Life After Higgs

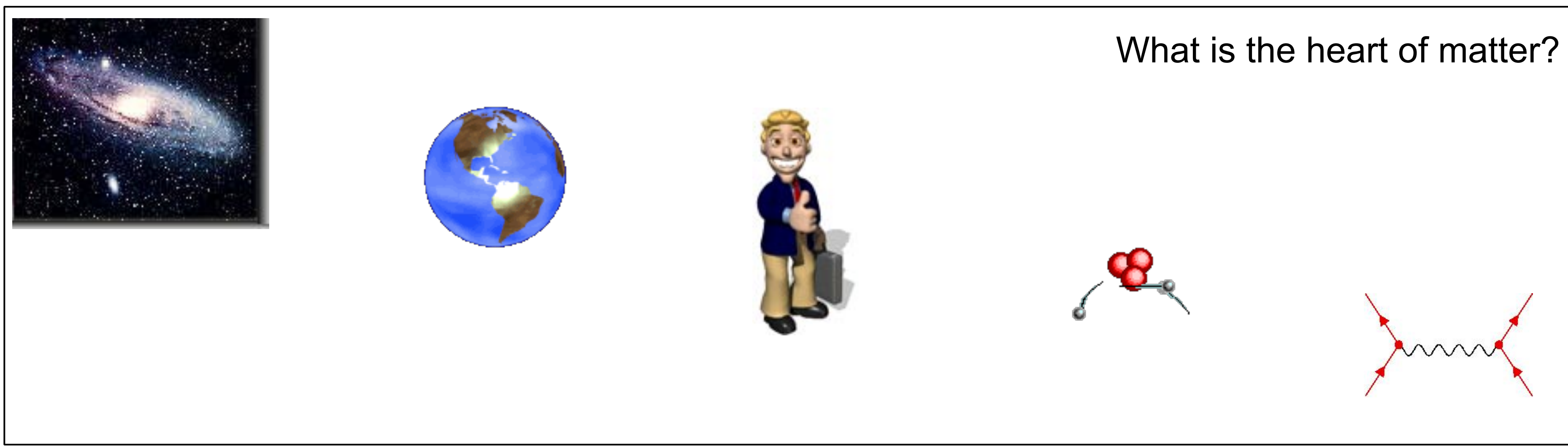
Tobias Golling, Yale

Colloquium, University of Geneva, Nov 27 2013


The Higgs Boson

Objective of Particle Physics

- Is as old as mankind:
  - Where do we come from?
  - What are we?
  - Where are we going?
- In line with Galileo, Newton, Einstein

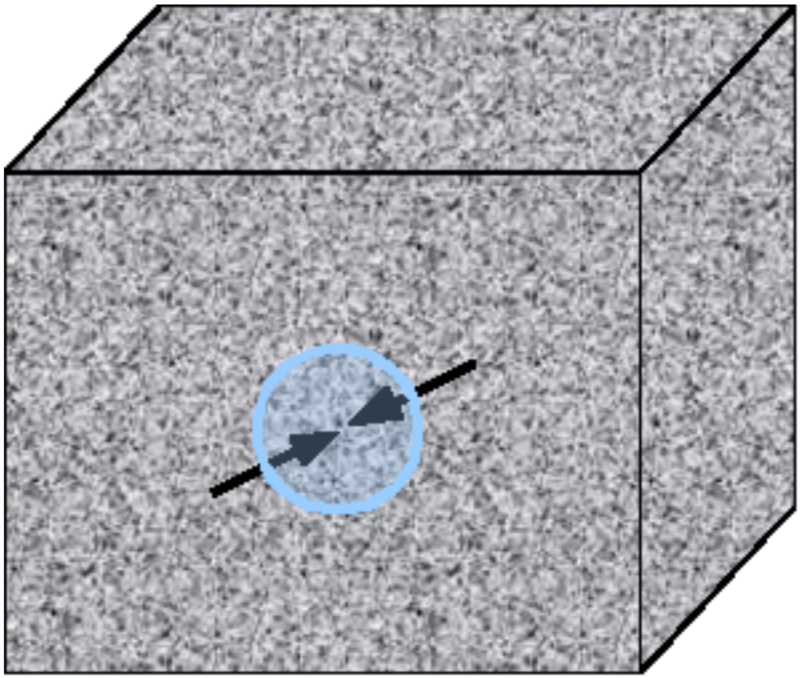


Fundamental structures & laws in nature

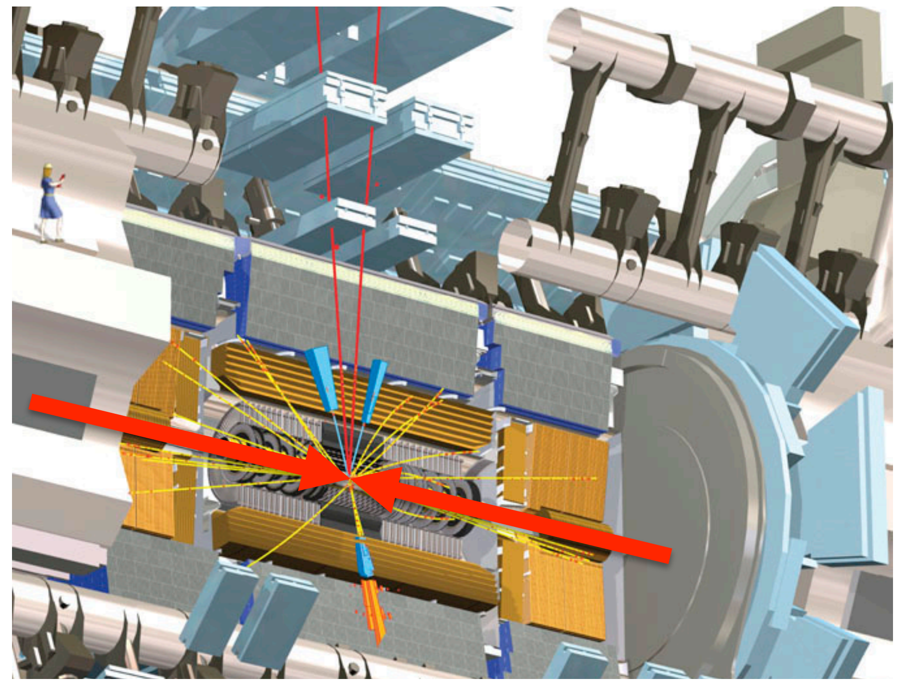
From the largest dimensions in the universe…

…to the smallest dimensions in microcosm

“Big Bang” in the Laboratory

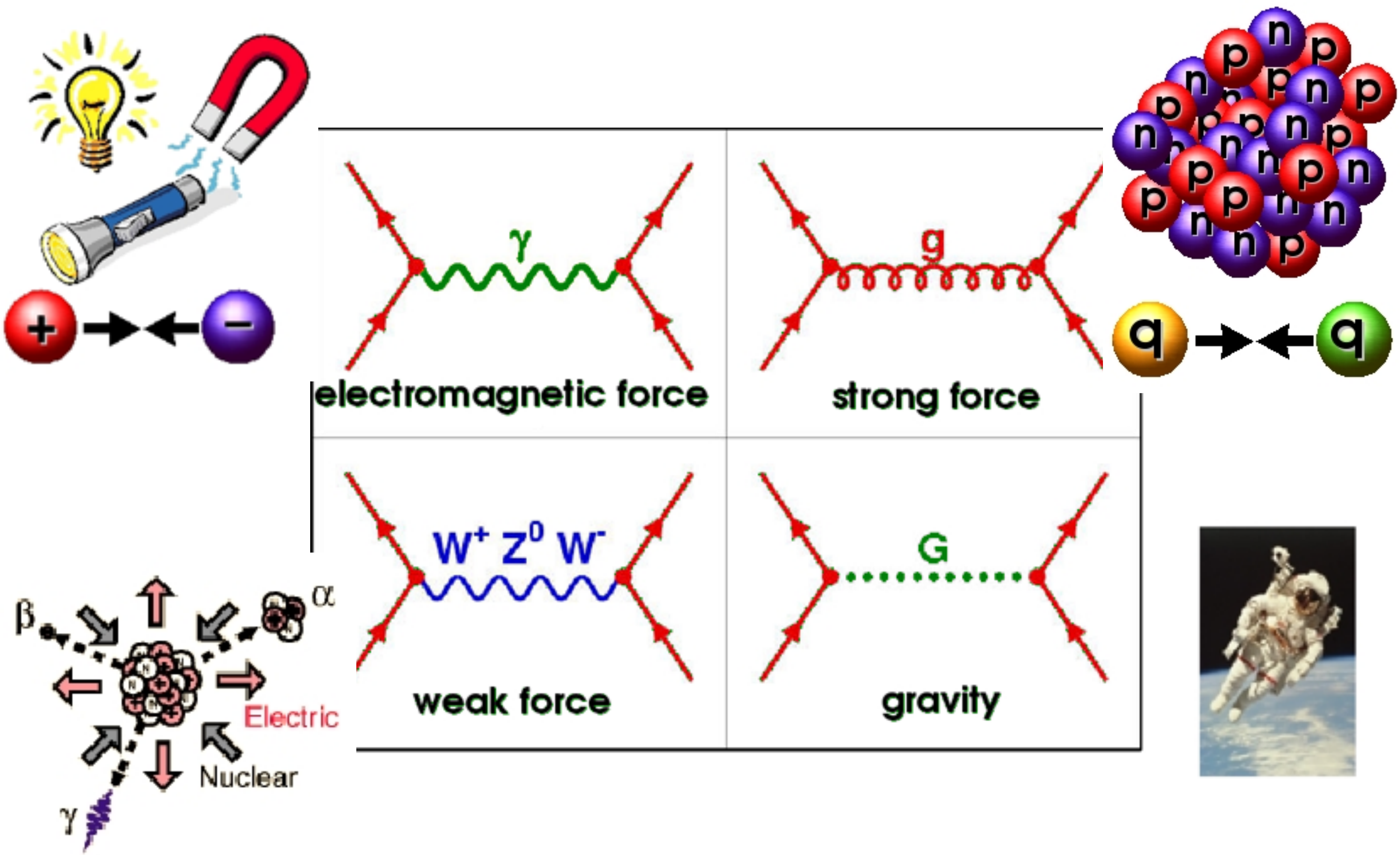


<u>A fraction of a second after the Big Bang:</u> All particles have high energy (temperature) and collide uncontrolled

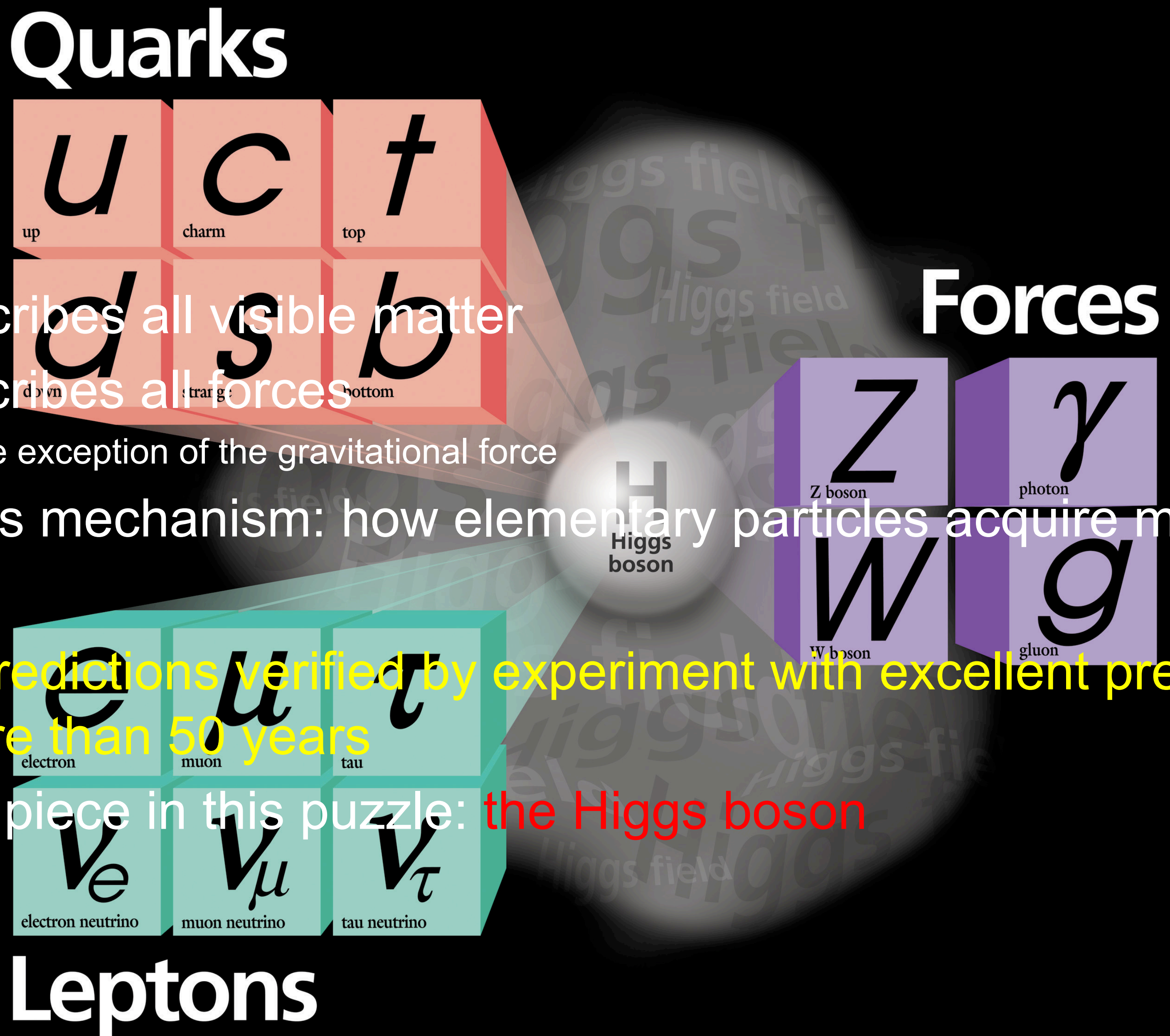


<u>At the LHC:</u> Select and control individual collisions (we call them events) and record them

Four Fundamental Interactions



The Standard Model of Particle Physics

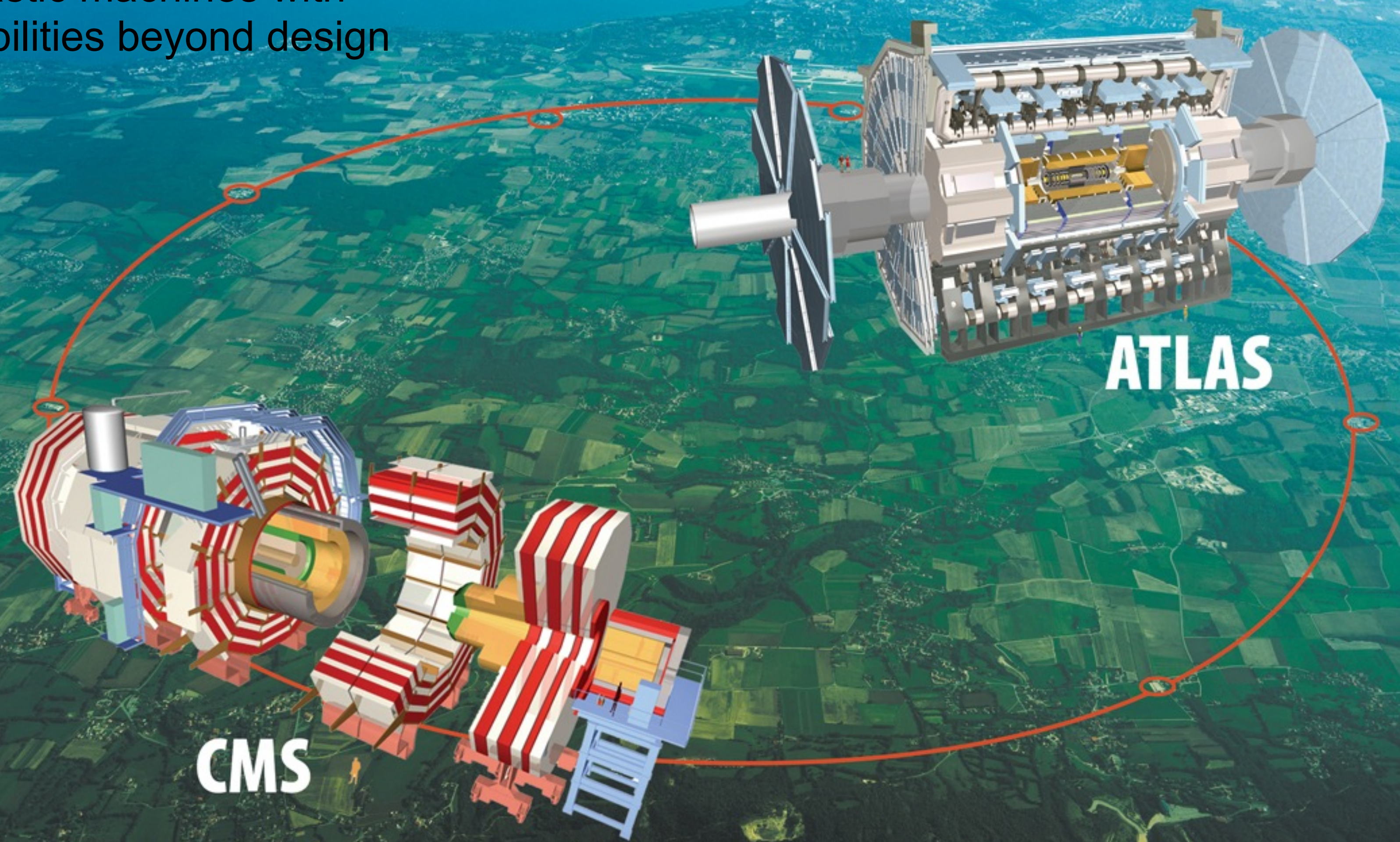


- ❑ Describes all visible matter
- ❑ Describes all forces
  with the exception of the gravitational force
- ❑ Higgs mechanism: how elementary particles acquire mass

- ❑ All predictions verified by experiment with excellent precision for more than 50 years
- ❑ Last piece in this puzzle: the Higgs boson

