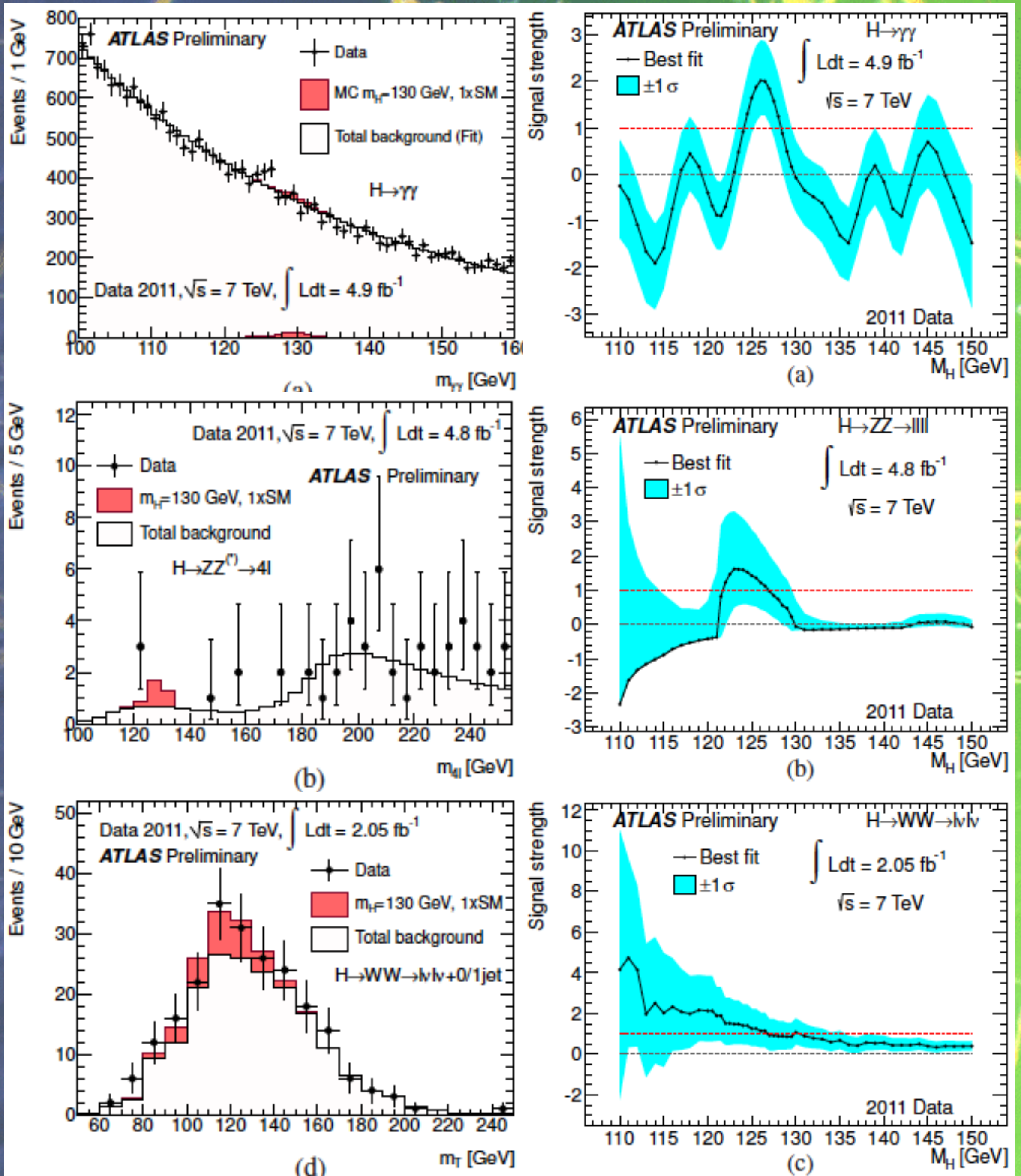


Interesting hints around 125 GeV in both experiments

- but could also be 119 GeV ?

