WILL FAWCETT, UNIVERSITY OF OXFORD

# SEARCHING FOR SUPERSYMMETRY

# WHAT IS THE UNIVERSE MADE OF?

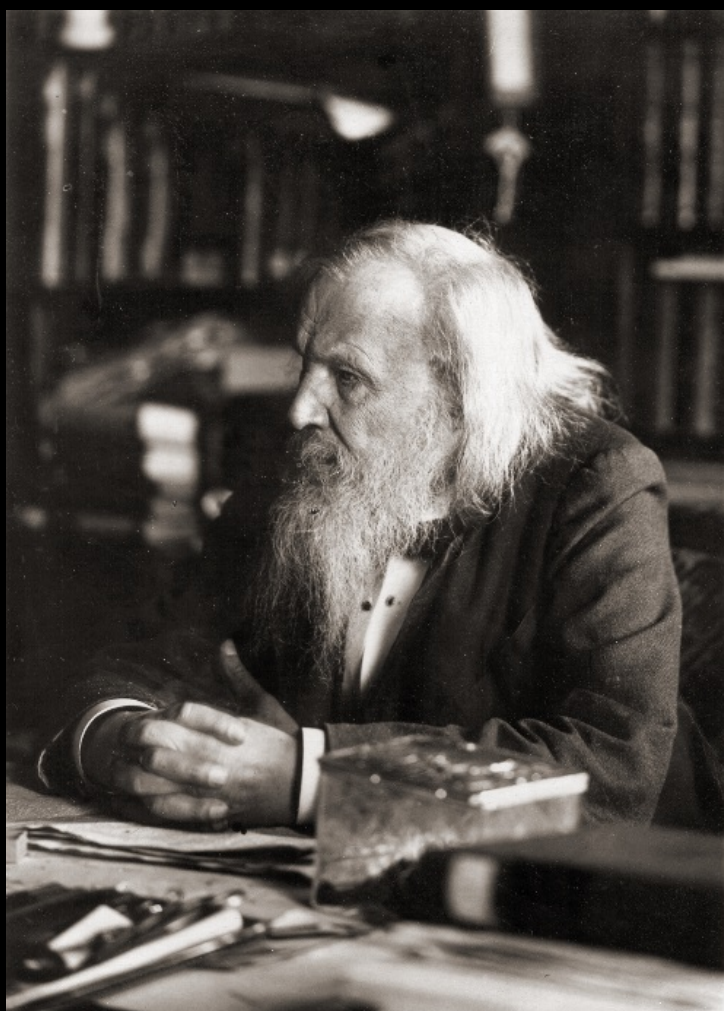
# 550 BC

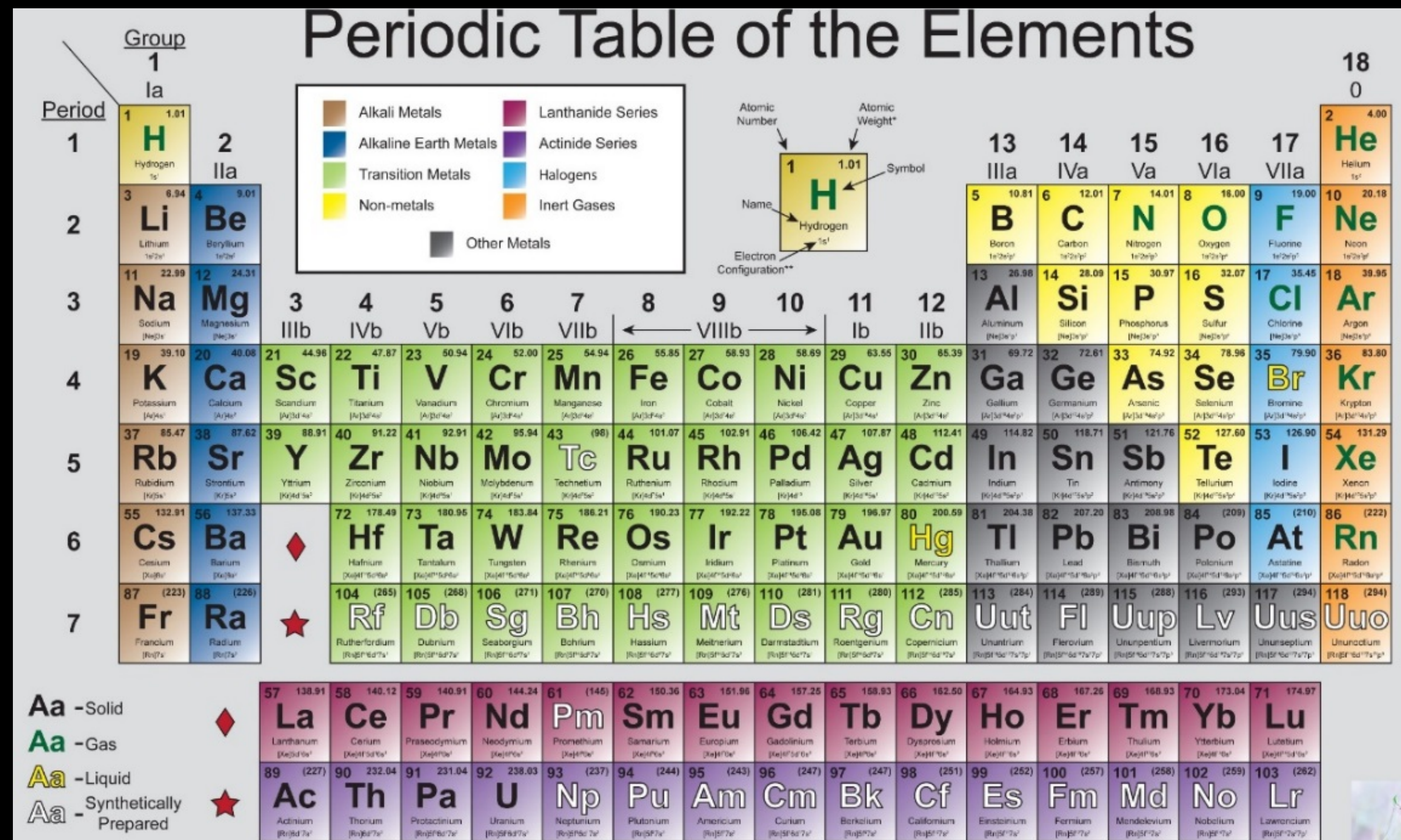
Anaximander

# 550 BC

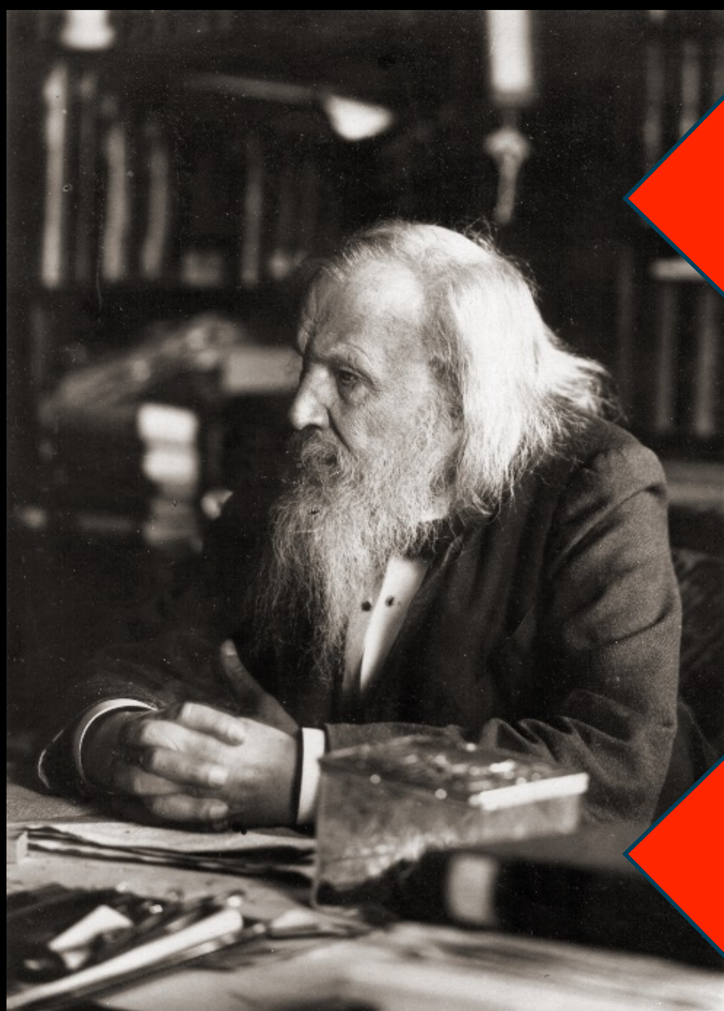
Anaxima

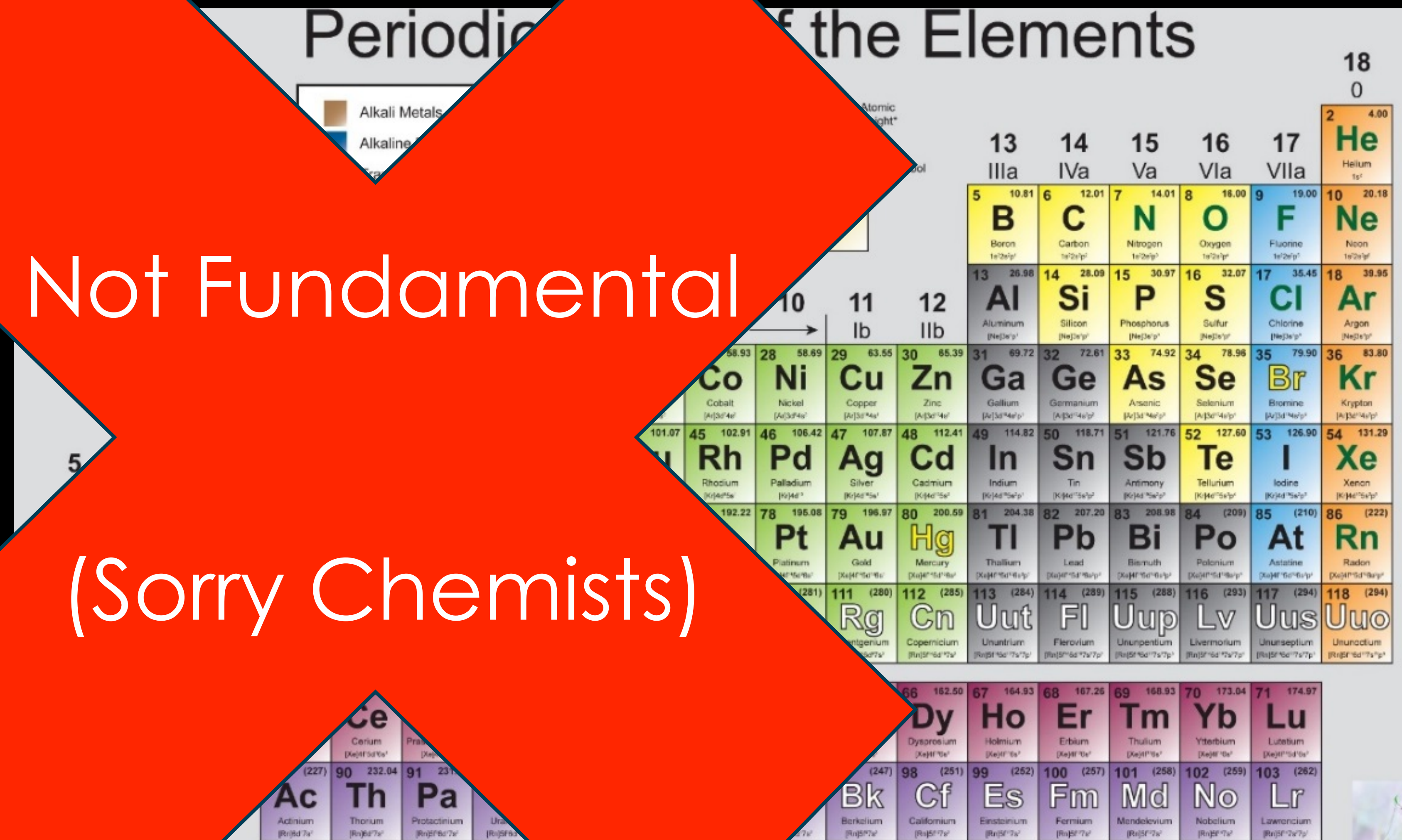
# 1869: PERIODIC TABLE





# 1869: PERIODIC TABLE



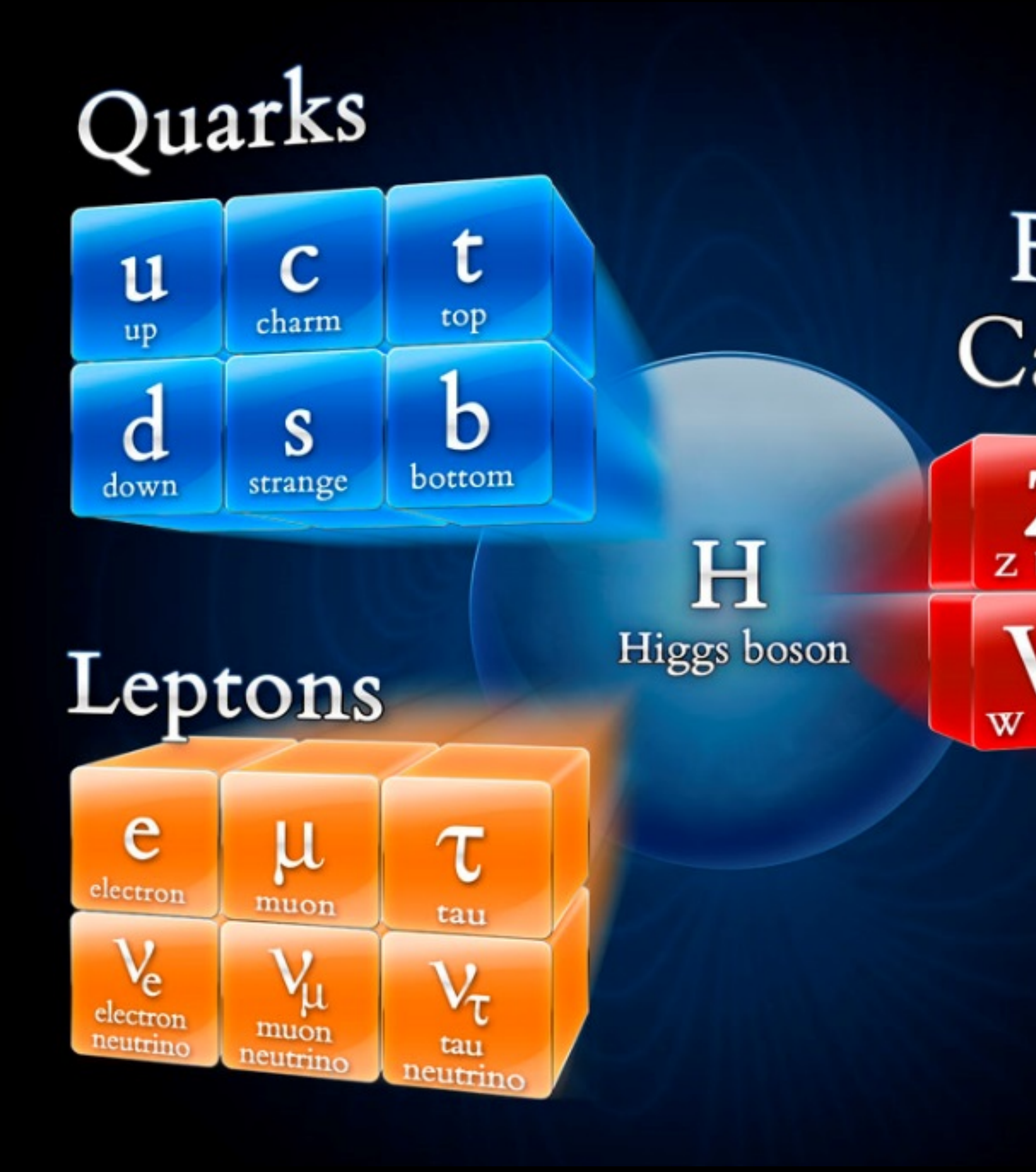



Not Fundamental

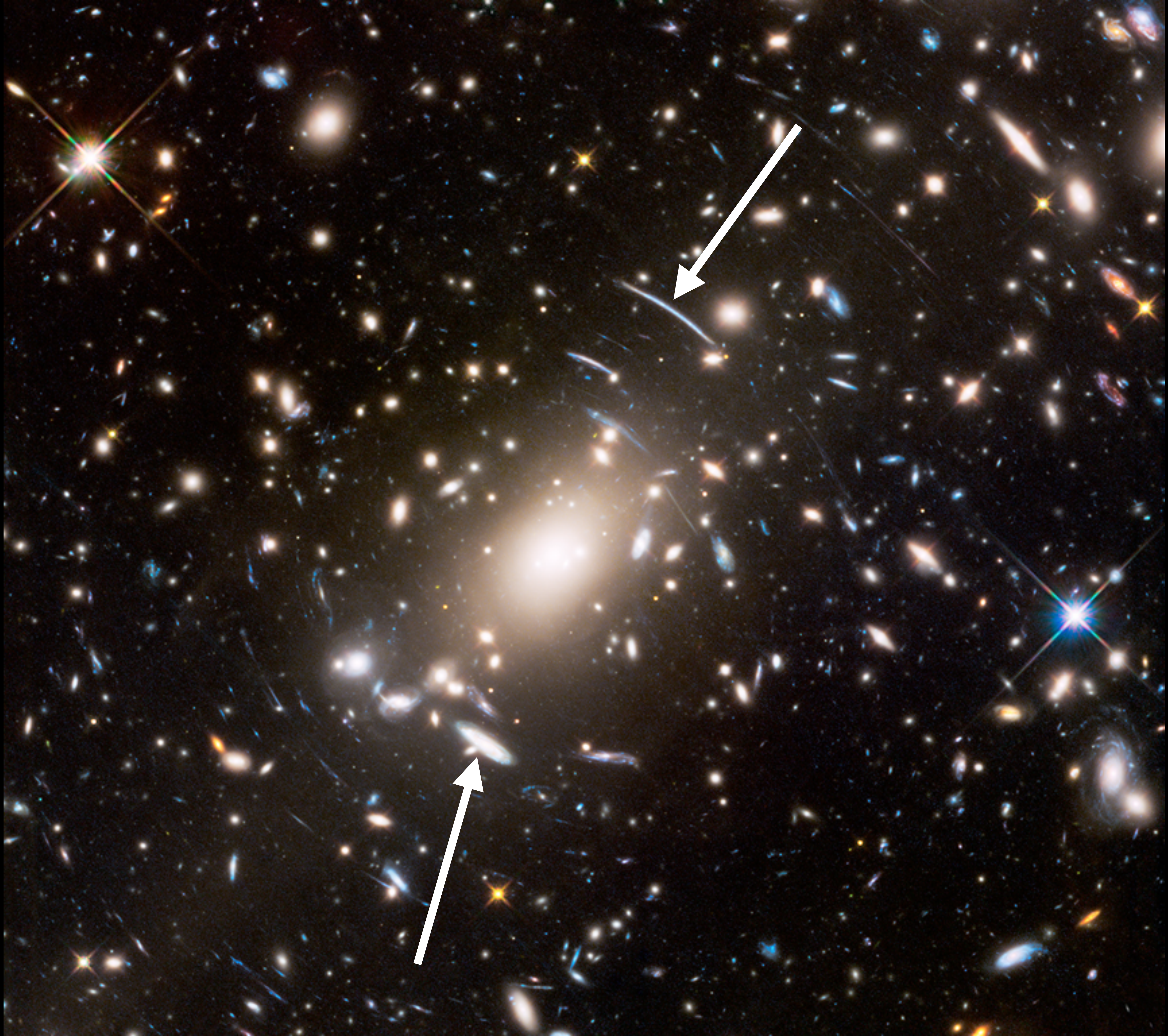
(Sorry Chemists)

# TODAY: THE STANDARD MODEL

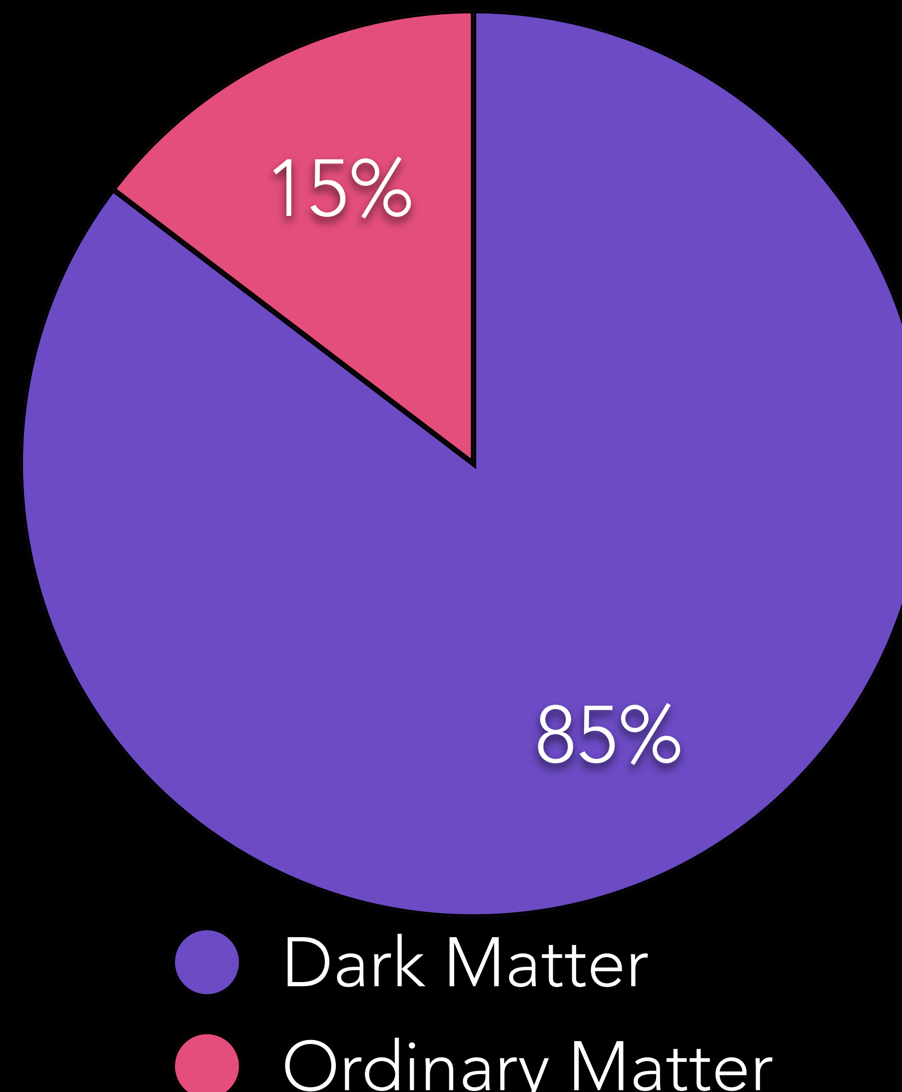
Fermions
"matter"