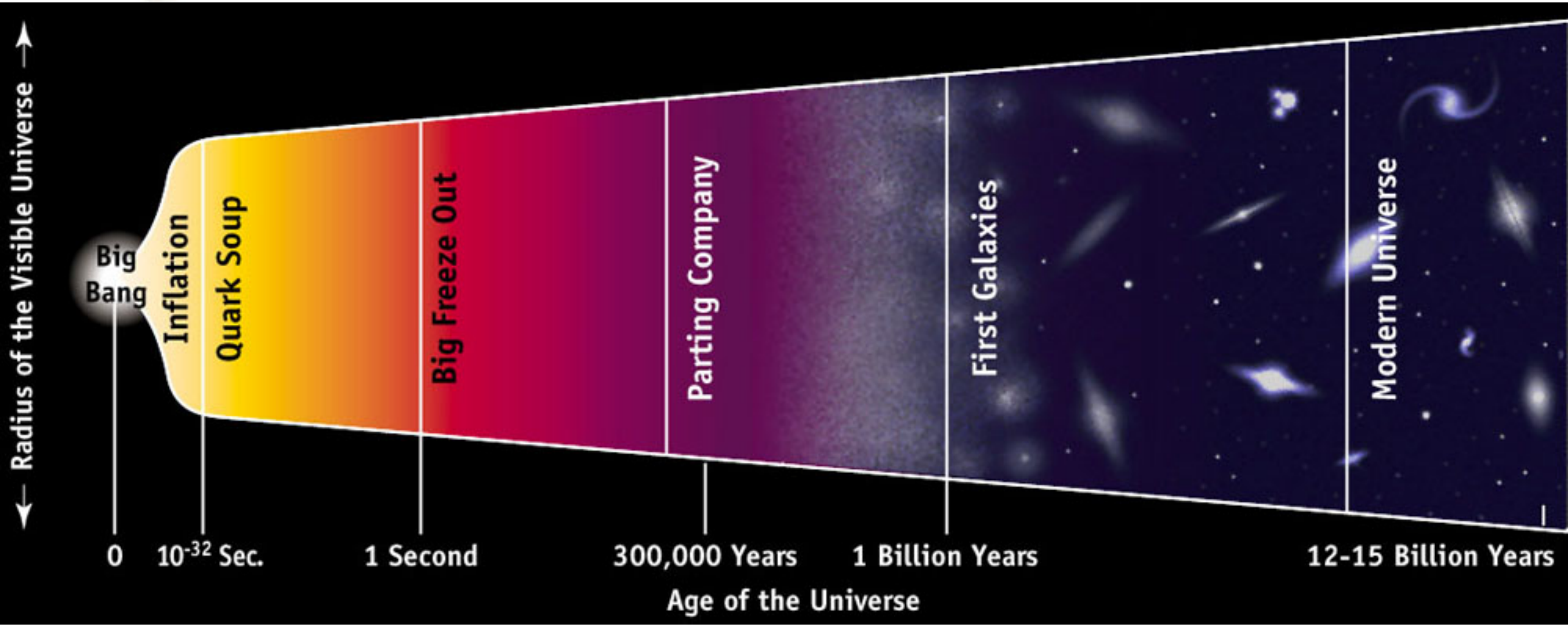
The Discovery Tools: LHC & ATLAS

Fantastic machines with
capabilities beyond design

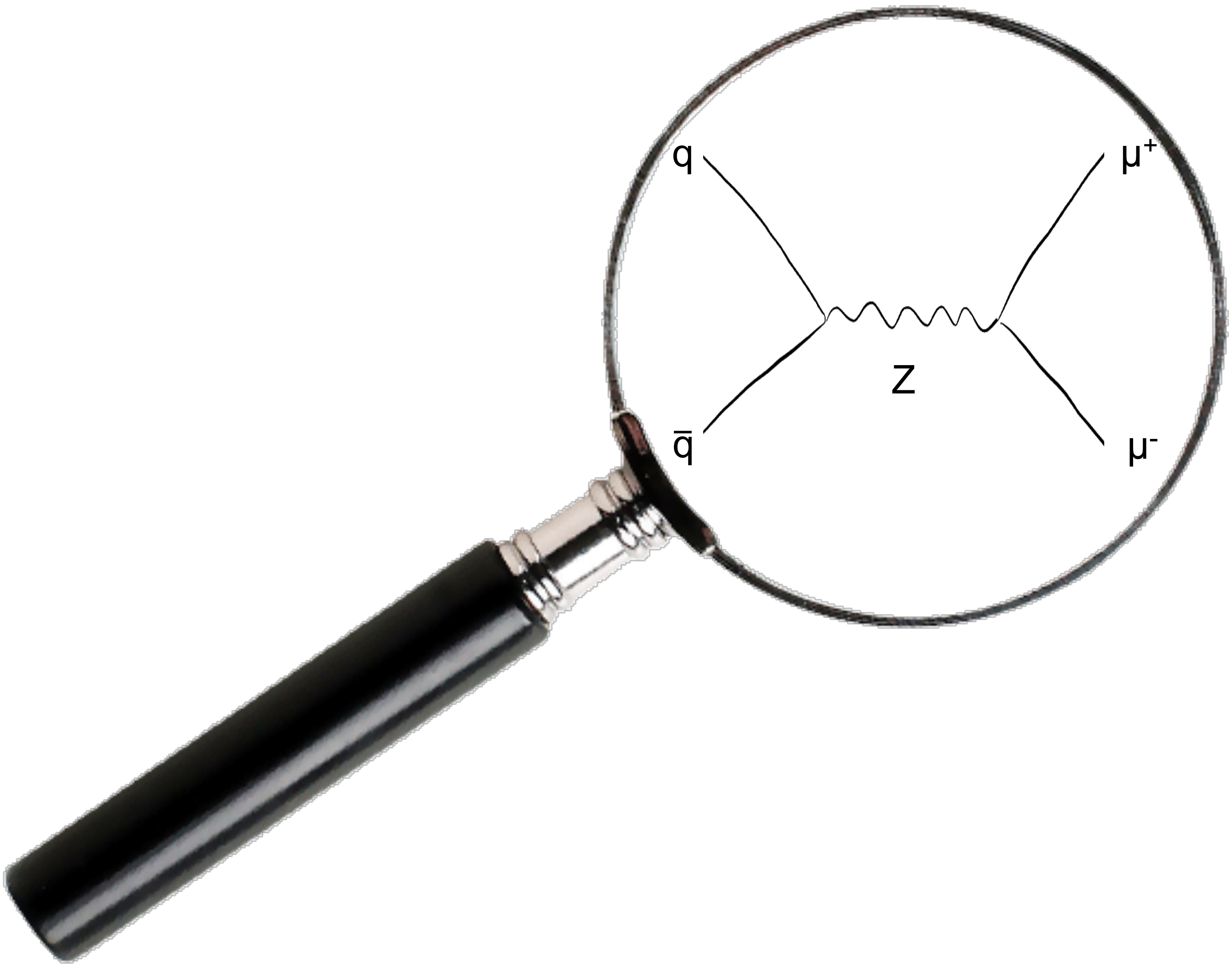



The LHC

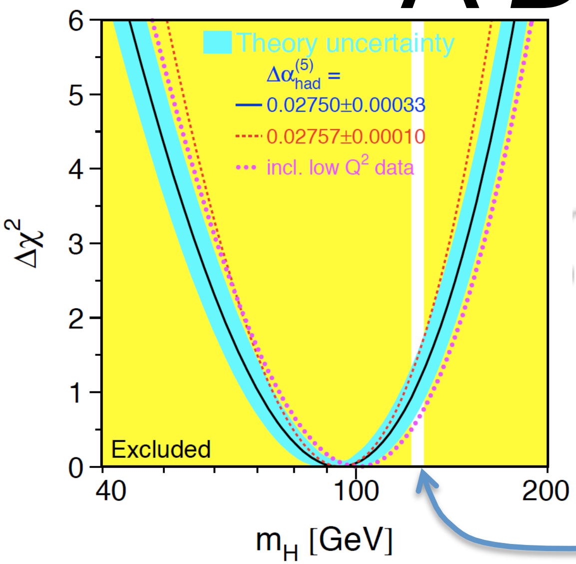
A Time Machine



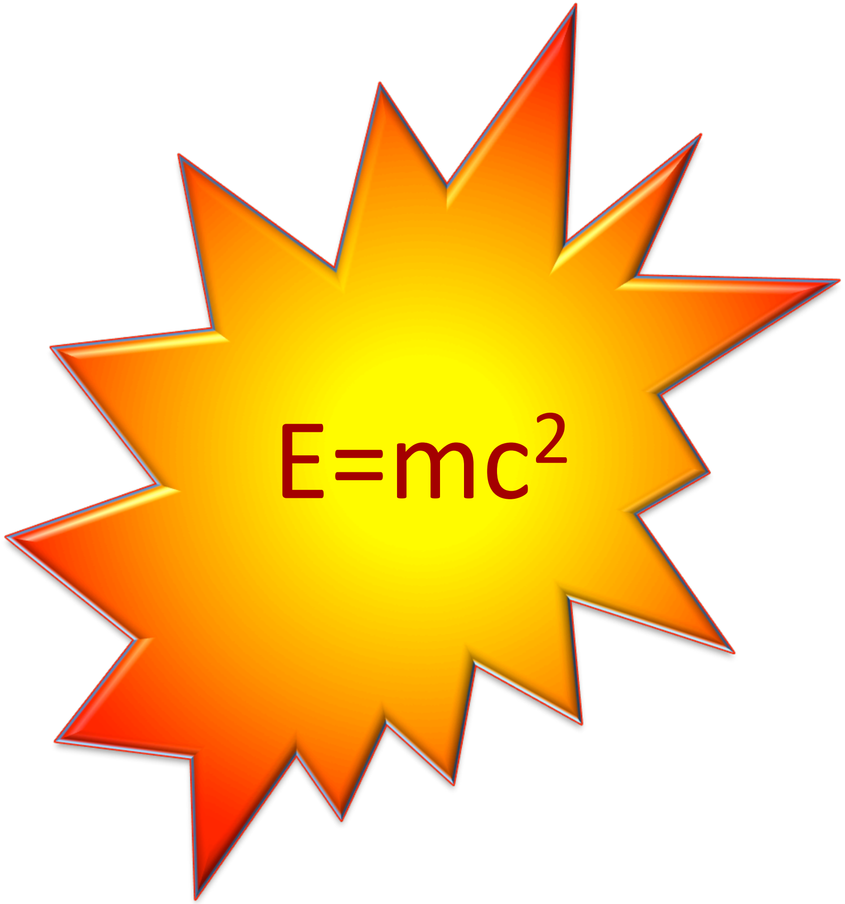
A Magnifying Glass

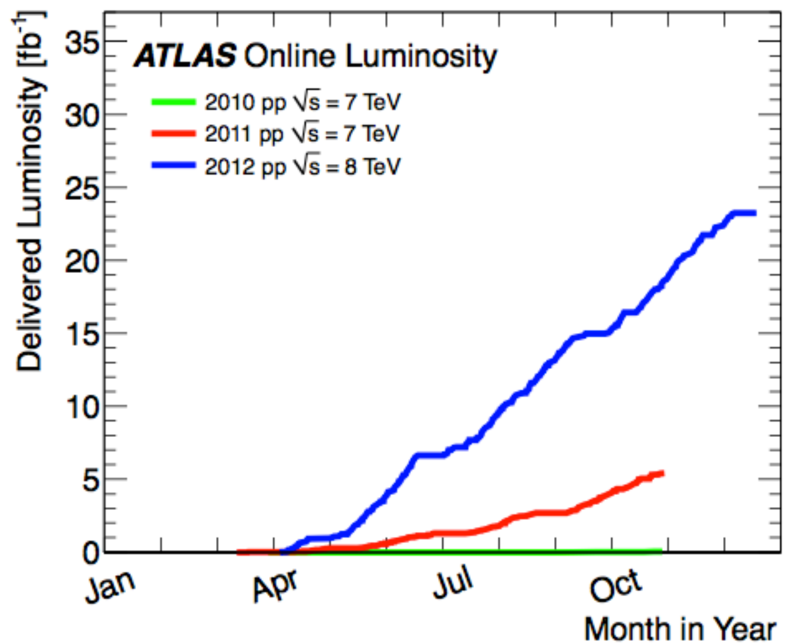


A *Discovery Machine*



LHC – Two Important Parameters





Energy √s

Luminosity L

ATLAS

- A camera with a 100 million pixels
- Shutter speed of 40 million times per second – operating ~24/7
- Sophisticated filtering to keep only 0.001% of the coolest pics!

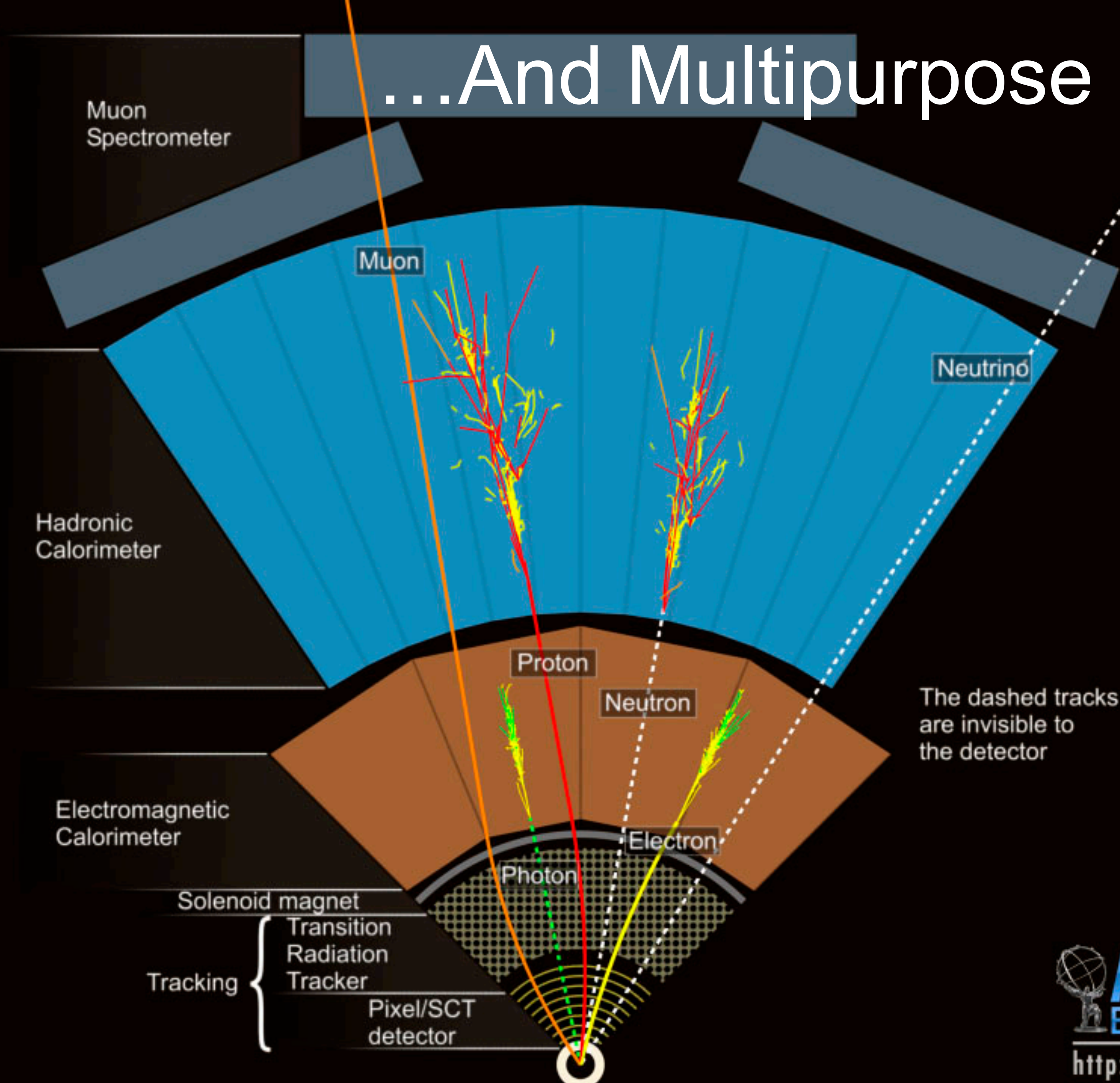
1 observed Higgs event in a trillion (10^{12}) pp collisons

Detectors are Huge…

…Heavy…

CMS is 30% heavier than the Eiffel tower

…And Multipurpose



- Leptons
  - e, μ, τ
- Quarks = jets
  - b ,c ,light jets
- Top quark
  - t →W + b

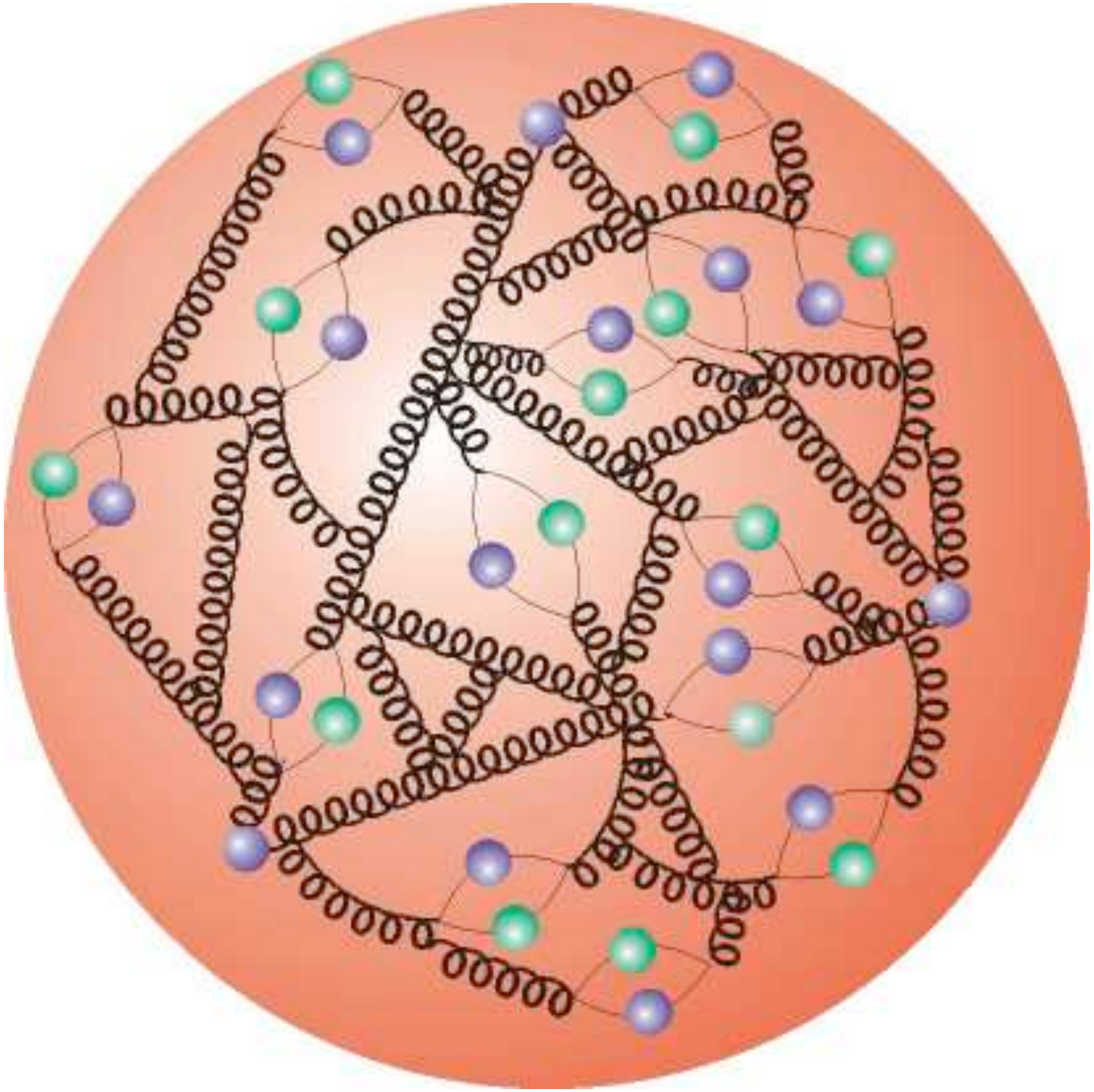
- Photon
- Gluon = jet
- W & Z bosons
- Higgs boson

- Neutrinos = Missing momentum

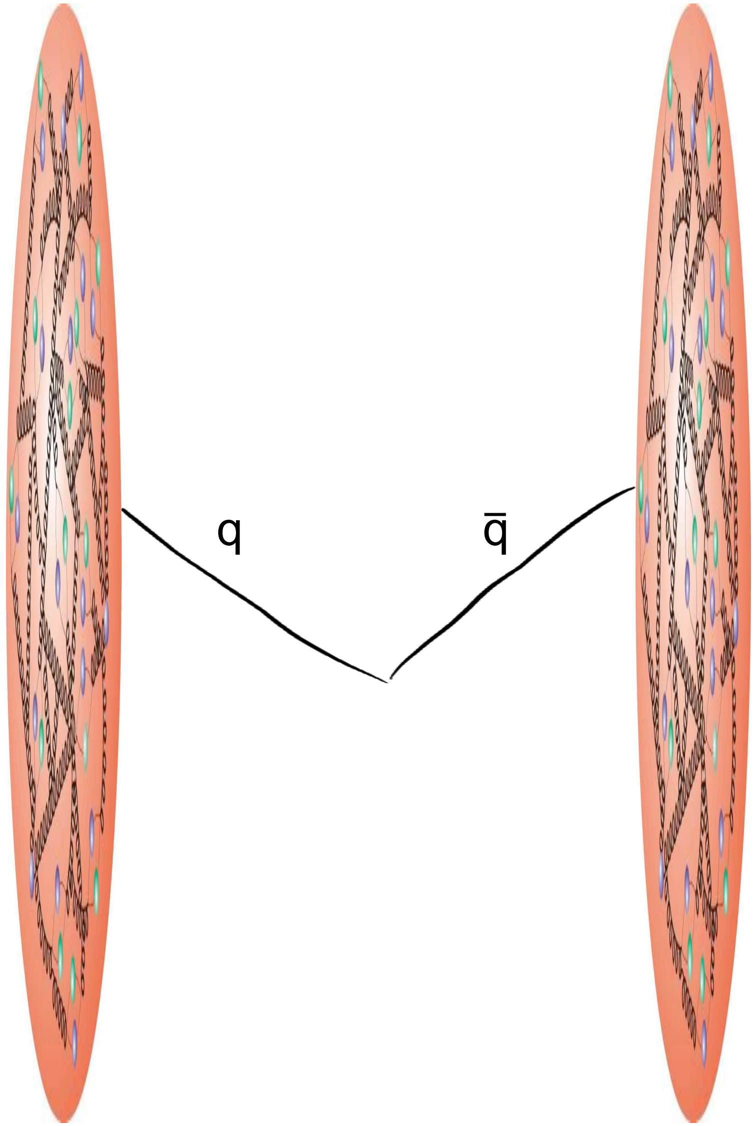
- New Physics ?