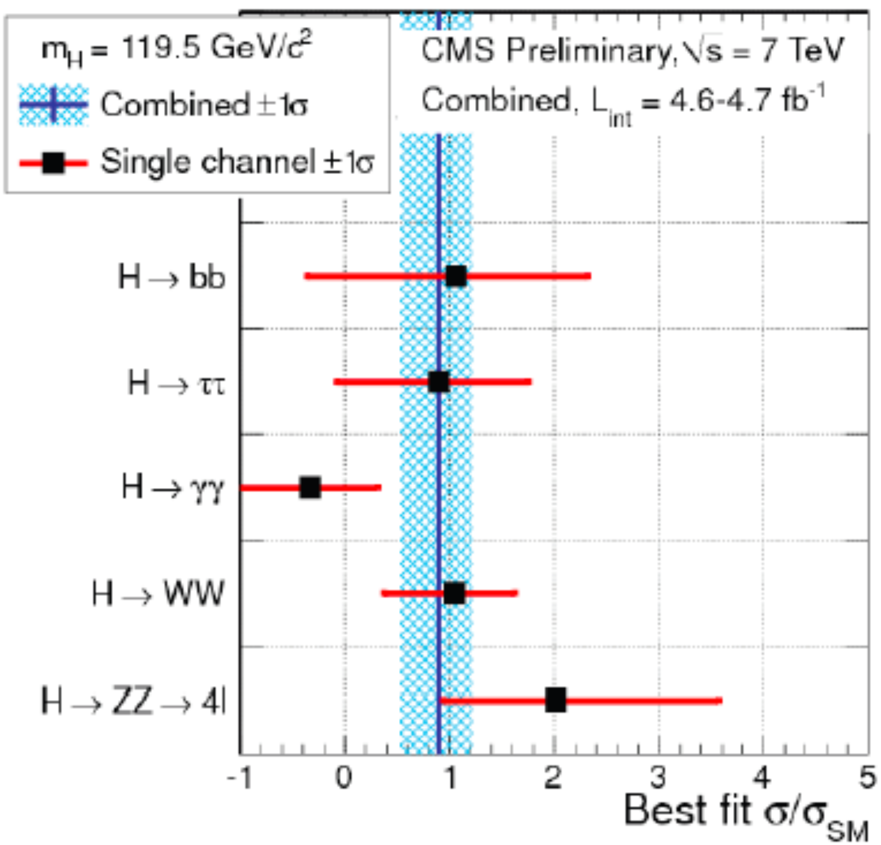
ATLAS Signals

- γγ: 2.8σ
- ZZ: 2.1σ
- WW: 1.4σ
- Combined: 3.6σ

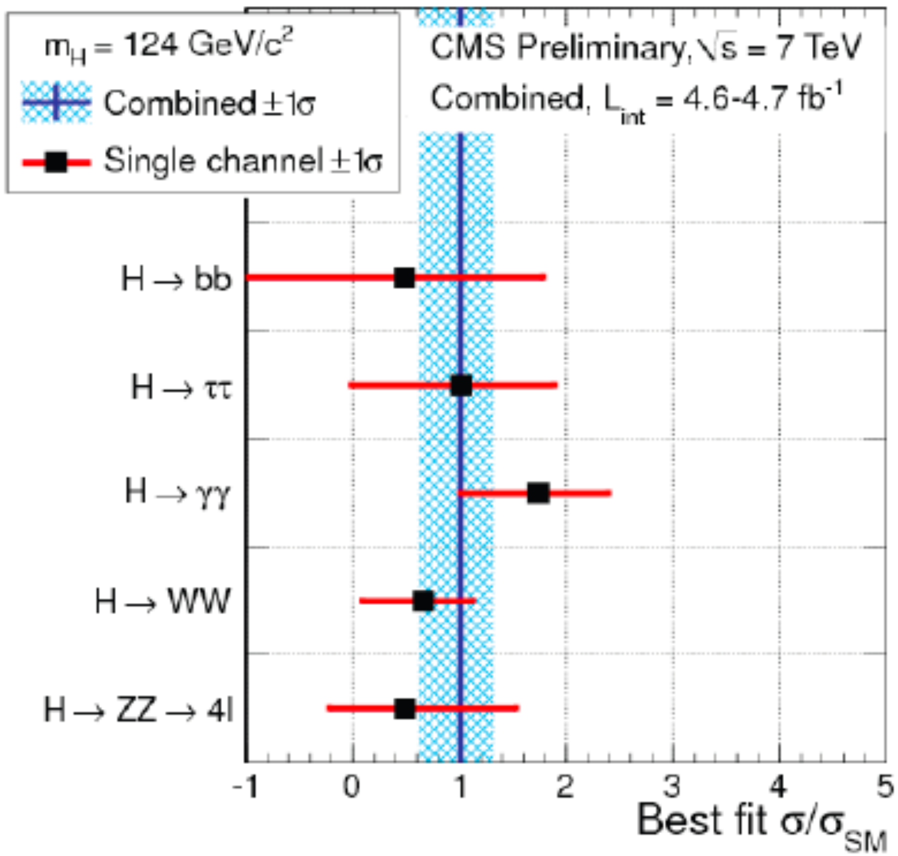


CMS Signals

119.5 GeV

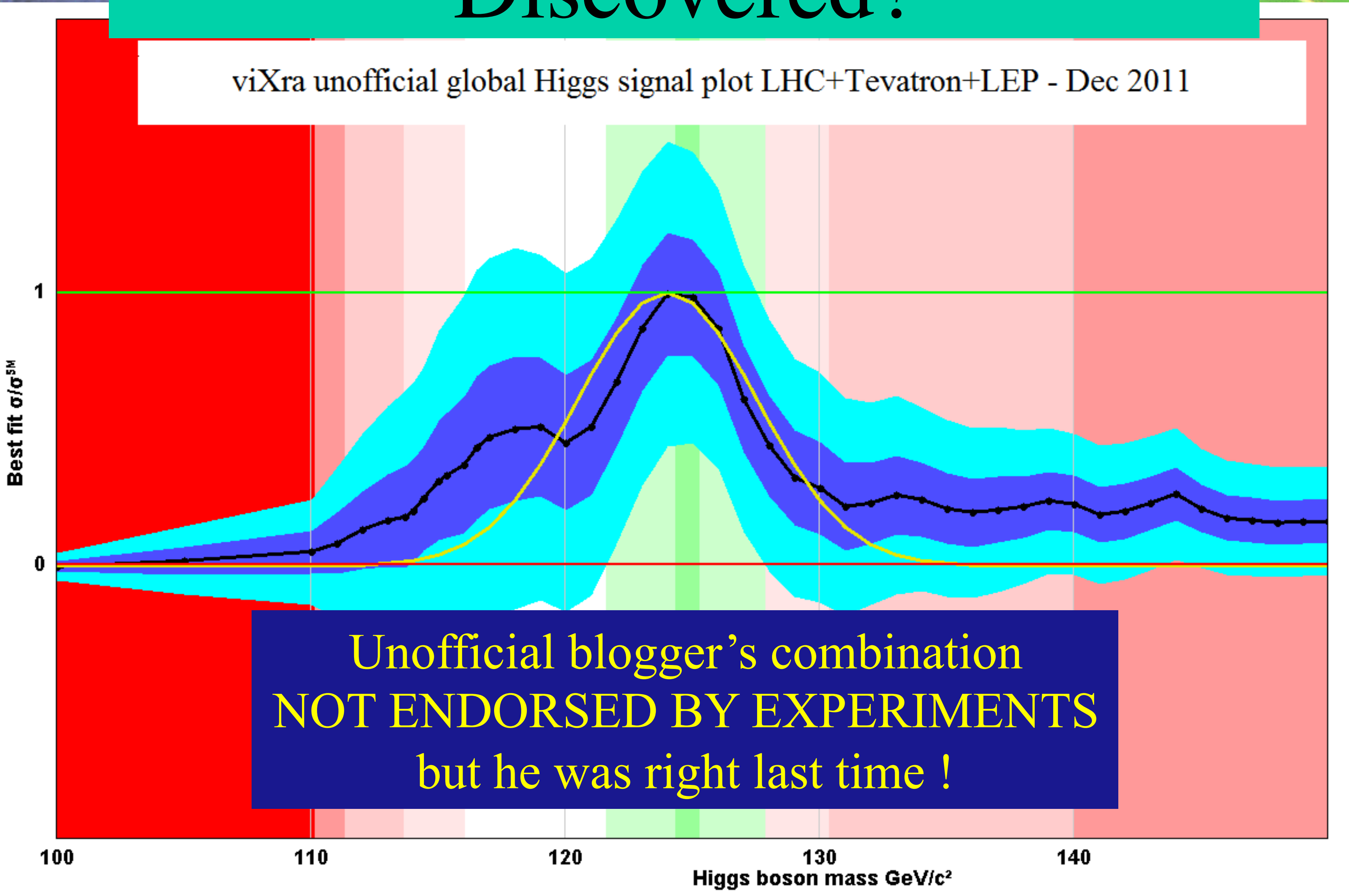


124 GeV



- Combined: 2.6σ

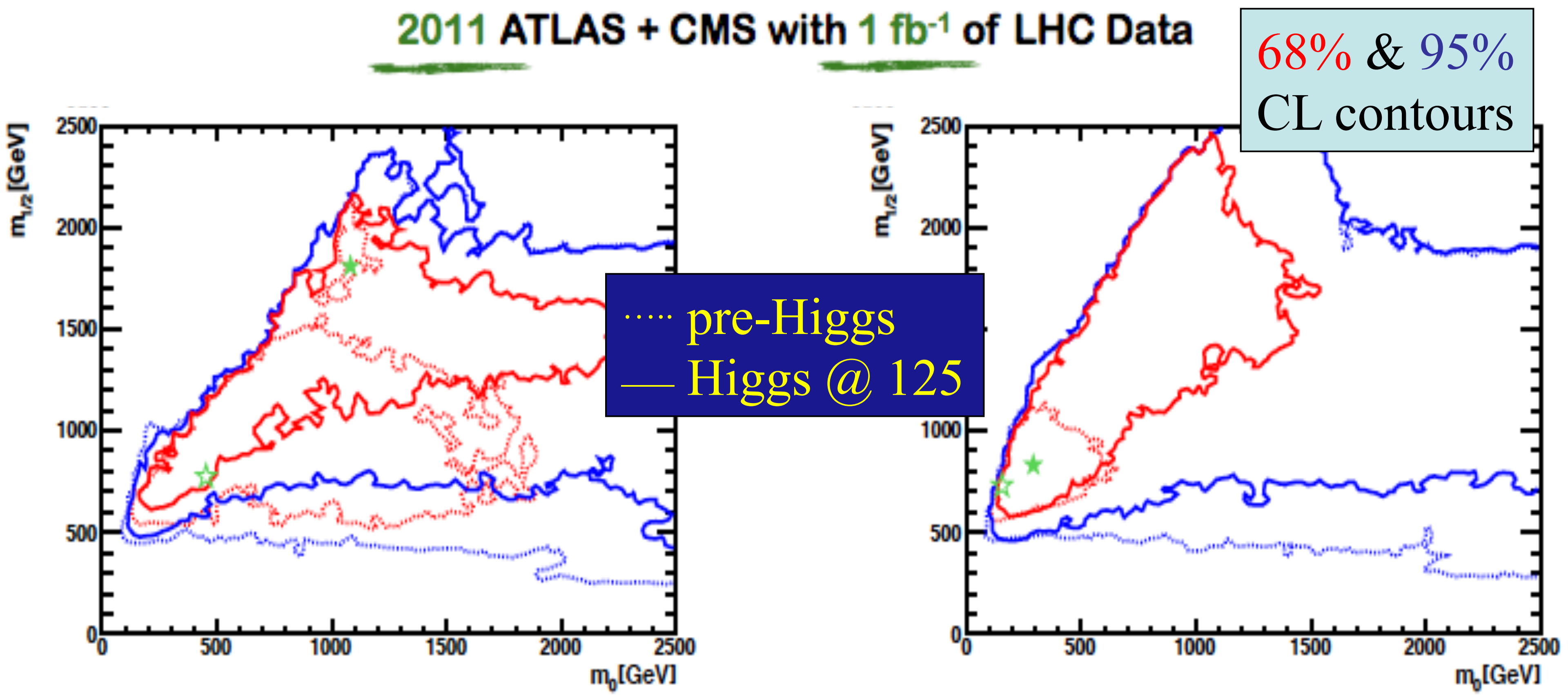
Has the Higgs Boson been Discovered?



Unofficial blogger's combination
NOT ENDORSED BY EXPERIMENTS