Bosons
"forces"

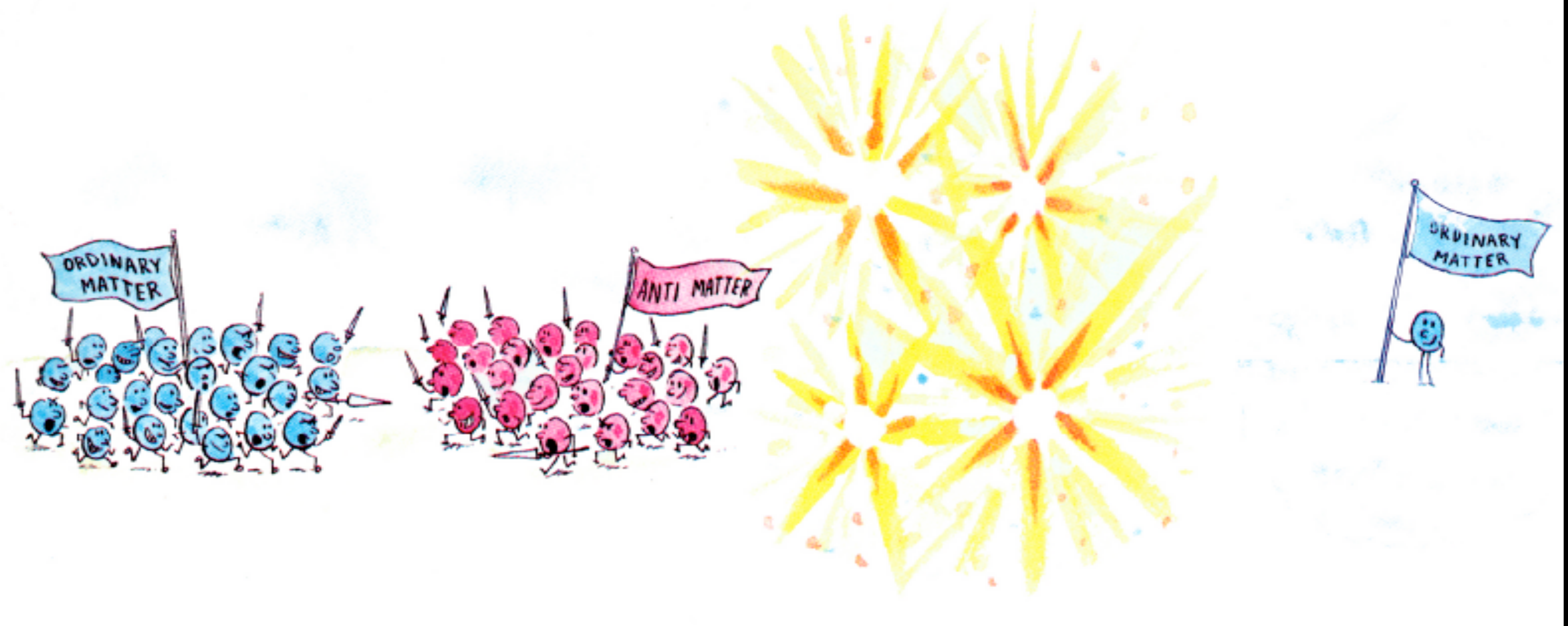


# SM PROBLEMS: DARK MATTER

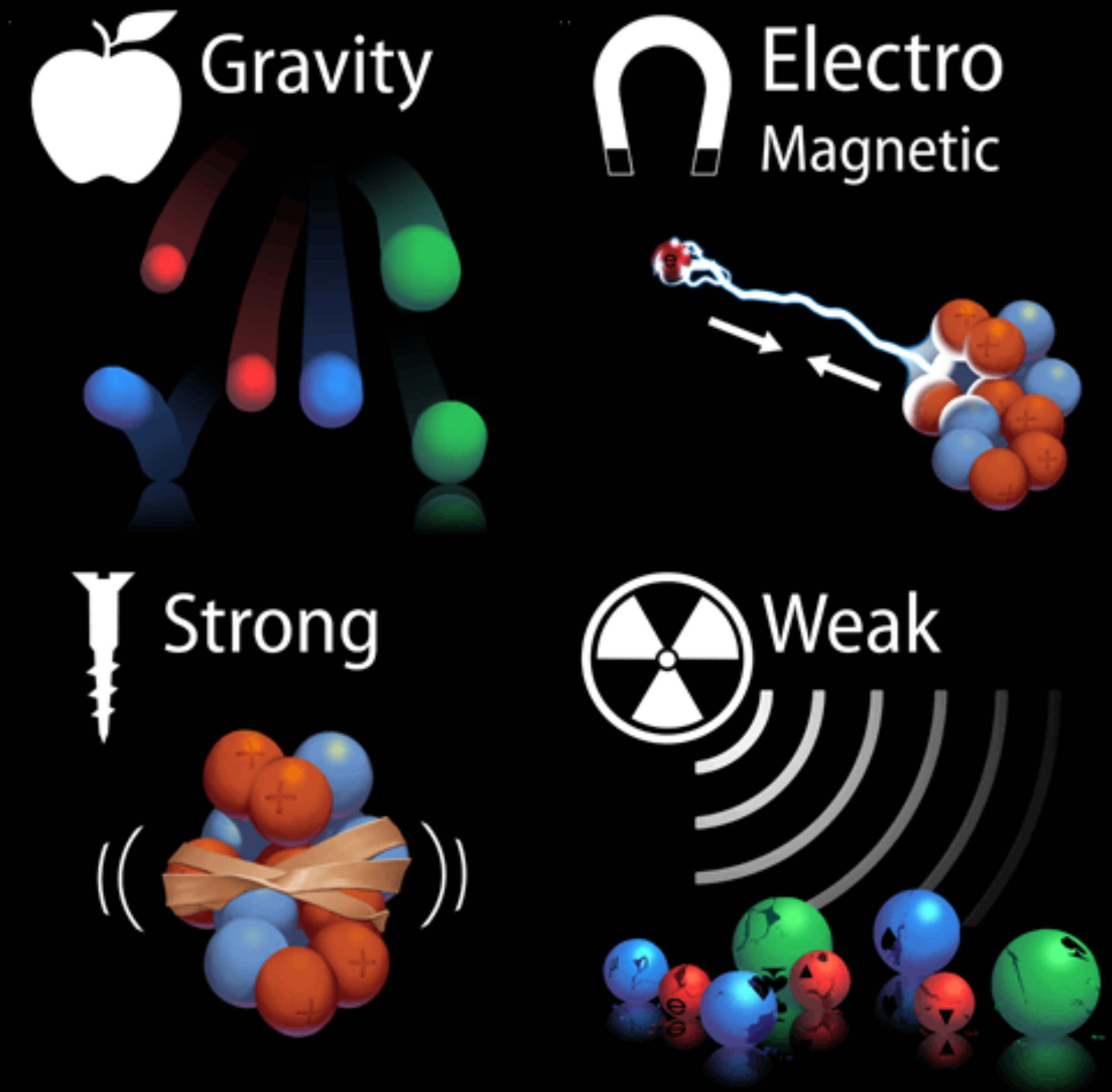



**Visible mass (gass) + dark mass**

# SM PROBLEMS: ANTIMATTER

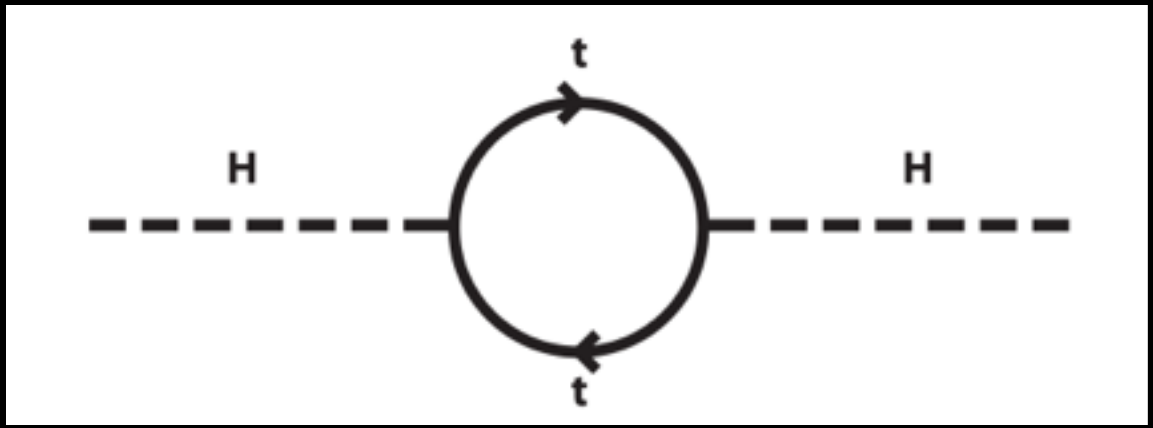


For every billion ordinary particles annihilating with antimatter in the early Universe, one extra was left "standing."


Gravity
Electro
Magnetic
Strong
Weak

# THE MASSIVE PROBLEM

- In 2012 the Higgs boson was discovered at the LHC, with a mass of 125 GeV
  - The Higgs field gives masses to fermions and bosons
  - But the Higgs mass itself is not fully explained …
  - It receives quantum mechanical corrections to its mass from other particles … including particles we don't know about




$$m_h^2 = m_{h,0}^2 + \delta m_h^2$$

Corrections from QM

# THE MASSIVE PROBLEM

$$m_h^2 = m_{h,0}^2 + \delta m_h^2$$

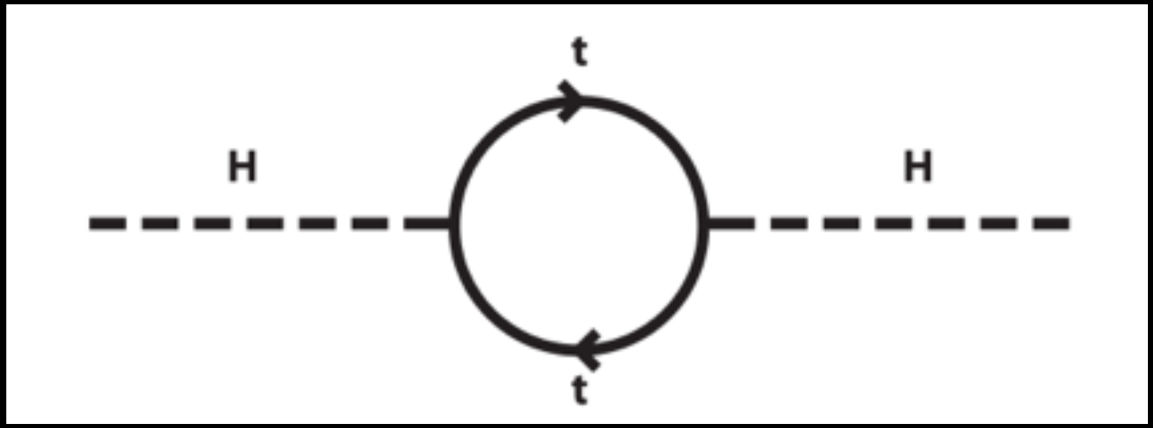
Correction from bosons

$$\delta m_{h,b}^2 \propto +g_b^2 m_b^2 \ln\left(\frac{m_b}{\mu}\right)$$

Correction from fermions

$$\delta m_{h,f}^2 \propto -g_f^2 m_f^2 \ln\left(\frac{m_f}{\mu}\right)$$

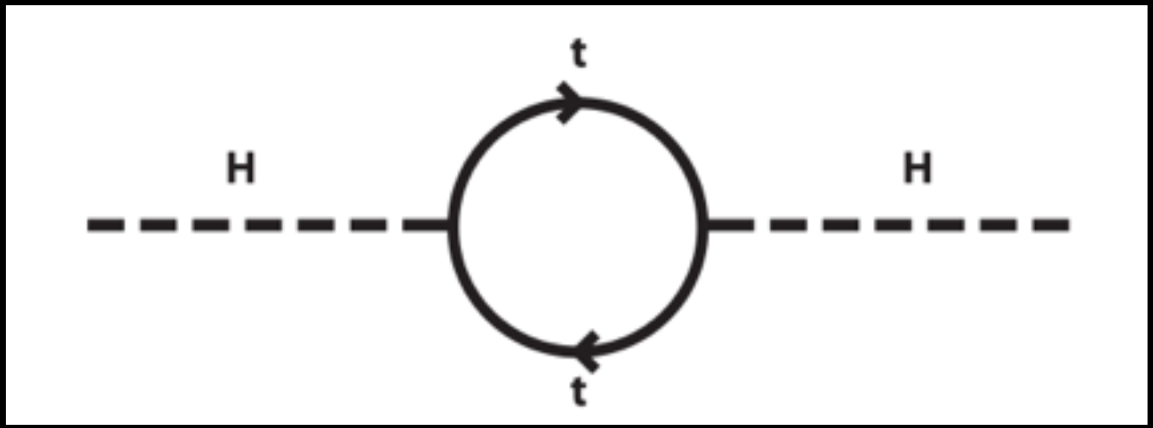
These masses could be very large, meaning the Higgs mass should be huge?

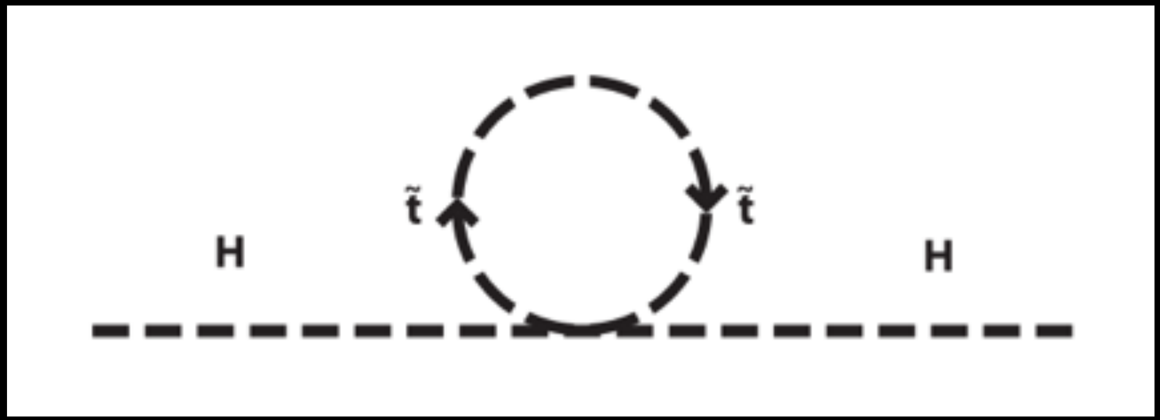


# SUPERSYMMETRY: HIGGS MASS

- Introduce a new boson for every fermion (+ vice versa)
- If they interact in the same way, and have the same mass, this new symmetry largely cancels out divergence!

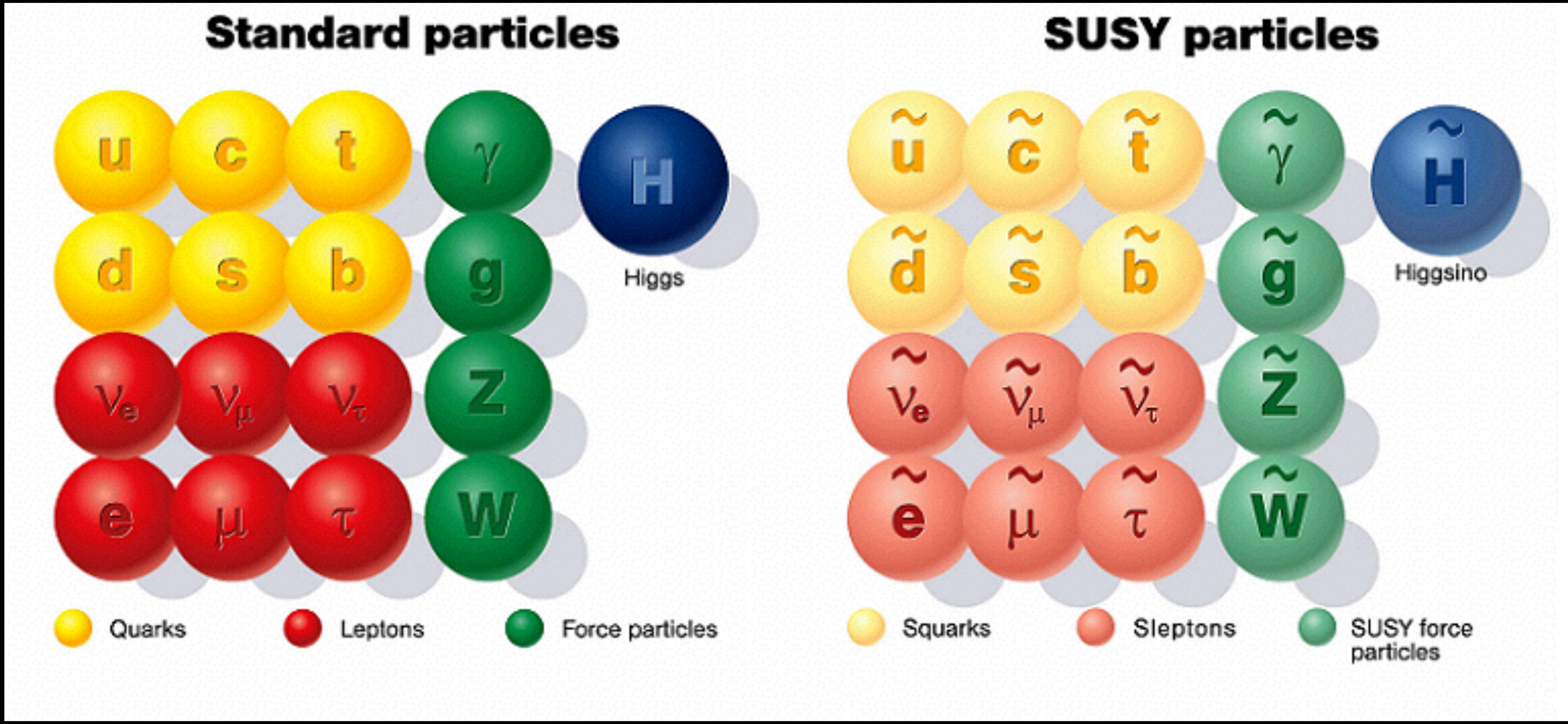
$$\delta m_h^2 \propto g^2(m_b^2 - m_f^2)\ln\left(\frac{m_b}{m_f}\right)$$



# SUPERSYMMETRY

Half of the particles the theory predicts have already been discovered



# SUPERSYMMETRY: DARK MATTER

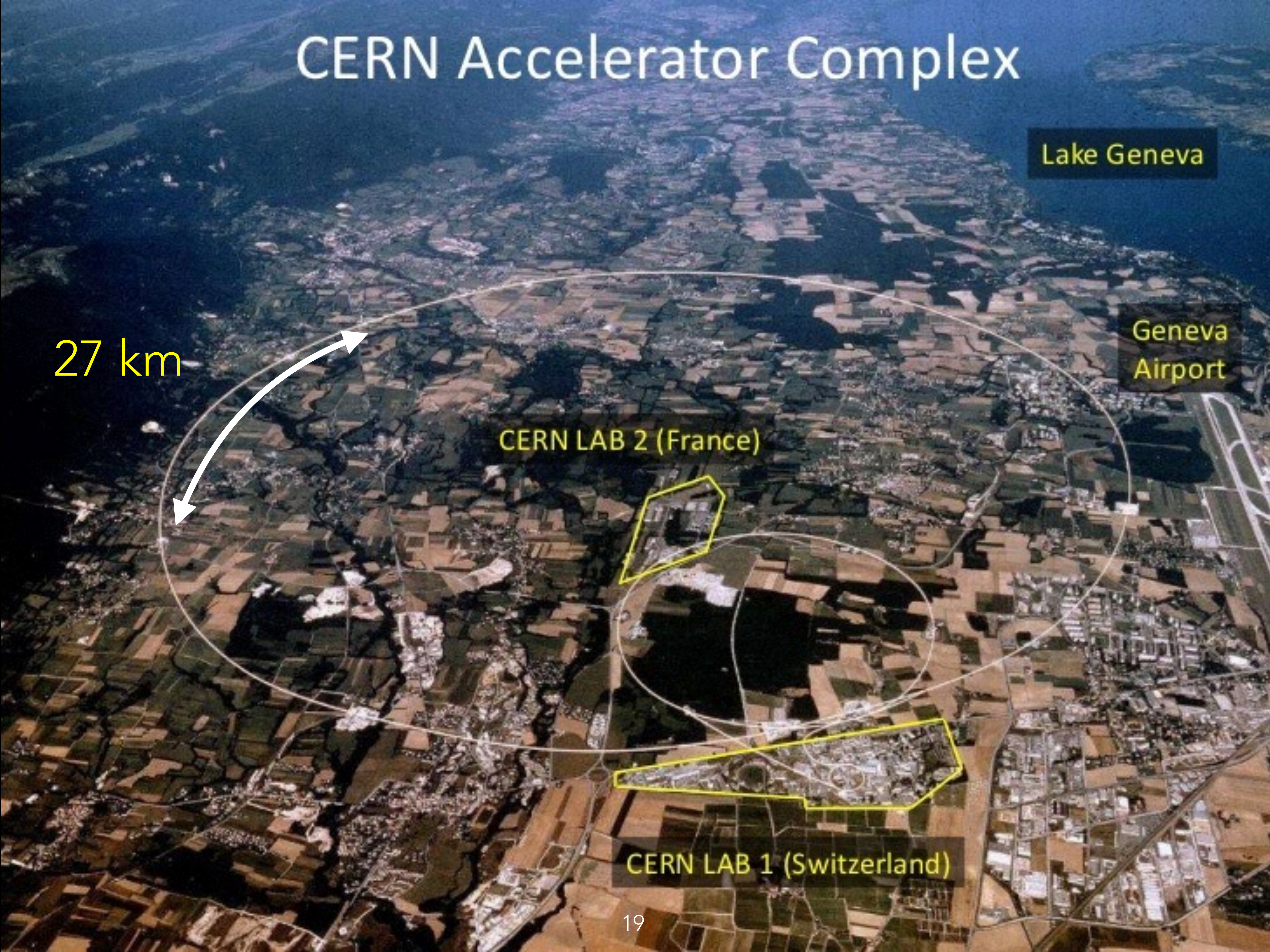
- SUSY particles can have strong, electromagnetic, weak and gravitational interactions
- If any of the particles were to have strong or EM interactions and were stable, we would notice them very quickly
- Therefore if there are any stable SUSY particles, they can only have weak+gravitational interactions
- This makes them an **ideal Dark Matter candidate**!