ATLAS EXPERIMENT
http://atlas.ch

The “Ugly” Truth about the Proton

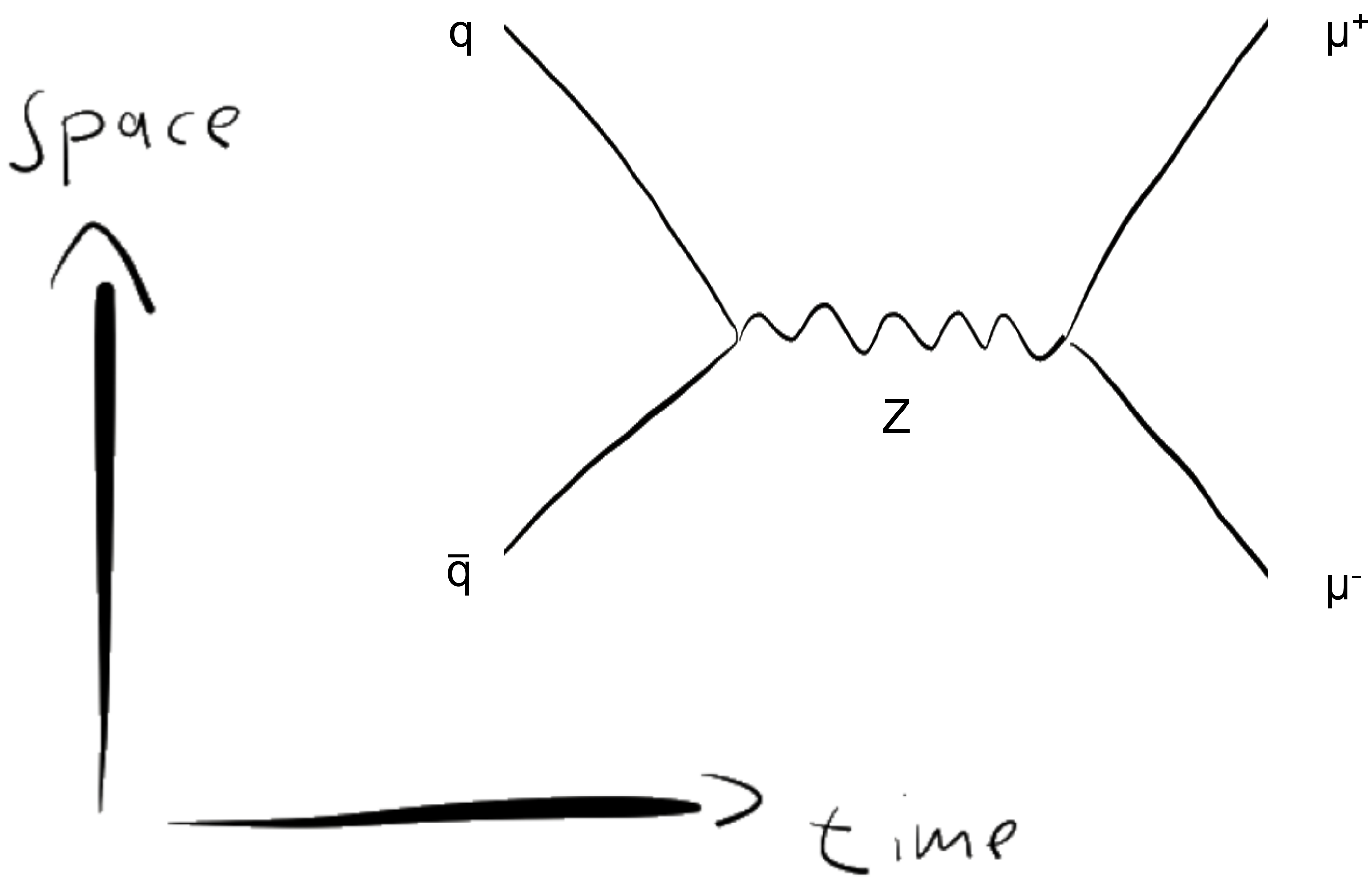


How We Imagine a pp Collision

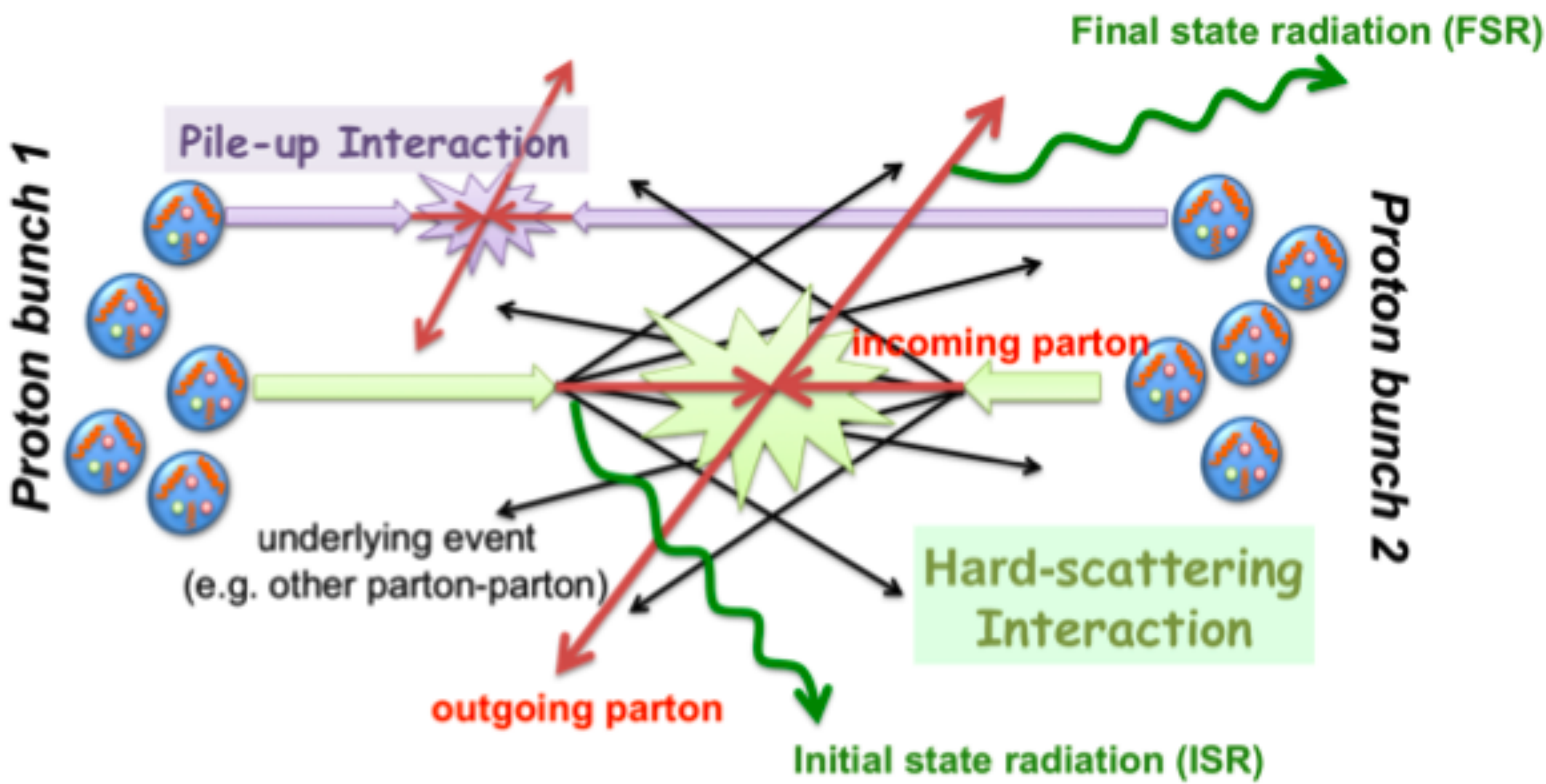


Feynman Diagram

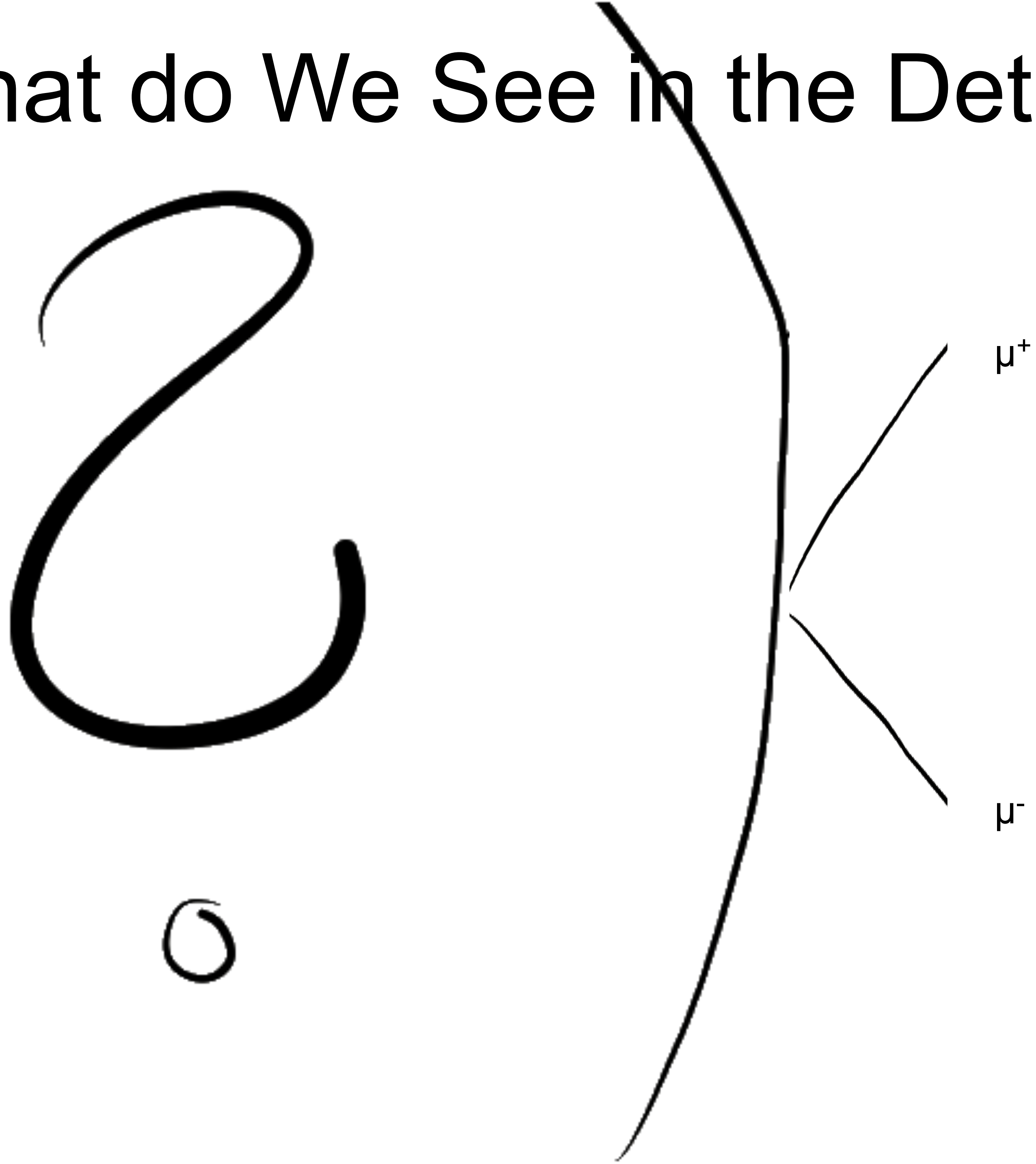
"collision event"



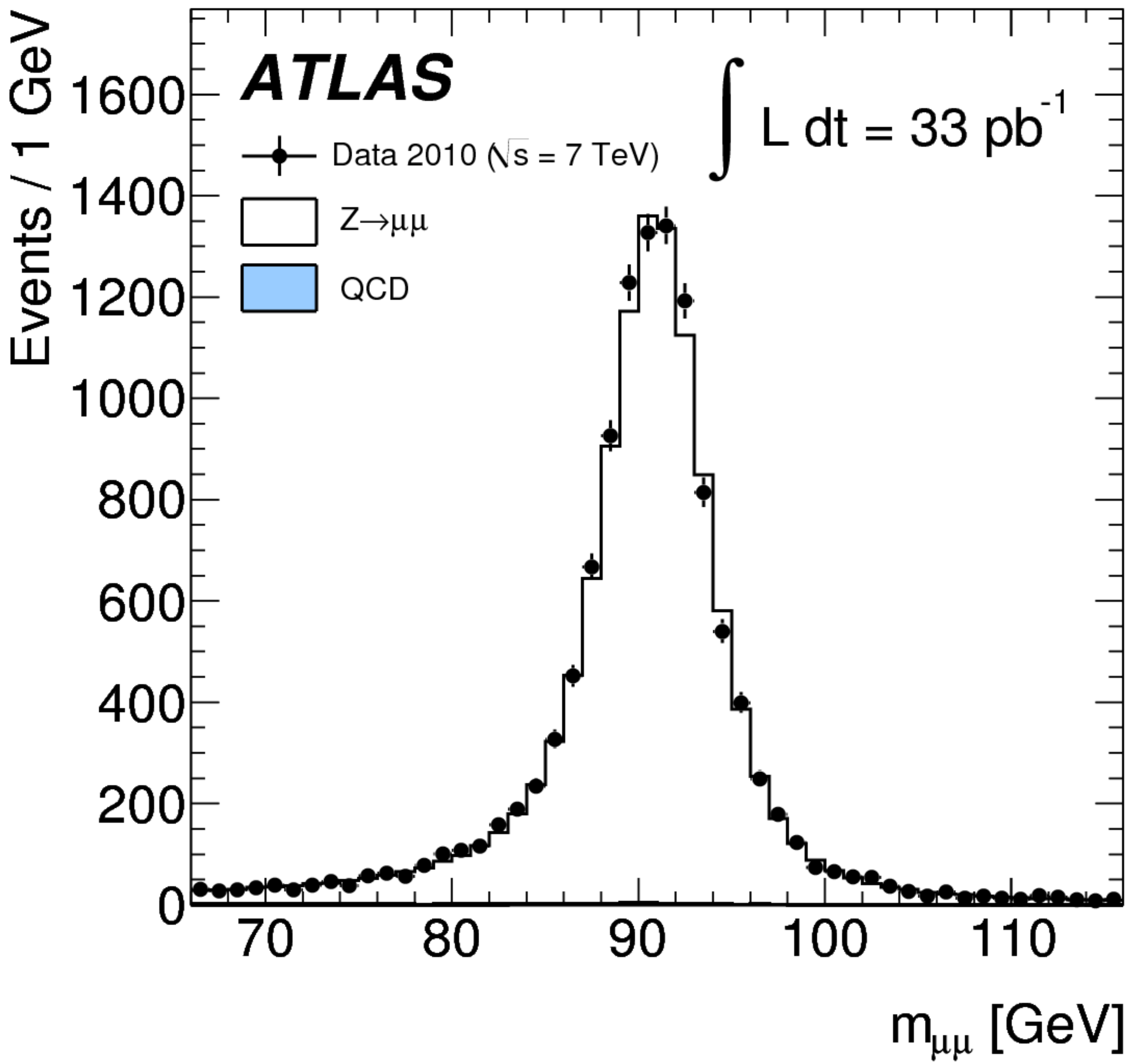
Real Life is More Complex…

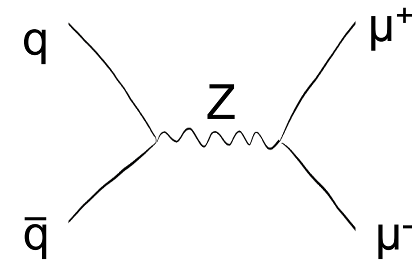


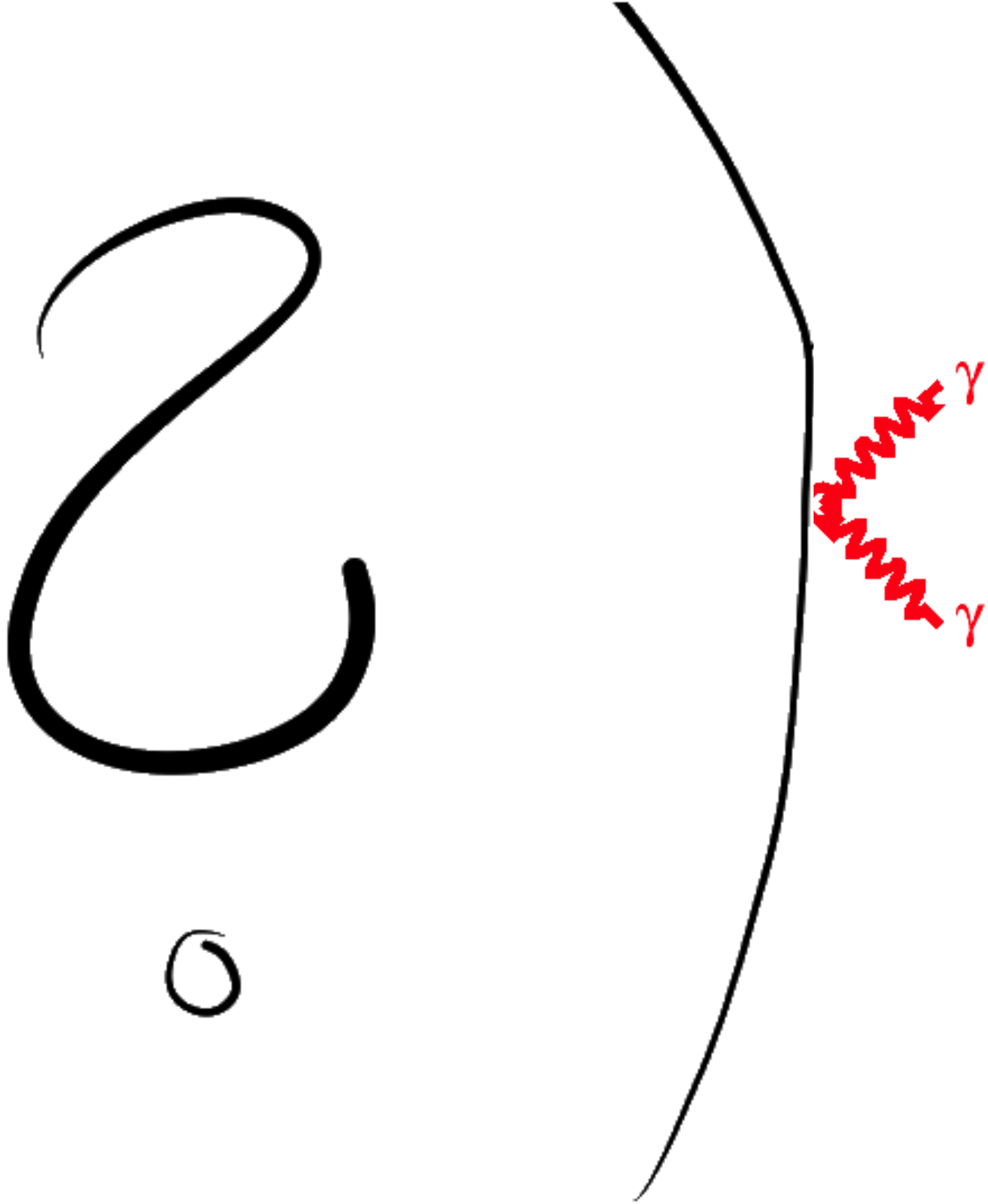
What do We See in the Detector?