but he was right last time !

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data



CMSSM
60 million points sampled

NUHM1
70 million points sampled

Buchmueller, JE et al: arXiv:1112.3564

Red and blue curves represent $\Delta\chi^2$ from global minimum, located at ☆

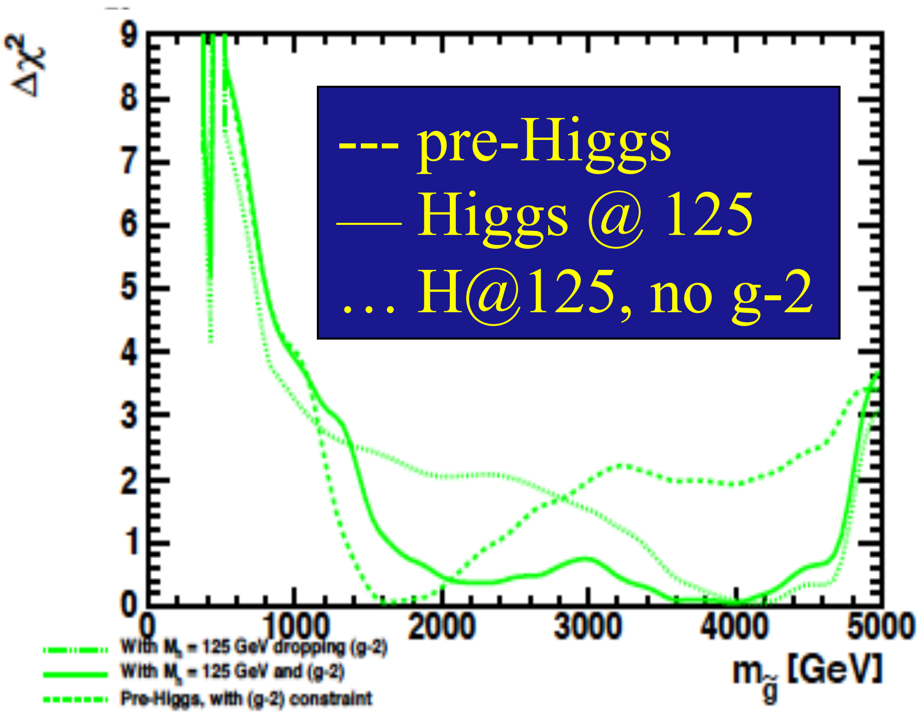
Preferred region "opens up" at cost of worsening global χ^2 value!