# HOW TO FIND SUSY IN 5 EASY STEPS

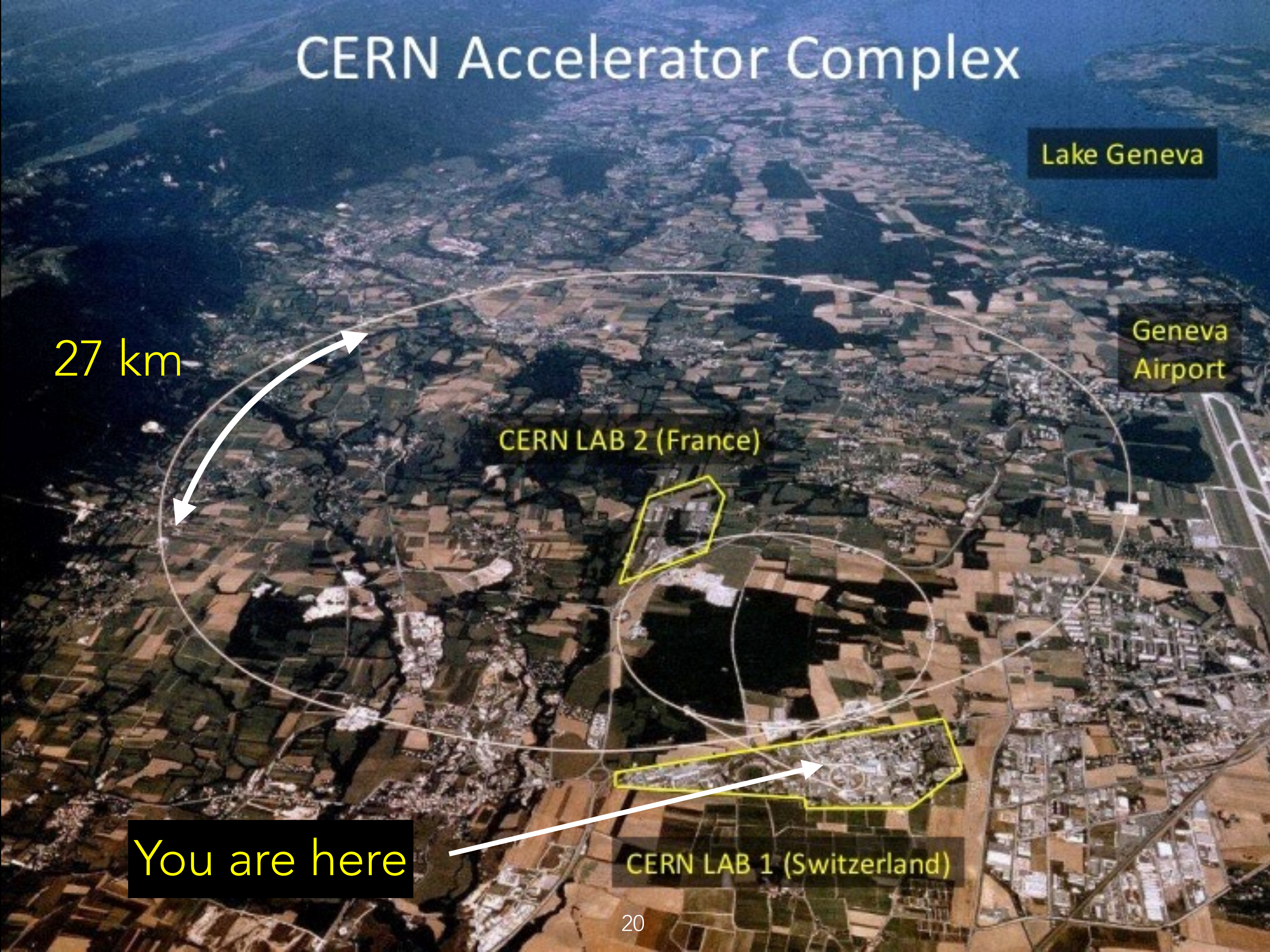
# HOW TO FIND SUSY IN 5 EASY STEPS

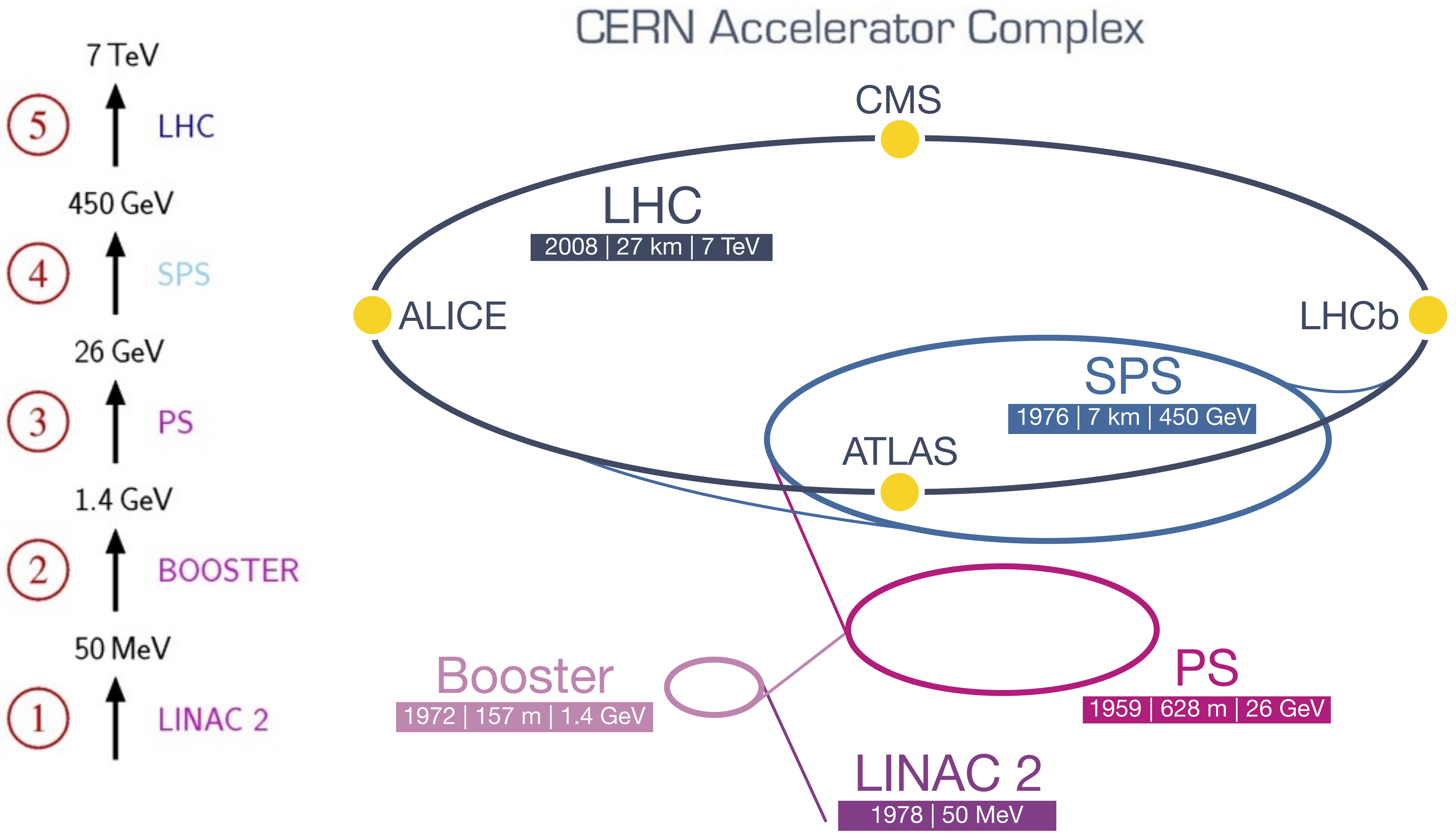
1. Build a Large Hadron Collider

# CERN Accelerator Complex



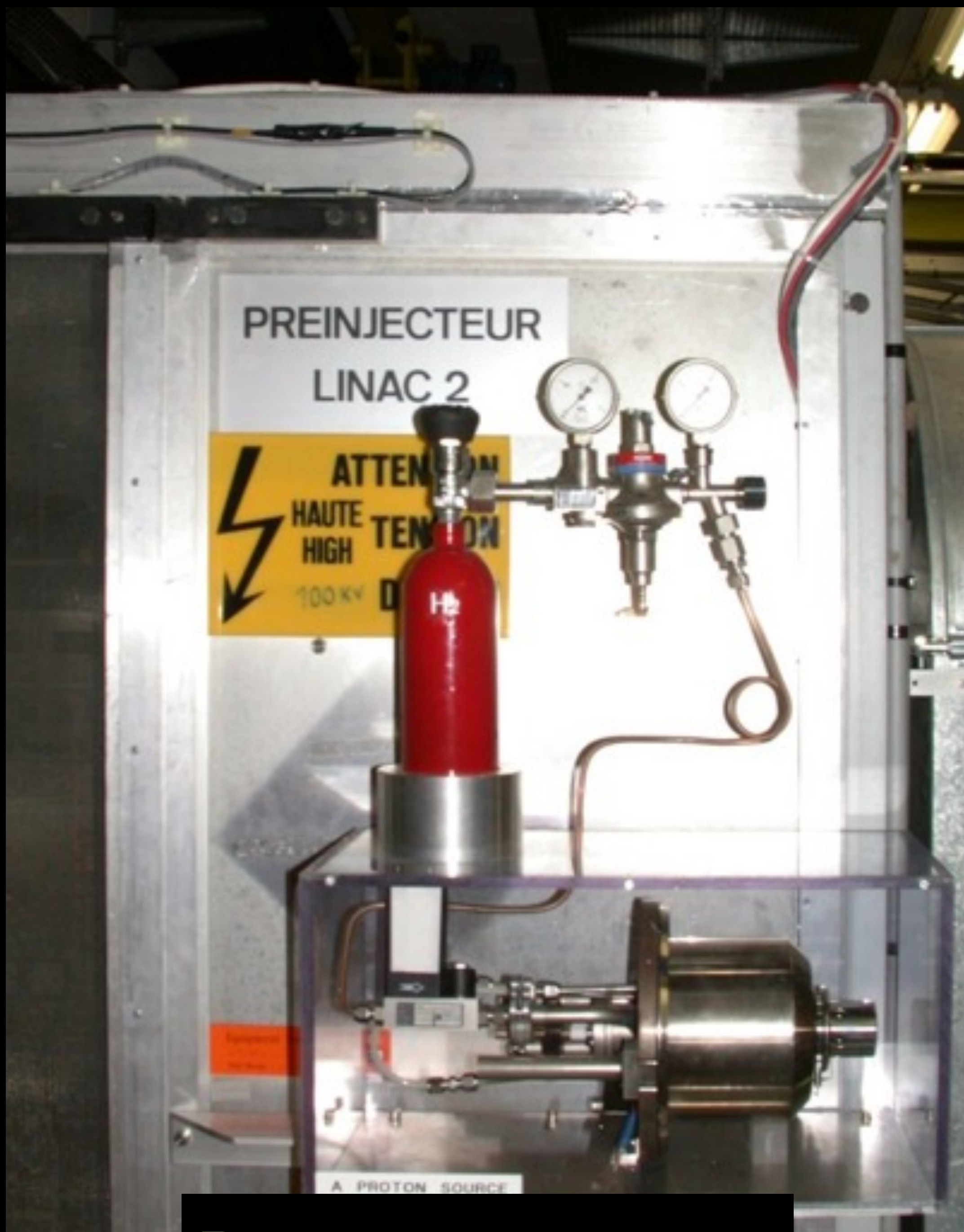
# CERN Accelerator Complex





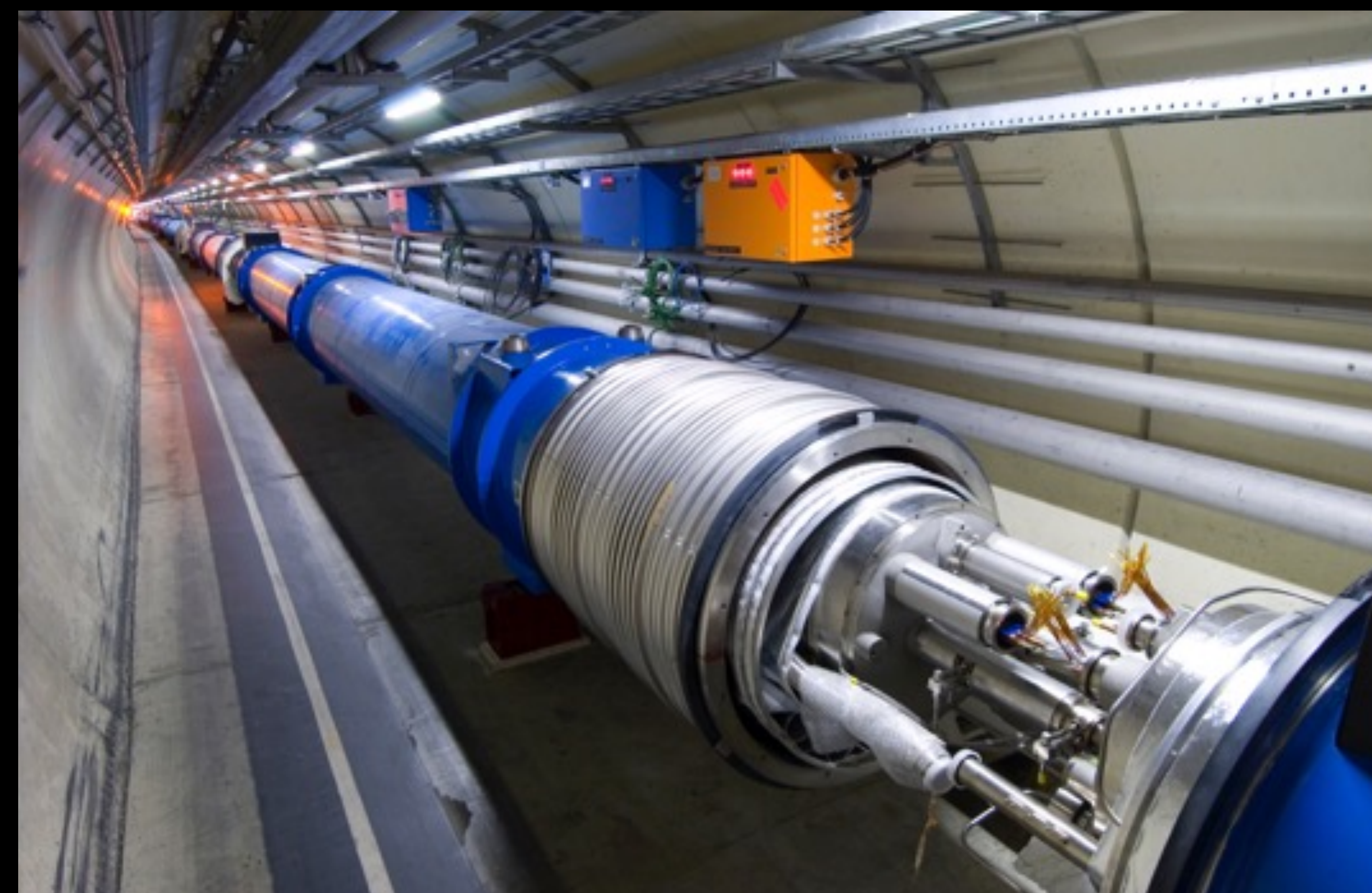

1 GeV = 1 proton mass

$E=mc^2$




Proton source

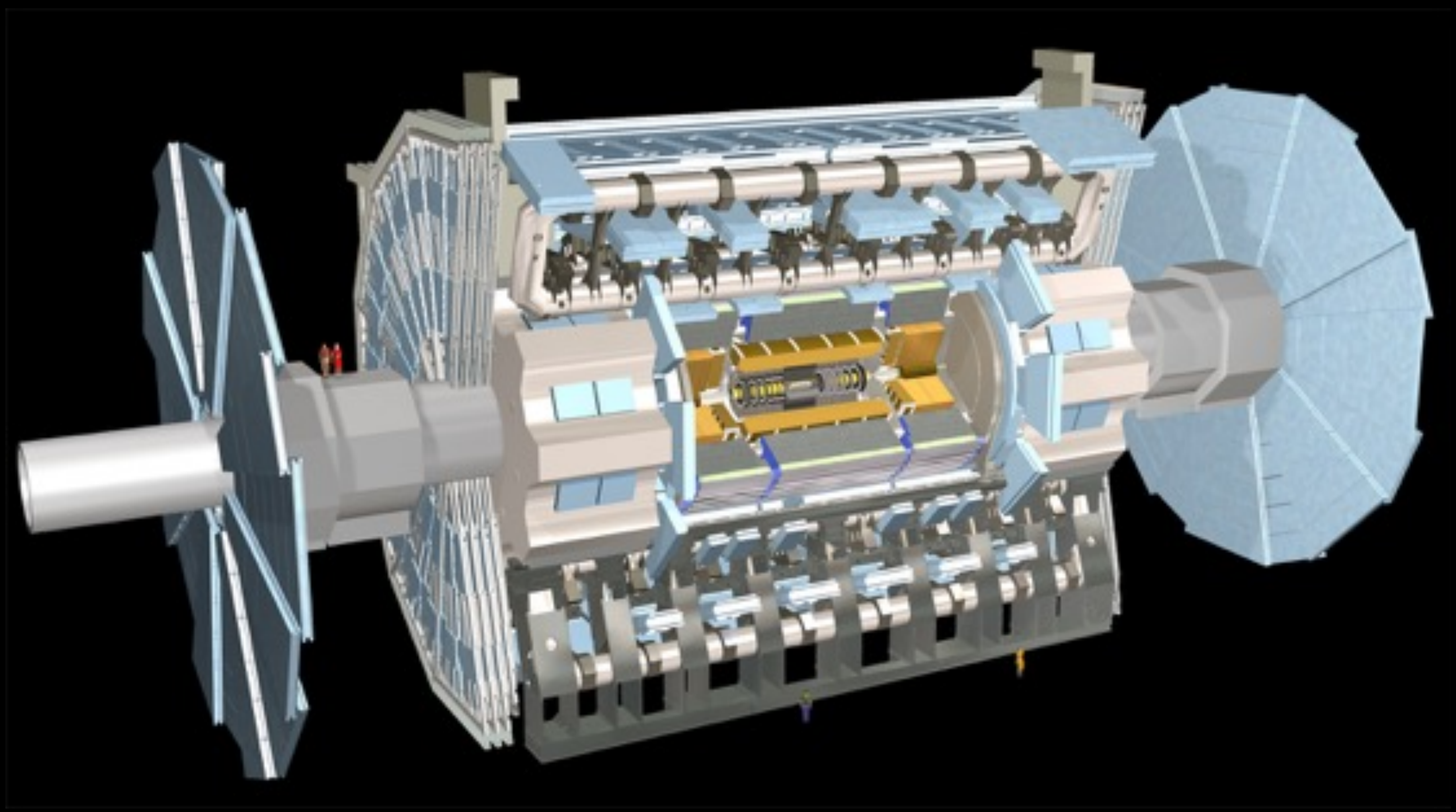
LHC beam pipe
100m underground



# HOW TO FIND SUSY IN 5 EASY STEPS

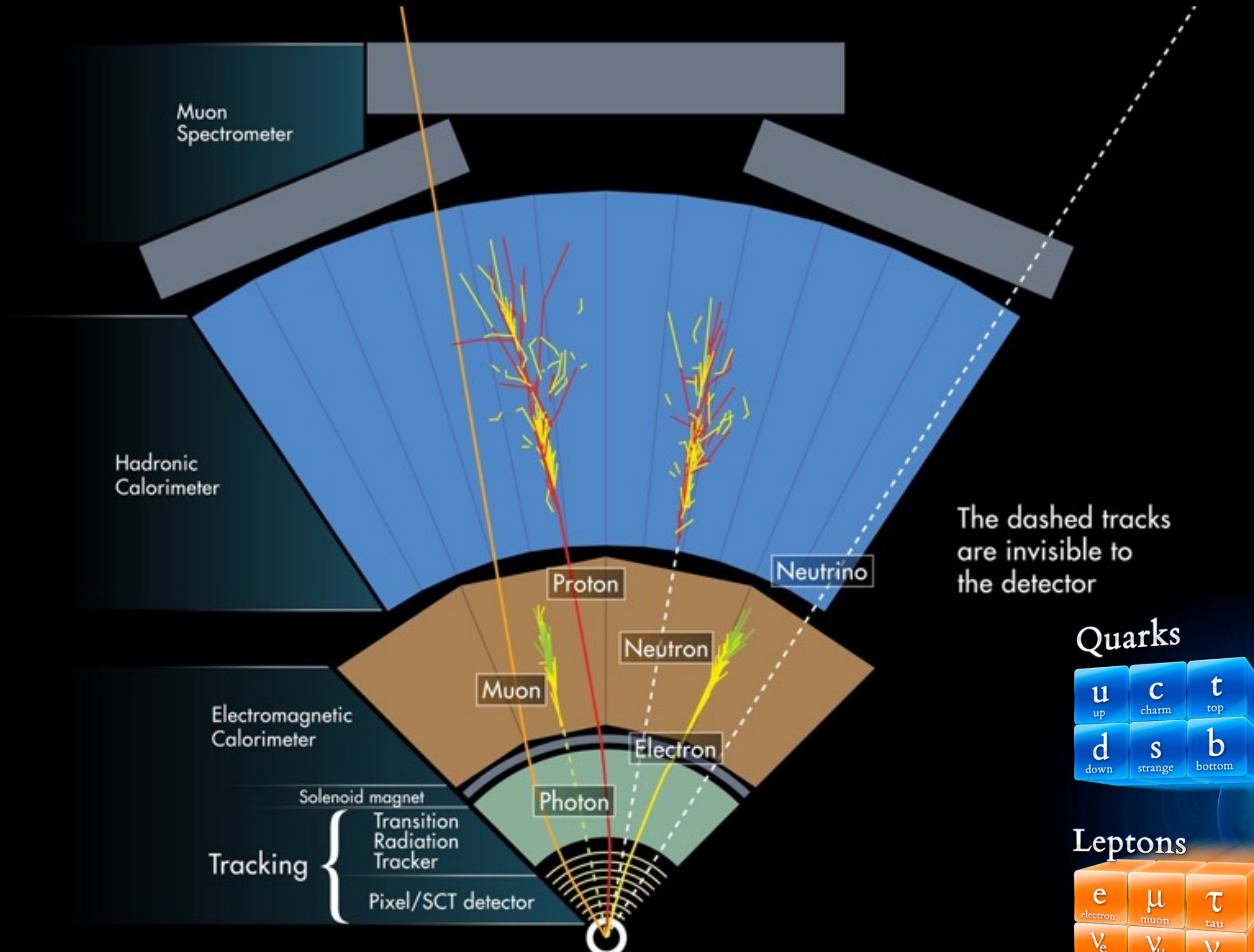
1. Build a Large Hadron Collider ✔
2. Build a particle detector — The ATLAS experiment

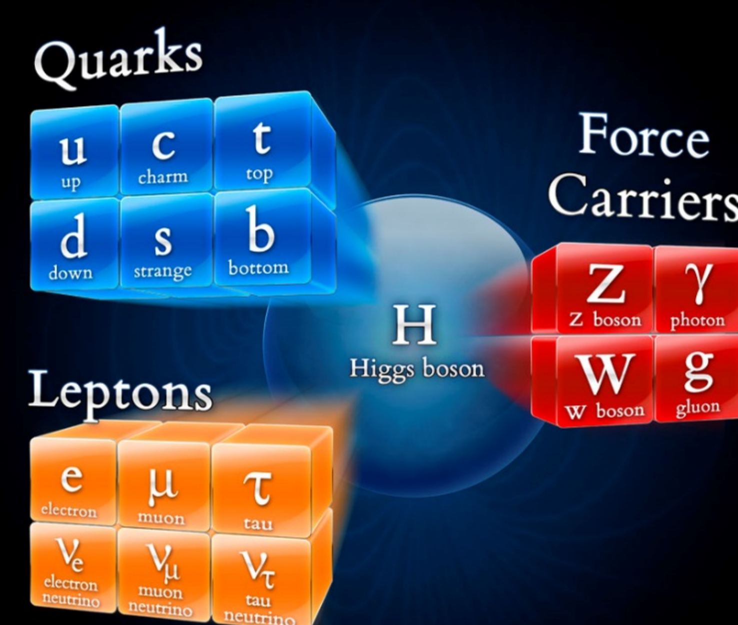
# THE ATLAS EXPERIMENT

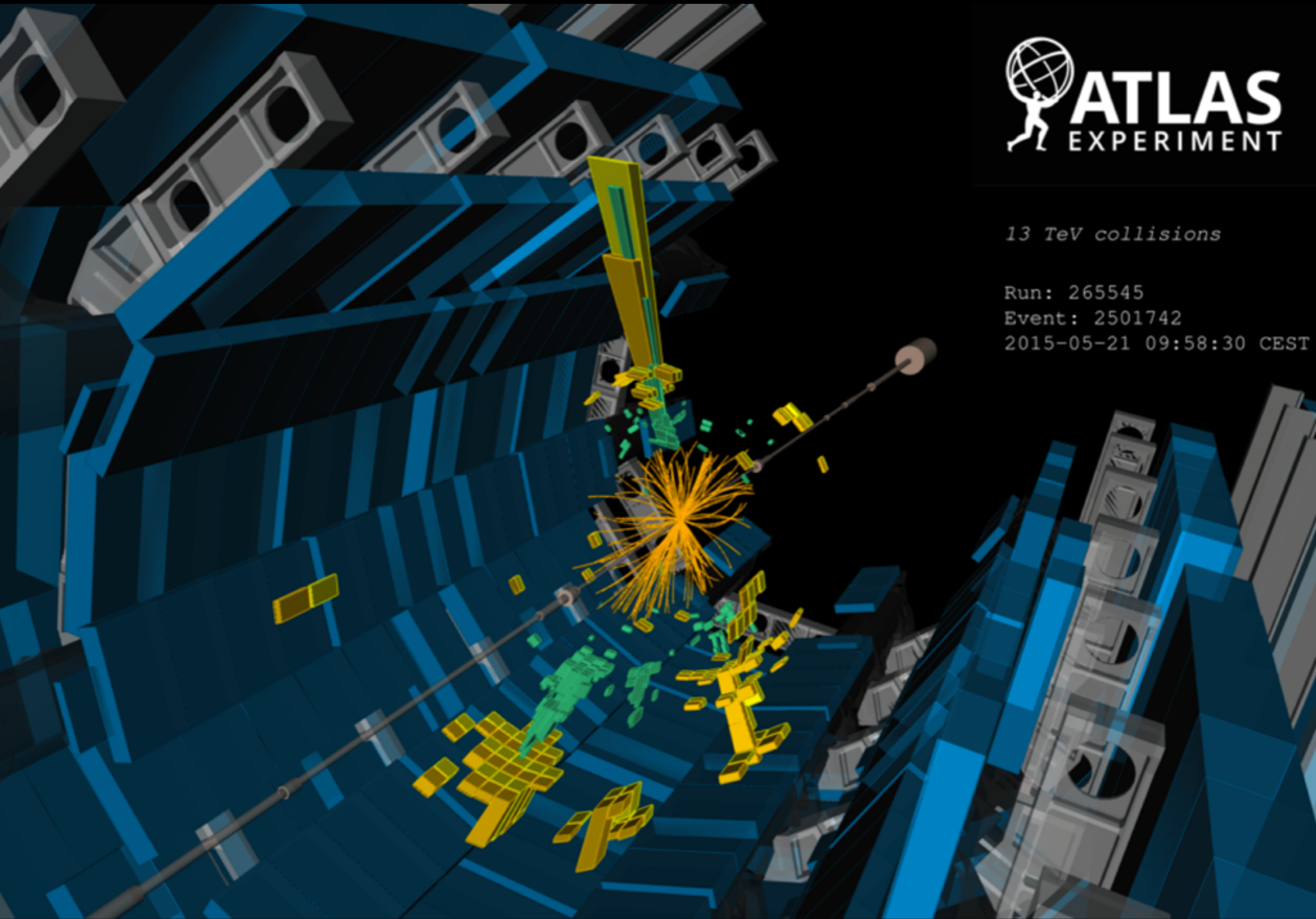


- Massive, custom built experiment
- 12 stories high, 46m long
- 7000 tonnes
- ~3000 physicists + engineers
- 160 Megapixel
  40M snapshots / second