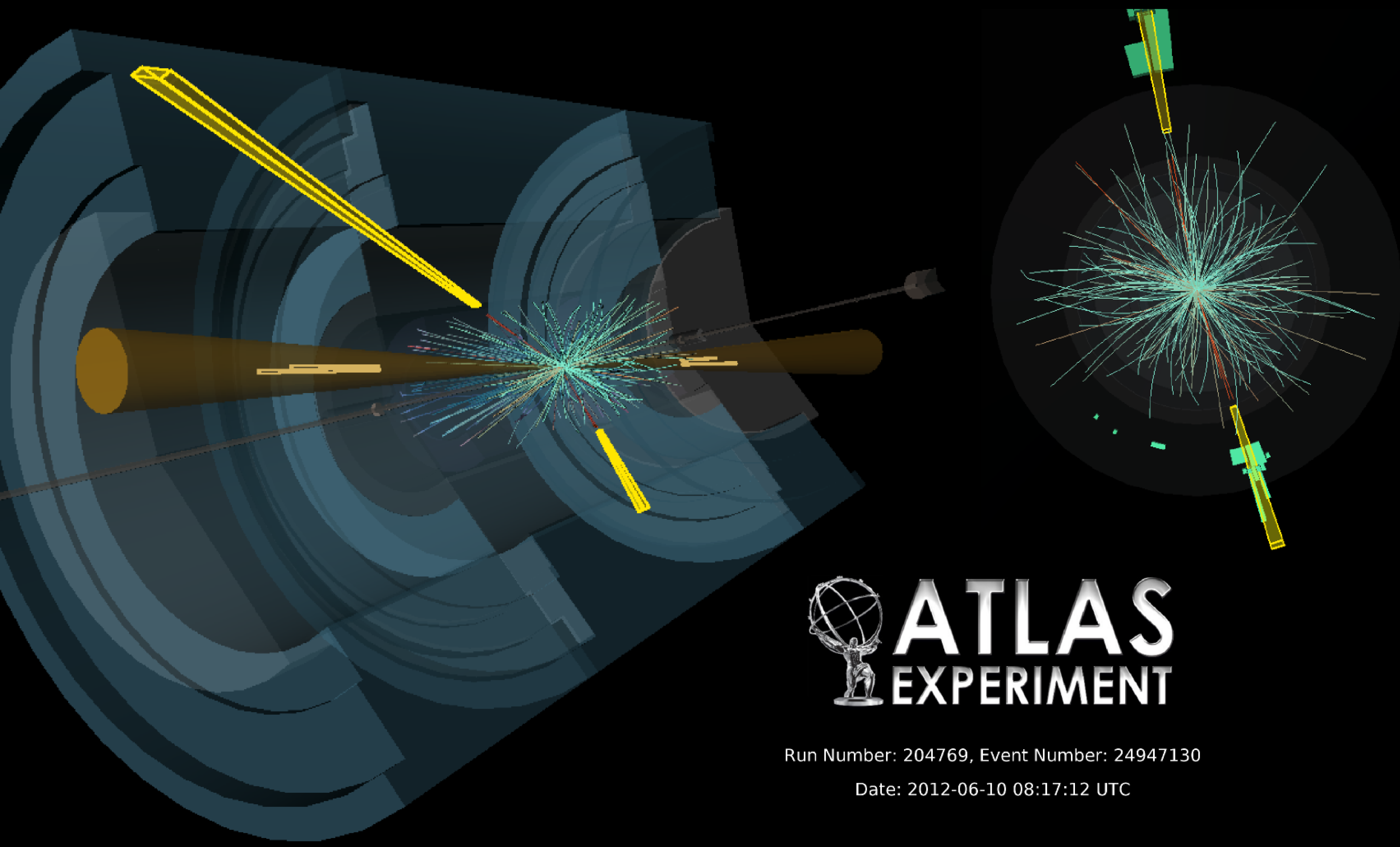


Z Mass Hypothesis

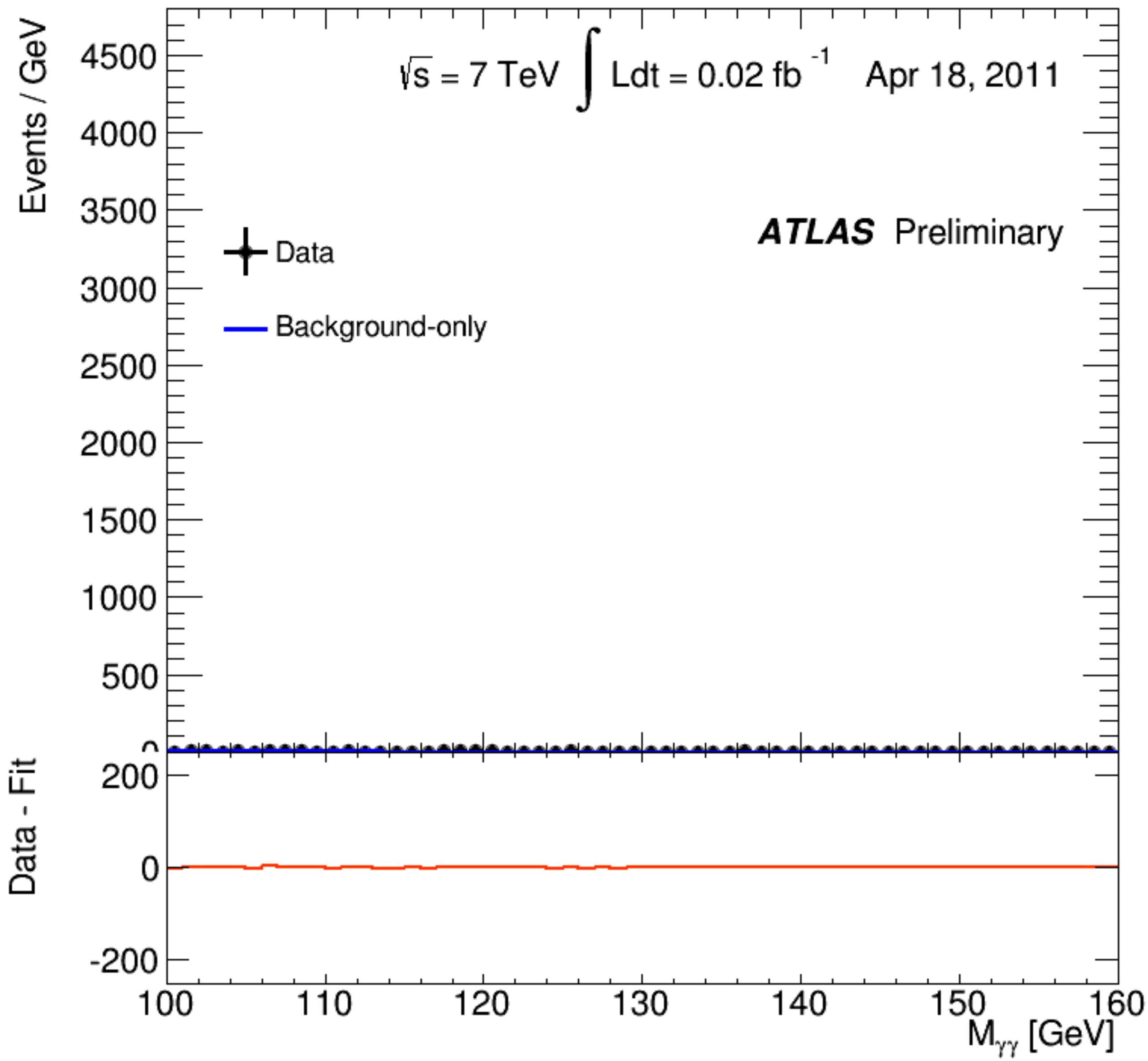




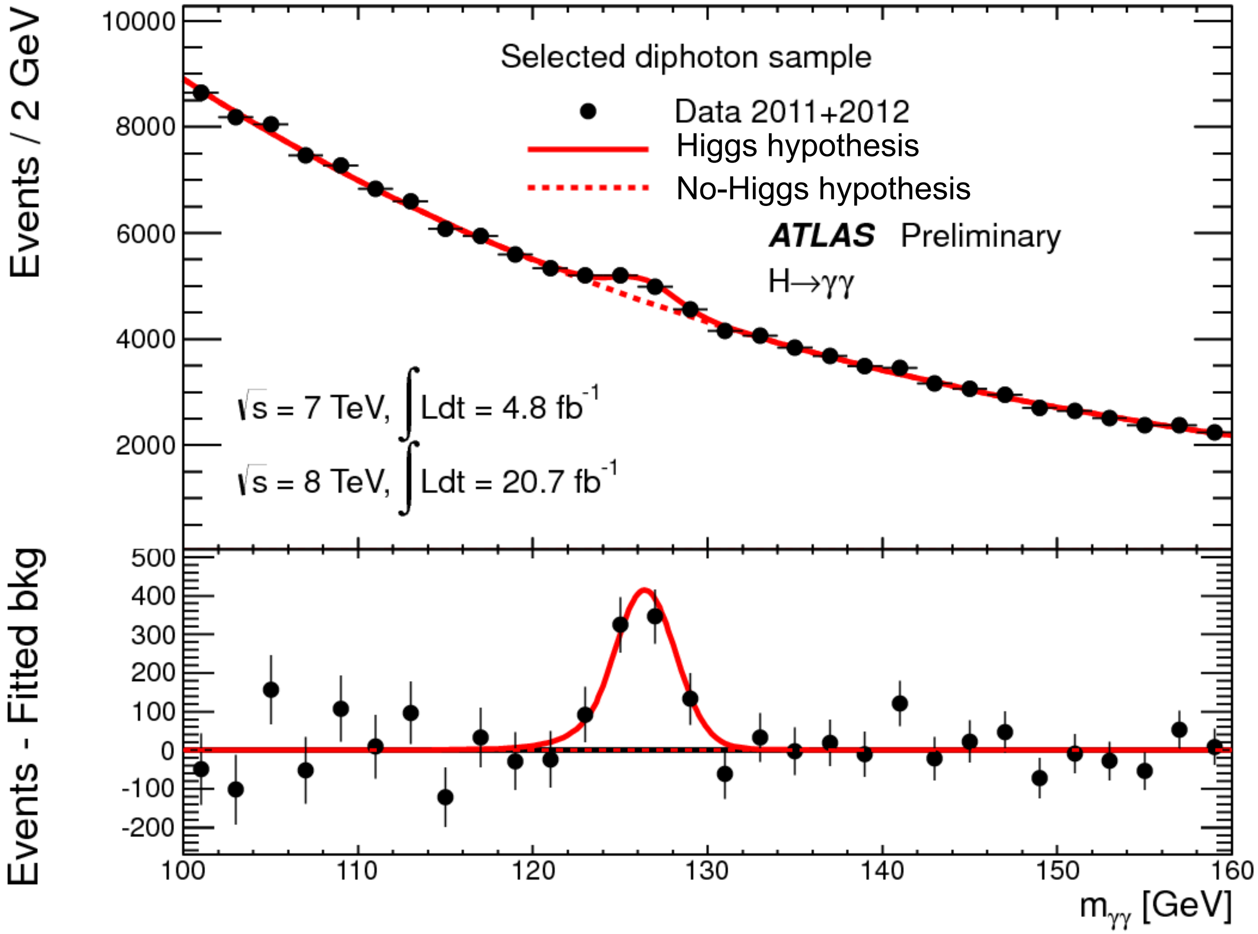

γ
γ


ATLAS
EXPERIMENT
Run Number: 204769, Event Number: 24947130
Date: 2012-06-10 08:17:12 UTC

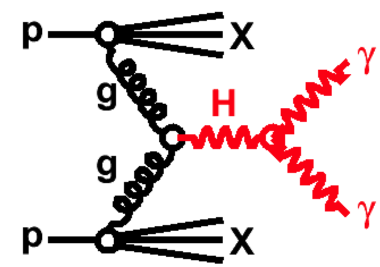
The Birth of a Particle



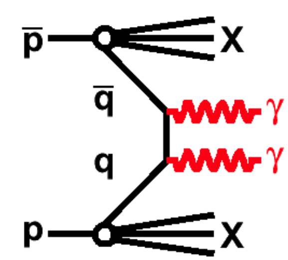
The Higgs Boson!



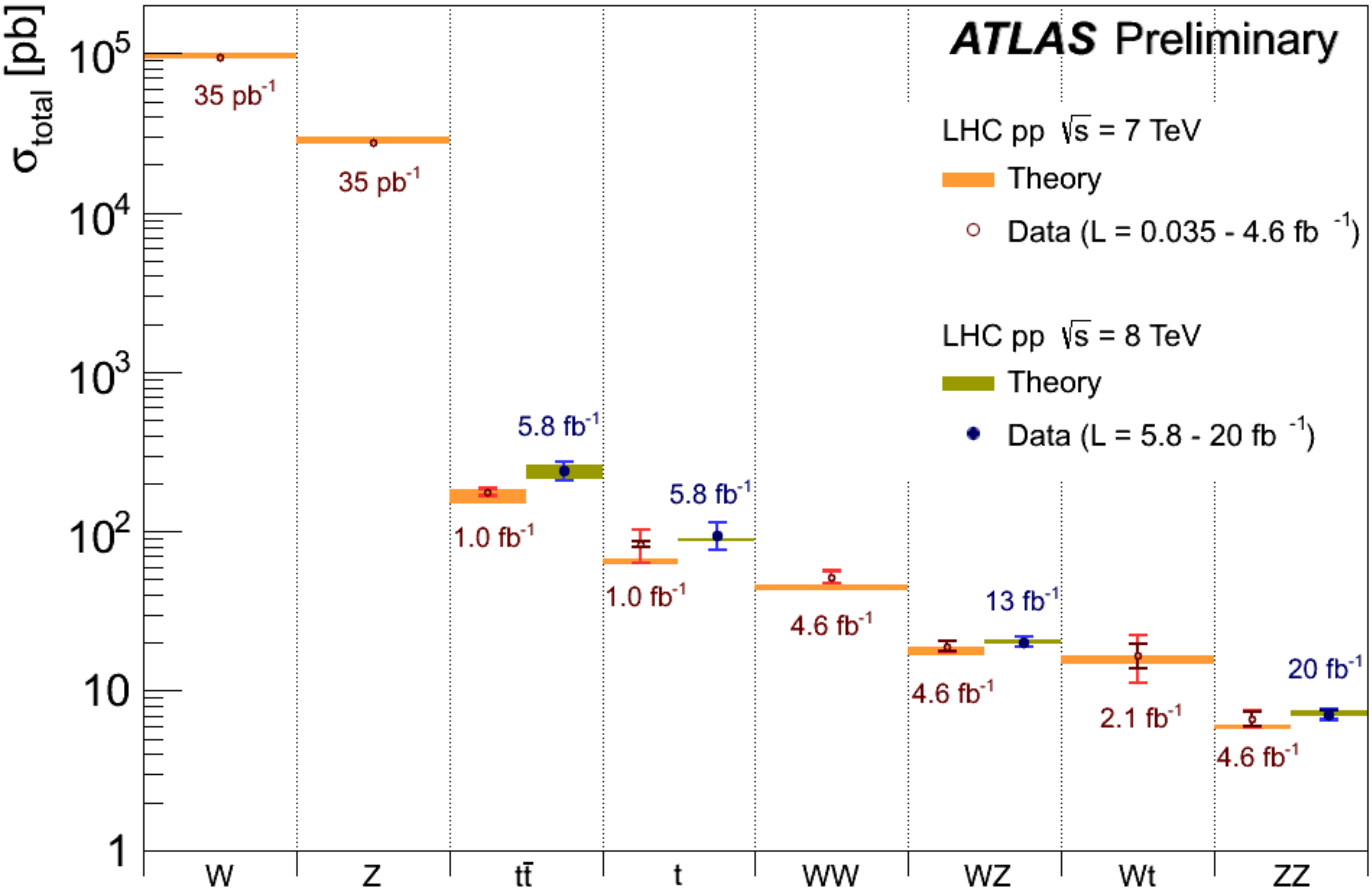
Signal:



Background:



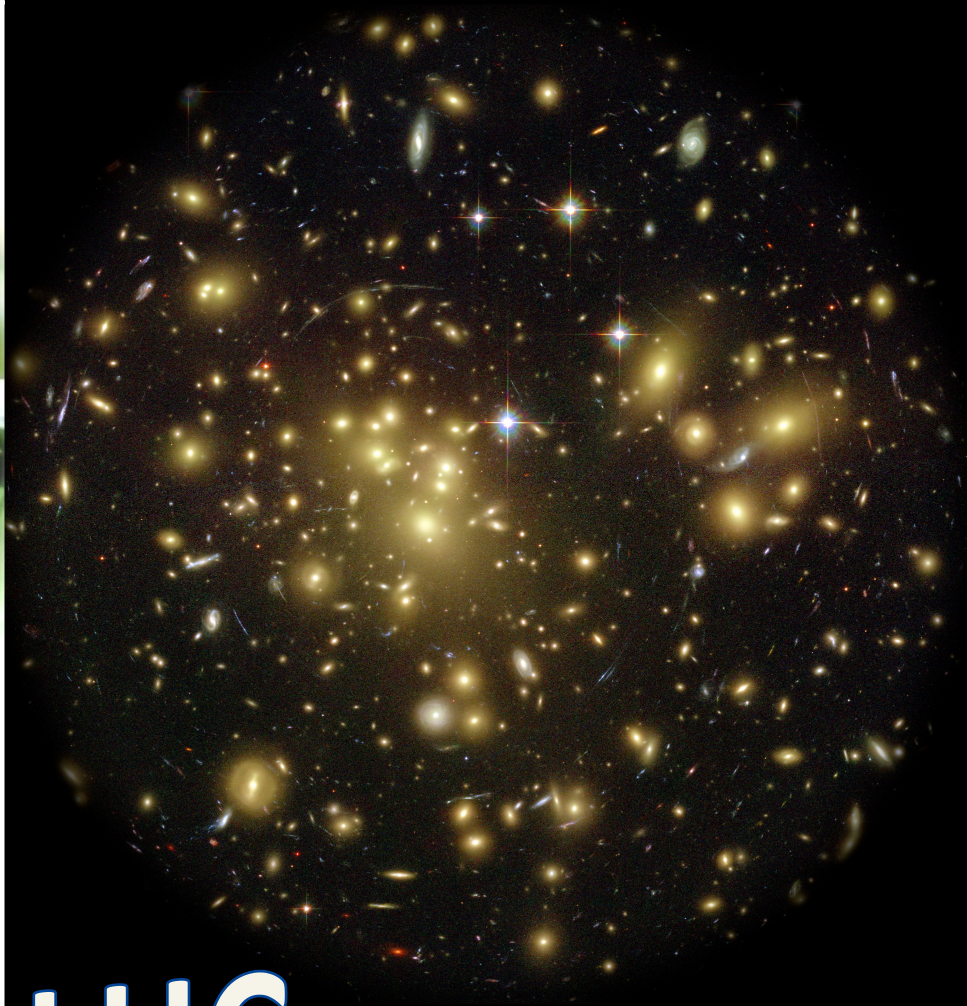
The Standard Model Appears Complete, But…