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data

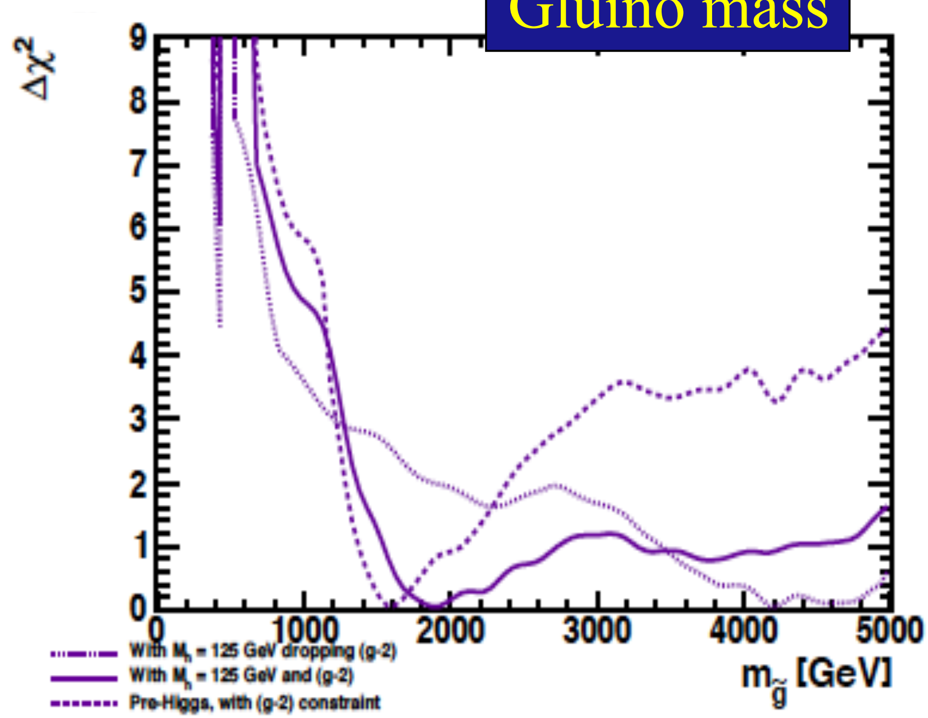
Gluino mass

--- pre-Higgs
— Higgs @ 125
… H@125, no g-2



CMSSM

60 million points sampled



NUHM1

70 million points sampled

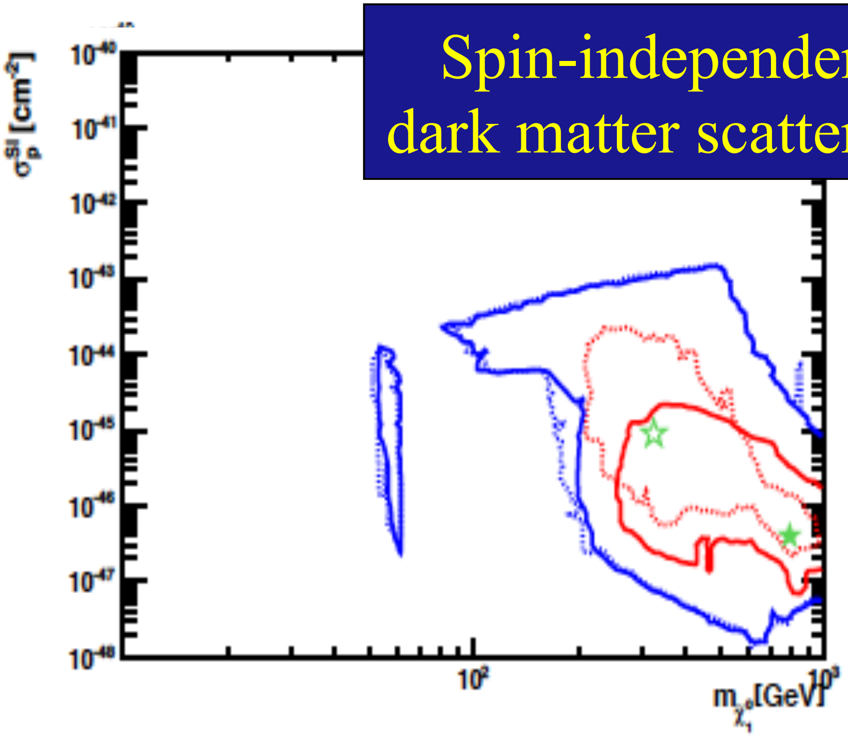
Buchmueller, JE et al: arXiv:1112.3564

Favoured values of gluino mass significantly above pre-LHC, > 2 TeV

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data

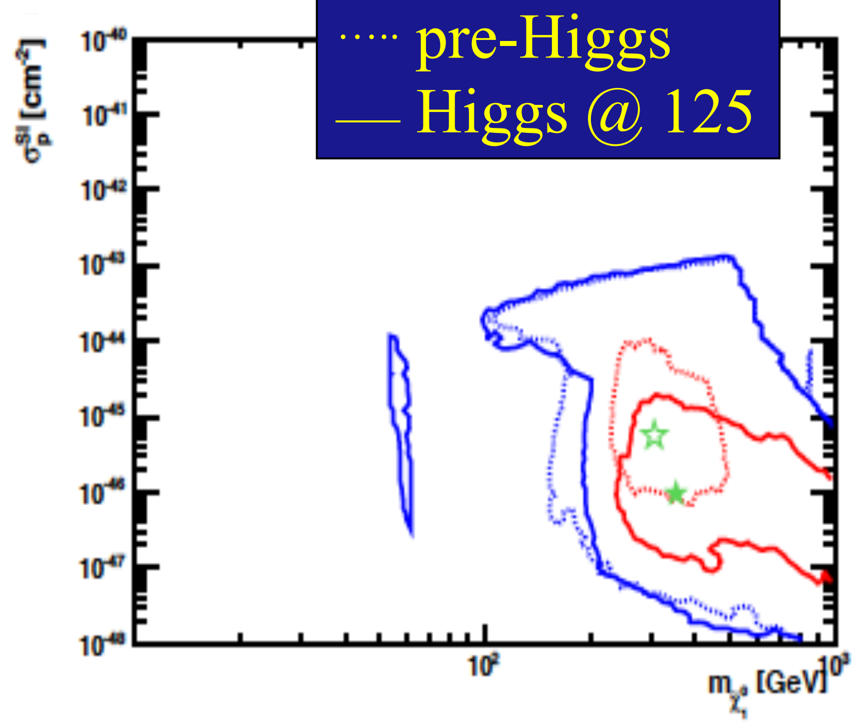
Spin-independent dark matter scattering