# PARTICLE DETECTION




ATLAS
EXPERIMENT
13 TeV collisions
Run: 265545
Event: 2501742
2015-05-21 09:58:30 CEST


dapnia
cea
saclay

# HOW TO FIND SUSY IN 5 EASY STEPS

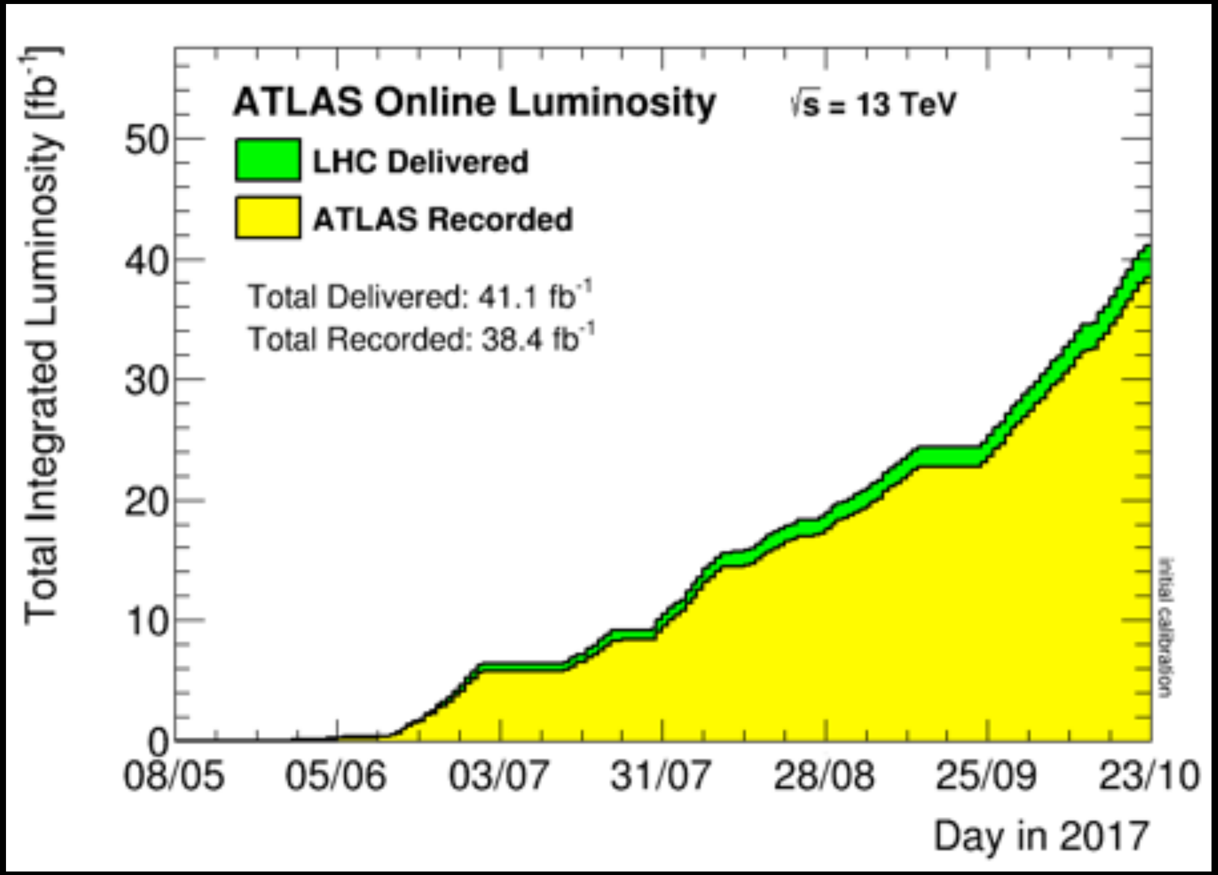
1. Build a Large Hadron Collider ✔

2. Build a particle detector — The ATLAS experiment ✔

3. Collect data — ongoing!

# DATA TAKING

- In 2015 data-taking resumed
- LHC centre-of-mass energy of 13 TeV
- 2000 bunches of protons in the machine
- $10^{11}$ protons per bunch
- 150 MJ of  evergy in the beam

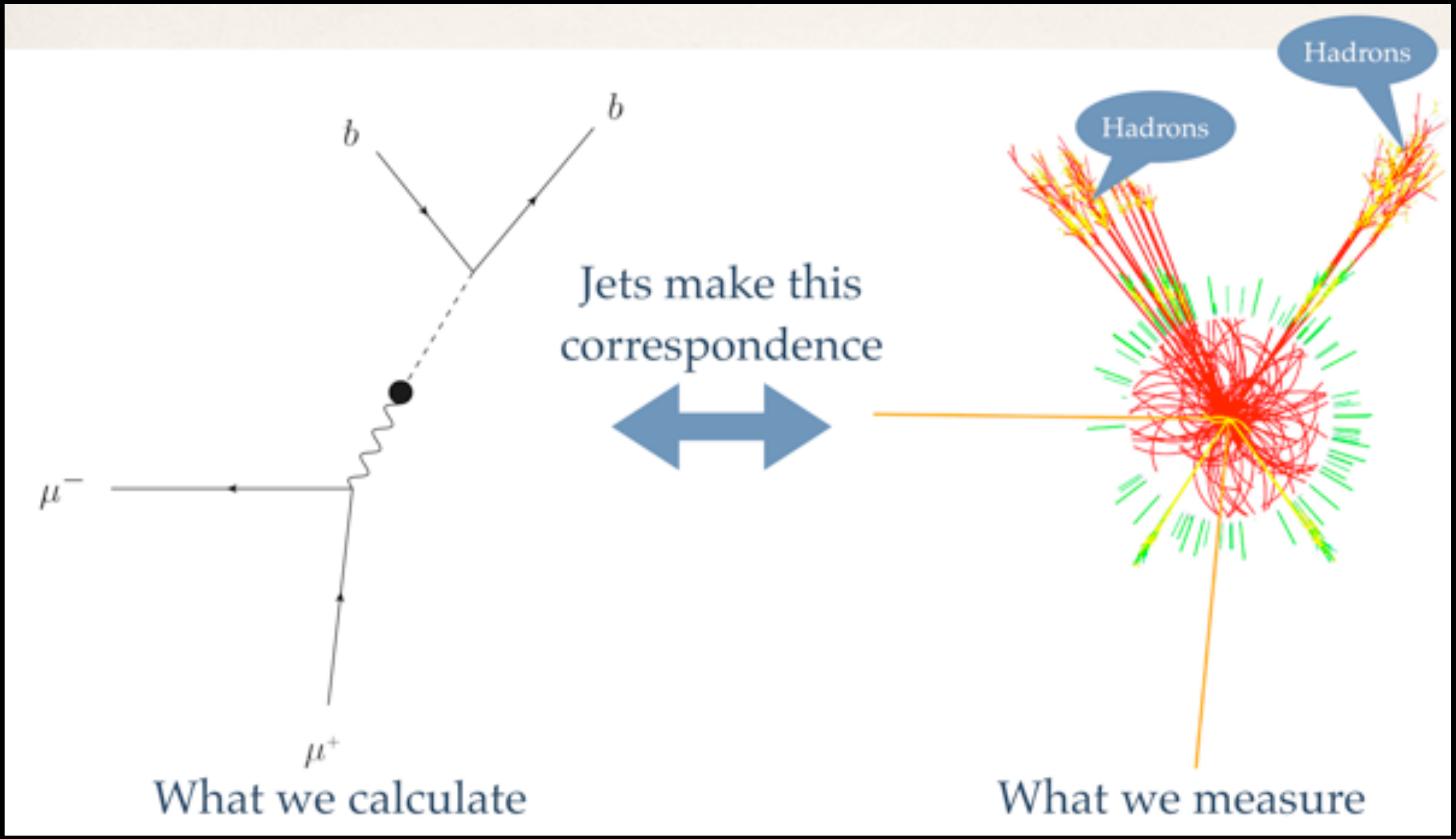



Tuesday June 2nd

# HOW TO FIND SUSY IN 5 EASY STEPS

1. Build a Large Hadron Collider ✔
2. Build a particle detector — The ATLAS experiment ✔
3. Collect data — Finished yesterday ✔
4. Analyse the data

# JETS

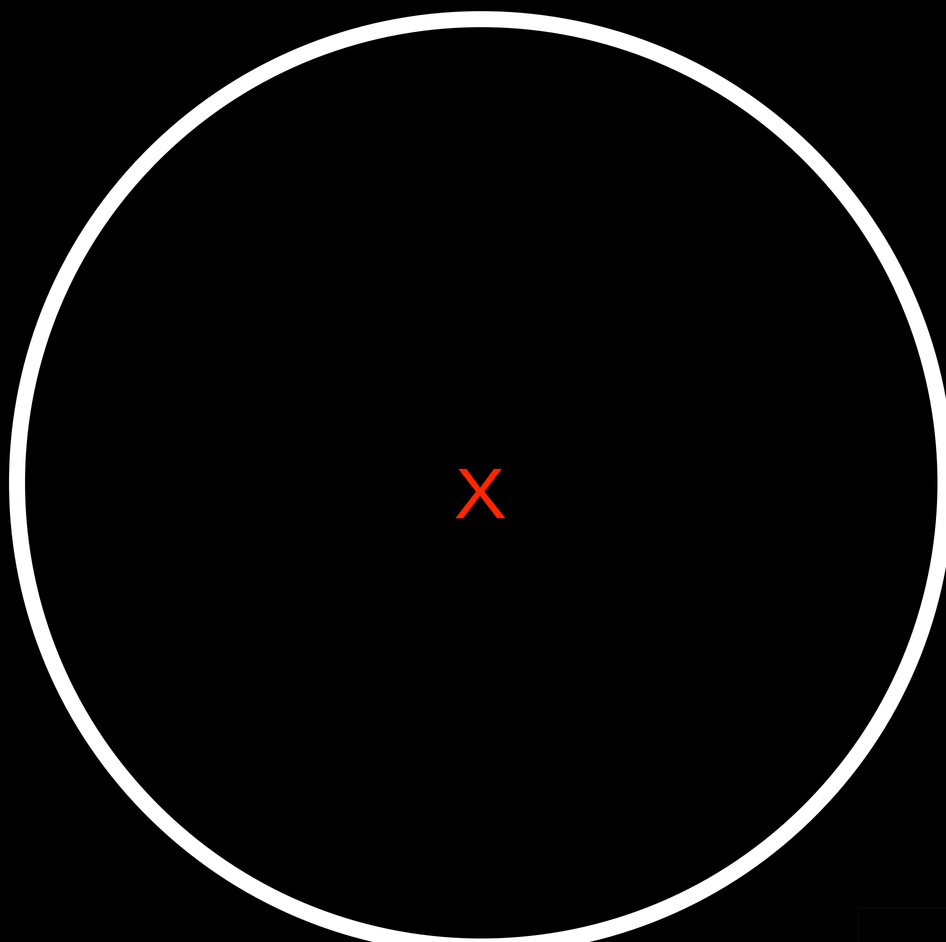


Hadrons
Hadrons
b
b
Jets make this correspondence
μ⁻
μ⁺
What we calculate
What we measure