There are Unanswered Questions

Naturalness

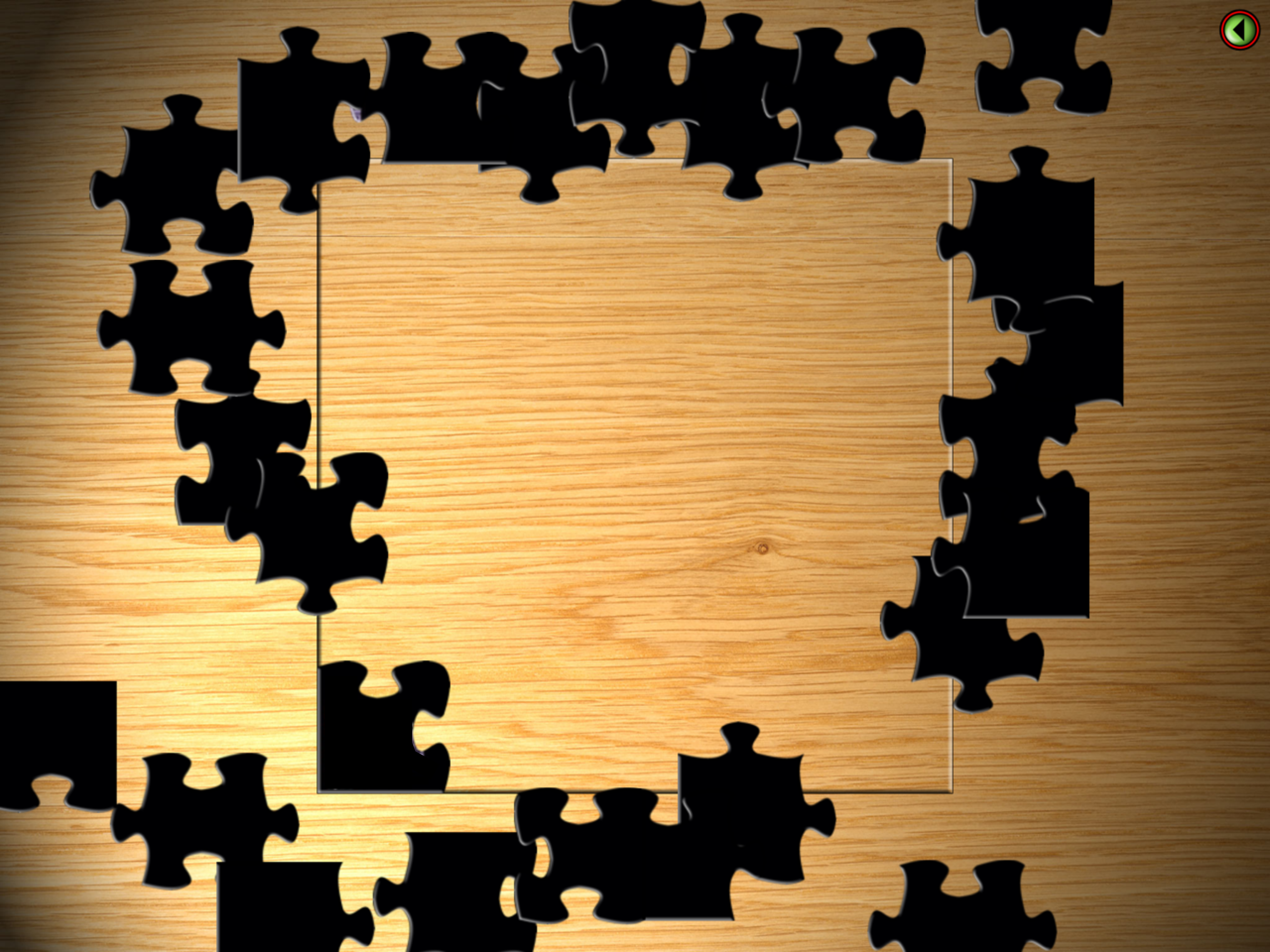
Dark Matter



The LHC

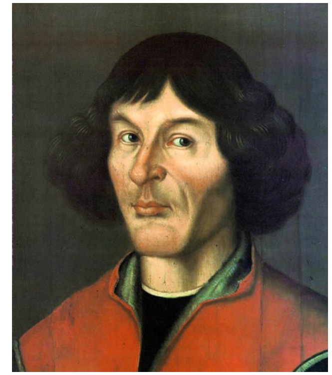
And More Puzzles

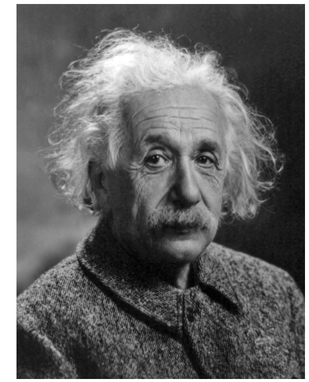
- Quantum gravity
- Matter-antimatter asymmetry
- Pattern of masses and mixings
- Unification
- …



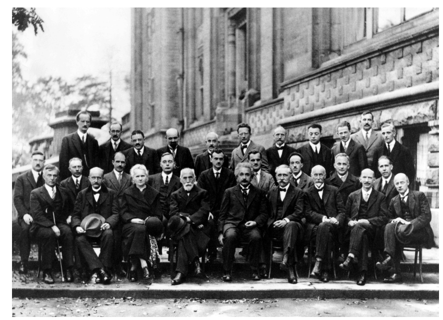
More Science Revolutions in Store for us?

- Copernican revolution



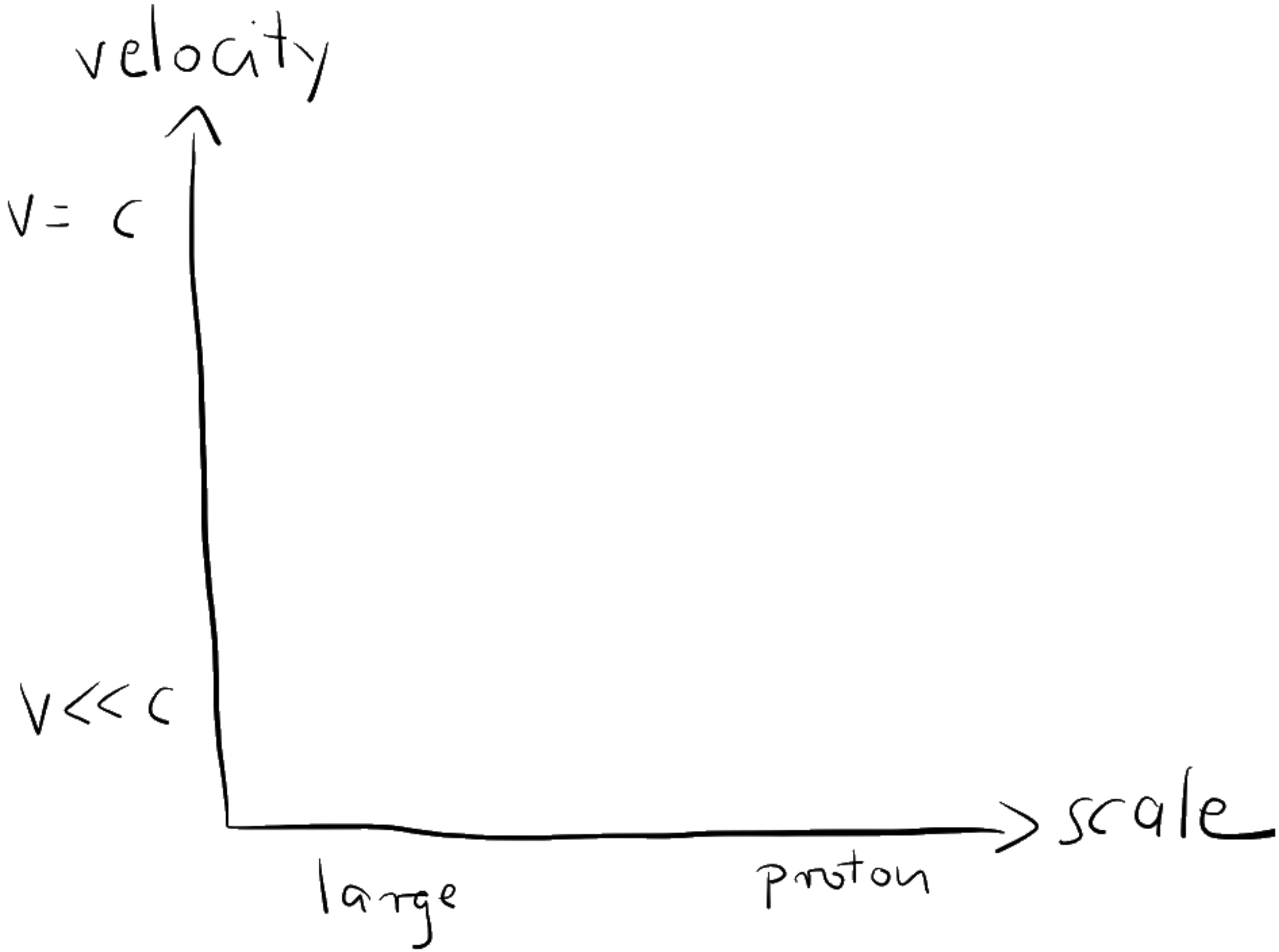


- Relativity
- Quantum Mechanics



- …
- Physics beyond the Standard Model (SM)?

Analogy: Standard Model and Newtonian Physics



Standard Model and New Physics


Naturalness
Aka fine-tuning or hierarchy problem

Why is the Higgs Mass so small?

Observed → Predicted

Observed M^2_{Higgs} 10^{32} times smaller than predicted

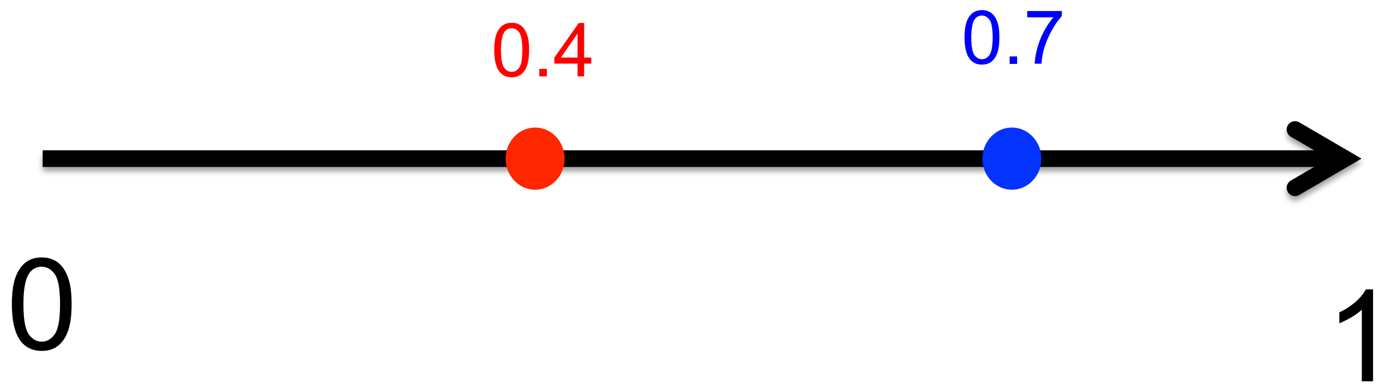
An Aside: even worse in Cosmology

Observed → Predicted

Observed cosmological constant 10^{120} times smaller than predicted

The Problem with Hierarchies

You can think of the Higgs mass as the difference between two numbers



0.7 – 0.4 = 0.3 = O(1)

Now Scale Example up by 10^{32}

361278909847893073945209328789289 33023 -

361278909847893073945209328789289 17398 =

$= m^2_H = 125^2$

Unnatural cancellation or fine-tuning: $O(10^{32})$ - $O(10^{32})$ = $O(1)$

In analogy to: 0.7 – 0.4 ≠ $O(10^{-32})$

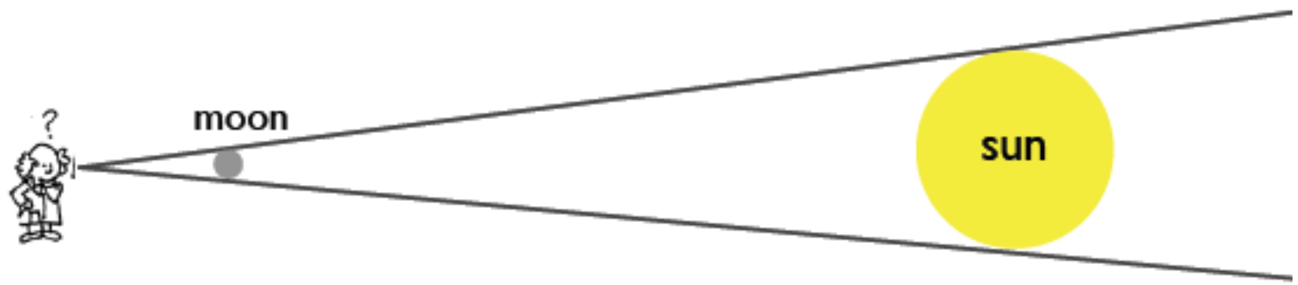
m^2_H in GeV^2

Fine-Tuning

Imagine a radio and you have to fine-adjust the knob to 1 part in 10^{32} in order to tune the channel

Fine-Tuning not Observed in Nature

- Angle of moon and sun agree to $1:10^2$
  - Ok with 1% fine-tuning

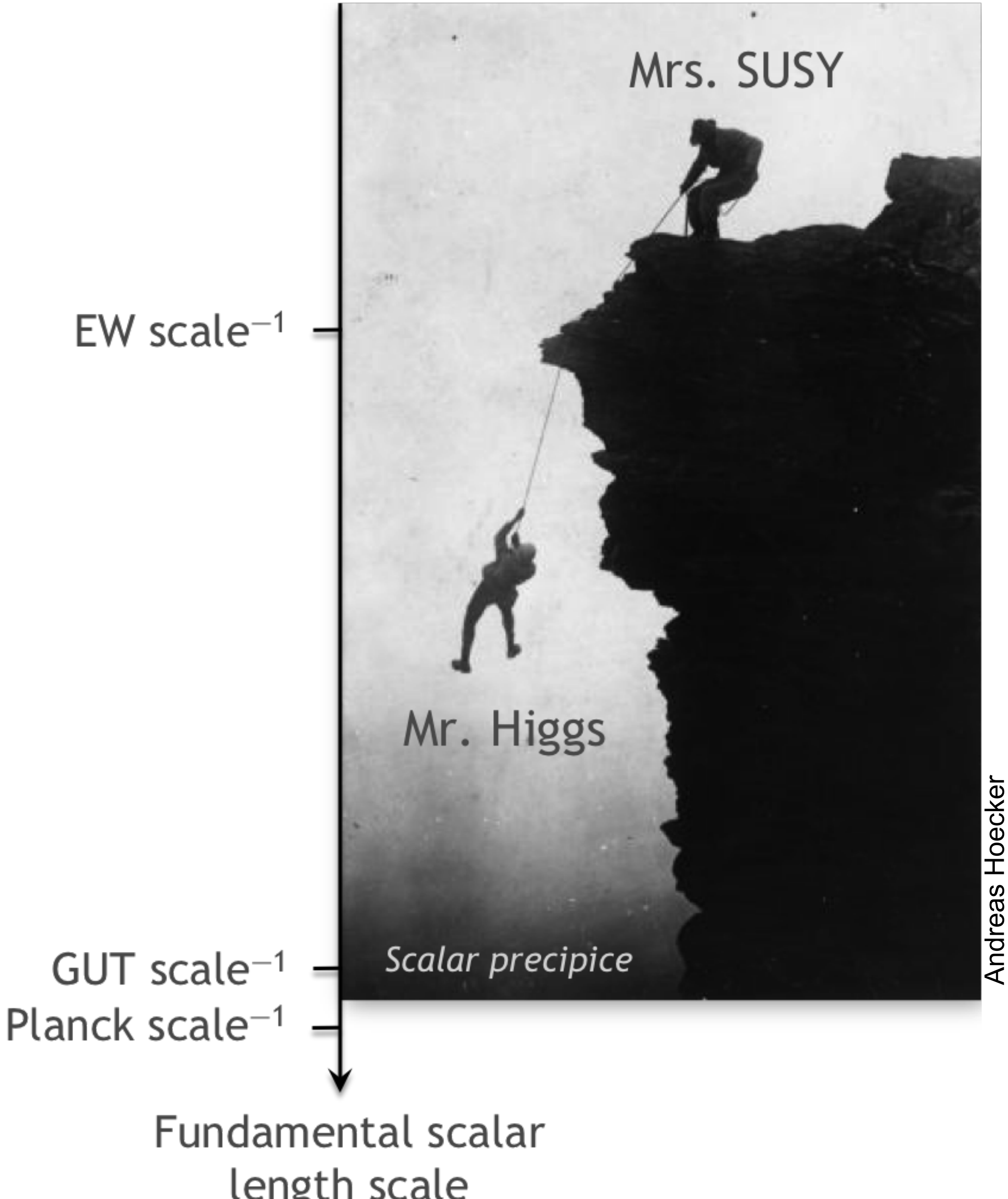


- Imagine they were equal to $1:10^{32}$

- Obvious question: what mechanism sets their precise distance (of 10^{-19} m!)

Summary or Naturalness

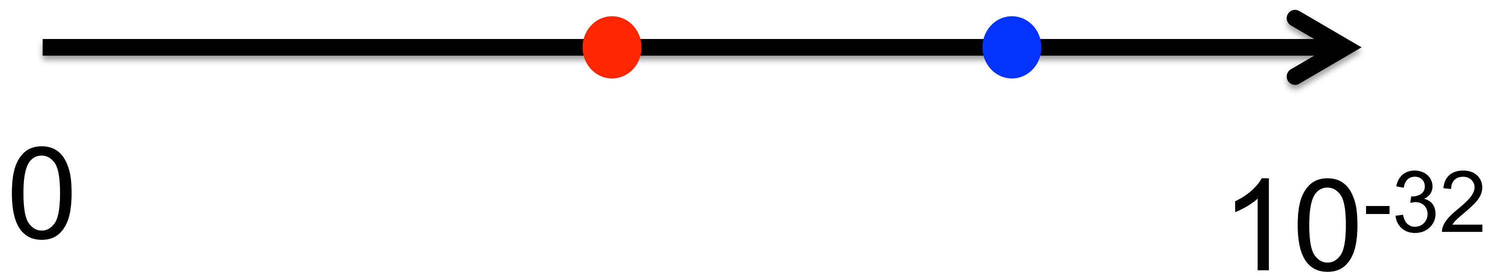
- Two very different scales involved – hierarchy problem
- There is fine-tuning of 1 part in 10^{32}
- This is unnatural


Mrs. SUSY
Mr. Higgs
Scalar precipice
EW scale^{-1}
GUT scale^{-1}
Planck scale^{-1}
Fundamental scalar length scale
Andreas Hoecker