CMSSM

60 million points sampled

····· pre-Higgs
— Higgs @ 125



NUHM1

70 million points sampled

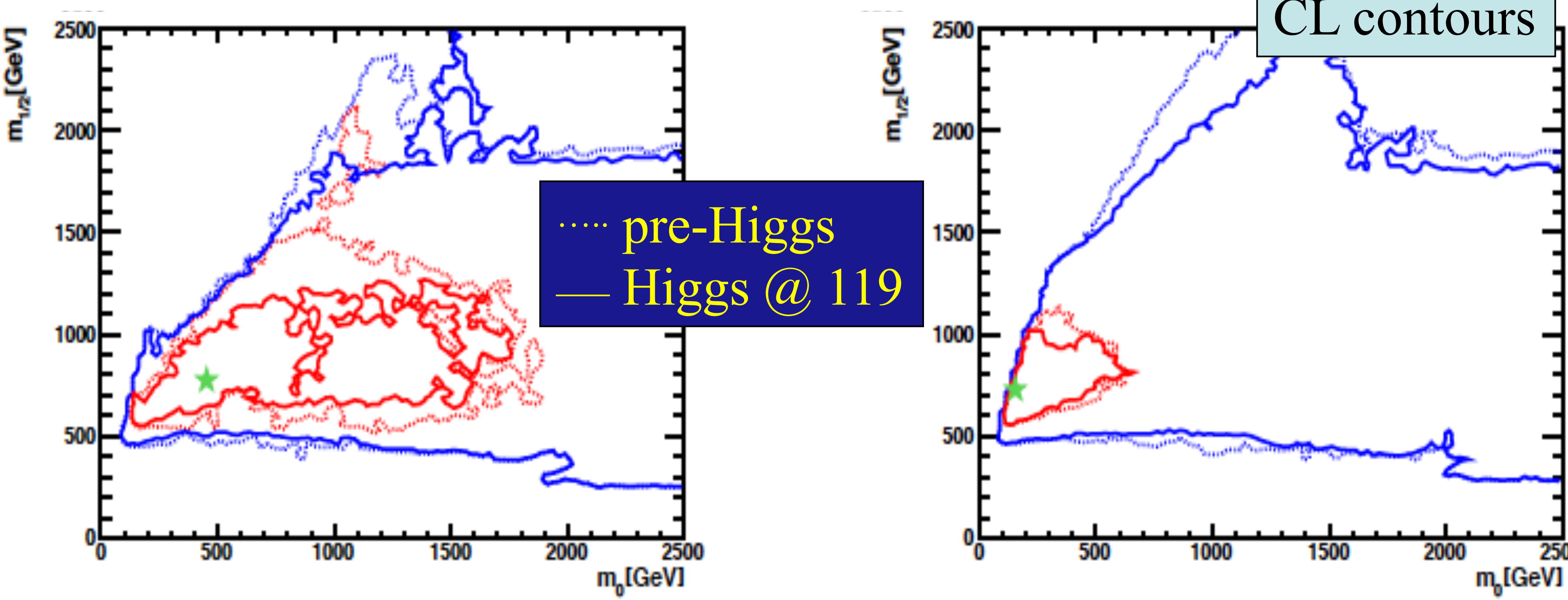
Buchmueller, JE et al: arXiv:1112.3564

Higgs @ 125 GeV reduces prospects for coming years ?

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data

68% & 95% CL contours



CMSSM

60 million points sampled

NUHM1

70 million points sampled

Buchmueller, JE et al: arXiv:1112.3564

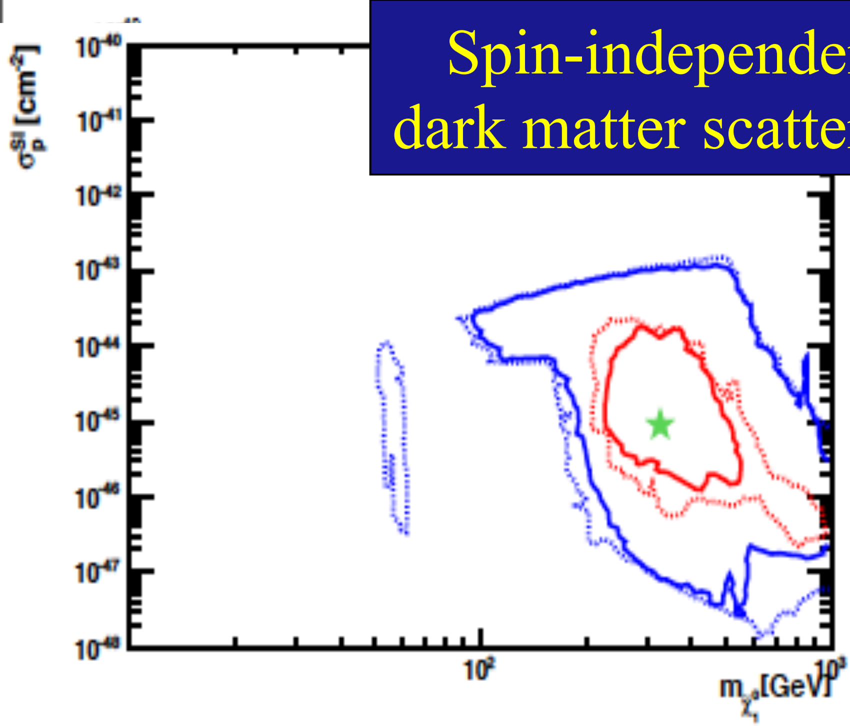
Higgs @ 119 GeV would enhance prospects for coming years ?