# MISSING TRANSVERSE ENERGY

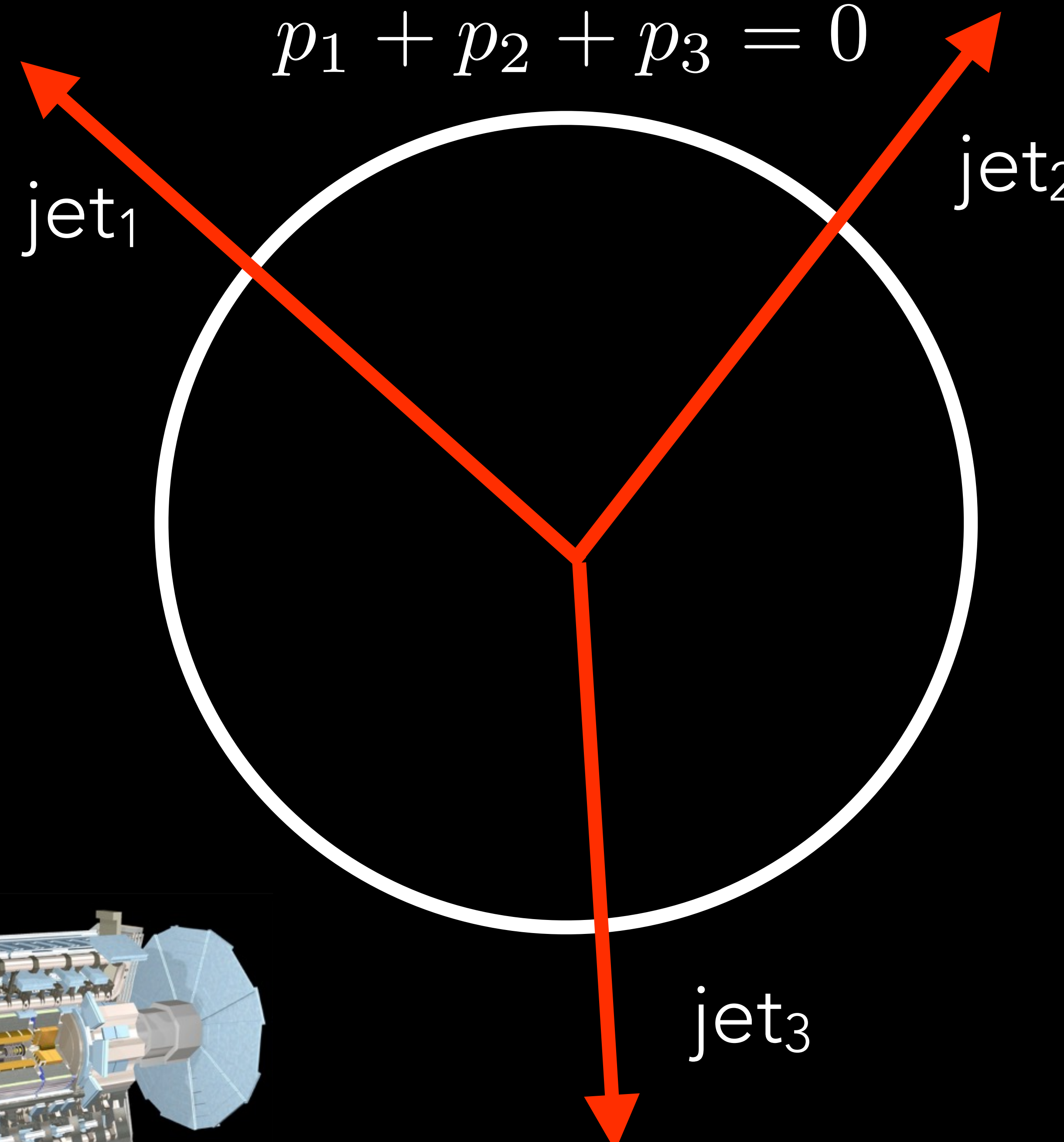
## Before

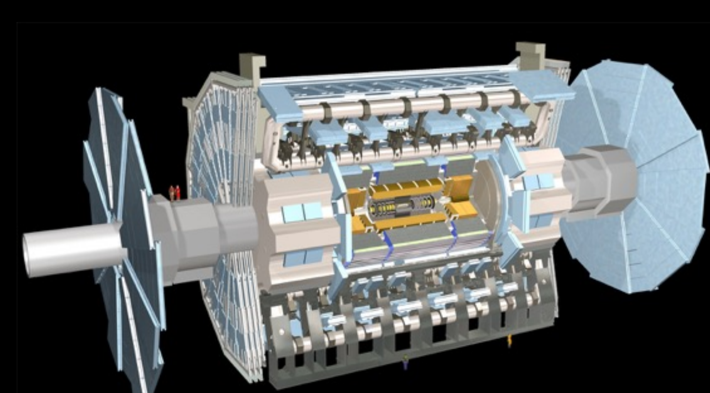
Momentum balances



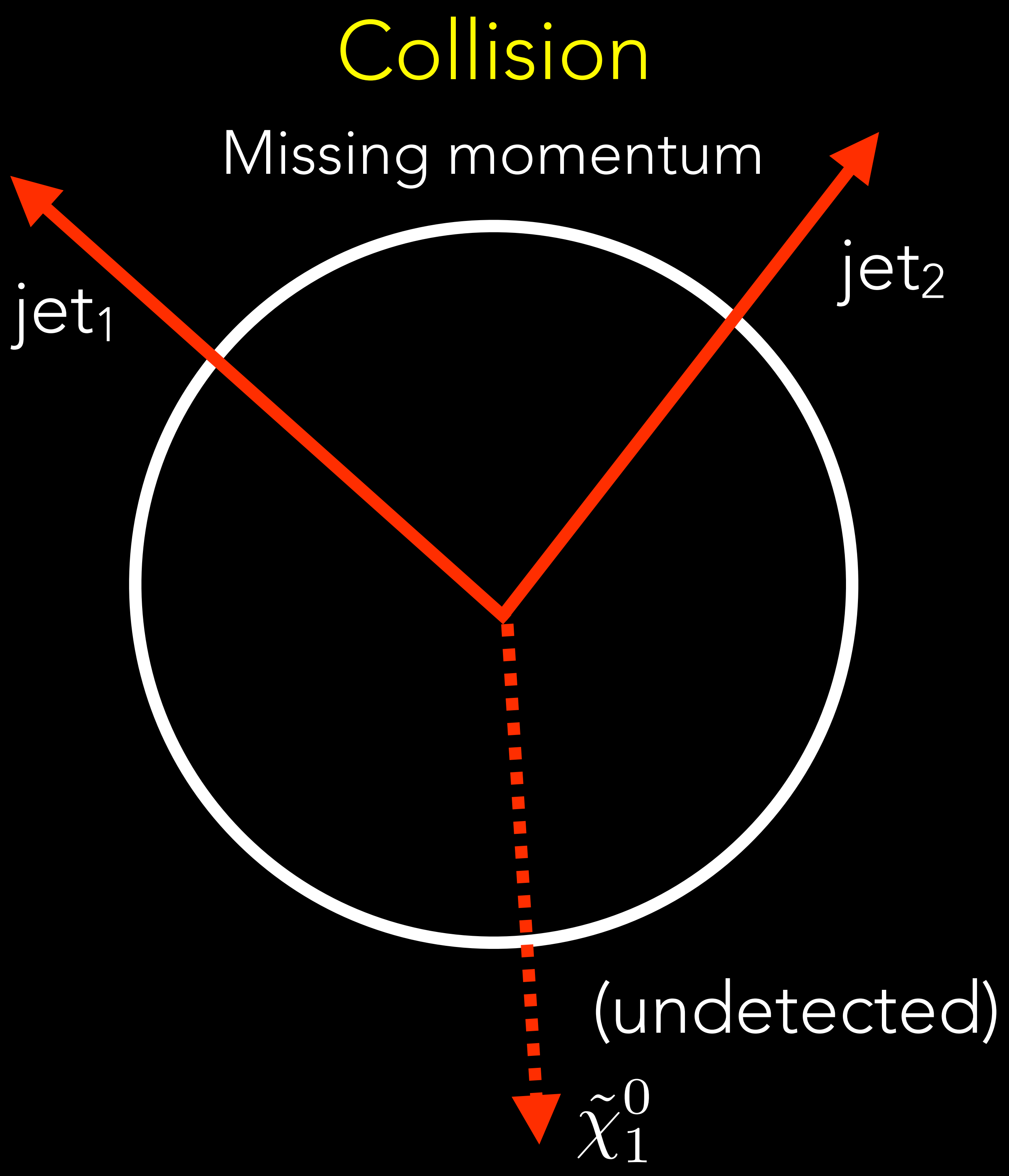

## Collision

$$p_1 + p_2 + p_3 = 0$$



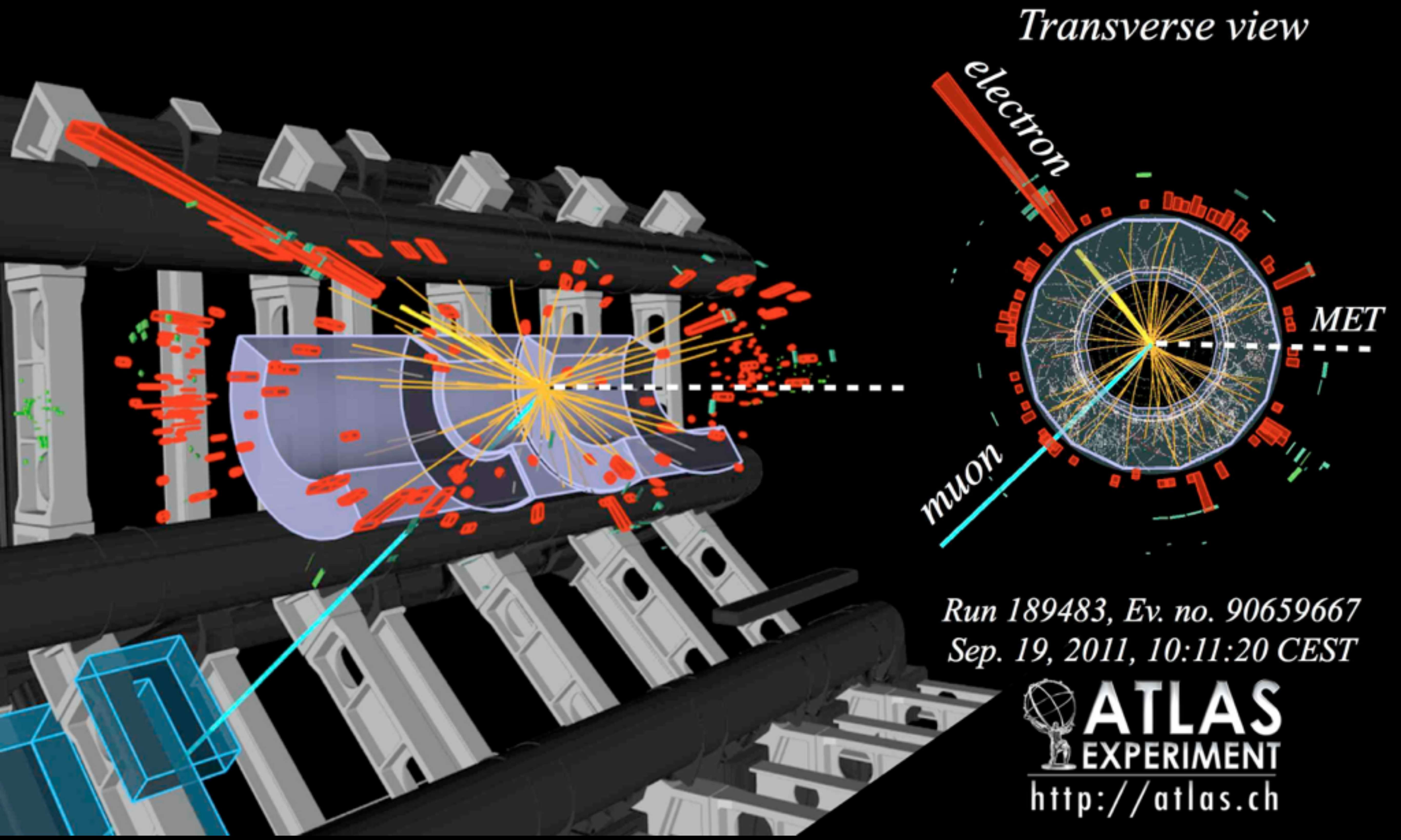



# MISSING TRANSVERSE ENERGY




$$p_3^{miss} = -(p_1 + p_2)$$

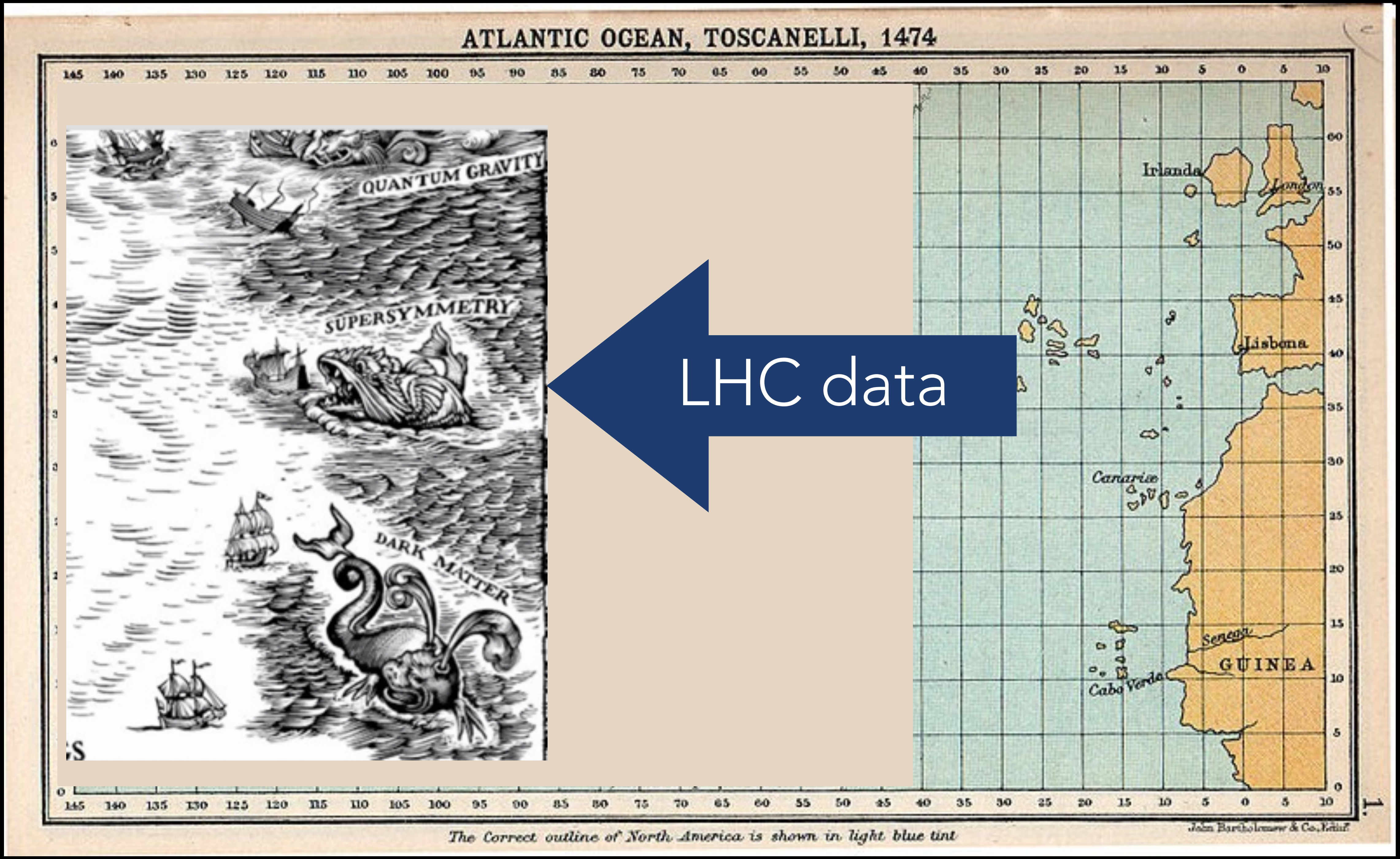
# MISSING TRANSVERSE ENERGY



# HOW TO FIND SUSY IN 5 EASY STEPS

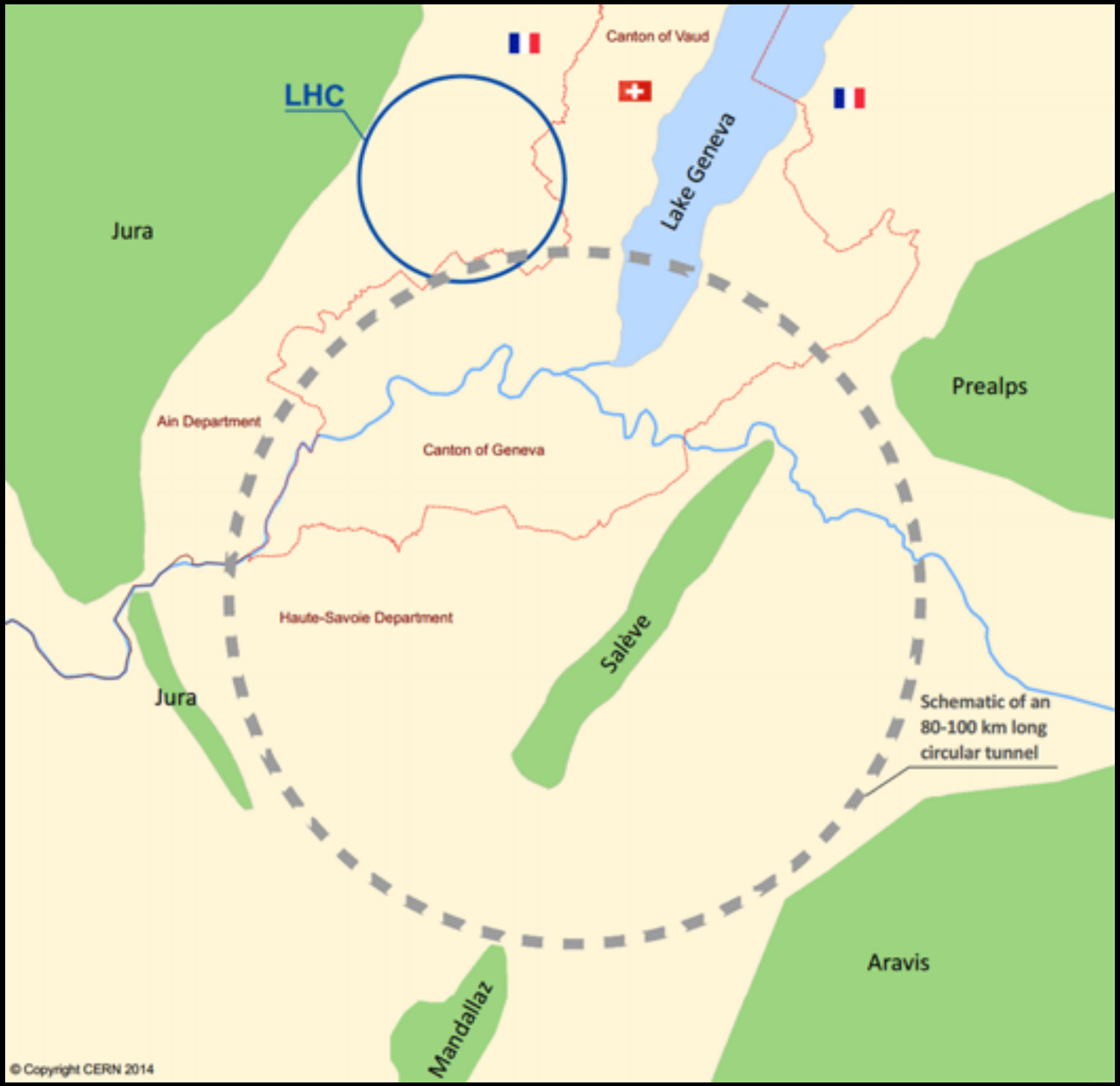
1. Build a Large Hadron Collider ✔
2. Build a particle detector — The ATLAS experiment ✔
3. Collect data — ongoing ✔
4. Analyse the data — ongoing
5. Find SUSY ???