Two Mechanisms to Establish Naturalness

1. Symmetry

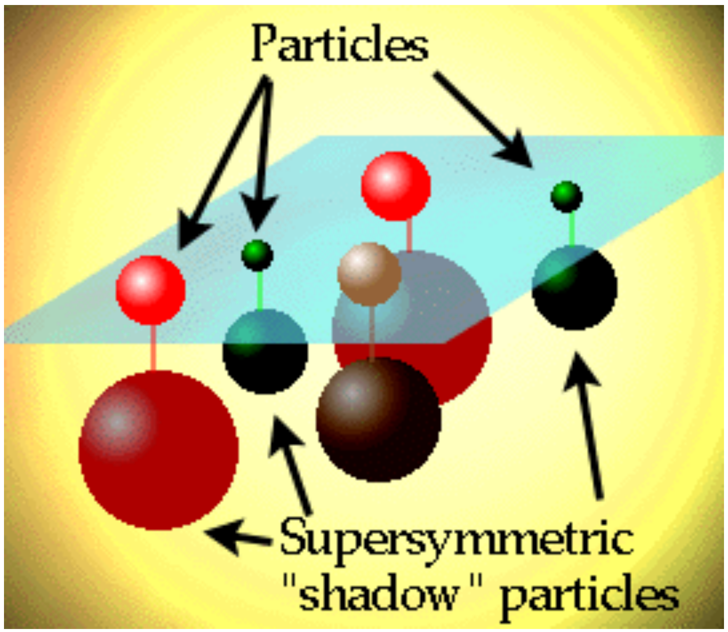
Two Mechanisms to Establish Naturalness



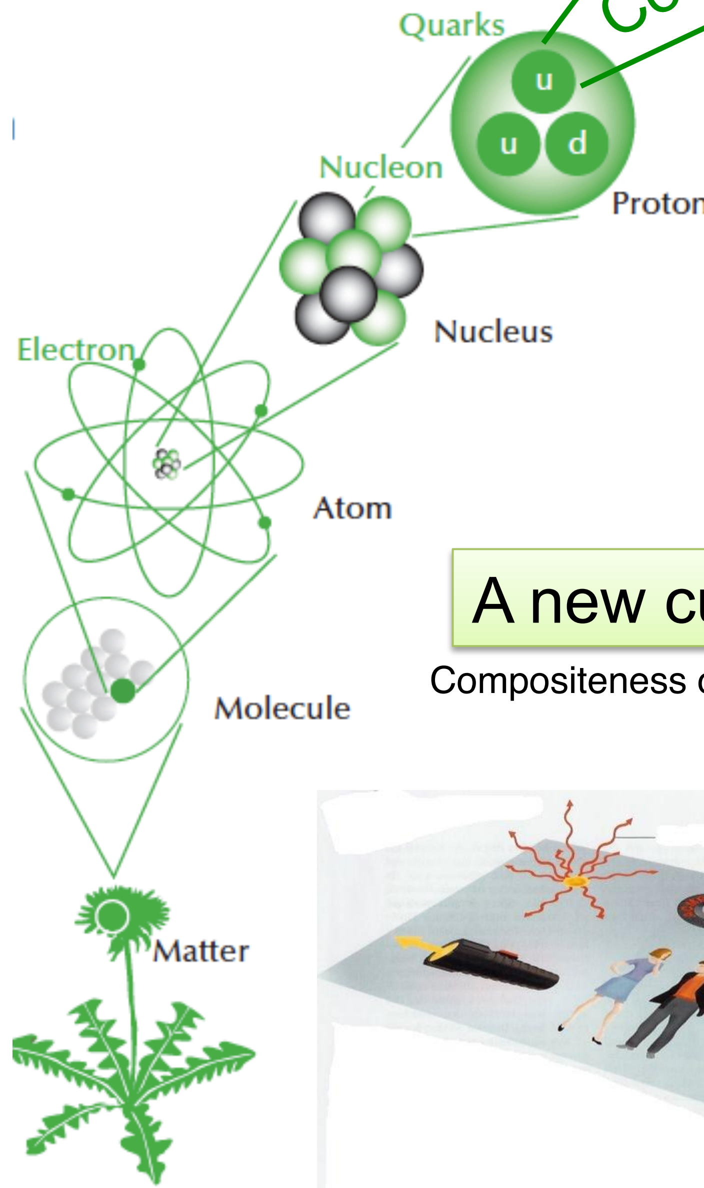
2. Modified cut-off scale

Two Grand Ideas

A new symmetry



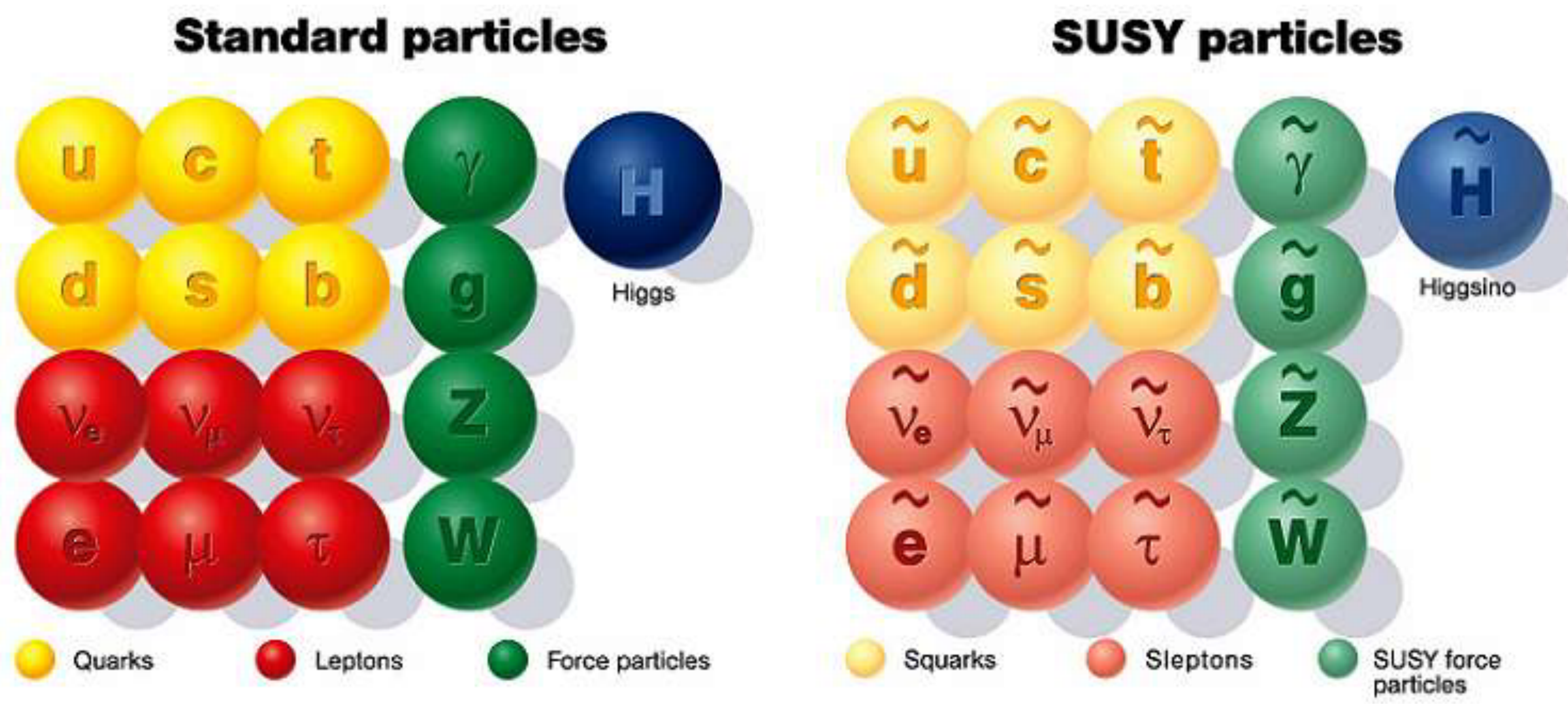
Compositeness?



A new cut-off scale

Compositeness or extra dimensions

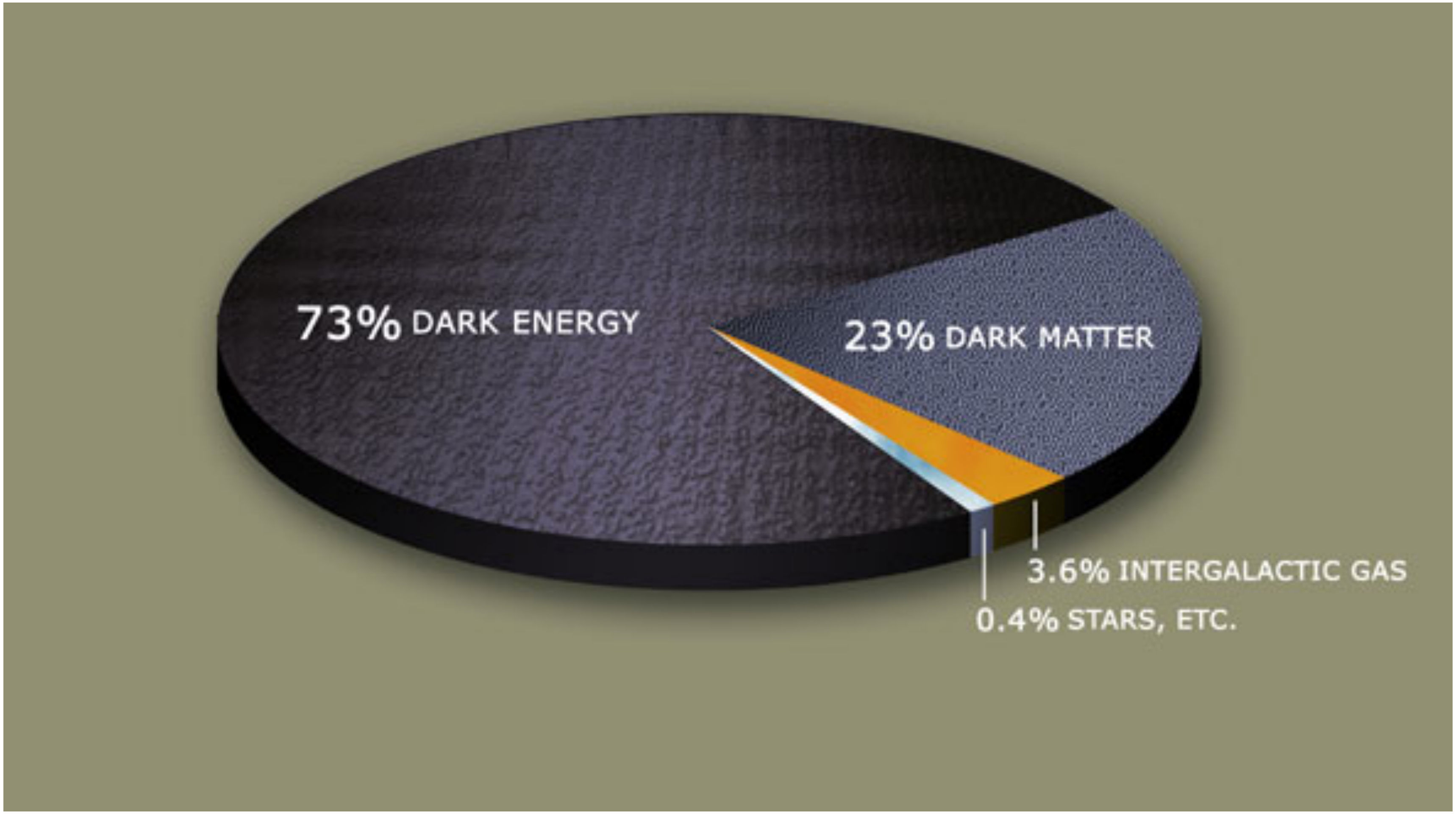
Supersymmetry



New symmetry between bosons and fermions

(Symmetry needs to be broken)

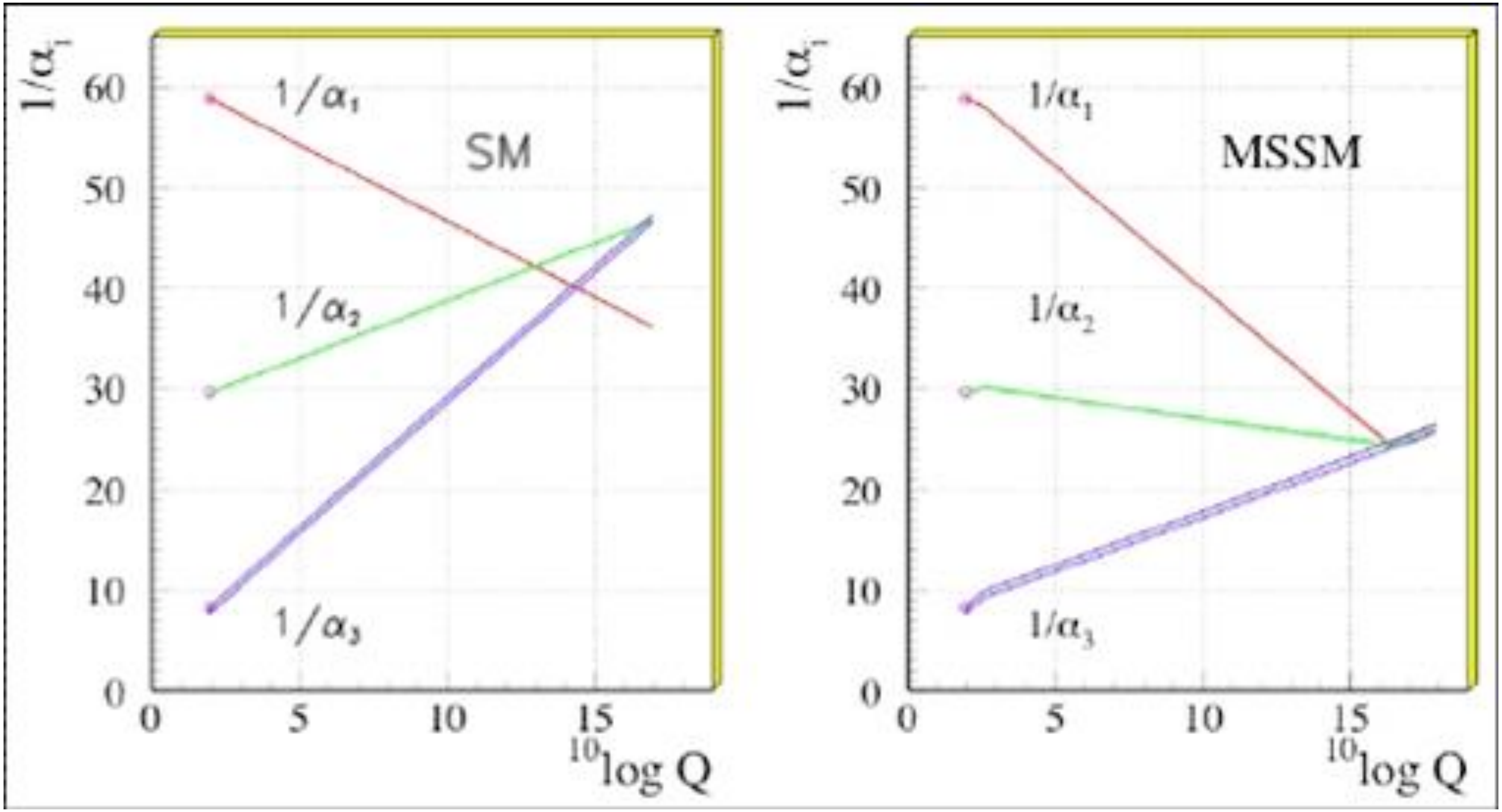
SUSY – Other Fixes to the Standard Model



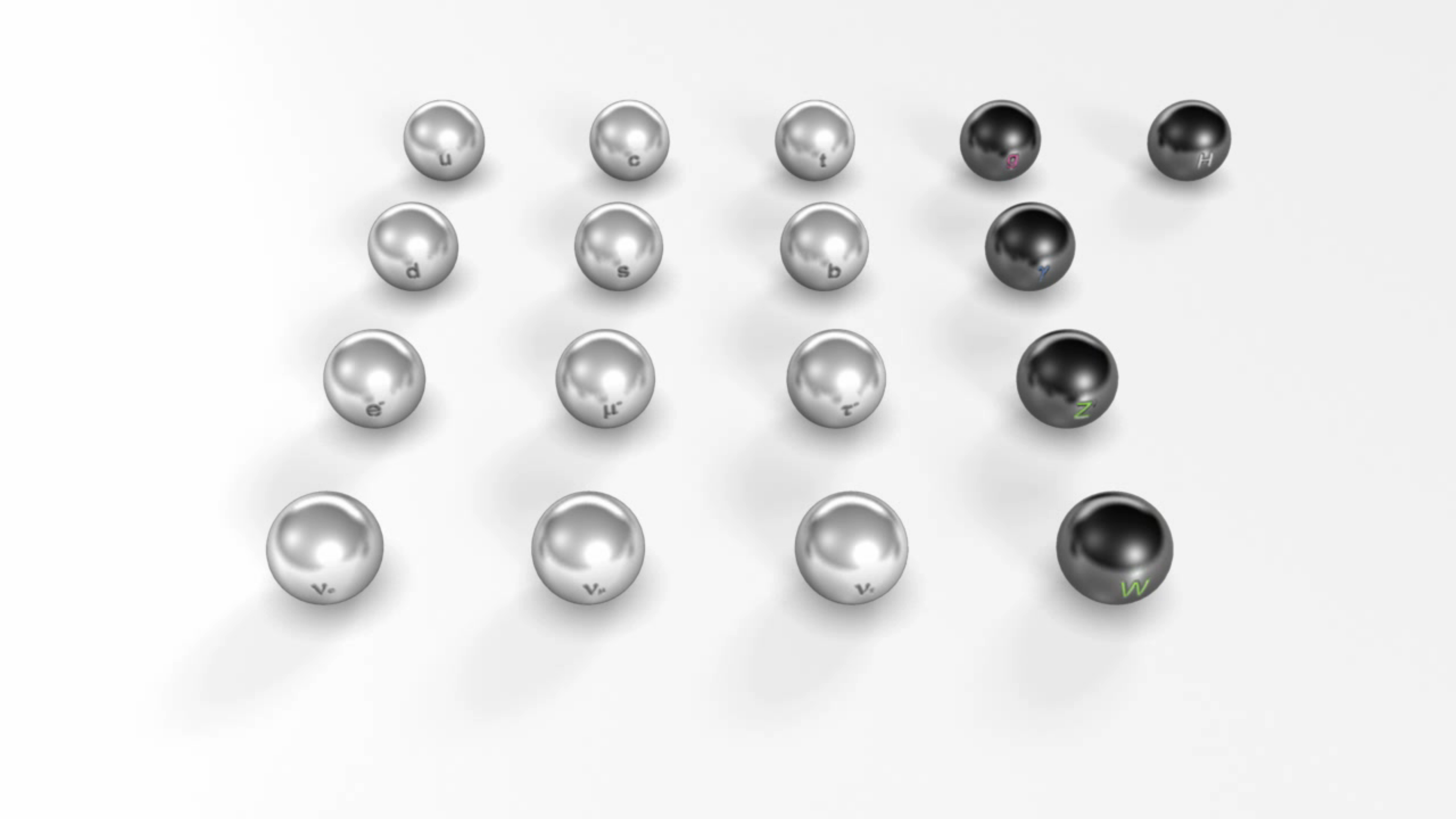
Dark matter candidate

(R-parity conserving)

SUSY – Other Fixes to the Standard Model

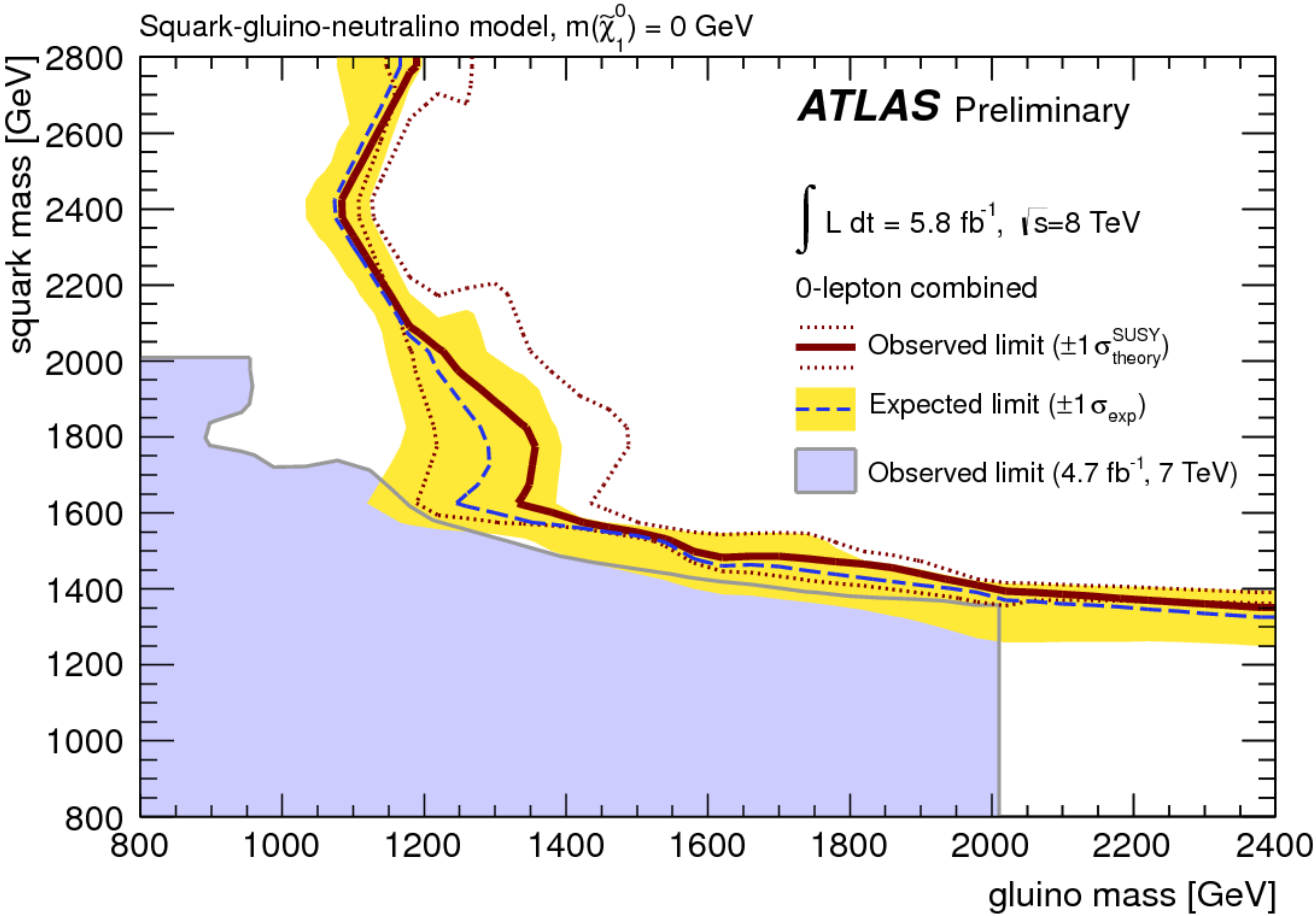


Gauge coupling unification



u
c
t
g
H
d
s
b
γ
e⁻
μ⁻
τ⁻
Z
W

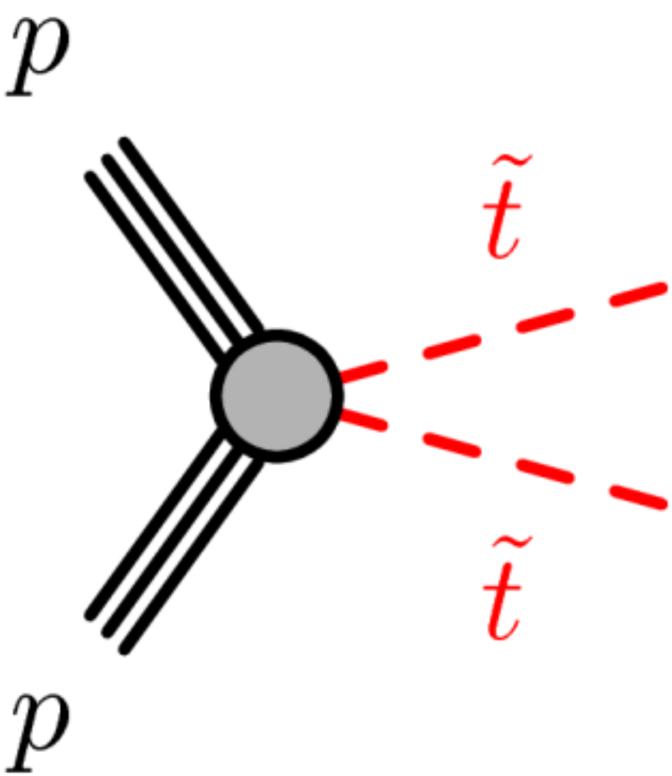
Where is SUSY?