Post-LHC, Post-XENON100

masterCODE

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data

Spin-independent dark matter scattering

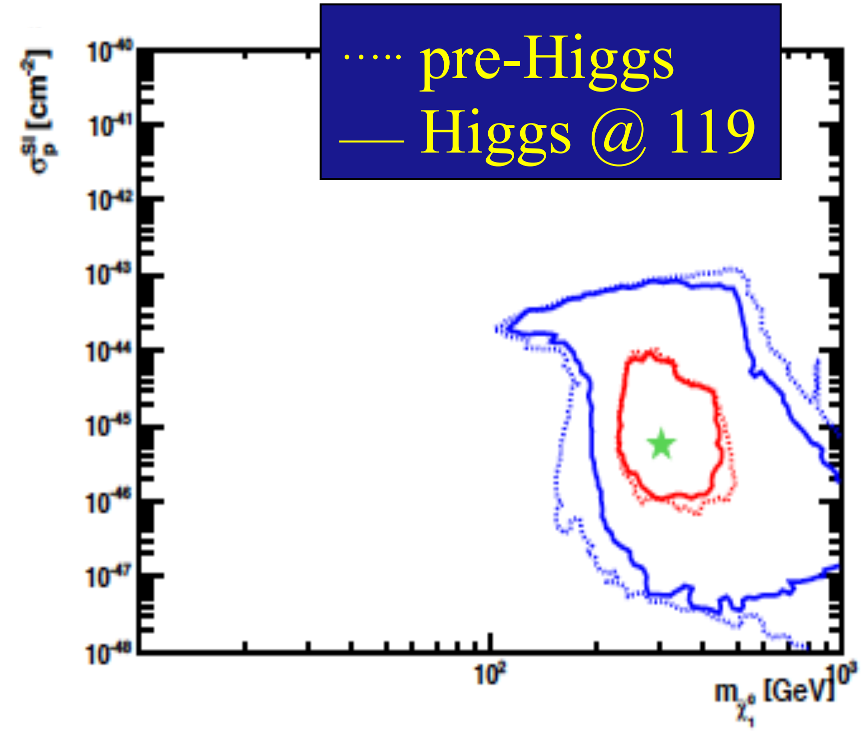


CMSSM

60 million points sampled

·.... pre-Higgs

— Higgs @ 119



NUHM1

70 million points sampled

Buchmueller, JE et al: arXiv:1112.3564

Significant impact on dark matter experiments:
Better prospects for coming years !

How to Create the Matter in the Universe?

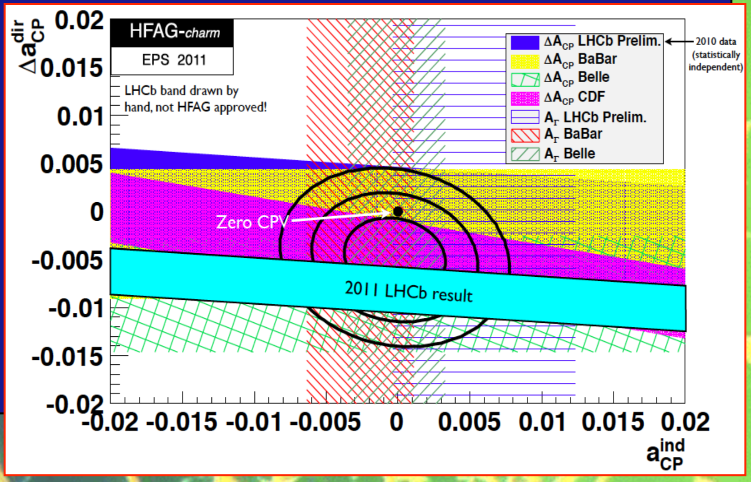
Sakharov

- Need a difference between matter and antimatter
  observed in the laboratory
- Need interactions able to create matter
  present in unified theories
  not yet seen by experiment
- Must break thermal equilibrium
  Possible in the decays of heavy particles

Will we be able to calculate using laboratory data?

Observations of Matter-Antimatter Diffferences

- Observed in strange particle decays in 1964
- Also measured in decays of b quarks
- Described within the Standard Model
- **Insufficient to explain matter in Universe**
- Matter-antimatter asymmetry now seen by LHCb in charm decays @ 3.5 σ level
- 10 × larger than SM estimate?
- **A new frontier opened up**