# THANKS FOR LISTENING



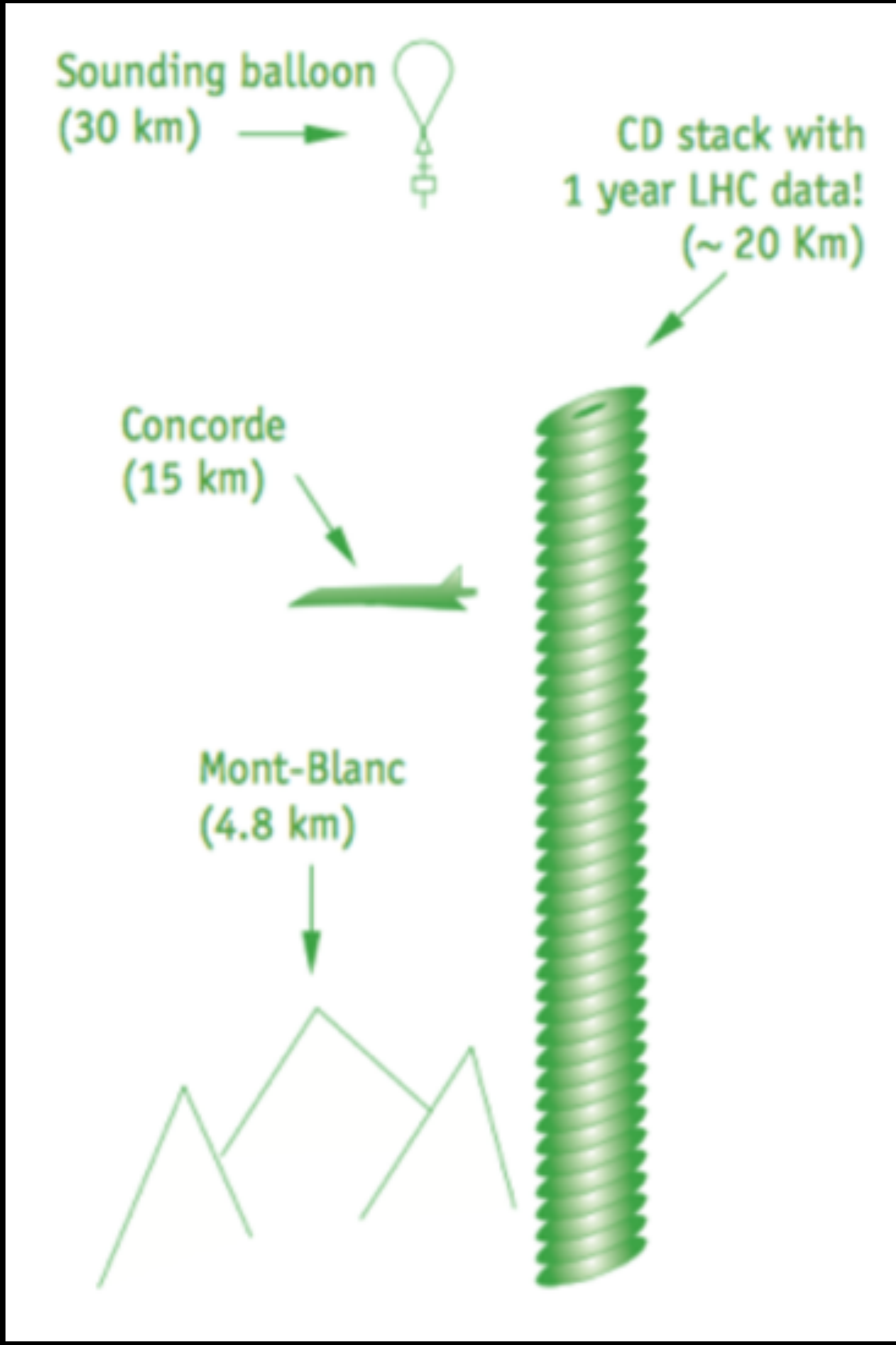
# EXTRA

# VERY LARGE HADRON COLLIDER



# DATA TAKING RATE

- LHC collides protons at 40 MHz
  - Each “event” (particle collision) takes ~1 MB to store
  - 40 GB/s
  - ~0.1 EB/month
- World: ~EB/year
- Cannot store all this. Must record most interesting events



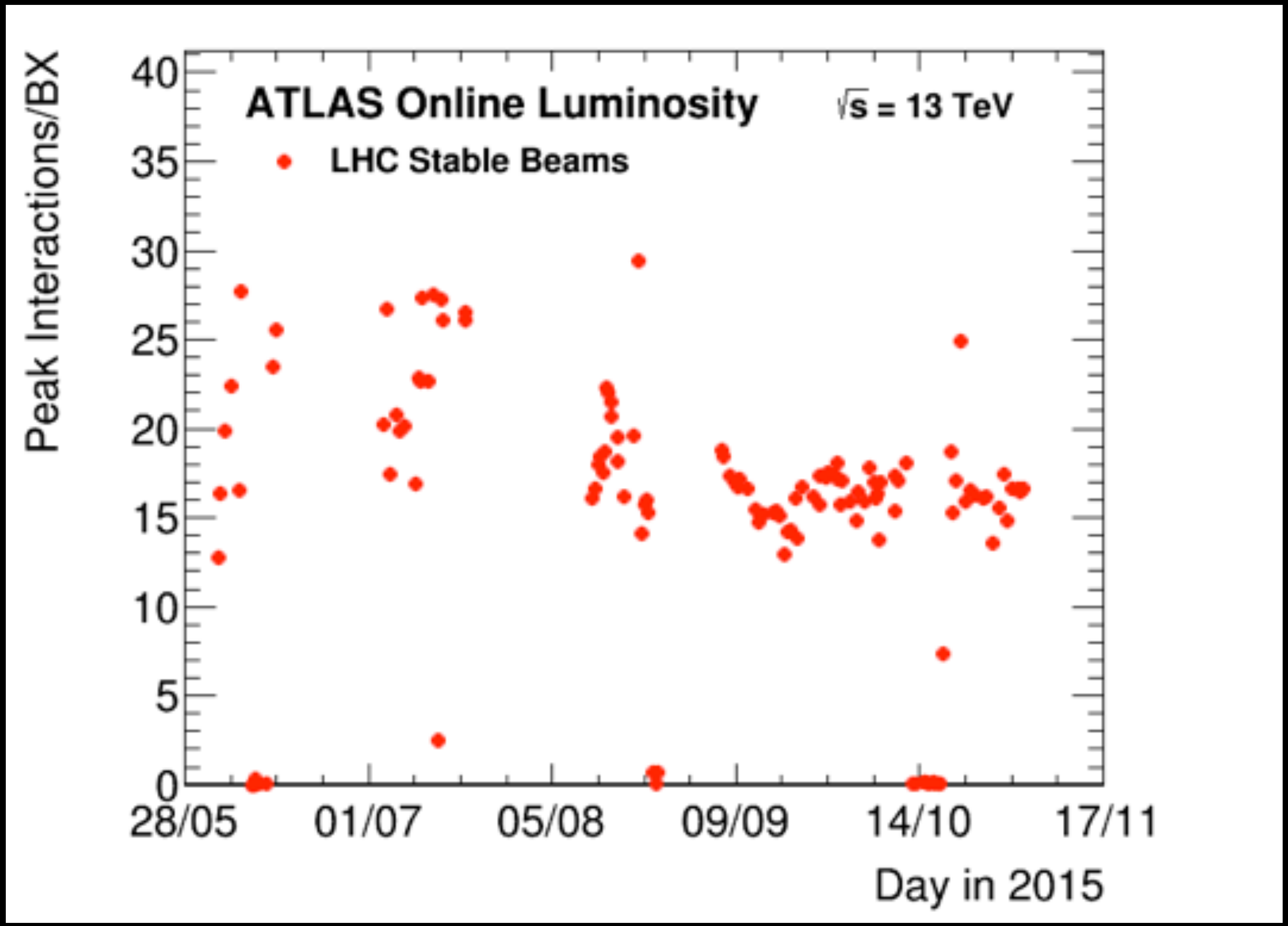
# ATLAS TRIGGER SYSTEM

- The “trigger system” is used to “fire” on interesting events
- Split into two levels: L1 (hardware). HLT (software)
- L1 rate: 1 kHz
- HLT rate: 100 Hz
- So only record 1 in 400,000 events
- 250 TB/month (although LHC not continuously running!)

# PILEUP

Mean:

13 interactions / BX



# BLIND ANALYSIS

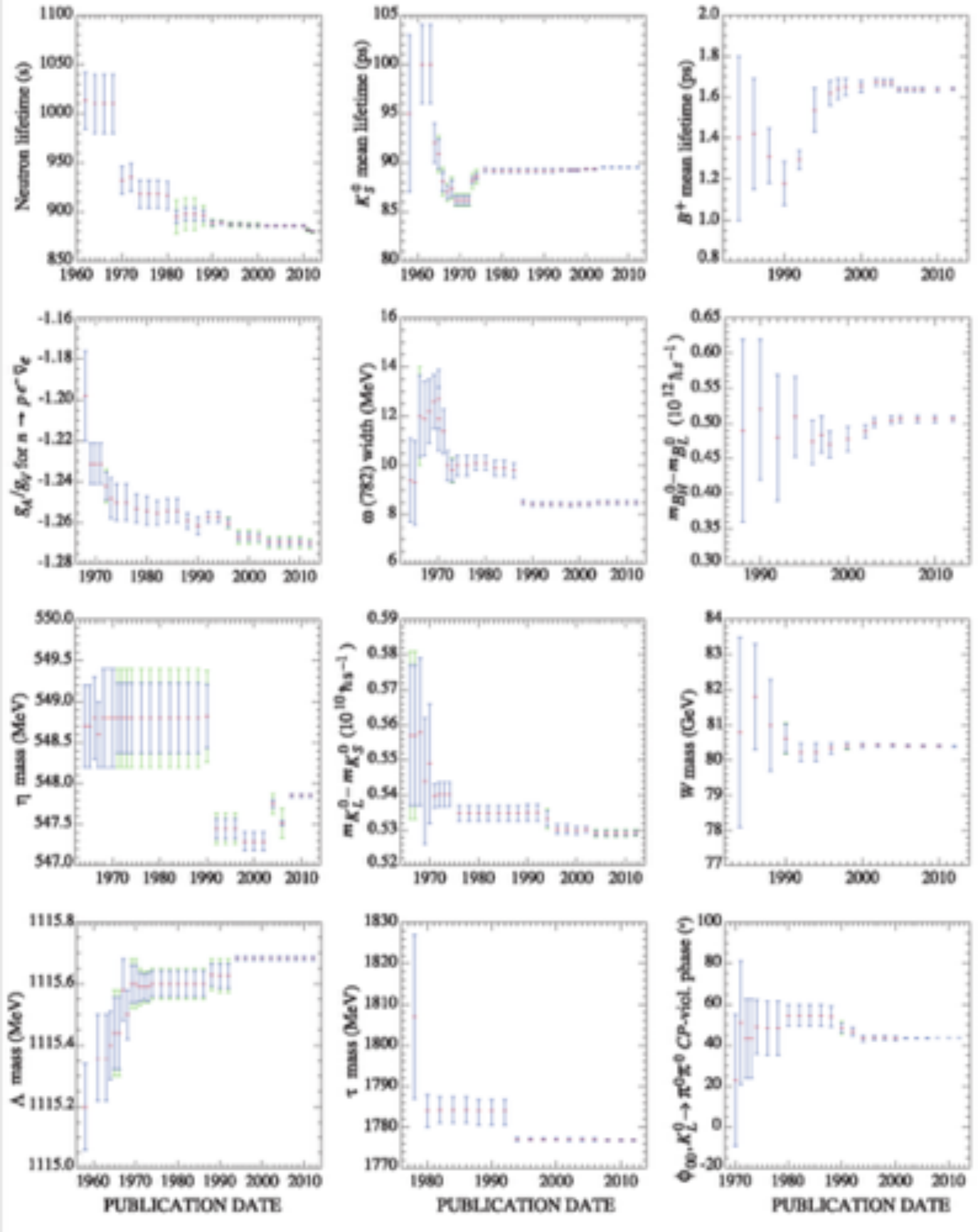
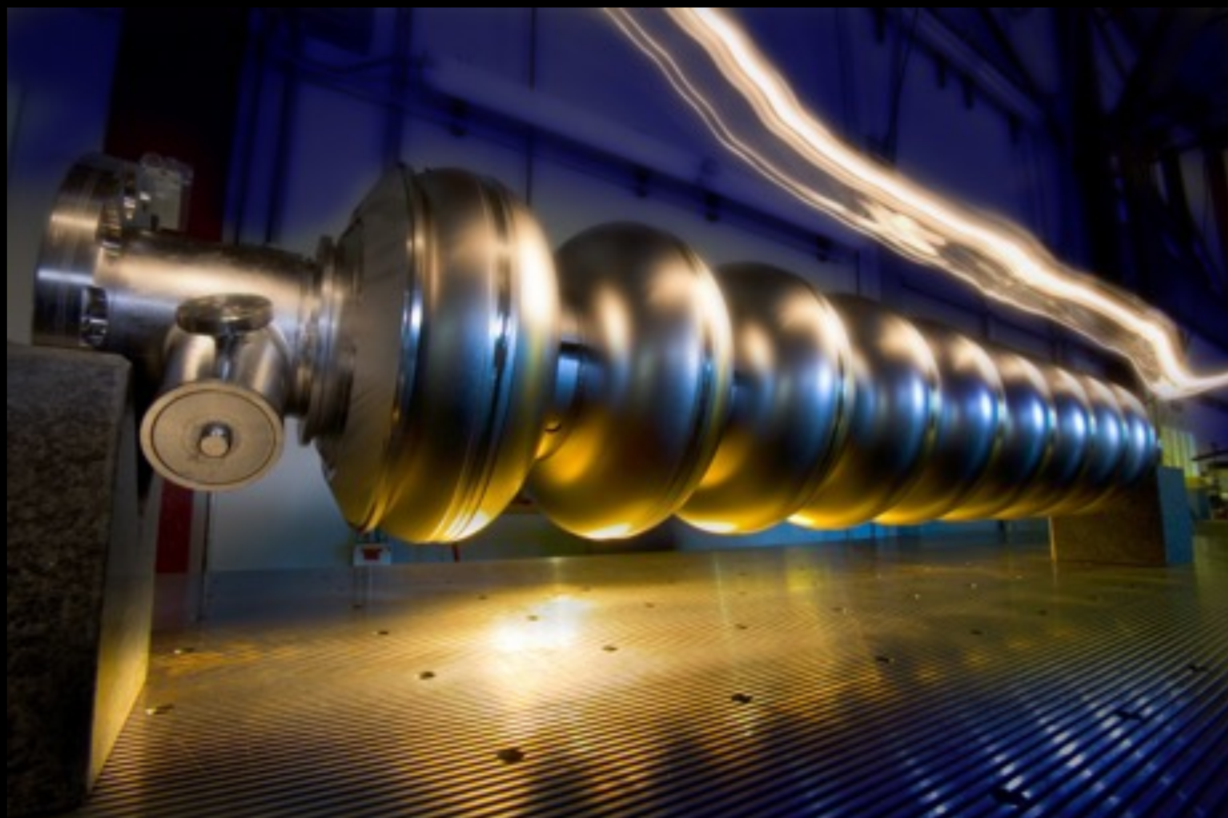
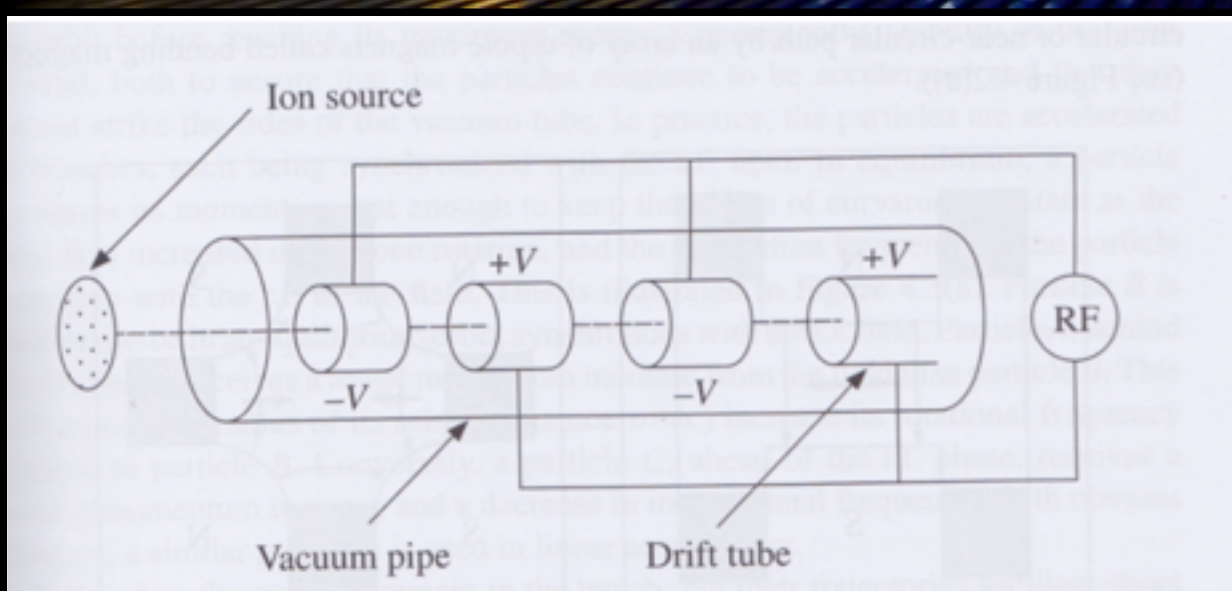
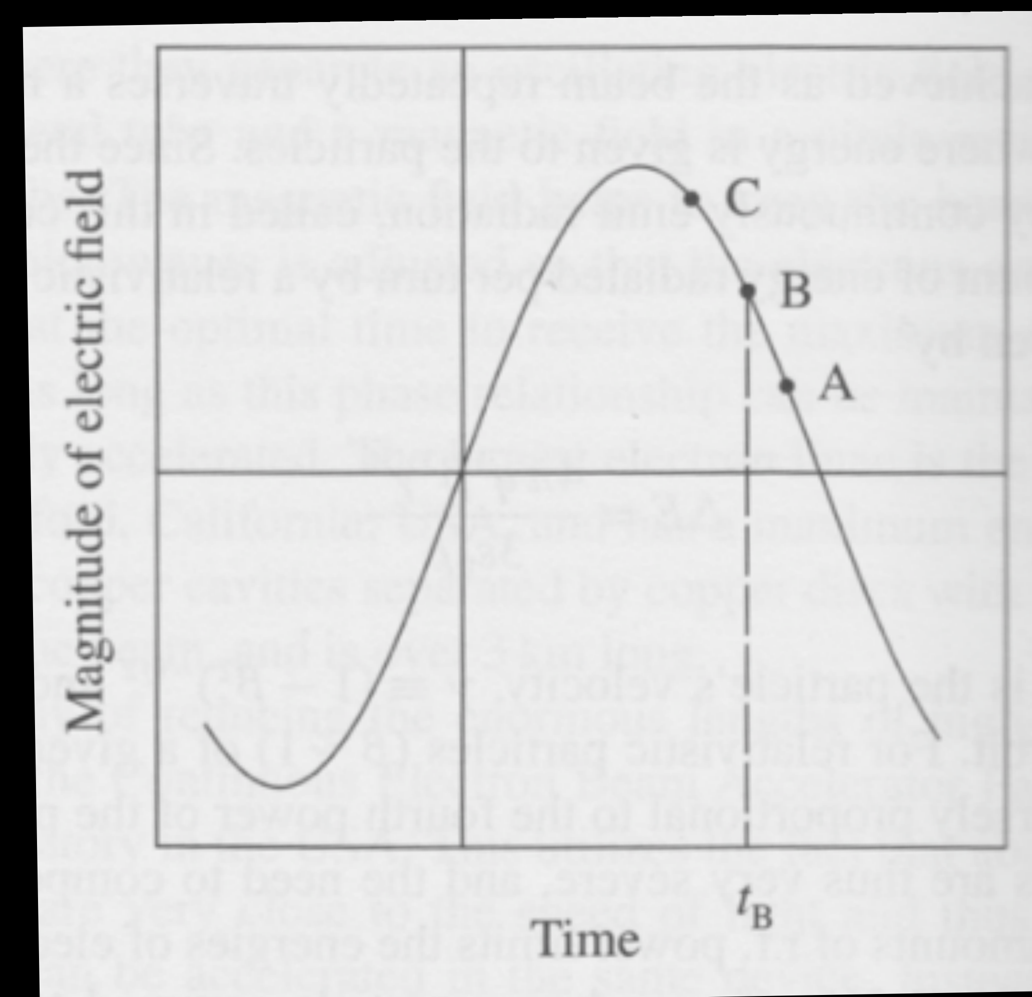



**Figure 2:** A historical perspective of values of a few particle properties tabulated in this *Review* as a function of date of publication of the *Review*. A full error bar indicates the quoted error; a thick-lined portion indicates the same but without the "scale factor."

# ACCELERATION: RF CAVITIES





# JET PRODUCTION

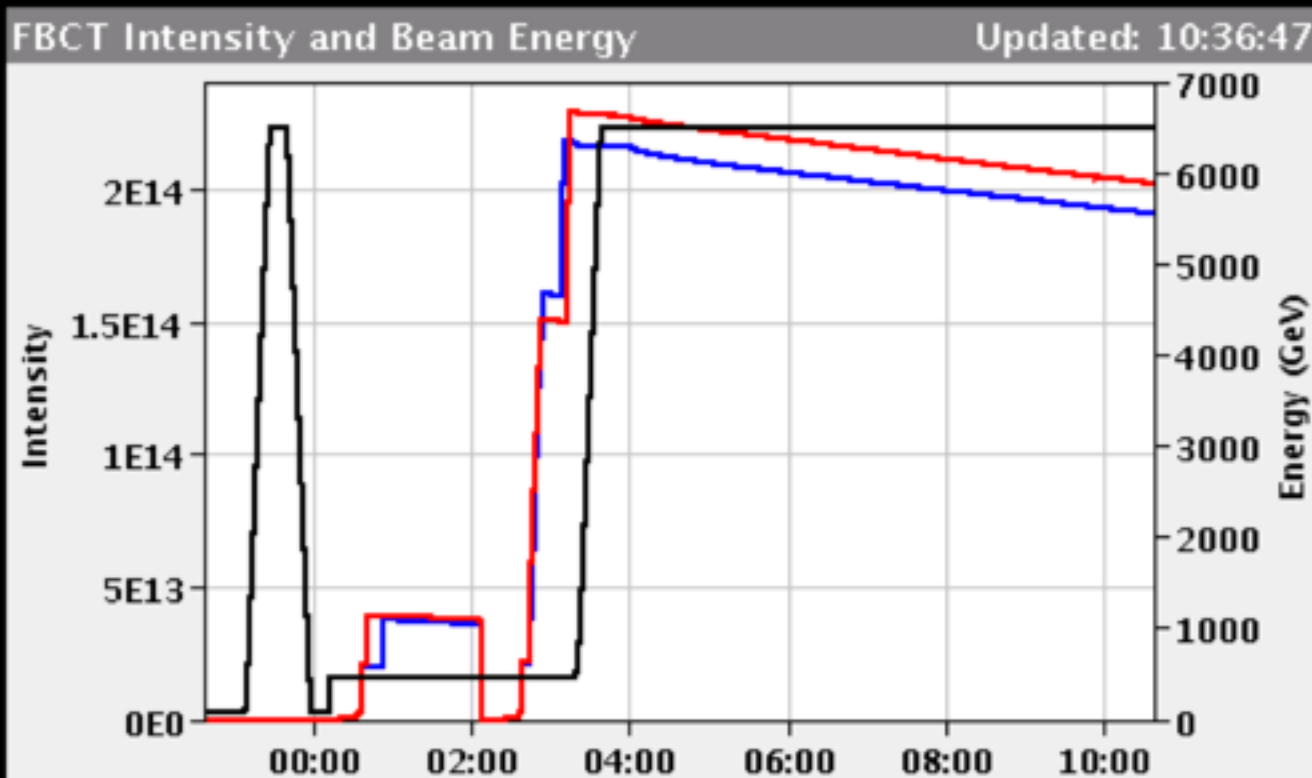
https://www.youtube.com/watch?v=wwmErmI8t6s