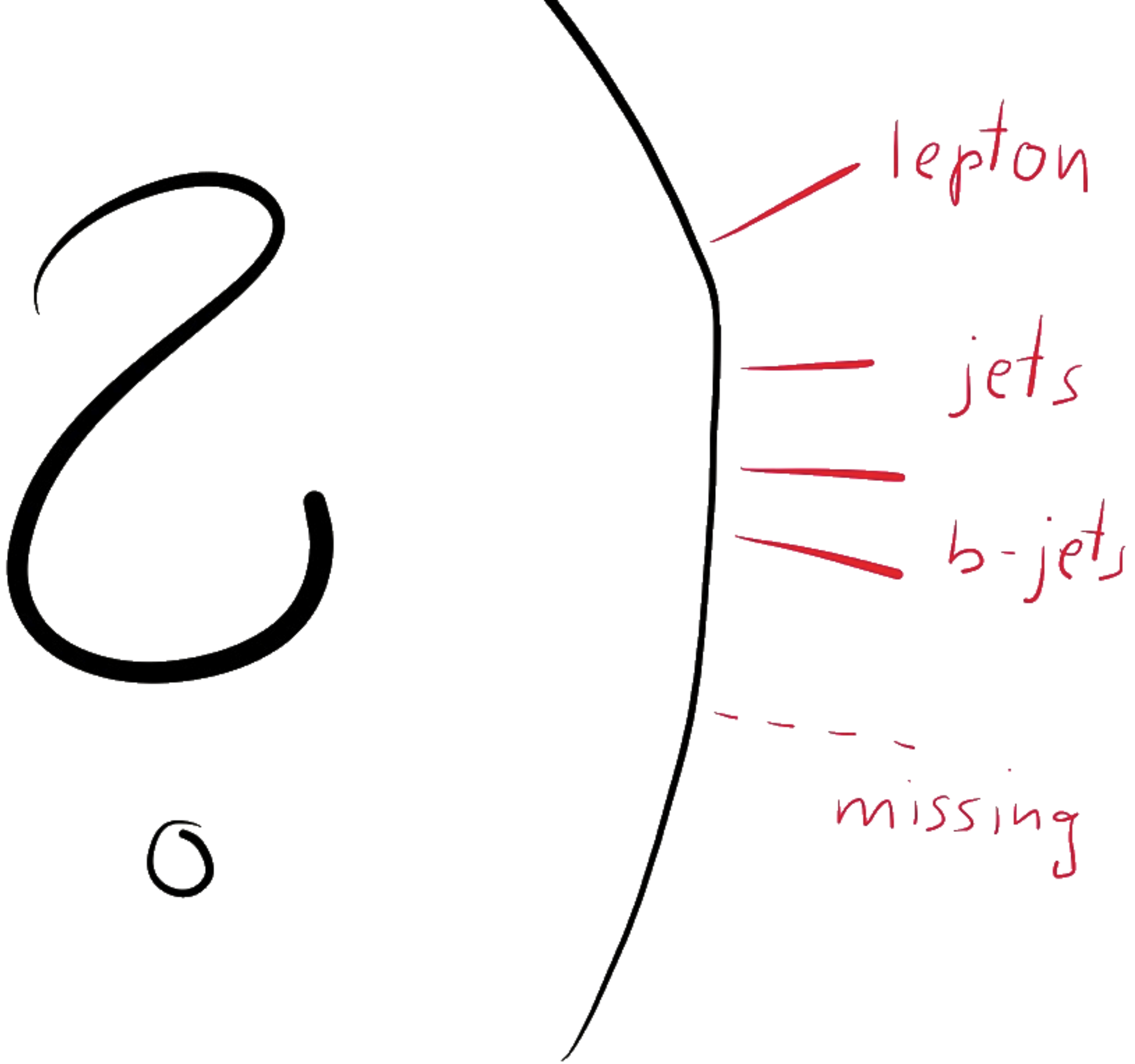


Minimum SUSY Requirement for Naturalness

- Only the supersymmetric partner of the top quark (referred to as “stop”) is light
- The heavier the stop the more fine-tuning
- Stop of ~1 TeV means ~1% fine-tuning

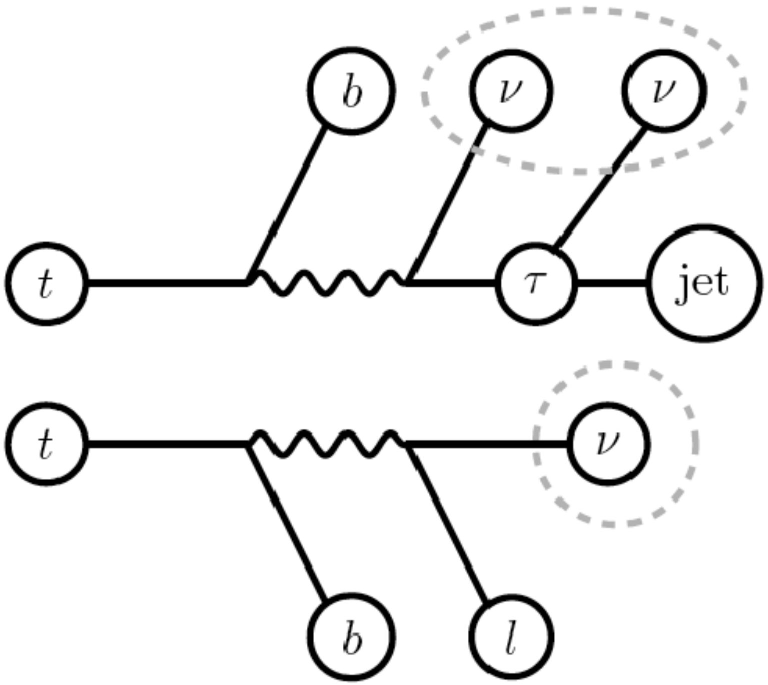
Stops



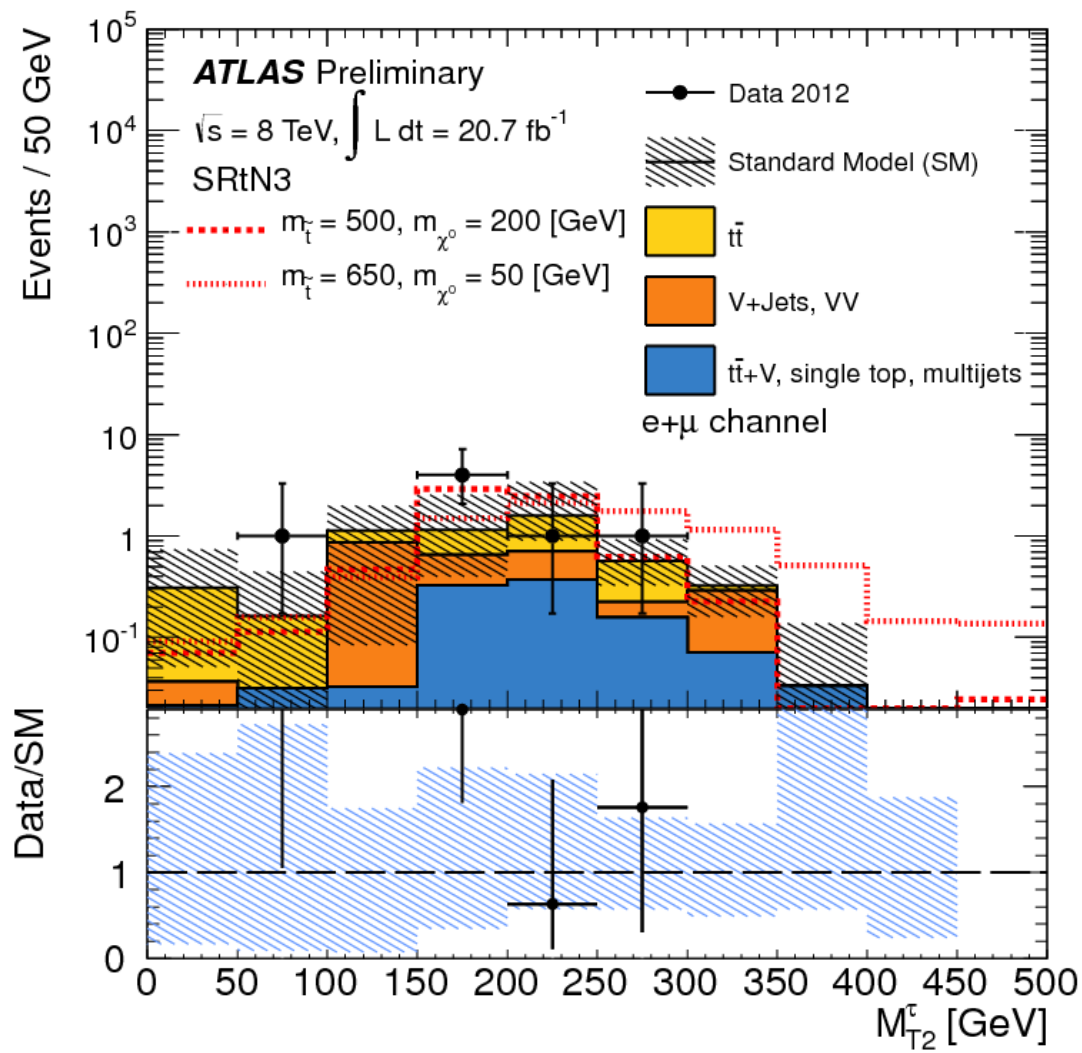

lepton
jets
b-jets
missing

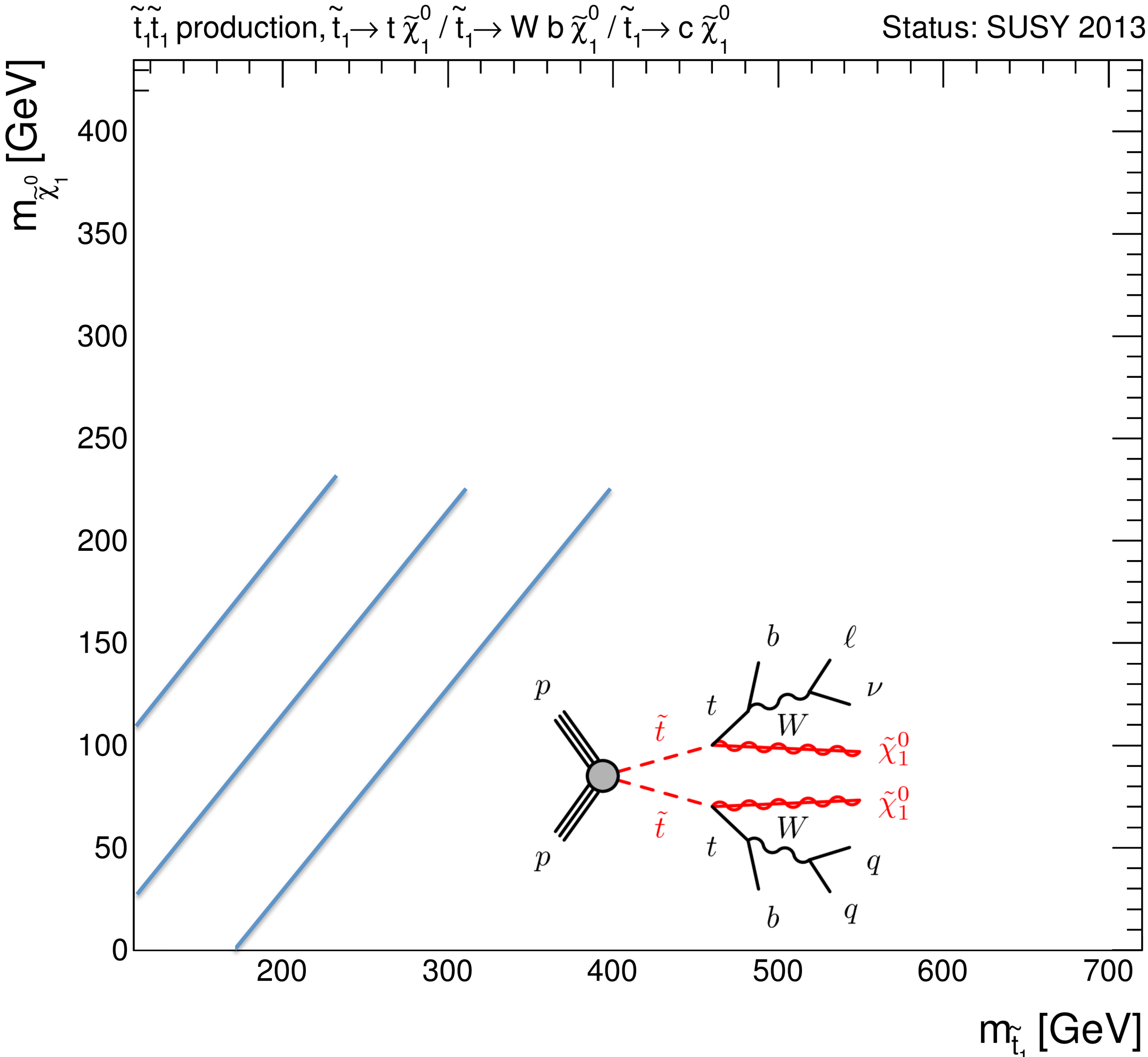
Confronting Data with the Stop Hypothesis

<u>The dominant background:</u>



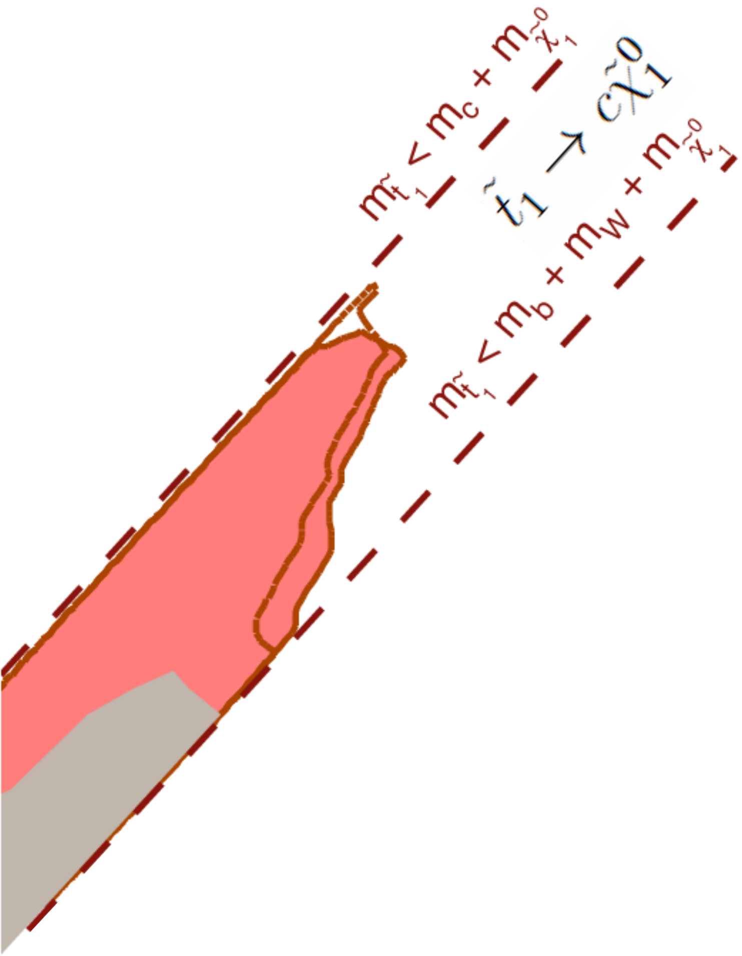
Test data against hypotheses

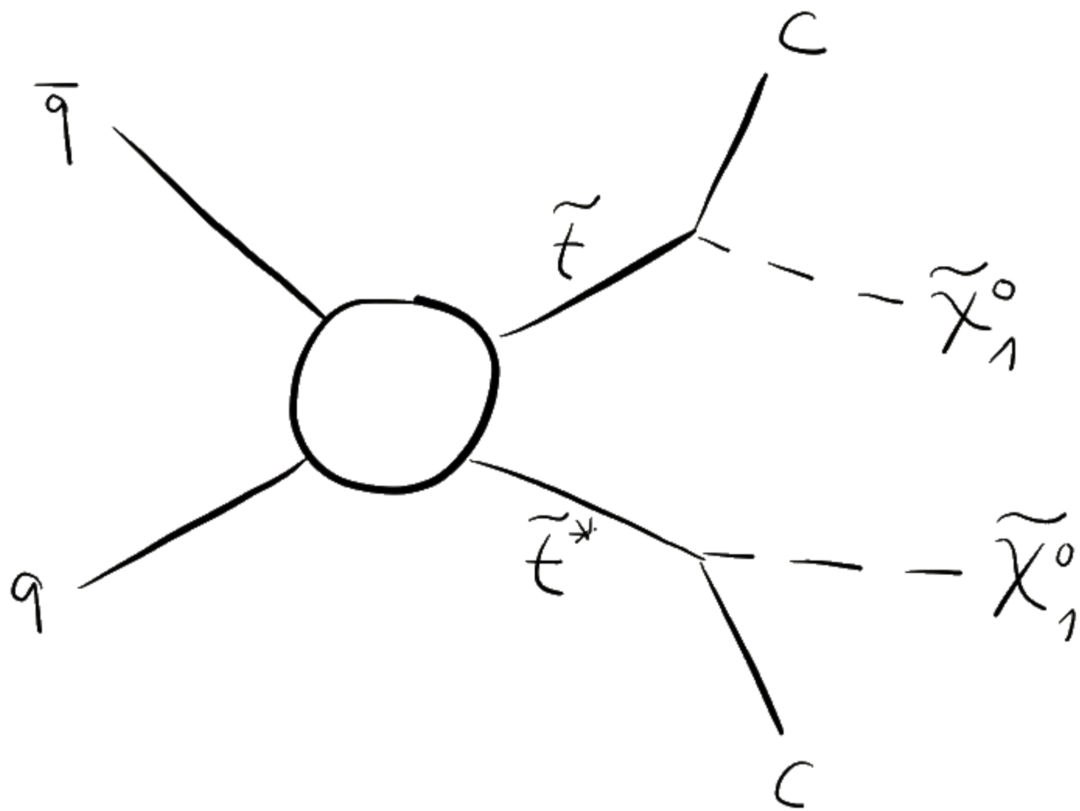




$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow W\,b\,\tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow c\,\tilde{\chi}_1^0$
Status: SUSY 2013
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
0
50
100
150
200
250
300
350
400
200
300
400
500
600
700
p
p
$\tilde{t}$
$\tilde{t}$
t
t
b
b
ℓ
ν
W
W
q
q
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$