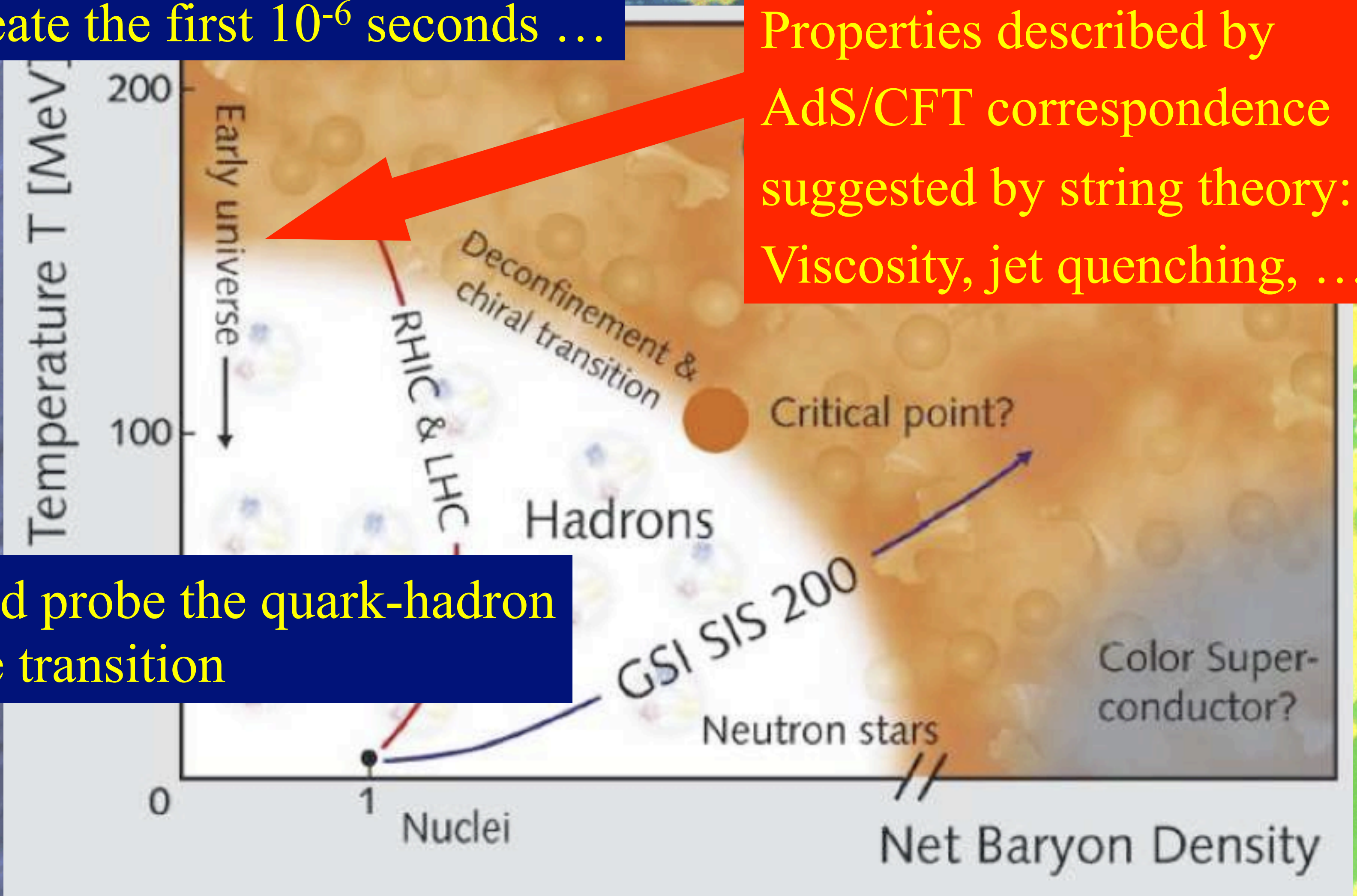


Collide heavy nuclei at high energies to create …

Hot and Dense Hadronic Matter

Recreate the first 10^{-6} seconds …

Properties described by AdS/CFT correspondence suggested by string theory: Viscosity, jet quenching, …?

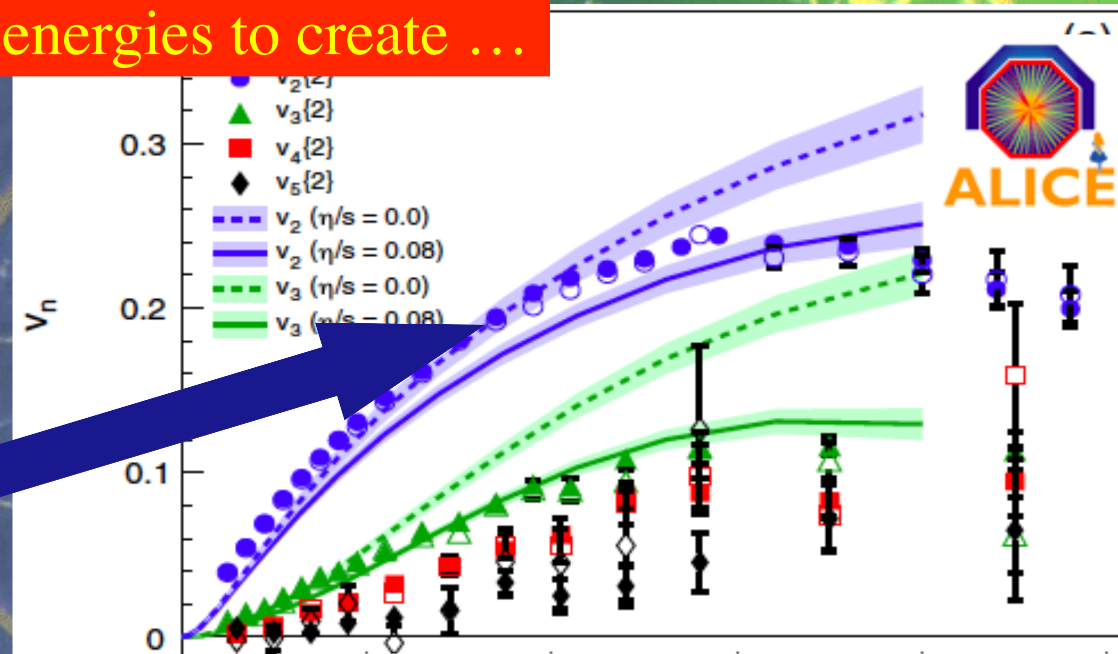


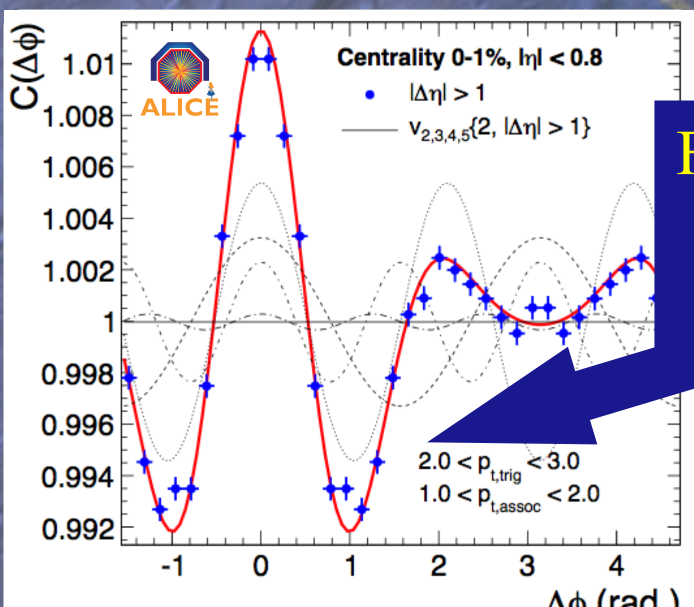
… and probe the quark-hadron phase transition