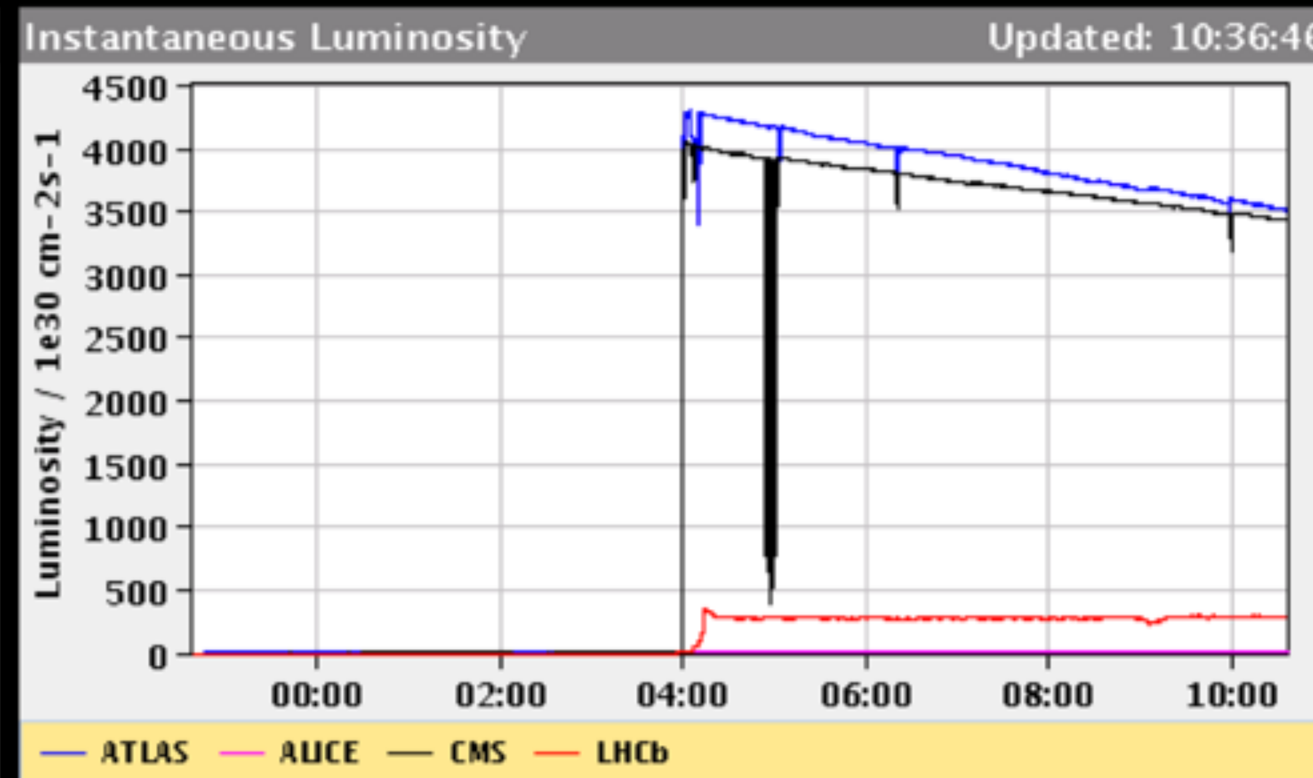
LHC Page1 | Fill: 4522 | E: 6499 GeV | t(SB): 06:27:41 | 21-10-15 10:36:47

# PROTON PHYSICS: STABLE BEAMS

| Energy: | 6499 GeV | I(B1): | 1.84e+14 | I(B2): | 1.84e+14 |
|---|---|---|---|---|---|

Inst. Lumi [(ub.s)^-1] IP1: 3507.53 IP2: 5.35 IP5: 3435.88 IP8: 284.31



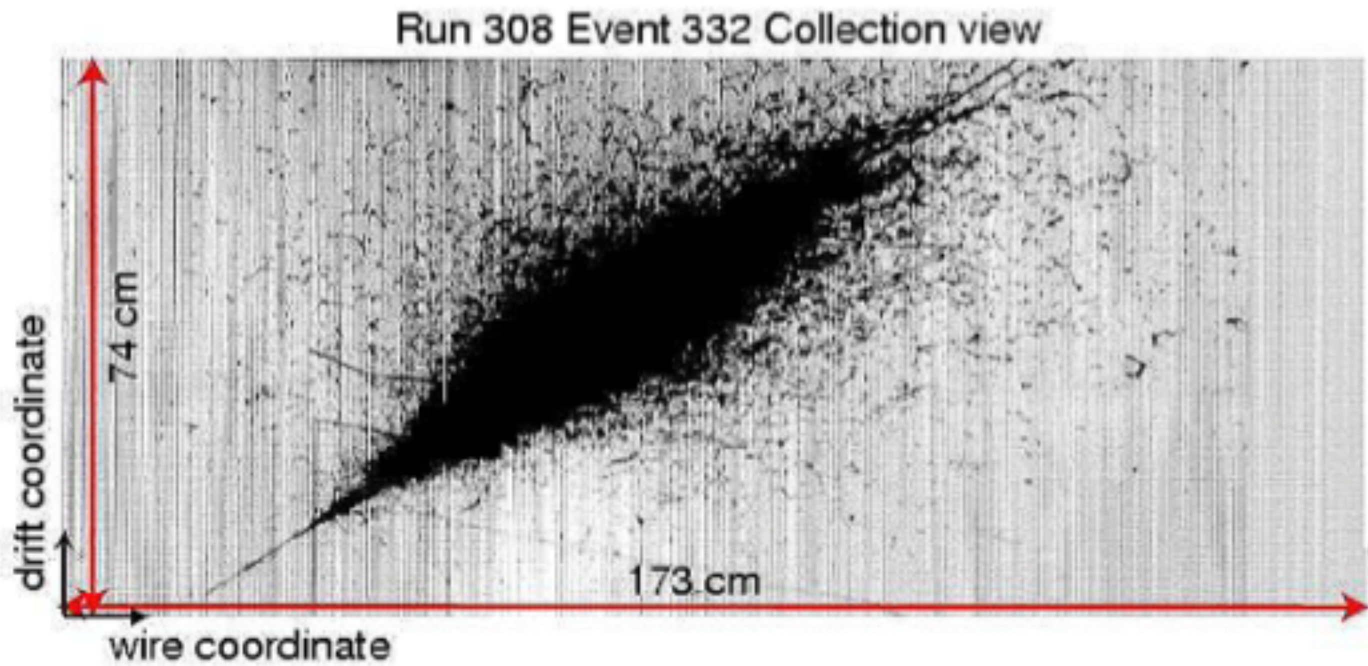




Comments (21-Oct-2015 10:01:42)

| BIS status and SMP flags | B1 | B2 |
|---|---|---|
| Link Status of Beam Permits | true | true |
| Global Beam Permit | true | true |
| Setup Beam | false | false |
| Beam Presence | true | true |
| Moveable Devices Allowed In | true | true |
| Stable Beams | true | true |

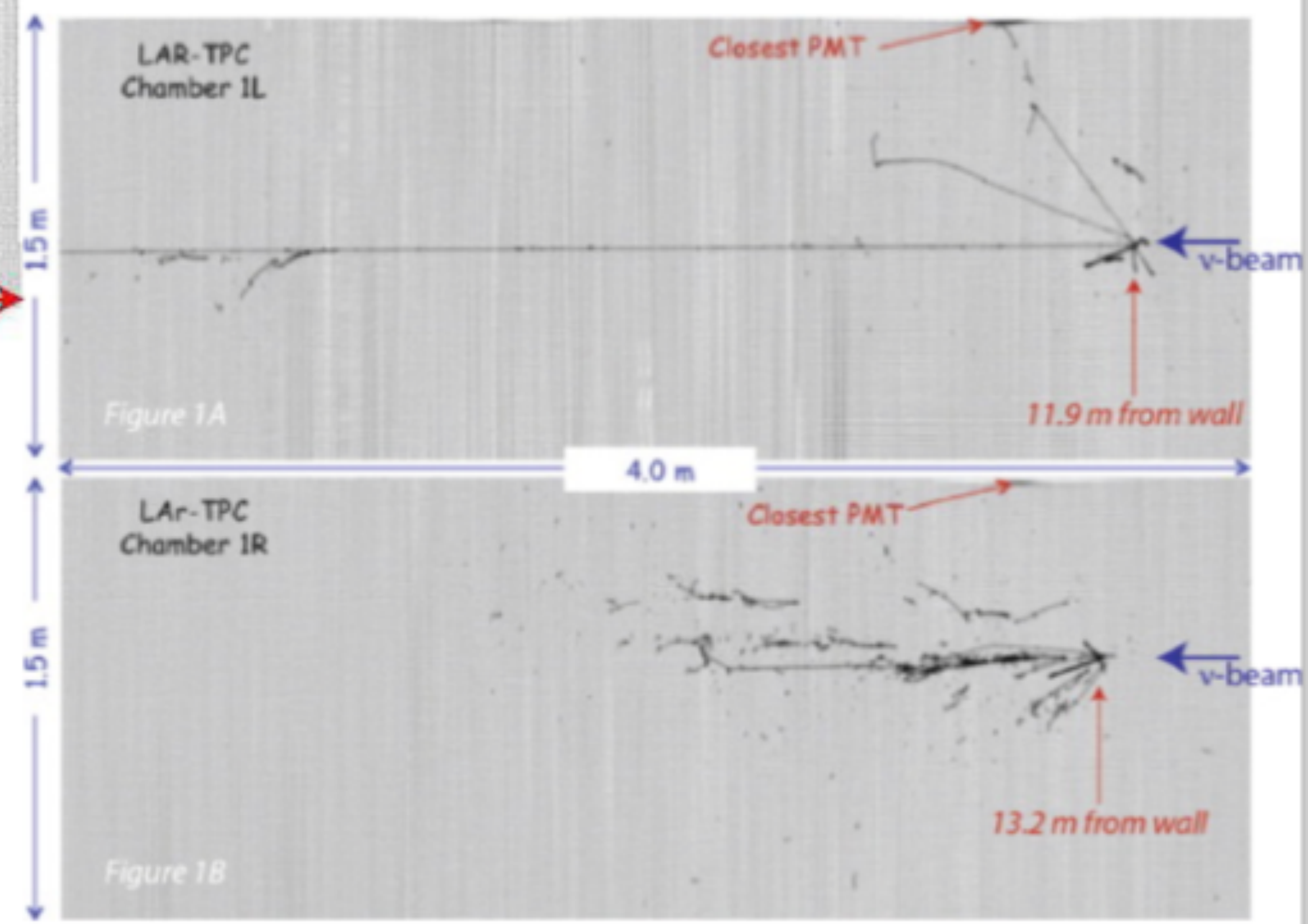
AFS: 25ns_1825b_1813_1495_1536_144bpi16inj_sp

PM Status B1 ENABLED PM Status B2 ENABLED

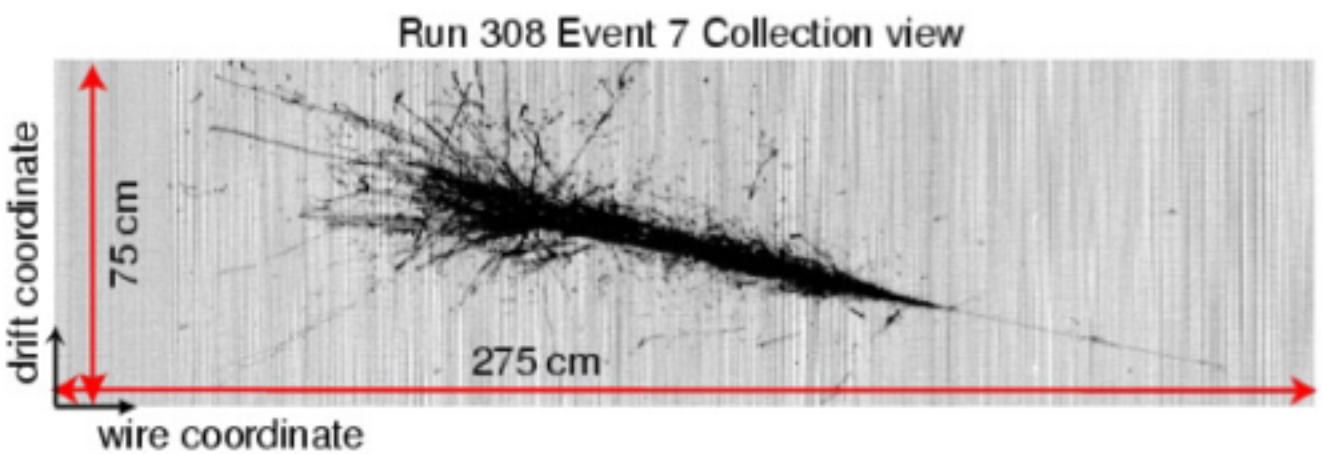



An **electromagnetic** shower

Tracks ionize liquid xenon. The free electrons drift to electrodes where time of arrival is measured