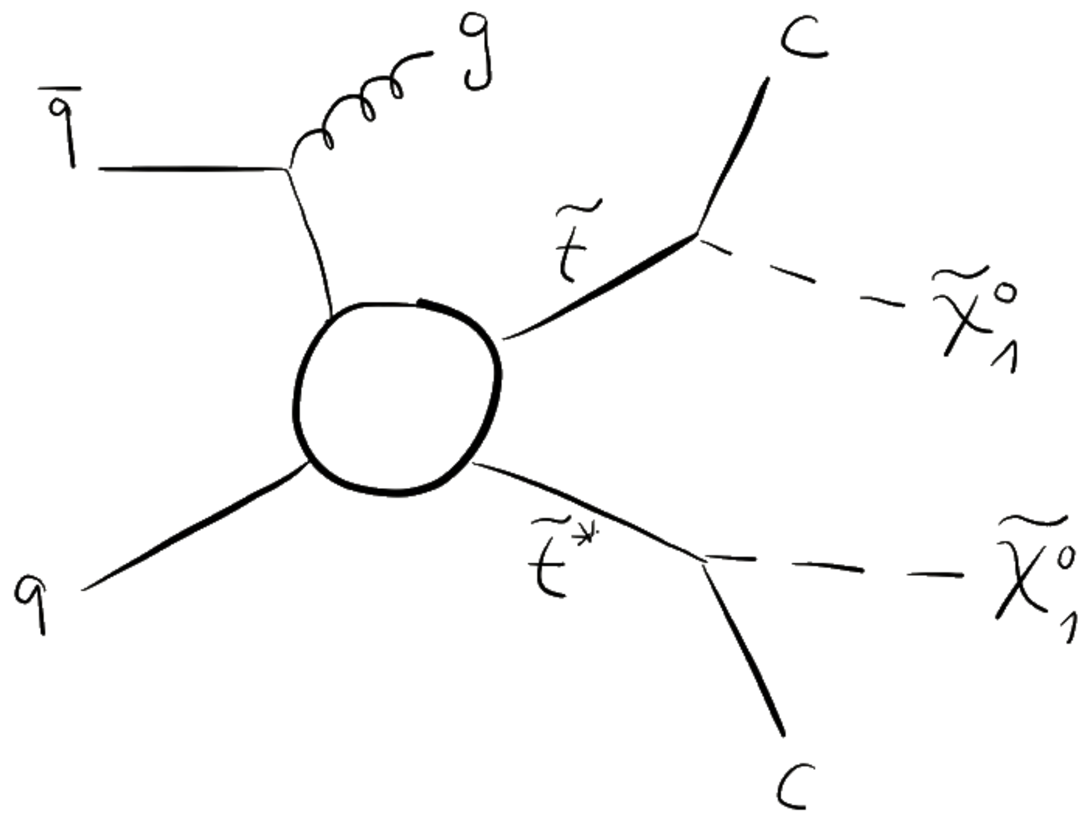
Stop→ Charm + Dark Matter



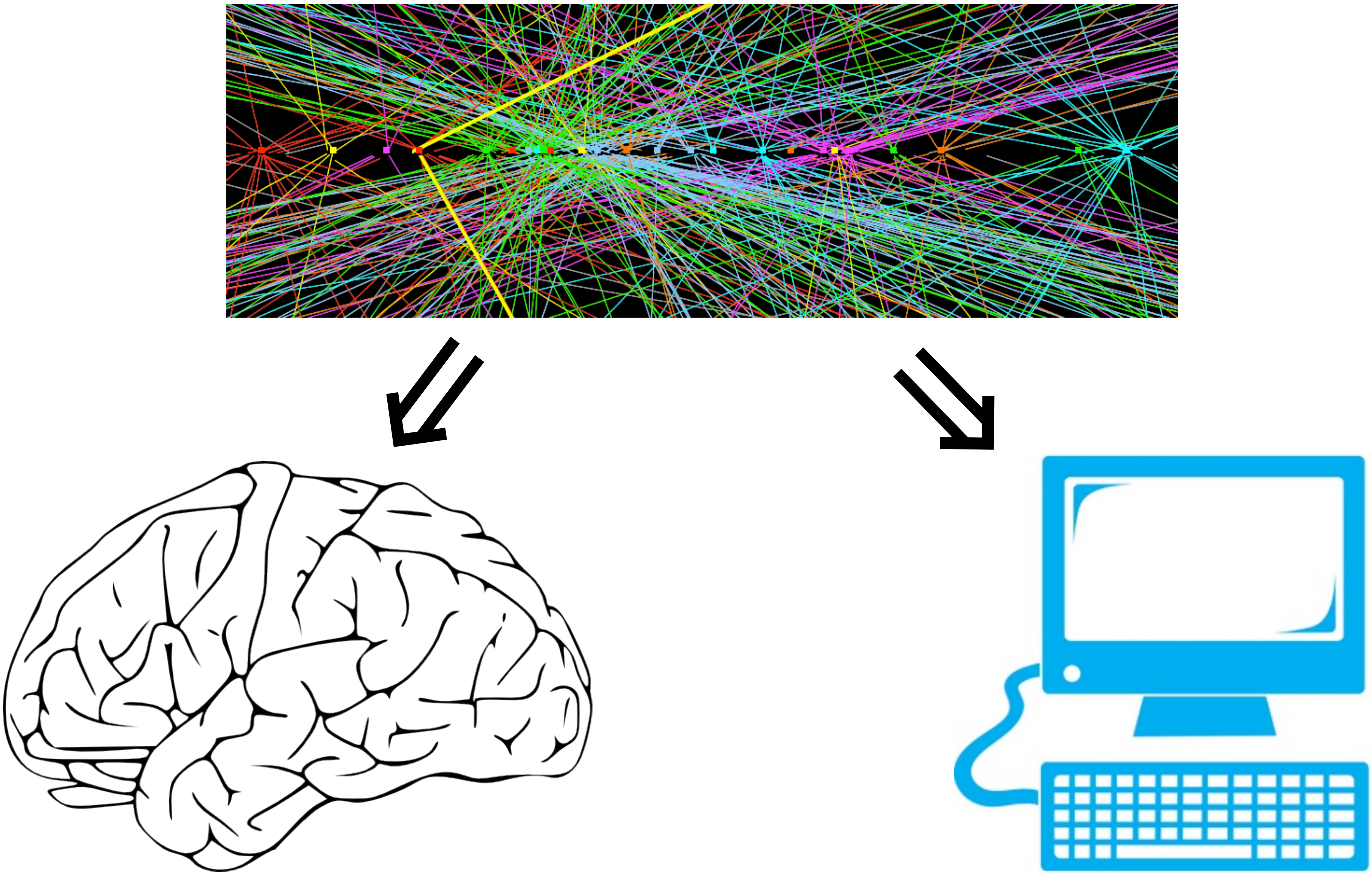


(stop-LSP coannihilation)

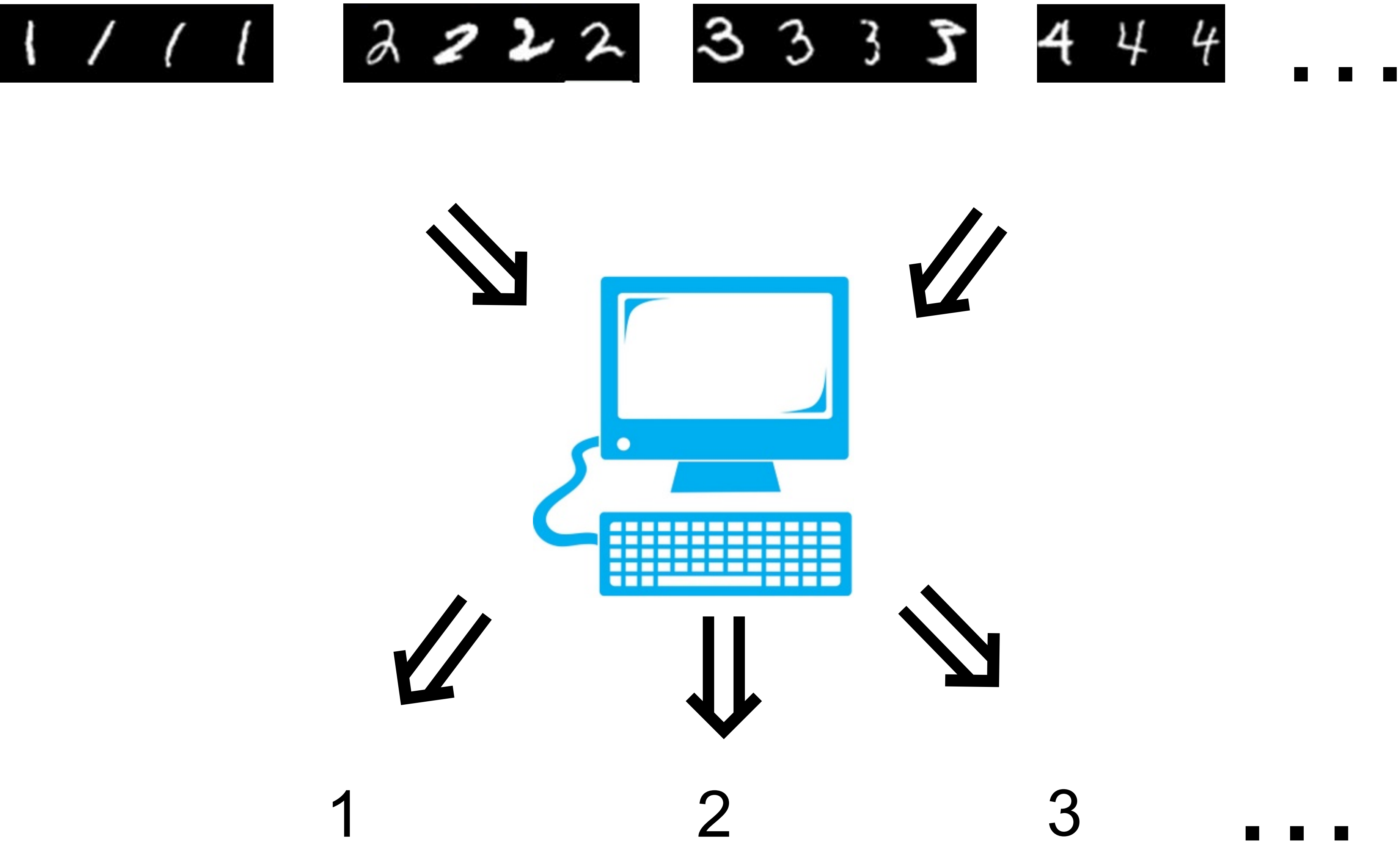
The Trick: Recoil



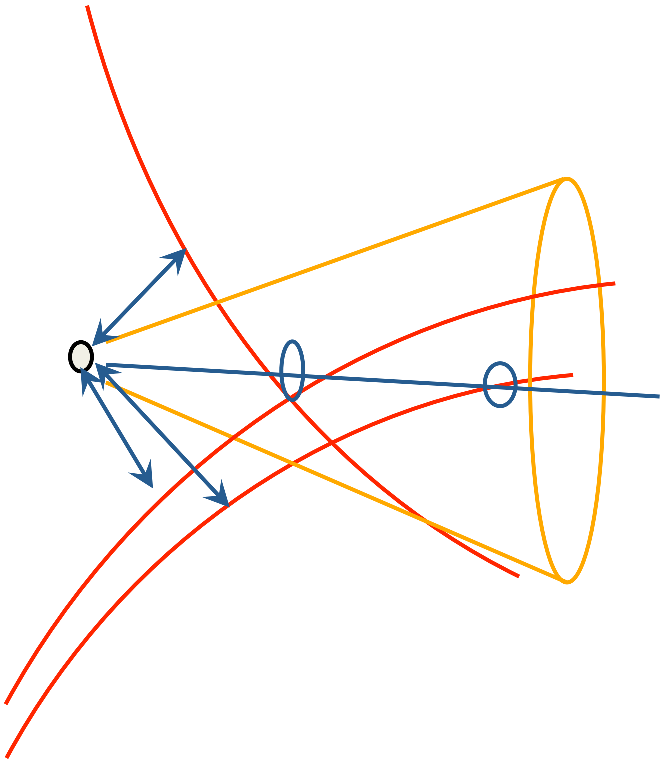
Identifying Charm – Recognizing Patterns



Machine Learning – Image Recognition

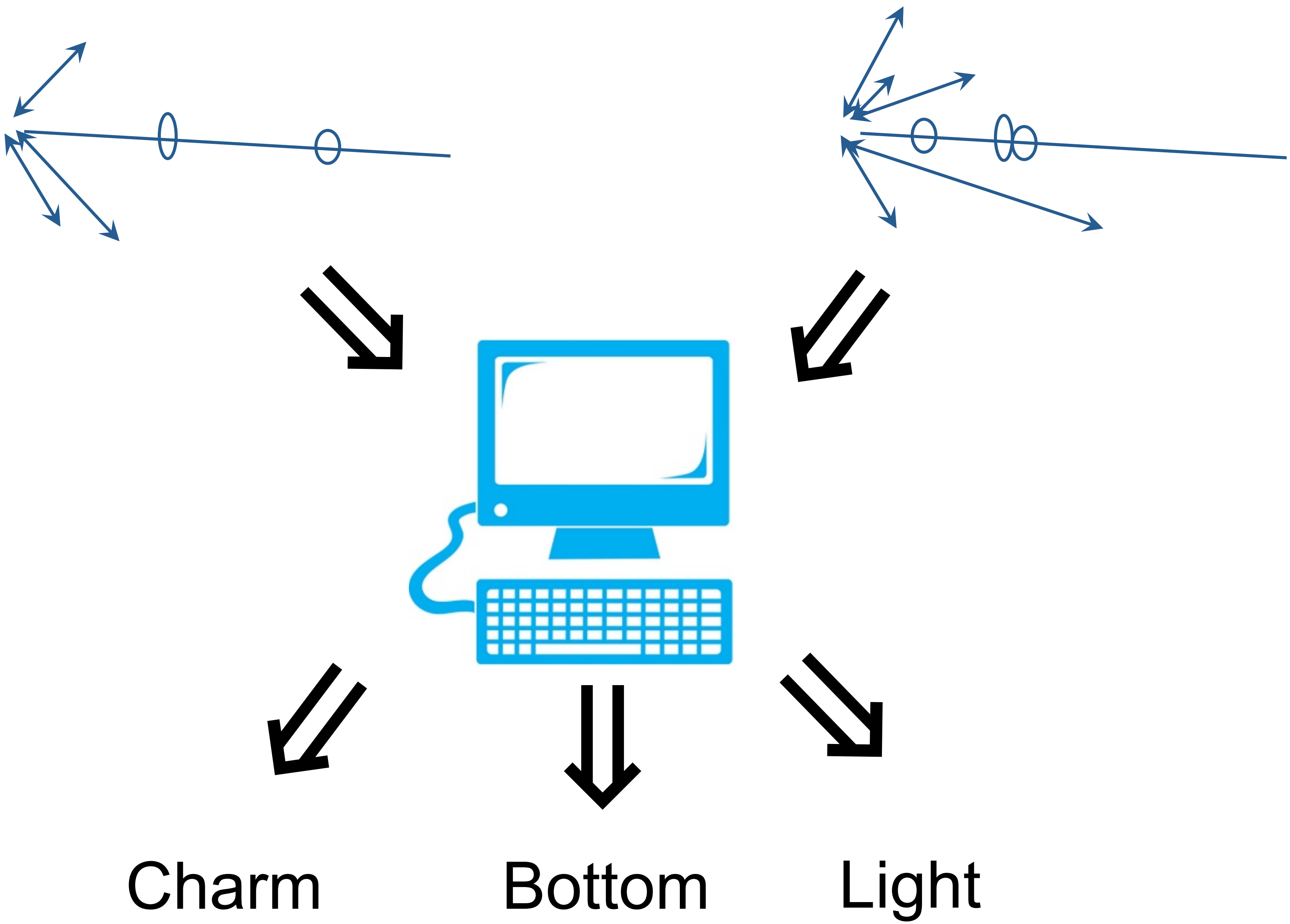


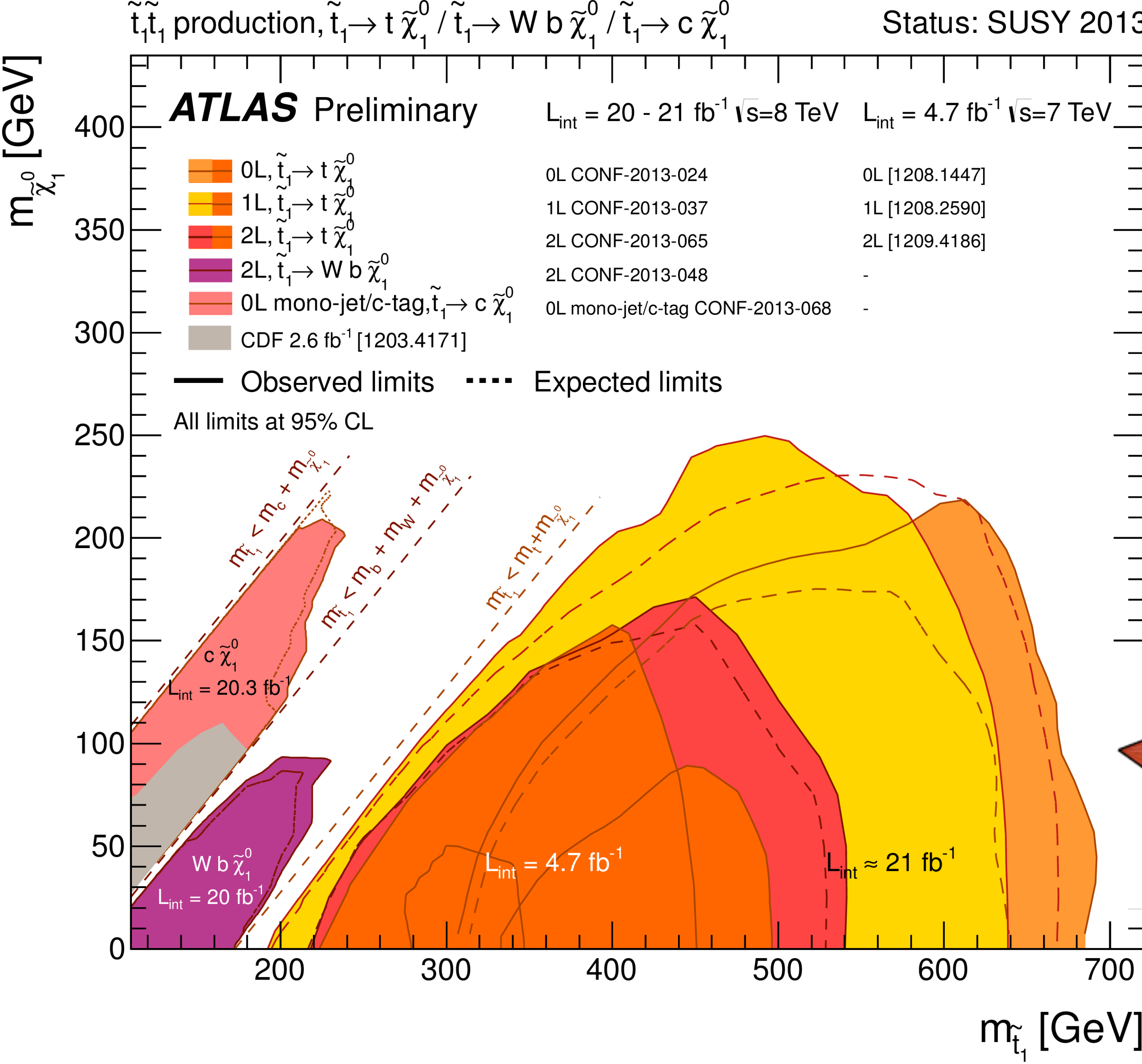
Charm Pattern

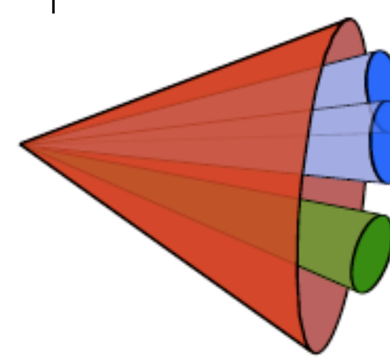


- Primary vertex
- Calorimeter jet
- Tracks – traces of charged particles
- Properties of tracks allow one to distinguish charm, bottom, light

Machine Learning – Charm Identification







Boosted top quarks

Conclusion

- Naturalness and Dark Matter point to new physics in reach of the LHC
  - Higher energy, more luminosity

- The grand ideas to solve the puzzles of the Universe are our guides in designing our searches

- Goal: discover new physics if it is in our data
  - Not a trivial task – complex data
  - Cast a wide net
  - Fully exploit the potential of our exquisite data
  - Open to innovations: new tools, new concepts
- We won’t give up!

We Might be this Close!

Thank You!