Collide heavy nuclei at high energies to create …

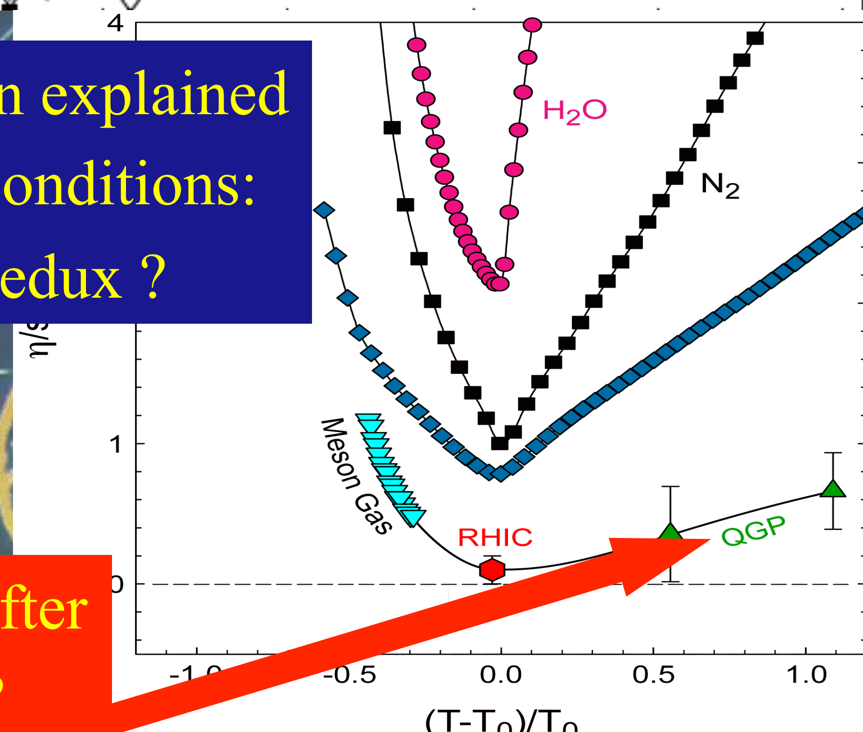
An Almost Perfect Fluid

Anisotropic flow with very low viscosity





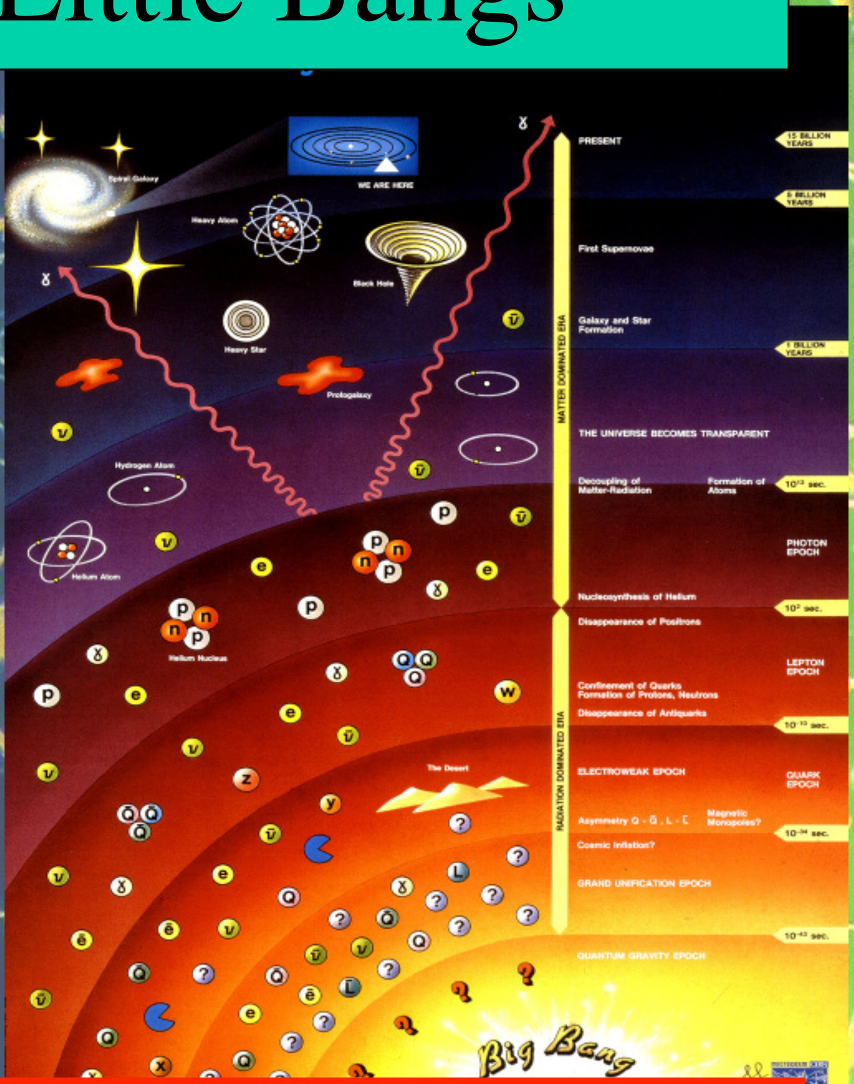
Flow pattern explained by initial conditions: CMB redux ?



Challenge: measure viscosity before/after minimum: Hard probes for high T?

Big Bang ↔ Little Bangs

- The content of the Universe
  - Dark energy
  - Dark matter
  - Origin of matter
- Particle experiments
  - Higgs boson
  - Supersymmetry
  - Matter-antimattter



Learn particle physics from the Universe
Use particle physics to understand the Universe