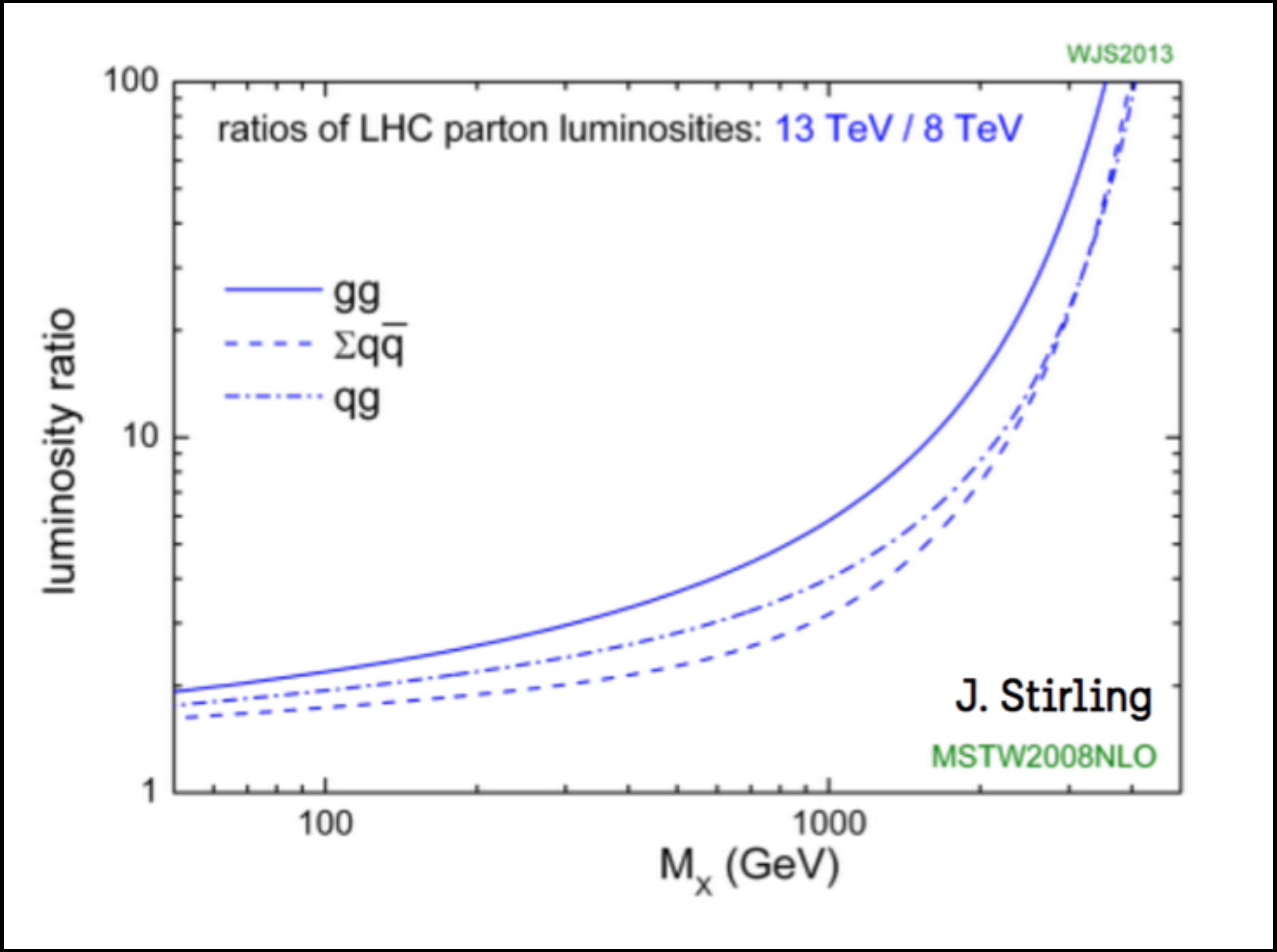


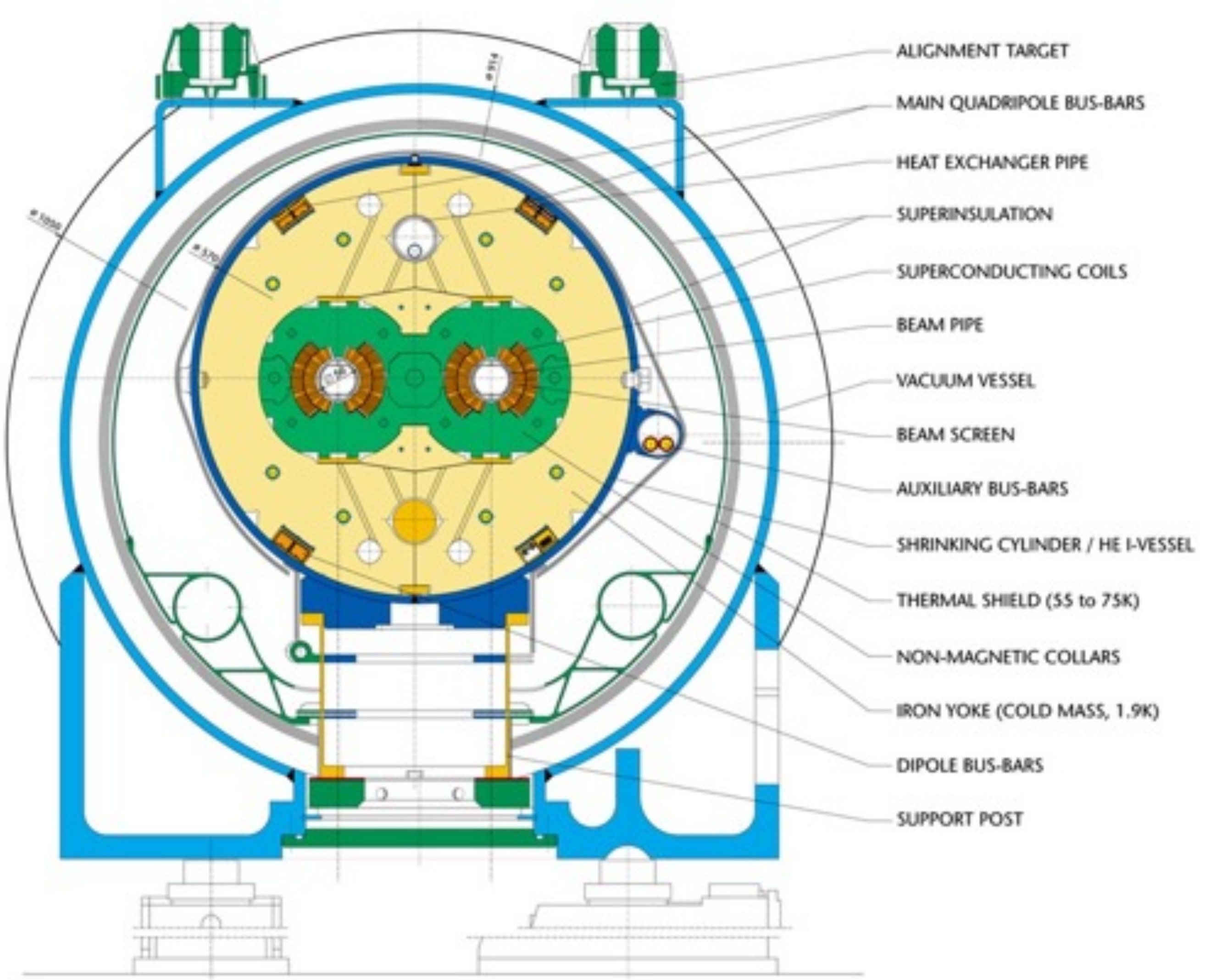

A **hadronic** shower

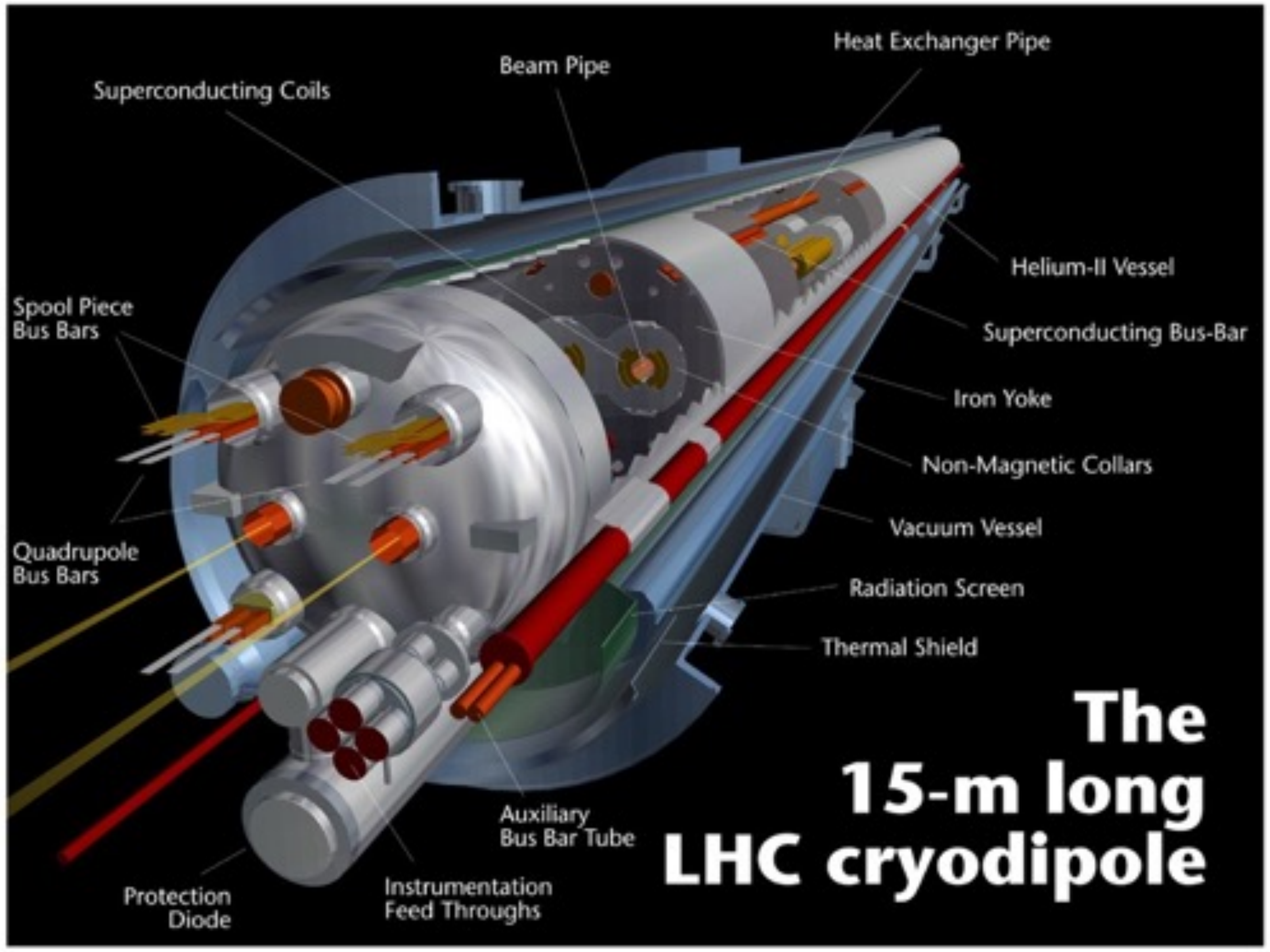



A **neutrino** interaction

# WHY IS COM ENERGY IMPORTANT?



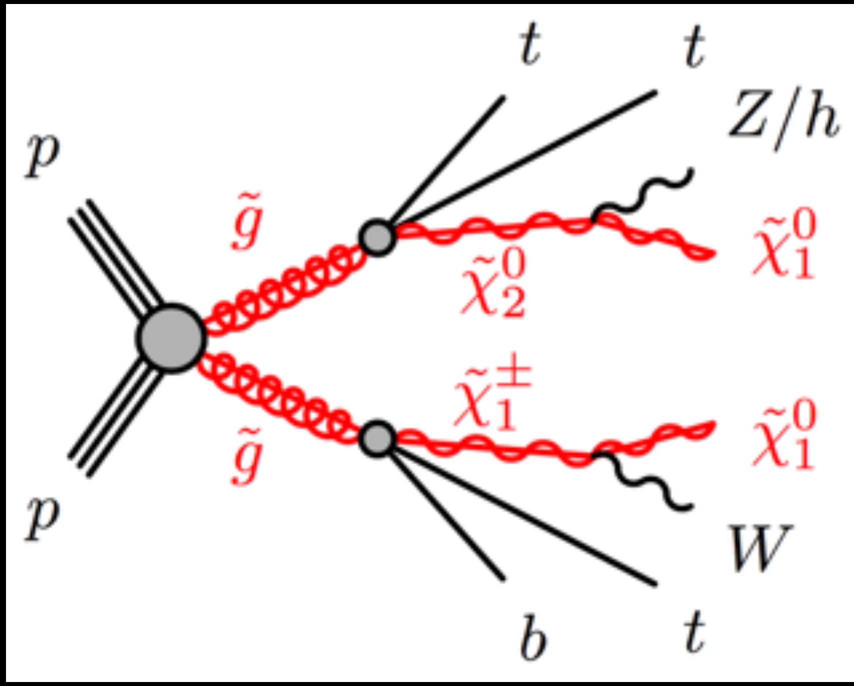

ALIGNMENT TARGET
MAIN QUADRIPOLE BUS-BARS
HEAT EXCHANGER PIPE
SUPERINSULATION
SUPERCONDUCTING COILS
BEAM PIPE
VACUUM VESSEL
BEAM SCREEN
AUXILIARY BUS-BARS
SHRINKING CYLINDER / HE I-VESSEL
THERMAL SHIELD (55 to 75K)
NON-MAGNETIC COLLARS
IRON YOKE (COLD MASS, 1.9K)
DIPOLE BUS-BARS
SUPPORT POST


Heat Exchanger Pipe
Beam Pipe
Superconducting Coils
Helium-II Vessel
Spool Piece
Bus Bars
Superconducting Bus-Bar
Iron Yoke
Non-Magnetic Collars
Vacuum Vessel
Quadrupole
Bus Bars
Radiation Screen
Thermal Shield
The
15-m long
LHC cryodipole
Auxiliary
Bus Bar Tube
Protection
Diode
Instrumentation
Feed Throughs

# MY WORK: ANALYSIS

- I look for new physics in final states with many "jets" (at least 7)
- Events with many jets are rare in the Standard Model (prob. 1 jet ~ 0.1)
- We design selection cuts to reduce background from the SM and enrich signal

Example model

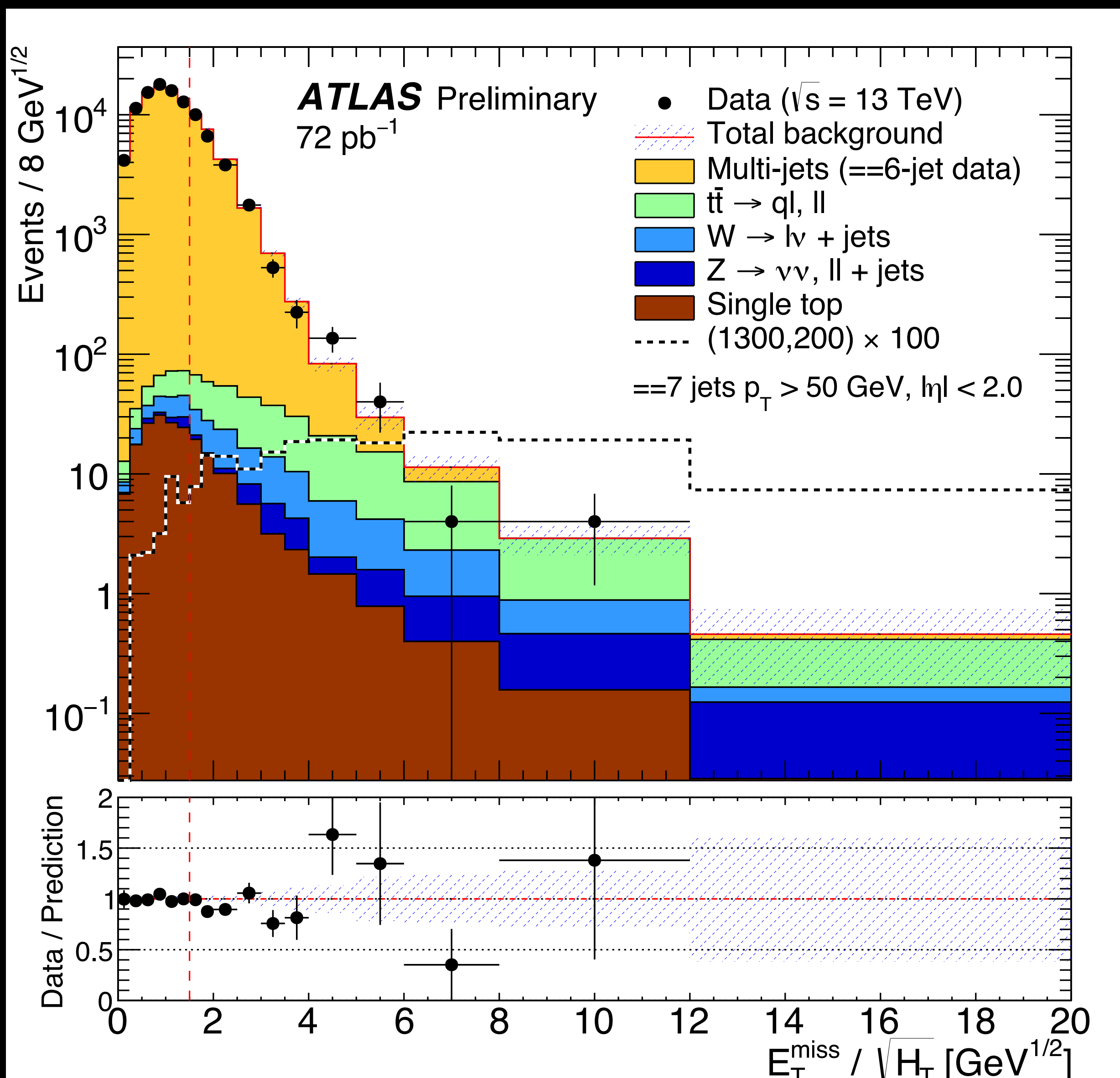



- $t$-quarks can produce 2 jets
- $\tilde{\chi}_1^0$ escape detection!
- How do we search for particles that we can't detect?

# ANALYSIS SELECTION

- SM events won't have as much missing transverse energy (MET)
- Can cut out events with small MET to increase Signal/Background
- Can also make other "cuts", like requiring there is a b-quark inside a jet (leads to the jet being produced ~mm from the proton-proton collision point)

# MISSING TRANSVERSE ENERGY

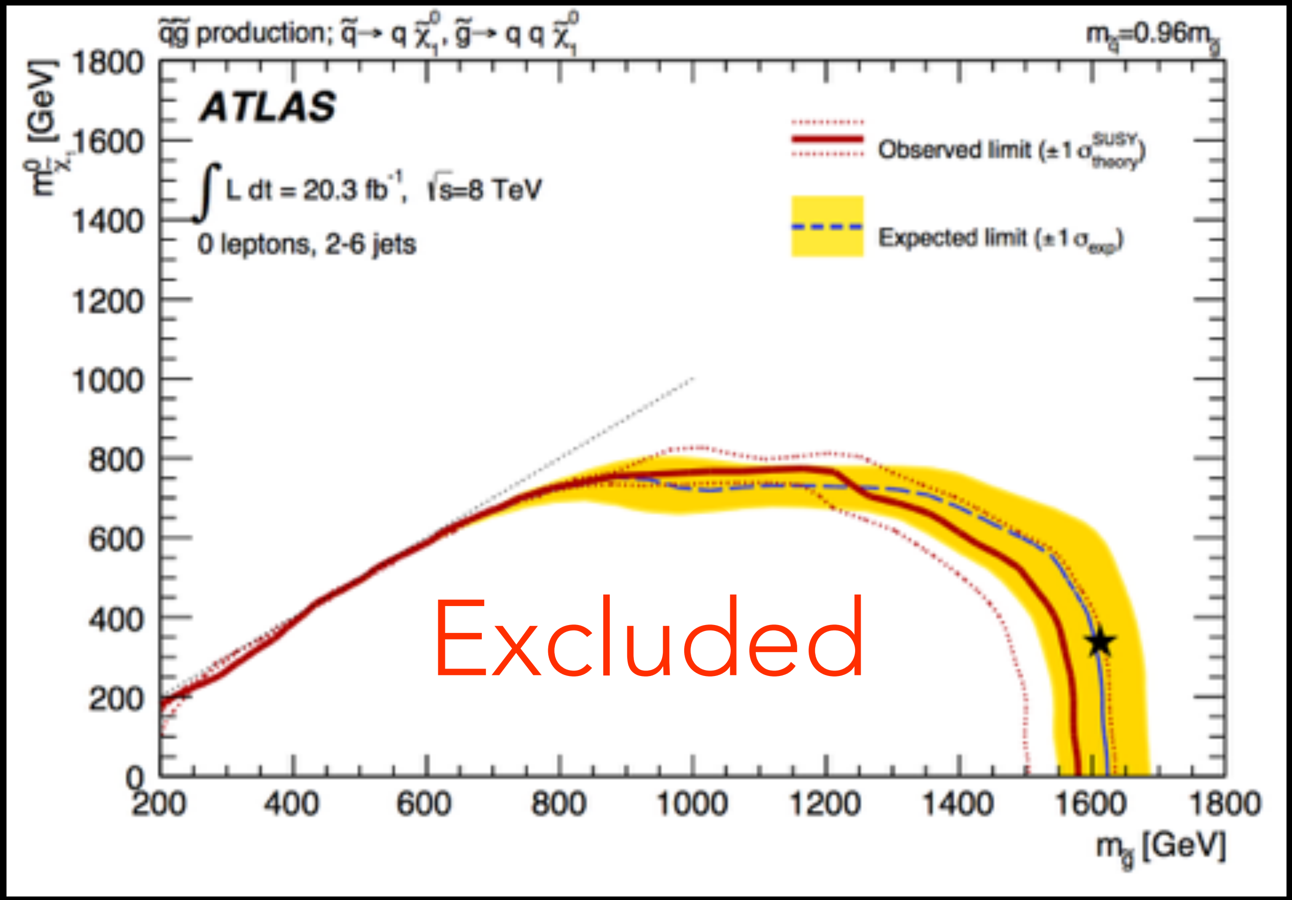



July 2015
ATL-PHYS-PUB-2015-030

- Very small amount of data represented in this figure
- Colours: Standard Model background
- Black dots: 13 TeV data
- Any excess in data/SM indicates new physics!

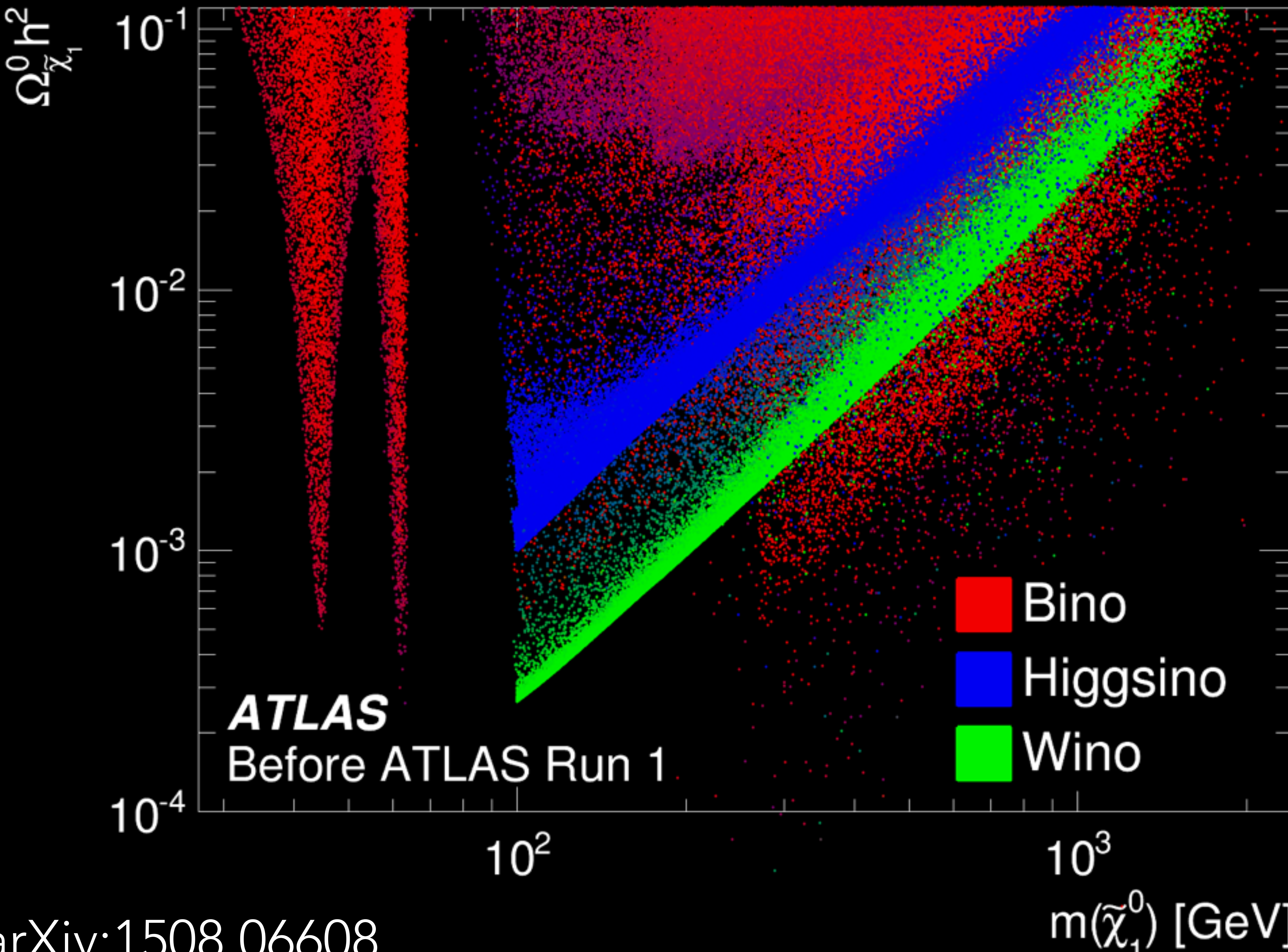
# SUMMARY OF RUN-1 RESULTS

- During run-1 of the LHC, no SUSY signals were found
- (Run-1 2010 — 2012)
- Limits on models are set by the null-results
- Typically, models only vary 2 of the many SUSY parameters

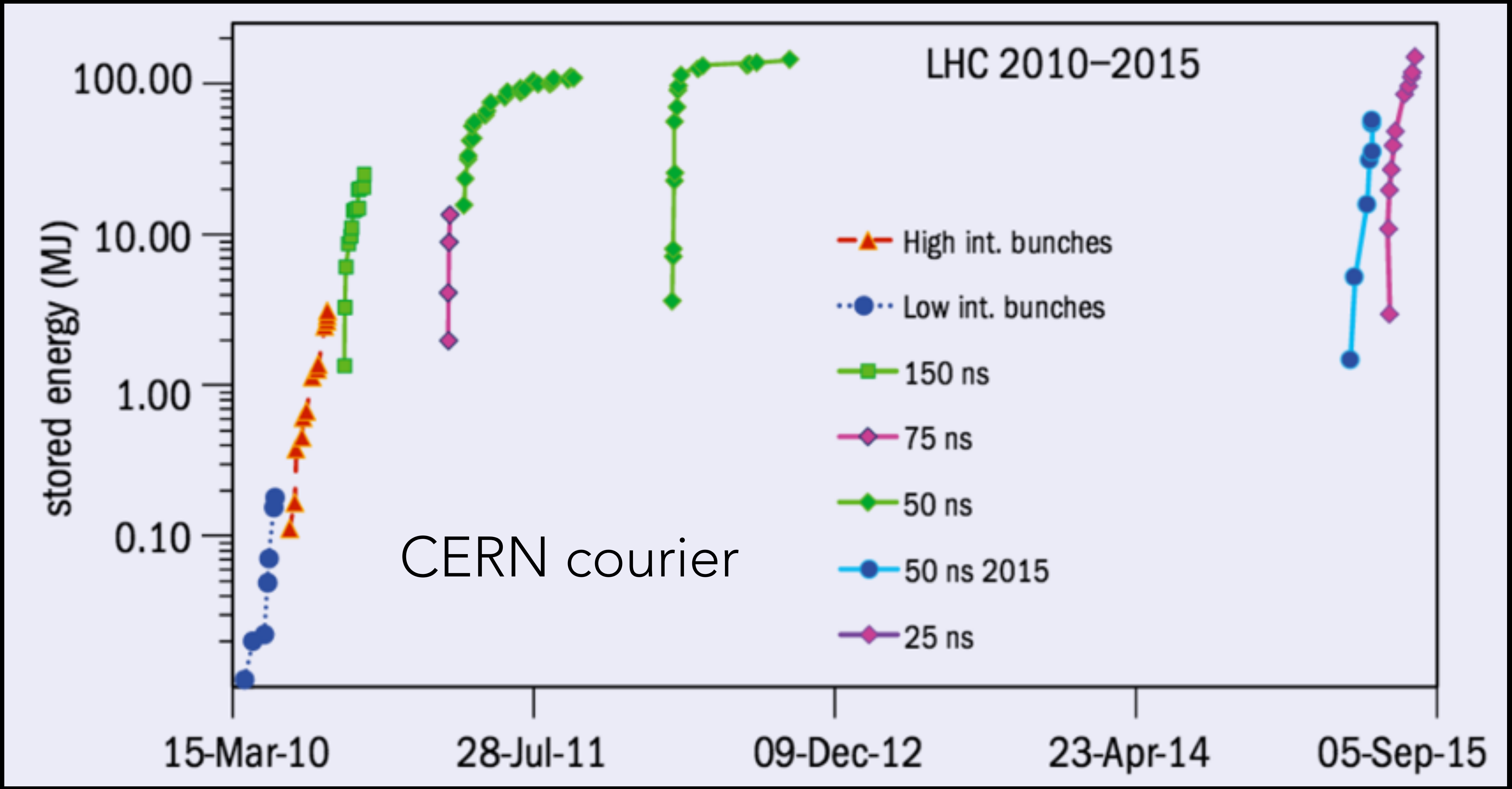


# SUMMARY OF RUN-1 RESULTS

- These limits are only accurate in the context of the particular model used
- Different models = different limits?
- Can we make a more general statement about what kinds of SUSY scenarios were excluded by ATLAS




arXiv:1508.06608




150 MJ of energy stored in the beam (new record)


- CERN summer student programme: http://home.cern/students-educators/summer-student-programme

  RAL summer studentships: http://www.ppd.stfc.ac.uk/ppd/students/38521.aspx